SIGNS OF PLANETS IN YOUNG DISKS

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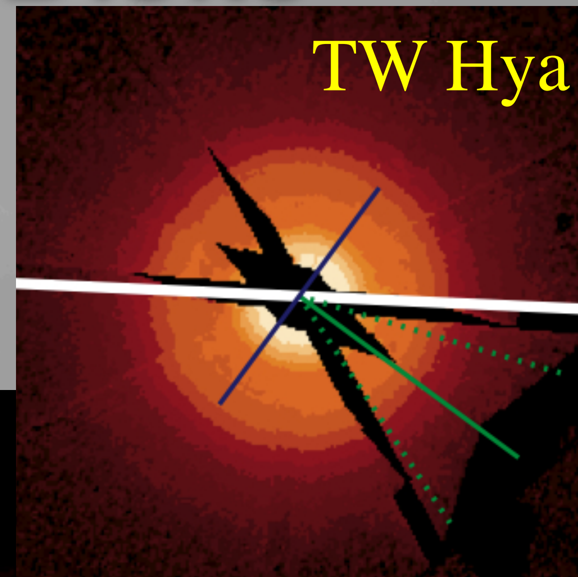
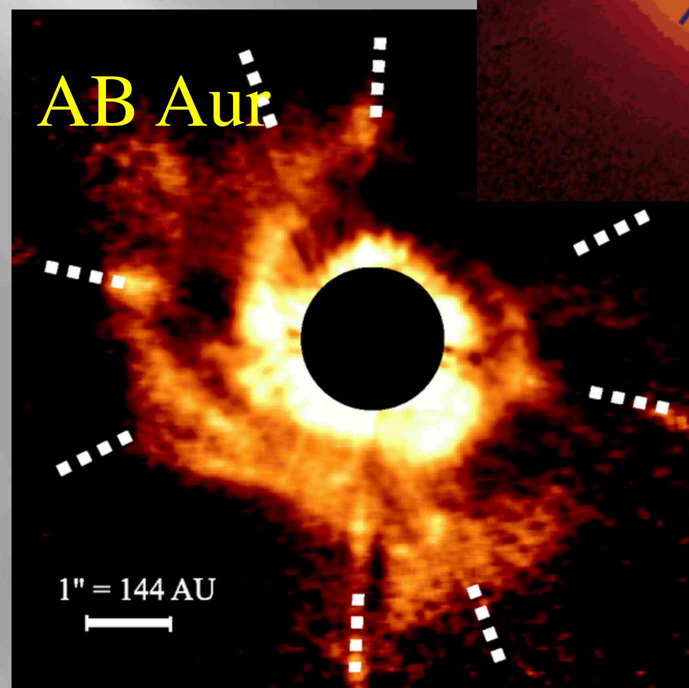
Protoplanetary Disks

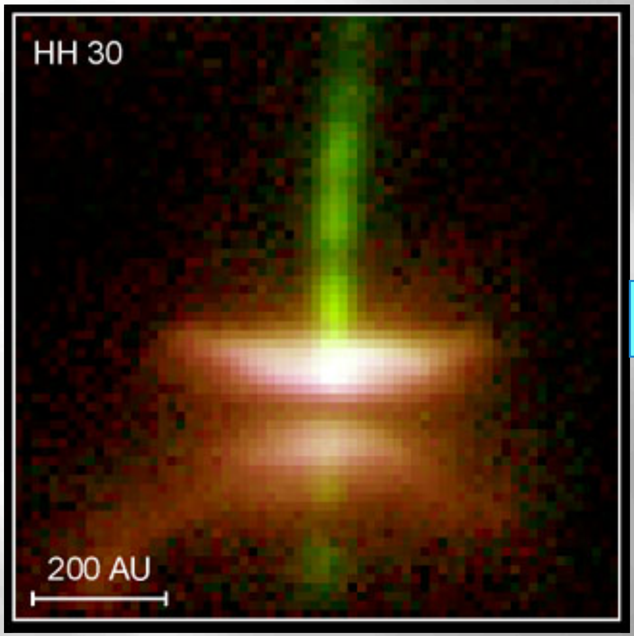
- T Tauri (F,G,K stars) or Herbig Ae/Be (A,B stars)
- Young (~1 Myr)
- Optically thick
- Gas-dominated
- Era of Giant Planet formation



Roberge, et al. 2005 (HST/STIS)

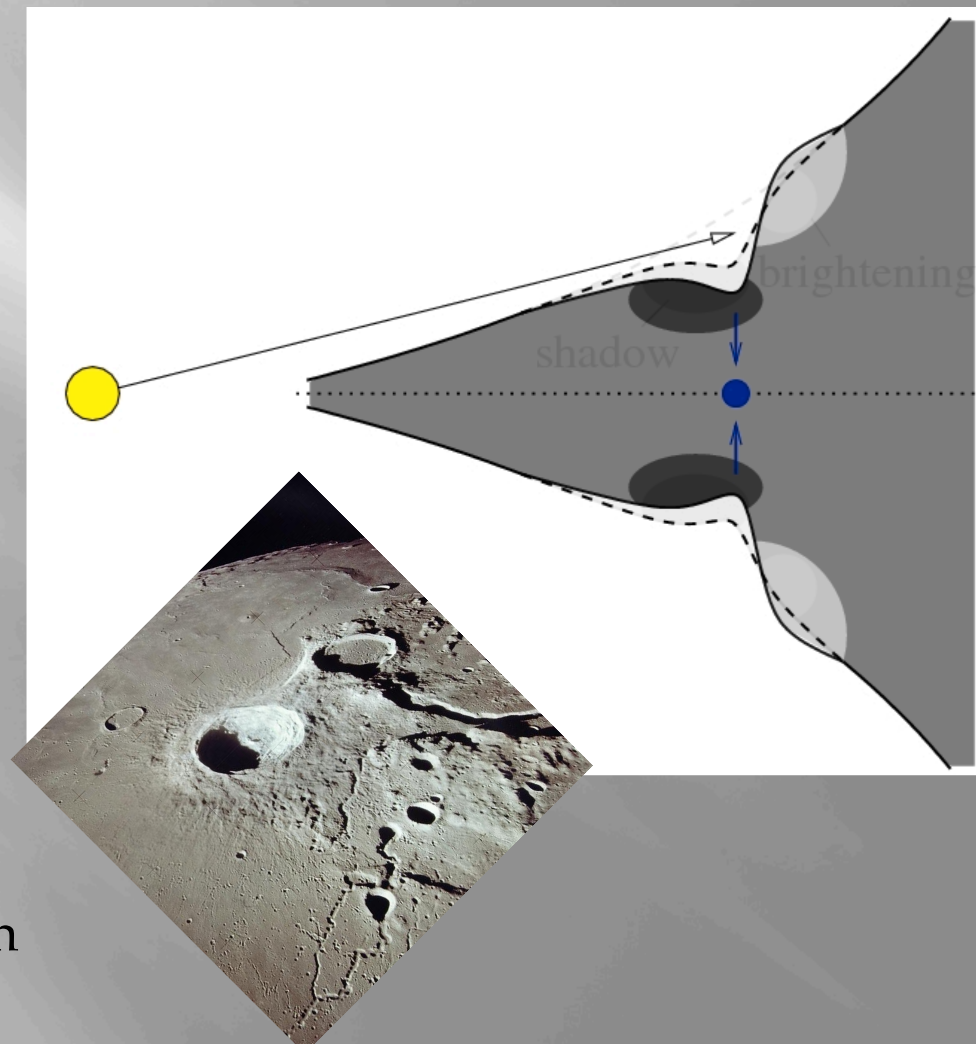


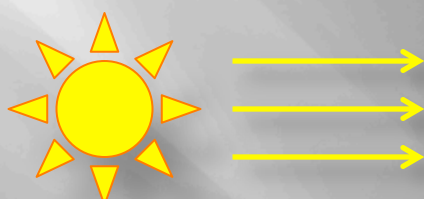
Fukagawa, et al. 2004 (Subaru)



Directly Probe the Epoch of Planet Formation

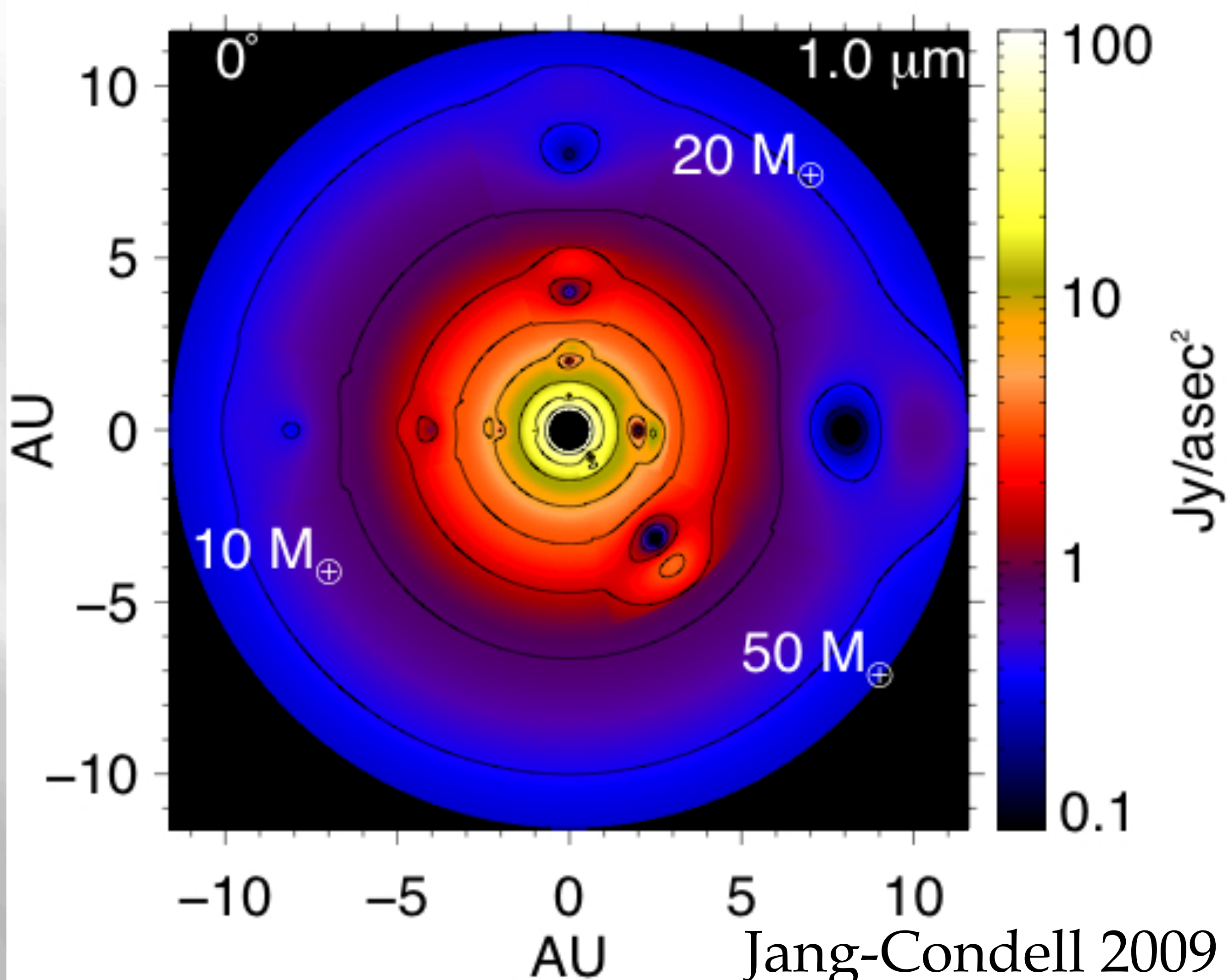
Disk Self-Shadowing





Aristarchus crater, the Moon
Credit: NASA (Apollo 15)

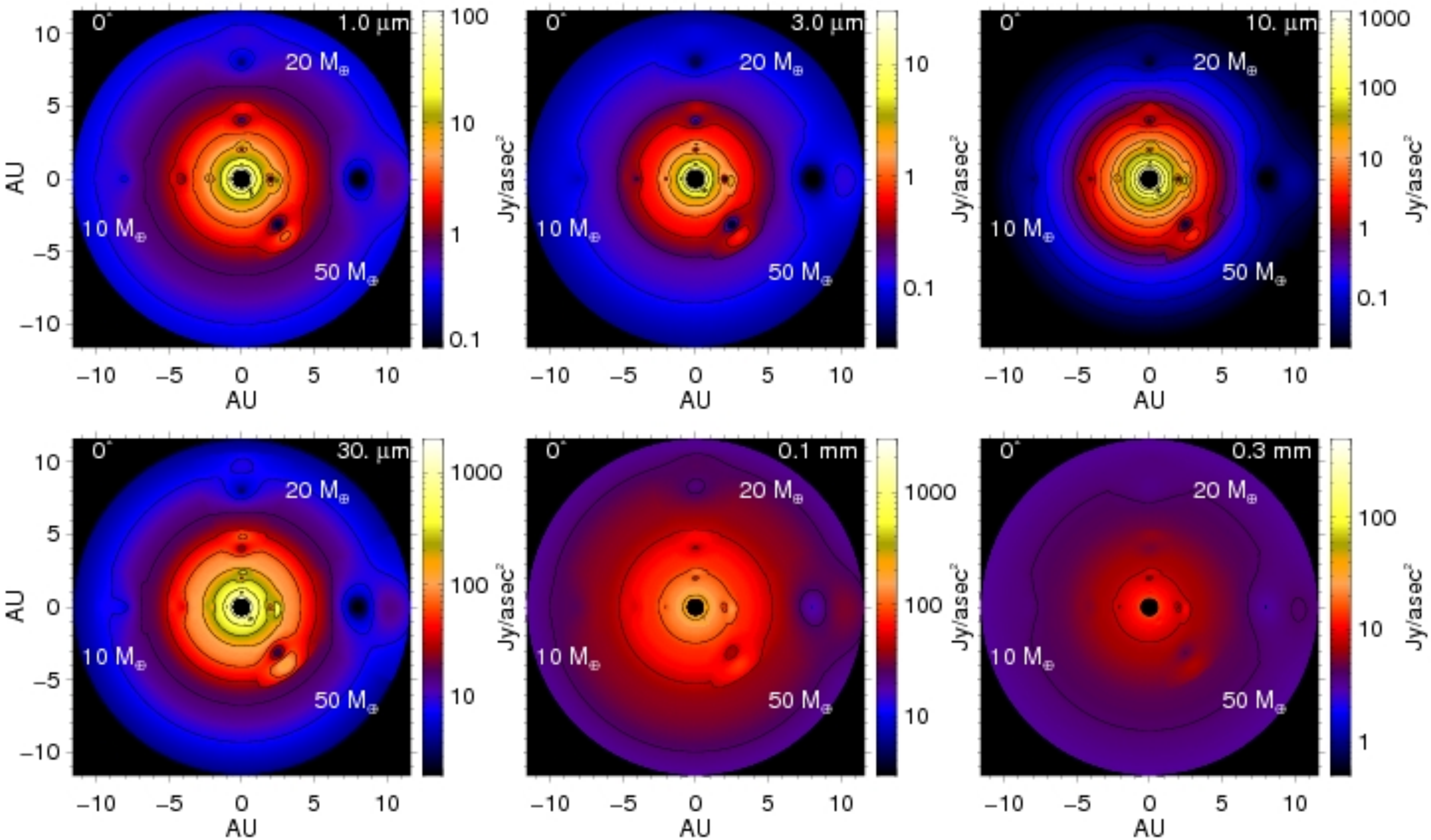
Planet Shadows at 1um



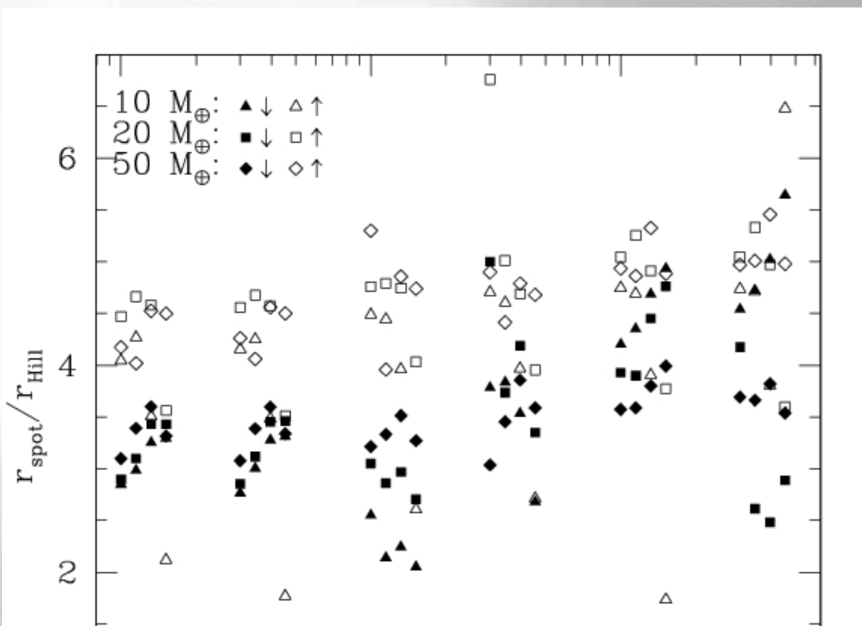
Jang-Condell 2009

Planet Shadows

Jang-Condell 2009

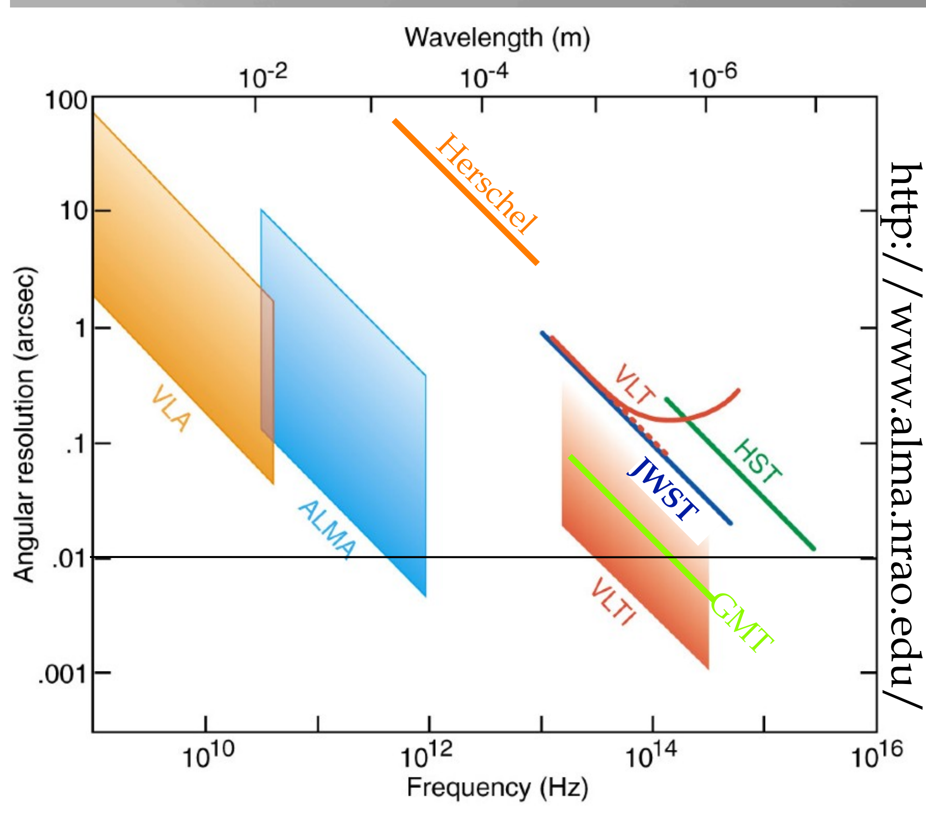


Angular Resolution



$r_{Hill} = (m_p/3M_*)^{1/3}a$

	1 AU	2 AU	4 AU	8 AU
10 M_{Earth}	0.02	0.04	0.09	0.17
20 M_{Earth}	0.03	0.05	0.11	0.22
50 M_{Earth}	0.04	0.07	0.15	0.29

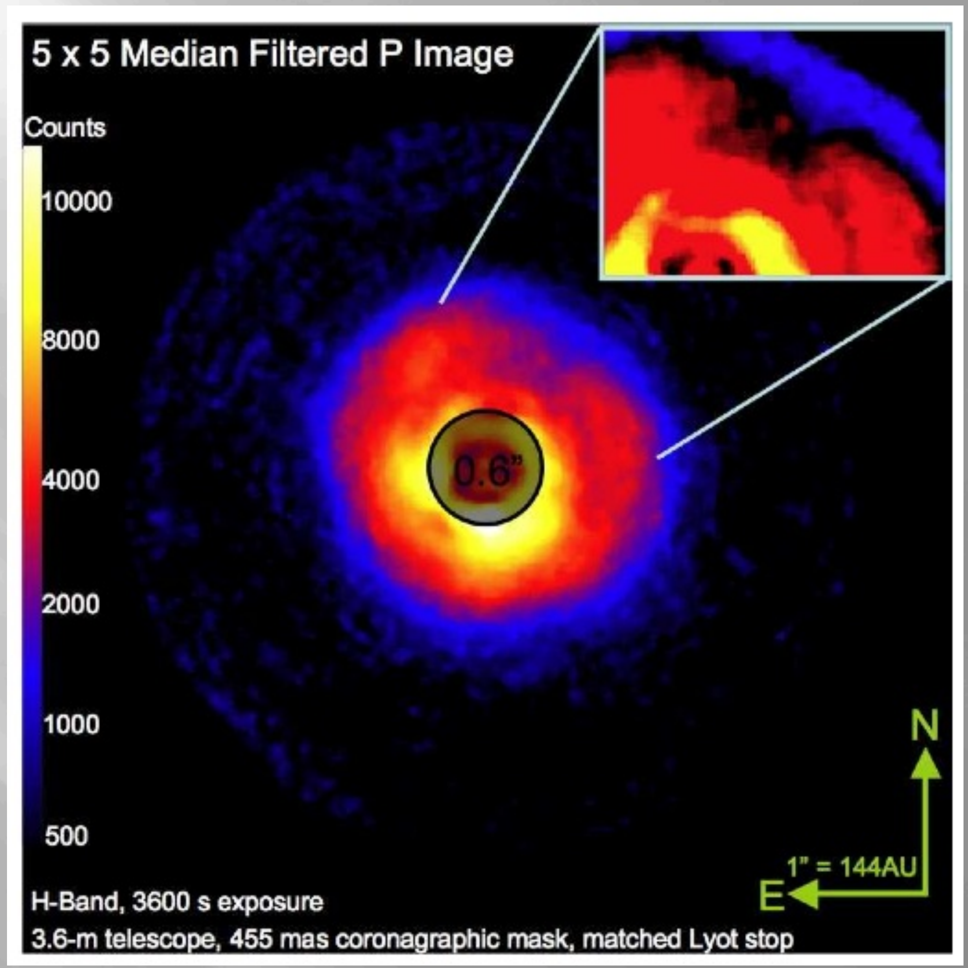


1 AU at 100 pc = 0.01”

Planet Shadows

- Increase in depth with planet mass
- Increase in size with
  - Planet mass
  - Planet distance
- A way to detect young, distant Jupiters?

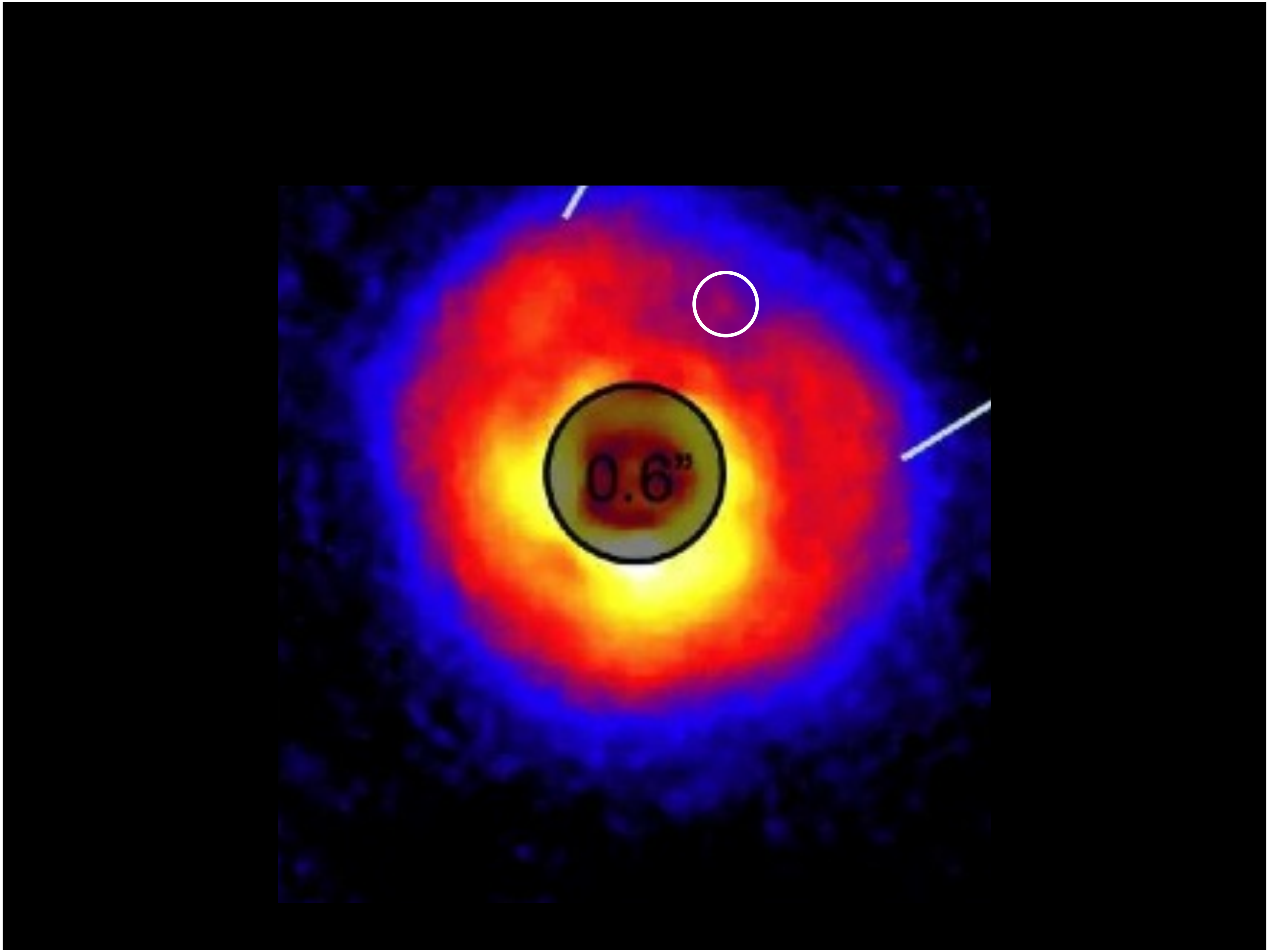
AB Aur

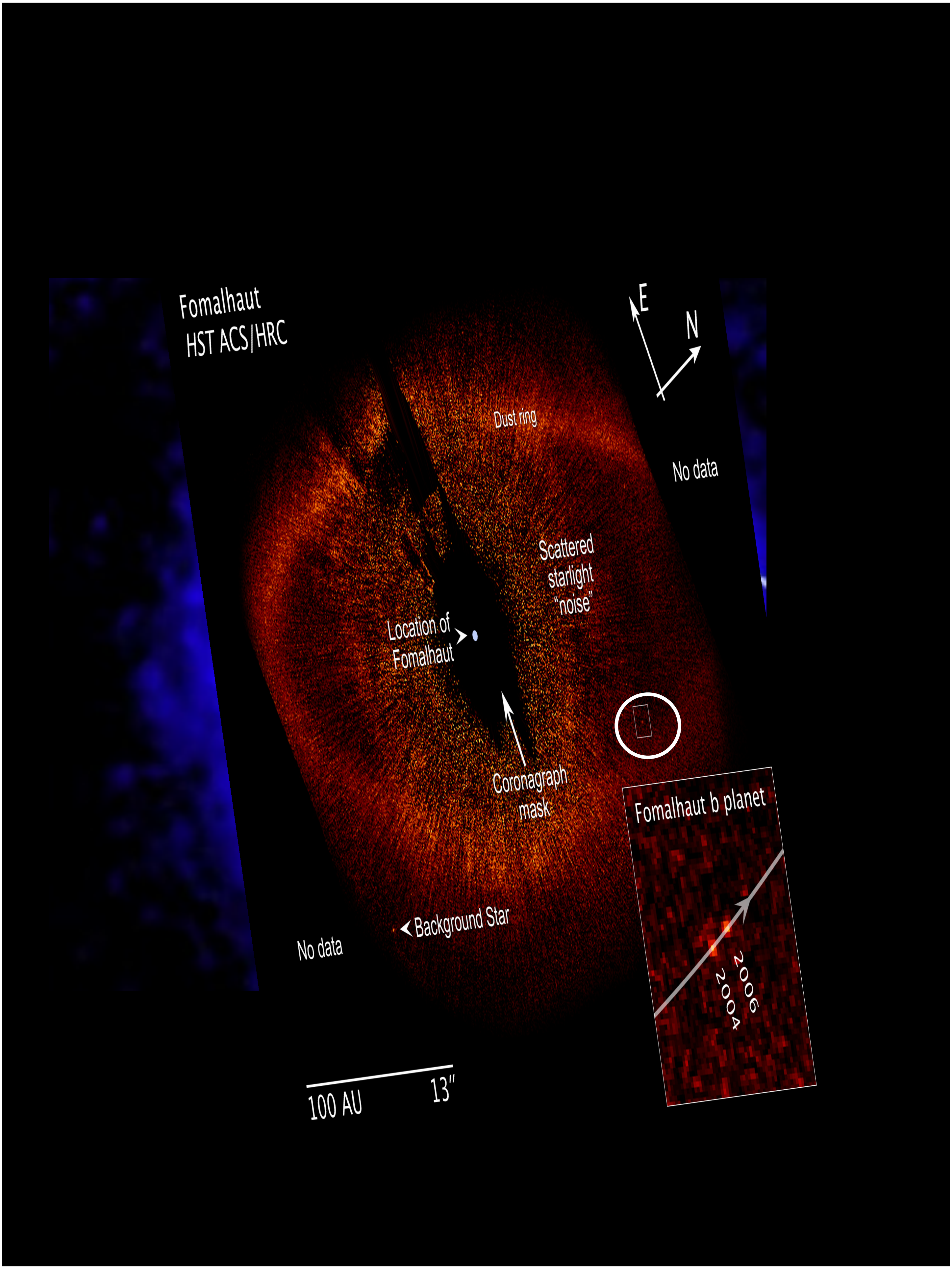


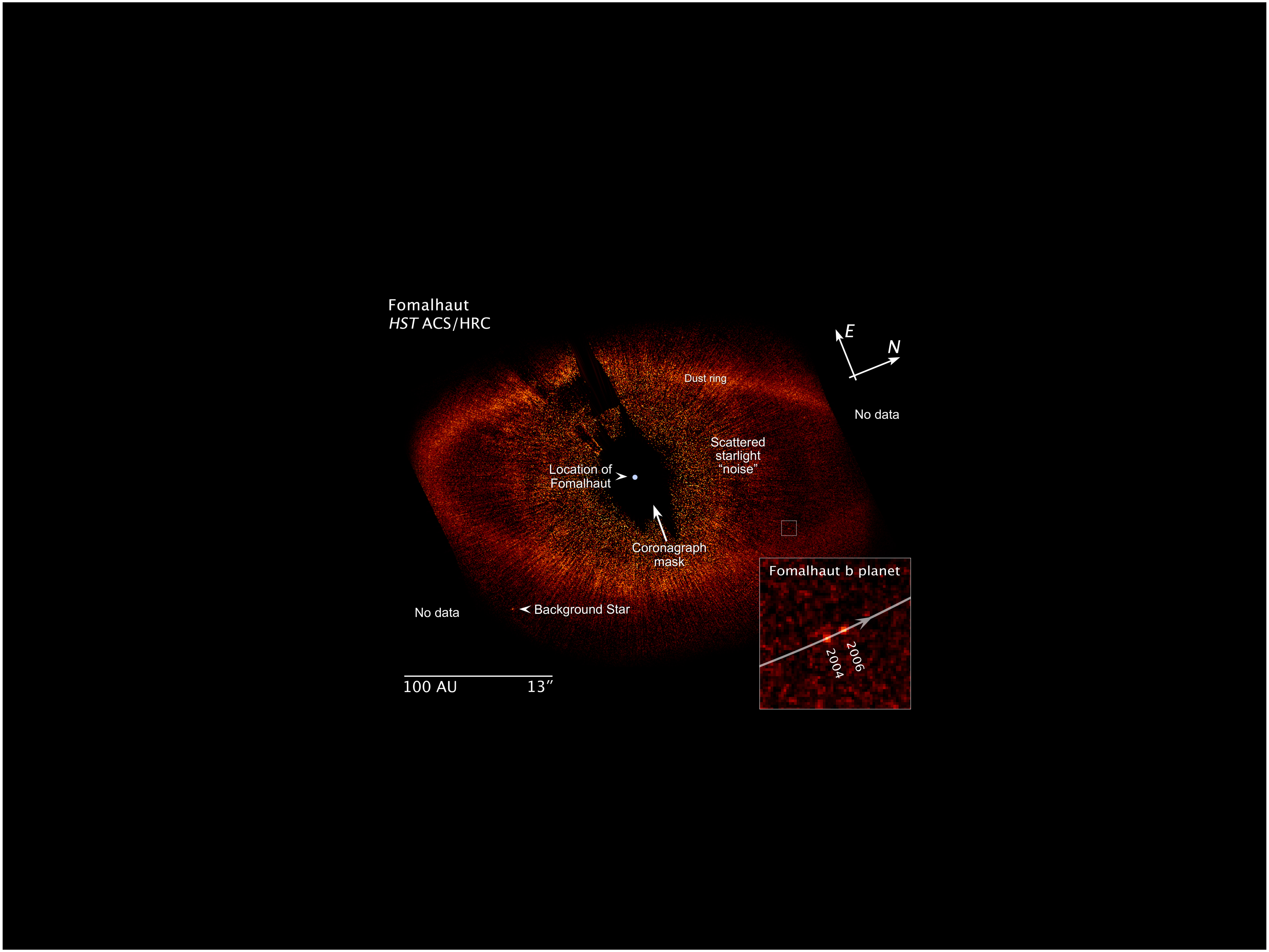
Oppenheimer, et al., 2008

"Spot"

- 2.8 σ
- 5-37 M_{Jup}


0.6"


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


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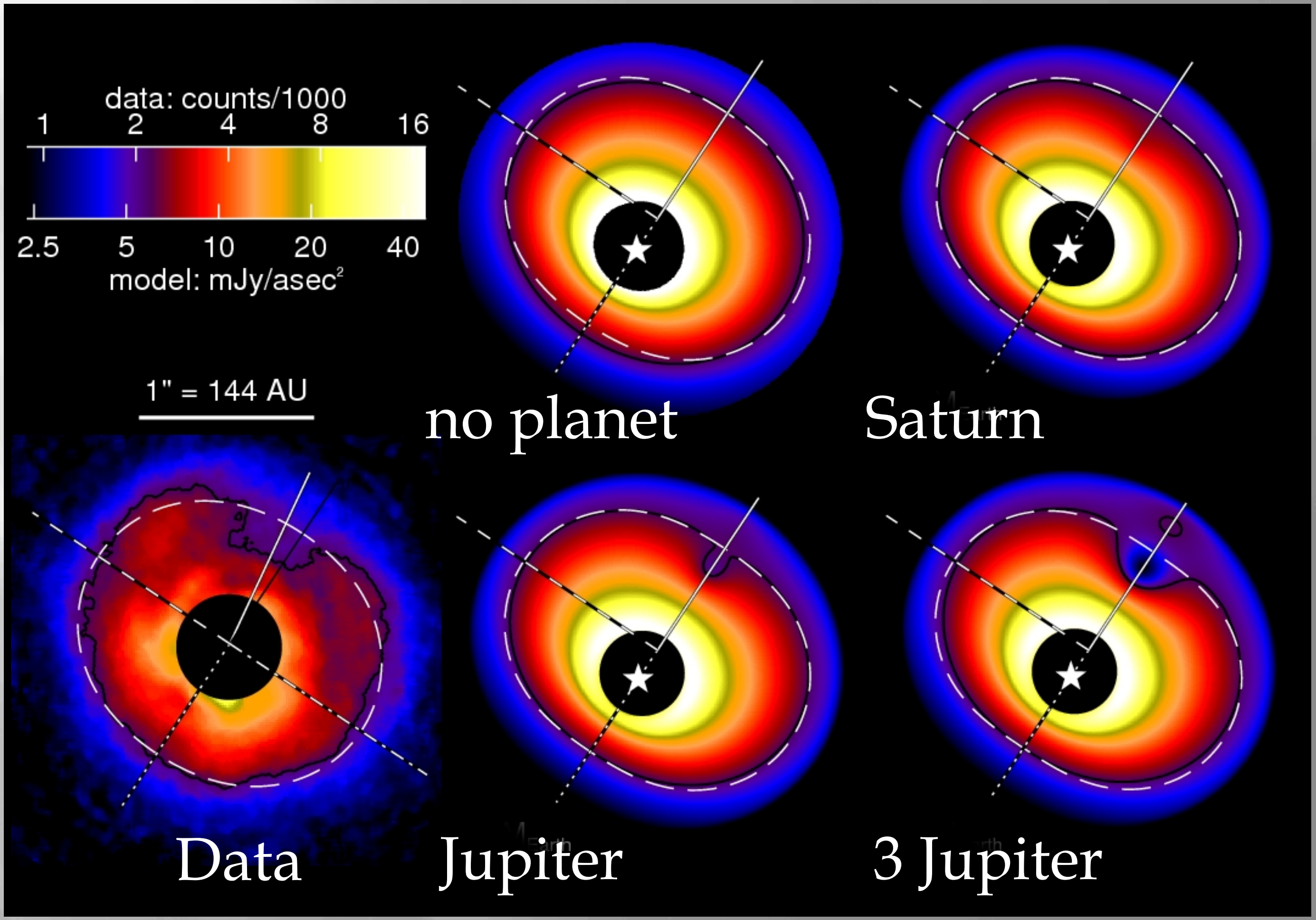
N
Dust ring
No data
Scattered starlight "noise"
Location of Fomalhaut
Coronagraph mask
Fomalhaut b planet
2004
2006
No data
Background Star
100 AU
13″

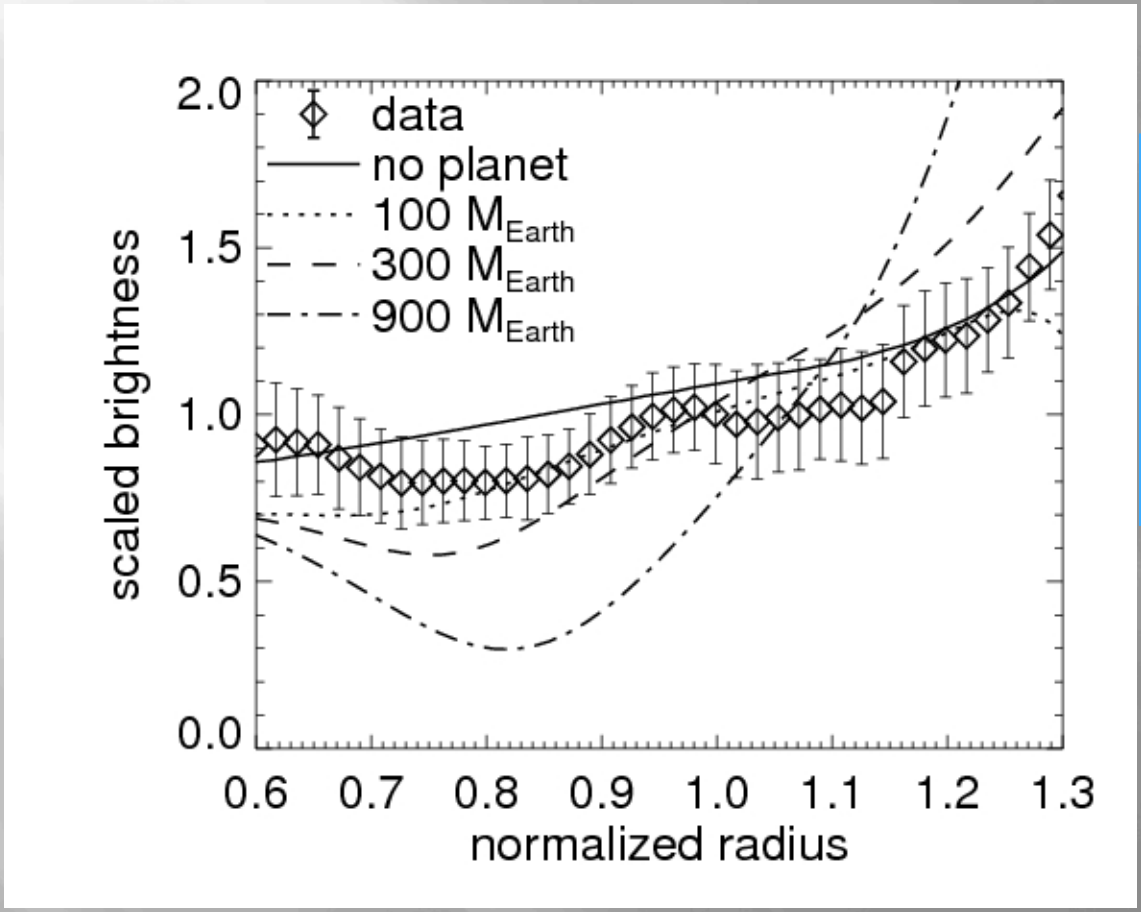
A planet in AB Aur?

Jang-Condell & Kuchner, 2010



< 1 M_{Jup} in AB Aur

Jang-Condell & Kuchner 2010



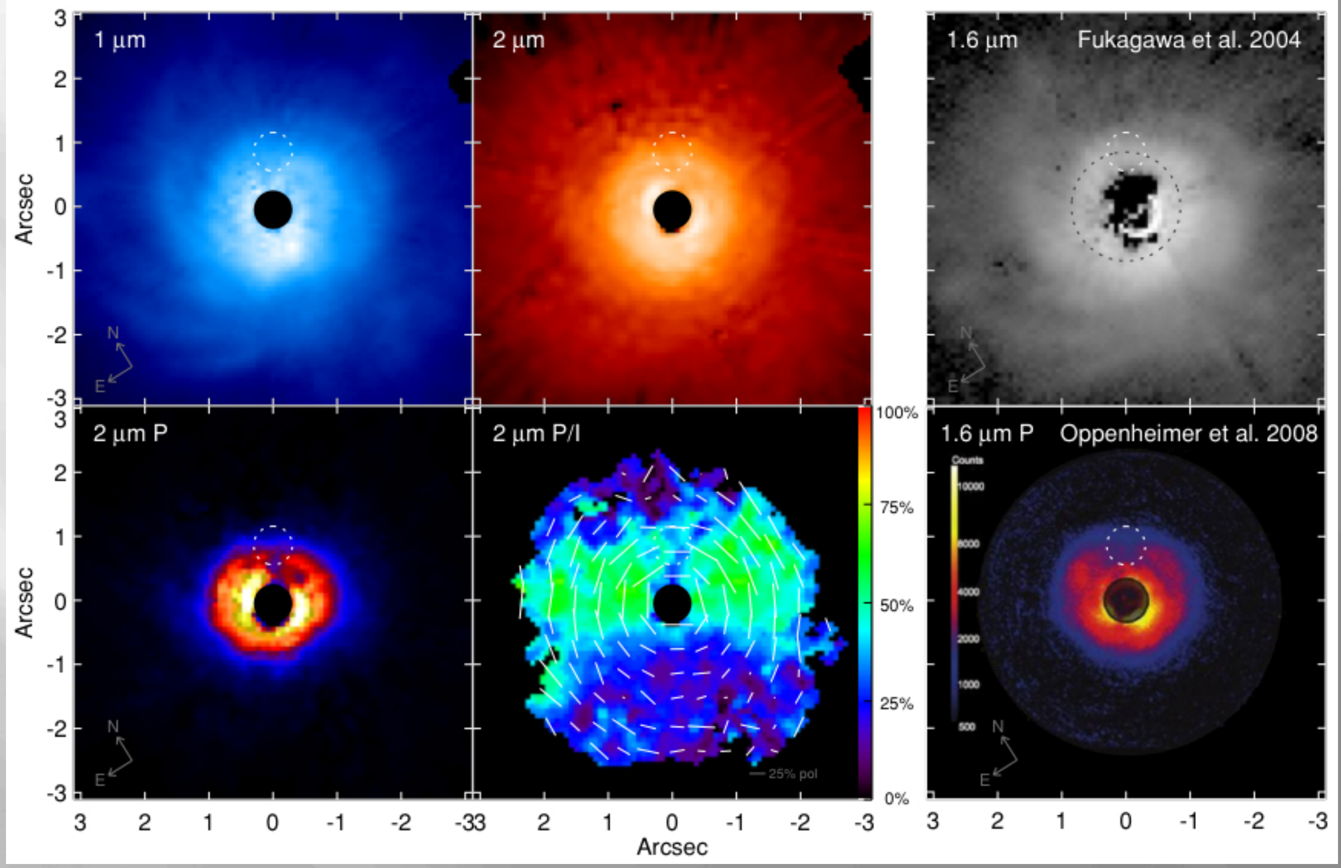
	χ_ν^2
No planet	0.8
Saturn	0.4
Jupiter	2.2
3 Jupiter	17

No 5-37 M_{jup} Planet!

Polarization “dimple”

Perrin, et al. 2009

NICMOS



Subaru

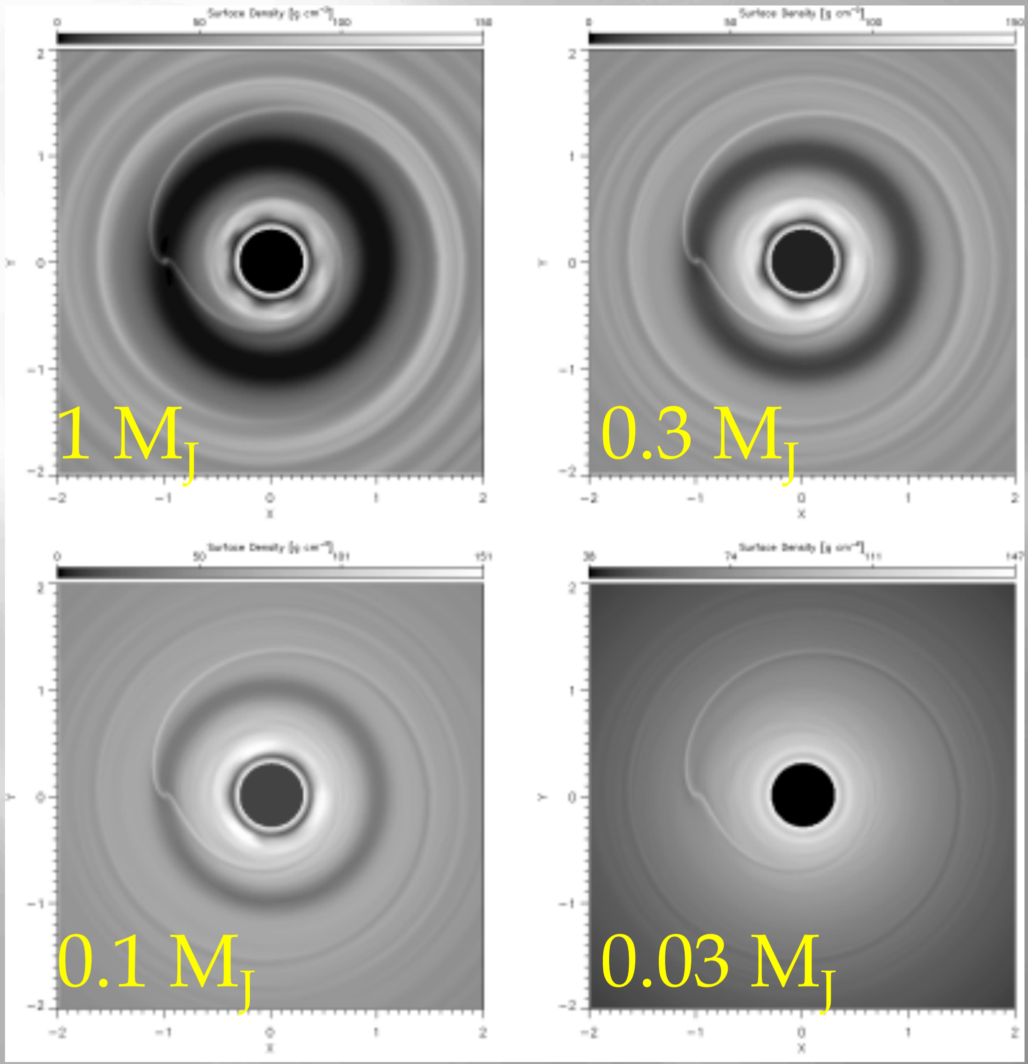
Lyot Project

A Cautionary Tale

- Scattered light doesn't tell the whole picture
- Be especially careful interpreting P images

- **Silver lining:** Jupiter-mass planets are detectable at ~100 AU in protoplanetary disks!

Gap Opening by Planets

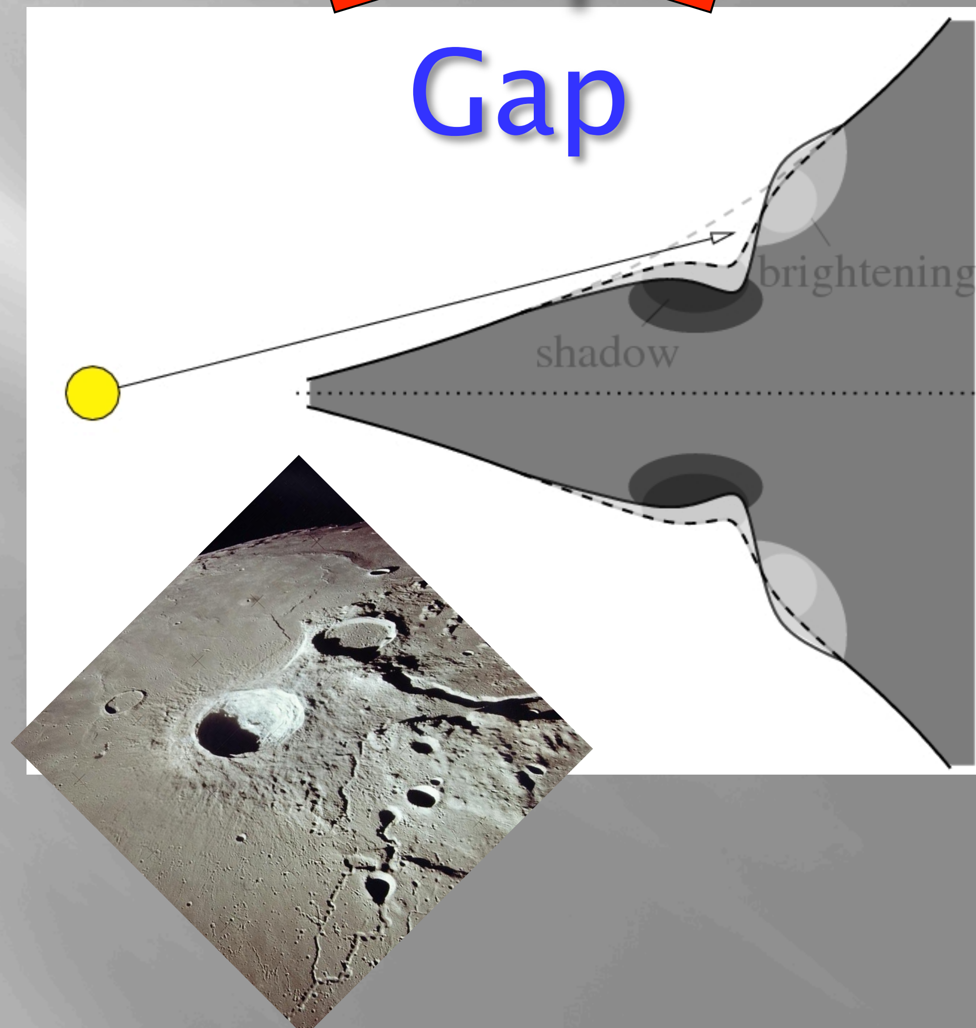


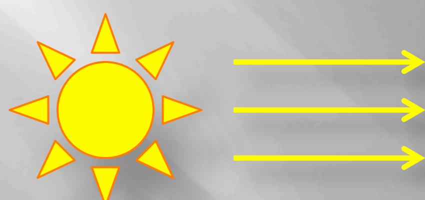
- Bate et al., 2003
- Gap-opening threshold (Crida, et al. '06

$$\frac{3H}{4r_{Hill}} + \frac{50}{q\mathrm{Re}} = 1$$

- $M_{crit} = 1\ M_J$

Shadowed ~~Dimple~~ Gap





Aristarchus crater, the Moon
Credit: NASA (Apollo 15)

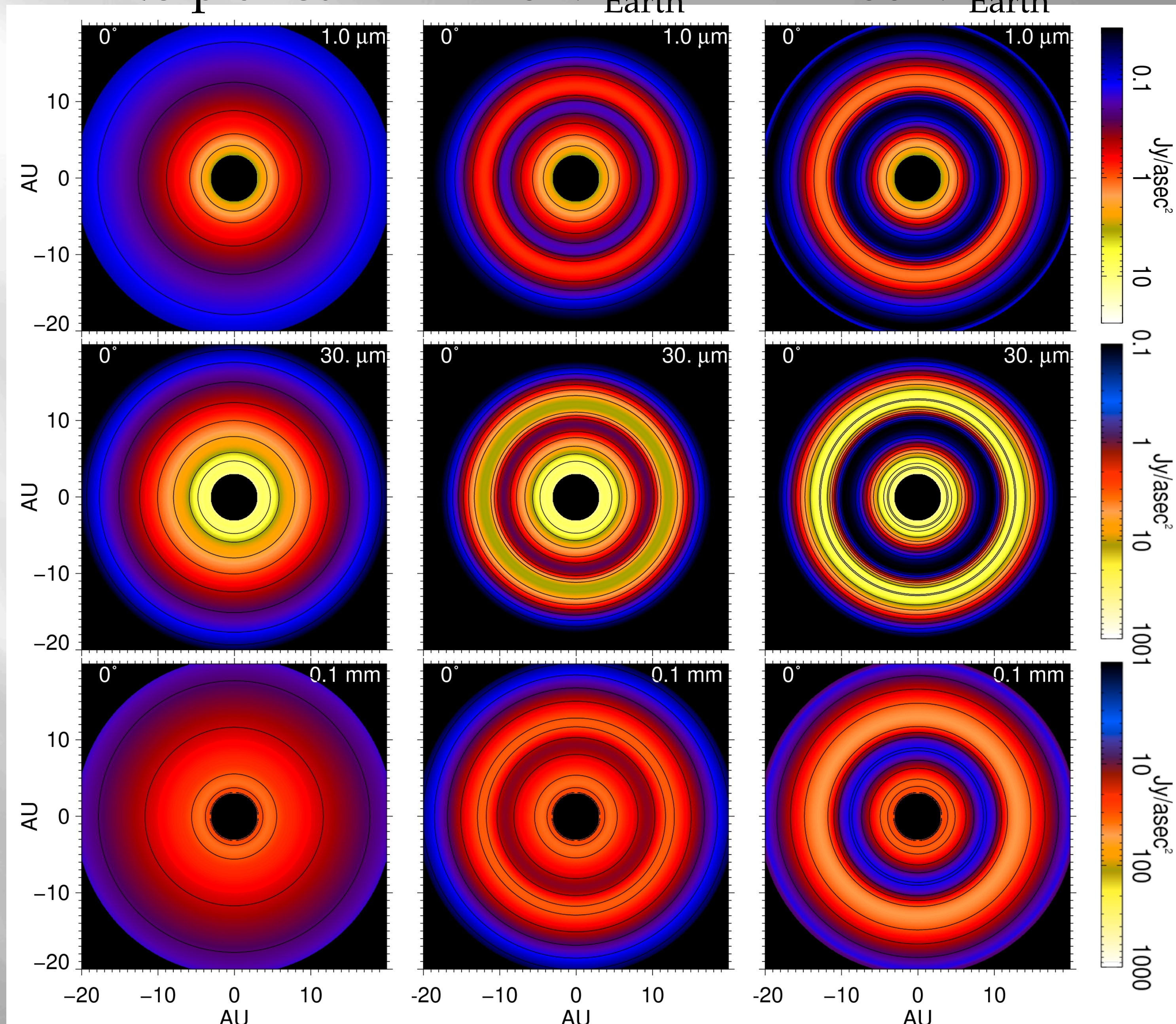
Gap At 10 AU

No planet | 70 M_{Earth} | 200 M_{Earth}

1 um

30 um

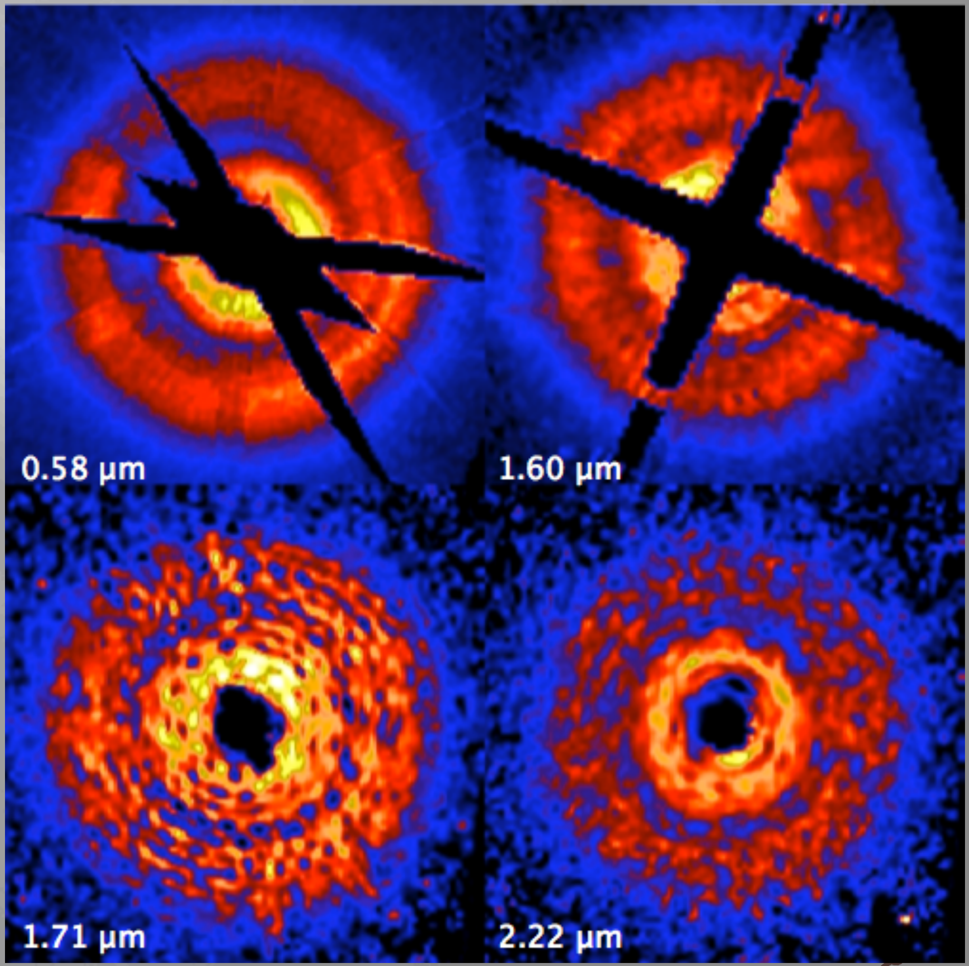
100 um



Jang-Condell & Turner 2011, submitted

TW Hya

- 56 parsecs
- Hubble observations
  - STIS
  - NICMOS
  - 7 wavelengths
- Debes, Jang-Condell, et al. (in prep)

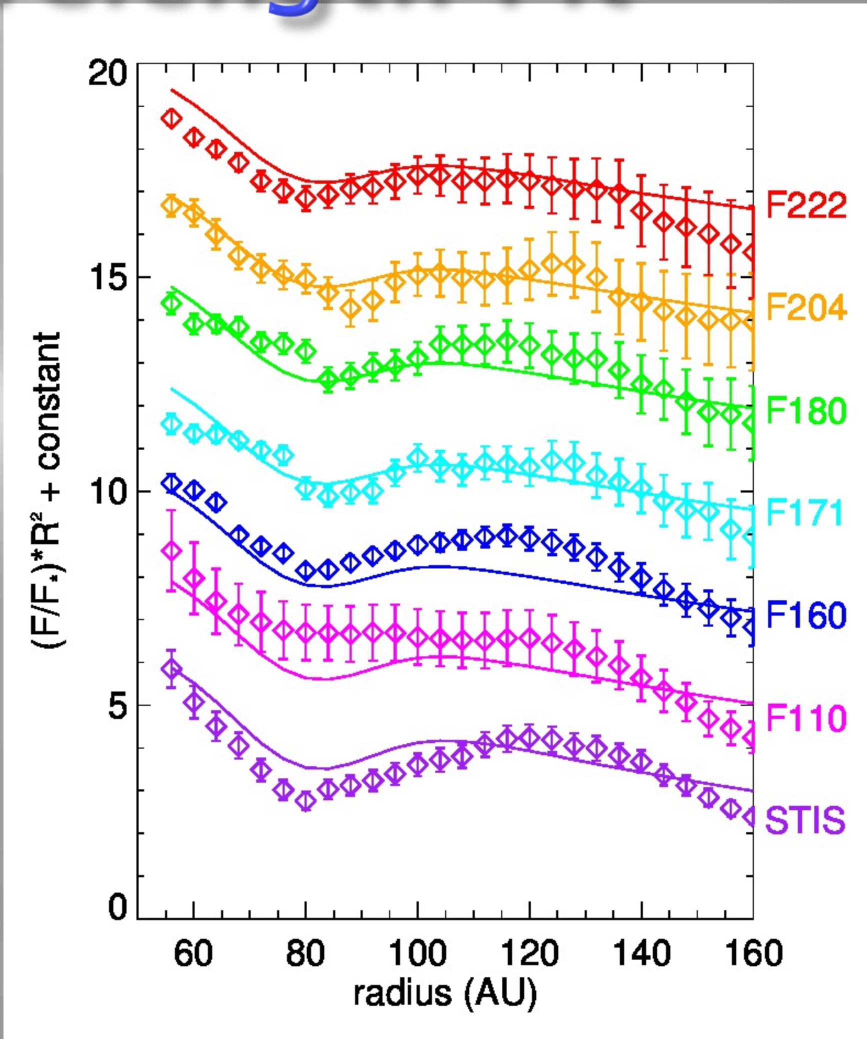


Multi-wavelength Fit

Fit parameters:

- Gap depth
- Gap width
- Grain size
- Disk truncation

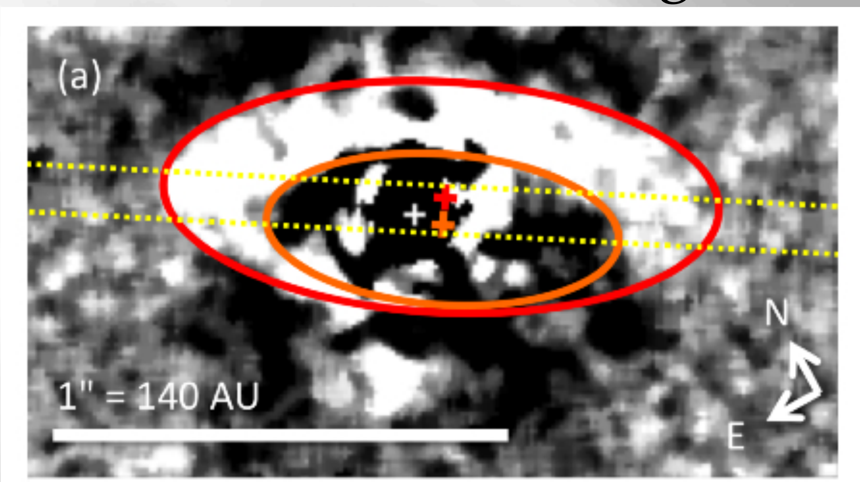
- **Gap depth 30%**
- **3-10 Earth mass planet**



Debes et al., in prep

LkCa 15

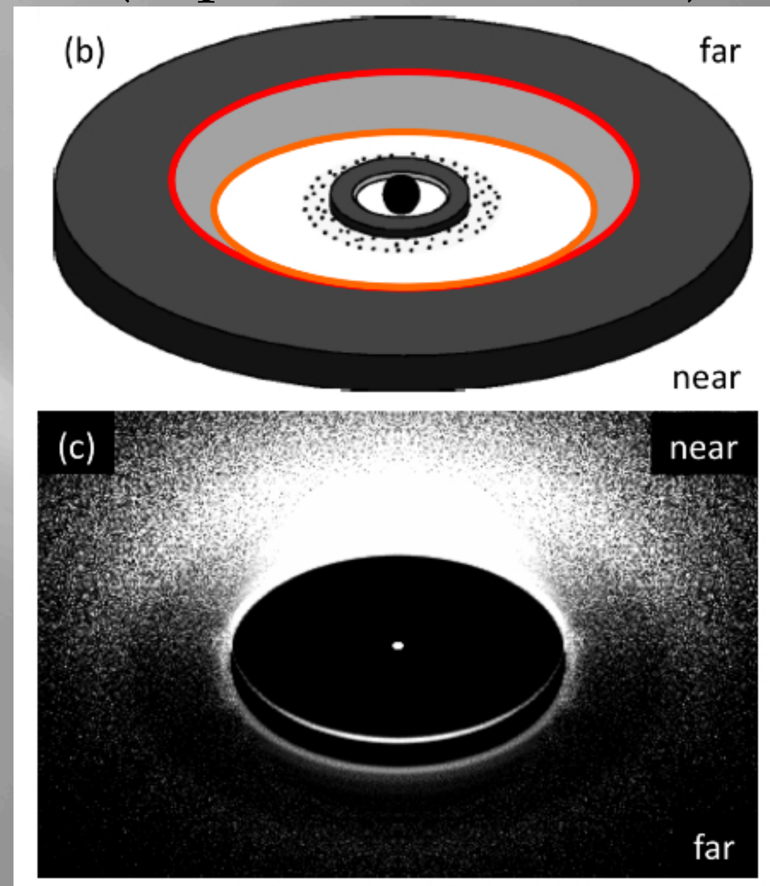
H-band scattered light



Thalmann et al., 2010

$$M_p < 6\ M_J$$

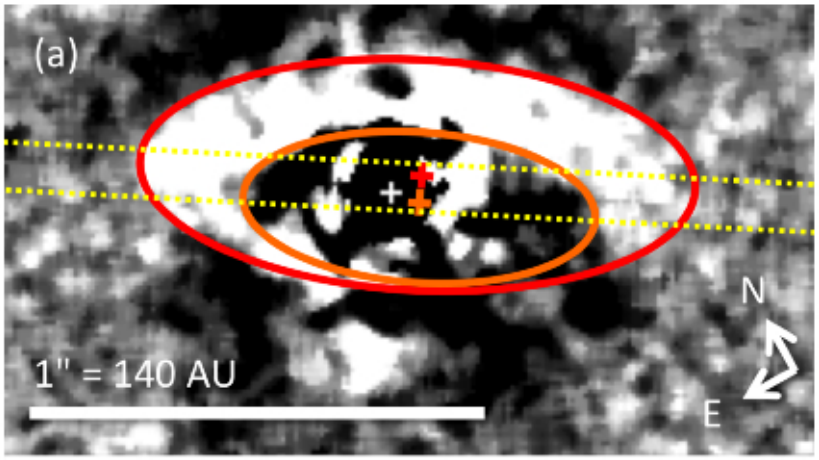
(Espaillat, et al. 2008)



(Mulders, et al. 2010)

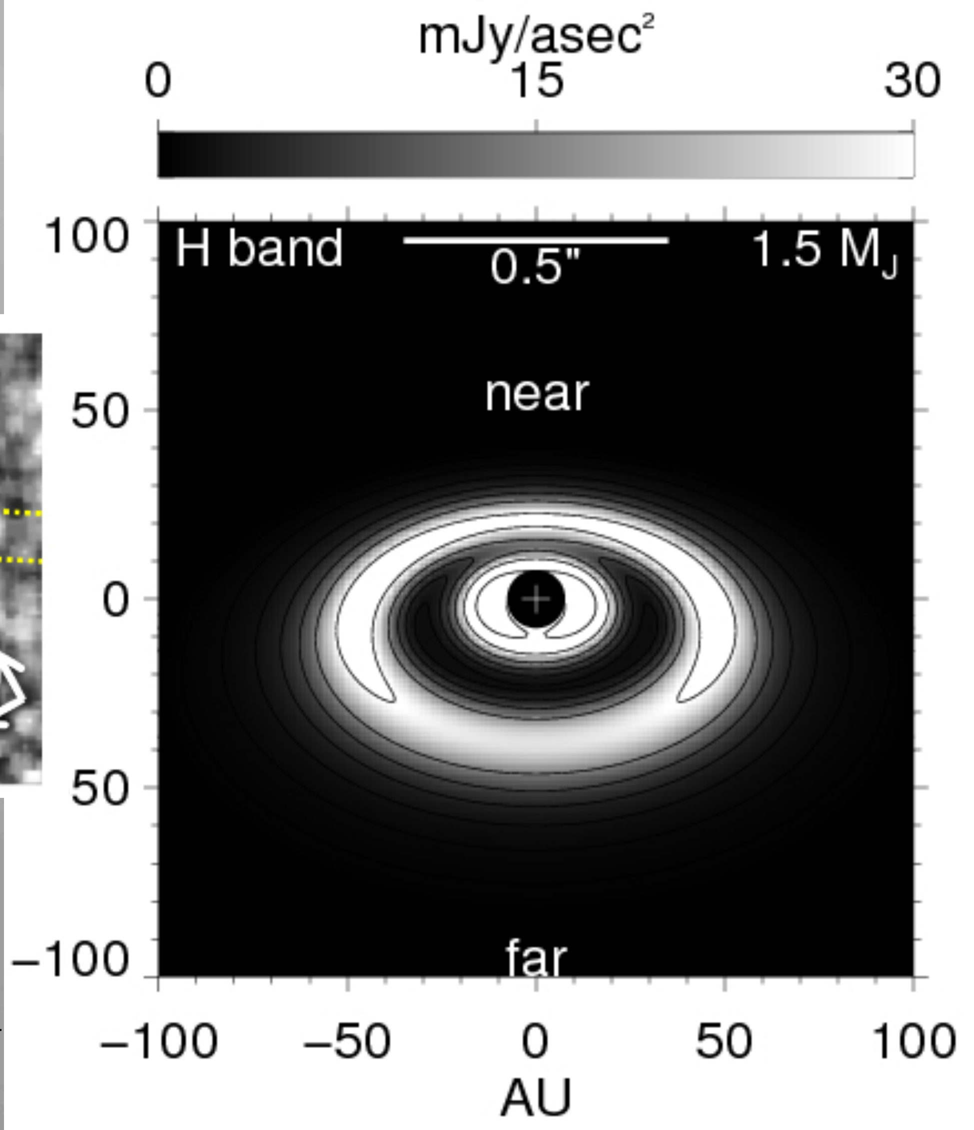
LkCa 15

H-band scattered light



Thalmann et al., 2010

$1.5\ M_J < M_p < 6\ M_J$



Jang-Condell & Turner 2011, submitted

Giant Planet Formation

Core Accretion

Terrestrial planet formation

Slow

~10^6-10^7 yr

Disk Instability

Fast

~10^3 yr

Distant Jupiters?

Disk Instability

- 3D hydrodynamic simulations of disk instability
- Self-gravitating clump formed

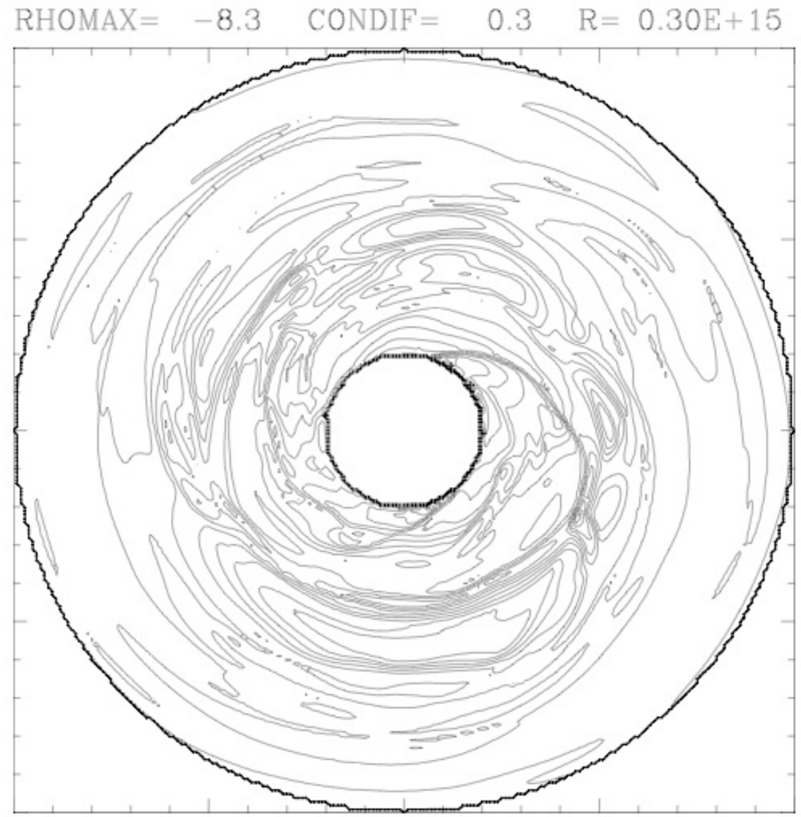
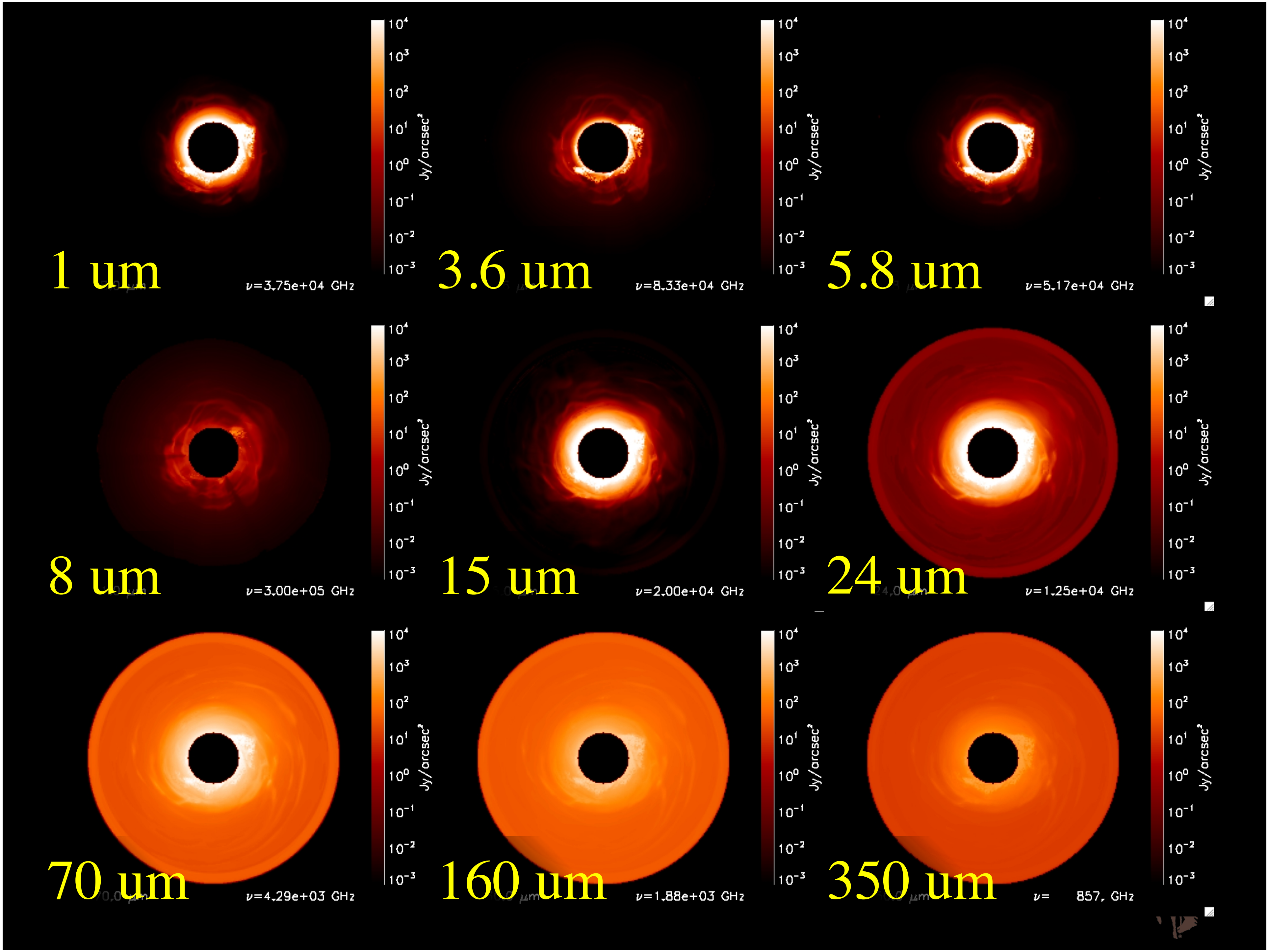
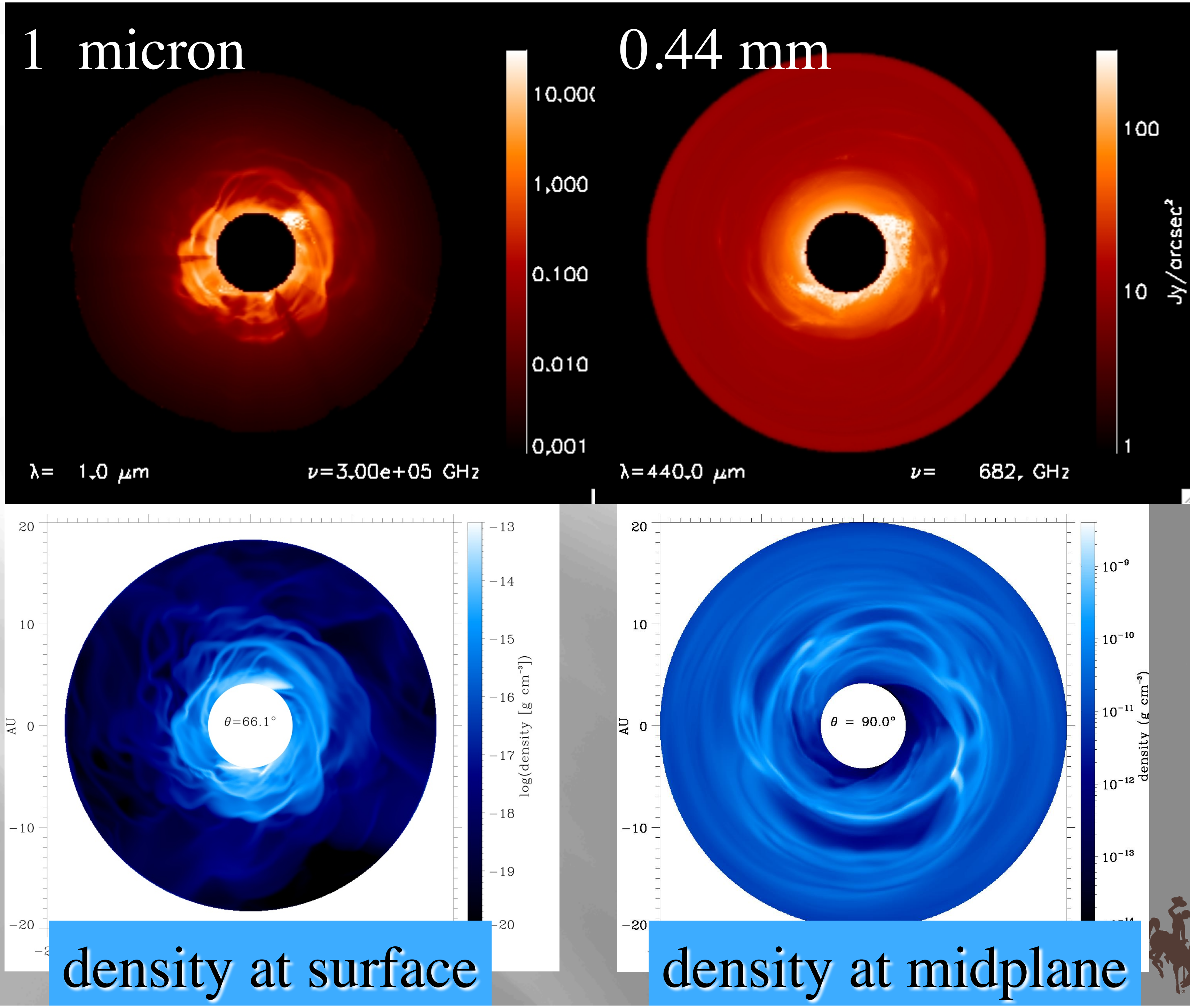


FIG. 2b

Boss 2001

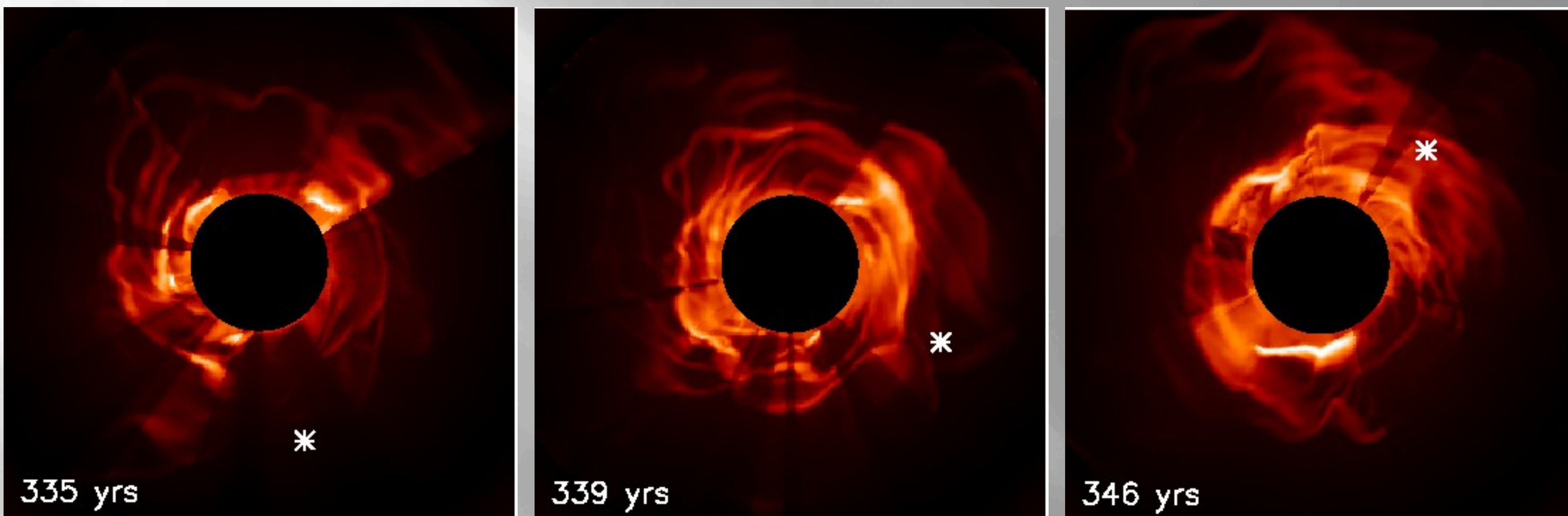


1 um
ν=3.75e+04 GHz
3.6 um
ν=8.33e+04 GHz
5.8 um
ν=5.17e+04 GHz
8 um
ν=3.00e+05 GHz
15 um
ν=2.00e+04 GHz
24 um
ν=1.25e+04 GHz
70 um
ν=4.29e+03 GHz
160 um
ν=1.88e+03 GHz
350 um
ν= 857. GHz
Jy/arcsec²
10⁴ 10³ 10² 10¹ 10⁰ 10⁻¹ 10⁻² 10⁻³



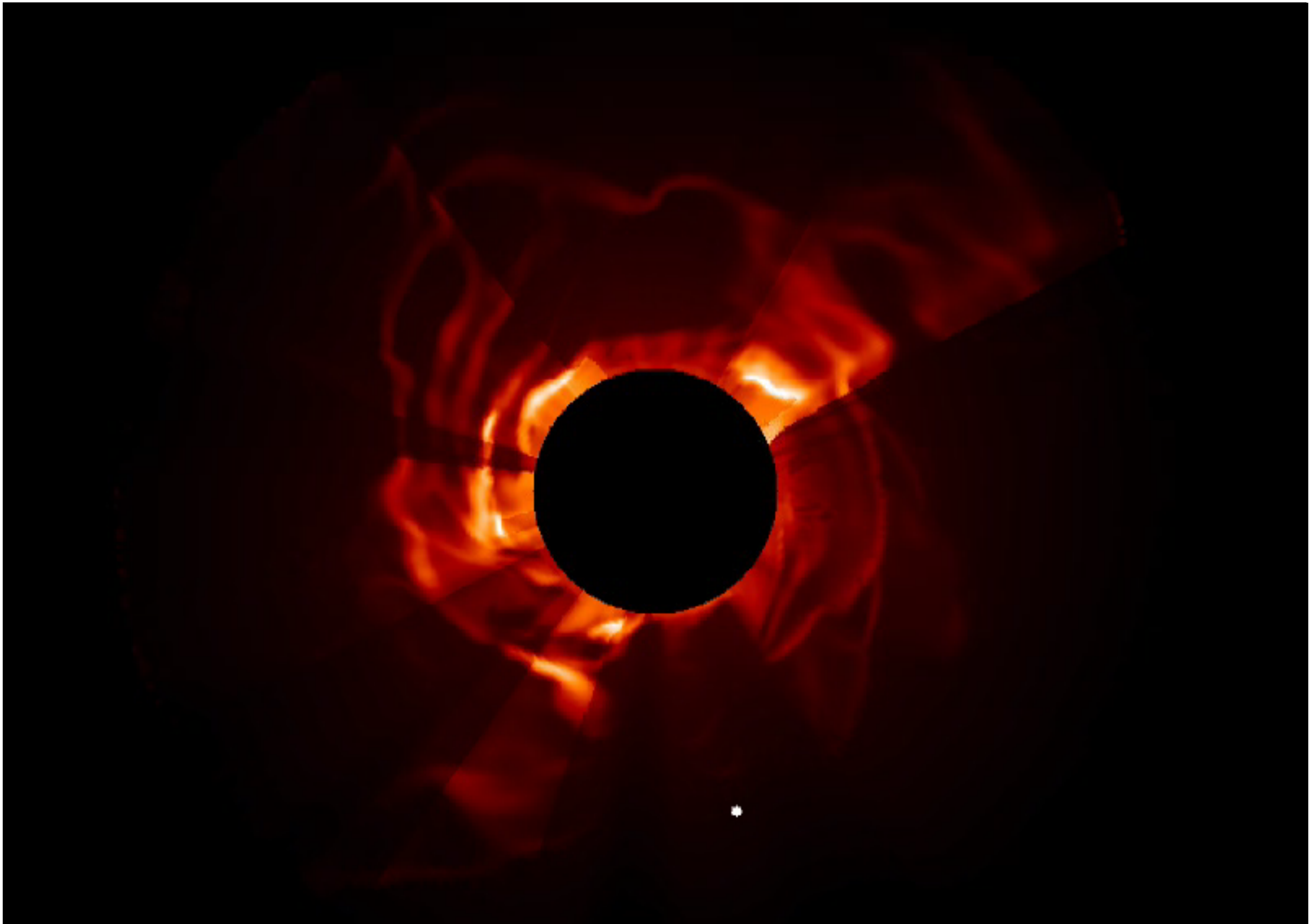
1 micron
0.44 mm
10,000
1,000
0.100
0.010
0.001
λ= 1.0 μm
ν=3.00e+05 GHz
100
10
1
Jy/arcsec²
λ=440.0 μm
ν= 682, GHz
AU
θ=66.1°
log(density [g cm⁻³])
θ = 90.0°
density (g cm⁻³)
density at surface
density at midplane

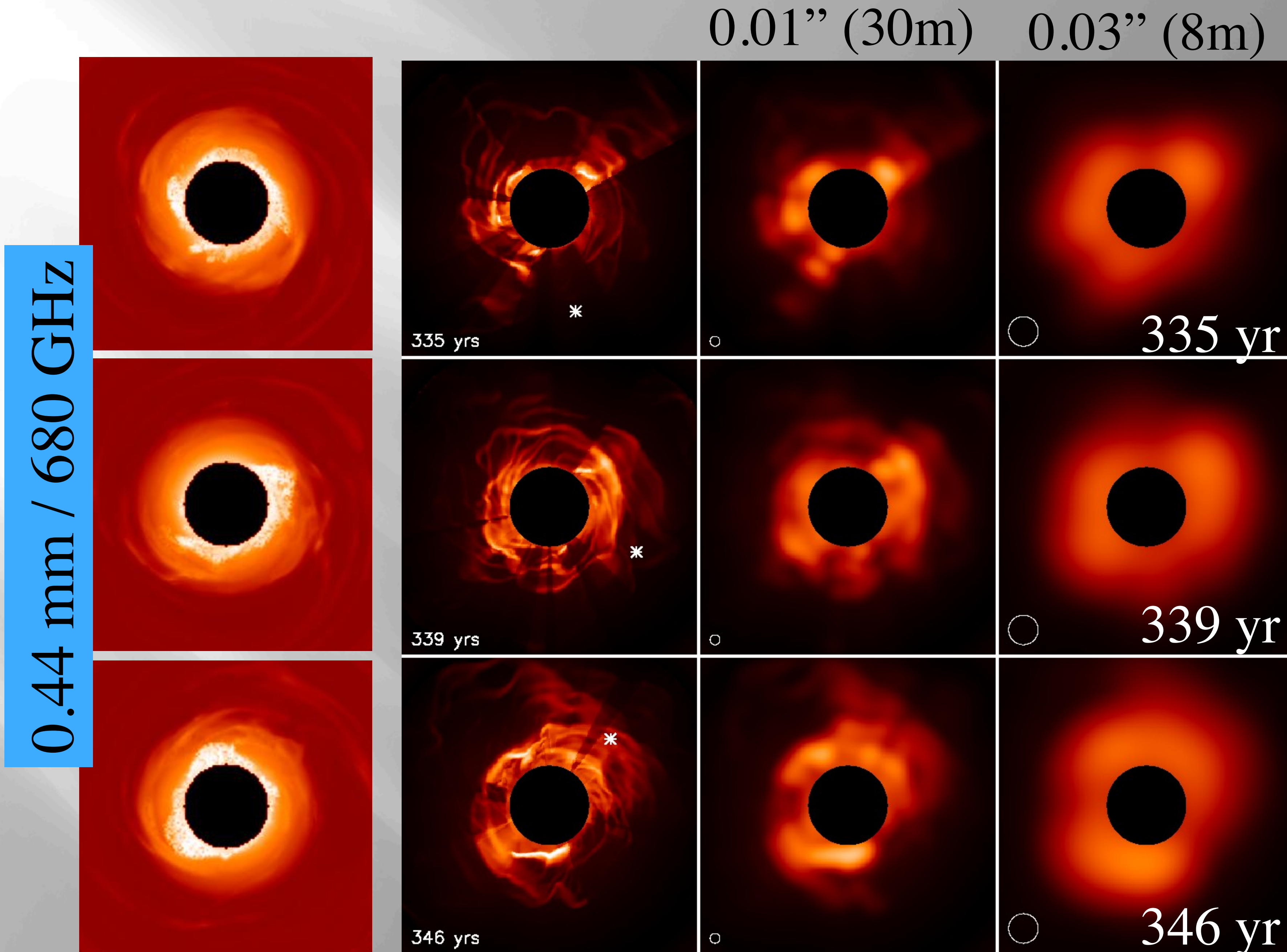
Variability



335 yr 339 yr 346 yr

Jang-Condell & Boss (2007)




0.01" (30m)
0.03" (8m)
0.44 mm / 680 GHz
335 yrs
339 yrs
346 yrs
335 yr
339 yr
346 yr

Infrared Variability

- See Flaherty & Muzerolle 2010, Espaillat et al. 2011, Morales-Calderon 2011, etc.
- Fluctuations in a gravitationally unstable disk + disk self-shadowing could cause variability in the near- to mid-infrared

Conclusions

- Finding planets in the process of forming will greatly improve our understanding of planet formation
- Detecting planets in protoplanetary disks is hard
  - Scattered light only probes surface layers
  - High resolution hard to obtain at long wavelengths
- Self-shadowing of gaps and dimples improves shadow contrast
- Variability could be an indication of disk instability