MOVIES

The Montreal-Ohio Victoria Echelle Spectrograph

- Team introductions & Collaboration
- Instrument overview
- Science context and science drivers
- Top level requirements and functional performance
- Key design features
- Risks and Project Management

The Pitch

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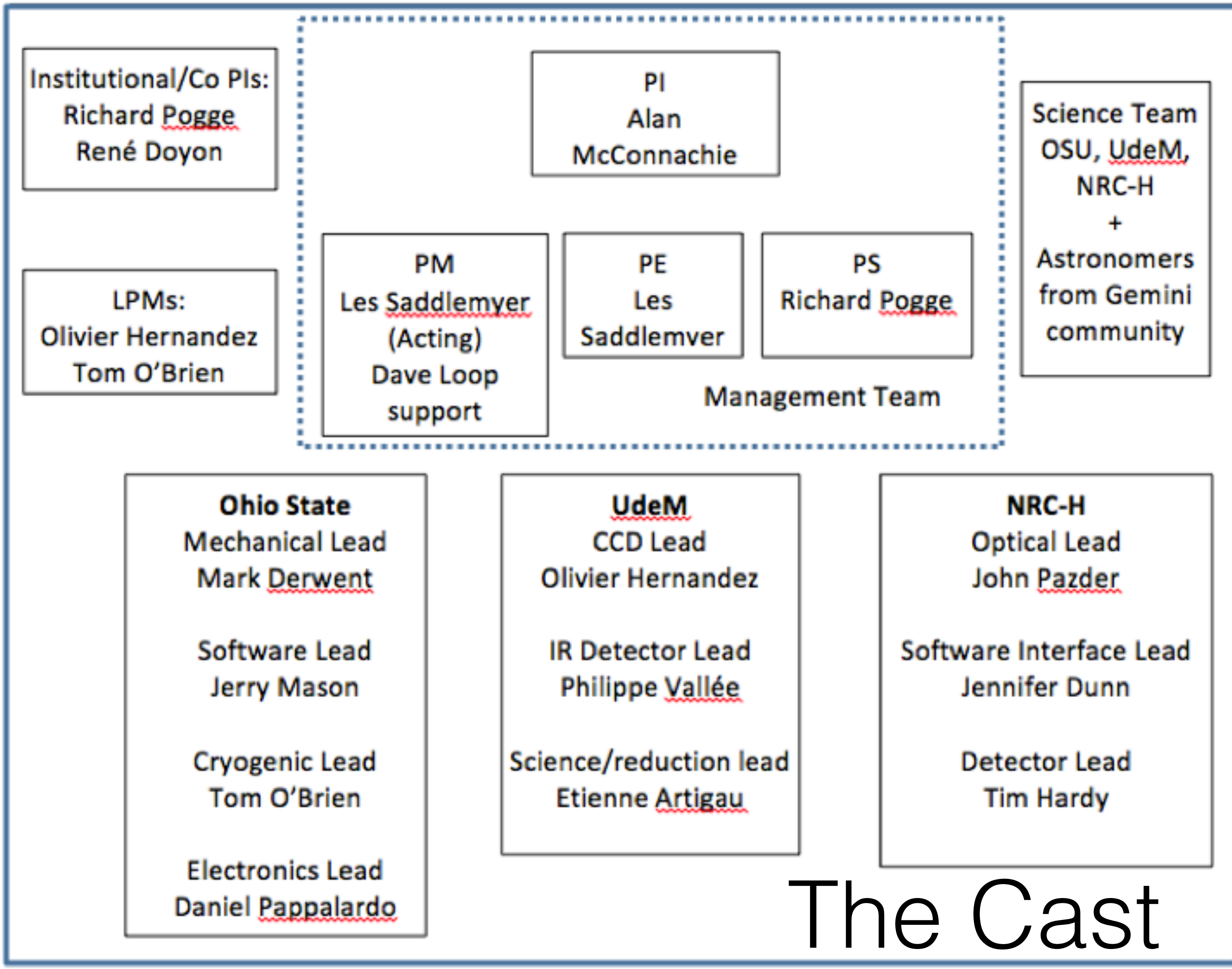
THE OHIO STATE UNIVERSITY
Université de Montréal

The Cast



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Science team:

Etienne Artigau (UdM)
Rene Doyon (UdM)
Patrick Dufour (UdM)
Wes Fraser (NRC-H/Queens University, Belfast)
Pascale Hibon (Gemini)
Julie Hlavacek-Larrondo (UdM)
Chris Kochanek (OSU)
David Lafreniere (UdM)

Lison Malo (CFHT)
Alan McConnachie (NRC-H)
Tony Moffat (UdM)
Richard Pogge (OSU)
Mara Taylor (NRC-H)
Ruben Sanchez-Janssen (NRC-H)
Nicole St-Louis (UdM)
Chris Wilott (NRC-H)

The Cast

Canada NRC·CNRC — The Ohio State University — Université de Montréal

- All three institutes share MOVIES responsibilities in full collaboration

- Ohio State University
  - Science lead (including Project Scientist)
  - Mechanical design lead
  - Instrument controls software and electronics lead
  - Cryogenic thermal and vacuum system lead
- Universite de Montreal
  - Camera design(s)
  - Detector lead
  - Data pipeline lead
- NRC Herzberg
  - Project Lead, Project Engineer
  - Optical Design
  - Integration lead
  - Detector support
  - Top level Gemini software interface
  - Cryogenic mechanical contributions

The scene-by-scene breakdown

Previous Roles

- All institutes involved in MOVIES have a long heritage of building proven and reliable instruments for their user communities:
    - NRC-H
        - GPI
        - GRACES
        - GHOST
        - GMOS-N Focal Plane upgrade
    - OSU
        - MODS 1 and 2
        - KOSMOS and COSMOS
        - KMTNet Detector System (Korean Microlensing Telescope Network)
    - UdM
        - JWST/FGS
        - GPI
        - SPIROU
        - ….

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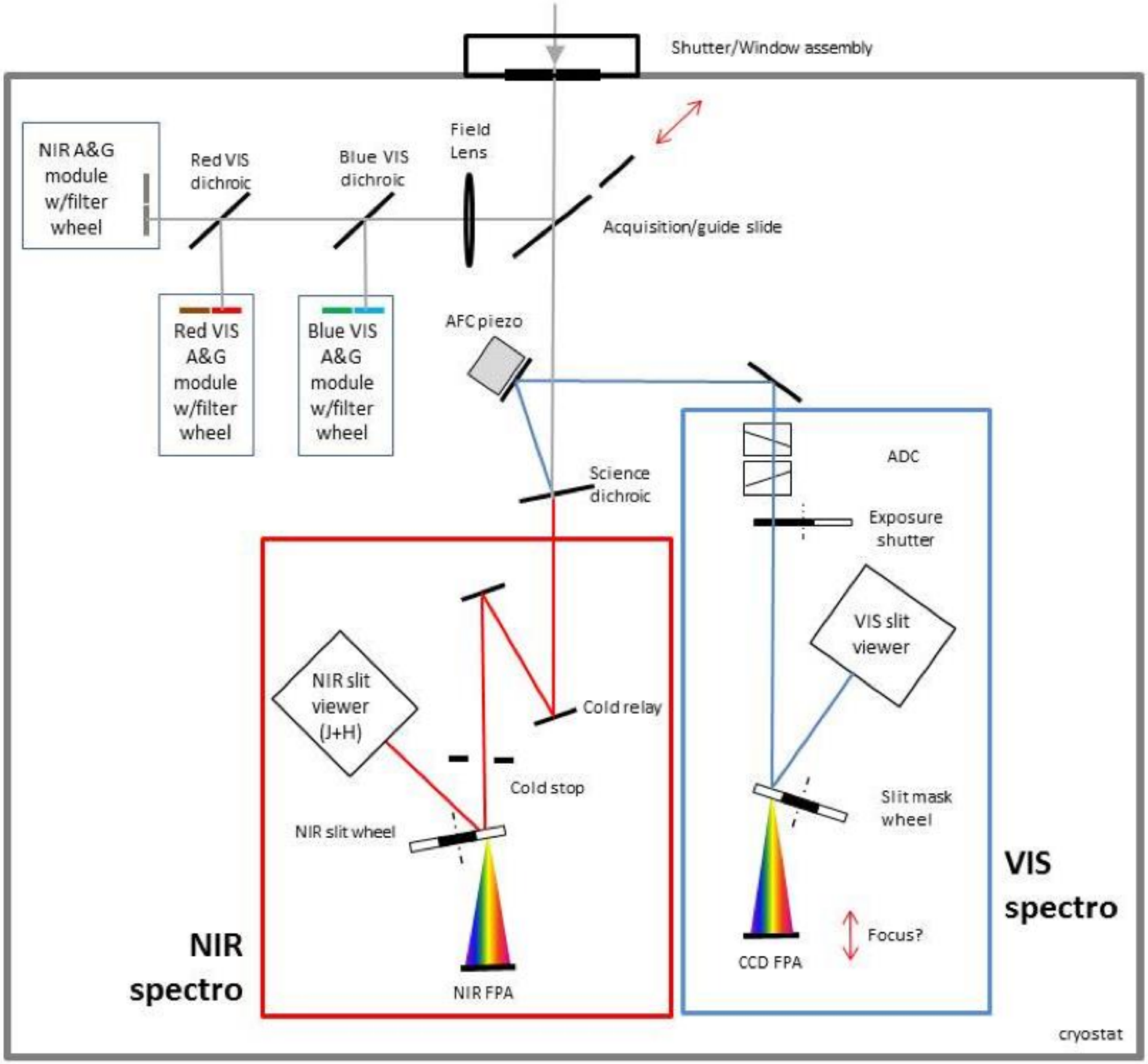

- MOVIES is a high throughput, broad bandwidth, moderate resolution (R3 - 10K) dual arm optical and near infrared (NIR echelon spectrograph that simultaneously covers 0.36 - 2.45um
- Supported by a rapid acquisition camera operating simultaneously at blue-optical, red-optical and NIR wavelengths

The Plot

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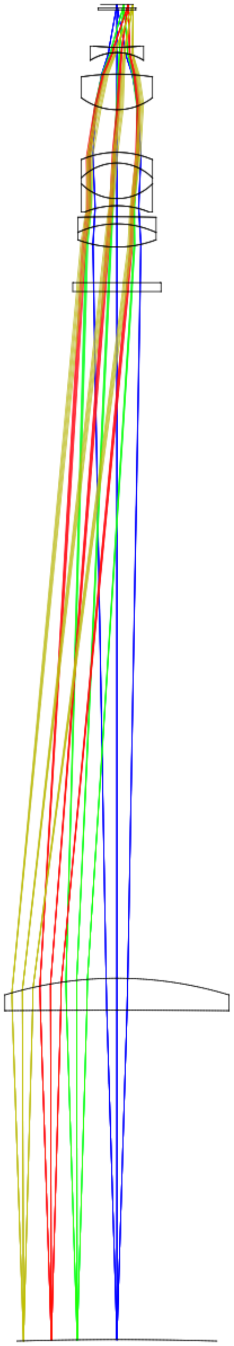
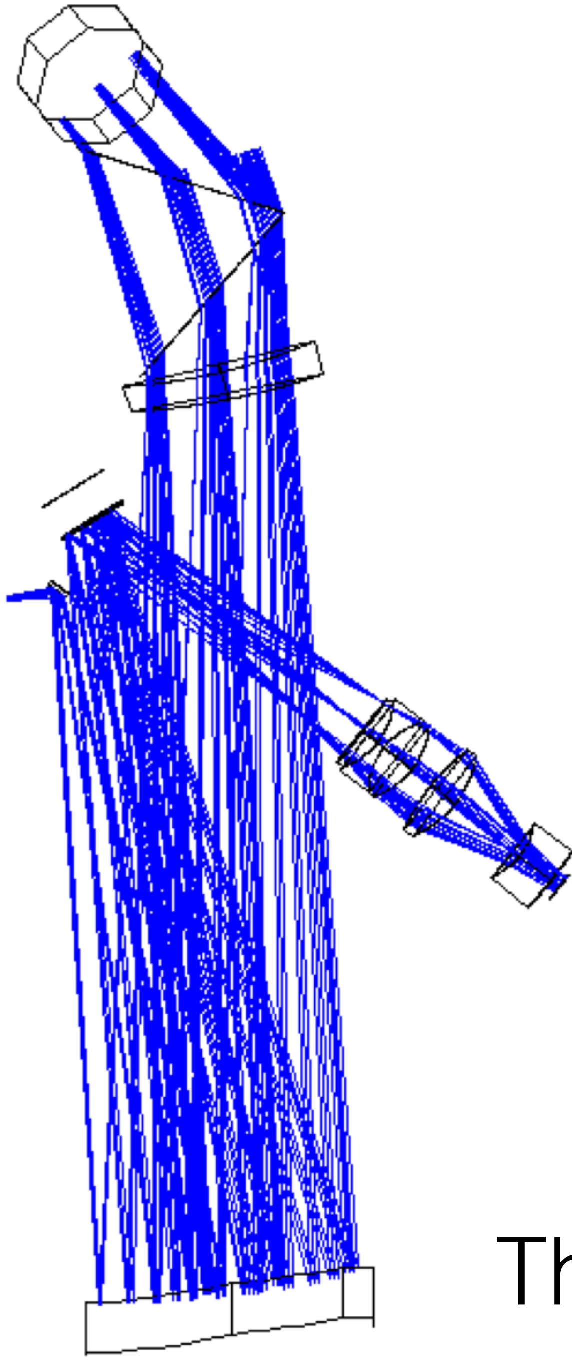
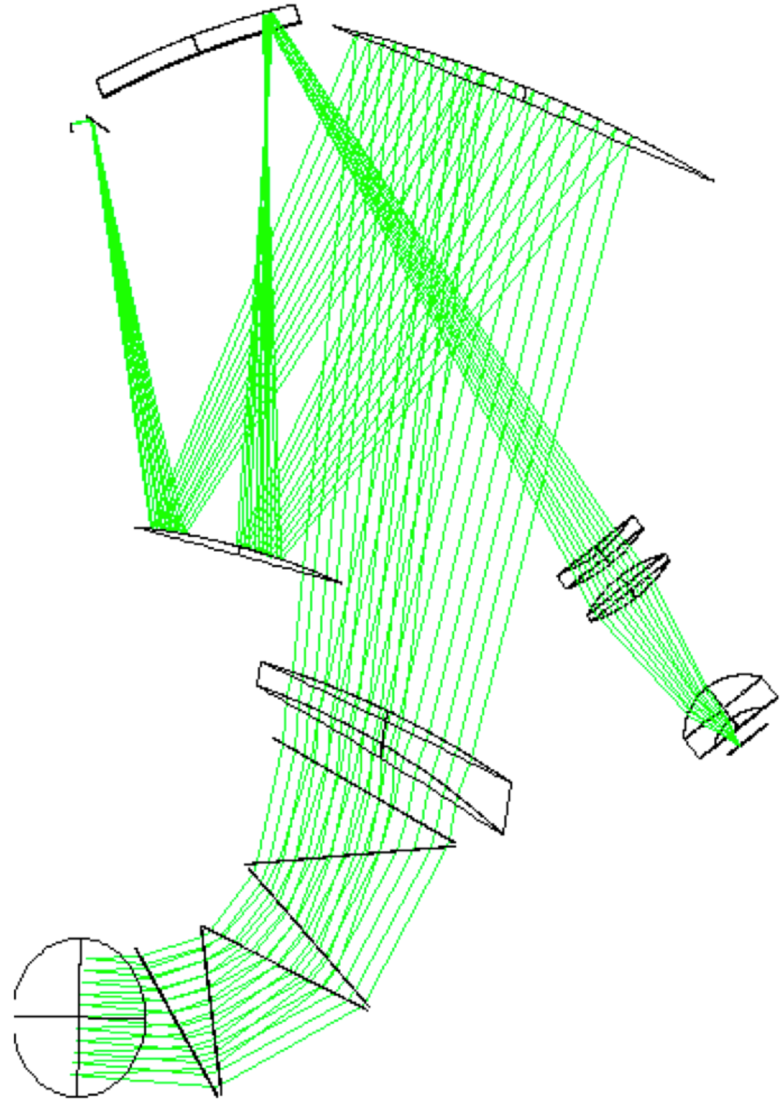

The Central Protagonists

MOVIES is

a workhorse spectrograph
a time domain spectrograph
a precision spectrophotometer

The Big Idea

- MOVIES is conceived as …
  - a complement to spectroscopic capabilities in space
  - a follow-up facility to major discovery machines like LSST, SKA, and WFIRST
  - a feeder facility for the ELTs
  - a highly efficient workhorse capability that enables new science

- MOVIES will build on the capabilities of Gemini:
  - target of opportunity
  - queue scheduling
  - rapid acquisition
  - NIR specialisation

	Broad Wavelength Range	Simultaneous bandwidth	Moderate Resolution	Faint targets	Rapid acquisition	Multi-band acquisition		High cadence read-out
Transients	✔	✔	✔	✔	✔	✔		✔
Solar System	✔	✔	✔	✔	✔	✔		✔
Stellar populations	✔	✔	✔	✔		✔		
Low mass stars	✔		✔	✔				
Massive Black Holes	✔	✔	✔	✔	✔			✔
High redshift Universe	✔	✔	✔	✔		✔		
Exoplanet atmospheres	✔	✔	✔	✔		✔		✔

- Broad wavelength coverage from 0.36 - 2.45um in a single exposure
- Operation at a range of spectral resolutions from ~3000 < R < 10000
- High sensitivity (throughput, low emissivity, excellent sky subtraction)
- Rapid and robust acquisition procedure
- Quasi-simultaneous imaging mode for excellent calibration
- Potential for high-cadence detectors

Supporting roles

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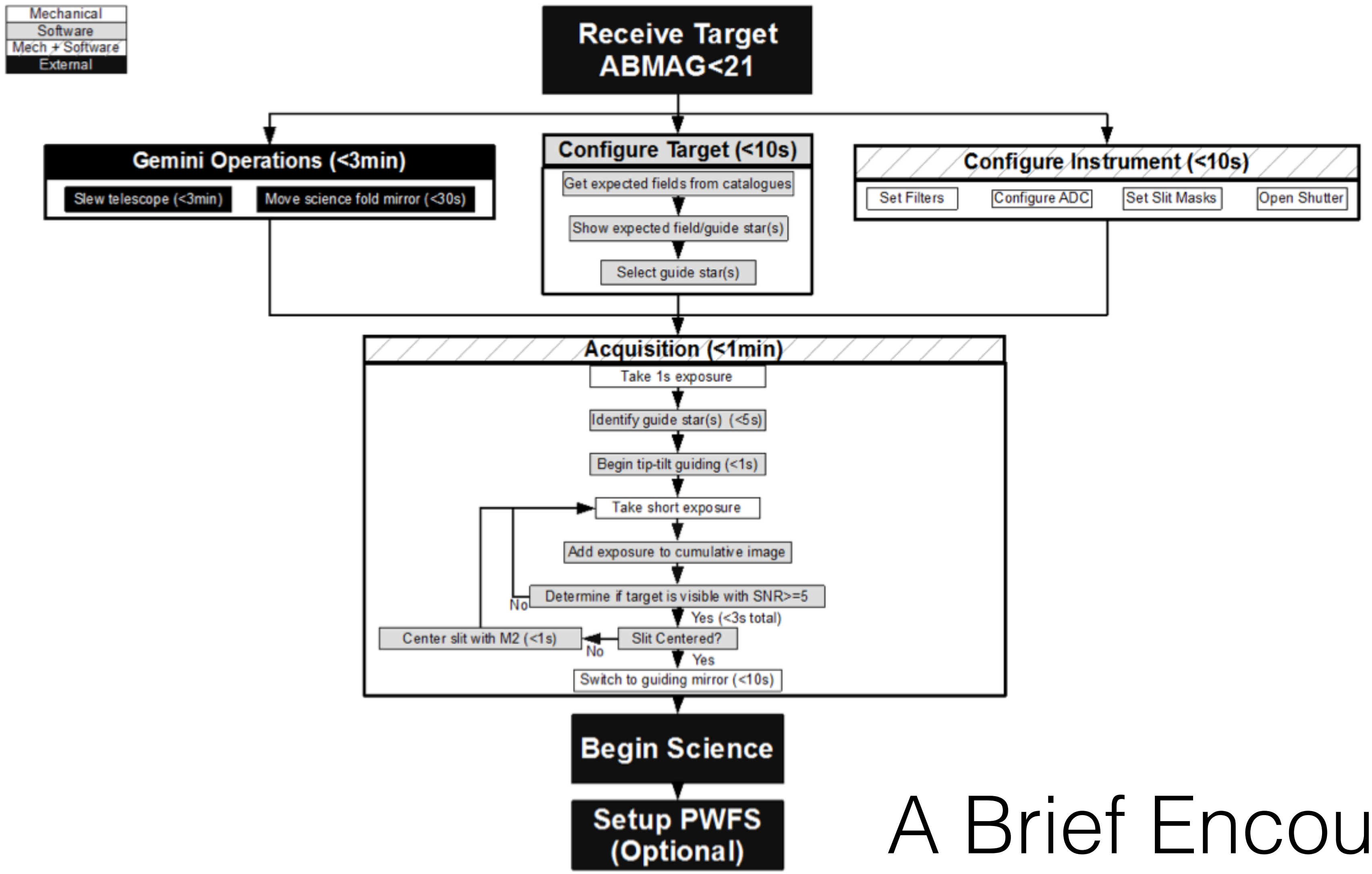
The Ohio State University

Université de Montréal

	GMOS (long slit only)			GNIRS (spectroscopy only)			FLAMINGOS-2 (long slit only)		**MOVIES**
Acquisition time	~16mins + redo every 3hrs			~12mins +6mins every 45mins			~20mins + redo every 2 hrs		**< 90 seconds**
Spectral coverage	0.36 – 0.94μm			0.85 – 2.5μm			0.95 – 2.4μm		**0.36 – 2.45μm**
Spectral resolution	600	–	4500	1700	5000	18000	1300	3000	**3500 – 10000**
Simultaneous bandwidth	Full	–	~0.2μm	Full	~0.2μm	~0.05μm	JH or HK	Y, J, H, or K	**Full**

MOVIES in the Gemini Playlist

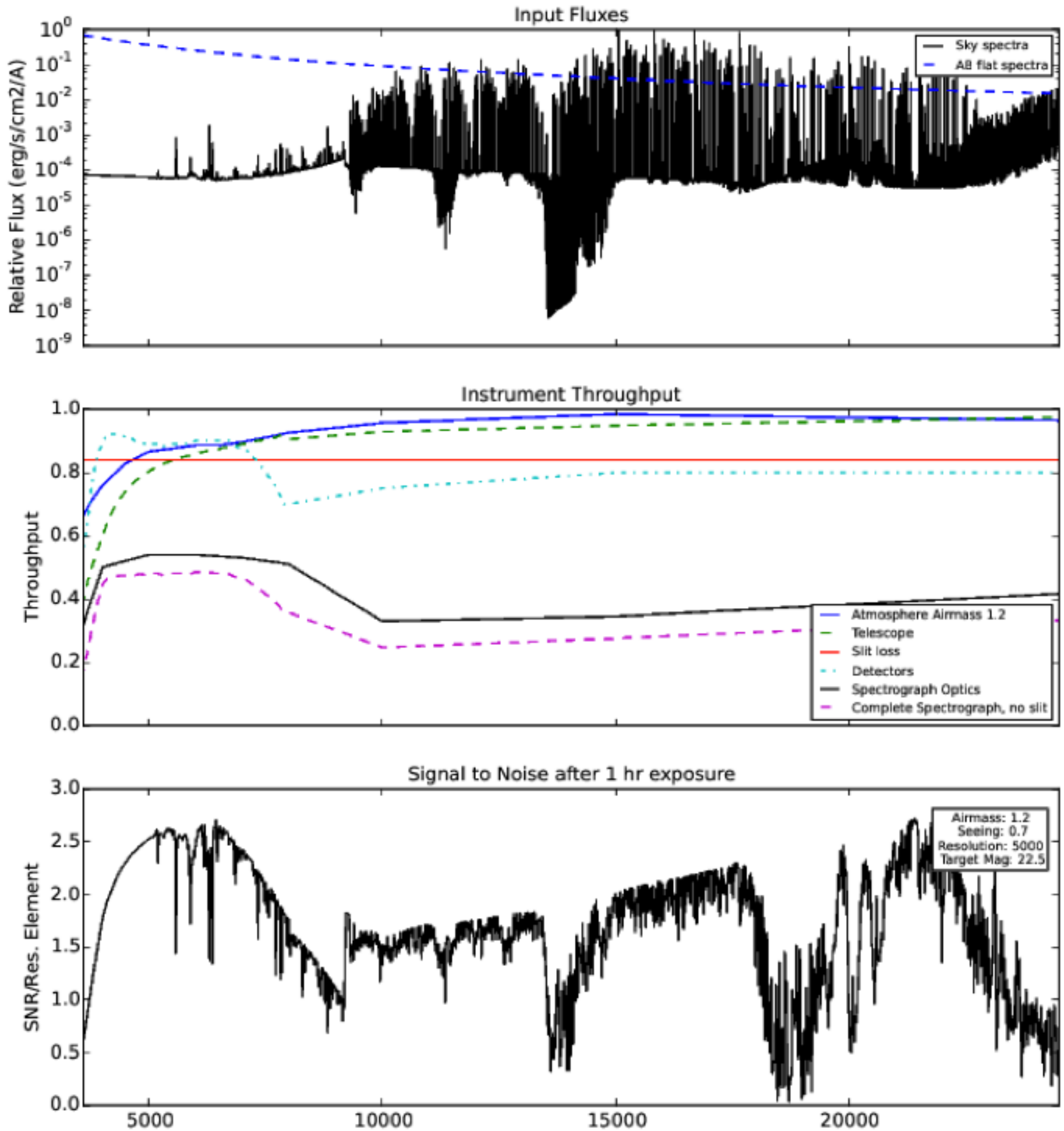
- Rapid and Robust acquisition is a central defining theme of the entire MOVIES concept
- Acquisition procedure developed by Mara Taylor, UBC Physics Undergraduate during a coop term at NRC Herzberg



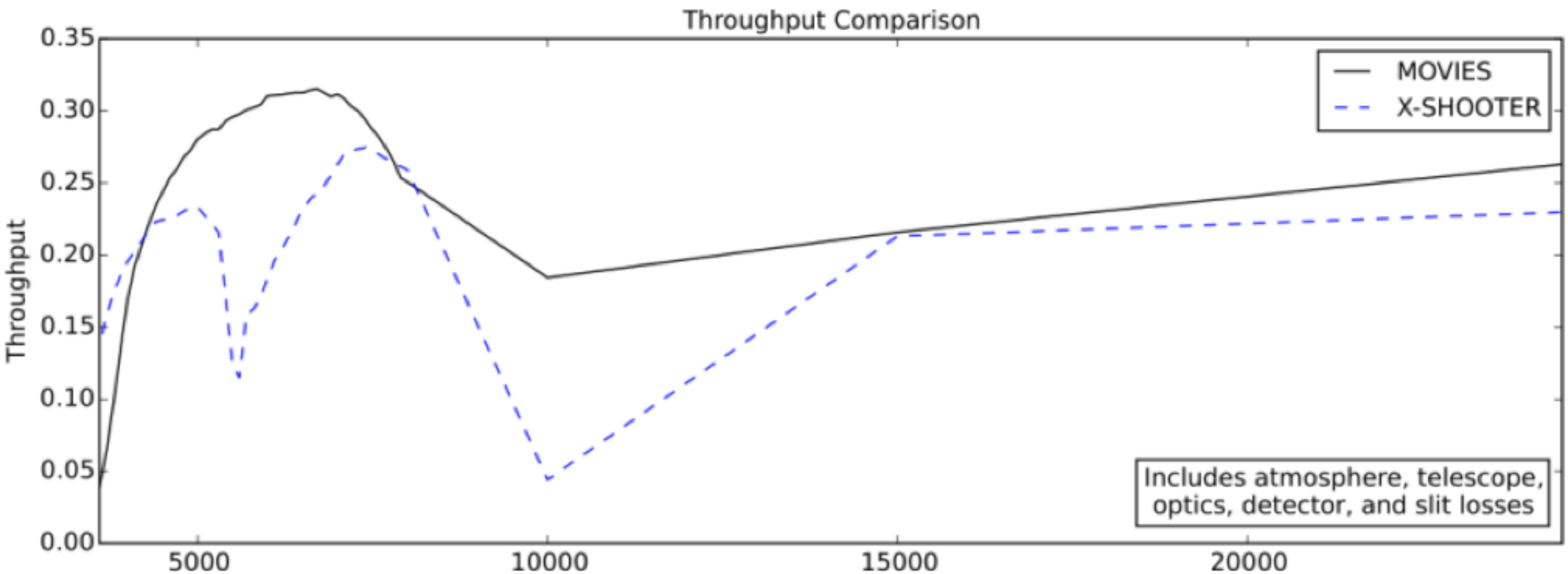
A Brief Encounter

- MOVIES is essentially three imaging/acquisition/guiding cameras and two spectrographs in a single package
- All five science modules operate simultaneously
  - broad bandwidth spectroscopy
  - simultaneous multi-color imaging of field (w/o target in spectroscopy mode)
- This enables
  - **simultaneous monitoring of the panchromatic response of atmosphere + telescope + instrument along same sight line as principal target**
  - **i.e., Precision spectrophotometry enabling key science**
    - **Spectroscopy of exoplanetary atmospheres**
    - **SED characterisation of variable sources**
    - **...**

"Only imperial stormtroopers are so precise"



Sense and Sensitivity



“That’s not a knife”

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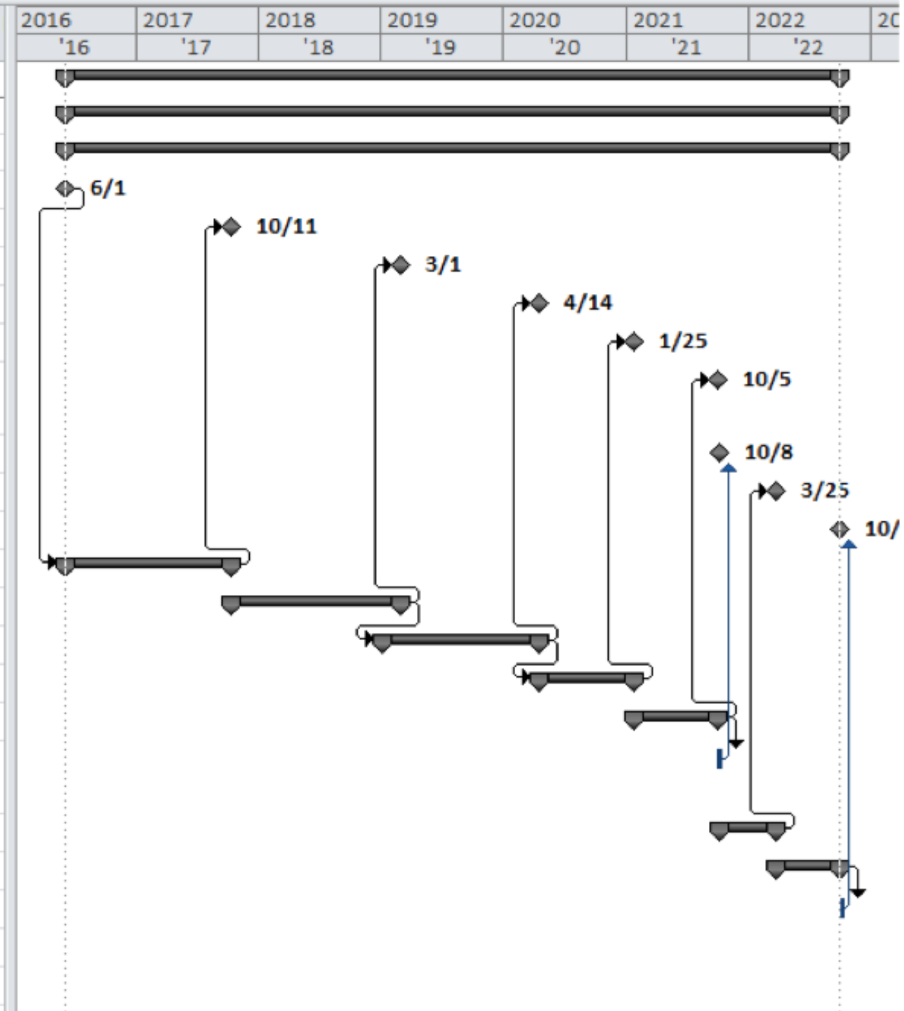
- Acquisition/guiding camera by default will be read with a high cadence (baseline EMCCDs, 1k x 1k, ~20Hz), although longer integrations are possible for those cameras not being used for guiding
- Baseline detector in optical spectrograph is standard CCD
- Potential for inclusion of large format EMCCD (4k x 4k), currently in development by NuVu Cameras and UdM.
- Essentially zero-read noise allows post processing spectral and temporal binning
- Builds on time-domain aspects of MOVIES science

If only I had more time... Wait, a minute, I got all the time I want! I got a time machine!

- MOVIES will obtain spectra of the faint Universe with
  - high throughput, high efficiency, high reliability and low risk
- This means:
  - dual arm design
  - a minimum number of elements and mechanisms
  - low emissivity
  - slit system to ensure excellent sky subtraction
  - highly stable system, ensuring ease of calibration
- MOVIES is influenced by a strong mandate to minimise risks: technical, schedule and cost.
  - Instrument inherits from existing technologies (e.g., well-established CCDs and NIR detectors and proven optical designs and materials)
  - Minimises mechanisms
  - Takes advantage of safe fall-back positions where necessary (eg coatings, detectors, etc).

Production notes

Task Name	Work	Duration	Start	Finish
MOVIES Design and Build	**25,550 hrs**	**1764.08 days?**	**Wed 6/1/16**	**Tue 10/4/22**
Milstones	**0 hrs**	**1764.08 days**	**Wed 6/1/16**	**Tue 10/4/22**
Gemini Milestones	**0 hrs**	**1764.08 days**	**Wed 6/1/16**	**Tue 10/4/22**
Kickoff	0 hrs	0 days	Wed 6/1/16	Wed 6/1/16
Preliminary Design	0 hrs	0 days	Wed 10/11/17	Wed 10/11/17
Final Design	0 hrs	0 days	Fri 3/1/19	Fri 3/1/19
Procurement/build	0 hrs	0 days	Tue 4/14/20	Tue 4/14/20
Subsystem I&T	0 hrs	0 days	Mon 1/25/21	Mon 1/25/21
Subsystem Acceptance	0 hrs	0 days	Tue 10/5/21	Tue 10/5/21
Ship to I&T	0 hrs	0 days	Fri 10/8/21	Fri 10/8/21
System I&T	0 hrs	0 days	Fri 3/25/22	Fri 3/25/22
Ship to Gemini	0 hrs	0 days	Tue 10/4/22	Tue 10/4/22
Preliminary Design	**4,025 hrs**	**377.78 days?**	**Wed 6/1/16**	**Wed 10/11/17**
Final Design	**7,300 hrs**	**386.9 days?**	**Wed 10/11/17**	**Fri 3/1/19**
Procurement/Build	**7,850 hrs**	**355.56 days**	**Thu 1/3/19**	**Tue 4/14/20**
Subsystem I&T	**2,800 hrs**	**217.89 days**	**Tue 4/14/20**	**Mon 1/25/21**
Subsystem Acceptance	**1,200 hrs**	**192.59 days**	**Mon 1/25/21**	**Tue 10/5/21**
Pack and Ship to Integration Facility	0 hrs	3.33 days	Tue 10/5/21	Fri 10/8/21
Integration	**1,775 hrs**	**128.33 days**	**Fri 10/8/21**	**Fri 3/25/22**
System Acceptance	**600 hrs**	**145.07 days**	**Fri 3/25/22**	**Mon 10/3/22**
Pack and Ship to Gemini	0 hrs	1.07 days	Mon 10/3/22	Tue 10/4/22



- Parametric costing estimates and full-up cost of MOVIES suggests total cost of ~USD10M*
  - Parts/travel: ~4.4 - 5.0M
  - Labor: 4.1 - 5.8M

* ~4% of Avatar

MOVIES Science

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MOVIES is

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a time domain spectrograph
a precision spectrophotometer

	Broad Wavelength Range	Simultaneous bandwidth	Moderate Resolution	Faint targets	Rapid acquisition	Multi-band acquisition		High cadence read-out
Transients	✔	✔	✔	✔	✔	✔		✔
Solar System	✔	✔	✔	✔	✔	✔		✔
Stellar populations	✔	✔	✔	✔		✔		
Low mass stars	✔		✔	✔				
Massive Black Holes	✔	✔	✔	✔	✔			✔
High redshift Universe	✔	✔	✔	✔		✔		
Exoplanet atmospheres	✔	✔	✔	✔		✔		✔

Philosophy behind selection of MOVIES science cases:

- workhorse: span all major scales of astronomy
  - solar system(s), stars, galaxies, black holes, high redshift)
- context: what are major priorities for the 2020s?
  - LSST has four driving science areas: the Solar System, The Milky Way, Cosmology and the Transient Universe
  - Solar System and Transients especially well suited to single object spectroscopy / modest field of view
- excellence: where can MOVIES excel?
  - Time domain
  - Exoplanet spectroscopy

• Workhorse science example 1: Resolving the Galaxy — Star Cluster Divide

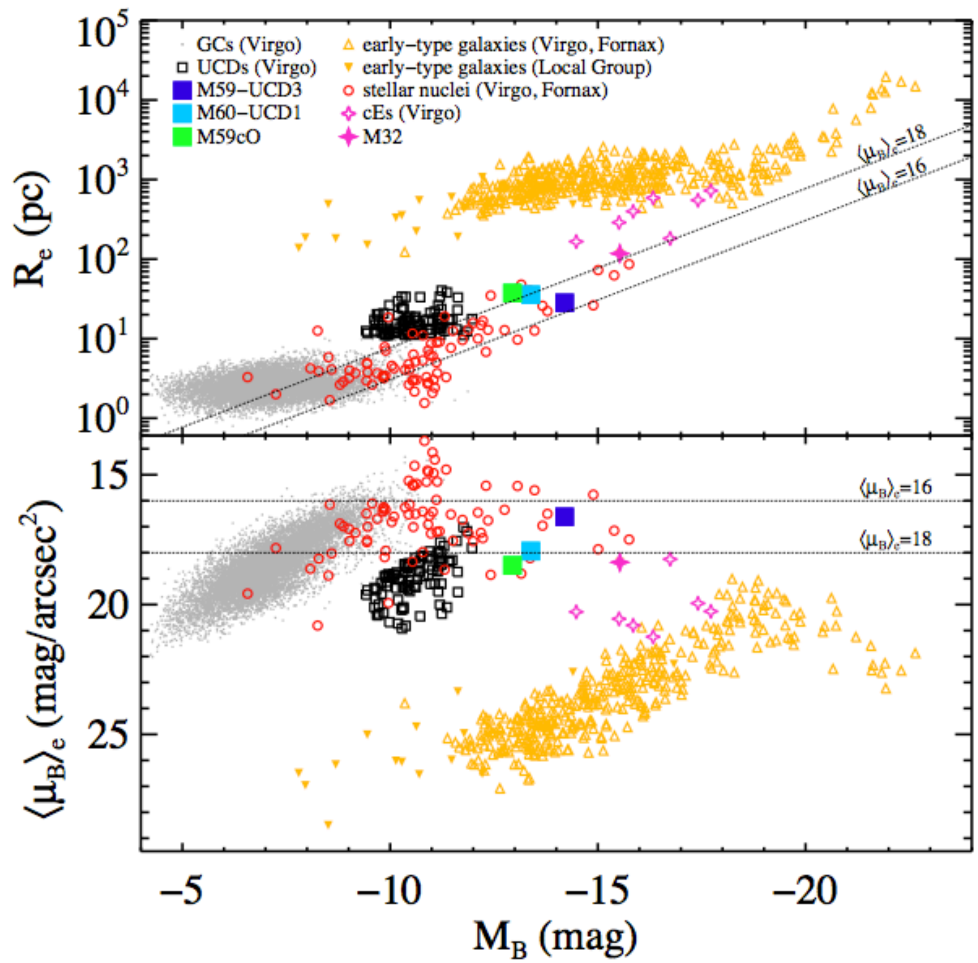
Moderate resolution spectra UV-to-Near IR.

Accurate stellar kinematics down to ~20 km/s

Metallicity measurements to ~0.05 dex or better.

To V~19 in Virgo, 35 targets to SNR~15 in 1800 seconds.

~50 hours with Gemini + MOVIES.

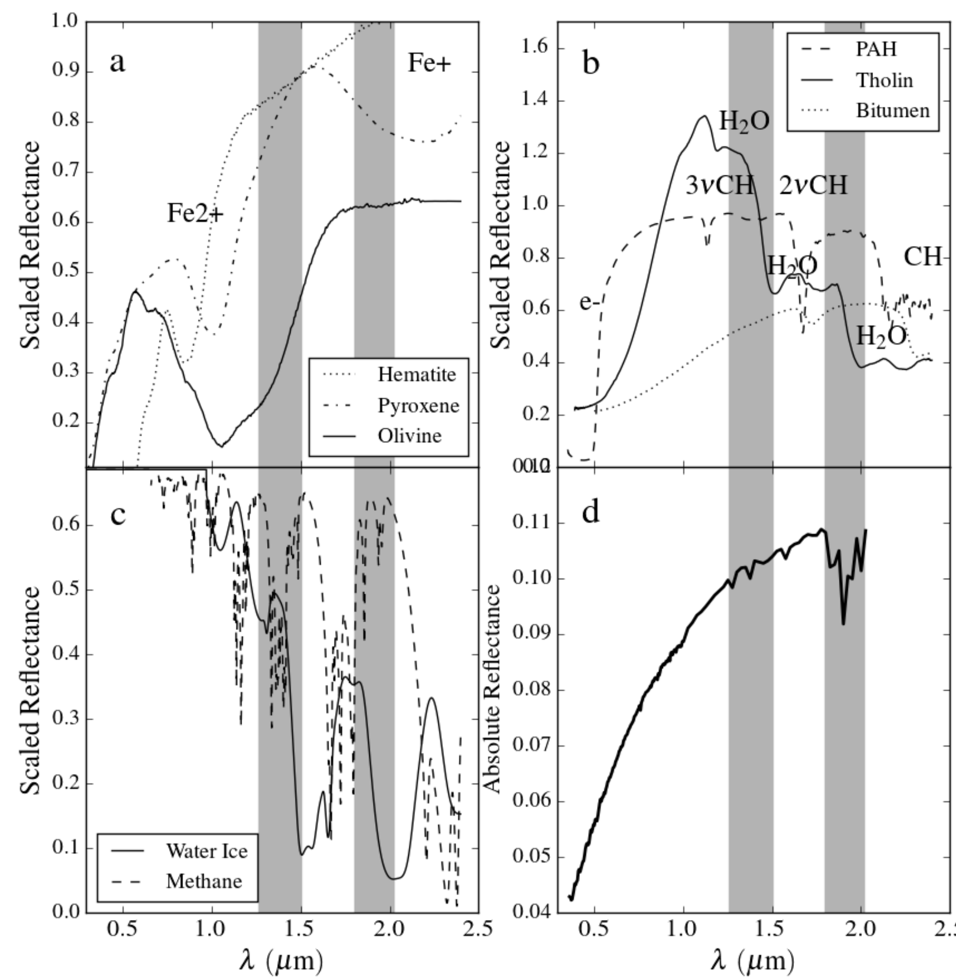


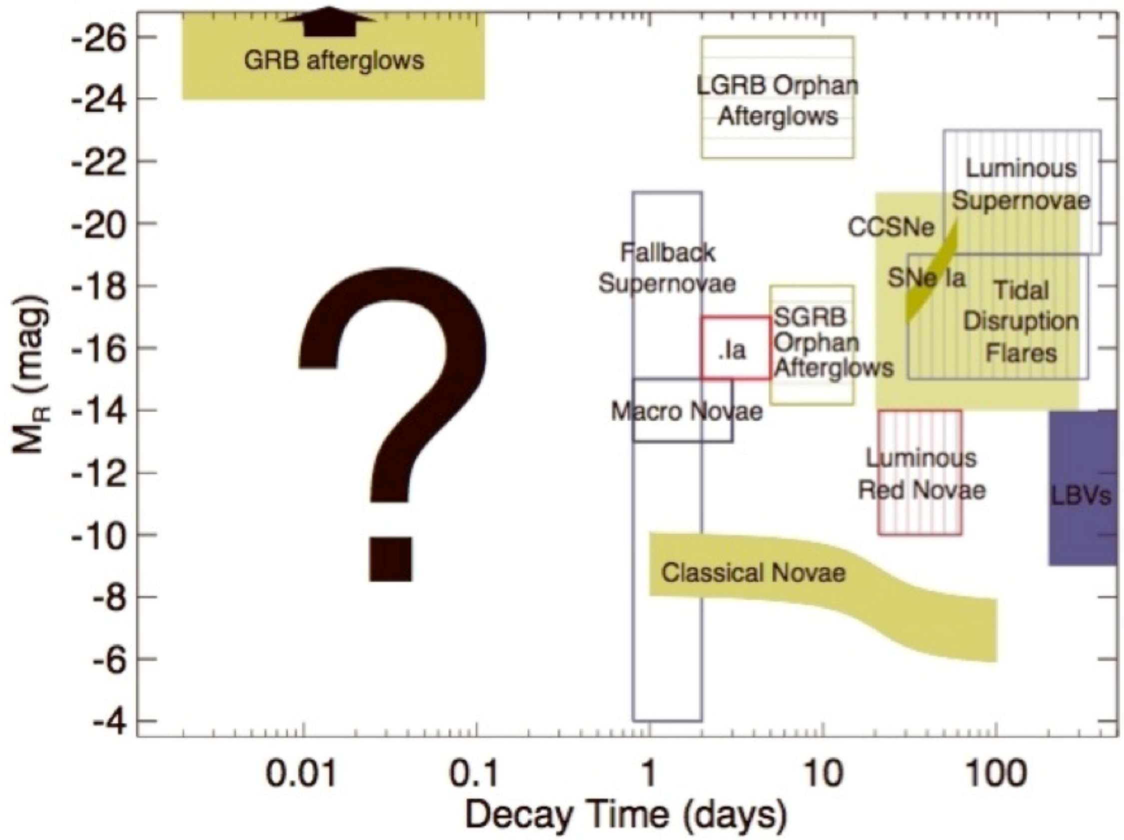
• Workhorse science example 2: The Solar System

Reflectance spectra from UV to Near-IR

SNR~50 per binned resolution element in ~1h to r=21.5 mag.

~150 KBOs bright enough to observe with MOVIES.





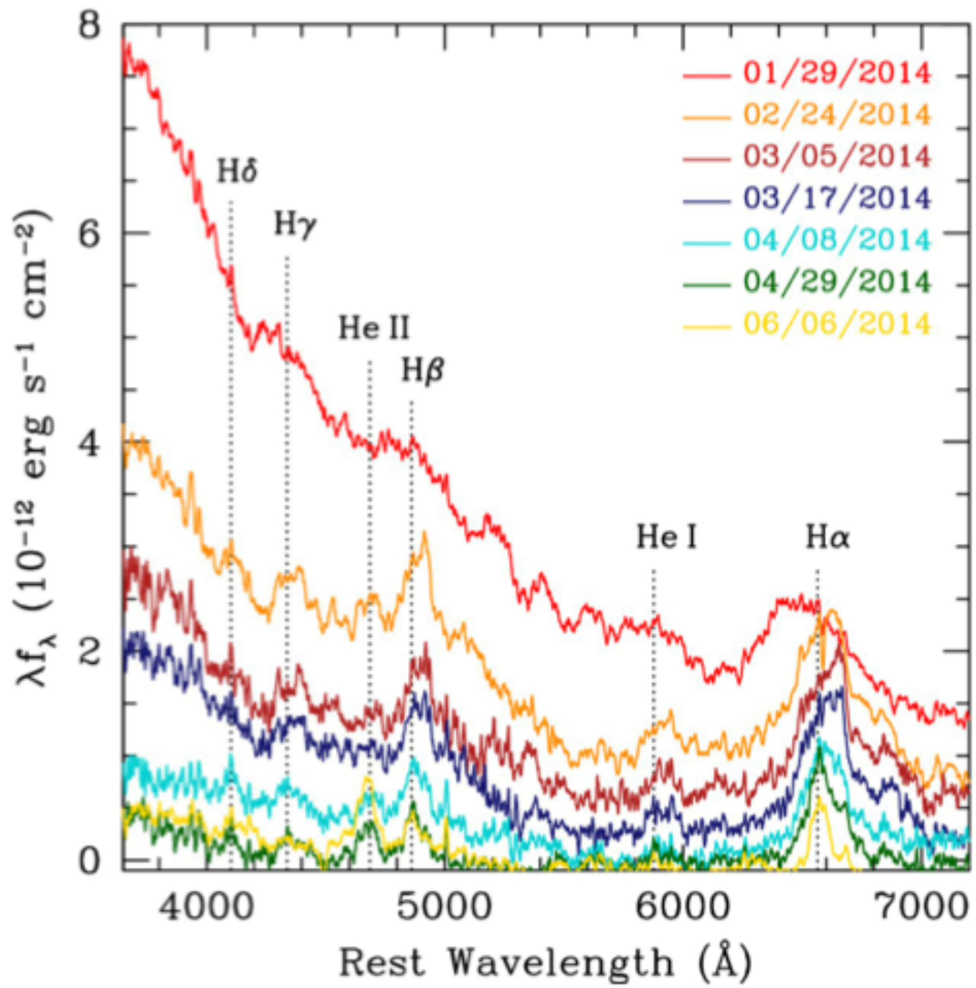
- The LSST ecosystem:
  - Event brokers filter 10^6 transient alerts per night to a handful for rapid follow-up
  - Gemini should aim to be the number 1 facility for follow-up of fainter transients

- Transient science: AGN disruption events

Sudden appearance and rapid UV-to-NIR spectral evolution

Rapid response on ToO trigger after discovery (~few/year)

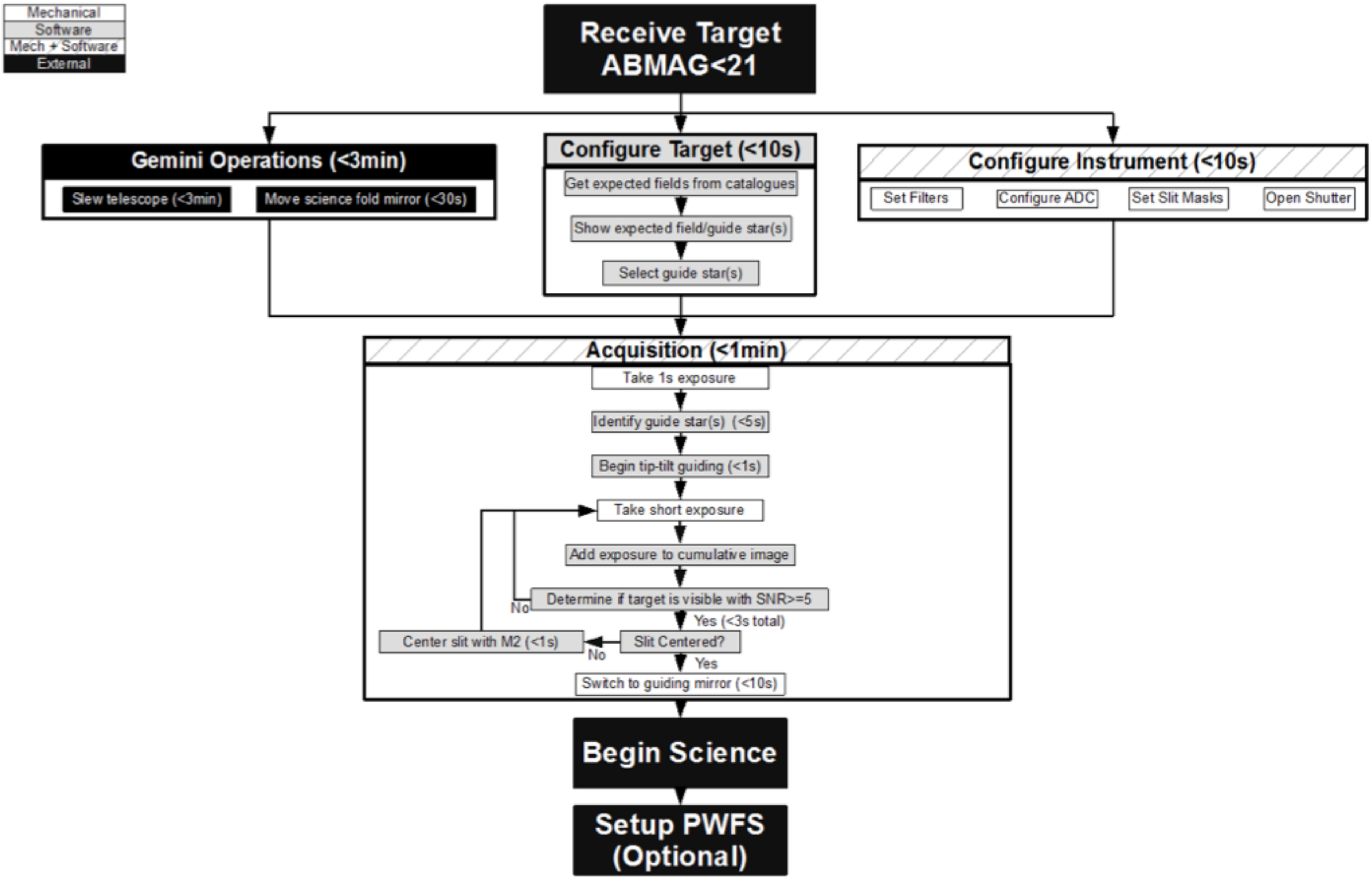
Follow-up over 6-12 months in queue mode.



- Identification of science enabling capabilities

Science case	Science considerations	Impact on Requirements
Transients	Unknown astrophysical phenomena	Moderate spectral resolution; Broad wavelength coverage
	Variable on short timescales (seconds, minutes, hours)	Rapid acquisition; Simultaneous wavelength coverage
	Variable on long timescales (weeks and months)	Stable spectrograph system and robust calibration

- Achieving rapid acquisition with Gemini/MOVIES: “bright” target



Simple Spectroscopic Target

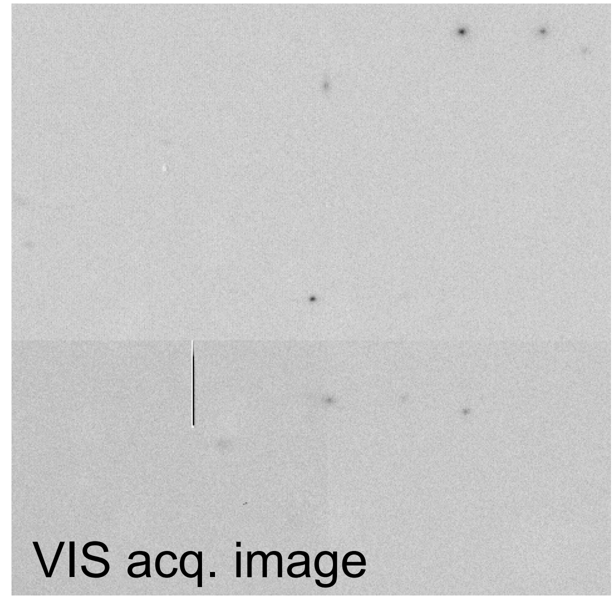
Single target using both spectroscopic channels

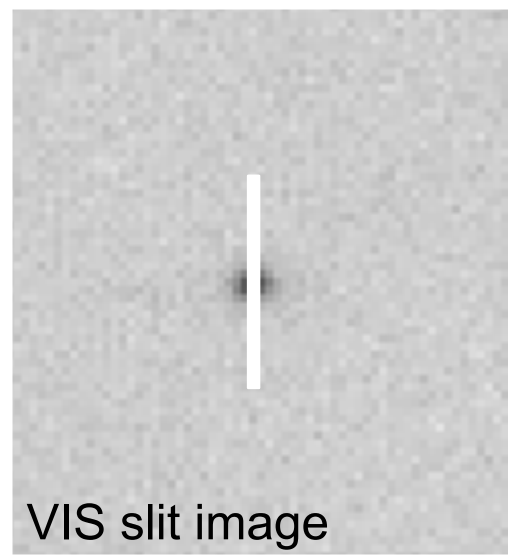
Procedure:

- Acquire with ACQ cameras
- Verify on slit with Slit cameras
- Begin science integrations

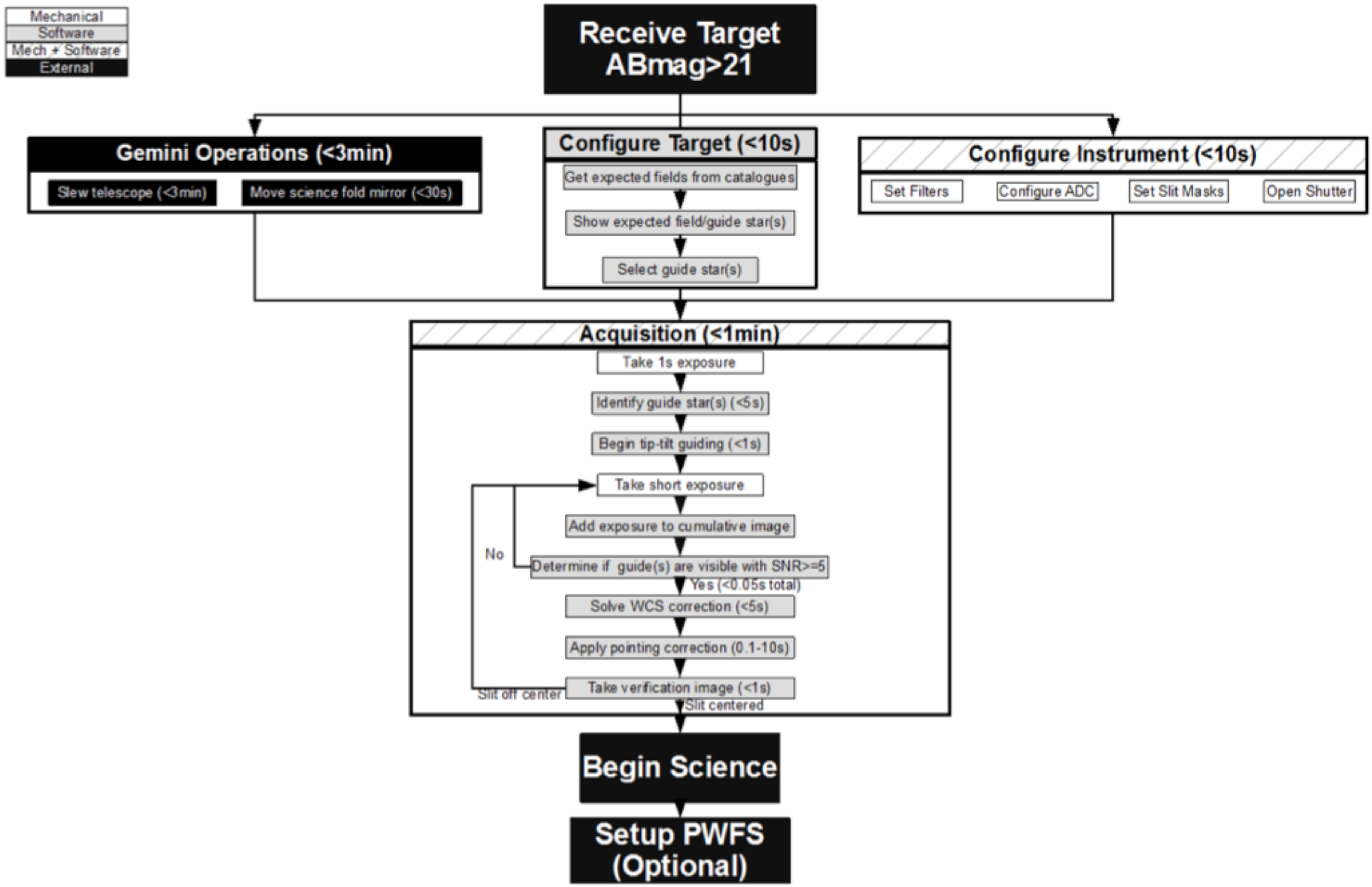
Delivered Data Products:

- ACQ and Slit Camera Images
- Science Data (raw & pipeline)





- Achieving rapid acquisition with Gemini/MOVIES: “faint” target

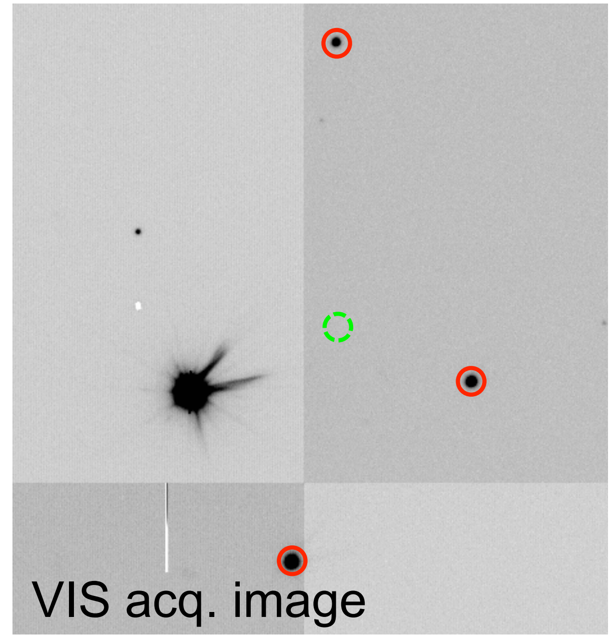


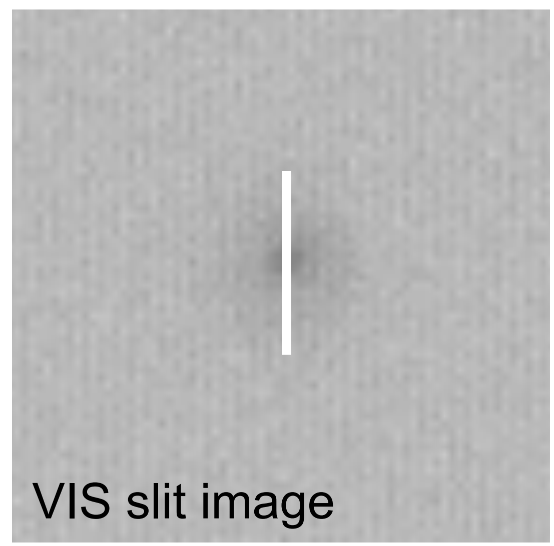
Very Faint Spectroscopic Target

Single target using both channels.
Target is too faint to acquire directly

Procedure:
"WCS" acquisition of bright nearby stars
Start science integrations once locked
Stack slit viewing images during first science integration to verify target.

Delivered Data Products:
ACQ and Slit Camera Image stacks
Science Data (raw & pipeline)





- Precision spectrophotometry: Exoplanet Atmospheres

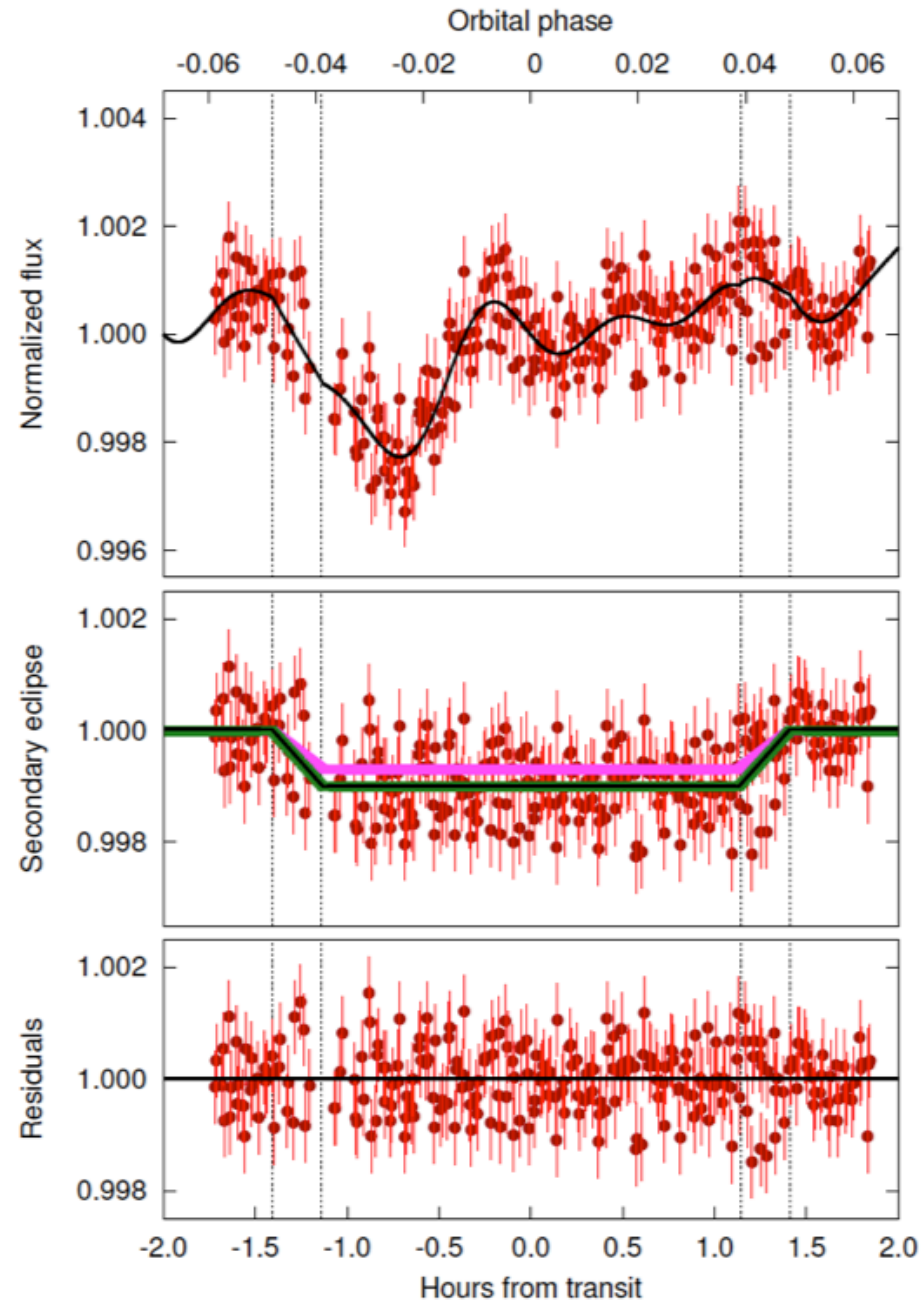
Spectra in and out of secondary eclipse from UV to Near IR.

Accurate stellar kinematics down to ~20 km/s

Rapid cadence spectra for 5-6 hours.

Simultaneous photometry with the ACQ cameras to detrend common-path transparency changes.

A defining science case for Gemini/ MOVIES



- Identification of science enabling capabilities

Science case	Science considerations	Impact on Requirements
Exoplanet atmospheres	Large number of spectral features of interest to be observed simultaneously	Broad wavelength coverage
	Contemporaneous monitoring of transparency and observing conditions along sight line	Simultaneous imaging of field
	Observing over entire period of ingress/egress	Highly stable system
	Small changes in spectral features due to planet transit	Sensitivity / SNR

Time-Resolved Spectroscopy

Transiting exoplanet spectra in 5” wide slit
Simultaneous multiband photometric monitoring

Procedure:

- Acquire science target and center in slit.
- One ACQ camera is the guide and T/T reference camera
- Other ACQ cameras start acquiring high-cadence imaging of the surrounding field and stars
- Start high-cadence spectra of the science target
- Acquire simultaneous spectroscopy & monitor photometry

Delivered Data Products:

- ACQ and Slit Camera **time series images**
- Science Data time series (raw & pipeline)

- MOVIES has a total of 9 science requirements

ID	Name	Requirement
REQ-SCI-001	Wavelength range	Gemini/MOVIES will obtain complete spectral coverage from 360nm to 2.45um in a single exposure for all spectra.
REQ-SCI-002	Spectral resolution	Gemini/MOVIES will be able to operate at a range of spectral resolutions between R~2000 and R~10000
REQ-SCI-003	Sensitivity	At a spectral resolution of R=5000, an extracted spectrum from Gemini/MOVIES will have a signal to noise per resolution element at a given wavelength that is greater than or equal to one for a 1 hour observation of a point source with a flux density of 3.6 x 10^-29 ergs/sec/cm2/Hz at that wavelength, for all wavelengths intervals between 0.36 - 2.45um free from airglow emission-line contamination and strong telluric absorption.

REQ-SCI-004	Acquisition time	Gemini/MOVIES will be able to acquire any target and begin taking a scientific spectral observation within 90 seconds
REQ-SCI-005	Sky coverage	Gemini/MOVIES will be able to identify suitable guide stars over at least 90% of the sky
REQ-SCI-006	Sky subtraction	(i) Gemini/MOVIES must allow for removal of (100 +/- 0.2)% of the sky flux, as estimated for sky-subtracted sky spectra. (ii) Gemini/MOVIES shall achieve a sky subtraction accuracy for atmospheric airglow emission-lines such that the mean residual error for spectral pixels, within 1 resolution element of known atmospheric emission-lines, is <N.n (TBD) times the Poisson limit indicated by the propagated variance spectrum for each resolution element.

REQ-SCI-007	Velocity accuracy	For any object with a known velocity, observed at multiple epochs by Gemini/MOVIES with a signal to noise ratio per resolution element of 5 at R=5000, the contribution from Gemini/MOVIES to the rms difference between the known velocity of the object and the measured velocity of the object will be less than or equal to 12km/s, and will have no systematic dependence on the wavelength region of the spectrum that is used (providing suitable features exist, i.e., any strong absorption or emission lines)
REQ-SCI-008	Spectrophotometry	For a spectrophotometric standard star, observed at multiple epochs by Gemini/MOVIES with a signal to noise ratio per resolution element of 5, the rms variation in the ratio of fluxes measured in any two wavelength intervals will be less than 1% (TBC) of the mean measured value.
REQ-SCI-009	Quick look data tools	Gemini/MOVIES will allow for initial inspection of science spectra within 60 seconds of completion of the observation, including the detrended detector image, extracted and sky-subtracted 2D and 1D spectra.

- Requirements described in considerable detail

ID	REQ-SCI-006
Name	Sky subtraction
Requirement	(i) Gemini/MOVIES must allow for removal of (100 +/- 0.2)% of the sky flux, as estimated for sky-subtracted sky spectra. (ii) Gemini/MOVIES shall achieve a sky subtraction accuracy for atmospheric airglow emission-lines such that the mean residual error for spectral pixels, within 1 resolution element of known atmospheric emission-lines, is <N.n (TBD) times the Poisson limit indicated by the propagated variance spectrum for each resolution element.
Derivation	MOVIES is designed for observations of very faint targets. In a one hour exposure, MOVIES can obtain a SNR per resolution element of 5 for a soure with a monochromatic AB magnitude of m=24 in median dark sky conditions. This corresponds to an object that is roughly 30 times fainter than the sky (20.7mags/arcsec). To do science on such a target requires sky subtraction much better than 1%. In the region of sky lines, it does not make sense to define the sky subtraction accuracy in the same way as for regions dominated by the sky continuum, hence this requirement is in two parts.
Science Cases	Transients; Low mass stars; Black holes; High redshift; Exoplanet atmospheres
Notes	For sky subtraction in the region of bright sky lines, we follow the definitions of the mean residual error as discussed in Sharp & Parkinson (2010, MNRAS,408, 2495)

- Calibration will use GCAL
- Study led by Ruben Sanchez-Jansen to determine calibration procedure and ensure GCAL sufficient
- MOVIES is a “standard” instrument, no special exposures are expected
- Imaging
  - Bias (VIS): CCD bias properties
  - Darks (NIR): bad pixel map
  - Flats (VIS & NIR): pixel-to-pixel variations
- Spectroscopy
  - Bias (VIS): CCD bias properties
  - Darks (NIR): bad pixel map
  - Slit flats (VIS & NIR): pixel-to-pixel variations, blaze function correction
  - Slit arcs (VIS & NIR): spectral resolution, wavelength calibration, and wavelength shift between multi-pinholes and slits (see below).
  - Multi-pinhole flats (VIS & NIR):, order localization, and multi-order definition
  - Multi-pinhole arcs (VIS & NIR): first guess of dispersion solution and spectral format check; wavelength and spatial scale determination/calibration

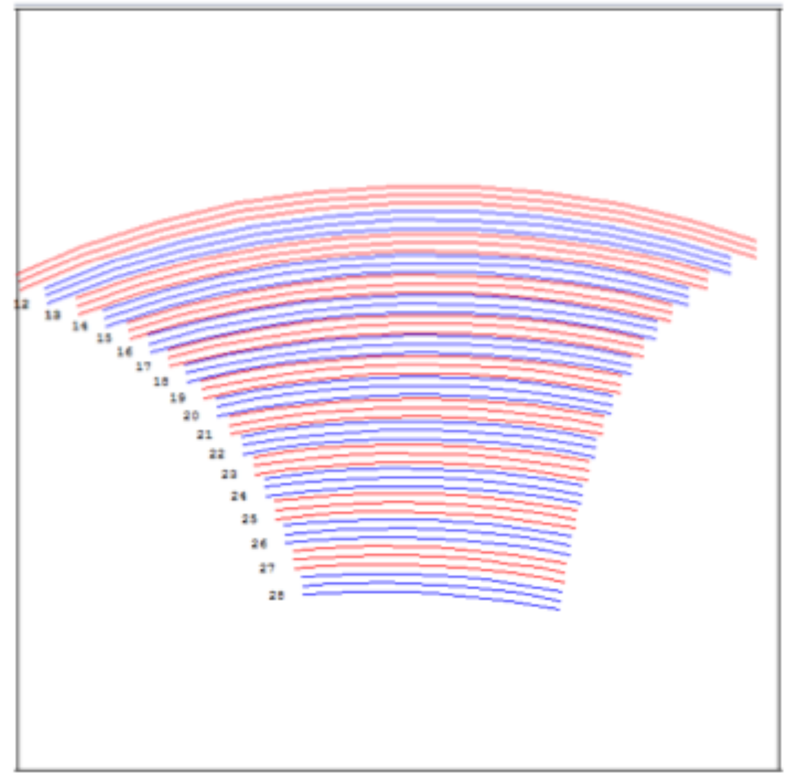
- Science software and data reduction

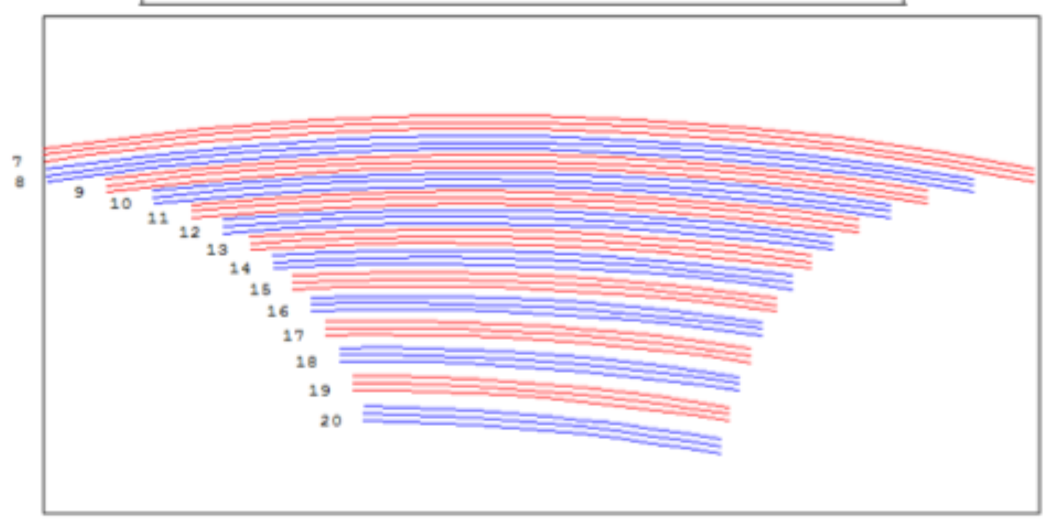
- High level MOVIES requirement on Quick Look Data Analysis
- cf software already written for LBT/MODS

ID	REQ-SCI-009
Name	Quick look data tools
Requirement	Gemini/MOVIES will allow for initial inspection of science spectra within 60 seconds of completion of the observation, including the detrended detector image, extracted and sky-subtracted 2D and 1D spectra.
Derivation	Observations of transient phenomena require rapid access to data to ensure successful observations and allow dynamic observing
Science Cases	Transients; Solar system; Black holes
Notes	The purpose of this software is to deliver to the queue observer an image and spectra for inspection shortly after the next spectrum in sequence has begun integrating. This greatly accelerates making decisions about how to tailor exposures times for rapidly-evolving transient sources whose brightness can be assumed to be unknown to a factor of a few, as well as providing crucial data for informed continue/abort decisions during marginal observing conditions.

- Science software and data reduction

- Also require specialized acquisition/guiding software e.g., automatic identification of guide stars, “finder charts”, etc
- Data reduction standard c.f. XShooter, other echelle spectrographs
- Anticipate making available a set of modules (Python?) to provide fully reduced spectra





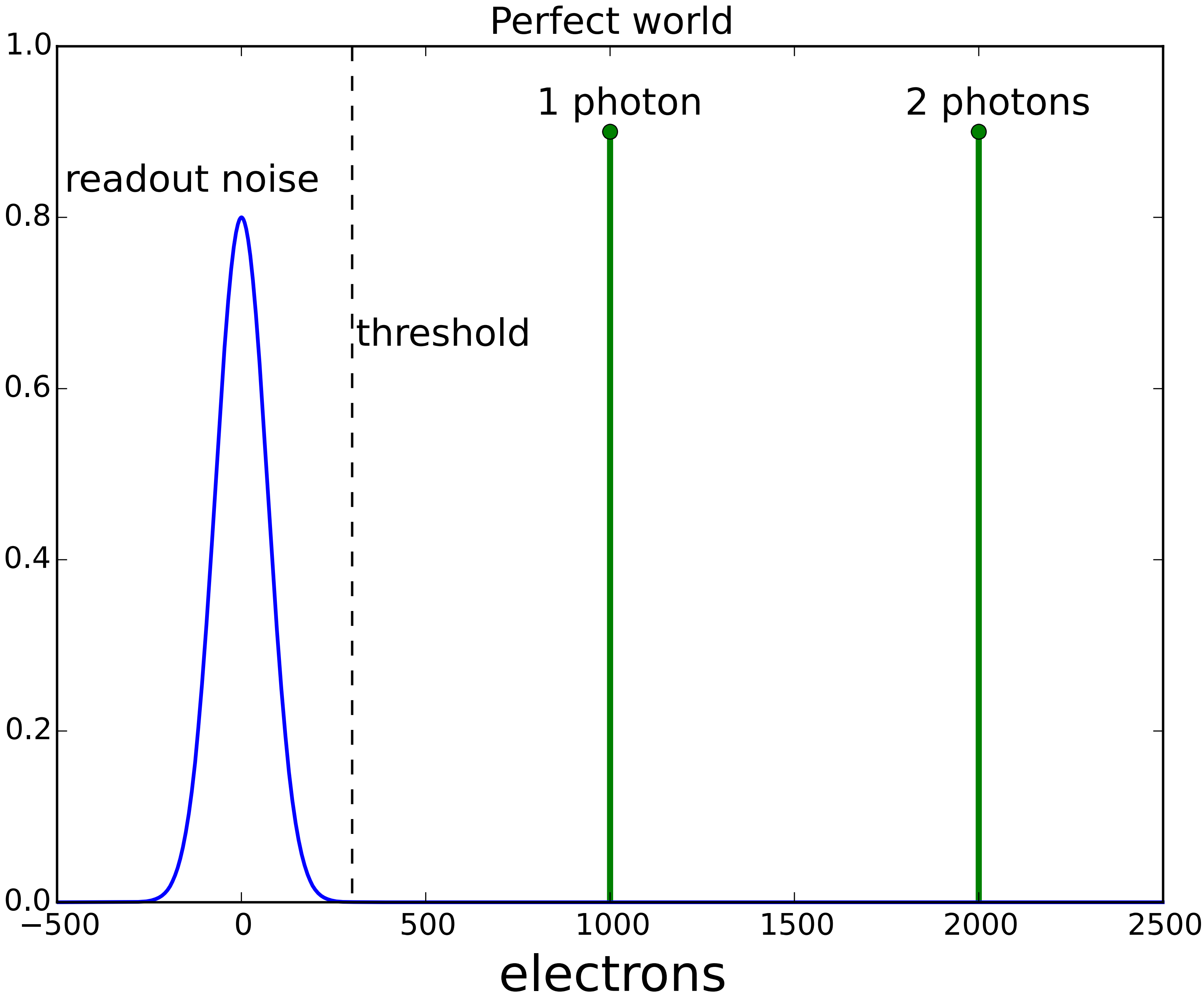
Everything you always wanted to know about EMCCDs in HR spectrographs but were afraid to ask

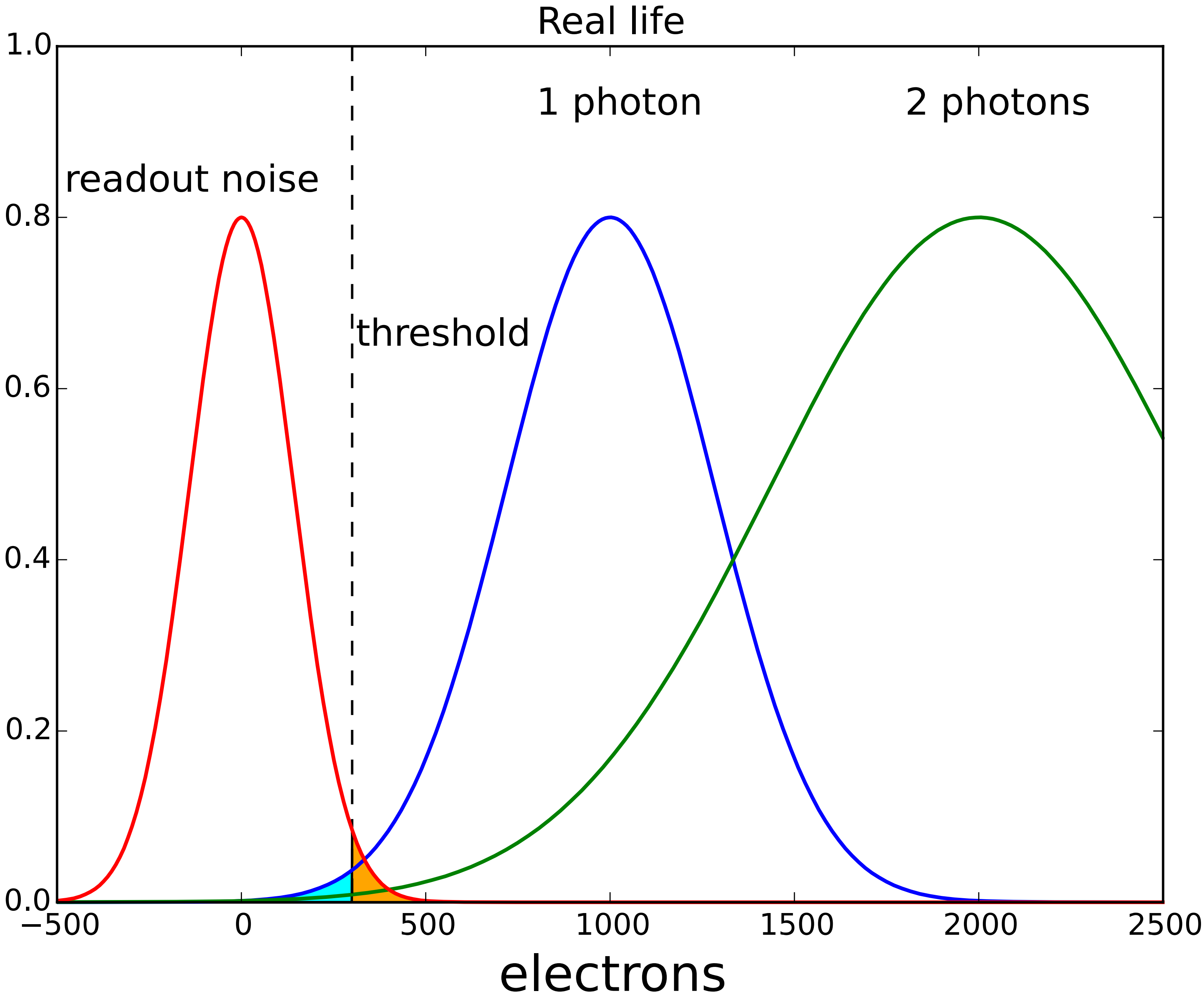
Étienne Artigau

September 30th, 2015

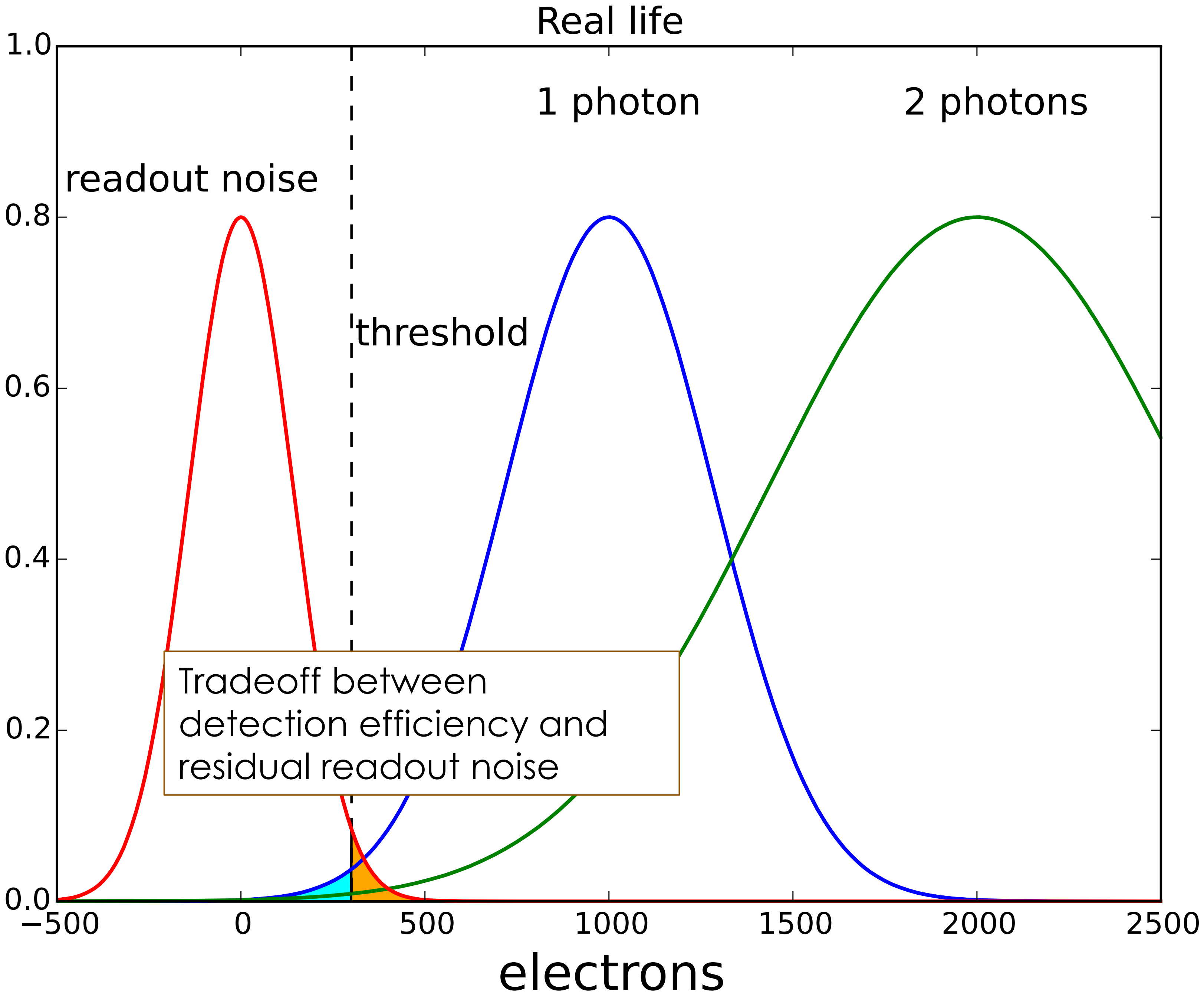
EMCCD 101

- **Huge gain** (~10^3 of e-/photon)
- Readout noise still present, and larger than for a normal CCD, but a single photon generates a signal well above RON level
- **Single photons** are detected by setting a threshold above the high-end tail of RON

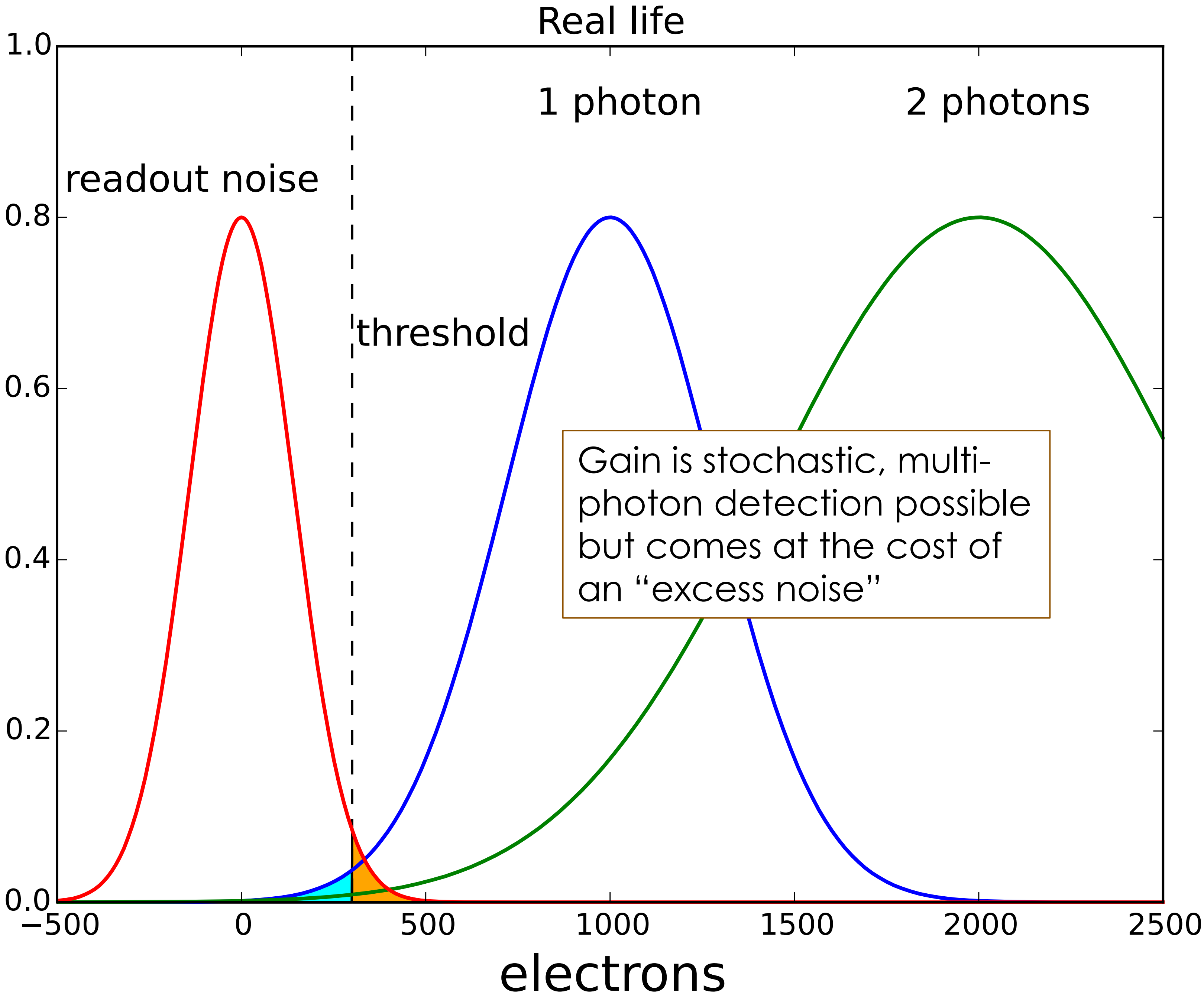

Perfect world
1.0
0.8
0.6
0.4
0.2
0.0
readout noise
threshold
1 photon
2 photons
−500
0
500
1000
1500
2000
2500
electrons



Real life
1 photon
2 photons
readout noise
threshold
1.0
0.8
0.6
0.4
0.2
0.0
−500
0
500
1000
1500
2000
2500
electrons



Real life
1 photon
2 photons
readout noise
threshold
Tradeoff between detection efficiency and residual readout noise
1.0
0.8
0.6
0.4
0.2
0.0
−500
0
500
1000
1500
2000
2500
electrons


Real life
1 photon
2 photons
readout noise
threshold
Gain is stochastic, multi-photon detection possible but comes at the cost of an "excess noise"
1.0
0.8
0.6
0.4
0.2
0.0
−500
0
500
1000
1500
2000
2500
electrons

EMCCD 101

- Readout of the CCD fast (>Hz)
- Thresholding done in post-processing
- In the very low flux regime (<0.3 e-/frame)
  - Count detections as 0 photon or 1 and above photon
  - Mild statistical correction can be applied for multi-photon events
- With a few photons/frame
  - Multiple photons are detected
  - Excess noise present, 2-fold loss in sensitivity
- Many photons/frame
  - Saturate the analog to digital converter
  - Wrong mode (but stay calm, there's a way out!)

EMCCD – other things to keep in mind

- Clock-induced charges lead to 10^{-3} to 10^{-2} e-/frame
  - Dominates over residual RON and behaves like RON
- Gain is adjustable and can be set close to 1 if need be
  - You know in advance if you are observing a bright or a very faint source
  - Dynamic range issues can be solved by lowering gain
    - Prior knowledge of target's brightness (order-of-magnitude) needed

On-sky demonstration

- Technology developed for Fabry-Perrot scanning spectroscopy
  - Upgrade over photon multipliers
- Currently used on-sky on a few 2 to 4-m class telescopes
  - Visiting instrument at CFHT, La Silla 4-m
  - OMM
- Lucky Imaging
- AO systems : SPHERE/SAXO
  - By the way, *that's why SPHERE outperforms GPI on faint stars!*

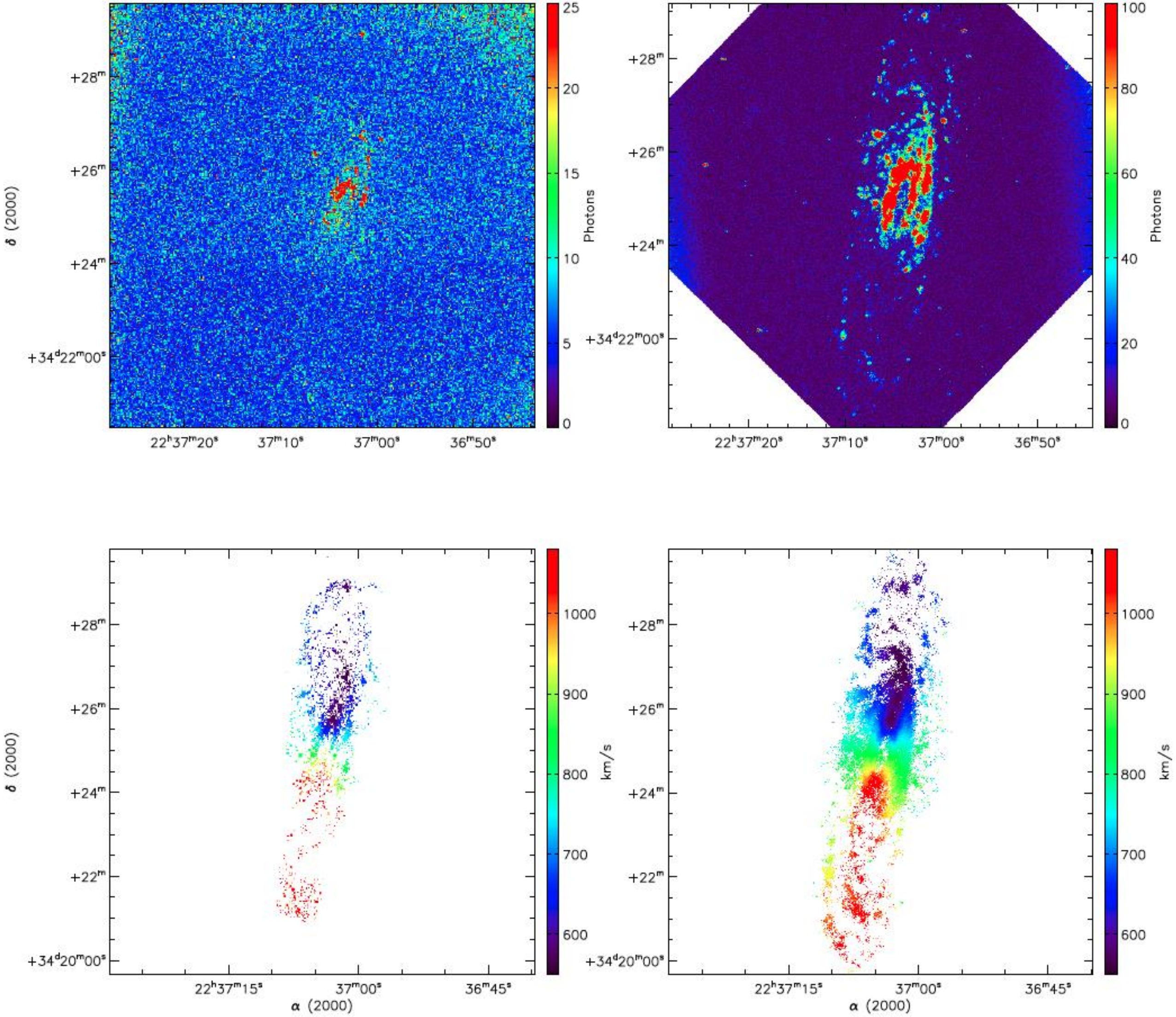
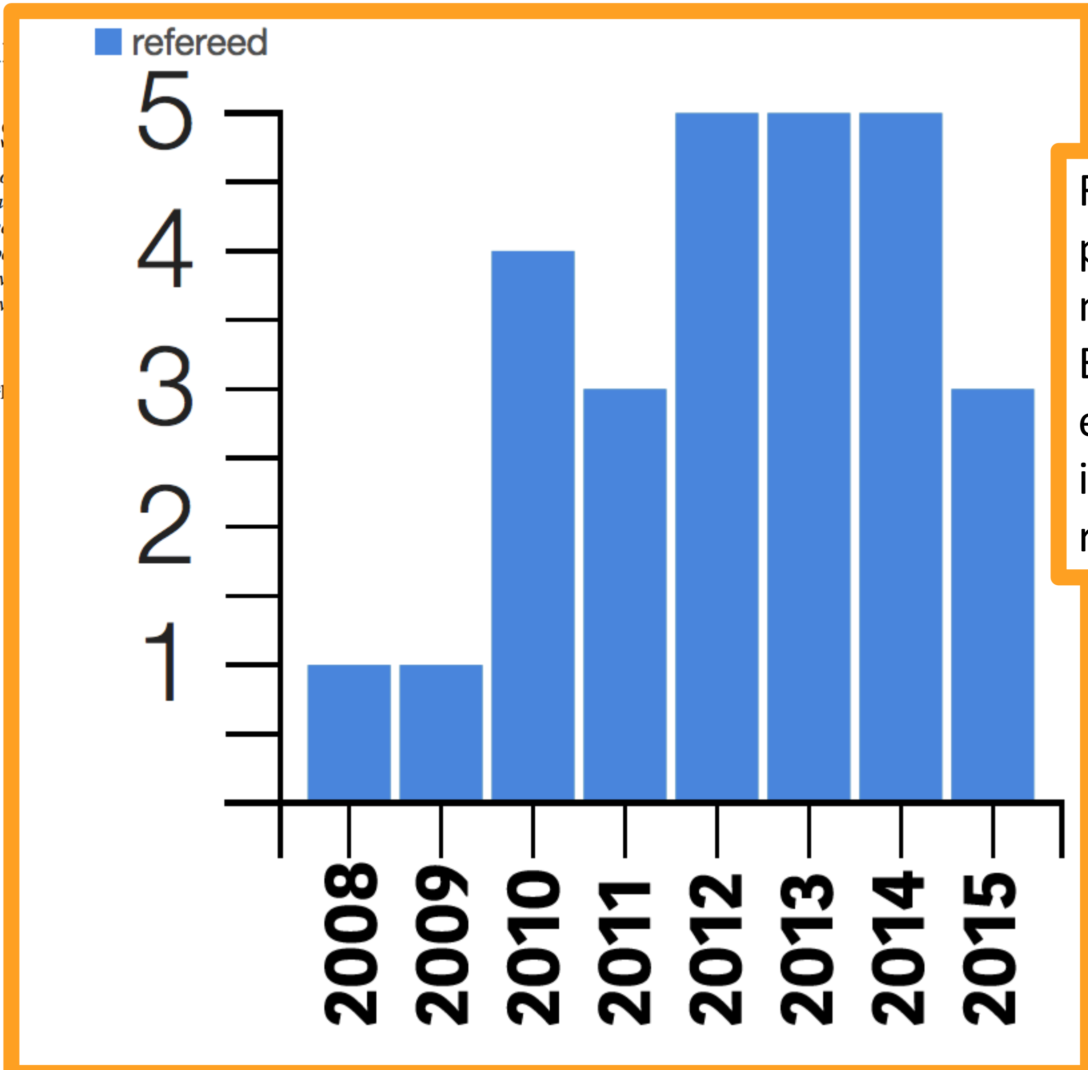


Fig. 5.— IFS images of NGC 7331 obtained with the IPCS (left) and with CCCP (right). The top images represents the monochromatic intensity of the Hα emission of the galaxy (continuum subtracted). The bottom images represent the velocity fields extracted from the IFS data. The observations were made in comparable sky conditions and the same total exposure time was used. The spectral resolution is about 15000.

Daigle et al. 2009; *Extreme faint flux imaging with an EMCCD*



From ADS labs, papers mentionning EMCCDs, excluding instrumentation-related keywords

Ki

roup galaxies,

Z.
[1] Lab
Cana
[2] Obs
[3] Dep
[4] Univ
[5] Univ

Accep

ll the way to the end of the H I disc,
NGC 253 (Bland-Hawthorn et al.).
t implications as to the distribution
is gas, we carried out a deep Hα
247 and 300. The Fabry–Perot data
Chile, offering a large field of view.
y faint diffuse emission is detected.
r NGC 247, emission extending up
in) is found, but no emission is seen
on the entirety of our field of view
embedded in a diffuse background.
obtained, as well as mass models.
far for these galaxies. We find no
d to account for our non-detection
arped galaxy NGC 253, our results
n by hot young stars in the central
terstellar medium in the outer parts.

Key words: instrumentation: interferometers – techniques: radial velocities – galaxies: individual: NGC 247 – galaxies: individual: NGC 300 – galaxies: ISM – galaxies: kinematics and dynamics.

Very-low fluxes

true photon counting

Cons

- assumes <0.3 photon/frame everywhere on the science array
- <5-10% loss in efficiency from thresholding

Pros

- vastly improved RON
  - CIC equivalent to ~10^{-3} RON
- time-resolution
- much improved post-processing possible

Intermediate fluxes

High gain "linear" mode

Cons

- assumes <10-20 photons/frame
- 50% loss in efficiency from excess noise (ambiguity on the effective gain)

Pros

- vastly improved RON and sensitivity
  - ~10^{-3} RON
- time-resolution
- much improved post-processing possible
- <0.3 photon/frame regions don't get excess noise

High fluxes
EM output at a~1 gain

Cons

- Saturates output if not planned for
- Mildly higher RON compared to state-of-the-art CCDs

Pros

- Flexibility
- Nearly identical to standard CCD

Overall
Pros & Cons

- Intermediate fluxes can generally be avoided
  - Shorter integrations to get **<0.3 photon/frame**
  - Longer integrations to get **> RON^2 photons/frame**
- Storage requirement: order-of-magnitude ~150 Gb/night with 4 Hz frame rate

Combining EMCCD+HR spectro

EMCCD + spectrograph …

- EMCDDs are most useful in low-flux and high temporal resolution regime
  - A few instruments now in regular operation and producing science
- EMCCD on a HR spectrograph?
  - Not done yet!
  - Low per-pixel flux criterion met
  - High-temporal resolution opens unexplored territory

EMCCD + spectrograph …

- One of the most exciting benefit of an EMCCD-equipped spectrograph has no equivalent in existing instruments
  - Unique post-processing possibilities
    - Posterior determination of optimal resolution
    - Masking of OH lines in low-resolution spectroscopy

OH subtraction with EMCCD

Outsmarting photons

- Spectroscopy of really faint targets can only be done at low-resolution
  - Think of R<100 spectroscopy of high-z galaxies or PMOs
- Sky background limits sensitivity for 2 reasons
  - Increased noise
  - Time-variation of OH lines that leave systematics
    - Nod-and-shuffle has been designed to handle this issue

Outsmarting photons

- Conceptually, there's a relatively simple solution to both problems
- OH lines consist of a comb of narrow emission lines
- At R<100 you are probing an SED
- The solution : disperse, mask OH lines and bin your spectrum to R<100

Outsmarting photons

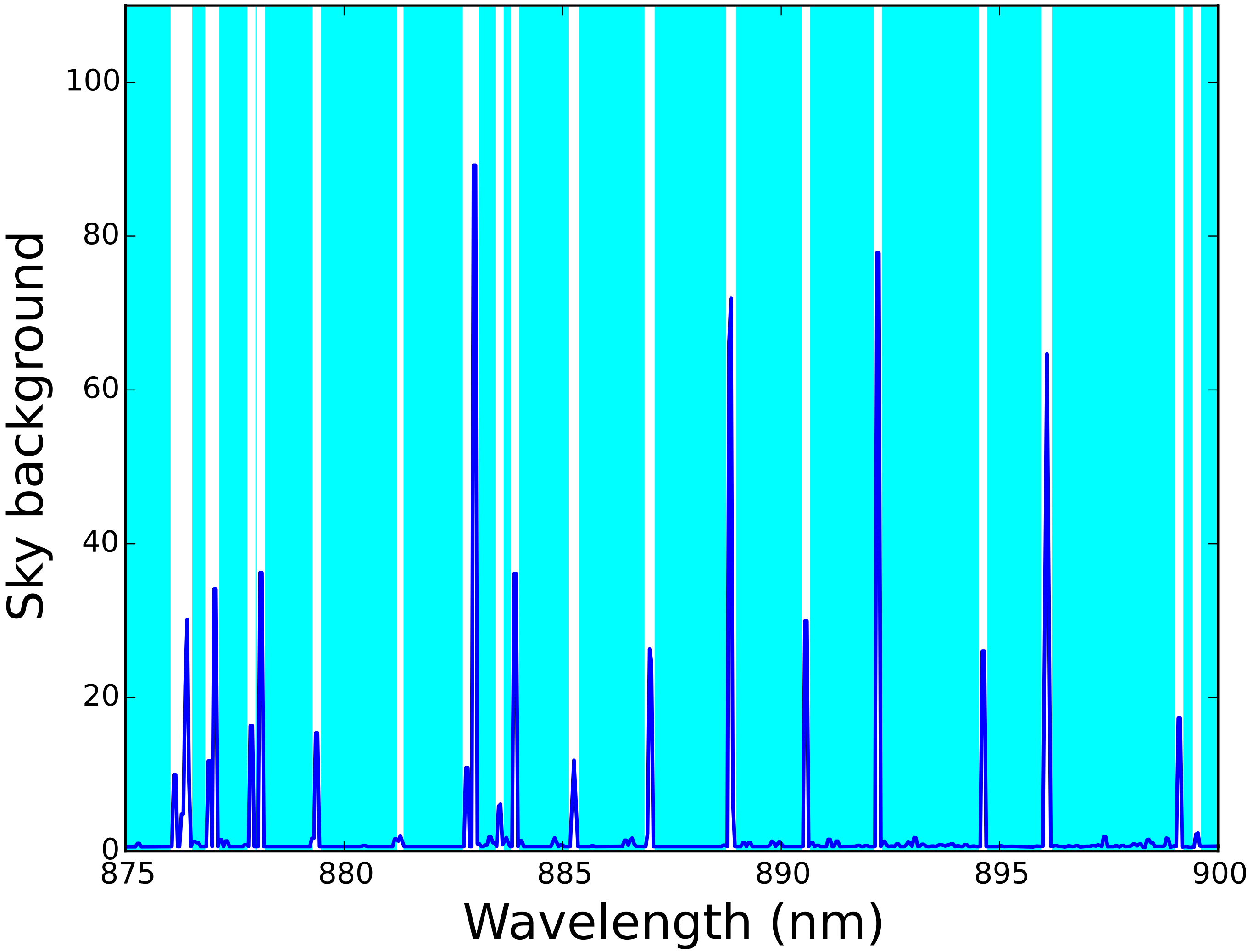
- Why is this not a standard way to proceed?
- Why do low-resolution spectrographs exist at all?
- Observe with GRACES and beat GMOS R150 by binning?
- Intuitively you all know that it should not work!

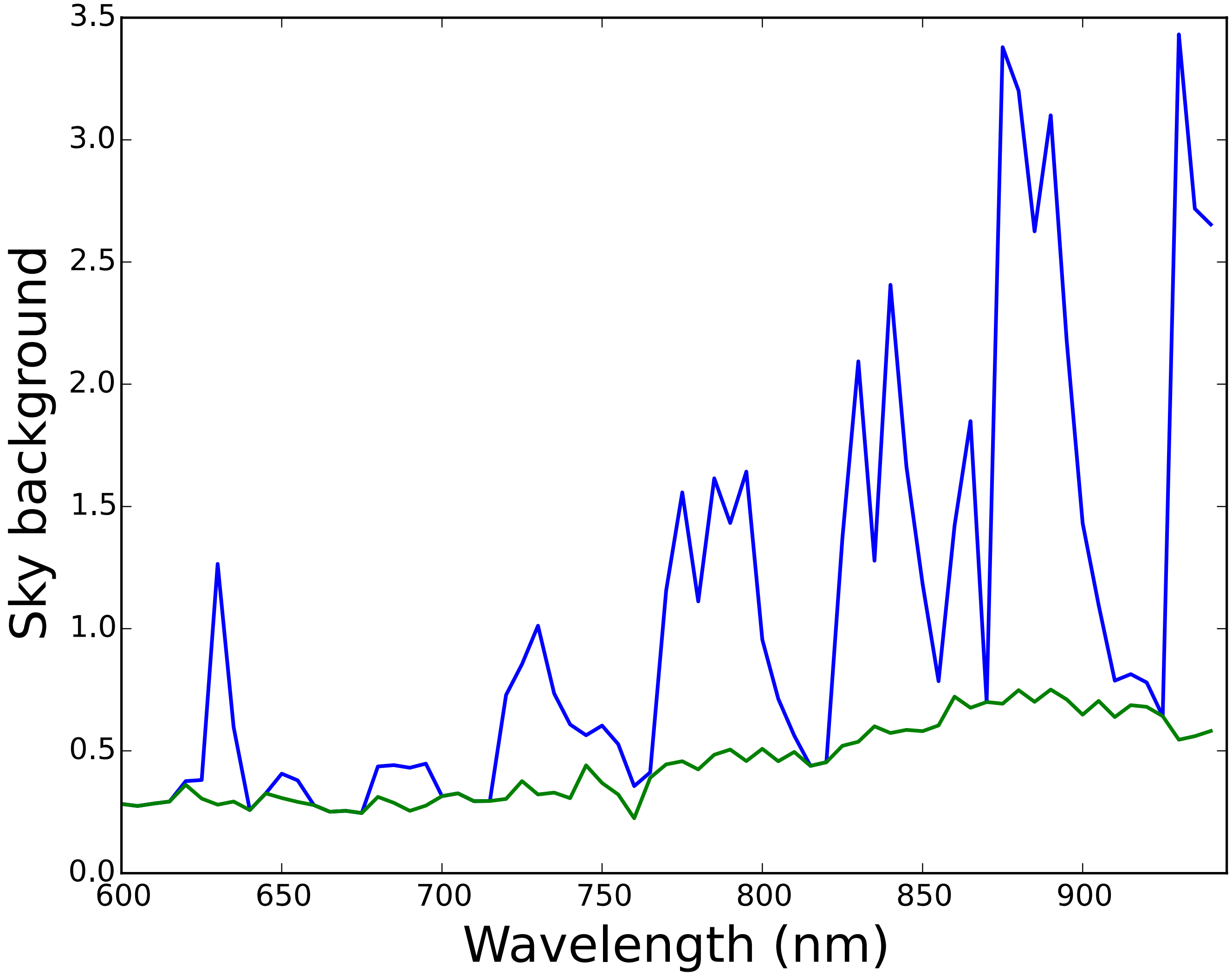
Outsmarting photons

- There are two reasons why this doesn't work
- Readout noise
  - Binning leads to a HUGE increase in effective RON
  - Binning a R=10 000 spectrum to R=100 leads to a 10-fold increase in effective per-element RON
  - GMOS-like RON (6-7 e-) would lead to unacceptable RON levels
- Efficiency
  - High-resolution spectrographs generally have lower throughputs

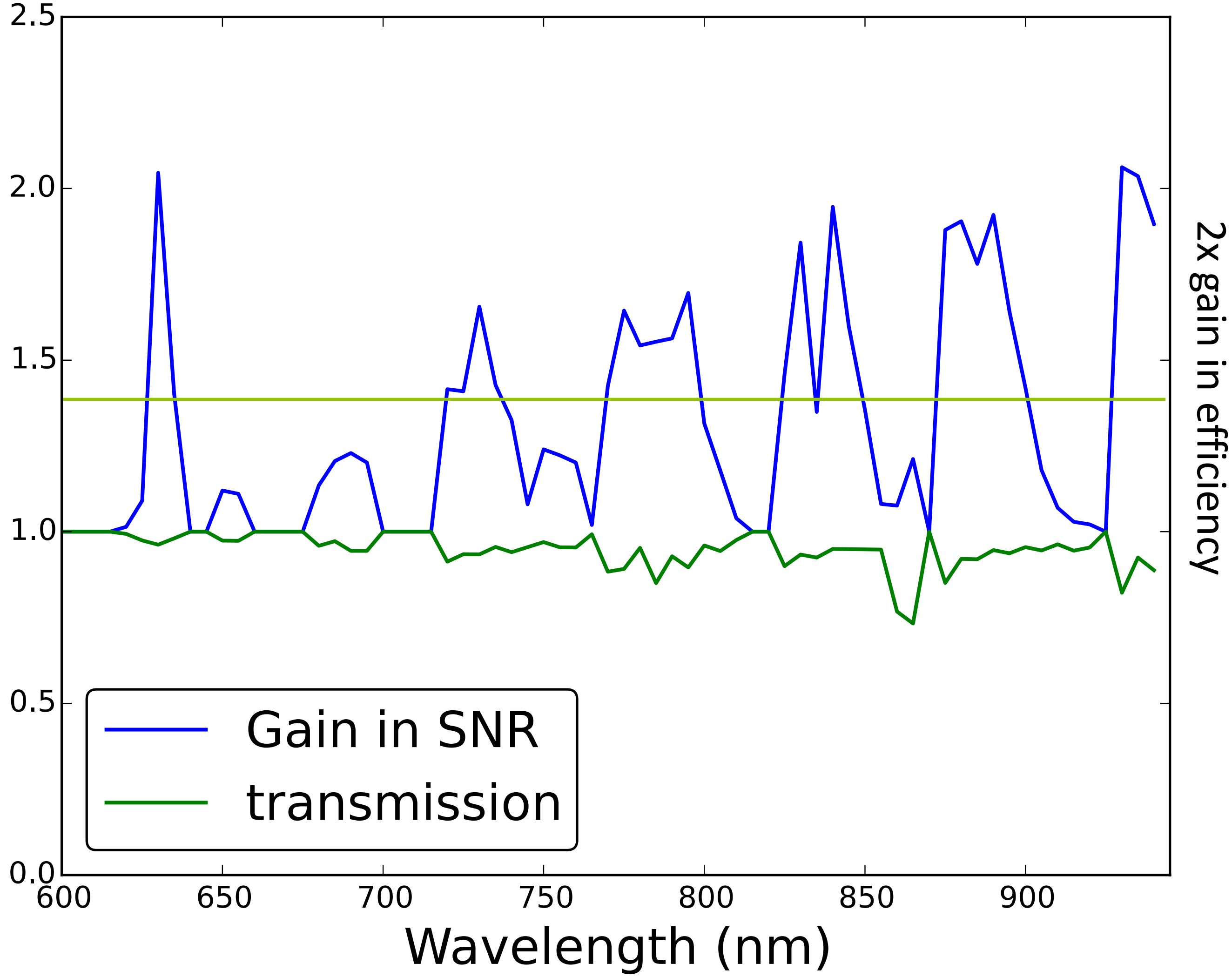
Outsmarting photons

- EMCCDs have vanishingly small effective RON
  - 1/100-1/1000 e- per frame
  - 10-fold increase in RON still below 0.1 e-/frame
  - If one accepts a *total* RON contribution of <10 e- RON per pixel in an hour-long integration, then a total of up to 10 000 frames can be taken (i.e., sampling at a few Hz)
    - <10 e- total in readout noise compares to the combination of 6 frames with 4 e- each


Sky background
Wavelength (nm)
0
20
40
60
80
100
875
880
885
890
895
900



Sky background
Wavelength (nm)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
600
650
700
750
800
850
900



Binning from R=10000 to 5 nm bins

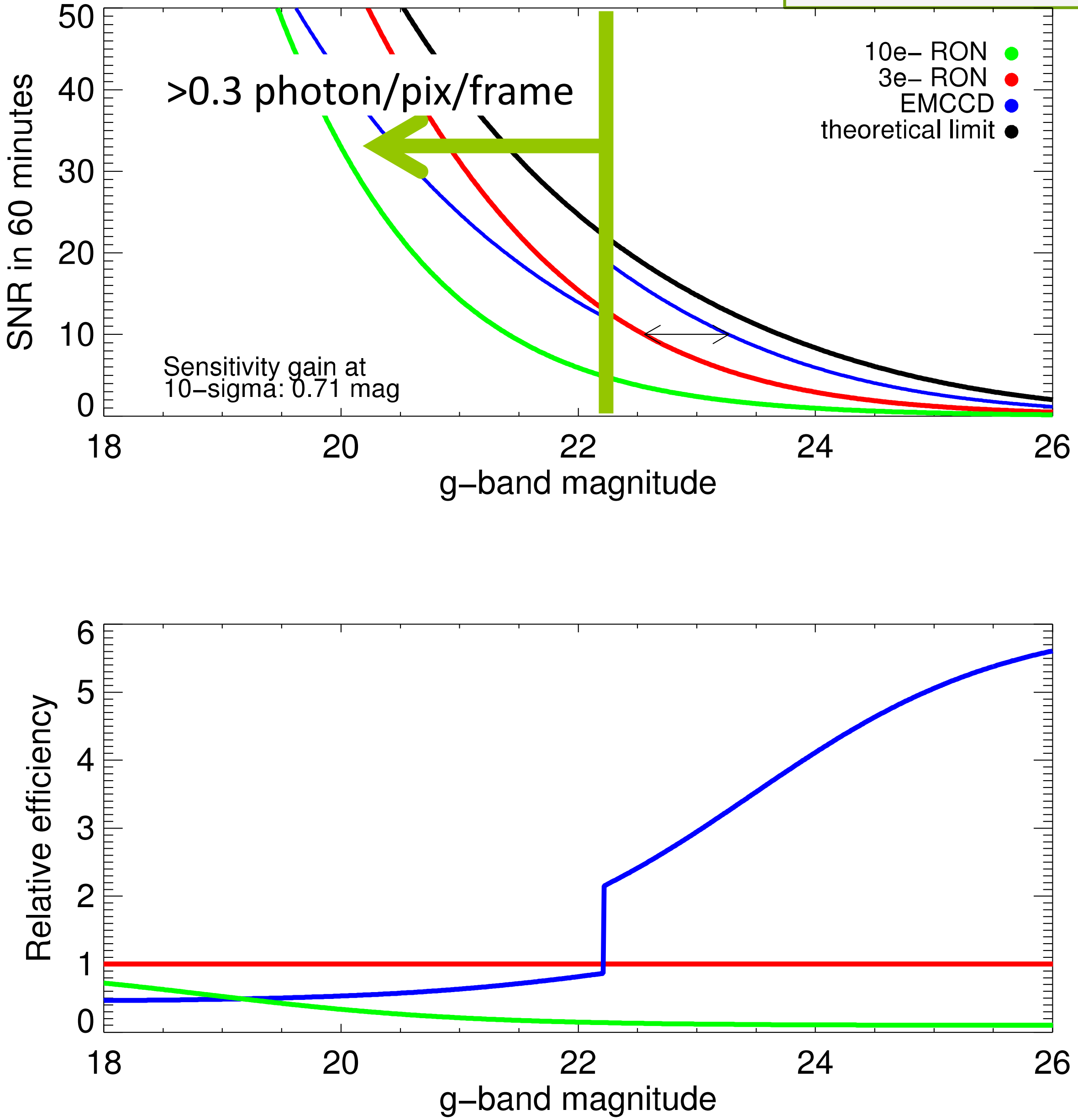
Outsmarting photons

- "nod-and-read-fast" instead of "nod-and-shuffle" to remove time-varying OH lines
  - Nod-and-shuffle only makes sense because of RON cost
  - Nodding every ~60s
  - No need to stick to ABBA dither
    - >2 positions is better in terms of sky background noise

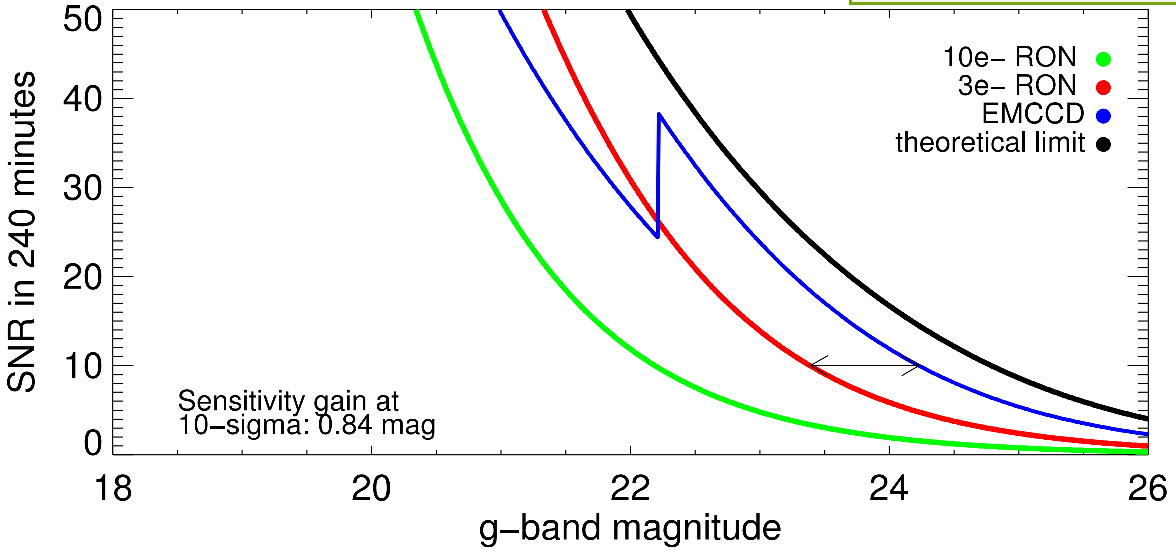
Increased sensitivity at very low fluxes

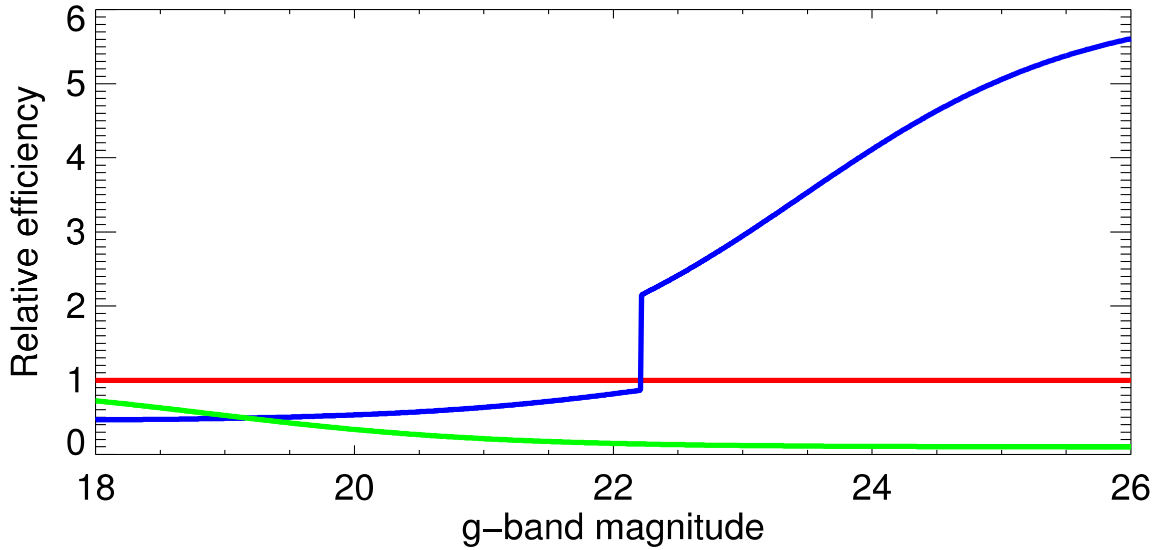
Outsmarting photons

- Over most of the optical domain blueward of ~600 nm, dark-time background is a very low-level grey continuum
- Flux level is such that most high-resolution spectrographs are RON-limited
  - Very long exposures are background-limited but lead to problems due to OH line variability (hence n&s)
  - No RON leads to a significant gain in sensitivity at high resolution



- g-band
- No OH suppression
- 1h integration
- 6 × 10 min for CCD
- 0.5 Hz for EMCCD
- Dark time
- g = 22.5-24
- >2 × gain in efficiency
- EMCCD read more slowly to reduce CIC (2s instead of 0.25s)





- g-band
- No OH suppression
- 4h integration
- 24 × 10 min for CCD
- 0.5 Hz for EMCCD
- Dark time
- >2 × gain in efficiency
- At g=24, SNR~10, **would require 16h with 3e- RON**

Caveats…

- Sensitivity gains from OH suppression *only relevant* when binning down to low resolution
- Sensitivity gain from low RON *only relevant at full resolution*. Low-resolution spectrograph also have low effective RON.

General thoughts on post-processing

Outsmarting photons

- Posterior determination of resolution …
  - Lyman-break galaxies at arbitrary redshift
    - Preserve optimal SNR on continuum without sacrifying line profiles
  - Follow-up of ultra-cool dwarfs
    - SNR varies considerably with wavelength
      - One could have R=10 000 at 0.9μm and R=100 at 0.5μm without RON penalty at the blue end
  - Objects with strong emission lines and weak continuum in general

Outsmarting photons

- Very fast frame rate at no RON cost
  - Cosmic rays
    - Very modest contribution to dark current
    - In photon-counting mode, seen as 1 e- only
  - **Poor weather** spectrograph
    - Once on target, spectra can be weighted by the instantaneous throughput
      - Seeing changes and passing clouds
    - No need to idle with a close shutter… just observe and you'll throw the data away at a later time

New science niches

Opening new scientific niches

- Time-resolved observations at ~4 Hz and R~10 000 would be a first
  - Could conceivable be much higher frame rate on sub-windows (e.g., short wavelength stretch)
  - Ongoing development at *nüvü camēras* for general-purpose windowed readout with their controller
    - Motivated by needs for very fast photometry in other instruments

Opening new scientific niches

- Flaring in very-low mass stars
  - Flaring well documented only down to timescale of a few minutes
- Accretion processes on compact objects
- Phase-resolved spectroscopy of pulsating white dwarfs

UdeM EMCCD status

EMCCD - Development History

- Long experience on IPCS (CIGALE / FanTOmM / GhaFaS)
- **2008** – CFI Grant to develop a set of 12 - 2k x 2k EMCCD involving Jean-Luc Gach's Team (LAM) and e2v
  - **2009**: Kick-off with e2v and Gach/Carignan
  - **2009**: 2k x 2k becomes 4x x 4k needs
  - **2010**: agreement between e2v and UdeM to build 6 detectors + 1 eng **: 3.5 M$CA** including in-kind of e2V (classical ccd, tests and development team)
  - **2011** : PDR
  - **2012** : CDR and package report
  - **Q4 - 2013**: mechanical chip
  - **Q3 - 2014**: engineering chip
  - **Q2 - 2015**: Test camera delayed @ e2V
  - **Q3 - 2015**: New test camera
  - **end Q4 – 2015**: first 3 science chips to be delivered
  - **Q1 – 2016**: last 3 science chips to be delivered

LAM LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

OBSERVATOIRE DU MONT-MÉGANTIC

INSTITUT DE RECHERCHE SUR LES EXOPLANÈTES INSTITUTE FOR RESEARCH ON EXOPLANETS iREx

Université de Montréal

INNOVATION.CA CANADA FOUNDATION FOR INNOVATION FONDATION CANADIENNE POUR L'INNOVATION

In parallel :

- Controller developed with LAM and Gach to fit design of the EMCCD (based on OCAM detector for ESO)
- Mechanical design for N2 cryostat made by UdeM Team
- Controller development with nüvü Camera for Canadian Space Agency

- In lab tests Q4 - 2015
- On sky test during Q4 2015 and Q1 2016 at OMM

1 chip among the 6 Science grade will be offered as in-kind from UdeM to the MOVIES project

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8th October 2012

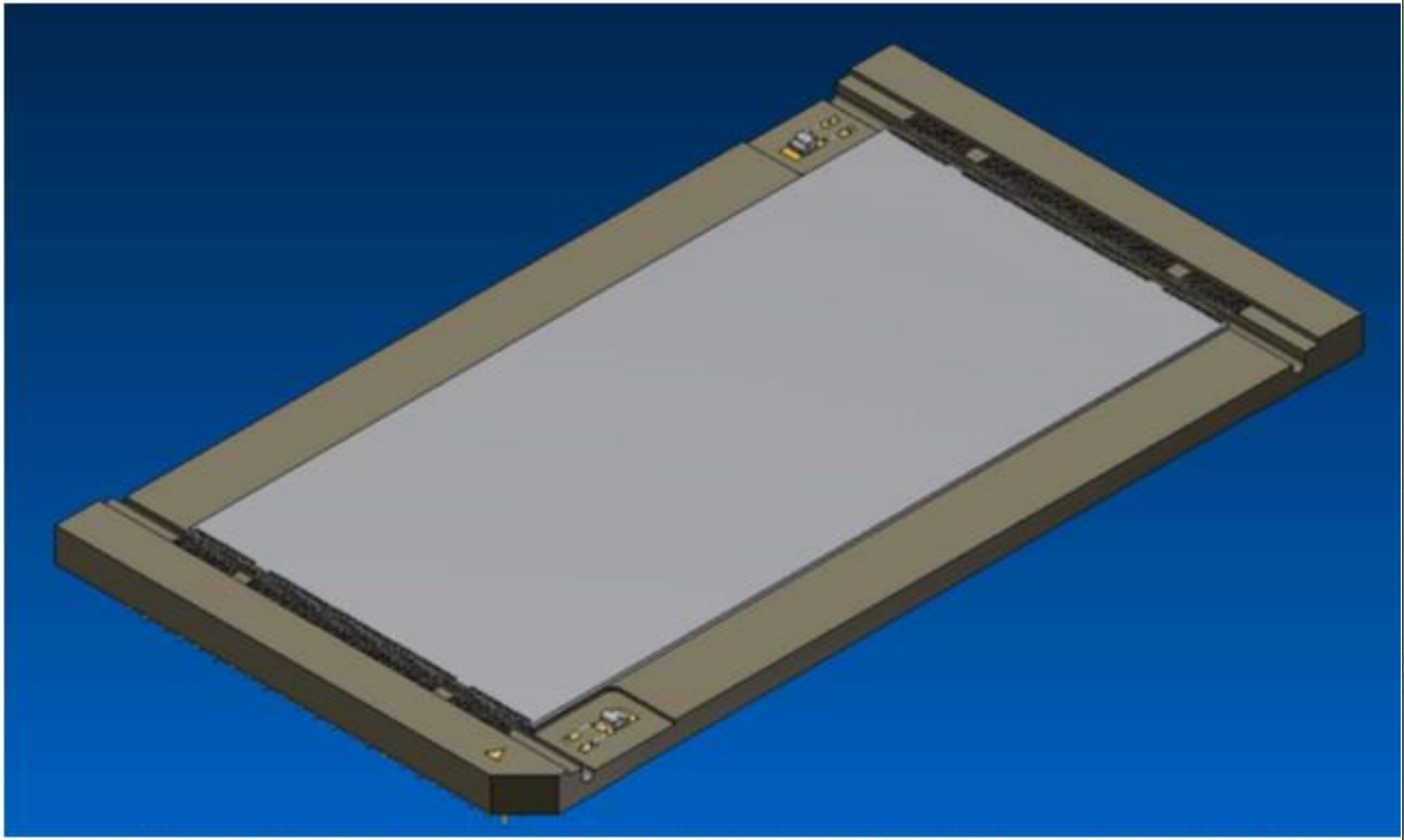
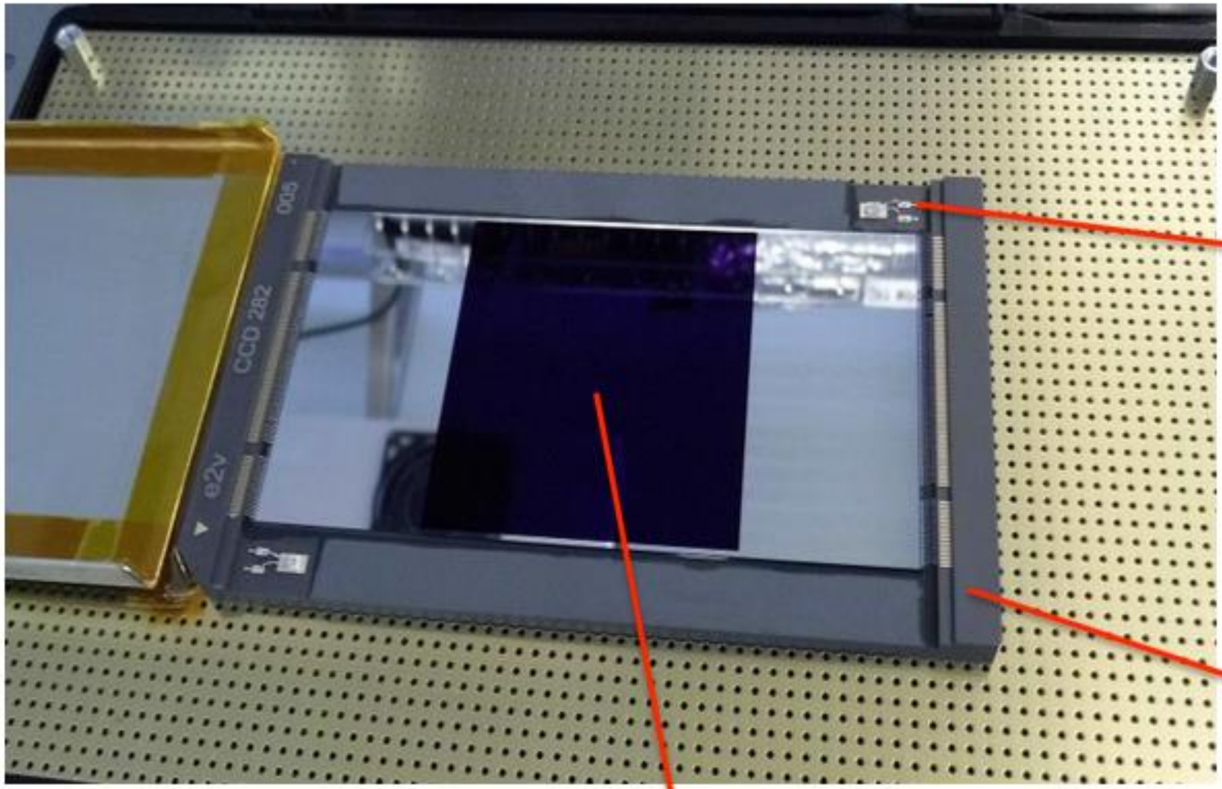


FIGURE 1: 3-D view of the package showing die, temperature sensors and ceramic package

E2V CCD282 : a 4kx4k EMCCD optimized for photon counting

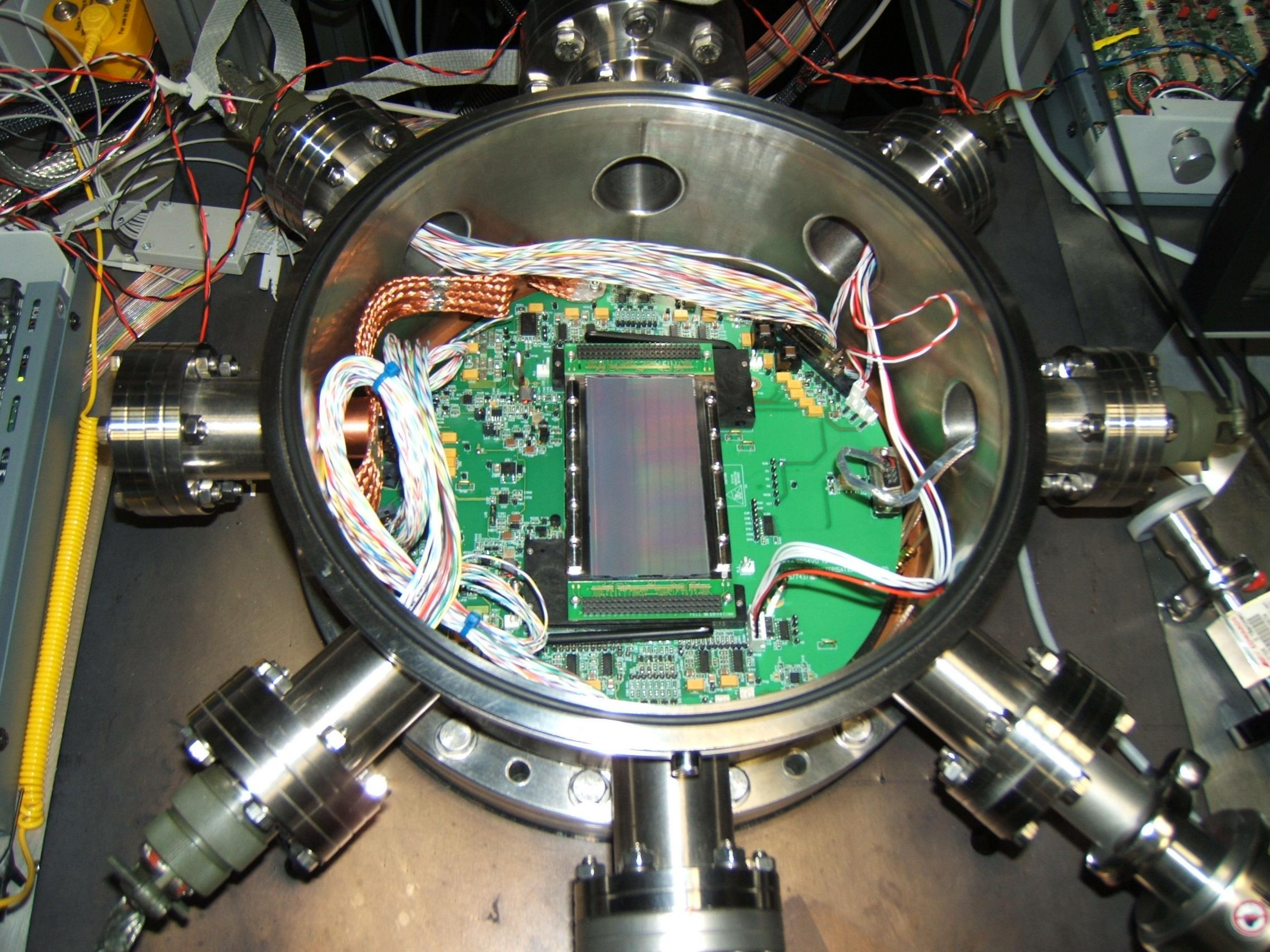
Chip size : 125 mm ! 20μm guaranteed flatness

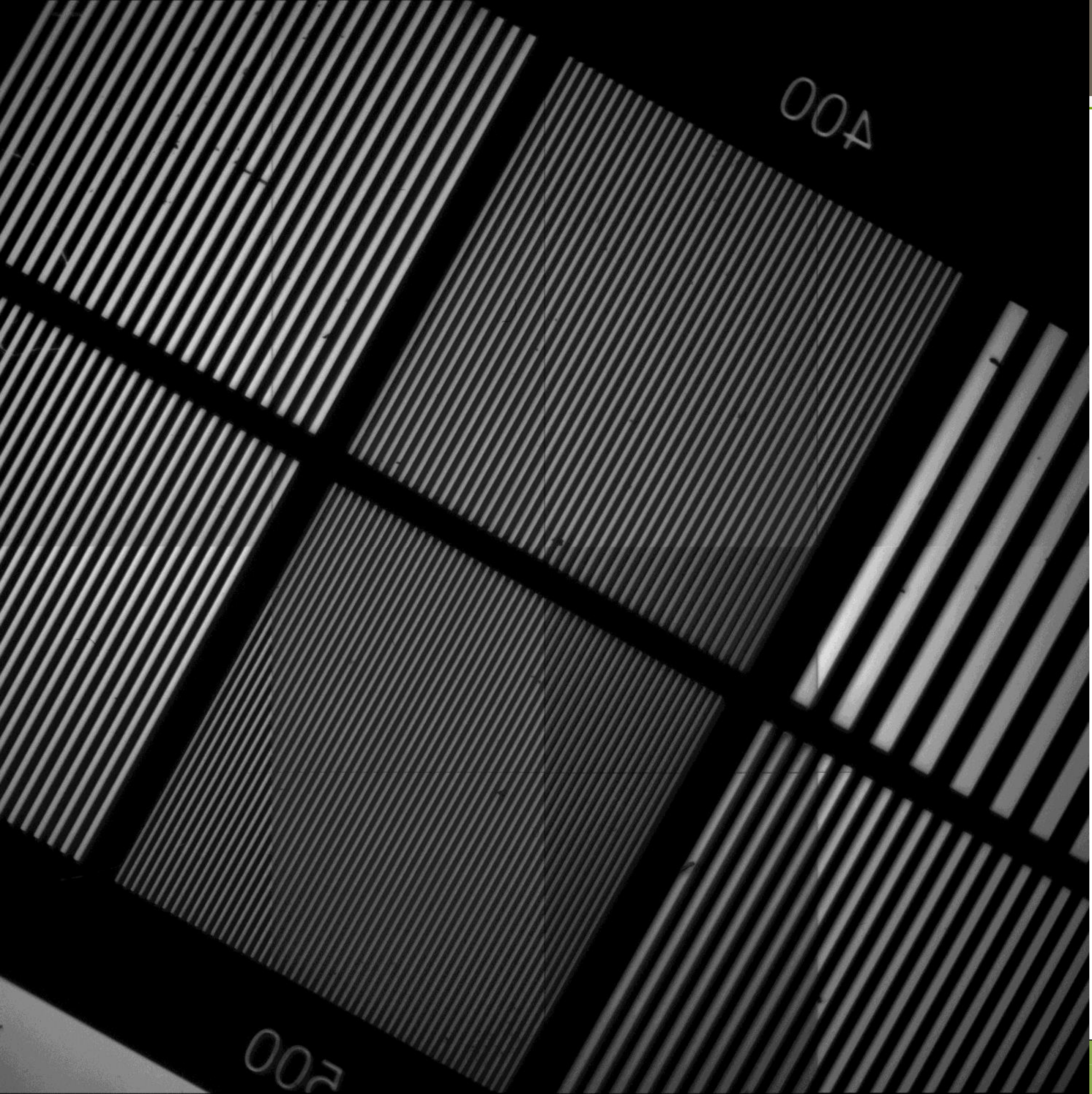


Pt1000 sensors

AlN multilayer PGA package

4kx4k split frame transfer image zone

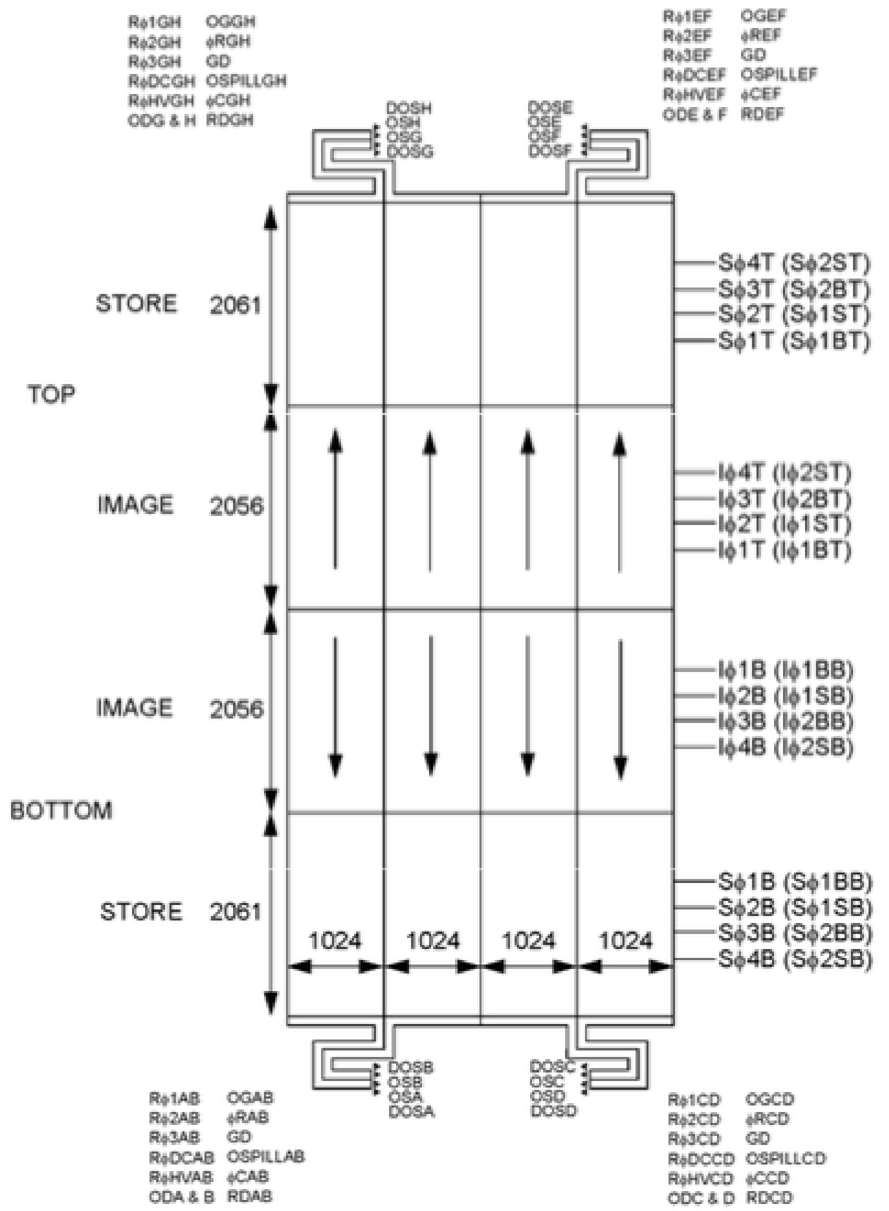




First image @ -60^{o}C

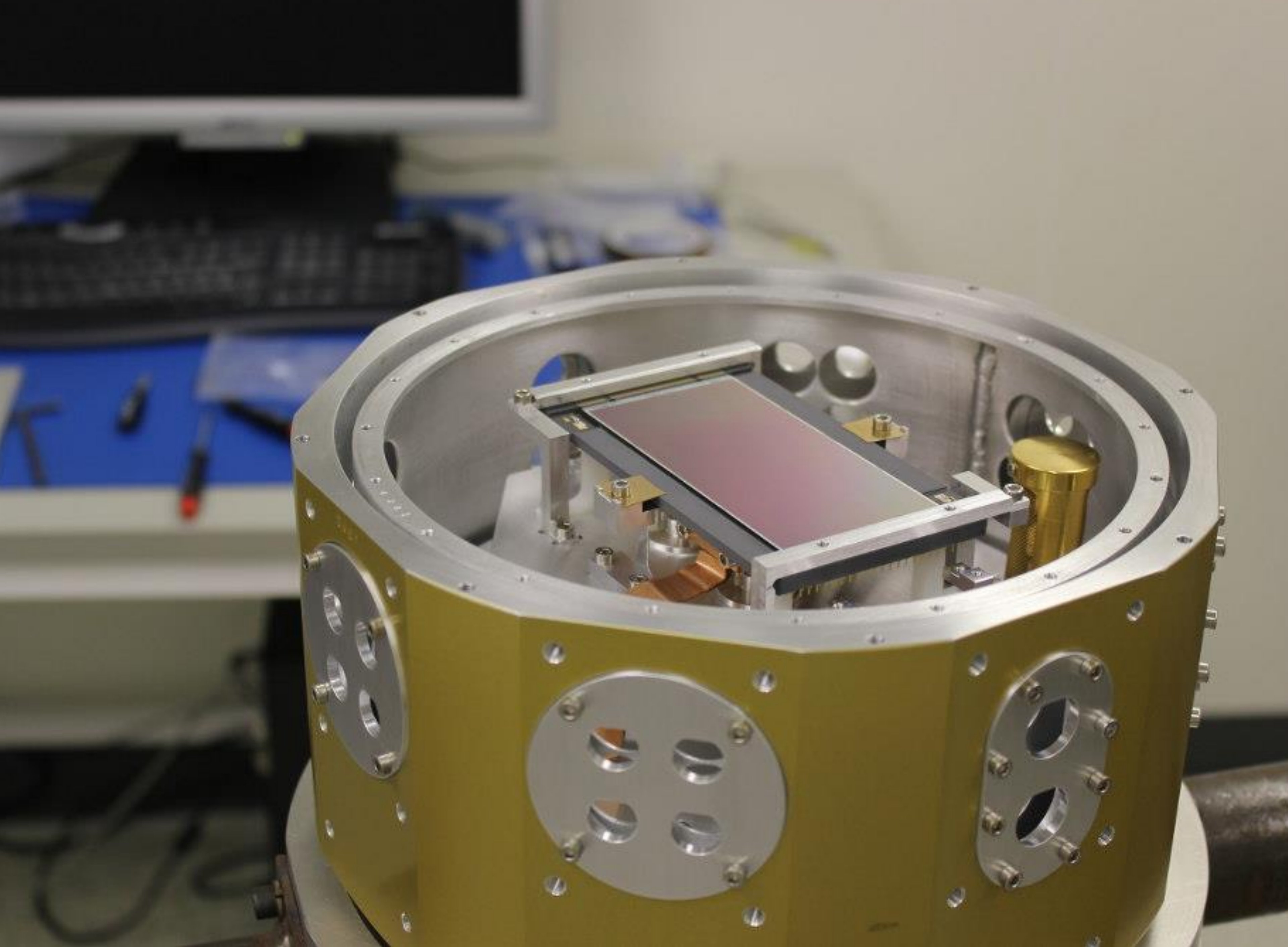
image courtesy e2v

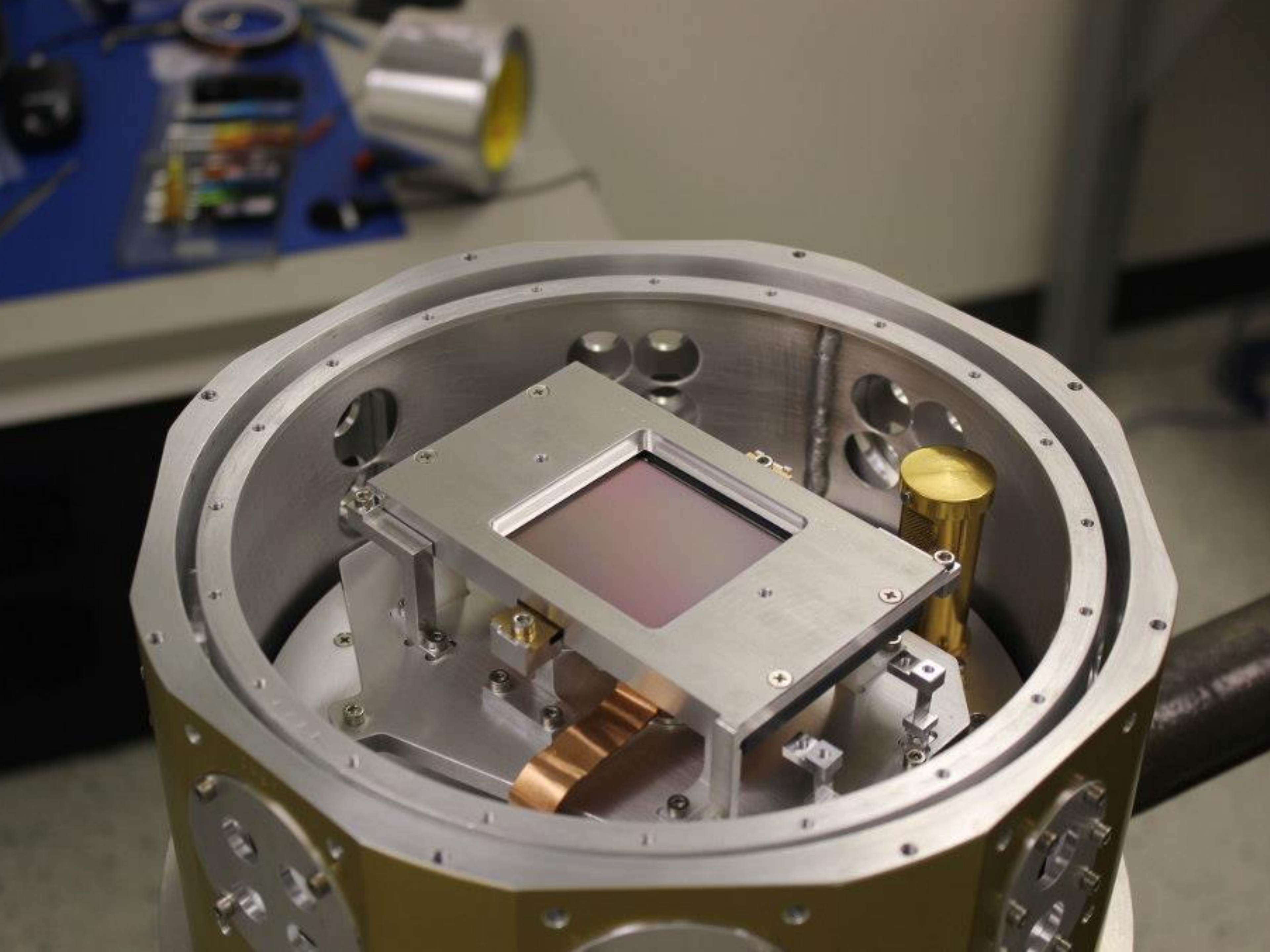
E2V CCD 282

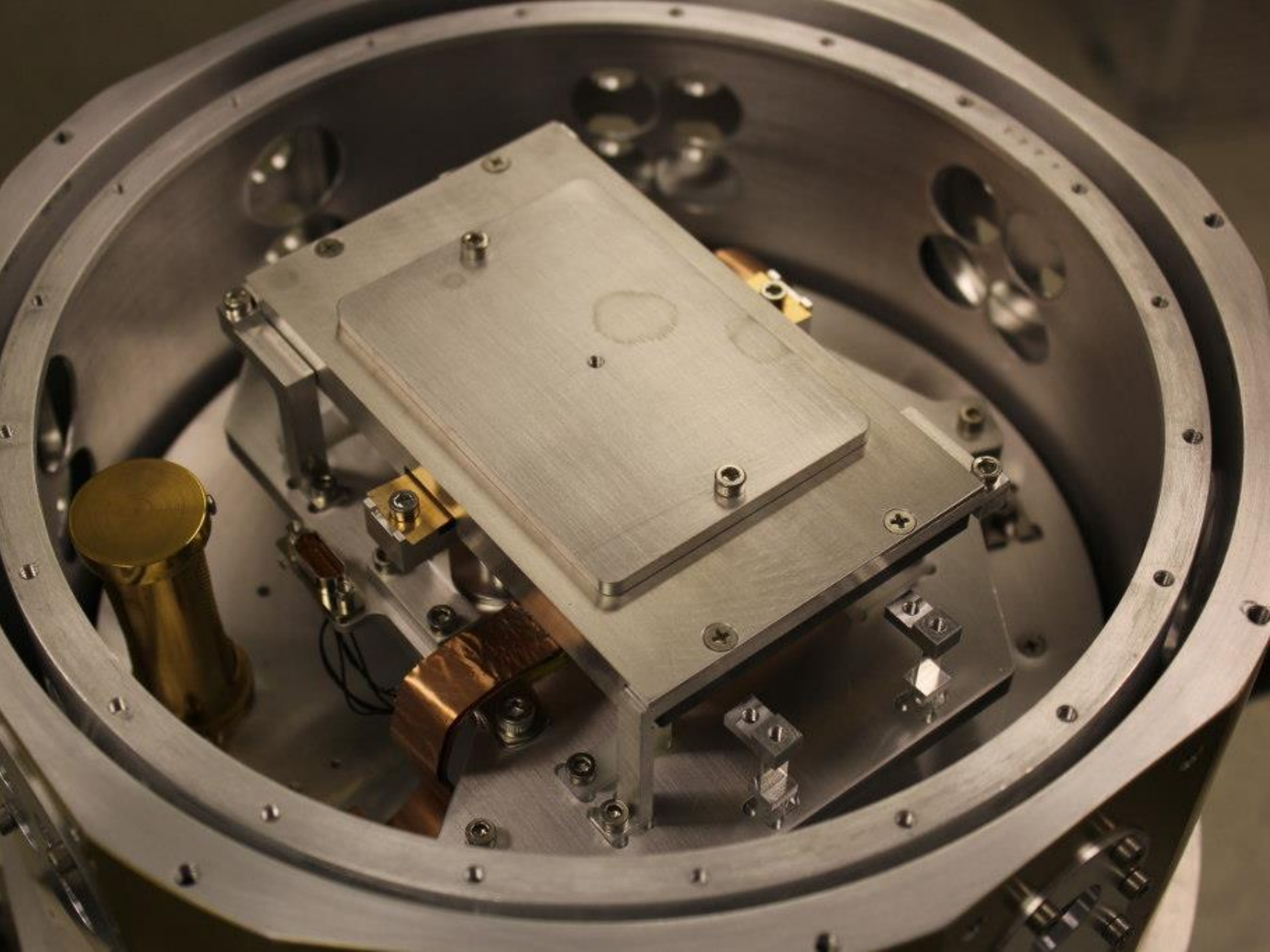


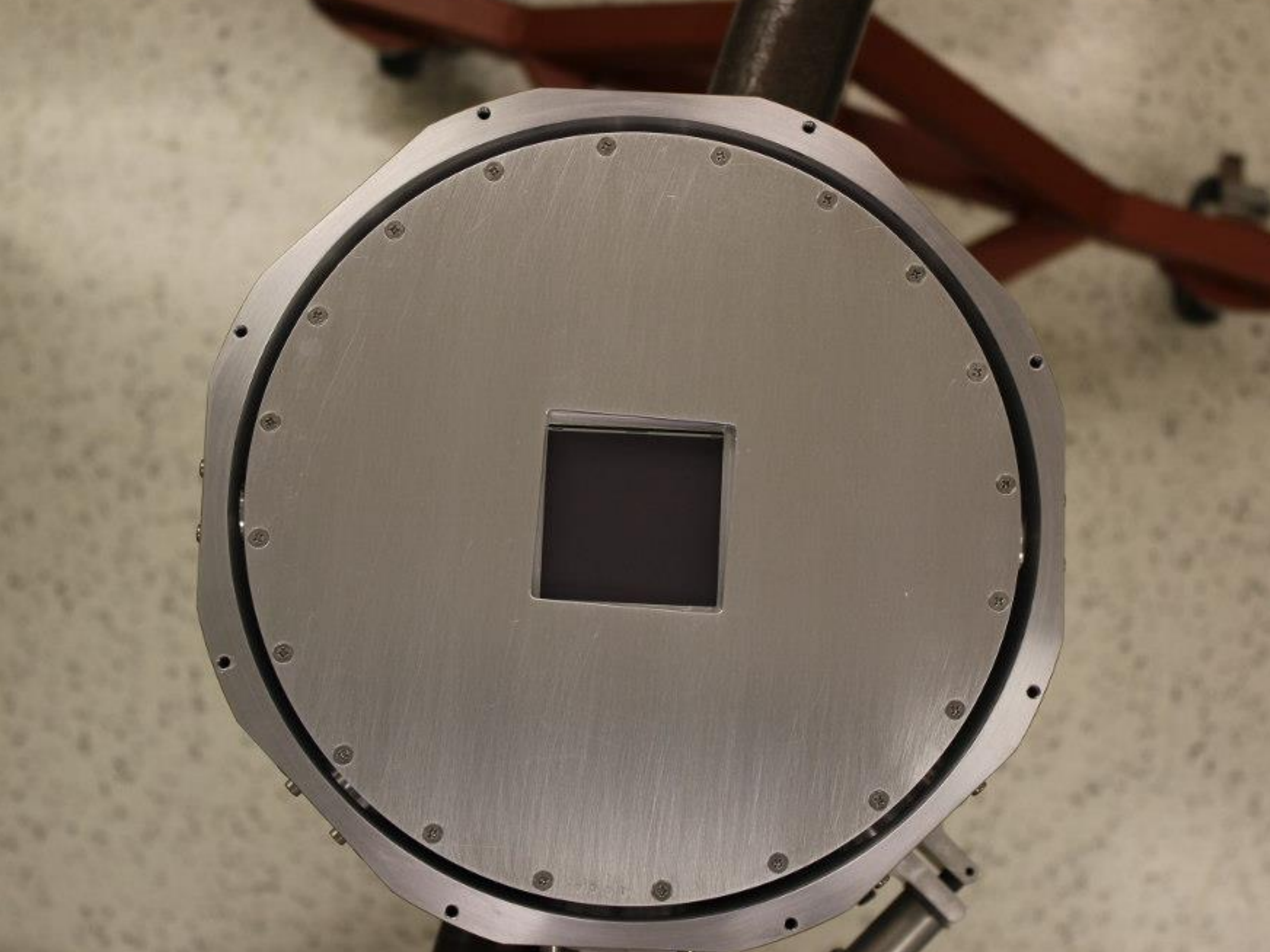
Bracketed names indicate image and store phase functions, barrier or storage, when operated 2-phase.

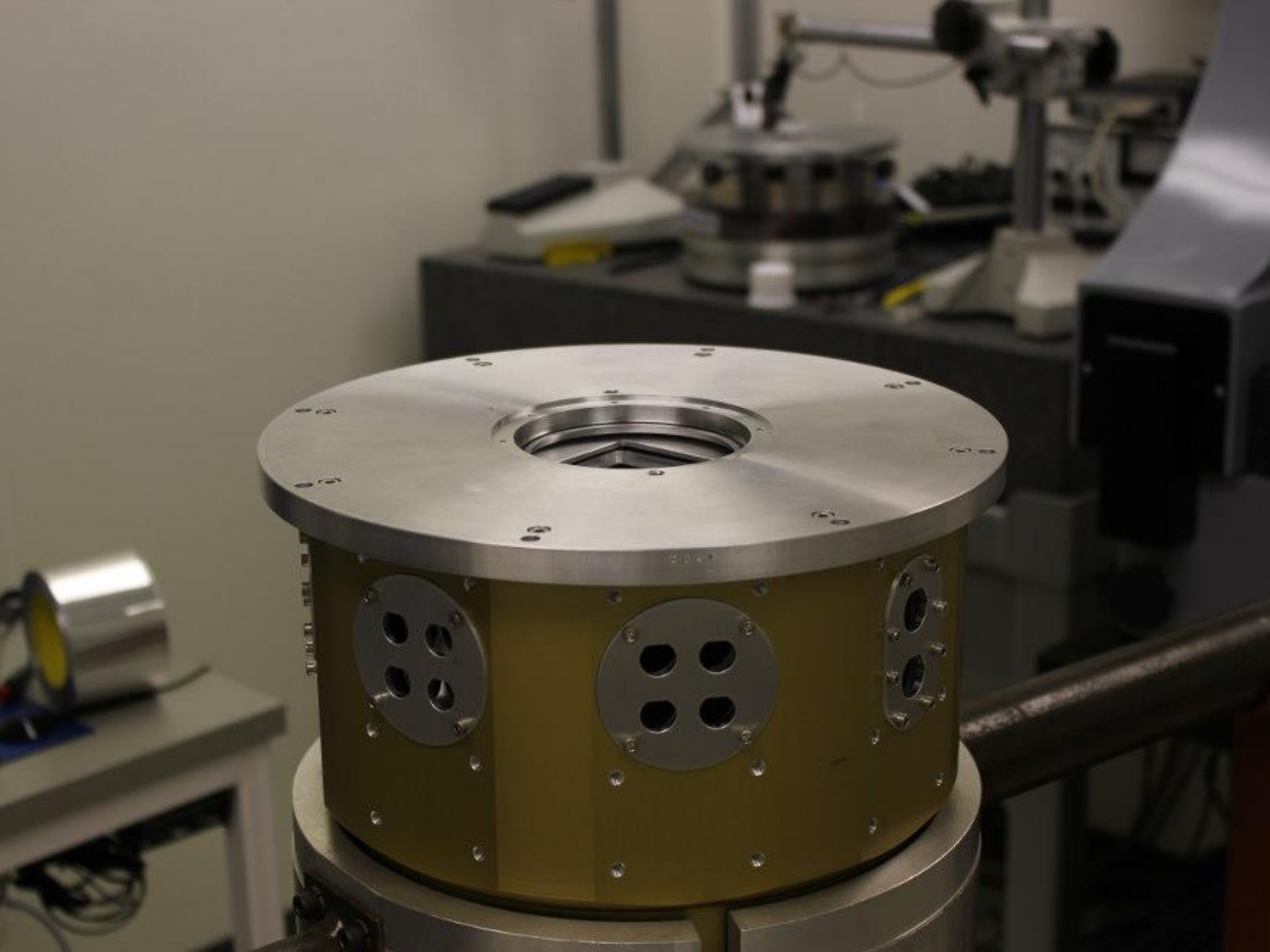
FIGURE 4: Chip schematic











MOVIES

Acquisition
Technical Choices and Trades
Instrument Design
Costing, Schedule & Risk

MOVIES Team

2015-09-30

ACQUISITION

Rapid, rapid, rapid

- Rely on identifying expected field during slew of telescope (as well as any configuration)
  - Implies that guide star boxes are defined
- Operate A&G cameras continuously
- Once telescope settles, ~1 sec required to identify guide object(s) and offset telescope
  - Longer if must identify faint target object
- Place A&G mirror in field stop position

Simple Interfaces
Solid-state OIWFS

- All offsets/guiding accomplished through M2
  - Simplifies interaction with the telescope.
- All actions performed by software whenever possible
  - "Single-step" possible of course
- T/T from at least one A&G band, possible multiple objects
- Software, phase diversity for focus
  - Relies on at least two cameras. NOT high speed
- Baseline cameras can operate full field at > 20 Hz
  - Multiple options, including utilizing A&G for calibration purposes

TECHNICAL CHOICES AND TRADES

Trades

- Blue Performance
- GCAL suitability
- Acquisition
- EMCCDs

Blue Performance

- Fundamentally, decide on the blue limit
  - Competing requirements/desires
  - Small changes have large impact due to 'steep cliff' of detector and coatings
    - Avoid a 3rd arm
  - Reaching into the blue opens up science
- Final decision based on where we felt we could push and retain some throughput

GCAL Suitability

- No surprises; GCAL will meet needs
  - Eliminating requirement for MOVIES built-in calibrations
- Require pretty standard extended sources
  - Flats
  - Arcs
- GCAL provides all the necessary calibration sources, levels and technical needs
  - Multiple simultaneous sources is advantageous
  - Flats will likely require range of ND filters
- Possible optimizations
  - DIffuser

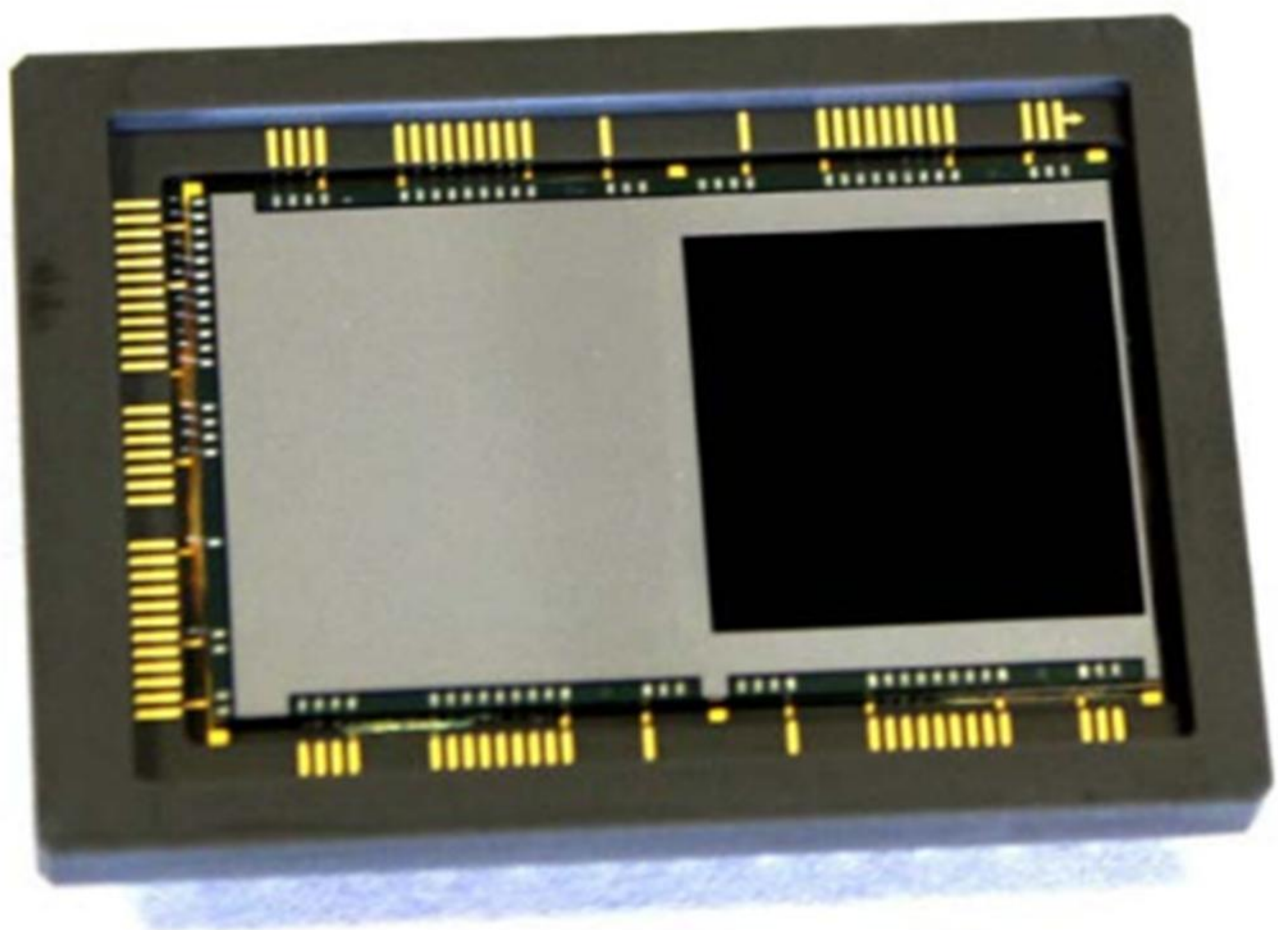
Acquisition

- Covered in separate section

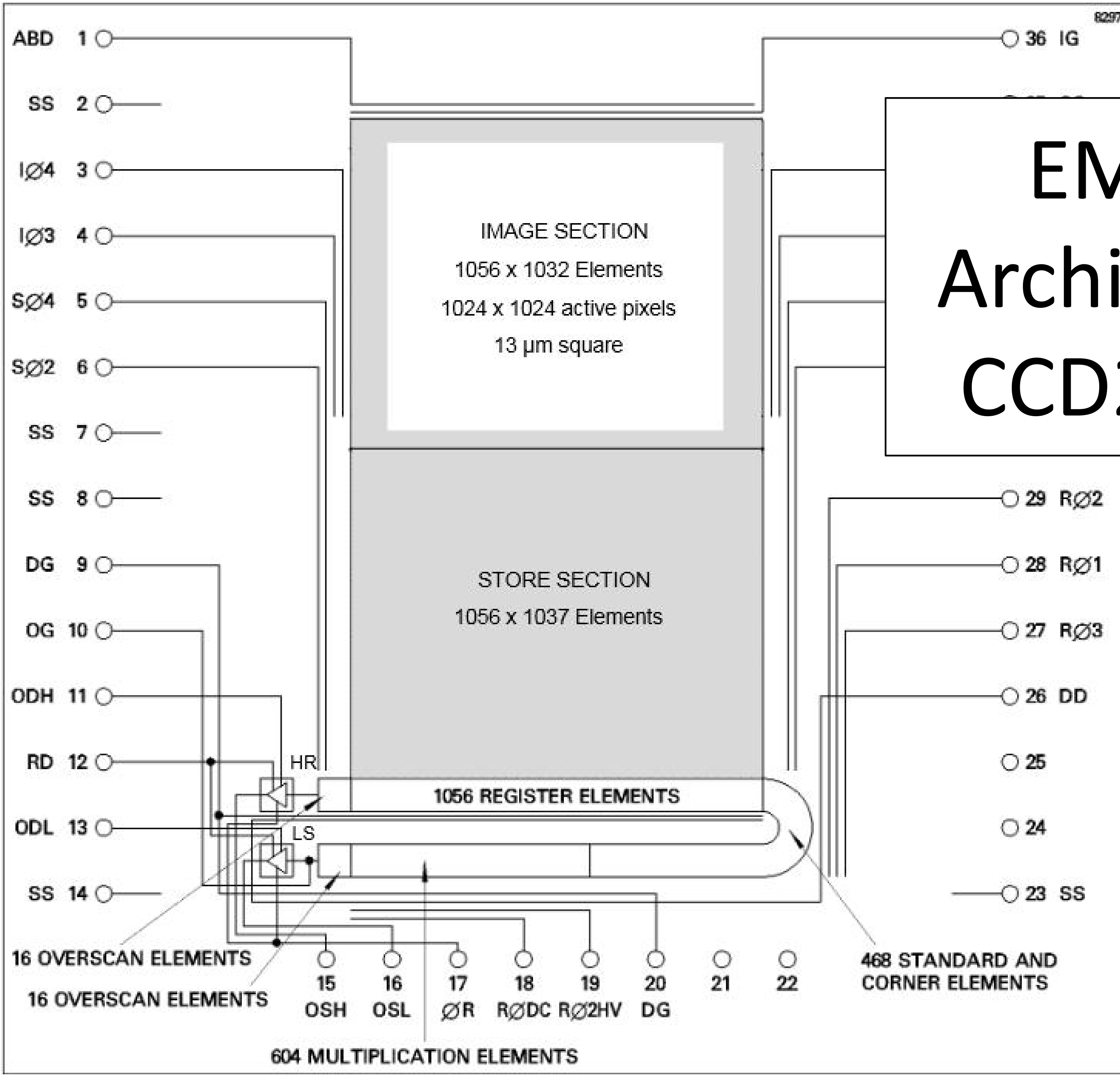
EMCCDs (Acqusition)

- Differentiate between acquisition and science
  - Acquisition EMCCD cameras are NOT considered a technological risk and are the baseline choice for the VIS acquisition arms
  - Commercial models with E2V CCD201-20 exist from multiple vendors (Andor, Nuvu, Princeton Instruments)
  - Multiple (3.5) modes
    - Photon counting (require < ~0.3 e/s/frame)
    - "Linear Mode"
    - Classic (no gain)
      - EMCCD amplifier (10's Mpixel/sec)
      - Classic amplifier (< 1Mpixel/sec)

CCD201-20



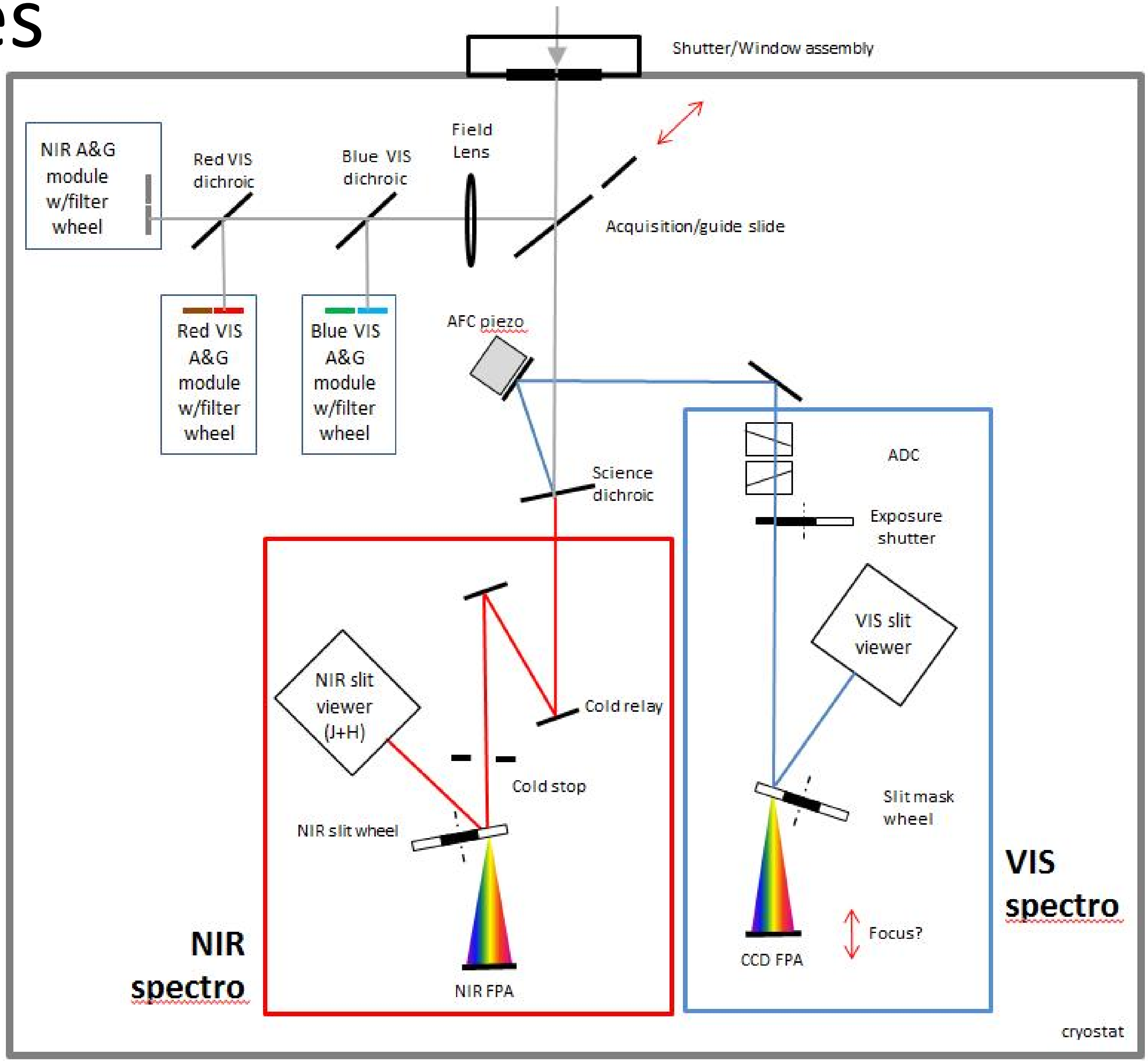
EMCCD Architecture CCD201-20



Spectrograph EMCCD

- Covered by UdeM
- Can enable additional exciting science
- As spectrograph, pixel fluxes lower, hence photon counting mode available

Choices


Shutter/Window assembly
NIR A&G module w/filter wheel
Red VIS dichroic
Blue VIS dichroic
Field Lens
Acquisition/guide slide
Red VIS A&G module w/filter wheel
Blue VIS A&G module w/filter wheel
AFC piezo
Science dichroic
ADC
Exposure shutter
VIS slit viewer
Cold relay
NIR slit viewer (J+H)
Cold stop
NIR slit wheel
Slit mask wheel
VIS spectro
NIR spectro
NIR FPA
CCD FPA
Focus?
cryostat

Choices (1)

- Simple
  - Minimise mechanisms
  - Minimal modes
  - Minimal arms/optical paths
    - Minimises flexure
    - Simplifies calibrations
  - Minimal electronics
  - OIWFS accomplished ‘on chip’
    - T/T/F

Choices (2)

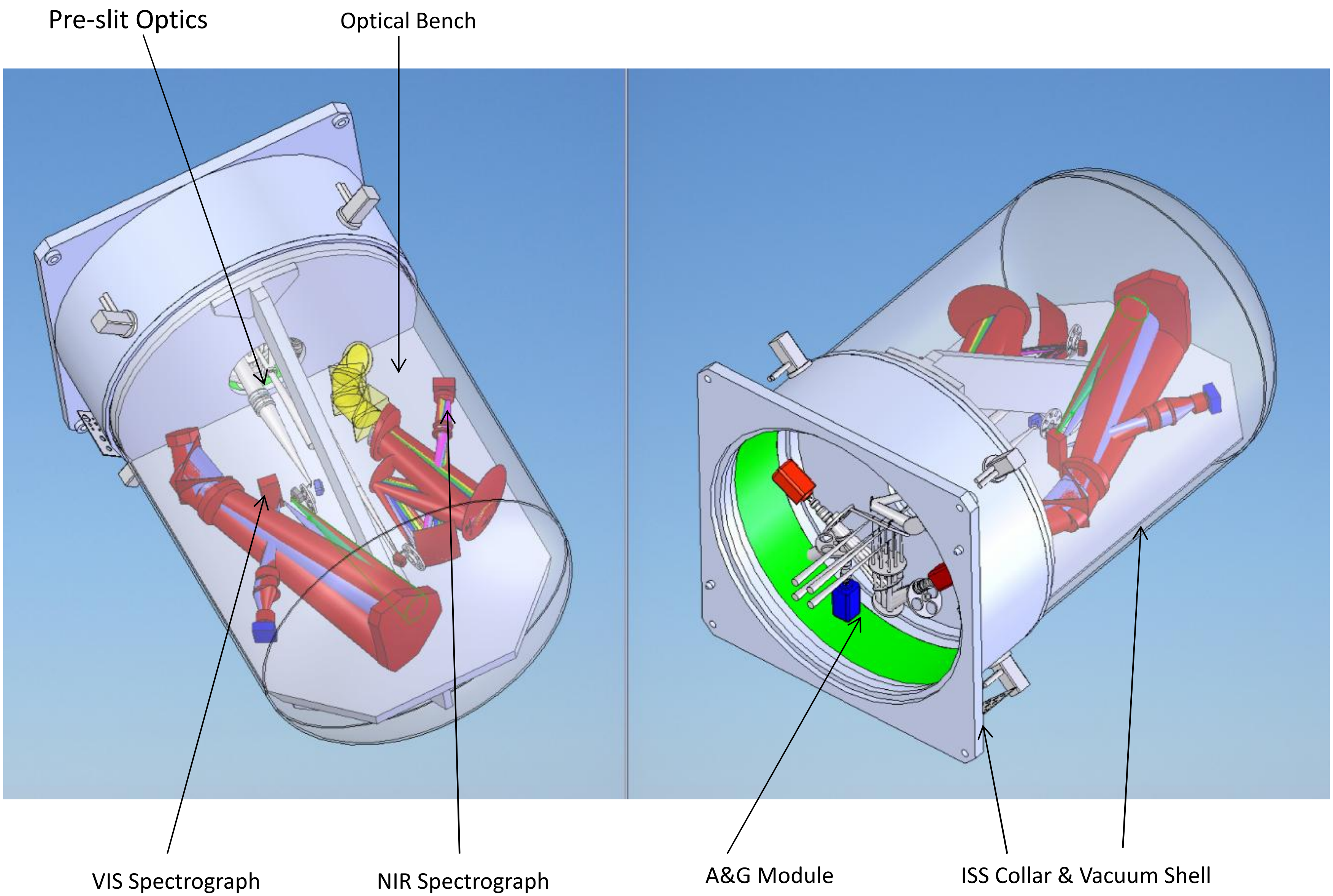
- Robust
  - Minimal mechanisms
  - Re-use of heritage mechanisms
  - Minimal modes
  - Fully cryostat

Choices (3)

- Stable
  - Minimal modes
  - Resources (space and mass) can go towards ensuring physically stable
  - All cryogenic/thermally controlled alleviates thermal changes

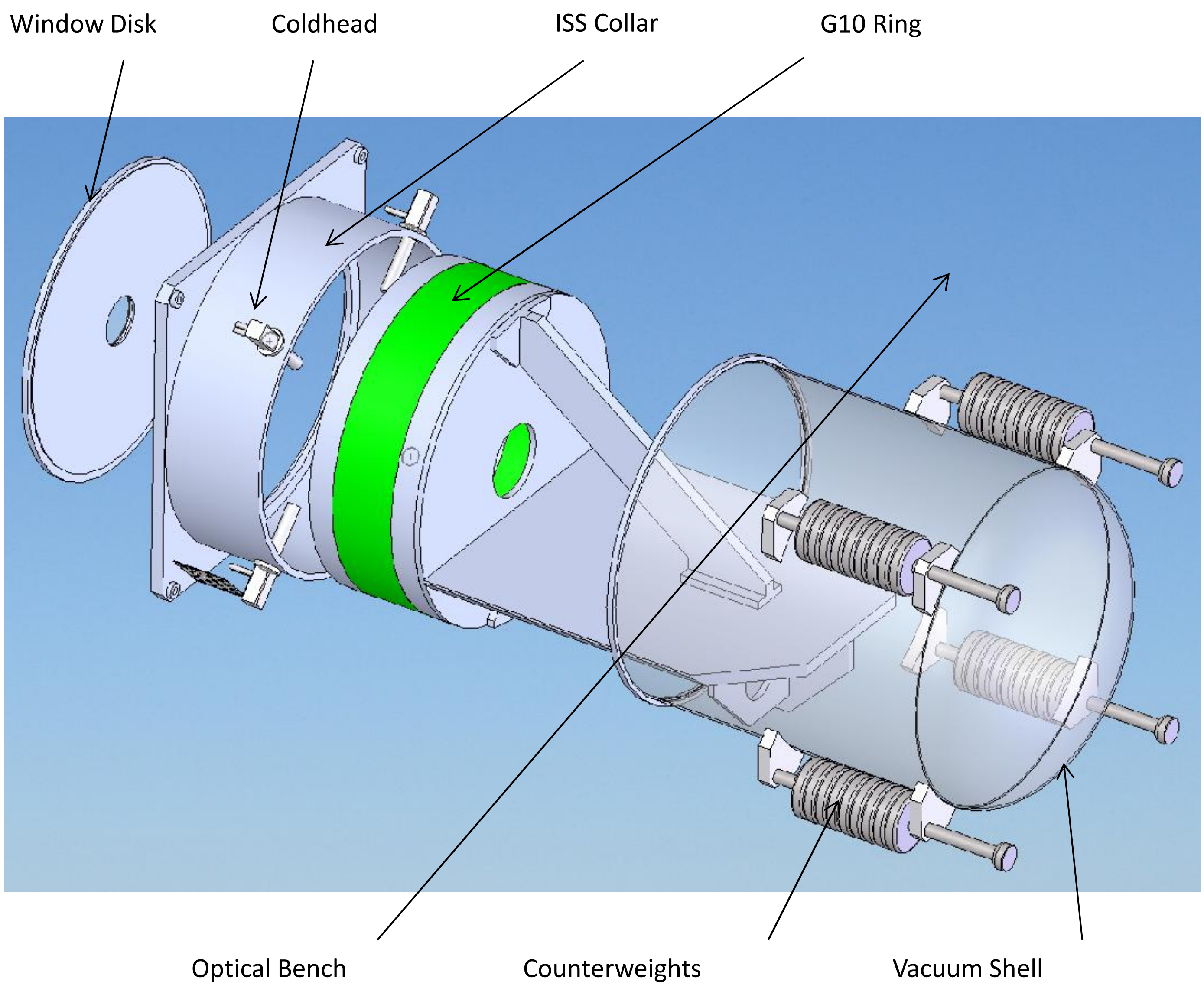
INSTRUMENT DESIGN

Fully Cryo

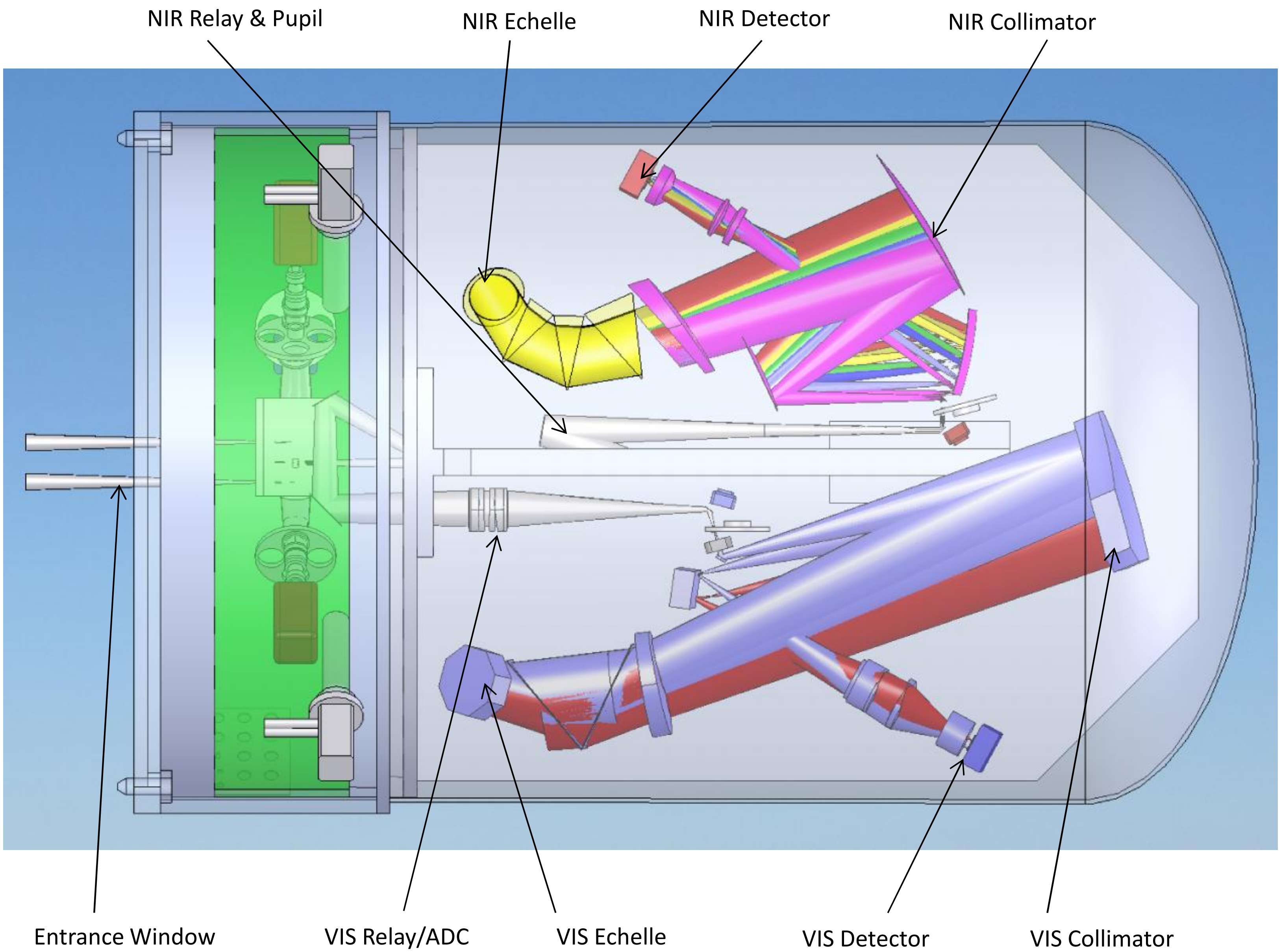


Pre-slit Optics
Optical Bench
VIS Spectrograph
NIR Spectrograph
A&G Module
ISS Collar & Vacuum Shell

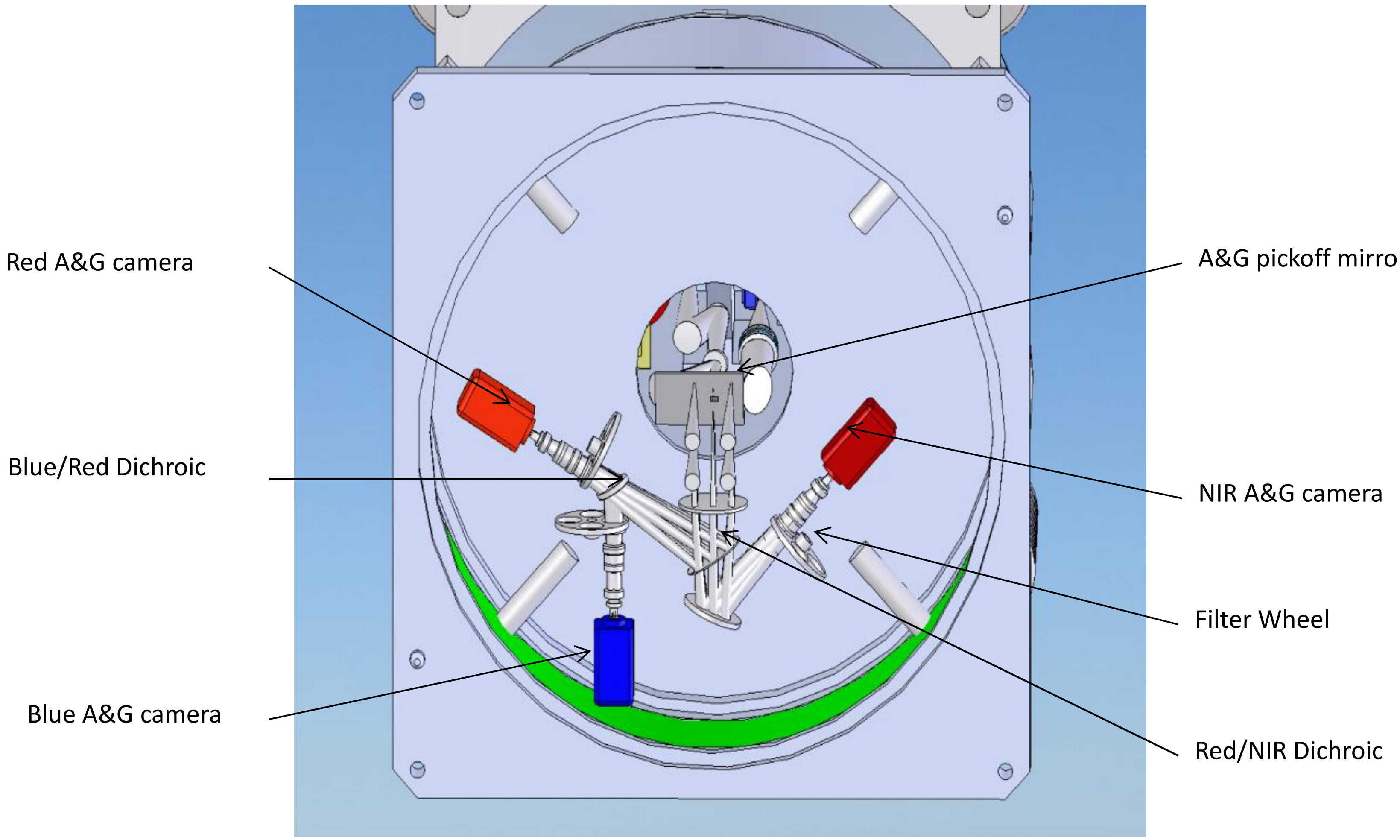
Main Sections



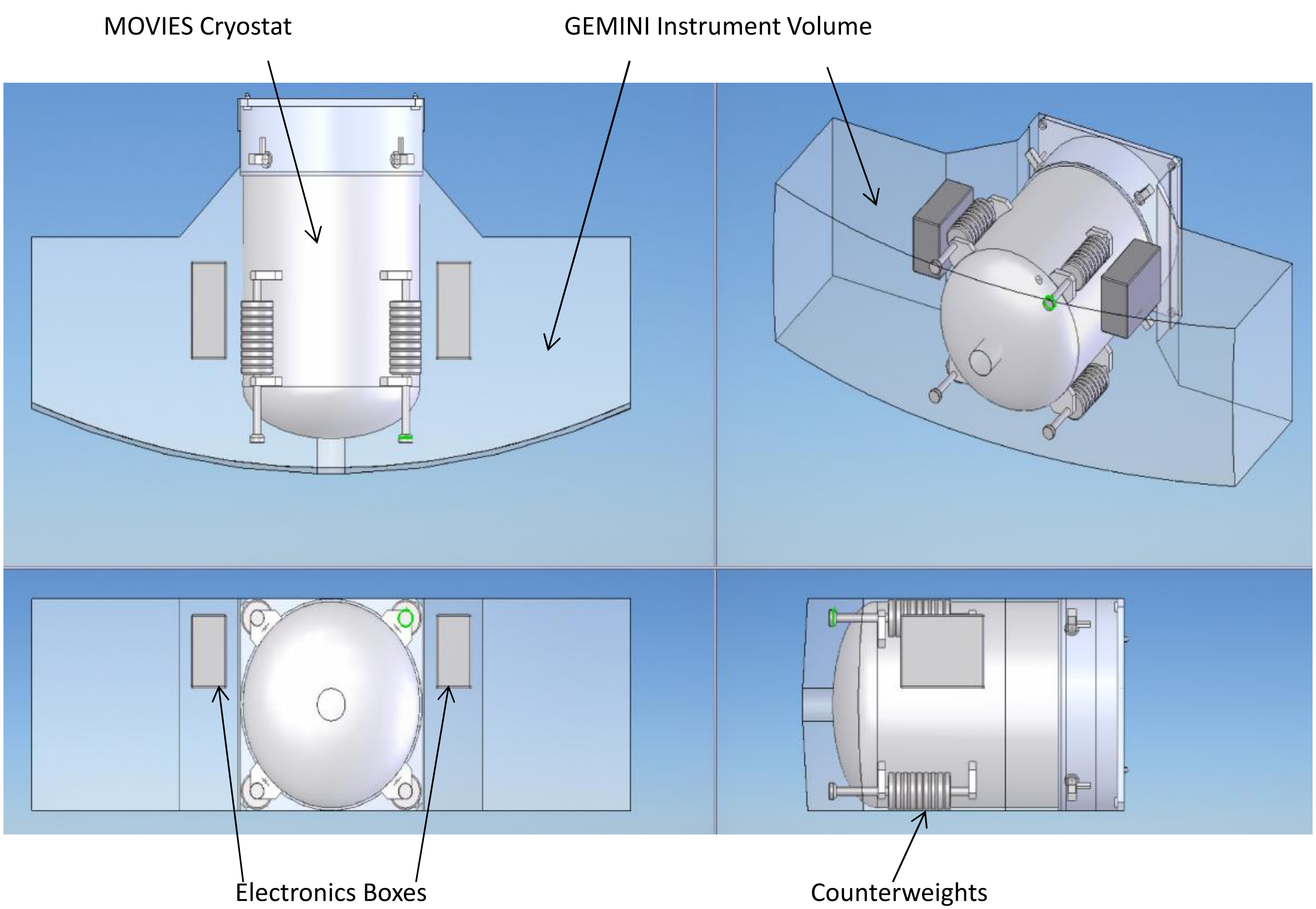
Bird's Eye View



A&G section
~-20C



Compact
Meets Gemini Space Envelope



BACKUP/SUPPORT SLIDES

OSU Cryogenic Instruments

- **OSIRIS** NIR imager and spectrograph
  - 1990, now on SOAR telescope
- **TIFKAM** NIR imager and spectrograph
  - Kitt peak MDM 2.4 meter
- **ANDICAM/DANDICAM** NIR & VIS imager
  - CTIO and SAAO
  - Long life IR dither mirror

OSU Cryostat Design Heritage

– Integrated thermal, structural, opto-mechanical modeling
– LN2 cooling, cryocoolers
– vacuum techniques
– Cooldown and Warmup methods
– Instrument safety, pressure relief, transient thermal stress, over-temp safety,

OSU Cryogenic Optics

- Lens & mirror mounting for cryo service
- Differential contraction managed with flexures
- Predictable cold alignment
- Warm & cold opto-mechanical performance and alignment modeling
- Lens cooling safety, transient thermal analysis

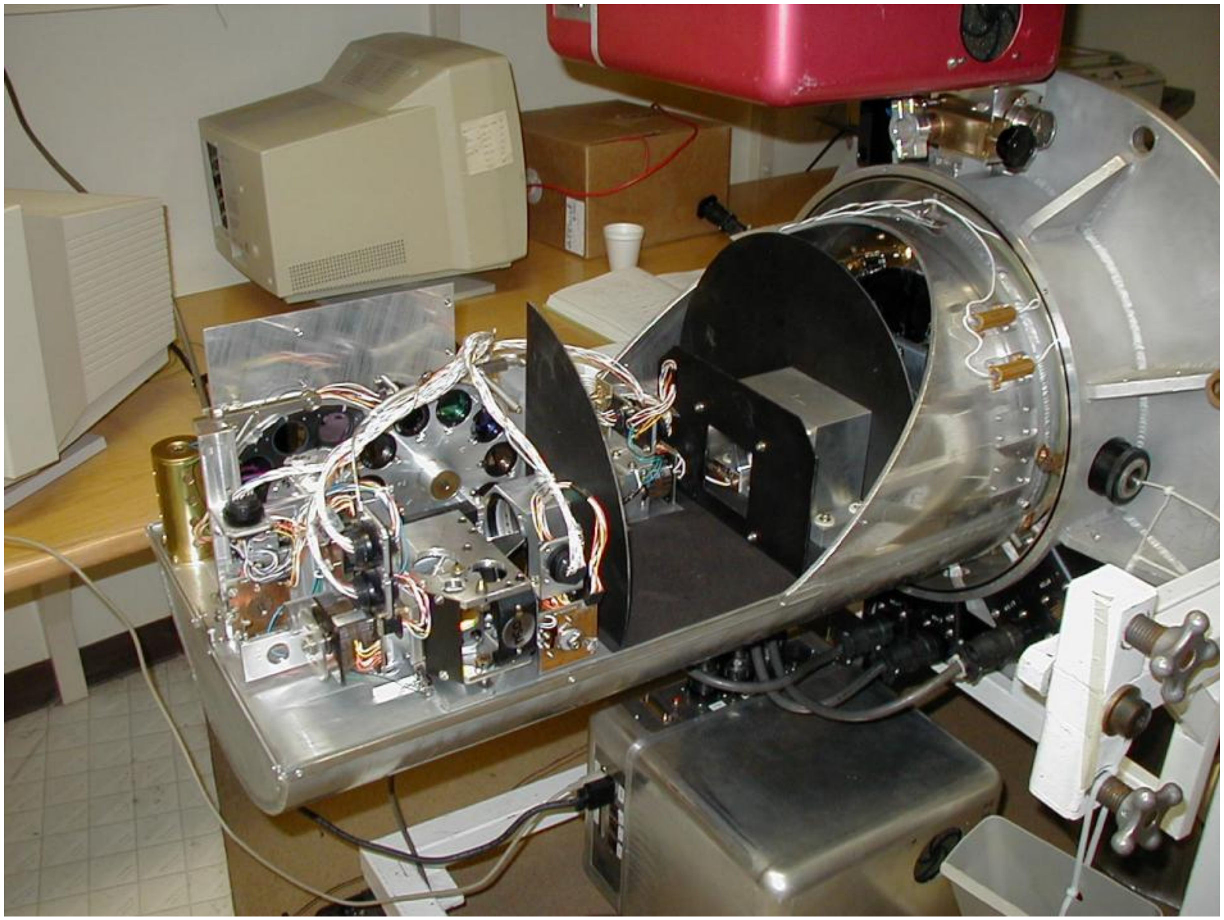
OSU Cryogenic Mechanisms

- Cryogenic mechanisms
  - Simple bag of tricks and materials used
  - Cold stepper motors, cryo ball bearings
  - VESPEL SP3 Moly-disulfide filled polyimide for sliding friction. Incredibly effective at high contact pressures and sliding velocities

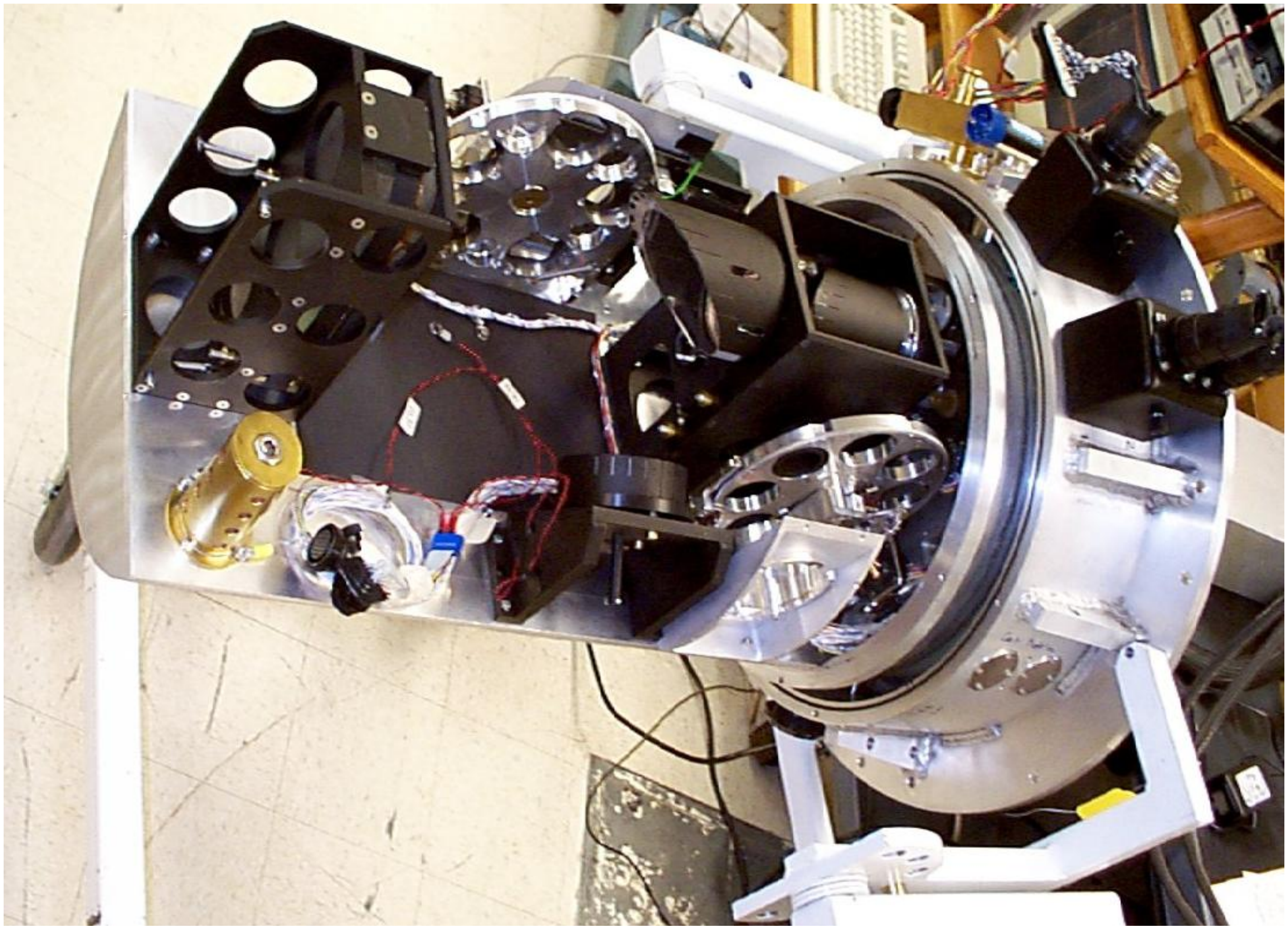
OSU Cryogenic Filter Wheel Design Features

- Zero failures: 11 filter or slit wheels on 4 instruments in service for ~ 20 years
- Roller/flexure tangent arm detents used for precise positioning. Repeatability ~ 2-3 microns at slit
- Micro-switches in grooves provide absolute position encoding

OSIRIS cryostat



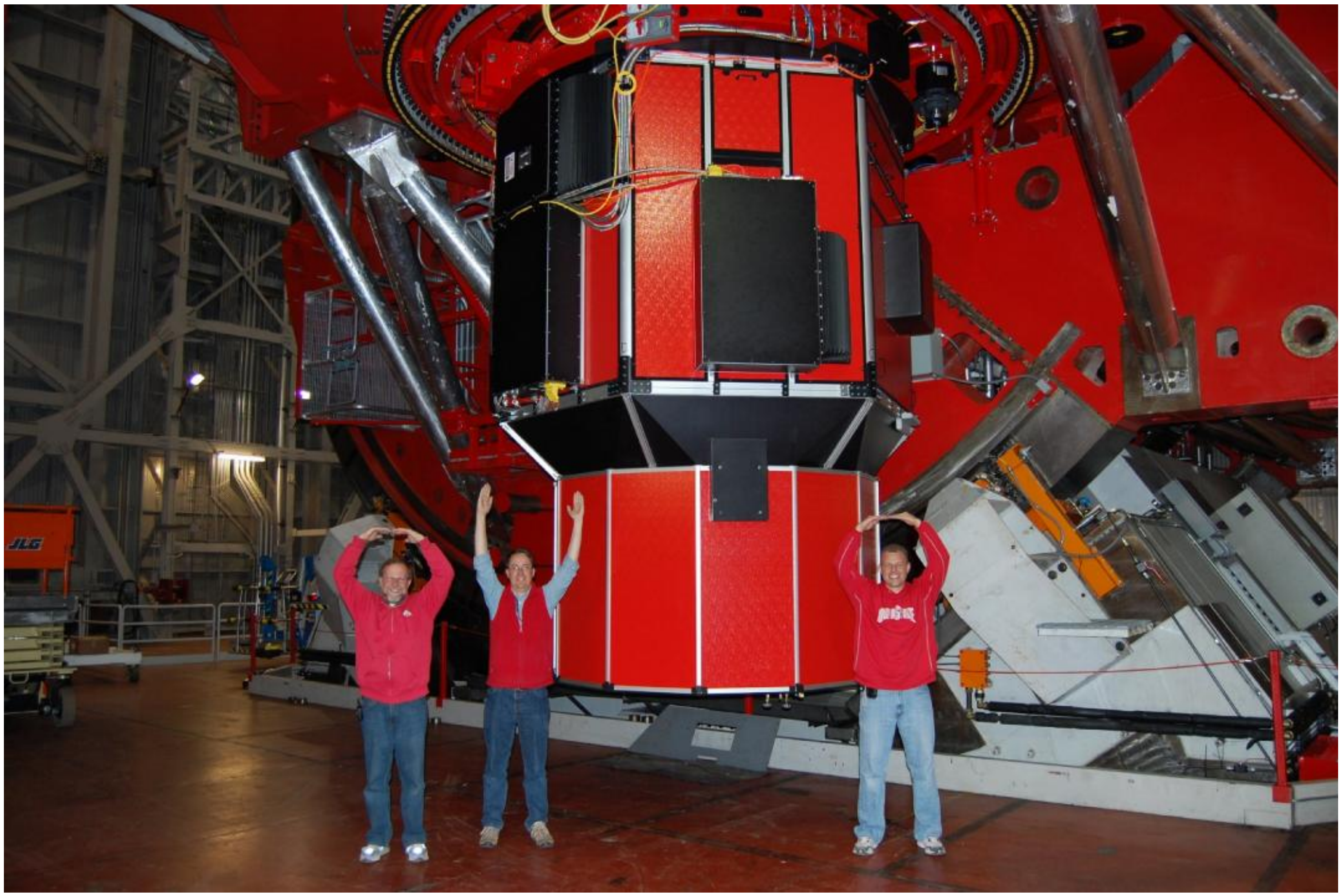
ANDICAM cryostat



OSU 8 meter Instruments

- MODS1 and MODS2 are both in operation at LBT observatory
- 2 arm optical spectrographs (U to I band)
- Imaging, grating spectroscopy, prism spectrtoscopy
- Multi-object mask change system
- 27 mechanisms in each
- Closed-loop image motion compensation

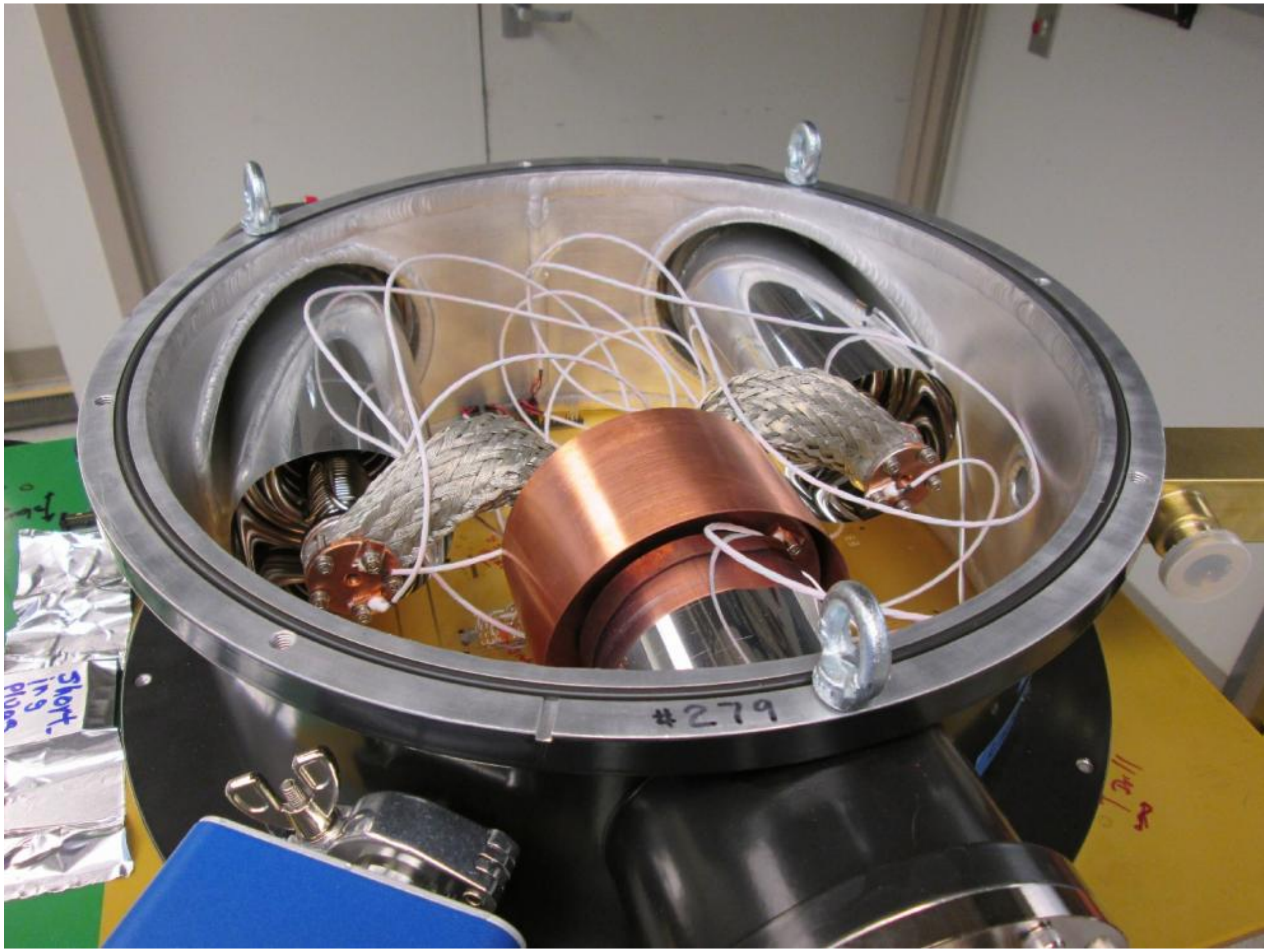
MODS Spectrtograph at LBT



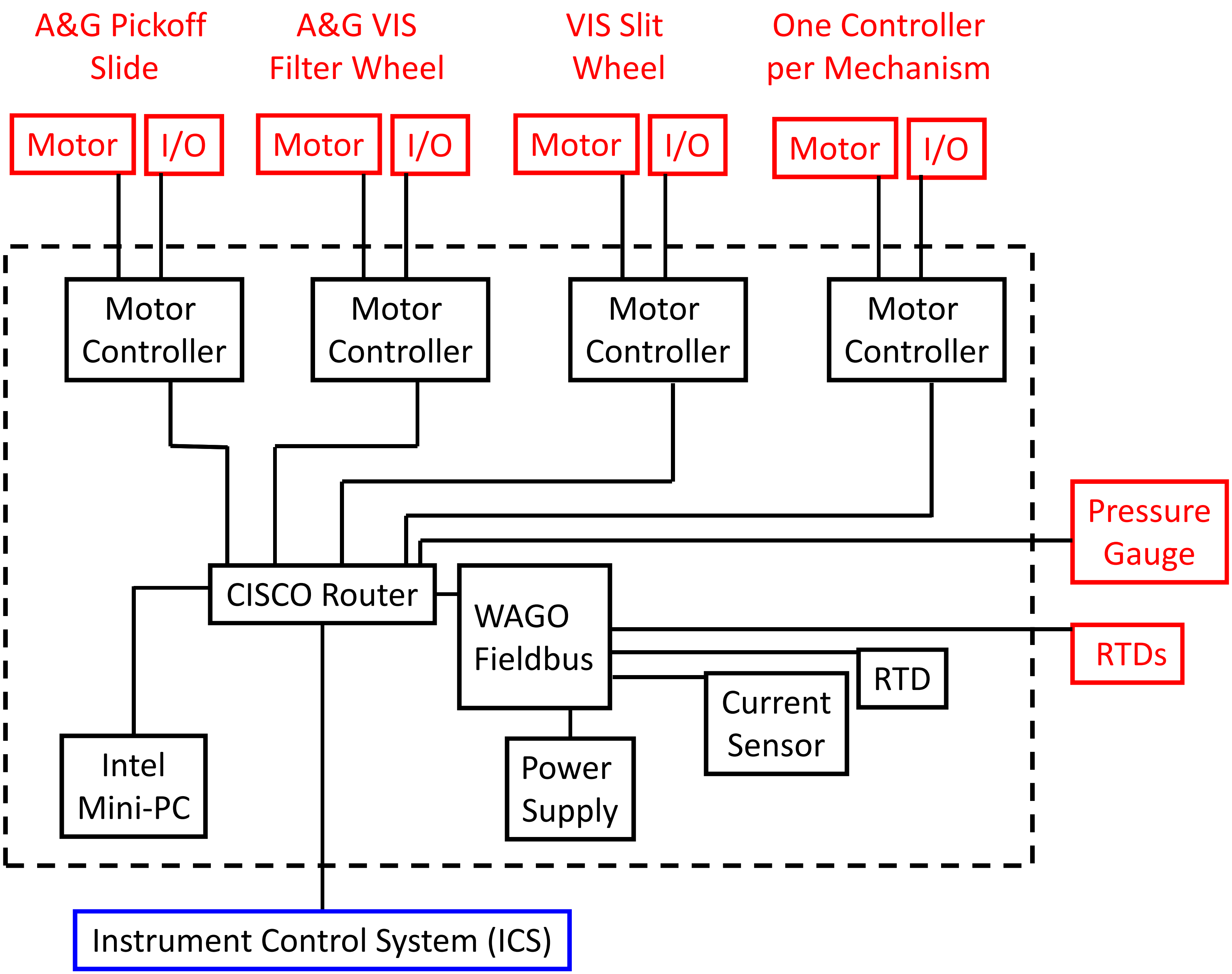
KMT cameras

- Three identical cameras for wide field imaging at three southern sites
- 320 Megapixel CCDs
- Cryocooler detector cooling
- Charcoal adsorption pump on cryocooler

KMT cryocoolers



Supplemental Slides


A&G Pickoff Slide
A&G VIS Filter Wheel
VIS Slit Wheel
One Controller per Mechanism
Motor
I/O
Motor
I/O
Motor
I/O
Motor
I/O
Motor Controller
Motor Controller
Motor Controller
Motor Controller
Pressure Gauge
CISCO Router
WAGO Fieldbus
RTDs
RTD
Current Sensor
Intel Mini-PC
Power Supply
Instrument Control System (ICS)

KMT focal plane