Direct Imaging of Extrasolar Planets

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JPL: Kent Wallace, Mitch Troy

UCLA: James Larkin, Jeff Chilcote, Mike Fitzgerald

Gemini: Stephen Goodsell, Markus Hartung

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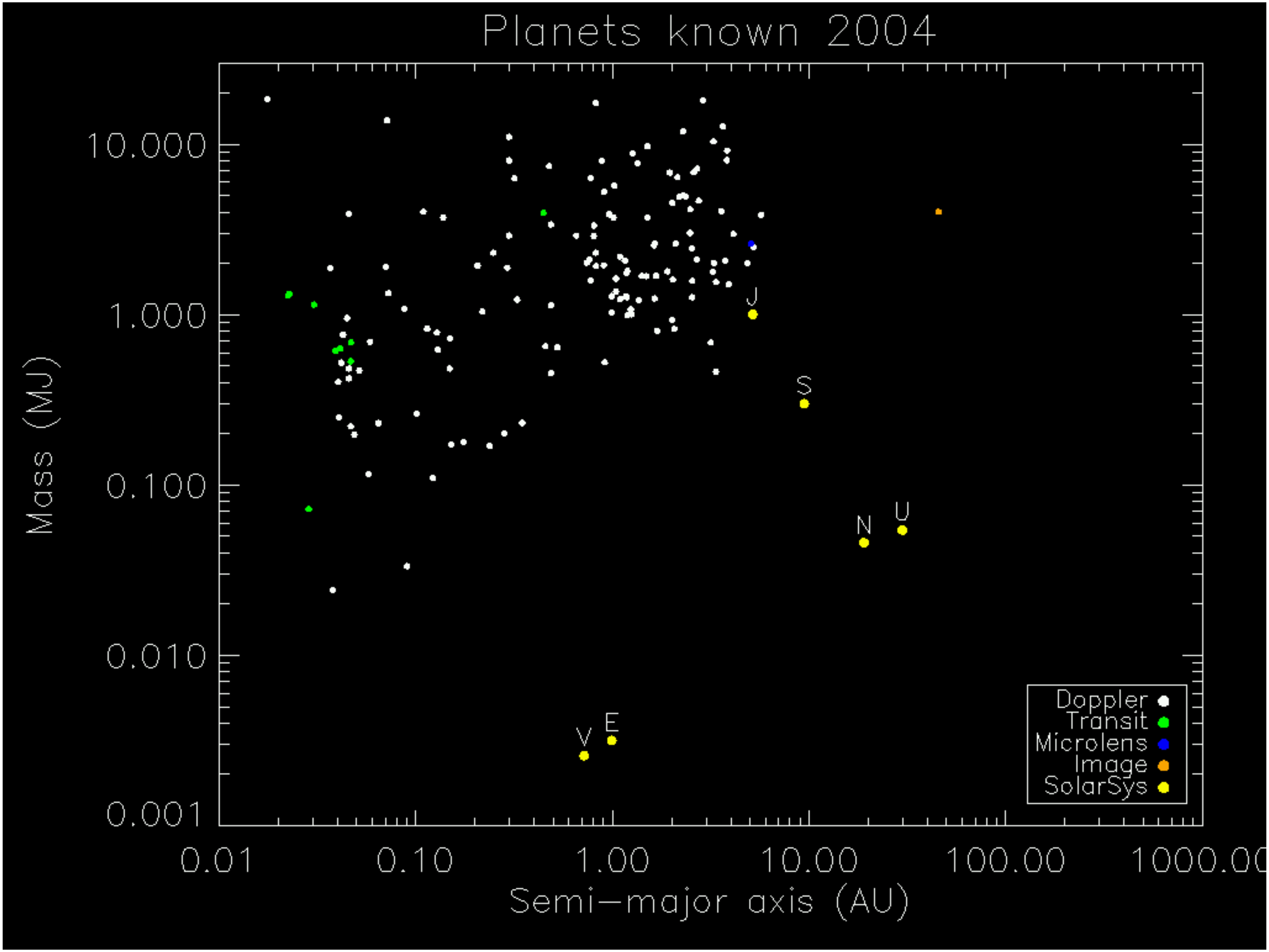
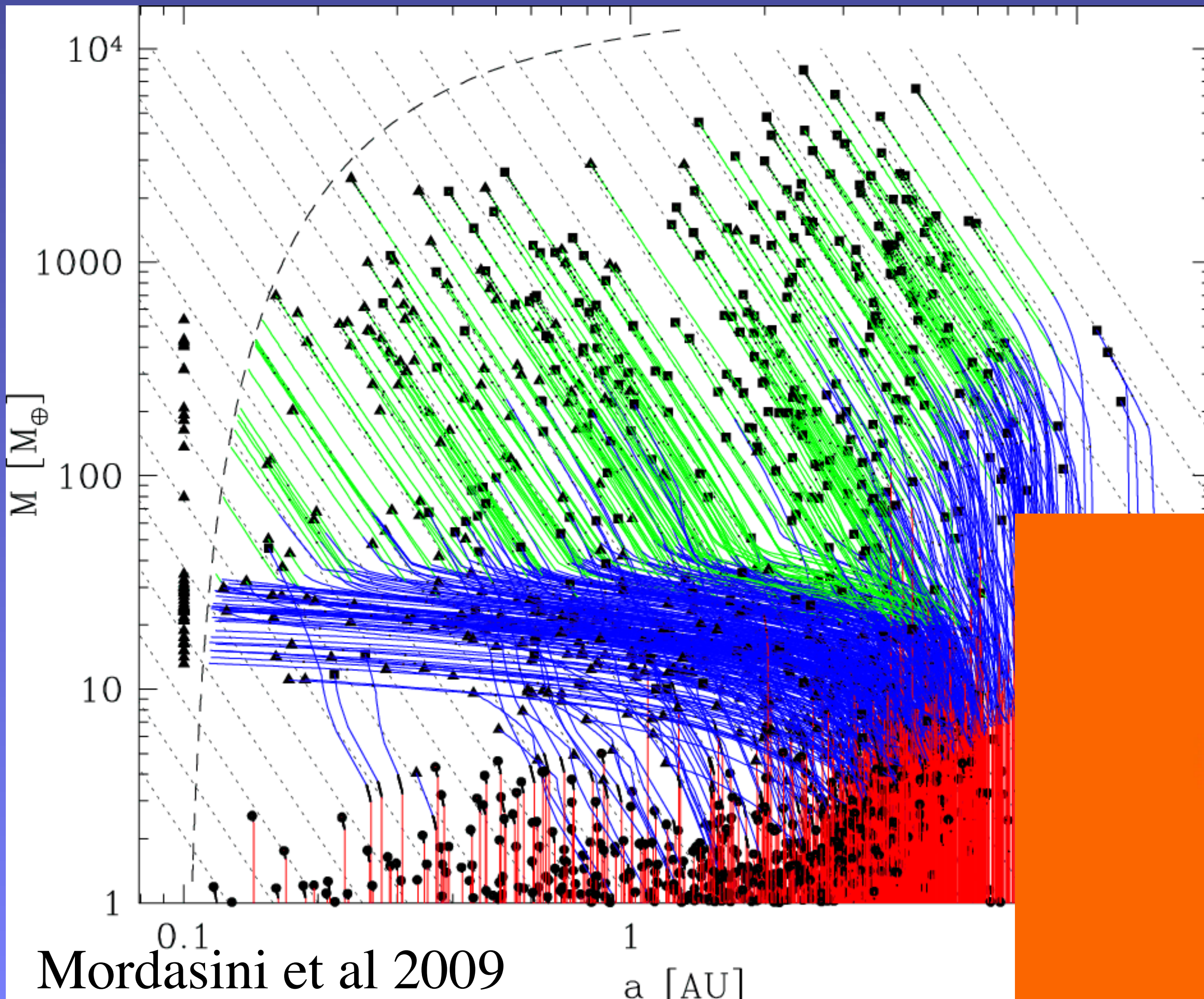
Outline

- **Motivation (generic and direct-imaging specific)**
- **Direct imaging with current AO: Keck search**
- **HR8799 system**
- **Comparison of science reach to microlensing**
- **Near-future: Gemini Planet Imager**
  - Science plans for the GPI campaign
- **Future: AO on Extreme Large Telescopes**
  - Science reach
- **Far future: Space-based planet detection**
  - Information microlensing can provide to plan space missions



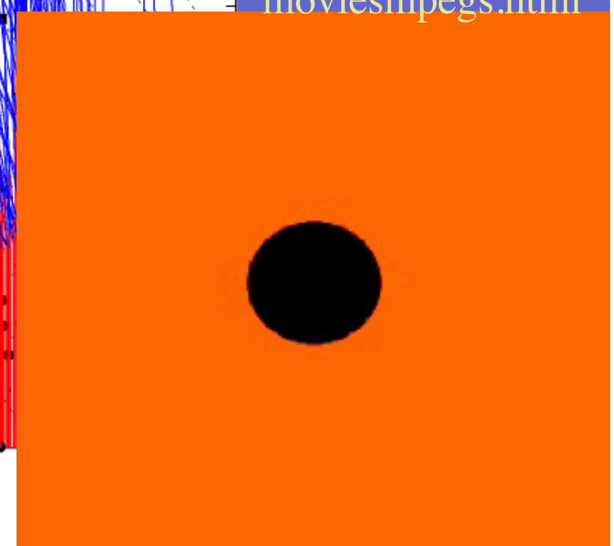
Planets known 2004
Mass (MJ)
10.000
1.000
0.100
0.010
0.001
0.01
0.10
1.00
10.00
100.00
1000.00
Semi−major axis (AU)
J
S
N
U
V
E
Doppler
Transit
Microlens
Image
SolarSys

Formation history is encoded in distribution: Core Accretion + Migration

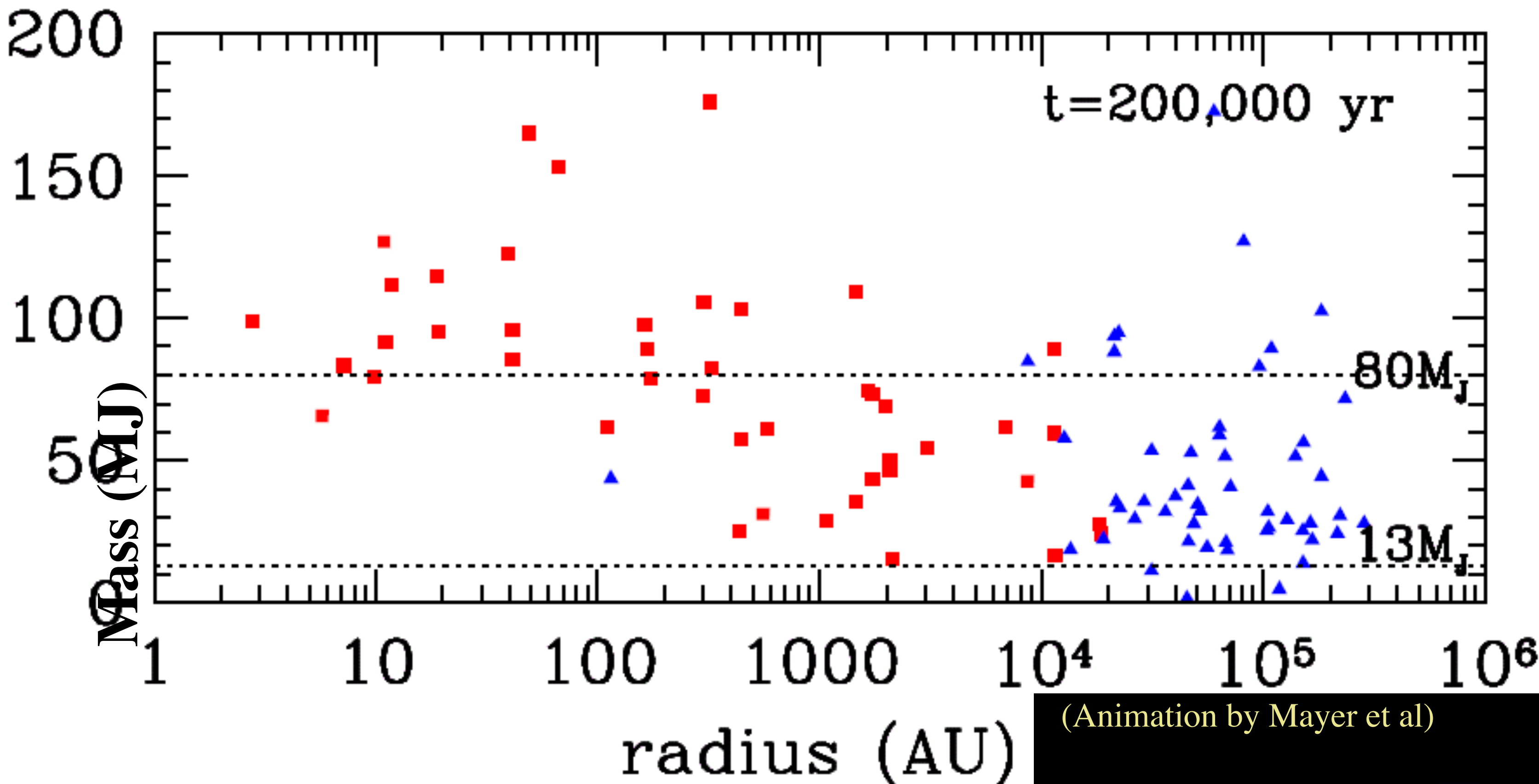


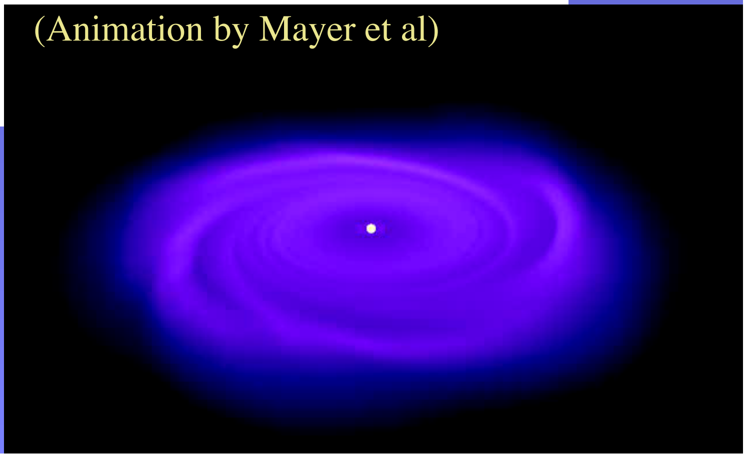
Mordasini et al 2009

(F. Masset http://www.maths.qmul.ac.uk/~masset/moviesmpegs.html

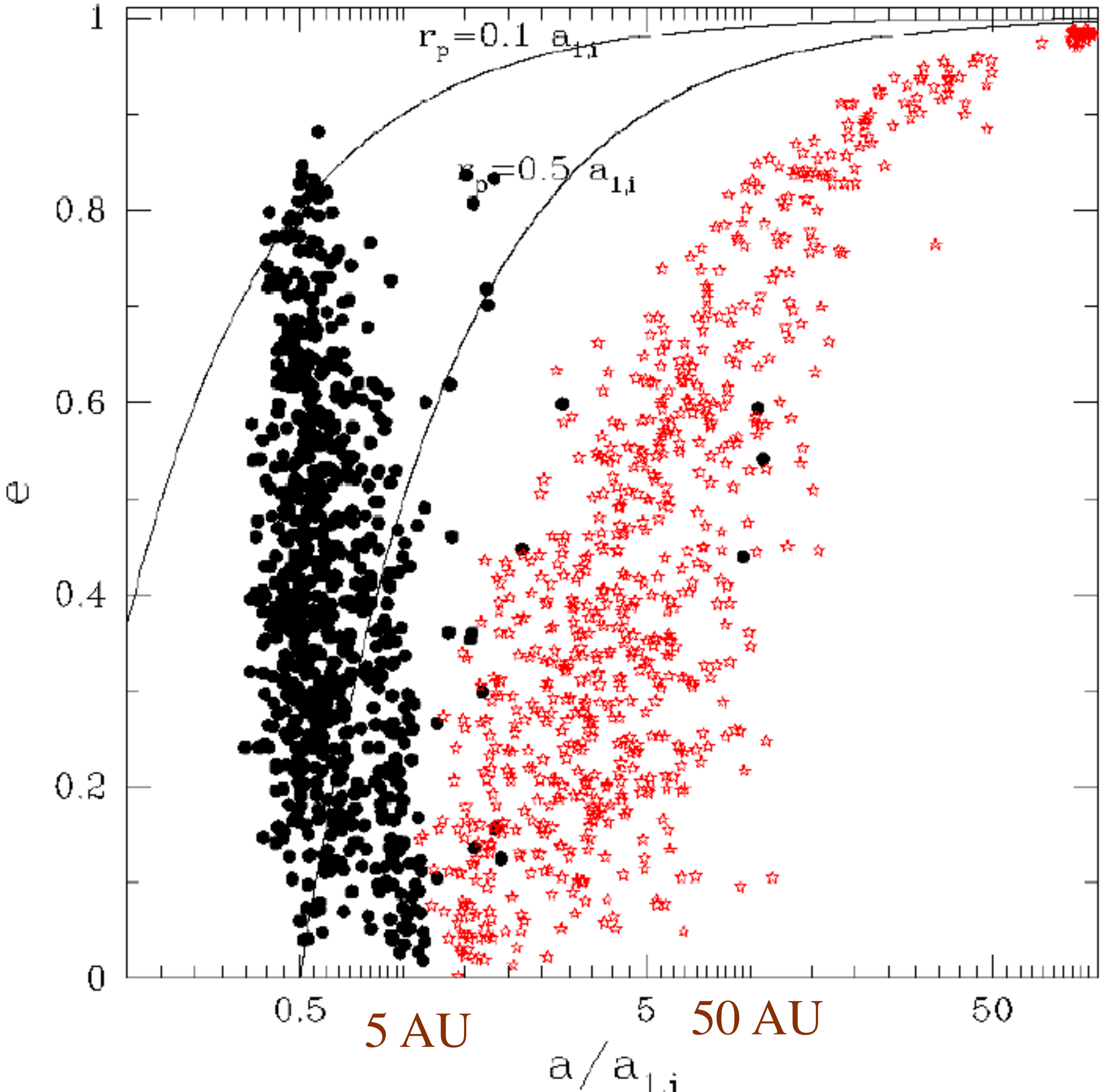


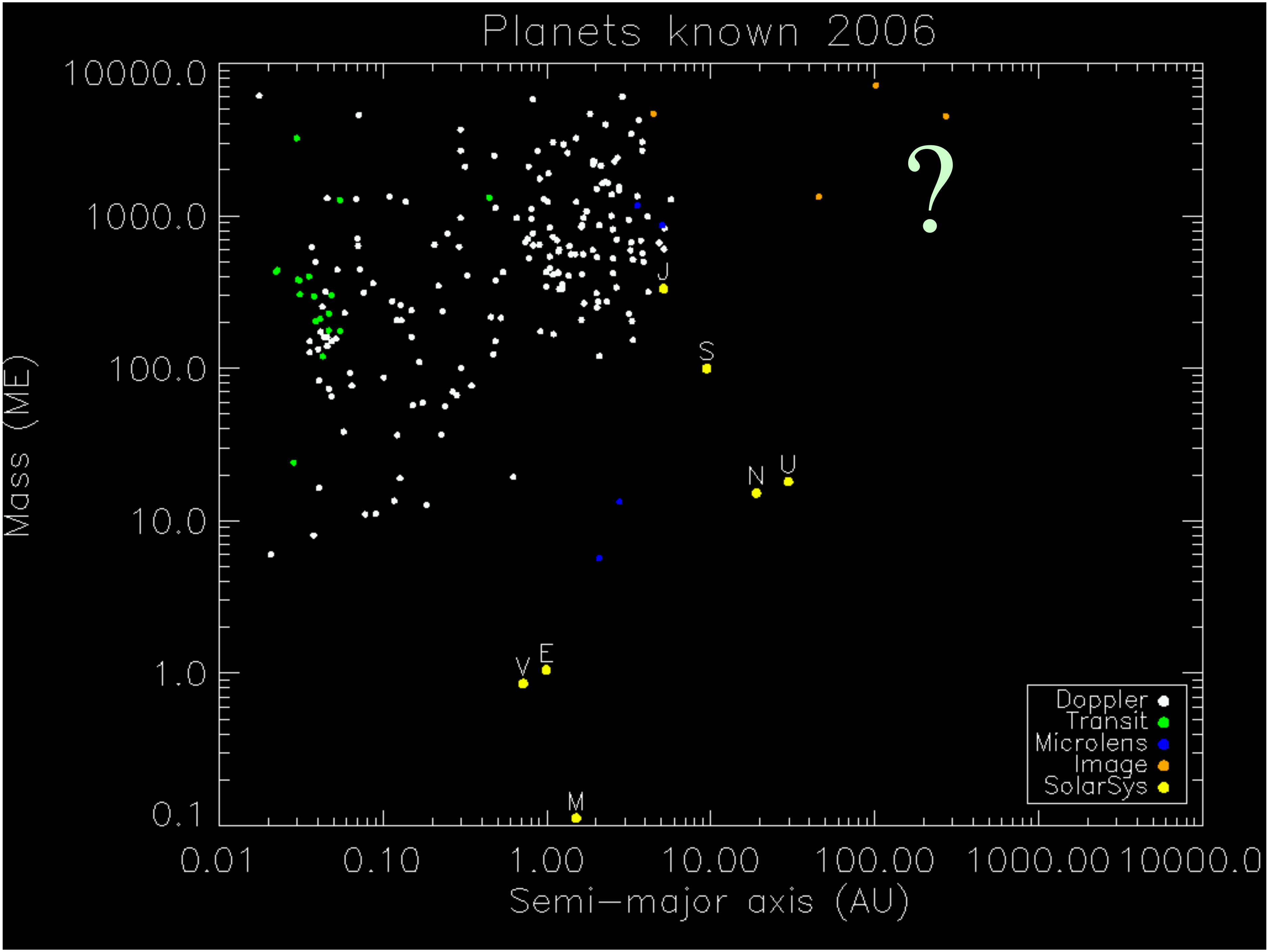
Disk instability distribution
Stamatellos & Whitworth 2008



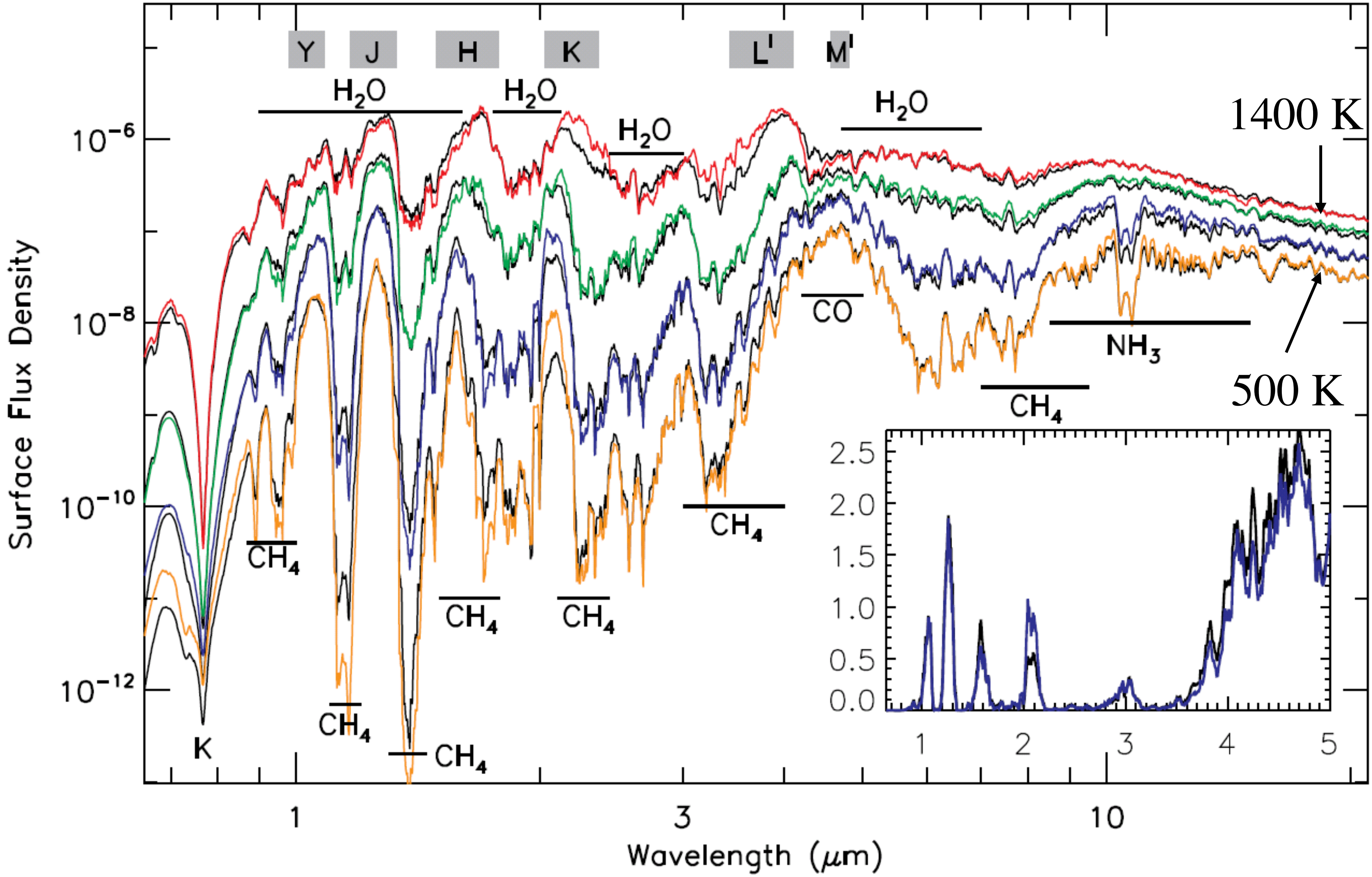


Orbital scattering in 3 body systems; Chatterjee et al. 2008

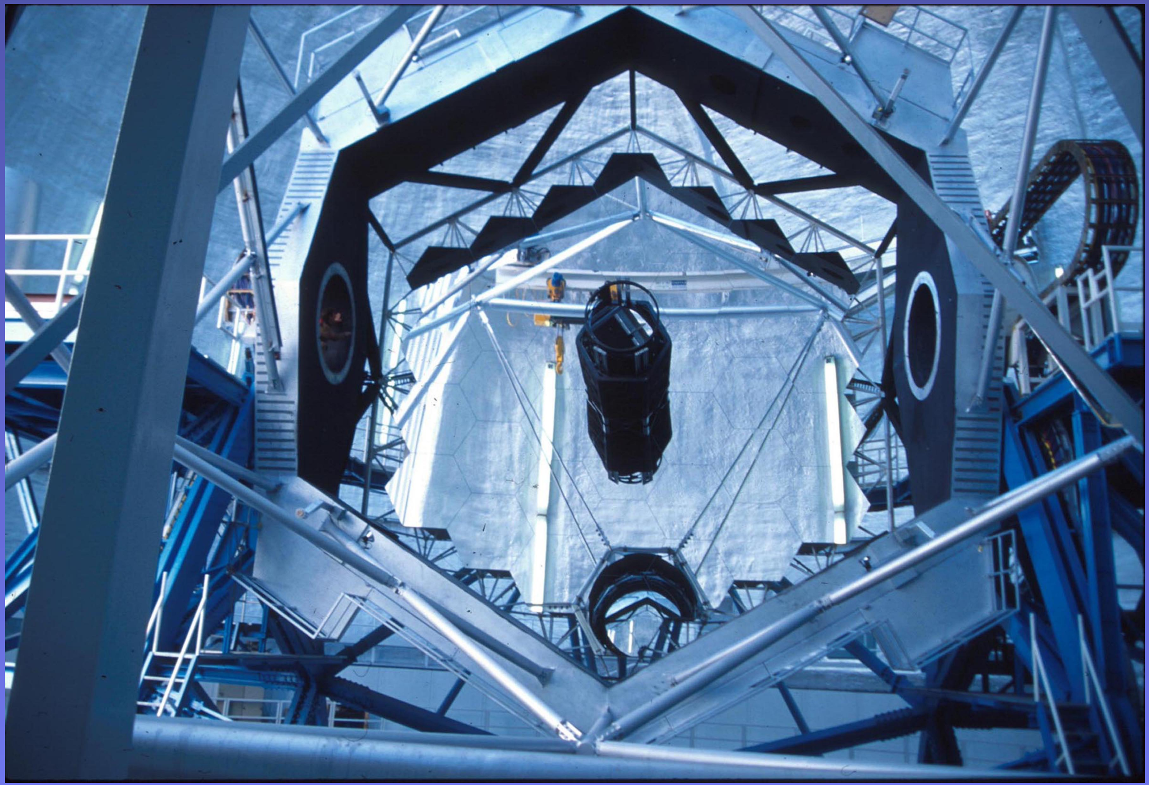



Planets known 2006
Mass (ME)
10000.0
1000.0
100.0
10.0
1.0
0.1
Semi−major axis (AU)
0.01
0.10
1.00
10.00
100.00
1000.00
10000.0
J
S
N
U
V
E
M
?
Doppler
Transit
Microlens
Image
SolarSys

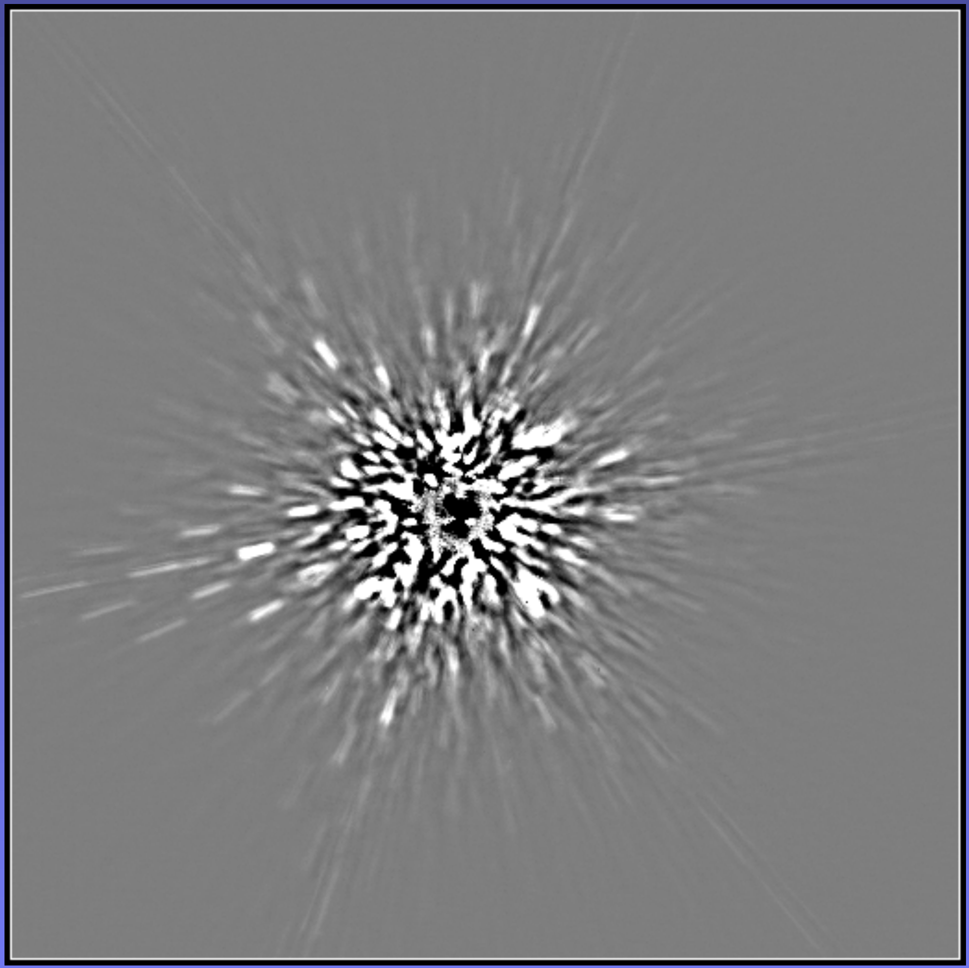
Composition is also a signature (Fortney et al 2008)

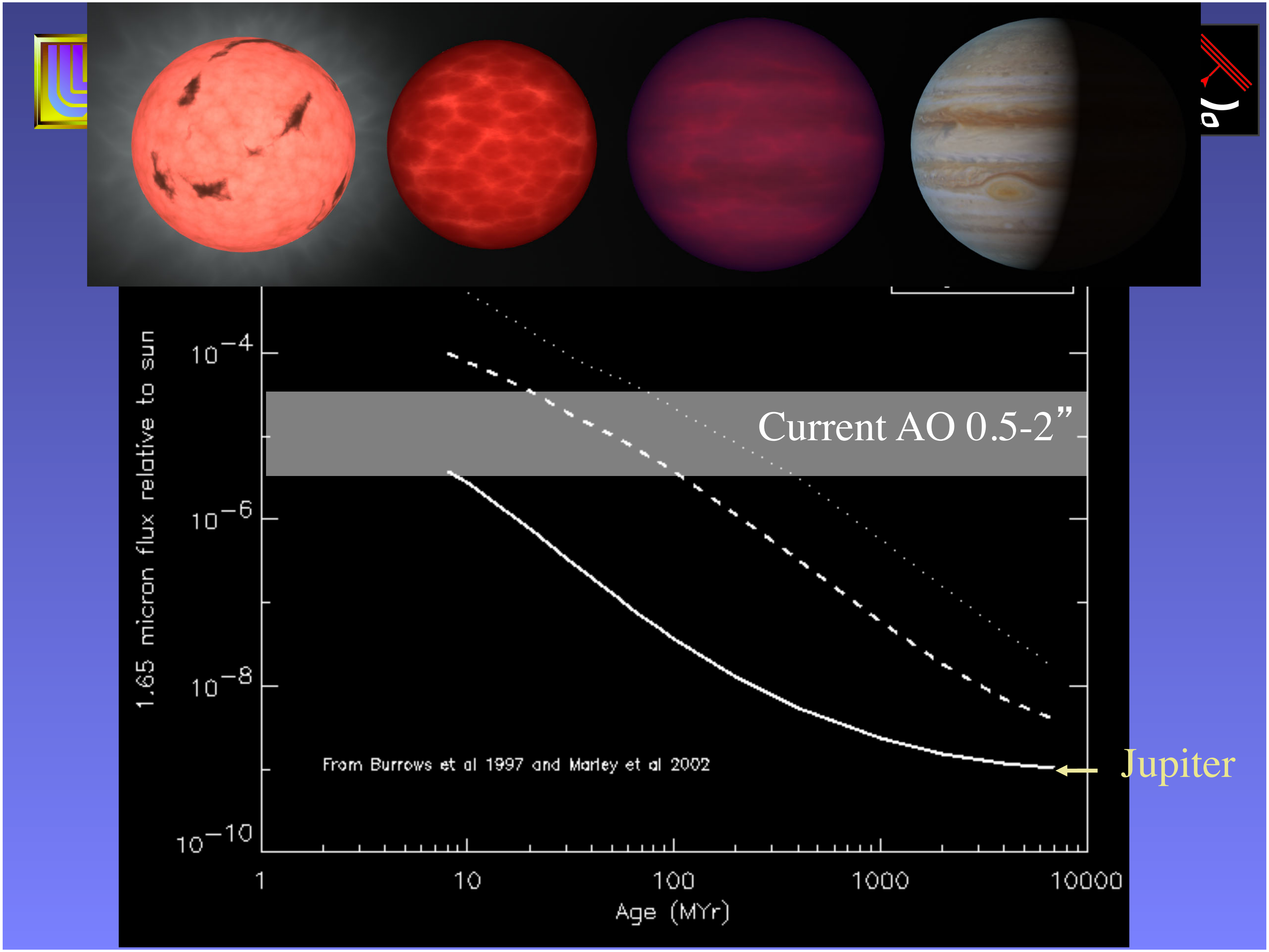


10-m W.M. Keck II Telescope



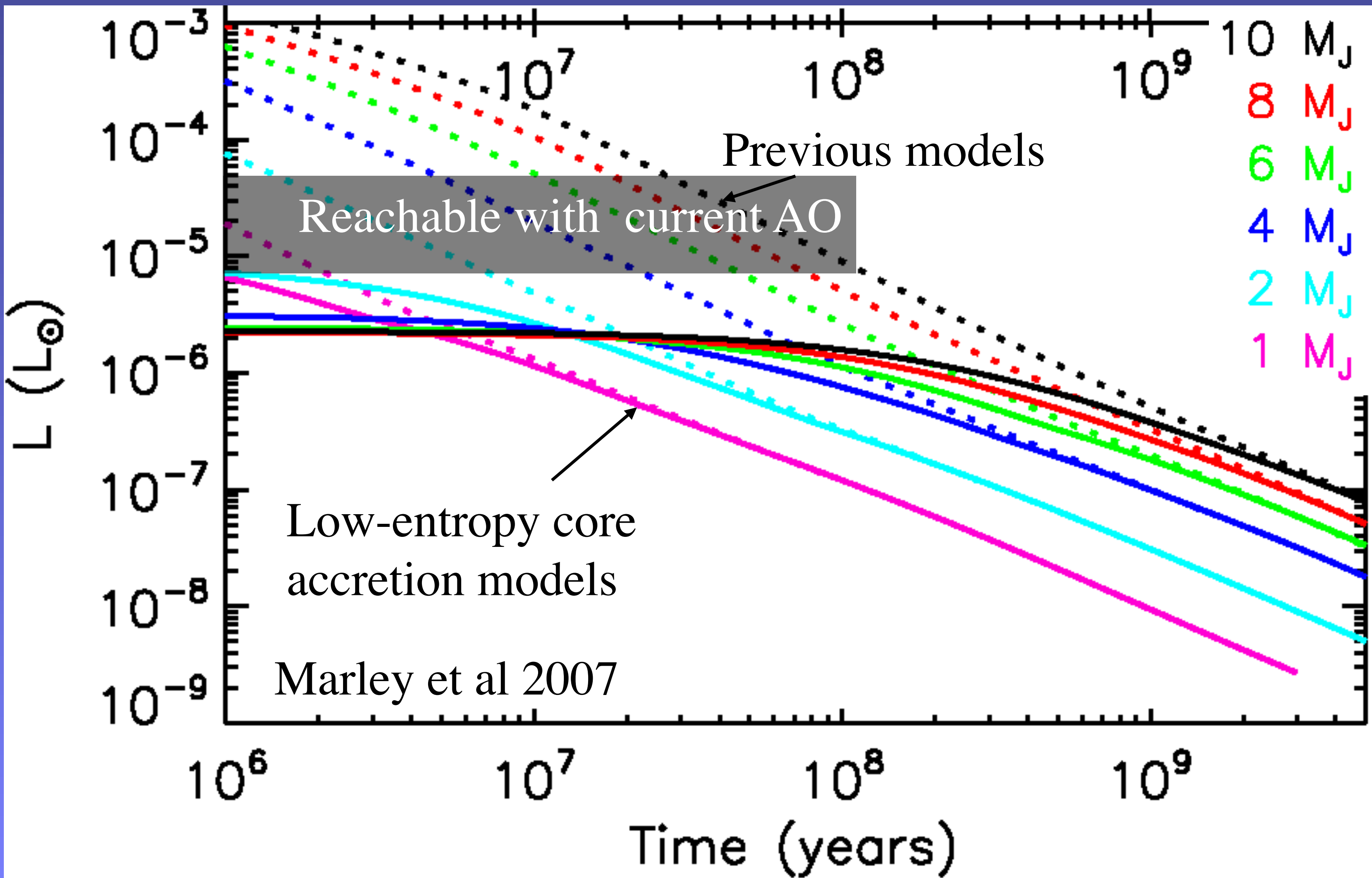
Keck AO Image of a bright star



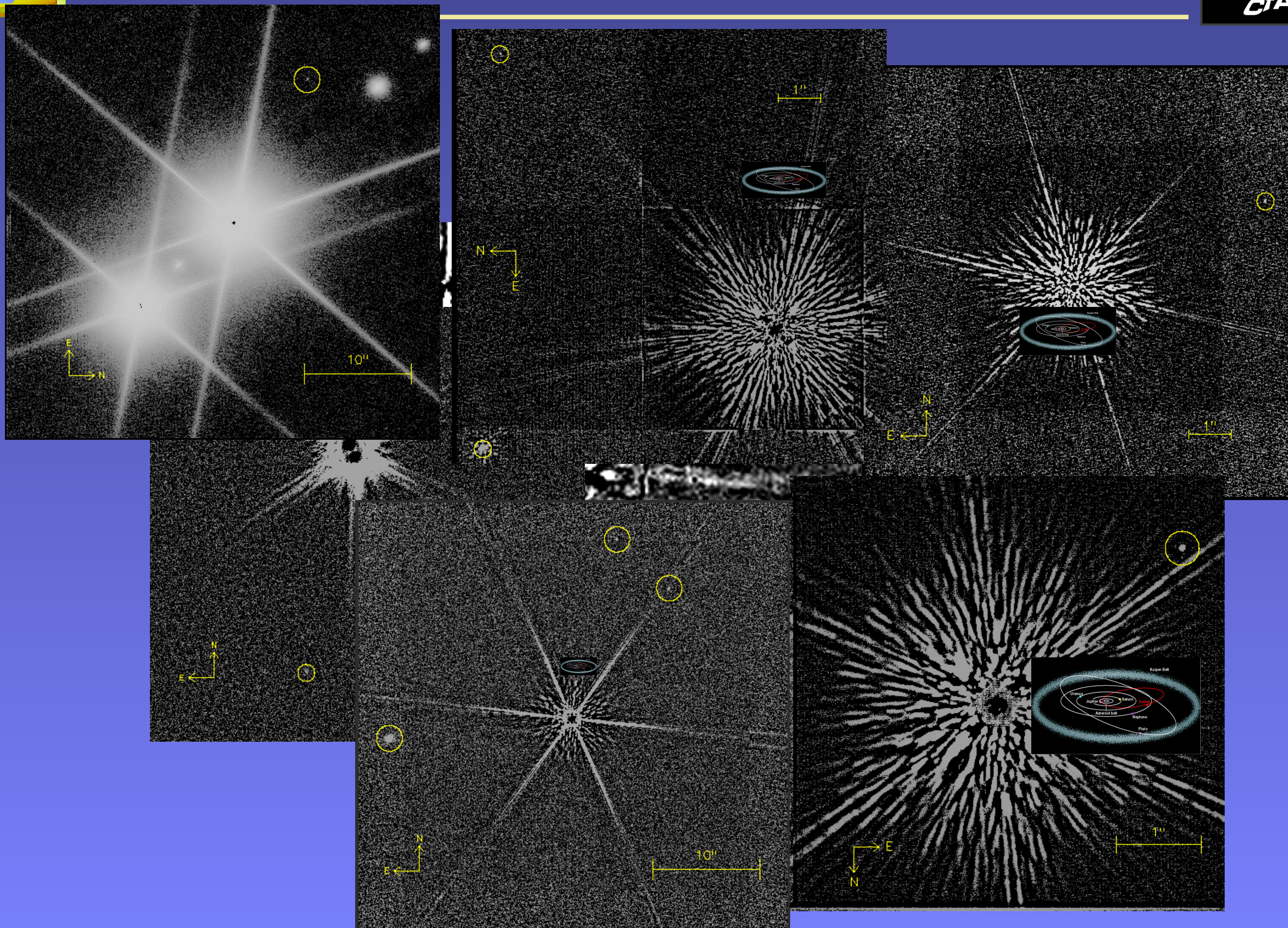


Current AO 0.5-2”
Jupiter
From Burrows et al 1997 and Marley et al 2002
1.65 micron flux relative to sun
Age (MYr)
10^{-4}
10^{-6}
10^{-8}
10^{-10}
1
10
100
1000
10000

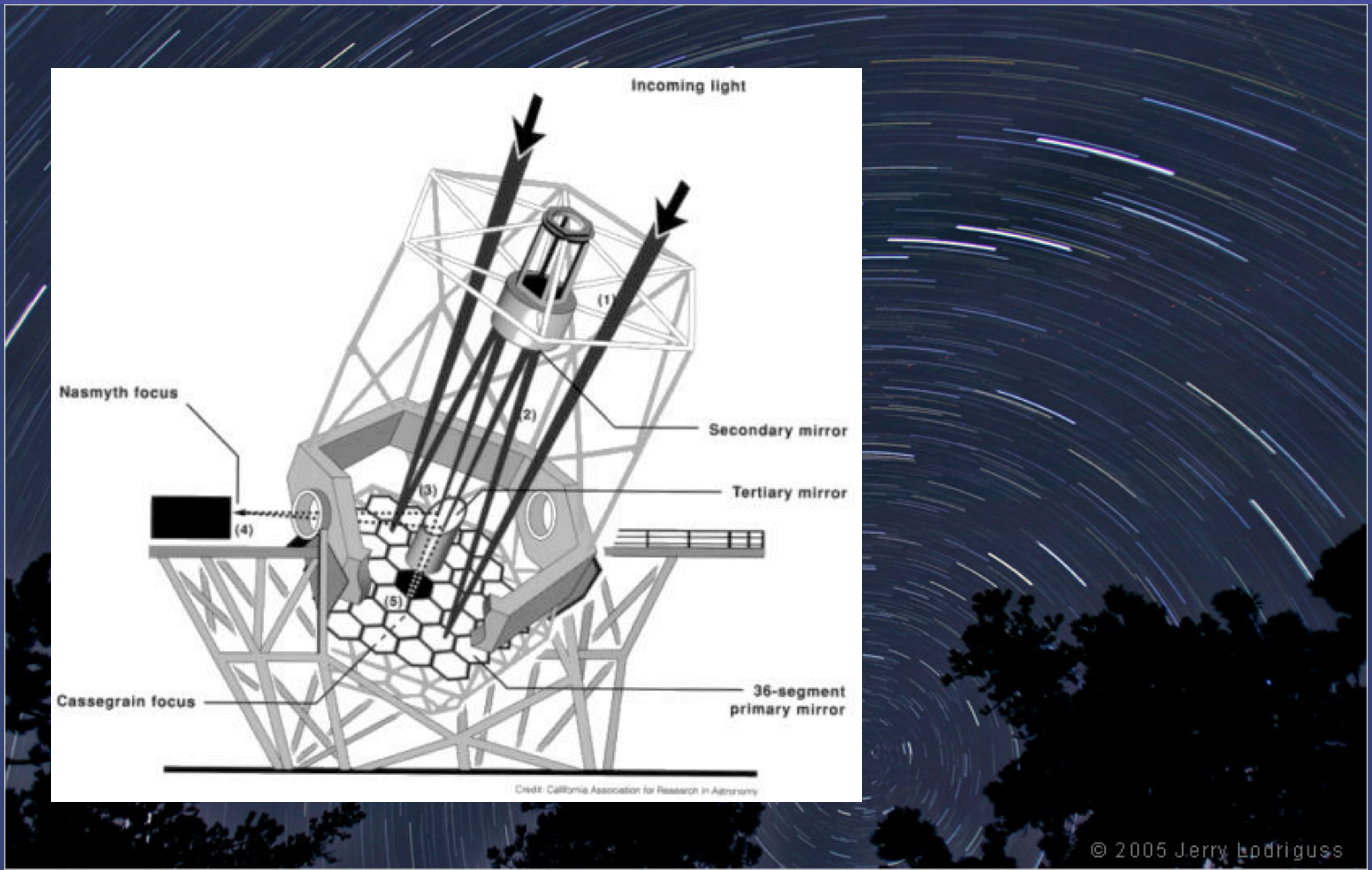
Luminosity encodes formation history



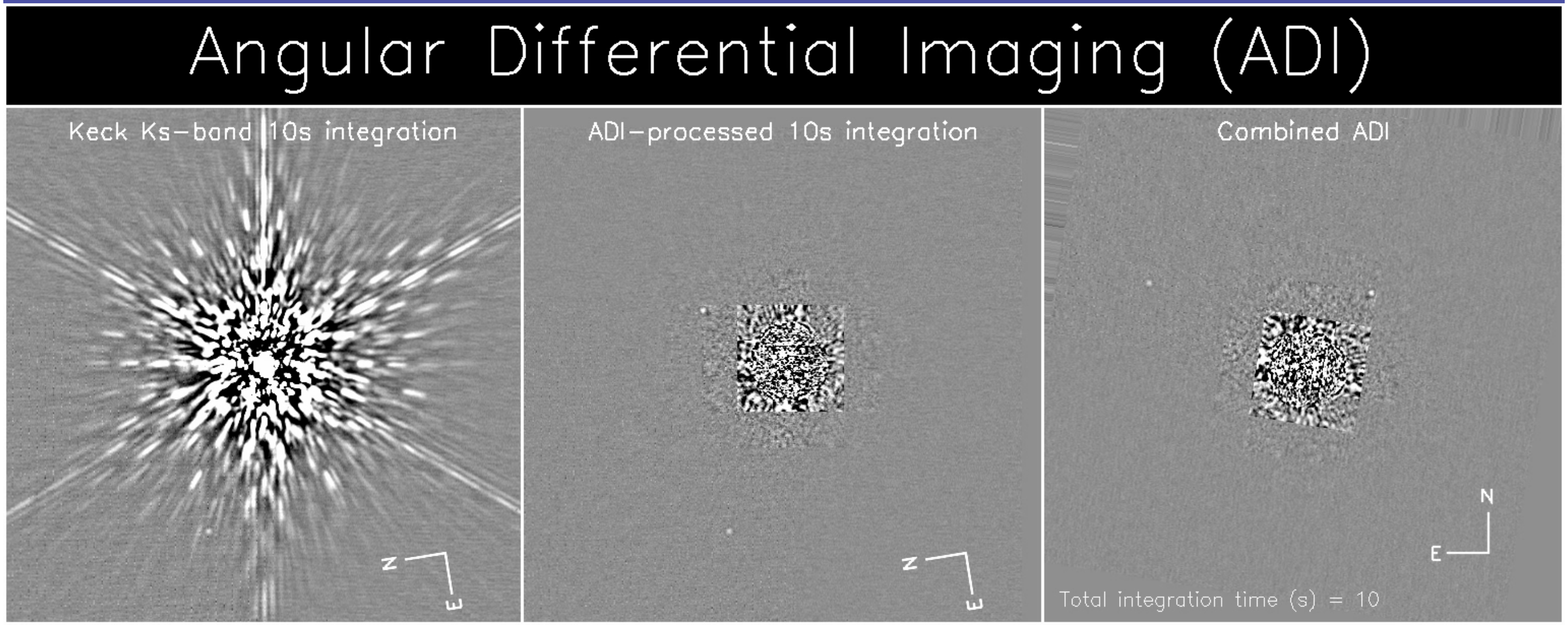
Keck planet search



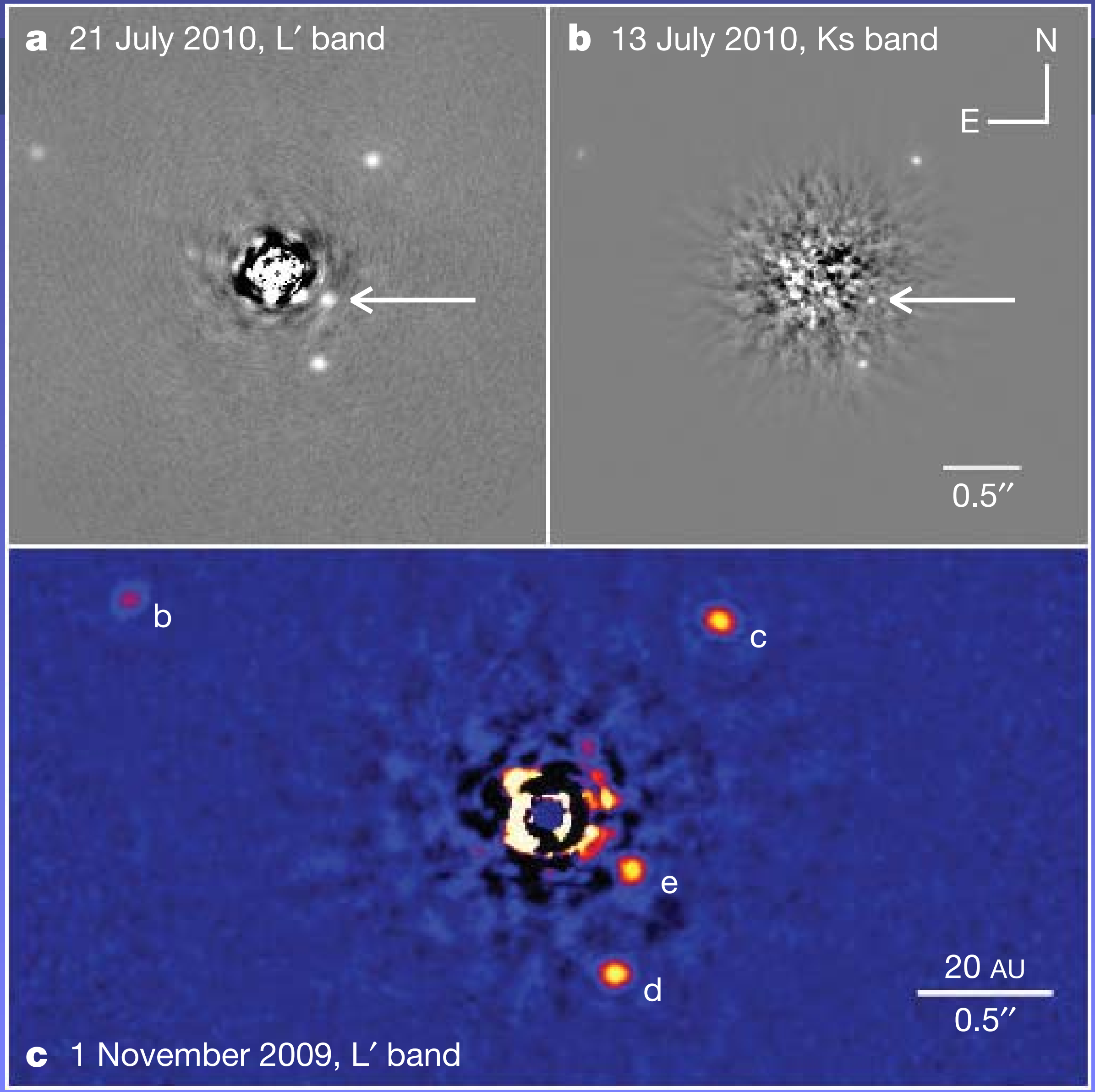
Rotation


Incoming light
(1)
(2)
(3)
(4)
(5)
Nasmyth focus
Secondary mirror
Tertiary mirror
Cassegrain focus
36-segment primary mirror
Credit: California Association for Research in Astronomy
© 2005 Jerry Lodriguss

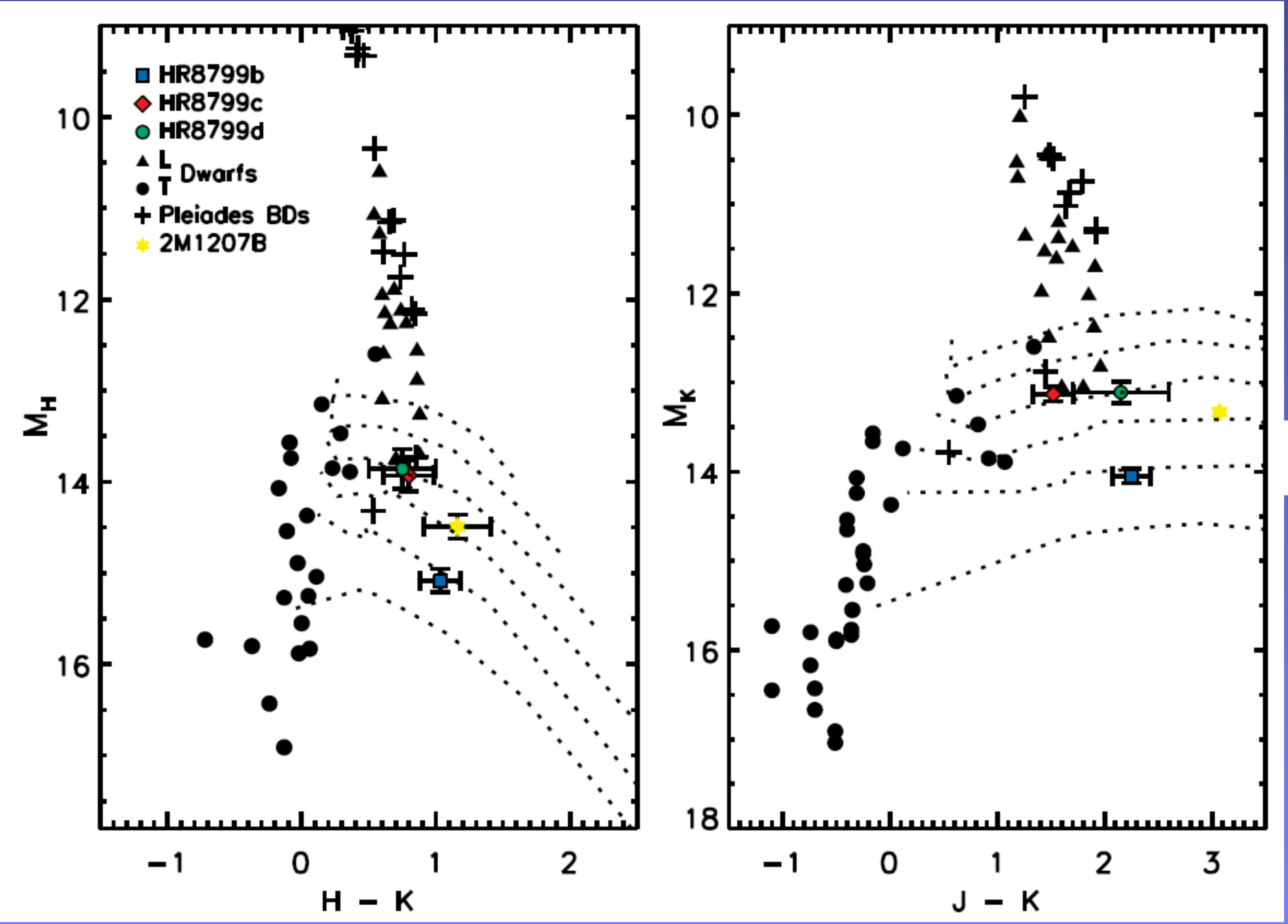
ADI processing sequence and example



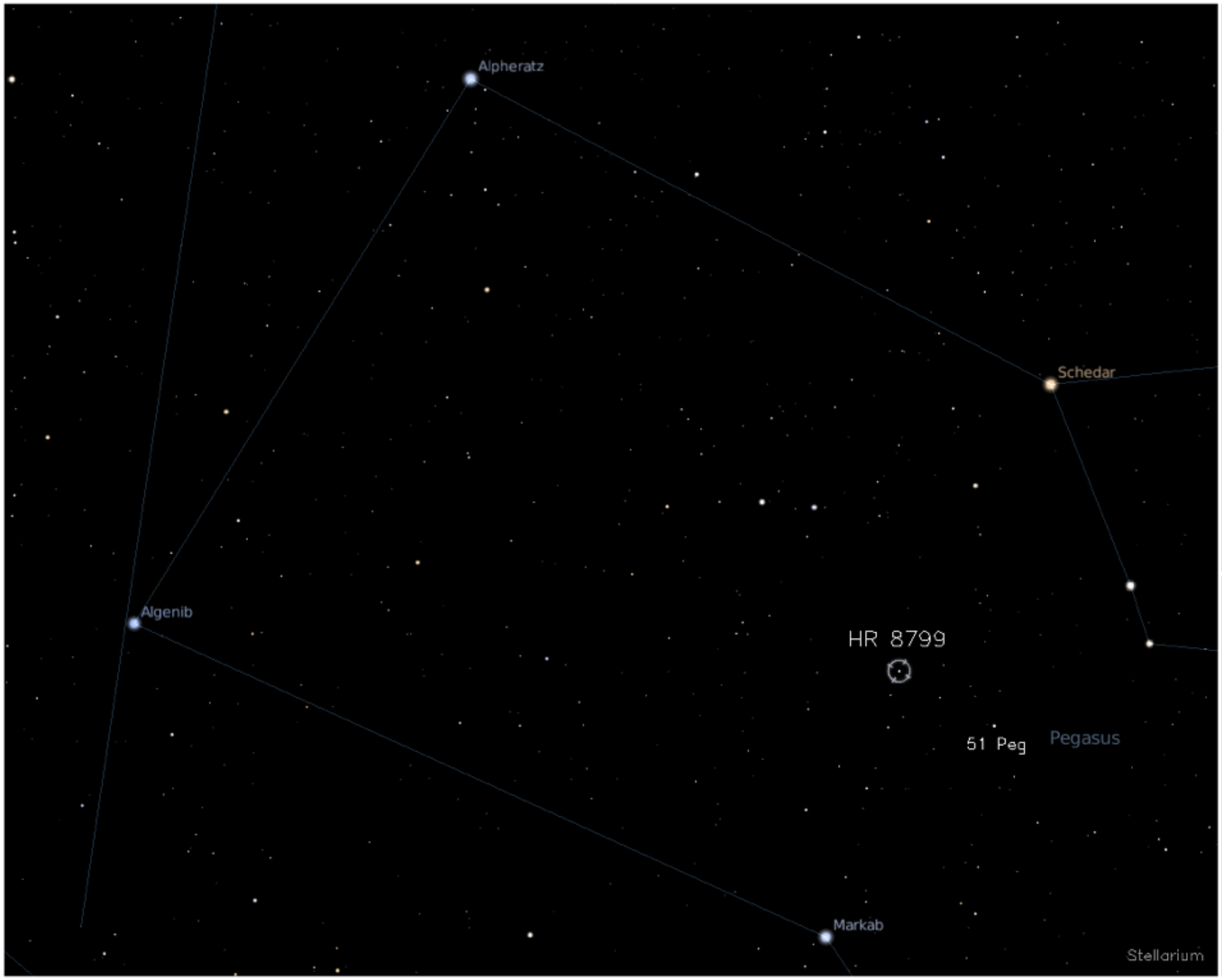
2009-2010 observations



HR8799 bcd color-magnitude (corrected)

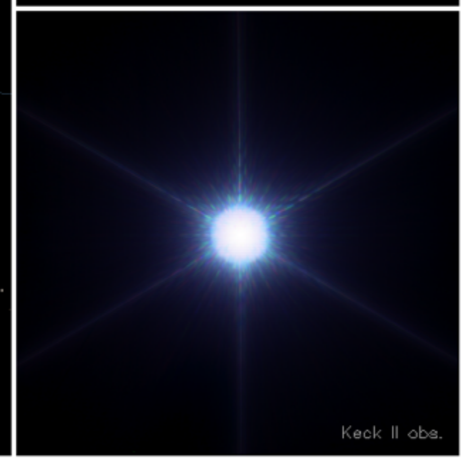


Properties of the star

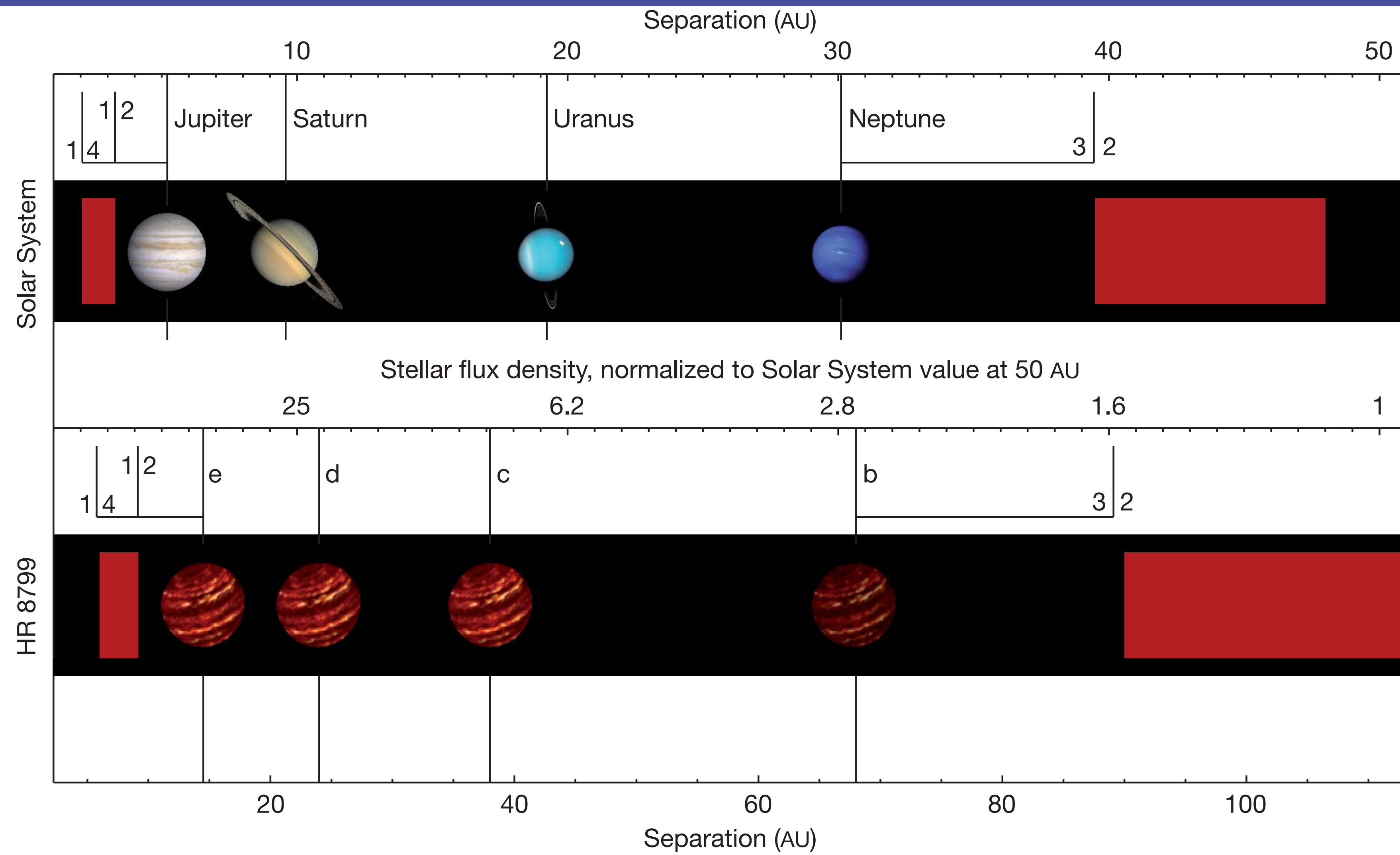


HR 8799

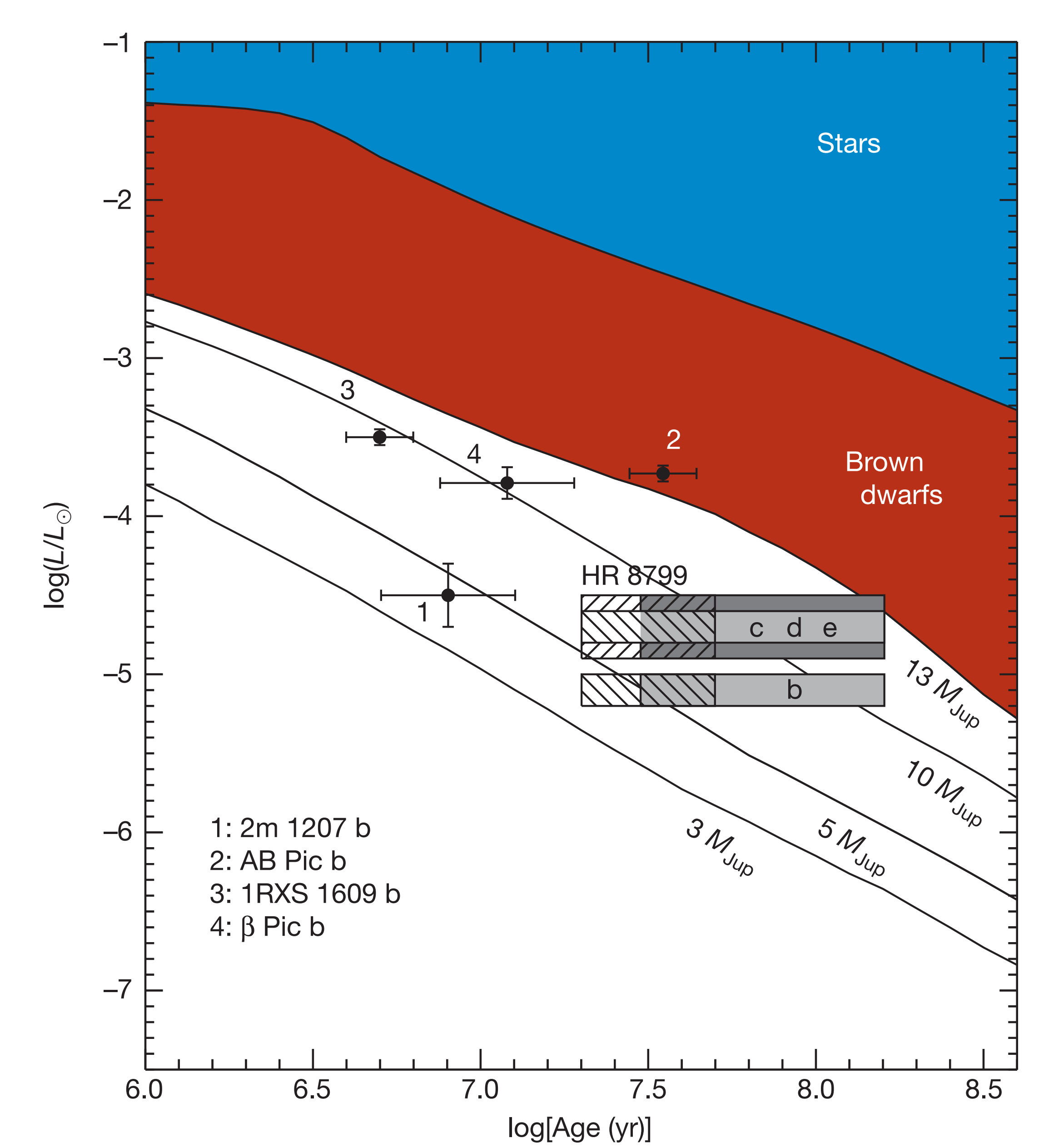
RA	23h 07 28.7
DEC	+21 08 03.3
Spectral type	A5V
Visual mag.	6.0
Distance	39 pc (130 ly)
Mass	1.5 M_{Sun}
Luminosity	5 L_{Sun}
Temperature	7400K (1.2 T_{Sun})
Age	60 Myr [30–160]



Gratuitous comparison to our solar system



Luminosity vs age ("hot start")



Nominal mass

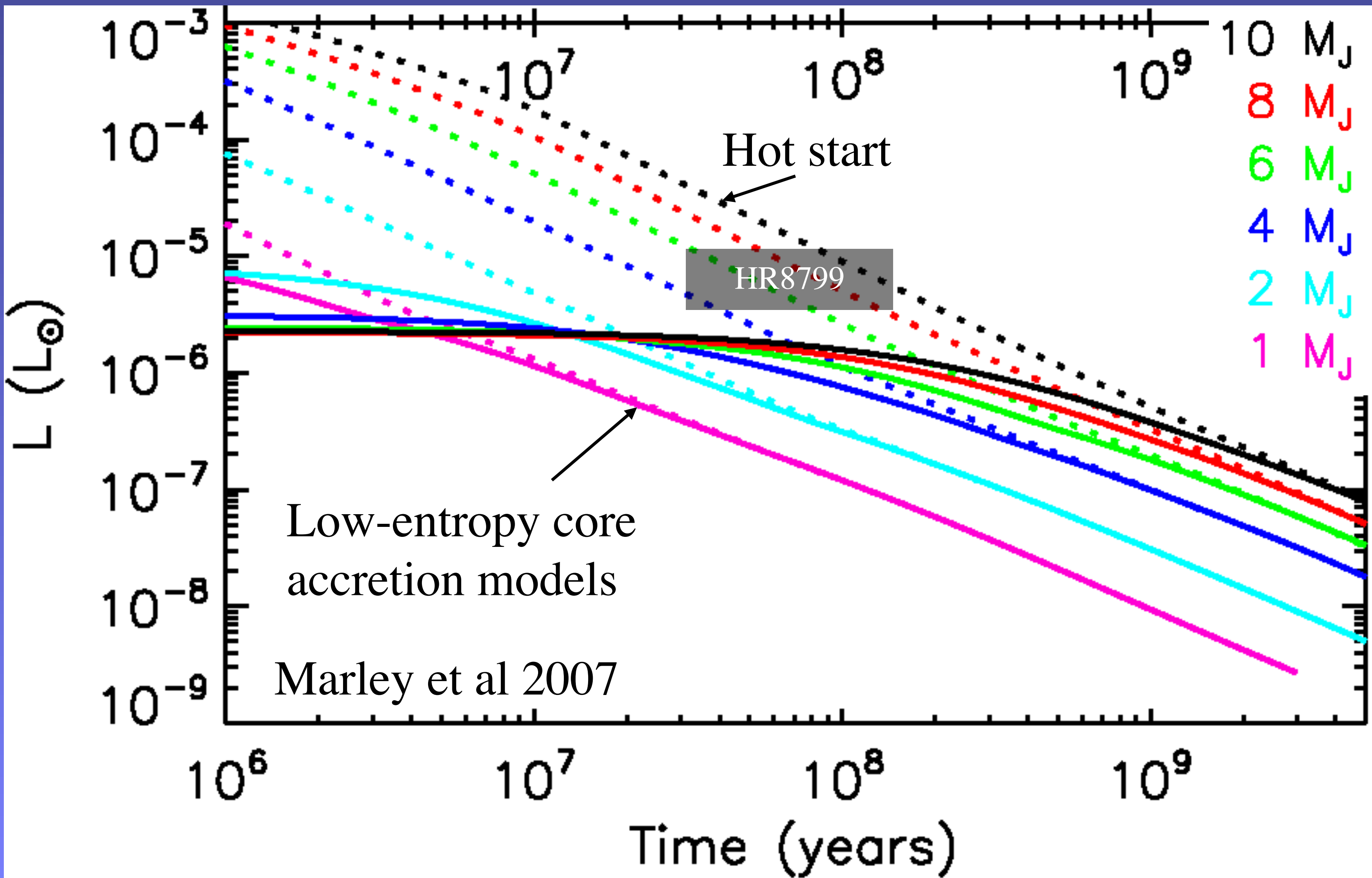
5+-2 M_J

7+-3 M_J

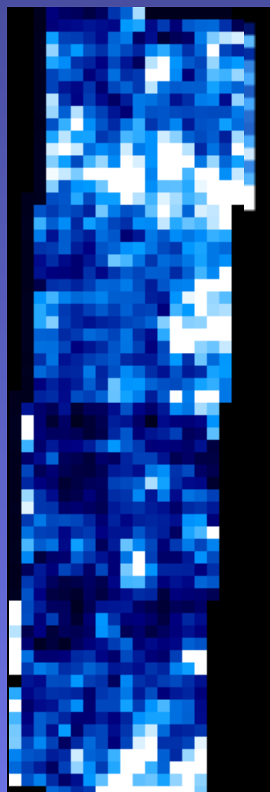
7+-3 M_J

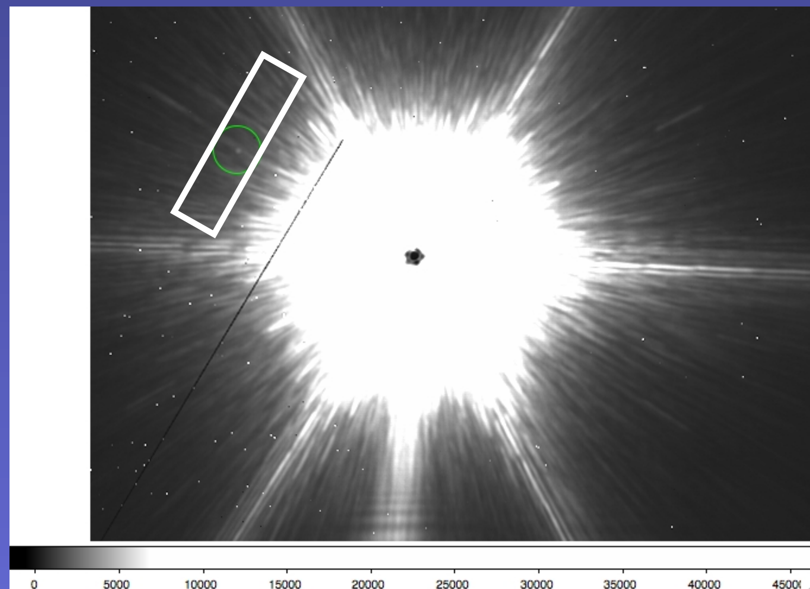
7+-3 M_J

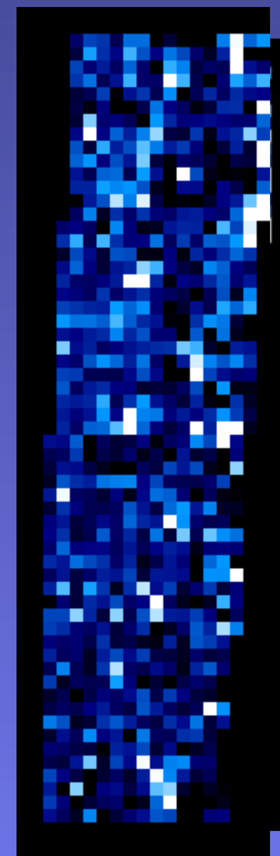
Objects not reproduced by extreme cold start



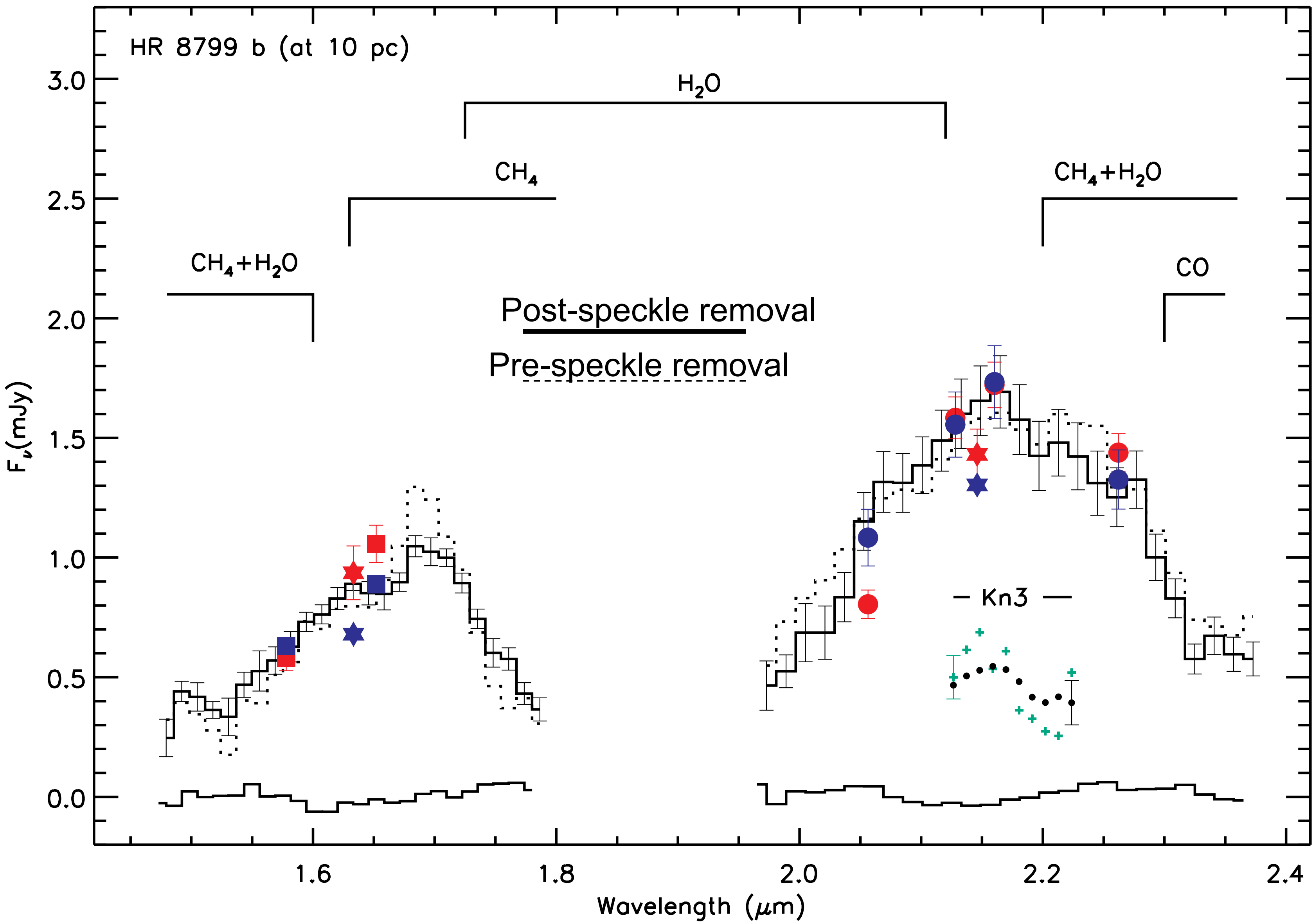
OSIRIS spectra of HR8799b (Barman et al 2011)

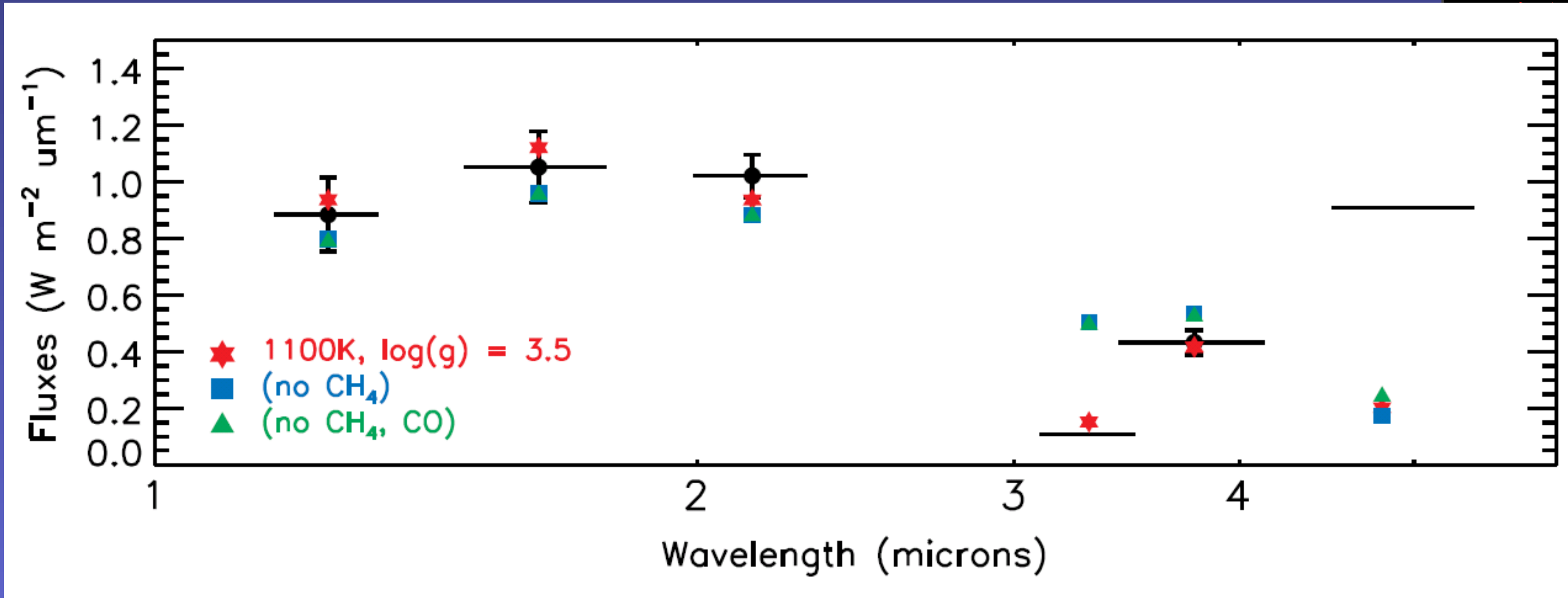




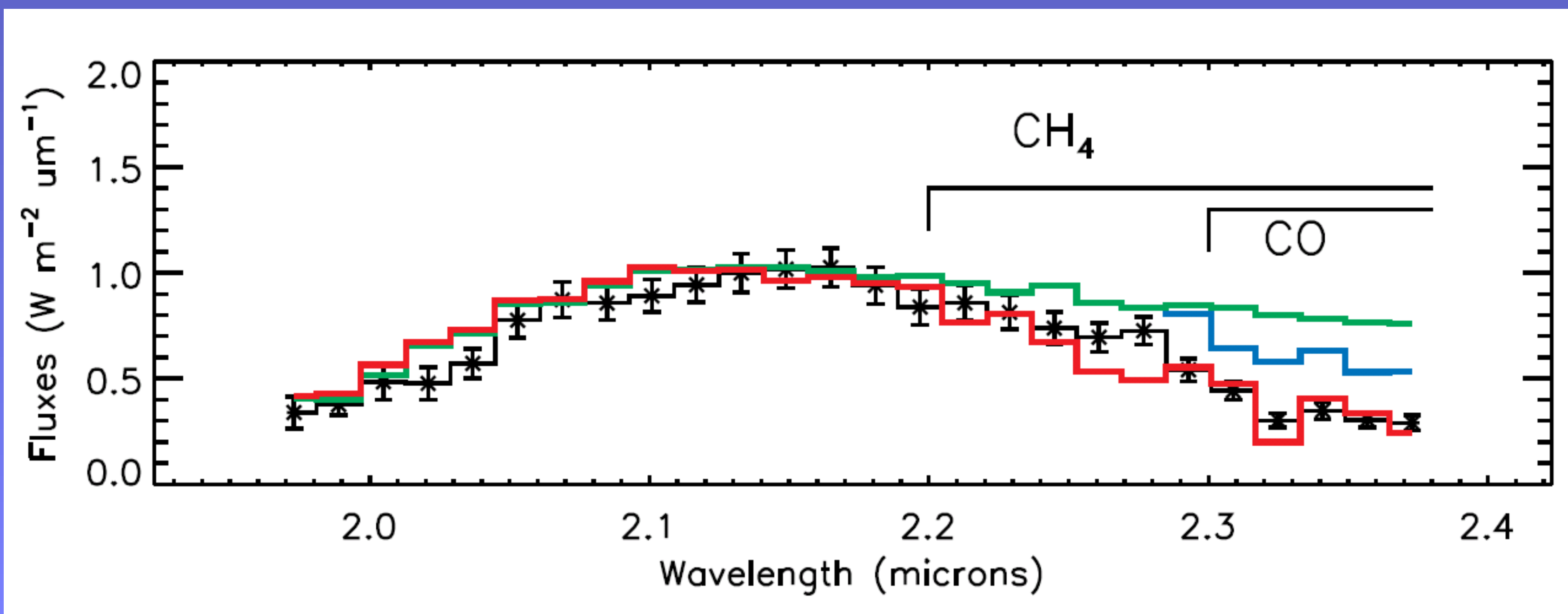


Extracted spectra of HR8799b



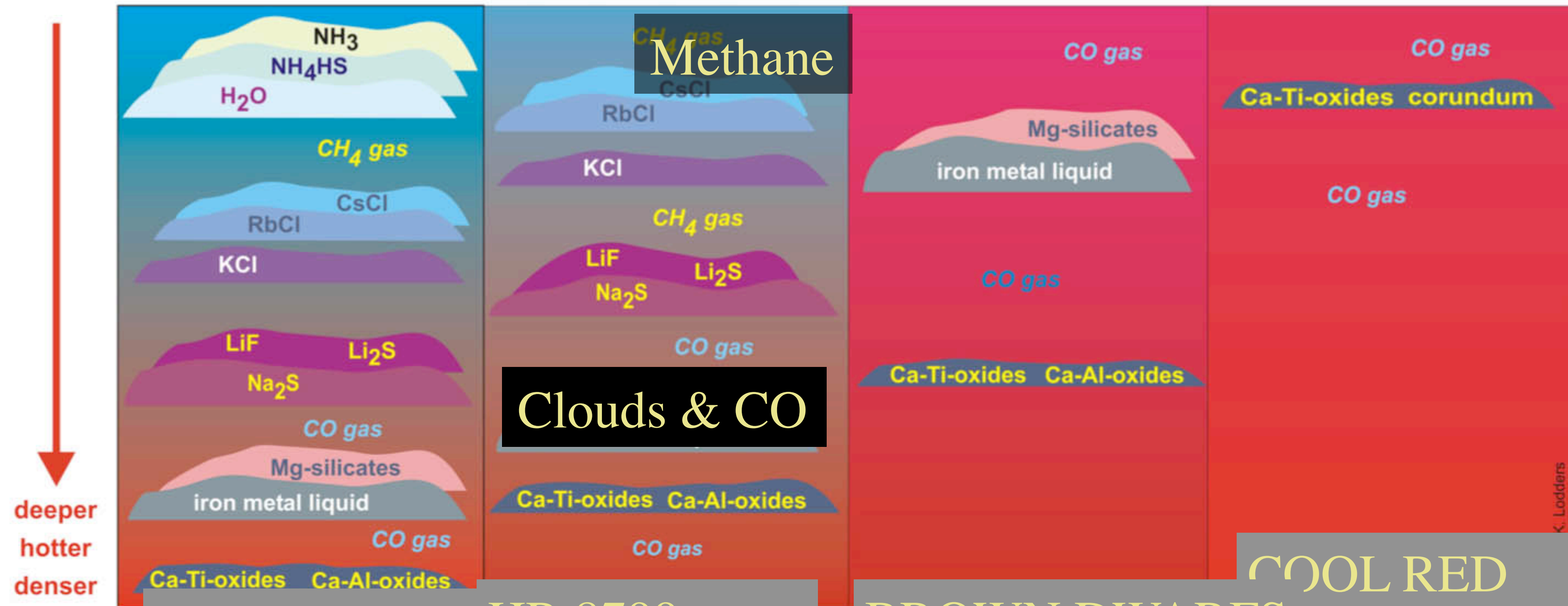


Fluxes (W m^{-2} um^{-1})
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1100K, log(g) = 3.5
(no CH_4)
(no CH_4, CO)
1
2
3
4
Wavelength (microns)



Fluxes (W m^{-2} um^{-1})
2.0
1.5
1.0
0.5
0.0
CH_4
CO
2.0
2.1
2.2
2.3
2.4
Wavelength (microns)

Atmosphere of HR8799 planets



Methane

Clouds & CO

Jupiter

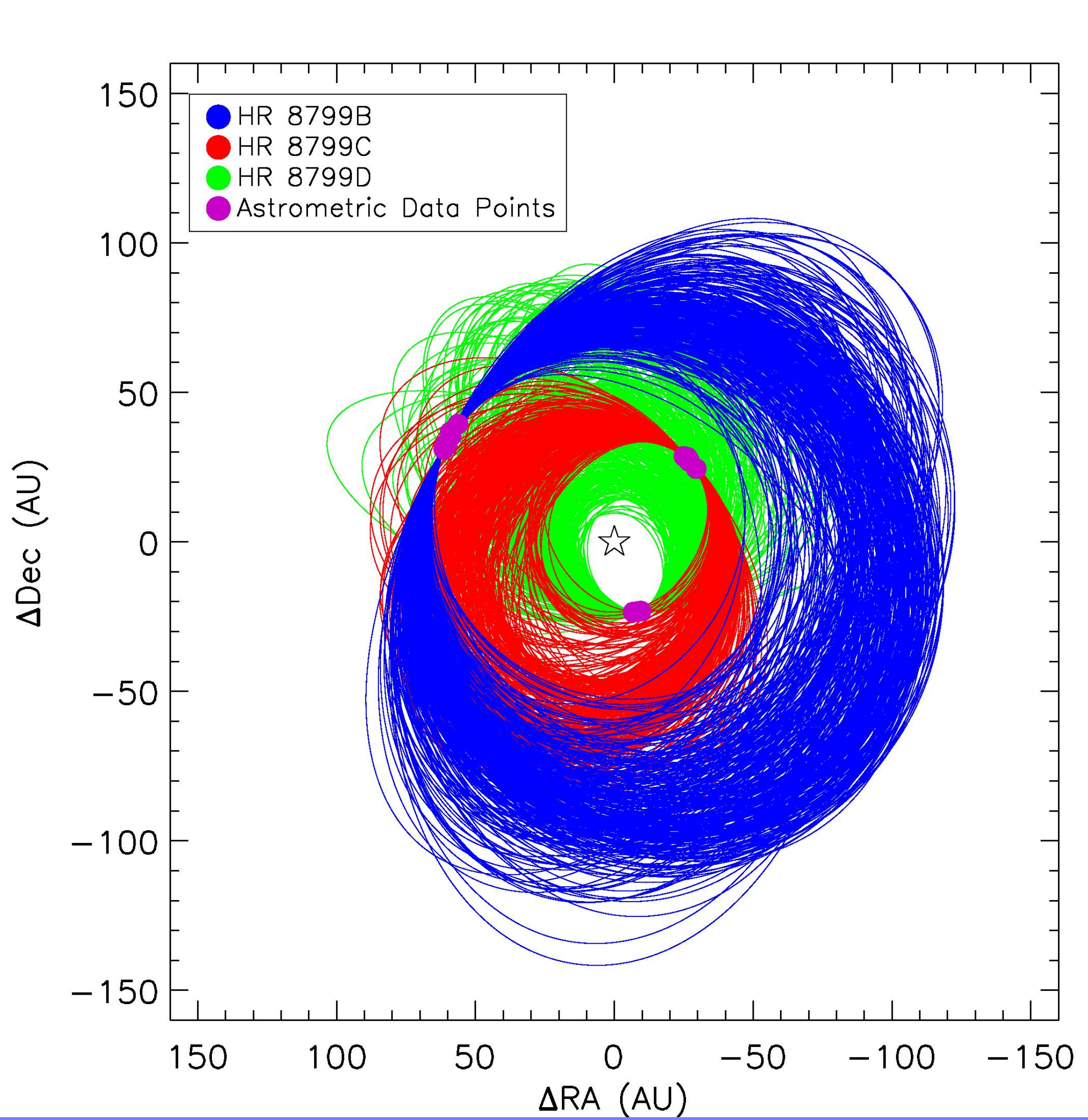
HR 8799 planets

BROWN DWARFS

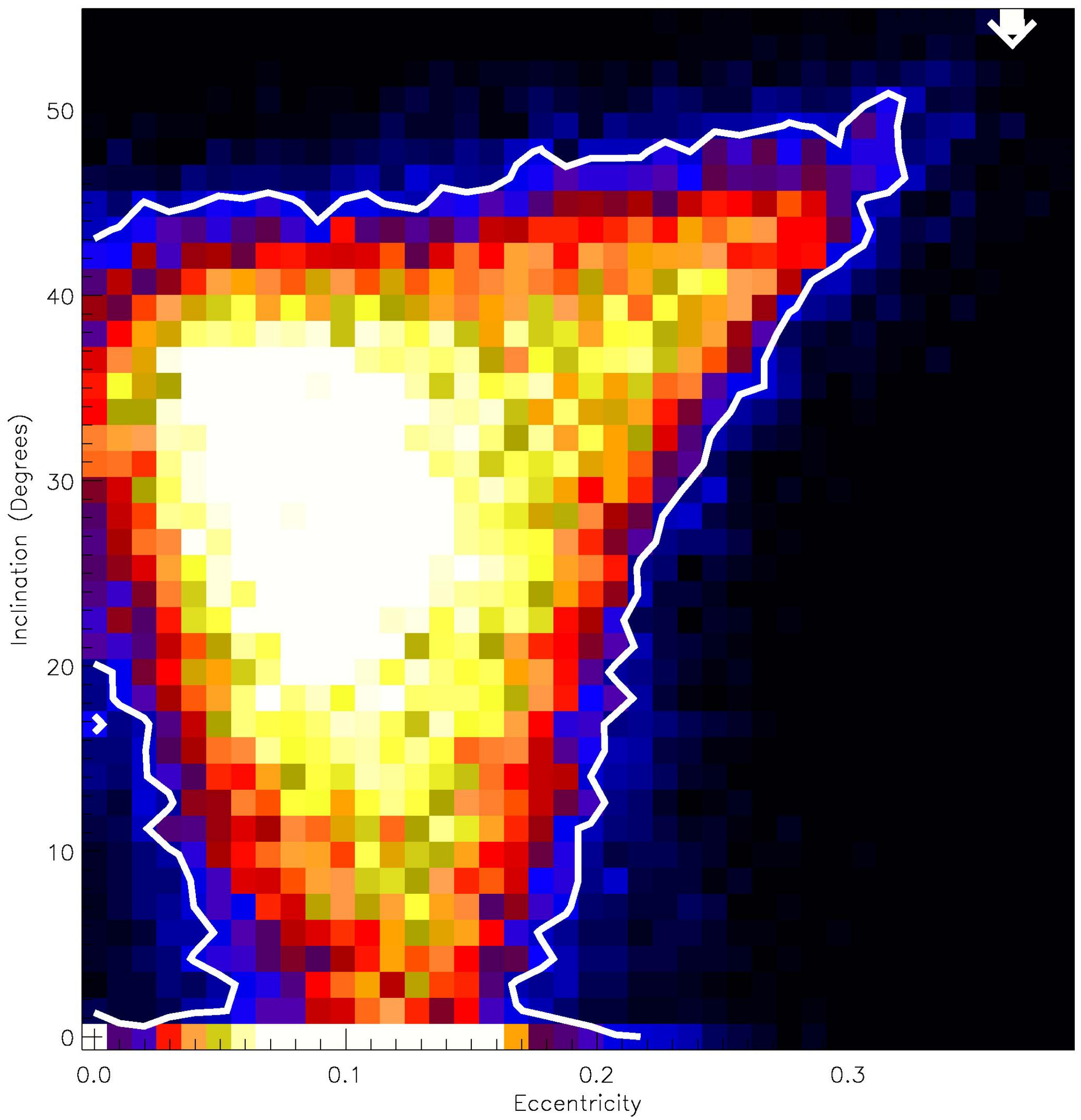
COOL RED DWARF STARS

Burgasser et al. 2009 white paper / after Lodders & Fegley 2006

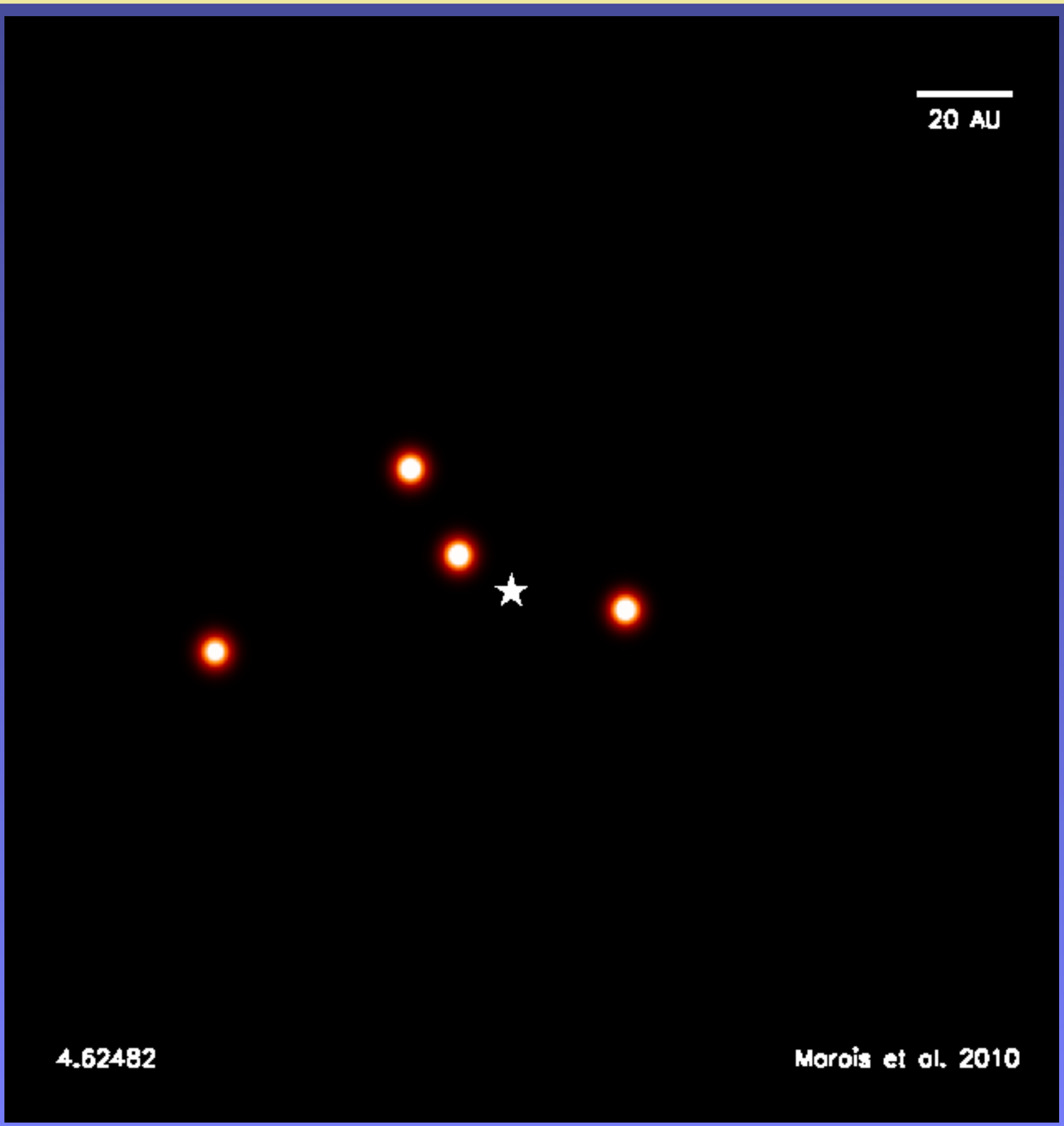
Estimating the orbits



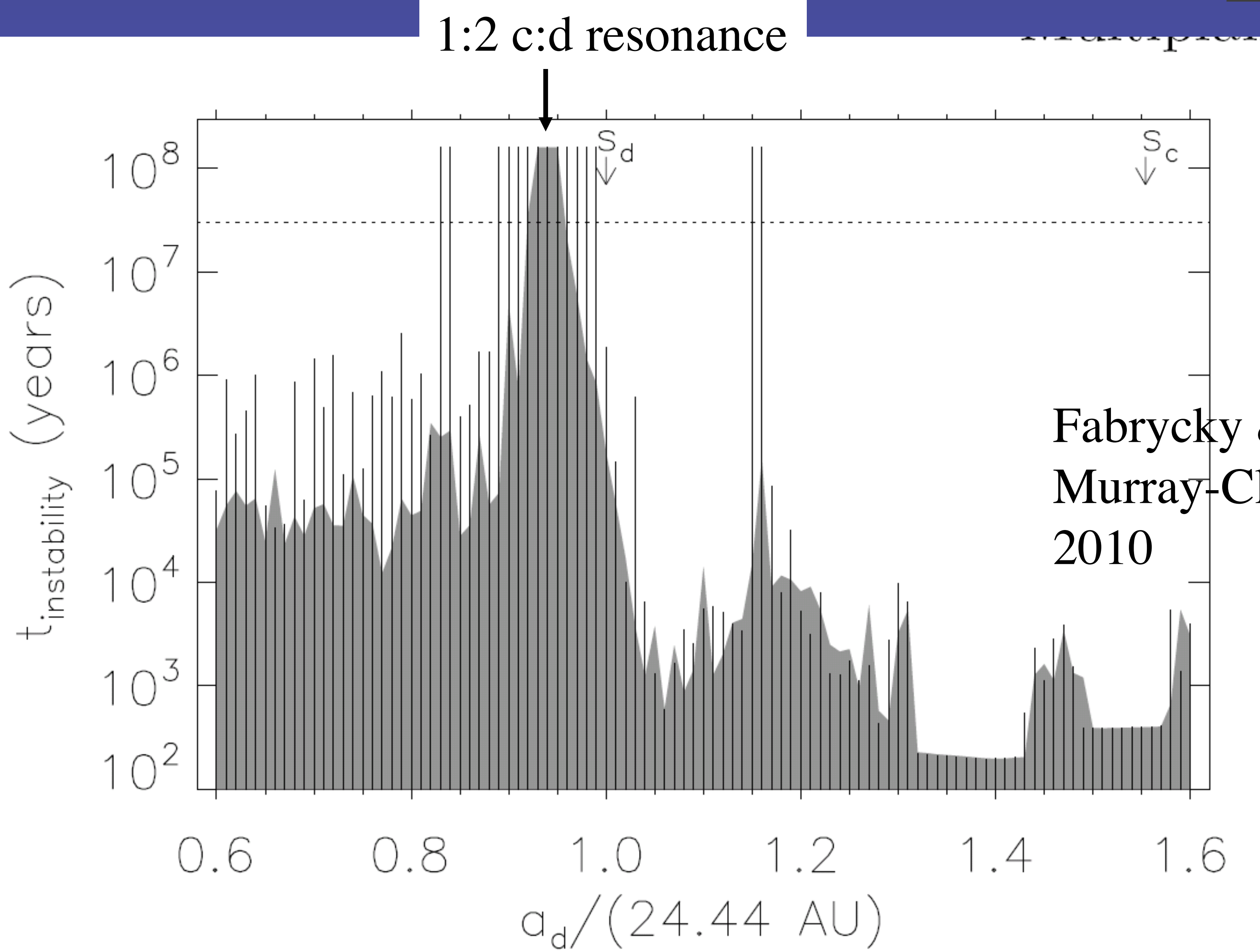
Orbital parameters



Numerical integration of orbits with MERCURY

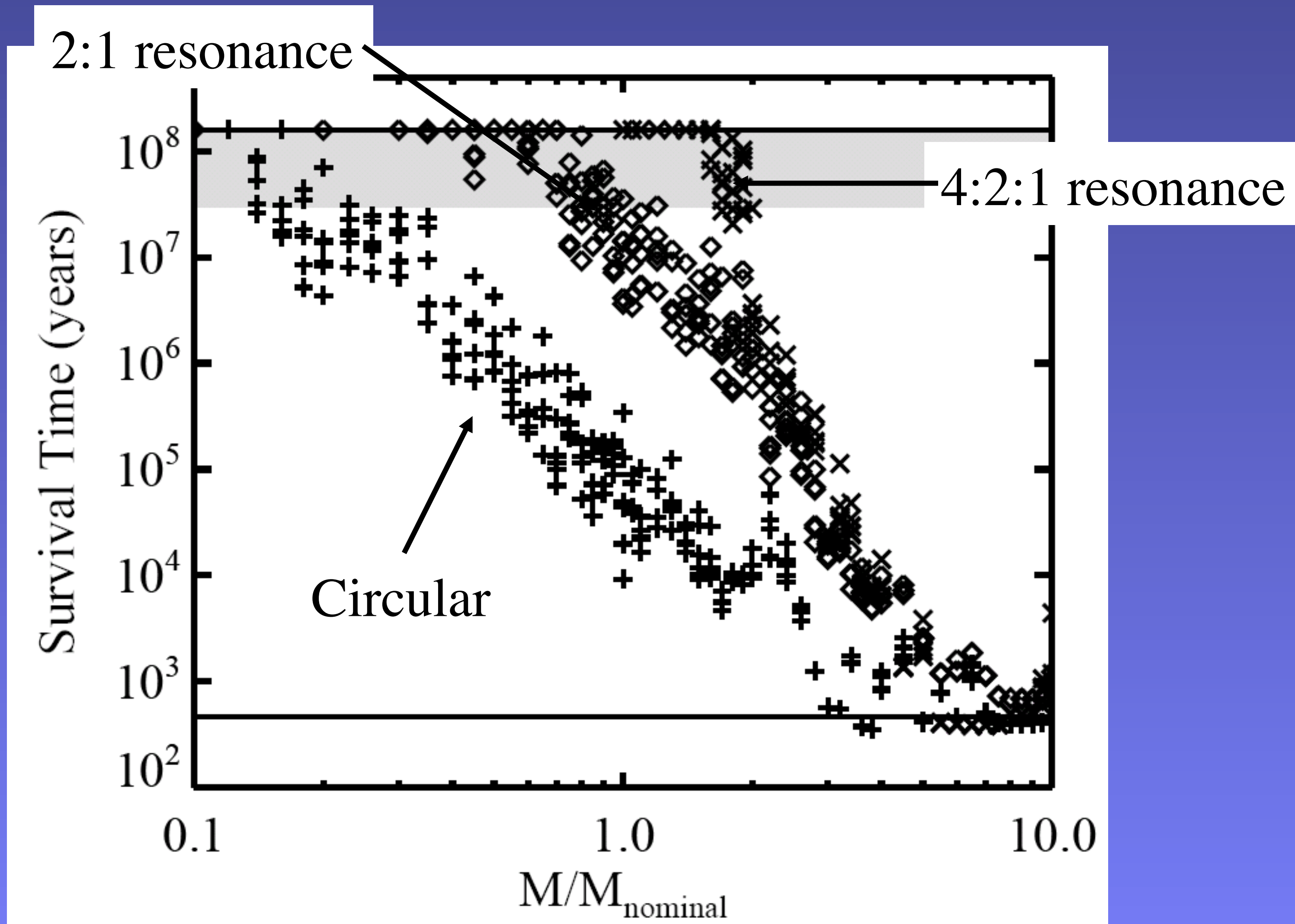


2010 Lifetime for M=5,7,7 as a function of a_d



Fabrycky & Murray-Clay 2010

Stability vs mass (FM2010)



Formation?

Core accretion + migration

+produces reasonably circular orbits

+can trap into resonances

-very hard to produce big planets this far out with plausible disks

-planet brightness not consistent with "cold start"

Core accretion + scattering

+can produce range of orbital separations

+evidence for dynamical instability

-predicts generally very elliptical orbits

-needs extra planets

Disk instability

+can produce big planets at wide separations

+can produce range of inclinations

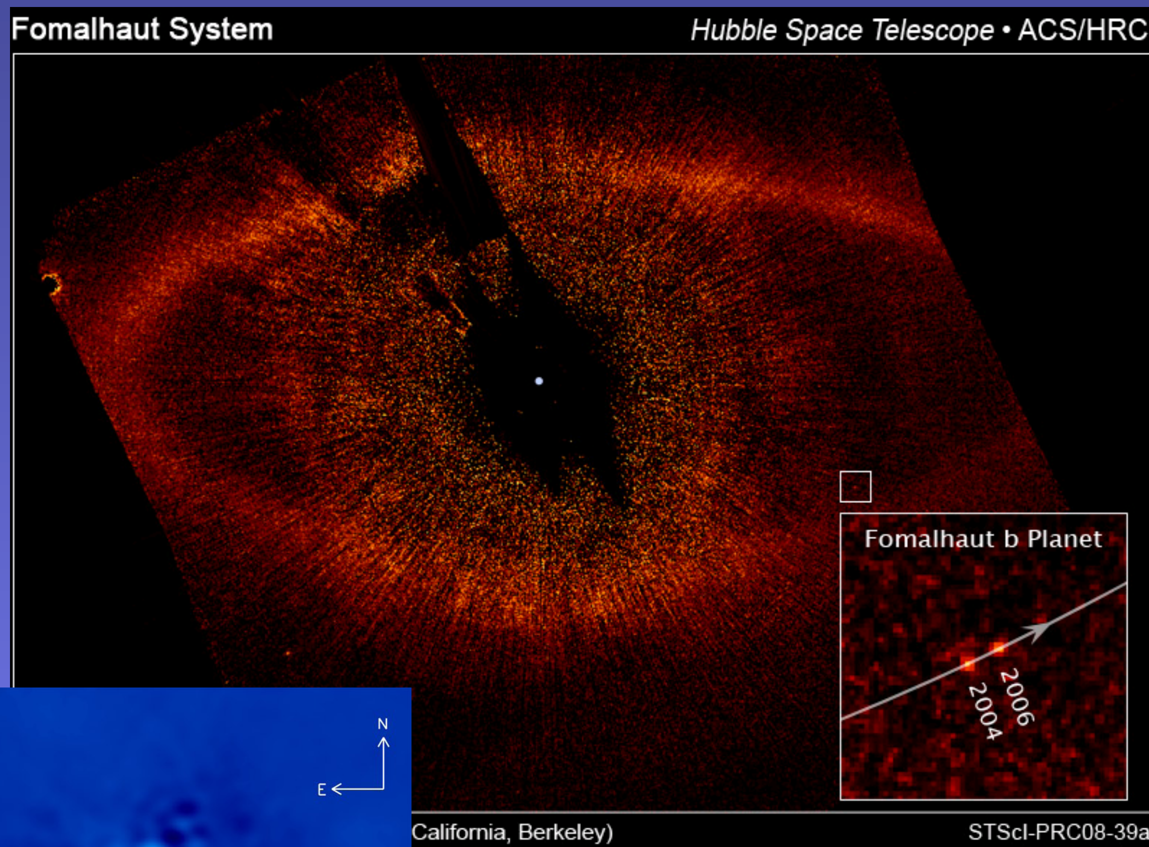
+planet brightness consistent with hot start

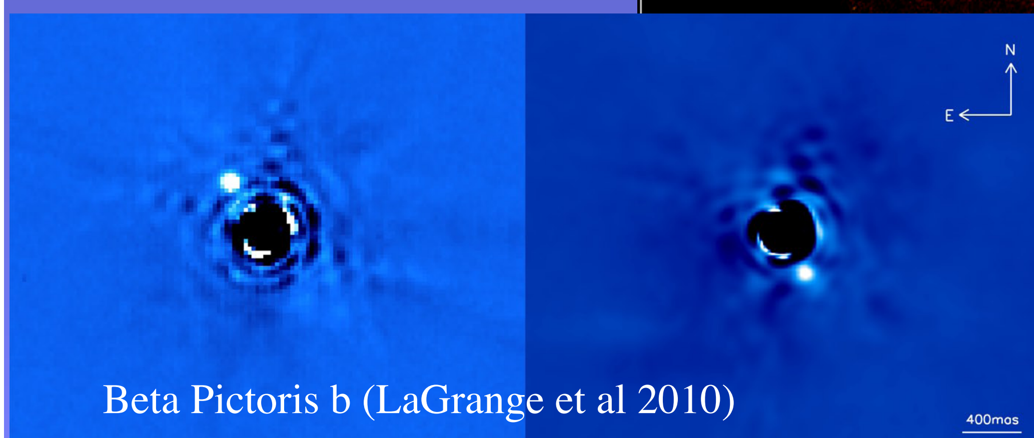
-has trouble producing objects this small

-no evidence of large population of high-mass equivalents

Other direct images

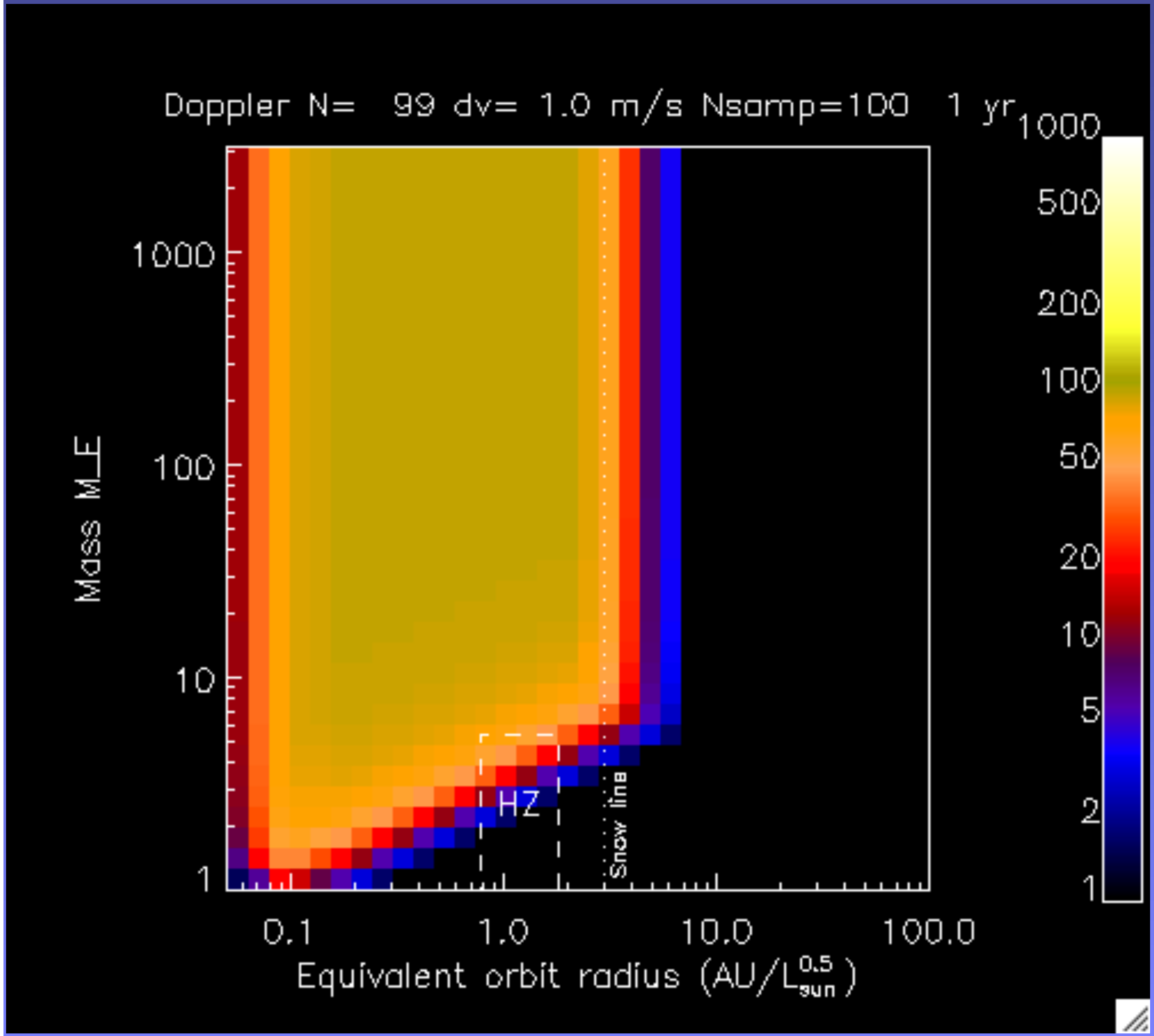
Wide-orbit massive planets more common around early-type stars?





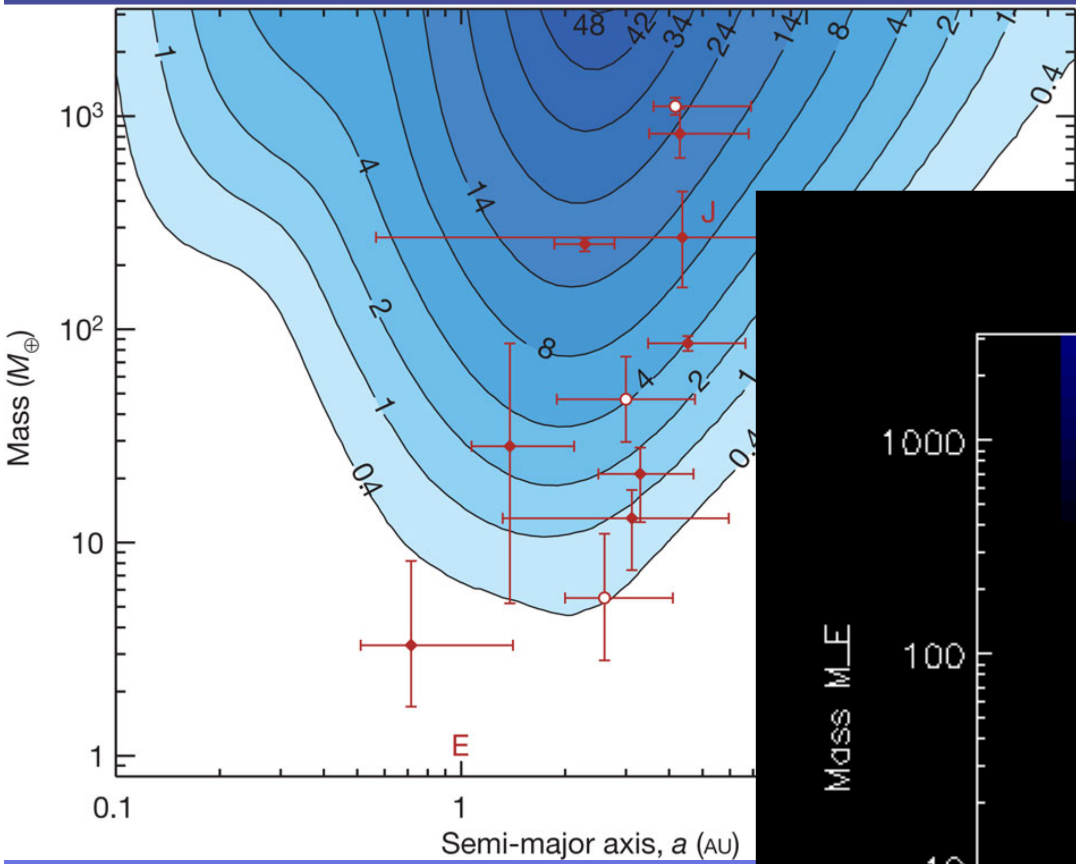
Beta Pictoris b (LaGrange et al 2010)

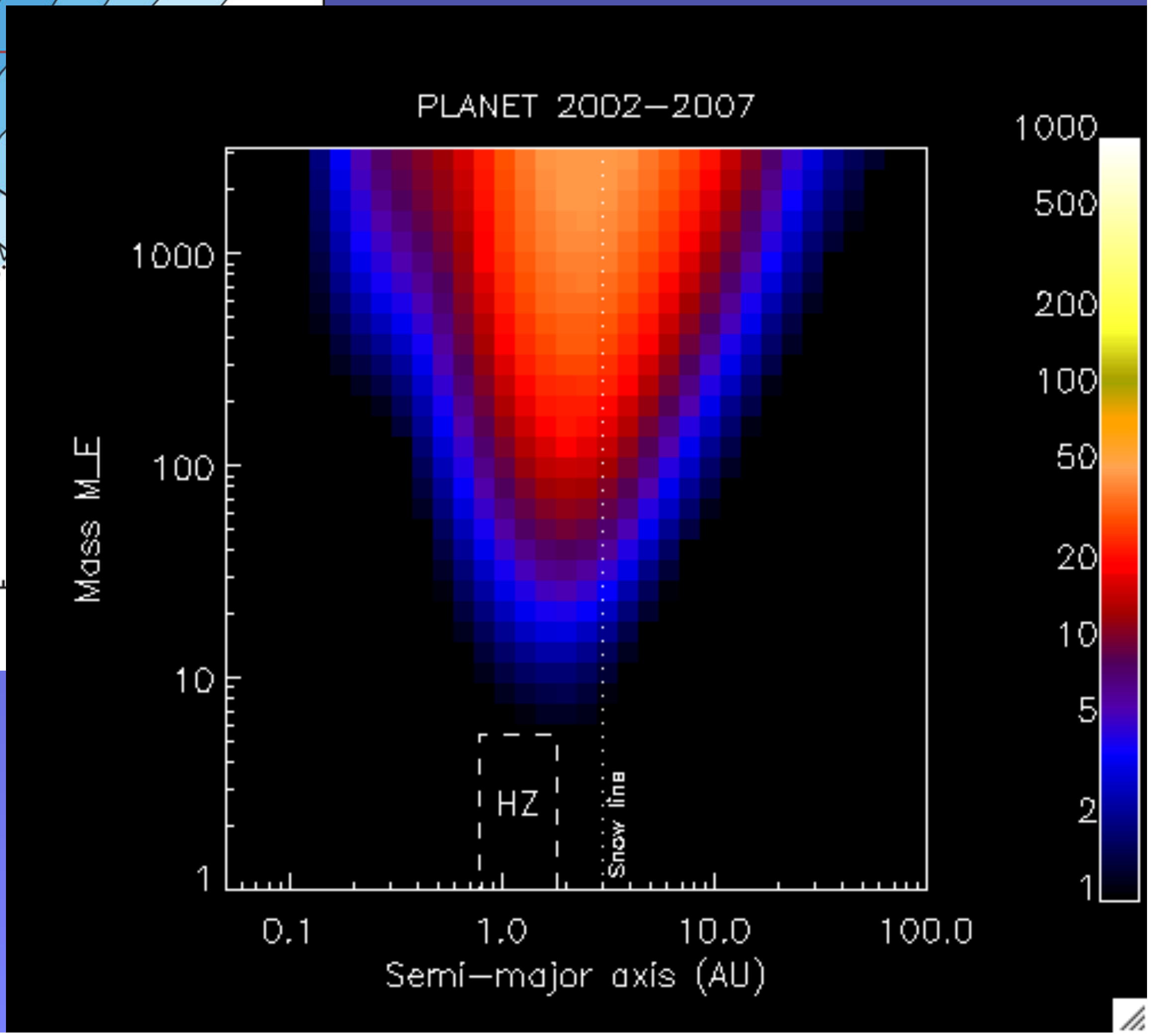
Depth of search comparisons (ExoPTF)



Sum of completeness for every star ="if every star had a planet…"

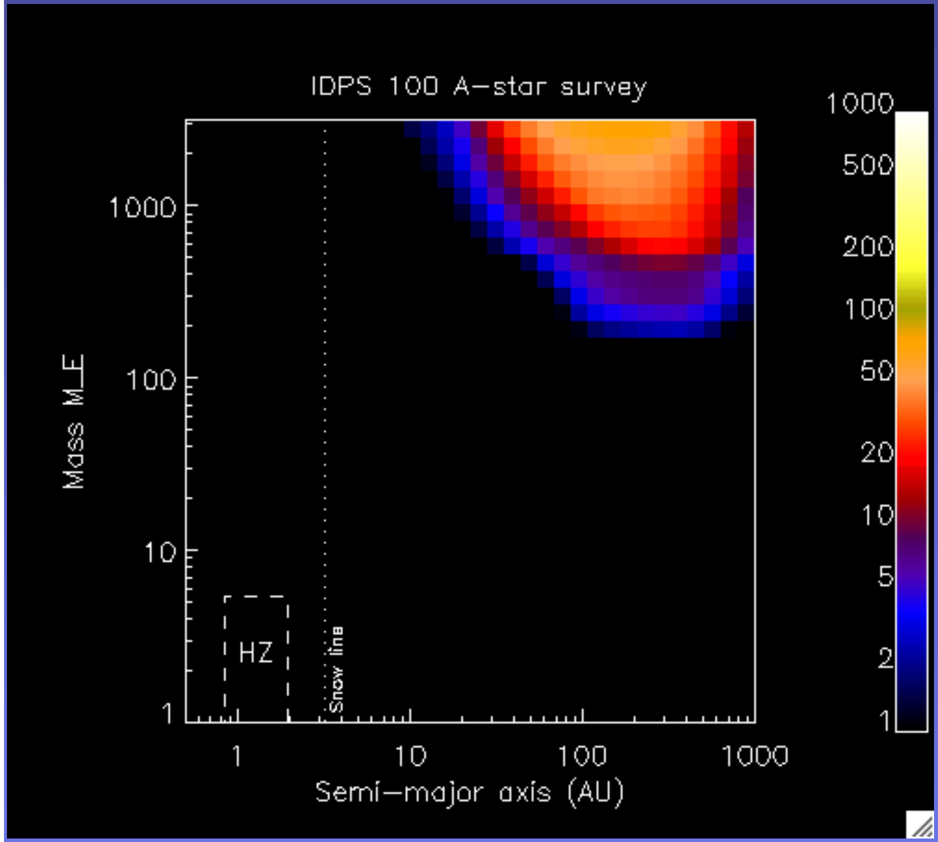
Cassan et al 2012

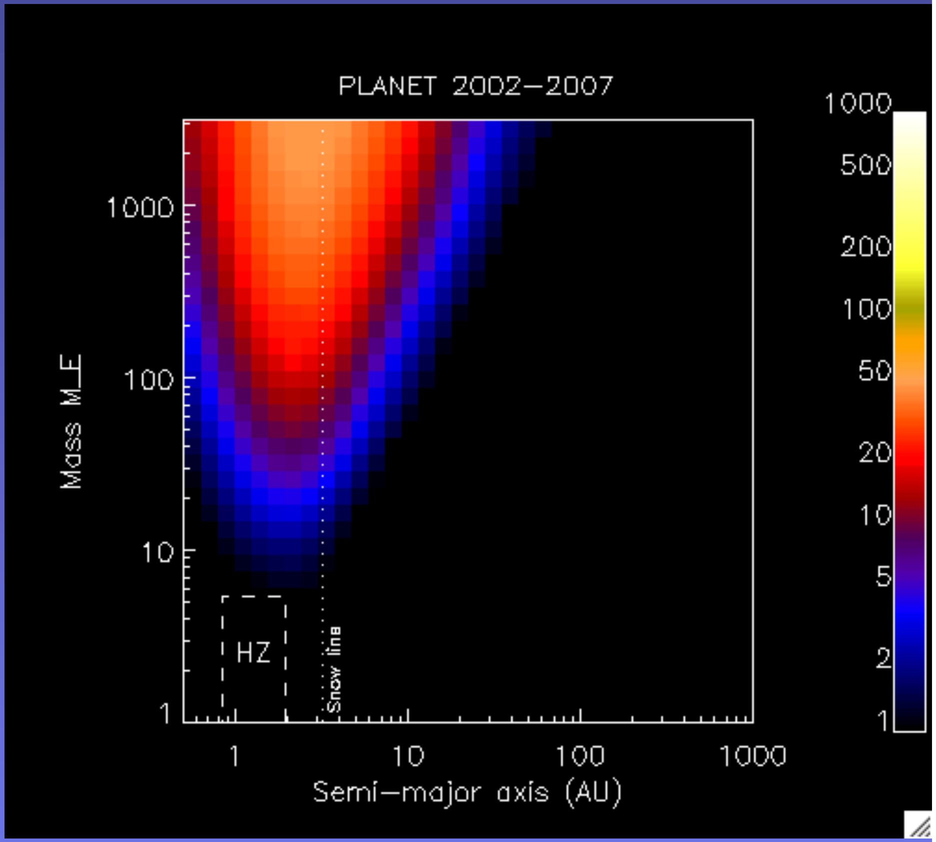




Thanks to
Arnaud Cassan
for data

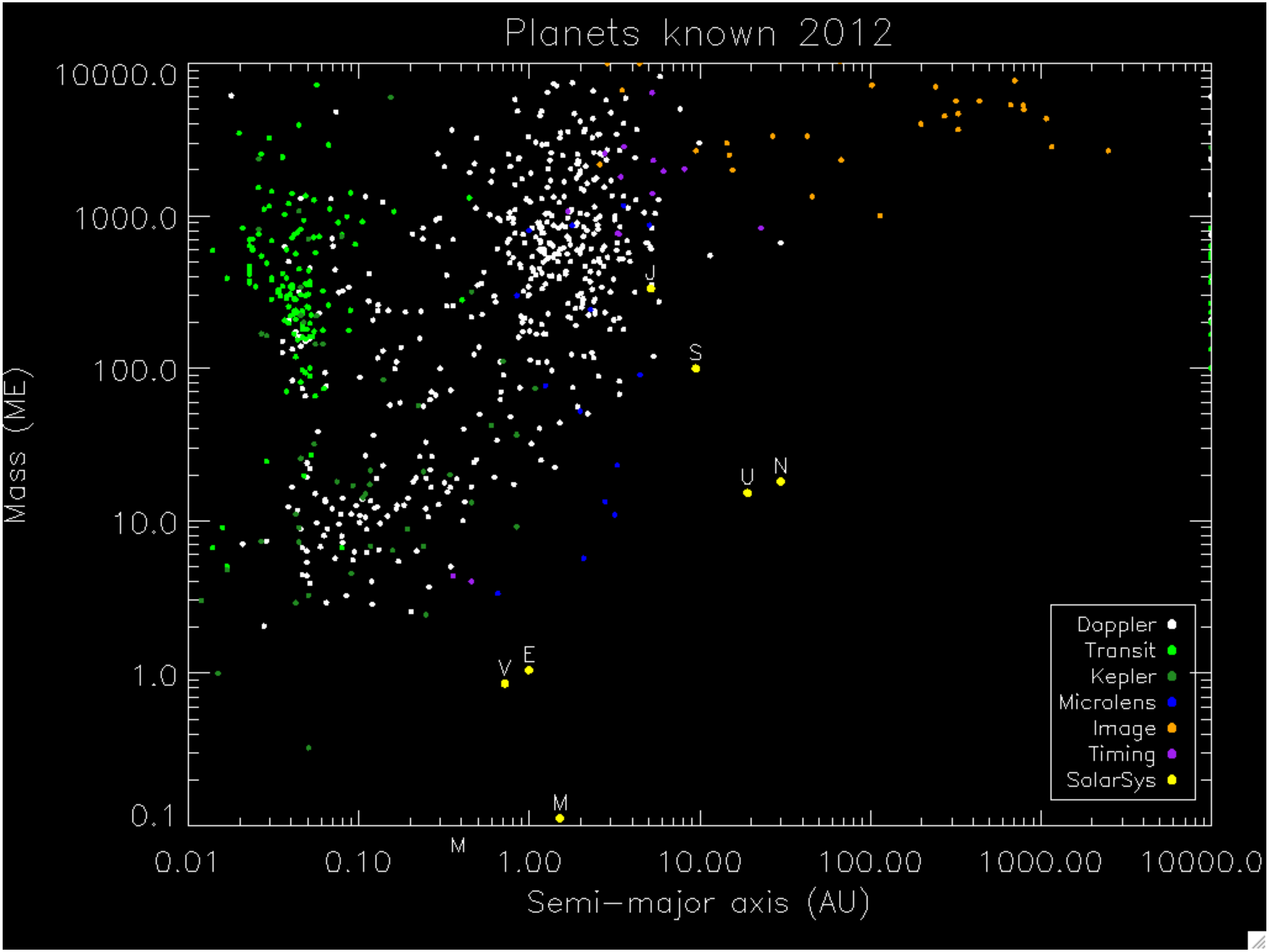
Survey comparison





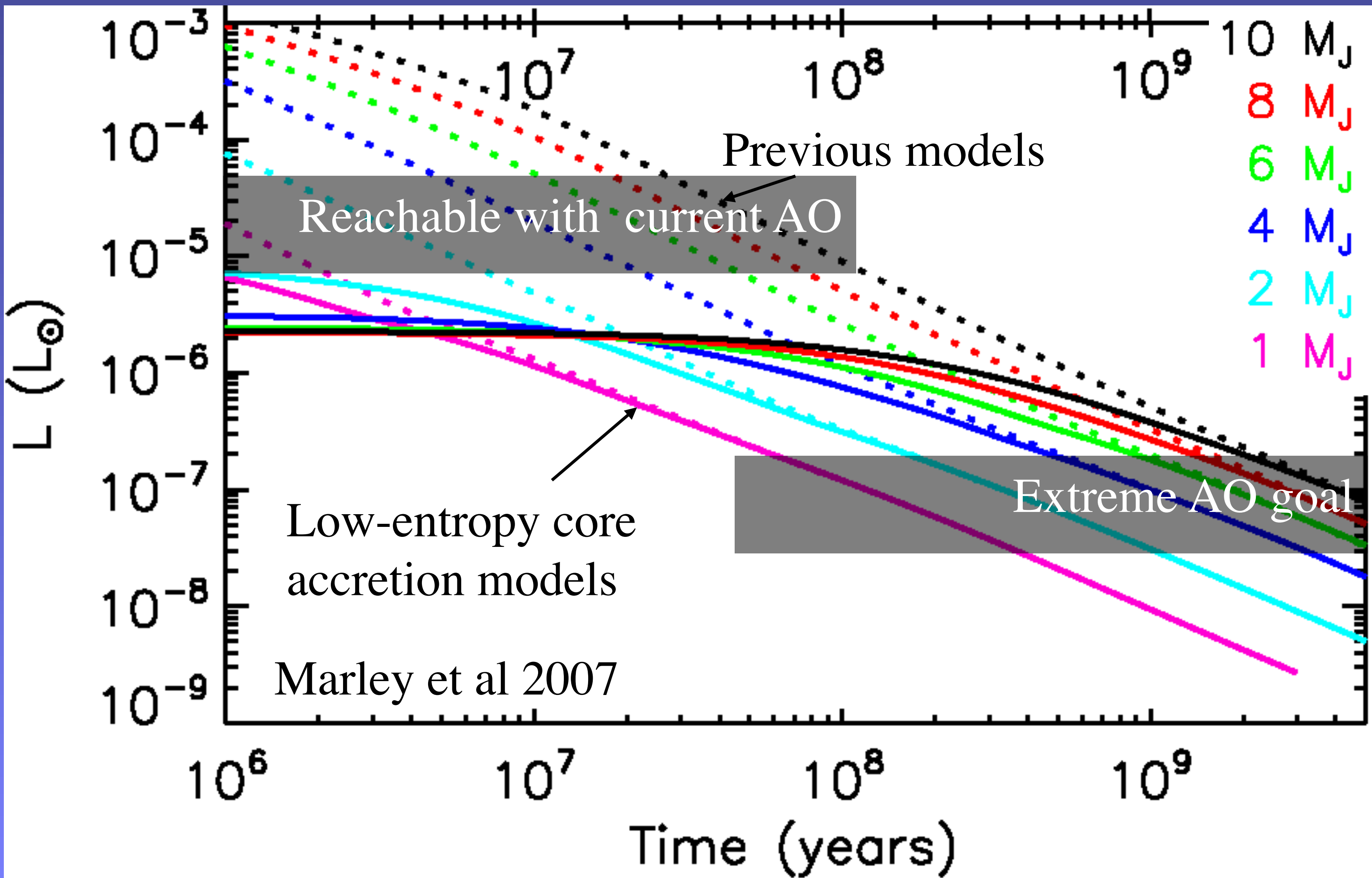
International Deep Planet Survey (A stars) from **Vigan et al (2012 submitted) and Galichier et al (2012 in prep)**; see also LaFrenier et al, Biller et al, etc.

PLANET from Cassan et al 2012

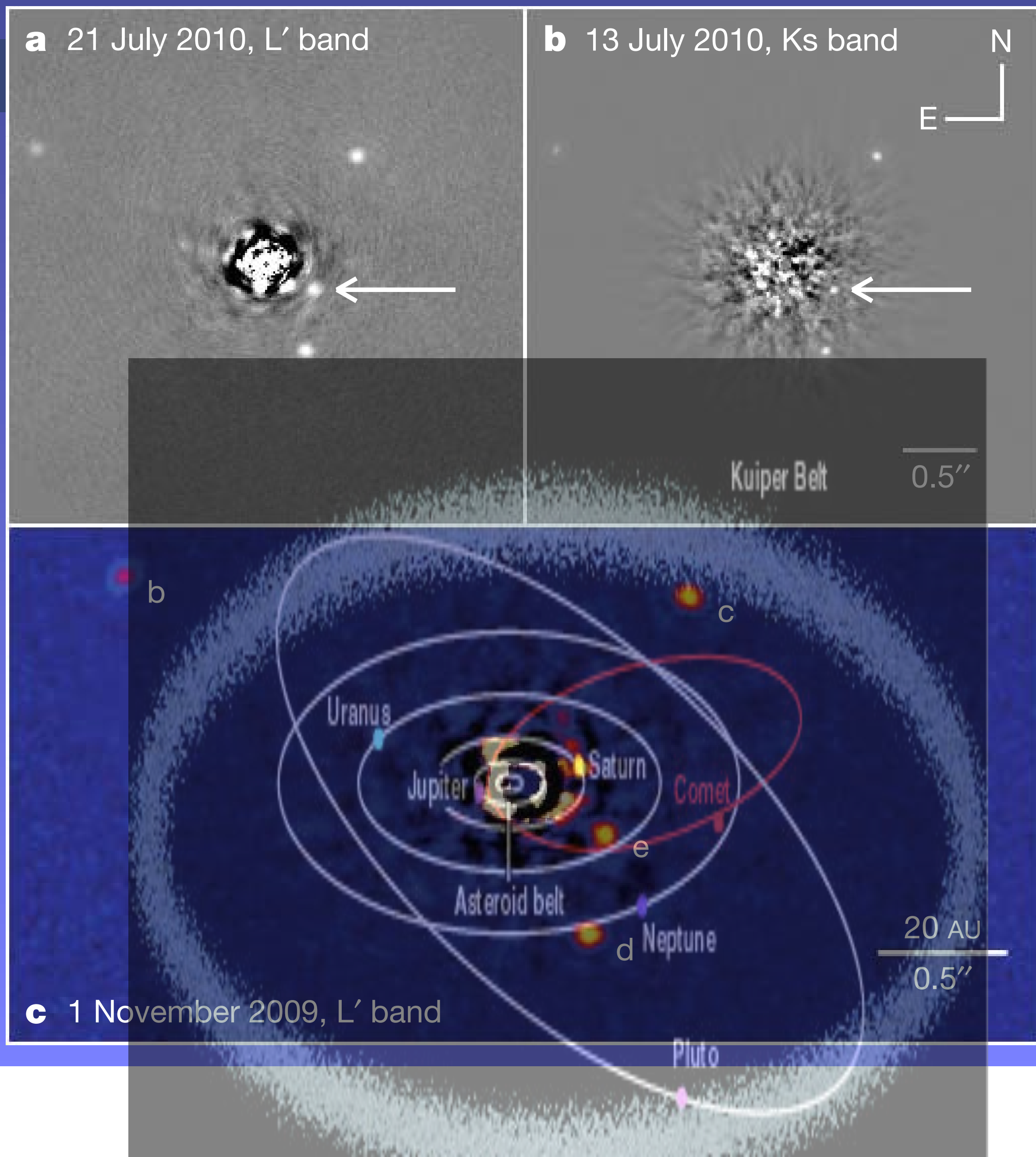


Planets known 2012
Mass (ME)
10000.0
1000.0
100.0
10.0
1.0
0.1
0.01
0.10
1.00
10.00
100.00
1000.00
10000.0
Semi−major axis (AU)
J
S
U
N
V
E
M
M
Doppler
Transit
Kepler
Microlens
Image
Timing
SolarSys

Older stars = more stars

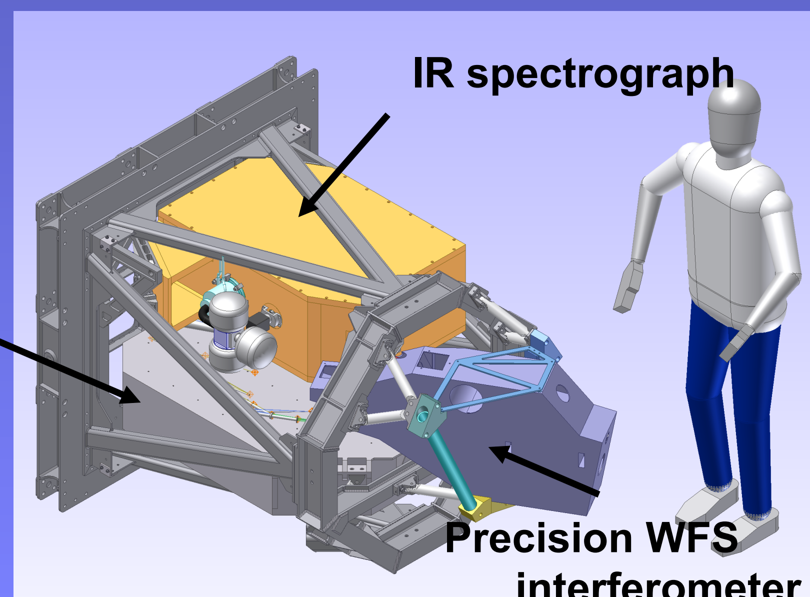


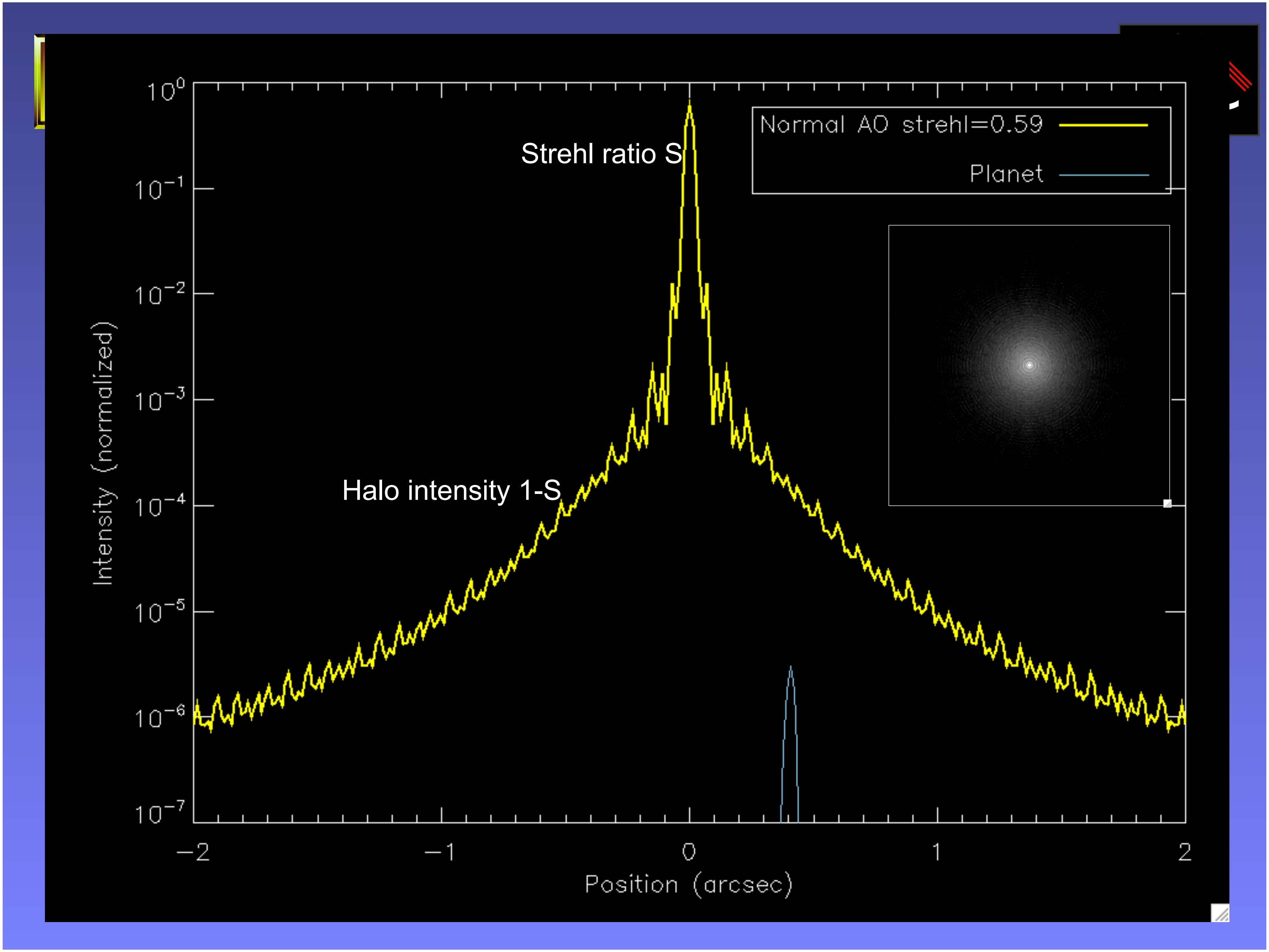
HR8799 system



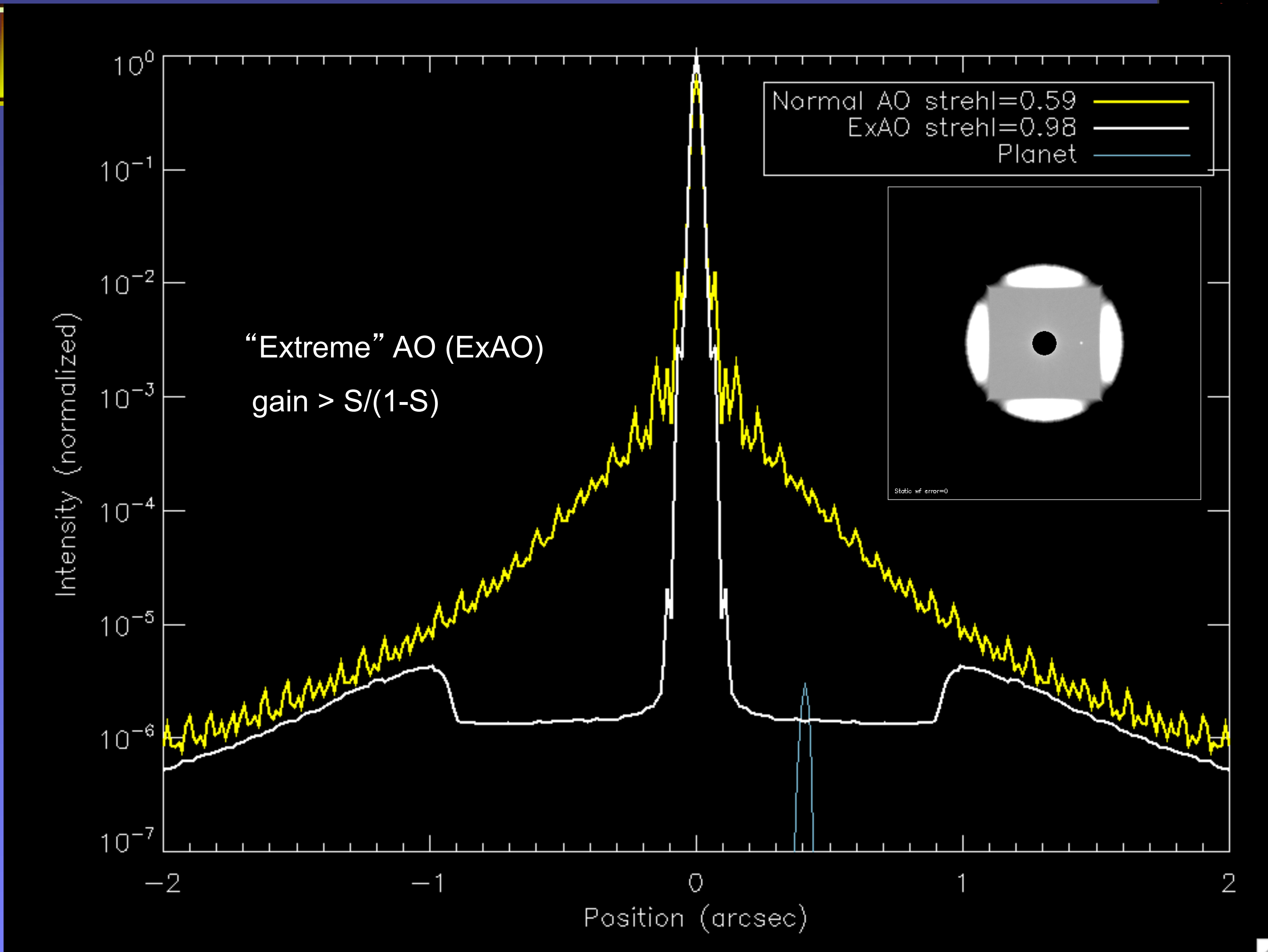
Gemini Planet Imager

AO + diffraction control

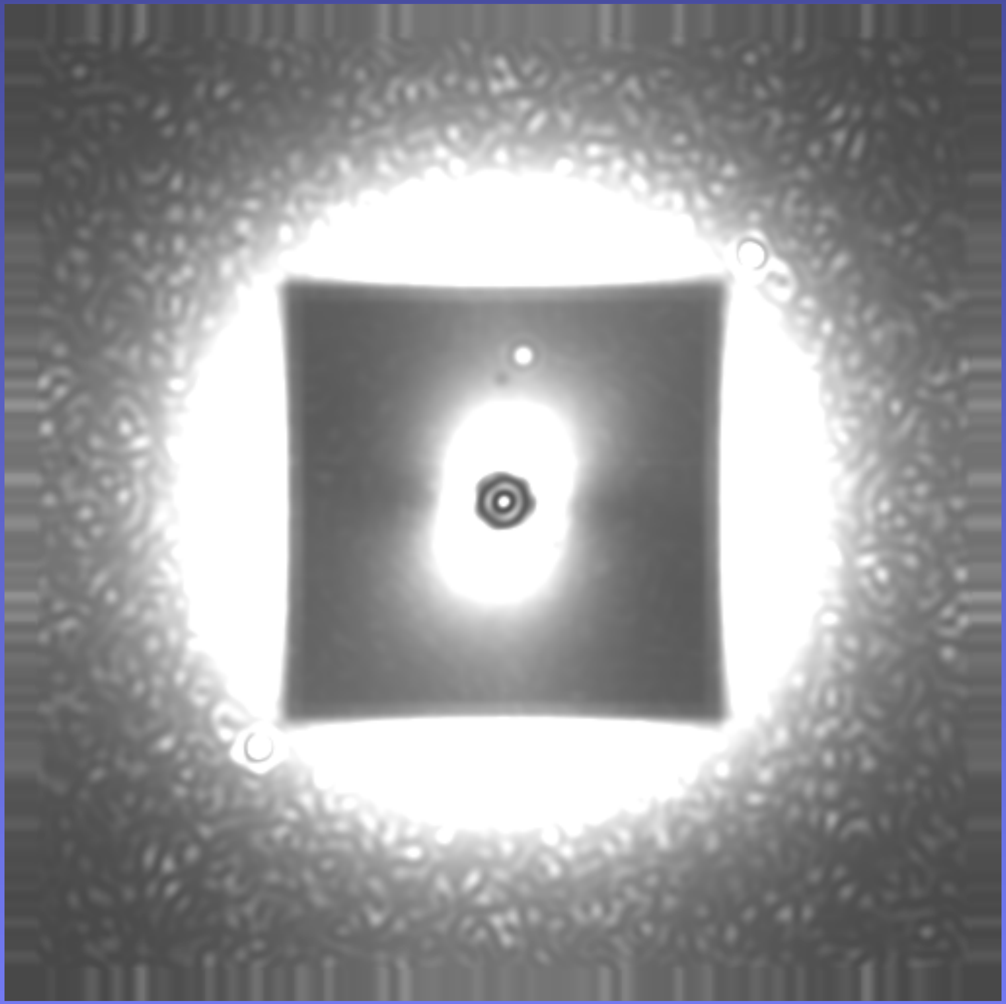




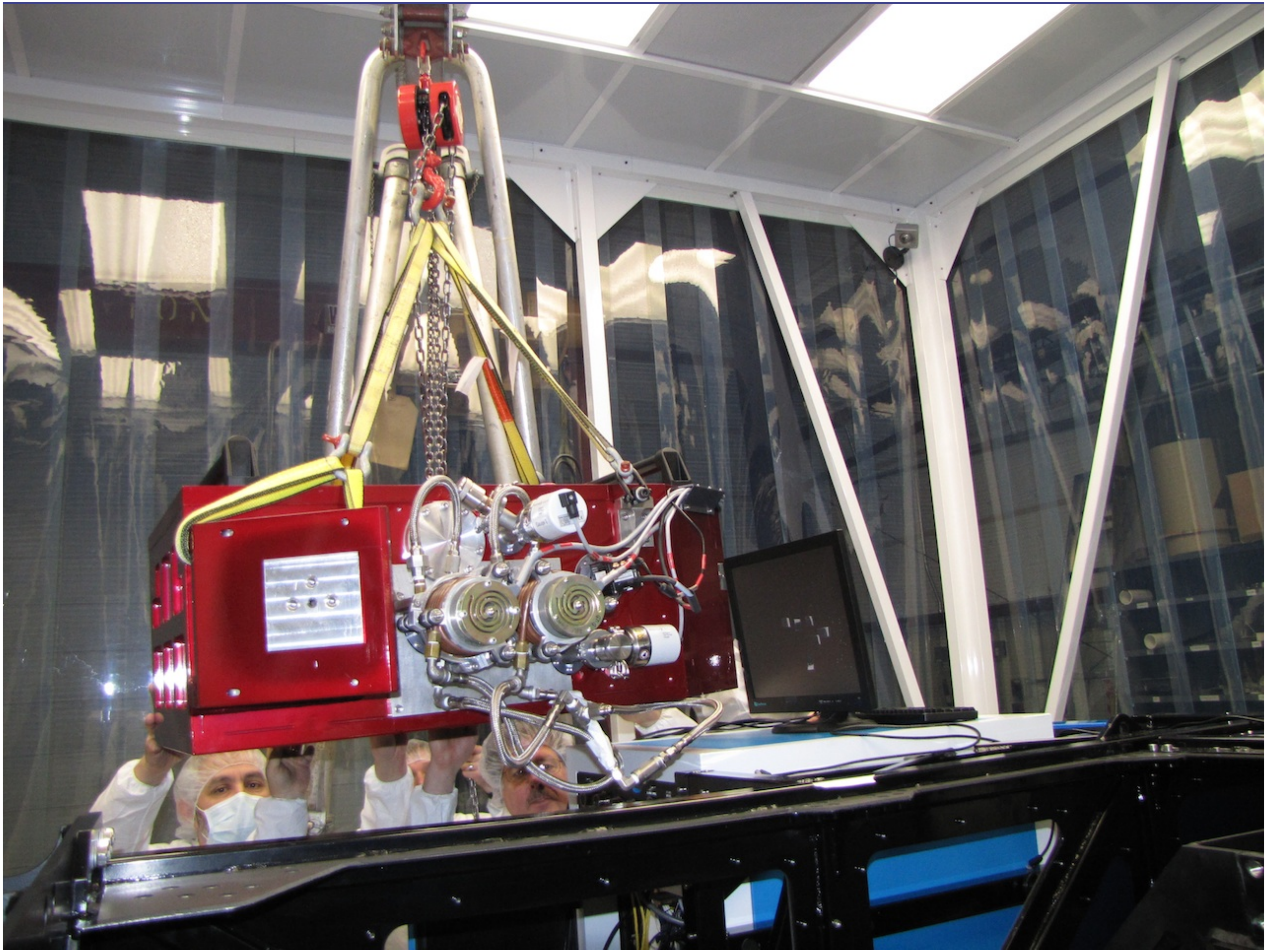
Strehl ratio S
Halo intensity 1-S
Normal AO strehl=0.59
Planet
Intensity (normalized)
Position (arcsec)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
−2
−1
0
1
2


"Extreme" AO (ExAO)
gain > S/(1-S)
Normal AO strehl=0.59
ExAO strehl=0.98
Planet
Intensity (normalized)
Position (arcsec)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
−2
−1
0
1
2

Multiwavelength data cube



Christian Marois, HIA

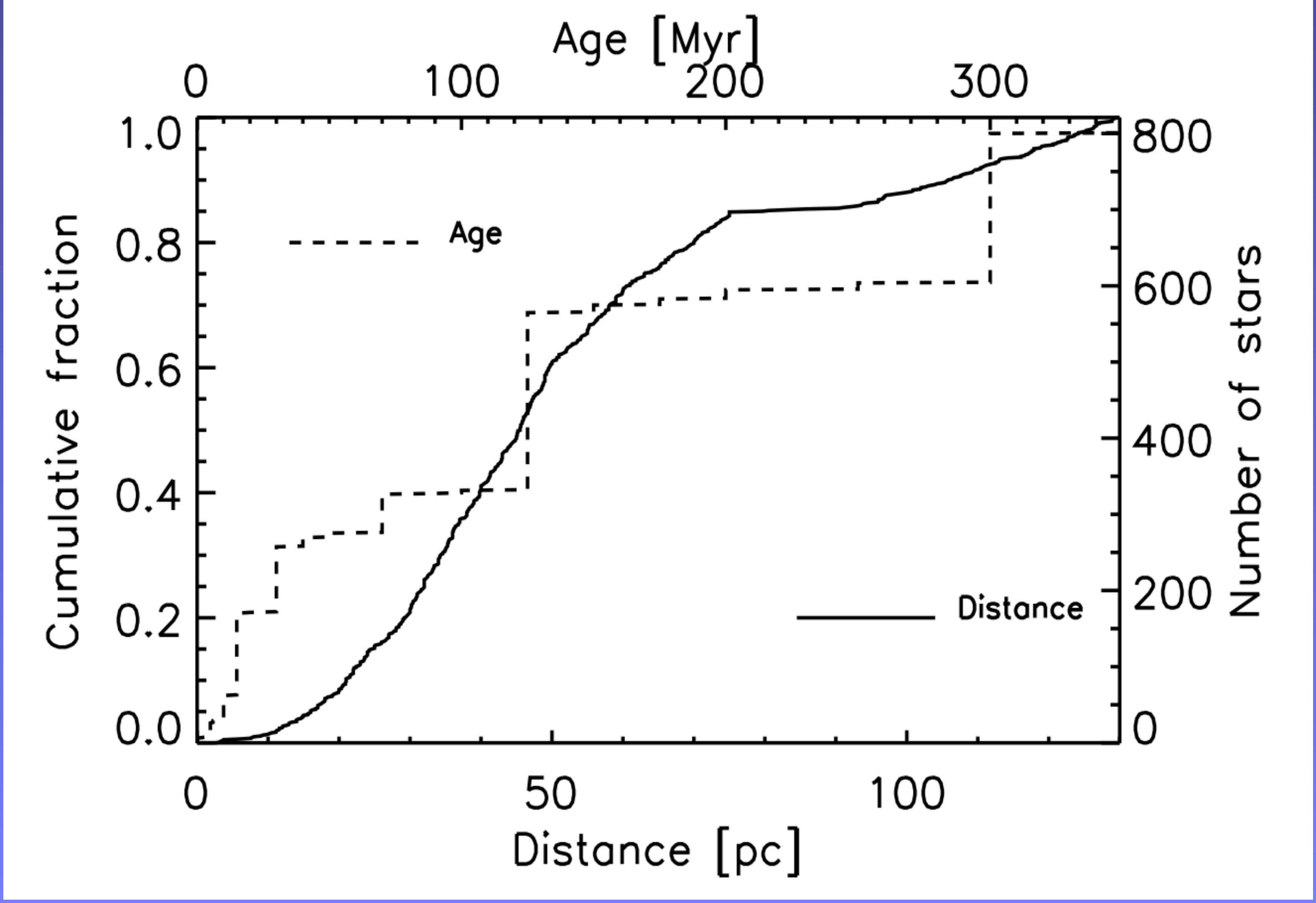


Gemini Planet Imager Exoplanet Survey

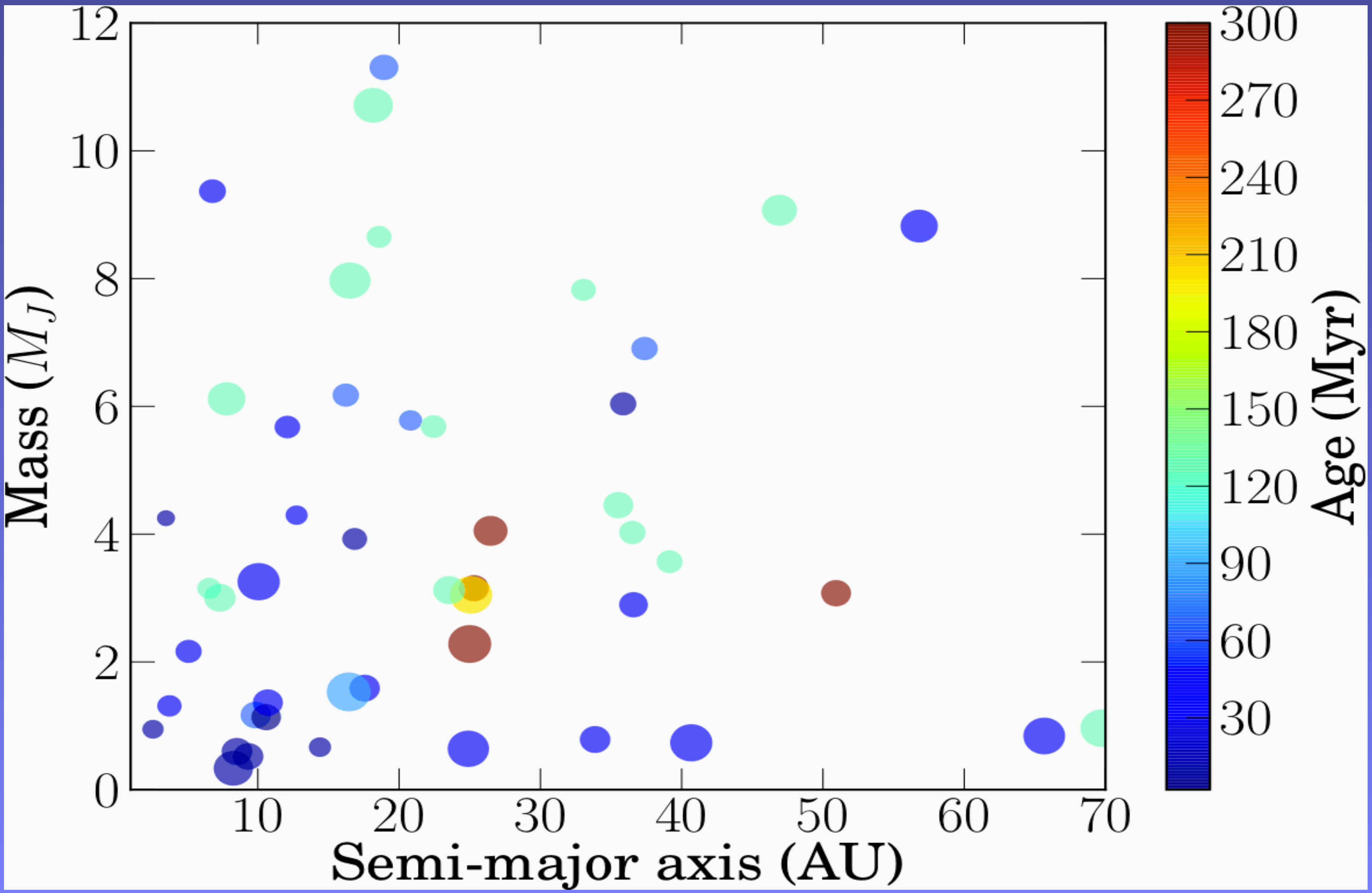
Gemini has allocated 890 hours for a 3 year exoplanet survey campaign

GPIES kickoff meeting
October 2011

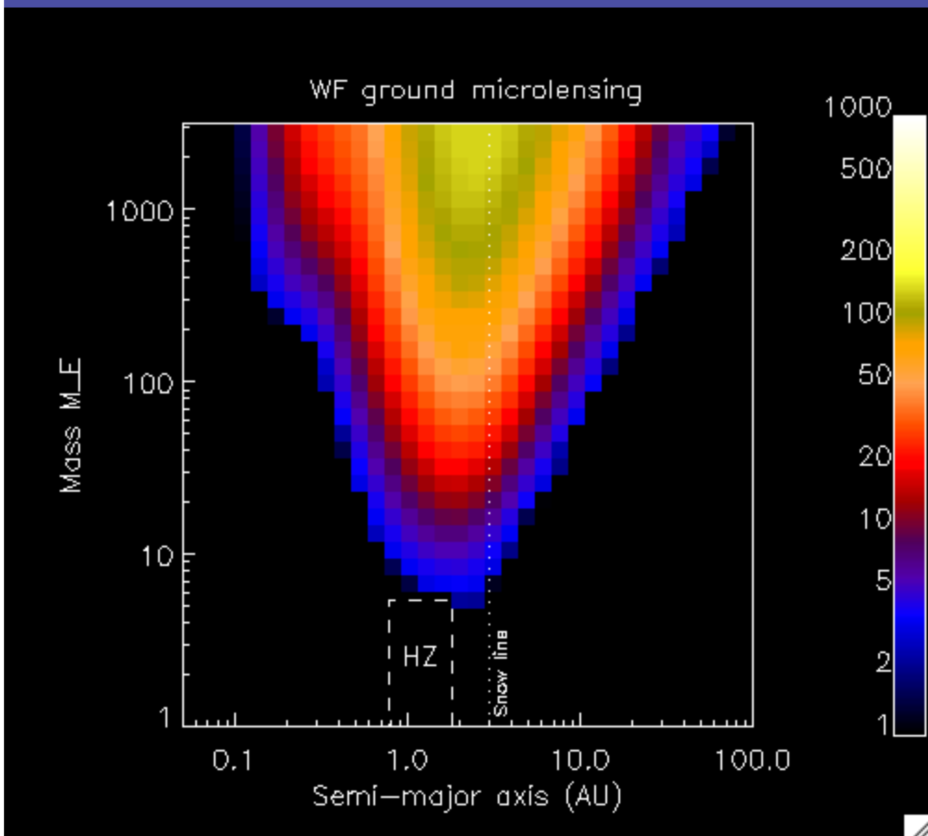
Target identification

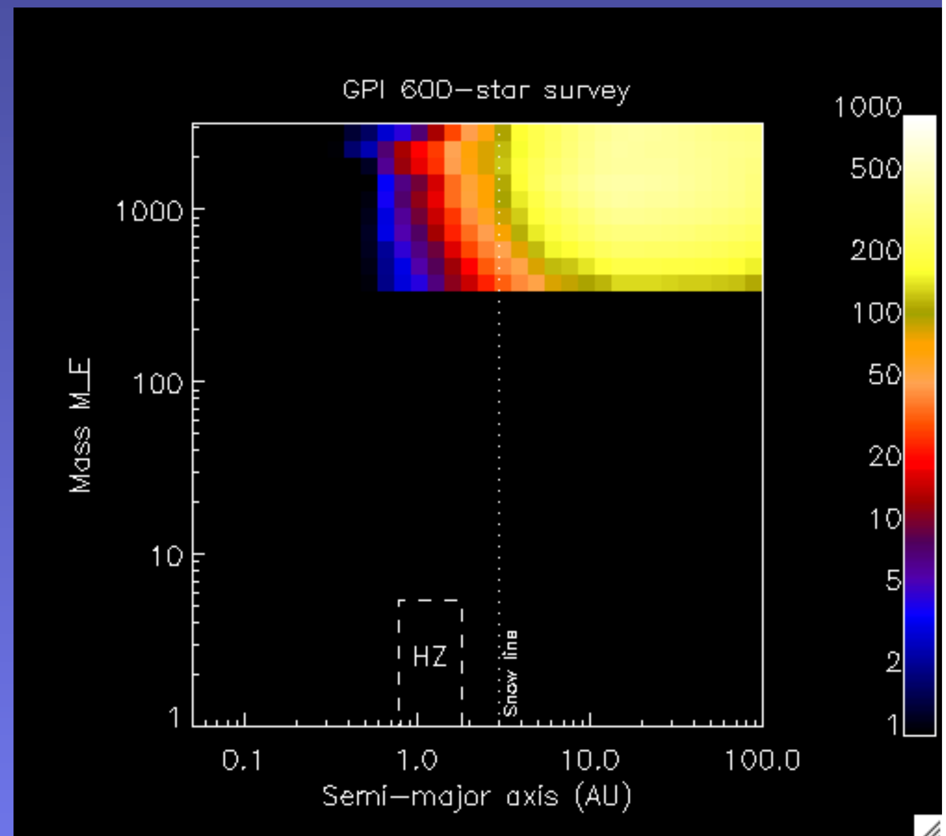


Model planet discoveries (McBride et al 2011)



Survey comparison

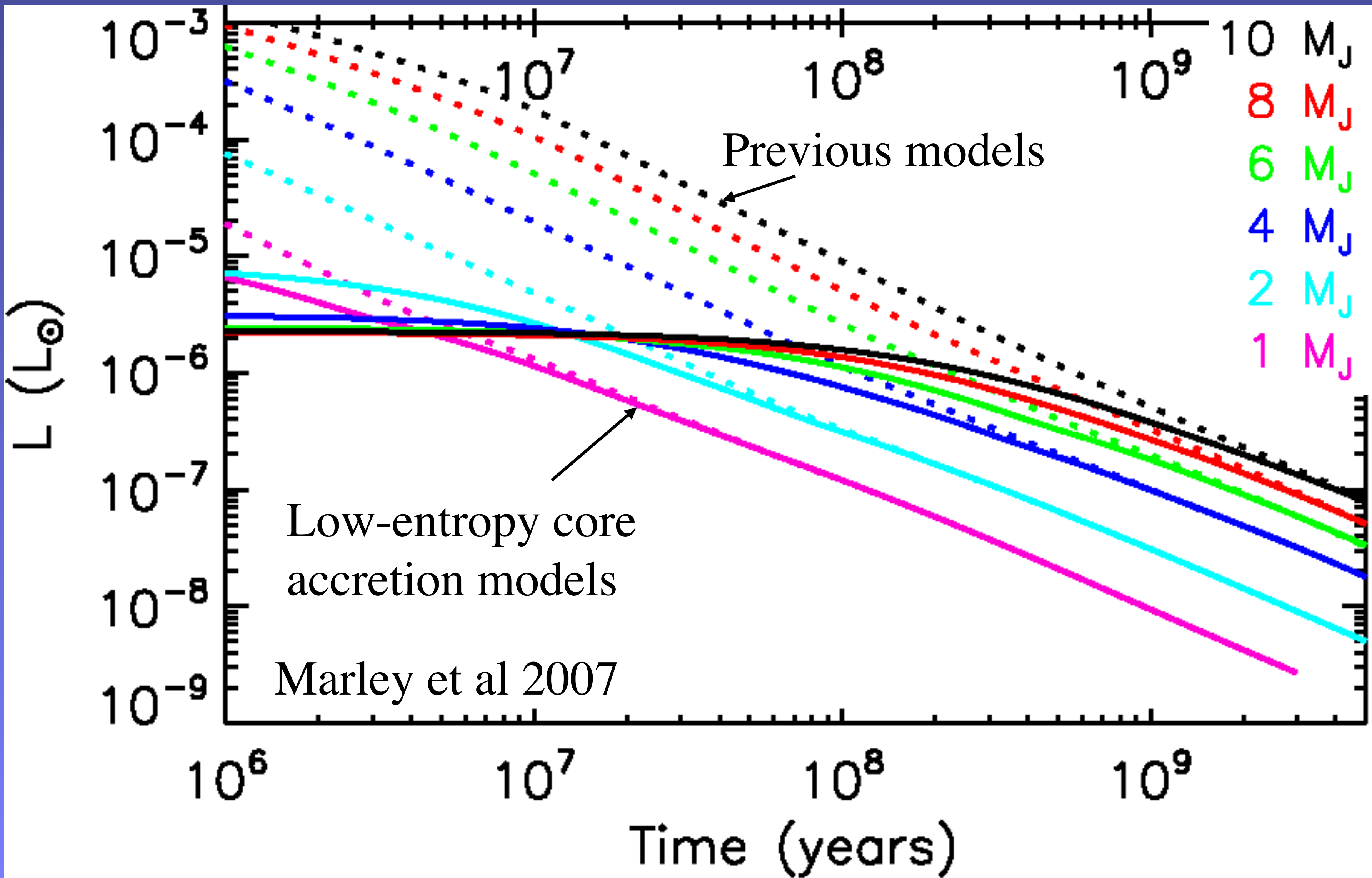




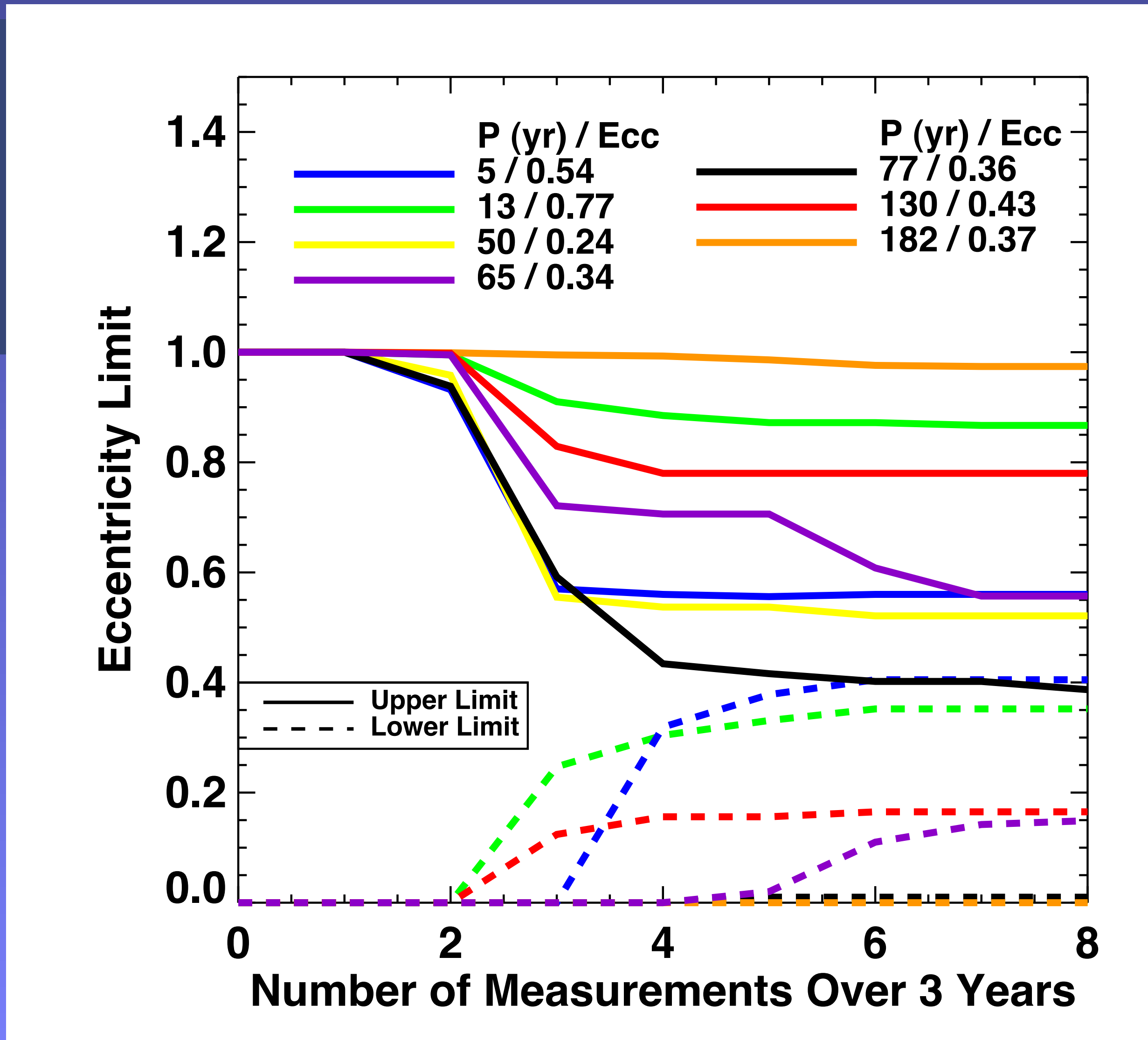
Future microlensing scaled from PLANET - J.P.Beaulieu priv.com

GPIES from McBride et al 2011

Mass and luminosity function comparisons will illuminate formation and evolution

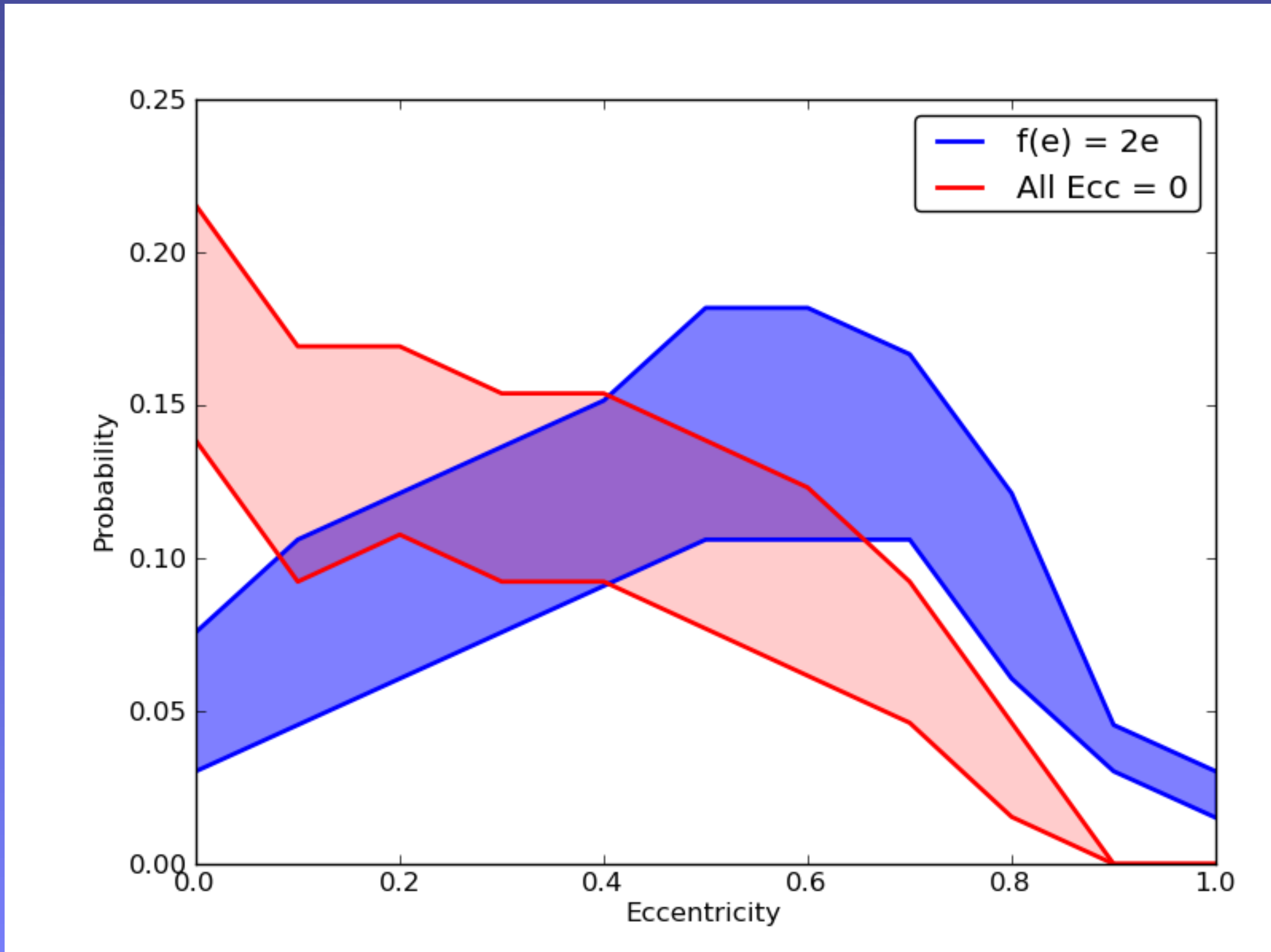


Orbital eccentricity measurements

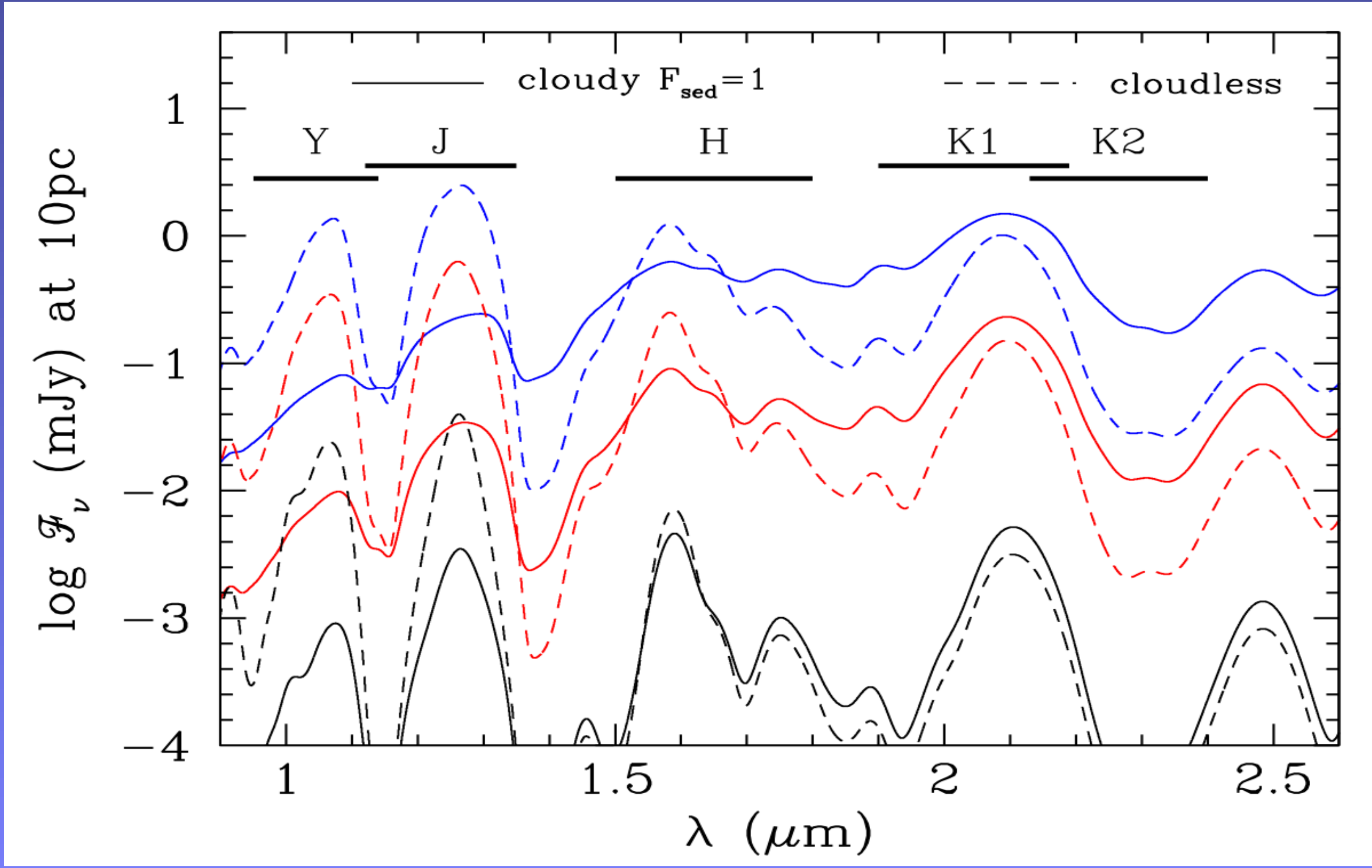


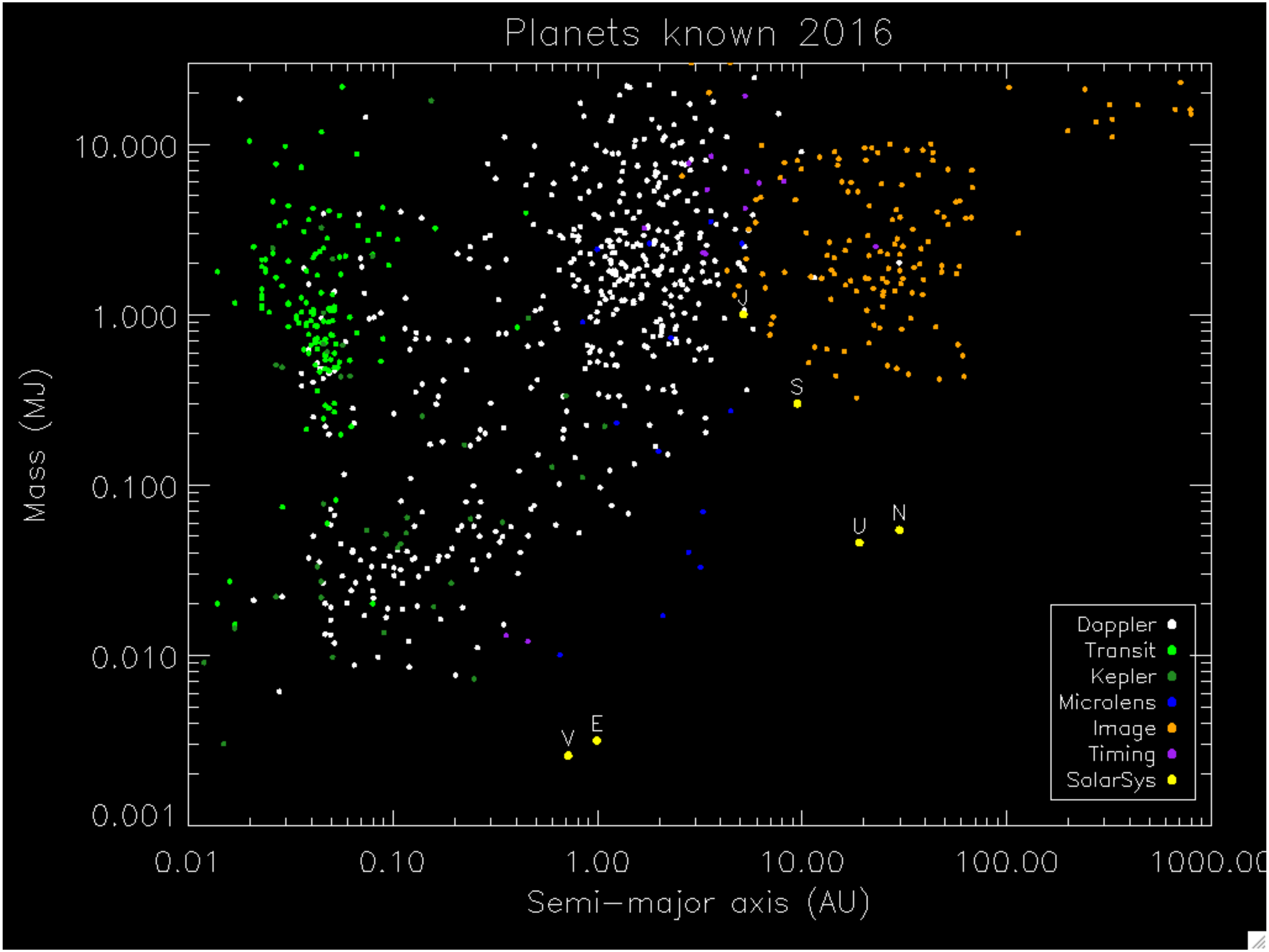
Quinn Konopacky

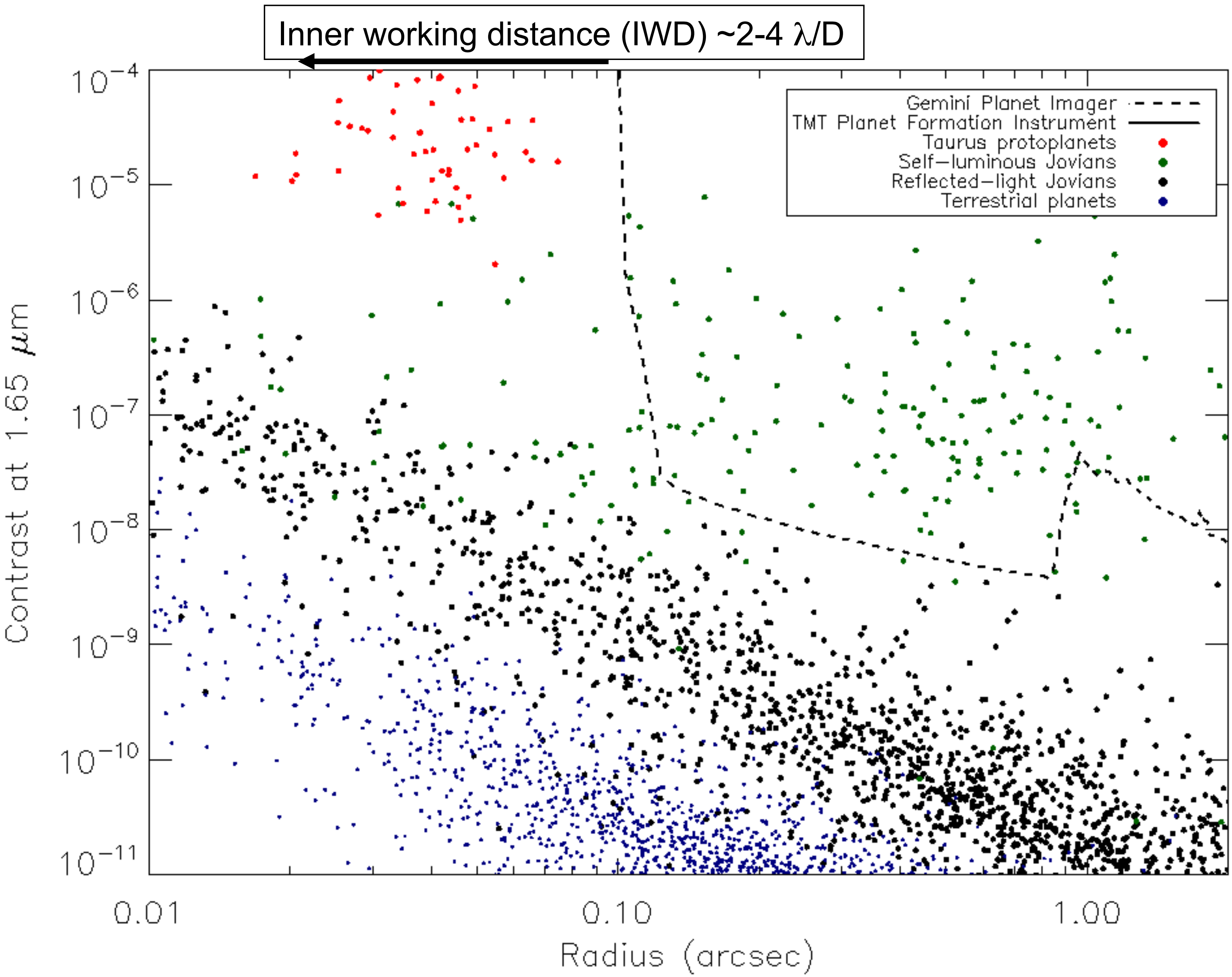
Distinguishing high and low-eccentricity populations



Spectral characterization T=400-800 K

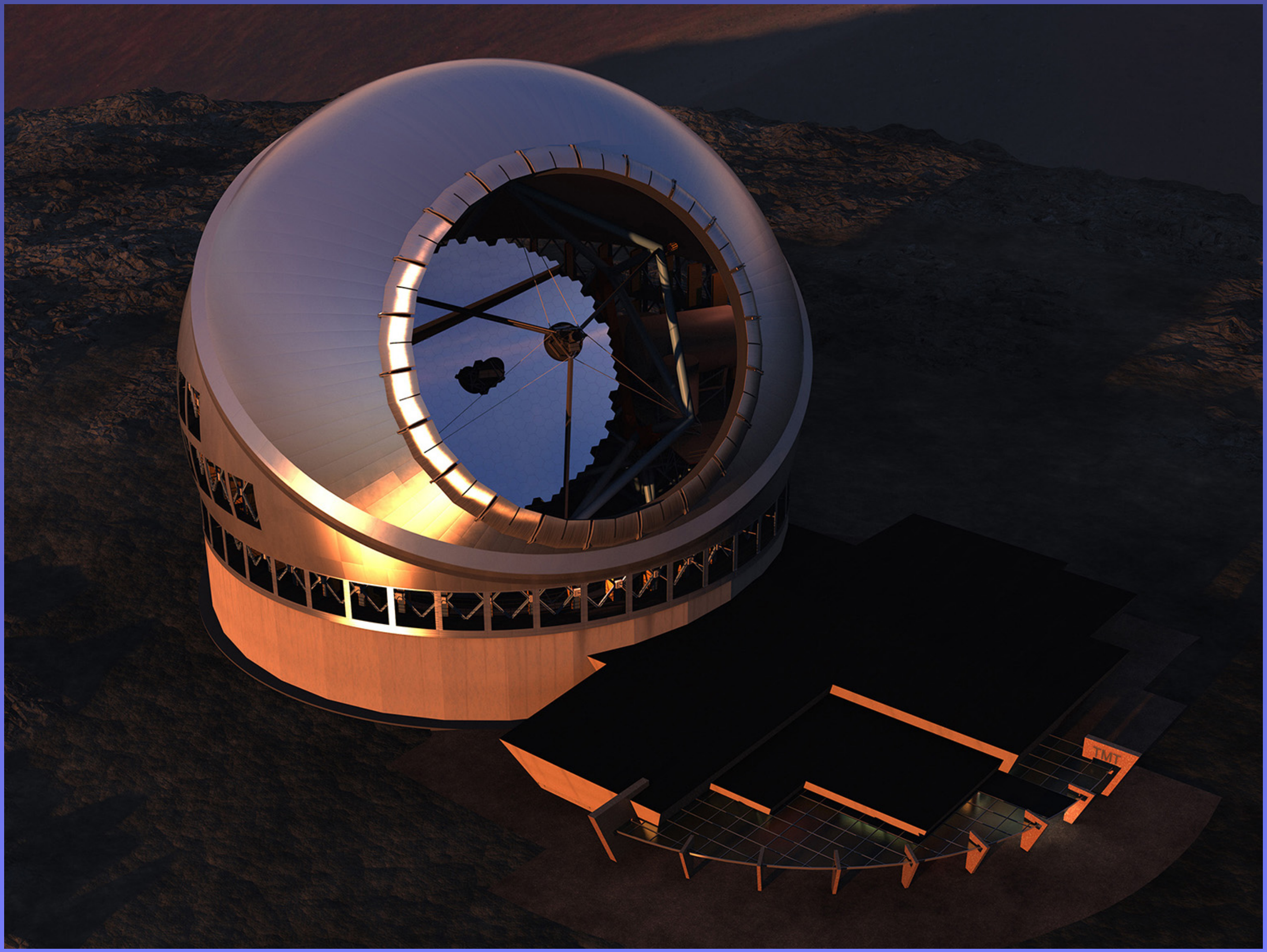


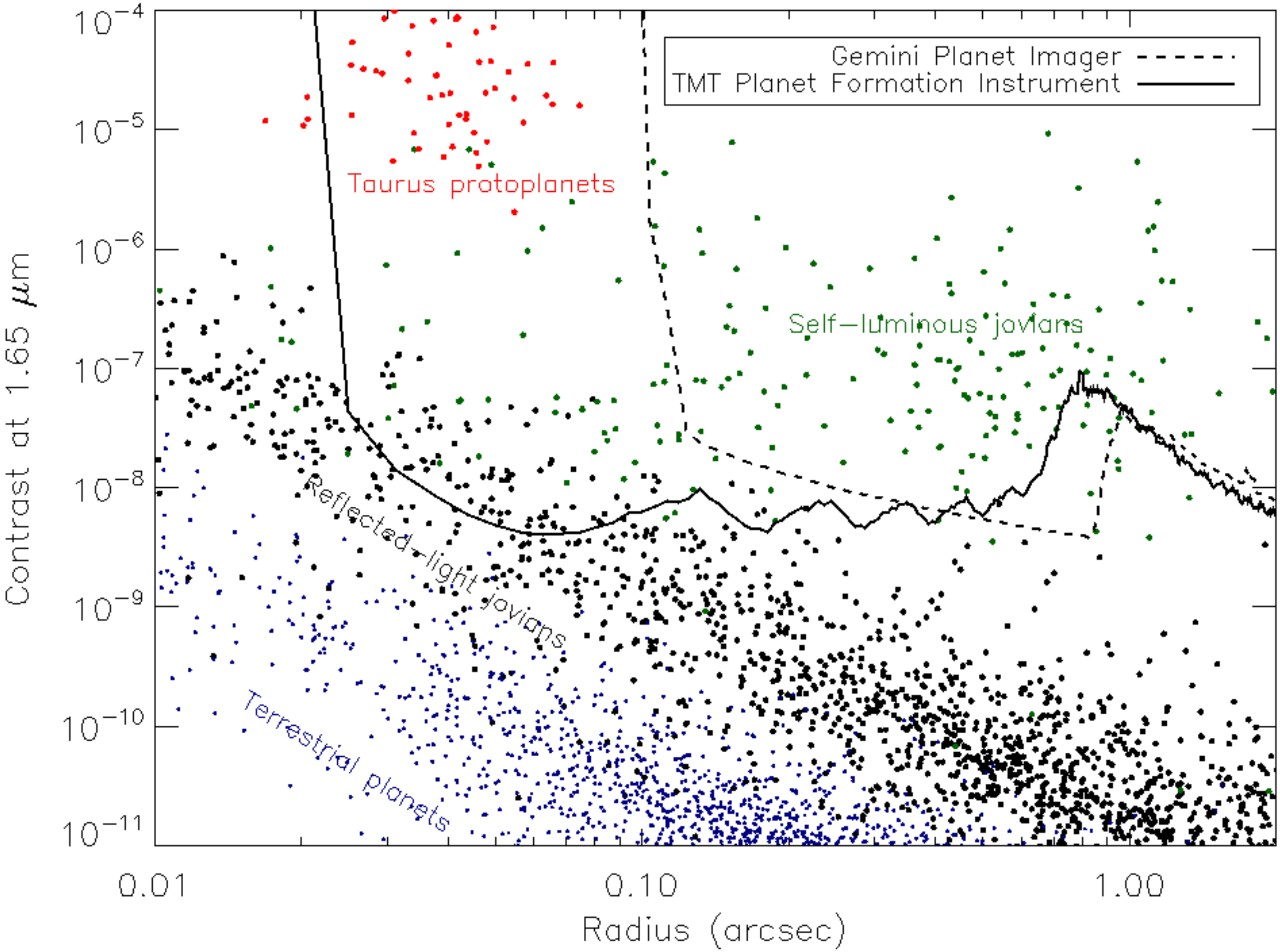

Planets known 2016
Mass (MJ)
10.000
1.000
0.100
0.010
0.001
0.01
0.10
1.00
10.00
100.00
1000.00
Semi-major axis (AU)
J
S
U
N
V
E
Doppler
Transit
Kepler
Microlens
Image
Timing
SolarSys



Inner working distance (IWD) ~2-4 λ/D
Gemini Planet Imager
TMT Planet Formation Instrument
Taurus protoplanets
Self-luminous Jovians
Reflected-light Jovians
Terrestrial planets
Contrast at 1.65 μm
Radius (arcsec)
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
0.01
0.10
1.00

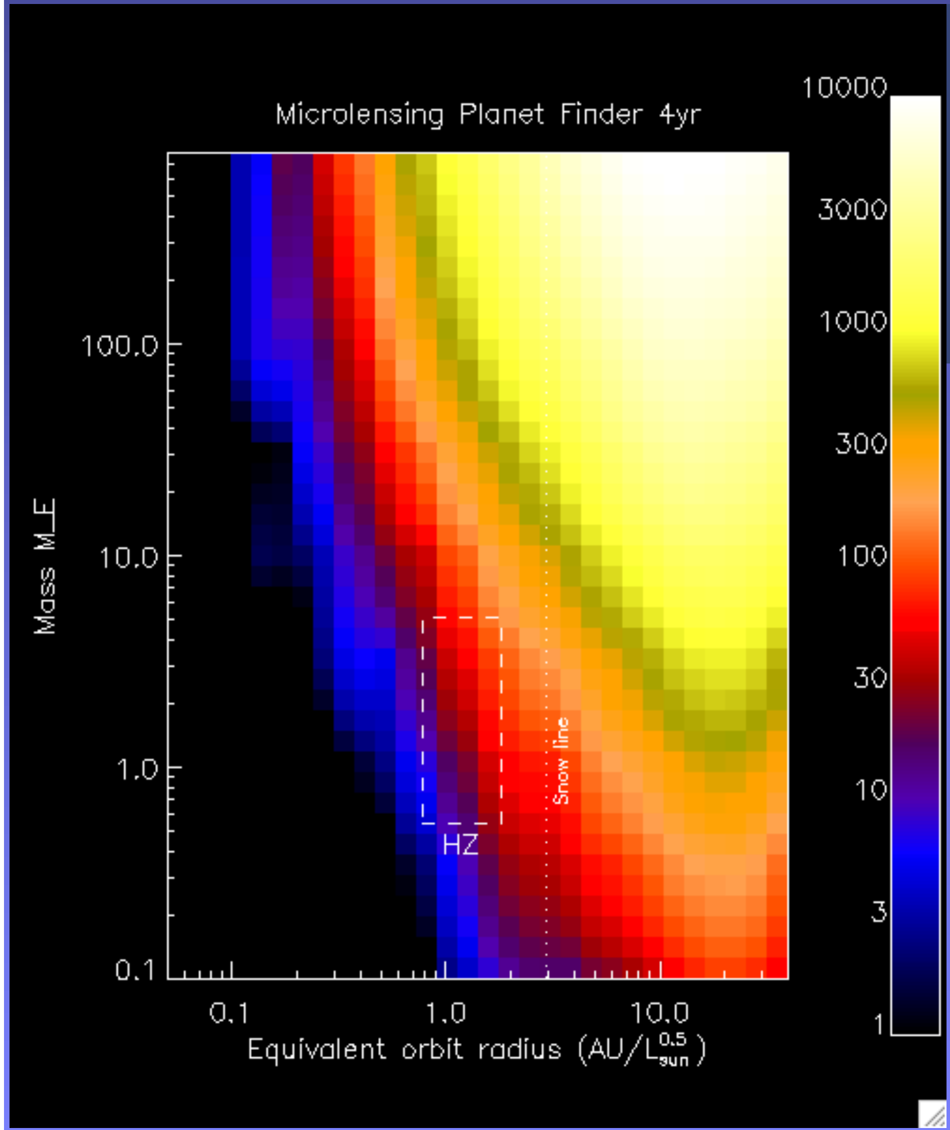
Future: Thirty Meter Telescope

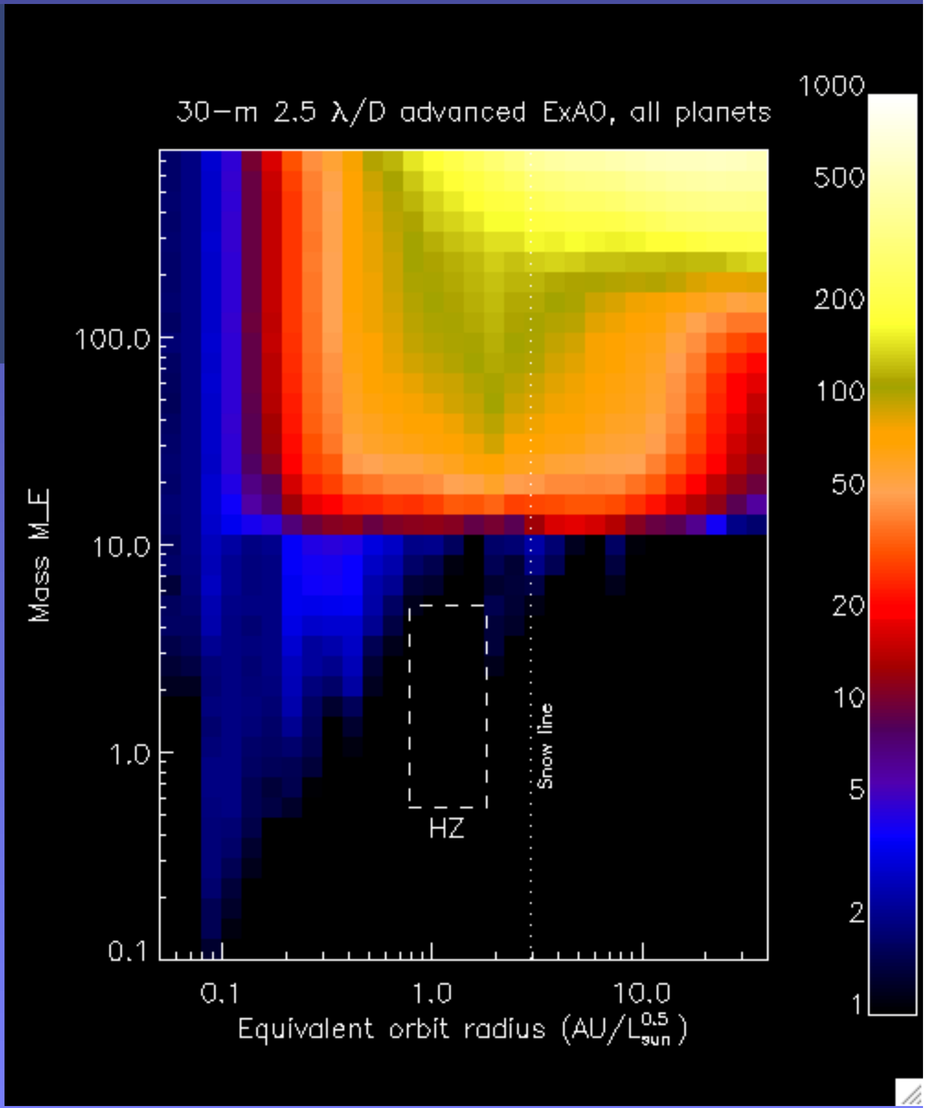


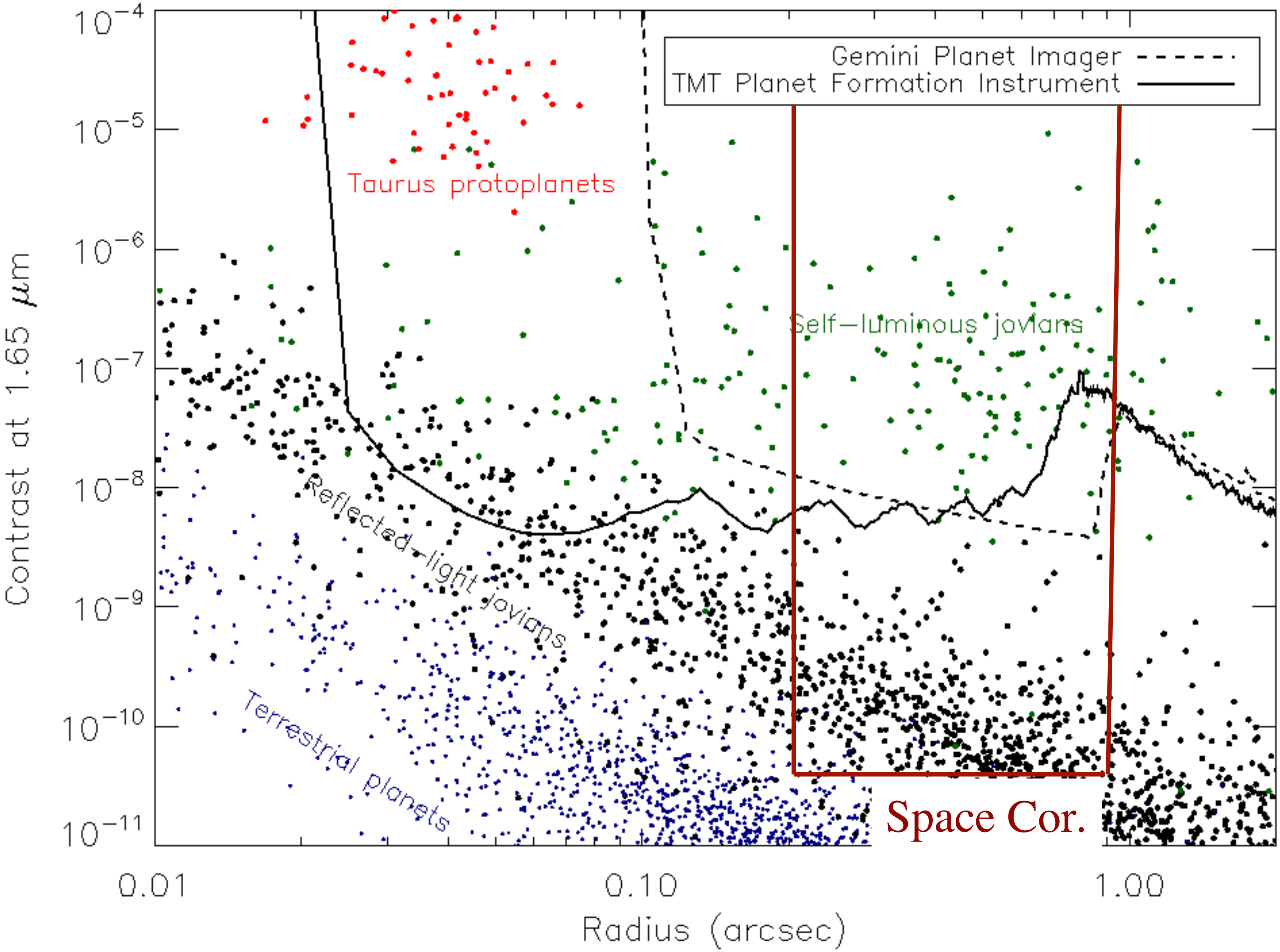


Gemini Planet Imager
TMT Planet Formation Instrument
Taurus protoplanets
Self-luminous jovians
Reflected-light jovians
Terrestrial planets
Contrast at 1.65 μm
Radius (arcsec)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.01
0.10
1.00

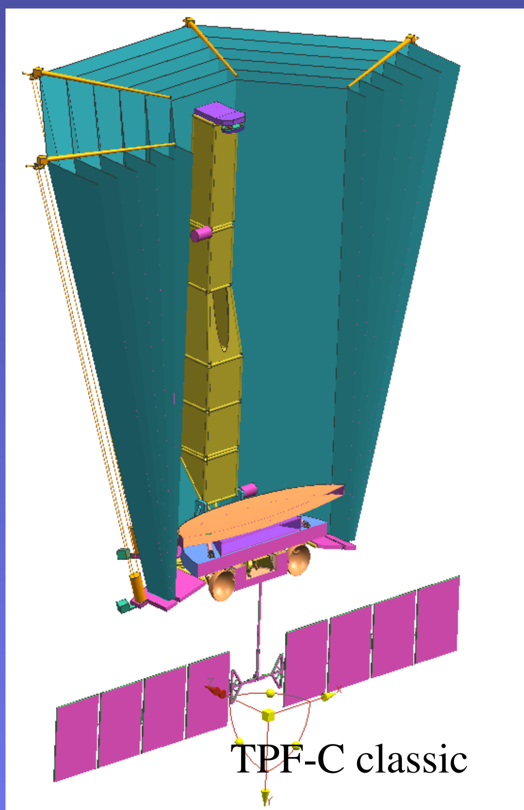
2020 capabilities

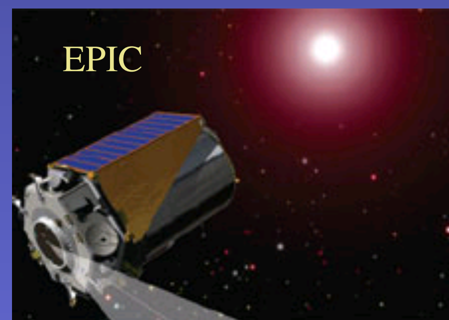


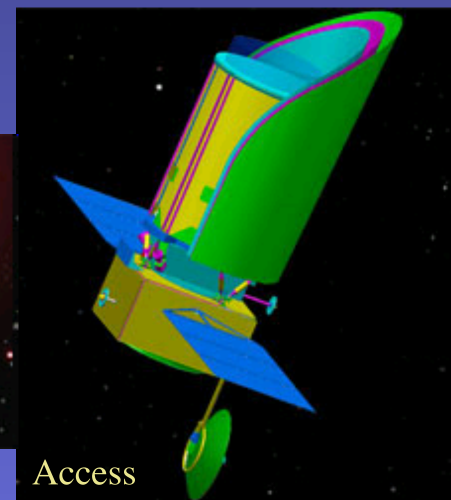


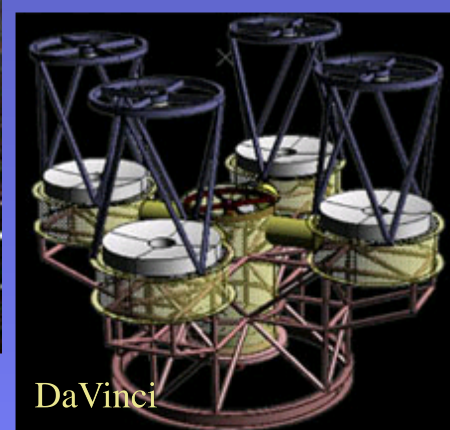

Gemini Planet Imager
TMT Planet Formation Instrument
Taurus protoplanets
Self–luminous jovians
Reflected–light jovians
Terrestrial planets
Space Cor.
Contrast at 1.65 μm
Radius (arcsec)
0.01
0.10
1.00
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}

Space coronagraphs

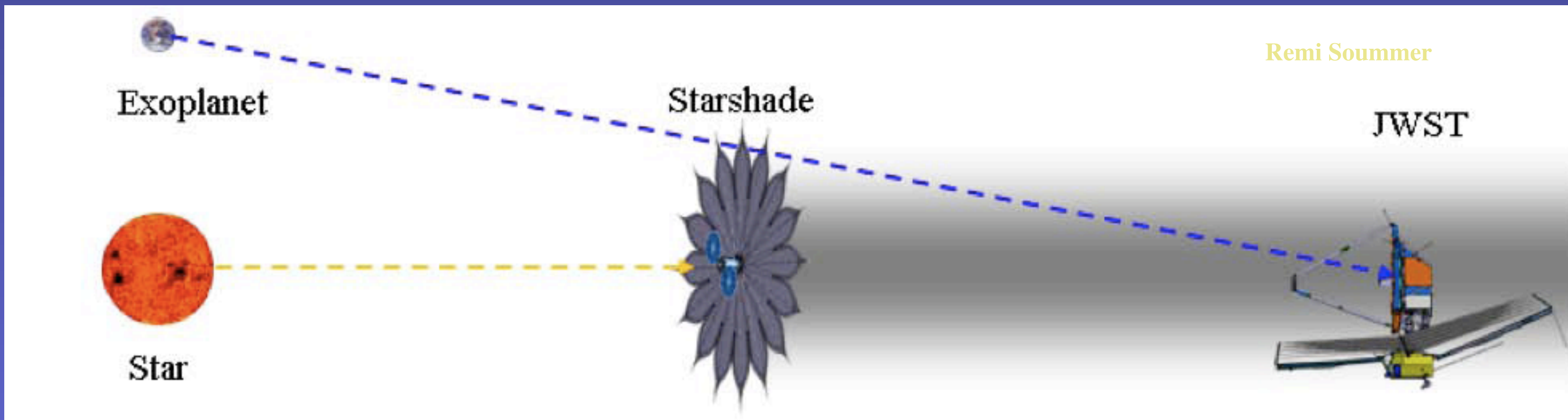


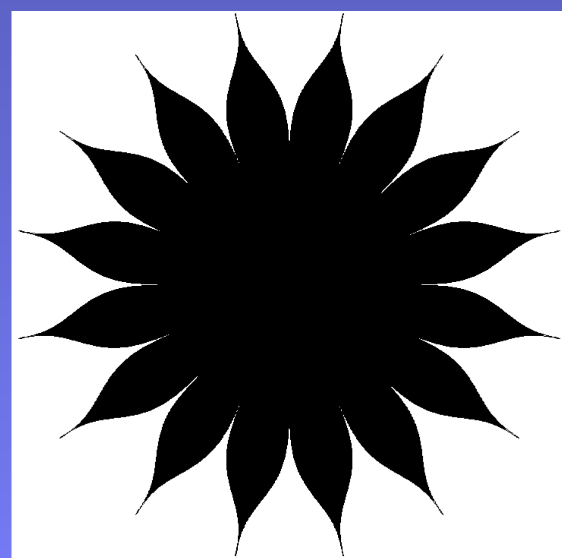






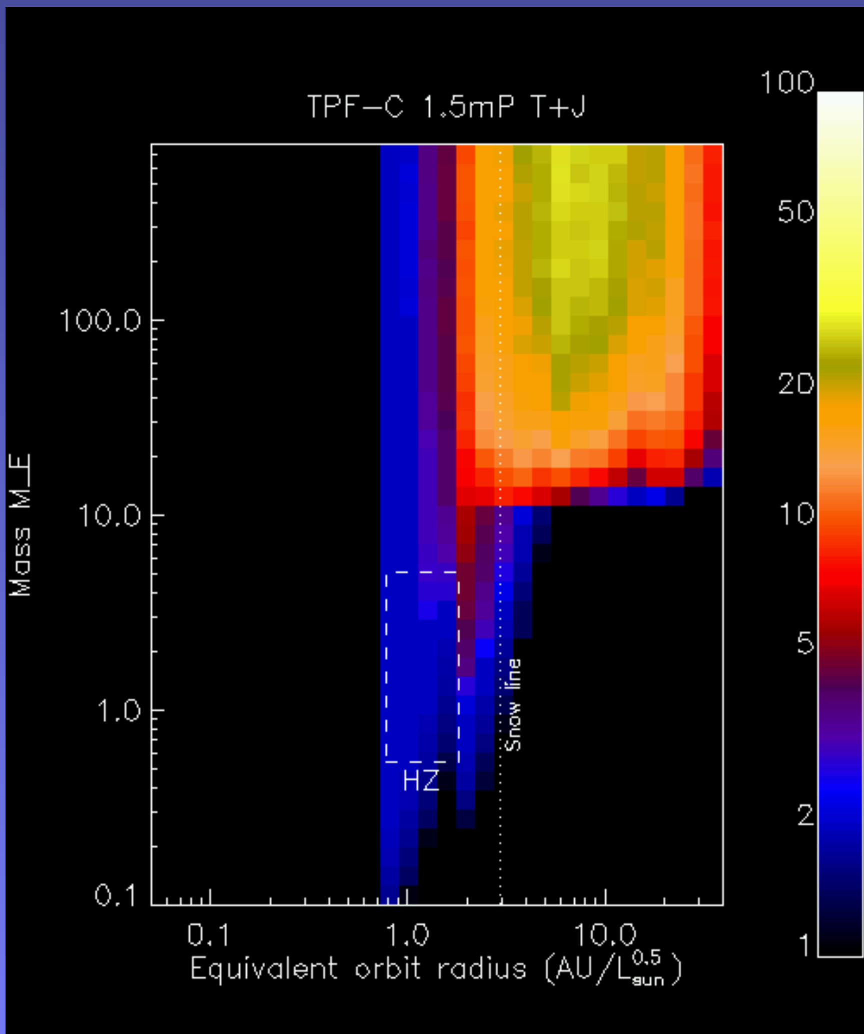
Occultor missions



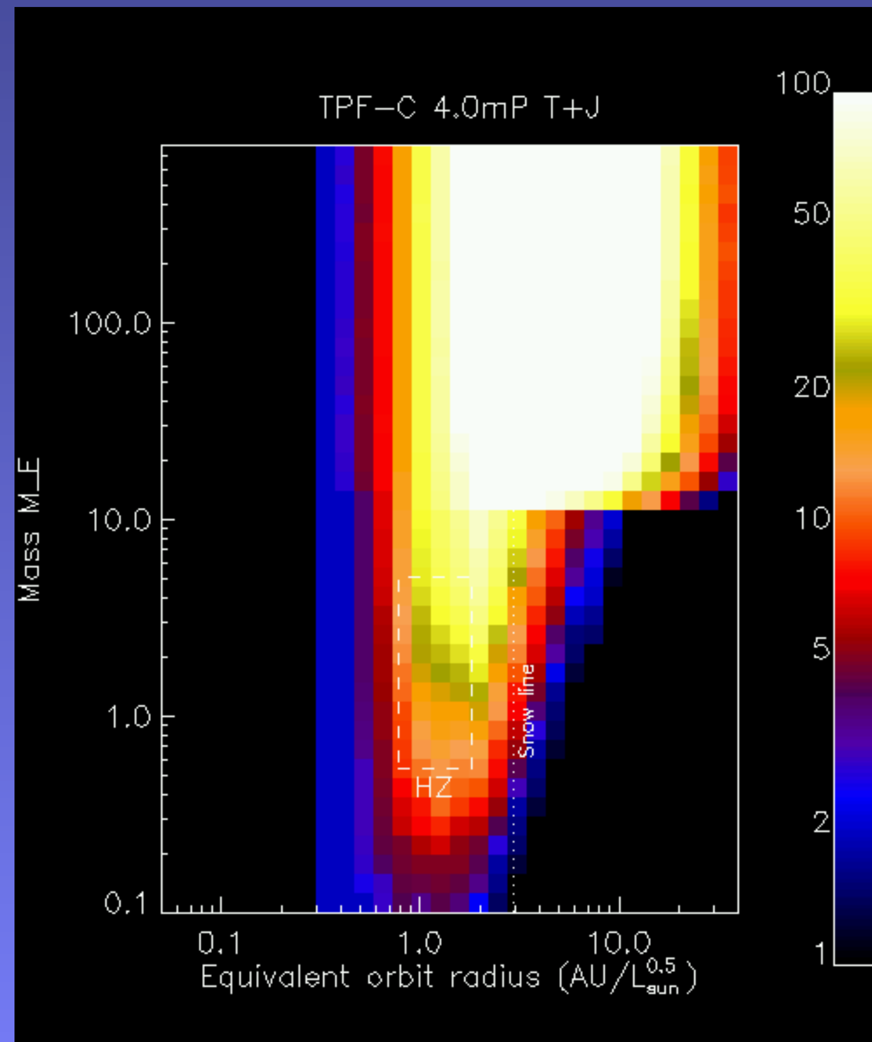


Jeremy Kasdin

Space coronagraphs

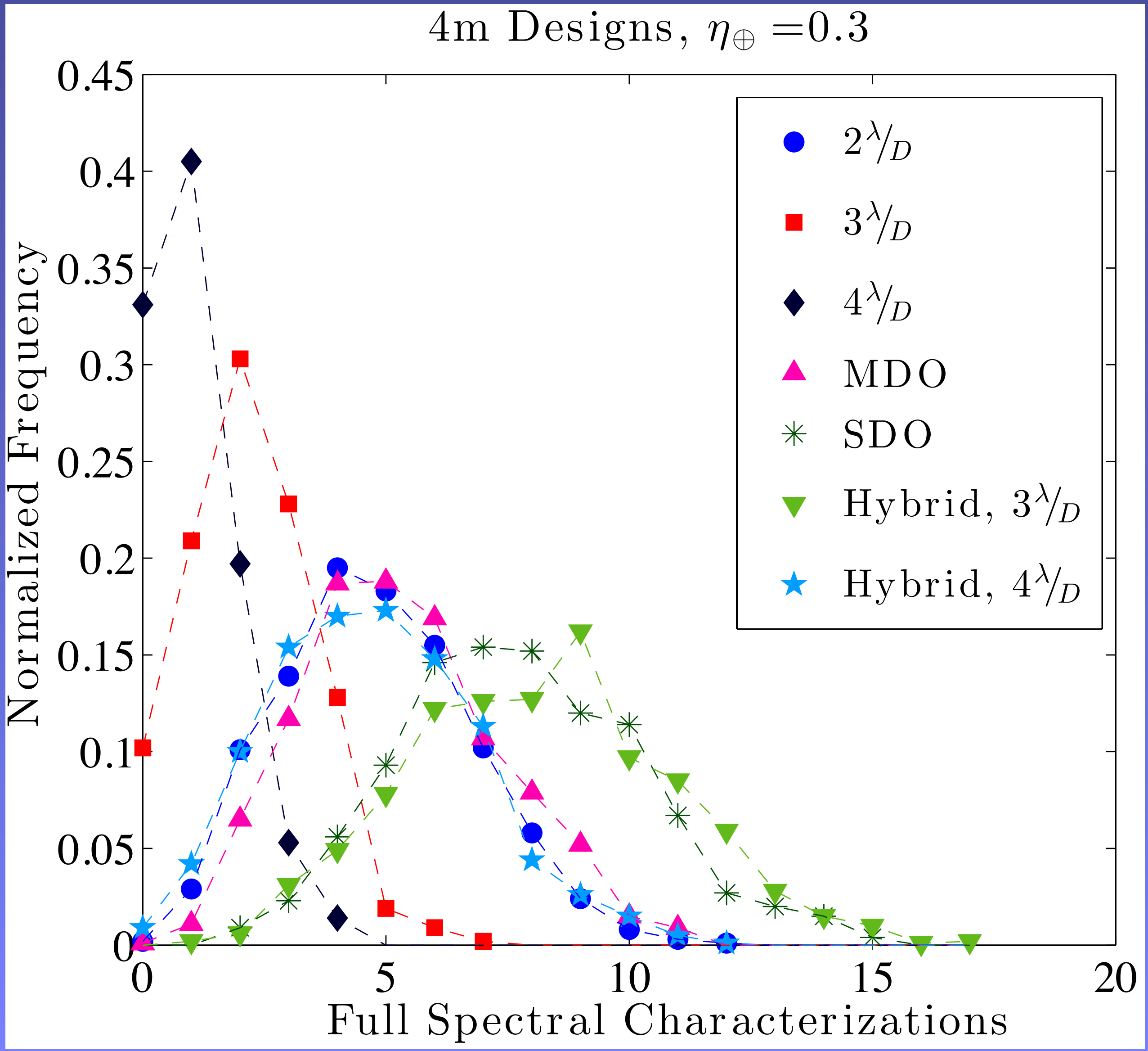


1.5-m advanced coronagraph

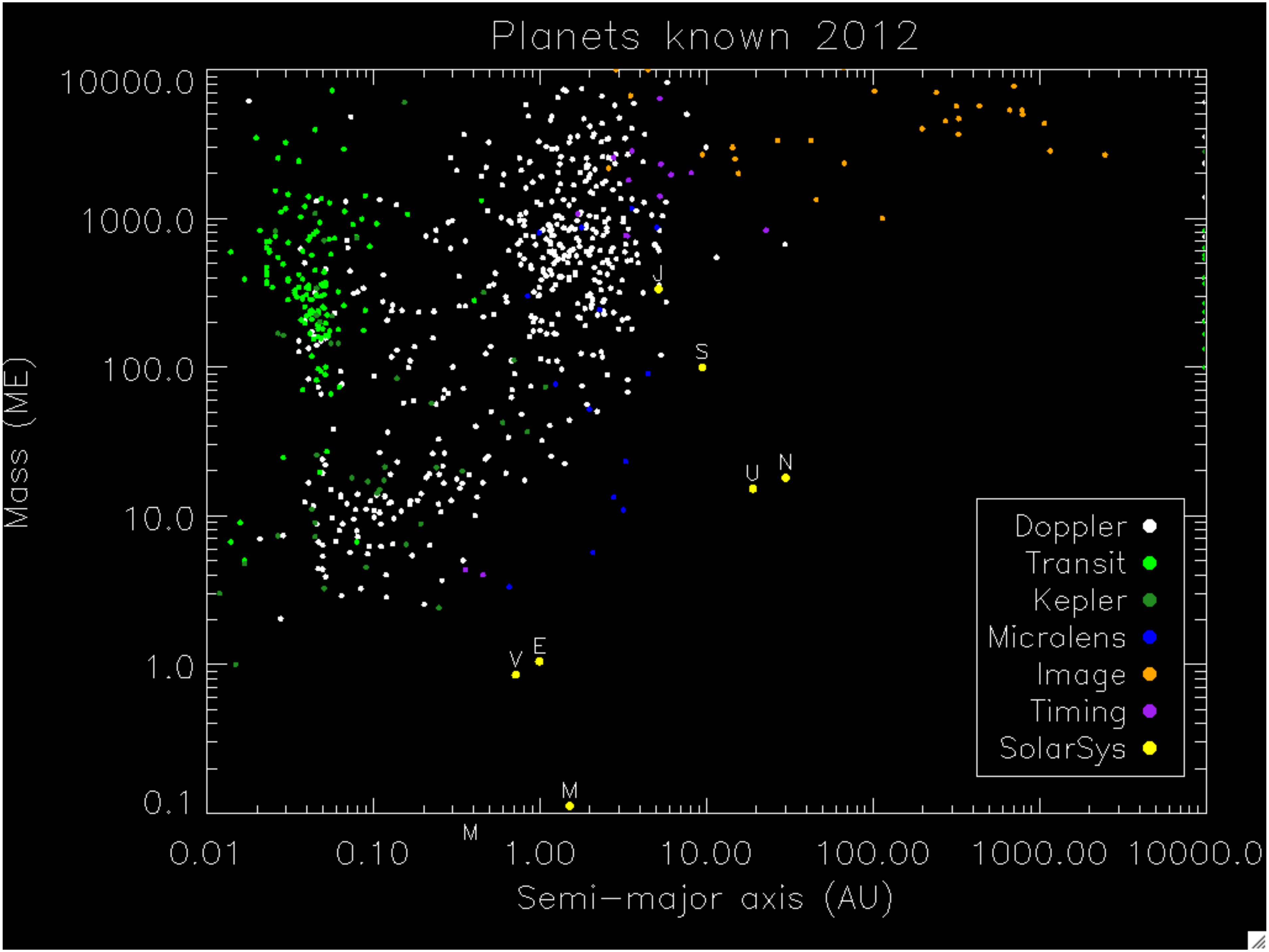


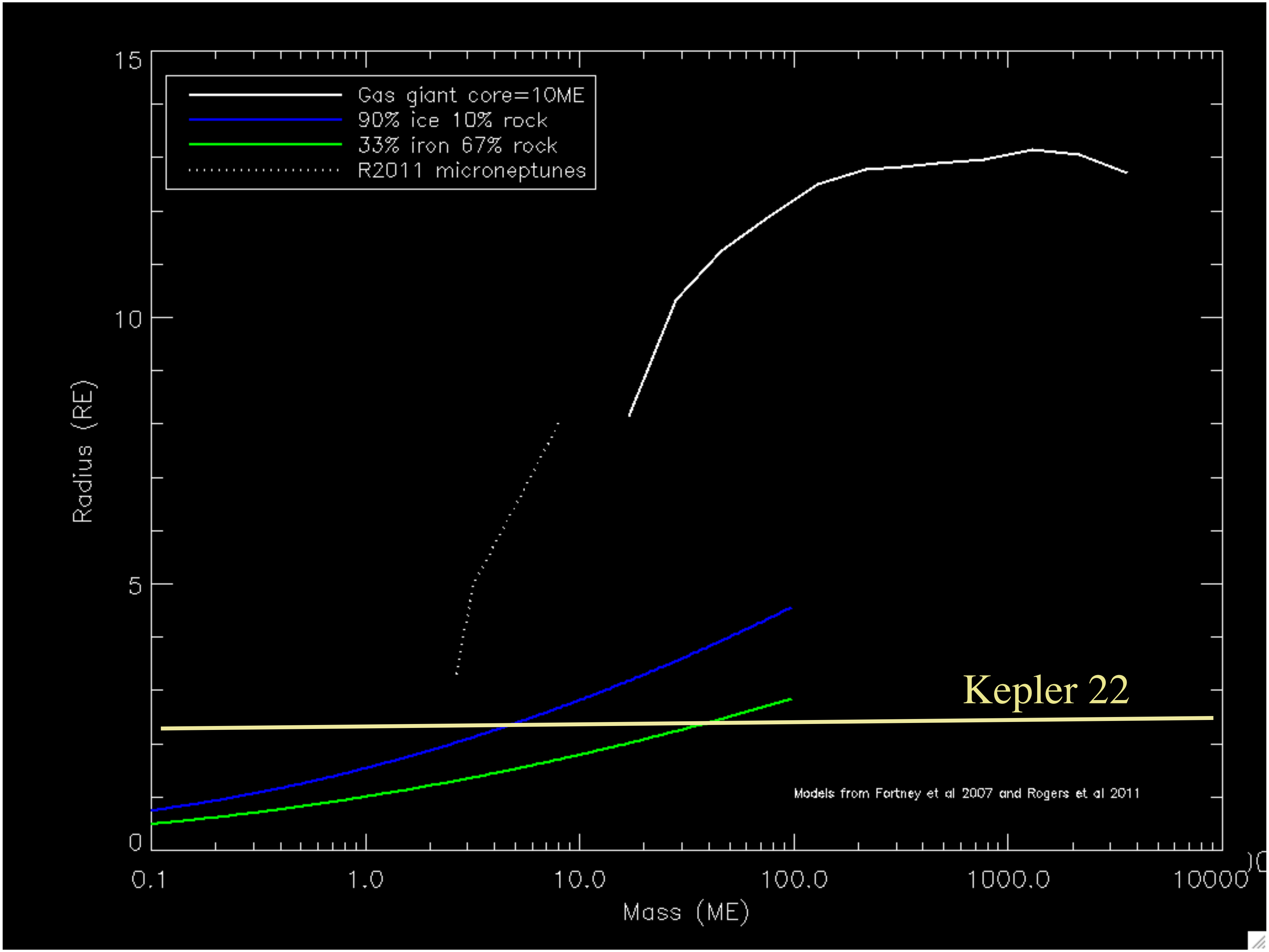
4-m advanced coronagraph

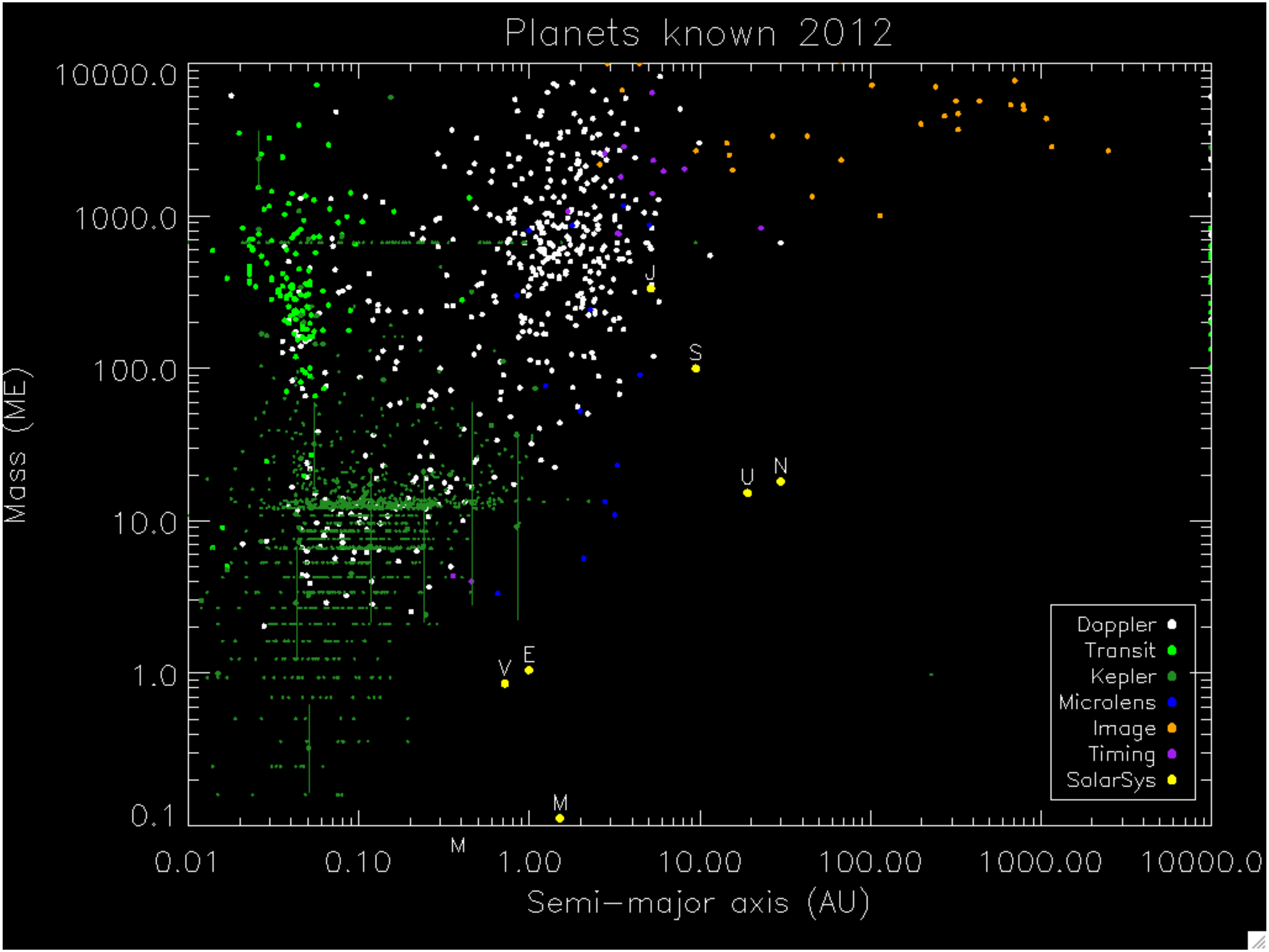
Capabilities are uncertain even for flagship-class missions



Models by Savransky & Kasdin

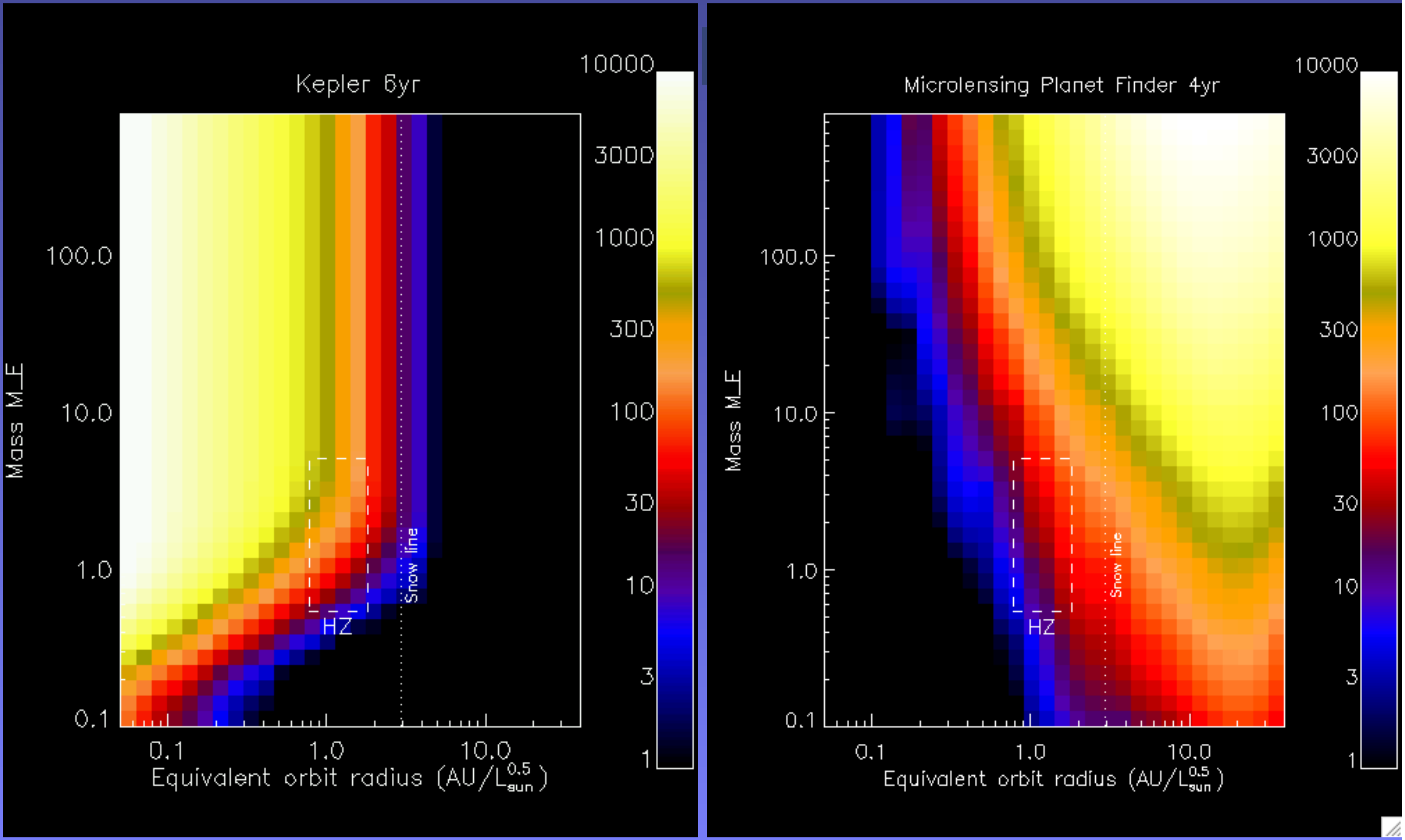

Planets known 2012
Mass (ME)
10000.0
1000.0
100.0
10.0
1.0
0.1
0.01
0.10
1.00
10.00
100.00
1000.00
10000.0
Semi−major axis (AU)
J
S
U
N
V
E
M
M
Doppler
Transit
Kepler
Microlens
Image
Timing
SolarSys


Gas giant core=10ME
90% ice 10% rock
33% iron 67% rock
R2011 microneptunes
Kepler 22
Models from Fortney et al 2007 and Rogers et al 2011
Radius (RE)
Mass (ME)
15
10
5
0
0.1
1.0
10.0
100.0
1000.0
10000



Planets known 2012
Mass (ME)
10000.0
1000.0
100.0
10.0
1.0
0.1
0.01
0.10
1.00
10.00
100.00
1000.00
10000.0
Semi-major axis (AU)
J
S
U
N
V
E
M
M
Doppler
Transit
Kepler
Microlens
Image
Timing
SolarSys

Microlensing Planet Finder (Dave Bennett)



Conclusions

- **Direct imaging and microlensing (and other techniques) have significant synergy**
  - Complete picture of planet distribution from 0.05 to 500 AU
- **Different techniques provide different windows beyond distribution**
  - Composition from imaging (or transit spectra)
  - Mass/radii comparisons
  - Planet population as a function of age
- **HR8799 system shows ability to characterize through dynamics, spectra**
  - Future free-floating planets?
- **Both microlensing and direct imaging have shown their promise and with next-generation surveys will achieve statistical maturity**

Occultor solar-system-twin simulation by B. Vanderbei (Princeton)