The Legacy of Spitzer Exoplanet Observations

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UCF Planetary Sciences

- University of Central Florida – ORLANDO!
- 2nd-largest US undergraduate univ., 64,000+, growing
- PhD in Physics, Planetary Sciences Track, ~15 grads
- 7 Planetary Science Professors: (next hire: a space instrumentalist!)
  - Humberto Campins (comets, OSIRIS-REX)
  - Daniel Britt (surfaces, meteorites)
  - Yanga Fernandez (comets)
  - Joseph Harrington (exoplanets & atmospheres)
  - Joshua Colwell (rings, ice, dust, Cassini)
  - Adrienne Dove (dusty plasmas)
  - Christopher Bennett (planetary surfaces)
- Florida Space Institute (self-funded, soft-money):
  - Phillip Metzger (ISRU), Todd Bradley (Mercury, Cassini)
  - Thomas Kehoe (orbits), Gal Sarid (orbits)
  - Noemi Pinilla-Alonso (comets), Julie Brisset (formation)

Outline

- Spitzer Exoplanet Milestones
- ...and Millstones
- Removing Systematics
- Lessons
- Conclusions

Spitzer Reality for Exoplanets

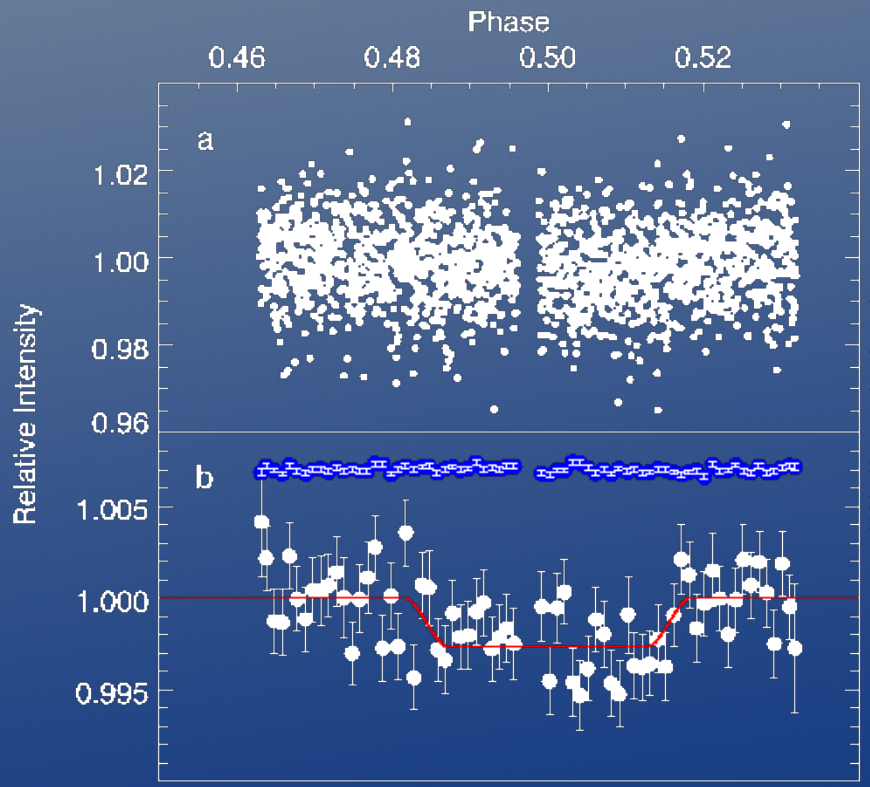
- Transits ~1% for Jupiters
- Eclipses ~0.01 – 0.25%, far below 1% design
- Most favorable planets discovered too late
  - Spectrometer, 16, 24 μm barely used
- Mirror small, typical theoretical S/N<~10/eclipse
- Systematics serious:
  - Baseline unstable at 5.8+ μm (“ramp”)
  - Intrapixel sensitivity variation >1% for 3.6, 4.5μm
- Underresolved pixels make photometry difficult

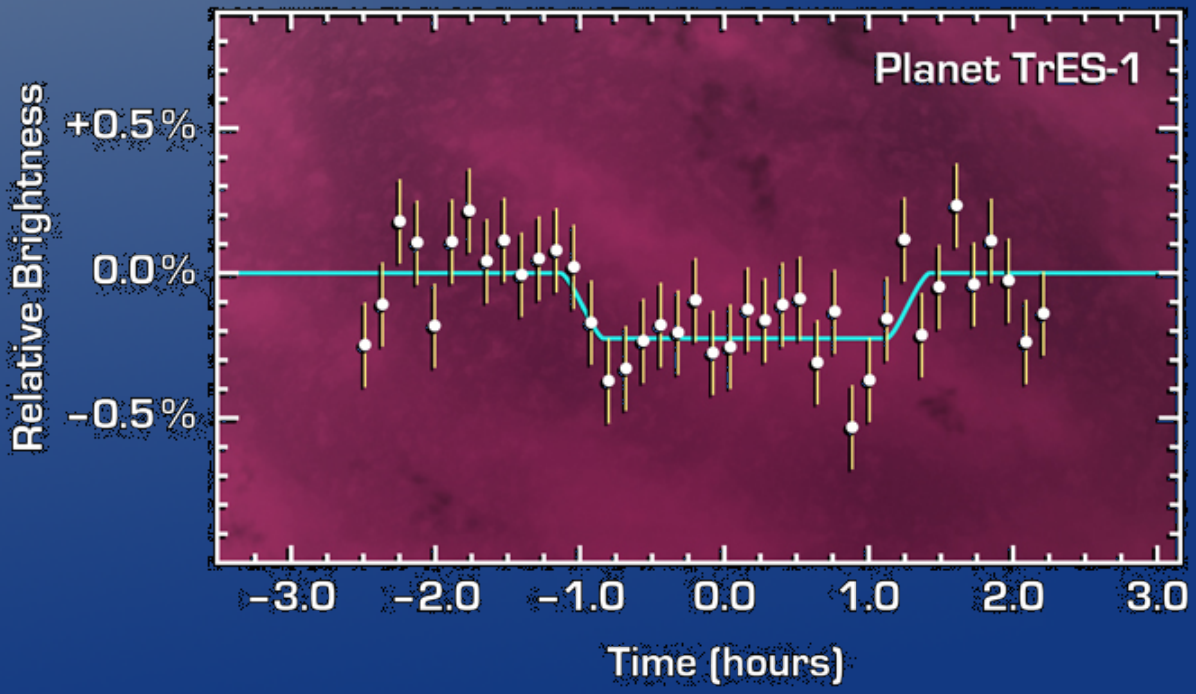
Spitzer Exoplanet Firsts (Methods)

- Eclipses
  - Photometric (Deming+05, Charbonneau+05)
  - Spectroscopic (Richardson+08, Grillmair+08, Todorov+14)
- Phase curves (Harrington+06, Knutson+08)
- Broadband eclipse and transit “spectra” (Knutson+08, Charbonneau+08)
- Dayside mapping (de Wit+12, Majeau+12)
- Habitable-zone M-dwarf planets (Gillon+17)

First Direct Photon Detections

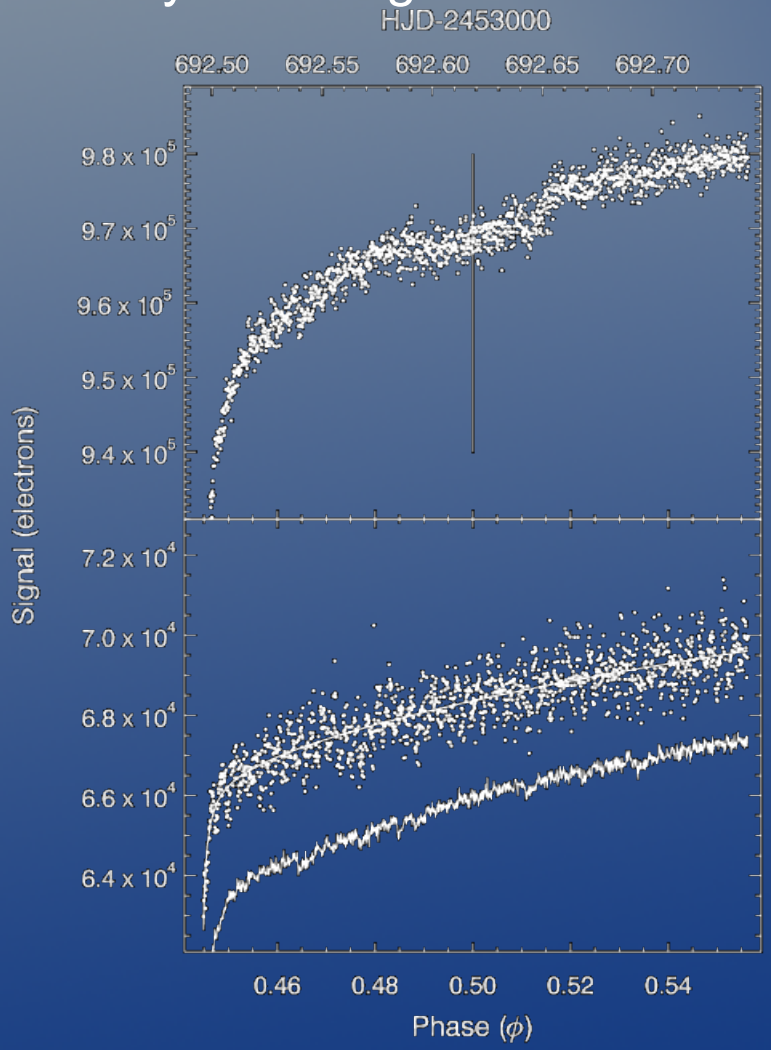
- HD 209458 b, MIPS24, Deming, Seager, Richardson, Harrington (2005, *Nature*)
- $F_{24\ \mu m}$ = 55 ± 10 μJy, F_P/F_* = 0.0026 ± 0.00046, T_b =1130 ± 150 K
- Charbonneau *et al.* (2005, *ApJ*) submitted TrES-1 the same day!
- F_P/F_*: 4.5 μm: 0.00066 ± 0.00013, 8 μm: 0.00225 ± 0.00036, T_b = 1060 ± 50 K

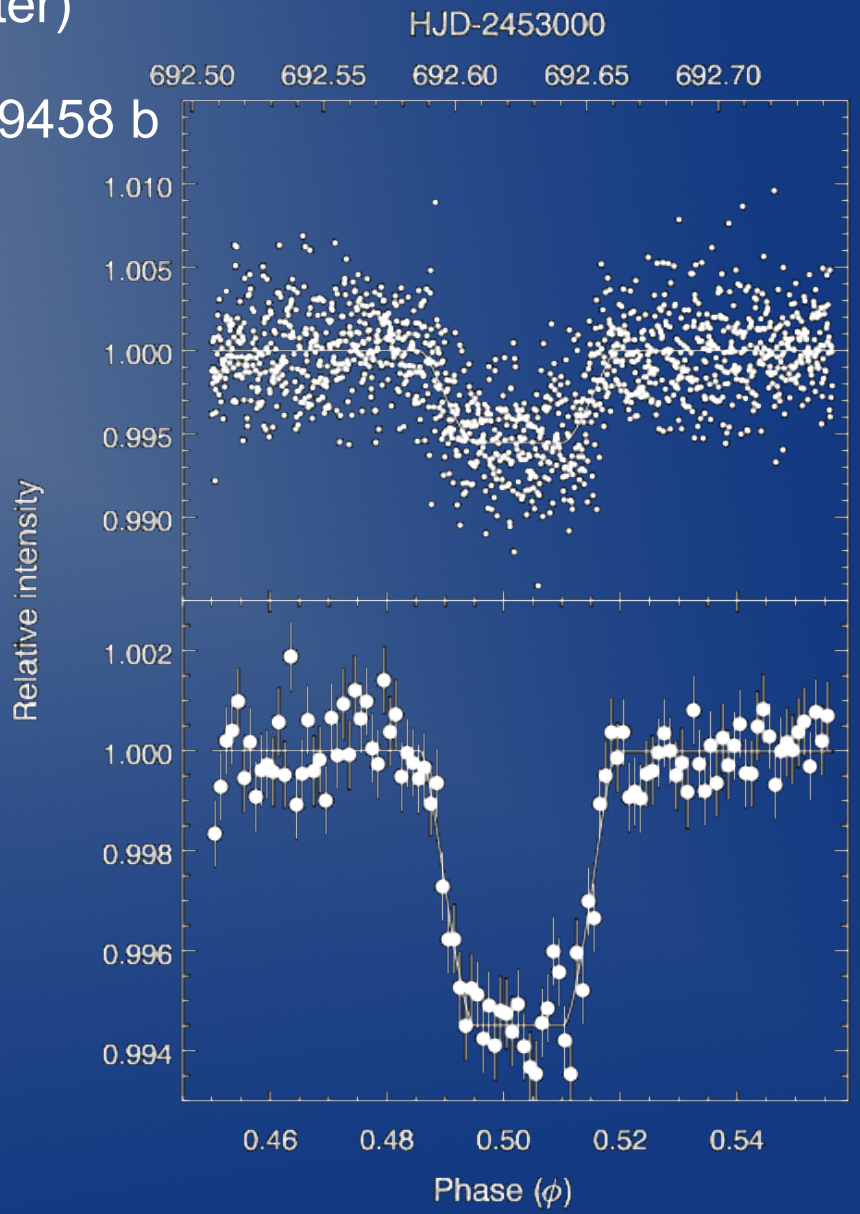




S/N Champ: HD 189733 b

- K1-K2 star (small, cool), close (19.3 pc), V = 7.67
- R_p = 1.26 R_{Jup} (bigish for a hot Jupiter)
- Many times higher S/N than HD 209458 b

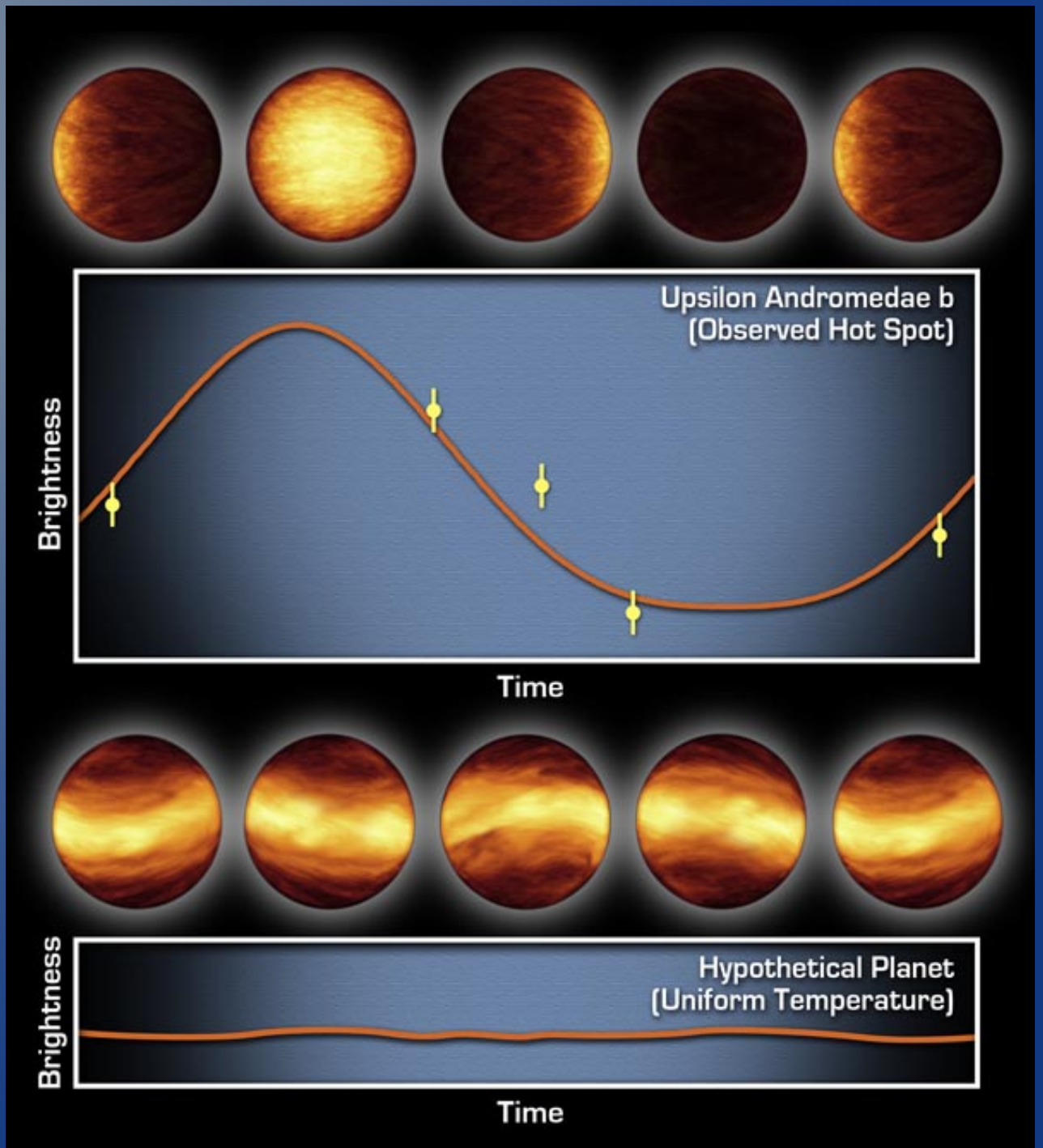




Deming *et al.* (2006, *ApJ* 644, 560)

Phase Curves

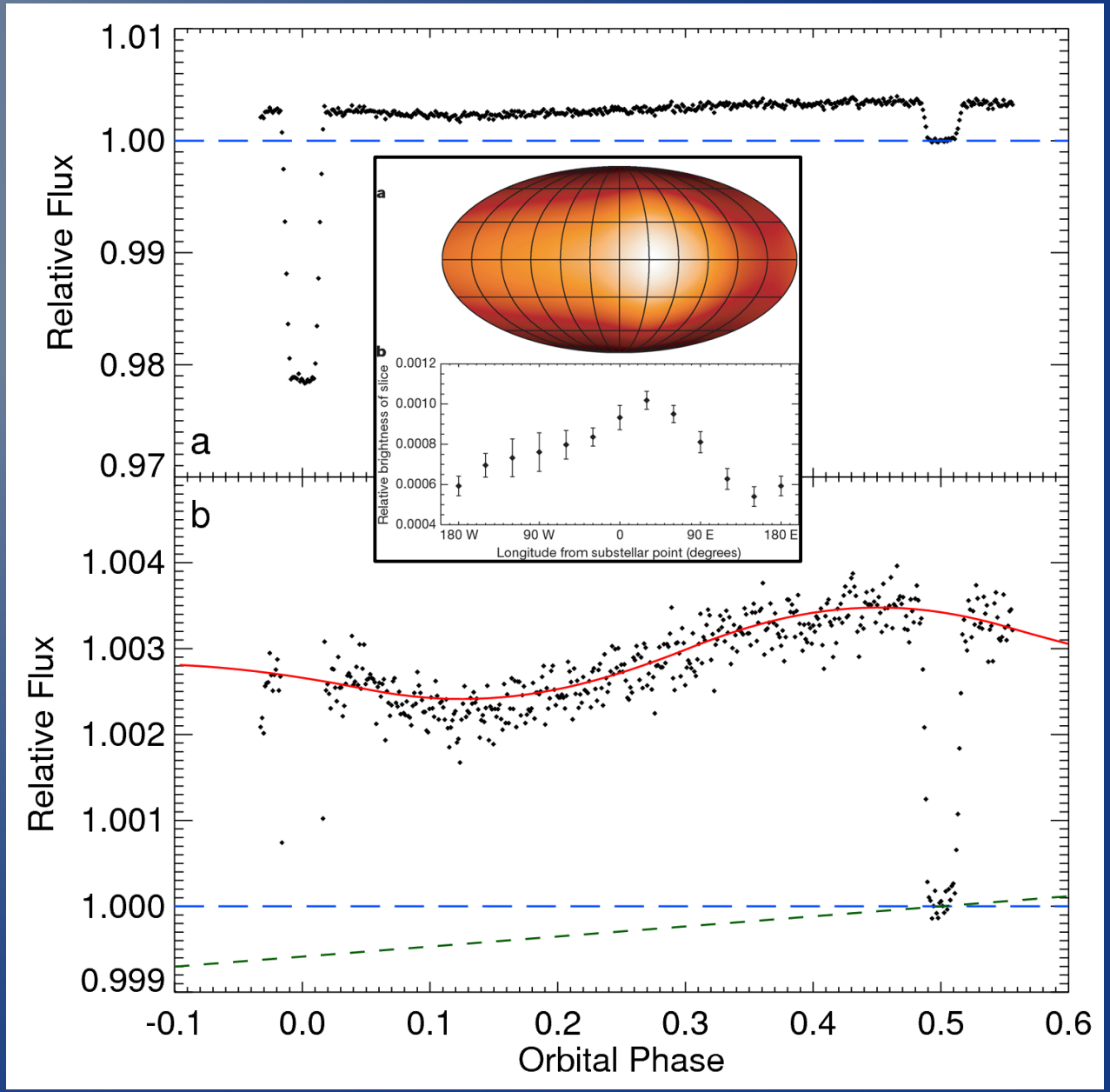
- Ups And b w/ Spitzer MIPS
- Non-transiting planet
- 5 epochs around orbit
- Big variation!
- ...but a reanalysis by Crossfield found a new systematic
- Hot spot moved from star-facing to near limb



after Harrington *et al.* (2006, *Science*)

Phase Curves

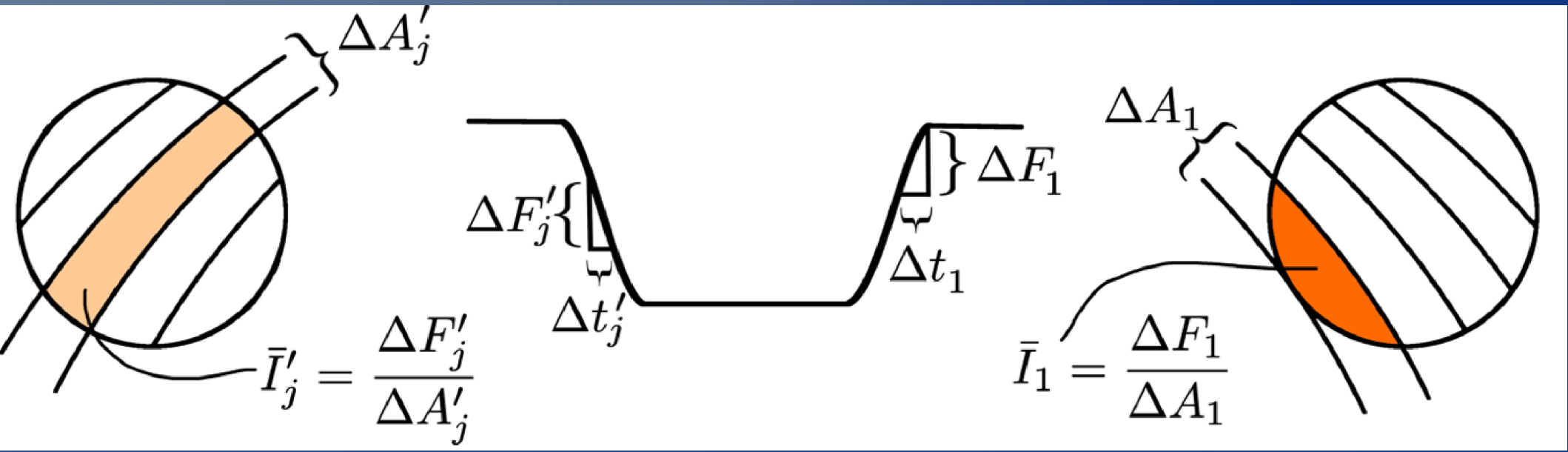
- HD 189733b
- IRAC 8 μm
- Small variation
- Temperature more homogenized
- 24 μm MIPS
- Also GJ 436b, HD 149026b, many others



Knutson *et al*. (2007, *Nature*)

Dayside Mapping

- Use different eclipse ingress and egress angles to map dayside flux
- Done historically for binary stars, Pluto/Charon, galactic center, etc.

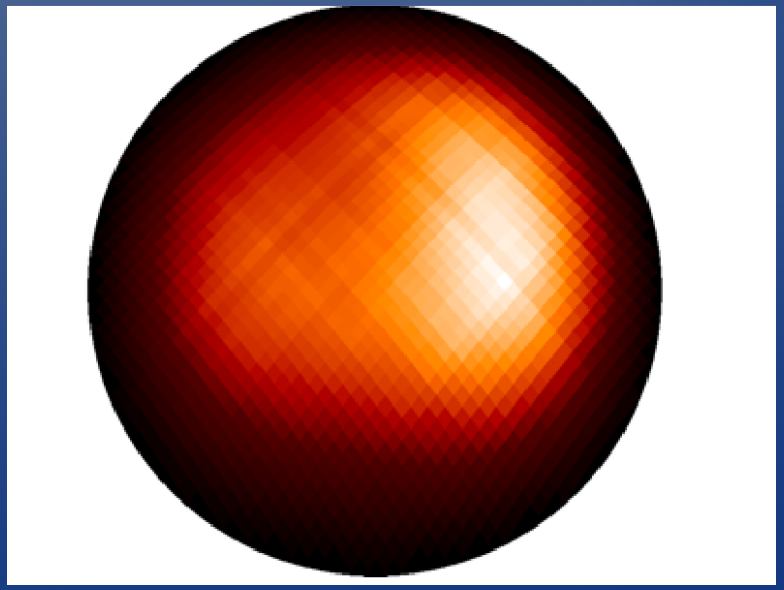


Majeau et al. 2012

Dayside Mapping

Majeau et al. 2012 and de Wit et al. 2012 did for HD 189733b at 8 μm

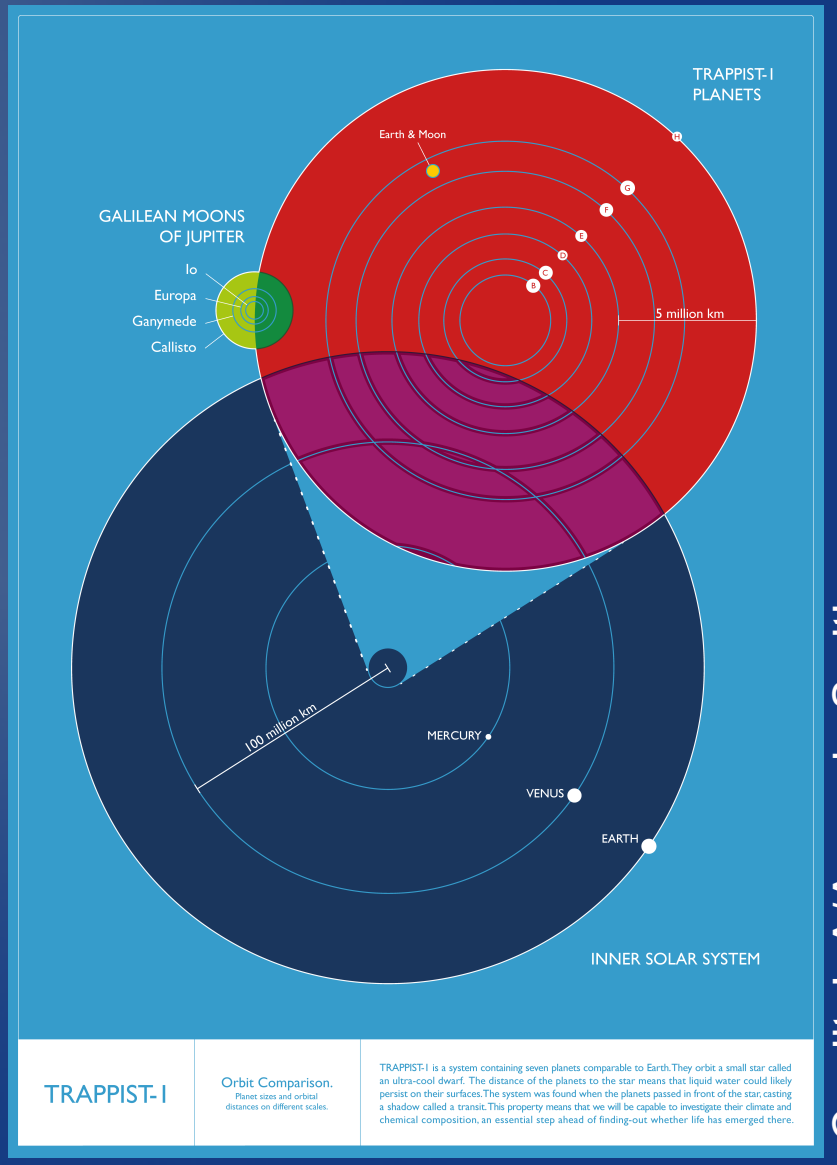
- Spitzer programs to map eccentric planets
- With different wavelengths, could do 3D T(p), 2D composition maps. Holy Grail!
- Proposing for Spitzer, JWST will clean up!



Majeau et al, 2012

TRAPPIST-1 Habitable(?) Planets

- 2 planets found in survey
- 5 more found by Spitzer
- “Habitable zone”
- Earth-sized (0.76-1.13 Re)
- Small M-dwarf star
- Gillon+17, *Nature*



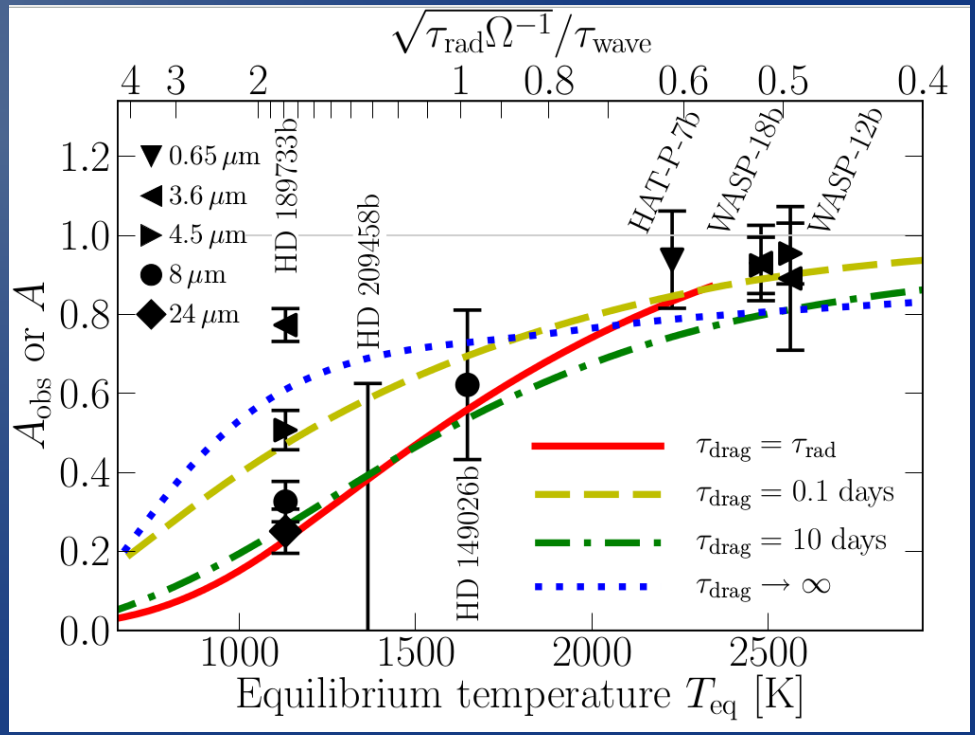
Credit: IoA/Amanda Smith

Spitzer Exoplanet Science

- Temperatures and extreme planets
  - 3000-3500+K (WASP-12b, 33b)
  - ~1000- K (GJ 436b, WASP-8b, W11-HAT-P-10b)
- Hot spots become central+hot with high temp., circulation breaks down (Perez-Becker and Showman 2013)
- Orbital eccentricity from eclipse timing
- Odd chemistry
  - Disequilibrium, GJ 436b (?)
  - C/O > 1, WASP-12b? (Madhu vs. Line battle)
- Inversions? ...or not... (Knutson first, then many, now fights)
- Attempts at population stats (us, Cowan, nothing clear)

Phase Curve Hot Spots

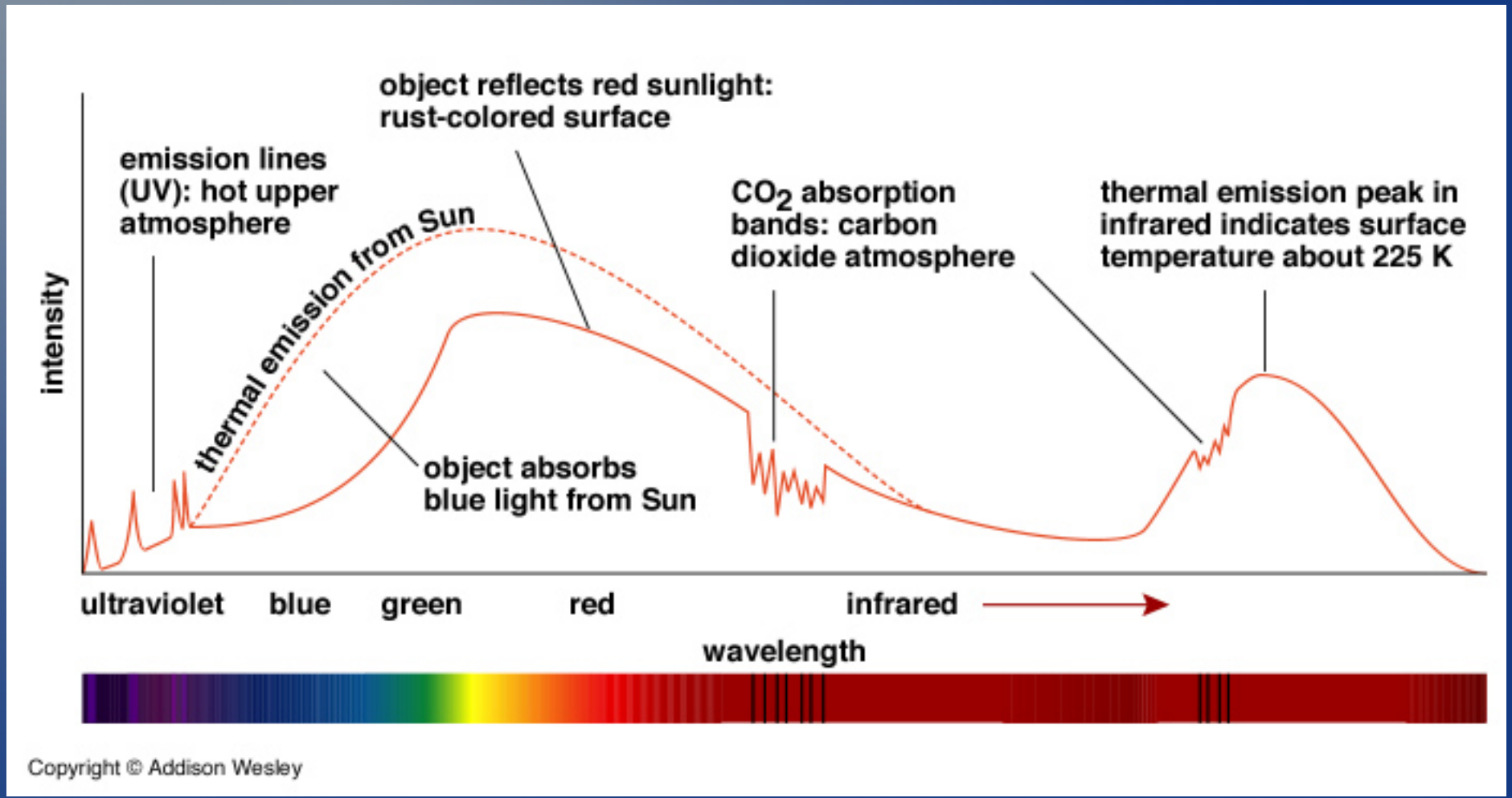
- Cooler planets: Fast winds blow heat to night side
  - Shallow phase curve
  - Hot spot toward limb
- Hotter planets: Radiation beats advection
  - Winds cool before reaching night side
  - Circulation breaks down
  - Deeper PC, central hot spot



Perez-Becker and Showman 2013

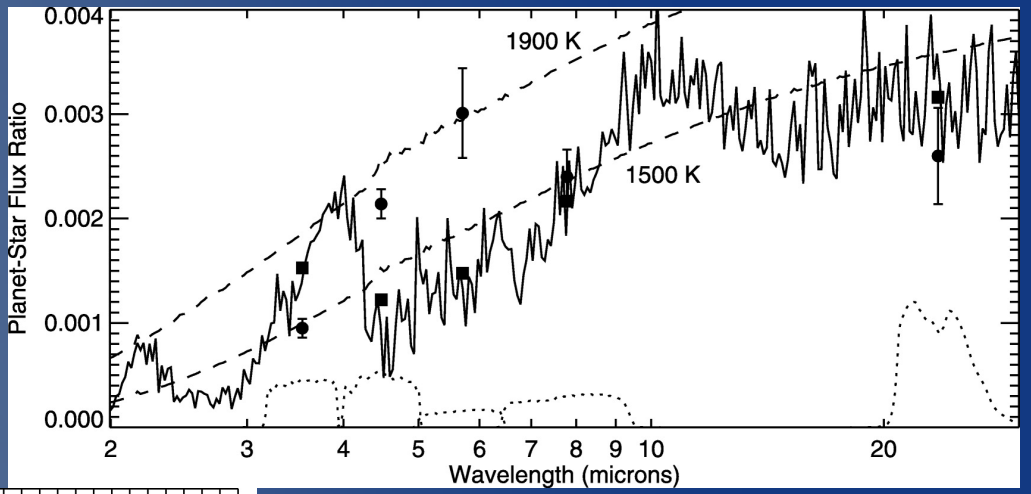
Measuring Atmospheres

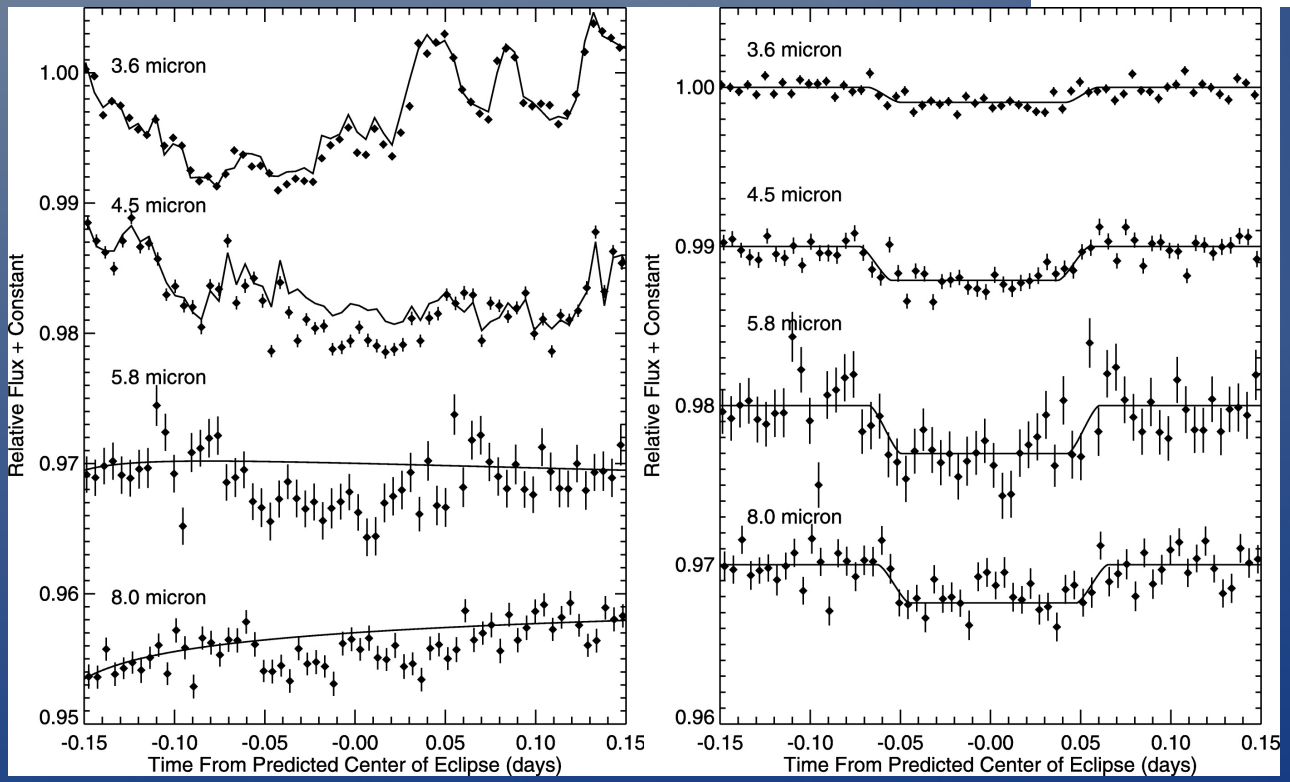
A planet's spectrum tells its story. Take Mars:



Broadband "Spectra"

- Knutson *et al.* (2008, *ApJ*)
- HD 209458b
- Spitzer 3.6, 4.5, 5.8, 8

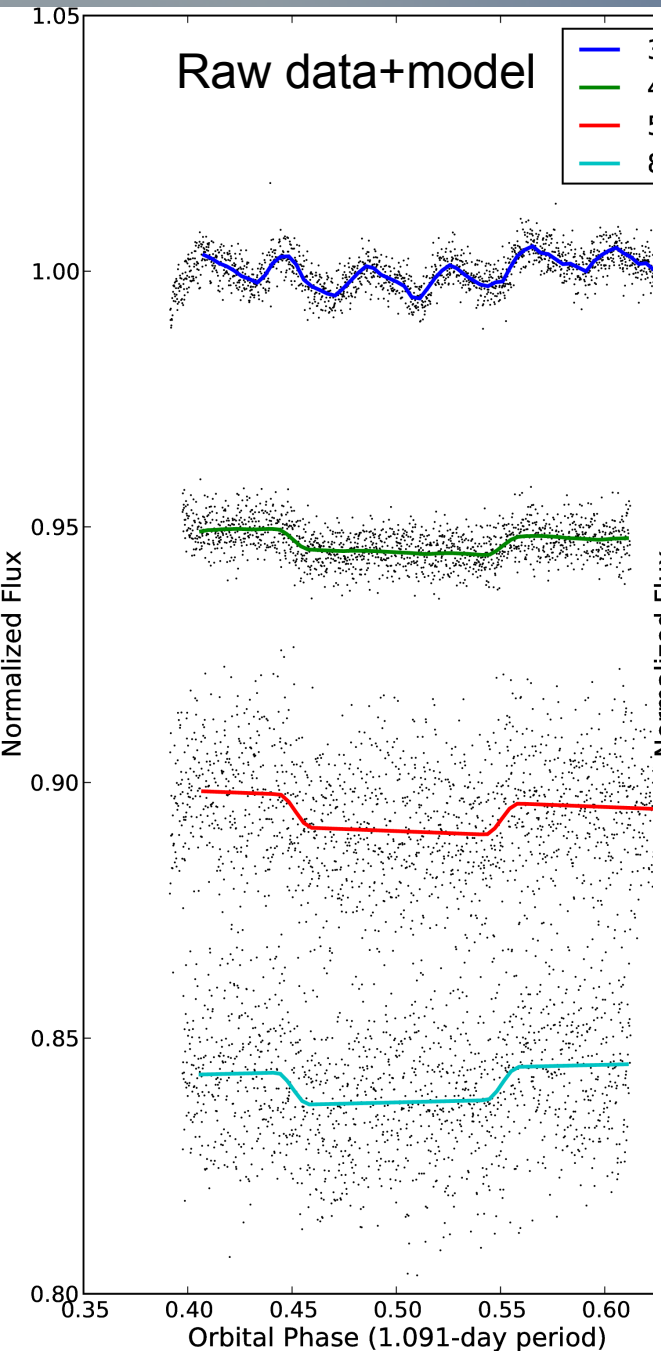


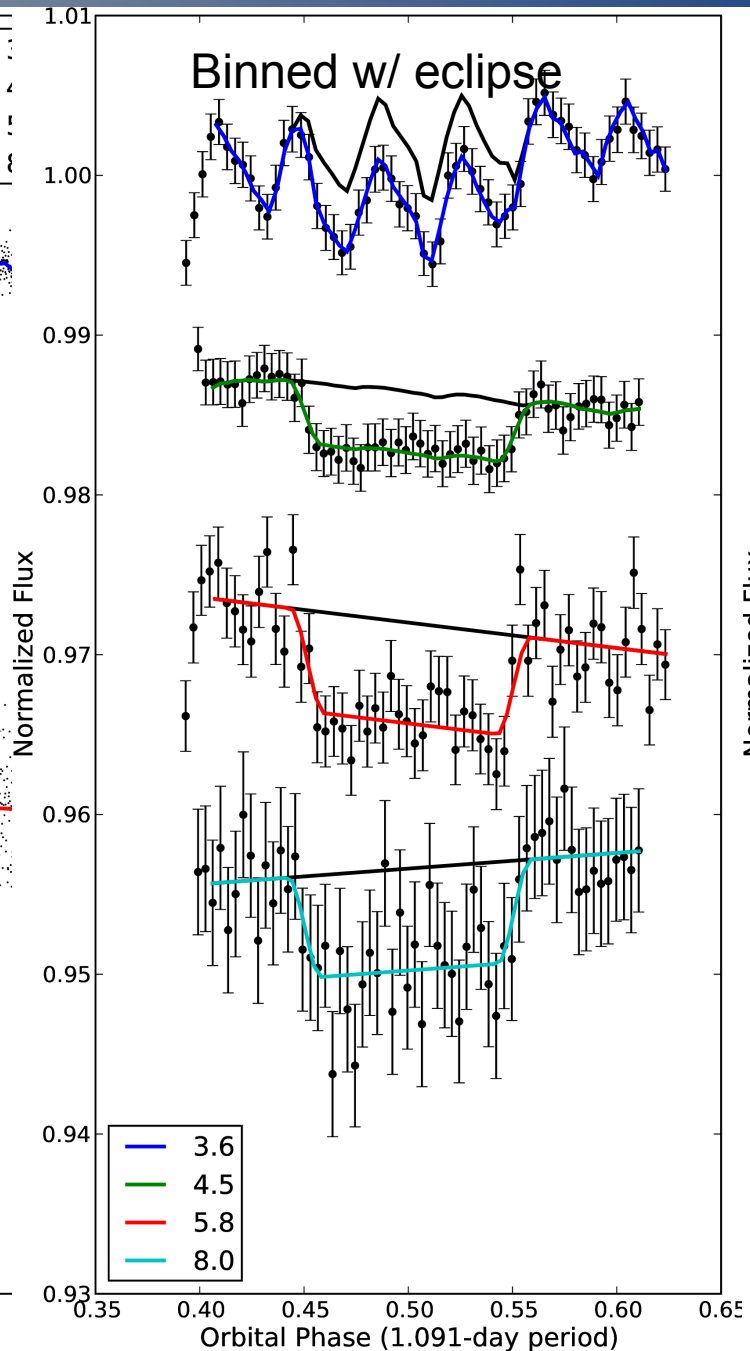


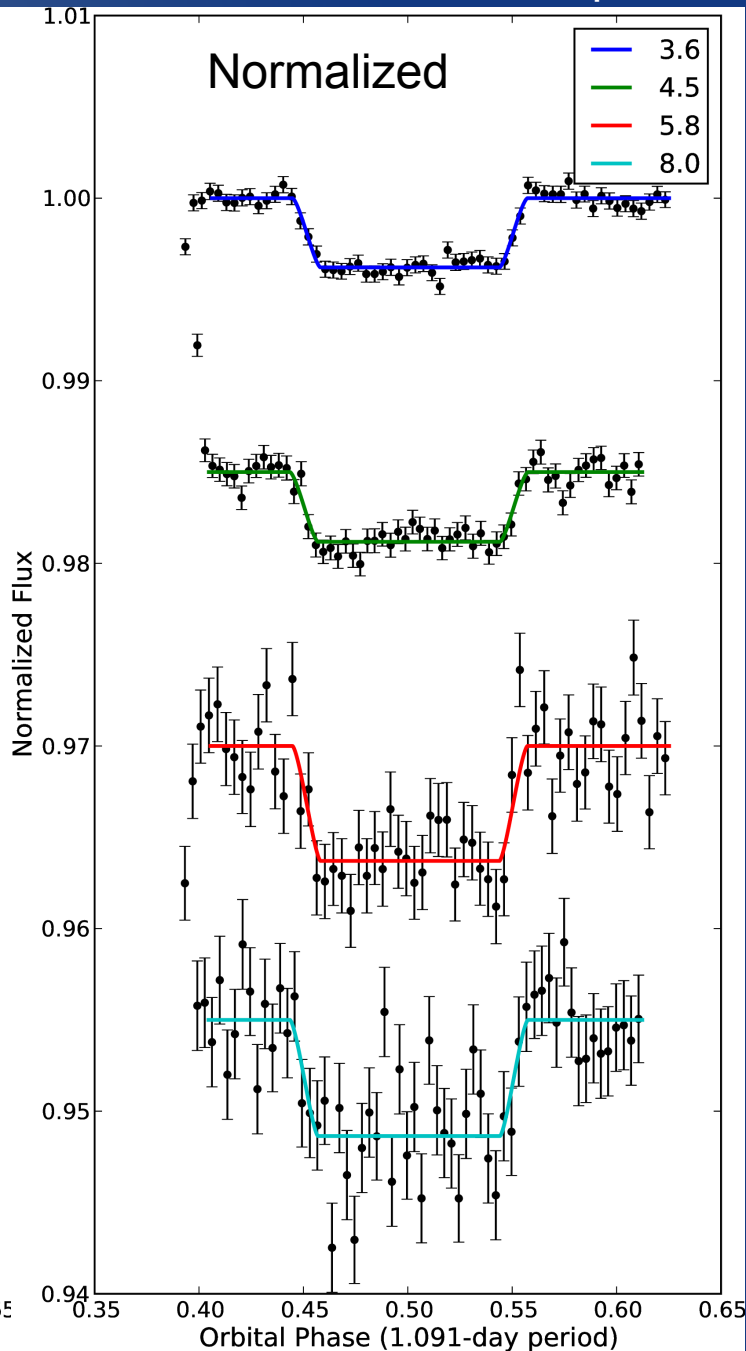
- In eclipse (dayside emission)
- Inversion...but...
- H_2O evidence

Detrending WASP-12b

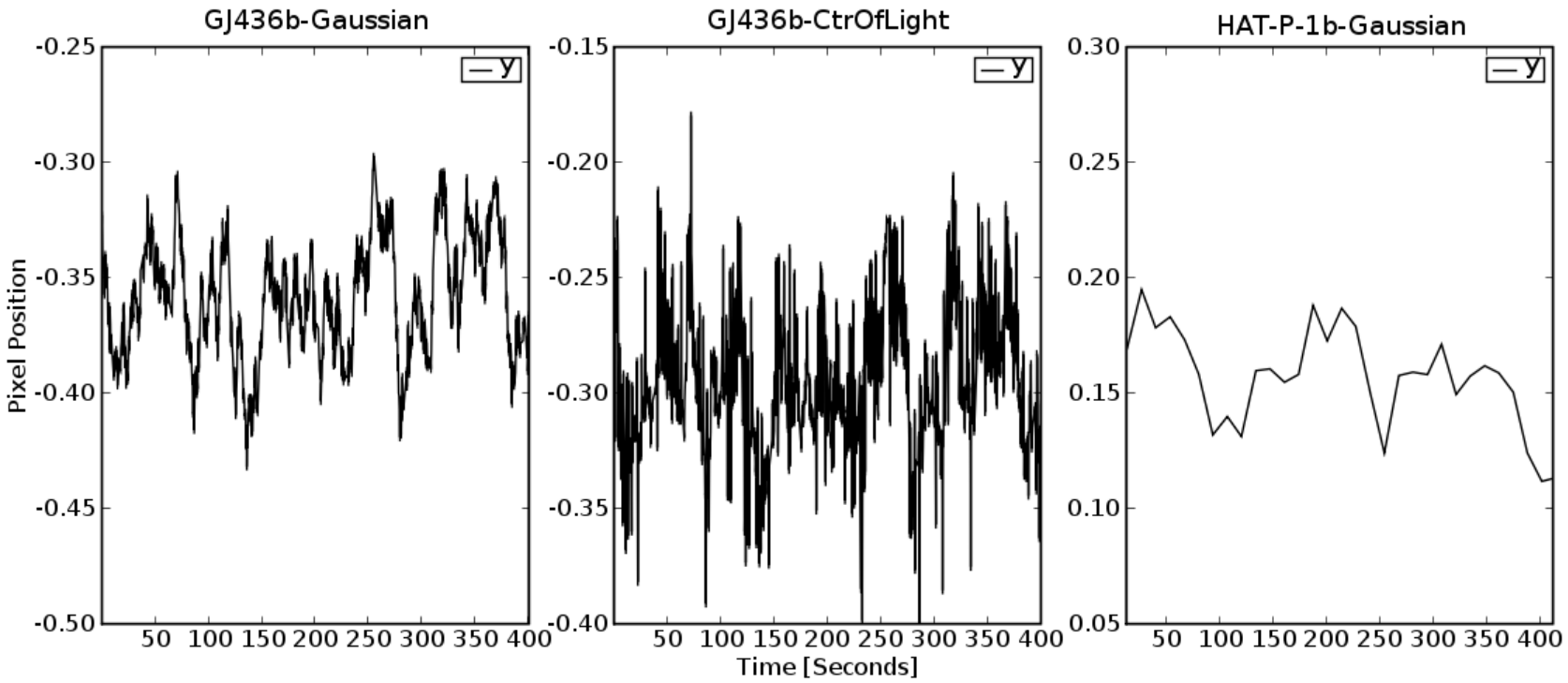
Campo+11

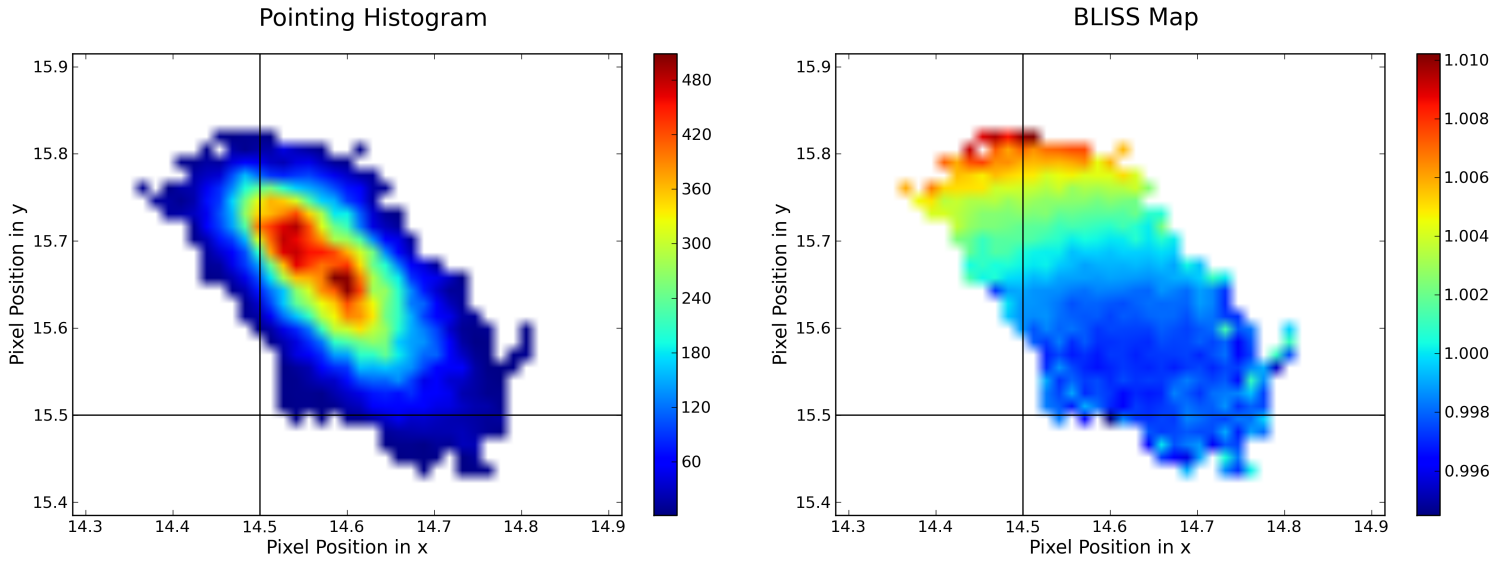




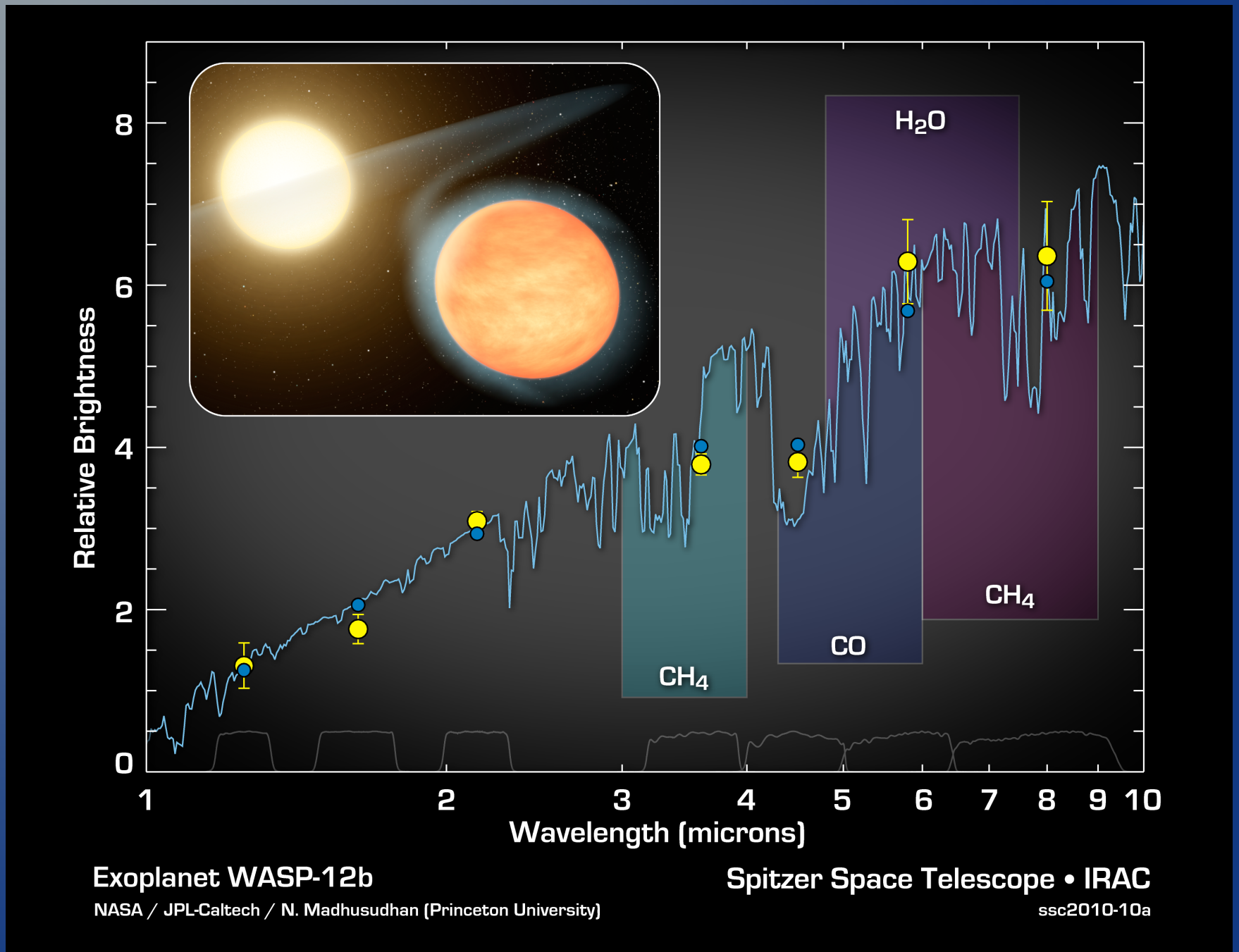


Pixel-Phase Effect

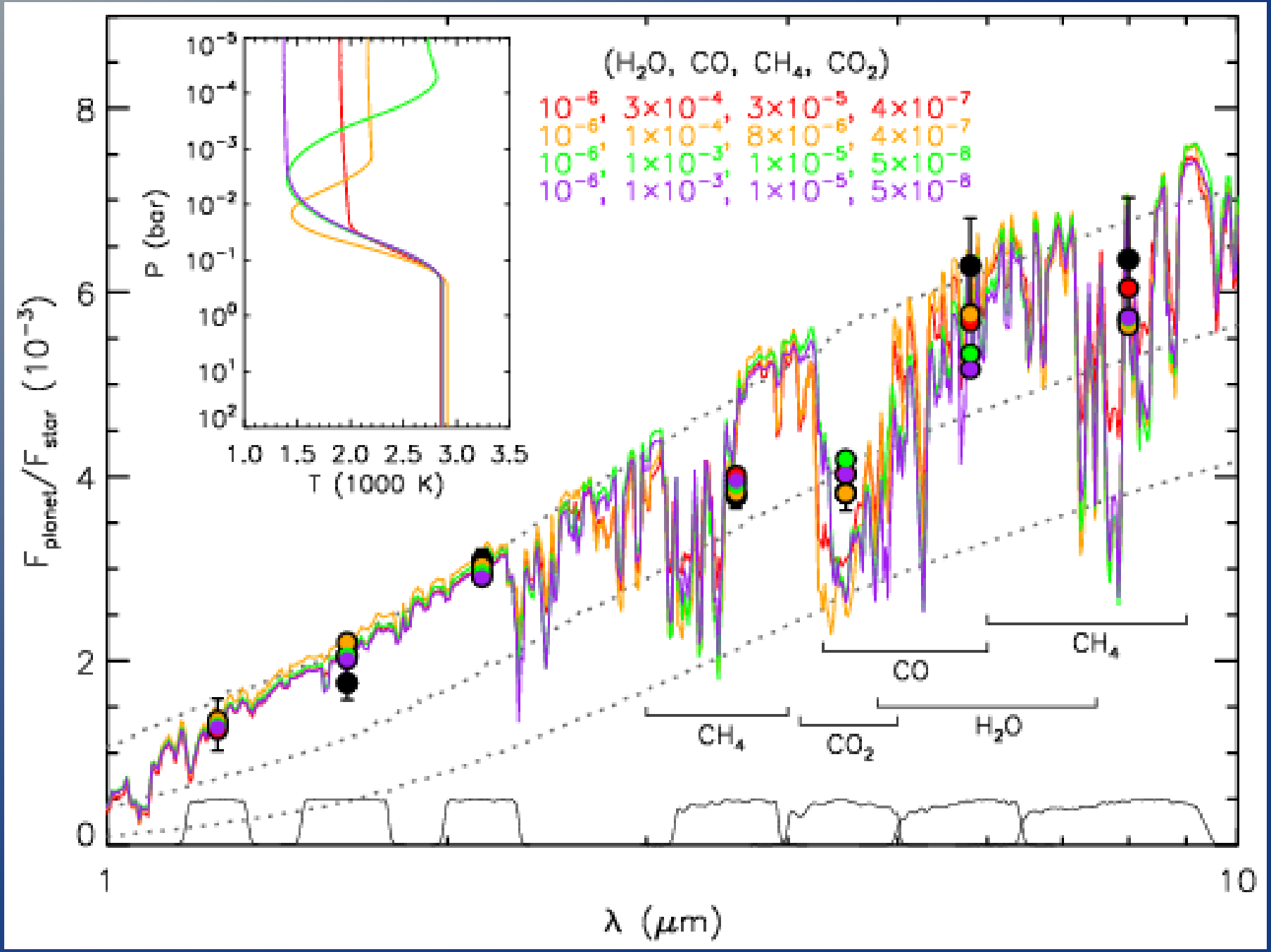




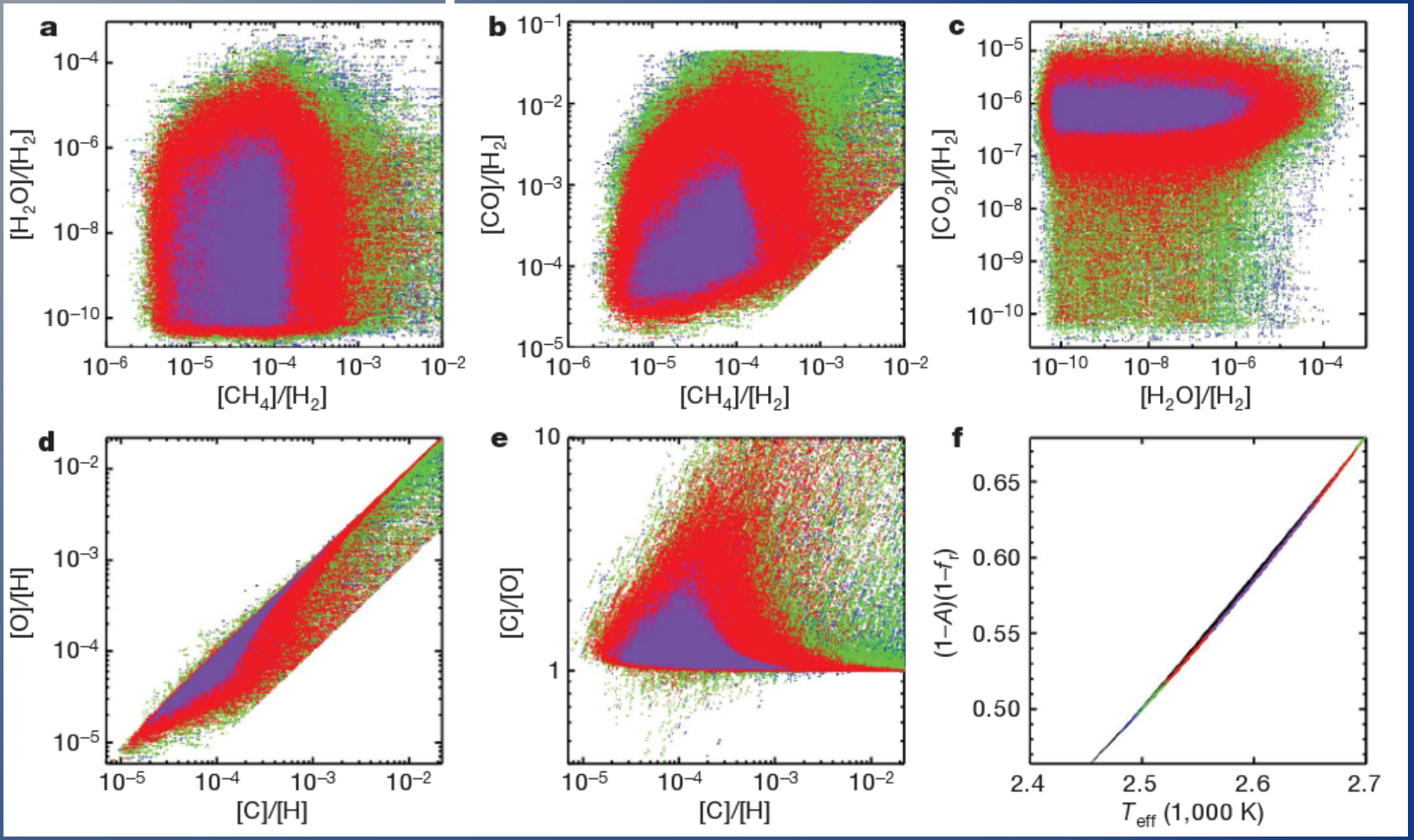
WASP-12b


Relative Brightness
0
2
4
6
8
1
2
3
4
5
6
7
8
9
10
Wavelength (microns)
H_2O
CH_4
CO
CH_4
Exoplanet WASP-12b
NASA / JPL-Caltech / N. Madhusudhan (Princeton University)
Spitzer Space Telescope • IRAC
ssc2010-10a

WASP-12b


(H2O, CO, CH4, CO2)
10-6, 3×10-4, 3×10-5, 4×10-7
10-6, 1×10-4, 8×10-6, 4×10-7
10-6, 1×10-3, 1×10-5, 5×10-8
10-6, 1×10-3, 1×10-5, 5×10-8
P (bar)
T (1000 K)
Fplanet/Fstar (10-3)
λ (μm)
CH4
CO2
CO
H2O
CH4

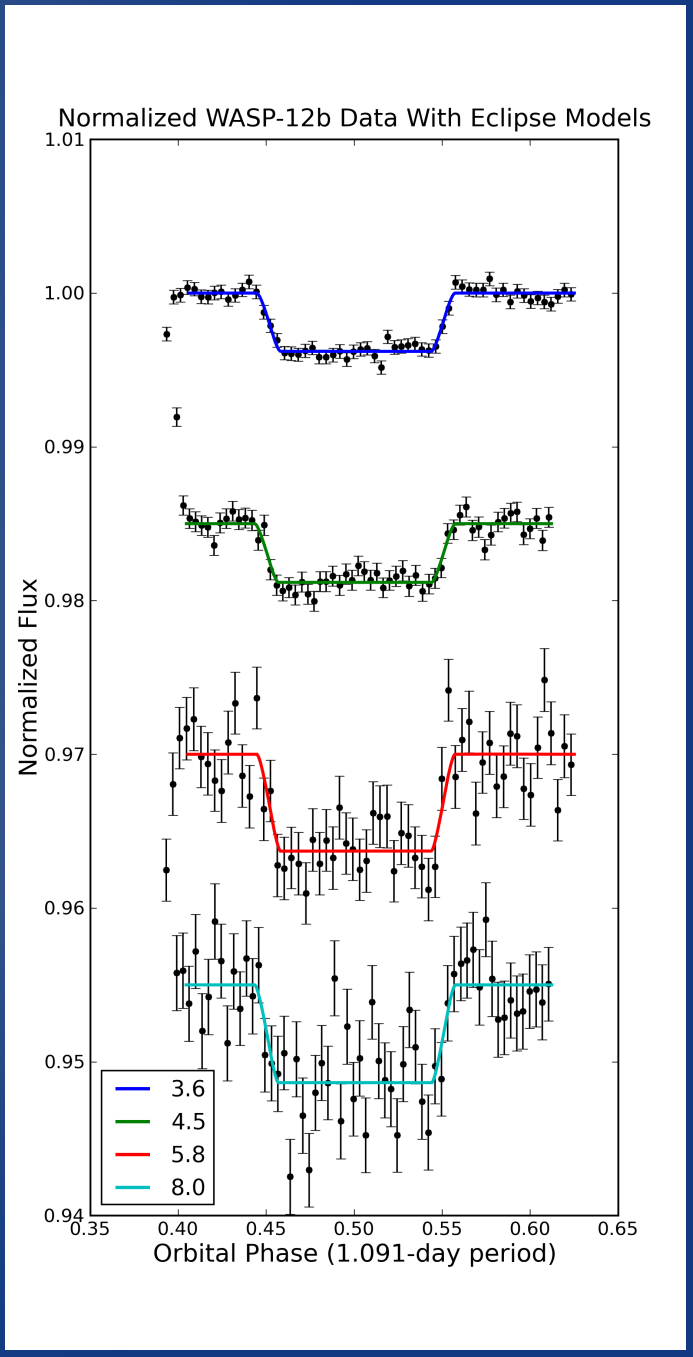
Atmospheric Constraints

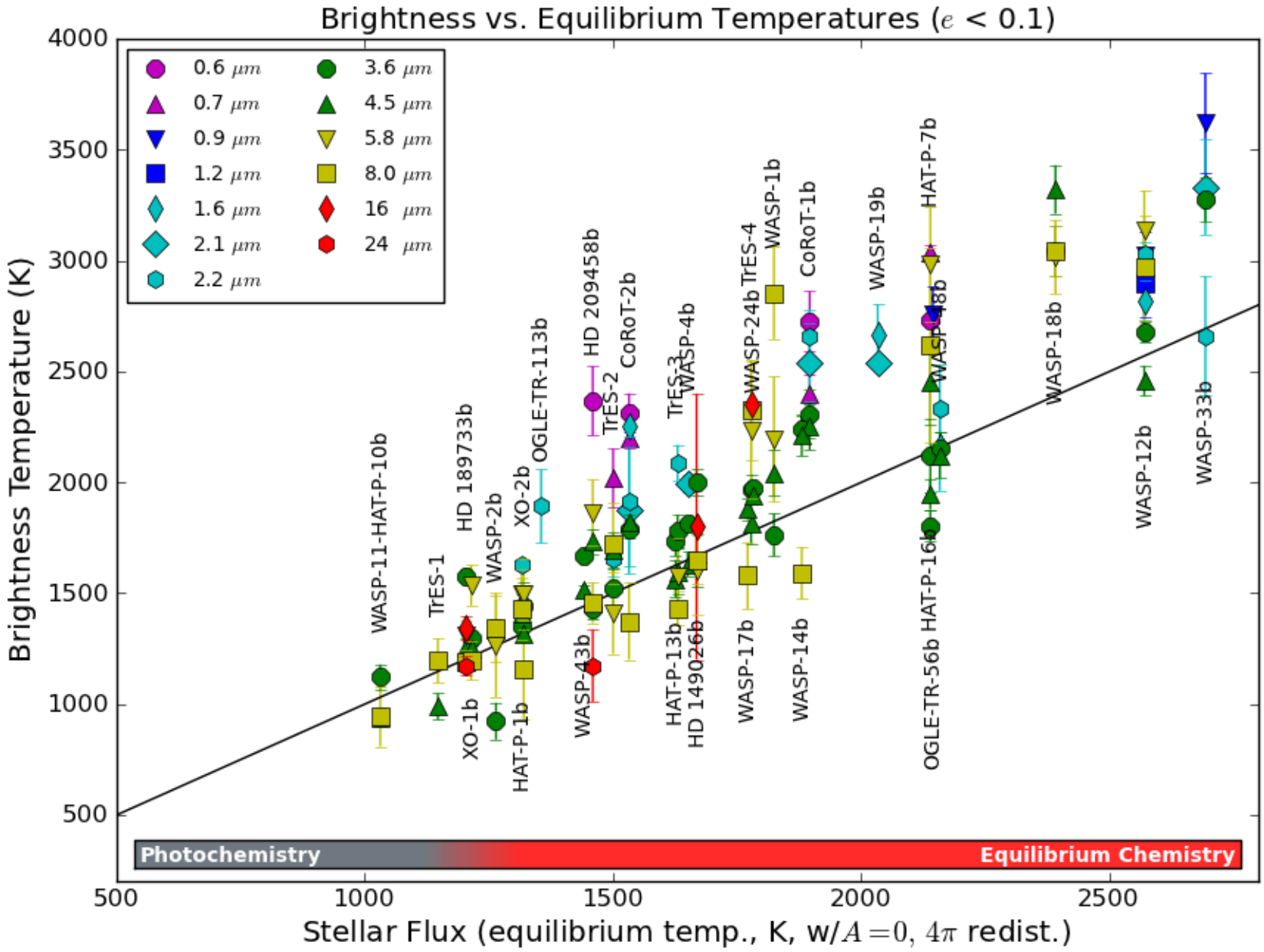


- MCMC tells what questions data can answer
- For WASP-12b, C/O > 1 jumps out
- Watch for BART, our open-source version!

WASP-12b

- One of the best, S/N-wise
- 4 Spitzer + 3 ground-based ecl.
- Strong detections in all channels
- LOTS of carbon! C/O > 1!
- First “carbon-rich” planet
- *Might* have diamond in its core
- Madhusudhan+2011, *Nature*
- Campo+2011, *ApJ*
- Line+2013, *ApJ* – normal C/O, lots of CO_2
- Stevenson+2014, *ApJ* – C/O > 1
- HST data equivocal: can hide O in H_2O,
  - Not well constrained by data



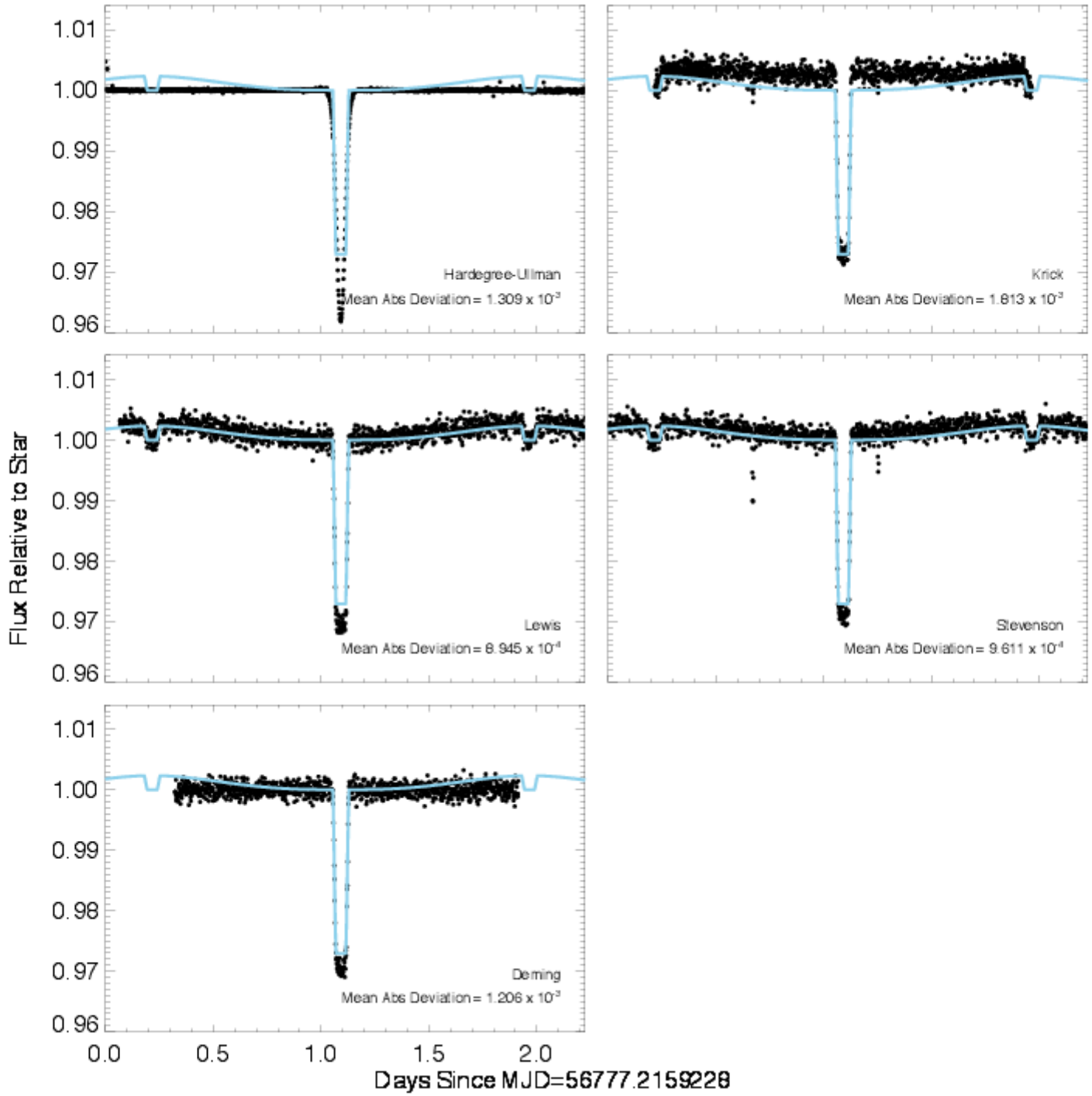

Brightness vs. Equilibrium Temperatures (e < 0.1)
0.6 μm
0.7 μm
0.9 μm
1.2 μm
1.6 μm
2.1 μm
2.2 μm
3.6 μm
4.5 μm
5.8 μm
8.0 μm
16 μm
24 μm
Brightness Temperature (K)
Stellar Flux (equilibrium temp., K, w/$A = 0$, 4π redist.)
Photochemistry
Equilibrium Chemistry
WASP-11-HAT-P-10b
TrES-1
HD 189733b
WASP-2b
XO-2b
OGLE-TR-113b
HD 209458b
TrES-2
CoRoT-2b
TrES-3
WASP-4b
WASP-24b
TrES-4
WASP-1b
CoRoT-1b
WASP-19b
HAT-P-7b
WASP-48b
WASP-18b
WASP-12b
WASP-33b
XO-1b
HAT-P-1b
WASP-43b
HAT-P-13b
HD 149026b
WASP-17b
WASP-14b
OGLE-TR-56b
HAT-P-16b

Eclipse-Depth Wars

- Eclipse depths depend on systematics method
- Polynomial (early) intrapixel methods inconsistent
- Independent pixel-mapping analyses agree
  - BiLnearly Interpolated Subpixel Sampling (Stevenson+12)
  - Kernel density estimator (Ballard+11/Lewis)
- Pixel-Level Decorrelation (Deming+15) may differ for weak/red-noisy signals
- Insufficient tests for new stats methods
- Overconfidence in new/aribtrary methods that produce pretty results

IRAC Data Challenge

- Spitzer created dataset using their best model
- Analyzed by 5 groups
- 2 Groups agreed and got right answer
  - Both used pixel mappers, MCMC
- Rest (3 others) omitted or approximated systematics
- They missed the eclipse depth
- Some also got very incorrect error bars


Flux Relative to Star
1.01
1.00
0.99
0.98
0.97
0.96
Hardegree-Ullman
Mean Abs Deviation = 1.309 x 10-3
Krick
Mean Abs Deviation = 1.813 x 10-3
Lewis
Mean Abs Deviation = 8.945 x 10-4
Stevenson
Mean Abs Deviation = 9.611 x 10-4
Deming
Mean Abs Deviation = 1.206 x 10-3
0.0
0.5
1.0
1.5
2.0
Days Since MJD=56777.2159228

UCF's POET Pipeline

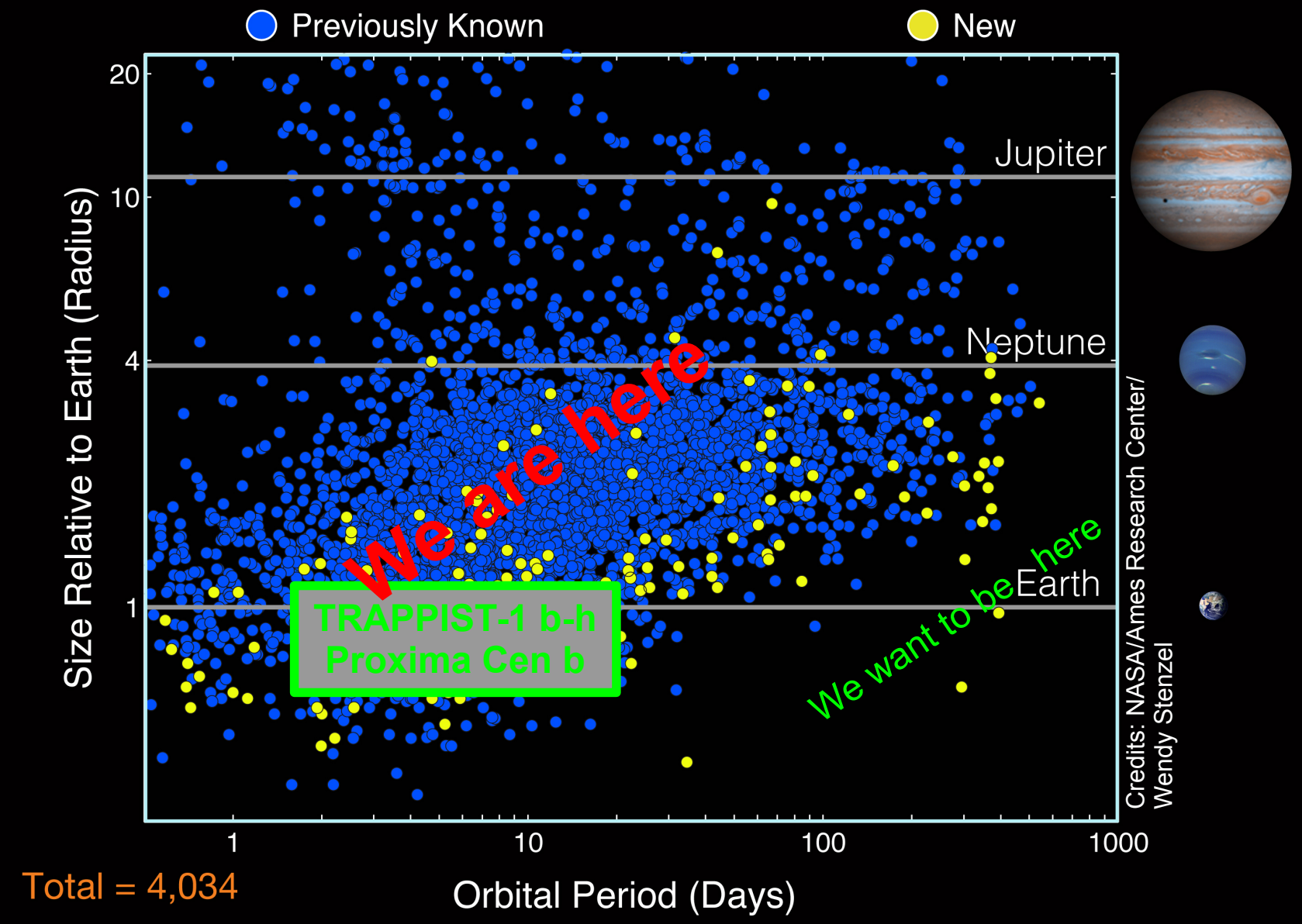
- Photometry for Orbits, Eclipses, and Transits
- Try all methods, evaluate analyses statistically
  - Invented BLISS (Stevenson+12)
  - Implemented PLD (Deming+15)
- Not scattershot! Ask *right* statistical questions
- Example: Select best aperture by SDNR, but select best ramp/intrapixel by BIC
  - If several analyses have similar BIC, solution encompasses them
- With up to 20 apertures and ~12 ramps, can do many dozens of analyses per eclipse

Search for Life?

- Public really wants exolife & exo-Earth-like planets
  - *Are we lonely?*
- Astronomers have been selling them life for 400 years!
  - *Maybe we should deliver?*
- Search for life motivates all exploration plans
- Planetary science piggybacks on that
- Works out well for us…

New Kepler Planet Candidates

As of June 2017



Total = 4,034

Community Lessons

- Exoplanets pushed Spitzer past its design
- Earth-sized exoplanets (etc.) will push JWST
- Start high-end analysis workshops *now* (done!)
- Fund and publicize community efforts to understand systematics (done!)
- Respond to consensus requests for changes
- Publish best practices for referees, editors, program managers
- Agency restraint in press releases!
  - S/N < 10? “Indication”, “Requiring verification”

Conclusions

- Spitzer broke out the combined-light exoplanet landscape
  - Eclipses, broadband spectroscopy, phase curves, dayside mapping, M-dwarf “Earths”
  - Winds decrease with temp., *T* contrast rises
- Rigor in analyses critical, often missing
- Risk of nasty PR gaffe with JWST
- Standards Leadership Needed!
  - Workshops, special issues on systematics
  - Educate researchers, reviewers, editors, managers
  - Specific requirements for low-S/N PR claims

Spitzer Analysis Checklist

- Just because model fits does not mean it's right
- Eclipses require 10^{-4} accuracy!
- Worry about 2nd- & 3rd-order effects
- Observe 3 hours before, 2 after
- Try many apertures, centering methods
- Use subpixel photometry
- Try many intrapixel and ramp functions
- Run variations in all reasonable combinations
- Use SDNR, BIC, AIC to choose best, report ties
  - ...or use Gaussian processes, marginalize models
- Atmos: Report *T(p)* and contribution functions

MCMC Checklist

- Find the minimum with a minimizer
  - Rescale errors after 1st good fit, Spitzer's high
  - Test RMS error vs. bin size (red noise)
  - DO NOT report peak/median of each parameter distribution as best joint solution!
  - If MCMC *ever* finds better χ^2, reminimize from there and restart MCMC
- Assess errors & correlations with MCMC
- Gelman-Rubin test for MCMC convergence
- Inspect traces, histograms, correlation plots