NICMOS: exoplanets through a prism

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With thanks to

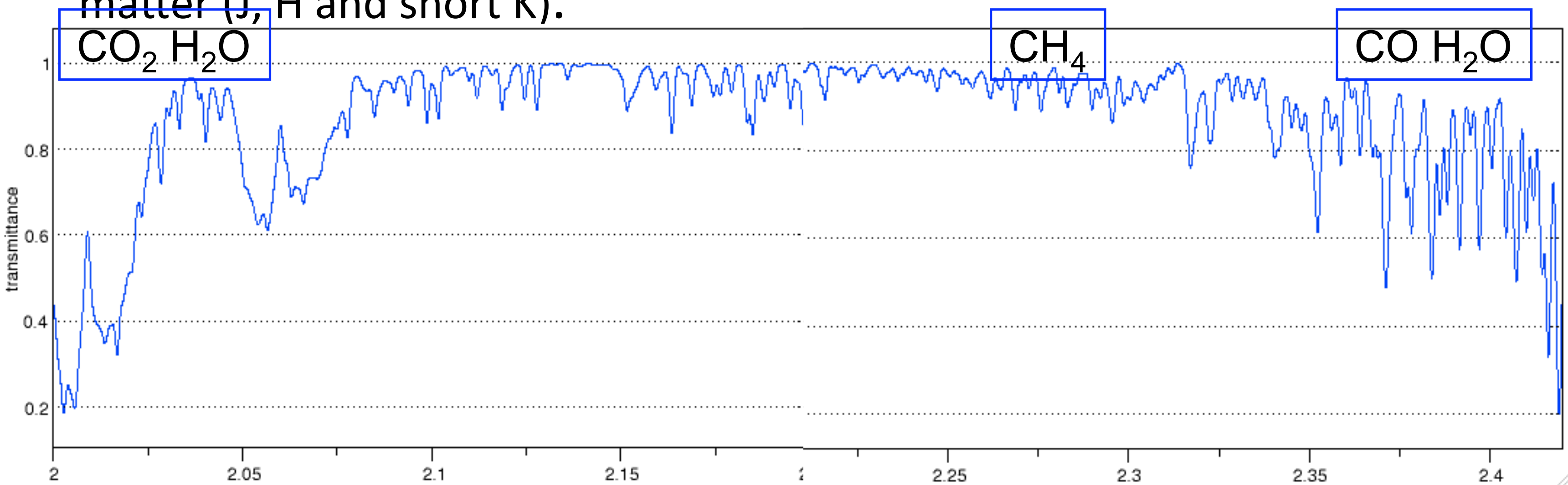
C. Burke (CfA), J. Carter (MIT), P. Deroo (JPL)

Outline

- Motivation
- NICMOS: capabilities & limitations

NIR from the Earth

- Earthbound NIR (or IR in general) precision photometry is extremely challenging. Line-of-sight variations in column densities of telluric absorbers and in emissions from chemically pumped species such as OH matter (J, H and short K).

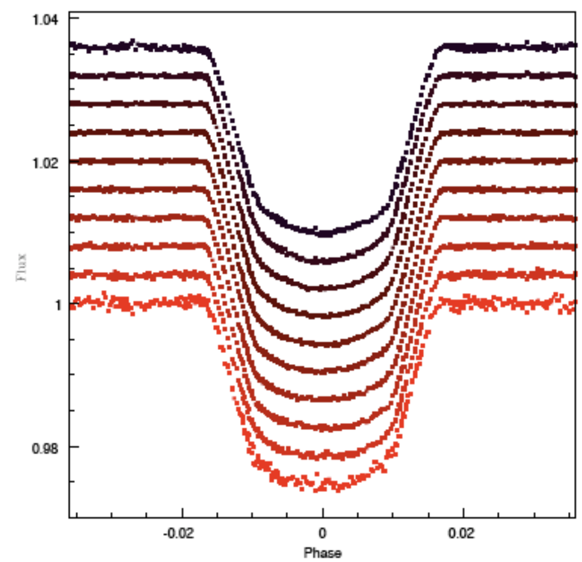


K-band transmission from a typical 4 km high site with US standard atmosphere at 260 K.

HST: the other spaceborne workhorse

- HST instruments have been used for high signal-to-noise lightcurve measurements
  - STIS spectrograph (Charbonneau et al. 2002, Na resonance absorption in HD 209458b)
  - STIS uv spectroscopy (Vidal-Madjar et al. 2004, Ly-α absorption by extended HI)
  - ACS (e.g. Pont et al. 2008, Hazes in HD 189733b)
  - NICMOS (Brown et al. 2005, unpublished)

    (Swain, Vasisht & Tinetti 2008; H_2O and CH_4 in HD 189733b)



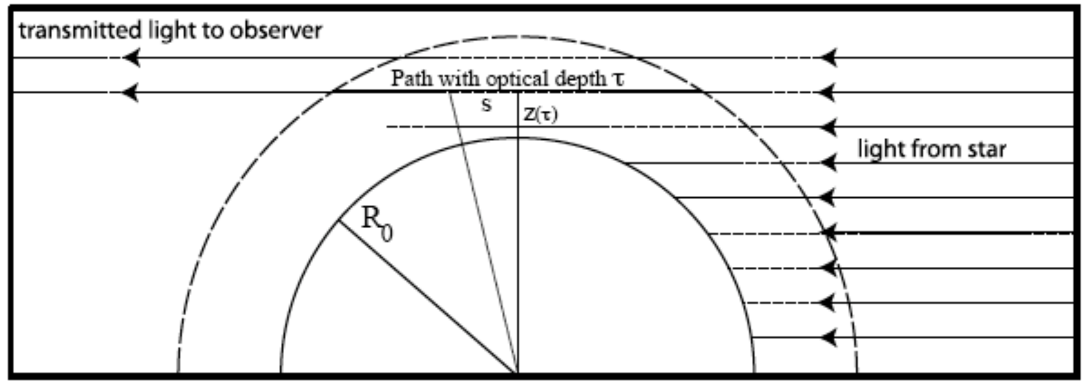
NICMOS

- Broadband photometry
- Spectrophotometry

… of primary transits and secondary eclipses

- Less well suited for phase-curve photometry

Transit Spectrophotometry



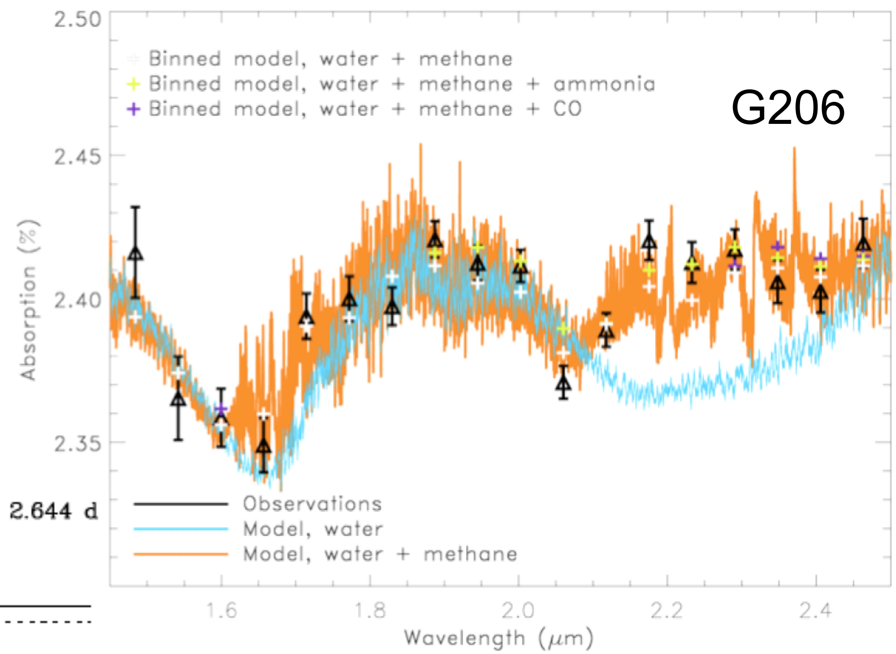
$$C/\delta C \propto \frac{2z(\lambda)R_p}{R_s^2}\sqrt{\frac{\lambda^2 F_s A\tau}{R}}$$

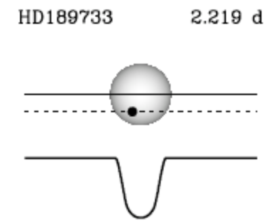
for an absorbing slant path…

$$z(\lambda,T) \propto n_0\sigma(\lambda,T)\sqrt{R_p H}, \quad H \textit{ is the scale height}$$

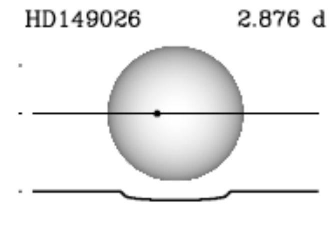
Main sources of continuum opacity are H_2-H_2 and H_2-He

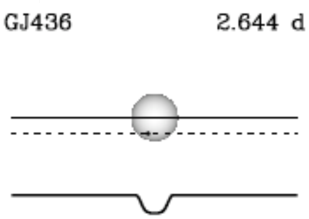
In the optical, z(λ) could be set by scattering off molecules (H_2) and/or hazes.

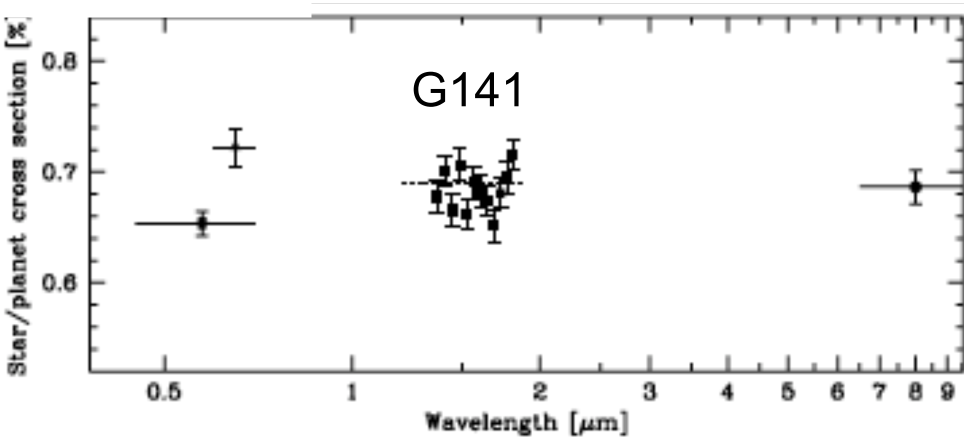


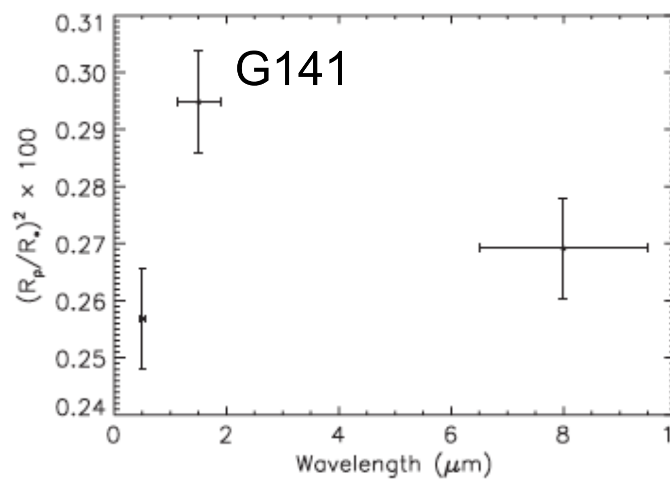


HD 189733b,
Swain, Vasisht, Tinetti 2008







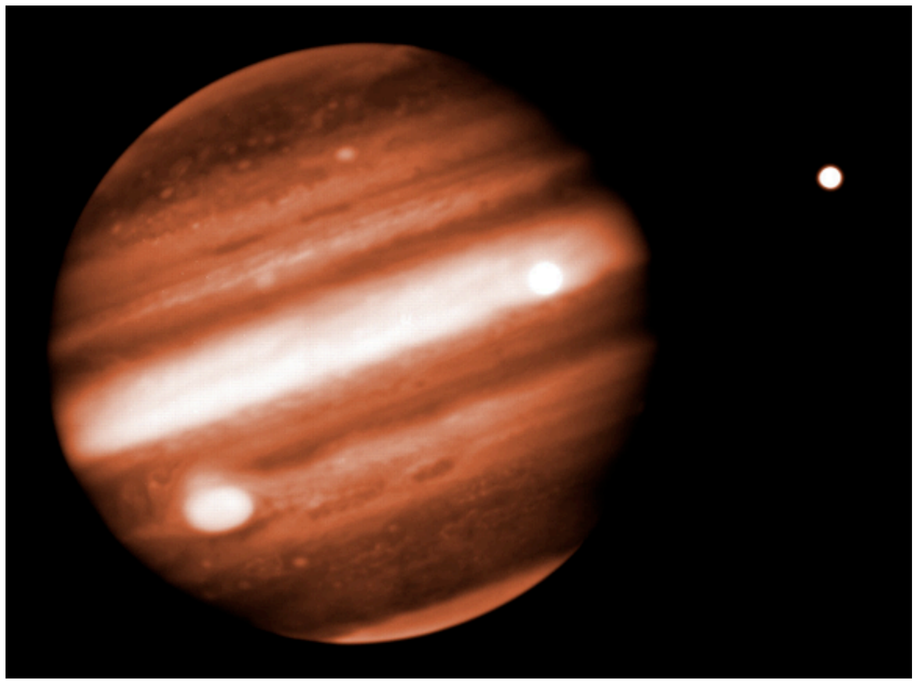


HD 149026b, Carter et al. 2009

GJ436b, Pont et al. 2009

Thermal Emission Spectroscopy

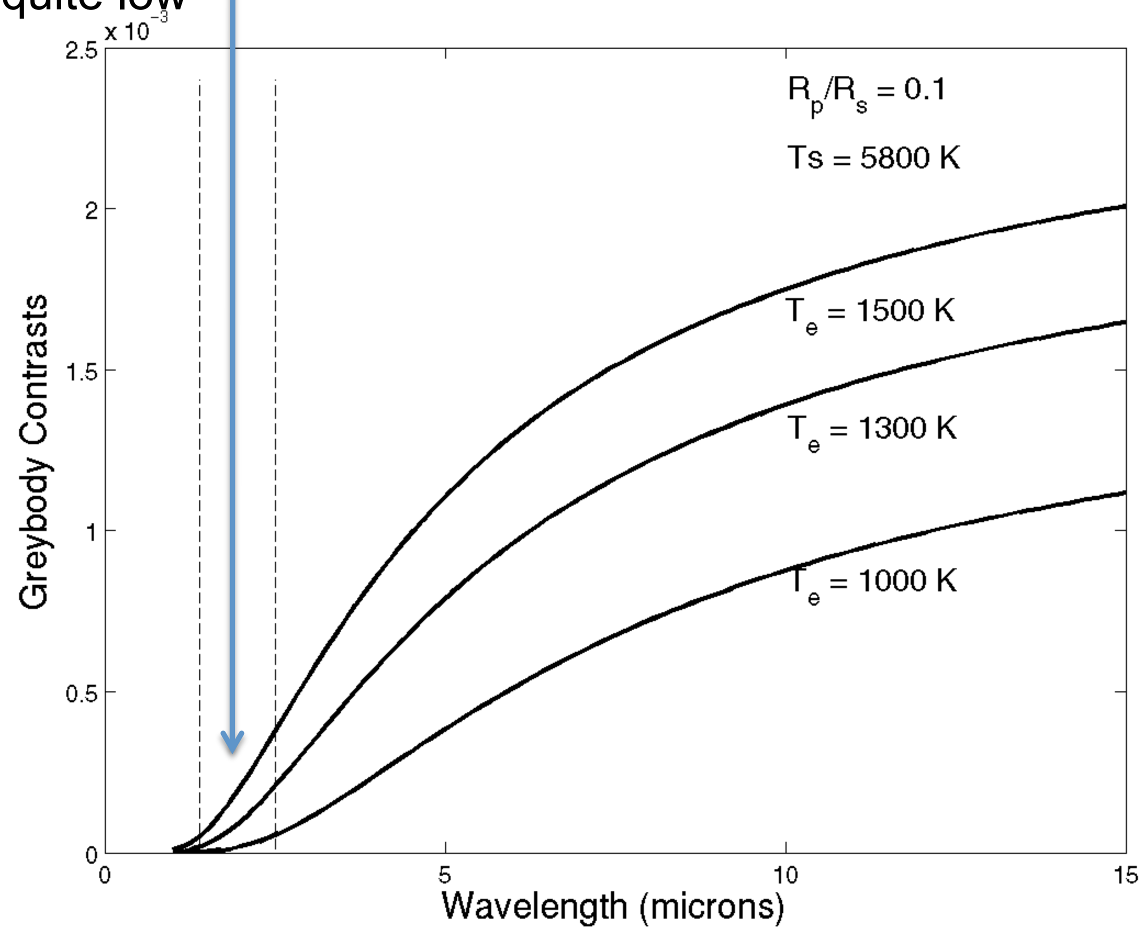
- Disk-averaged spectra of the dayside thermal emission



Gemini NIRI, Jupiter at 1.69 um

Graybody Contrasts

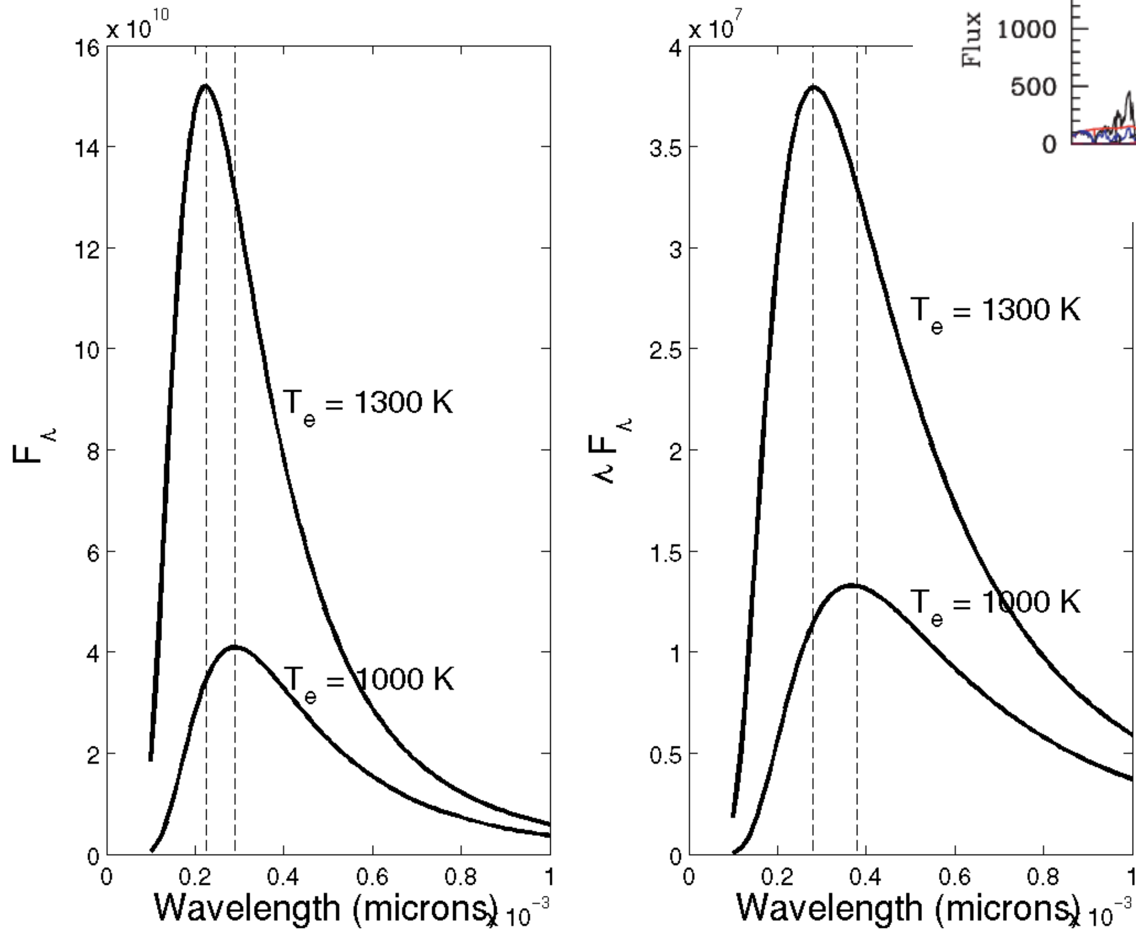
Average NIR contrasts
are quite low

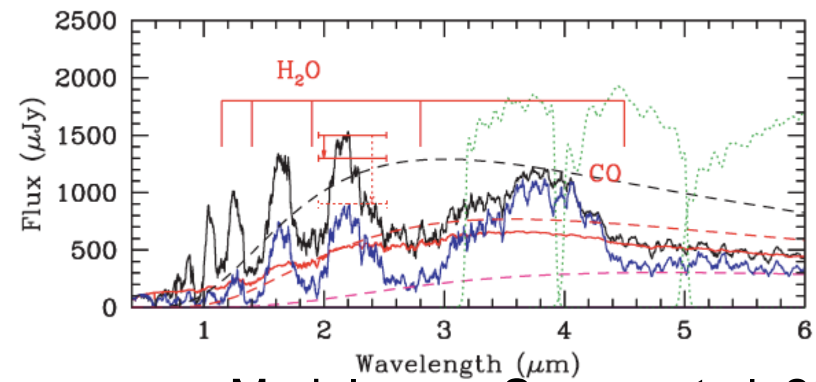


At long λs,

$$C \sim \left(\frac{R_p}{R_s}\right)^2 \frac{T_p}{T_s}$$

High contrasts in
the mid-infrared





Models: e.g. Seager et al. 2005

Radiated flux can depart from that from a blackbody by an order-of-magnitude

SWIR energetically important

Sec. Eclipse Spectrophotometry

- What is the best waveband for spectroscopy with resolution R?

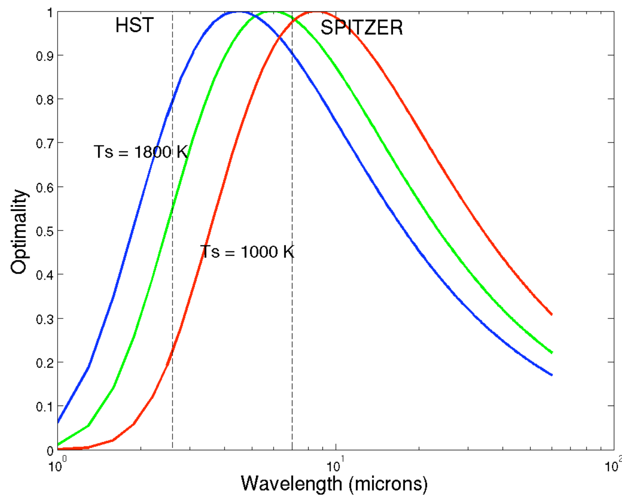
$$for\ photon\ ltd.\ case,$$

$$\delta C \approx \sqrt{R} / \sqrt{\lambda^2 F_s A \tau}$$

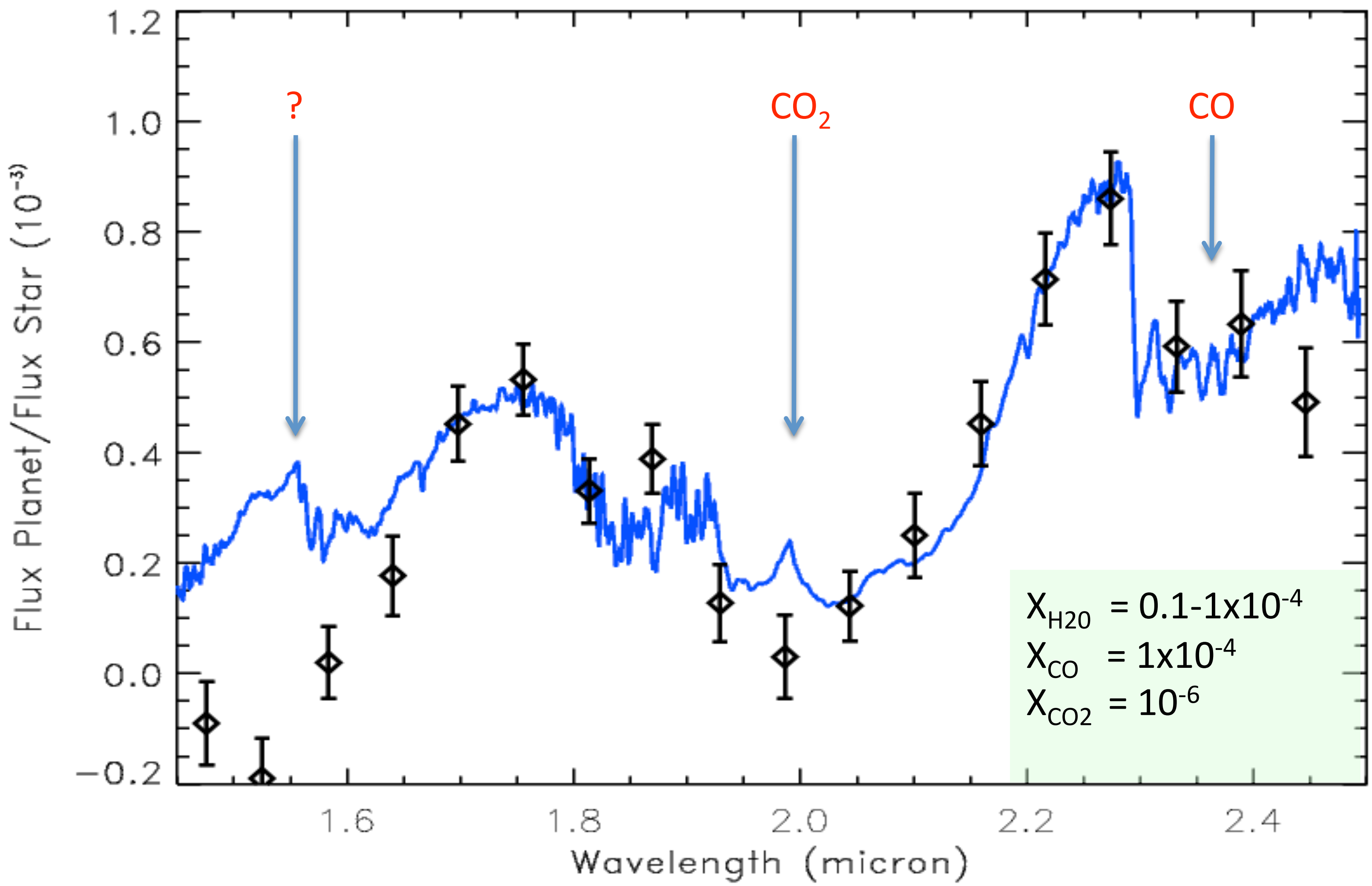
$$ability\ to\ sense\ C,$$

$$C / \delta C \propto \left(F_p^\lambda / F_s^\lambda \right) \left(\sqrt{\lambda^2 F_s^\lambda A \tau / R} \right) \propto \lambda \left(\frac{F_p^\lambda}{\sqrt{F_s^\lambda}} \right) D \sqrt{\frac{\tau}{R}}$$

Spitzer D < HST D
Even for $T_{telescope}$=0,
zodiacal background matters



Swain et al. 2009



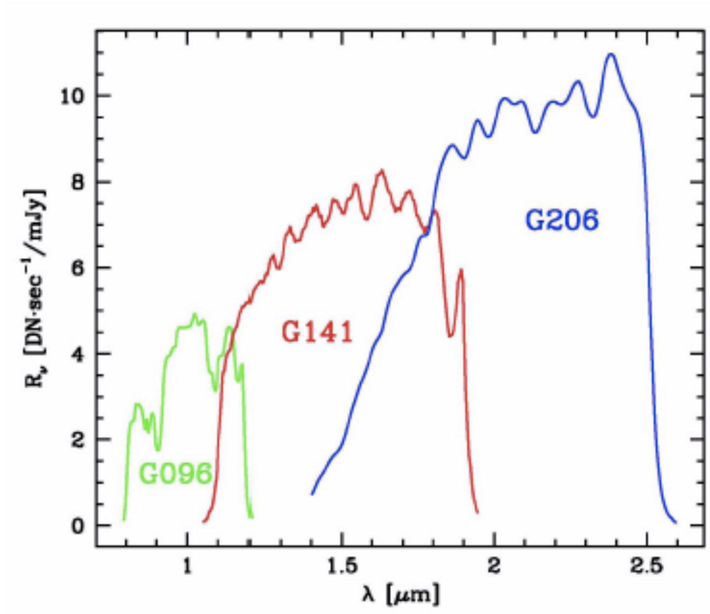
HD 189733b Emergent-flux Contrast Spectrum

NICMOS: Instrument Basics

NICMOS consists of 3 separate cameras offering a variety of observing modes

Camera 3 allows objective mode grism spectroscopy

- Three separate grisms allow coverage between 0.8 – 2.5 microns
  - Grisms are located in a filter wheel (important tidbit for potential users)
  - R = 200 native spectral resolution
  - Camera 3 is severely under-sampled at 0.2”/pixel (~λ/D @ 2 um, 52” FOV; also important tidbit for potential users)

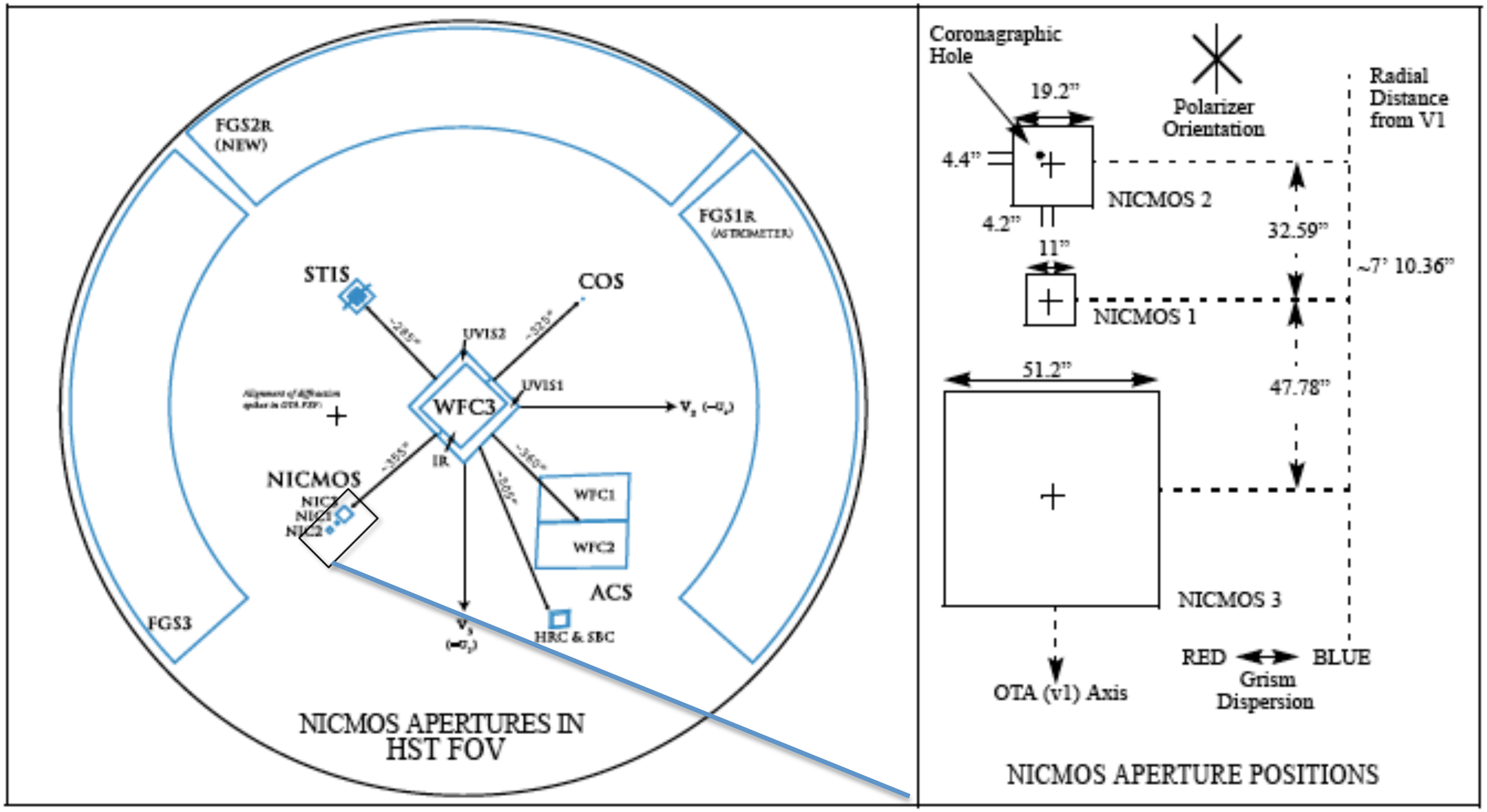


Transiting planet datasets have been acquired with all grisms. G141 has been overarchingly popular.

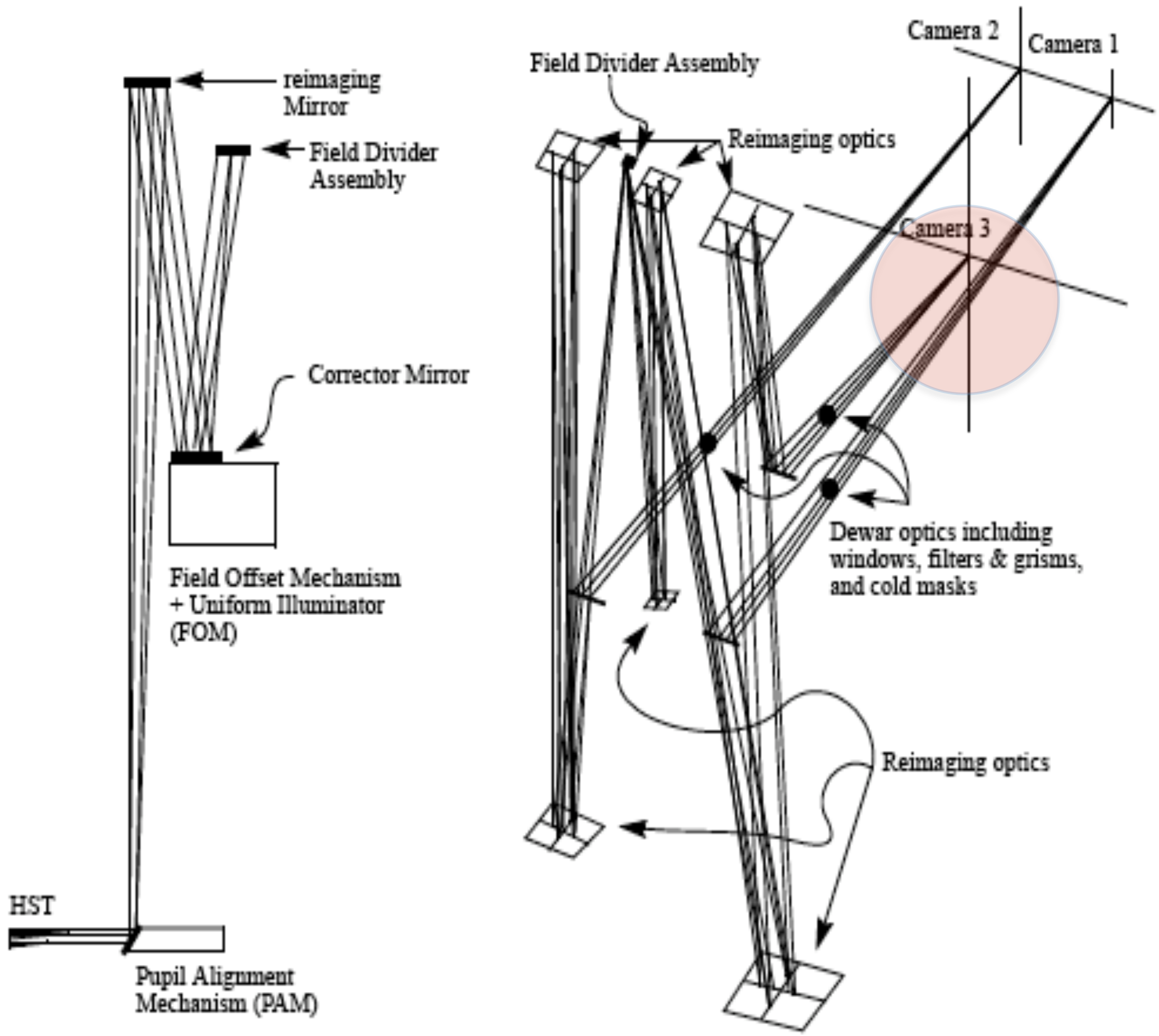
NICMOS: outright confessions …

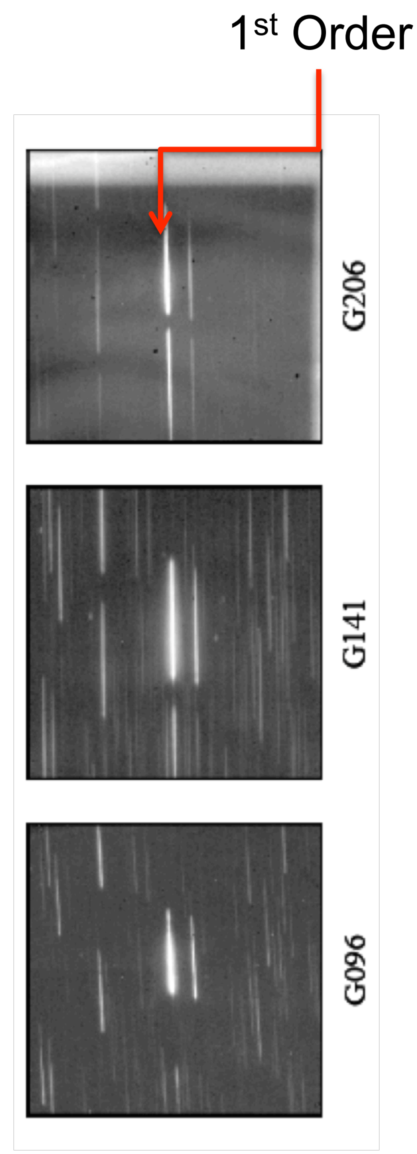
- NICMOS spectrophotometry is definitely of “varied quality.”
- Can be tedious (or even impossible) to calibrate to levels required extract buried astrophysical signature.
- I’ll attempt to explain why?

The HST Focal Plane

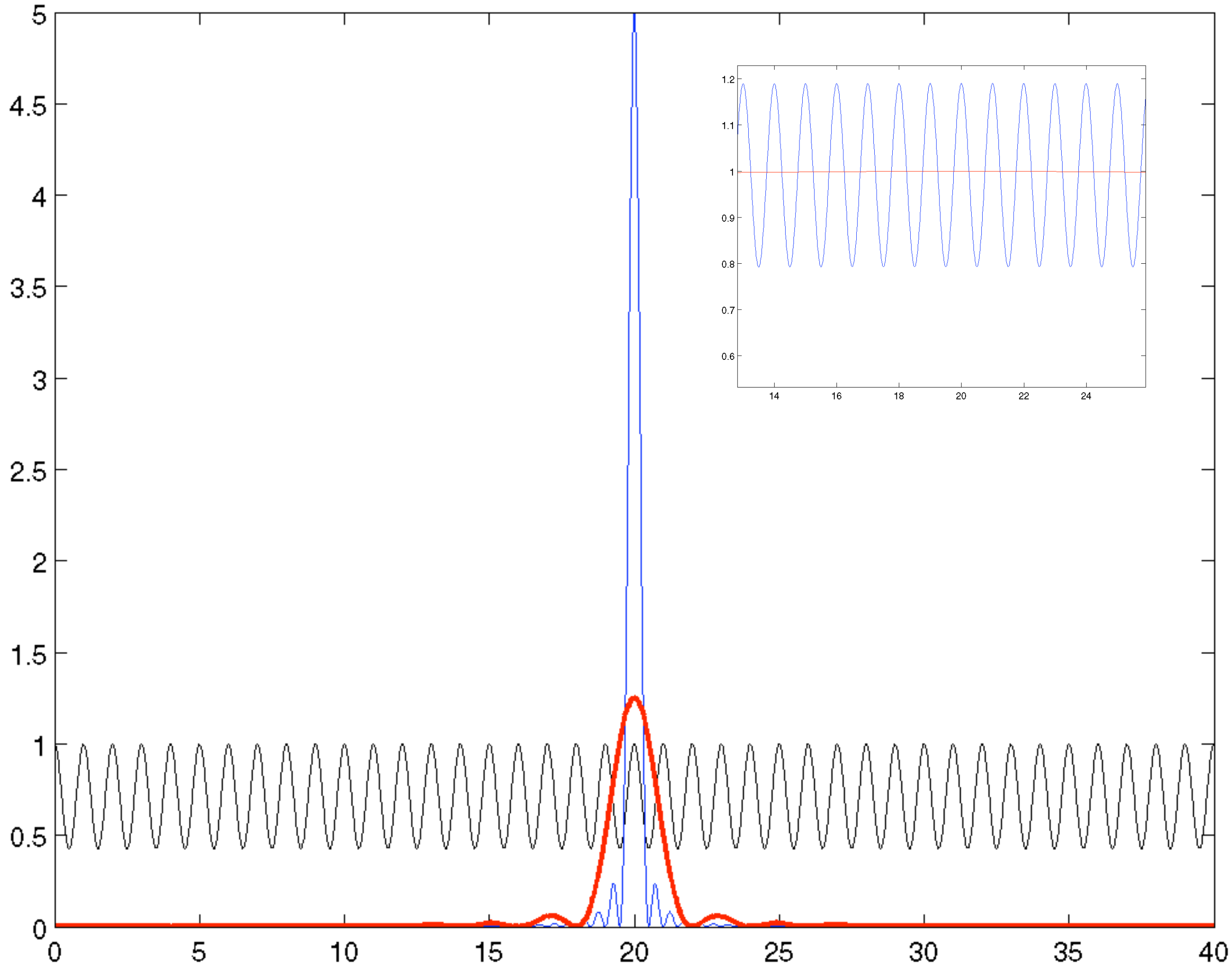


Nicmos: Journey into the bowels





PAM offset enables defocus: tidbit for potential user


5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
30
35
40
1.2
1.1
1
0.9
0.8
0.7
0.6
14
16
18
20
22
24

Why Defocus

Pipeline calibrated light-curves

A-List of Blemishes

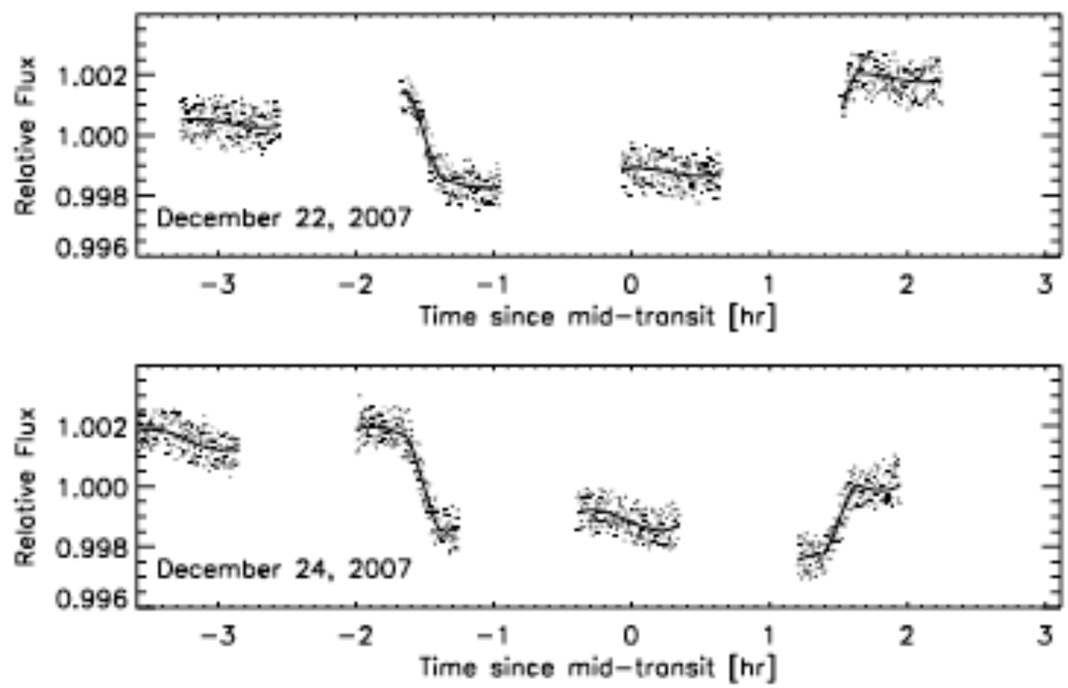
↓

HST light-curves are segmented.

Periodic variations are apparent within the segments.

There are jumps in total counts from segment to segment.

The counting statistics appears to be non-Gaussian.



Carter et al. 2009

Correlated Noise

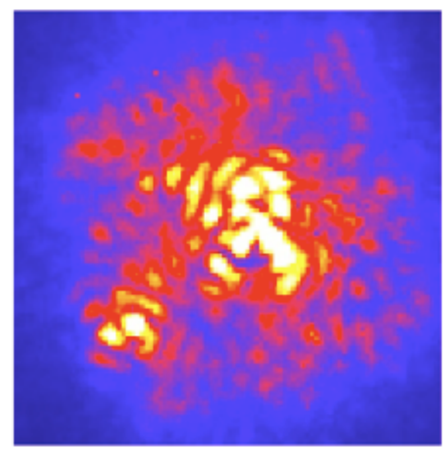
$$S/N = \frac{F\tau}{\sqrt{\underbrace{F\tau}_{poisson} + \underbrace{\kappa^2 F^2 \tau^2}_{systematic}}}$$

$$\delta C = \frac{1}{S/N}$$

$$when \quad F\tau < \frac{1}{\kappa}, \quad \delta C = \frac{1}{\sqrt{F\tau}} \; and \quad \tau_t \propto \delta C_t^{-2} D^{-2}$$

$$when \quad F\tau >> \frac{1}{\kappa}, \quad C = \kappa \; with\, no\; further\, improvement$$

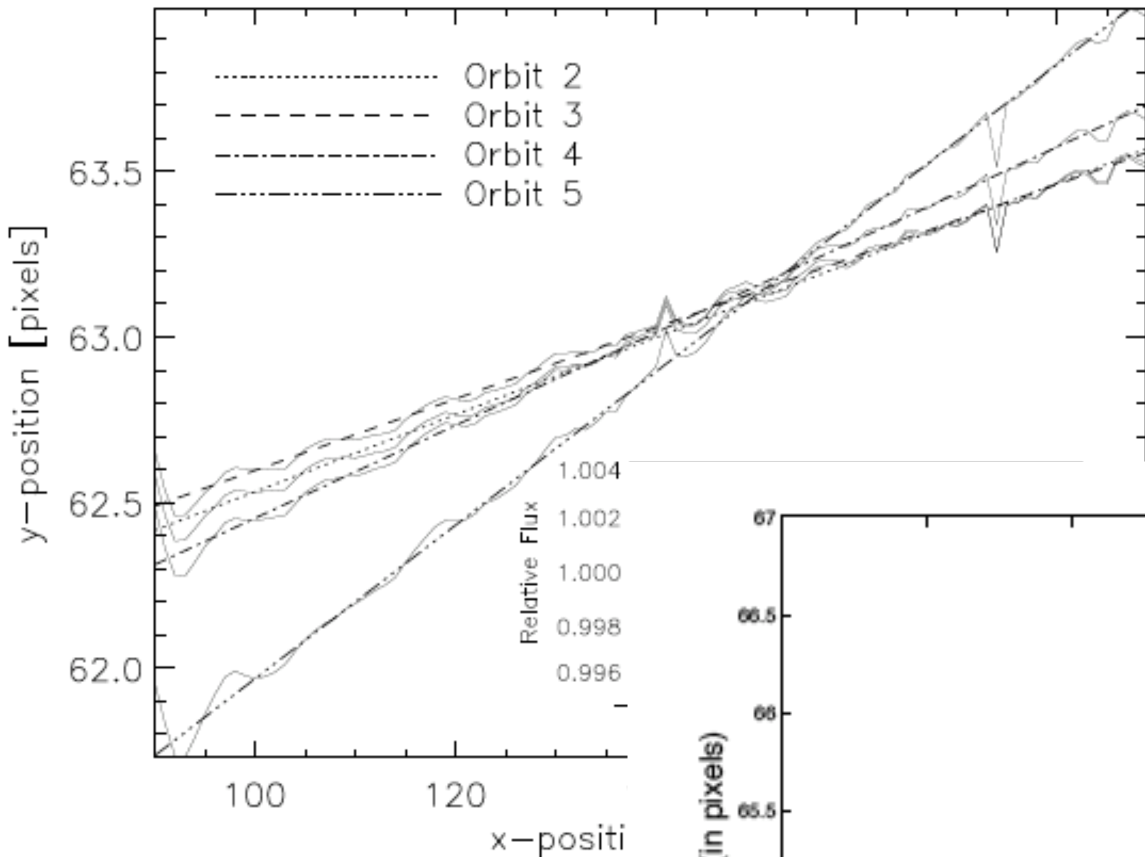
NICMOS
κ~10^{-3} for regular observations
κ~$5x10^{-4}$ for a CVZ target
κ~$5x10^{-5}$ post-modeling

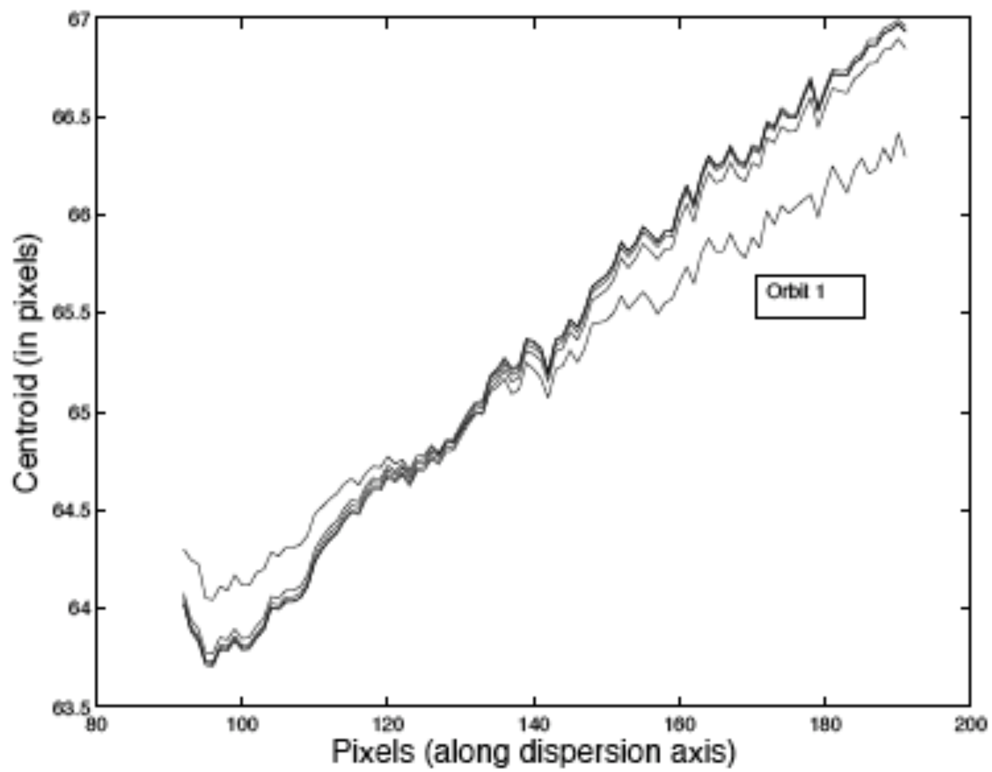


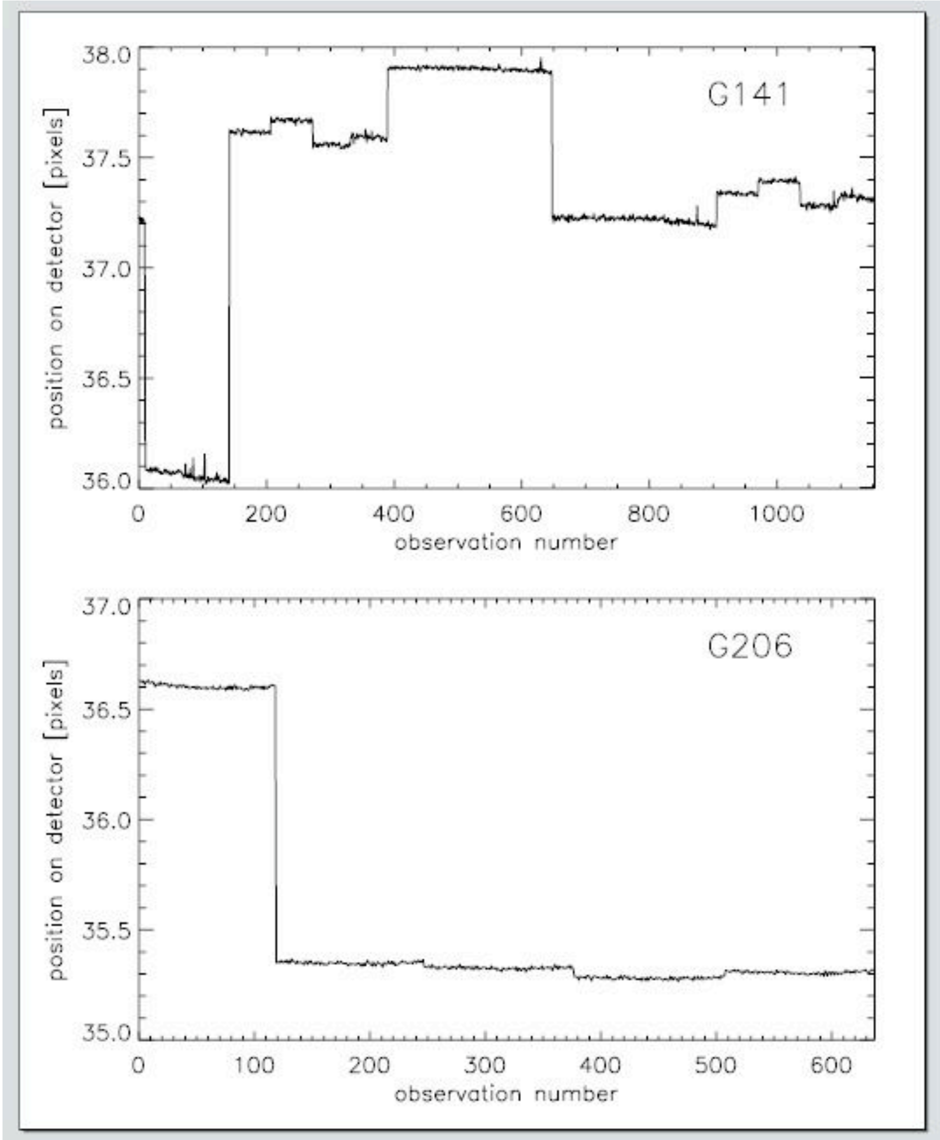
Count-rate jumps

- Orbit to orbit count-rate jumps are the most egregious
- During Earth occultation the filter-wheel is stowed away to a blank to protect the detector
- The repositioning is imperfect
- Consequently, the light sees practically a new part of the detector (by a fraction of a pixel)
- Given ~5 orbits during a single visit, can the count-rate jump be easily modeled?

$$N(\delta\vec{x}) = N(0) + \vec{\nabla} N \cdot \delta\vec{x} + \mathrm{O}(2)$$

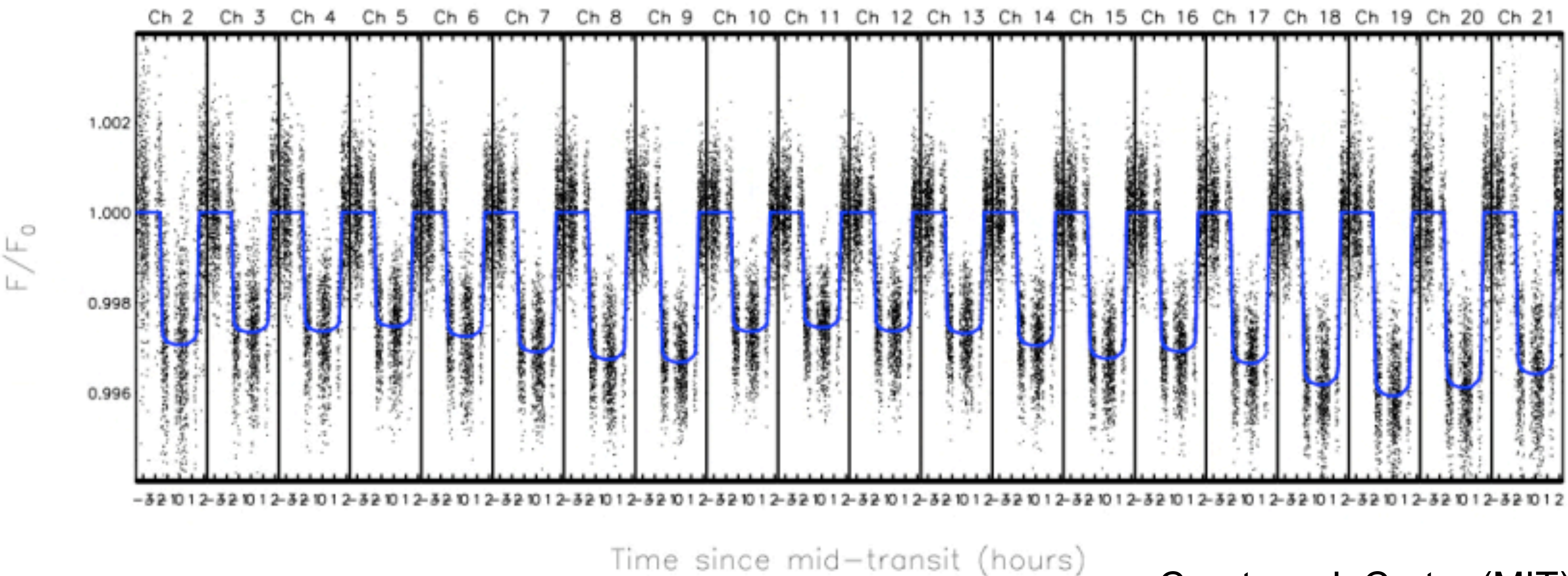

Orbit 2
Orbit 3
Orbit 4
Orbit 5
63.5
63.0
62.5
62.0
y−position [pixels]
100
120
x−positi
Relative Flux
1.004
1.002
1.000
0.998
0.996


67
66.5
66
65.5
65
64.5
64
63.5
80
100
120
140
160
180
200
Centroid (in pixels)
Pixels (along dispersion axis)
Orbit 1



G141
position on detector [pixels]
observation number
G206
position on detector [pixels]
observation number

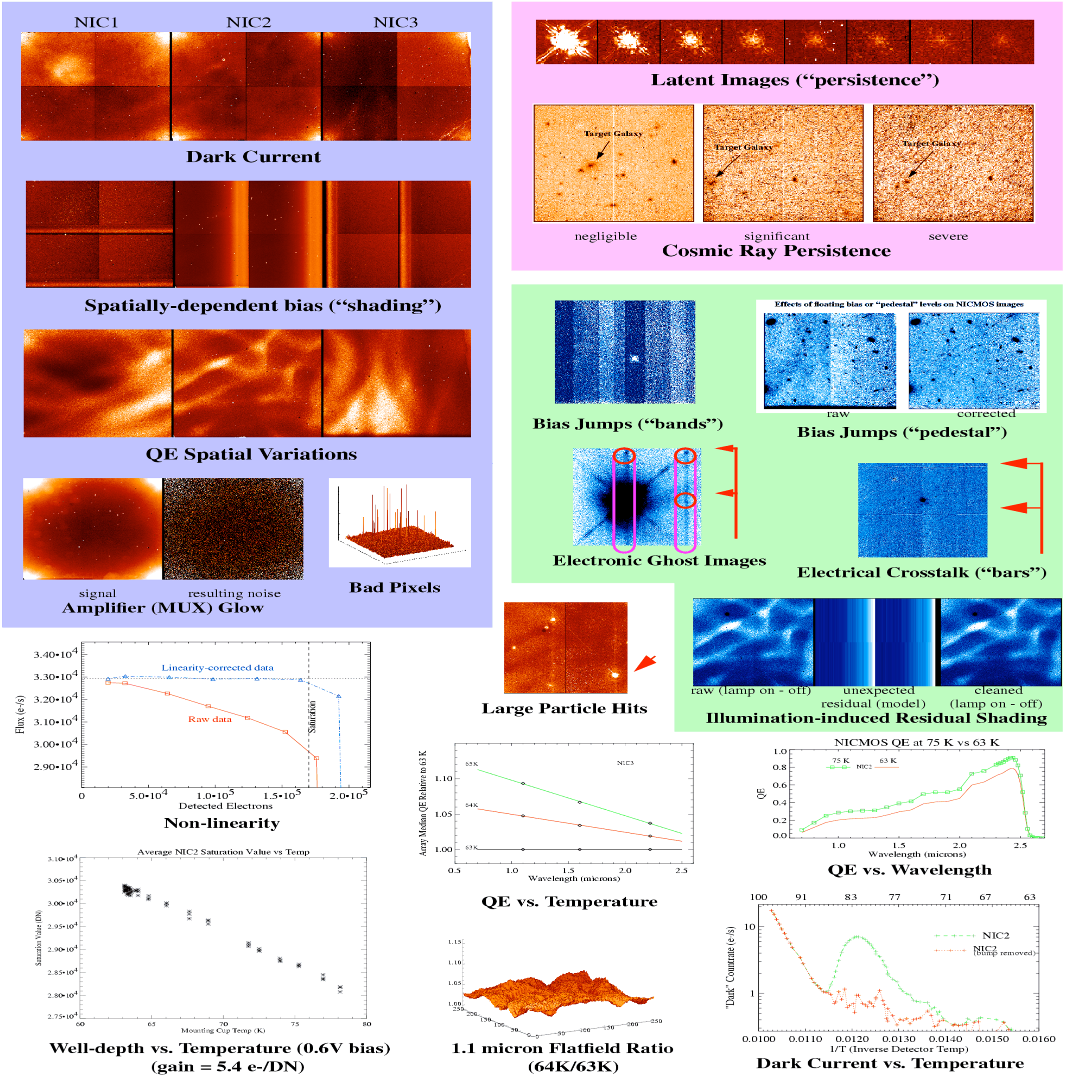
With Systematics Modeled Out …



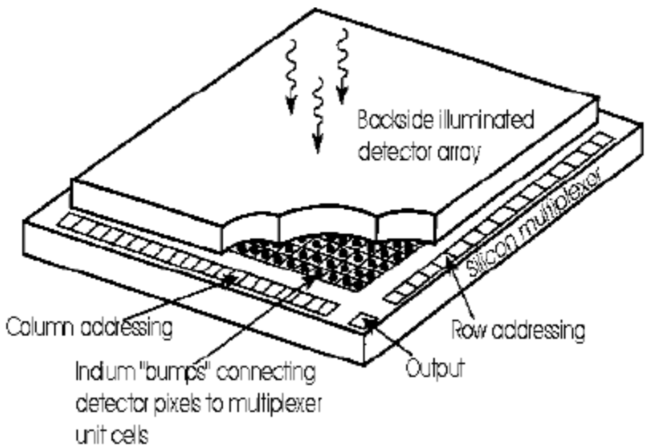
Courtesy J. Carter (MIT)

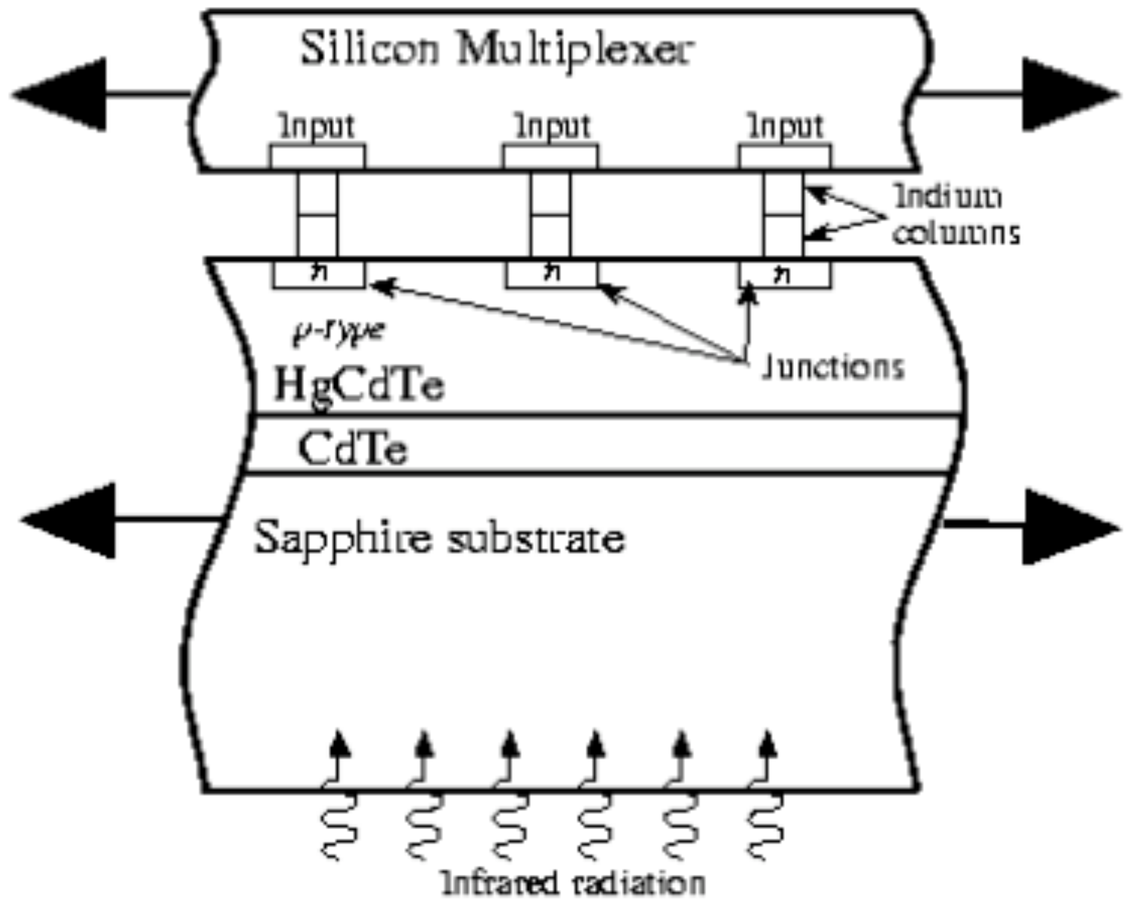
Effects in NICMOS and other NIR detector arrays

- Stress induced structure in the detector response
- Pixel-to-Pixel stochastic response variations
- Spatial structure from medium to large scales
- Intrapixel structure in the response
- T-dependence

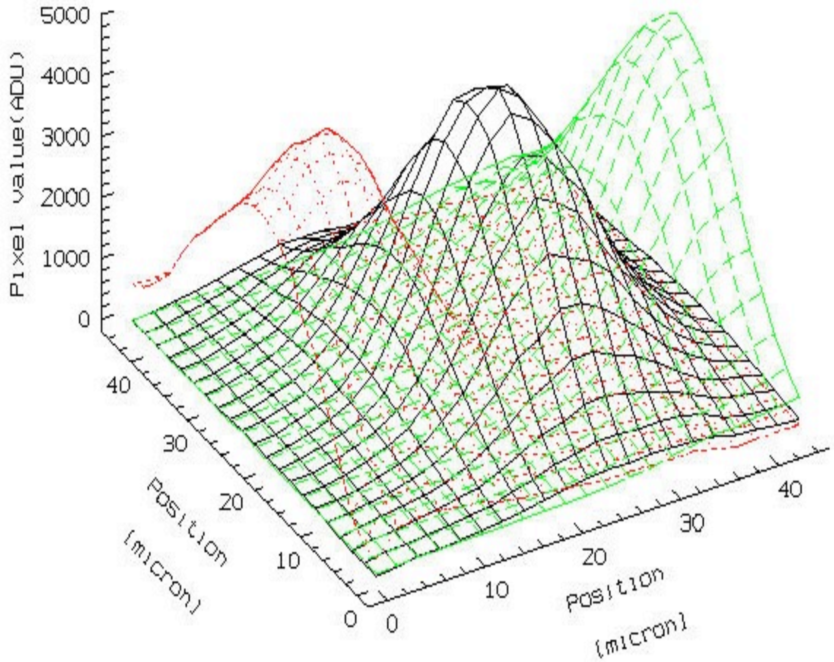


Figer et al. 2002

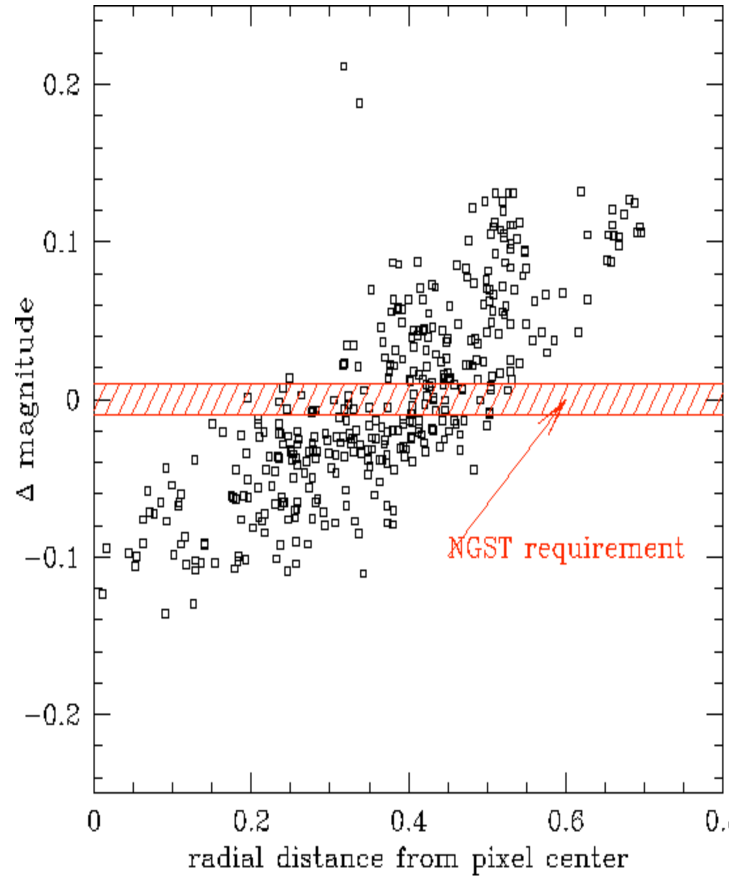

Backside illuminated
detector array
silicon multiplexer
Column addressing
Row addressing
Indium "bumps" connecting
detector pixels to multiplexer
unit cells
Output


Silicon Multiplexer
Input
Input
Input
Indium
columns
n
n
n
p-type
HgCdTe
Junctions
CdTe
Sapphire substrate
Infrared radiation

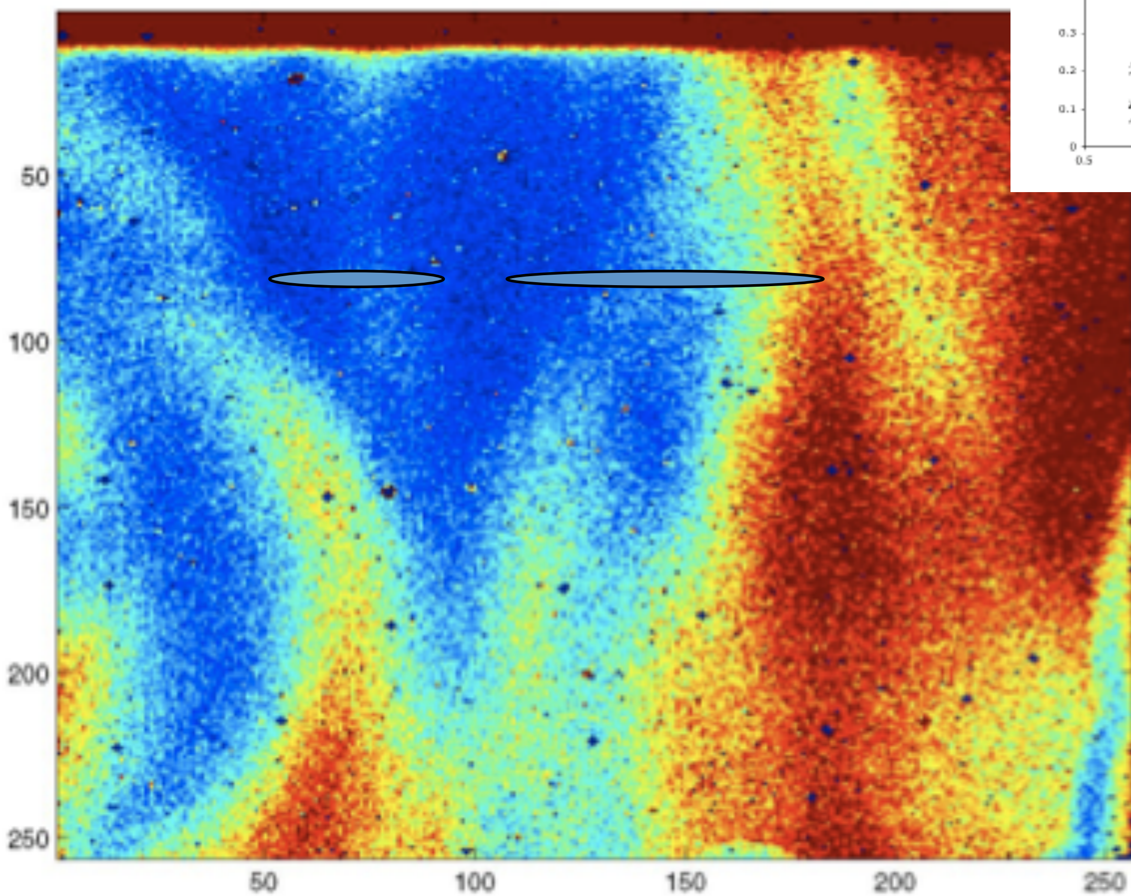
Small scale structure and MTF

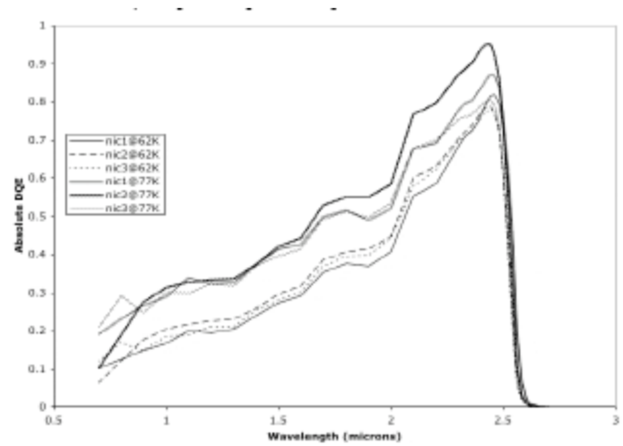


Finger et al. 2000



Stiavelli et al.





Detector response plot at single color

1. Response variations on all scales
2. Variations not measured well enough
3. Scene changes as a function of color

$$C\left(x',y'\right) = \iint\limits_{x,y} dxdy\ I(x'-x,y'-y)R(x,y) = I*R$$

$$C(x'+\delta x',y'+\delta y') = \iint\limits_{x,y} I(x'+\delta x'-x,y'+\delta y'-y)R(x,y)$$

Ask the question what the quantity

$$\left\langle \left(C(\vec{r}+\delta\vec{r}) - C(\vec{r})\right)^2 \right\rangle = \sigma_C^2\ is?$$

Best evaluated in Fourier domain as,

$$\sigma_C{}^2 = 2\iint\limits_{k_x,k_y} dk_x dk_y\ \Im\left(\vec{k}\right)\overbrace{\Re\left(\vec{k}\right)}^{response}\underbrace{\left(1-\cos(\vec{k}\cdot\delta\vec{r})\right)}_{highpass\ filter}$$

$\Im$ *is psd of* I

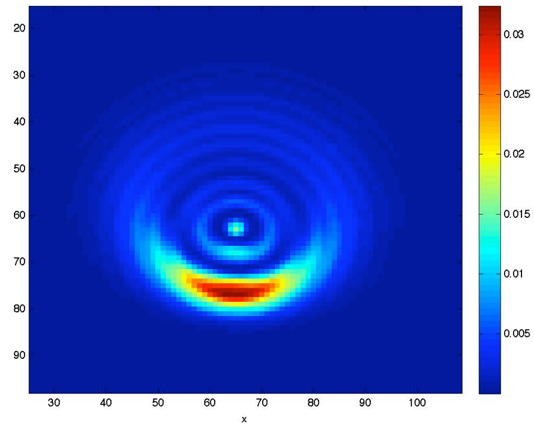
$\Re$ *is psd of* R.

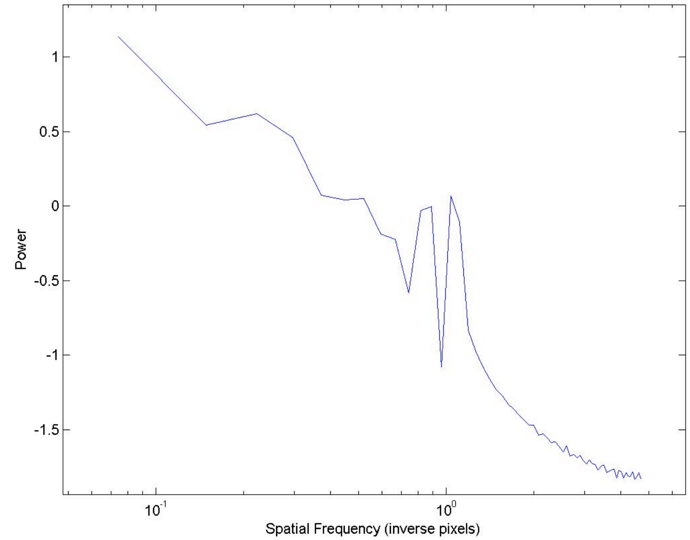
$$\sigma^2 = 2\iint_{k_x, k_y} d^2k \, \underset{\uparrow \text{apodization}}{\Im\left(\vec{k}\right)^2} \overbrace{\Re\left(\vec{k}\right)^2}^{response} \underbrace{\left(1 - \cos(\vec{k}\cdot\Delta\vec{x})\right)}_{highpass}$$

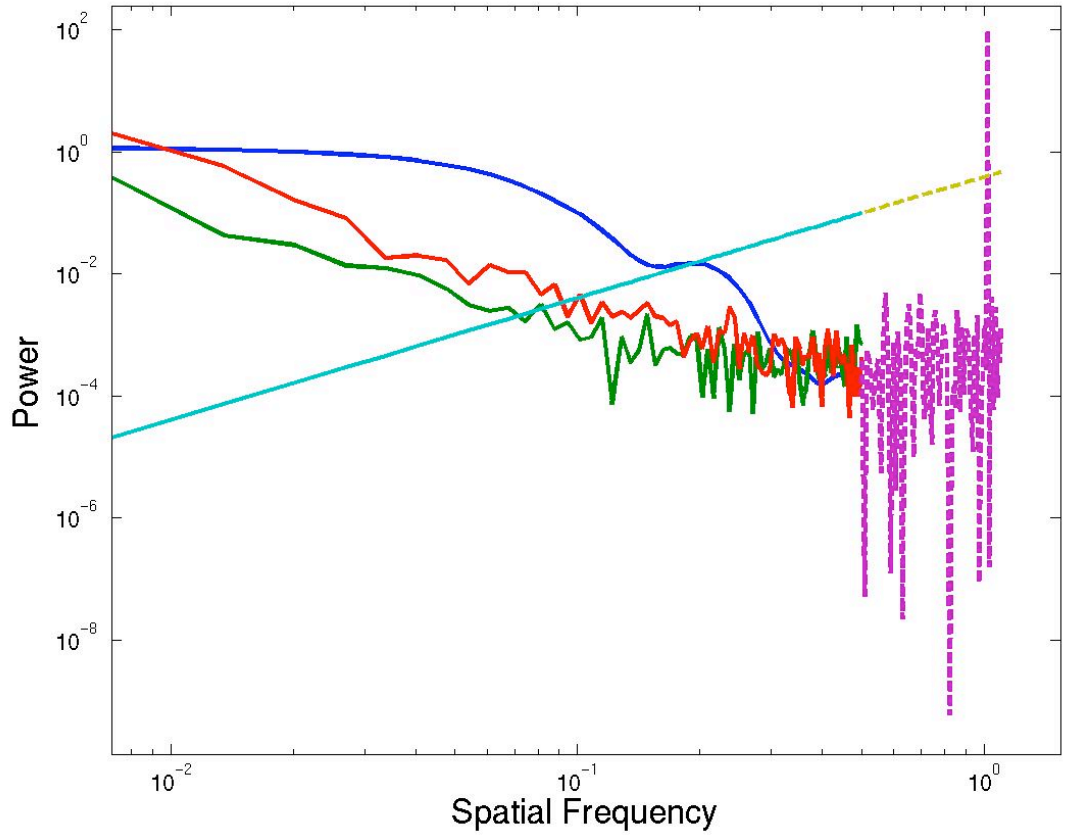
Nothing magical here:

Even when there are tiny displacements, contributions to photometric fluctuations arise from all sorts of spatial scales.

Defocus is a mixed bag:
1. critical for reducing intrapixel terms (but not totally effective).
2. at the expense of picking up lots of power at large spatial scales.







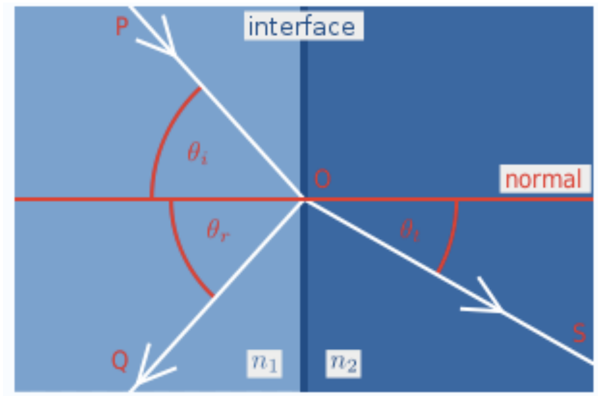
Take away: Despite defocus to 5 pixel FWHM, photometry can show large "wander" effects.

Significant power on the scale of a pixel.

Wander of < 0.1 pixel is amenable to linear modeling.

Optical Systematics: … and one cannot ignore the plumbling

- PSF evolution with breathing
- Quick example (Fresnel reflection)
-



- Rotation/translation of a grating
  - Changes in efficiency or migration of light between orders
  - Shadowing of the light by grooves
  - Wood's anomalies …

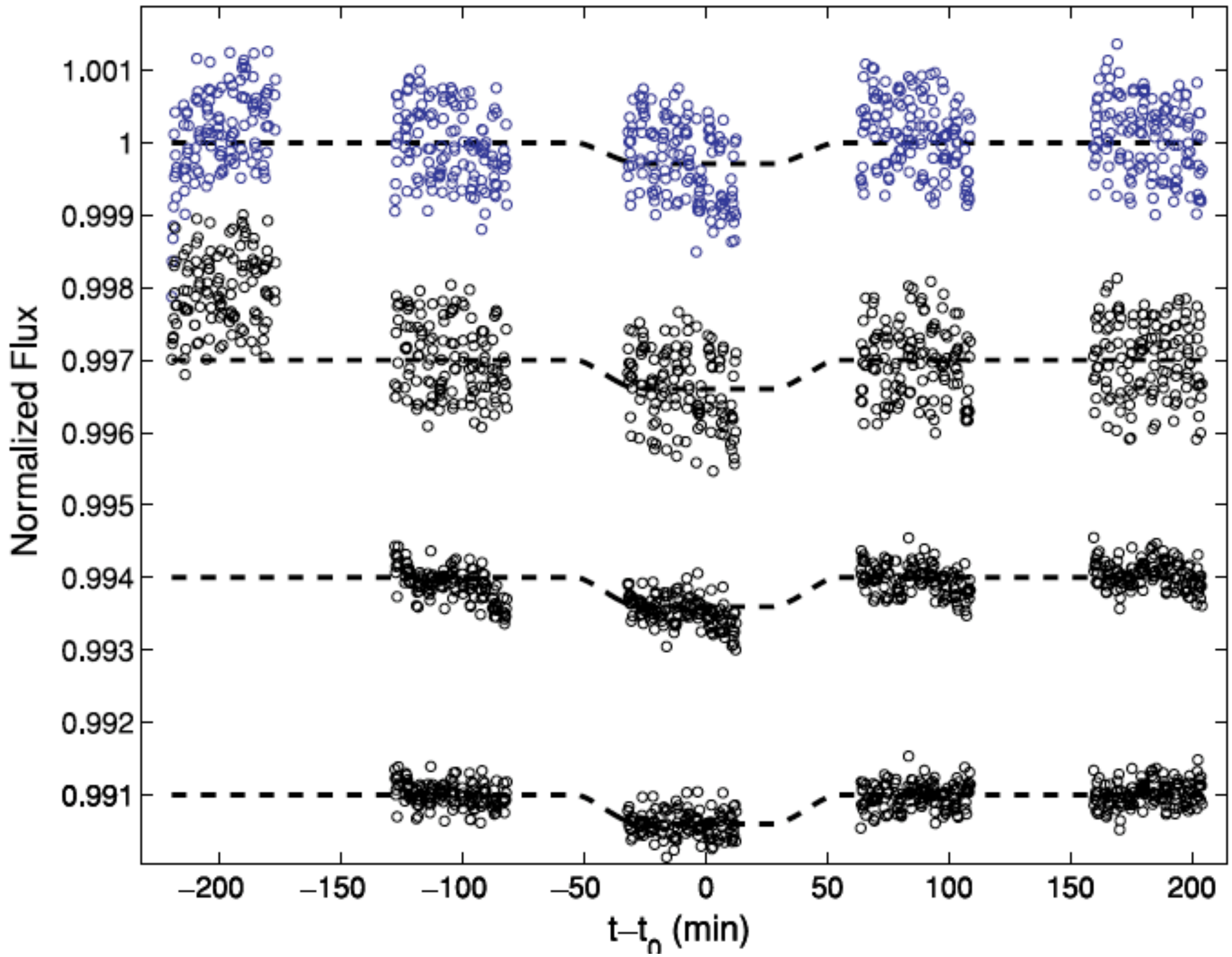
NICMOS States & Temperatures

- NICMOS detectors are extremely sensitive to changes in the operating temperature and the supply voltage. Variations affect QE, dark current and biases in such a way as to limit the overall sensitivity of observations.
- Operating temperatures can be derived using the diode properties of the detector-cell, using the 0^{th} read in an exposure and corrected for HST bus voltage induced variations (E. Bergeron STSCI)

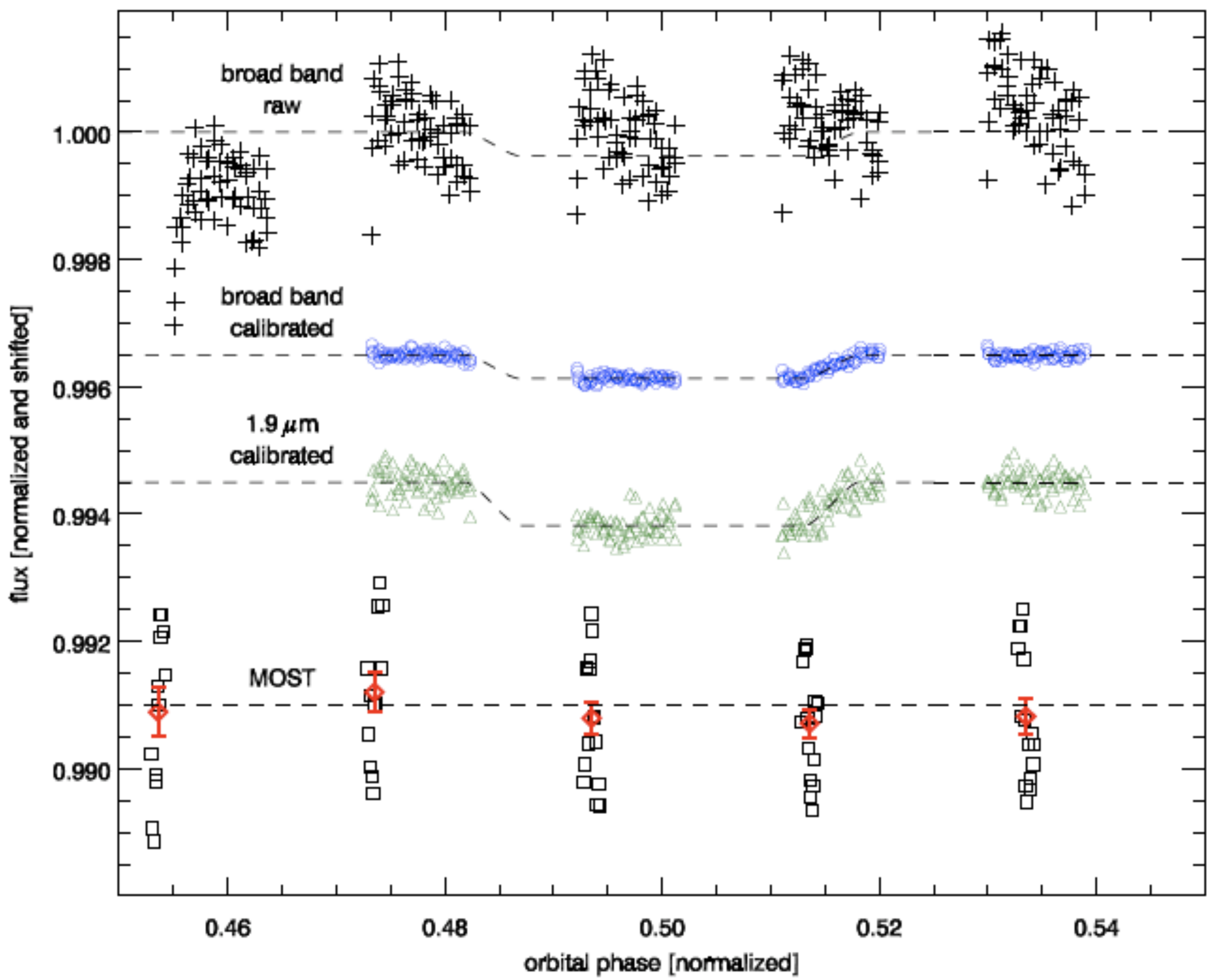
NICMOS States

- The non-Gaussianity of the data: NICMOS exposures live in seven preferred states (which can be ascertained and corrected for).
- Voltage variations seen in the HST bus voltage make their way to the NICMOS detectors.
- The seven states of the instrument can be seen as seven effective exposure times.

C. Burke (private comm.), source E. Bergeron (STSCI).



1.001
1
0.999
0.998
0.997
0.996
0.995
0.994
0.993
0.992
0.991
Normalized Flux
−200
−150
−100
−50
0
50
100
150
200
t−t0 (min)

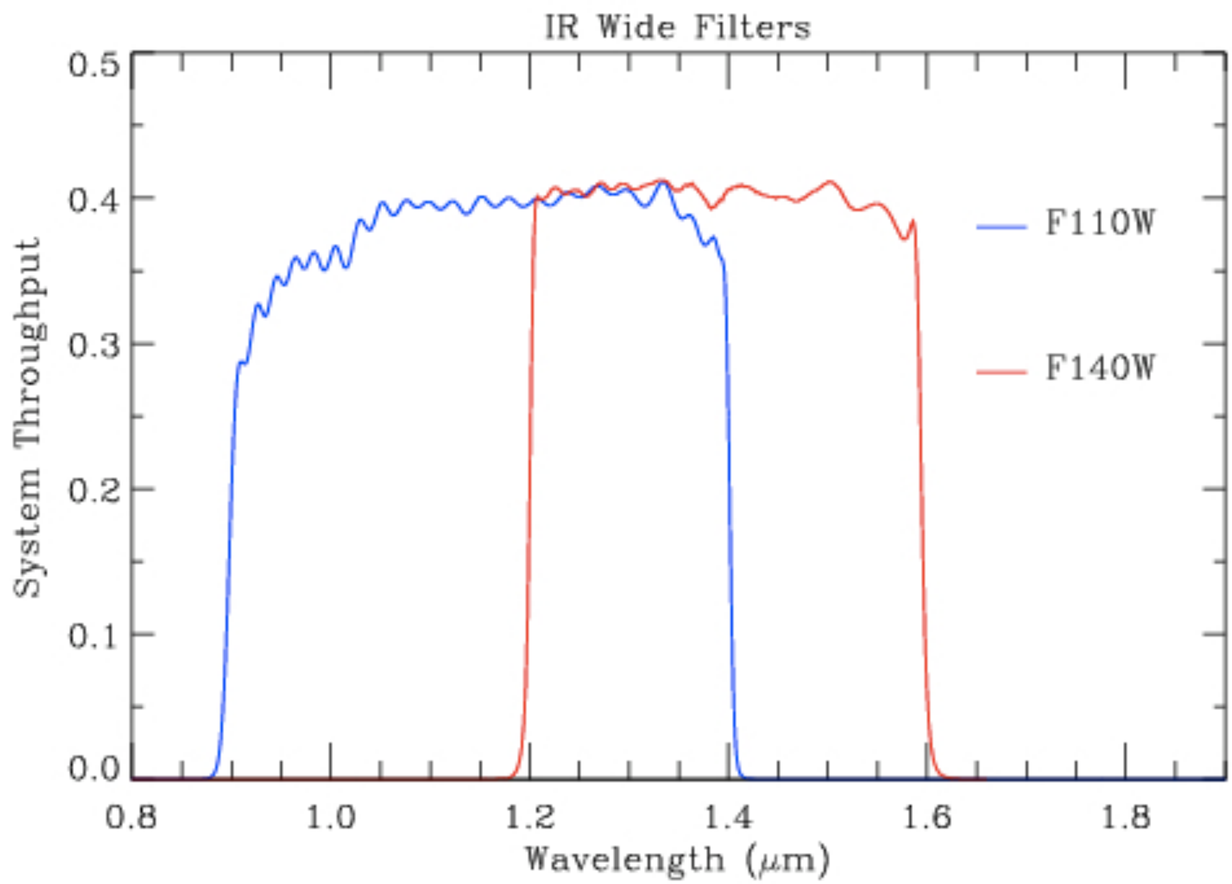


broad band raw
broad band calibrated
1.9 μm calibrated
MOST
1.000
0.998
0.996
0.994
0.992
0.990
flux [normalized and shifted]
0.46
0.48
0.50
0.52
0.54
orbital phase [normalized]

NICMOS Prospects

- Plan: restart of cryocooler when schedule allows
  - Followed by full recalibration of the instrument
- Compressor loops need to be in certain temperature range at restart
  - Allows freeze out of moisture in the Ne on a cold surface

The scion: passing the baton



Summary/Salient Points

- The near-infrared is an indispensable wavelength band for spectroscopy of hot planets.
- “Dirty” NICMOS lightcurves do respond to the virtues of modeling (of instrumental effects) in a fairly well understood regime.
- … but not always, but that may be limited only by tools available and the imagination of the practitioner.

Reading Materials

NICMOS (WFC3) Instrument handbook

NICMOS Data handbook

NICMOS Instrument science reports

Papers:

Swain, Vasisht & Tinetti, *Nature*, 452, 329 (2008), and supplementary index.

Swain et al., *ApJ Letters*, 690, L114 (2009)

Carter et al., *ApJ*, 696, 241 (2009)

A Quick History of Vulcans

- O. Struve (1952) pontificates: no reason why giant-planets should not exist at separations of 1/50th of an AU, imposing a large velocity signal on the star, and possibly even occulting the stellar disk.
- Hot Jupiters discovered (1995)
- RV hot-Jupiter HD 209458b shown to transit (1999).

But there seems to be no compelling reason why the hypothetical stellar planets should not, in some instances, be much closer to their parent stars than is the case in the solar system. It would be of interest to test whether there are any such objects.

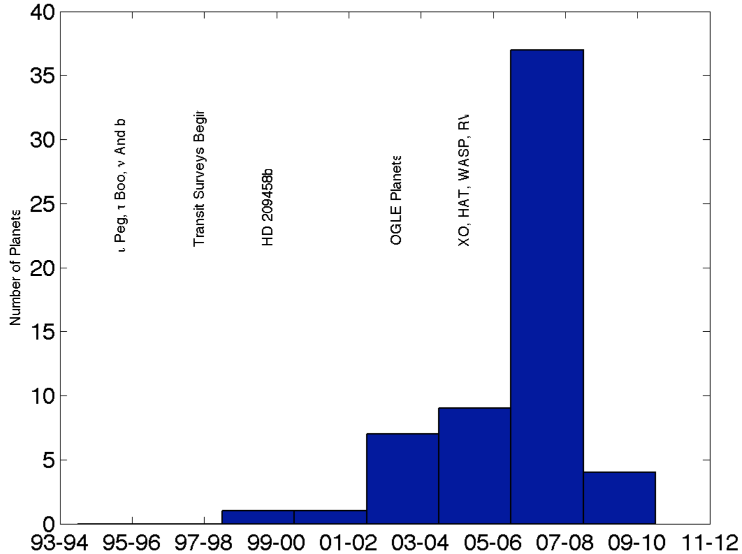
We know that *stellar* companions can exist at very small distances. It is not unreasonable that a planet might exist at a distance of 1/50 astronomical unit, or about 3,000,000 km. Its period around a star of solar mass would then be about 1 day.

We can write Kepler's third law in the form $V^3 \sim \frac{1}{P}$. Since the orbital velocity of the Earth is 30 km/sec, our hypothetical planet would have a velocity of roughly 200 km/sec. If the mass of this planet were equal to that of Jupiter, it would cause the observed radial velocity of the parent star to oscillate with a range of ± 0·2 km/sec—a quantity that might be just detectable with the most powerful Coudé spectrographs in existence. A planet ten times the mass of Jupiter would be very easy to detect, since it would cause the observed radial velocity of the star to oscillate with ± 2 km/sec. This is correct only for those orbits whose inclinations are 90°. But even for more moderate inclinations it should be possible, without much difficulty, to discover planets of 10 times the mass of Jupiter by the Doppler effect.

There would, of course, also be eclipses. Assuming that the mean density of the planet is five times that of the star (which may be optimistic for such a large planet) the projected eclipsed area is about 1/50th of that of the star, and the loss of light in stellar magnitudes is about 0·02. This,

Comparative Vulcanology

Charbonneau 2008



$$M_p \quad R_p \qquad \rho \propto M_p / R_p^3 \qquad g \propto M_p / R_p^2$$

Masses, radii, interiors, formation and evolution (from transit timing).

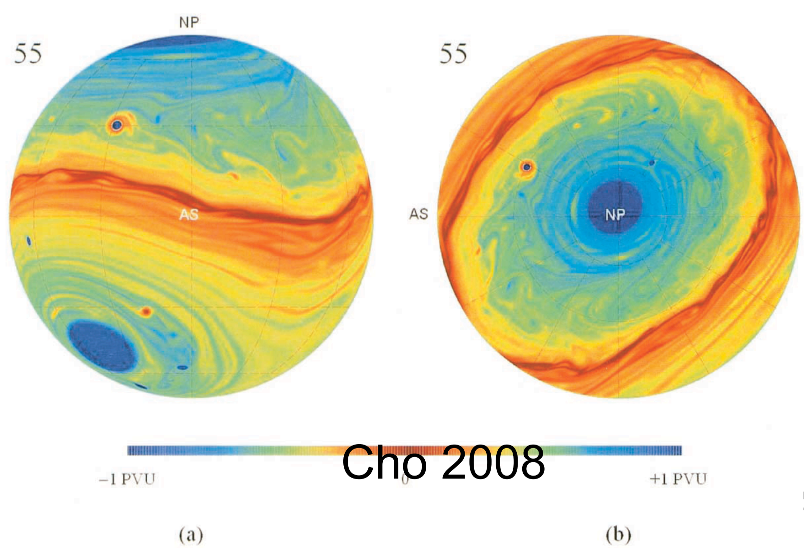
$$very\ likely\ that \quad \Omega_s : \Omega_p :: 1:1$$

Intense stellar dosage on permanent dayside leads to high effective temperatures.

chemistry (photons streaming can perturb chemical equilibrium fairly deep in the atmosphere).

drives planetary scale weather (the effects of which are eminently observable).

infrared atmosphere, structure and composition, are also observable.



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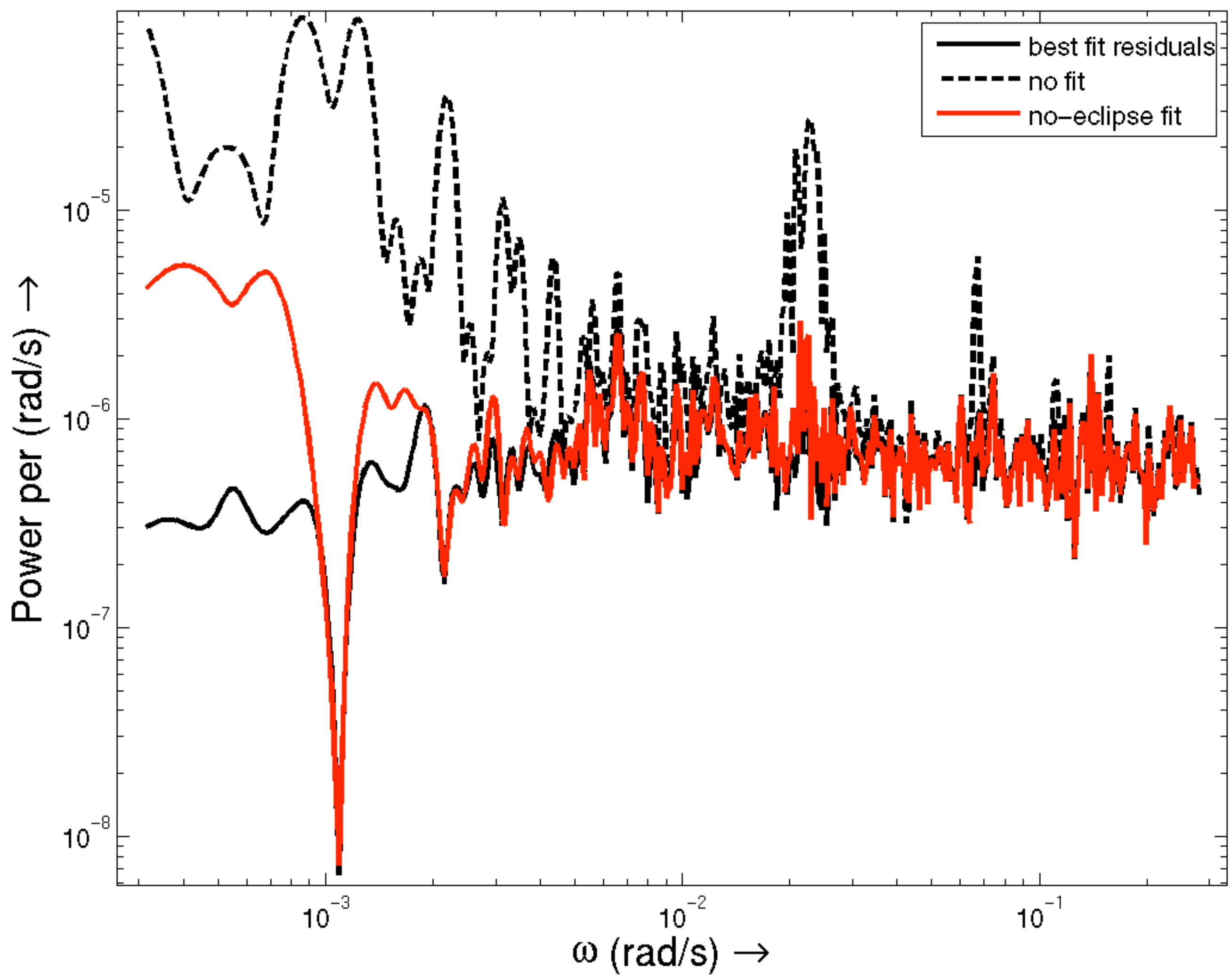
best fit residuals
no fit
no−eclipse fit
Power per (rad/s) →
10^−5
10^−6
10^−7
10^−8
10^−3
10^−2
10^−1
ω (rad/s) →