Direct imaging of exoplanets: Remote sensing of planetary systems and processes

Katie Morzinski
NASA Sagan Fellow, University of Arizona

Exoplanets & Brown Dwarfs: Mind the Gap
2 Sep. 2013

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High-contrast imaging with adaptive optics: Removing scattered starlight

Direct Imaging

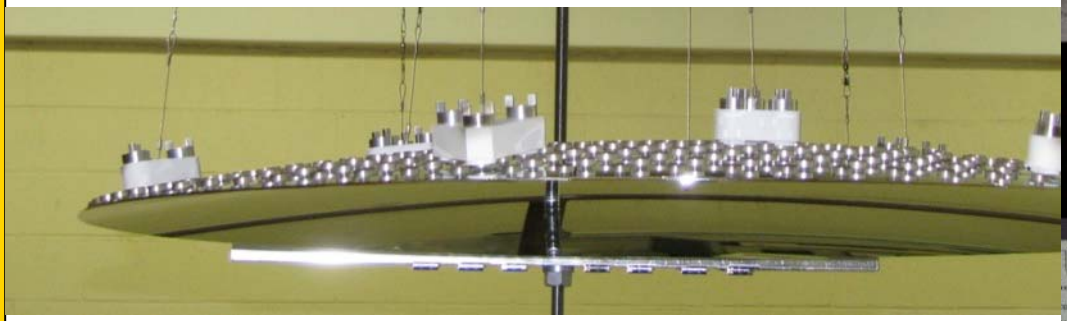
Where are we going?

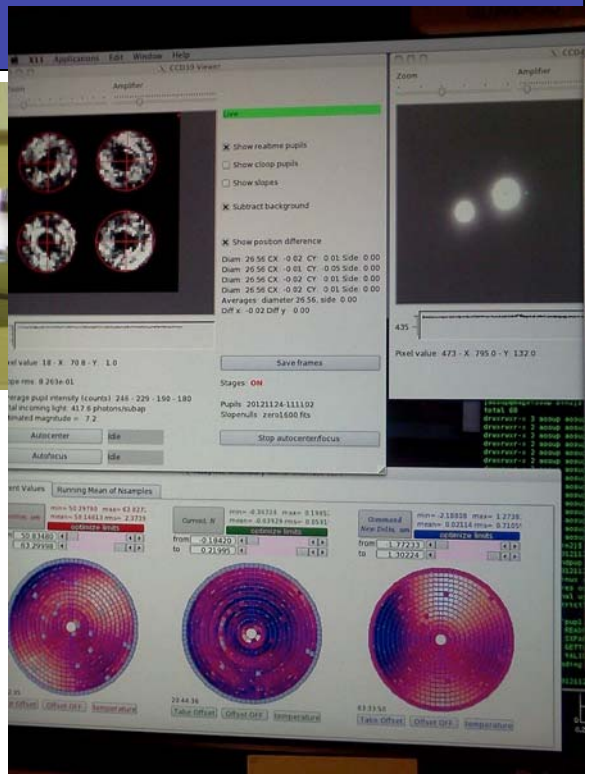
Where are we now?

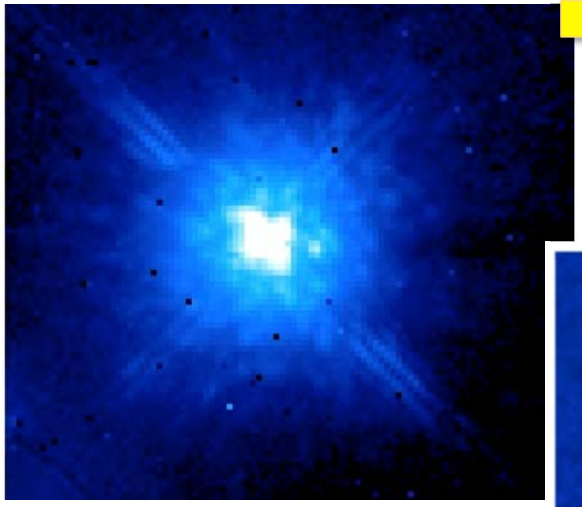
Why is it hard?

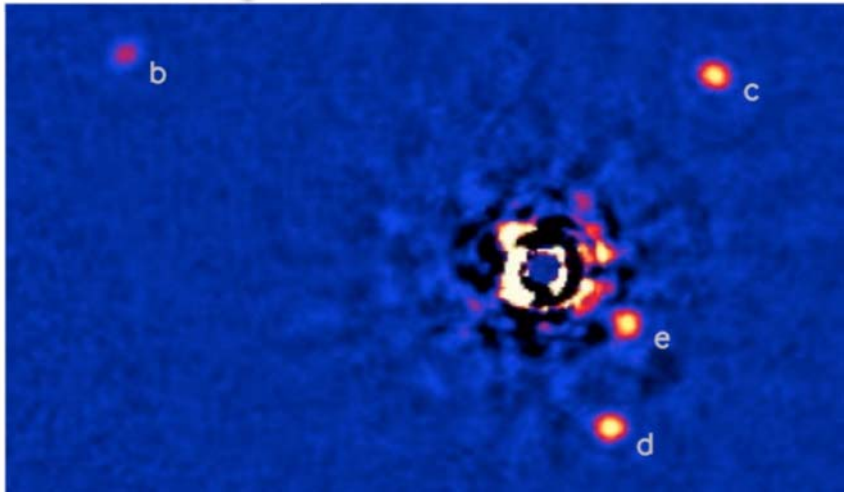
What's next?

K. Morzinski









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Direct imaging of planets…

Direct Imaging

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Voyager 1, NASA, 1990

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…has gone beyond our solar system

Direct Imaging

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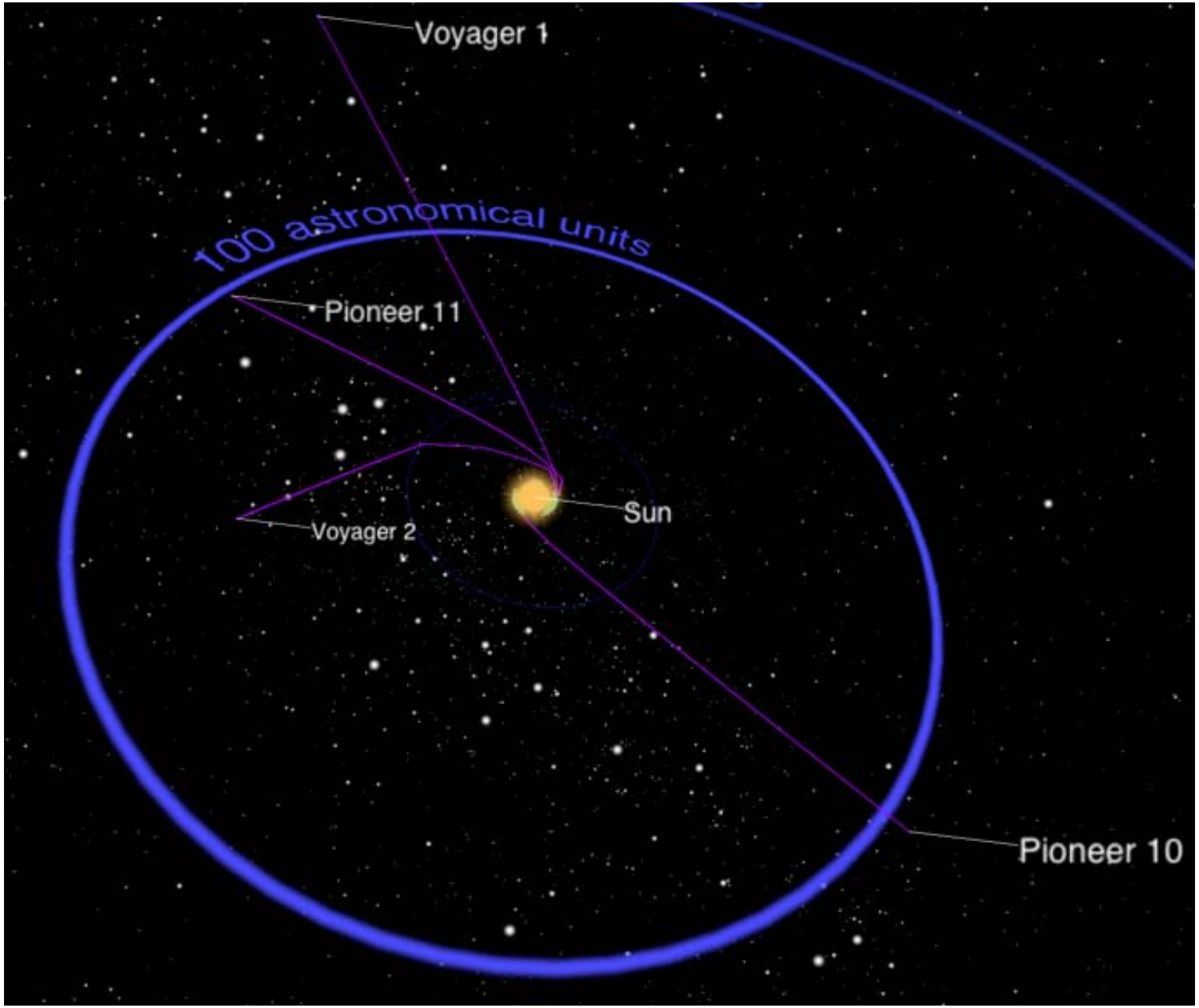

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Direct imaging presents our best opportunity to thoroughly characterize exoplanets

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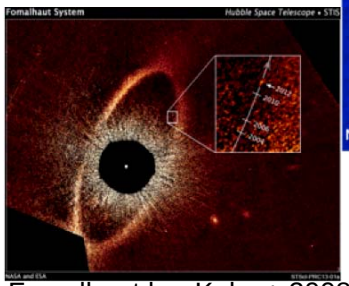
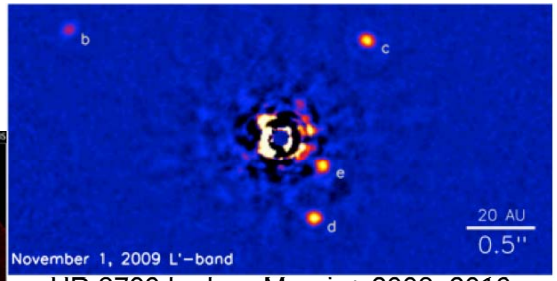
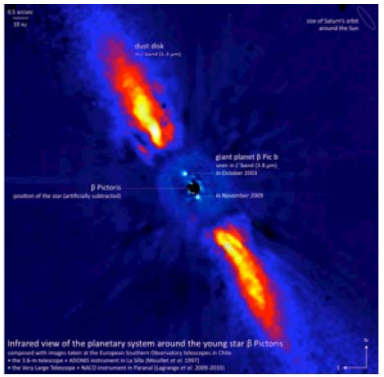


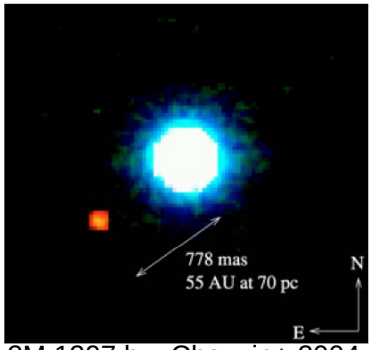
Fomalhaut b – Kalas+ 2008



HR 8799 bcde -- Marois+ 2008, 2010

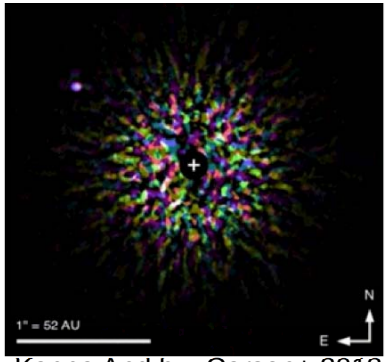


Beta Pic b – Lagrange+ 2009



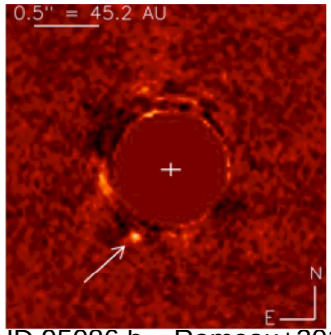
2M 1207 b – Chauvin+ 2004

M



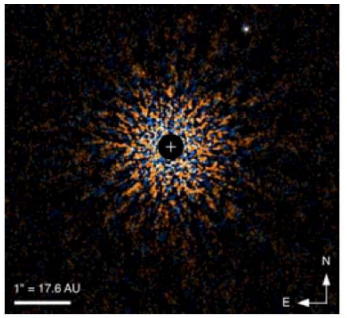
Kappa And b – Carson+ 2013

B



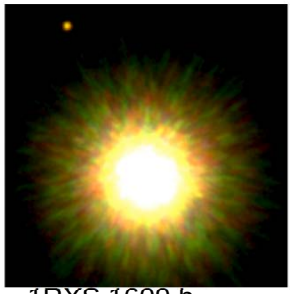
HD 95086 b – Rameau+2013

A



GJ 504 b – Kuzuhara+ 2013

G



1RXS 1609 b
Lafreniere+ 2010

K

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Directly imaged low-mass objects

Direct Imaging

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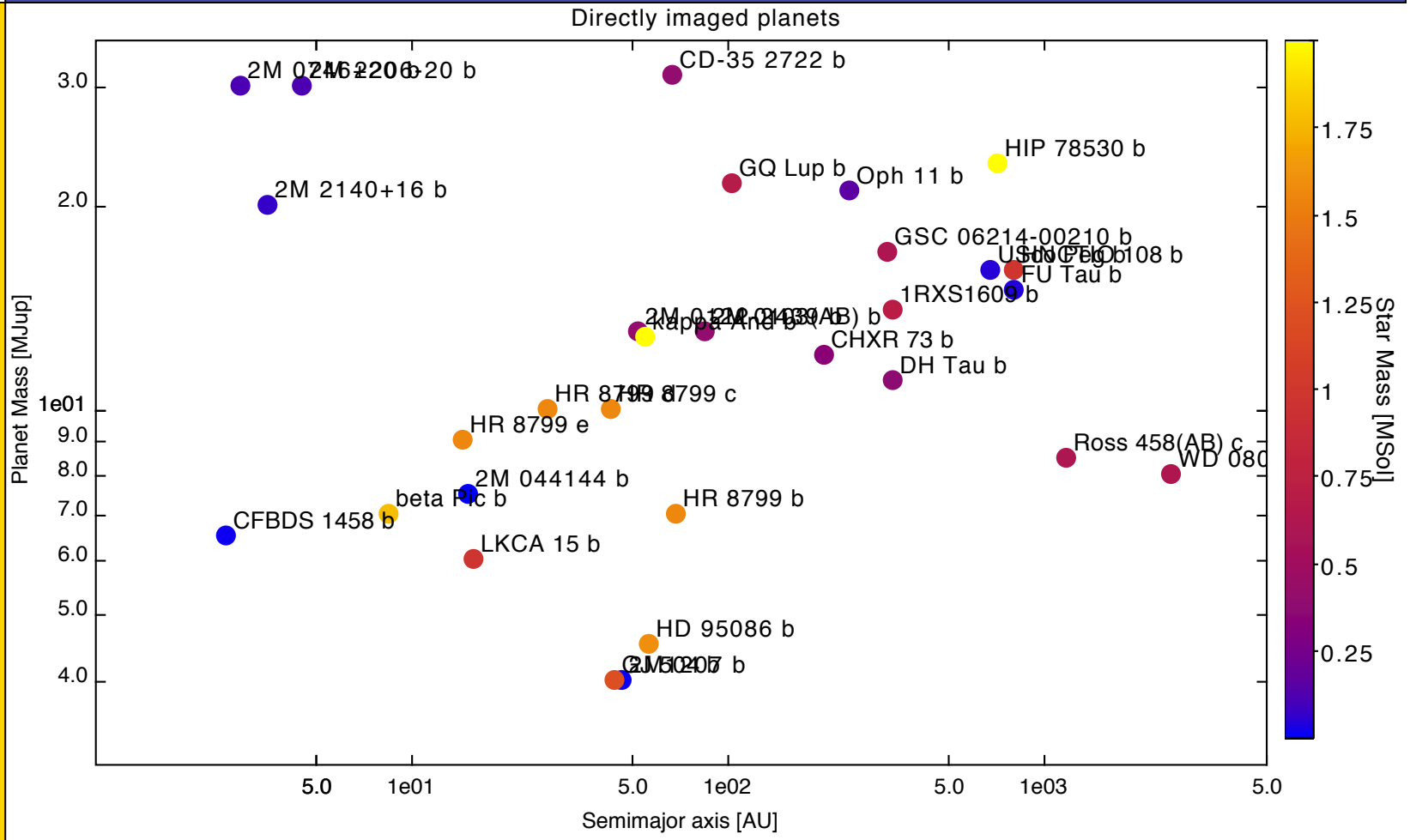

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Jupiter's SED: reflectivity, deep atmospheric windows, and thermal blackbody emission

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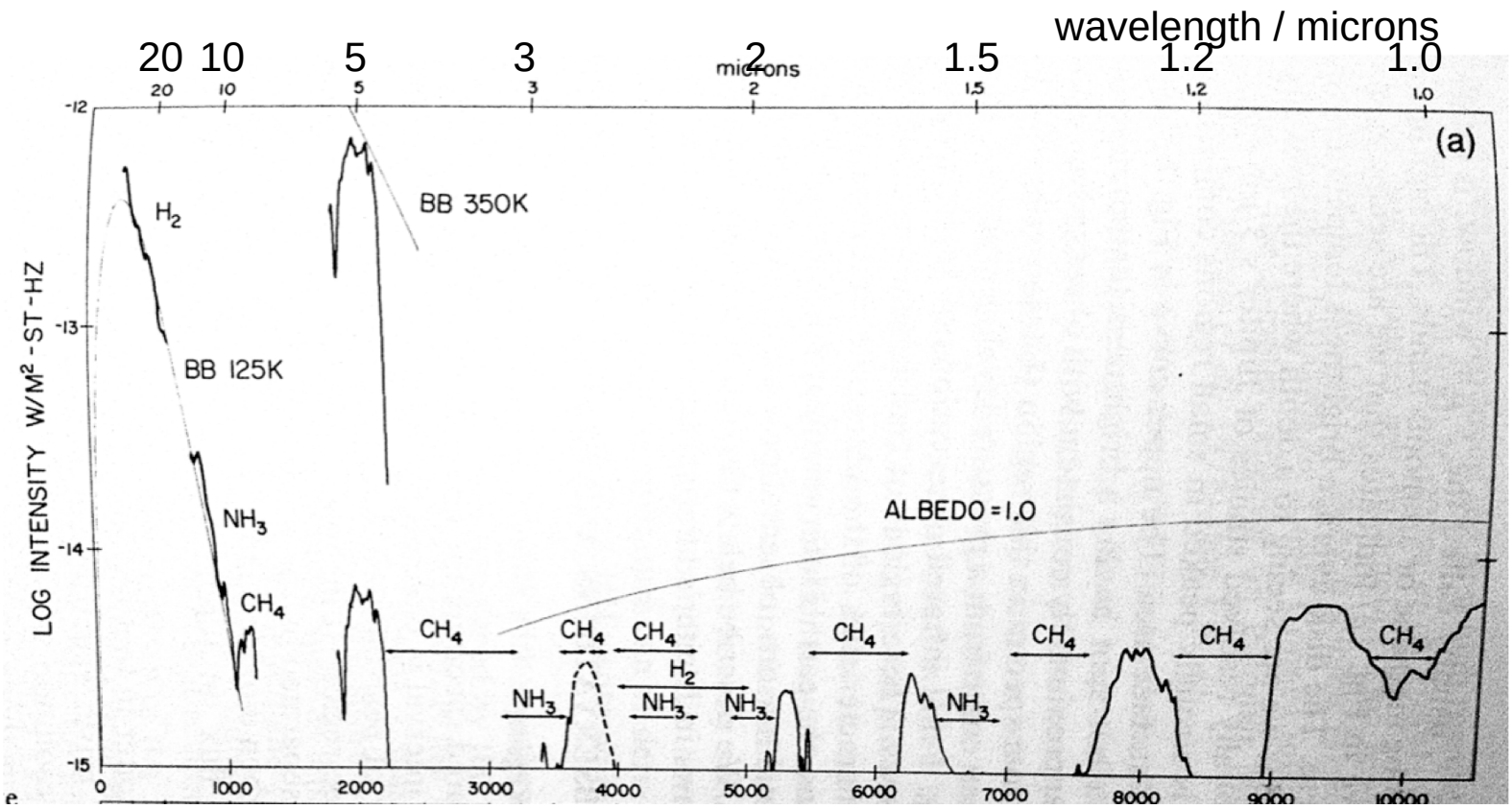

Energy balance indicates internal heat source

Gehrels, ed. 1976
Jupiter: studies of the interior, atmosphere, magnetosphere, and satellites

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Where we'd like to be with exoplanets

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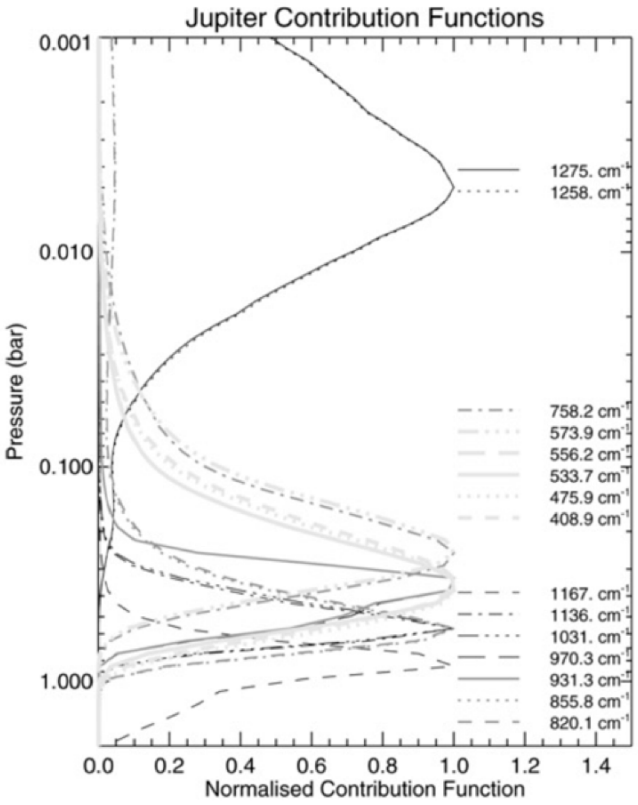

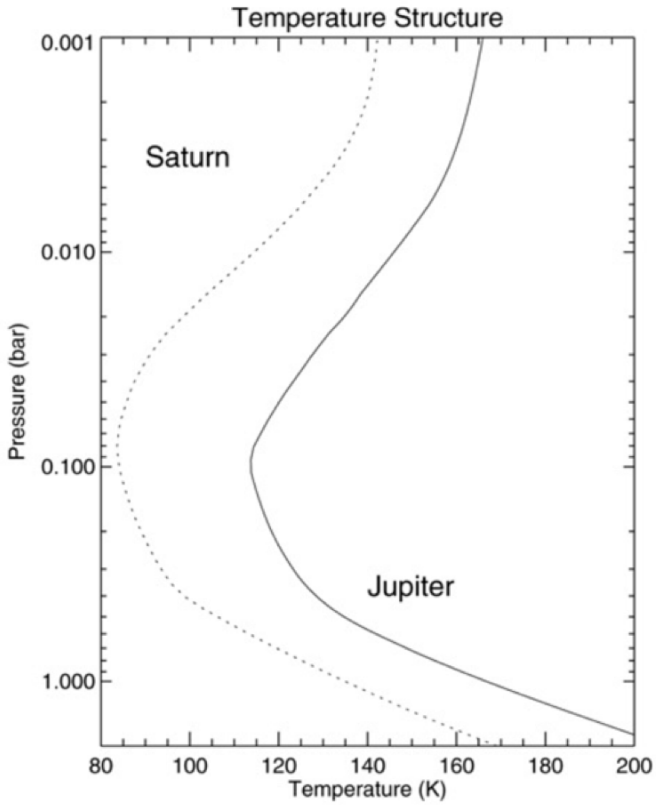

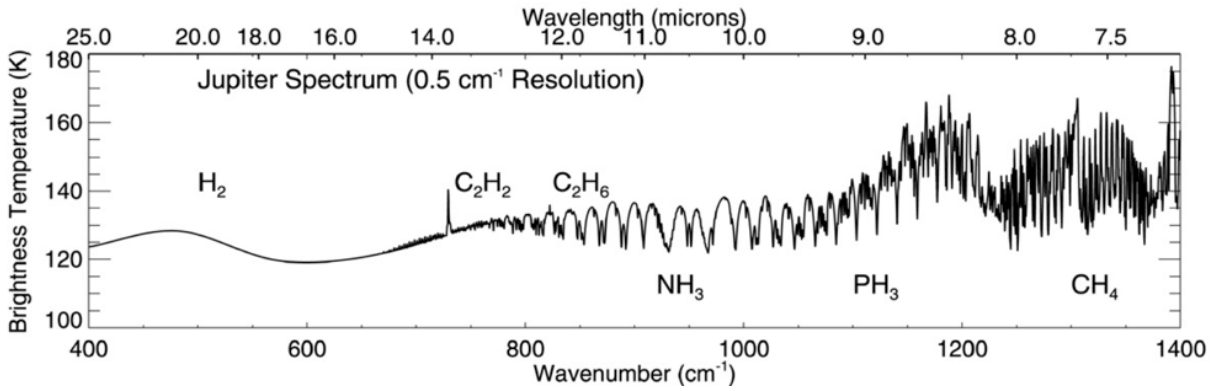

L.N. Fletcher et al. / Icarus 200 (2009) 154–175

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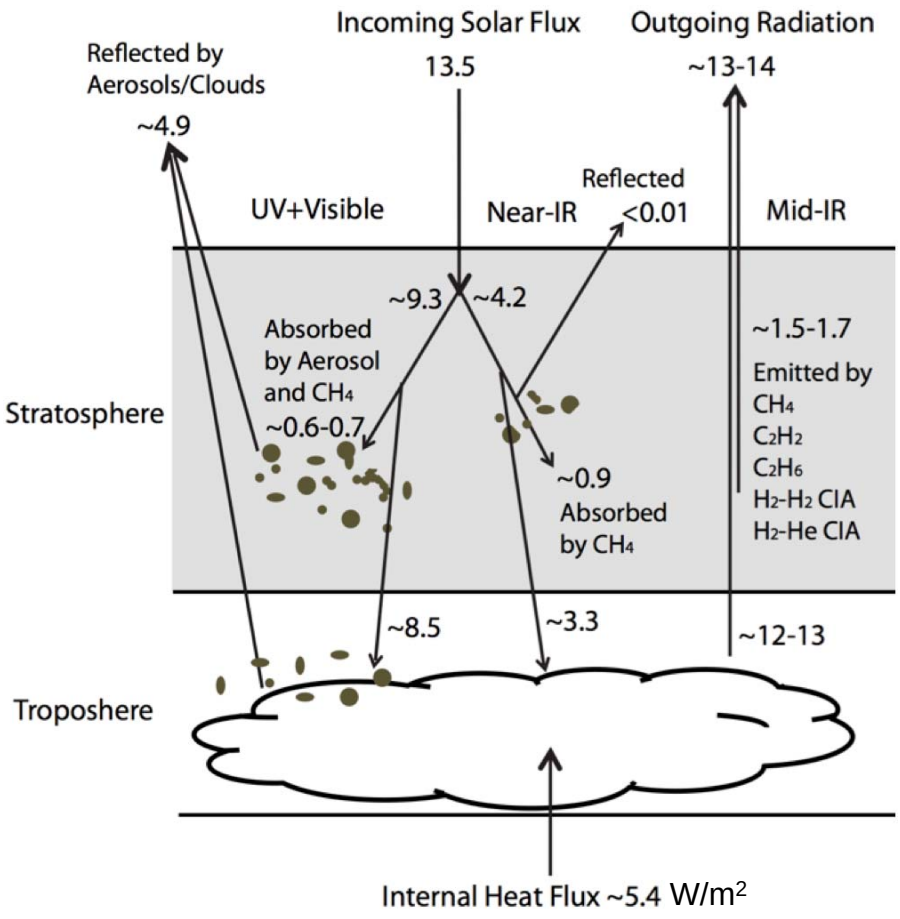
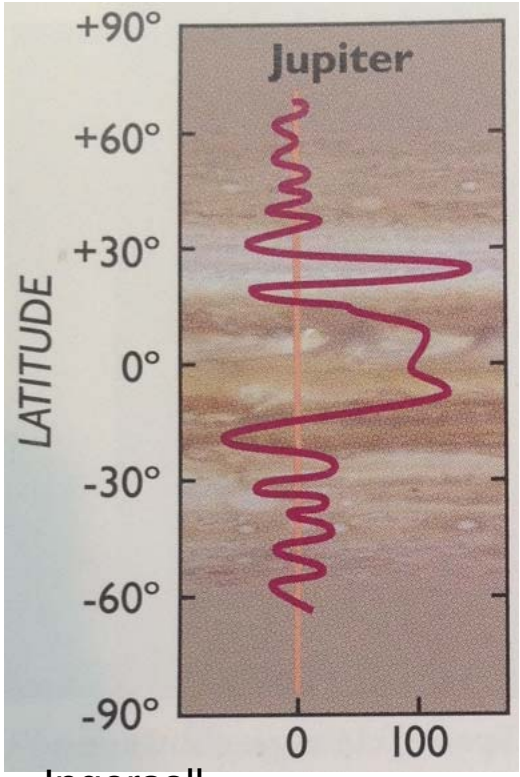


Zhang 2013

Energy balance
Energy transport
Winds, storms
Composition, clouds
Energetic processes



The New Solar System – Ingersoll

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Ammonia clouds on Jupiter & Saturn vs. strong methane absorption on Uranus & Neptune

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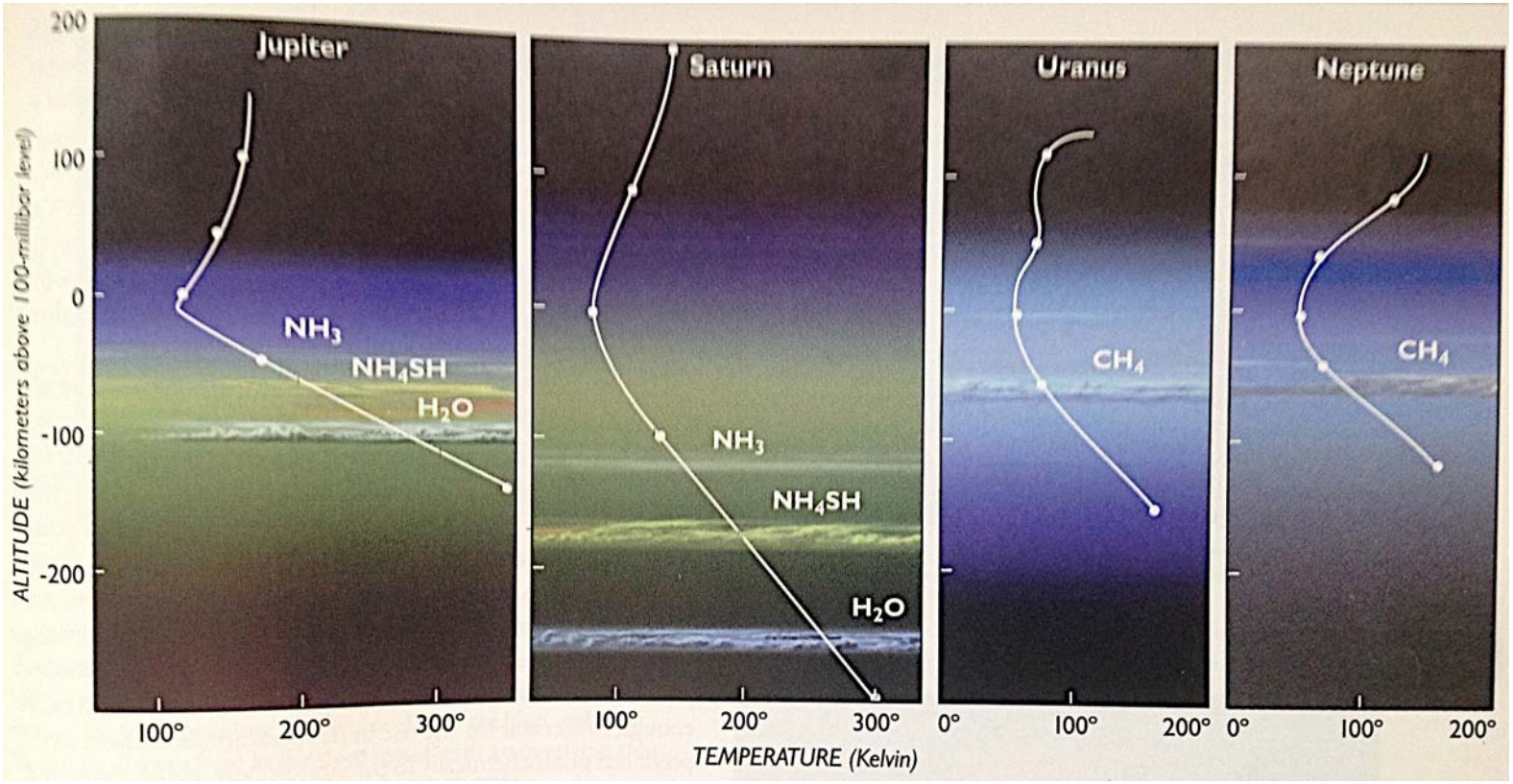

The New Solar System – Ingersoll 1999

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Four co-eval gas giant planets in the same system

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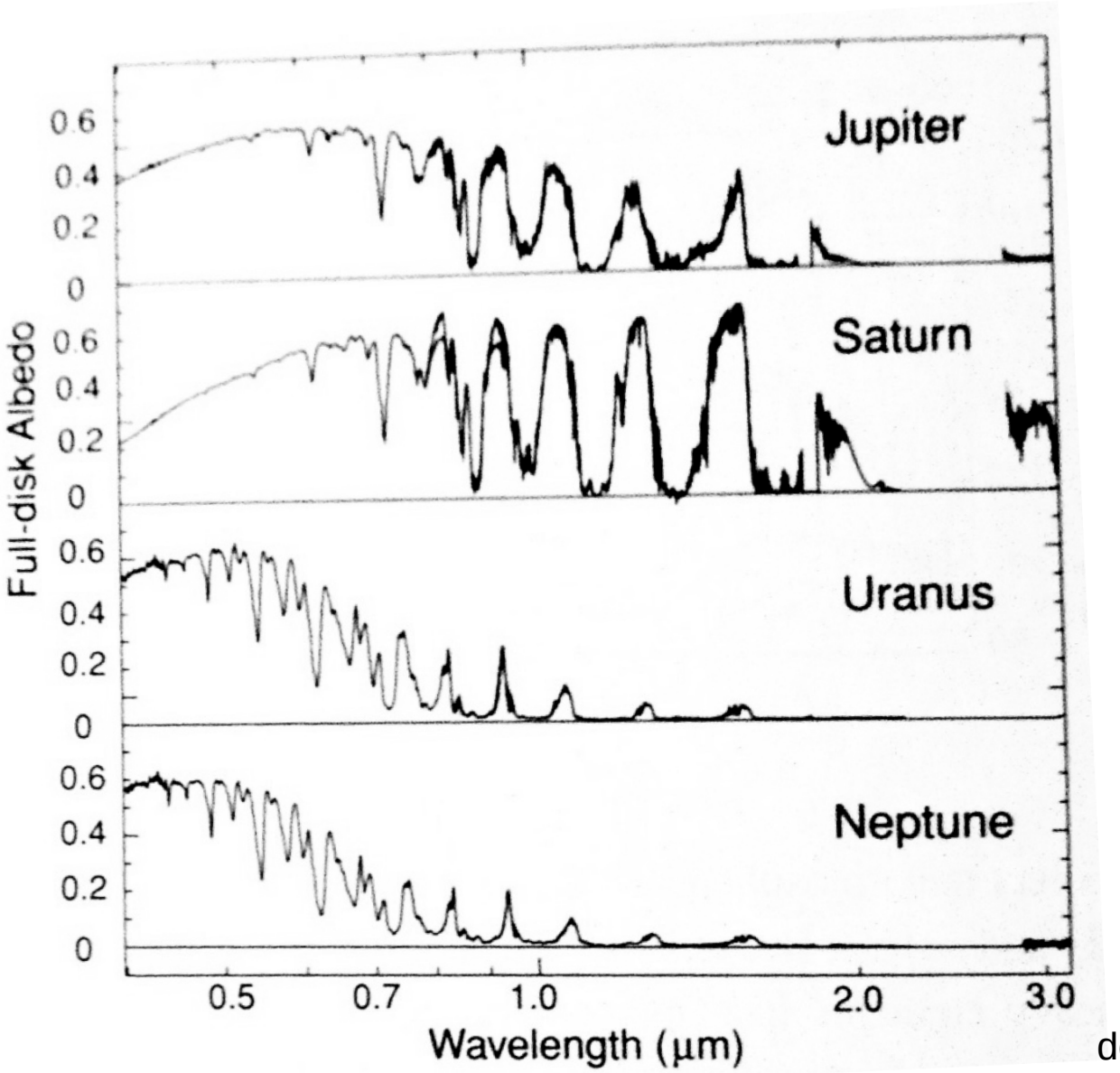

de Pater
Planetary Sciences

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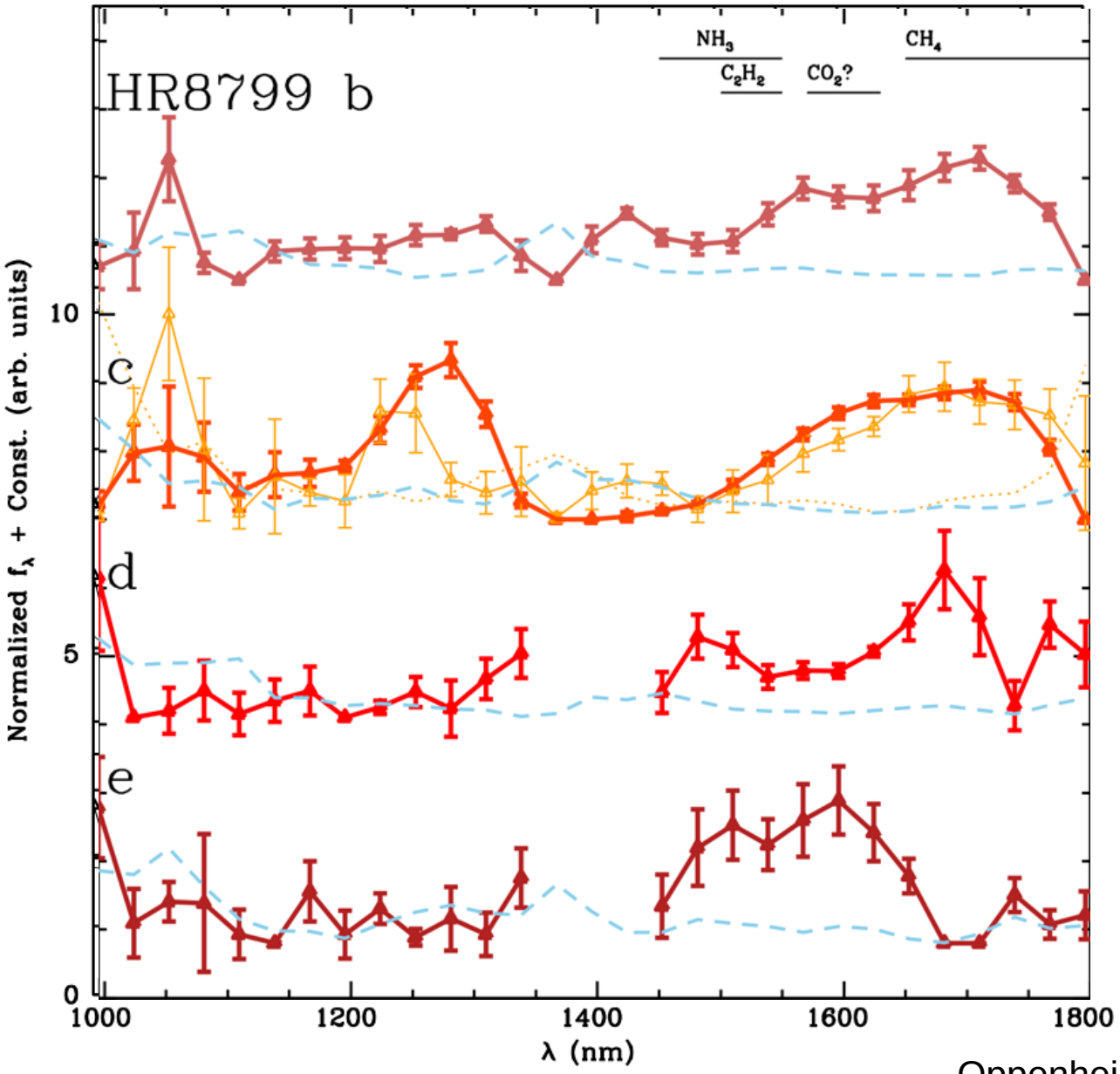

Oppenheimer et al 2013

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Equilibrium chemistry models underpredict the HR 8799 planets' 3.3um fluxes

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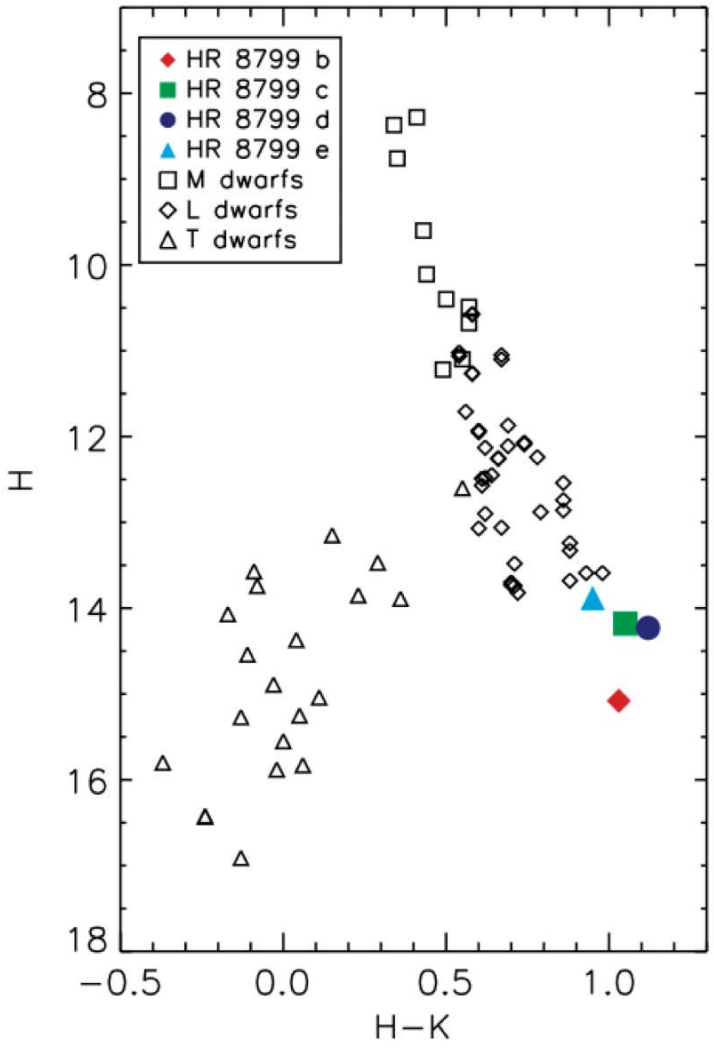

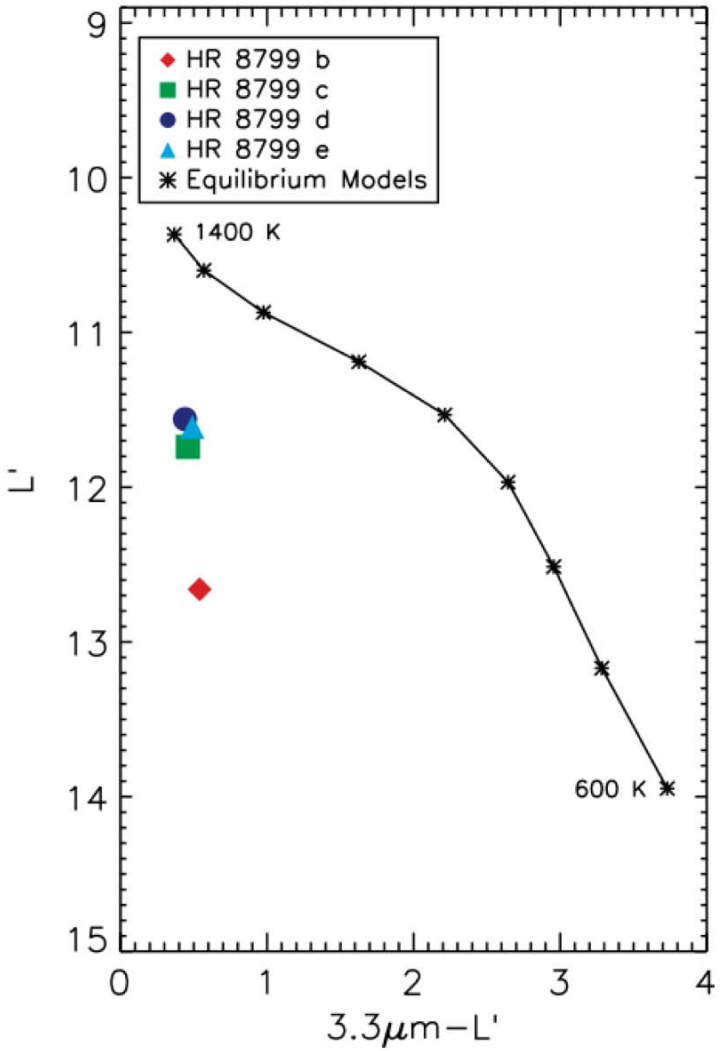

Skemer et al 2012

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HR 8799 b fit with inverse model

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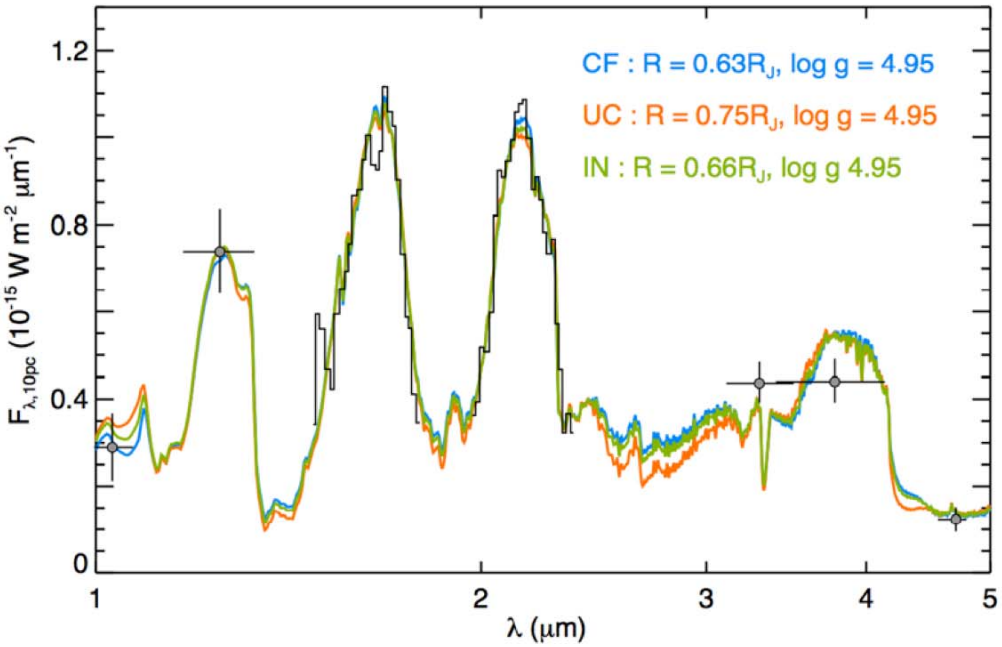
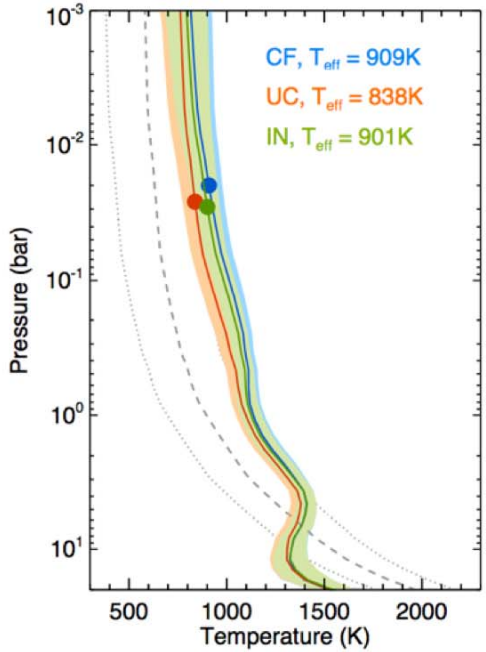
HR 8799 b





Cloud-free with high mean molecular weight OK, or intermediate clouds.
Heavy element enhanced, high C:O.
Radius too small in model.

CF = Cloud Free
UC = Uniformly Cloudy
IN = Intermediate

Lee et al 2013

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Clues about formation – Enrichment of C:O ratio in HR 8799 c

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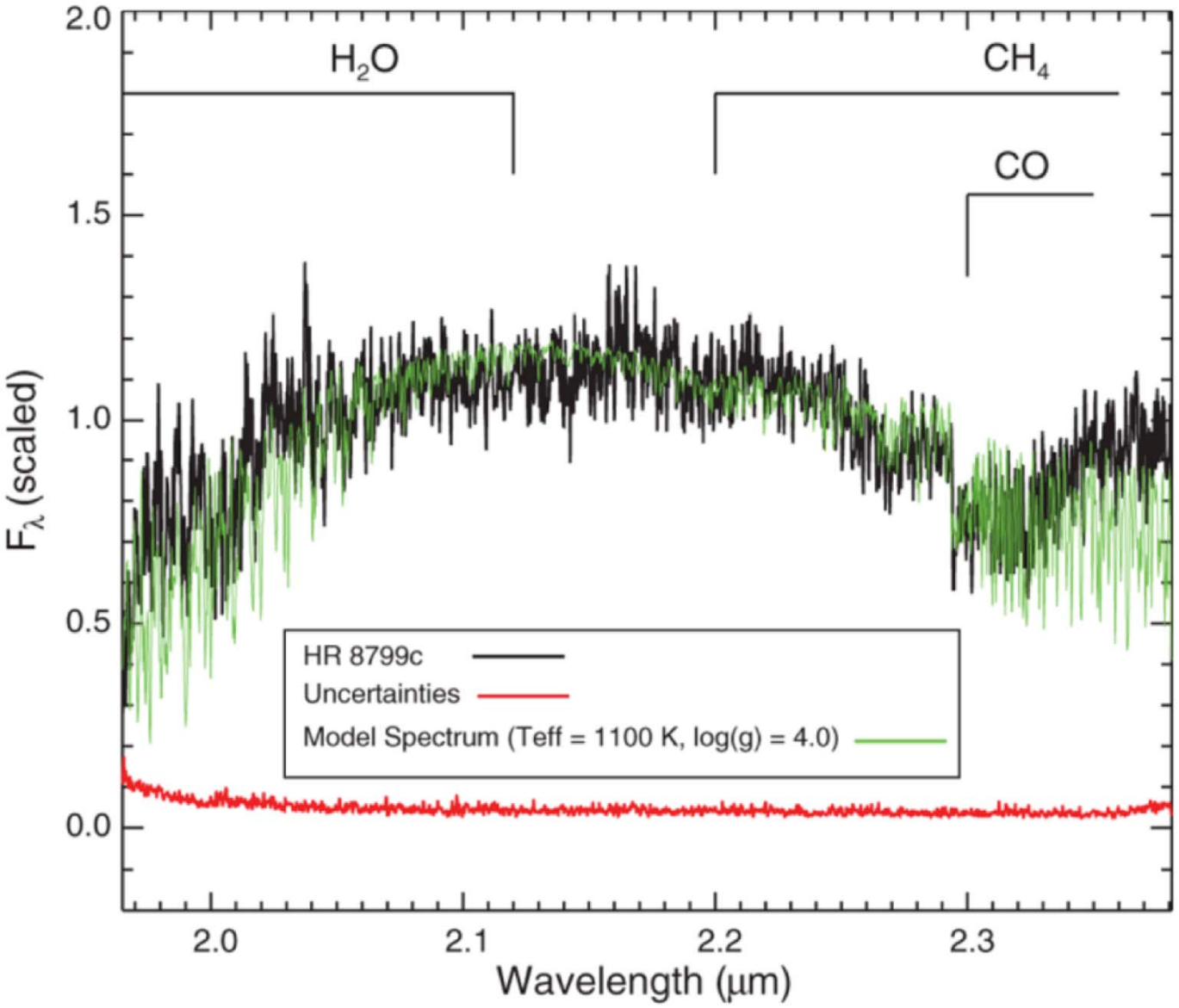

Konopacky et al 2013

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The effect of clouds and non-equilibrium chemistry – 2MASS 1207 b

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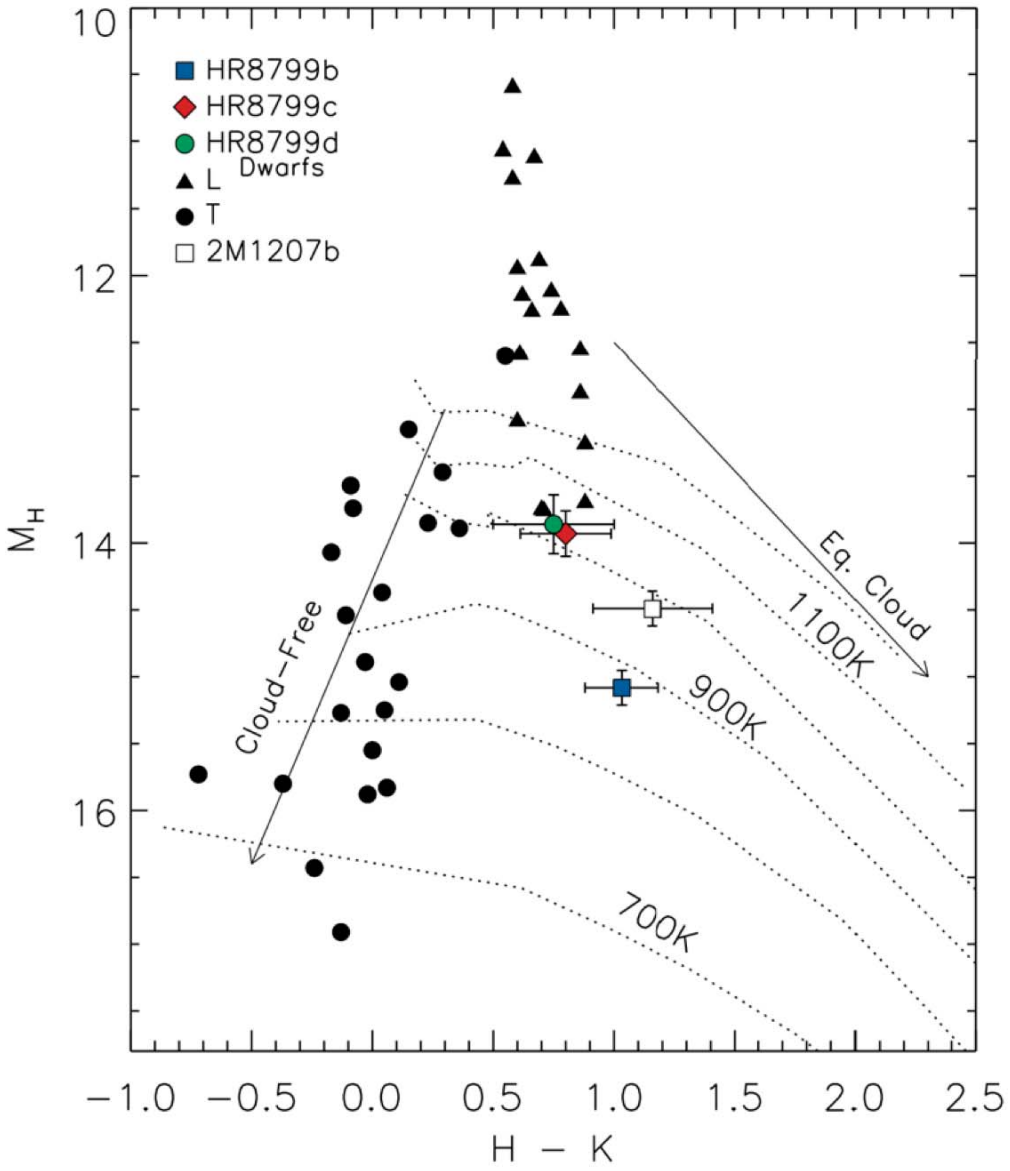

Barman et al 2011

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Comparing HR 8799 b, c, and 2M 1207 b

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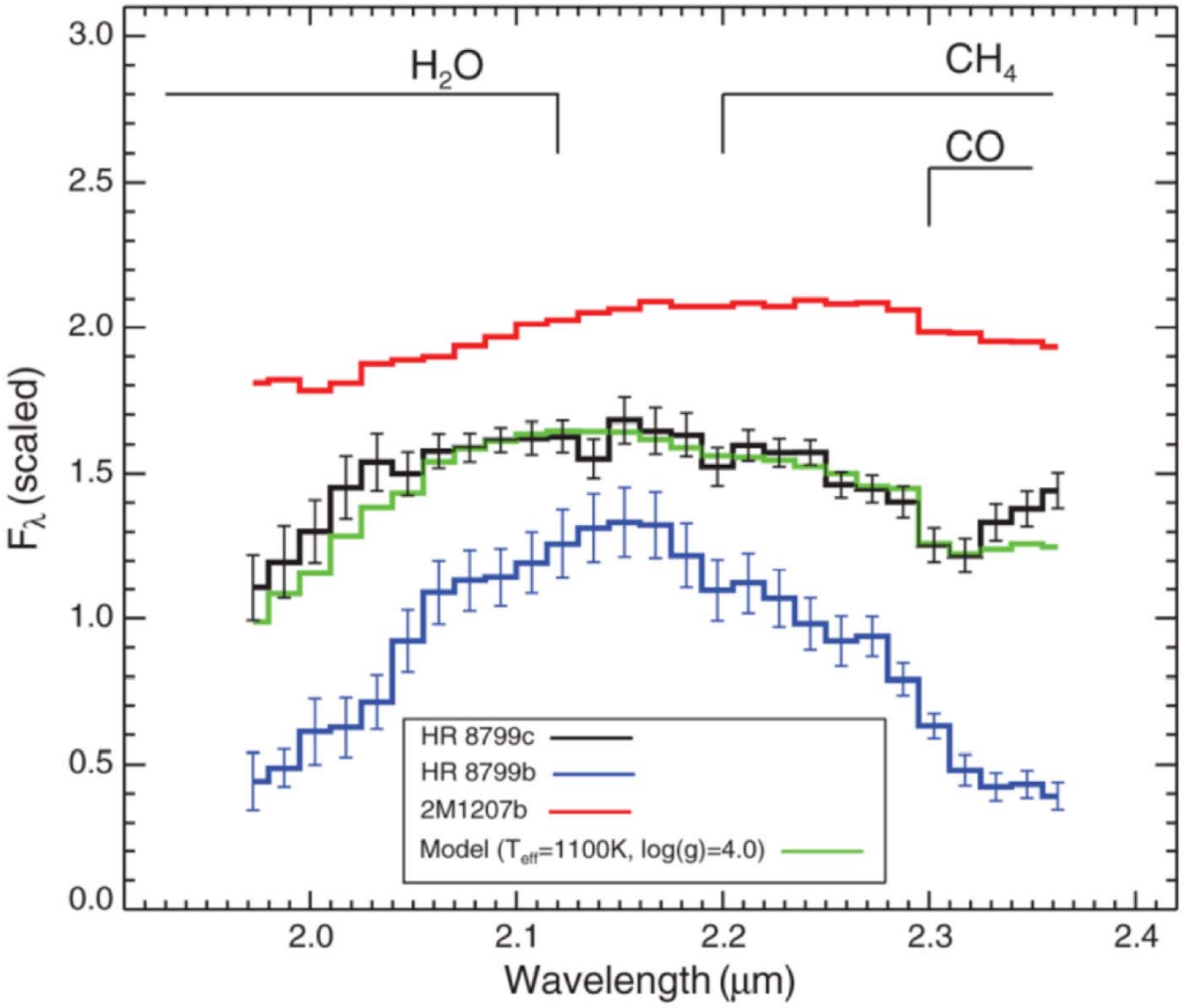

Konopacky et al 2013

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Searching for planetary systems like our own

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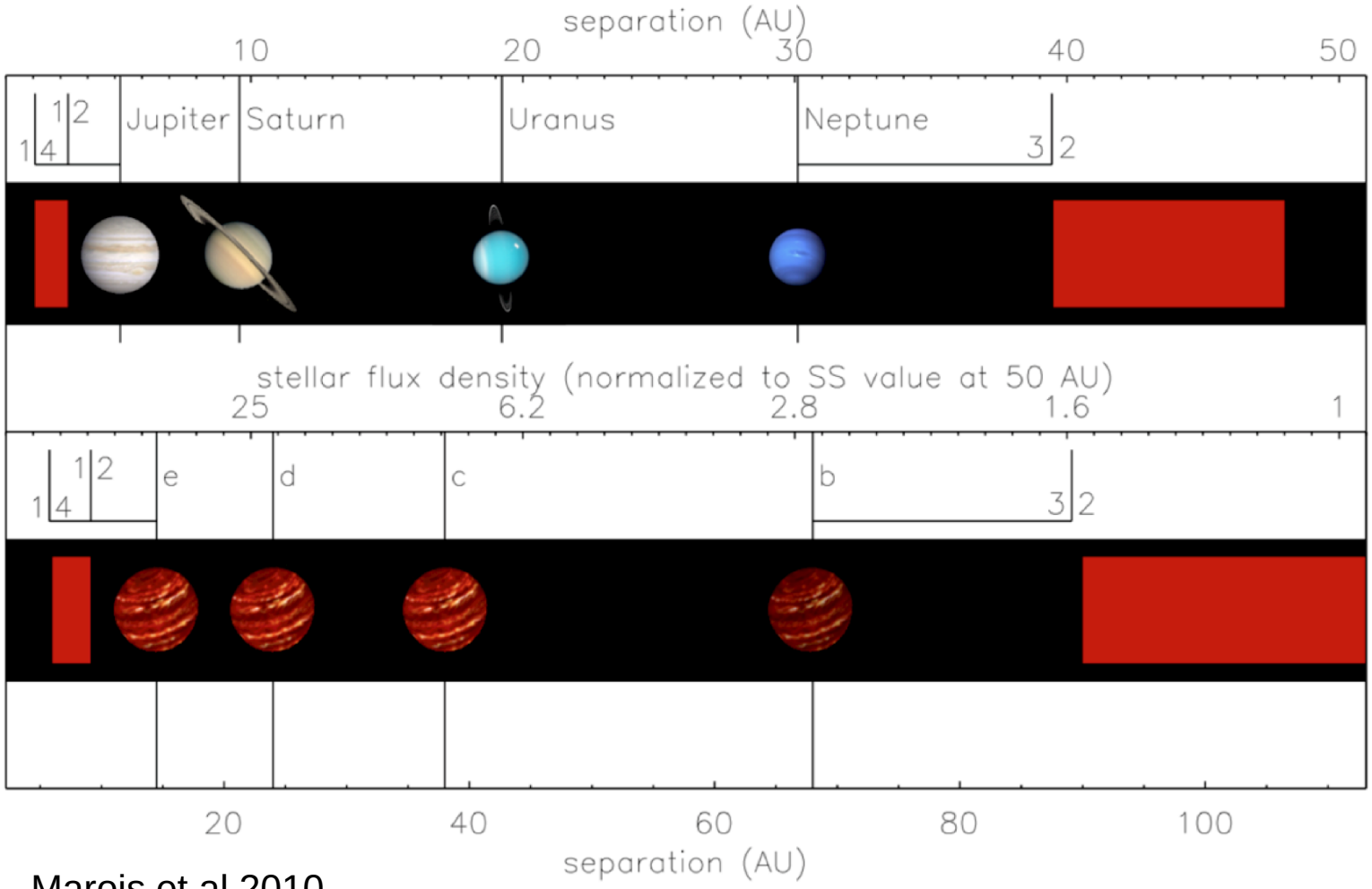

Marois et al 2010

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Are dust zones signposts of multiple planets in debris disks?

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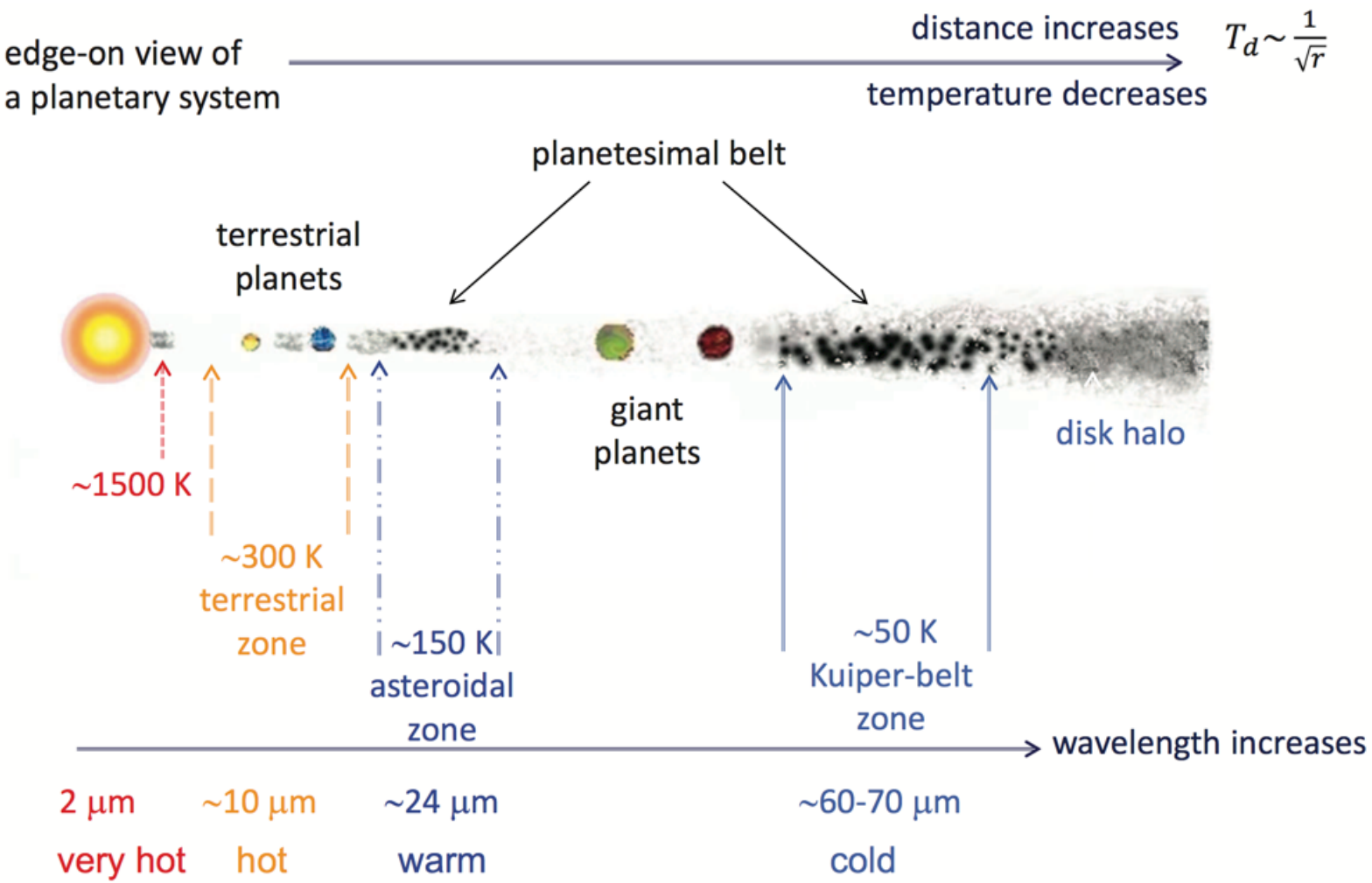

Su et al 2013

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Fomalhaut b is not the object sculpting the disk

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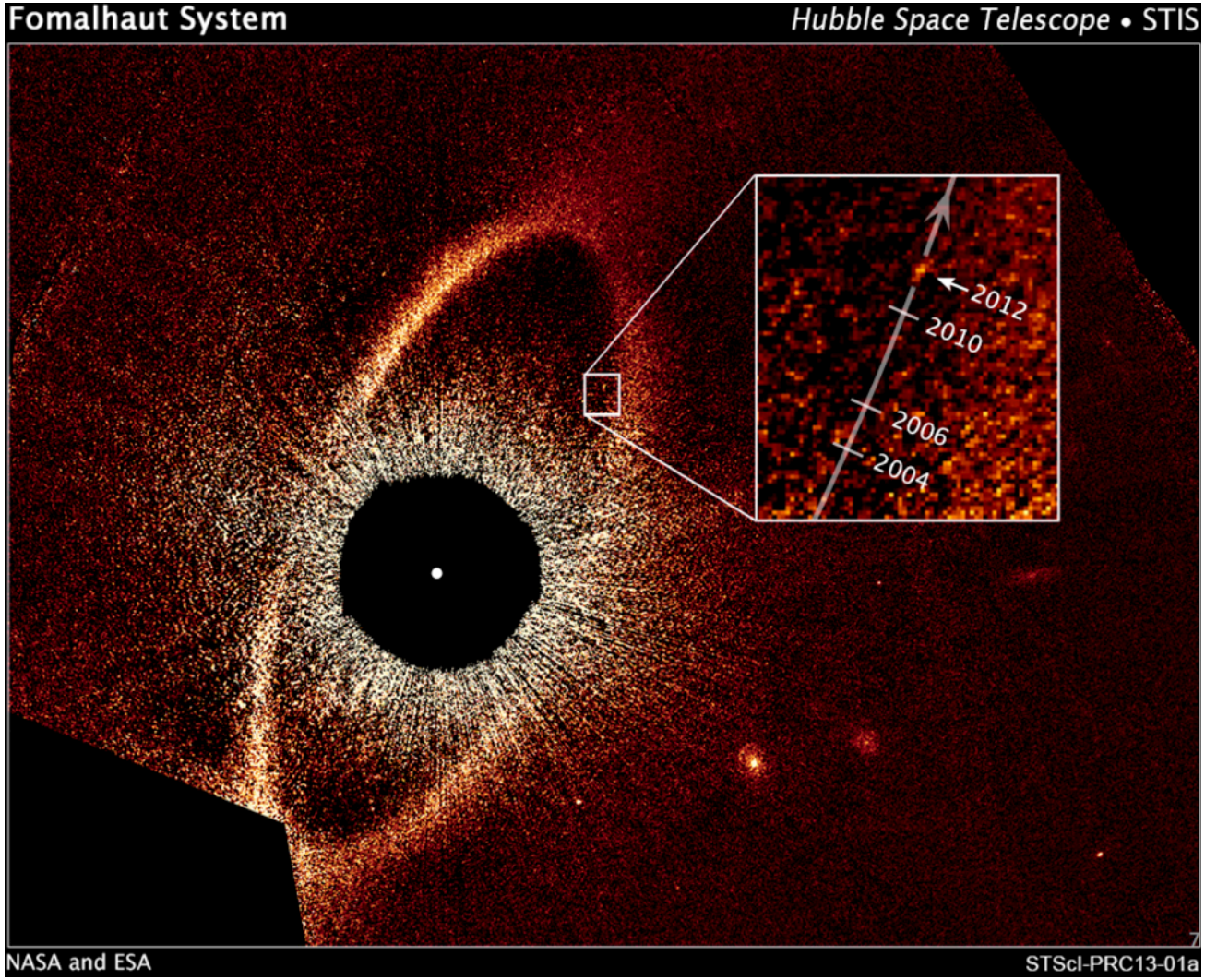

(if any; see Lyra et al 2013)

Kalas et al 2012

Beta Pictoris – One of the first stars known to host an analagous system to ours –> Comets

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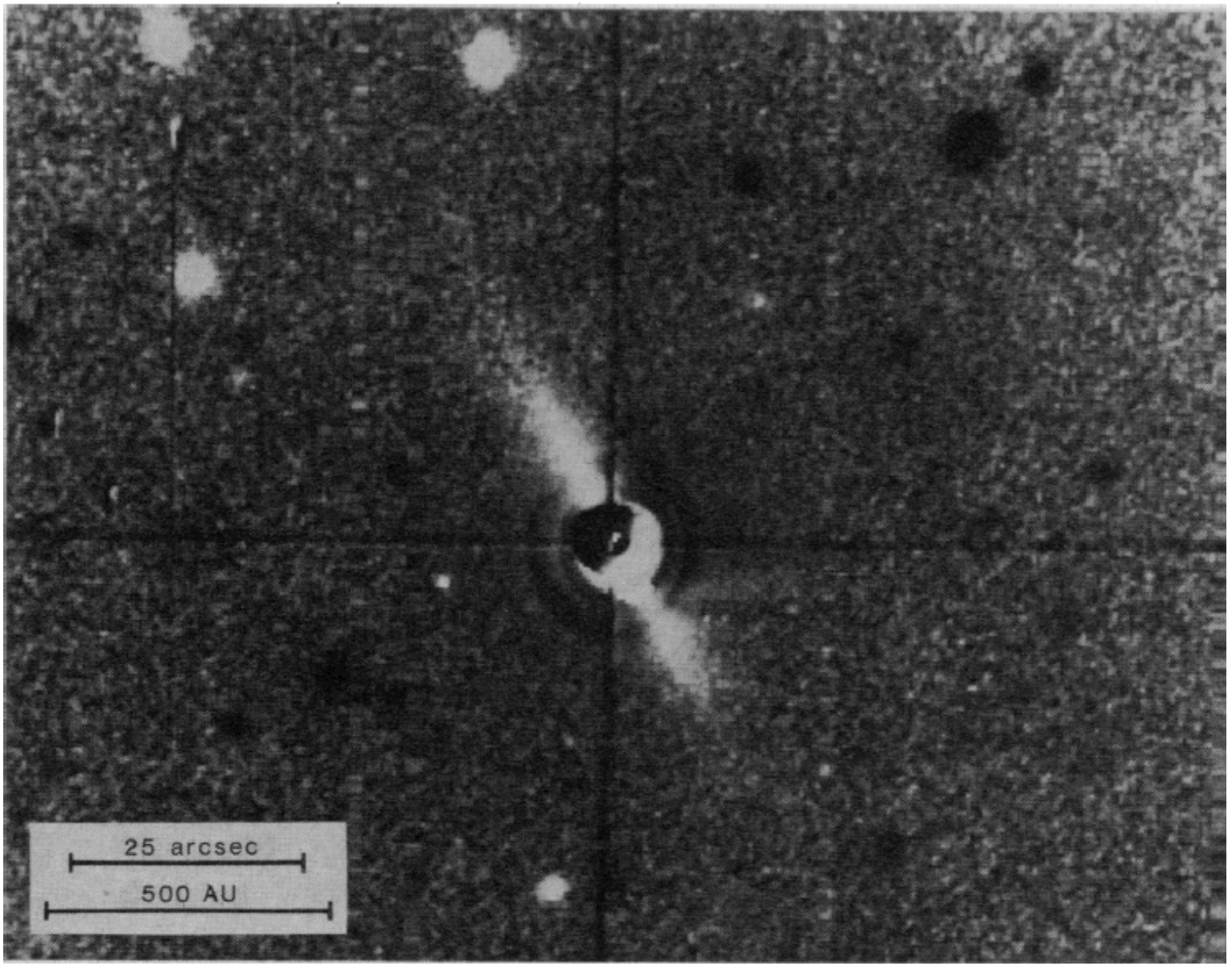

Smith & Terrile 1984

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The existence of a planet around Beta Pictoris was long suspected, due to the inner disk warp

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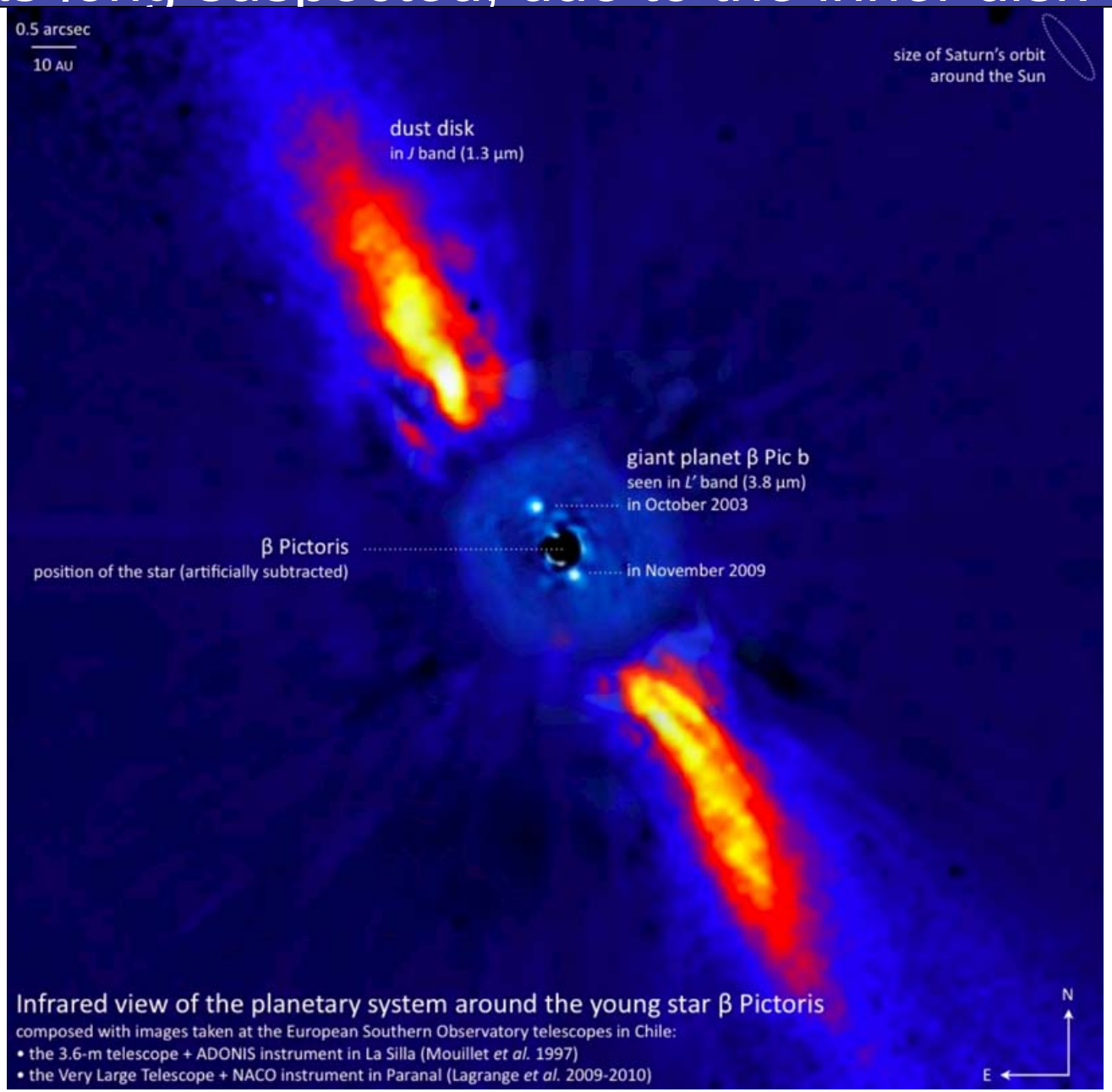

Lagrange et al 2009

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Magellan adaptive optics imaging of Beta Pic b

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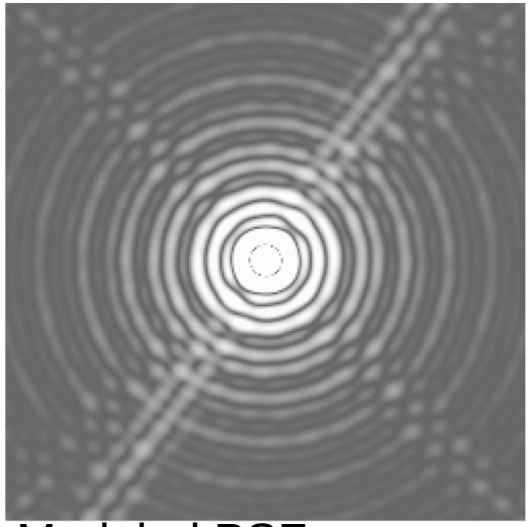
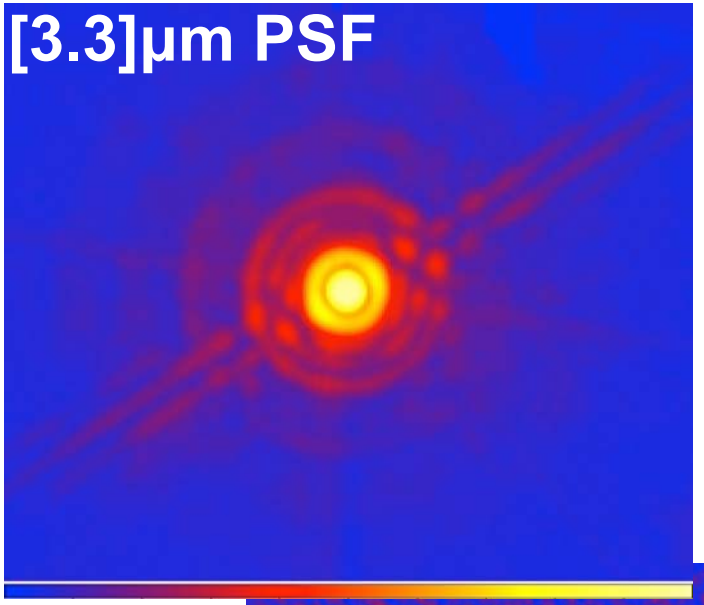
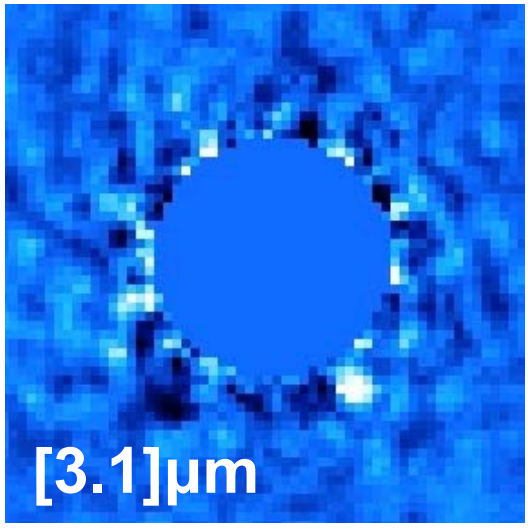
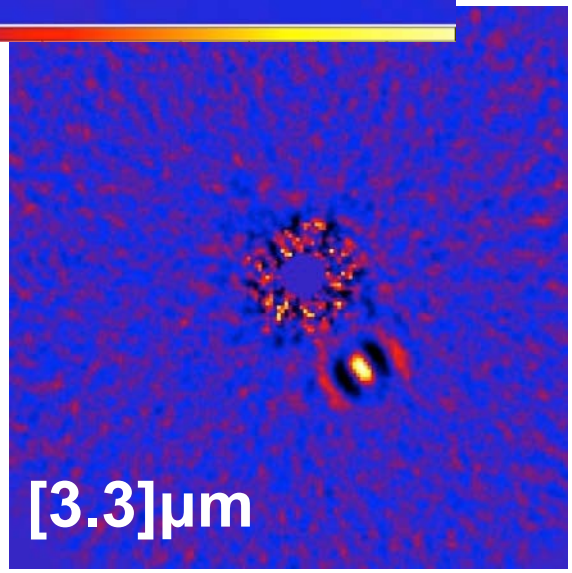


Modeled PSF







Morzinski et al 2013 in prep

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Cloudy atmosphere, Teff 1700±100 K

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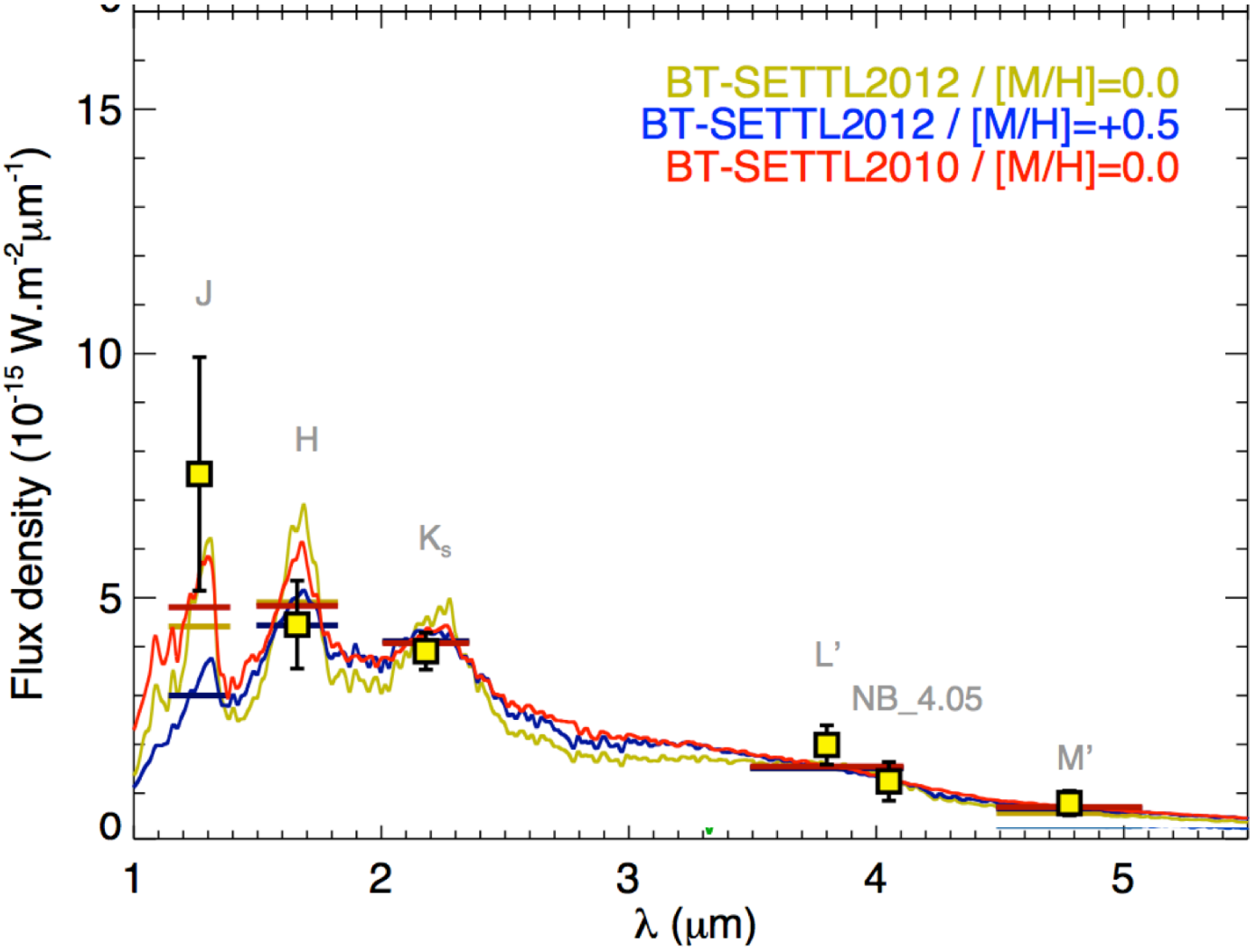

Bonnefoy et al 2013

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Are wide low-mass (<30 MJup) companions to B and A-type stars over-represented?

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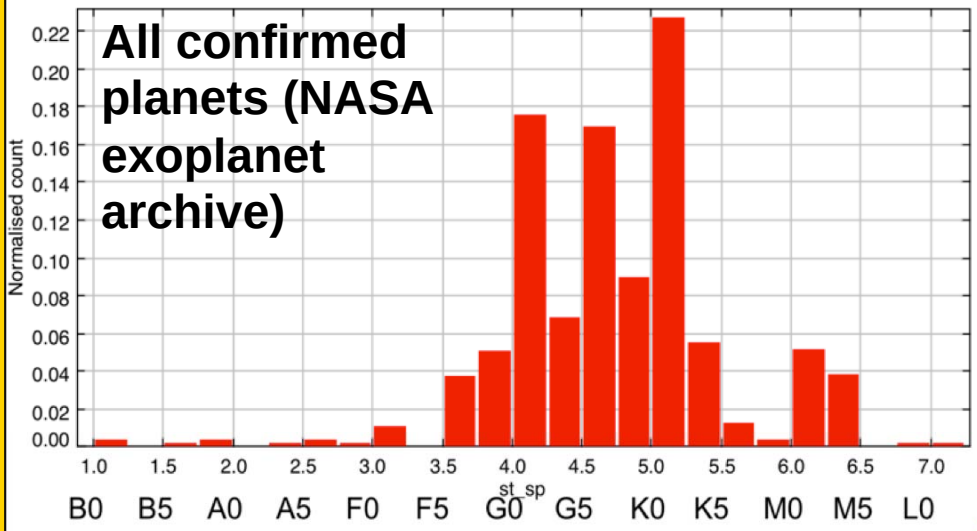

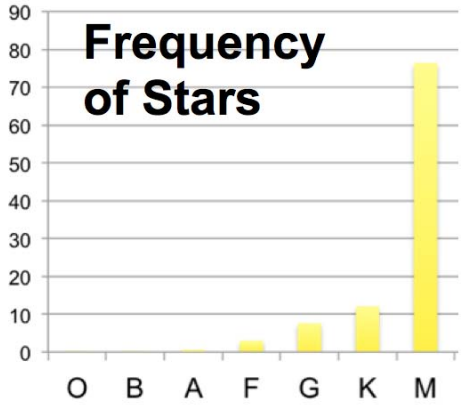

2M1207
2M2140+16
2M2206-20
2M0122-2439
2M044144
Ross 458
FU Tau
DH Tau
GSC 06214-00210
Oph 11
USco CTIO 108
USco 1602-1800
CHXR 73

GQ Lup
LkCa 15
AB Pic
SR 12
1RXS 1609
USco 1610-1913
USco 1602-2401
CT Cha

Kappa And
HD 100546
Hip 77900
Hip 78530

HR 8799
Fomalhaut
Beta Pic
HD 95086

GJ 504
HN Peg
HD 203030

2M 0746+20

CFBDS 1458

WD 0806-661

CFBDS 1R2149
Sigma Ori objects

O B A F G K M L T WD ⊘

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No systems imaged with low mass ratio <50 AU

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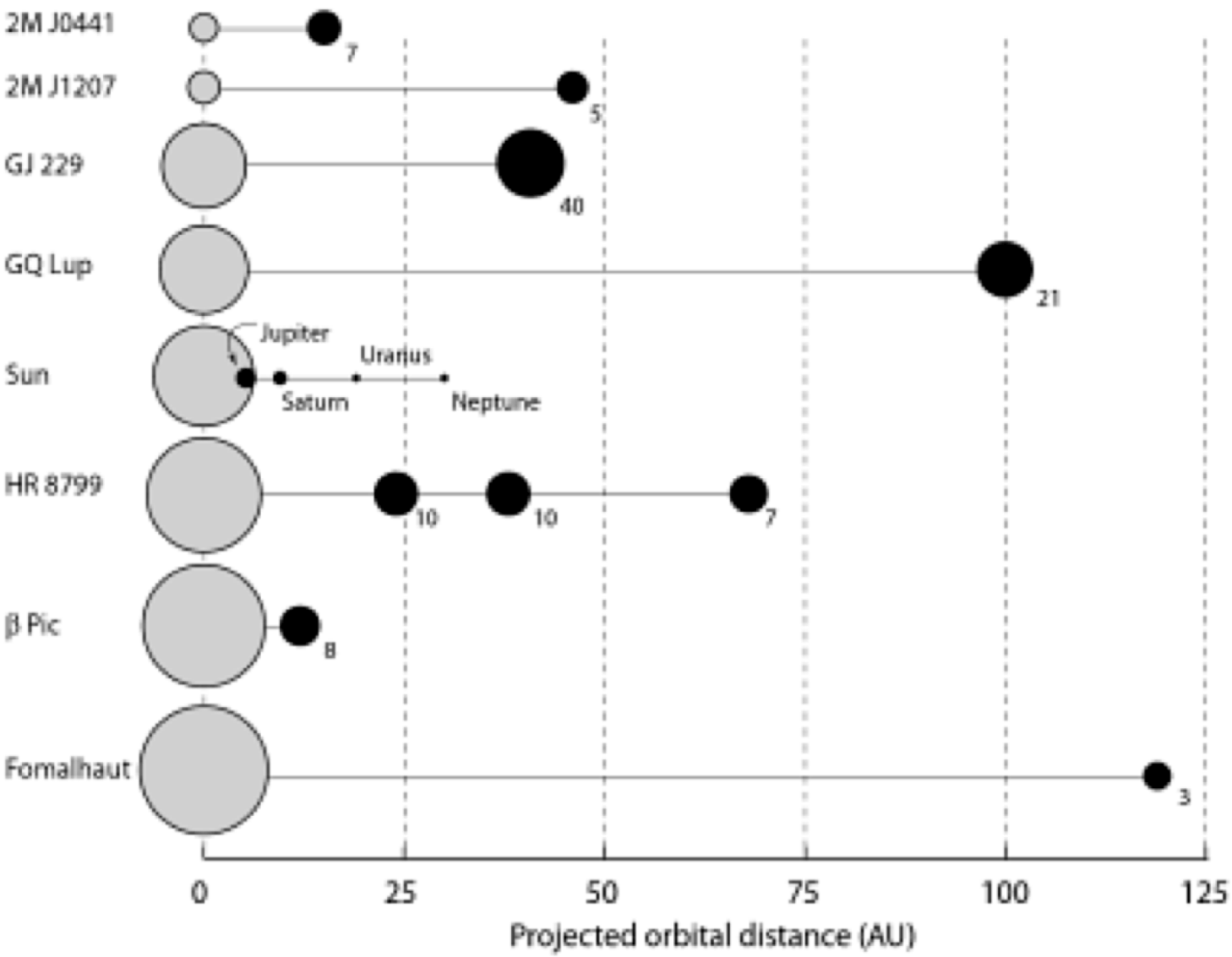

Perryman 2011 Exoplanet handbook

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NICI results for companion search around B and A stars find that HR 8799 is a rare system

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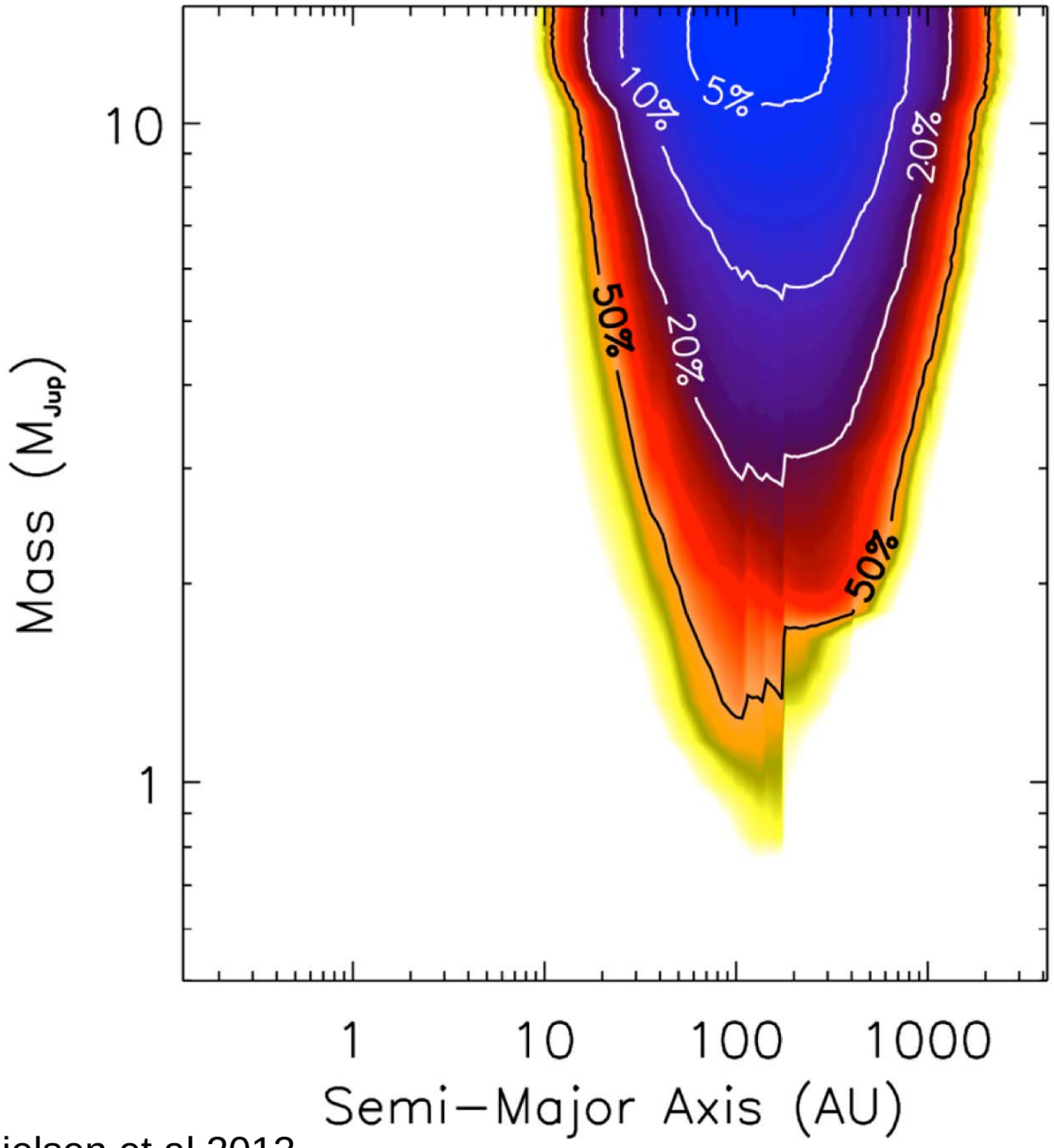

Nielsen et al 2013

<20% of B & A stars have planets >4 MJup beyond 60 AU.

<10% of B & A stars have planets >10 MJup beyond 40 AU.

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IDPS results for companion search around A stars find similar results

Direct Imaging

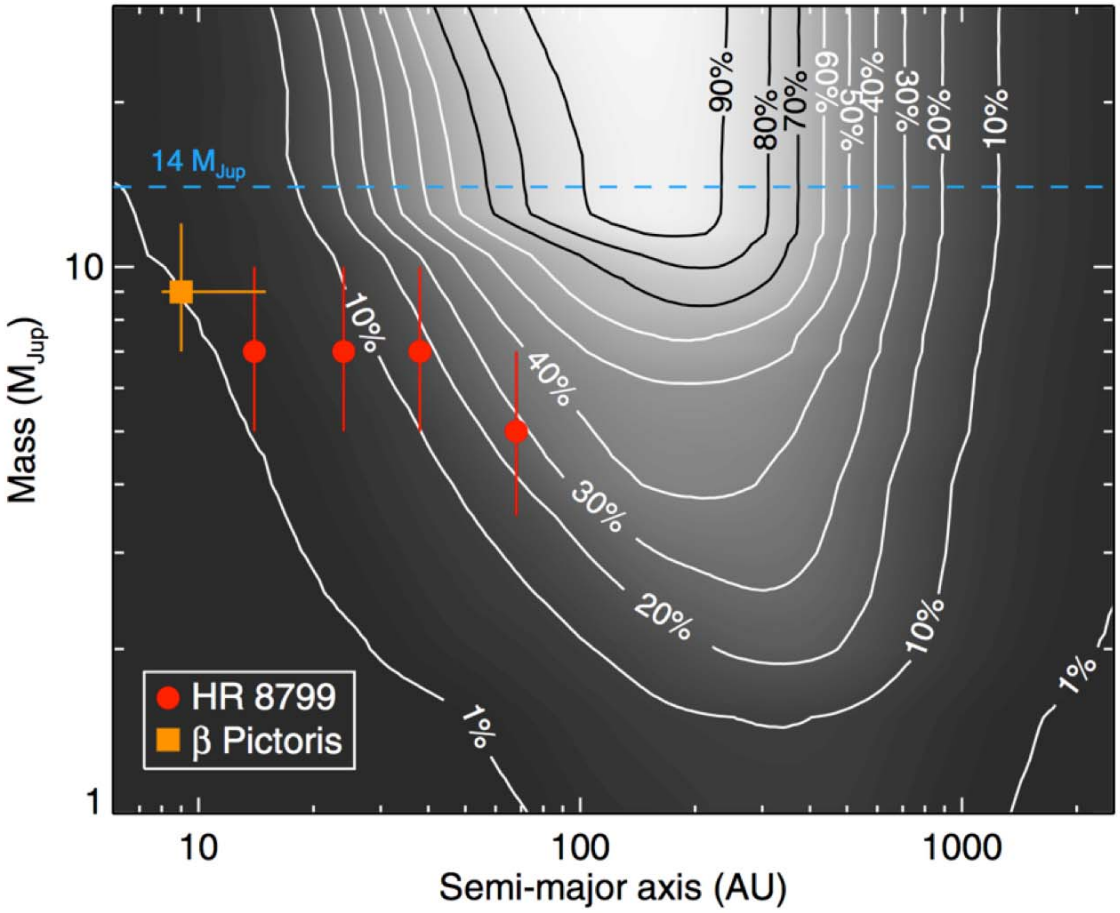
Where are we going?

Where are we now?

Why is it hard?

What's next?

K. Morzinski



<20% of A stars have planets >3 MJup beyond 5 AU.

<10% of A stars have BDs >15 MJup beyond 5 AU.

Vigan et al 2012

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Disk mass as a function of stellar mass

Direct Imaging

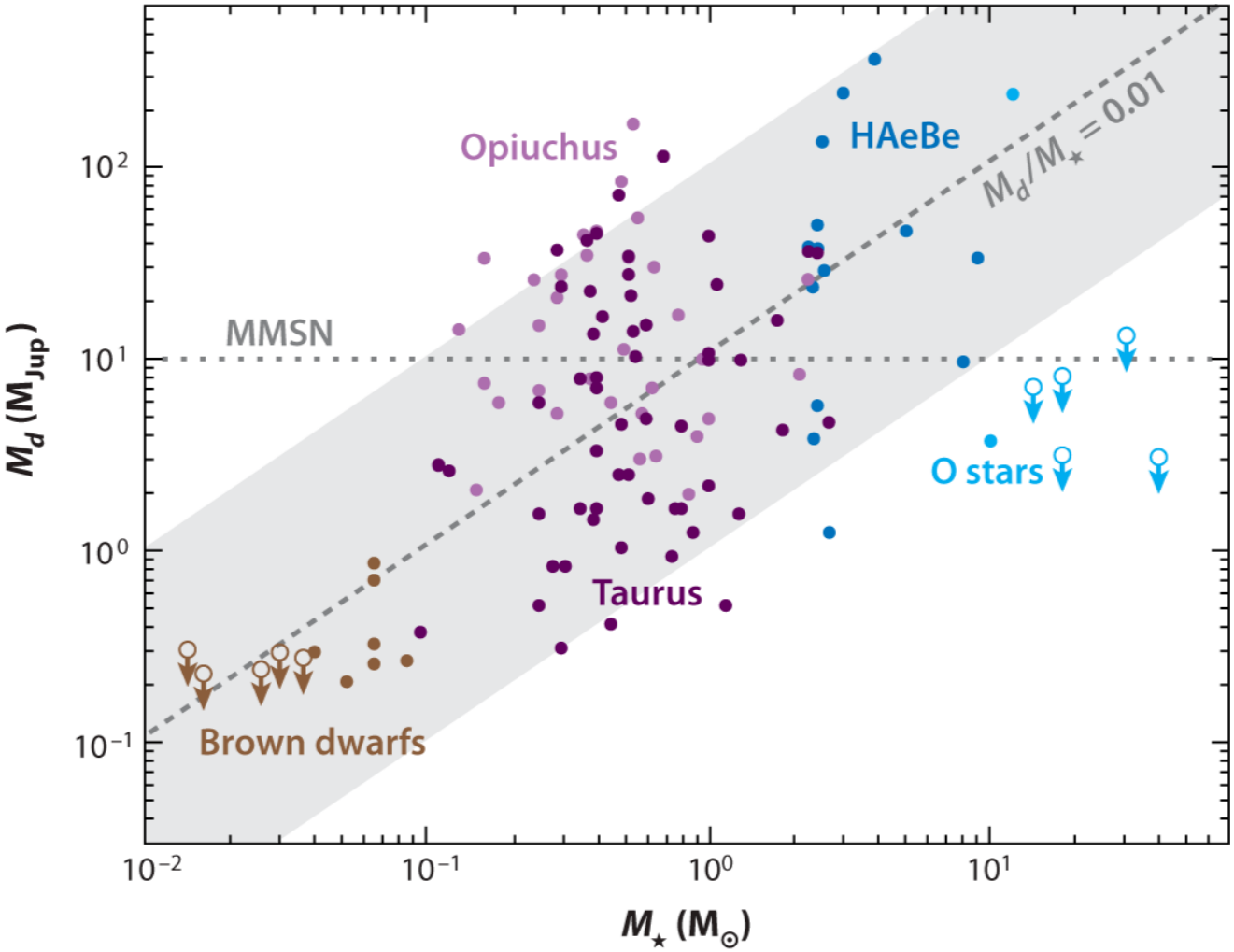
Where are we going?

Where are we now?

Why is it hard?

What's next?

K. Morzinski



Williams JP, Cieza LA. 2011.
Annu. Rev. Astron. Astrophys. 49:67–117

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Survey results – Stars with debris disks

Direct Imaging

Where are we going?

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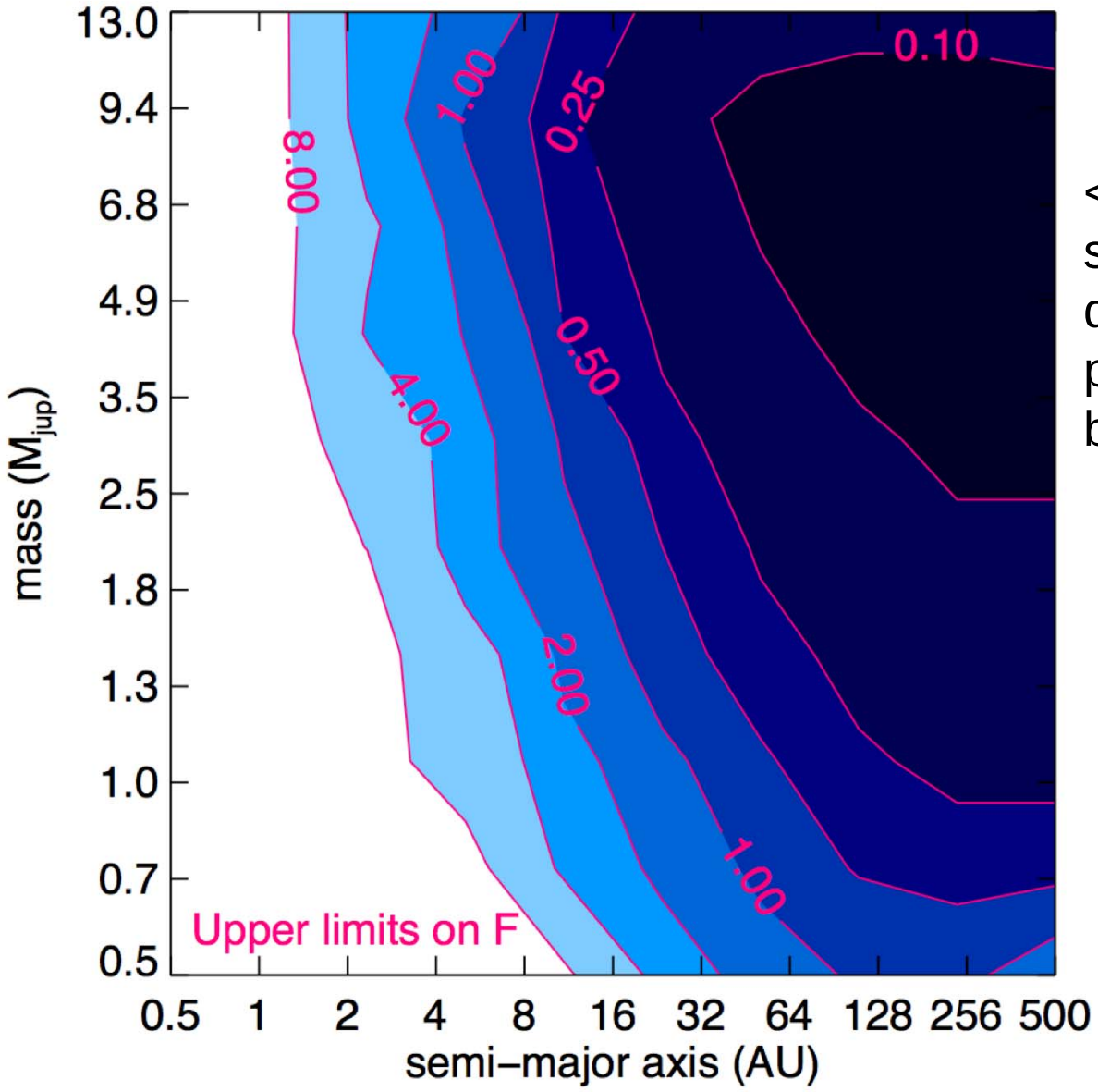
Why is it hard?

What's next?

K. Morzinski



<13% of 57 stars with debris disks have planets >5 MJup beyond 80 AU

Wahhaj et al 2013

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There is a lot of parameter space yet to be observed

Direct Imaging

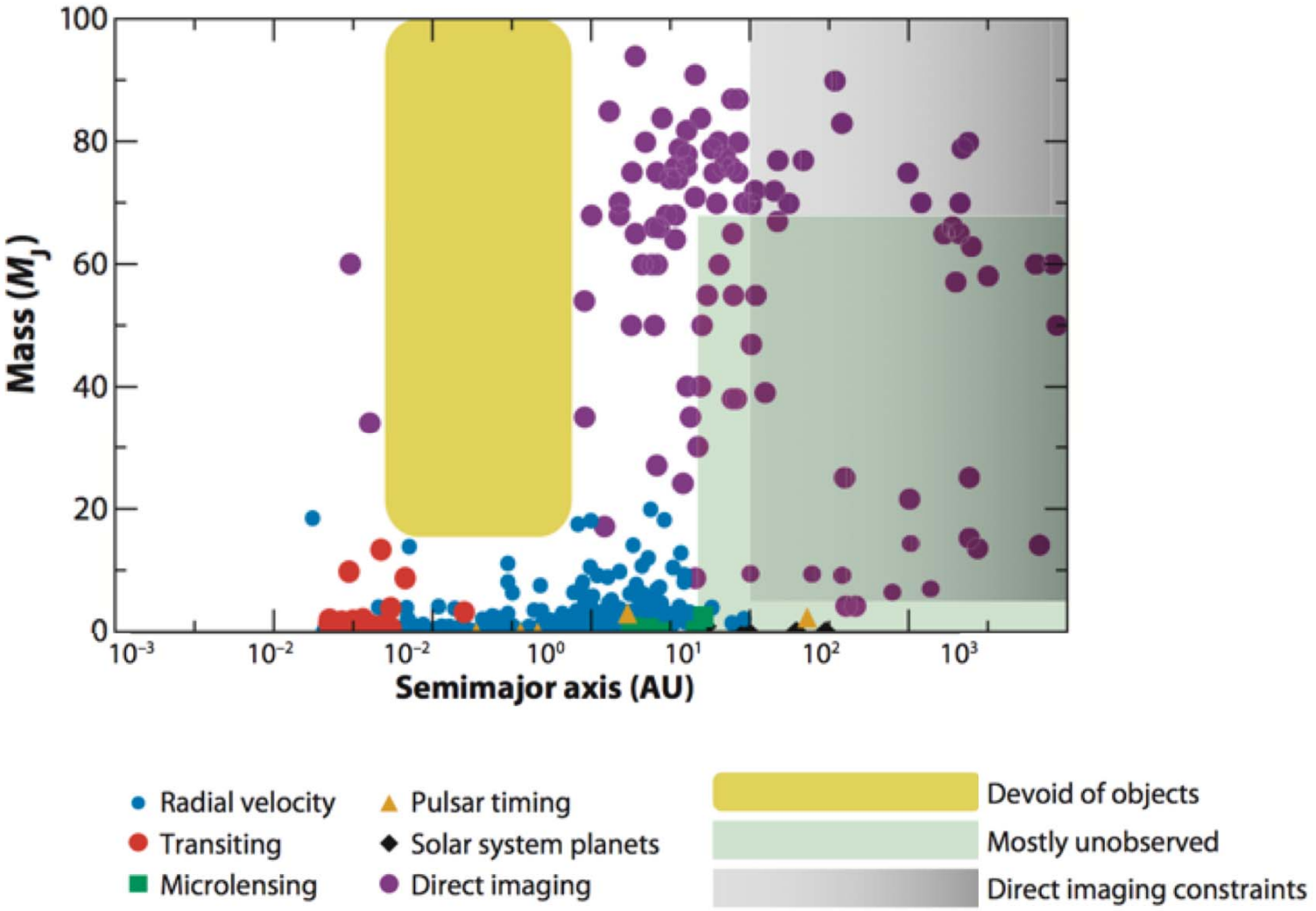
Where are we going?

Where are we now?

Why is it hard?

What's next?

K. Morzinski



Oppenheimer & Hinkley 2009 ARA&A

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L-band contrast curves vs search space

Direct Imaging

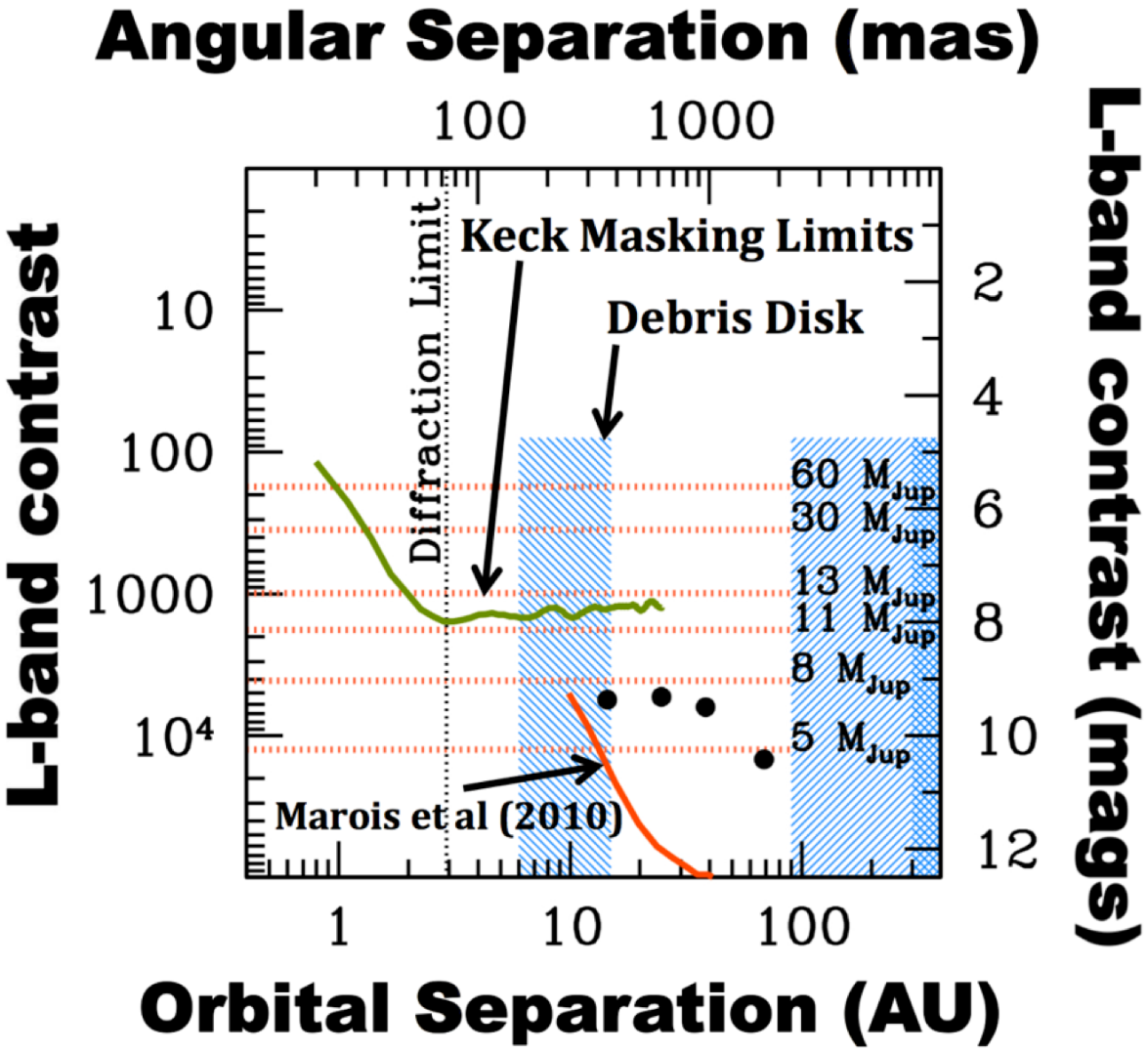
Where are we going?

Where are we now?

Why is it hard?

What's next?

K. Morzinski



Hinkley 2011

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H-band contrast vs. guide star magnitude, GPI

Direct Imaging

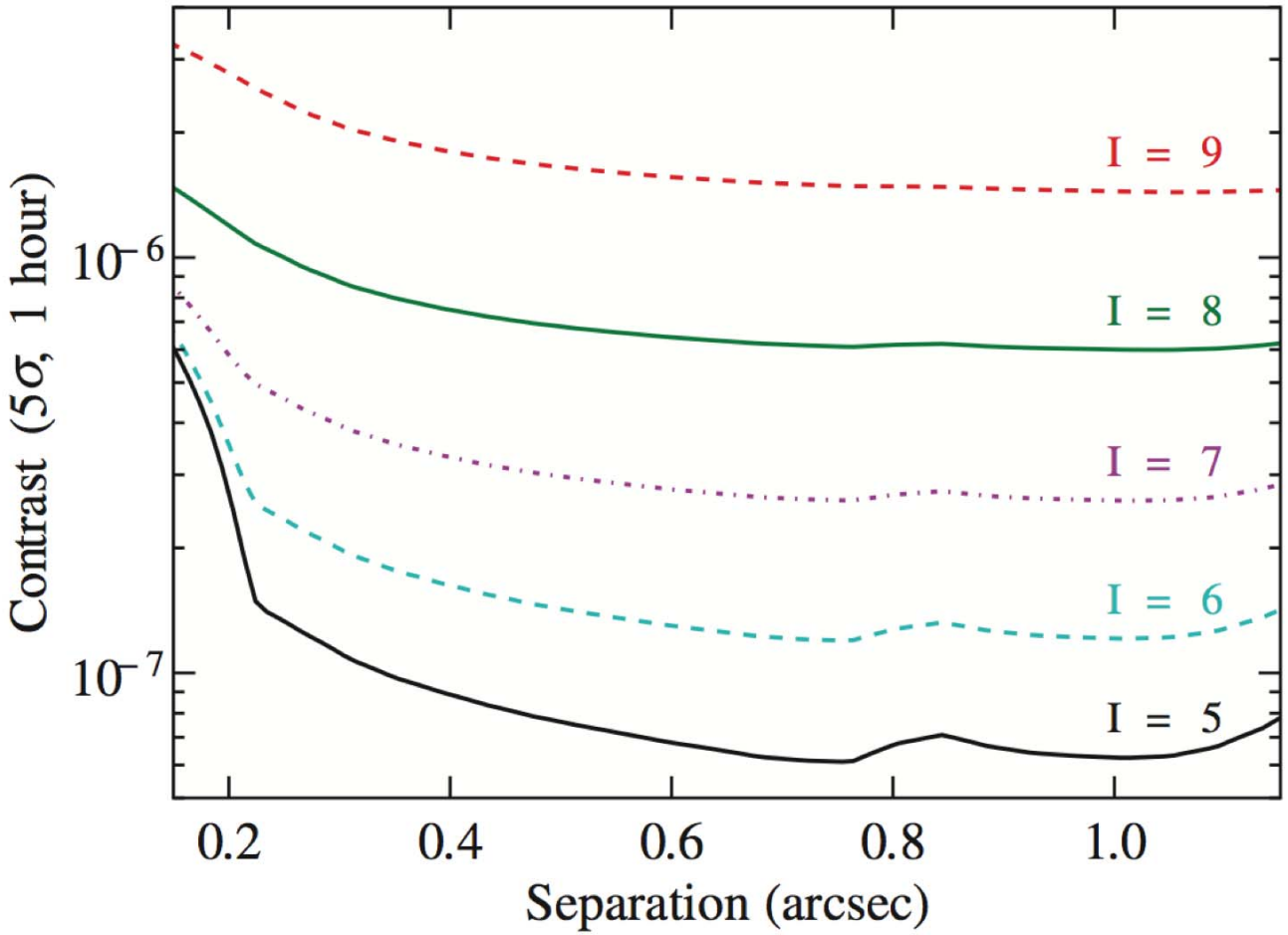
Where are we going?

Where are we now?

Why is it hard?

What's next?

K. Morzinski



McBride et al 2011

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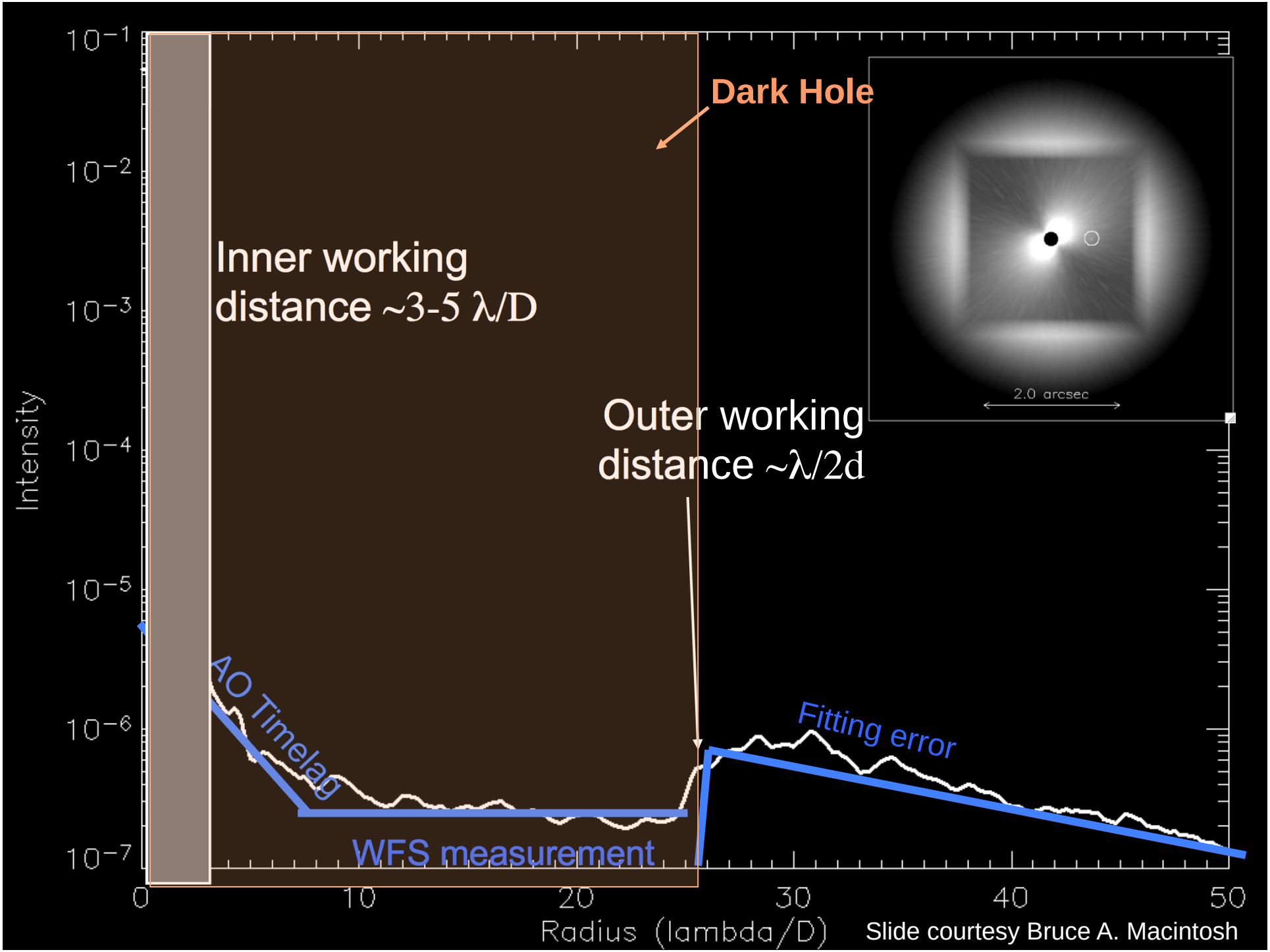


Slide courtesy Bruce A. Macintosh

Speckle noise sets a fundamental limit to sensitivity

Direct Imaging

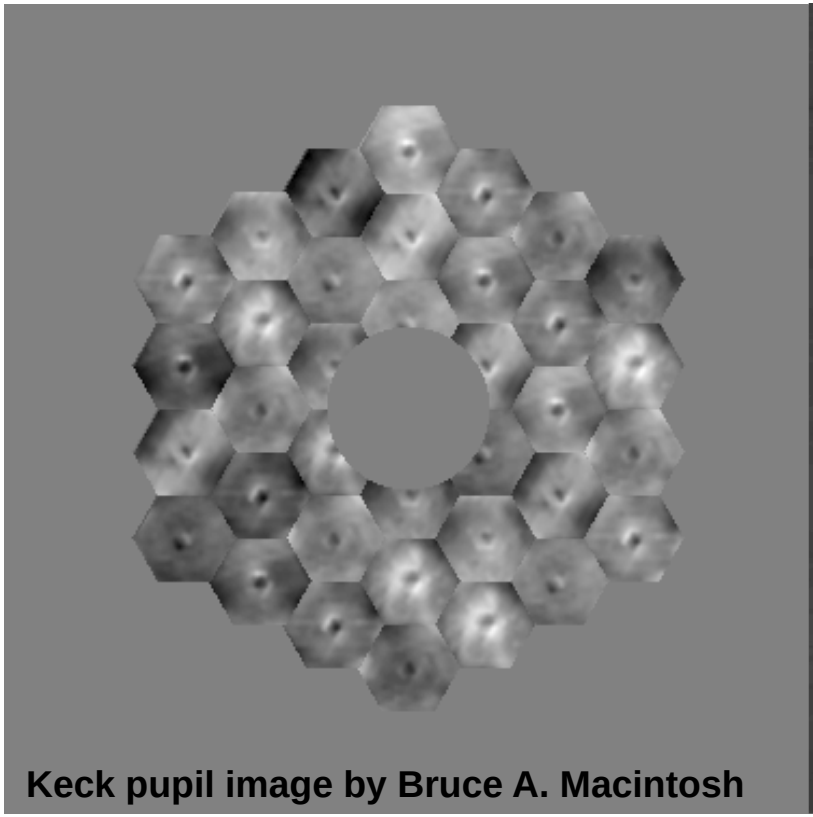
Where are we going?

Where are we now?

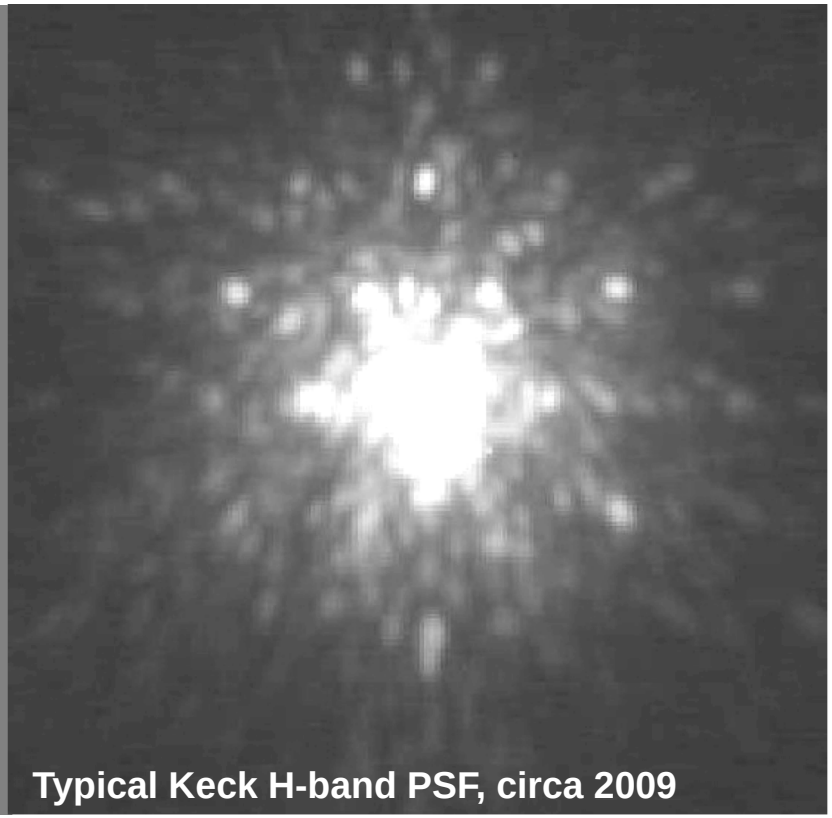
Why is it hard?

What's next?

K. Morzinski



Keck pupil image by Bruce A. Macintosh



Typical Keck H-band PSF, circa 2009

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MagAO & LBTAO are 2nd-gen. adaptive optics

Direct Imaging

Where are we going?

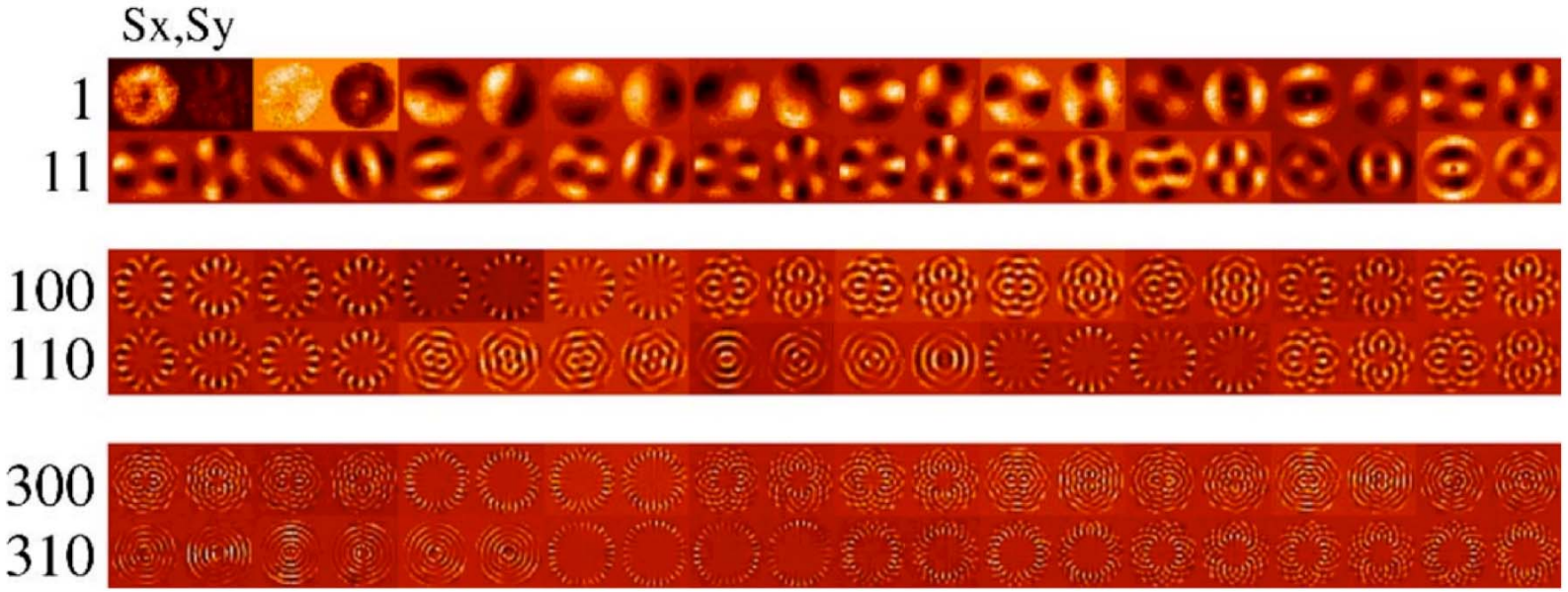
Where are we now?

Why is it hard?

What's next?

K. Morzinski

- Pyramid
  - Better low-spatial-frequency performance
  - Fainter guide stars
- Adaptive Secondary Mirror
  - Thermal throughput
- Control
  - 1/10th pixel camera lens loop
  - Optimized for each set-up
- Calibrations
  - 378 modes interaction matrix
  - Calibrated on the telescope, including secondary and tertiary



Fernando Quiros-Pacheco, Arcetri

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Magellan adaptive optics imaging of Beta Pic b

Direct Imaging

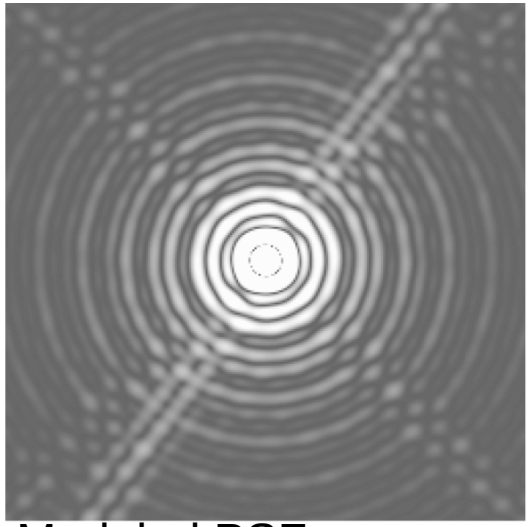
Where are we going?

Where are we now?

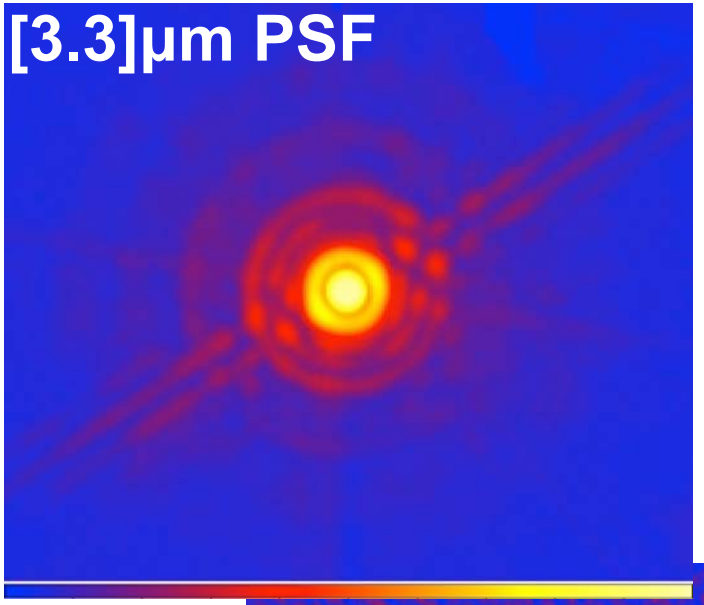
Why is it hard?

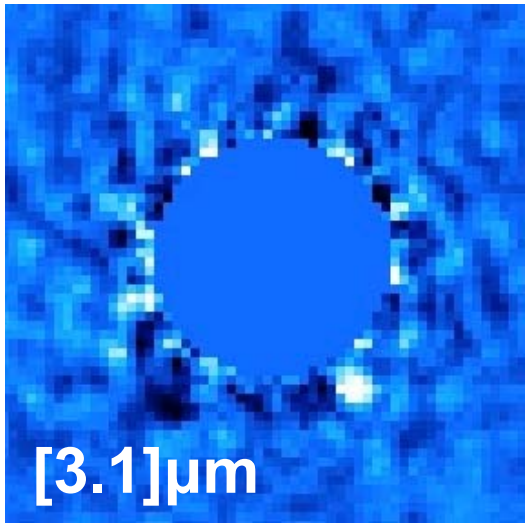
What's next?

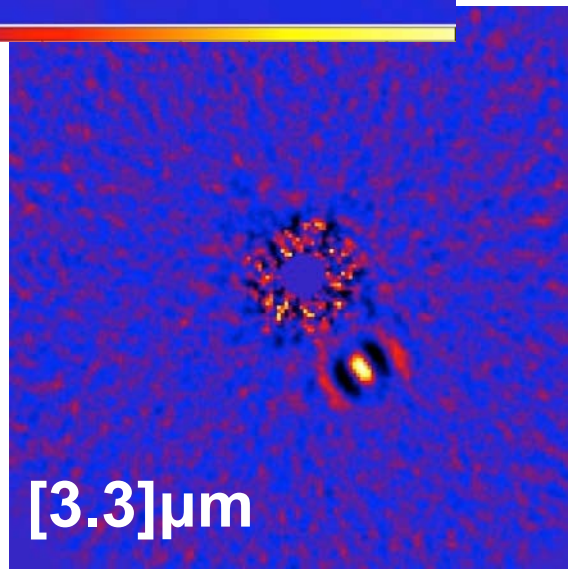
K. Morzinski



Modeled PSF







Morzinski et al 2013 in prep

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Diffraction suppression with a coronagraph

Direct Imaging

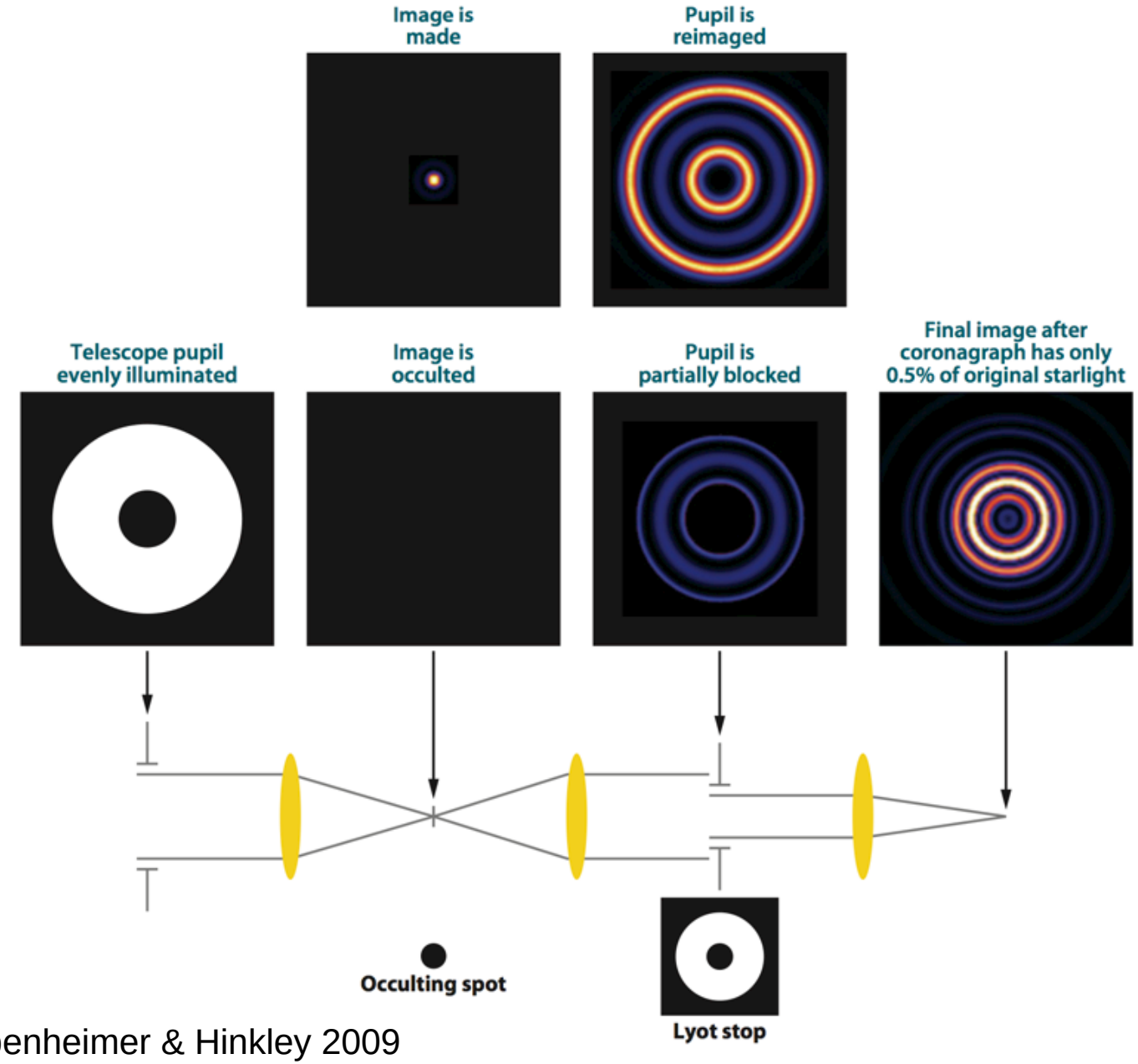
Where are we going?

Where are we now?

Why is it hard?

What's next?

K. Morzinski



Oppenheimer & Hinkley 2009

Why is it hard? –Kepler's laws: Planets orbit their stars.

Direct Imaging

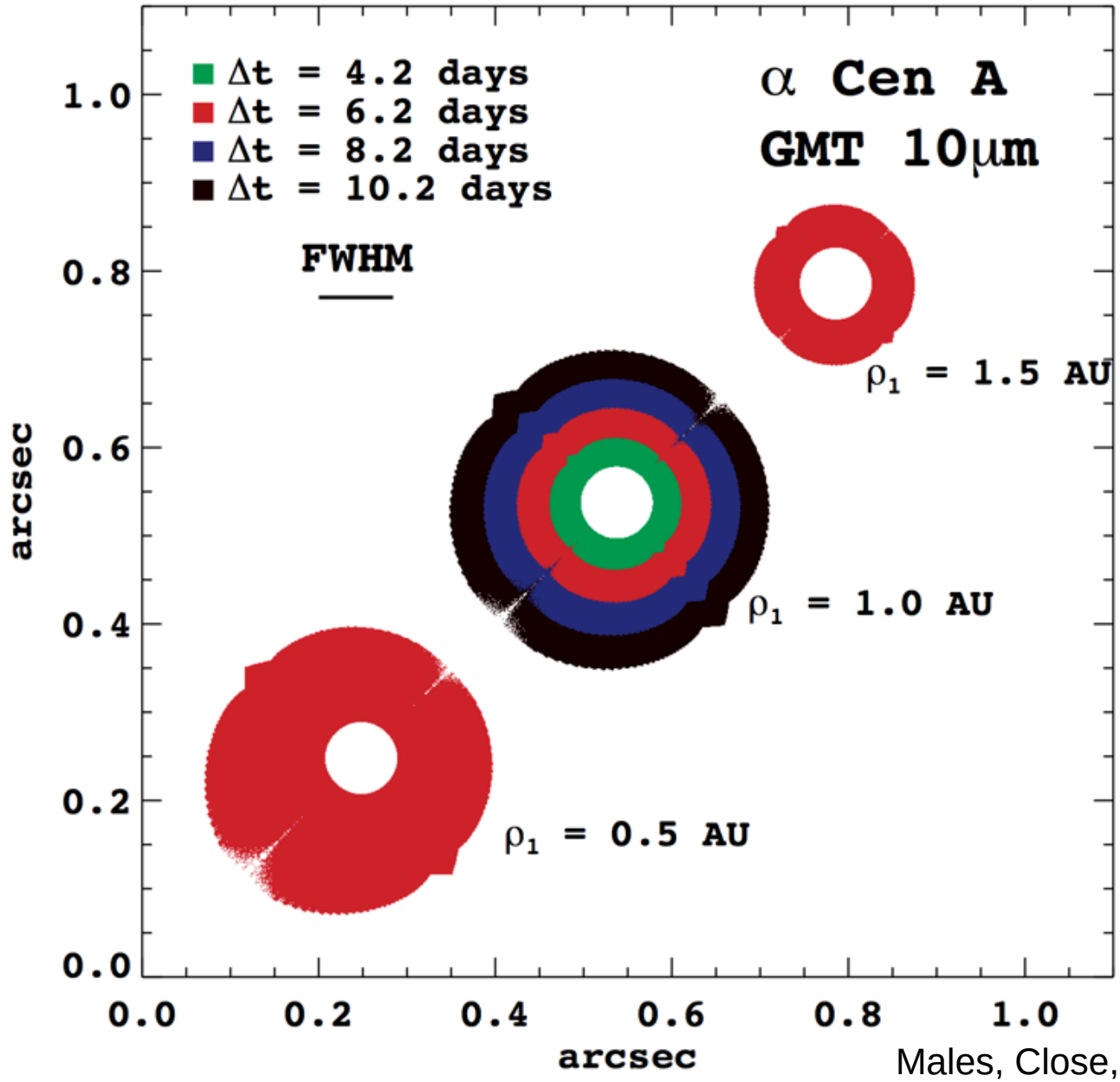
Where are we going?

Where are we now?

Why is it hard?

What's next?

K. Morzinski



Males, Close, & Skemer 2013

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Extreme AO around the world

Direct Imaging

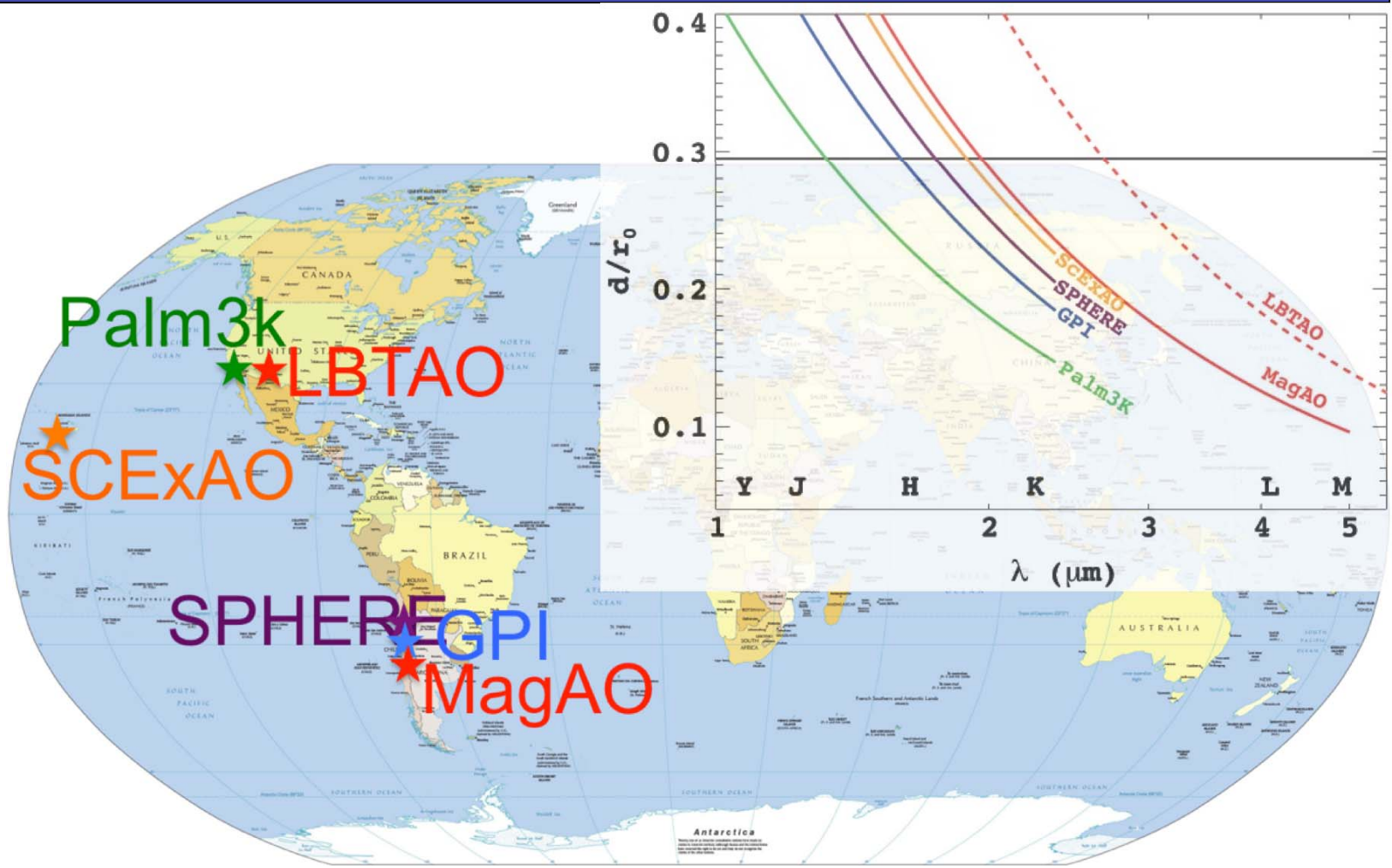
Where are we going?

Where are we now?

Why is it hard?

What's next?

K. Morzinski



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New surveys link first-generation imaging surveys with on-going r.v. surveys

Direct Imaging

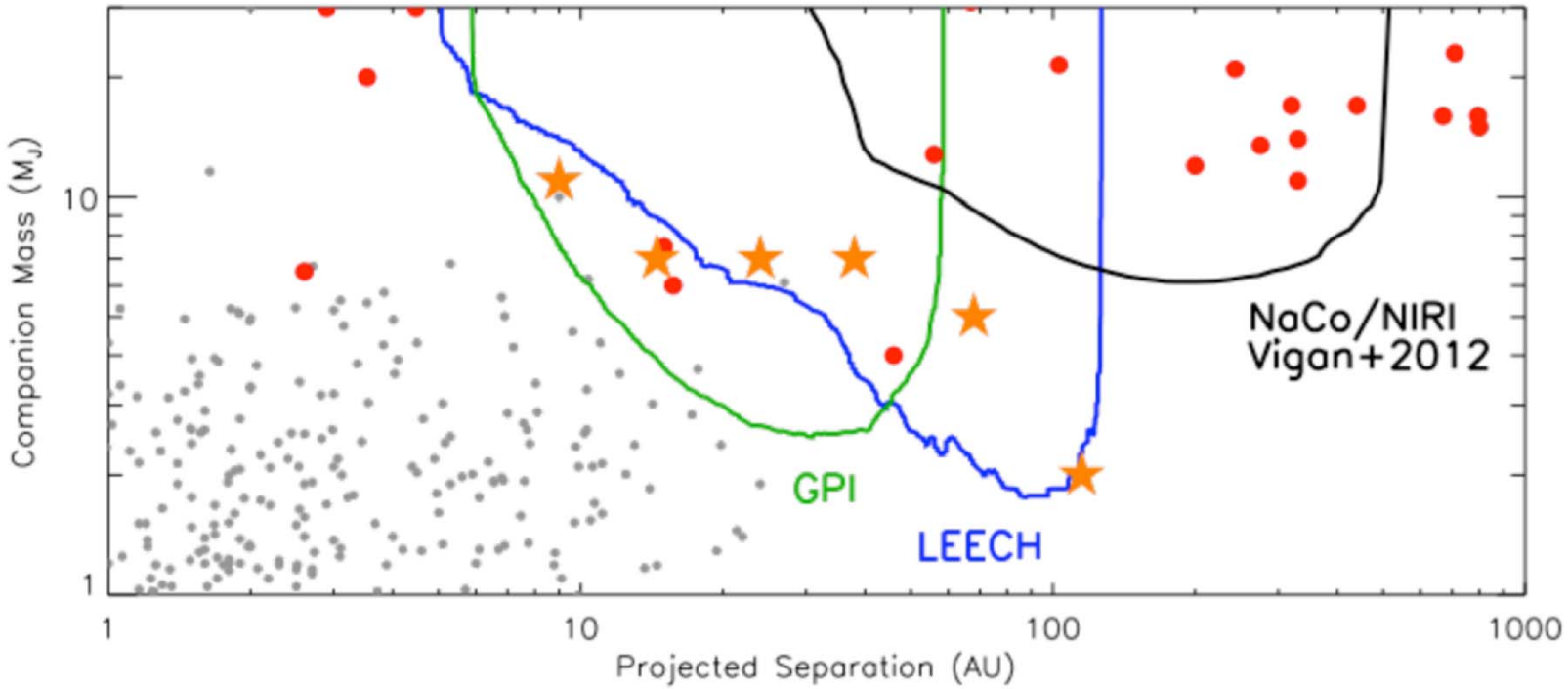
Where are we going?

Where are we now?

Why is it hard?

What's next?

K. Morzinski



- GPI – Gemini Planet Imager – Gemini South, Chile
- LEECH – LBTI Exozodi-Exoplanet Common Hunt – LBT, Arizona
- NaCo/NIRI – IDPS – International Deep Planet Survey – VLT, Chile & Gemini N, Hawaii

Skemer et al 2013

GPI Exoplanet Survey will target 600 A–M dwarfs, detecting ~25–50 planets

Direct Imaging

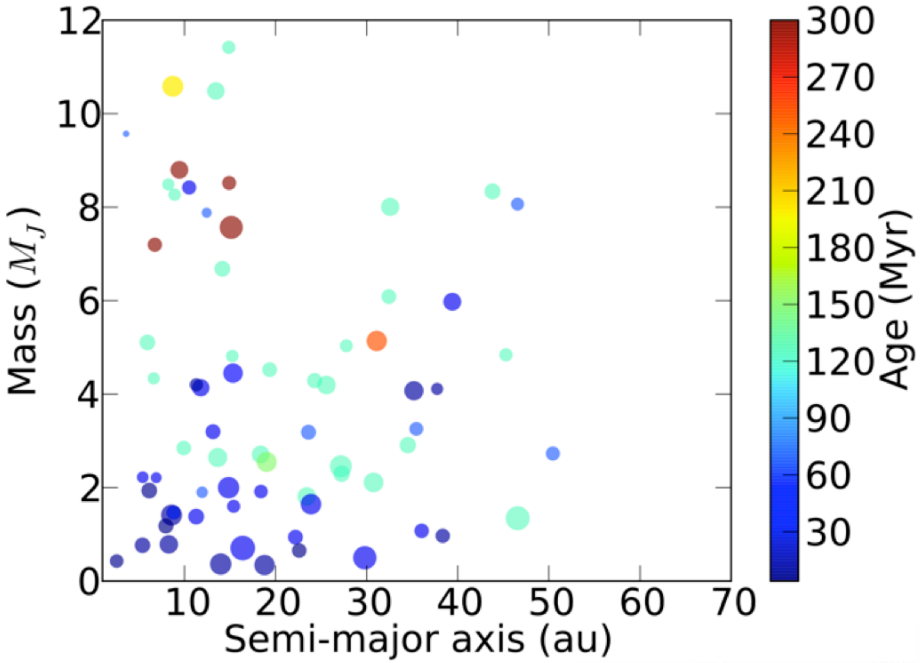
Where are we going?

Where are we now?

Why is it hard?

What's next?

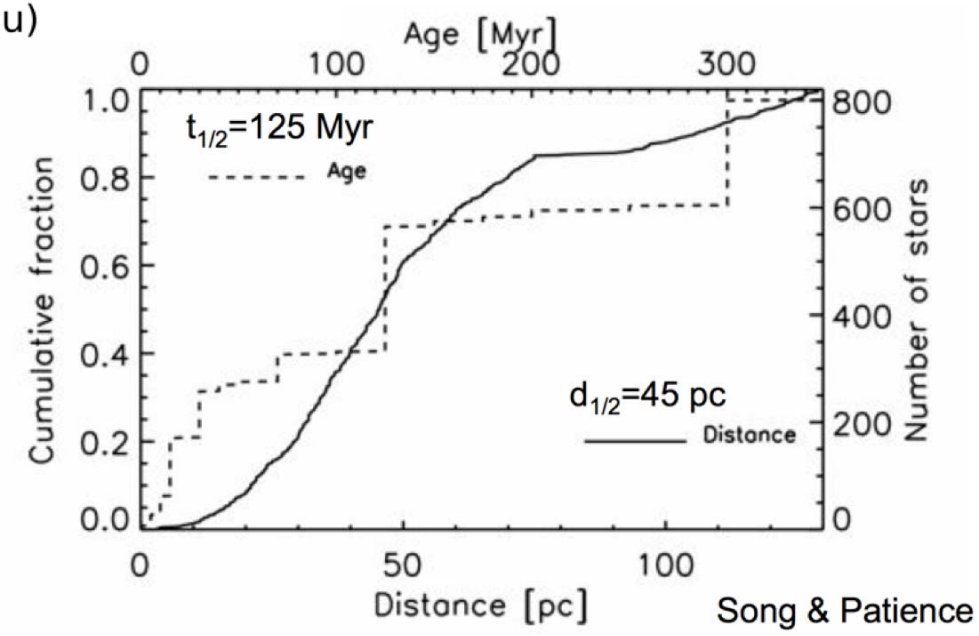
K. Morzinski



McBride et al 2011

Young stars:
t <100 Myr
d <75 pc

Adolescent stars:
t <300 Myr
d <35 pc



Song & Patience

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Modern instrumentation for exoplanet surveys and characterization missions

Direct Imaging

Where are we going?

Where are we now?

Why is it hard?

What's next?

K. Morzinski

- Ground
  - MagAO
    - VisAO
  - LBTI
  - GPI
  - SPHERE
  - CHARIS
- ELTs
  - E-ELT
  - GMT
  - TMT
- Space
  - JWST
  - NWO
  - TPF/Darwin/AFTA…

Observations and data areas of advancement

Direct Imaging

Where are we going?

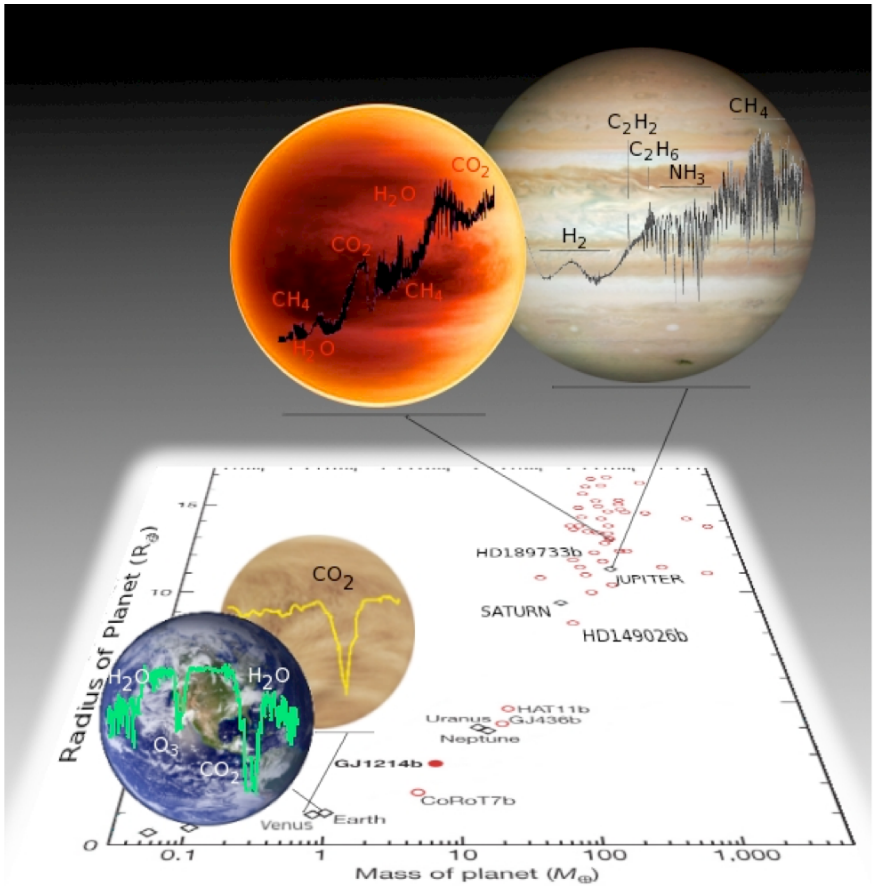
Where are we now?

Why is it hard?

What's next?

K. Morzinski

- System and population statistics
  - Architecture of planetary systems
  - Frequency of planets
- Atmospheric characterization
  - Constituents
  - Thermal balance
  - Winds, dynamics
  - Variability



Echo

MagAO

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Theory and modeling areas of advancement

Direct Imaging

Where are we going?

Where are we now?

Why is it hard?

What's next?

K. Morzinski

MagAO

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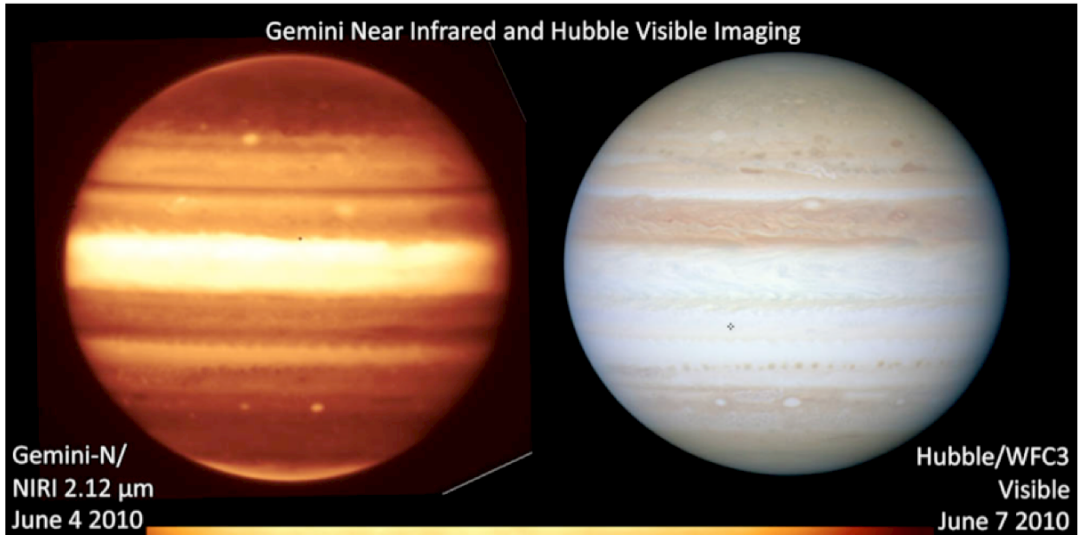
- Opacities, model atmospheres
  - Unidentified lines
  - Pressure broadening
  - Temperature-intensity anomalies
- Where observers should be looking
  - spectrally
  - spatially
- Formation models
  - Pebble accretion
  - Migration
- Population synthesis



Summary – Surveys for directly-imaged planets

Direct Imaging

Where are we going?

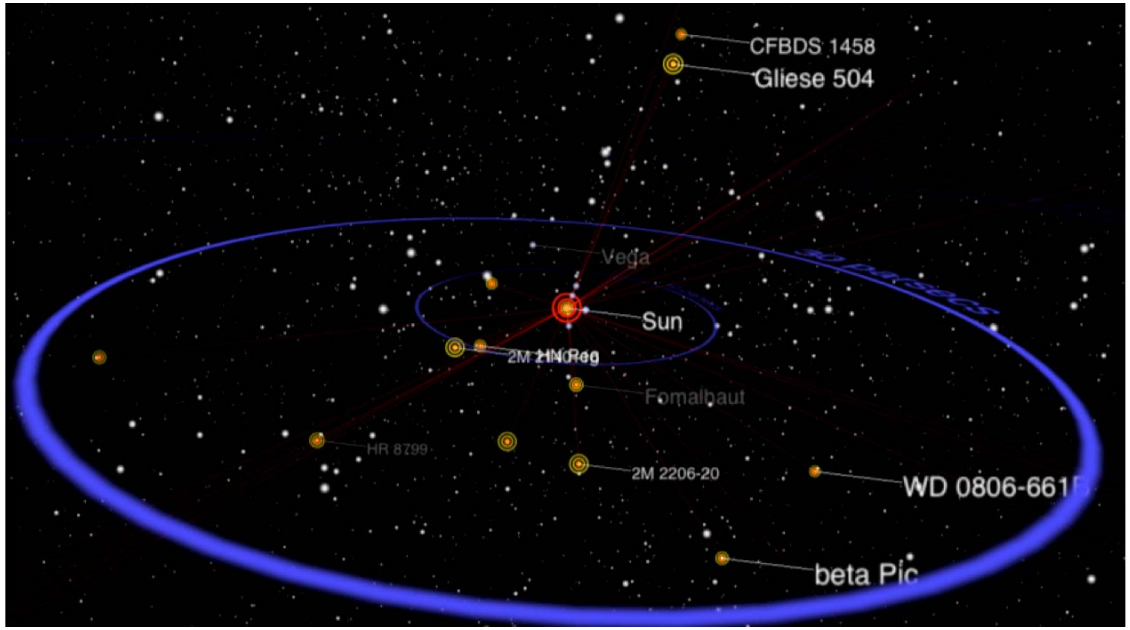
Where are we now?

Why is it hard?

What's next?

K. Morzinski

- Imaging results have found ~ <10-20% of stars host wide massive planets
  - Have not yet probed solar-system-like parameter space
  - Kepler: ~15% stars have an Earth-size planet in the habitable zone
  - Microlensing: ~17% stars host Jupiter-mass planets



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Summary – Remote sensing of exoplanets

Direct Imaging

Where are we going?

Where are we now?

Why is it hard?

What's next?

K. Morzinski

- 2M 1207 b
  - Thick clouds, low gravity effects
- HR 8799
  - b – Little CH4, non-equilibrium chemistry. Thick mixed clouds? Or cloud-free with high mean-molecular weight atmosphere? Or what?
  - c – High C:O, core accretion
- Beta Pic b – Is it an early-L brown dwarf? Is it a planet that is similar to the early-L dwarfs?
  - Further characterization, and formation modeling
  - Orbital analysis – Disk warp, also upper limit on mass from r.v.
- Fomalhaut b – what is it?
  - Is there another object in there responsible for the disk?

Conclusions

Direct Imaging

Where are we going?

Where are we now?

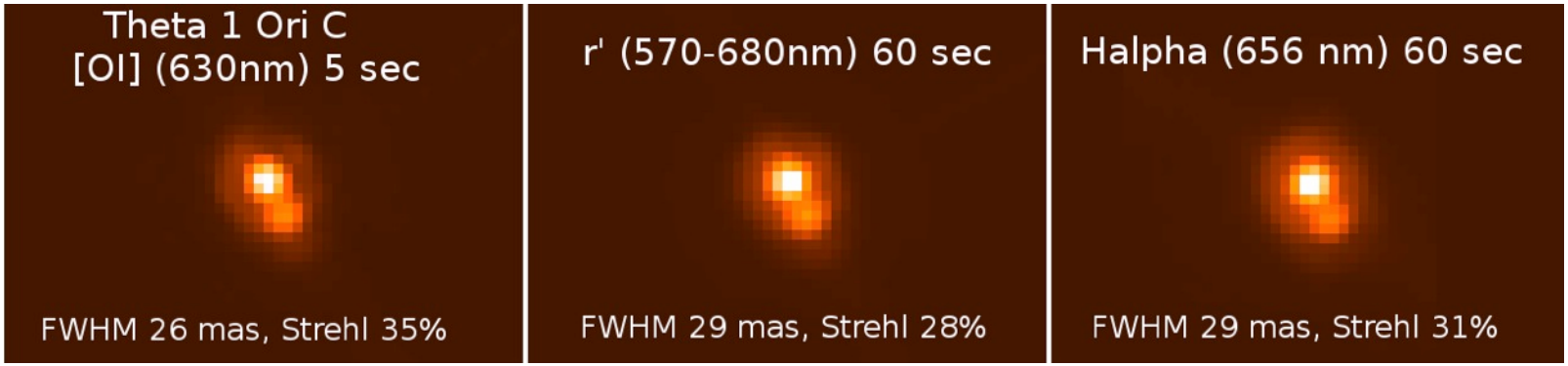
Why is it hard?

What's next?

K. Morzinski

- We are still in a data-driven discovery space
  - Modeling is crucial but data is critical to improve models too
  - Finally the r.v. and direct imaging search spaces are starting to overlap. Kepler and microlensing too – Diverse ways to probe planetary systems will help improve understanding
  - New instrumentation and new techniques will continue to provide big payoff

MagAO/VisAO: Diffraction-limited visible-light imaging – Close et al 2013



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