Gemini Instrument Feasibility Studies

Study Review for the

Gemini Multi-Object eXtra-wide-band Spectrograph (GMOX)

Gemini HQ - Hilo

24 September 2015

Part 1.

PROJECT OVERVIEW

What Gemini needs?

STAC Principles for Gemini RFP – GEN4#3:

1. **workhorse facility instrument**
2. **synergies with new capabilities (e.g. LSST, JWST, TMT, E-ELT, etc) , follow-up survey discoveries**
3. **highly efficient, wide-bandwidth moderate-resolution spectrograph**

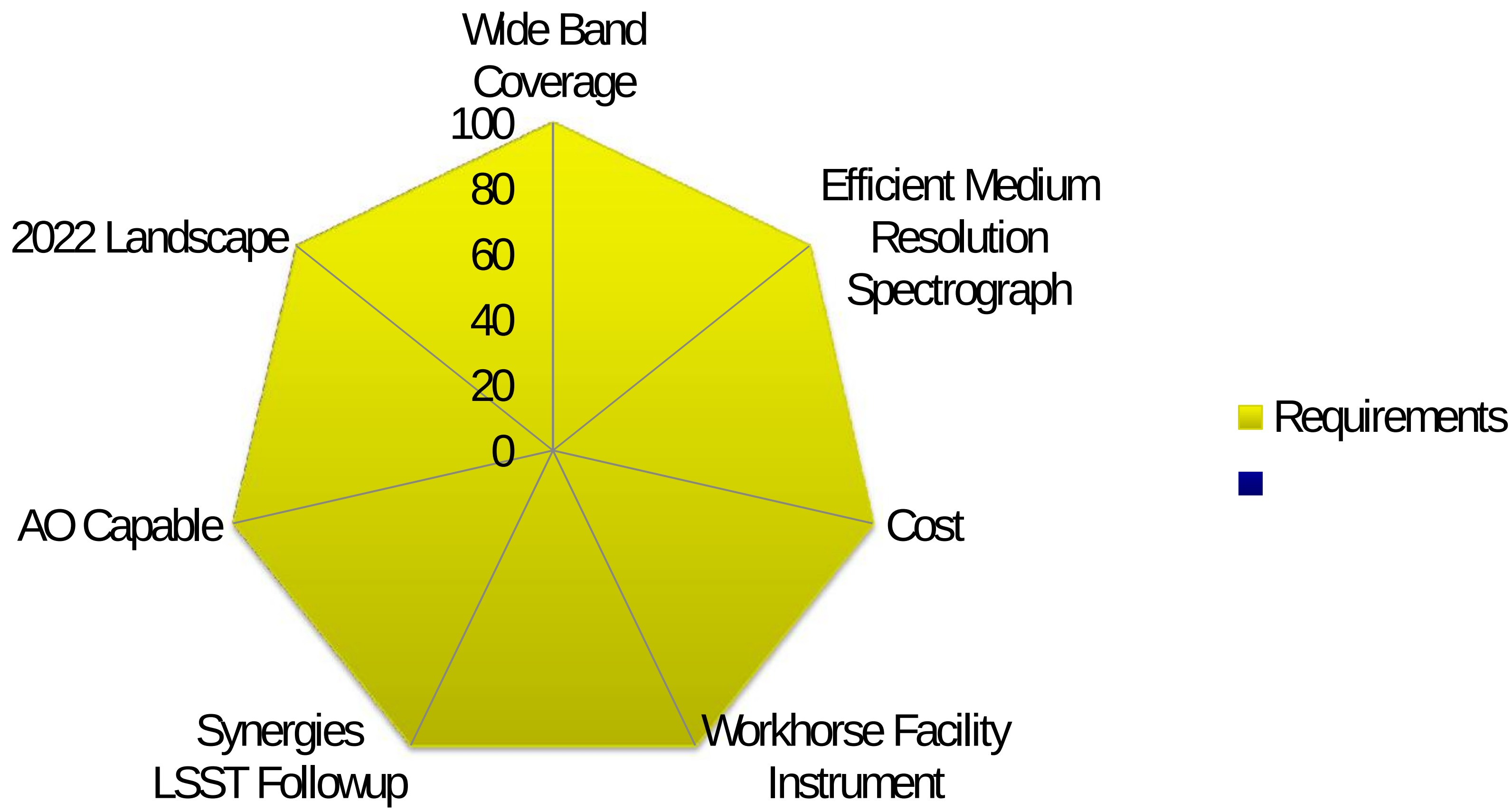
NRC Report "A strategy to Optimize the US Optical and IR System in the Era of the LSST"

1. **Rapidly configurable, high-throughput, moderate resolution spectrograph with broad wavelength coverage**
2. **Enhance coordination among the federal components of medium to large-aperture telescopes in the Southern Hemisphere, including Gemini-South.**

From Toronto Meeting: consider 2022 landscape

1. **Eleven 8-m class telescopes with more or less the same partners**
2. **Unique characteristics of Gemini telescopes**
3. ***"What can you do with Gemini that we cannot do better with ELT first light instruments?"***

Requirements Metric



What is GMOX

- **Wide-bandwith spectrograph: 0.32 – 2.4µm**
- **Moderate resolution: R ~ 5,000**
- **Multi-object spectrograph: 2.1M selectable slits over a few arcmin field.**
- **Seeing limited, GLAO & MCAO-fed**
  - We assume moderate AO correction (GLAO-level) will be available most of the time at Gemini in 2022.

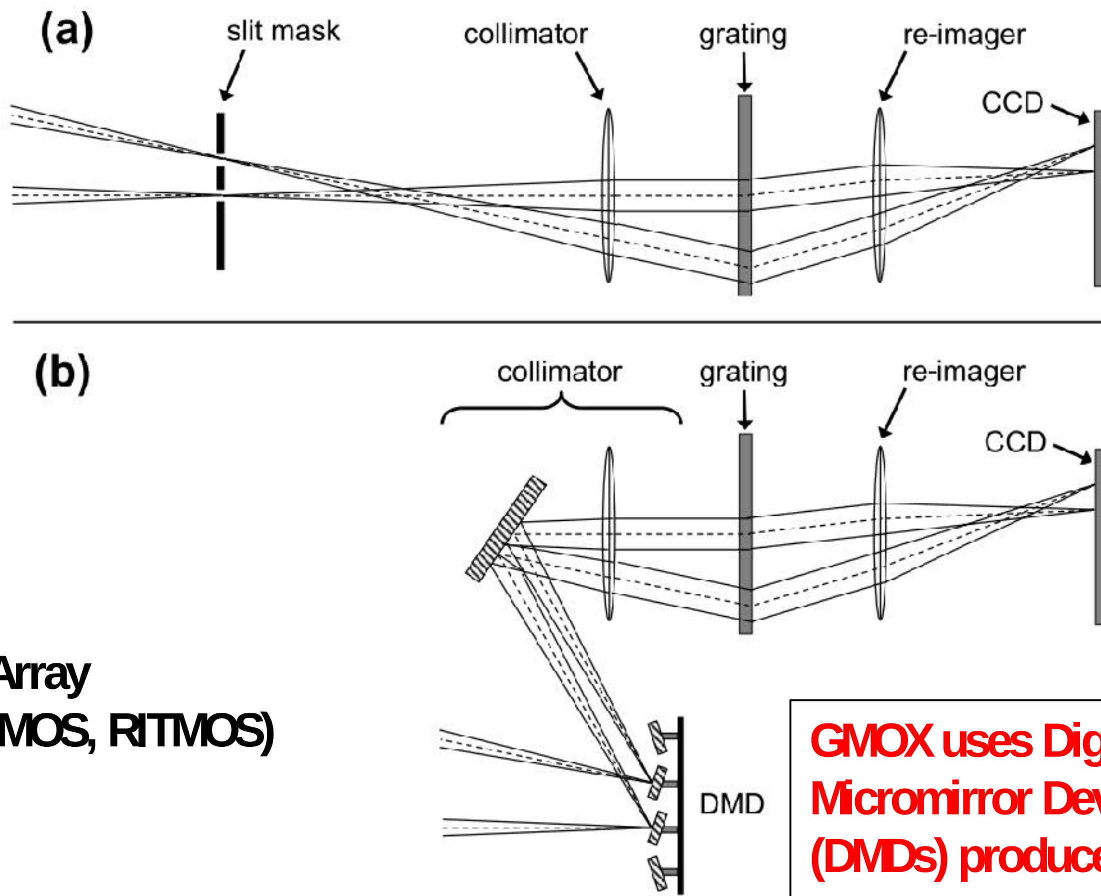
ADVANTAGES:

- **Exploits Gemini strength: unvignetted field of view, AO**
- **Versatile workhorse instrument**
- **Excellent follow-up capabilities: <u>wide-band spectroscopy</u> <u>and parallel imaging</u>.**
- **Uses existing, commercial MEMS technology**
- **Unparalleled, "next-generation" concept**

GMOX basic idea: MEMS Slits

Micro-Shutter-Array (e.g. JWST/NIRSpec)

Micro-Mirror-Array (e.g. KPNO/IRMOS, RITMOS)

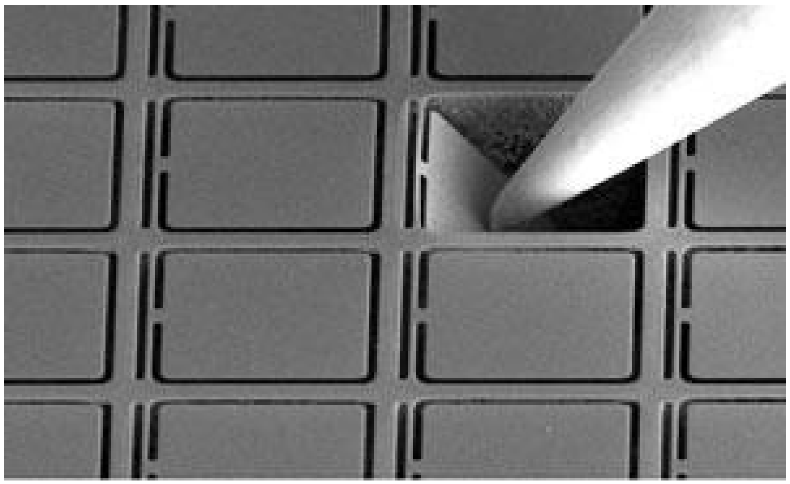


GMOX uses Digital Micromirror Devices (DMDs) produced by Texas Instruments

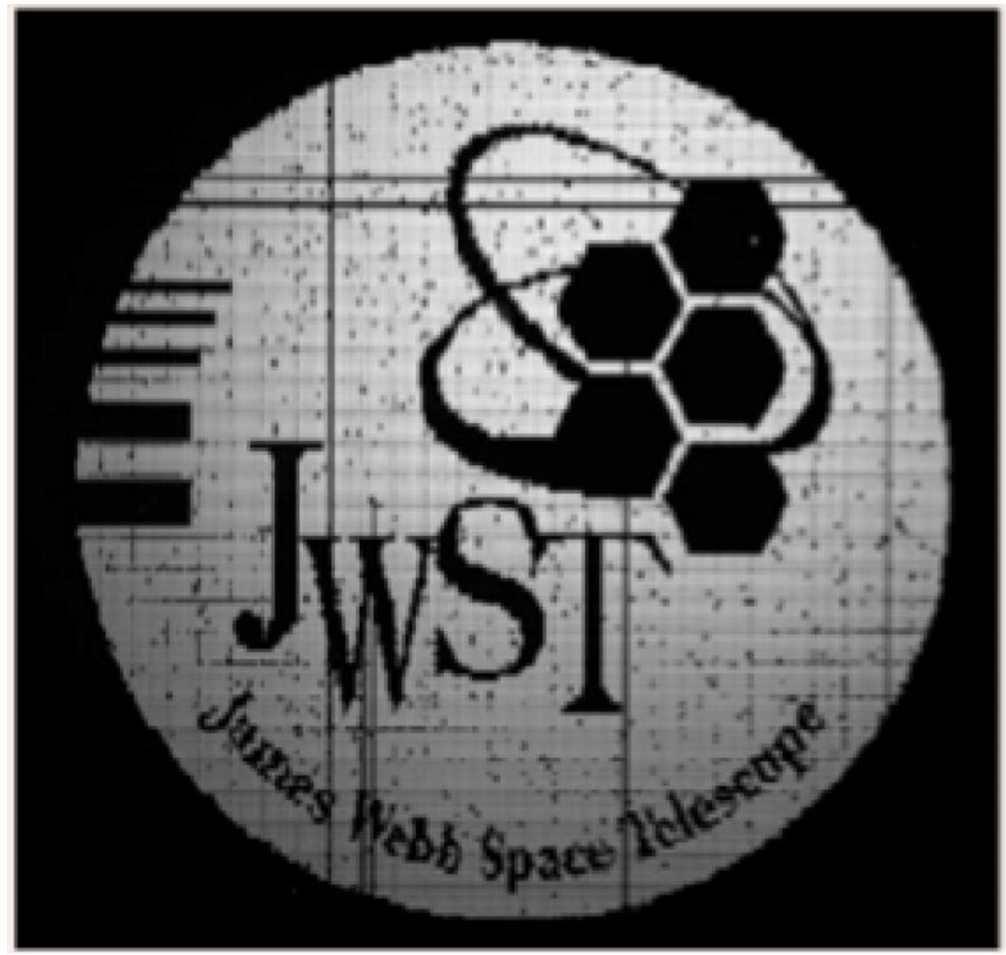
Meyer et al. SPIE 5492,200 (2004)

Micro-shutter arrays (MSA)

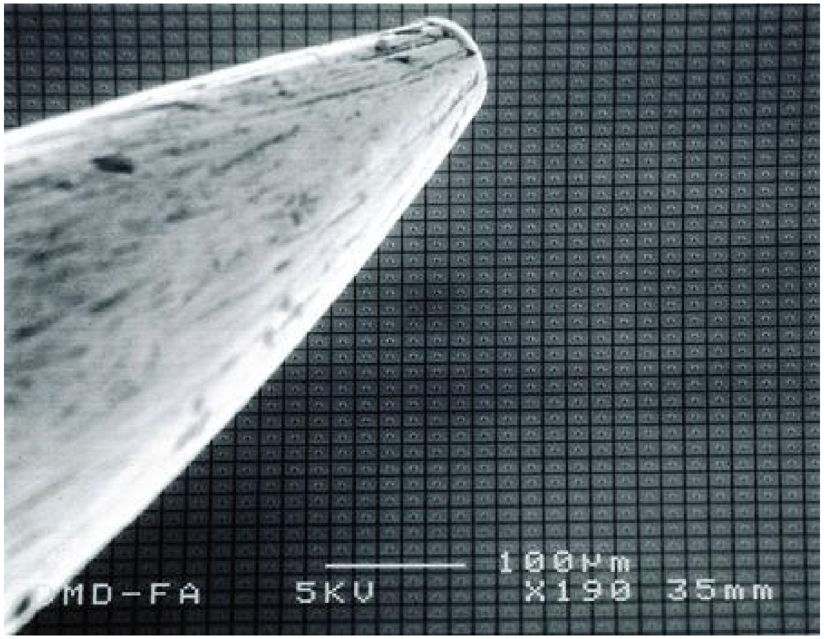
Developed by NASA/GSFC for NIRSPEC on JWST



- 171x365 elements
- 100x200 micron slits
- designed to operate at ~35K
- limited production for JWST



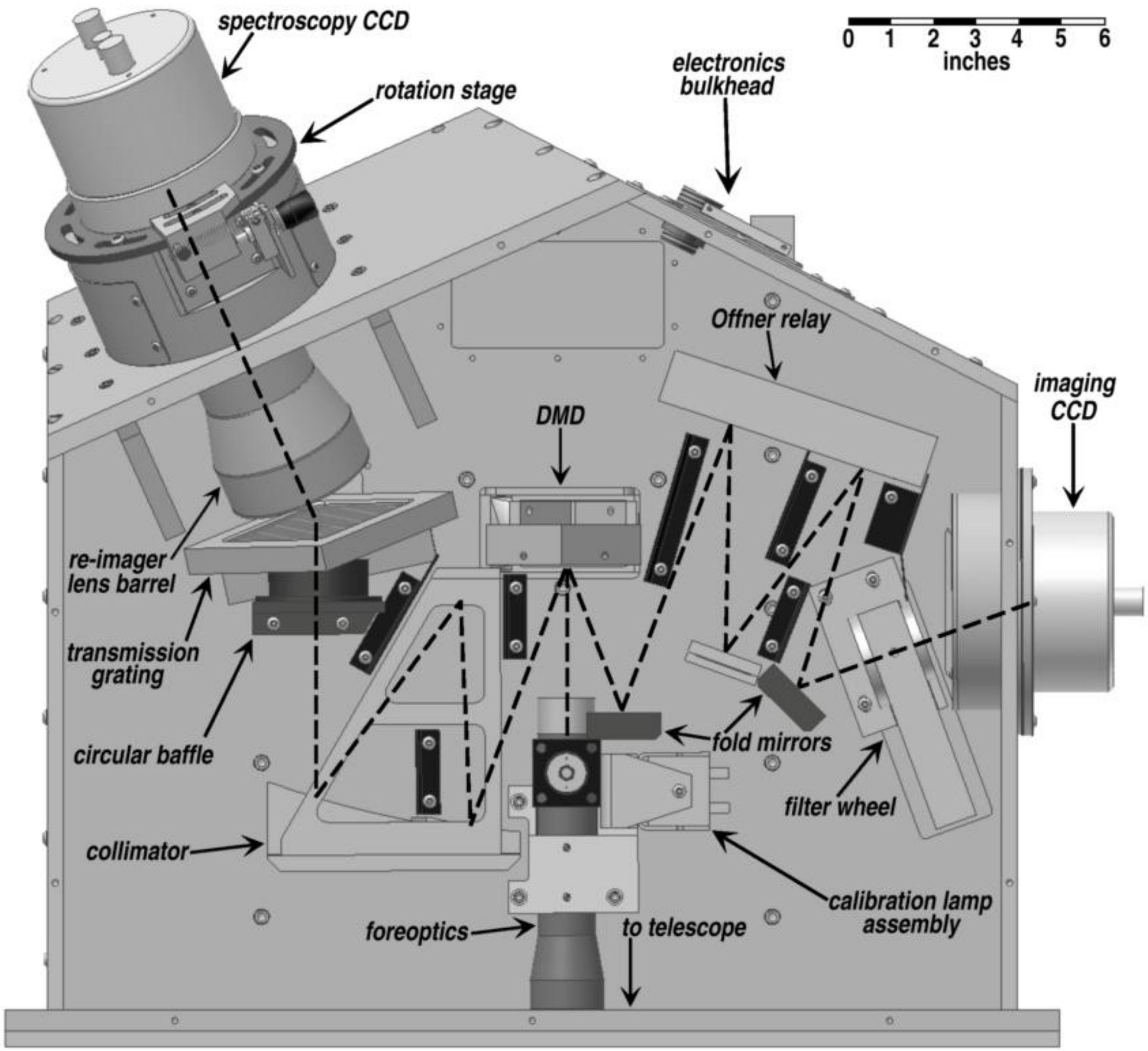
Digital Micromirror Devices



- 2048×1080 elements
- Square mirrors, up to 14µm side
- Designed for consumer market

DMDs come in different format;
Tens of million pieces have been produced

A GMOX precursor: RITMOS

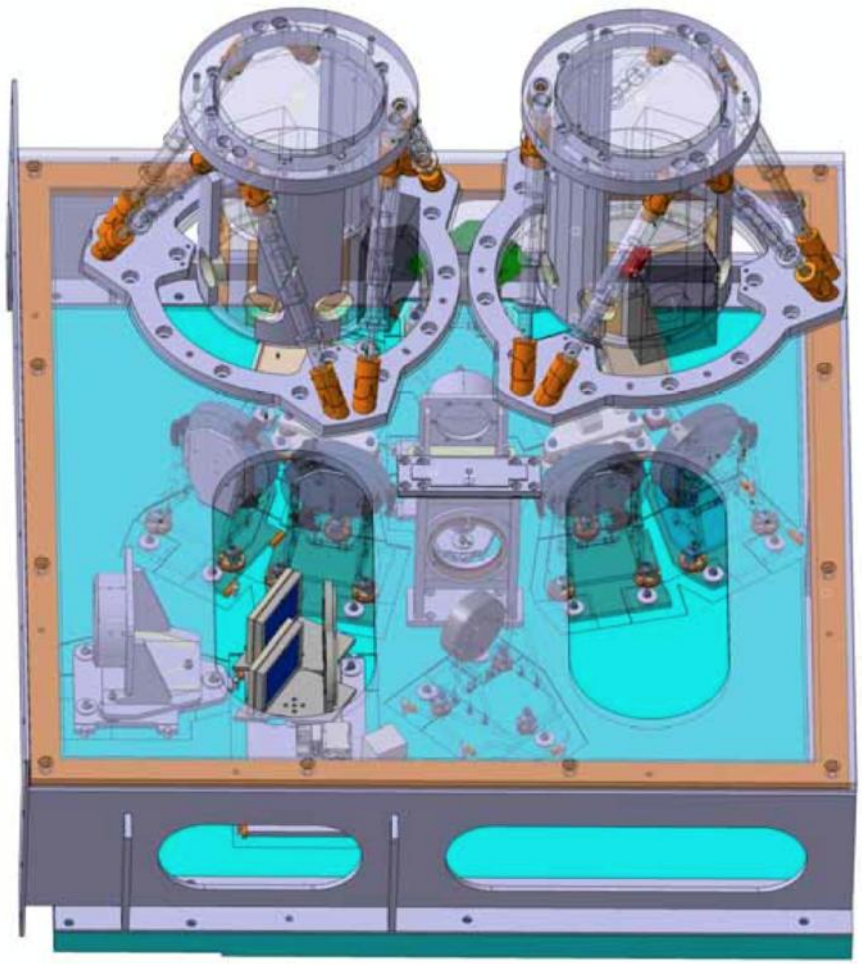


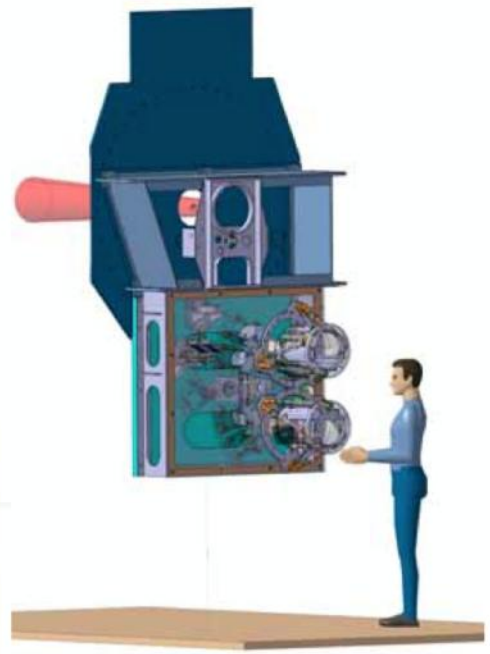
Meyer et al. SPIE 5492,200 (2004)

More under construction…

BATMAN: the opto-mechanics

♦Current design
(new box)



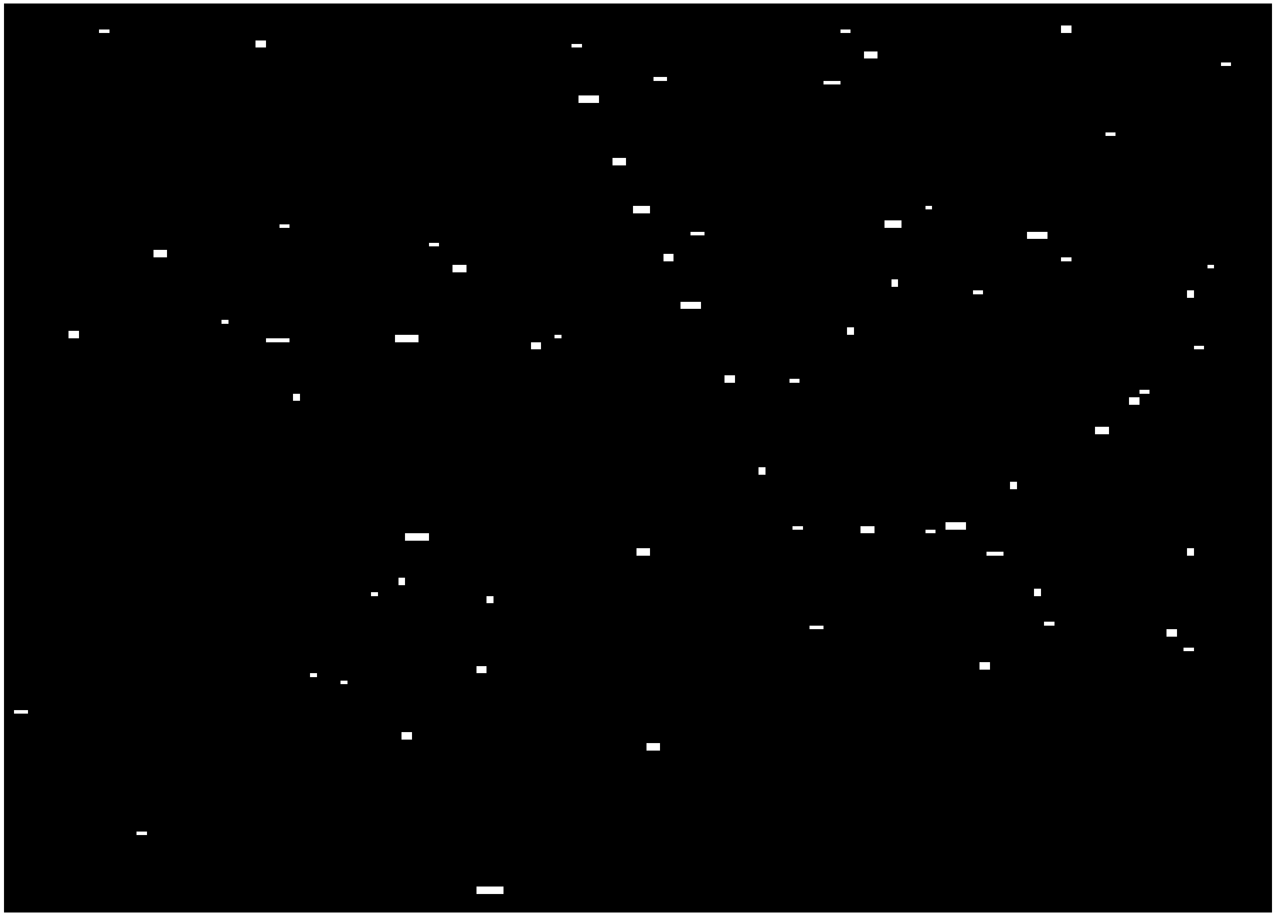


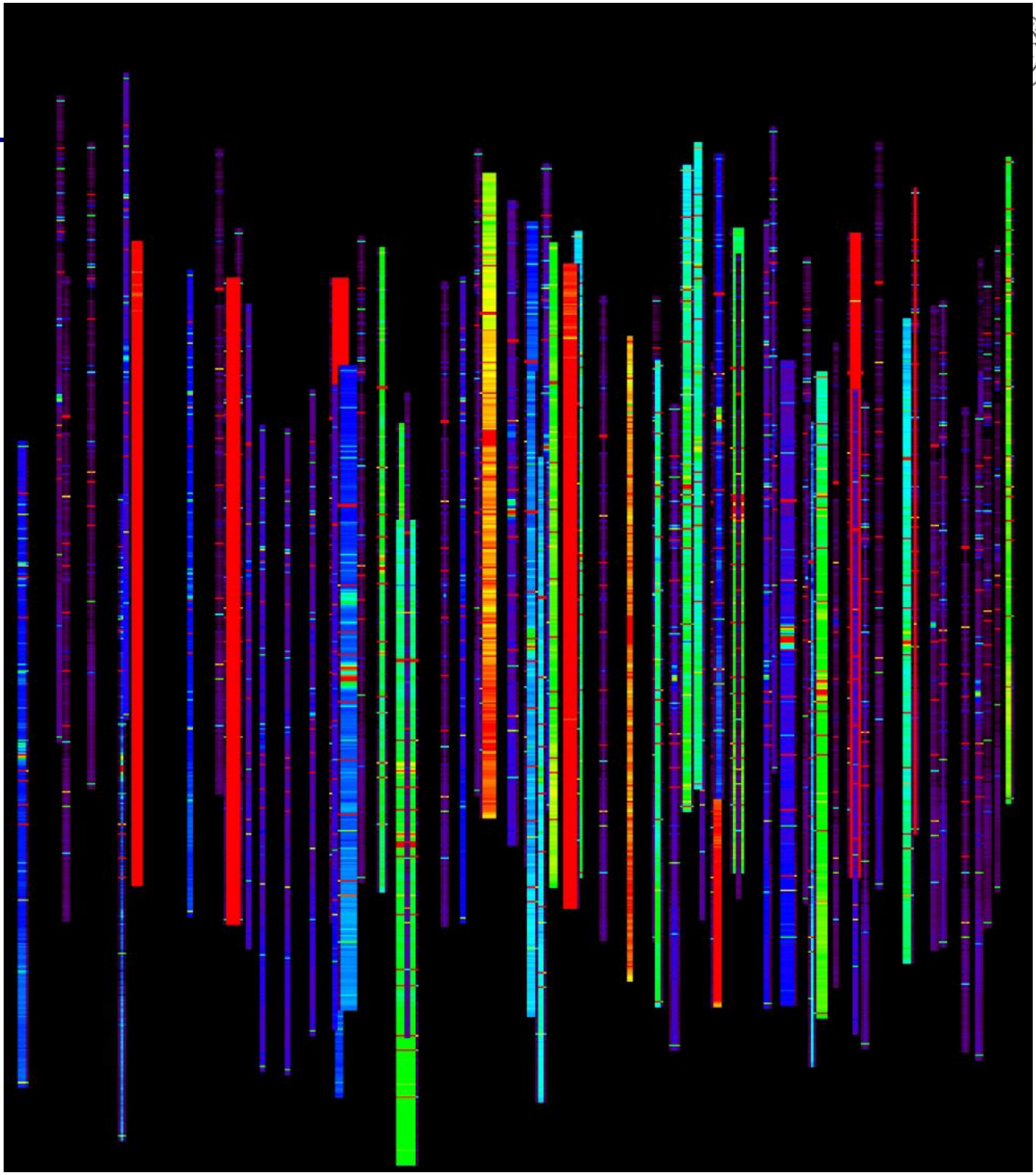
Videocon BATMAN, 18 June 2015

Field acquisition image

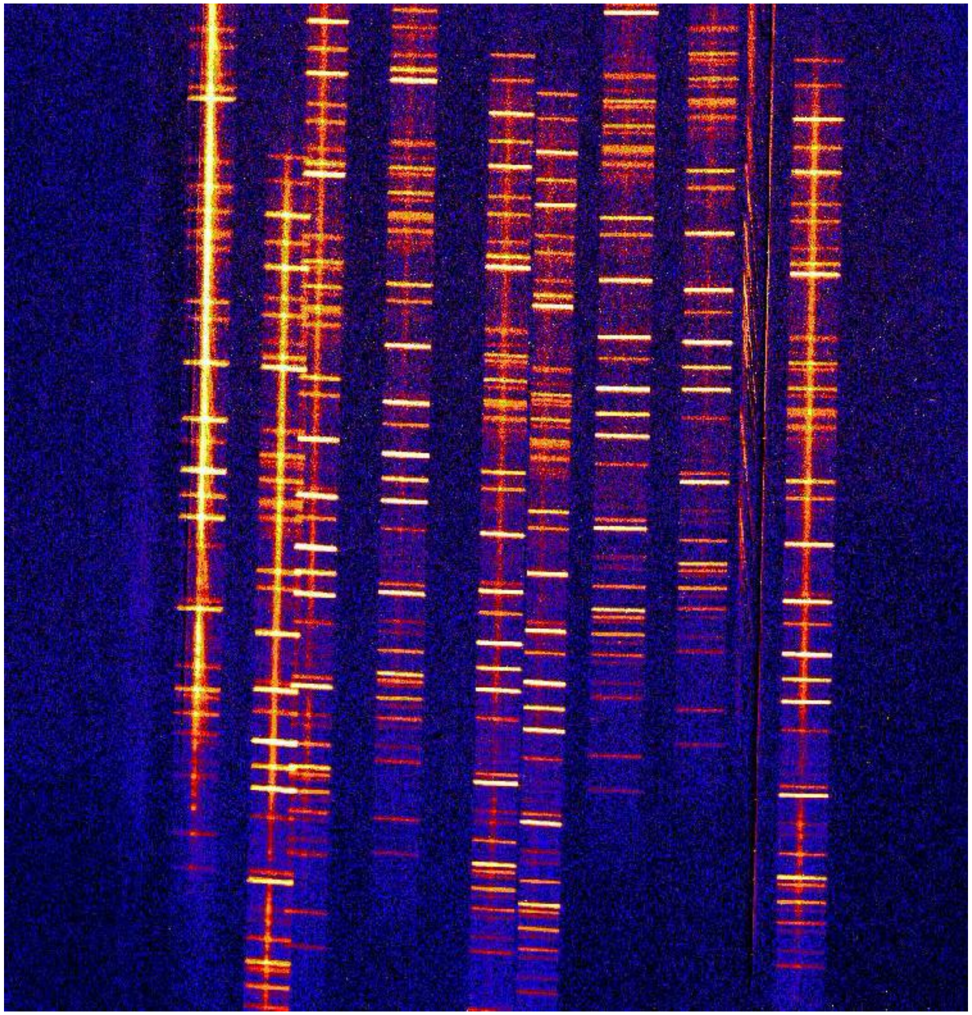
Target selection; imager as Slit monitor

Spectroscopic Channel

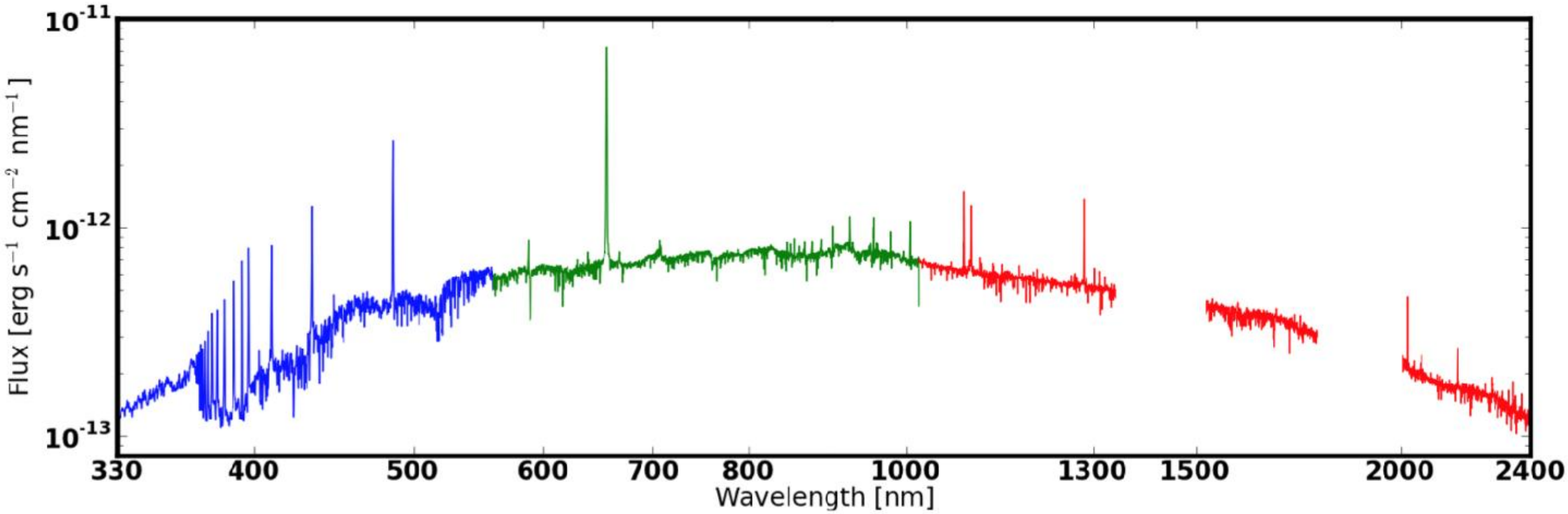




Real data (IRMOS @ KPNO 4m)



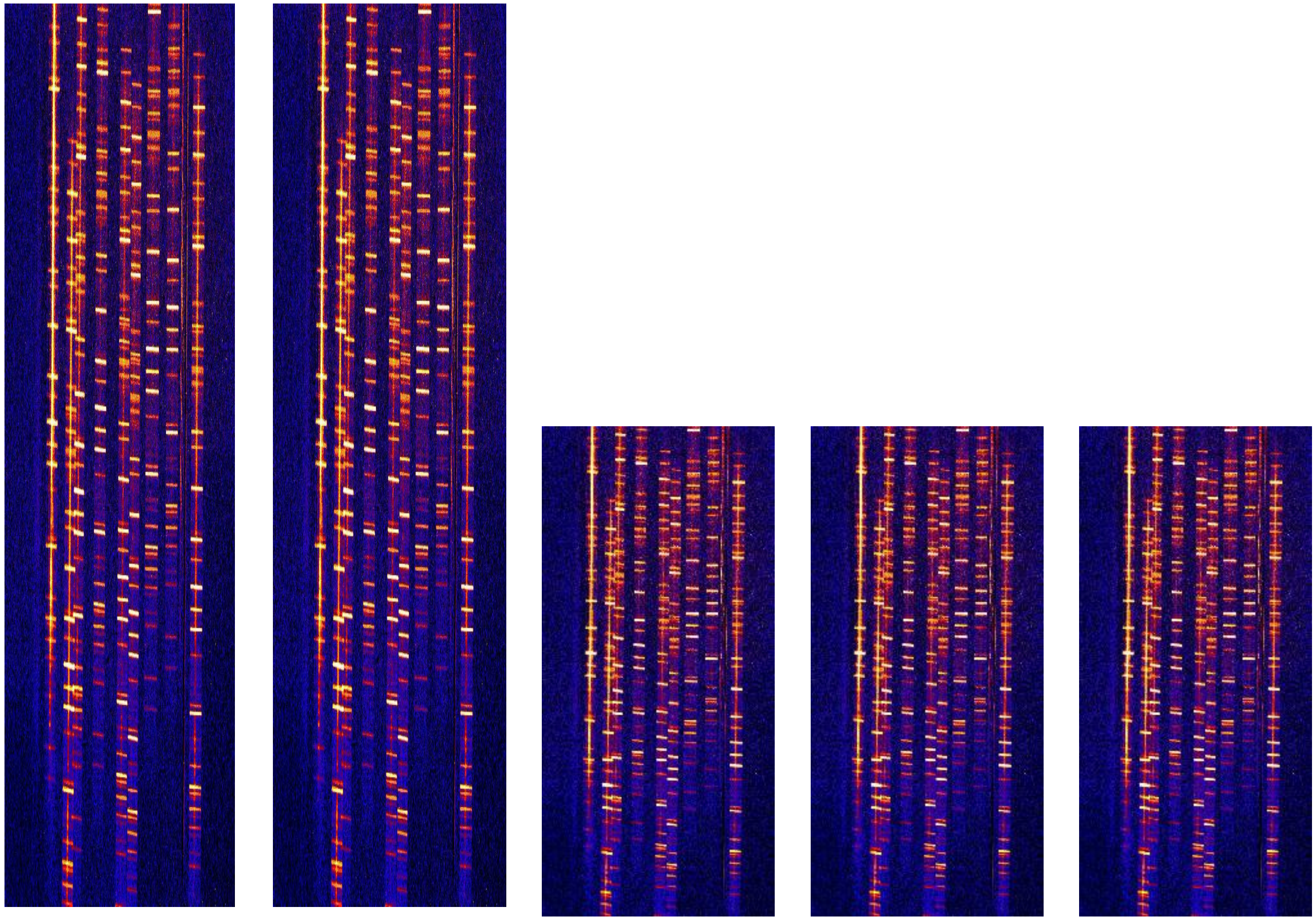
U – K spectral coverage



ESO/X-Shooter spectrum of accreting T-Tauri star

GMOX Data Products, single exposure

~400 spectra
U-to-K
R~1,500-10,000

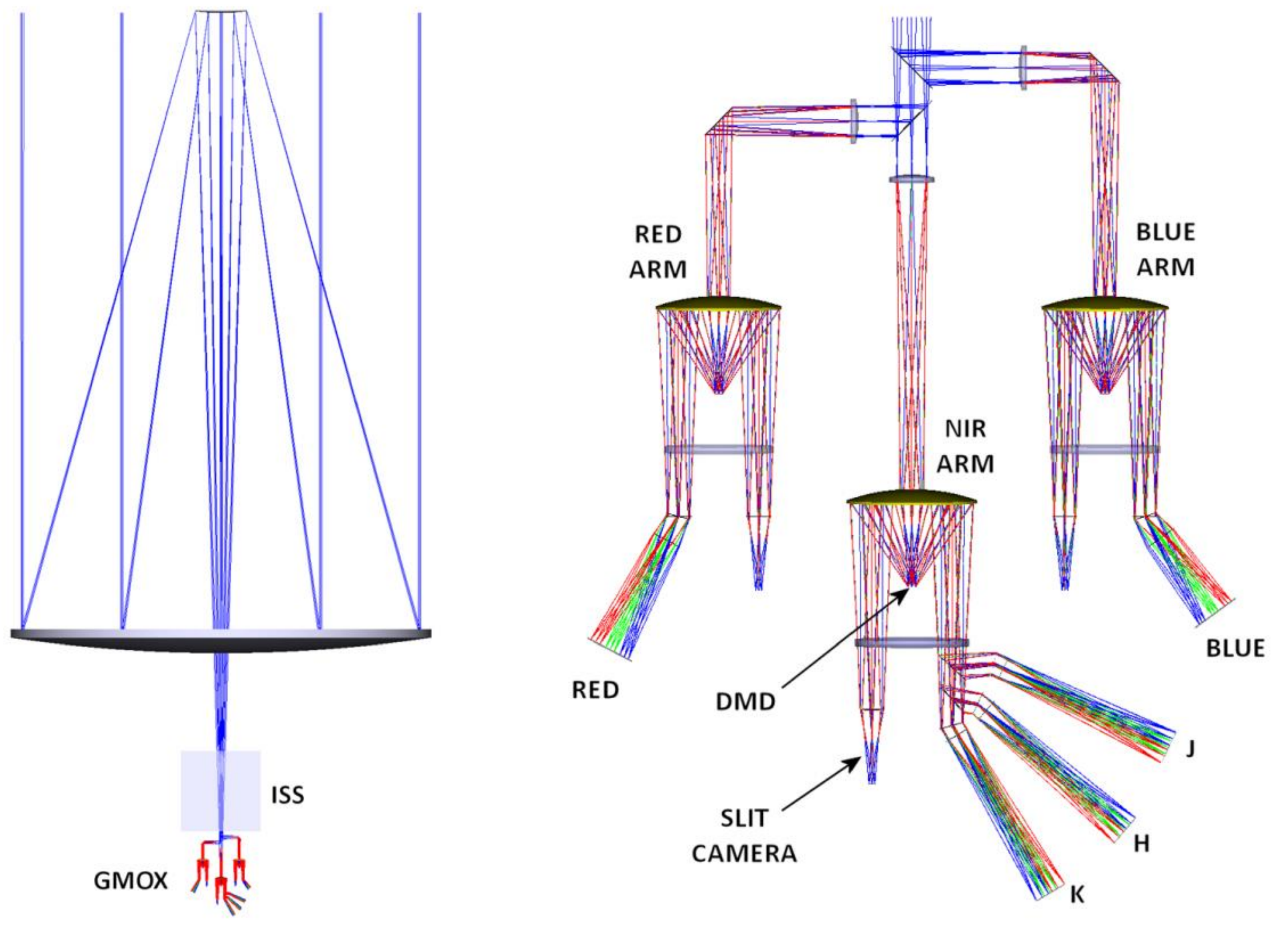


Blue Red YJ H K

180"x90"
images

Blue Red IR

GMOX Schematic Layout



Optical layouts of a preliminary concept for GMOX. (a) GMOX on Gemini, shown beneath an ISS-sized cube for scale. (b) Schematic of a 3-arm arrangement for GMOX.

GMOX baseline parameters

Nr. of Channels	**3 (Blue, Red, NIR arm)**

GMOX Arms/Channels	• Blue arm: 3,300 - 5,890Å
	• Red arm: 5,890 – 9,700Å
	• NIR arm:
	    • YJ-channel: 0.97 - 1.37μm (1.45μm dichroic)
	    • H-channel: 1.50 - 1.80μm (1.9μm dichroic)
	    • K-channel: 2.01 - 2.42μm

Field of view	171" x 90" @ f/16 (Gemini N+S+ALTAIR) 83" x 44" @ f/32 (GEMS)
DMD type	Cinema 2K, 2048 x 1080 mirrors 13.0μm side, 13.7μm center-to-center
Mirror scale	83.3 mas/mirror @ f/16 40.0 mas/mirror @ f/33.2
Nominal resolving power	R = 5,000

GMOX baseline parameters

Nominal slit-width & sampling	Blue: 0.41" (5 DMD mirrors) - 3 CCD pixels/slit Red: 0.33" (4 DMD mirrors) - 3 CCD pixels/slit NIR: 0.25" (3 DMD mirrors) - 2.75 FPA pixels/slit
Detectors	Blue, Red: CCD E2V290-99, 9,216 x 9,232 pixels (baseline) or CCD STA1600, 10,560 x 10,560 pixels NIR: 3 FPAs, model HI4RG, 4,096x 4,096 pixels
Nr. of spectra	~ 400, assuming 5 mirrors/target
Acquision + Slit-viewing + Tip-tilt control camera	Present on • Blue Channel • Red Channel • IR Channel

Observing with GMOX

CAMERA

- **Target acquisition**
  - Point and click (transients, ToO, LSST follow-up…)
  - from source catalog
- **Slit viewer/monitor during integration**
- **Tip-tilt on source (also in the IR)**
- **Parallel deep imaging**

SPECTROGRAPH

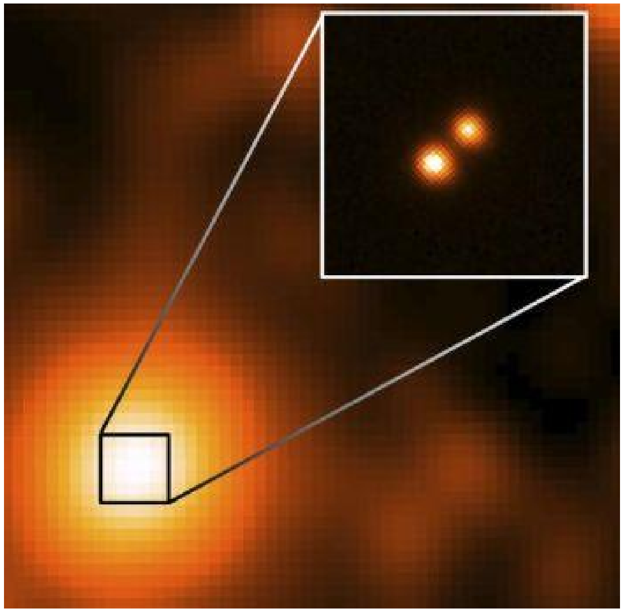
- **Perfect alignment of narrow slit on target**
- **Optimal slit size per target**
- **Multi-object spectroscopy**
- **Optimal observing strategy (nod & Shuffle; dithered observations…)**
- **Hadamard Transform Spectroscopy (IFU over full field)**

GMOX Versatility

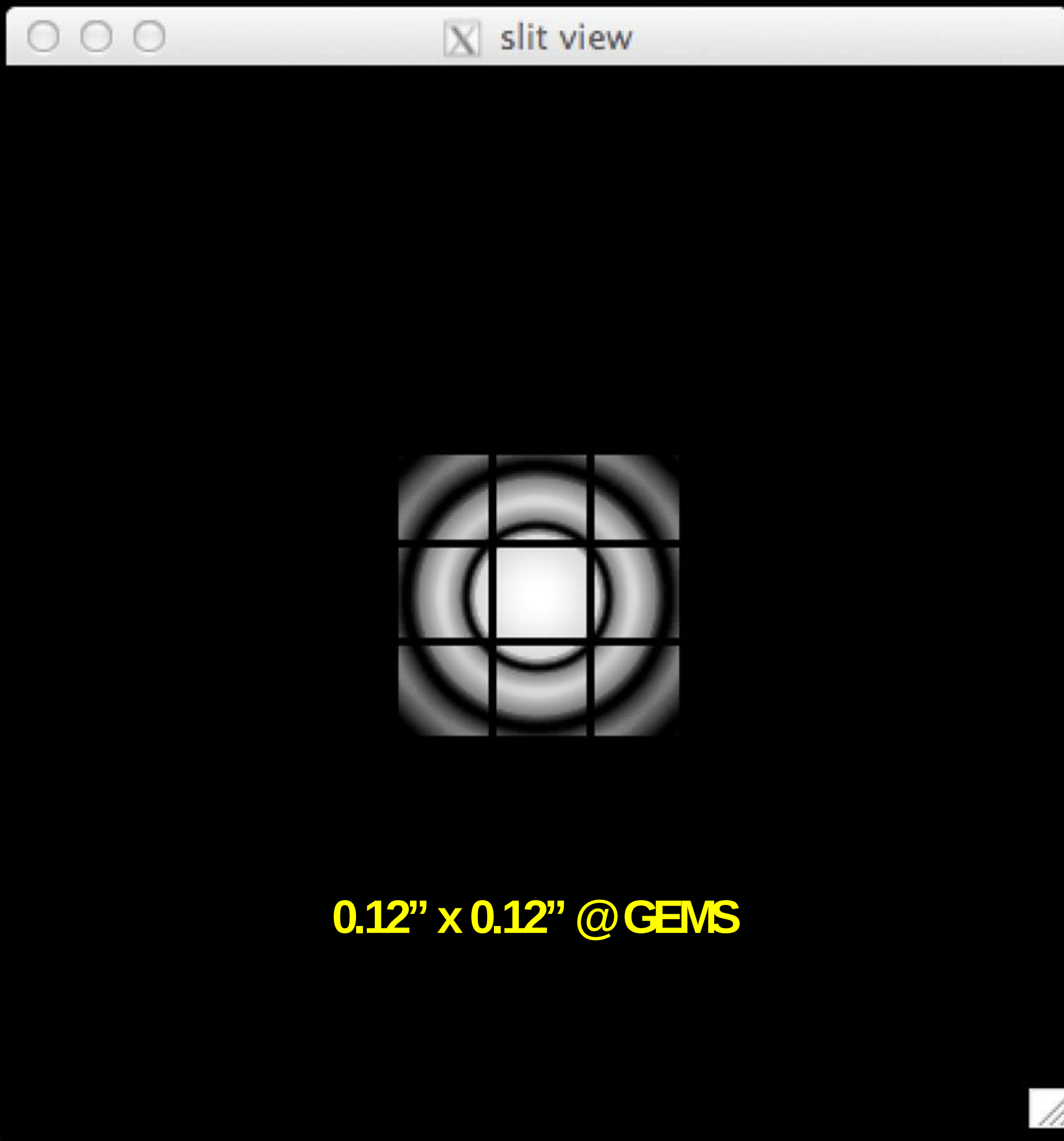
Slit width (arcsec)	Blue		Red		IR	
	R(l/Dl)	Pix/slit	R(l/Dl)	Pix/slit	R(l/Dl)	Pix/slit
0.083	22500	0.60	18000	0.75	13500	0.92
0.167	11250	1.20	9000	1.50	6750	1.83
0.250	7500	1.80	6000	2.25	**4500**	**2.75**
0.333	5625	2.40	**4500**	**3.00**	3375	3.67
0.417	**4500**	**3.00**	3600	3.75	3700	4.58
0.500	3750	3.60	3000	4.50	2250	5.50
0.583	3214	4.20	2571	5.25	1929	6.42
0.667	2812	4.80	2250	6.00	1687	7.33
0.750	2500	5.40	2000	6.75	1500	8.25
0.833	2250	6.00	1800	7.5	1350	9.17
0.917	2045	6.60	1636	8.25	1227	10.1
1.000	1875	7.20	1500	9.00	1125	11.0

J-band PSF on DMD @ GEMS

Wise J1049 @ GEMS

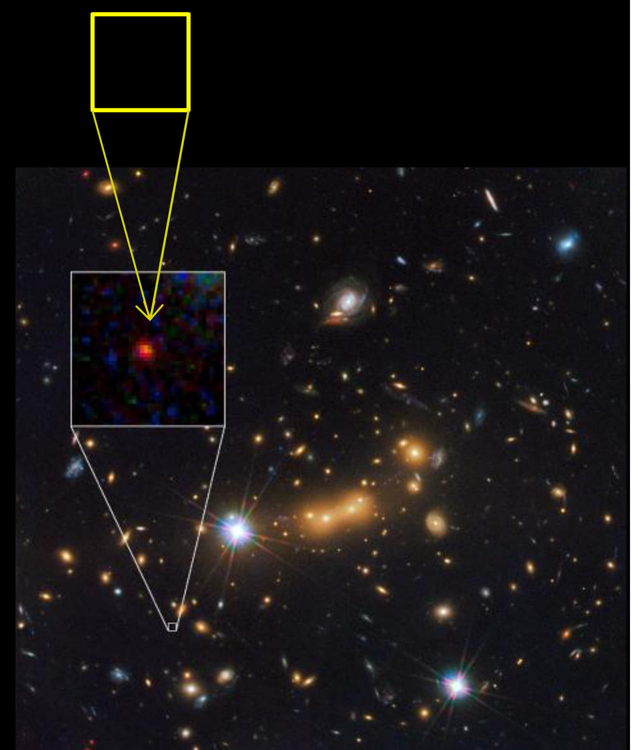


J-band PSF on DMD @ GEMS

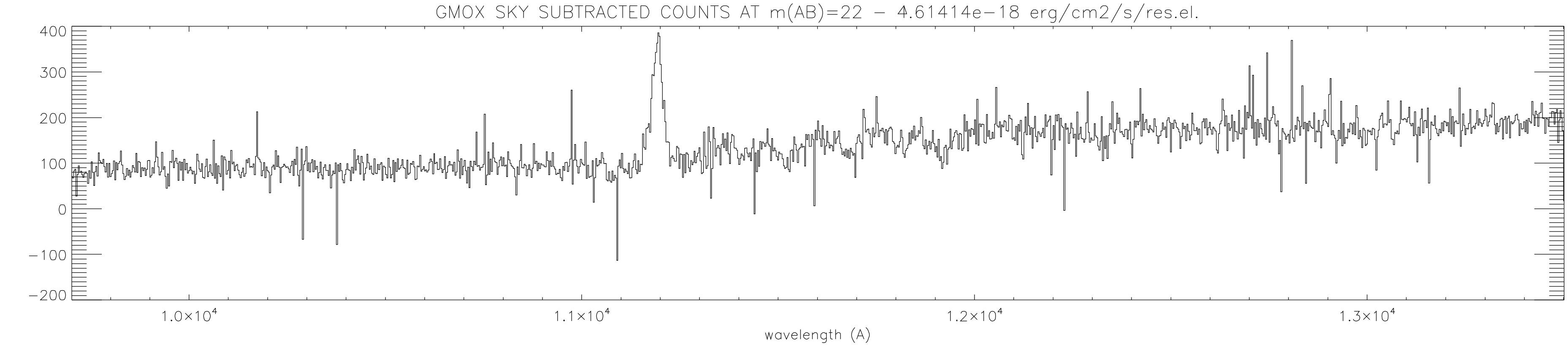


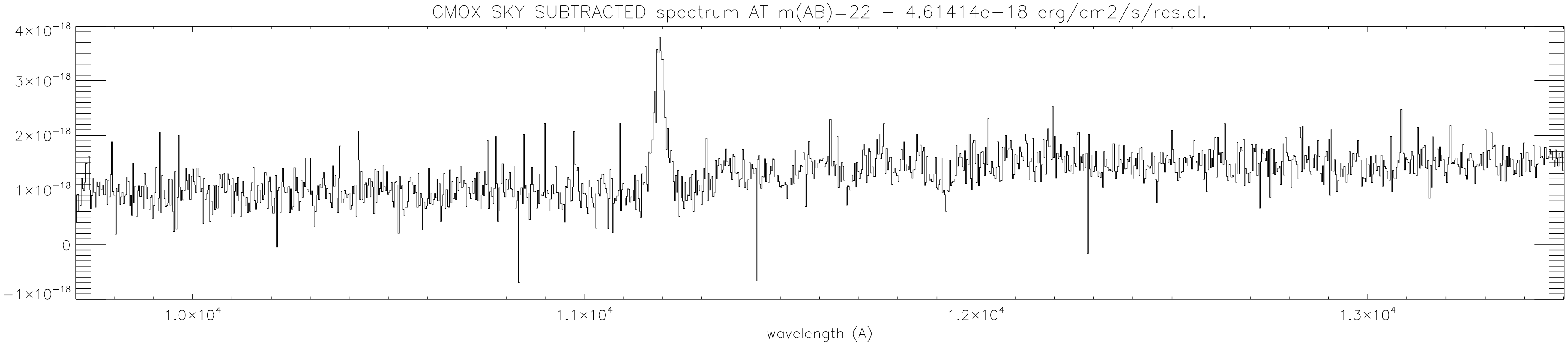
0.12” x 0.12” @ GEMS

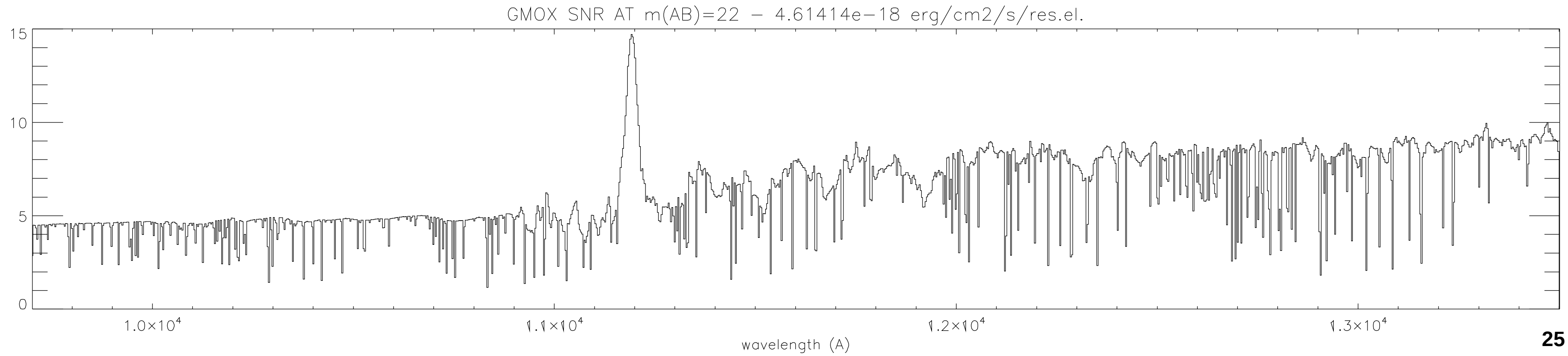
40x40mas corresponds to
<250 pc everywhere in the Universe

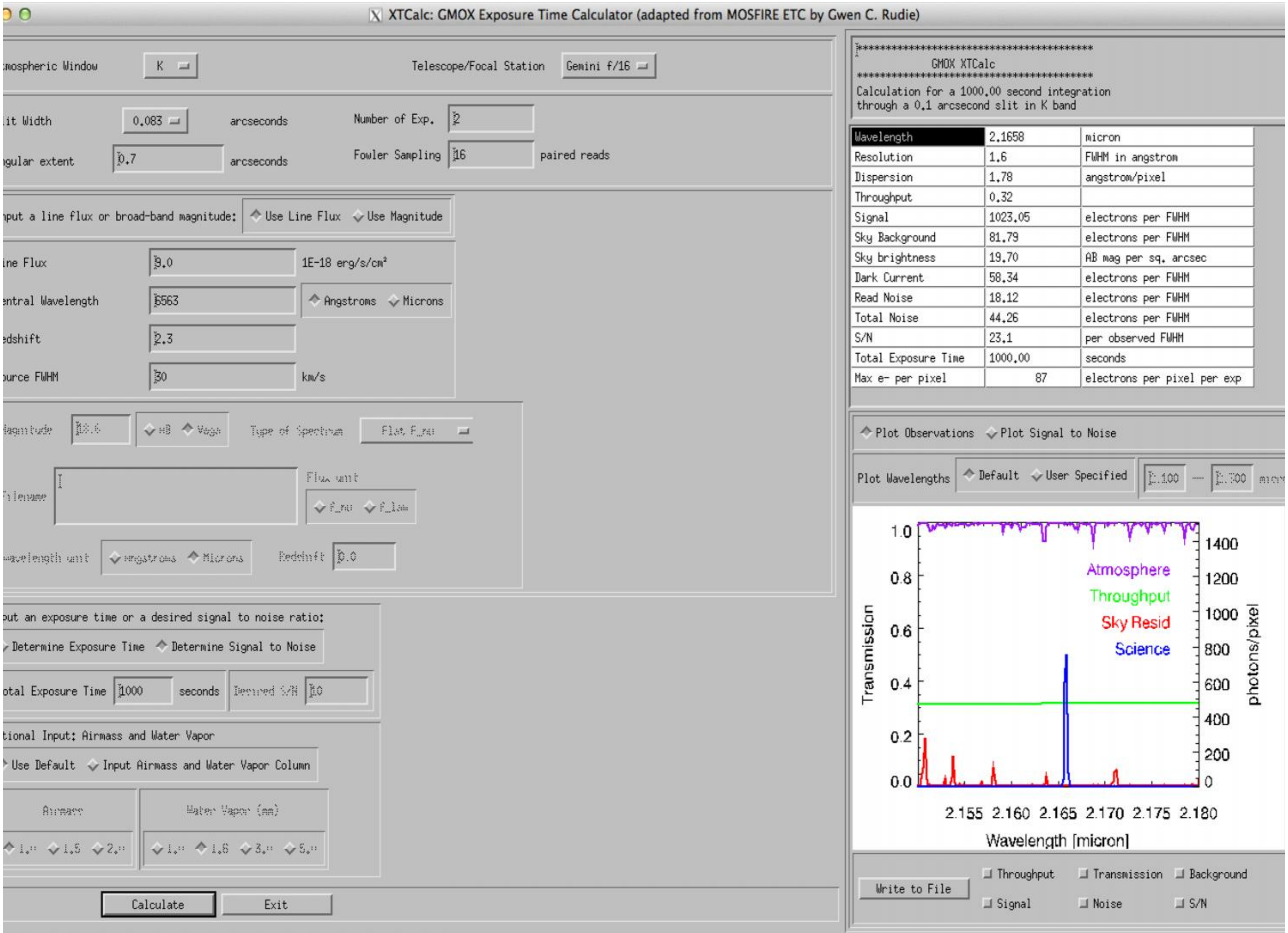


ETC Generated Spectra








XTCalc: GMOX Exposure Time Calculator (adapted from MOSFIRE ETC by Gwen C. Rudie)
mospheric Window
K
Telescope/Focal Station
Gemini f/16
lit Width
0.083
arcseconds
Number of Exp.
2
gular extent
0.7
arcseconds
Fowler Sampling
16
paired reads
nput a line flux or broad-band magnitude:
Use Line Flux
Use Magnitude
ine Flux
9.0
1E-18 erg/s/cm²
entral Wavelength
6563
Angstroms
Microns
edshift
2.3
ource FWHM
30
km/s
Type of Spectrum
Flux unit
Redshift
put an exposure time or a desired signal to noise ratio:
Determine Exposure Time
Determine Signal to Noise
otal Exposure Time
1000
seconds
Desired S/N
10
tional Input: Airmass and Water Vapor
Use Default
Input Airmass and Water Vapor Column
Airmass
Water Vapor (mm)
Calculate
Exit
GMOX XTCalc
Calculation for a 1000.00 second integration
through a 0.1 arcsecond slit in K band
Wavelength | 2.1658 | micron
Resolution | 1.6 | FWHM in angstrom
Dispersion | 1.78 | angstrom/pixel
Throughput | 0.32 |
Signal | 1023.05 | electrons per FWHM
Sky Background | 81.79 | electrons per FWHM
Sky brightness | 19.70 | AB mag per sq. arcsec
Dark Current | 58.34 | electrons per FWHM
Read Noise | 18.12 | electrons per FWHM
Total Noise | 44.26 | electrons per FWHM
S/N | 23.1 | per observed FWHM
Total Exposure Time | 1000.00 | seconds
Max e- per pixel | 87 | electrons per pixel per exp
Plot Observations
Plot Signal to Noise
Plot Wavelengths
Default
User Specified
Atmosphere
Throughput
Sky Resid
Science
Transmission
photons/pixel
Wavelength [micron]
2.155 2.160 2.165 2.170 2.175 2.180
Write to File
Throughput
Transmission
Background
Signal
Noise
S/N

Summary of performance

GMOX at f/16: Gemini North and South without AO; Gemini North with ALTAIR

Field of View Sampling	171” × 90” 83 mas/micromirror				
	Blue Arm 3200 – 5890 Å	Red Arm 5890 – 9700 Å	IR Arm YJ: 0.97 – 1.35 μm	H: 1.46 – 1.81 μm	K: 1.83 – 2.45 μm (K)
	Nominal: GLAO 0.3″ Seeing at V				
Mirrors/slit Slit Width $R = \lambda/\Delta\lambda$ sampling (pixel/slit) AB limit mag.	5 0.42″ 4500 3 21.6	4 0.33″ 4500 3 21.3	3 0.25″ 3700 2.75 21.6	3 0.25″ 4500 2.75 21.1	3 0.25″ 4500 2.75 20.9
	Regular Seeing: 0.6″ Seeing at V				
Mirrors/slit Slit Width $R = \lambda/\Delta\lambda$ sampling (pixel/slit) AB limit mag.	12 1.00″ 1875 7.2 21.4	10 0.83″ 1800 7.5 21.0	8 0.67″ 1590 7.3 20.5	8 0.67″ 1930 7.3 19.3	8 0.67″ 1930 7.3 19.8
	ALTAIR: FWHM = 0.05″ at J				
Mirrors/slit Slit Width $R = \lambda/\Delta\lambda$ sampling (pixel/slit) AB limit mag.	3 0.25″ 7500 1.8 21.8	2 0.16″ 9000 1.5 21.5	1 0.08″ 11100 0.9 22.3	1 0.08″ 13500 0.9 22.3	1 0.08″ 13500 0.9 21.9

Table 3: GMOX spectrograph characteristics.

AB limit magnitude in 3600s, SNR=10 per pixel

GMOX Science

GMOX shines in deep single and multi-object spectroscopy over a few arcmin fields, without or with (any level of) AO correction

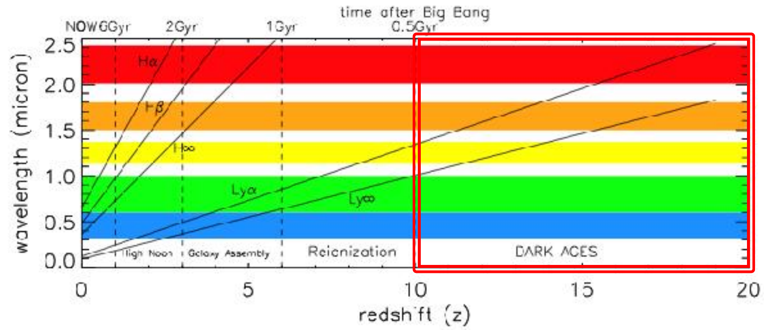
1. *Galaxy Formation and Evolution [including QSOs]*
2. *Clusters of Galaxies [Highly magnified sources]*
3. *Star Formation in Local Universe [Local Group Dwarfs]*
4. *Magellanic Clouds [including kinematics]*
5. *Globular Clusters [nature of multiple populations]*
6. *Galactic Bulge [formation, planets]*
7. *Galactic Young Cluster [late accretion, disk-planet transition, BDs]*
8. *SN, Transients (also as LSST Followup)*

Non-GMOX themes:

- *Cosmology with large scale structures (BAO)*
- *Bright, old stars in the Galactic Halo*
- *Magellanic Streams*
- *R>20,000 spectroscopy*
- *~ 1km/s or less radial velocity*
- *…*

1. Galaxy Evolution

1.1 Dark ages and primordial objects



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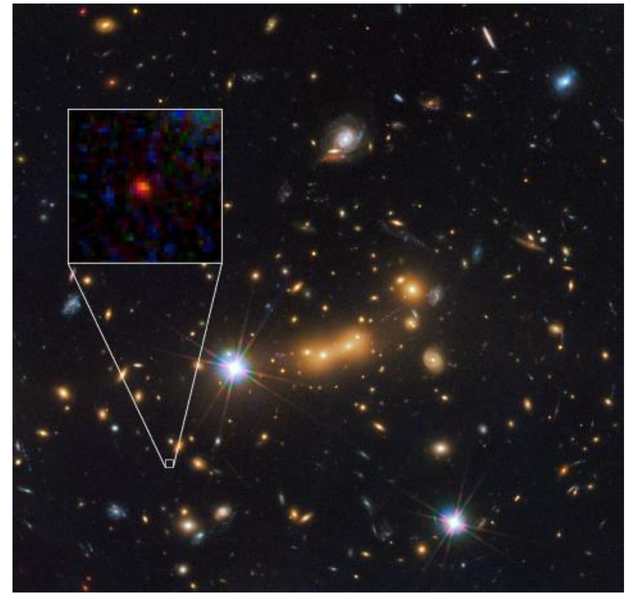
- First 500 Myr of cosmic history, “Dark-Ages”; appearance of the first stars causing the reionization of the Universe.
- z>10 region
- Ly-break in the near-IR: JWST regime



Example:

MACS0647 z~10.7 candidate in HST CLASH FIELD

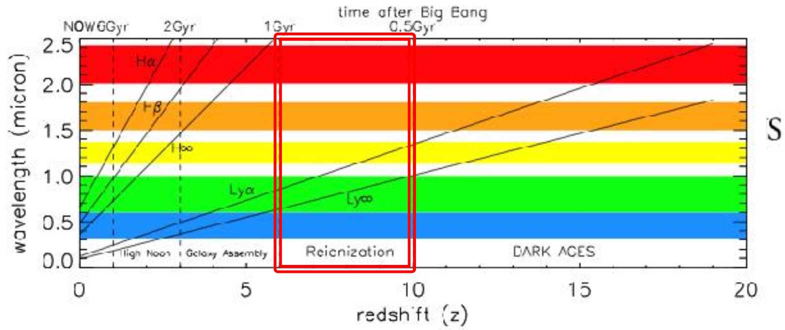
GMOX science:

- identify low redshift interlopers against good JWST candidates
- lensed high-z candidates in clusters of galaxies will provide hundreds of deep spectra of lensing and lensed galaxies (these observations require tens of hours)

Operated for NASA by AURA

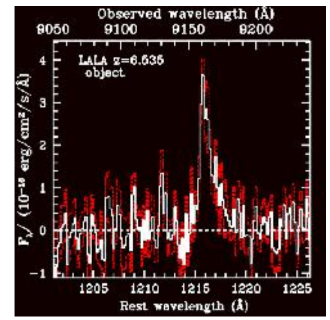
1. Galaxy Evolution

1.2 Reionization and Early Galaxy Formation



- Epoch of reionization, completed about 1Gyr after the Big Bang. Early embryos of present day galaxies are assembled
- 6<z<10 regime; Ly-break in CCD-red region

Ly-a in J band



Rhoads et al. 2004, ApJ 611, 59

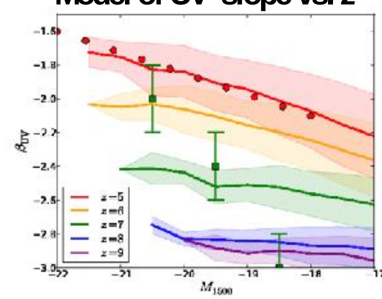
GMOX science:

a) detect Ly-alpha line, increasing nr. of known sources

b) clarify UV luminosity function $f(l) \propto l^{b}$, tracer of escaping ionizing photons, disentangling effects of dust and emission lines and showing how they depend on redshift

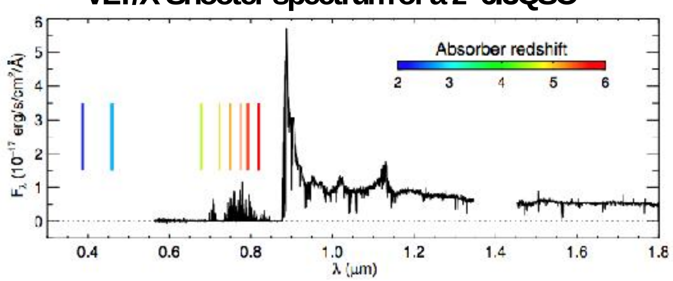
c) Map the reionization of the IGM through QSO spectroscopy. Current understanding of IGM at z>6 highly limited by low nr. of high z QSOs.

Model of UV slope vs. *z*



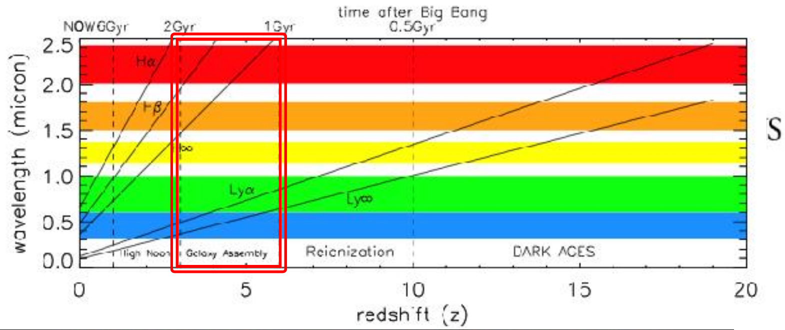
Gnedin, N. 2014, ApJ 793, 29

VLT/X-Shooter spectrum of a z=6.3QSO

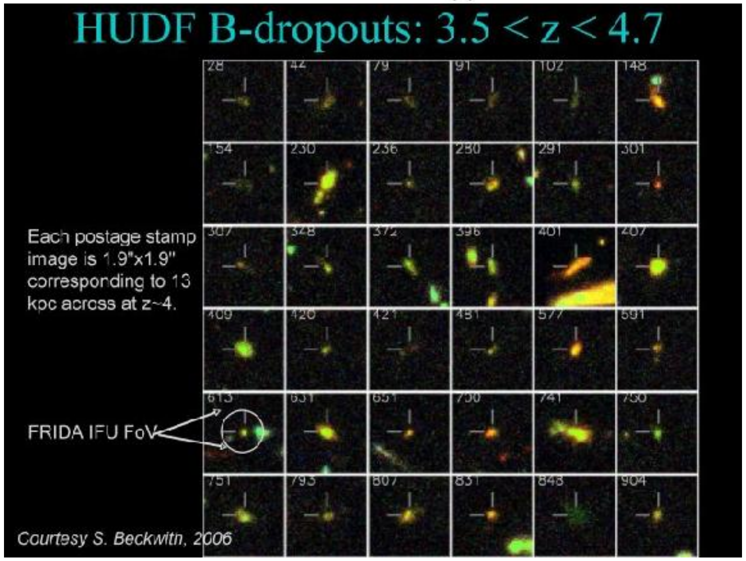


1. Galaxy Evolution

1.3 Galaxy Building Epoch



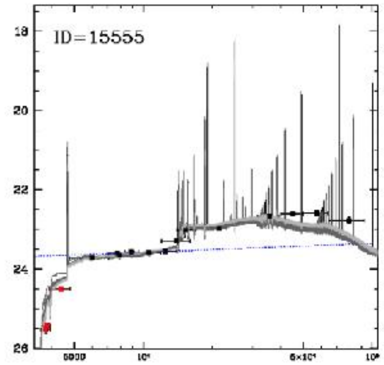
- 1-2Gyr after Big Bang; 3<z<6 regime
- Stellar mass of the universe grows from ~1% of its present value to ~10%, with significant enhancement of heavy elements.
- Balmer/4000A break in HK bands;
- Ly-break in CCD-blue bands



GMOX science:

- All spectroscopic diagnostics in GMOX regime
- provide the most accurate information on recent/current star formation rate
- Spatially resolve starburst from red clumps and mergers

z=3 galaxy spectrum

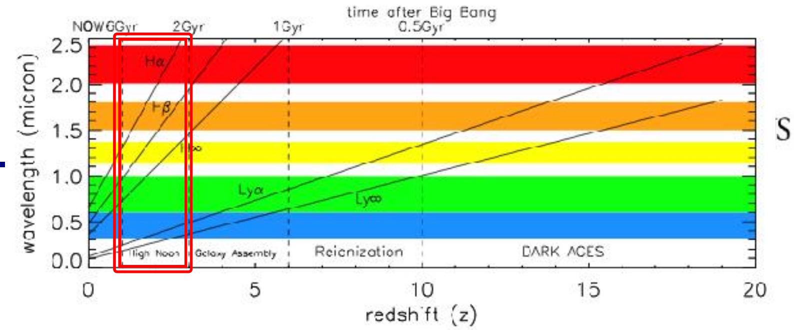


Castellano et al. 2014, A&A 566, A19

SPACE TELESCOPE SCIENCE INSTITUTE
Operated for NASA by AURA

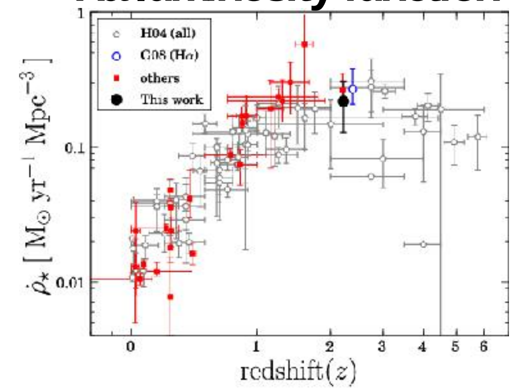
1. Galaxy Evolution

1.4 High Noon of Cosmic History



- 2-6G yr of cosmic history; 1>z>3 regime
- Galaxies build most of their mass and the star formation efficiency and AGN activity reach their maximum.
- All Balmer lines in GMOX range

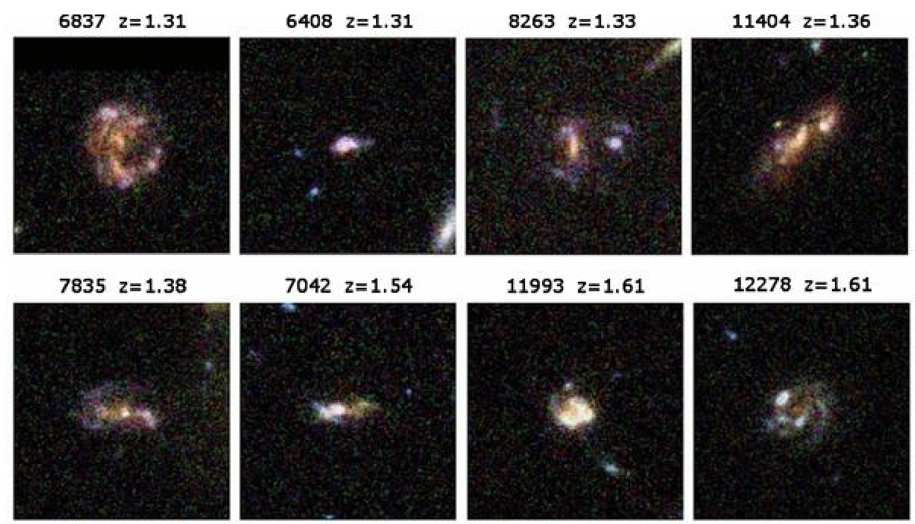
Ha luminosity function



Hayes et al. 2010, A&A 509, L5

GMOX science

- Reconstruct SED of individual galactic substructures;
- Discriminate stellar populations by age, mass, SFR…;
- Kinematic studies enabled by wide spectral coverage.



Trump et al. 2013, ApJ763, L6

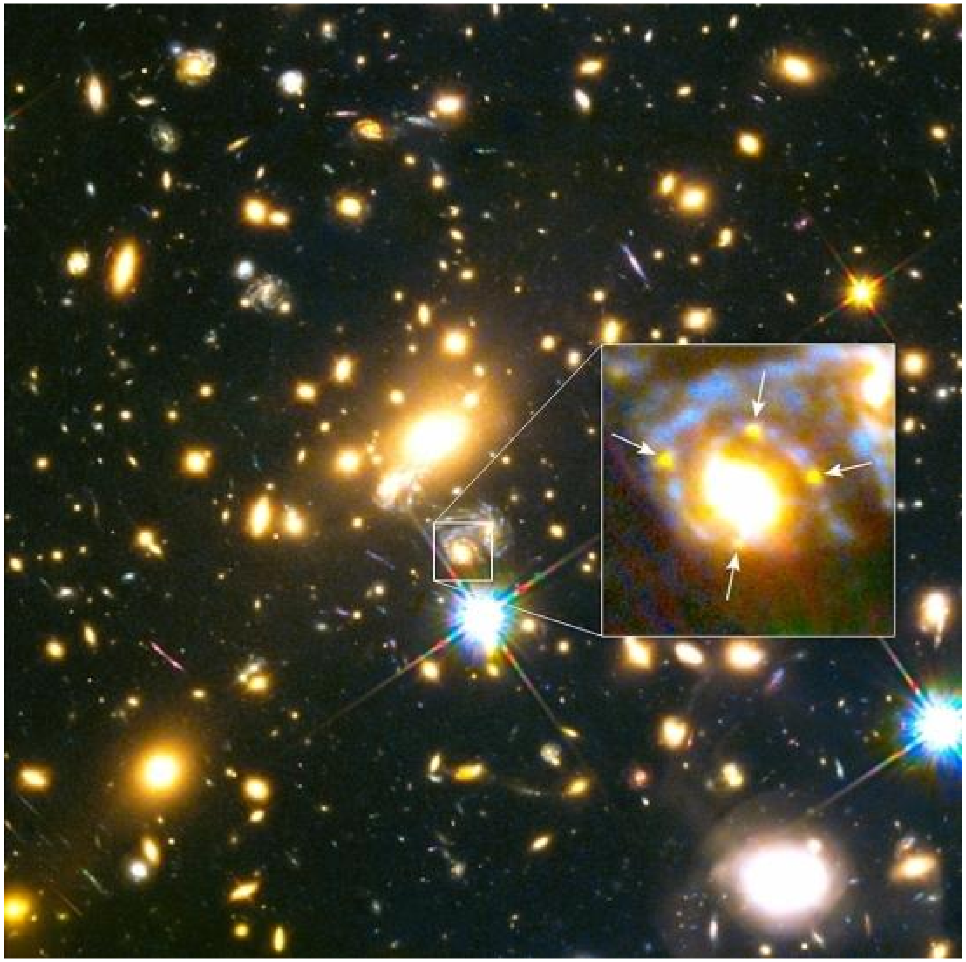
2. Clusters of Galaxies

GMOX 90” x 90” FoV is well-matched to the ~1 Mpc scales of rich clusters at z ~ 0.3 - 0.6, such as those observed by the HST CLASH survey and Frontier Fields.

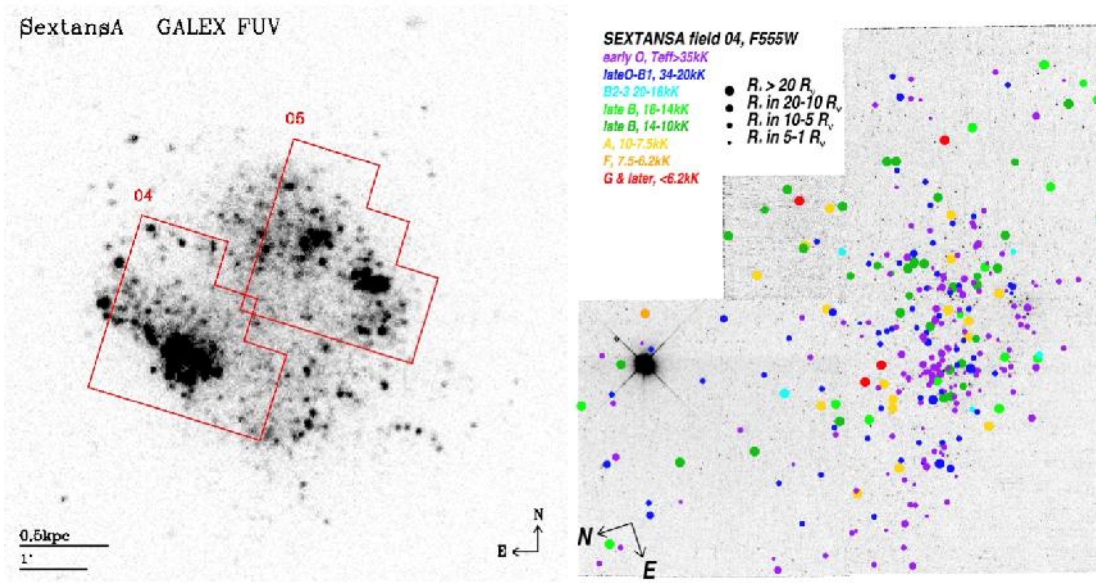
The core of the Frontier Fields cluster Abell 2744 at z~0.308, contains ~150 galaxies with I<22 mag.

Lines like [OII]3727, CaH+K 4000 break, Hbeta, [OIII]5007, Mg b, NaI, [OI]6300, Halpha, [NII], and [SiII] trace the chemical abundances of stars and gas, central AGN activity, ionization, and star-formation rates.

GMOX can also constrain dark matter distribution, frequency of mergers, ram-pressure stripping, accreting filaments, etc…



3. Massive Star Formation In Local Group Dwarfs

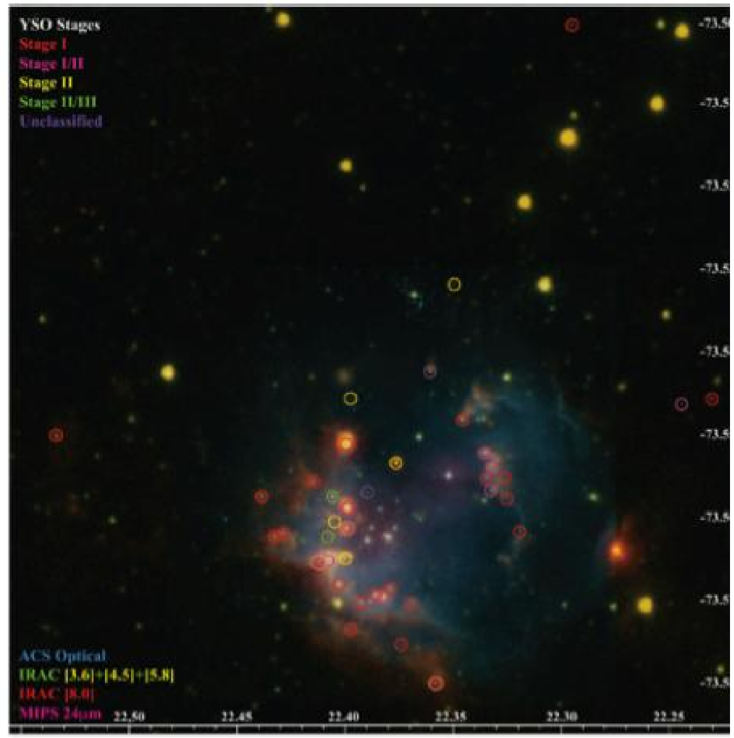


Left: GALEX image of the dwarf galaxy Sextans A, with superimposed the footprints of the HST/WFPC2 observations. This galaxy represents a typical example of star-forming, low- metallicity, Local Group dwarf galaxy. Right: stellar temperature estimates from photometric SED fitting. HST observations like these can be used for GMOX target selection. The WFPC2 FoV can be covered with 3 GMOX pointings.

Given their typically low metallicity, dwarfs galaxies in the LG are ideal laboratories to study SF and evolution in conditions similar to the early Universe.

- **What is the efficiency of metal enrichment of the ISM? Is it different from Milky Way and M31?**
- **Is low metallicity due to quiet SFH or inefficiency in retaining and mixing nucleosynthetic products?**
- **Targeting massive stars and A-type stars one can reconstruct current IMF and metallicity of young and intermediate-age populations.**

4. MAGELLANIC CLOUDS

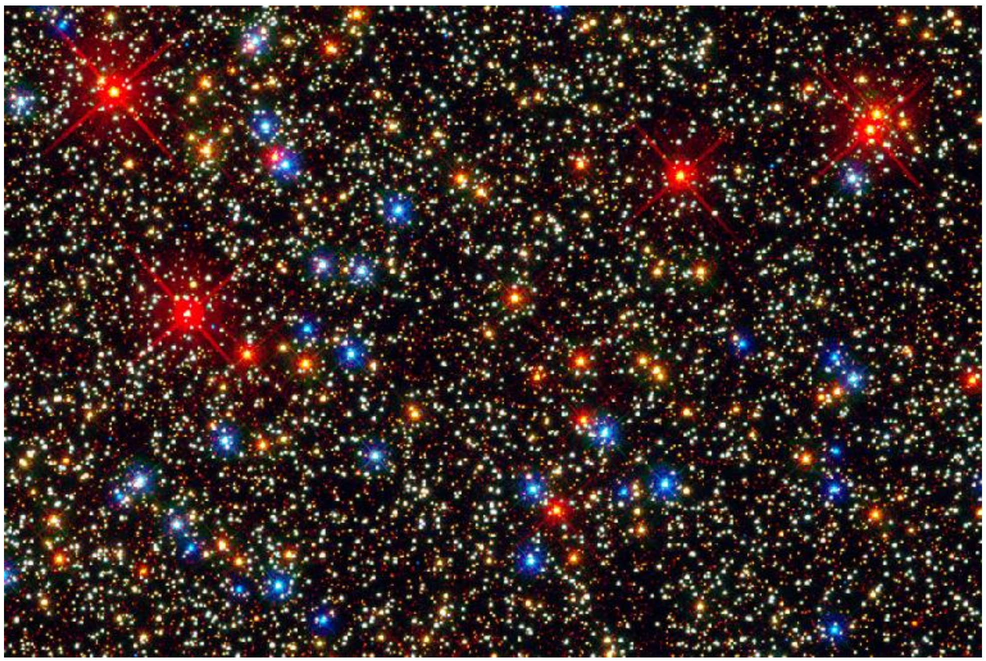


HST image (left), and Spitzer/HST combined image (right) of NGC 602 in the Small Magellanic Cloud. This region can fit into the GMOX FoV and spectra of all YSO candidates and young massive stars can be obtained in one night.

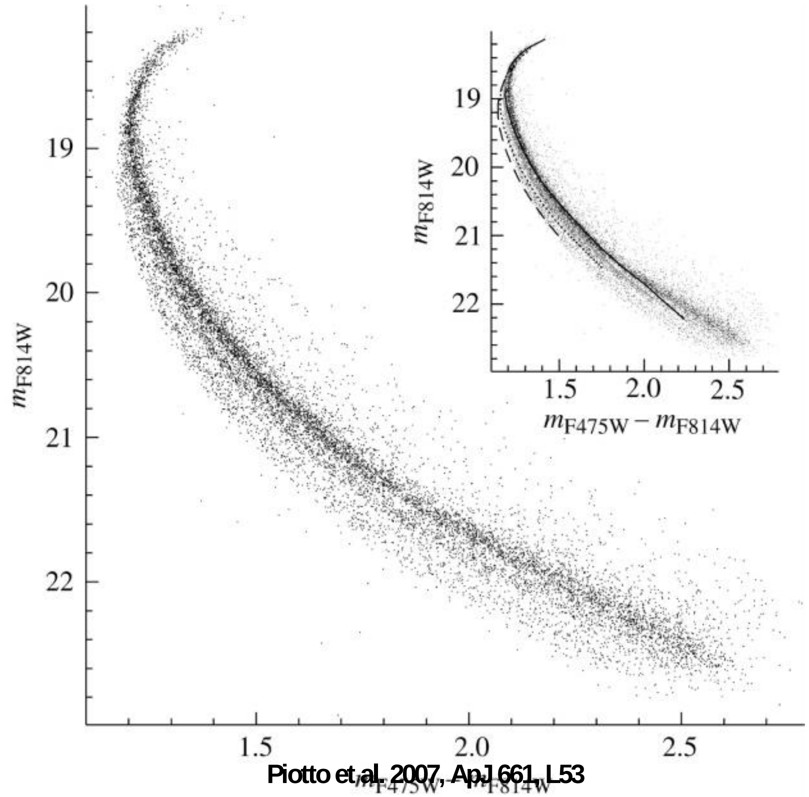
GMOX science

- classify stars probing the inner and outer, more embedded regions;
- Reconstruct star formation history, triggering, cluster lifetime.
- derive both gas and stellar radial velocity, ejection scenarios, mass segregation, binary fraction, etc.

5. GLOBULAR CLUSTERS



Triple main sequence of the globular cluster NGC 2808

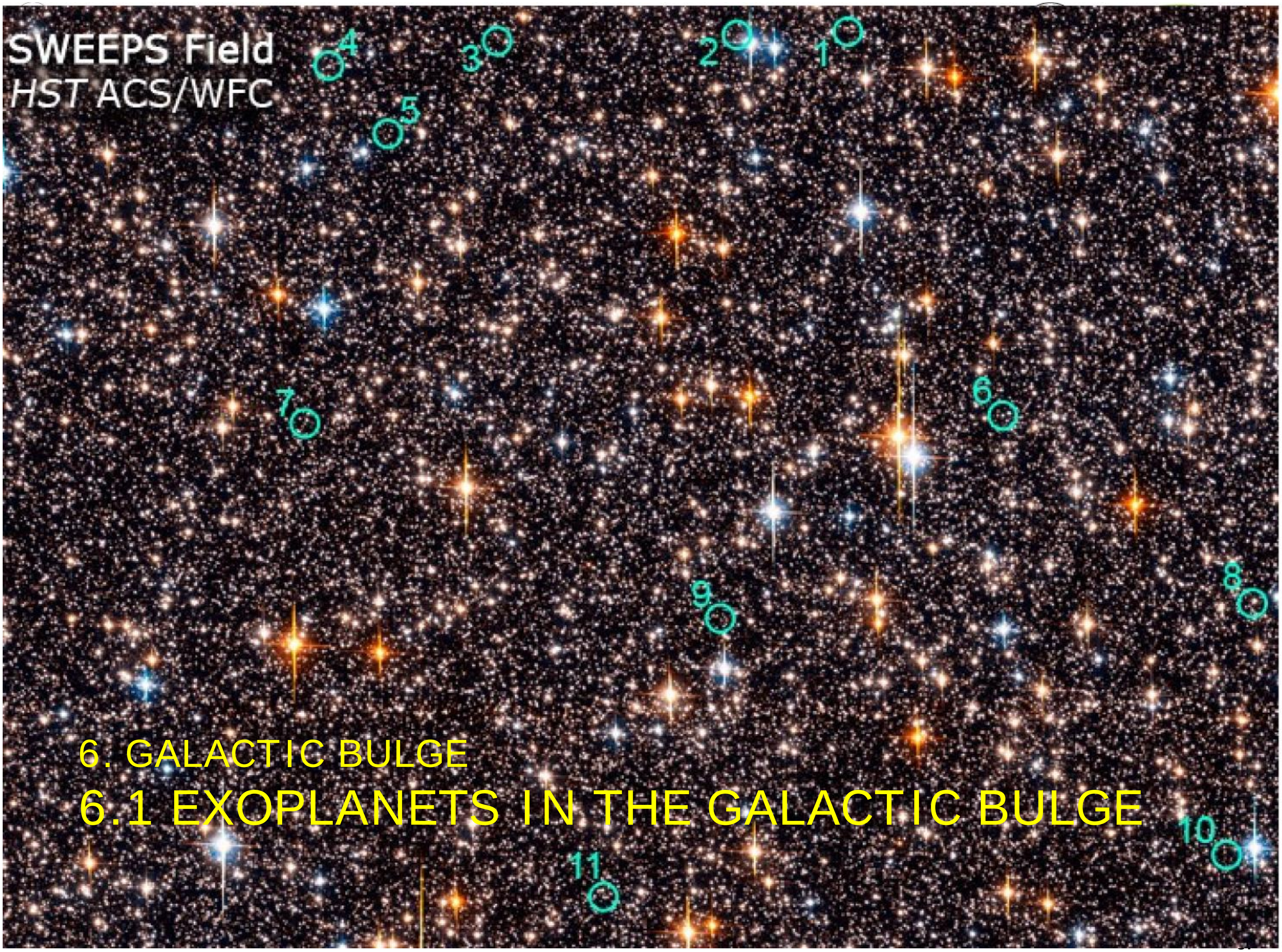


Piotto et al. 2007, ApJ 661, L53

Different stellar populations due to He abundance, controlled by processes (CNO, NeNa, MgAl cycles) that affect the concentration of other metals.
GMOX can clarify the relation between He enhancement and the simultaneous depletion/increase in light elements.

6. GALACTIC BULGE

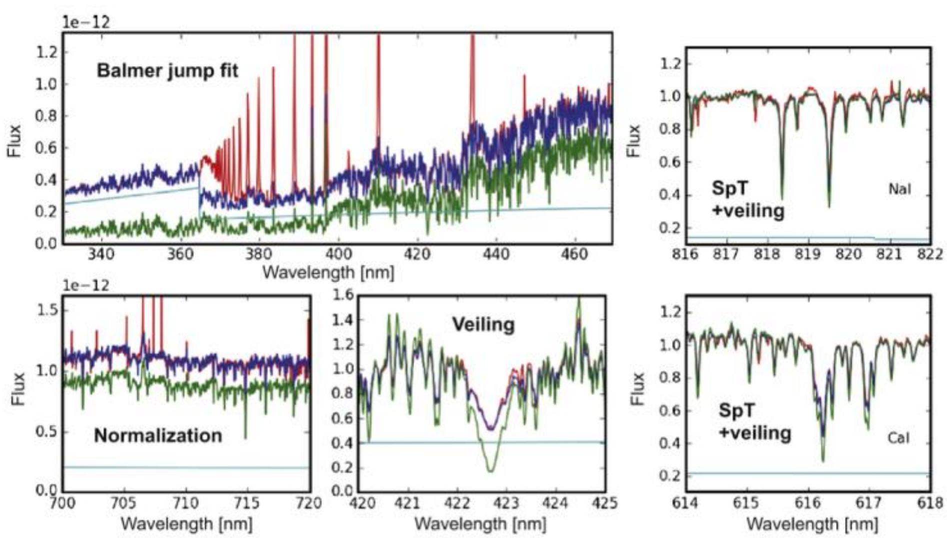
6.1 EXOPLANETS IN THE GALACTIC BULGE

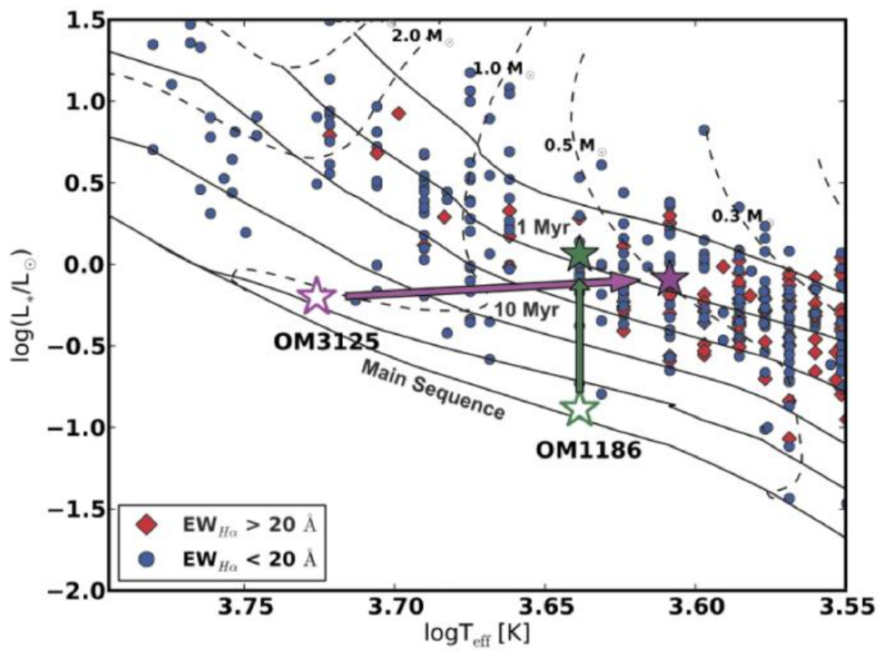


6. GALACTIC YOUNG CLUSTERS

Young stellar clusters should nicely trace the cluster isochrone. Instead they show Strong scatter in luminosity (radius), and thus Isochronal age.

Orion Nebula Cluster represents a typical case.





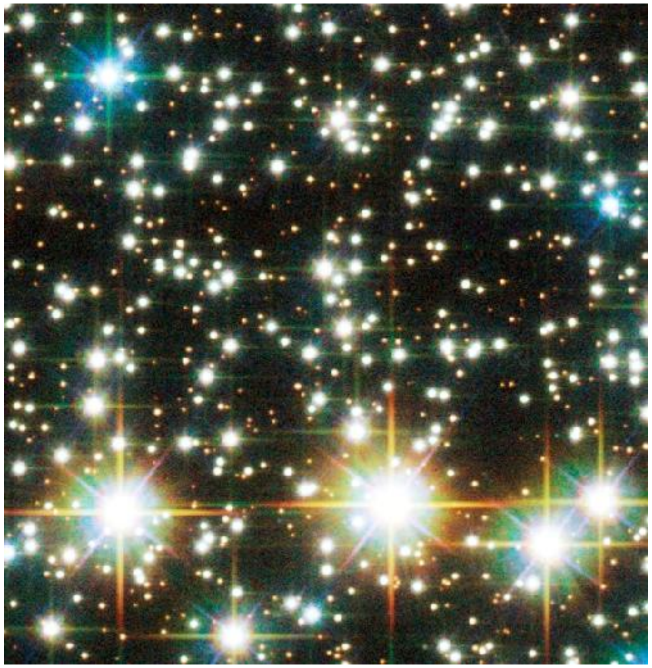
In fact, locating correctly a PMS star in the HR diagram is difficult, due to the effect of accretion and extinction on top of the PMS SED.
Wide-band spectroscopy with X-shooter allows to disentangle these effects and clean the HR diagrams

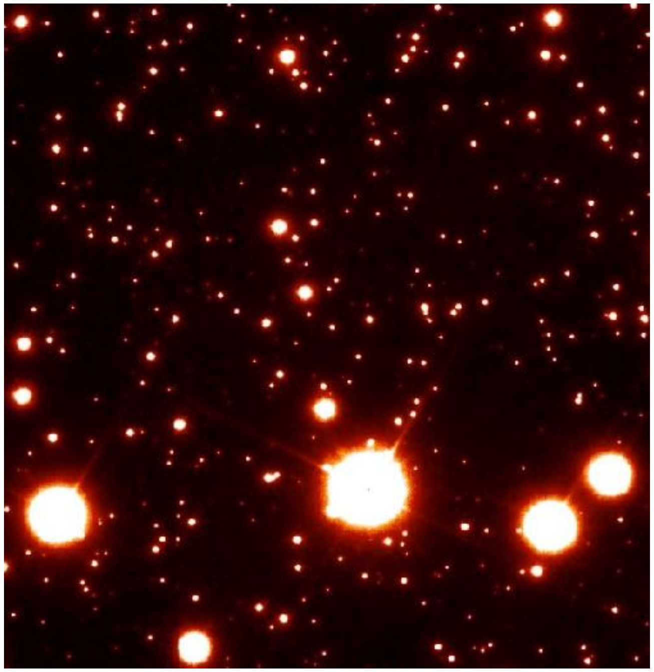
Science Summary

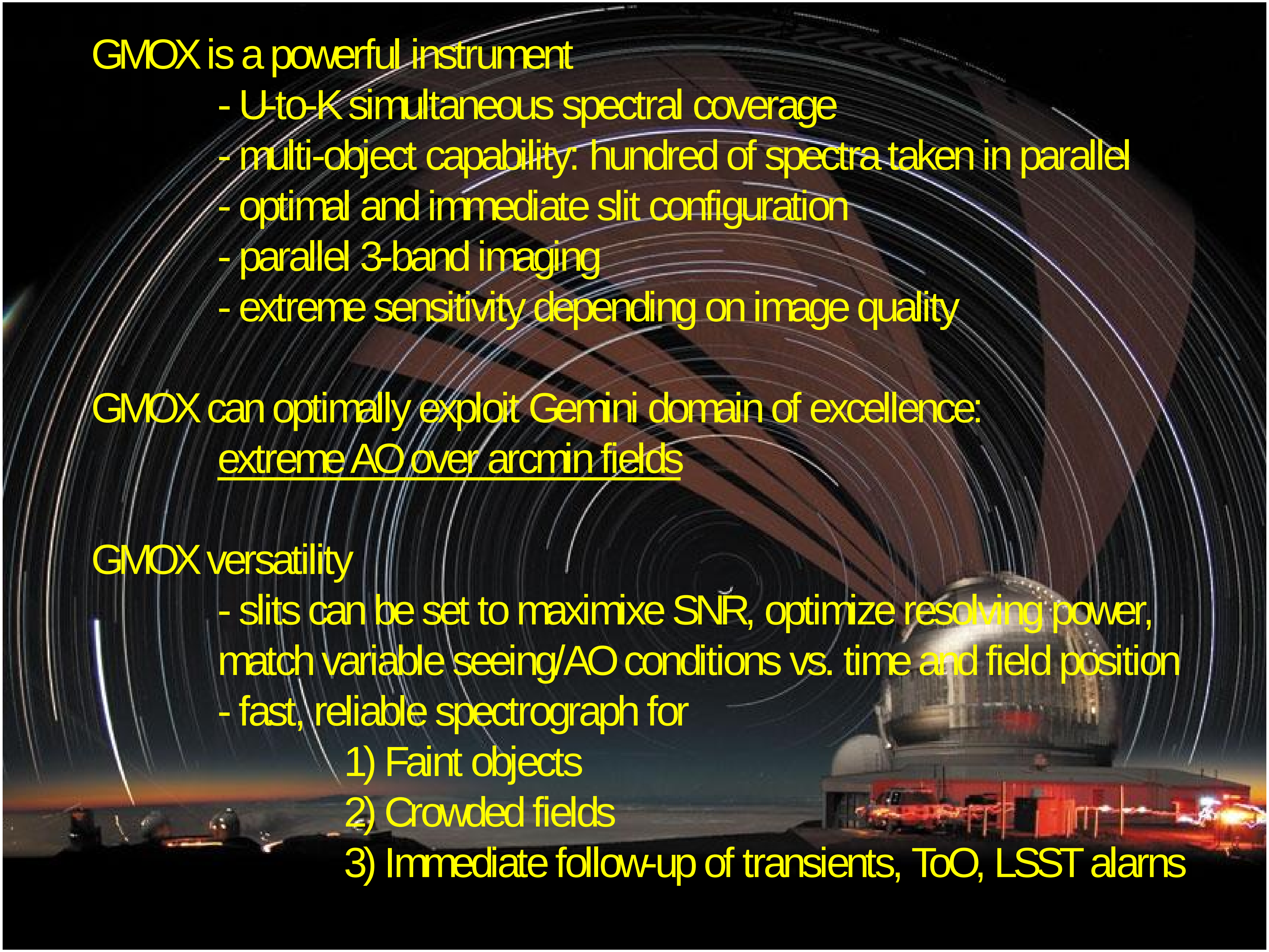
- **GMOX**
  - Science case
  - Design parameters
  - Performance

  remind a HST instrument

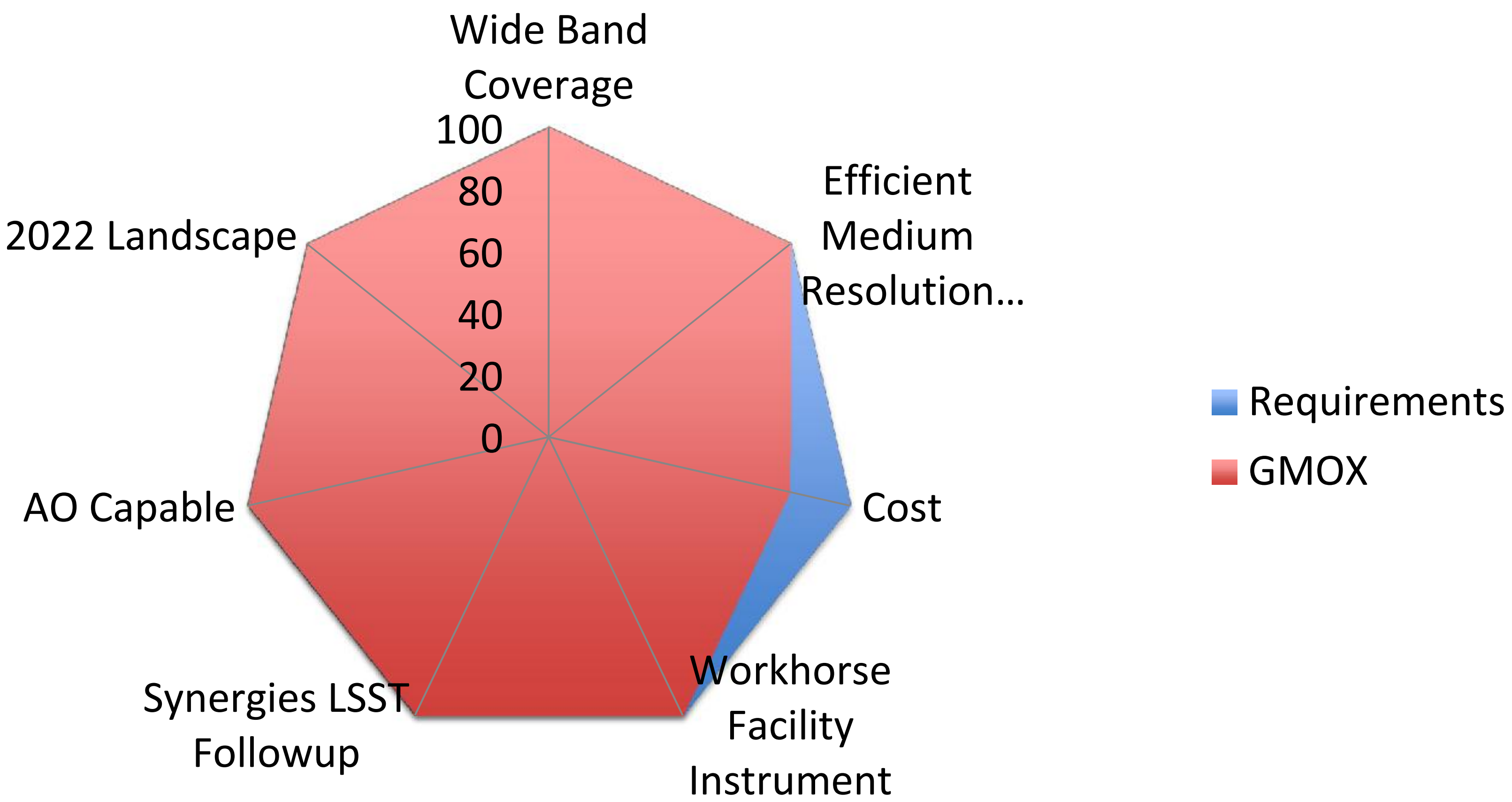
- **GMOX is optimally matched with unique telescopes like Gemini N and S that can outperform HST in the near IR.**






GMOX is a powerful instrument
- U-to-K simultaneous spectral coverage
- multi-object capability: hundred of spectra taken in parallel
- optimal and immediate slit configuration
- parallel 3-band imaging
- extreme sensitivity depending on image quality
GMOX can optimally exploit Gemini domain of excellence:
extreme AO over arcmin fields
GMOX versatility
- slits can be set to maximixe SNR, optimize resolving power, match variable seeing/AO conditions vs. time and field position
- fast, reliable spectrograph for
1) Faint objects
2) Crowded fields
3) Immediate follow-up of transients, ToO, LSST alarns

GMOX Metric



Wide Band Coverage
Efficient Medium Resolution…
Cost
Workhorse Facility Instrument
Synergies LSST Followup
AO Capable
2022 Landscape
100
80
60
40
20
0
Requirements
GMOX

GMOX Team

- **PI: M. Robberto (JHU, STScI)**
- **Science Team Lead: T. Heckman (JHU)**
- **Science Team Deputy: M. Gennaro (STScI)**
- **Technical Lead and Project Manager: S. Smee (JHU)**
- **Optical Design: R. Barkhouser (JHU)**
- **SW & Electronics: J. Orndorff (JHU)**
- **DMD System Lead: Z. Ninkov (RIT)**
- **Fast Guiding Systems: S. Sivanandam (Dunlap Institute, under negotiation)**

- **Science Team:**

Massimo Robberto Tim Heckman, Mario Gennaro, Susana Deustua, John MacKenty, Zoran Ninkov, George Becker, Luciana Bianchi, Andrea Bellini, Rongmon Bordoloi, Annalisa Calamida, Jason Kalirai, Jennifer Lotz, M. Meixner, A. Rest, Elena Sabbi, Jason Tumlinson

Part 2.

SCIENCE CASES AND SCIENCE REQUIREMENTS

Summary

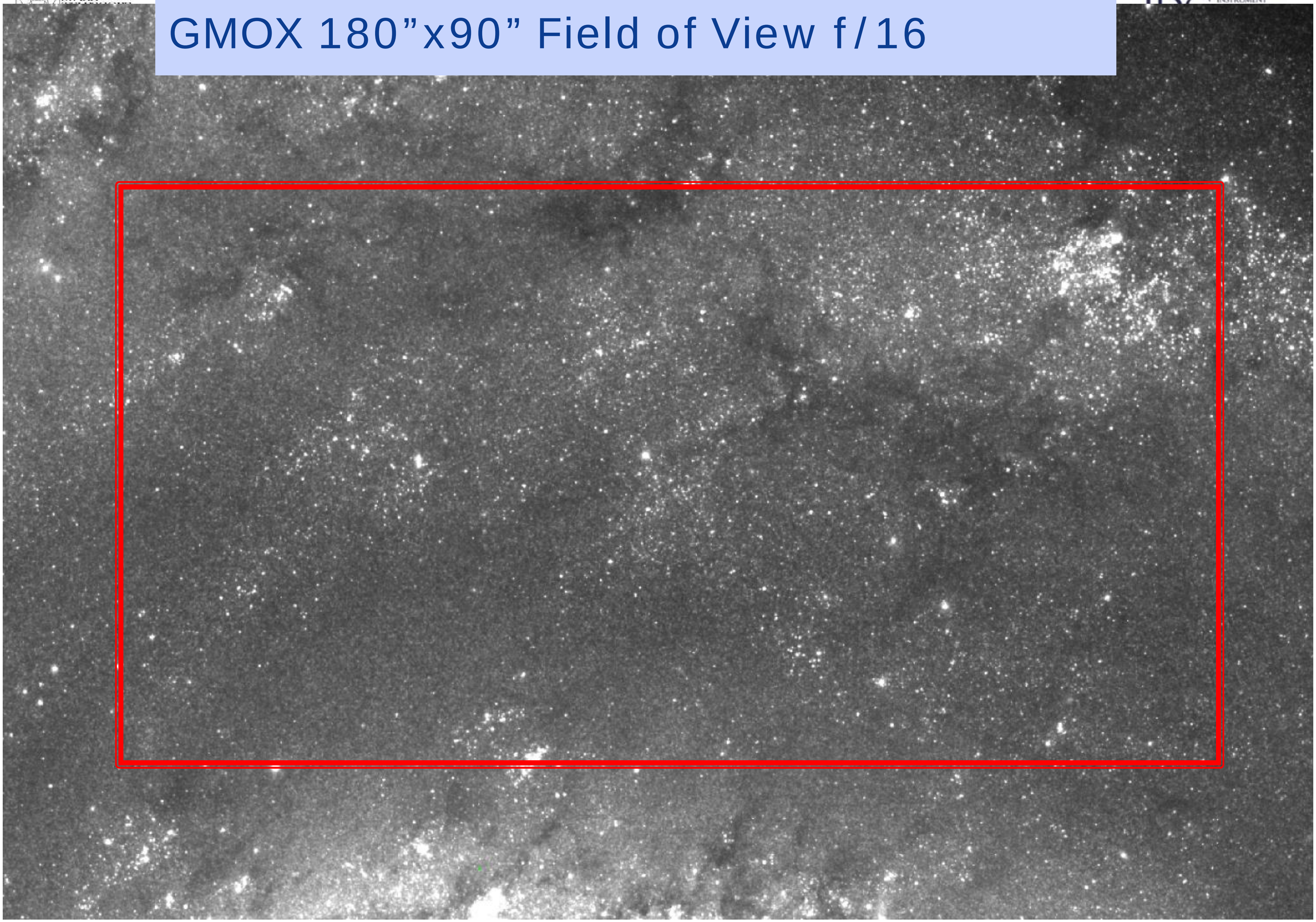
- **GMOX facts:**
  - Current Landscape
  - GMOX Field of View
  - GMOX Sensitivity
- **GMOX Science and requirements**
  1. Galaxy Origin and Evolution
     1. GMOX slit vs. redshift
  2. Galaxy Clusters
  3. The Local Universe
  4. Magellanic Clouts
  5. Globular Clusters
  6. Local Star Formation
  7. Unique GMOX observations: examples from Science Team
- **Summary of Requirements**
- **GMOS and LSST Followup**
  - "LSST Science Book"
  - "Spectroscopy in the Era of LSST"

The current landscape: existing IFU

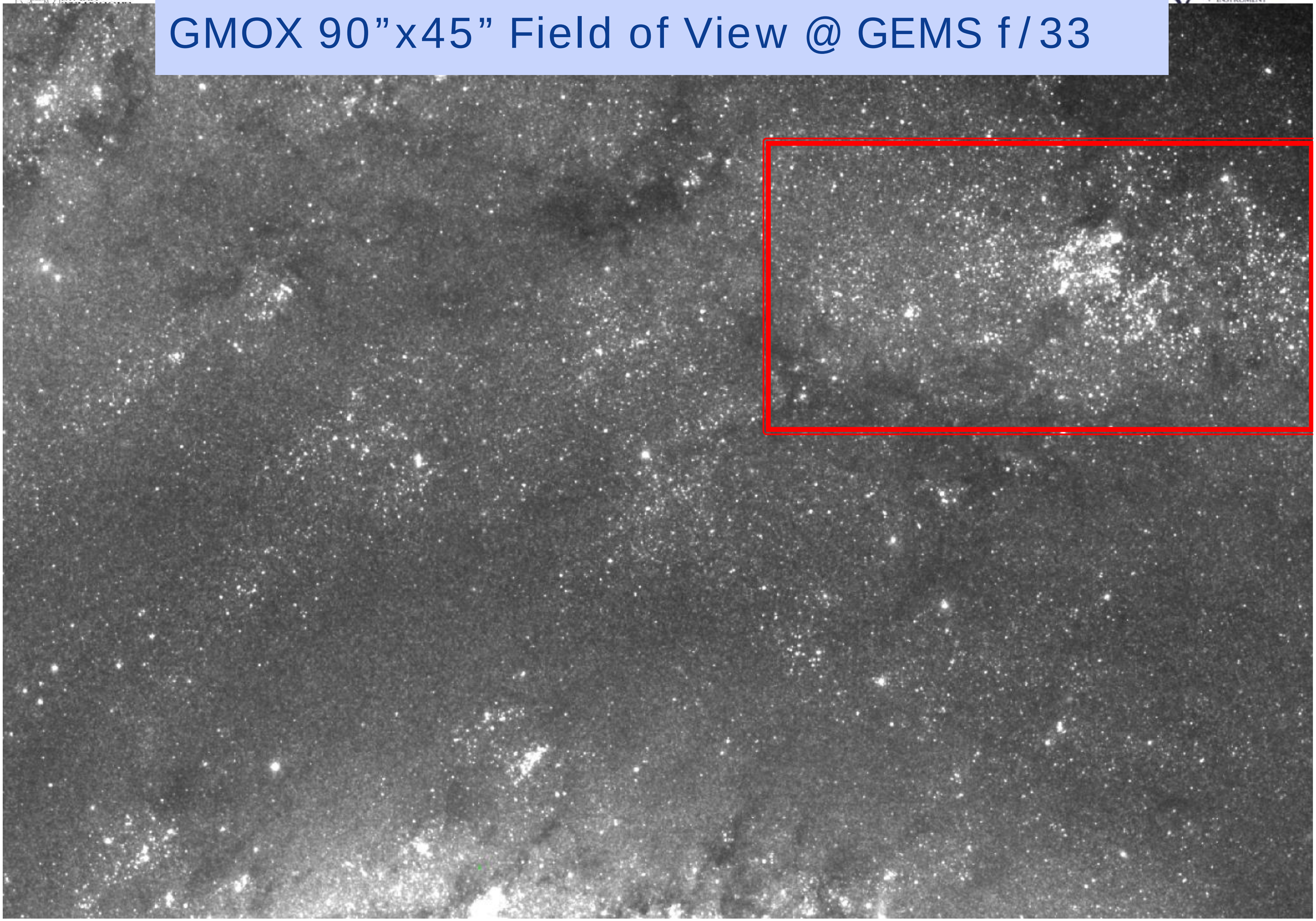
Instrument	Type	Range [Å]	Resolution	Field of View	Pixel Size
ARGUS	II	3700 – 9500	5600-46000	12″×7″	0.52″
				6.6″×4.2″	0.30″
GMOS	I	4000 – 11000	630–4300	5″×7″	0.2″
Integral	II	3700 – 8000	< 1.3Å-22Å	6.3″×5.4″	0.45″
	I			–33.6″×29.4″	– 2.7″
Kyoto 3DII	I	3600 – 9200	1200	3.6″×2.8″	0.096″
OASIS	I	4000 – 10000	200–4400	3.7″×2.7″	0.09″
				–10.3″×7.4″	– 0.2″
PMAS	II	3500 - 9000	1000 – 25000	8″×8″	0.5″
				12″×12″	0.75″
				16″×16″	1.0″
SAURON	I	4500 – 7000	∼ 1500	41″×33″	0.94″
				11″×9″	0.27″
VIMOS	II	4000 - 11500	200–3000	13″×13″	0.33″
				–54″×54″	– 0.67″
VIRUS-P	II	3500 - 6800	1.6Å-4.9Å	102″×102″	4.3″
VIRUS-W	II	4340 – 6040	2500	105″×75″	3.2″
		4850 – 5740	6 800	105″×75″	3.2″
MUSE	III	4650 – 9300	2.6 Å	60″×60″	0.2″
				8″×8″	0.025″
GMOX	MEMS	3650 -24000	4500	90″×45″	n×0.083″

Table 2: Selection of available IFUs for the optical domain in comparison to GMOX. The types are (I) lenslets, (II) fibers and (III) image-slicer. ARGUS, VIMOS and MUSE are operating at the VLT, while Integral, OASIS and SAURON are instruments of the William Herschel Telescope on La Palma. The GMOS instrument is available for the both Gemini telescopes (North on Hawaii & South in Chile) and Kyoto 3DII is attached to the Subaru telescope on Hawaii. The PMAS IFU is mounted on the 3.5m telescope on Calar Alto, Spain, and both VIRUS instruments are working at the 2.7 m Harlan J. Smith Telescope at the McDonald Observatory.

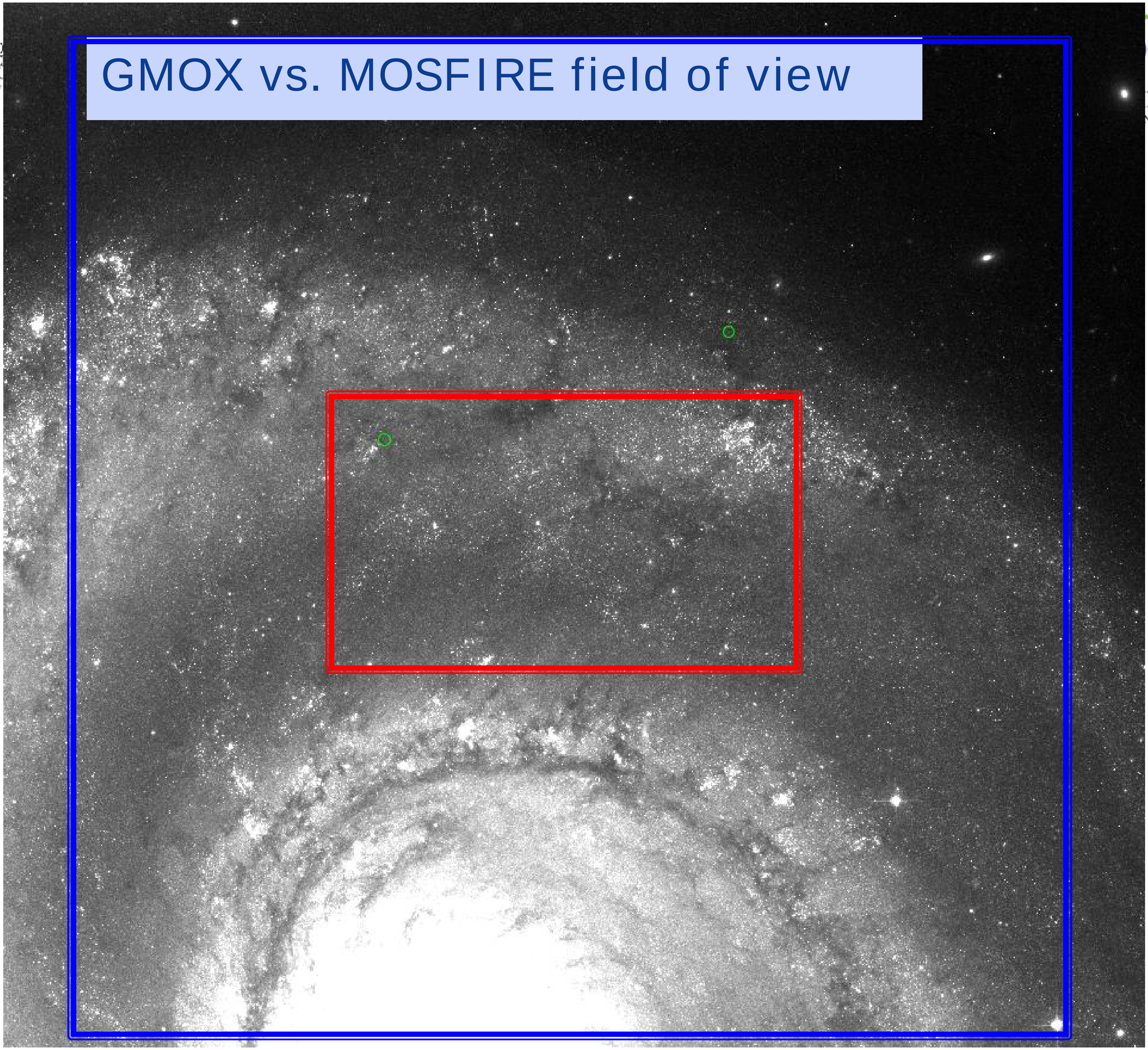
GMOX 180”x90” Field of View f/16



GMOX 90”x45” Field of View @ GEMS f/33



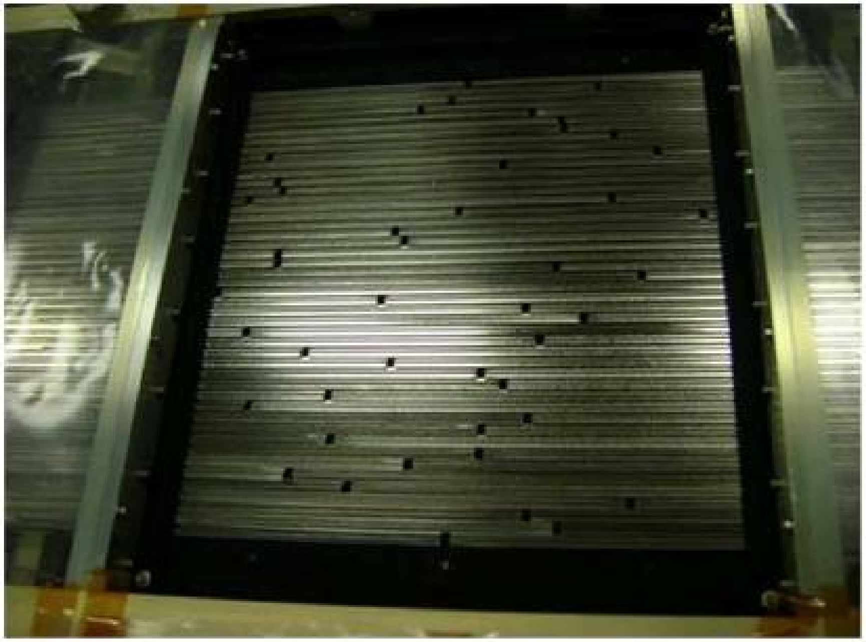
GMOX vs. MOSFIRE field of view

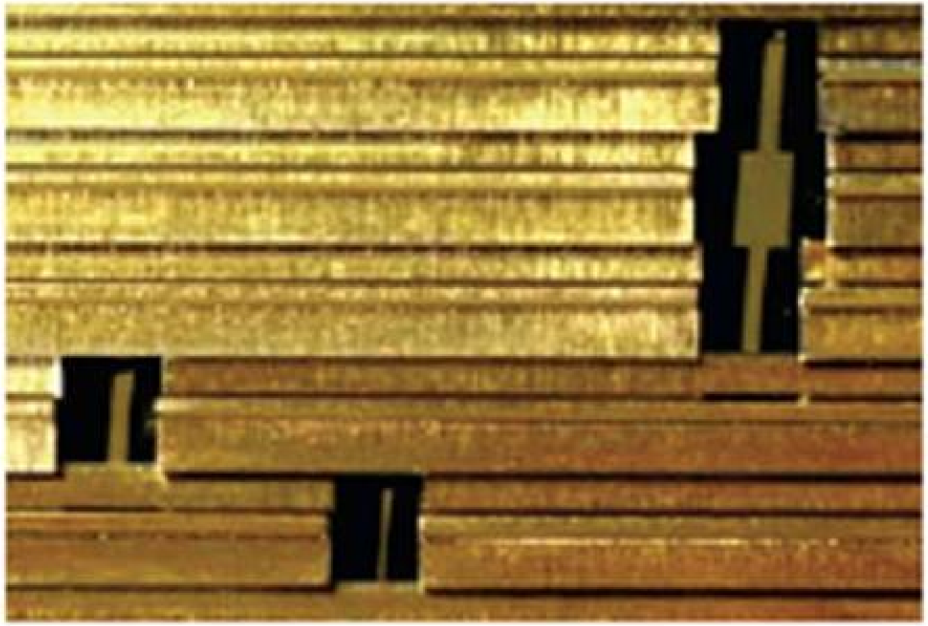


Current State of the art

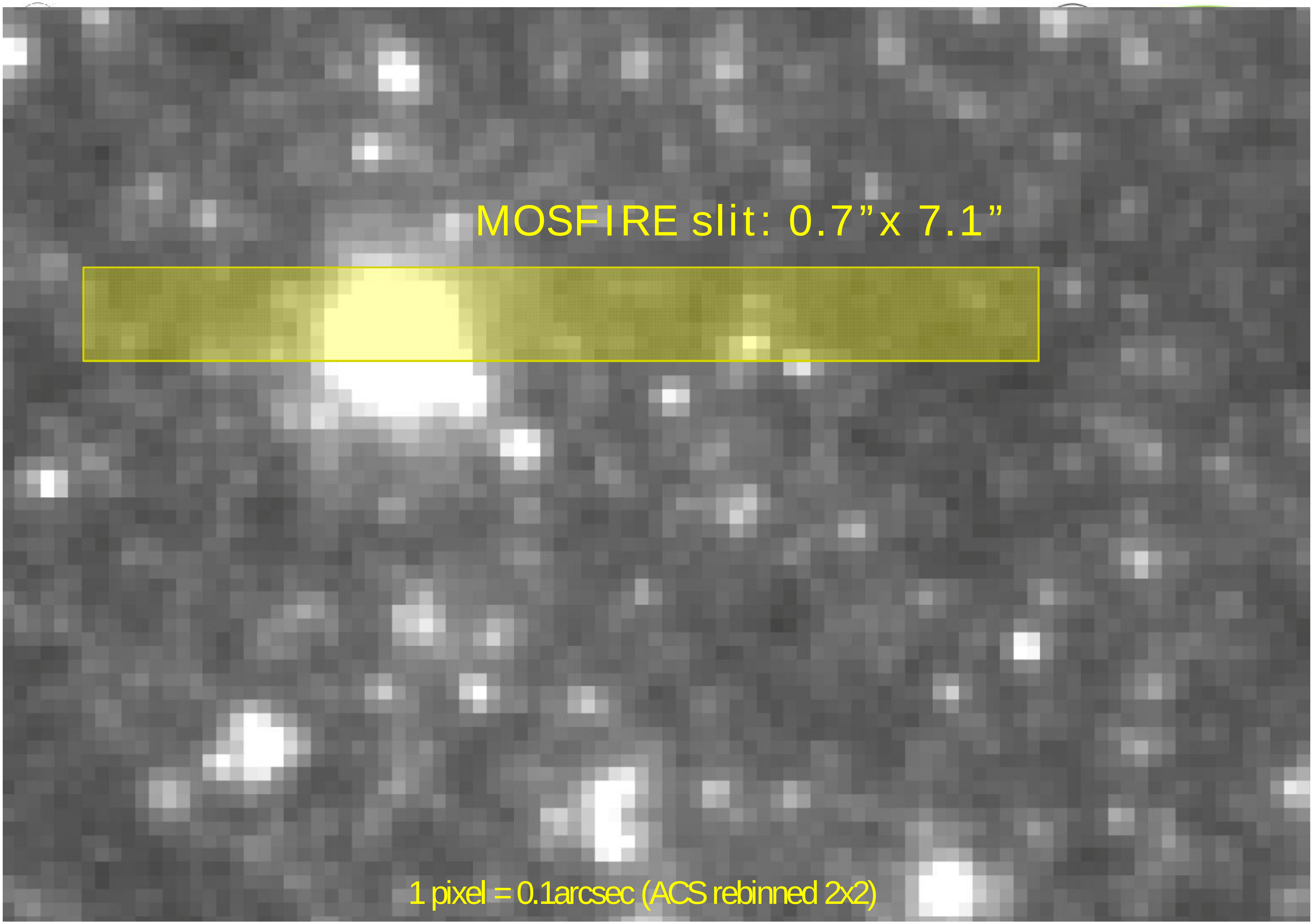
MOSFIRE @ Keck

46 slits, each 7.1" x 0.7" (nominal), 6.12'x6.14 'FoV

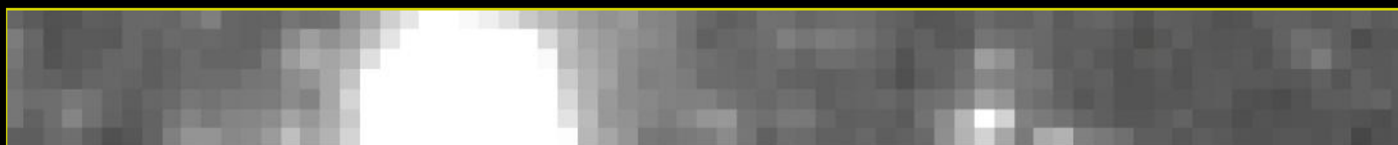


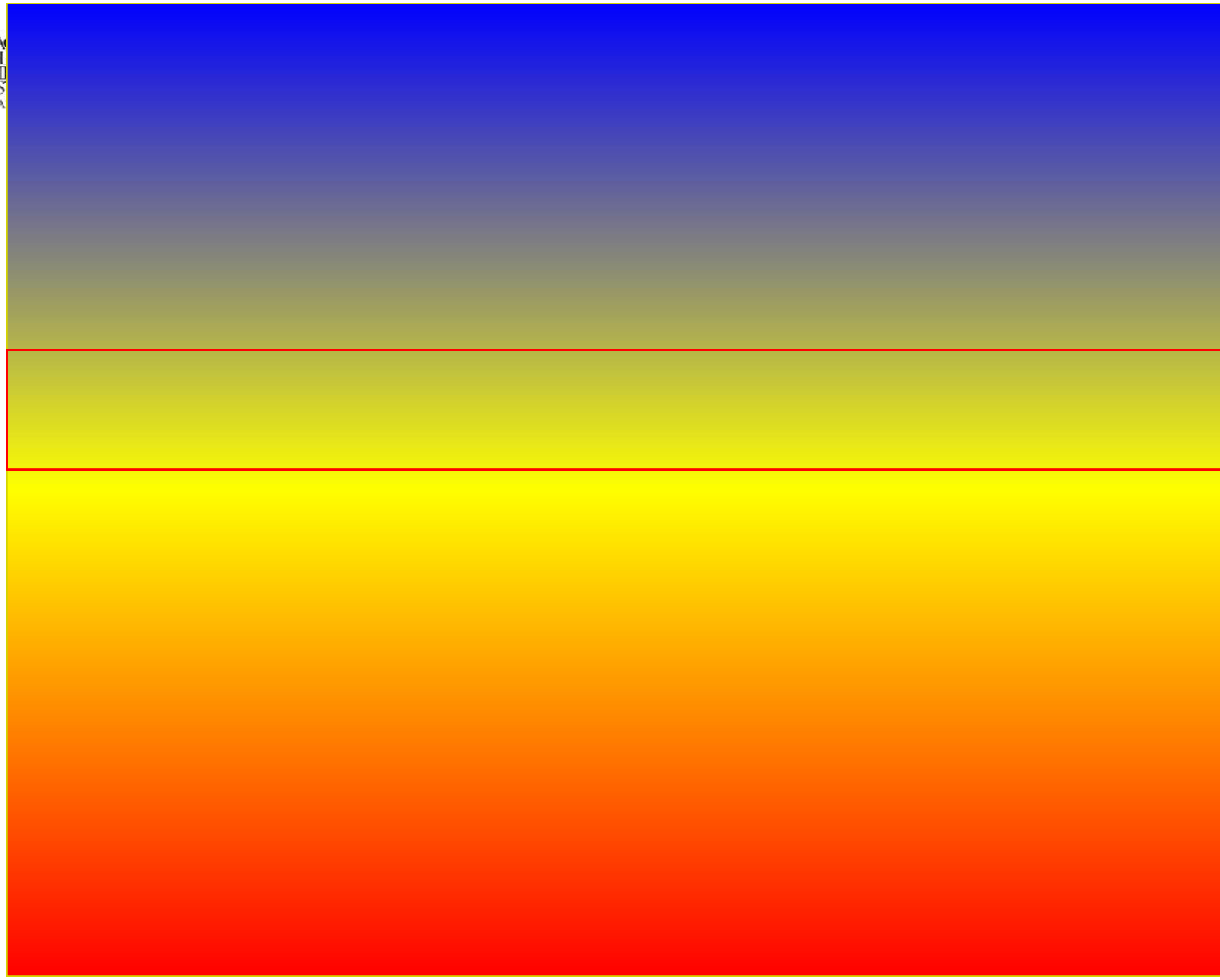


Left: a picture of the Configurable Slit Unit showing a mask configuration. Right: a close-up showing the black knife-edge slits. (from McLean et al. 2010, SPIE 7735m 77351E)


MOSFIRE slit: 0.7”x 7.1”
1 pixel = 0.1arcsec (ACS rebinned 2x2)

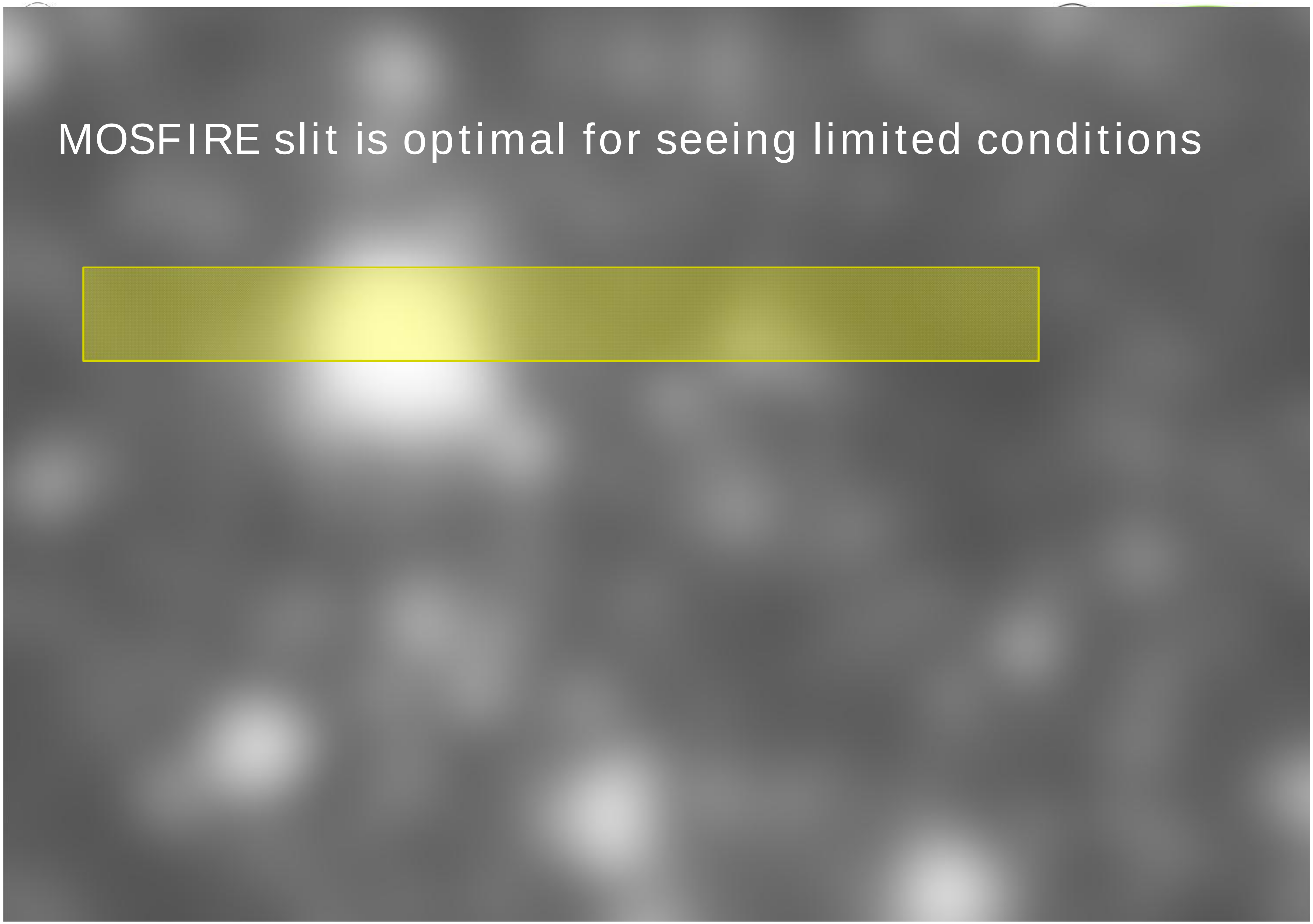
MOSFIRE slit

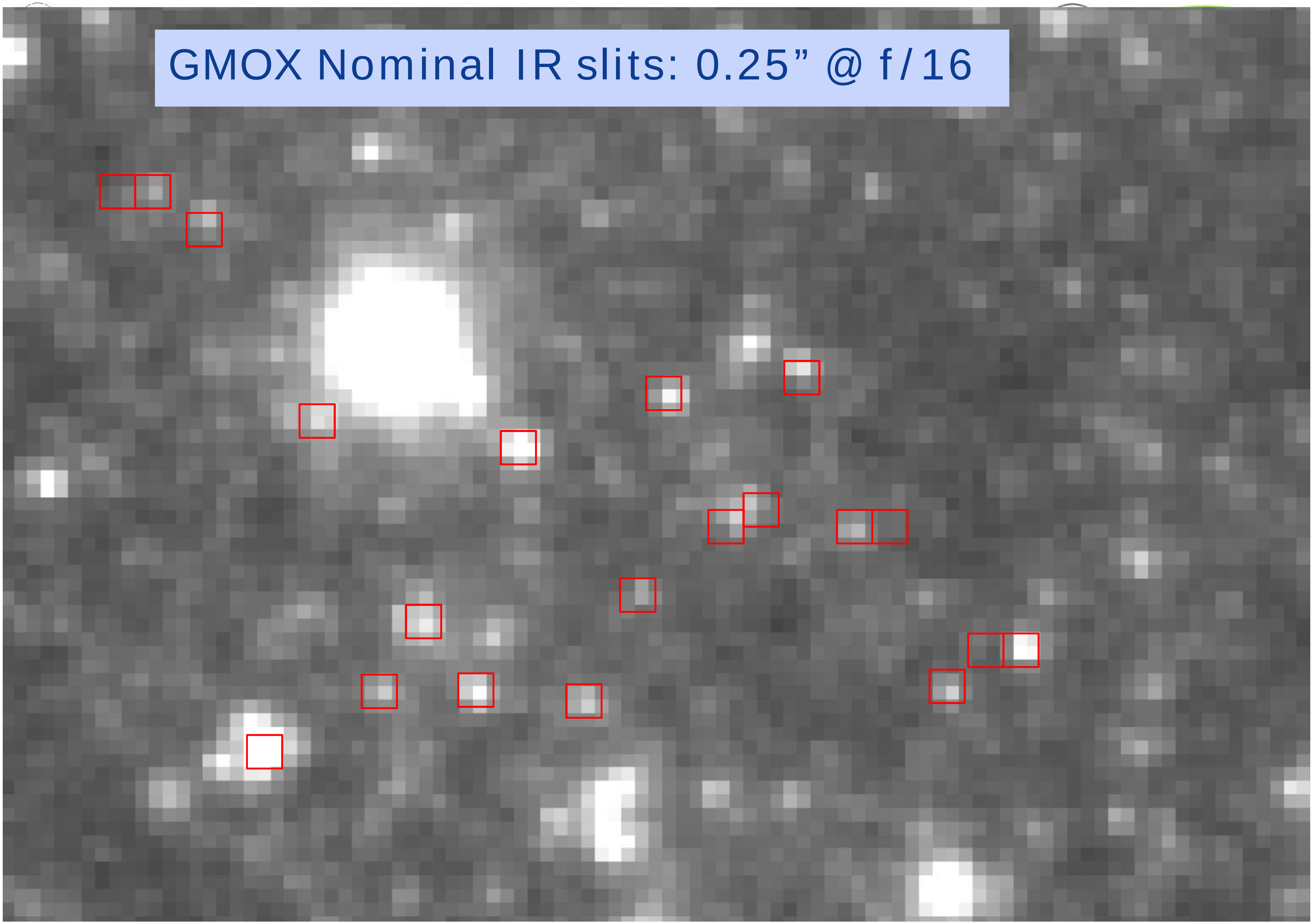




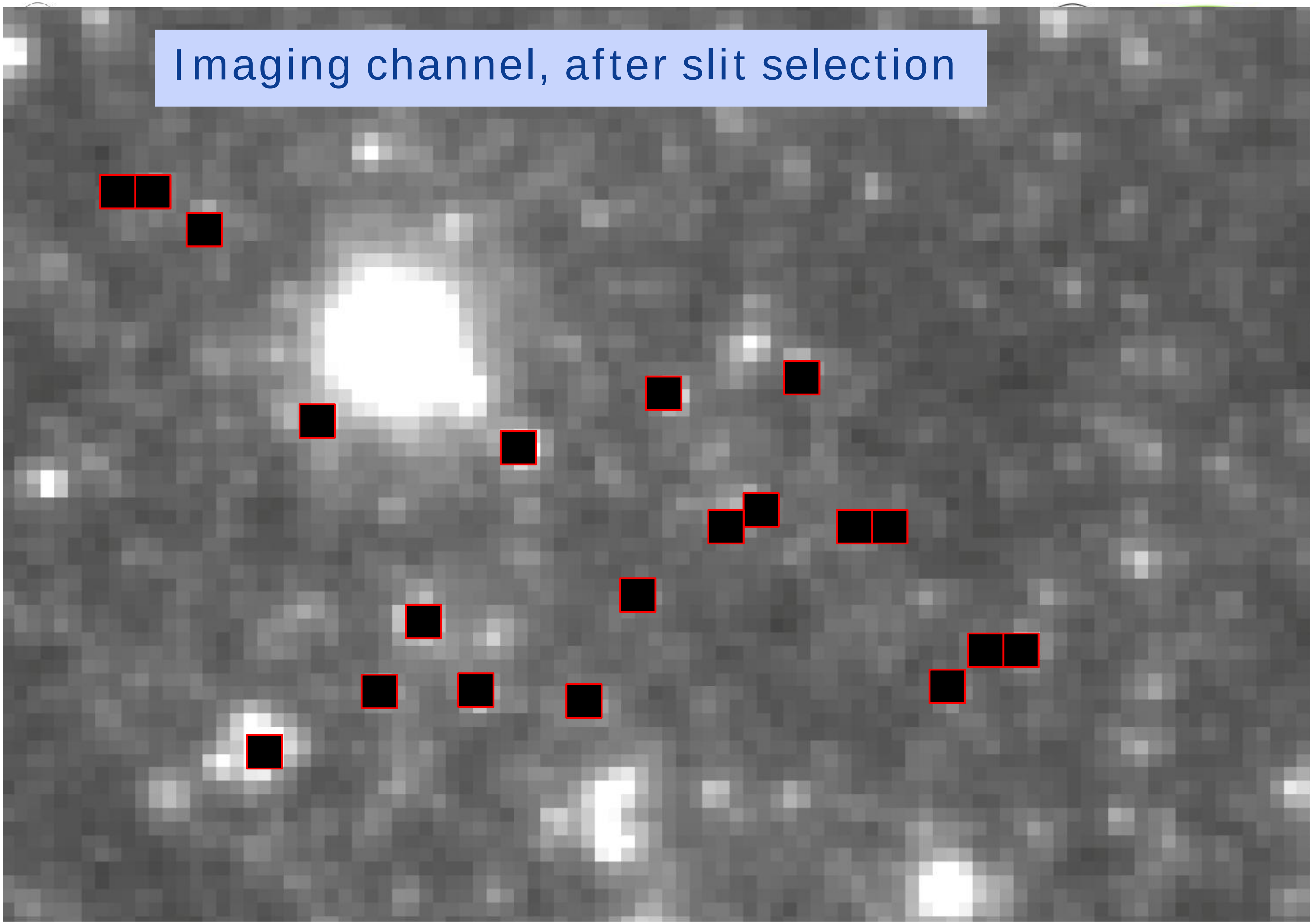
MOSFIRE Spectrum (cartoon)

MOSFIRE slit is optimal for seeing limited conditions

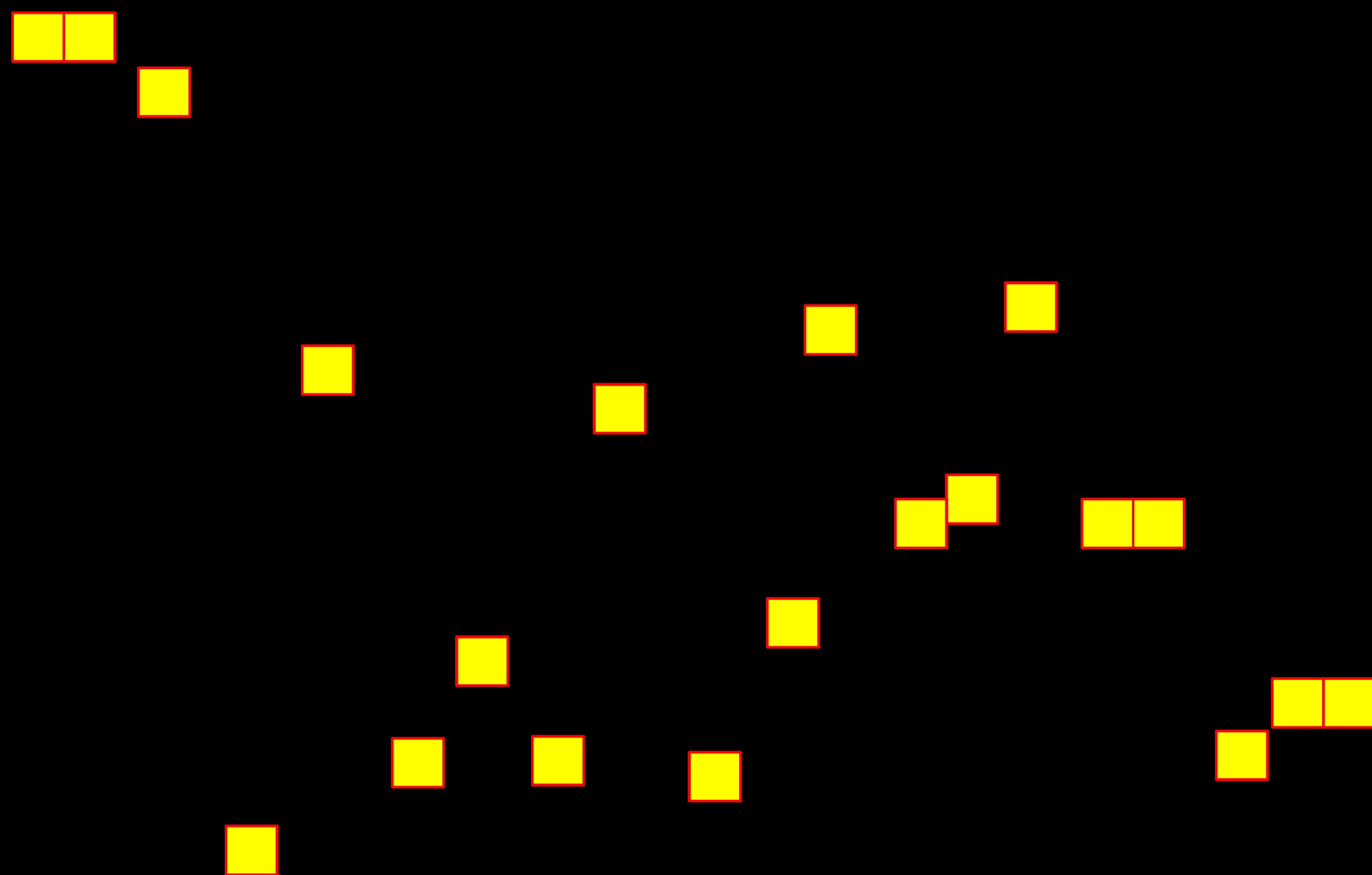


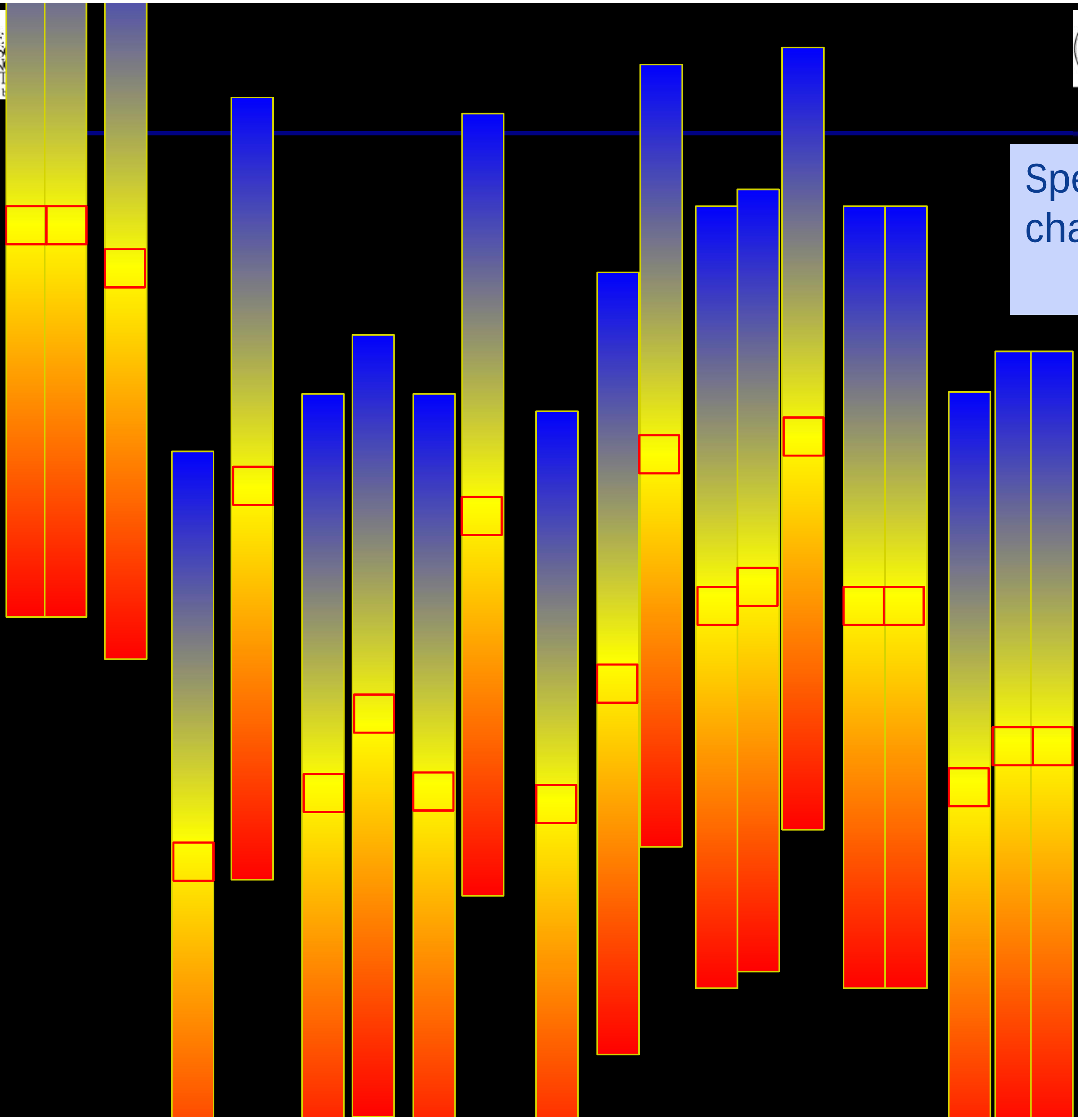

GMOX Nominal IR slits: 0.25” @ f/16

Imaging channel, after slit selection



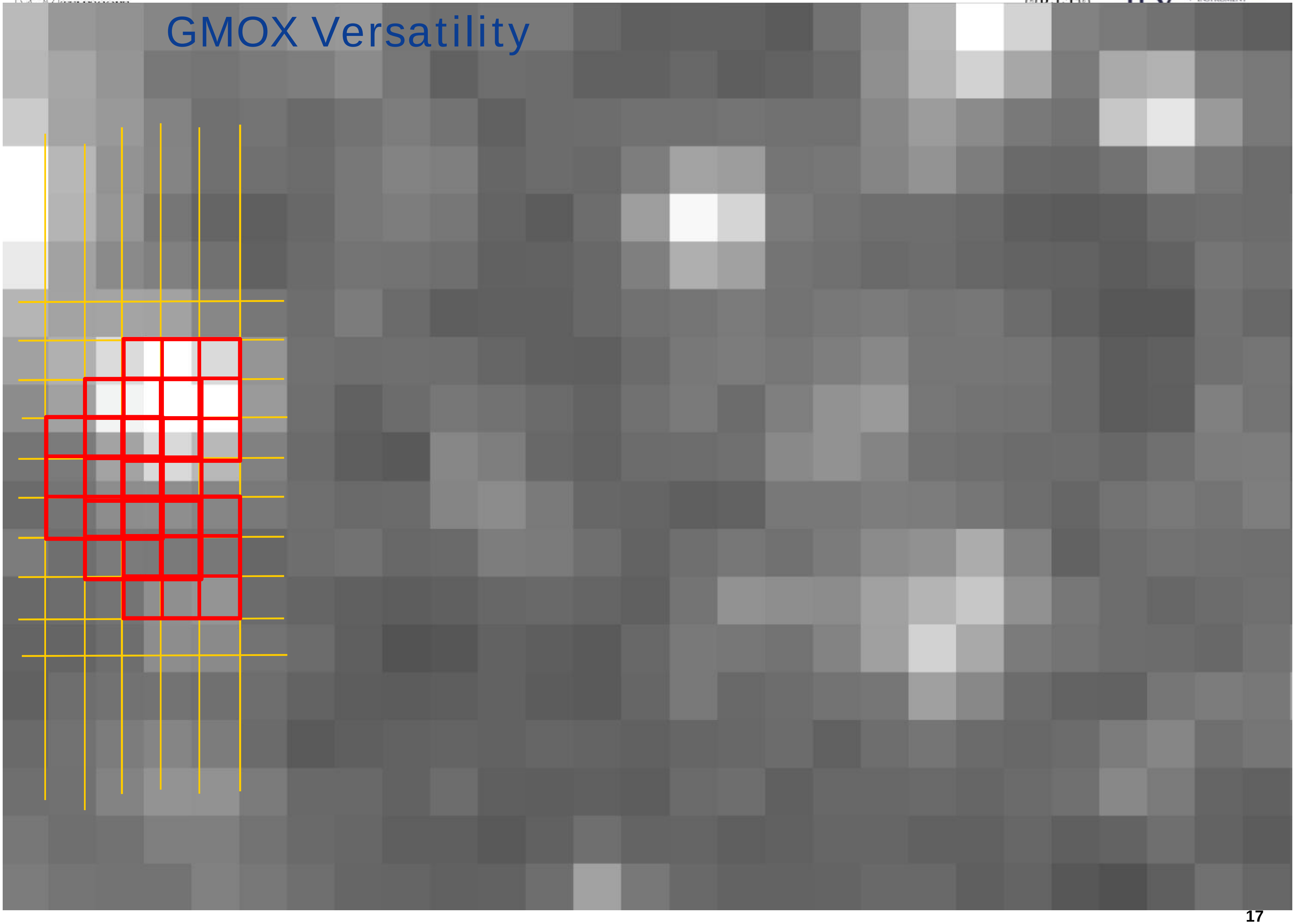
Spectroscopic channel (no grating)



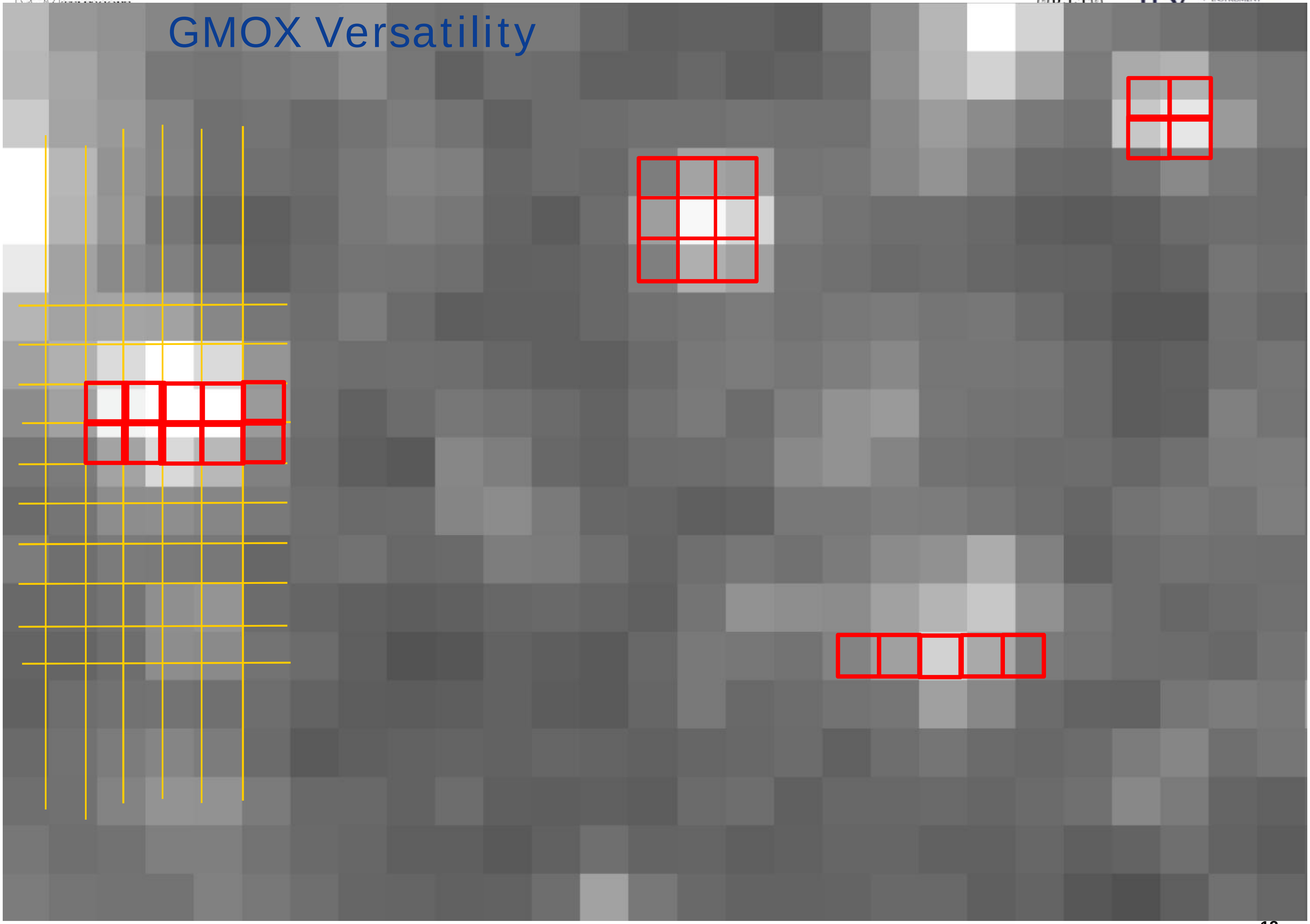


Spectroscopic channel (actual)

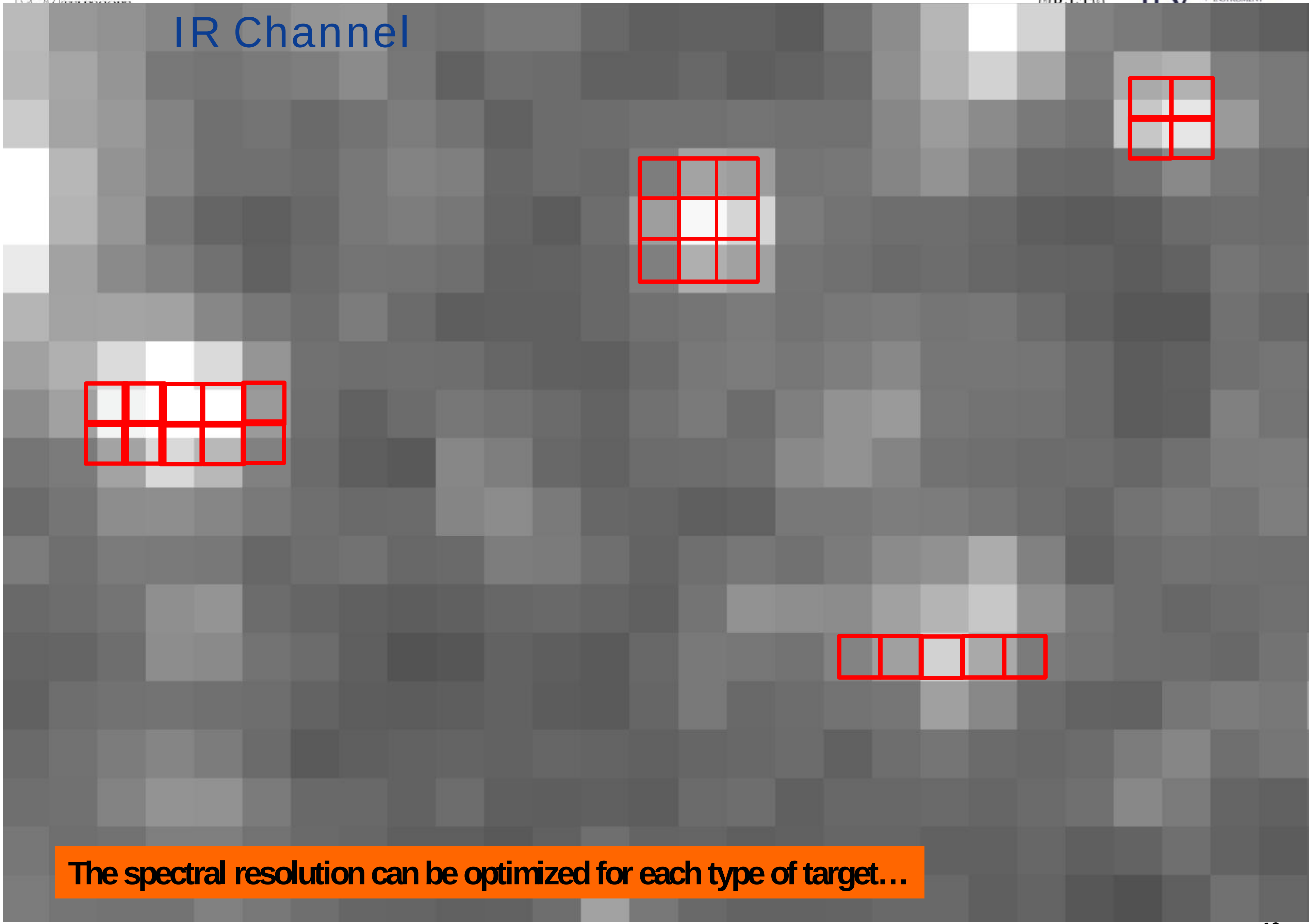
GMOX Versatility



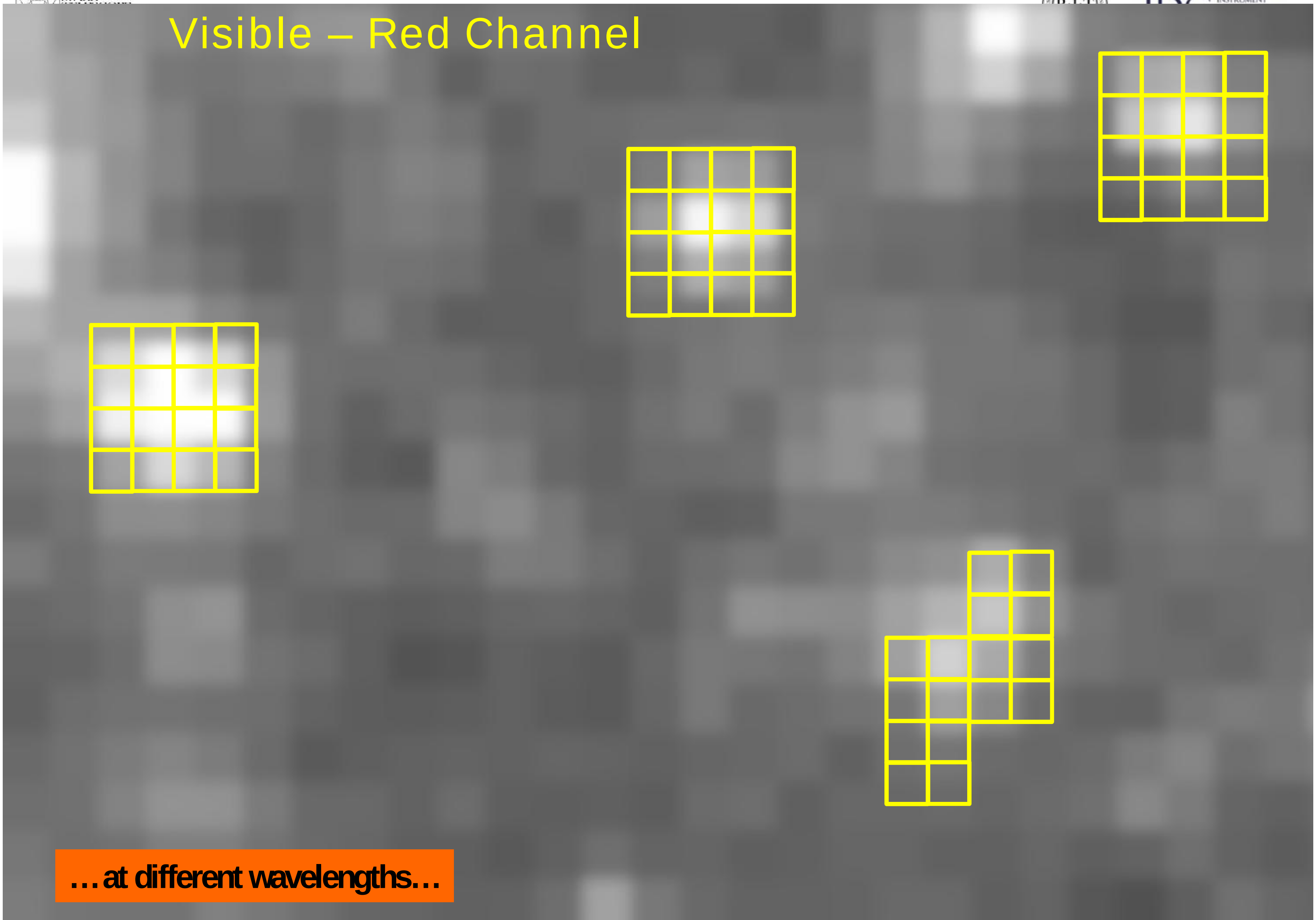
GMOX Versatility



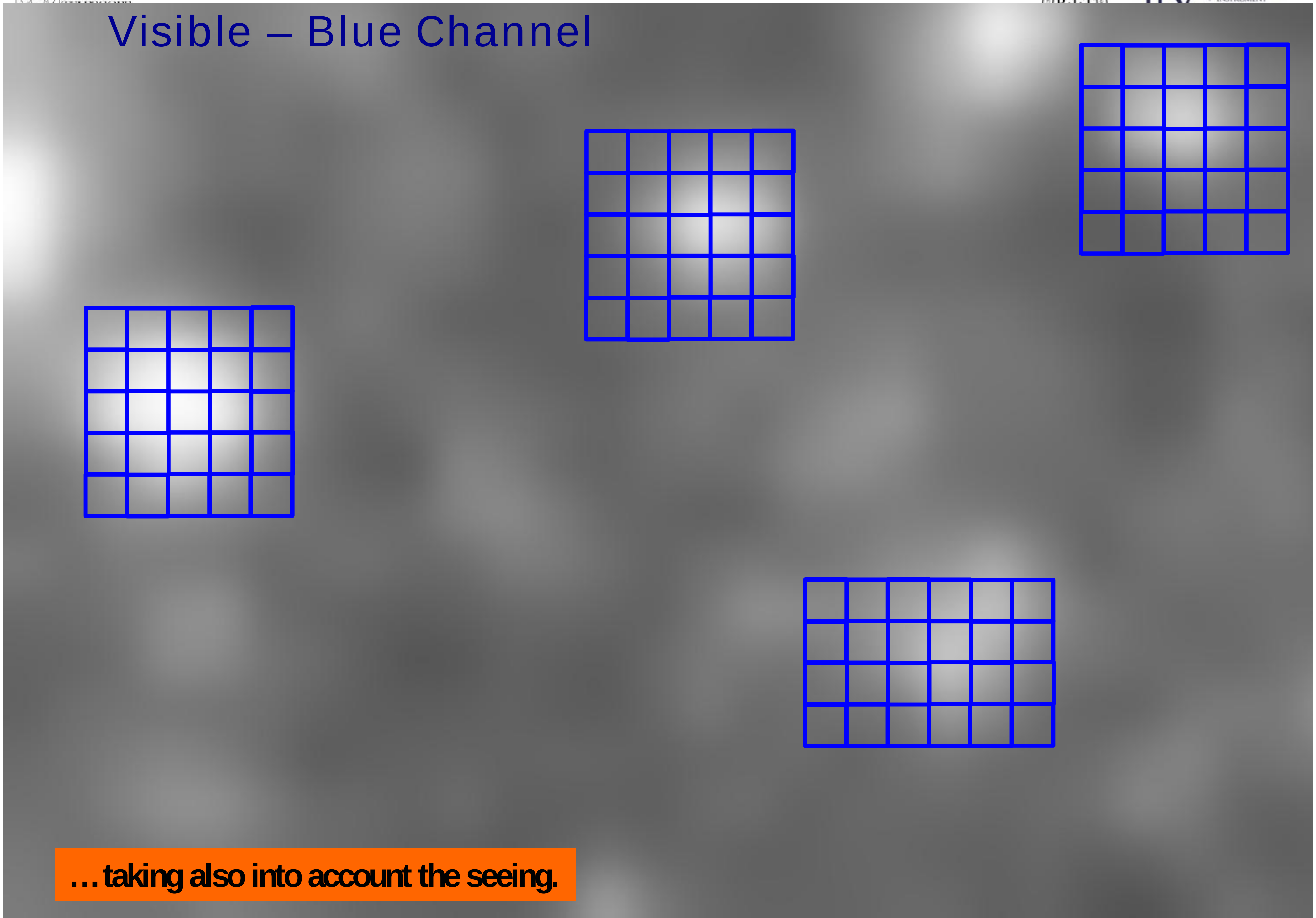
IR Channel


The spectral resolution can be optimized for each type of target…

Visible – Red Channel



Visible – Blue Channel



…taking also into account the seeing.

Slit losses due to misalignment

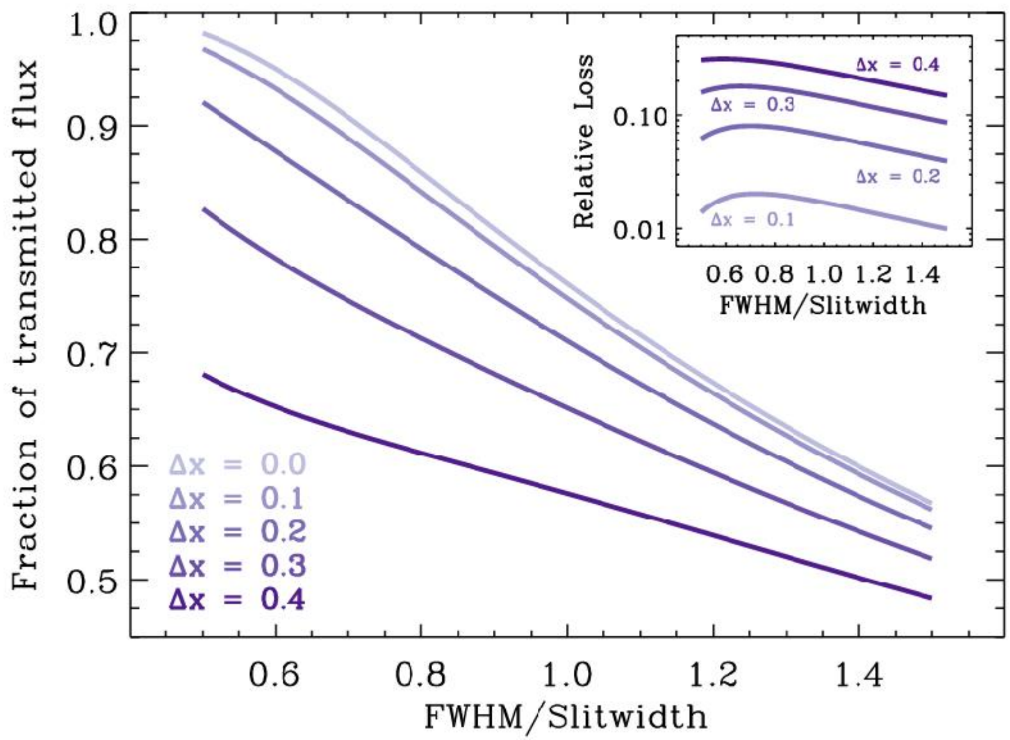
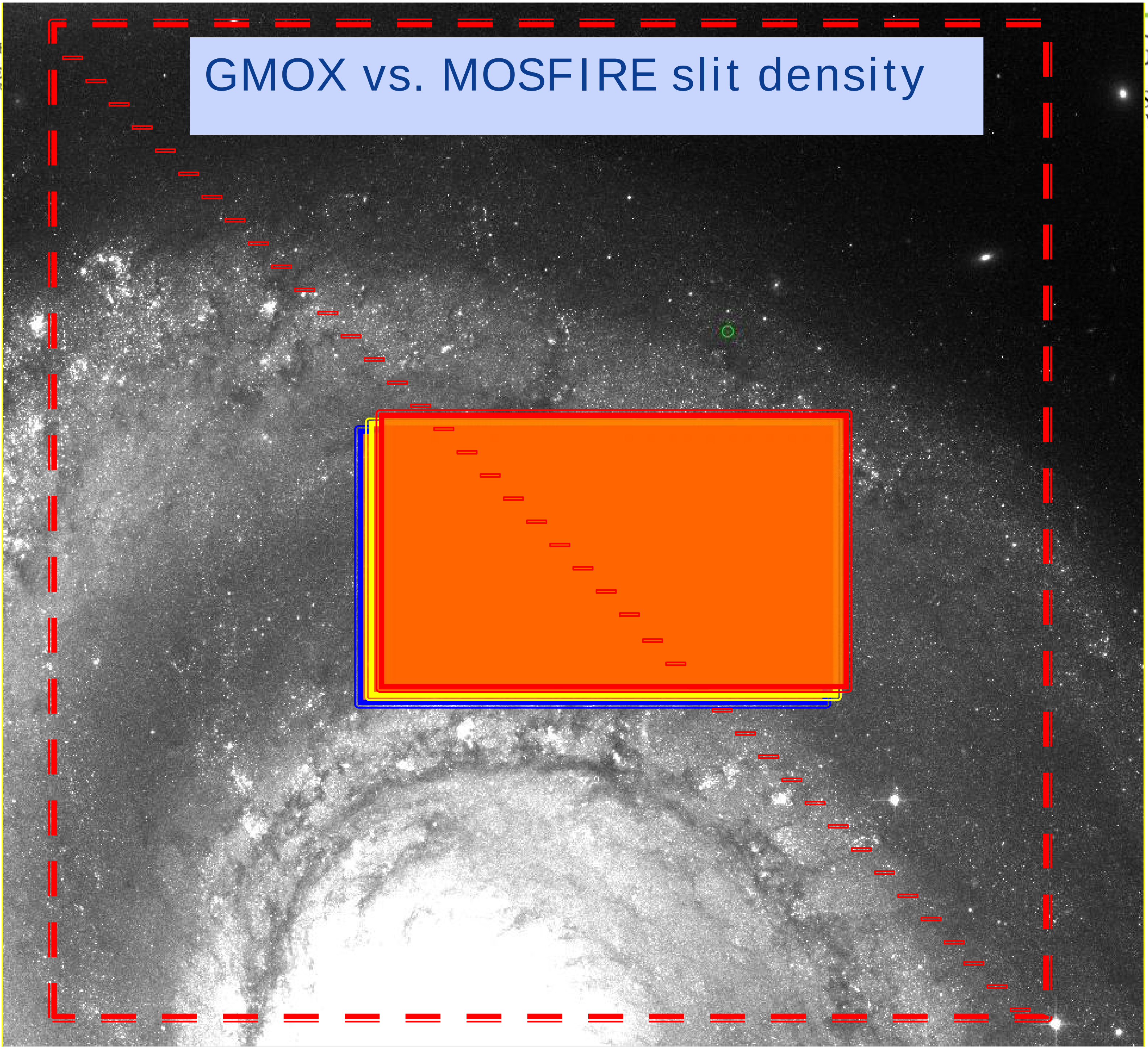


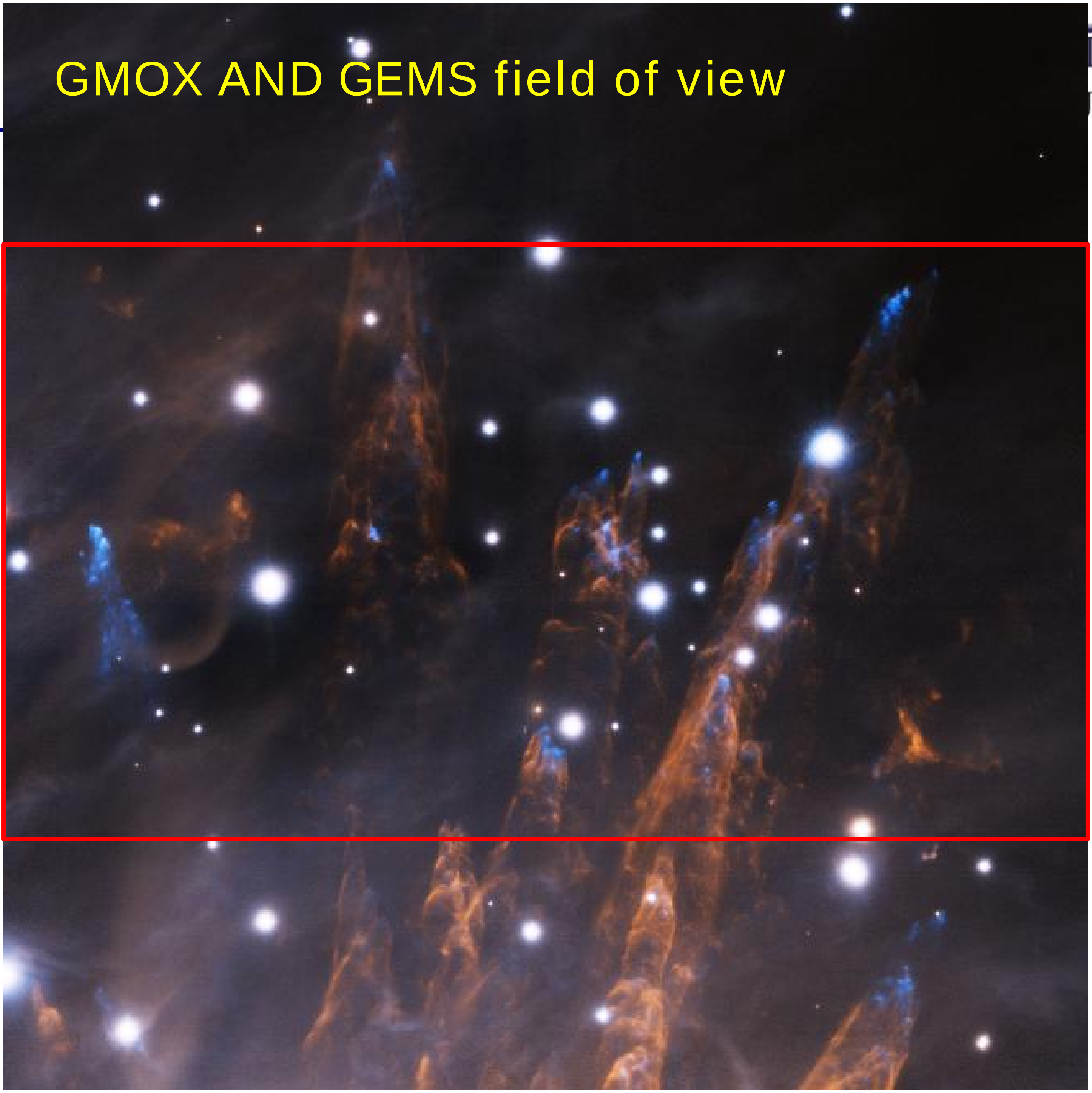
Fig. 2. Fraction of transmitted flux as a function of FWHM-to-slitwidth ratio, for a Gaussian point source that is displaced perpendicular to the slit by a fractional amount of the slitwidth, $\Delta x = (x - x_0)/w$. The inset panel shows the flux loss relative to the case where the object is perfectly centred within the slit. A slitlength $l = 10\,w$ is assumed.

http://arxiv.org/pdf/1402.5970.pdf

GMOX vs. MOSFIRE slit density



GMOX AND GEMS field of view



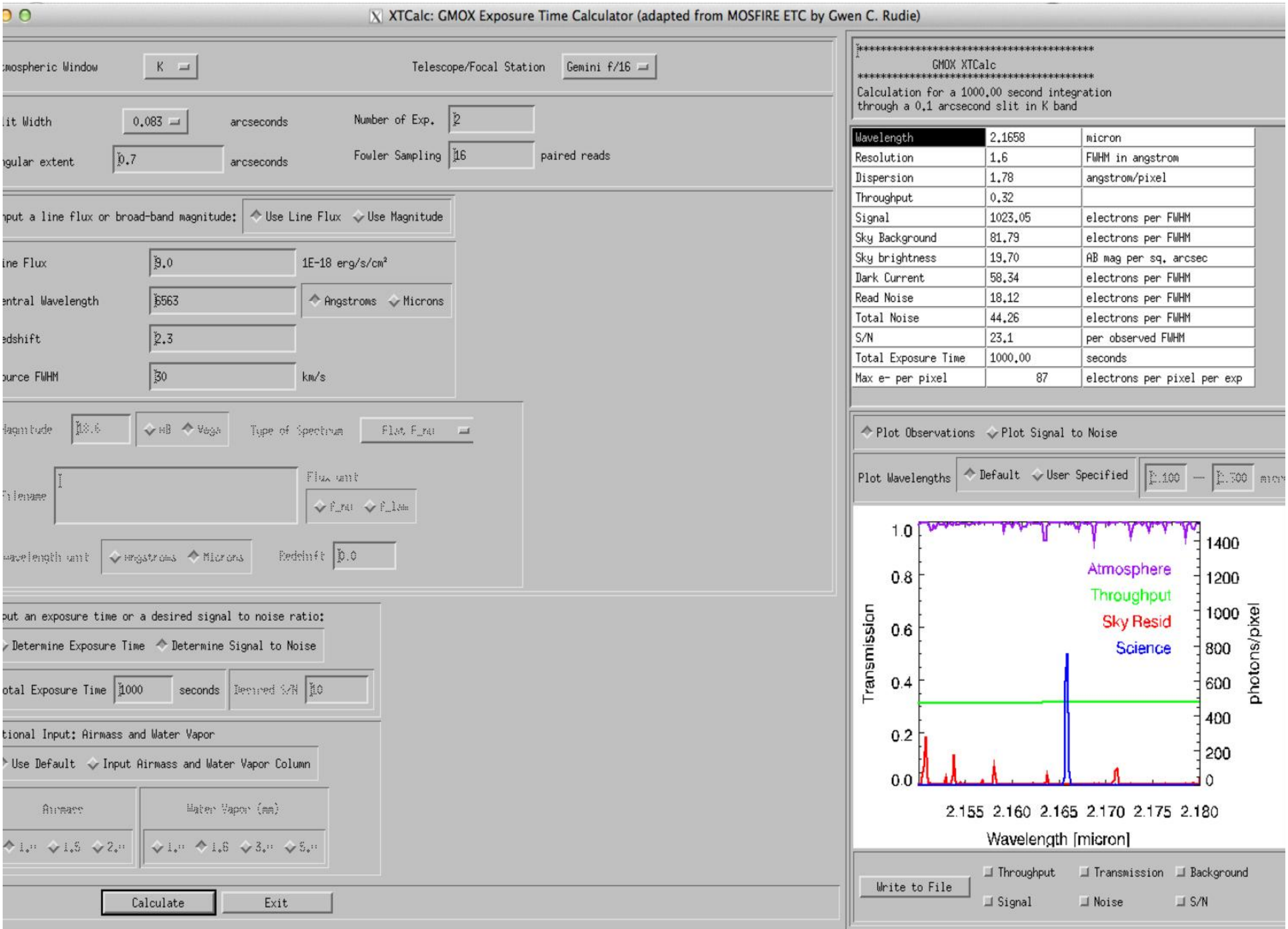
GMOX Exposure Time Calculator

- **Available at**
  - https://stsci.box.com/s/v0nf7m1ajp5zh545mesgy11m8kr2dvv8

- **Adapted from MOSFIRE ETC developed by Gwen C. Rudie in IDL**
  - Runs under IDL 8.0 or higher

1. Download and unzip GMOX_ETC_2015Sep24.zip
2. Start the IDL session
3. In the IDL session run:

```
IDL> .r run_XTcalc
IDL> .r XTcalc
IDL> .r events_XTcalc
IDL> run_XTcalc
```


XTCalc: GMOX Exposure Time Calculator (adapted from MOSFIRE ETC by Gwen C. Rudie)
mospheric Window
K
Telescope/Focal Station
Gemini f/16
it Width
0.083
arcseconds
Number of Exp.
2
gular extent
0.7
arcseconds
Fowler Sampling
16
paired reads
nput a line flux or broad-band magnitude:
Use Line Flux
Use Magnitude
ine Flux
9.0
1E-18 erg/s/cm²
entral Wavelength
6563
Angstroms
Microns
edshift
2.3
ource FWHM
30
km/s
put an exposure time or a desired signal to noise ratio:
Determine Exposure Time
Determine Signal to Noise
otal Exposure Time
1000
seconds
tional Input: Airmass and Water Vapor
Use Default
Input Airmass and Water Vapor Column
Calculate
Exit
GMOX XTCalc
Calculation for a 1000.00 second integration
through a 0.1 arcsecond slit in K band
Wavelength 2.1658 micron
Resolution 1.6 FWHM in angstrom
Dispersion 1.78 angstrom/pixel
Throughput 0.32
Signal 1023.05 electrons per FWHM
Sky Background 81.79 electrons per FWHM
Sky brightness 19.70 AB mag per sq. arcsec
Dark Current 58.34 electrons per FWHM
Read Noise 18.12 electrons per FWHM
Total Noise 44.26 electrons per FWHM
S/N 23.1 per observed FWHM
Total Exposure Time 1000.00 seconds
Max e- per pixel 87 electrons per pixel per exp
Plot Observations
Plot Signal to Noise
Plot Wavelengths
Default
User Specified
Atmosphere
Throughput
Sky Resid
Science
Transmission
photons/pixel
Wavelength [micron]
Write to File
Throughput
Transmission
Background
Signal
Noise
S/N

Summary of performance

GMOX at f/16: Gemini North and South without AO; Gemini North with ALTAIR

Field of View Sampling	171" × 90" 83 mas/micromirror				
	Blue Arm	Red Arm	IR Arm		
	3200 – 5890 Å	5890 – 9700 Å	YJ: 0.97 – 1.35 μm	H: 1.46 – 1.81 μm	K: 1.83 – 2.45 μm (K)
	Nominal: GLAO 0.3″ Seeing at V				
Mirrors/slit	5	4	3	3	3
Slit Width	0.42″	0.33″	0.25″	0.25″	0.25″
$R = \lambda/\Delta\lambda$	4500	4500	3700	4500	4500
sampling (pixel/slit)	3	3	2.75	2.75	2.75
AB limit mag.	21.6	21.3	21.6	21.1	20.9
	Regular Seeing: 0.6″ Seeing at V				
Mirrors/slit	12	10	8	8	8
Slit Width	1.00″	0.83″	0.67″	0.67″	0.67″
$R = \lambda/\Delta\lambda$	1875	1800	1590	1930	1930
sampling (pixel/slit)	7.2	7.5	7.3	7.3	7.3
AB limit mag.	21.4	21.0	20.5	19.3	19.8
	ALTAIR: FWHM = 0.05″ at J				
Mirrors/slit	3	2	1	1	1
Slit Width	0.25″	0.16″	0.08″	0.08″	0.08″
$R = \lambda/\Delta\lambda$	7500	9000	11100	13500	13500
sampling (pixel/slit)	1.8	1.5	0.9	0.9	0.9
AB limit mag.	21.8	21.5	22.3	22.3	21.9

Table 3: GMOX spectrograph characteristics.

AB limit magnitude in 3600s, SNR=10 per pixel

GMOX Total Throughput

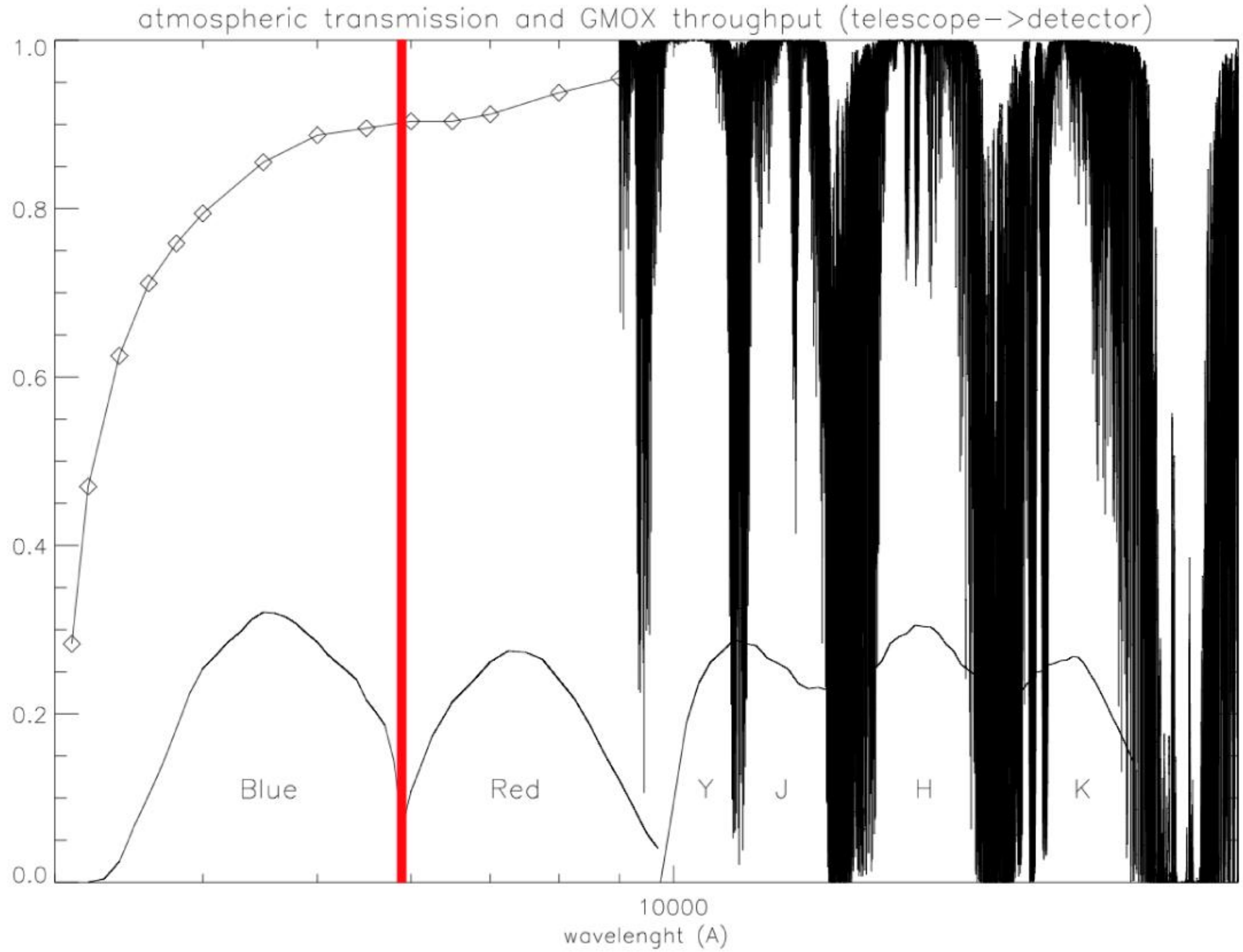
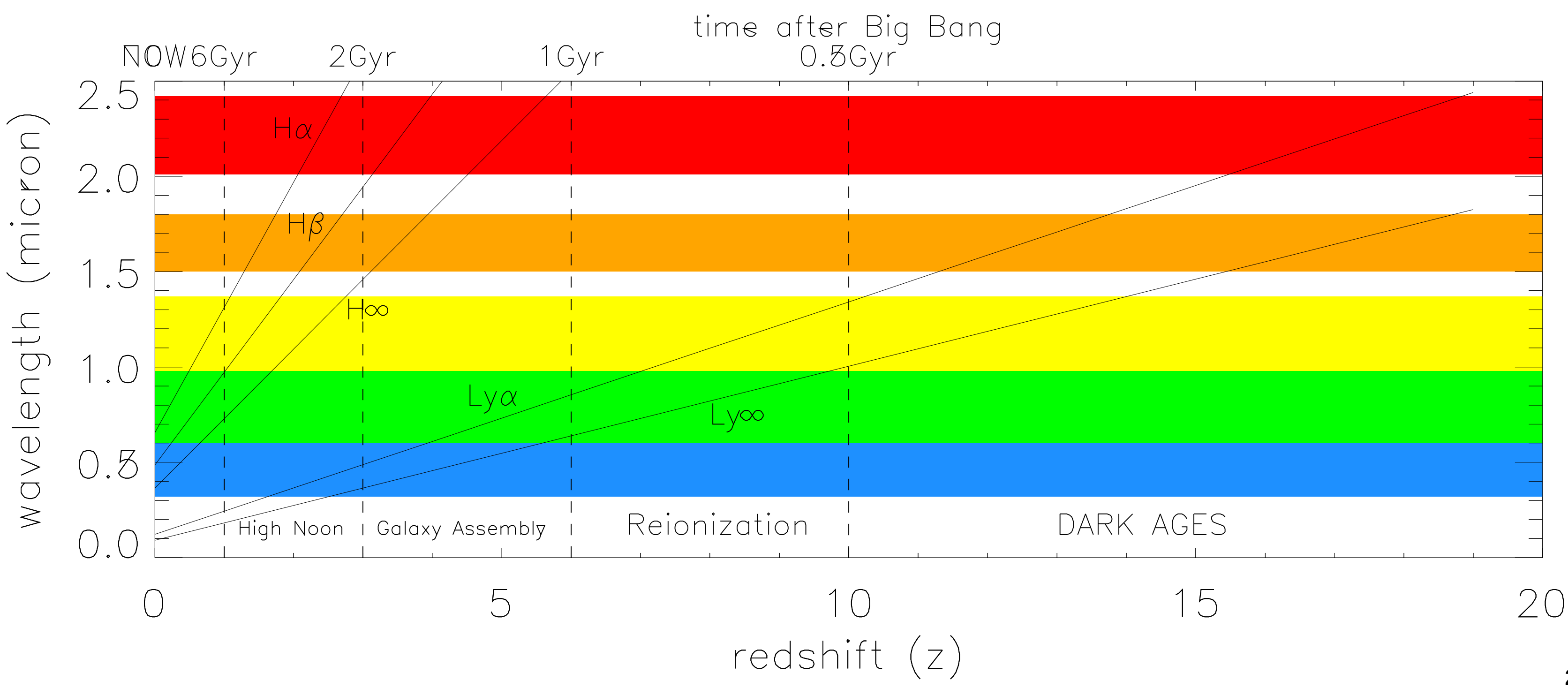


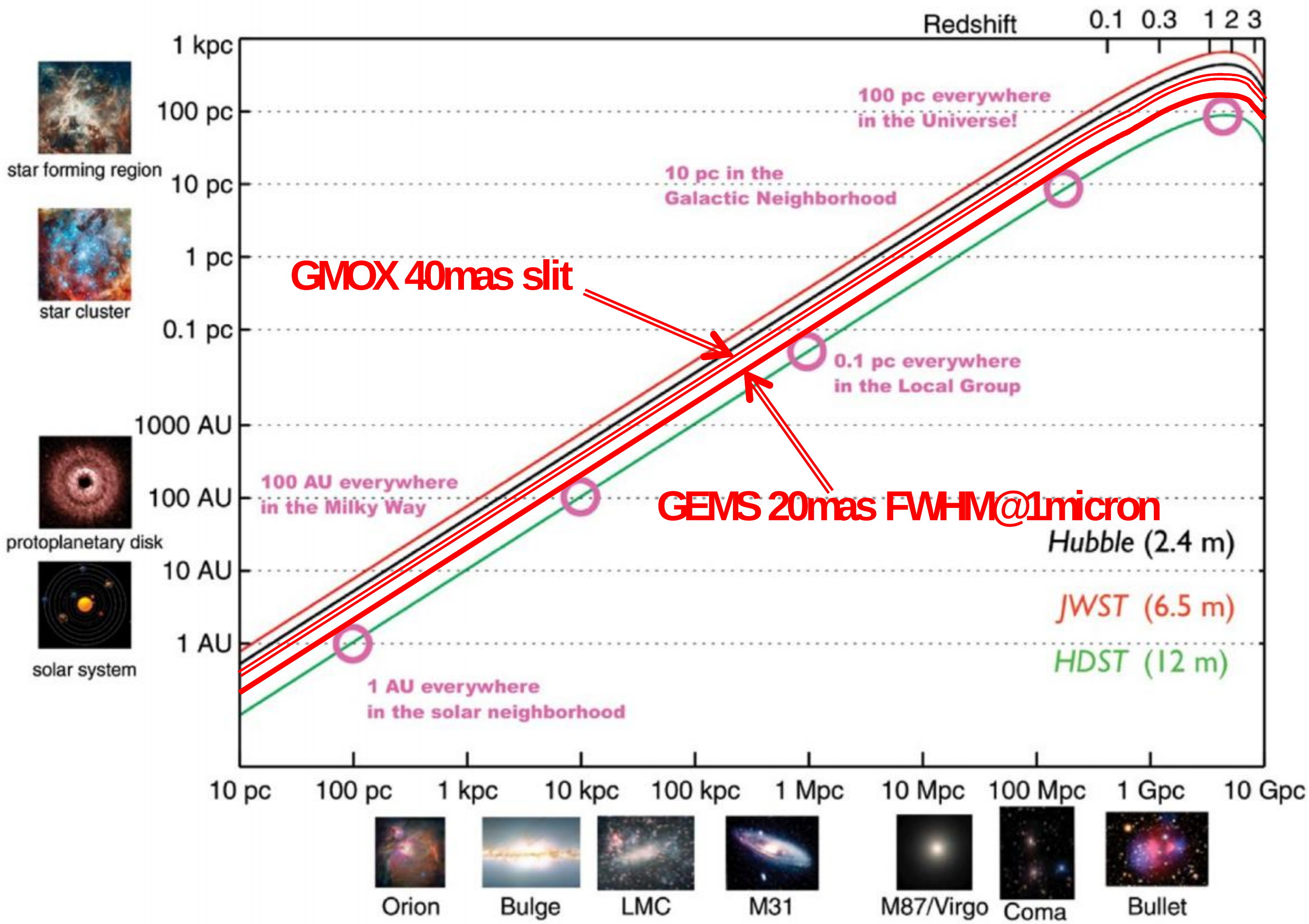
Figure 17: Predicted GMOX throughput from the telescope to the detectors included, together with the atmospheirc transmission at Mauna Kea. The red line indicates the 5890Åline of the Na laser.

1. Galaxy Evolution

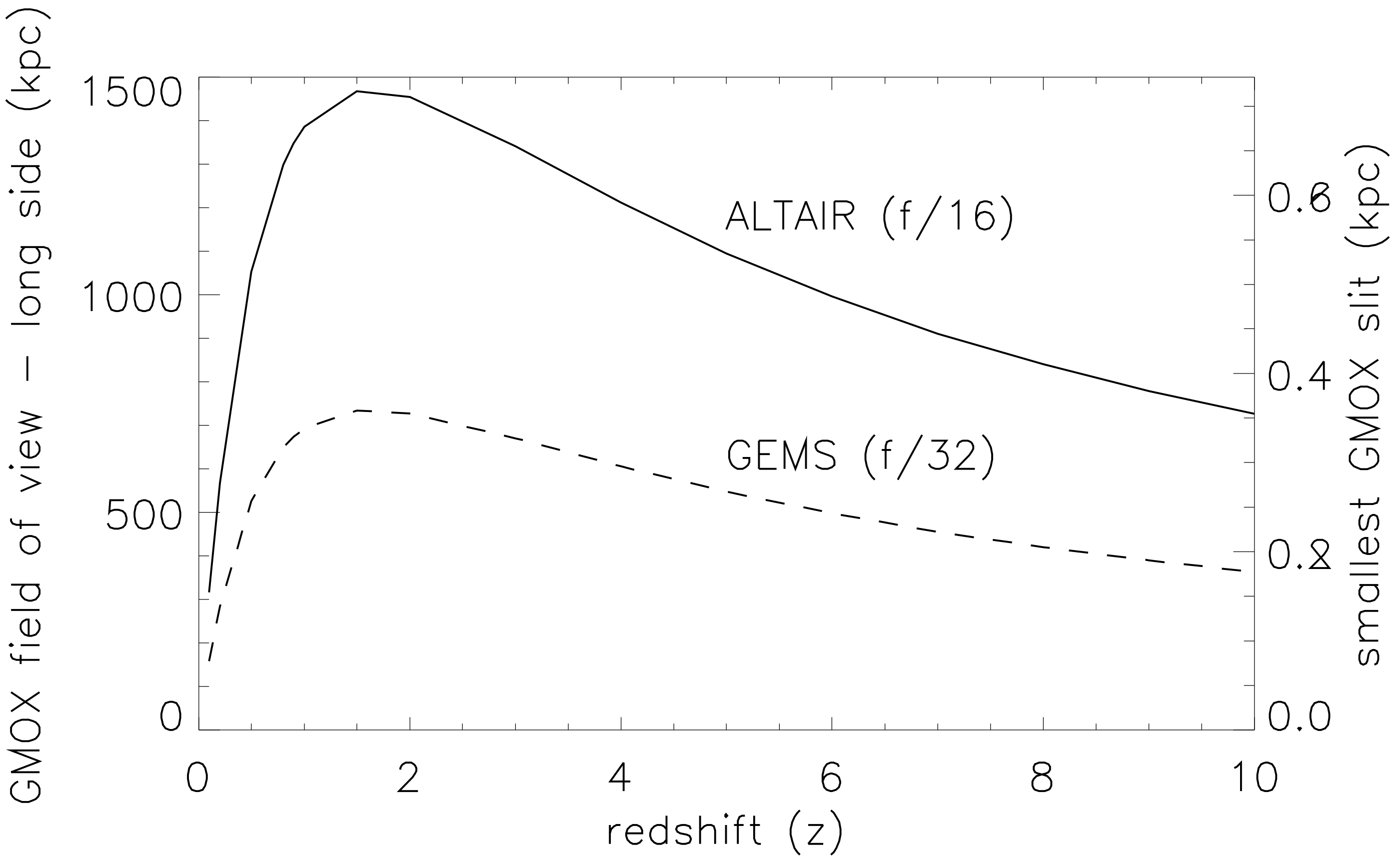
Phase	Cosmic Time	Redshift range
"Dark ages"	< 500Myr	>10
Reionization	500Myr - 1Gyr	6<z<10
Galaxy building	1Gyr-2Gyr	3<z<6
"High noon"	2Gyr – 6Gyr	1<z<3



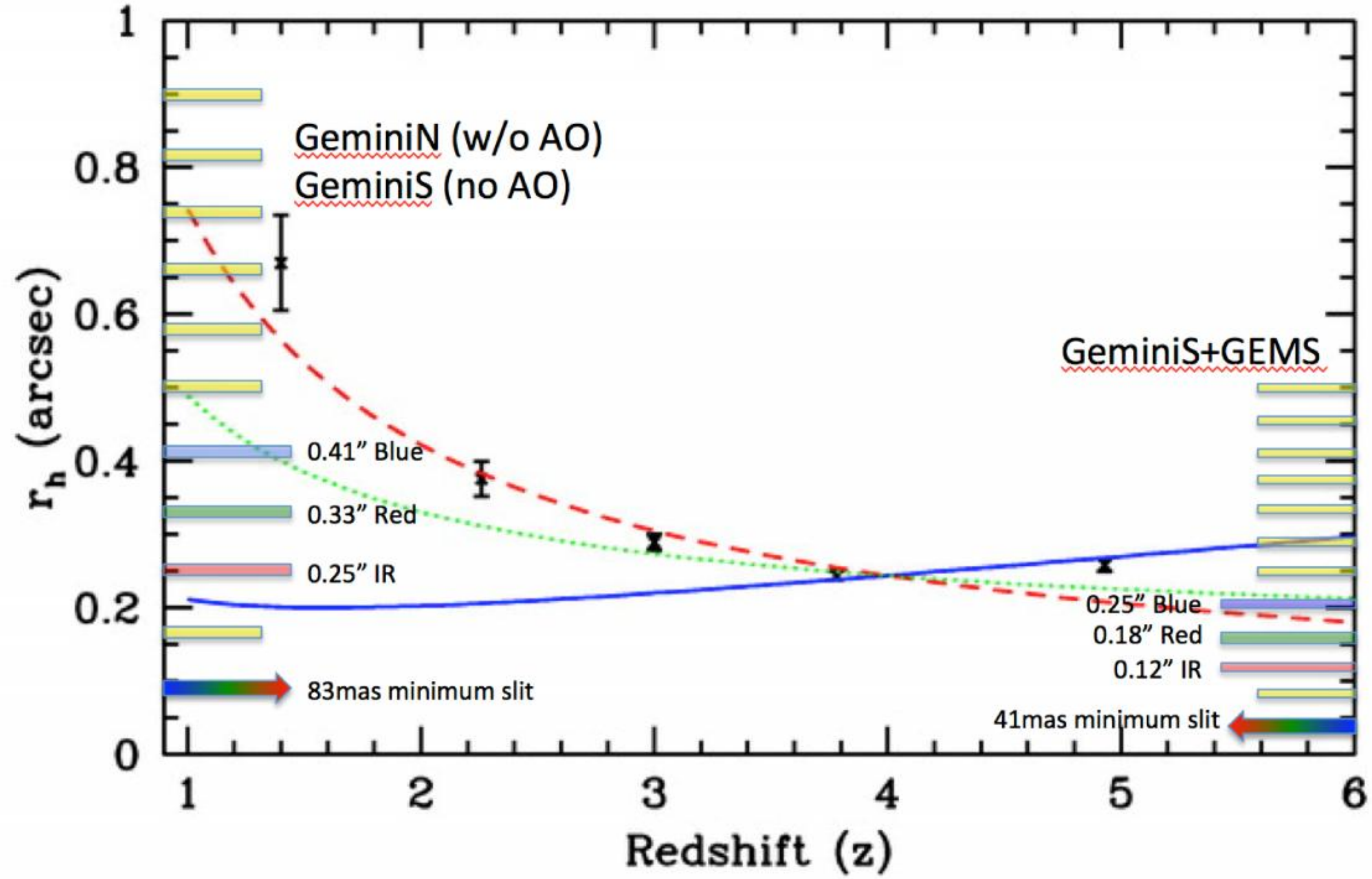
GMES+GMOX vs. space



GMOX slits: <700pc/350pc everywhere in the Universe



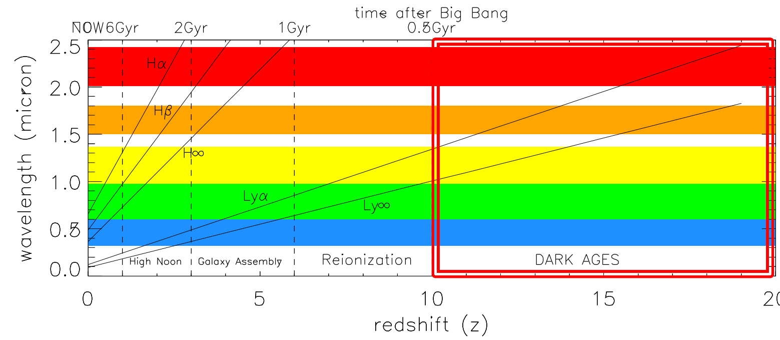
GMOX slit vs. galaxy size



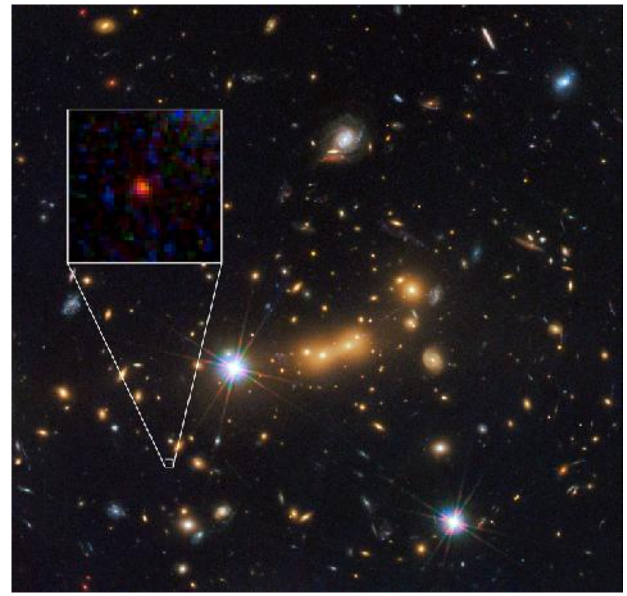
Ferguson et al.

1. Galaxy Evolution

1.1 Dark ages and primordial objects



- First 500 Myr of cosmic history, “Dark-Ages”; appearance of the first stars causing the reionization of the Universe.
- z>10 region
- Ly-break in the near-IR: JWST regime



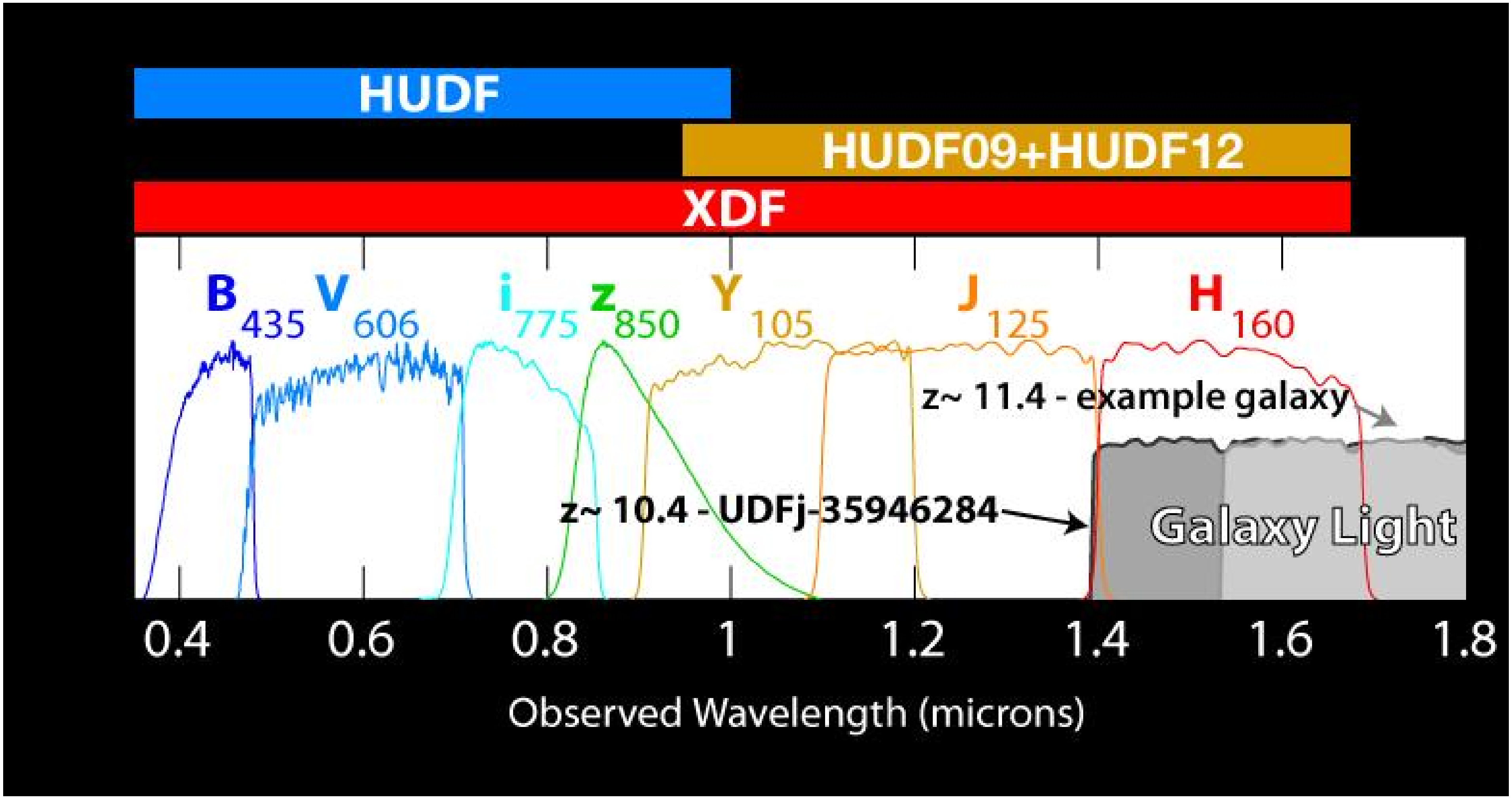
Example:

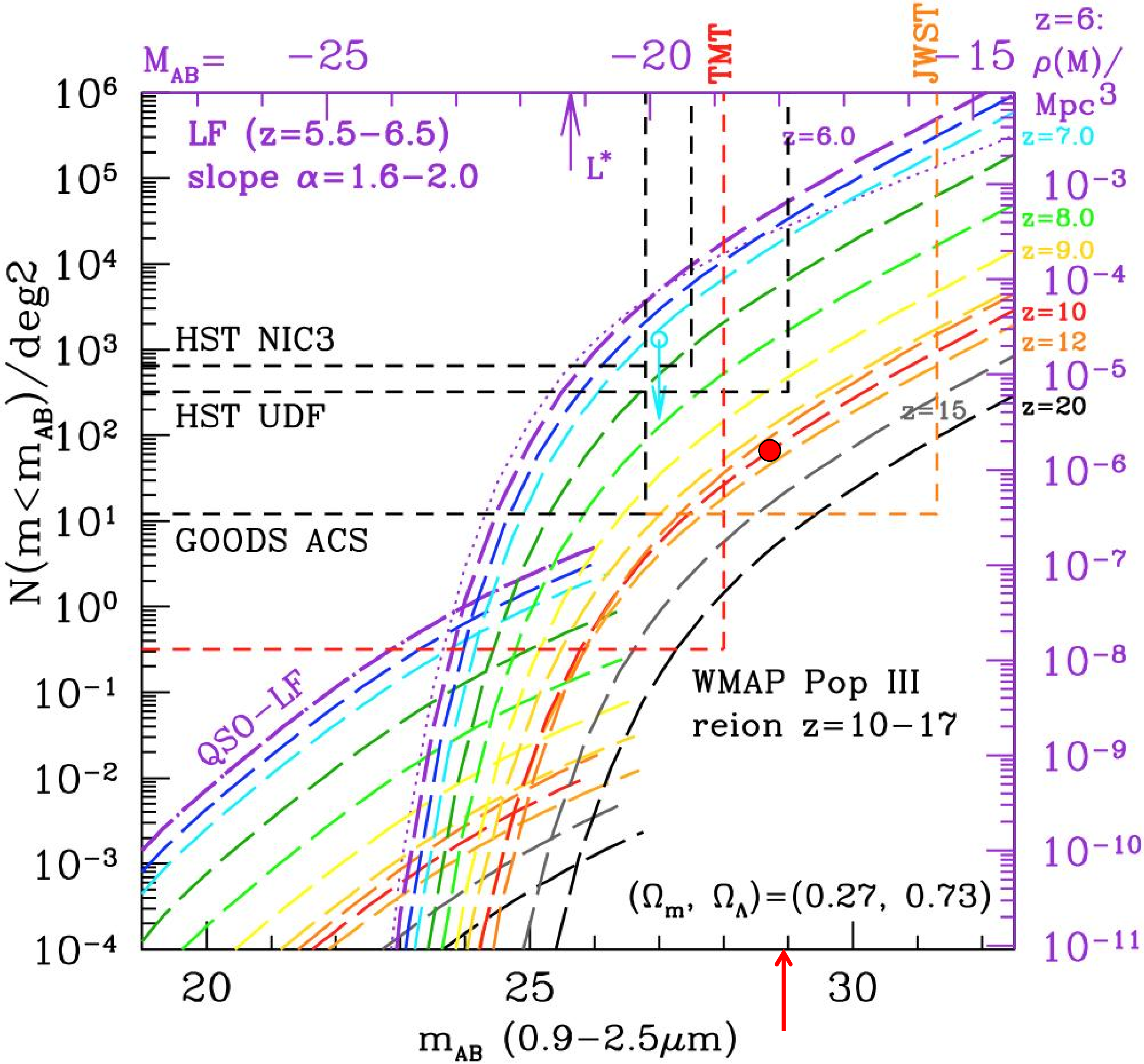
MACS0647 z~10.7 candidate in HST CLASH FIELD

GMOX science:

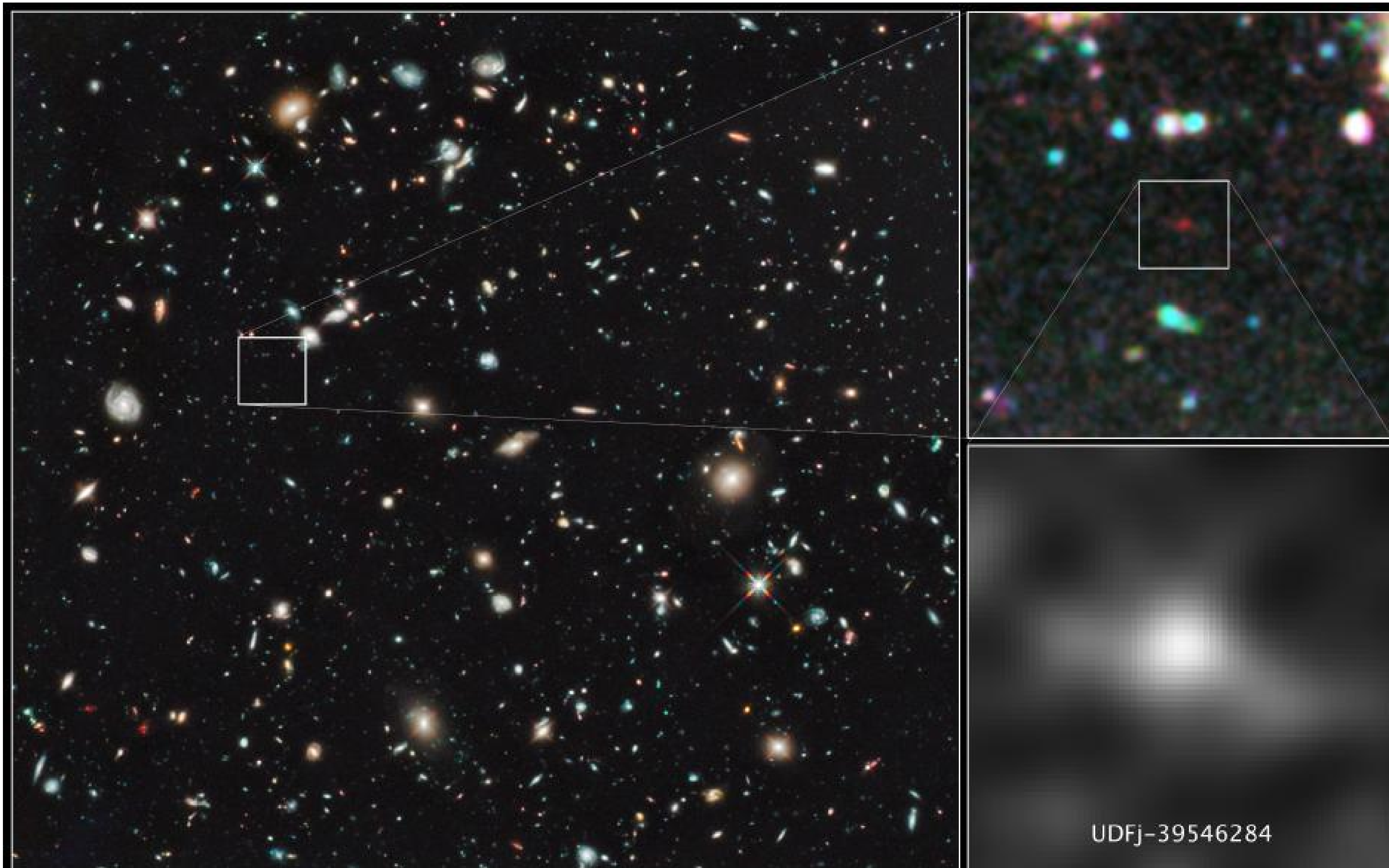
- **identify low redshift interlopers against good JWST candidates**
- **lensed high-z candidates in clusters of galaxies will provide hundreds of deep spectra of lensing and lensed galaxies (these observations require tens of hours)**

HST vs JWST territory





M_AB= −25 −20 −15
TMT
JWST
z=6: ρ(M)/Mpc^3
LF (z=5.5−6.5)
slope α=1.6−2.0
L*
z=6.0
z=7.0
z=8.0
z=9.0
z=10
z=12
z=15
z=20
HST NIC3
HST UDF
GOODS ACS
QSO−LF
WMAP Pop III
reion z=10−17
(Ωm, ΩΛ)=(0.27, 0.73)
N(m<m_AB)/deg2
m_AB (0.9−2.5μm)
20 25 30
10^6 10^5 10^4 10^3 10^2 10^1 10^0 10^−1 10^−2 10^−3 10^−4
10^−3 10^−4 10^−5 10^−6 10^−7 10^−8 10^−9 10^−10 10^−11



Hubble Ultra Deep Field 2009–2010
Hubble Space Telescope • WFC3/IR

NASA, ESA, G. Illingworth and R. Bouwens (University of California, Santa Cruz), and the HUDF09 Team

STScI-PRC11-05

Test case: UDFj-39546284

- **A z=10.4 candidate with H_{AB}=28.9**
- **GEMS+GMOX to the limit:**
  - 80hr exposure
  - 40mas slit with 50mas FWHM
- **ETC returns SNR = 0.4 per pixel**
- **Spectrum spread over 2500 pixels (80% of total). Coadd SNR 0.4x50 = 20**

  - resample: 16 bands at SNR=5, R=64

  - analyze for emission lines from z~2 interloper

Requirements

- Extreme AO delivering excellent performance
- Several nights
- Dark time

- Spectroscopic information for the most primordial galaxies, at the sensitivity limit of JWST/NIRSPEC
- Spectroscopy of thousand of sources in the fundamental deep fields

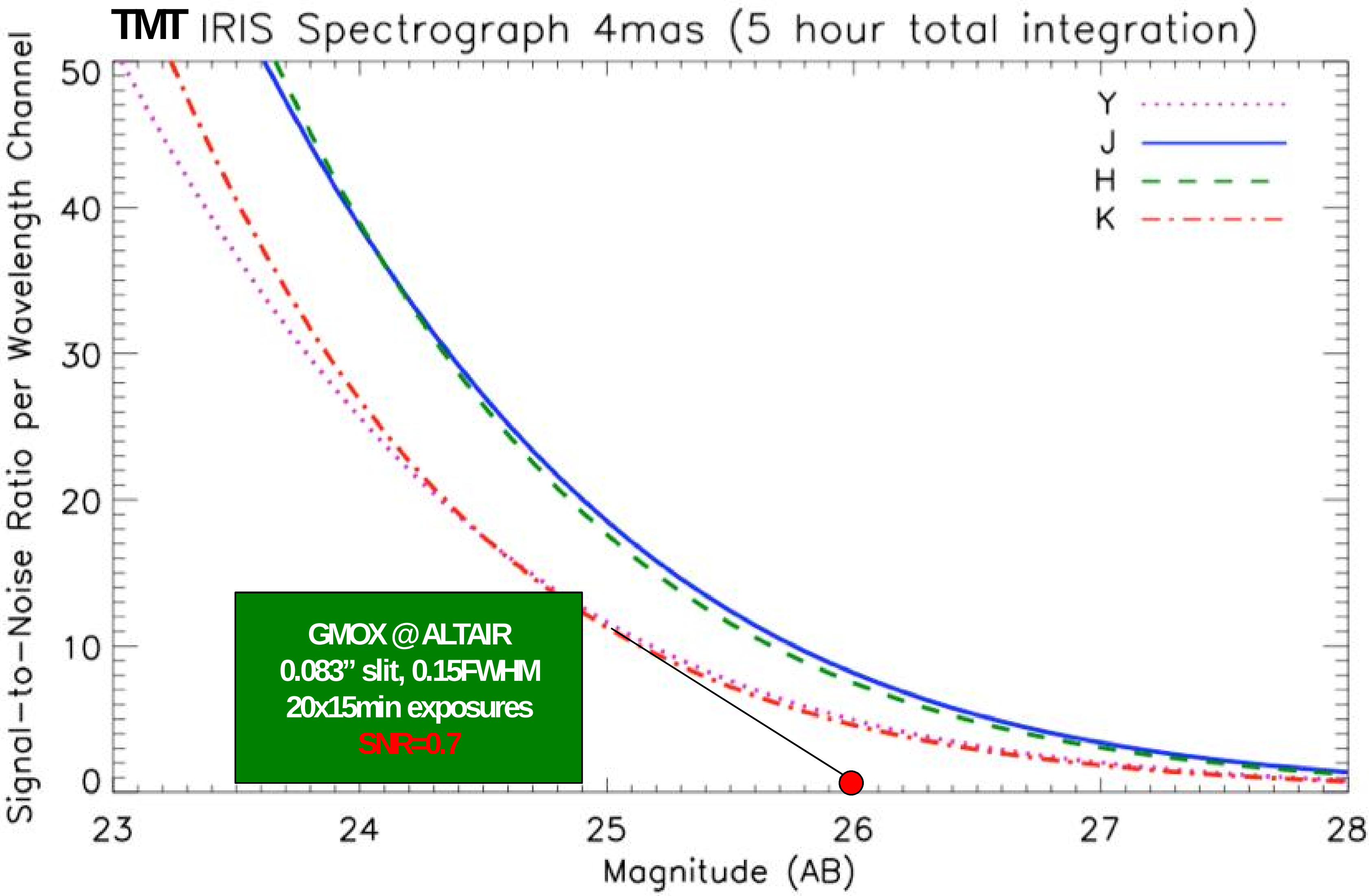


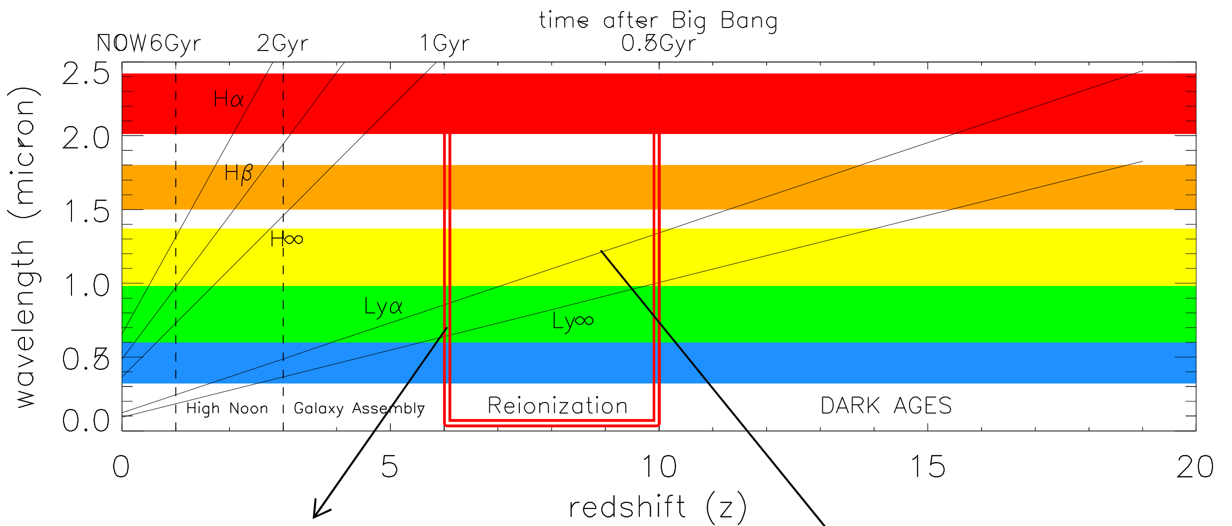
Figure 4: Estimated signal-to-noise ratio per wavelength channel versus a given magnitude (AB) illustrating the sensitivities for the integral field spectrograph at the 0.004" per spatial element scale in each broadband filter (Y, J, H, K) using a 2λ/D aperture size over a single point source. The central wavelength of the broadband filter is used to define the aperture size. A total integration time of 5 hours was made up of single exposures of 900 seconds stacked 20 times in Y, J, and H, and K.

From Wright et al. http://arxiv.org/pdf/1007.1975.pdf

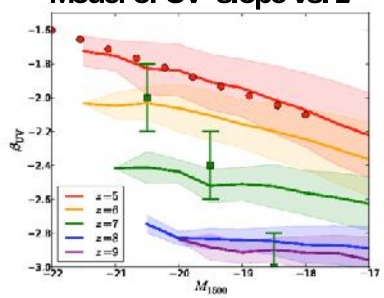
1. Galaxy Evolution

1.2 Reionization and Early Galaxy Formation

Early embryos of present day galaxies are assembled

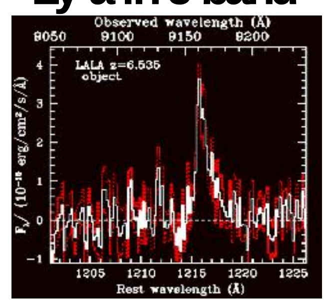


Model of UV slope vs. *z*



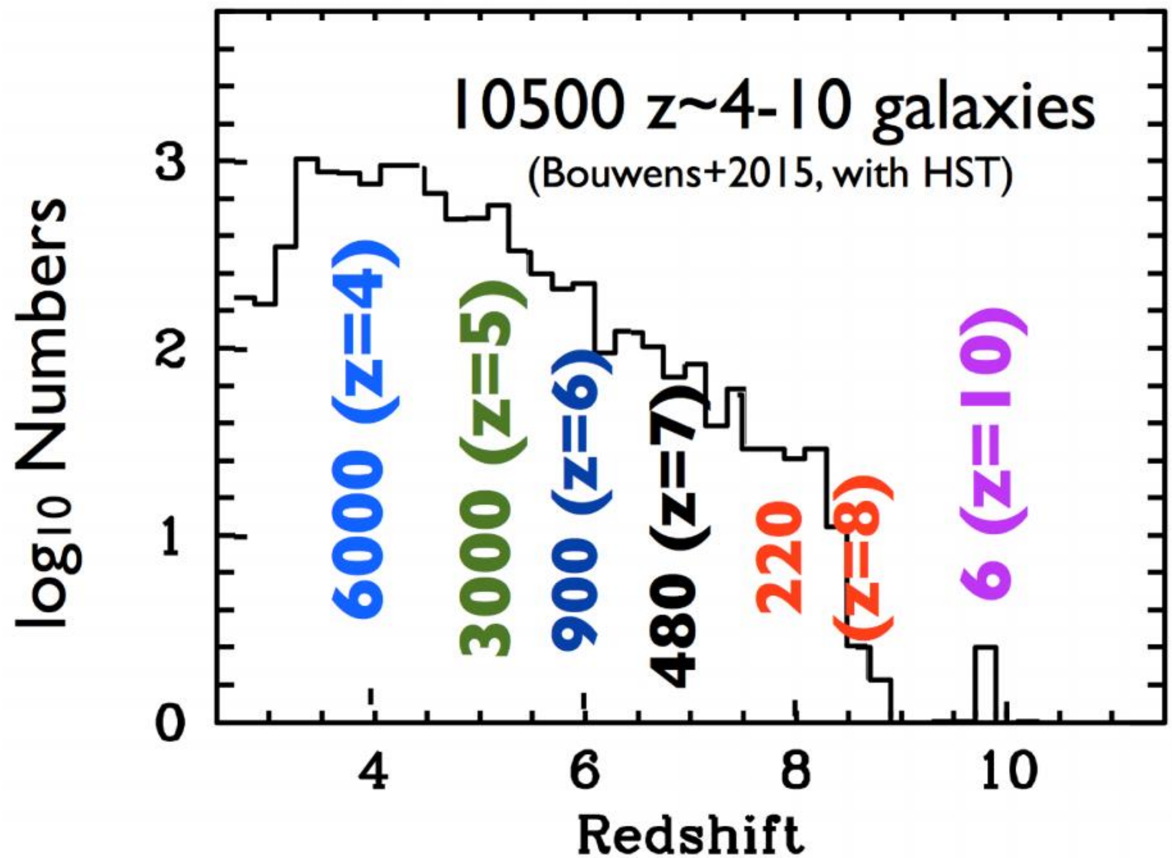
Gnedin, N. 2014, ApJ 793, 29

Ly-a in J band



Rhoads et al. 2004, ApJ 611, 59

Nr. of galaxies in deep HST fields



1. Galaxy Evolution

1.2 Reionization and Early Galaxy Formation

GMOX science:

a) detect Ly-alpha line, increasing nr. of known sources

b) clarify UV luminosity function $f(l) \propto l^{b}$, tracer of escaping ionizing photons, disentangling effects of dust and emission lines and showing how they depend on redshift

c) Map the reionization of the IGM through QSO spectroscopy. Current understanding of IGM at z>6 highly limited by low nr. of high z QSOS.

New record just set

The Astrophysical Journal Letters, 810:L12 (6pp), 2015 September 1
doi:10.1088/2041-8205/810/1/L12

Lyα EMISSION FROM A LUMINOUS $z = 8.68$ GALAXY: IMPLICATIONS FOR GALAXIES AS TRACERS OF COSMIC REIONIZATION

Adi Zitrin[1,8], Ivo Labbé[2], Sirio Belli[1], Rychard Bouwens[2], Richard S. Ellis[1], Guido Roberts-Borsani[2,3], Daniel P. Stark[4], Pascal A. Oesch[5,6], and Renske Smit[7]

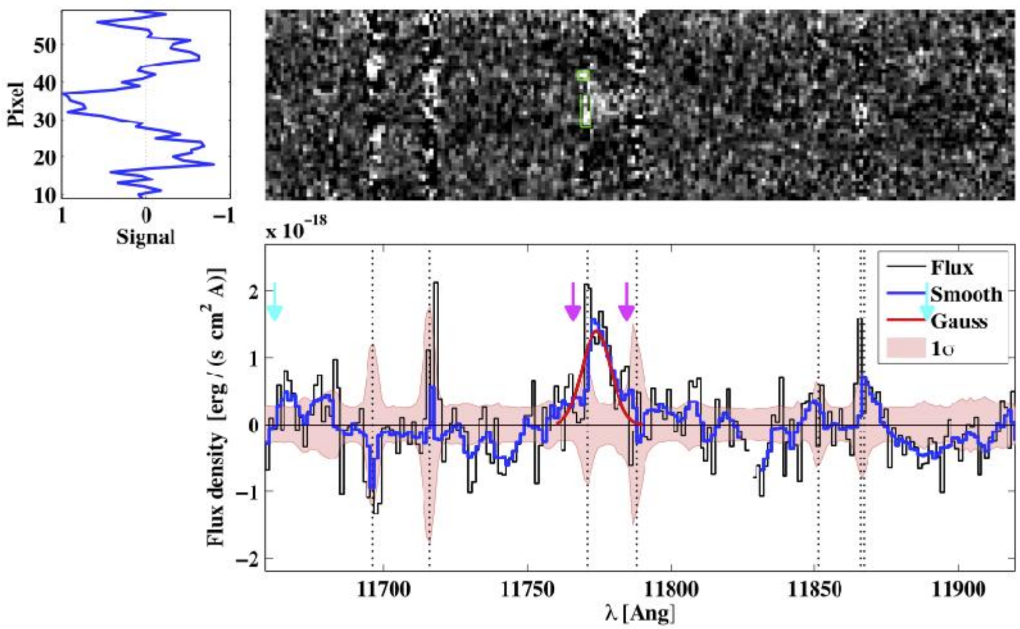


Figure 1. Spectroscopic detection of emission in EGSY8p7 with MOSFIRE. Upper panel: the 2D spectrum below which we plot the raw (black line) and smoothed (blue line) 1D spectrum and its error (faint red shading). The red line shows an example best-fit model of the data (Section 3). Vertical lines mark OH skyline positions. Upper left panel: shows a normalized signal map extracted along the slit within a 5-pixel (≃6.5 Å) wide box centered on the line. The pattern of two negative peaks bracketing the positive peak exactly matches that expected from the dithering scheme used. Arrows show the predicted locations of other lines for a lower-redshift interpretation of the line. Green boxes on the 2D spectrum mark the skyline region typically masked out in our calculations. See Section 3 for more details.

EGSY-2008532660

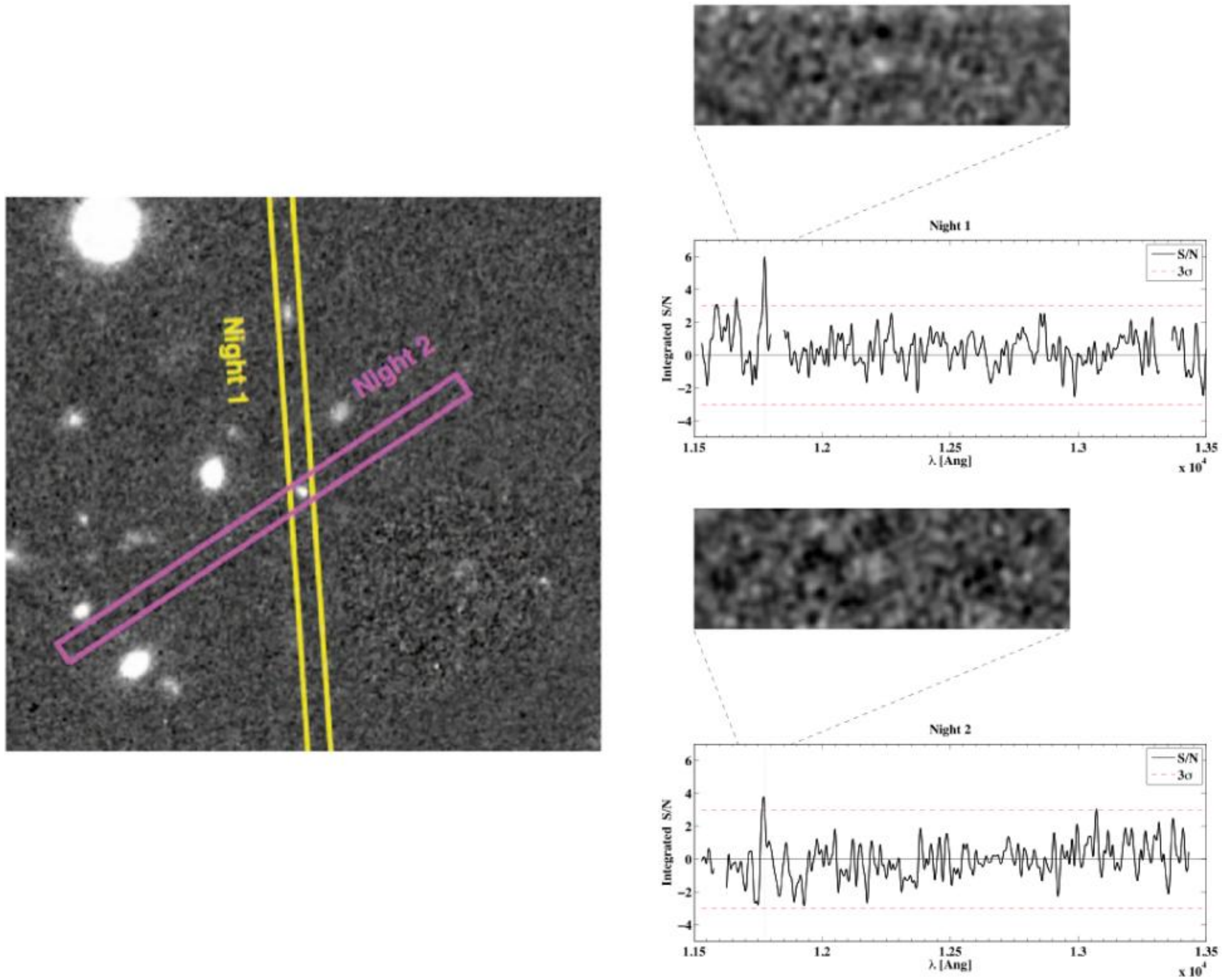
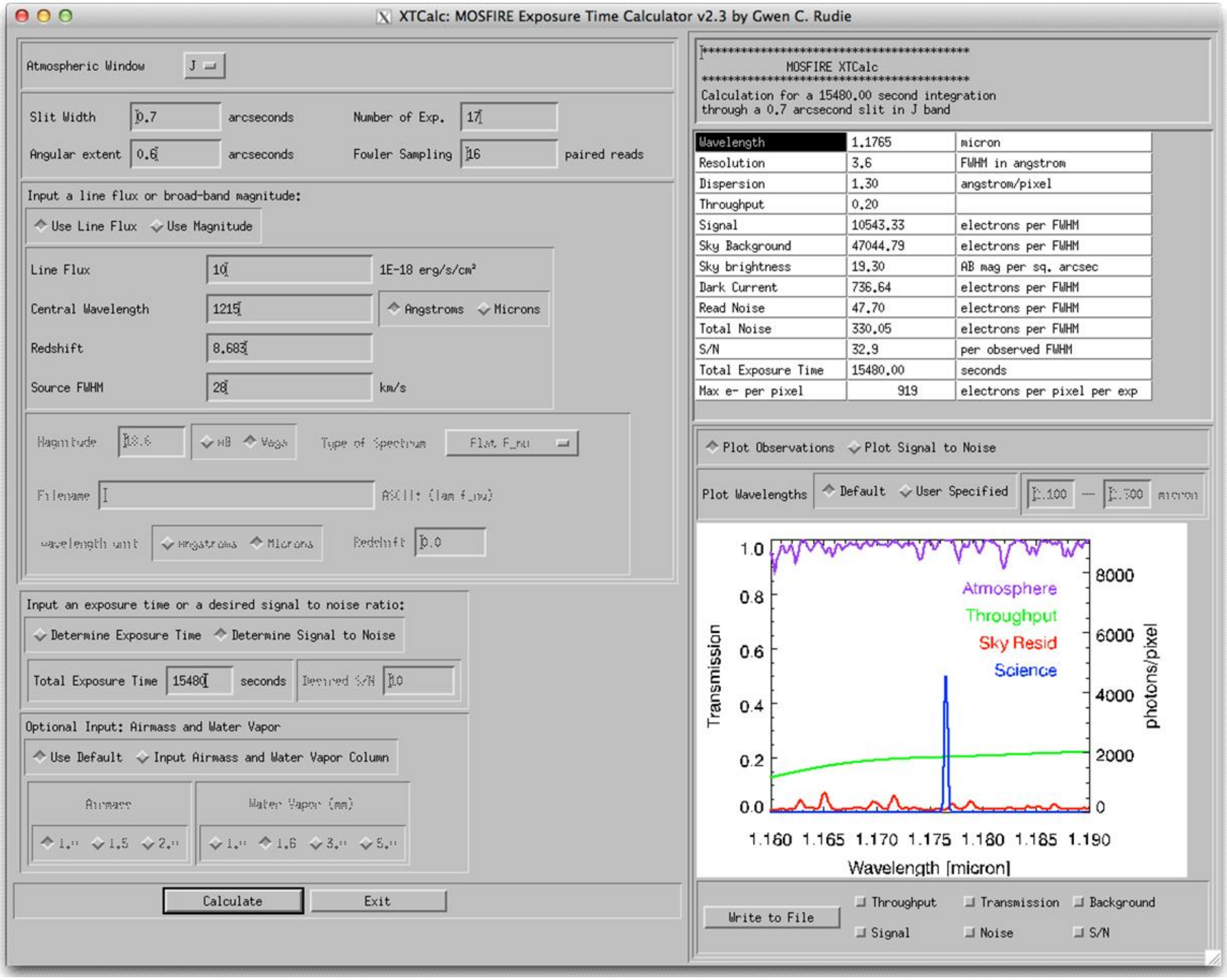


Figure 2. Confirmation of line detection in EGSY8p7 over two nights. *Left:* HST F160W image of the EGSY8p7 field with the slit orientations adopted in two successive nights. *Right:* extracted 1D signal-to-noise spectra across the *J* band for each night with a zoom of the 2D data around the line, marked with a vertical blue line. The 2D spectra are smoothed with a 3-pixel Gaussian for better illustration of the data. The 1D spectrum is smoothed with a Gaussian of $\sigma = 5$ Å, comparable to the measured line width. The *Y* axis is scaled so that the peak signal to noise matches the integrated value (e.g., F13). Horizontal dashed lines mark the $\pm 3\sigma$ region. On both nights, the signal to noise at the line location significantly exceeds that elsewhere.

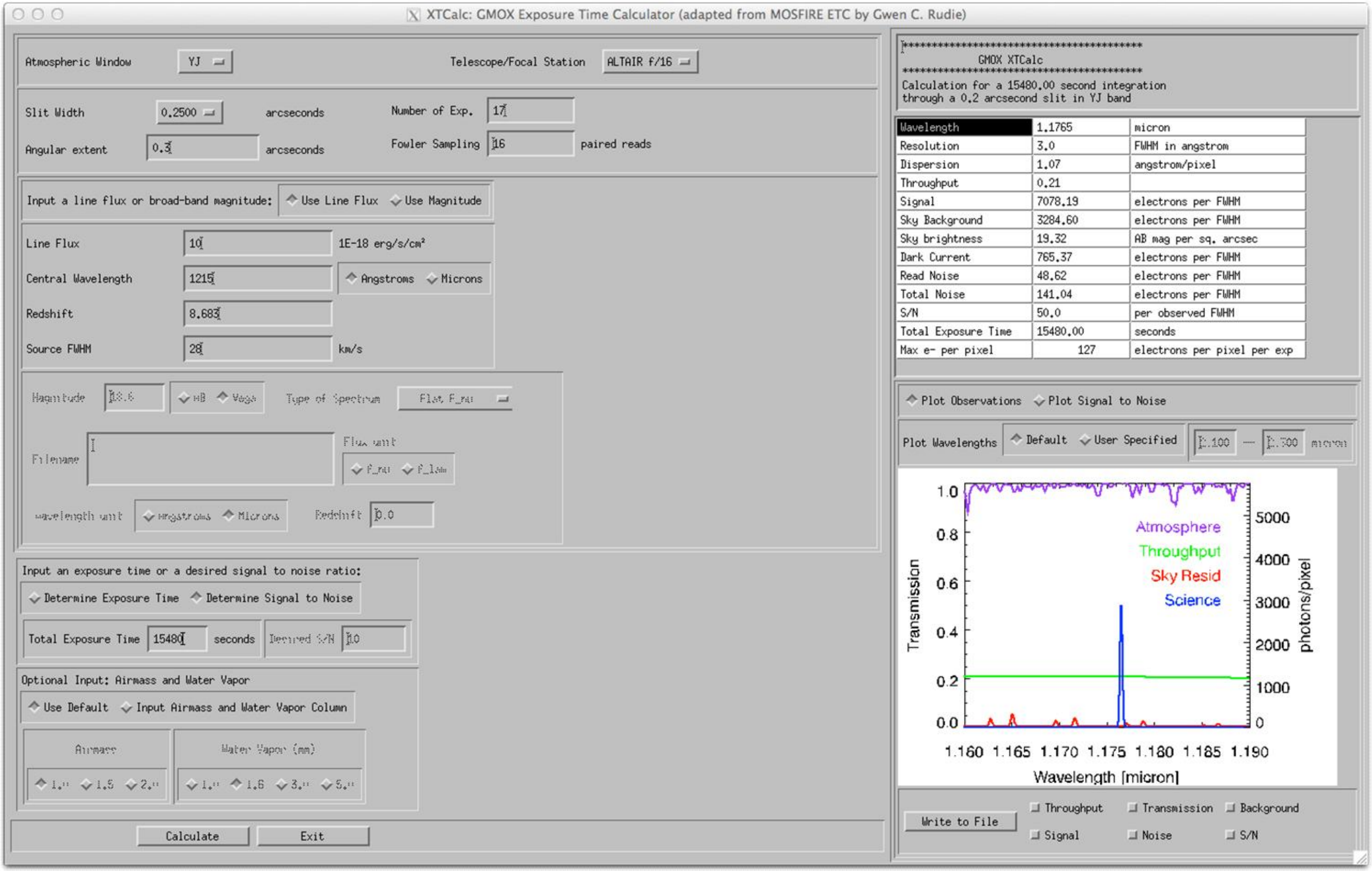
ETC comparison: MOSFIRE: SNR=32.9



SPACE TELESCOPE SCIENCE INSTITUTE
Operated for NASA by AURA

ETC Comparison: GMOX: SNR=50.0

R·I·T
IDG INSTRUMENT DEVELOPMENT GROUP
JOHNS HOPKINS UNIVERSITY



SPACE TELESCOPE SCIENCE INSTITUTE
Operated for NASA by AURA

HeII (1640A) at z=8

- tracer of primordial PopIII stars

Flux = 5 x10^{-19} erg cm^{2} s^{-1}

(10x fainter than Lya)

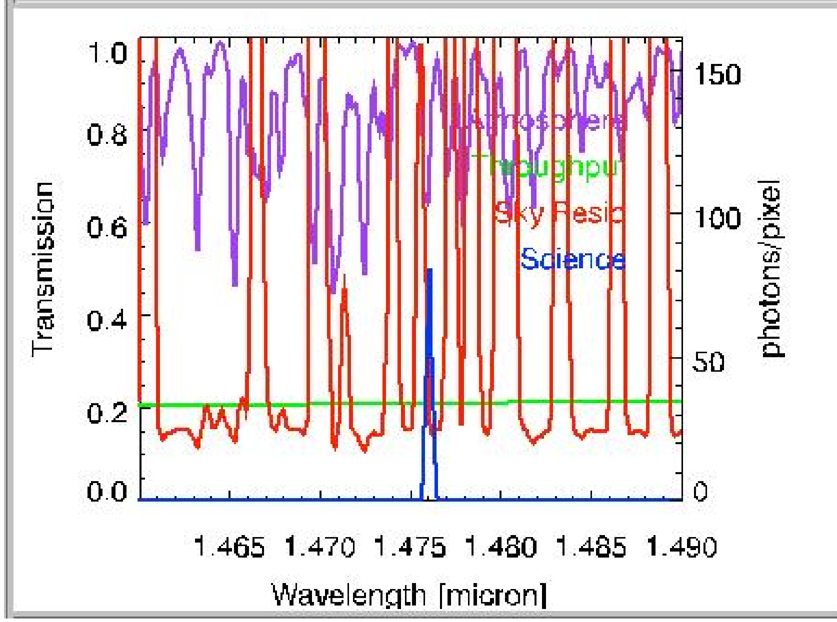
GMOX: 3hr exposure
0.25"slit
0.3" seeing (H)
Altair f/16
12 exposures x 900s = 3hr
SNR=1.8

```
******************************************
              GMOX XTCalc
******************************************
Calculation for a 10800.00 second integration
through a 0.2 arcsecond slit in H band
```

Wavelength	1.4760	micron
Resolution	3.3	FWHM in angstrom
Dispersion	1.33	angstrom/pixel
Throughput	0.21	
Signal	172.57	electrons per FWHM
Sky Background	3478.29	electrons per FWHM
Sky brightness	19.86	AB mag per sq. arcsec
Dark Current	481.14	electrons per FWHM
Read Noise	38.78	electrons per FWHM
Total Noise	102.92	electrons per FWHM
S/N	1.8	per observed FWHM
Total Exposure Time	10800.00	seconds
Max e- per pixel	169	electrons per pixel per exp

Plot Observations   Plot Signal to Noise

Plot Wavelengths   Default   User Specified



However…

Flux = 5 x10^{-19} erg cm^{-2} s^{-1}
(10x fainter than Ha)

GMOX: 3hr exposure
0.083"slit
0.1" seeing (H)
Altair f/16
12 exposures x 900s = 3hr
SNR=4.6

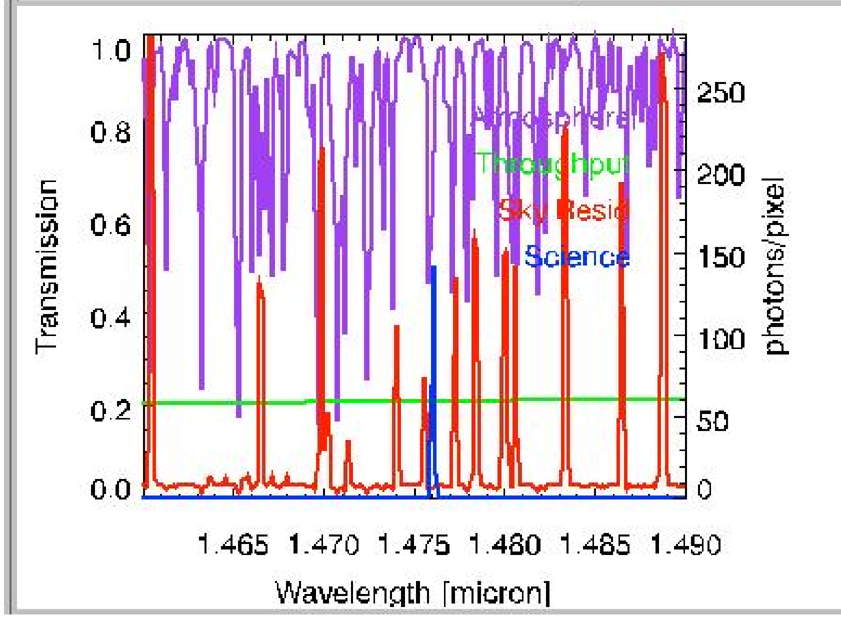
GMOX XTCalc

Calculation for a 10800.00 second integration through a 0.1 arcsecond slit in H band

Wavelength	1.4760	micron
Resolution	1.1	FWHM in angstrom
Dispersion	1.33	angstrom/pixel
Throughput	0.21	
Signal	144.68	electrons per FWHM
Sky Background	66.21	electrons per FWHM
Sky brightness	19.98	AB mag per sq. arcsec
Dark Current	81.81	electrons per FWHM
Read Noise	15.99	electrons per FWHM
Total Noise	30.84	electrons per FWHM
S/N	4.6	per observed FWHM
Total Exposure Time	10800.00	seconds
Max e- per pixel	55	electrons per pixel per exp

Plot Observations   Plot Signal to Noise

Plot Wavelengths   Default   User Specified



Ly-a at z=8

Flux = 5 x10^{-18} erg cm^{-2} s^{-1}
= 5sigma at MOSFIRE
(Treu et al. 2013, ApJ775, L29)

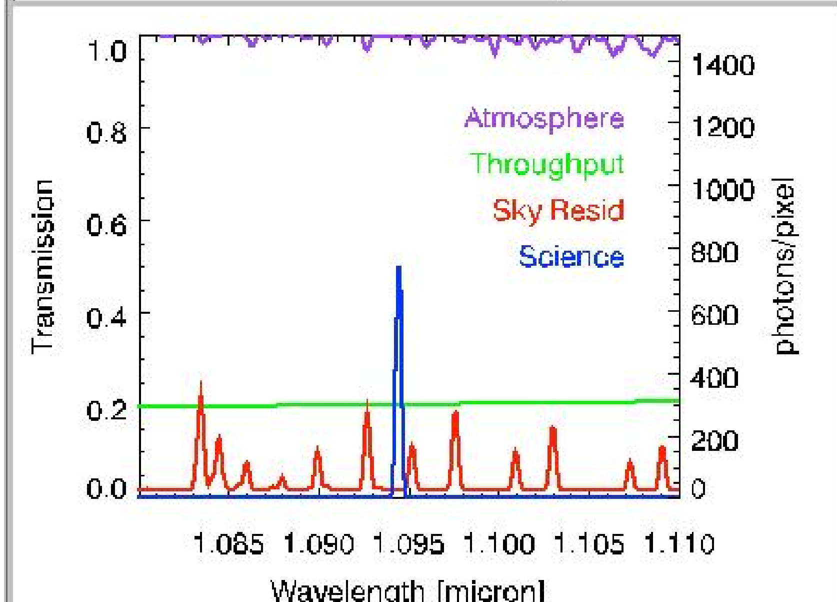
GMOX: 3hr exposure
0.25" slit
0.3" seeing (YJ)
Altair f/16
12 exposures x 900s = 3hr
SNR=16.5

****
GMOX XTCalc
****
Calculation for a 10800.00 second integration
through a 0.2 arcsecond slit in YJ band

Wavelength	1.0944	micron
Resolution	2.8	FWHM in angstrom
Dispersion	1.07	angstrom/pixel
Throughput	0.20	
Signal	1696.30	electrons per FWHM
Sky Background	2327.74	electrons per FWHM
Sky brightness	19.28	AB mag per sq. arcsec
Dark Current	501.00	electrons per FWHM
Read Noise	39.57	electrons per FWHM
Total Noise	102.38	electrons per FWHM
S/N	16.5	per observed FWHM
Total Exposure Time	10800.00	seconds
Max e- per pixel	97	electrons per pixel per exp

Plot Observations Plot Signal to Noise

Plot Wavelengths Default User Specified

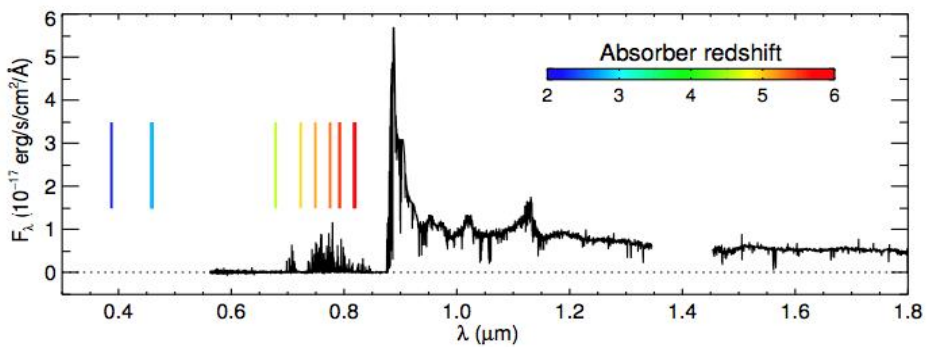


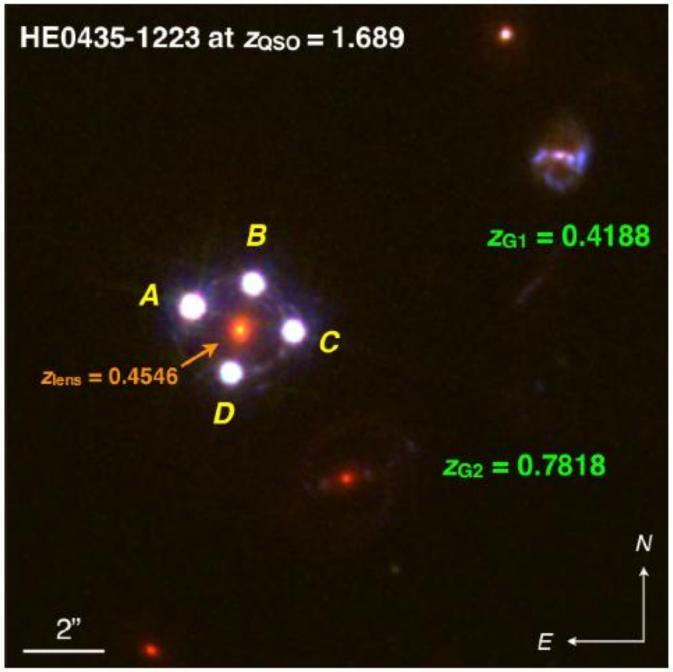
QSOs

- **What is their redshift?**
- **What is their status?**
- **Absorption-line spectroscopy of Ly-alpha forest**
- **Spectroscopy of foreground galaxies (outflows/feedback)**
- **Multiply-lensed QSOs near a known foreground galaxy to map the halo around the galaxy:**
  - galaxy built-up,
  - growth of cosmic structures
  - halo kinematics

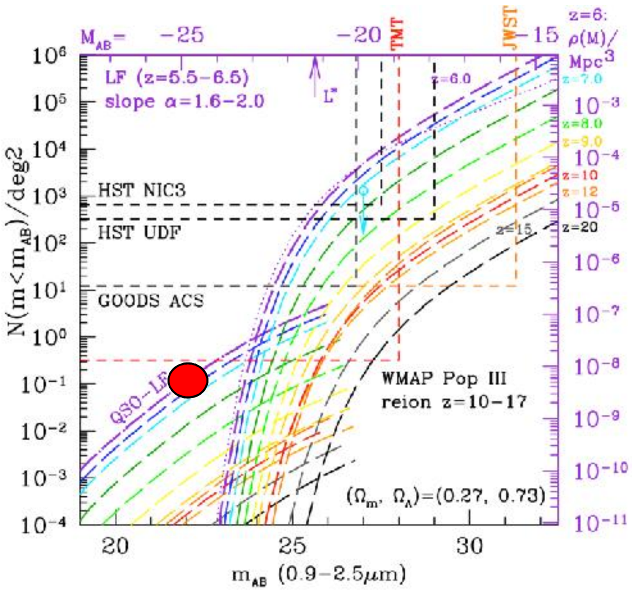
    (e.g. Chen et al. 2013, MNRAS)

VLT/X-Shooter spectrum of a z=6.3QSO





QSO at z=6, J_{AB}=22



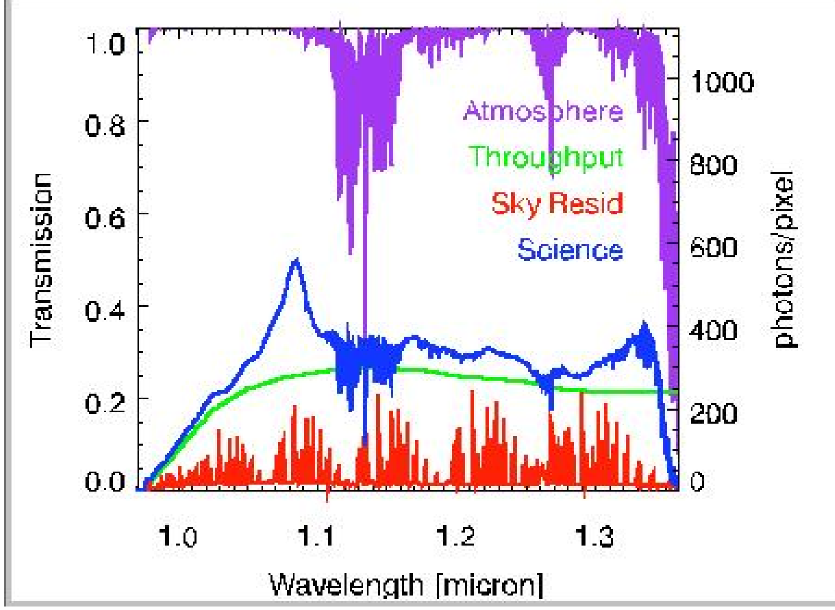
GMOX: 0.25"slit
0.3" seeing
2 exposures x 1800s = 1hr
SNR=7.7

****
GMOX XTCalc
****
Calculation for a 3600.00 second integration
through a 0.2 arcsecond slit in YJ band

Wavelength	1.1500	micron
Resolution	2.9	angstrom
Dispersion	1.07	angstrom/pixel
Throughput	0.21	
Signal	313.52	electrons per spectral pixel
Sky Background	302.79	electrons per spectral pixel
Sky brightness	17.48	AB mag per sq. arcsec
Dark Current	59.42	electrons per spectral pixel
Read Noise	9.64	electrons per spectral pixel
Total Noise	35.14	electrons per spectral pixel
S/N	7.7	per spectral pixel
Total Exposure Time	3600.00	seconds
Max e- per pixel	18052	electrons per pixel

◇ Plot Observations ◇ Plot Signal to Noise

Plot Wavelengths ◇ Default ◇ User Specified



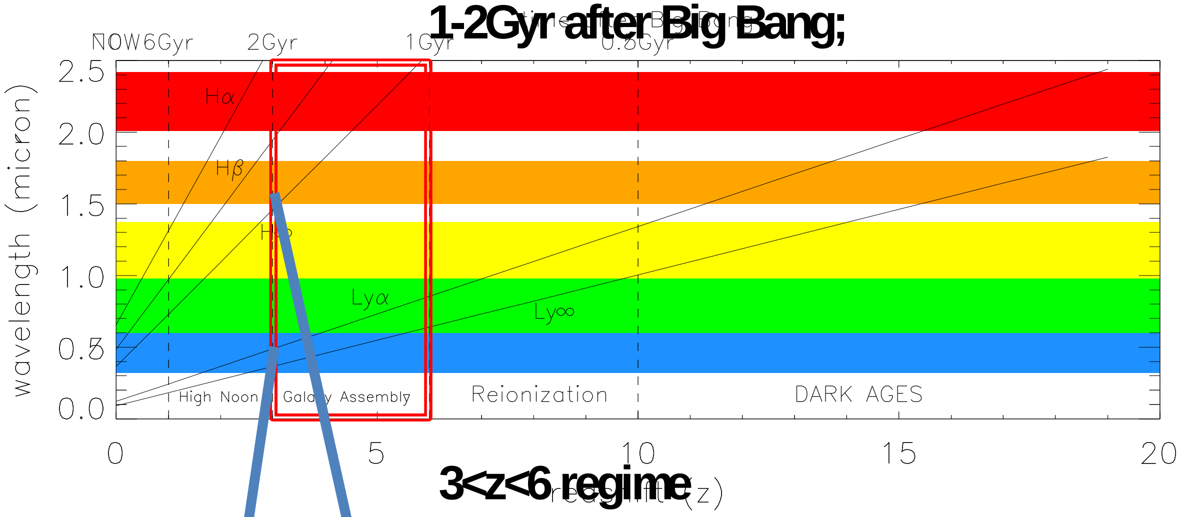
Requirements

- **Ly-a and HeII as reionization probes:**
  - access to IR wavelengths: YJH(K)
  - R>4000 to work between OH lines
  - AO + ultra-narrow slits to go faint
- **QSOs and galaxy-IGM interaction:**
  - Wide spectral coverage
  - multi-object mode to map halo structure and kinematics

1. Galaxy Evolution

1.3 Galaxy Building Epoch

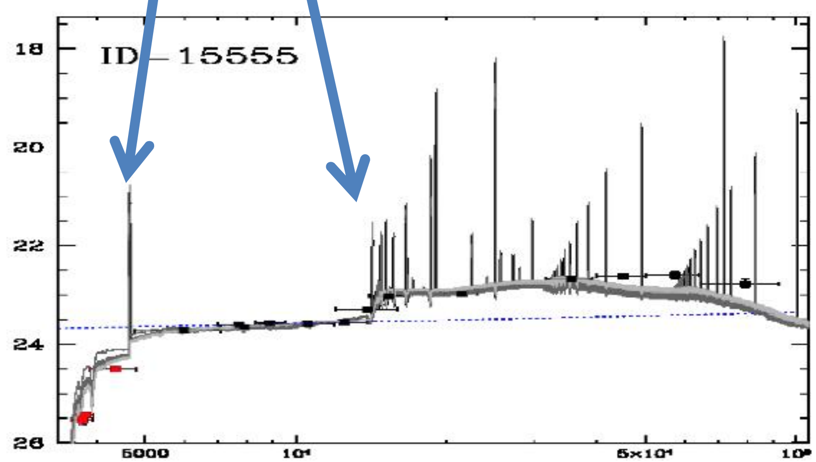
1-2Gyr after Big Bang;



3<z<6 regime

- **Ly-a in the Red band + Balmer/4000A in HK-bands**

z=3 galaxy spectrum

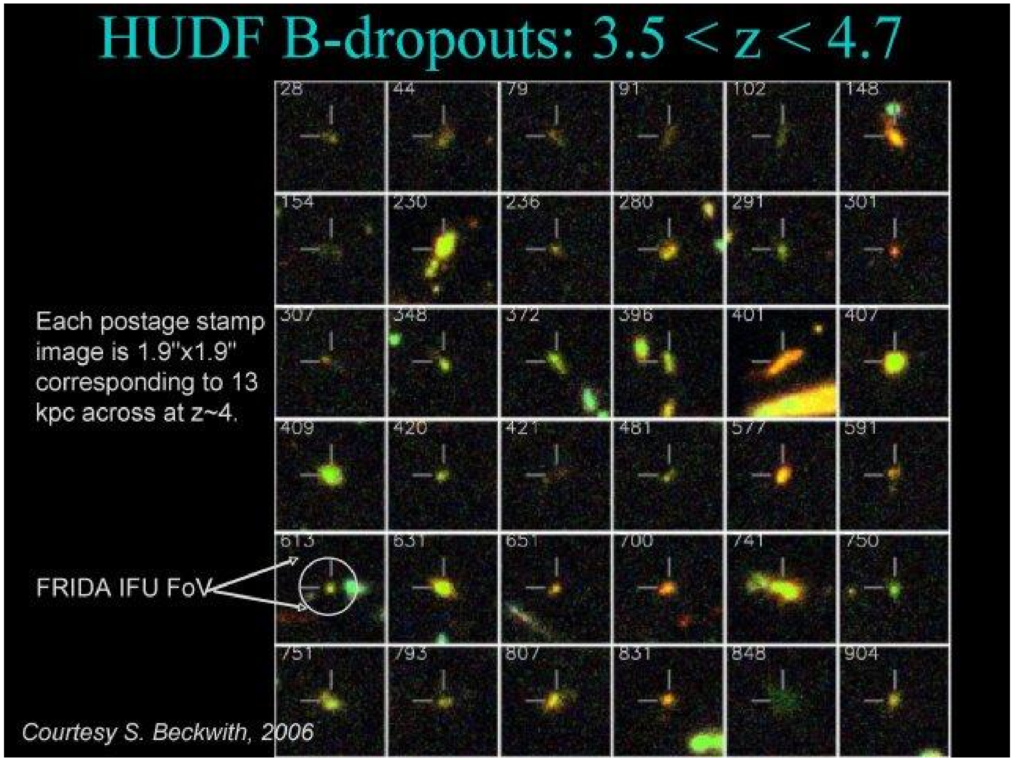


Castellano et al. 2014, A&A 566, A19

1. Galaxy Evolution

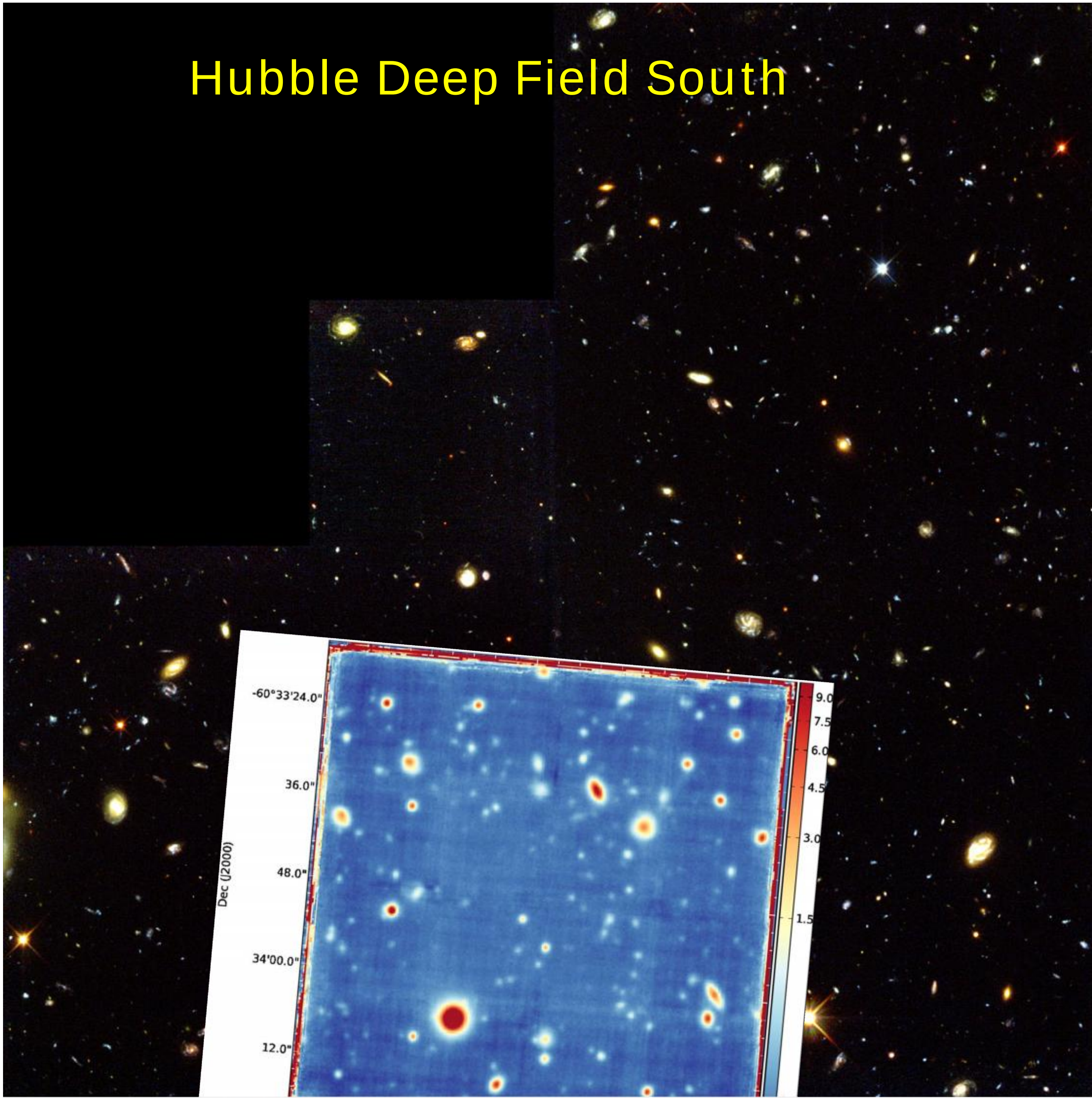
1.3 Galaxy Building Epoch

Stellar mass of the universe grows from ~1% of its present value to ~10%, with significant enhancement of heavy elements.



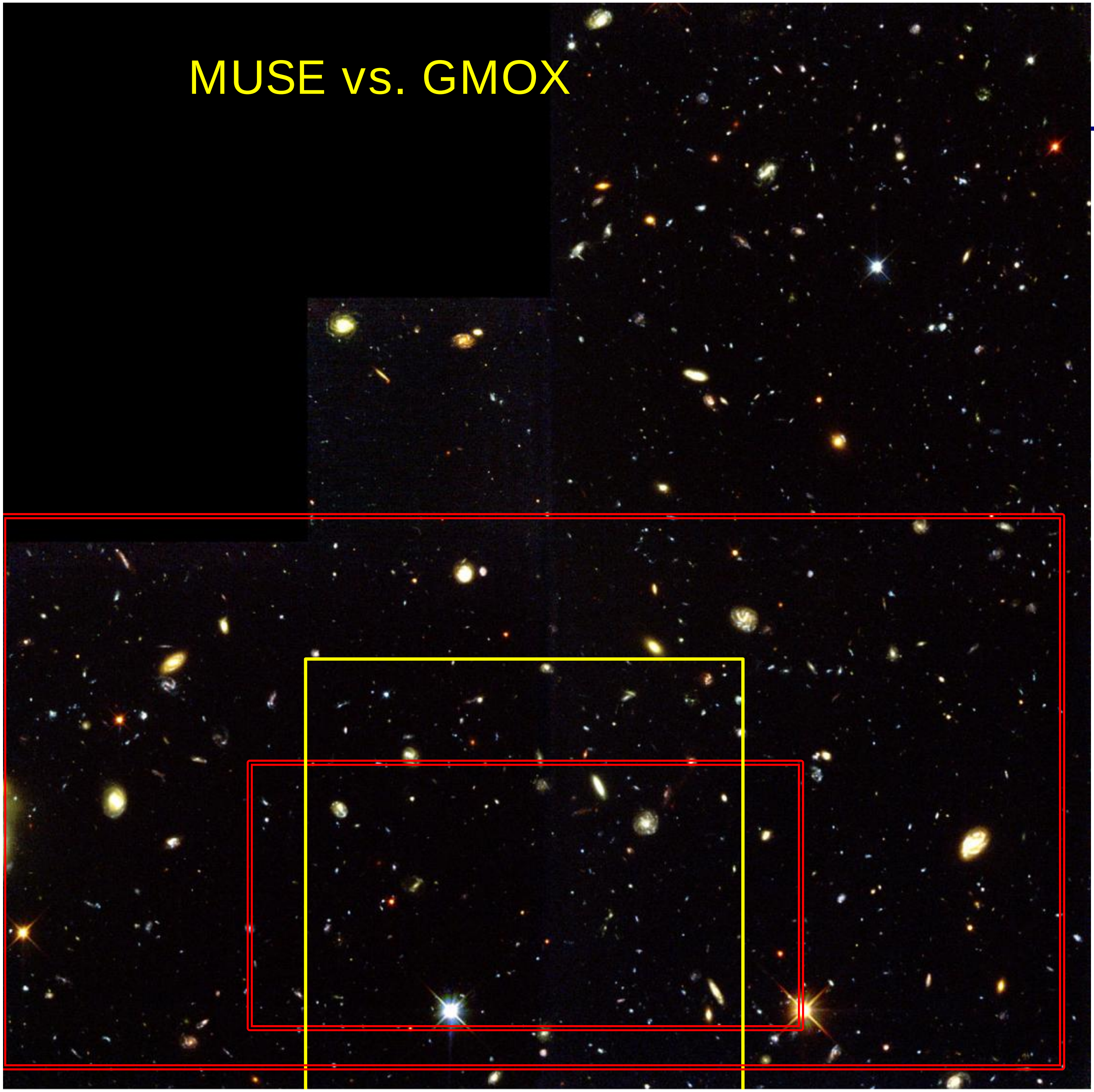
- **GMOX can determine redshift, estimate star formation rate, disentangle degeneracies between models ("single vs. multiple" stellar populations).**
- **Multiplexing critical: 90% of the galaxies in HST deep fields are in this redshift range.**

Hubble Deep Field South



MUSE 27hr
Bacon et al 2015

MUSE vs. GMOX



Requirements

- Access to the full wavelength range, from the UV to the K-band, to bracket the rest-frame spectra between the Lyman and Balmer breaks.
  - **Wide bandpass, U to K**

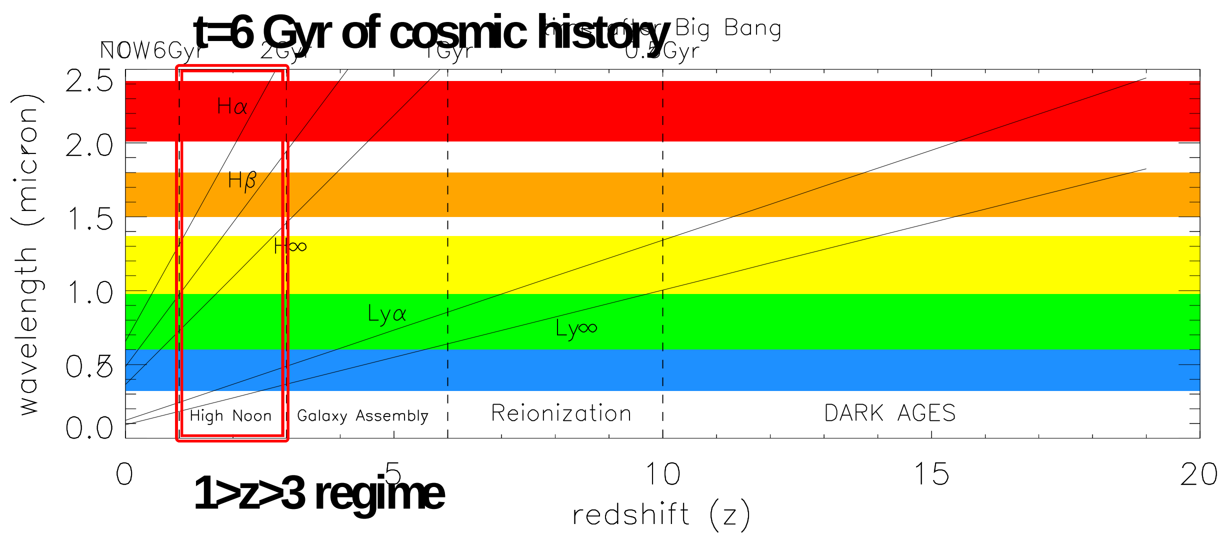
- Resolution R ~ 3, 000 provides accurate spectroscopic redshifts and assess the contribution of line emission to the photometric fluxes for different classes of objects.
  - **Medium resolution spectrograph**

- Reaching the line-free continuum level of high redshift galaxies requires spectral resolution R~4000 to work between the OH lines. High throughput and the capability to synthesize narrow slits are also required to boost sensitivity.
  - **High throughput – narrow slits (especially in the IR) to boost sensitivity**

- High density of targets
  - **Strong multiplexing across the full wavelength range**

1. Galaxy Evolution

1.4 “High Noon” of Cosmic History

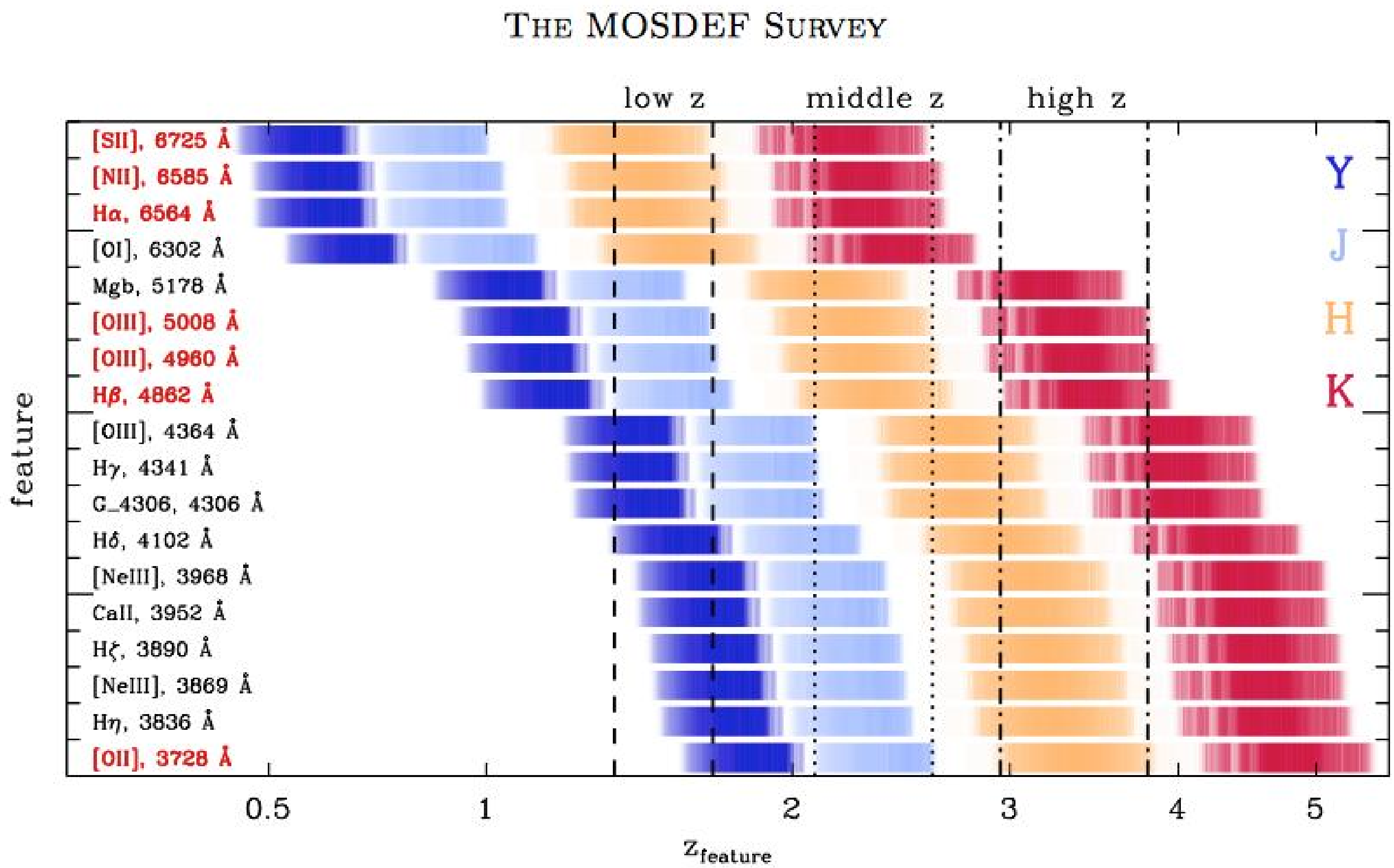


Galaxies build most of their mass and the star formation efficiency and AGN activity reach their maximum.

All Balmer lines in GMOX range

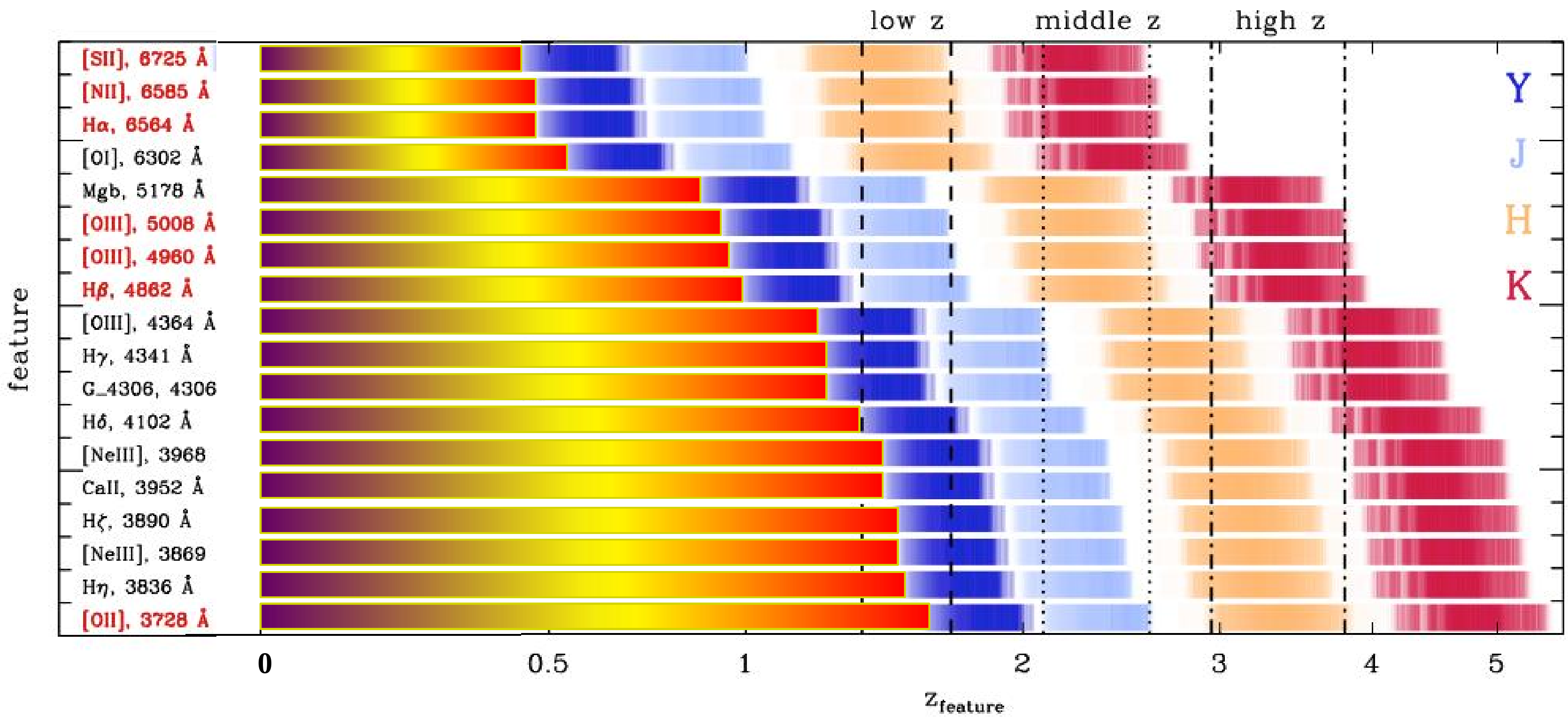
….and many more

MOSFIRE Diagnostics



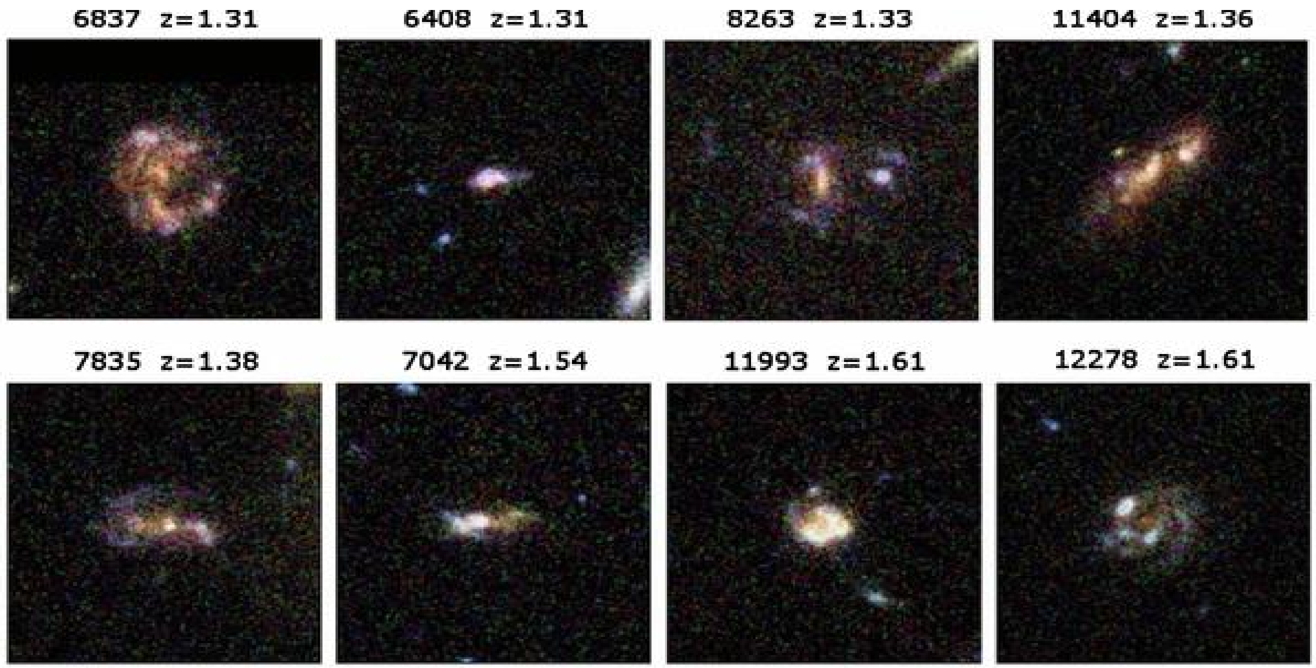
Kriek et al 2015, ApJS

GMOX



low z
middle z
high z
[SII], 6725 Å
[NII], 6585 Å
Hα, 6564 Å
[OI], 6302 Å
Mgb, 5178 Å
[OIII], 5008 Å
[OIII], 4960 Å
Hβ, 4862 Å
[OIII], 4364 Å
Hγ, 4341 Å
G_4306, 4306
Hδ, 4102 Å
[NeIII], 3968
CaII, 3952 Å
Hζ, 3890 Å
[NeIII], 3869
Hη, 3836 Å
[OII], 3728 Å
Y
J
H
K
feature
0
0.5
1
2
3
4
5
$z_{feature}$

All sources are well resolved

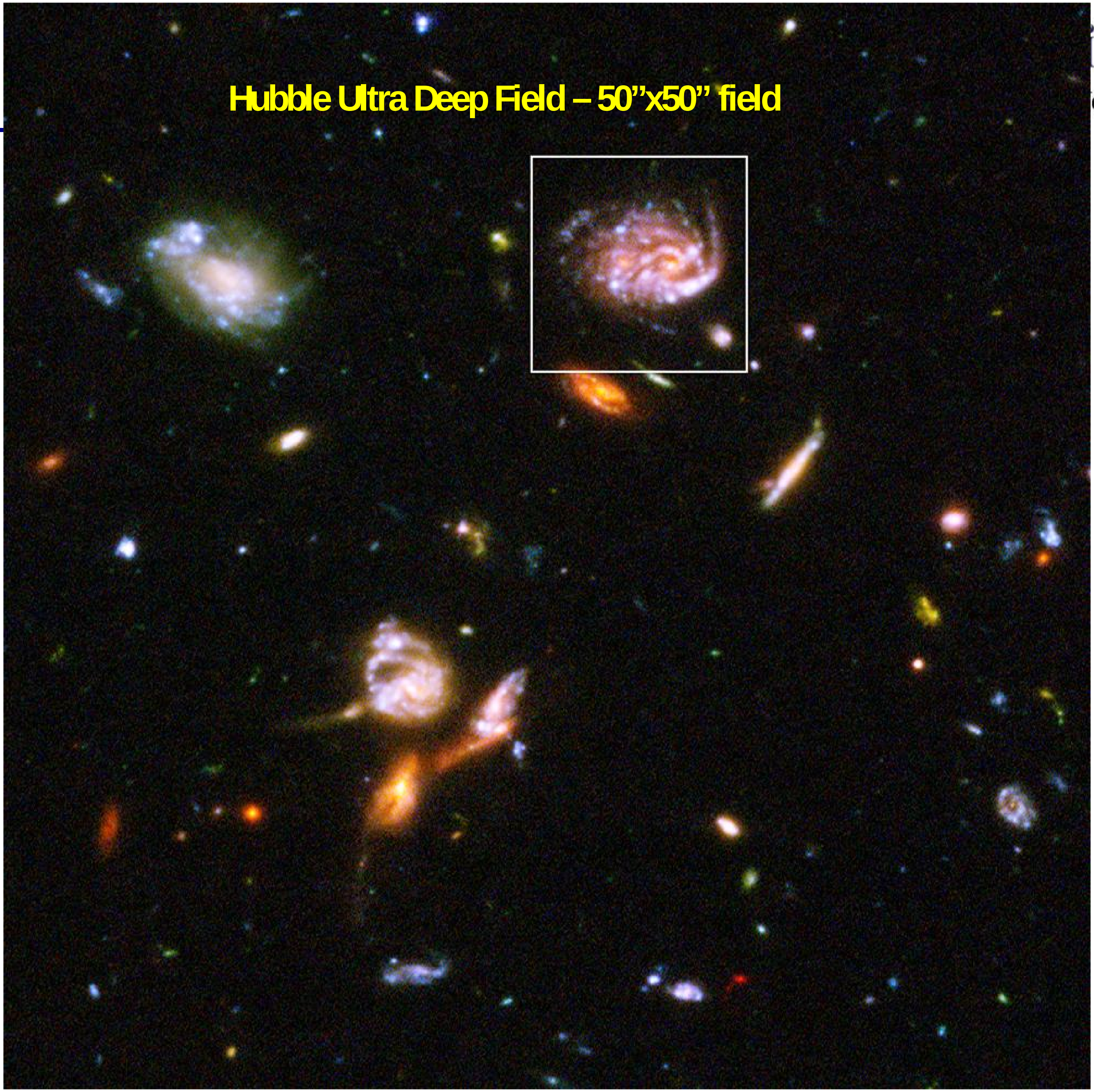


Trump et al. 2013, ApJ763, L6

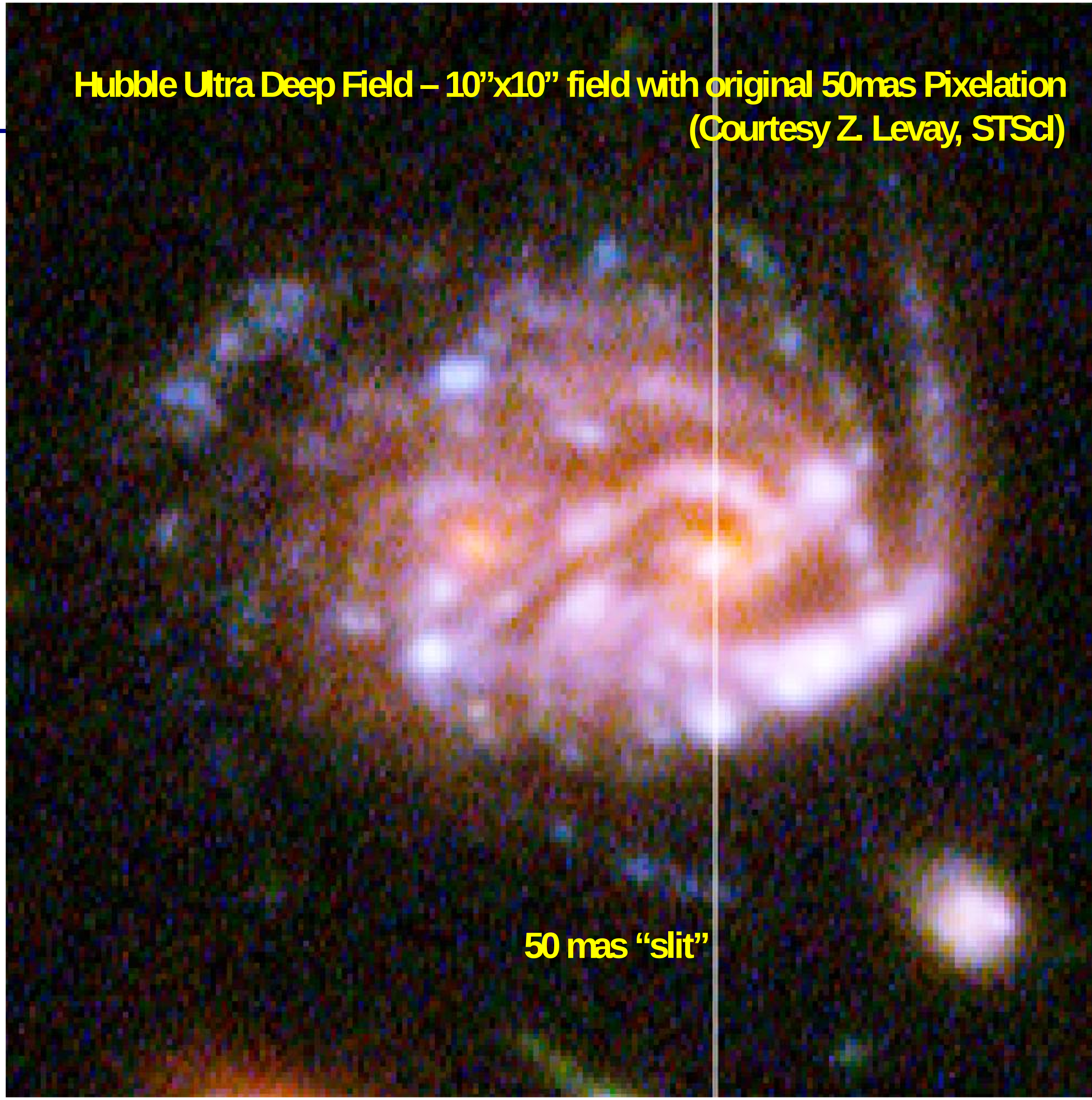
GMOX science

- **Reconstruct SED of individual galactic substructures**
- **Discriminate stellar populations by age, mass, SFR…**
- **Kinematic studies enabled by wide spectral coverage of rich line spectra.**

Hubble Ultra Deep Field – 50”x50” field



Hubble Ultra Deep Field – 10”x10” field with original 50mas Pixelation (Courtesy Z. Levay, STScI)



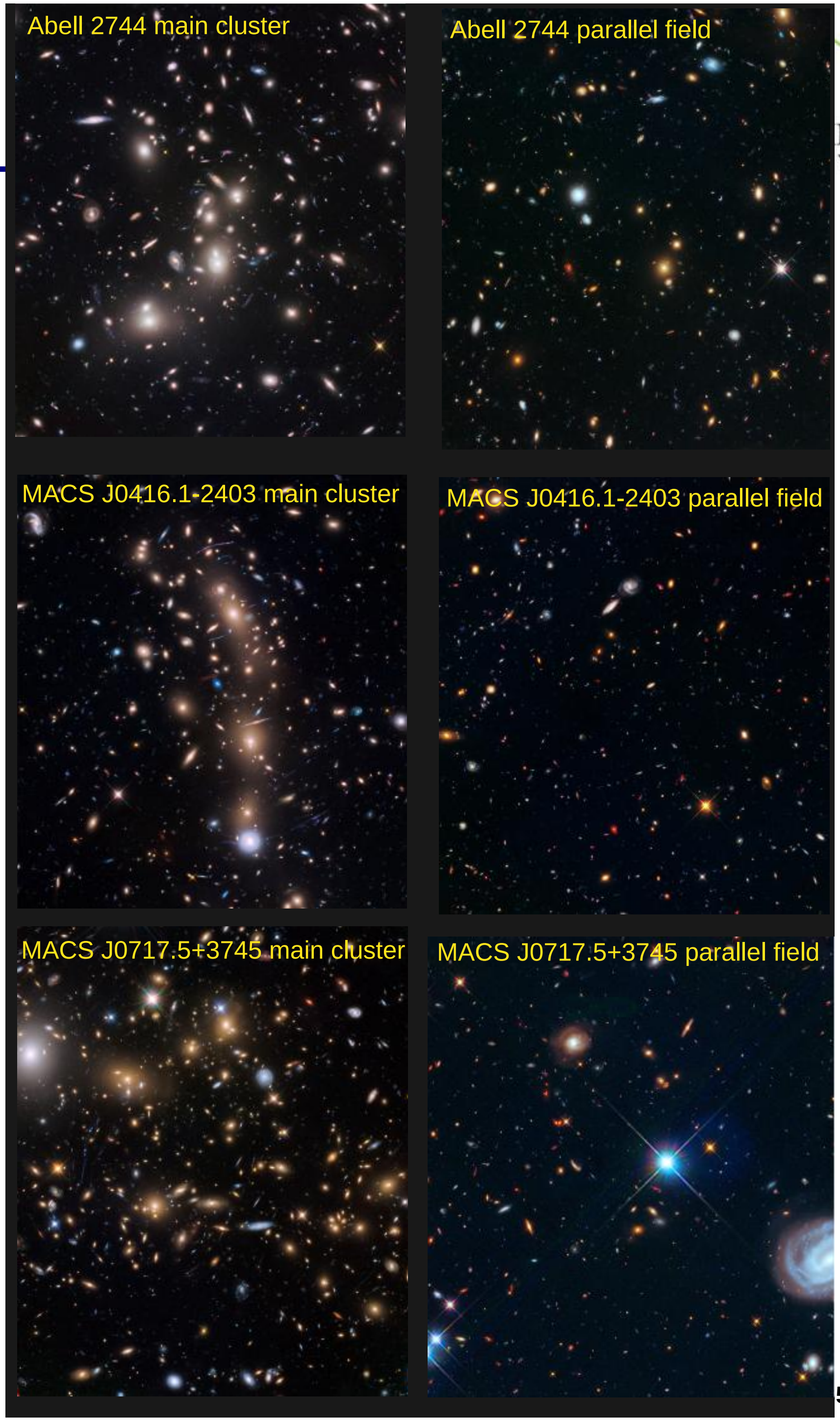
Requirements

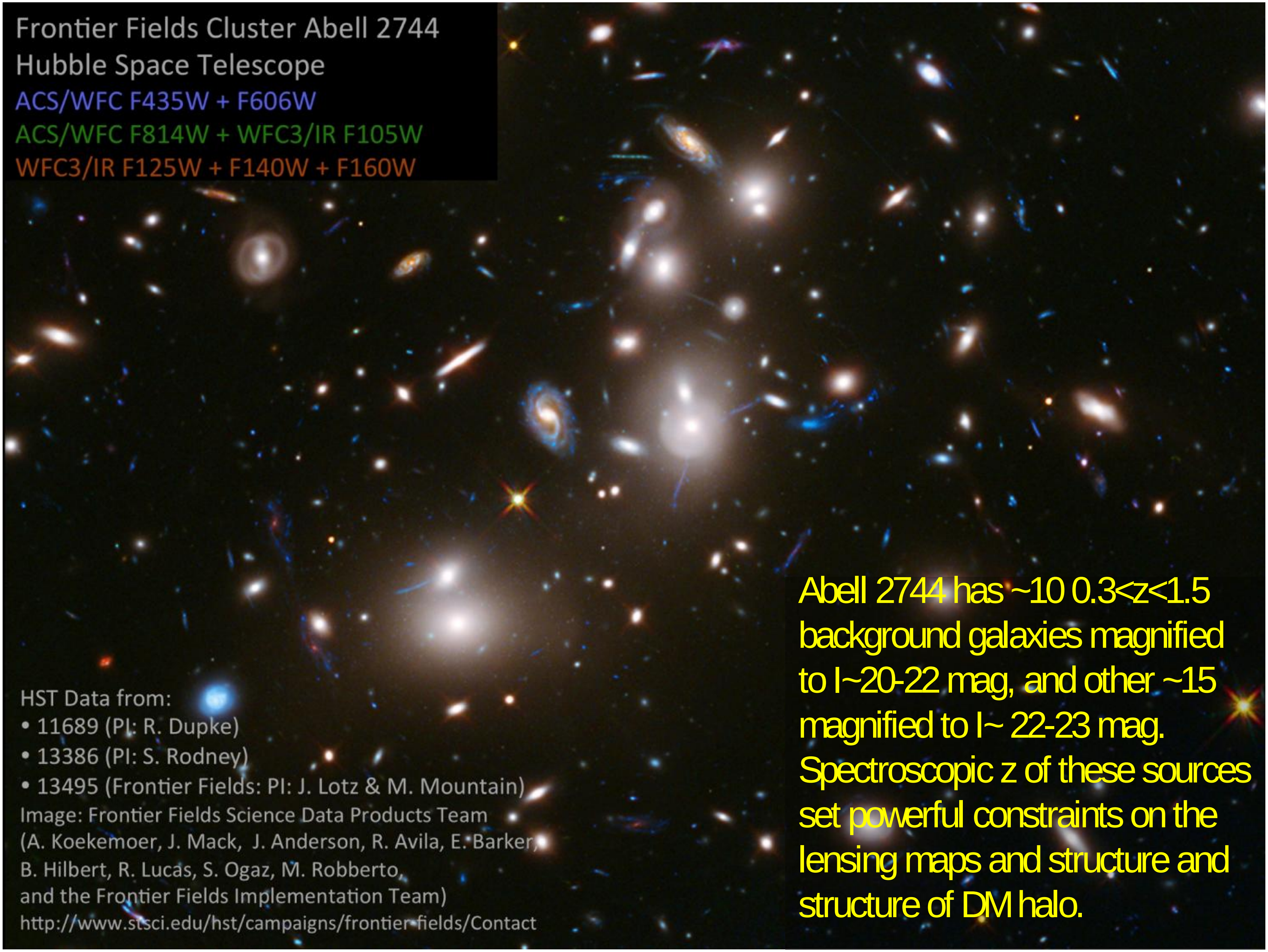
- Study the intensity of strong nebular emission lines (e.g., [O II]3727, 3730, Hβ, [O III]4960, 5008, Hα, [NII]6550, 6585, and [SII]6718, 6733) and stellar continuum and absorption features (e.g., Balmer lines,CaIIHandK,Mgb,4000Å break
  - **Wide spectral coverage from the UV to the near IR**
- Measure H emission lines to derive Star Formation Rate and Balmer decrement (Hα/Hβ) to account for dust attenuation.
  - **Medium resolution spectrograph**
- Target single regions of enhanced star formation, measuring spectral variations across individual galaxies of size <0.5”**.**
  - **High spatial resolution**

2. Clusters of Galaxies

Clusters of galaxies offer a unique opportunity to study the assembly and dynamics of the largest over-densities in the Universe, the impact of these environments on galaxy evolution, and the evolution of the background lensed galaxies.

Detailed maps of the cluster galaxy dynamics can place additional constraints on the cluster dark matter profile, and help reconstructing the galaxy accretion history of the cluster.



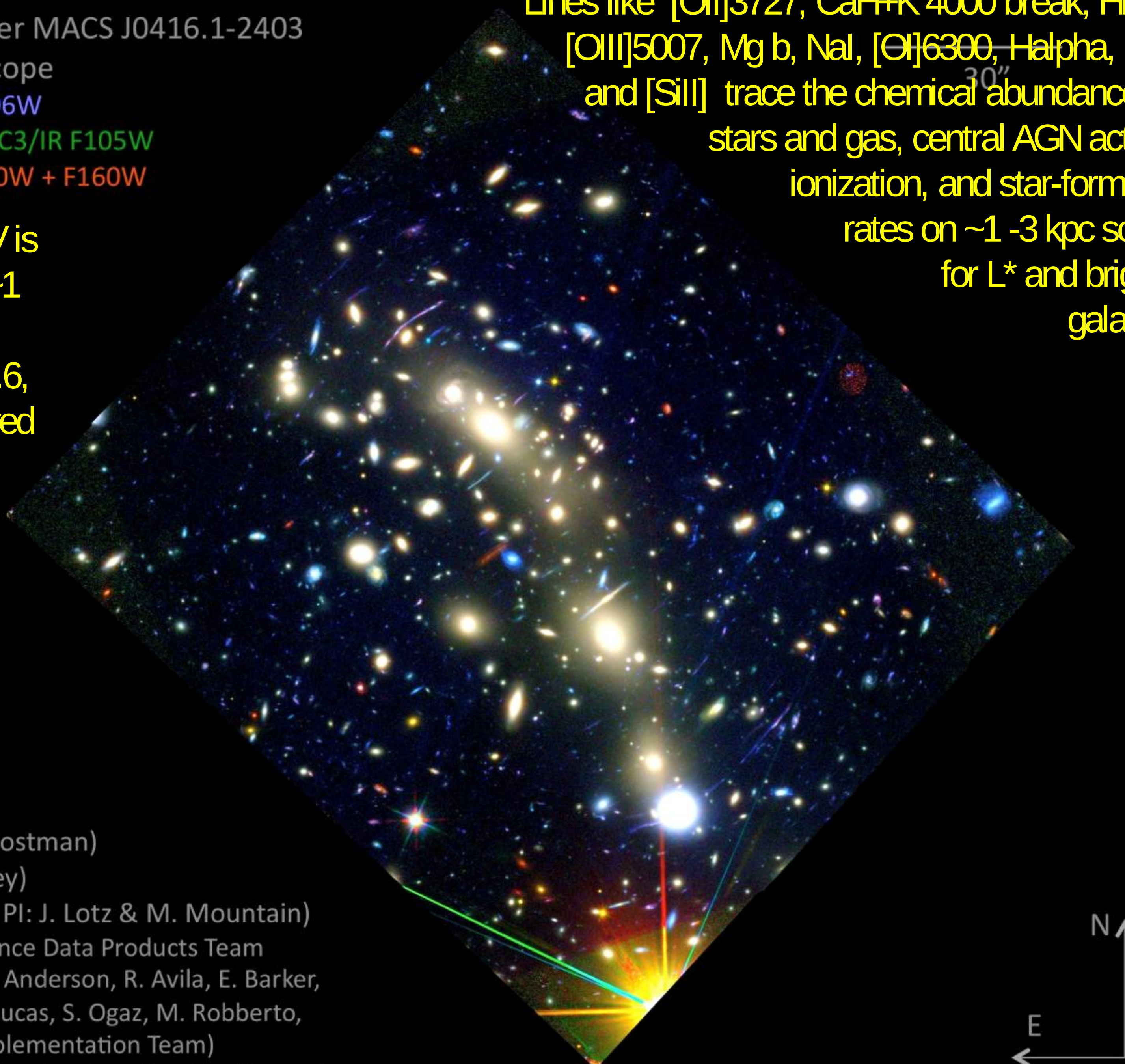


Abell 2744 has ~10 $0.3<z<1.5$ background galaxies magnified to I~20-22 mag, and other ~15 magnified to I~ 22-23 mag. Spectroscopic z of these sources set powerful constraints on the lensing maps and structure and structure of DM halo.

Frontier Fields Cluster MACS J0416.1-2403
Hubble Space Telescope
ACS/WFC F435W + F606W
ACS/WFC F814W + WFC3/IR F105W
WFC3/IR F125W + F140W + F160W

Lines like [OII]3727, CaH+K 4000 break, Hbeta, [OIII]5007, Mg b, NaI, [OI]6300, Halpha, [NII], and [SiII] trace the chemical abundances of stars and gas, central AGN activity, ionization, and star-formation rates on ~1 -3 kpc scales for L* and brighter galaxies.

GMOX 90" x 90" FoV is well-matched to the ~1 Mpc scales of rich clusters at z ~ 0.3 - 0.6, such as those observed by the HST CLASH survey and Frontier Fields.



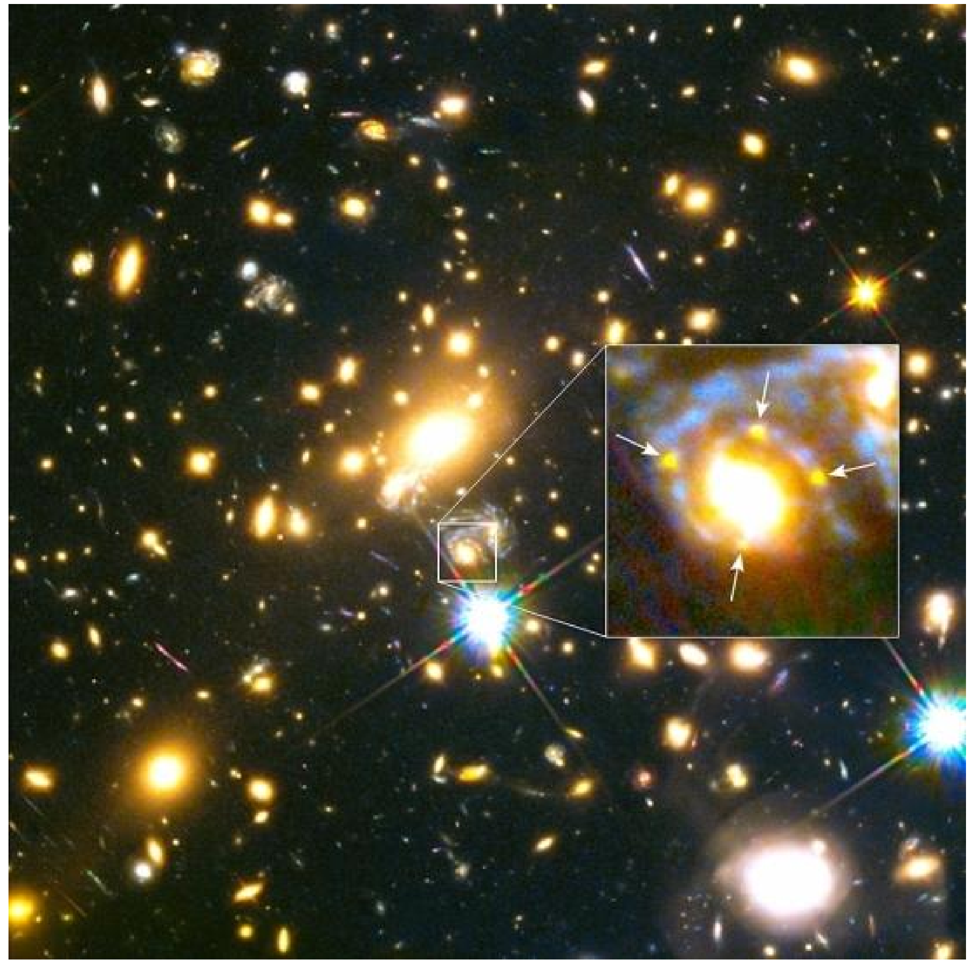
HST Data from:

- 12459 (CLASH; PI: M. Postman)
- 13386 (SN: PI: S. Rodney)
- 13496 (Frontier Fields: PI: J. Lotz & M. Mountain)

Image: Frontier Fields Science Data Products Team (A. Koekemoer, J. Mack, J. Anderson, R. Avila, E. Barker, D. Hammer, B. Hilbert, R. Lucas, S. Ogaz, M. Robberto, and the Frontier Fields Implementation Team)
http://www.stsci.edu/hst/campaigns/frontier-fields/Contact

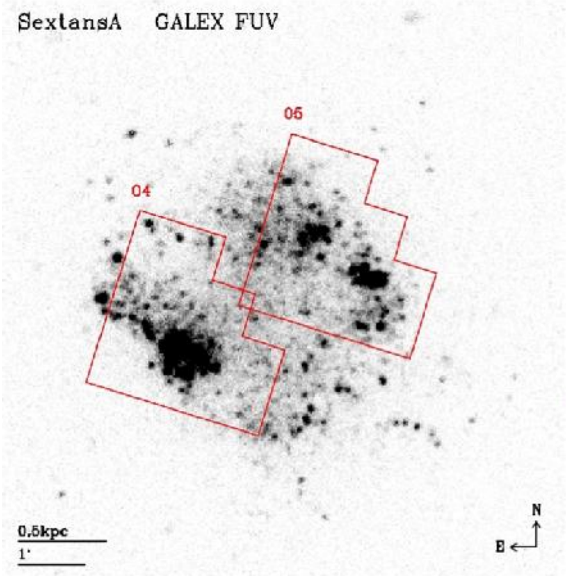
Requirements

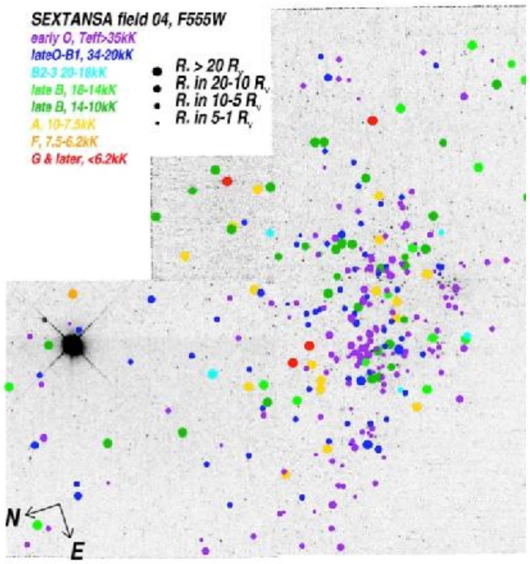
- R>3000 spectroscopy over a broad spectral range to measure redshift of both lensing and lensed objects.
- Extnsive multi-object capability in crowded fields of the order of ~1 square arcmin needed to produce accurate dark matter maps.
- AO capability to analyze faint objects on the critical curves and highly magnified galaxies.



Refsdal Supernova

3. Massive Star Formation In Local Group Dwarfs





Left: GALEX image of the dwarf galaxy Sextans A, with superimposed the footprints of the HST/WFPC2 observations. This galaxy represents a typical example of star-forming, low-metallicity, Local Group dwarf galaxy. Right: stellar temperature estimates from photometric SED fitting. HST observations like these can be used for GMOX target selection.

Given their typically low metallicities, dwarfs galaxies in the LG are ideal laboratories to study SF and evolution in conditions similar to the early Universe.

- What is the efficiency of metal enrichment of the ISM? Is it different from Milky Way and M31?
- Is low metallicity due to quiet SFH or inefficiency in retaining and mixing nucleosynthetic products?
- Targeting massive stars and A-type stars one can reconstruct current IMF and metallicity of young and intermediate-age populations.

Requirements

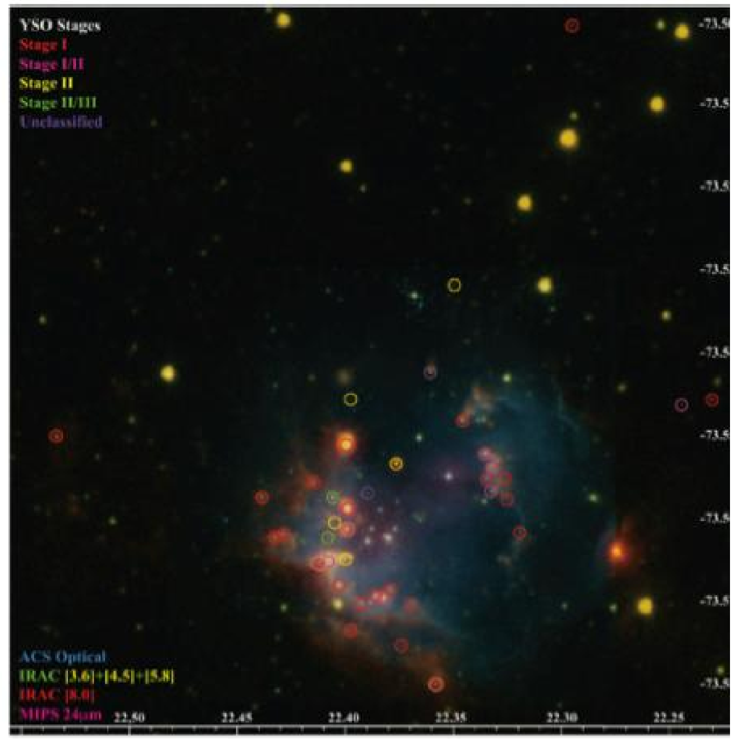
- **Crowded fields ~a few sq. arcmin. size**
  - Strong multiplexing capability, also di discover rare populations
  - Spatial Resolution: AO aided Visible observations (GLAO-type).

- **Resolving different stellar populations by kinematics, metallicity and spatial distribution**
  - medium resolution spectroscopy, R~3000, >5000 optimal to derive the spectral type and kinematics stars from O to G
  - Moderate resoution can distinguish AGB subtypes vs. core He-burning stars

- **Spectral range**
  - Blue, Visible, JHK.
  - Including a filter longward of H-band increases ability to separate AGB subtypes (O-rich, C-rich, etc).

4. MAGELLANIC CLOUDS

A 3D VIEW OF MASSIVE CLUSTER FORMATION IN THE MCS



HST image (left), and Spitzer/HST combined image (right) of NGC 602 in the Small Magellanic Cloud. This region can fit into the GMOX FoV and spectra of all YSO candidates and young massive stars can be obtained in one night.

GMOX science

- classify stars probing the inner and outer, more embedded regions;
- Reconstruct star formation history, triggering, cluster lifetime.
- derive both gas and stellar radial velocity, ejection scenarios, mass segregation, binary fraction, etc.

Low mass end of the PMS

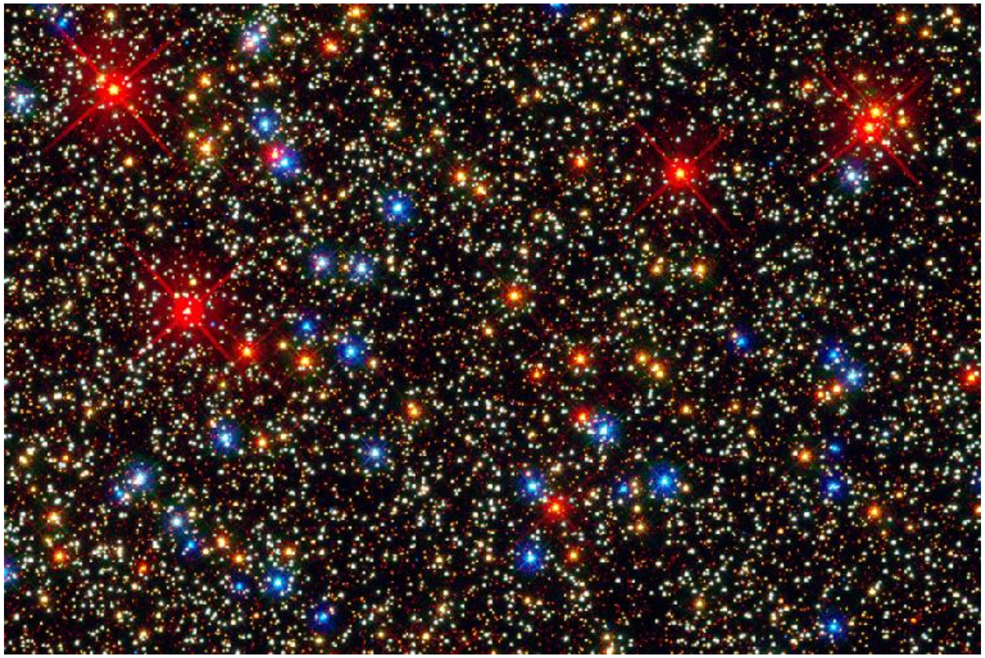
- GMOX in 1 hr can detect with minimal confusion the continuum of a T Tauri star in the LMC, opening the possibility of studying in detail Pre-Main-Sequence stars (PMS) outside the Milky Way.
- Thousands of PMS stars and Young Stellar Objects (YSOs) have been identified with Spitzer and Herschel, creating the largest and most complete census of young stars in an extragalactic environment.
- Confusion, contamination, and reddening vs. temperature de- generacy, however, hamper progress when using only photometry, even from HST.

Requirements

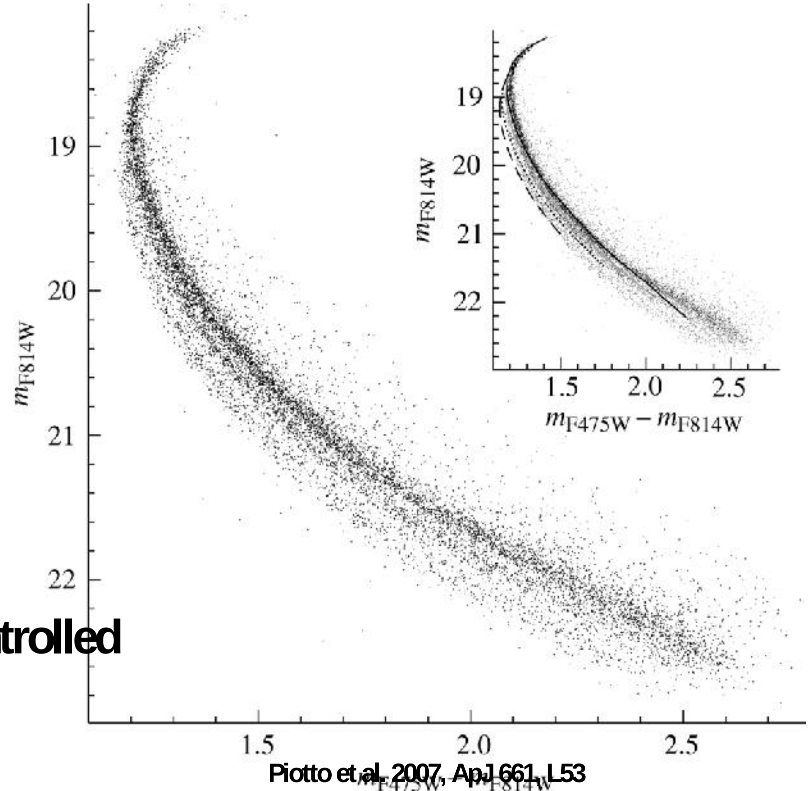
- **Multiplexing capability in crowded fields**
- **Classify OB stars using the numerous HI, HeI, HeII and metal lines that can be found in the wavelength range λλ=390-508 nm.**
- **Measure radial velocities with ~5km/s accuracy**
  - Spectral resolution R ~5, 000, fitting several lines with high SNR (~80) at V~18.
  - Wiide spectral range paired with multi-slit capability is needed to efficiently sample different poplulations of nearby galaxies.
- **Probe the youngest, reachest and most crowded clusters liken NGC602, reach below 1Msun:**
  - Determine spectral type, measure accretion, and discriminate between optically bright YSOs and post-asymptotic giant branch stars.
  - 3700–8800A range with R>1500R
  - Spectral typing to disentangle reddening vs. intrinsic color for GK stars
  - Access to infrared wavelengths allows probing more embedded and younger regions.

5. GLOBULAR CLUSTERS

SPECTROSCOPY OF MULTIPLE STELLAR POPULATIONS IN GLOBULAR CLUSTERS



Triple main sequence of the globular cluster NGC 2808

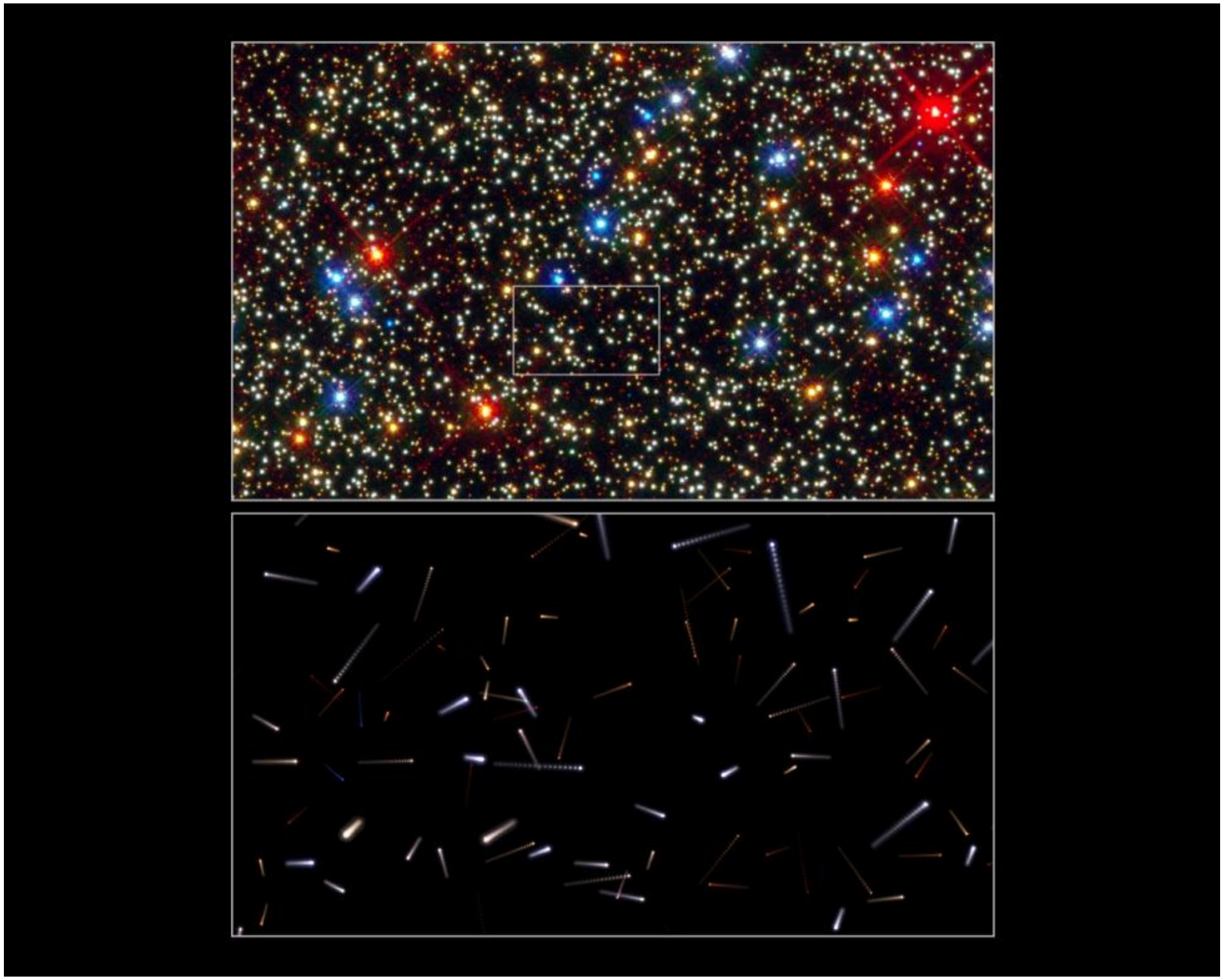


Piotto et al. 2007, ApJ 661, L53

Different stellar populations due to He abundance, controlled by processes (CNO, NeNa, MgAl cycles) that affect the concentration of other metals.

GMOX can clarify the relation between He enhancement and the simultaneous depletion/increase in light elements.

Globular Cluster kinematics



Line-of-sight velocities of GC stars have been measured so far only for the brightest giant stars. Quite a few number of interesting dynamical properties (e.g., mass segregation, energy equipartition) can only be studied using proper motions of fainter Main Sequence stars.

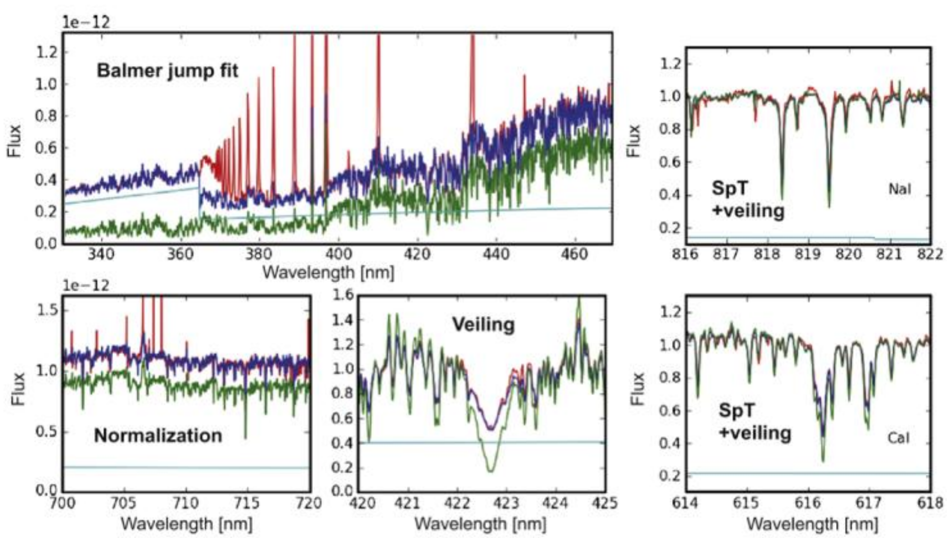
Requirements

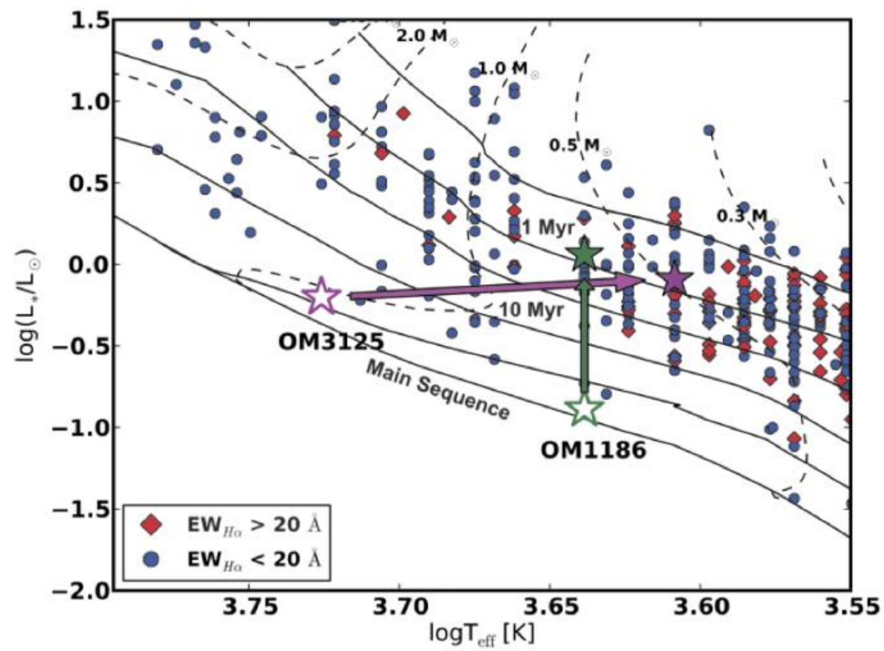
- **Spectra of turnoff and sub-Giant Branch stars in Galactic globular clusters, targeting e.g.CN(3883A) and CH(4305A) molecular bands to derive nitrogen and carbon abundances**
  - Low-medium resolution spectroscopy in the blue range (R>1500) is adequate to get
- **Measure line-of-sight velocities with higher precision than that achievable with proper motions**
  - R~3000-5000
- **Strong multiplexing in crowded field**
- **Extreme Horizontal Branch stars:**
  - Blue and visual coverage will provide the unique opportunity to observe simultaneously lines of both Carbon (CIII: 4647, 4650, 4651, 4665, 5696Å; CIV: 4658, 5801, 5811A) and Nitrogen (NII:4040,4240A,NIII:4634,4640A)
  - beat FLAMES and FORS2 at VLT

6. GALACTIC YOUNG CLUSTERS

Young stellar clusters should nicely trace the cluster isochrone. Instead they show Strong scatter in luminosity (radius), and thus Isochronal age.

Orion Nebula Cluster represents a typical case.





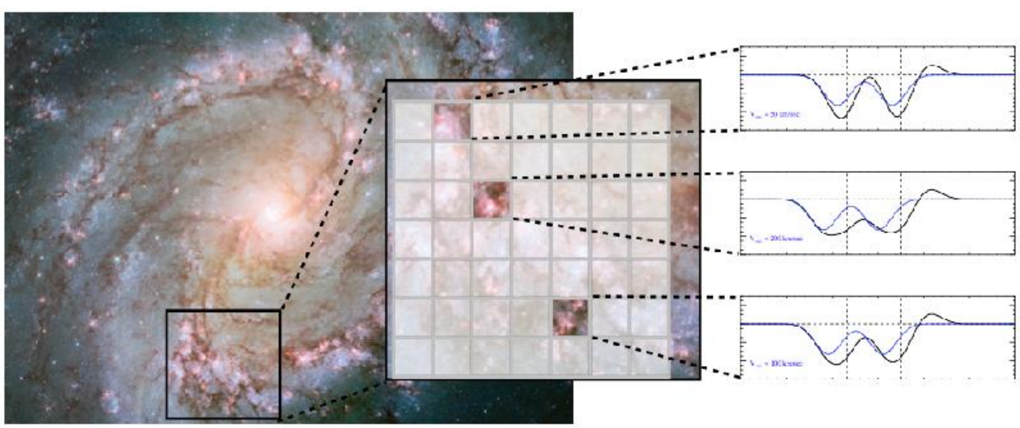
In fact, locating correctly a PMS star in the HR diagram is difficult, due to the effect of accretion and extinction on top of the PMS SED.
Wide-band spectroscopy with X-shooter allows to disentangle these effects and clean the HR diagrams

EXAMPLES OF CORE TEAM SCIENCE

Galaxy Outflows

Galaxies with high star-formation rates are the source of large galactic-scale winds that enrich the IGM and regulate the inflow of material.

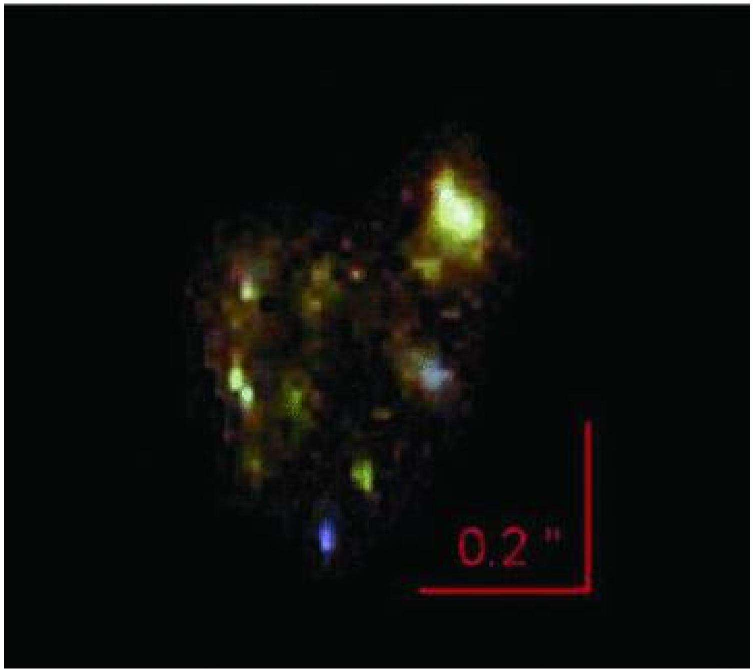
These are seen as blue shifted absorption features in galactic spectra. GMOX will be able to map this distribution in 3-d velocity/space. High spatial/spectral resolution will allow to associate the flow parameters to the properties of the local driving sources.



HST image of M83, degraded at 0.5” resolution with superimposed a footprint of the GMOX FoV. The three windows highlight three star clusters, where slits can be placed. The three mock spectra, show the blue shifted NaD doublet, with three out- flow velocities (50, 100 and 200 km/sec respectively), seen at GMOX resolving power R=5000.

Gravitational zoom lensing

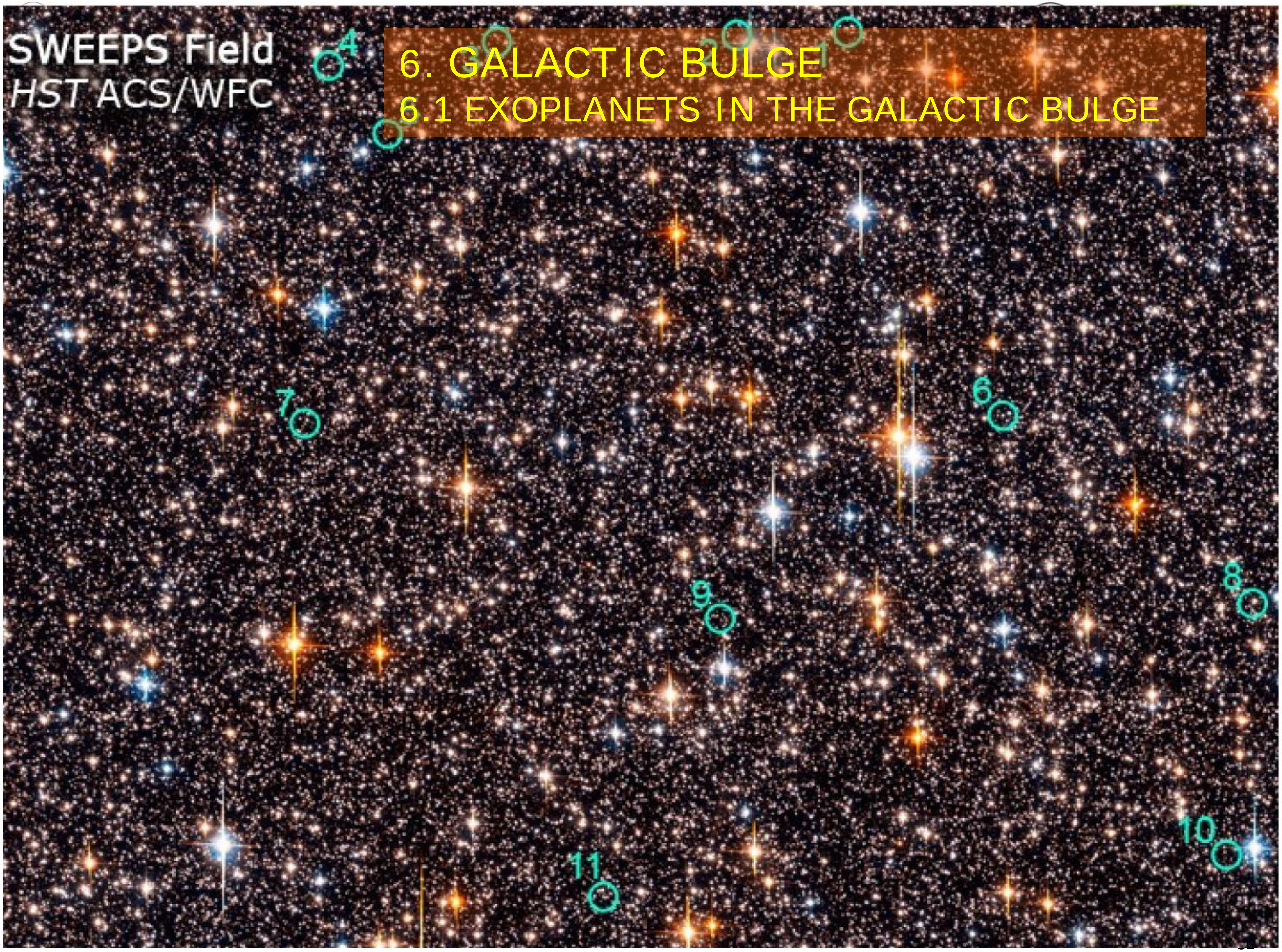
- High magnifications (factors of 2-20) allow detailed spectroscopic studies of galaxies at higher spatial resolution and fainter than those typically probed by blank field studies. Zitrin et al. reconstruct the morphology of a z~4.92 lensed galaxy in Abell 1703 magnified 25 times by cluster lensing.
  - **GMOX at GEMS can use strong lensing to probe structures as small as ~10pc when the Universe was 1 Gyr old: e.g. use the [OII]3727 line to measure the star formation rate of Globular Clusters in Formation!**



A. Zitrin et al. MNRAS 413, 1753 (2011)

6. GALACTIC BULGE

6.1 EXOPLANETS IN THE GALACTIC BULGE



Summary

Science case	Parameter	Requirement	Baseline	Goal
Dark ages z>10 candidates	Resolving power	>4000 in the IR	4500	10,000
	Spectral range	>10,032 A (Ly-a@z>10)	YJ	Y to H
	YJ Sensitivity	SNR=3 at AB=26 per pixel	80hr	40hr
	Capability	Full AO	SCAO	MCAO
Reionization, early QSOs	Resolving power	>3000	3000	5000
	Spectral range	>6000 A	Red-YJ	Red to H
	YJ Sensitivity	SNR=10 at 10^{-17} erg $cm^{-2}s^{-1}$	4hr	2hr
	Capability	Full AO	SCAO	MCAO
Galaxy Formation	Resolving power	>3000	3000	5000
	Spectral range	>3700 A (Lya @ z=2)	Blue to K	Blue to K
	Blue Sensitivity	SNR=10 at 10^{-17} erg $cm^{-2}s^{-1}$	2hr	1hr
	Capability	Seeing limited, multiplexing	0.7"seeing	MCAO

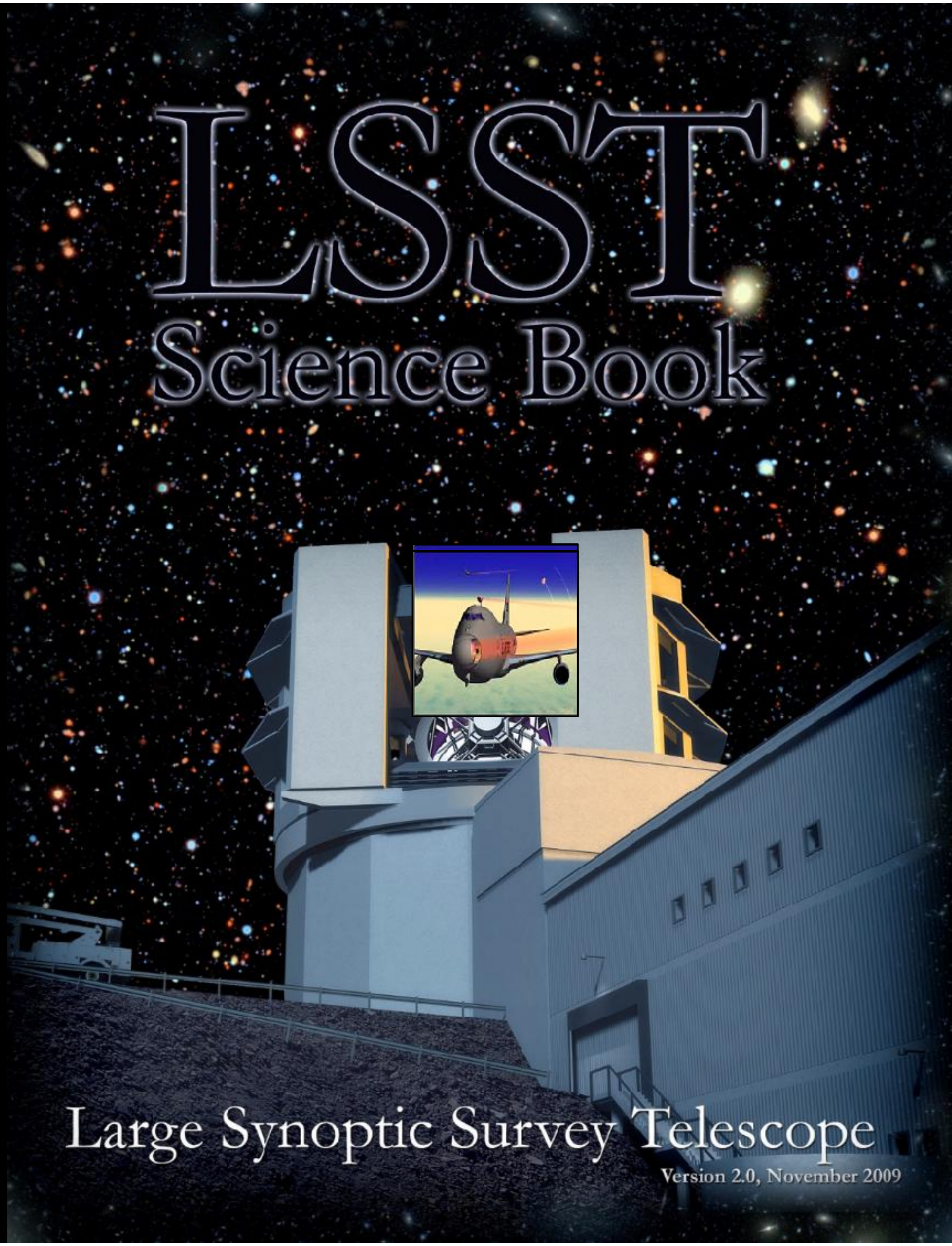
Summary

Science case	Parameter	Requirement	Baseline	Goal
"High noon"	Resolving power	>3000	4500	10,000
	Spectral range	Blue to K	Blue to K	Blue to K
	Sensitivity	SNR=3 at AB=24 per pixel	8hr	4hr
	Capability	Seeing limited, multiplexing	0.7" seeing	MCAO
Galaxy Clusters	Resolving power	>3000	3000	5000
	Spectral range	Blue to K	Blue to K	Blue to K
	Sensitivity	SNR=3 at AB=22	1	30min
	Capability	Seeing Limited, multiplexing	0.5" seeing	MCAO
Local Group Dwarfs	Resolving power	>3000	3000	5000
	Spectral range	Blue to K	Blue to K	Blue to K
	Sensitivity	SNR=3 at AB=22	1	30min
	Capability	Partial AO, multiplexing	GLAO	MCAO

Summary

Science case	Parameter	Requirement	Baseline	Goal
Magellanic Clouds	Resolving power	>3000	4500	10,000
	Spectral range	Blue, Red	Blue to K	Blue to K
	Sensitivity	SNR=8 at V=18 per pixel	2hr	1hr
	Capability	Partial AO, multiplexing	GLAO	MCAO
Galactic Globular Clusters	Resolving power	>3000	3000	10,000
	Spectral range	Blue	Blue	Blue to H
	Sensitivity	SNR=3 at AB=22	1	30min
	Capability	Partial AO, multiplexing	GLAO	MCAO
Local Star Formation	Resolving power	>3000	3000	10,000
	Spectral range	Blue to K	Blue to K	Blue to K
	Sensitivity	SNR=50 @ AB=18	2hr	1hr
	Capability	Seeing limited	Seeing limited	MCAO

LSST FOLLOWUP


LSST
Science Book
Large Synoptic Survey Telescope
Version 2.0, November 2009

Solar System

Stellar Populations

Milky Way and Local Volume Structure

GMOX provides Chemical Composition and Radial Velocities of faintest (oldest) stars

The Transient and Variable Universe

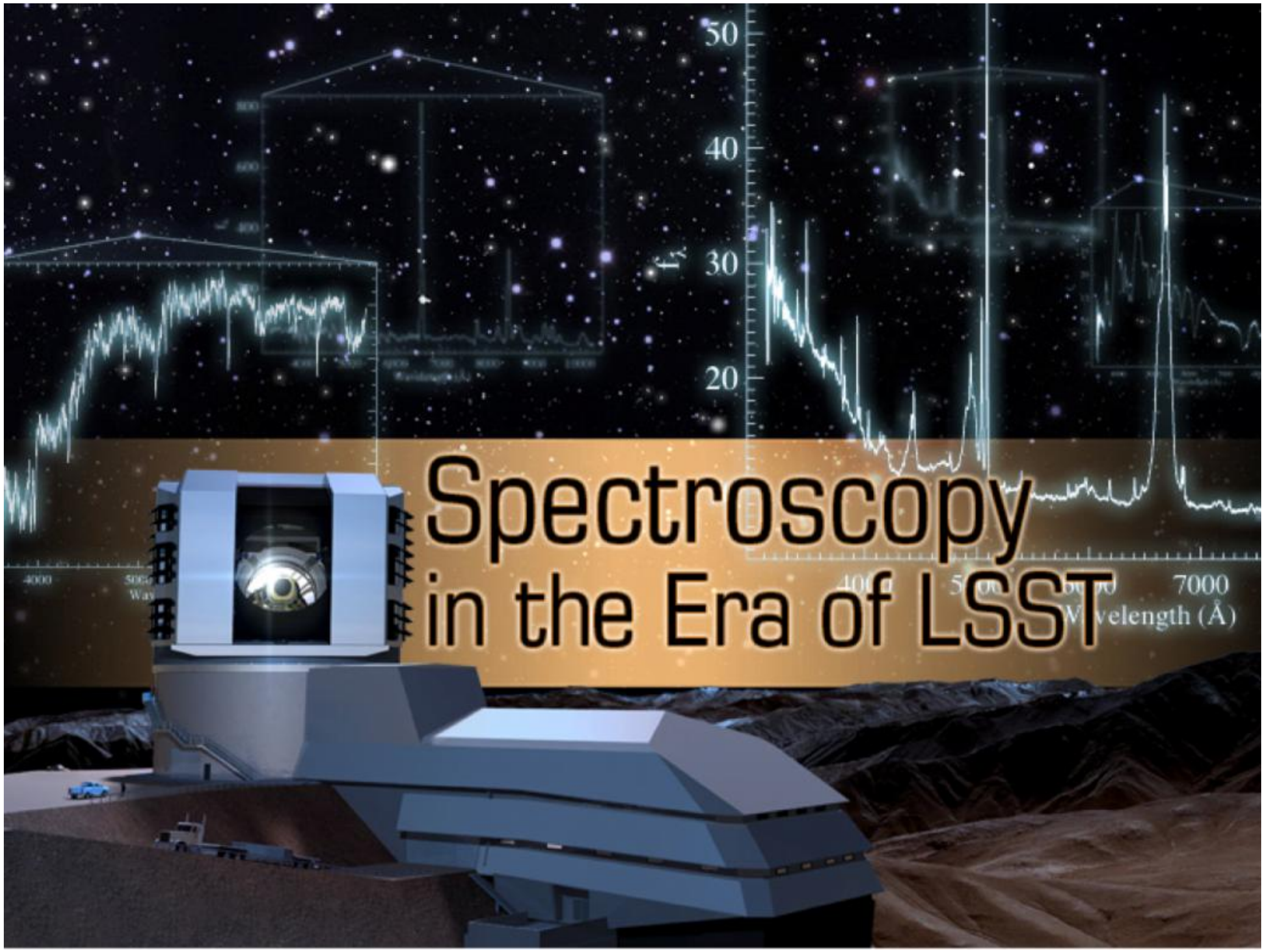
Galaxies

Supernovae

Strong Lenses

BAO, Weak Lensing, Cosmology

LSST Followup



Spectroscopy in the Era of LSST
Tucson, Arizona, April 11-12, 2013

Low-Resolution Spectrographs

- *[…] For truly **transient events**, when an object appears where none has before, LSST will provide only a magnitude at discovery. There will be no history to help characterize the event**. For these objects, a rapid, low-resolution spectrum can provide more information**. Because of their low resolution (**R~100- 500**) and high throughput, they can be deployed on smaller aperture facilities (**2- 4m**). A suite of such spectrographs on a range of telescope apertures would greatly enhance the identification of rare and interesting objects in the LSST alert stream. It would also help to identify SNe Ia for cosmological use, AGNs for variability and reverberation mapping.*

- **GMOX reaches SNR=10 per pixel at AB=24 (LSST single image sensitivity) in ~10hr, Red Channel, 0.75” slit, R=2000.**
  - Most LSST transients will be beyond 2-4m class telescopes.

Single-Object, High-Throughput, Wide-Wavelength Coverage Spectrographs

- *For many objects, the density on the sky at any given time will be low enough that there is no advantage to a multi-object spectrograph. While this will apply mainly to time-domain events, it is also true of* ***rare non-variable objects (such as high-redshift AGN and galaxies****). The general requirement for resolution is to split the [O II] doublet, so* ***R~3500****, but this is also high enough to separate the OH night sky lines and thus produce better spectra of faint objects in the infra-red. Most time-domain targets will be unknown and the known targets will cover a wide redshift range, so the widest possible wavelength coverage is important. This covers from the atmospheric cutoff at* ***0.32μm to the K band. A single instrument that encompasses all these capabilities may be difficult, but a suite of instruments deployed on a range of telescope apertures from 4m to 10m would fulfill most of the need.***

- **GMOX can be operated as a single object "point-and-click" spectrograph, with immediate slit alignment, R=1125 (1" slit in the IR) to 22500 (83mas at U, nominal).**

Highly Multiplexed Spectrographs

- *There are many science cases from across the breakout sessions that require spectra of many thousands of objects. Some would like orders of magnitude more. The instruments would be wide field, with a field of view of 1-3 degrees. There would be capacity for hundreds (minimal) to thousands (highly desirable) of spectra in a single observation. These cases focus mainly on optical wavelengths, but IR capability is also important.*

- *For the multi-object cases, there is less commonality when it comes to resolution. Most extragalactic programs and some Galactic structure science could use low-to- moderate resolutions of R~1000-3000. The Galactic science programs also desire higher resolutions of R~20,000-30,000. These would be deployed on telescopes with apertures of 4m to 10m, with the larger telescopes taking most of the demand.*

- **Gemini unvignetted FoV is 3.5 arcmin.**
- **GMOX can deliver R~1000 to R~20000, optimized for each target**

Single-Object High-Resolution Optical and Near-IR Spectrographs

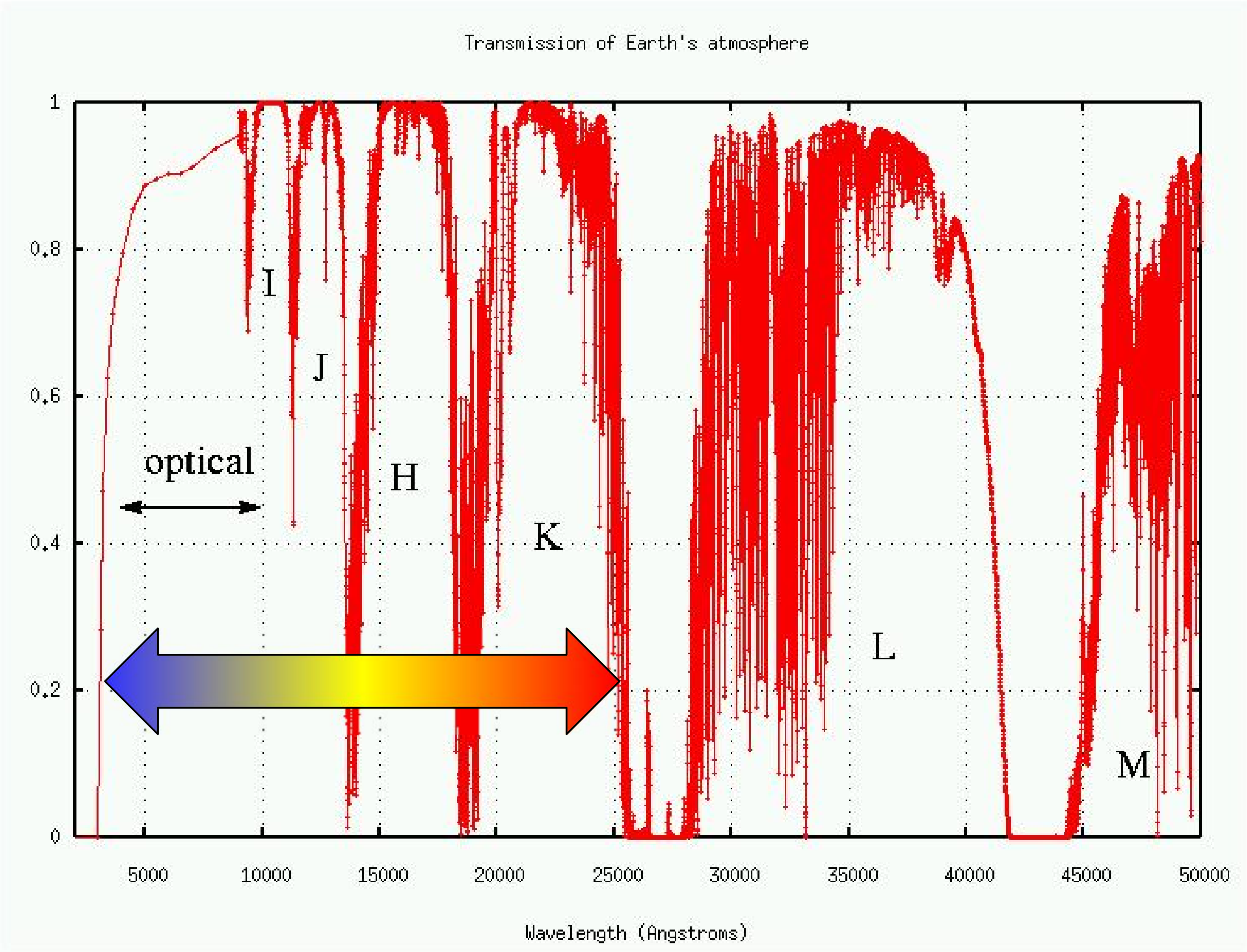
- *For **Galactic science**, availability of high-resolution optical and near-IR spectrographs on the largest telescopes is very important. High-resolution optical spectrographs, **with R~20,000** and higher, are particularly important for measuring the properties of the rare extremely metal-poor stars in the Galactic halo, from which we will have a unique window into the early Universe. High-resolution near- IR spectrographs, with **R~40,000–50,000**, are critical for deriving masses of ultracool dwarfs in low mass binary systems.*

- **GMOX is not designed for high-resolution spectroscopy, but can reach nominal resolving power as high as R=22500 (Blue), R=18000 (Red) and R=13500 (IR)**

Part 3

DESIGN CHOICES (ENABLING AO)

Wide Band Coverage



Wide Band coverage

- **From the U-band (~3200A) to the K-band (~2.5micron)**
- **Split in 3 arms to optimize throughput:**
  - Blue
  - Red
  - IR
- **Cutoffs:**
  - Blue starts at shortest possible wavelength: 3200A Goal
  - Red ends at CCD cutoff: about 10,000A: set to 9,800A
  - IR: from 10,000A to about 2.5micron, limited by thermal emissivity
  - Blue-red cutoff at ~6000A
    - » Na Laser provides “natural” boundary at 5890A
- **Bandpass**
  - BLUE: 3200A-5890A
  - RED: 5890A-9,800A
  - IR: 0.98micron-2.5micron

SPACE TELESCOPE SCIENCE INSTITUTE
Operated for NASA by AURA

Spectral Resolution -> detector size

R·I·T

IDG INSTRUMENT DEVELOPMENT GROUP

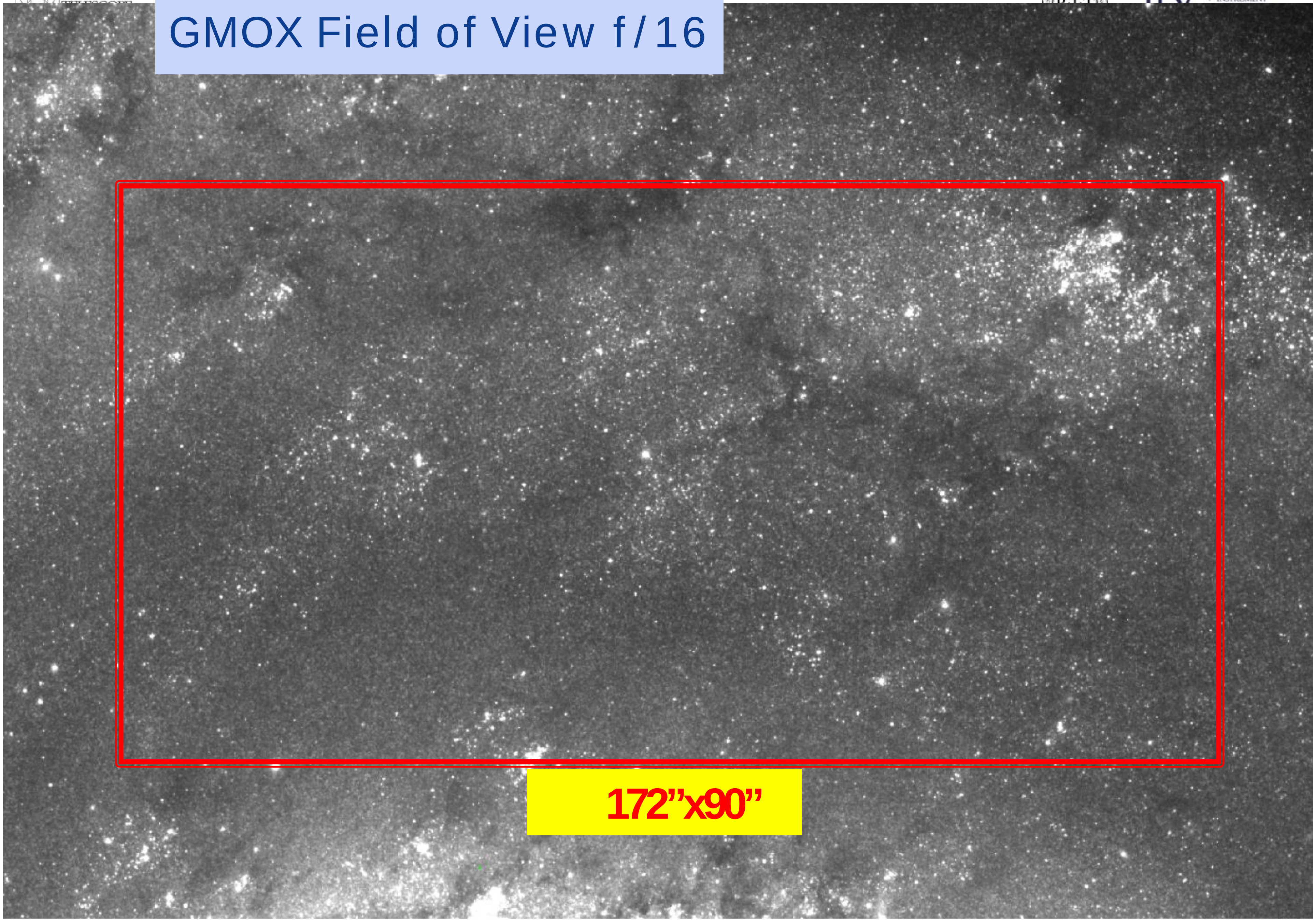
JOHNS HOPKINS UNIVERSITY

- **Resolving power: R=5000 goal**
- **Central wavelengths**
  - Blue: 4545A
  - Red: 8000A
  - IR:17500A
- **Delta lambda=central wavelength/R**
  - Blue = 0.909A
  - Red = 1.569A
  - IR = 3.48A
- **Nr. of dispersing elements**
  - Blue: 2959
  - Red: 2492
  - IR: 4368
- **Sampling: 3 pixel/dispersing element**
  - Blue: 8,877 pixels => Very Large Format CCD
  - Red: 7,476 pixels => Very Large Format CCD
  - IR: 13104 pixels => 3x Hi4RG IR FPAs: YJ, H and K band

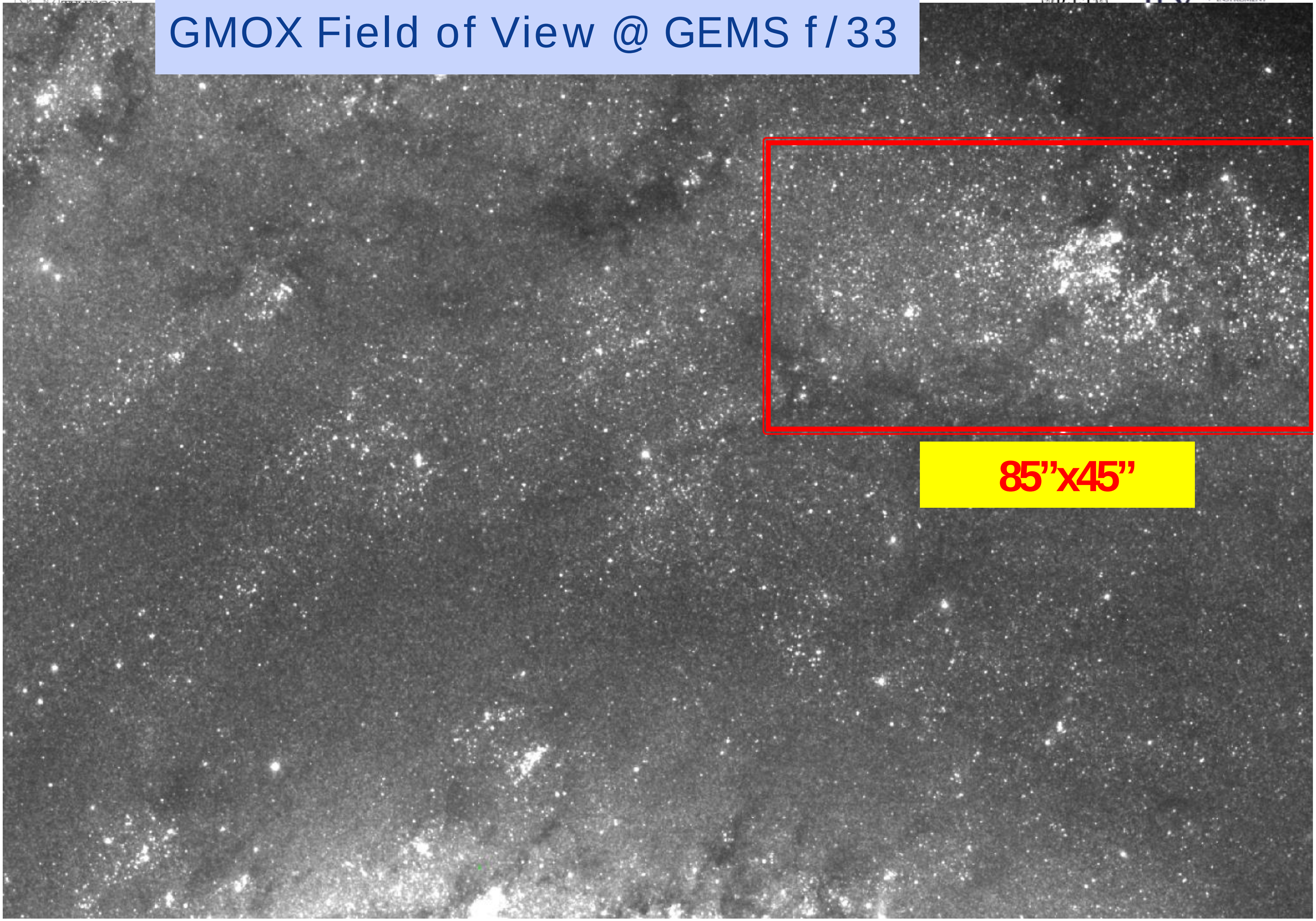
DMD: scale and FoV

- **Assume Cinema 2K device**
  - 2048x1080 mirrors
  - 13.7 micron pitch
    - » Largest format with 13.7micron mirrors
- **Scale on DMD**
  - f/4: sweet spot between field (fast beam) and cost/throughput
    - » f/2.8 theoretical limit
  - Needs reimaging optics f/16 -> f/4: 4x magnification
  - EFL = 32m
  - Scale: 83.3mas/DMD
  - Field of view: 172”x90”
- **GeMS is f/33**
  - 4x magnification produces EFL = 66m
  - Scale 40mas/DMD
  - Field of view: 85”x45”

GMOX Field of View f/16



GMOX Field of View @ GEMS f/33



Slit size

- **The scale 83.3mas/mirror is the same for the 3 modules**
- **Slit size can be optimized for typical conditions**
- **We assume “intermediate level” of AO correction**
  - “Ground Layer” correction cuts 50%-70% the PSF
  - Altair with field flattener
  - Laser Guide without Tip-Tilt correction

Arm	Typical Seeing	AO aided PSF
Blue	0.8”	0.4”
Red	0.7”	0.35”
IR	0.5”	0.25”

- **Nominal slit sizes**
  - Blue: 0.42” = 5 mirrors
  - Red: 0.33” = 4 mirrors
  - IR: 0.25” = 3 mirrors

GEMS: Blue: 0.20”
Red: 0.16”
IR: 0.12”

Rθ values (resolution with 1" slit)

- **f/16**
  - Blue: 5000 x 0.42 = 2082
  - Red: 5000 x 0.33 = 1666
  - IR: 5000 x 0.25 = 1250
- **f/33**
  - Blue: 5000 x 0.20 = 1000
  - Red: 5000 x 0.16 = 800
  - IR: 5000 x 0.12 = 600
- **Max Resolution: Rθ/0.083" @ f/16**
  - Blue: 25,000 sampled with 0.6pixel/slit
  - Red: 20,000 sampled with 0.75pixel/slit
  - IR: 15,000 samples with 1.00 pixel/slit

A more refined version

Slit width (arcsec)	Blue		Red		IR	
	R(l/Dl)	Pix/slit	R(l/Dl)	Pix/slit	R(l/Dl)	Pix/slit
0.083	22500	0.60	18000	0.75	13500	0.92
0.167	11250	1.20	9000	1.50	6750	1.83
0.250	7500	1.80	6000	2.25	4500	2.75
0.333	5625	2.40	4500	3.00	3375	3.67
0.417	4500	3.00	3600	3.75	3700	4.58
0.500	3750	3.60	3000	4.50	2250	5.50
0.583	3214	4.20	2571	5.25	1929	6.42
0.667	2812	4.80	2250	6.00	1687	7.33
0.750	2500	5.40	2000	6.75	1500	8.25
0.833	2250	6.00	1800	7.5	1350	9.17
0.917	2045	6.60	1636	8.25	1227	10.1
1.000	1875	7.20	1500	9.00	1125	11.0

Imaging field

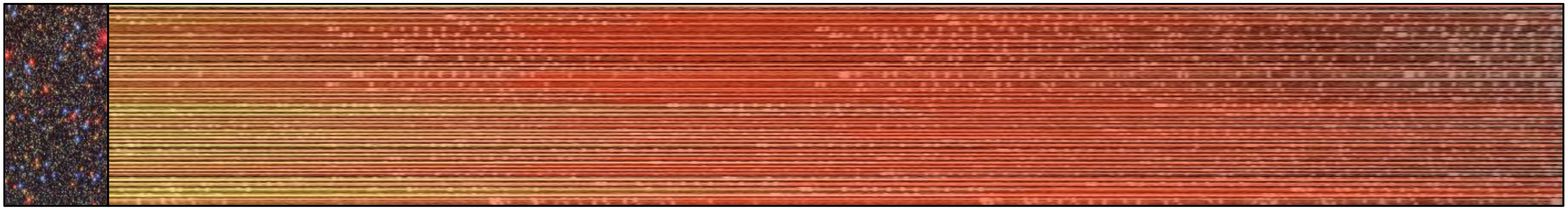
- **Slit sampling affects size of the field on detector**
  - Blue: 3CCDpix/5DMDmirrors => 1228 x 648 pixels
  - Red: 3CCDpix/4DMDmirrors => 1536 x 810 pixels
  - IR: 3CCDpix/3DMDmirrors => 2048 x 1080 pixels
- **Total field size**
  - Blue: X = 1228 Y = 648 + 8877 = 9525
  - Red: X = 1536 Y = 810 + 7476 = 8286
  - IR: X = 2048 Y = 1080 + 13104/3 = 5448

=> compromise needed on Rθ, see Barkhouser presentation

Spectrographs field of view (pixel)

Blue

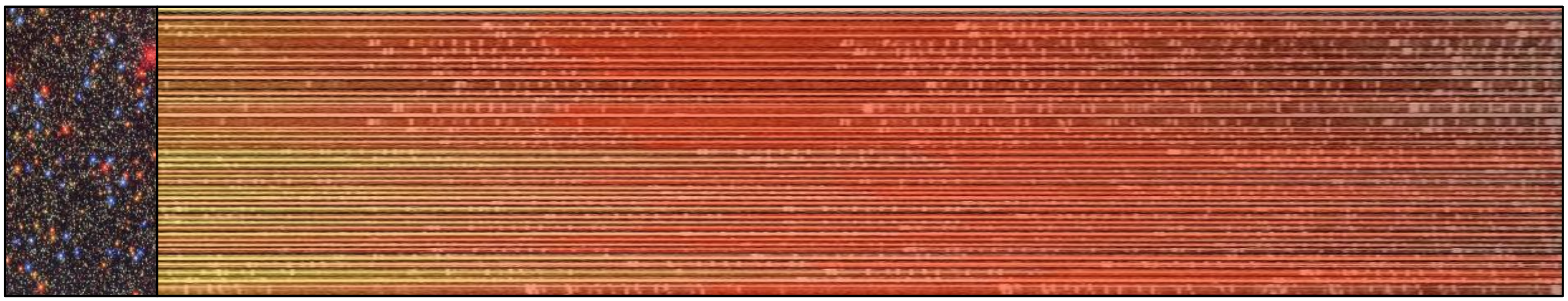
1228



648 8877

Red

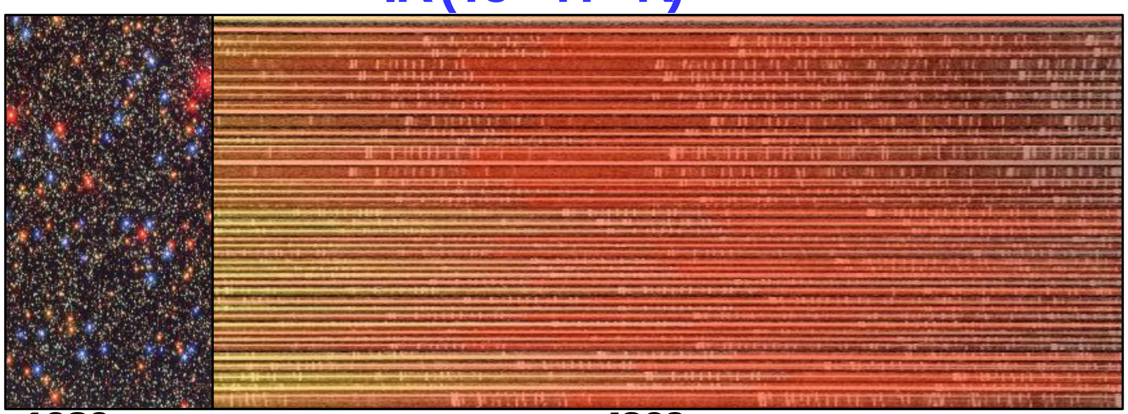
1536



810 7476

IR (YJ – H – K)

2048



1080 4369

ENABLING AO

GMOX and AO

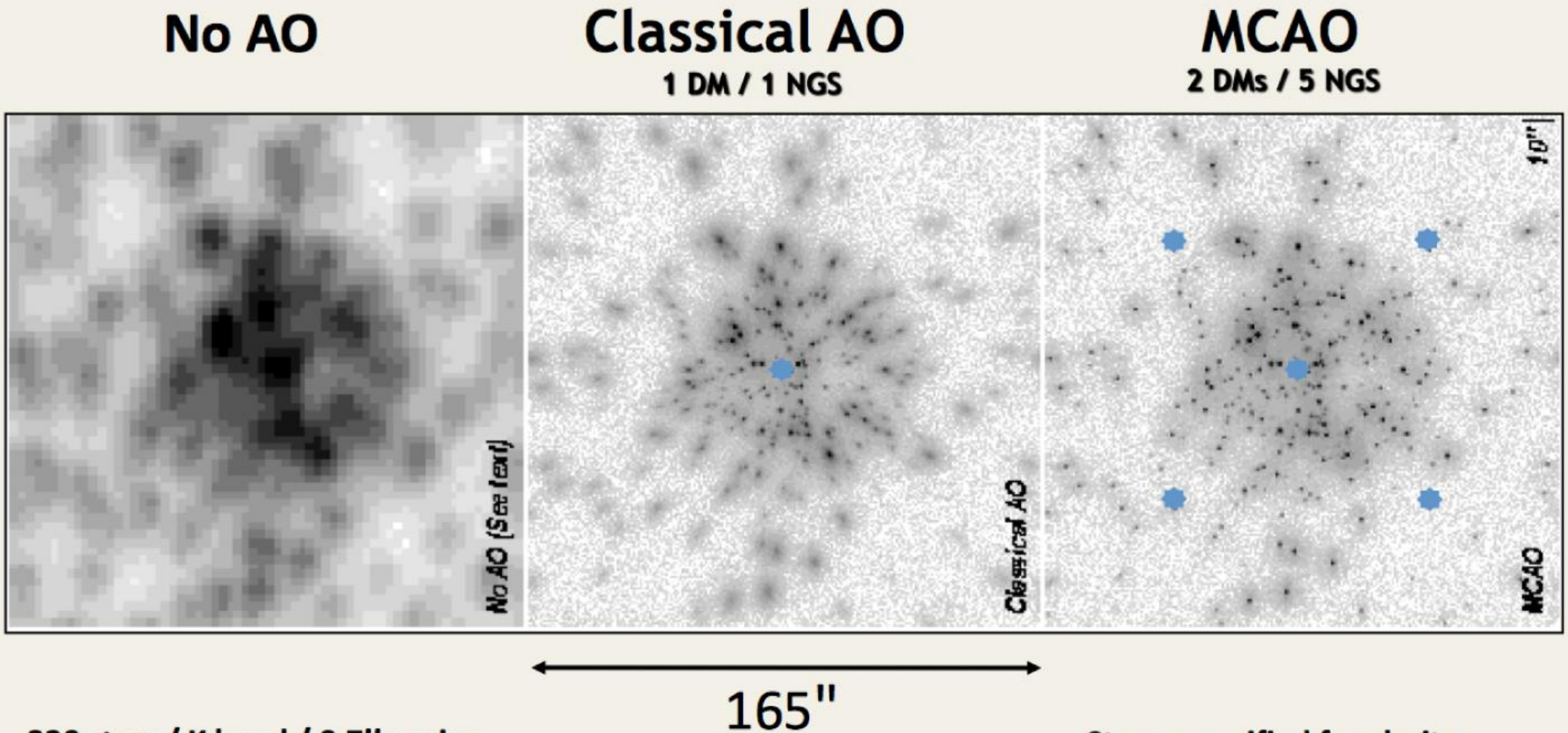
- **GMOX design parameters are mainly driven by**
  - Telescope focal ratio
  - DMD physical size
  - Size of available detectors

- **It would be nearly impossible e.g. to double the field size or sample e.g. 200mas/slit (like JWST).**
  - JWST had to rebuild the slit selection mechanism
  - It becomes possible on smaller telescopes

- **"By chance", these parameters are optimal**
  - For the unvignetted Field of View of Gemini
  - For an AO system
  - especially for a MCAO system

GMOX IS NOT "DESIGNED" FOR AO, BUT OPTIMALLY EXPLOITS AO ADAPTING "IN REAL TIME" TO THE LEVEL OF CORRECTION

MCAO Performance Summary



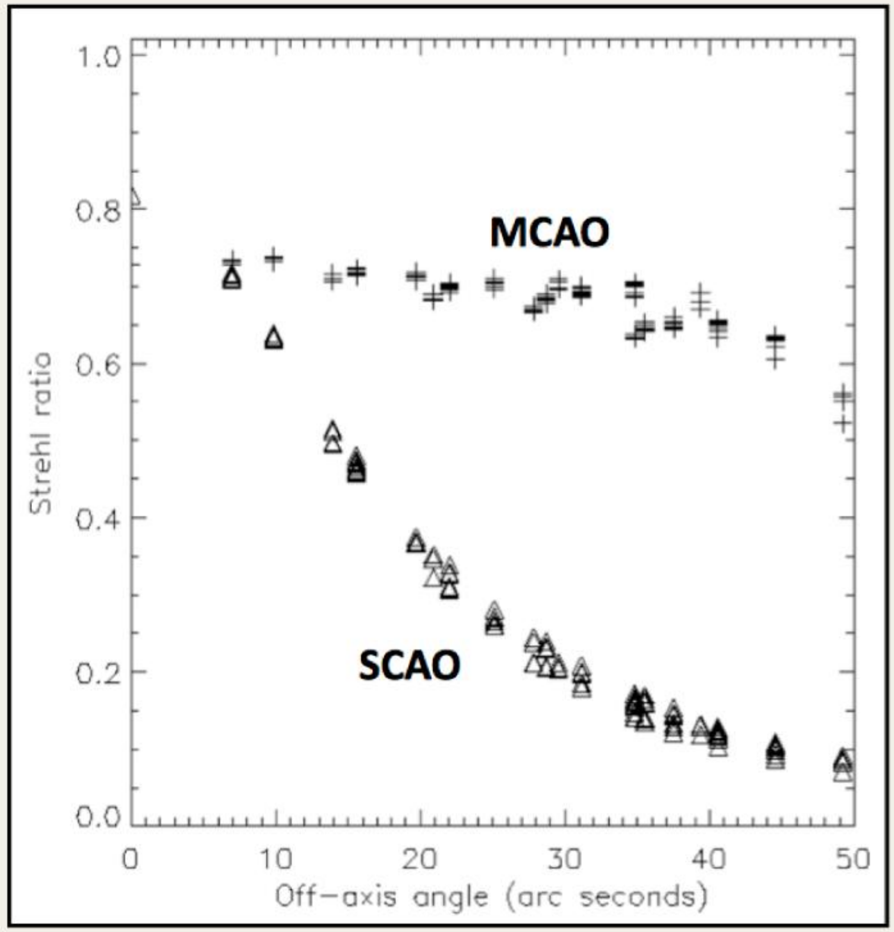
320 stars / K band / 0.7'' seeing

Stars magnified for clarity

From https://www.noao.edu/meetings/ao-aas/talks/Christou_Gemini_AO_AAS.pdf

GeMS Performance

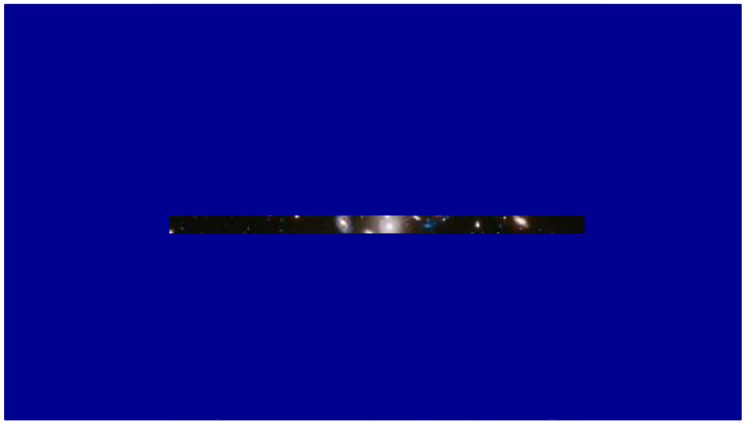
- Strehl under median seeing conditions (0.7")
  - J ➜ 20% ; H ➜ 40% ; K ➜ 60%
  - Strehl uniformity: J ➜ 5% ; K ➜ 2%
- Sky coverage:
  - Need 3 TT guide stars (R_{lim} = 18.5)
  - Galactic pole ➜ 10%
  - Average over whole sky ➜ 30%
  - Compatible with degraded modes of operation (1 or 2 TTGS)

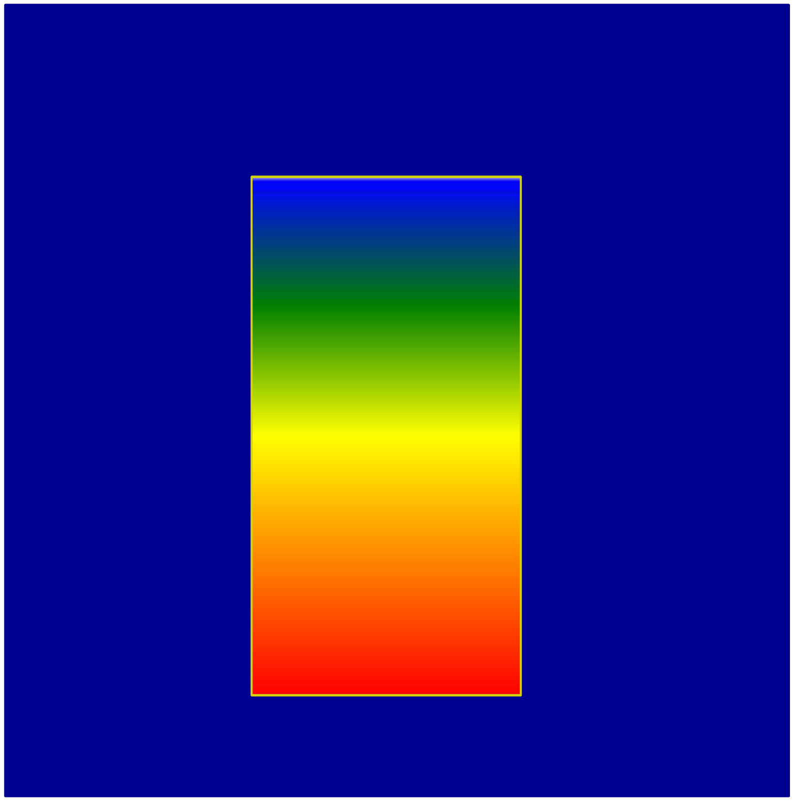


GMOX IN IFU MODE

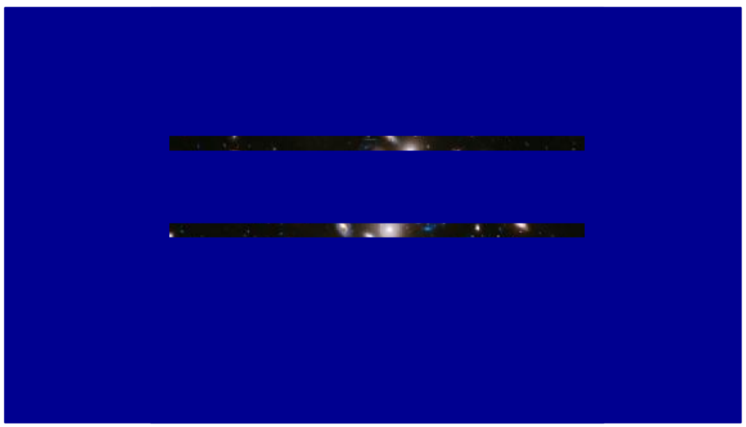
DMDs enable Hadamard Transform Spectroscopy

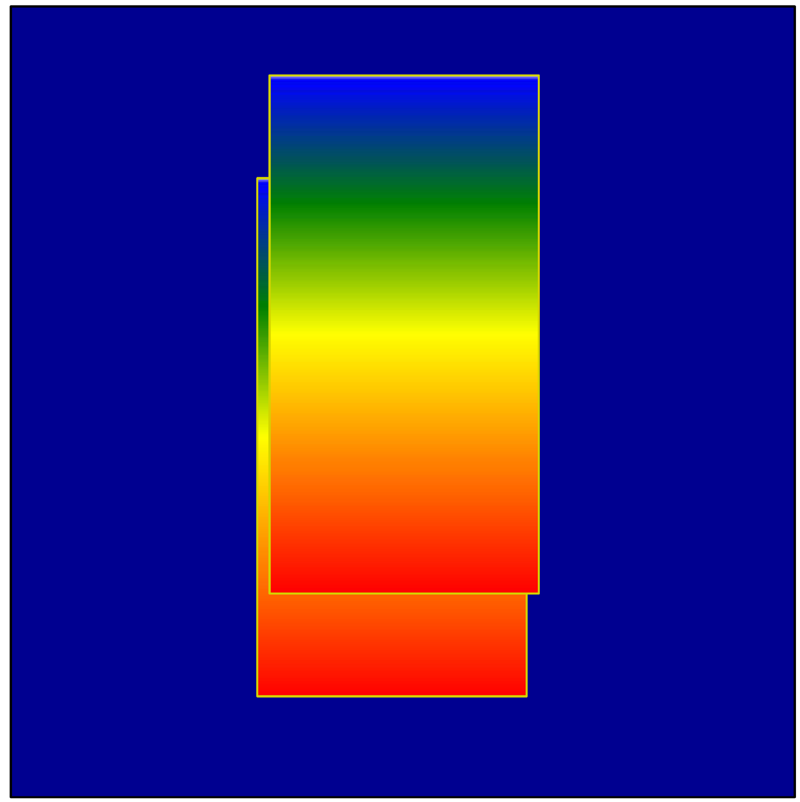
A Long Slit spectrum



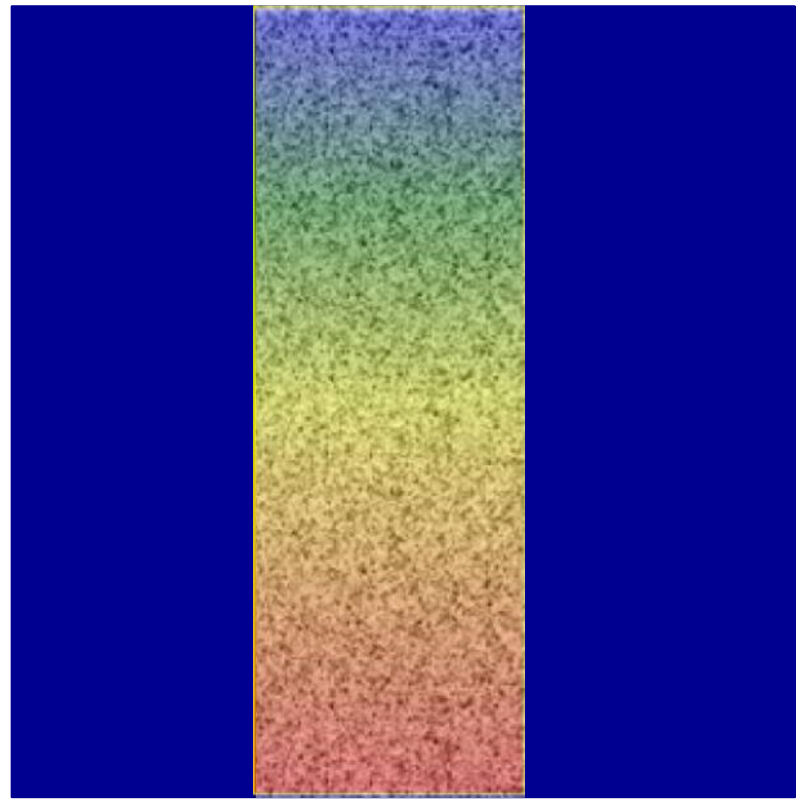


Multiple slits produce overlapped spectra





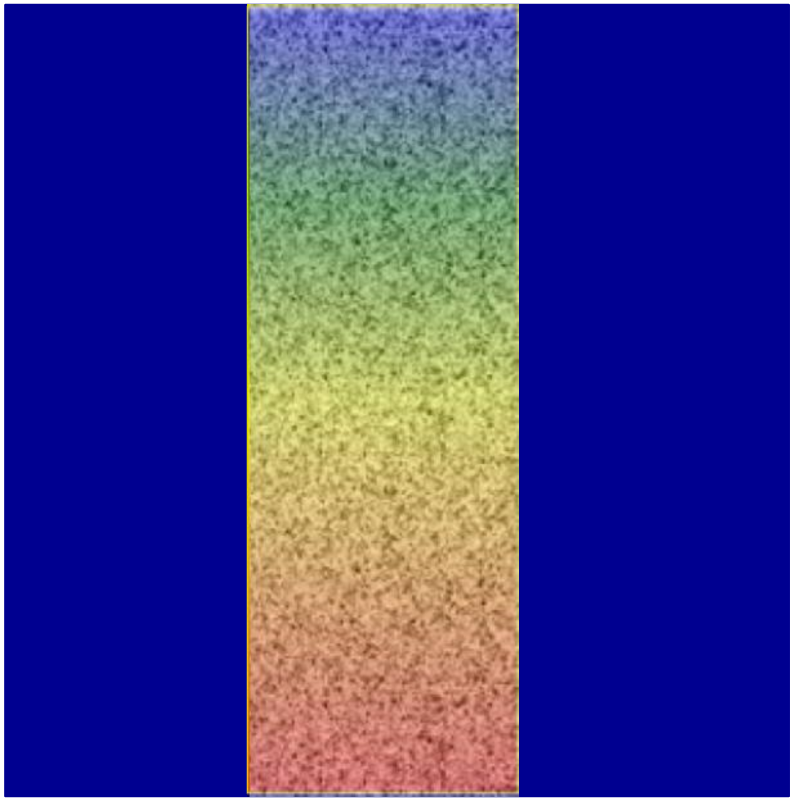
50% of the field: “semi-slitless”



Space Telescope Science Institute — Operated for NASA by AURA

Slits can follow a binary code

Changing the pattern and taking more spectra…

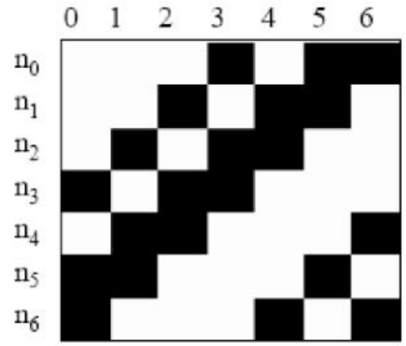


The datacube can be reconstructed!

How Hadamard works

First mask pattern →
Second mask pattern →
Third…. →

ROWS REPRESENT ORTHOGONAL VECTORS



$$n_0 = \psi_0 + \psi_1 + \psi_2 + \psi_4 + \varepsilon_0$$
$$n_1 = \psi_0 + \psi_1 + \psi_3 + \psi_6 + \varepsilon_1$$
$$n_2 = \psi_0 + \psi_2 + \psi_5 + \psi_6 + \varepsilon_2$$
$$n_3 = \psi_1 + \psi_4 + \psi_5 + \psi_6 + \varepsilon_3$$
$$n_4 = \psi_0 + \psi_3 + \psi_4 + \psi_5 + \varepsilon_4$$
$$n_5 = \psi_2 + \psi_3 + \psi_4 + \psi_6 + \varepsilon_5$$
$$n_6 = \psi_1 + \psi_2 + \psi_3 + \psi_5 + \varepsilon_6$$

On the left is the code for the 7 binary masks, providing $n_0 \ldots n_6$ read values; The masks select 4 out of 7 element of the (x,l) cube, indicated by y $_0$…y $_6$

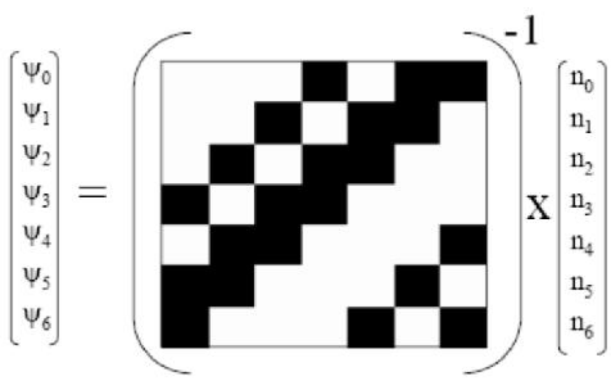
Let's do the inversion

ORTHOGONAL MATRIX:

$Q^TQ=QQ^T=1$

and

$Q^T=Q^{-1}$



Hadamard: the inverted matrix is equal to the direct one!

Hadamard SNR

RON single scan:

$$SNR_0 = \frac{S_{ph}}{\sqrt{\sigma_{ron}^2 + \sigma_{ph}^2}}$$

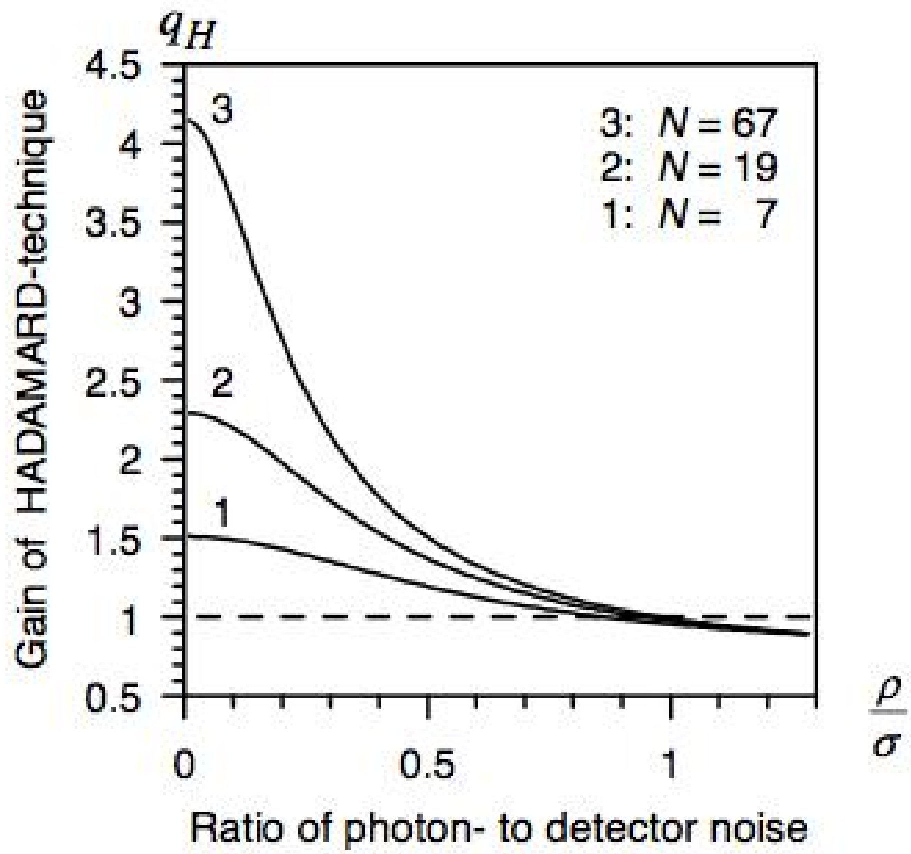
RON Hadamard:

$$SNR_H = \frac{\frac{(N+1)}{2} S_{ph}}{\sqrt{N}\sqrt{\sigma_{ron}^2 + \left(\frac{N+1}{2}\right)\sigma_{ph}^2}}$$

Fellgett advantage:

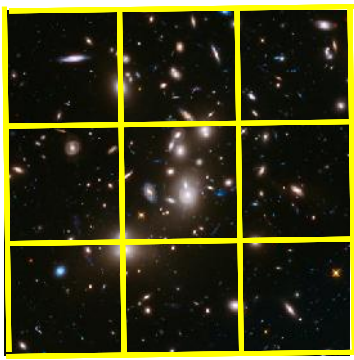
$$q = \frac{SNR_H}{SNR_0} = \frac{N+1}{2\sqrt{N}} \frac{\sqrt{\sigma_{ron}^2 + \sigma_{ph}^2}}{\sqrt{\sigma_{ron}^2 + \left(\frac{N+1}{2}\right)\sigma_{ph}^2}} \cong \frac{\sqrt{N}}{2} \text{ (RON limited)}$$

Fellget advantage

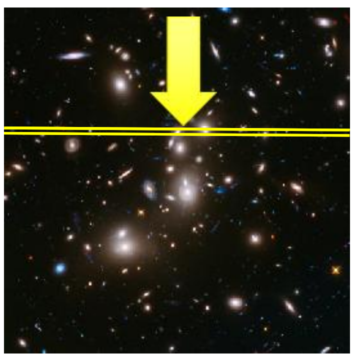


A simple comparison

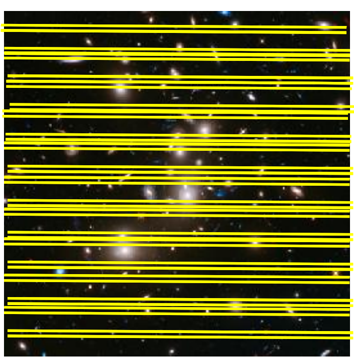
180”



MUSE: 0.2” pixel, 60”x60”
9 pointing: 9min to get SNR(1min) on full field



SCAN:
180”/0.2” SCAN = 900 pointing: 900min to get SNR(1min) on full field



HADAMARD-Wide Bandpass: 1600 resolution elements at 0.2”
1600 patterns x 2 GMOX fields = 3200 minutes

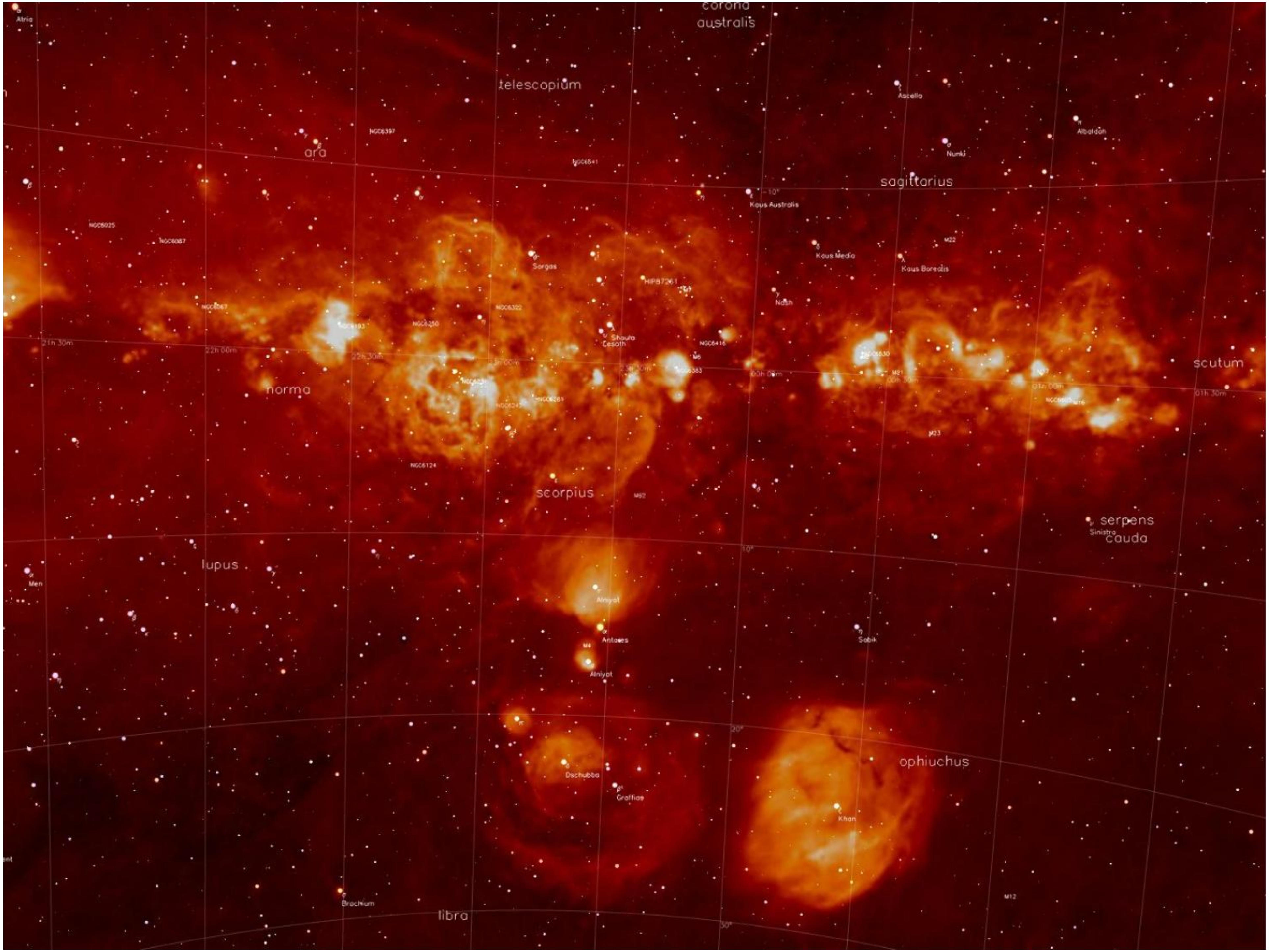
In 3200 min GMOX gets SNR(1min)xSQRT(1600)/2 = SNR(1min)*20
=> SNR(400min) on full field [RON limited]

Filter limiting bandpass: 100 resolution elements => SNR(1min)xSQRT(100)/2 = SNR(1min) x 5 in 200min

More new science…

- **With the addition of filter wheels, GMOX can operate in IFU mode.**
- **Uniquely wide field of view**
- **Unique wide spectral range, enabling new science**
  - Example:
    - » GMOX can observe in IFU mode the kinematics of
      - Ha line, in the Red channel
      - Hb line, in the Blue channel
      - Br gamma, in the IR channel
    - » With 3 lines, it is possible to derive (Osterbrock, AGN^2)
      - Electron density
      - Emission temperature
      - Extinction

      of each kinematic component of ionized gas.

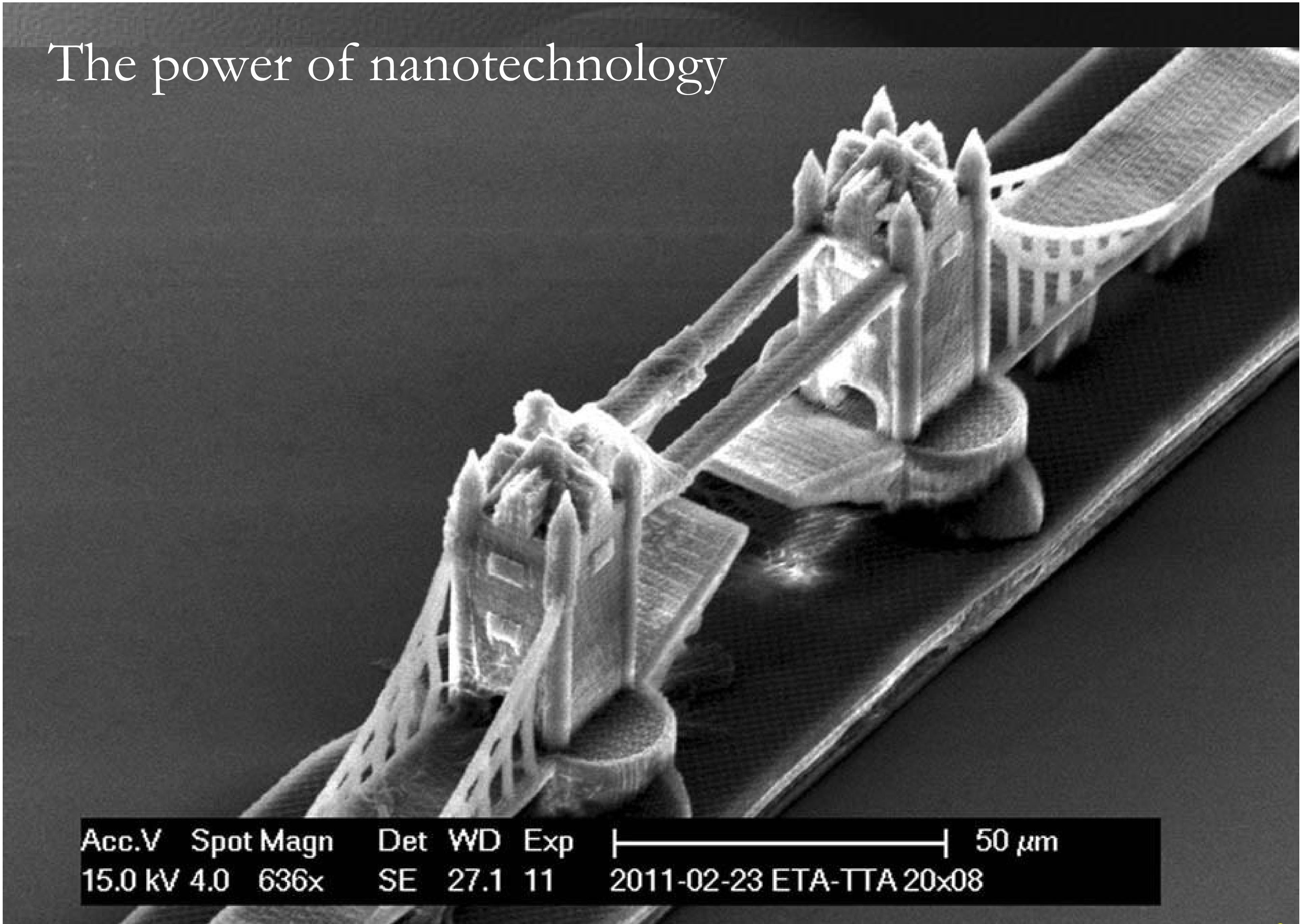


corona australis
telescopium
ara
sagittarius
Kaus Australis
Kaus Media
Kaus Borealis
Ascella
Albaldah
Nunki
Sargas
Shaula
Lesath
norma
scorpius
scutum
lupus
serpens cauda
Alniyat
Antares
Sabik
ophiuchus
Dschubba
Graffias
Khan
Brachium
libra

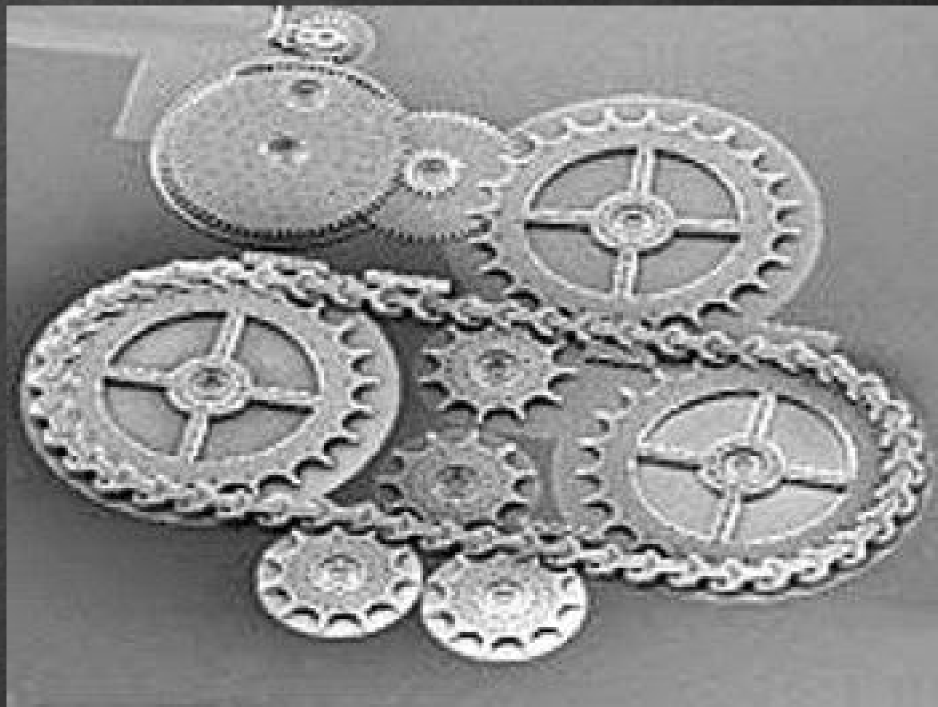
DMD Devices

M. Robberto,
with Z. Ninkov and D. Vorobiev (RIT)

The power of nanotechnology



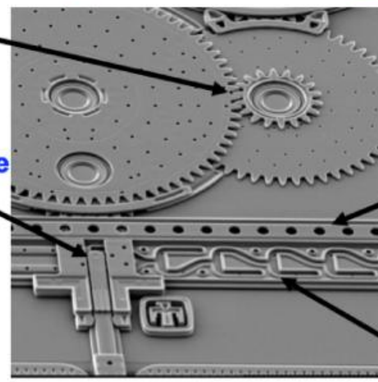
Micro-Electro-Mechanical-Systems (MEMS)



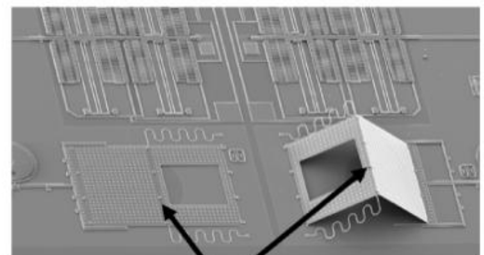
A different regime in Physics

Allowing contact between MEMS surfaces significantly broadens the design space

Complex Mechanical Logic



Pop-up Mirrors



<u>but</u> ...

static friction can dominate the forces required
dynamic friction can dominate energy loss
adhesion, friction and wear become the most important failure mechanisms of contacting MEMS

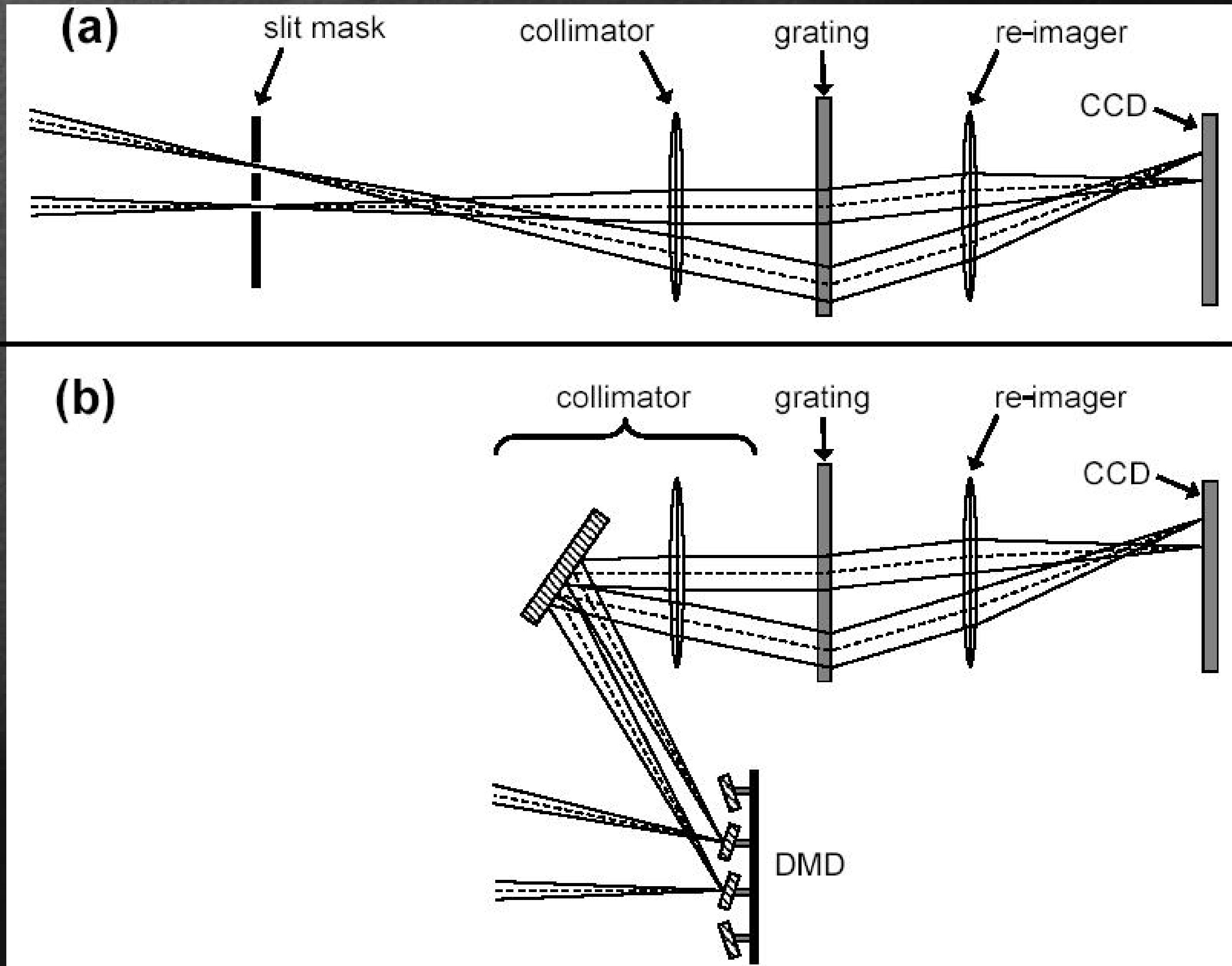
slide 4

Sandia National Laboratories

MEMS as slit: transmission vs. reflection

MSA:

DMD:

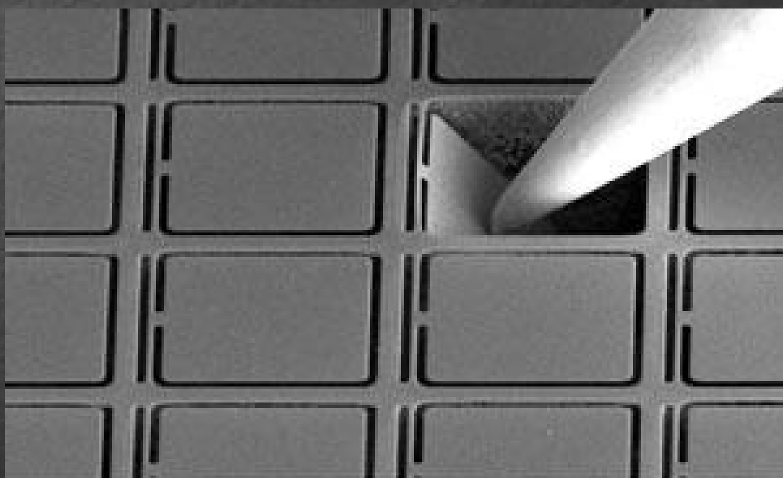


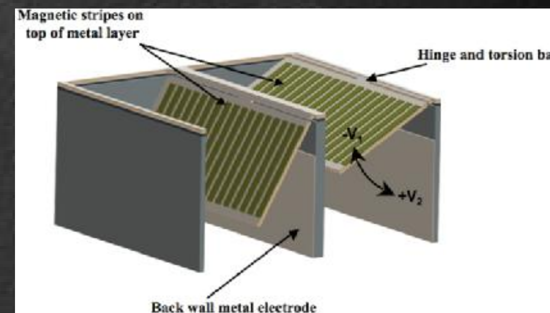
A bit of history: 1) NASA

- About 15 years ago, for JWST/NIRSPEC, NASA decided to develop MEMS as slit selection devices.
- Two approaches, three teams funded:
  - Microshutter MSA (GSFC)
  - Micromirror DMD (Sandia)
  - Micromirror DMD (GSFC)
- Requirements: 35K, 100micron size, contrast 1:2500
- TI provided support to Micromirror/GSFC team.
- In 2002 NASA selected MSA against DMDs.

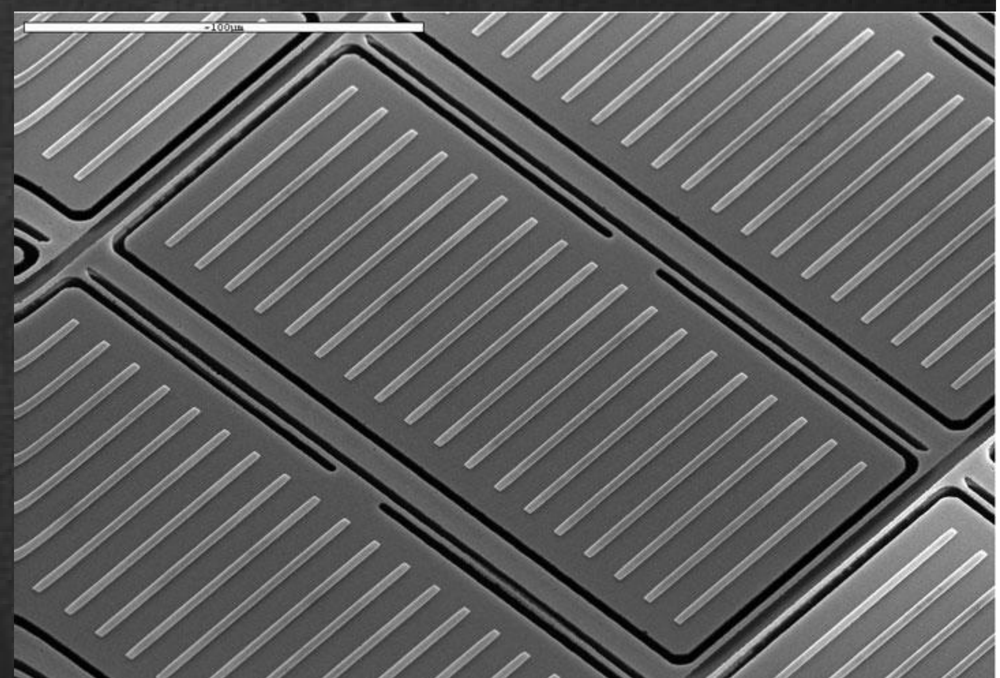
Micro-shutter arrays (MSA)

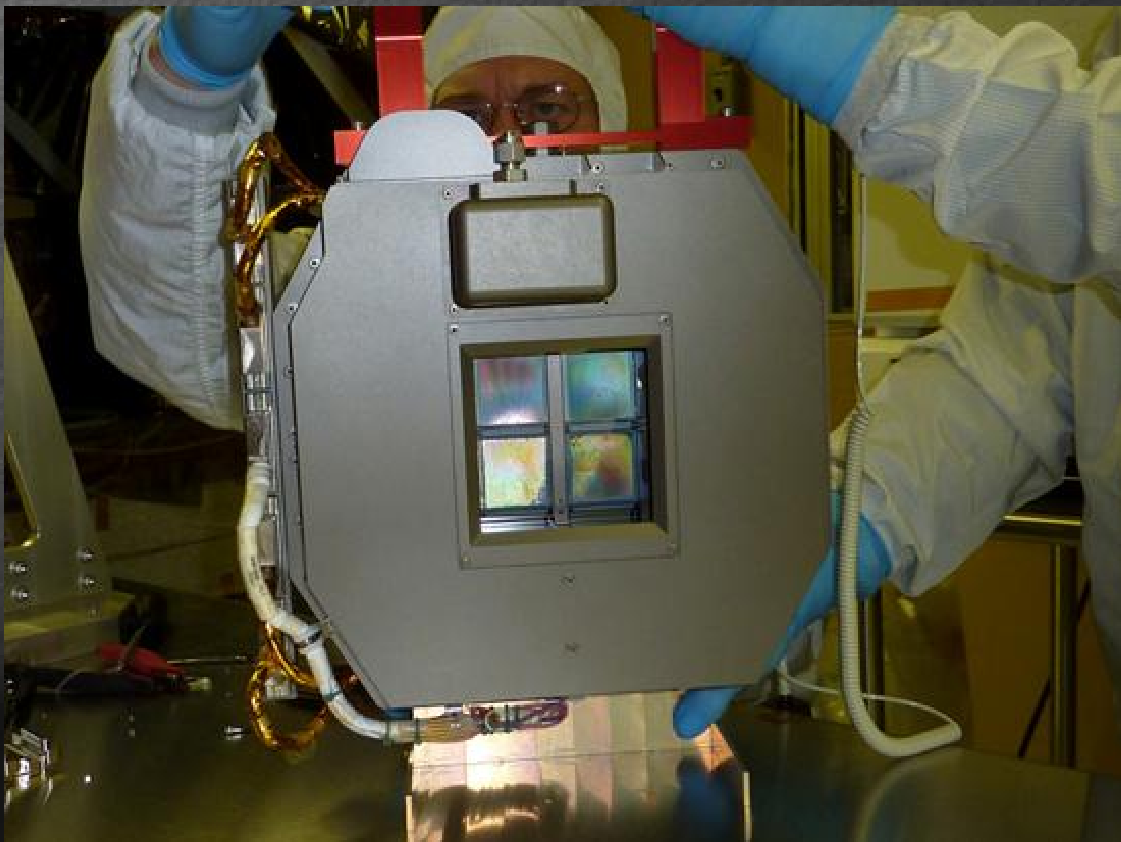
Developed by NASA/GSFC for NIRSPEC on JWST

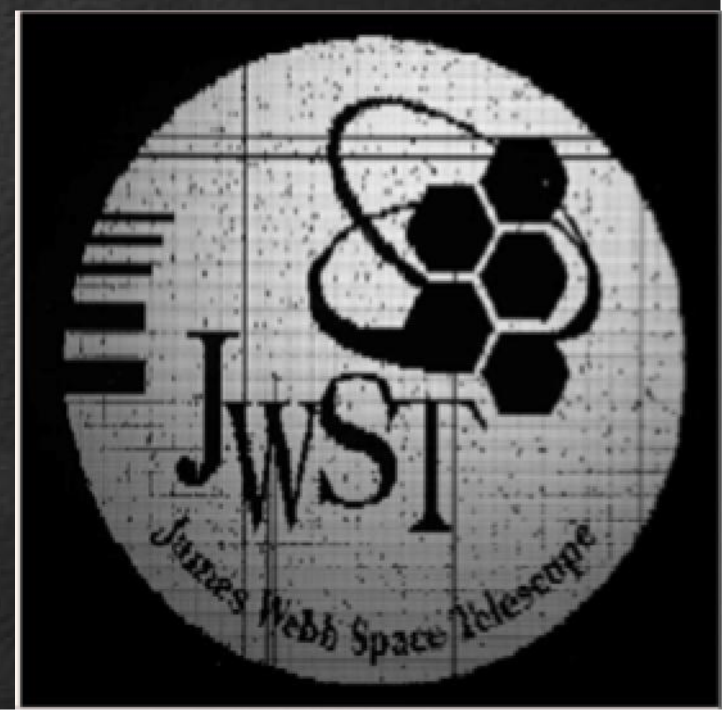




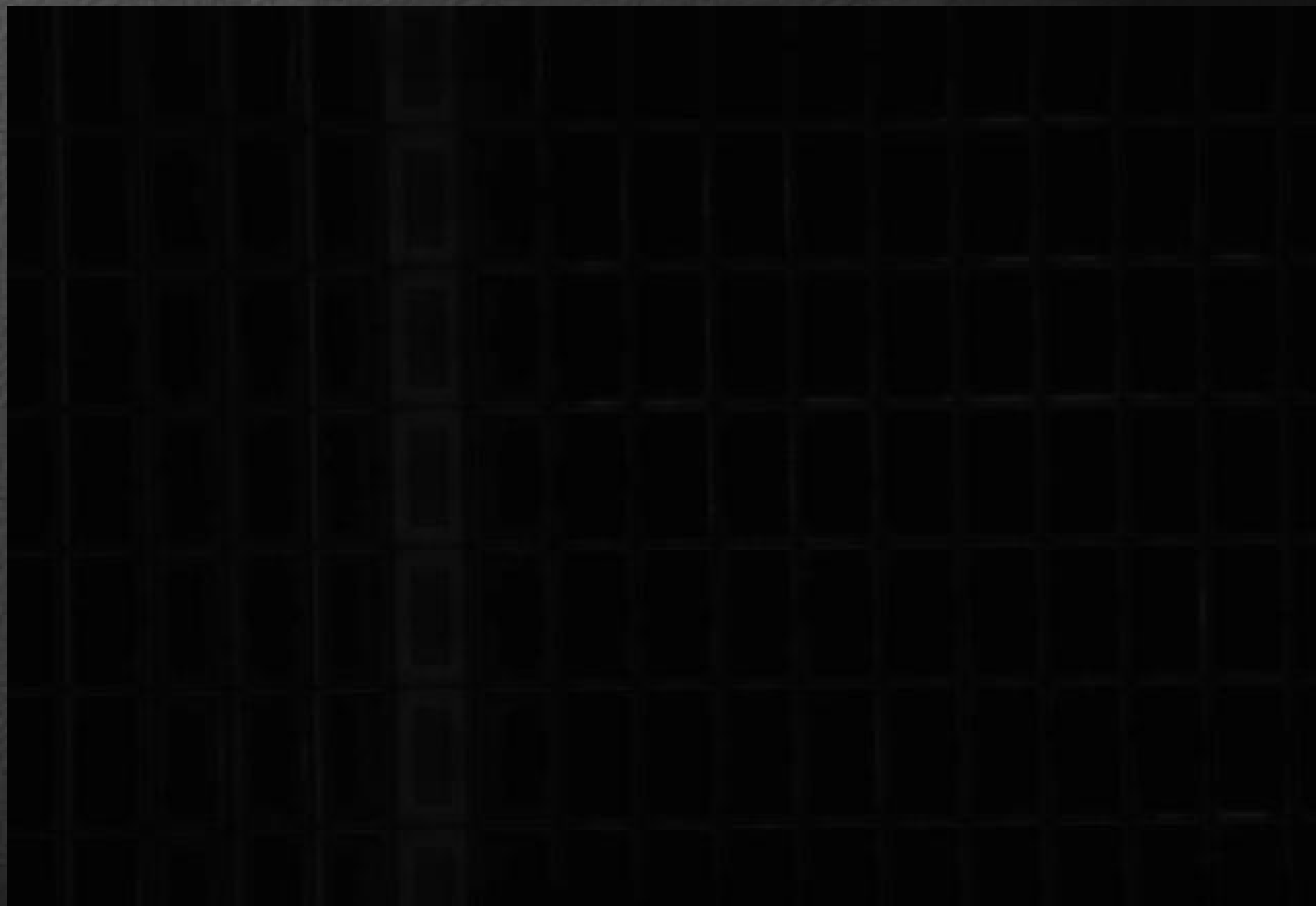
- 100x200 micron
- operate at ~35K
- 171x365 element
- limited production for JWST



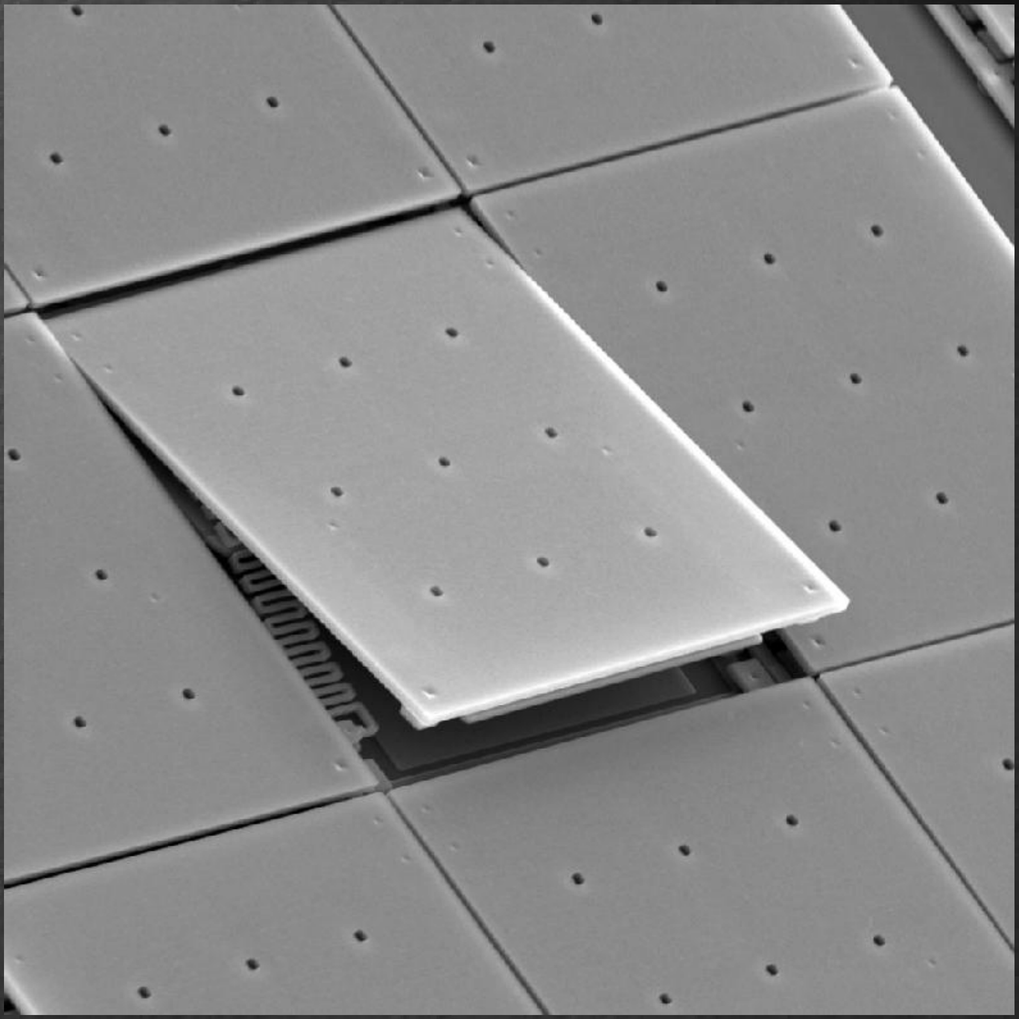



JWST
James Webb Space Telescope

MSA Demo



SANDIA Micromirror (~1999)



From http://www.sandia.gov/media/NewsRel/NR1999/images/jpg/mirror1.jpg

GSFC DMD development (~2002)

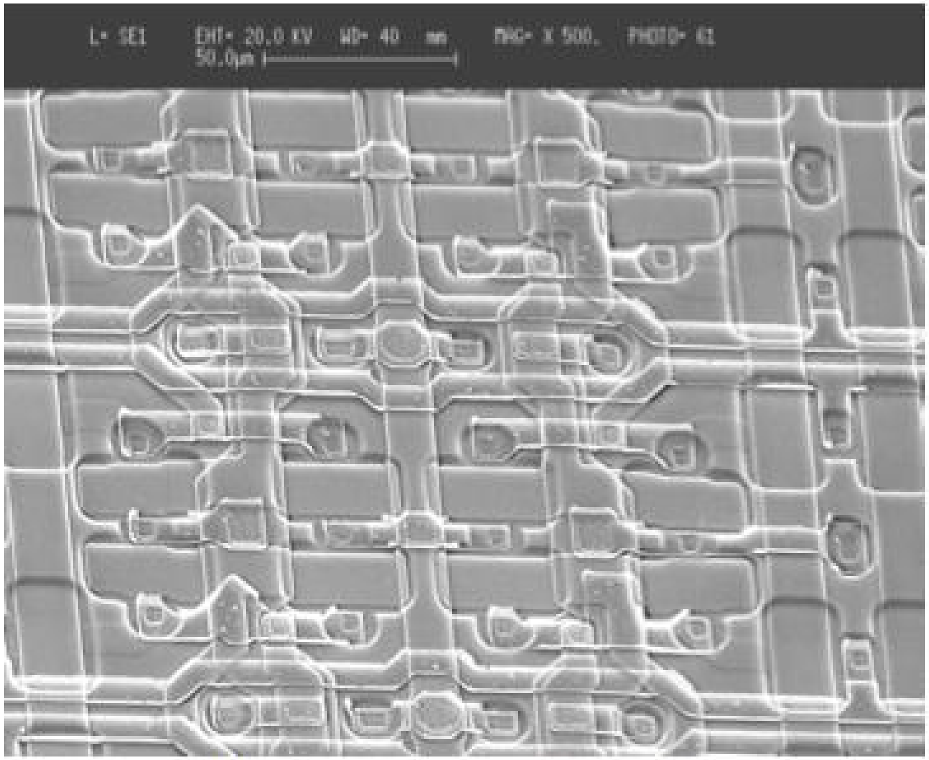


Figure 4: SEM photograph of CMOS wafer before planarization

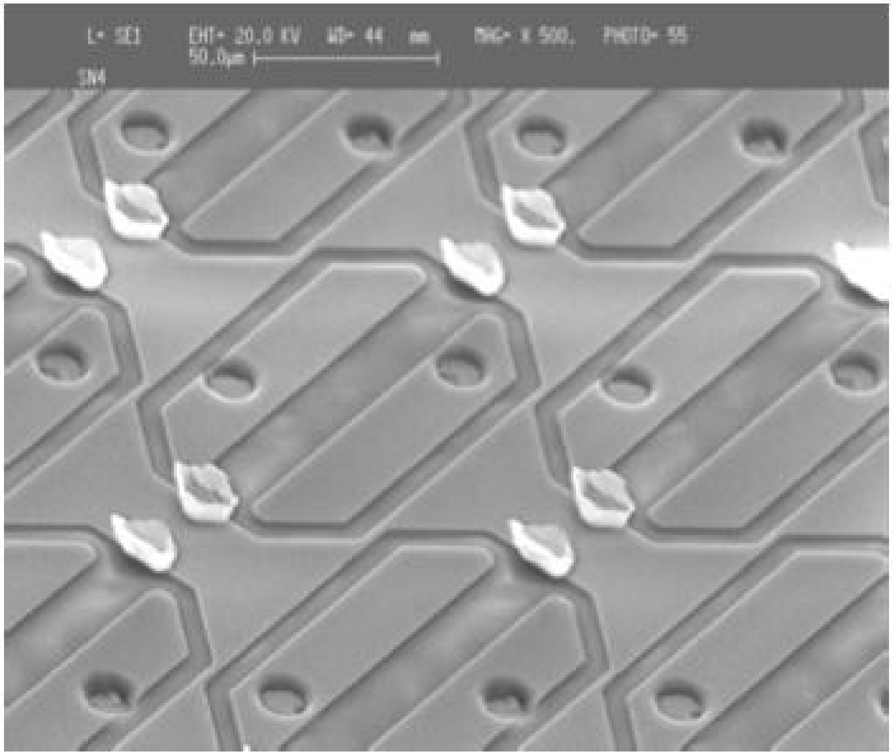
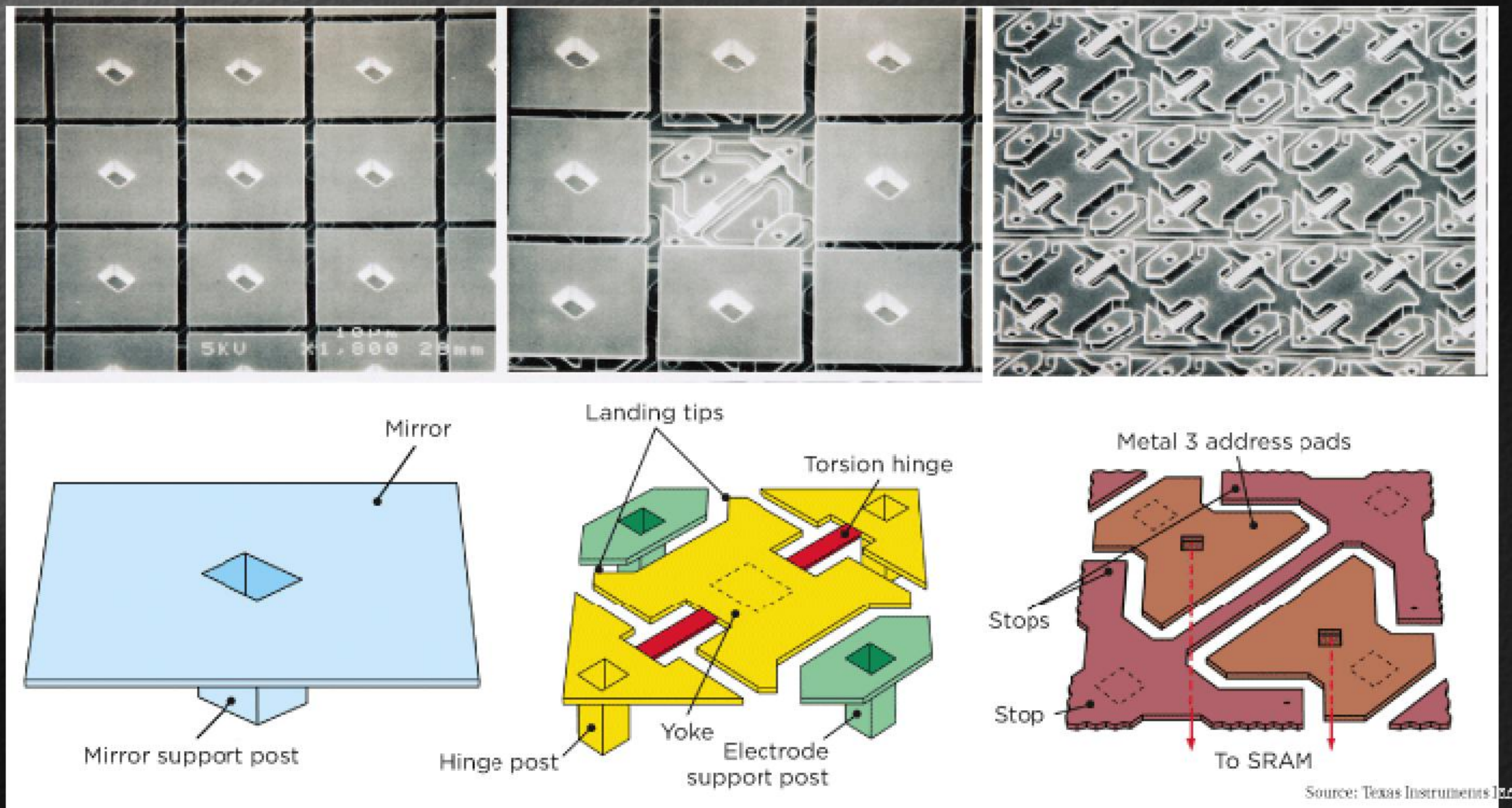


Figure 5: SEM photograph of CMOS wafer after planarization

From Zhen et al. 2002, SPIE 4689-0277-786X

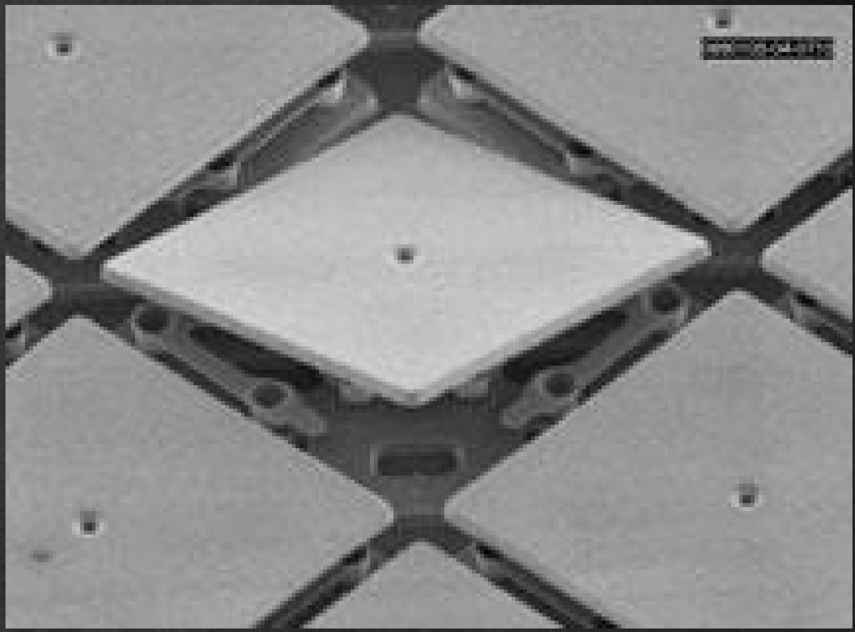
Texas Instrument DMDs (~1995)



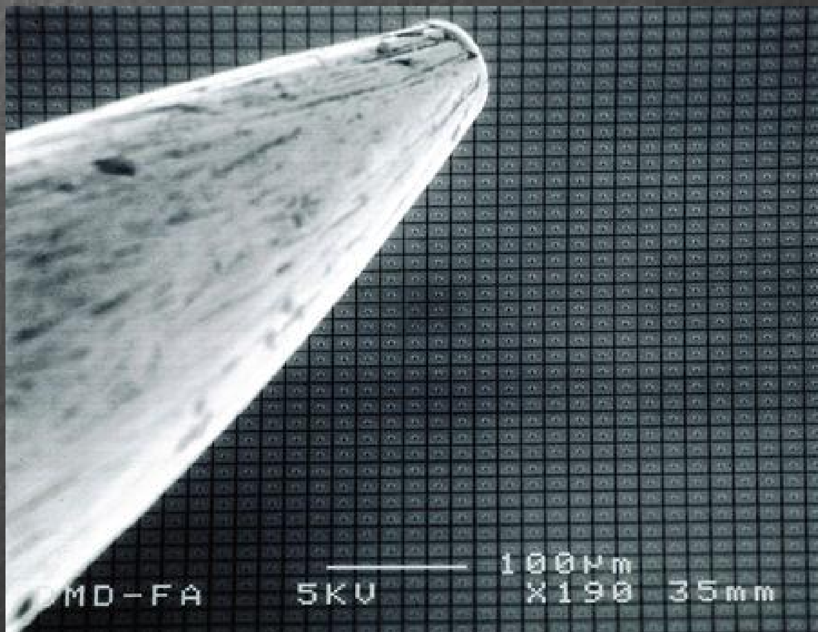
Digital micromirror array showing nine mirrors (top left), the central one removed (top center) to show hinges, and below that the mirror substructure (top right). The bottom row shows detailed diagrams of an individual mirror.

Texas Instrument DMDs

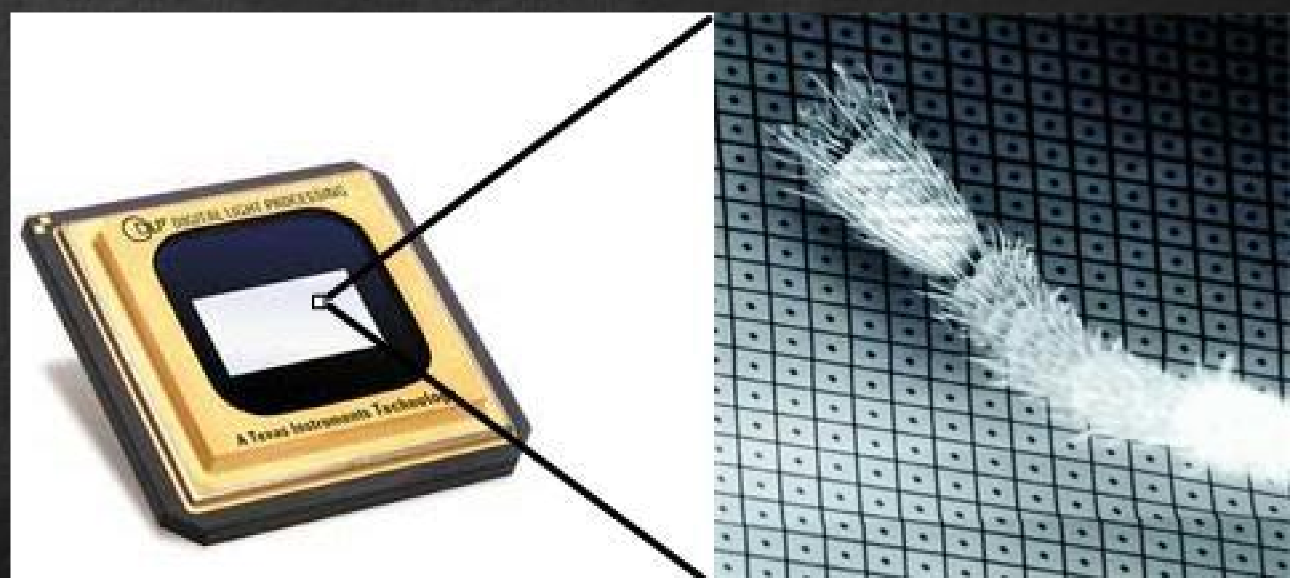
- A DMD is a microelectrical mechanical system (MEMS) built on top of a memory array.
- It primary purpose is a spatial light modulator (SLM).
- The mirrors tip about the diagonal $\pm 12^\circ$



Digital Micromirror Devices



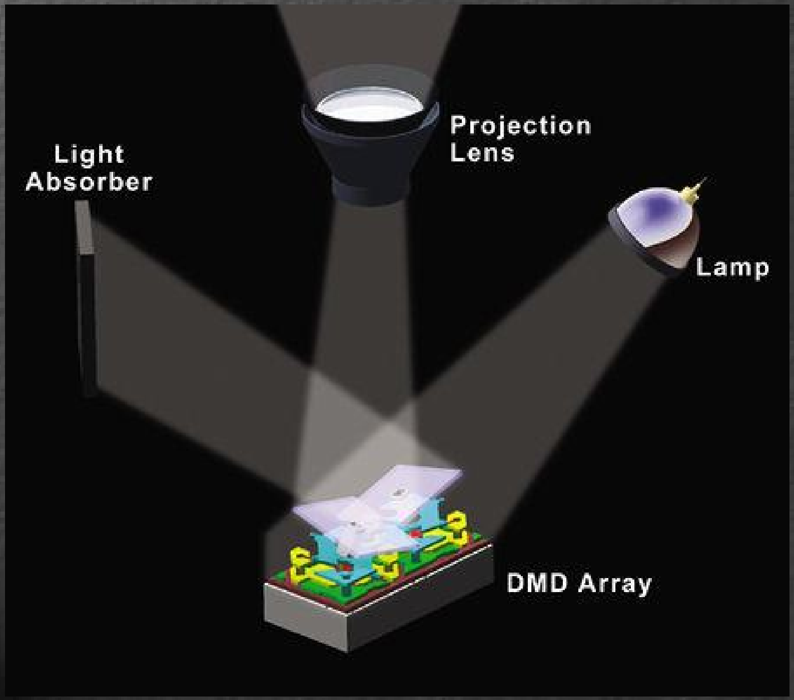
DMDs come in different format;
Together, more than 20 million pieces have been produced (2010)



Various current TI DMD Types

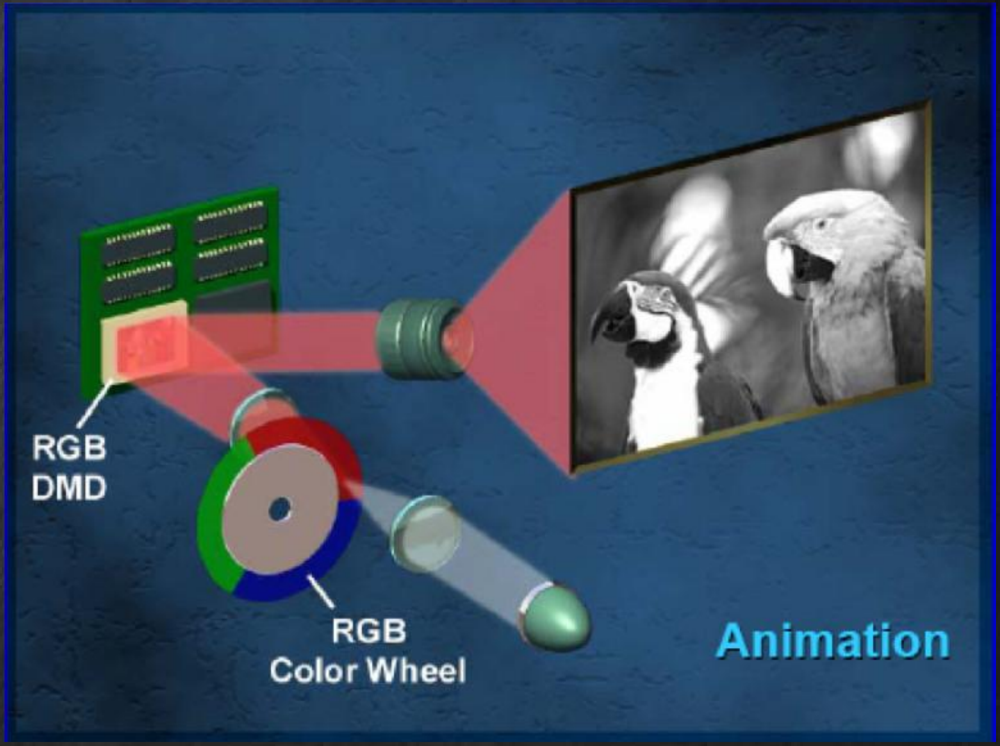
name	diagonal (inches)	pixels	pitch (microns)
S2K	0.69	2048 x 1080	7.6
Cinema	0.98	2048 x 1080	10.8
Cinema	1.2	2048 x 1080	13.6
Enhanced 4K	1.38	4096 x 2160	7.6
0.95 1080p	0.95	1920 x 1080	10.8
0.7 XGA	0.7	1024 x 768	13.6
0.55 XGA	0.55	1024 x 768	10.6
0.45 XGA	0.45	912 x 1140	7.6
0.3 WVGA	0.3	608 x 684	7.6

DLP Technology

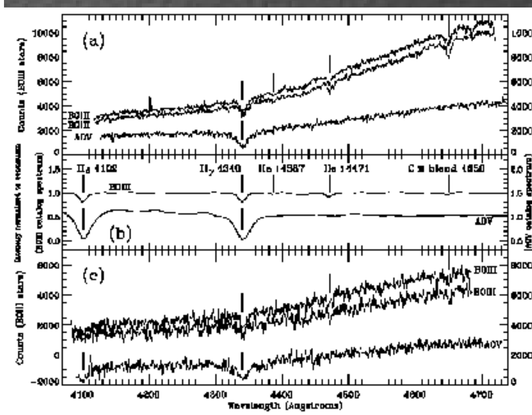


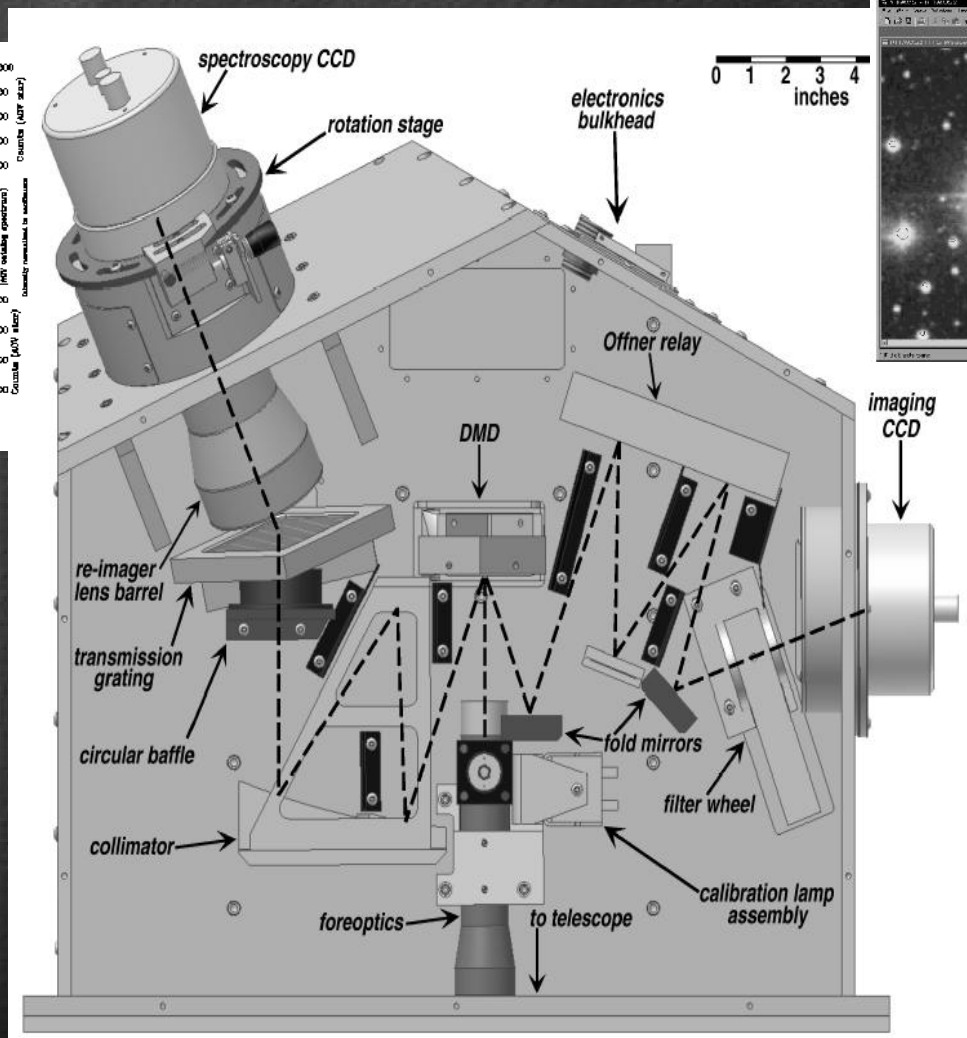
•On projectors, image is produced by the DMD ON/OFF pattern.
•Duty cycle ON/OFF controls the gray scale of each pixel

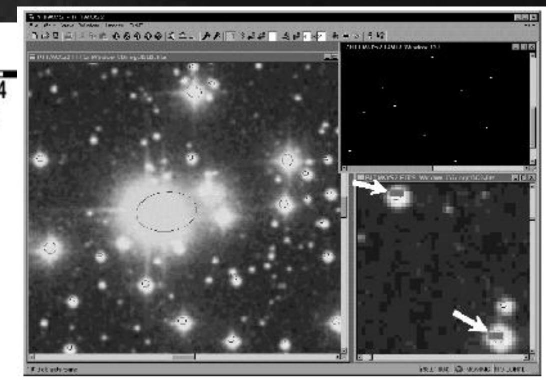
256 gray levels x 3 colors
=> 10 frames/s at 7KHz tilt rate (coding increases rate)



Existing DMD-based instruments:
1) RITMOS







based on a TI DMD of 848 ×600 elements

From Meyer et al. 2004, SPIE 5492, 0277-786X

2) IRMOS at Kitt Peak

KPNO 4m telescope

in the lab (2004)

at the telescope (2005-2010)

- ✓ *848 × 600 TI DMD*
- ✓ *0.8-2.5micron (near-IR)*
- ✓ *DMD operated at ~-45C*
- ✓ *Pathfinder for JWST/NIRSPEC*

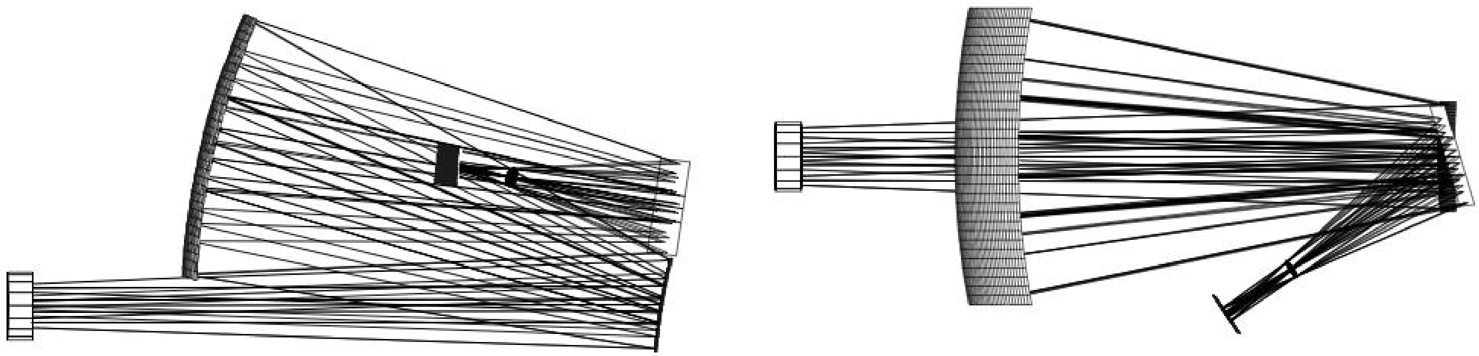


Figure 3.1. Layout of the front-end optics, showing a side view (left) and a top view (right). At the far left in each picture is the dewar window. The focal plane of the telescope is approximately 5" in front of this window.

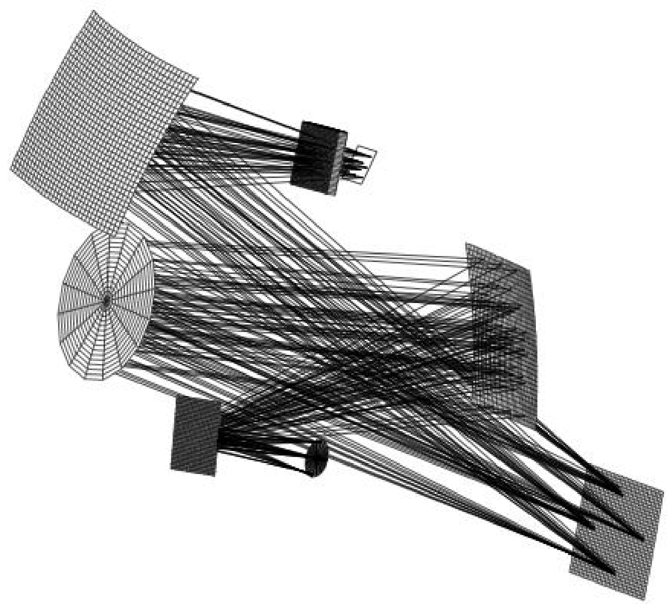
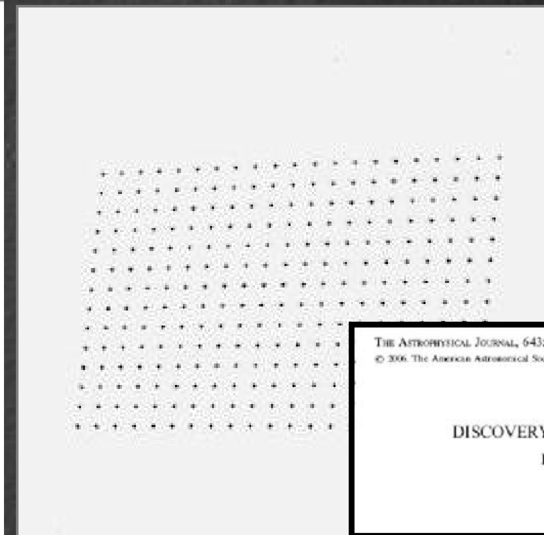


Figure 3.2. The layout of the spectrometer. Included in this view is the pupil from the front-end optics, and the DMD can be seen as the square shape in the lower-left side of the picture.

Observing with IRMOS

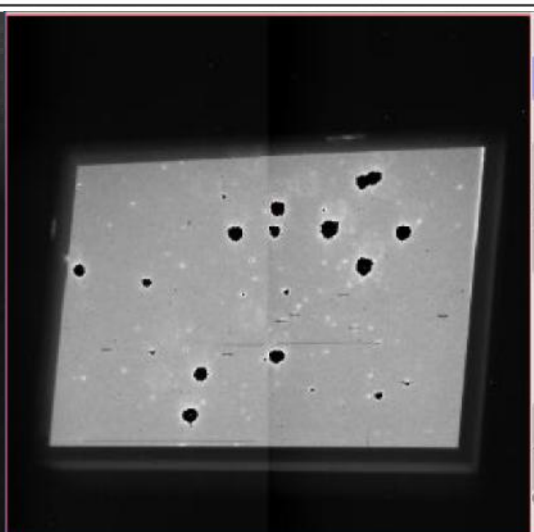
Figure 8: Texas Instruments DMD in test dewar operating at -50C in IRMOS custom socket (without baffle). Note Lakeshore thermal diode mounted at top.

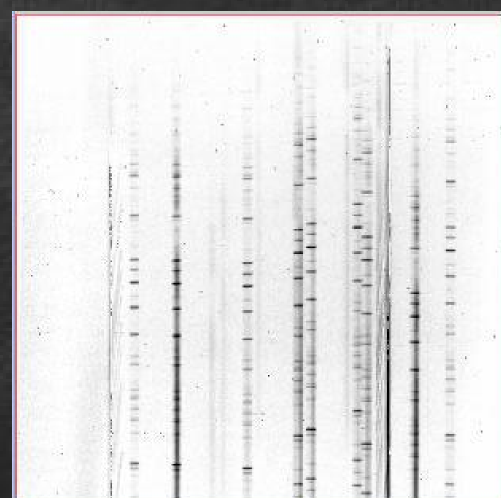


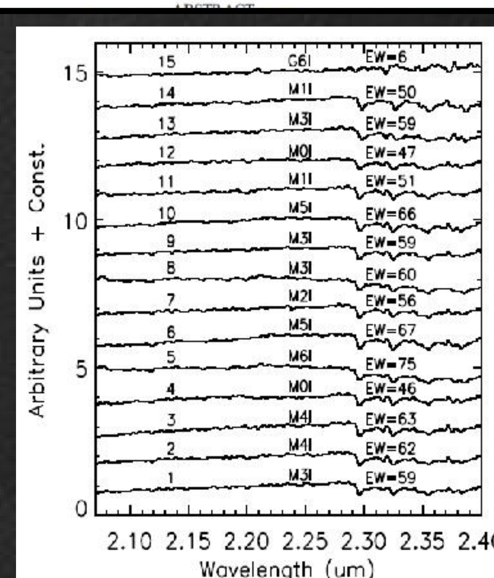
THE ASTROPHYSICAL JOURNAL, 643:1166–1179, 2006 June 1

DISCOVERY OF AN EXTRAORDINARILY MASSIVE CLUSTER OF RED SUPERGIANTS

DONALD F. FIGER,[1] JOHN W. MACKENTY,[2] MASSIMO ROBBERTO,[2] KESTER SMITH,[2]
FRANCISCO NAJARRO,[3] ROLF P. KUDRITZKI,[4] AND ARTEMIO HERRERO[5]
Received 2005 November 16; accepted 2006 February 7







Microshutters vs DMD

22 years ago

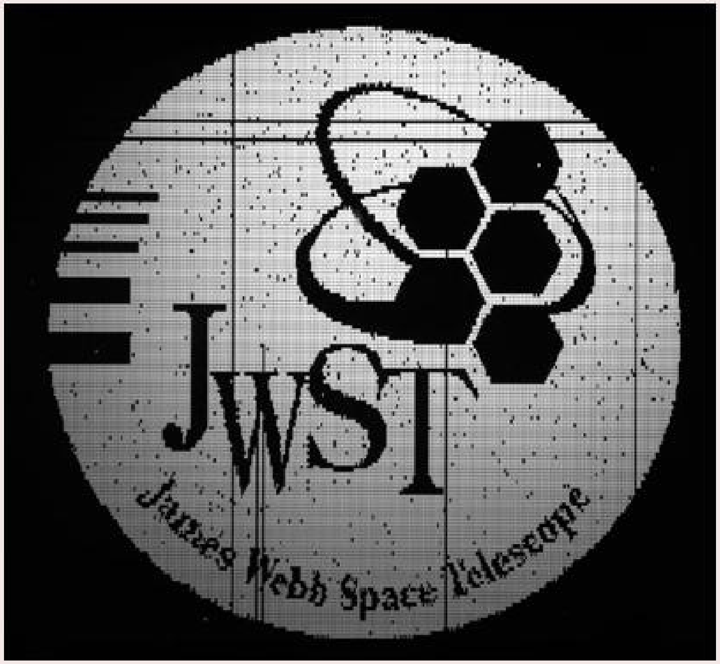


Figure 1: Micro-shutter array (MSA) programmed with the *Webb* symbol. Four MSAs will be used for the three-by-three arcminute field of the Near-Infrared Spectrometer. Although a small fraction of the apertures are dark and appear to be stuck shut, very few apertures are unintentionally white—i.e., stuck open—and those are the main concern for science operations, as a potential source of light contamination.

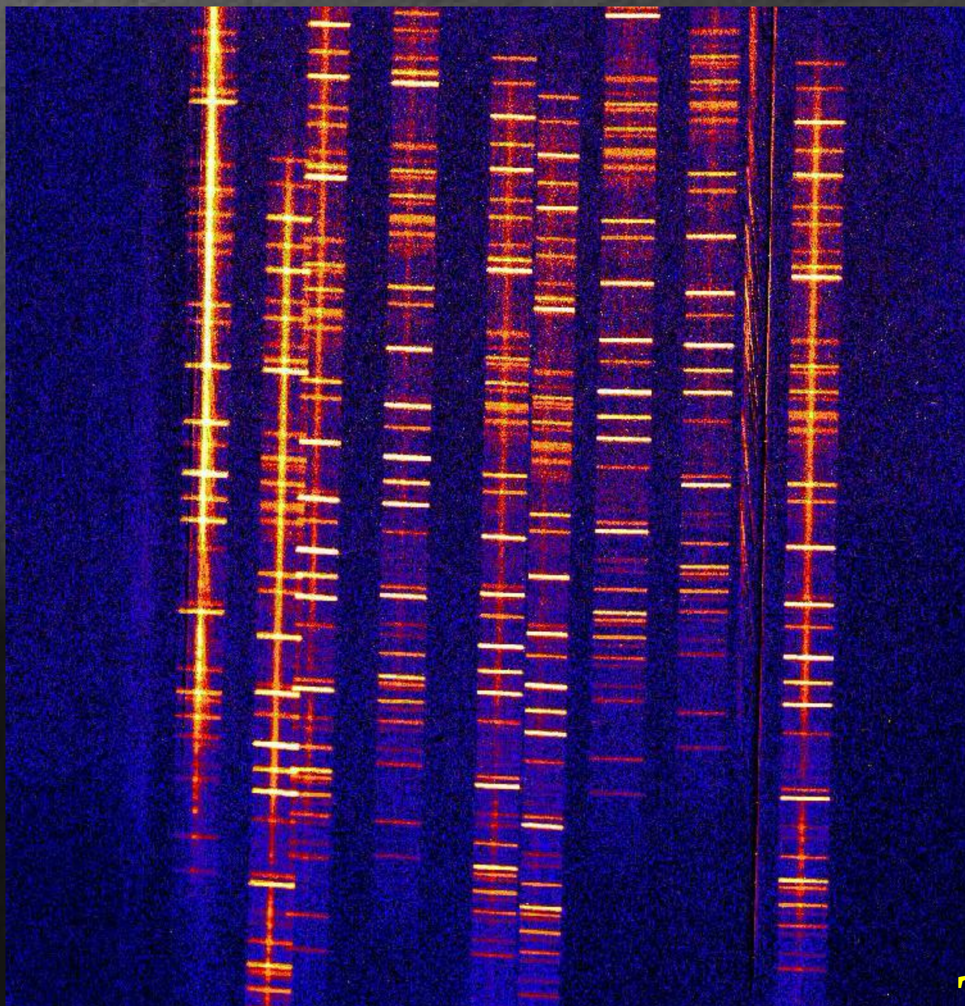
1981

(Hornbeck, TI Technical Journal, Jul-Sep. 1998, p.31)

2007

(Stockman, STScI Newsletter, Spring 2007, p.16)

Microshutters vs DMD



RITMOS

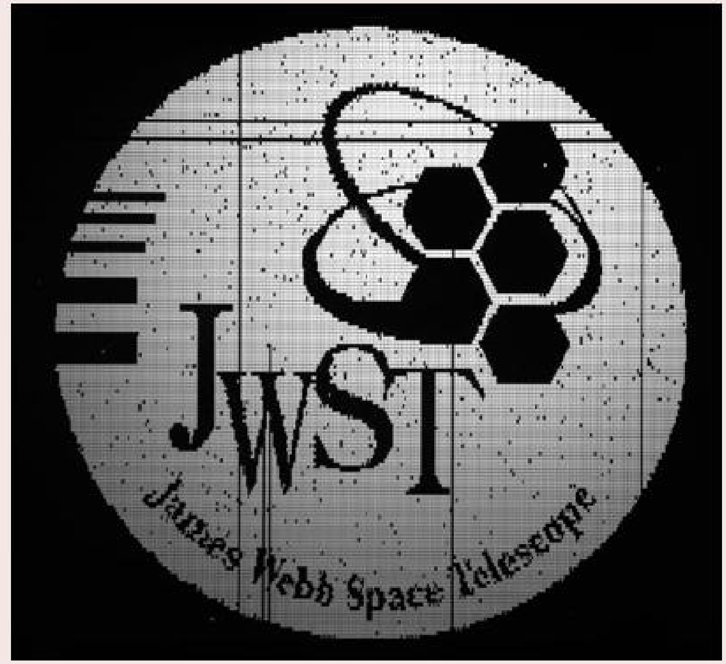


Figure 1: Micro-shutter array (MSA) programmed with the *Webb* symbol. Four MSAs will be used for the three-by-three arcminute field of the Near-Infrared Spectrometer. Although a small fraction of the apertures are dark and appear to be stuck shut, very few apertures are unintentionally white—i.e., stuck open—and those are the main concern for science operations, as a potential source of light contamination.

2007

(Stockman, STScI Newsletter, Spring 2007, p.16)

SPACE: Spectroscopic All-Sky Cosmic Explorer

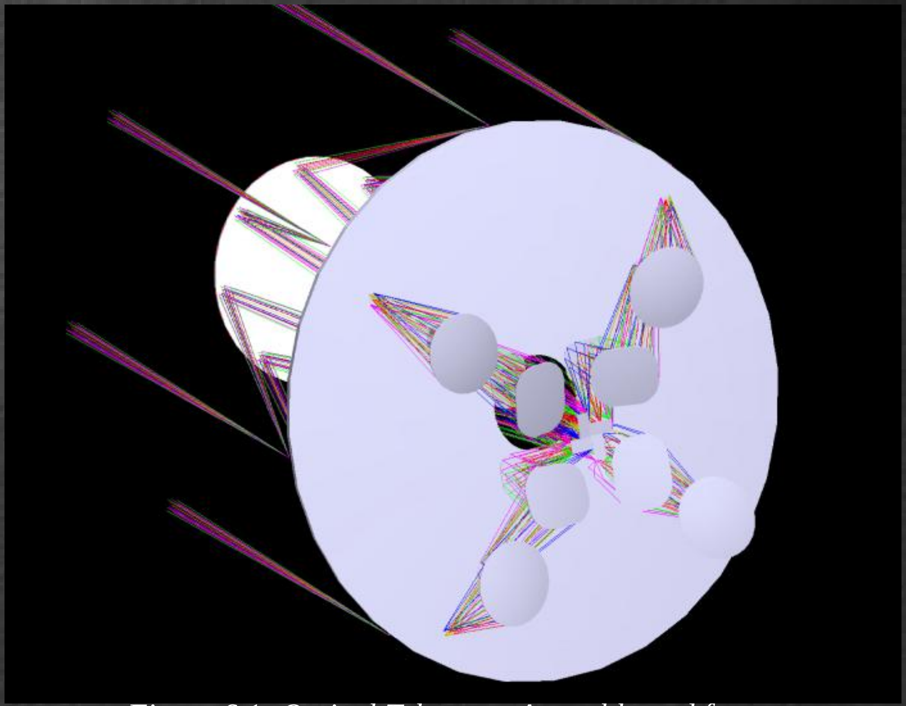


Figure 6.1: Optical Telescope Assembly and fore-optics system (four channels).

4 TI “Cinema” DMD–based spectrograph
1/2 square degree @ 1.5m telescope
1-1.8micron, R=400; ~500 Million galaxies at AB~23

SPACE and Euclid

- MR conceives SPACE in spring 2008; proposal to ESA submitted in Fall 2008, Cimatti & Robberto co-PIs.
- SPACE is the top-ranked ESA medium-class mission proposal.
- However, ESA is skeptic that DMDs may reach TRL6 before down-selection and match the 2018 launch date
- SPACE and DUNE are merged into Euclid.
- DMDs are descoped to "option"; slitless new baseline (like NASA/ADEPT).
- ESA directs industry to ignore DMDs for pre-phase A study; DMDs treated in an appendinx of Euclid "Yellow Book".
- Euclid finally configured with a slitless spectroscopic mode: grism is added to the IR imaging channel.
- ESA evaluation of DMDs concludes in 2011 that they have "full ability for space instrumentation, especially in multi-object spectroscopy applications" (Zamkotsian et al 2011, SPIE 7932, 79320A)

MEMS RELIABILITY AND PERFORMANCE

Take home points

1. Extensive literature is available both from TI (white papers, SPIE papers,…) and academic work

2. Our team has the strongest experience with DMDs for astronomical applications. LAM Marseille other pole in Europe.

3. <u>DMDs are generally regarded the most successful example of MEMS technology</u>

DMD Issues

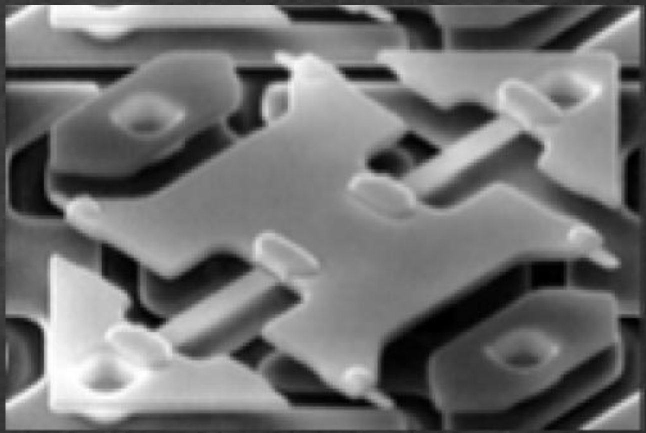
- Lifetime: fatigue, stiction, contamination
- Low-T operations
- Radiation hardness (space environment)
  - DMD
  - Chipset
- Vibrations, acoustic (launch environment)

Also important for science performance

- Optical quality (surface flatness)
- Stray light, contrast
- Throughput (reflectivity, window coating)

Lifetime: hinge fatigue

Virtual absence of 3-d structure (no crystal lattice) means that mechanical stresses are relieved at the hinge surface.

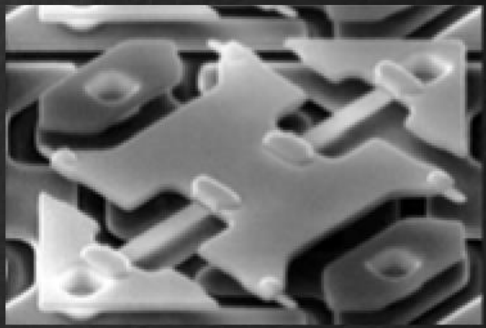


A batch of DMDs has been operated per years in parallel at full speed: total 1.4x 10^{19} cycles without a single breaking!

DMDs are the most reliable mechanical system ever built (and tested)

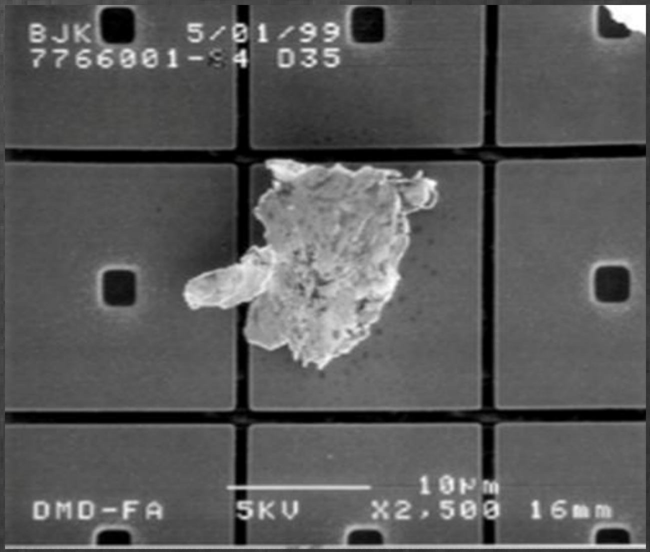
Stiction

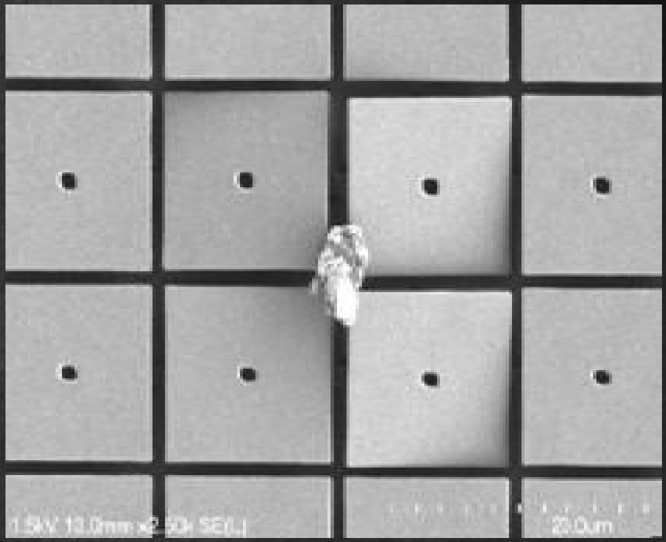
- Electrostatic forces hold the mirrors ON/OFF
- Surface effects (capillarity and Van der Waals forces) could cause the mirrors to stick
- TI are designed with:
- - anti-stick coating
- - mirror landing tips
- - hermetic packaging



STICTION VIRTUALLY ELIMINATED

Contamination (both dust and humidity)





Class 1 manufacturing allows for 100% defect free parts

DMDs are encases with protective window

Thermal operations

– Overheating is generally the main concern of the industry
– TI SPECS are typical of microelectronics industry:
  - Operation temperature: 10 – 65° C
  - Storage temperature: -40 – 80° C

IRMOS@KPNO-4m operates routinely at -40C

ESA tests on DMDs

Space evaluation of 2048x1080 mirrors DMD chip for ESA EUCLID mission

Frederic Zamkotsian[1], Patrick Lanzoni[1], Emmanuel Grassi[1], Rudy Barette[1], Christophe Fabron[1], Kyrre Tangen[2], Luca Valenziano[3], Laurent Marchand[4], Ludovic Duvet[4]

Space Telescopes and Instrumentation 2010: Optical, Infrared, and Millimeter Wave, edited by Jacobus M. Oschmann Jr., Mark C. Clampin, Howard A. MacEwen, Proc. of SPIE Vol. 7731, 773130 · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.861969

Proc. of SPIE Vol. 7731 773130-1

Successful evaluation for space applications of the 2048x1080 DMD

Frederic Zamkotsian[1], Patrick Lanzoni[1], Emmanuel Grassi[1], Rudy Barette[1], Christophe Fabron[1], Kyrre Tangen[2], Luca Valenziano[3], Laurent Marchand[4], Ludovic Duvet[4]

Emerging Digital Micromirror Device Based Systems and Applications III, edited by Michael R. Douglass, Patrick I. Oden, Proc. of SPIE Vol. 7932, 79320A · © 2011 SPIE
CCC code: 0277-786X/11/$18 · doi: 10.1117/12.876872

Proc. of SPIE Vol. 7932 79320A-1

Experimental setup at LAM Marseille

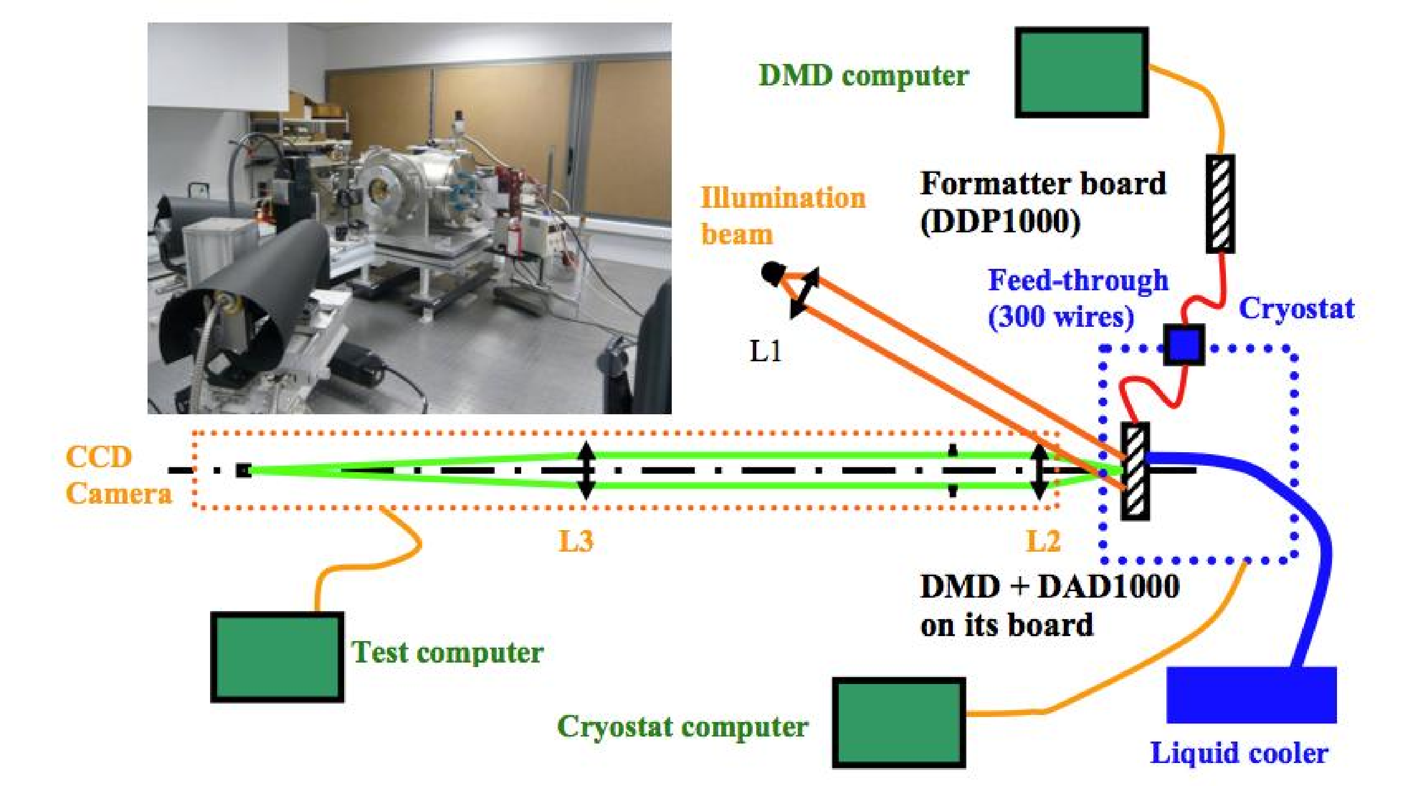


Fig. 3: Cold temperature test set-up

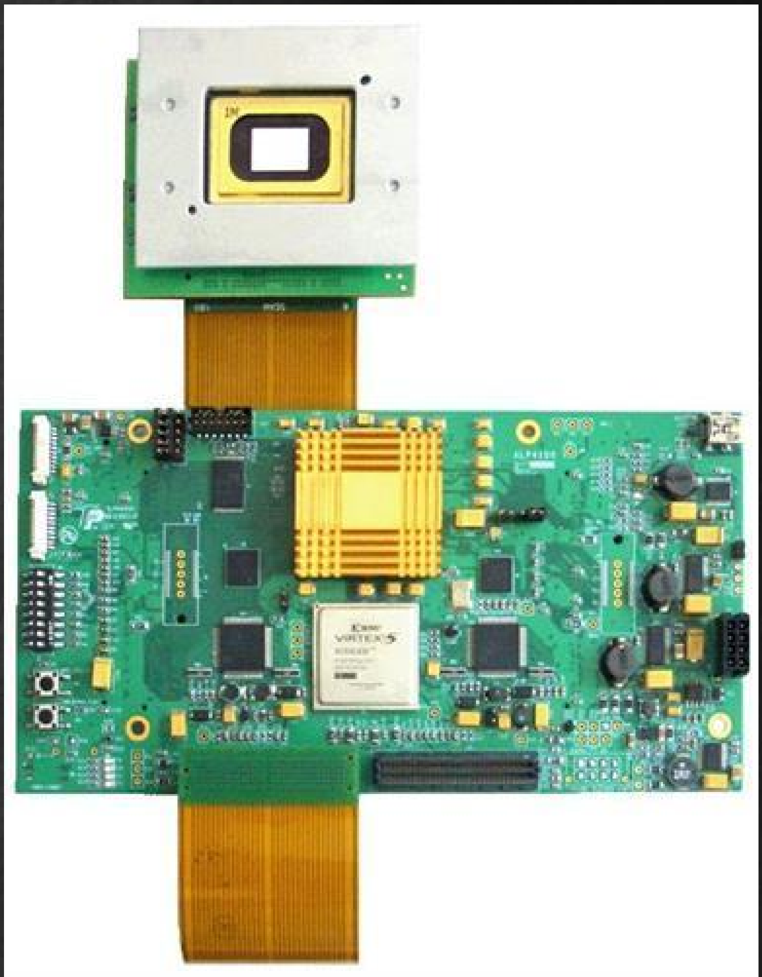
Results: thermal

"…The cold temperature step stress test has been done from room temperature down to -60° C.[…] This test shows that permanent failure, i. e. stuck mirrors, is appearing on some mirrors when the device is taken down to -55° C. […] Based on these results, the nominal temperature condition for EUCLID has been set to -40° C…"

"…562 thermal cycles have been applied. No anomaly was observed... In particular no cracks, no flakes were observed. The results for the measurement at -40° C after a series of 313 cycles show 0 stuck mirrors, 6 lossy (throughput loss >20%), and 30 weak mirrors (throughput loss <20%) due to misalignment…"

Low Temperature Tests at RIT

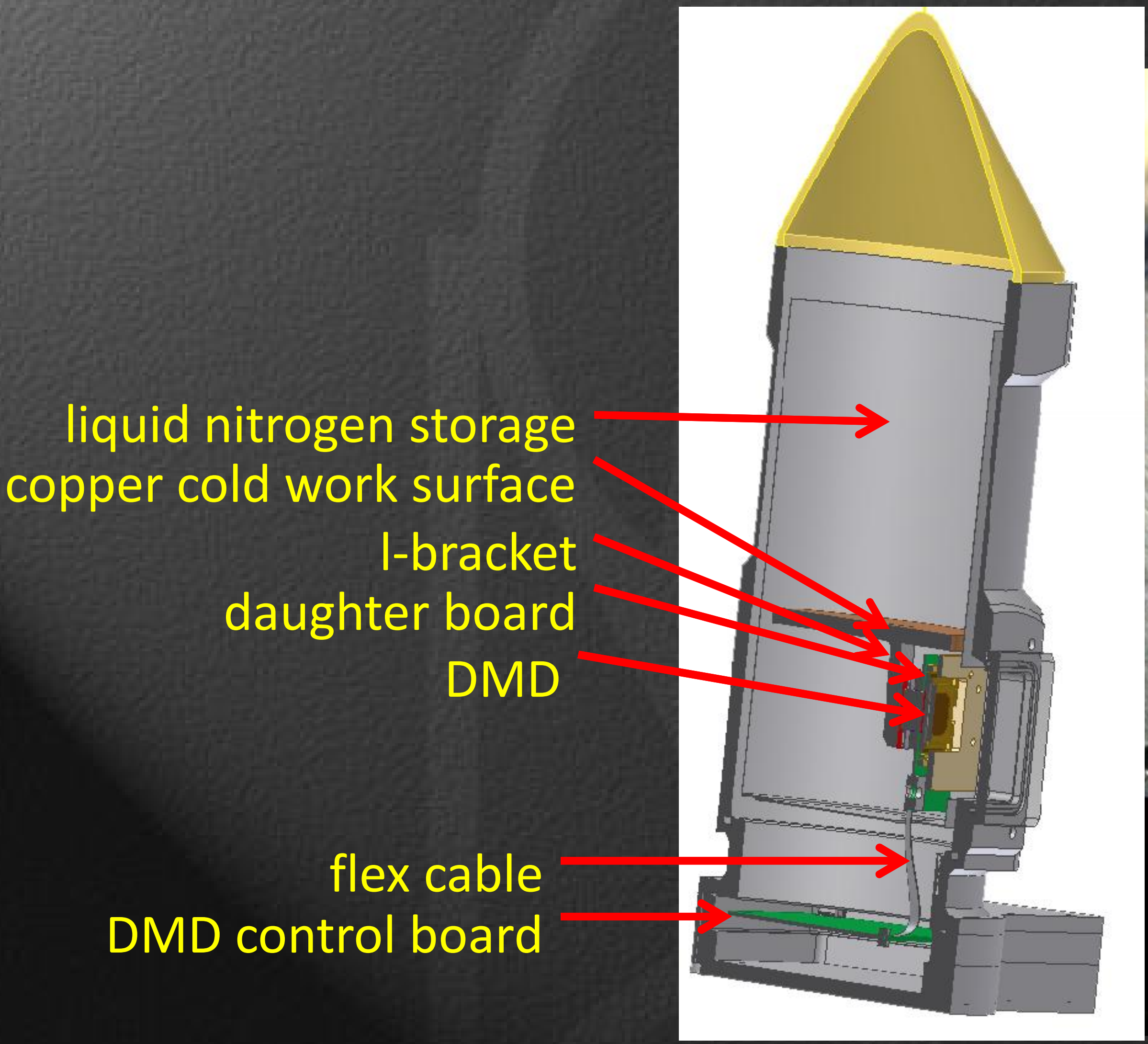
- A dewar was constructed to house the DMD electronics board and test DMD.
  - DMD requires many electrical interconnects ~(200), so for the low temperature experiment routing this many high speed electrical interconnects through the dewar was not practical.

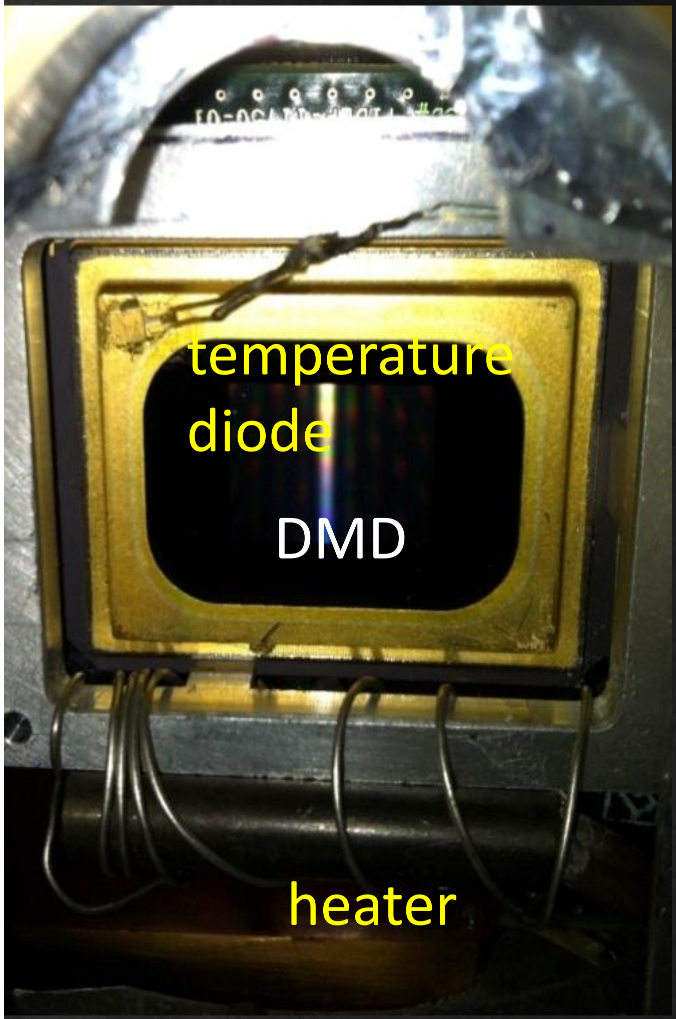


- only electrical feed-thoughts for power, heater, and temperature monitoring wired through the dewar.

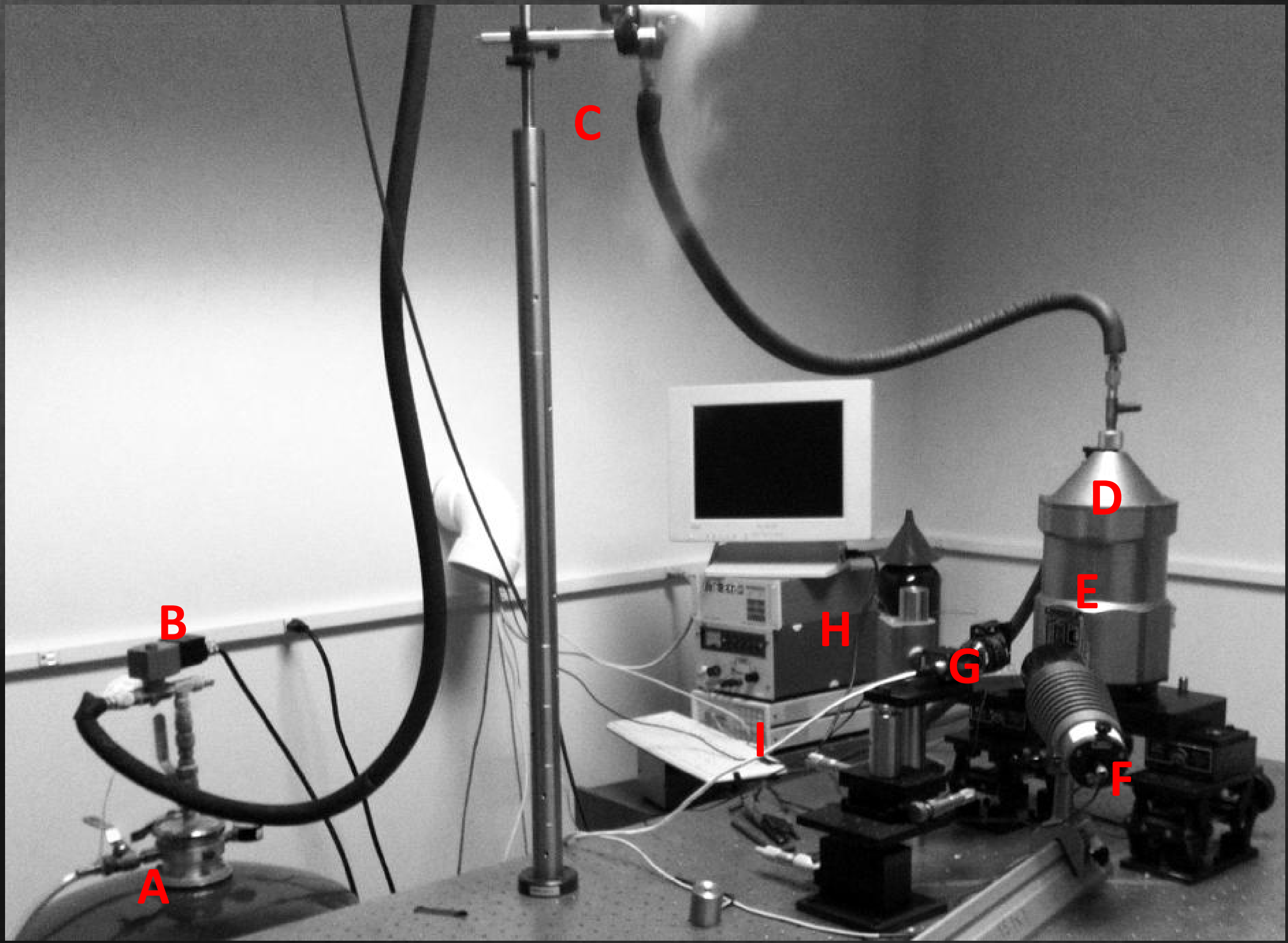
- A hermetic USB feed-through was used to control the DMD with an external control computer.

Low Temperature Testing at TIT





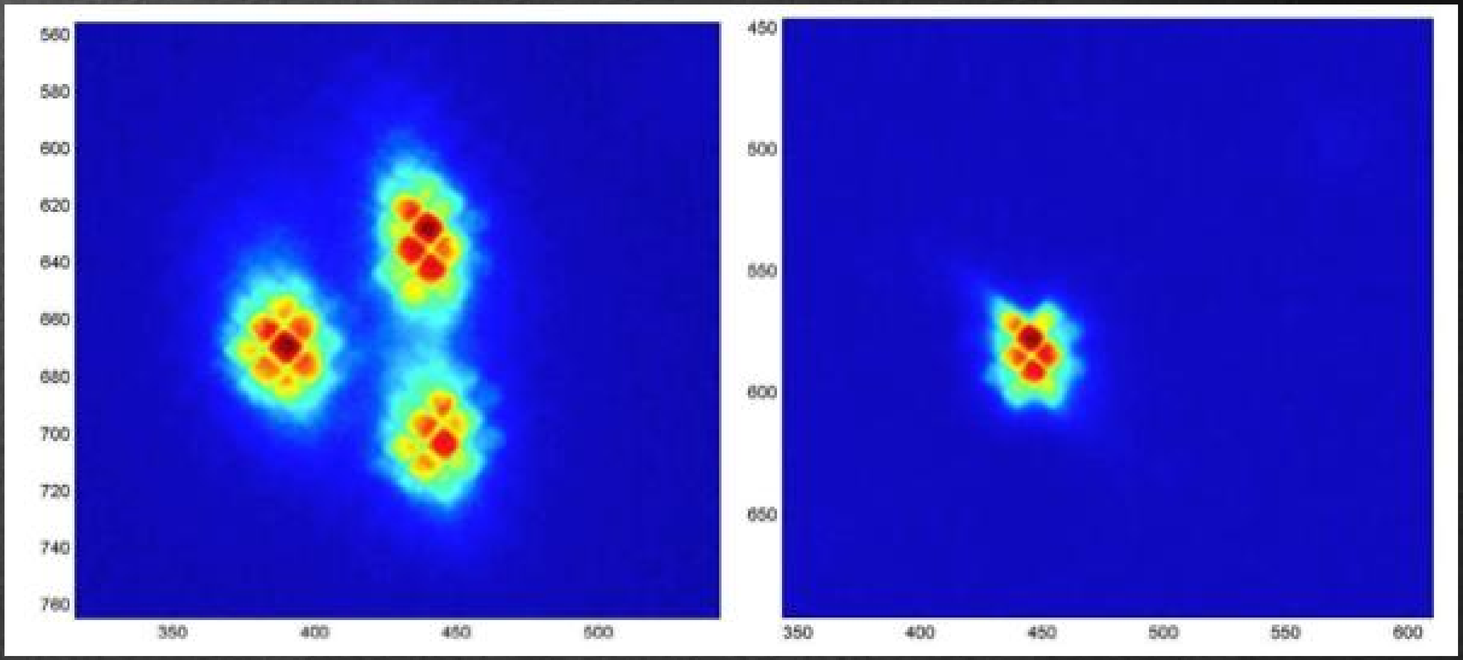
RIT Low Temperature Test Setup



Low Temperature Experiment

- DMD was cooled from room temperature to ~130 K.
  - Liquid nitrogen was added to slowly cool the DMD.
  - The temperature was monitored by a Lakeshore diode affixed to the DMD package.
  - Every 10 K a new set-point was set into the Lakeshore controller, and the heater was turned on to momentarily stabilize the temperature.
  - At each temperature a series of test patterns were latched in the DMD.
    - all "ON", all "Off", checkerboard 1, checkerboard 2, vertical stripes, horizontal stripes, all mirrors off
    - 100 "test" images
- DMDs can be latched for at least 30 minutes at low temperature without hinge memory problems
- Repeatedly re-landing the DMDs during cool down is not required for low temperature operations.

Imaging and contrast

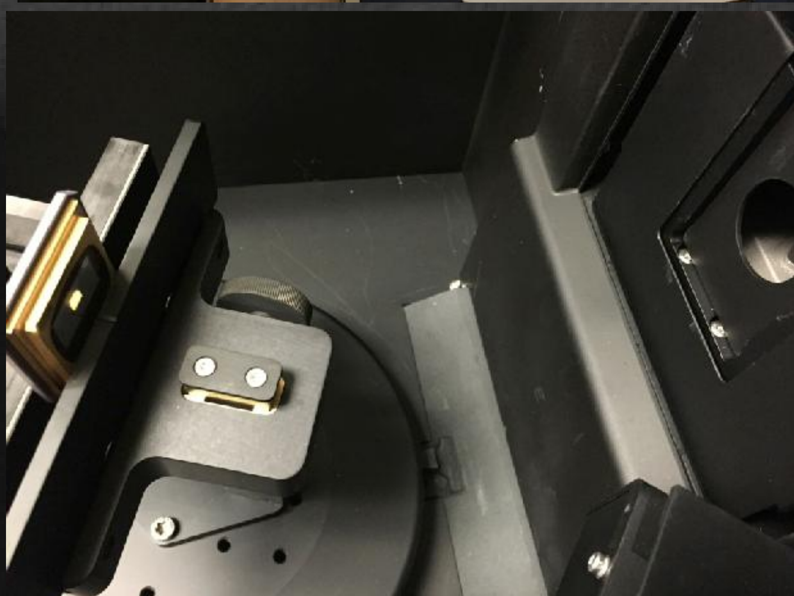


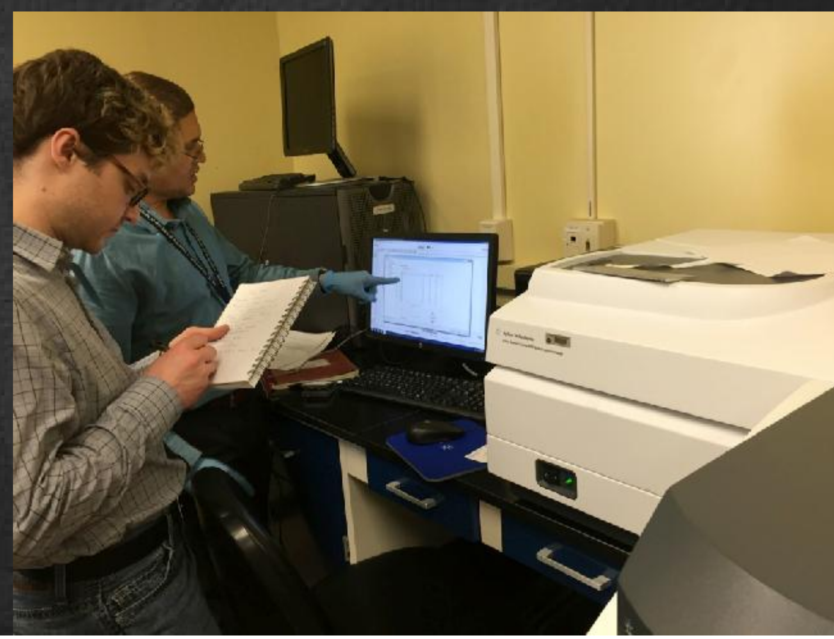
Complementary pattern have been generated; camera images 9x9 CCD pixel per micromirror for high precision photometry; illumination at f/3; neutral density filter to maximize dynamic range, etc...

Measured contrast is 2,250:1

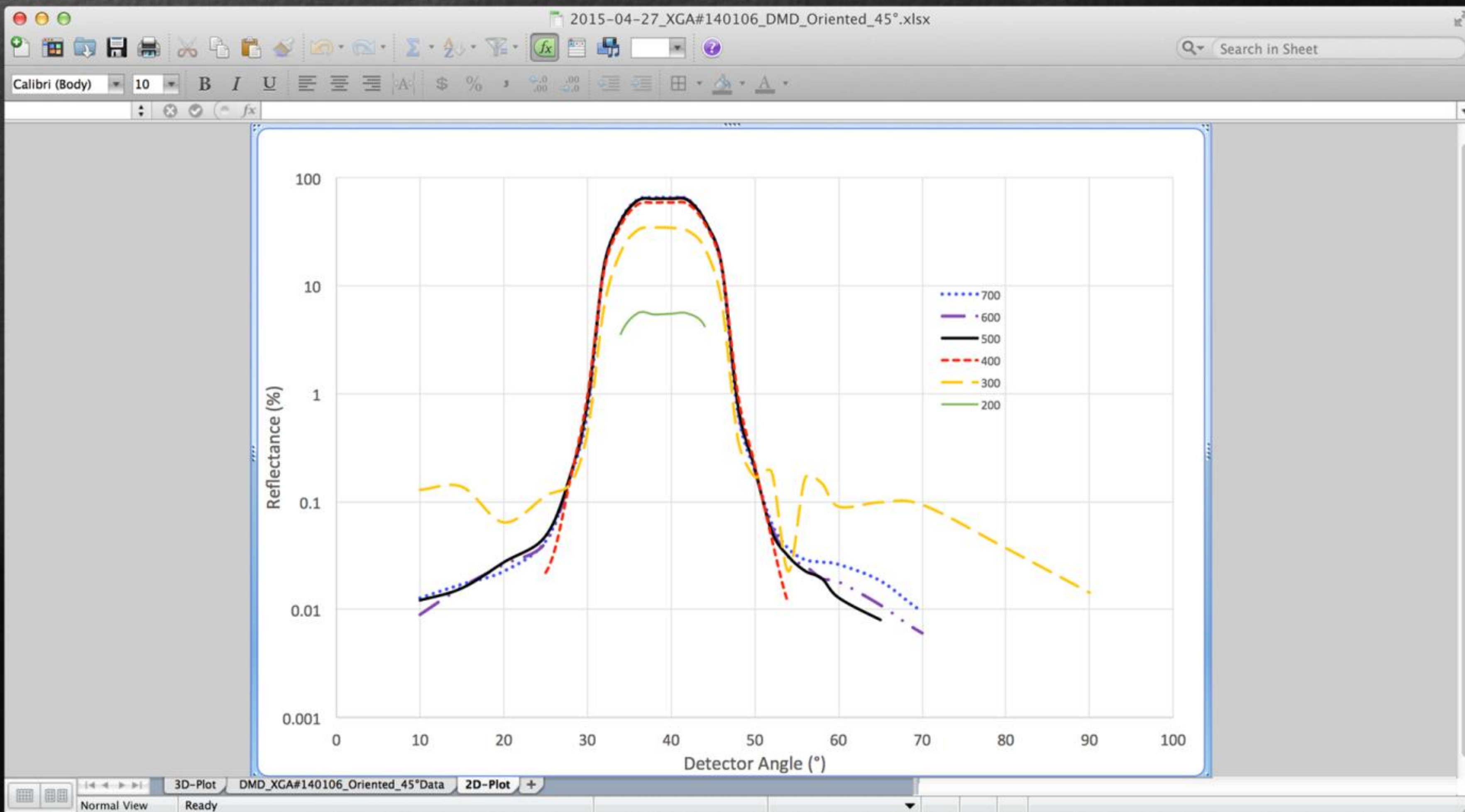
(MSA were selected for JWST mostly because the could reach 2,500:1)

Scattering tests at GSFC

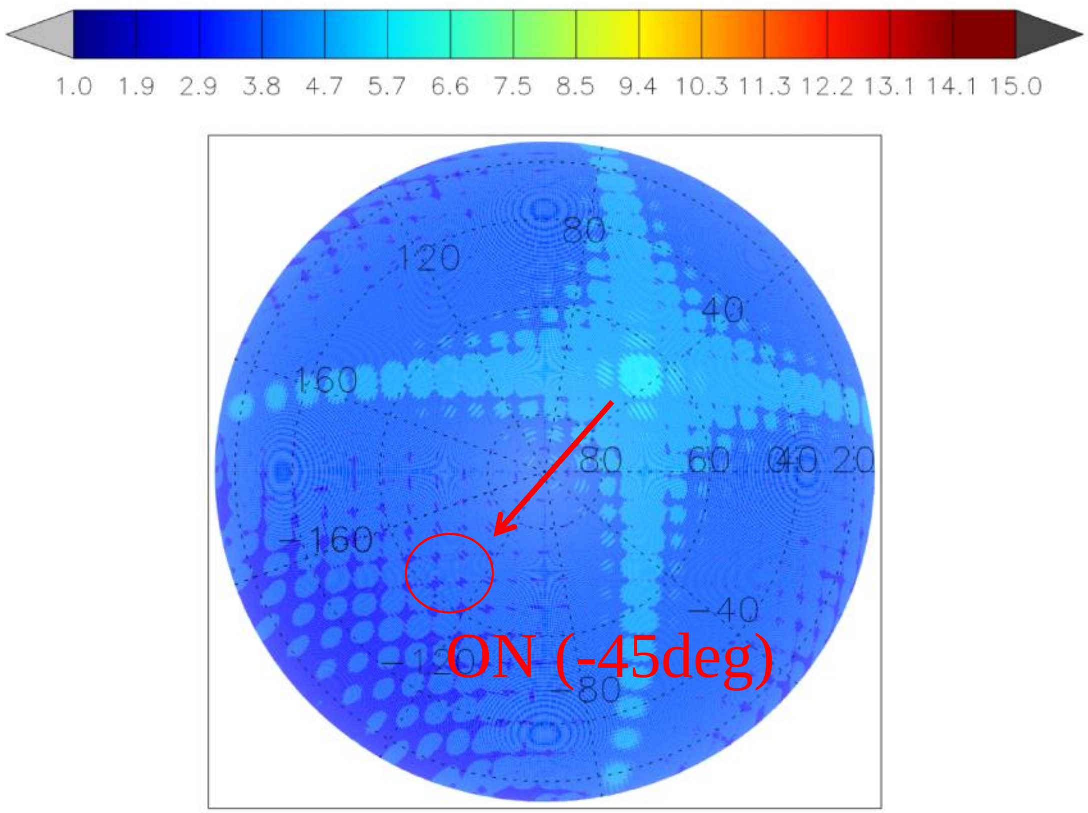




GSFC Test (Spring 2015-present): contrast 1:3600

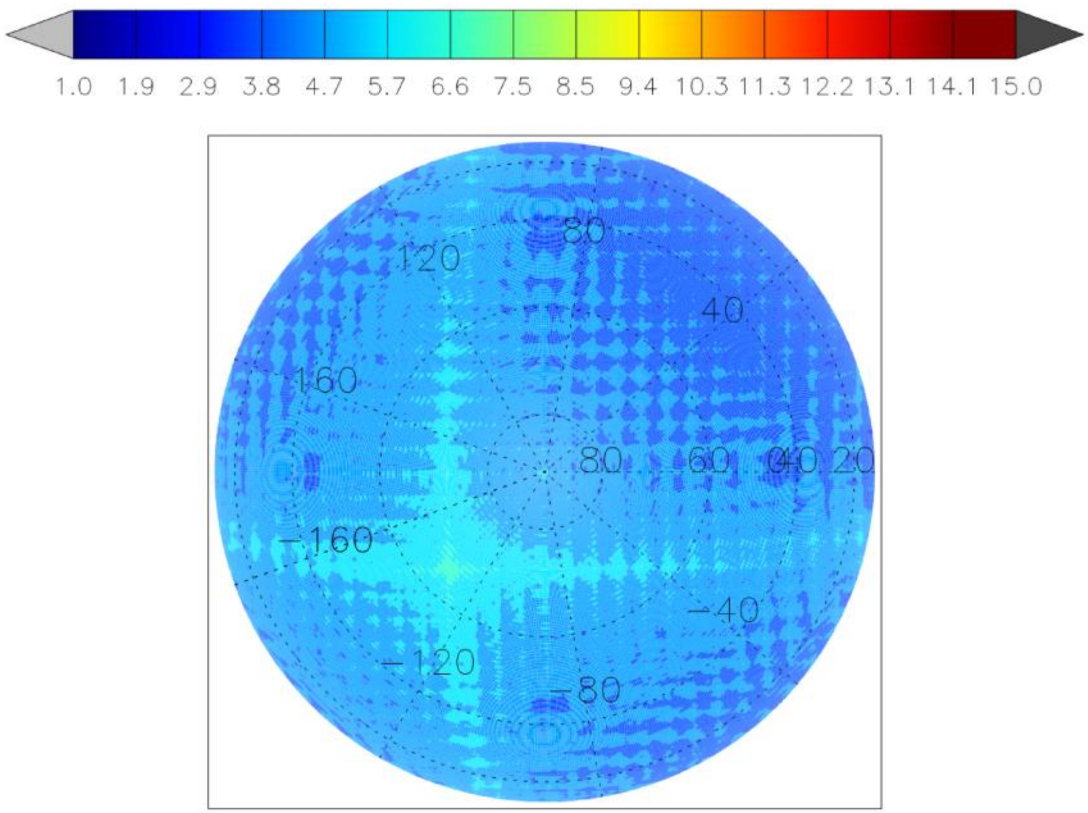


2) Diffraction from a single facelet oriented +45 degrees (OFF Beam)



Orthographic polar projection
(view from the top)

4) Diffraction from 3x3 facelets oriented -45 degrees (ON Beam)



Orthographic polar projection
(view from the top)

Results from my model

- DMDs, as two dimensional gratings with a 12degrees blaze angle tilted toward the diagonal, have a complex diffraction pattern.
- The pattern depends on the direction of illumination and on the wavelength.
- I have modeled the diffraction pattern assuming that:
  - The “sky” pattern can be modeled as diffraction by the full array
  - The “source” pattern can be modeled as diffraction by a small (3x3) array pointing in the opposite direction.
- The maps (in logarithmic scale) typically show that the sky “offends” the source beam by an amount ~1E-3-1E-4 of its level, consistent with the measures in the literature and at GSFC.

TI windows

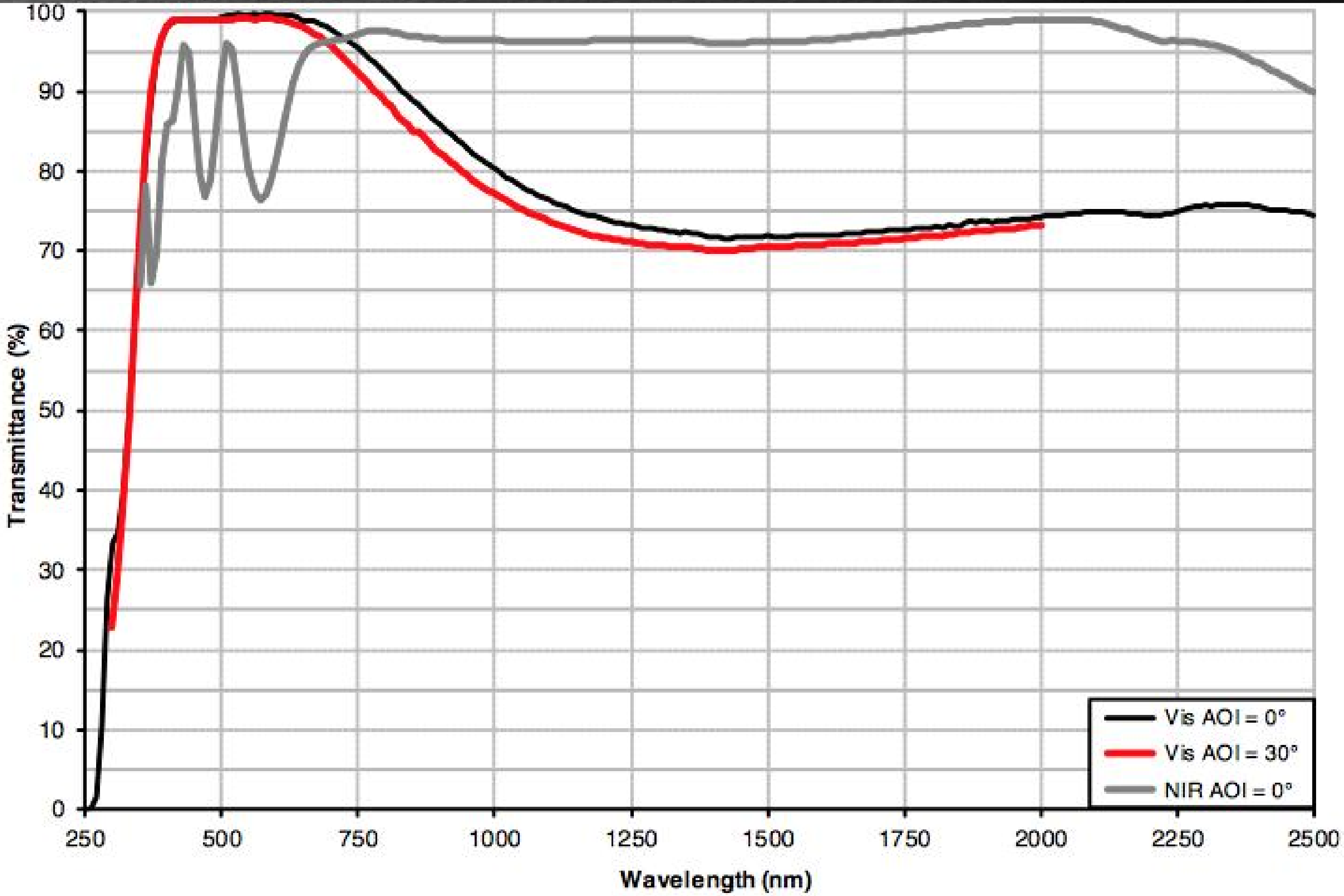
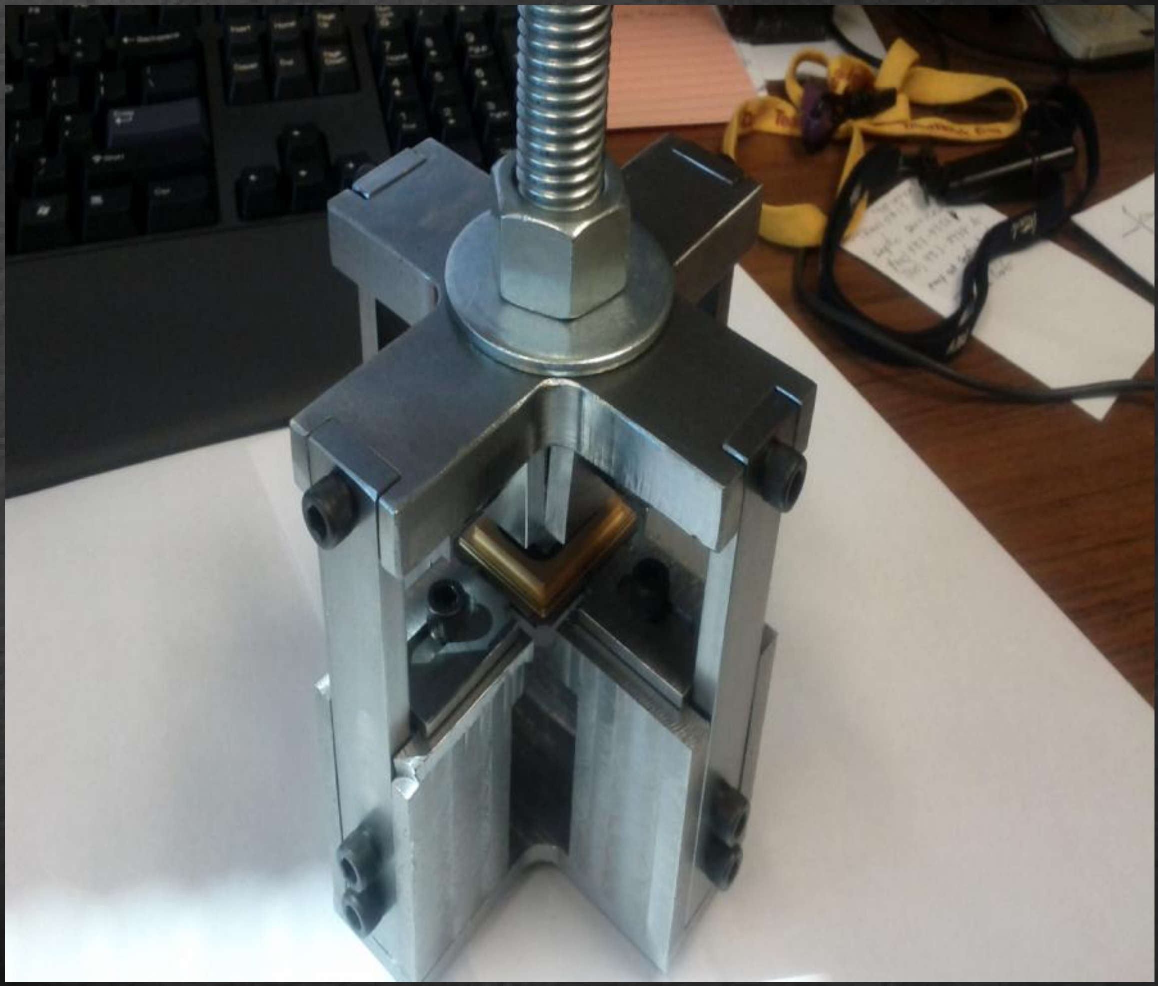


Figure 4. Corning Eagle XG Window AR Coating Options

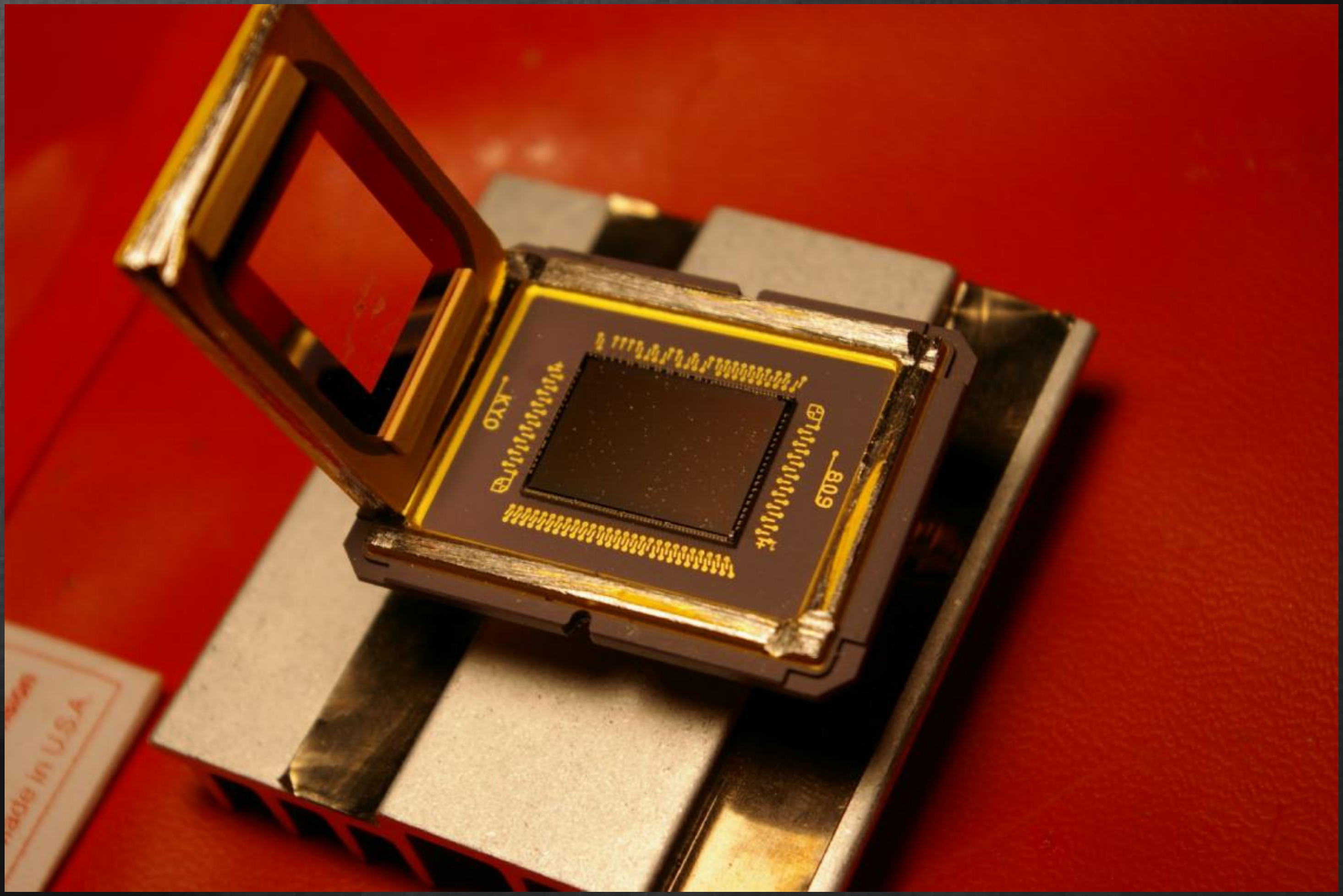
Window Replacement

- DMD devices as delivered by Texas Instruments (TI) are supplied with a protective sealed window
- Window is borosilicate glass which has no transmission at 200nm.
- DMD mirrors as delivered by TI are in an inert environment with a fluorocarbon backfill.
- Looking to develop process to remove window and replace with either MgF2 or HEM Sapphire window.
- The HEM sapphire has a good thermal expansion co-efficient match with Kovar frame/housing.

RIT DMD Window Removal Tool

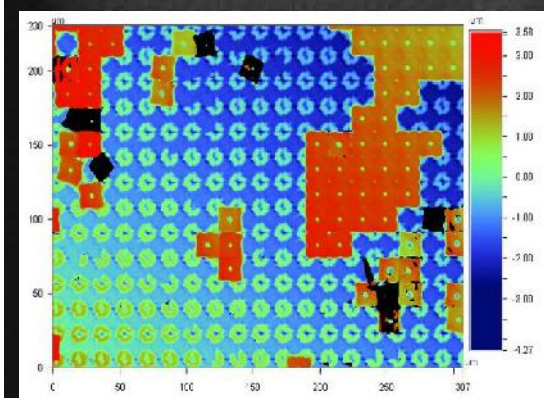


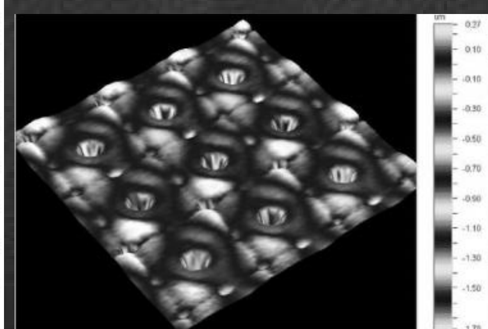
Window Removal

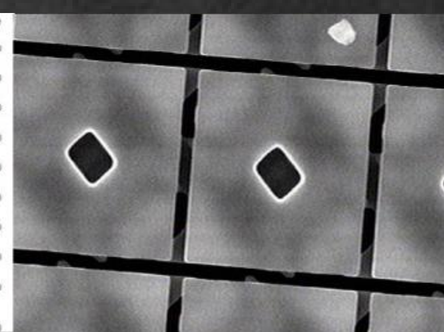


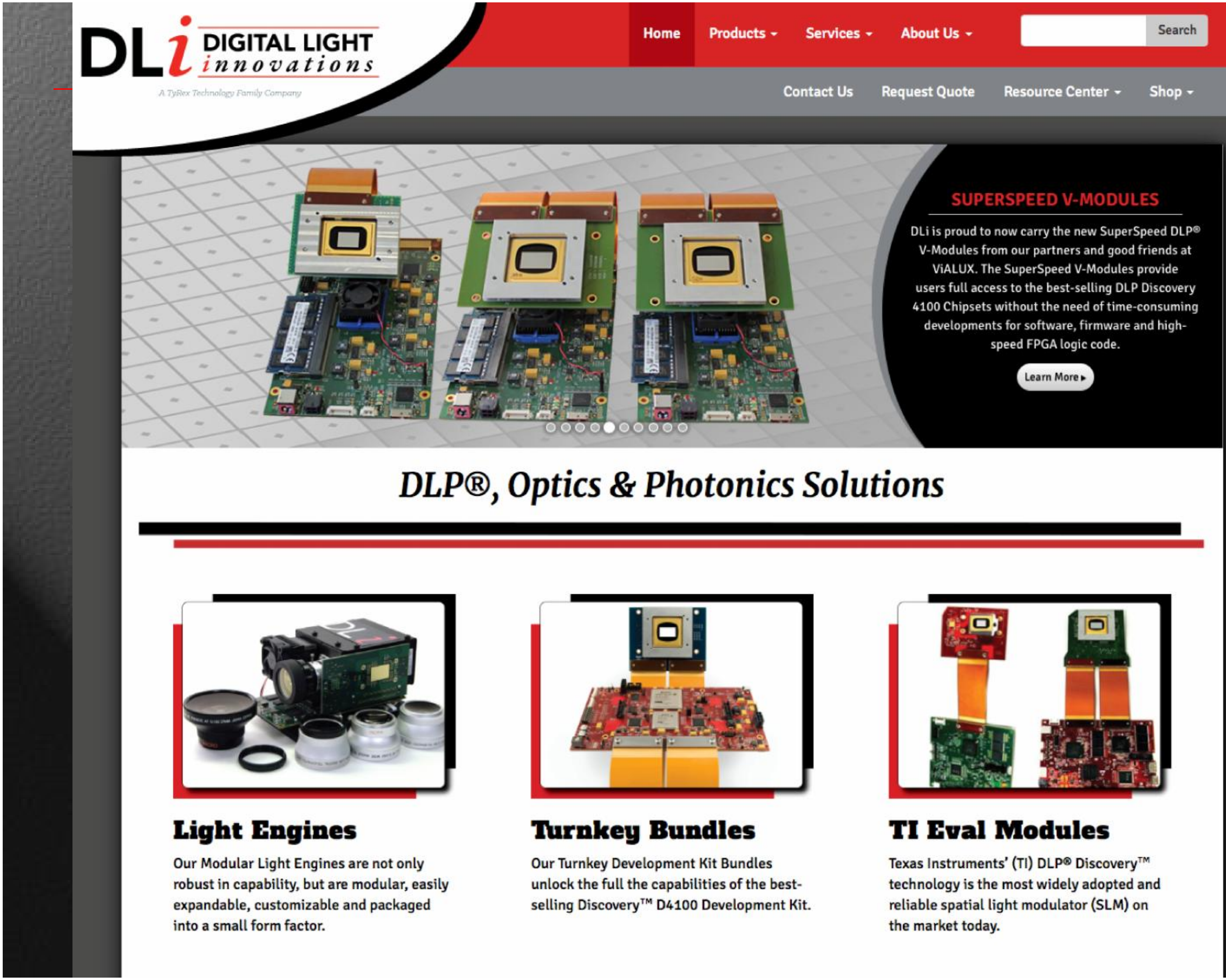
The Window Removal

- The window was removed from a non-functional digital micromirror device.
  - Further analysis was performed on this device.
    - Interferometry measurements of surface roughness
    - Scanning electron microscopy (SEM) images were taken of mirrors and underlying structures.





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DMD format

name	diagonal (inches)	pixels	pitch (microns)
S2K	0.69	2048 x 1080	7.6
Cinema	0.98	2048 x 1080	10.8
Cinema	1.2	2048 x 1080	13.6
Enhanced 4K	1.38	4096 x 2160	7.6
0.95 1080p	0.95	1920 x 1080	10.8
0.7 XGA	0.7	1024 x 768	13.6
0.55 XGA	0.55	1024 x 768	10.6
0.45 XGA	0.45	912 x 1140	7.6
0.3 WVGA	0.3	608 x 684	7.6

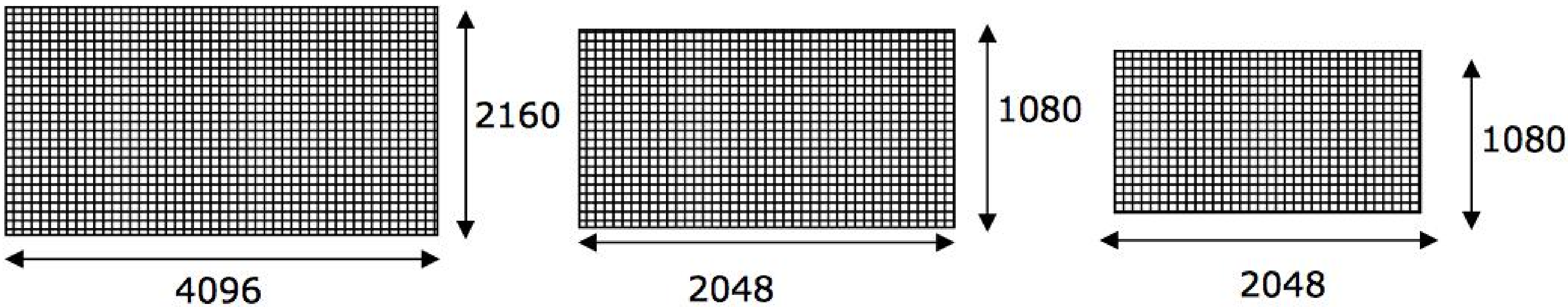
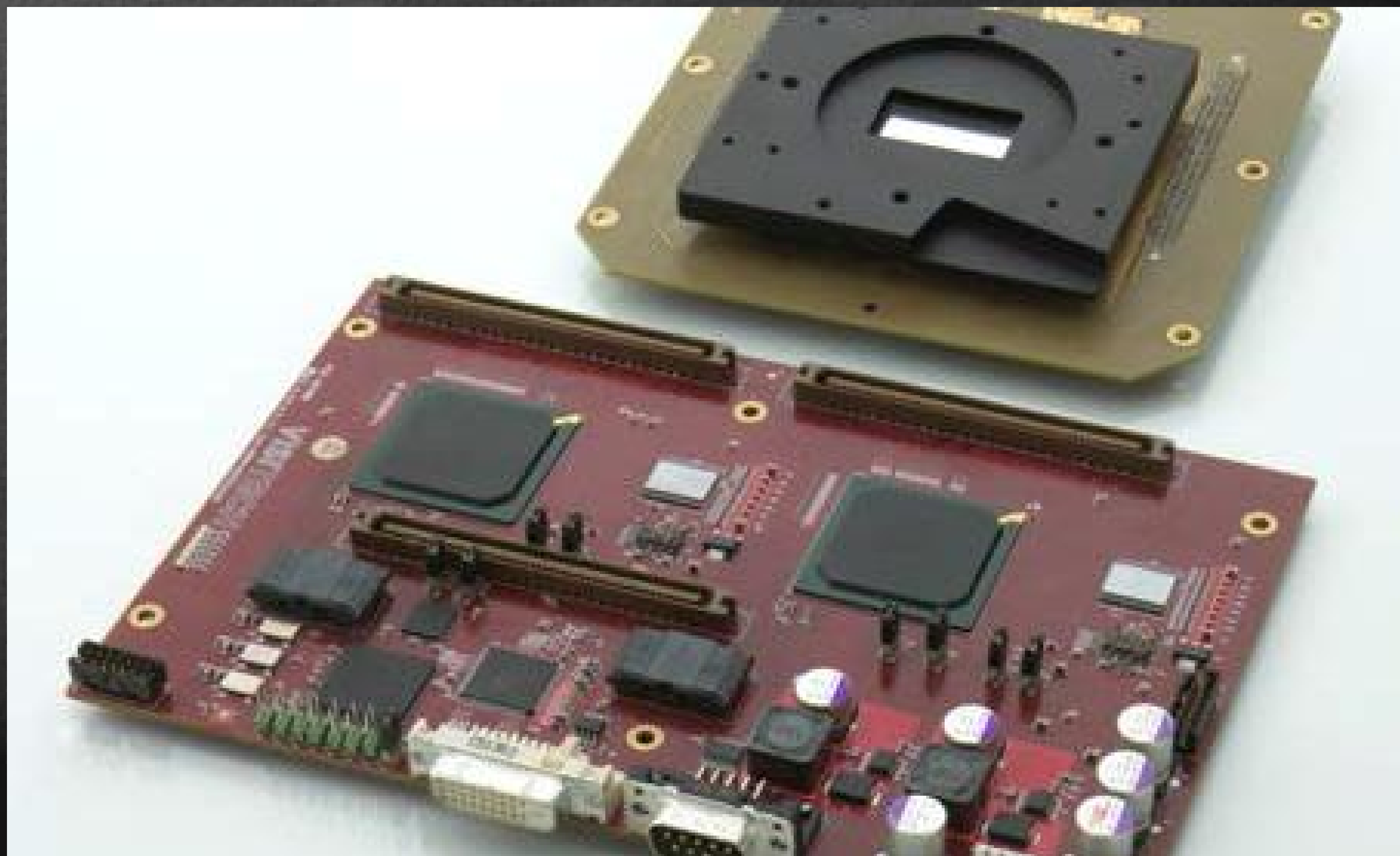


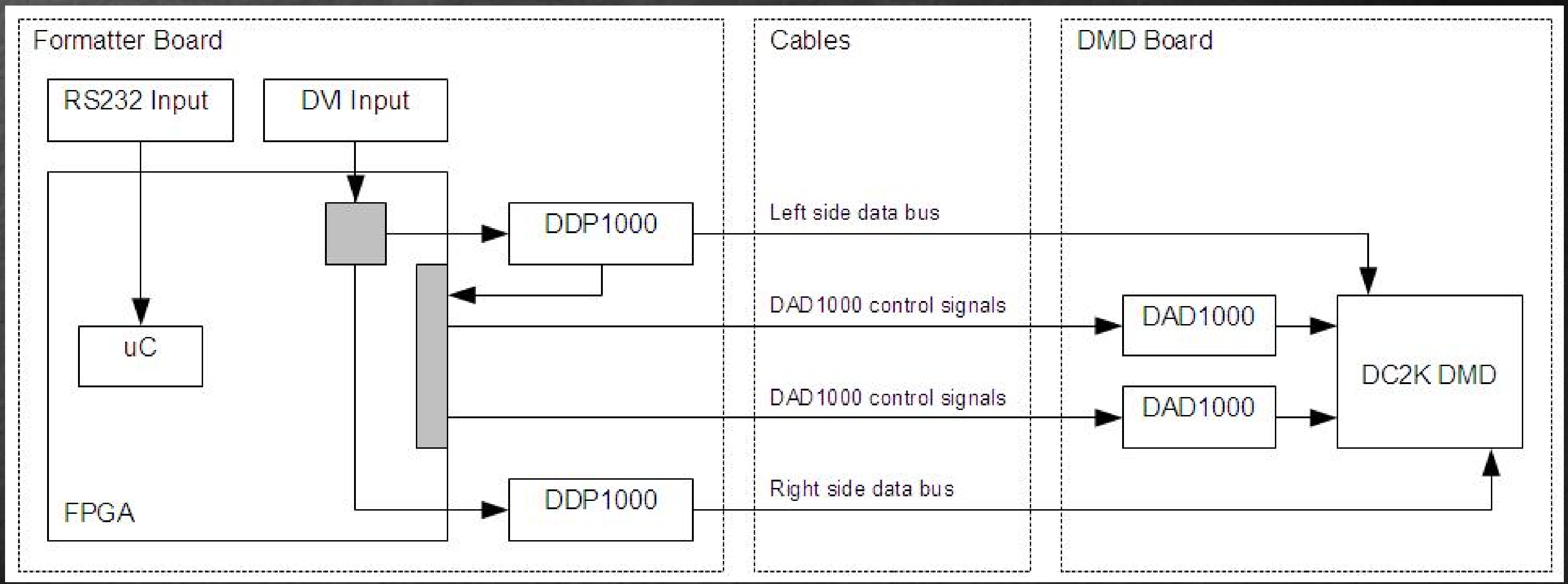
Figure 1. Comparison of the resolution and relative sizes of Digital Cinema DLP chips. From left to right: 1.38" — 4K, 1.2" — 2K and 0.98" — 2K

From http://www.barco.com/projection_systems/downloads/WhitePaper_4K_more-than-meets-the-eye.pdf

Visitech Formatter + DMD board



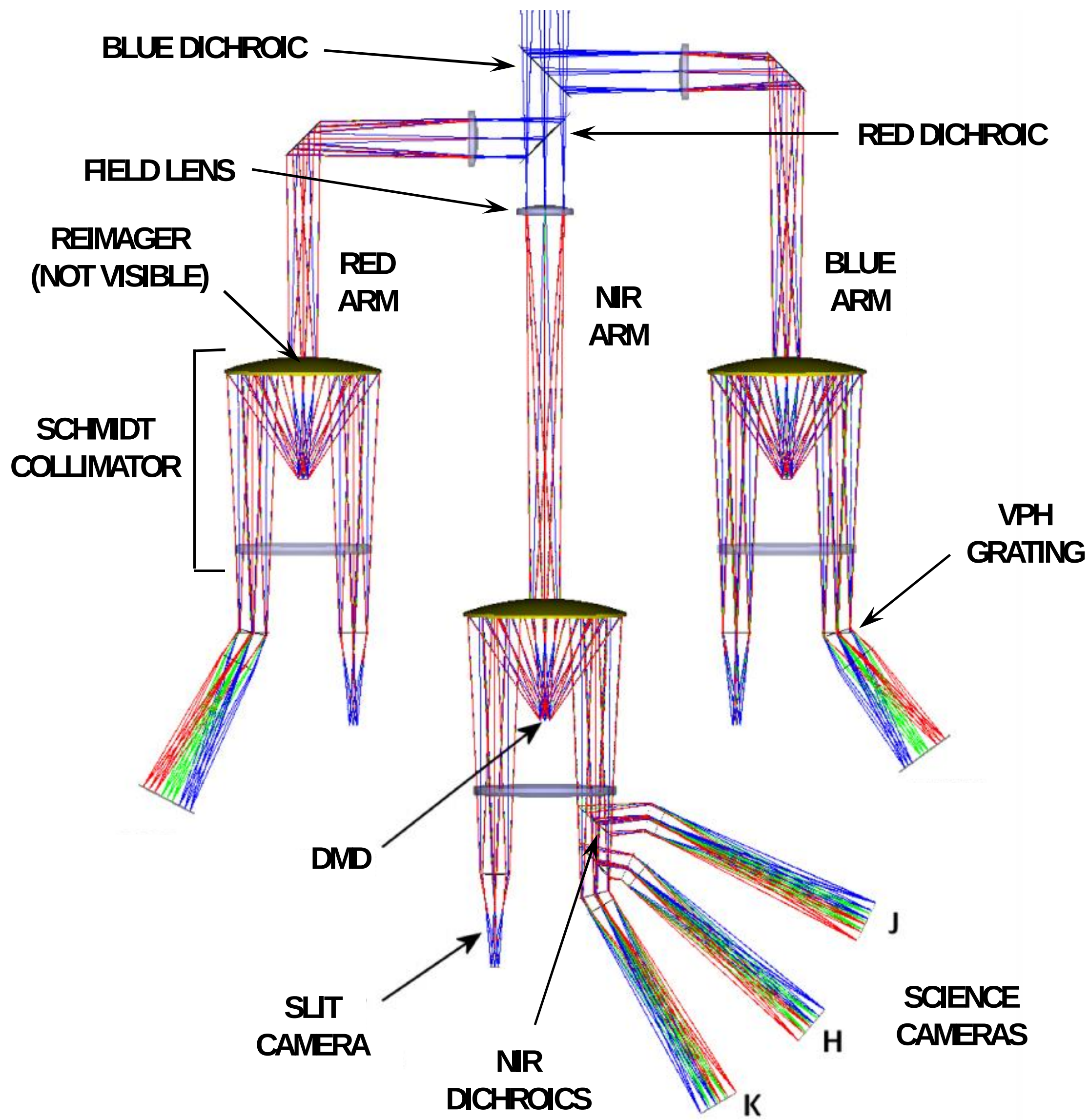
Visitech Luxbeam DC2K Platform

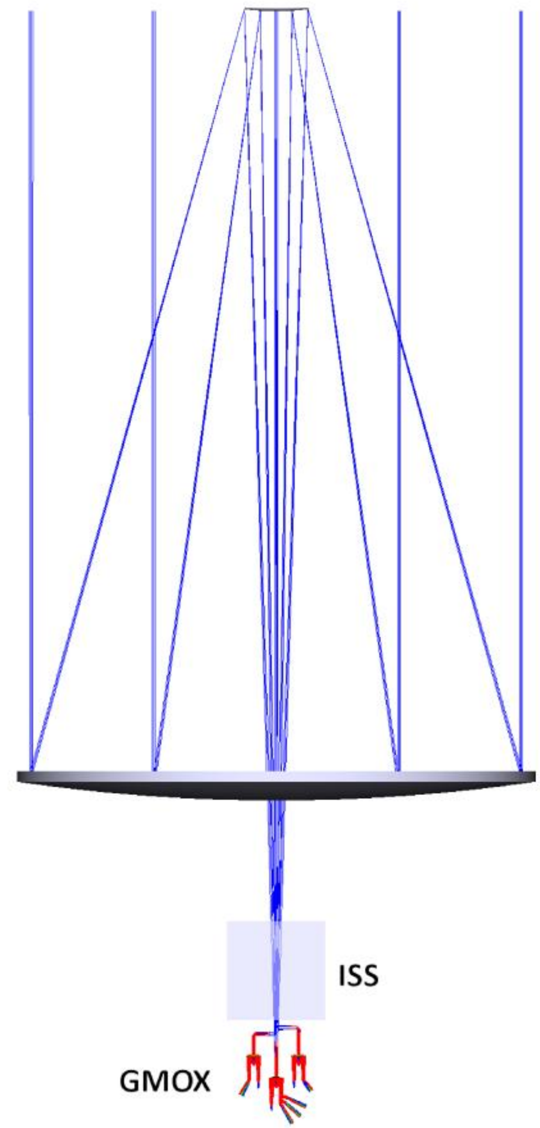


DC2K = Digital Cinema 2K DMD

Optical Design

Schematic Optical Layout

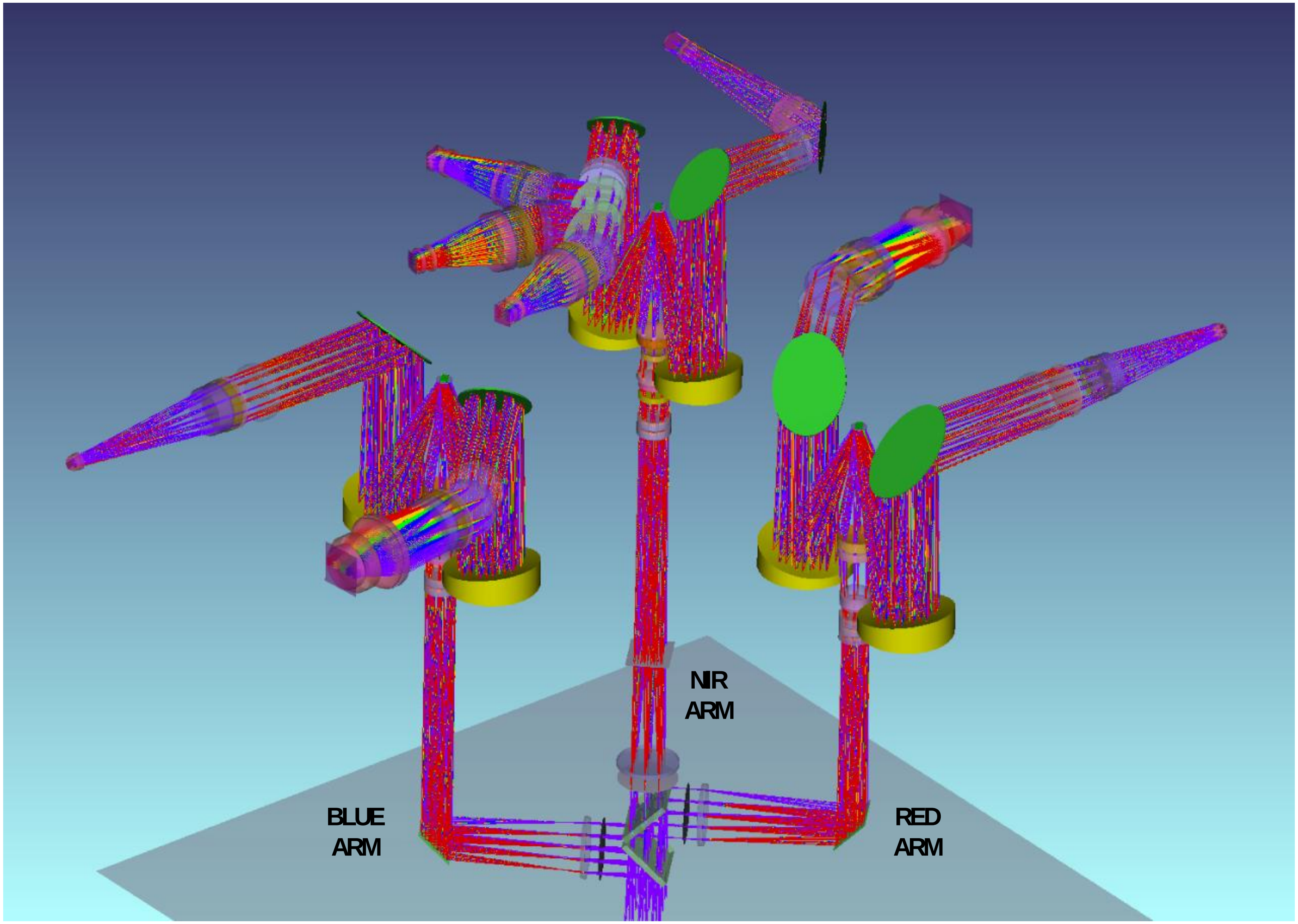




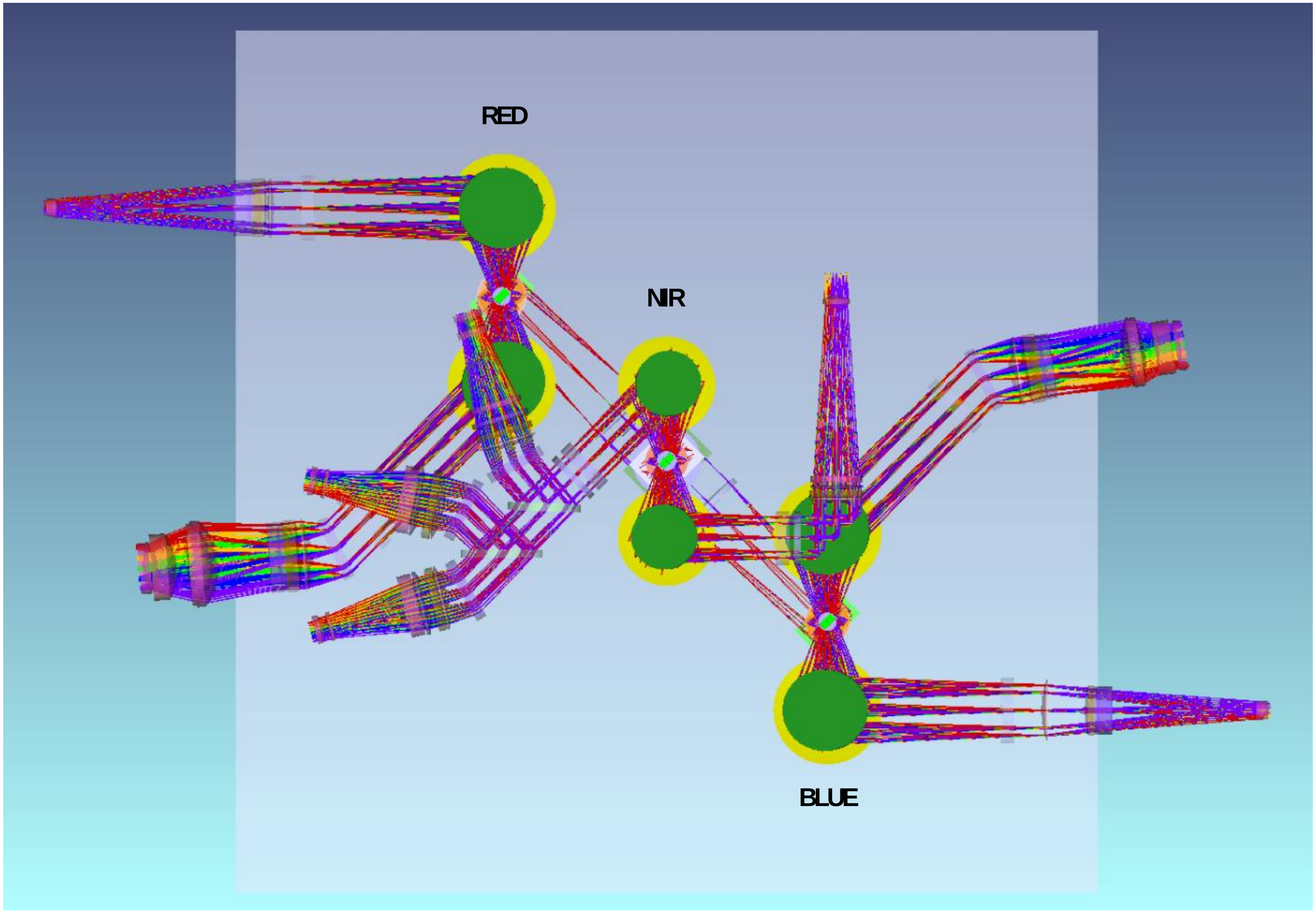
Spectroscopic Channel Parameters

Channel	WL (nm)	R	Slit width			Grating		Spectral length		Beam Ø	Camera		
			arcsec	mirrors	pixels	angle	l/mm	mm	pixels	(mm)	f/#	FL (mm)	FOV (deg)
Blue	320.0 458.5 589.0	3132 4500 5765	0.417	5	3.0	20.1	1493	80.9	8085.2	101	1.834	183.4	23.3
Red	589.0 797.2 1000.0	3681 5000 6250	0.333	4	3.0	18.0	772.5	78.2	7815.6	101	2.293	230.8	18.9
Y+J	970.0 1160.6 1350.0	2757 3300 3837	0.250	3	2.75	11.3	337.5	29.8	2976.3	81	2.802	227.1	16.7
H	1460.0 1636.8 1810.0	4461 5000 5530	0.250	3	2.75	16.9	354.3	29.5	2947.0	81	2.802	227.0	16.6
K	1930.0 2191.9 2450.0	3962 4500 5030	0.250	3	2.75	15.3	240.0	29.4	2942.0	81	2.802	227.0	16.6

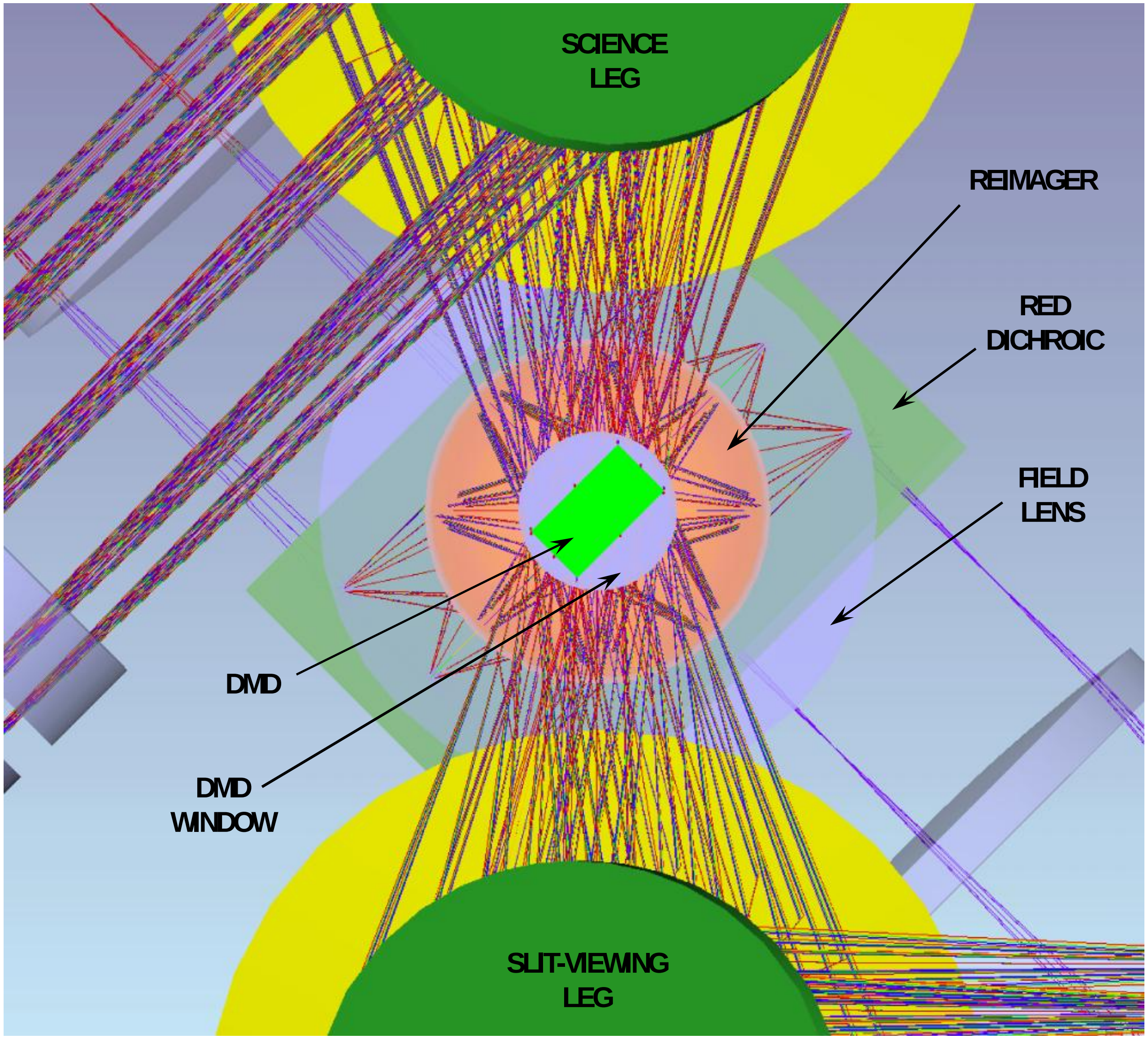
Full Optical Layout



End-on View of Optical Layout

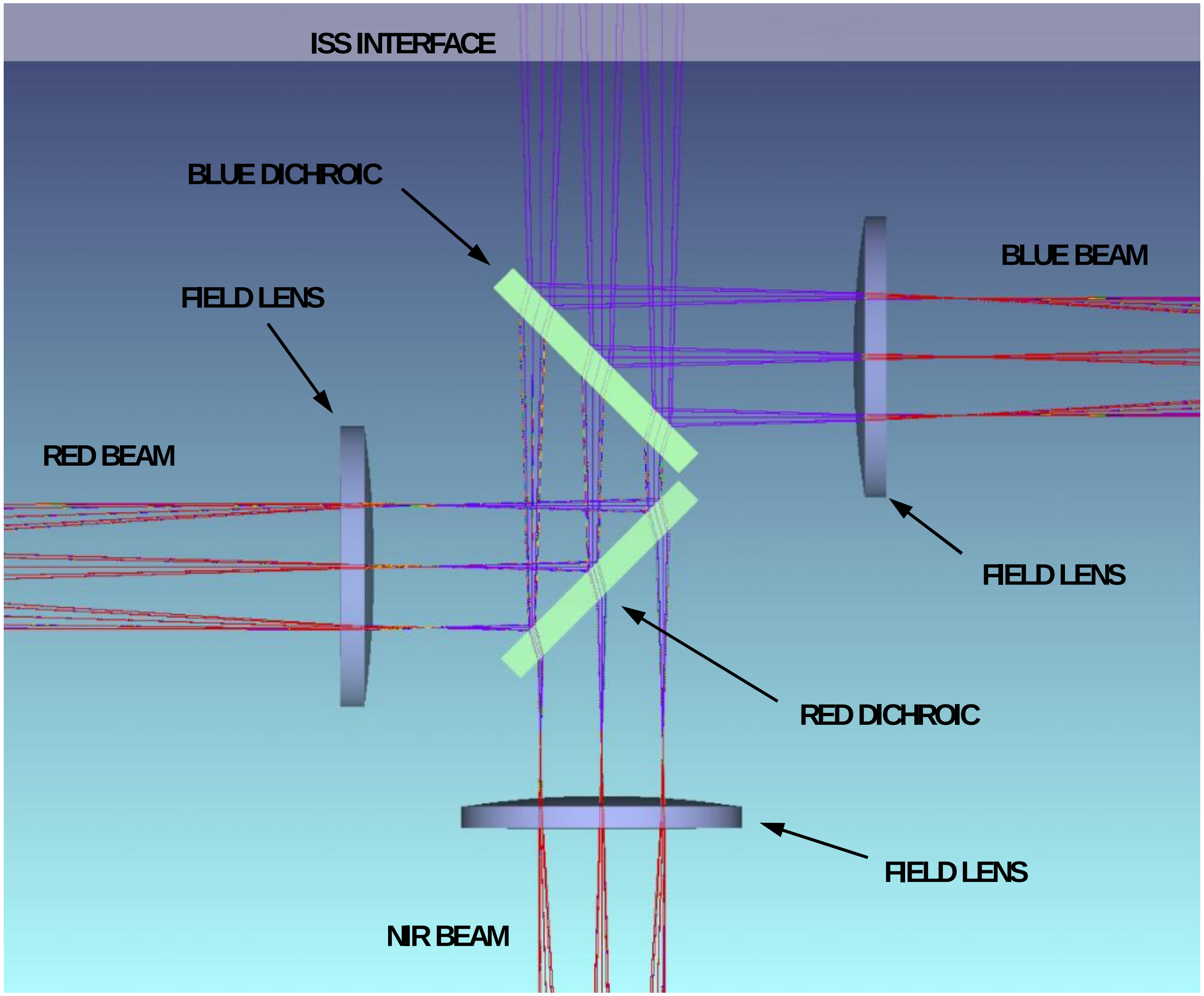


DMD/Field Orientation (NIR Arm)



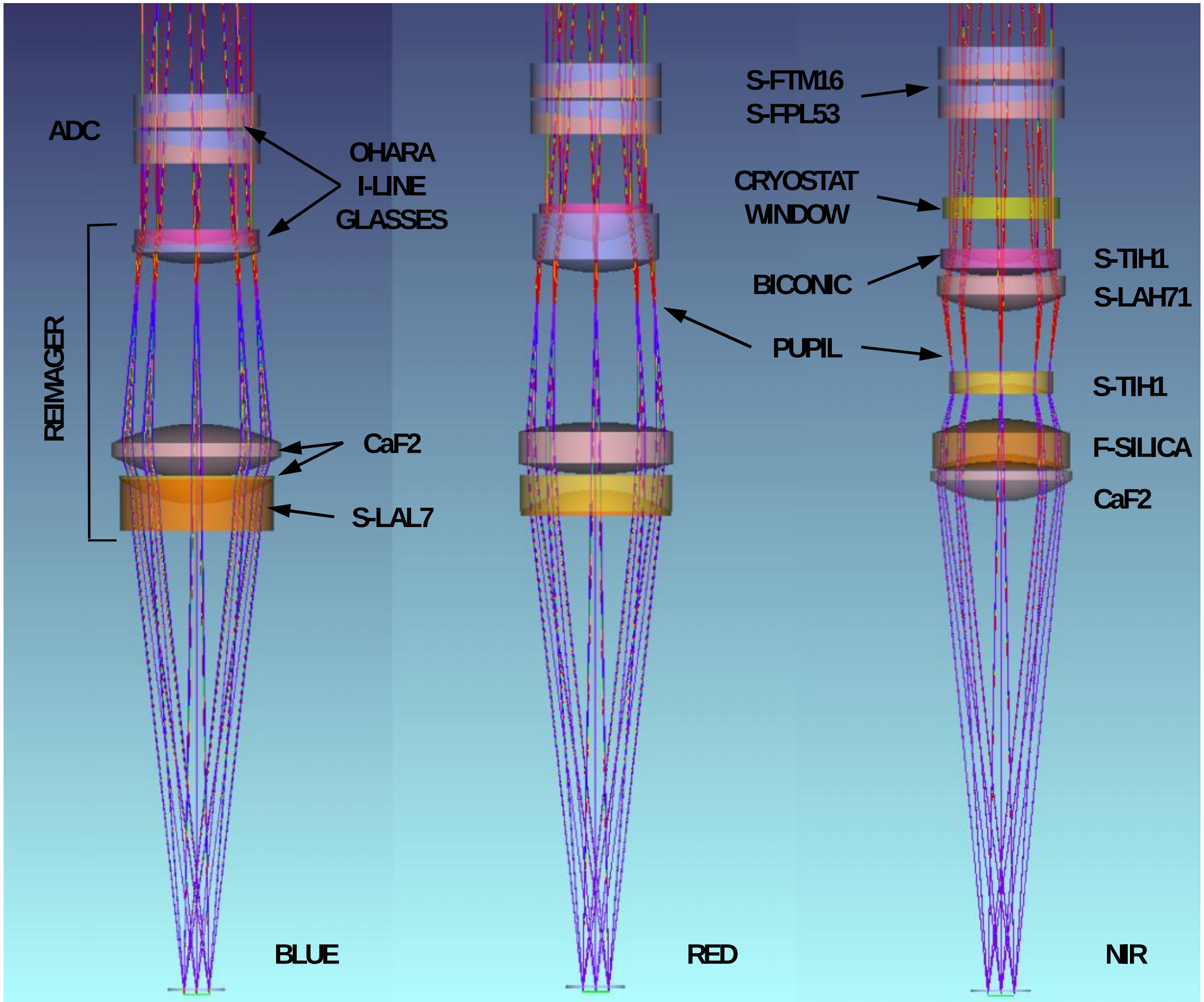
The rectangular field of view is oriented with respect to the rectangular DMD. In this view the 4 corner and 4 edge field points can be seen around the perimeter of the DMD. The ±12° tilt of the micromirrors about their *diagonals* effectively rotates the field 45° after re-flection off the DMD.

Fore-Optics

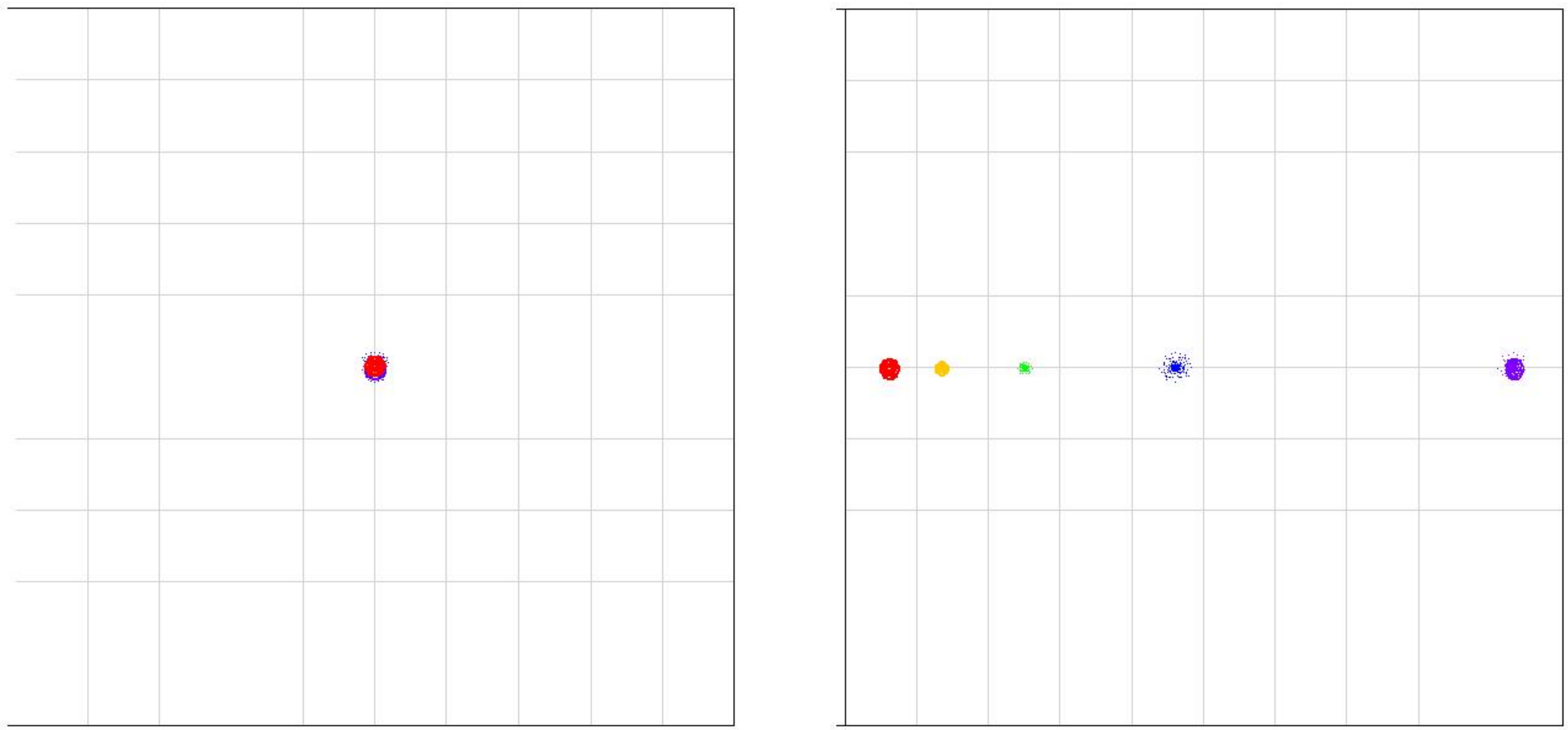


ISS INTERFACE
BLUE DICHROIC
BLUE BEAM
FIELD LENS
RED BEAM
FIELD LENS
RED DICHROIC
FIELD LENS
NIR BEAM

ADCs and Reimagers

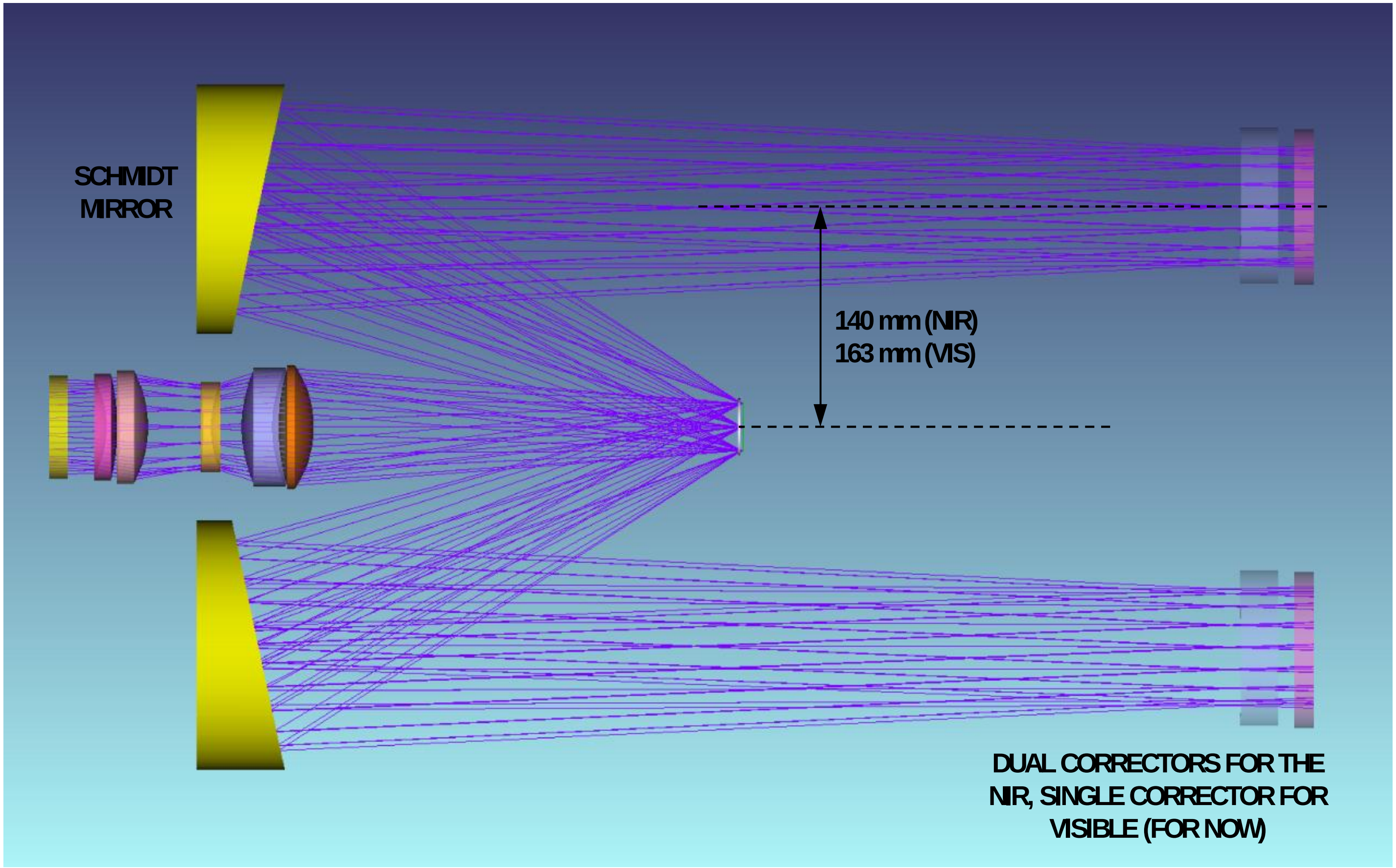


ADC Range (Blue ADC shown)

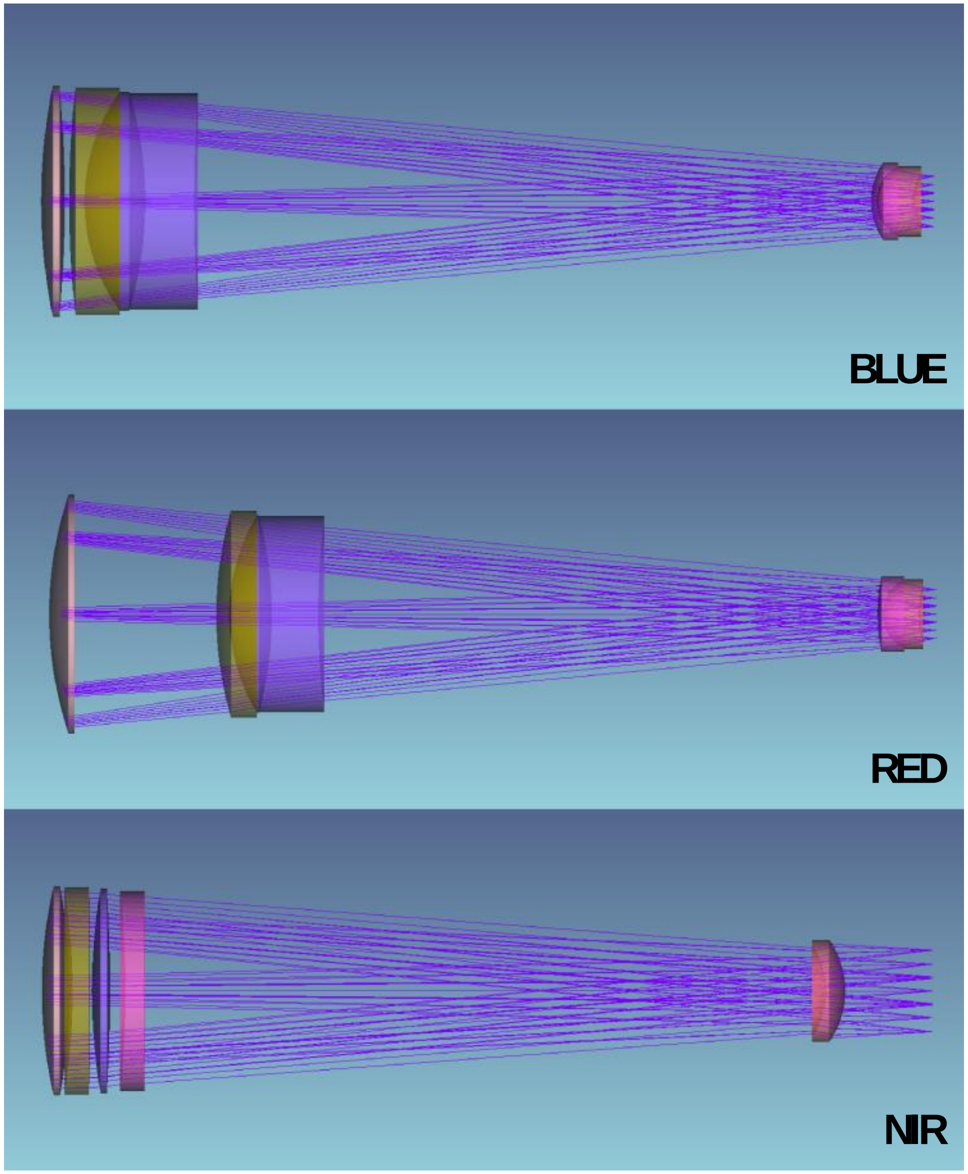


At the DMD. Box is 1 mm square, corresponding to 6”. Required dispersion for the blue channel is 3.9” at an airmass of 2.

Schmidt Collimators (NIR shown)

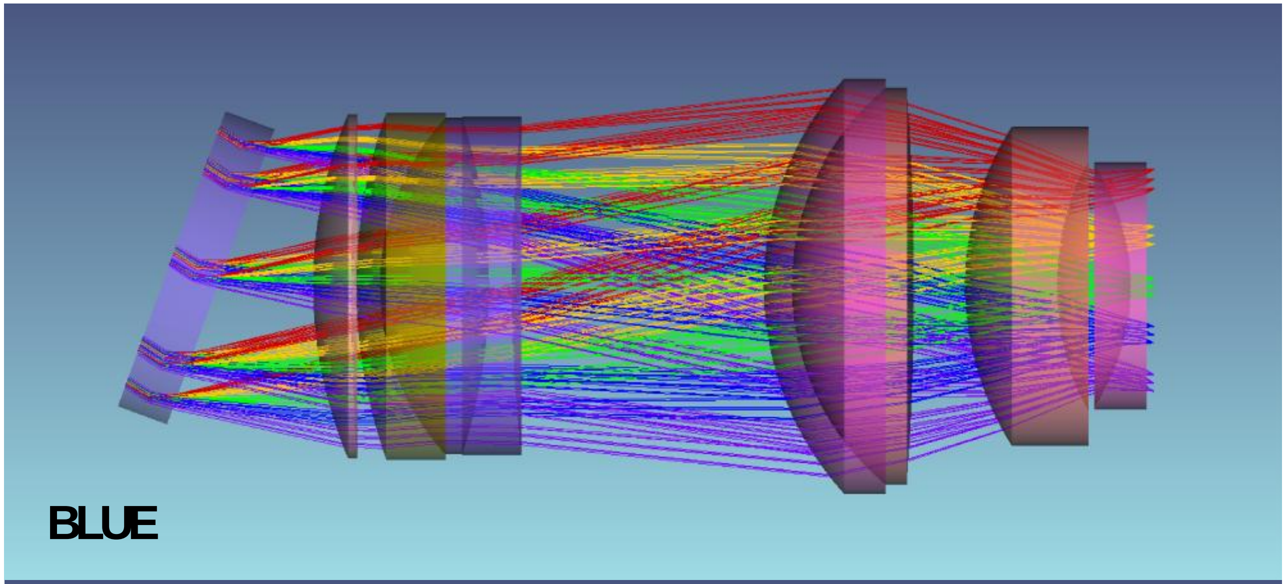


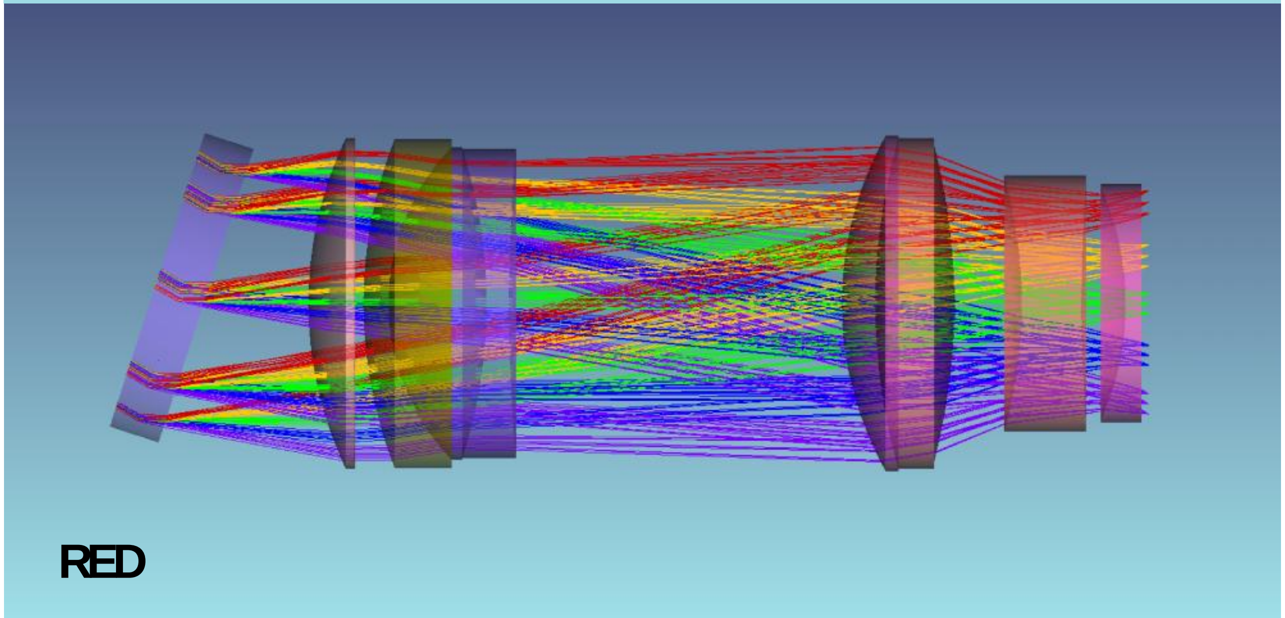
Slit-Viewing Cameras

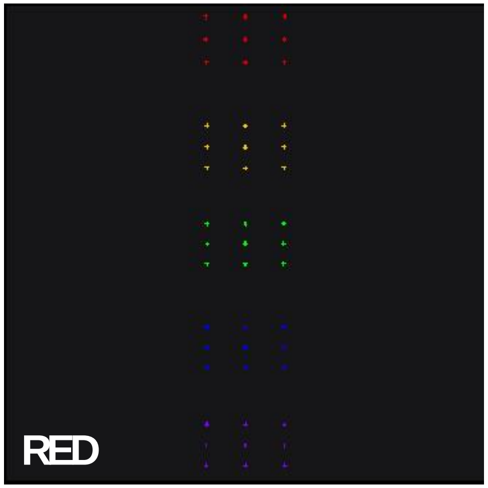


The blue and red slit-viewing cameras are designed to reimage the DMD at a scale of 0.88. This maps one micromirror onto a single 12 µm pixel (e.g. Andor fast readout camera). The NIR slit-viewing camera is designed to reimage the DMD at a scale of 1.31. This maps one micromirror onto a single 18 µm pixel of the H2RG detector.

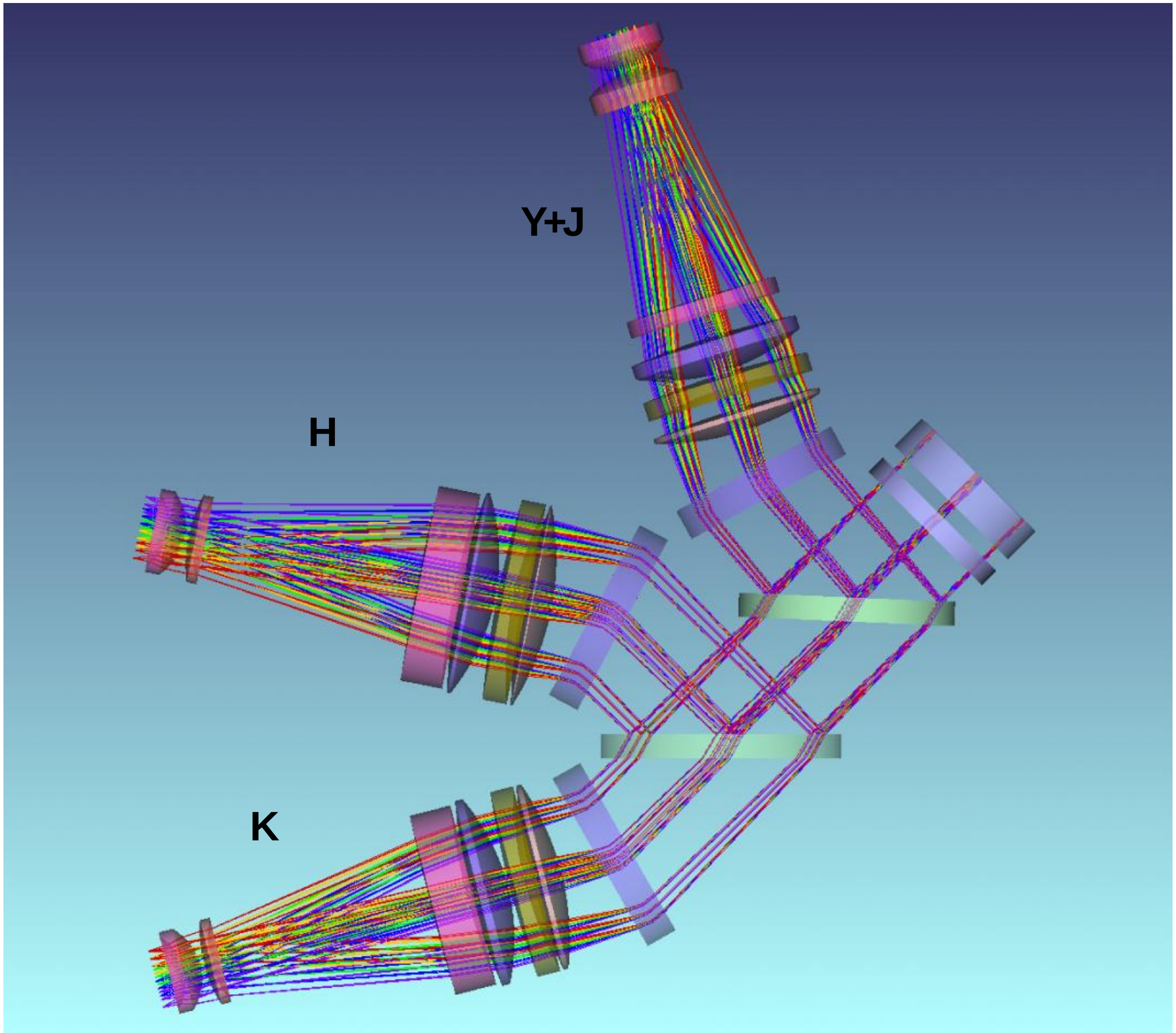
Visible Science Cameras & Detector Format

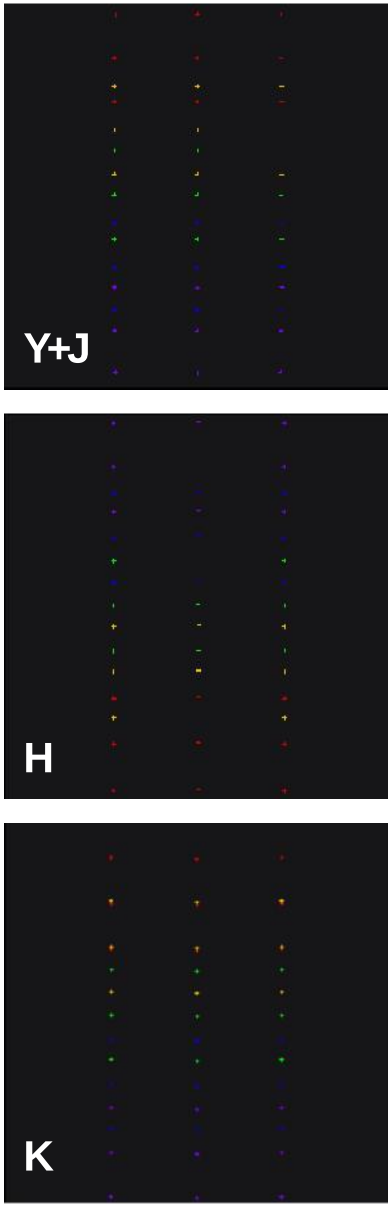






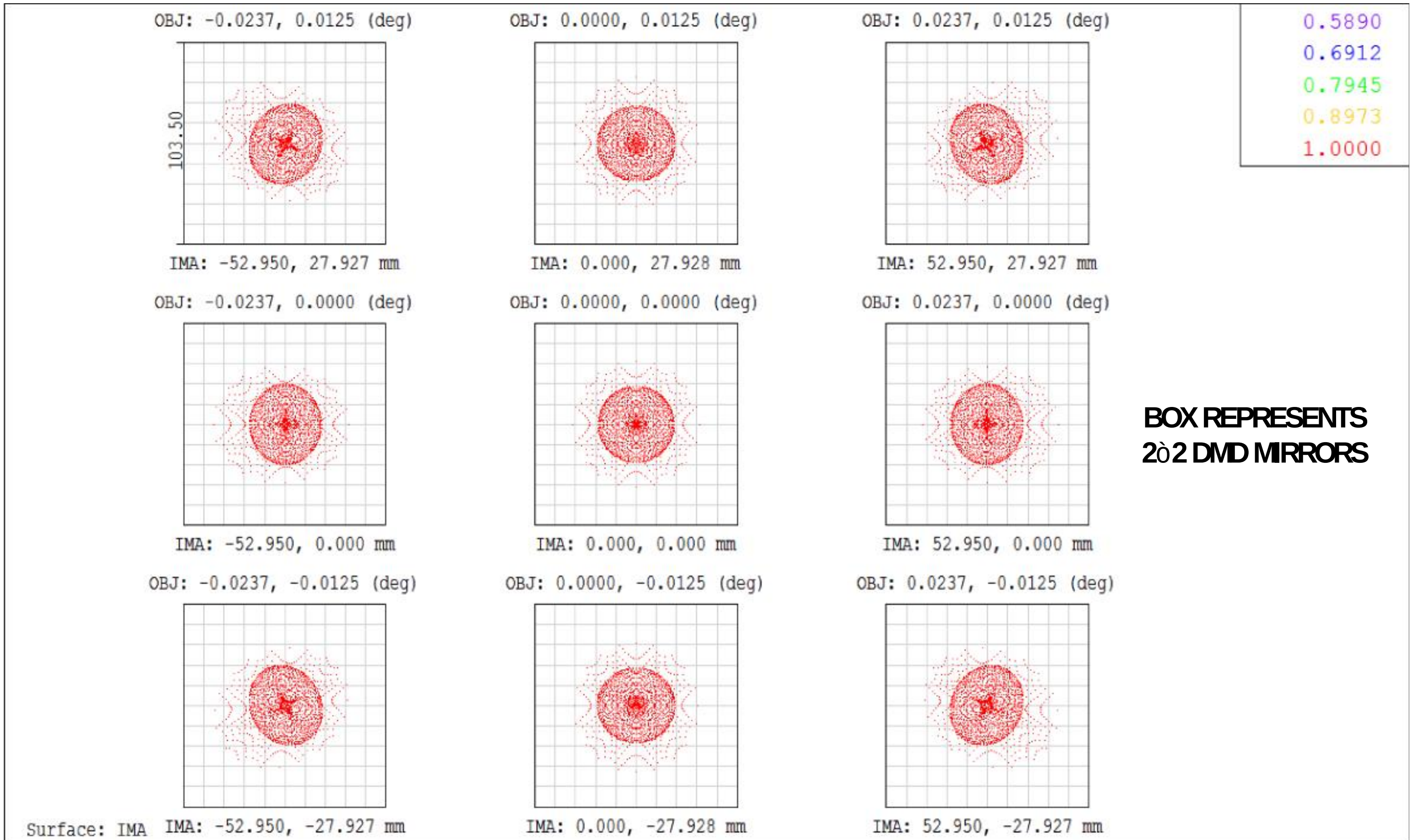
NIR Science Cameras & Detector Format





Optical Performance

Spots at Telescope Focal Surface



BOX REPRESENTS 2ò2 DMD MIRRORS

Spot Diagram

Gemini Telescope
8/26/2015 Units are µm.

AVERAGE RMS DIAMETER ~ 0.05"

Field :	1	2	3	4	5	6	7	8	9
RMS radius :	16.113	15.955	16.113	16.051	15.947	16.051	16.113	15.955	16.113
GEO radius :	37.165	33.834	37.165	36.426	32.241	36.426	37.165	33.834	37.165

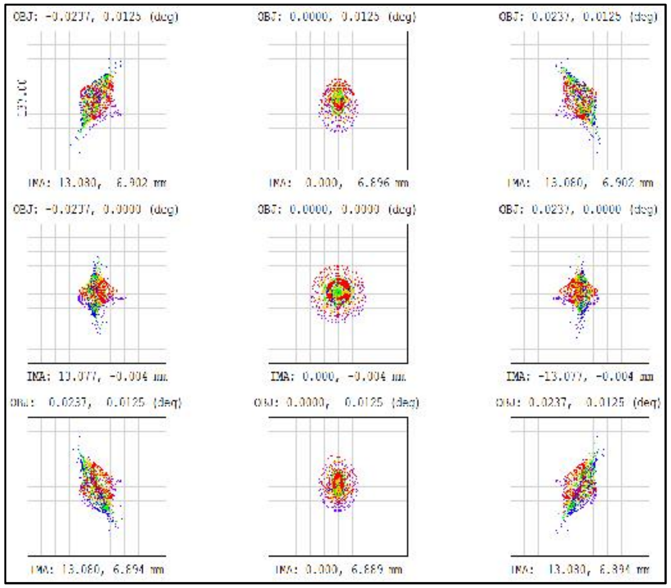
Box width : 103.5 Reference : Centroid

Johns Hopkins University
Instrument Development Group
Baltimore, Maryland

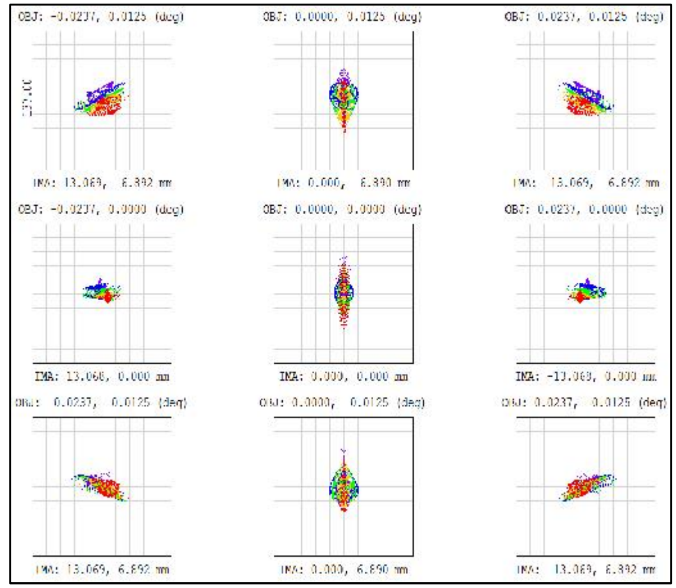
gemini_only.ZMX
Configuration 2 of 4

Spot Sizes at DMDs

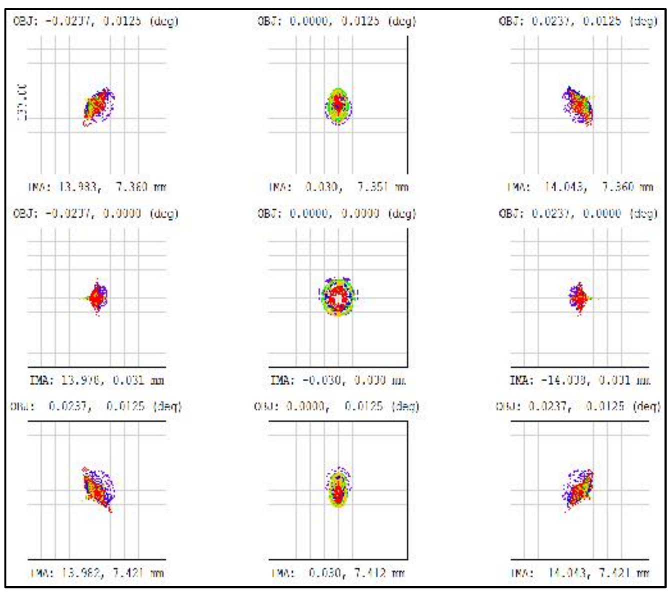
Blue



Red



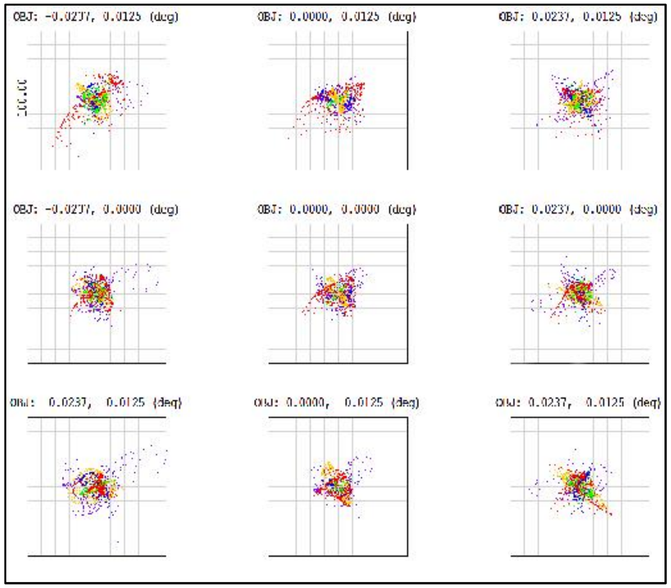
NIR



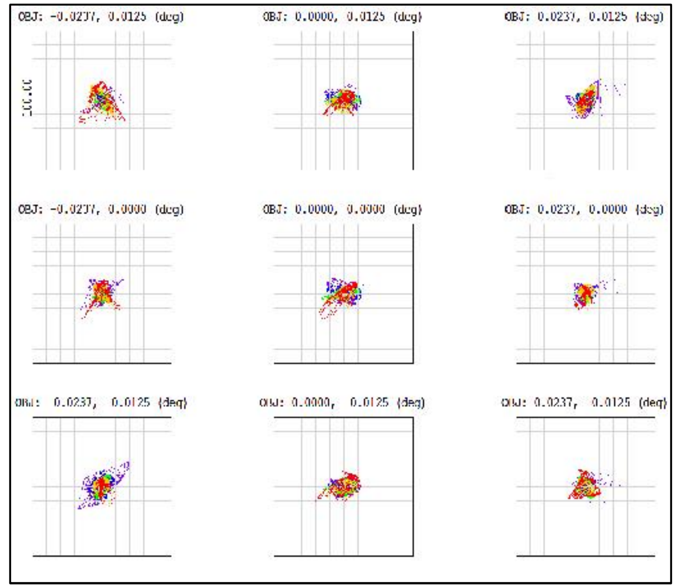
Boxes are 137 µm square
(10 x 10 micromirrors)

Chnl	Wavelengths (nm)	Avg. RMS Radius (µm)
Blue	330 – 589	13.85
Red	589 – 1000	10.72
NIR	970 – 2400	8.71

Spot Sizes at Visible Science Detectors



Blue



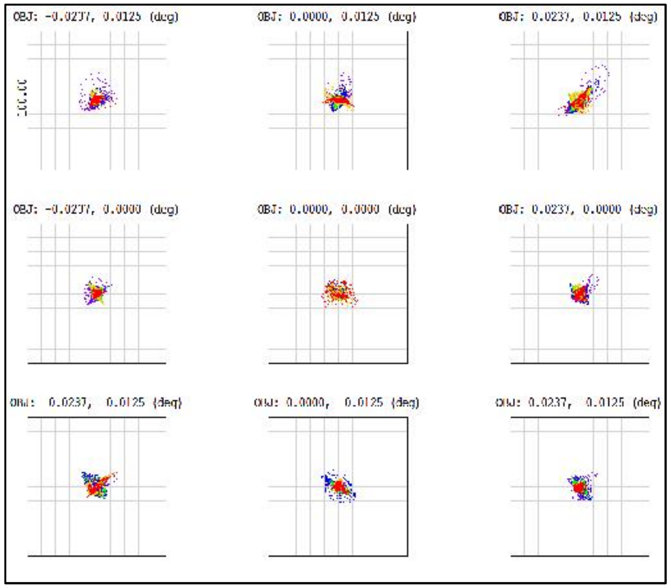
Red

Boxes are 100 μm square
(10 x 10 pixels)

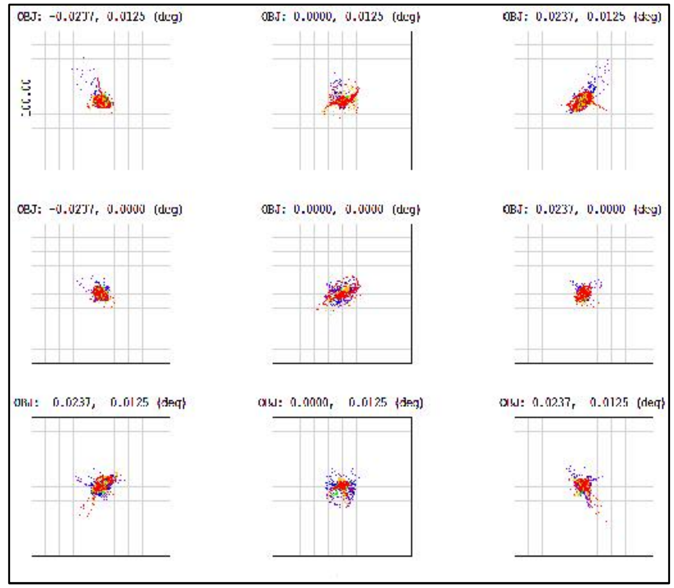
Chnl	Wavelengths (nm)	Avg. RMS Radius (μm)
Blue	330 – 589	10.03
Red	589 – 1000	6.70

Spot Sizes at NIR Science Detectors

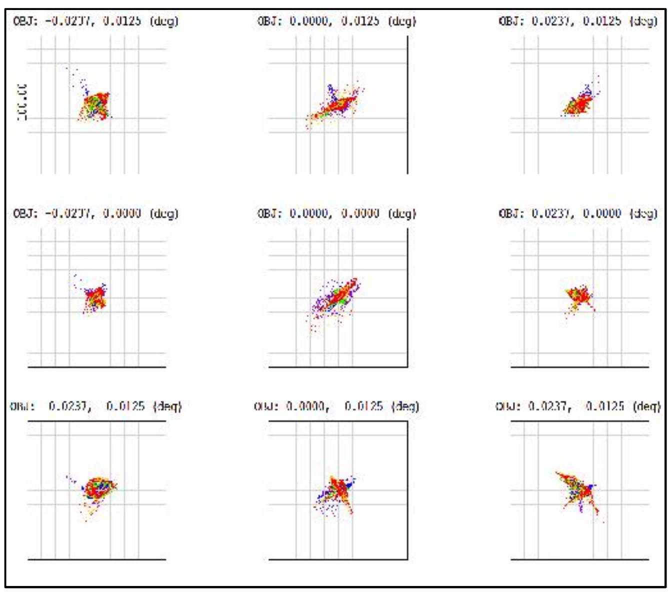
Y+J



H



K

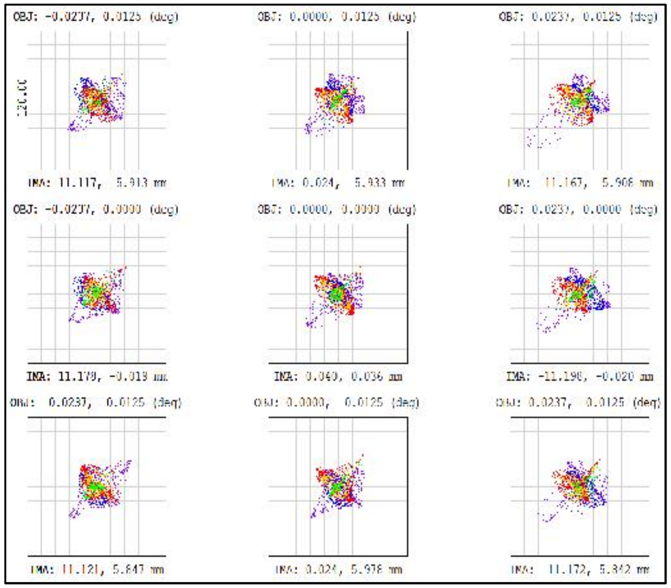


Boxes are 100 µm square
(10 x 10 pixels)

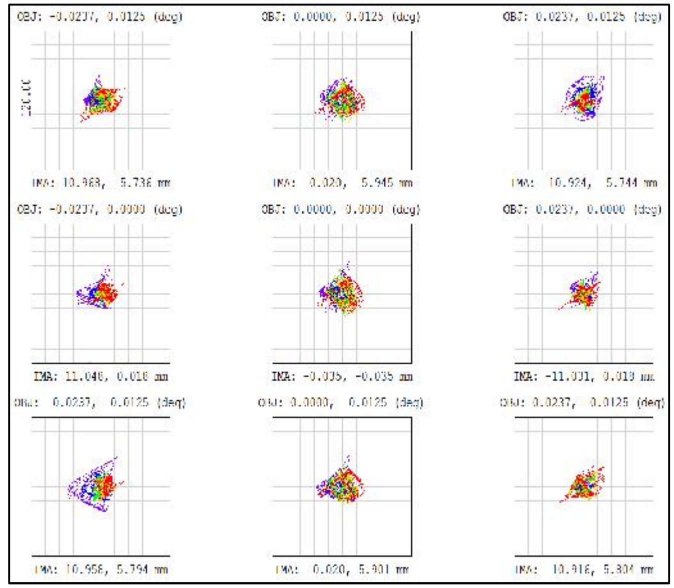
Chnl	Wavelengths (µm)	Avg. RMS Radius (µm)
Y+J	0.97 – 1.35	5.07
H	1.46 – 1.81	5.18
K	1.93 – 2.40	6.53

Spot Sizes at Slit-Viewing Detectors

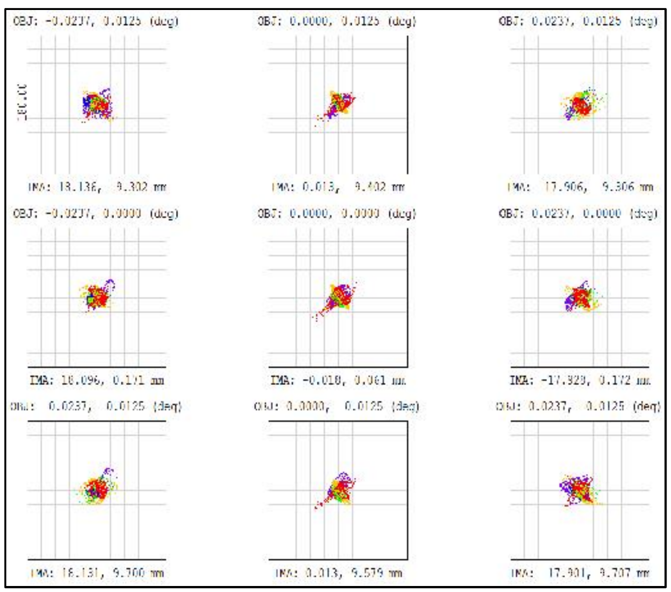
Blue



Red



NIR



Visible boxes are 120 µm square

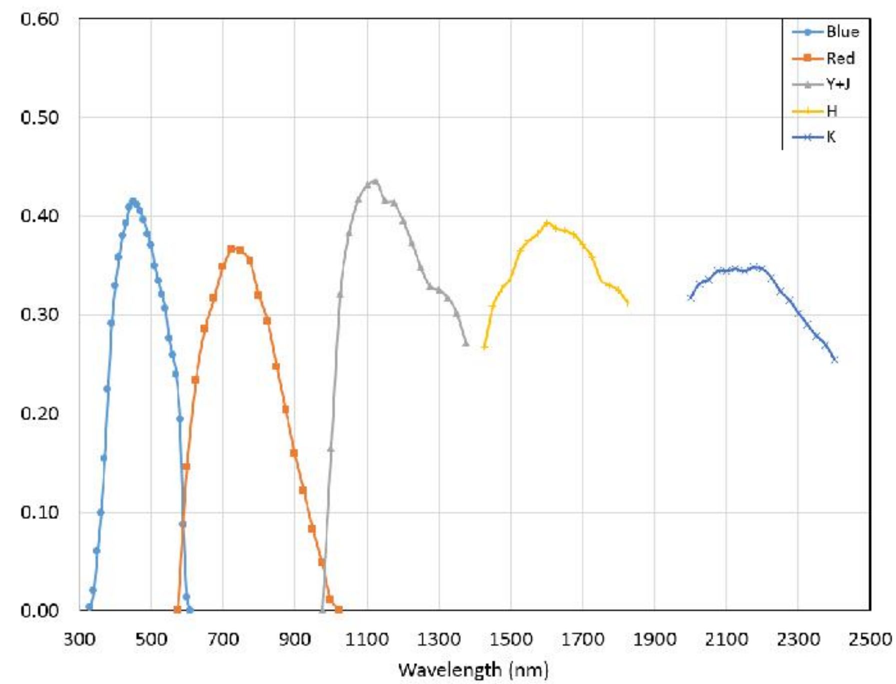
NIR boxes are 180 µm square

(10 x 10 pixels)

Chnl	Wavelengths (nm)	Avg. RMS Radius (µm)
Blue	330 – 589	12.64
Red	589 – 1000	8.81
NIR	970 – 2400	10.30

Instrumental Efficiency

- **Throughput model has been developed for the five science channels**
- **Includes all instrumental effects except slit loss and scattered light**
- **Lenses and mirrors**
  - AR coatings
  - Mirror reflectivities (Al, Ag, Au)
  - Glass internal transmission
- **Dichroics**
  - R/T curves based on measured curves for BOSS dichroics (JDSU)
- **DMDs**
  - Mirror reflectivity (Al)
  - Fill factor (90%)
  - Window in double pass (assume replacement window for NIR)
- **Gratings**
  - First-look, unoptimized design curves from Kaiser Optical
  - Includes manufacturing tolerances



- **Detector QE, e2v CCD290-99**
  - Astro multi-2 coating
  - QE curve from e2v datasheet
- **Detector QE, H4RG-10 (WFIRST-AFTA)**
  - Published QE curves, 2014 SPIE paper
  - Piquette et al, Proc. of SPIE, Vol. 9154

Mechanical & Cryogenic Design

Stephen Smee

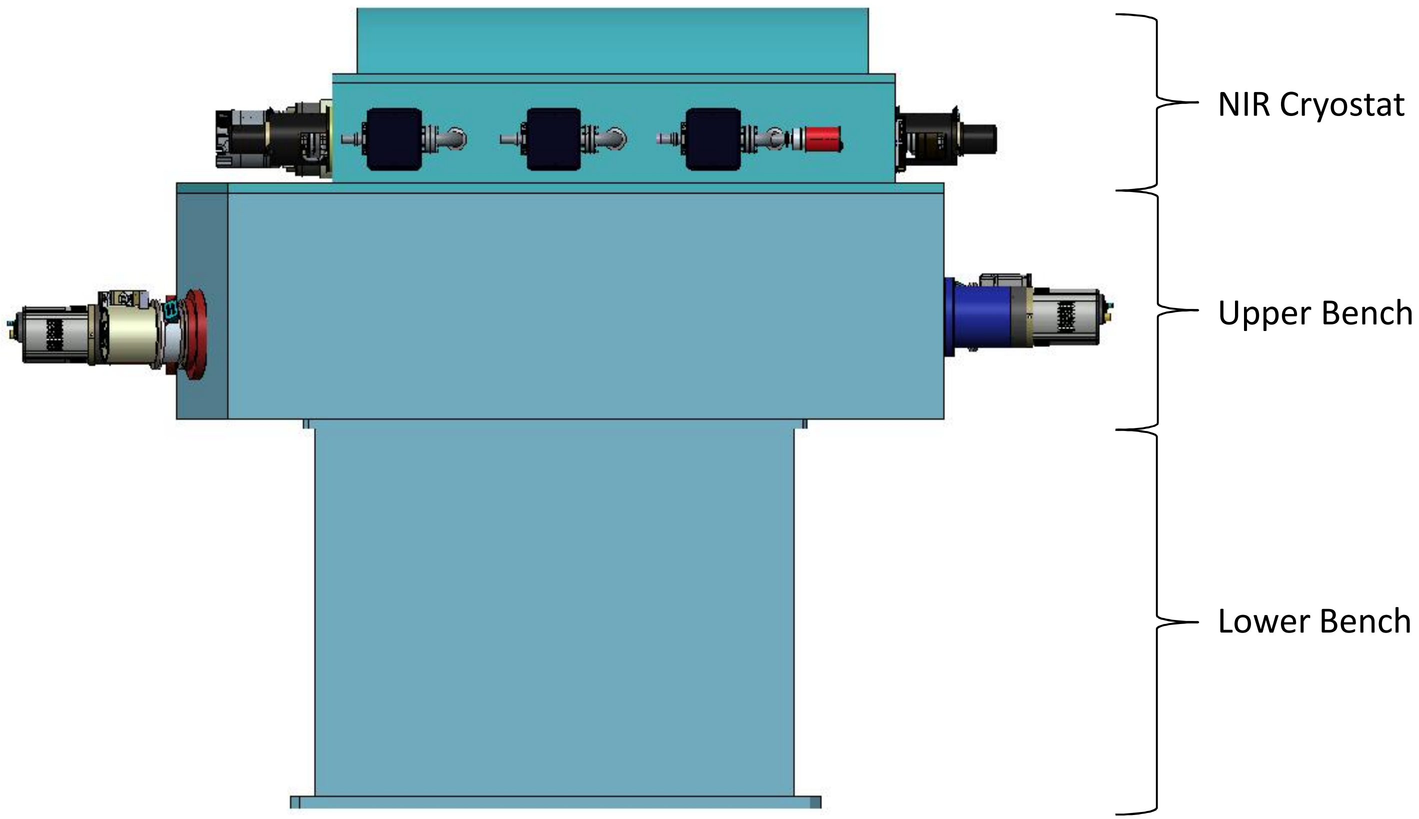
Key Requirements/Considerations

- **The instrument must fit within an irregular-shaped control volume**
  - Hammerhead shaped
- **Mass and center of gravity are specified**
  - 2000 kg at 1 m from the ISS surface
  - Provision for trim weights needed
- **Cassegrain mount necessitates a gravity variant design**
  - Flexure must be considered
- **Detector cooling by closed-cycle coolers**
  - No liquid nitrogen
- **Optical alignment**
  - Ease of alignment paramount given the number of optics and interfaces

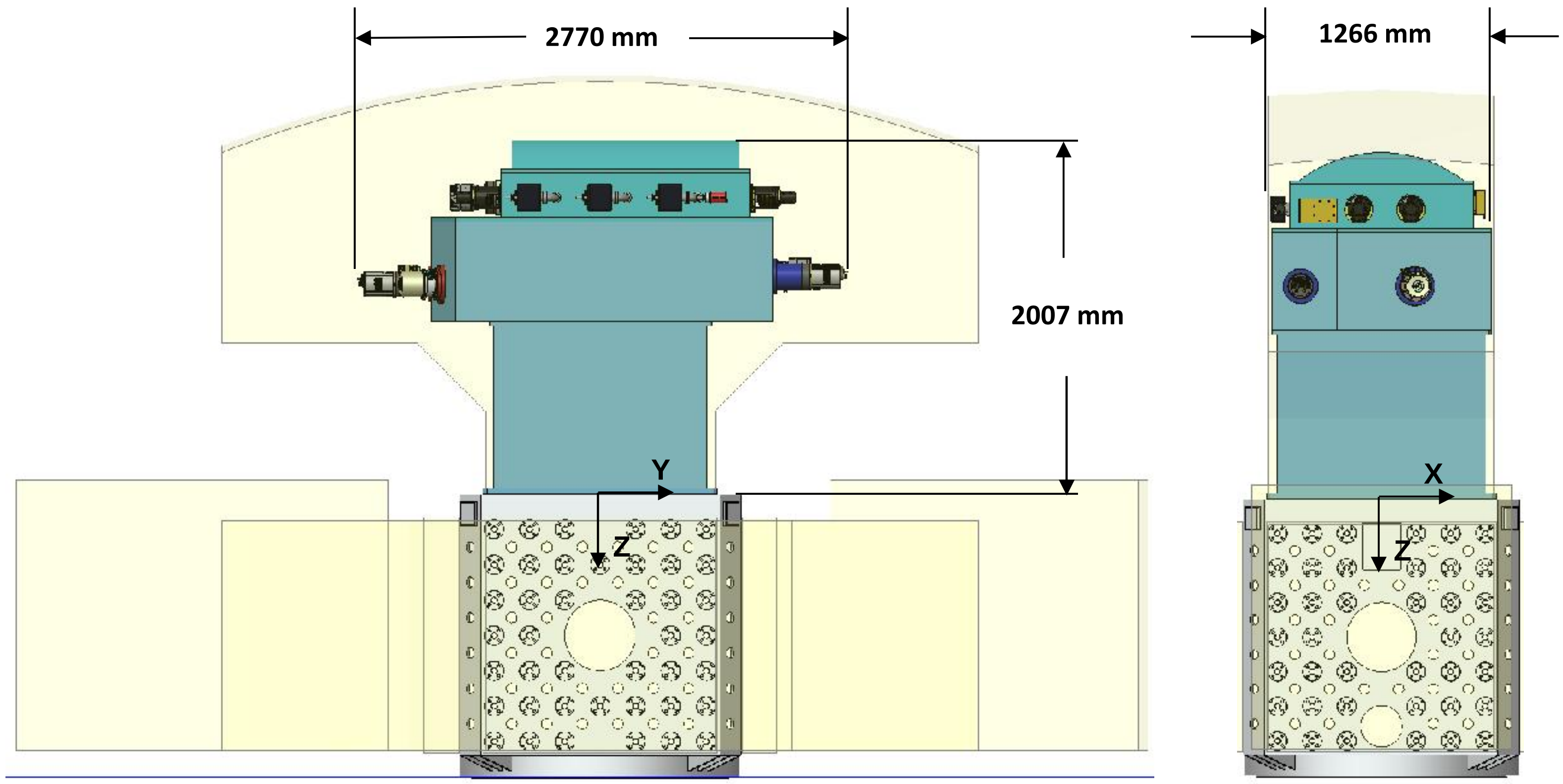
Optics Packaging

- **The GMOX optics are, for the most part, packaged in functional and testable units**
  - This eases alignment, integration and testing
- **The instrument is divided into three modules**
  - Lower bench: fore-optics and blue and red arm Schmidt collimators and ADCs
  - Upper bench: red and blue arm DMD sub-benches, and science and slit-viewing cameras, as well as the NIR ADC
  - NIR cryostat: the near infrared optics
- **The lower and upper benches are aluminum weldments designed with stiffness in mind**
- **Pinned interfaces ensure precise repeatable assembly of the bench sections**

GMOX Mechanical Configuration



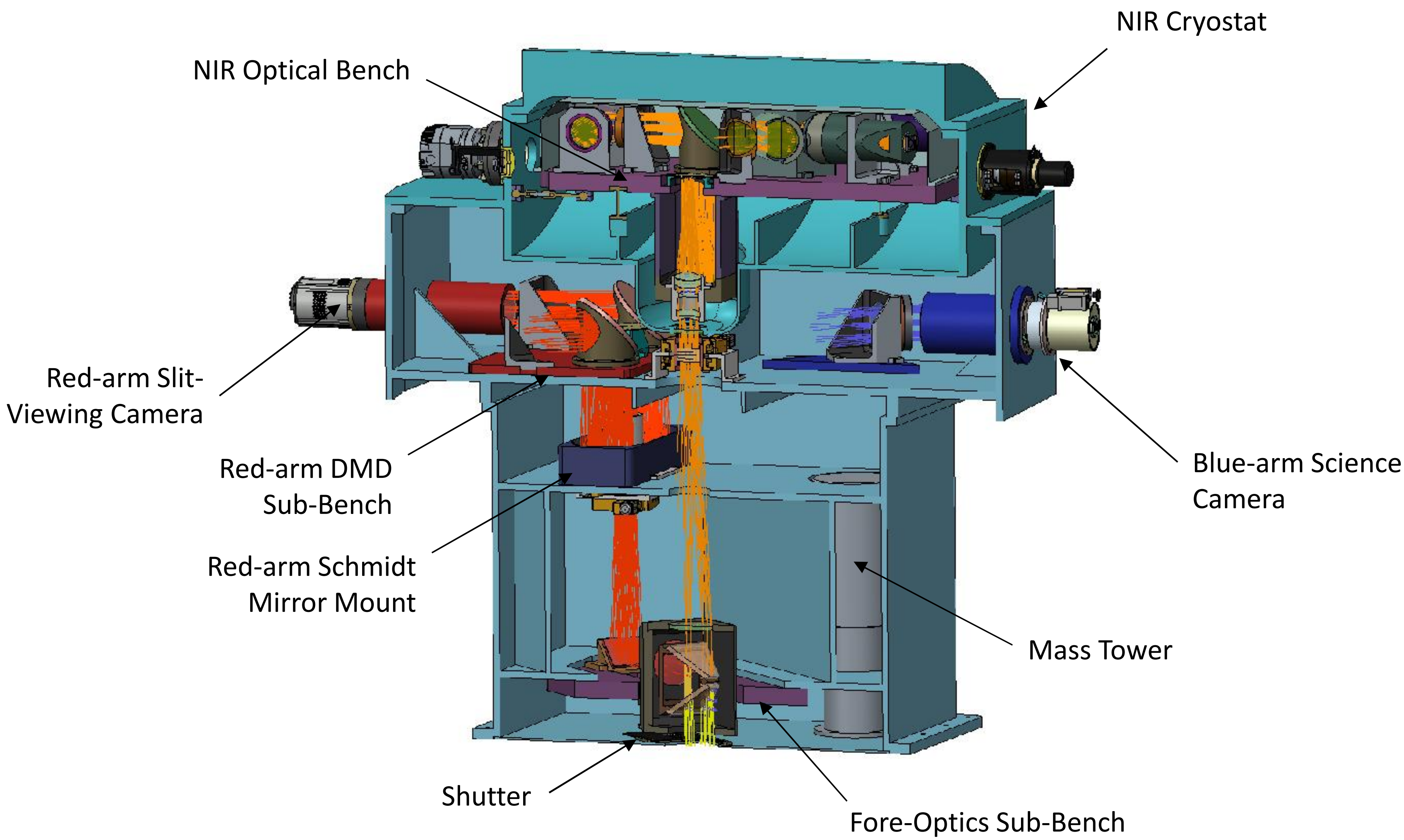
GMOX on the ISS



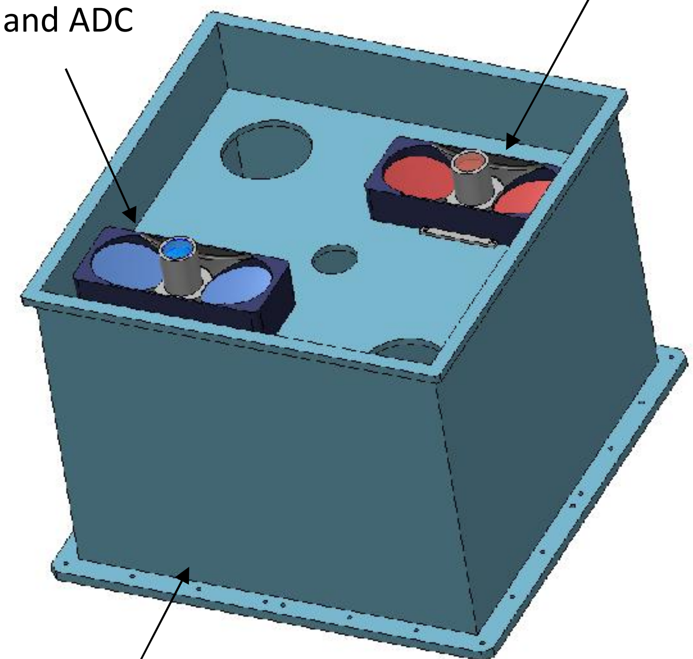
Mass: 1659 kg (Without Ballast)
CG (X, Y, Z): -2.6 mm, 38 mm, - 1095 mm

Mass: 2002 kg (With Mass Towers)
CG (X, Y, Z): -2.2 mm, 31 mm, - 994 mm

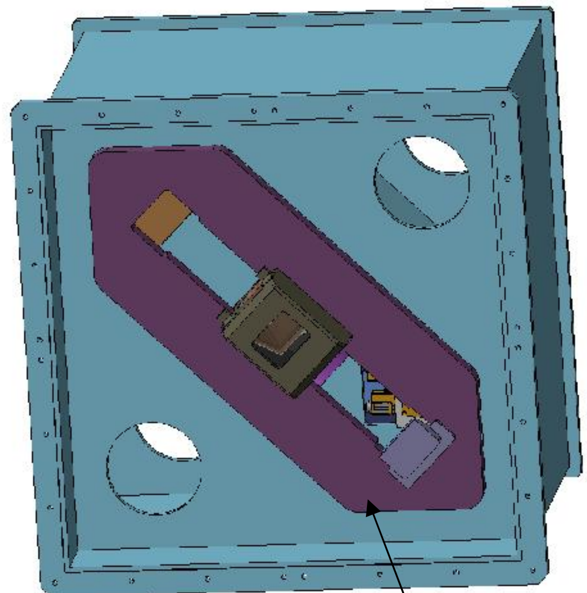
GMOX Cross-Section



Lower Bench

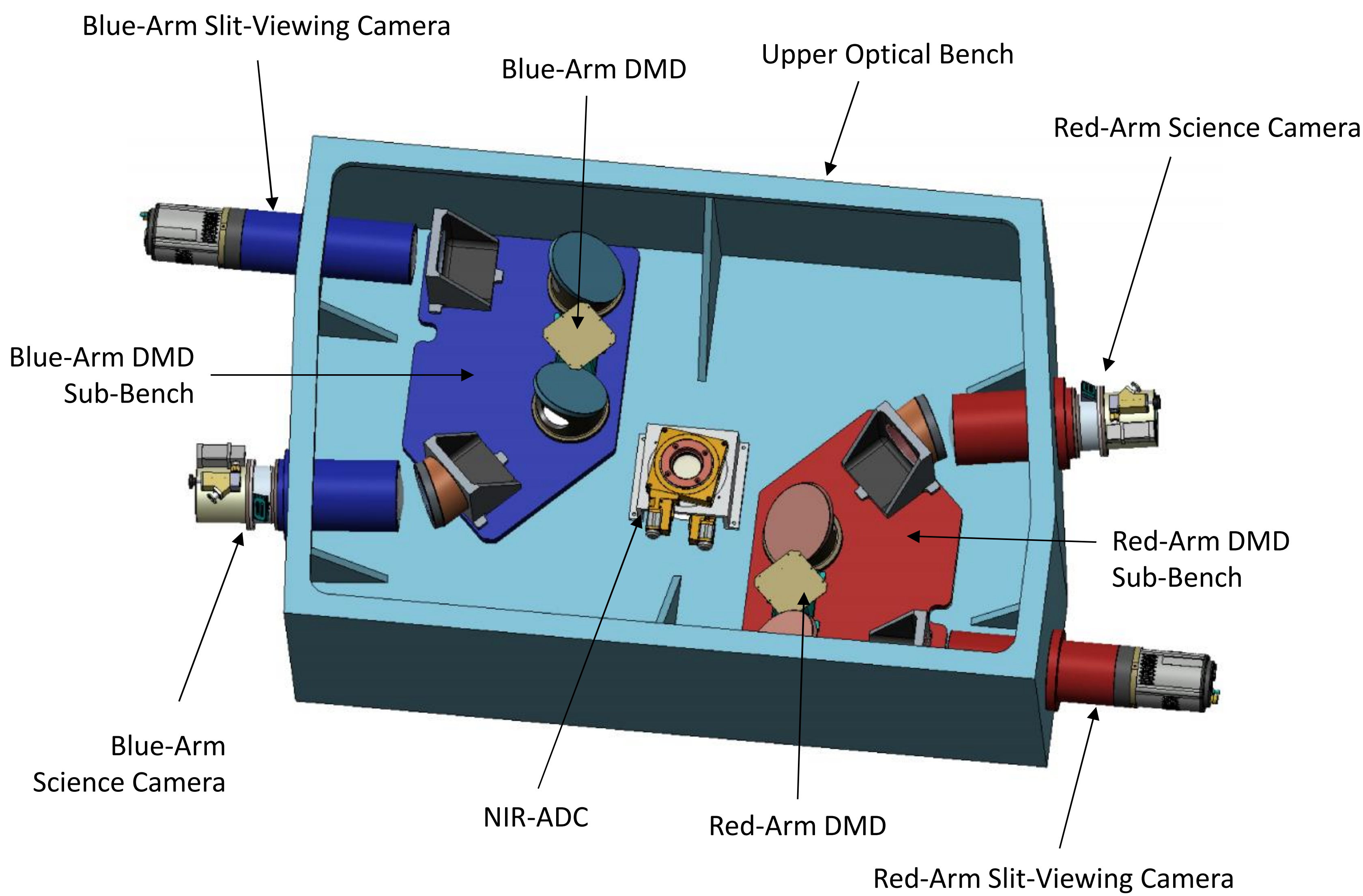


Blue-Arm Schmidt Mirror Mount, Re-imager, and ADC
Red-Arm Schmidt Mirror Mount, Re-imager, and ADC
Lower Optical Bench



Fore-Optics Sub-Bench

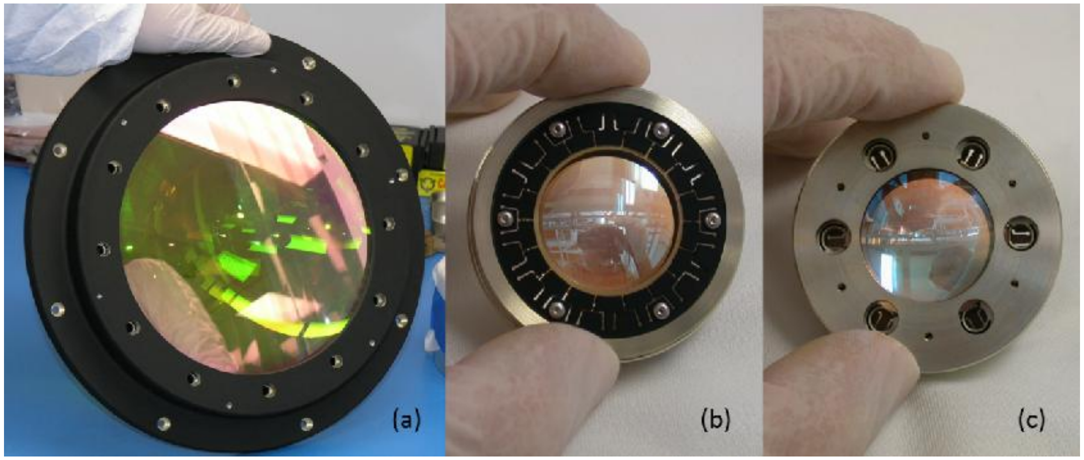
Upper Bench



Blue-Arm Slit-Viewing Camera
Blue-Arm DMD
Upper Optical Bench
Red-Arm Science Camera
Blue-Arm DMD
Sub-Bench
Red-Arm DMD
Sub-Bench
Blue-Arm
Science Camera
NIR-ADC
Red-Arm DMD
Red-Arm Slit-Viewing Camera

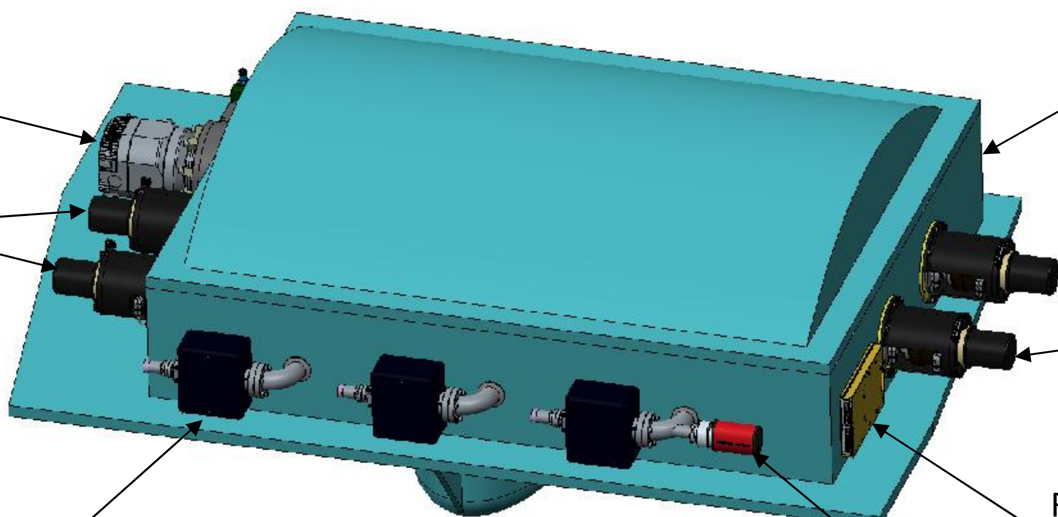
Optical Mounts

- **GMOX contains both refractive and reflective optics**
  - Modest size, 200 mm or less
- **Optics are packaged in logical units to aid assembly, alignment, and verification**
- **As a rule, optics are mounted by dead-reckoning, i.e. without adjustment**
  - Nominal shims are used for one-time adjustments where manufacturing tolerance stackup exceeds placement tolerances.
- **Lens mounts in the visible arms would likely be athermal designs**
- **Lens mounts in the NIR arm would utilize flexures to accommodate the thermal excursion and differential CTE**

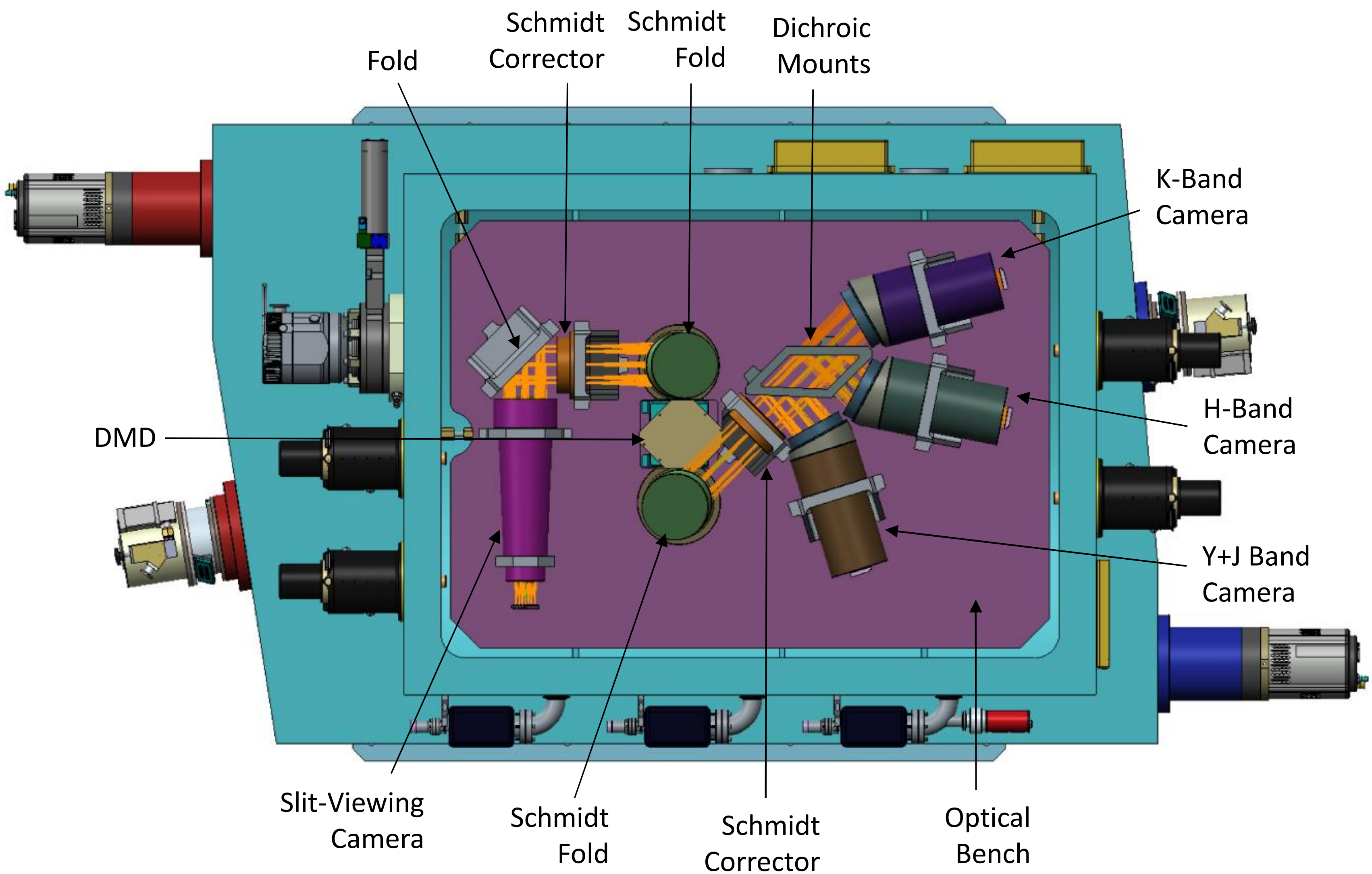


NIR Cryostat

- **The NIR cryostat houses all the optics in the near infrared arm**
- **Rectangular form factor**
- **6061-T6 welded construction**
- **70 mm diameter window**
- **Coolers, pumps, and feedthroughs populated the sidewalls of the cryostat**
- **Pinned interface to the upper bench**



NIR Optomechanical Layout

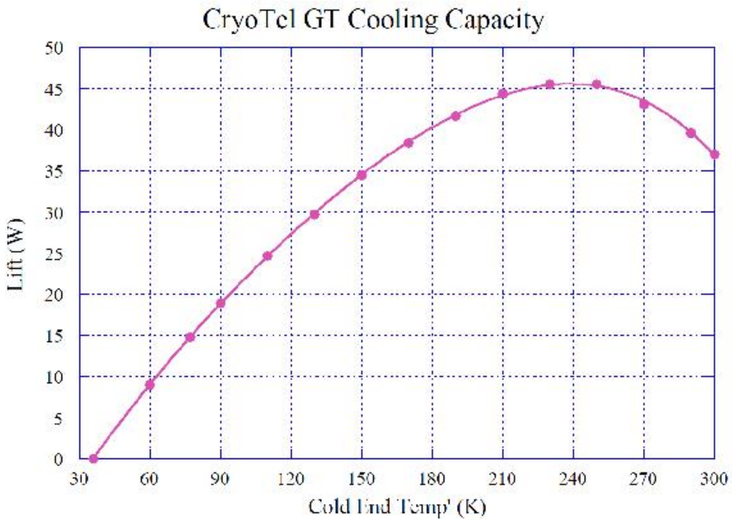


NIR Cryostat High-level Details

- **Vacuum System**
  - 500 liters.
  - Pumpdown with a dedicated 240 liter/sec turbo.
  - Steady-State pumping from three VacIon Plus 20 liter/sec ion pumps.
  - Monitor pressure using a Pfeiffer MPT 200 combination (Pirani/Cold Cathode).
- **Thermal Design**
  - Two thermal regimes.
    - » 120 K optical bench and optics.
    - » 77 K detector operation.
  - Two Sunpower Cryotel GTs cool the bench and optics.
    - » Heat load expected to be of order 15 W.
    - » Each cooler is capable of 22 W lift at 105 K .
  - Two Sunpower Cryotel CTs cool the detectors.
    - » One for J,H,K science detectors.
    - » One for the slit-viewing detector.
    - » Lift is 11 W per cooler at 77 K.
    - » Coolers would run at fractional power to further minimize vibration.

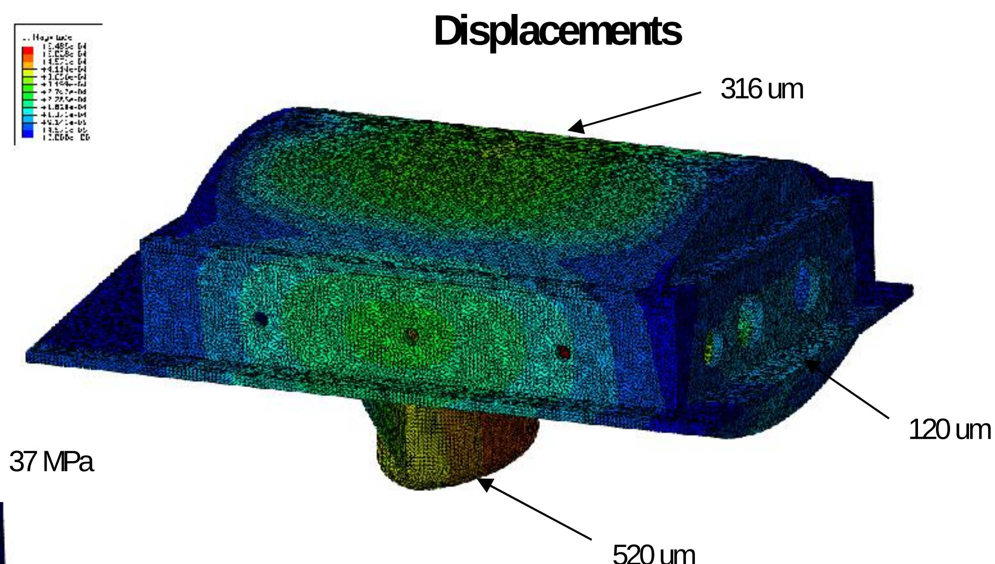
Sunpower Cryotel GT

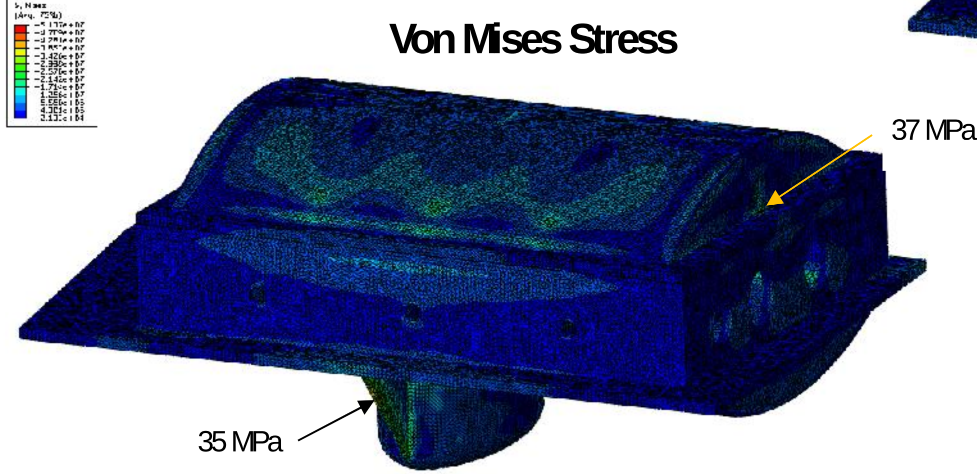
- **Free piston Stirling cycle cooler**
- **16 W lift at 77K at full power**
- **240 W dissipation removed by glycol/water**
- **Active damping control significantly reduces vibration**
  - on-axis: ~ 3 mG at full power (measured at the rear of the unit)
  - off-axis: ~ 100 mG at full power (measured at the rear of the unit)
- **MTBF in excess of 100,000 hrs (Barry Penswick 2008)**
- **Significant heritage with the Prime Focus Spectrograph cameras**



Cryostat Structural Analysis

- **Structural design guided by finite element analysis**
- **6061 aluminum weldment**
  - Thick walls (25 mm)
  - Thin, rolled lid and bottom (12 mm)
    - » Gussets stiffen these structures, and in the base provide mount points for the bench.





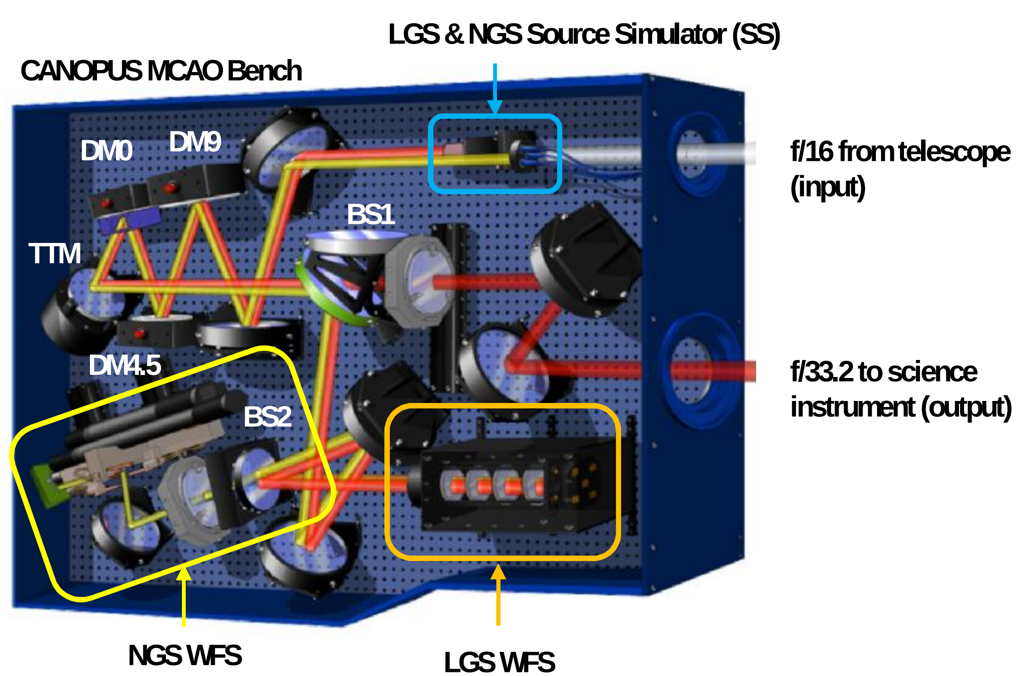
ASME code allowable stress in weld region is 55 MPa, and 100 MPa in non-welded regions.

AO & Instrument Software

Stephen Smee

GeMS Adaptive Optics

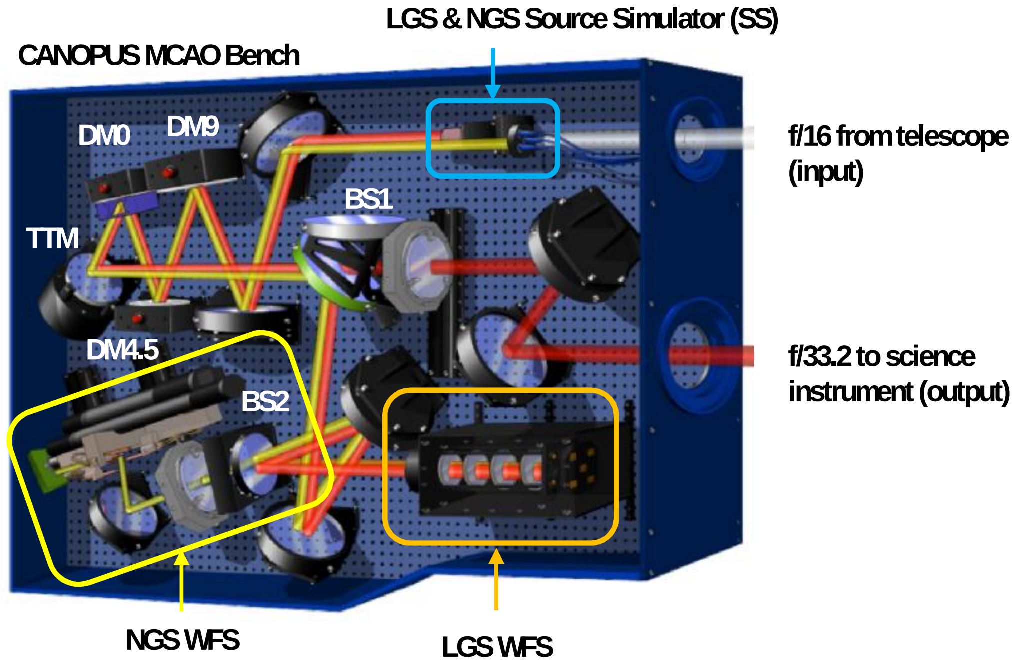
- **GeMS is the multi-conjugate adaptive optics system for Gemini South**
  - Five laser beacons
  - Three natural guide star probes
  - 0.8 um < λ < 2.4 um
  - Port 4 of the ISS
  - Transfers f/16 native beam to f/33.2, which feeds the science instruments



Rigaut et al. Mon. Not. R. Astron. Soc. 000 1-17 (2013)

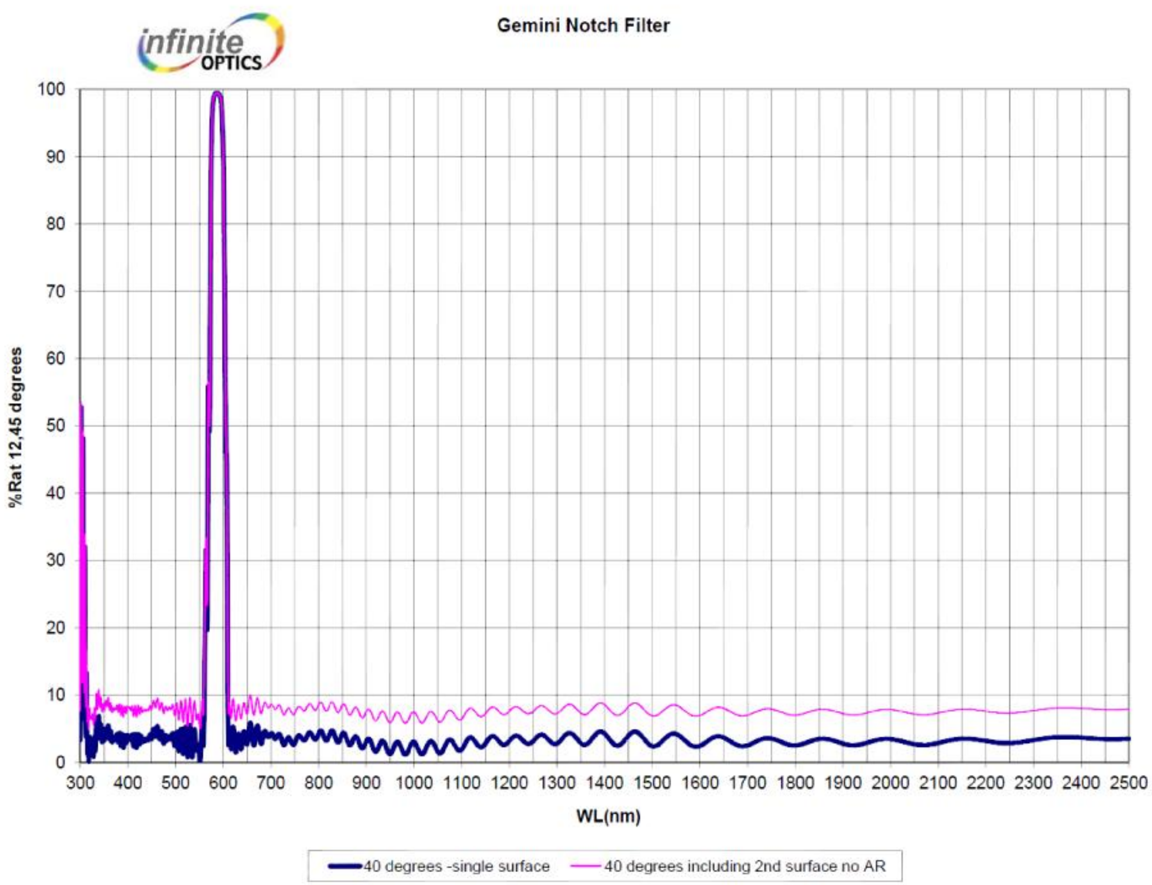
GMOX Compatibility with GeMS

- **Compatibility considerations for GMOX with GeMS**
  - Primary issue: GeMS uses visible light for NGS loop
    - » The use of a notch dichroic fixes this
      - Install in secondary location of BS1 turret
  - Secondary issue: If GMOX takes the visible light the NGS loop is lost
    - » NGS loop provides feedback for tip/tilt/focus and scale correction
    - » GMOX would have to provide tip/tilt and scale correction input
    - » Acquisition and Guiding unit could provide slow focus feedback



Notch Dichroic

- **To allow visible light into GMOX we would replace the secondary beam splitter at station BS1 with a notch dichroic**
  - The secondary beam splitter is currently not used
  - The primary beam splitter would be used for non-GMOX observations



Tip/Tilt Feedback to the RTC [1 of 2]

- **GMOX must provide tip/tilt feedback to the RTC**
  - Three guide star centroids from the slit-viewing camera
    - » Presently we could do this from either the blue, red, or NIR arms
  - Feedback from three guide stars is required
  - High data rate required: ~ 400 fps
  - Low latency is required: ~ 2.5 ms
- **Feedback from the visible arms provided by Andor 4k x 4k sCMOS sensors**
  - Based on a sensor built for DKIST
  - Low read noise: < 3 e- target
  - High QE: ~80% (back illuminated)
  - Frame rate, full resolution: 80 fps
    - » 1k x 4k frame rate: 320 fps
    - » Three 20 x 4k sub-region frame rate: ~ 4400 fps
  - Latency: ~ 40 µs delay in row read + read time + processing time
    - » Processing time is TBD
      - Could use DSP for centroid calculation

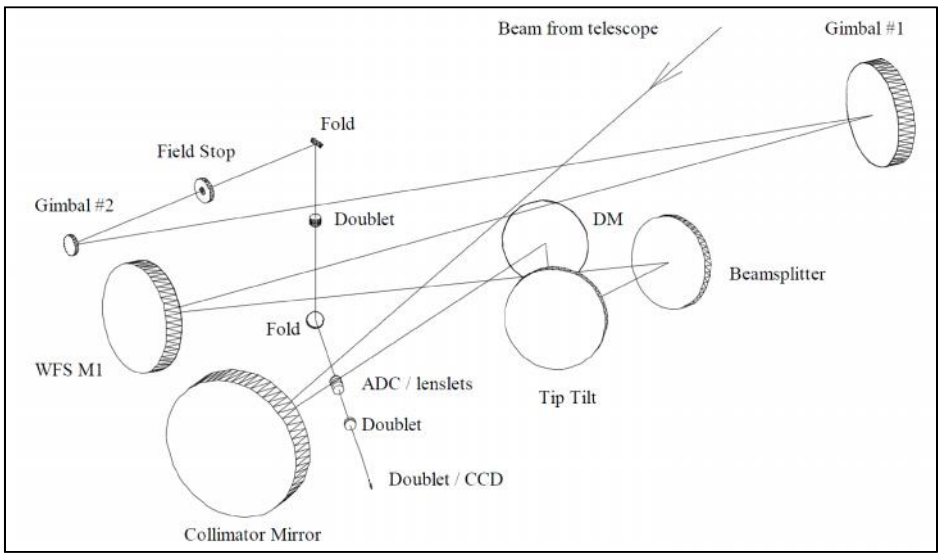
Tip/Tilt Feedback to the RTC [2 of 2]

- **Feedback from the NIR arm provided by H2RG**
  - Read noise: ~ 15 e-
  - High QE: ~80%
  - Frame rate, 3X sub-windows (10 x 10): ~384 fps
    - » ASIC readout with custom code
    - » Read-reset-read cadence
    - » 400 kHz read rate
  - Latency: ~ 30 µs + read time + processing time
    - » Centroid calculated by the SAM FPGA (M. Loose)
      - Would require customization

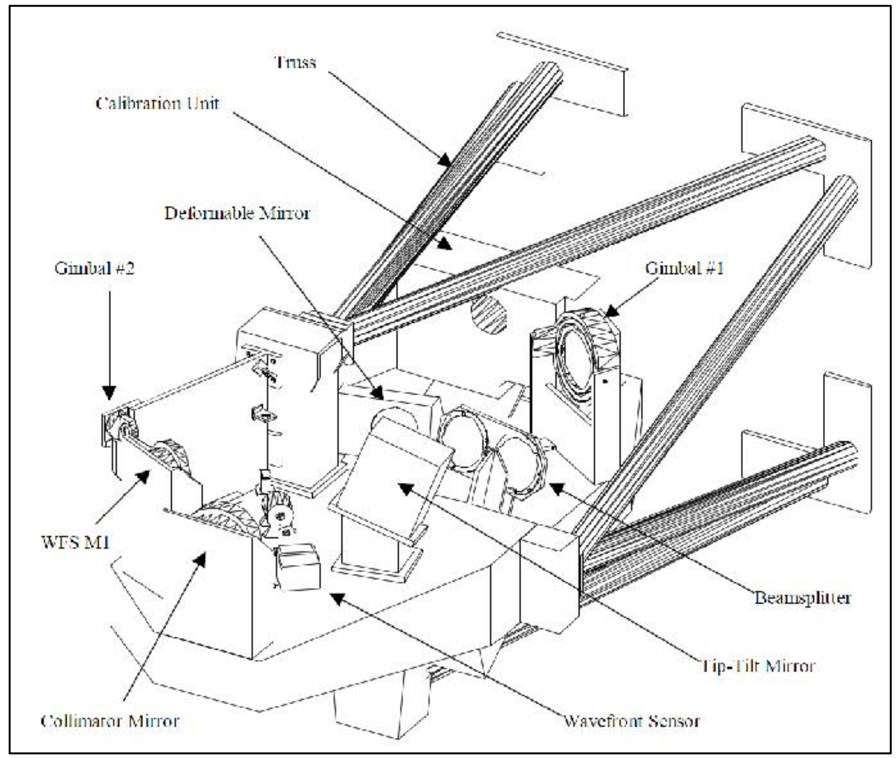
GMOX with Altair

- **Altair is the facility adaptive optics system for Gemini North**
  - Single laser guide star conjugate to ground
  - Suite of natural guide stars
  - 1.0 um < λ < 2.5 um
  - Port 4 of the ISS
  - f/16 input beam is preserved

Altair NGS WFS Optics



Altair Bench



GMOX Compatibility with Altair

- **Same issue as with GMOX on GeMS**
  - Visible light is used by Altair for the NGS loop
  - The use of a notch dichroic alters the functionality of Altair
  - The NGS loop is lost if visible light goes to GMOX
- **Solution**
  - Use a notch dichroic to pass visible light to GMOX
    - » The two-position beam-splitter mechanism provides a convenient location to install it, without impacting the present operating mode of Altair
    - » LGS loop preserved
  - Use the peripheral wavefront sensor (PWFS) to provide tip/tilt/focus correction

Software Function [1 of 2]

- **GMOX instrument control software would be divided into two separate systems**
  - Instrument control
  - Detector readout and DMD control
- **Instrument Control Software**
  - Monitor health of the instrument
    - » Temperatures
    - » Cryotat vacuum
    - » Camera dewar vacuum
    - » …
  - Control
    - » ADCs
    - » Shutter
    - » Active flexure compensation (if required)
    - » Pumps
    - » Calibration sources
    - » …

Software Function [2 of 2]

- **Detector readout and DMD control software**
  - Initialize exposures
  - Process flats and calibration frames
  - Process science images
  - Provide quick-look tools
  - Process slit-viewing images
  - Process target selection and slit-mapping
  - …
- **Compliant with Gemini queue observing and software interface**

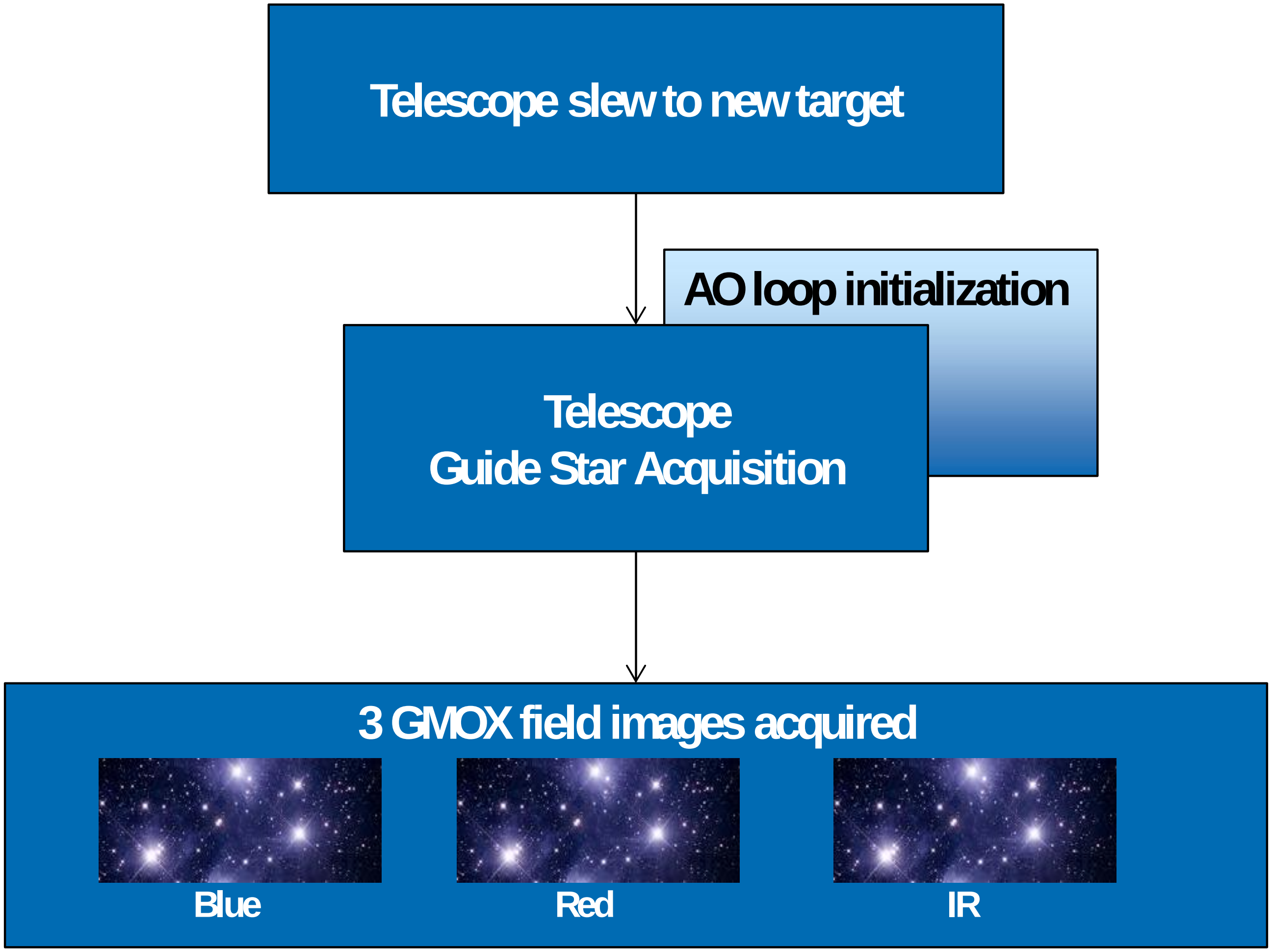
Instrument Software Architecture

- **The GMOX instrument control software would be divided into four main components**
  - A command and telemetry database
    - » Located on a computer in instrument rack
    - » Self-contained Microsoft SQL Server database
    - » Repository for device configuration and system parameter storage
  - A server application
    - » Multi-threaded application reads and routes commands from the command table
    - » Provides critical health and safety monitoring of instrument hardware
    - » Processes incoming UDP telemetry data
  - A Web application
    - » GUI for executing commands and monitoring telemetry
  - Firmware
    - » Device specific code localized with the hardware

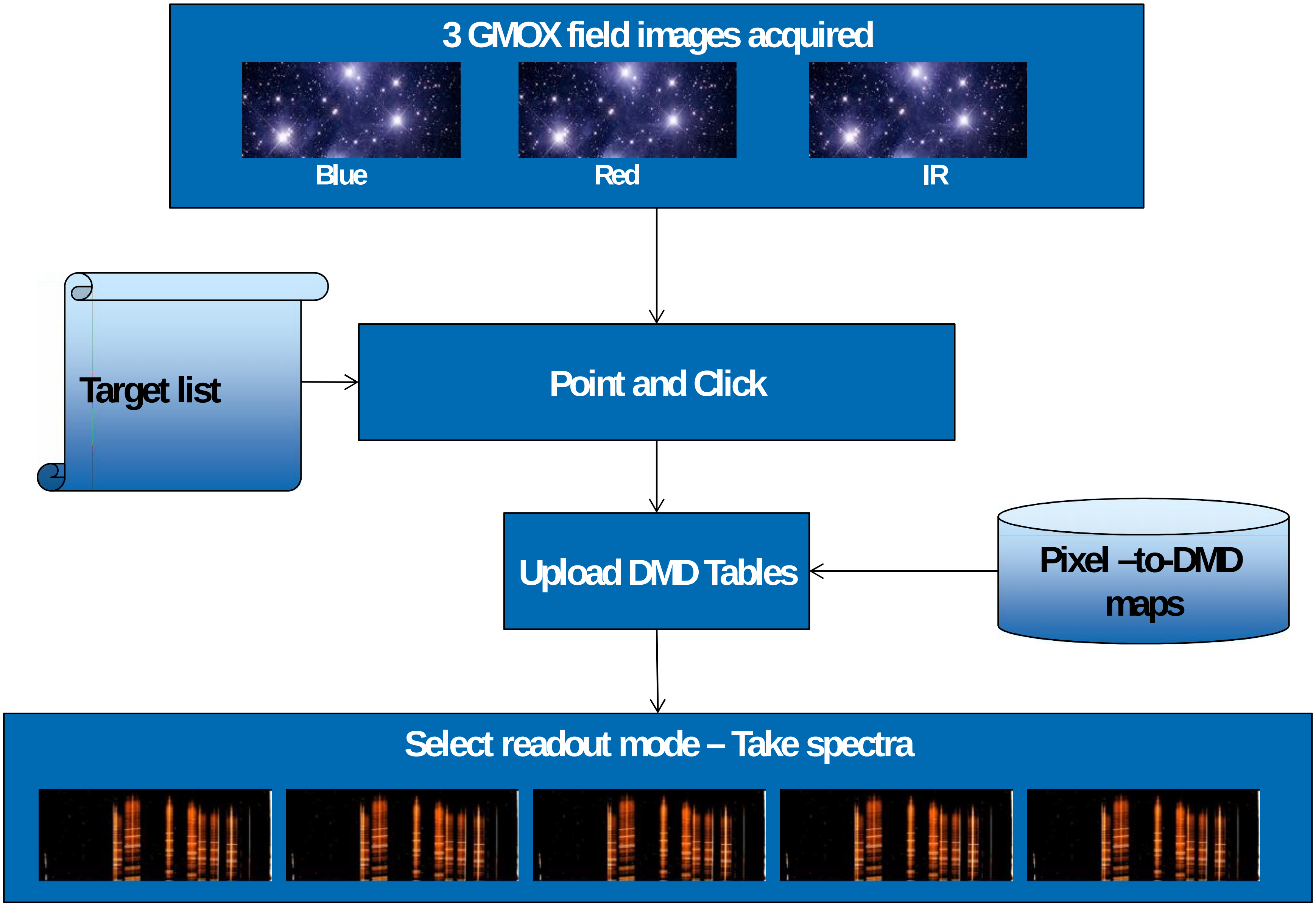
Part 4

CONCEPT OF OPERATIONS

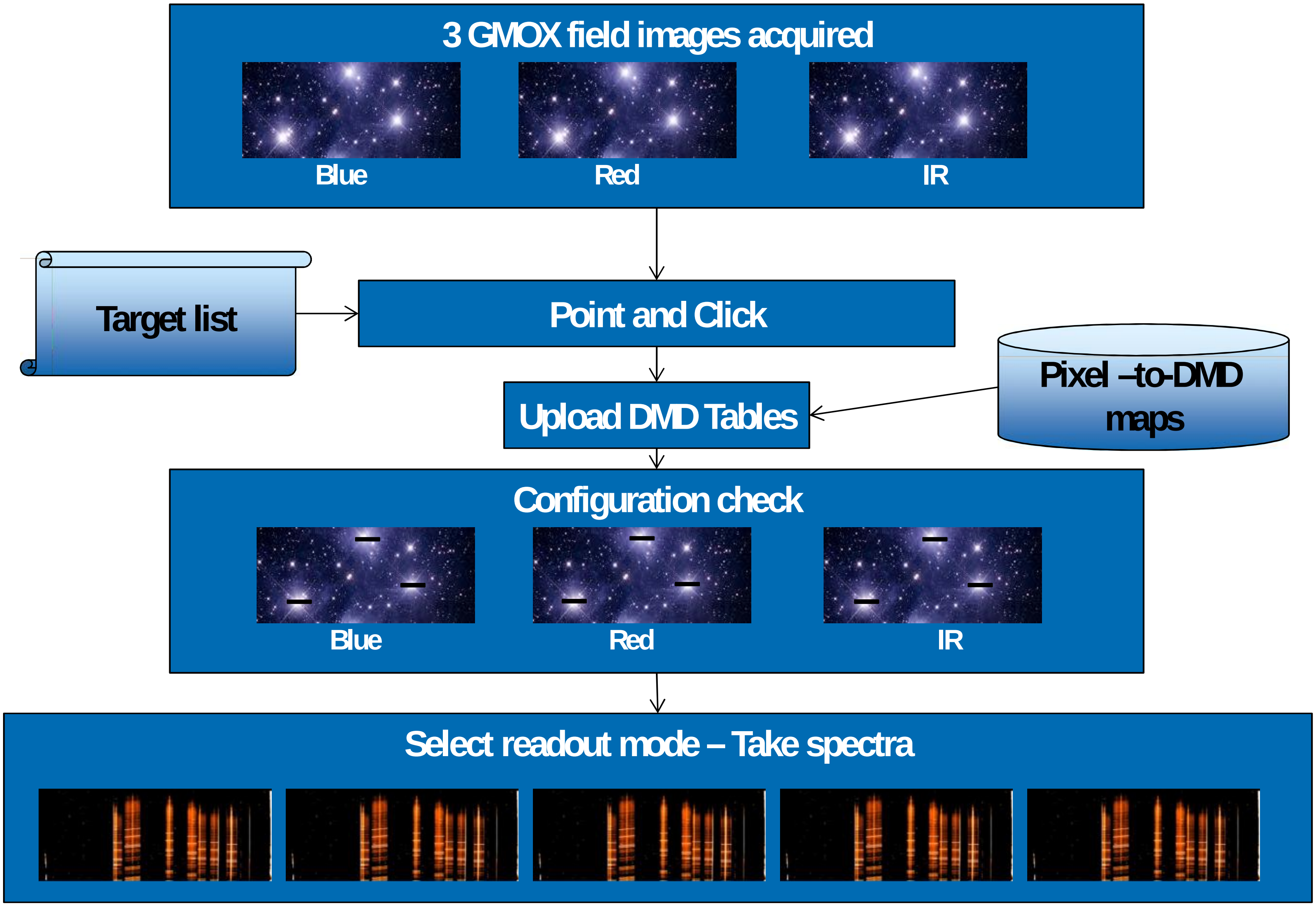
1) Initial Set-up



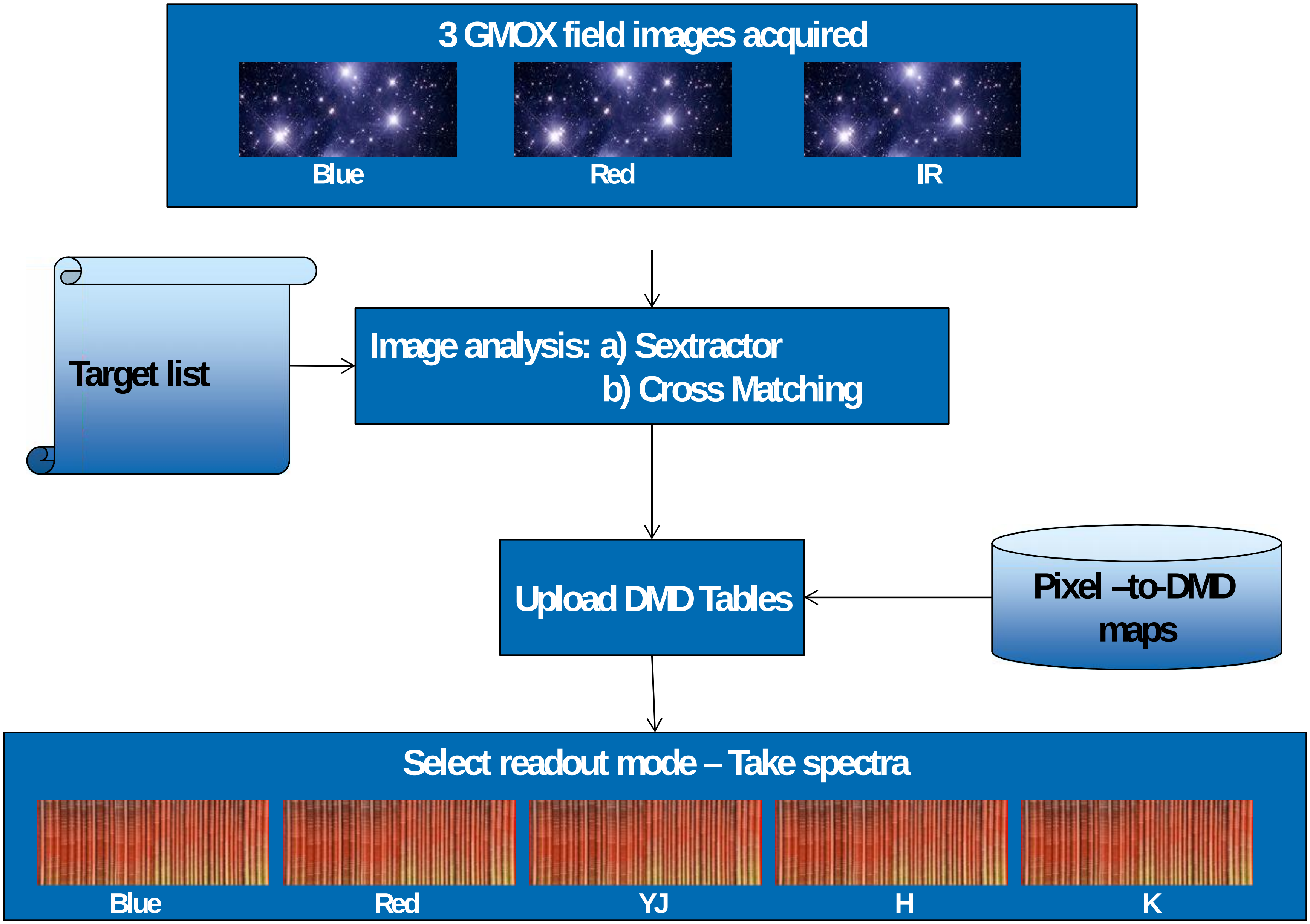
2) Point and click



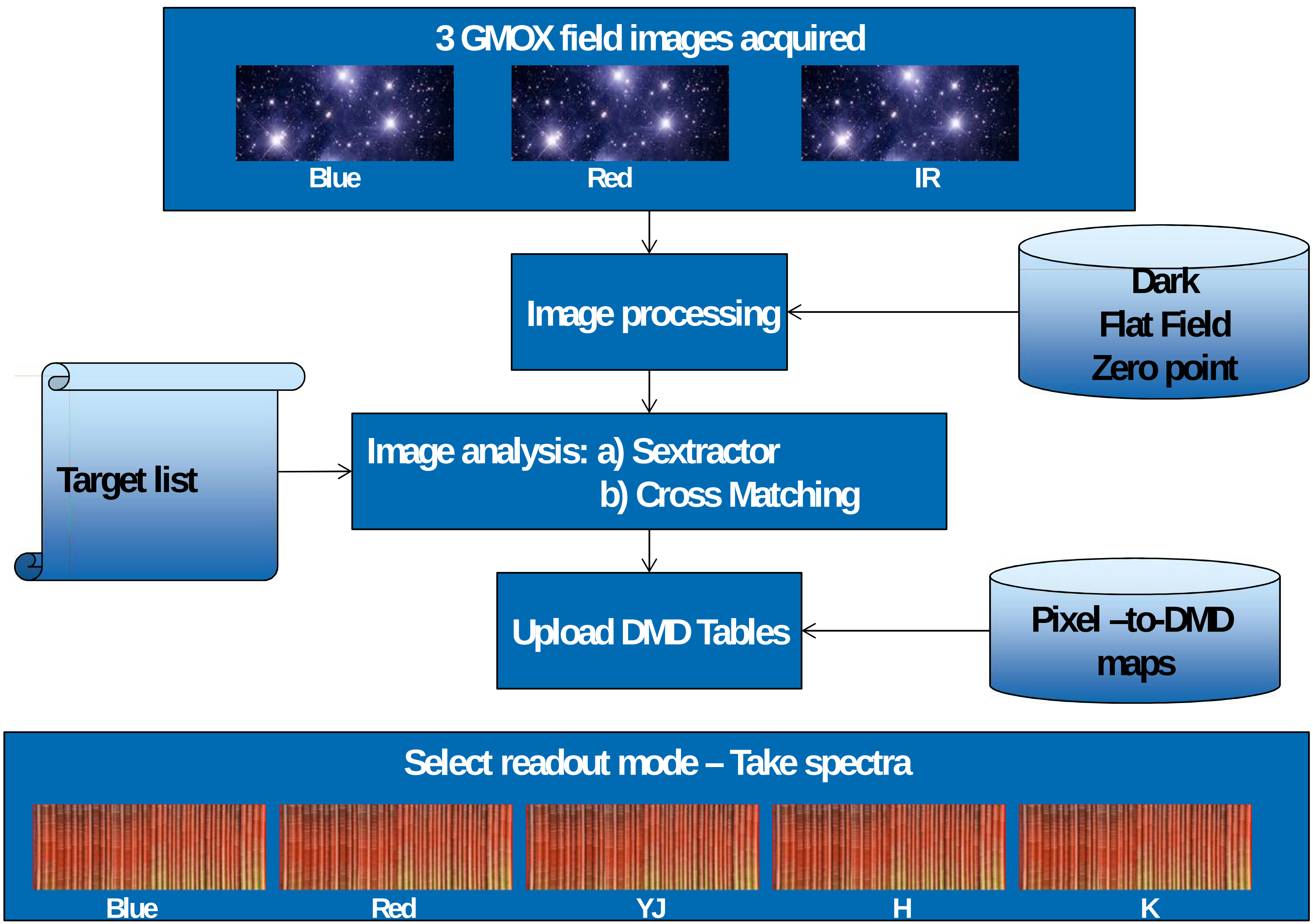
3) Add configuration check



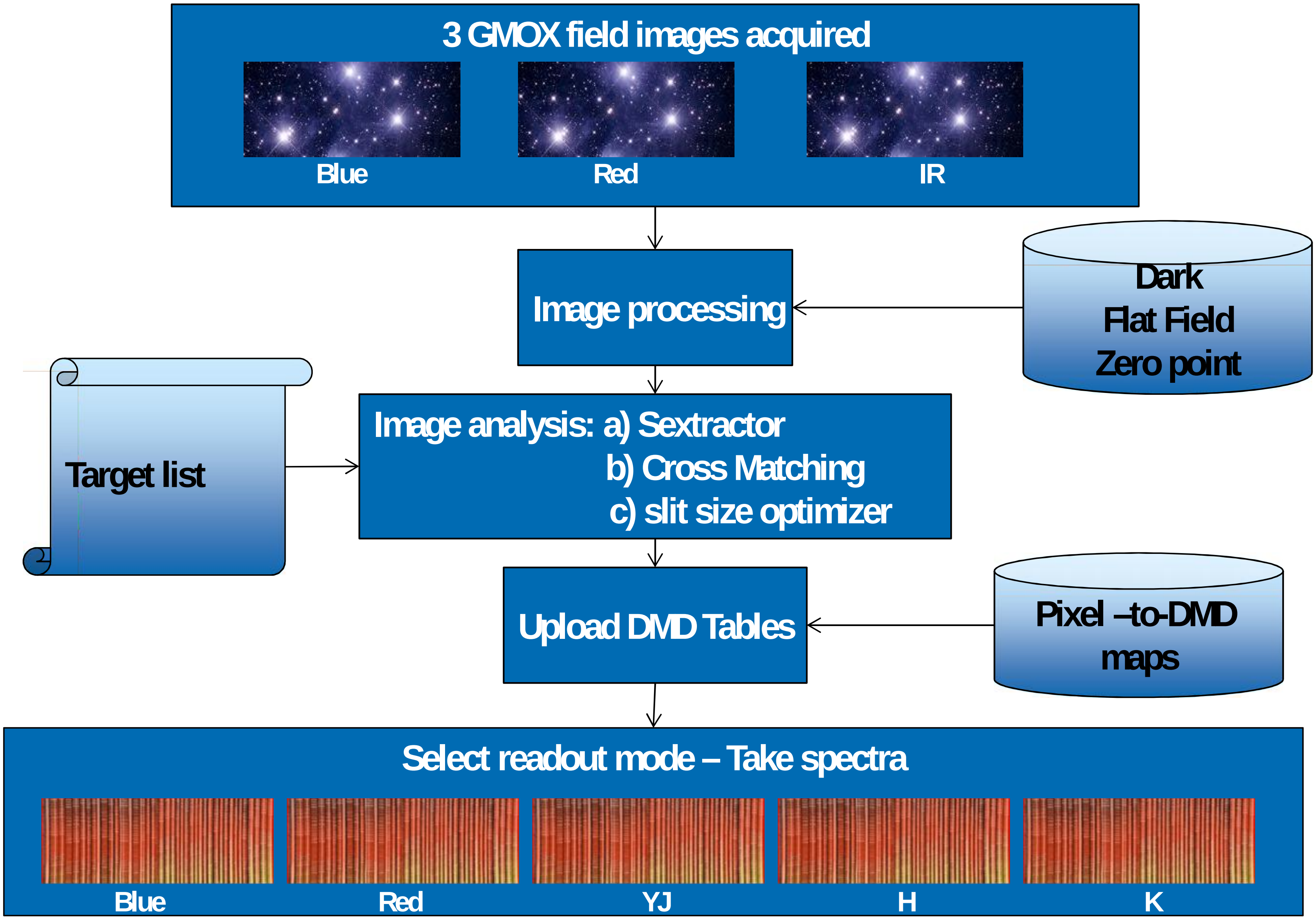
4) Target list



5) Target list – faint sources



6) Target list – optimal slits (AO)

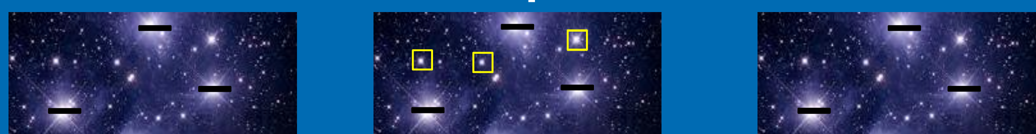


7) Imaging channels

Slit viewing mode

Blue Red IR

Tip-tilt

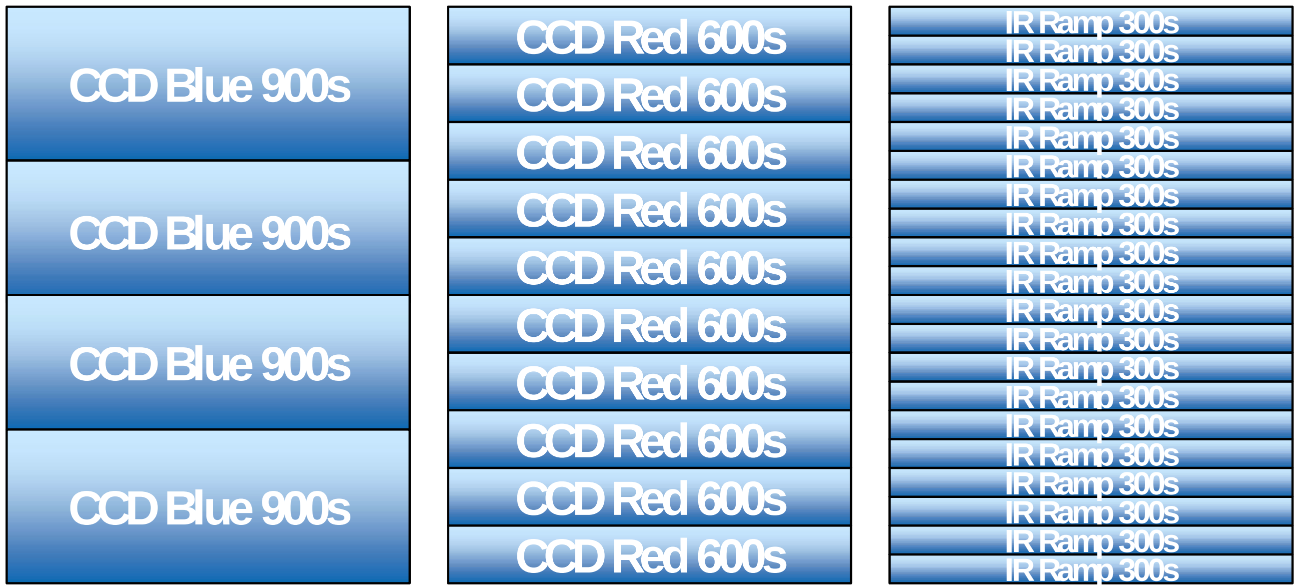


Blue Red IR

Deep imaging

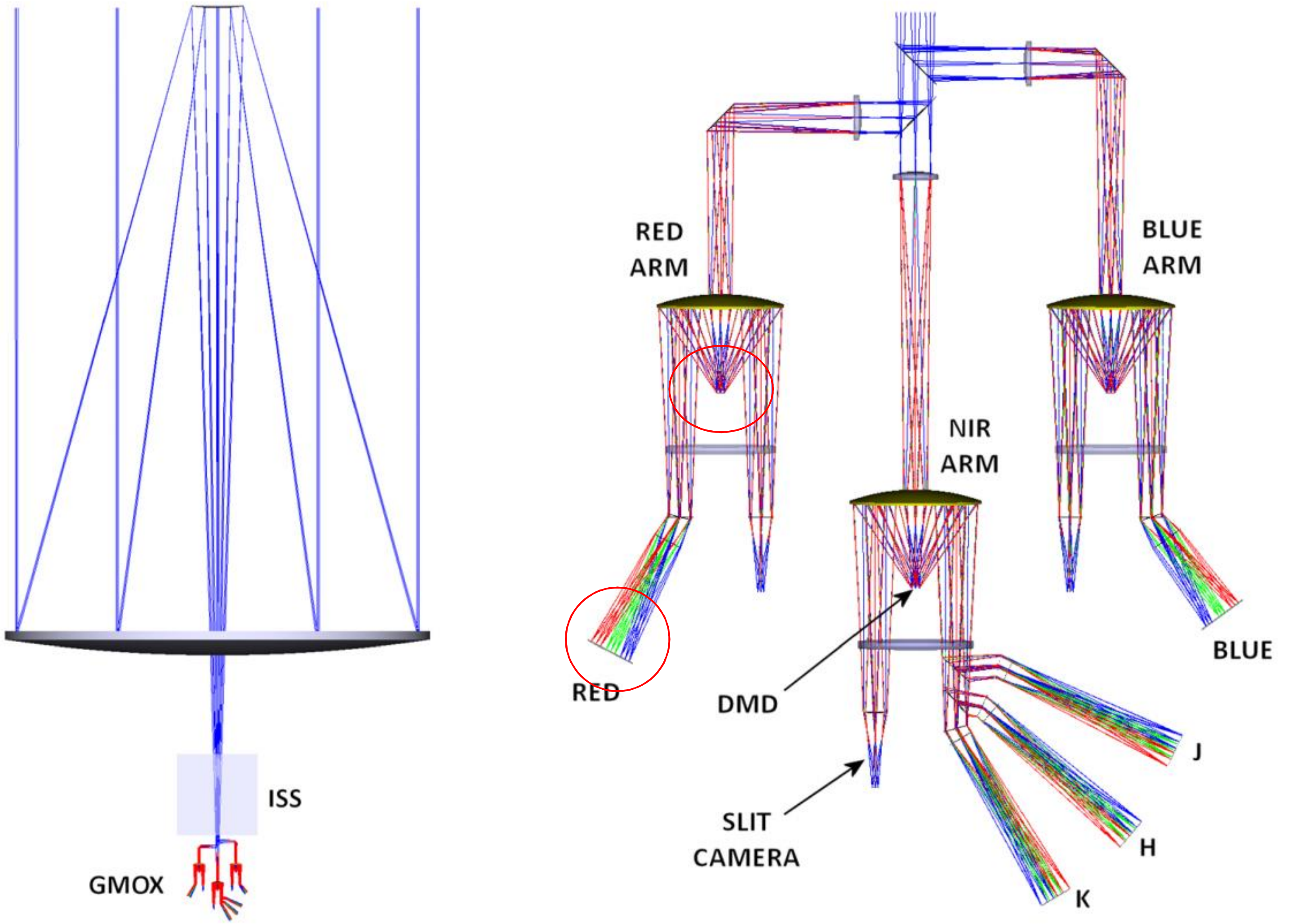
Blue Red IR

Nested Science Exposures



Also accounting for dithering moves

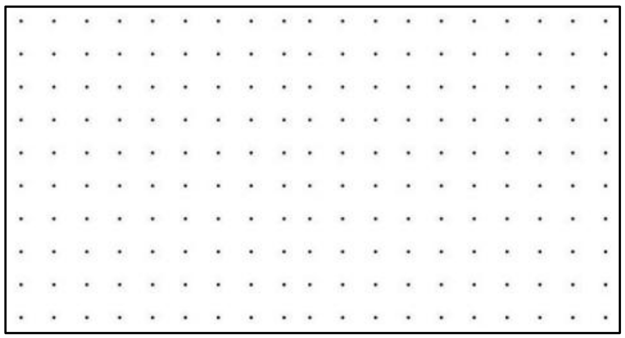
Calibration – 1) Detector on DMD



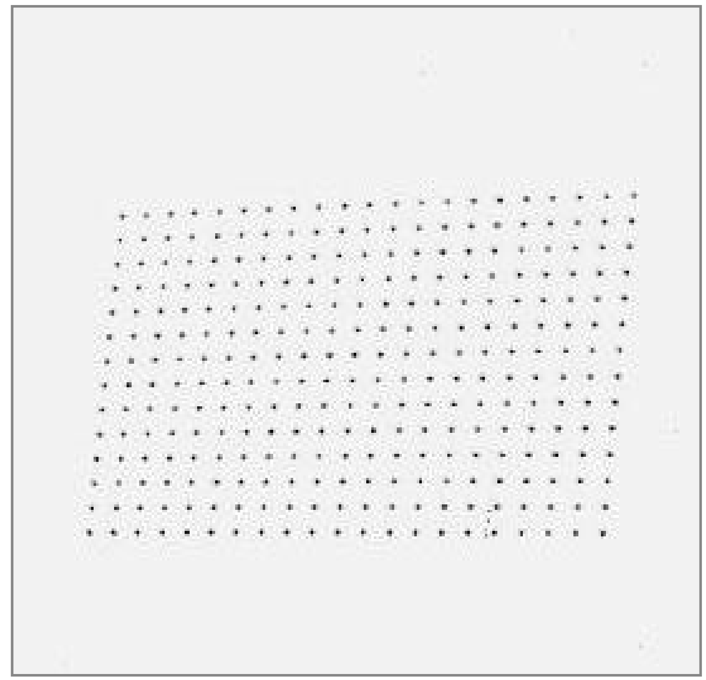
Optical layouts of a preliminary concept for GMOX. (a) GMOX on Gemini, shown beneath an ISS-sized cube for scale. (b) Schematic of a 3-arm arrangement for GMOX.

Grid on DMD – Grid on Detector

Three maps, one for each DMD-imager pair



DMD plane



Detector plane

Frequency: sporadic (every few months)

2) DMD on sky

- Point astrometric field to derive WCS of each channel

Frequency: sporadic (every few months)

Note: this enables to map each DMD on each Detector, and viceversa

3) Other calibration files

- **Bad pixel masks, for all 8 detectors**
- **Darks, for all 8 detectors**
- **Flat field for the 3 imaging detectors**

-=> Day-time, sporadic

Spectroscopic Calibration:

- **Flat fields can be taken during day time for each DMD pattern**
    - **Eventually, a library can be built to generate flat field by interpolation/model. JWST/NIRSPEC strategy.**

-=> Day-time, end of night

- **Dispersion Calibration: same as spectroscopic flat fields**

-=> Day-time, end of night

-- Telluric correction (Red and IR only)

-Follow standard procedure, a few stars/night.

-Fotometric Calibration:

-Imaging channel with suit of filters can provide absolute spectrophotometry.

Calibration summary

Calibration Step	Method	Frequency (minimum)	Frequency (goal)
GMOX geometry: DMD vs Detector	Cal. Flat Field on DMD grid	Every week	Every few months
Astrometry: DMD vs Sky	Astrometric Field	Every month	Every year
Spectroscopy: Flat Fields	Cal. Flat Field on DMD pattern	End of night/daytime	Every week
Spectroscopy: Dispersion solution	Cal. Arcs on DMD pattern	End of night/daytime	Every week
Spectroscopy: telluric correction	Telluric standard stars	2-3 times per night	2-3 times per night
All detectors: dark and bad-pixel map	Dark shutter	Every week	Every few months
Imaging Detectors: Flat Field	Cal. Flat Field	End of night/daytime	Every week

Concept of operations

- **GMOX is a versatile instrument that can rapidly adapt to any type of observing conditions.**
- **We consider three representative cases, that may be encountered even on the same night.**
  - 1) Poor seeing
    - » ~30% of the nights the V-band seeing is > 0.8”
  - 2) Good seeing
    - » ~50% of the nights the V-band seeing is between 0.8” and 0.4”
  - 3) Excellent seeing
    - » 20% of the nights the V-band seeing is better than 0.4”
- **As the seeing improves, IR channel becomes “primary” driving science and observing strategy.**

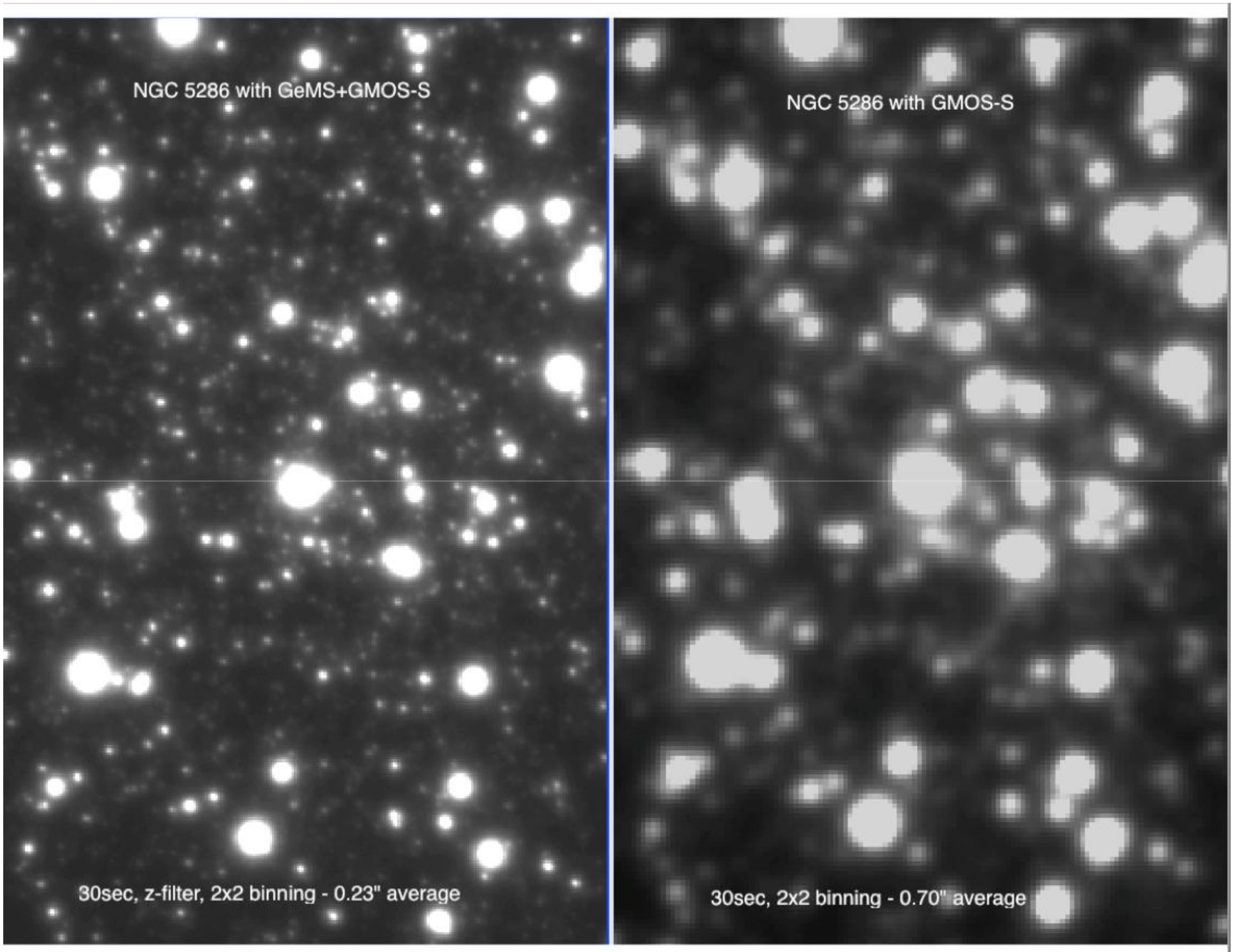
GMOX Versatility

Slit width (arcsec)	Blue		Red		IR	
	R(l/Dl)	Pix/slit	R(l/Dl)	Pix/slit	R(l/Dl)	Pix/slit
0.083	22500	0.60	18000	0.75	13500	0.92
0.167	11250	1.20	9000	1.50	6750	1.83
0.250	7500	1.80	6000	2.25	4500	2.75
0.333	5625	2.40	4500	3.00	3375	3.67
0.417	4500	3.00	3600	3.75	3700	4.58
0.500	3750	3.60	3000	4.50	2250	5.50
0.583	3214	4.20	2571	5.25	1929	6.42
0.667	2812	4.80	2250	6.00	1687	7.33
0.750	2500	5.40	2000	6.75	1500	8.25
0.833	2250	6.00	1800	7.5	1350	9.17
0.917	2045	6.60	1636	8.25	1227	10.1
1.000	1875	7.20	1500	9.00	1125	11.0

Poor seeing

- **No AO**
  - (and no AO throughput losses)
- **GMOX operates at R~2000**
  - Blue channel: 1” slit => R=2028
  - Red channel: 0.85” slit => R=1960
  - IR channel: 0.7” slit => R=1785
- **Relatively minor impact on Blue-red range**
  - Stellar spectroscopy
  - QSOs
  - LSST transients follow-up
- **Use narrow slits/high spectral resolution on bright objects**
  - MW bulge and halo
- **Bright time: IR prime**
  - PMS objects
  - Bright, high-z QSOs

Sorry, no AO tonight…



From http://www.gemini.edu/science/public/gnao2012/Program_files/gnao2012_Neichel-Intro%20to%20GeMS.pdf

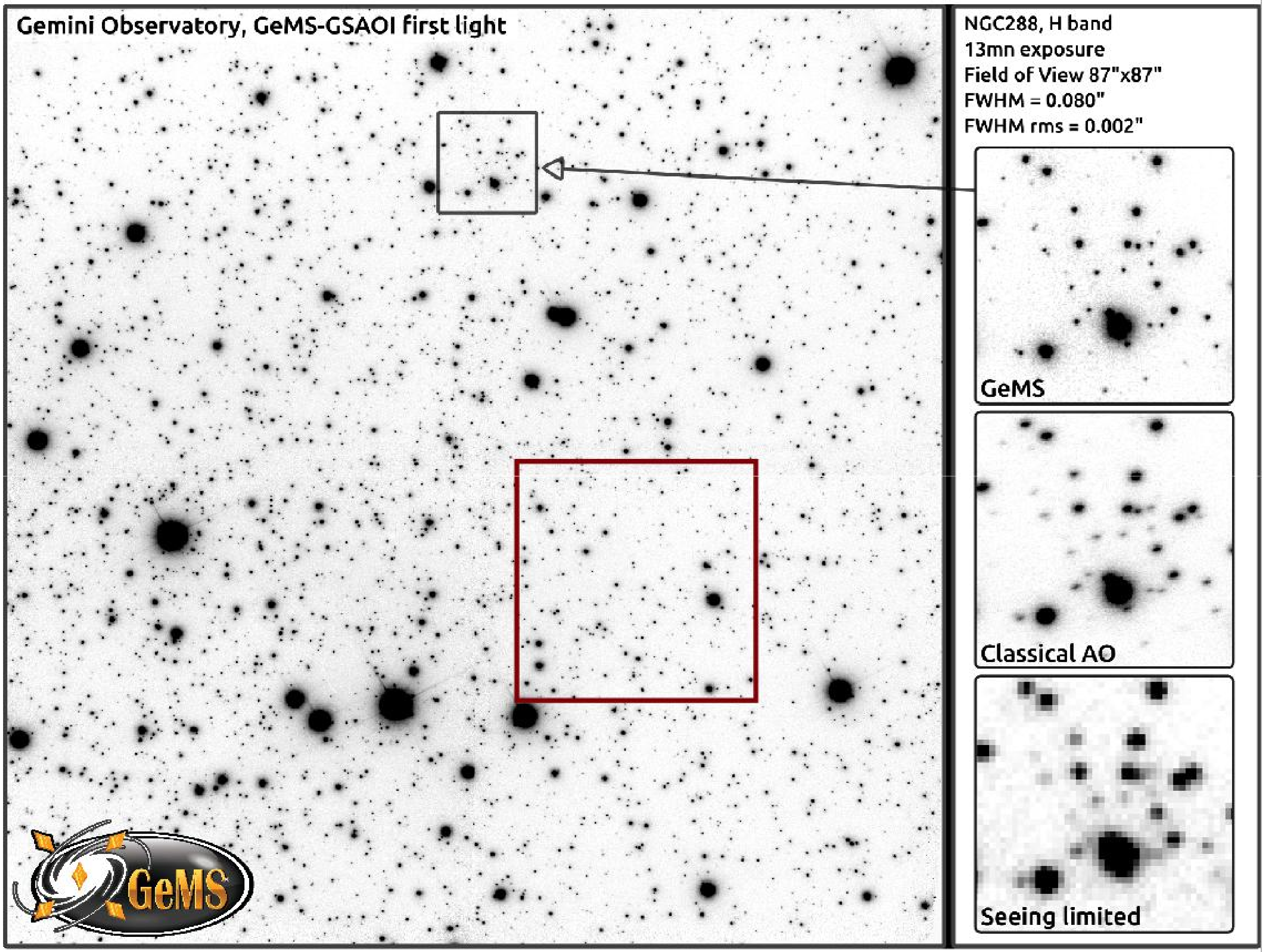
Good seeing

- **Partial AO Correction**
  - Ground Layer correction: PSF reduces by 1/2-1/3
  - Altair with field corrector for wide field coverage
  - LGAO without tip-tilt: 0.2” FWHM with 100% sky coverage
- **Typical observing conditions at Gemini (2022!)**
  - GMOX baseline is tuned for this regime: R~5000, 3pixel/res.element.
- **Large majority of science programs can be carried out in these conditions**
  - Deep extragalactic fields
  - Everything else!

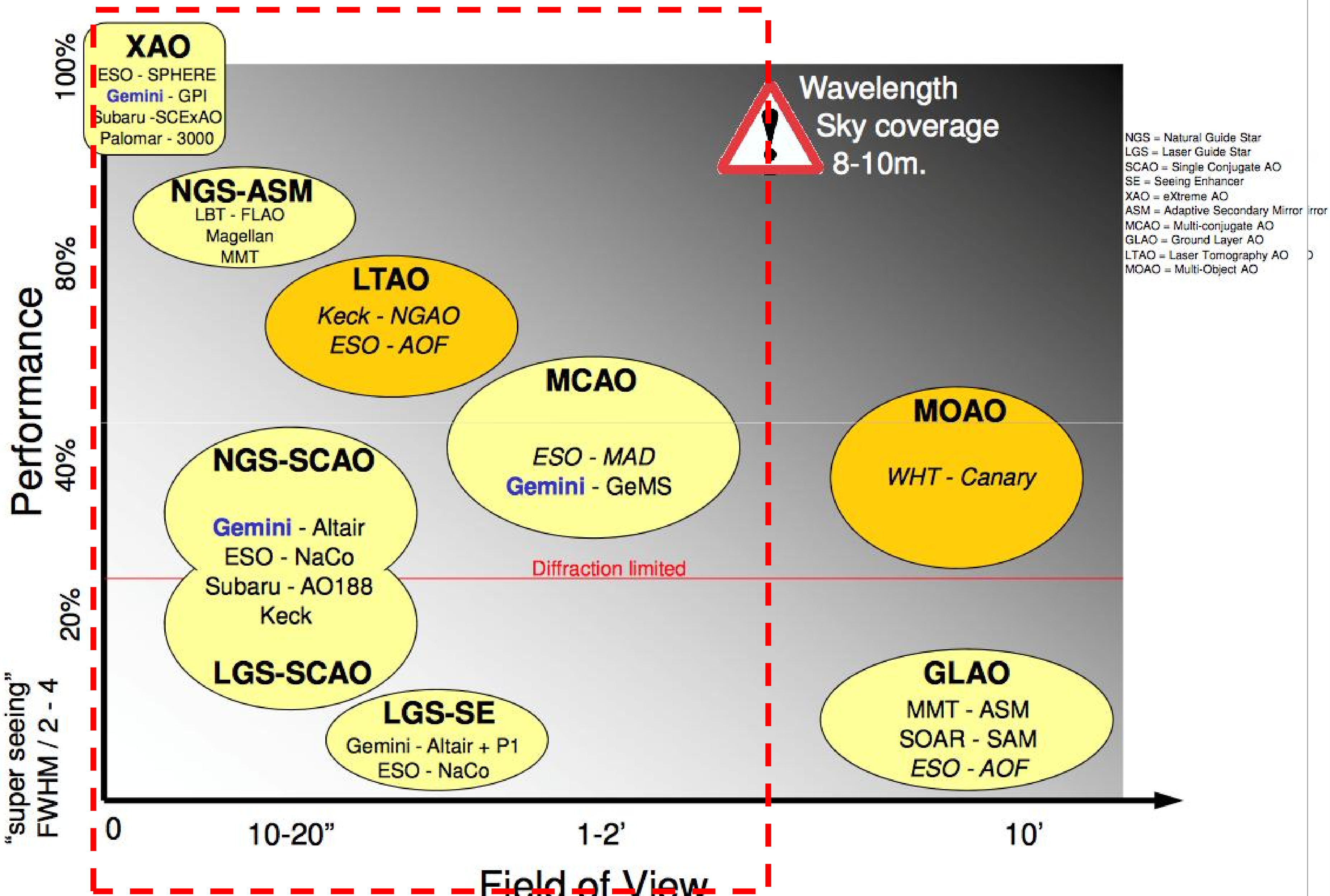
Excellent seeing

- **Extreme AO correction provides nearly diffraction limited images in the near-IR**
  - GEMS
  - Altair
- **GMOX can take full advantage of exceptional conditions (20% of the time) using slits as small as 83 mas at Gemini-N and 40m at Gemini-S**
- **Resolving power can increase above R=10,000**
- **Enable unique science cases because of gain in**
  - A) Sensitivity: primordial galaxies, low-mass stars, absorption features…
  - B) Spatial resolution: extremely crowded fields
    - » Galaxy Clusters
    - » Nearby Galaxies
    - » Galactic Bulge
    - » Galactic Center
    - » Globular Clusters
    - » Magellanic Clouds (Gemini-S only)

MCAO vs SCAO vs seeing-limited



What's your favorite AO flavor ?



From http://www.gemini.edu/science/public/gnao2012/Program_files/gnao2012_Neichel-Intro%20to%20GeMS.pdf