Optical and Infrared Instrumentation

ASIAA

Assistant Research Engineer

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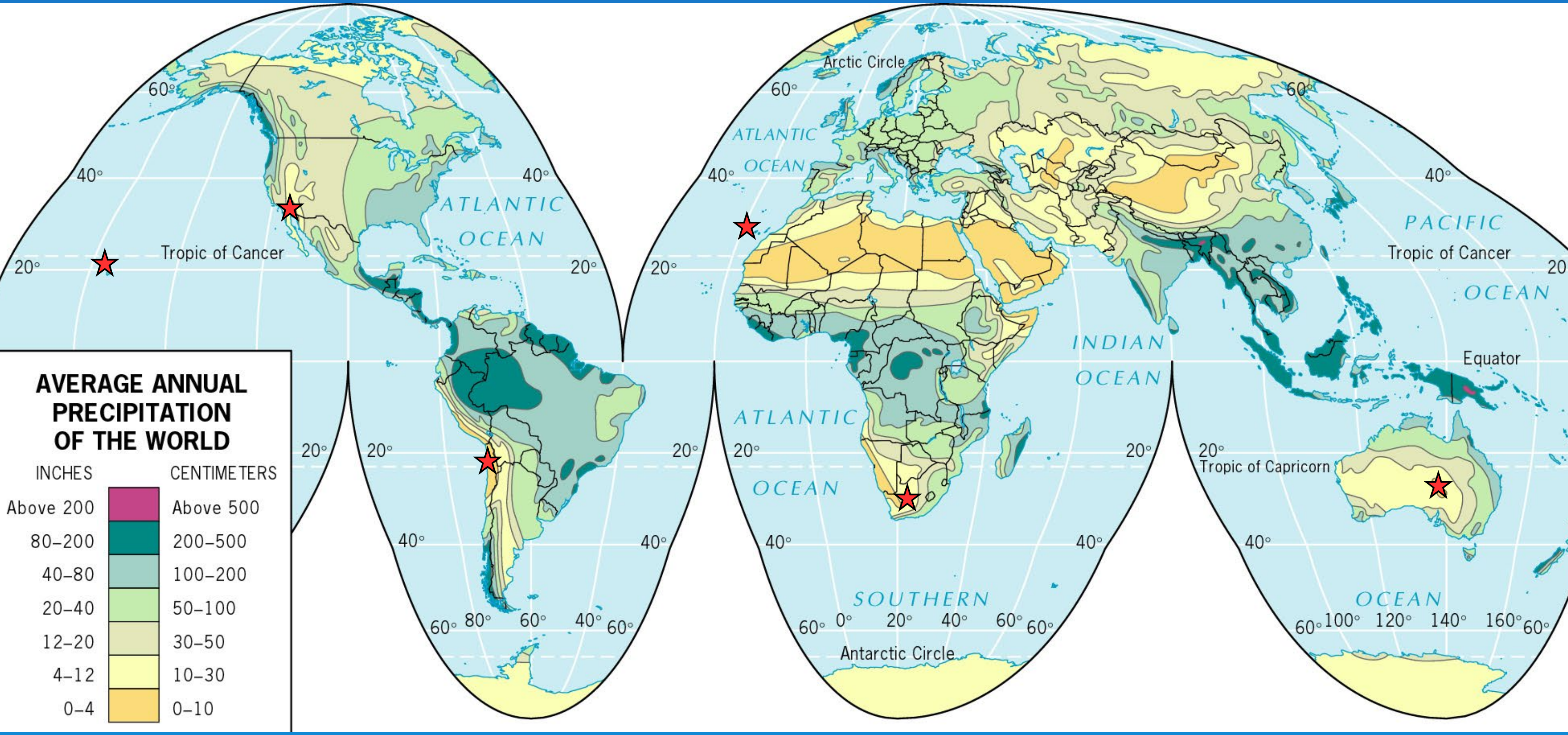
Outline

- Site for optical/IR observation
- Telescopes and sensors
- Basics for optical/IR instruments (with examples of some instruments developed at ASIAA)

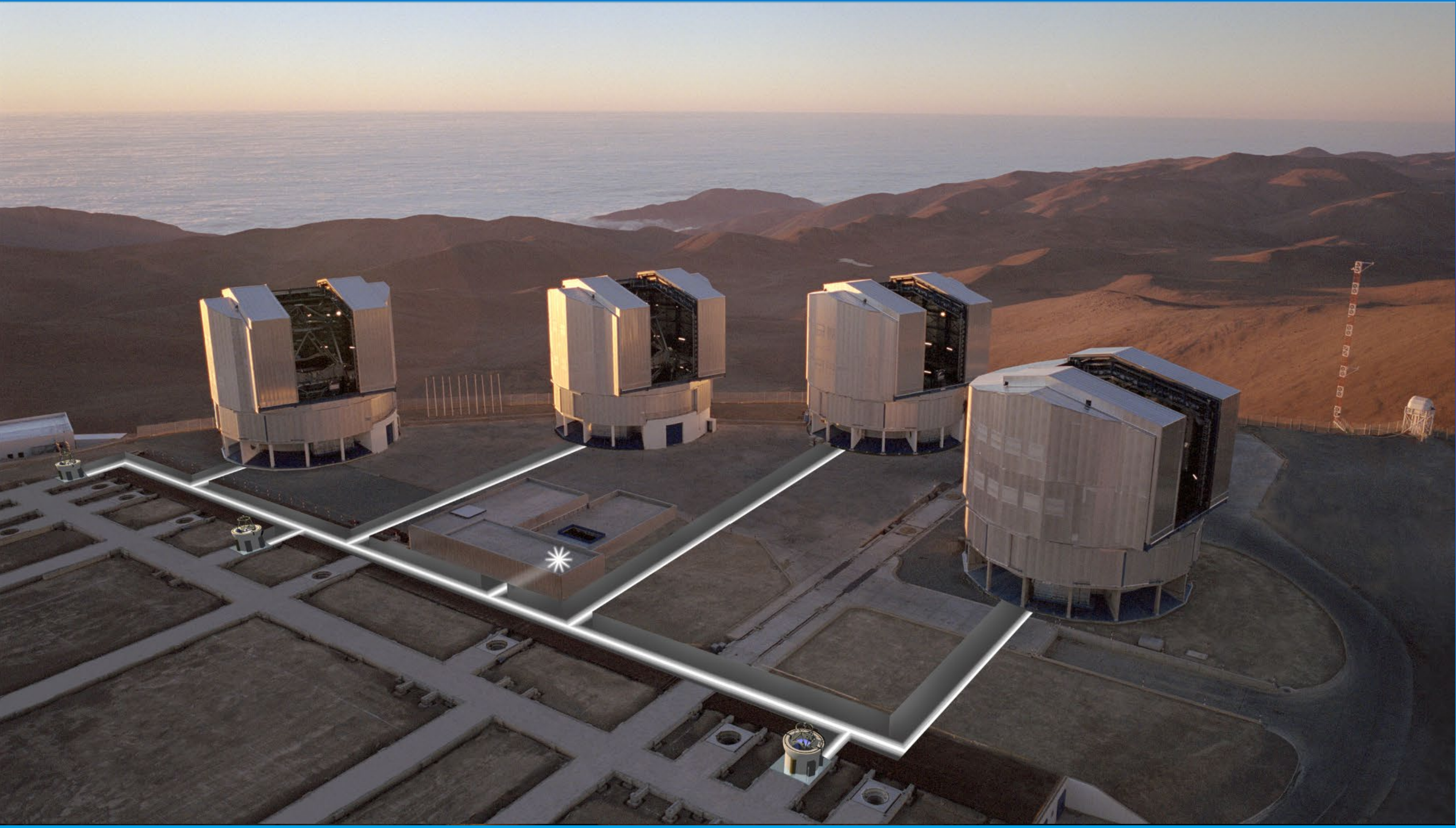
Good Observation Sites: Factors to Consider on the Ground

- Clear sky (> 250 – 300 nights/year)
- Atmospheric transmission
- Photometric condition
- Background level
- Seeing
- Others: Aerosol/dust, wind speed, seismic activity, accessibility, infrastructure

Good Sites in the World



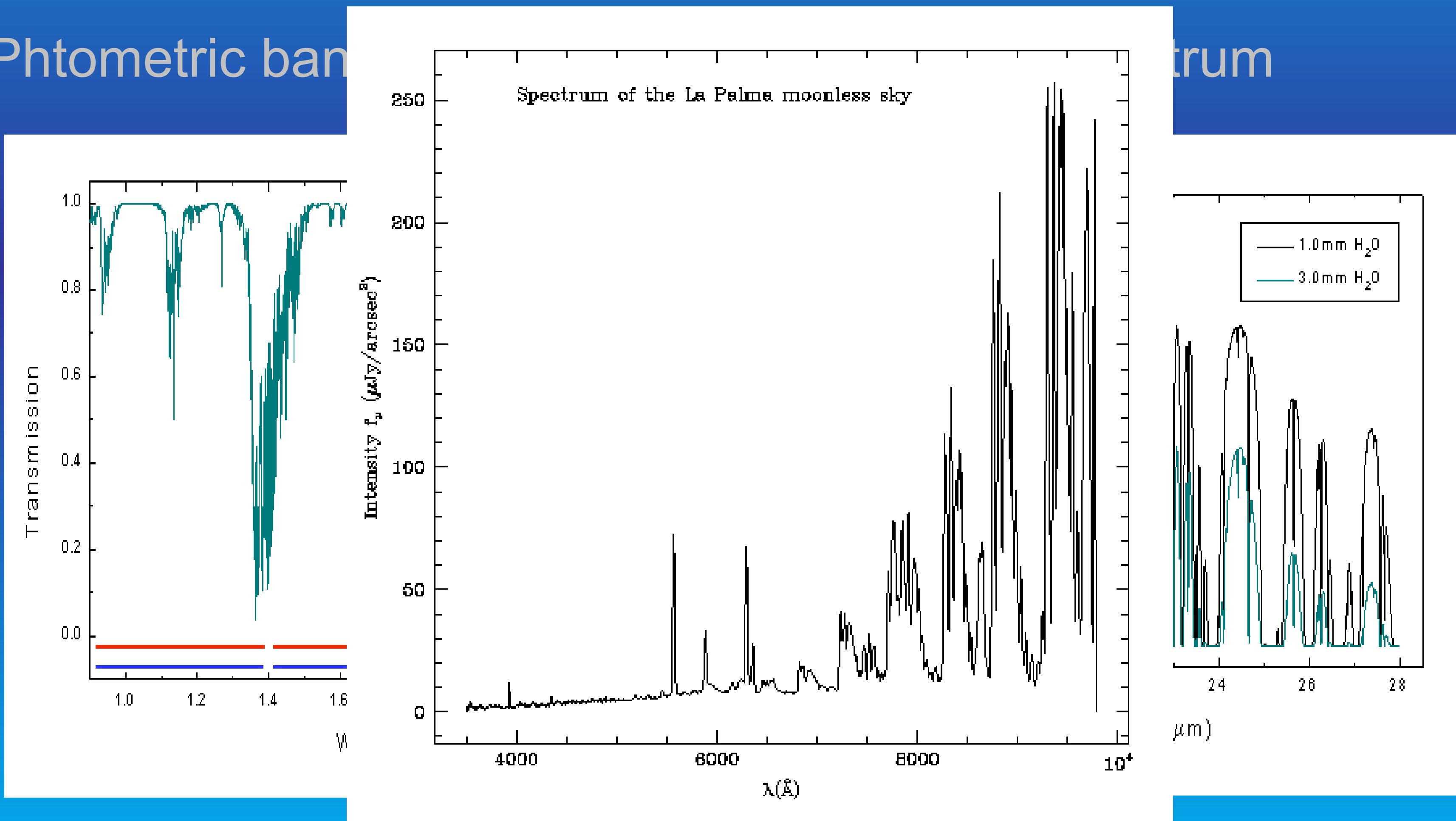
Good Sites



Low Absorption (Atmospheric transmission)

Water vapor is the most important variable factor to the site

Phtometric ban   trum



2. Low Sky background (photometric condition)

Sources of Sky Background

- Outdoor light: Na Hg lamps
  - Na 5890-6, Hg 4046,4358
- Fluorescent emission: The emission of OH radical is very important in the near infrared region. O, Na, H is important in visible.
- Thermal emission: Main source! The thermal emission from the atmosphere can be approximated with a blackbody around 250 K (peak ~ 10μm). This makes Mid-IR observations difficult!
- Scattering: Rayleigh scattering of air molecules and Mie scattering of aerosols.

Seeing (Air Turbulence)

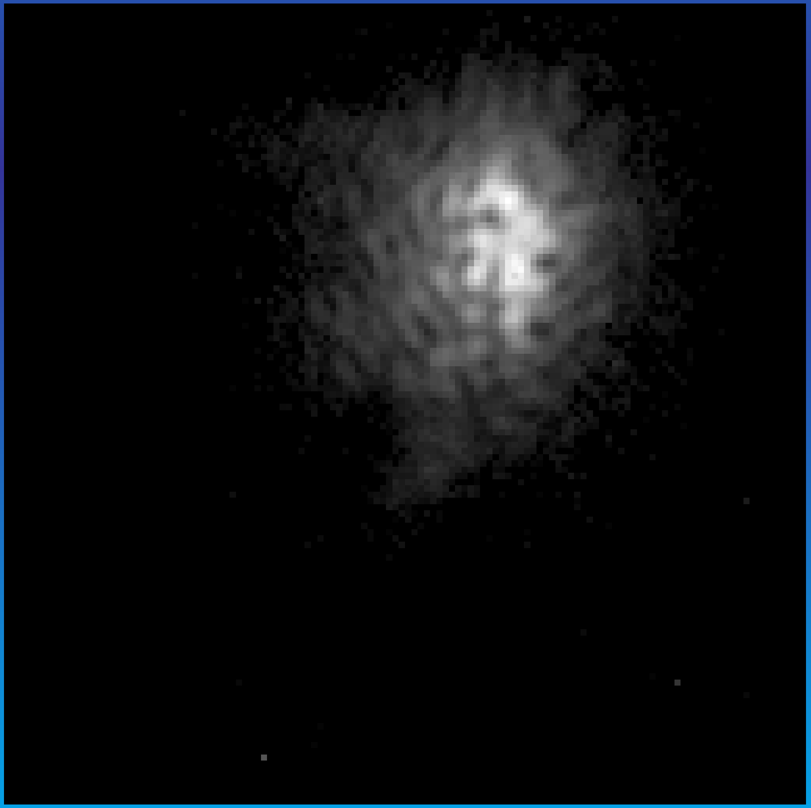
Turbulence: air convection in lateral direction => refraction & scintillation of the star light.

Strong turbulence degrade the image quality

Ground layer turbulence is the strongest

High altitude turbulence is important to the seeing

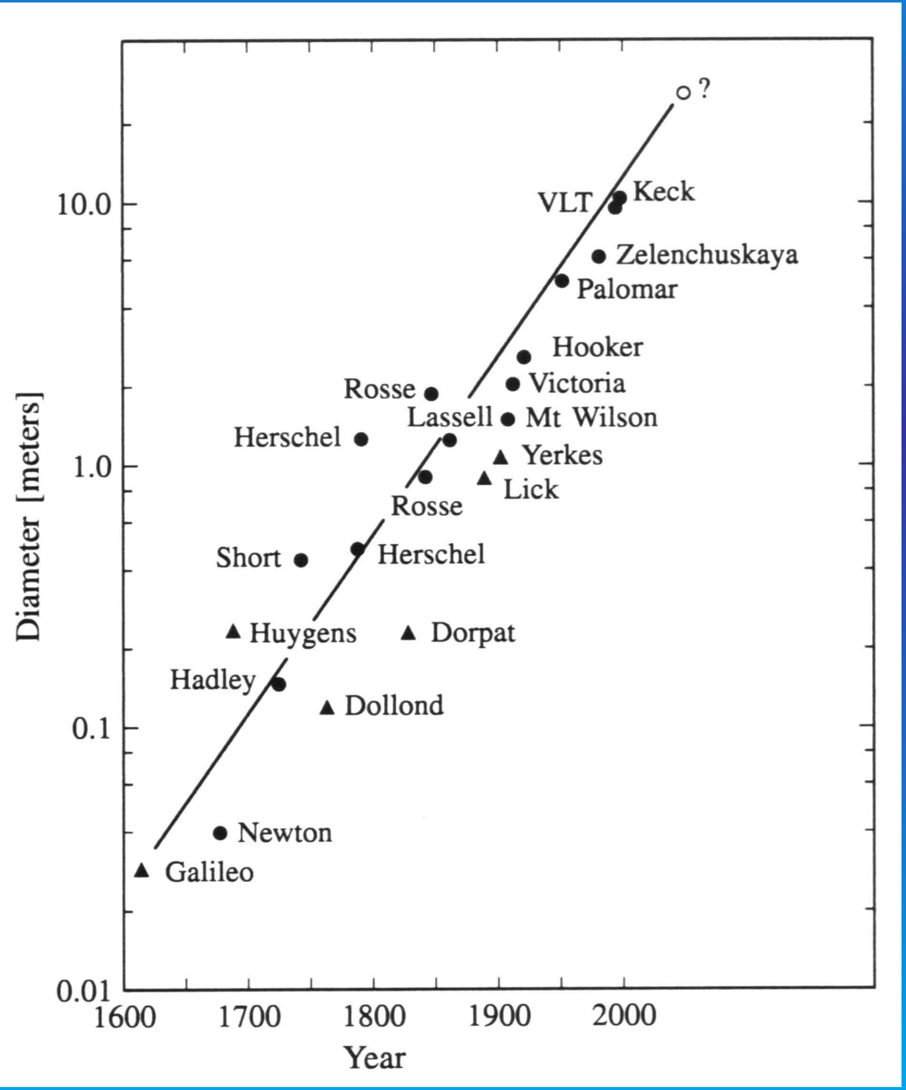
=> Small seeing matters!!
Average seeing ~ 0.8”



Telescopes & Sensors

Evolution of OIR Telescope Size

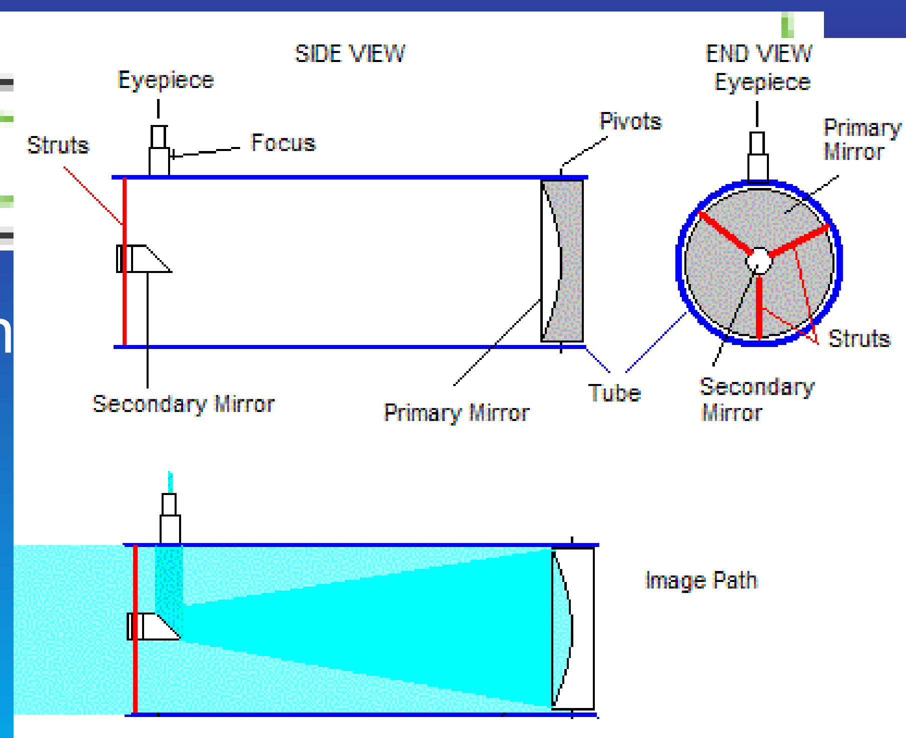
1610	The first astronomical observation using telescope by Galileo
1663	The invention of reflective telescope
1840	Photography was first used to record images
1864	Spectra of sun and stars observed
1879	Silvered glass substrate used as reflector
1948	200 inch Palomar telescope established
1993	10 meter segmented mirror Keck telescope established
203x	38mE-ELT, 24m GMT, 30m TMT



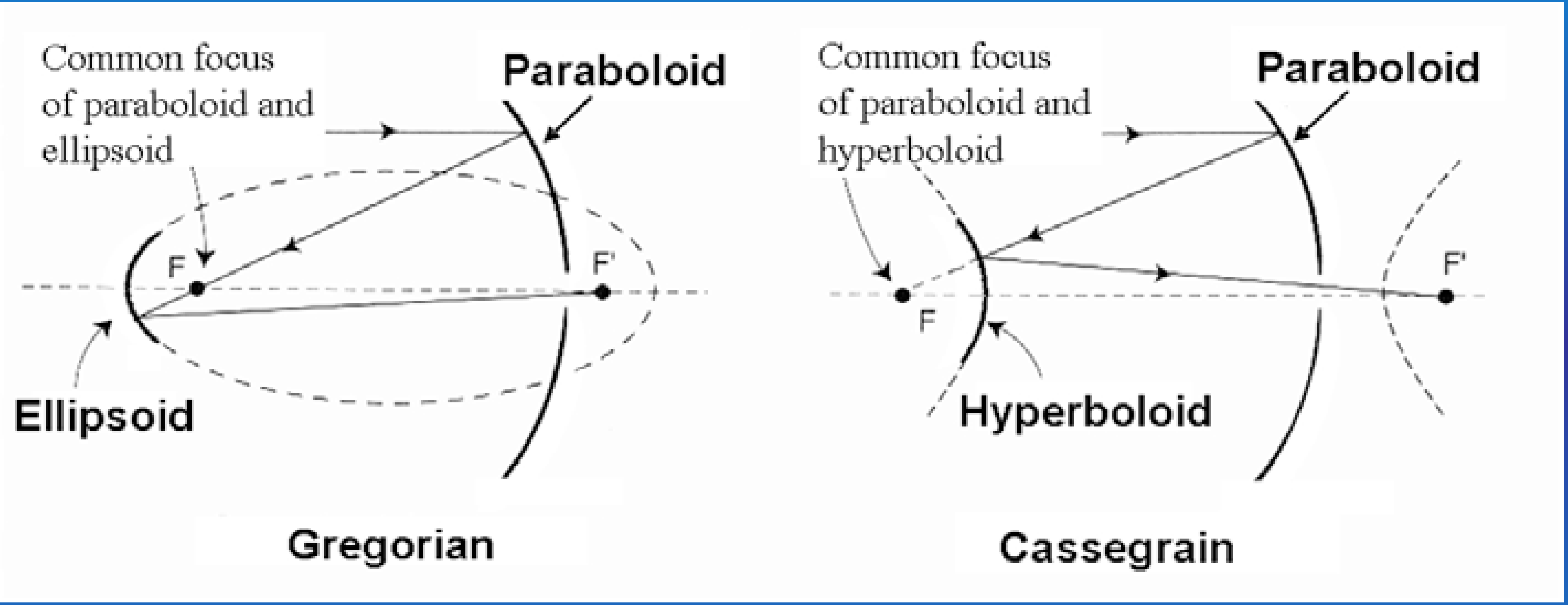
Optical Telescopes

- Refractive telescope:
  - Limited in size (max 1m) and wavelength
  - Chromatic aberration

  - Compact and cheaper
  - Various types (Newton
    etc.)



Modern Reflective Telescopes

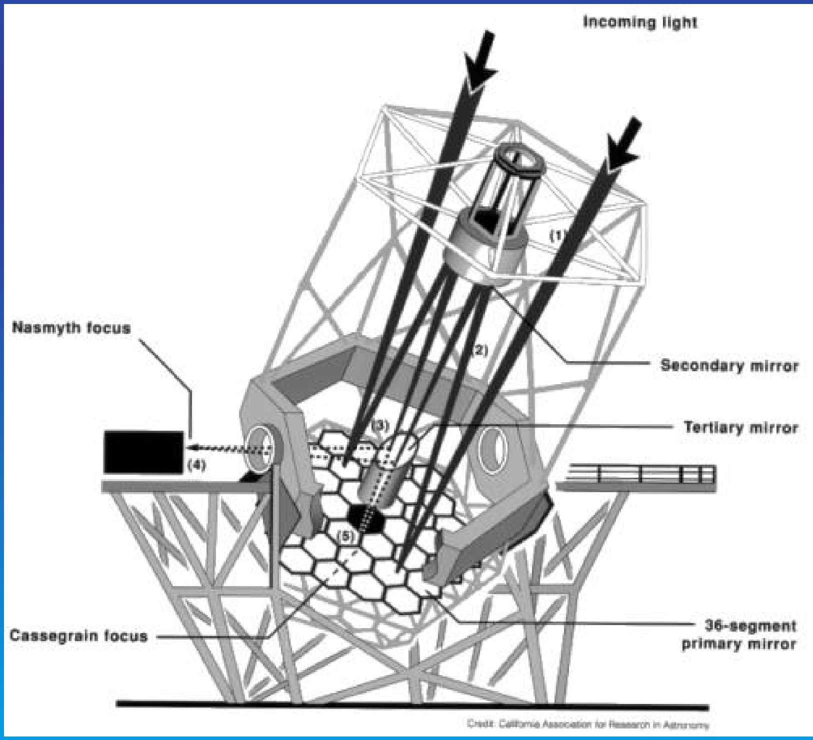


- These models were proposed in 17th century.
- Until early 20th century regain people's attention and become the main stream of modern telescope.

Telescope Mount

Foci of optical telescope

- Primary focus
  - Wide field application, size and weight limits
- Cassegrain focus
  - High resolution
- Nasmyth focus
  - Bulky, heavy instruments
- Fiber feed coupling
  - Flexible, space saving option



How to Detect Photons?

- Nuclear interaction
- Ionization of gas or solid
- Photochemical reaction: photographic plate
- Photo-electron reaction: PMT, CCD, CMOS, photodiode, photoconductor
- Thermal effect: Bolometer, Pyrometer….
- Electric field effect: Antenna

Photographic Plate

- AgBr reaction
- Certain threshold to generate signal
- Bad linearity
- QE~1%
- Easy to make large plate

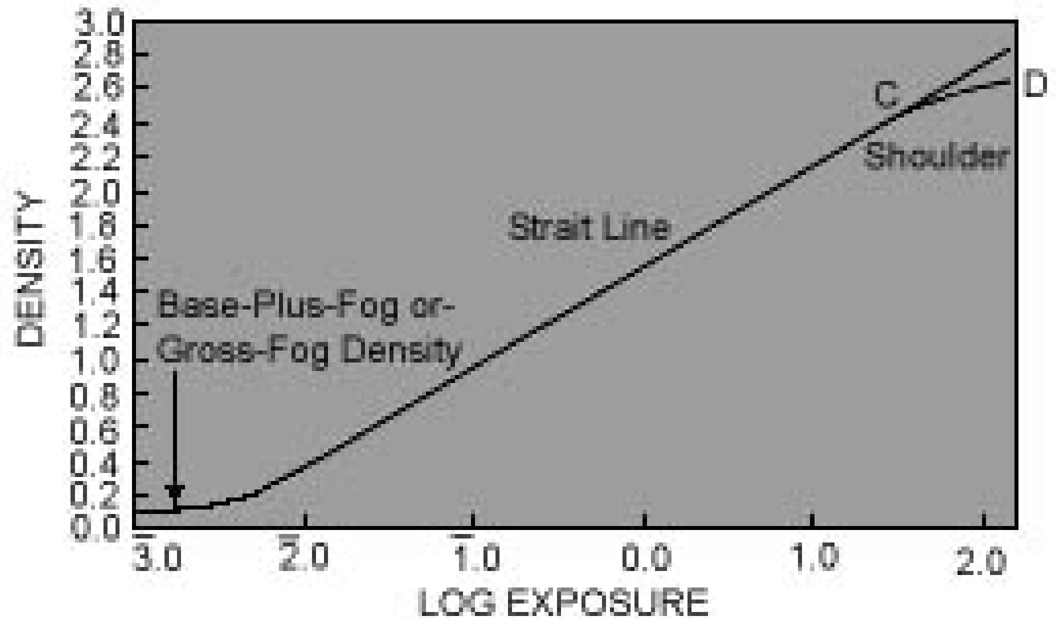
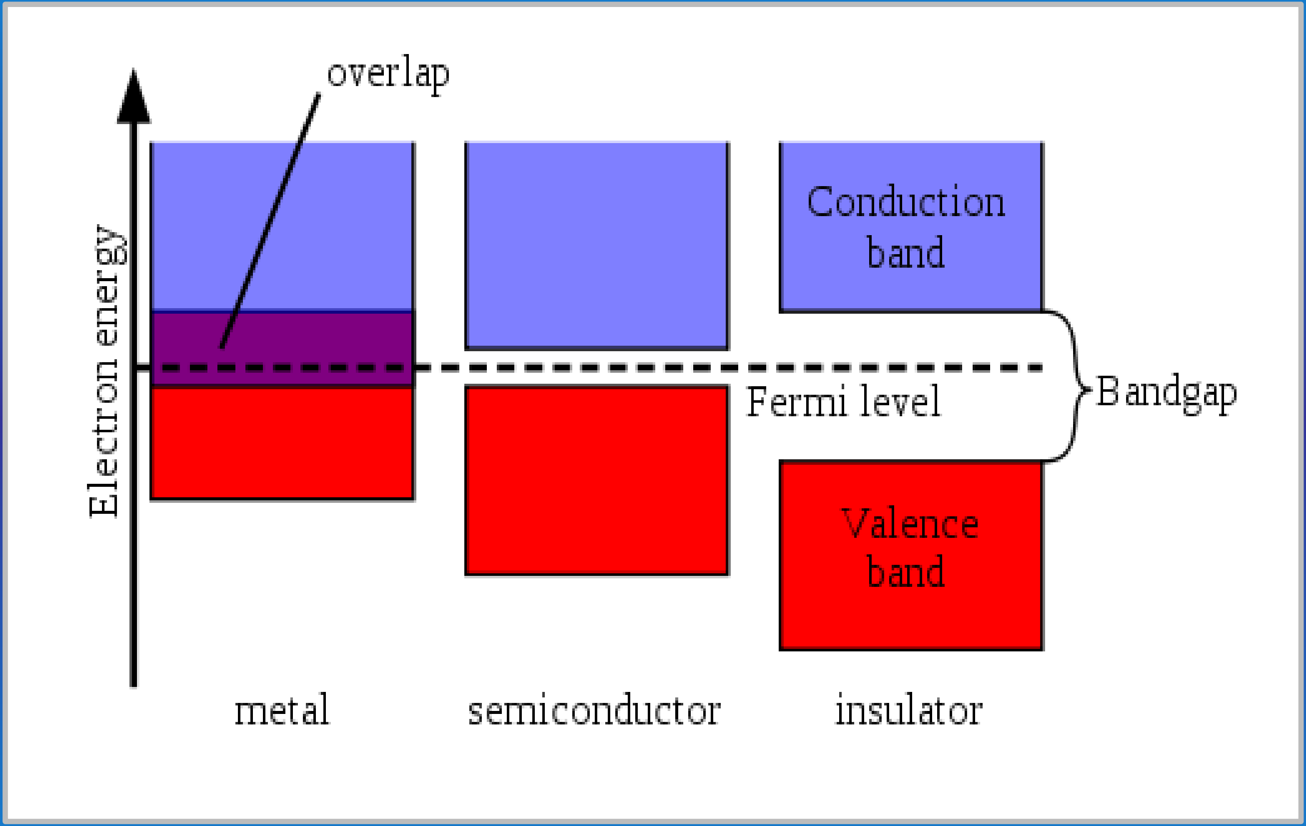


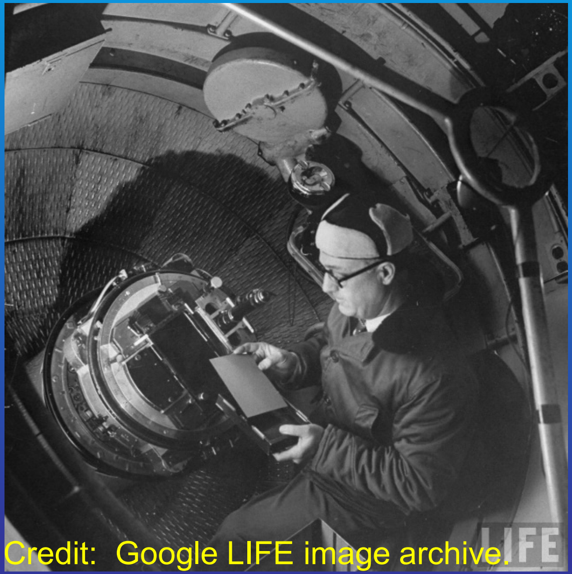
Figure 23
Typical characteristic curve

Semiconductors



Semiconductor: bandgap E < 2ev
Insulator: bandgap E > 2ev

The 200" Photographic Plate
William Miller at 1940s

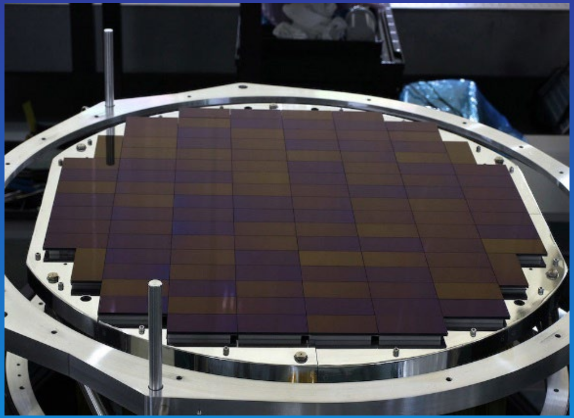


Credit: Google LIFE image archive.

Willard S. Boyle & George E. Smith @ Bell Lab. 1969 (2009 Nobel prize in Physics)

Credit: https://aip.scitation.org/doi/full/10.1063/1.3578638

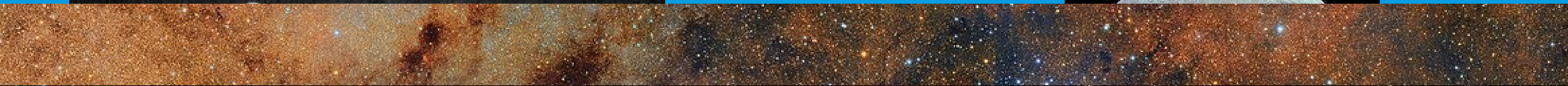
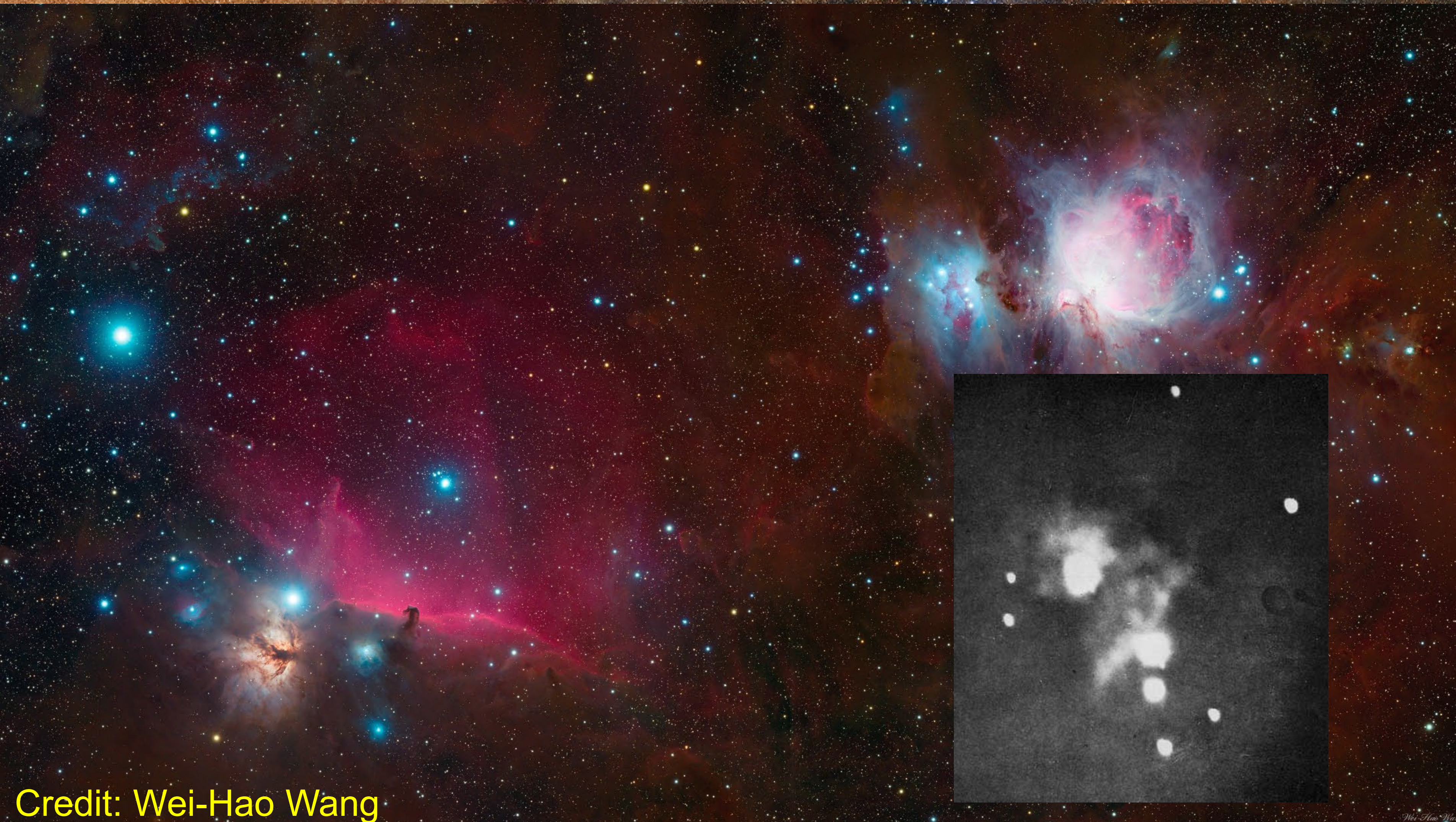
40 2048 x 4608 CCD, CFHT, MegaCam 2003



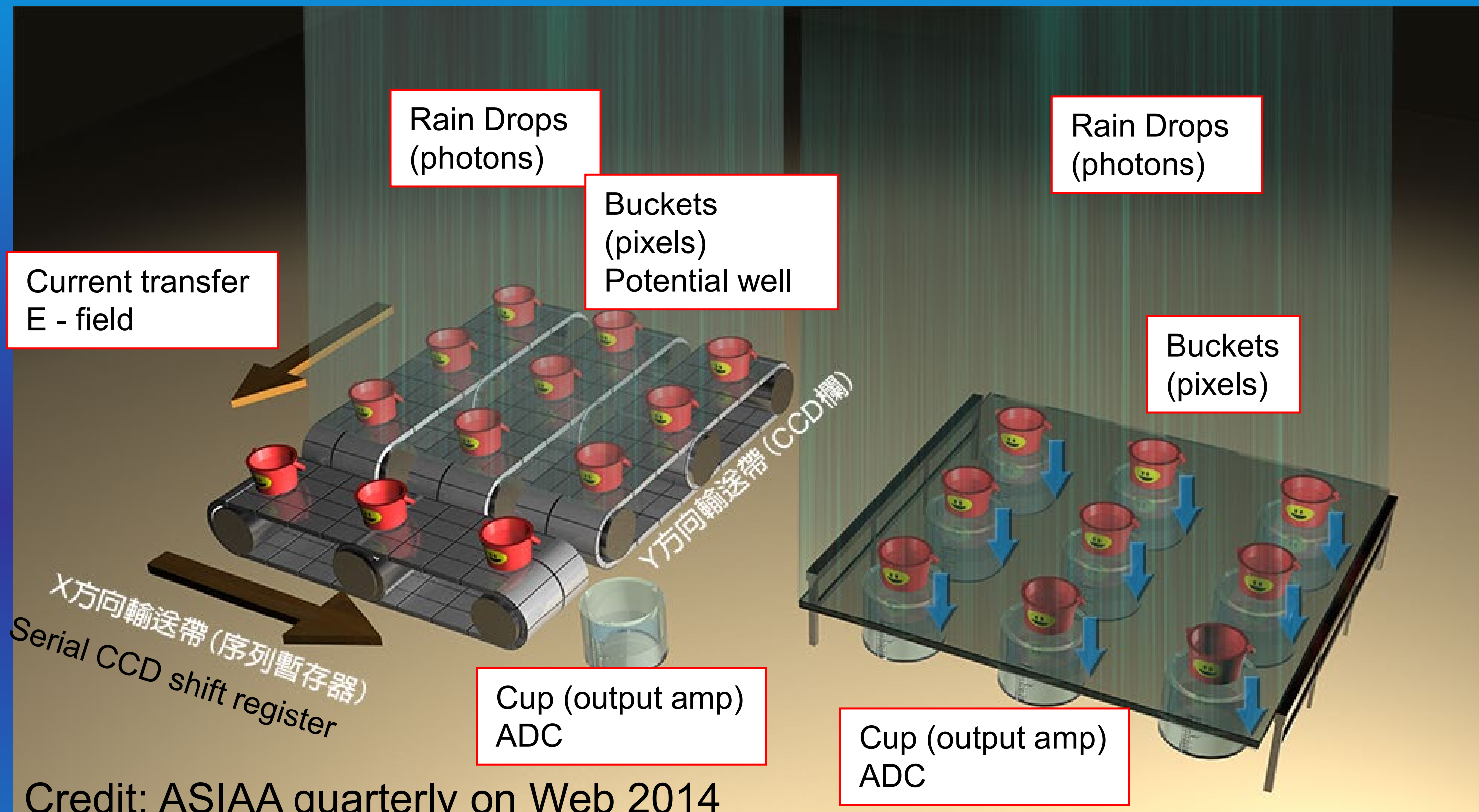
104 2048 x 4096 CCD, Subaru Hyper Supreme Cam 2014

189 4k x 4k CCD, LSST camera 2025





Credit: Wei-Hao Wang

CCD & CMOS

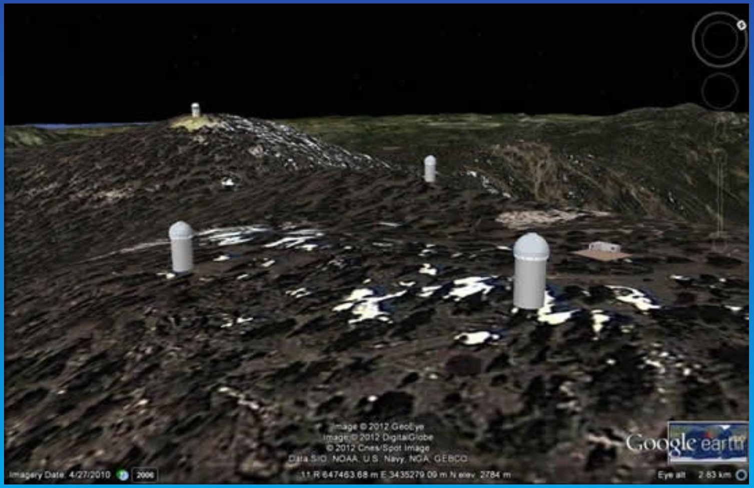


- Larger pixel sizes (8um or 14um)
- QE~90% (peak depends on AR coating)
- Full well around 100,000e-
- Maximum speed is around 3MHz
- Dark level ~1e/pixel/hr
- Readout noise few e-

- An alternative and cheaper choice of CCD
- Close performance to CCDs nowadays.
- Active pixel sensor
- Low power consumption
- Small full well is the current drawback

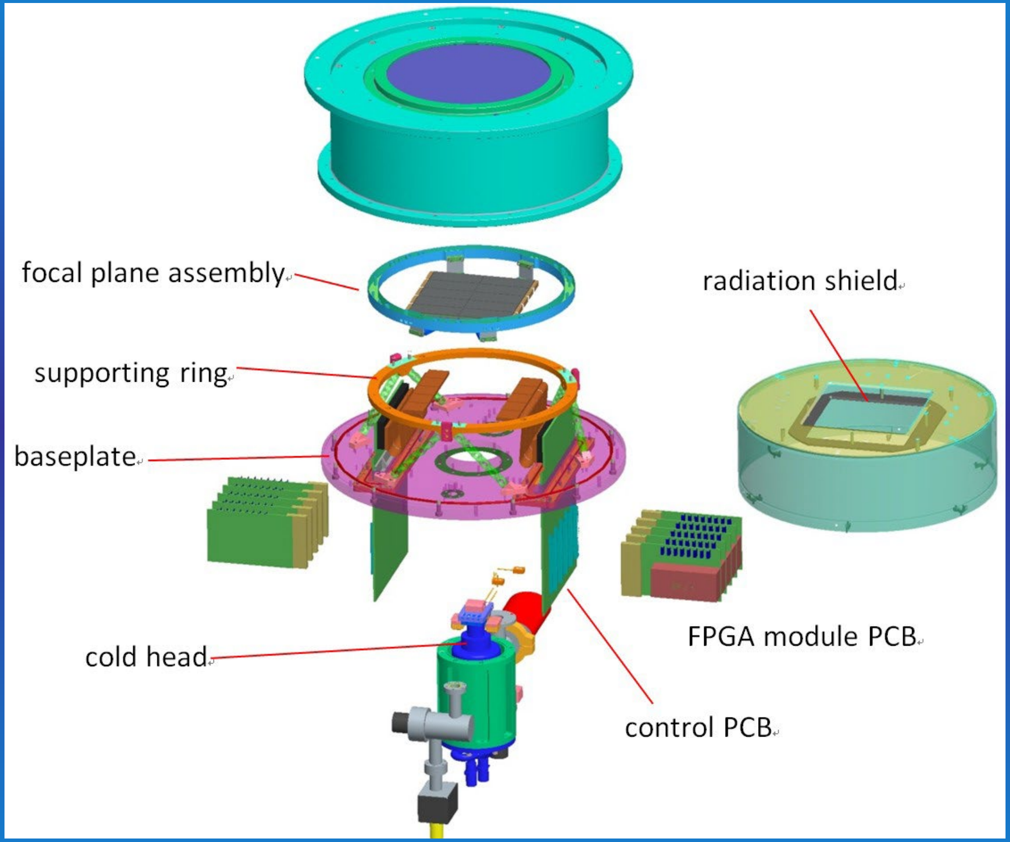
TAOS II

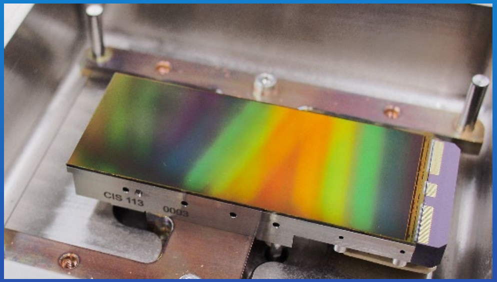
- Transneptunian Automated Occultation Survey
- Goal: to understand the number/distrib ution of Kuiper belt objects
- Asteroids are too dim to observe, use o ccultation method to study.
- Locate at SPM, Baja California.
- Three 1.3m telescopes, FoV 1.3deg.

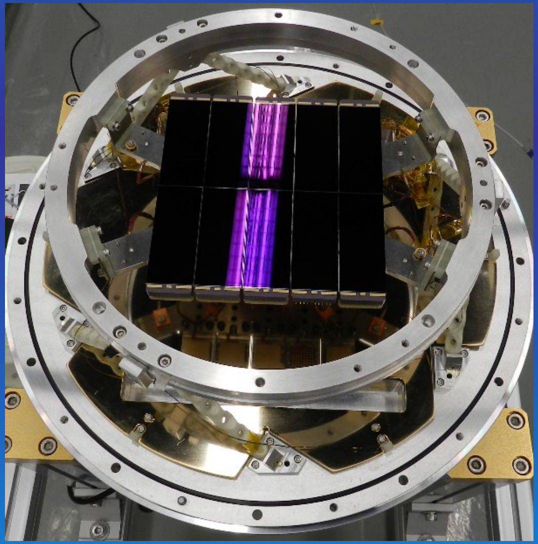


1.3m x 3

TAOS II Customized Camera

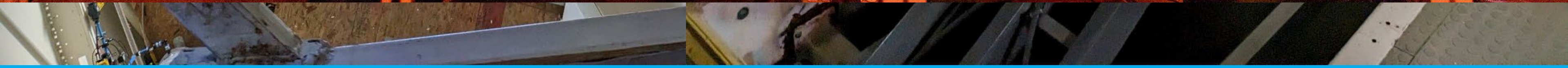


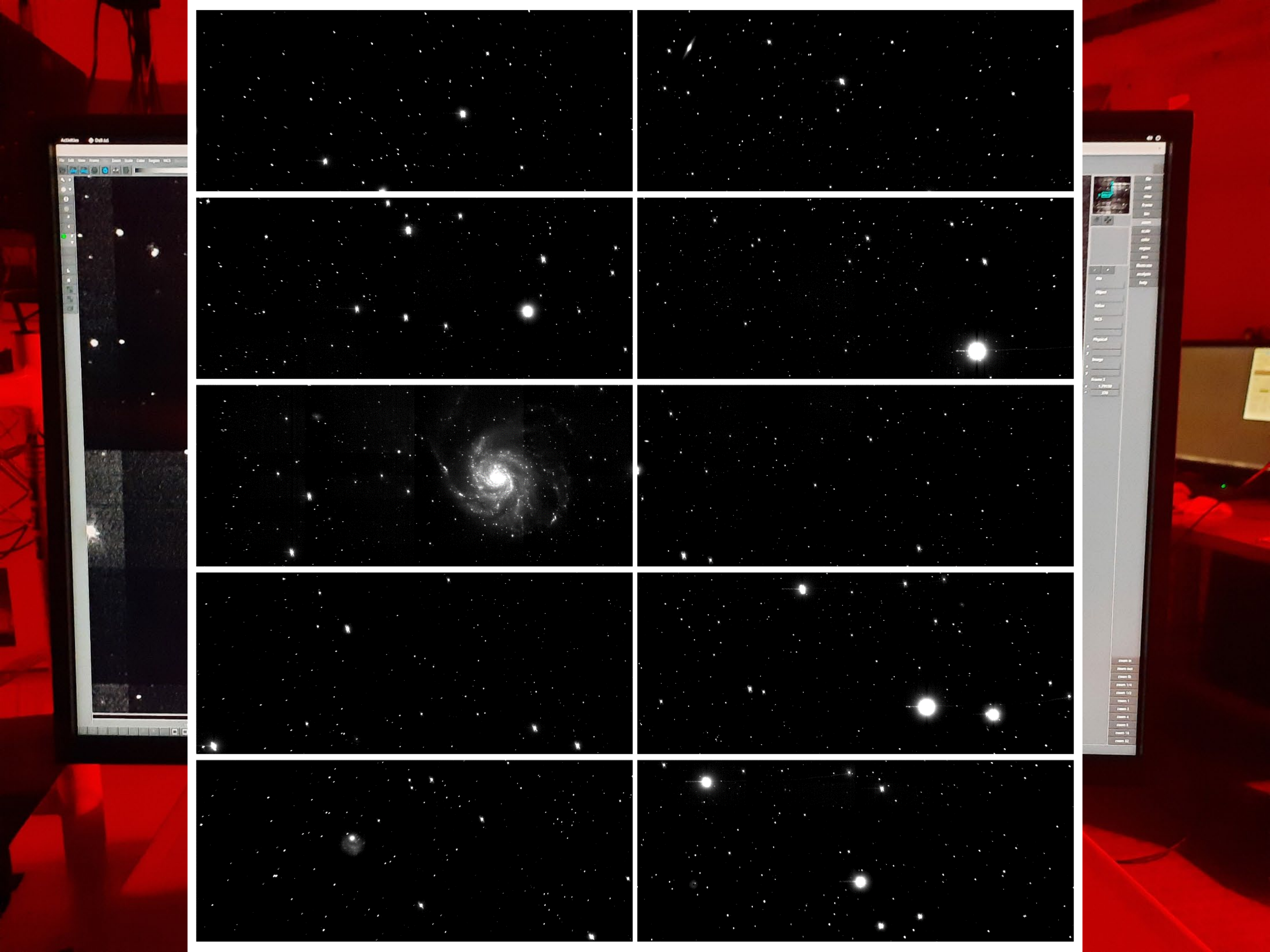




10,000 Stars Monitoring with 20 Hz Frame Rate
E2V 3 edge buttable sensor, one chip 1920 x 4608 pixels. Total 10 chips.


Fan pipe (with conne





Concepts of OIR instrument

imagers
&
spectrometers

Optical Jargons

1. Focal length: f
2. Aperture size: D
3. Focal ratio or f-numebr: f/D,
4. Small f#, larger FoV, large aberrations; large f#, higher resol ution (smaller FoV), less aberrations.

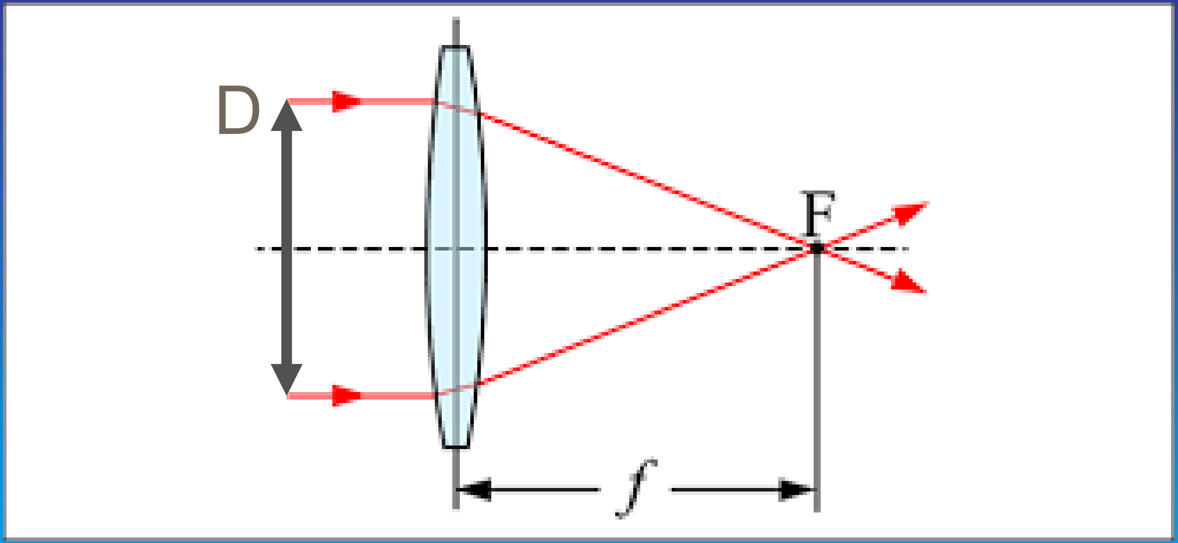
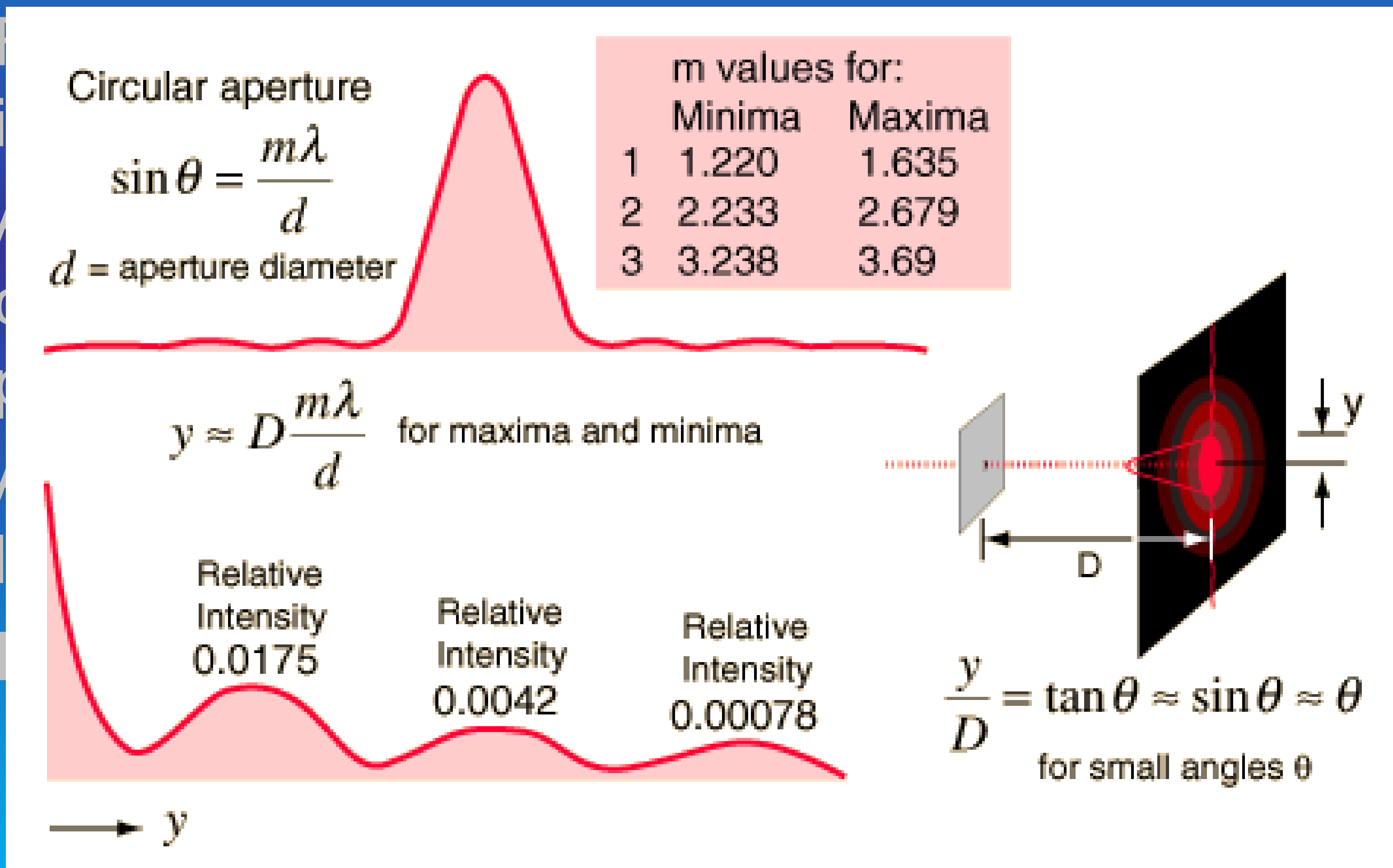


Image Quality

- Theoretical limit: Diffraction pattern of circular aperture (Airy disk)

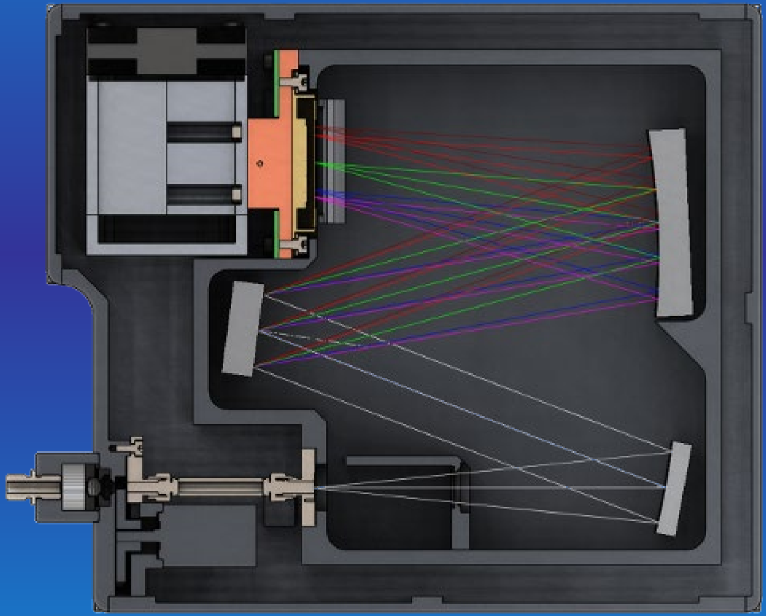


Instruments in OIR

Camera

- Take Images

Spectrograph



- Take dispersed slit images

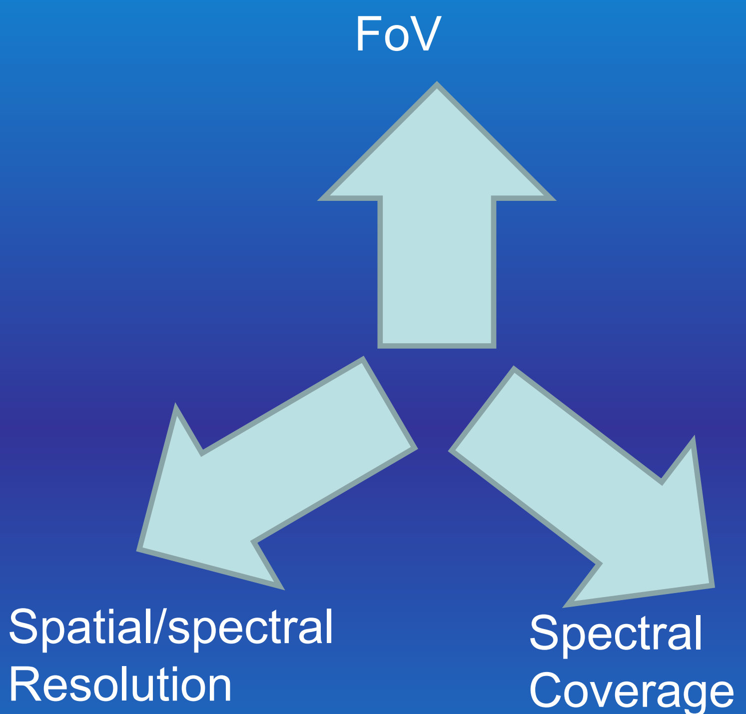
(Slit images in different λ)

How to build an instrument

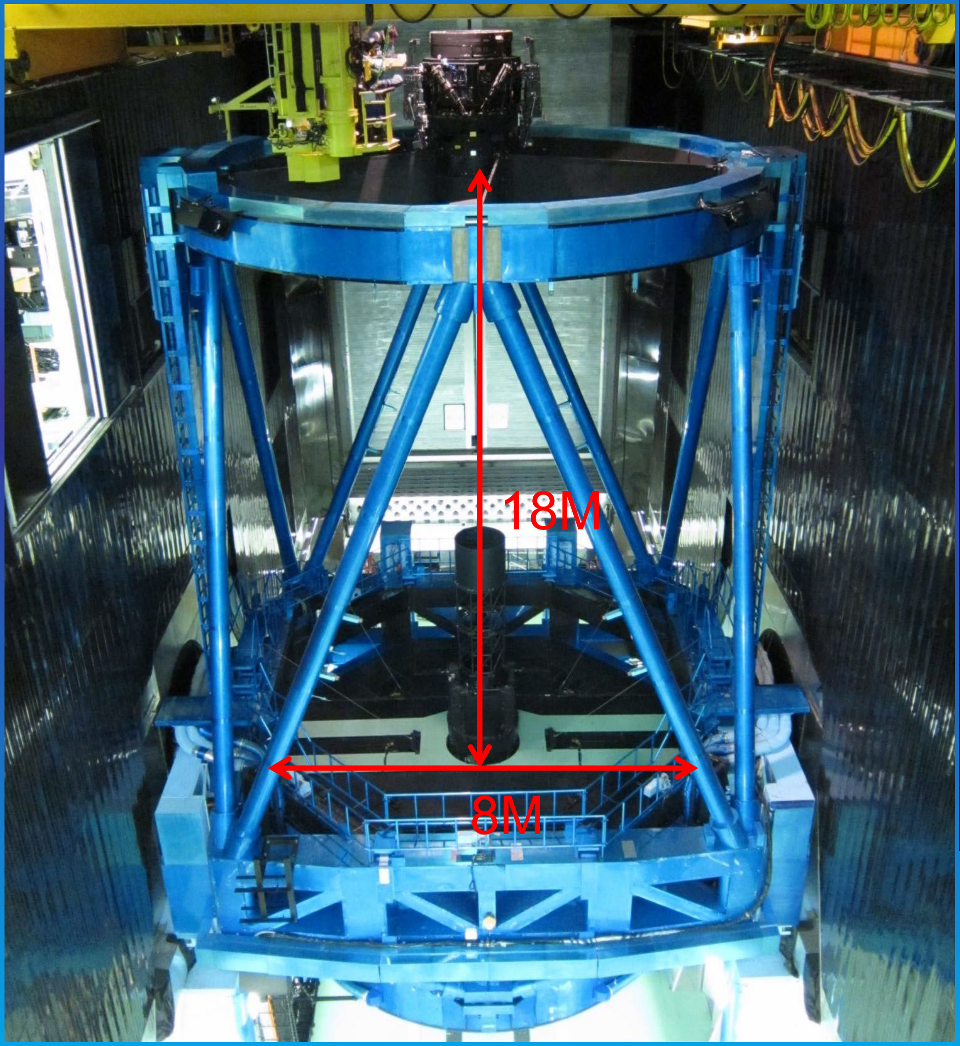
Define instrument parameter space

- Main constraint: limited size of detector!! Compromise between FoV, Res. & ΔW

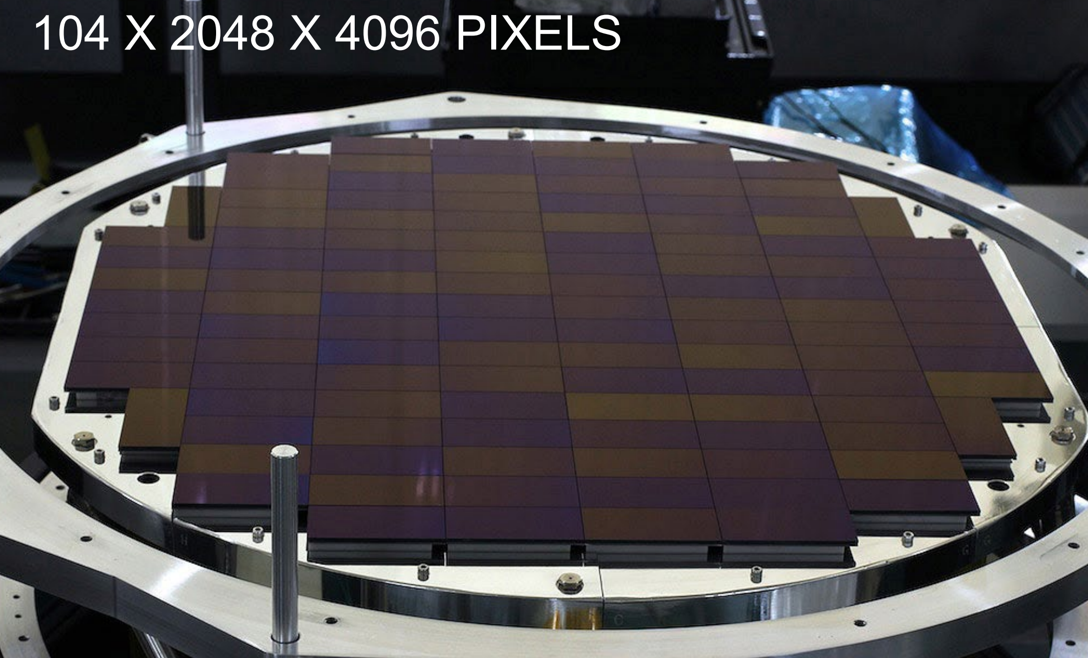
1. How many pixels per star (PSF)
   – Min 2 pixel sampling, 3 – 5 pixel sampling is acceptable.
2. Work out field of view
   – Based on pixel sampling (plate scale ("/pixel).
3. Work out wavelength coverage
   – Based on science requirements (imager)
   – Based on spectral resolution (spectrometer)

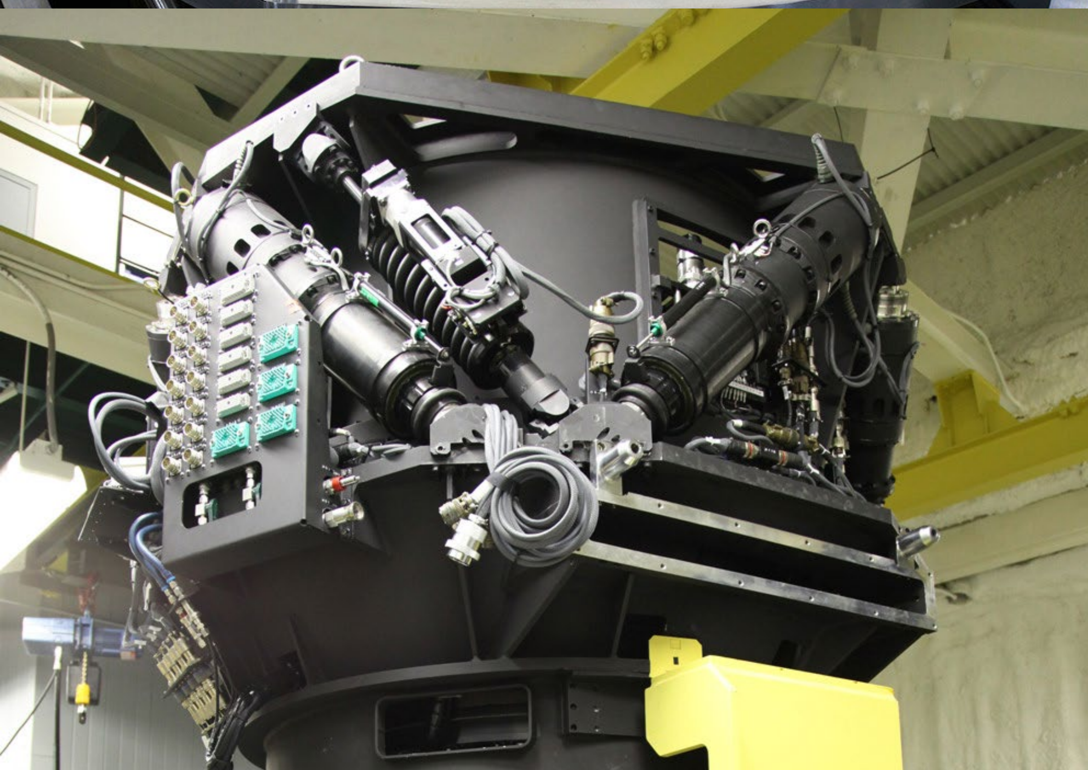


Subaru Hyper Suprime-Cam

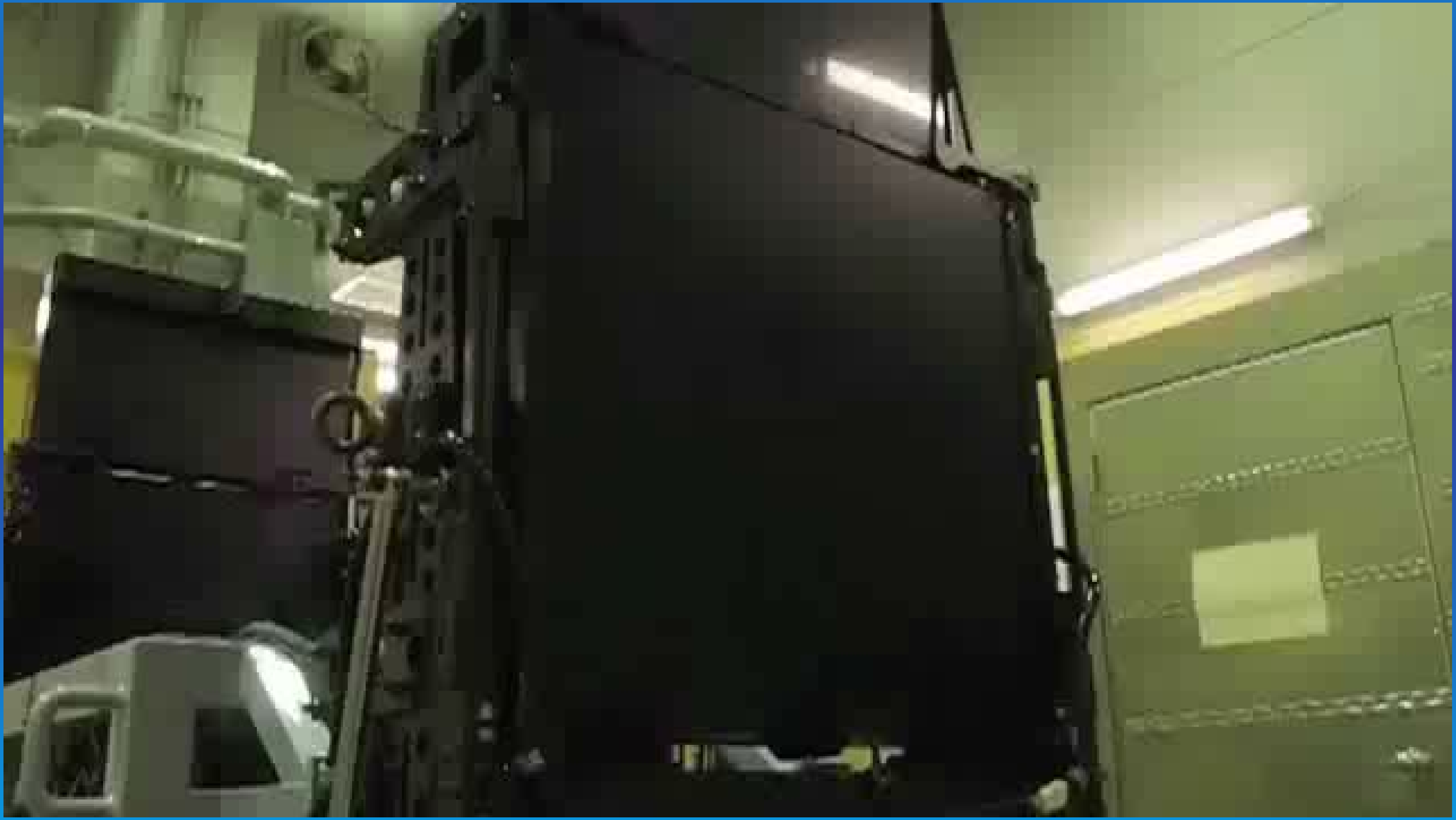


Detectors	Hamamatsu Photonics KK 2048x4096 (S10892-02)
Number of CCDs	104 + AG 4 + AF 8(1)
Pixel size	15 um
Pixel scale	0.17"
Field of view	90 arcmin diameter
Gain	3.0 e/ADU
Read noise	4.5 e^-
Readout time	20 s(2)
Camera f-number	$f \sim 2.2$
Number of filters	maximum of 6
Filter exchange time	~30 min(3)(4)


104 X 2048 X 4096 PIXELS



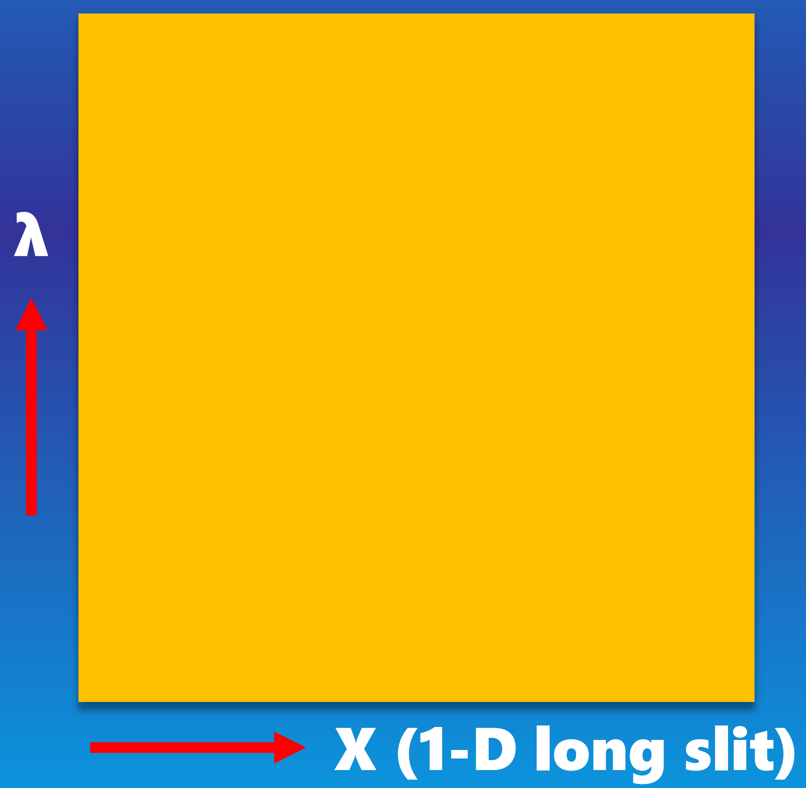
Filter Exchange System

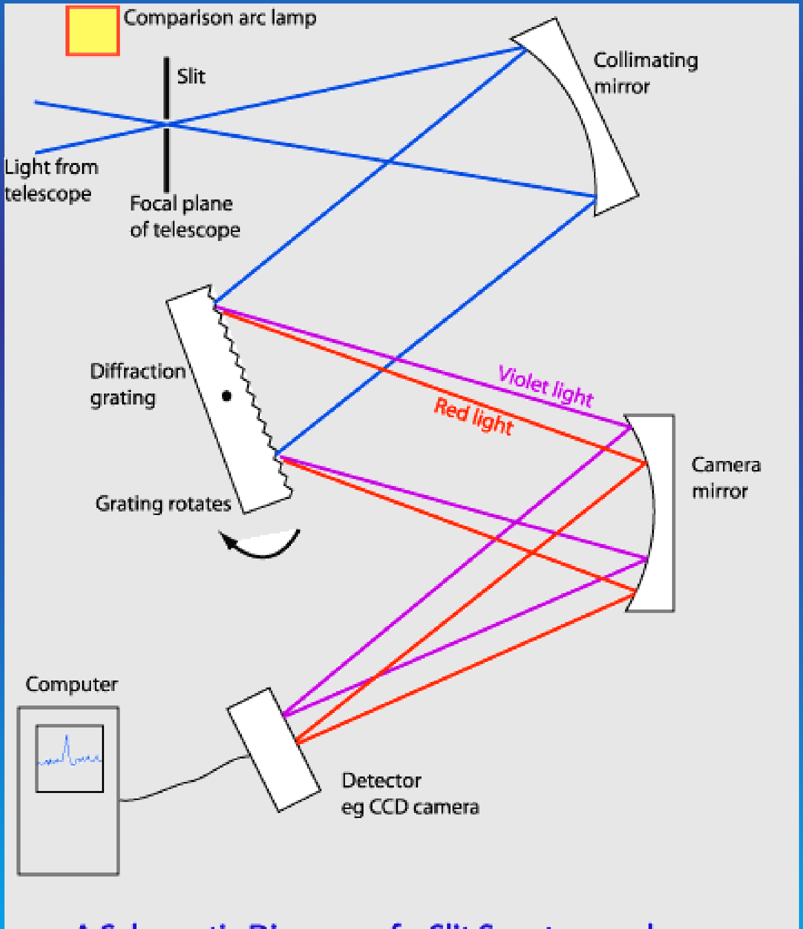


Total 6 filters, 3 on each side. Filter exchange takes 16 mins.

Long Slit Spectrometer

Spectrometer: sacrifice 1D in spatial direction. Imager of dispersed slit light.





A Schematic Diagram of a Slit Spectrograph

Long Slit Spectrometer

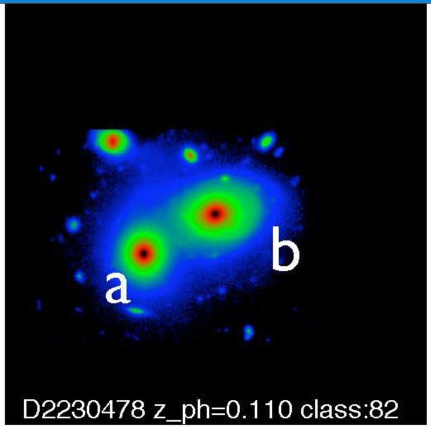


Fig: The i' band image of the merger, with words "a" and "b" denote the two separate galaxies in the merging system.

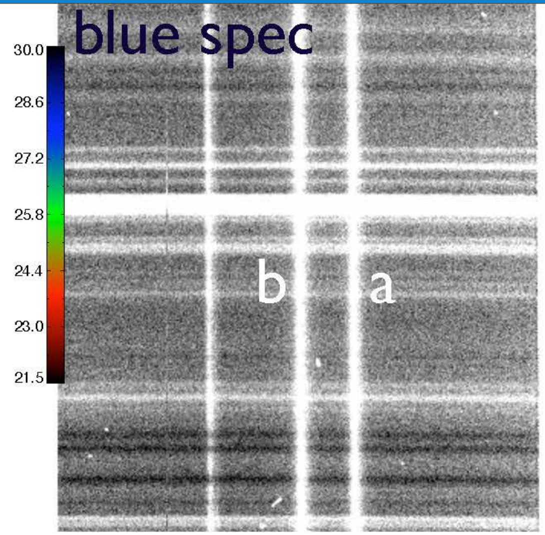


Fig: The reduced image of the blue and red spectrograph. The words "a" and "b" denote the spectrum of two separate galaxies in the merging system.

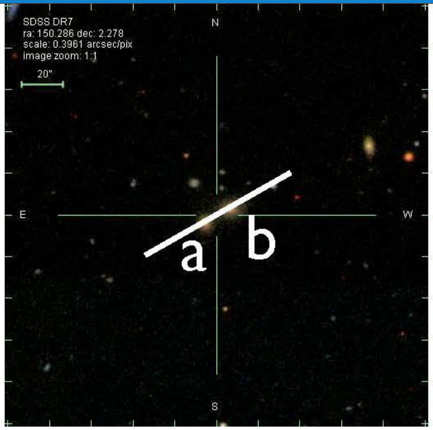
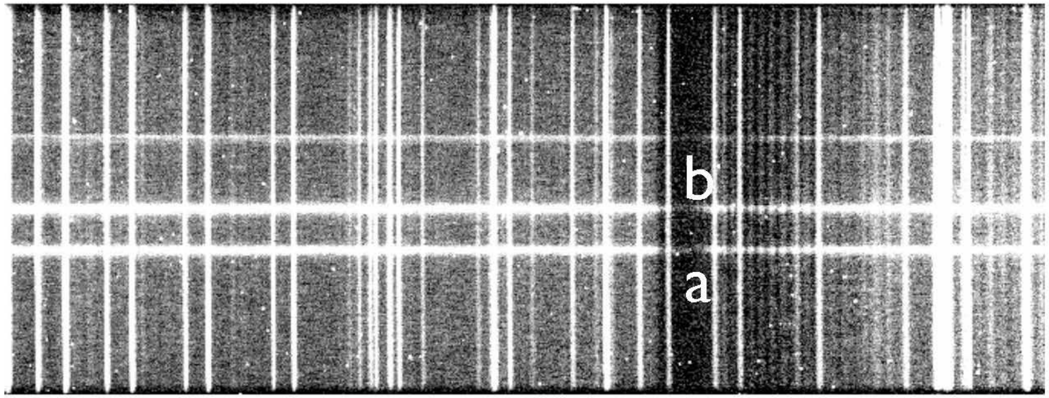


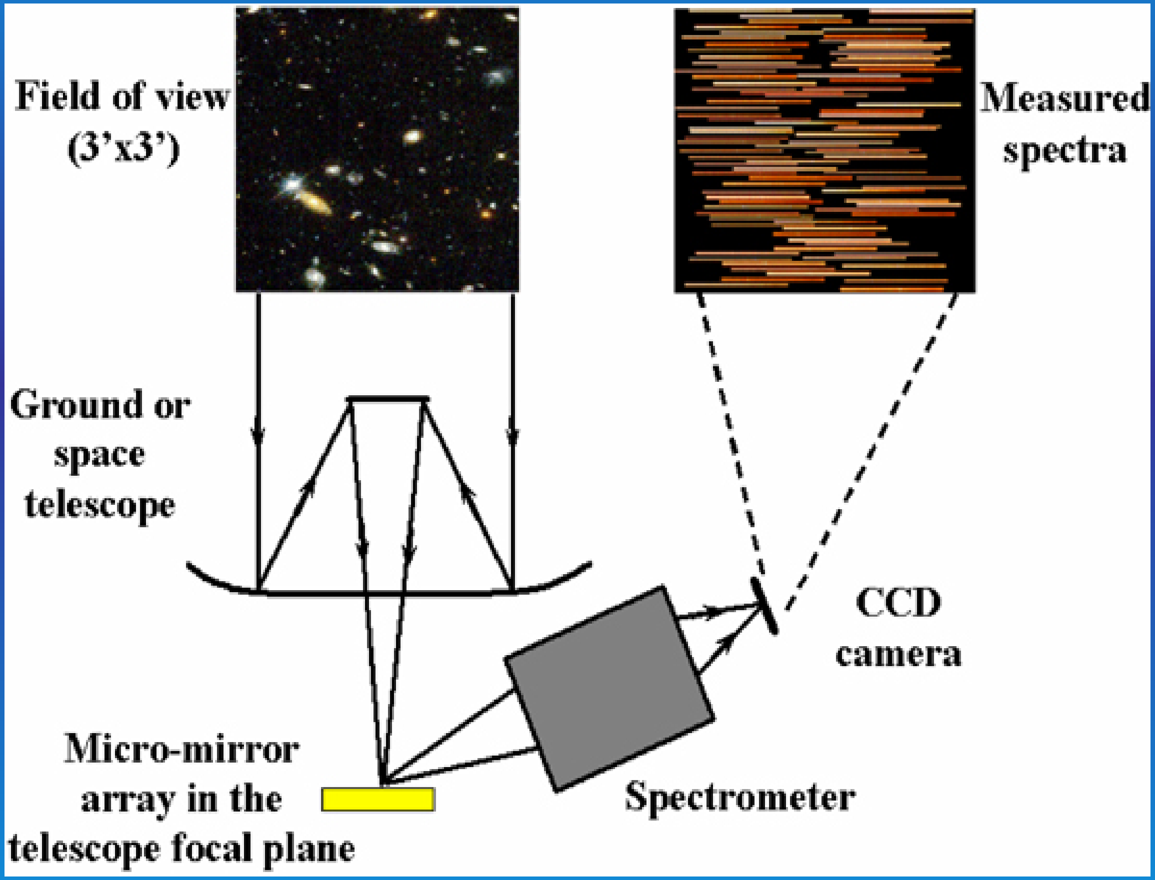
Fig: The picture from the finder chart with the white bar indicates the orientation of the slit.

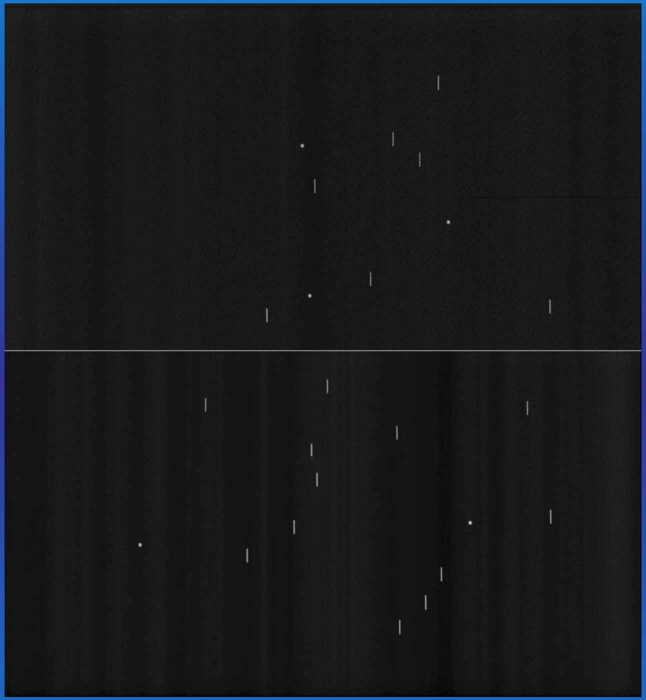
red spec



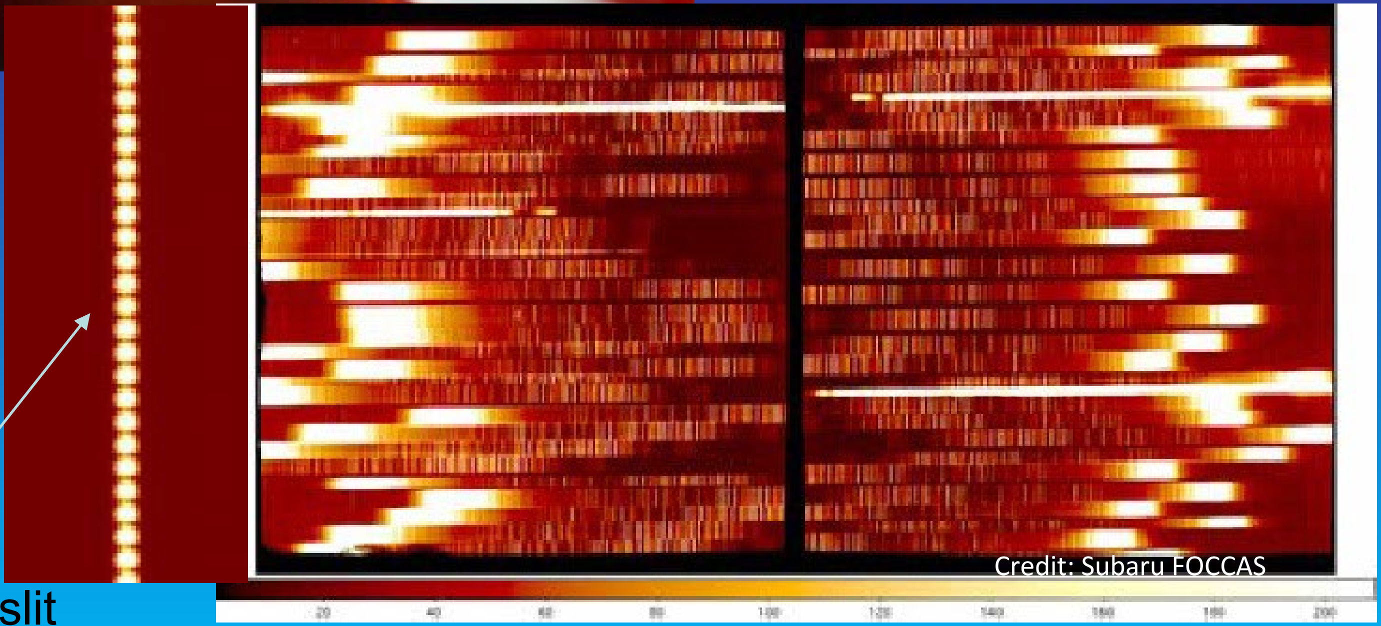
Spectrum of an interacting galaxy pair, Palomar double spectrograph

Multi-object Spectrograph slit mask type



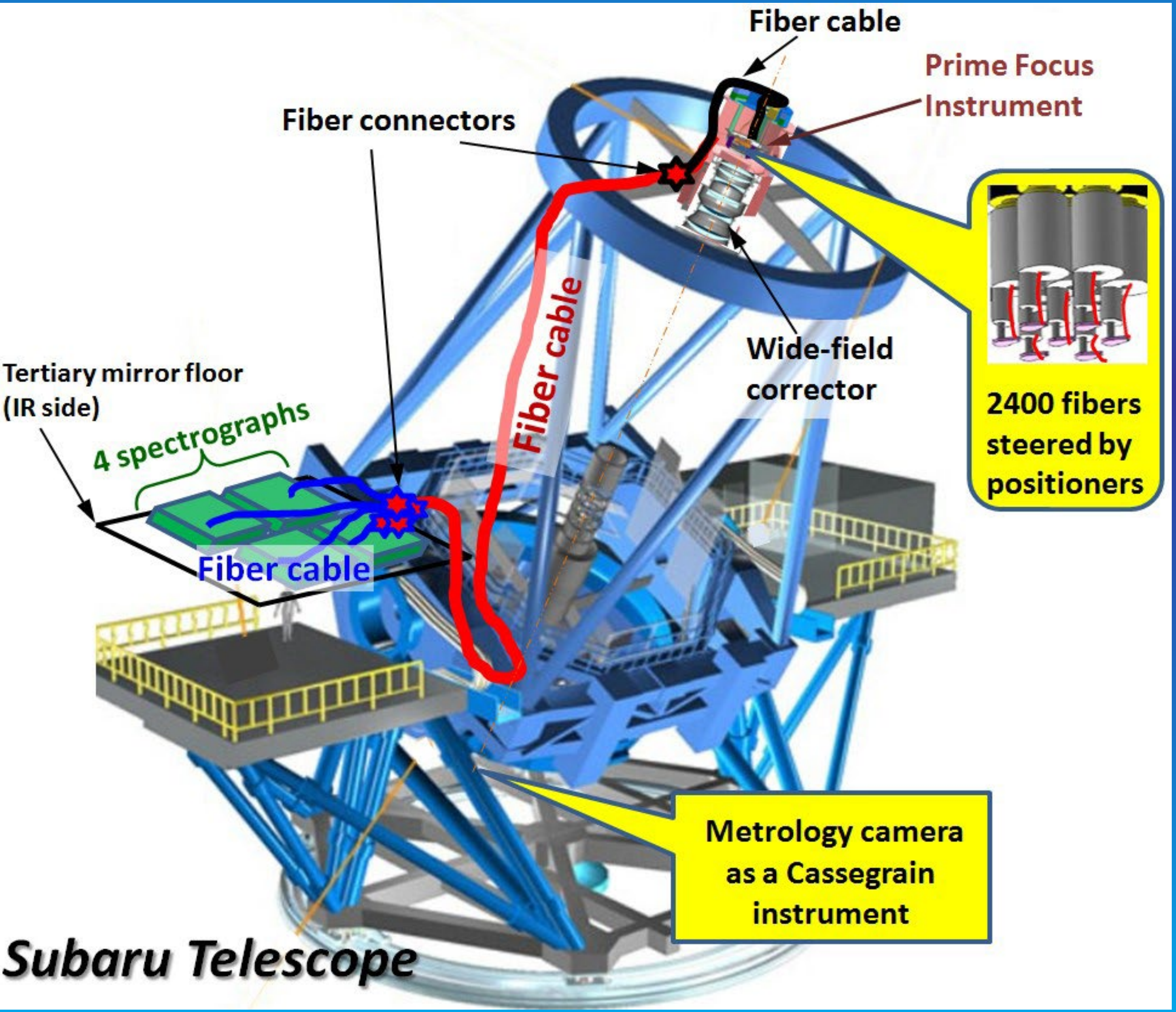


Multi-object Spectrograph fiber based



Pseudo long-slit

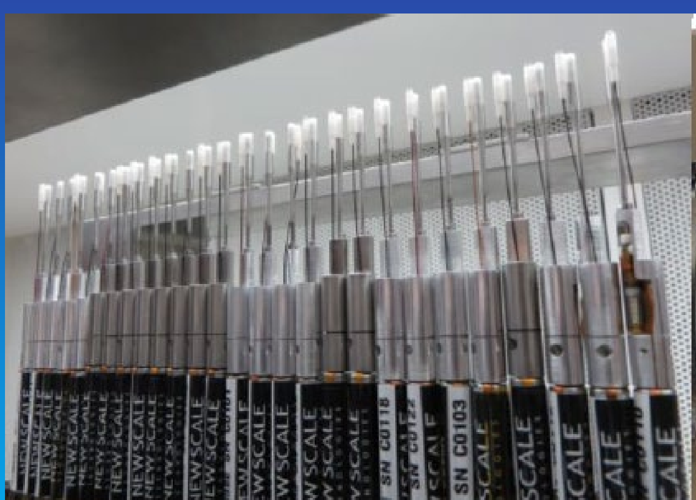
Prime Focus Spectrograph

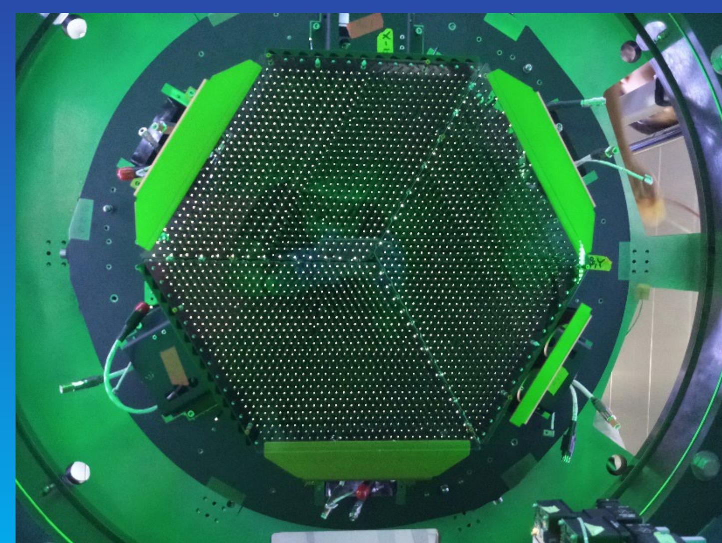


- Fiber based multi-object spectrograph.
- 2400 motorized fiber covered by 4 identical spectrographs (600 fibers each), Δλ 0.38 - 1.26μm; blue, red, NIR arms.
- FoV 1.3 deg^2.
- R ~ 2A (low res. mode) or 1.2A (medium res. mode).
- PFS locates at telescope prime focus, a challenging design. Fiber focal ratio f/2.8, collimator f/2.5, spectrograph camera f/1.1.
- Three detectors, two optical one NIR (4k x 4k array).

Prime Focus Spectrograph

Delivery in June, 2021

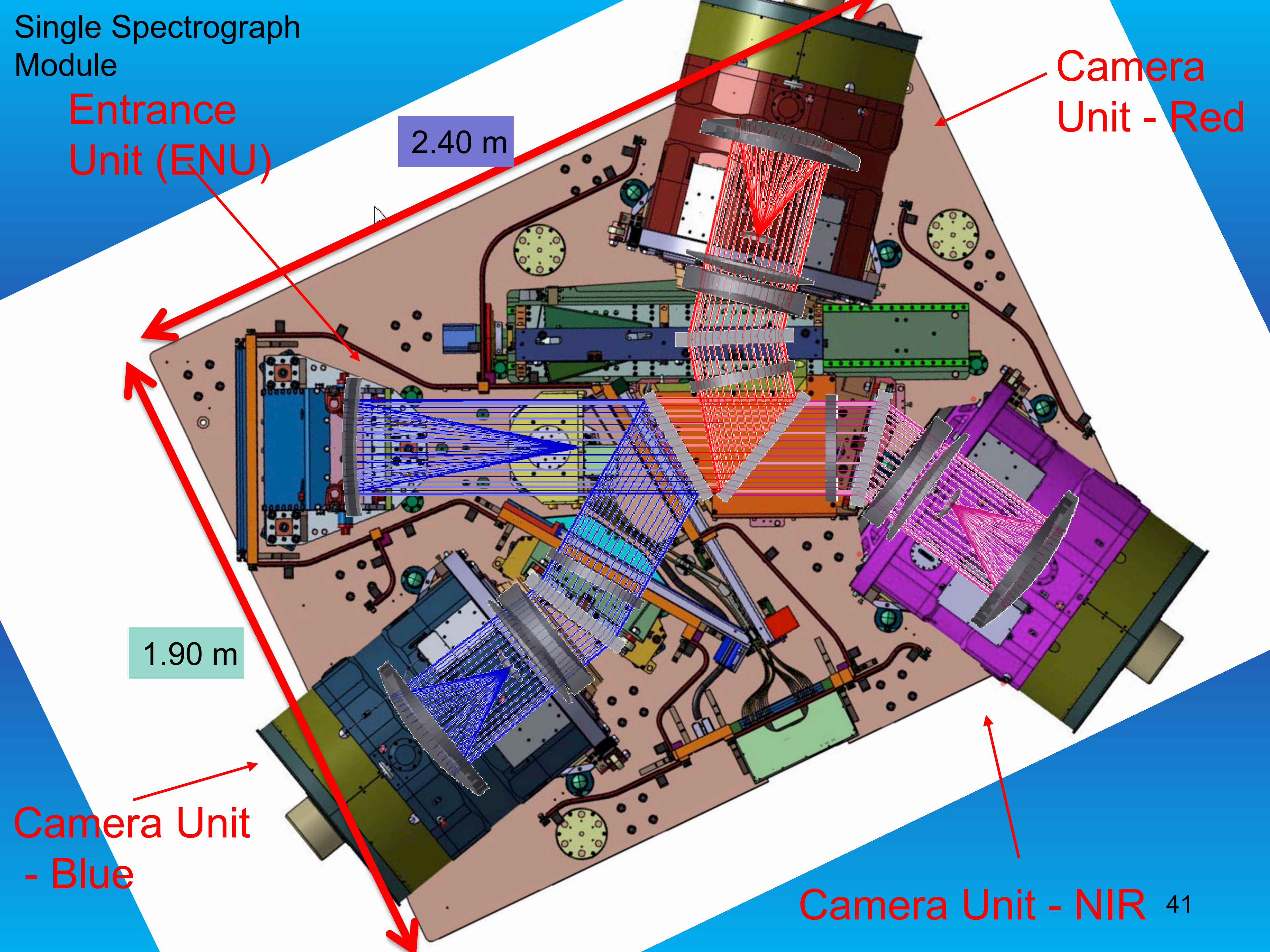


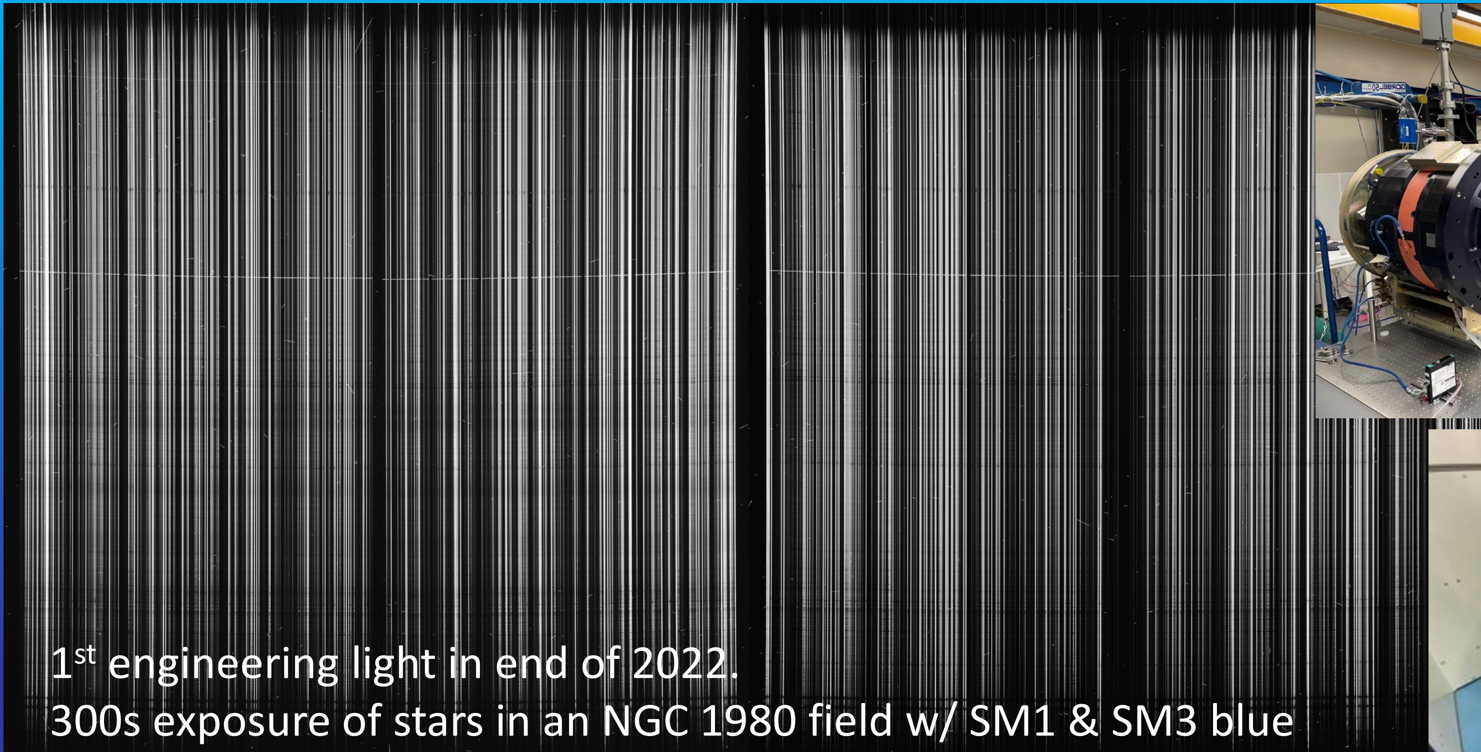


Prime Focus Spectrograph

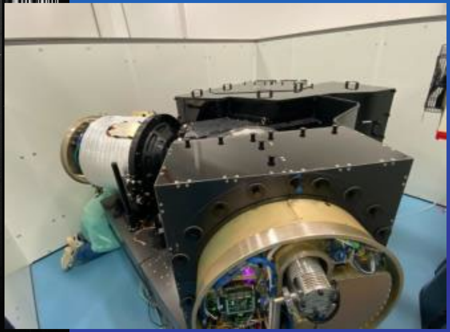
Delivery in April, 2018

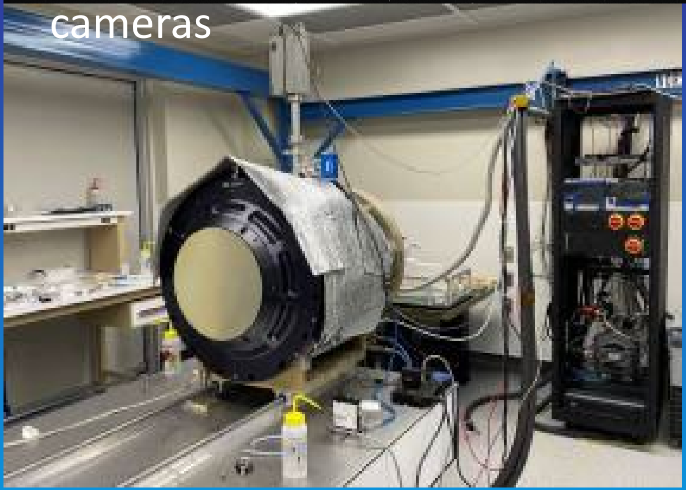
Single Spectrograph Module





1st engineering light in end of 2022.
300s exposure of stars in an NGC 1980 field w/ SM1 & SM3 blue cameras



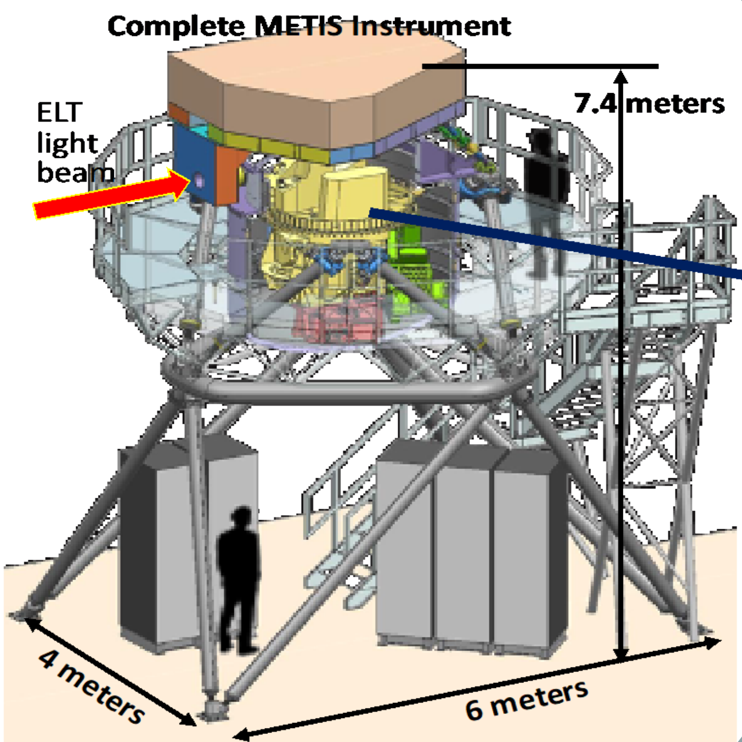


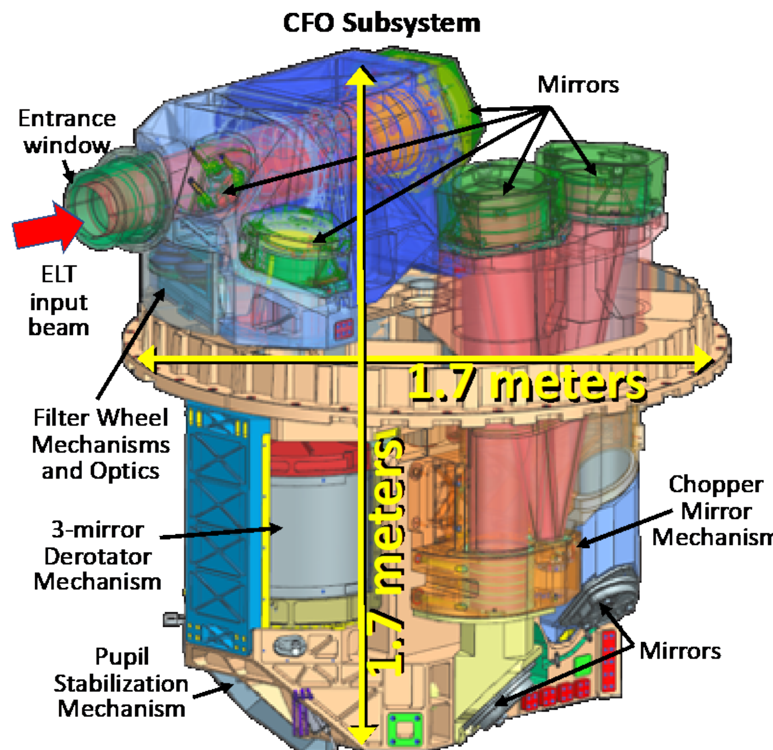
NIR Cam. N2 arrives (March, 2023)

Currently conducting science operations (summer, 2026)

Other on-going OIR project in ASIAA

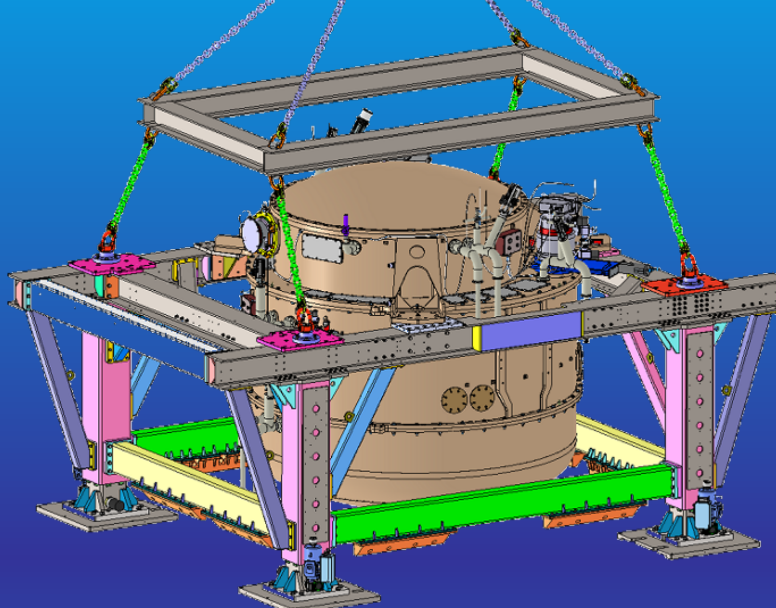
Mid-infrared ELT Imager & Spectrograph (METIS)

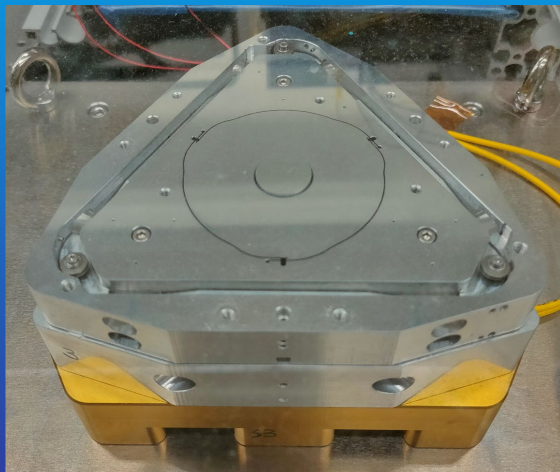




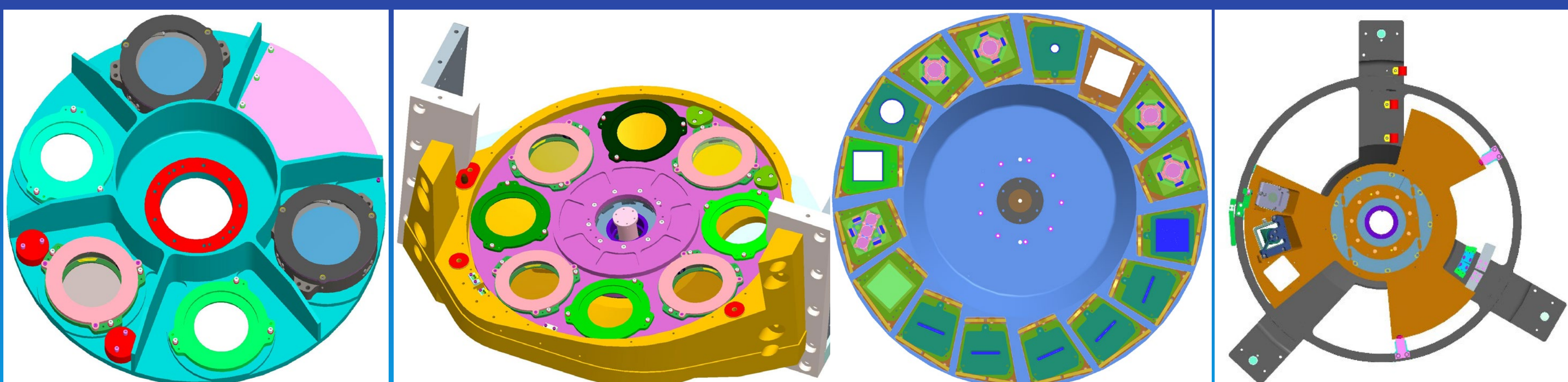
1. 1st gen ELT instrument,
2. Contains imager & spectrograph
3. Wavelength 3 - 13μm
4. Science goal: exoplanet atmosphere, formation proto-stars, etc.

Supporting equipment (ASF)





Chopping algorithm

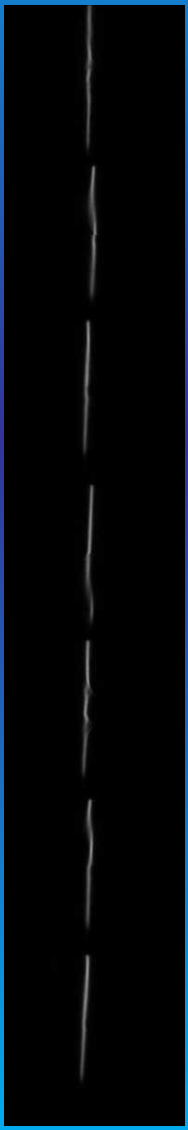


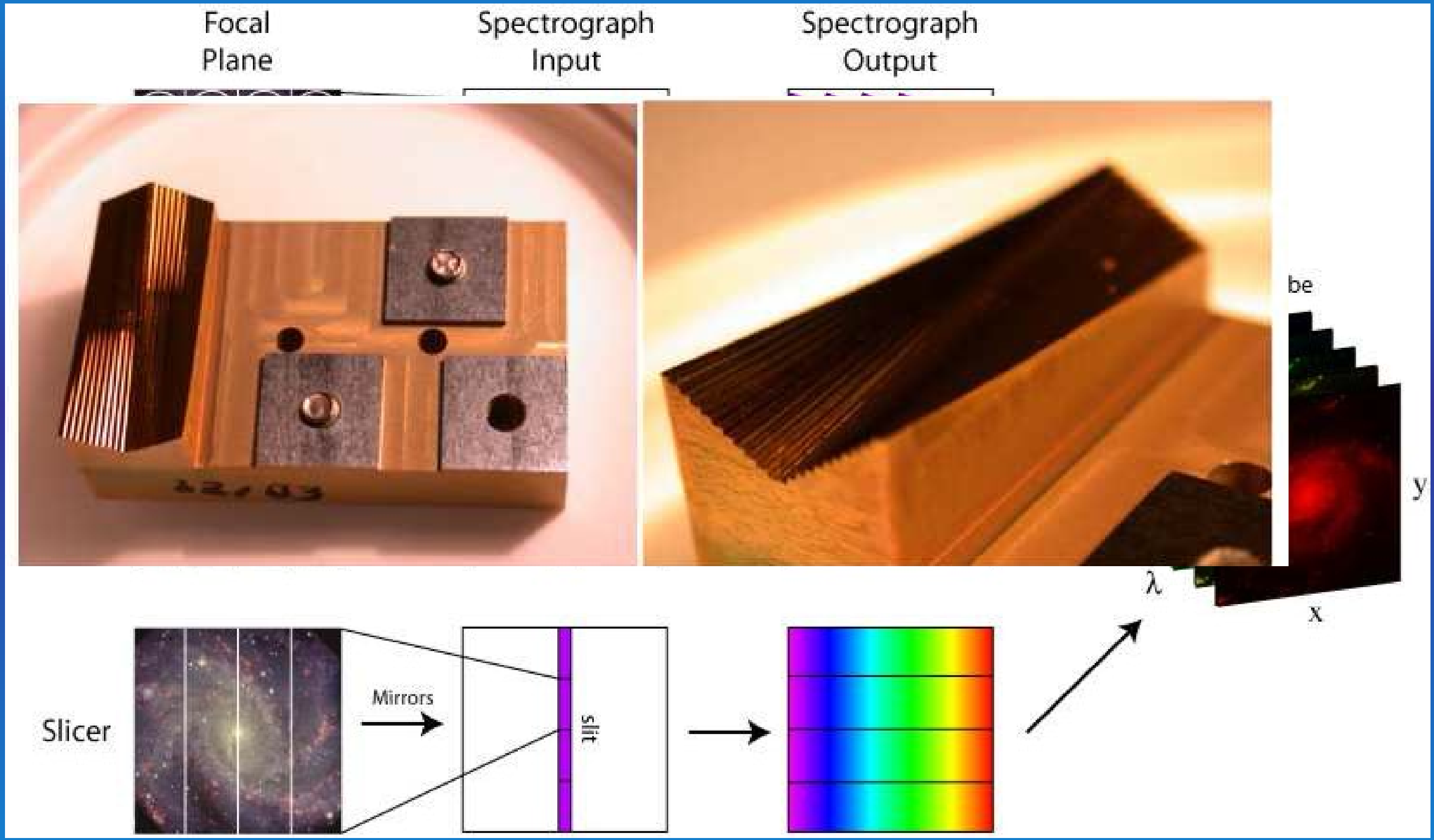
Delivered Jan. 2026

Four filter/mask wheels

Fin

Integral Field Spectrograph

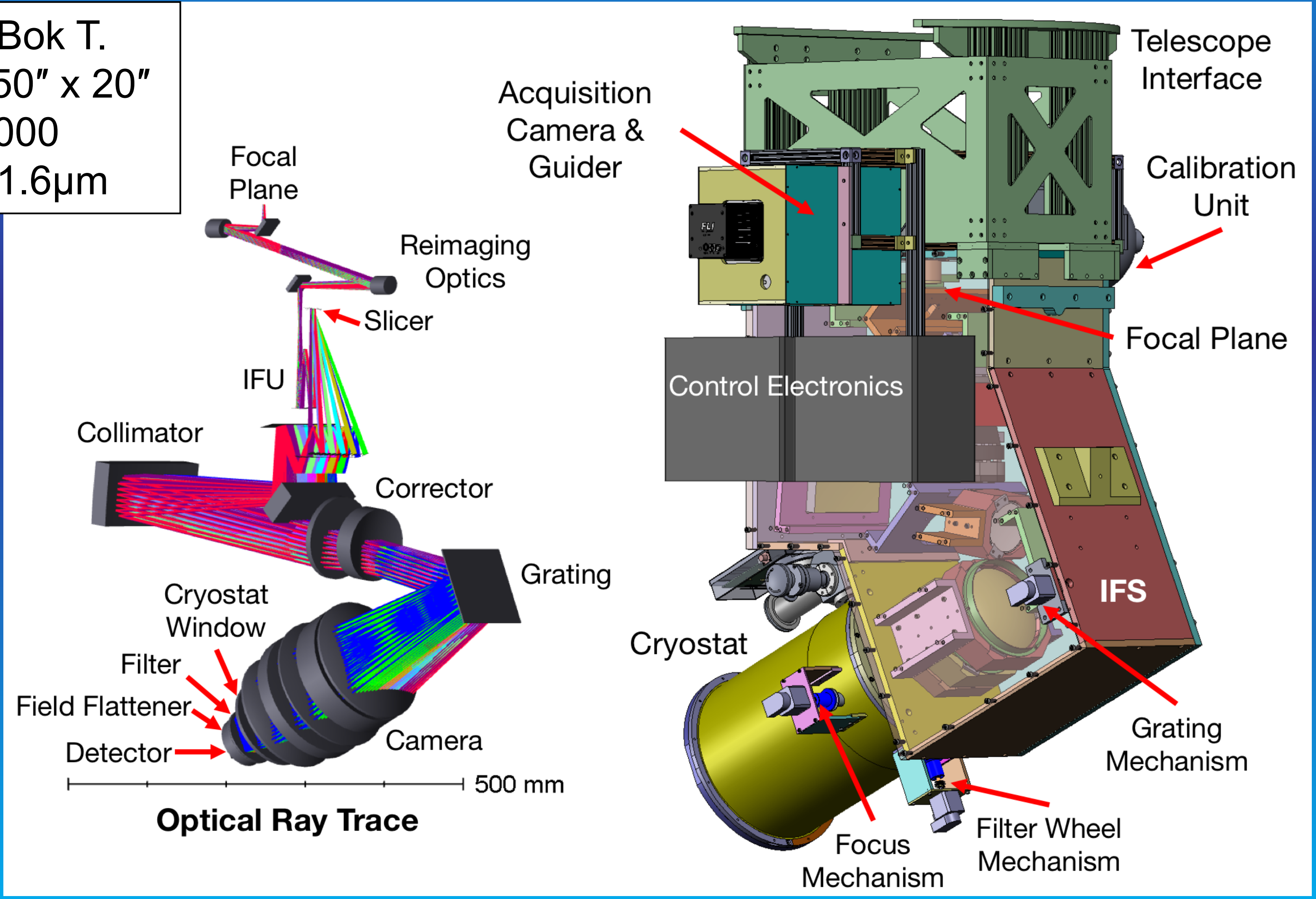




Obtaining 3-D info using 2-D sensor
FoV -> Spectrum

Wide Integral Field Infrared Spectrograph (WIFIS)

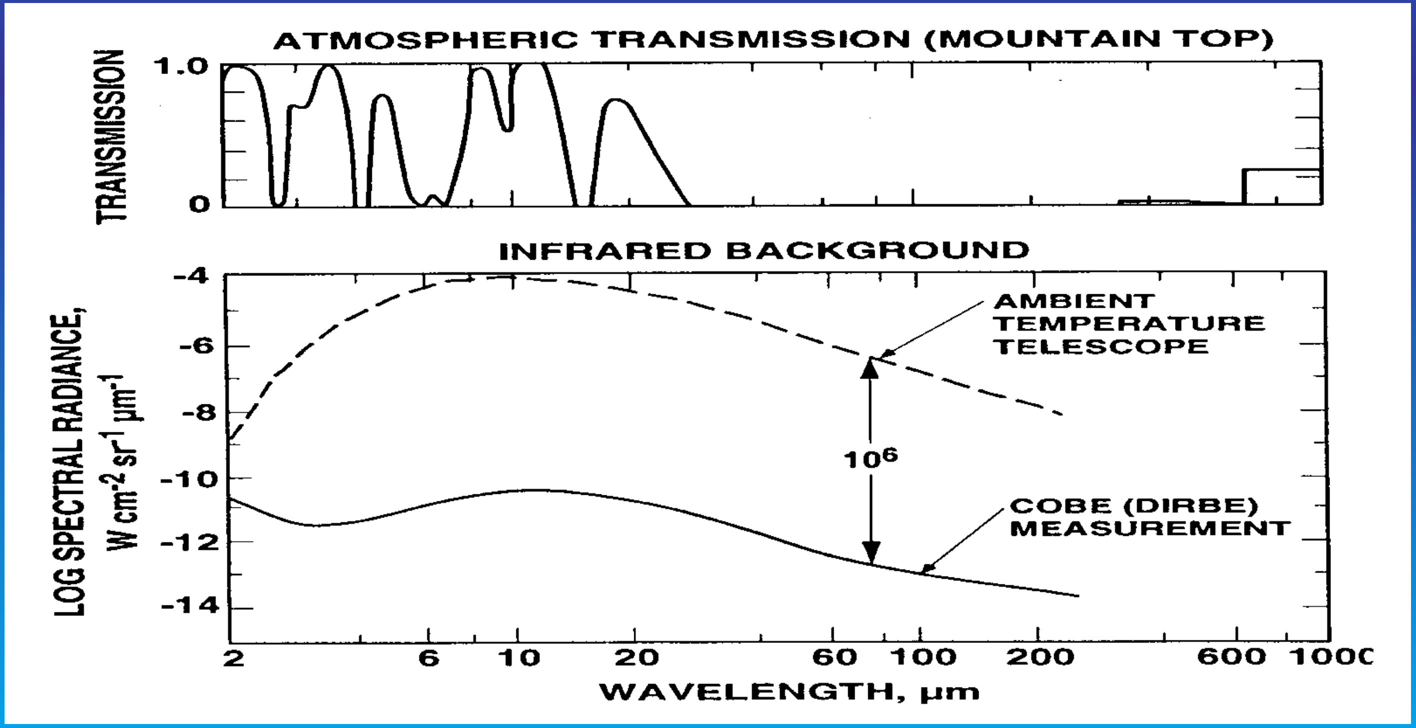
* 2.3m Bok T.
* FoV: 50″ x 20″
* R ~ 3000
* 0.9 – 1.6μm



Background in Space

Zodiacal nebula: The dust around the zodiacal plane is heated by the sunlight and also scatters the sunlight. This is the main source of background of space observation.

Cosmic Background Radiation: 2.7 K CMB.



Example: La Silla

Sky	J	H	K
Dark	16.7	15.0	13.0
Bright	15.8	13.8	12.7

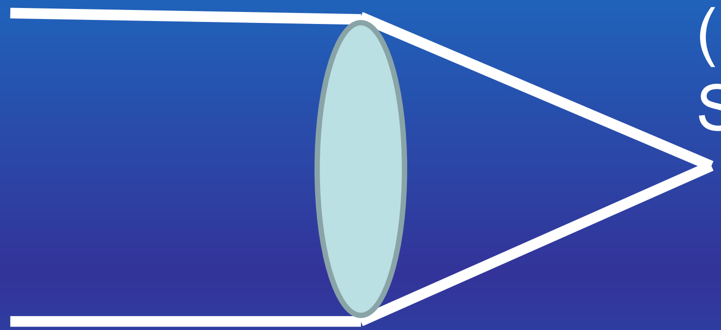
Astronomical magnitude:

$m1 - m2 = -2.5\log[F2/F1]$

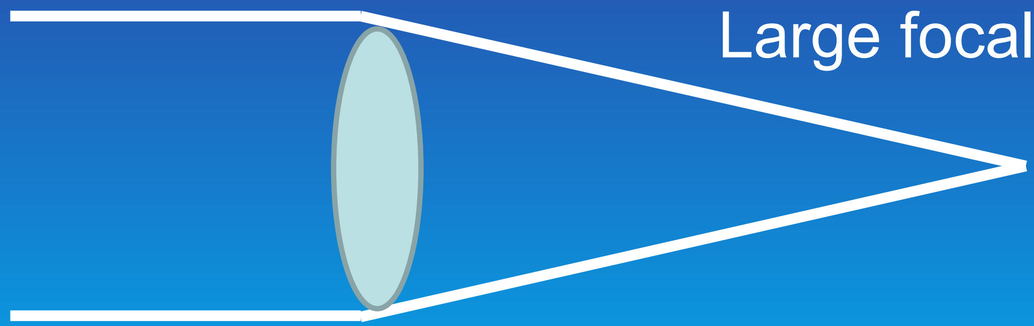
In the unit of $\mathrm{Mag/arcsec^2}$

Site	U	B	V	R	I
La Silla	21.9	22.7	21.9	21.1	19.9
Paranal	22.0	22.5	21.5	20.8	20.0
Tololo	22.0	22.7	21.8	20.9	19.9

Optical Jargons

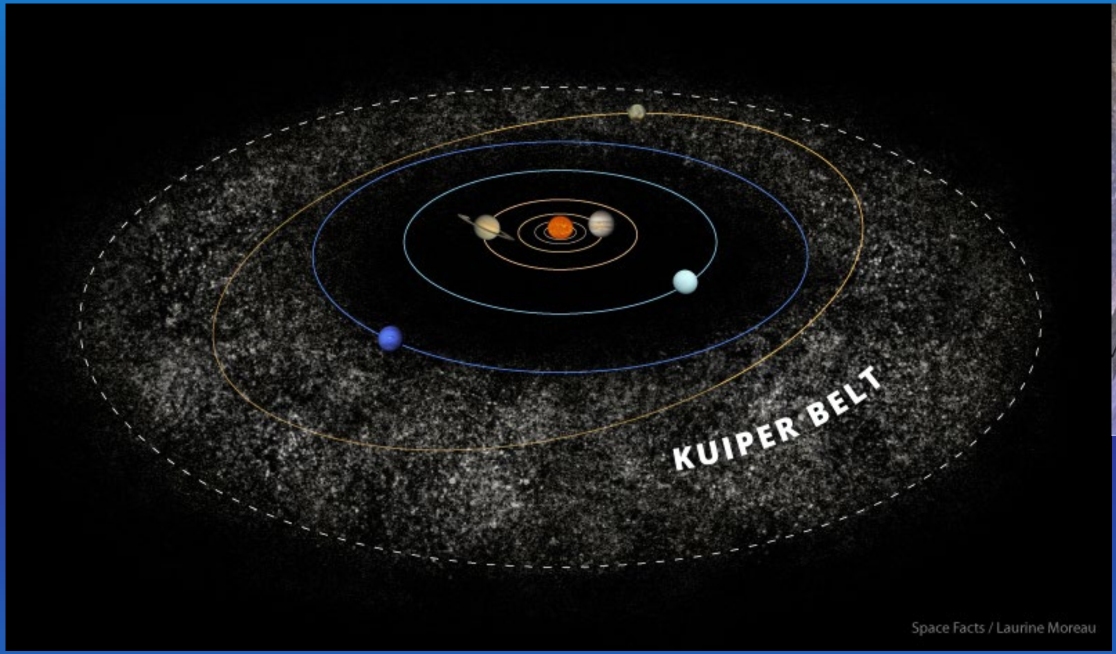


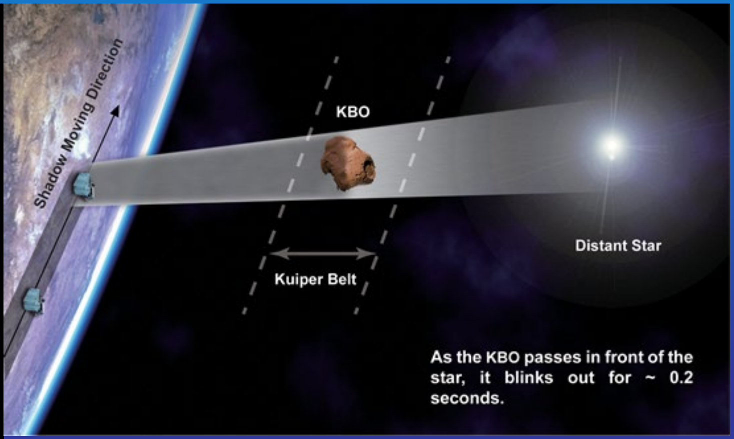
Fast system
(more light into sys.)
Small focal ratio



Slow system
(less light into sys.)
Large focal ratio

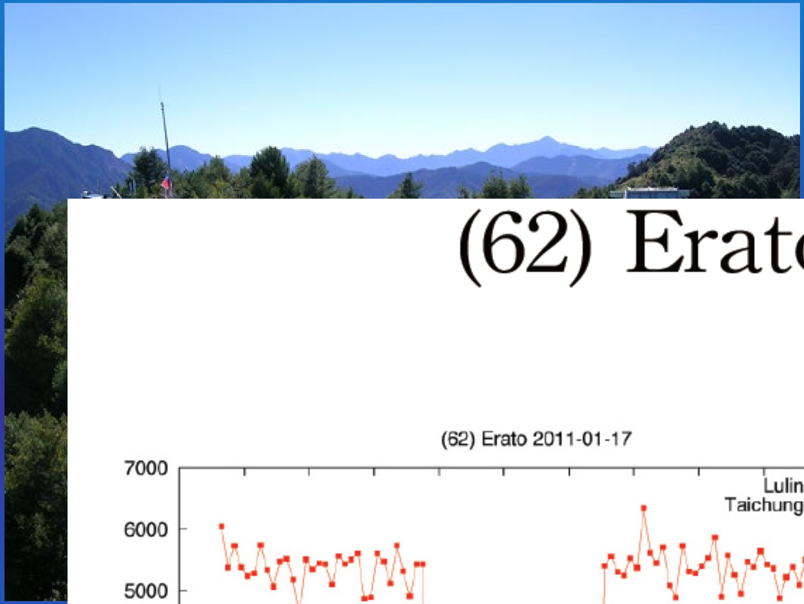
TAOSI, II

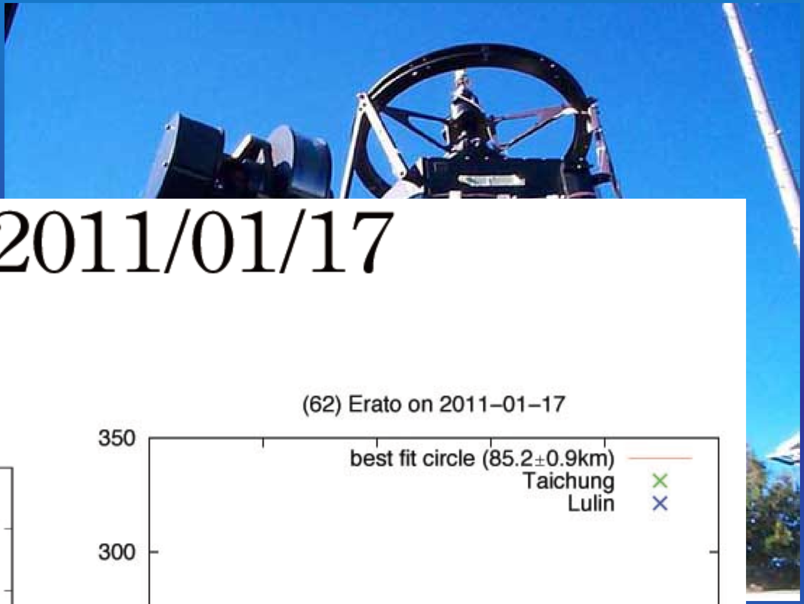




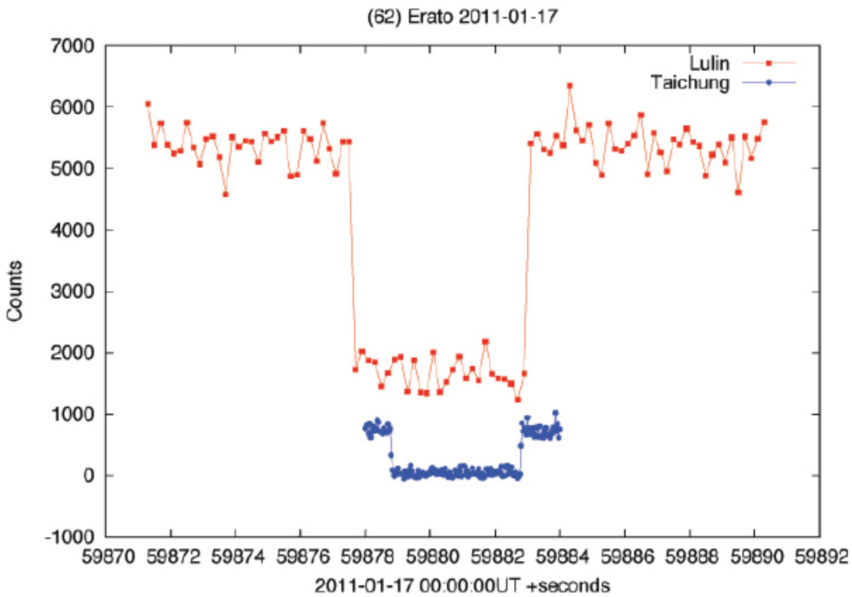
- Transneptunian Automated Occultation Survey
- Goal: to understand the number/distribution of Kuiper belt objects
- Asteroids are too dim to observe, use occultation method to study

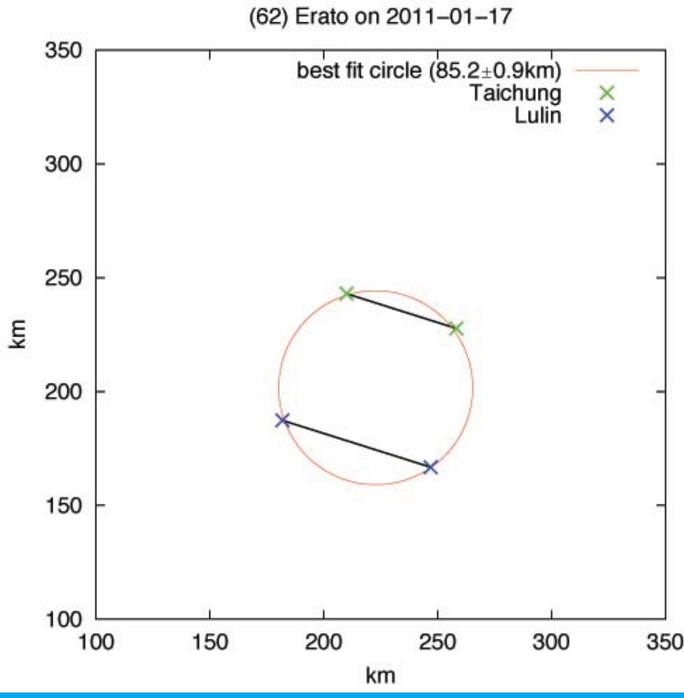
TAOS I





(62) Erato 2011/01/17



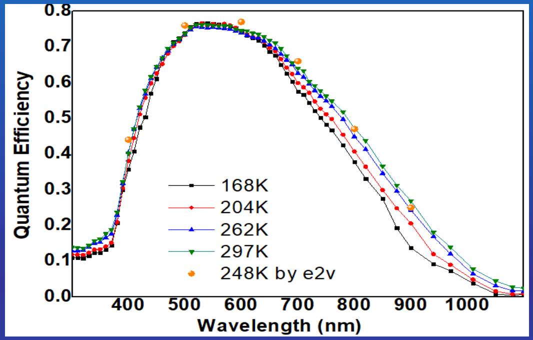


Technical Requirements

10,000 Stars Monitoring with 20 Hz Frame Rate

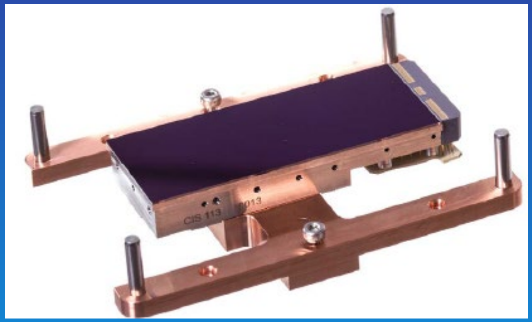
Camera Specs:

- 88 Mpix camera (3 of them)
- 20 Hz readout
- 3-4 TB of raw image data per night!
  - Sub-aperture readout
  - 250 TB/night (full frame)



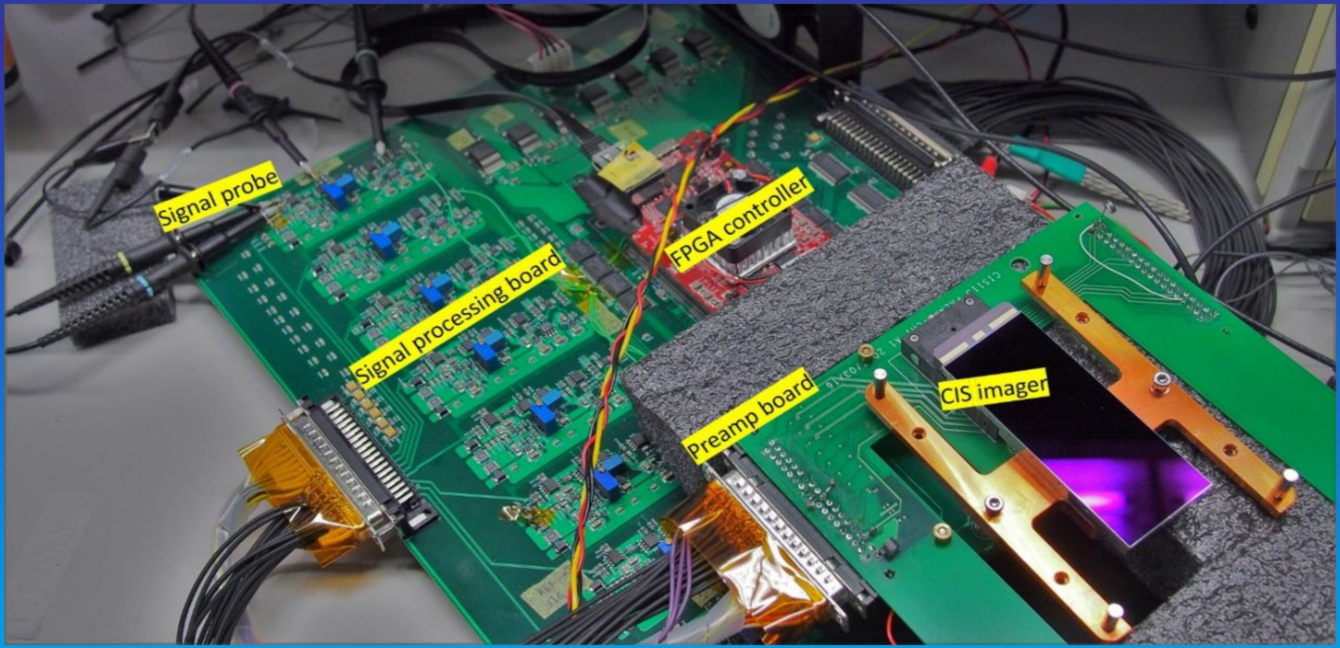
Custom CMOS from e2v

- 1920×4608 3-edge buttable
- Back side illuminated



Camera Control System

- Control electronics is based on the SAO CCD control electronics
  - FPGA based digital circuit + analog bias system and video processor
  - One system per chip, 10 FPGAs for one camera



What are needed in an instrument

- Optics: lenses or mirrors. define f/#, optical quality
- Dispersion elements: gratings, polarizer, prism, resolution needed, spectral coverage.
- Mechanical structure: enclosure, spiders.
- Sensor array: sensitivity, readout speed
- Temp controller: control working temperature
- Shutter & filters: exposure time, photometric bands
- Electronics : clock generator, ADC, preprocessing, noise
- Software : data acquisition, imaging processing pipeline