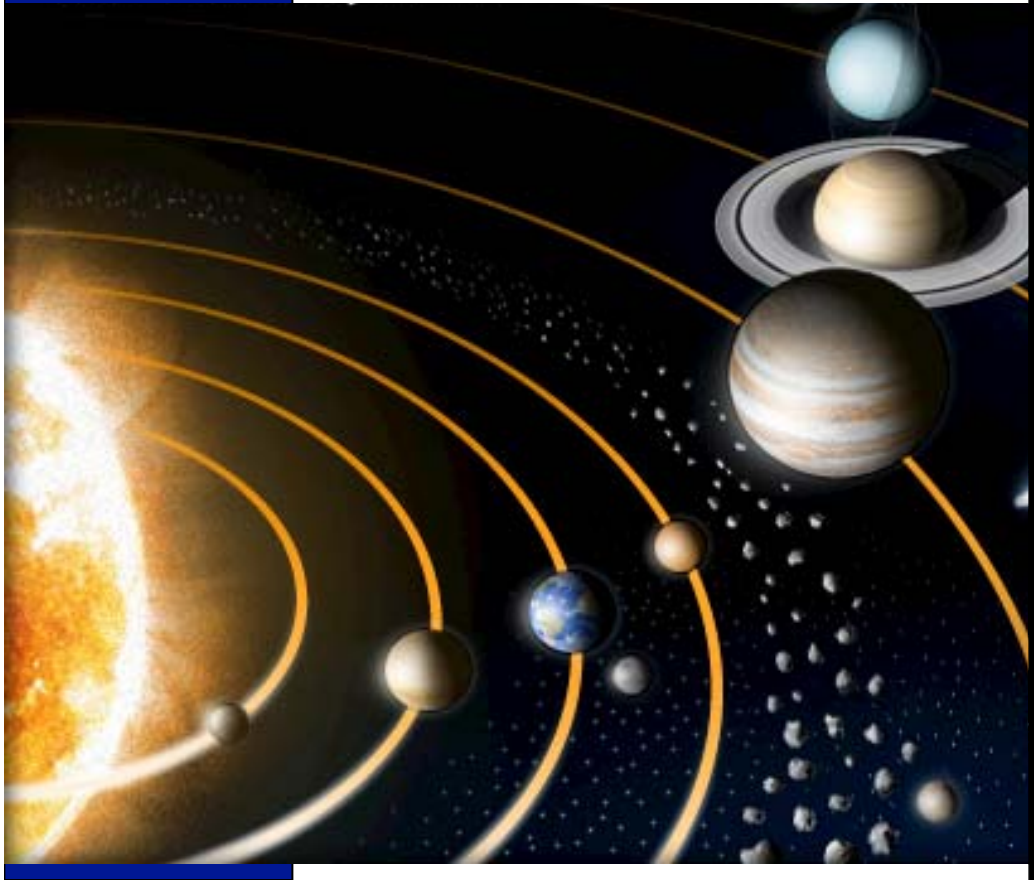
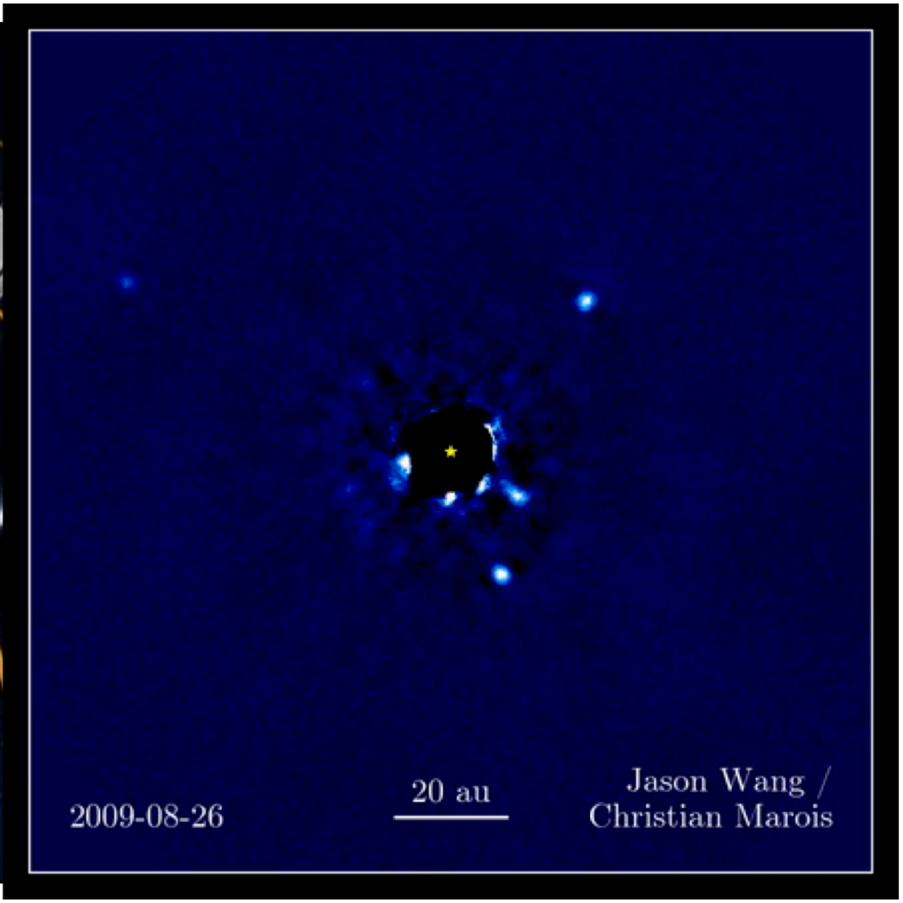
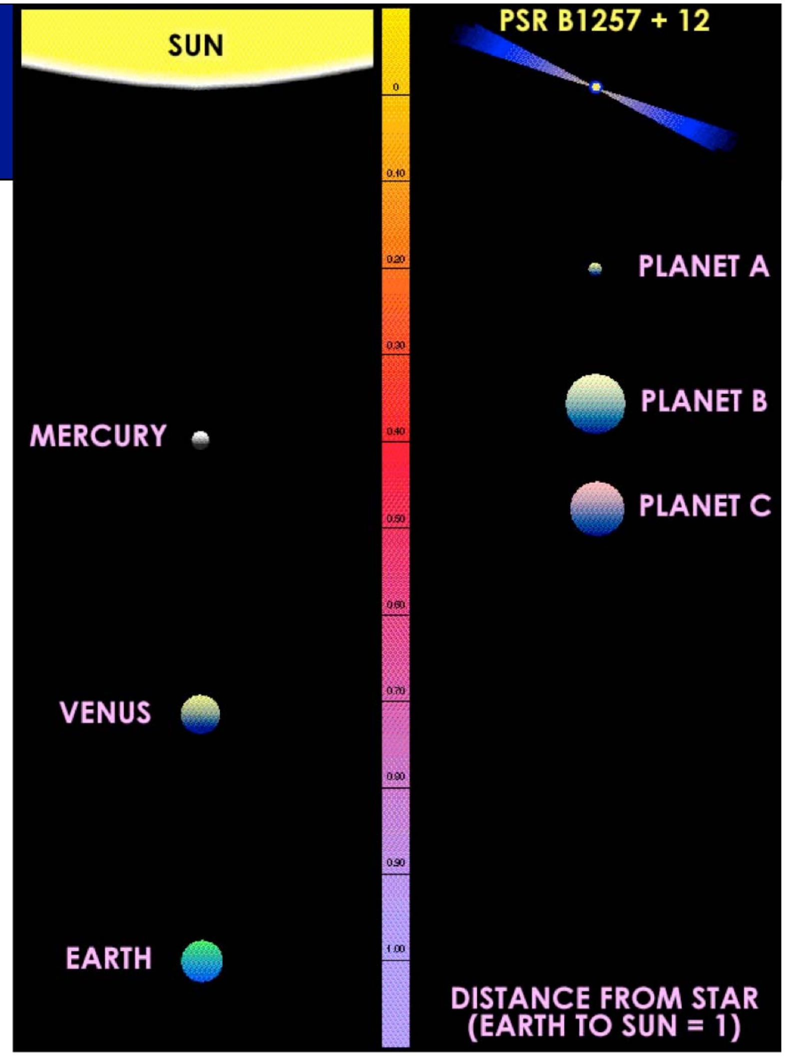
Katie M. Morzinski – University of Arizona
9 Nov. 2017 – Michelson/Sagan Symposium

What do we really know about extrasolar planets?





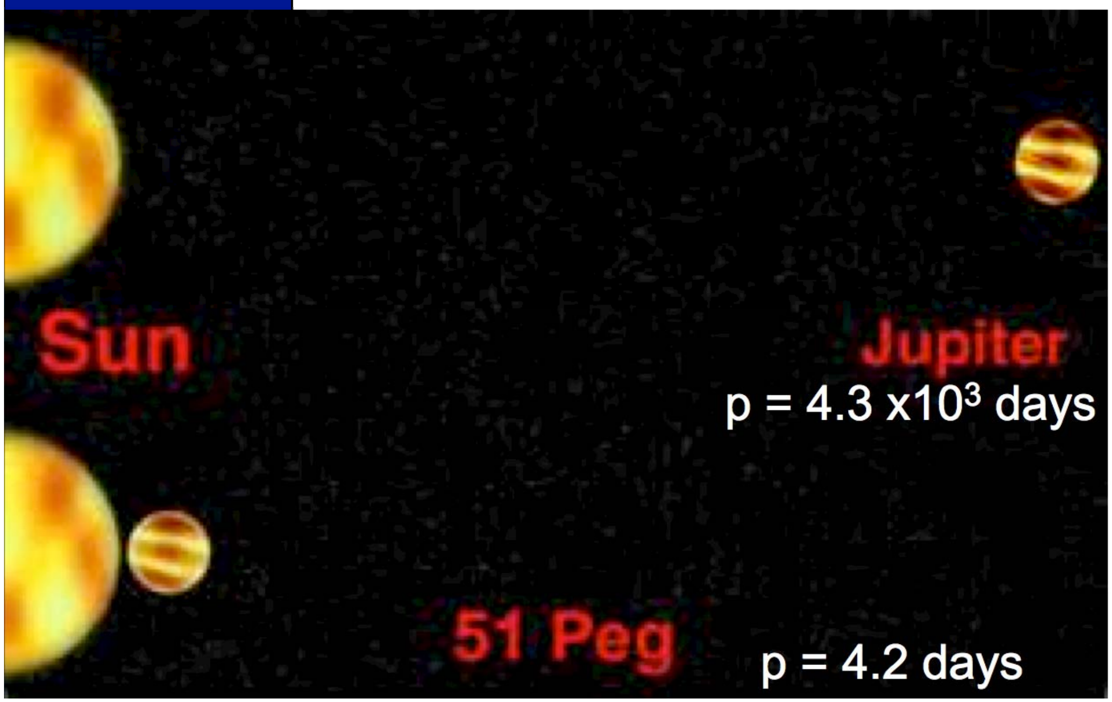
1992: Pulsar Planets
1995: Hot Jupiters



Pulsar Planets:

- exotic
- rare

Wolszczan + 1992, 1994



Hot Jupiters:

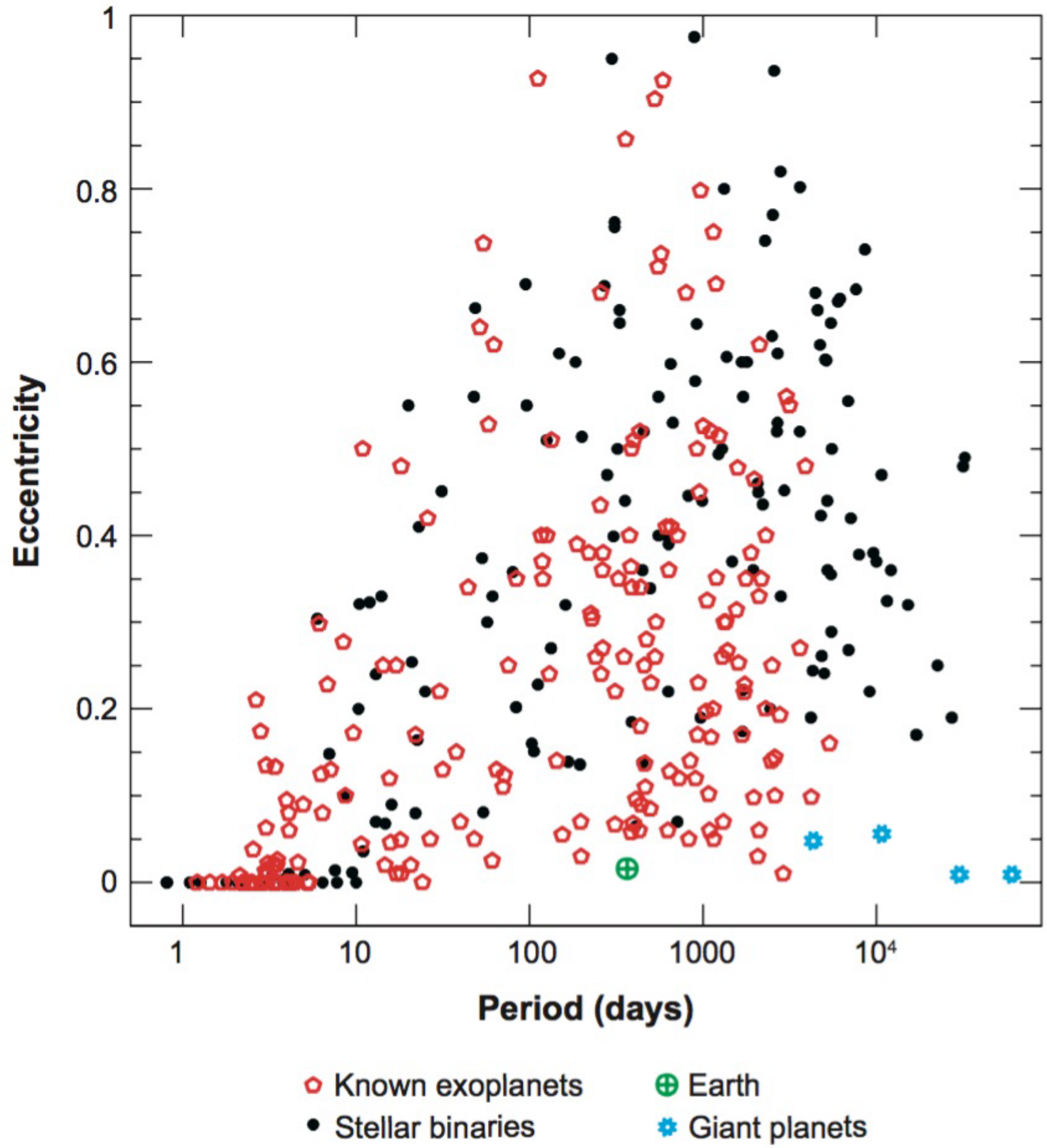
- exotic
- rare

Mayor & Queloz 1995

2007: RV surveys found orbital eccentricities of exoplanets >> solar system – Migration?

"With a median eccentricity of 0.29, extrasolar planets with orbital periods longer than about 6 days have eccentricities significantly larger than those of giant planets in the Solar System."

Udry & Santos 2007 ARA&A



What do we really know about extrasolar planets?

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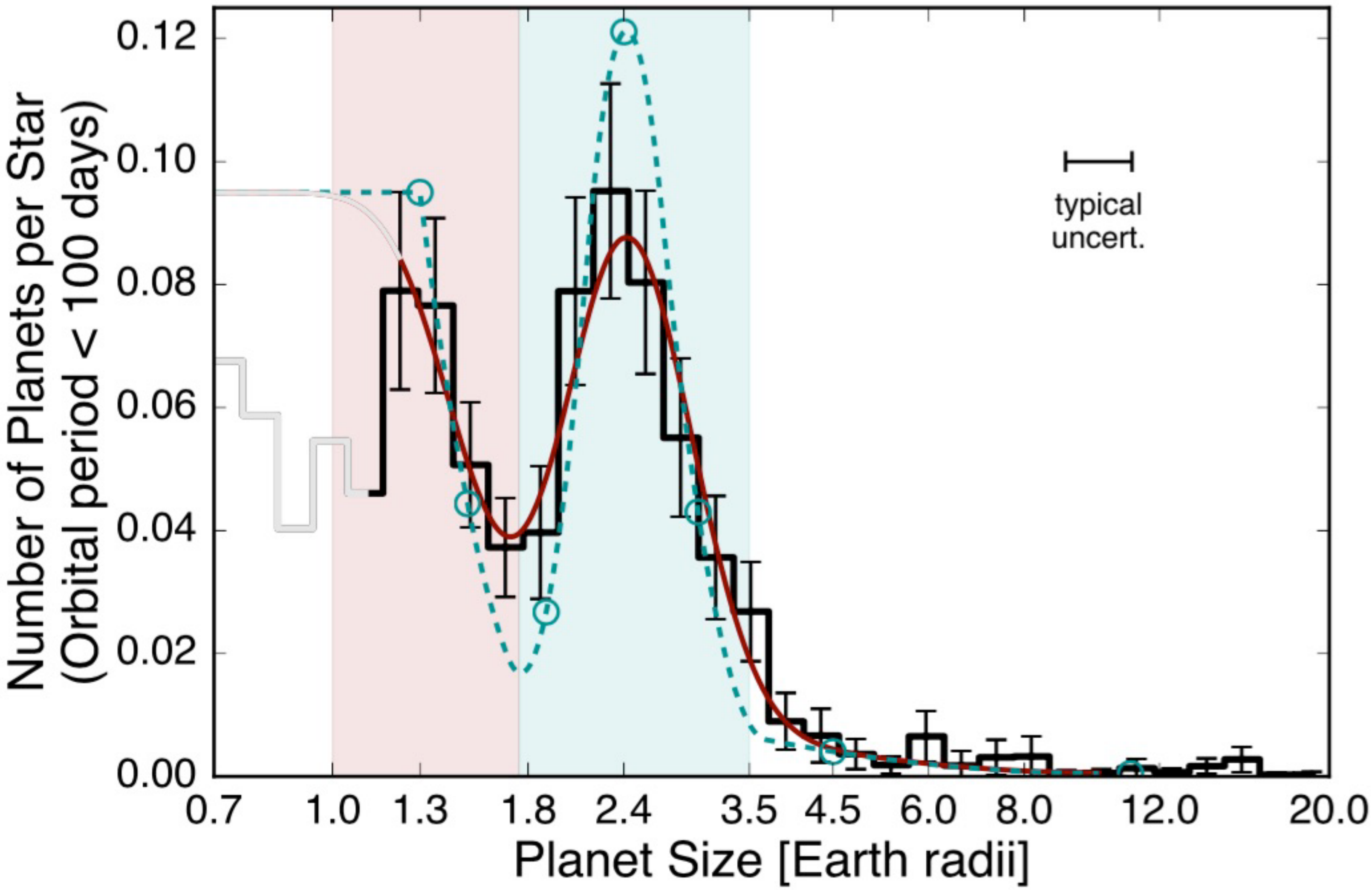
2017: The most-frequent exoplanet radii are super-Earths & mini-Neptunes (closer-in orbits)



Fulton + 2017
Kepler

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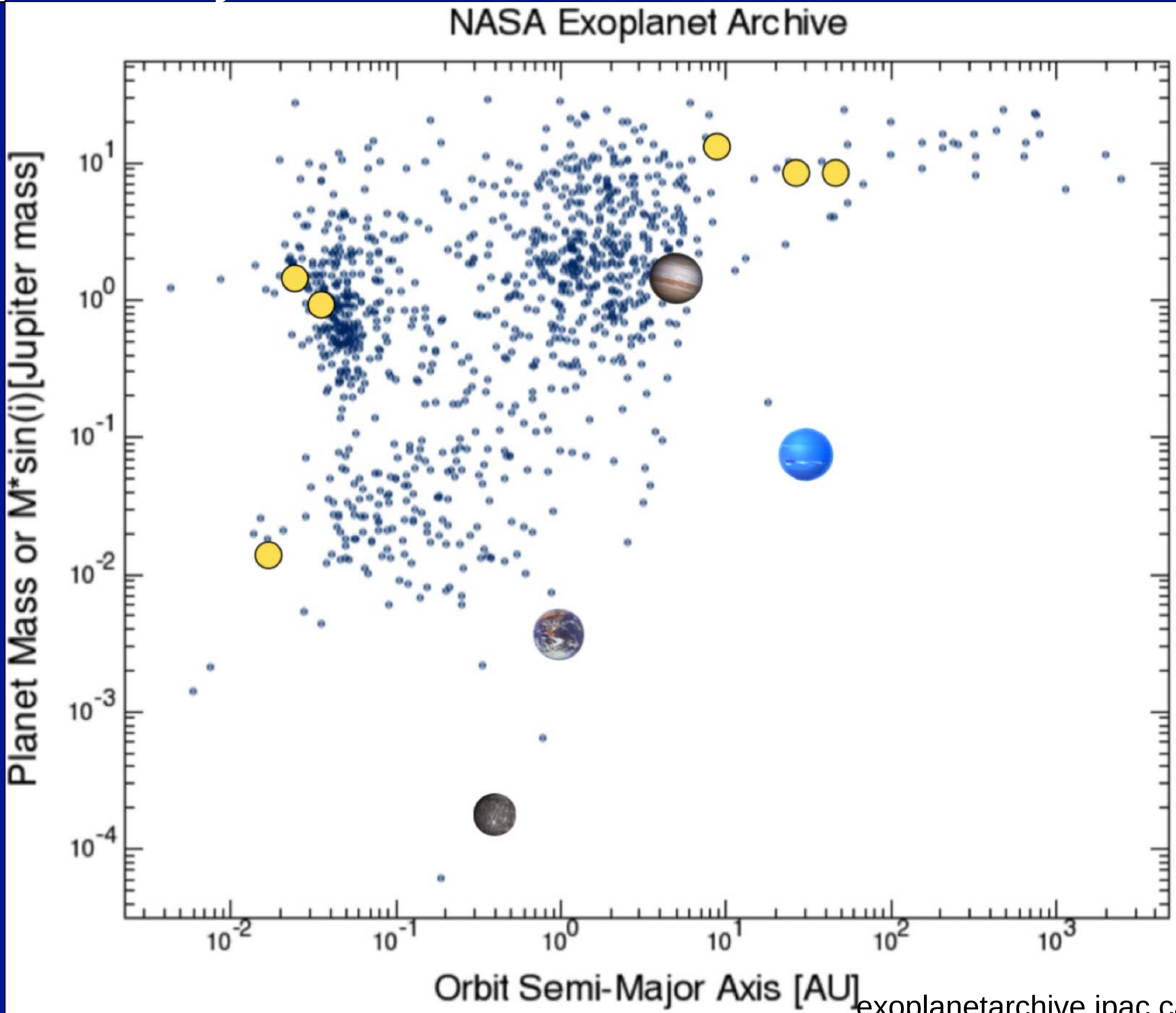
Exoplanets come in all masses and orbits – But they are hard to characterize in detail



exoplanetarchive.ipac.caltech.edu

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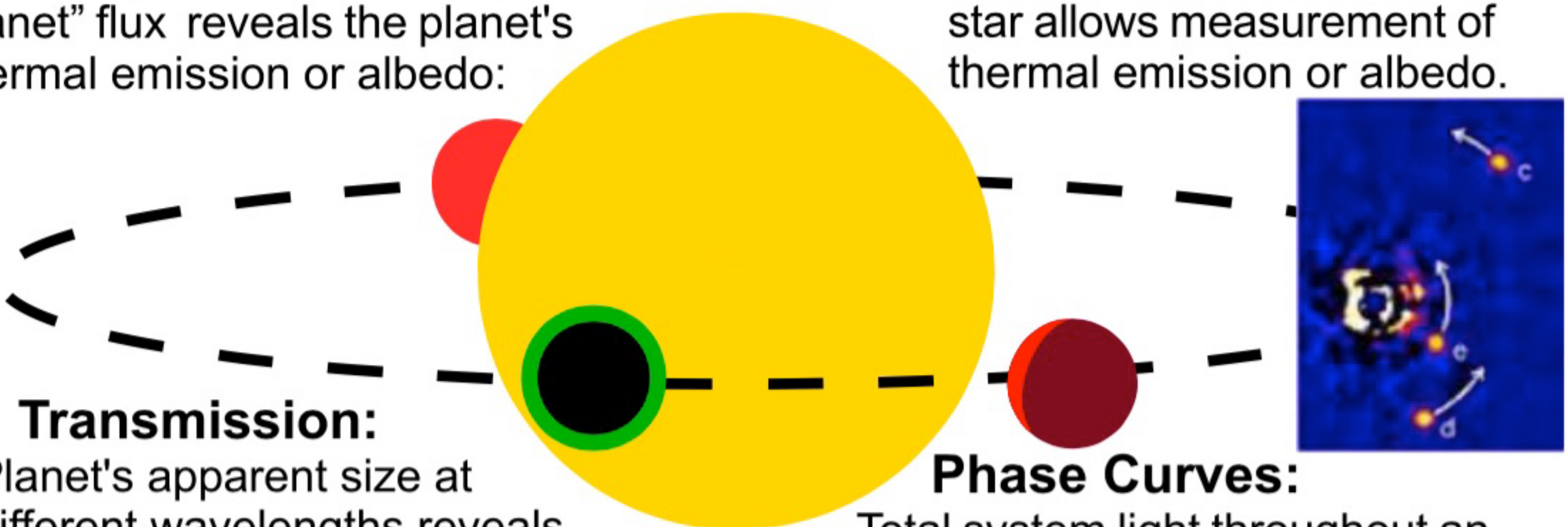
Observing the atmosphere of an exoplanet

Eclipse:
Removing "star" from "star plus planet" flux reveals the planet's thermal emission or albedo:

Direct Imaging:
Spatially resolving planet from star allows measurement of thermal emission or albedo.



Transmission:
Planet's apparent size at different wavelengths reveals atmospheric opacity and composition.

Phase Curves:
Total system light throughout an orbit constrains atmospheric circulation and/or composition.

Crossfield 2015 PASP

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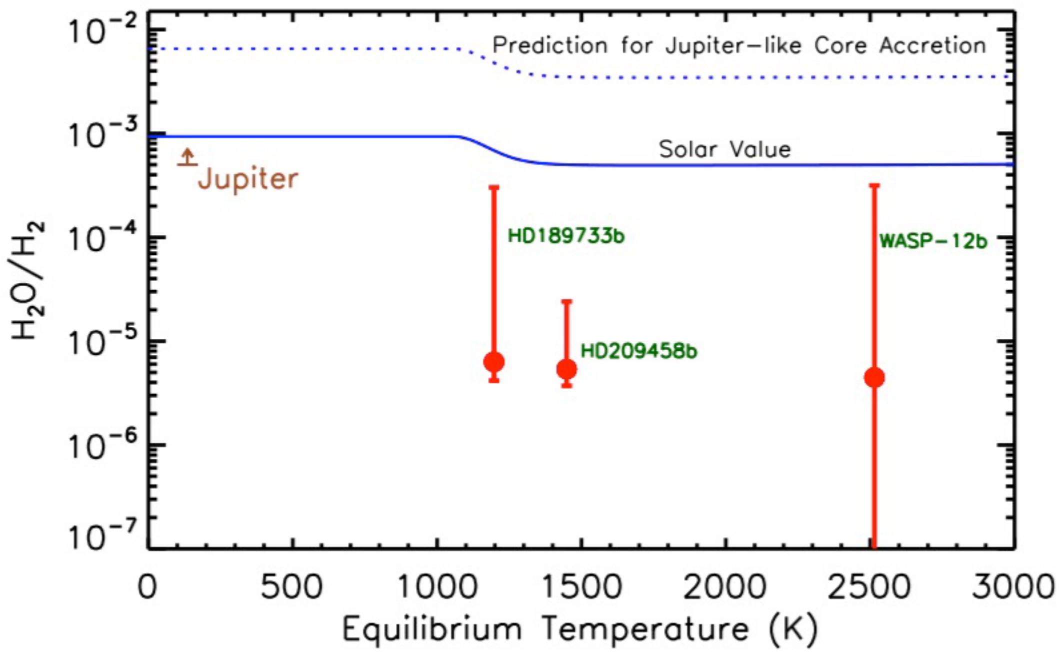
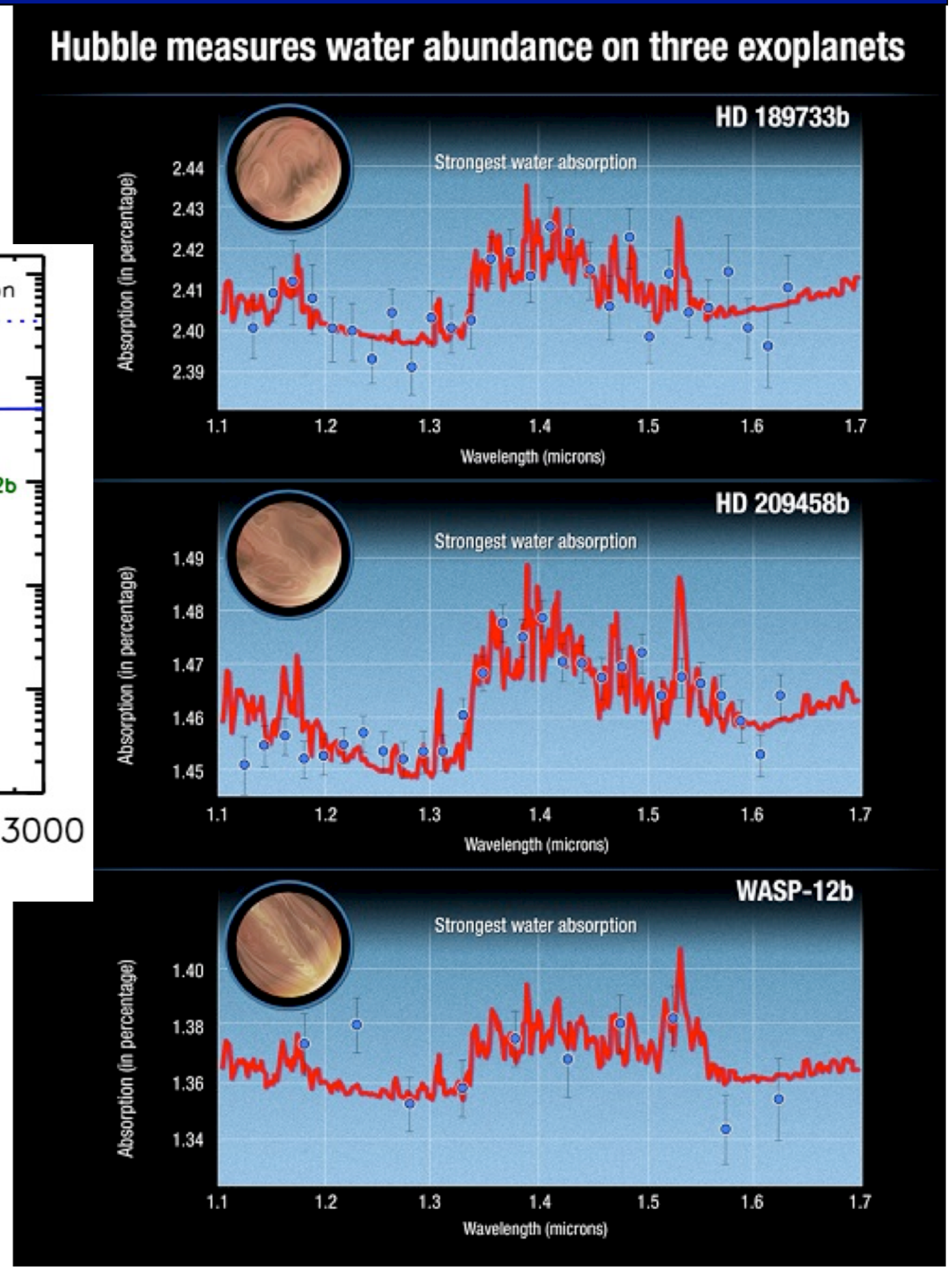
Water abundance of hot jupiters





Madhusudhan + 2014 ApJL

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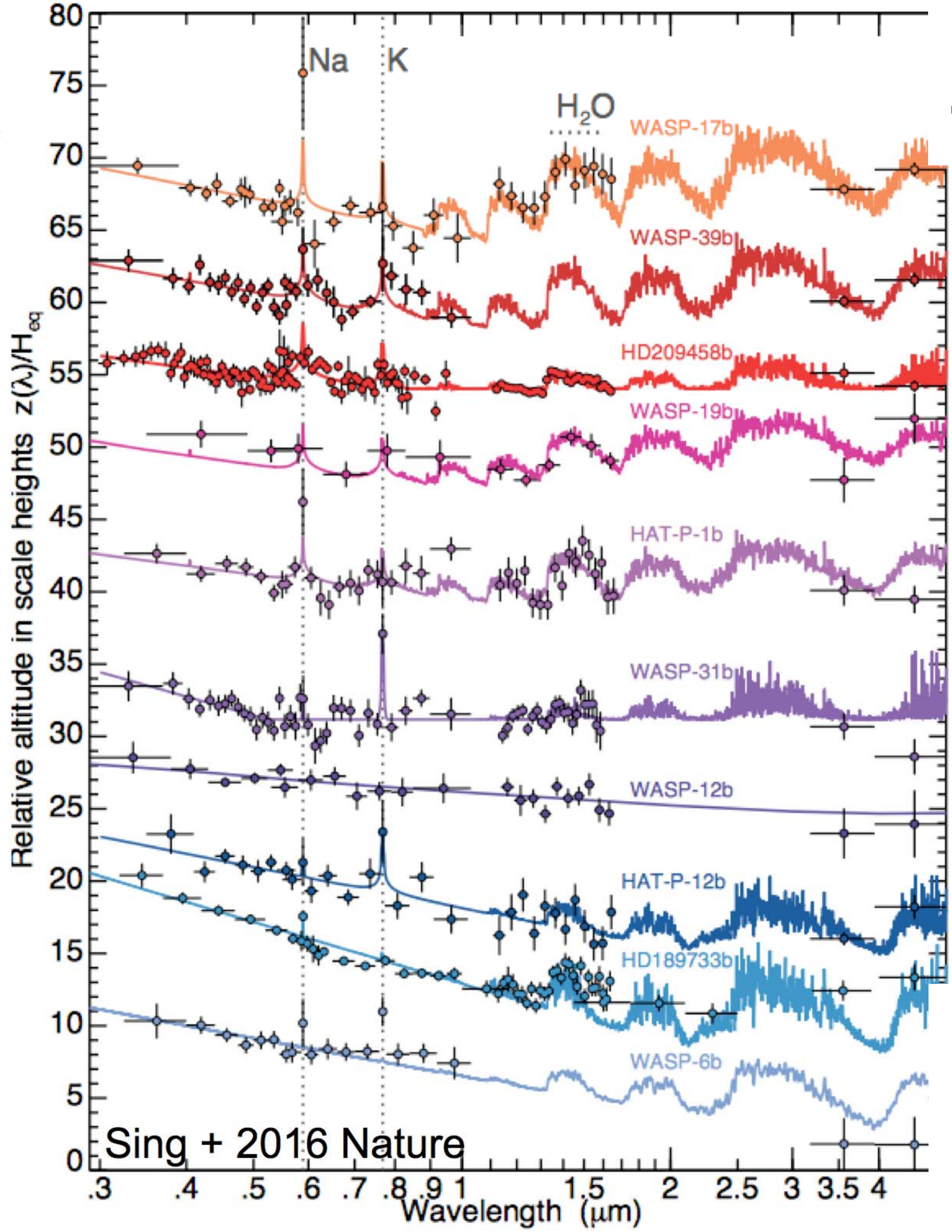
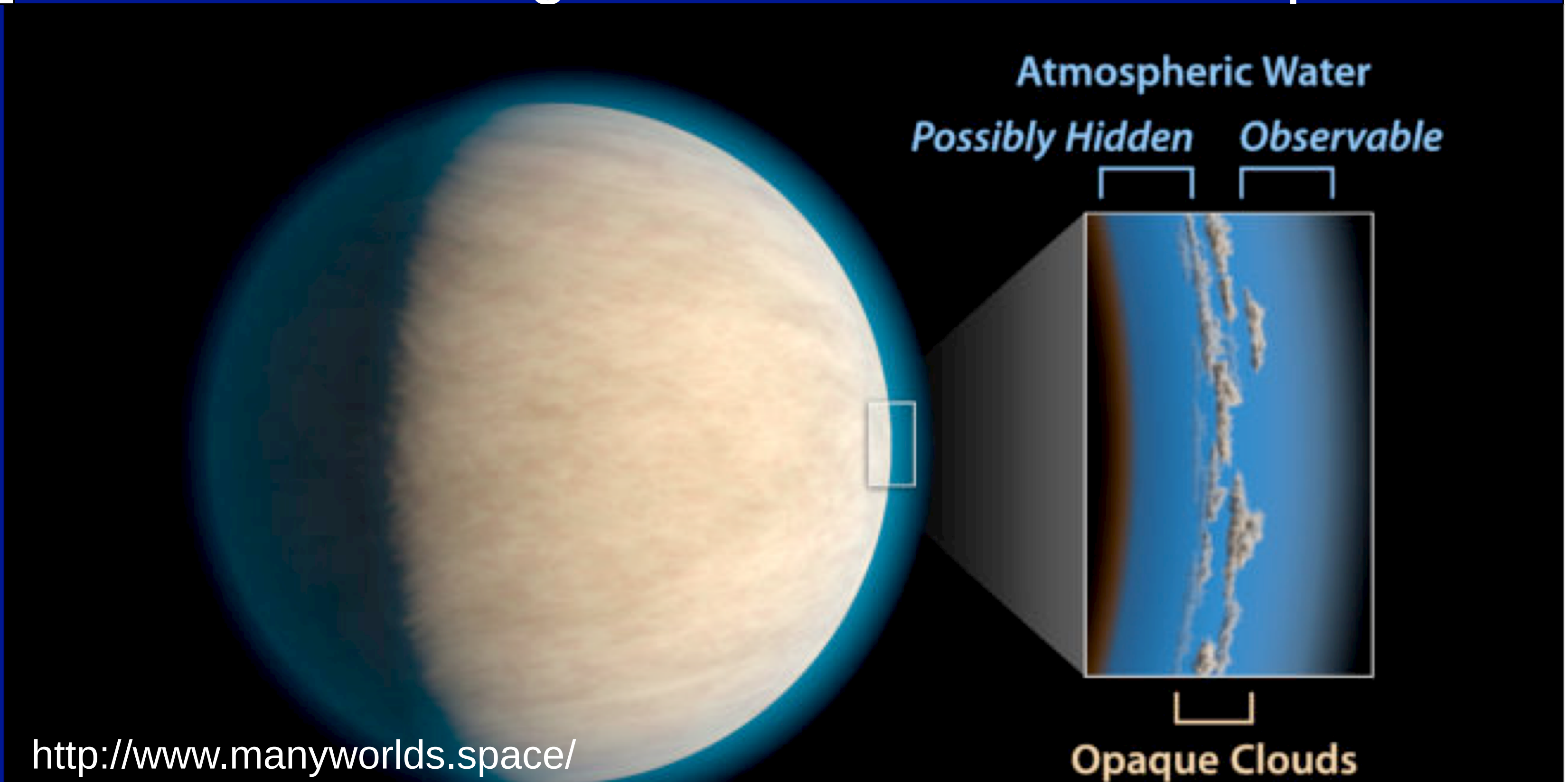
Continuum
Clear->Cloudy



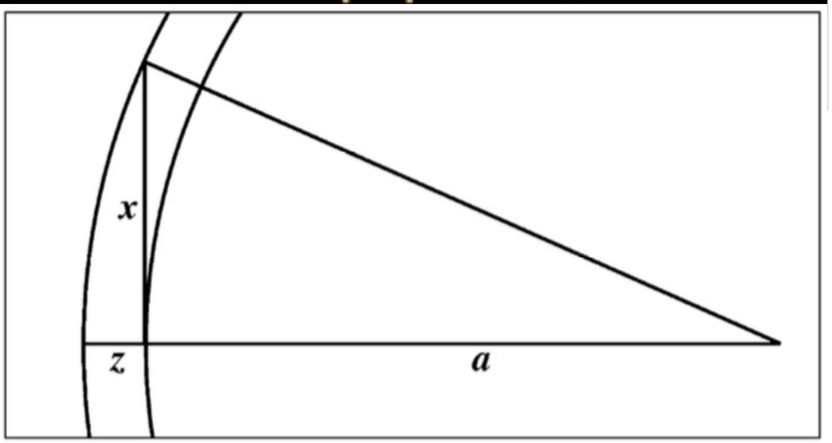
clear

cloudy

Water abundances can be incomplete when measured through the limb of the atmosphere



http://www.manyworlds.space/index.php/2016/10/21/exoplanet-clouds-friend-and-foe



Fortney 2005 MNRAS

What do we really know about extrasolar planets?

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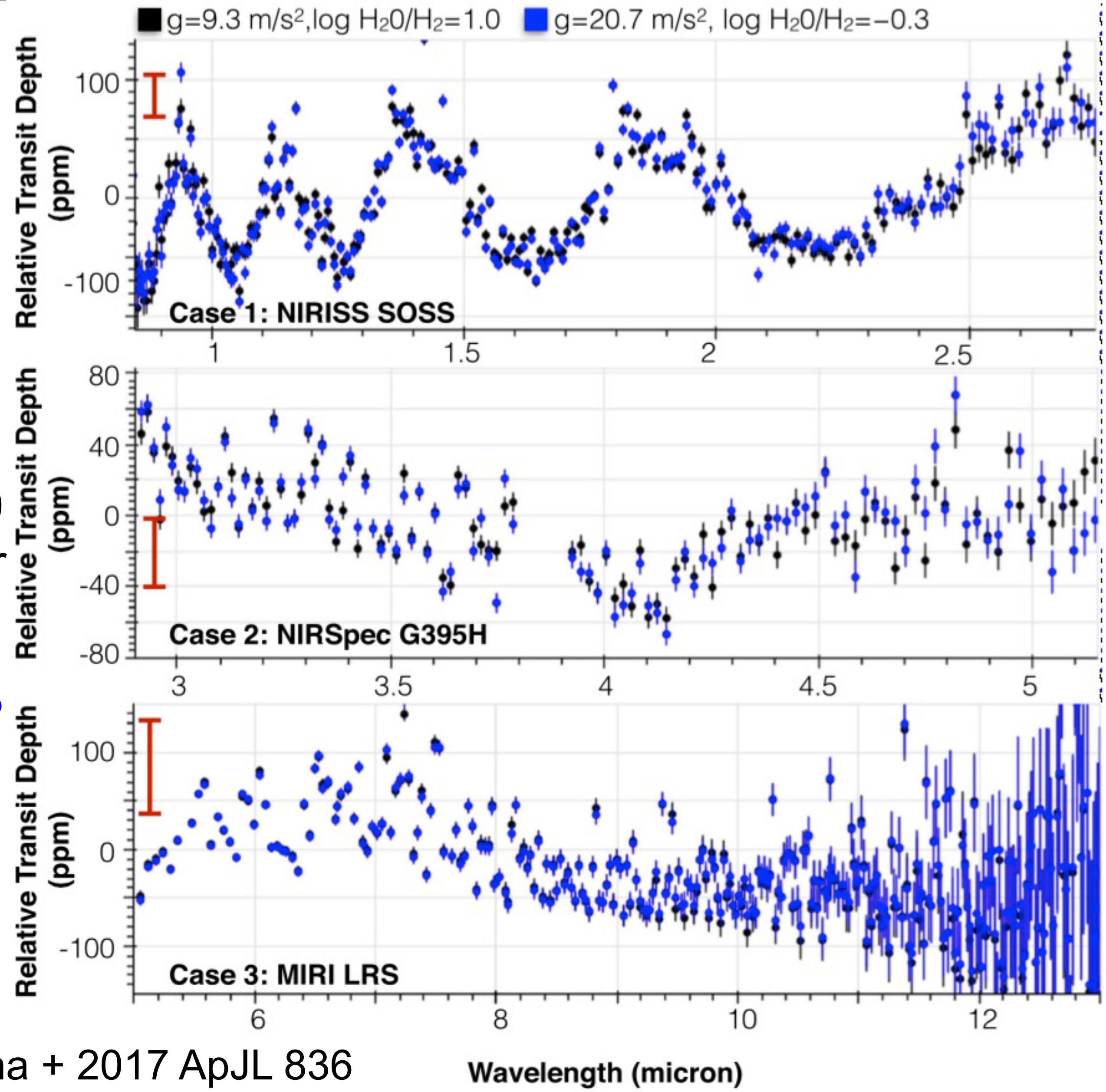
Degeneracies between gravity (mass) and composition in small (R=1.5 R_Earth) planets

Atmospheric scale height
$H = k_B T/\mu g$

■ log(g)=3.0 water-world or mini-Neptune

■ log(g)=3.3 rocky planet with H envelope



Natasha Batalha + 2017 ApJL 836

What do we really know about extrasolar planets?

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Determining fundamental physical parameters of exoplanets – 1.

- Radial velocity (RV) planets
  - Radial velocity curve
    - Get M sin i & orbital period P -> semi-major axis a

$$K_{\mathrm{RV}} \equiv \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_p \sin\ i}{(M_\star + M_p)^{2/3}} (1 - e^2)^{-1/2},$$

- Transiting planets
  - Light curve
    - Depth of transit = $(R_p/R_*)^2$
    - Duration -> orbital period P -> semi-major axis a
- Directly-imaged planets
  - Observe Flux, Projected separation a_proj
  - Infer Age, assume Formation/Evolution model
    - Get Mass

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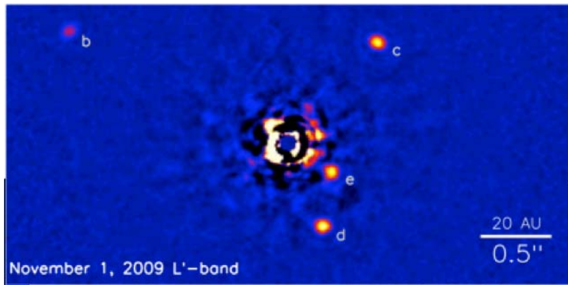
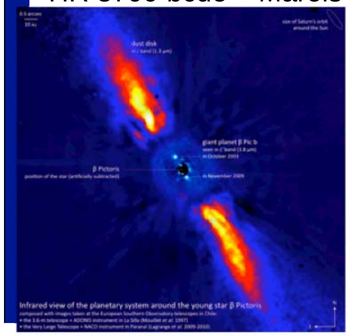
Directly-imaged exoplanets



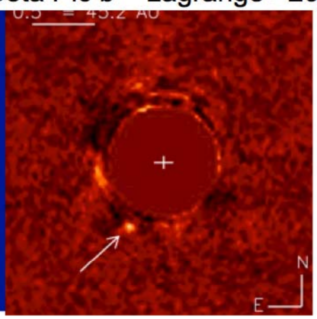
HR 8799 bcde – Marois+ 2008, 2010

SpT	# stars	10-100 AU	30-300 AU	10-1000 AU	100-1000 AU
BA	110	7.7^{+9}_{-6}%	2.8^{+4}_{-2}%	3.5^{+5}_{-3}%	<6.4%
FGK	155	<6.8%	<4.1%	<5.8%	<5.1%
M	119	<4.2%	<3.9%	<5.4%	<7.3%
All	384	0.8^{+1}_{-1}%	0.6^{+1}_{-1}%	0.8^{+1}_{-1}%	<2.1%

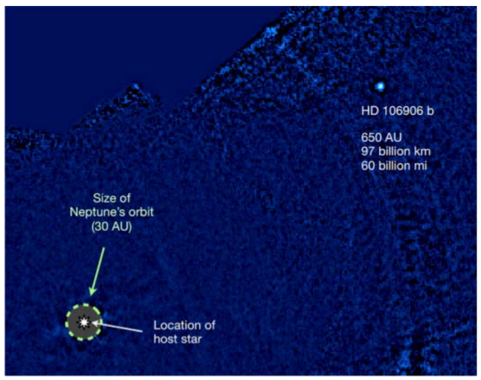
Bowler 2016 PASP



Beta Pic b – Lagrange+ 2009



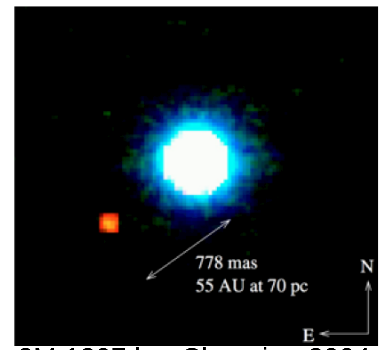
HD 95086 b – Rameau+ 2013



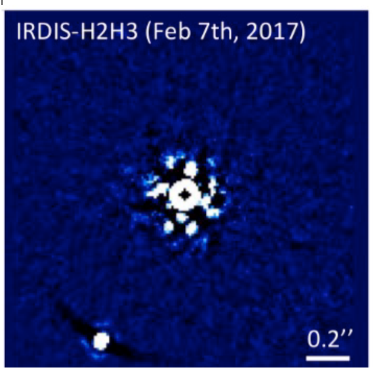
HD 106906 AB b – Bailey+ 2014

Wide Super-Jupiters

- exotic
- rare

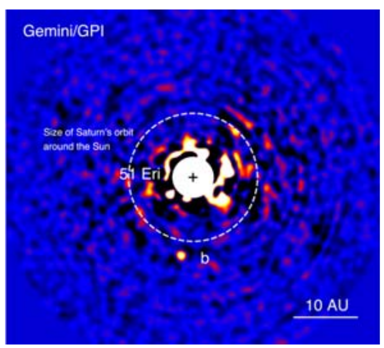


2M 1207 b – Chauvin+ 2004



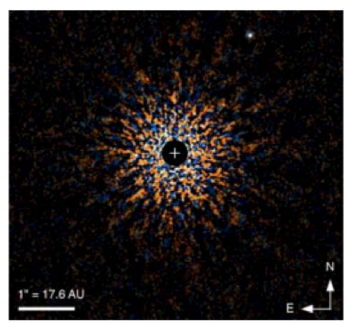
A

HIP 65426 b – Chauvin+ 2017



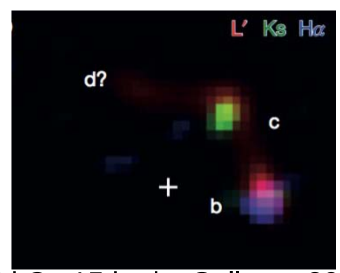
51 Eri b – Macintosh+ 2015

F



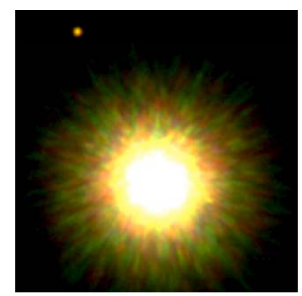
GJ 504 b – Kuzuhara+ 2013

G



LkCa 15 bcd – Sallum+ 2015

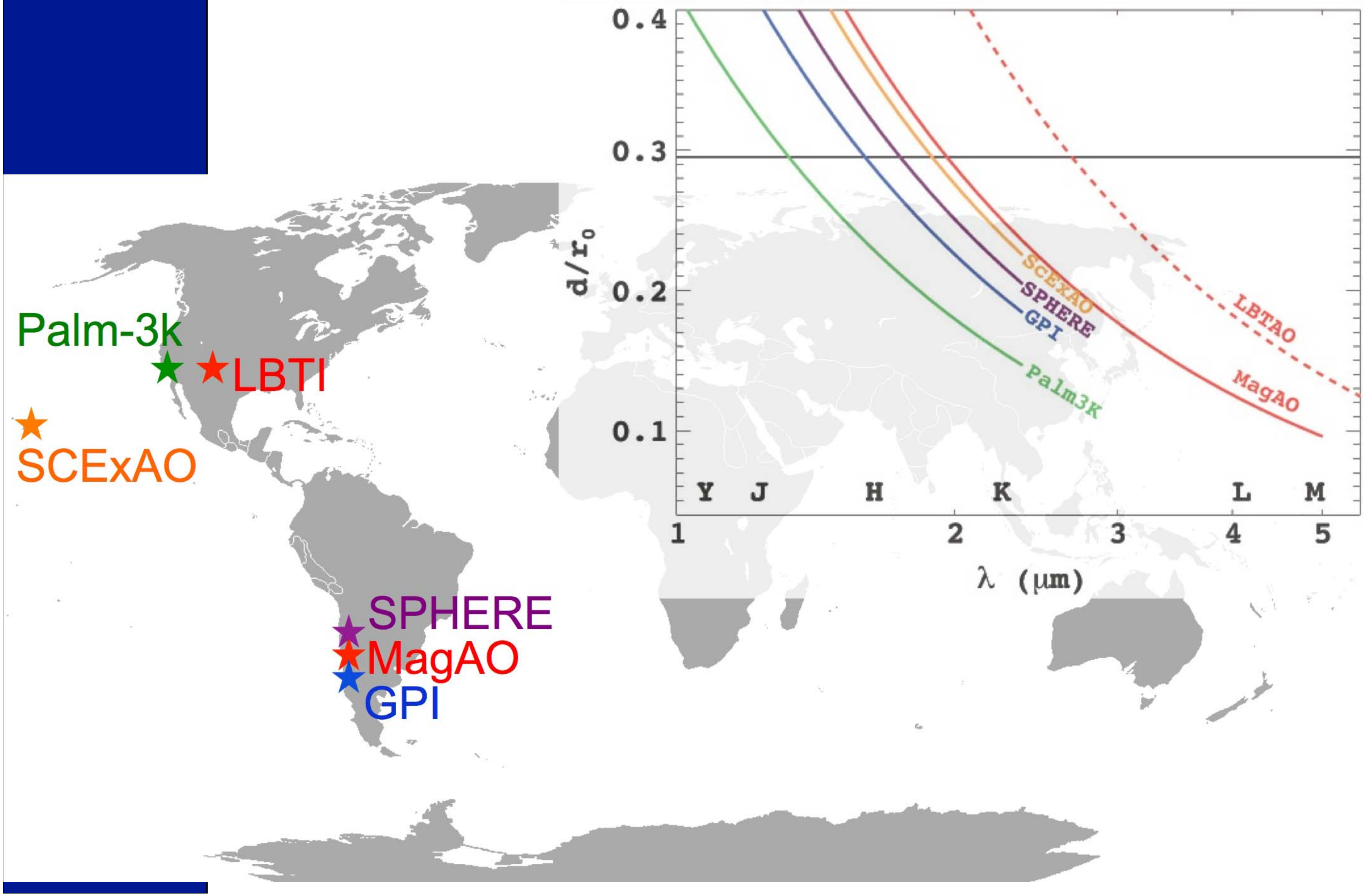
K



1RXS 1609 b
Lafreniere+ 2010

M

Direct-imaging adaptive optics around the world



Magellan AO

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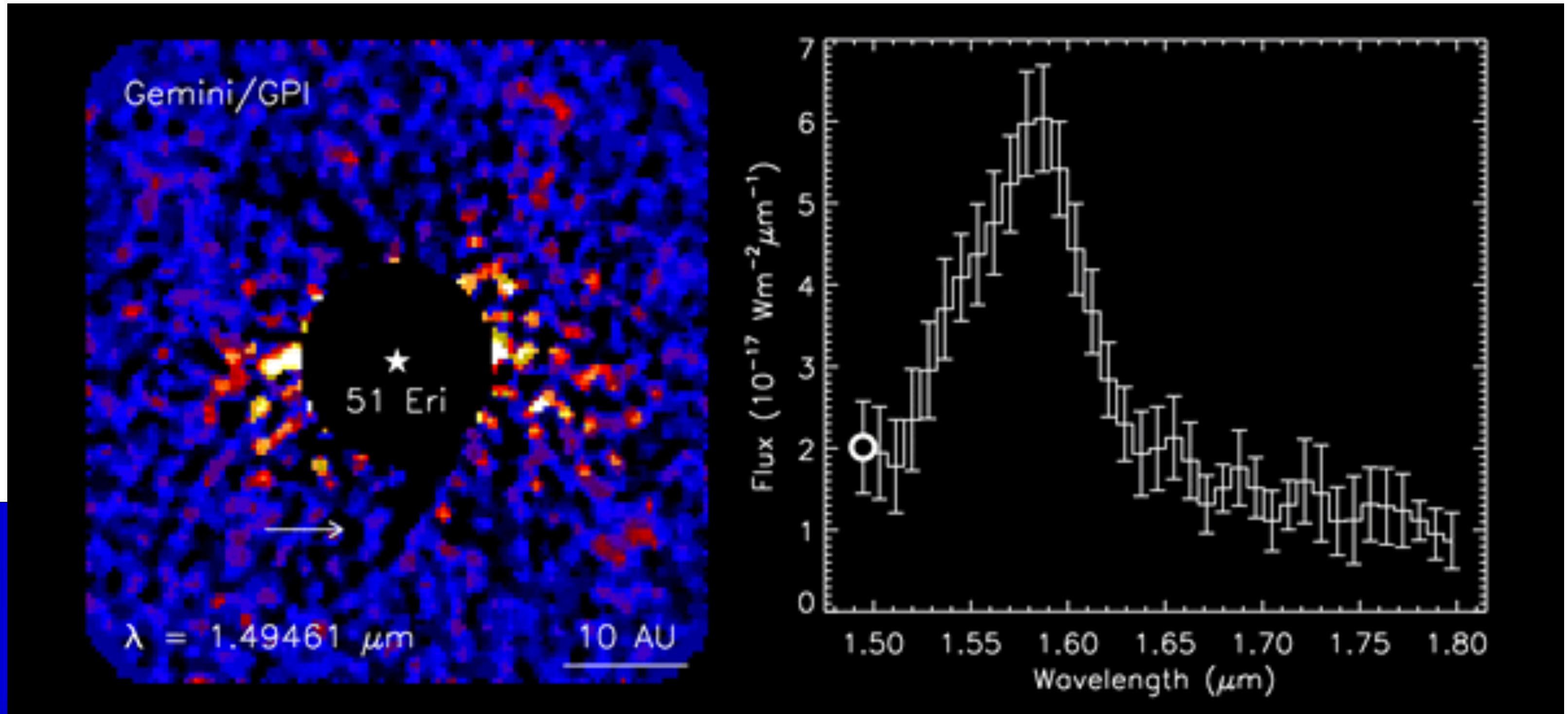
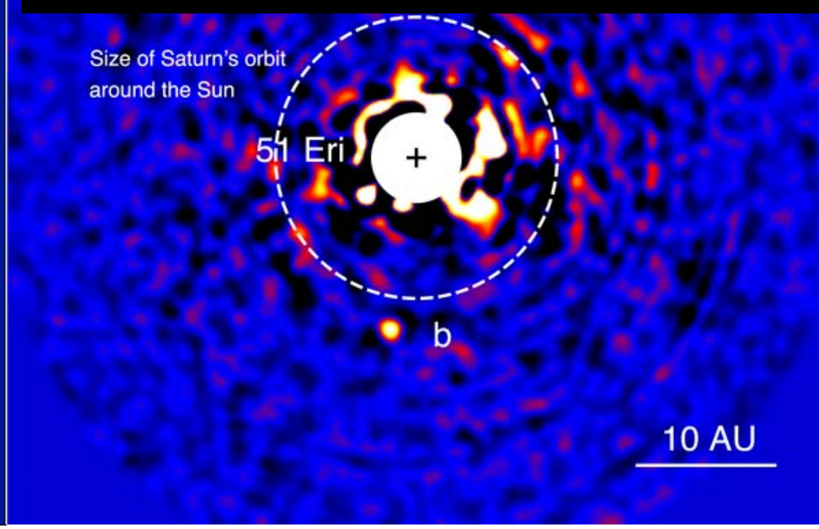
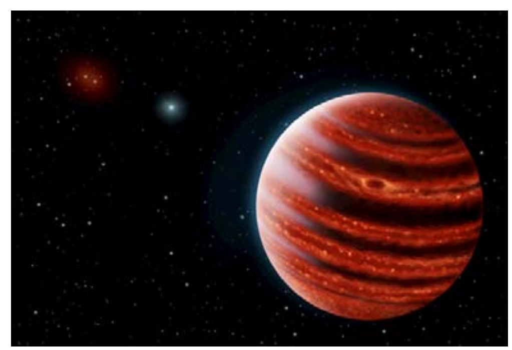
Gemini Planet Imager (GPI)

GPI new exoplanet 51 Eri b







Macintosh+ 2015

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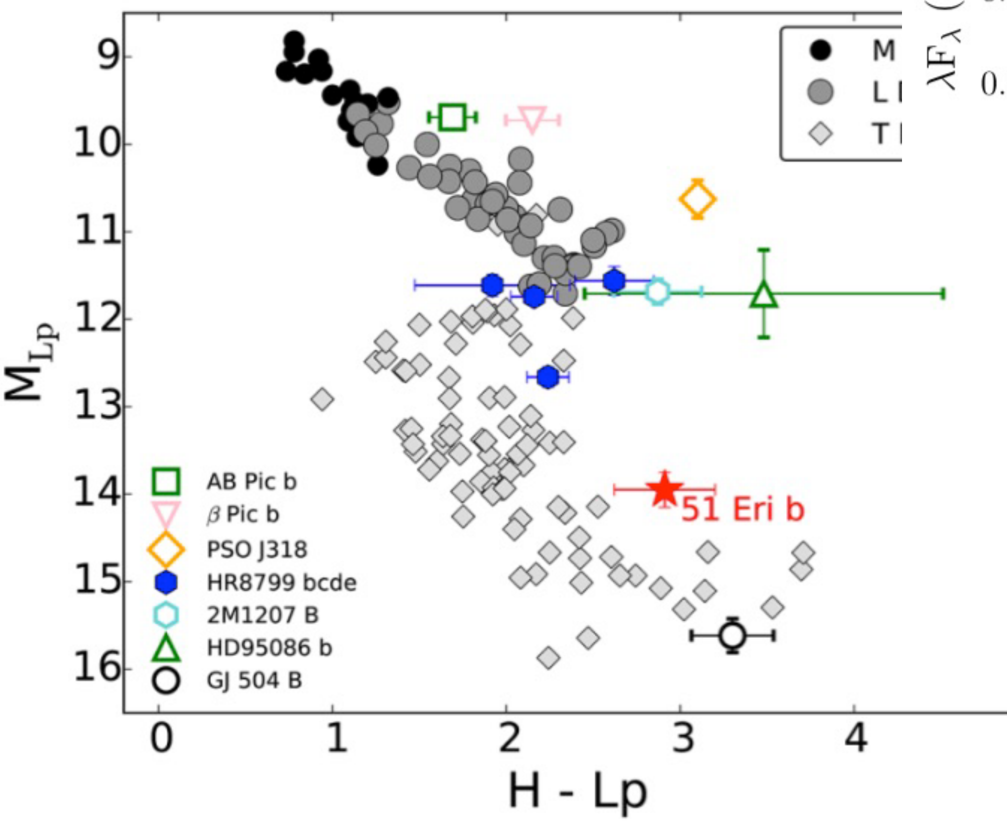
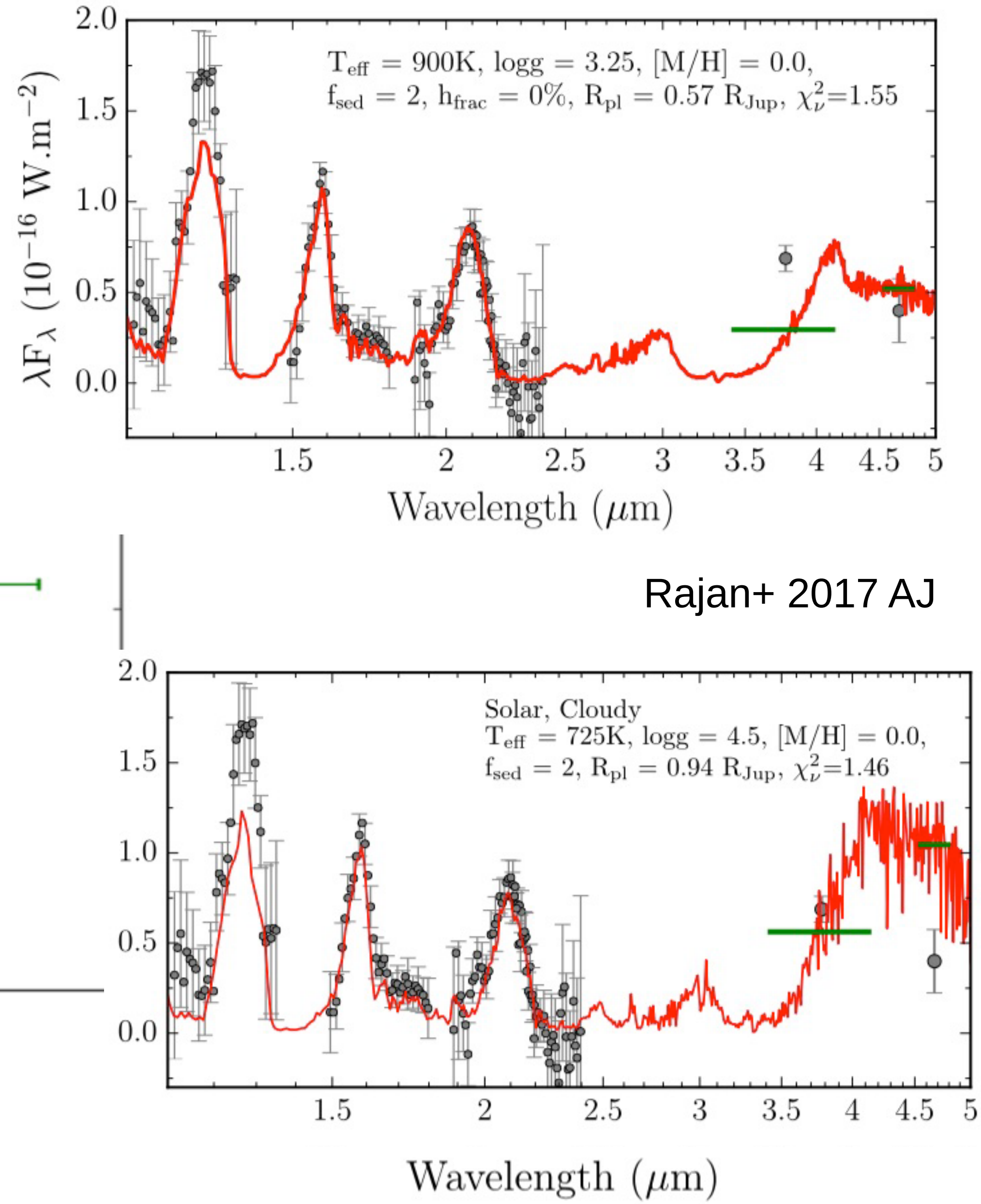
Red – possibly in the L-T transition
Cool – first cold-start DI planet



Macintosh+ 2015 Science



Rajan+ 2017 AJ

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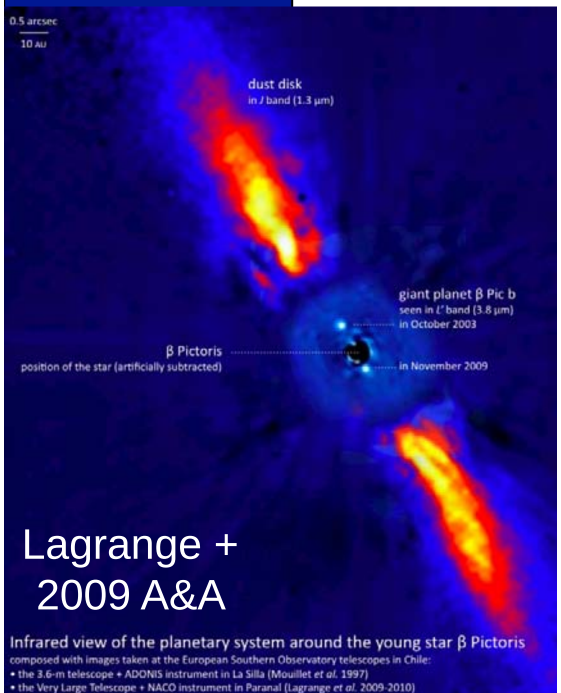
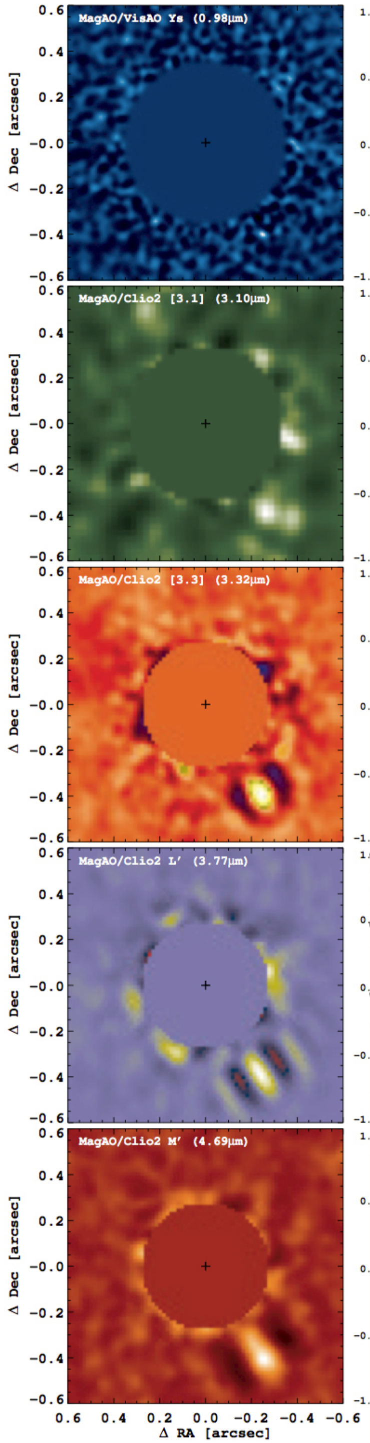
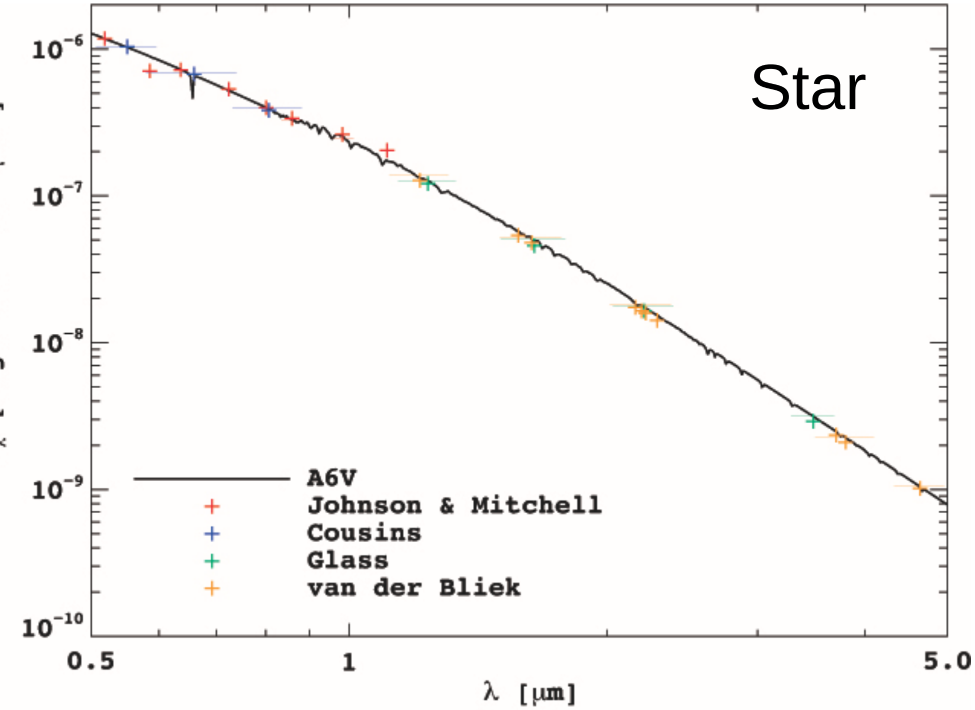
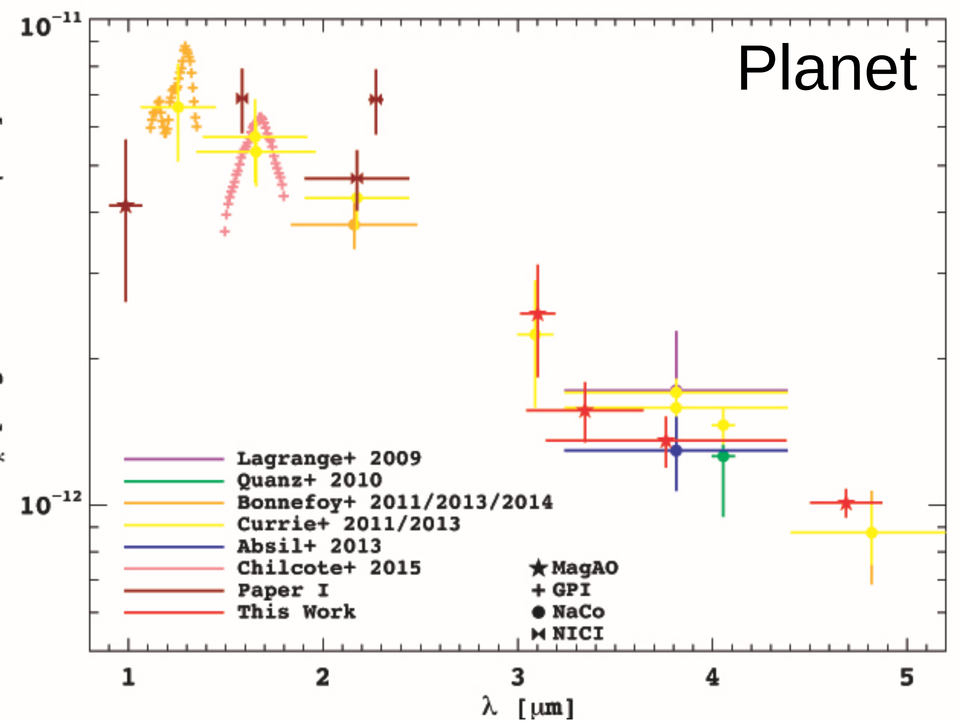
SED of β Pic b



Lagrange + 2009 A&A







Morzinski + 2015 ApJ

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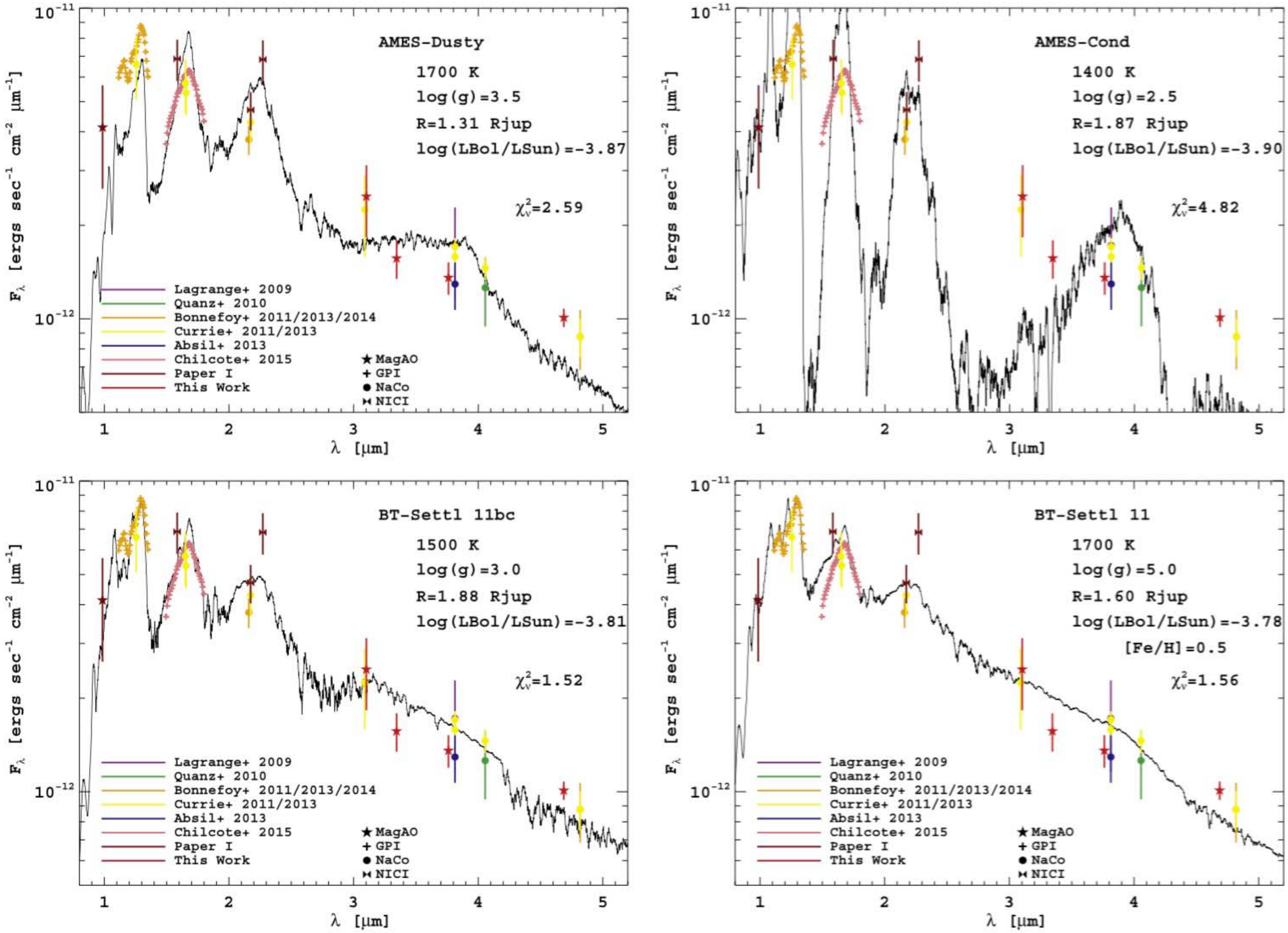
Model fitting ... Looks cloudy!



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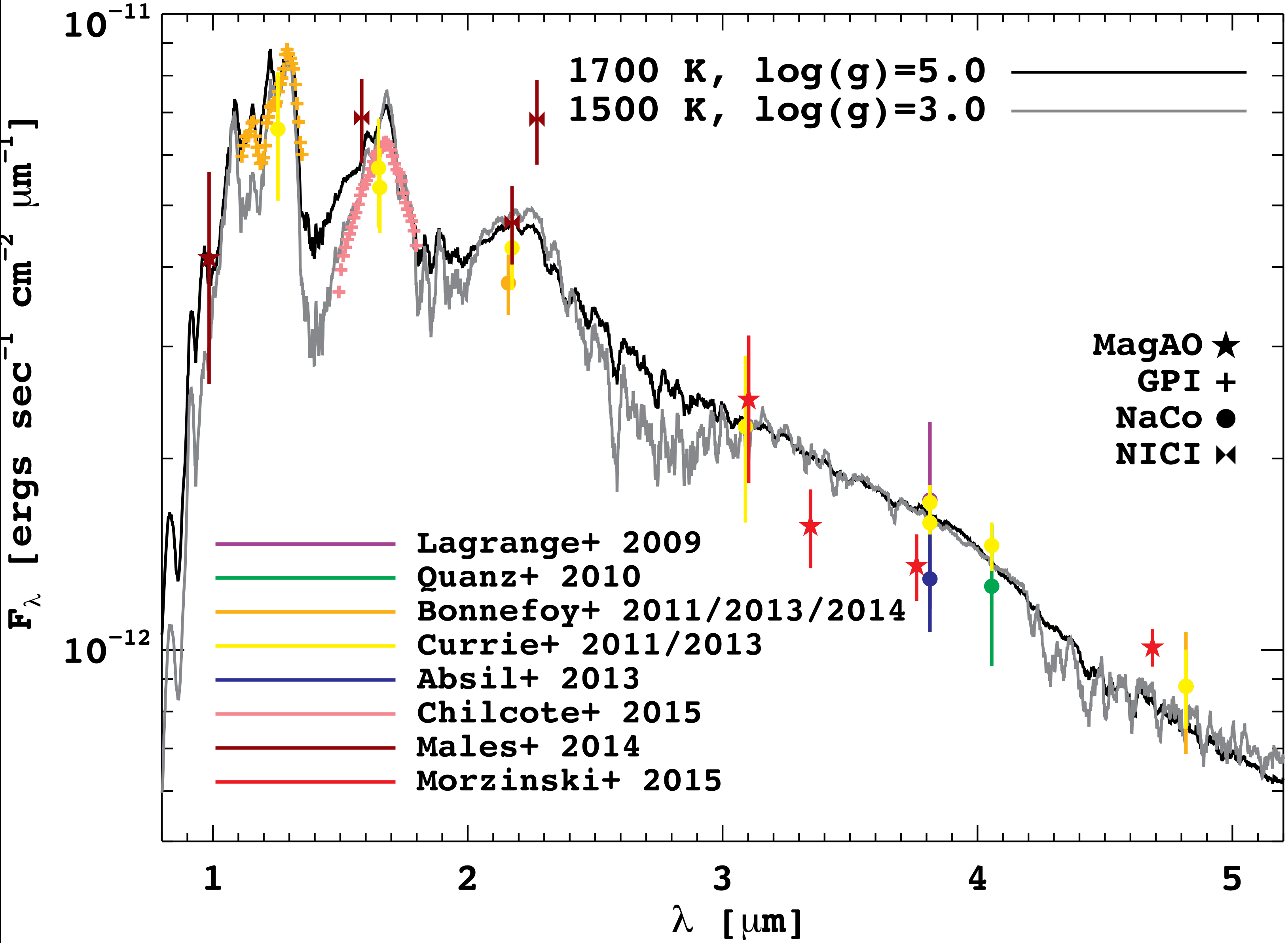
Morzinski + 2015 ApJ

But what's the Teff ?? …Degenerate with log(g)



Morzinski + 2015 ApJ

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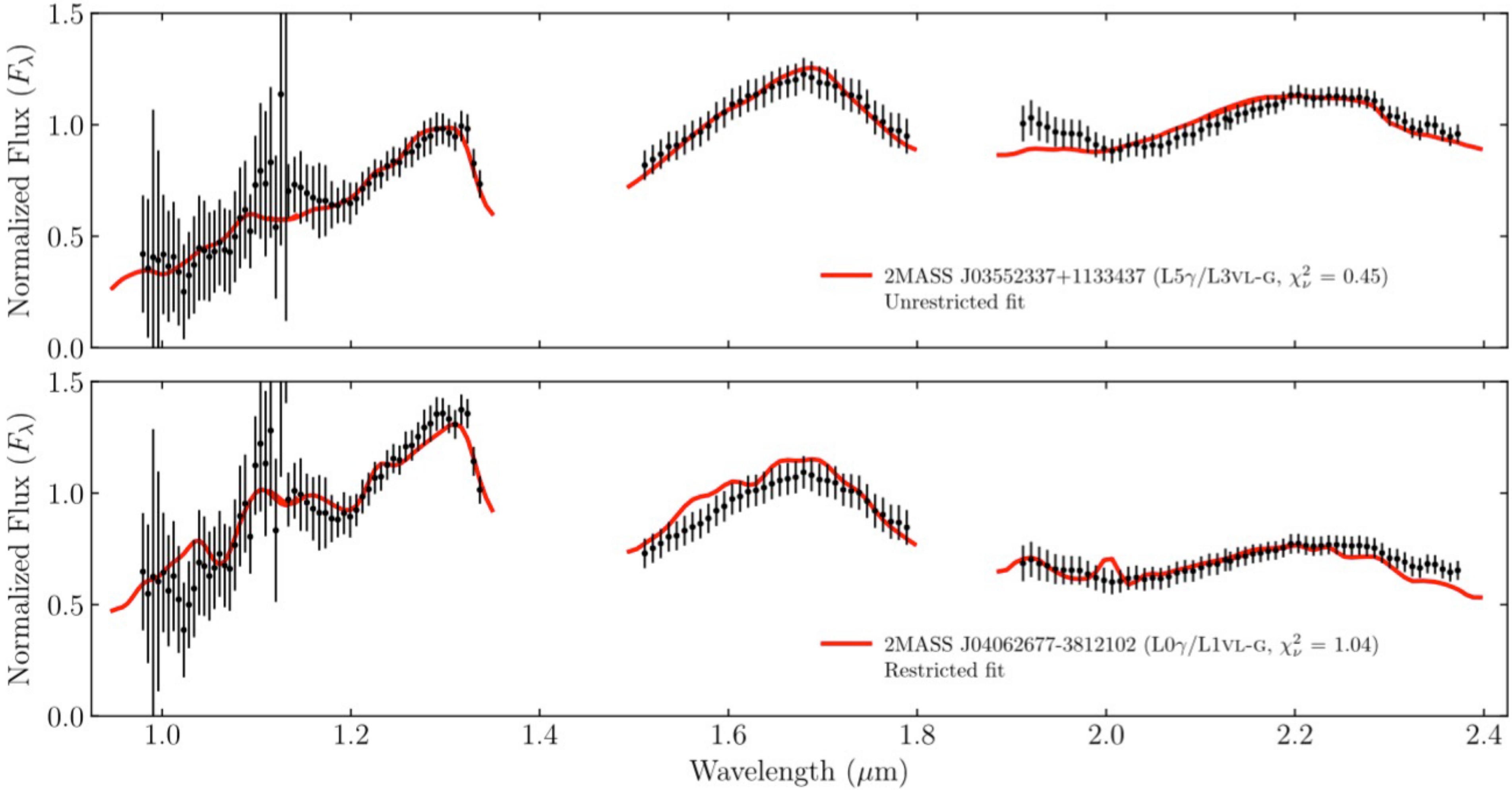
Gravity best constrained by fitting field L dwarfs: log(g)~3.5-4.0



extrasolar planets?

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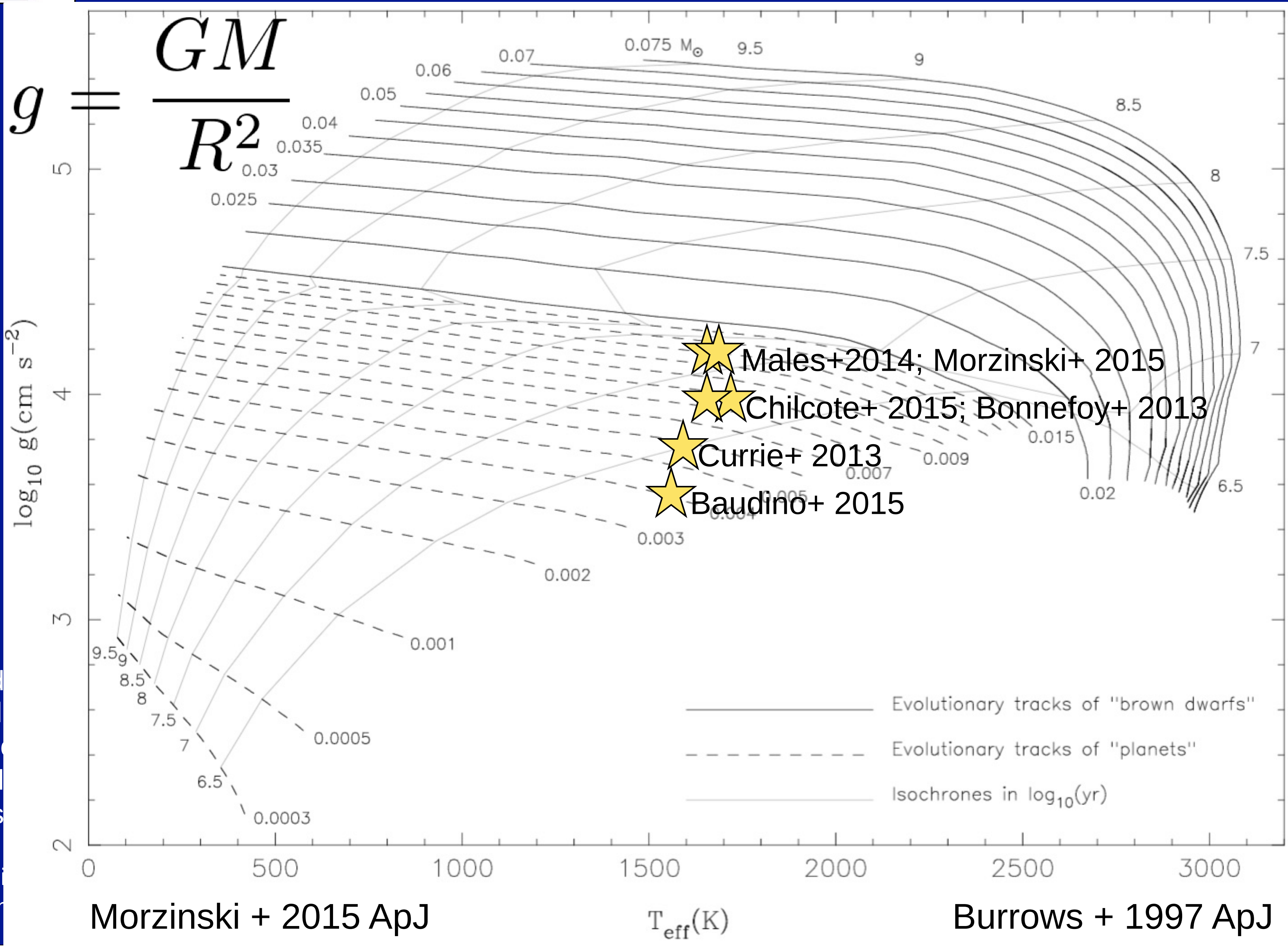
Chilcote + 2017 AJ

Teff vs. log(g) measurements of beta Pic b

$$g = \frac{GM}{R^2}$$



Morzinski + 2015 ApJ

Burrows + 1997 ApJ

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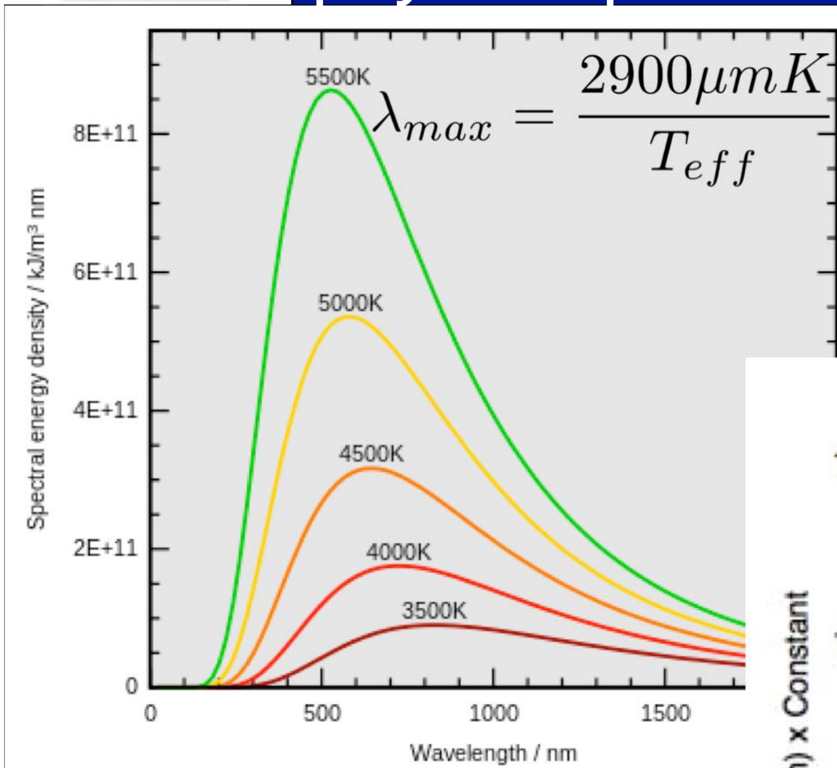
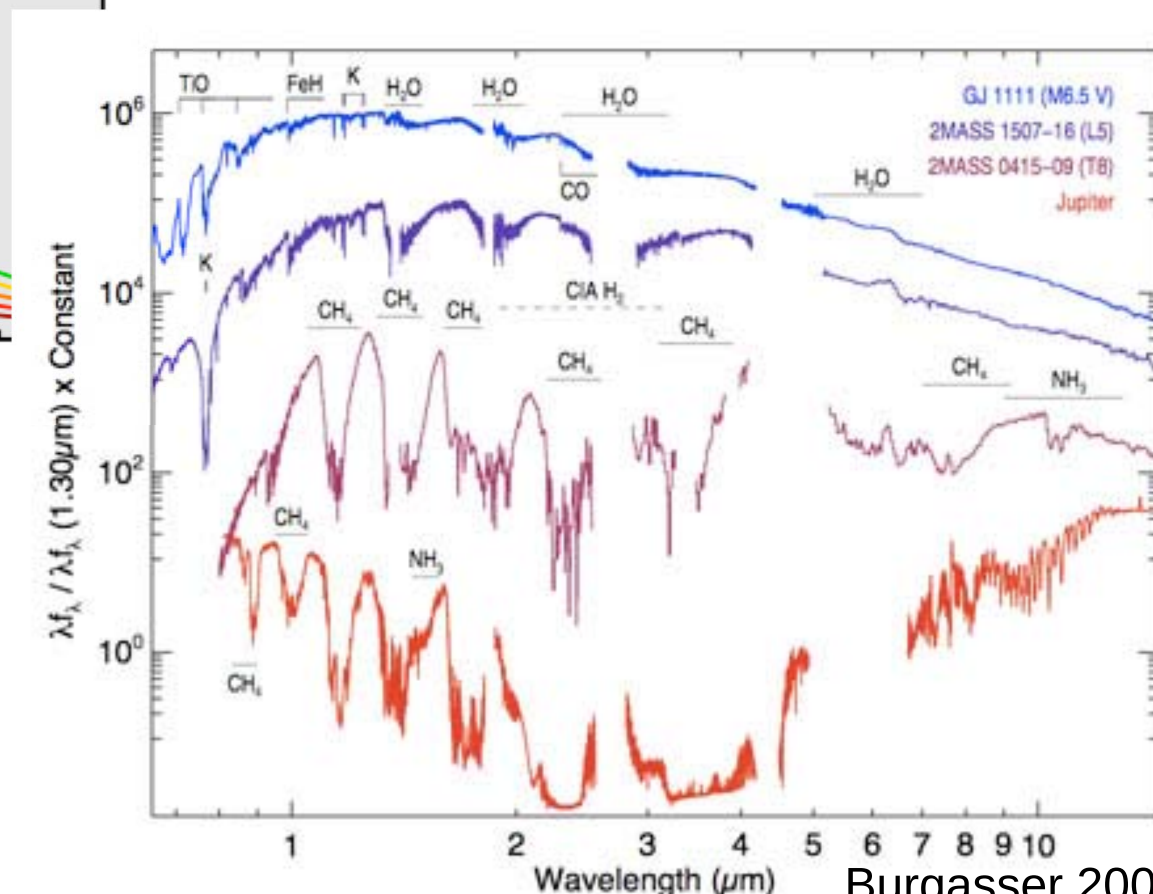
Teff is a defined quantity, not a fundamental physical parameter



$$\lambda_{max} = \frac{2900 \mu m K}{T_{eff}}$$

$$T_{\rm eff} = \left(\frac{L_{\rm bol}}{4\pi R^2 \sigma_B} \right)^{1/4}$$



Burgasser 2009

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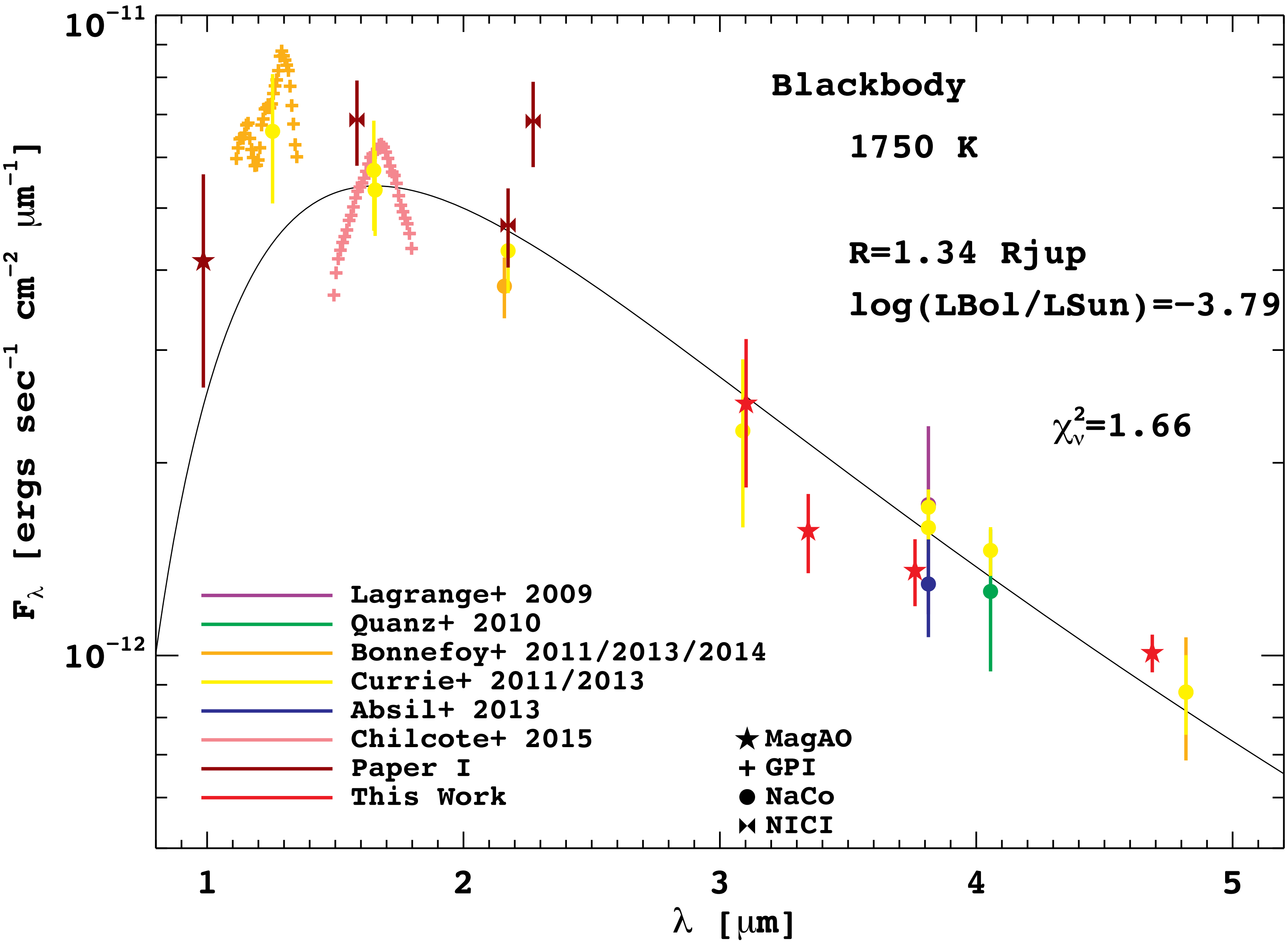
A plain blackbody fits just as well



Morzinski + 2015 ApJ

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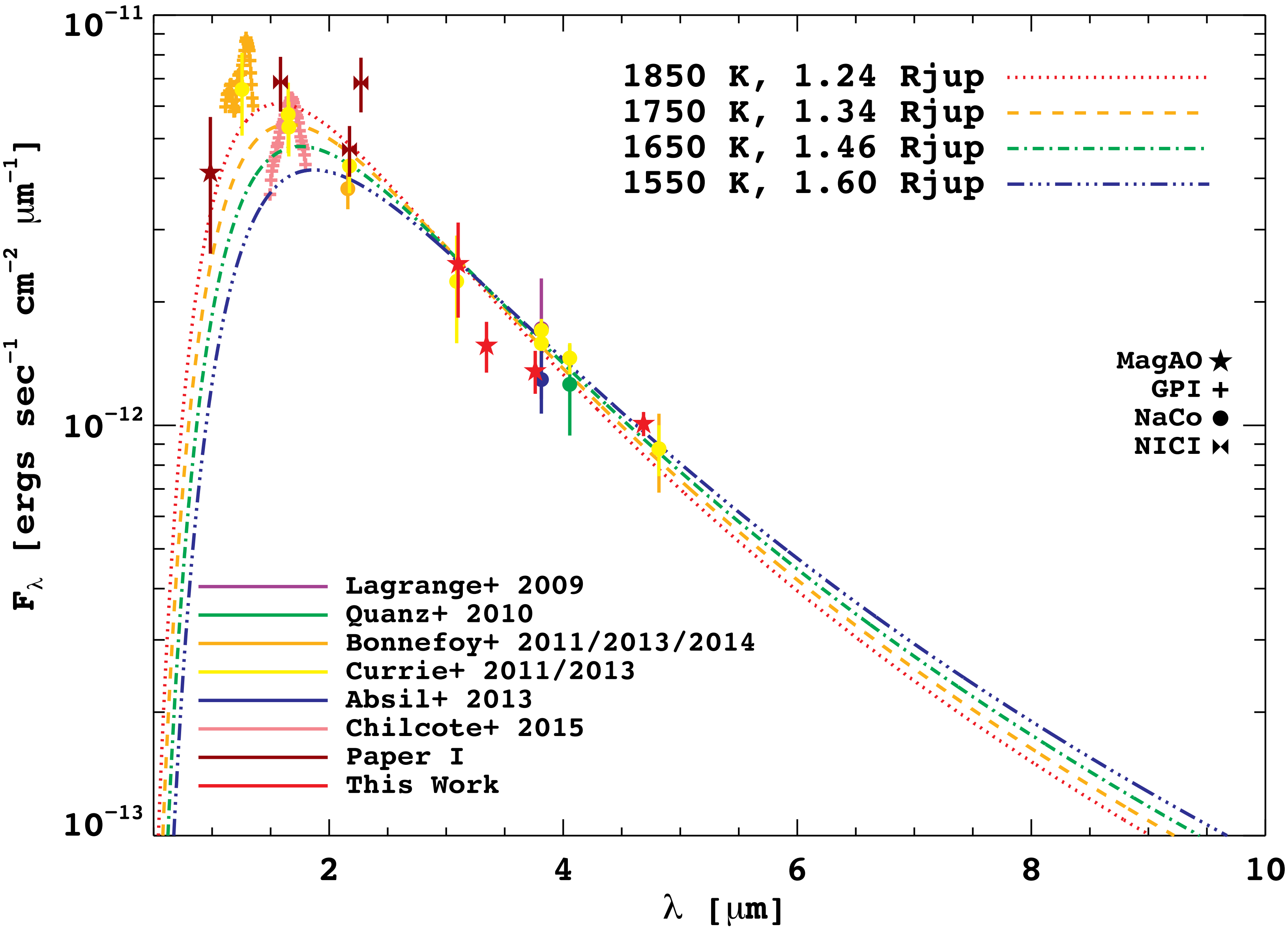
By spanning the blackbody peak, optical constrains Teff while IR then constrains R



Morzinski + 2015 ApJ

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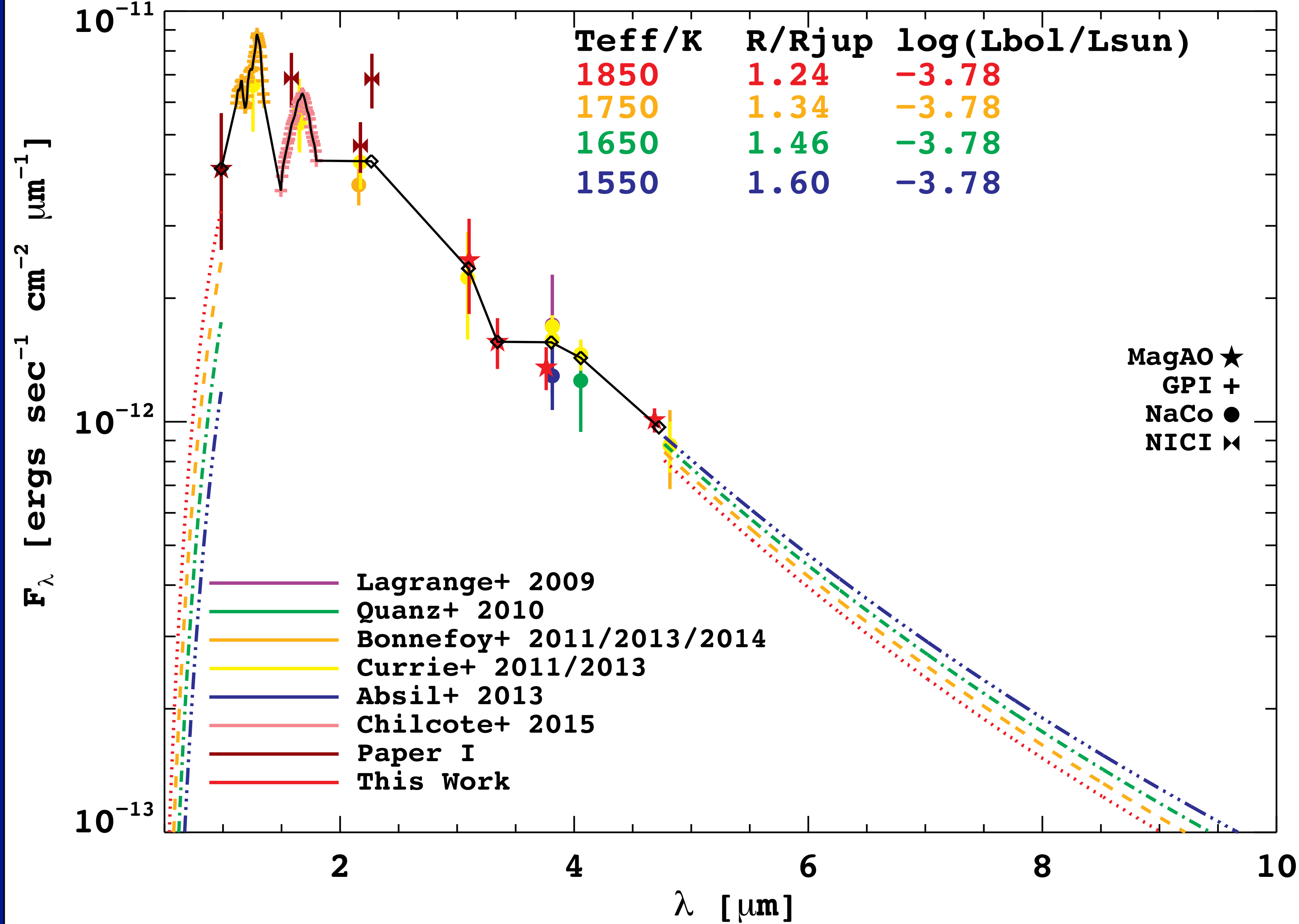
Observations cover >80% of the planet's energy – Measure L_{Bol} empirically



Morzinski + 2015 ApJ

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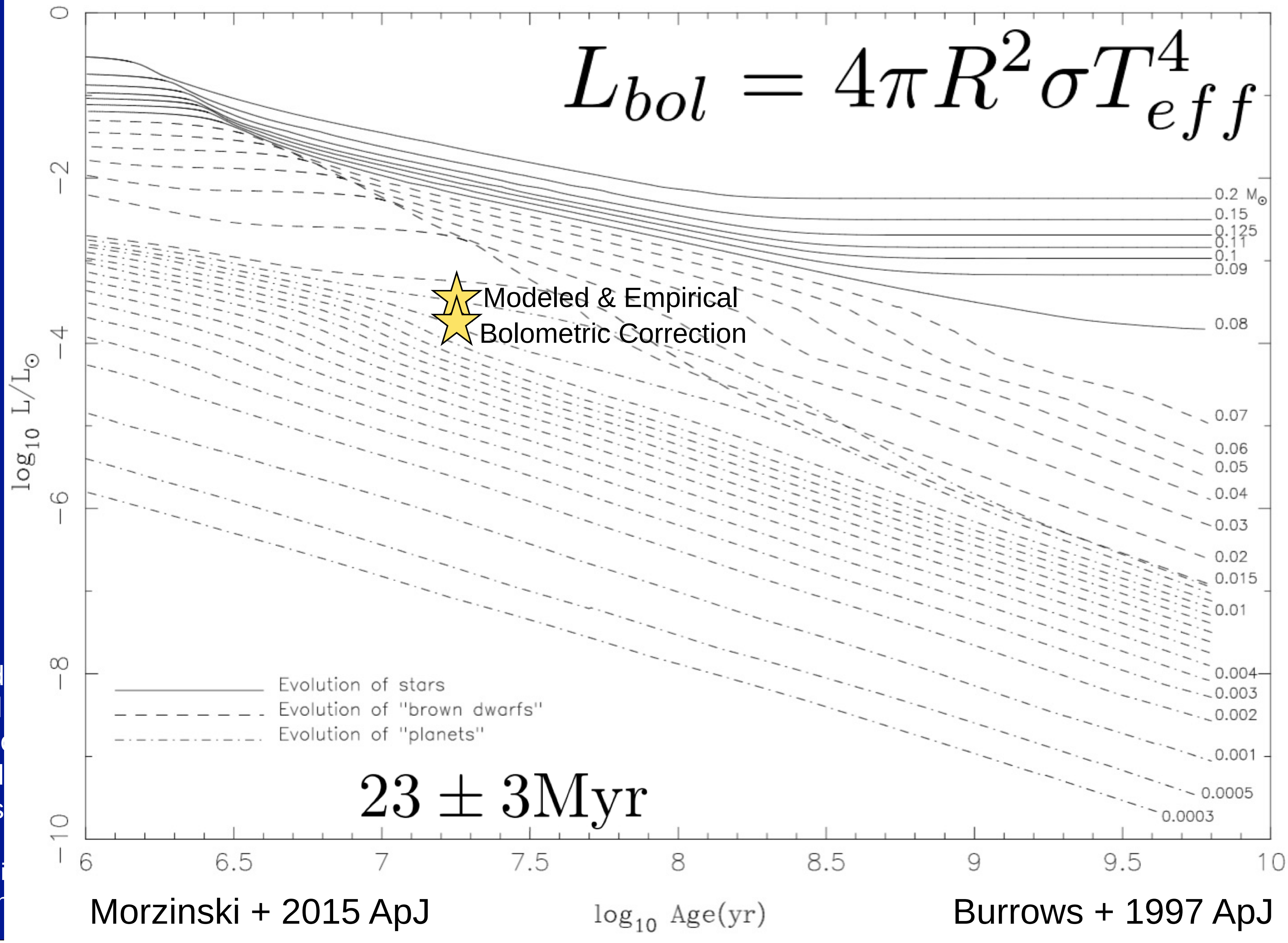
Luminosity and age much better constrained



Morzinski + 2015 ApJ

Burrows + 1997 ApJ

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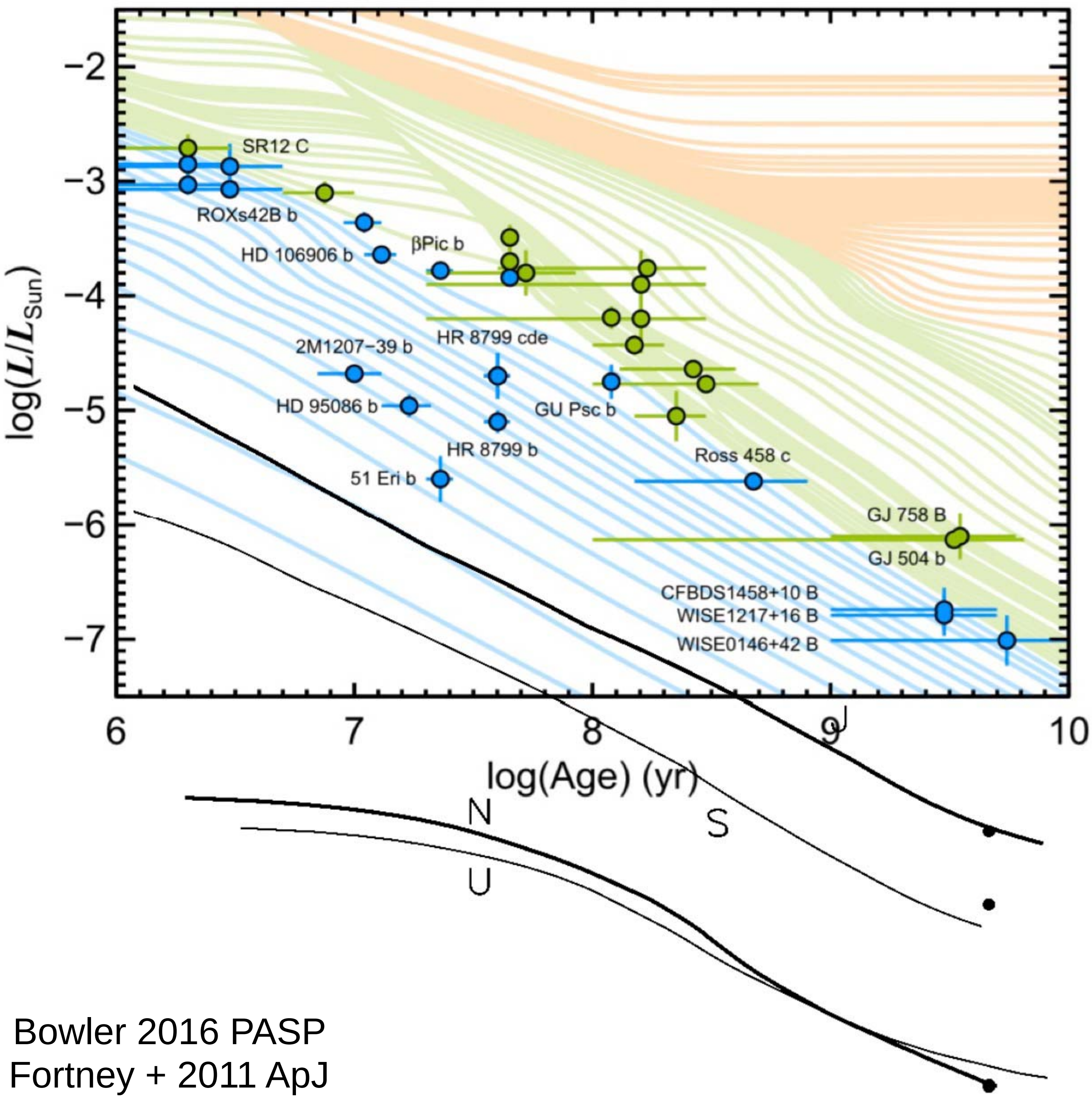
Evolutionary cooling tracks: Limited by age errors & modeling unknowns



Bowler 2016 PASP
Fortney + 2011 ApJ

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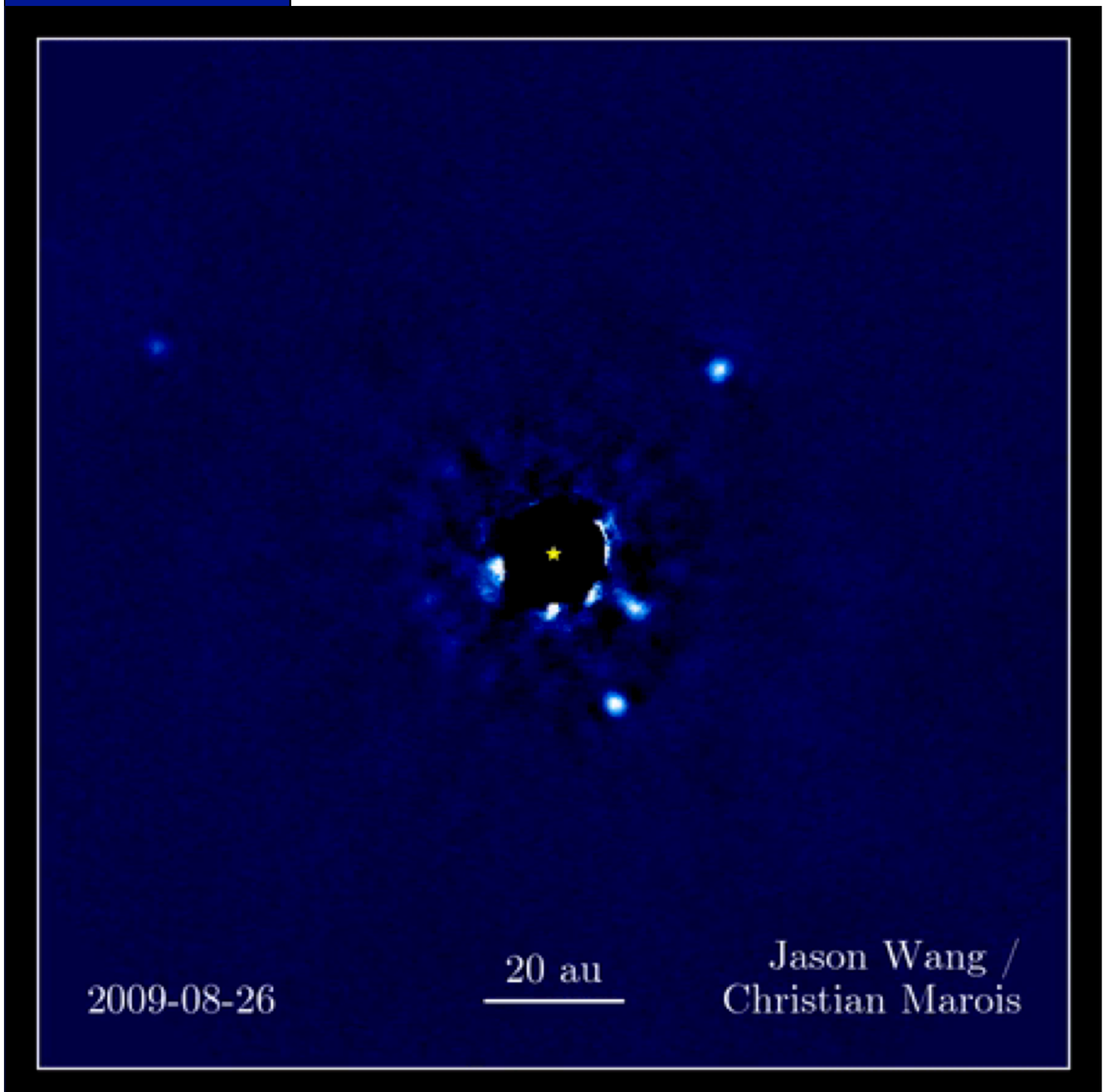
Pathways towards mass and radius for directly-imaged planets



- RV constraints
- Dynamical stability
- Orbits
  - GSMT AO relative astrometry + absolute astrometry from *Gaia*, *WFIRST*, etc.
- Surface gravity measurement
  - brown dwarf calibration
  - high-resolution spectroscopy

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U. Arizona

High-Dispersion Coronagraphy (HDC) = high-resolution spectroscopy + high-contrast imaging

Combine spatial & spectral information to separate planet from star

- Star suppression – Better AO+Coronagraph (+ Telescope D)
- Spectral resolution – Can use more lines on (bright) star to get more information for separating planet from star

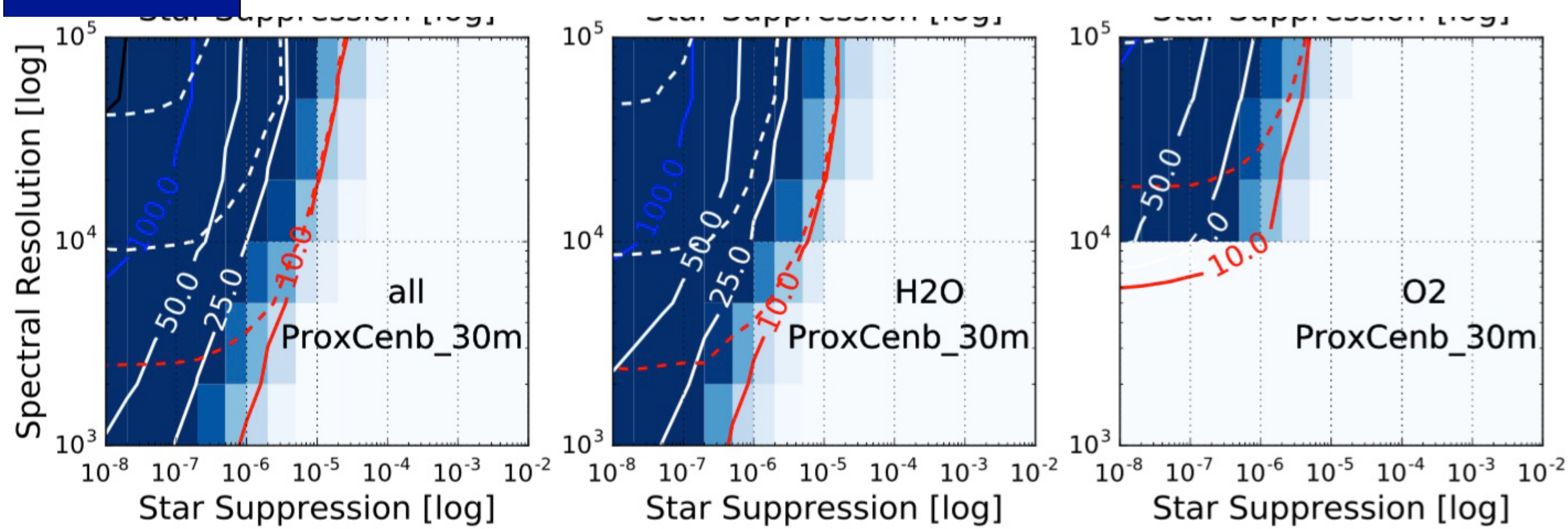
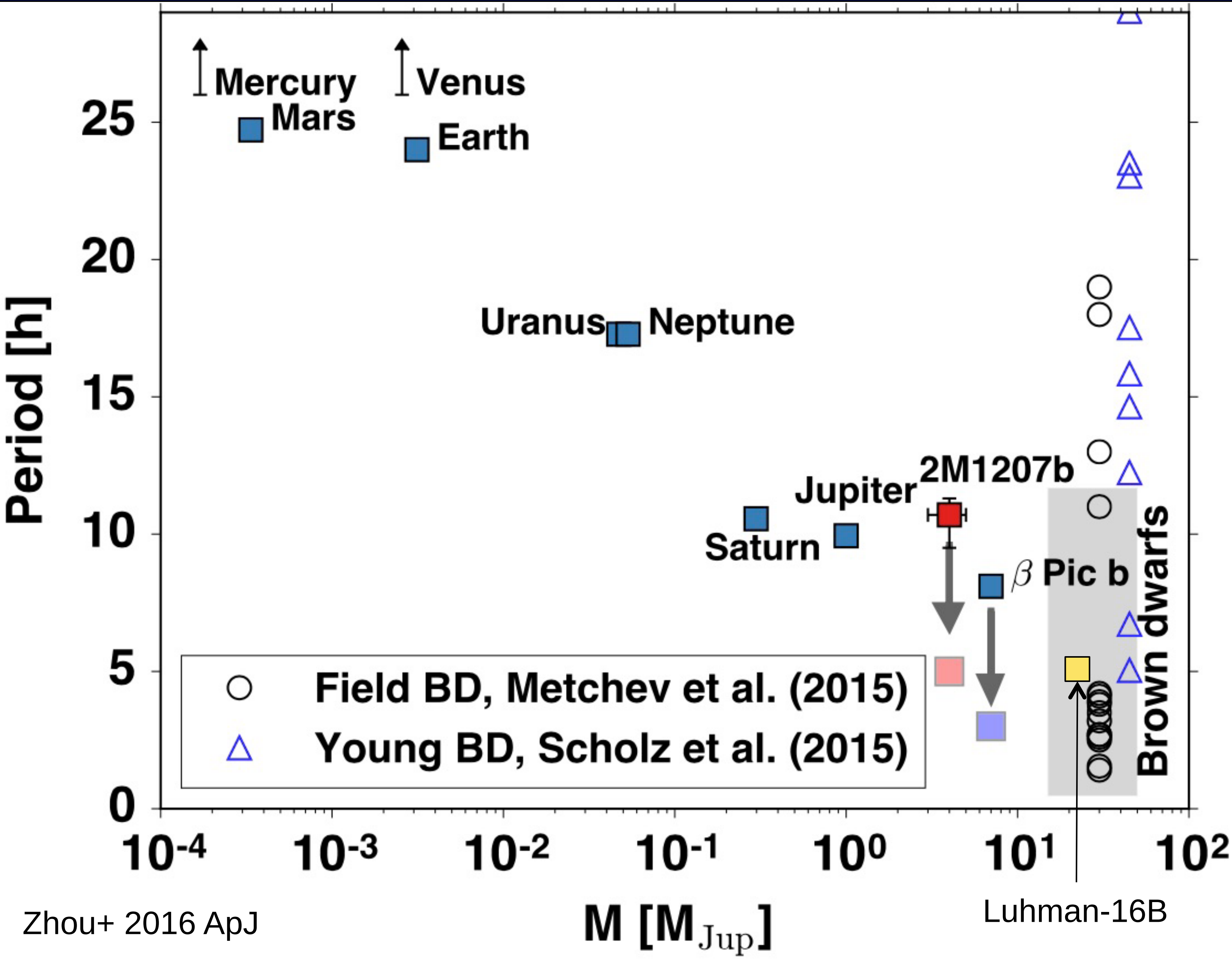


Figure 9. CCF S/N contours for the *J*-band simulation in phase space of spectral resolution and star light suppression level for different molecular species for three cases: (1) a 30 m telescope on a Earth-like planet around an M dwarf at 5 pc (top rows), and (2) a 30 m telescope on Proxima Cen b (bottom rows). Solid contours are for the photon-noise-limited case and dashed contours are for the CCF structure-limited case. Each panel is marked with the name of a molecular species, which indicates that only the lines of a given molecular species are used in the cross-correlation. "All" means that all lines are used.

Ji Wang+ 2017 AJ 153

Rotation periods



Zhou+ 2016 ApJ

What do we really know about extrasolar planets?

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Determining fundamental physical parameters of exoplanets – 2.

- Microlensing planets
  - Observe Magnification, Timescale
  - Assume: IMF -> mass of Lens star M_L
    - Galactic disk model -> distance to Lens star D_L
    - Isotropic velocity dispersion -> Source-Lens relative velocity $v_{S\text{-}L}$
  - The distance D_L is degenerate in M_L, D_S, $v_{S\text{-}L}$
    - Angular Einstein radius θ_E from D_L, D_S, M_L, $v_{S\text{-}L}$
    - Then Einstein radius r_E in AU follows from θ_E, D_L
    - Projected separation r in AU from d [in r_E] & D_L
    - Semi-major axis a from projected separation r assuming circular orbits
    - Mass of planet M_p from mass ratio q times M_L

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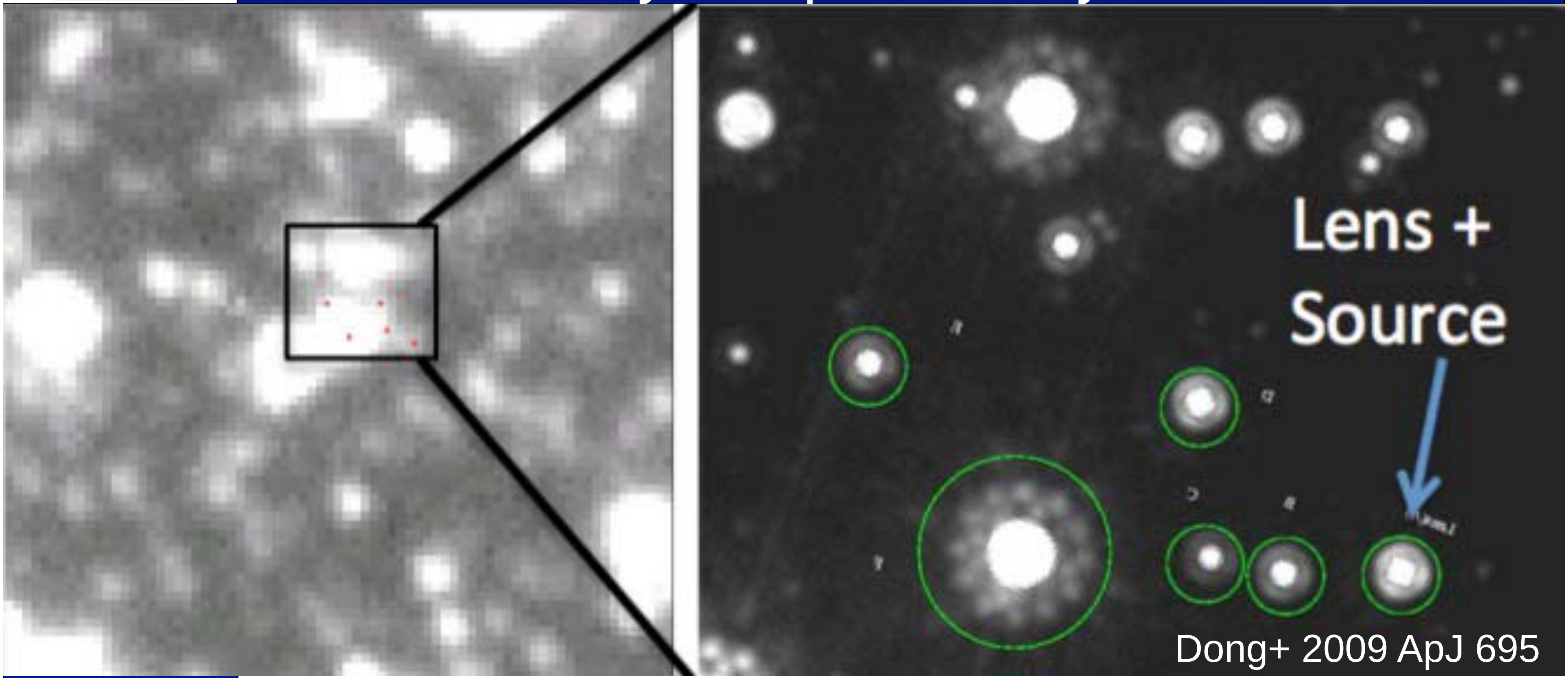
Microlensing planets follow-up with crowded-field astrometry and photometry



- mass of Lens star M_L
- distance to Lens star D_L
- Source-Lens relative velocity $v_{S\text{-}L}$

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Vetting of RV and transiting planets

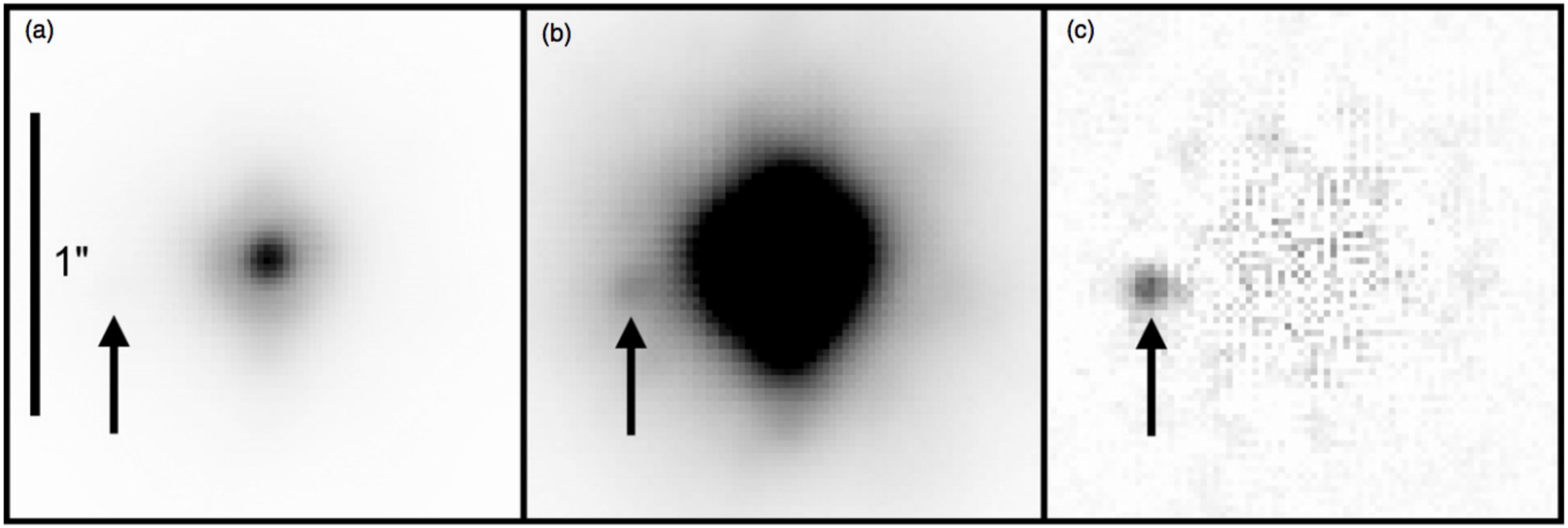

Figure 2. Robo-AO visible-light observation of a star revealing a faint close companion as indicated by an arrow. (a) Linear scaling to the peak intensity of the stellar PSF. (b) Linear scaling to 10% of the peak intensity of the stellar PSF. Quasi-static instrumental and atmospheric speckles are revealed in the stellar halo. (c) Image after PSF subtraction, linear scaling to 2% of the peak intensity of the primary stellar PSF. Speckles are suppressed and a faint companion is revealed.

Baranec + 2014 ApJL

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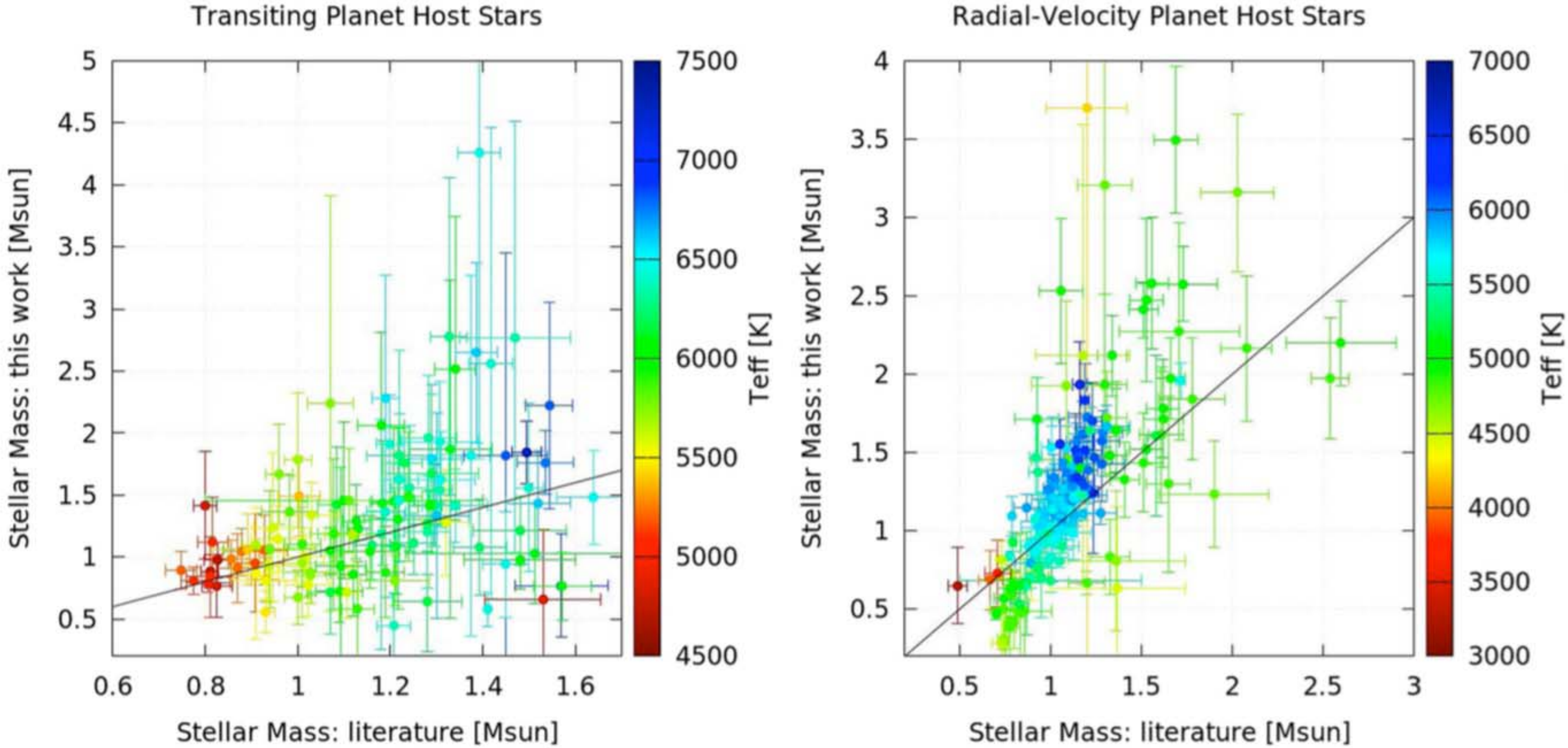
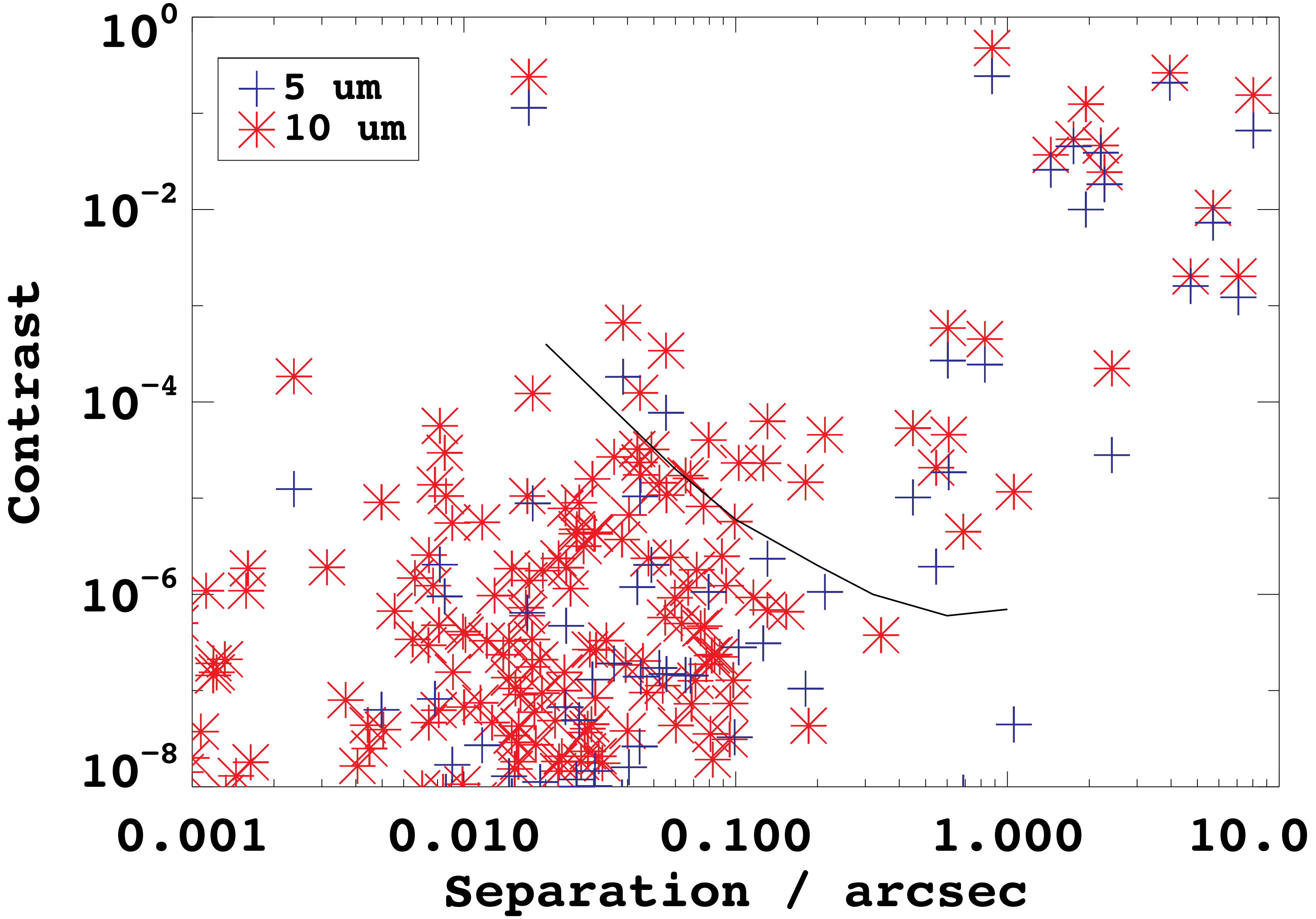
U. Arizona

Host stars: Masses & radii empirically via *Gaia* for improved accuracy (no model systematics)



Stassun + 2017 AJ 153

Contrasts of currently-known exoplanets visible from Chile – Need improved 10 micron imaging



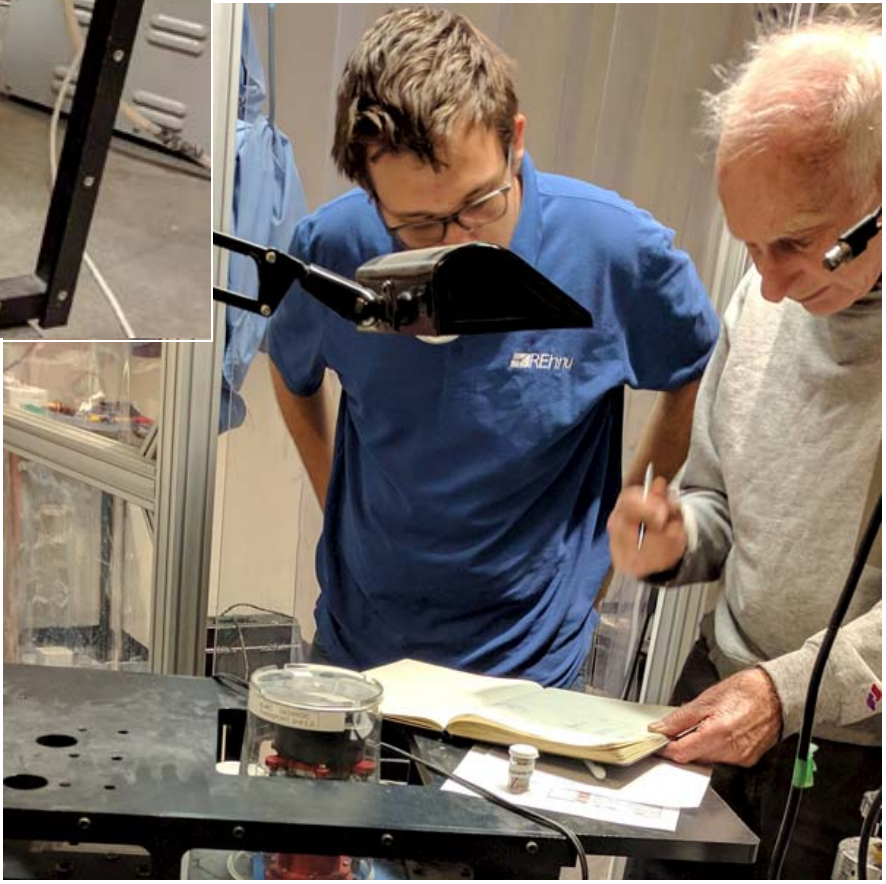
Morzinski

What do we really know about extrasolar planets?

Katie Morzinski
U. Arizona

New: 10-micron "GeoSnap" HgCdTe detectors from Teledyne

- Higher QE
- Lower dark current



Testing with plans for installation on Magellan MagAO & LBTI AO

Grant West and Bill Hoffmann
at the University of Arizona

What do we really know about extrasolar planets?

Katie Morzinski
U. Arizona

What do we really know about exoplanets?

- Mass – Know lower limit for RV planets; Break sin i degeneracy with further orbital info
  - Modeled for transiting & DI (directly-imaged) planets; Estimated/ assumed for microlensing planets
- Radius – Known to the precision of either the stellar-radius or the transit-depth for transiting planets
  - Modeled for RV and DI planets
- Teff – Need full SED; L_{Bol} plus knowledge of R
  - For now we know L_{Bol} for a handful of planets
- Composition – Need optical data for Rayleigh scattering and IR data for molecular features. Need gravity (Mass, Radius) to break degeneracy in scale height. Also degeneracy in P-T profile & molecular absorption.
  - For now we know which planets are cloudy and which aren't.
  - Know a few molecules & inversions in a few planets.
- Need to know the host star's age, radius, mass, Teff, distance
- Data-limited field (well-calibrated/understood data)
- Need multiwavelength O/IR data for many more planets

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