HST Imaging of Dusty Debris Disks and their Planetary Systems

Paul Kalas

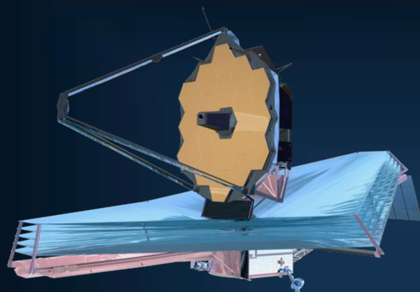
University of California

& SETI Institute

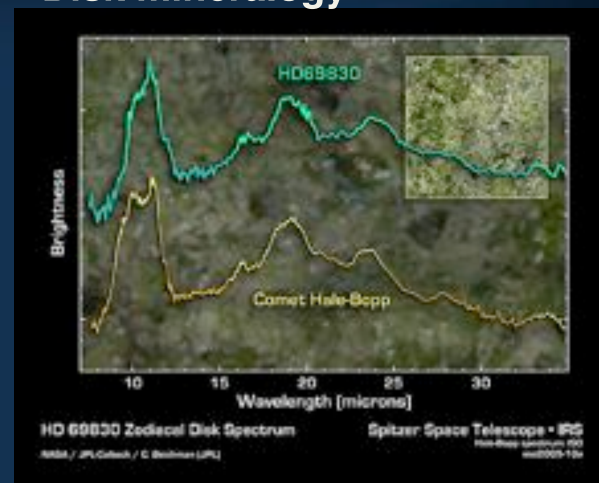
Collaborators: James Graham, Mike Fitzgerald, Mark Clampin

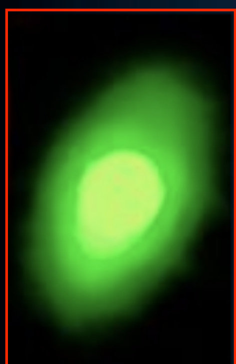
Eugene Chiang, Edwin Kite, Karl Stapelfeldt, John Krist, Mark Wyatt, Matt Kenworthy, John Wisniewski, Ansgar Reiners, Andreas Seifahrt, Stefan Dreizler, Brenda Matthews

Disks & Planets with JWST

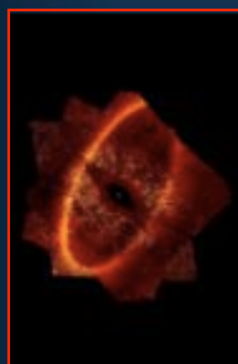


- Spatially resolved spectroscopy
- Disk mineralogy

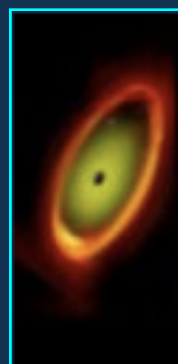




Spitzer (24 μm)



ACS (Visible)



JWST (20 μm)

- Disk morphology:
  - ➡ scattered light (NIRCam)
  - ➡ emission (NIRCam/MIRI)

- Indirect evidence of exoplanets
  - e.g. Kalas et al. (2008), Stark and Kuchner (2008)

TFI: Simulation of HR 8799 - Beaulieu (2009)

Paul Kalas, Science with HST-III, Venice, Italy Nov. 11-14, 2010

STATE of AFFAIRS

Observations

Theory

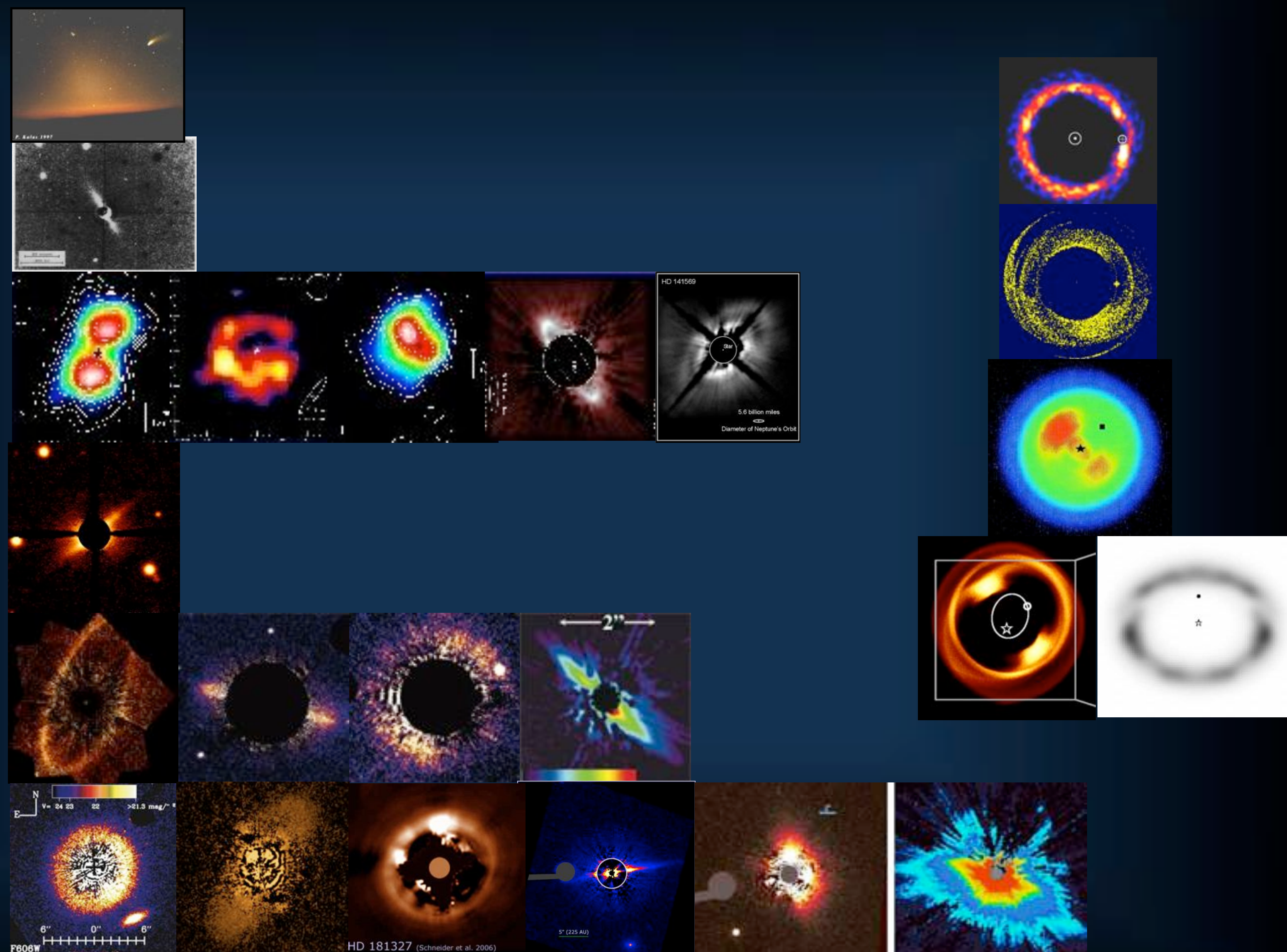
1500

1984

1998

2004

2010



STATE of AFFAIRS

Observations

1500

Terrestrial vs. Extraterrestrial Erosion

Extraterrestrial

Terrestrial: Leonardo Da Vinci (1500)

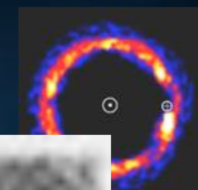
STATE of AFFAIRS

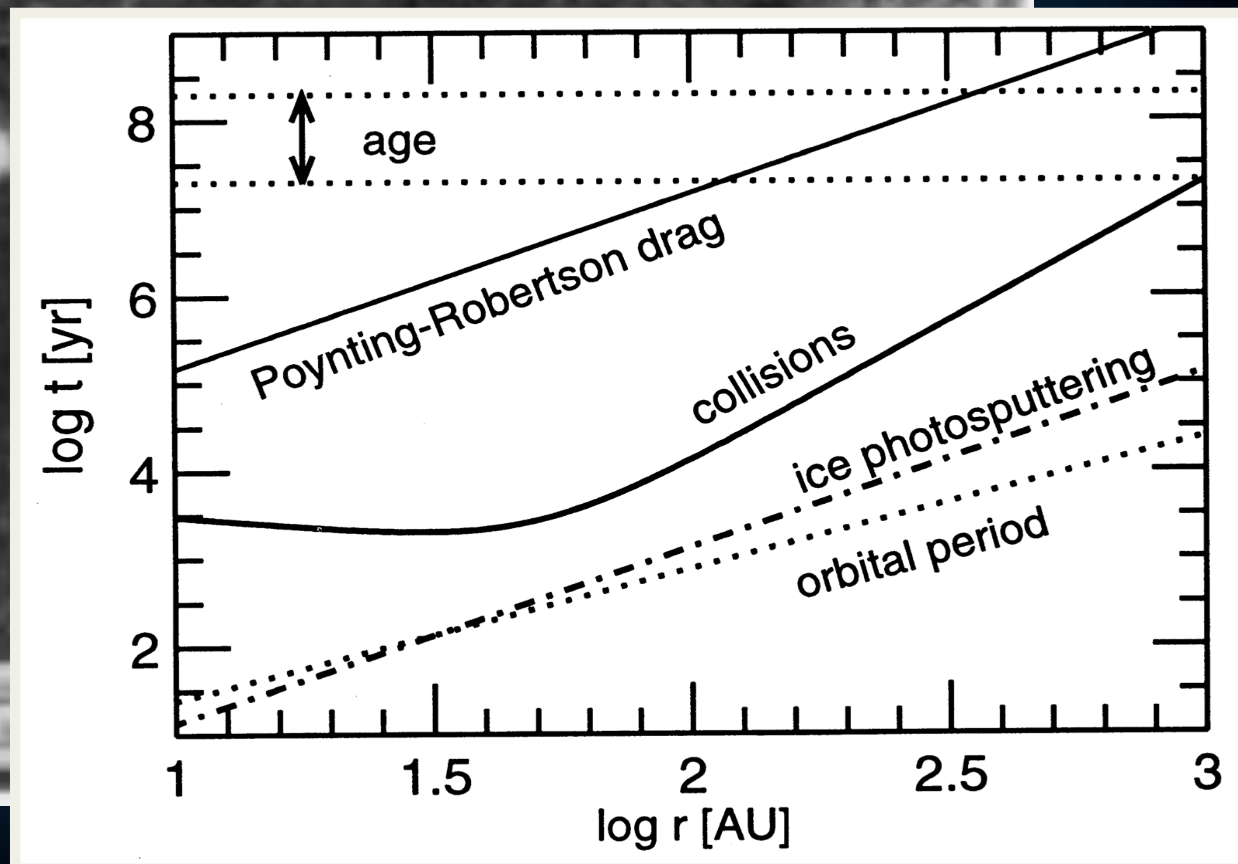
Observations

Theory

1700

1984





Smith & Terrile 1984, Aumann et al. 1984, Dermott et al. 1994, Artymowicz 1997

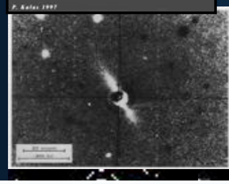
Paul Kalas, Science with HST-III, Venice, Italy Nov. 11-14, 2010

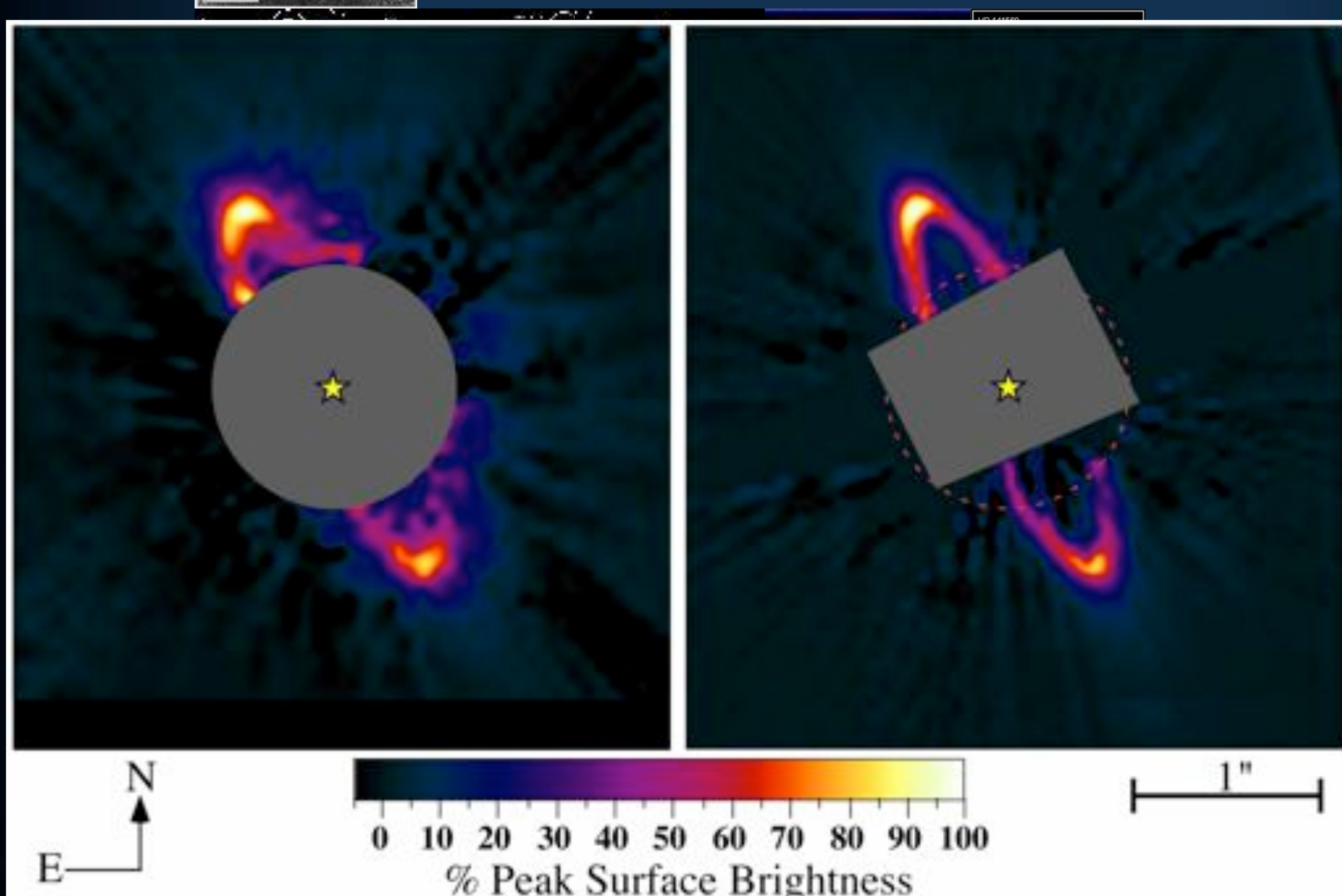
STATE of AFFAIRS

Observations

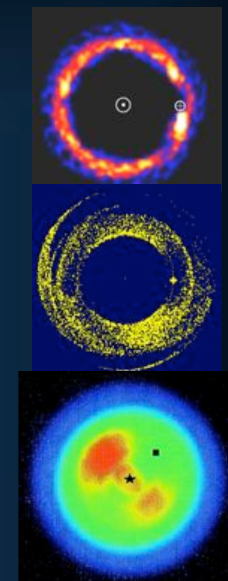
1700

1984





Theory



STATE of AFFAIRS

Observations

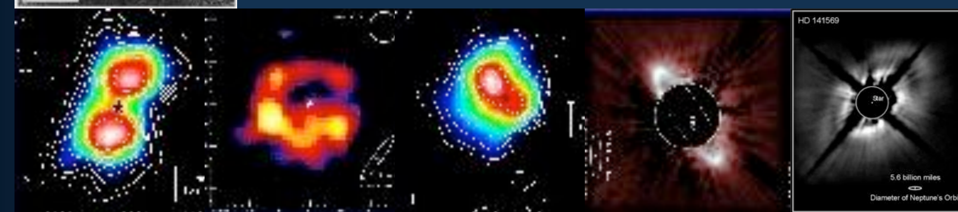
Theory

- Unexpected diversity
- Hints for planetary systems
- Rapid progess & many new questions
- Future: GPI, SPHERE, JWST, ALMA

1700

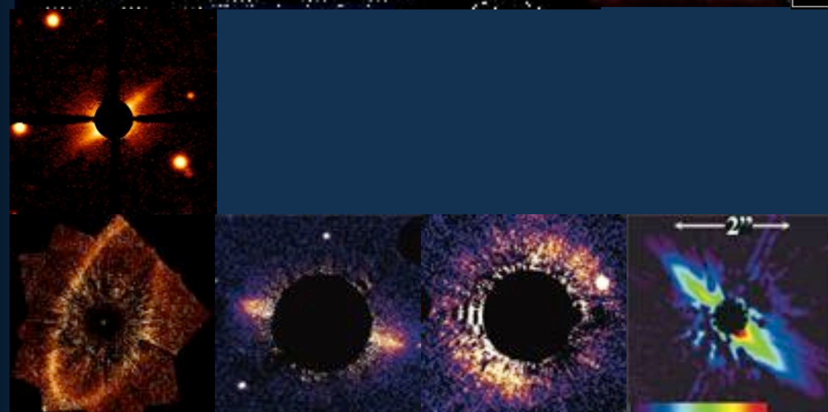
1984

1998

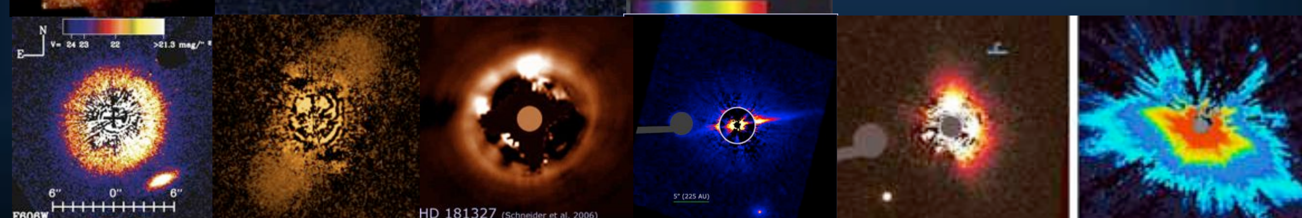


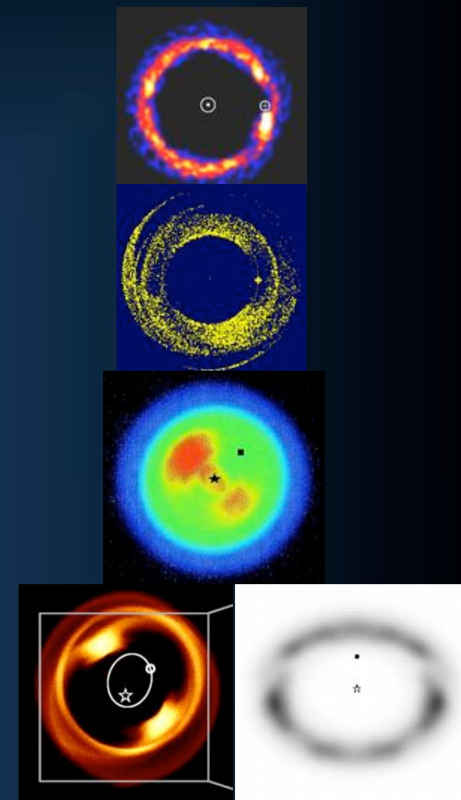
2004

ACS



2010

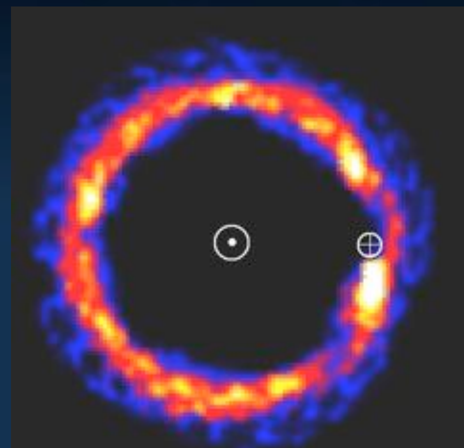




One way to find exosolar planets: Follow the dust

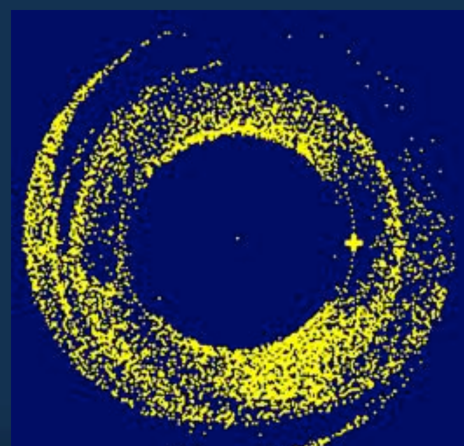
But quite a few challenges before getting something to look like the theoretical simulations.

Azimuthal
(Zody & KB)



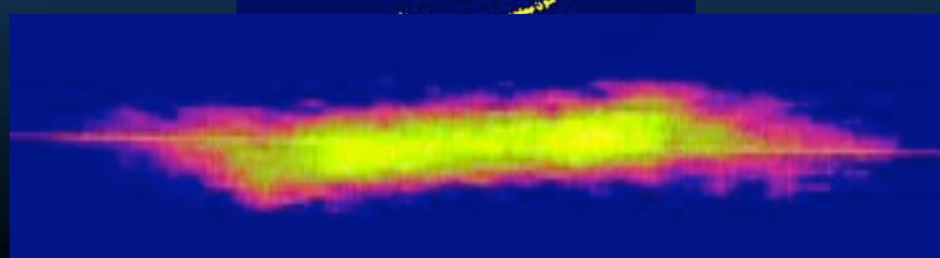
Dermott et al. 1994

Radial
(most common)



Roques et al. 1994

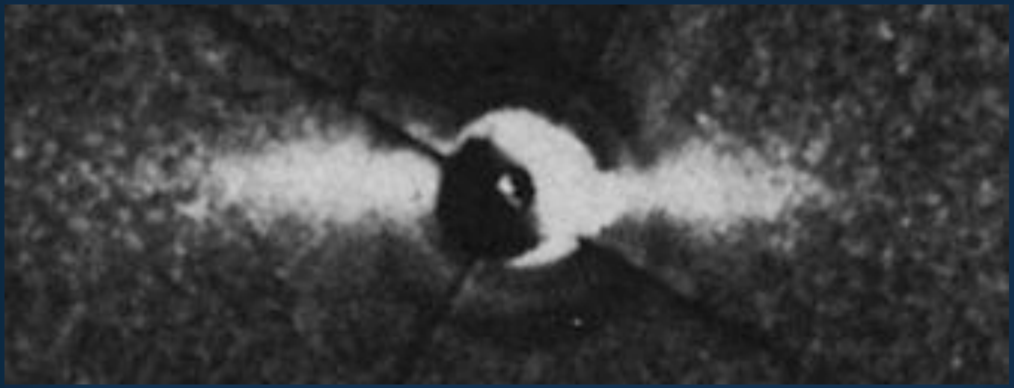
Vertical
(β Pic)



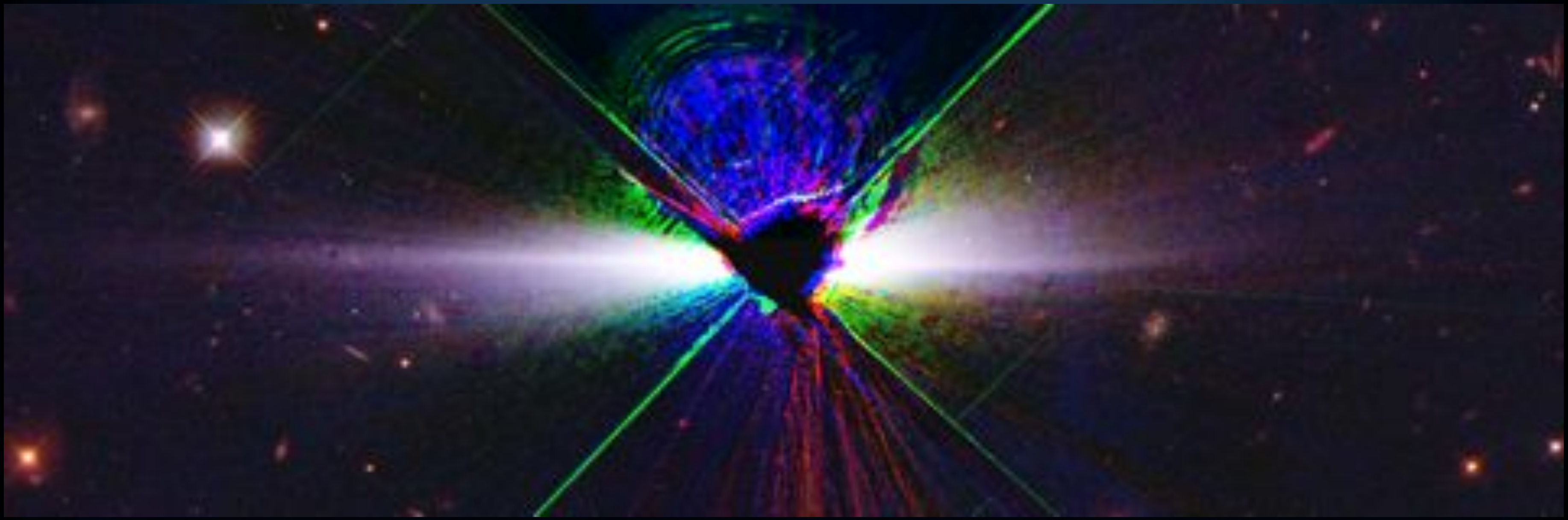
Mouillet et al. 1997

Fidelity of High Contrast Imaging

Separating artifacts from the astrophysical



Smith & Terrile 1984

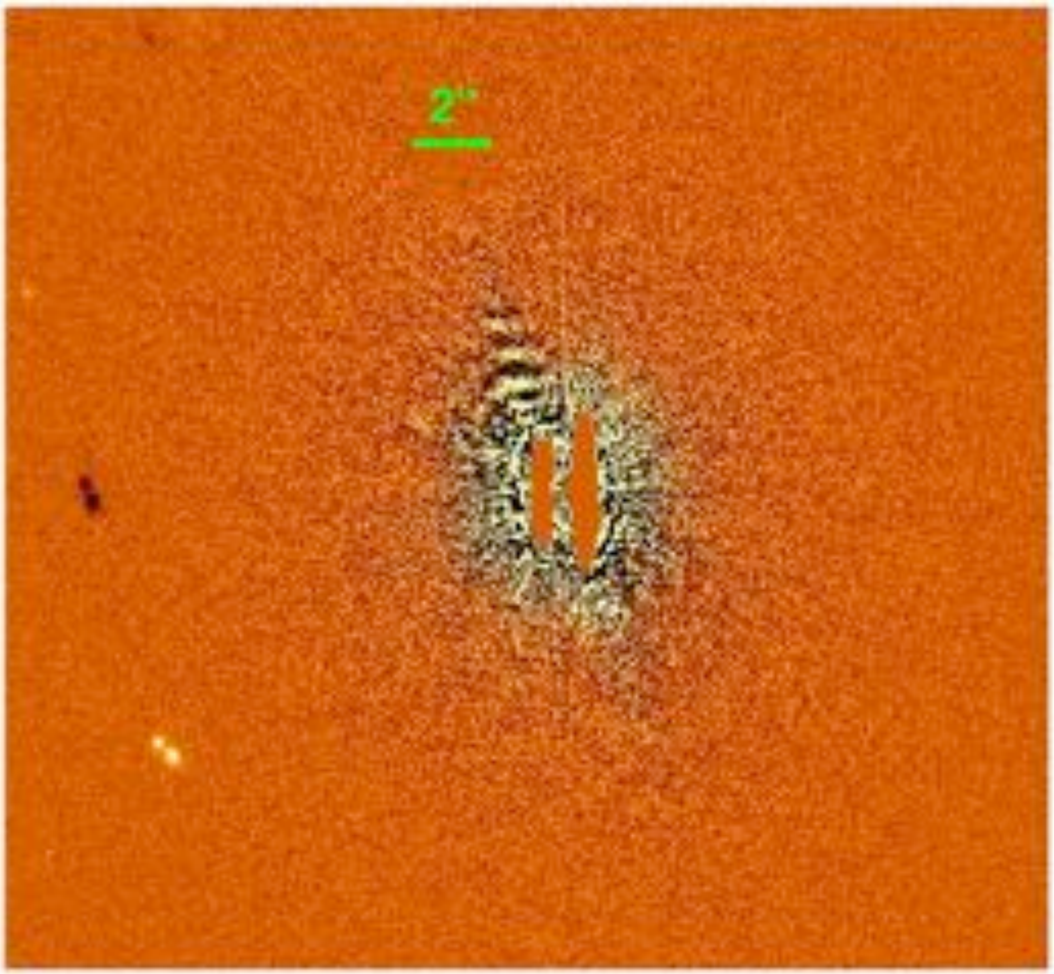


ACS Coronagraphic Survey for Debris Disks Around Nearby Stars
PI: Kalas

ζ Lep, V=3.5, SpT=A2V, d = 22 pc, τ_{IR} = 0.1 x β Pic

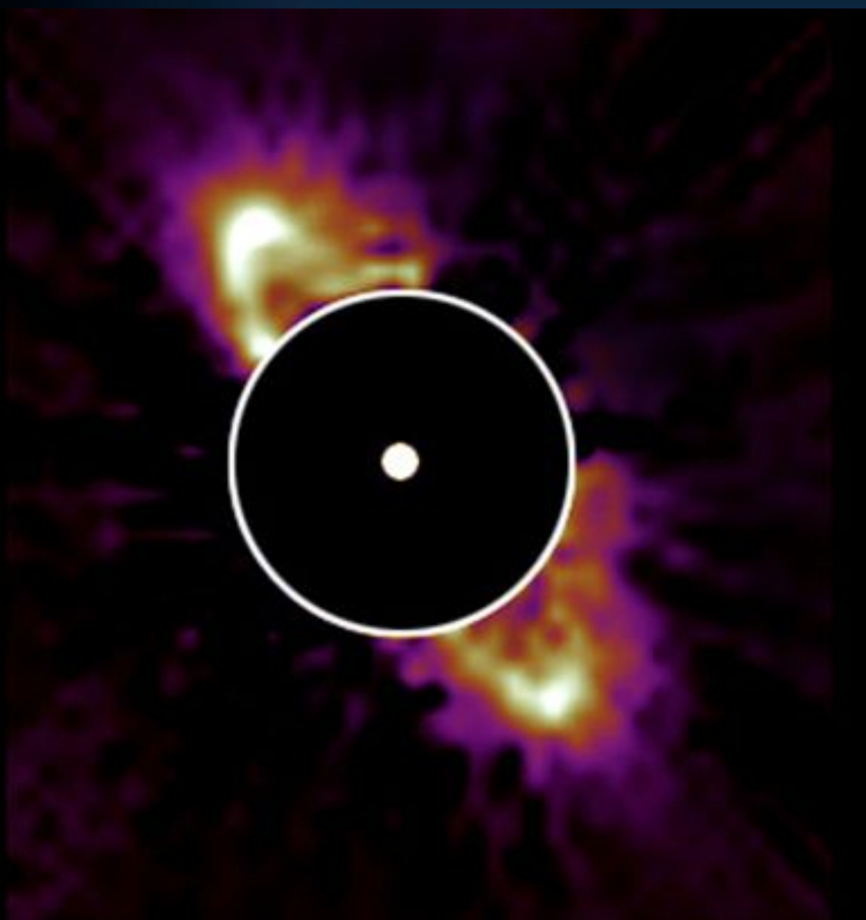
Telescope Roll with PSF Self Subtraction

ζ Lep, V=3.5, SpT=A2V, d = 22 pc, τ_{IR} = 0.1 x β Pic



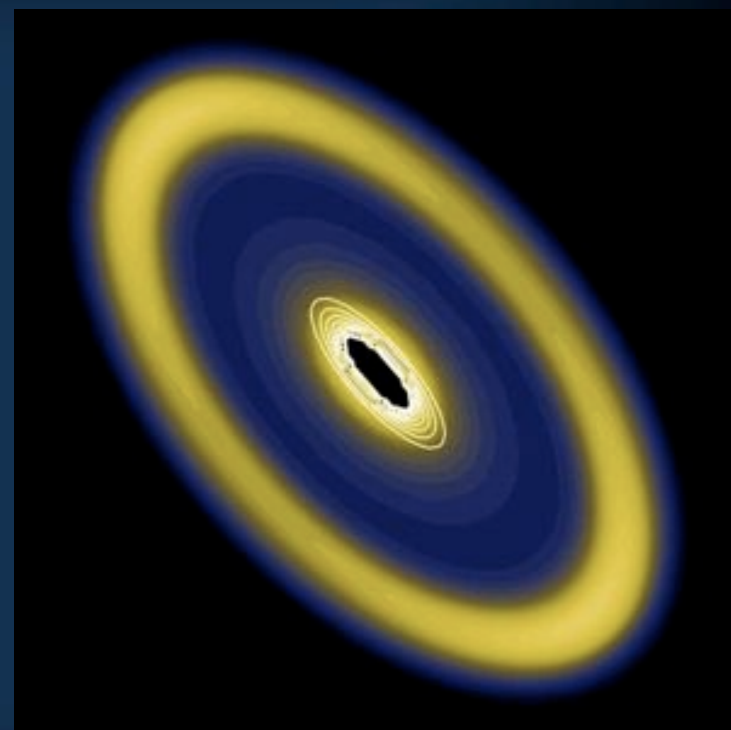
Which astrophysical features are due to planets?

HR 4796A



Schneider et al. 1999

Model

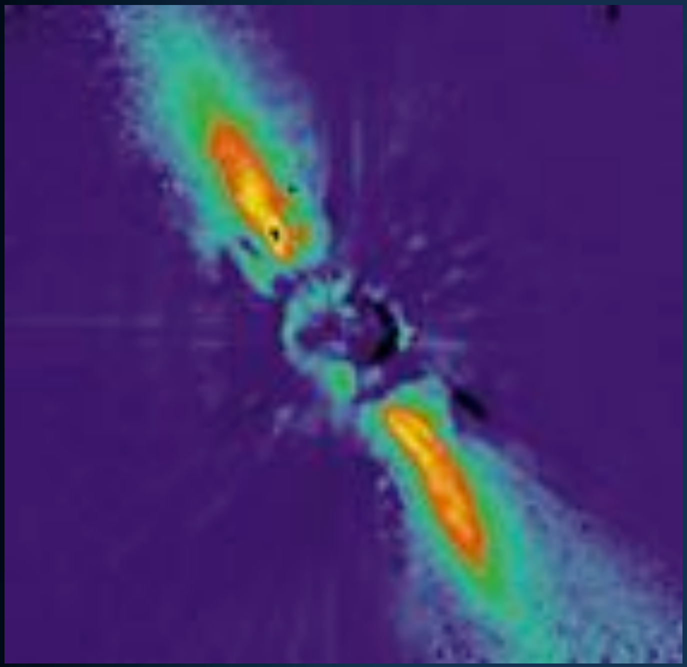


Gas & Dust; small grains find stable orbits where they corotate with the gas disk (Takeuchi & Artymowicz 2001, see also Klahr & Lin 2005)

Beta Pictoris

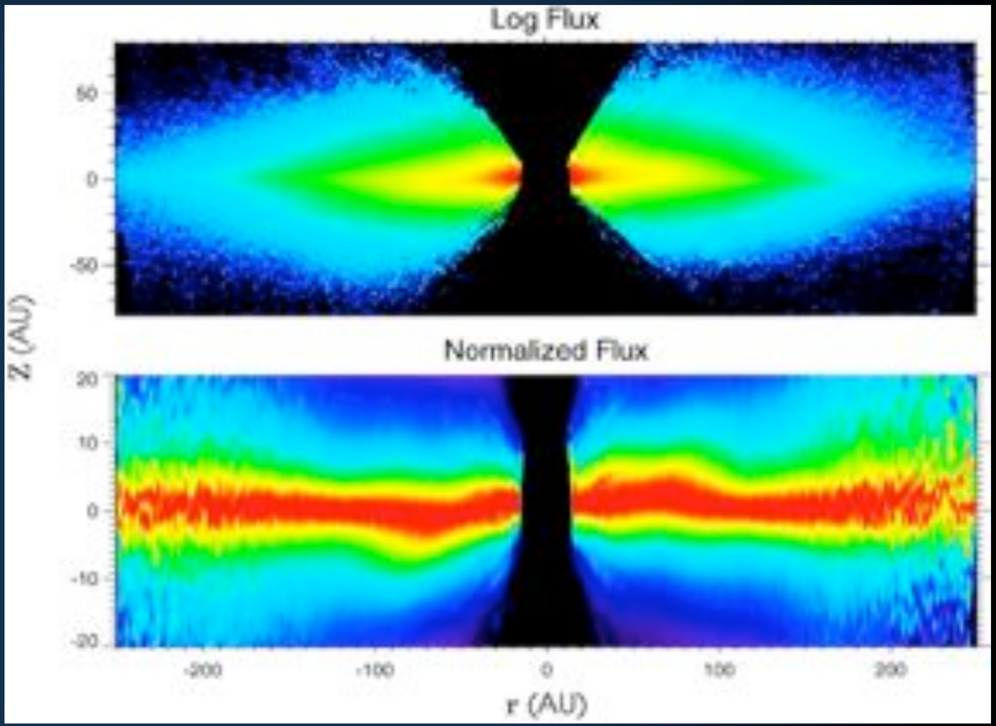
Beta Pic Inner Disk: Indirect evidence for a planet

near-IR / ground



Mouillet et al. 1997
Beuzit et al. 1997

optical / space

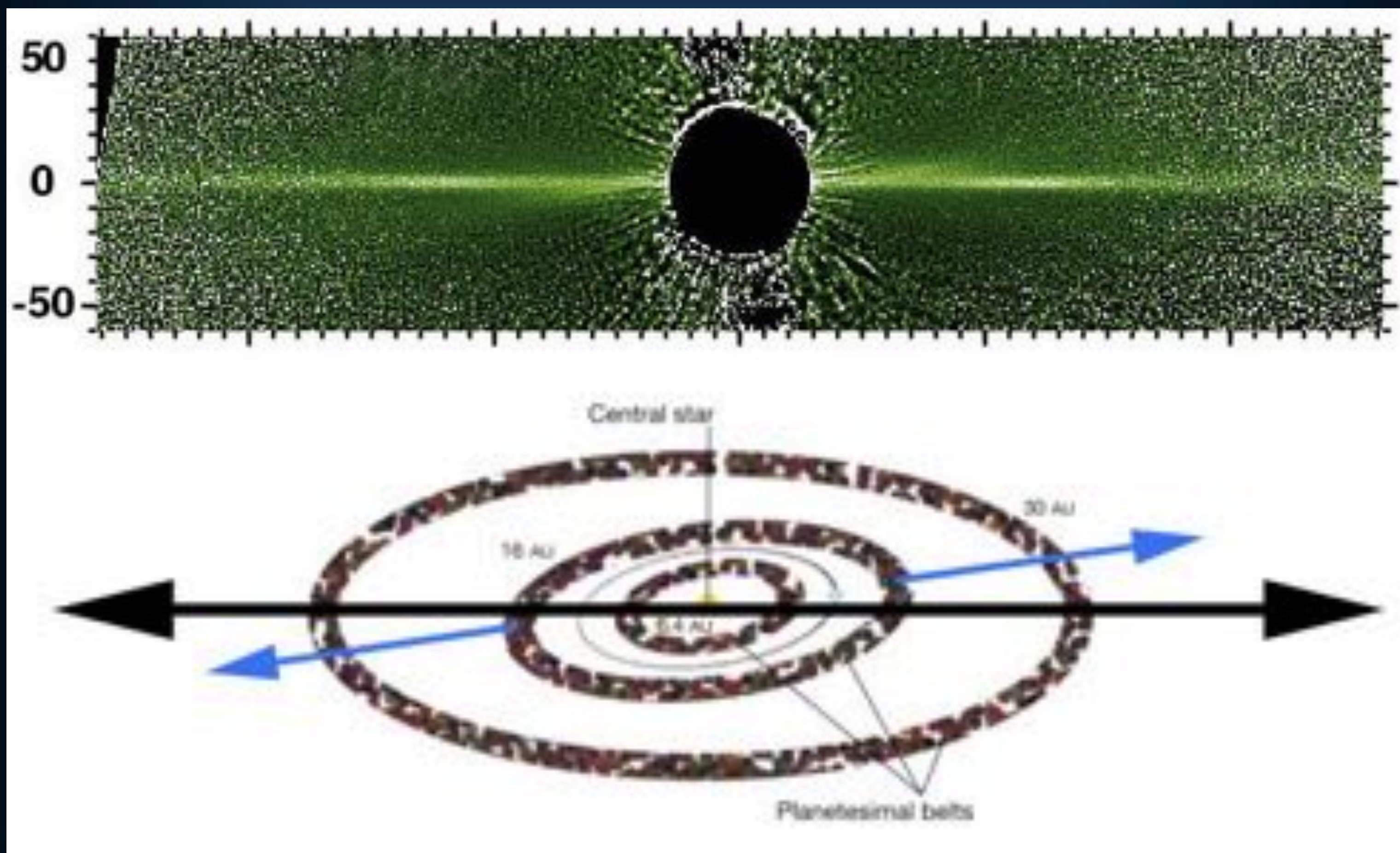


Burrows et al. 1995 (WFPC2)
Heap et al. 2000 (STIS)

Planet at 1-20 AU radius, with mass 6000 - 6 $M_{\oplus}$, inclined relative to mean disk plane by a few degrees produces local vertical warp in β Pic disk.

Beta Pic's Double Disk

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

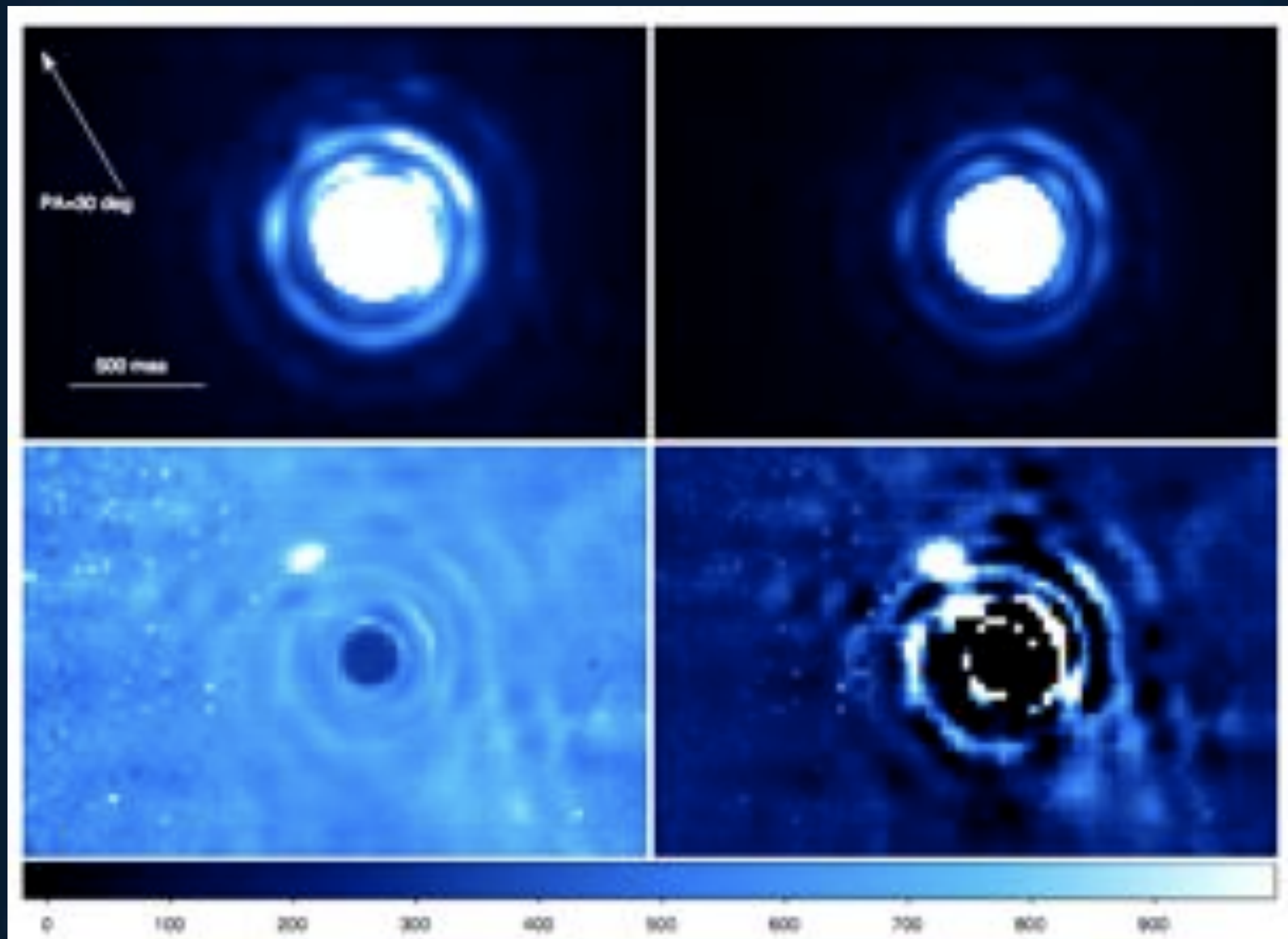


Okamoto et al. 2005

L-prime imaging of Beta Pic b

Lagrange et al. 2009

Data from 2003 with VLT

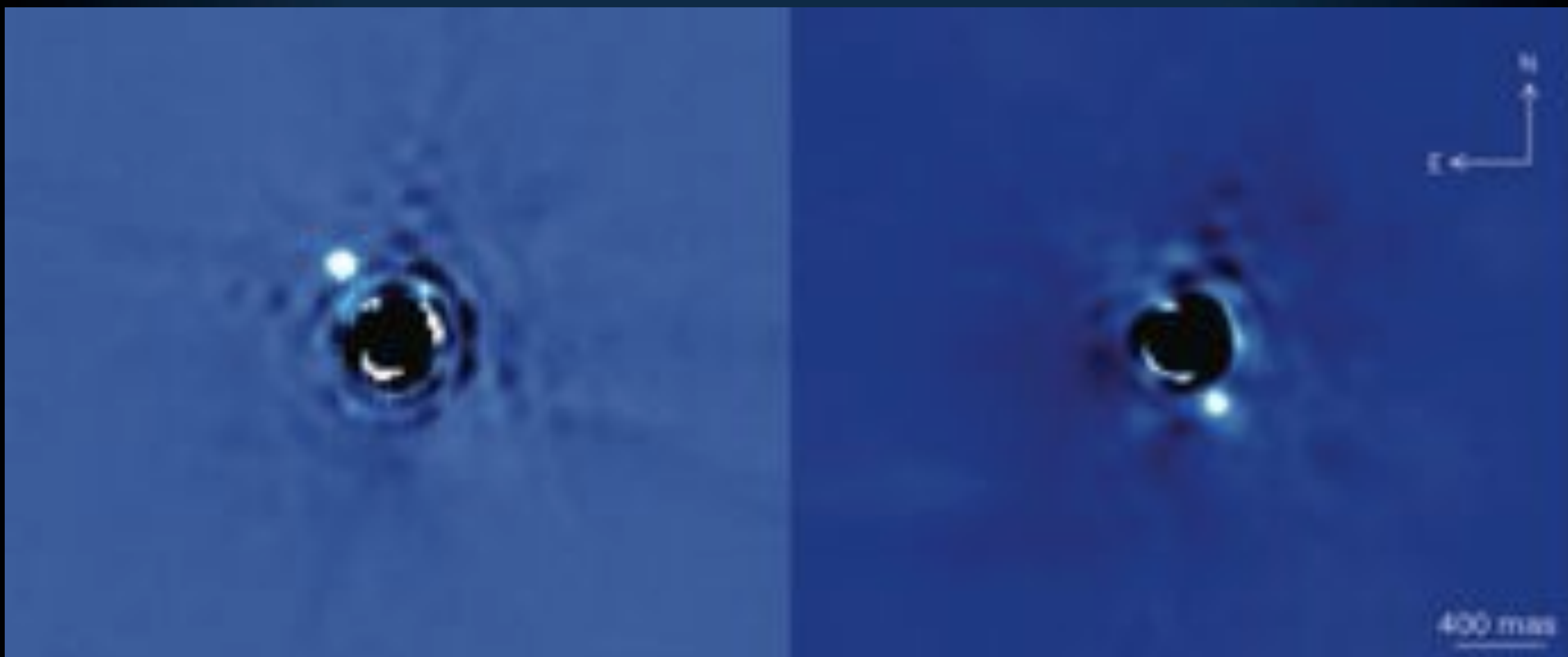


6 - 12 M_J

Could it be spurious feature of diffraction rings?
Lagrange et al. 2008

Beta Pic b *CONFIRMED*

Lagrange et al. 2010

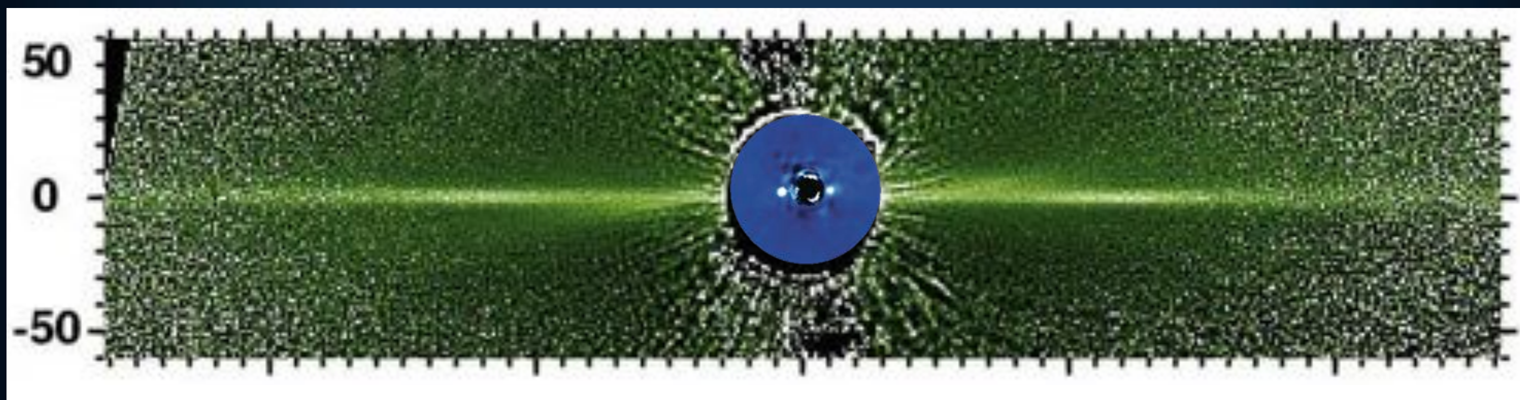


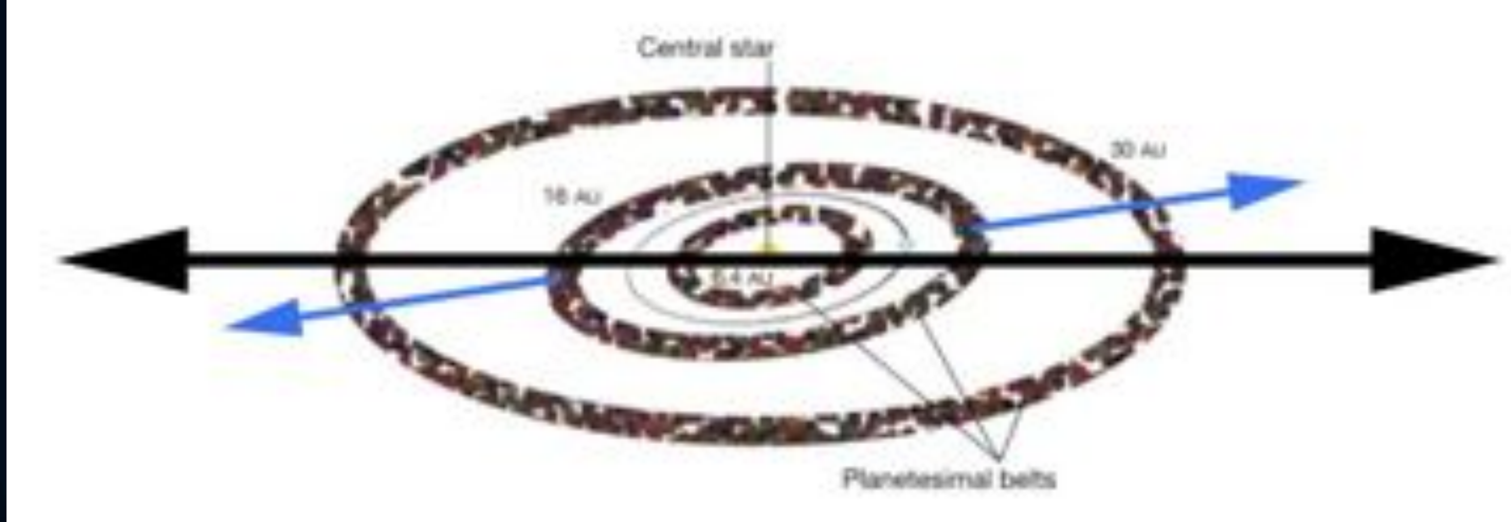
2003 2009-2010

a ~ 8 AU (near ice-line, Jupiter analog), P ~ 17yr

Beta Pic's Double Disk & Planet

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





Okamoto et al. 2005

Fomalhaut

Why search for a planet around Fomalhaut?

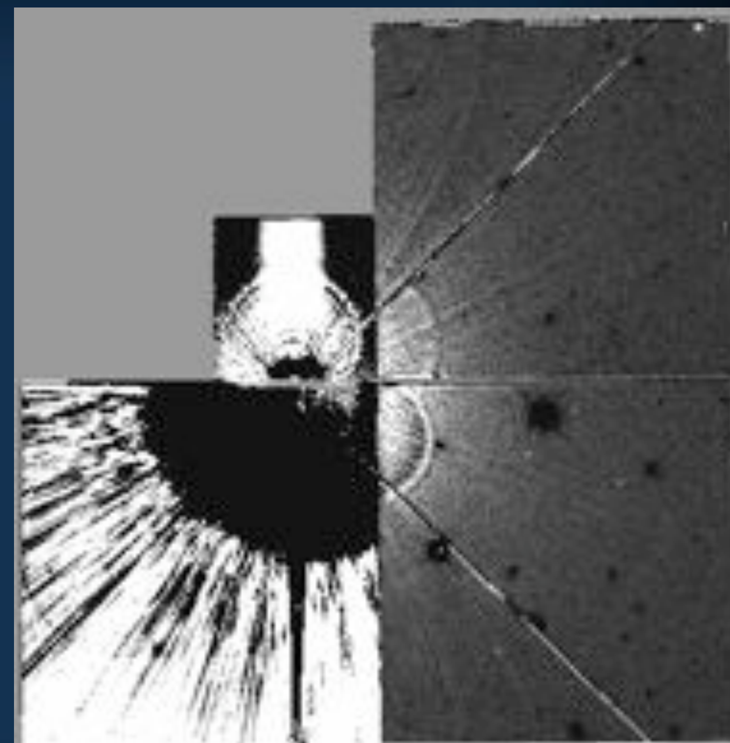
- 1984 : IRAS mission finds dust grains orbiting Fomalhaut, as well as other stars such as Epsilon Eridani, Vega, and Beta Pictoris
- Fomalhaut is nearby (7.7 pc). High proper motion (0.4”/yr).
- Fomalhaut is a young, main sequence star (200 ± 100 Myr).
- Fomalhaut planets are finished with their formation, but they are still glowing hot because not enough time has passed for them to cool down.

Fomalhaut

IRAS excess star, but no disk detected in scattered light

Older and less dusty than b Pic

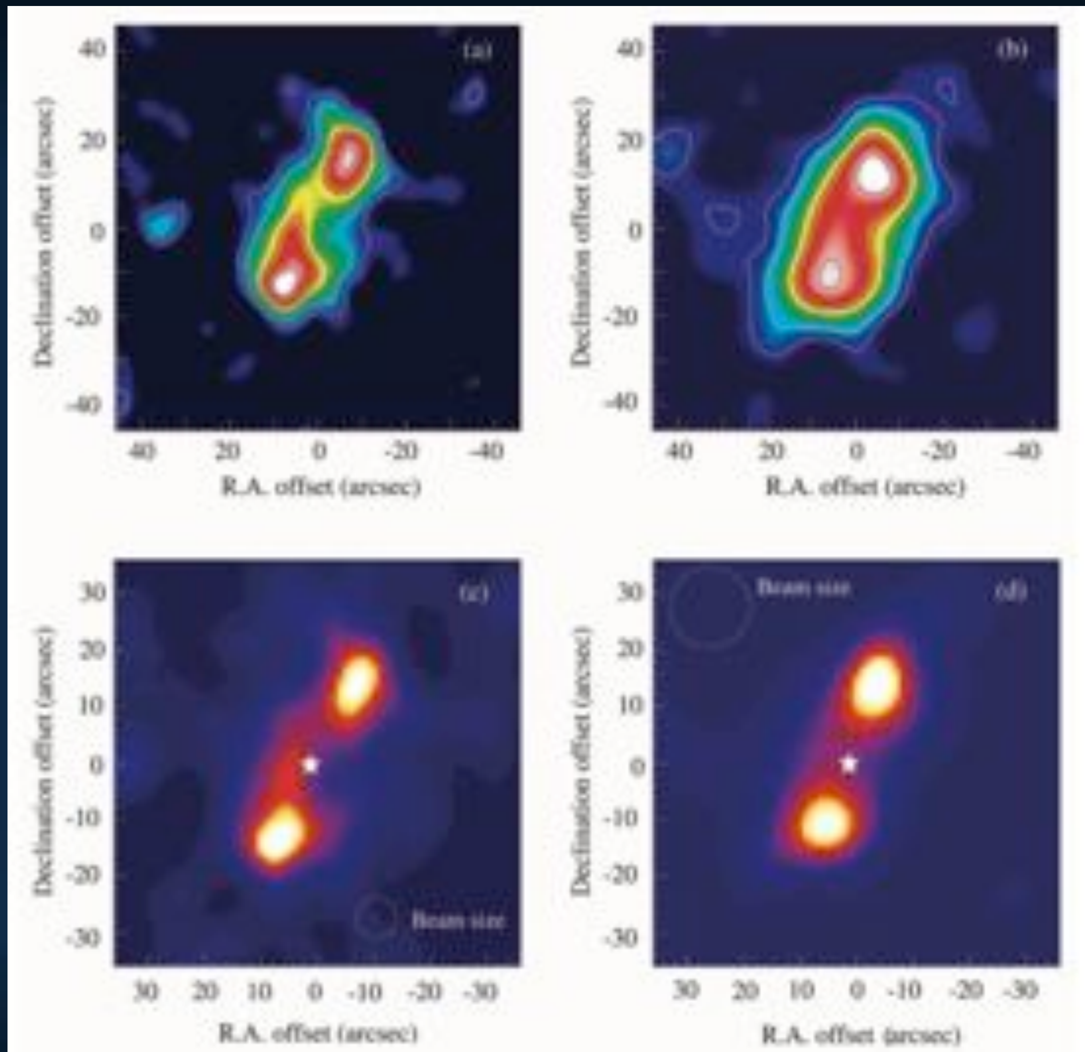
1993: Optical observations from Mauna Kea (Paul Kalas)



1999: Hubble observations with WFPC2 (Al Schultz)

m_v = 1.3 mag

FOMALHAUT: 450 & 850 microns



smoothed

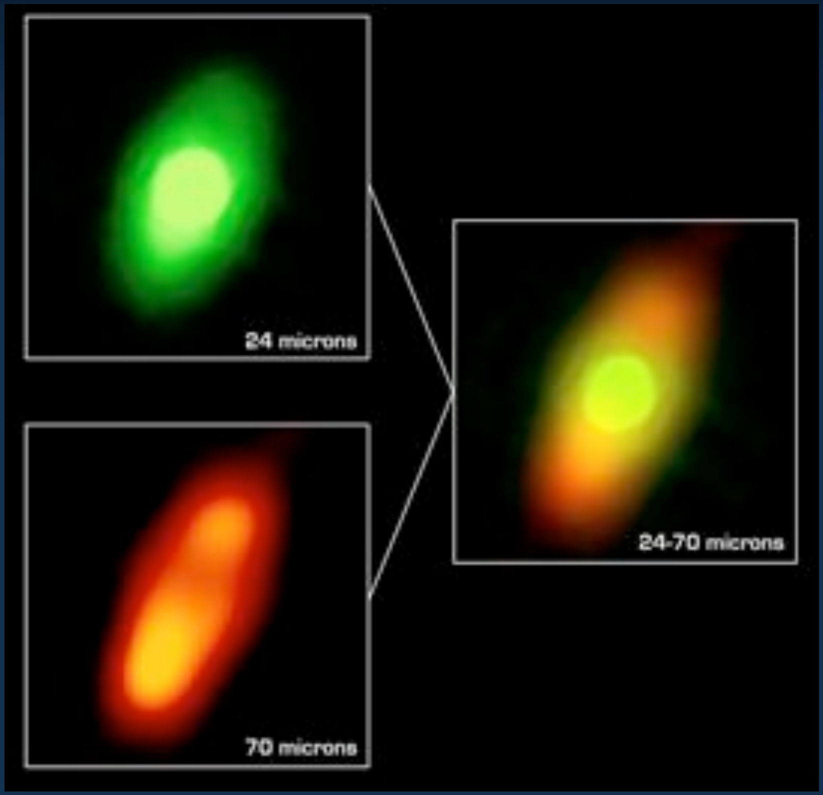
deconvolved

Holland et al. 2003; also Wyatt & Dent 2002

A non-uniform ring

Fomalhaut’s debris belt with Spitzer

Stapelfeldt et al. 2004



spatially resolved at 24, 70 & 160 μm

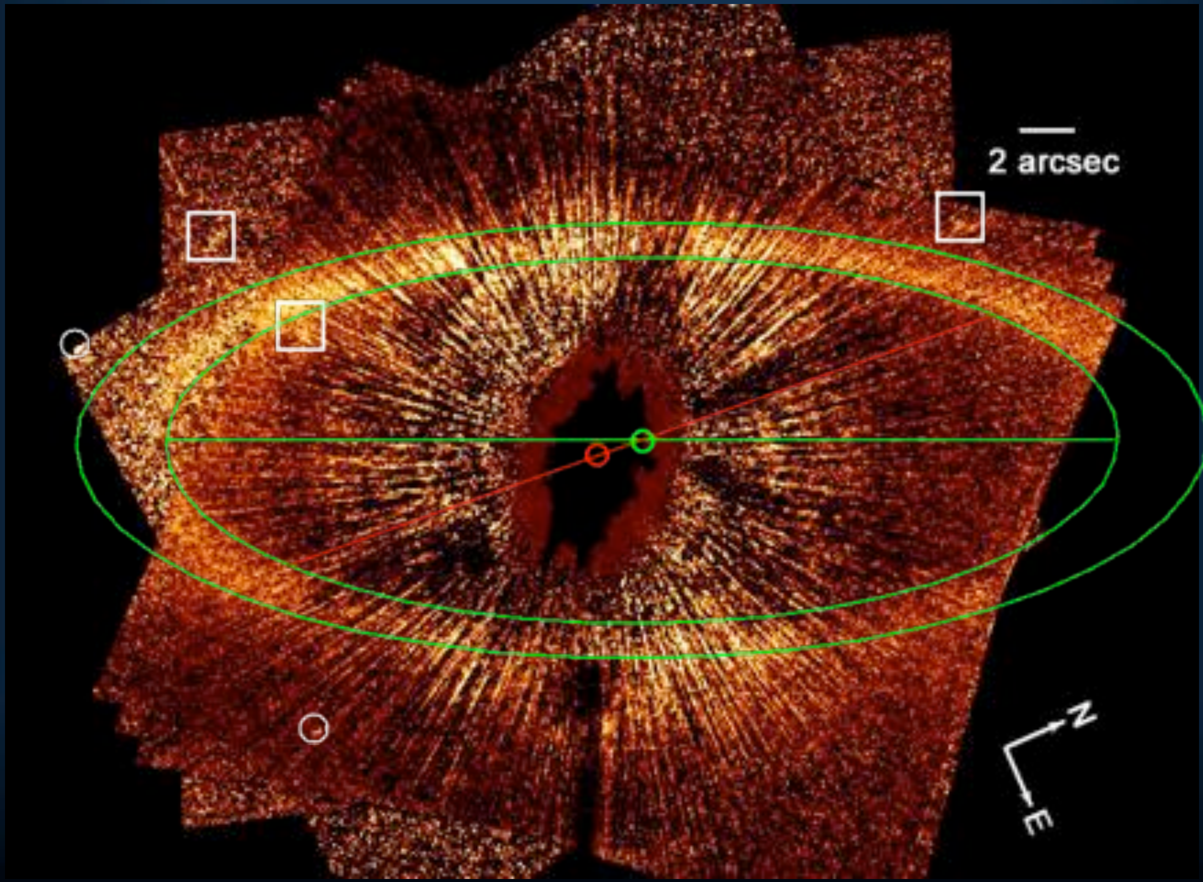
Asymmetry could be due to a secular perturbation of a planet at 40 AU.

(see also Marsh et al. 2005, planet at 86 AU)

2004 Planet Search *Using the Advanced Camera for Surveys*

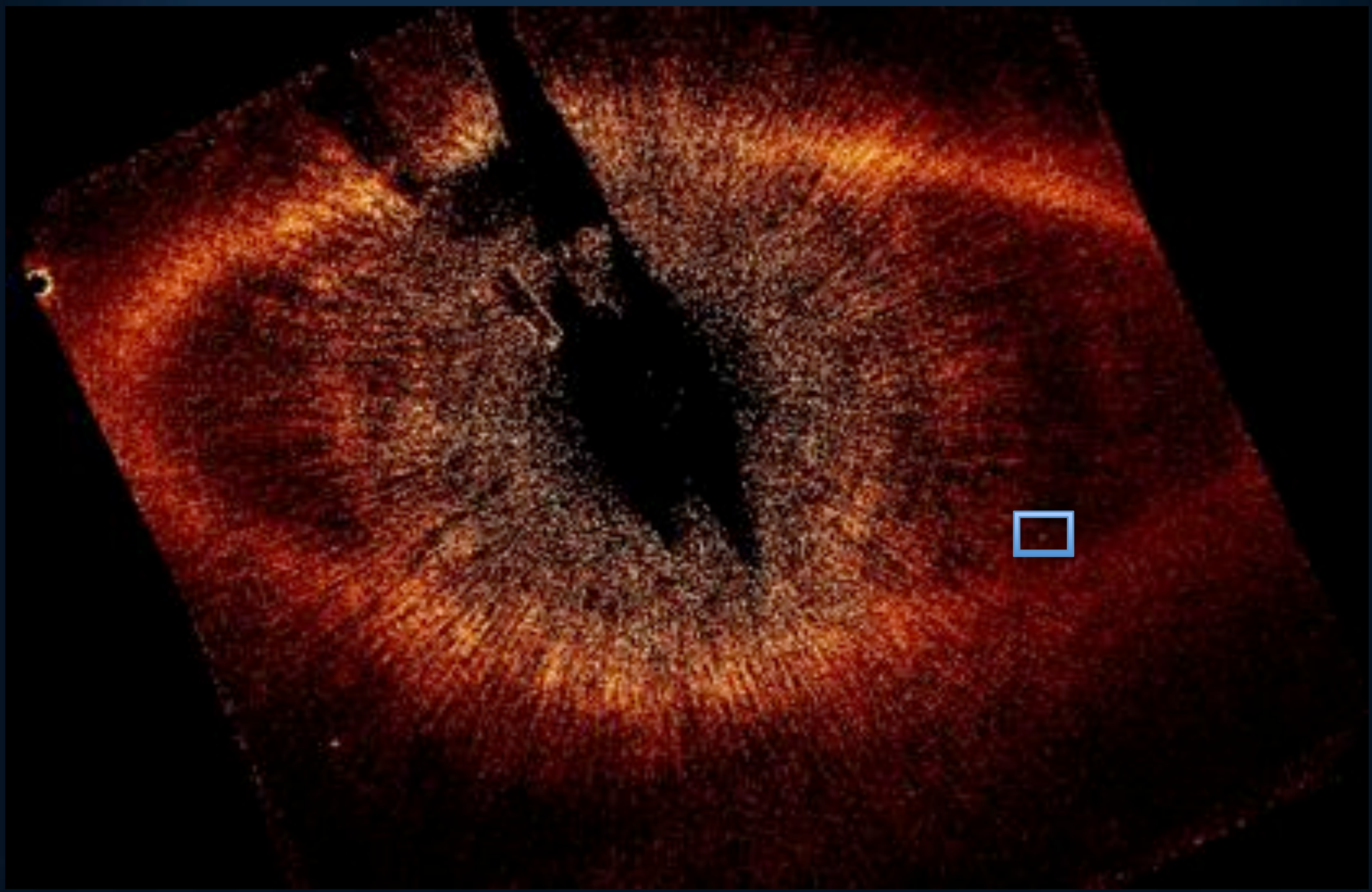
Kalas, Graham & Clampin
"A planetary system as the origin of structure in Fomalhaut's dust belt"
2005, *Nature*, Vol. 435, pp. 1067

- 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)



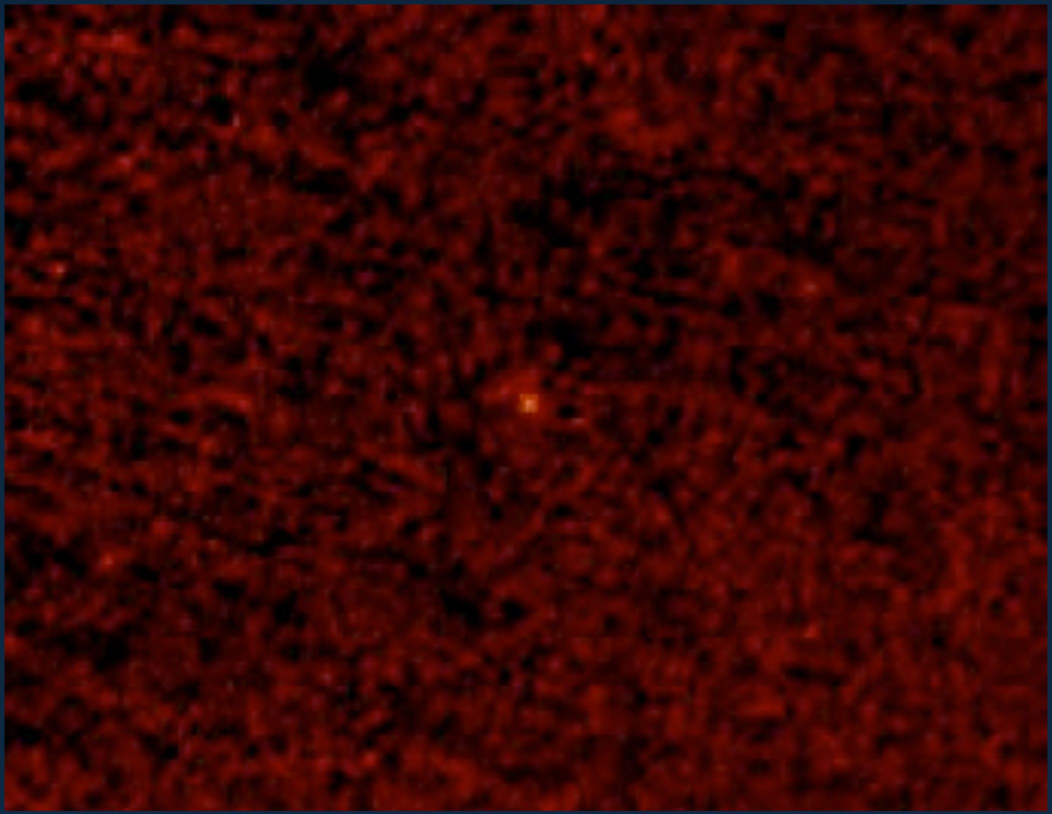
2006: HST/ACS deep multi-wavelength imaging

F435W, F606W, F814W



Fomalhaut b

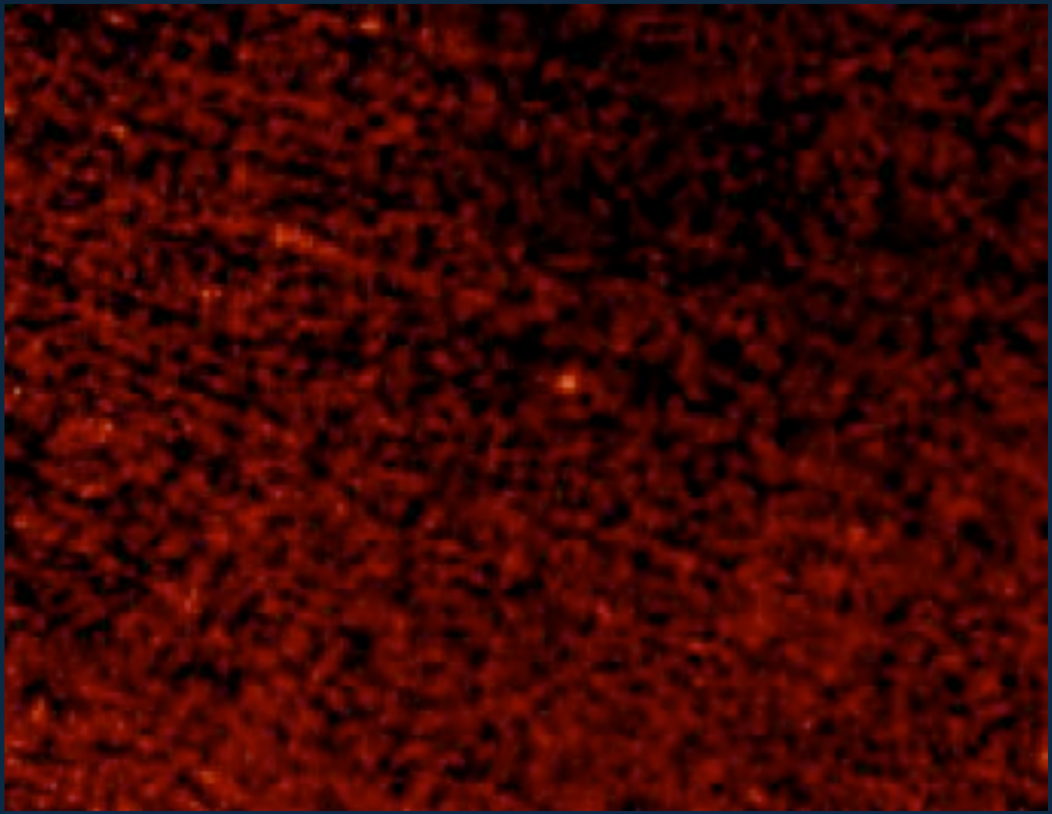
2004



Paul Kalas (University of California, Berkeley)

Fomalhaut b

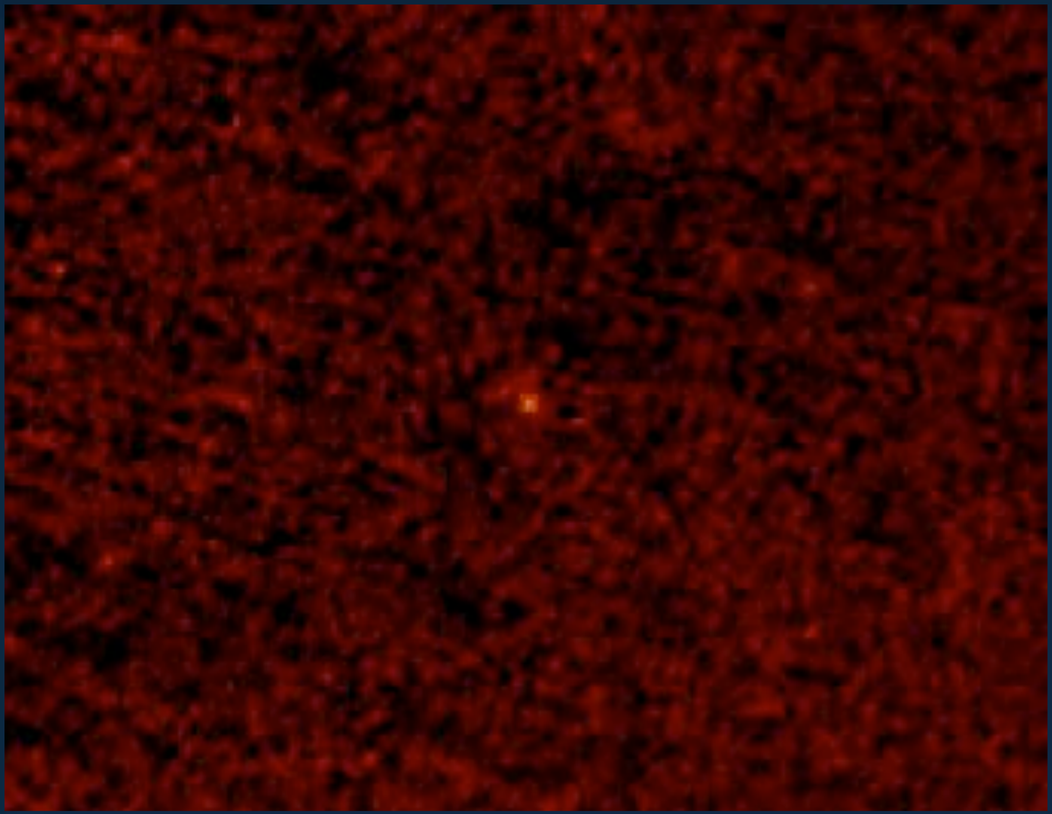
2006



Paul Kalas (University of California, Berkeley)

Fomalhaut b

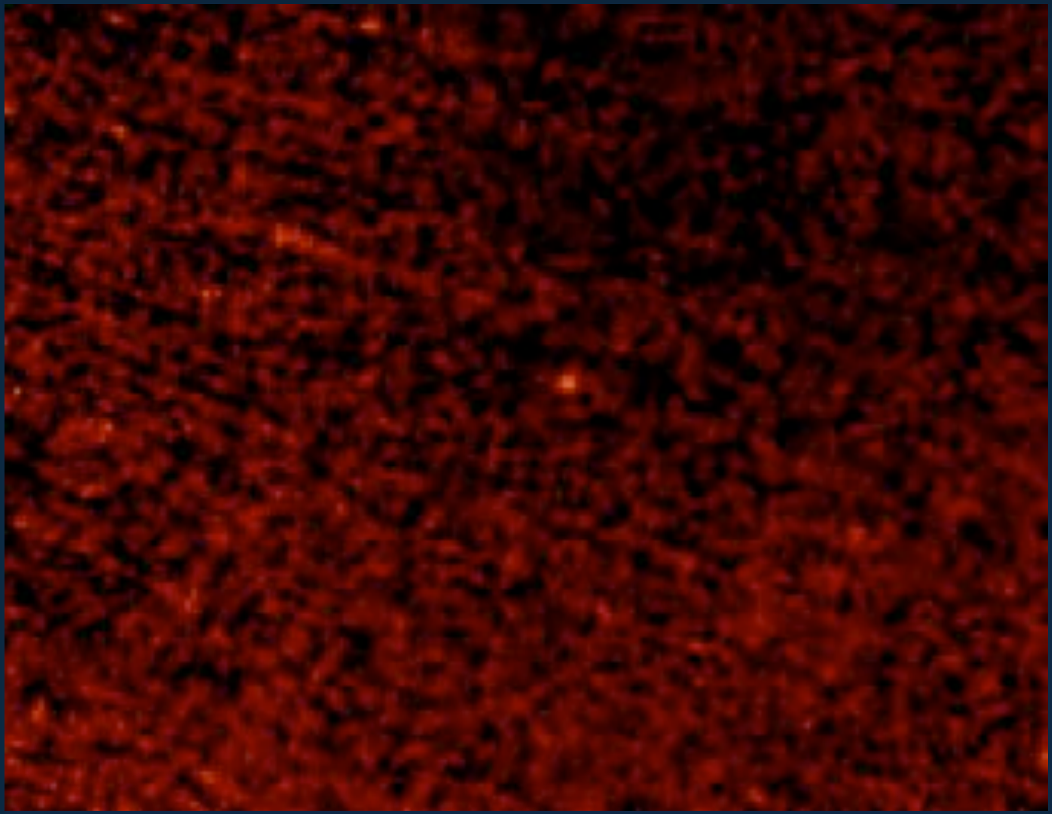
2004



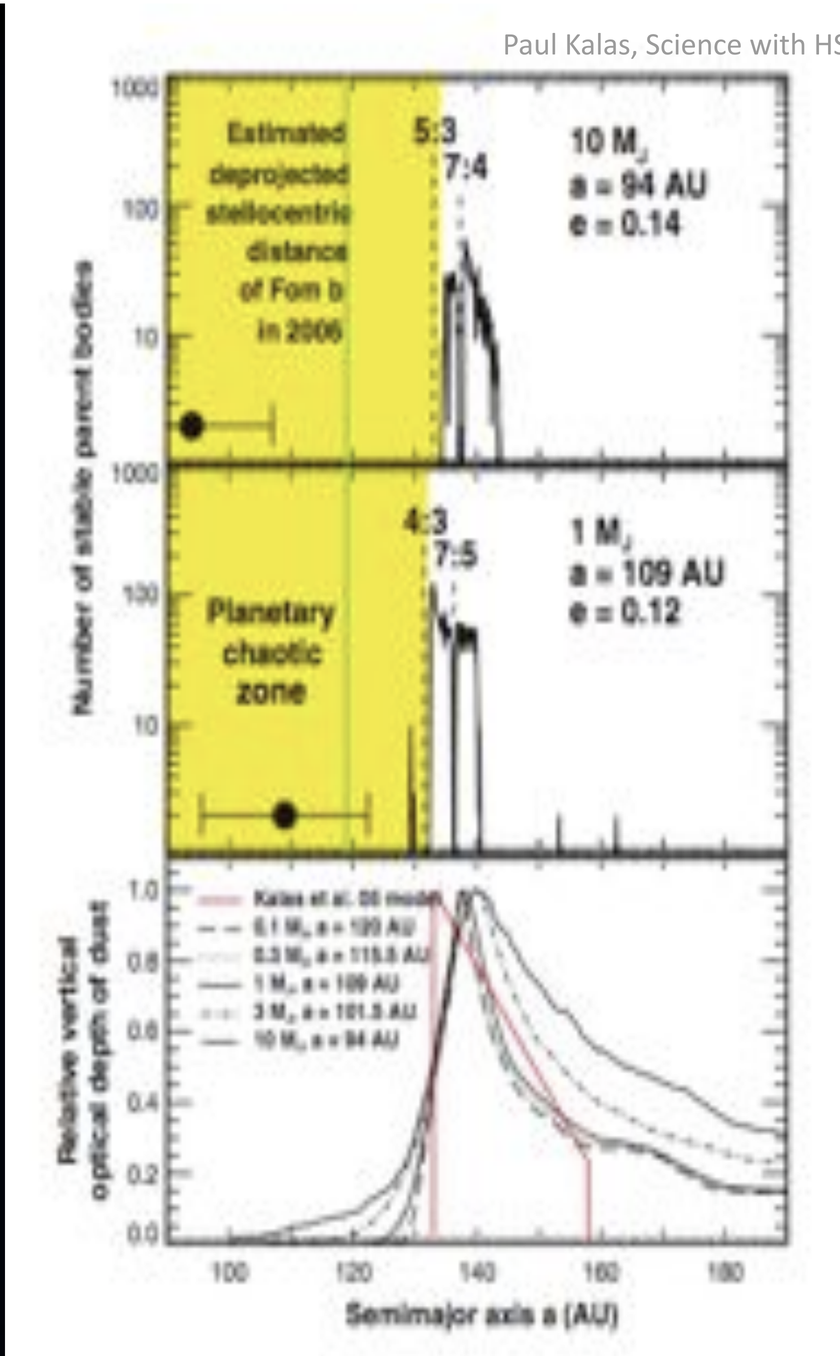
Paul Kalas (University of California, Berkeley)

Fomalhaut b

2006



Paul Kalas (University of California, Berkeley)



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

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

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

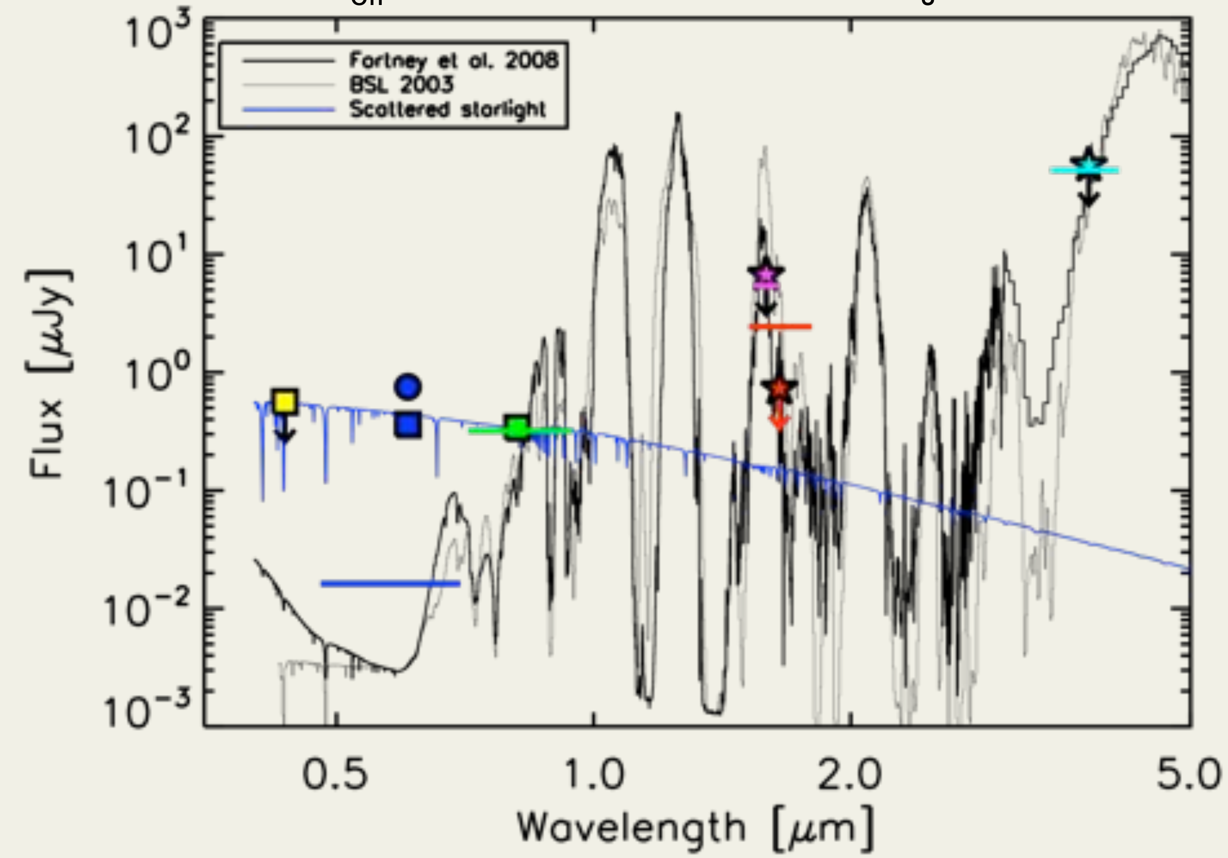
Also, Quillen (2006)

What is the mass of Fomalhaut b?

#2 From how bright it is in the optical, and non-detection 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

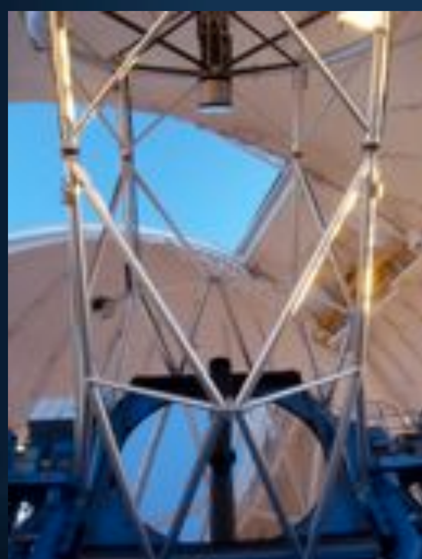
T_{eff} = 400 K, M = 1.7 – 3.5 M_J

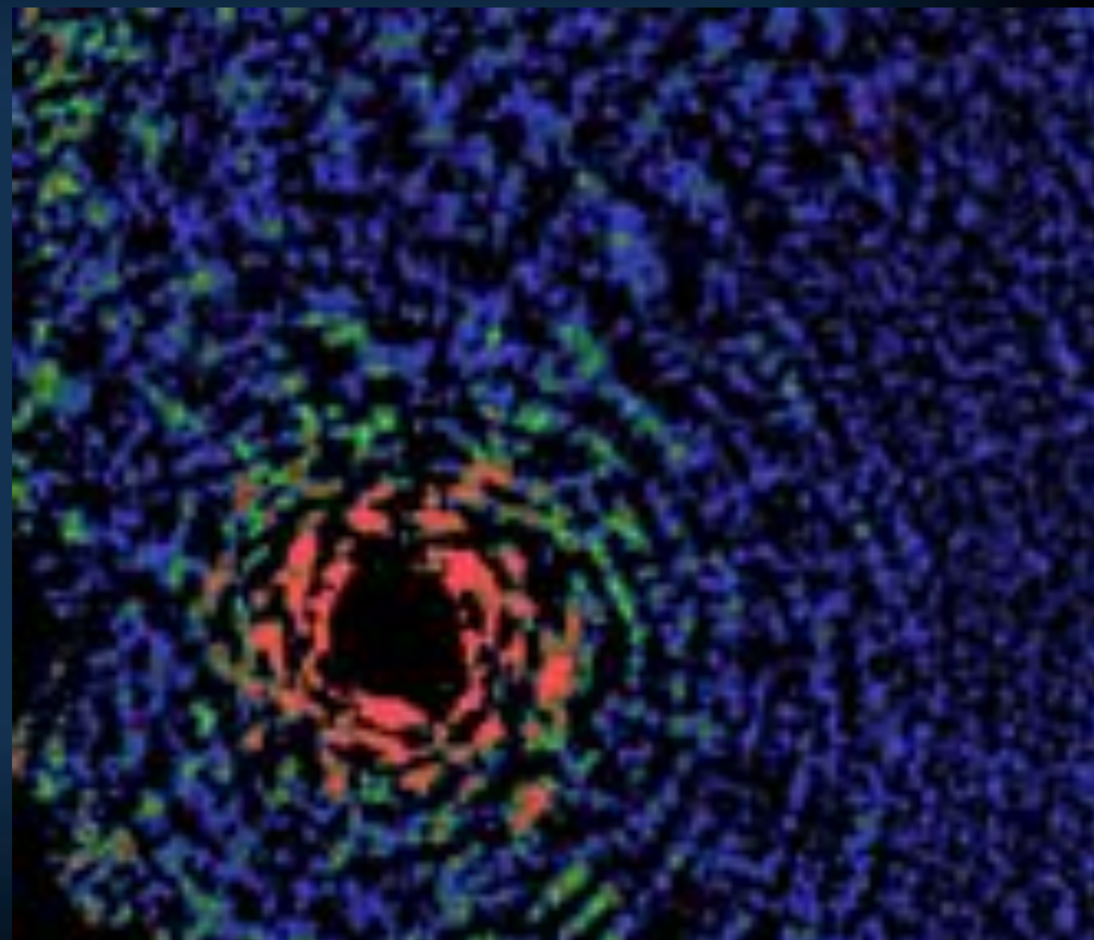


Fomalhaut b not detected, yet, at infrared wavelengths Keck (1.6 – 2.2 mm) and Gemini (3.8 mm)

see also Marengo et al. 2009 for Spitzer/IRAC 3-8 mm upper limits

L' (3.8 microns)
Gemini North 8-m
NIRI 22"x22" field
1-σ limit 19 mJy





Michael Fitzgerald (UCLA)

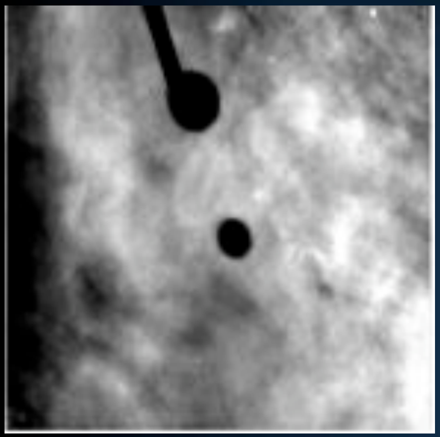
Wait a minute…

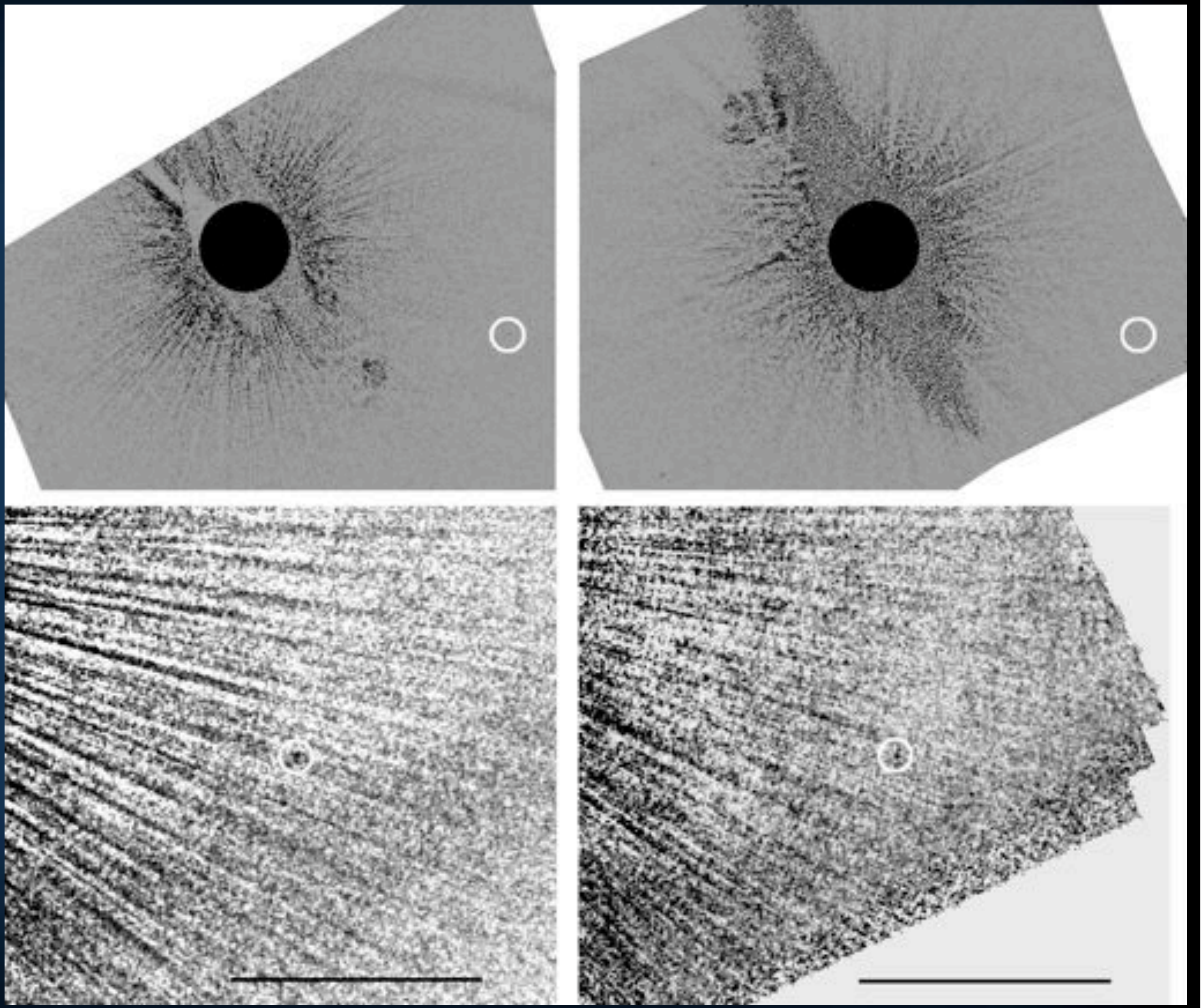
Is the optical detection of Fomalhaut b real?

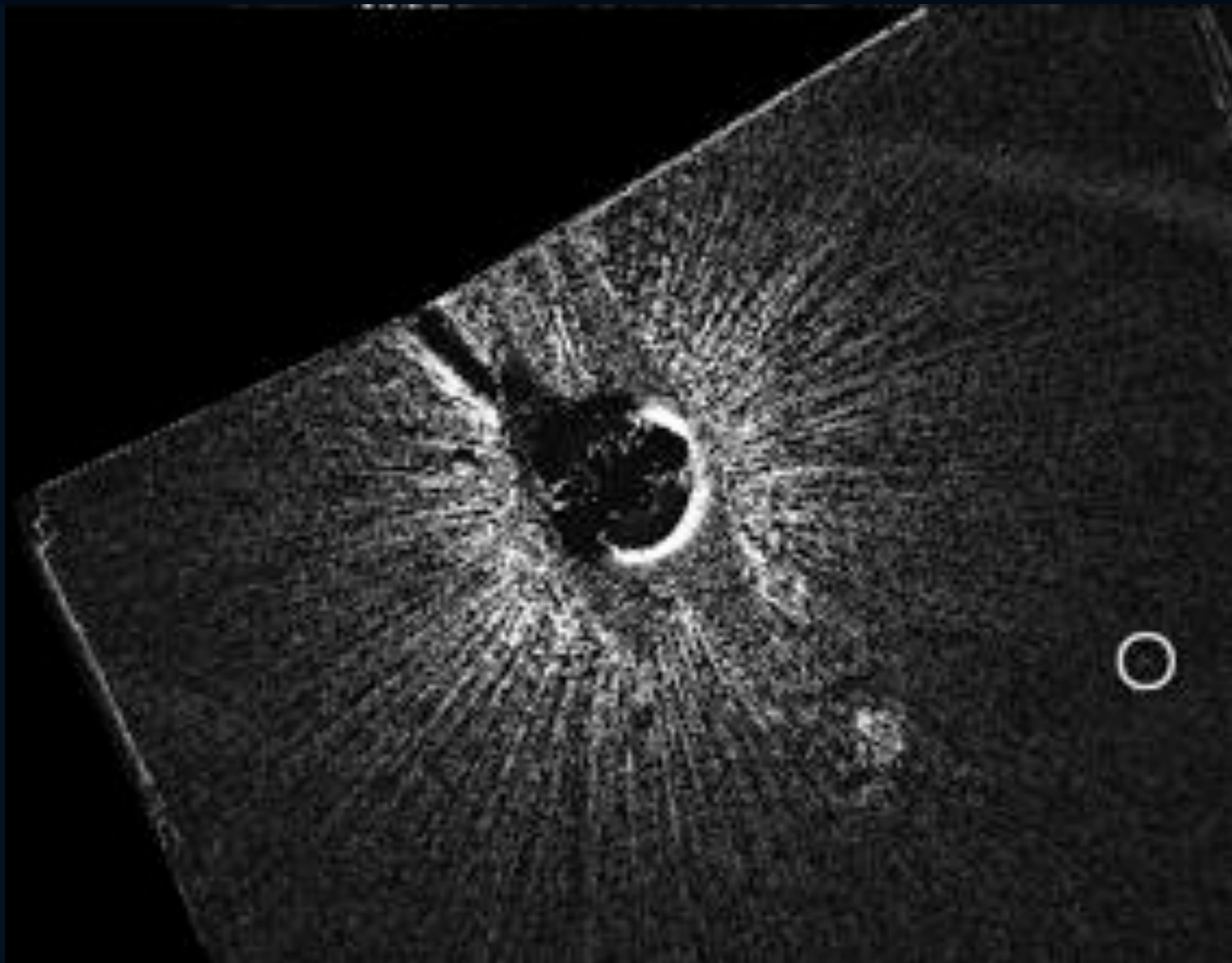
Some possibilities?

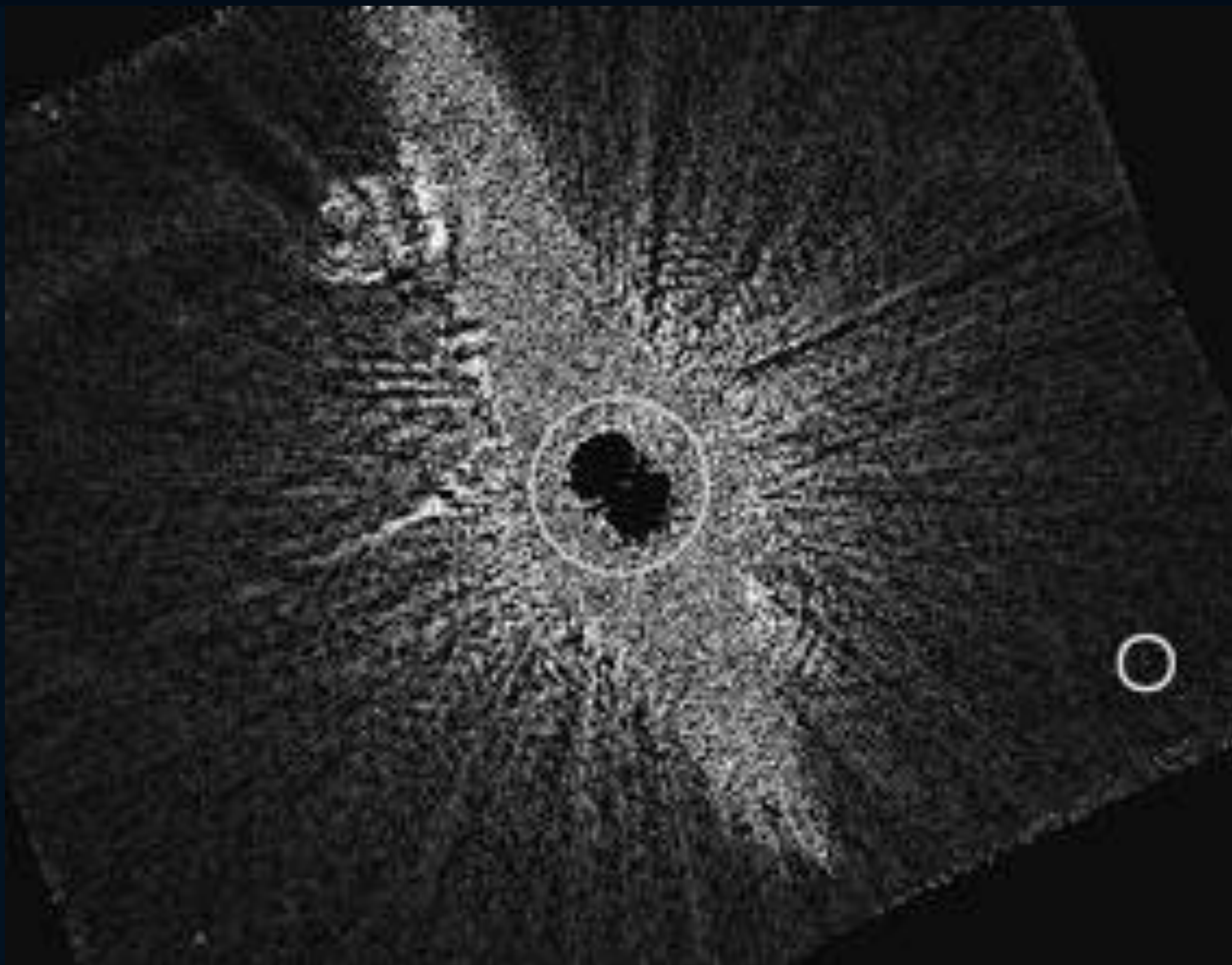
- Two speckles.
- Background star.

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

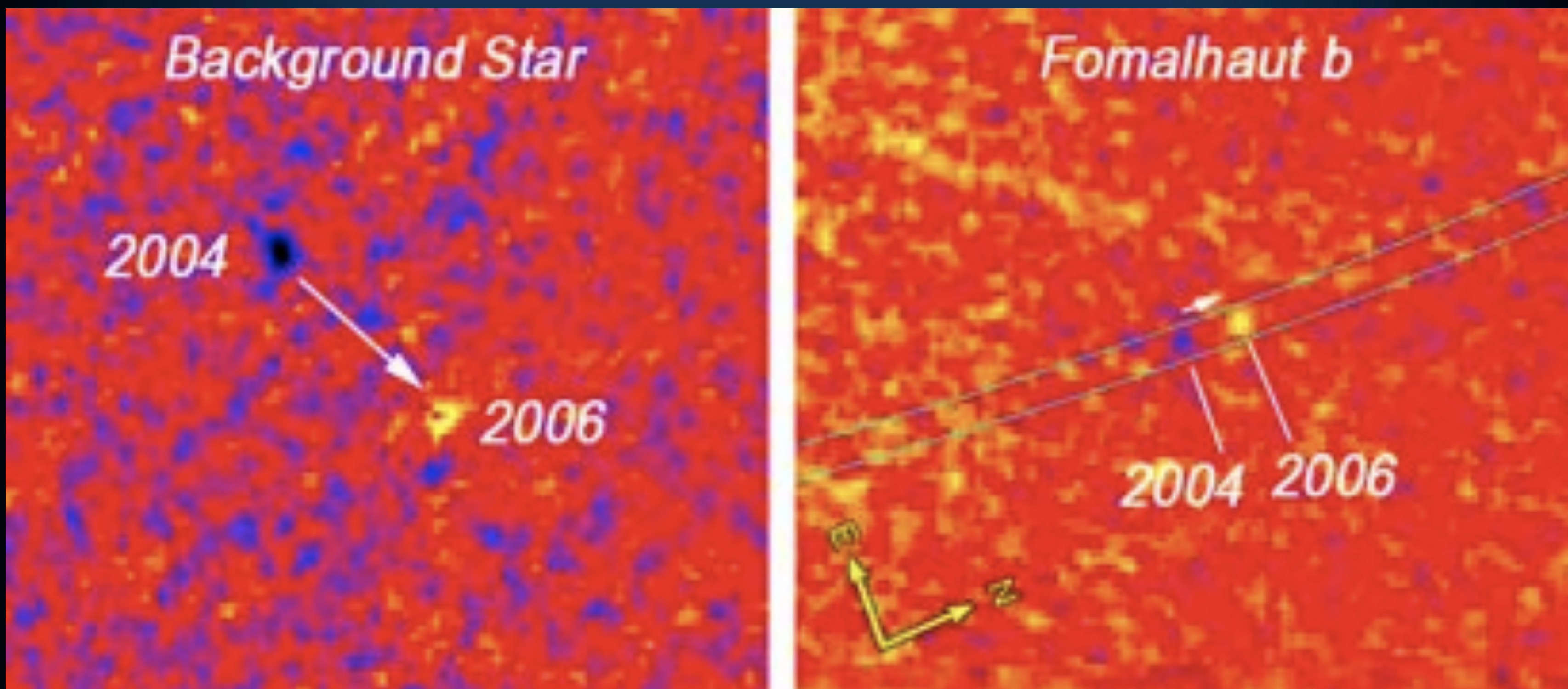








Background star?



Protogalilean, circumplanetary disk

Planet + 16 - 35 R_p rings

For comparison, Callisto at ~27 Jupiter radii

or

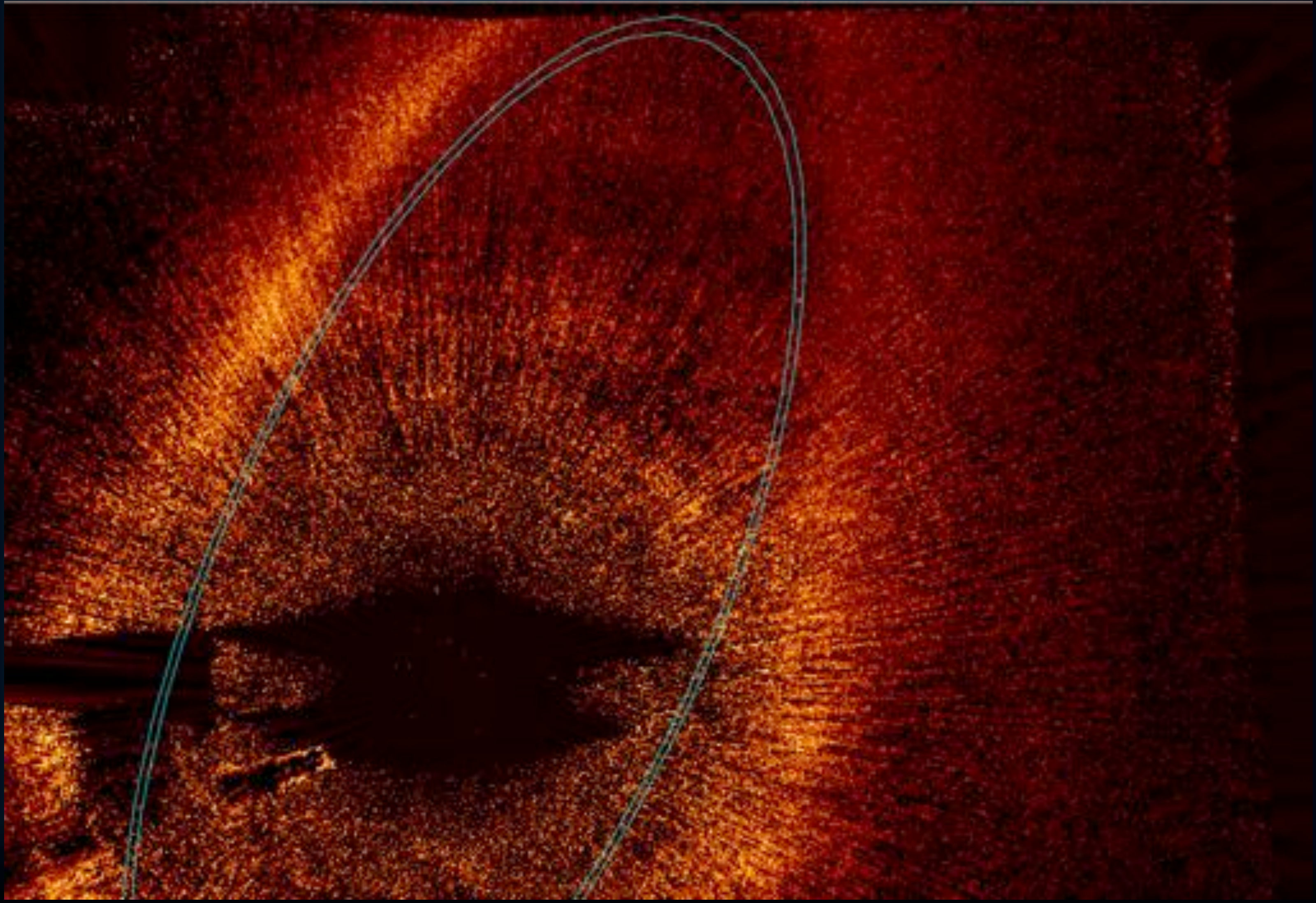
Irregular Satellite Cloud

Kennedy & Wyatt 2010, submitted

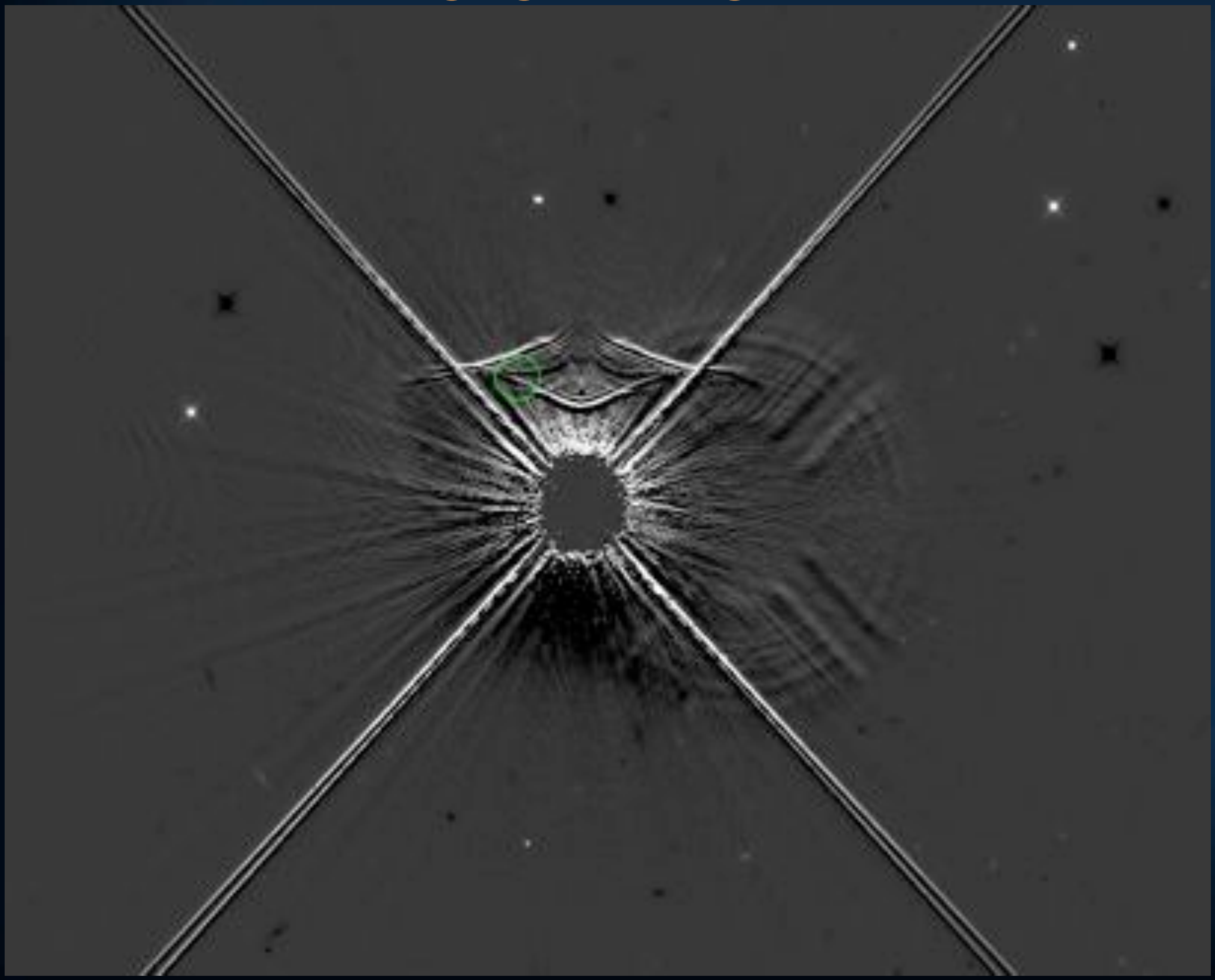
"The observations of the planet Fomalhaut b can be explained as scattered light from dust produced by the collisional decay of an irregular satellite swarm around a ~10 $M_\oplus$ planet. Such a swarm comprises about 5 Lunar masses worth of irregular satellites."

- Planet mass <<3 M_J
- Belt crossing orbit?

2009 - 2010
WFC3/IR Follow Up

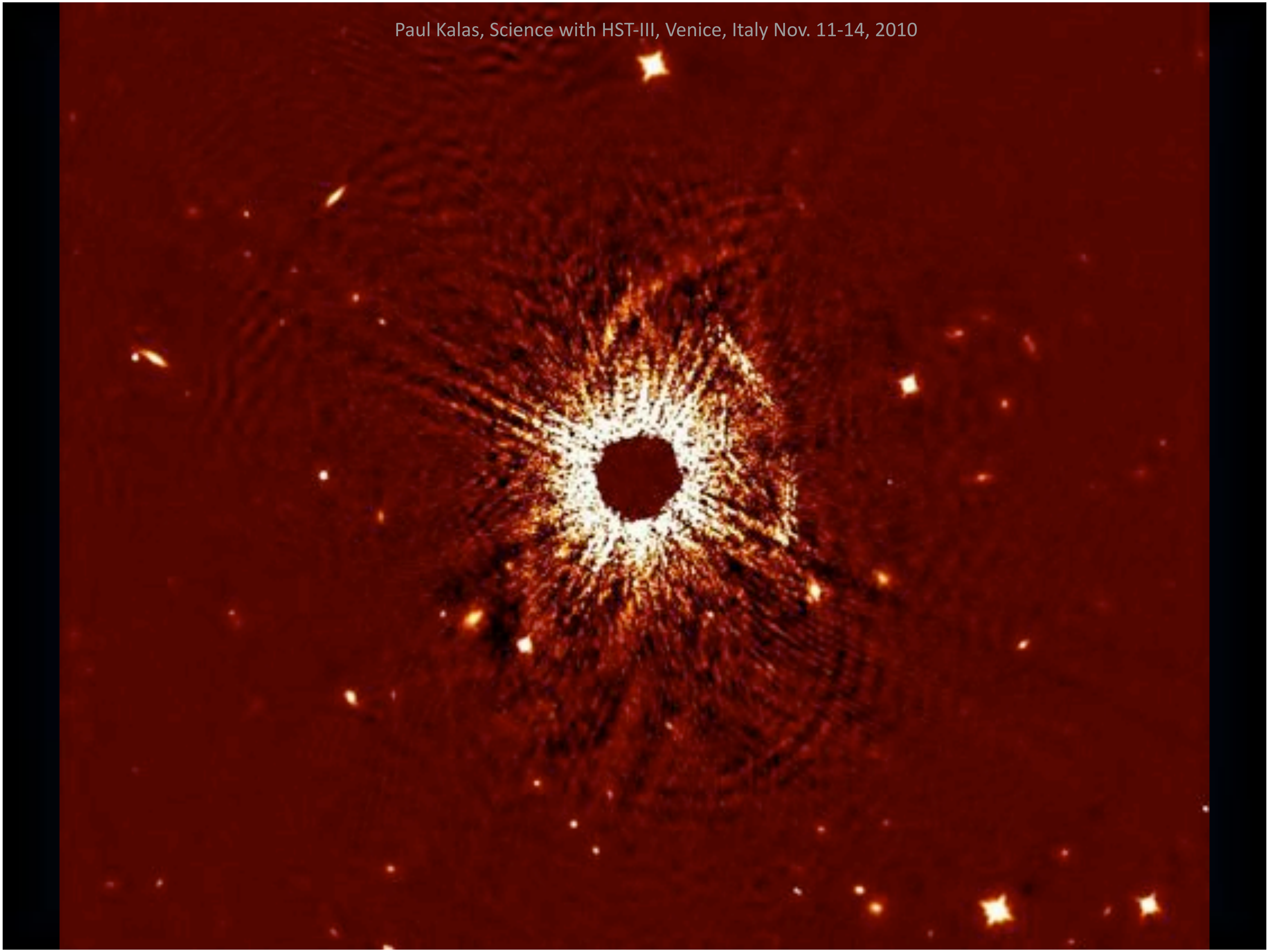


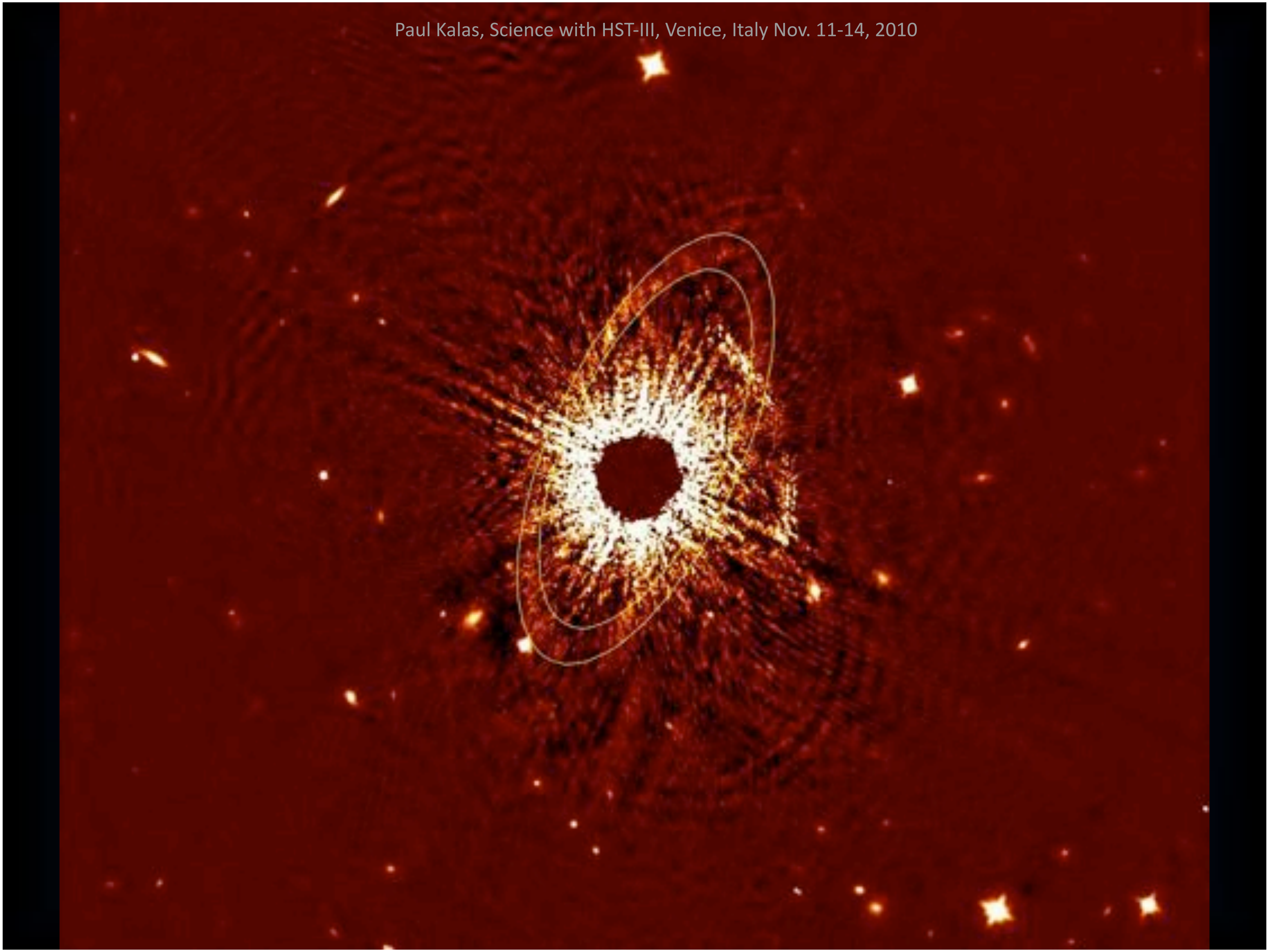
WFC3/IR
F110W, Four Telescope Rolls
First direct imaging of a bright star with WFC3/IR



Difference image between two rolls

“Cat’s Whiskers”


Paul Kalas, Science with HST-III, Venice, Italy Nov. 11-14, 2010


Paul Kalas, Science with HST-III, Venice, Italy Nov. 11-14, 2010

Paul Kalas, Science with HST-III, Venice, Italy Nov. 11-14, 2010

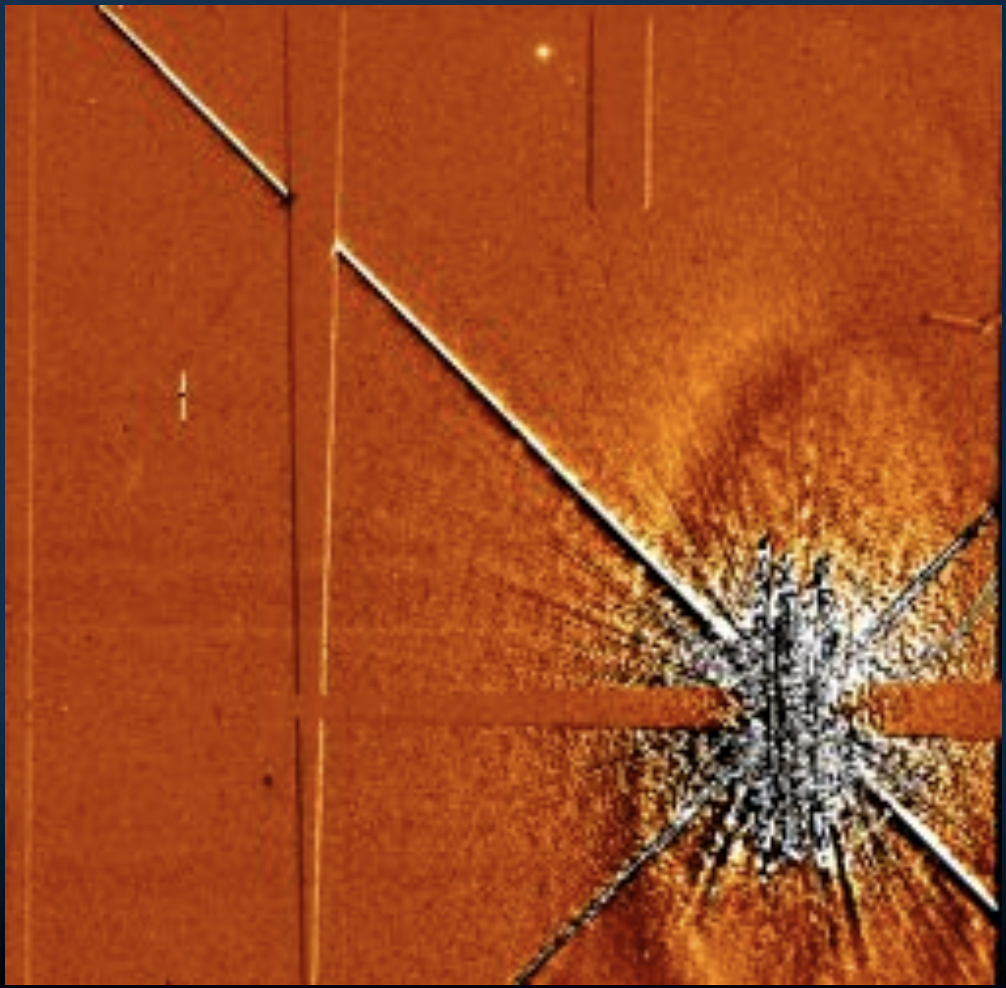
New work in progress

STIS coronagraphy

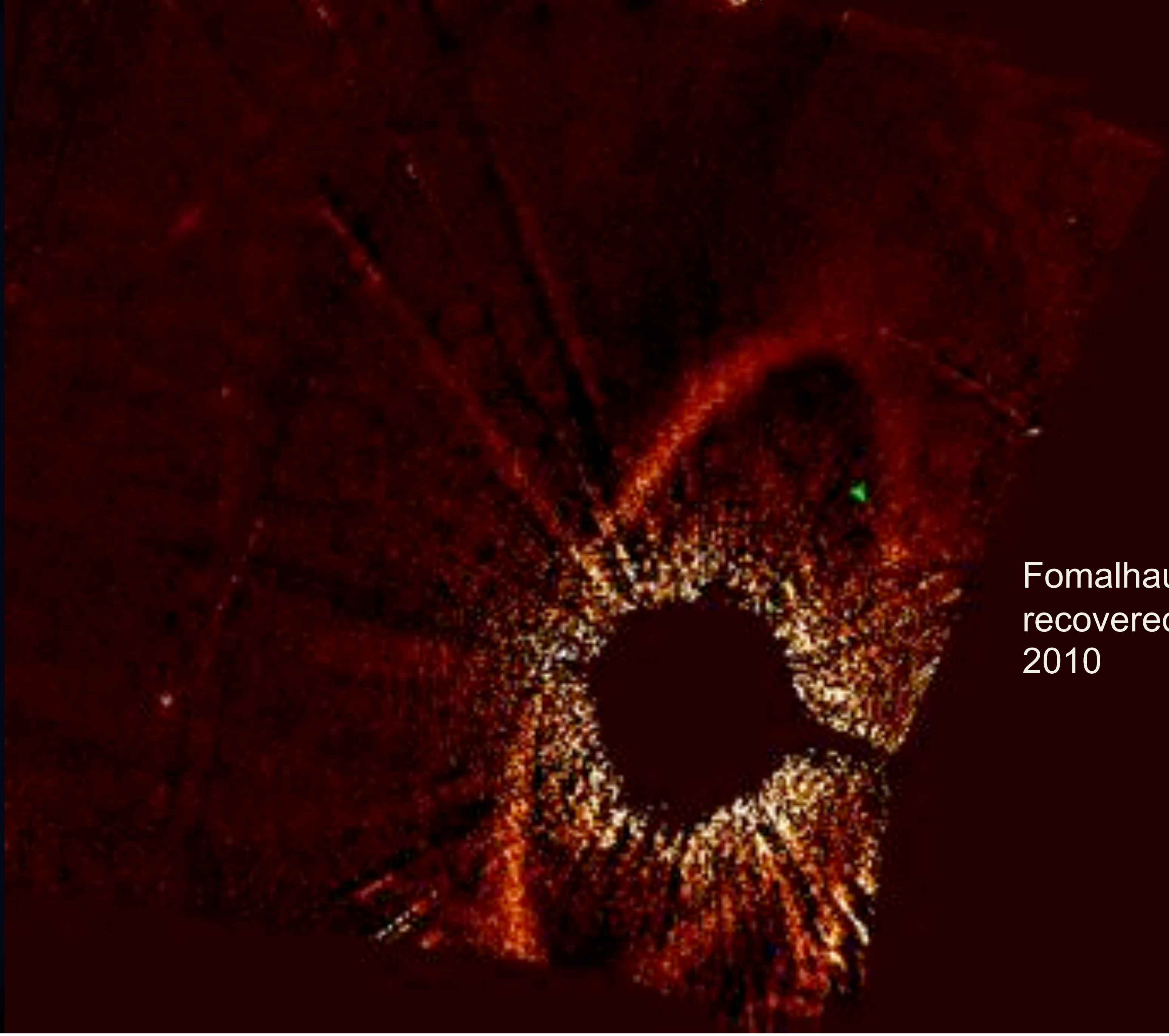
Sep. 13, 2010

4 orbits (4 rolls) - Wedge B2.5

Many thanks to Matt Mountain, Galina Soutchkova & Van Dixon

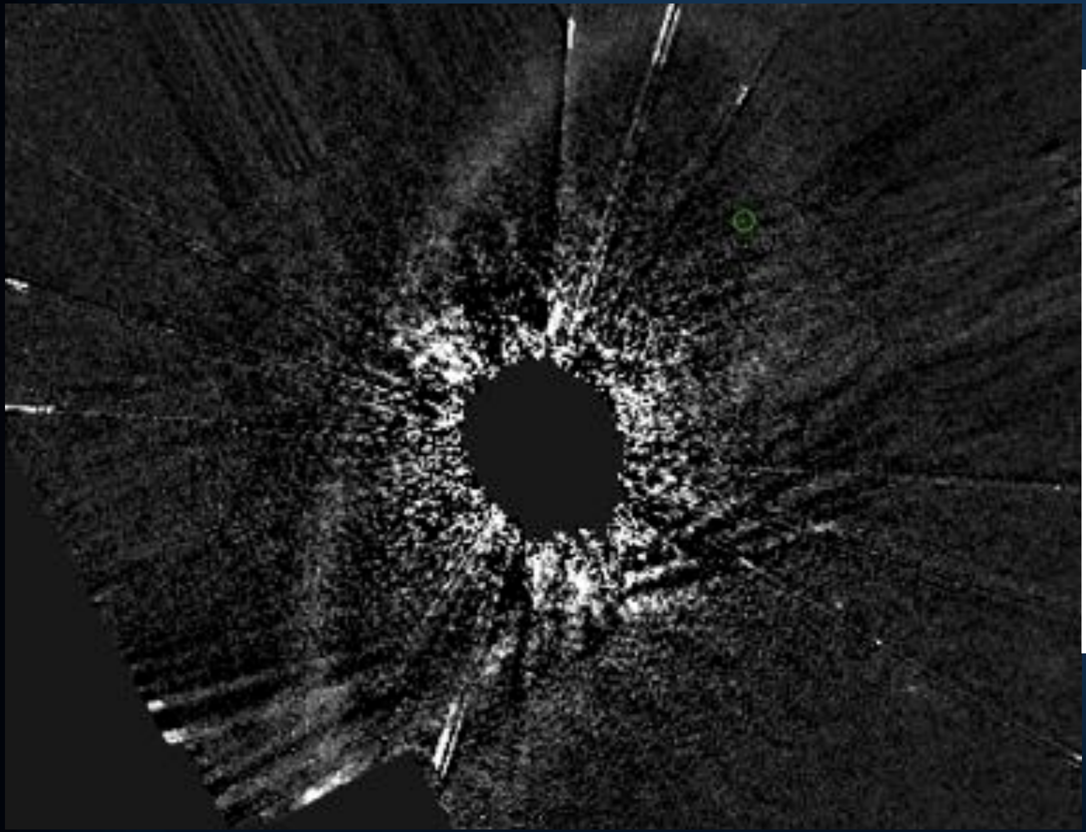


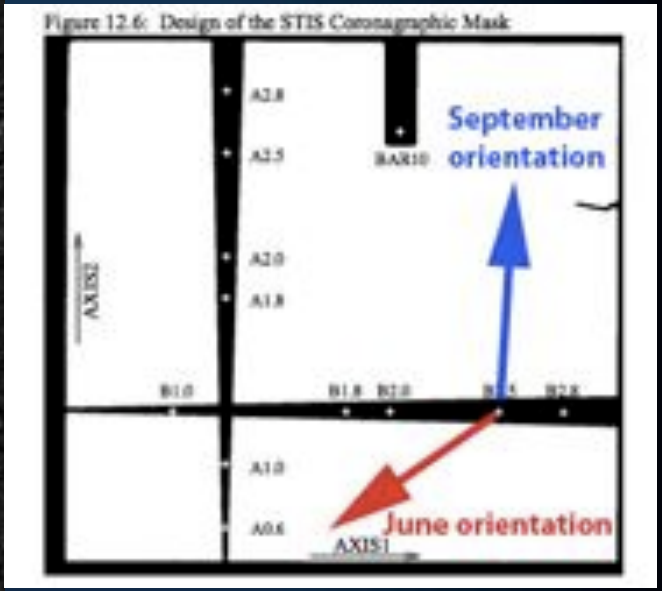
Fomalhaut's belt detected in two orbits



Fomalhaut b
recovered in
2010

Fomalhaut b had also been flagged in June data obtained with a different telescope orientation



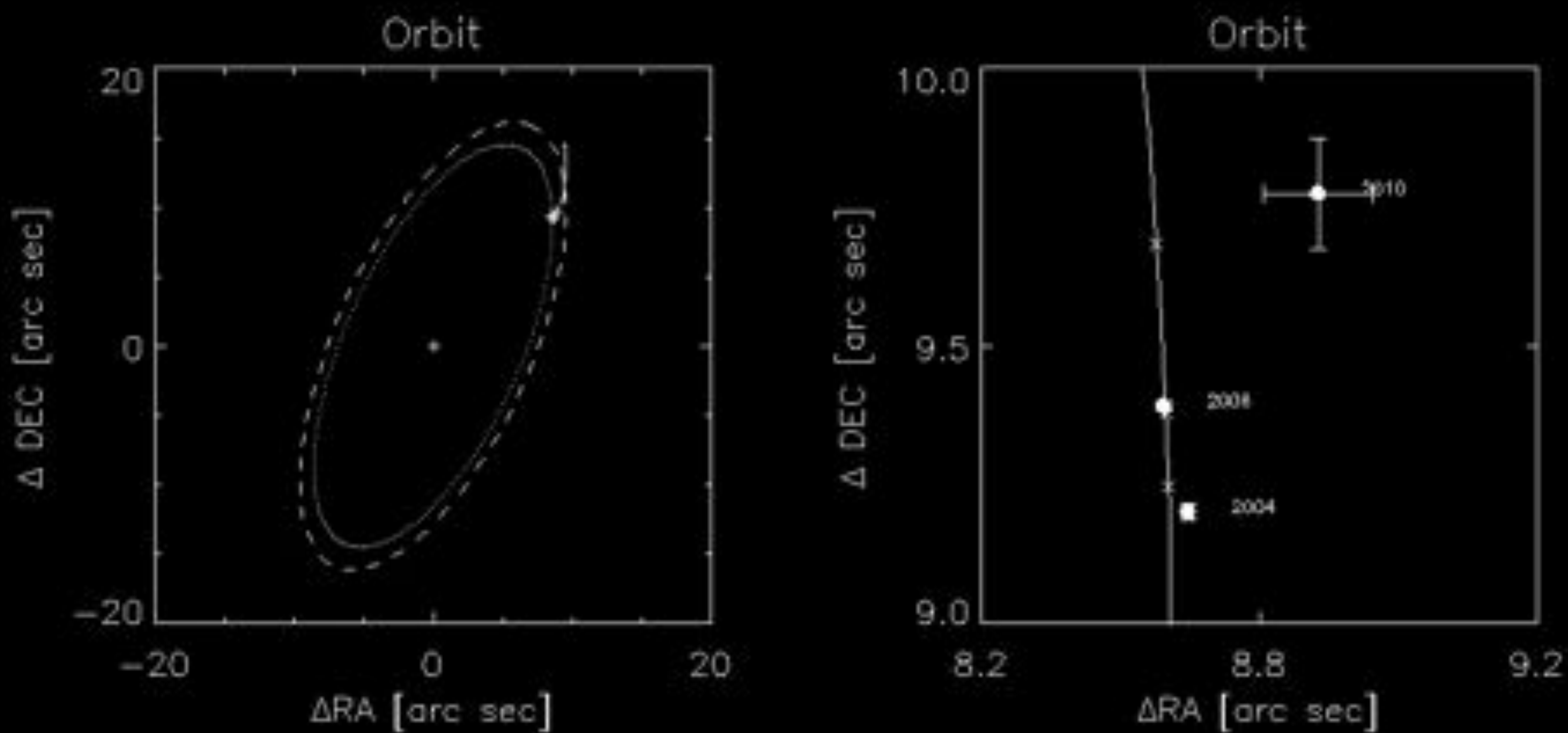


Preliminary Astrometry

Systematic Errors not Corrected

(geometric distortion and position angle)

Nested Orbit Shown

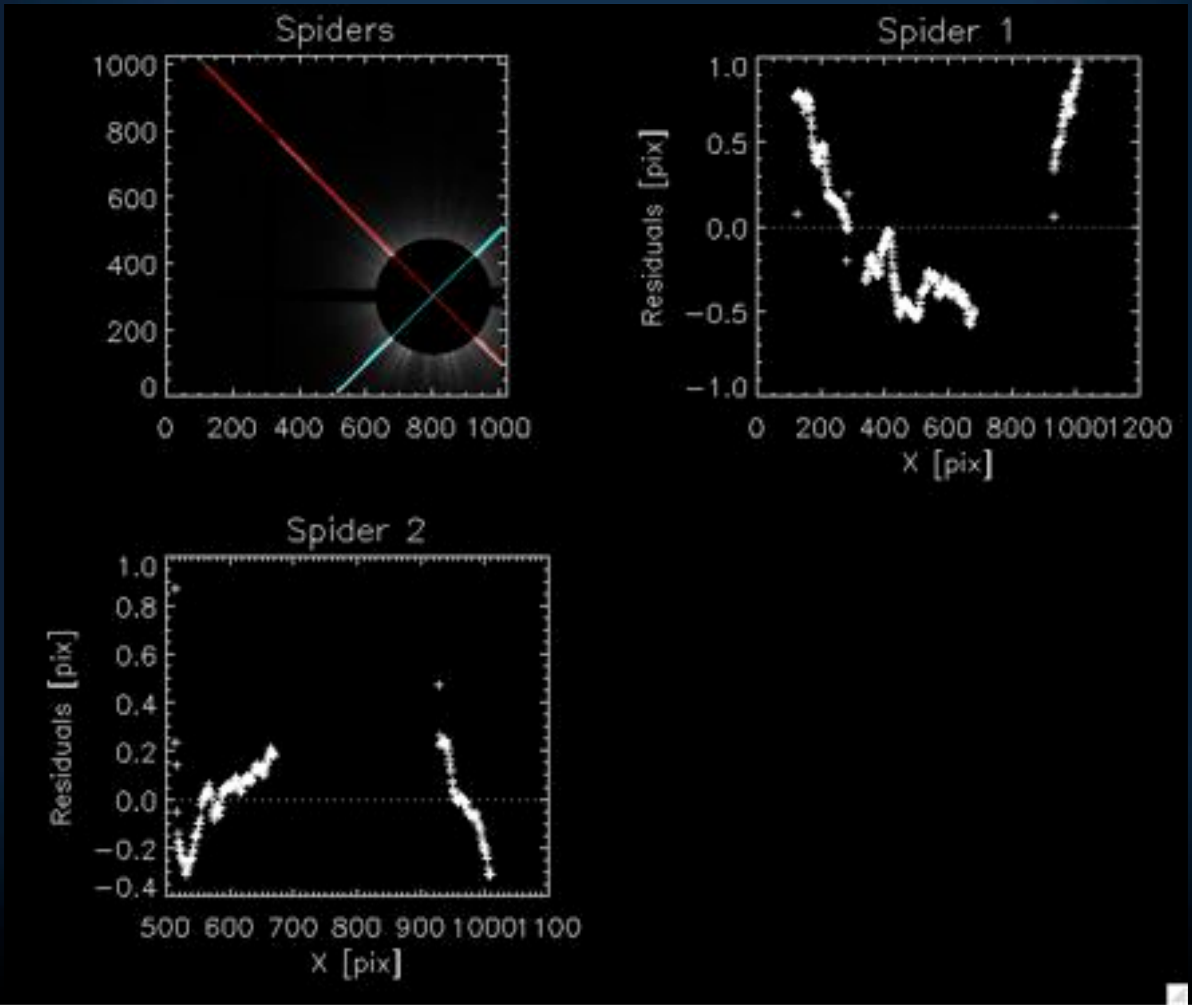


Work in progress

Significant sources of astrometric error

!. Distortion? We find parabolic diffraction spikes after using pipeline geometric correction

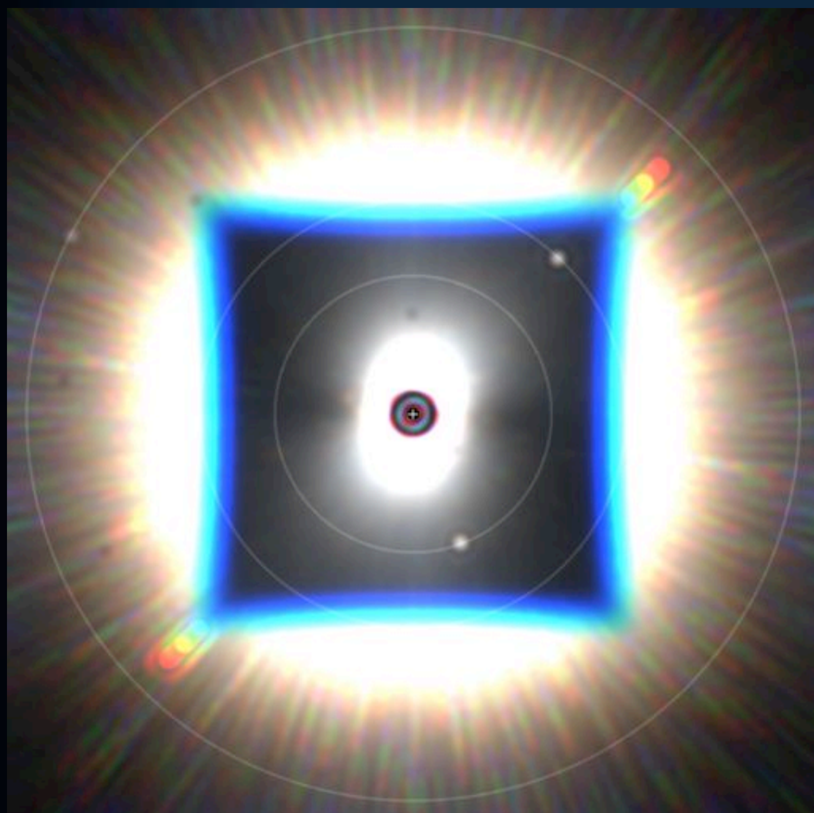
2. Position angle uncertainty ~1˚ [250 mas at Fom b] due to single guide star used.



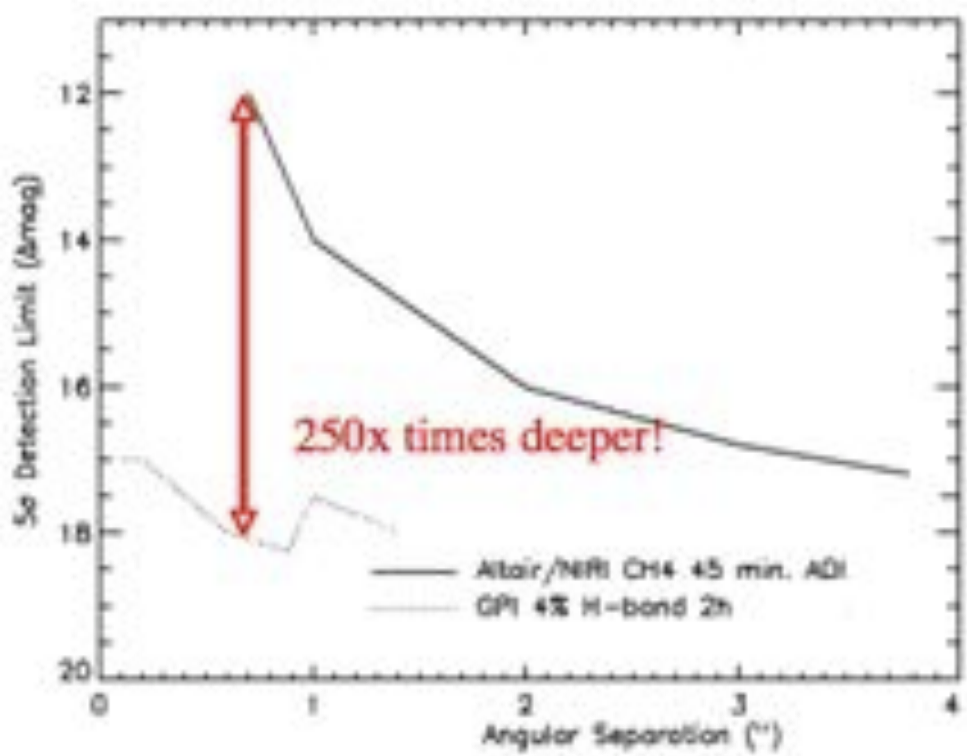
Summary

- Fomalhaut's belt and planet imaged with ***STIS*** in four orbits
- ***Work in progress* regarding error analysis, such as quantifying uncorrected distortion.**
- Belt-crossing orbits not ruled out, yet.
- If belt crossing, then many new observations possible,such as SL-9 impacts to explore atmospheric chemistry.
- If belt crossing, why is it belt crossing? Study dynamical evolution.
- Must revisit Fomalhaut in future HST Cycles

The near future with the Gemini Planet Imager



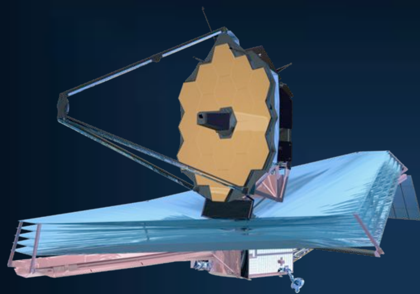
When: 2011
Where: Gemini South
Who: PI's B. Macintosh
How: High-order AO with coronagraphy
What: 0.9 – 2.4 μ, $m_I < 9$ mag stars, polarimetry, R~40 spectroscopy



GPI Collaboration

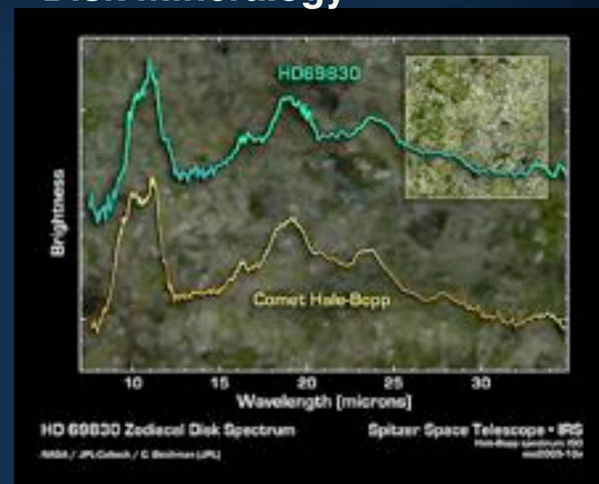
Herzberg Institute of Astrophysics
Université de Montréal
Lawrence Livermore National Laboratory
American Museum of Natural History
University of California Los Angeles
University of California Berkeley
University of California Santa Cruz
Jet Propulsion Laboratory

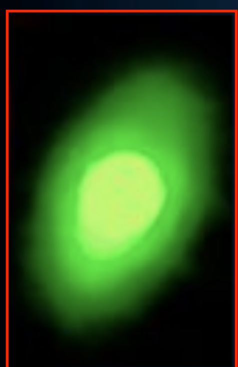
Disks with JWST



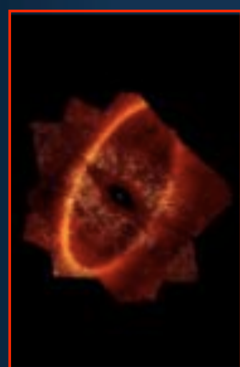
- **Spatially resolved spectroscopy**

- Disk mineralogy

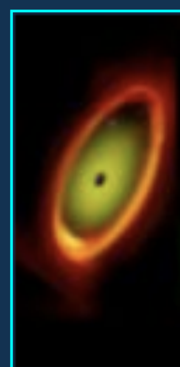




Spitzer (24 μm)



ACS (Visible)



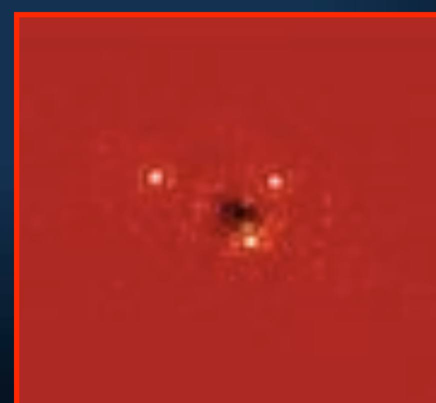
JWST (20 μm)

- **Disk morphology:**

➡ **scattered light (NIRCam)**

➡ **emission (NIRCam/MIRI)**

- **Indirect evidence of exoplanets**
  - **e.g. Kalas et al. (2008), Stark and Kuchner (2008)**



TFI: Simulation of HR 8799 - Beaulieu (2009)