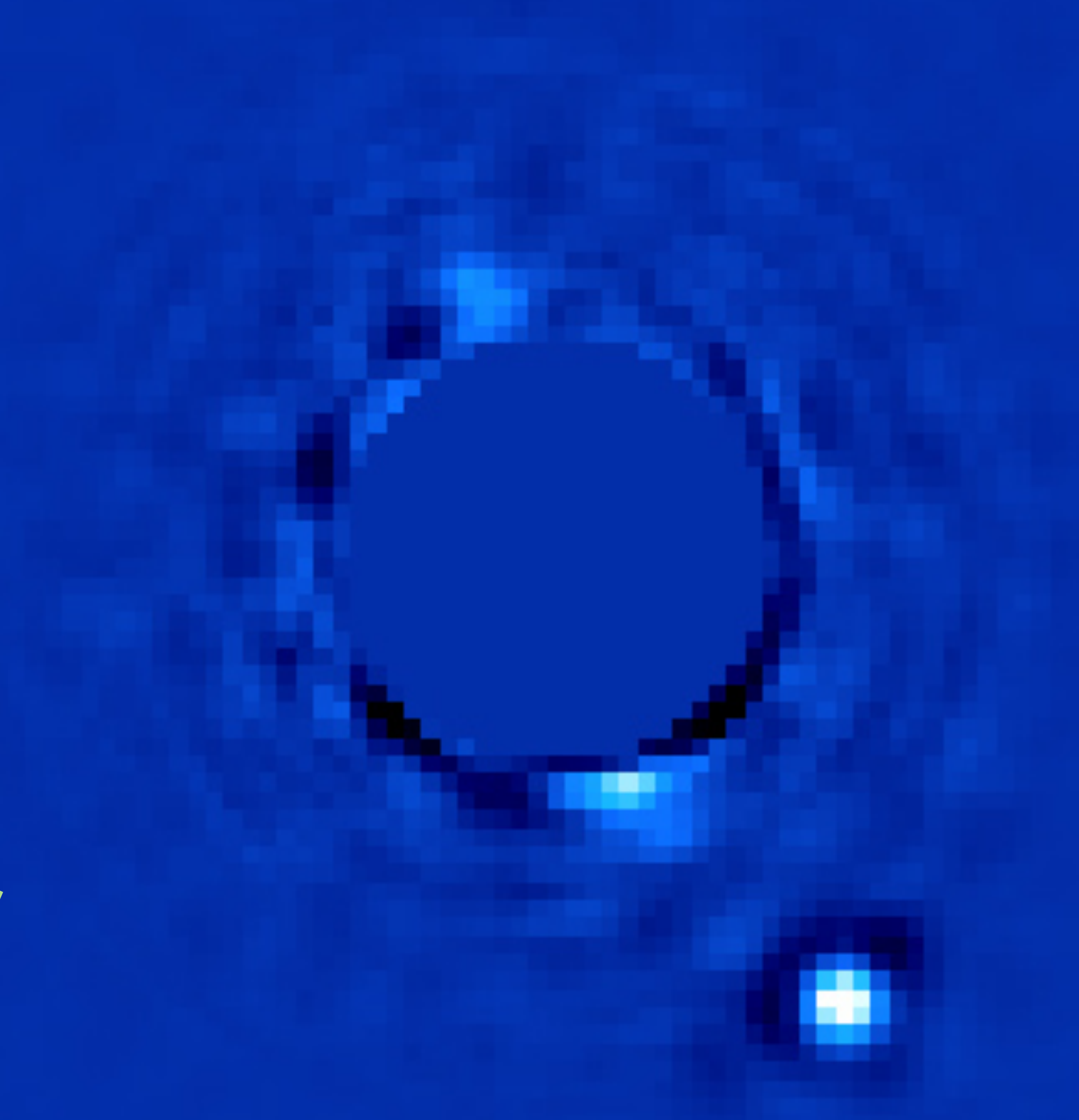
Ground and Space-Based Imaging of Exoplanets Before WFIRST



Brendan Bowler

Caltech JCPA Fellow

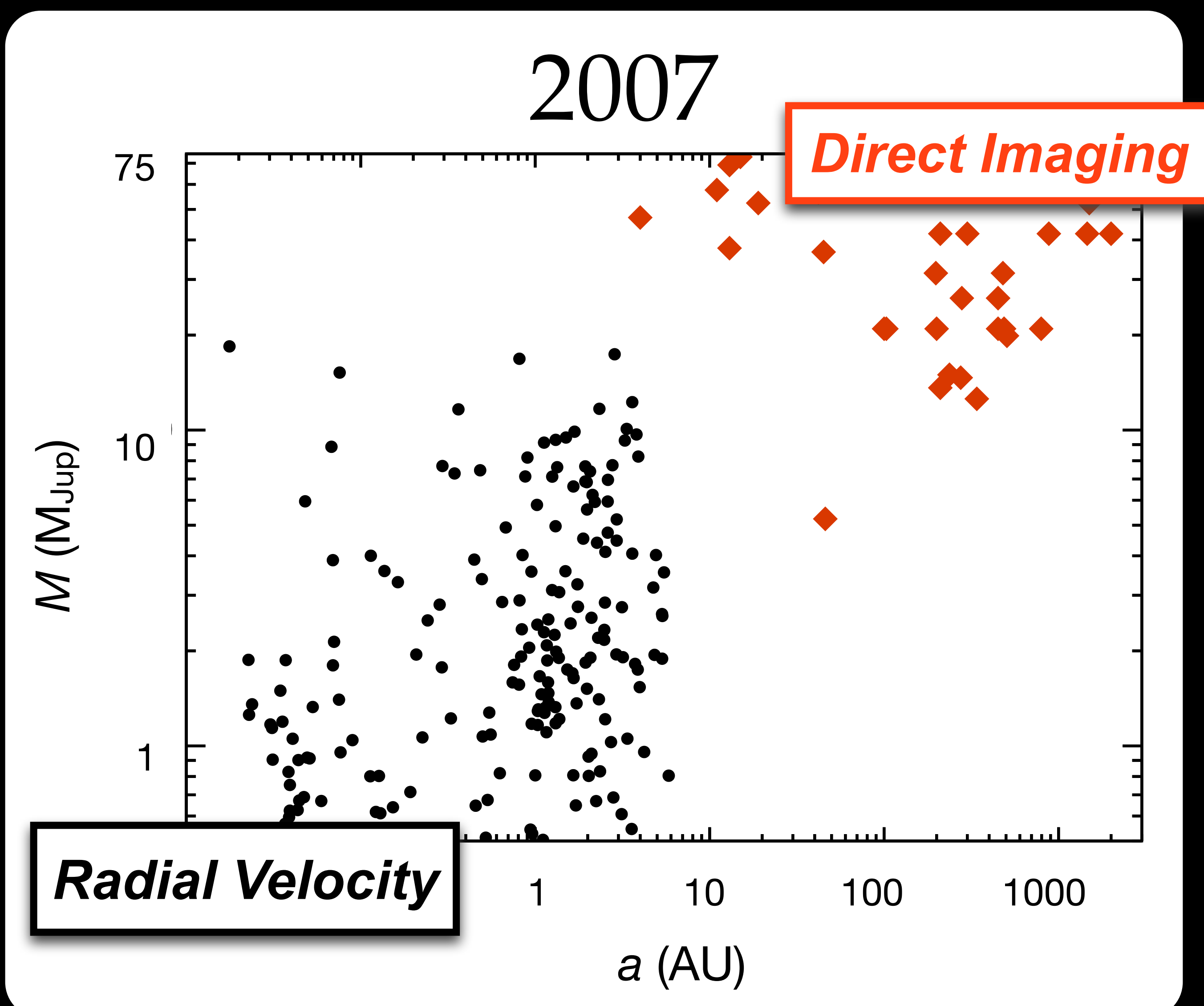
Nov 17 2014

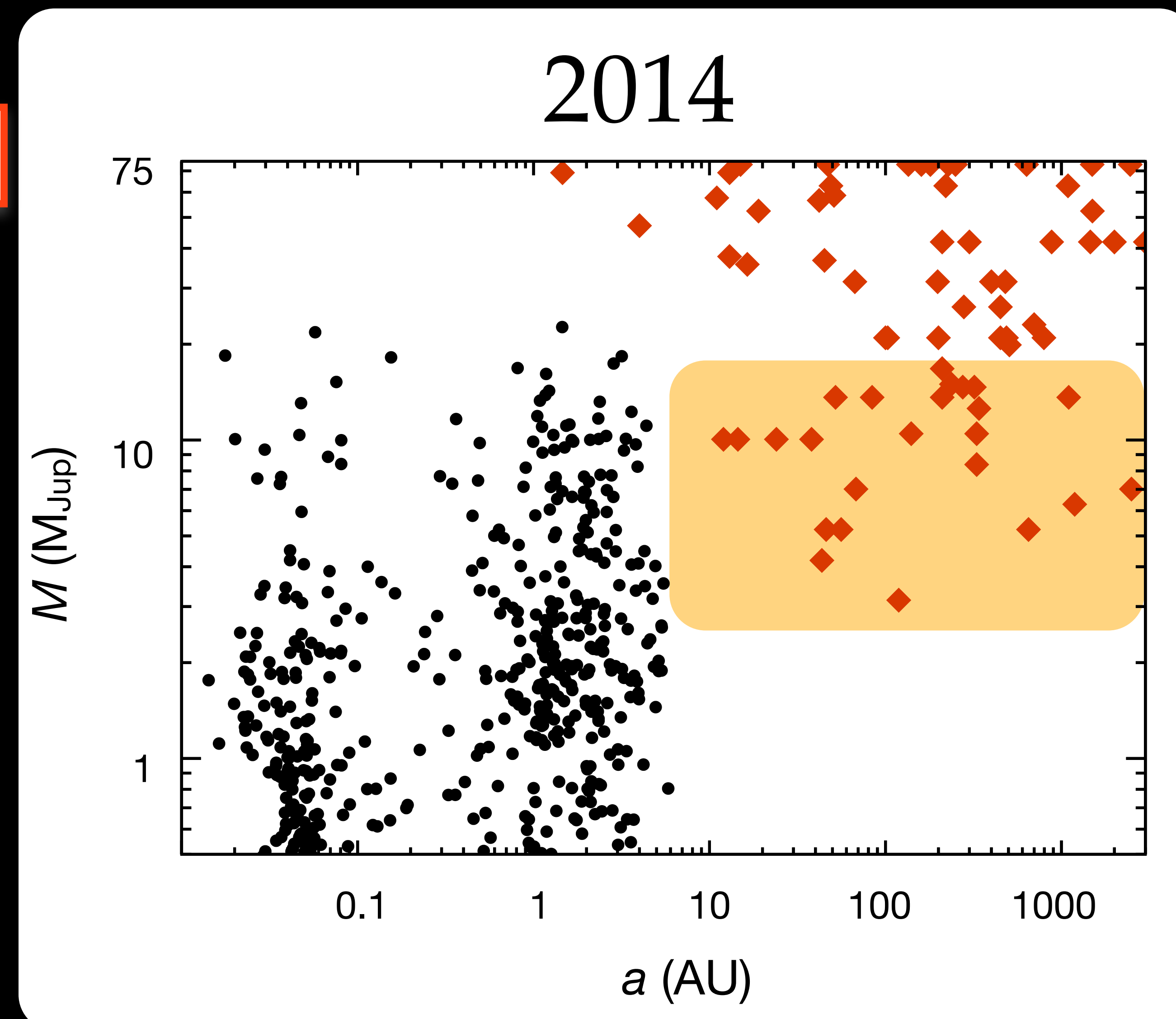
Wide-field InfraRed Surveys: Science and Techniques

β Pic b with GPI
Macintosh et al. (2014)

The **architectures** of planetary systems span 5 orders of magnitude in separation

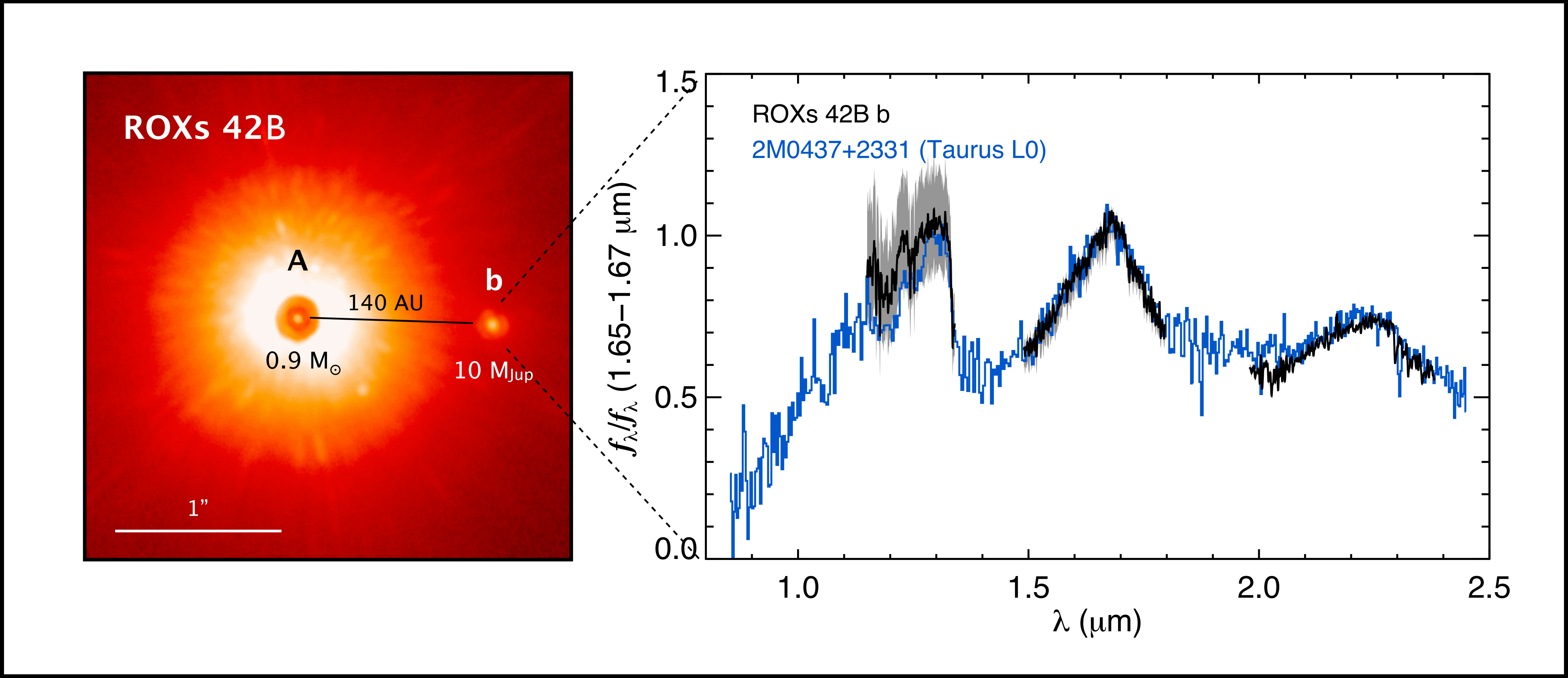
Determining how they **form** is one of the goals of direct imaging.





Planetary atmospheres probe physical properties

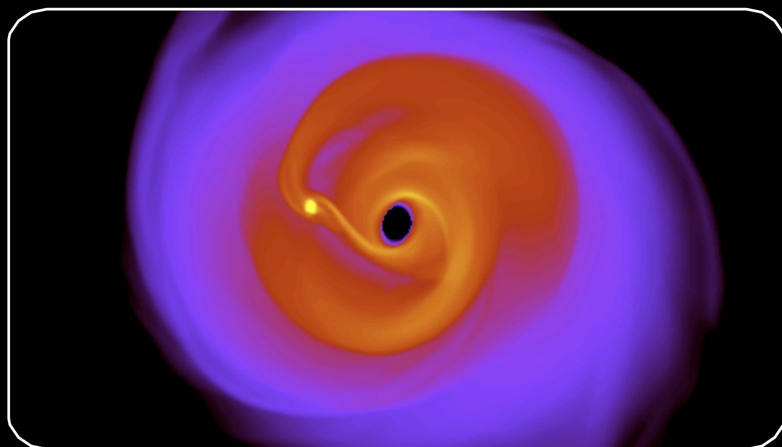
Their evolution and diverstiy teach us about atmospheric physics, chemistry, and clouds.



Kraus et al. (2014)
Currie et al. (2014)

Bowler et al. (2014a)

The origin of long-period planets

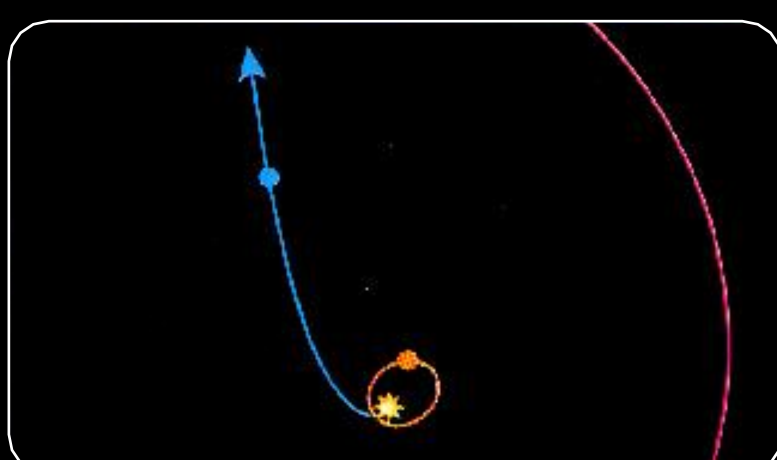


Disk Instability

- Giant planet frequency and mass scale with protostellar (and protoplanetary disk) mass (Boss 2011).
- Bimodal distribution in semi-major axis (Boley 2009).
- "Runts of the litter" (Kratter et al. 2010).

Turbulent Fragmentation

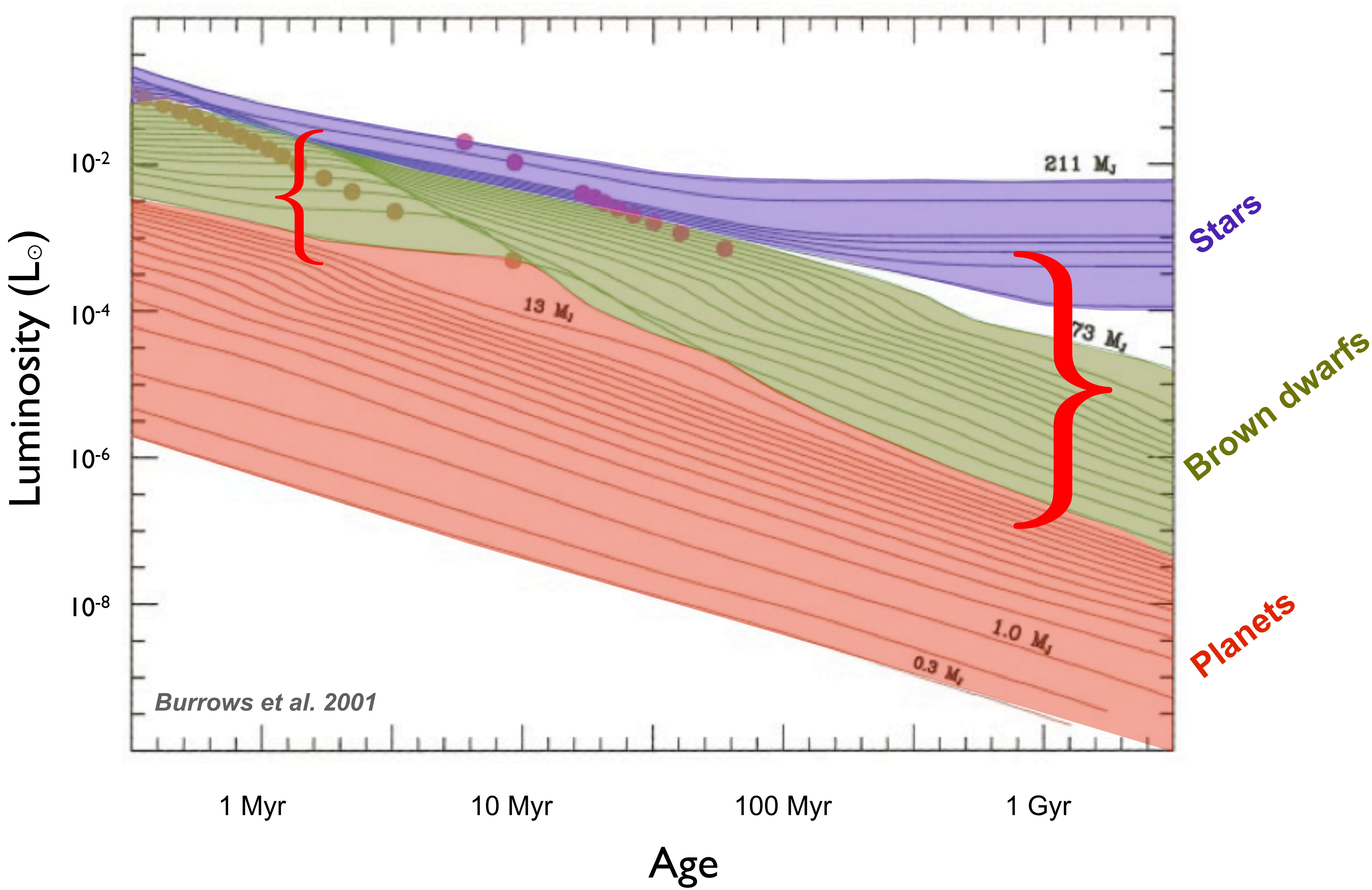
- BD companion separations scale with stellar host mass (Bate 2009).
- BD companion frequency independent of stellar host mass (Bate 2009).
- Identical planet/host-star metallicities



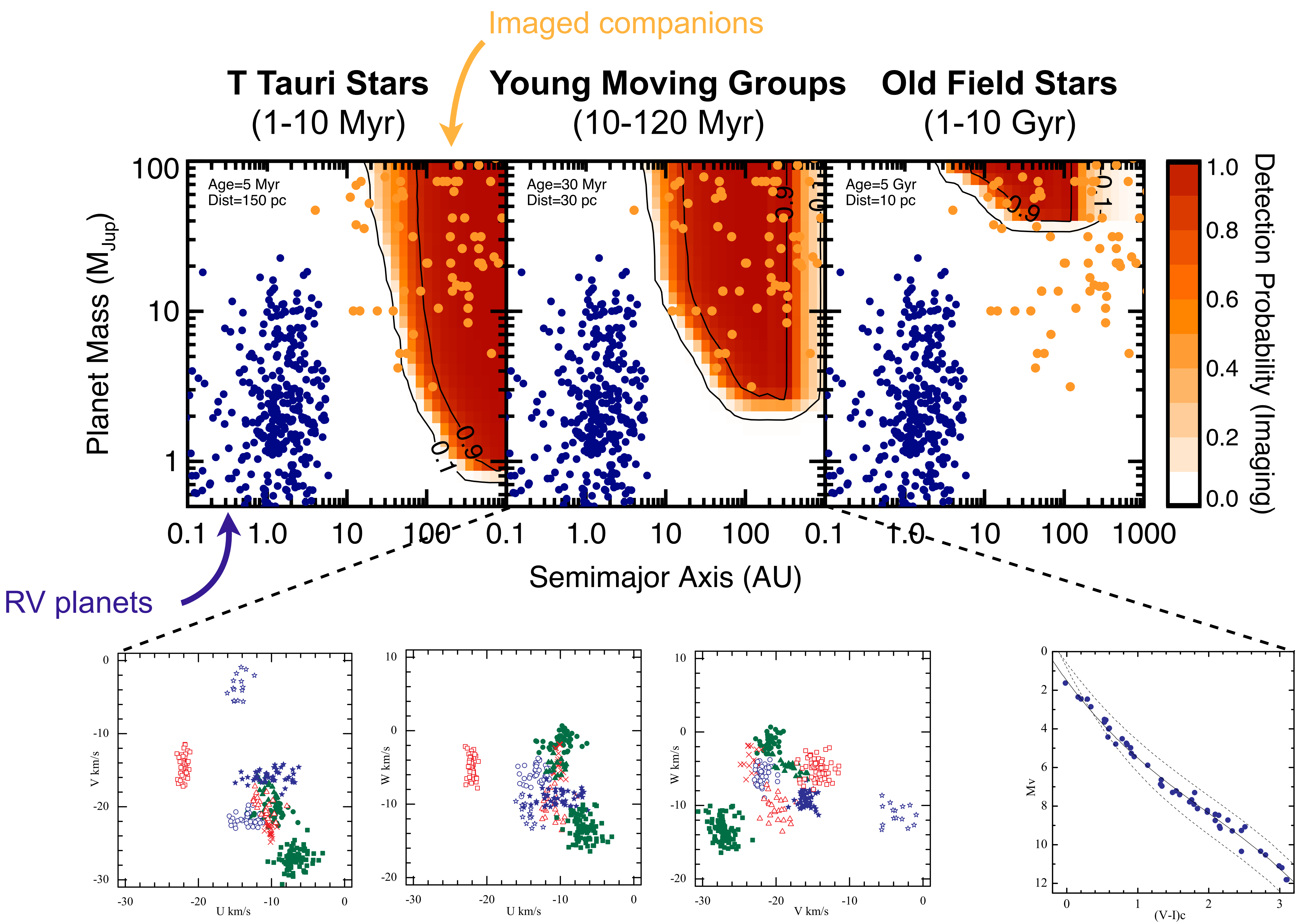
Planet Scattering

- High eccentricities (Scharf & Menou 2009).
- Mass(scatterer) > Mass(scattered)
- Enriched metallicities (Helling et al. 2014).

Young stars are the best targets for direct imaging



Young stars are the best targets for direct imaging



Torres et al. 2008

1. **Discoveries**

The good, the "bad", and the ugly.

2. **Atmospheres and evolution**

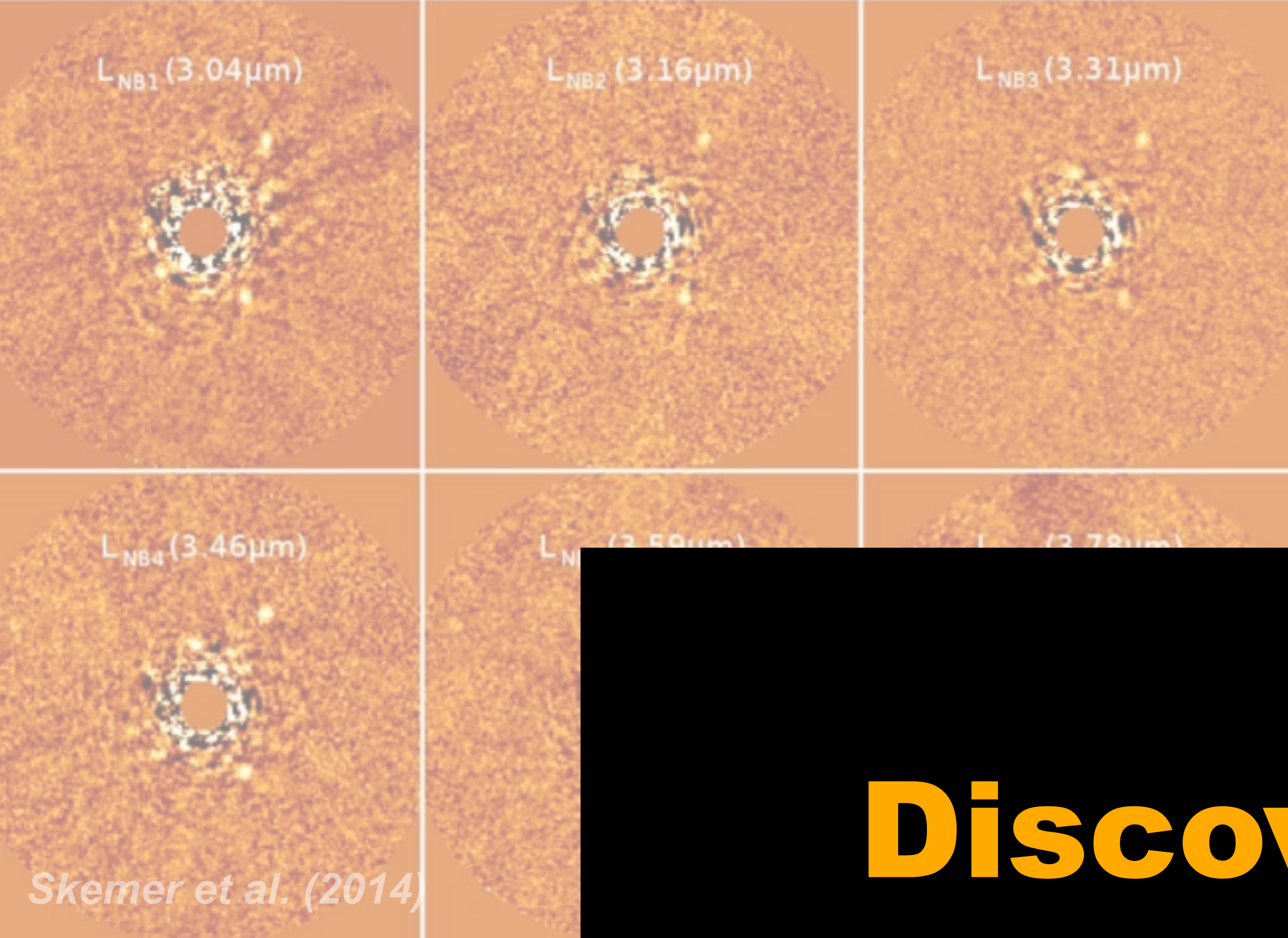
Giant planets don't look like old brown dwarfs.

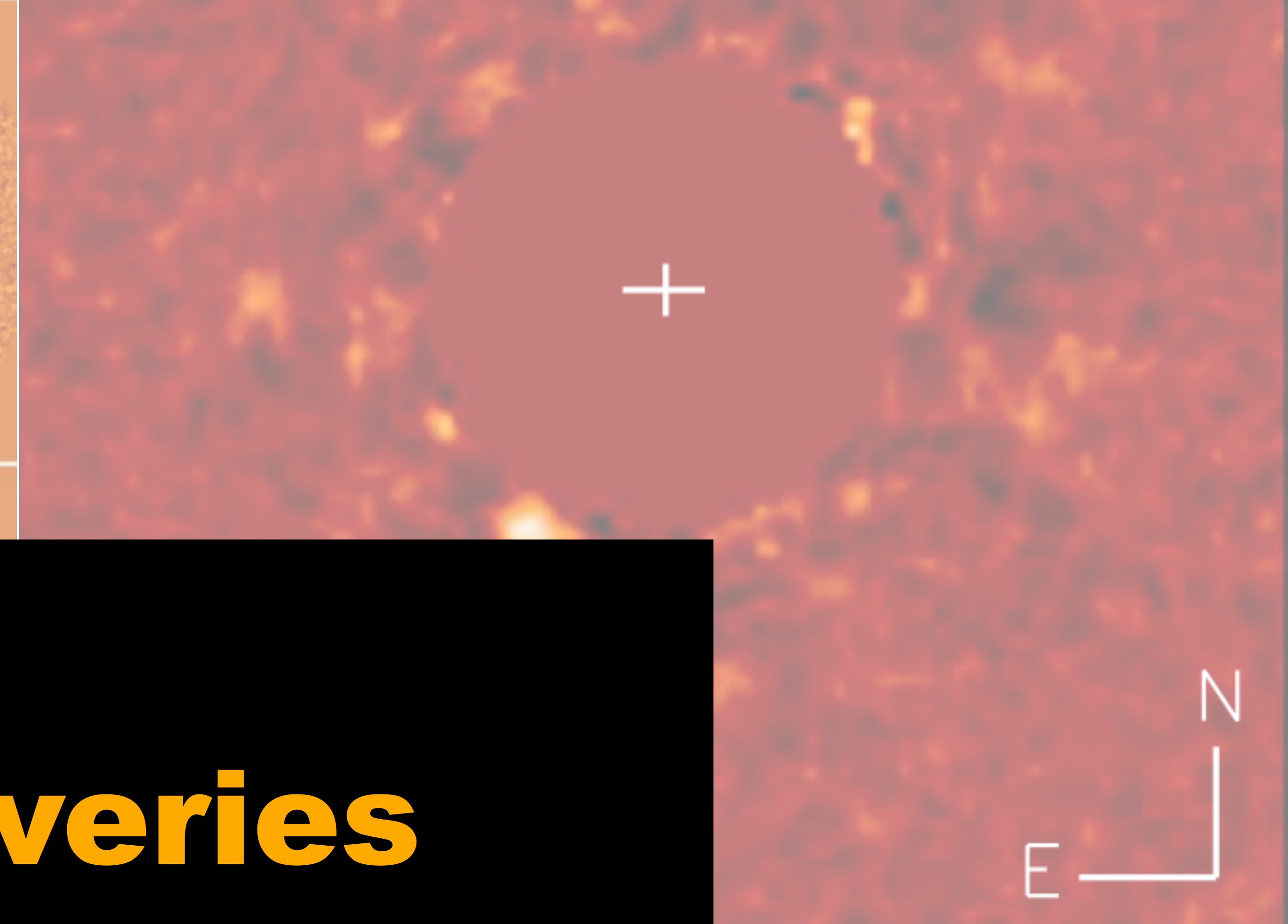
3. **Modern surveys and statistics**

Still more questions than answers.

ROXs42 B with Keck/NIRC2

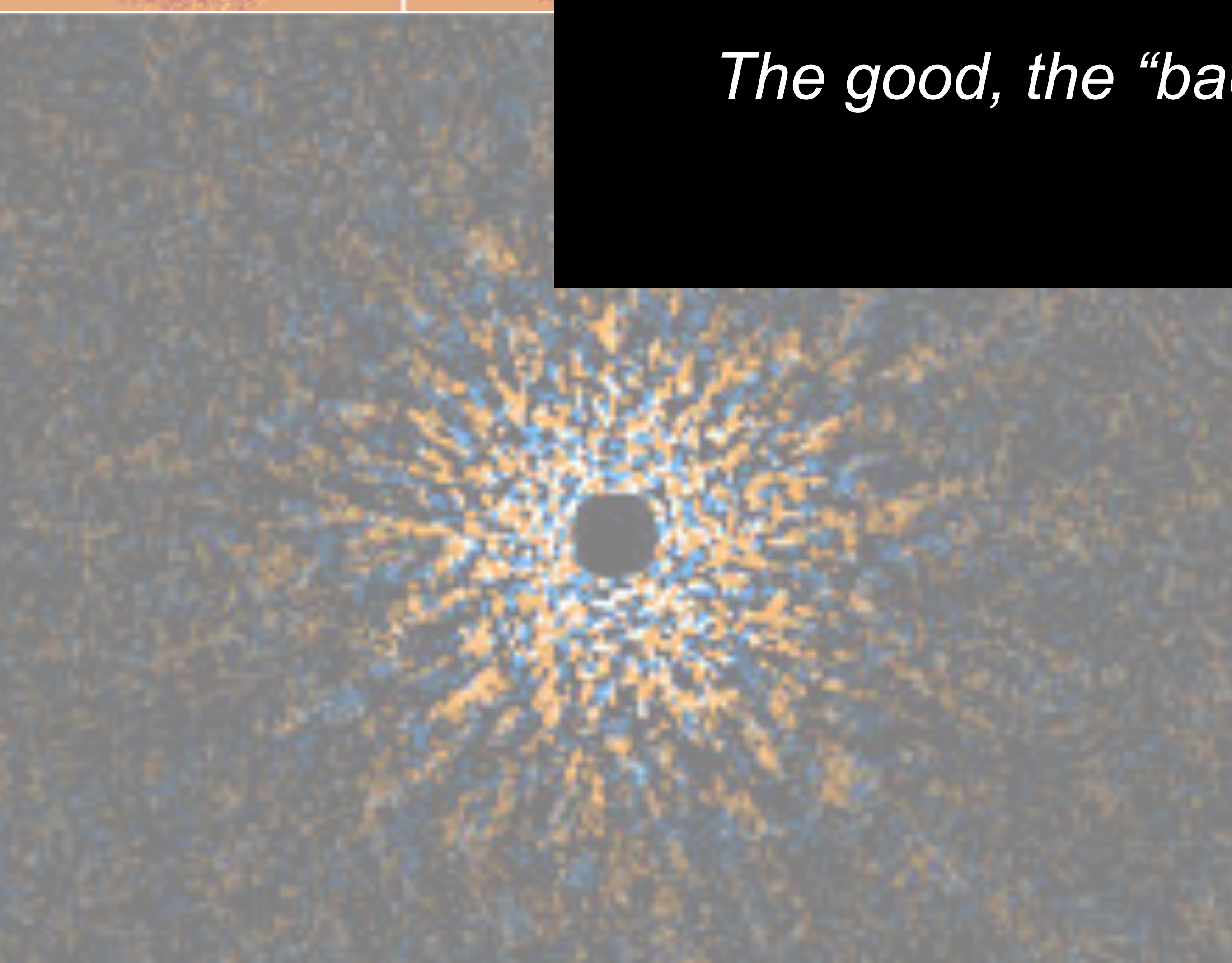
Kraus et al. (2014)

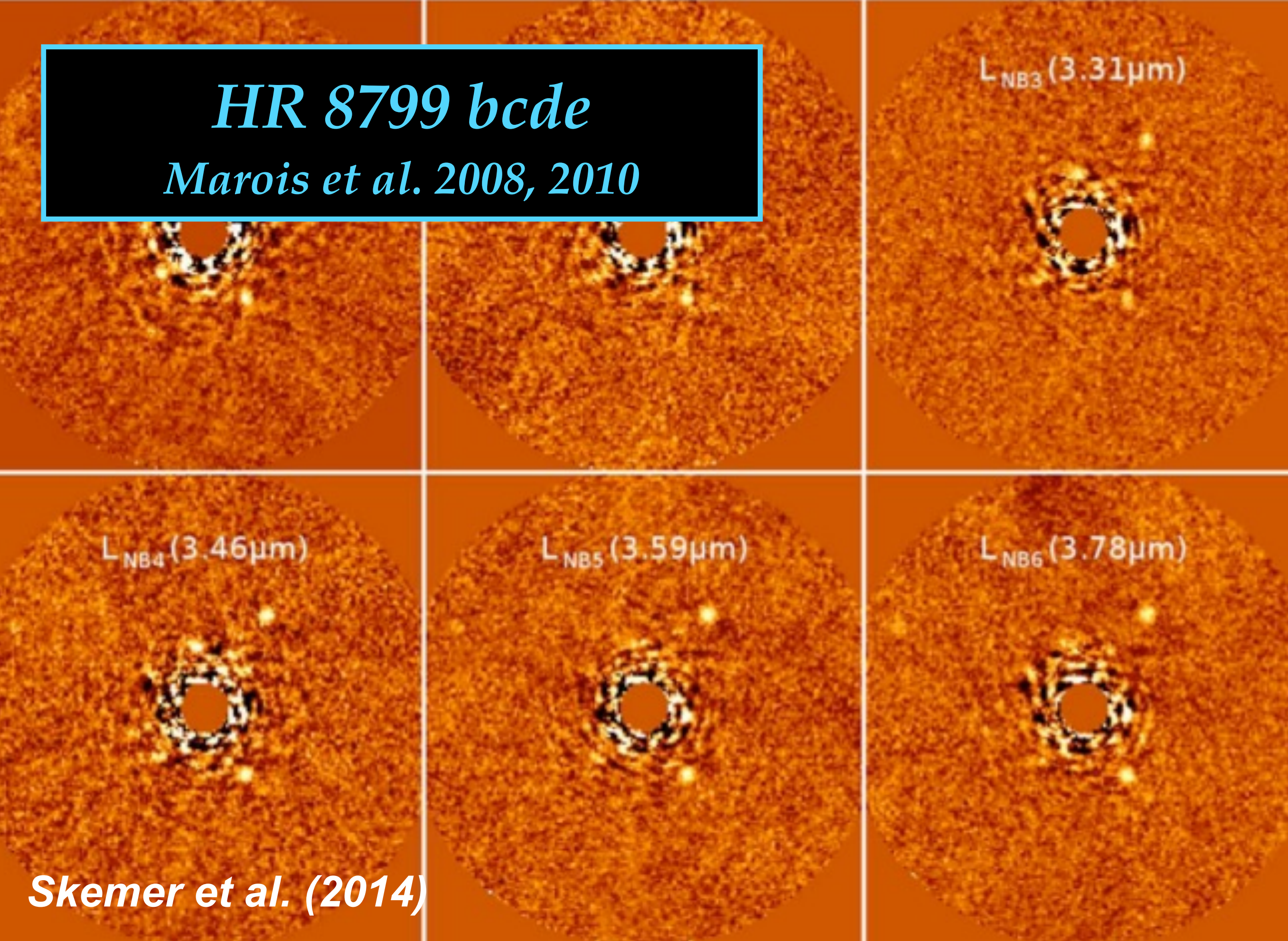


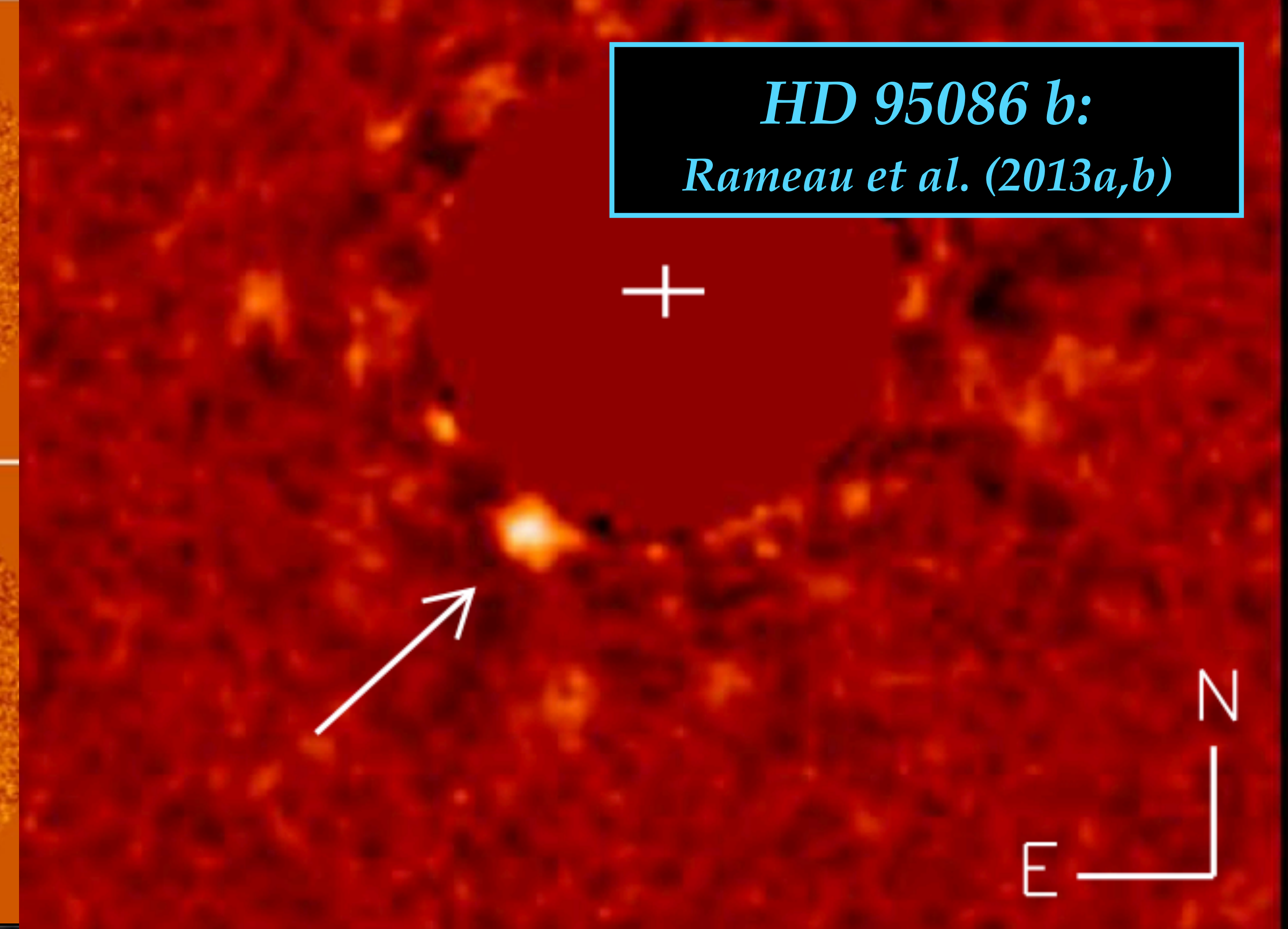


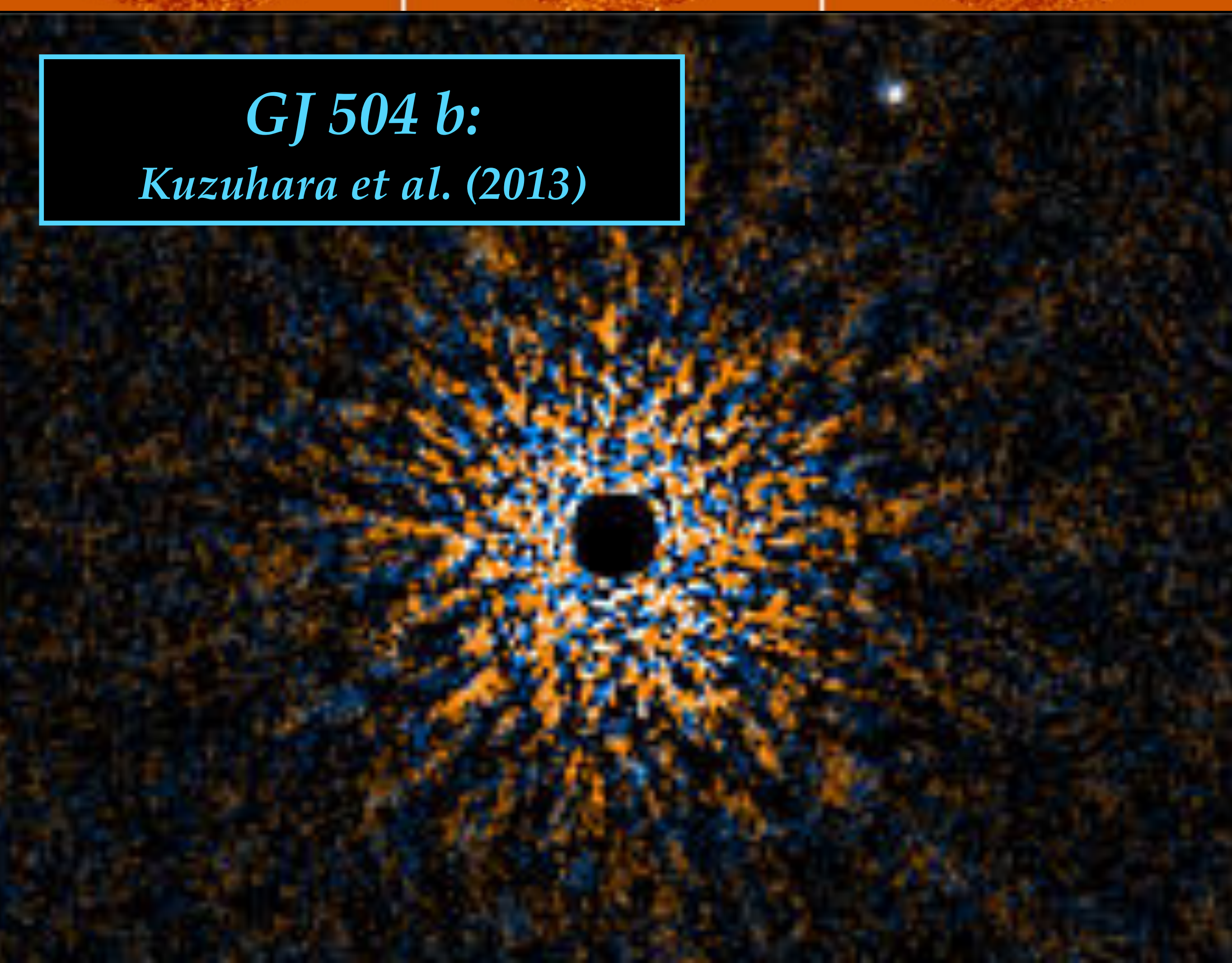
Discoveries

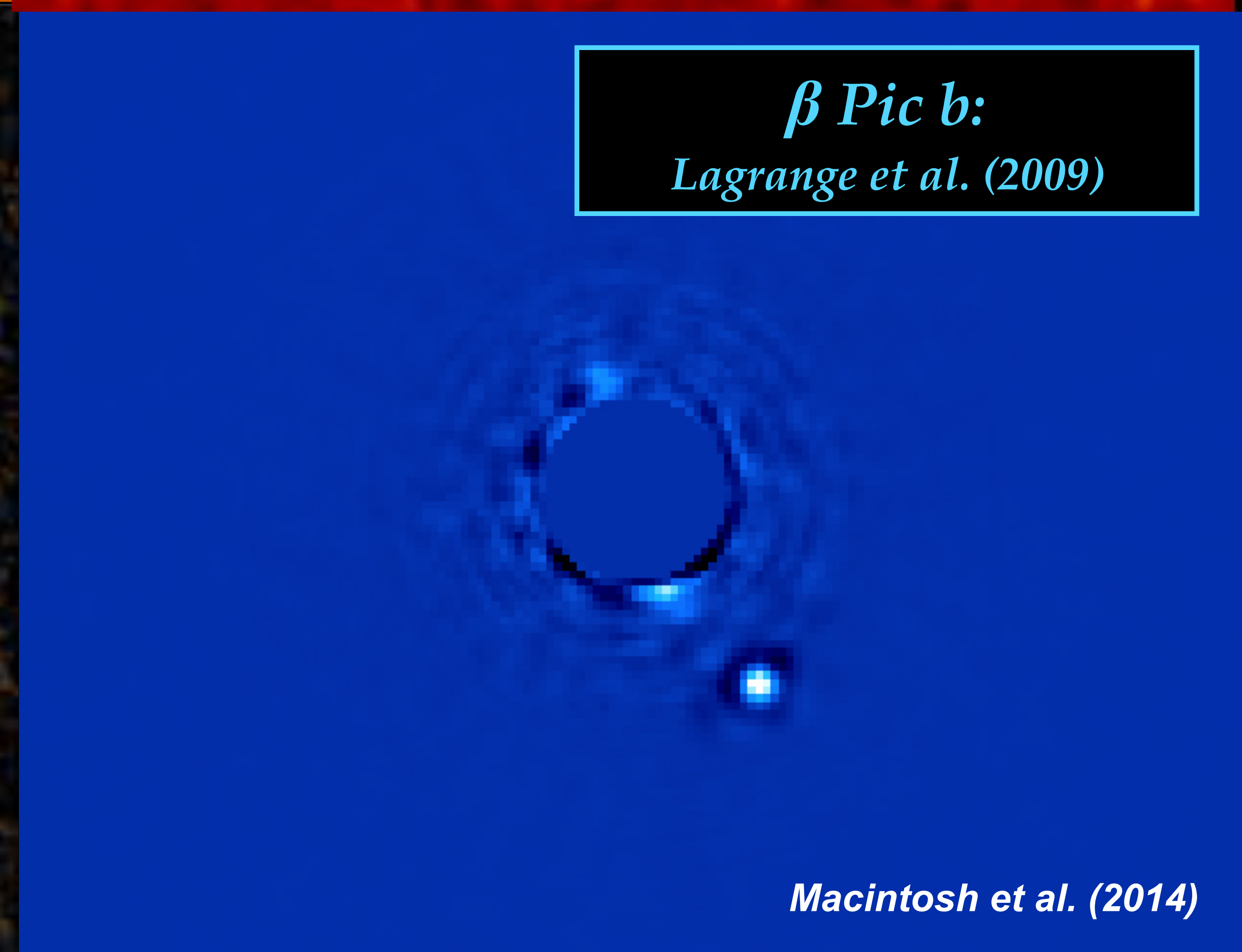
The good, the "bad", and the ugly.




HR 8799 bcde
Marois et al. 2008, 2010
L NB3 (3.31μm)
L NB4 (3.46μm)
L NB5 (3.59μm)
L NB6 (3.78μm)
Skemer et al. (2014)


HD 95086 b:
Rameau et al. (2013a,b)
N
E

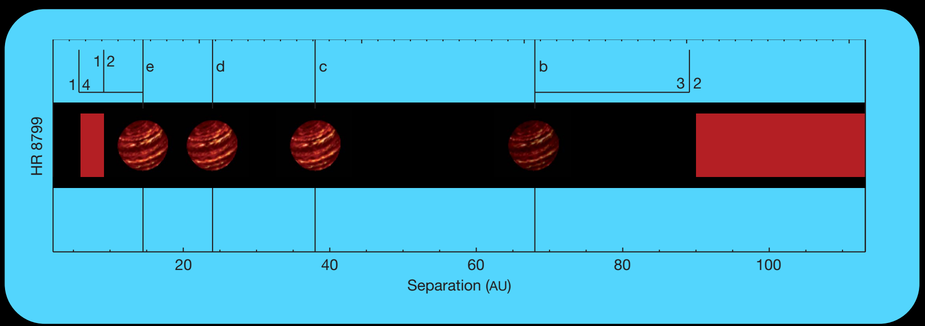

GJ 504 b:
Kuzuhara et al. (2013)

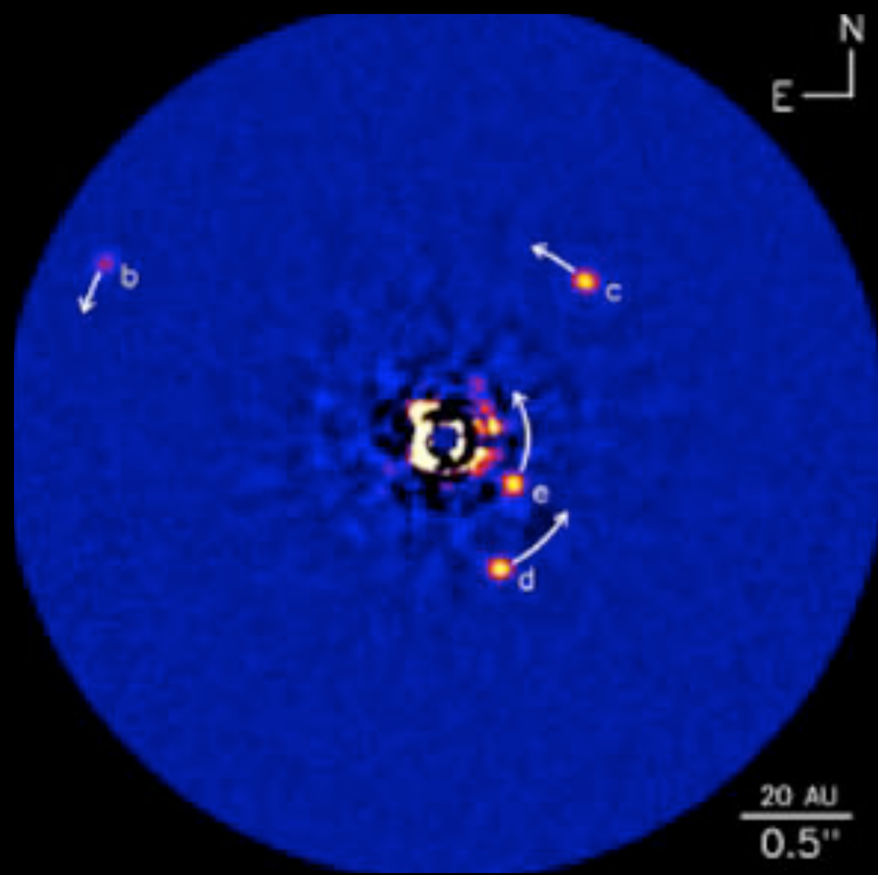

β Pic b:
Lagrange et al. (2009)
Macintosh et al. (2014)

HR 8799 bcde

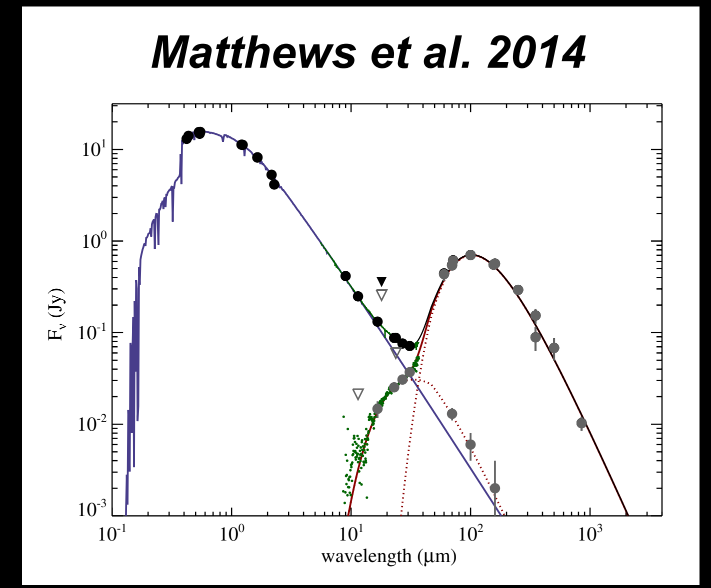
Marois et al. 2008, 2010

- A5 host star (1.5 $M_\odot$)
- 39 pc, ~30 Myr (Col MG)
- Planets cde: ~7-10 M_{Jup}
- Planet b: ~5-7 M_{Jup}
- 15-70 AU



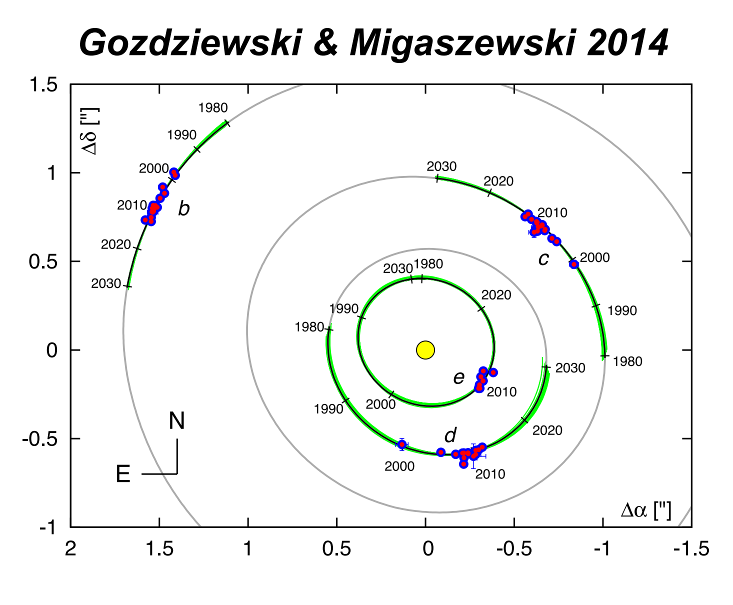


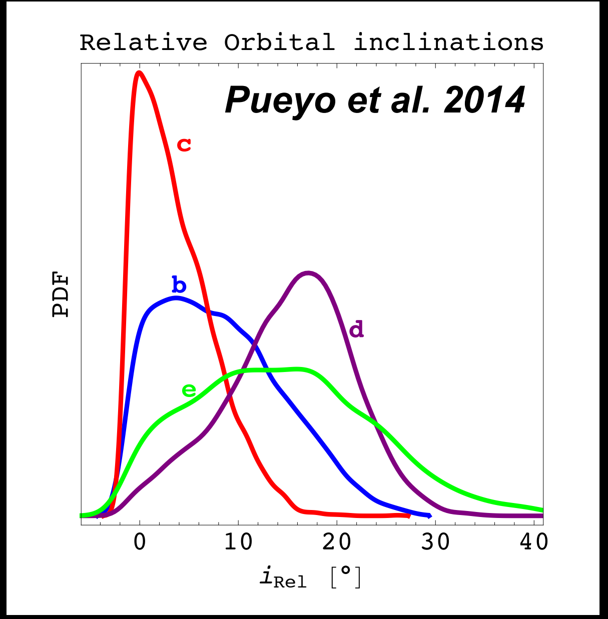
Two Debris Disks



Orbits, Stability, and Masses

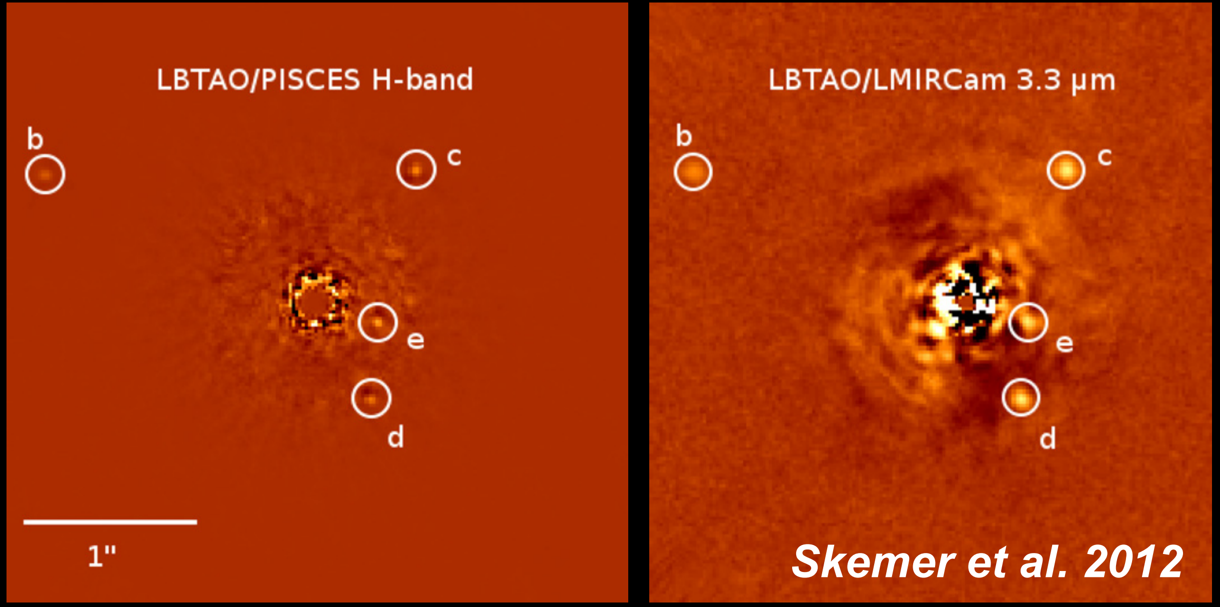
e.g., Soummer et al. 2011, Esposito et al. 2013, Godziewski & Migaszewski 2014, Pueyo et al. 2014





Photometry and spectroscopy from 1-5 μm

e.g., Bowler et al. 2010; Barman et al. 2011, Konopacky et al. 2013, Skemer et al. 2014



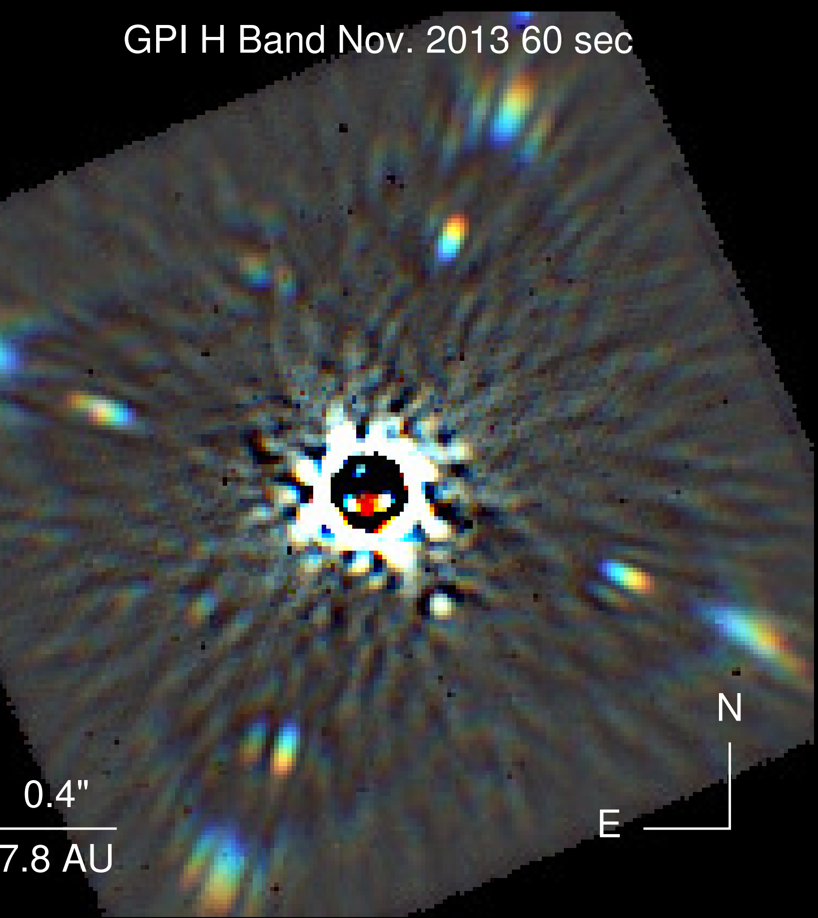
β Pic b

Lagrange et al. 2009, 2010

- A6 host star (1.8 $M_\odot$)
- 19 pc, ~23 Myr
- Mass: ~7-10 M_{Jup}
- Semi-major axis: 9 AU

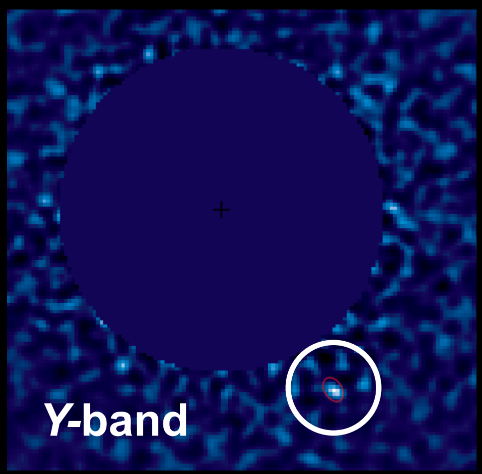
A 1500 AU main disk, an inclined inner disk, and exocomets

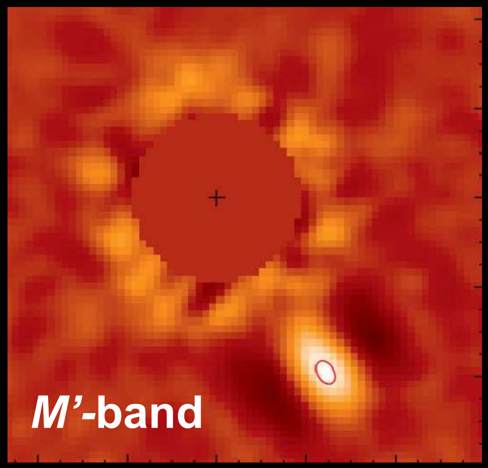
Photometry and spectroscopy



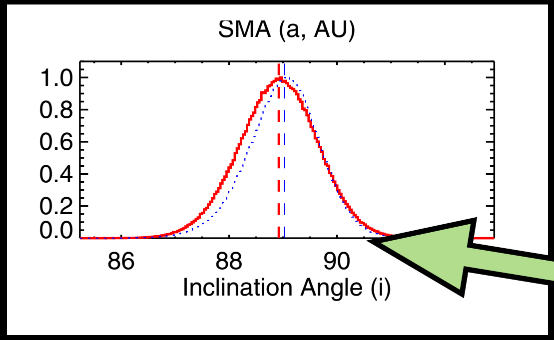
Macintosh et al. (2014)

Males et al. (2014)



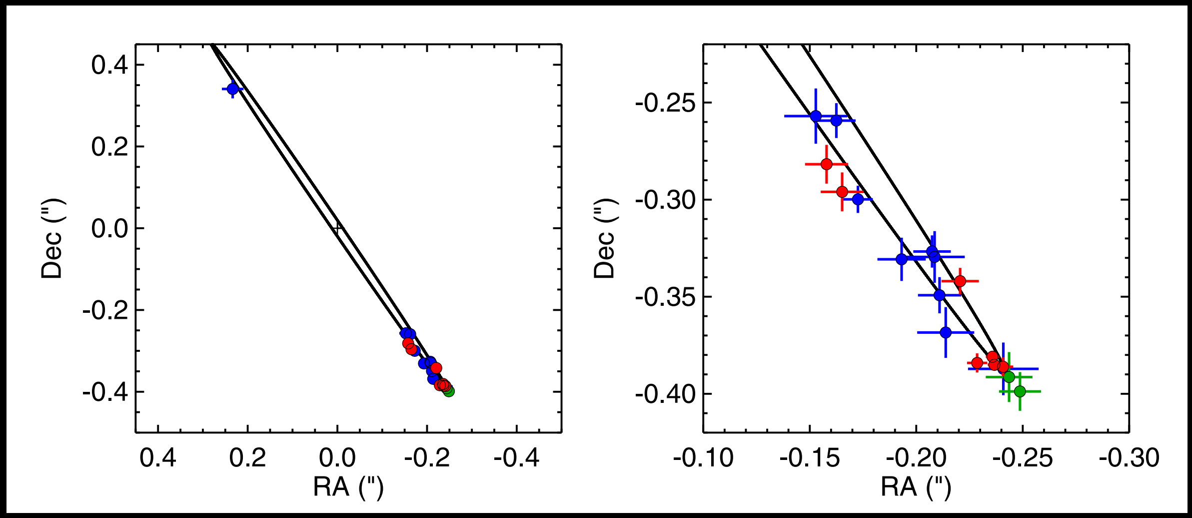


Astrometry spanning 2003-2014



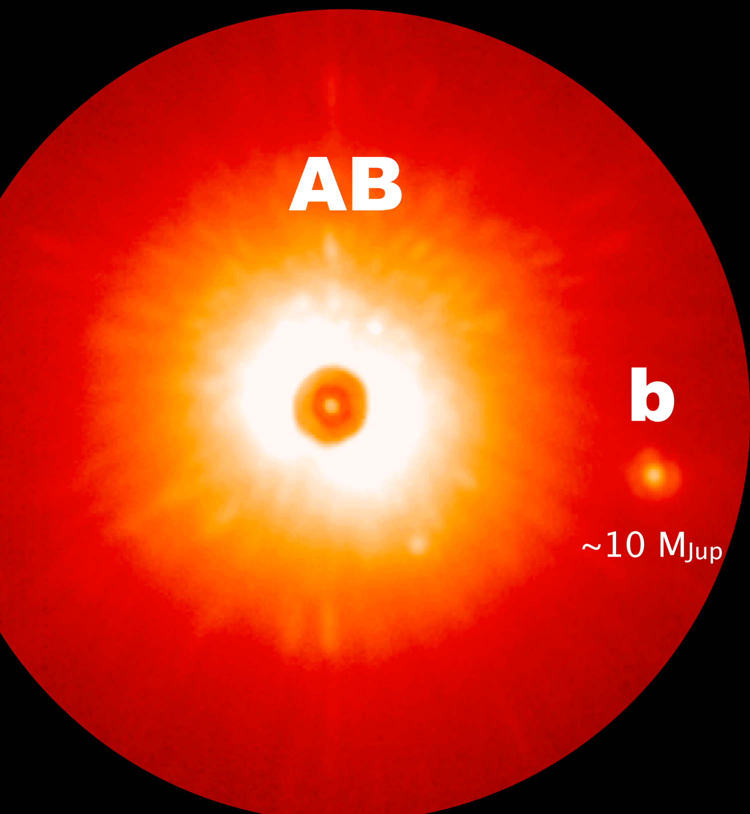
Transit?

e.g., Nielsen et al. 2014, Macintosh et al. 2014, Chauvin et al. 2012, Lagrange et al. 2012

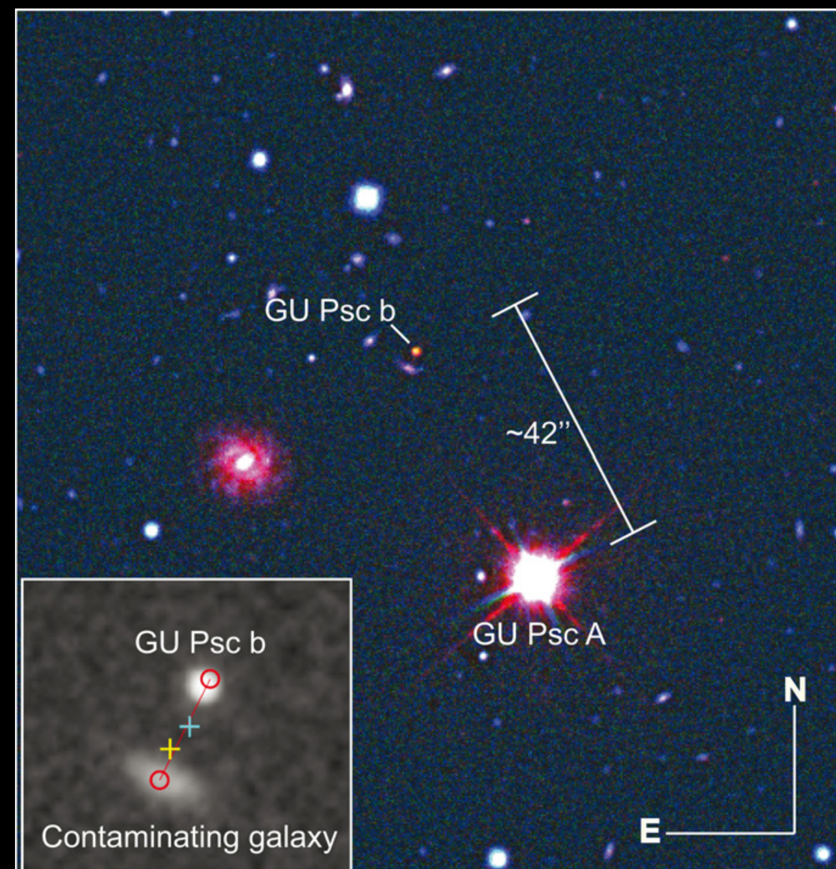


Planetary-Mass Companions Beyond 100 AU

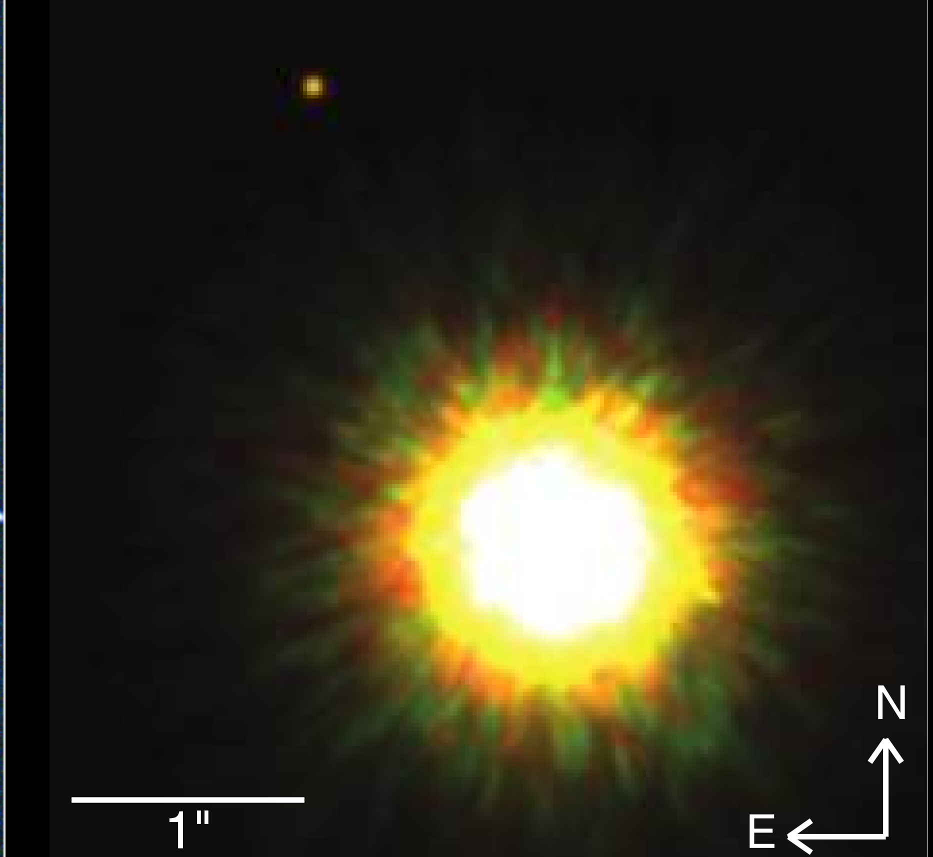
ROXs 42 B
Kraus et al. 2014
Currie et al. 2014



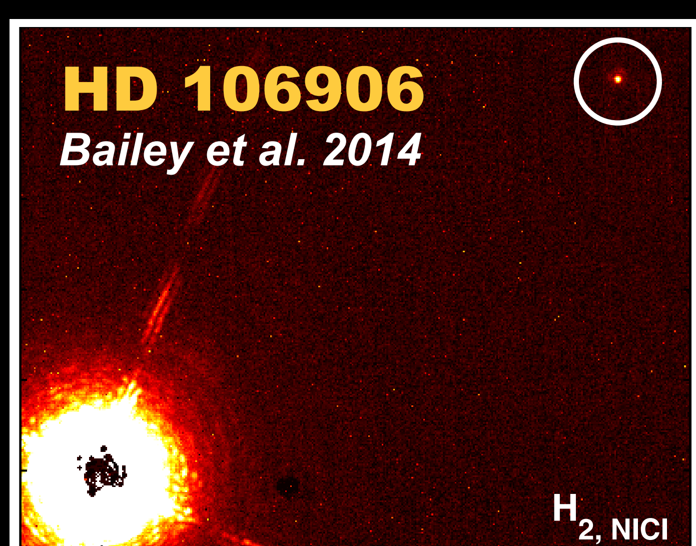
GU Psc b
Naud et al. 2014



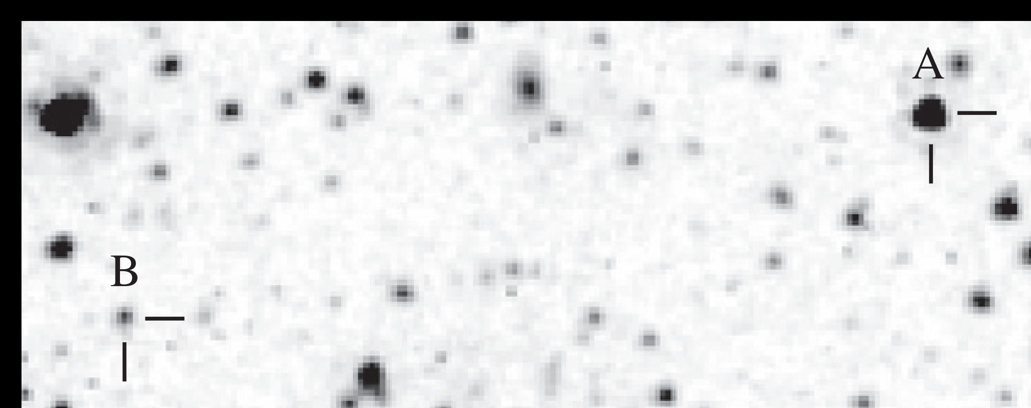
1RXS 1609-2105 b
Lafreniere et al. 2008, 2010
Ireland et al. 2011

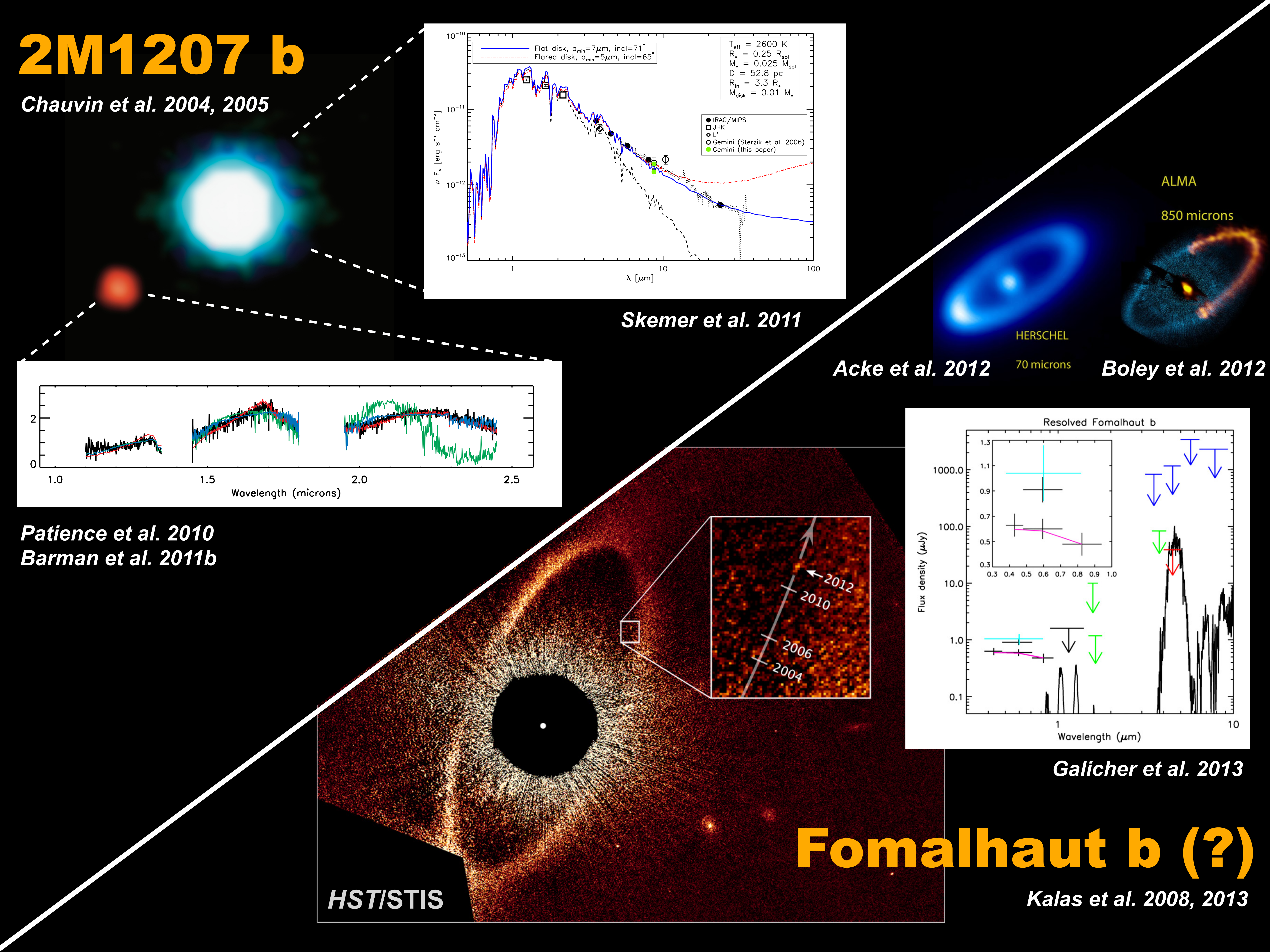


HD 106906
Bailey et al. 2014

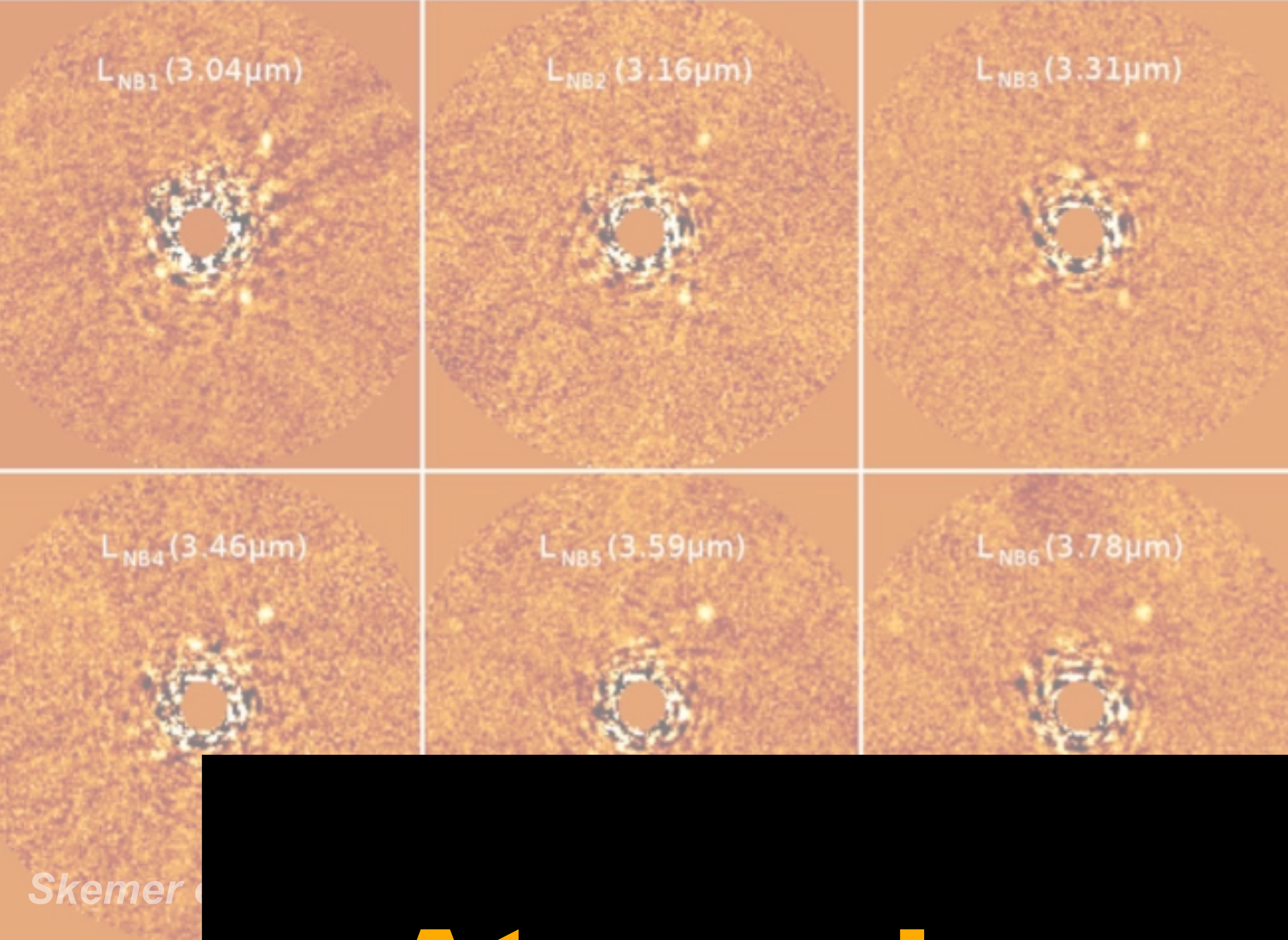


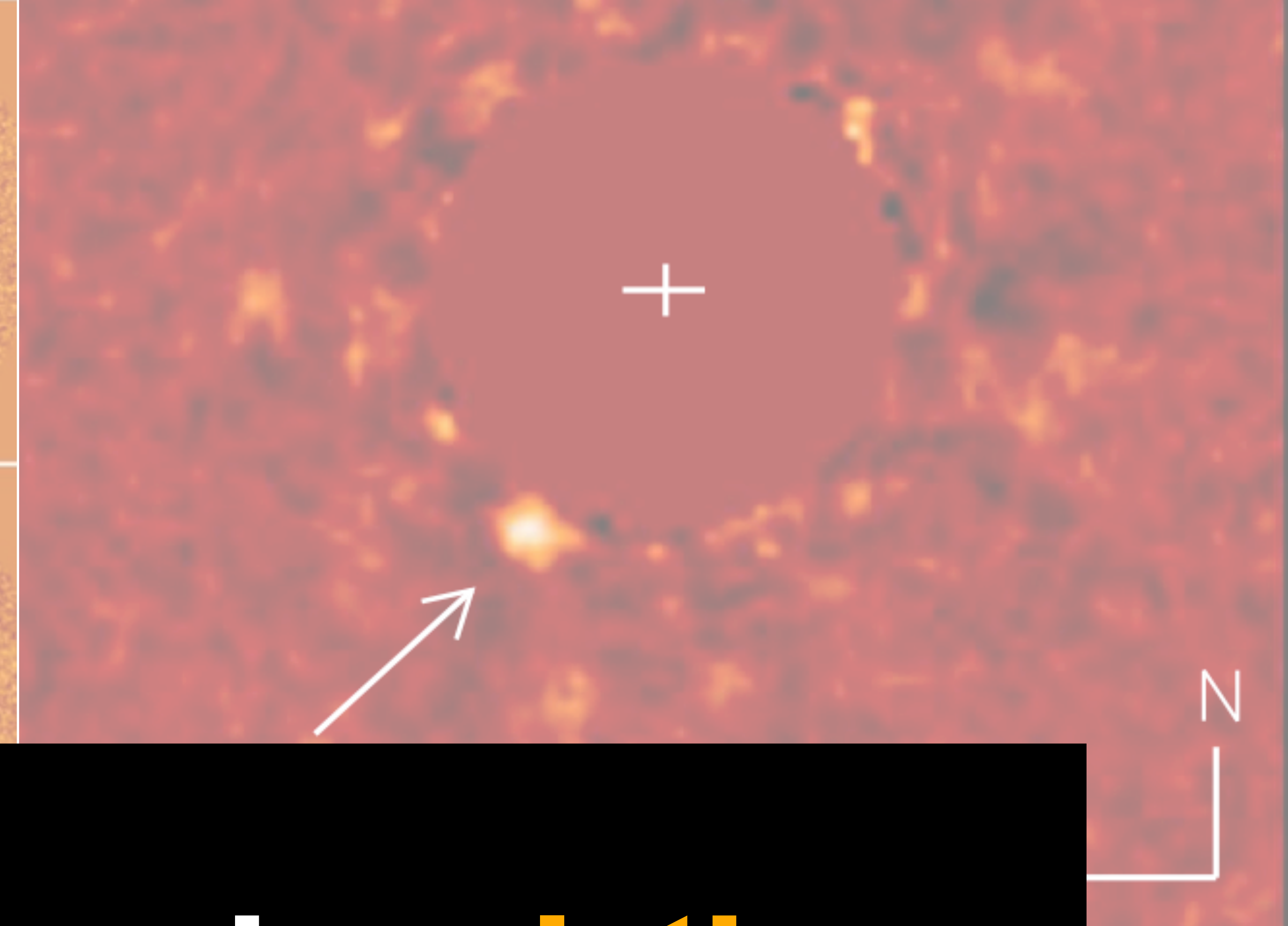
WD 0806-661 b
Luhman et al. 2011, 2012

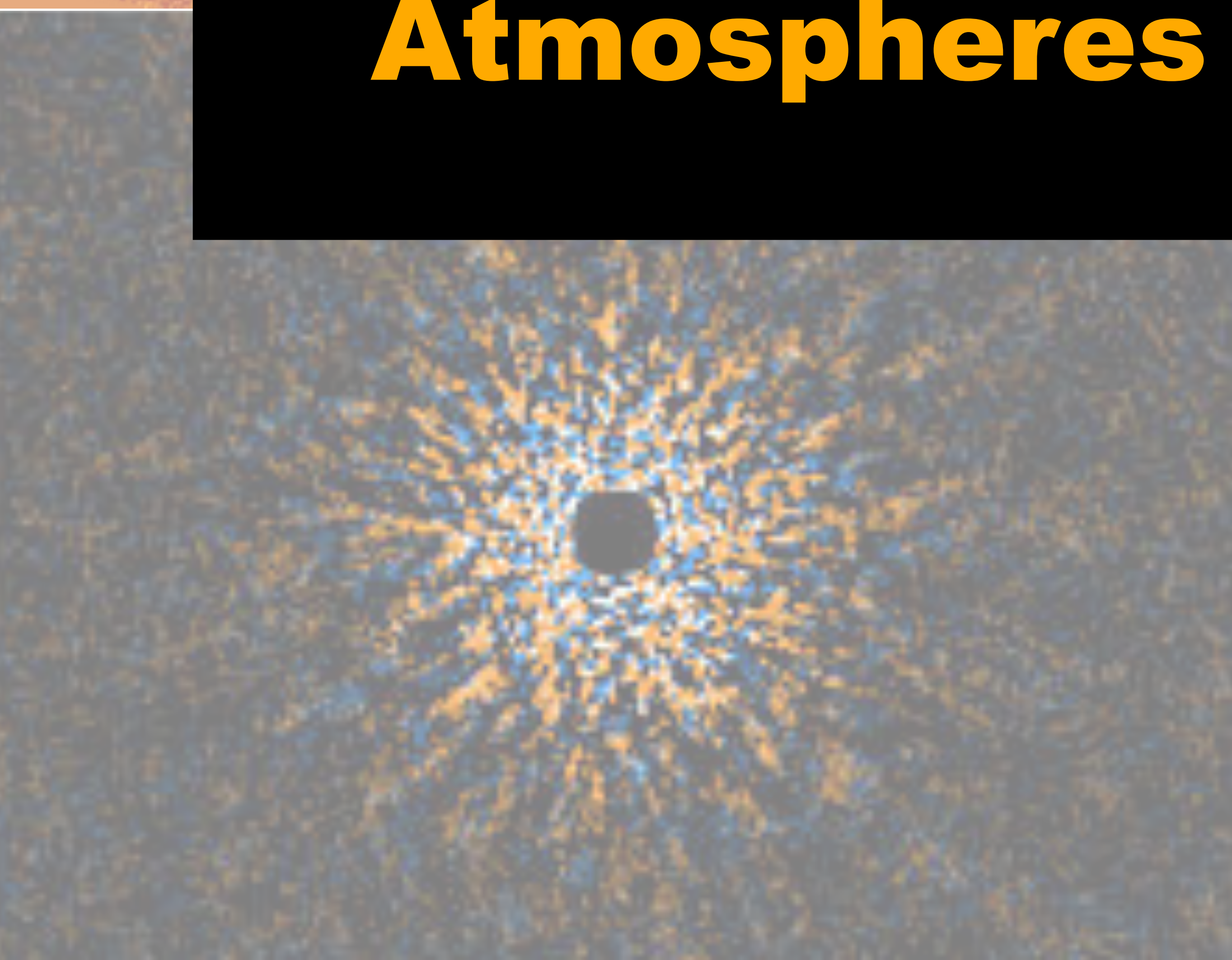



2M1207 b
Chauvin et al. 2004, 2005
Skemer et al. 2011
λ [μm]
Flat disk, a_min=7μm, incl=71°
Flared disk, a_min=5μm, incl=65°
T_eff = 2600 K
R* = 0.25 R_sol
M* = 0.025 M_sol
D = 52.8 pc
R_in = 3.3 R*
M_disk = 0.01 M*
IRAC/MIPS
JHK
L'
Gemini (Sterzik et al. 2006)
Gemini (this paper)
Wavelength (microns)
Patience et al. 2010
Barman et al. 2011b
ALMA
850 microns
HERSCHEL
70 microns
Acke et al. 2012
Boley et al. 2012
Resolved Fomalhaut b
Flux density (μJy)
Wavelength (μm)
Galicher et al. 2013
2012
2010
2006
2004
HST/STIS
Fomalhaut b (?)
Kalas et al. 2008, 2013

Atmospheres and evolution



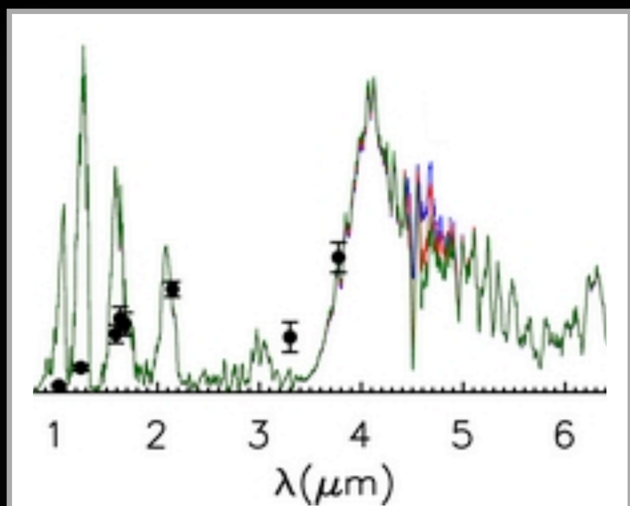




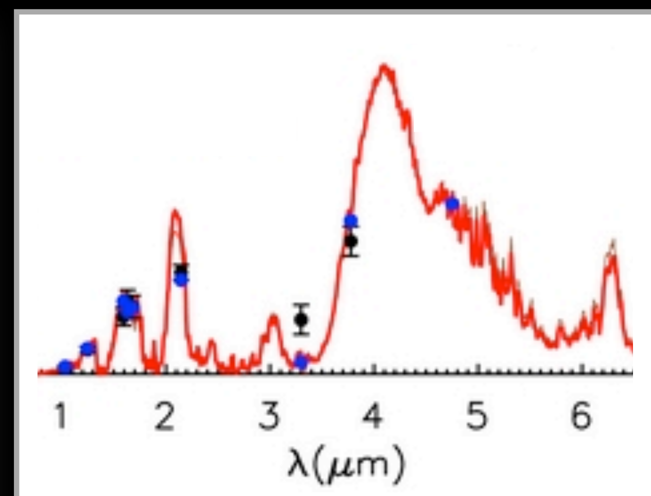
Dusty, low gravity atmospheres

Recently, evidence for non-equilibrium chemistry and patchy clouds

1000 K
No Dust

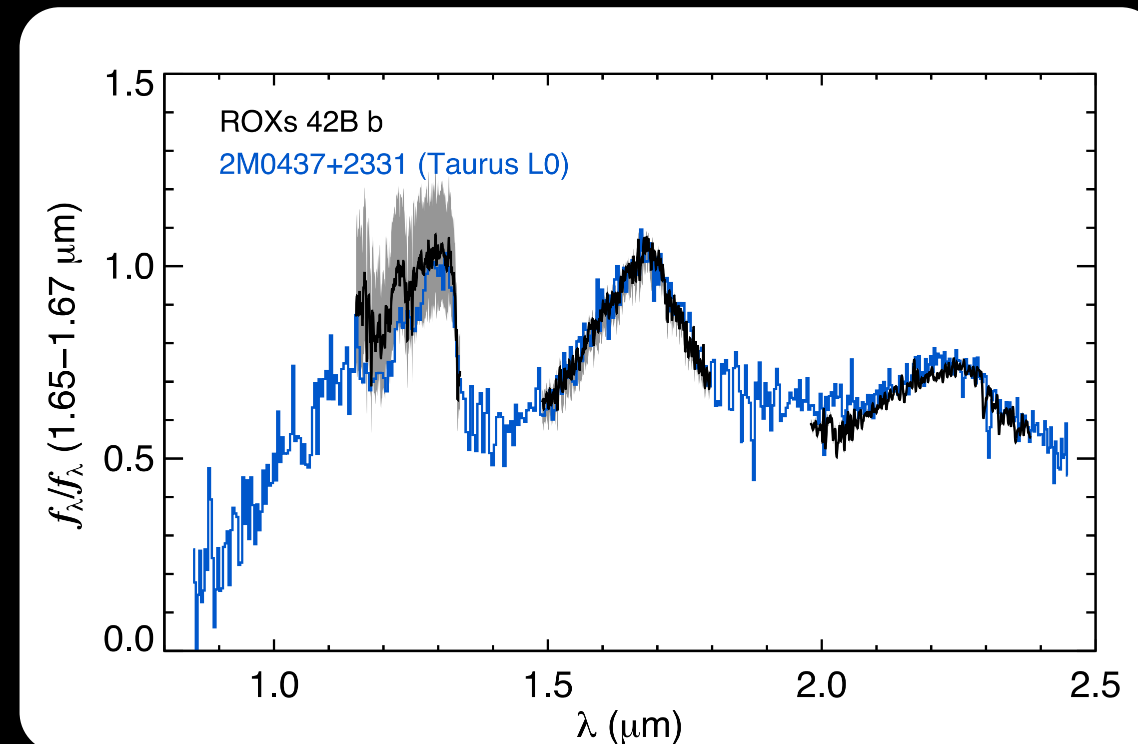


1000 K
Dust



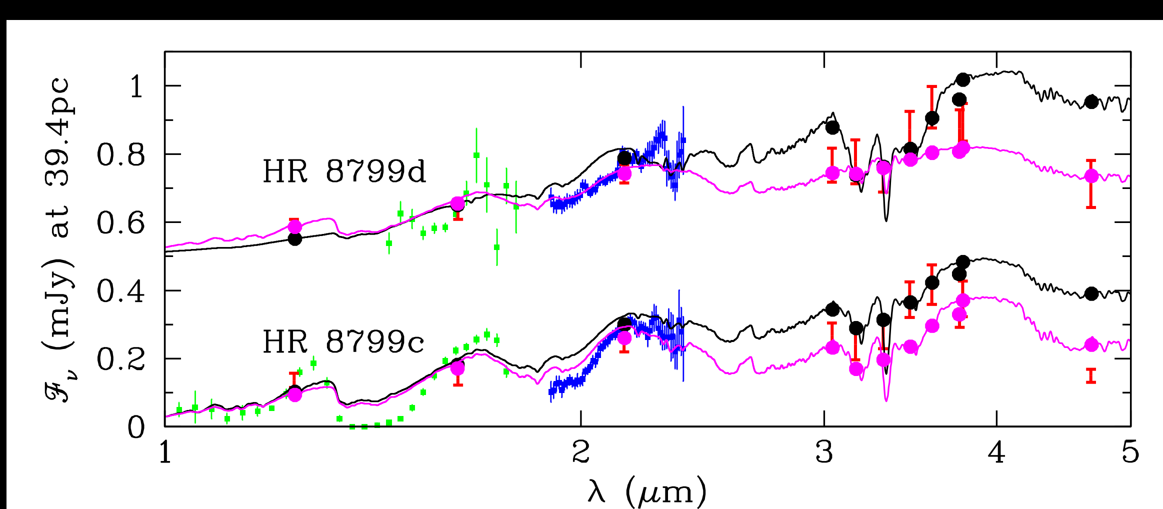
e.g., Madhusudhan et al. 2011, Barman et al. 2011

ROXs42B b



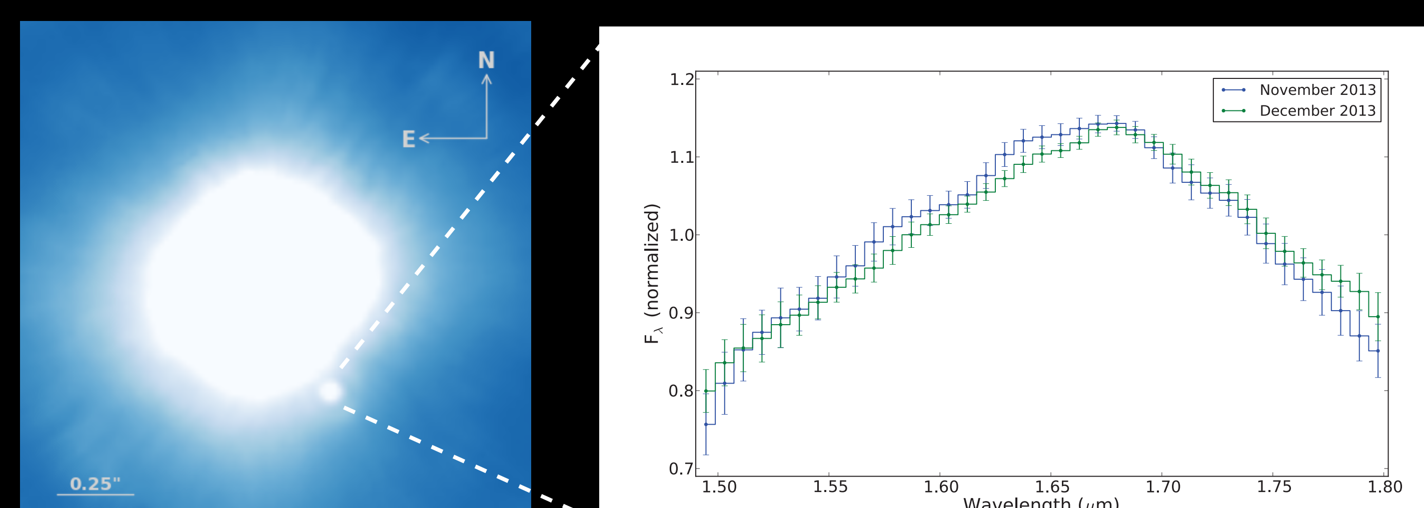
Bowler et al. 2014a

HR 8799 c,d with GPI



Ingraham et al. 2014

β Pic b with GPI



Chilcote et al. 2014

The evolution of giant planets

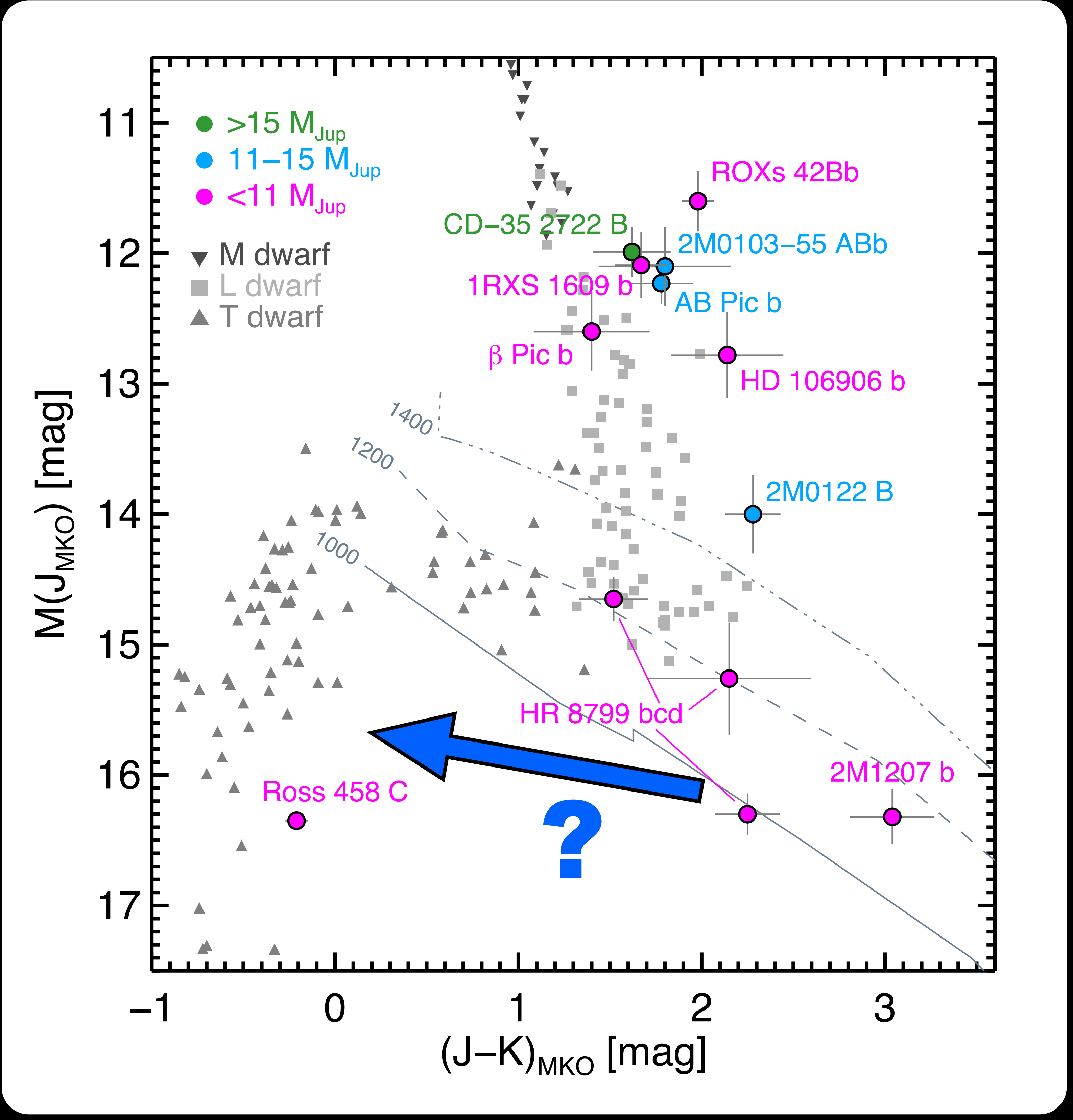
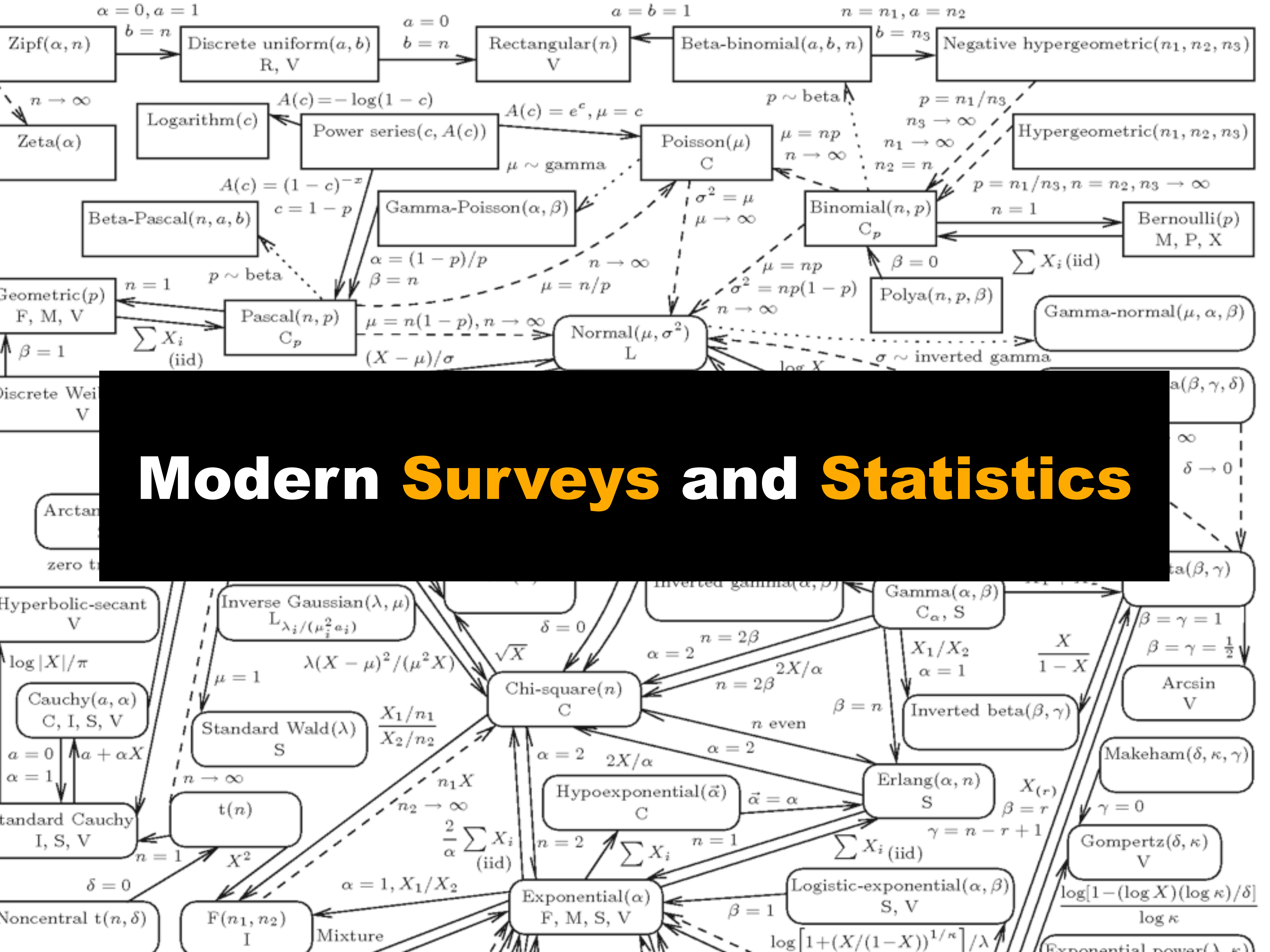


Figure courtesy M. Liu

See also:
Barman 2011,
Marley 2012
Zahnle & Marley 2014

Modern Surveys and Statistics



Many direct imaging surveys...

Table 1. Deep imaging surveys of young (< 100 Myr) and intermediate-old to old ($0.1 - 5$ Gyr), nearby (< 100 pc) stars dedicated to the search for planetary mass companions. We have indicated the telescope and the instrument, the imaging mode (Cor-I: coronagraphic imaging; Sat-I; saturated imaging; I: imaging; SDI: simultaneous differential imaging; ADI: angular differential imaging; ASDI: angular and spectral differential imaging), the filters, the field of view (FoV), the number of stars observed (#), their spectral types (SpT) and ages (Age).

Reference	Telescope	Instr.	Mode	Filter	FoV ($'' \times ''$)	#	SpT	Age (Myr)
Chauvin et al. 2003	ESO3.6m	ADONIS	Cor-I	H, K	13×13	29	GKM	$\lesssim 50$
Neuhäuser et al. 2003	NTT	Sharp	Sat-I	K	11×11	23	AFGKM	$\lesssim 50$
	NTT	Sofi	Sat-I	H	13×13	10	AFGKM	$\lesssim 50$
Lowrance et al. 2005	HST	NICMOS	Cor-I	H	19×19	45	AFGKM	$10 - 600$
Masciadri et al. 2005	VLT	NaCo	Sat-I	H, K	14×14	28	KM	$\lesssim 200$
Biller et al. 2007	VLT	NaCo	SDI	H	5×5	45	GKM	$\lesssim 300$
	MMT		SDI	H	5×5	-	-	-
Kasper et al. 2007	VLT	NaCo	Sat-I	L'	28×28	22	GKM	$\lesssim 50$
Lafrenière et al. 2007	Gemini-N	NIRI	ADI	H	22×22	85		10-5000
Apai et al. 2008[a]	VLT	NaCo	SDI	H	3×3	8	FG	12-500
Chauvin et al. 2010	VLT	NaCo	Cor-I	H, K	28×28	88	BAFGKM	$\lesssim 100$
Heinze et al. 2010ab	MMT	Clio	ADI	L', M	15.5×12.4	54	FGK	100-5000
Janson et al. 2011	Gemini-N	NIRI	ADI	H, K	22×22	15	BA	20-700
Vigan et al. 2012	Gemini-N	NIRI	ADI	H, K	22×22	42	AF	10-400
	VLT	NaCo	ADI	H, K	14×14	-	-	-
Delorme et al. 2012	VLT	NaCo	ADI	L'	28×28	16	M	$\lesssim 200$
Rameau et al. 2013c	VLT	NaCo	ADI	L'	28×28	59	AF	$\lesssim 200$
Yamamoto et al. 2013	Subaru	HiCIAO	ADI	H, K	20×20	20	FG	125 ± 8
Biller et al. 2013	Gemini-S	NICI	Cor-ASDI	H	18×18	80	BAFGKM	$\lesssim 200$
Brandt et al. 2013[b]	Subaru	HiCIAO	ADI	H	20×20	63	AFGKM	$\lesssim 500$
Nielsen et al. 2013	Gemini-S	NICI	Cor-ASDI	H	18×18	70	BA	50-500
Wahhaj et al. 2013[a]	Gemini-S	NICI	Cor-ASDI	H	18×18	57	AFGKM	~ 100
Janson et al. 2013[a]	Subaru	HiCIAO	ADI	H	20×20	50	AFGKM	$\lesssim 1000$

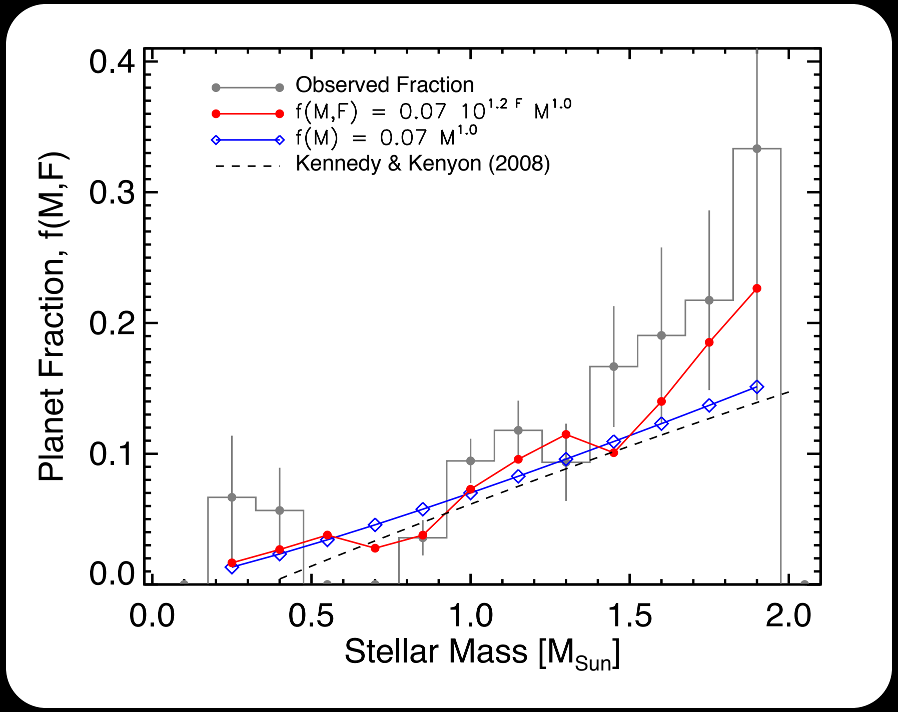
- ([a]): surveys dedicated to planets around debris disk stars.
- ([b]): paper submitted.

From Chauvin et al. (2014)

...but few planets

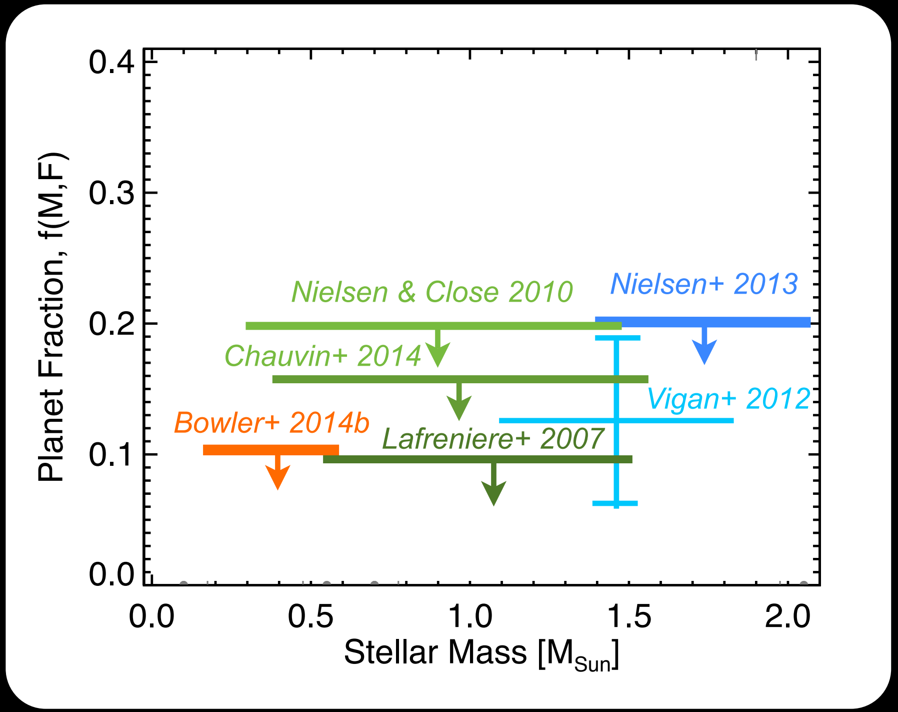
The planet frequency-stellar host mass correlation

Small separations (<2.5 AU)



Johnson et al. 2010

Wide separations (~10-100 AU)

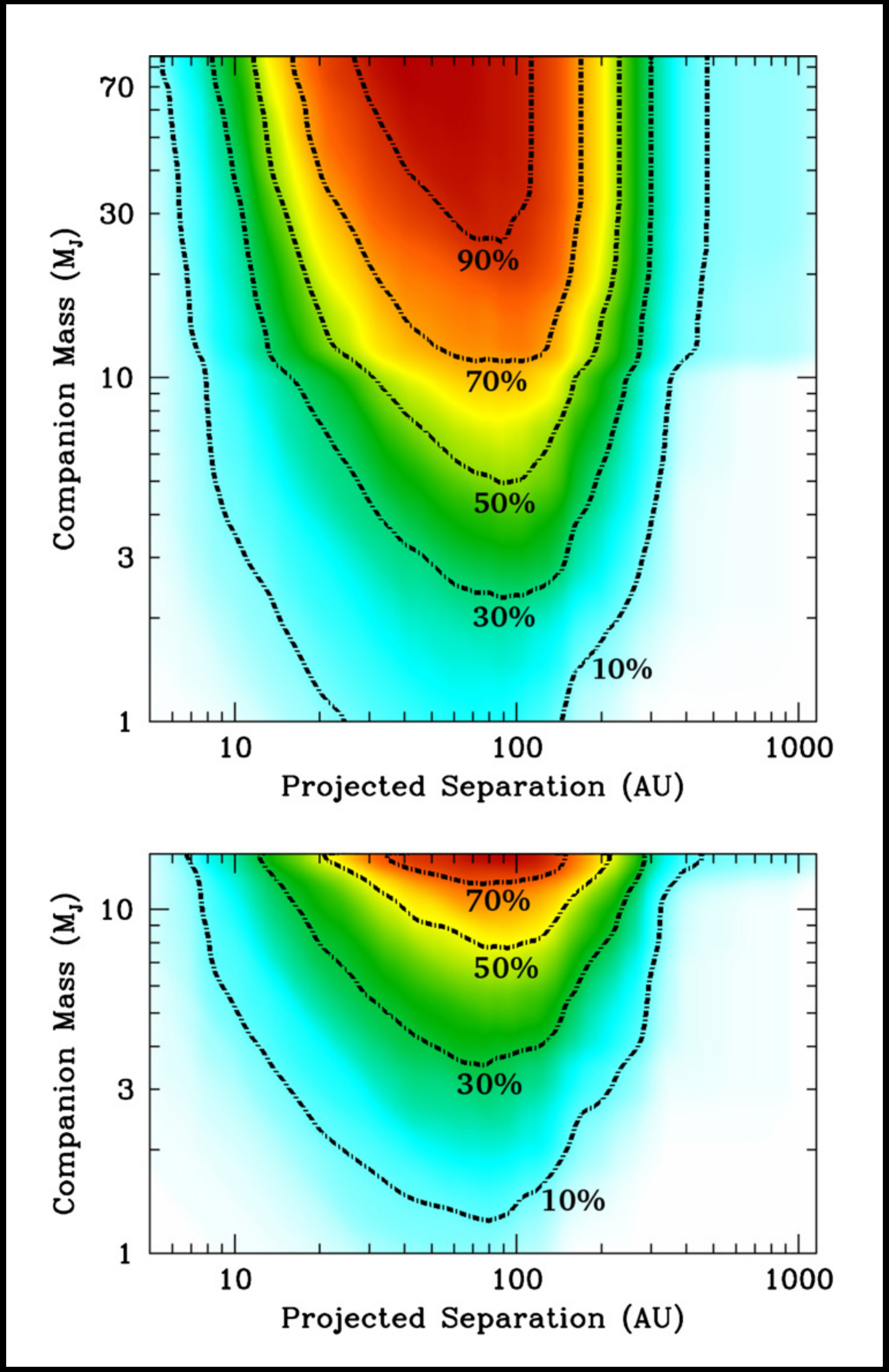


- Mostly upper limits, implying low intrinsic frequencies beyond 10 AU.
- Currently no evidence for a frequency-host mass correlation beyond 10 AU.
- Samples need to be in hundreds to distinguish differences at the few percent level.
  - *e.g., if f=3% for AFG-stars and f=1% for M dwarfs, N=500 is needed to distinguish at 95% CL*
- Ongoing surveys will reach these numbers
  - GPI Campaign, SPHERE Campaign, PALMS, LEECH, SEEDS, NICI, IDPS

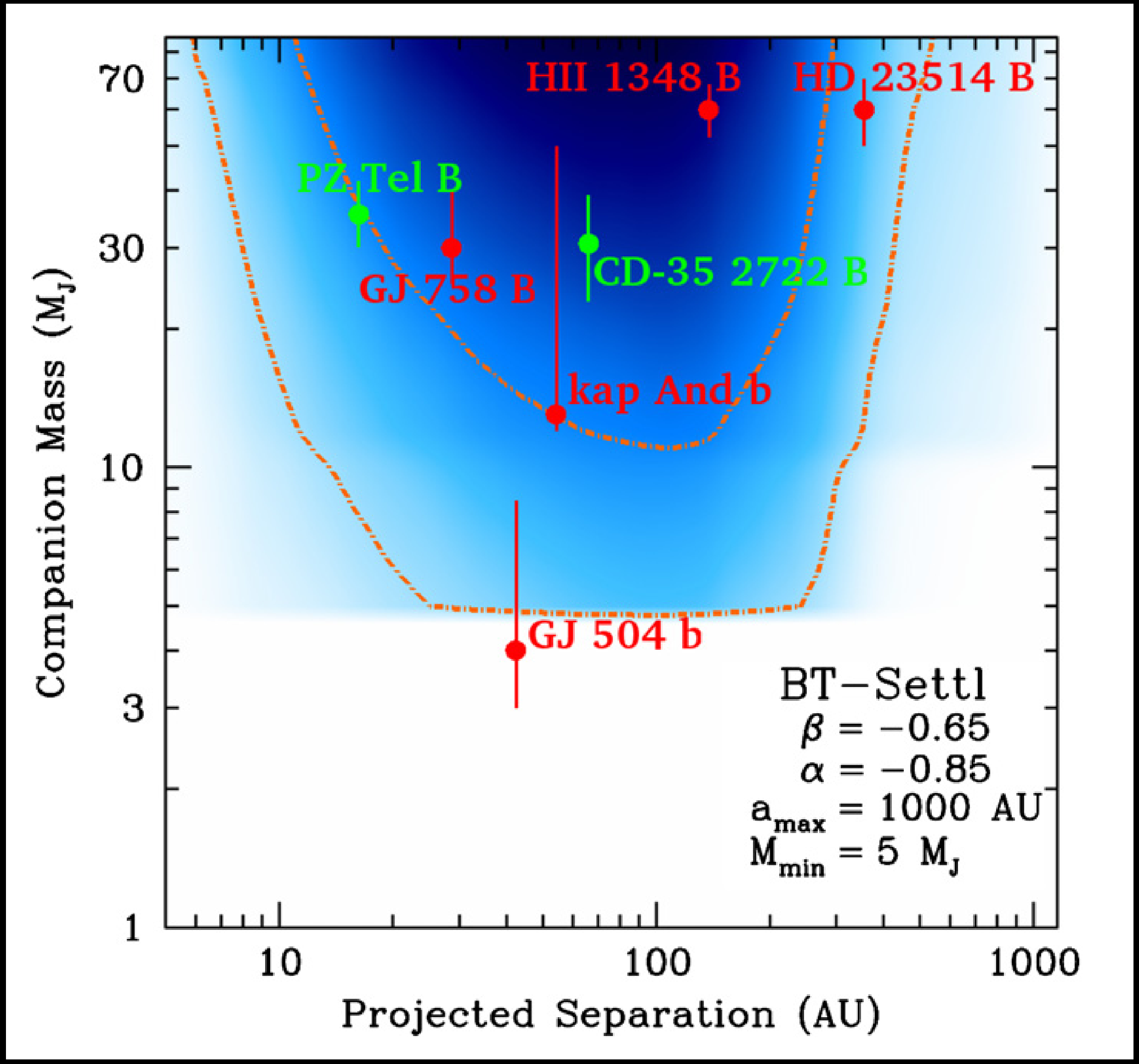
The companion mass function

***Brandt et al. 2014*: 250 star meta-analysis of SEEDS and NICI**

- **Substellar companions (5-70 M_{Jup}) are well-described by a single, smooth power law distribution in *m* and *a***

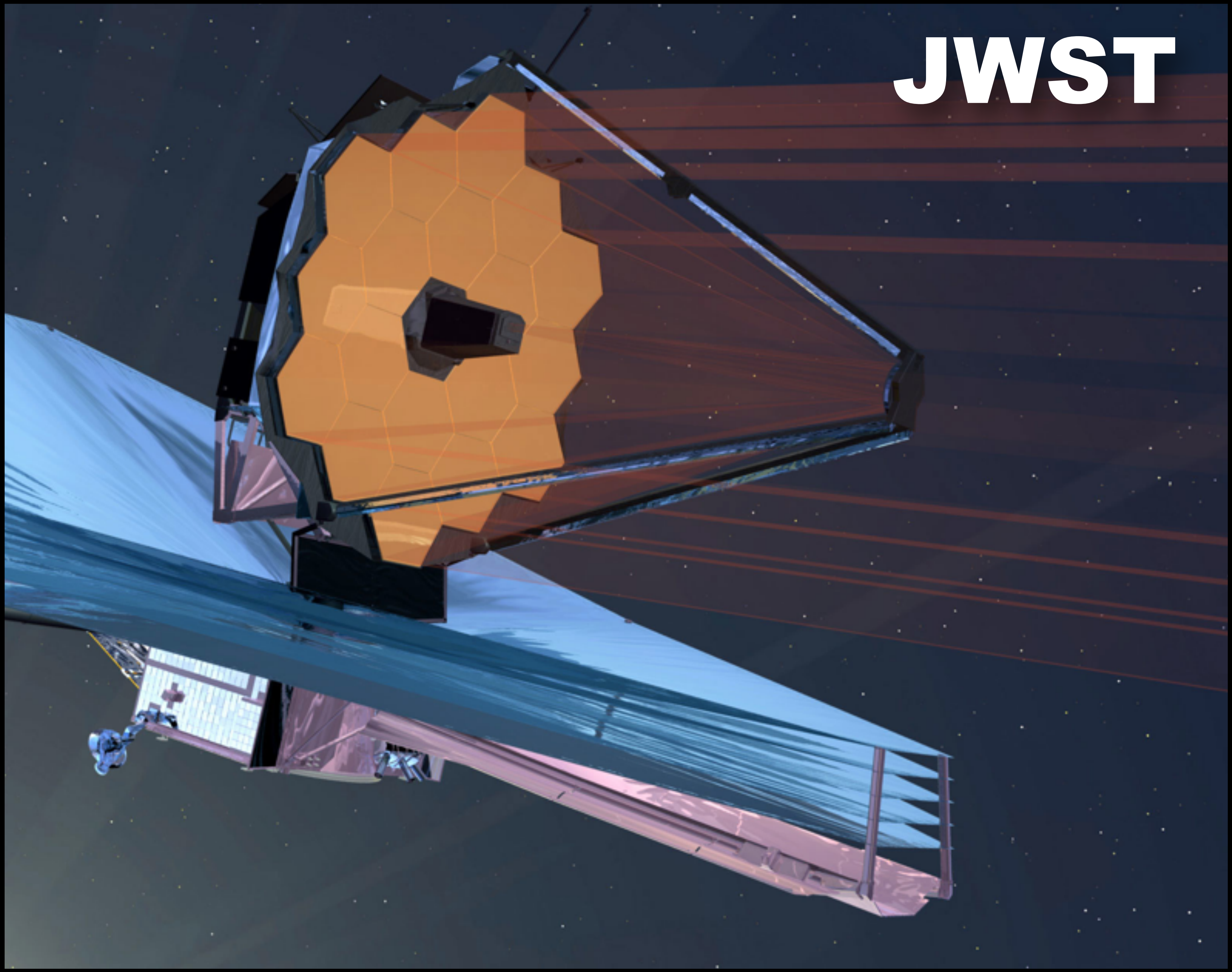


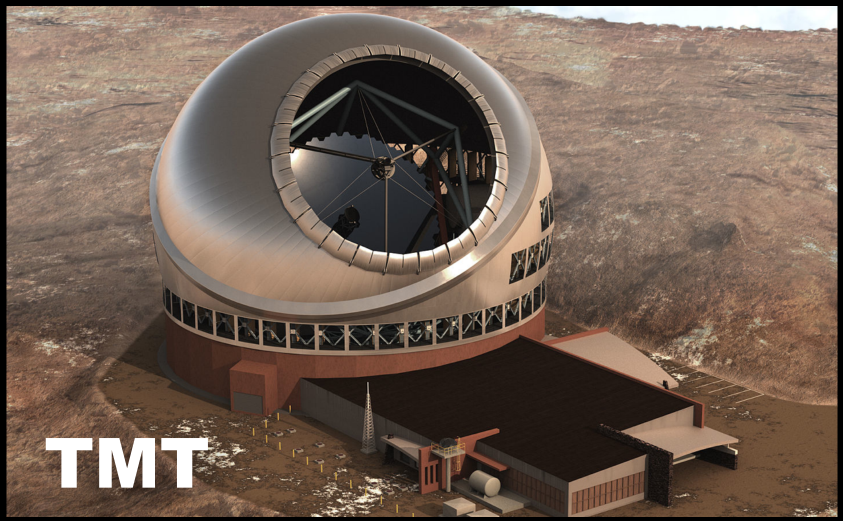
$$p(M, a) \propto M^{-0.65\pm0.60} a^{-0.85\pm0.39}$$

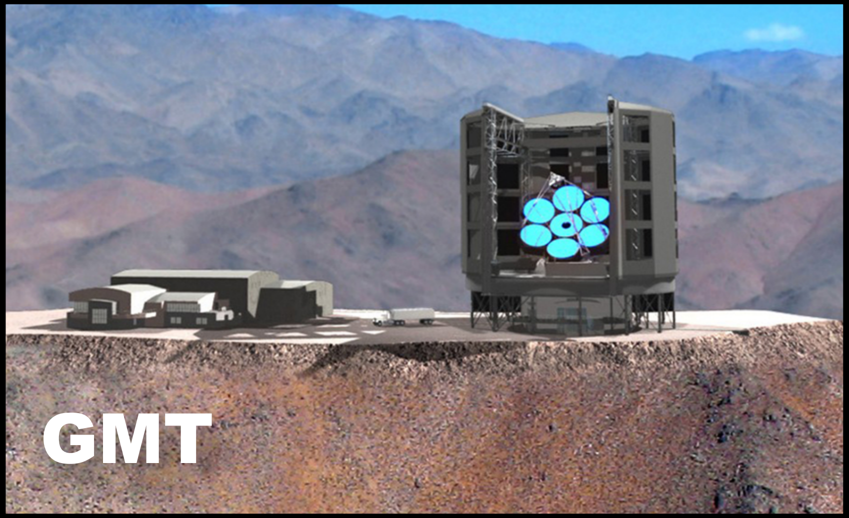


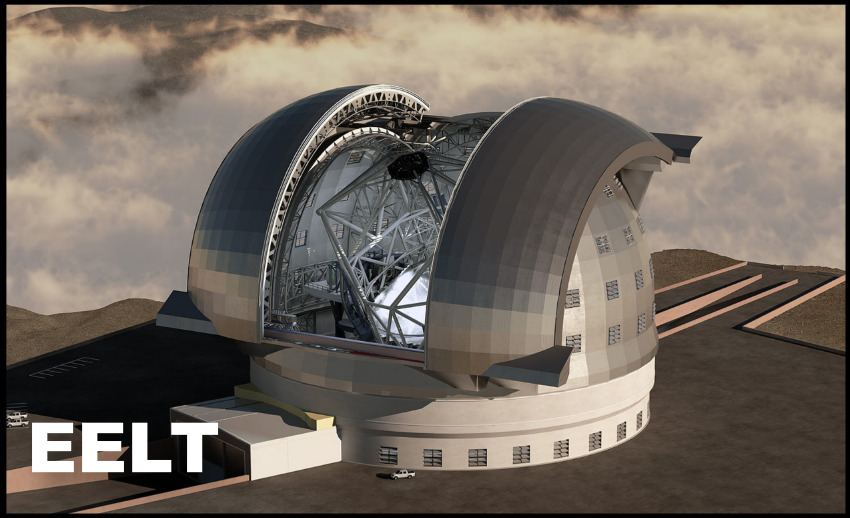
The not-too-distant future...

Statistics in the 3-10 AU, 0.5-5 M_{Jup} range.

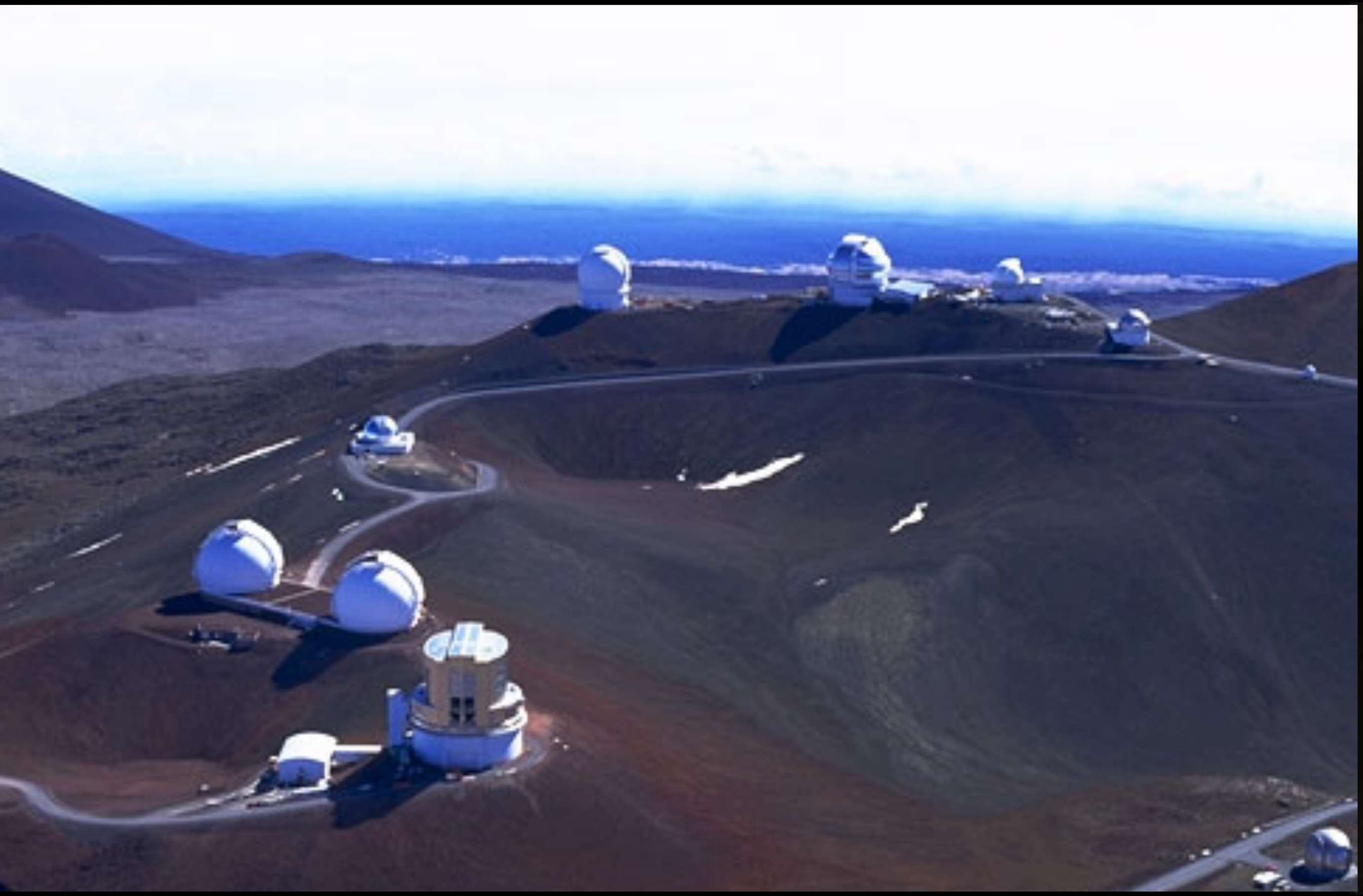






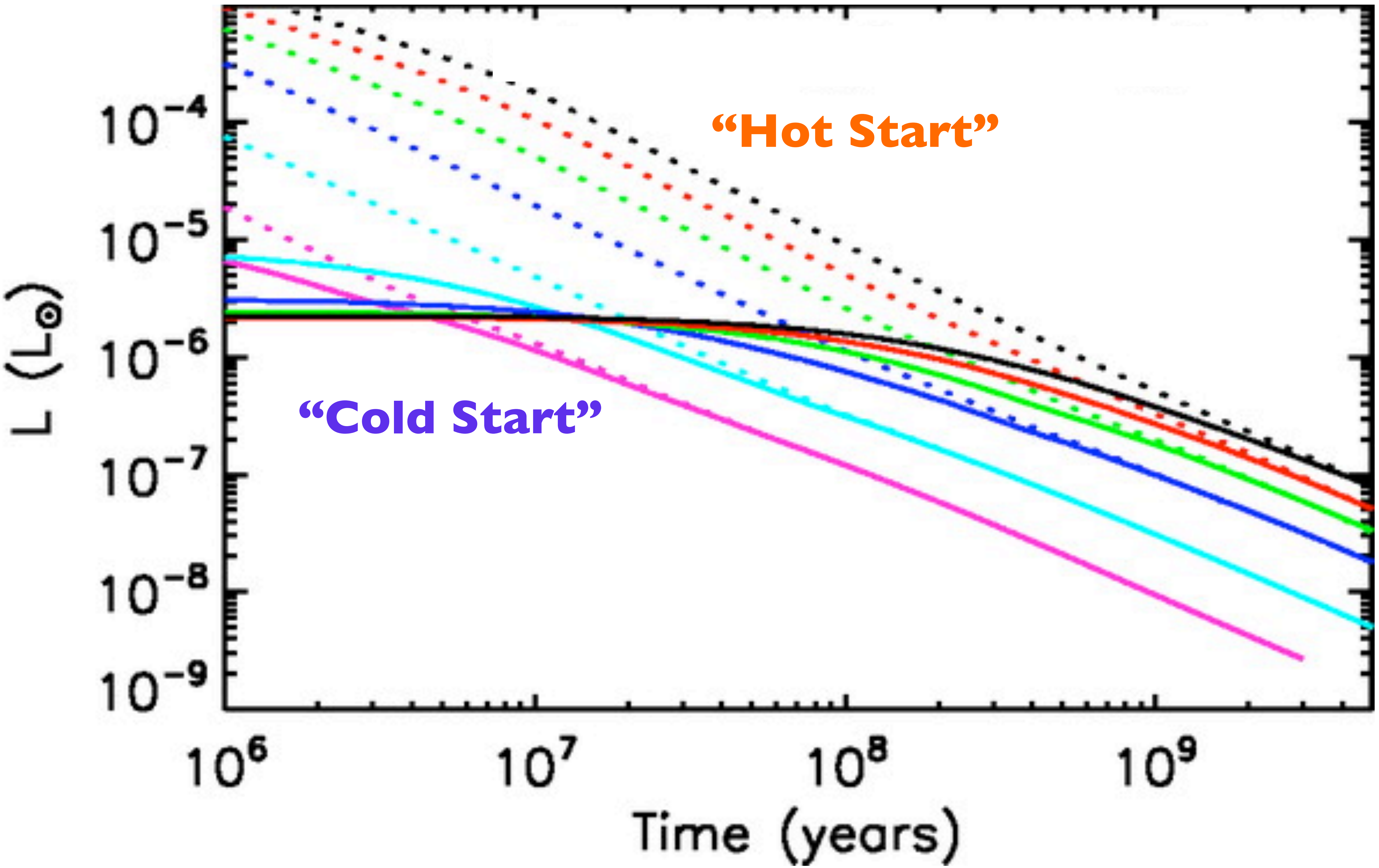


WFIRST will complement current imaging capabilities



- Search for planets in the NIR
- Detect planets in thermal emission
- Classic/extreme adaptive optics
- Sweet spot: ~5-100 AU (disk instability)
- Primarily probes young stars

- Search for planets in visible light
- Detect planets in reflected light
- Stable PSF in space
- Sweet spot: ~2-10 AU (core accretion)
- Primarily probes old nearby stars



Marley et al. 2007
Fortney et al. 2008