Precise Spectro-Photometry from Space

Jeroen Bouwman

Astro Tech Talk, February 19, 2016

Spectro-Photomeytry

=

Relative flux calibration for each spectral channel

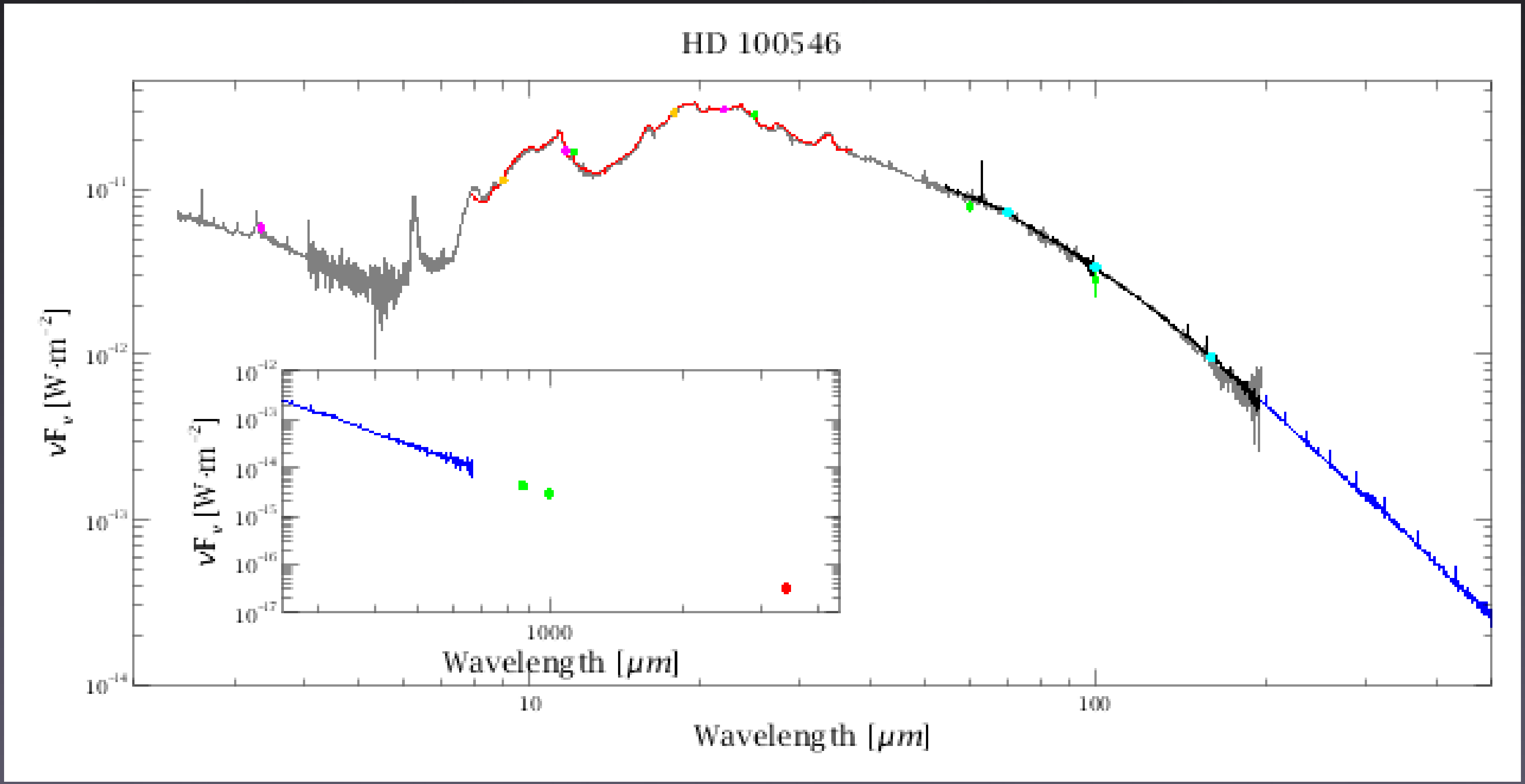
+

Absolute flux calibration

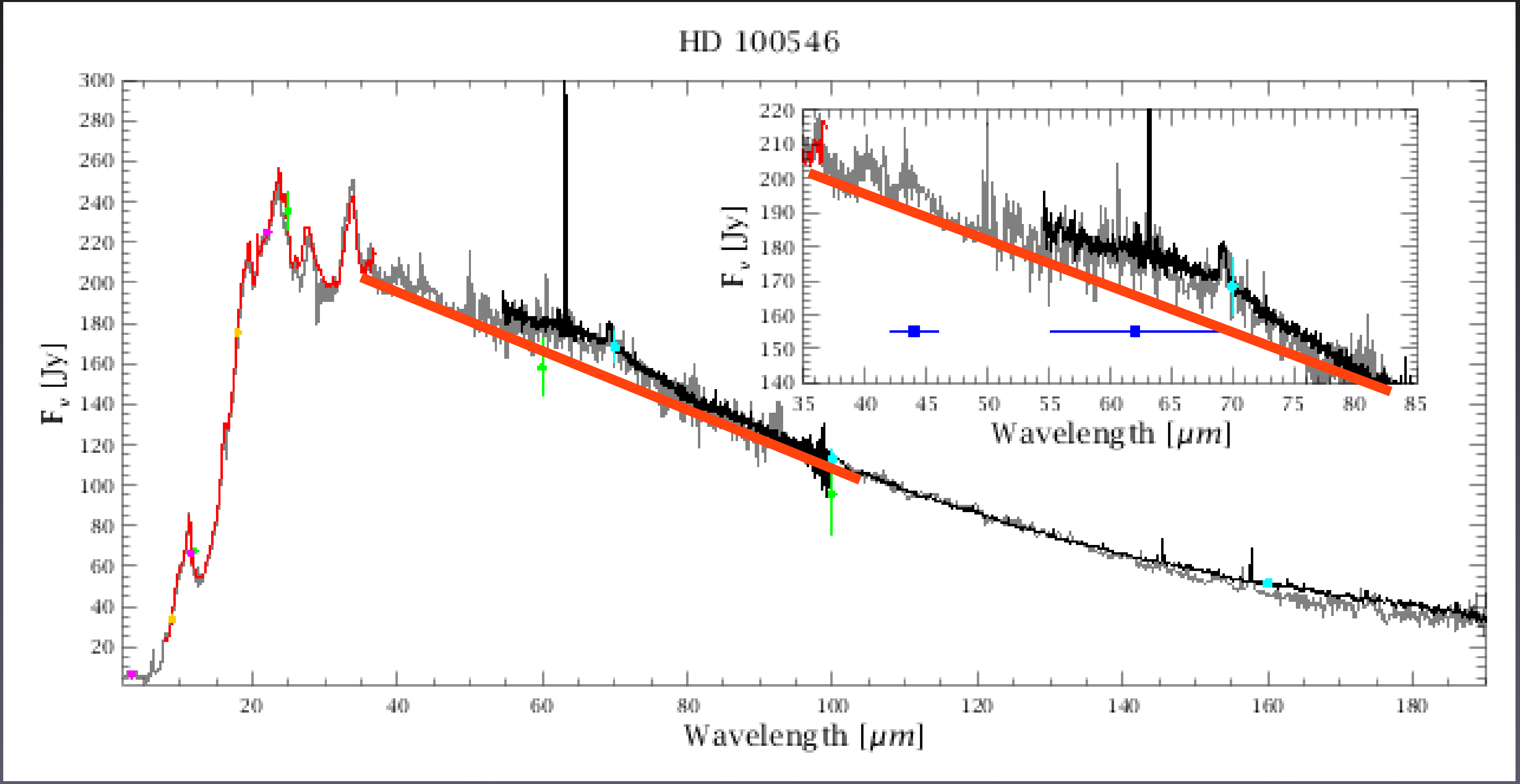
Why do we care

(apart from having a job which pays your mortgage)

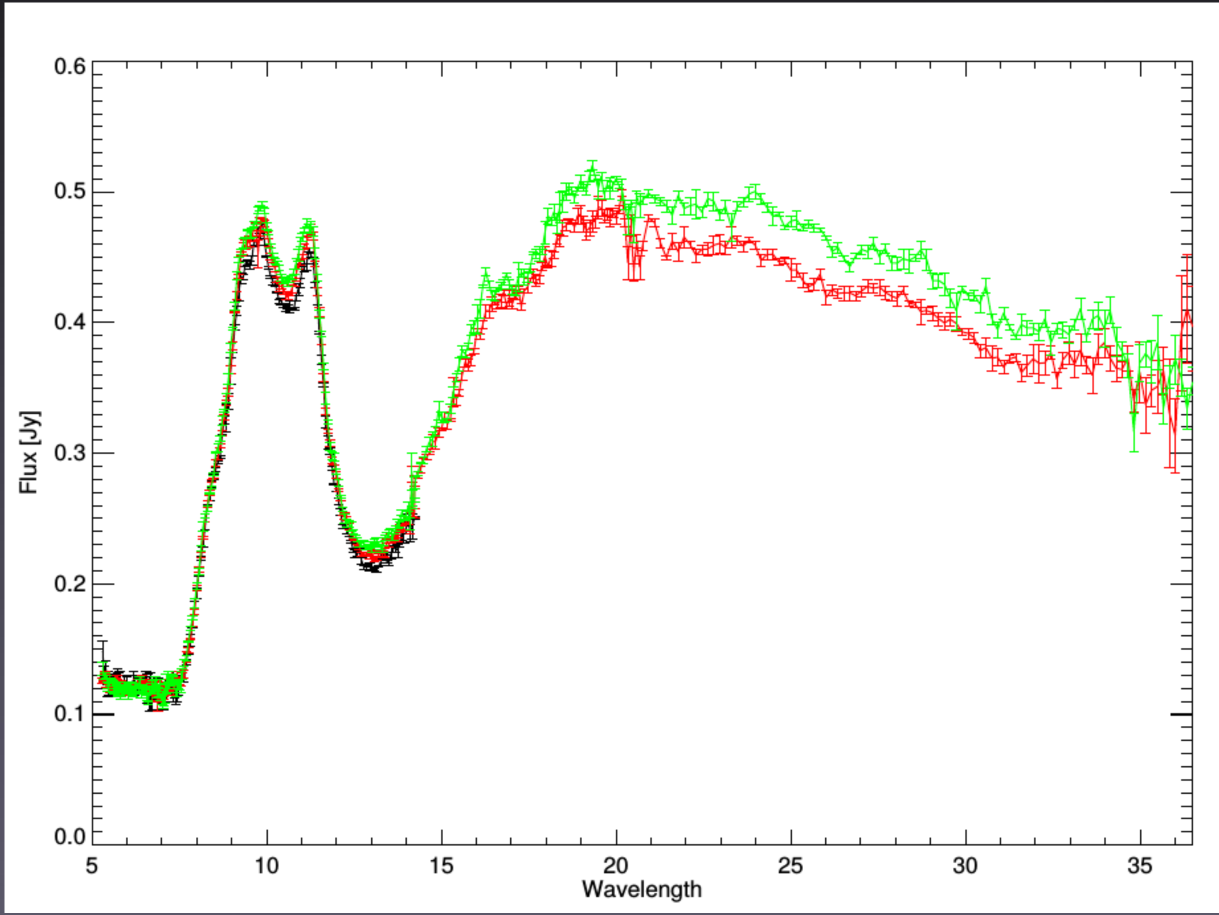
SEDs: Combining data of multiple instruments over a broad wavelength range



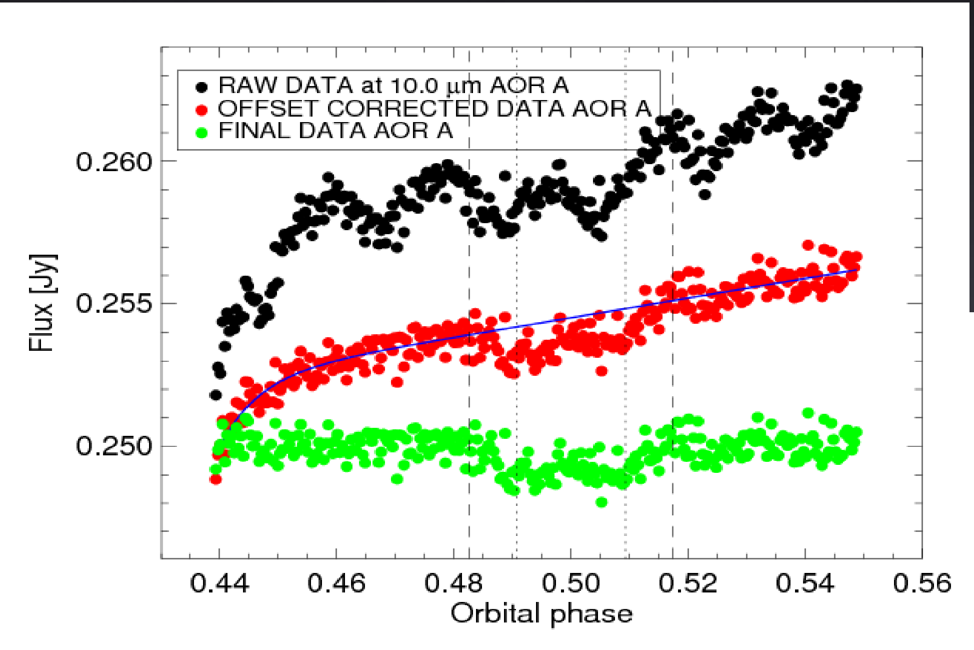
Very broad emission features: Ice bands in the spectra of HD100546

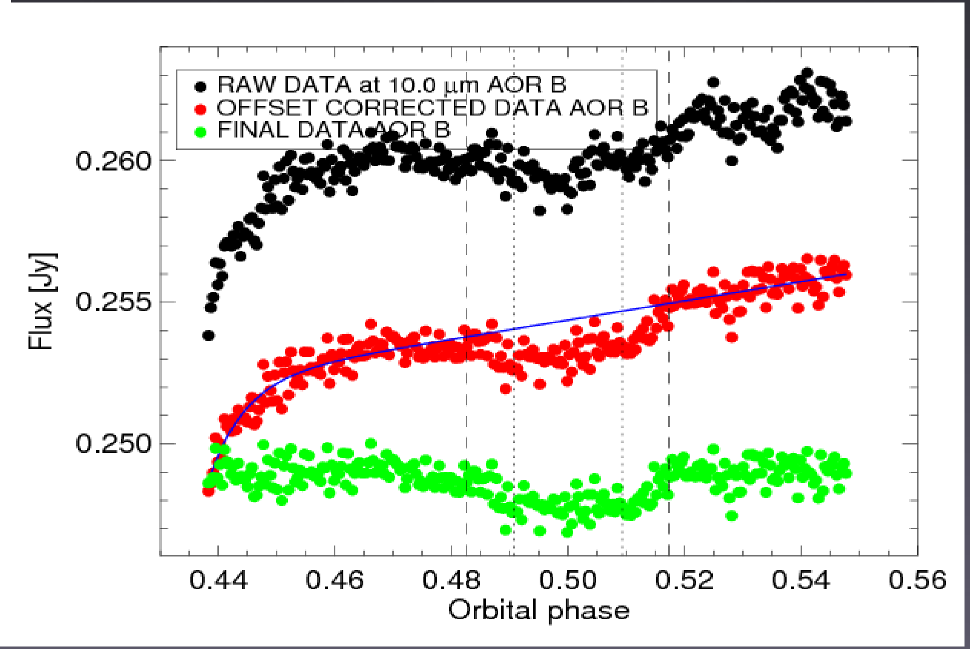


Time variability: criation and dispertion of dust in debris disks.

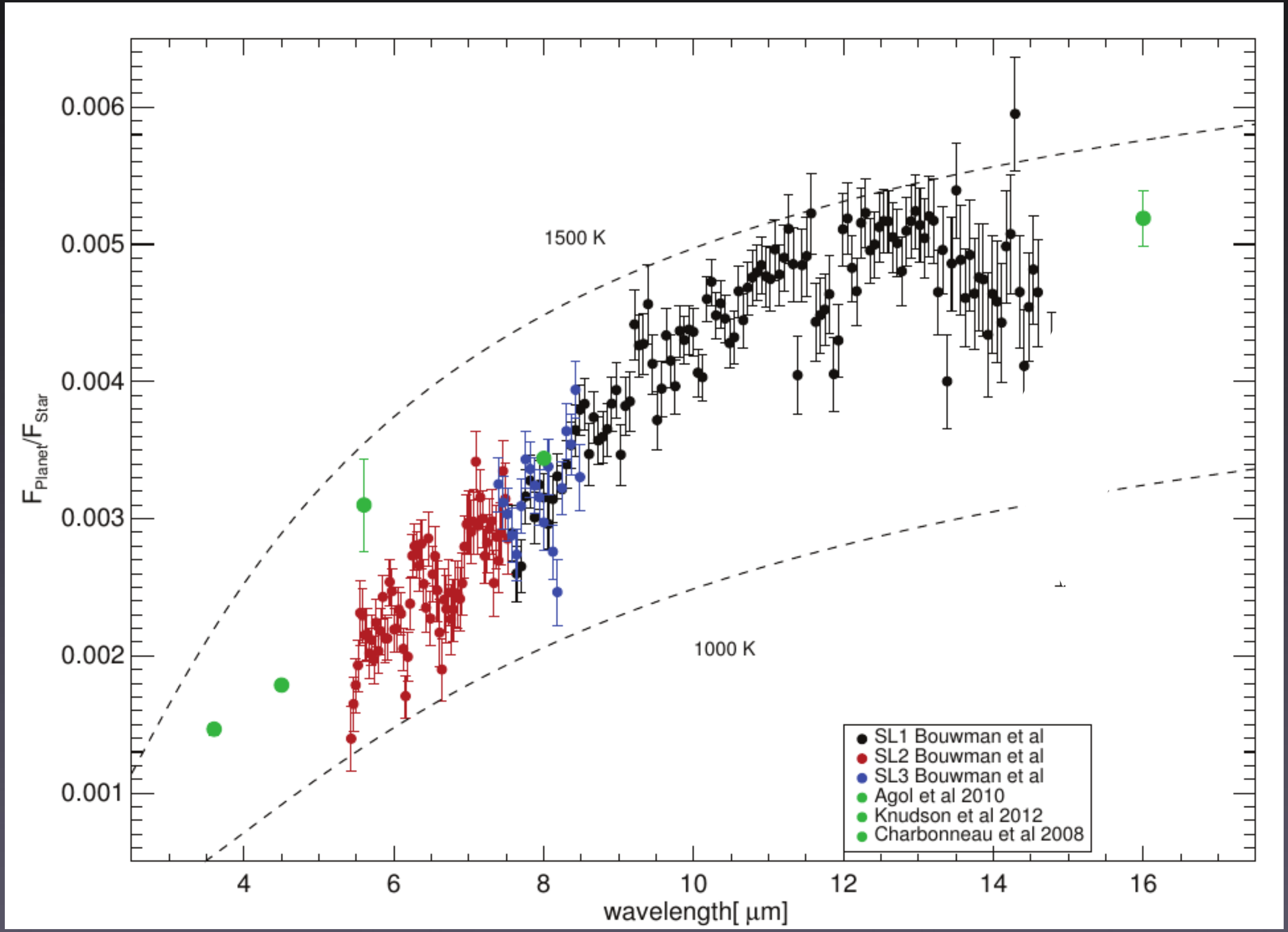


Timeseries: light-curves of the transiting exoplanet HD189733 b observed with Spitzer





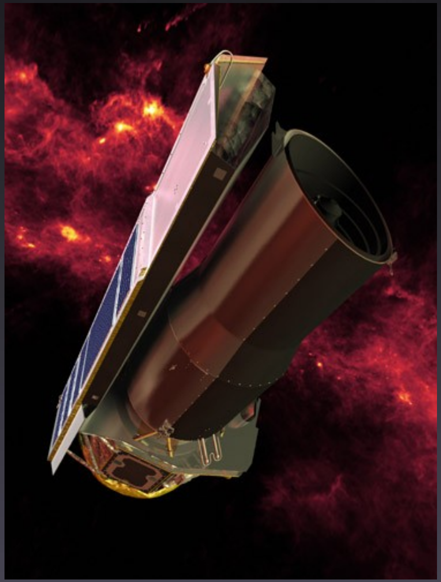
Emission Spectrum of HD189733 b



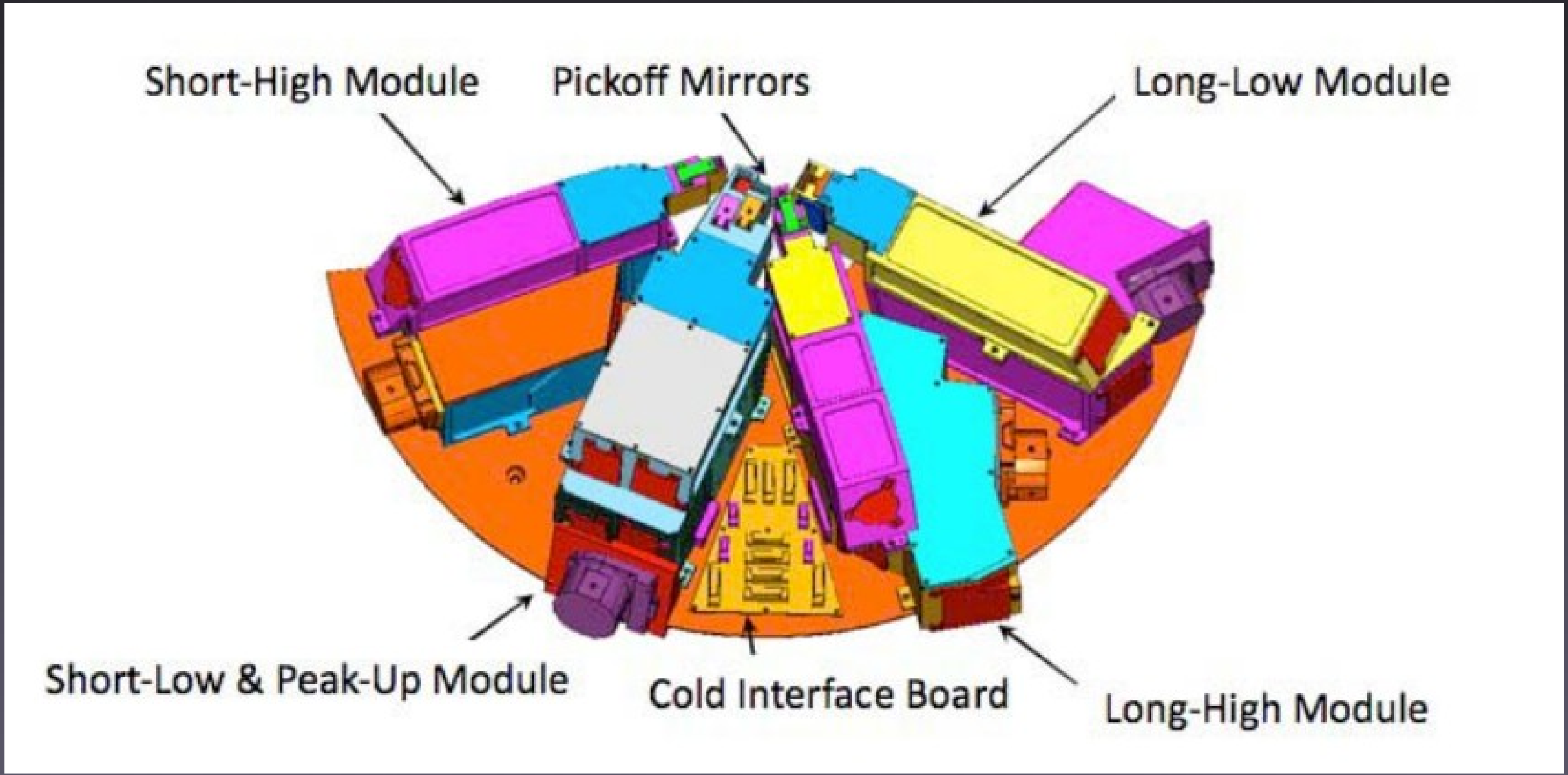
Spectroscopy used ~90h of observing time with16 transits.
(photometry about a dozen transits)

Examples of Space Telescopes/Instruments

Spitzer Space Telescope



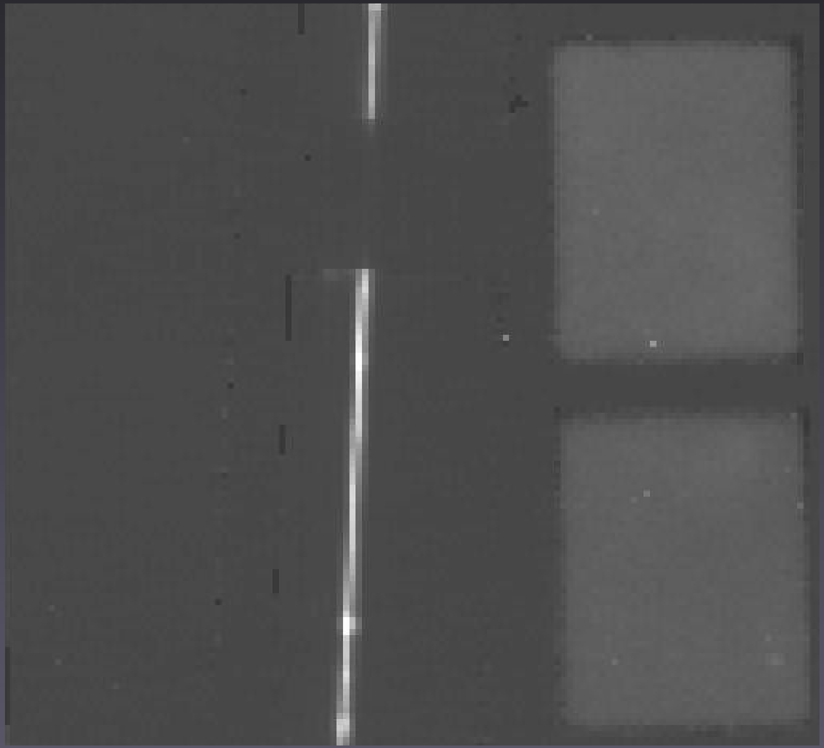
The Spitzer Space Telescope:
- 85 cm telescope, fully cooled
- three instruments:
  – near/mid IR imager : IRAC
  – mid IR spectrograph and imager : IRS
  – mid/far IR imager: MIPS


Short-High Module
Pickoff Mirrors
Long-Low Module
Short-Low & Peak-Up Module
Cold Interface Board
Long-High Module

The low resolution spectrograph of Spitzer

Short wavelength channel:
- grating
- long narrow slit (2 pixels wide; 3.6”)
- Spectral resolution of ~ 100
- Spectra between 5 to 15 micron in 3 orders
- 128x128 pixels (effectively 30x128 in 1 order)
- Detector type: arsenic-doped silicon (Si:As) array

Example data Spitzer low resolution Spectrograph

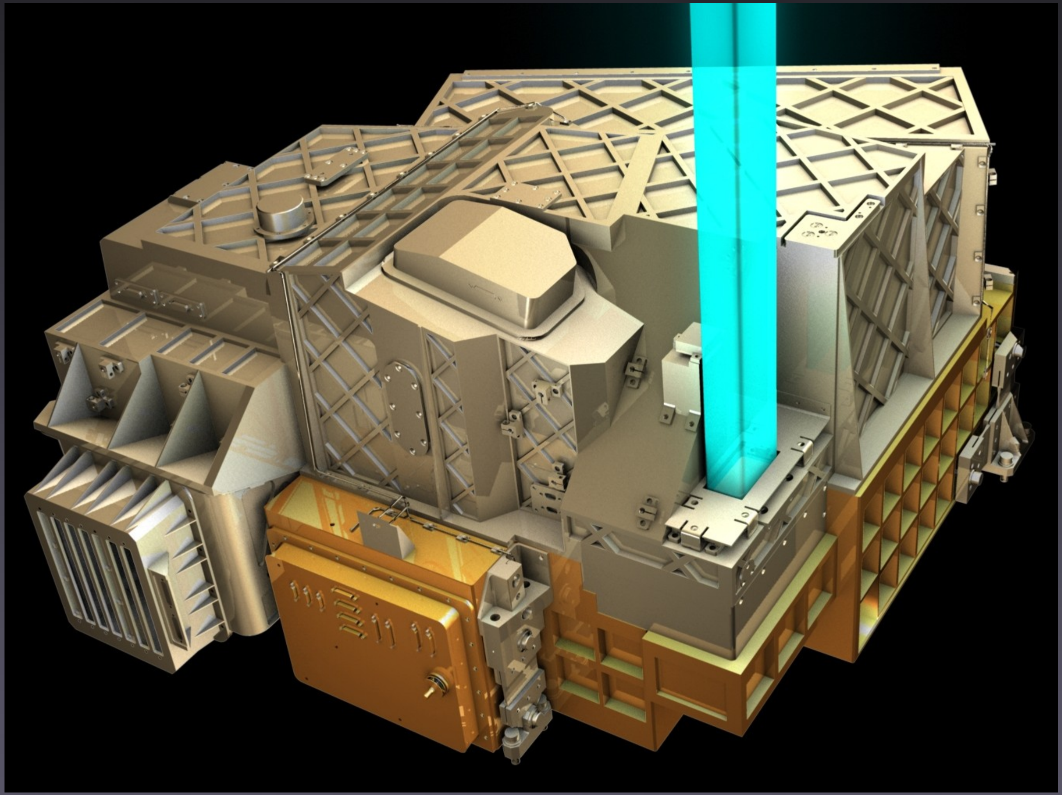


Herschel Space Observatory

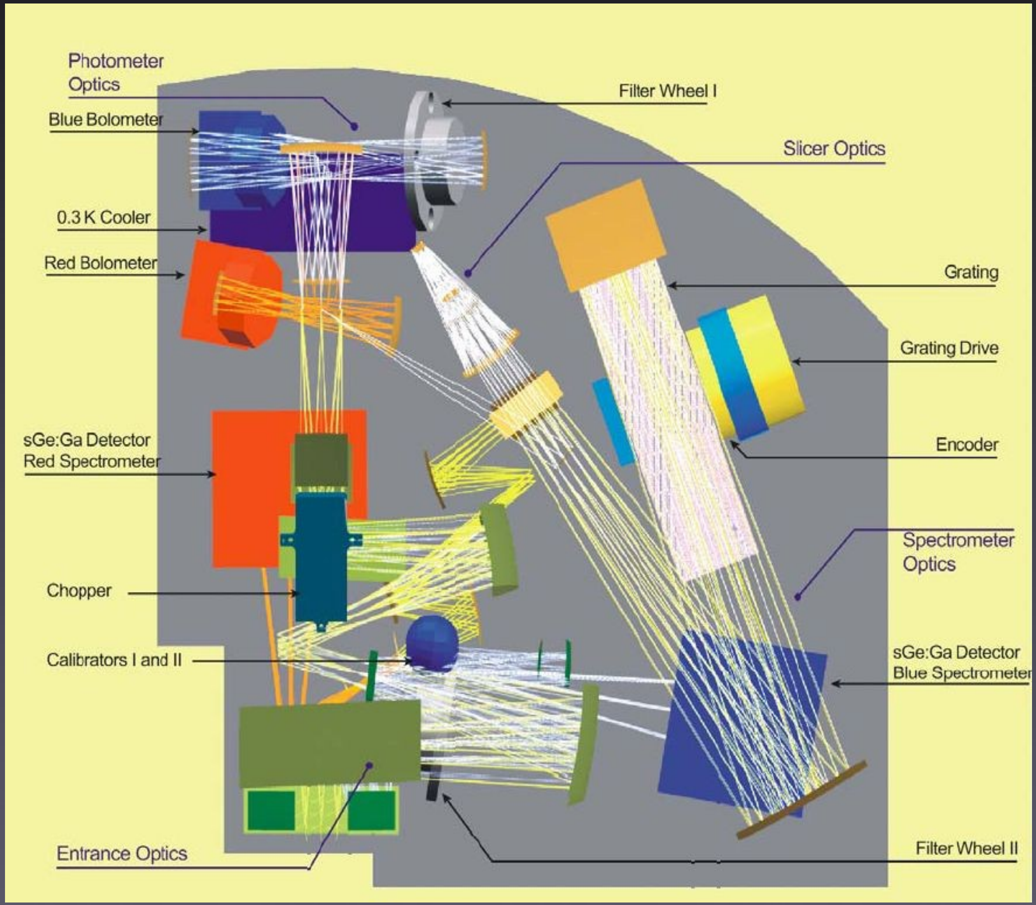
3 meter class telescope for the far IR
Instruments cooled but not the mirror.
Three instruments:

- PACS spectroscopy (52-210 microns) + photometry (70, 100, 160 microns)
- SPIRE photometry + spectroscopy for wavelengths between 200 and 500 microns
- HIFI high resolution spectroscopy (200-400 microns)

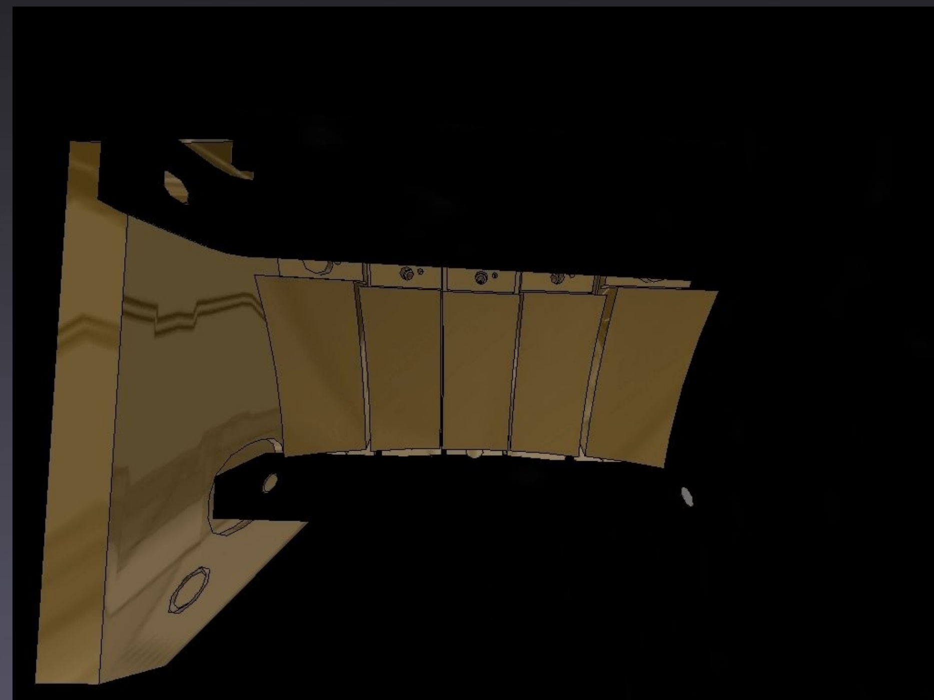
The photoconductor array camera and spectrometer (PACS)



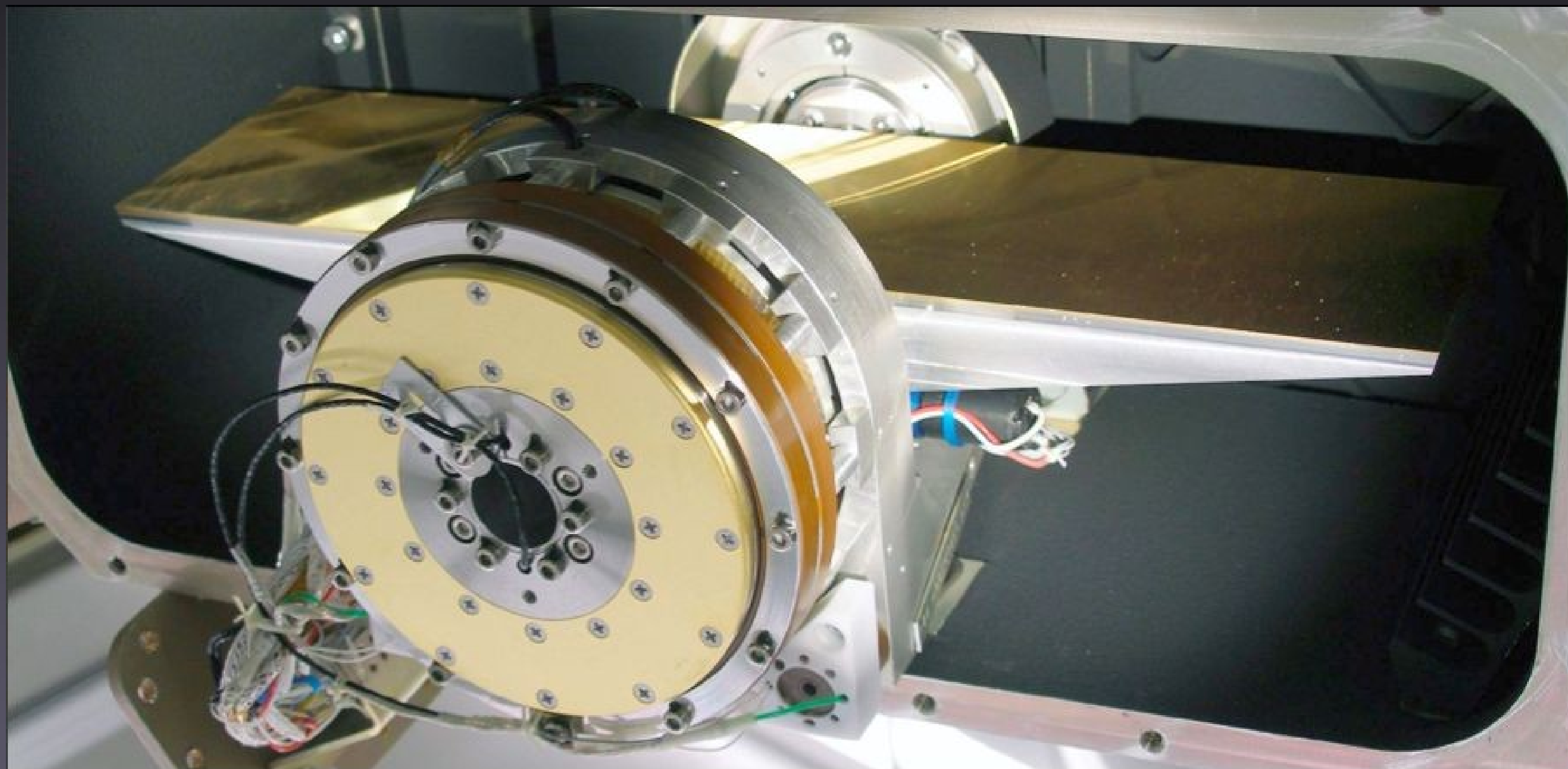
PACS floorplan



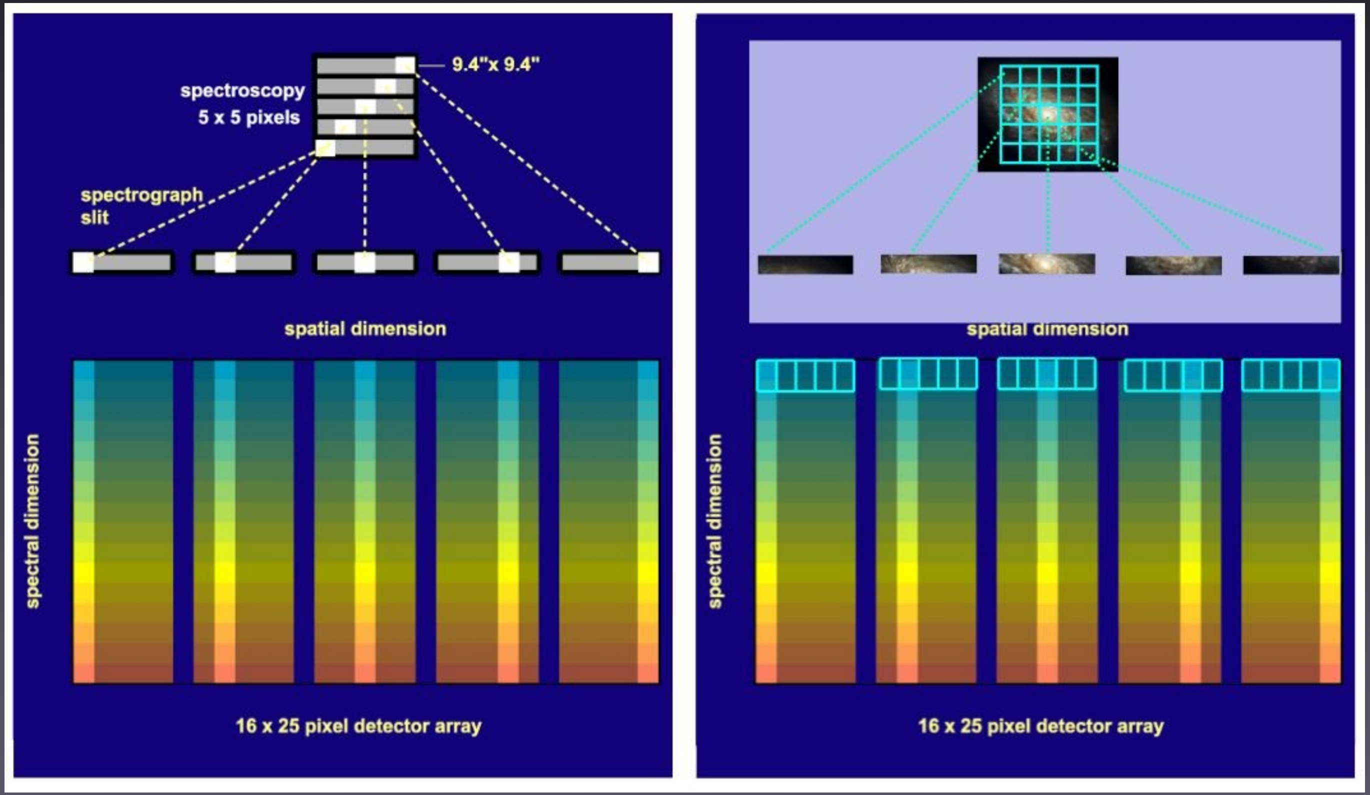
PACS Image Slicer



PACS scanning grating



PACS spectrometer

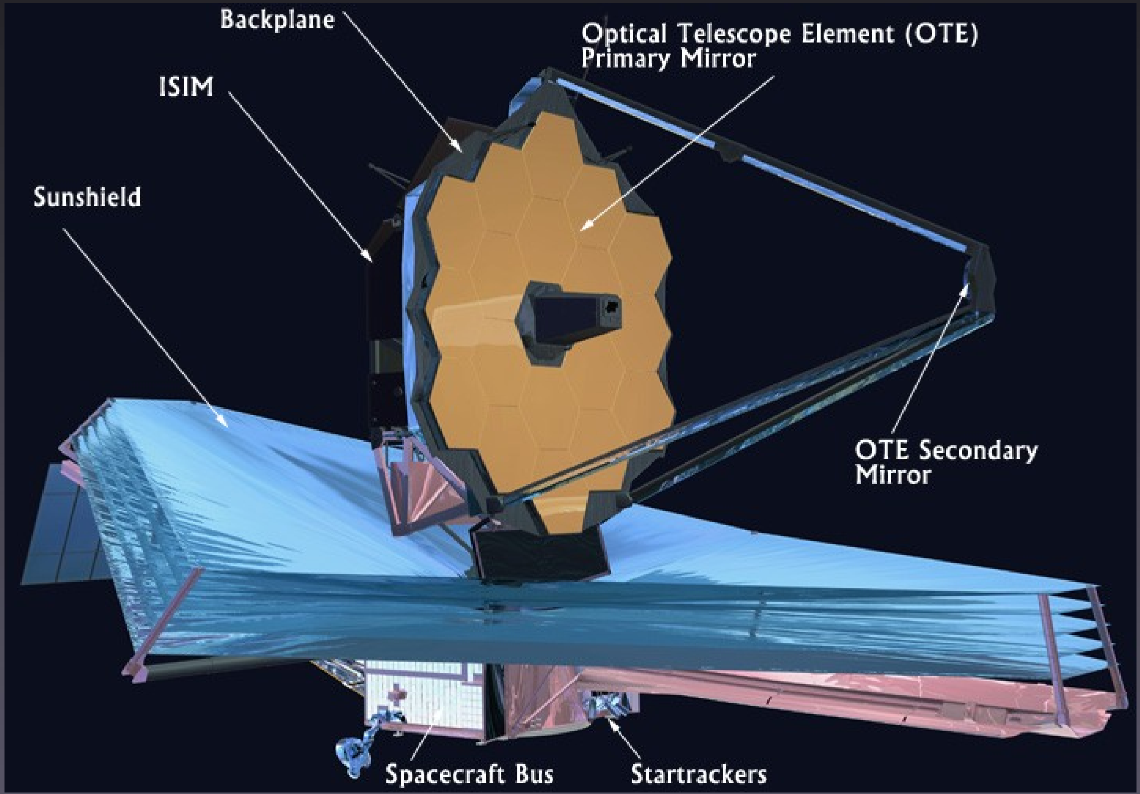


PACS chopper

(must be shown when giving talk at mpia)

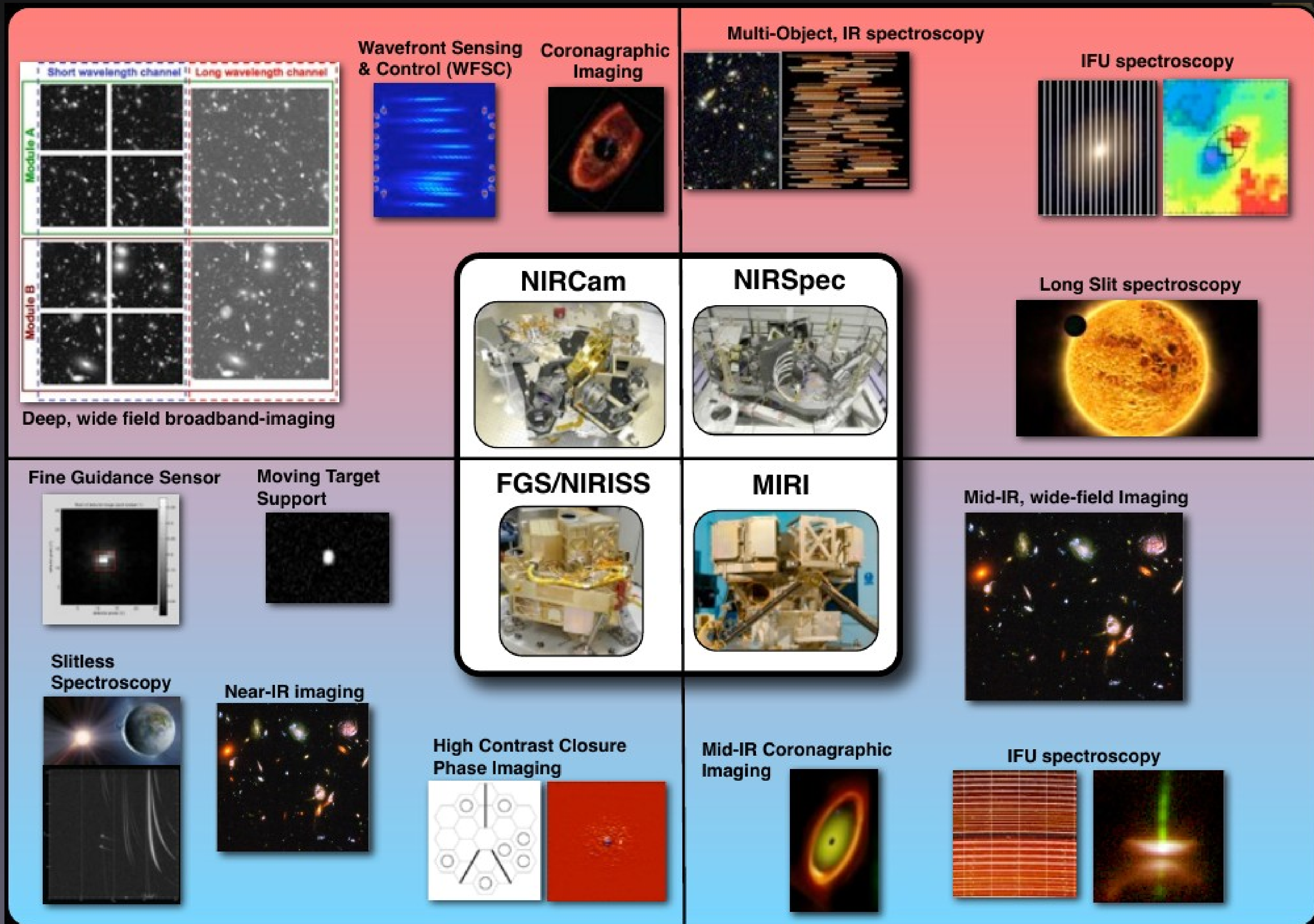
The James Web Space Telescope

Six meter class telescope
Four instruments:
- NIRIS
- NIRCAM
- NIRSPEC
- MIRI

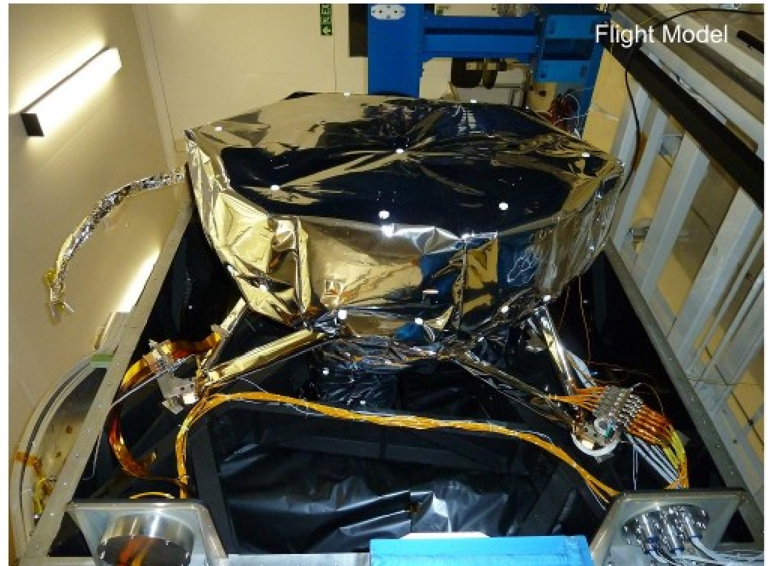


The near IR instruments are passively cooled, MIRI is actively cooled.

The instruments of JWST



The MIRI instrument on JWST



Developed by a consortium of 10 European countries and NASA/JPL

- Operating wavelength: 5 - 28 microns
- Spectral resolving power: R = 5, 70, 2000+
- Broad-band imagery: 1.9 x 1.4 arc minutes FOV
- Coronagraphic imagery
- Spectroscopy:
  - R ~ 70 long slit spectroscopy 5 x 0.5 arc sec (LRS prism)
  - R ~ 2000+ spectroscopy: 3.5 x 3.5 and 7 x 7 arc sec FOV integral field units
- Detector type: Si:As, 1024 x 1024 pixel format, 3 detectors, <7 K cryo-cooler
- Reflective optics, Aluminum structure and optics

MIRI Fields of View

It is not possible to simultaneously observe the same field with imager and spectrometer

Imager
75 x 113 arcsec

Medium Resolution Spectrometer
> 3.5 x 3.5 arcsec

4QPM Coronagraphs
15.5µm
11.4µm
10.65µm
24 x 24 arcsec.

Low Resolution Spectrometer
5 x 0.6 arcsec

Lyot Mask 23µm
30” x 30”

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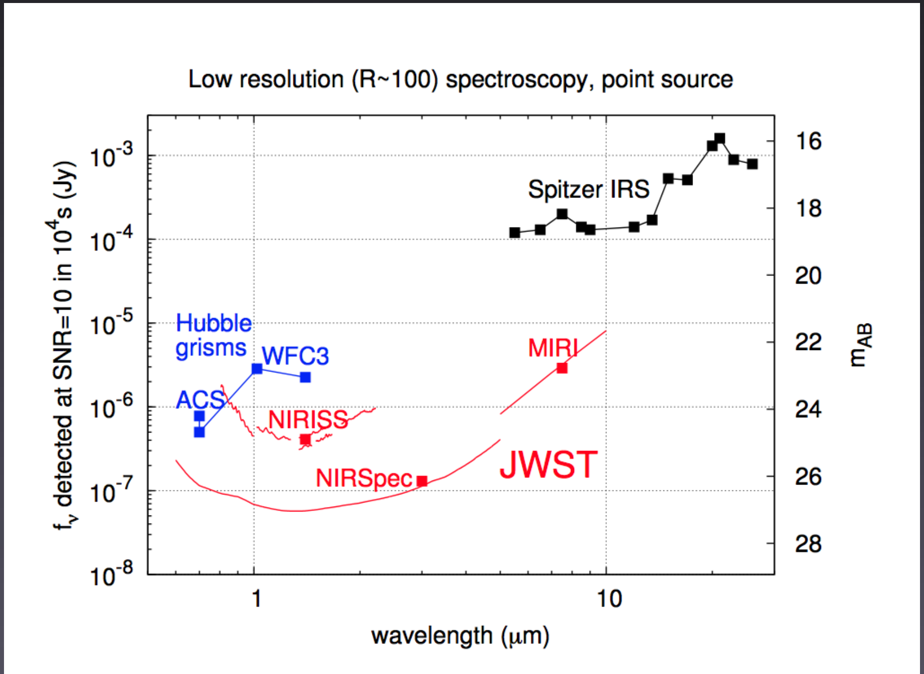
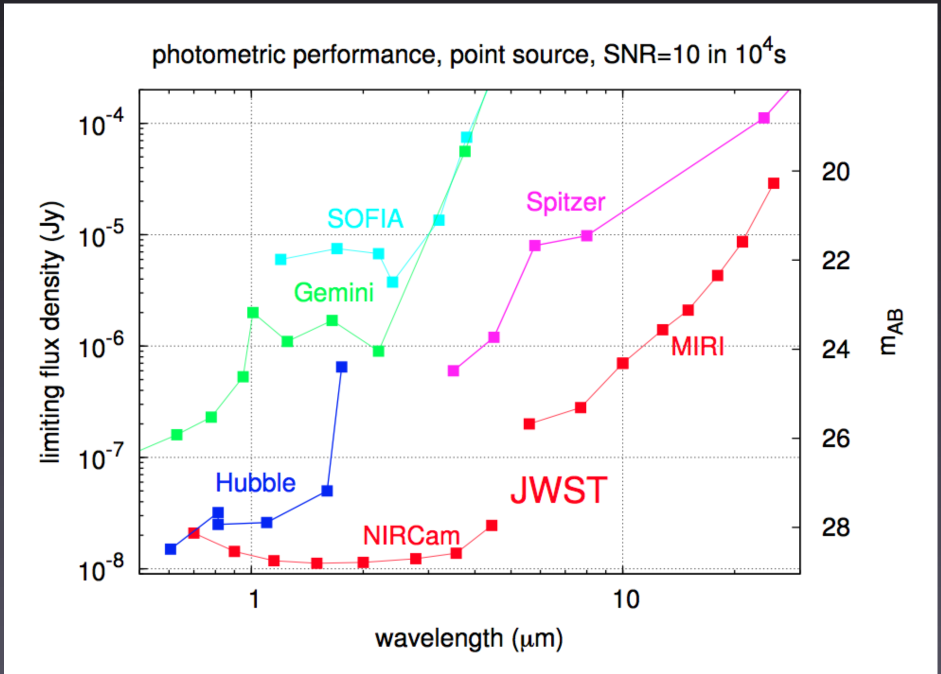
JWST sensitivity

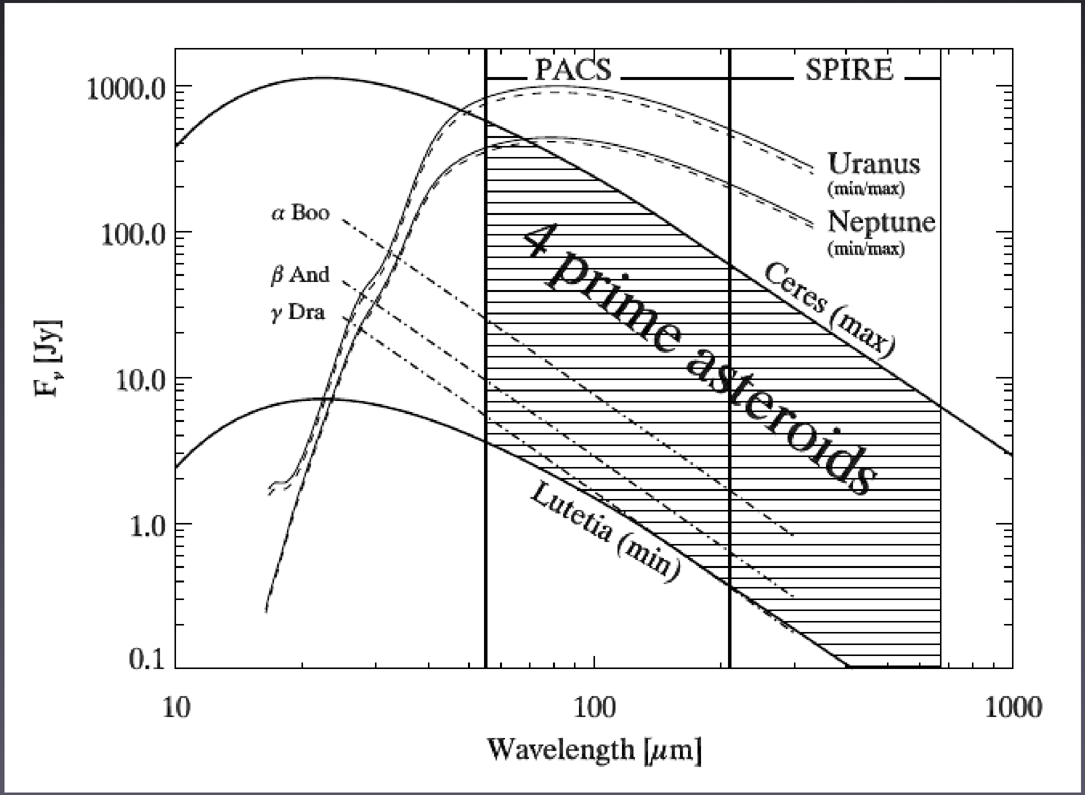




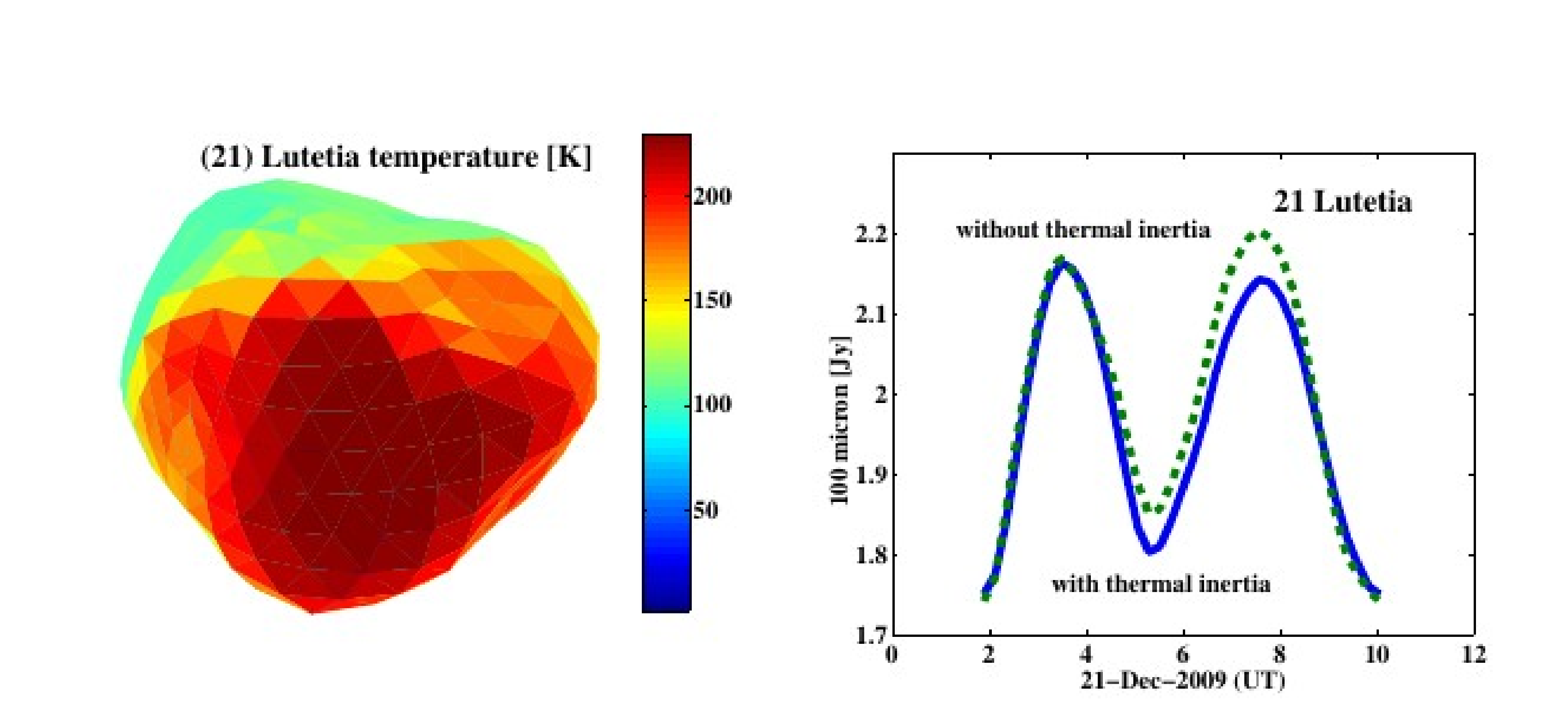
With JWST MIRI one can do spectroscopy on all targets one could observe with Spitzer IRAC.

Absolute flux calibration

Absolute Flux Calibration: Example PACS

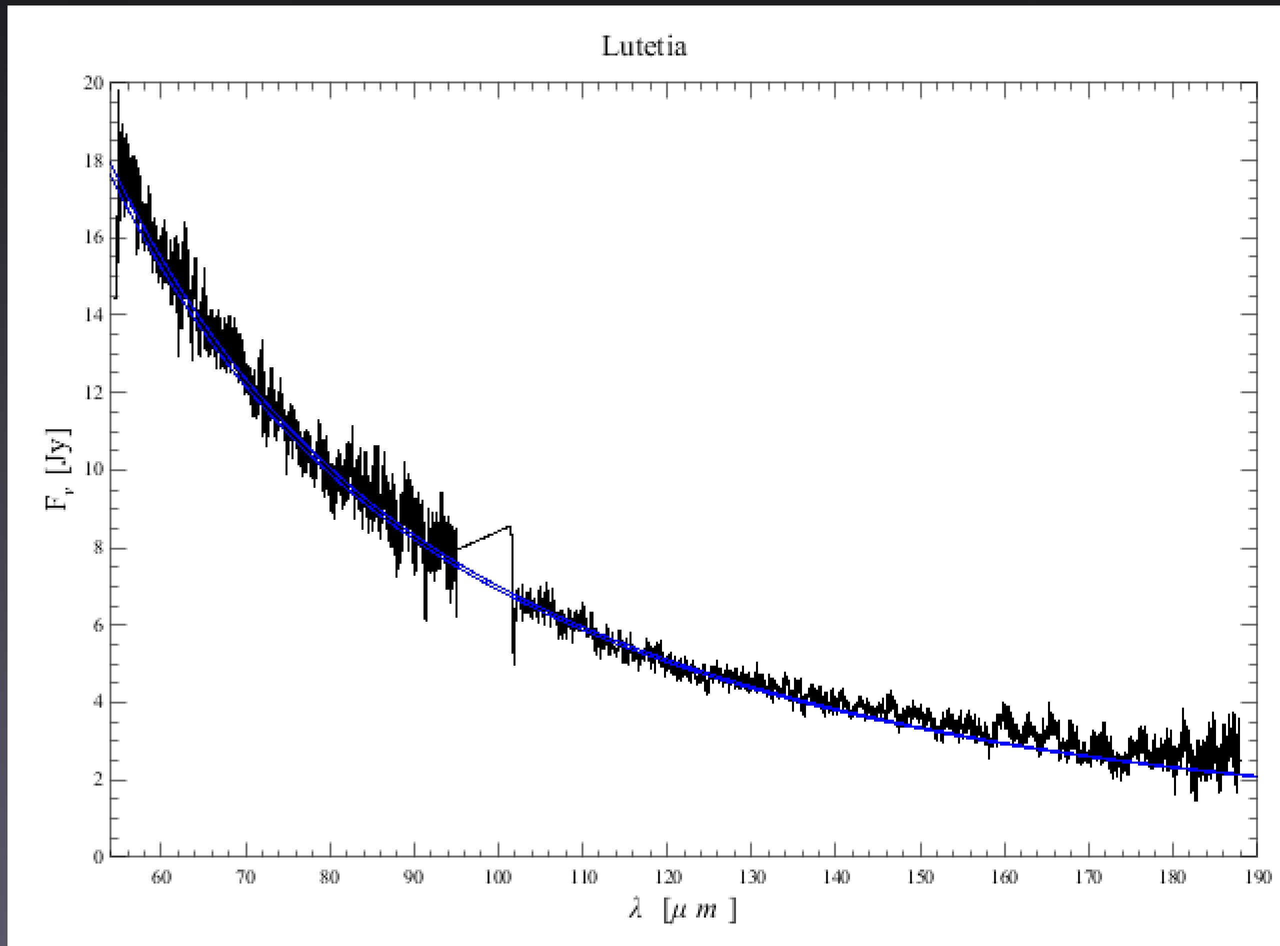


Absolute FLUX Calibration: Example PACS



Model accuracy typical a few percent

Absolute FLUX Calibration: Example PACS



Relative Flux Calibration

Noise

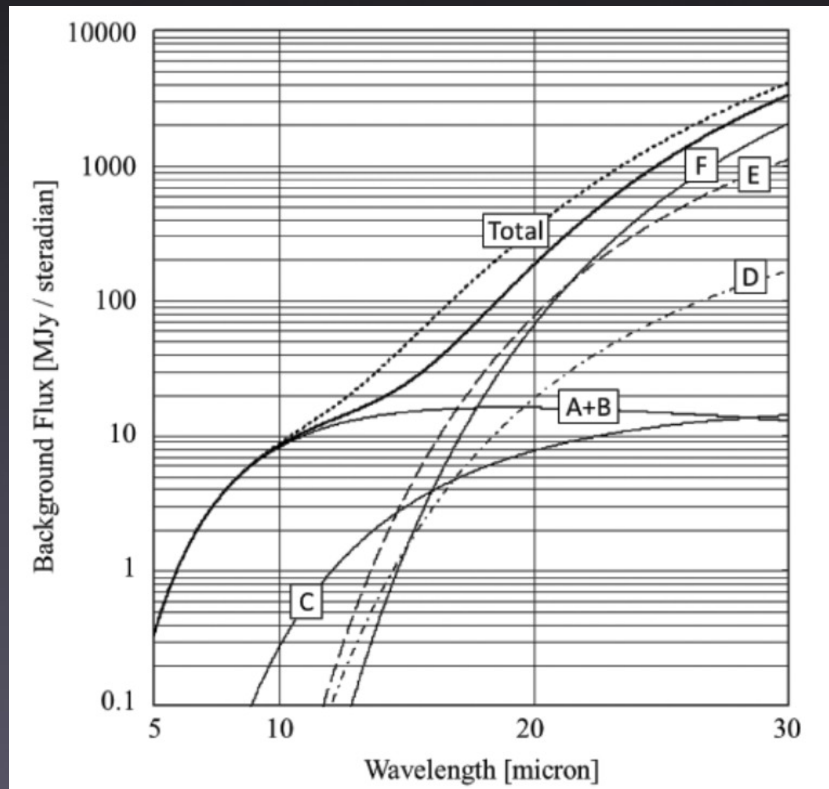
- Random noise
  - Read noise
  - Dark noise
  - Photon Noise of background

- Systematics
  - Optics
  - Detector/Electronics

Example noise: MIRI detector

Parameter	baseline array	contingency array
format	1024 x 1024	1024 x 1024
pixel size	25 μm	25 μm
read noise*	14 e^-	14 e^-
dark current	0.2 e^-/s	0.07 e^-/s
quantum efficiency**	$\geq$ 60%	$\geq$ 50%
nominal detector bias***	2.2V	2.2V
well capacity	$\sim$ 250,000 e^-	$\sim$ 250,000 e^-

Example noise: JWST background



Compare: PACS ~2.5 x 10^5 Mjy/sterradian @ 50 microns

Example noise: MIRI detector+background

$$S_{int} = i_{sig} t_{int}$$

$$N_{int}^2 = k1 \; (i_{sig} + i_{bgd}) \, t_{int} + k2 \; i_{dark} \; t_{int} + k3 \; R_N^2$$

$$k1 = k_{exc} \frac{6}{5} \left(\frac{n_{read}^2 + 1}{n_{read}^2 - 1} \right)$$

$$k2 = 1$$

$$k3 = k_{RNobs} \frac{12 \, n_{read}}{n_{read}^2 - 1}$$

$K_{exc} = 1.3$

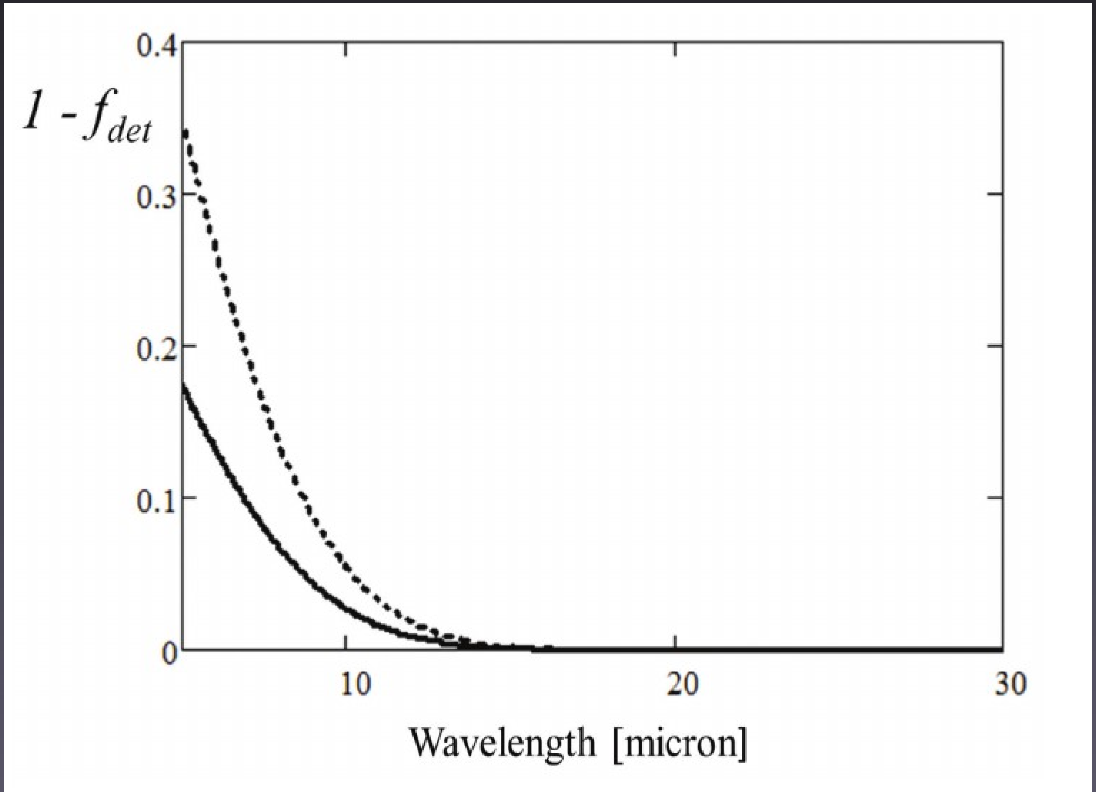
$K_{RNobs} = 1.23$

Noise floor 50 ppm

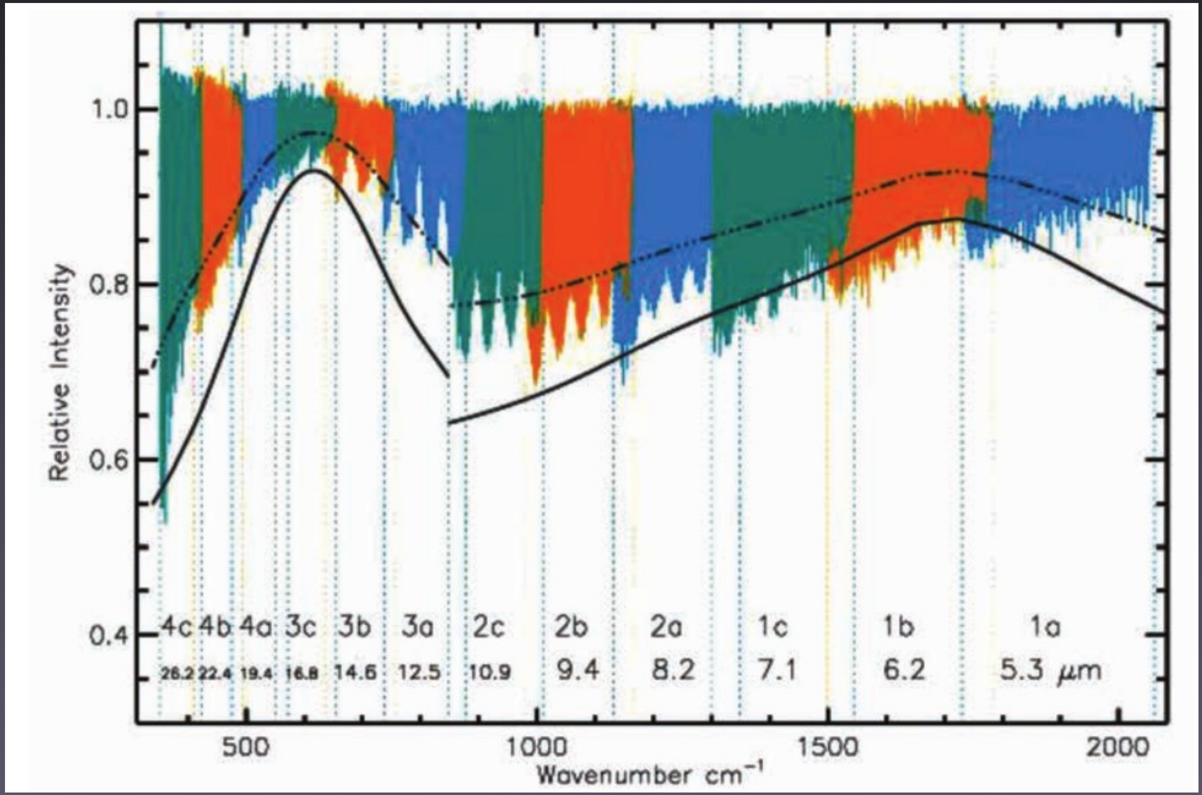
Sytematics 1

Optical Problems

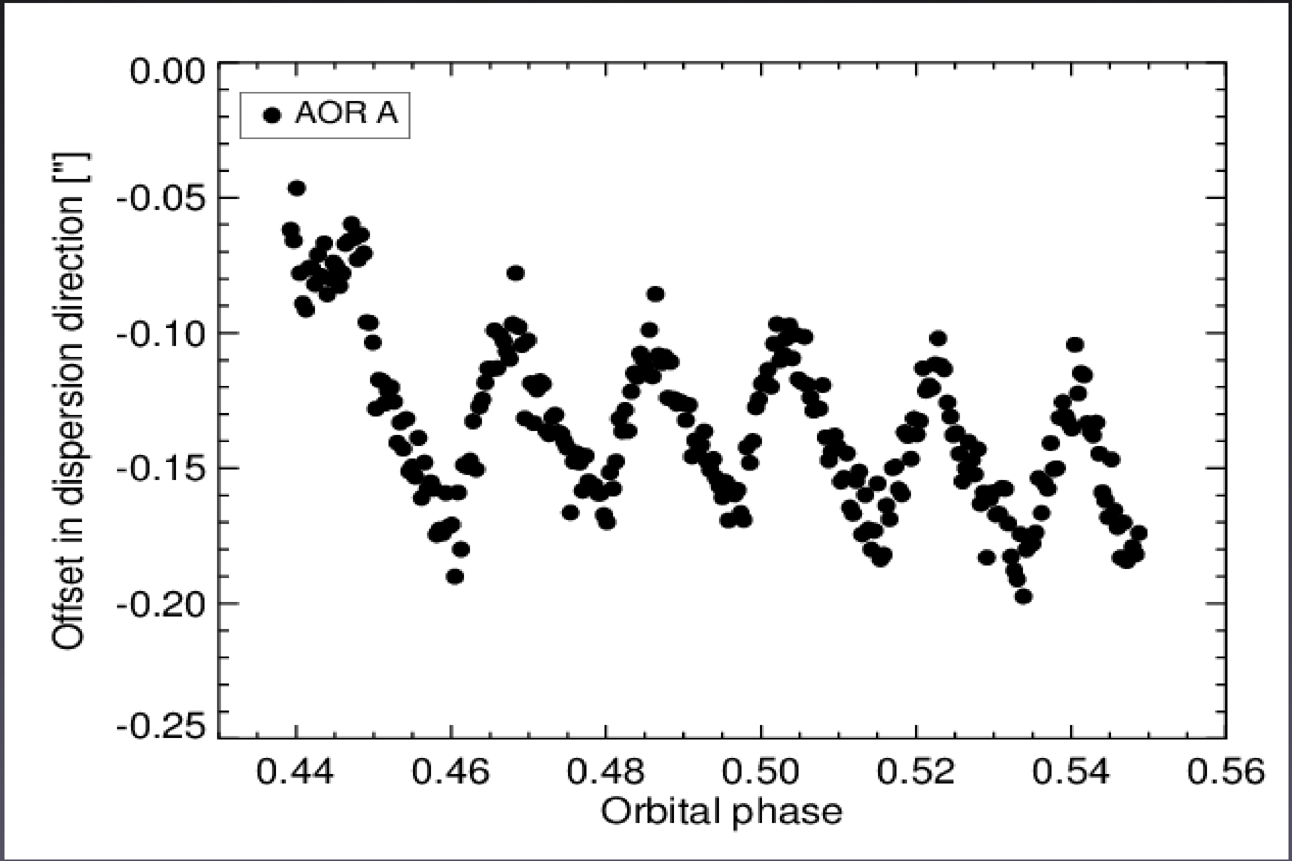
Example Systematics: Light scattering out of detector pixel



Example systematics: MIR MRS detector fringing

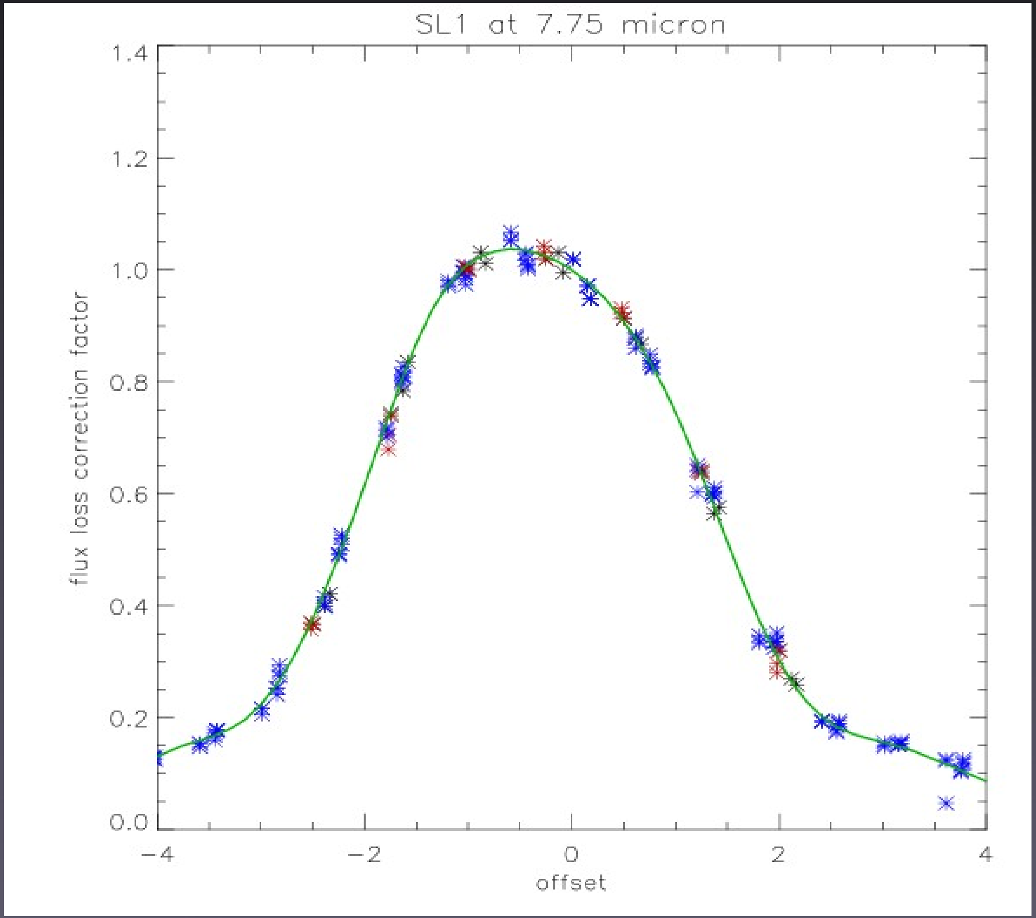


Major Problem: Pointing

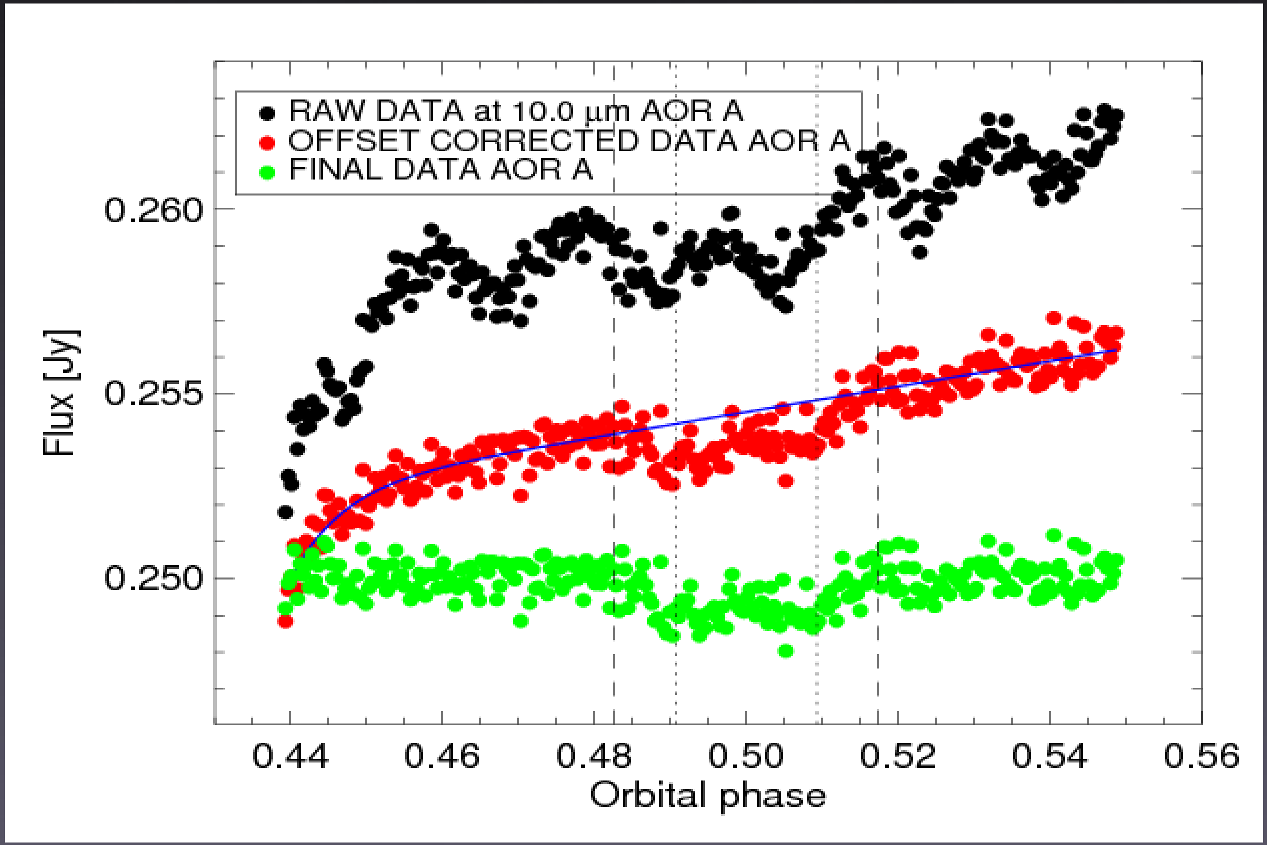


Pointing accuracy:
Spitzer: 0.2 arcsec, Herschel: 1arcsec, JWST: 0.007 arcsec

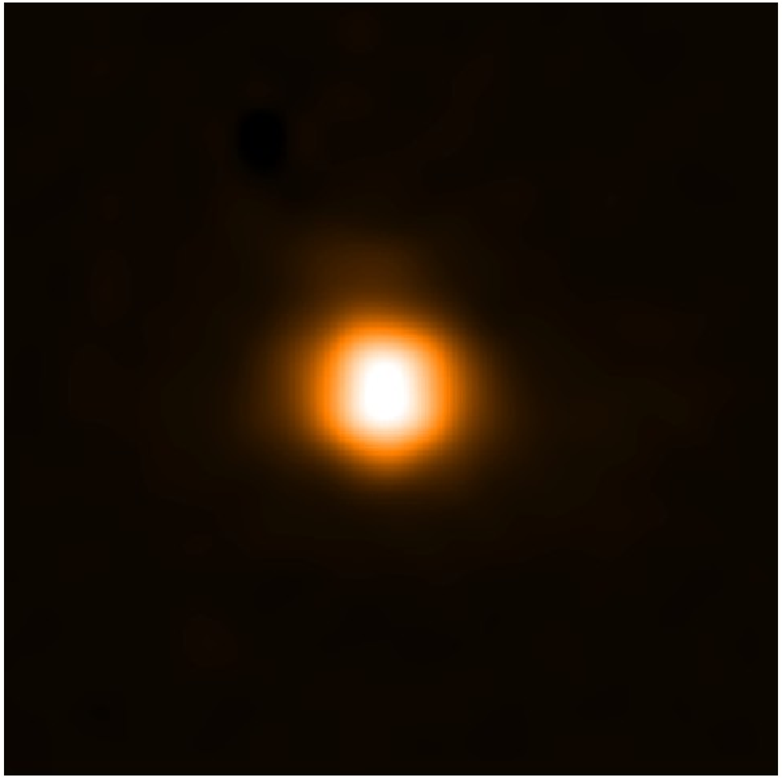
Example Systematics:Slit Throughput



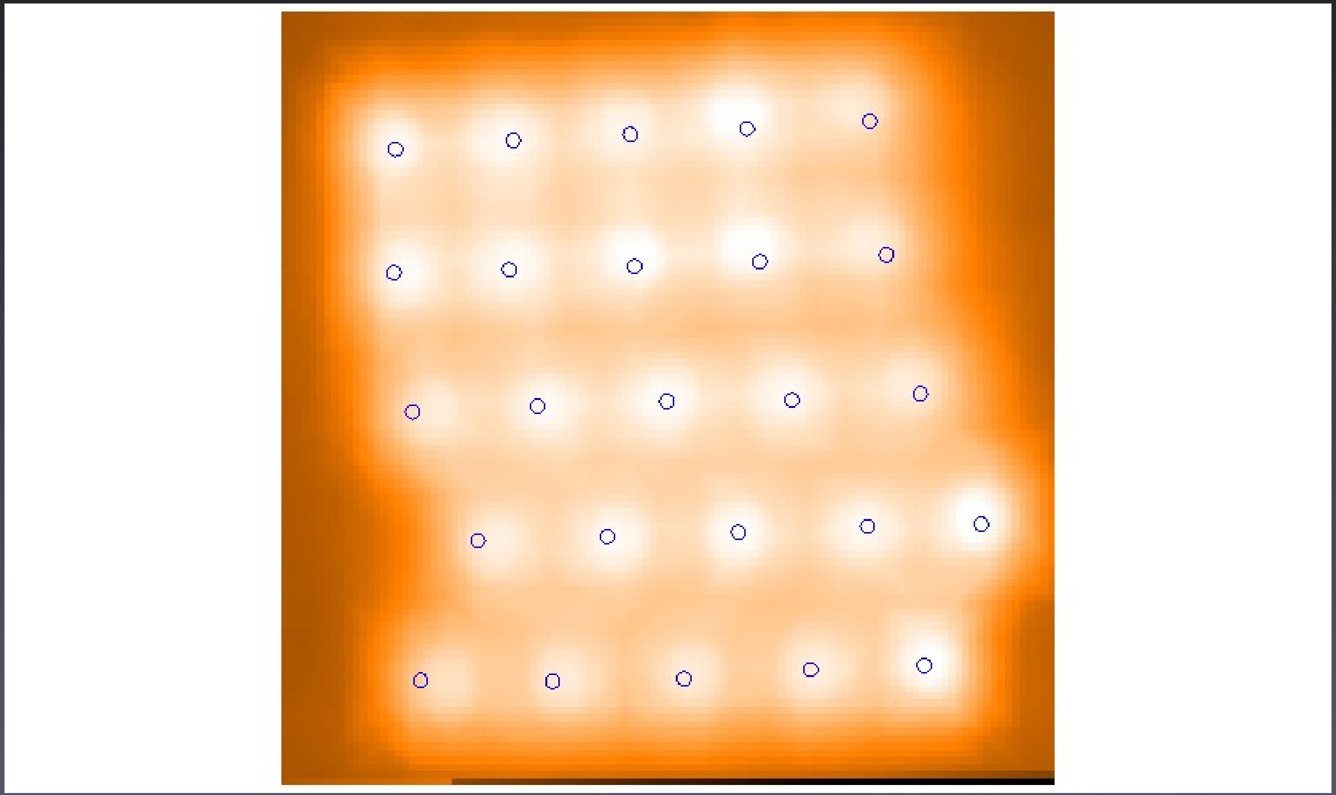
Example Systematics: Correcting Throughput Variations



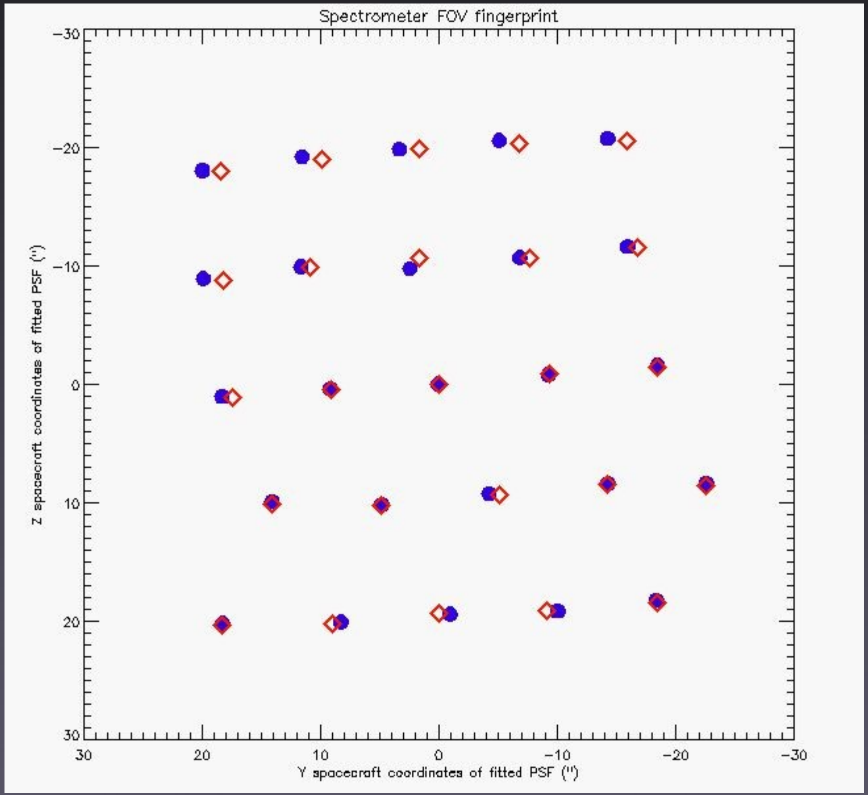
Example Systematics: PACS Beam



Example systematics: Throughput variations of the PACS IFU



Example Systemetics: Shifts in slitlet optical center



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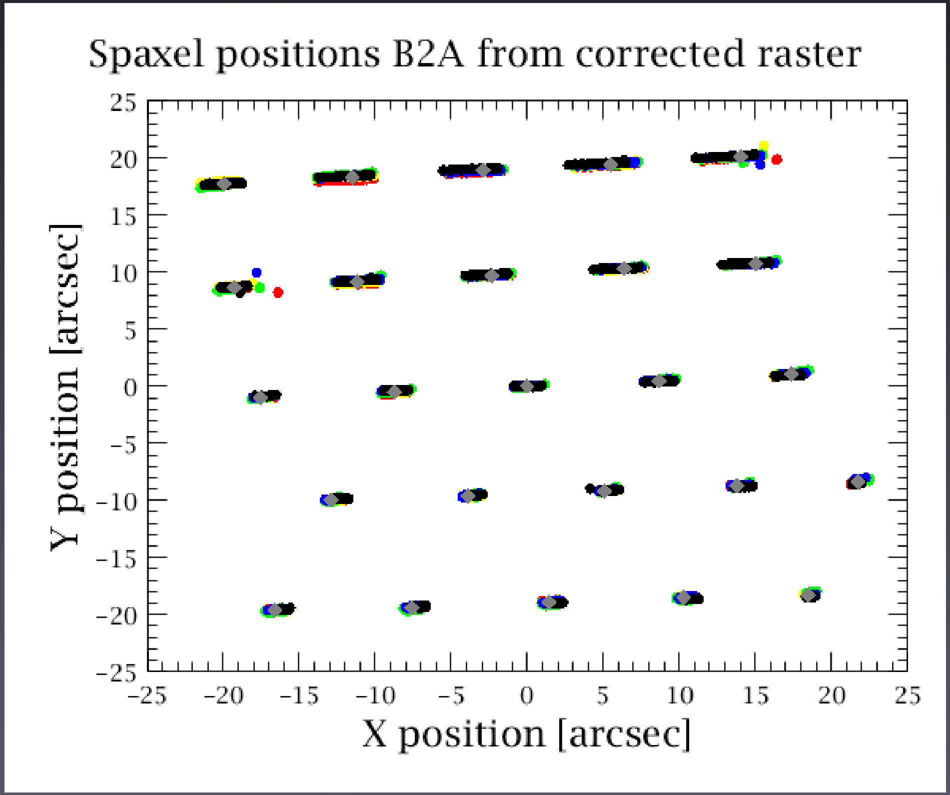

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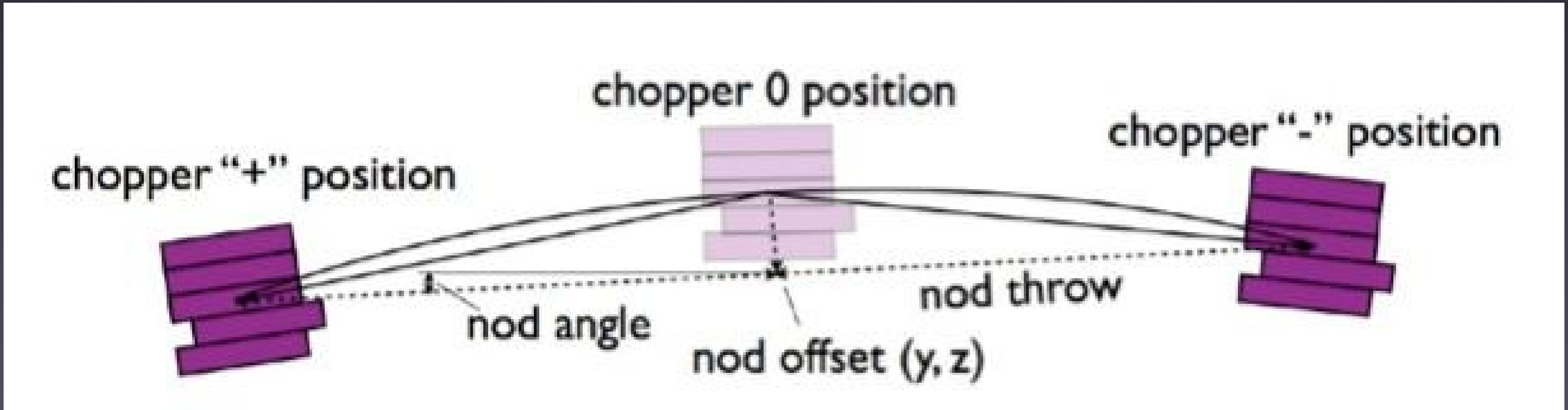
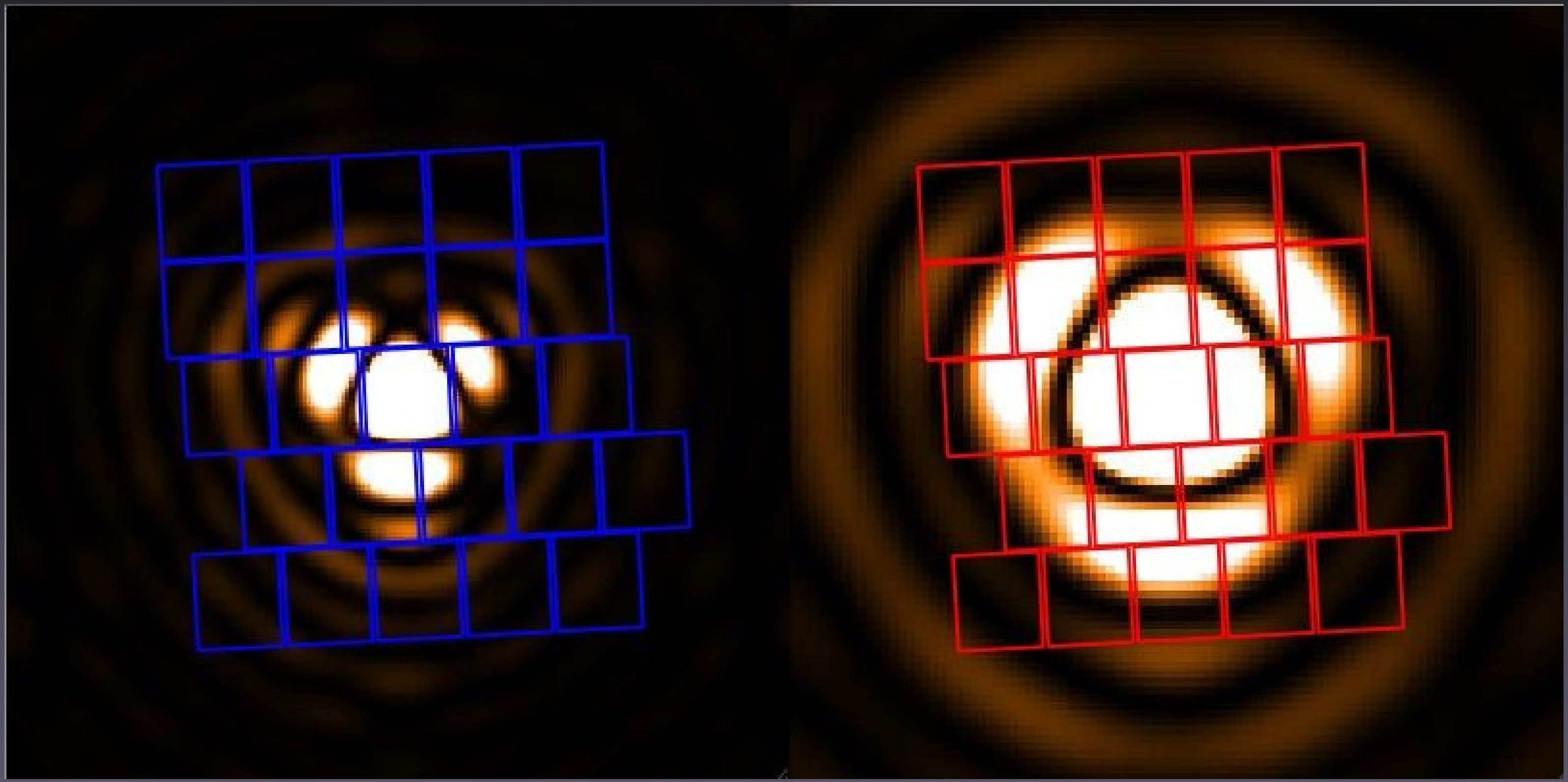


Example Systematics: Correcting flux-losses in the IFU



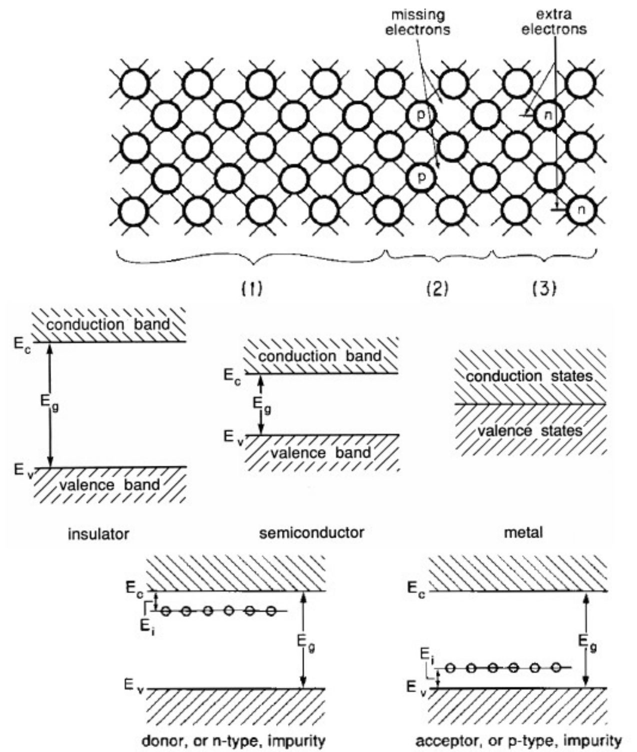
Systematics 2:

Detector/Electronics Problems

Detector 101

Photon absorption and creation of free charge carriers in semiconductors is the basic process behind photo-detectors.

Compare the diagram of crystal structure (above) with the band gap diagrams (below). To free an electron in intrinsic material (1) requires a certain energy indicated by the band gap. It takes less energy to free charge carriers from impurities (2) and (3). A freed charge carrier can move through the detector to produce a photocurrent, which is what we measure.

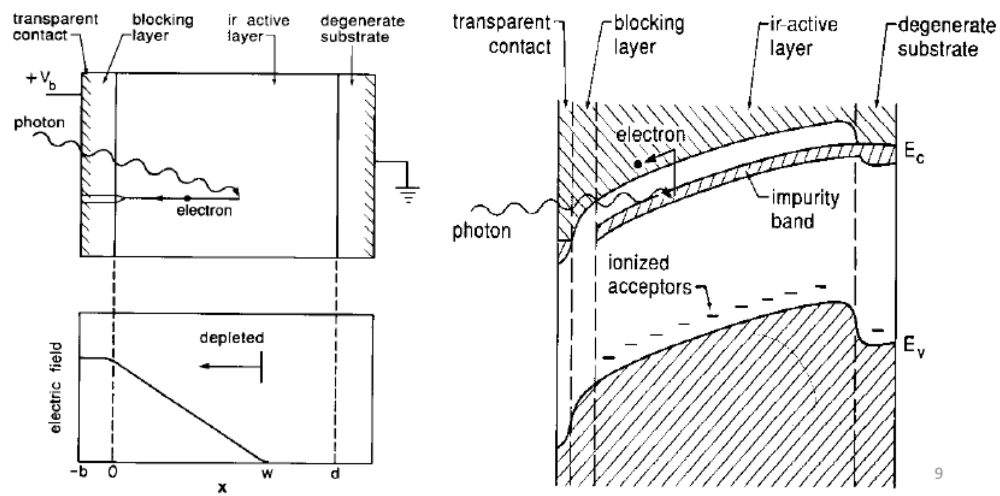


See books and papers by George Rieke

Detector 101

Detector type #1, Si:X IBC

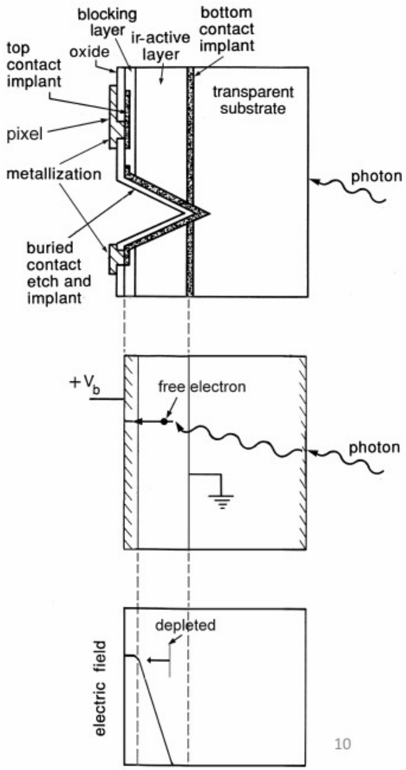
- Physical structure to left, band diagram to right; structure is a thin intrinsic layer, then to right of it a heavily doped absorbing layer, then to right, a contact
- An absorbed photon elevates an electron to the conduction band, from which it can migrate to the contact unimpeded. Thermal charges in the impurity band are stopped at the blocking layer, so dark current is low.
- Detector type of choice for 5 – 35μm
- Notice the separation of zones for electrical properties and photo-response



Detector 101

Use of these detectors in an array requires some architecture changes, to allow attaching the readout (to the left in these drawings).

Also, very high purity must be achieved in the silicon to allow for complete depletion of the IR-active layer, or not all of the charge carriers will be collected and the quantum efficiency will suffer. If one tries to increase the depleted zone by increasing the bias, avalanching can occur where the field is largest, increasing the noise.



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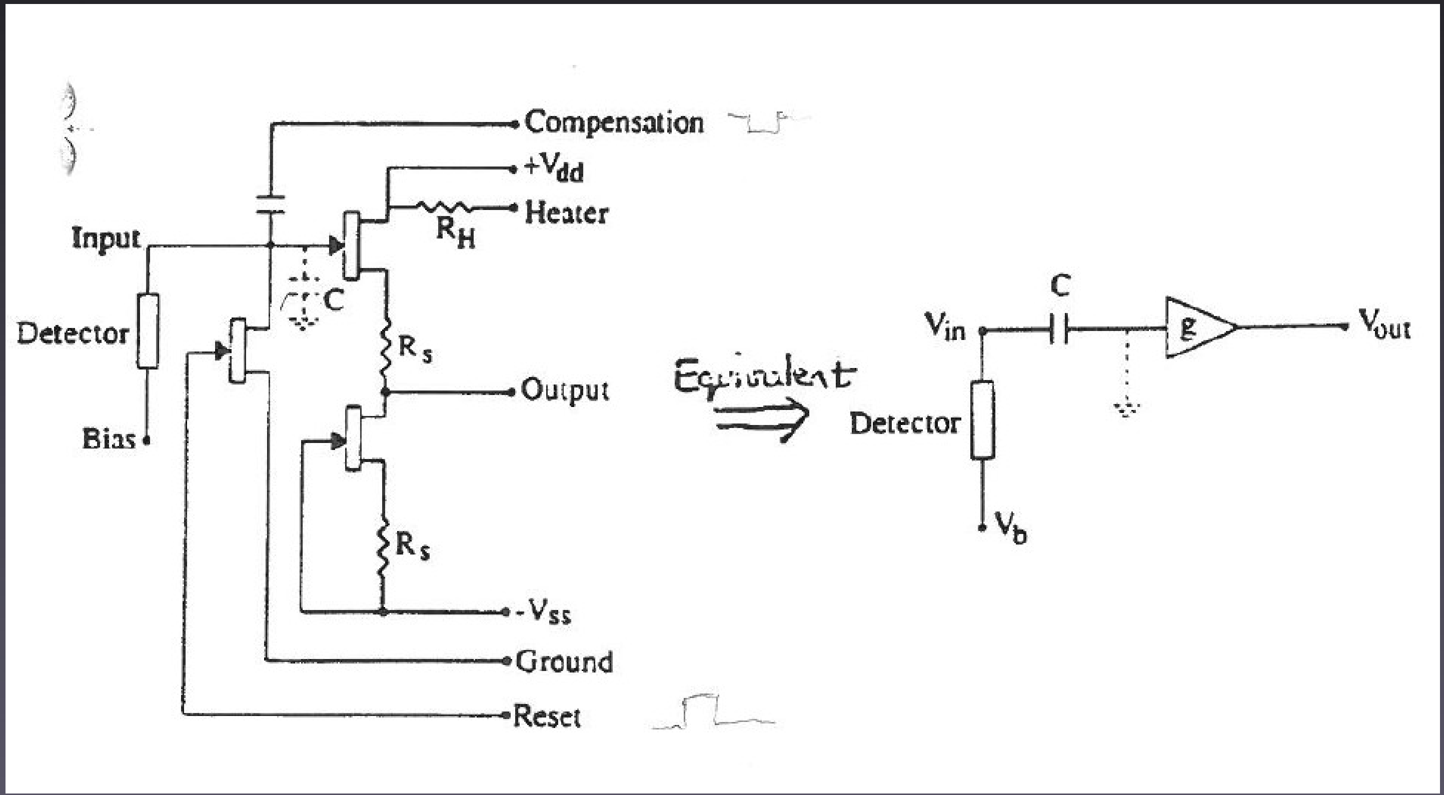
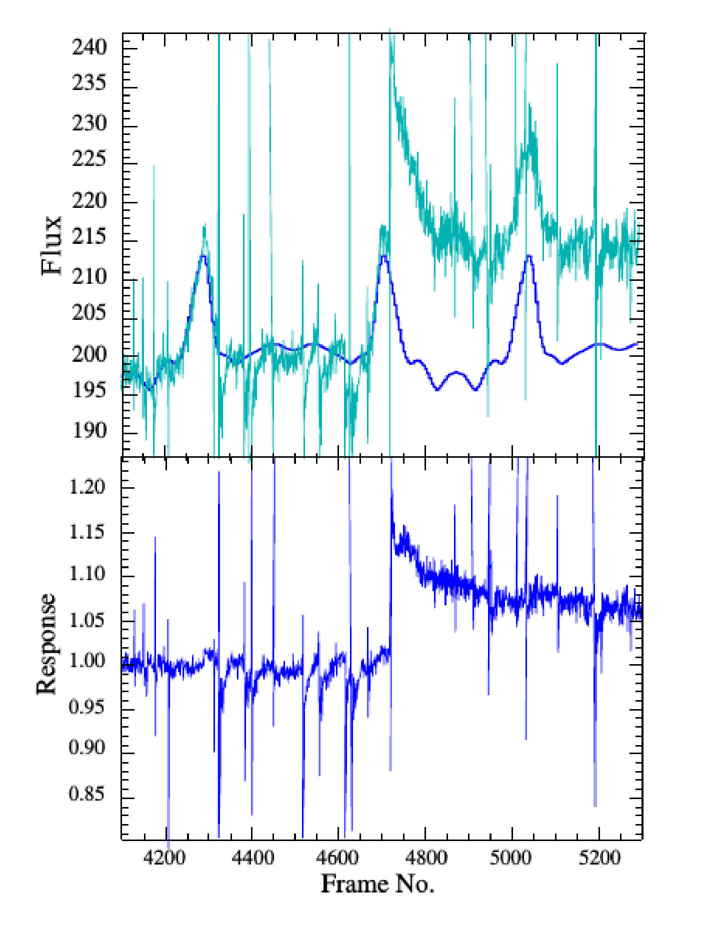


Detecor systematics

Flatfielding errors
Inter pixel sensitivity variations
Intra pixel sensitivity variations
Non linearity of detector ramps
Zero point drifts
Charge trapping (latents)
....

Temperature stability
Stability of power supplies
....

Example Detector Systematics: Response drifts of PACS



Example Detector Systematics: Response drifts of PACS

Solution:

chopping and calibration against the telescope background

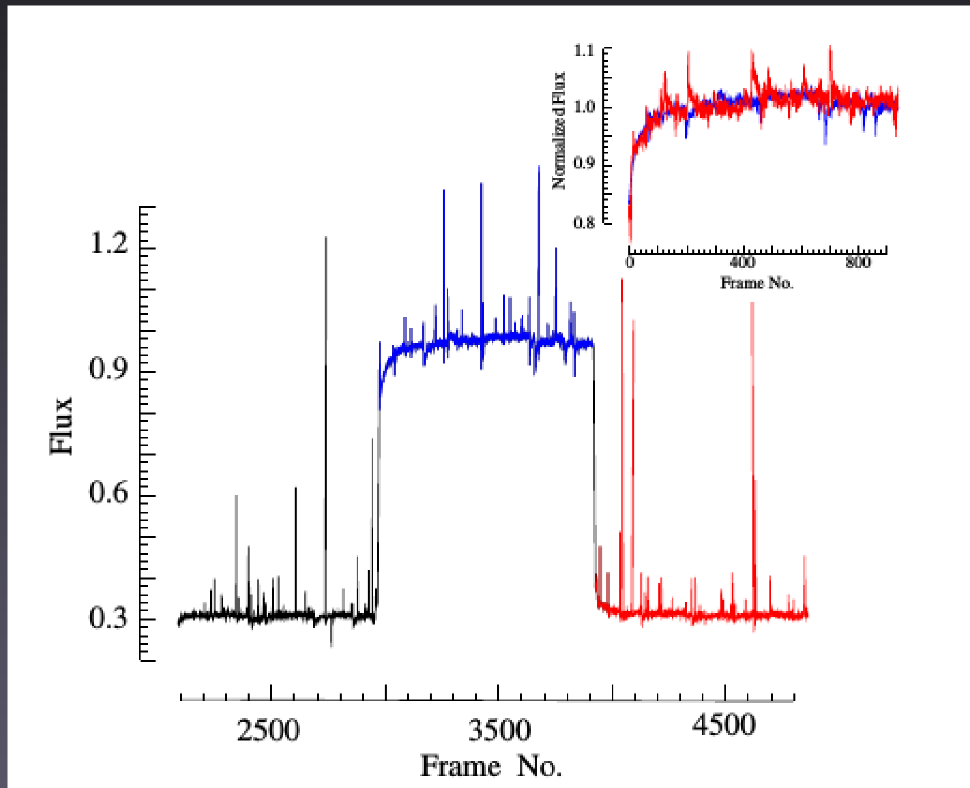
$$norm = \frac{A - B}{A + B},$$

$$x = \frac{f - 1 - norm \times (f + 1)}{f \times (norm - 1)}$$

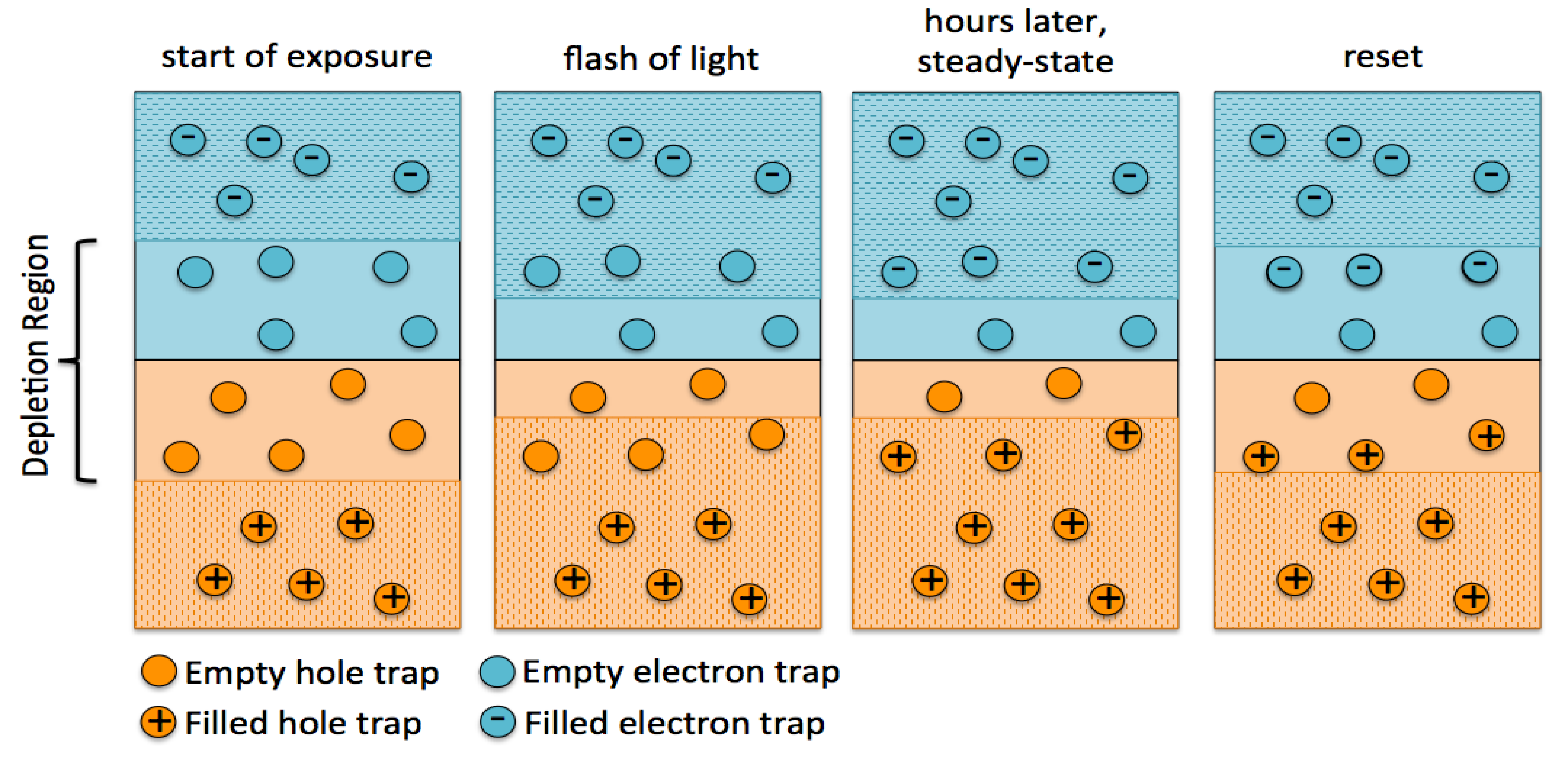
$$f = \frac{T_{\mathrm{A}}}{T_{\mathrm{B}}}$$

Note: Telescope background dominates and must be predictable

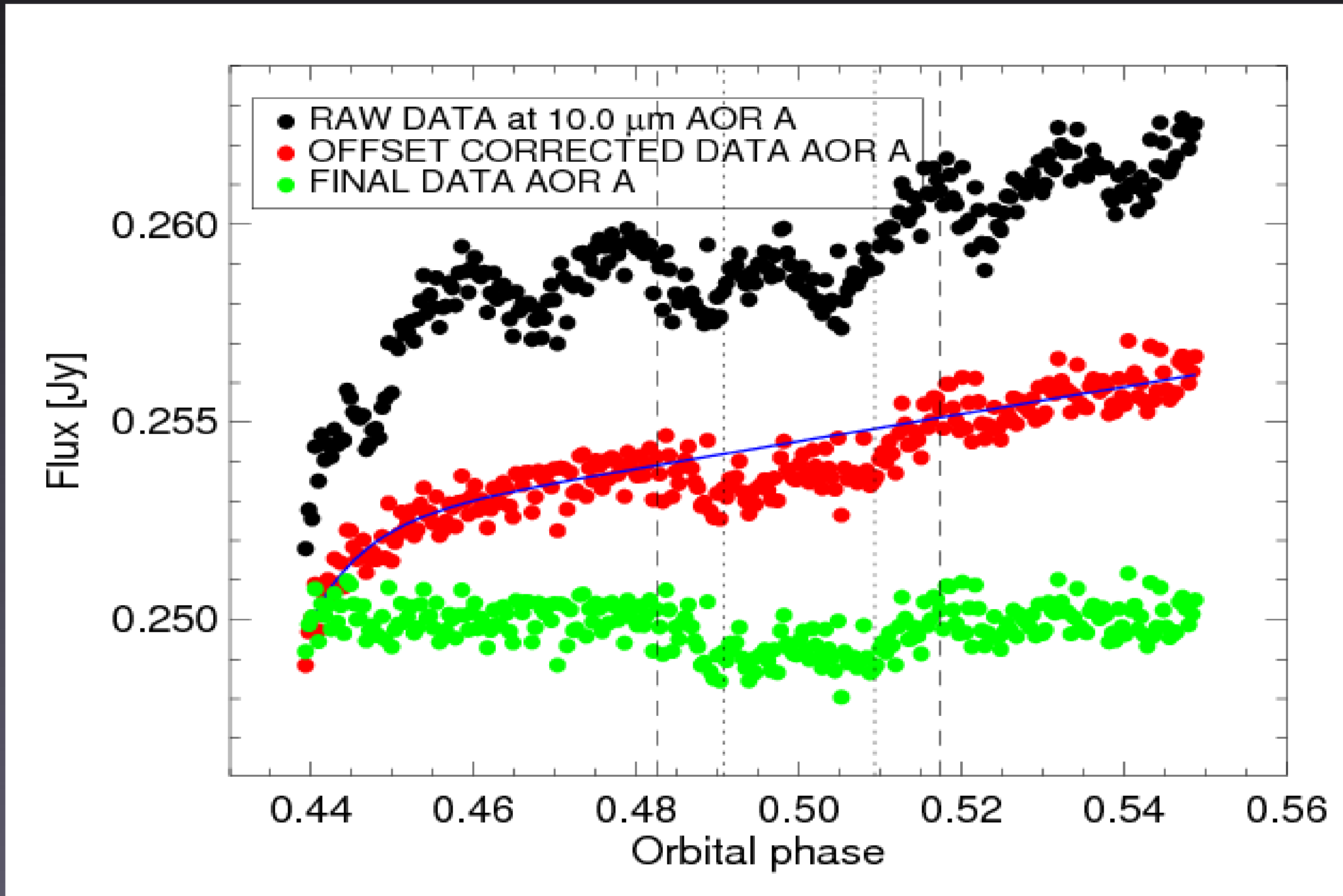
Example Detector Systematics: Response drifts of PACS



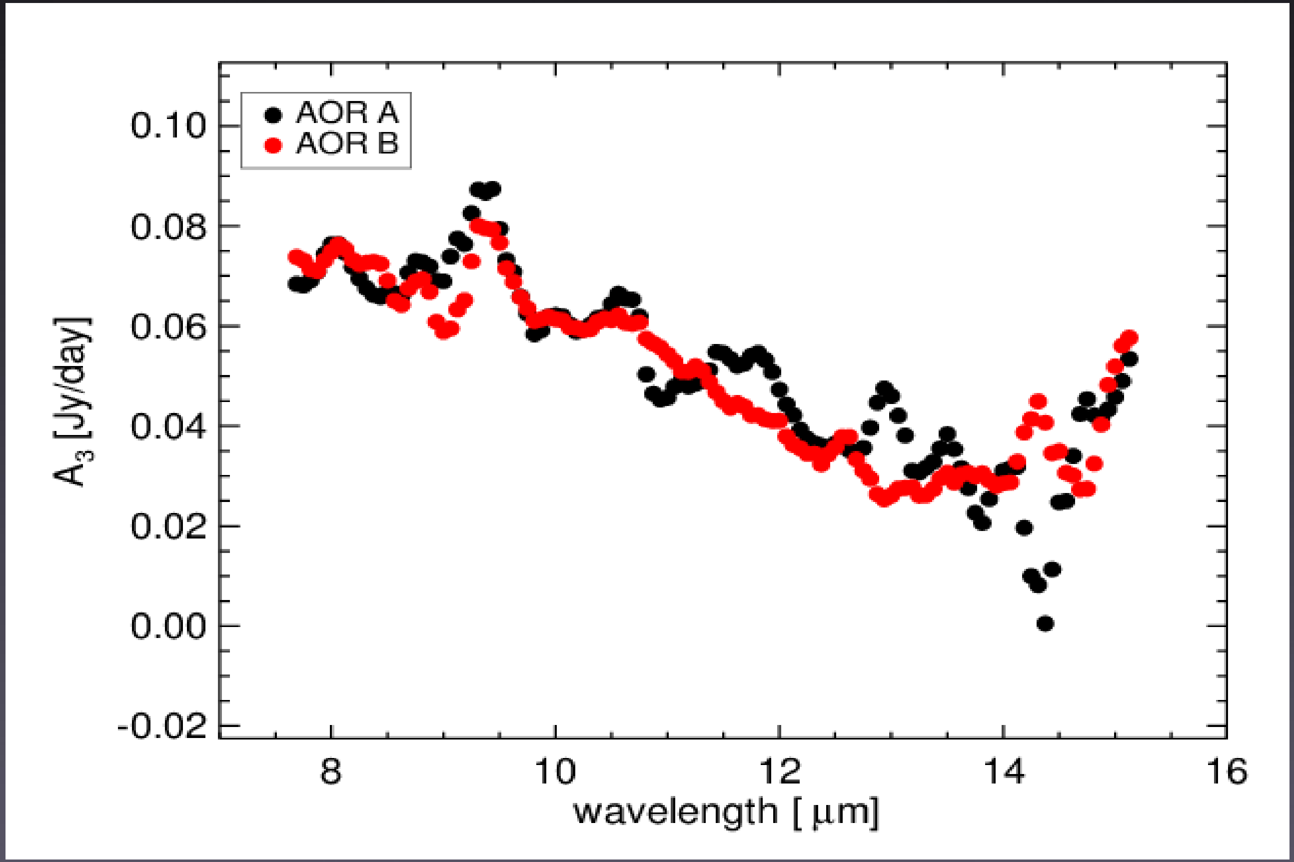
Example Detector Systematics: Charge trapping



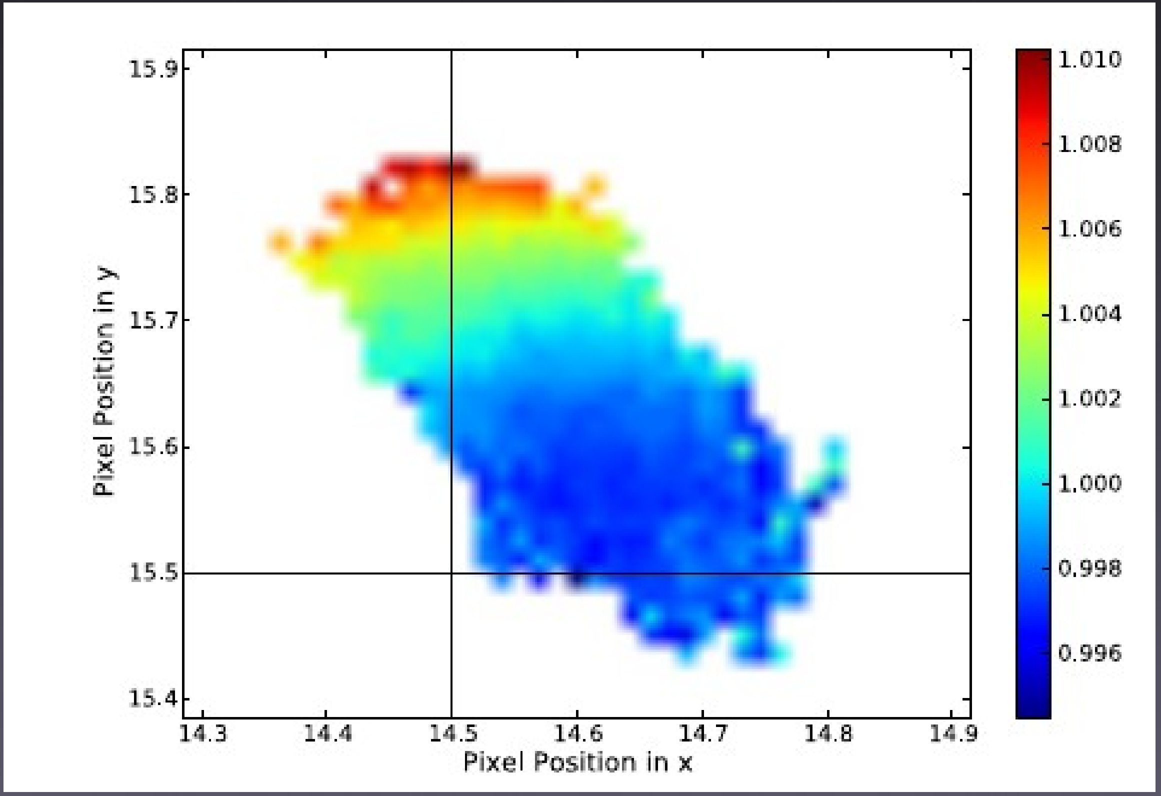
Example Detector Systematics: Charge trapping effects with the Spitzer IRS detector



Example Detector Systematics: Charge trapping effects with the Spitzer IRS detector



Example Detector Systematics: inter-pixel variations with the Spitzer IRAC detector



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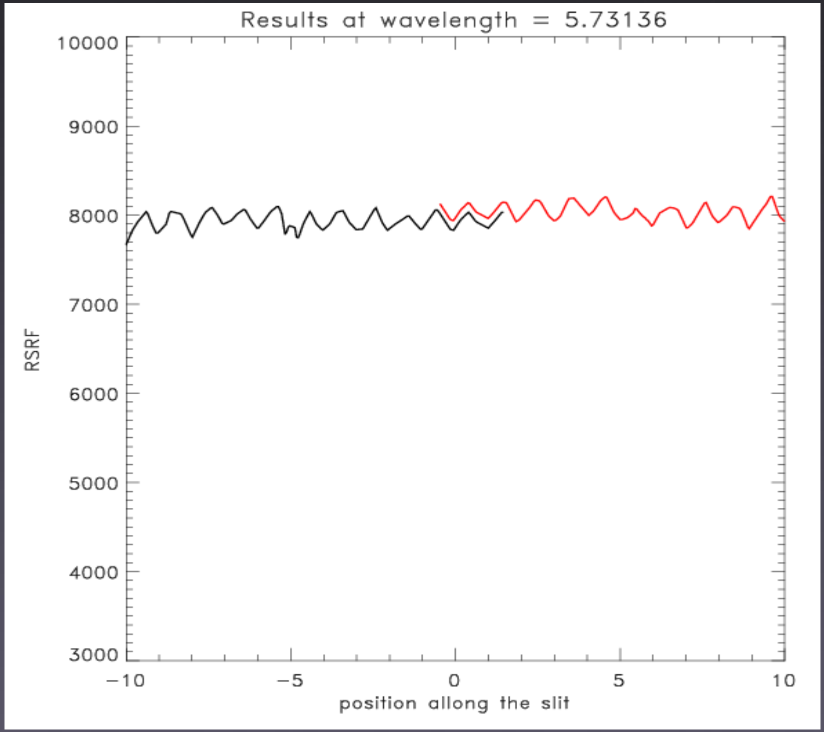
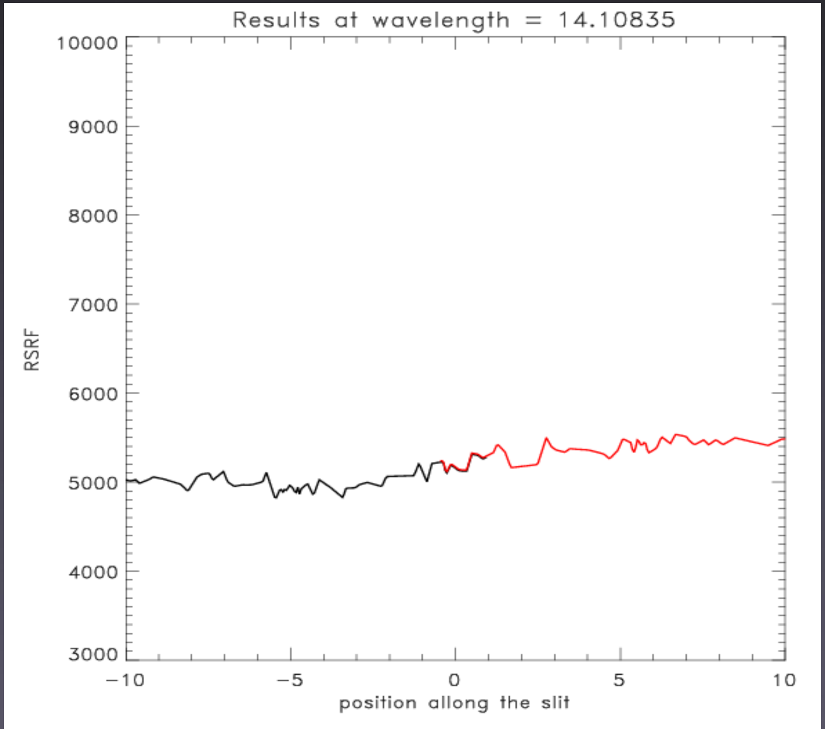
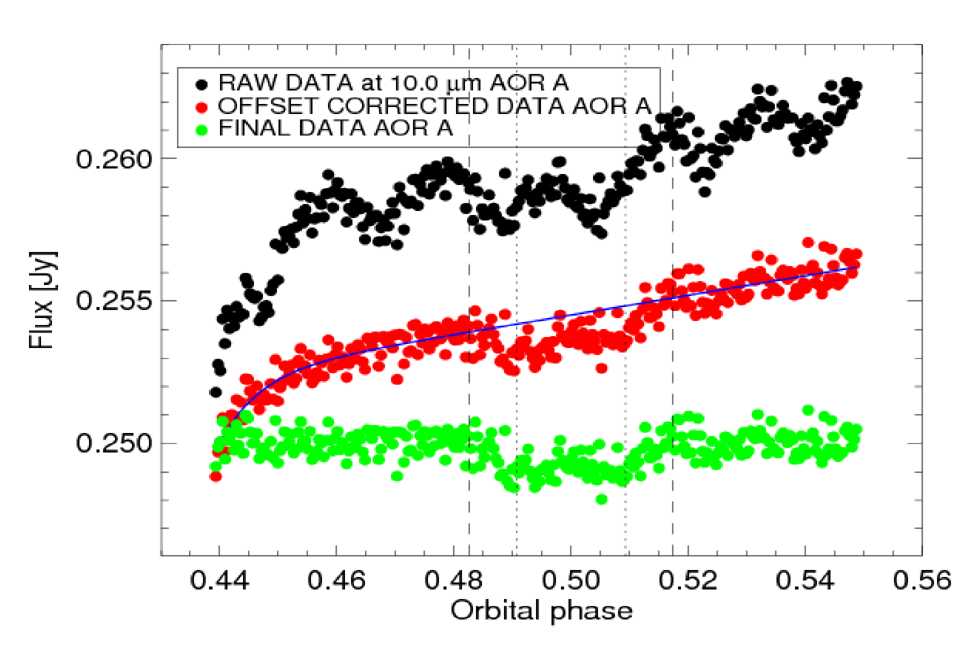
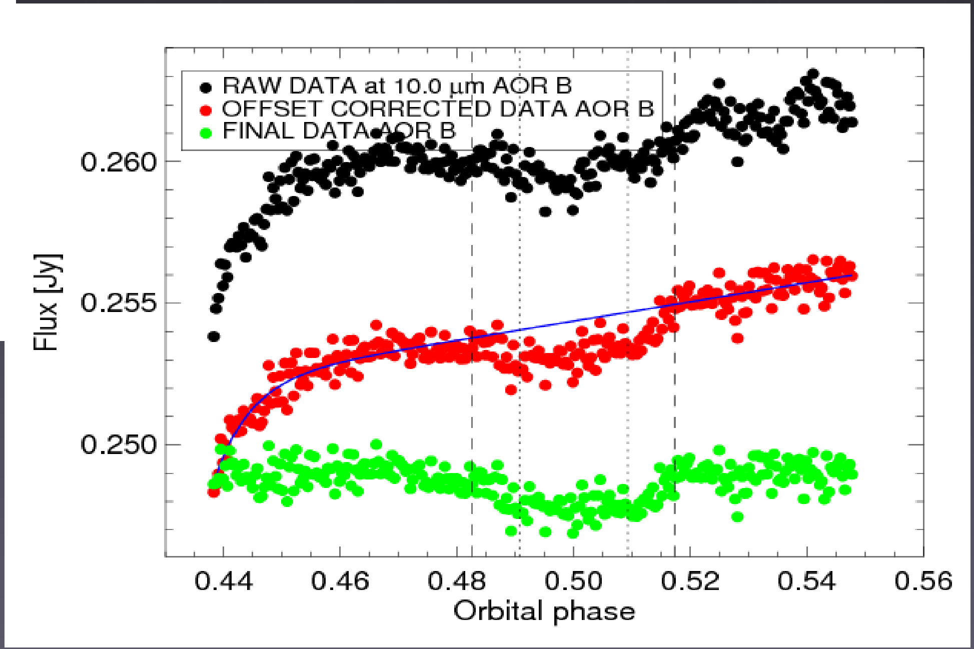




Timeseries: light-curves of the transiting exoplanet HD189733 b observed with Spitzer





Thank you for your attention