Future Breakthroughs in Understanding the Fomalhaut Planetary System using ALMA

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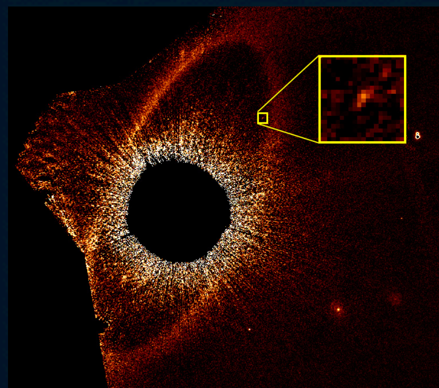
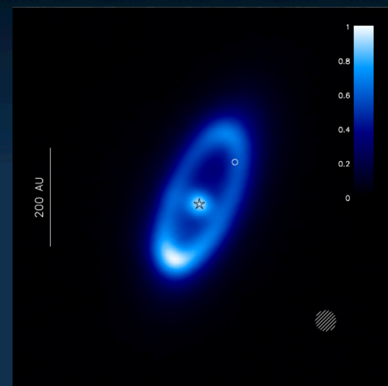
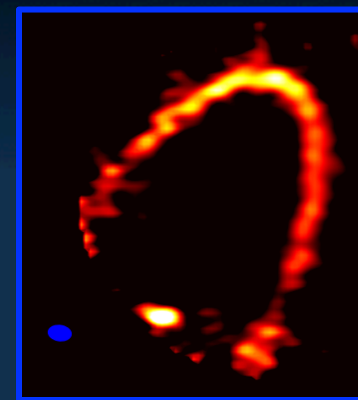
Transformational Science with ALMA: From Dust to Rocks to Planets
Formation and Evolution of Planetary Systems

Very Brief Introduction


Kalas et al. 2013


Acke et al. 2012

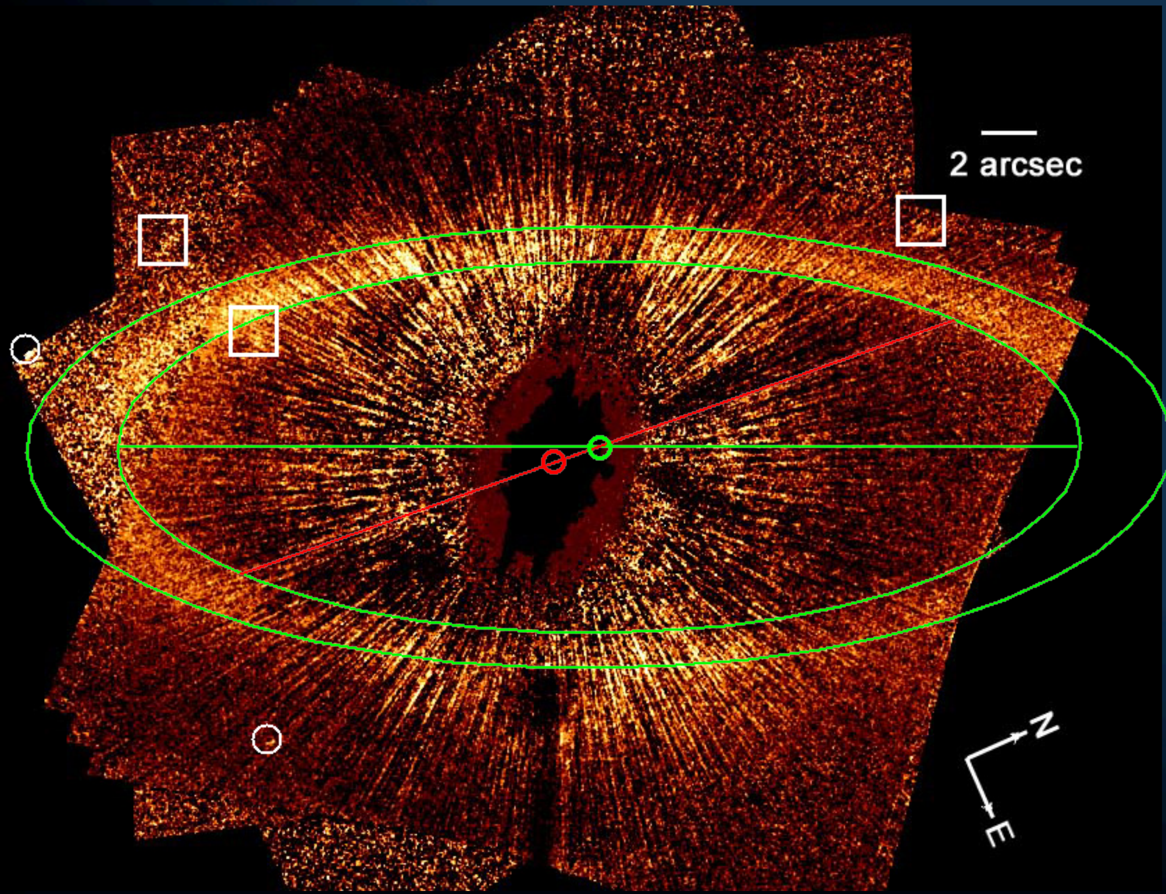

Boley et al. 2012

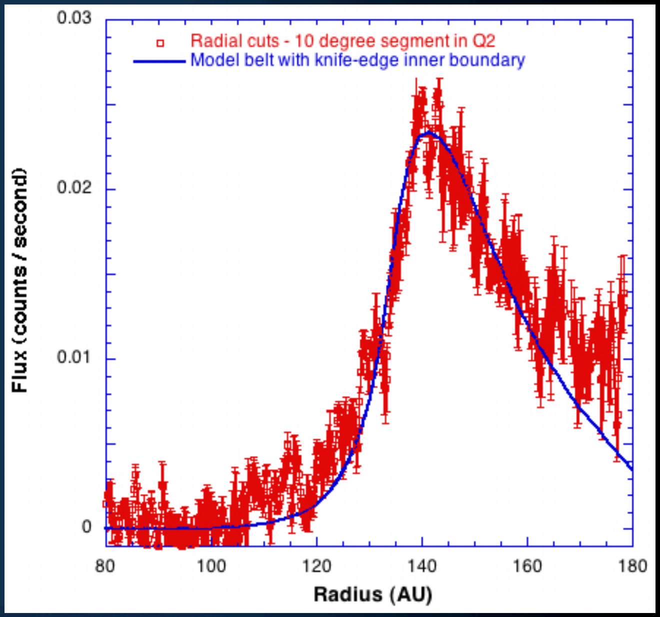
- Fomalhaut is a 2 solar mass, 440 Myr-old, A star at 7.7 pc
- Dusty debris belt at 140 AU radius mapped from optical to millimeter wavelengths.
- Dust belt stellocentric offset (15 AU) and sharp edge indicates the existence of a perturbing planet.

Planetary System around Fomalhaut: Indirect Evidence

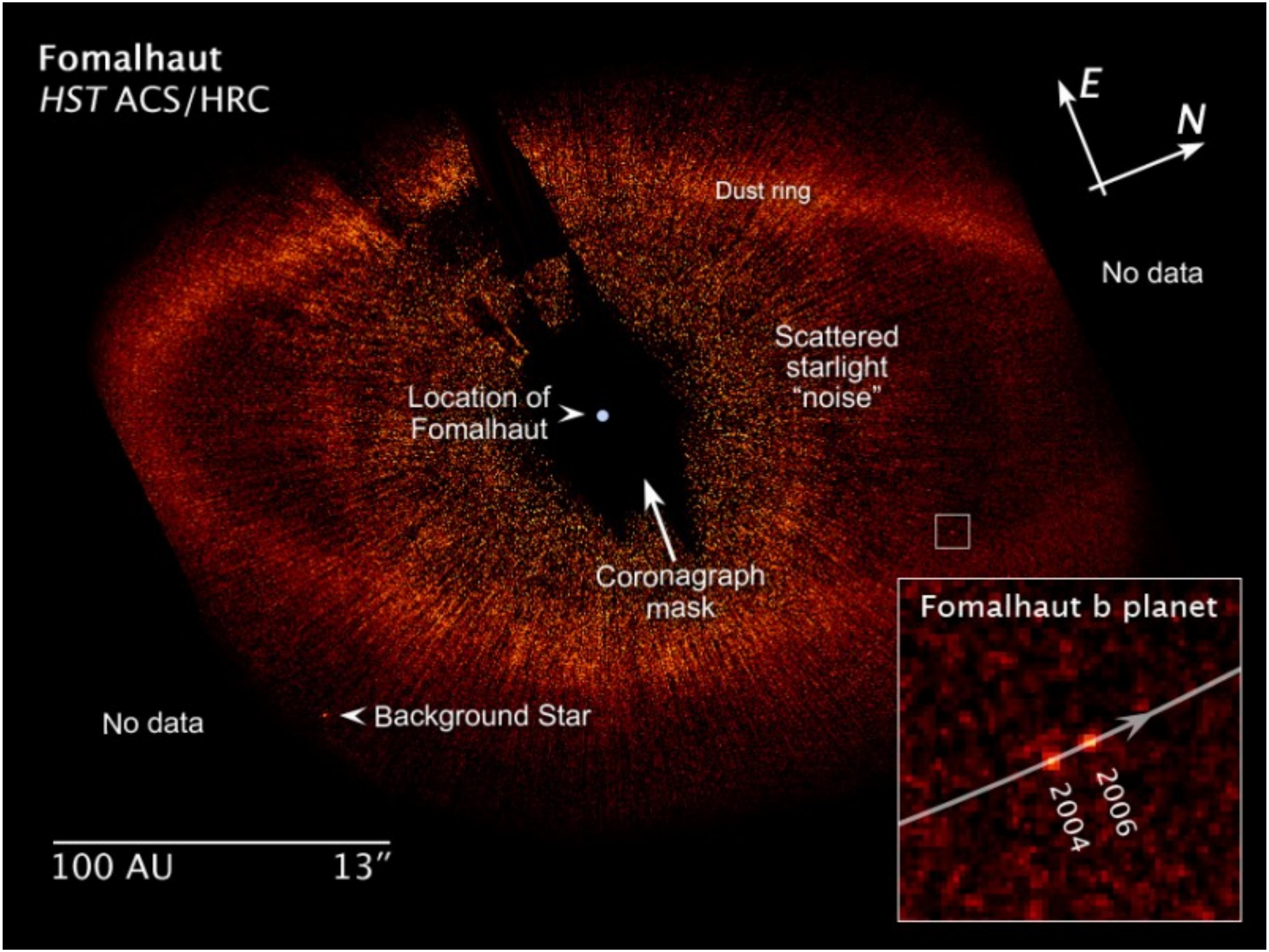
Kalas, Graham & Clampin
"A planetary system as the origin of structure in Fomalhaut's dust belt"
2005, *Nature*, Vol. 435, pp. 1067

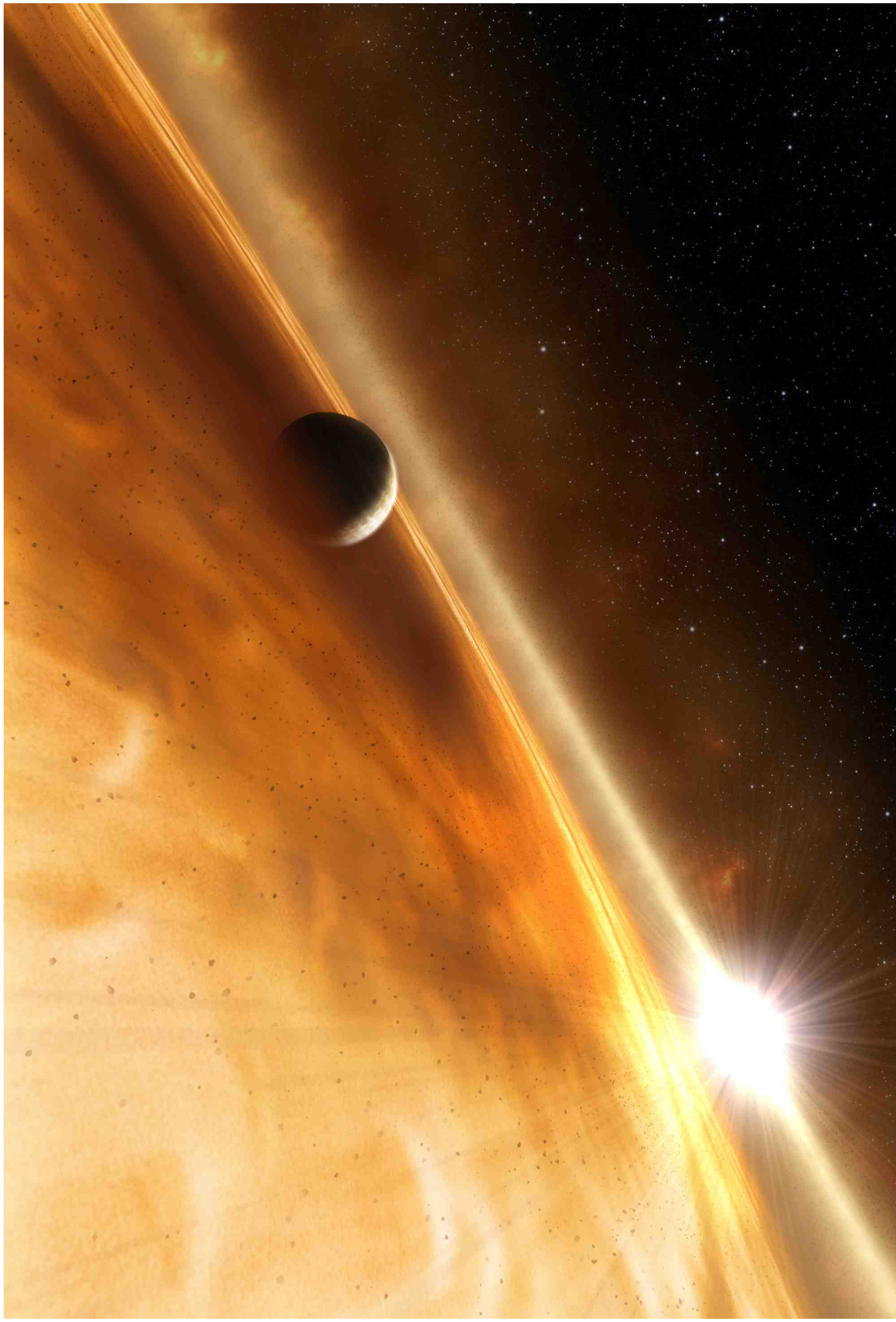
- **Dust belt not centered on the star and very sharp inner edge**
- Explanation: Gravitational Perturbations by a Planet (Wyatt et al. 1999, Moro-Martin & Malhotra 2002)





Kalas, Graham & Clampin 2005


Fomalhaut
HST ACS/HRC
E
N
Dust ring
No data
Scattered starlight "noise"
Location of Fomalhaut
Coronagraph mask
Fomalhaut b planet
2006
2004
No data
Background Star
100 AU
13″



Why is Fomalhaut b optically bright?

Circumplanetary disk

Kalas et al. 2008

Planet + 16 - 35 R_p rings

For comparison, Callisto at ~27 Jupiter radii

or

Irregular Satellite Cloud

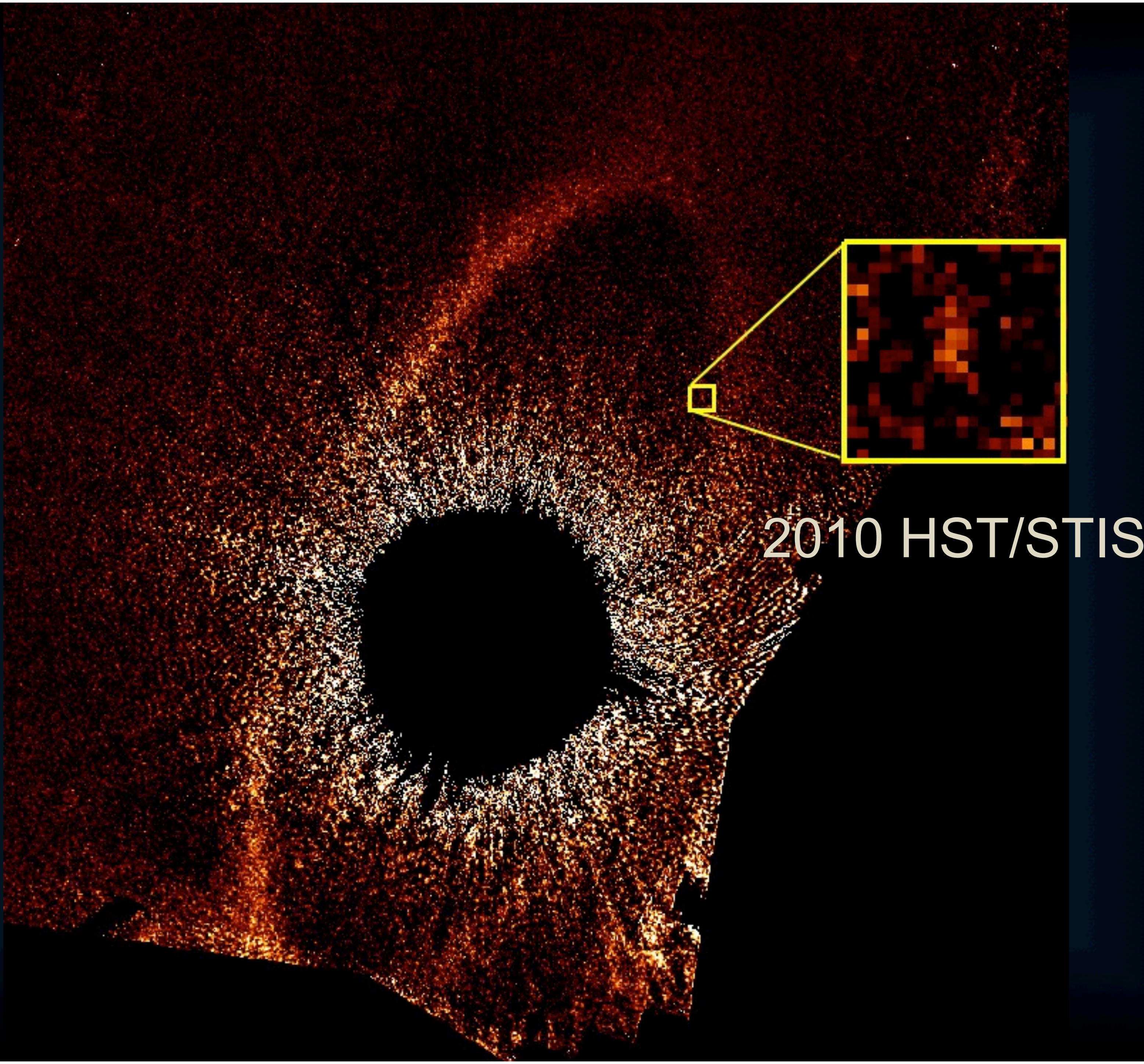
Kennedy & Wyatt 2011

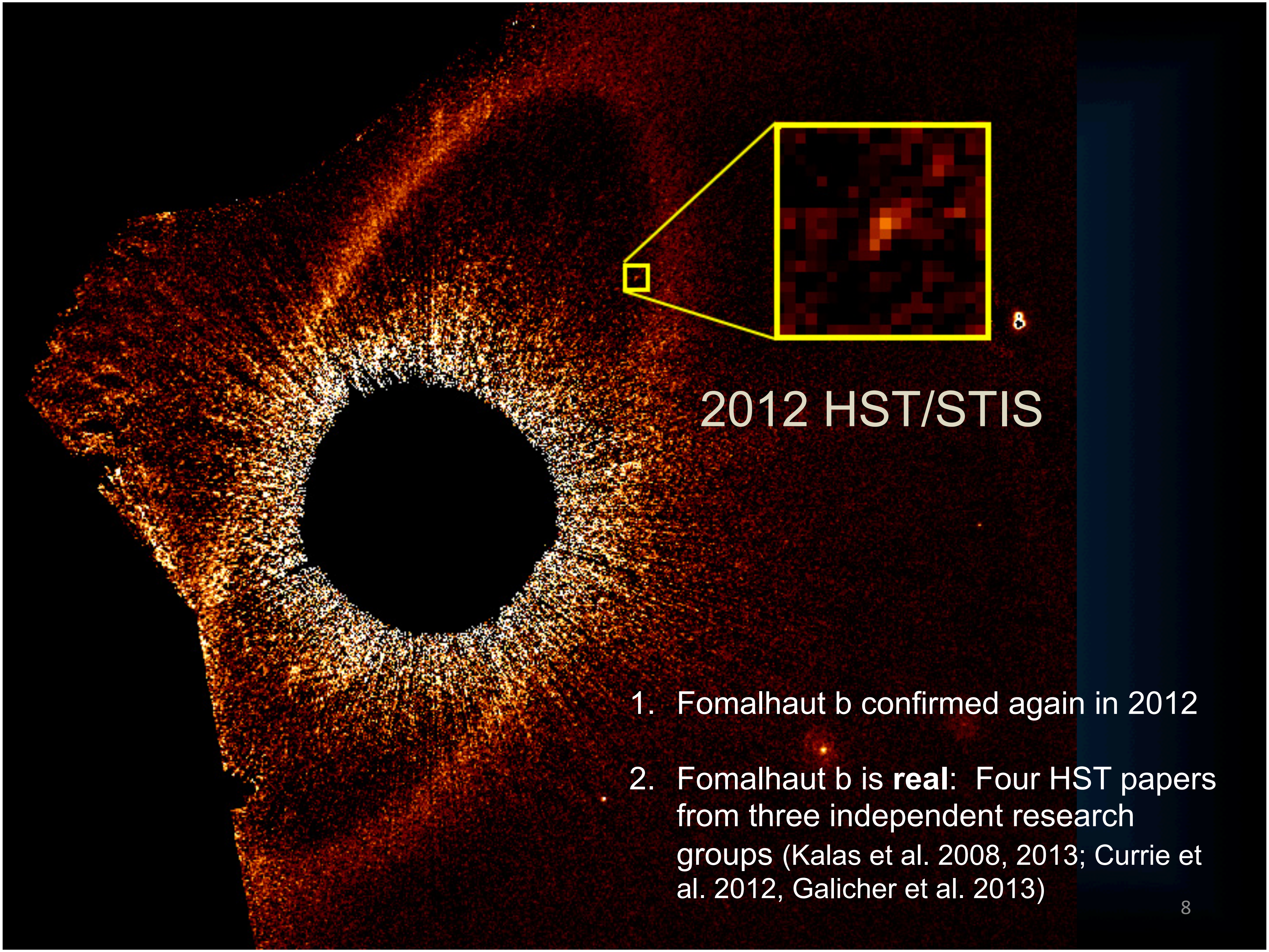
"The observations of the planet Fomalhaut b can be explained as scattered light from dust produced by the collisional decay of an irregular satellite swarm around a ~10 $M_\oplus$ planet. Such a swarm comprises about 5 Lunar masses worth of irregular satellites."

New results

(submitted to ApJ; http://arxiv.org/abs/1305.2222)

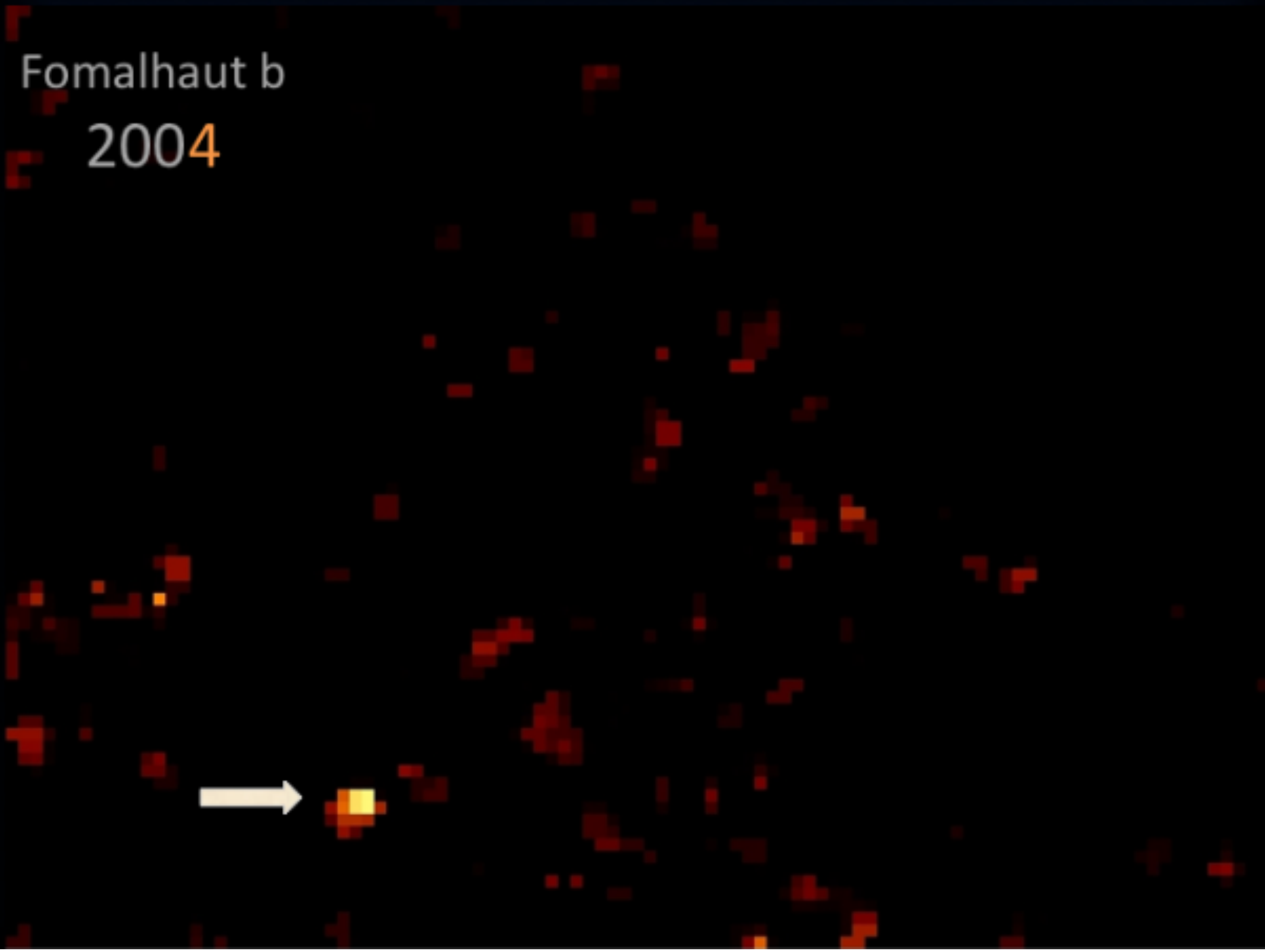
- Re-analysis of astrometry and error sources for 2004, 2006 ACS data, and 2010 STIS data.
- New Observations with HST/STIS obtained May 2012
  - 12 orbits, 12 roll angles
  - STIS coronagraphic wedge, blocks 2.5 arcsec
  - 0.05077"/pix, no filters, 0.2-1.0 micron
  - Use self-subtraction at multiple rolls, no PSF star

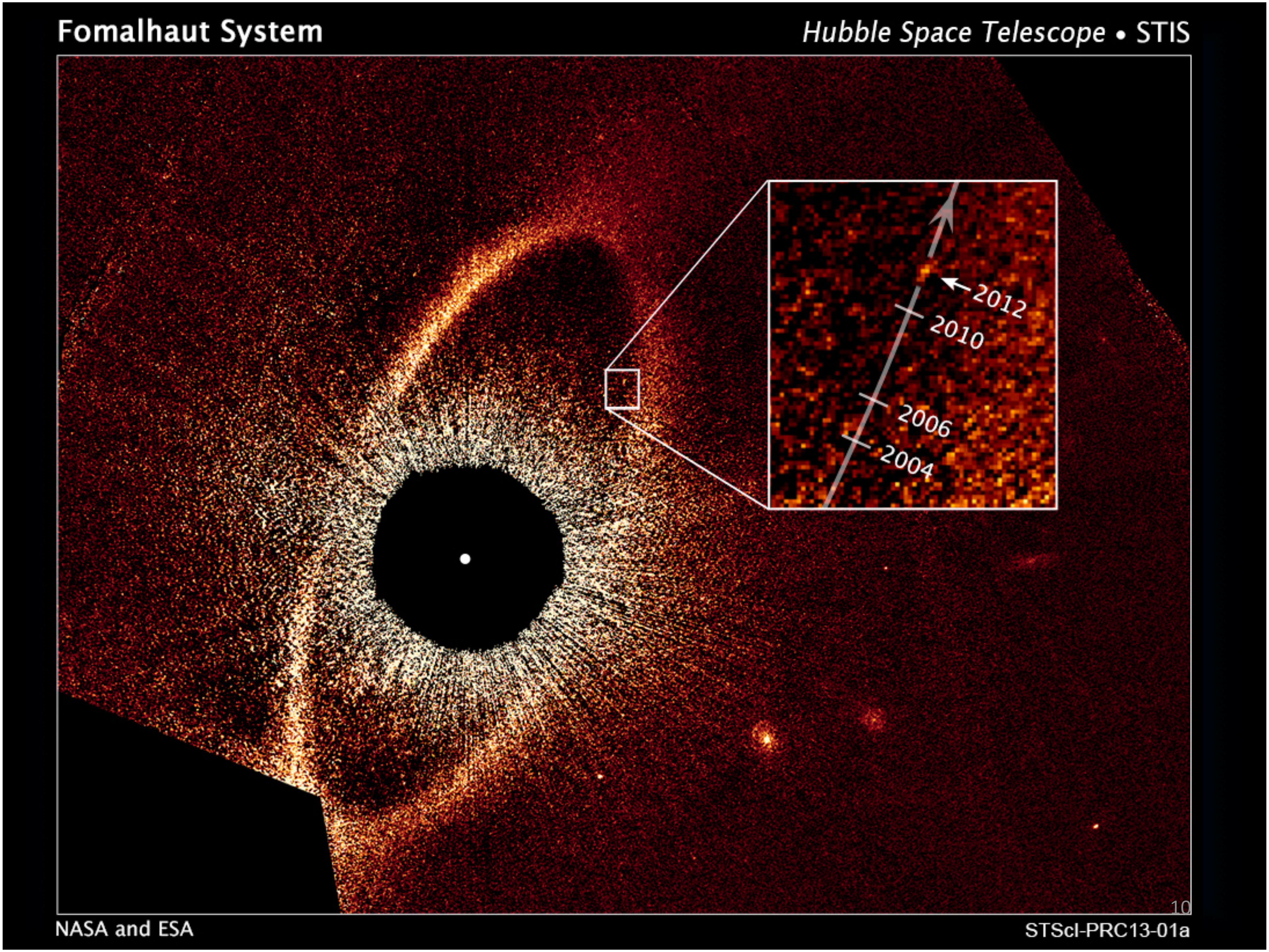

2010 HST/STIS


2012 HST/STIS
1. Fomalhaut b confirmed again in 2012
2. Fomalhaut b is real: Four HST papers from three independent research groups (Kalas et al. 2008, 2013; Currie et al. 2012, Galicher et al. 2013)

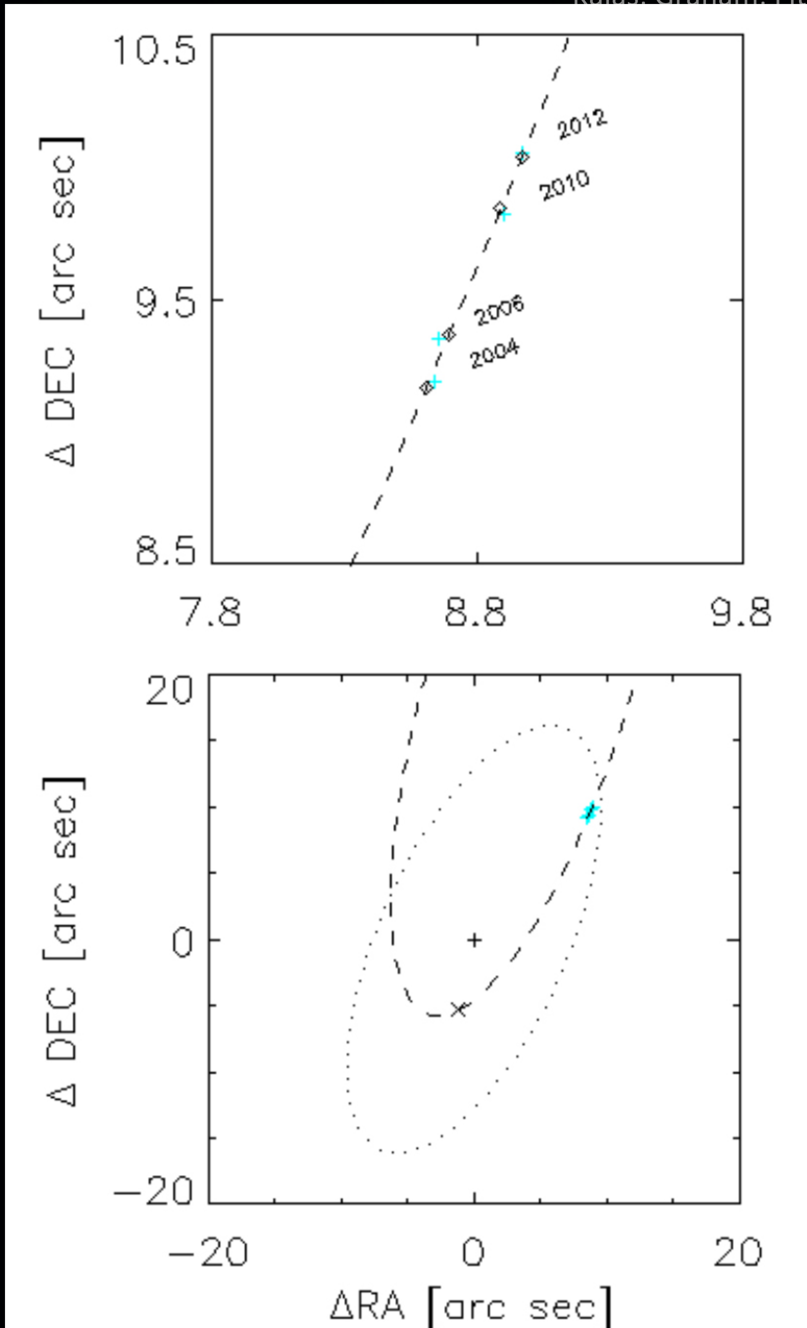
Kalas, Graham, Fitzgerald, & Clampin, ALMA April 2013

Tracking Fomalhaut b for eight years with Hubble



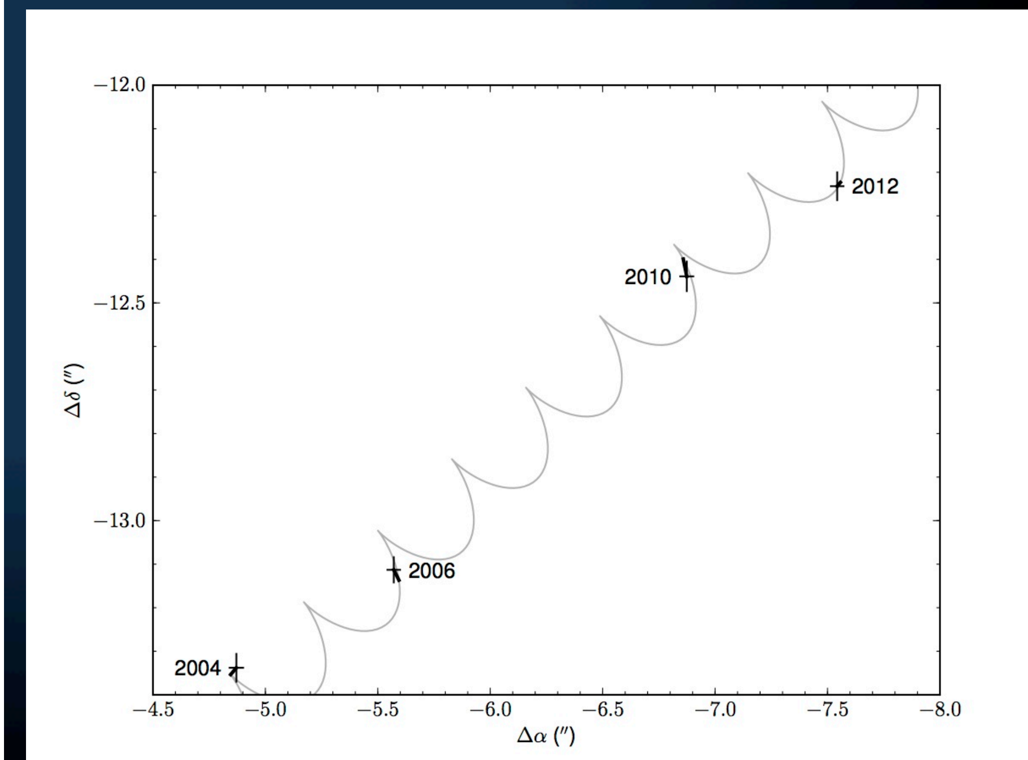

Fomalhaut System
Hubble Space Telescope • STIS
2012
2010
2006
2004
NASA and ESA
STScI-PRC13-01a

Kalas, Graham, Fitzgerald, & Clampin, ALMA April 2013

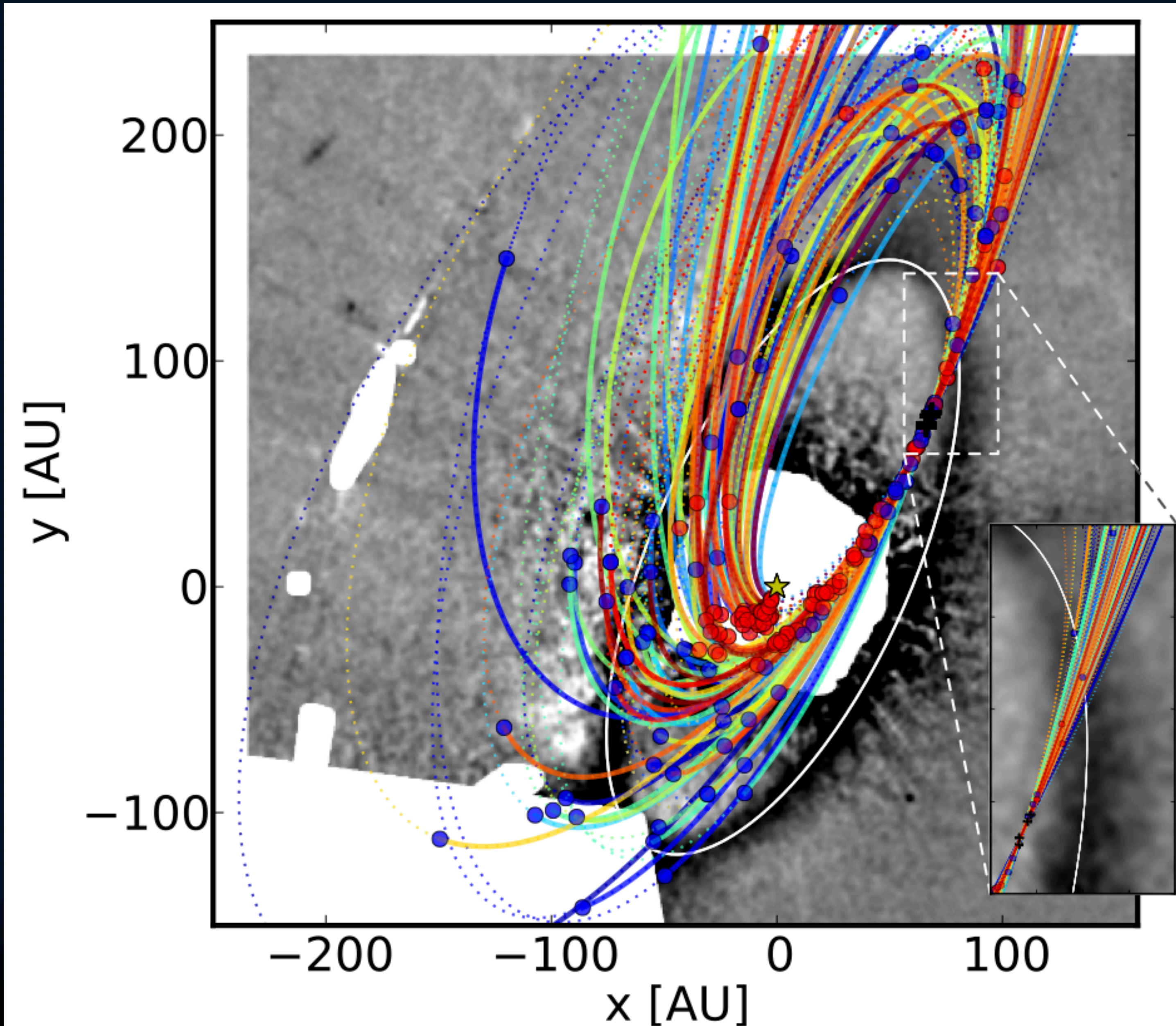


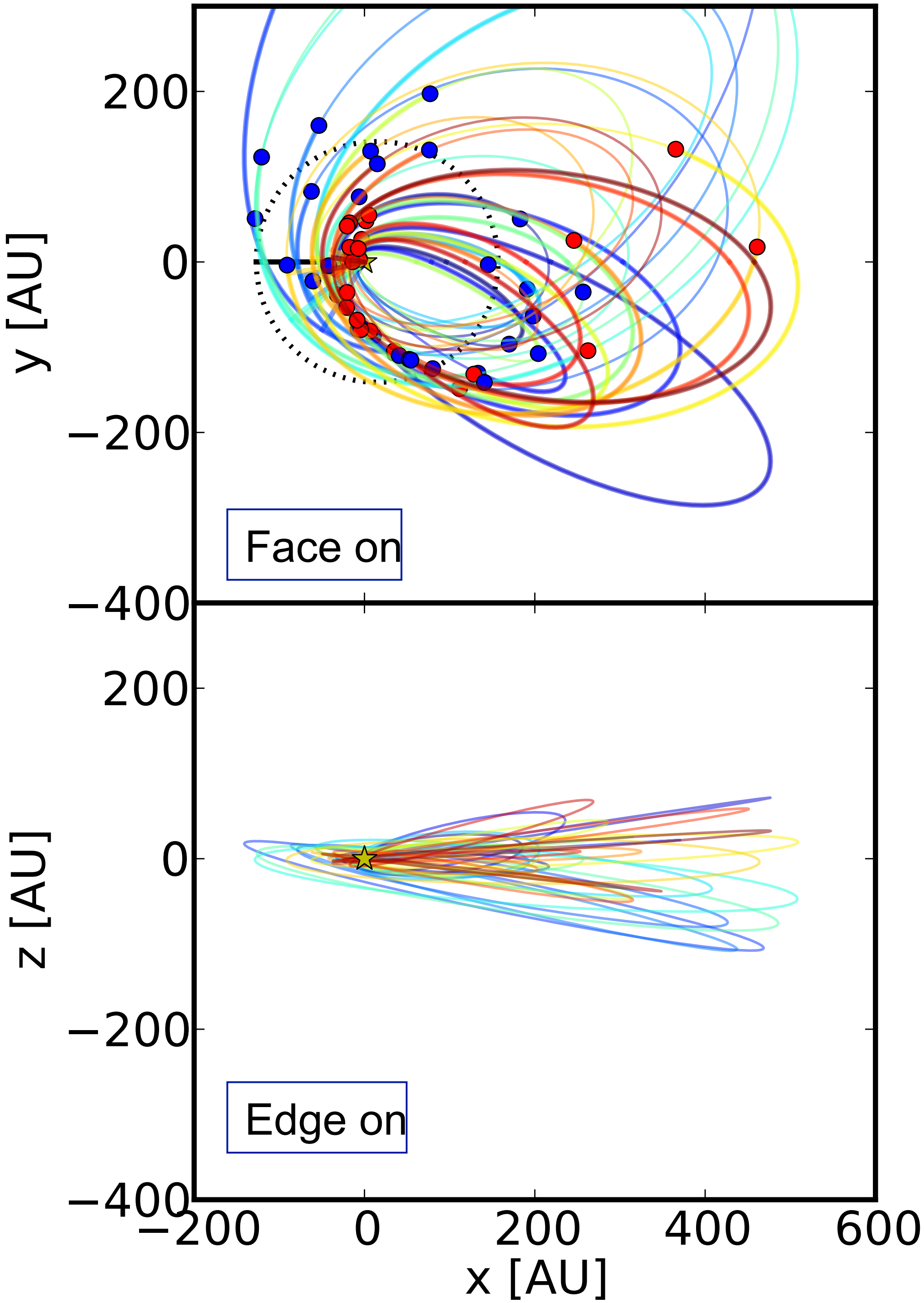
Fomalhaut b's highly eccentric orbit is confirmed

Background star at expected location



MCMC method to sample posterior probability distribution for the orbital elements based on 4 epochs of astrometry





New estimate for the Fomalhaut b orbital elements.

a = 177± 68 AU [Main Belt ~ 140 AU]

e = 0.8 ± 0.1 [Main Belt ~ 0.1]

q = 32 ± 24 AU, Q = 322 ± 119 AU

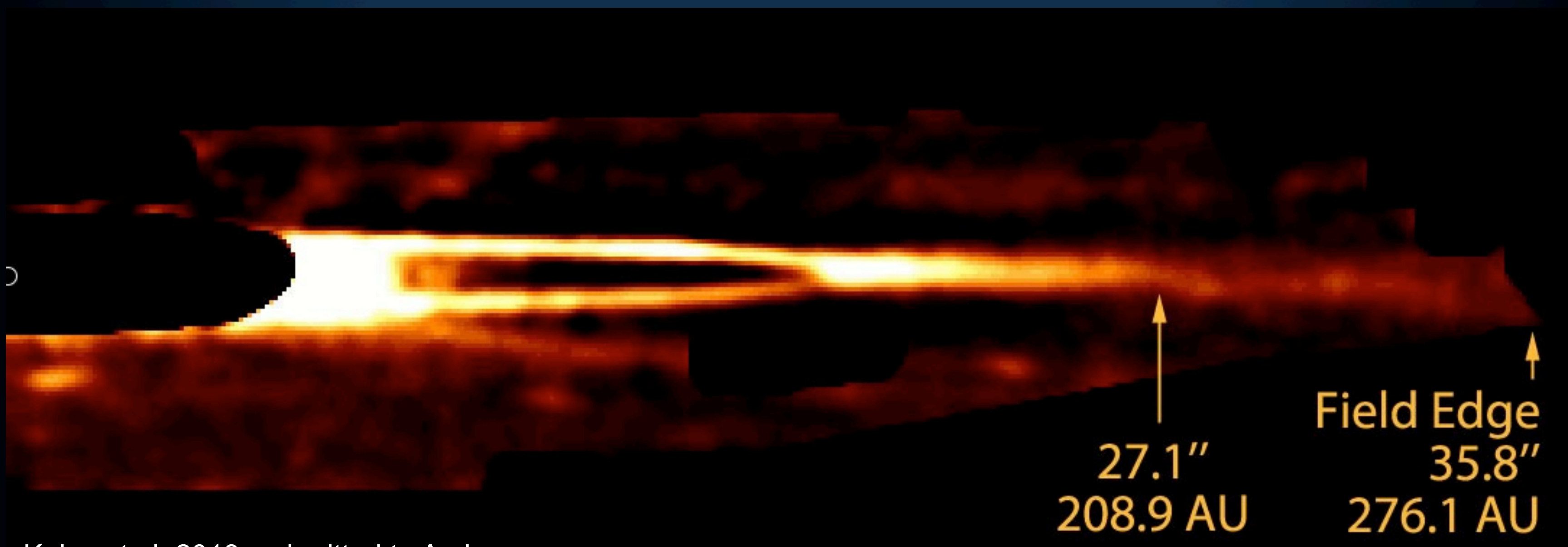
I = 17° ± 12°

P ~ 2000 yr [Main Belt~1100-1400 yr]

Kalas et al. 2013, submitted to ApJ

Discovery of Extended Belt Halo

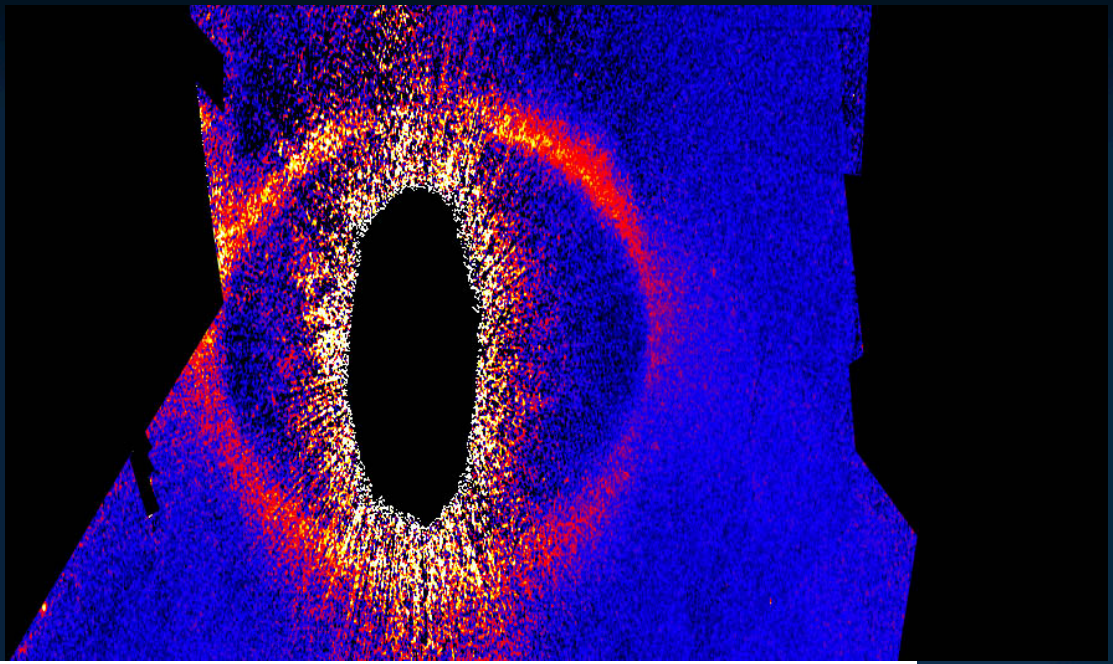
Extended halo of dust out to 209 AU, possibly >276 AU with bending morphology

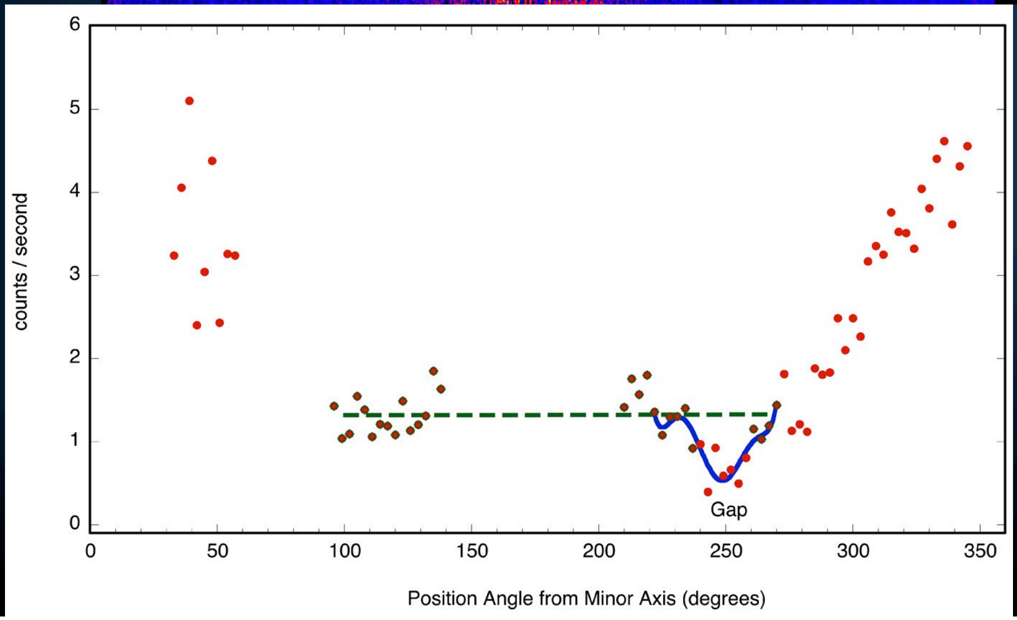


Kalas et al. 2013, submitted to ApJ

Kalas, Graham, Fitzgerald, & Clampin, ALMA April 2013

Discovery of Main Belt 331˚ Gap

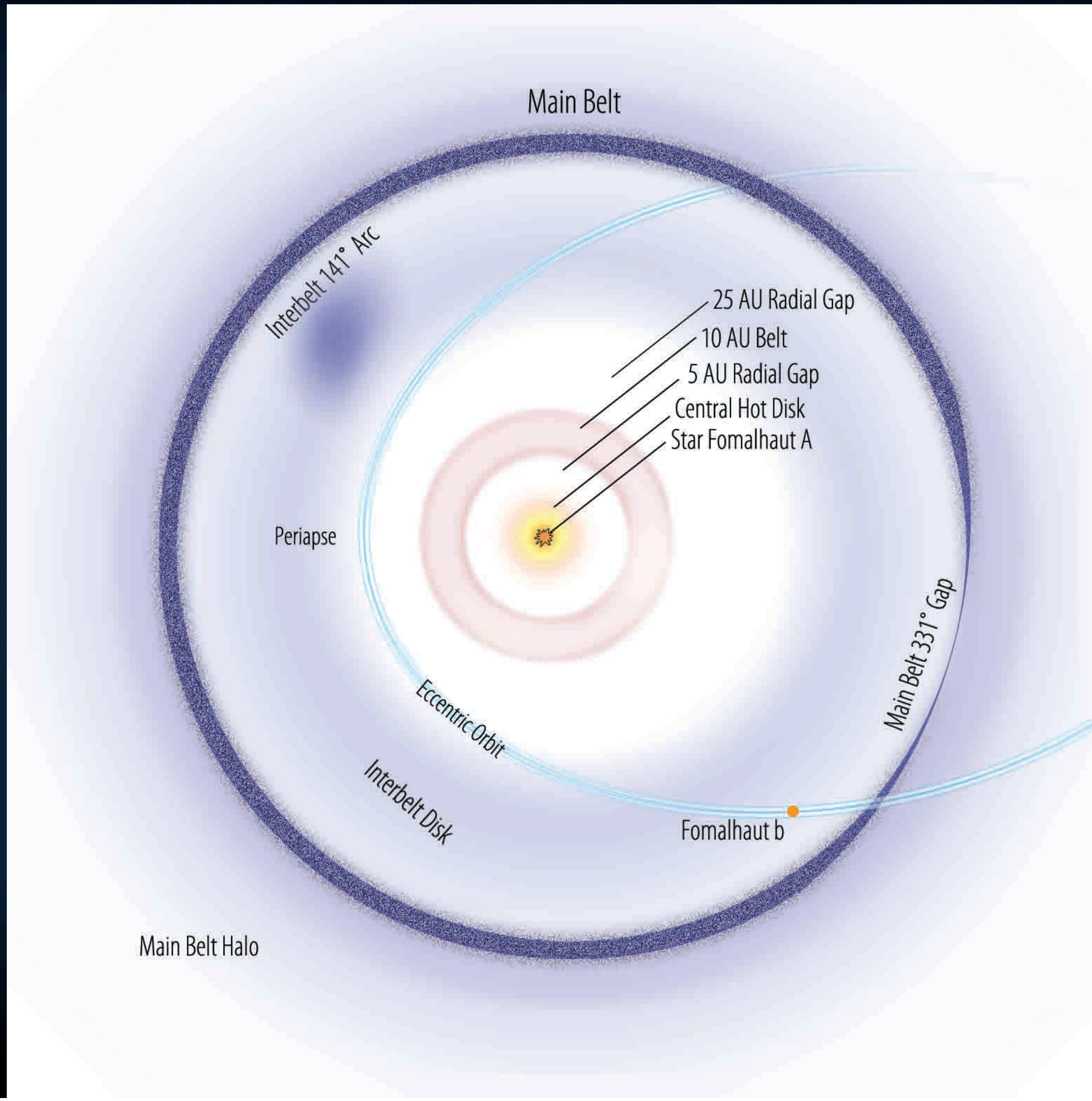




Not totally empty,
FWHM=50 AU

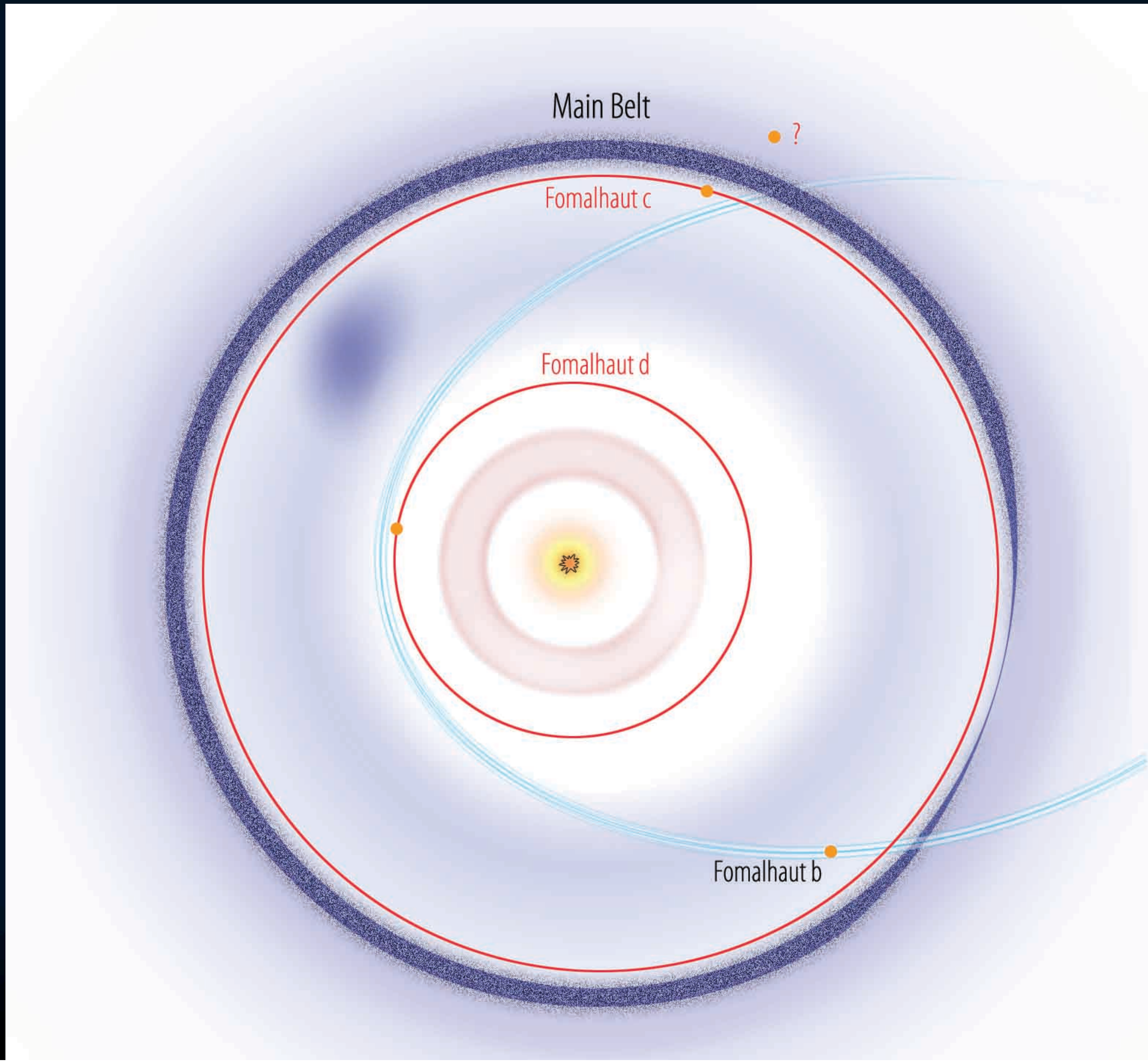
Kalas et al. 2013, submitted to ApJ

Sketch of the Fomalhaut system based on *observations*

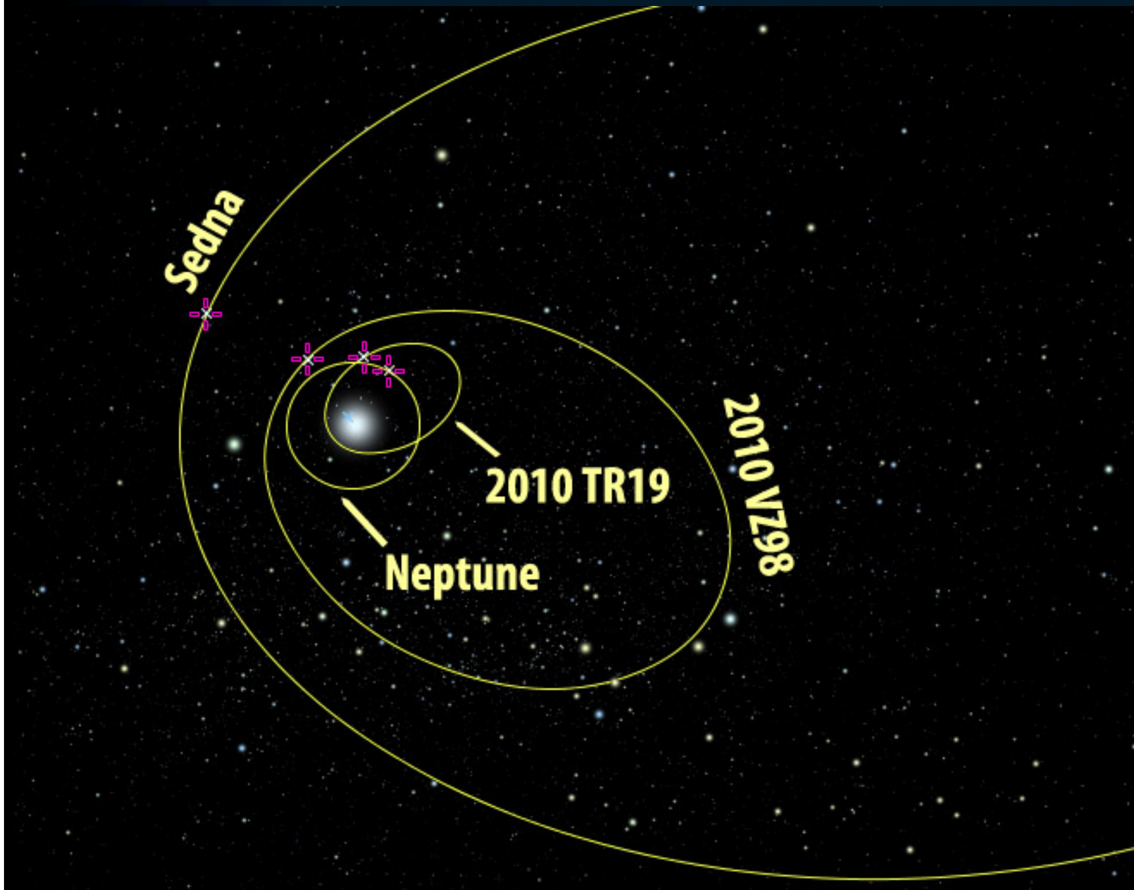


What accounts for Fomalhaut b's high eccentricity?

Multi-planet system: Was Fomalhaut b scattered in, or out?



Fomalhaut b scattered in



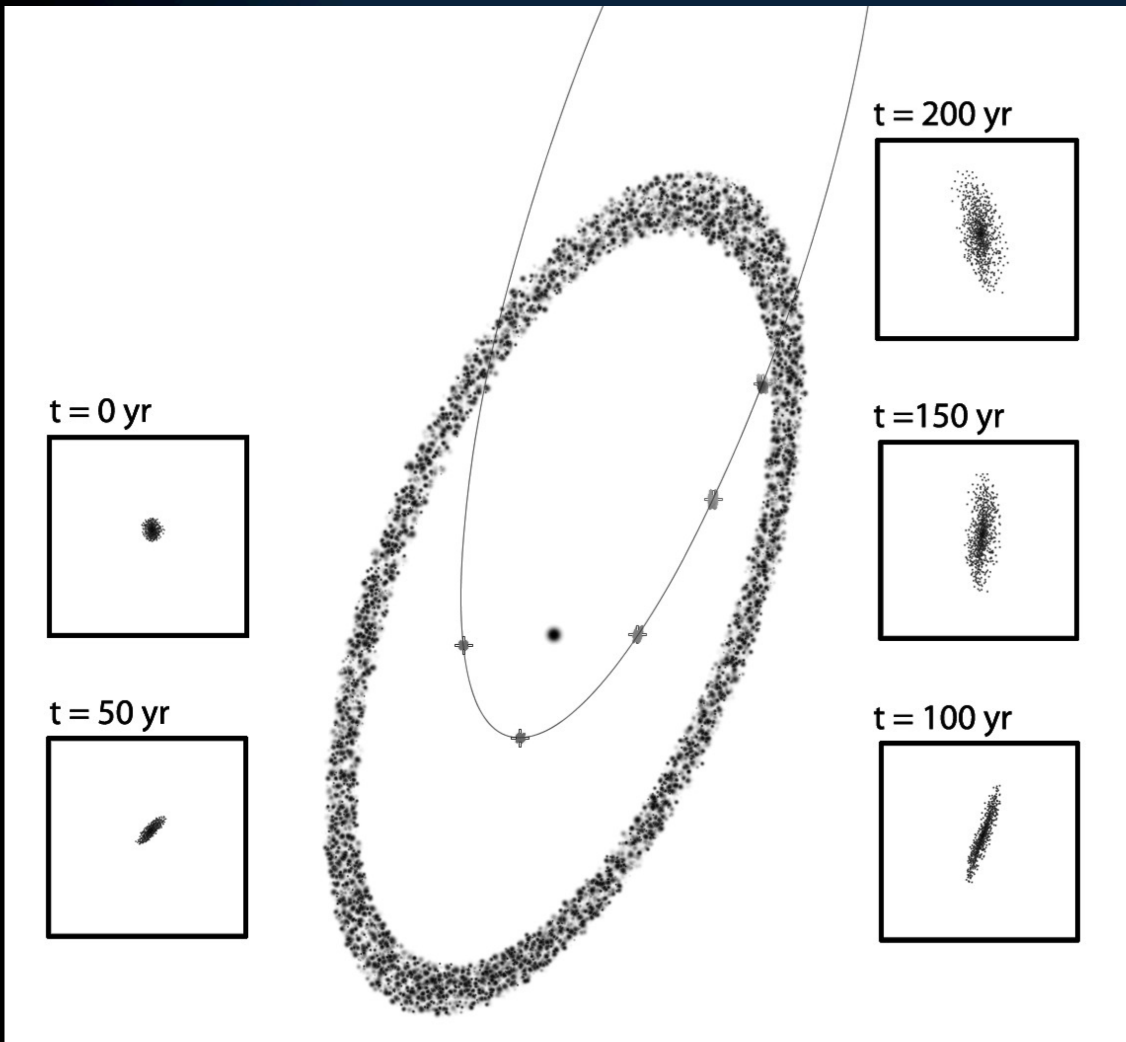
Fomalhaut b's orbit is similar to a minority of Centaurs, such as 2010 TR19, which enters into our planetary system (crosses Neptune's orbit) on a very elliptical orbit.

Implication:

(1) Fomalhaut b has a *short-lived* orbital configuration.

(2) Fomalhaut b is very low-mass.

Fomalhaut b is a low-mass, Centaur-like object?



Question: How massive does a central object have to be so that an 30 R_J (0.014 AU) radius cloud is not disrupted by tidal shearing at periapse?

Answer: 5 x10^{21} kg
~500 km radius
>Ceres, <Pluto

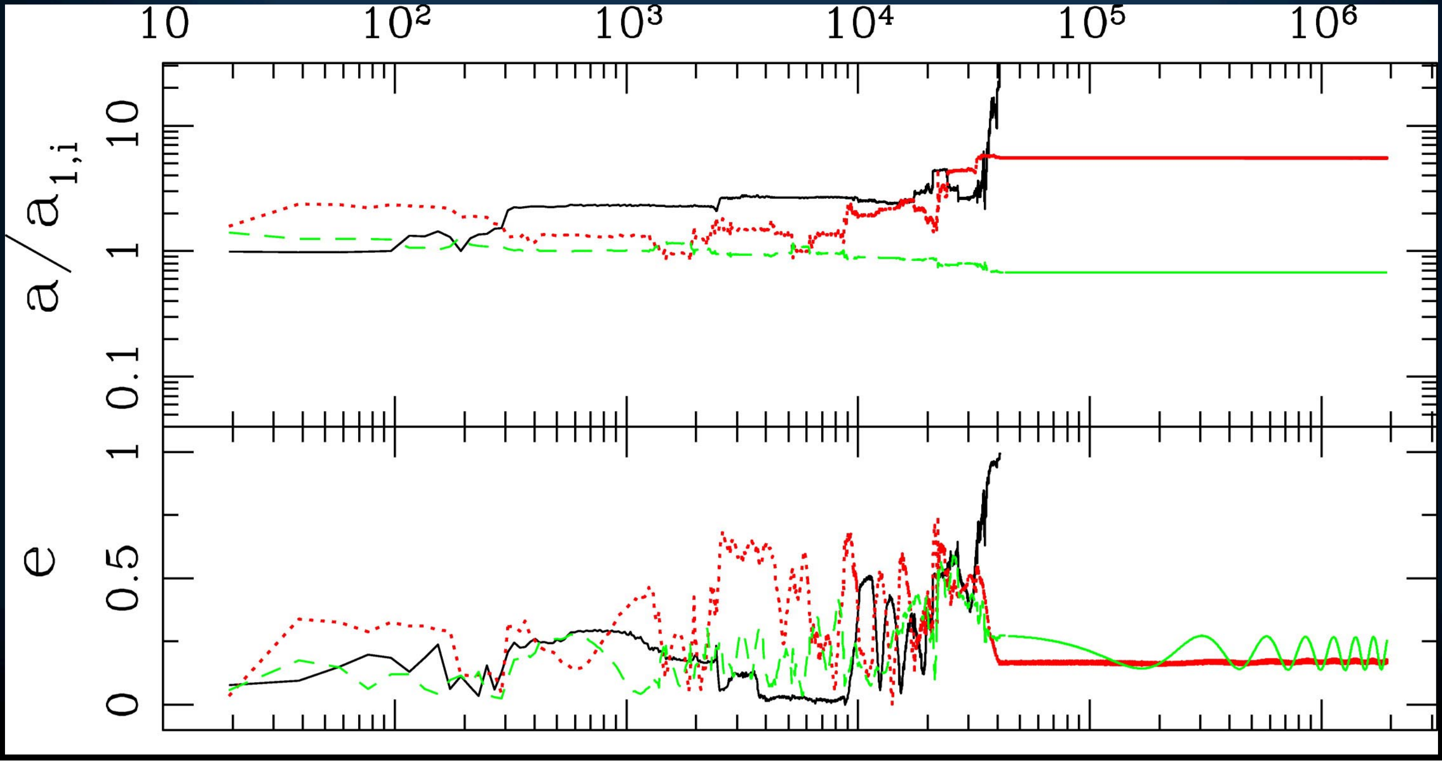
Mass of dust required consistent with a single cratering impact on the dwarf planet.

Numerical model (Kalas et al. 2013)

Fomalhaut b scattered out?

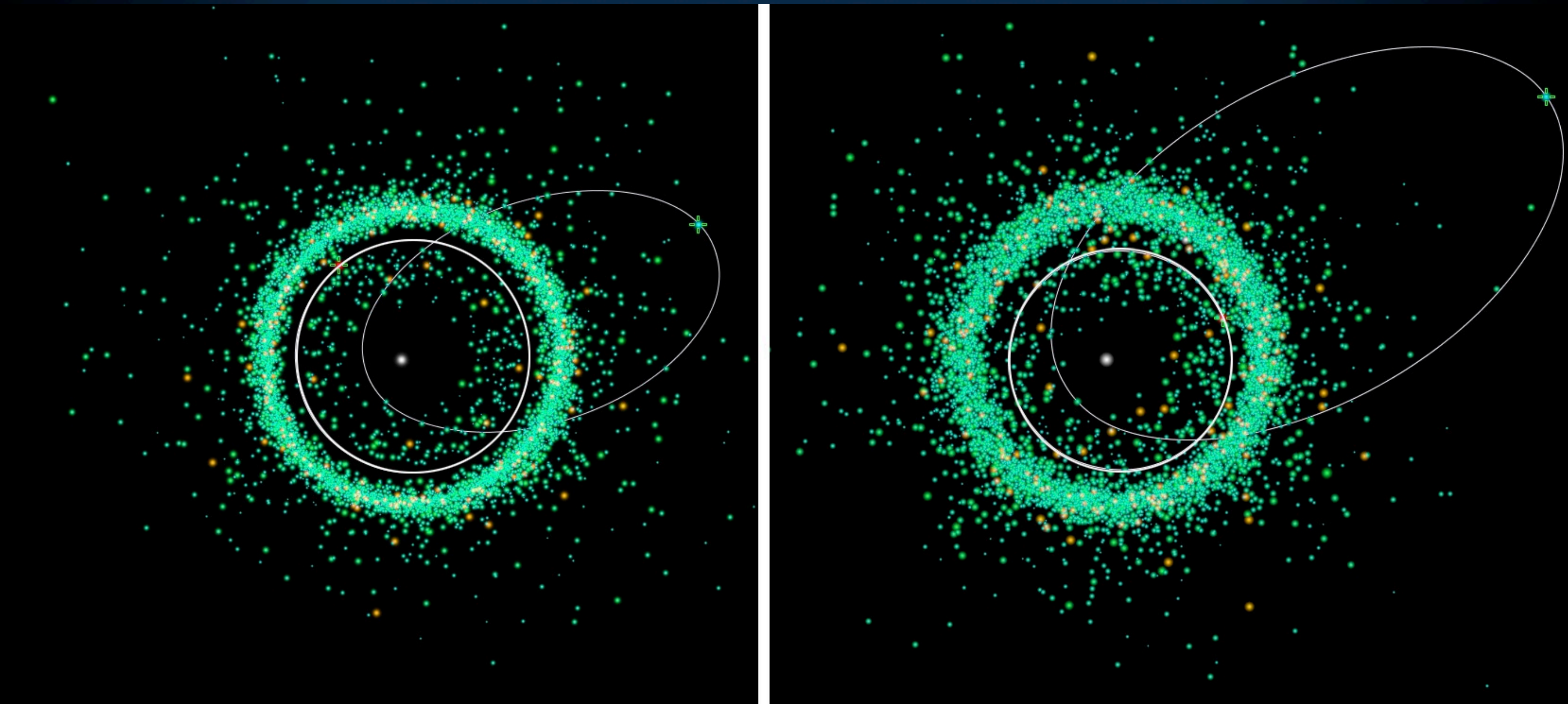
Example from Chatterjee et al. 2008

- Simulate 3-planet systems, variety of mass ratios, inclinations, separations
- Massive planets eject lesser mass planets.
- Mutual inclinations change
- Planet with outer final orbit tends to have higher eccentricity.



Does Fomalhaut b with a planet mass disrupt the belt if coplanar?

Belt edges erode, timescale depends on mass



Neptune mass after 300 kyr

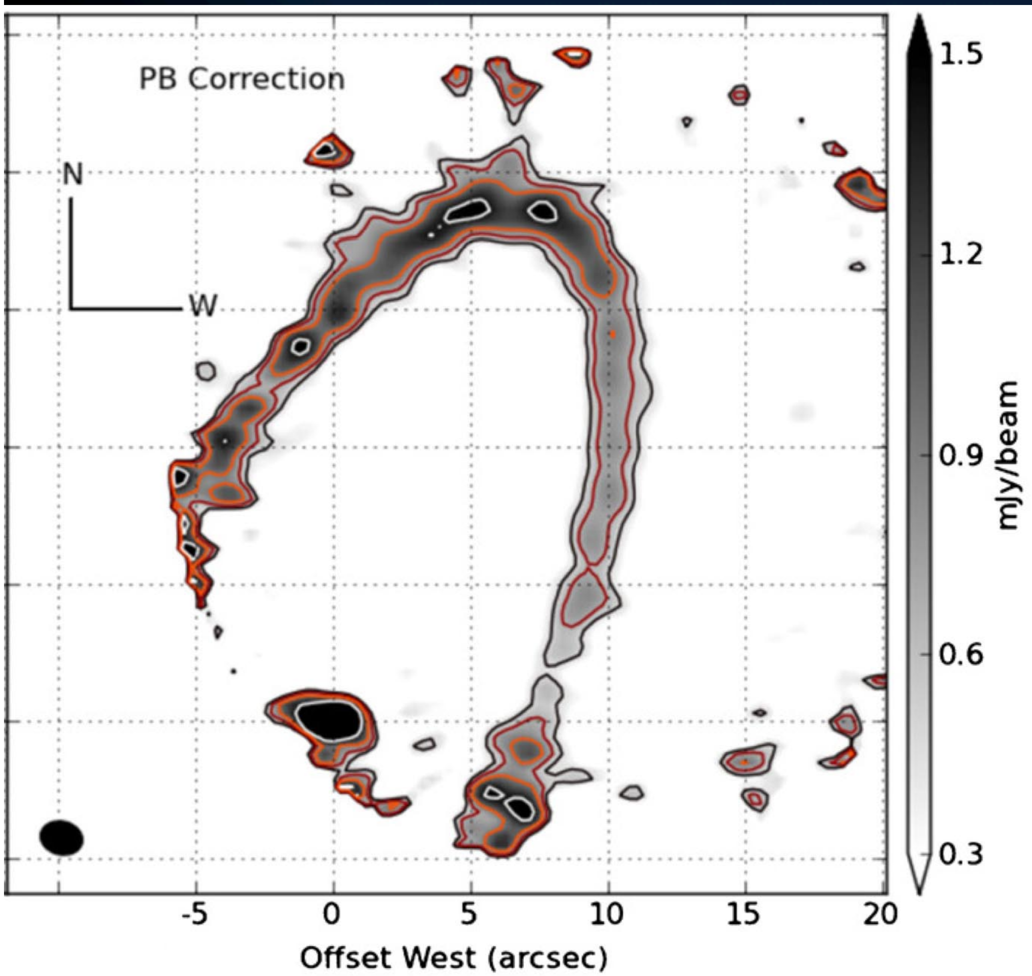
Saturn after 75 kyr

Numerical model (Kalas et al. 2013)

Future Breakthroughs with ALMA

- Future = 2 year to 100 years from now
- Detect Fomalhaut b, understand its nature
- Map the azimuthal gap – why is it there?
- Are there other azimuthal and radial variations?
- Map other dust belts in the system with indirect detections of other planets
- Detect changes in the system over decade timescales

Current ALMA 870 μm Map (band 7)

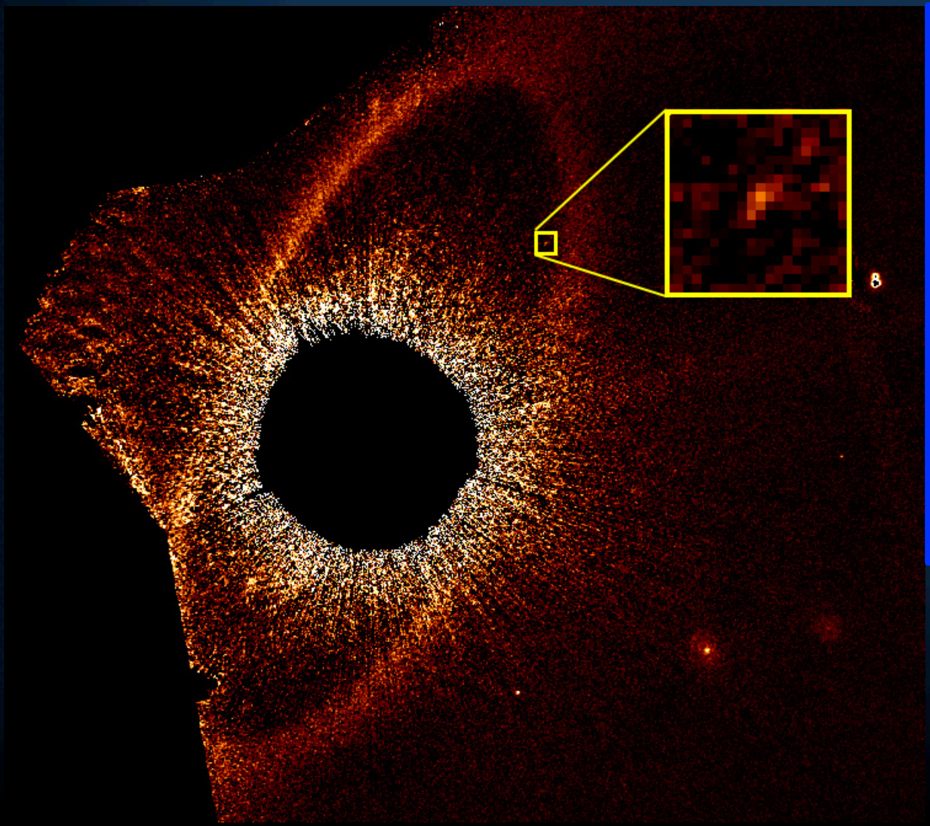


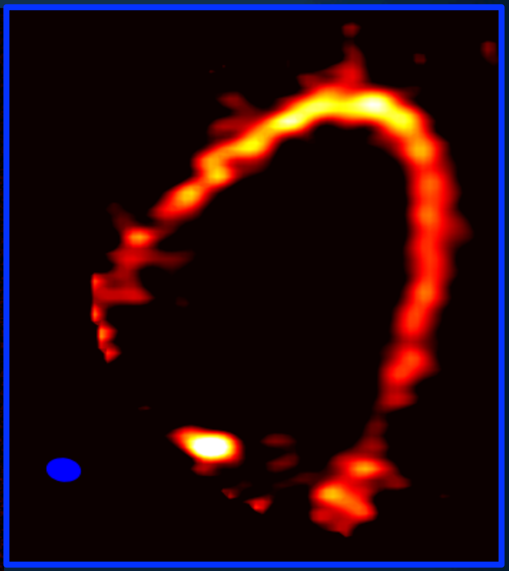
Boley et al. 2012

- Northern half of Fomalhaut
- 140 min, 13/15 ant., 150 m
- rms ~ 60 microJy/beam
- 1.5" x 1.2" beam
- ~85 mJy total dust emission
- ~1.4 mJy excess from star
- Ring FWHM ~ 14 AU
- M_{mm} ~ 1.4 Moon
- Clumpy structure? TBD
- Excess emission north? yes

Future Breakthroughs with ALMA

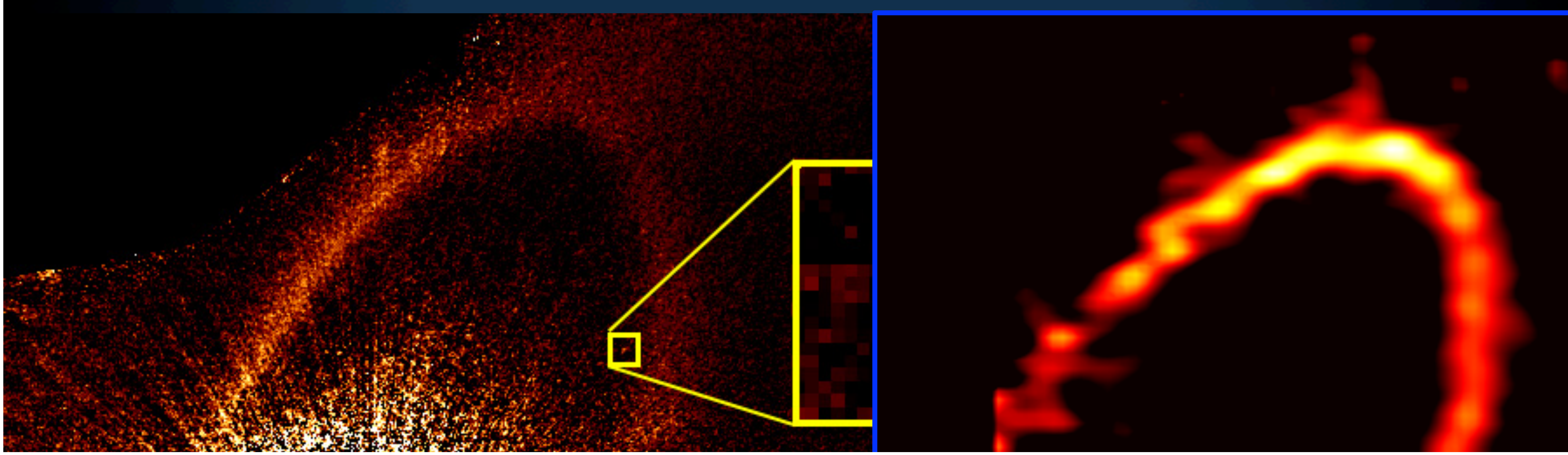
- Detect Fomalhaut b, understand its nature, and then monitor for 30 years as it passes within or close to the main belt.





Deep ALMA images of Fomalhaut b also would include the azimuthal gap region

- If due to a planet within the belt (gap represents tadpole/horseshoe orbits of belt particles), then the gap will rotate 360˚/1200 yr = 0.3˚/yr
- Due to projection effects, the gap will move 0.4" in the sky plane in 10 years.



Future Breakthroughs with ALMA

- Are there other azimuthal and radial variations?
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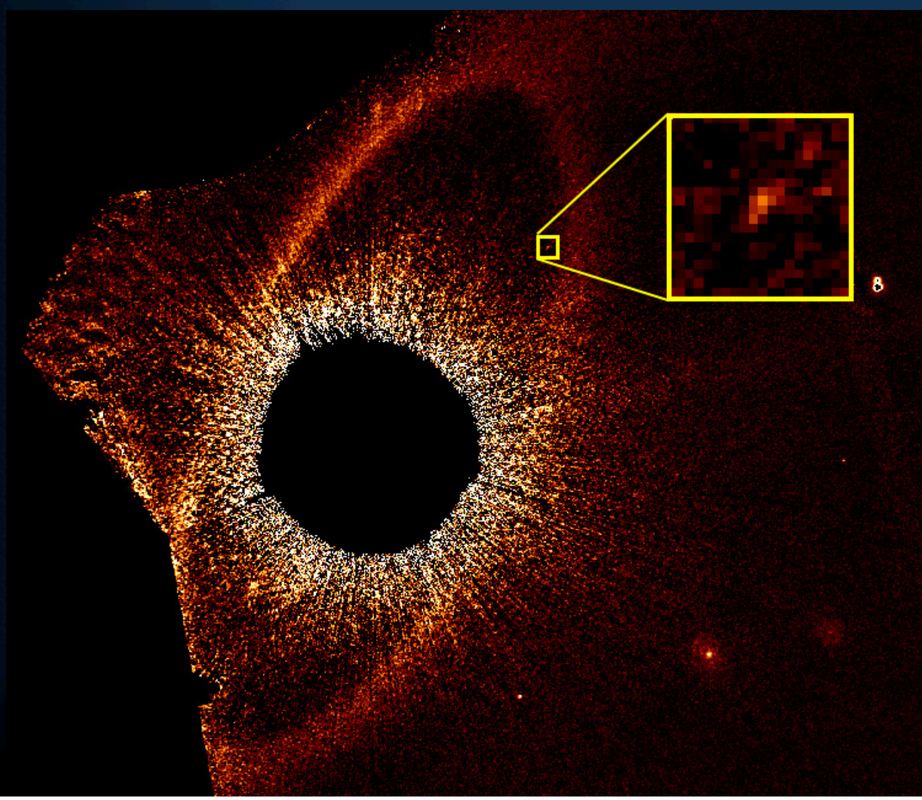

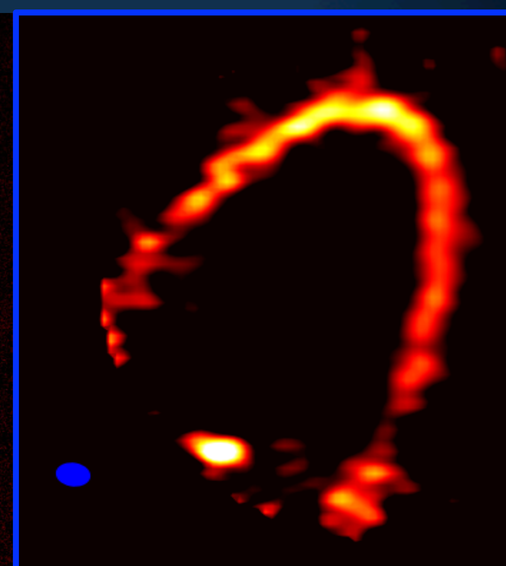

Potential transformational ALMA science

- Detect the satellite system of an extrasolar planet
- Observe the physics of its dynamical encounter with an extrasolar Kuiper Belt
- Map the dynamical details of a planet-planet scattering events
- Understand how planetary systems, including our own, rearrange their architectures at early epochs.

Conclusions

- Four epochs of HST astrometry (ACS+STIS) from 2004-2012 impose significant constraints on the orbital elements of Fomalhaut b
- The orbit is:
  - Eccentric: e=0.8±0.1
  - "Belt crossing" *in projection*
  - Periastron at 32±24 AU
  - Mutual inclination w.r.t. belt 17˚± 12˚
- The mass is between Ceres and 1 Jupiter
- The main belt has a 50 AU wide azimuthal gap