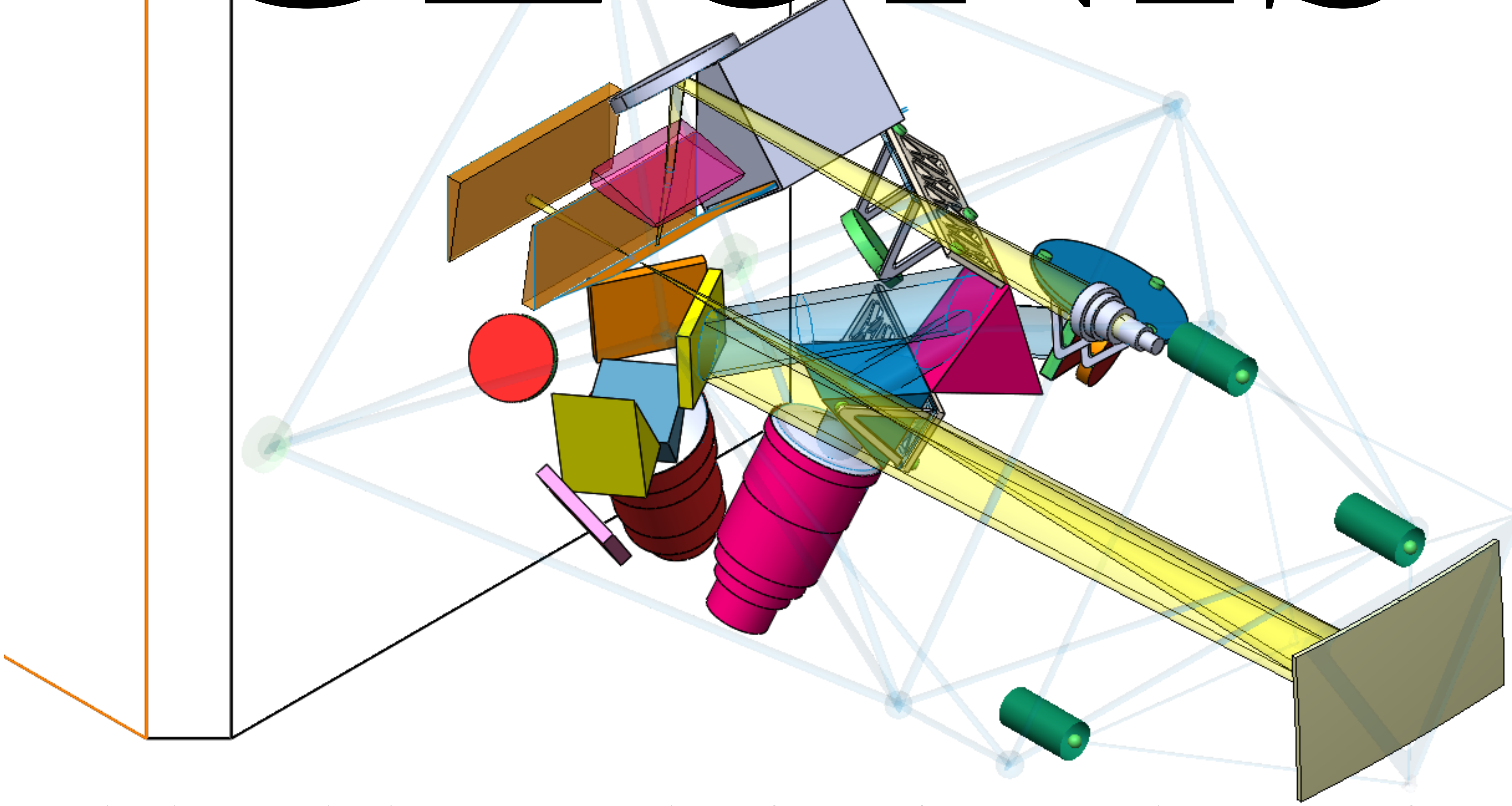
GEONIS



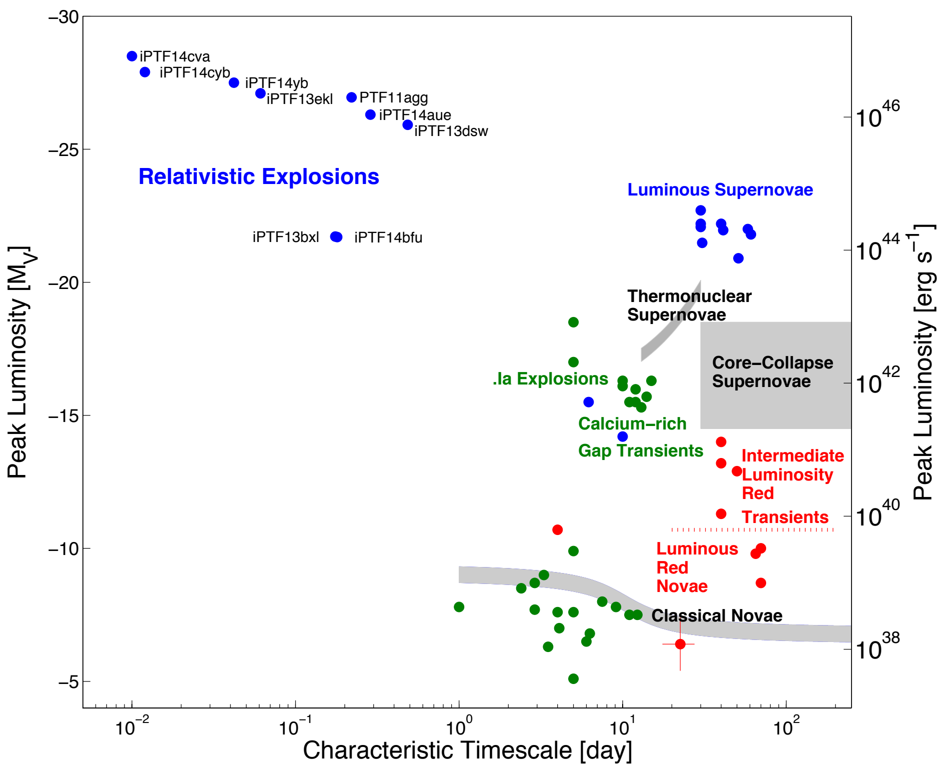
Gemini Efficient Optical and Near-infrared Imager and Spectrograph

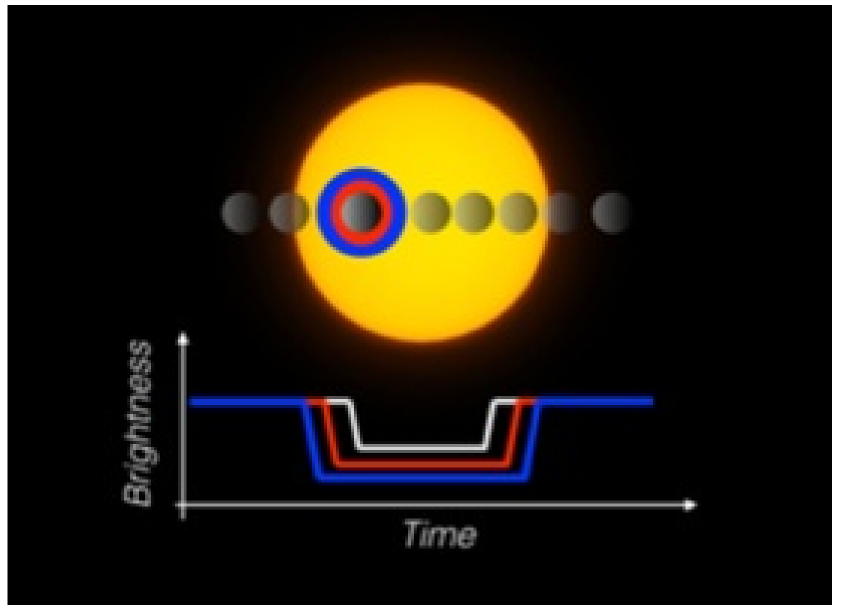
Team

- J.M. Desert
- D. Fox
- M. Kasliwal (project scientist)
- M. van Kerkwijk
- N. Konidaris (principal investigator)
- J. Masiero
- T. Matheson
- D. Reiley
- + Gemini: M. Close, S. Goodsell, R. Mason, B. Rambold

Overview

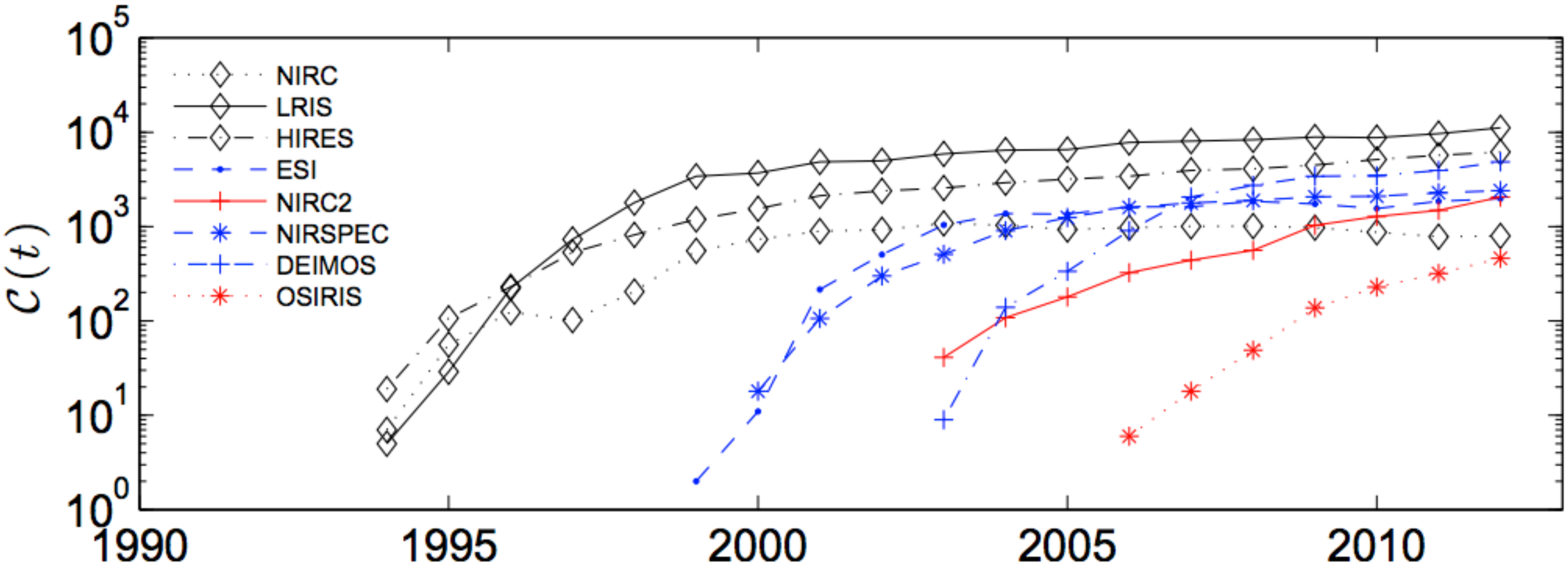
- Major requirements
- Key Science cases:
  - Transients
  - Exoplanets
  - NEOs
- Why G4#3 now?
- GEONIS Instrument





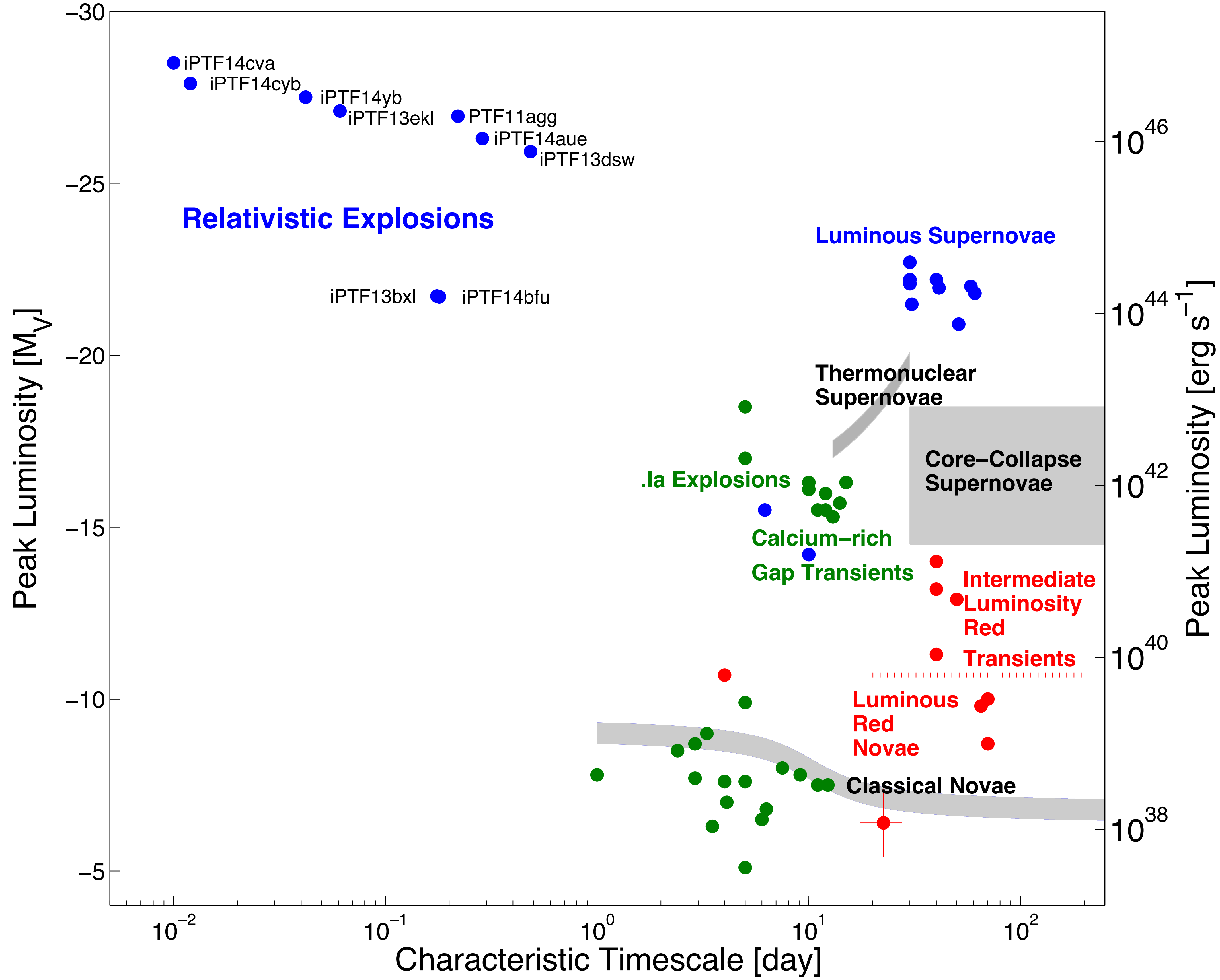
Key Driving Requirements

- $12 Million Cost Cap + 2.0 ton mass limit (and volume limit)
- STAC Mandate:
  - "a wide-bandwidth moderate-resolution spectrograph is likely to prove most compelling."
    - Broad wavelength coverage means CCD + Teledyne/Hawaii
  - "In the STAC's discussions 4gen3 is viewed as needing to be a **workhorse** instrument, as well as being a significant LSST followup instrument."
    - Followup of LSST means spectroscopy + imaging
- GEONIS team wants to capitalize on Gemini's Strength in queue observing:
  - Transients
  - Exoplanets
  - NEOs
- ∴ GEONIS is an optical/near-ir spectrograph and imager



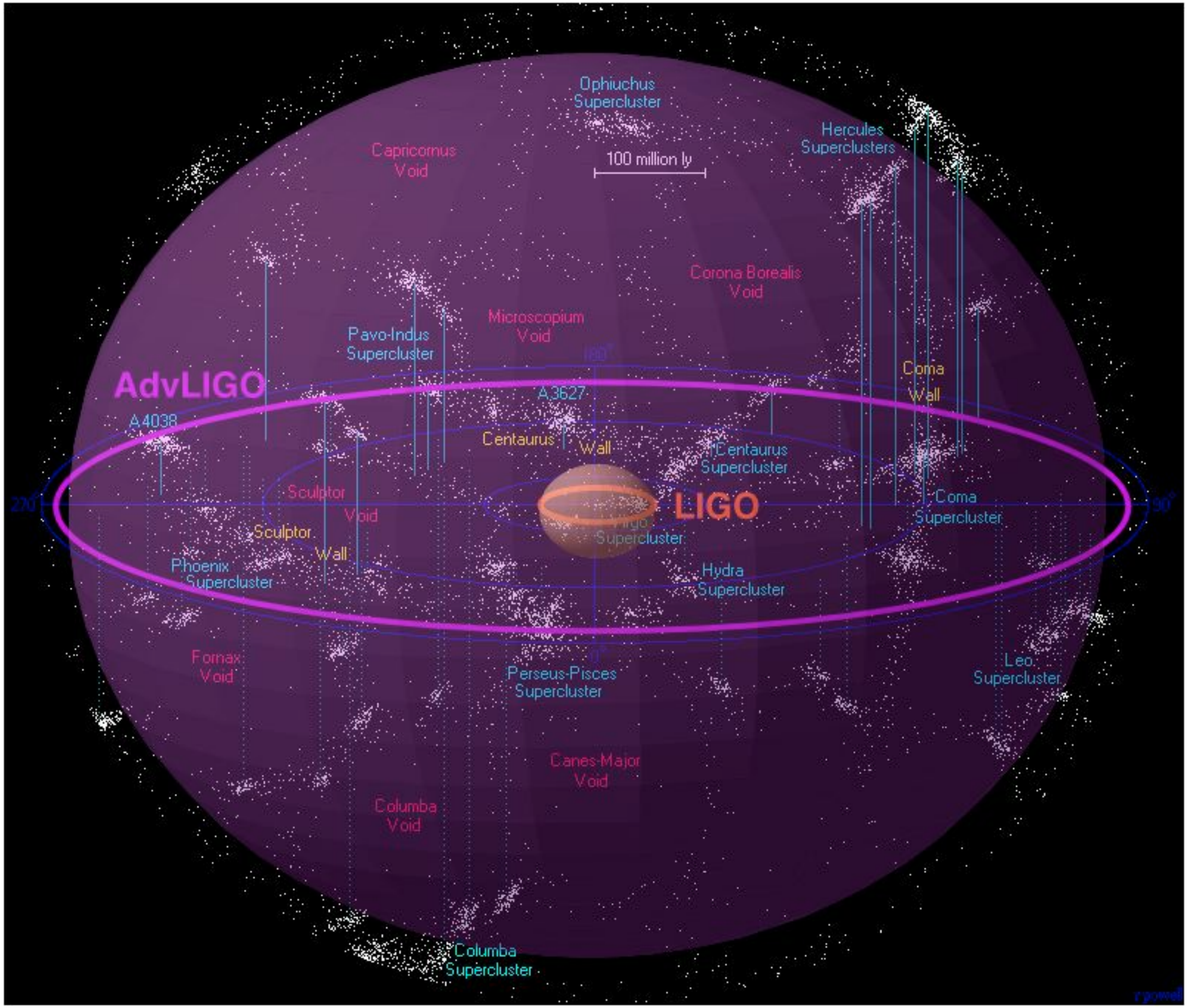
Kulkarni (2014)

Transients: Kasliwal Diagram



Why Now?

- Surveys are and will become more abundant: LSST, Evryscope, ZTF, PanSTARRS, ATLAS, Catalina, DECAM, HSC, etc…
- Non-electromagnetic phenomenology (Advanced LIGO started on the 18th)



LIGO web page

Q: How can we design GEONIS to make an impact?

- Earth's atmosphere defines the addressable wavelength range.
    - Blue end (<400 nm) limited by transmission + mirrors.
    - Red end requires cryogenic instrument.
- Solid state physics defines the quantum efficiency. There's not much room for improvement in either CCDs or Teledyne devices.
- **LATENCY** is the low hanging fruit. Latency can go from hours to minutes.

We combat latency with:

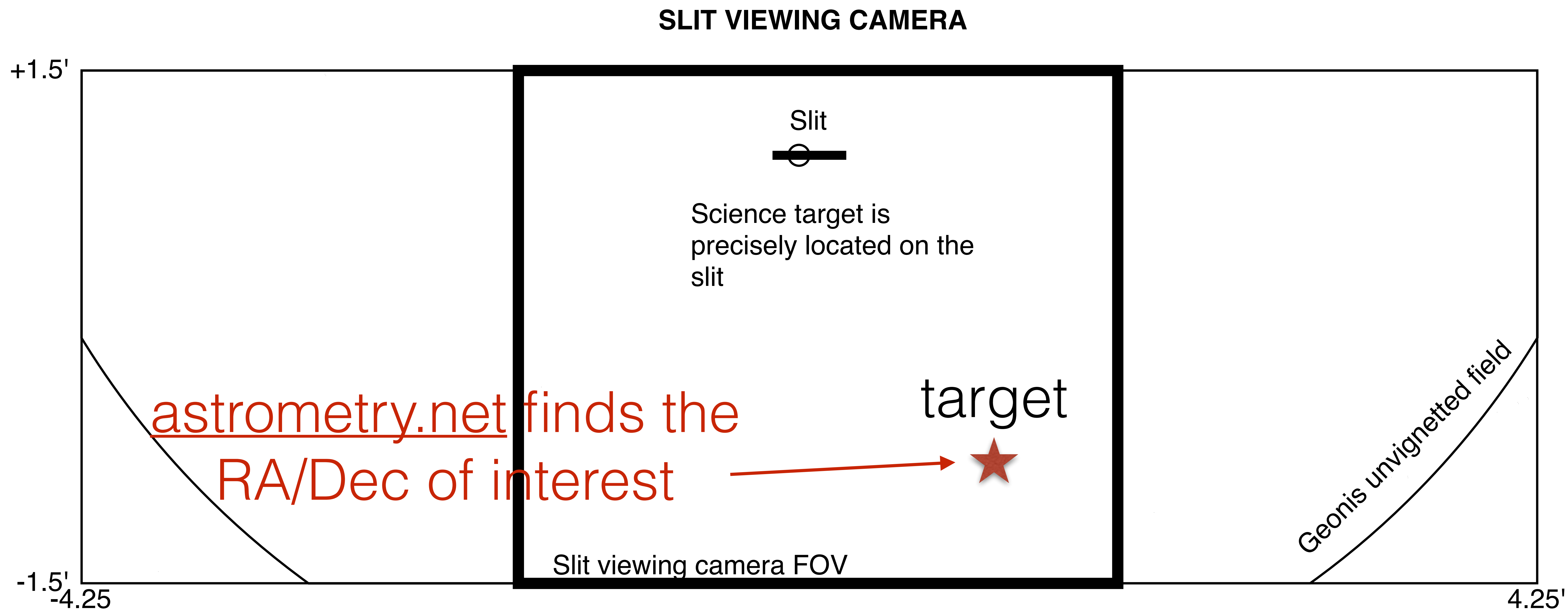
Slit viewing camera

Fast read detectors

Rock solid data format

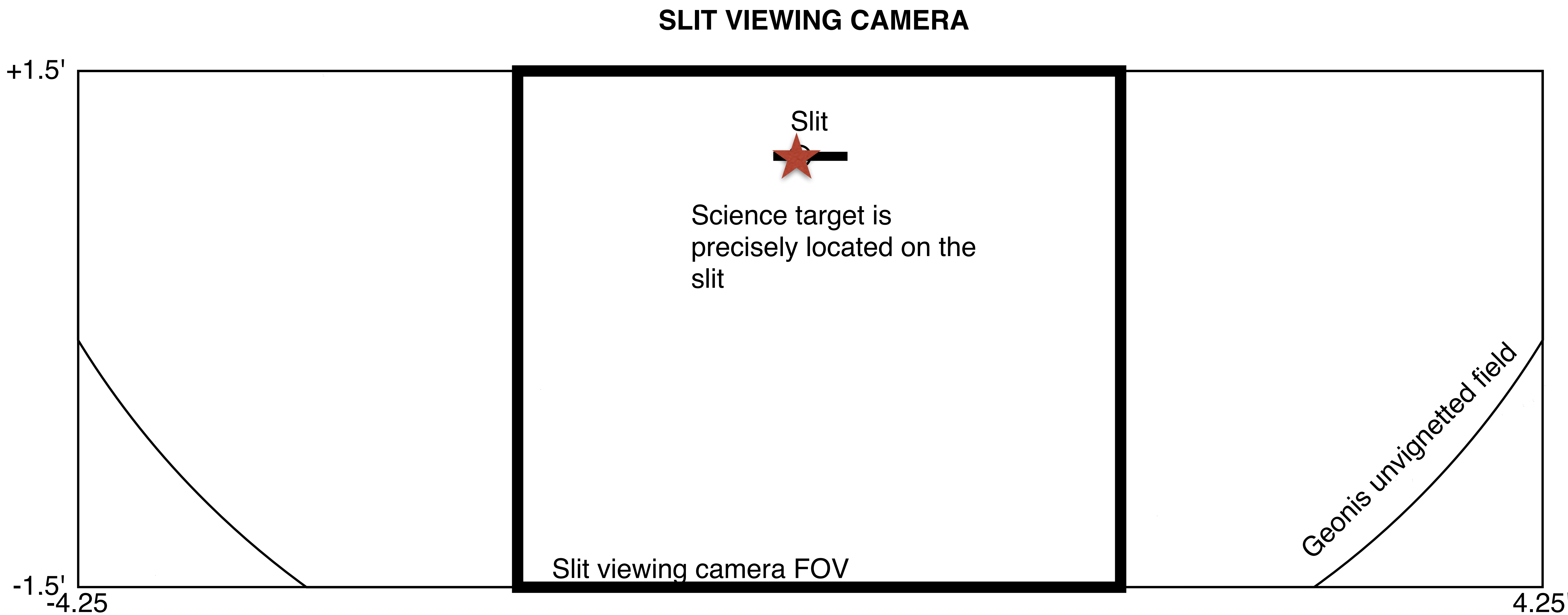
Brilliant observing community and “pipelines”

Data Reduction I: Slit Viewer



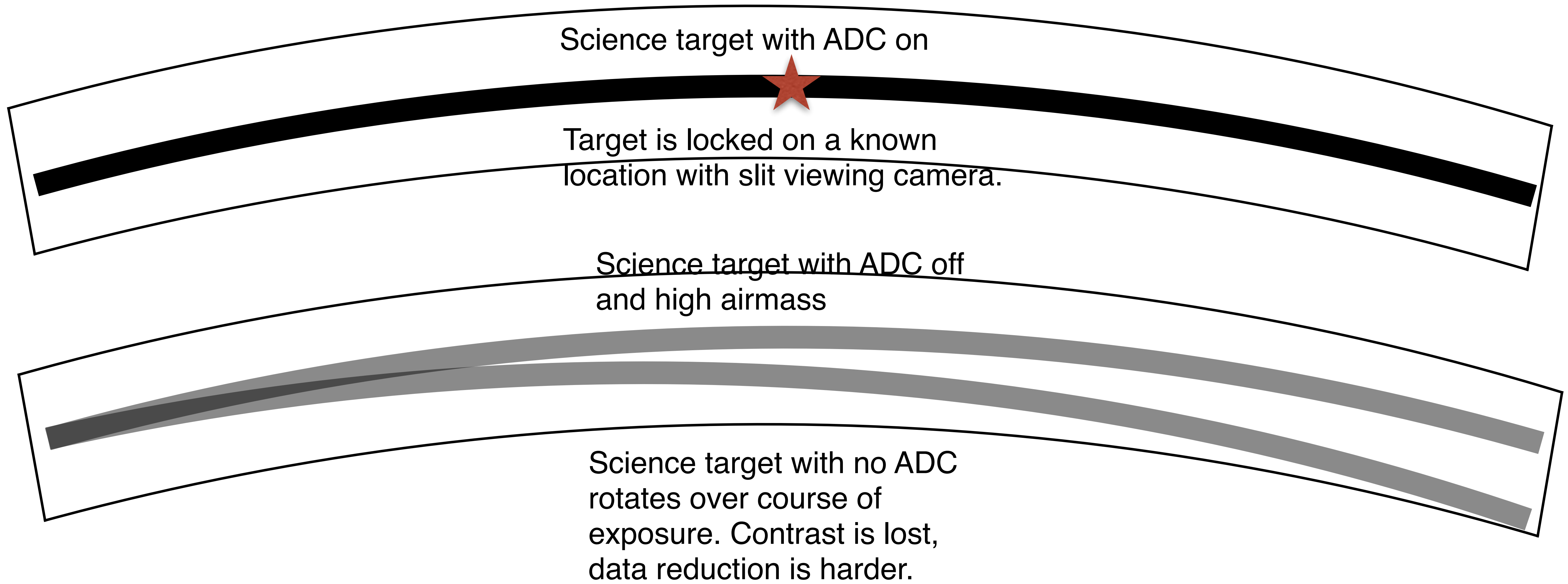
Slit viewing is common on large telescopes
See FLOYDS + SED Machine

Data Reduction I: Slit Viewer



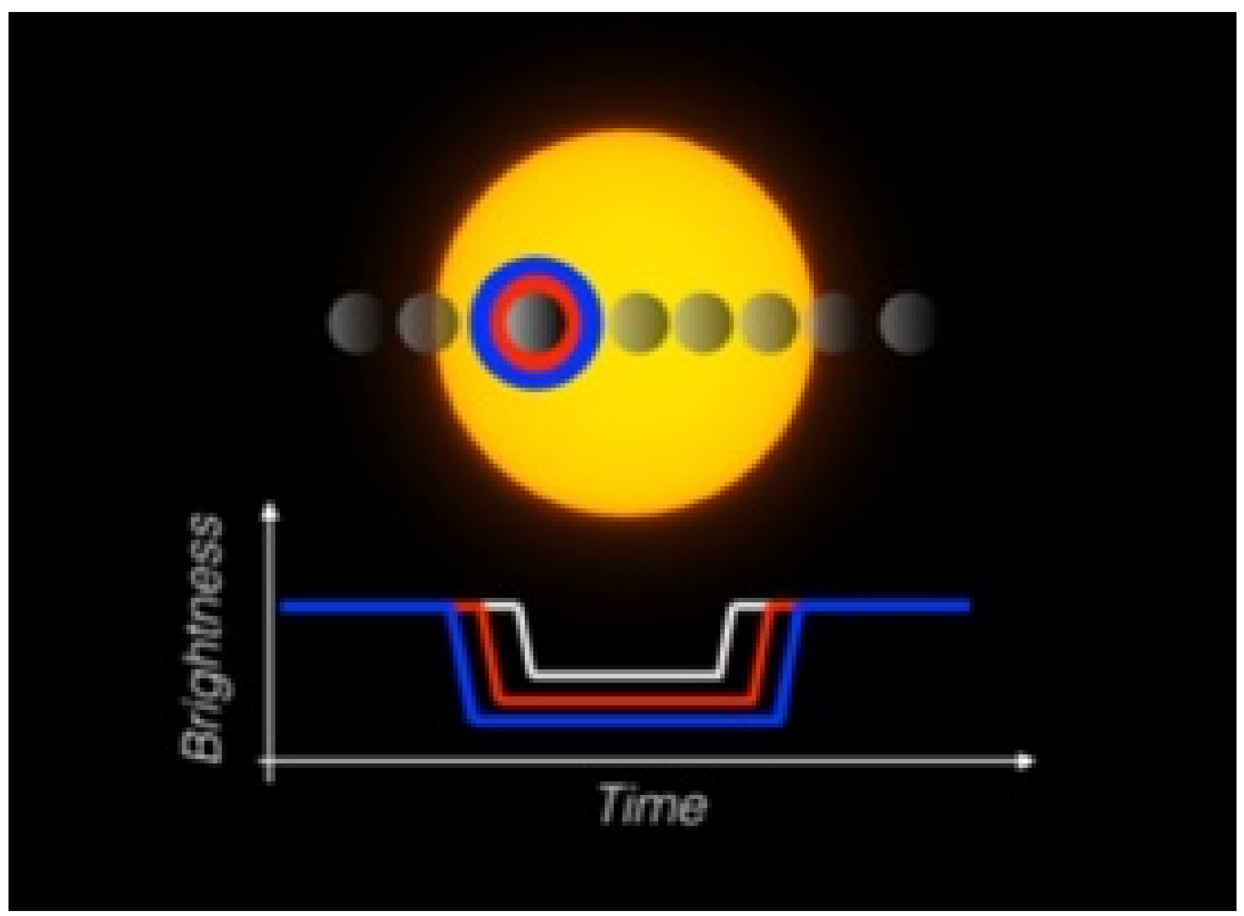
Data Reduction II: Rock Solid Detector Format

Slit viewer + ADC + Flexure correction!

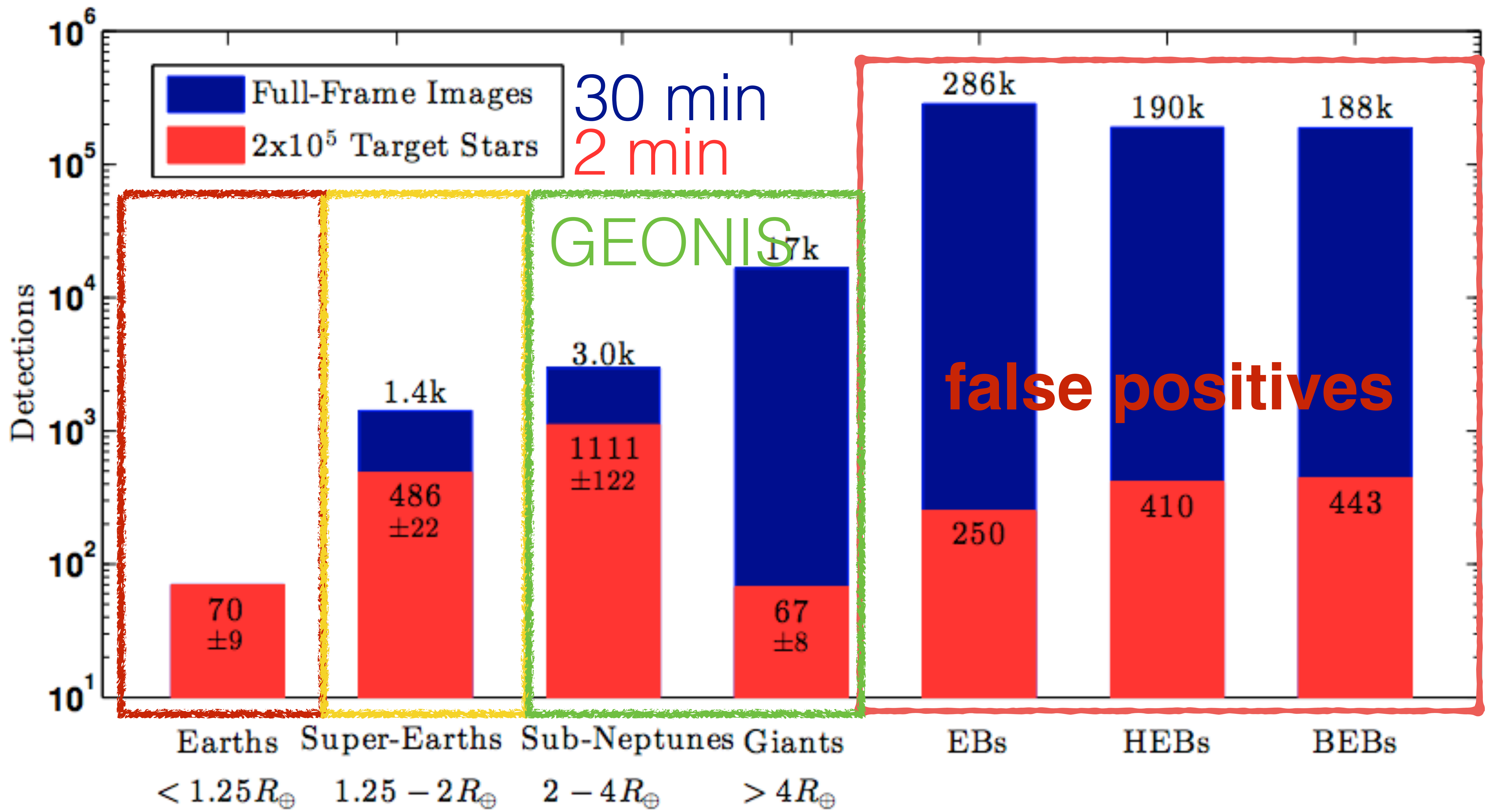


Exoplanets

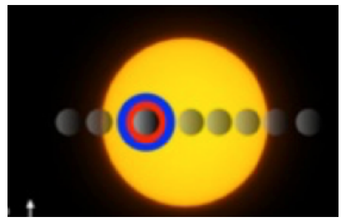
- Transiting exoplanets allow us to study compositions, atmospheres, and orbital dynamics of planets beyond the solar system.
- From the ground, precision is hard (because of our earth's atmosphere), but spectroscopy is possible.



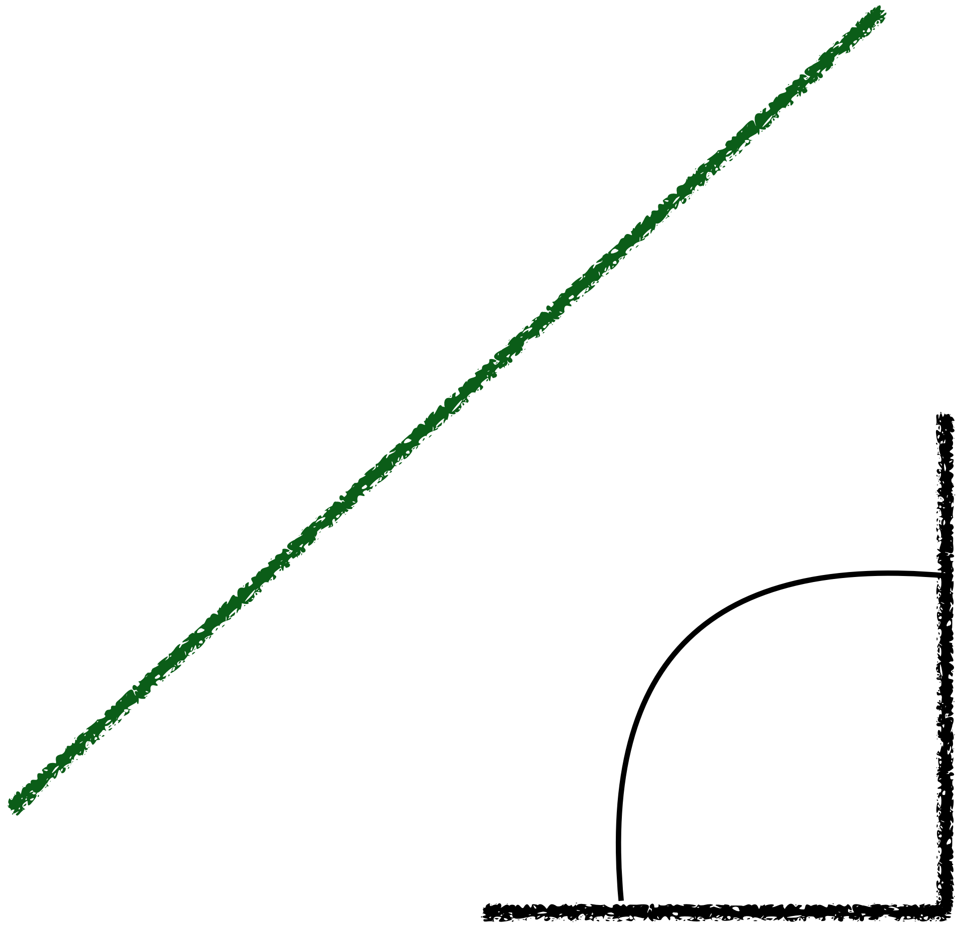
Immense Planet Yield to choose targets up to **12th** magnitude starting in **2017**!



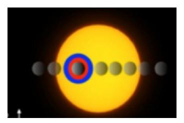
Sullivan+ (2015)



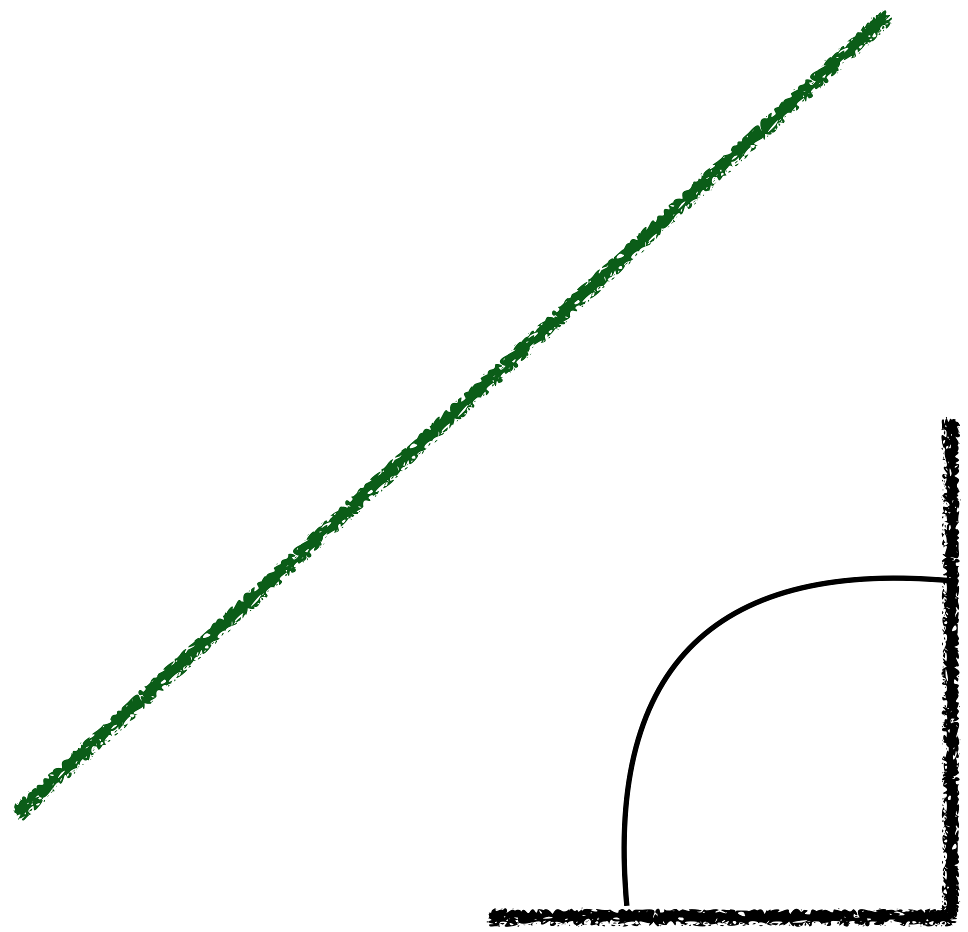
Earth’s Atmosphere



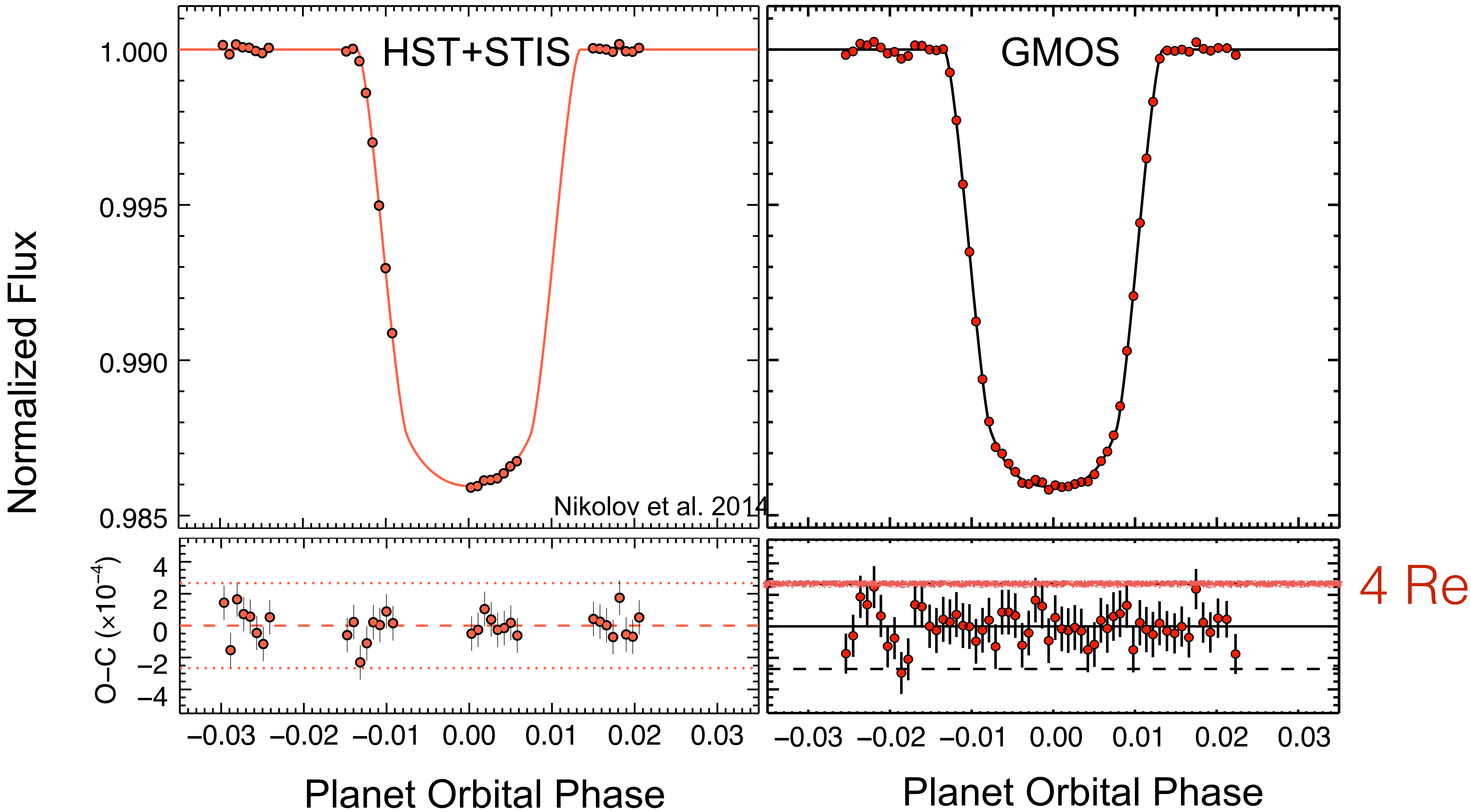
The larger the FOV, the more companion field stars we can address!



Earth's Atmosphere

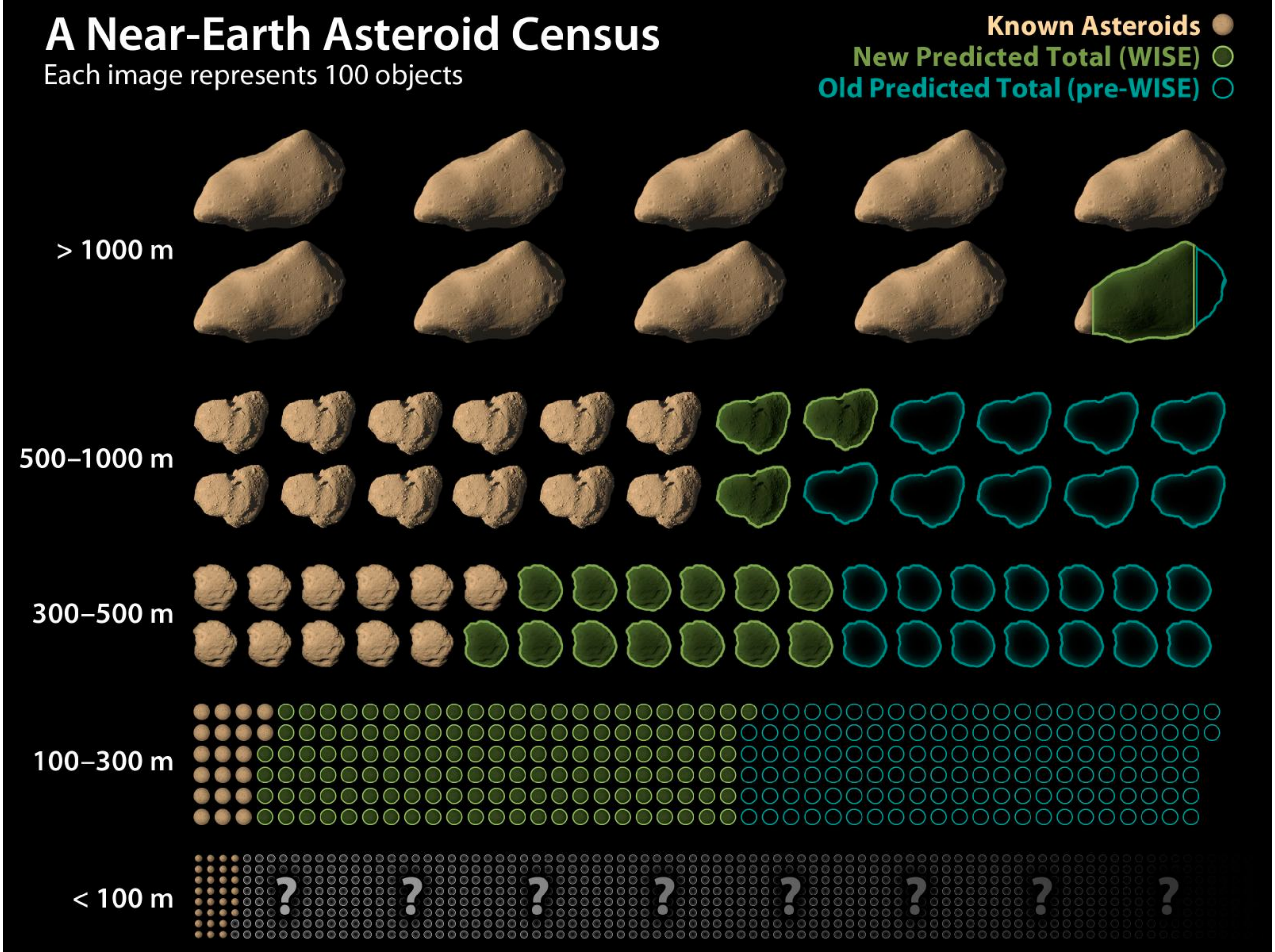


HST Versus Gemini/GMOS

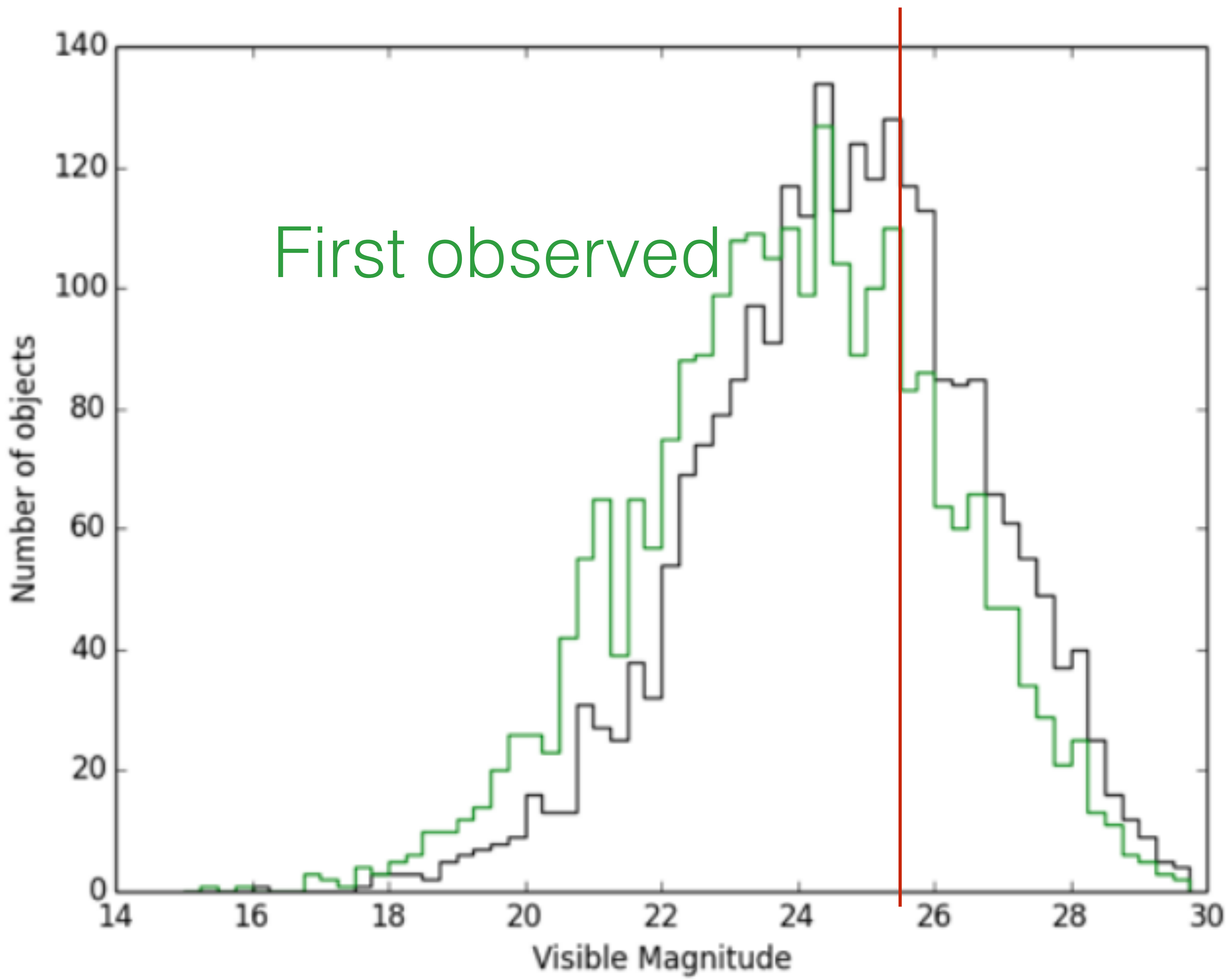


Near Earth Objects

- We want a full history of our Solar System and we must thus study its asteroids and comets. What are NEOs, how many are there, and how much of a threat do they pose to Earth?
- This science requires a wide field imager to determine ephemeris quickly.
- GEONIS baseline design FOV covers similar field as GMOS; and it has higher duty cycle.


A Near-Earth Asteroid Census
Each image represents 100 objects
Known Asteroids
New Predicted Total (WISE)
Old Predicted Total (pre-WISE)
> 1000 m
500–1000 m
300–500 m
100–300 m
< 100 m
?
?
?
?
?
?
?
?

S/N~10 in 5 m w/ GEONIS



Mainzer+ (2015)

Ultimate “sample return”

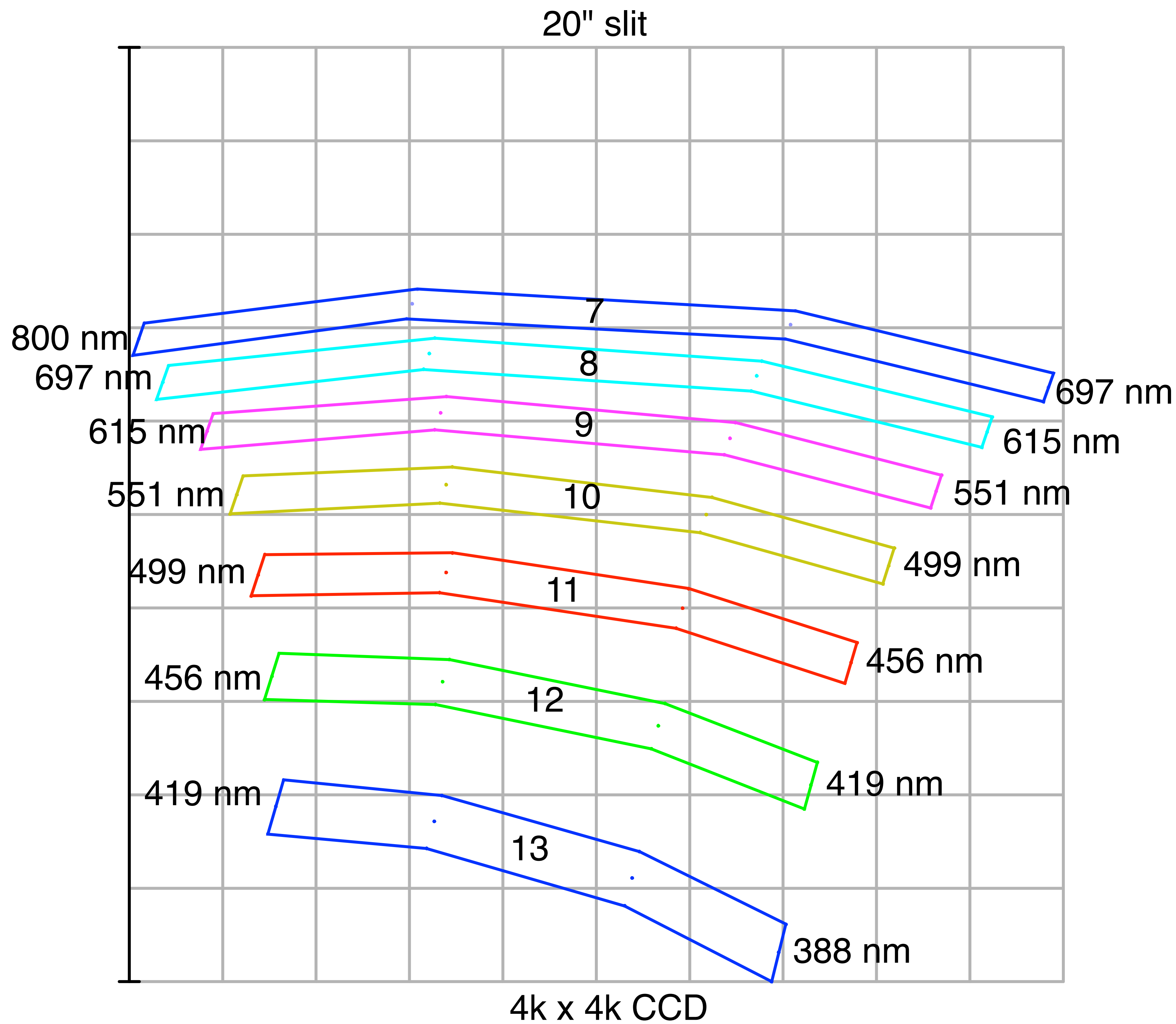
NASA / SETI / P. Jenniskens

Work through the design

- Echelette
- Long slit
- Imaging

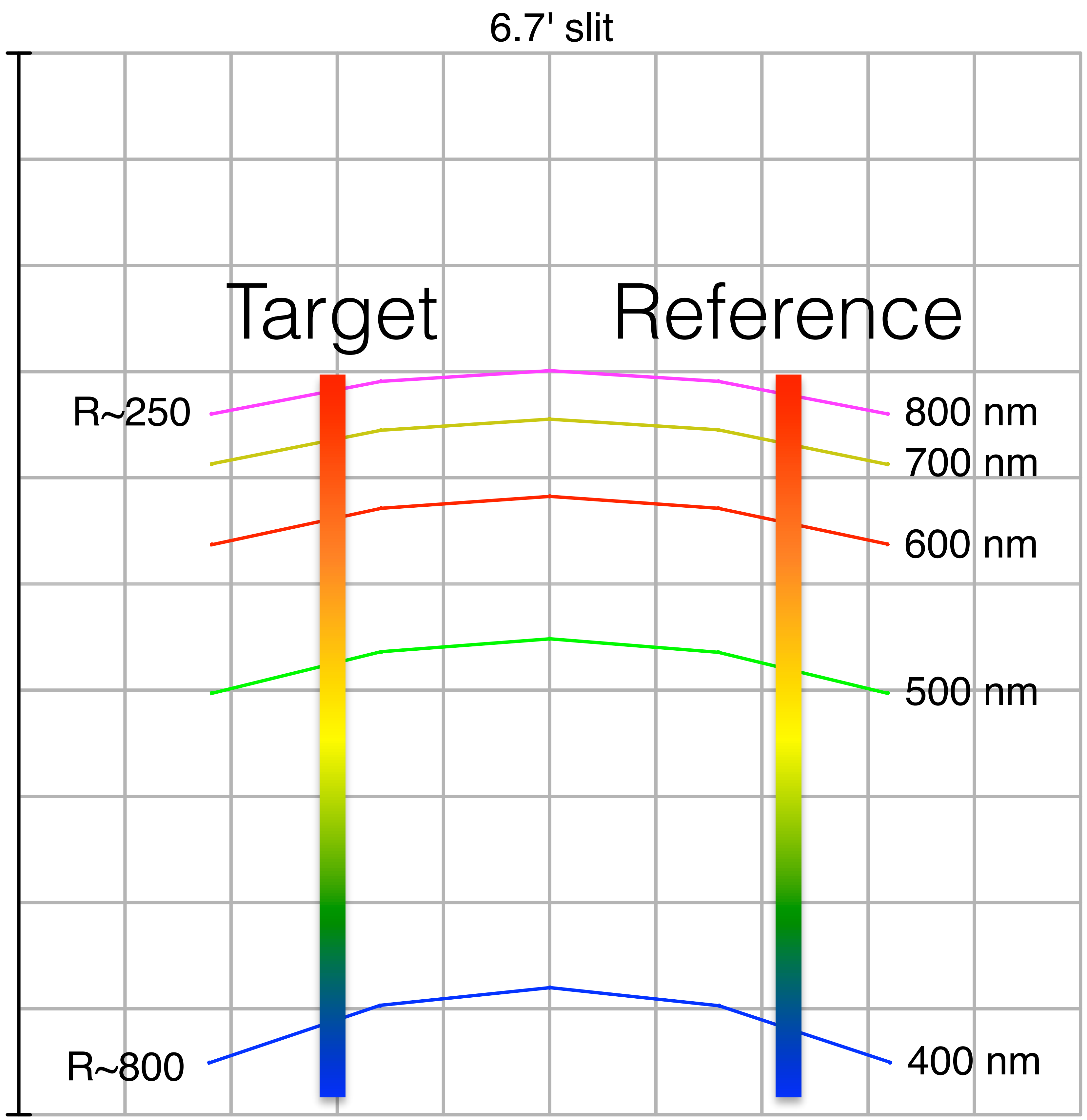
Echelette mode: Why? What?

- Transients
- Efficient
- Rock solid
- 400 — 1600 nm (baselined)
- 20″ x 1″ slit
- R~4,000 (hardware)
- Software adapted resolution



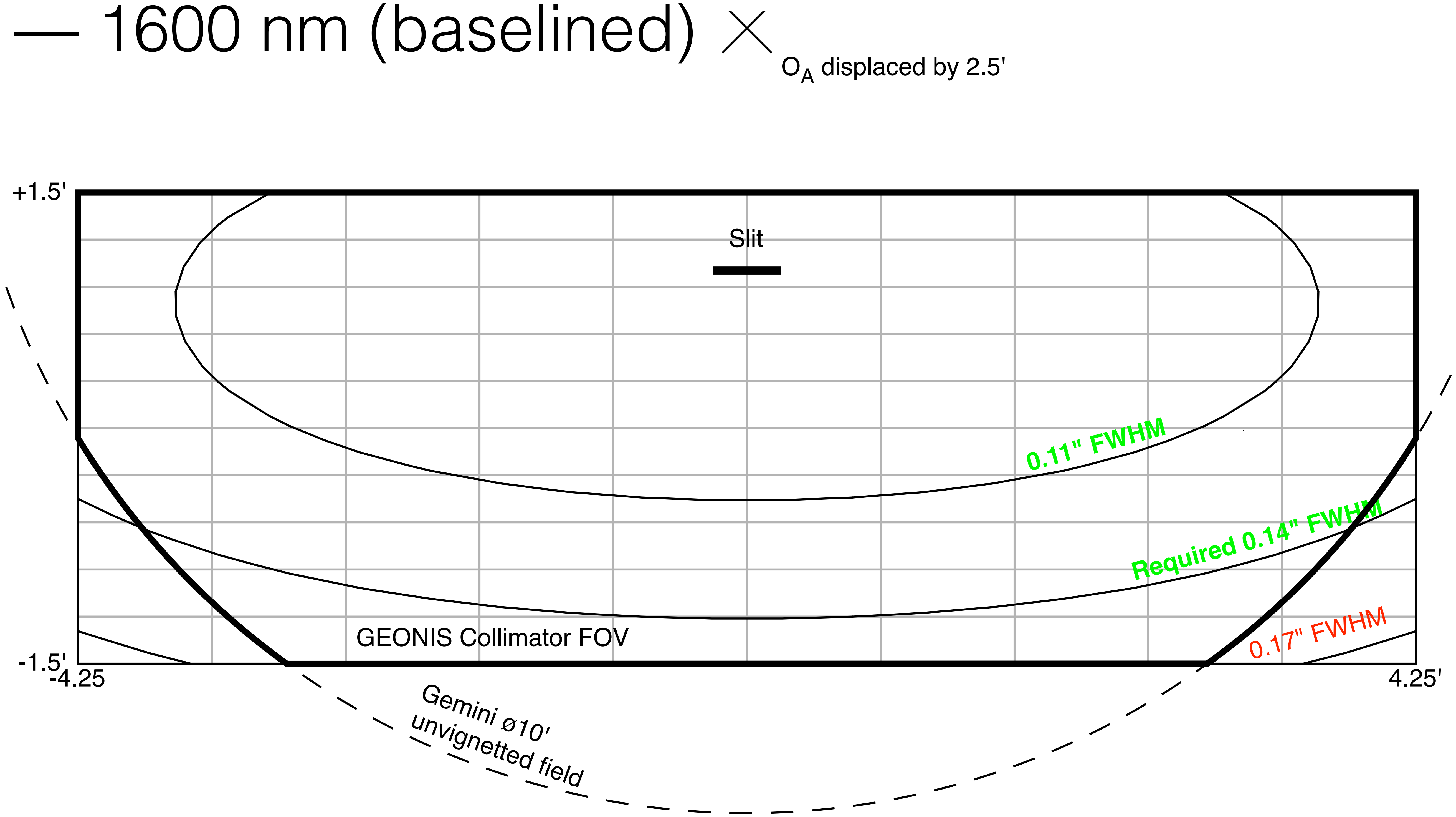
Lowres mode: Why? What?

- Exoatmospheres
- Highest Efficiency
- 400 — 1600 nm
- Highest Precision
- 6.7′ x 10″ slit



Imaging Mode: Why? What?

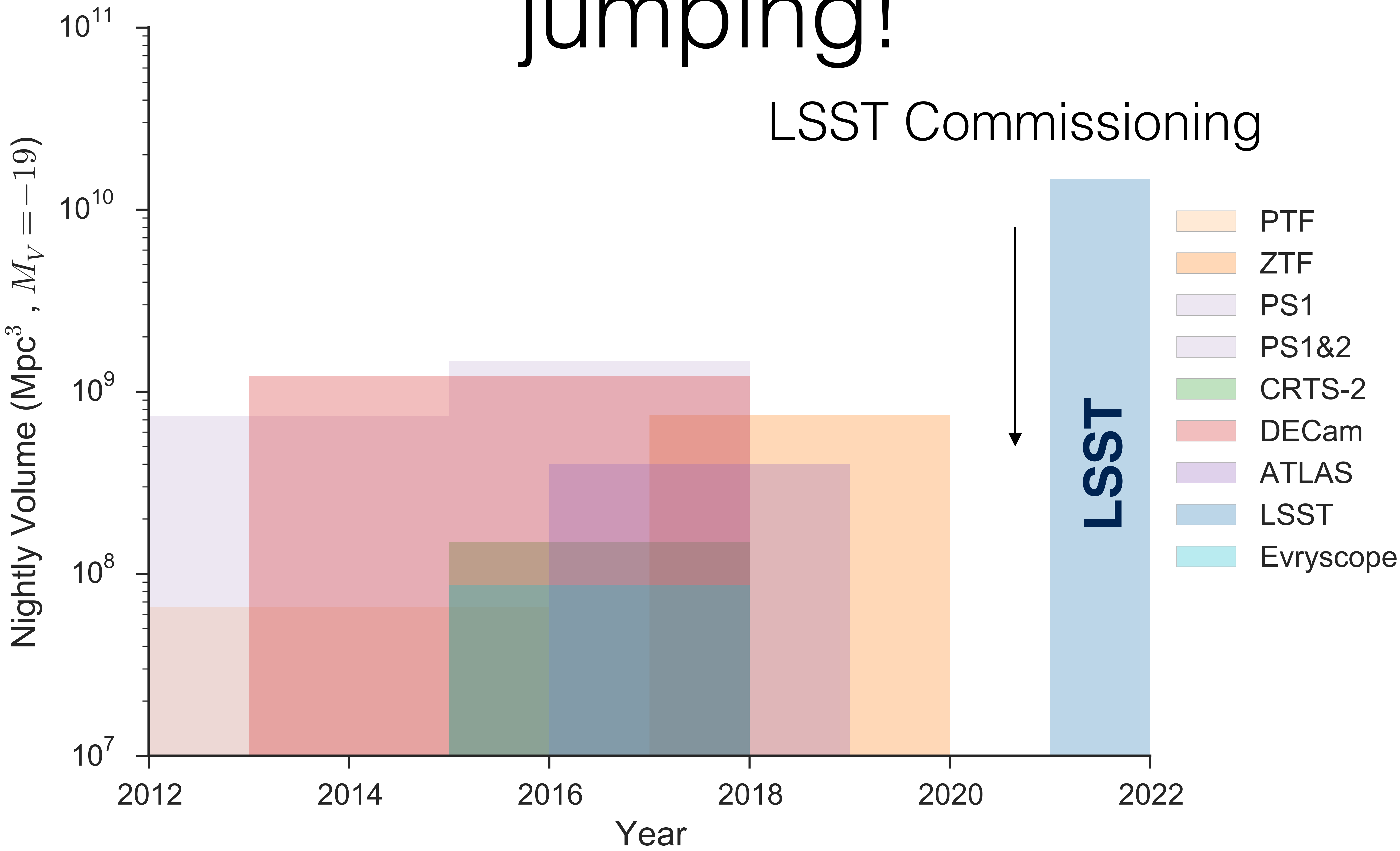
- Imaging for NEOs
- 400 — 1600 nm (baselined)



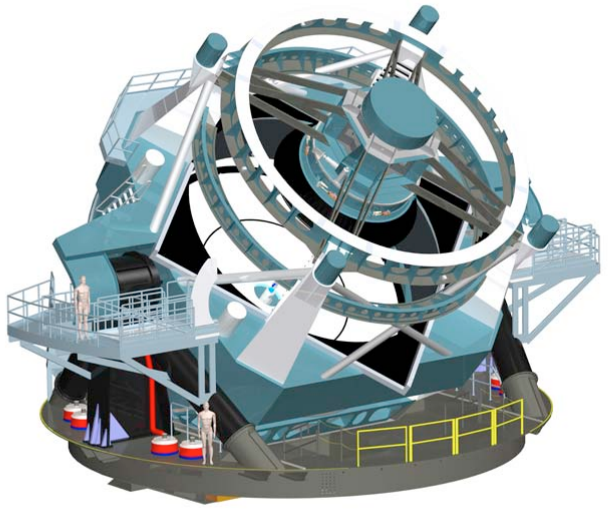
Why Gen4#3 at Gemini?

- Aforementioned science cases indicate that queue-based observing will be important.
- Hard to imagine the range of capabilities coming online:
    - LSST, LIGO, NEOCAM, TESS, JWST, WFIRST, …

Volume probed / night is jumping!



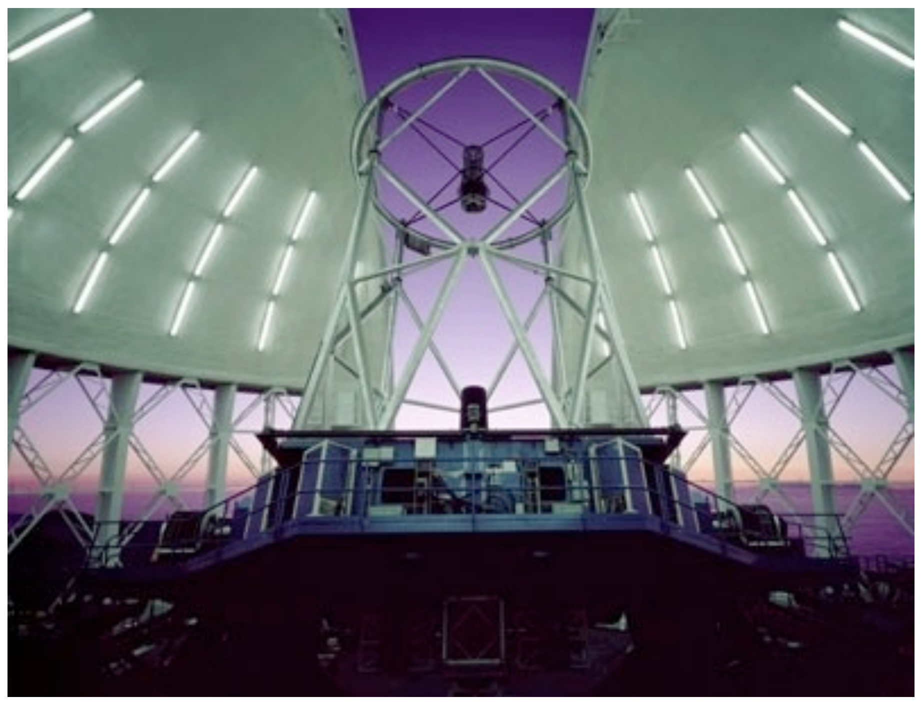
Gemini is poised to change our field.



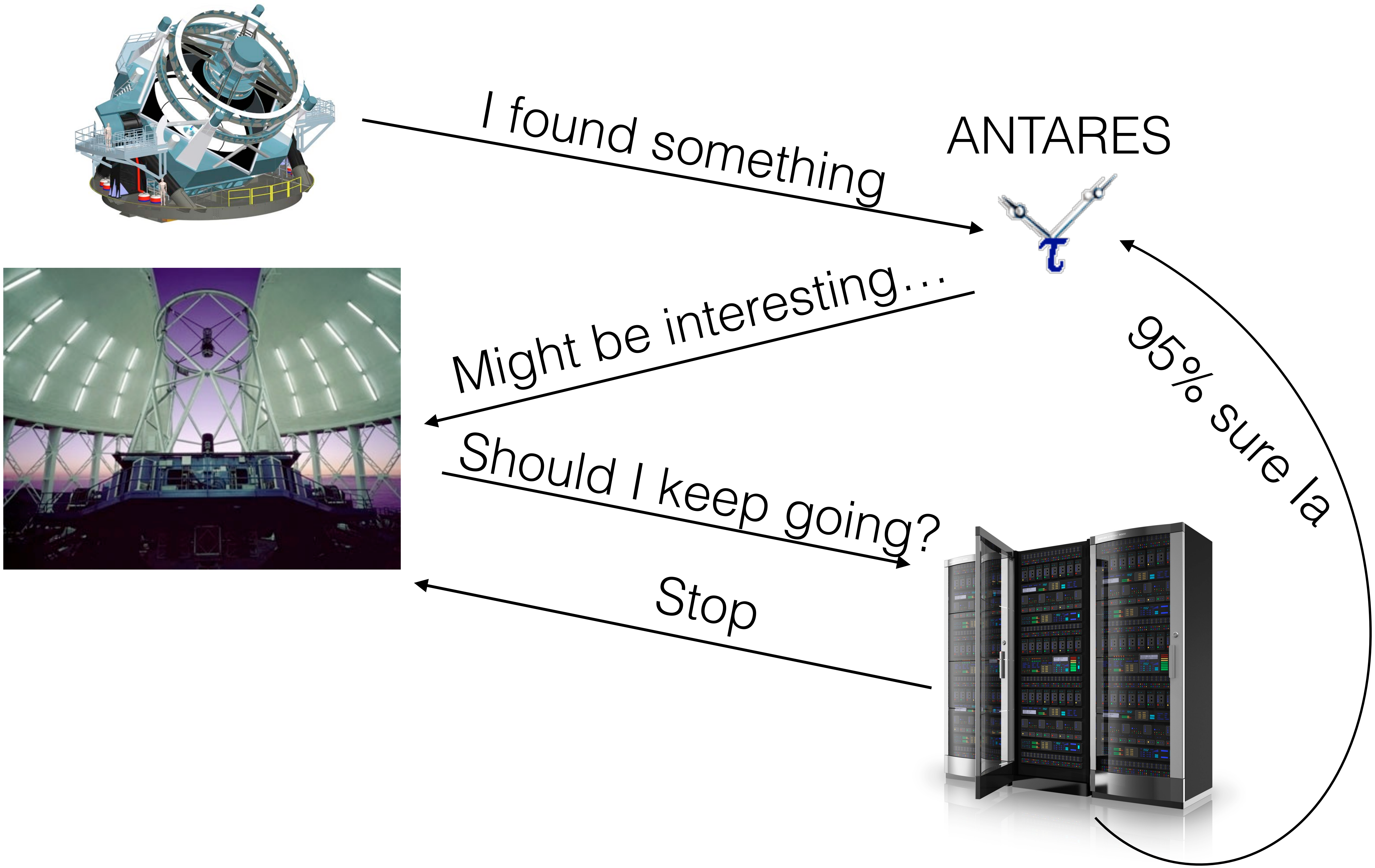
I found something

ANTARES

Might be interesting…



Long term future



GEONIS Summary

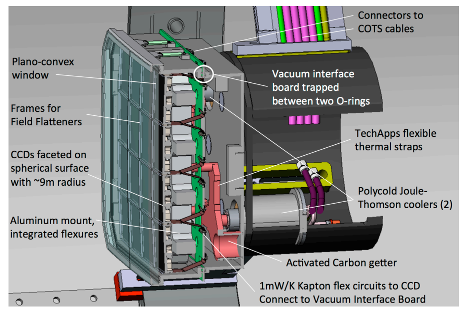
- GEONIS is a workhorse O/IR spectrograph and imager.
- Transients: think Echelette: optical (400-800 nm) and NIR (800 - 1600 nm) at R~4,000 with 1 as slit.
- Exoplanets: think long slit: two arms, > 6′ slit length.
- NEOs: think imaging: two arms, 8.5′ x 3′.
- Data reduction: ultra high stability, instantly available reductions, plays with LSST event broker system to deliver probabilistic classifications.

GEONIS Science Highlights

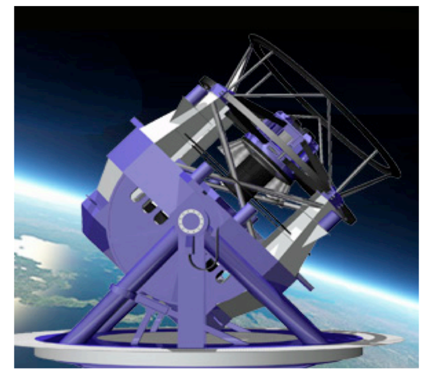
J.M. Desert, D. B. Fox, M. M. Kasliwal, M. van Kerkwijk,
N. Konidaris, J. Masiero, T. Matheson, D. Reiley

A Renaissance in Time-Domain Astronomy

Evryscope, ASASSN, HATPI



ZTF, CSS-II, PS, BG



DECAM, HSC, LSST

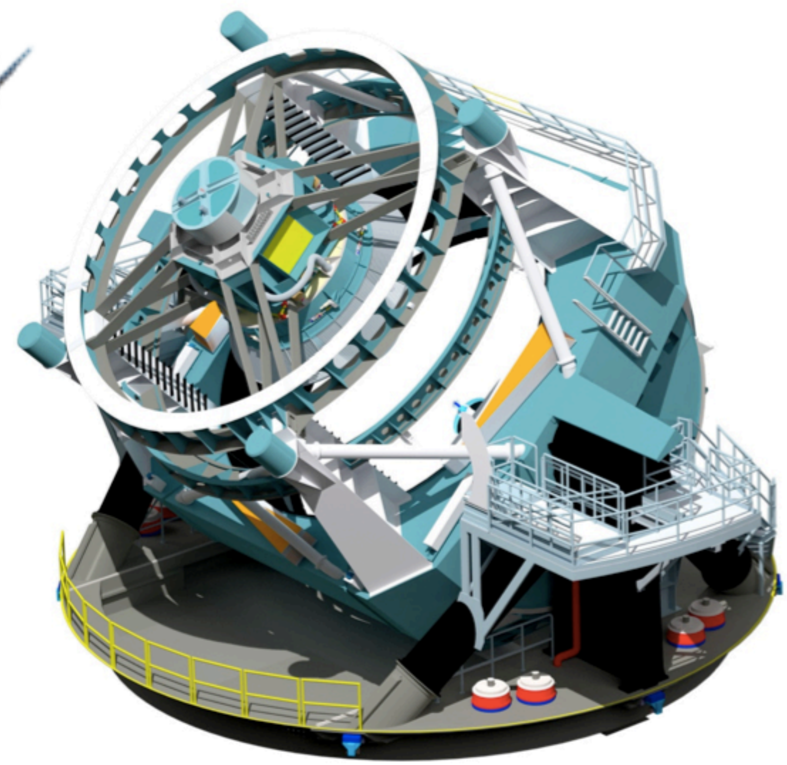
LOFAR, MWA and LWA: meter and decameter-mapping

Apertif, Meerkat and Askap: decimetric mapping

SPIRITS, Gattini and WFIRST: infrared mapping

Event Rate is increasing by two orders of magnitude

PTF: 4 x 10^4 events/night
ZTF: 3 x 10^5 events/night
LSST: 2 x 10^6 events/night



Technical	develop algorithms & software for detection & classification
Scientific	discover new transient & variable phenomena
Organizational	organize collaborations and followup strategies with real data

Science Case for GEONIS

I. Flash Spectroscopy of Newborn Supernovae
  - Drives the need for rapid queue response and classification mode

II. Relativistic Explosions and Orphan Afterglows
  - Drives the need for wide wavelength coverage and low resolution

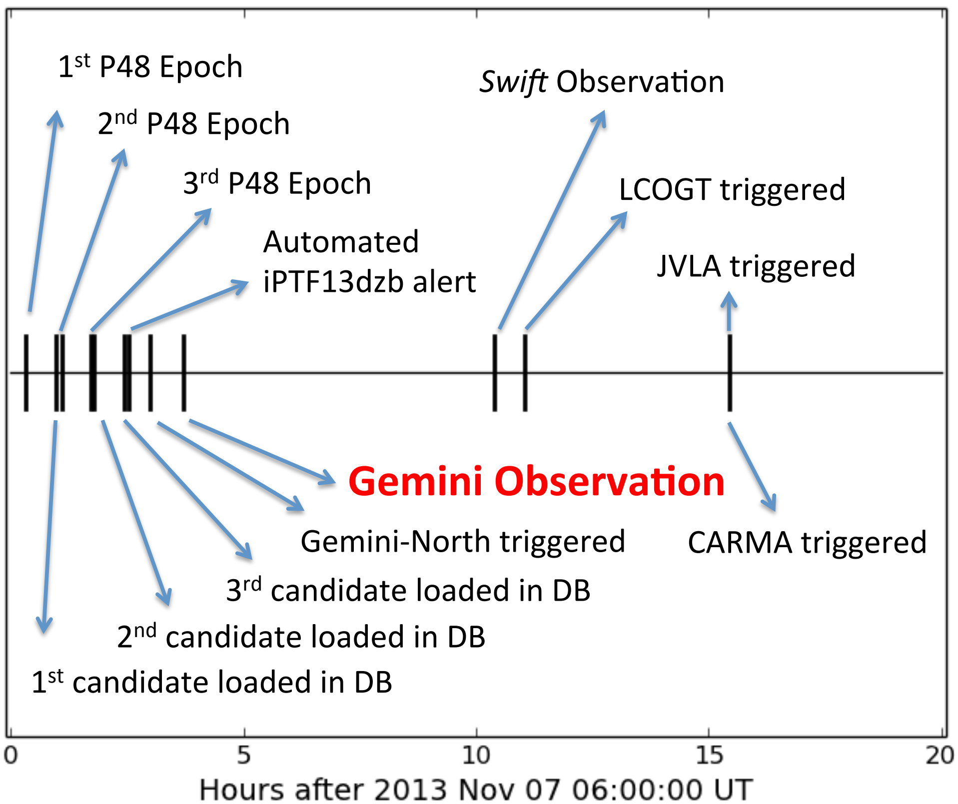
III. Electromagnetic Follow-up of Gravitational Waves
  - Drives the need for a red arm

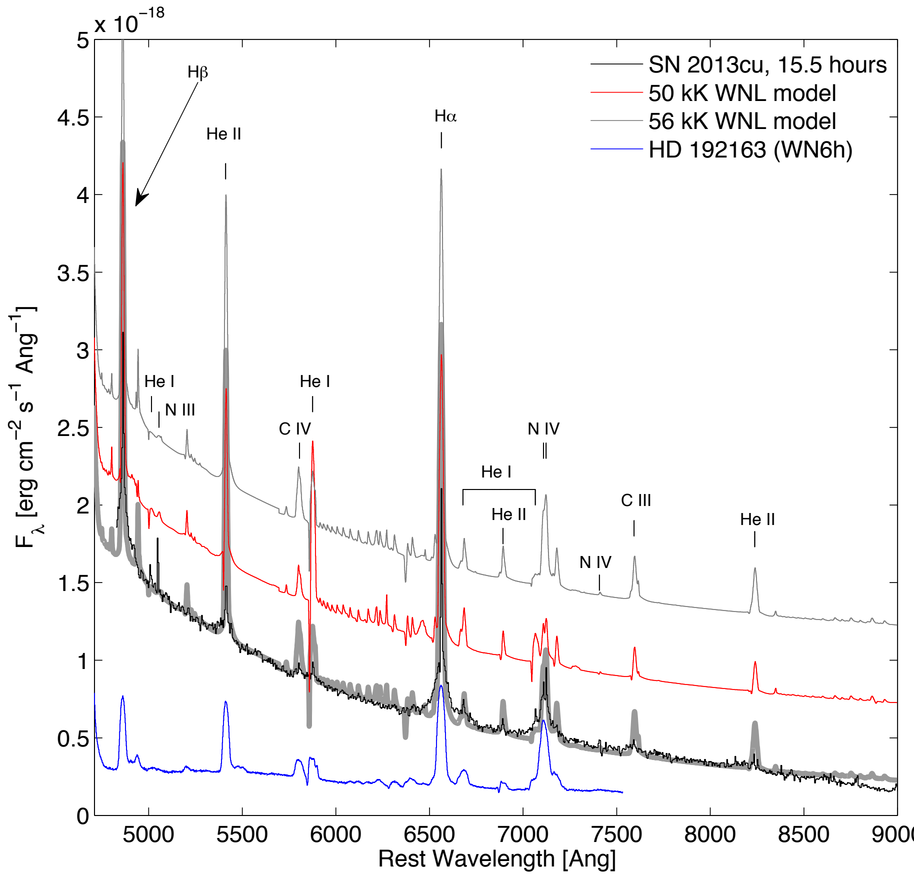
IV. Extrasolar Planet Atmospheres
  - Drives length and width of slit and requires instrument stability

V. Asteroids
  - Drives pixel scale and a large FoV

I. Flash Spectroscopy:

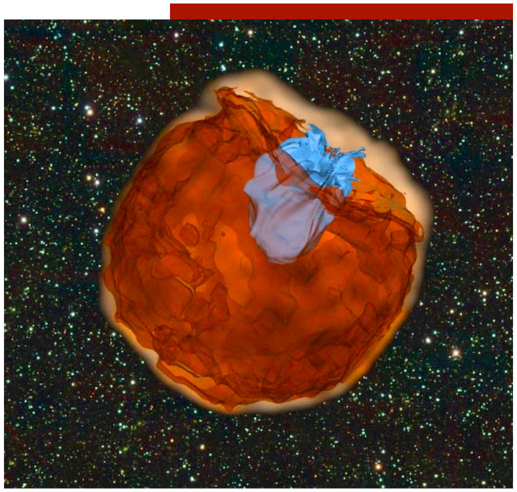
Rapid queue response of newborn supernovae

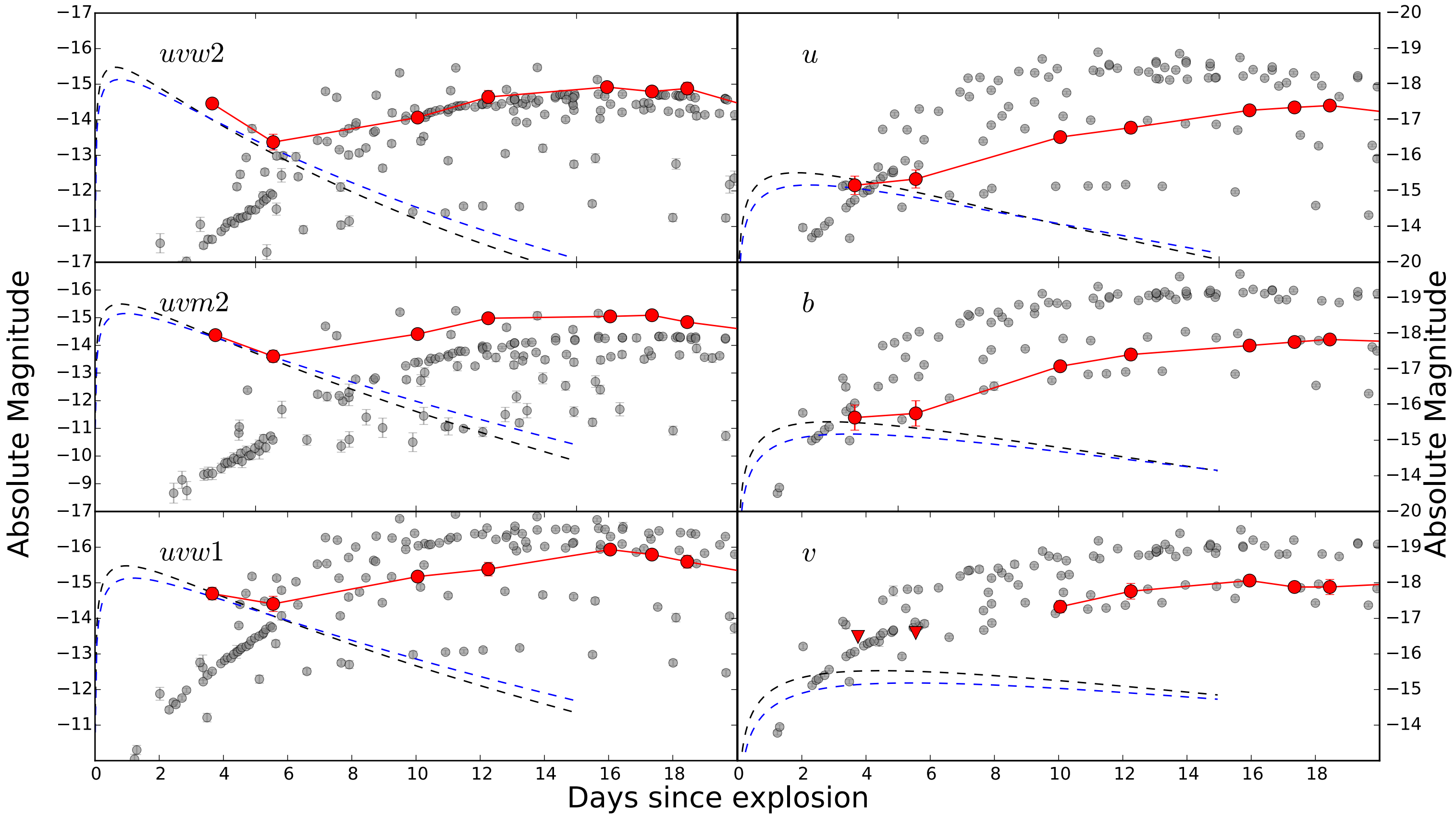




Gal-Yam et al. 2014, Nature

Classification-driven observing:
Type Ia Supernova Companion Interaction

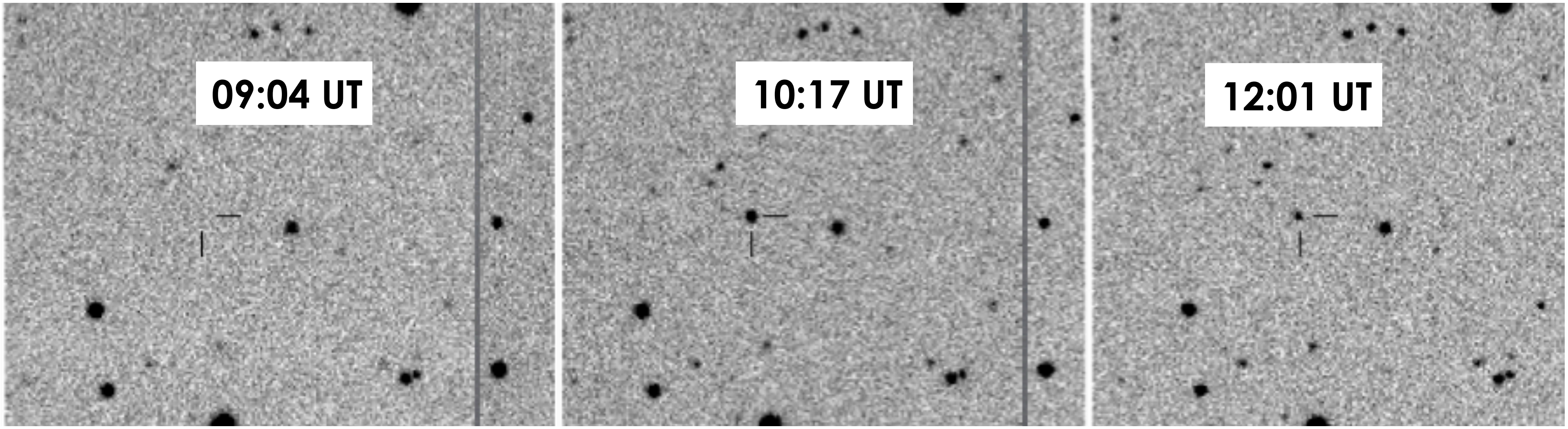




Cao et al. 2015, Nature

II. Orphan Afterglows

On 2014 Feb 23…



@ 14:21 CARMA and EVLA radio triggered
@ 15:26 Keck Optical Spectrum: z=1.98!
@ 17:11 Swift X-ray & Ultraviolet observations

Case of iPTF14yb: Gamma-Ray Parents Found Afterwards!
Untriggered afterglow
Case of PTF11agg: Gamma-Ray Parents Missing! Dirty fireball?

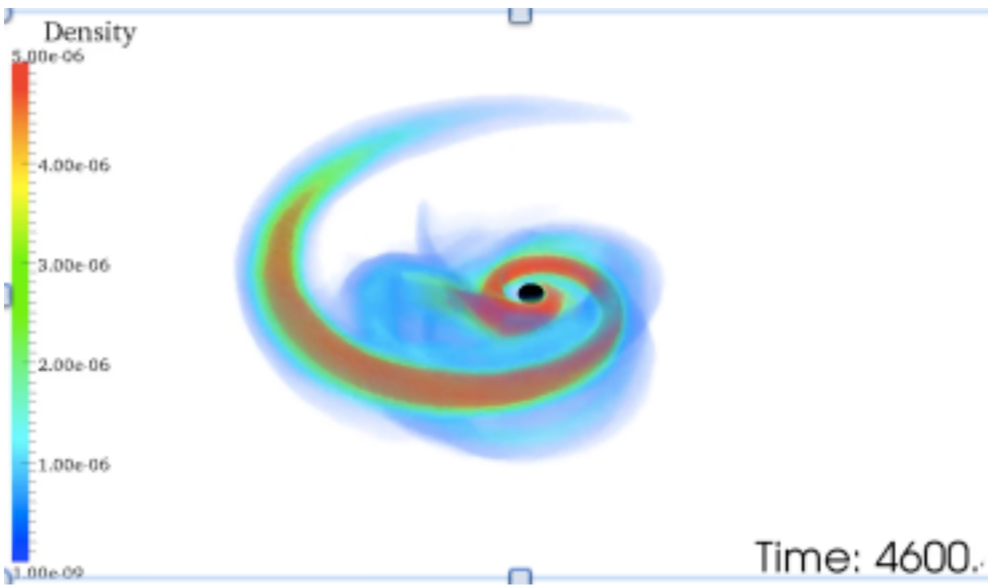
Cenko et al. 2013, 2015

III. Seeing the Sound:

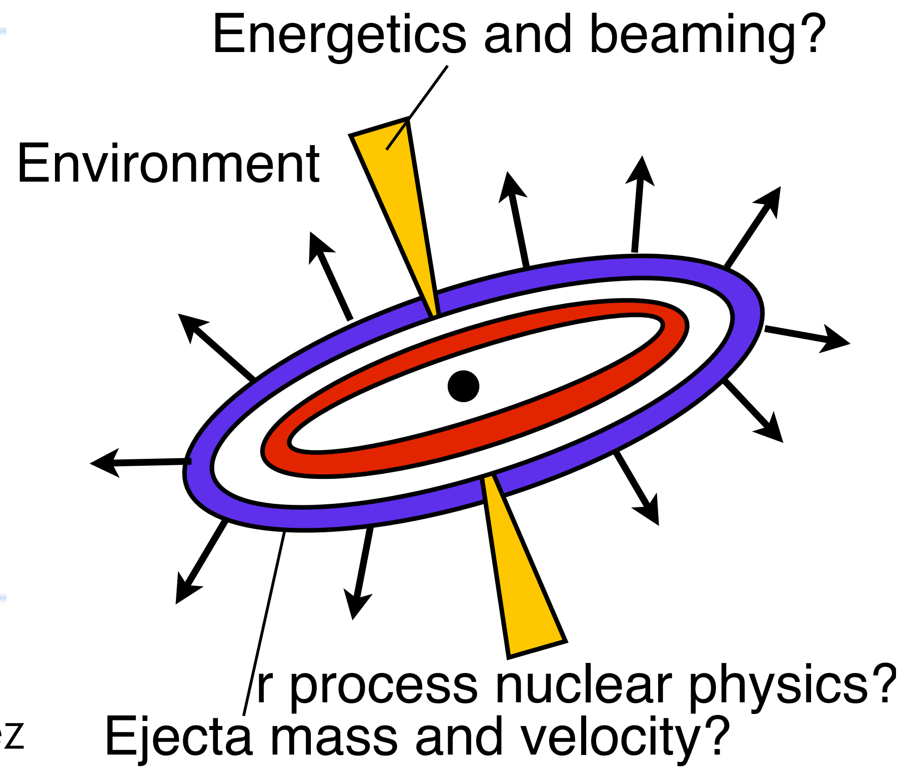
Bridging Gravitational Wave Physics & Electromagnetic Astronomy

GEONIS

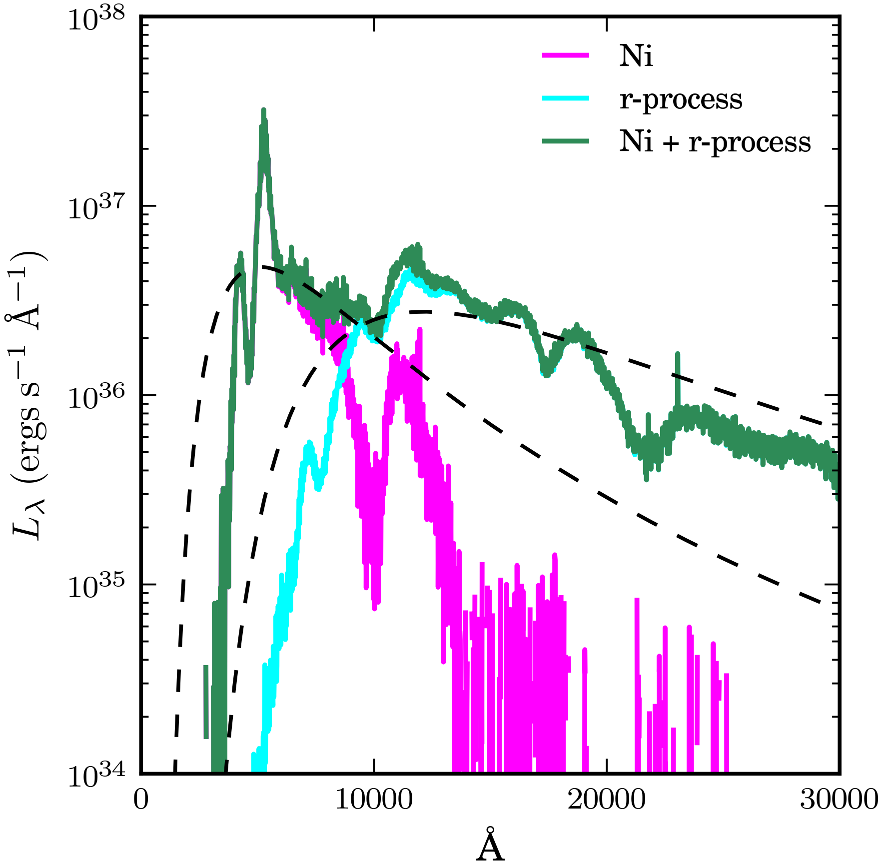
Strong Field Gravity: Masses, Spins, Inclination



Simulation: M. Duez

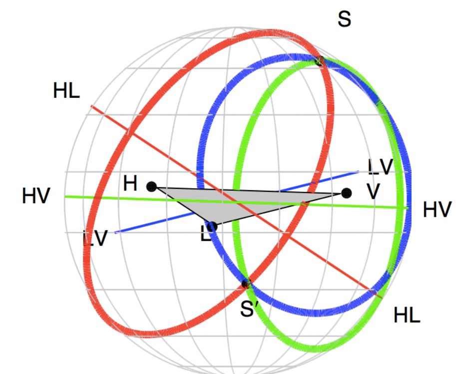


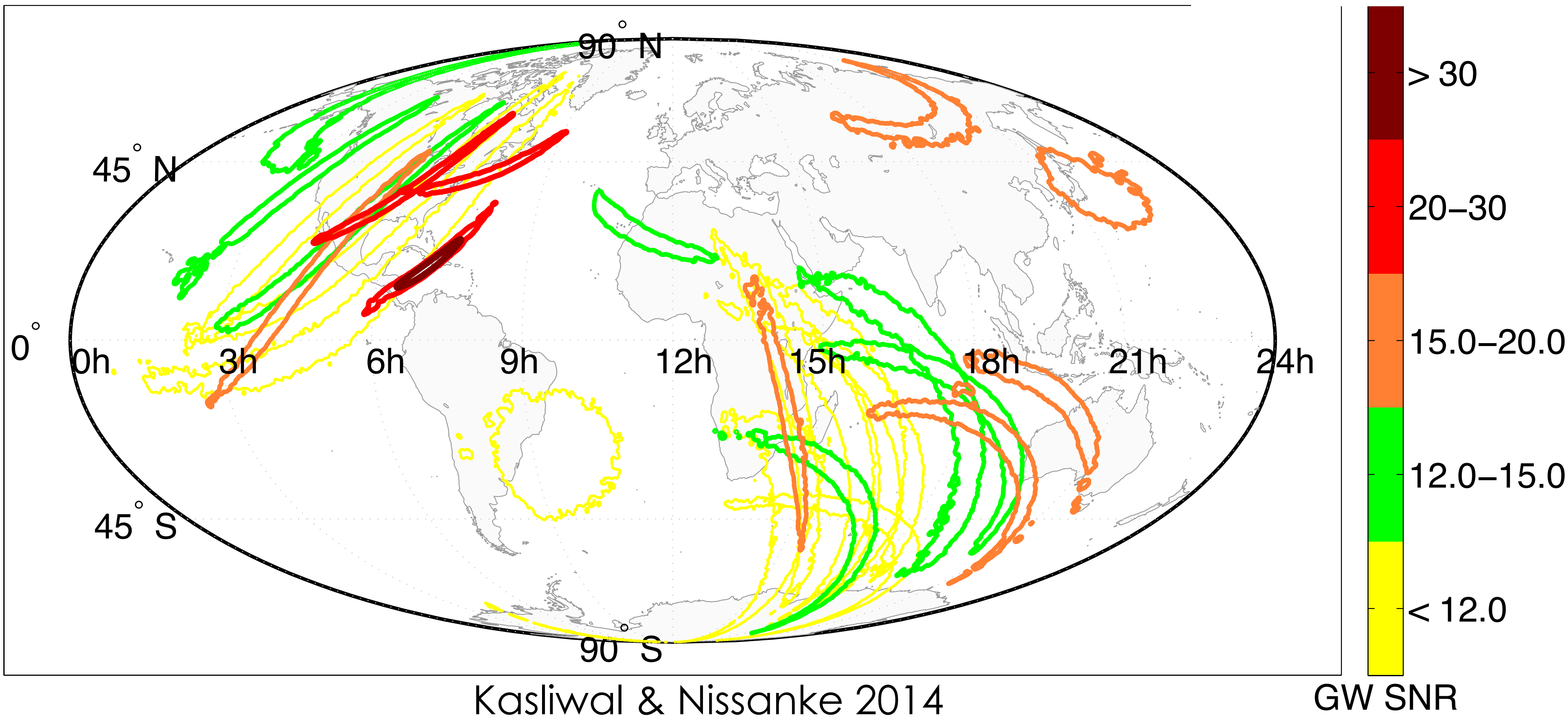
Sites of r-process nucleosynthesis?



Barnes & Kasen 2013

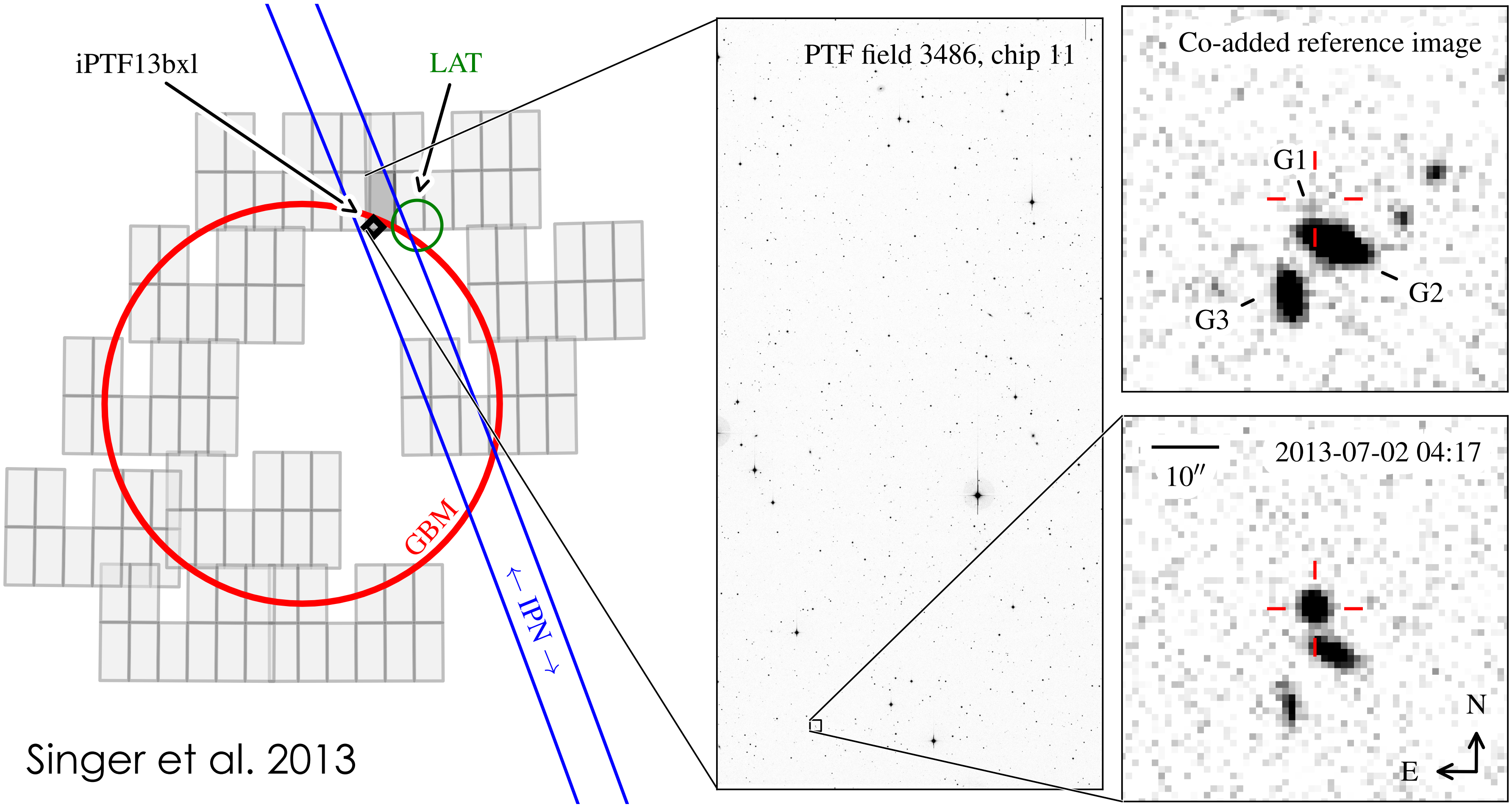
The Challenge: Coarse LIGO Localizations





Kasliwal & Nissanke 2014
(See also Singer et al. submitted)

Proof-of-concept: First optical afterglow in 71 deg^2



Singer et al. 2013

Needle in 70 deg^2 haystack

27004 candidates in subtraction images

26960 are NOT known asteroids

4214 are astrophysical with machine learning score > 0.1

2740 do NOT have a quiescent stellar source

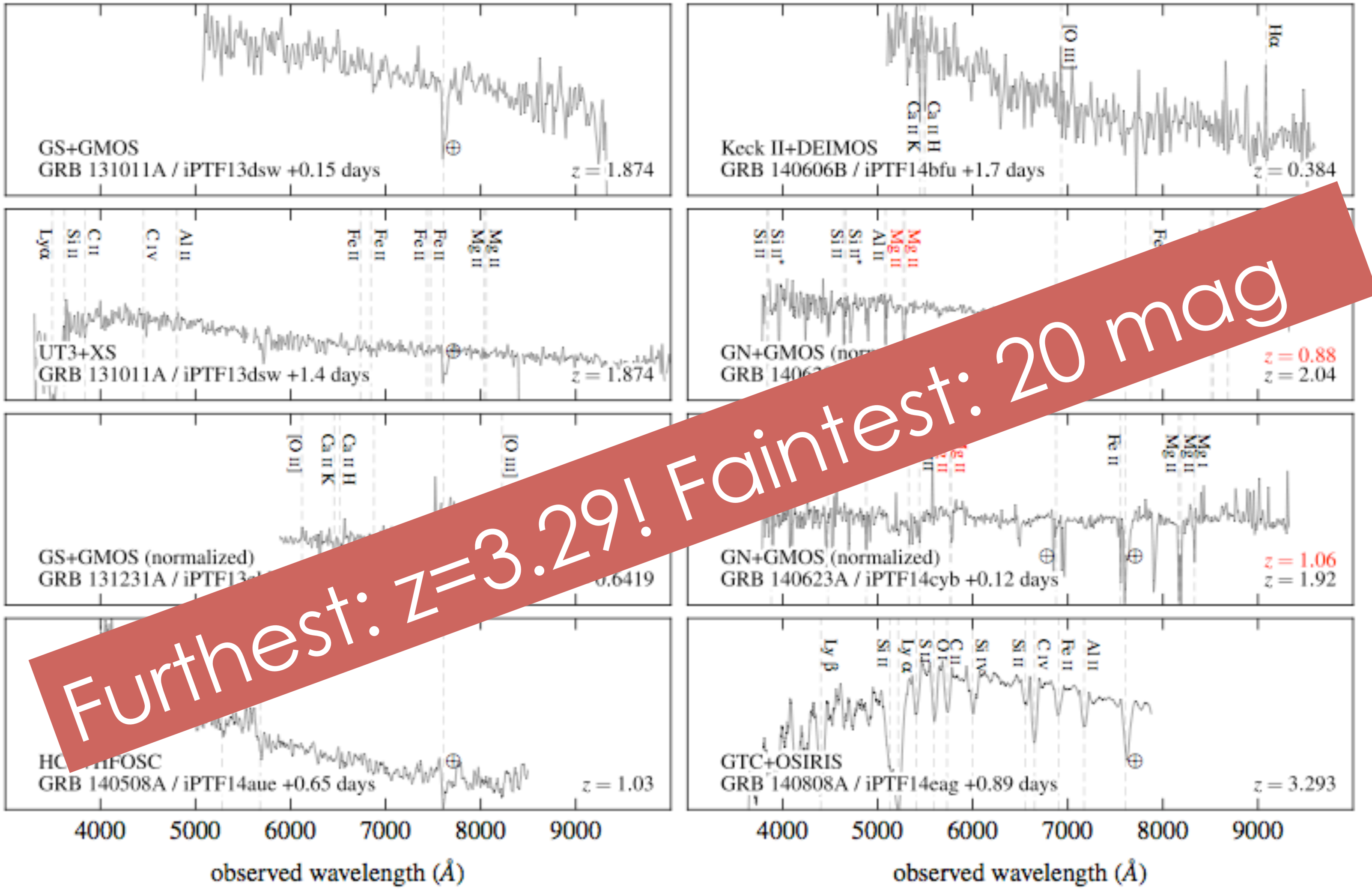
43 are detected in both visits and presented to human scanners

7 are deemed high-value by humans and saved with an iPTF name

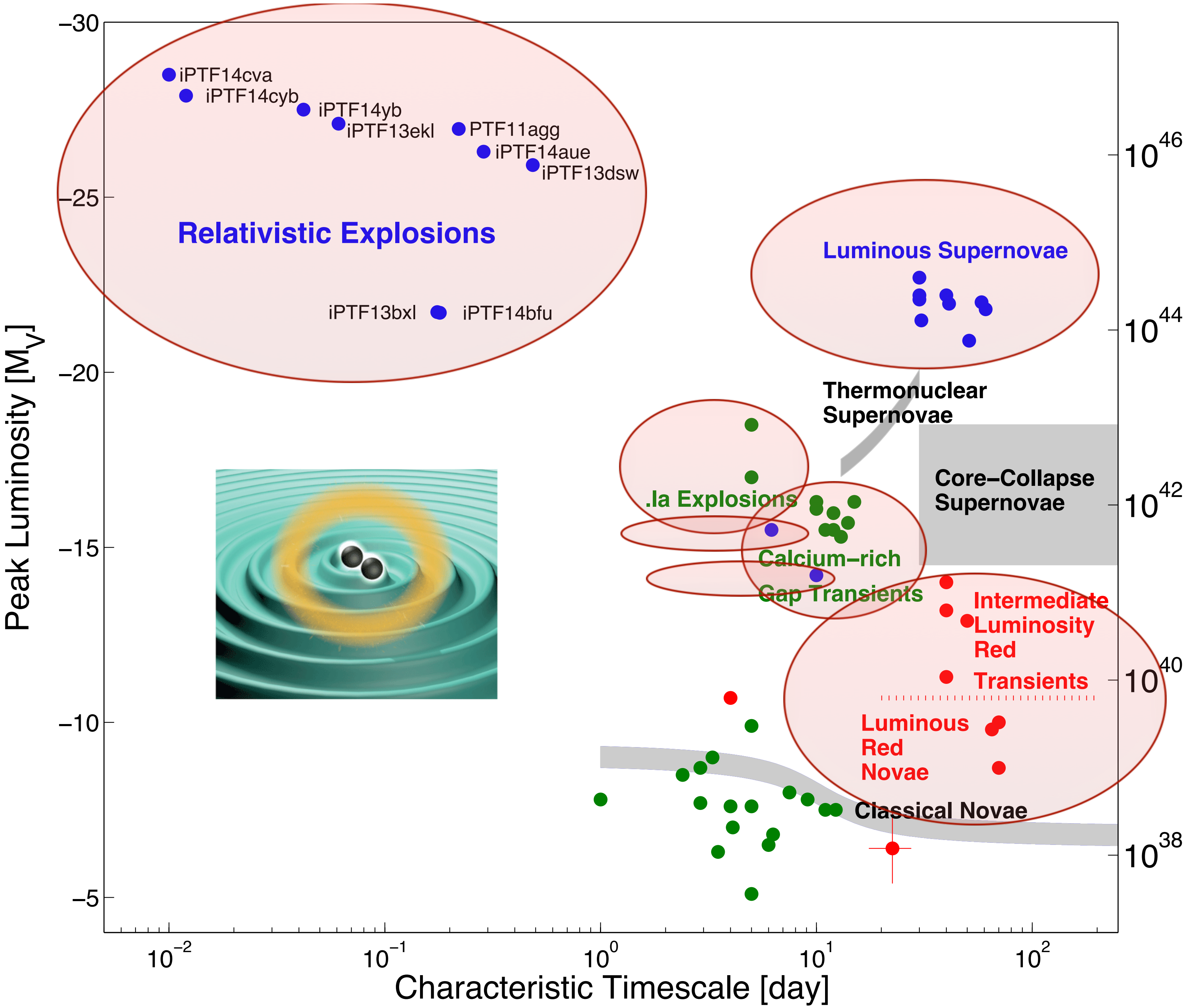
3 are scheduled for follow-up spectroscopic observations

1 is the true afterglow

iPTF-Fermi Afterglow Sample

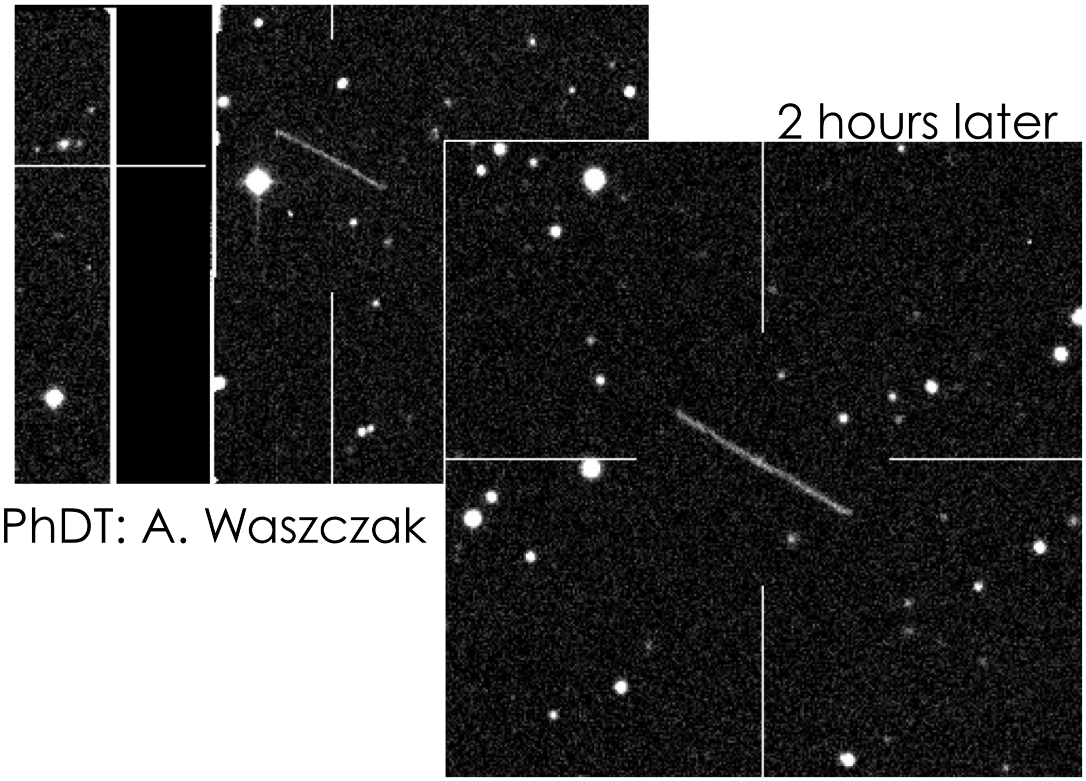


L. Singer, PhdT 2014



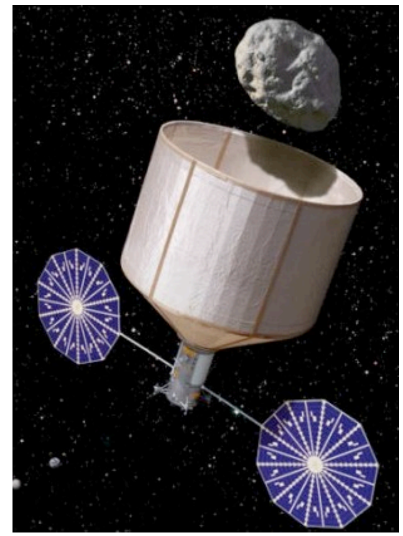
Updated from Kasliwal 2011 (PhDT)

IV. Asteroids:
iPTF discovery of NEA 2014 JG55



2 hours later

PhDT: A. Waszczak

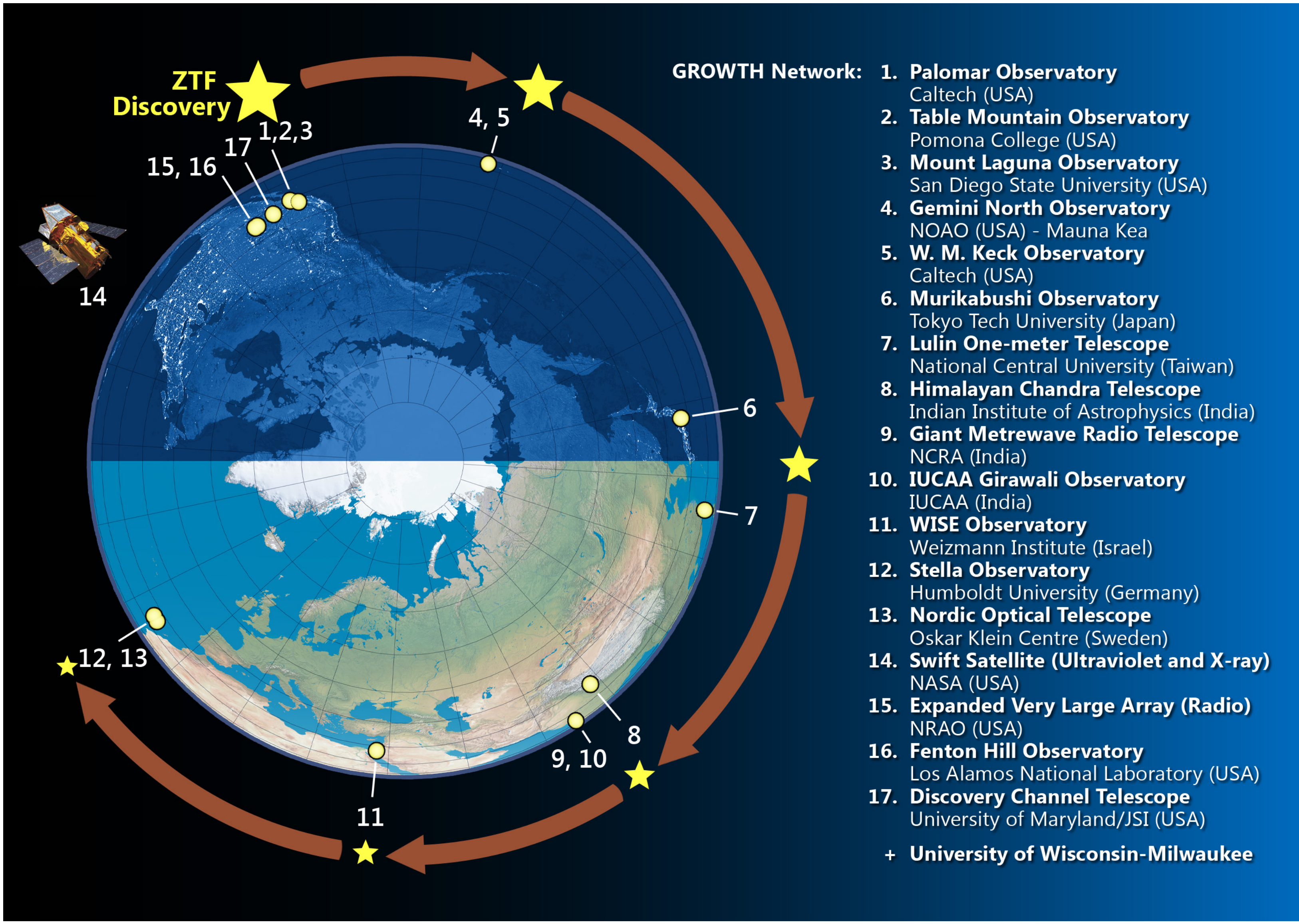


NASA
Asteroid Redirect Mission

This 10m asteroid came within ¼ of the earth-moon distance!
The streak became brighter by 1 mag and faster by 50% in 2 hours.

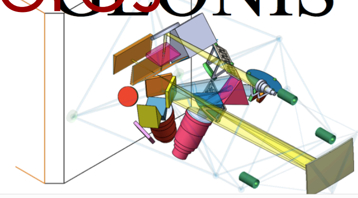
ZTF, NEOCAM and LSST are game-changers

GROWTH: Global Relay of Observatories Watching Transients Happen

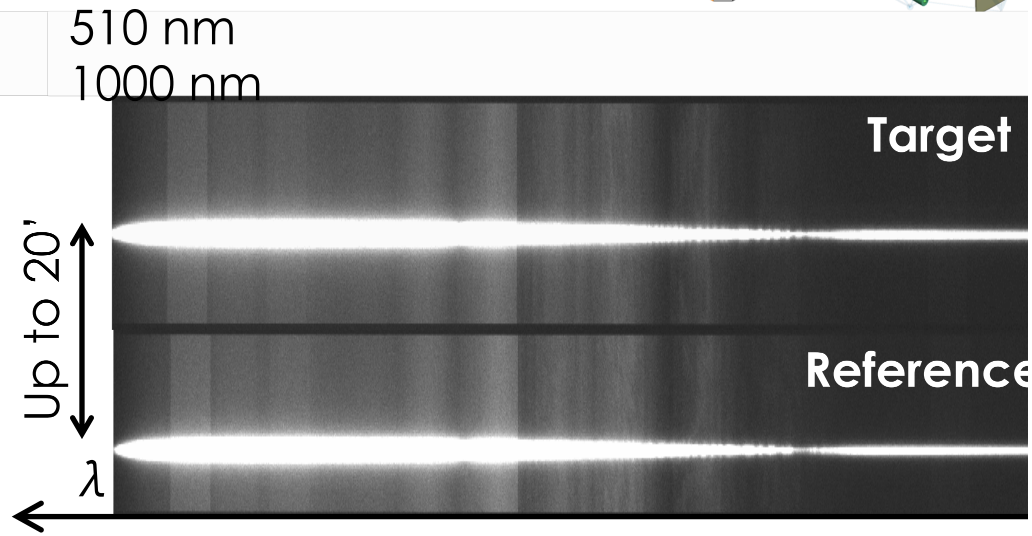


Characterizing Exoplanet Atmospheres with GMOS

GEONIS



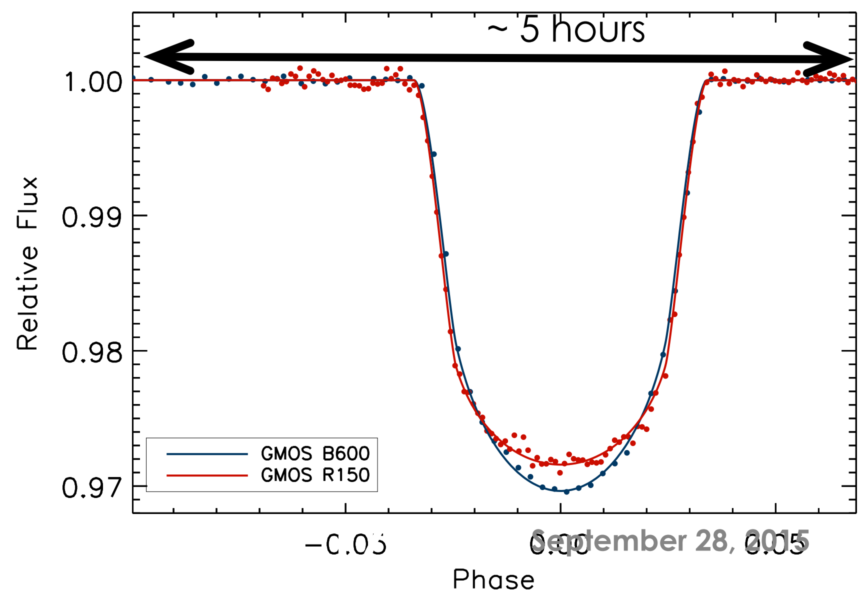
- Target + reference stars: same magnitude & spectral type



- This technique allows us to correct for systematics wavelength by wavelength

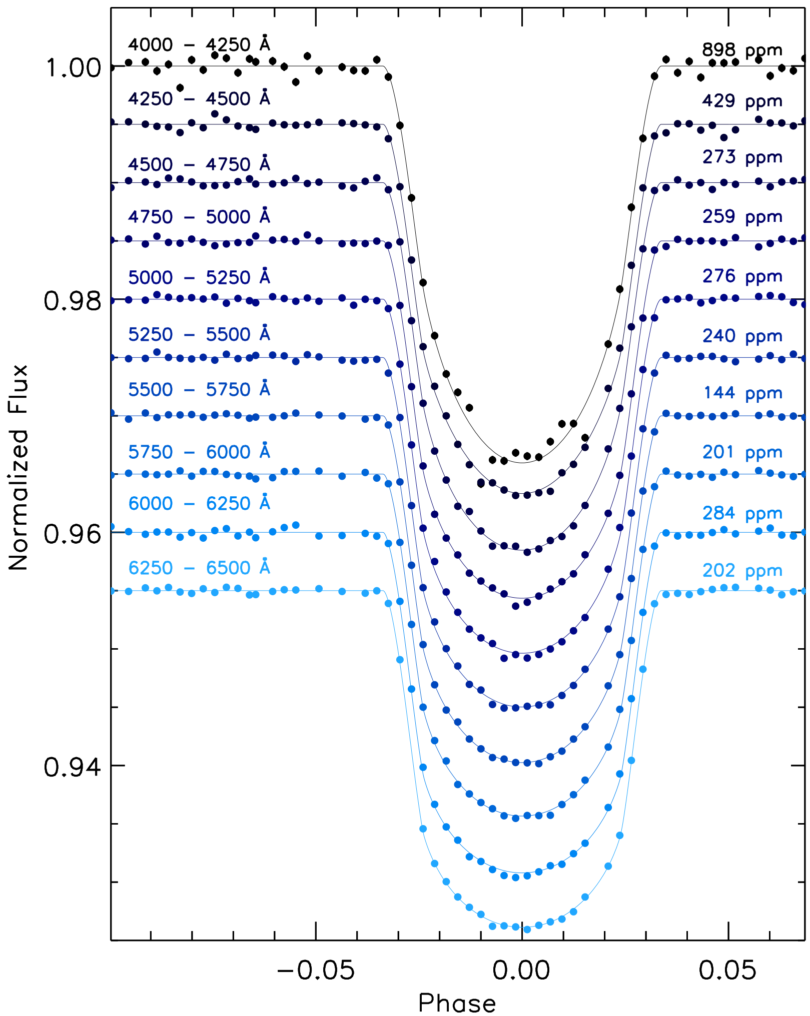
- Wide 10" slit to improve spectrophotometric precision (avoid slit losses)

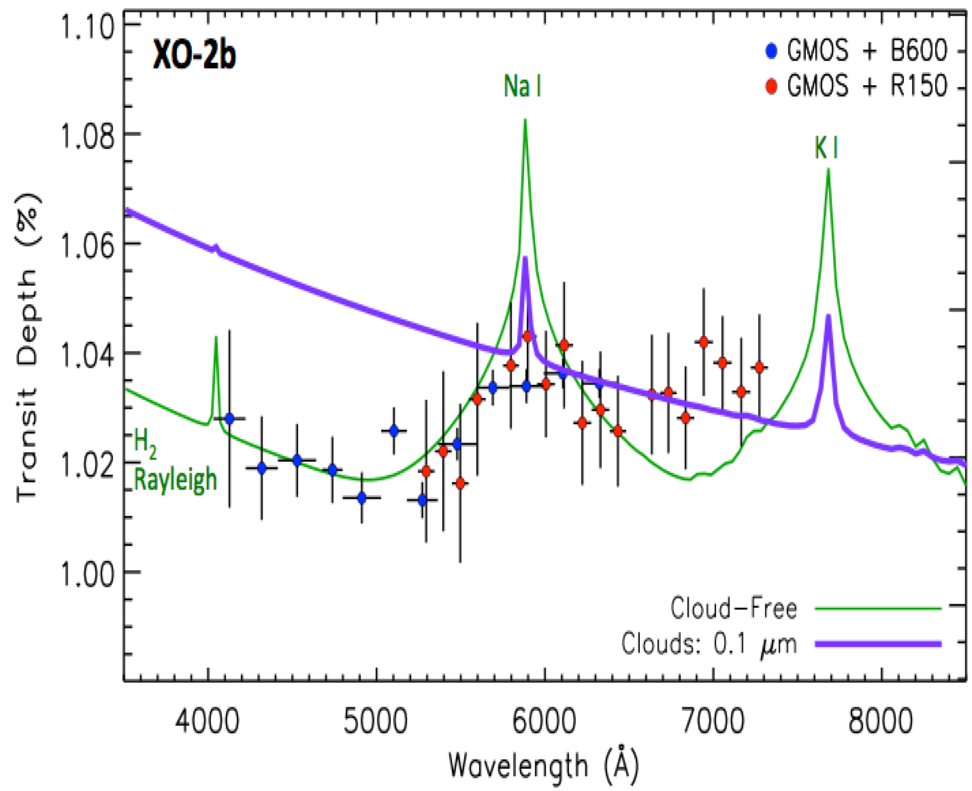
- We get a frame every ~ 50 s and build transit lightcurves



Transmission Spectra

GMOS B600

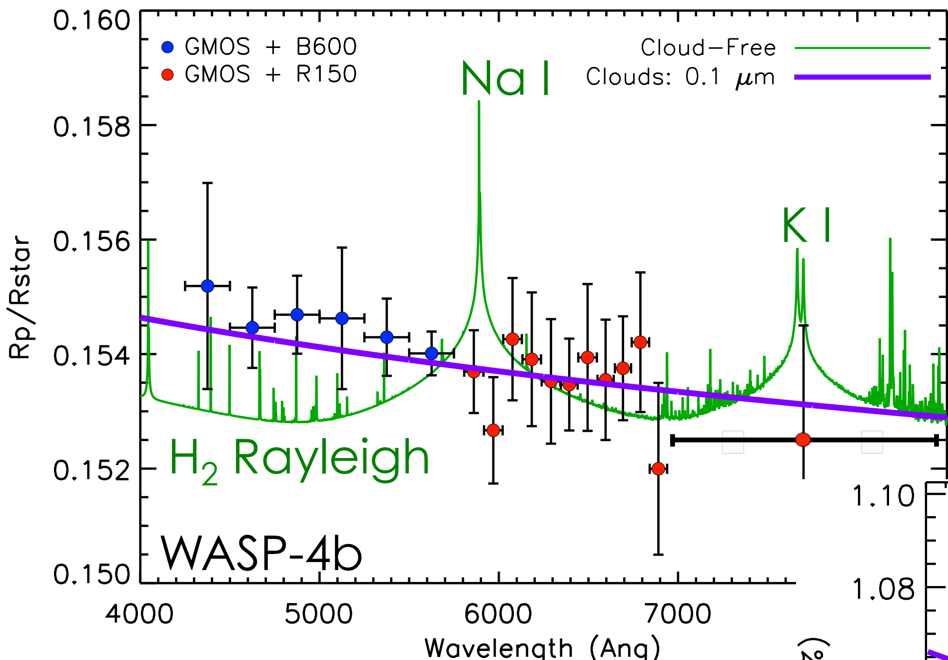




First Results from GMOS observations

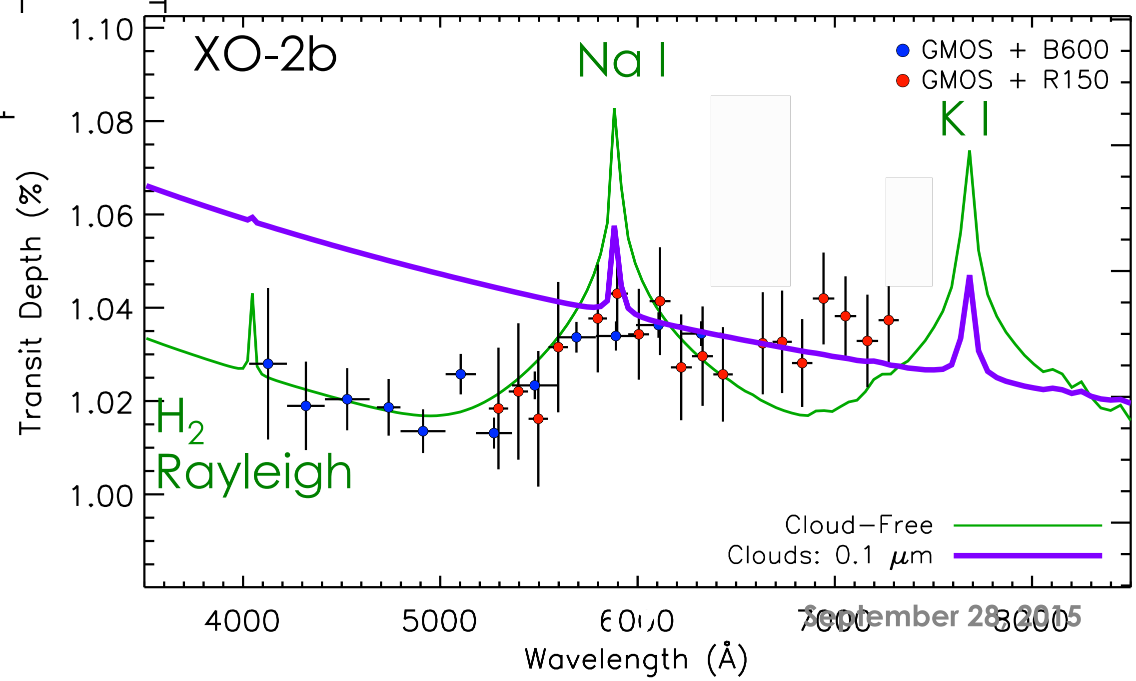
GEONIS

Clouds detected



<u>First Important Result</u>
Two similar planets, yet two different atmospheres

No Clouds, detection of Na



<u>Next step</u>
A large survey with GEONIS

Drives Instrument Stability

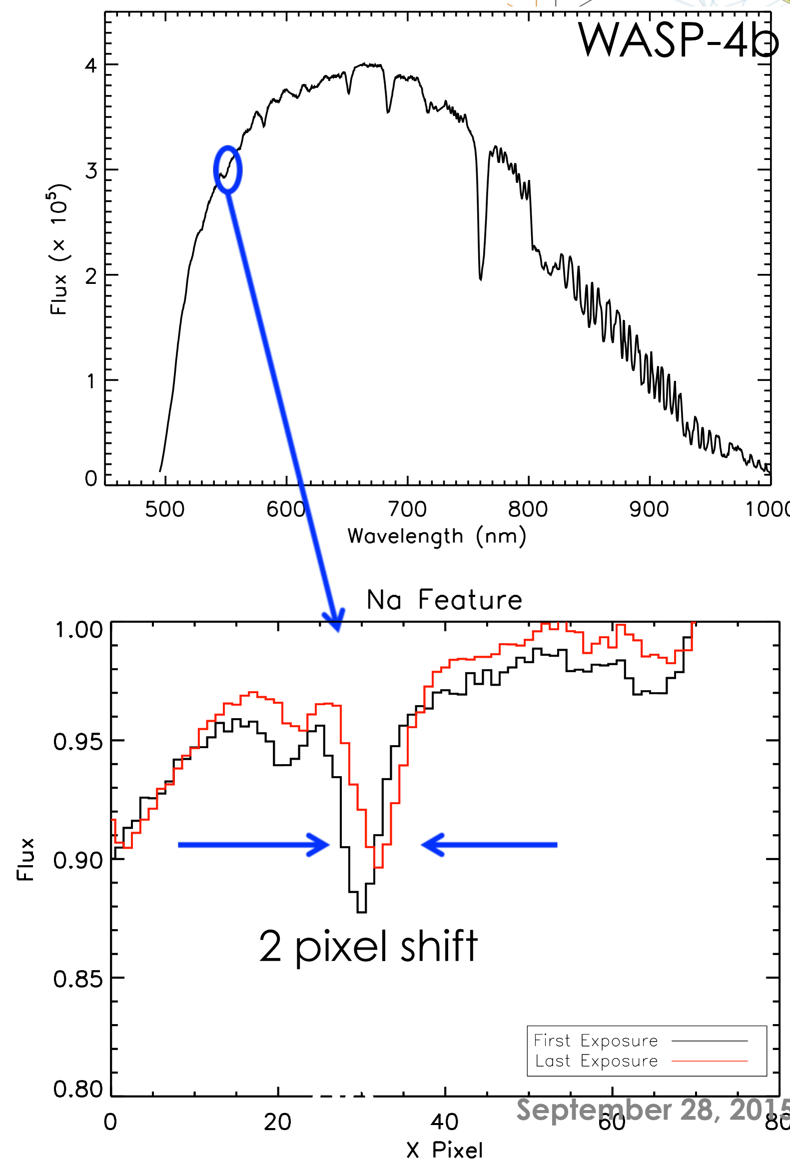
GEONIS

- Requirement:

  200 ppm/10 nm

- Problems: 1) moving instrument (e.g., wavelength solution changes in time, flat-fielding issues, etc…). 2) Fringing

- Solution: Stabilized instrument, better detectors



Workhorse Instrument: Many many Science Cases

- High-redshift galaxies
- High-redshift AGN
- Metal-poor stars
- Weather on brown dwarfs
- Extinction Laws etc.

It's efficient, it's stable, it's wide wavelength coverage, it's low to medium resolution, it's pipelines, it's wide-field, it's wide-slit, it's long-slit…

Thank You

GEONIS: Technical

Outline

- Systems Engineering (IQ, mass, volume, collimator)
- Spectrograph design + modes of operation
- Camera design
- Electronics/Software (control + DRP)
- Risks

GIFS Activities

- Major objectives include
  - Establish technical requirements.
  - Produce feasibility designs.
  - Base on feasibility designs, develop a cost and management model.

Systems Engineering- IQ

Goal: Do not degrade telescope images too much (too much is ~10% for the best quartile seeing). Sample seeing well (~0.2″ pixels).

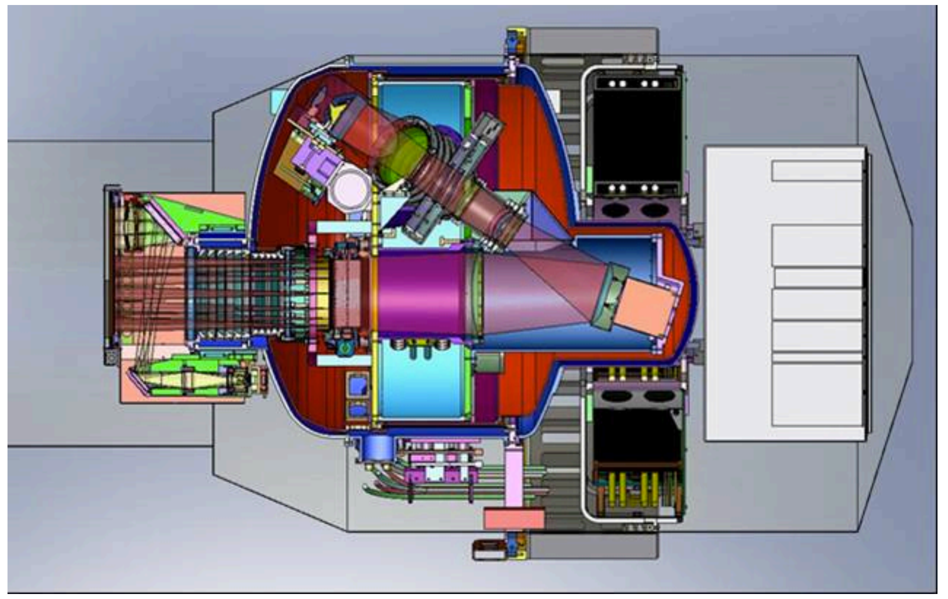
Element	Fraction of budget	FWHM (arcsec)	RMS (″)	RMS (μm)
Requirement	100%	0.25	0.15	12.5
ADC	5%	0.06	0.03	2.8
Collimator + Telescope	30%	0.14	0.08	6.8
Camera	48%	0.17	0.10	8.6
Grating	0%	0.00	0.00	0.0
Rotator	0%	0.00	0.00	0.0
Guider	0%	0.00	0.00	0.0
Flexure	0%	0.00	0.00	0.0
Fabrication (and margin)	10%	0.08	0.05	3.9
Dynamic	7%	0.07	0.04	3.3
Total, FWHM, or RMS value	100%	0.25	0.15	12.5

Systems Engineering:
Mass

Table 9: Mass budget.

System	Mass (% of total)	Mass (kg)
GEONIS	100%	2000 kg
Space Frame	14%	289 kg
Cooling	8%	150 kg
Mirror inserters	8%	150 kg
Grating Turrets	5%	100 kg
Acquisition mechanics	5%	100 kg
Electronics cabinet	5%	100 kg
Electronics	5%	100 kg
Filters and wheel	4%	85 kg
Mask exchanger	4%	80 kg
Camera barrels	3%	66 kg
Camera glass/crystal	2%	43 kg
Double pass prisms	1%	26 kg
ADC	1%	26 kg
Dewars	1%	22 kg
Collimator mirror	1%	20 kg
Single pass prisms	1%	19 kg
Insulating Foam	1%	12 kg
Acquisition	0%	8 kg
Gratings	0%	2 kg
Lowres mirrors	0%	2 kg
Dichroic/mirrors	0%	2 kg
Total	**80%**	**1590 kg of 2000 kg**

GEONIS inherits from ESI + MOSFIRE



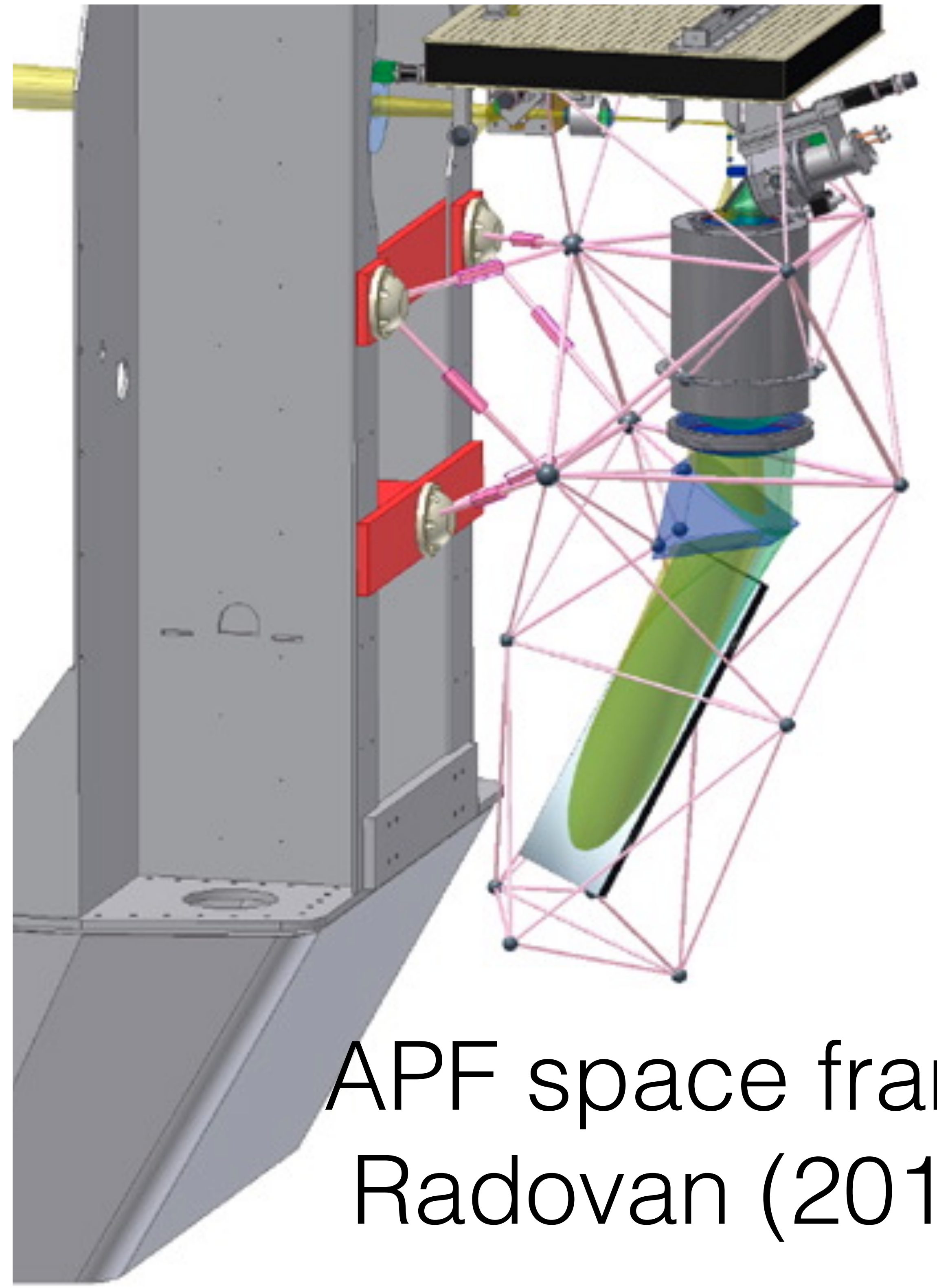
ESI Spectrograph
2.5 Ton
Guesstimate $6 M in 2002
$9 M today

MOSFIRE Spectrograph
2.725 Ton (exceeded 2.5 T)
$16 M in 2015
65% of mass in structure

Both instruments employee fast cameras, big pupils

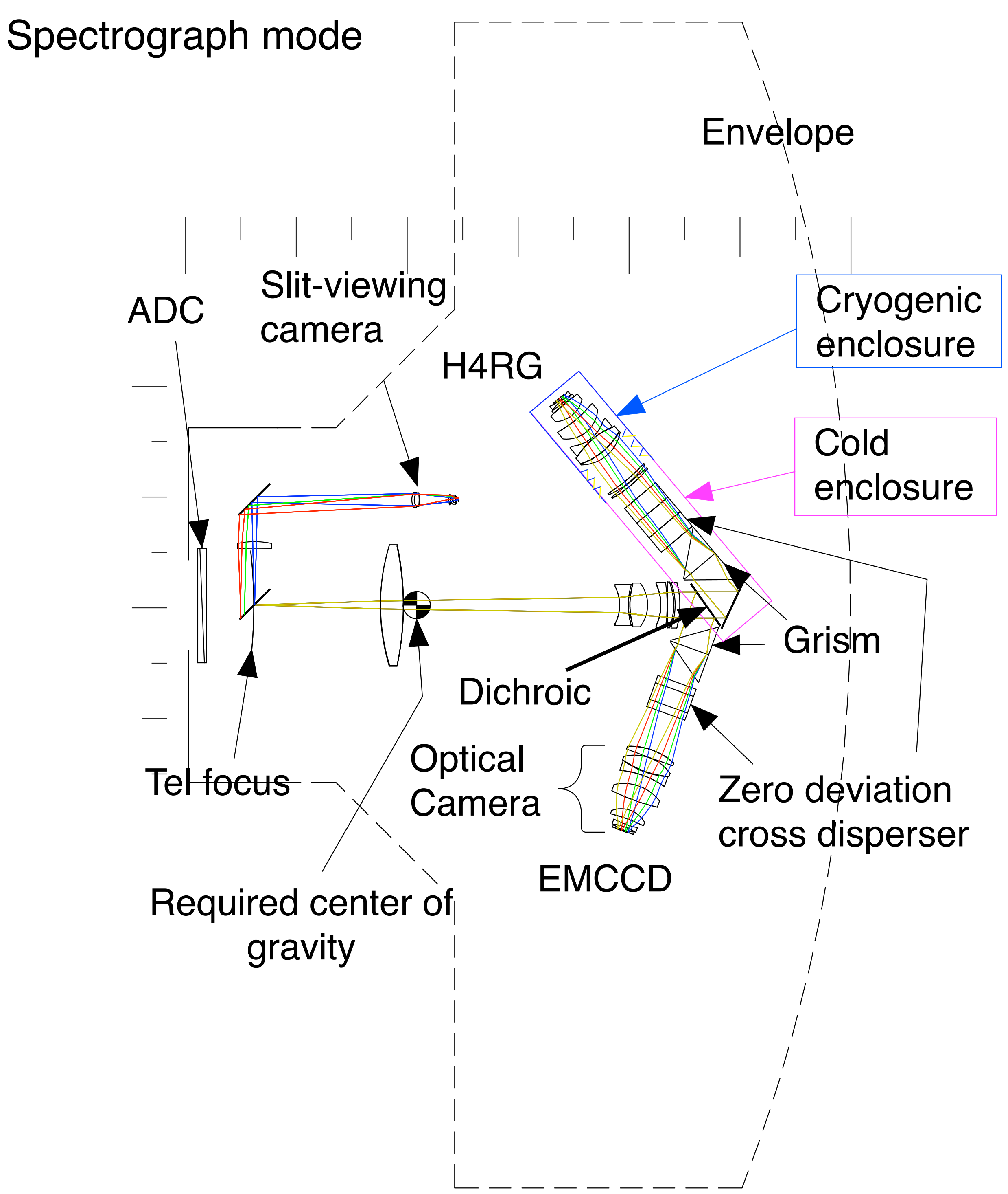
Space Frame Design

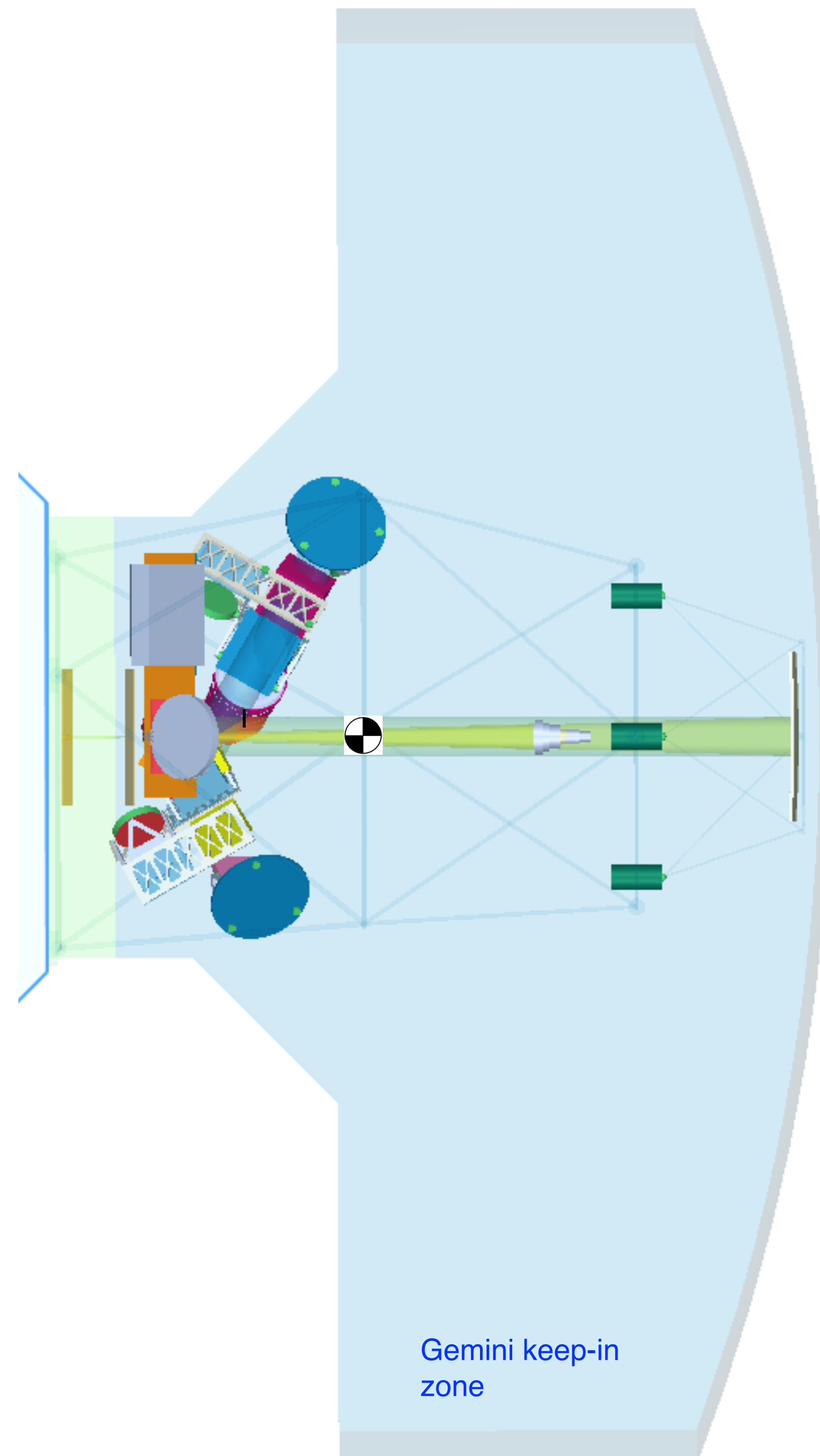
- GEONIS requires high stiffness and low hysteresis.
- The mass requirement of 2 T leads to a high efficiency design.
- Determinate space frames are, by definition, modeled using simple linear models.
- We see no alternative approach.
- Currently a concept.



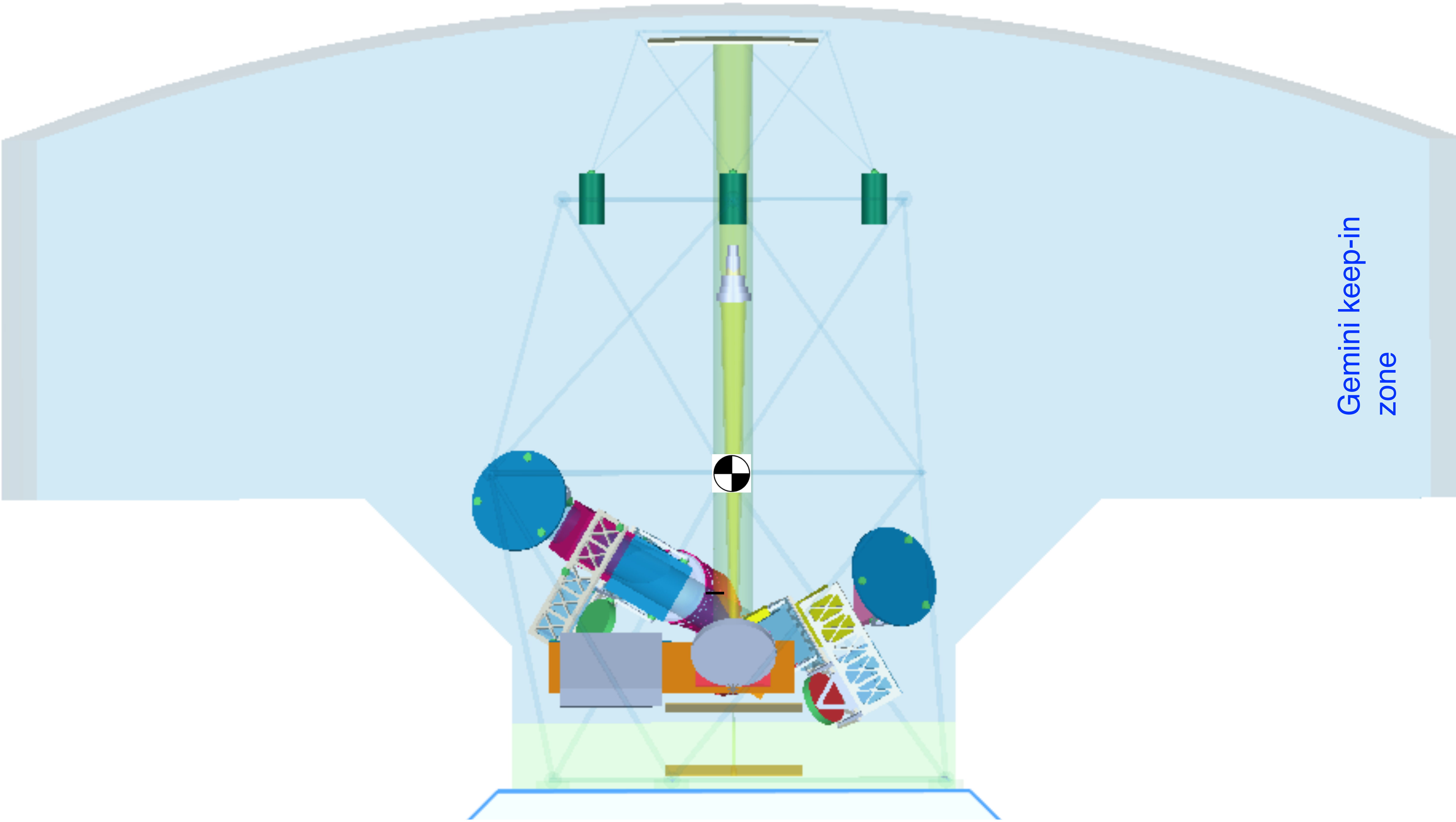
APF space frame
Radovan (2010)

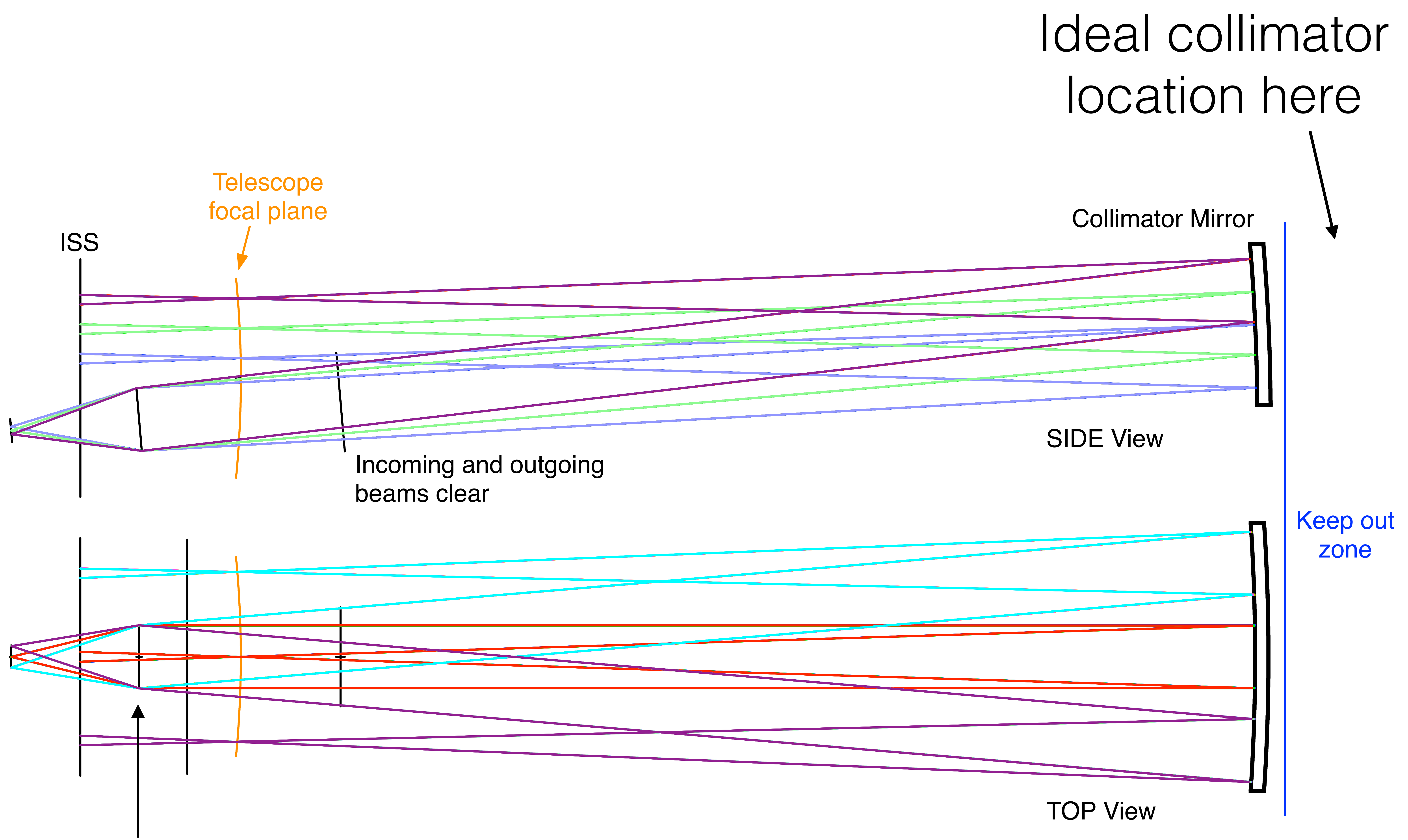
Design- Volume + COM



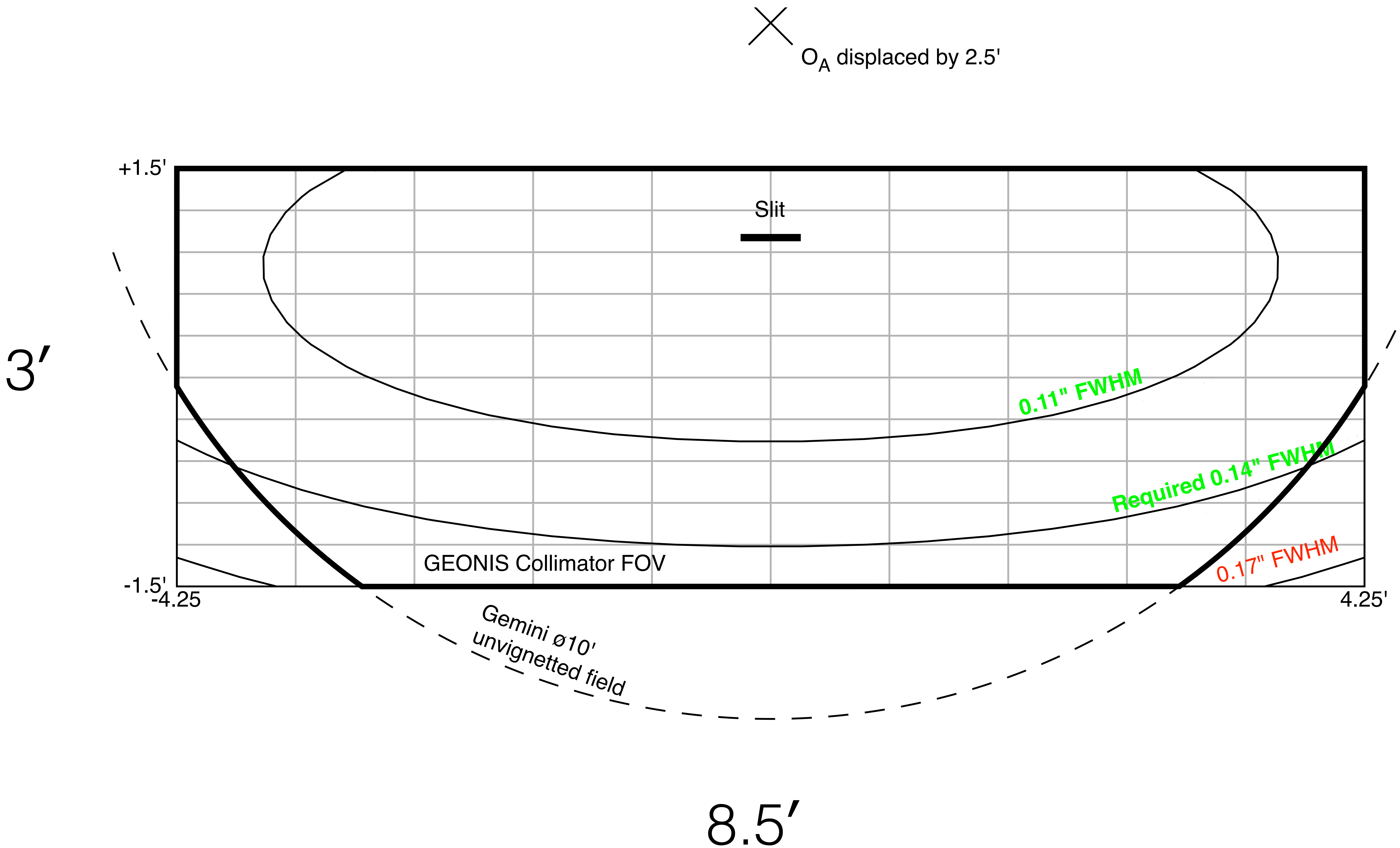


100 mm collimator-to-keep-out-zone distance

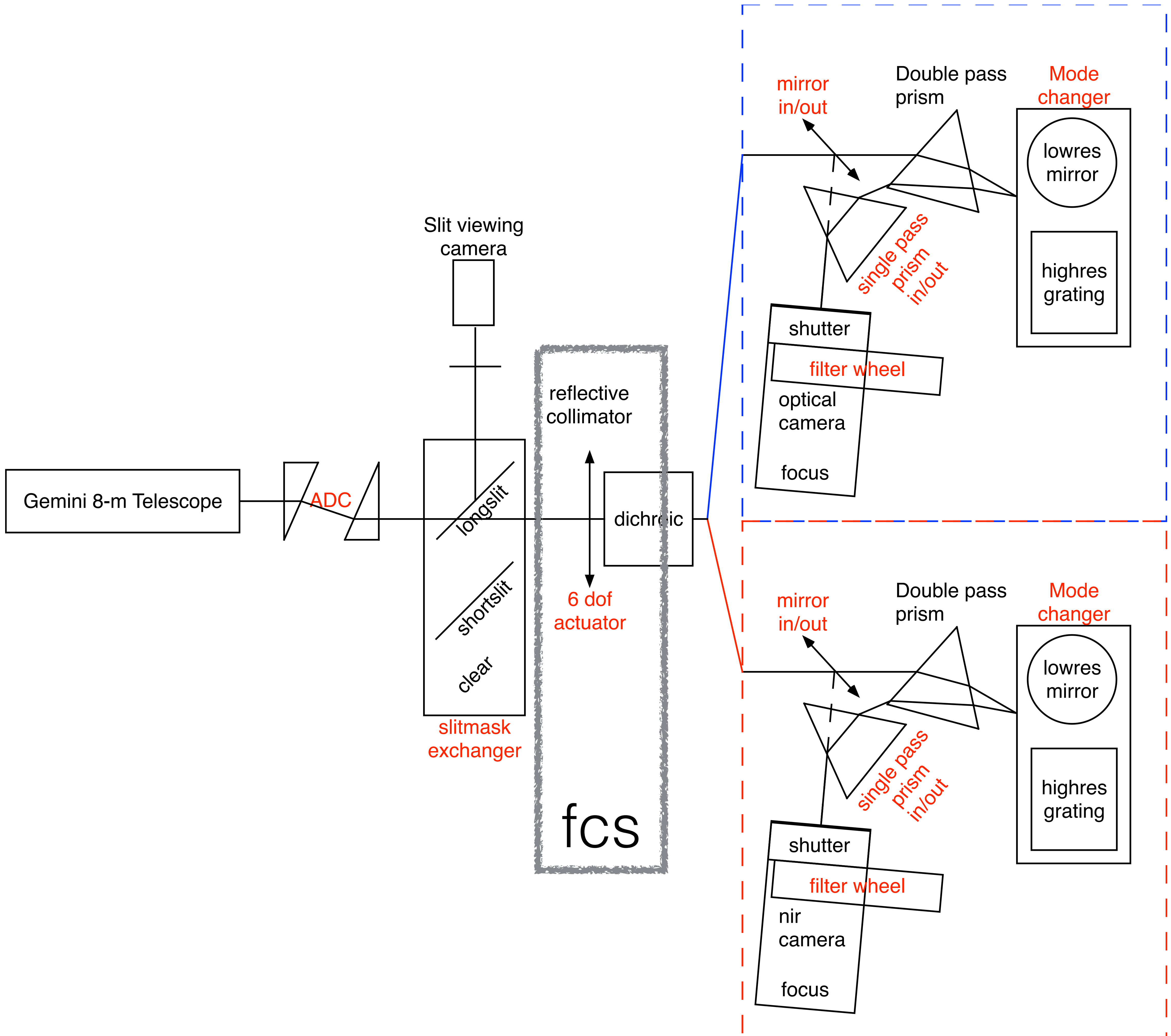


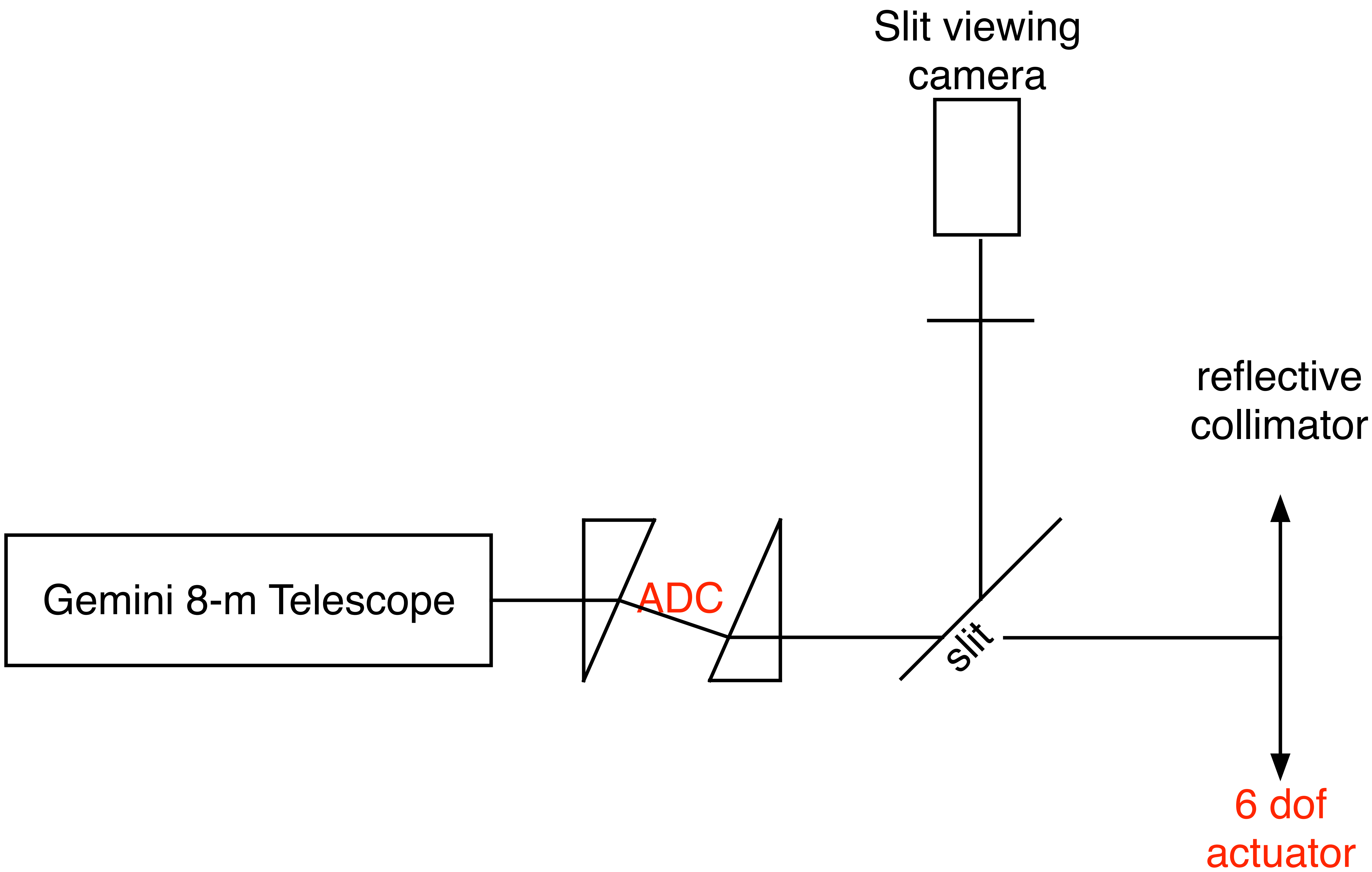


Pupil Diameter = Collimator distance/(f/#)$_{telescope}$


O_A displaced by 2.5'
+1.5'
Slit
3′
0.11" FWHM
Required 0.14" FWHM
0.17" FWHM
GEONIS Collimator FOV
-1.5'
-4.25
4.25'
Gemini ø10'
unvignetted field
8.5′

Modes of Operation

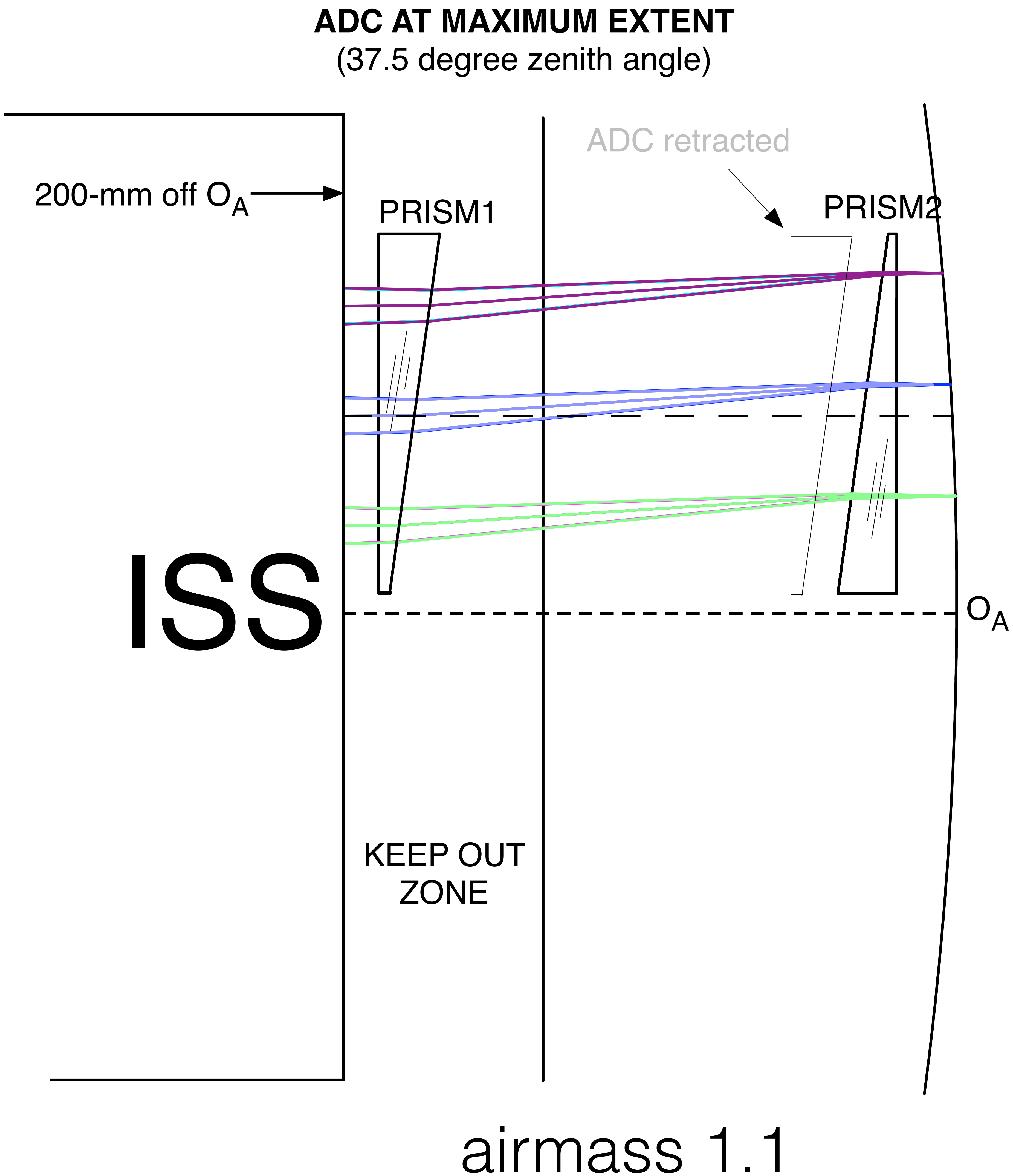

Gemini 8-m Telescope
ADC
Slit viewing camera
longslit
shortslit
clear
slitmask exchanger
reflective collimator
6 dof actuator
dichroic
fcs
mirror in/out
Double pass prism
Mode changer
lowres mirror
highres grating
single pass prism in/out
shutter
filter wheel
optical camera
focus
mirror in/out
Double pass prism
Mode changer
lowres mirror
highres grating
single pass prism in/out
shutter
filter wheel
nir camera
focus



Slit viewing
camera
reflective
collimator
Gemini 8-m Telescope
ADC
slit
6 dof
actuator

ADC Design

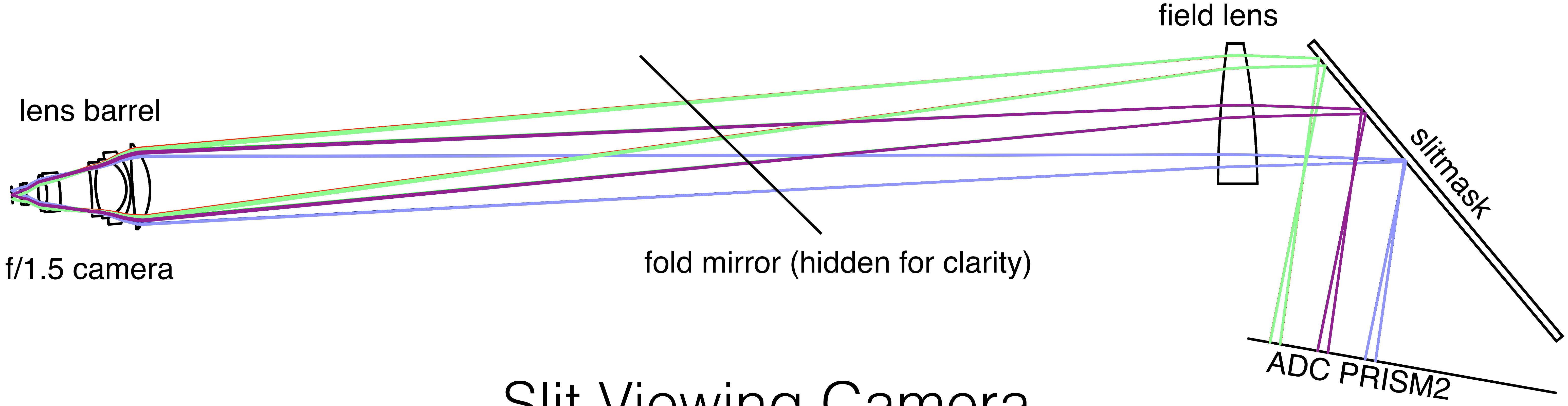
1. ADC does not package well when put near collimator exit pupil.
2. Explored only linear (trombone) ADC because of familiarity.
3. Linear ADC performs well, but requires exception from observatory.
4. Linear ADC shifts collimator exit pupil. No problem for imaging or transients, but loss of precision in exoplanets.
5. Apex angle dictates IQ + exit pupil shift.



ADC Limitations

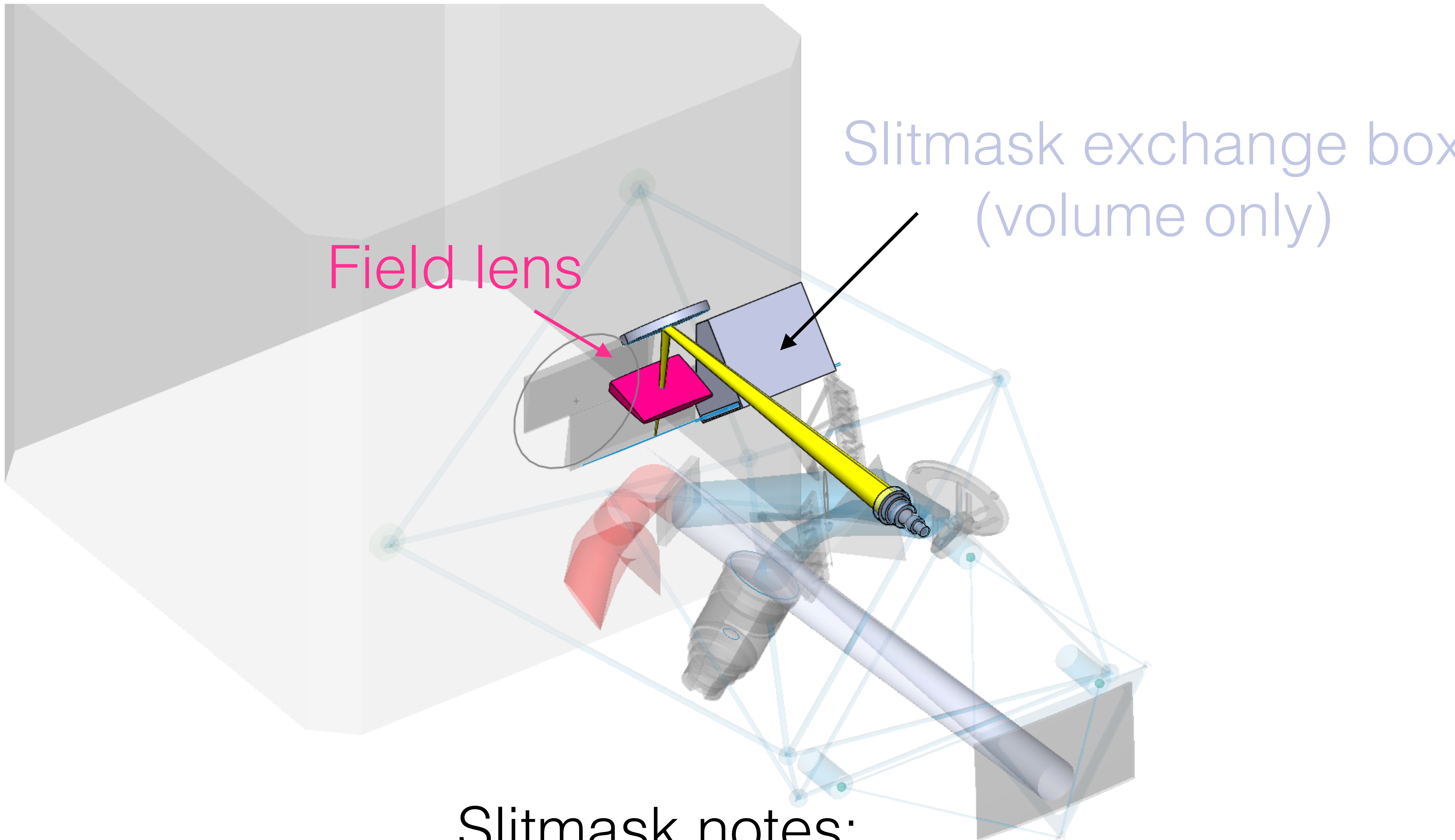
- Baselined ADC is designed to minimize image quality degradation. Steeper apex angles cause more optical damage but work over broadest airmass range.
- Baselined ADC is perfect to airmass 1.26 and 80% efficient at airmass 1.56 (70% of the sky to airmass 2).
- More trade space to explore in the future.

Slit viewing camera



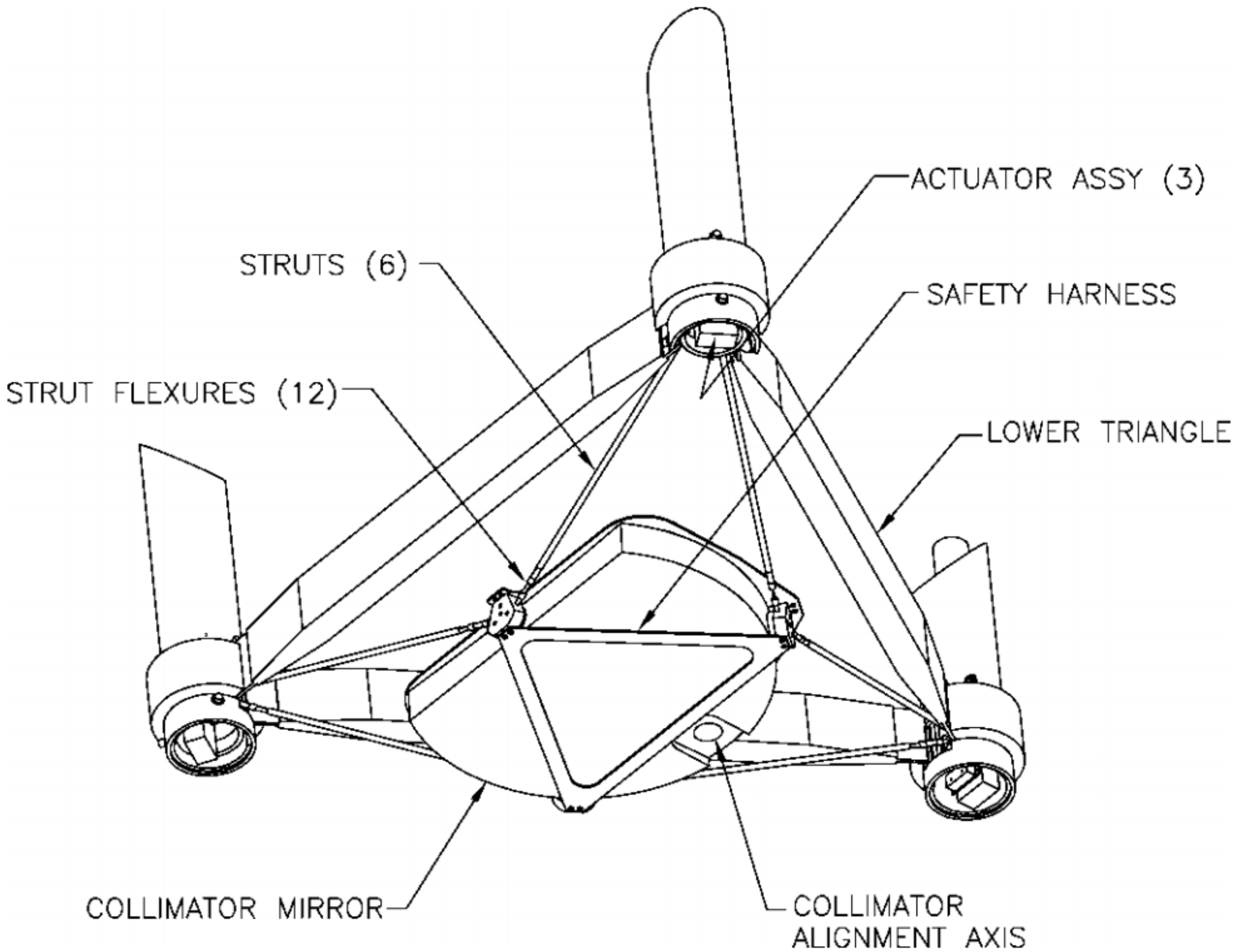
Slit Viewing Camera

- Optically fast system
- Baseline is all custom optics; likely a COTS lens will be OK.
- A custom field lens is required.
- Slit viewer could be converted into a low-order WFS, but emCCD bandwidth limited to 50 Hz.

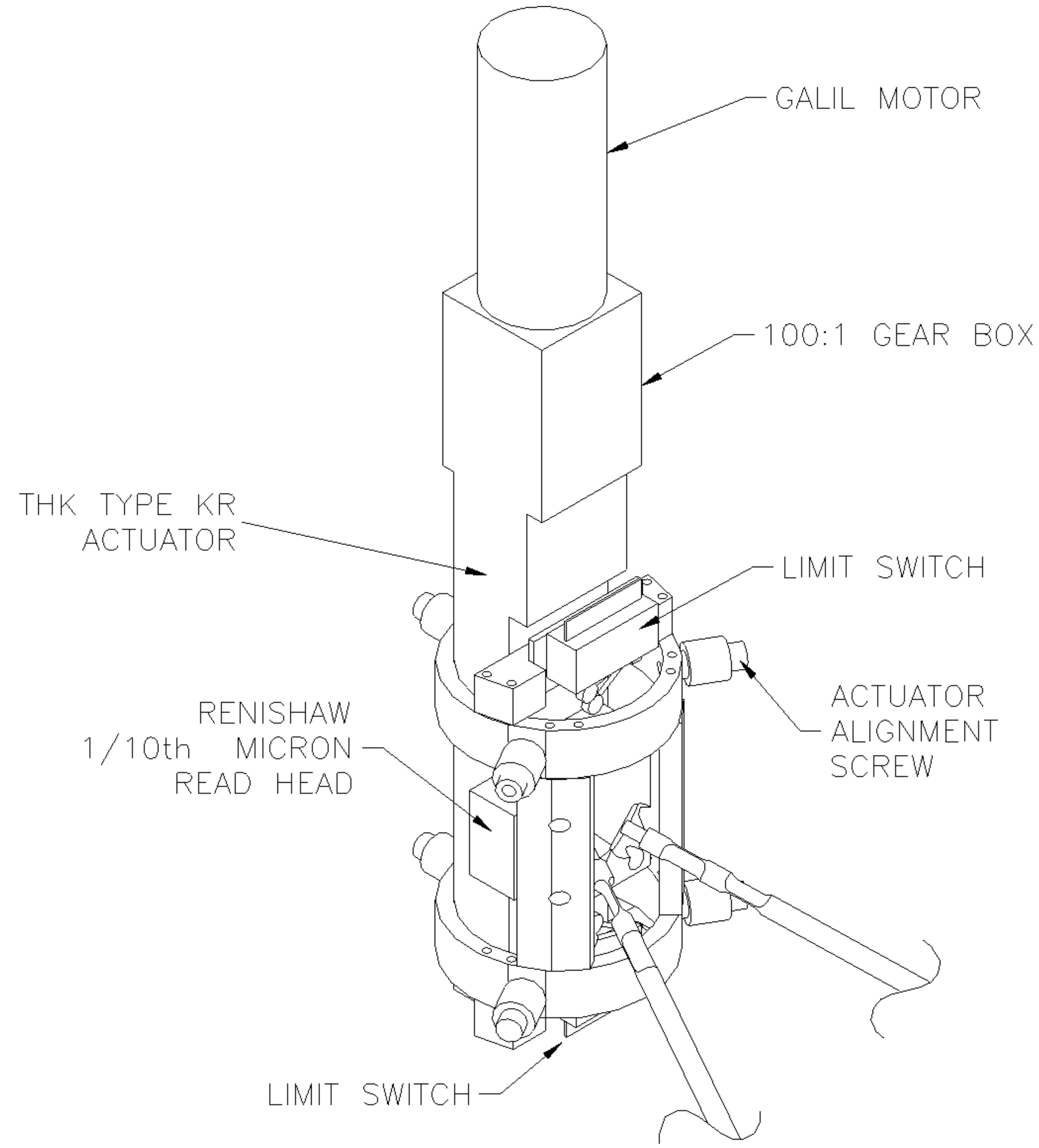


Slitmask notes:
Current baseline is 4 slitmasks; but likely more are needed.
From volume considerations a 10-unit slitmask system is fine.

ESI Flexure compensation



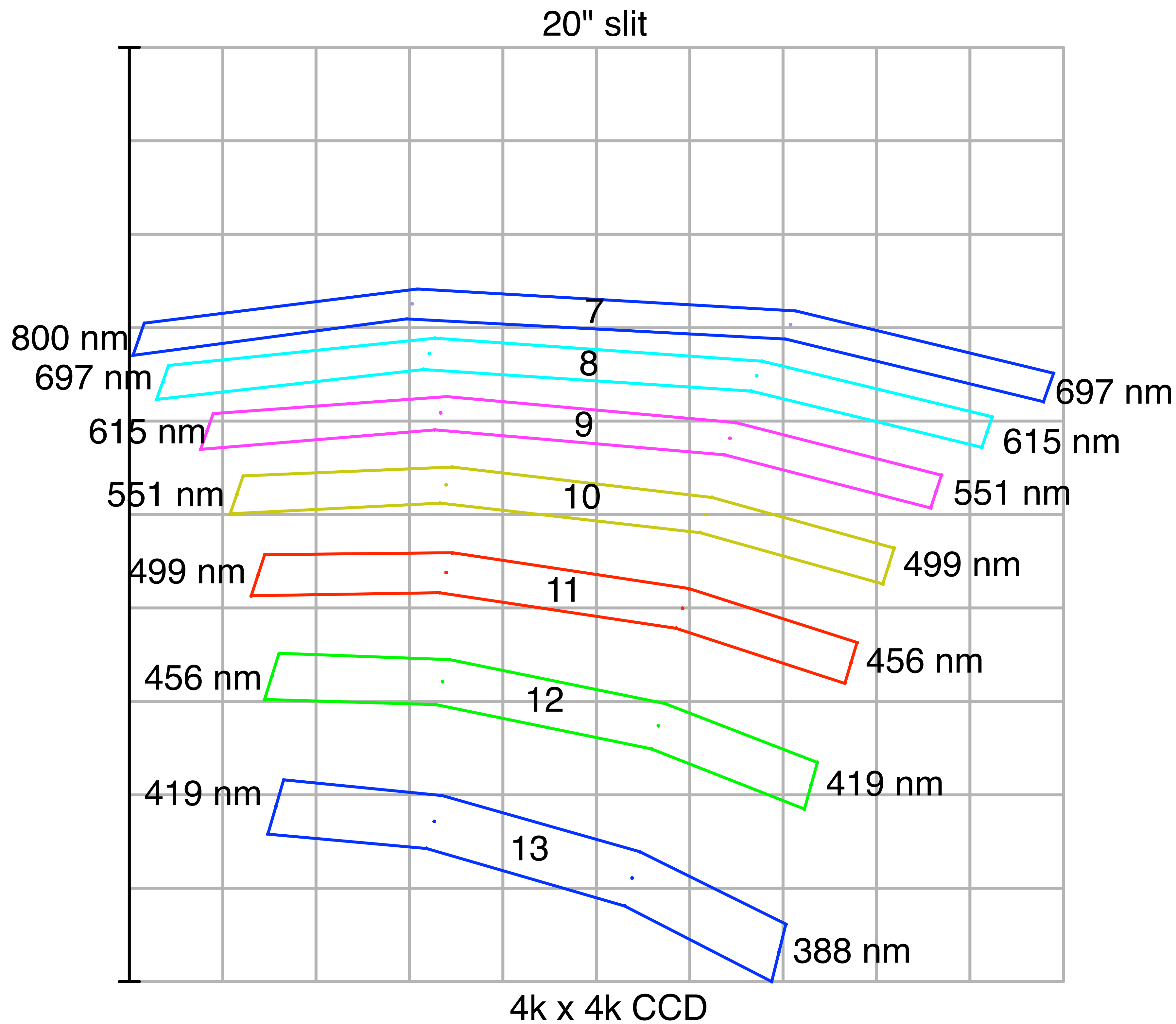
Sheinis+ (2002)



Radovan+ (2002)

Echelette mode: Why? What?

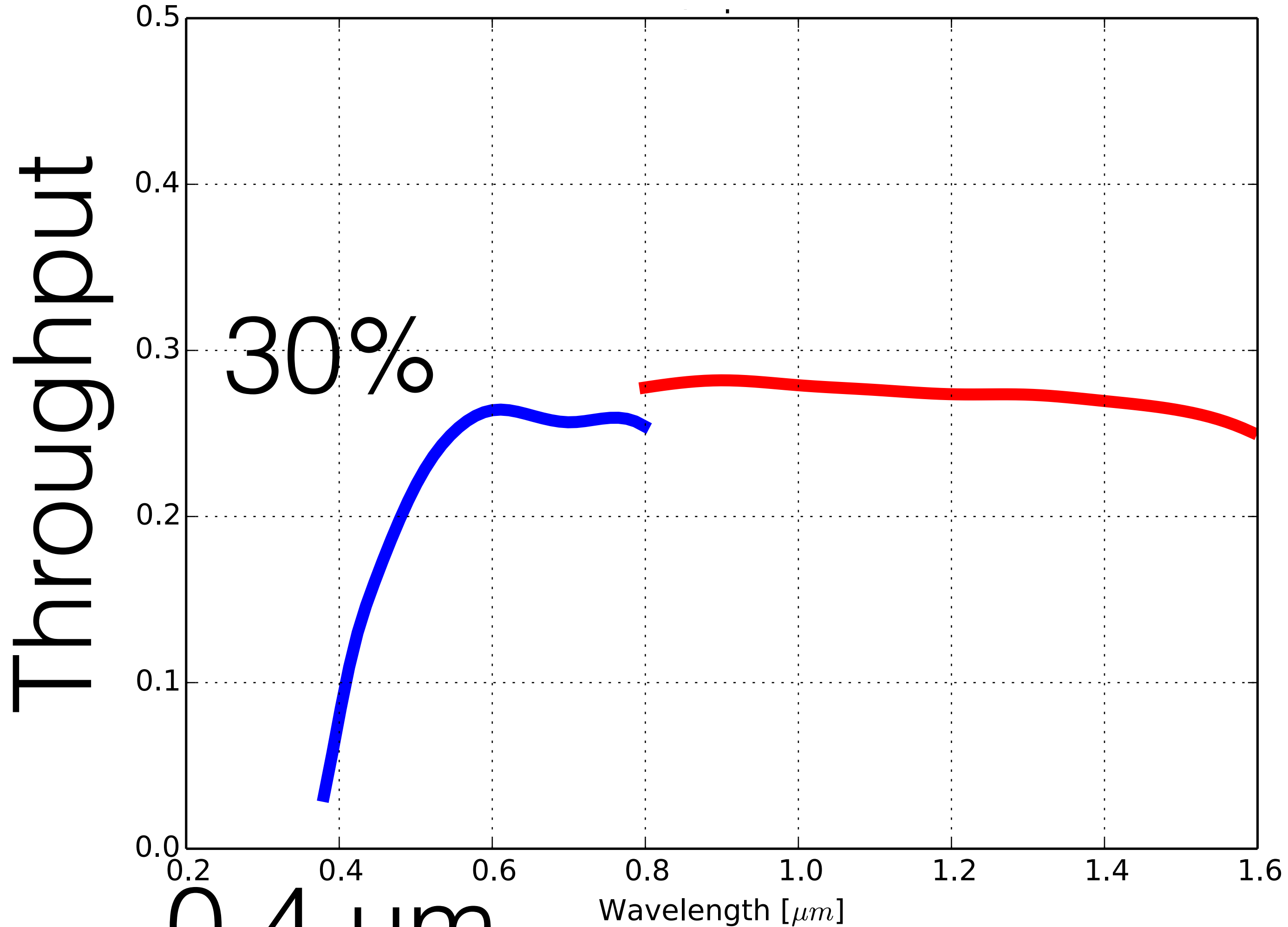
- Transients
- Efficient
- Rock solid
- 400 — 1600 nm (baselined)
- 25″ x 1″ slit
- R~4,000 (hardware)
- Software adapted resolution



Throughput

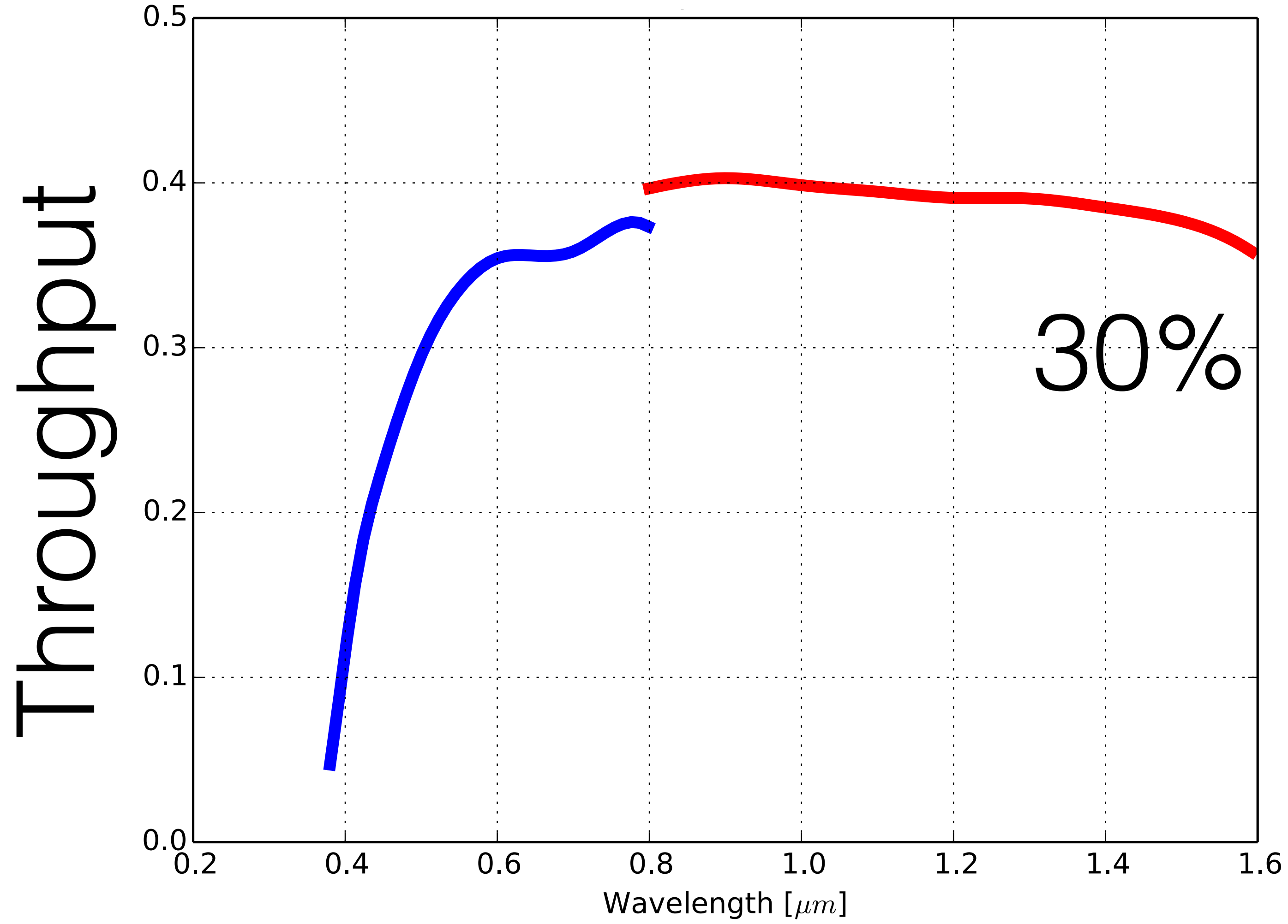
- Possible to increase wavelength range further in blue, throughput will be poor there.

Echelette Mode

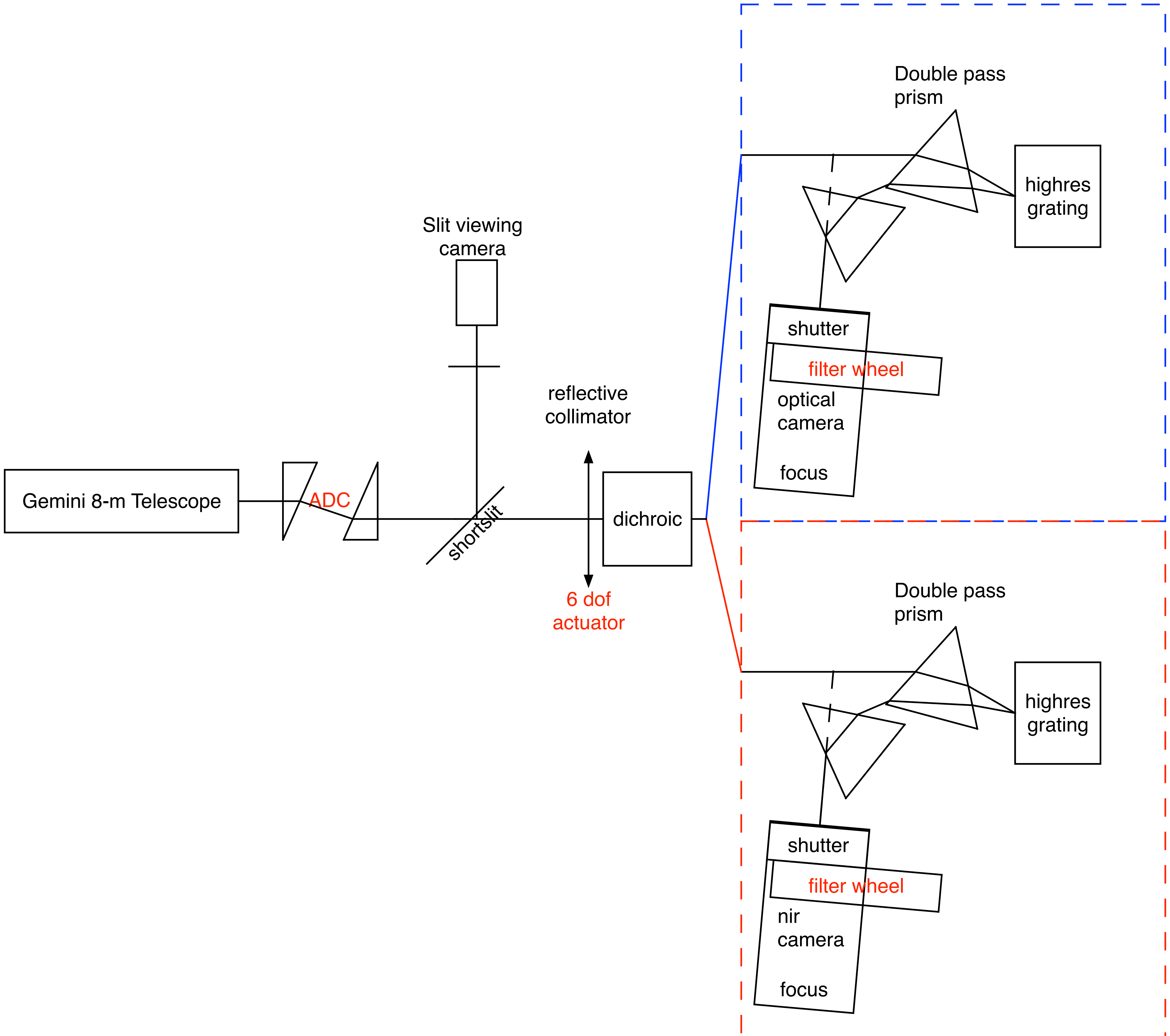


0.4 µm

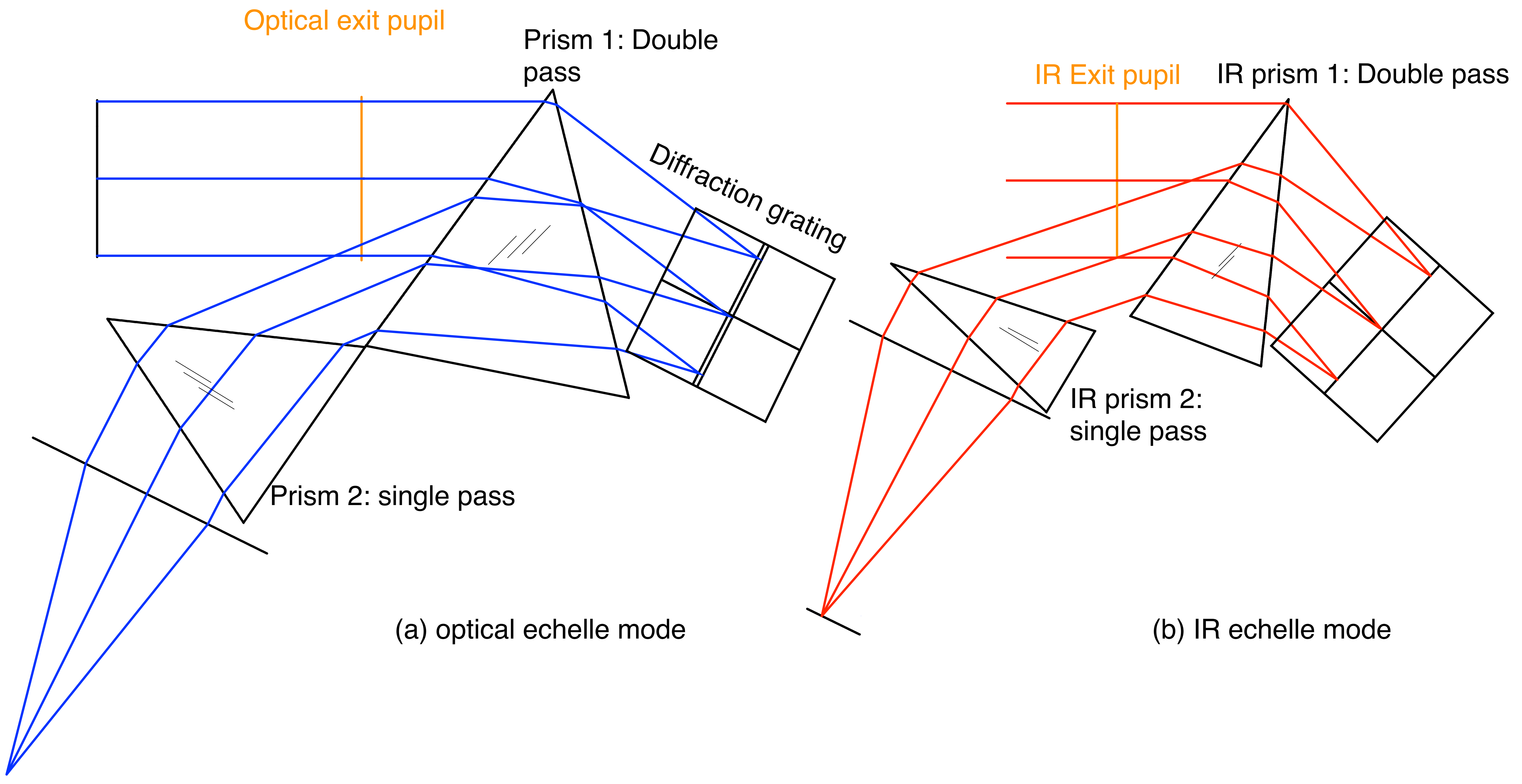
Lowres Mode



M1 × M2 × Atm (1.2) × 20% Slit loss × Efficiency

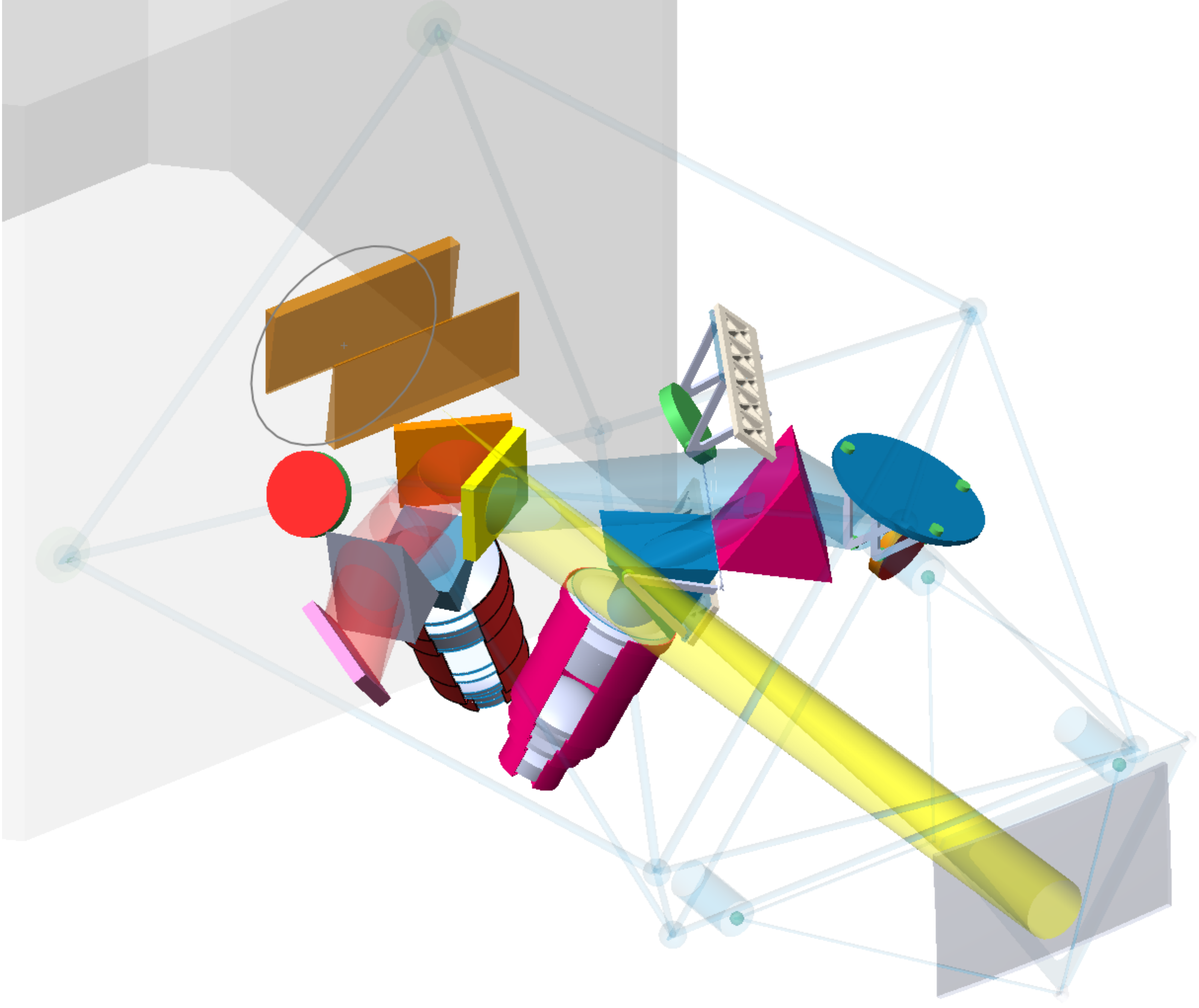


Double pass
prism
highres
grating
shutter
filter wheel
optical
camera
focus
Slit viewing
camera
reflective
collimator
Gemini 8-m Telescope
ADC
shortslit
dichroic
6 dof
actuator
Double pass
prism
highres
grating
shutter
filter wheel
nir
camera
focus



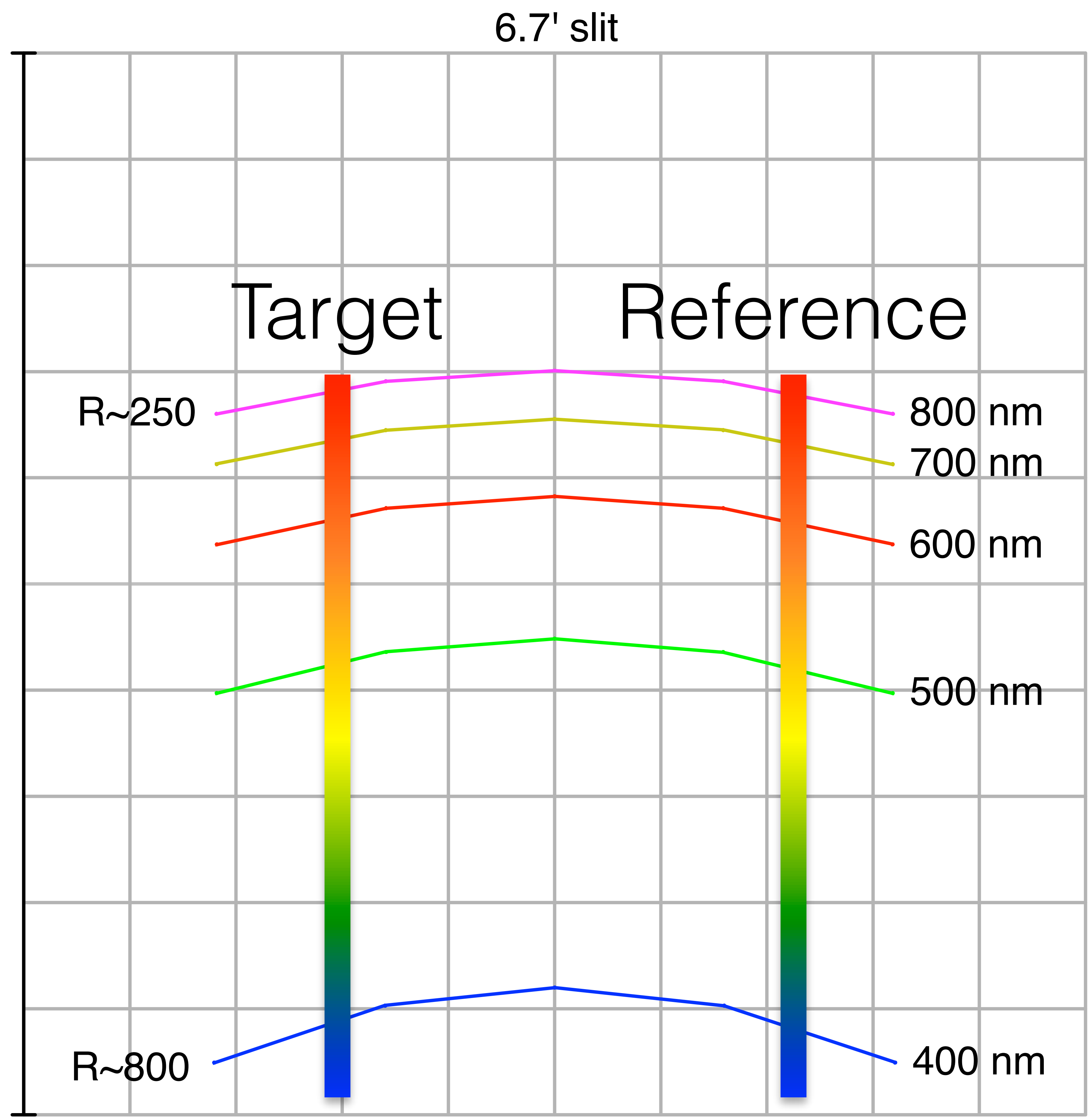
(a) optical echelle mode

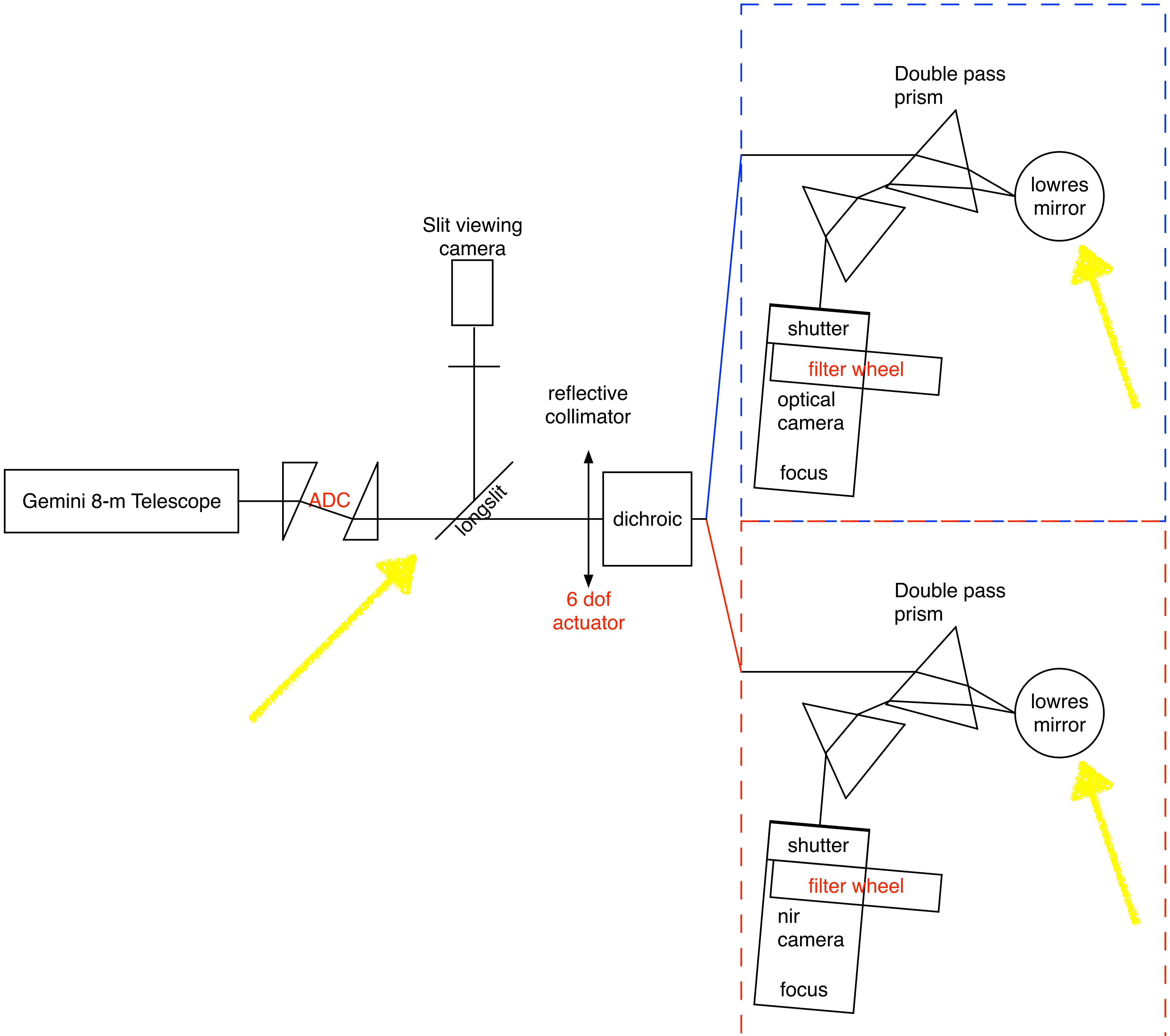
(b) IR echelle mode

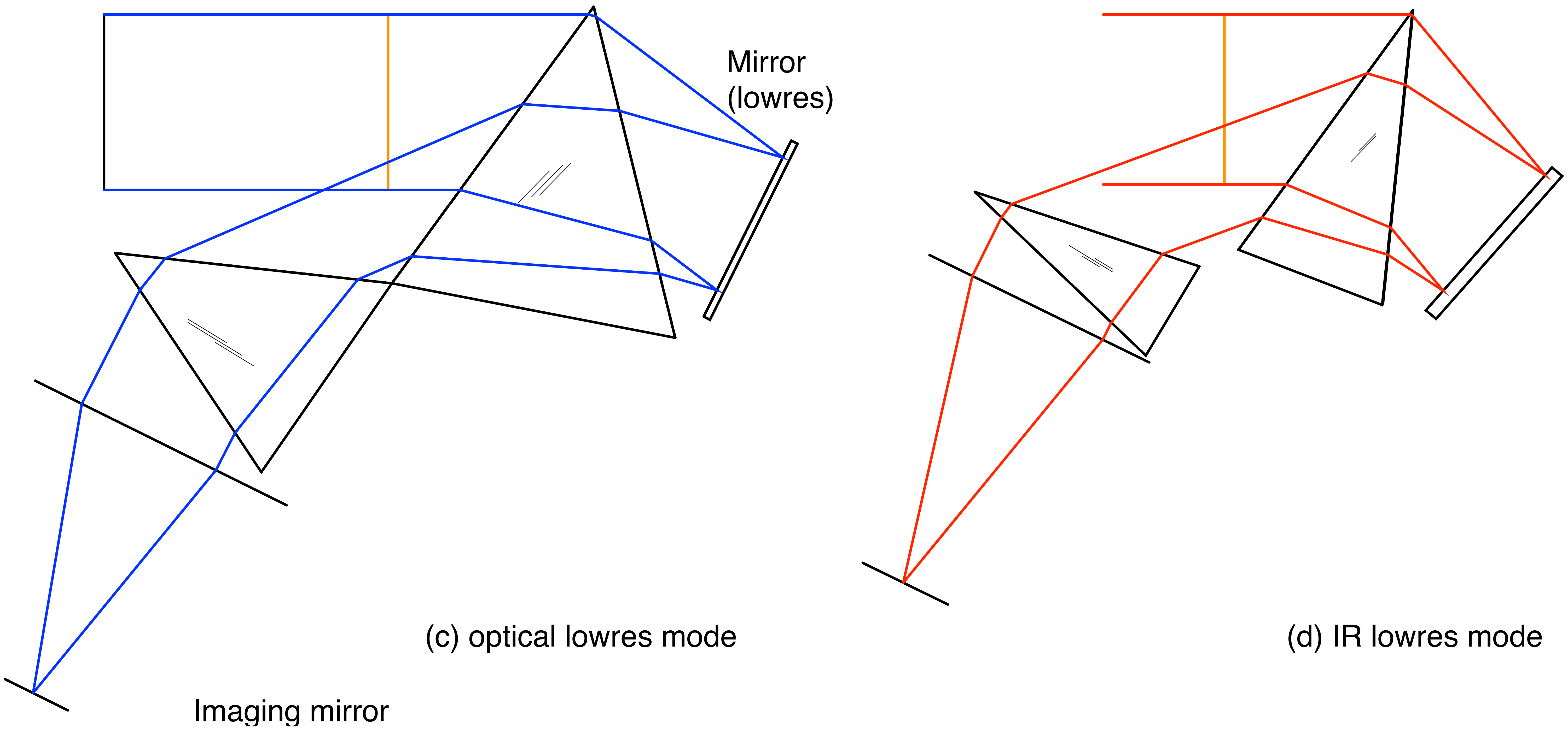


Lowres mode: Why? What?

- Exoatmospheres
- 400 — 1600 nm
- Highest Precision
- 6.7′ x 10″ slit
- Resolution varies across format.




Gemini 8-m Telescope
ADC
Slit viewing camera
longslit
reflective collimator
6 dof actuator
dichroic
Double pass prism
lowres mirror
shutter
filter wheel
optical camera
focus
Double pass prism
lowres mirror
shutter
filter wheel
nir camera
focus



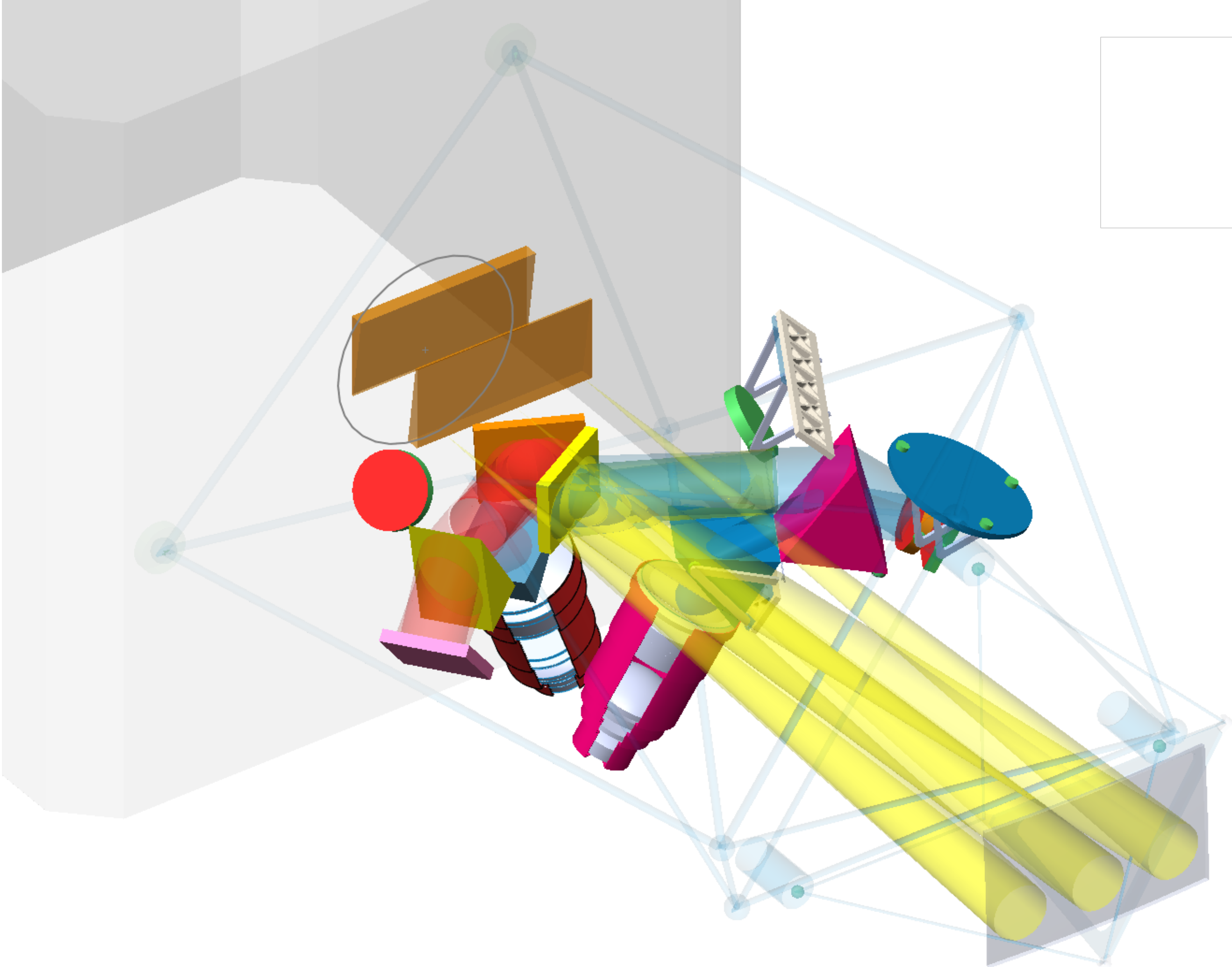
(c) optical lowres mode

(d) IR lowres mode

- In the “lowres” mode, the key driving requirements have to do with instrument *precision*.
- In future designs, we may need a pupil mask at the collimator exit pupil to control non-common path errors.
  - (The packaging of the current design does not allow for a ful mask.)

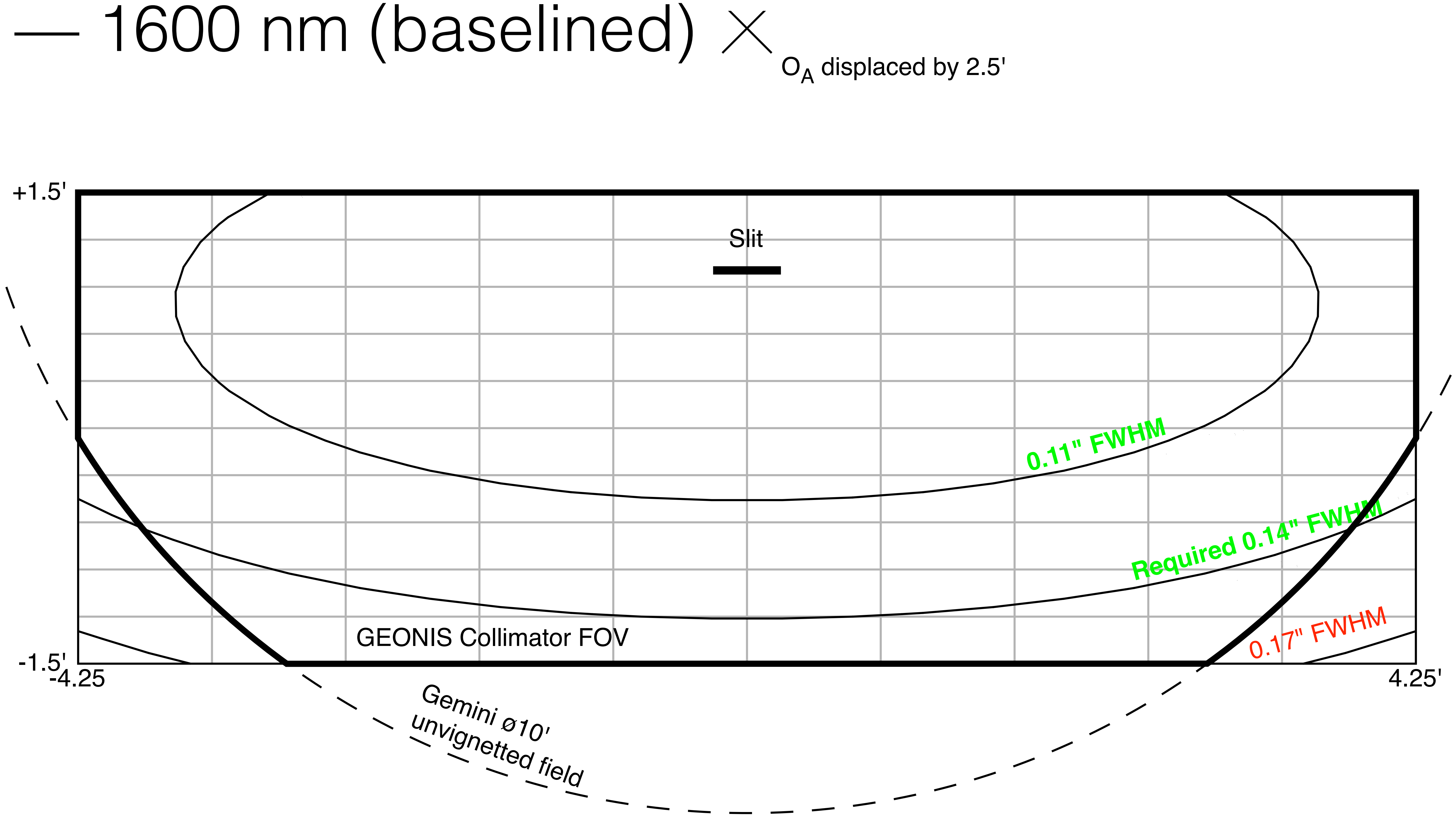
Lowres precision

- How to avoid non common path error between the science + reference target?
- Thermal isolation (thick styrofoam box + temperature control inside).
- Pupil mask to ensure optical path does not wander.
- We should consider using a grating instead of a mirror to stabilize spectral resolution.
- Minimize pupil wander:
    - Lock ADC into a single position? Null position?
    - Minimize system flexure (not just minimize hysterisis).

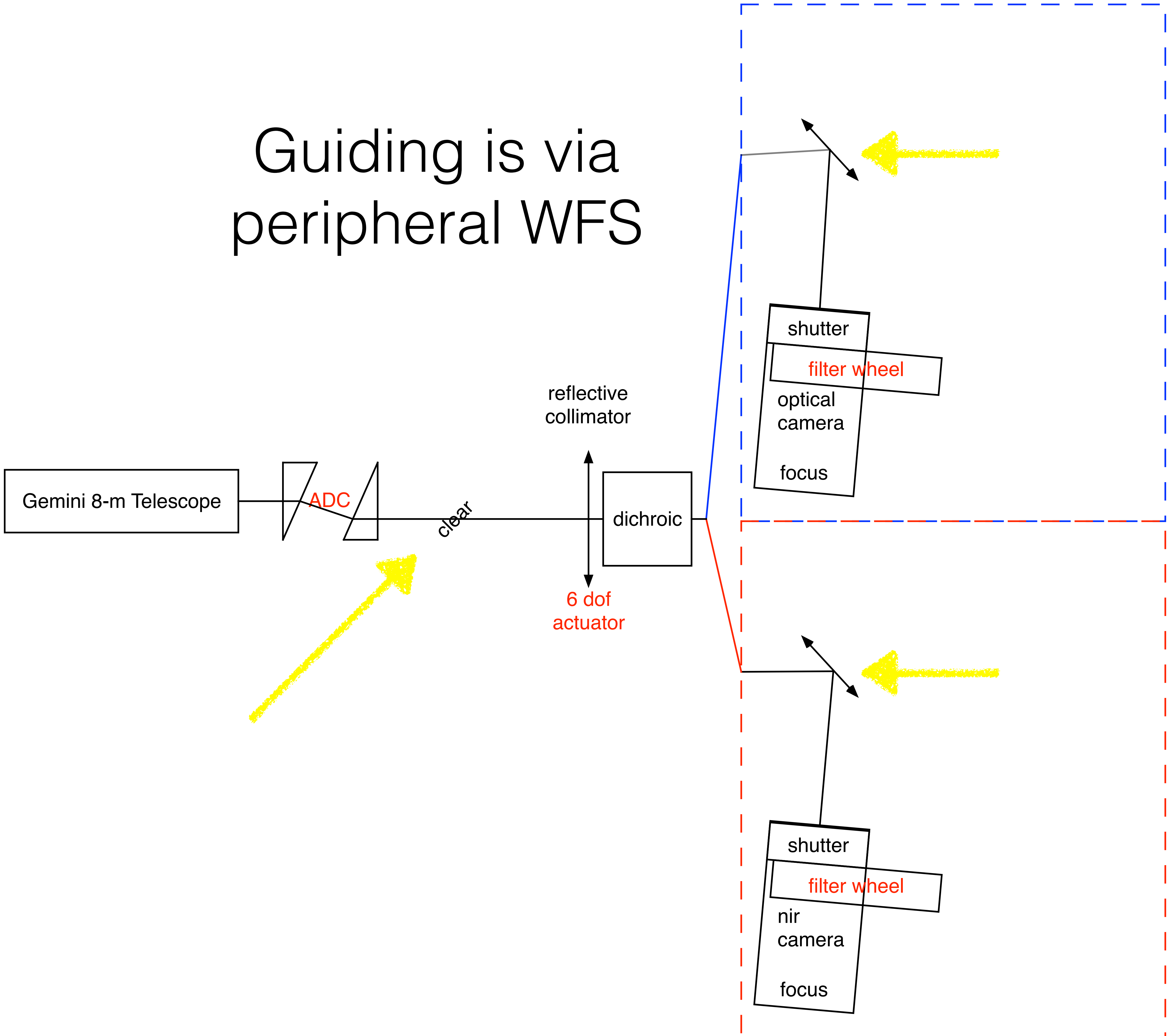


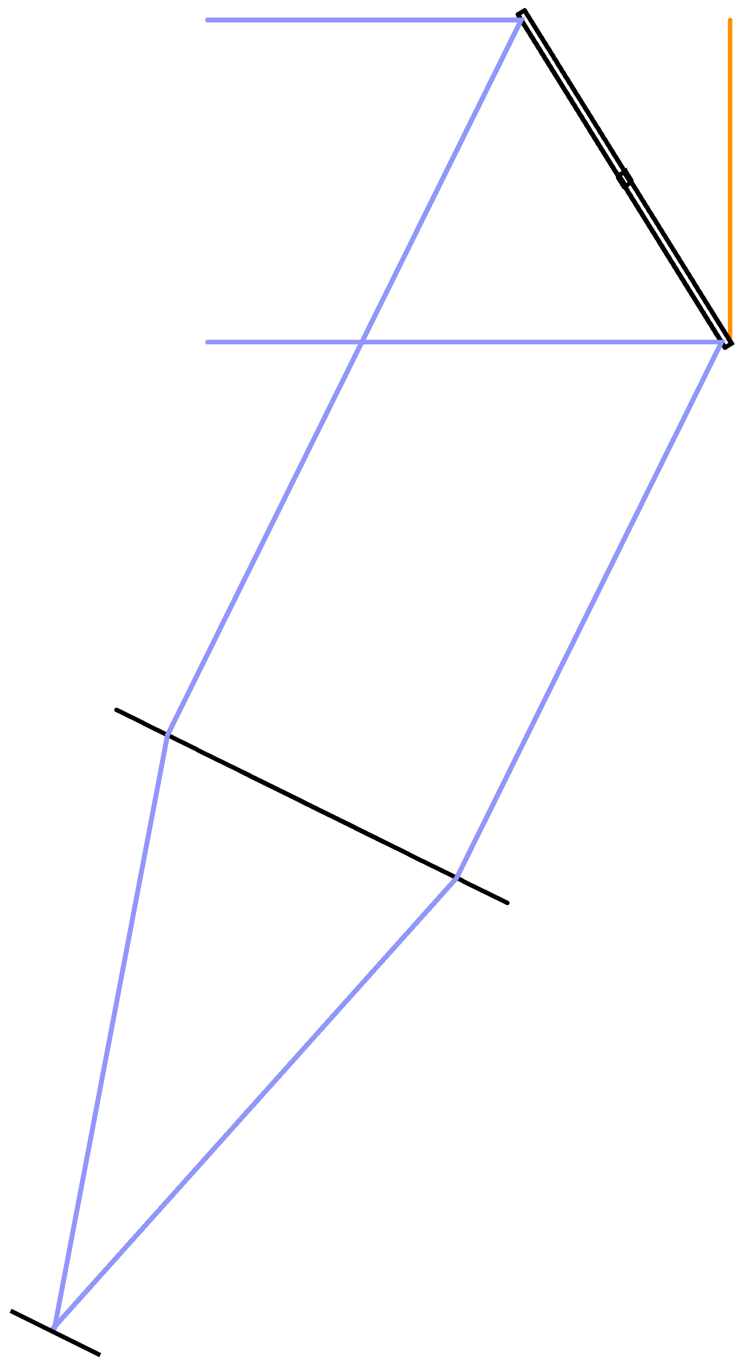
Imaging Mode: Why? What?

- Imaging for NEOs
- 400 — 1600 nm (baselined)

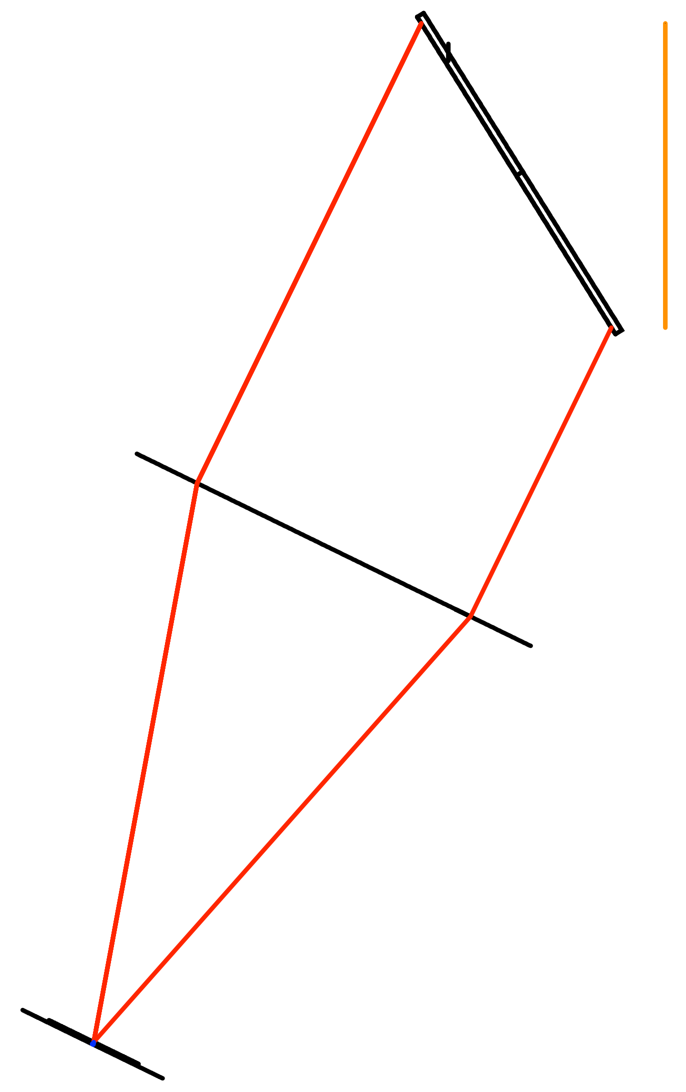


Guiding is via peripheral WFS

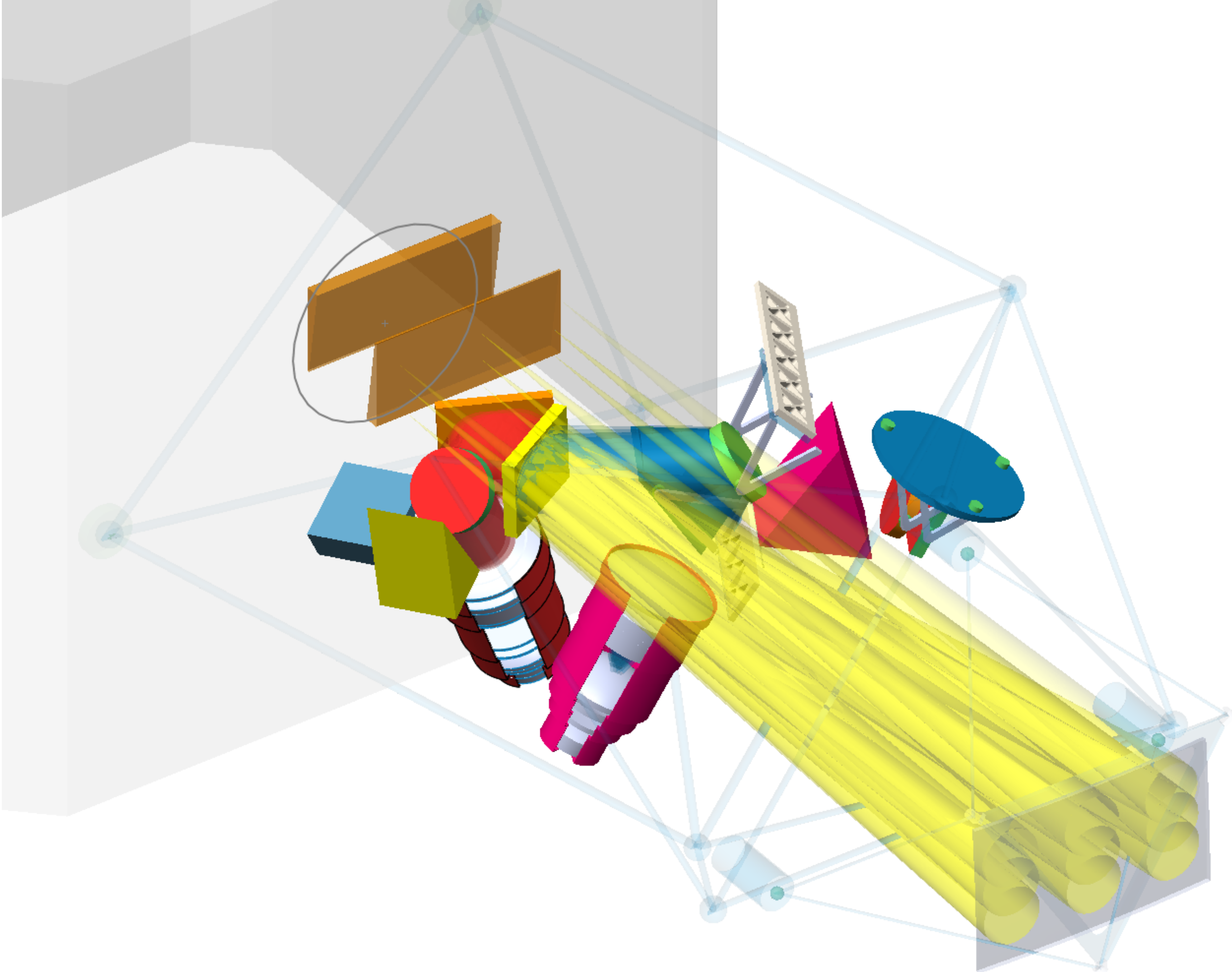




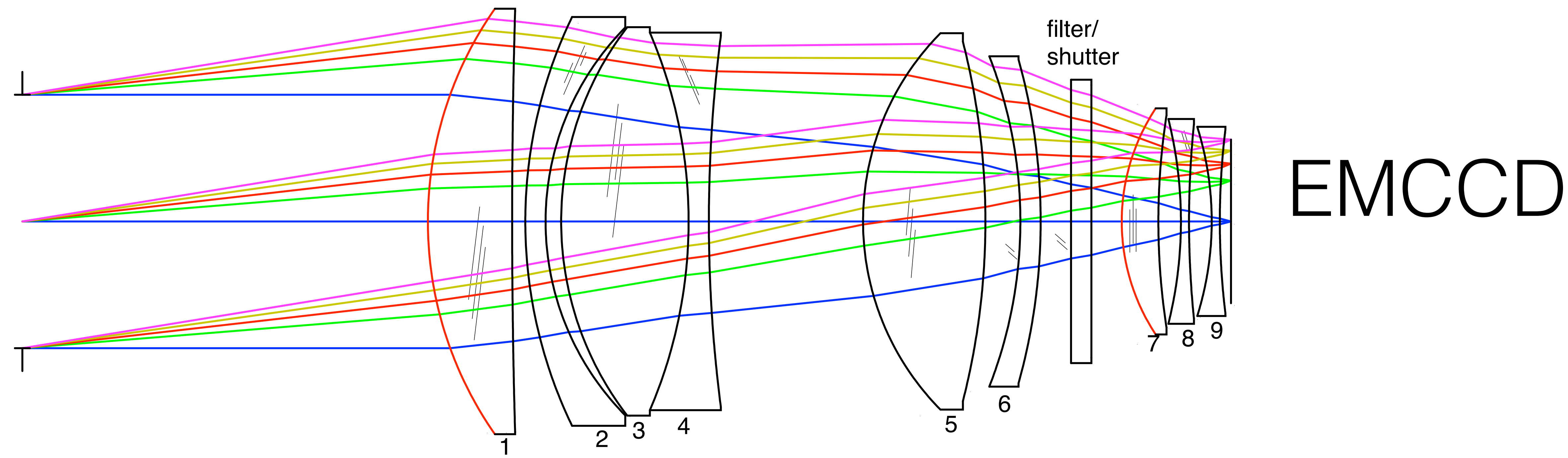
(e) optical imaging mode

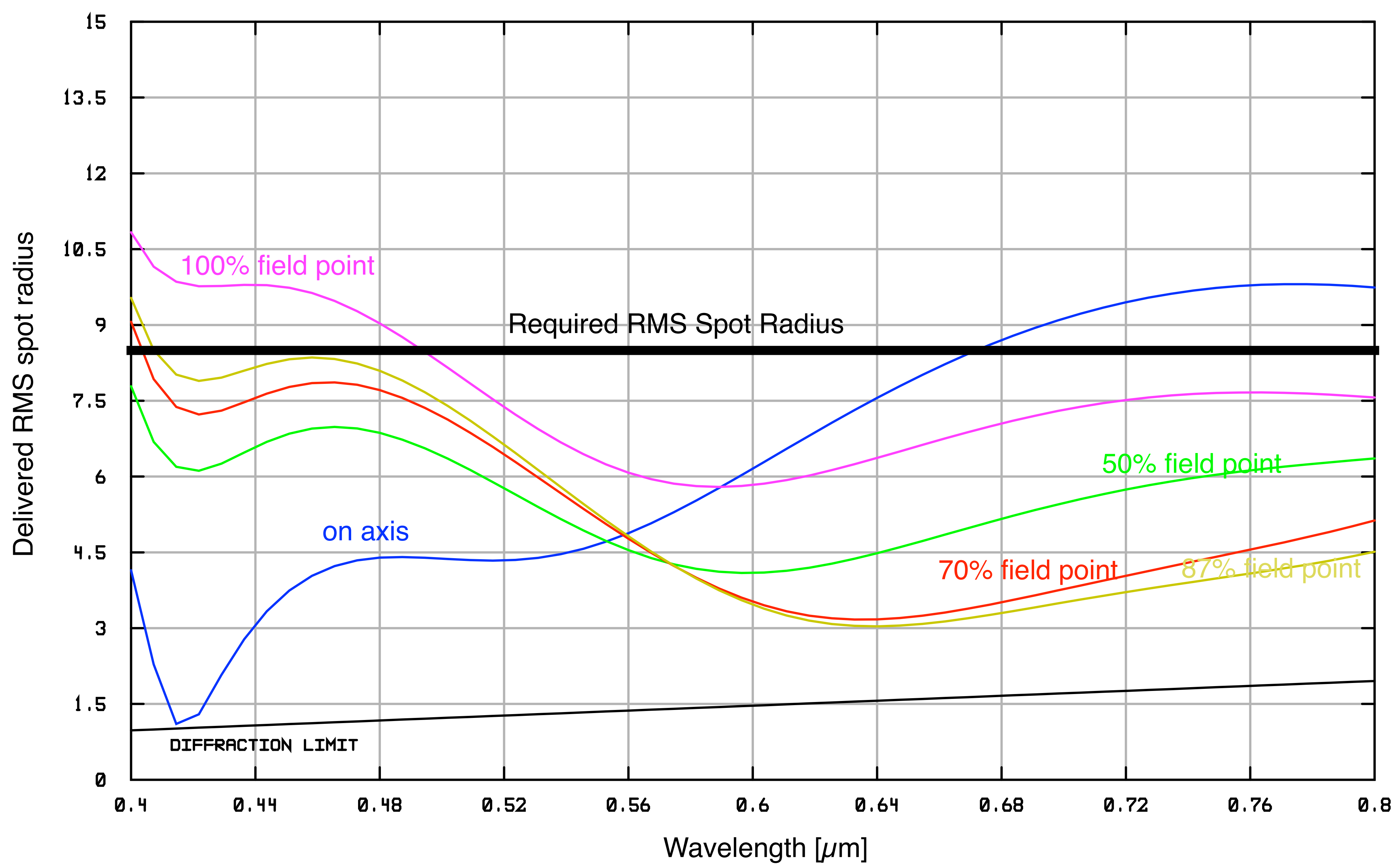


(f) IR imaging mode

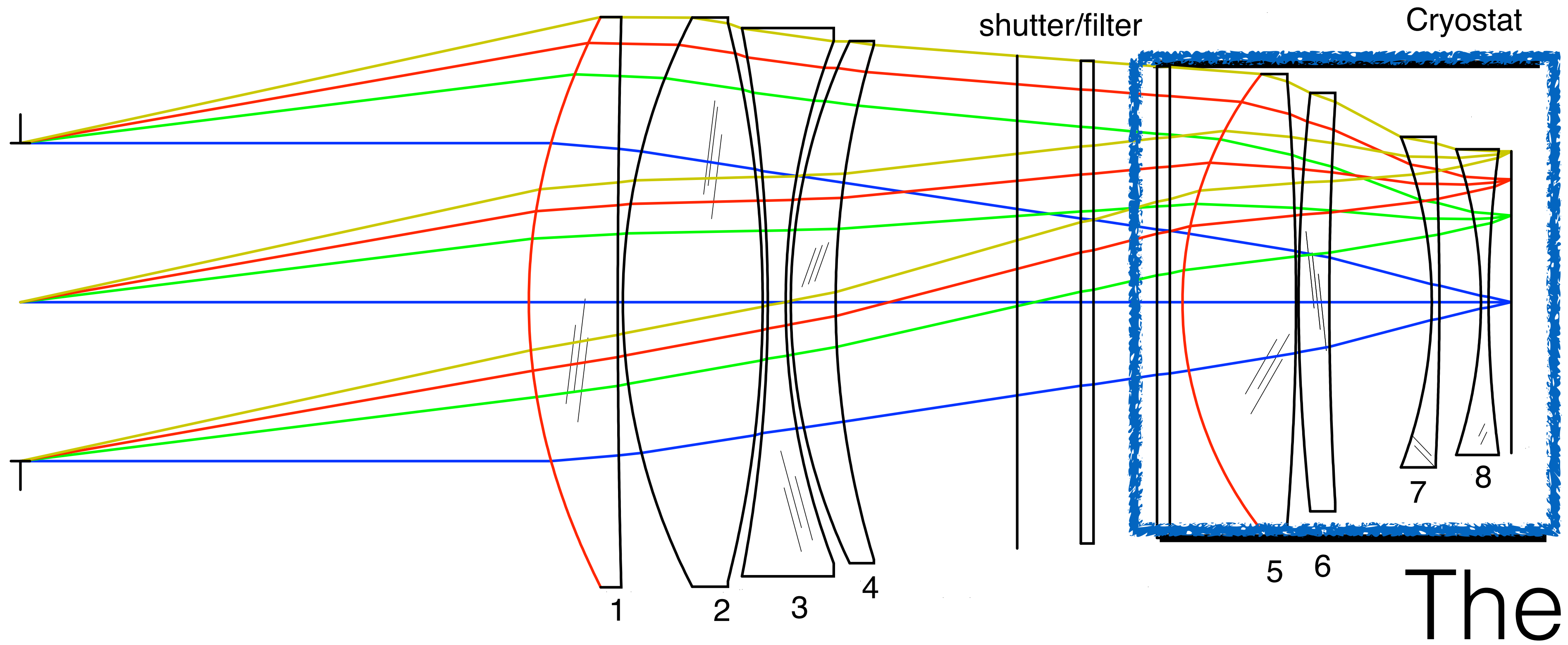


f/2 camera


filter/
shutter
1
2
3
4
5
6
7
8
9
EMCCD

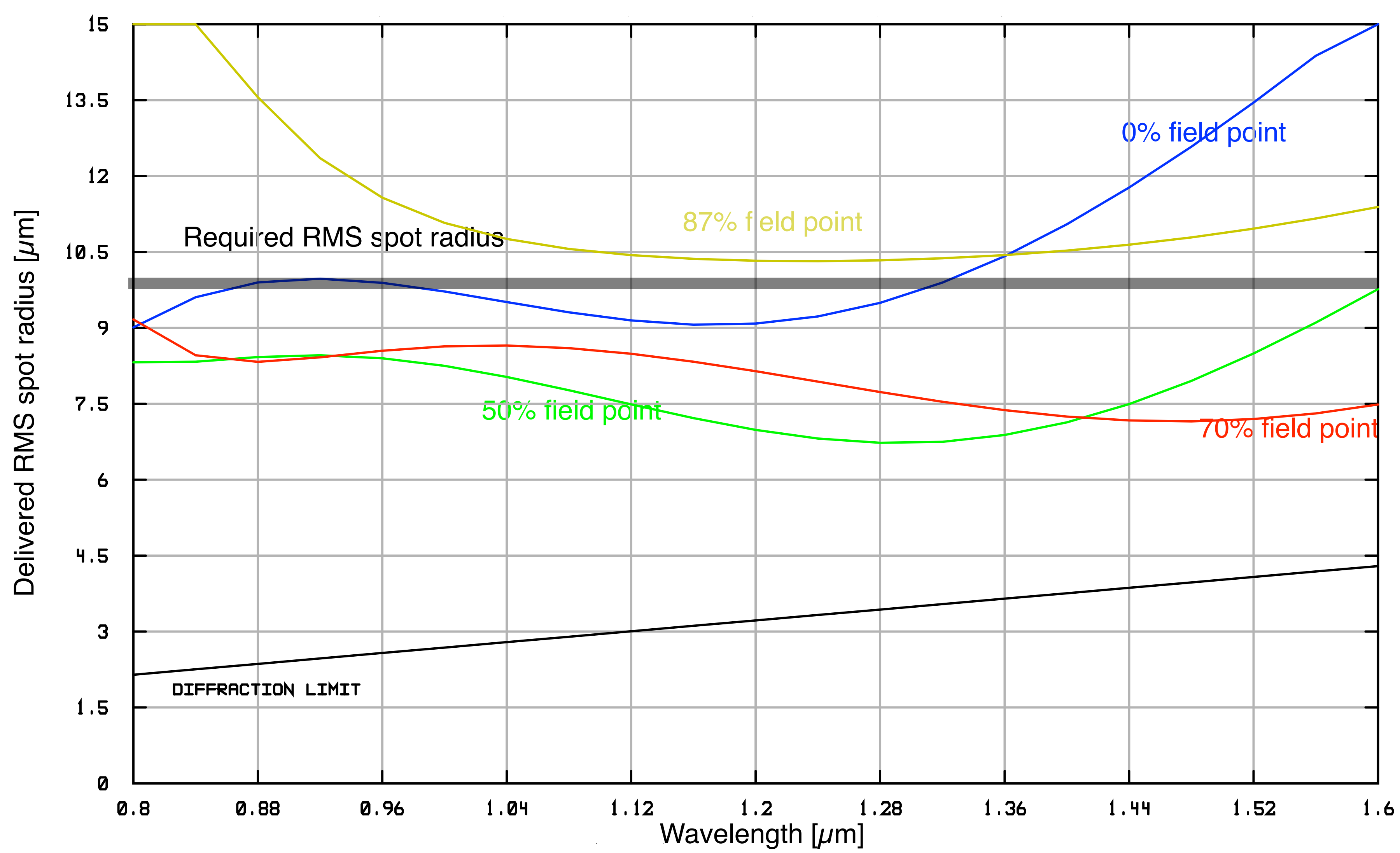

Delivered RMS spot radius
Wavelength [μm]
100% field point
Required RMS Spot Radius
50% field point
on axis
70% field point
87% field point
DIFFRACTION LIMIT
0
1.5
3
4.5
6
7.5
9
10.5
12
13.5
15
0.4
0.44
0.48
0.52
0.56
0.6
0.64
0.68
0.72
0.76
0.8

f/2.3 camera



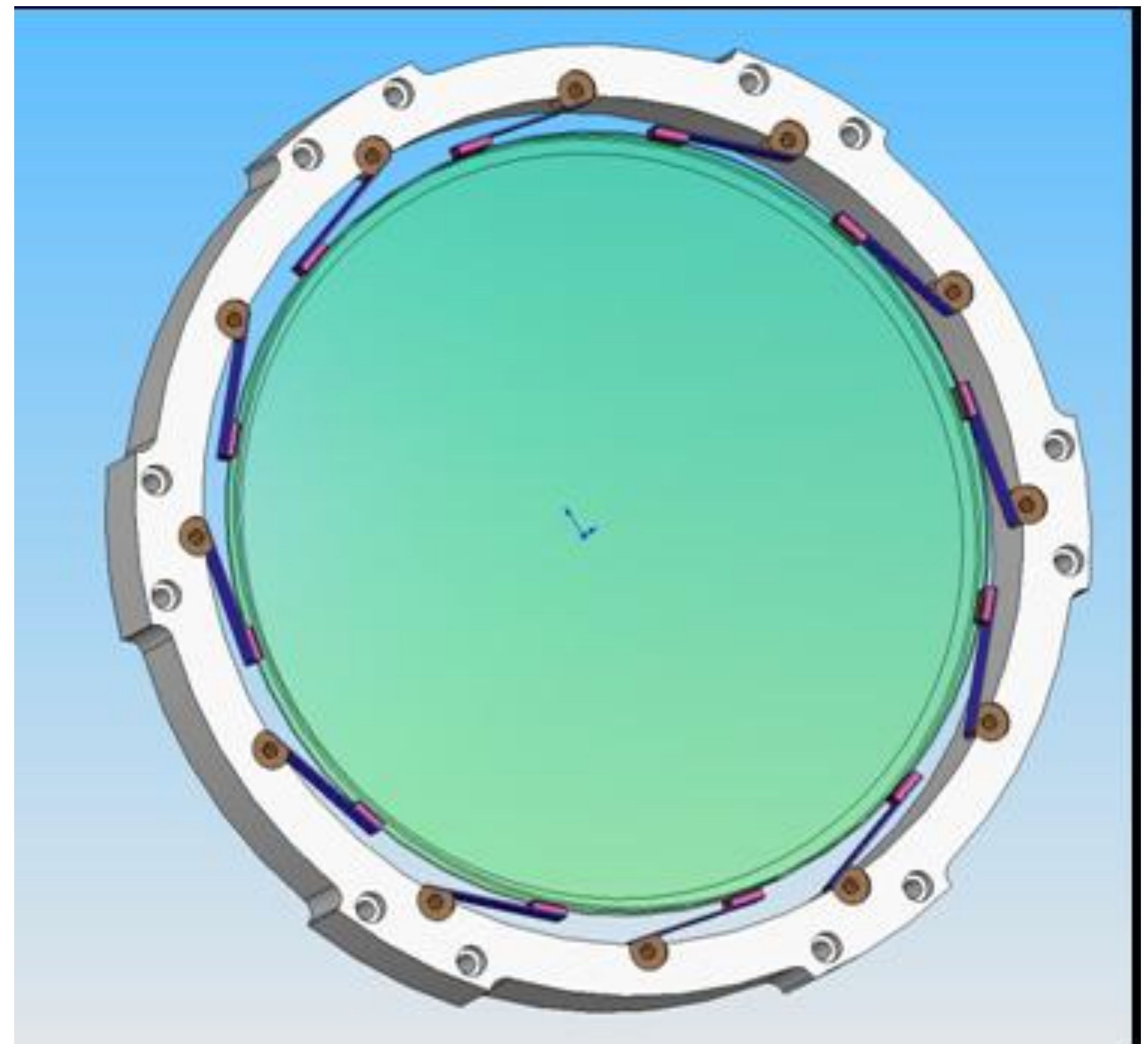
H4RG-short wave

Thermal IR Blocking Filter. (Scheme has risk)

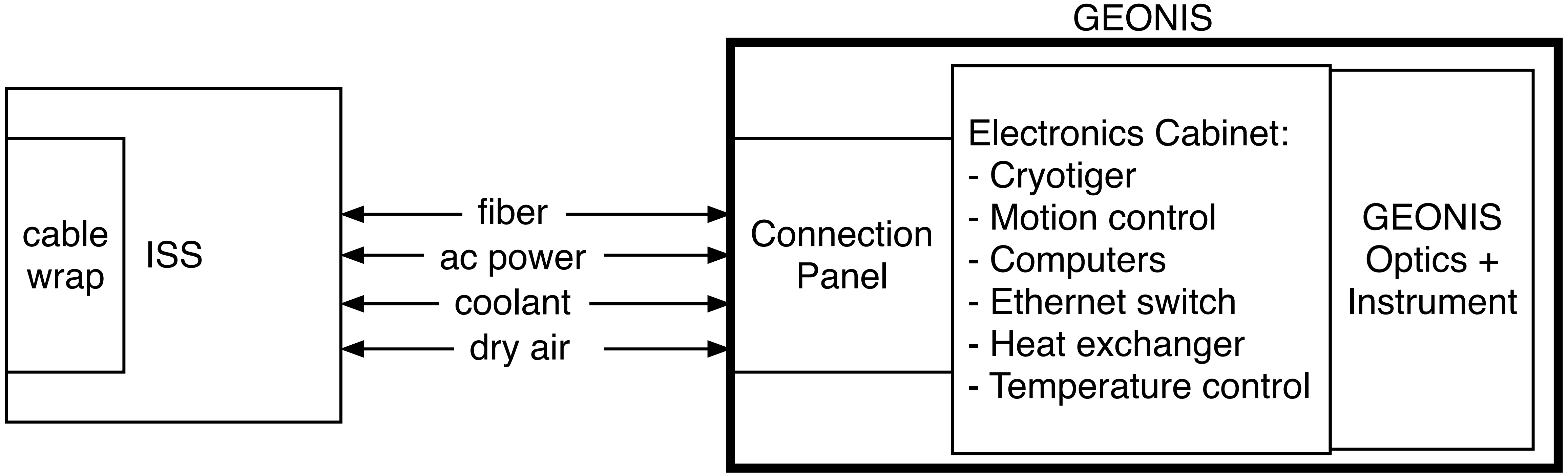


Lens mounts

- Each lens is mounted in a cell.
- Lenses are supported by flexures.
- Attachment is at the end of a “pad”.
- Demonstrated with MOSFIRE to introduce negligible stress and total overall flexure.



Electronics



Components

1. Detectors, shutters, and controllers x 3
2. Galil (or equivalent) control system:
    1. FCS
    2. Slitmask control
    3. ADC
    4. Rotary
    5. Linear controls
    6. Focus
3. Power control
4. Telemetry

Control Software

- GEONIS conforms to ICDs
- GEONIS provides
  - Detector controllers (two science detectors + slit viewing camera) including shutter control + timing.
  - Flexure compensation + collimator focus.
  - Mechanism controls: two rotary systems, 7 linear systems, 2 focus systems.
  - Power control
  - Telemetry + Safety (temperatures, glycol, vibration, etc).
- Acquisition/guiding + ADC — observatory provided.

Data reduction software

- GEONIS is costed around a minimal useful data reduction pipeline.
- We would like to work with Gemini to think in broader terms about the data reduction capabilities it could provide. Esp. real time reduction.
- Real time classification software is clearly out of Gemini’s domain.

Technical Risks (1)

- Thermal background reduces effective wavelength range below 1.6 μm. *Mitigation*: Accept or remove NIR arm.
- Instrument is over $12 M cost limit. *Mitigations:* (a) phase delivery of channels. (b) Minor tweaks to reduce size.
- Instrument is way over $12 M cost limit. *Mitigations:* (a) drop IR arm; (b) drop observing modes.
- Instrument is <10% over mass limit. Mitigation: Request exception.

Technical Risks (2)

- Instrument is <20% over mass limit. *Mitigation:* Reduce field size.
- Hawaii 4RG device is not available by decision point. *Mitigation:* Phase delivery of NIR arm or tile H2RGs
- EMCCD and or control electronics not available. *Mitigation:* Use frame-transfer rather than an EM device.

Summary

- GEONIS is an optical (400—800 nm) + NIR (800 nm — 1600 nm) spectrograph + imager.
- We demonstrated a feasible instrument concept.

Table 1: Transients technical requirements.

Transients			
Parameter	Value	Source	Justification
Measurement	Echelette	Instrument	Workhorse mode.
Wavelength range	400 - 1,600 nm	§B.1.2/SR1 §B.1.4/SR1	Broadest range within desired risk posture and expected UV performance.
Spectral Resolution	500 - 4,000	§B.1.1/SR2	Will perform both discovery and diagnostic science.
Slit-to-detector Throughput	>30%	§B.1.1/SR7	Must meet or exceed current generation of instruments with a one-arcsecond slit.
Atmospheric dispersion correction	<0.25″ to airmass 2	§B.1.1/SR7	ADC correction maximizes throughput.
Slit viewing camera	Yes	SR9	Slit viewing camera maximizes throughput. Simplifies DRP.
Plate solve time (acquisition)	< 10 s	§B.1.1/SR9	Required to maintain high system throughput. The slit viewer allows us to keep the object fixed on the slit for fast reductions.
Pixel scale	>0.15″	§B.1.1/SR4	Fast cameras mean short exposures.
Image quality	∼0.3″	§B.1.1/SR3	Do not degrade Gemini's excellent delivered image quality by more than 10%.
Slit length	>20″	§B.1.1/SR8	Excellent sky subtraction and slit nods.
Quick look reduction	Yes	§B.1/SR10	Desire quick-look data reduction pipeline to determine SNR.
RMS Residual Flexure	< 0.1 pix	SR2, SR3, SR7, SR8	Impacts image quality, quick-look pipeline, and final pipeline ease
Instant look reduction	Desired	§B.1.3/SR10	Maximizes observatory throughput, see discussions.

Table 2: Exoplanet science case technical requirements.

Transients			
Parameter	Value	Source	Justification
Measurement	Long slit	Instrument	Must observe science target and fiducial target simultaneously.
Wavelength range	400 – 1,600 nm	§B.3	Covers Na I, K I, H_2O, TiO, and VO species.
Spectral Resolution	200 – 1,000	§B.3/SR11	Sufficient for exoplanet atmosphere
Precision	200 ppm	§B.3/SR10	To measure exoatmospheres as they pass in front of their host star.
Slit length	$>6'$	§B.3/SR12	Cover more than 50% of TESS exoplanets.
Slit width	$> 13''$	§B.3/SR13	Ensure most light from science target enters slit.
Frame transfer duty cycle	> 90%	§B.3/SR14	Ensures operational efficiency of > 90%
Flexure correction	subpixel	§B.3/SR5	Ensures high stability and precision.

Table 3: NEO technical requirements.

Transients

Parameter	Value	Source	Justification
Measurement	Wide field imaging	Instrument	For ephemeris of NEAs.
Wavelength range	400 – 1,600 nm	§B.2	Peak of SED in the near-optical range is 1 μm.
Throughput	> 50%	§B.2/SR7	Must meet or exceed current generation of instruments.
Frame transfer duty cycle	> 90%	Throughput	Ensures high operational efficency.
Image quality	0.3"	§B.2/SR15	Centroid uncertainty is proportional to image quality.
Atmospheric Dispersion Corrector	Yes	Image quality	ADC requirement flows from image quality requirement.
Field of view	$8'$x $3'$	§B.2/SR4	Largest possible imaging FOV.

Scientific Advantages of EMCCD Spectroscopy

Nick Konidaris

Outline

- Review spectroscopy with an eye towards EMCCD techniques.
- EMCCD v CCD
- EMCCD Signal to noise
- What’s next?

How is a spectrum constructed?

– 4 –

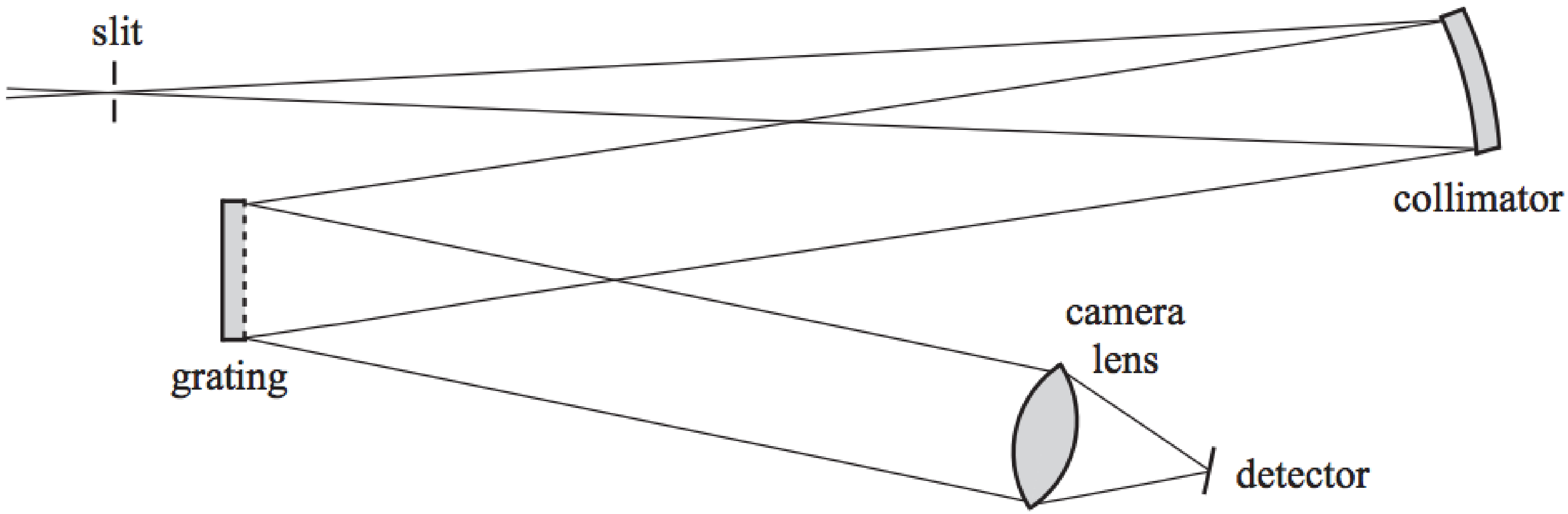
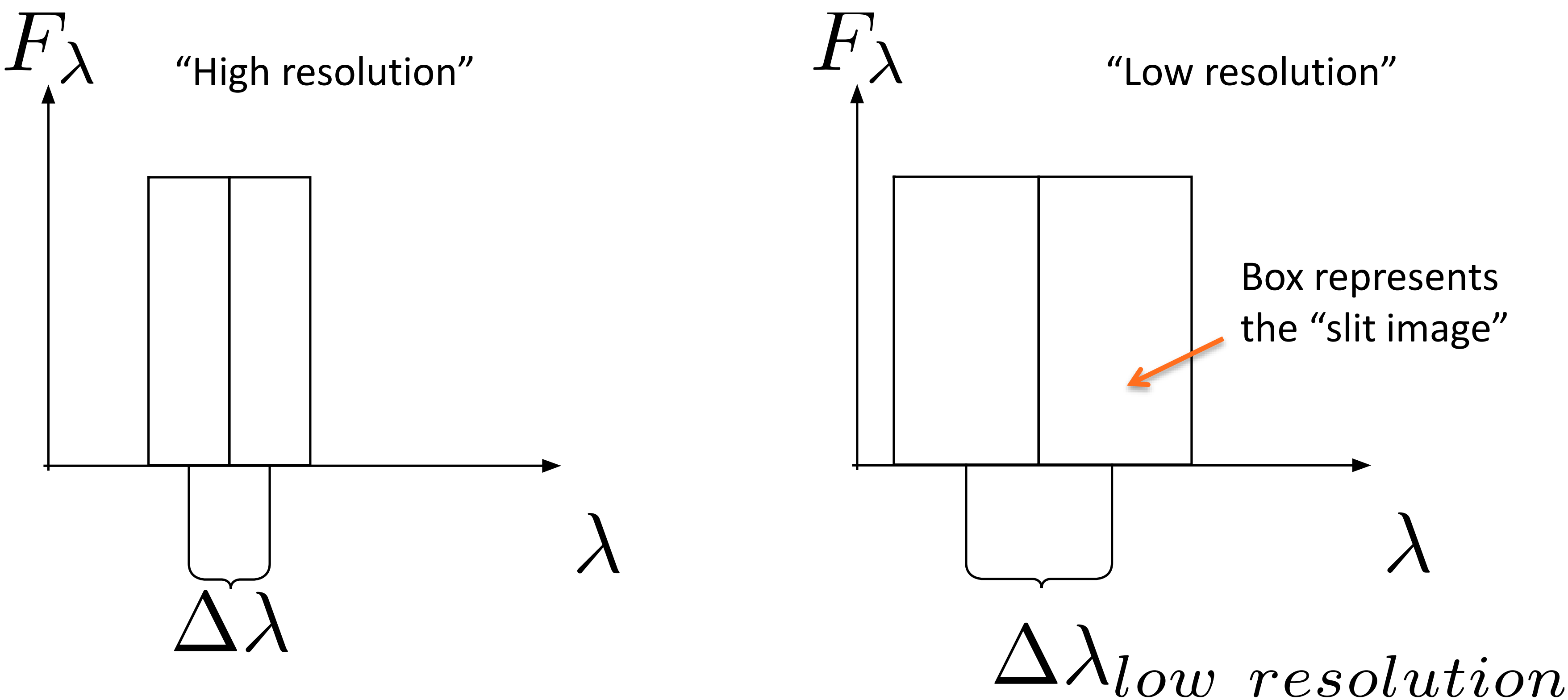


Fig. 1.— The essential components of an astronomical spectrograph.

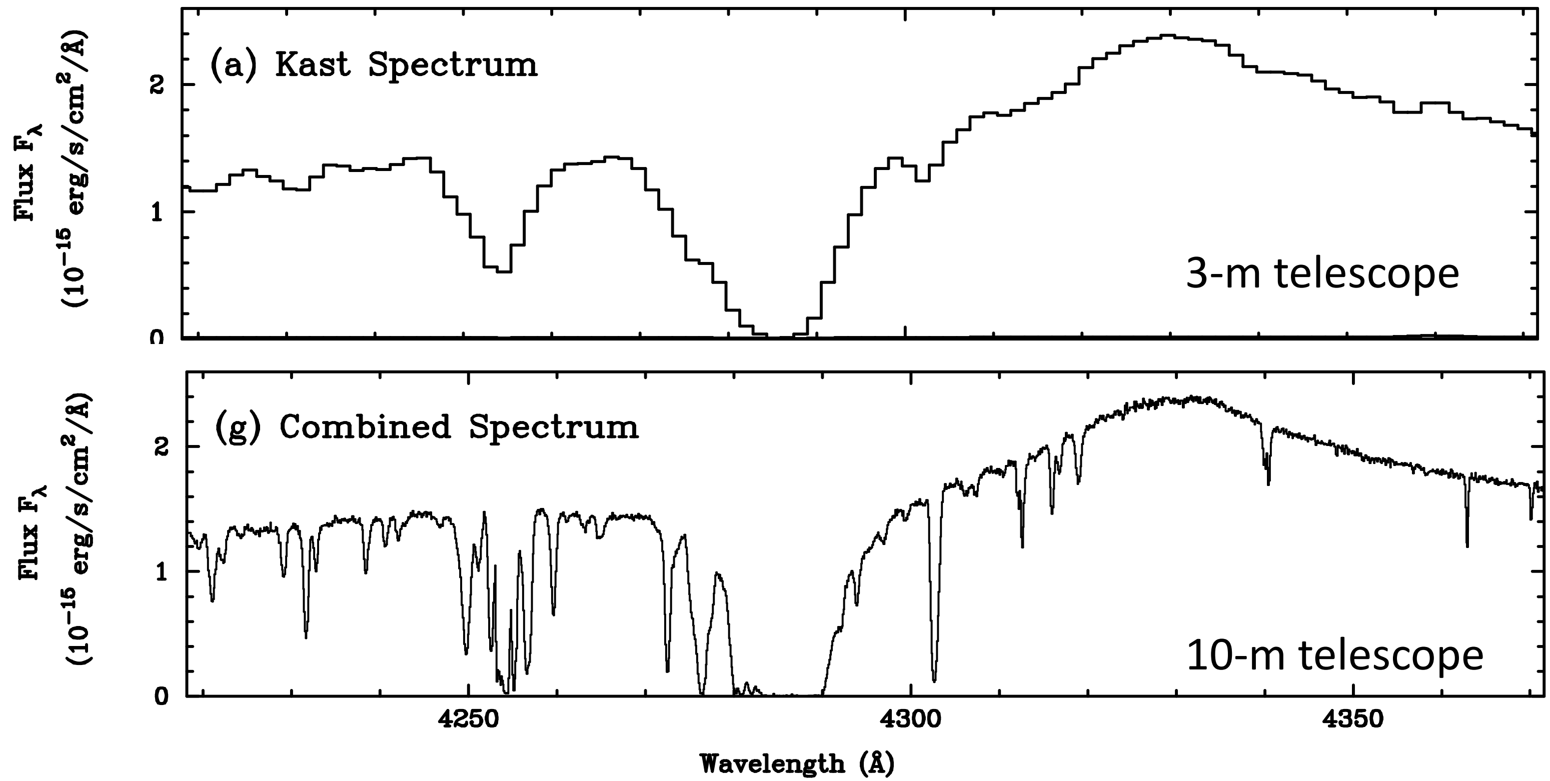
Masey, Hanson (2010)

Big Idea: Spectral Resolution



$$R = \frac{\lambda}{\Delta\lambda}$$

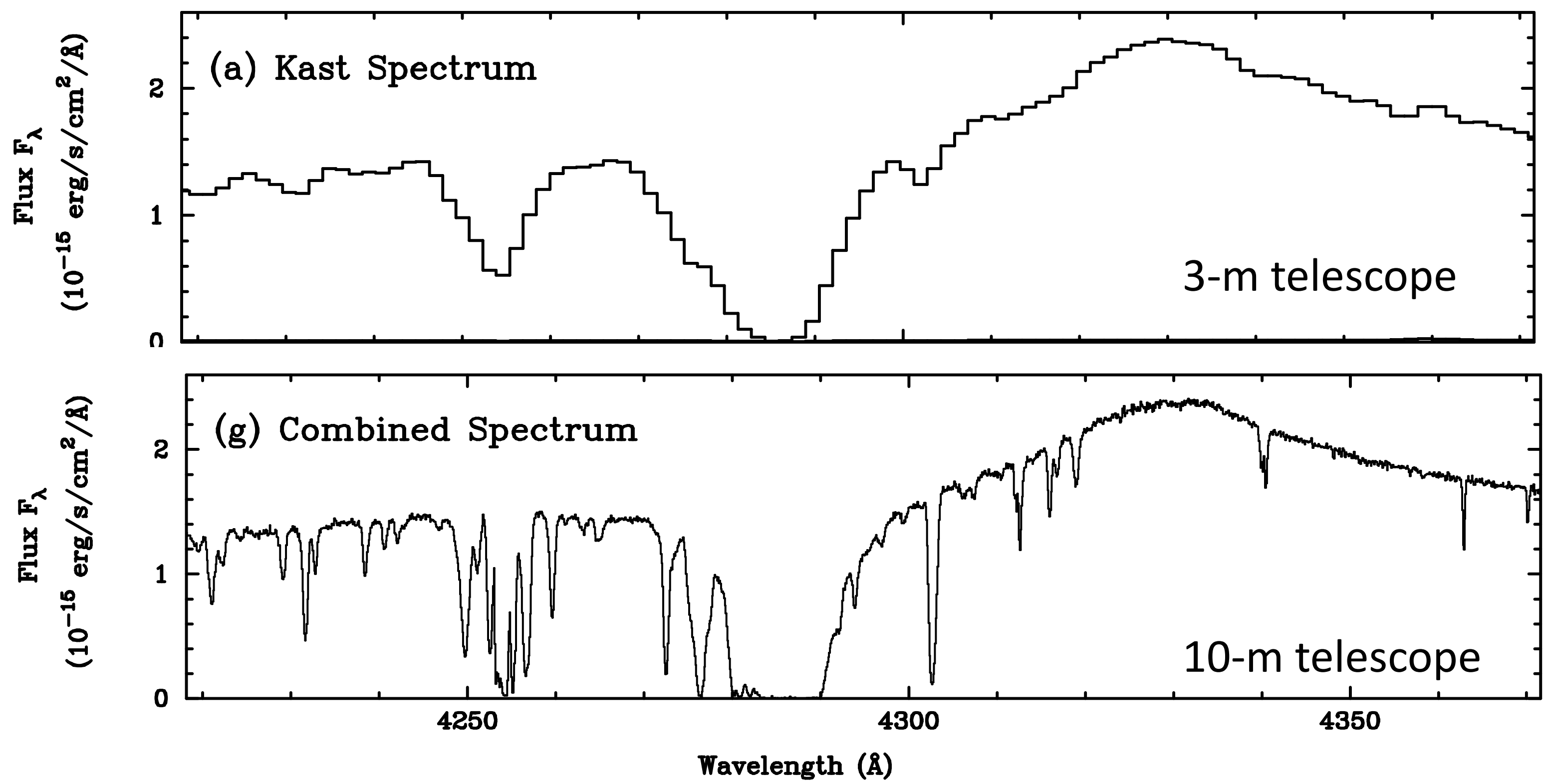
Effect of increasing spectral resolution=more science



Suzuki+ (2003)

Caltech

Effect of increasing spectral resolution=more exposure time



Suzuki+ (2003)

Effect of increasing spectral resolution=more pixels

$$N_{pixels} \propto N_{resolution\ elements} \cdot Bandwidth$$

$$= \frac{Bandwidth}{\Delta\lambda} = Bandwidth \cdot R$$

Effect of increasing spectral resolution=bigger instrument

Resolution Summary:

- Provides more details
- Requires:
  - More exposure time/bigger aperture
  - More pixels
  - Bigger instrument

Big Idea II: Sources of Signal, Sources of Noise.

Signal

- The object of interest

Noise

- The object of interest
- Background
- Detector noise sources
  - Read noise
  - Clock induced charge
  - Dark current noise
- Systematics
  - Flexure (fringing)

Sky Subtraction

Empirical Models

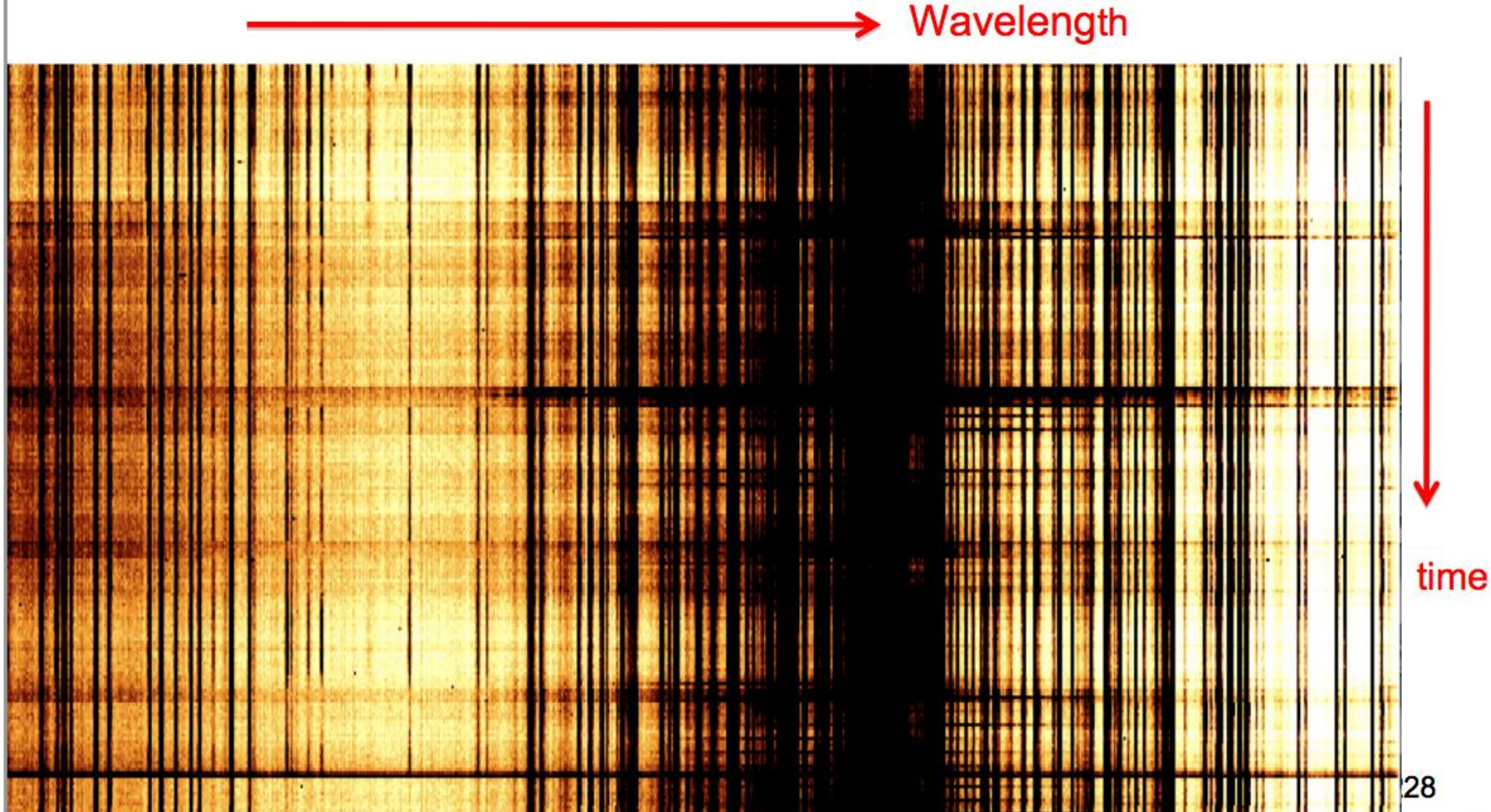
- Detector grunge hurts and systematics make data reduction impossible.

Chopping

- Adds sqrt of 2 more noise, but simplifies data reduction.

Sky Background Variation Tests

P200/Triplespec 220 x 600s (H-band shown)
exposures over 5 nights in April 2009



W. M. KECK OBSERVATORY

Steidel+Konidaris- Night sky over Palomar

Remaining noise sources

- Read noise
- Dark current noise
- CIC noise (~0 for CCDs).

$$SNR = \frac{signal}{\sqrt{signal + sky + RN^2 + Dark + CIC}}$$

EMCCD (side trip: linear mode)

- When operating with gain of 10 – 100 one reduces the read noise, but pays a root-2 penalty (see Tubbs 2003).

$$SNR = \frac{signal}{\sqrt{2}\sqrt{signal + sky + (RN/gain)^2 + Dark + CIC}}$$

Caltech

EMCCD Photon Counting Mode

$$SNR_{ideal} = \sqrt{N}$$

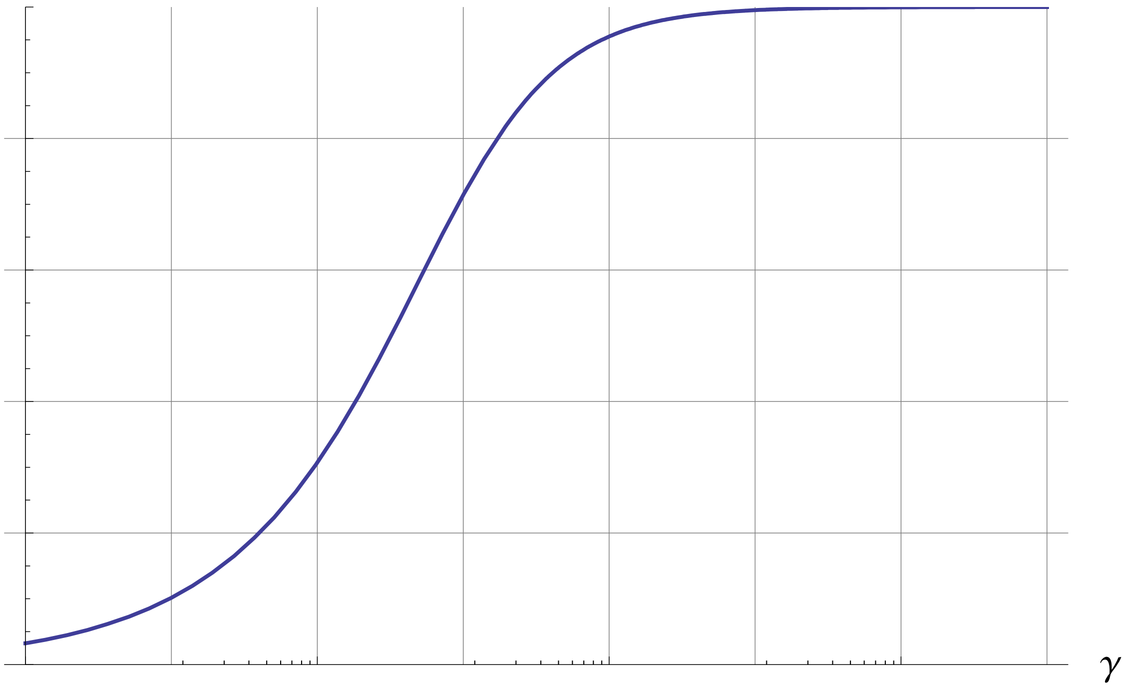
- In “true” photon counting mode, signal to noise is dictated by photon statistics with coincidence noise:

$$SNR_{pc} = \frac{N}{\sqrt{e^N - 1}}$$

But, this idealized equation does not tell the whole story.

Photon Counting Mode v. Conventional Mode

With no read noise or DC noise, ratio=1, but curve shows 3.1 e- of read noise.



Photon Counting Detection Rate ~ 0.90

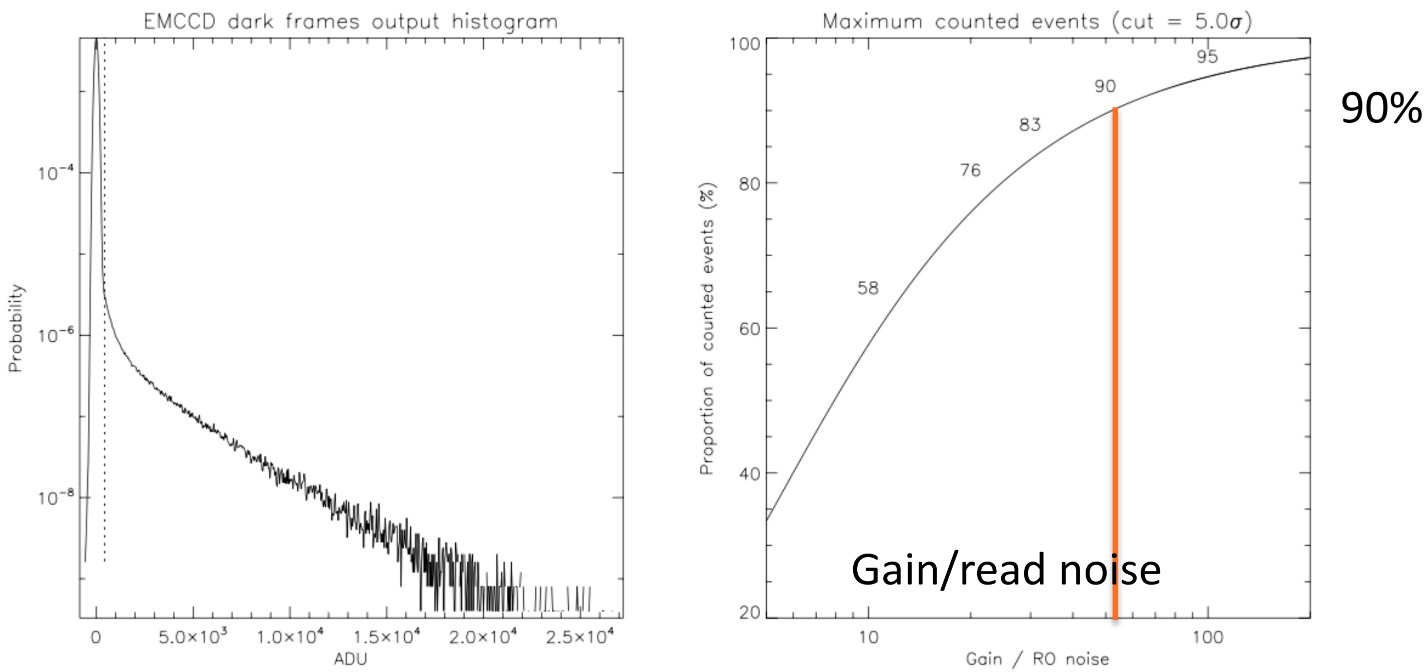
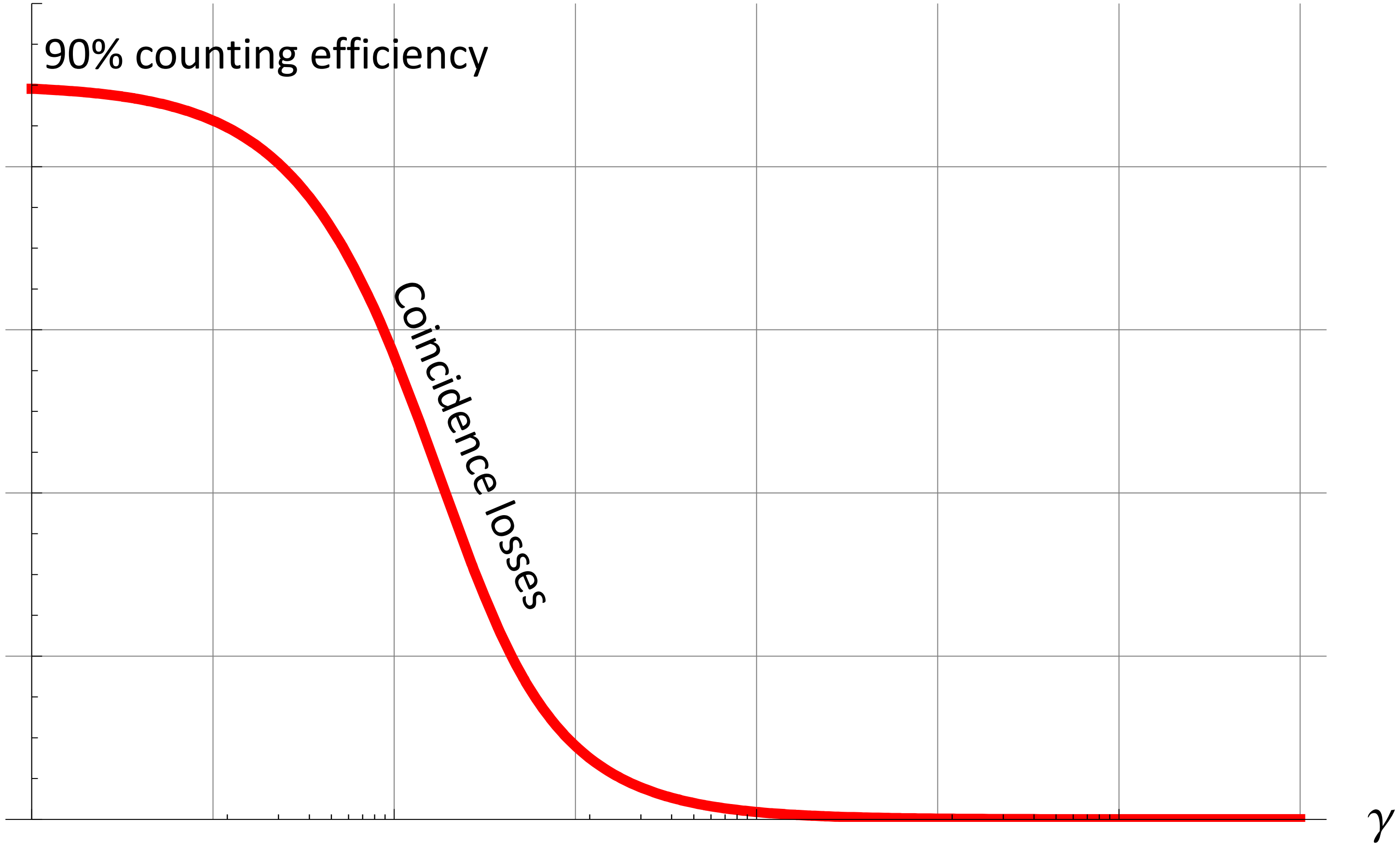


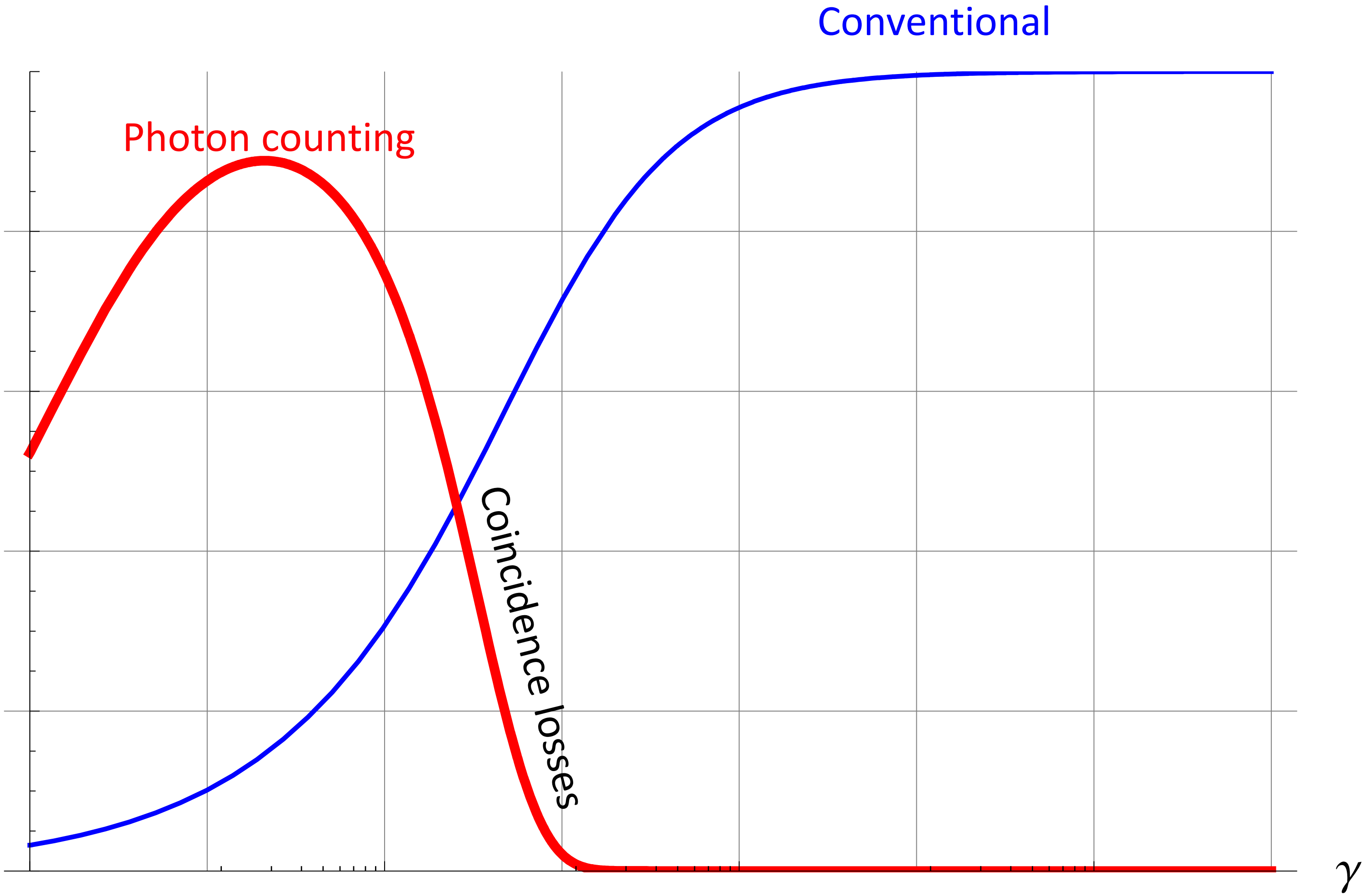
Figure 1. **Left**: Histogram of an EMCCD operated under low flux, at an EM gain of ∼2750. Only a few pixels underwent more than one event per frame. The vertical dotted line shows the threshold at 5.5σ. The mean event rate is 0.0018 event per pixel per image. **Right**: Proportion of counted events as a function of the ratio of the EM gain over the readout noise. A cut level of 5σ is used. Values for ratios of 10, 20, 30, 50 and 100 are printed.

Daigle+ (2010)

Fate of our photons



Final SNR



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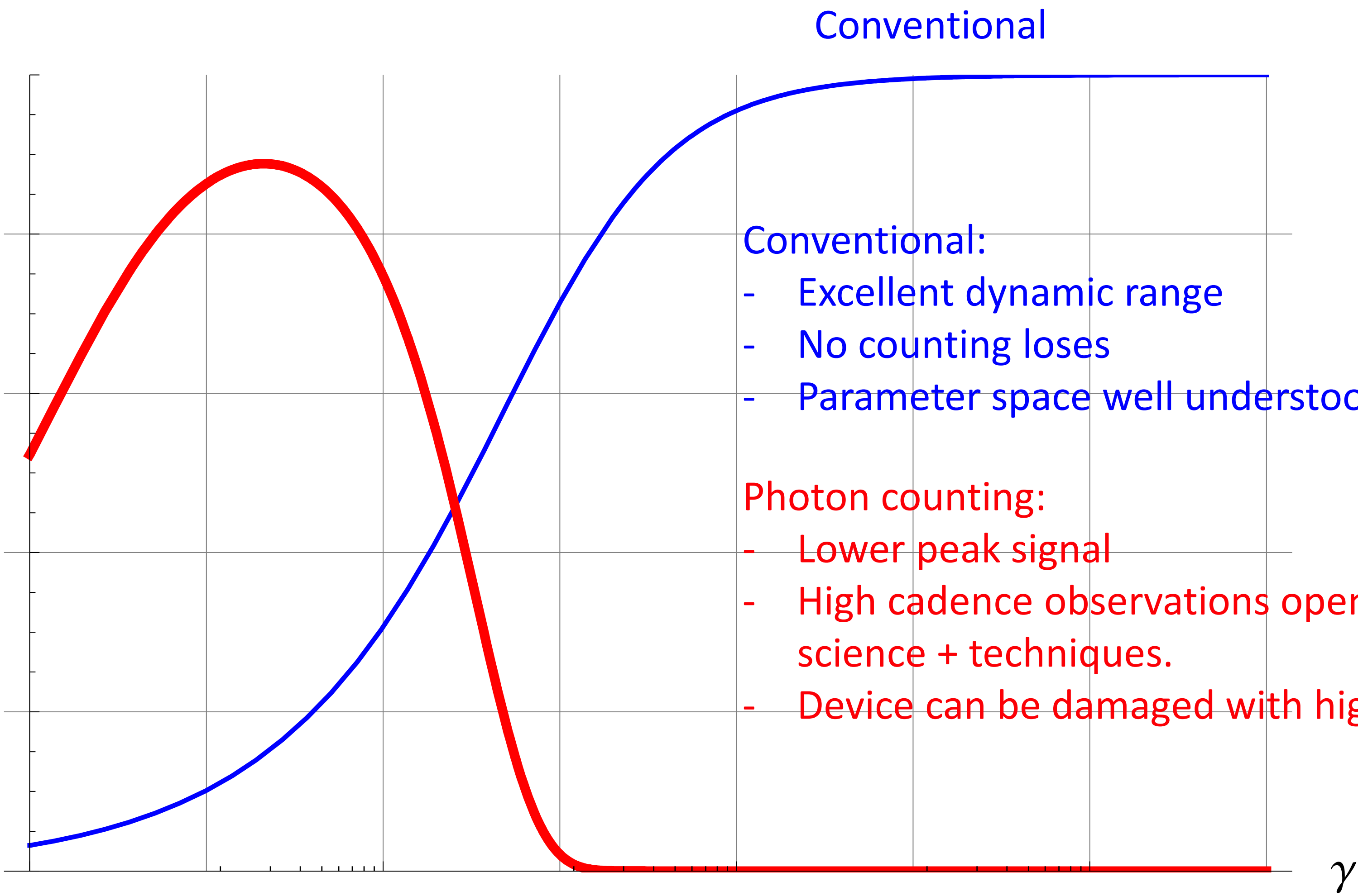
Final SNR



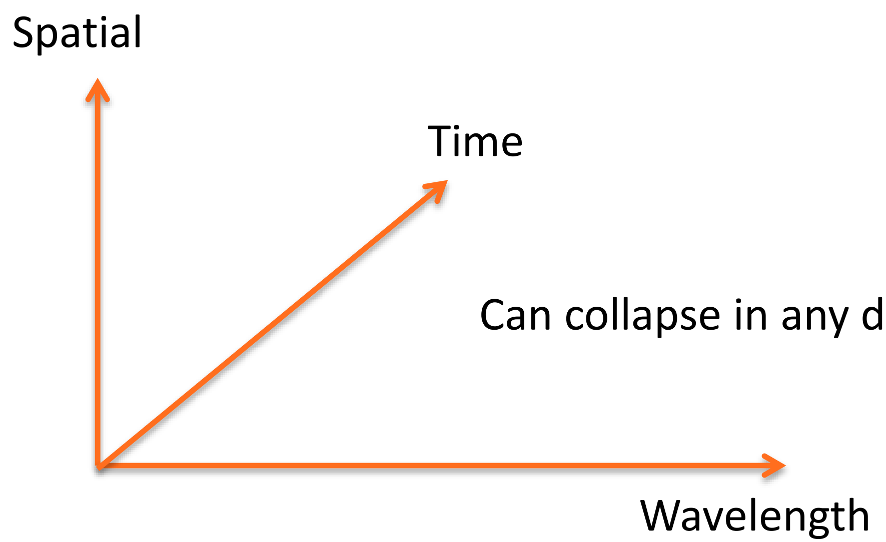
Conventional:
- Excellent dynamic range
- No counting loses
- Parameter space well understood

Photon counting:
- Lower peak signal
- High cadence observations open new science + techniques.
- Device can be damaged with high gain

Clearly winning case

- Single-object spectroscopy with software designated resolution.
- Resolution decided post facto by binning (even adaptive binning)
- No complicated moving parts allows for robust data reduction, and simplified mechanical design.

Result of EMCCD spectroscopy: "Data Cube"



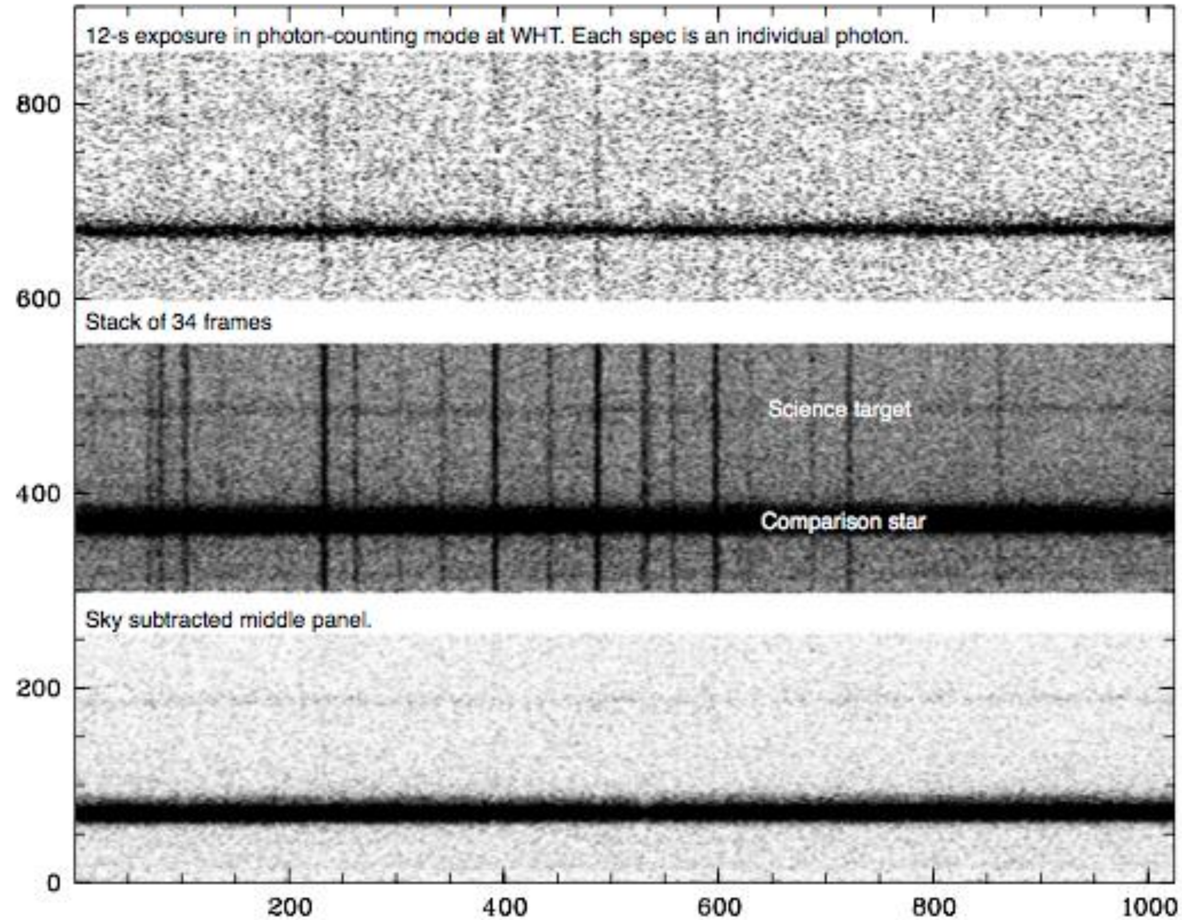
Can collapse in any dimension- no penalty.

Some Data

Step 1: Accumulate Signal

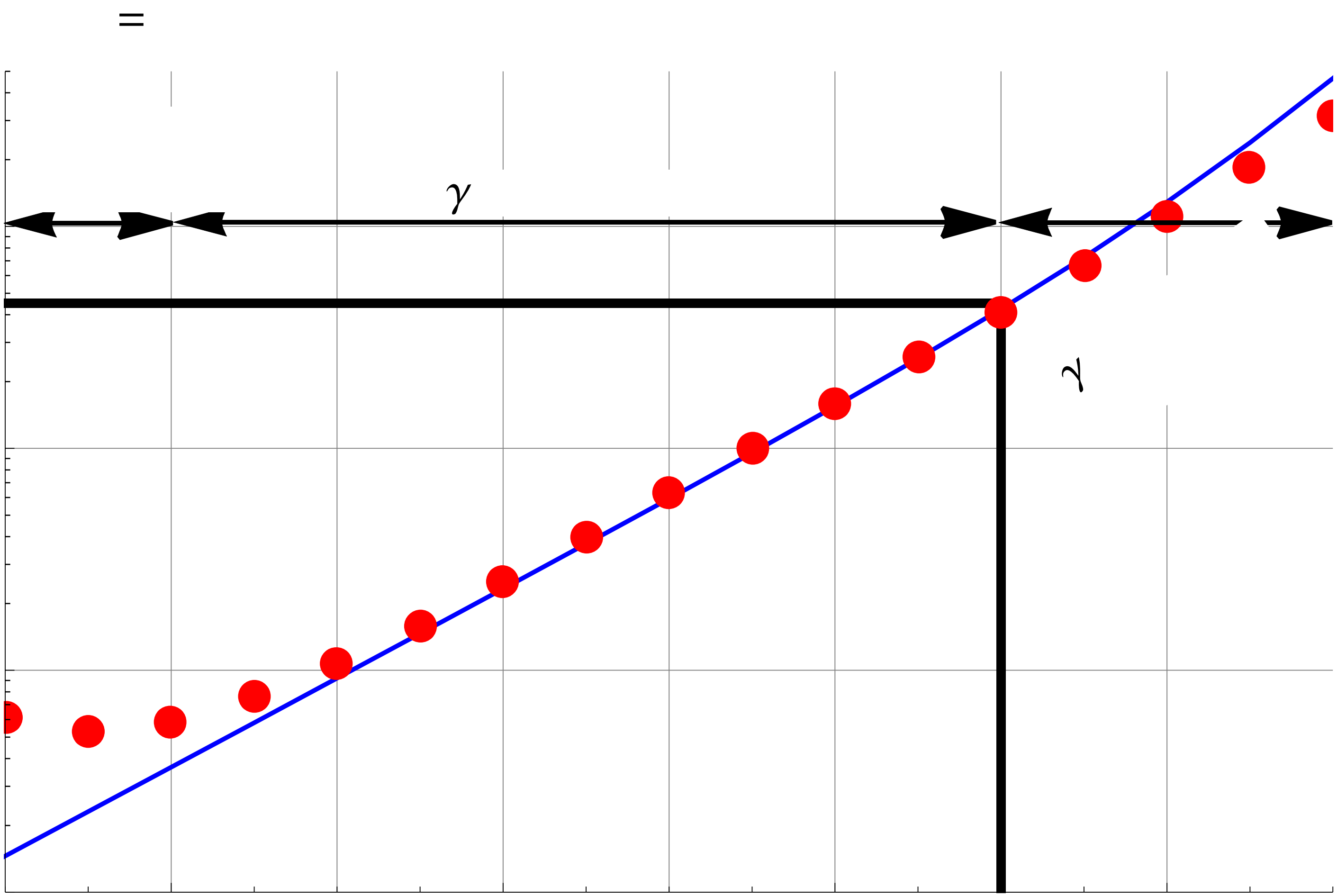
Step 2: Reject cosmic rays, bad seeing, and stack frames.

Step 3: Sky subtraction.



van Kerkwijk (2014; email)

EMCCD spec “sweet spot”



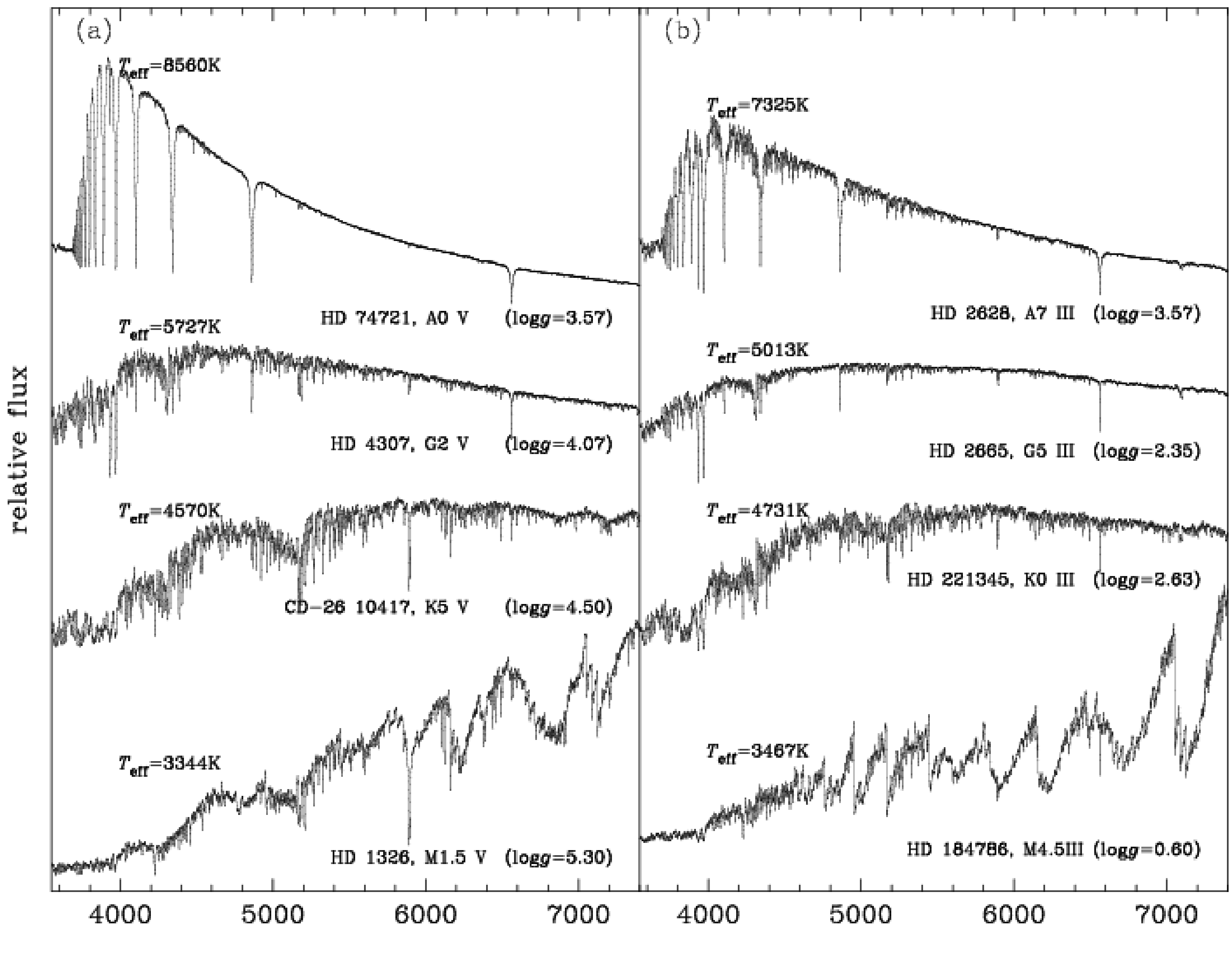
Caltech

How to observe with a "traditional" slit spectrograph

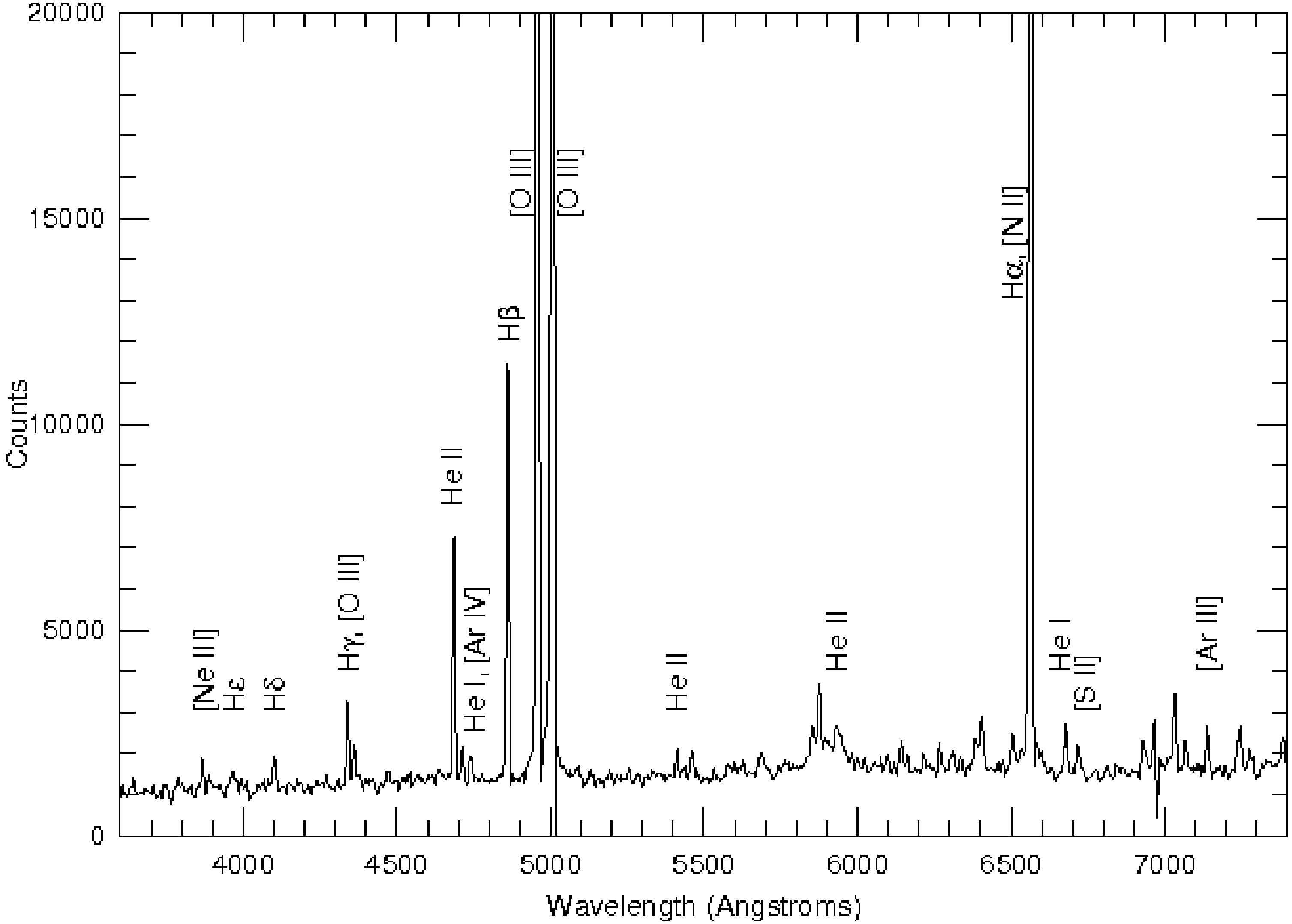
1. Select the target
2. Tune the exposure time such that typical count rate is about 0.1 photon/pixel/exposure.
3. If the object is bright, might as well integrate.
4. There's a "sweet spot" relative to sky background where EMCCD spectroscopy wins.

EMCCD Disadvantages

- Dynamic range
  - No multiplexing

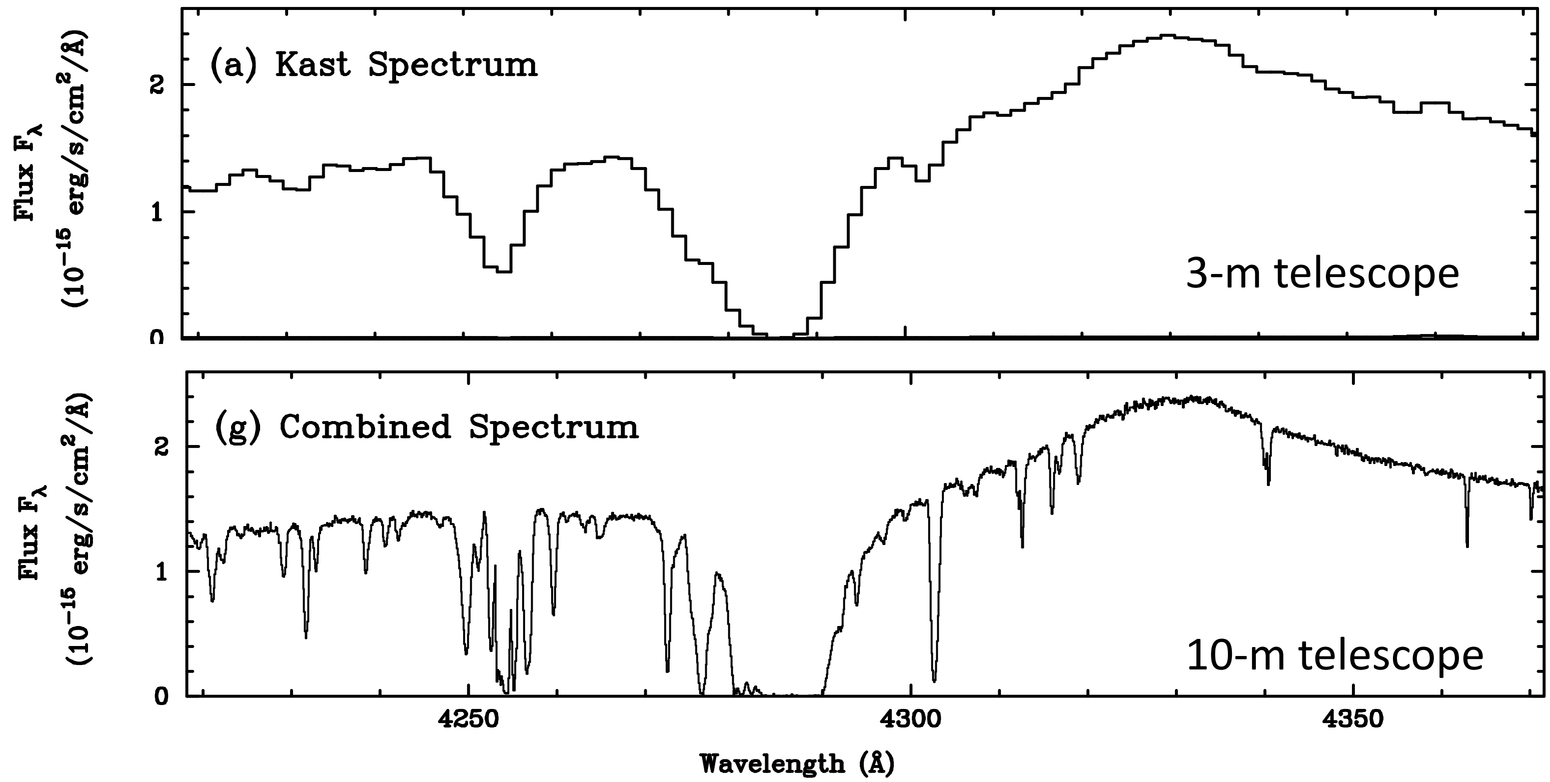


Vazdekis+ (2012)



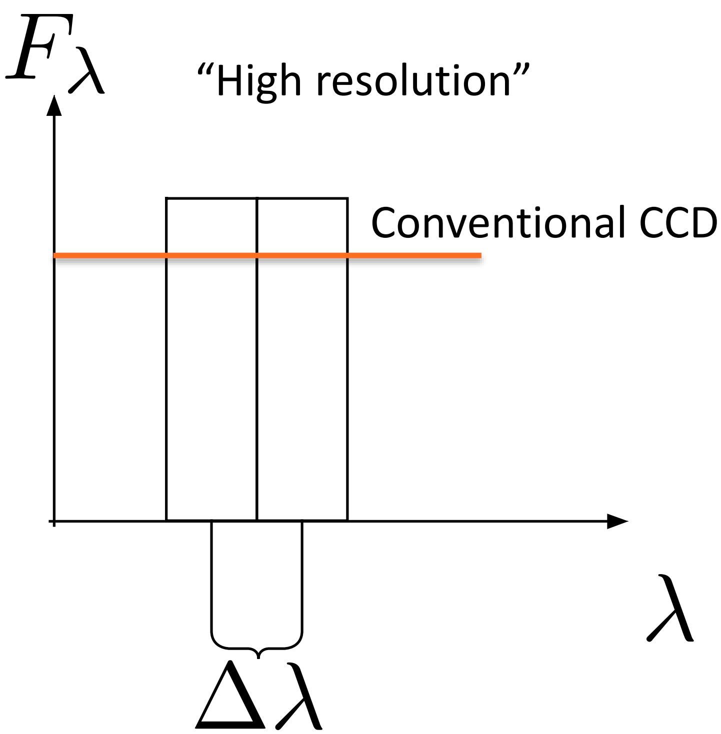
Counts
Wavelength (Angstroms)
20000
15000
10000
5000
0
4000
4500
5000
5500
6000
6500
7000
[Ne III]
Hε
Hδ
Hγ, [O III]
He II
He I, [Ar IV]
Hβ
[O III]
[O III]
He II
He II
Hα, [N II]
He I
[S II]
[Ar III]

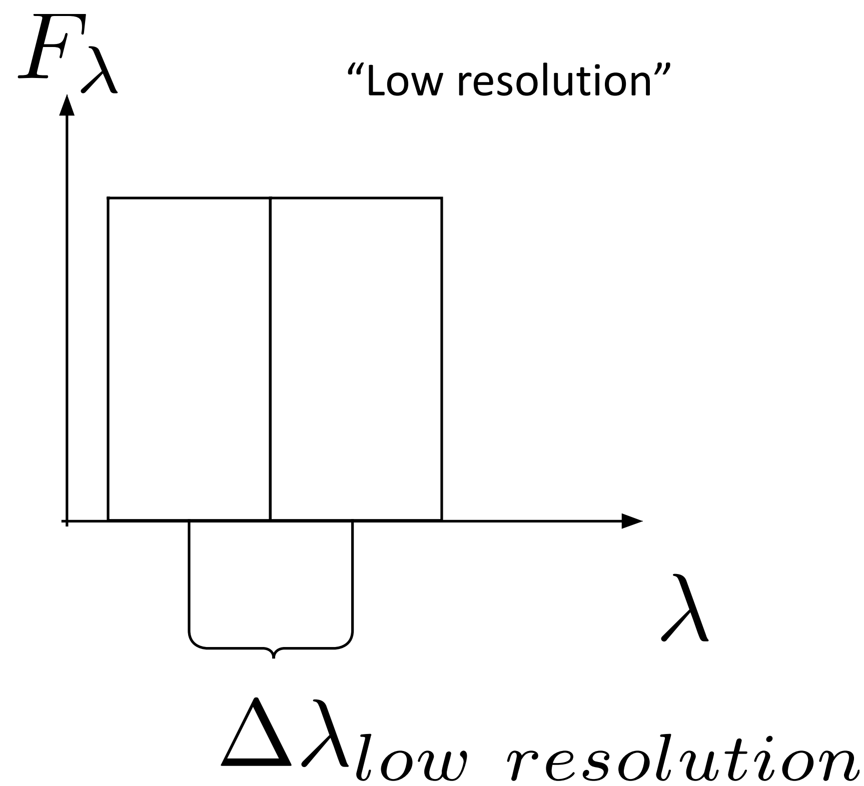
more science/more exposure time



Suzuki+ (2003)

Software-designated resolution





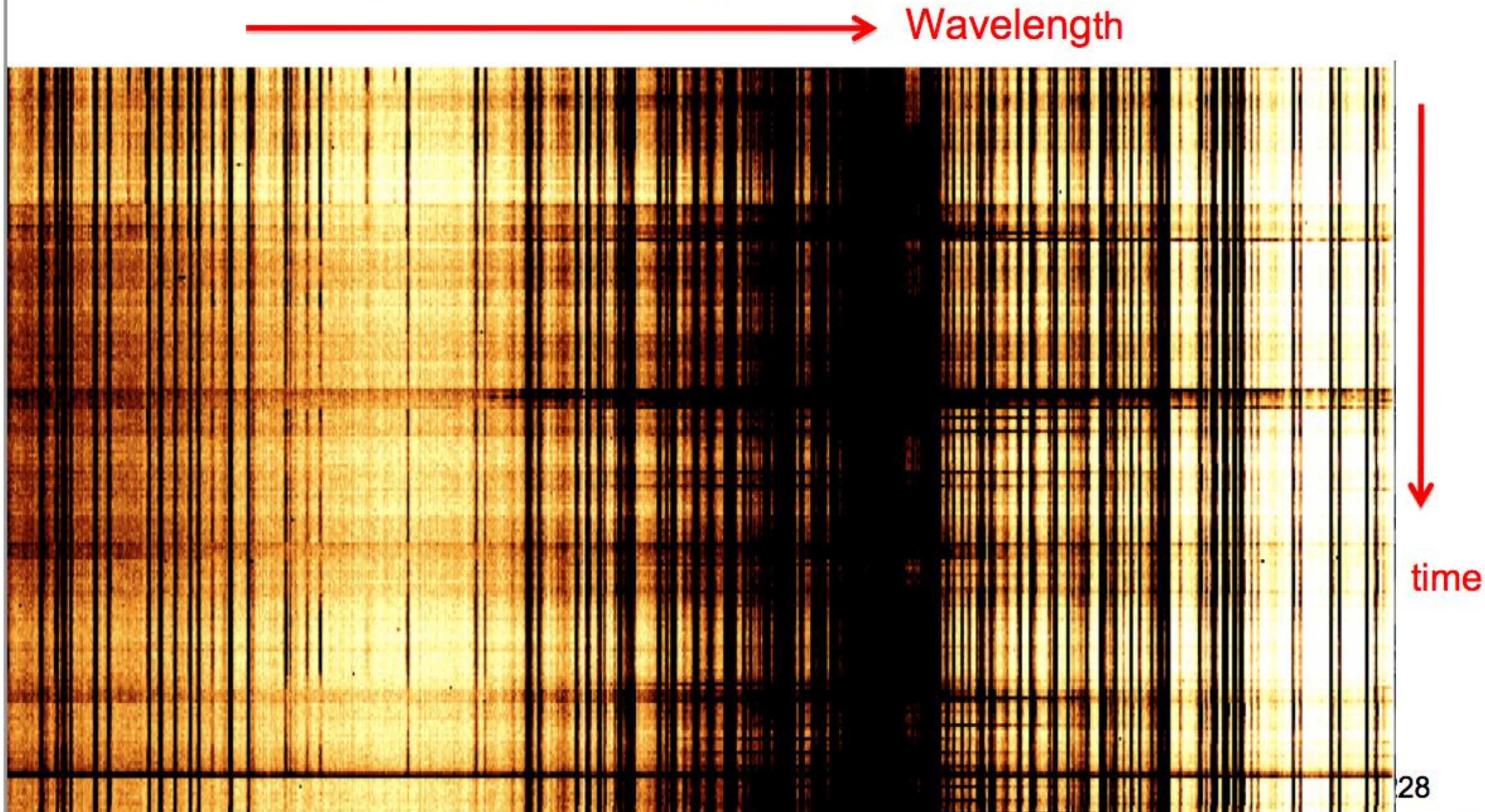
Readnoise per bin is tiny.

Some Notes

- While observing, the spectrum appears in front of your eyes. It’s possible to estimate SNR during the exposure.
- The impact of flexure with such short integrations is worth rethinking (keep fringing in mind).
- Ultra-short exposures with no read penalty would allow for perfect sky subtraction.
- Possible to remove sky in the high-resolution mode, and bin down to any arbitrary resolution → this may be more efficient than simply building a low resolution spectrograph.

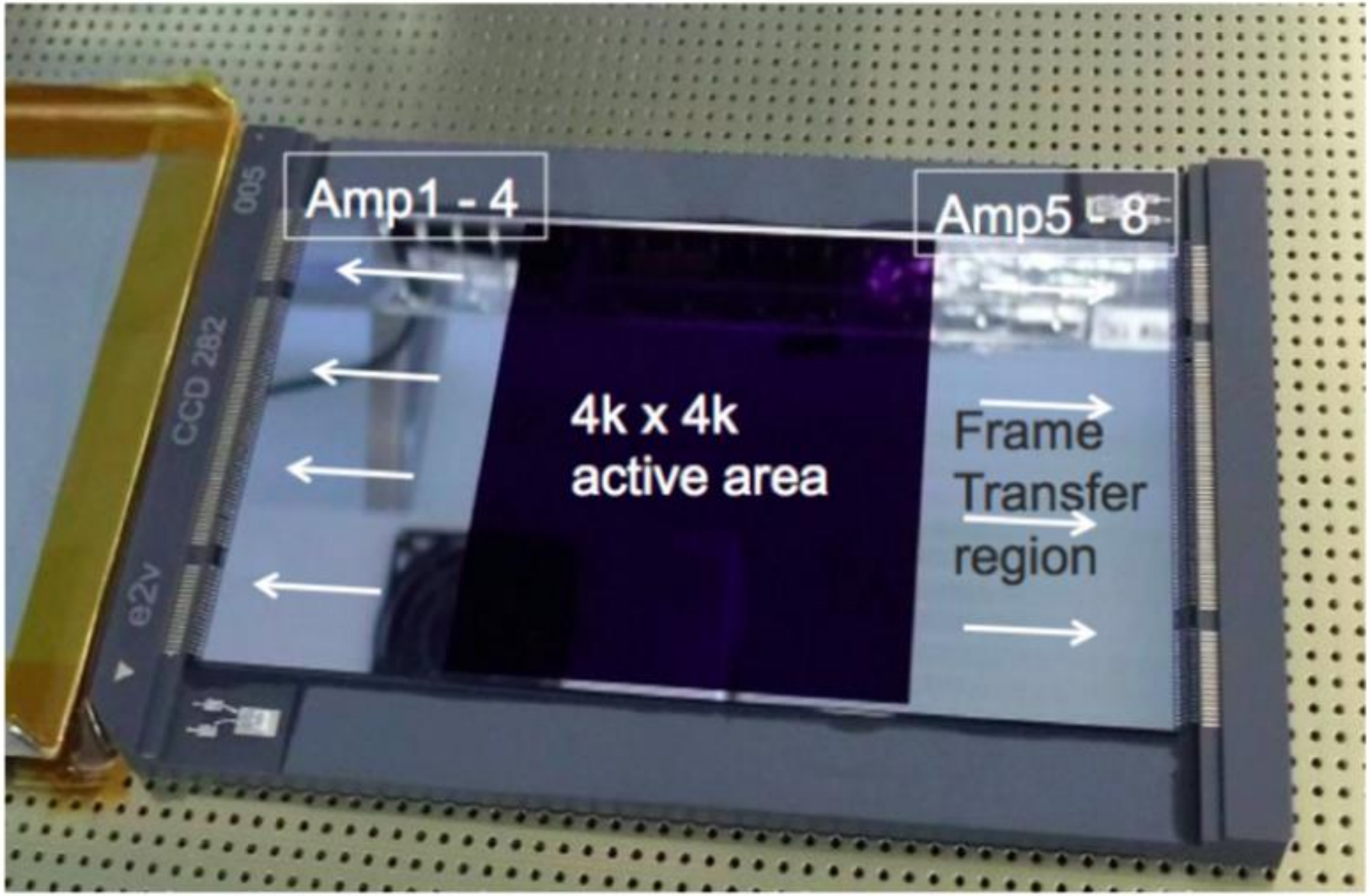
Sky Background Variation Tests

P200/Triplespec 220 x 600s (H-band shown)
exposures over 5 nights in April 2009



Steidel+Konidaris- Night sky over Palomar

e2v CCD 282 – allows R~6,000



Gach+ (2014)

How can we improve?

- Science CCD measures instrument flexure
- Adaptive thresholding
- Coincidence noise with fancy statistics

Summary

1. We discussed basic spectroscopy concepts
2. We reviewed signal to noise
3. Discussed using EMCCD as a tool for software-adaptive spectroscopy.
4. Next:
   – See talks by Erika Hamden, Leon Harding, & Gregg Hallinan.

Operations Concept

Overview

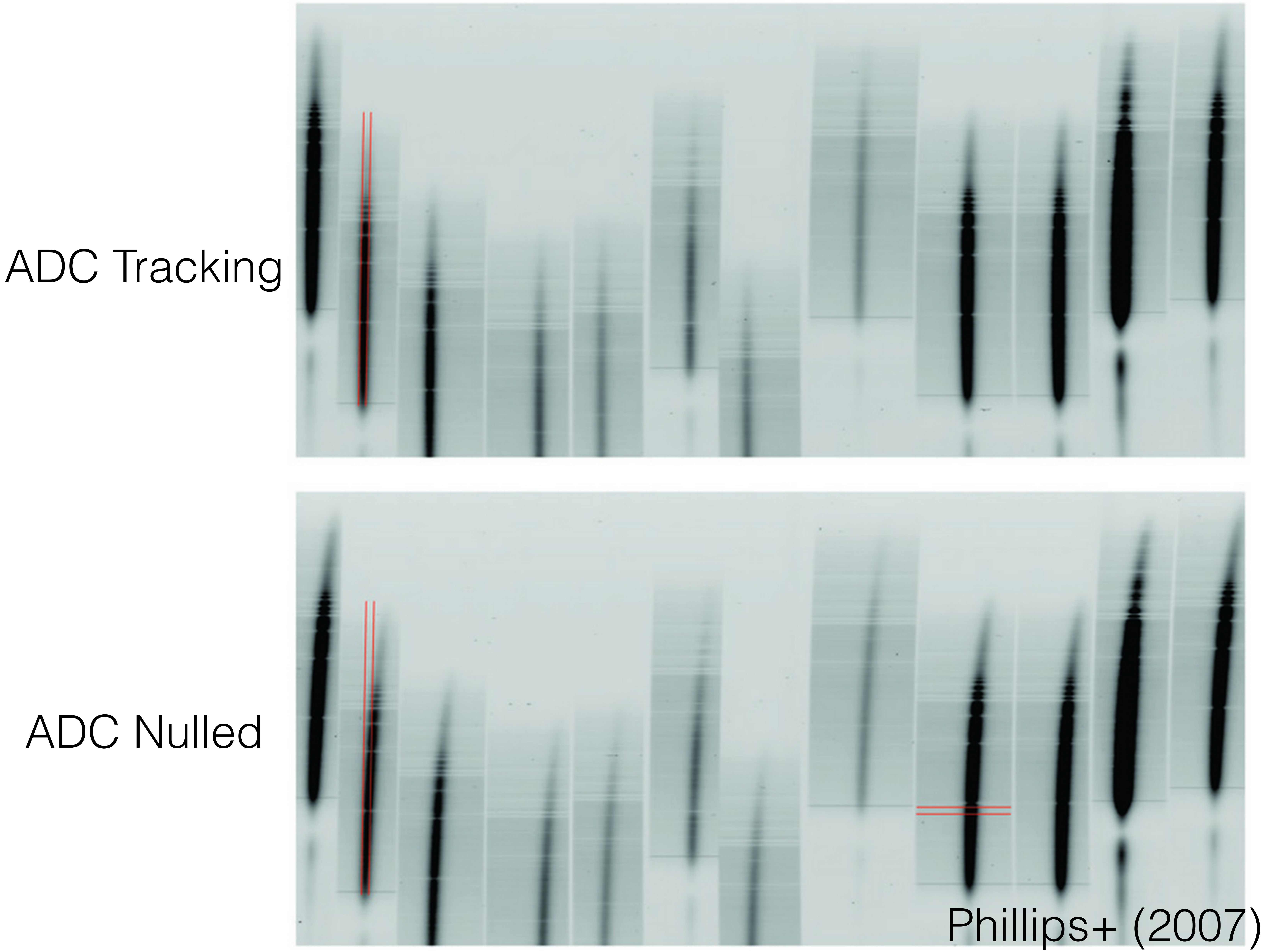
- We present the preliminary operations concept for GEONIS.
- GEONIS is optical + near IR spectrograph, imager, and slit viewing camera.
- The focal plane of the telescope is corrected with the pre-focus ADC.
- Both channels operate independently.
- Each channel has a 4k x 4k detector and ~ 0.19″ pixel scale.
- There are three observing modes

What we review

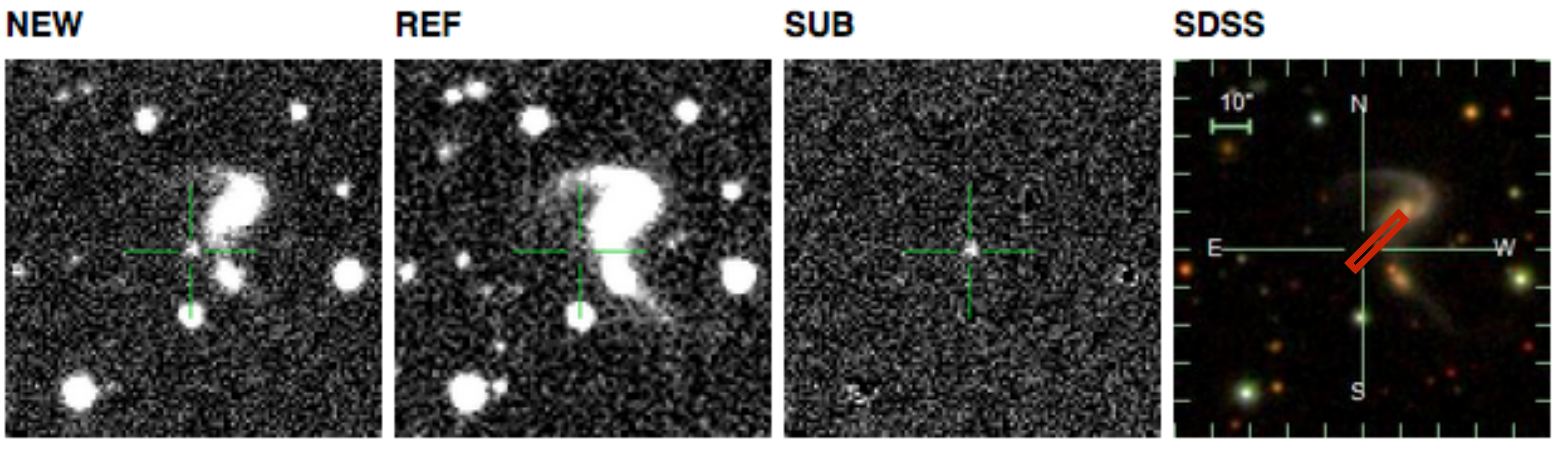
- For each mode (imaging, lowres, echelette):
  - Preobserving
  - Calibration
  - Operations
    - Calibrations
    - Acquisition
    - Science
  - Data reduction

Guiding

- GEONIS has an on-instrument slit viewer + guider.
- The guider might serve as a low-order wavefront sensor (requires hardware change)
- The guider might be used for photometry of object (nothing should preclude this). If the guider is used for photometry, it will need calibrations taken.
- Can be used to estimate slit loss, and atmospheric extinction.


ADC Tracking
ADC Nulled
Phillips+ (2007)

Imperative to Align Slit with Object + Host



100″

Requirements 1

- Imaging, lowres, echelette modes of operation.
- Atmospheric dispersion compensator (ADC) will operate over a well defined airmass range.
  - Beyond airmass range of operation, ADC might be nulled or maximized.
  - TCS will communicate with ADC to adjust PO
- Slitmasks:
  - “Clear” — imaging
  - >25″ slit — echelette
  - >6.7′ slit — lowres

Requirements 2

- GEONIS should not affect the delivered images from Gemini by more than 10% in best quartile seeing.
- Distortion must be stable and characterizable. Details to follow at later design phase.
- GEONIS requires high observing efficiency to:
  - 1. Open up scientific areas that are unknown.
  - 2. Increase the total system throughput of the instrument.

Requirements 3

- The following elements increase instrument efficiency and their stages + software should introduce small amounts of overhead:
  - ADC
  - Slit viewing camera
  - Flexure compensation system (open loop)
  - Control software

Generic Calibrations

- CCDs + HgCdTe:
  - Bias frames for each mode (not sure for HgCdTe).
  - Flat frames for each mode + filter.
  - Arc lamp spectra for each spectroscopic mode.
  - Twilight flat fields as necessary.
- HgCdTe (rare)
  - Linearity correction measurements
  - Bad pixel determination (may evolve over time?)

Echelette Spectroscopy

- Driving science case is transients; however, any point source will do.
- Preobserving:
  - Finding chart as needed
- Observing:
  - Calibration- Standard stars to determine atmospheric response at similar airmass to observations near observation (for most precise measurements) or at a variety of airmass (and apply a gray correction).
  - Acquisition- Acquisition performed via slit viewer with automatic plate solving software (many instruments use slit viewer, FLOYDS + SED Machine use automated method).
  - Science:
    - Bright targets- Straight observing in the “A” position.
    - Faint targets- May require “A-B” observing; however, the slit is long enough to perform ABCD observing + the like.

Longslit spectroscopy

- Driving science case is exoplanets; however, point sources, diffuse objects or extended objects are fine.
- Preobserving:
  - Similar to echelette
- Observing:
  - Calibration- Standard stars to determine atmospheric response at similar airmass to observations near observation (for most precise measurements) or at a variety of airmass (and apply a gray correction).
  - Calibration along the enormous slit may be required.
  - Acquisition- (See echelette)
  - Science:
    - (See echelette).

Exoplanet Precision

- Driving consideration for exoplanetology is precision.
- May be best to use nulled ADC:
  - Calibrate with a “known” light path
  - Minimize pupil wander
- May be best to use fixed ADC
  - Minimizes pupil wander
- May require a pupil mask (not baselined) or the like to ensure pupil wander has smallest impact on precision.

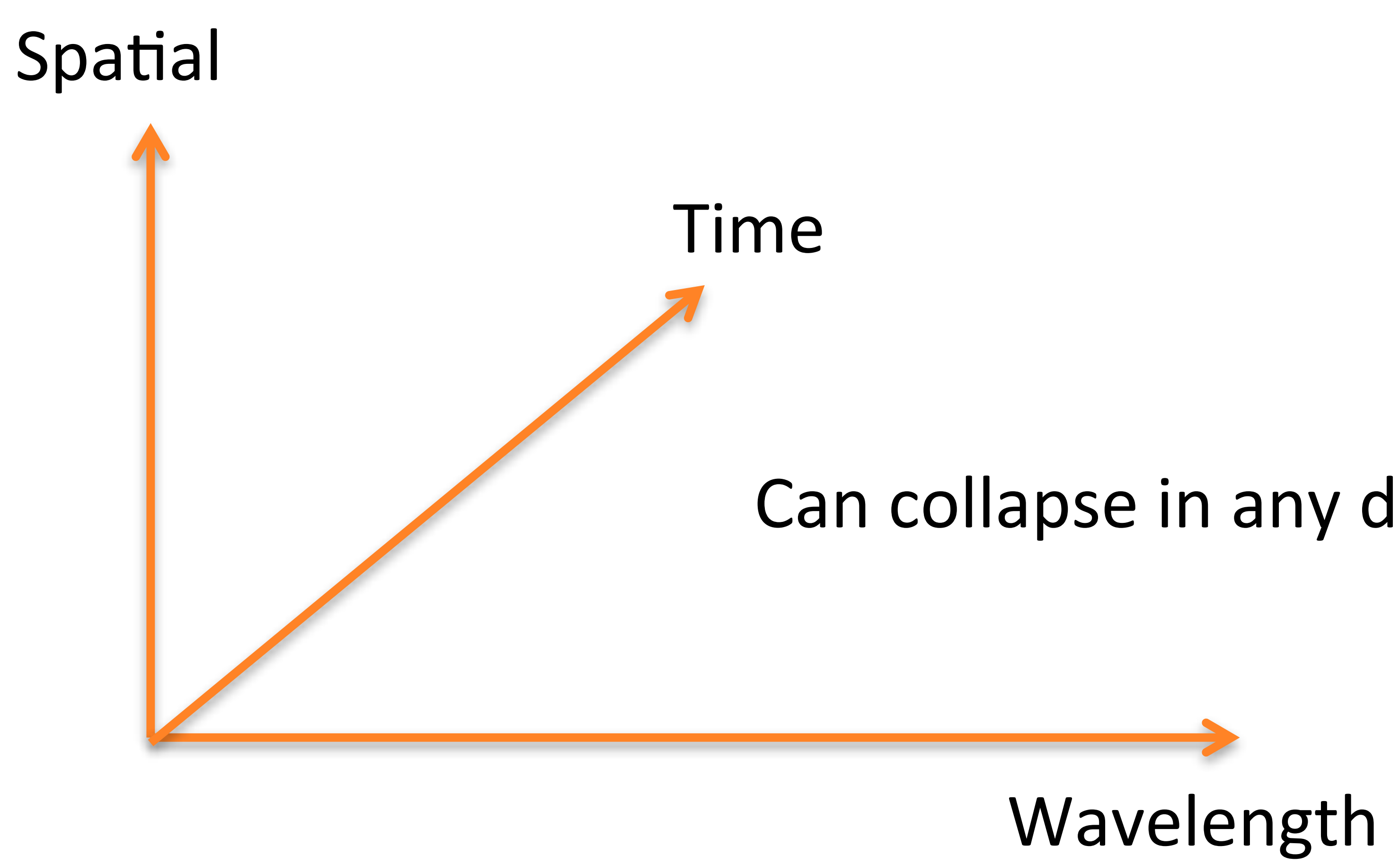
Imaging

- Driving science case is NEOs, but GEONIS is a high-quality imager (will be the sharpest visible imager on Gemini due to ADC).
- Guiding performed off-instrument as slit mask is cleared
- Preobserving:
  - Finding charts
- Science
  - Classical imager: standard stars, telluric stars, science targets.

Data Reduction

- GEONIS formats are "standard" in spectroscopy
- Echelette mode/imaging mode reduced with iraf.
- Some thought about the exoplanetology pipeline is required. Exoplanetology is technique driven, and so the pipeline may deliver lower-level products.
- Note: Baselined pipeline is bare bones.

Result of EMCCD spectroscopy: “Data Cube”



Can collapse in any dimension- no penalty.

Summary

- We presented the baselined operations concept document.
- GEONIS uses formats and modes that are "standard".

Photon counting with Electron Multiplication CCDs

Roger Smith

Caltech

2015-09-28

With thanks to those who have posted slides on the internet, such as Peter Sinclair (ESO) and Jim Janesick.

Outline

Photon counting in general:

- What's photon counting and when is it useful.
- How it was done prior to CCDs?
- Trade-offs common to all photon counting technologies
- Early problems

EM CCDs:

- How does an EM CCD work?
- How CCDs improve photon counting.
- Remaining problems and what can be done.
- Pushing the limits.

WHAT'S PHOTON COUNTING

and when is it useful

The Challenge

Faint target or
time resolved

High spectral or
spatial resolution

Dark side of the Moon
Pink Floyd, 1973

- For high dispersion spectroscopy or time resolved observations, few photons per pixel per frame.
- For some applications we would like to identify when each photon arrives.

Current performance

- >80% QE from UV to ~900 nm

- Only 3 spurious counts per second

  per million pixels !

- All the features of standard CCDs, especially the ability to *calibrate* accurately since performance is *stable*.

The big idea

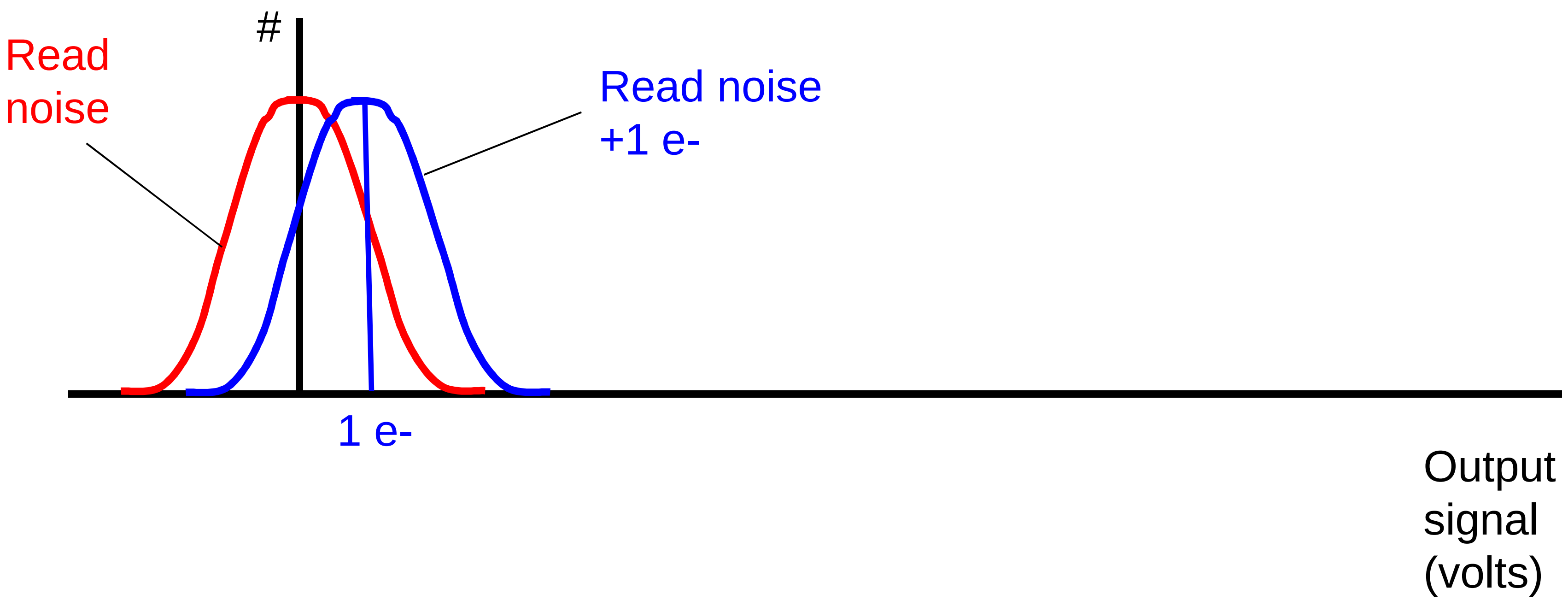
- In the optical we get one electron (or none) per photon.
- We can never totally eliminate the noise floor in the measurement of this charge.
  - Best median noise ~ 1 e-, but broad distirbution.

So….

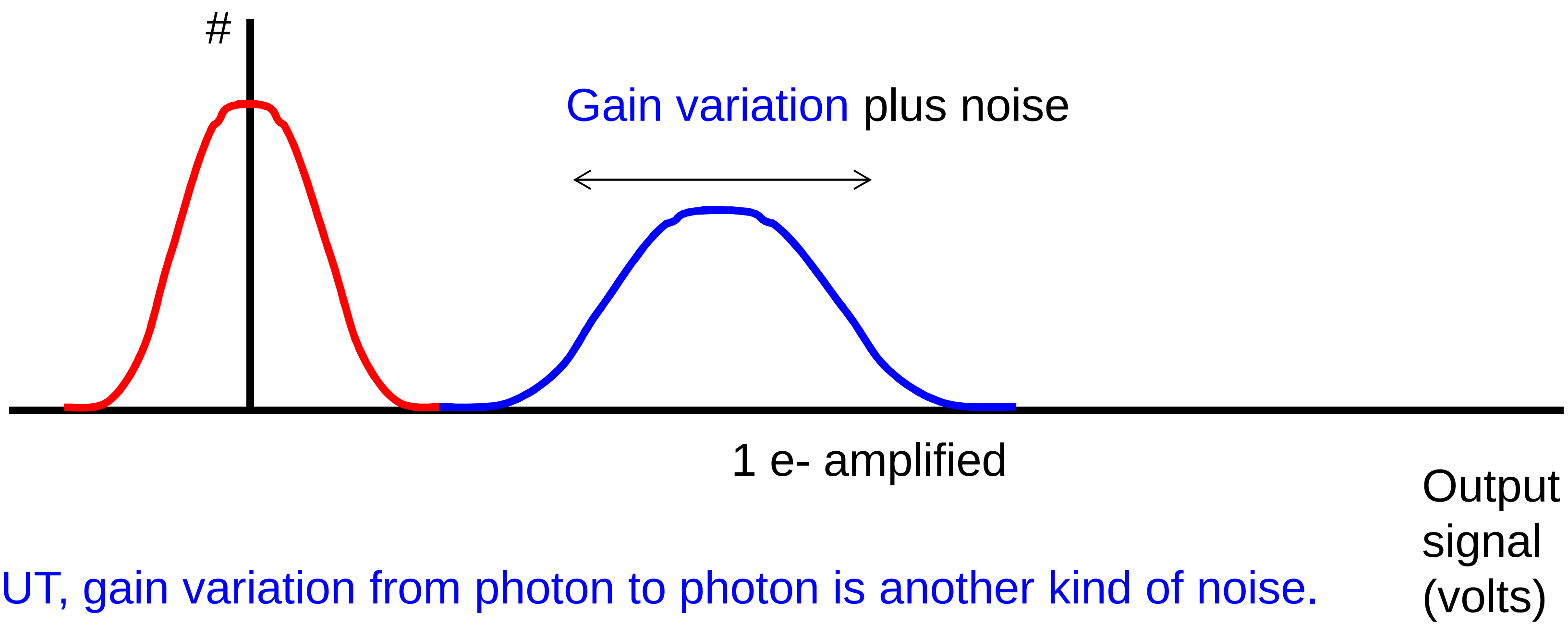
- (Somehow) endow each electron with energy and use this to dislodge many electrons.

→ raise signal above noise floor

Signal Histograms



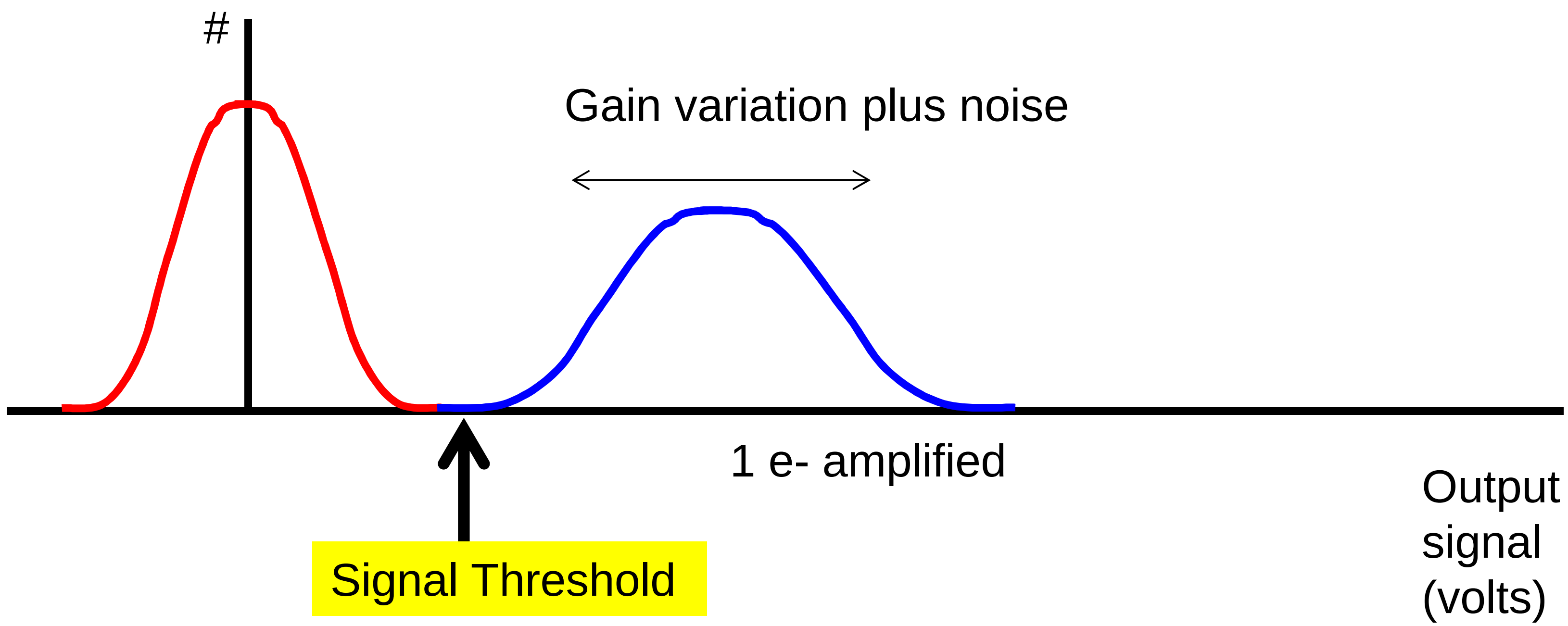
Amplify the signal → exceeds noise



- BUT, gain variation from photon to photon is another kind of noise.
- In fact it's a worse kind of noise since it applies to bright signals not just faint ones.
- THIS IS VERY BAD.
- WHAT TO DO ????

Ideal case

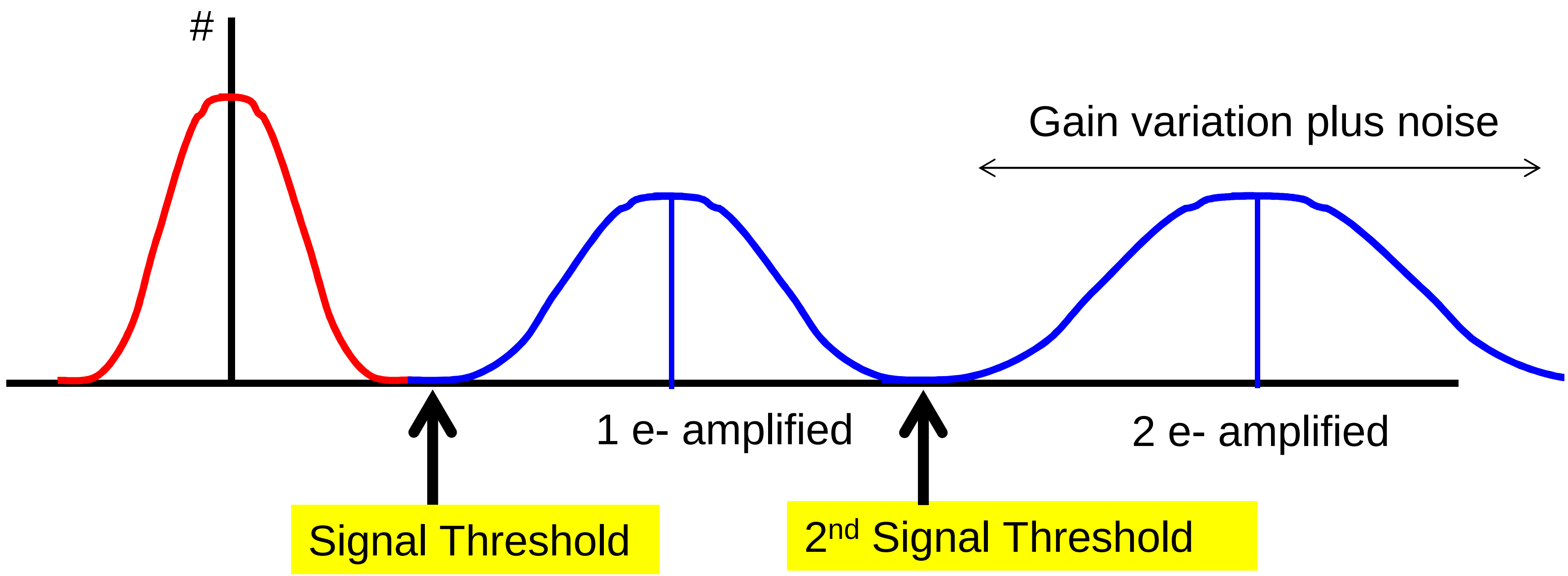
Apply threshold → count photons



Single photon events unambiguously identified.

- No read noise.
- Signal-to-noise ratio is given by Poisson statistics (variance=mean).
- High frame rate with no penalty (at least in theory)
- Photon arrivals can be time tagged.
- Read-modify-write to memory in sync with sensor readout to count photons.
  → Image available for inspection during exposure.

Multiple events per pixel

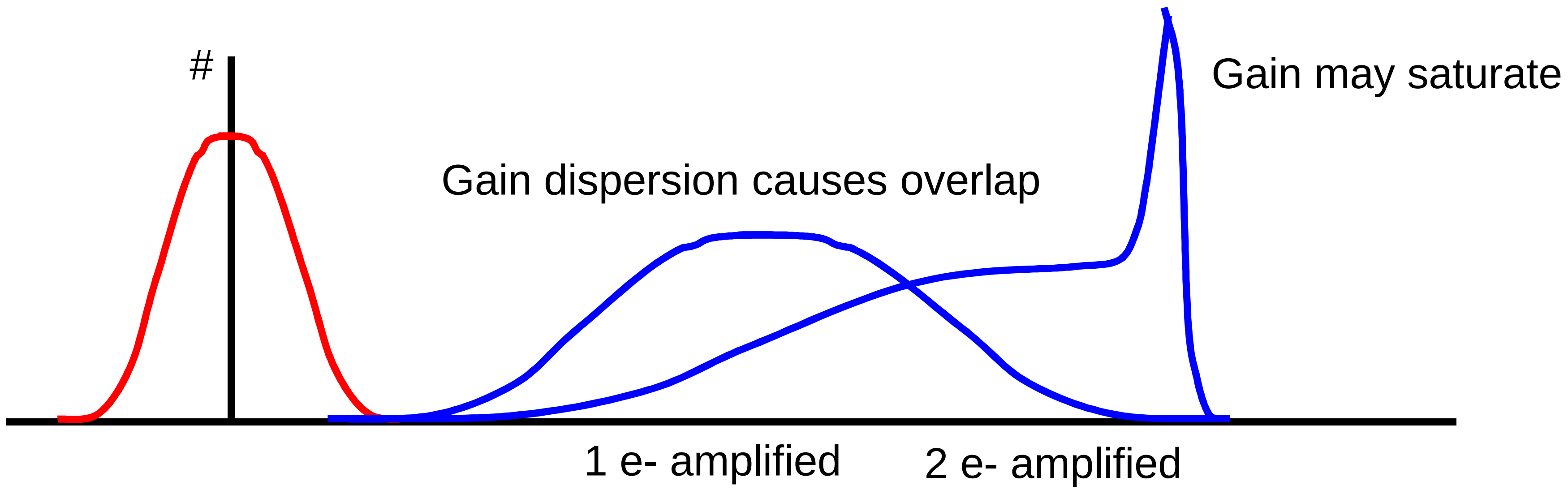


Maybe multiple events can be distinguished … ?

Cosmic rays are off scale and might be filtered out …?

Real world

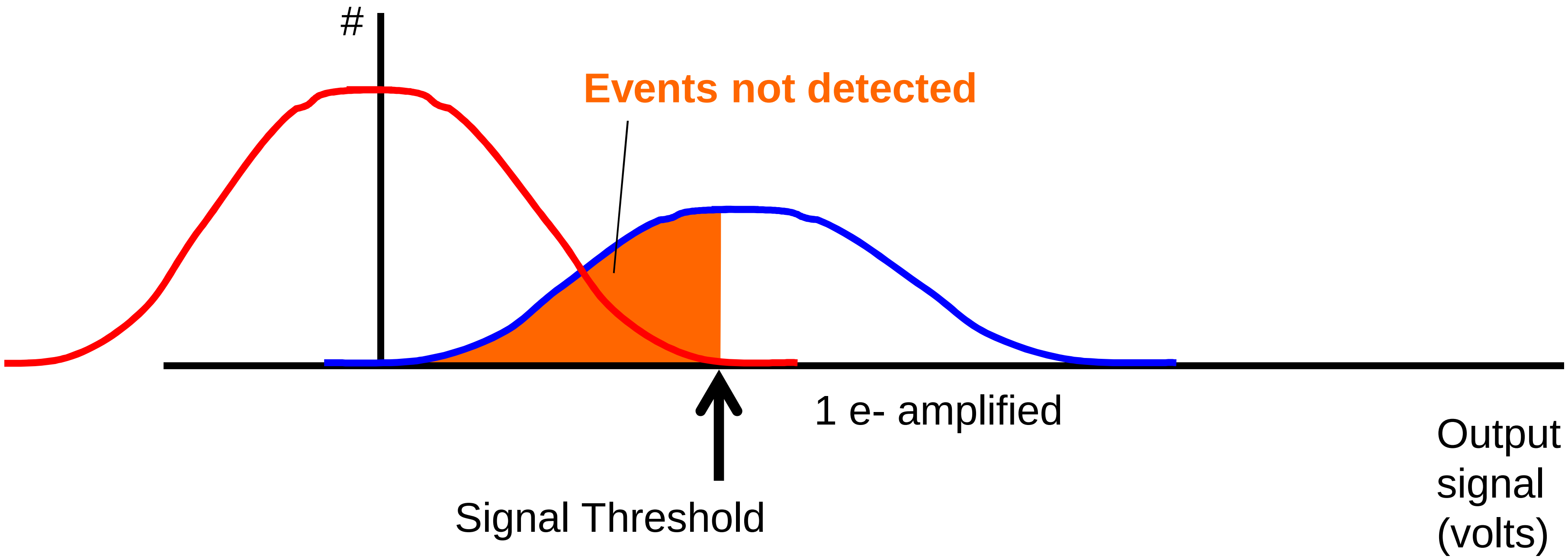
Multiple events per pixel



In practice multiple events are not reliably distinguished
→ counted as one event

Need high frame rate or to limit flux to avoid *“coincidence losses”*

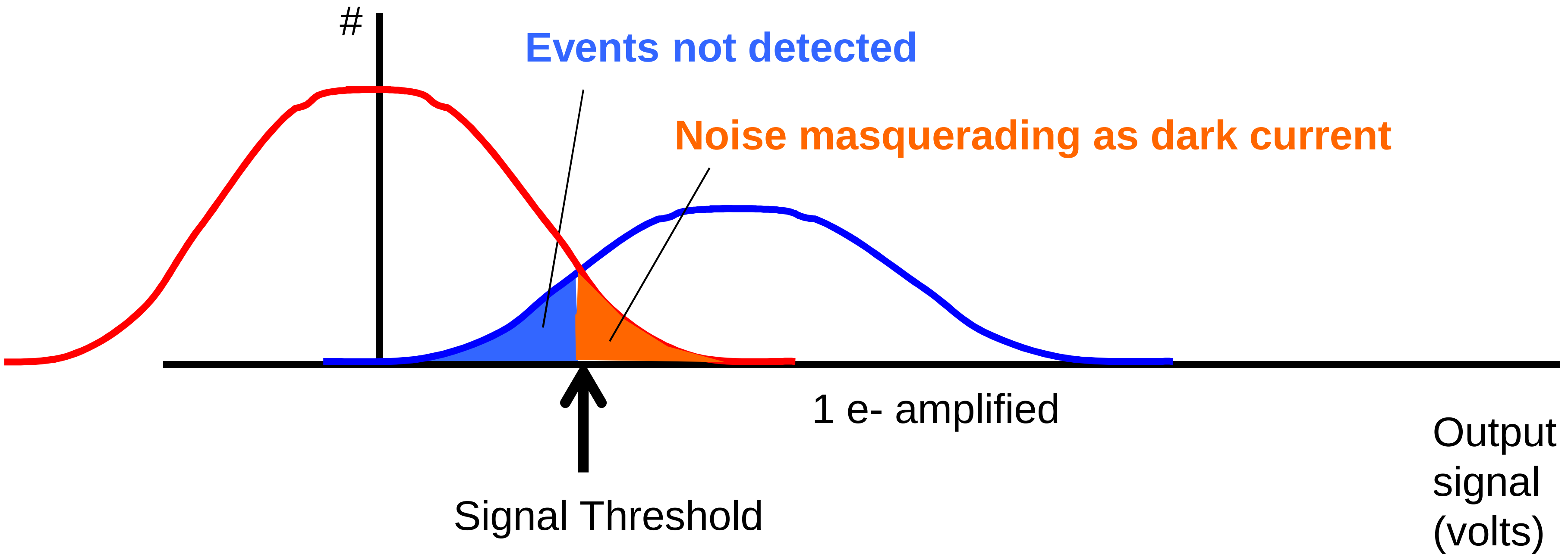
Higher noise at high frame rate



The higher frame needed to avoid coincidence losses requires higher bandwidth output amplifier (faster settling) → for white noise, **total noise increases** as √(pixel_rate).

Real world

Higher noise at high frame rate

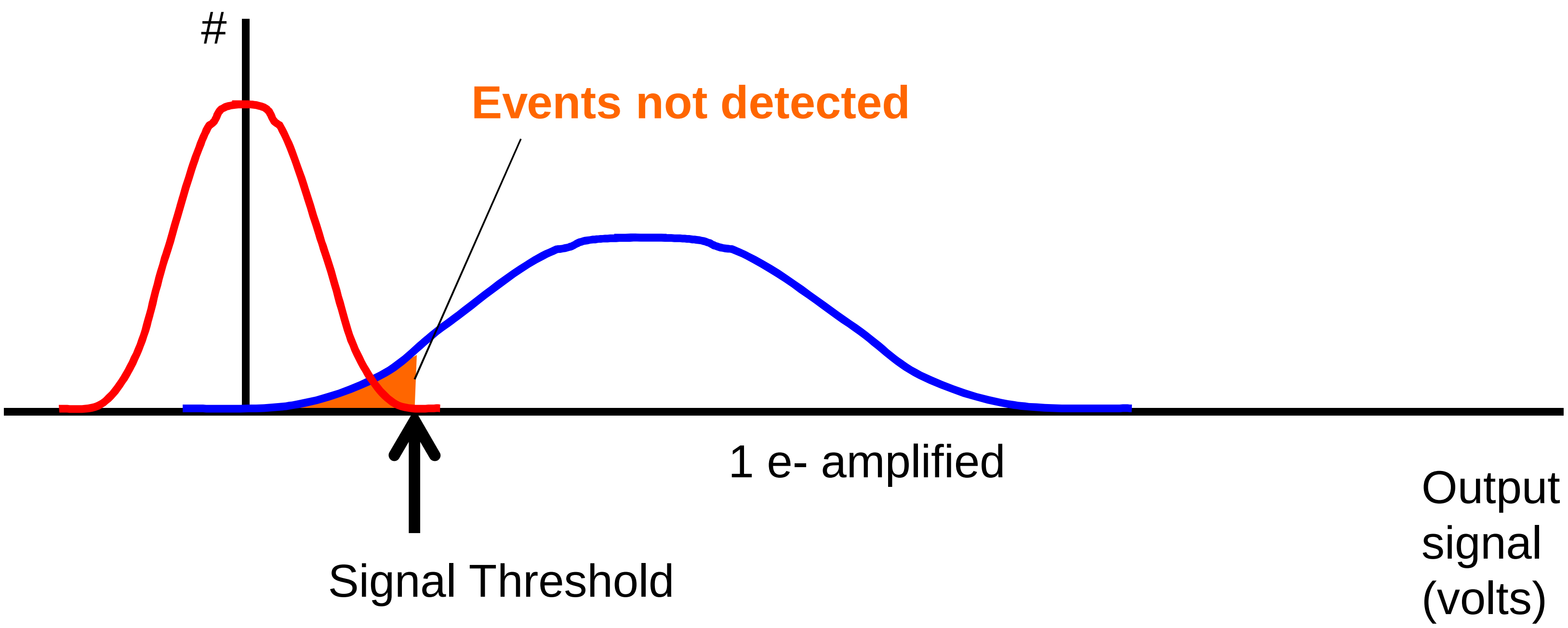


Attempting to recover these real events by lowering threshold
results in elevated dark counts due to electronic noise.

Need more gain or lower noise = slower frame rate = lower bright limit

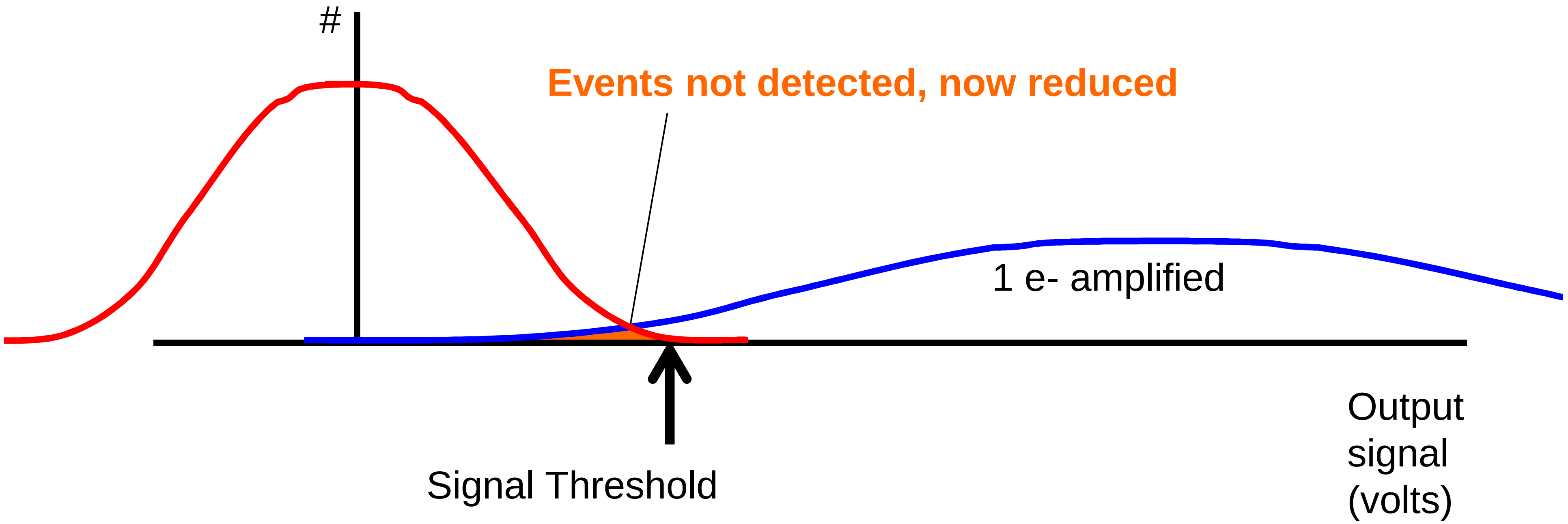
Real world

Lower noise (slower readout, less dynamic range)



Real world

Increase gain



Later we will return to the downsides of higher gain.

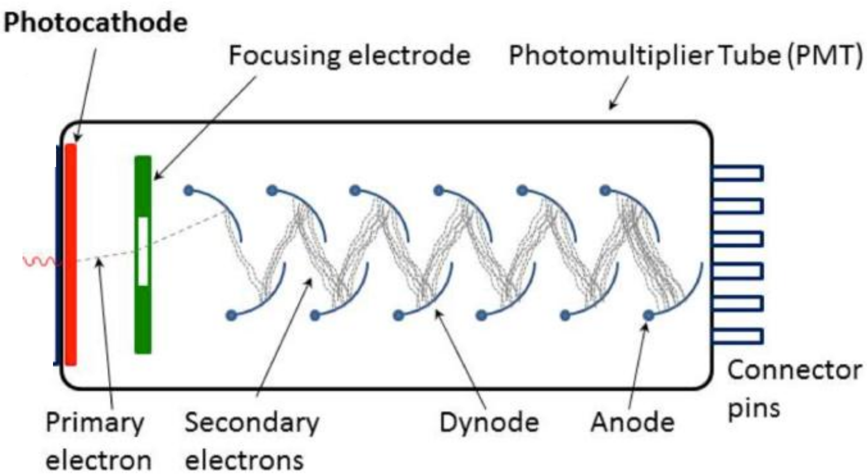
To see why we like EMCCDs consider

EARLY PHOTON COUNTING IMAGERS

Precursor to image intensifiers…

Photo-multiplier tubes 1934-today

Photo-electric effect works best for higher energy photons (blue/UV)

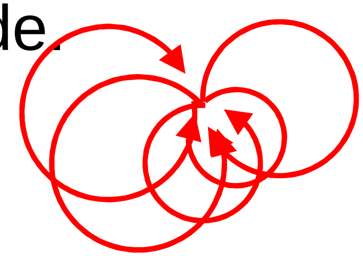


- Photoelectric effect (Heinrich Hertz, Albert Einstein): photon liberates electron from metal alloy.
- Accelerate with electric field
- Impact liberates secondary electrons to provide gain (Westinghouse, 1919)
- Very fast photon counting possible. No imaging capability

Magnetically focused image intensifier

FIG. 4 Alexander Boksenberg, circa 1980, shown with an image-intensifier tube from the Image Photon Counting System. (Source: Image courtesy of the Emilio Segrè Visual Archives at the American Institute of Physics, College Park, Maryland.)

- Charge spirals around axial magnetic field lines
- Tune ratio of electric and magnetic fields to charge makes integer number of circles about magnetic field lines → charge location at output phosphor matches input, independent of velocity when leaving photocathode.



IPCS comes to Palomar in 1973

He arrived in Pasadena during autumn 1973 with the IPCS packed into huge wooden crates that contained electronics, power supplies, a computer, and the detector's cooling system. A digital electronics expert and a software specialist also came along. In short order, the whole operation was nicknamed "Boksenberg's Flying Circus" (BBC was still airing the British comedy series *Monty Python's Flying Circus*). The traveling version of the IPCS had a loudspeaker and a small light on the side of the equipment. When a photon was recorded, the light would flash and the speaker would chirp, letting an observer know that the instrument had collected data. As one astronomer noted: "You could actually hear the photons coming in—*bip, bip, bip*—and watch the image build up. You could know you had observed the right length of time to get what you wanted. The ICPS was very exciting to use."[63]

3C 68.1: A VERY RED QSO WITH AN INTERMEDIATE REDSHIFT

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Department of Physics and Astronomy, University College, London
AND
J. B. Oke
Hale Observatories, California Institute of Technology, Carnegie Institution of Washington
Received 1976 February 2; revised 1976 March 24

ABSTRACT

Spectroscopic observations of the red stellar object identified with 3C 68.1 show it to be a QSO with redshift 1.238. The spectral index of the optical continuum is found to be about 6, a value considerably steeper than that previously found for QSOs.
Subject headings: galaxies: redshifts — quasars — radio sources: general

I. INTRODUCTION AND OBSERVATION

The object 3C 68.1 is a highly asymmetric double radio source with separation 58″ and component intensities in the ratio 9:1 (McKay 1969). The radio spectrum is a power law with spectral index 0.85 (Véron, Véron, and Witzel 1972), with no strong evidence for variability. Longair and Gunn (1975) have identified this source with a 19th magnitude red stellar object lying between the two radio components.

Spectroscopic observations of 3C 68.1 were made in 1973 November in conditions of good ($<2''$) seeing using the University College London Image Photon Counting System (IPCS) (Boksenberg 1972; Boksenberg and Burgess 1973) mounted on the Oke-Gunn Cassegrain spectrograph at the Hale 5 m telescope. Object and sky spectra were recorded simultaneously through two 2″ diameter apertures over 512 channels each, at a dispersion at the camera focus of 240 Å mm^{-1}. Useful coverage was from about 3300 Å to over 7000 Å,

TABLE 1

Emission Lines

Observed Wavelength (Å)	Equivalent Width (Å)	Identification	Redshift
3461...........	~100	C IV λ1549	1.235
4278...........	~ 50	C III] λ1909	1.241

though only approximate values could be determined, especially for C IV λ1549 where the continuum is poorly known. These lines show up more clearly in Figure 2, where the spectrum has been divided by a best-fit power law. At the redshift of 1.238 we should normally expect Mg II λ2798 to be visible at 6262 Å, but we find only weak evidence for an emission feature there. In this region the photocathode response is lower than at shorter wavelengths, hence the signal-to-noise ratio is lower and a line such as that identified

Image Photon Counting System

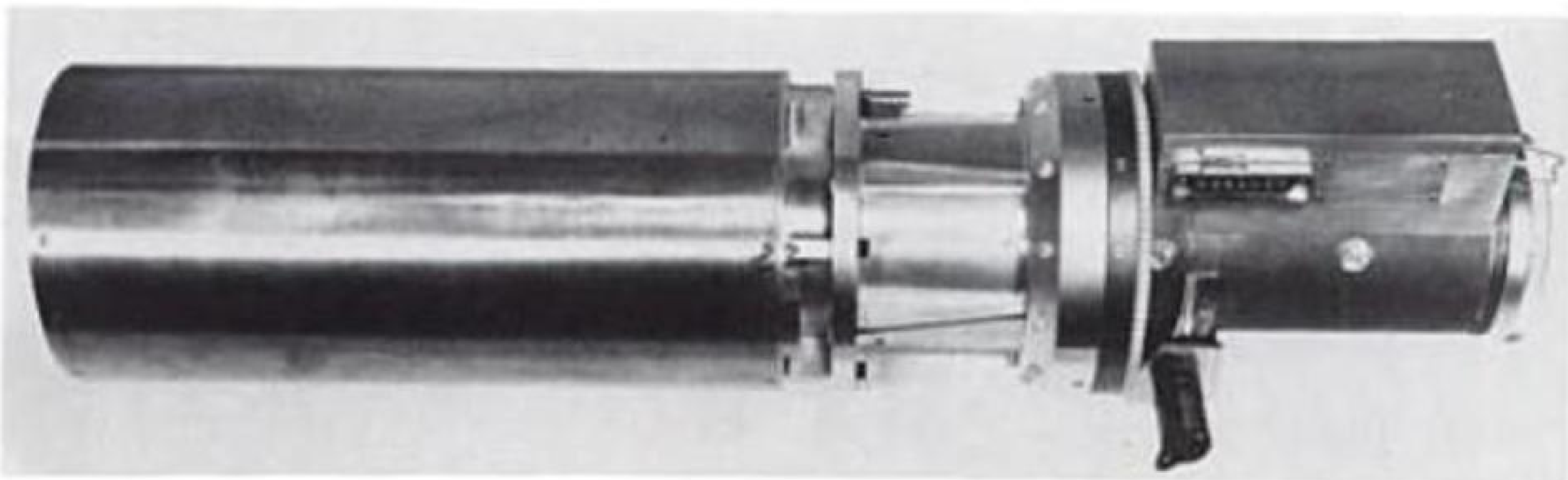


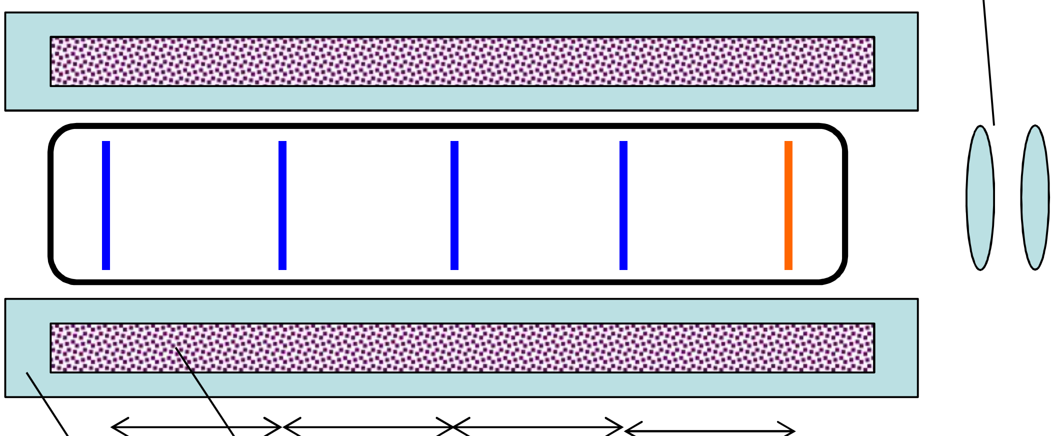
Fig. 19.5. The IPCS detector head unit, containing image intensifier, coupling lens and television camera.

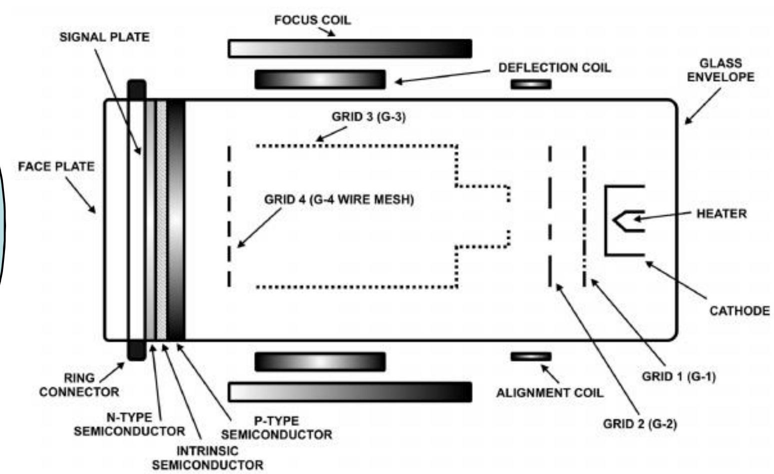
Schematic

Relay lenses

Plumbicon TV Tube with
magnetic deflection

RCA 4 stage image intensifier





10 KV per stage

7 amps in solenoid at ~30V

Water cooled to ~0 C to keep dark current low

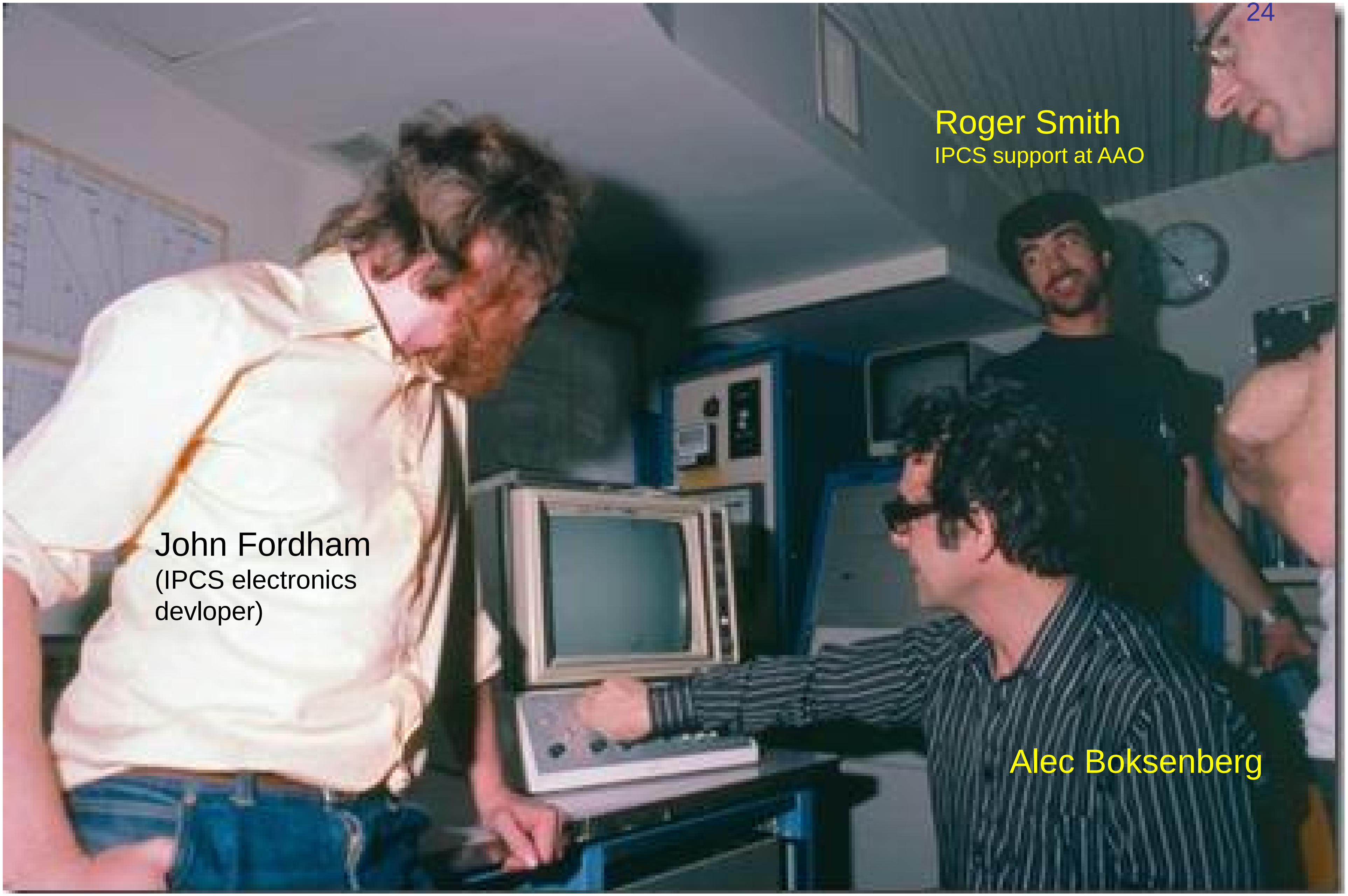
Pros Cons

- No read noise
- Time of photon arrival recorded
- Programmable pixel size and location

Image visible as it accumulates

- QE ~20%; cannot exceed 50%
- Pixel can move in response to
  - Drift in electronics
  - External magnetic fields
- Count rate limit ~ 1ph/s/pix
  - Calibrations are very slow.
  - 3 hours to get 1% SNR.
- Complex and dangerous…

AAO control room, 1980



Now in science museum

Intensifier + CCD, or strip line

Galex UV camera

- Microchannel plate image intensifiers more stable
- Plumbicon TV replaced by CCDs with lower noise so better counting efficiency

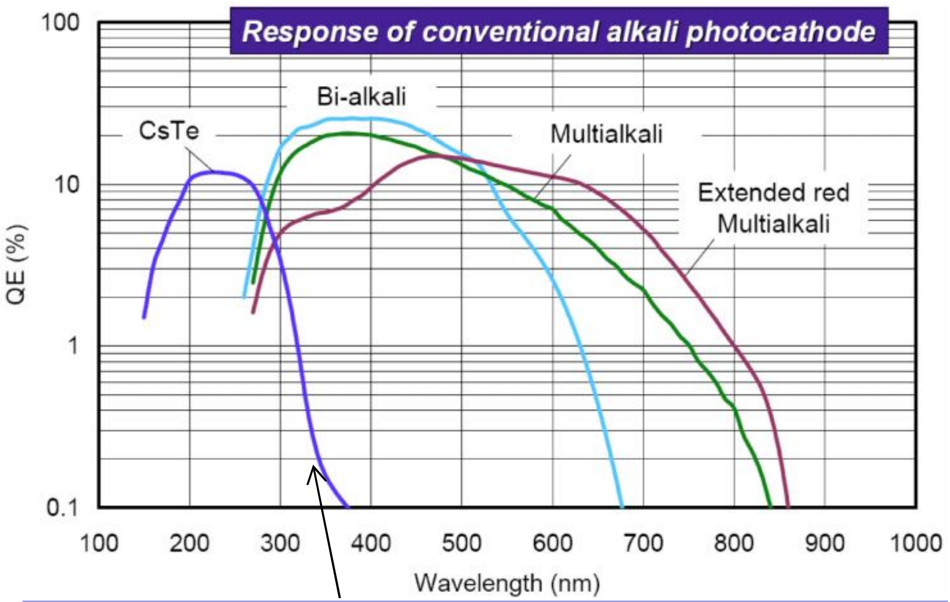


Image intensifiers still useful where solar blind UV sensor or fast gating is required, but….

- Photocathode's can't match CCD QE.
- Low noise of CCD has eroded parameter space in which photon counting is needed.

Photon counting applications shrank to niche applications like UV space missions, where solar blind photocathodes were advantageous

Photon counting is back, since….

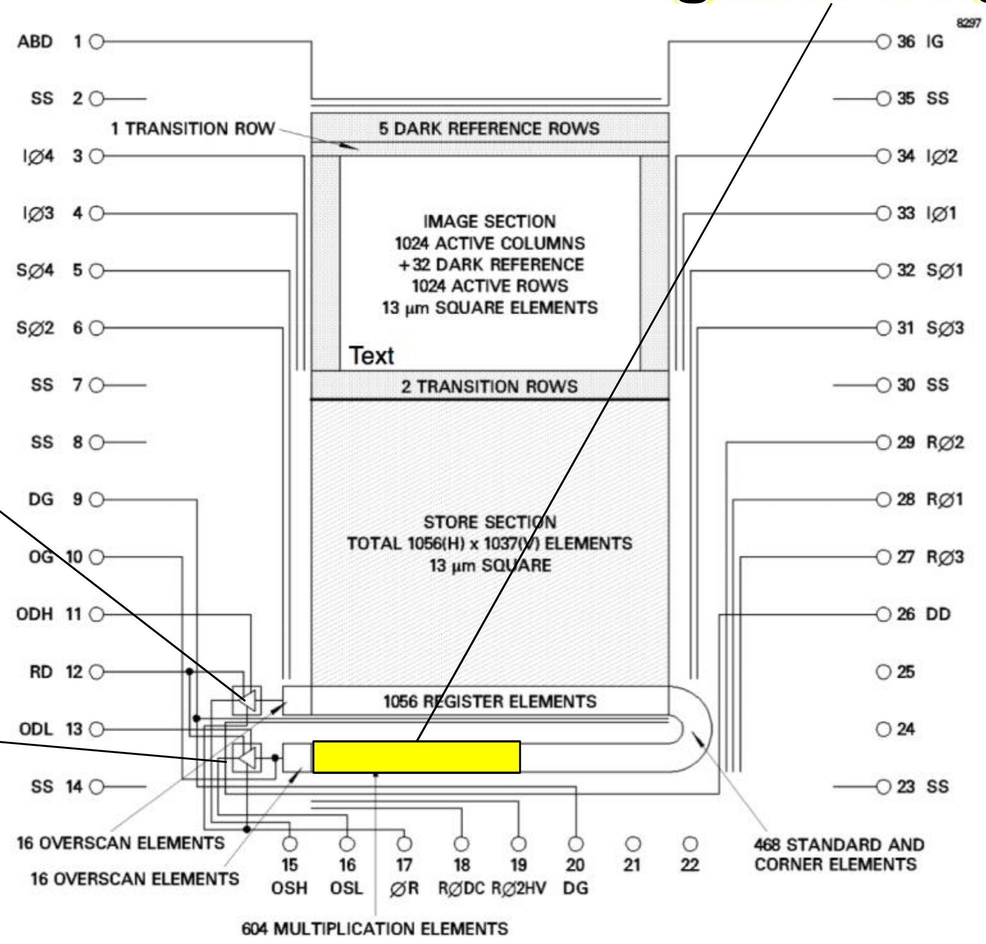
EMCCDs deliver high QE

Intensified CCD = Photocathode → intensifier → CCD

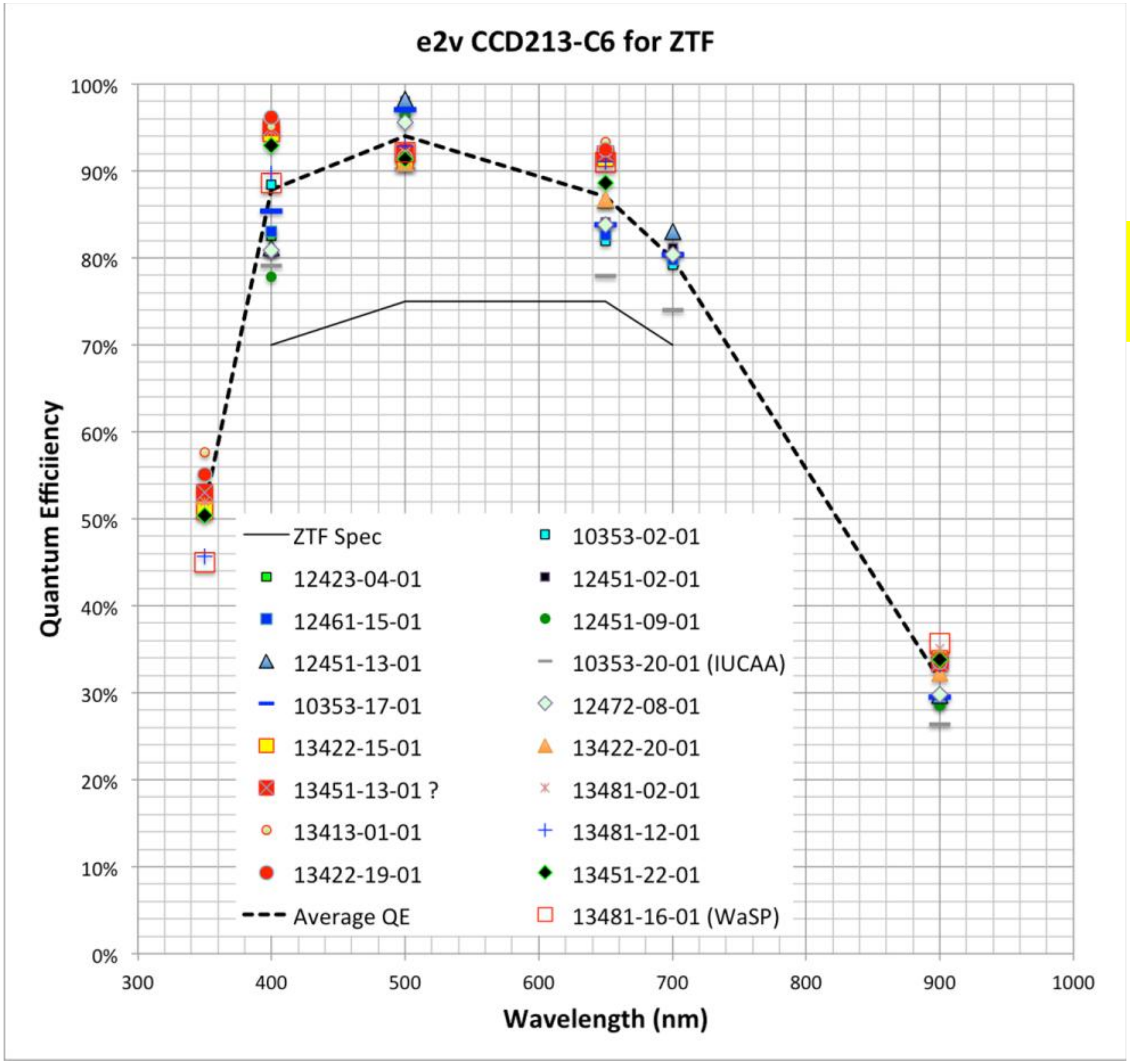
EMCCD = Conventional CCD → **gain register**

Normal output

Photon counting output



Typical QE for scientific CCD



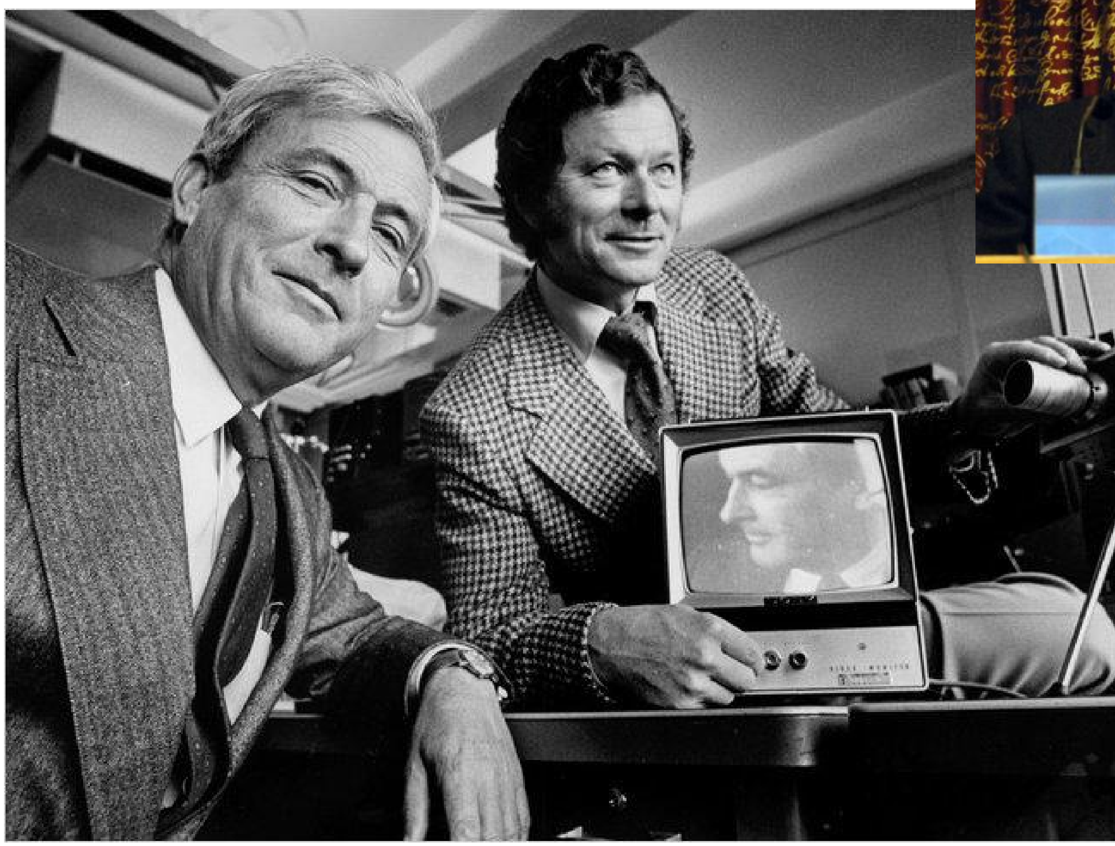
6Kx6K CCDs recently procured for ZTF

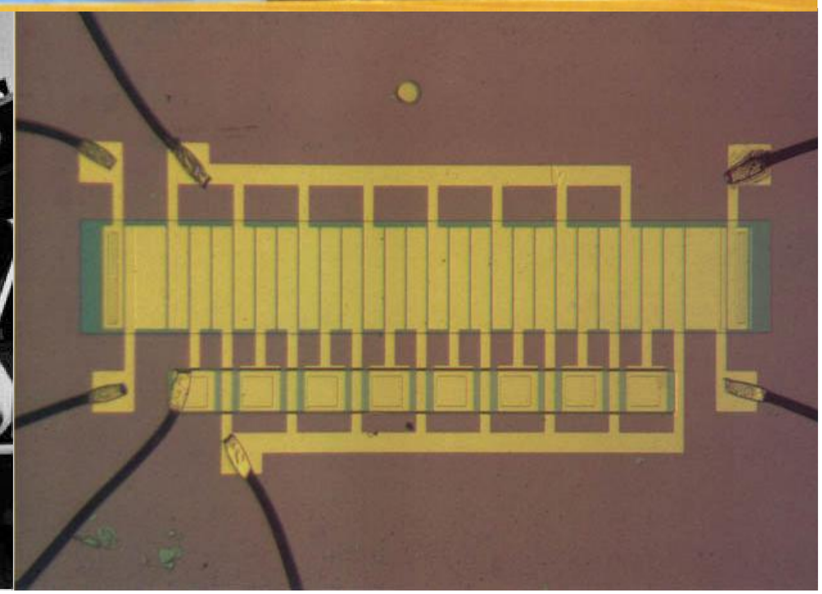
We can have this for photon counters too!

CCD was invented in 1969

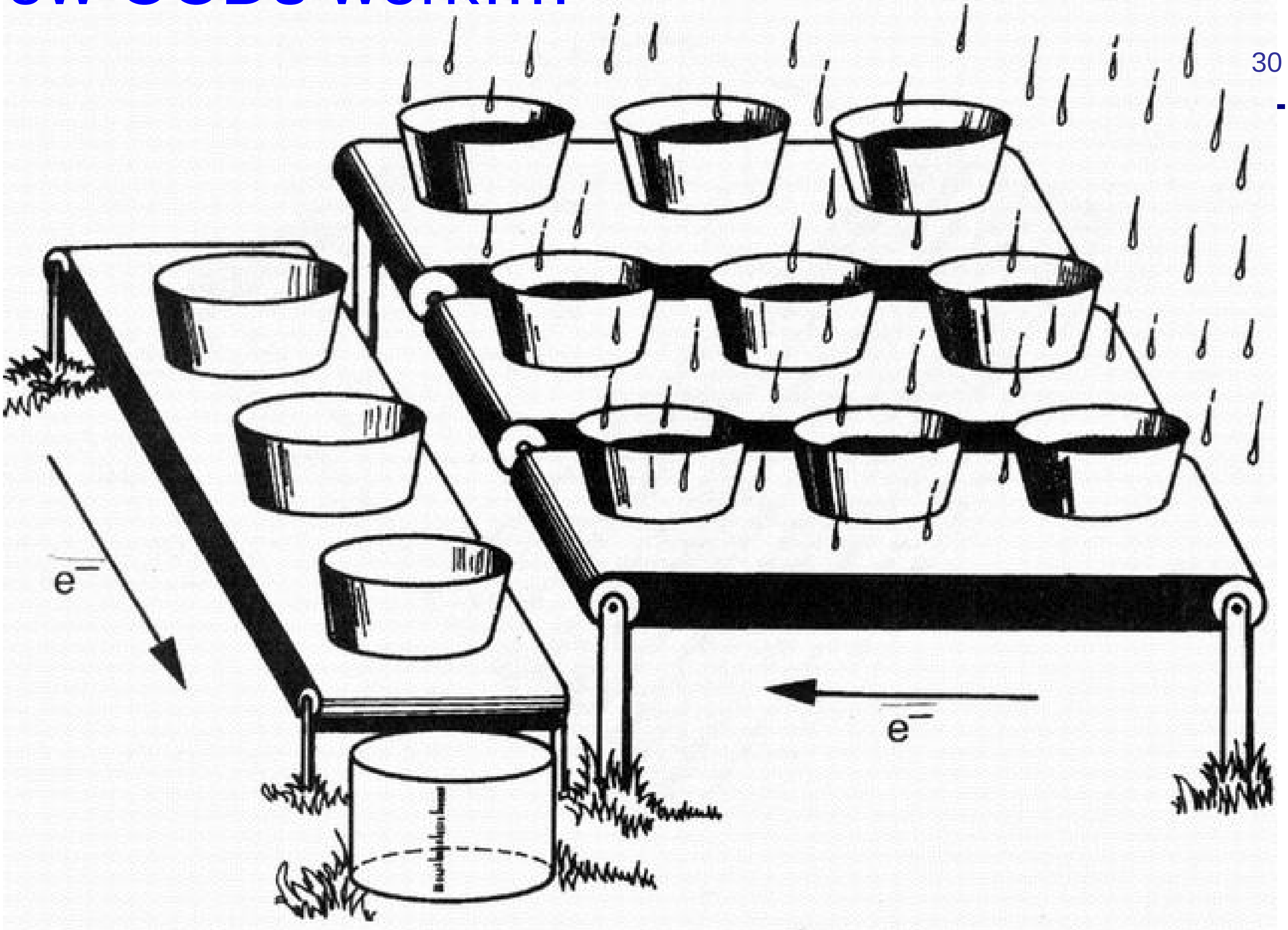
Nobel Prize in 2006

Willard Boyle and George Smith

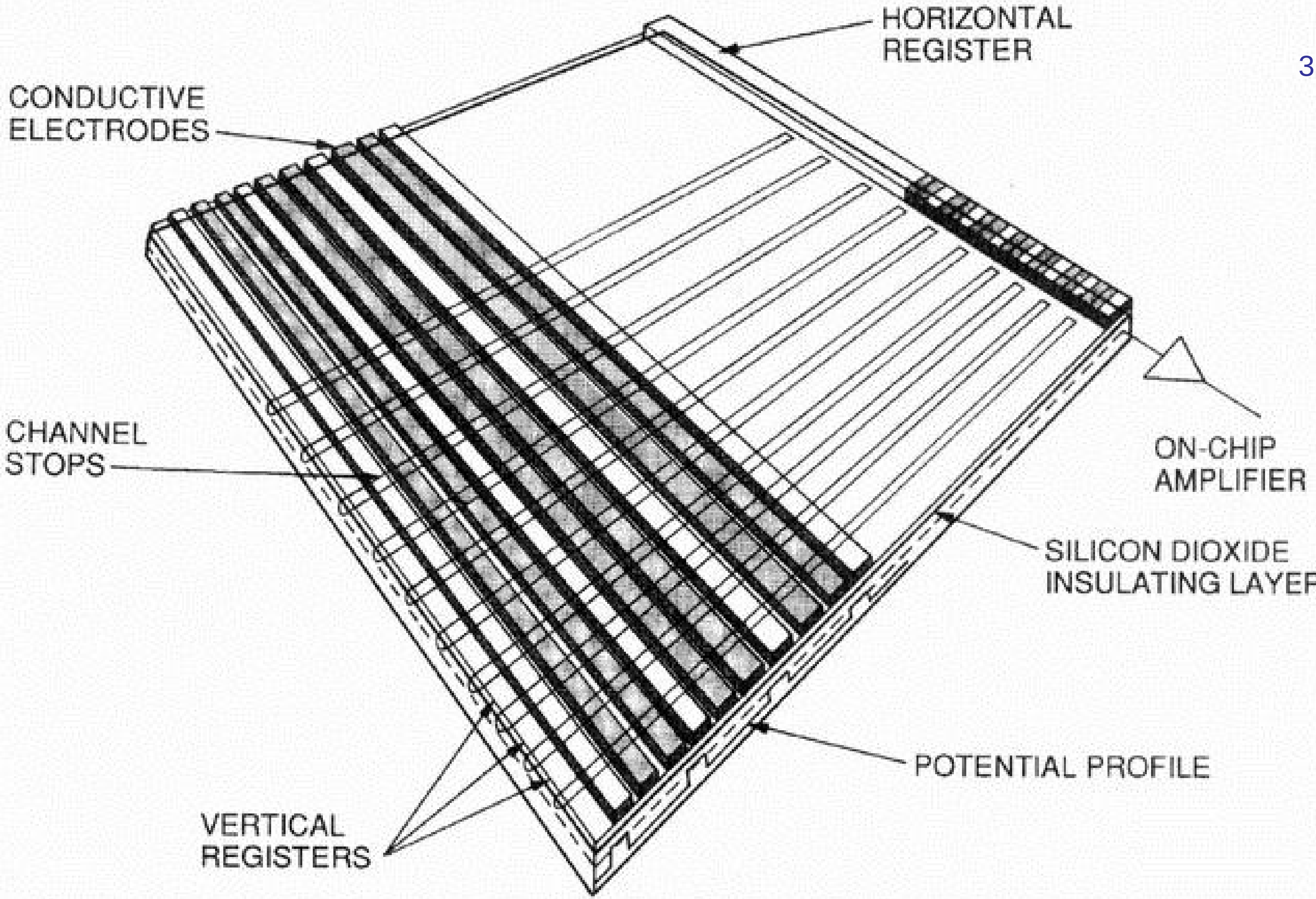




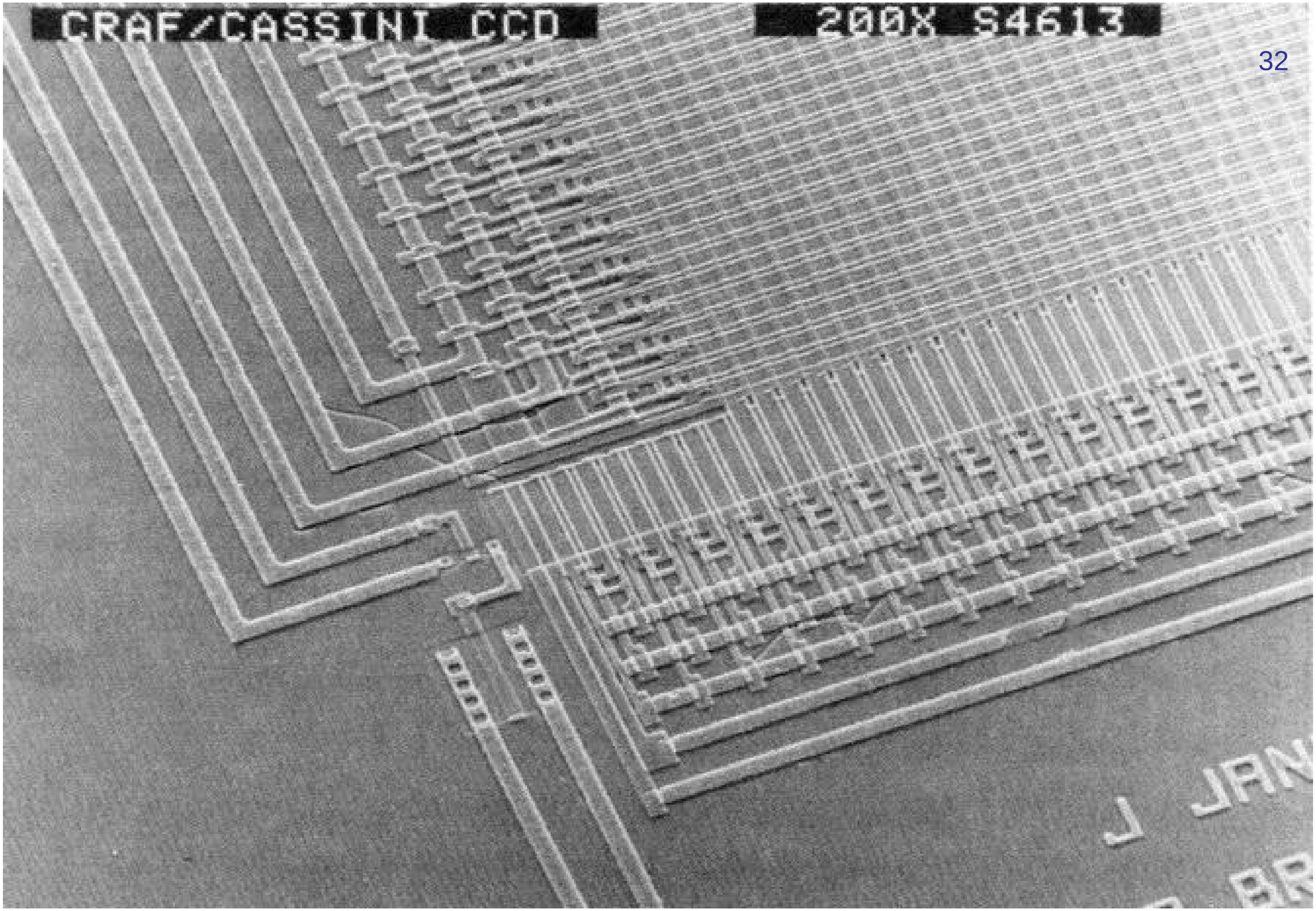
How CCDs work….



Bucket analogy used to describe CCD operation.



Primary components that make up a three-phase CCD.

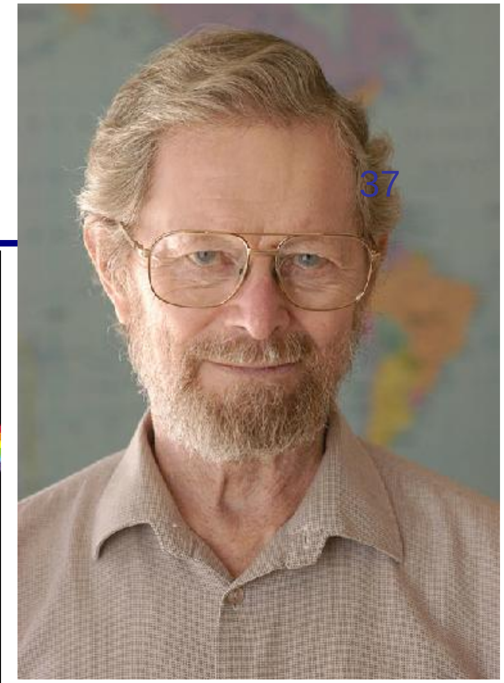

CRAF/CASSINI CCD
200X S4613
J JAN
BR

CCD basics

- Every photon (λ<1 µm) not reflected, is absorbed making electron-hole pair.
- Electrons are confined by electric field under capacitor plate.
- p-n junction doped into silicon keeps charge away from traps at surface.
- Manipulate voltages on capacitor plates to shift entire charge map towards output …without mixing pixels !!
- Move charge onto ~32 fF output capacitance to produce ~ 5 µV per electron signal.
- Low noise MOSFET relays output voltage to external electronics.

Charge transport

Gain register patented in 1973



Semiconductor charge transfer devices

US 3761744 A

ABSTRACT

Shift register devices of the type that transfer charge along a semiconductor wafer through the appropriate formation of successive potential wells in the wafer are described. Transferred charge is regenerated by designing the parameters of the device such that, if charge is to be transferred from one storage region to the next, the potential well for causing the transfer is of sufficient value to cause avalanche breakdown; whereas if no charge is to be transferred, the potential well is insufficient to cause avalanche breakdown. Selective breakdown in this manner regenerates the charge being transferred through the production of additional current carriers.

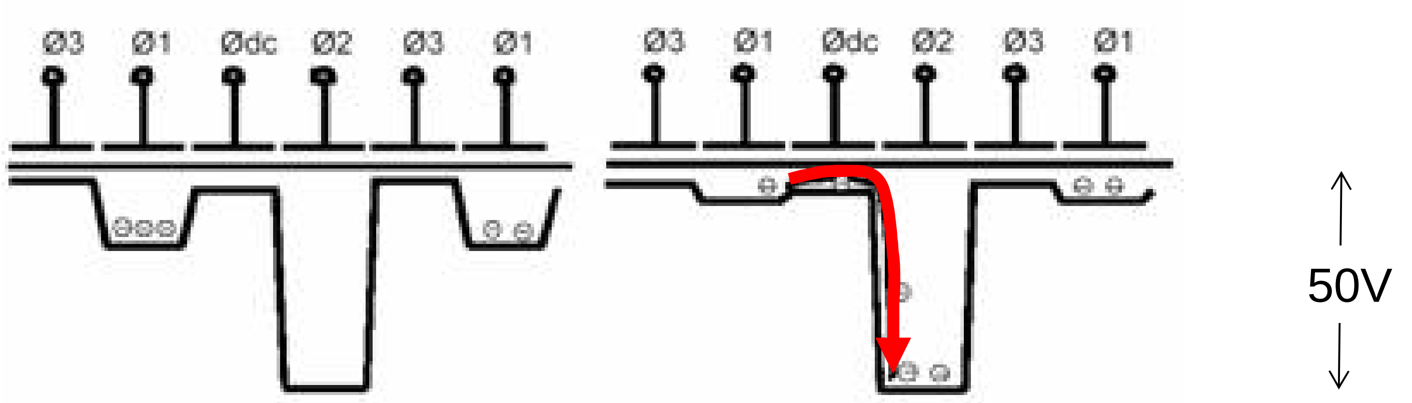
Publication number	US3761744 A
Publication type	Grant
Publication date	Sep 25, 1973
Filing date	Dec 2, 1971
Priority date	Dec 2, 1971
Inventors	Smith G
Original Assignee	Bell Telephone Labor Inc
Export Citation	BiBTeX, EndNote, RefMan

Patent Citations (1), Referenced by (8), Classifications (21)

External Links: USPTO, USPTO Assignment, Espacenet

George Smith had memory devices in mind, not photon counting.

Avalanche mechanism



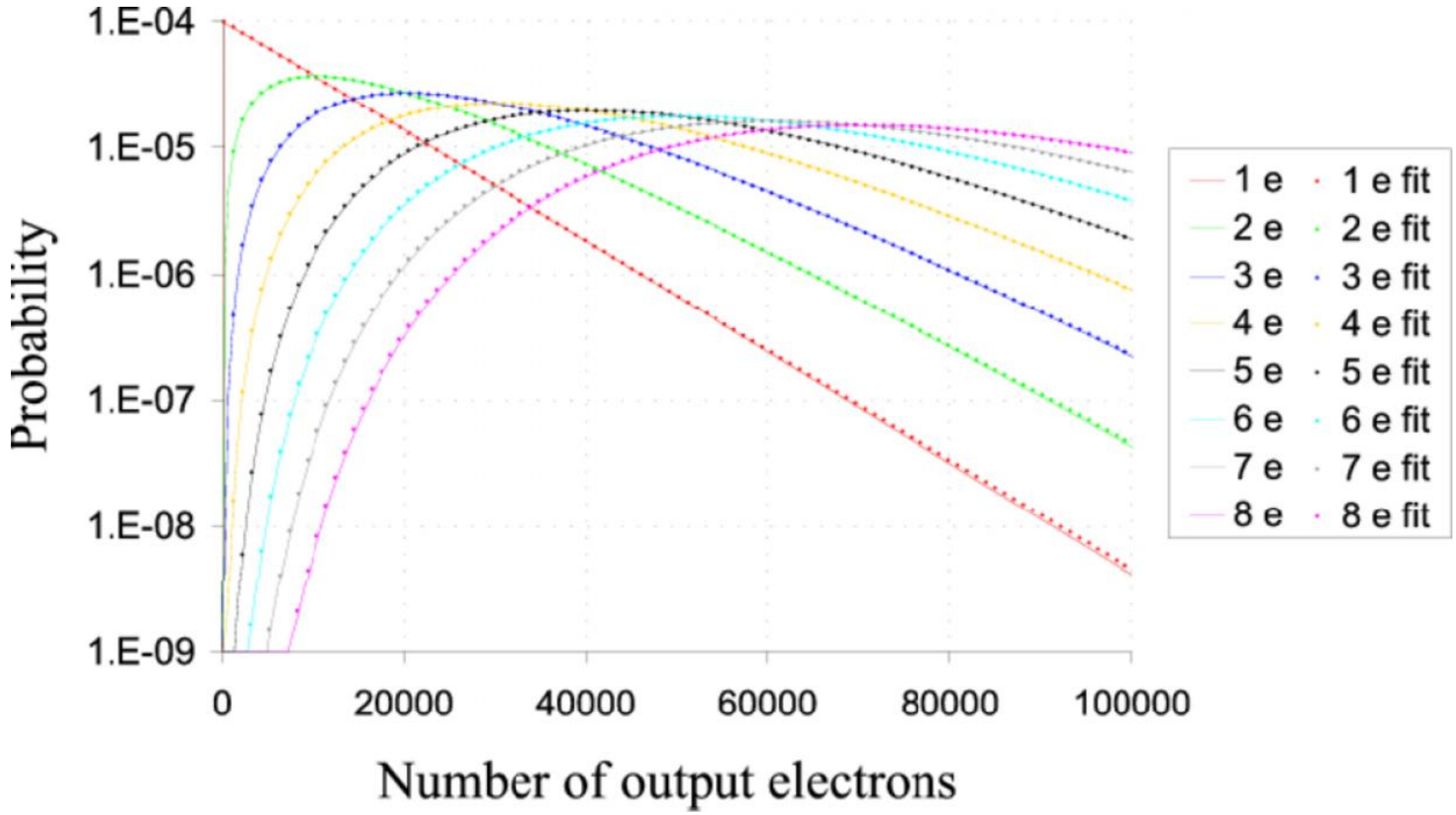
With 40-50V on ϕ2 electrode, conduction band electrons falling into potential well gain enough kinetic energy to sometimes dislodge a valence band electron.

Probability of impact ionization is only a few percent but after ~600 transfers gain can be substantial.

Gain distribution

$$P(n) = \frac{(n-m+1)^{m-1}}{(m-1)!\left(g-1+\frac{1}{m}\right)^{m}} \exp\left(-\frac{n-m+1}{g-1+\frac{1}{m}}\right) \text{ if } n \geq m$$

where *P* is the probability of getting *n* output electrons given *m* input electrons and a total mean multiplication register gain of *g*.



Exponential output distribution for 1e- input

$$P\left(n\right)=\frac{\left(n-m+1\right)^{m-1}}{\left(m-1\right)!\left(g-1+\frac{1}{m}\right)^{m}}\exp\left(-\frac{n-m+1}{g-1+\frac{1}{m}}\right)\text{ if } n\geq m$$

where *P* is the probability of getting *n* output electrons given *m* input electrons and a total mean multiplication register gain of *g*.

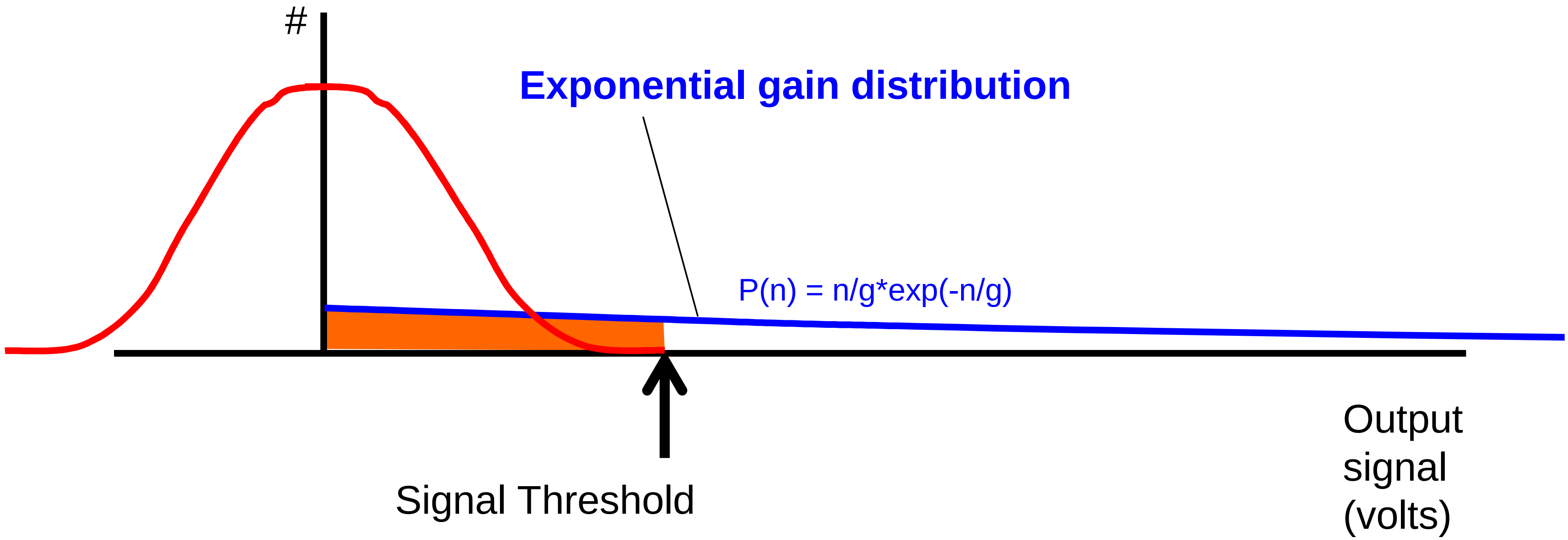
For one input electron (m=1), probability of n output electronics is exponential

P(n) = n/g * exp(-n/g)

Must operate at high enough gain to push most events above noise floor.

……What could go wrong with that?

EMCCD gain histogram

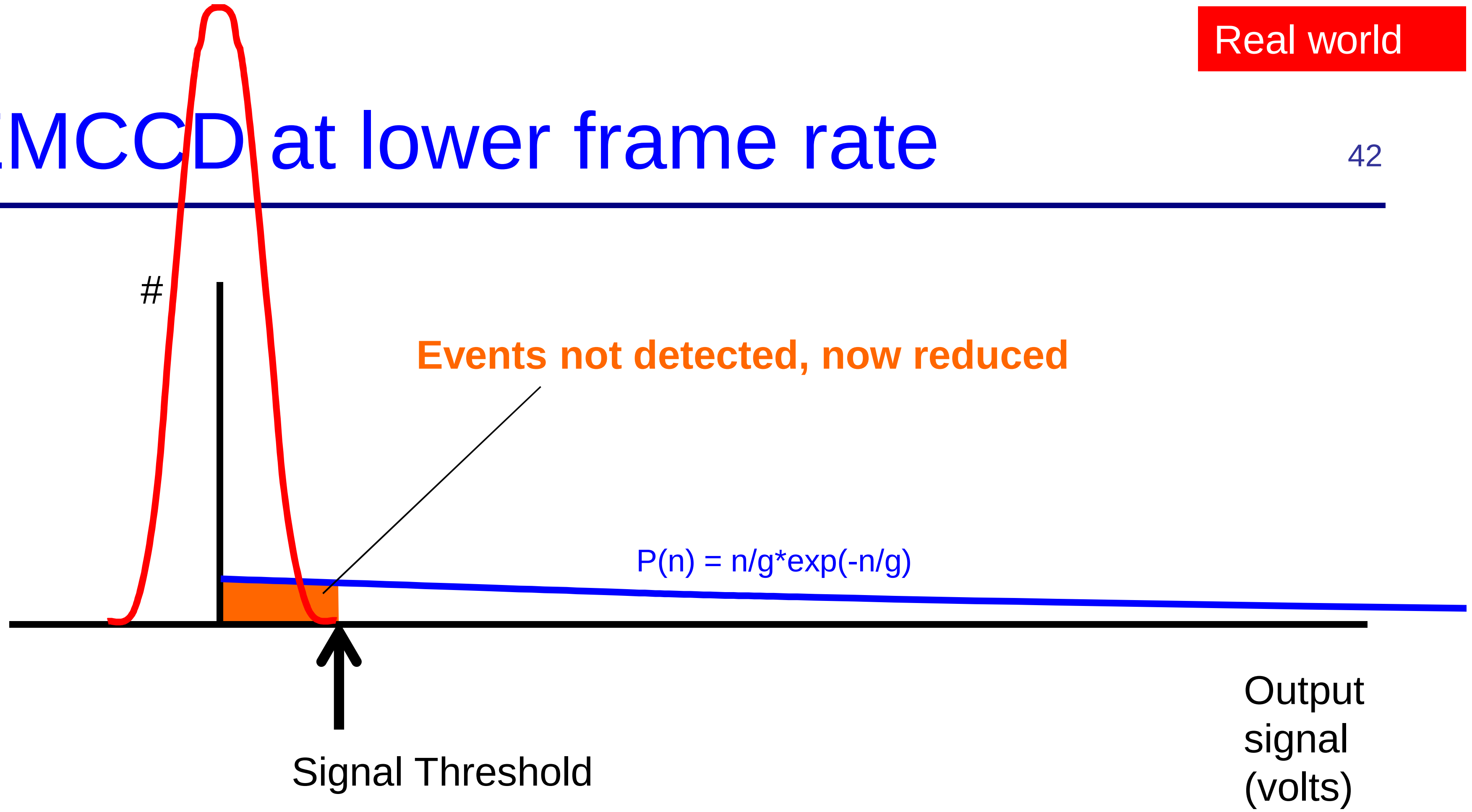


For EMCCD lowest gain has high probability.

Must operate at high gain to get most events out of noise band.

Minimizing pixel rate to reduce output noise will improve counting efficiency.
(lower frame rate, region of interest, mosaic of smaller CCDs)

EMCCD at lower frame rate



Lower pixel rate → reduce output noise to improve counting efficiency.

- lower frame rate
- region of interest
- more output amplifiers
- Mosaic of smaller CCDs)

Intensified CCD mode

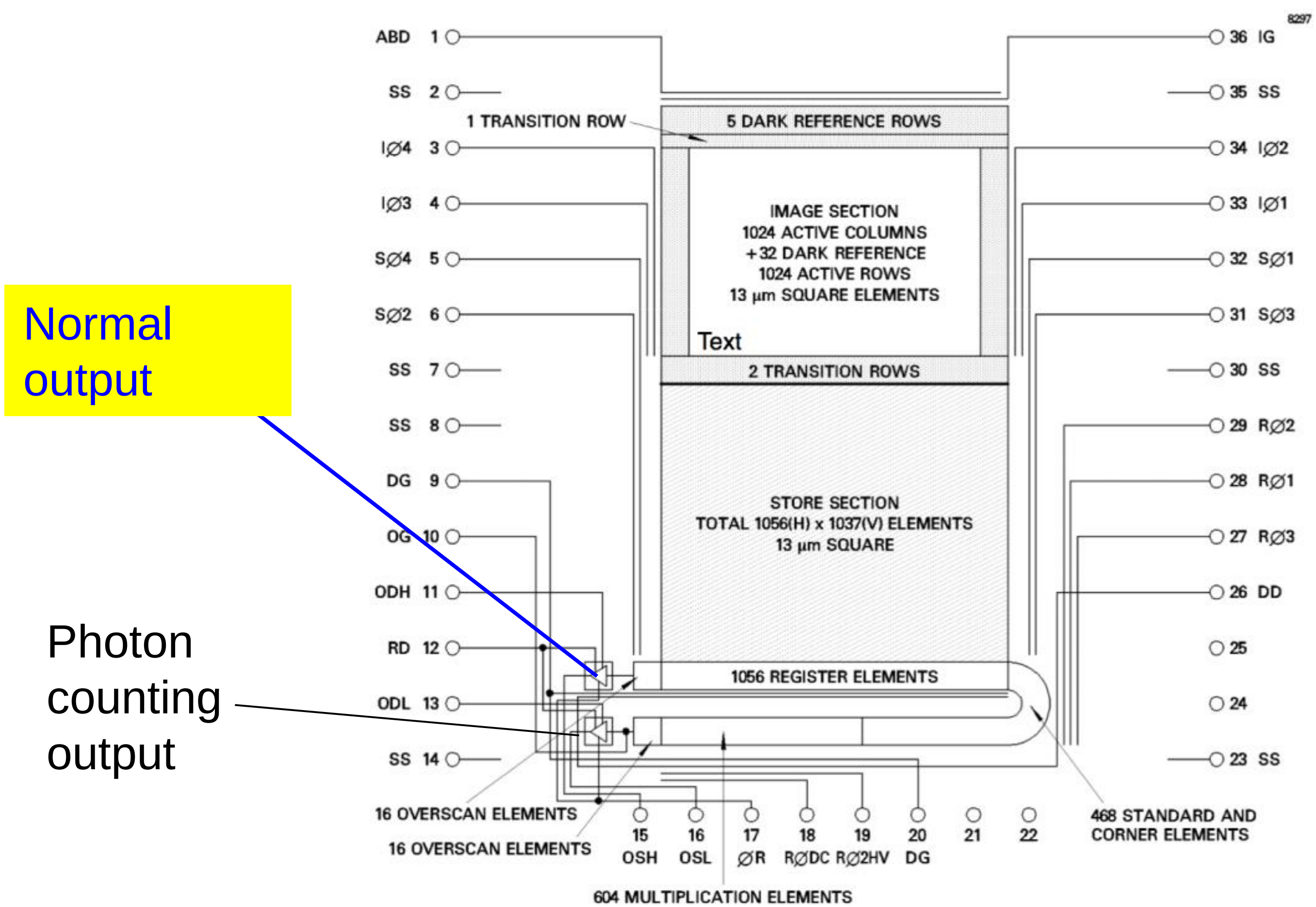
- When coincidence losses begin to become significant, one can switch to coadding frames *without threshold detection.*
- The exponential distribution of gains results in noise that is proportional to signal with net effect of degrading S/N by $\sqrt{2}$ and is equivalent to halving the QE.
- There is a narrow range of signals where this is preferable to conventional direct integration with unamplified readout.

EMCCDs can be operated in any of the modes:

- **Photon counting** (high gain, threshold detection)
- **Intensified** (moderate gain, no threshold detection)
- **Integrating** (unity gain, no threshold detection)

Calibrations – major advantage of EMCCD

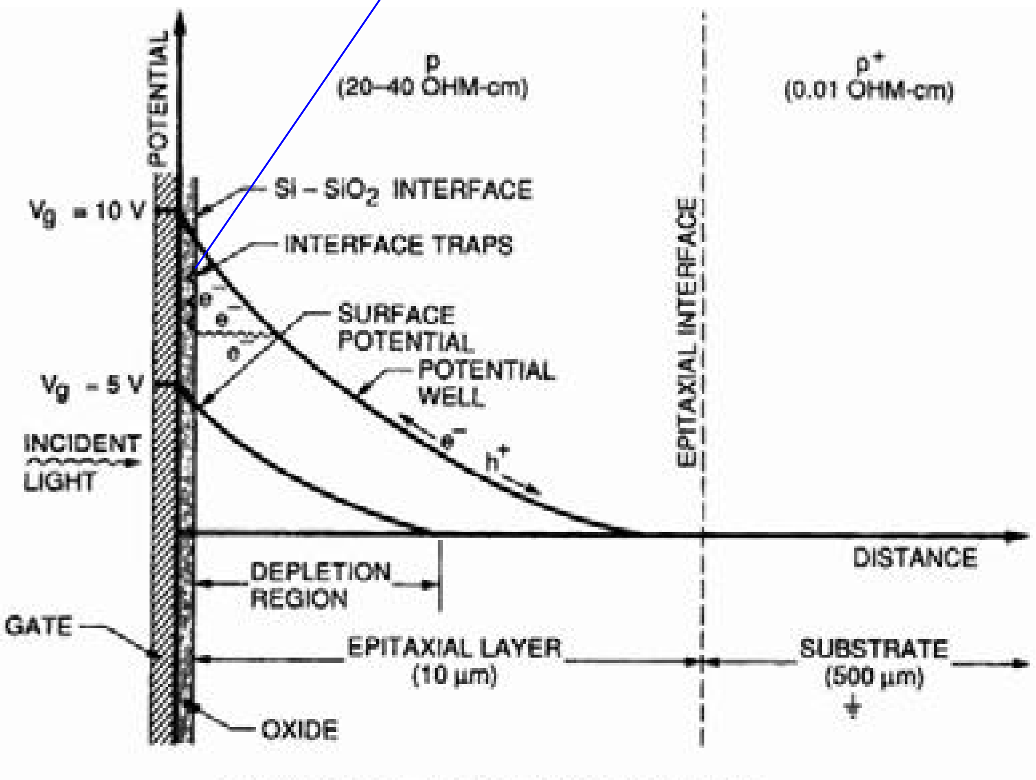
Normal output can be used (or unity gain) for calibrations at the *higher count* levels needed for good S/N.



PERFORMANCE LIMITS

Problem: surface traps capture charge

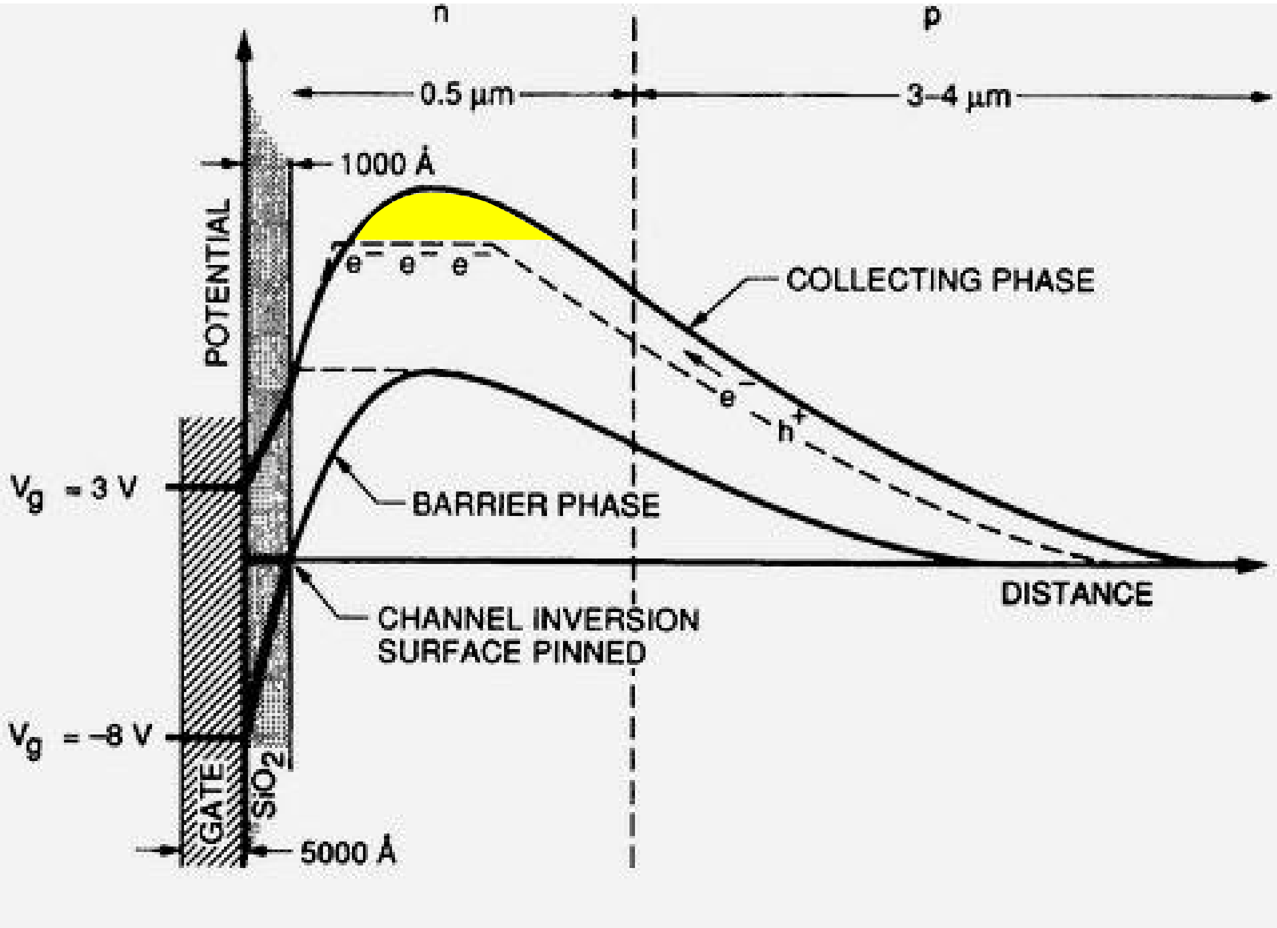
Eliminating this was key to the invention of the original CCD



Surface channel potential well.

Solution: “buried channel”

Created by n-type implant into p-type substrate

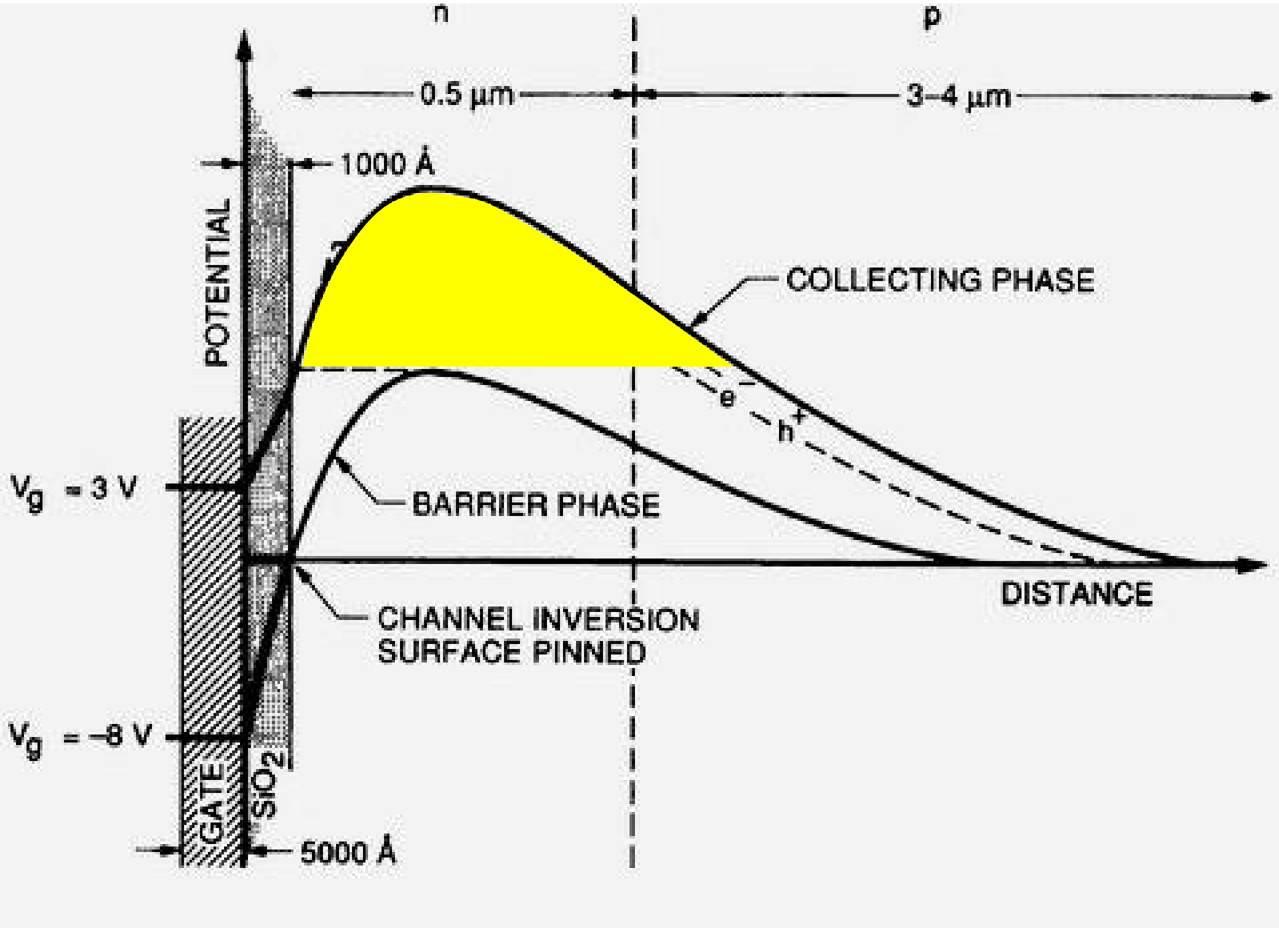


Buried-channel potential well.

Charge stored below surface

Solution: “buried channel”

Created by n-type implant into p-type substrate



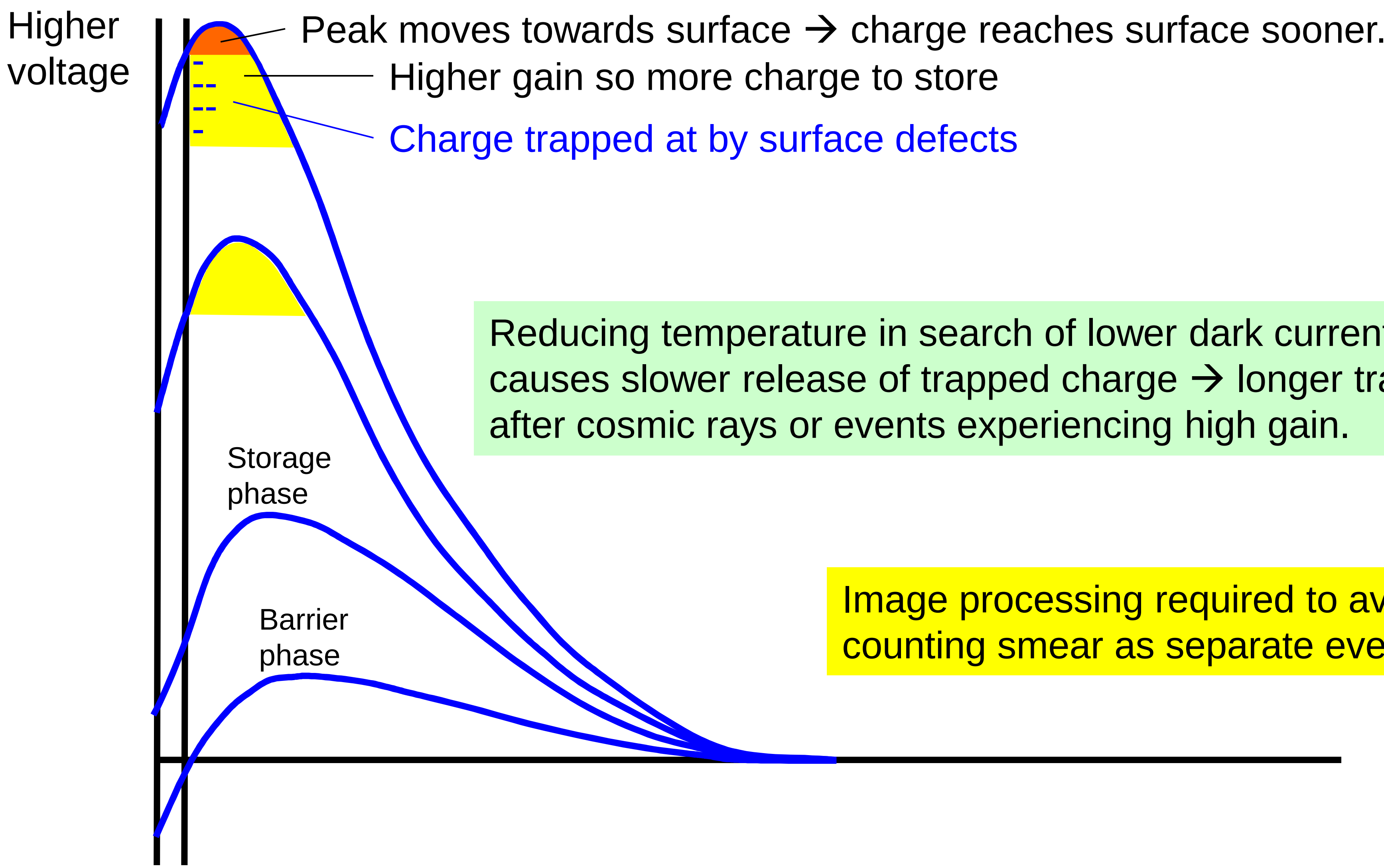
Buried-channel potential well.

When pixel fills…

charge spills over barrier just before reaching surface

to avoid surface traps.

Potential at higher clock voltage



Reducing temperature in search of lower dark current causes slower release of trapped charge → longer trails after cosmic rays or events experiencing high gain.

Image processing required to avoid counting smear as separate event.

Clock Induced Charge (CIC)

Typically less than 0.1 e-/pixel/frame liberated by normal clocking. Normally negligible but photon counting requires frequent enough readout to minimize coincidence losses so CIC can easily exceed dark current.

Mitigations:

→ Avoid surface inversion (holes moving in and out of channel stops)

→ Reduce parallel clock swing (image area needs negligible pixel capacity)

→ Slower edges (on parallel clocks)

→ Use minimum frame rate allowed by coincidence losses. Accept (and correct for) some coincidence losses.

→ Faster serial clocks (10MHz) are required to reduce serial CIC (i.e. this always true … some dissenting opinion). This makes clock driver, and waveform design more challenging, and raises noise floor.

→ Temperature dependence ??

Charge trapping in image area

Since pixels are mostly empty, even shallow charge traps will defer charge.

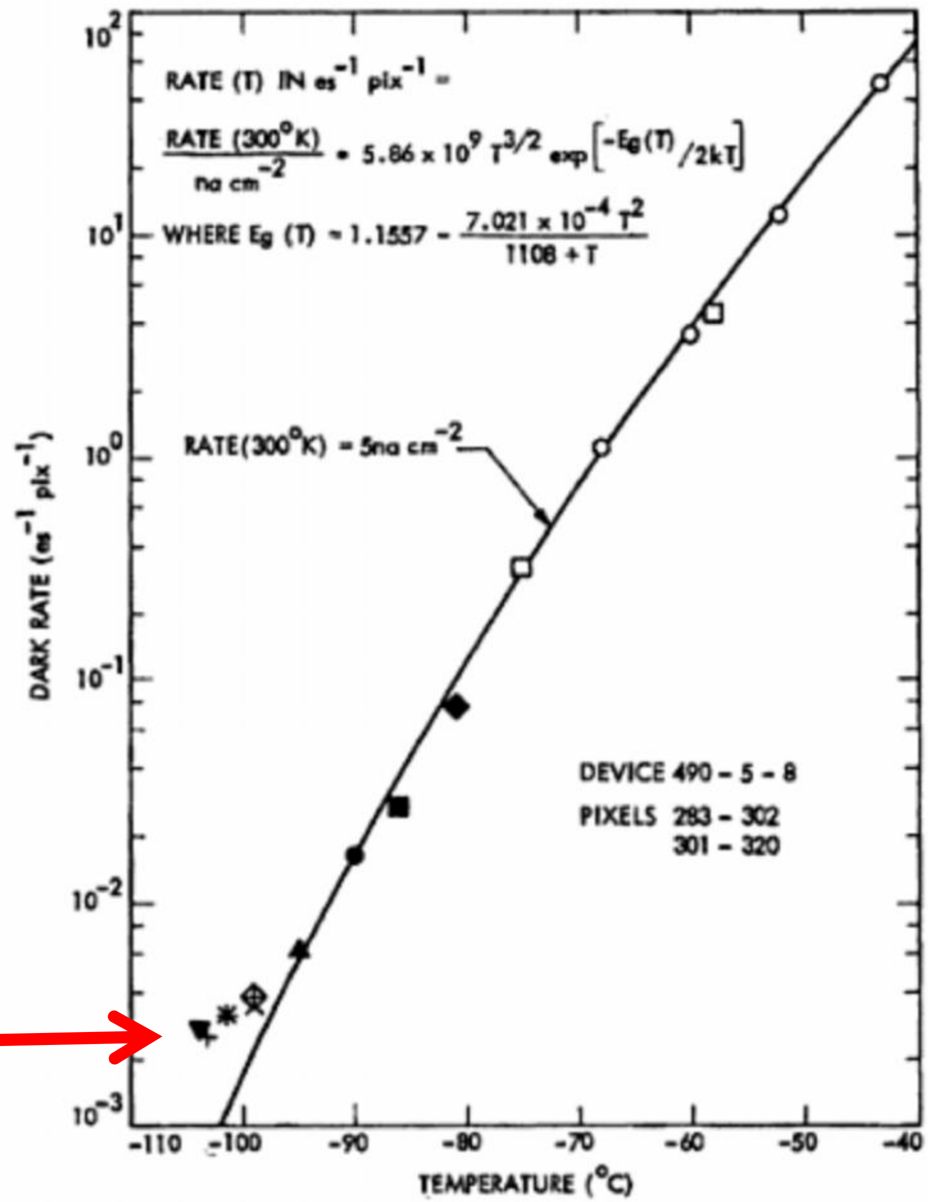
- Need particularly good quality silicon to minimize trap density.
- If light levels are low enough, use slow tri-level parallel clocking to allow trapped charge time to be released and returned to pixel.
- If running very cold charge can be injected (single bright line) between frames to fill traps. Eventually these will release resulting in higher dark current at trap site but preferable to blocked column.

Dark current floor

Classic CCD dark current
from *Scientific CCDs*
by *J.* Janesick

Dark current floor remains even when all phases inverted.

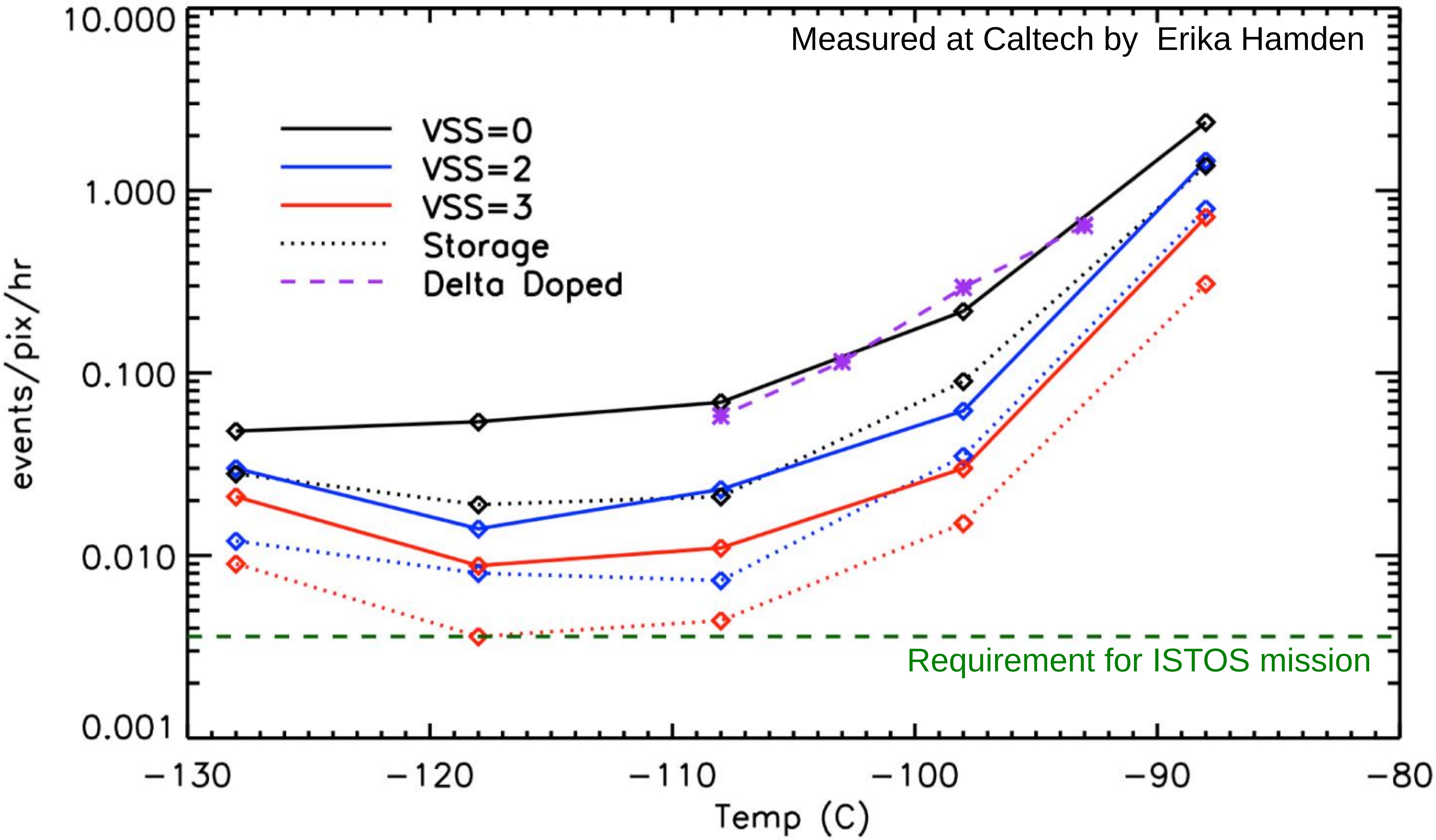
Why no temperature dependence below about -120C



??

Figure 7.29(b) Dark current transfer showing surface residual charge at very cold operating temperatures.

L3CCD Dark Current



Summary of Advantages

- Noiseless, like original photon counters
- Excellent QE, as for conventional CCDs
- **Stable performance → accurate calibrations.**
- For more dynamic range, easily switched to “intensified” or “integrating” modes → high S/N for calibrations in relatively short exposures.
- All features and modes of standard CCD available.
- Extremely low dark current achieved:

  0.01 e-/hr = 1e- per 360,000 pixels in one second

Residual issues

- Clock Induced Charge, especially serial.
- Traps in image area.
- Need high gain for good counting efficiency → poor serial CTE at low temperature, complicates event recognition when running very cold for low dark current.
- Mysterious dark current floor at low temperature. ← under investigation at Caltech.

For UV: ← particular interest for proposed spectrograph in space

- Lower bandgap of silicon compared to UV photocathode requires lower temperature to achieve similarly low dark current.
- Wider passband problematic in applications which need to be “solar blind”