Direct Detection Results

Exosolar planets & Kuiper Belts

Paul Kalas

University of California, Berkeley

30 March, 2010

KITP Conference: Exoplanets Rising

Santa Barbara, CA

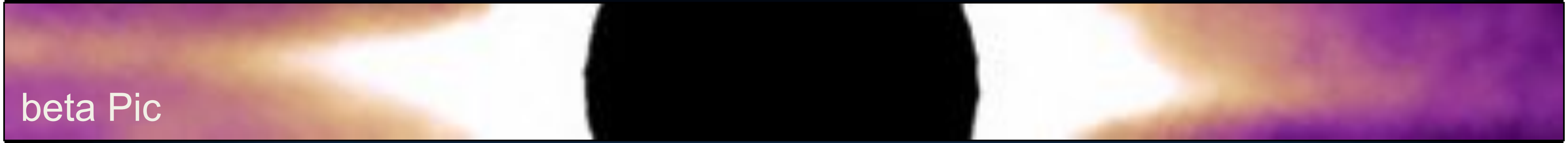
Collaborators: James Graham, Mark Clampin, Mike Fitzgerald, Eugene Chiang, Holly Maness, Edwin Kite, Karl Stapelfeldt, John Krist, Mark Wyatt, Matt Kenworthy, John Wisniewski, Ansgar Reiners, Andreas Seifahrt, Stefan Dreizler

The direct-detection planet candidates

Host	SpT	Dist. (pc)	Sep. (AU)	Mass (M_J)	Age (Myr)	Reference
Fomalhaut	A3V	7.69	119	<3.0	100 - 300	Kalas et al. ‘08
HD 182488	G8V	15	>14, >29	10 - 40	700 – 8700	Thalmann et al. ‘09
Beta Pic	A5V	19.3	8	6 - 12	8 - 20	Lagrange et al. ‘08
HR 8799	A5V	39.4±1.0	>68, >38, >24	5-11 7-13	30 - 160	Marois et al. ‘08
AB Pic	K2	47.3±1.8	258	11 - 25	30 – 40	Chauvin et al. ‘05
2M1207	M8	52.4±1.1	54	2 – 25	5 – 12	Chauvin et al. ‘04
GQ Lup	K7	140 ± 50	100	4 – 39	<2	Neuhauser et al. ‘05
1RXJ160929	G	145±20	330	6 – 12	5	Lafreniere et al. ‘08
CT Cha	K7	160±30	440	11 - 23	<2	Schmidt et al. ‘08

Disk Morphologies indicate planetary systems

>>800 AU

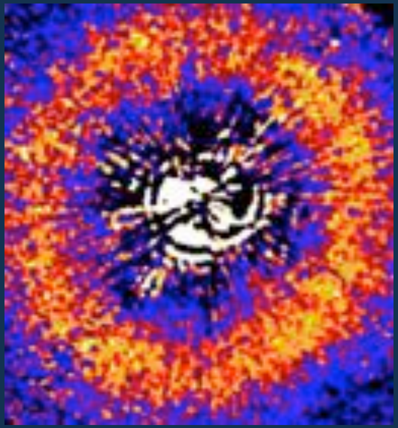


beta Pic

AU Mic

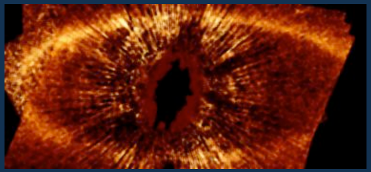
>200 AU

HD 107146



170 AU

Fomalhaut



140 AU

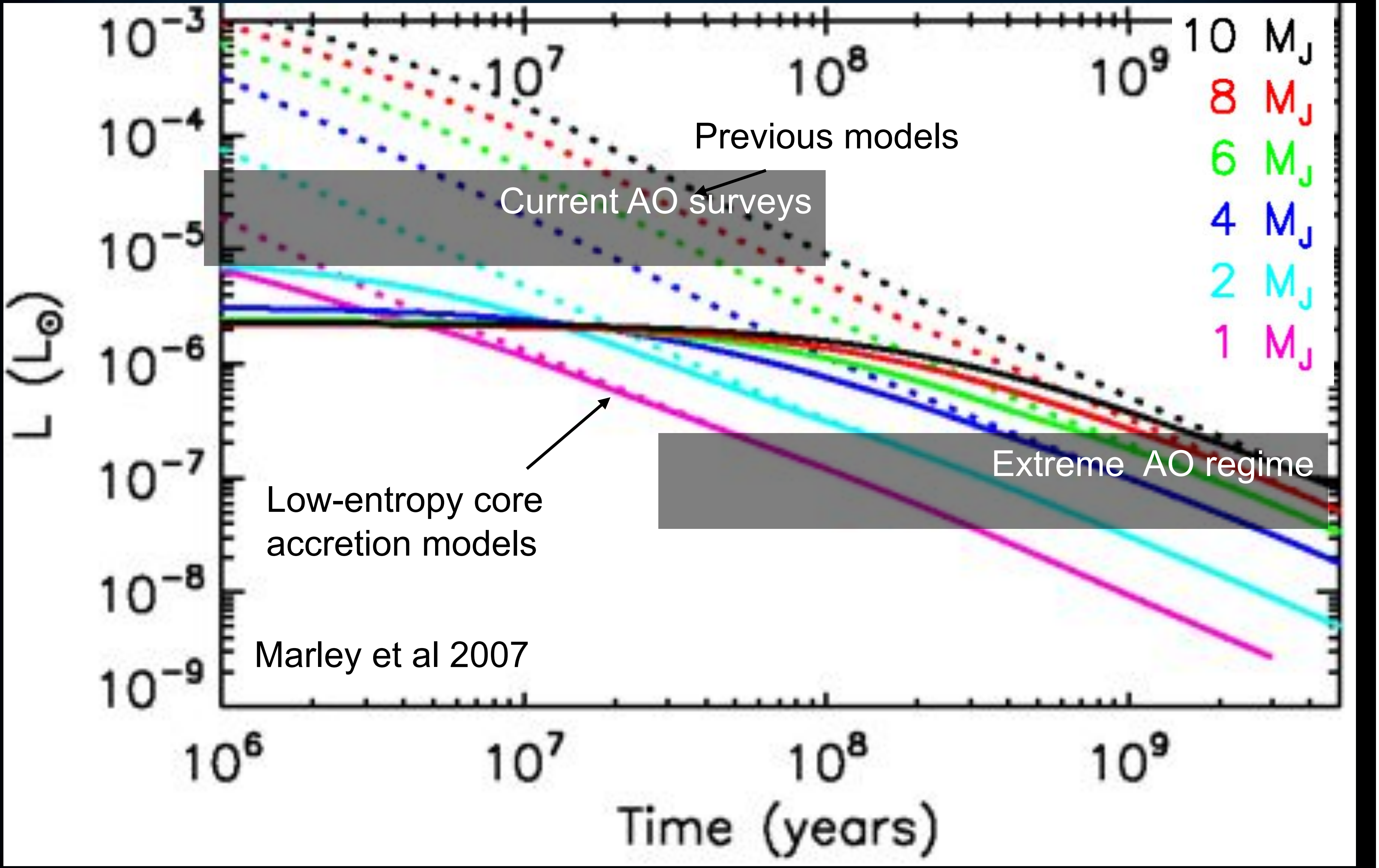
HR 4796A

70 AU

Sun

50 AU

Youth → Self-luminous planets detectable in infrared



Previous models

Current AO surveys

Low-entropy core accretion models

Extreme AO regime

Marley et al 2007

The direct-detection planet candidates

Host	SpT	Dist. (pc)	Sep. (AU)	Mass (M_J)	Age (Myr)	Reference
Fomalhaut	A3V	7.69	119	<3.0	100 - 300	Kalas et al. ‘08
HD 182488	G8V	15	>14, >29	10 - 40	700 – 8700	Thalmann et al. ‘09
Beta Pic	A5V	19.3	8	6 - 12	8 - 20	Lagrange et al. ‘08
HR 8799	A5V	39.4±1.0	>68, >38, >24	5-11 7-13	30 - 160	Marois et al. ‘08
AB Pic	K2	47.3±1.8	258	11 - 25	30 – 40	Chauvin et al. ‘05
2M1207	M8	52.4±1.1	54	2 – 25	5 – 12	Chauvin et al. ‘04
GQ Lup	K7	140 ± 50	100	4 – 39	<2	Neuhauser et al. ‘05
1RXJ160929	G	145±20	330	6 – 12	5	Lafreniere et al. ‘08
CT Cha	K7	160±30	440	11 - 23	<2	Schmidt et al. ‘08

Earliest detected planet candidates

GQ Lup

2M1207

AB Pic

Also...

J1609
Lafrenier et al. 2008

CT Cha
Schmidt et al. 2008

Summary of Targets

- ***HD 182488 (GJ 758)***
- Beta Pic
- HR 8799
- Fomalhaut

HD 182488 (GJ 758)

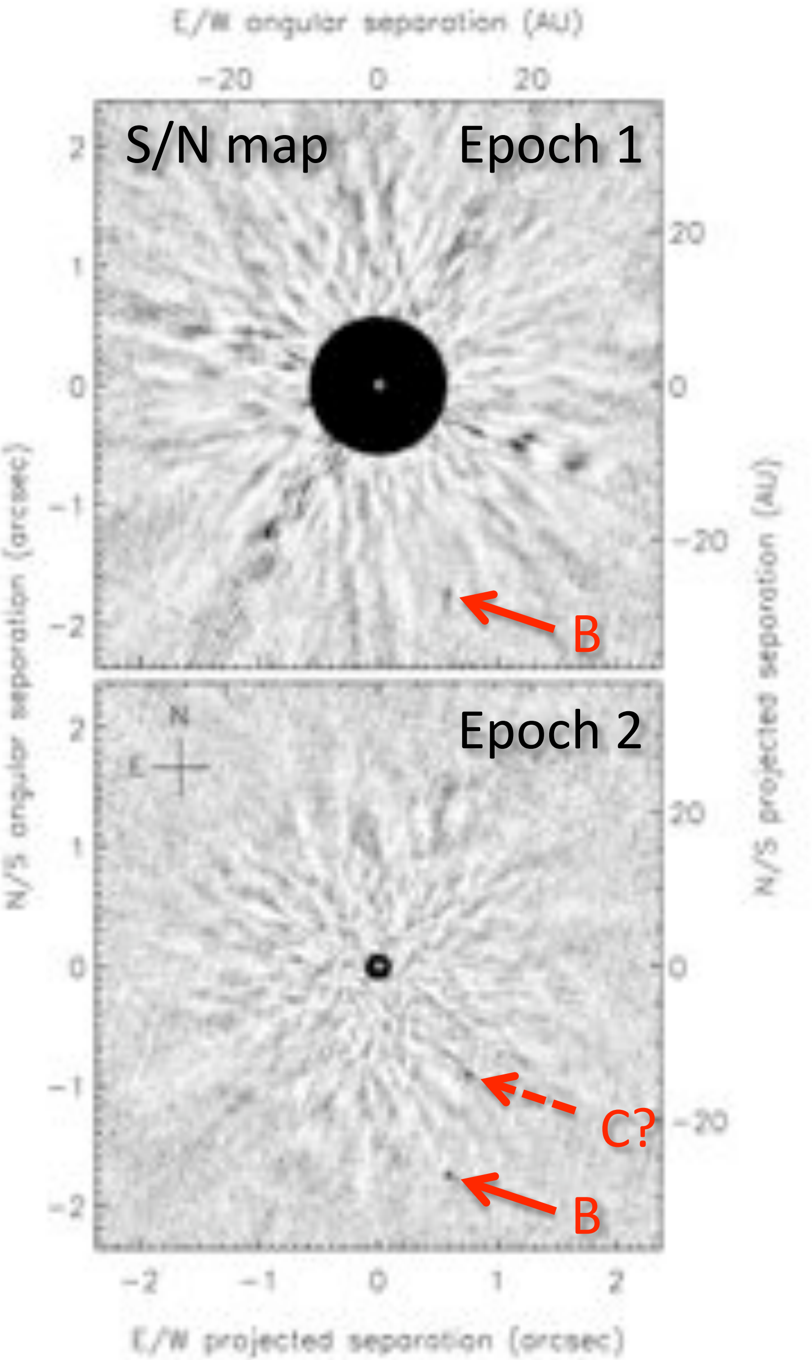
Imaging detection of coldest resolved companion of a Sun-like star.

Thalmann, et al. 2009

Mass:	10 – 40 M_{Jup}
Temperature	550 – 640 K
Separation	1.9" = 29 AU
Host type:	G star
Host distance:	15 pc

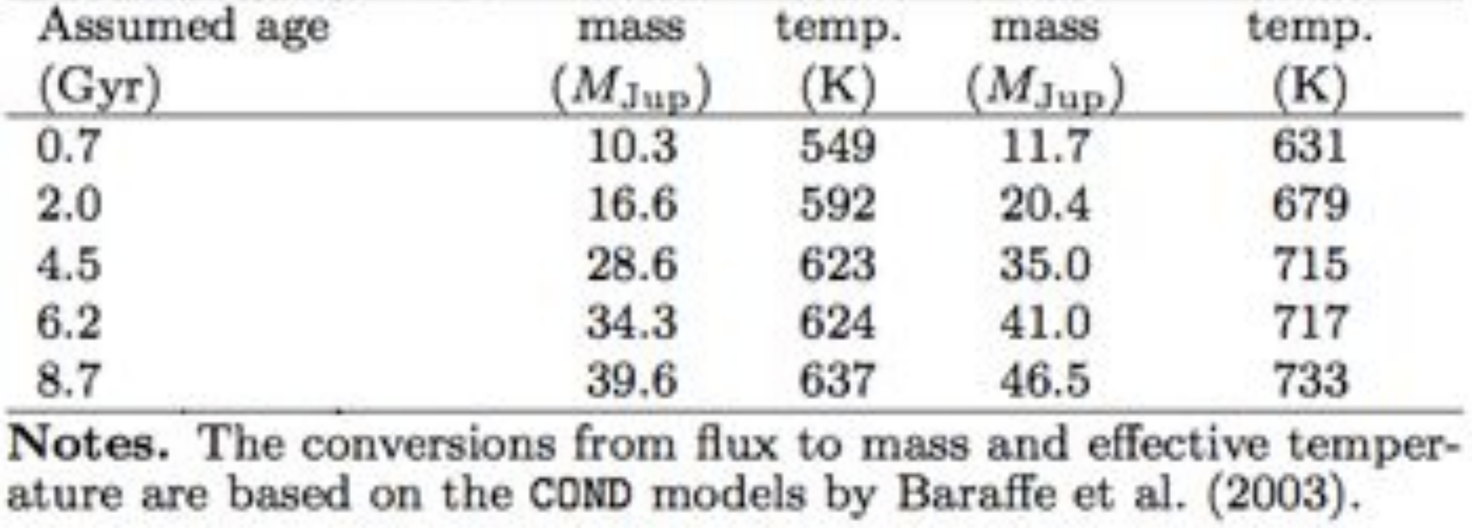
- H-band ADI at Subaru/HiCIAO, reduced with LOCI (Lafrenière et al. 2007)
- Clear common proper motion.
- Orbital motion.
- Possible second companion in one epoch.

Prepared by Christian Thalmann



HD 182488

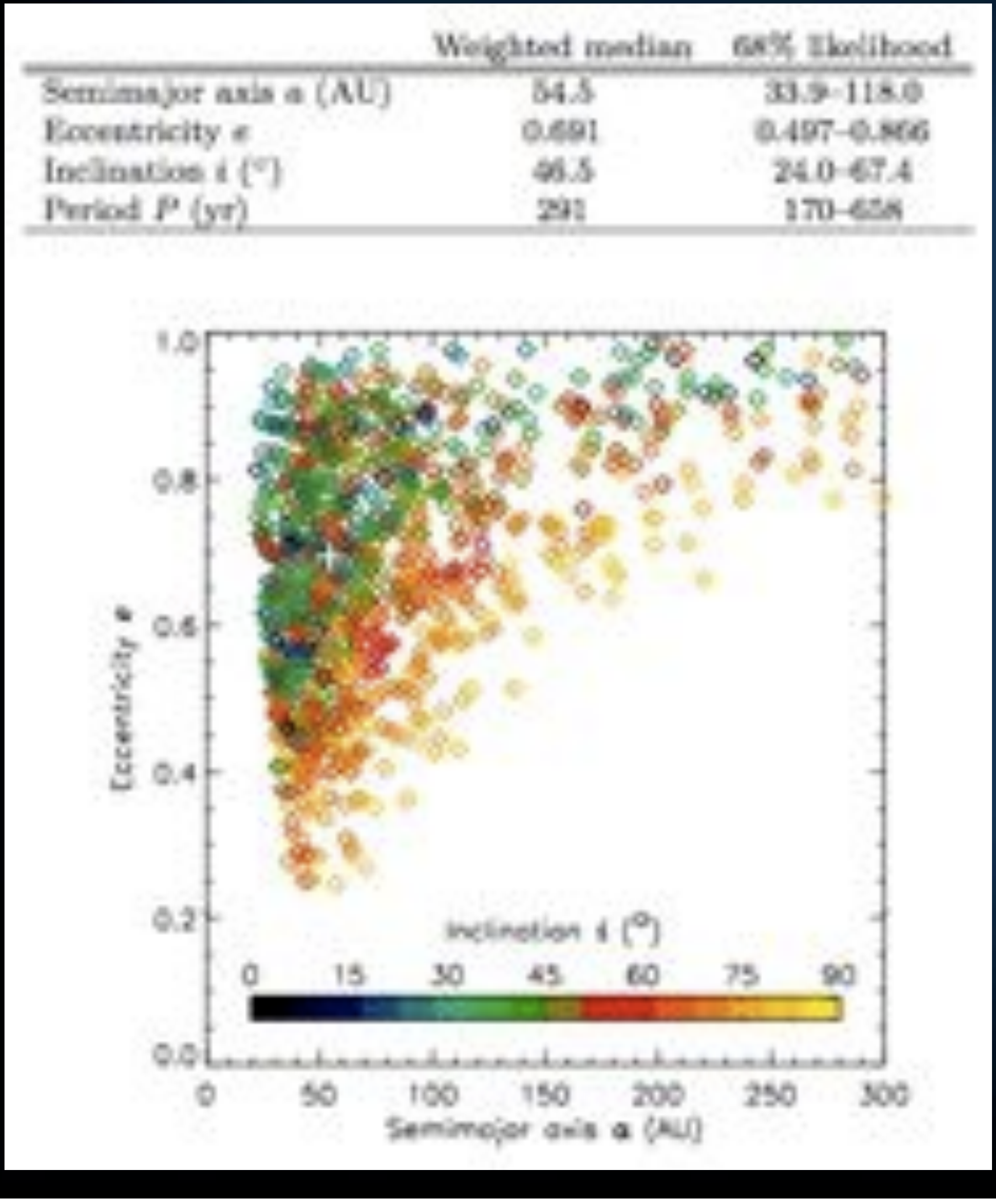
- On the RV target lists, no RV detections, so far
- There are seven field stars, improves astrometry (e.g. relative to HR 8799, Beta Pic, Fomalhaut)
- Metal rich star [Fe/H] = +0.21
- Infrared excess due to a debris disk? Upper limit from Spitzer 70 μm photometry is $L_{dust} / L_{bol} < 2.7 \times 10^{-5}$ (Beichman et al. 2006)
- Few age indicators (rotation, chromospheric activity)



Assumed age (Gyr)	mass ($M_{\rm Jup}$)	temp. (K)	mass ($M_{\rm Jup}$)	temp. (K)
0.7	10.3	549	11.7	631
2.0	16.6	592	20.4	679
4.5	28.6	623	35.0	715
6.2	34.3	624	41.0	717
8.7	39.6	637	46.5	733

Notes. The conversions from flux to mass and effective temperature are based on the `COND` models by Baraffe et al. (2003).

HD 182488: Orbit?



	Weighted median	68% likelihood
Semimajor axis a (AU)	54.5	33.9–118.0
Eccentricity e	0.691	0.497–0.866
Inclination i (°)	46.5	24.0–67.4
Period P (yr)	291	170–658

Monte-Carlo result:

- probably very eccentric
- evidence for planet-planet scattering?
- evidence for low masses if “c” turns out to be a real companion?

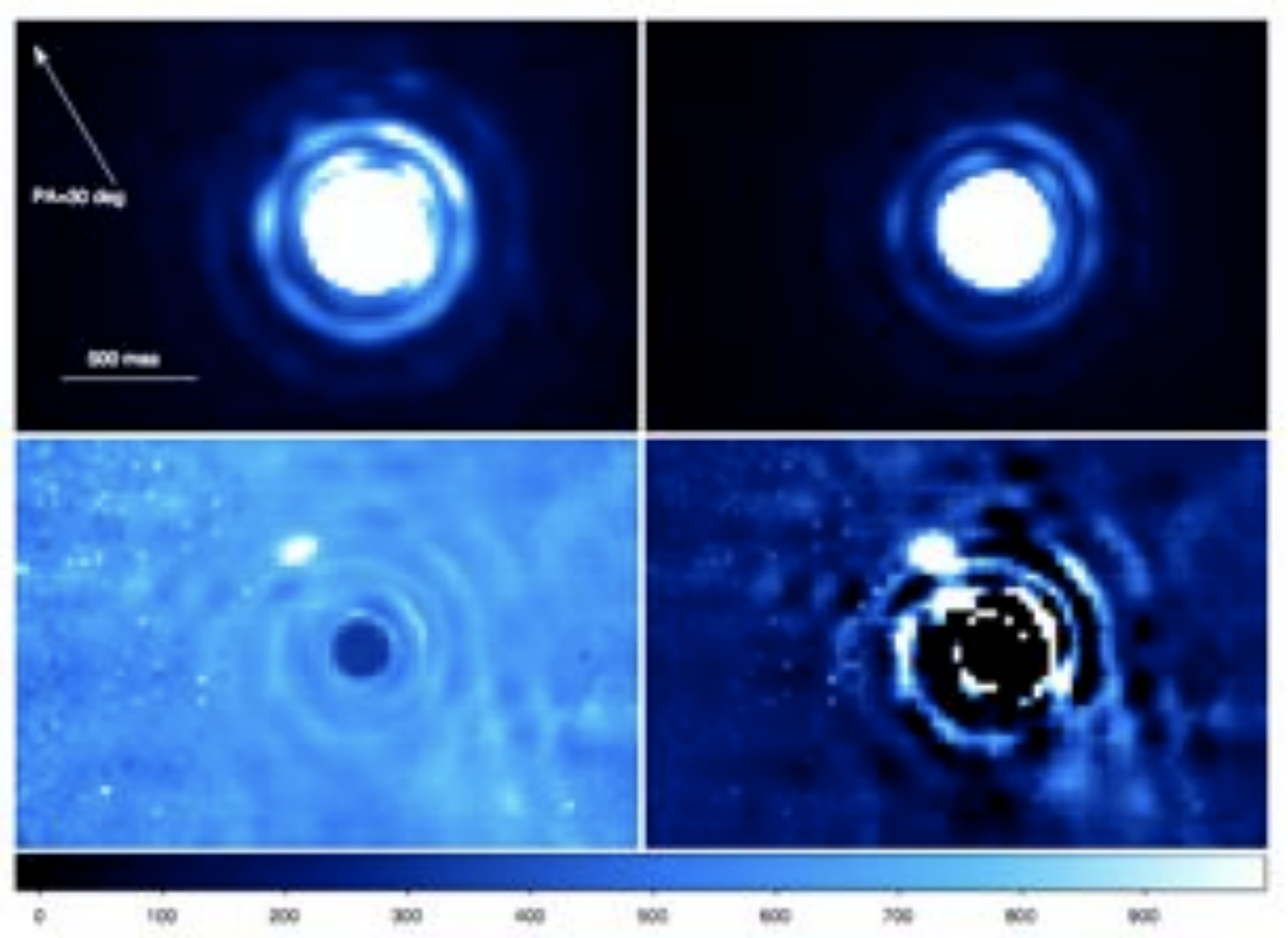
Thalmann et al. 2009

Summary of Targets

- HD 182488 (GJ 758)
    - Solar type star: G9V, 0.7 – 8.7 Gyr, 15.6 pc
    - 10 – 40 M_J at 29 AU
- ***Beta Pic***
- HR 8799
- Fomalhaut

L-prime imaging of Beta Pic

November 2003, VLT (Lagrange et al. 2008)



8 AU

6 - 12 M_J

T~1500 K
P~17 yr

Using the PSF subtraction technique

Beta Pic b at L-prime (3.8 microns)

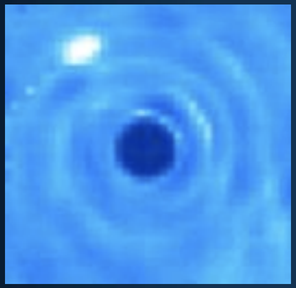
December 2008, Keck AO

Fitzgerald, Kalas, & Graham 2009

Beta Pic b

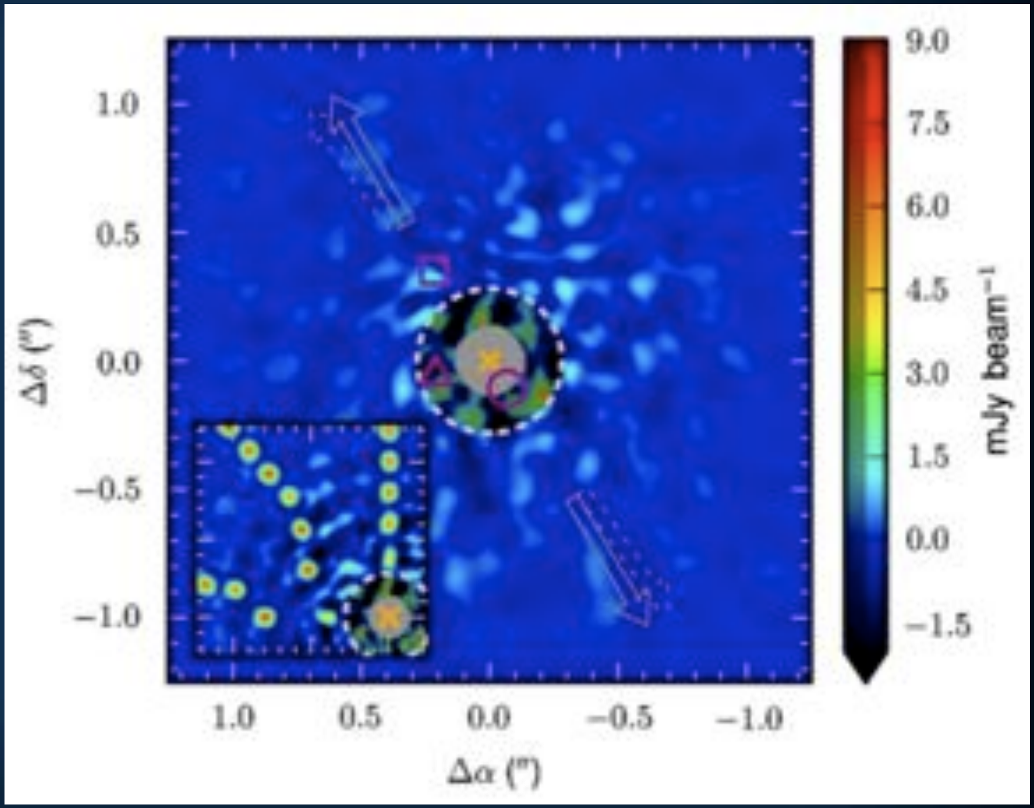
Lagrange et al. 2009

November 2003, VLT



8 AU from star

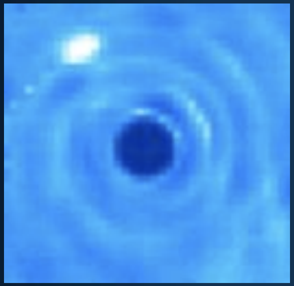
6 – 12 M_J



Non detection also by Lagrange et al. 2009 reobserving in early 2009

Beta Pic b at L-prime (3.8 microns)

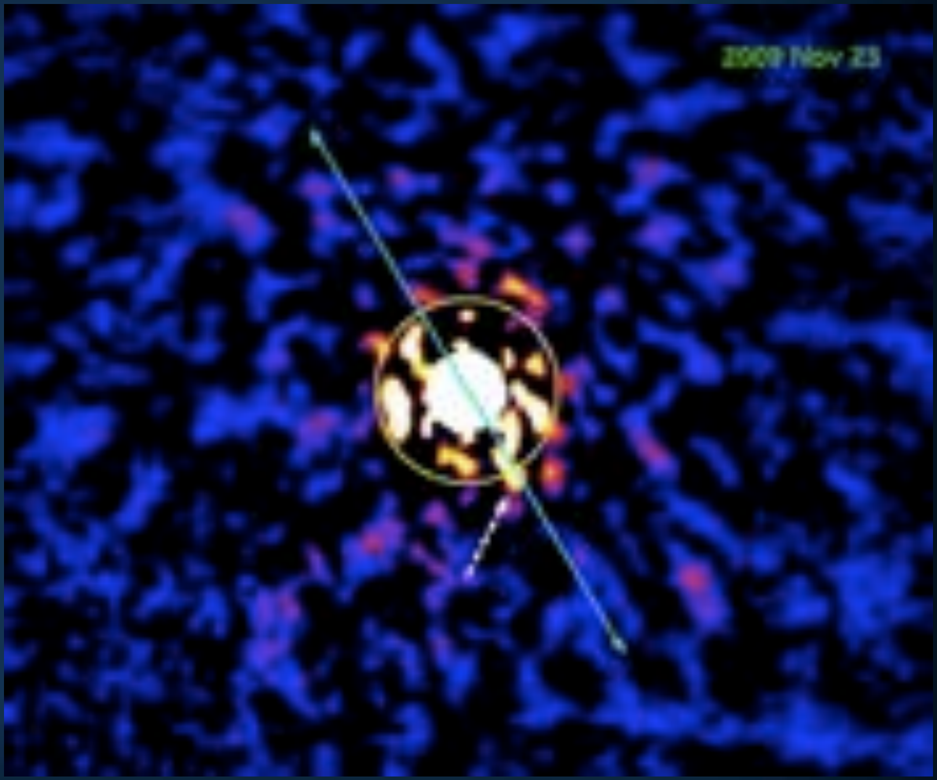
Beta Pic b
Lagrange et al. 2009
November 2003, VLT



8 AU from star
6 – 12 M_J

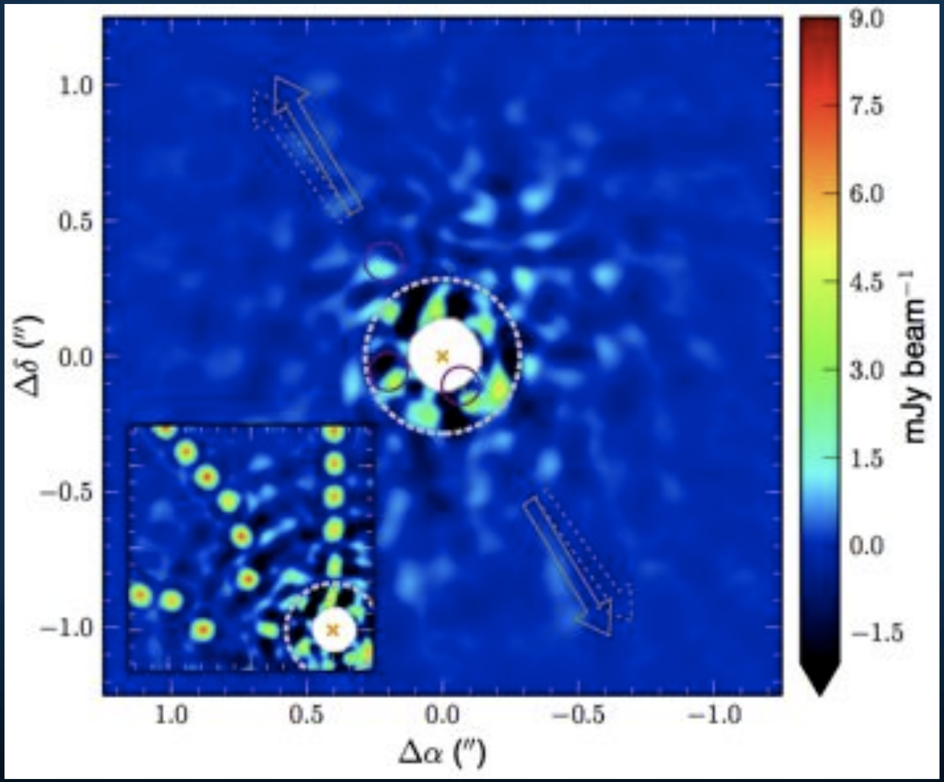
November 2009, Keck AO

Fitzgerald, Kalas, & Graham, continuing



b Pic b summary and status :

β Pic b discovered NE of the star in data from 2003
NOT detected in 2008 => orbital motion?
Not detected in 2009 -> possible confirmation within 2010, SW of the star?
(need non-detections through 2013 to show that it's spurious or background)

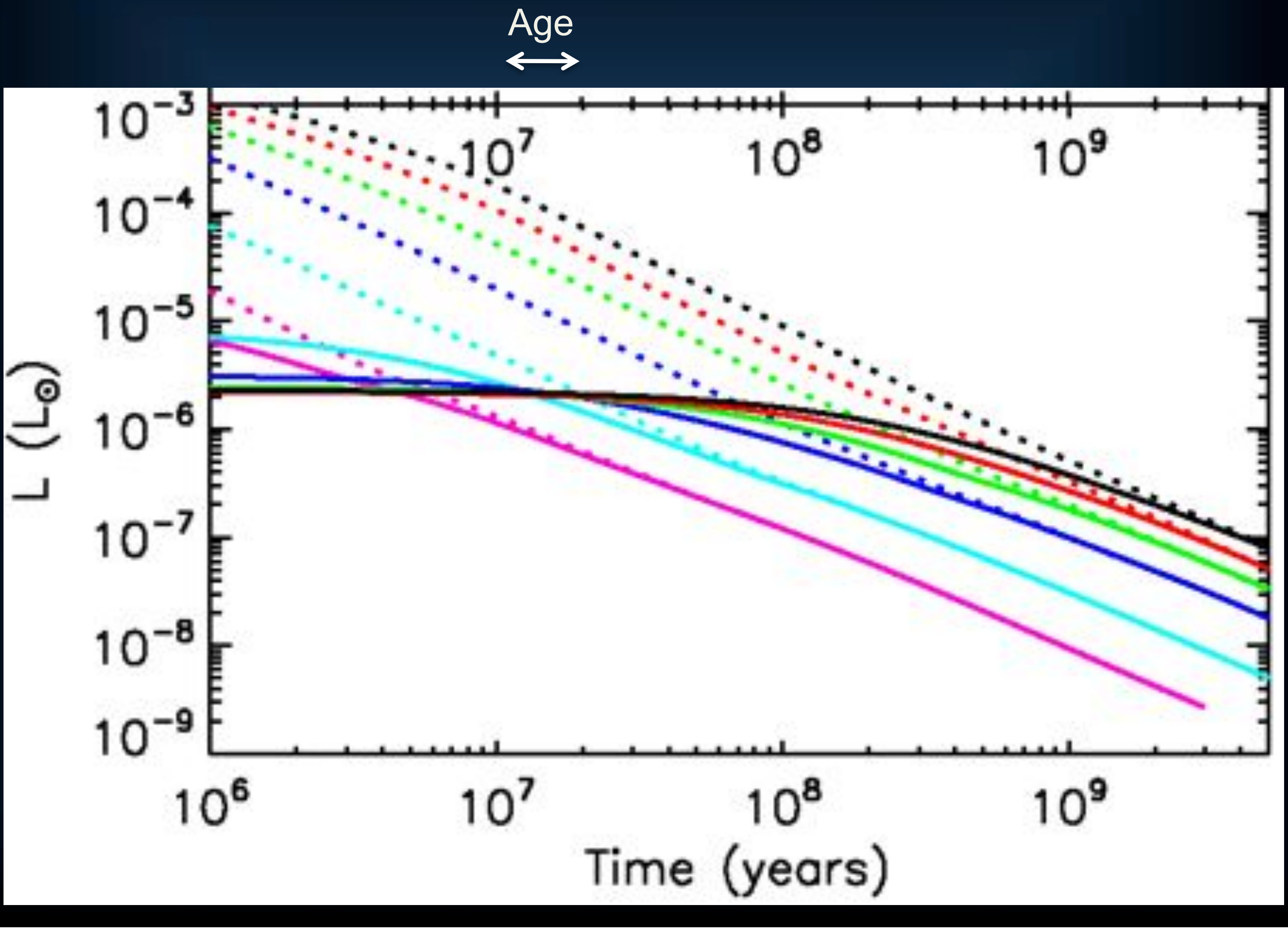


Starting early 2011:
Gemini Planet Imager

Fitzgerald, , Kalas, & Graham 2009, Lagrange et al. 2009

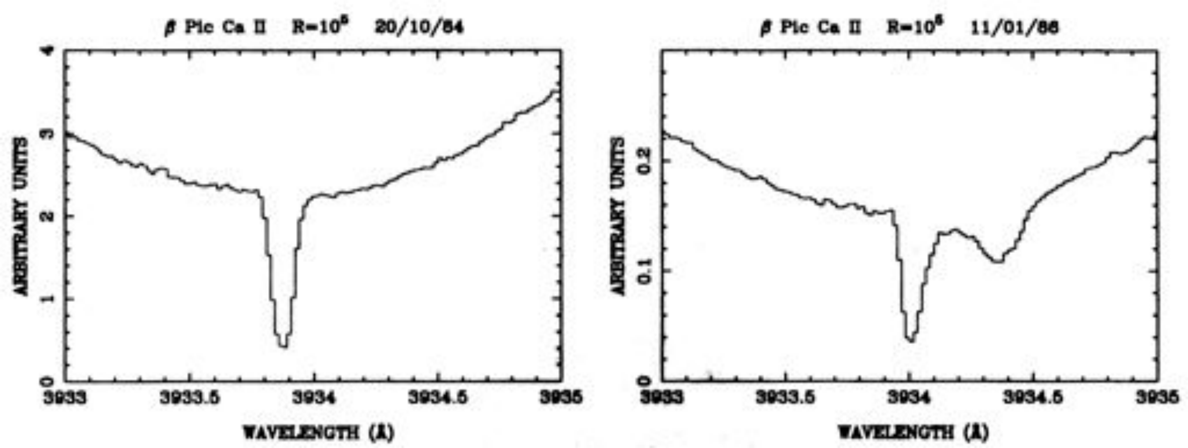
Why all the fuss about b Pic b?

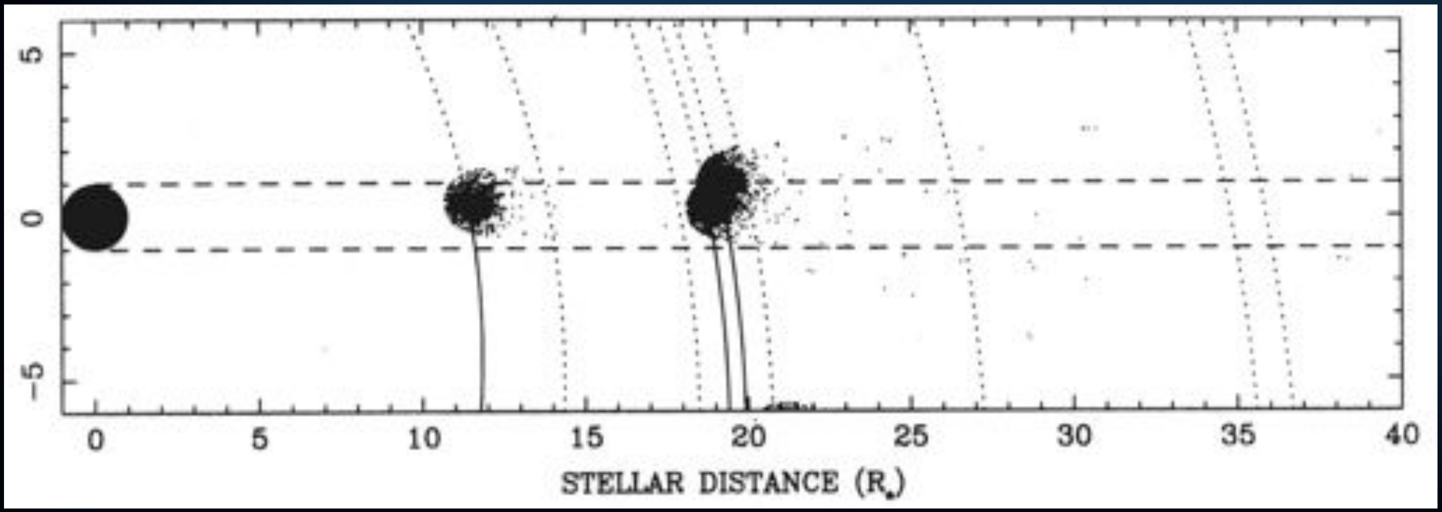
Interesting age to test planet formation models



Why all the fuss about b Pic b?

Dynamical evolution of a planetary and planetesimals





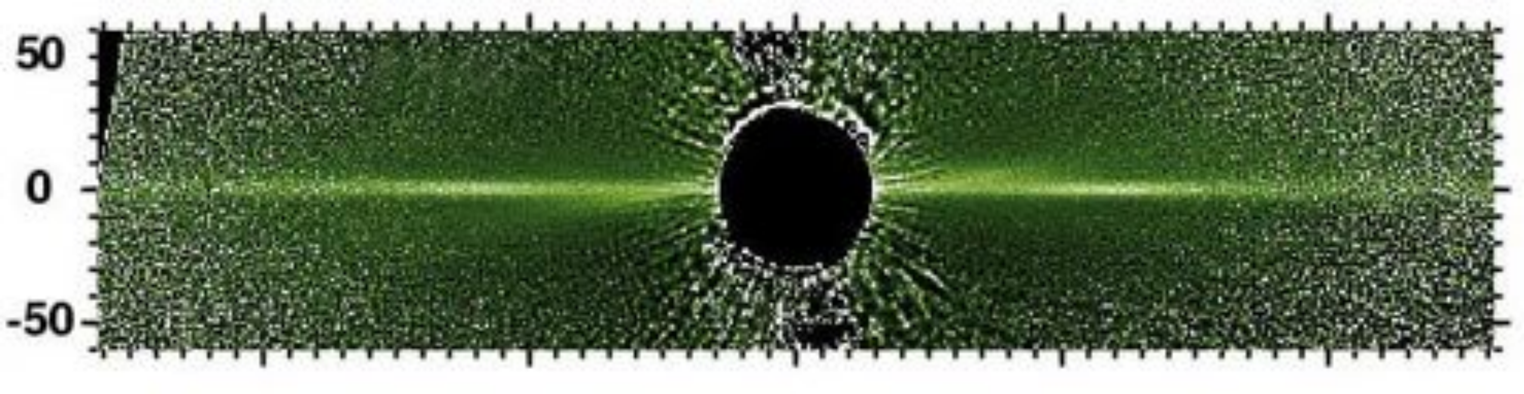
SpT = A5V

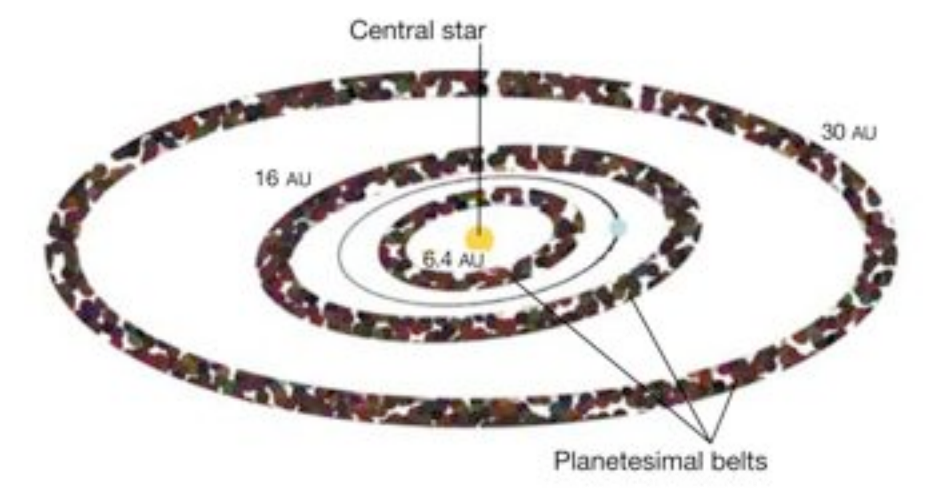
d = 19.3 pc

Beust
Deleuil
Ferlet
Knacke
Lagrange
Lamers
Lecavelier des Etangs
Morbidelli
Vidal Madjar

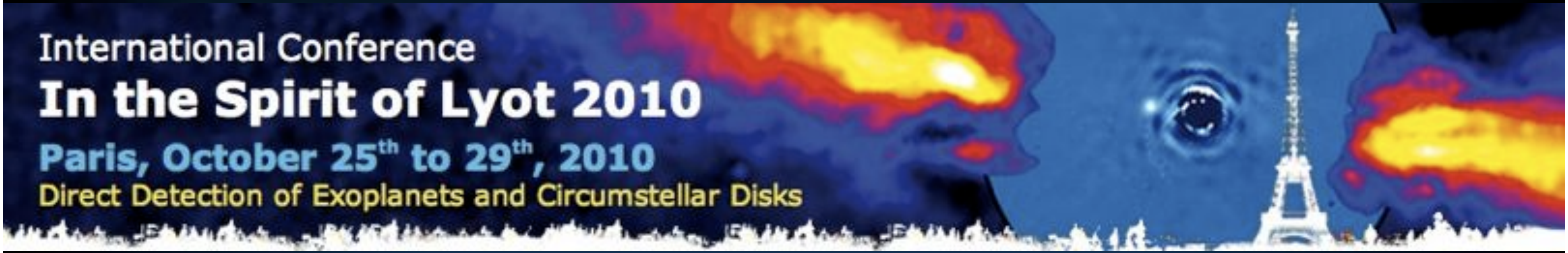
Beta Pic's Double Disk

The Very Latest Optical Image with Hubble
Golimowski et al. 2006





Okamoto et al. 2004, See also Freistetter et al. 1997, Mouillet et al. 1997, Crossley & Haghighipour 2004



International Conference

In the Spirit of Lyot 2010

Paris, October 25th to 29th, 2010

Direct Detection of Exoplanets and Circumstellar Disks

http://lyot2010.lesia.obspm.fr/

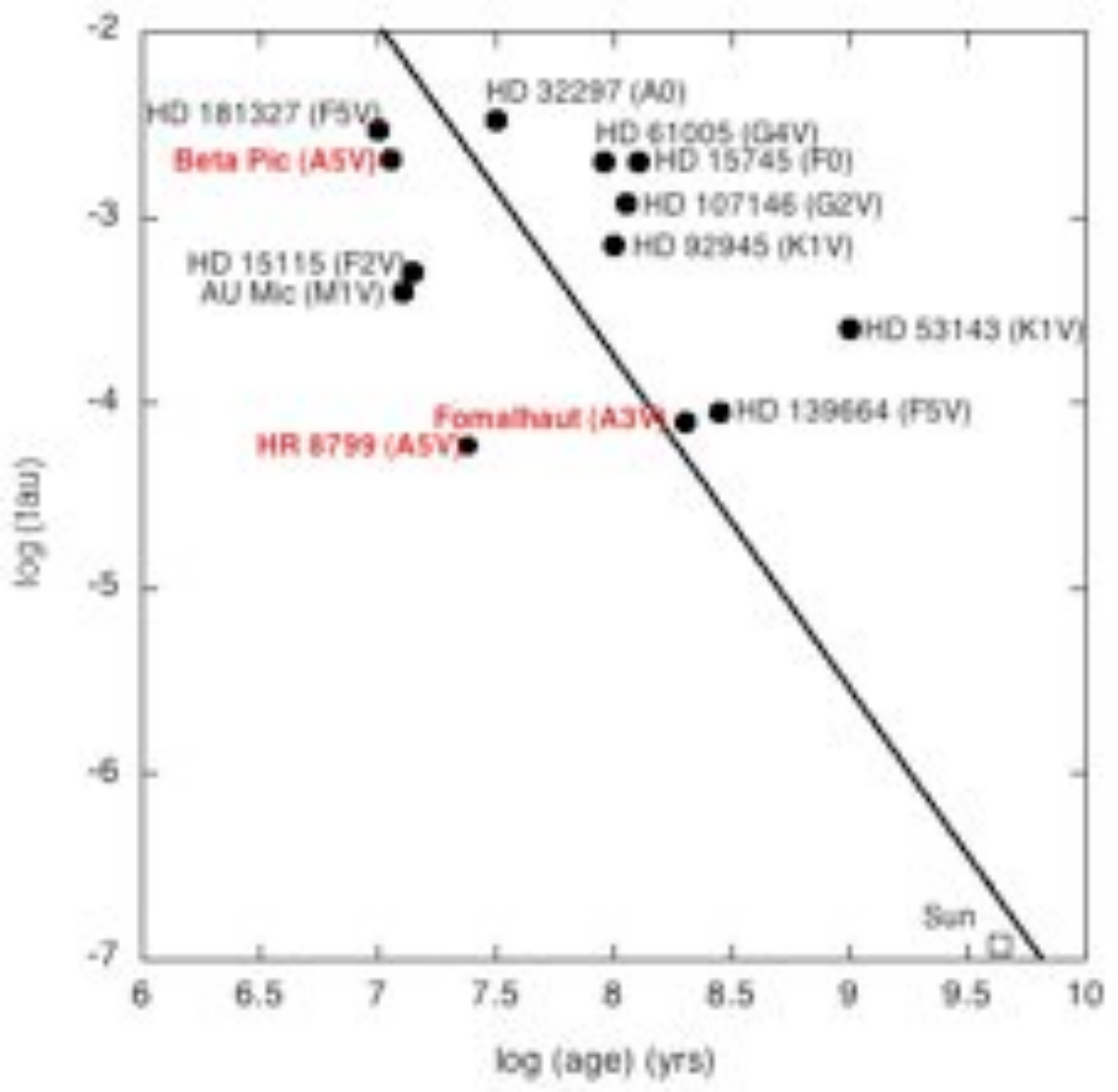
Summary of Targets

- HD 182488
    - Solar type star: G9V, 0.7 – 8.7 Gyr, 15.6 pc
    - 10 – 40 M_J at 29 AU
- Beta Pic
    - Mass 6 - 12 M_J
    - Orbit a = 8 AU, requires follow-up, but consistent with many other observed phenomena.
- ***HR 8799***
- Fomalhaut

HR 8799: IRAS infrared excess star since 1987

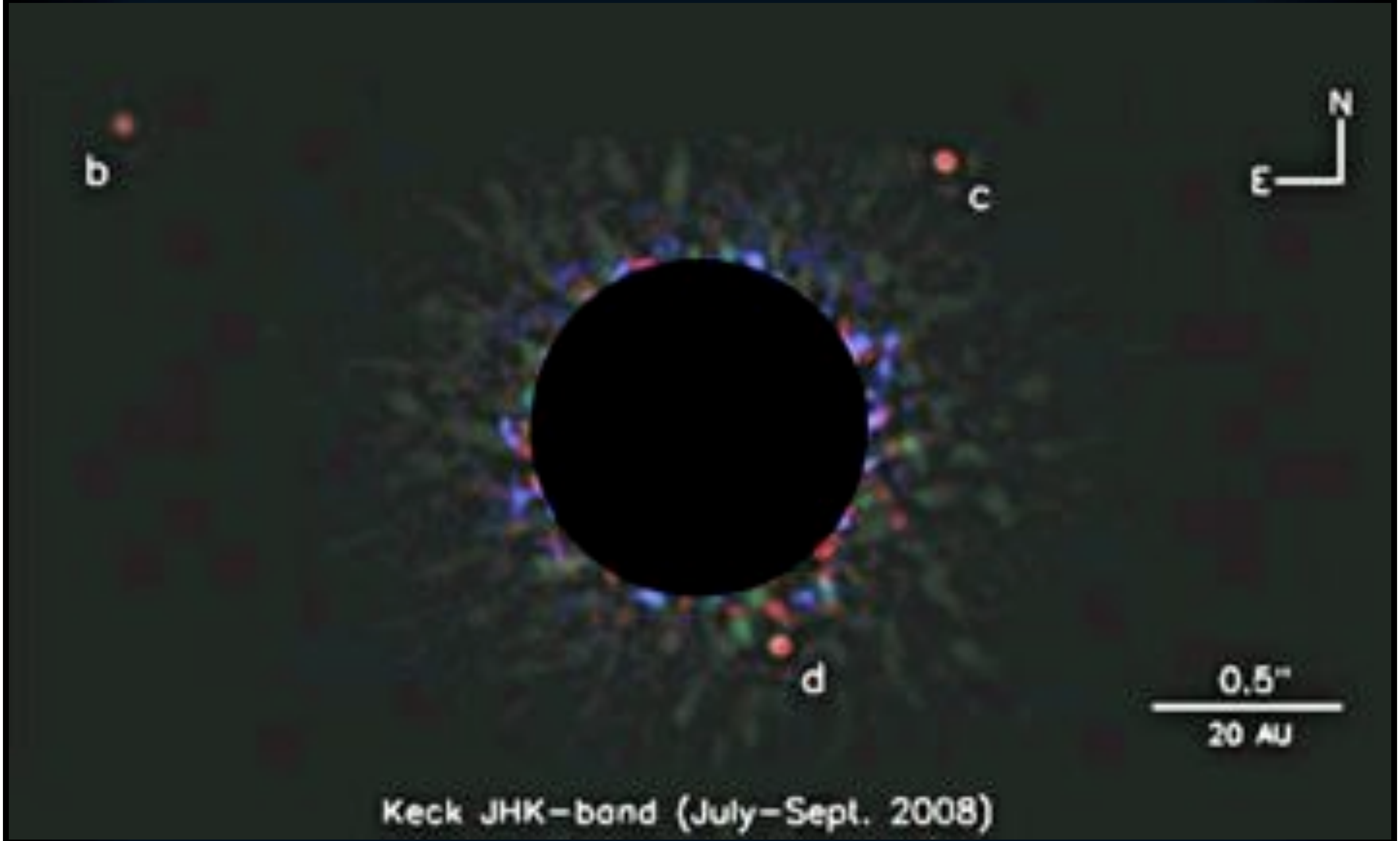
$10^7 - 10^8$ yr

dust
optical
depth

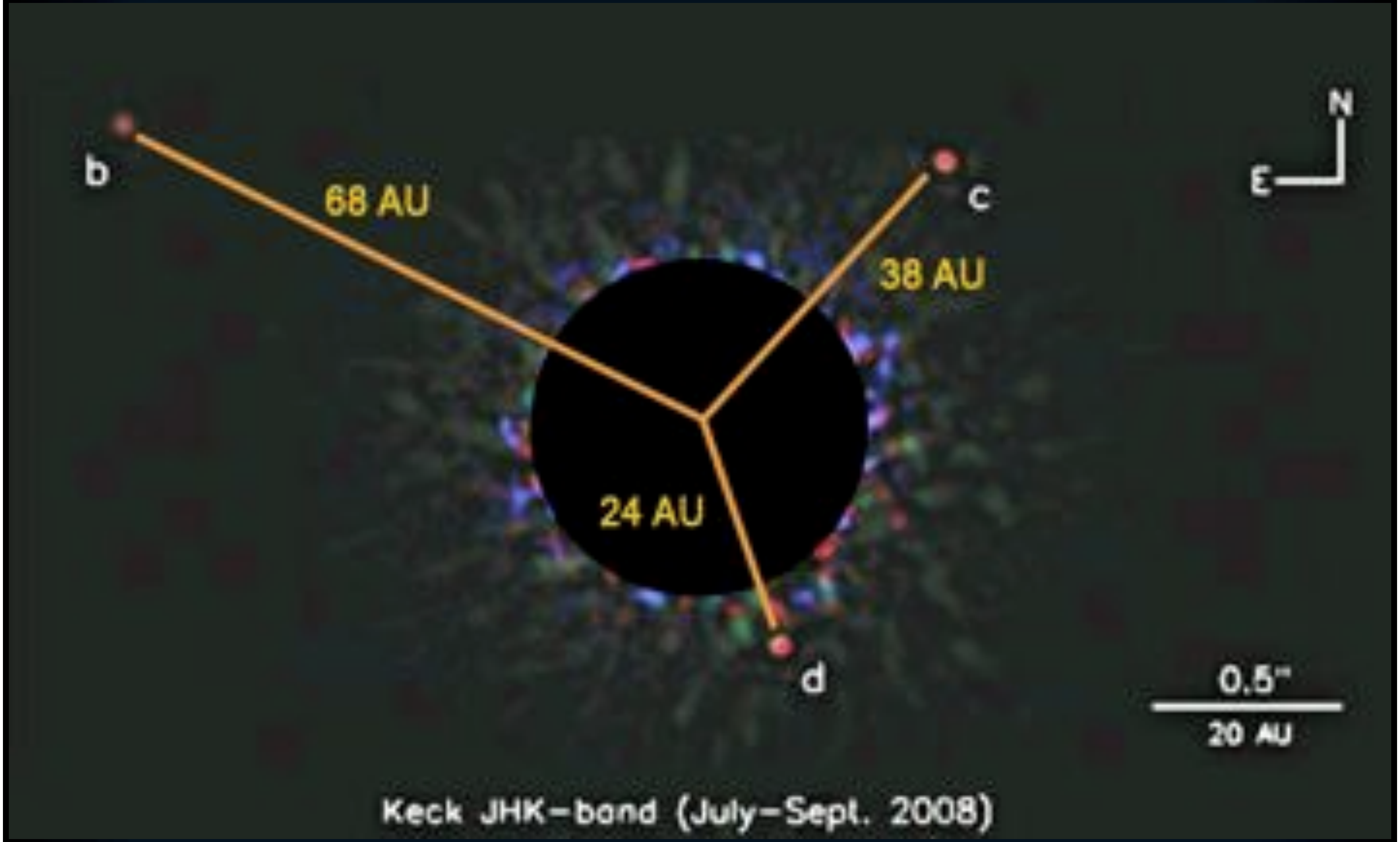


Plot shows nearby stars with debris disks

Adapted from Zuckerman



Marois et al. 2009



dynamical stability: Fabrycky & Murray-Clay 2010, Gozdziewski & Migaszewski 09, Reidemeister et al. 09

HR 8799 Planets Masses?

can use luminosity/evolutionary tracks *AND* orbital stability to find masses

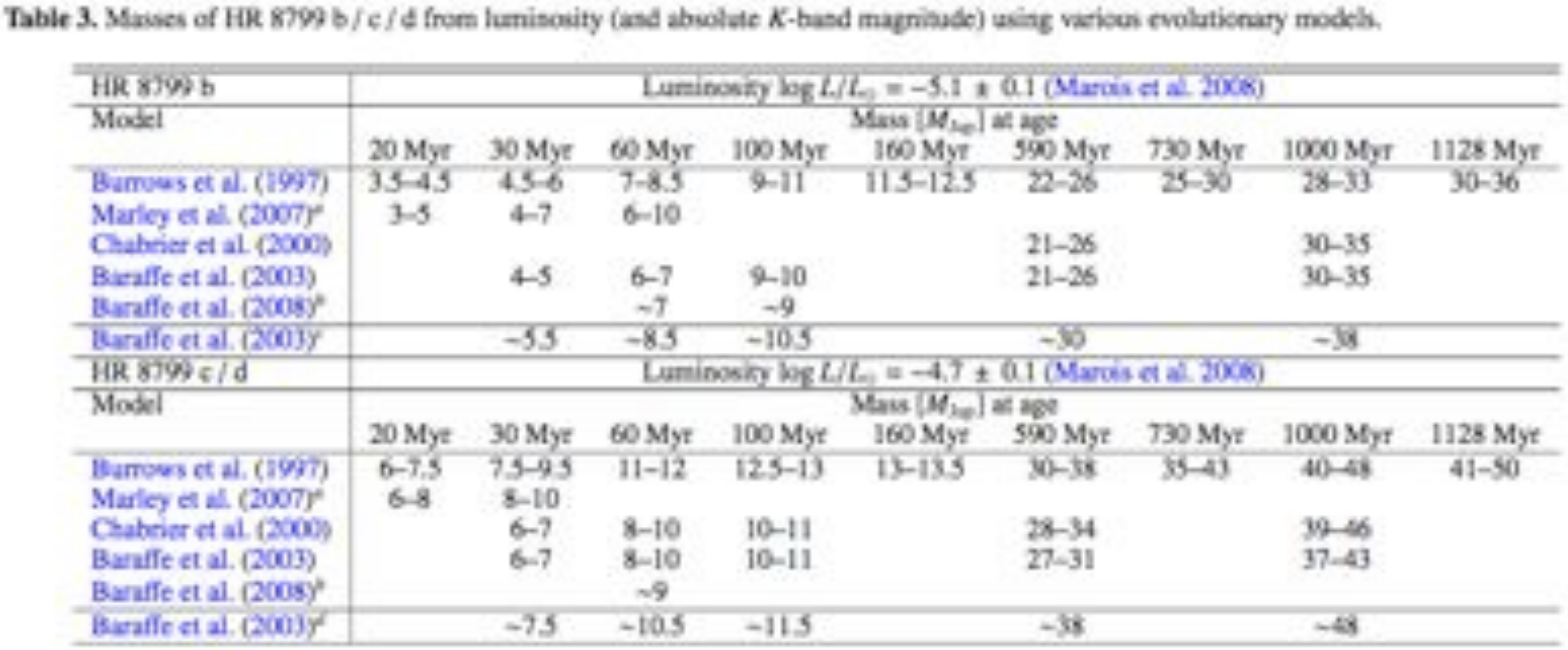


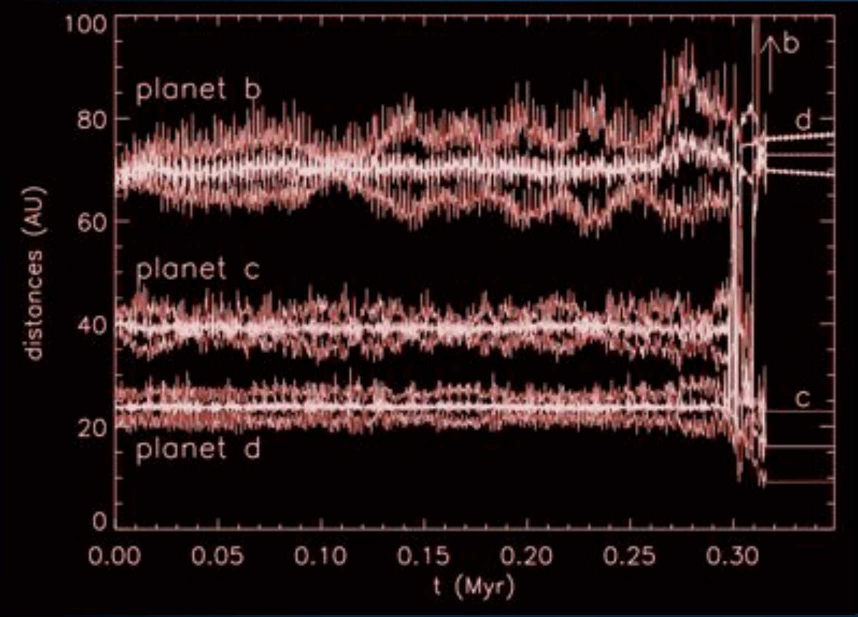
Table 3. Masses of HR 8799 b / c / d from luminosity (and absolute *K*-band magnitude) using various evolutionary models.

HR 8799 b	Luminosity log $L/L_\odot = -5.1 \pm 0.1$ (Marois et al. 2008)								
Model	Mass [$M_{\rm Jup}$] at age								
	20 Myr	30 Myr	60 Myr	100 Myr	160 Myr	590 Myr	730 Myr	1000 Myr	1128 Myr
Burrows et al. (1997)	3.5–4.5	4.5–6	7–8.5	9–11	11.5–12.5	22–26	25–30	28–33	30–36
Marley et al. (2007)[a]	3–5	4–7	6–10						
Chabrier et al. (2000)						21–26		30–35	
Baraffe et al. (2003)		4–5	6–7	9–10		21–26		30–35	
Baraffe et al. (2008)[b]			~7	~9					
Baraffe et al. (2003)[c]		~5.5	~8.5	~10.5		~30		~38	
HR 8799 c / d	Luminosity log $L/L_\odot = -4.7 \pm 0.1$ (Marois et al. 2008)								
Model	Mass [$M_{\rm Jup}$] at age								
	20 Myr	30 Myr	60 Myr	100 Myr	160 Myr	590 Myr	730 Myr	1000 Myr	1128 Myr
Burrows et al. (1997)	6–7.5	7.5–9.5	11–12	12.5–13	13–13.5	30–38	35–43	40–48	41–50
Marley et al. (2007)[a]	6–8	8–10							
Chabrier et al. (2000)		6–7	8–10	10–11		28–34		39–46	
Baraffe et al. (2003)		6–7	8–10	10–11		27–31		37–43	
Baraffe et al. (2008)[b]			~9						
Baraffe et al. (2003)[d]		~7.5	~10.5	~11.5		~38		~48	

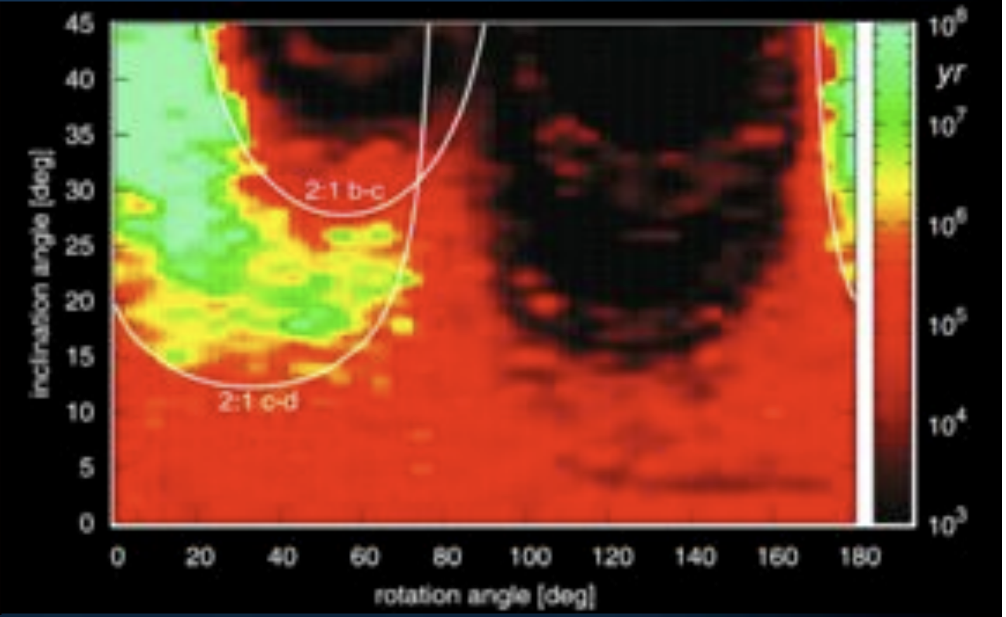
Reidemeister et al. 2009

Masses also from the dynamics

- For planets 10 – 20 M_J, system is unstable unless 1:2:4 resonance
- With resonances planets can avoid close encounters & instability
- If c:d are 2:1, b:c not necessarily in resonance if b's mass <10 M_J



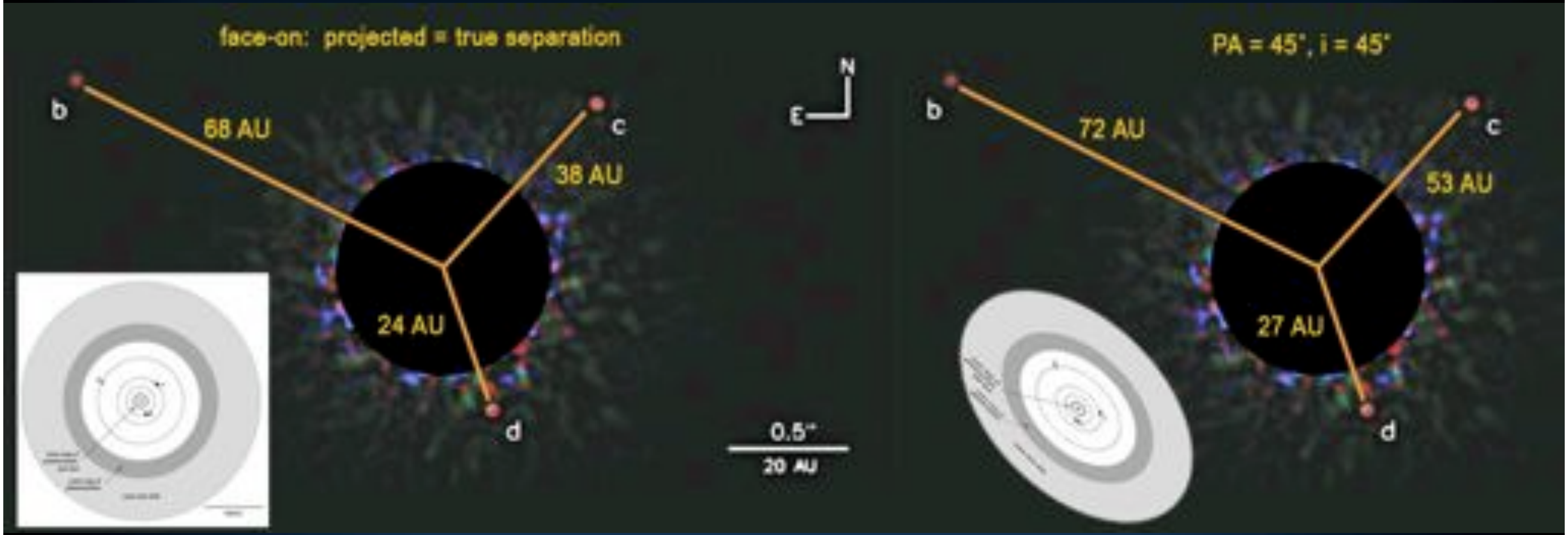
Fabrycky & Murray-Clay 2010



Reidemeister et al. 2009

b:c:d = 7:10:10 M_J

What is the system line-of-sight inclination and position angle?

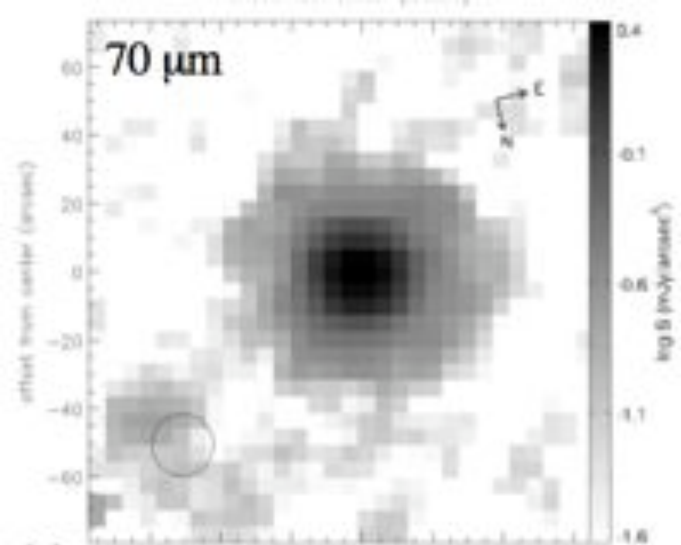


$i = 90^\circ$
PA = any
Planets in 1:2:4 resonance
Stable

$i = 45^\circ$
PA = 45°
d:c = 2:5 resonance
c:b = 2:3 resonance
Stable?

The HR 8799 debris disk

Reidemeister et al. 2009



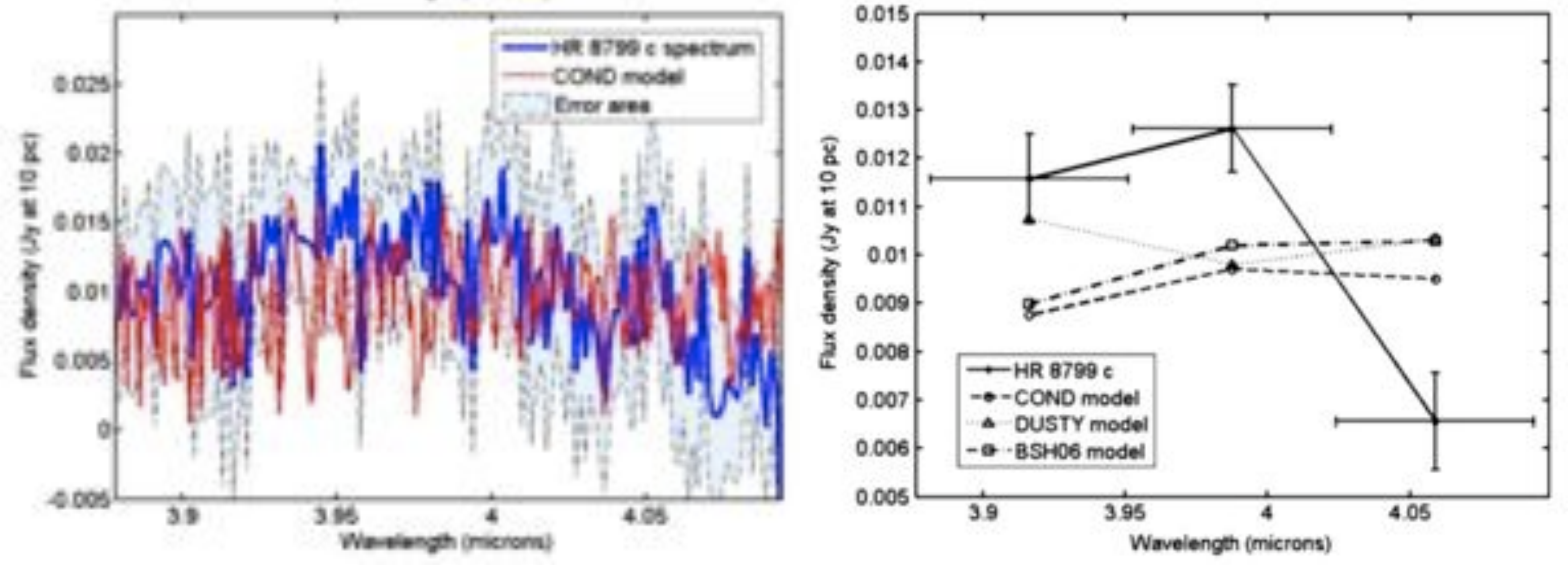
SPITZER data from Su et al. 2009

$i < 25^\circ$

Recent work, e.g., L’ spectrum of HR 8799c (38 AU)

Janson et al. 2010

Spectrum vs. COND model with T_{eff}=1100 K, log g = 4.0, R_{pl} = 1.3 R_{Jup}



BSH is Burrows model

Peak near 4 mm observed

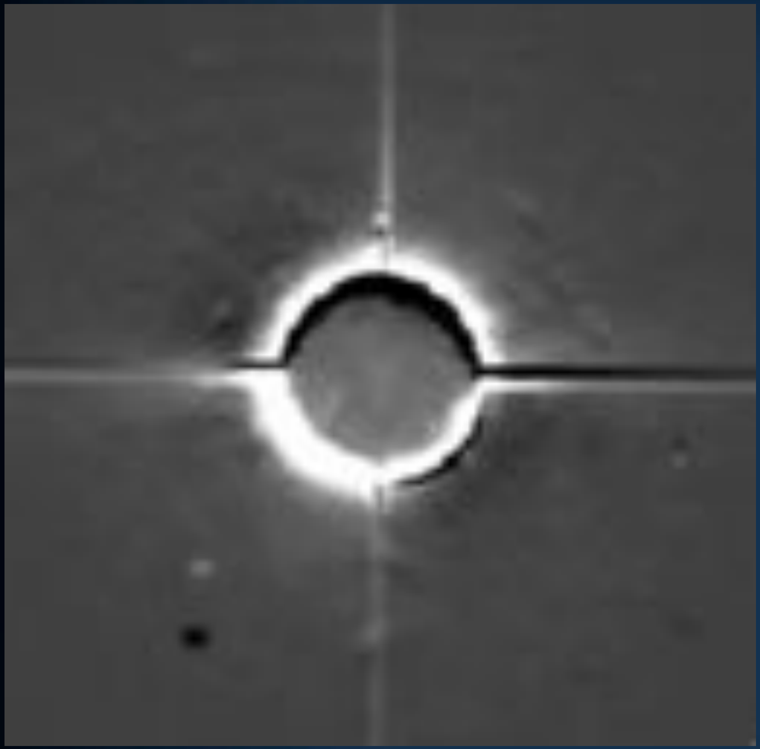
Need models with non-equilibrium chemistry (e.g. Fortney et al. 2008)

Summary of Targets

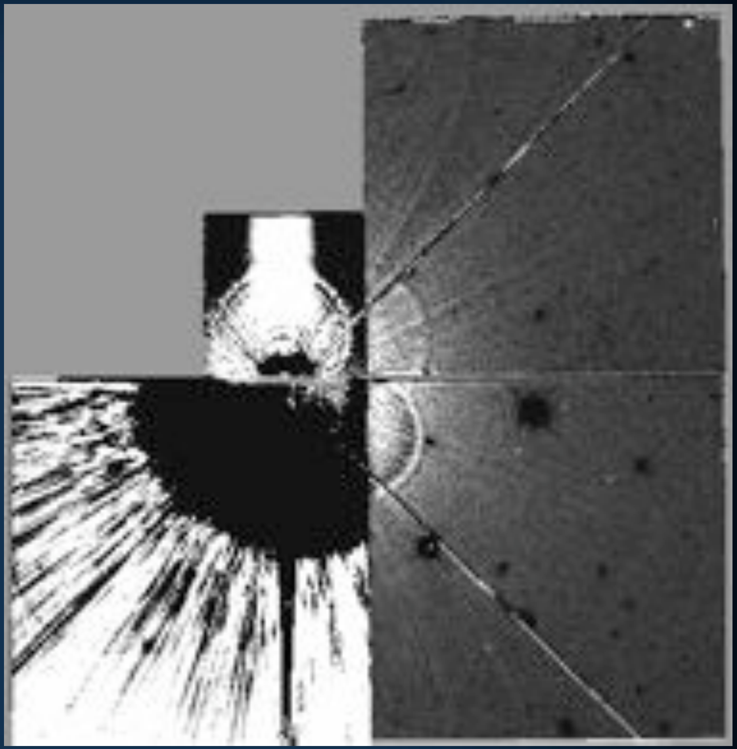
- HD 182488
  - Solar type star: G9V, 0.7 – 8.7 Gyr, 15.6 pc
  - 10 – 40 M_J at 29 AU
- Beta Pic
  - Mass 6 - 12 M_J
  - Orbit a = 8 AU, requires follow-up, but consistent with many other observed phenomena.
- HR 8799
  - Masses 5 - 13 M_J *determined by luminosity & dynamics*
  - Orbits *in resonances, perhaps Laplace, perhaps other.*
- **Fomalhaut**

Fomalhaut

IRAS excess star, but no disk detected in scattered light
Older and less dusty than b Pic, possibly older than HR 8799



1993: Optical observations from Mauna Kea (Paul Kalas)



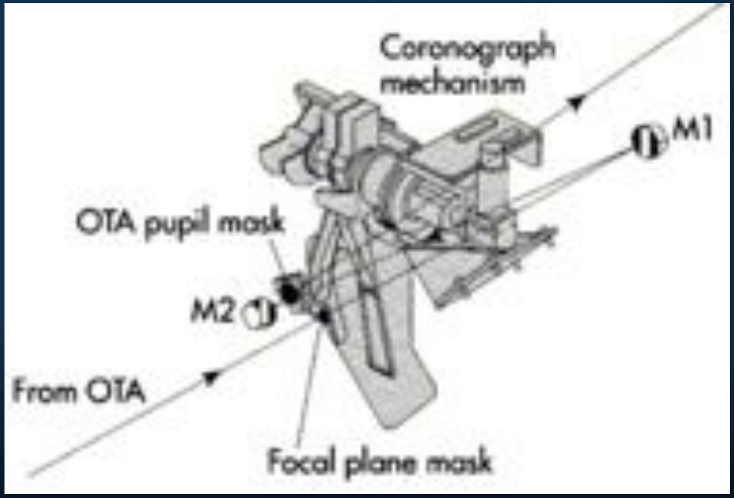
1999: Hubble observations with WFPC2 (Al Schultz)

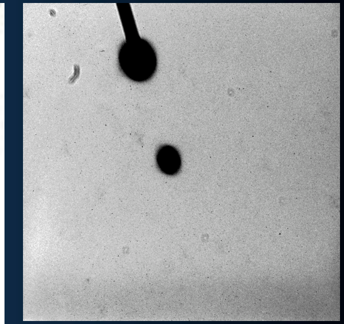
m_v = 1.3 mag (Beta Pic at 3.8 mag and HR 8799 at 5.9 mag)

HST Advanced Camera for Surveys

2002 STS-109

- ***High Resolution Channel (HRC)***
  - **Optimized for NUV band**
  - **26” x 29” field of view**
  - **0.025”/pixel plate scale**
  - **Stellar Coronograph mode**





2001-2004 Planet Search Using the Advanced Camera for Surveys

Kalas, Graham & Clampin

"A planetary system as the origin of structure in Fomalhaut's dust belt"

2005, *Nature*, Vol. 435, pp. 1067

- No planet found, but dust belt seen for the first time in reflected light
- Remarkable properties: Not centered on the star and very sharp inner edge
- Explanation: Gravitational Perturbations by a Planet (Wyatt et al. 1999, Moro-Martin & Malhotra 2002)

Are the belt's brightness asymmetries due to planets?

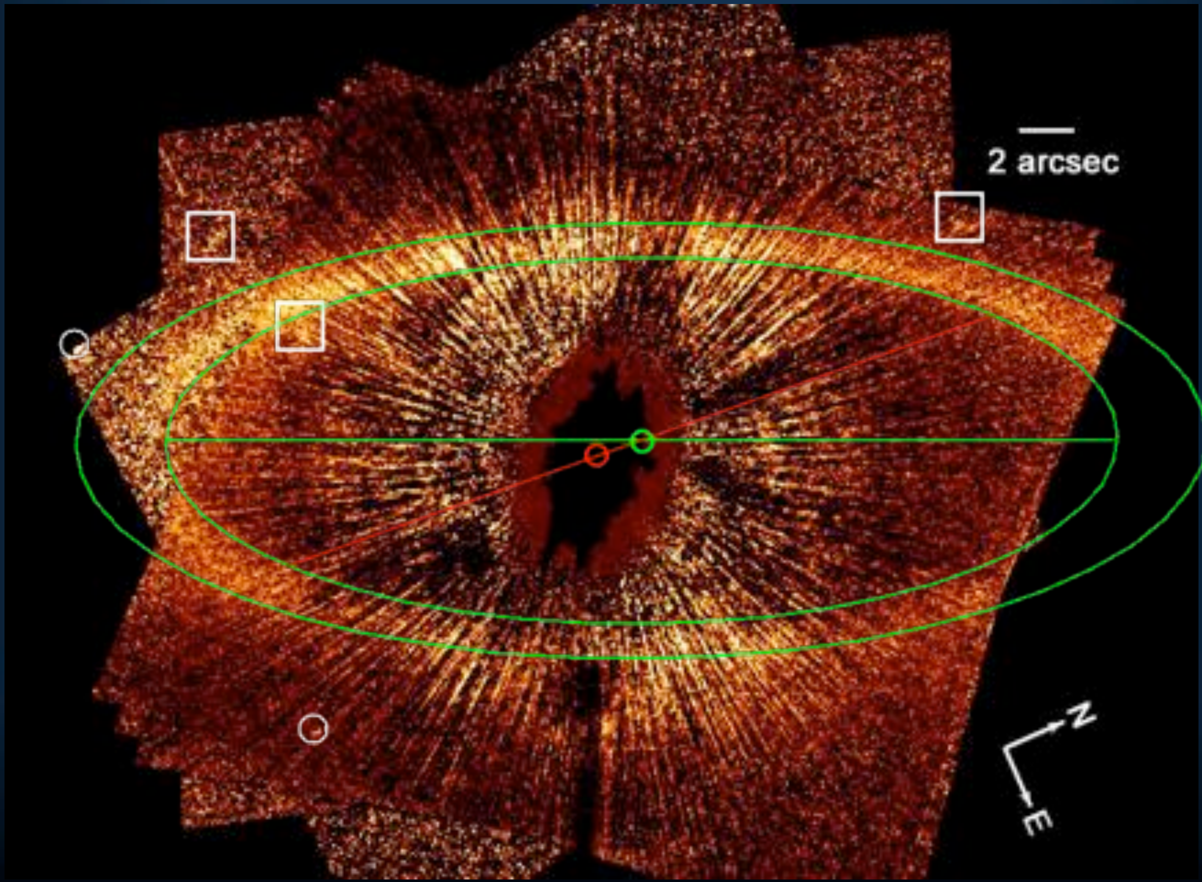
orbital period at 140 AU = 1200 yr

2001-2004 Planet Search *Using the Advanced Camera for Surveys*

Kalas, Graham & Clampin
“A planetary system as the origin of structure in Fomalhaut’s dust belt”
2005, *Nature*, Vol. 435, pp. 1067

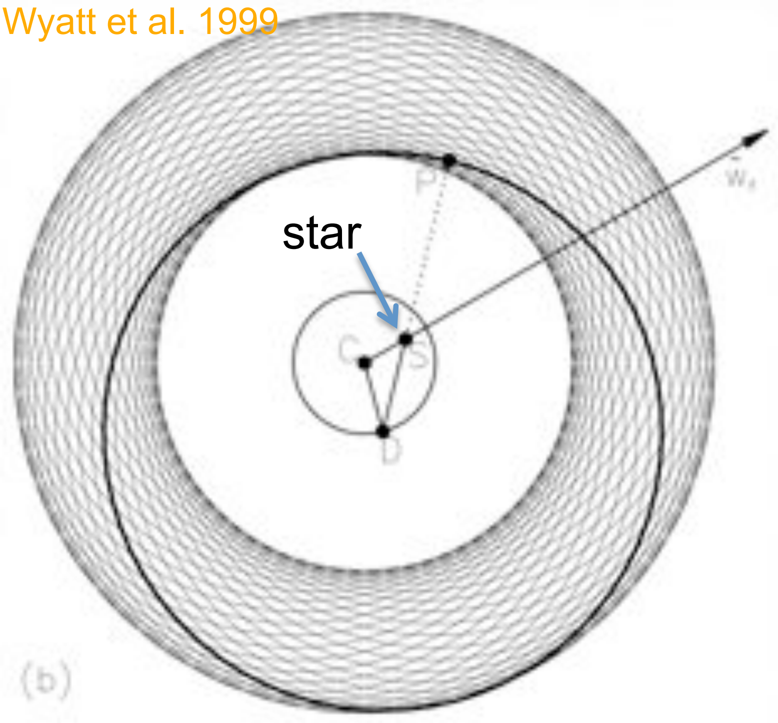
- No planet found, but dust belt seen for the first time in reflected light
- Remarkable properties: Not centered on the star and very sharp inner edge
- Explanation: Gravitational Perturbations by a Planet (Wyatt et al. 1999, Moro-Martin & Malhotra 2002)

Are the belt’s brightness asymmetries due to planets?



orbital period at 140 AU = 1200 yr

Evidence for a planetary system: Center of symmetry offset

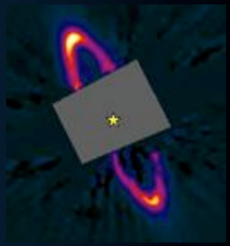


Wyatt et al. 1999

S = stellar position
D = center of particle orbit
C = center of precession circle
P = pericenter of a particle orbit
DP = a, semi-major axis of a particle orbit
w_f = direction of forced pericenter
SD = $a\ e$ SC = $a\ e_{forced}$ CD = $a\ e_{proper}$
Torus inner radius = $a\ (1 - e_{proper})$ = 133 AU
Torus outer radius = $a\ (1 + e_{proper})$

How Observations of circumstellar disk asymmetries can reveal hidden planets:Pericenter glow and its application to the HR 4796A disk
Wyatt, M.C. et al. 1999, ApJ, 527, 918

G. Schneider, STIS



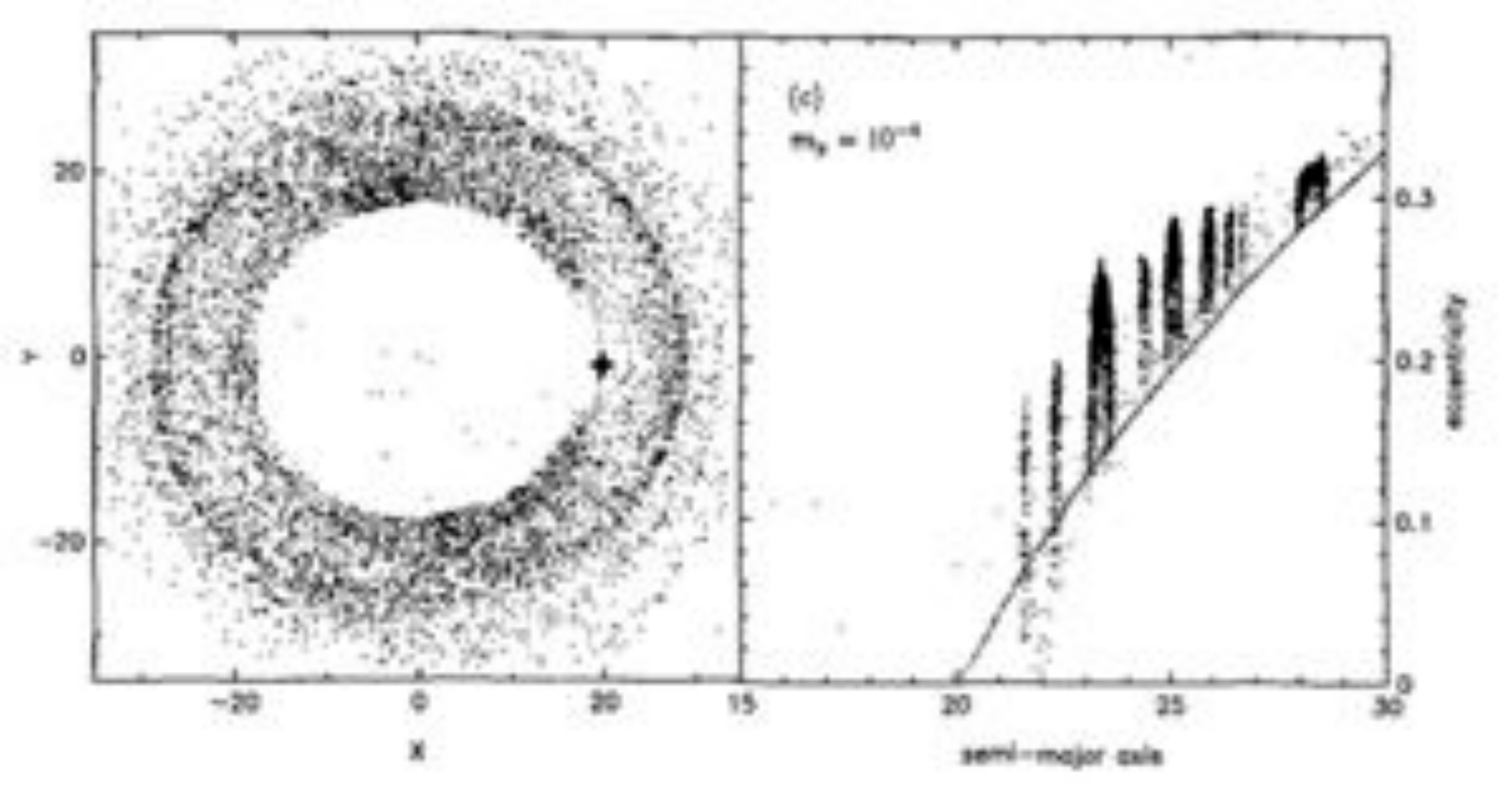
- Particle eccentricity composed of a *proper* (free) eccentricity, inherent to the particle, and a ***forced*** eccentricity due to a perturber. The pericenter also has a free and a forced component.

- The orbital distribution of particles with common forced elements will be a ***torus*** with center, *C*, ***offset*** from the stellar position, *S*.

- The forcing is due to an eccentric companion *that could be either inside or* ***outside*** *the belt*.

Roques et al. (1994, Icarus, 108, 37)

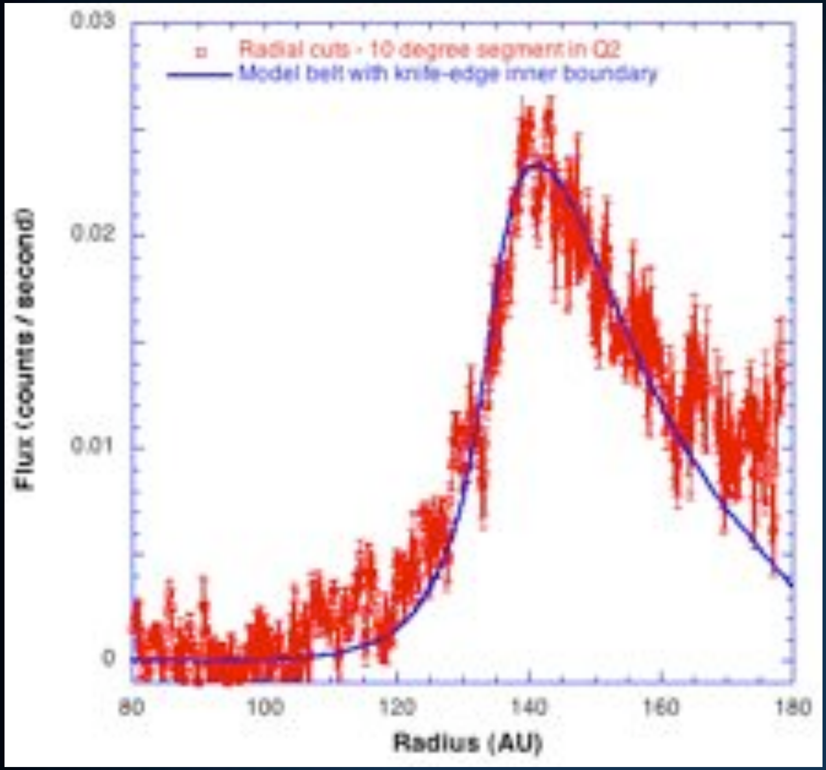
“Is there a planet around beta Pictoris? Perturbations of a planet on a circumstellar disk.”



Planet with 50 M_earth at 20 AU

Key prediction for a planetary system

Knife-edge inner boundary means that perturber is inside the belt.



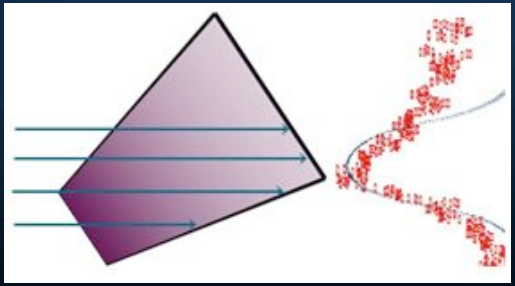
Radial cut along 10˚ segment Q2 (apastron), in the illumination corrected image; cut traces the material surface density of the structure rather than its brightness.

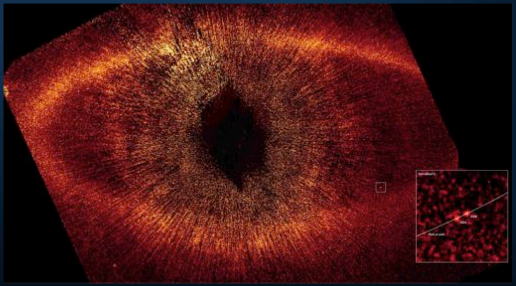
Blue line is the model fit:

1) Knife-edge inner edge = 133 AU

2) $n(r) = n(r_o)\ r^{-9}$

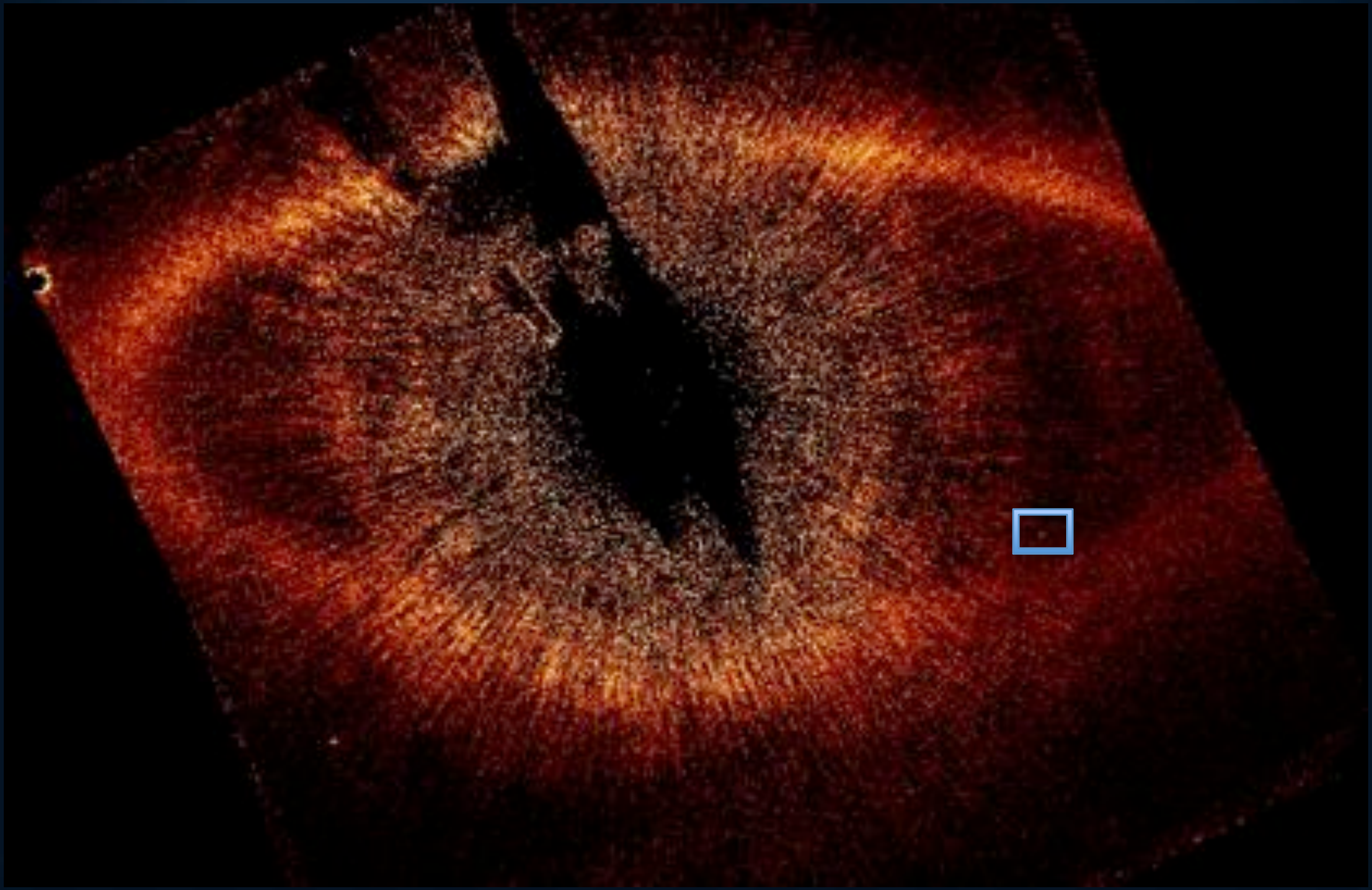
3) Scale height = 3.5 AU at 133 AU





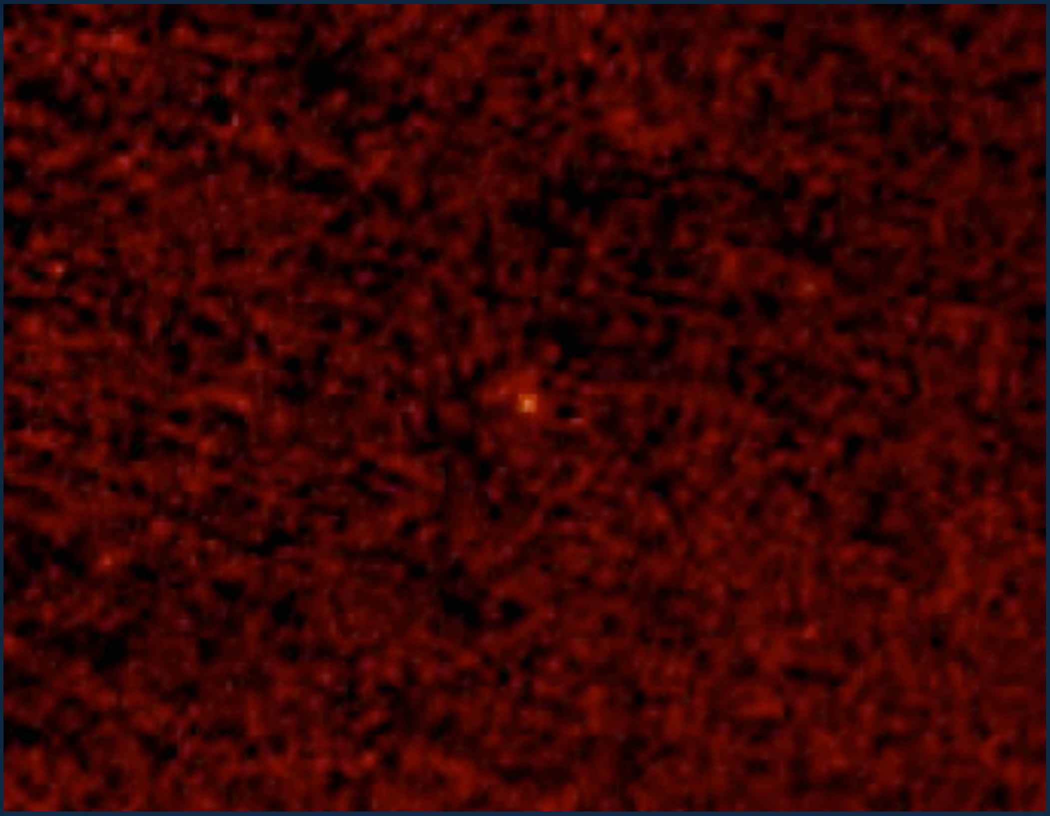
2006: HST/ACS deep multi-wavelength imaging

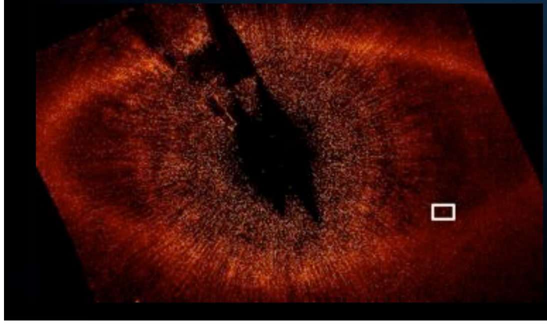
F435W, F606W, F814W



Fomalhaut b

2004

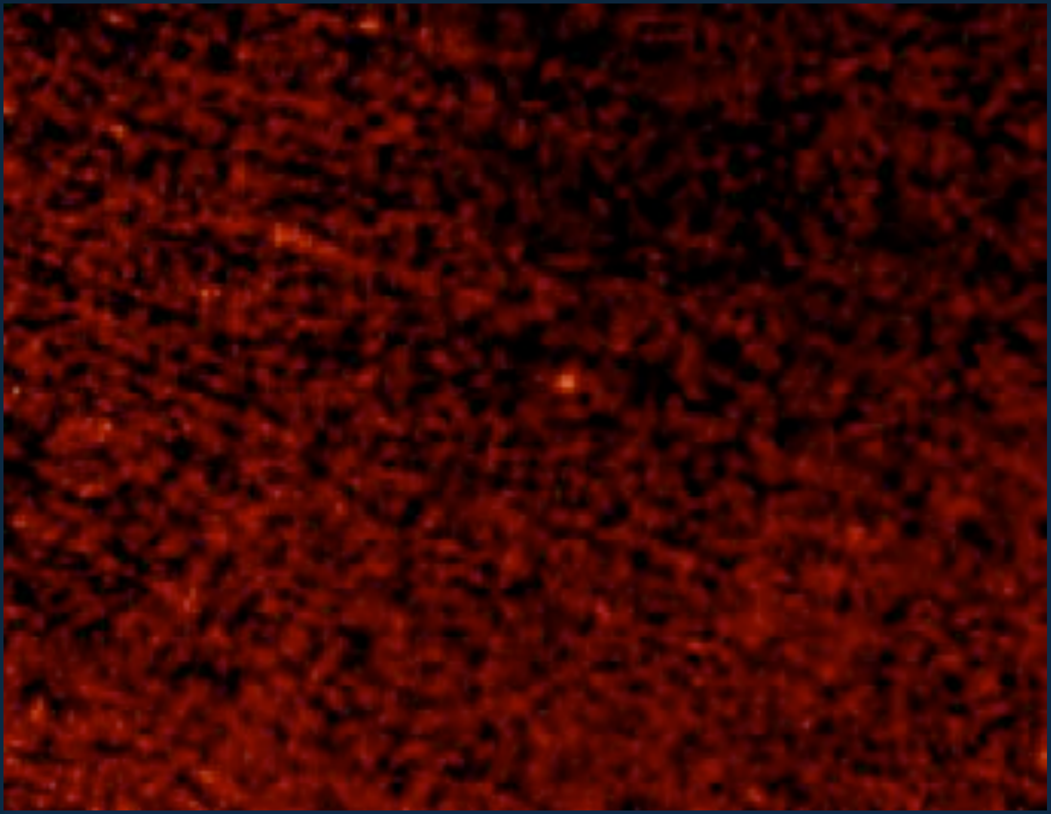


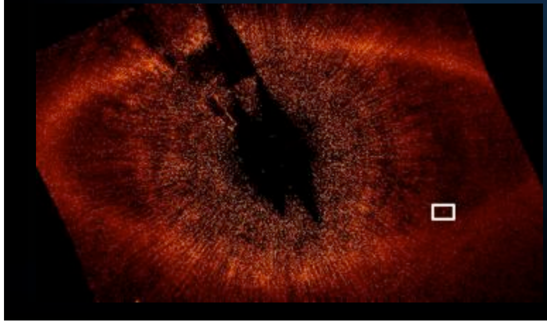


Paul Kalas (University of California, Berkeley)

Fomalhaut b

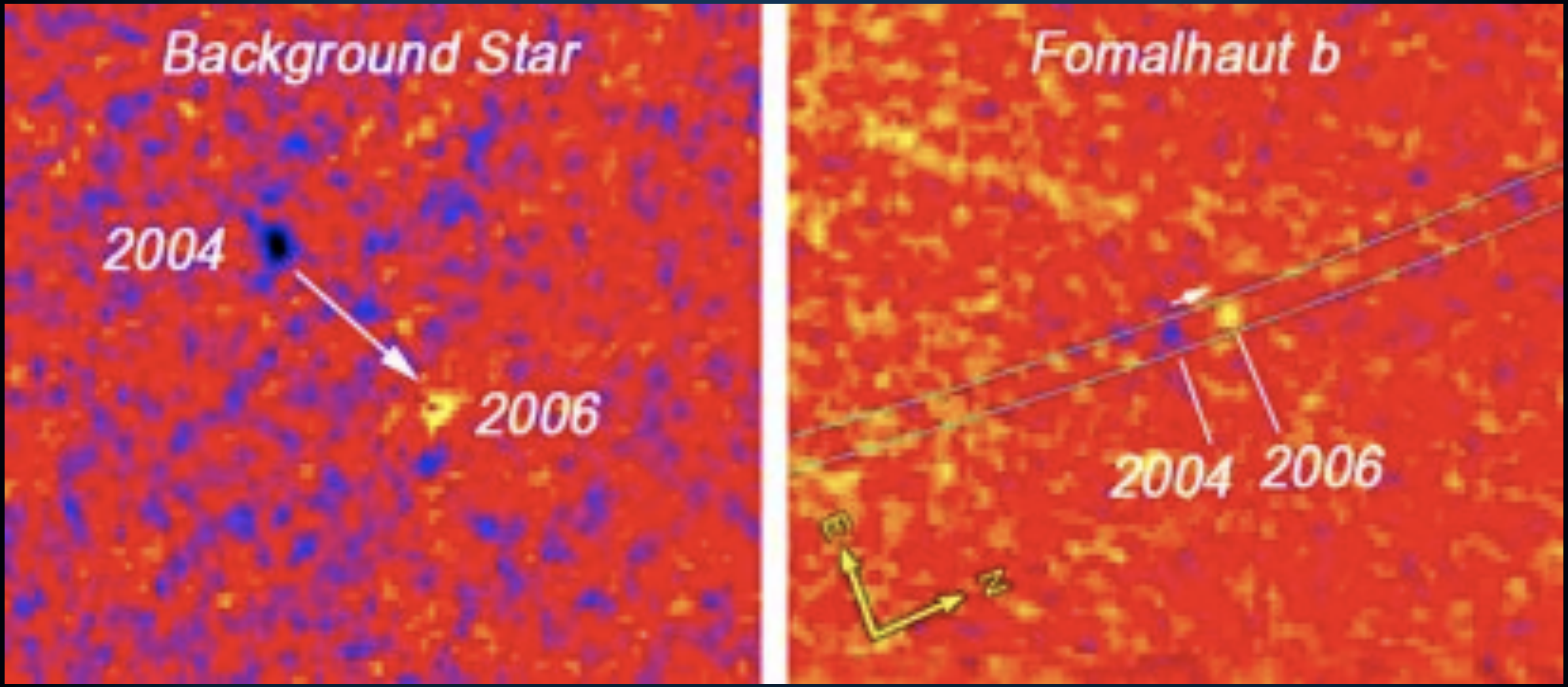
2006





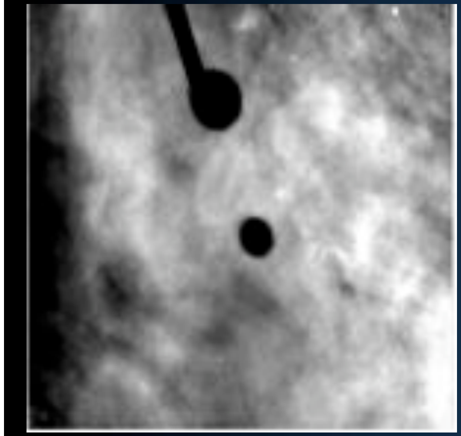
Paul Kalas (University of California, Berkeley)

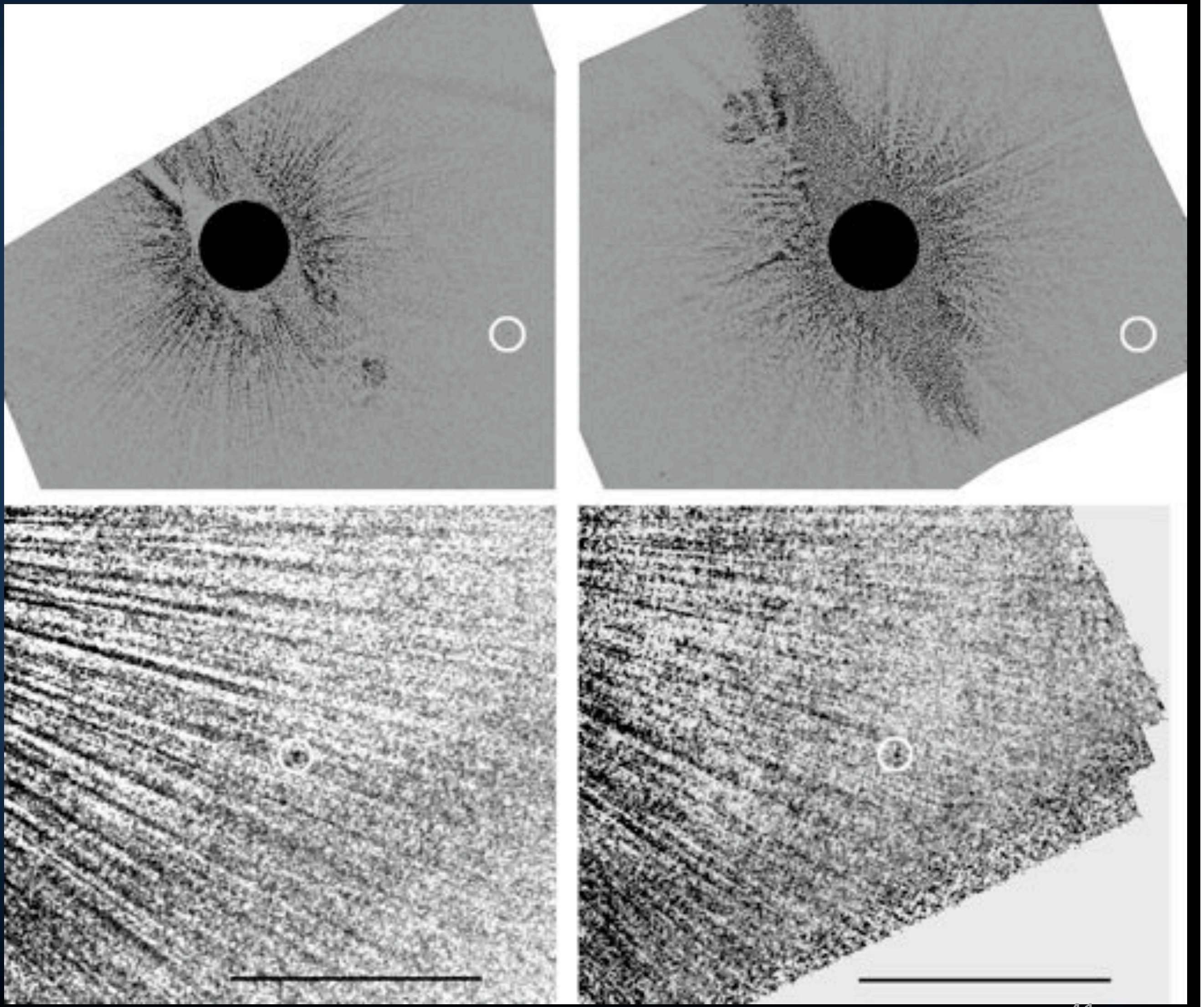
Background star?

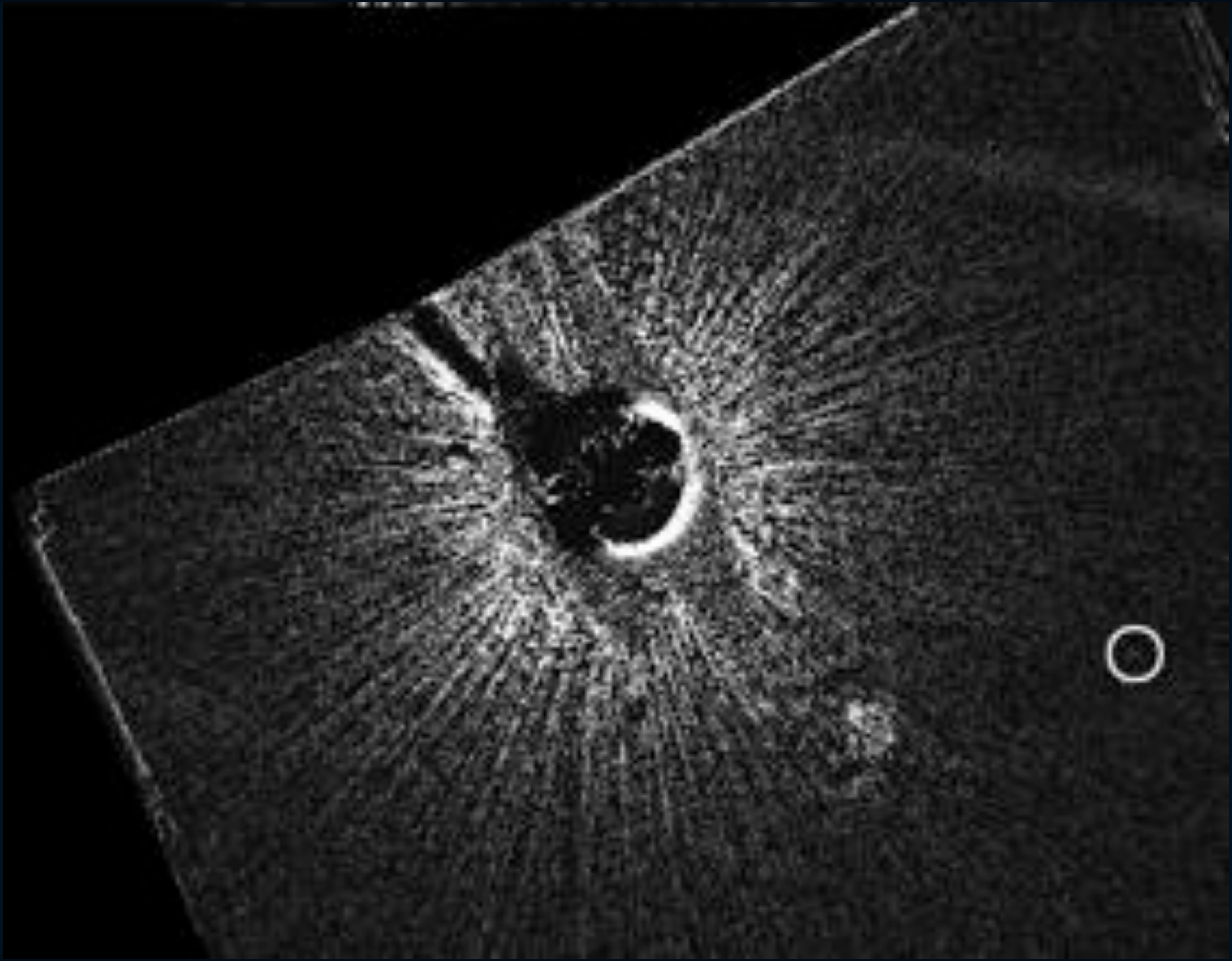


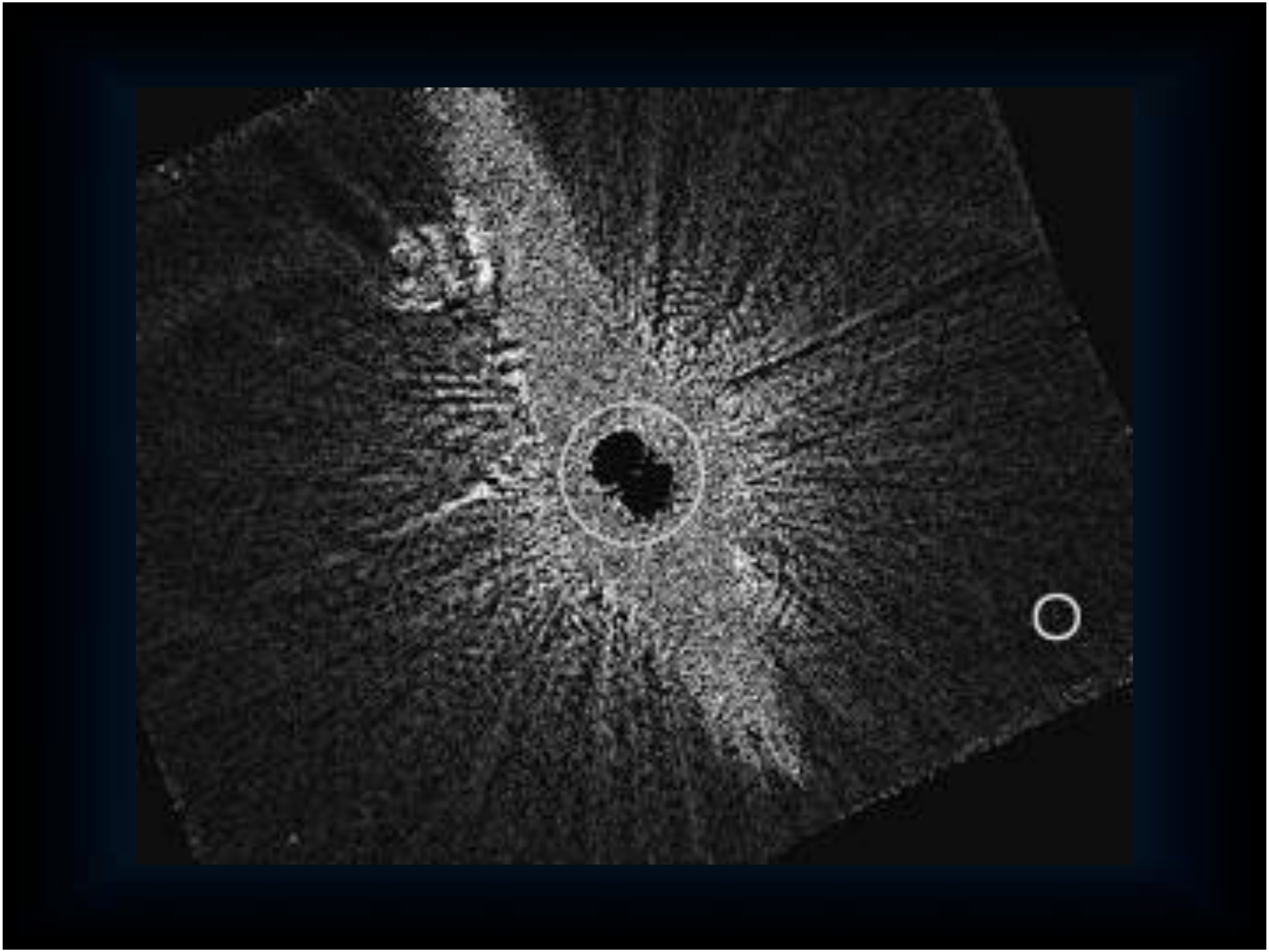
Speckle Noise?

Confirmed in dithered observations, two wavelengths, two types of PSF subtraction



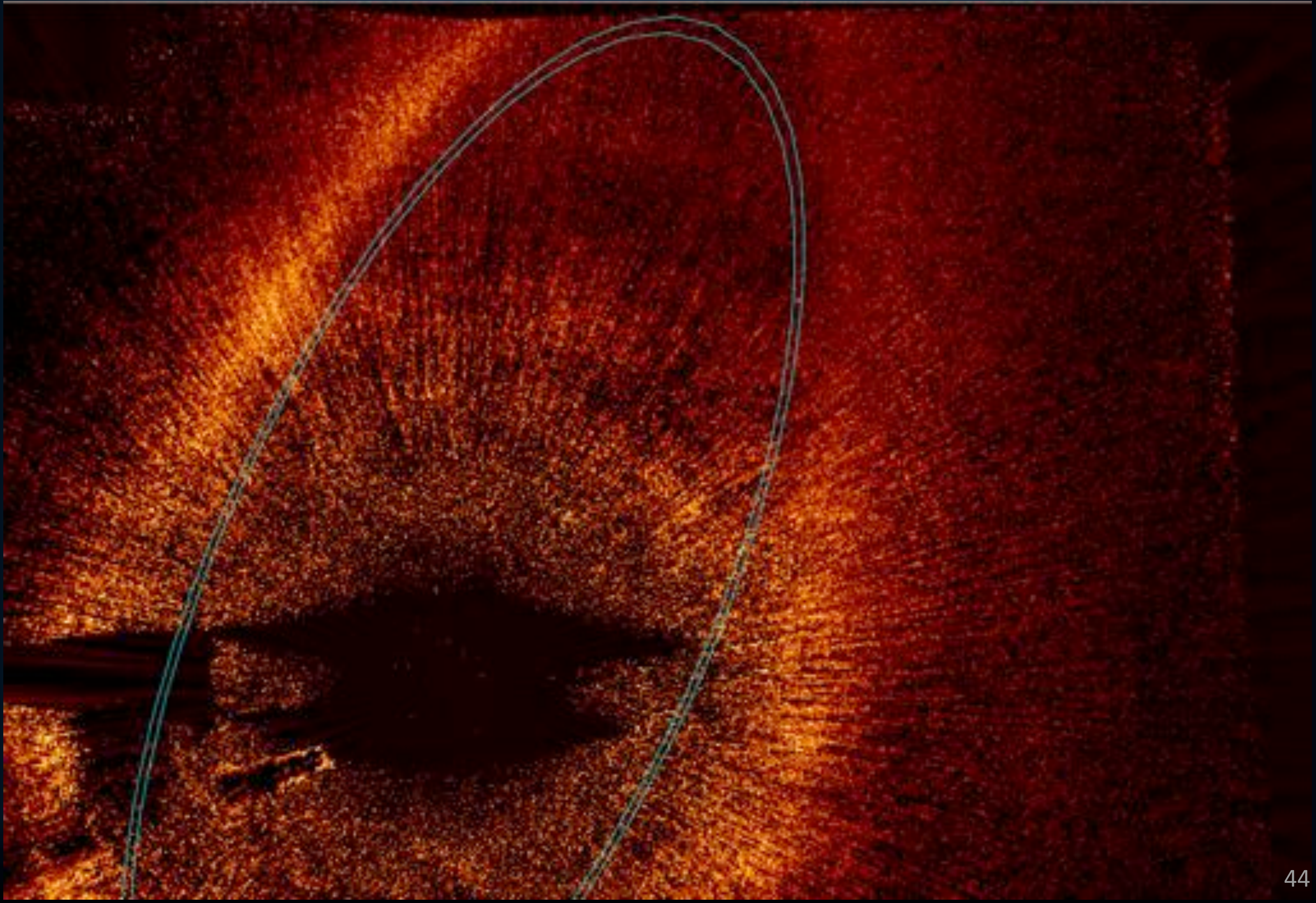


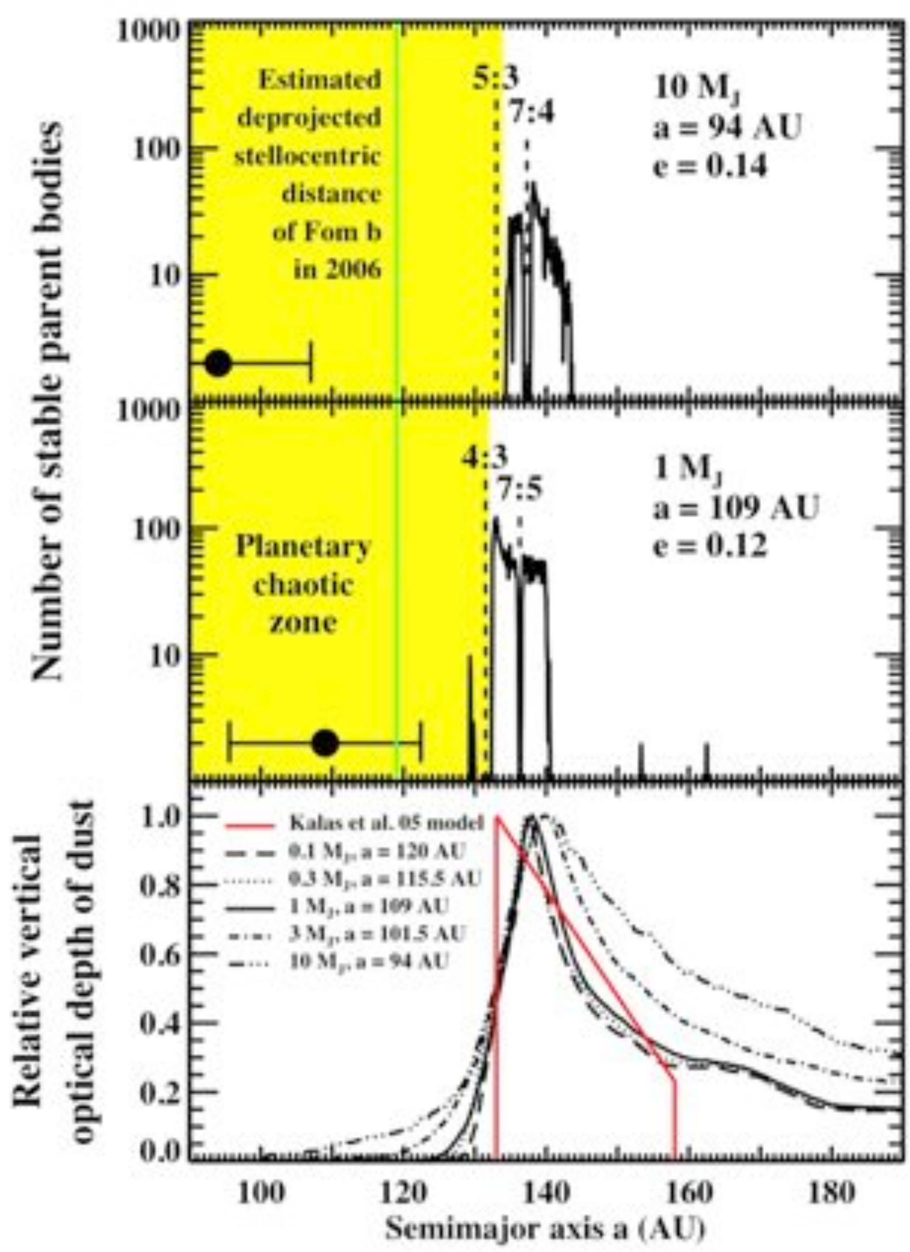




Fomalhaut b: Counterclockwise orbit

(below: north up, east left)





Chiang et al. 2009, Kalas et al. 2009

What is the mass of Fomalhaut b?

From the observed proximity of Fom-b to the belt inner edge (18 AU), and the shape of the radial dust profile:

10 M_J unlikely, <3.0 M_J most probably with a > 101.5 AU, e = 0.11-0.13

0.5 M_J if apsidally aligned

$$a_{\rm inner} - a_{\rm pl} = 2.0\,\mu^{2/7} a_{\rm pl}$$

Chiang et al.
2009, *Astrophysical Journal*, 693, 734

Quillen (2006) gives:
a ~ 119 AU, e ~ 0.1, $0.05 < M_J < 0.33$

Based on pericenter glow only:

Stapelfeldt et al. 2005 gives
a ~ 40 AU, *e* ~ 0.15

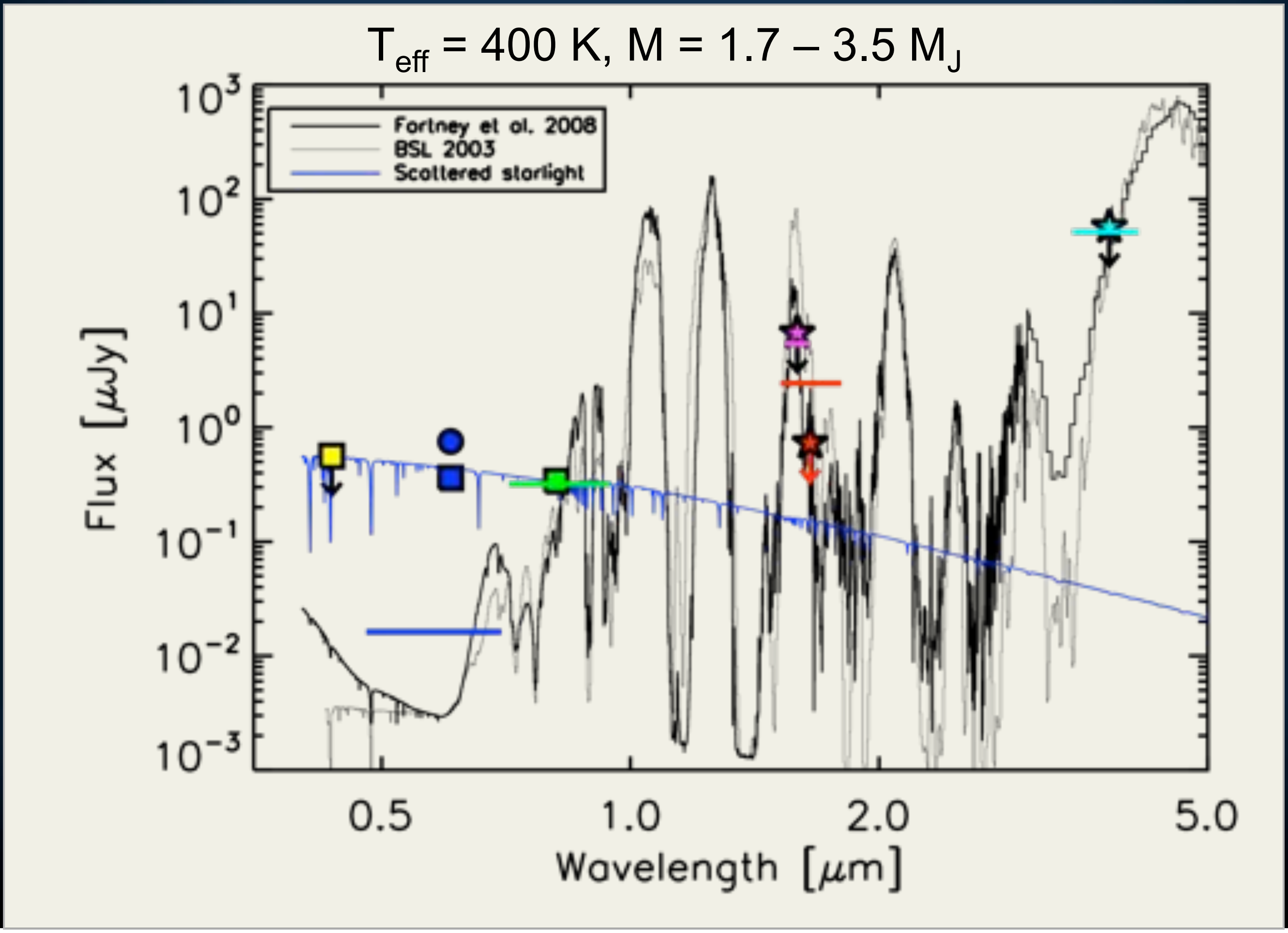
Marsh et al. 2005 give
a ~ 86 AU, *e* ~ 0.07

What is the mass of Fomalhaut b?

#2 From how bright it is in the optical, and non-detections in the infrared…. less than 3 Jupiter masses.

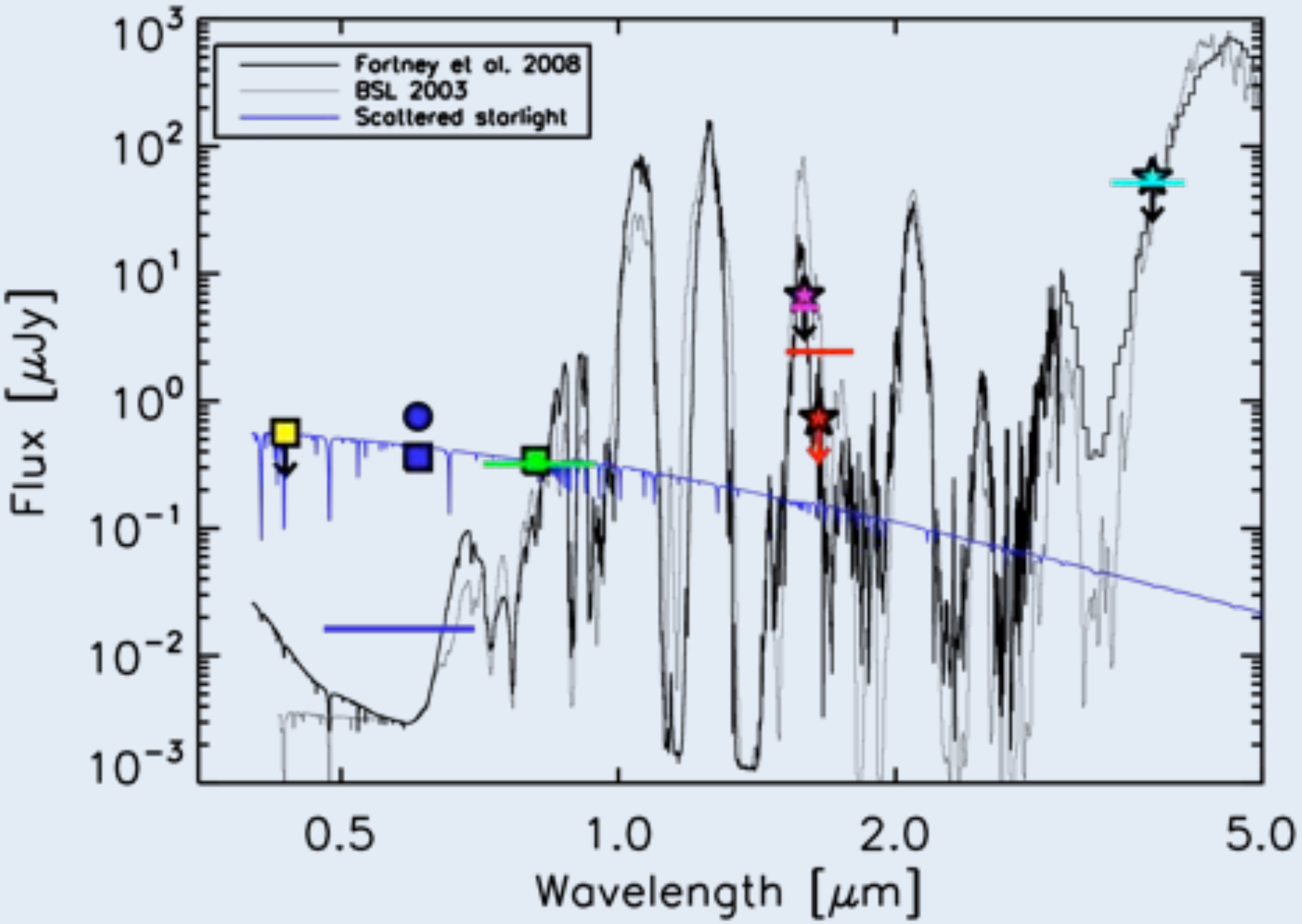
Other sources of optical luminosity are possible: glowing hot gas and/or reflected light from a circumplanetary disk

T_{eff} = 400 K, M = 1.7 – 3.5 M_J



Spitzer limits too
Marengo et al. 09
$M_{pl} < 3 M_J$

Are we seeing a planet or something else?


Fortney et al. 2008
BSL 2003
Scattered starlight
Flux [μJy]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0.5
1.0
2.0
5.0
Wavelength [μm]

Protogalilean, circumplanetary disk
How much flux from Fom-b received at Earth?

$$f_p = \frac{f_o}{4\pi\ D^2} = \frac{\sigma_p Q_s \times 1.70\ \mathrm{Wm}^{-2}}{4\pi\ (2.379 \times 10^{17})^2} = \sigma_p Q_s \times 2.390 \times 10^{-36}\ \mathrm{Wm}^{-2}$$

s_p = projected geometric surface area of the planet+rings
Q_s = scattering efficiency (geometric albedo times phase function at given phase)

Observations:	m_v = 25.0 mag
Planet only (1.2 R_J, Q_s = 0.5):	m_v = 30.0 mag
Planet + Rings to Roche Radius	m_v = 29.5 mag
Planet + 20 R_p rings (Q_s = 0.4)	m_v = 25.0 mag
Planet + 35 R_p rings (Q_s = 0.1)	m_v = 25.0 mag

For comparison, Callisto at ~27 Jupiter radii

Protogalilean? circumplanetary disk

Planet with 16 - 35 R_p rings

- How does it survive 200 Myr?
- Callisto forms in 1 Myr (Mosqueira & Estrada 2003)
- Belt crossing orbit?
- Planet mass <<3 M_J

Or, Saturnian?

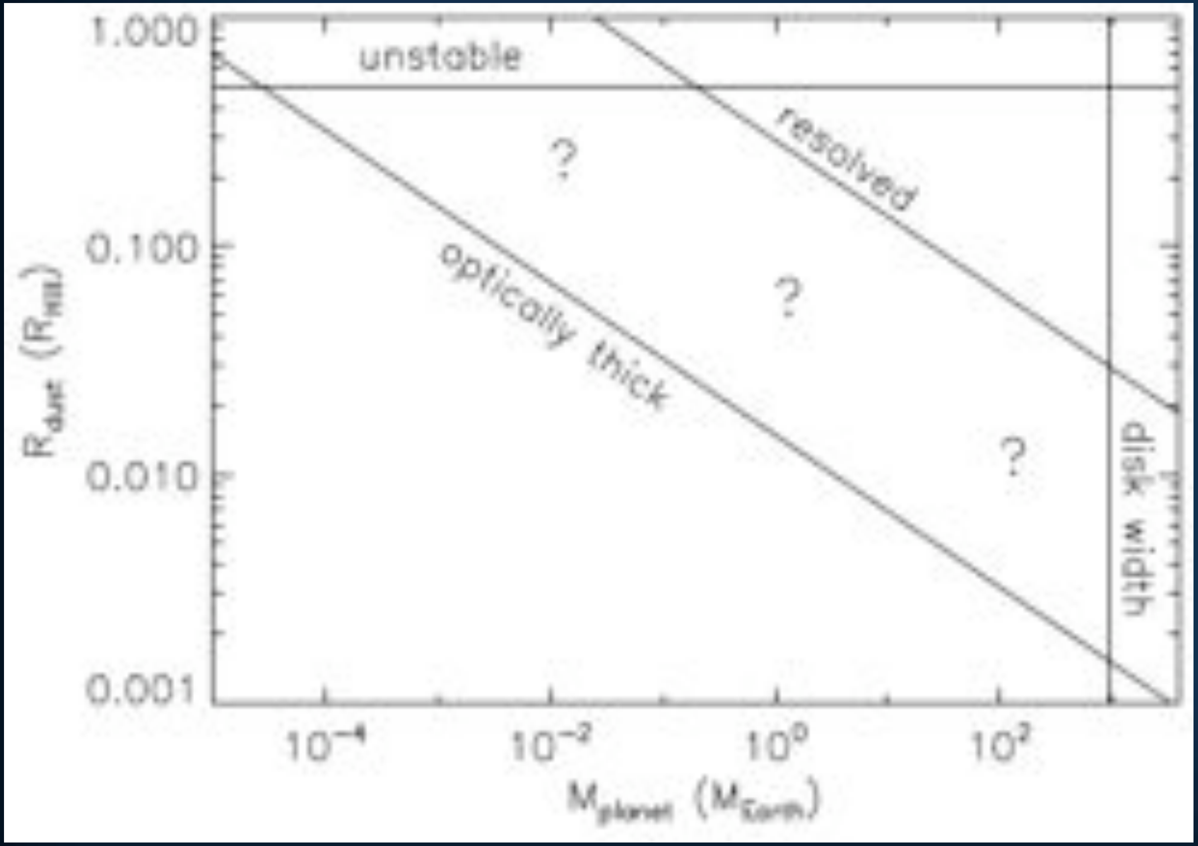
100 - 200 R_p rings
$\tau_{perp} \sim 10^{-8}$ (1 km crater)

(Verbiscer, Skrutskie & Hamilton 2009)

Fom b circumplanetary dust disk

Kennedy & Wyatt, in prep

collisional evolution of satellitesimals



R_H = 6 AU for 1 M_J

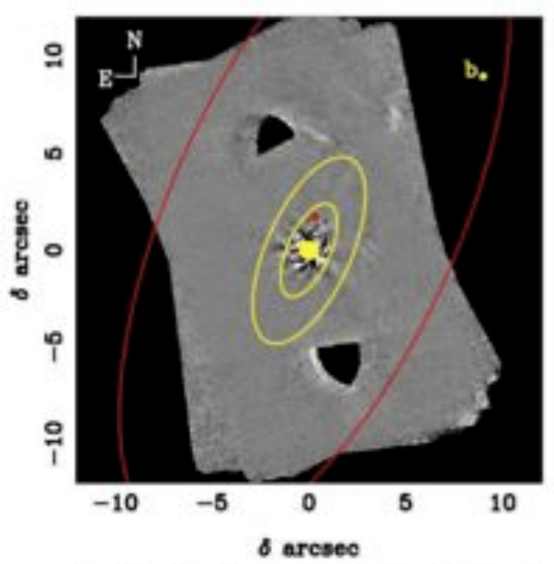
Fom b could be very low mass, and therefore the perturber of the belt is a second more massive planet in the system

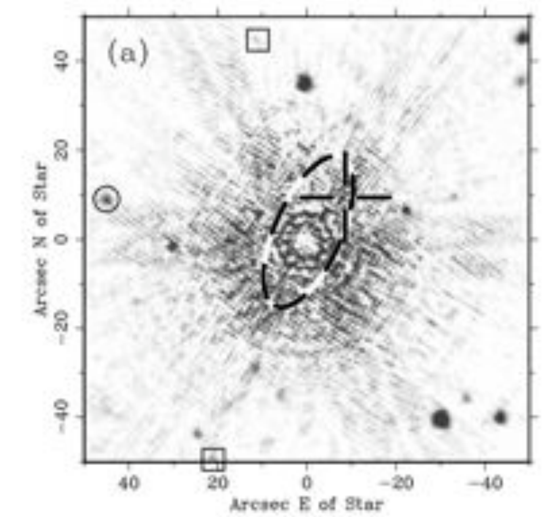
Terrestrial ring system

Other planets orbiting Fomalhaut?

- MMT at 5 μm, no planets >2 M_J between 13 - 40 AU
  - Kenworthy et al. 2009

- Spitzer / IRAC planet search: No detection of planets with mass $M > 3.0\ M_J$
  - Marengo et al. 2009

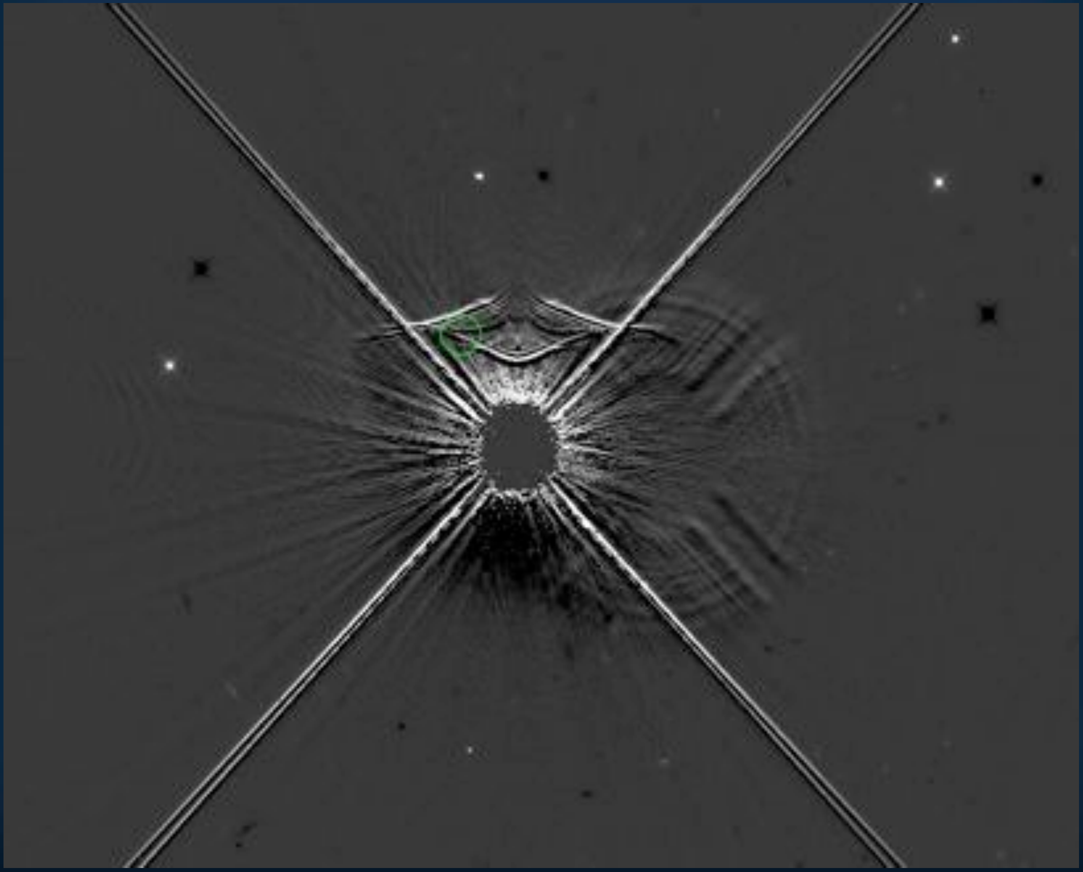




Fomalhaut 3rd epoch – Nov. 2009

HST WFC3/IR

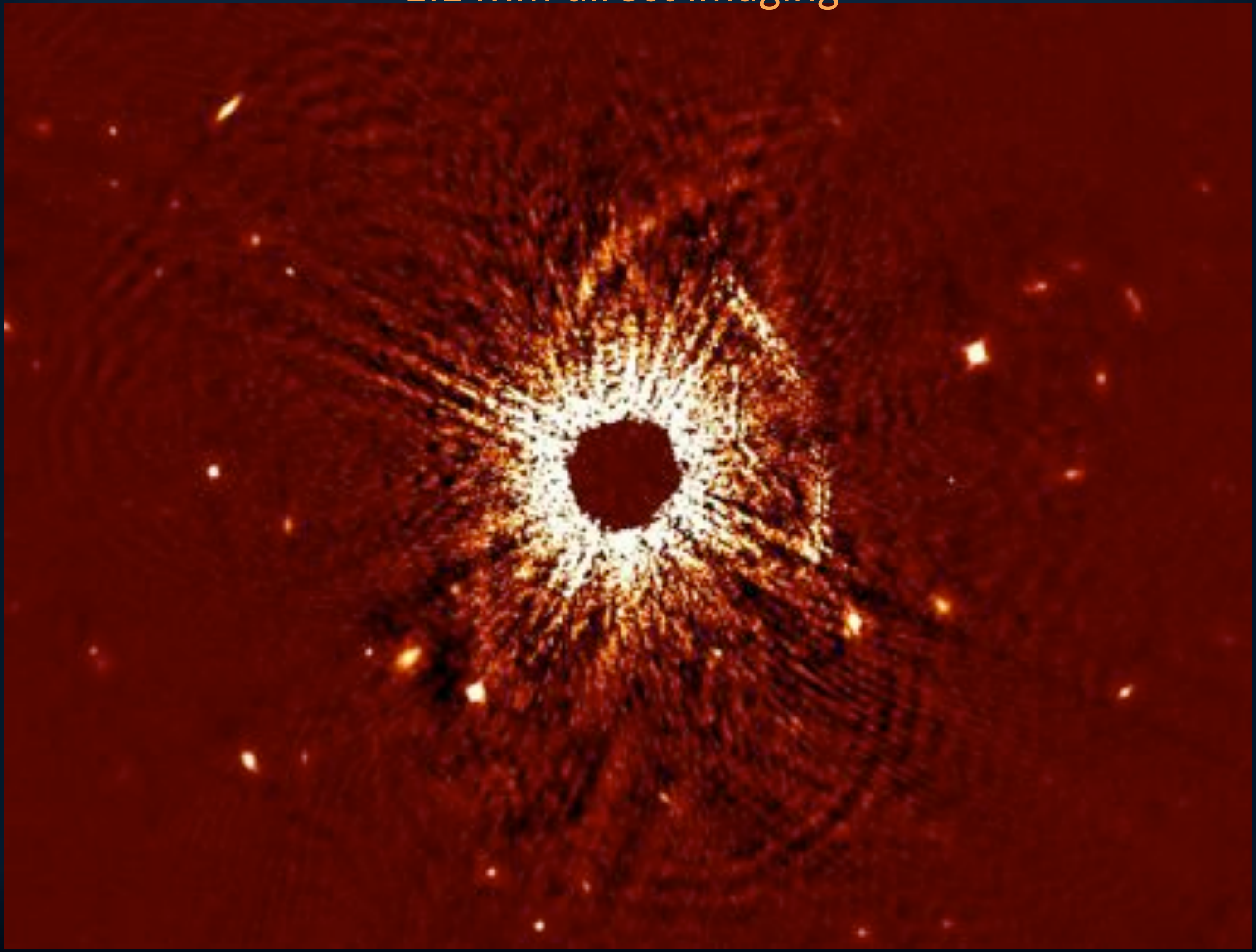
1.1 mm direct imaging



Fomalhaut 3rd epoch – Nov. 2009

HST WFC3/IR

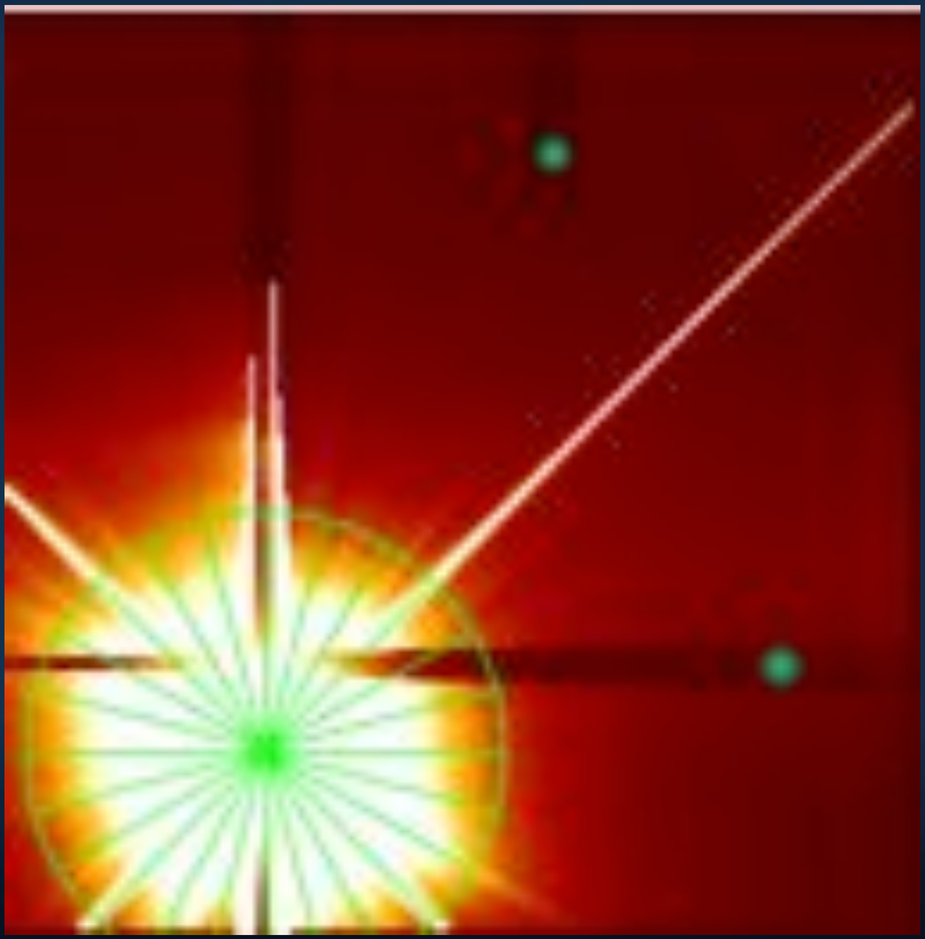
1.1 mm direct imaging



Fomalhaut 3^{rd} epoch – June 2010

HST STIS

opical coronagraphic imaging



Summary of Targets

- HD 182488
  - Solar type star: G9V, 0.7 – 8.7 Gyr, 15.6 pc
  - 10 – 40 M_J at 29 AU
- Beta Pic
  - Mass 6 - 12 M_J
  - Orbit *a* = 8 AU, requires follow-up, but consistent with many other observed phenomena.
- HR 8799
  - Masses 5 - 13 M_J *determined by luminosity & dynamics*
  - Orbits *in resonances, perhaps Laplace, perhaps other.*
- ***Fomalhaut***
  - Very low mass, <3 M_J
  - Orbit lacks 3rd epoch, eventually will help determine the mass independent of atmosphere models.
  - Formation *in situ* via GI (Nero & Bjorkman 2009) or migration that includes a second planet (Crida et al 2009).

Future Work:

2011 - 2013

Gemini Planet Imager

gpi.berkeley.edu

Host	SpT	Dist. (pc)	Sep. (AU)	Mass (M_J)	Age (Myr)	Reference
Fomalhaut	A3V	7.69	119	<3.0	100 - 300	Kalas et al. '08
HD 182488	G8V	15	>14, >29	10 - 40	700 – 8700	Thalmann et al. '09
Beta Pic	A5V	19.3	8	6 - 12	8 - 20	Lagrange et al. '08
HR 8799	A5V	39.4±1.0	>68, >38, >24	5-11 7-13	30 - 160	Marois et al. '08
AB Pic	K2	47.3±1.8	258	11 - 25	30 – 40	Chauvin et al. '05
2M1207	M8	52.4±1.1	54	2 – 25	5 – 12	Chauvin et al. '04
GQ Lup	K7	140 ± 50	100	4 – 39	<2	Neuhauser et al. '05
1RXJ160929	G	145±20	330	6 – 12	5	Lefreniere et al. '08
CT Cha	K7	160±30	440	11 - 23	<2	Schmidt et al. '08

When:	12 months from today
Where:	Gemini South
Who:	PI's B. Macintosh & J. Graham
How:	High-order AO with coronagraphy
What:	0.9 – 2.4 μm, m_I < 9 mag stars, polarimetry, R~100 spectroscopy

NICI: Current planet imaging search at Gemini
See poster, PI Mike Liu

Direct Detections
Add 100+ rows from GPI
and SPHERE results

Some questions:

What have we learned from the non-detections? see the following:

- Apai et al., 2008, ApJ, 672, 1192
- Biller et al., 2007, ApJS, 173, 143
- Carson et al., 2009, AJ, 137, 218
- Chauvin et al., 2009, AIPC, 1158, 183
- Jenkins et al., 2010, arXiv:1003.2430
- Nielsen et al., 2010, EAS, 41, 107
- Nielsen et al., 2008, ApJ, 674, 466