
# Debris disks at high resolution

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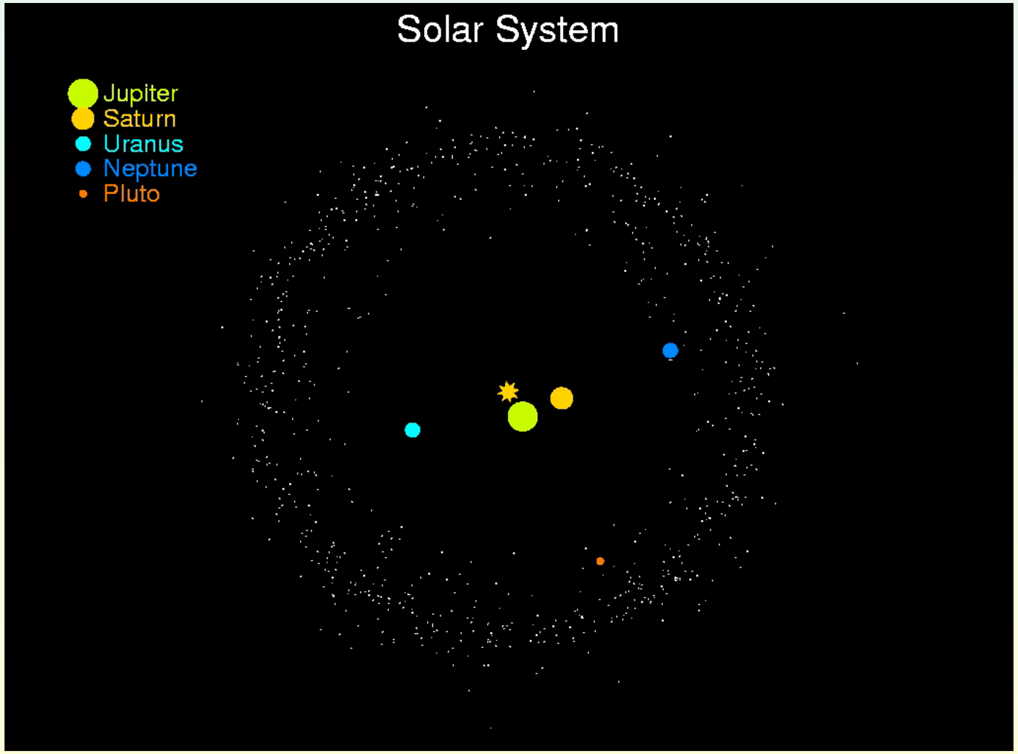
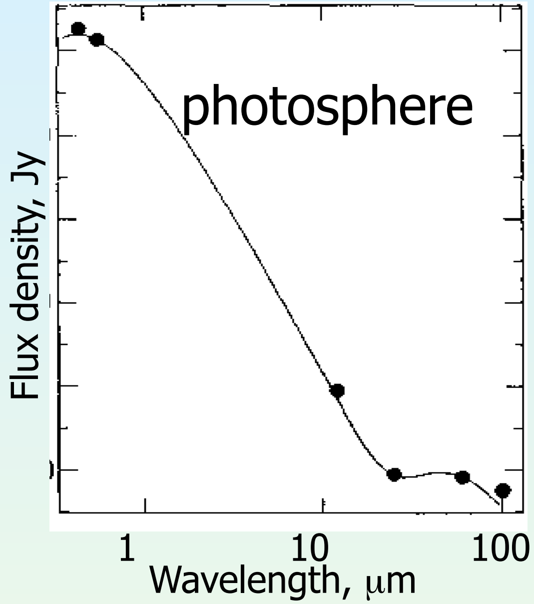
# Debris disk overview

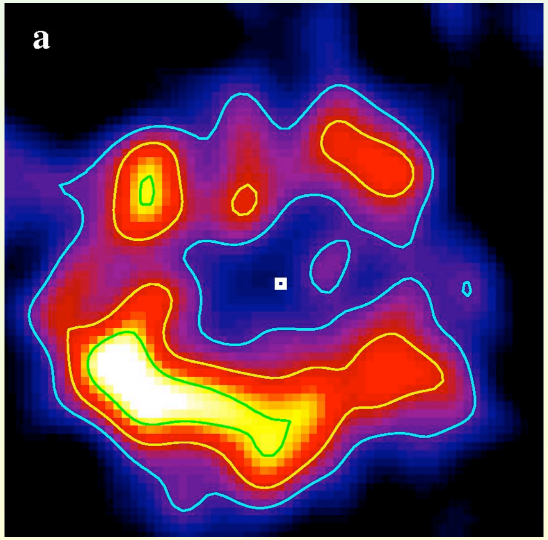
Debris disks are remnants of planet formation, planetesimals which failed to grow into planets; that in the Solar System is comprised of the Kuiper and asteroid belts



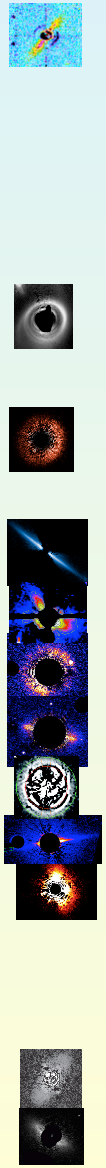
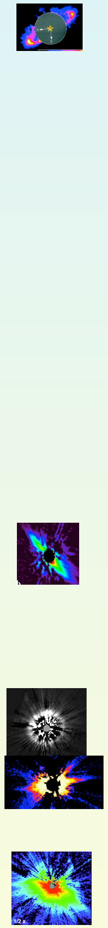
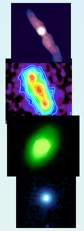
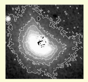
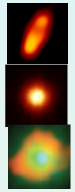
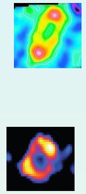
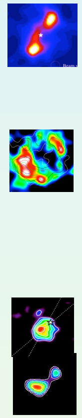
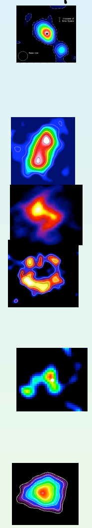
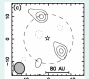

15% of nearby stars host debris disks detected from an excess of flux at >10μm

The nearest and brightest can be imaged, such as ε Eridani



# Debris Disk Image Gallery

| | | Optical <1μm | NIR 1-5μm | Mid-IR 10–25μm | Far-IR 70–200μm | Submillimetre 350μm | Submillimetre 450μm | Submillimetre 850μm | Millimetre 1.3mm |
|---|---|---|---|---|---|---|---|---|---|
| 1984 | β Pictoris | | | | | | | | |
| 1998 | HR4796 | | | | | | | | |
| 1998 | Fomalhaut | | | | | | | | |
| 1998 | Vega | | | | | | | | |
| 1998 | ε Eridani | | | | | | | | |
| 2000 | HD141569 | | | | | | | | |
| 2004 | τ Ceti | | | | | | | | |
| 2004 | HD107146 | | | | | | | | |
| 2005 | $\eta$ Corvi | | | | | | | | |
| 2005 | AU Mic | | | | | | | | |
| 2005 | HD32297 | | | | | | | | |
| 2006 | HD53143 | | | | | | | | |
| 2006 | HD139664 | | | | | | | | |
| 2006 | HD181396 | | | | | | | | |
| 2007 | HD15115 | | | | | | | | |
| 2007 | HD15745 | | | | | | | | |
| 2007 | HD61005 | | | | | | | | |
| 2008 | δ Vel | | | | | | | | |
| 2008 | HD92945 | | | | | | | | |
| 2008 | HD10647 | | | | | | | | |

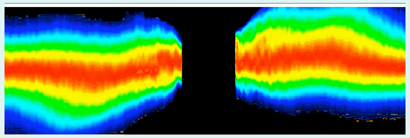










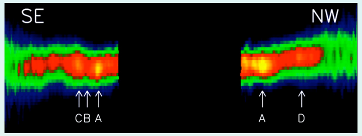
+ ACS images of HD207129, HD202917, AG Tri
+ 11 new Spitzer 70μm images (Bryden et al.)
+ 1 new mid-IR image (Smith, Wyatt et al.)

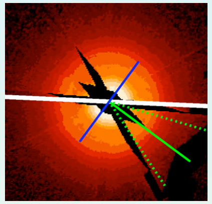
**Over 20 debris disks have now been imaged**

# Extrasolar debris disks are not axisymmetric

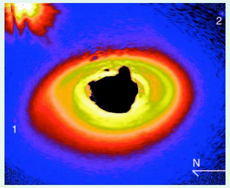
**Warps**



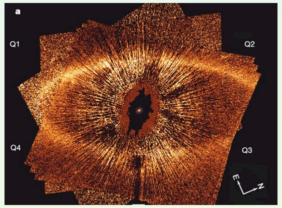


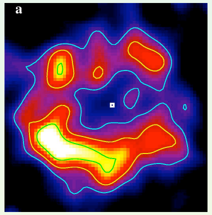



**Spirals**

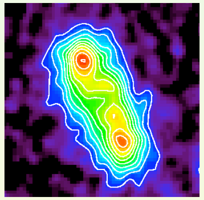


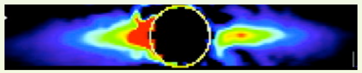
**Offsets**

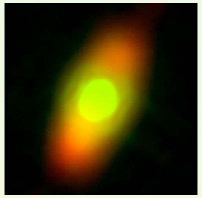


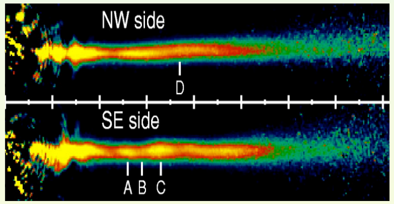


**Brightness asymmetries**

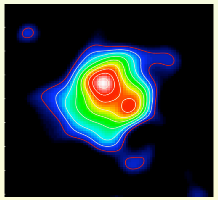


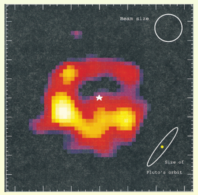


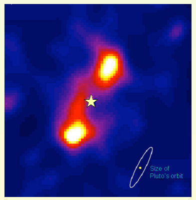


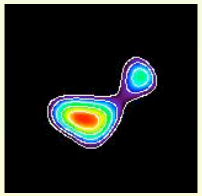


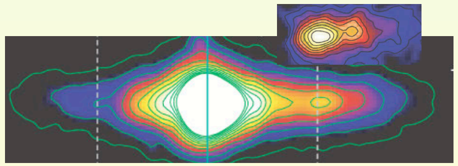

**Clumpy rings**





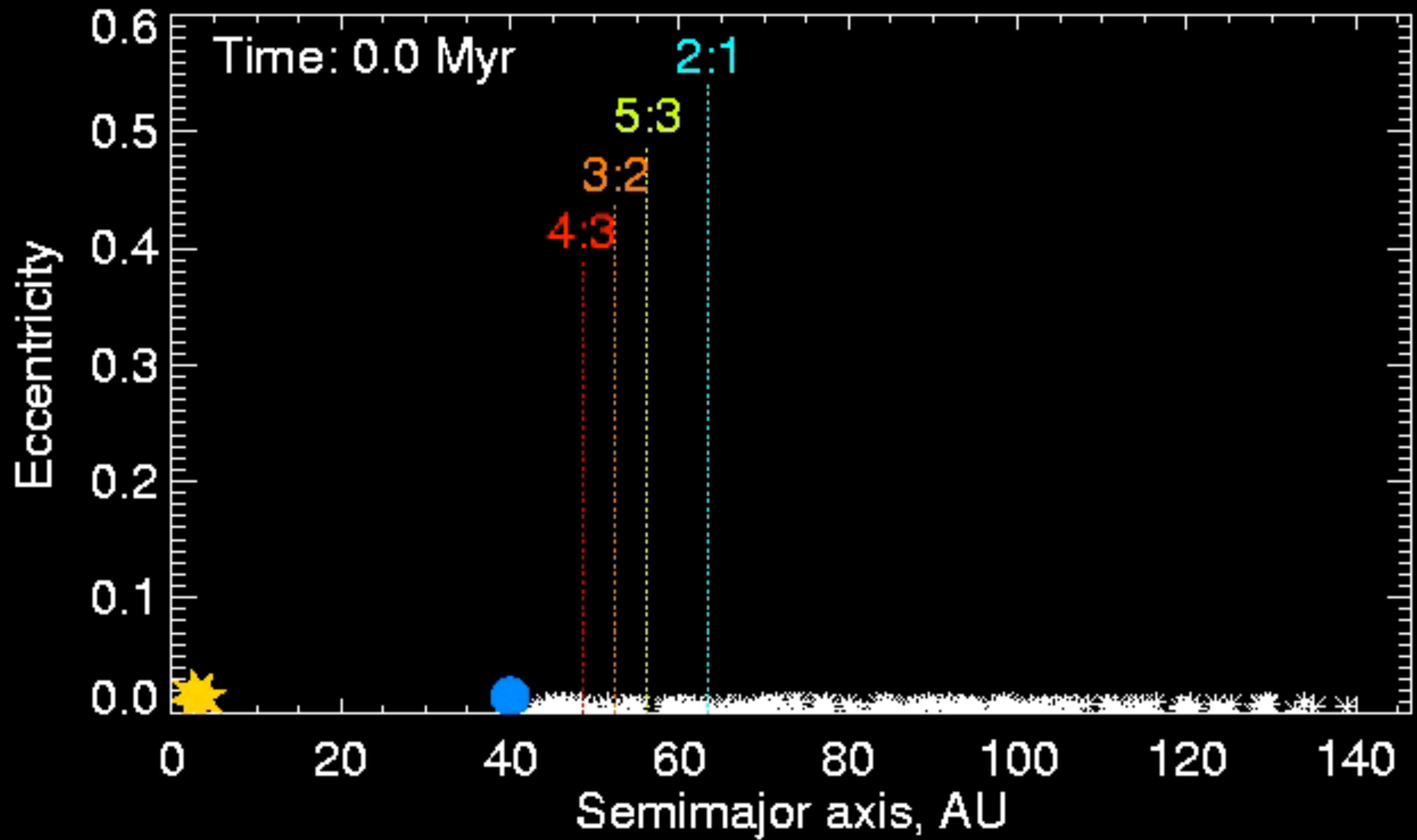






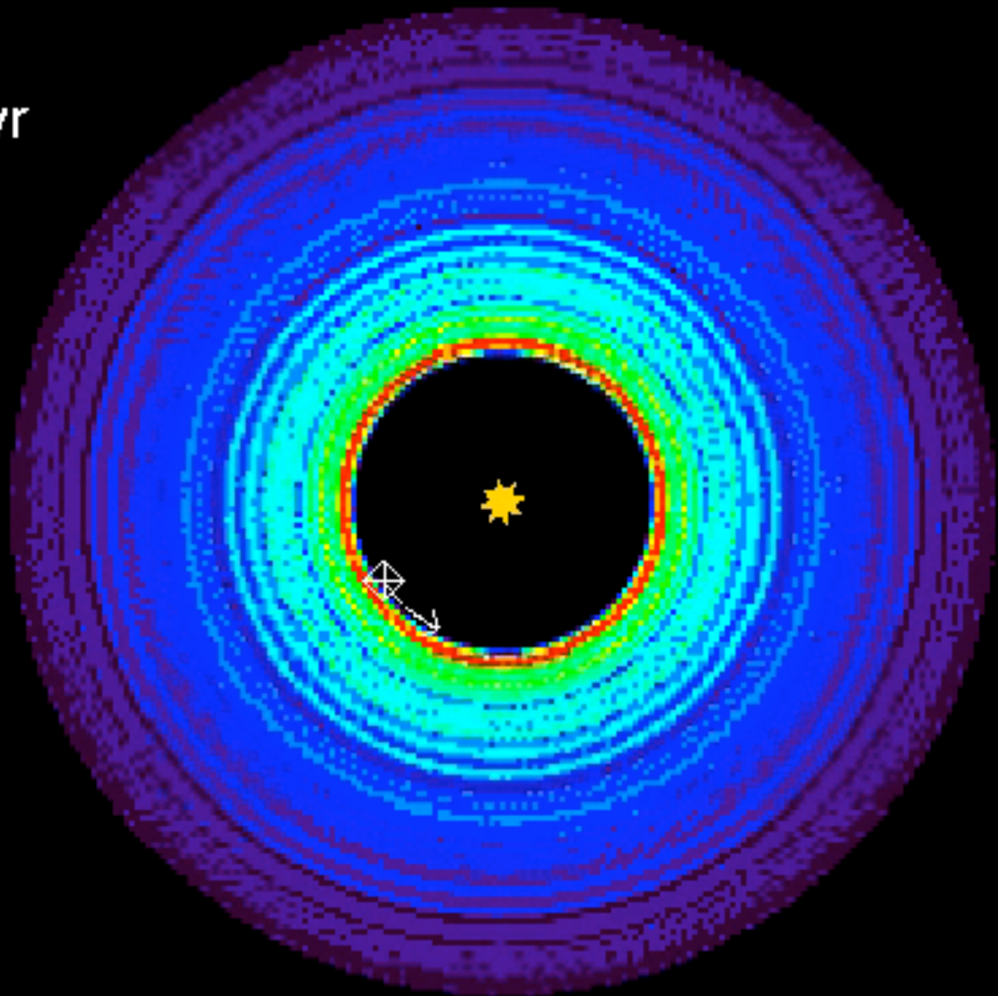
All of these structures can be explained by dynamical perturbations from unseen planets orbiting the star

The outward migration of a Neptune mass planet (●) around Vega sweeps many comets (*) into the planet's resonances



The trapping of comets in Vega's disk into planetary resonances causes them to be most densely concentrated in a few clumps

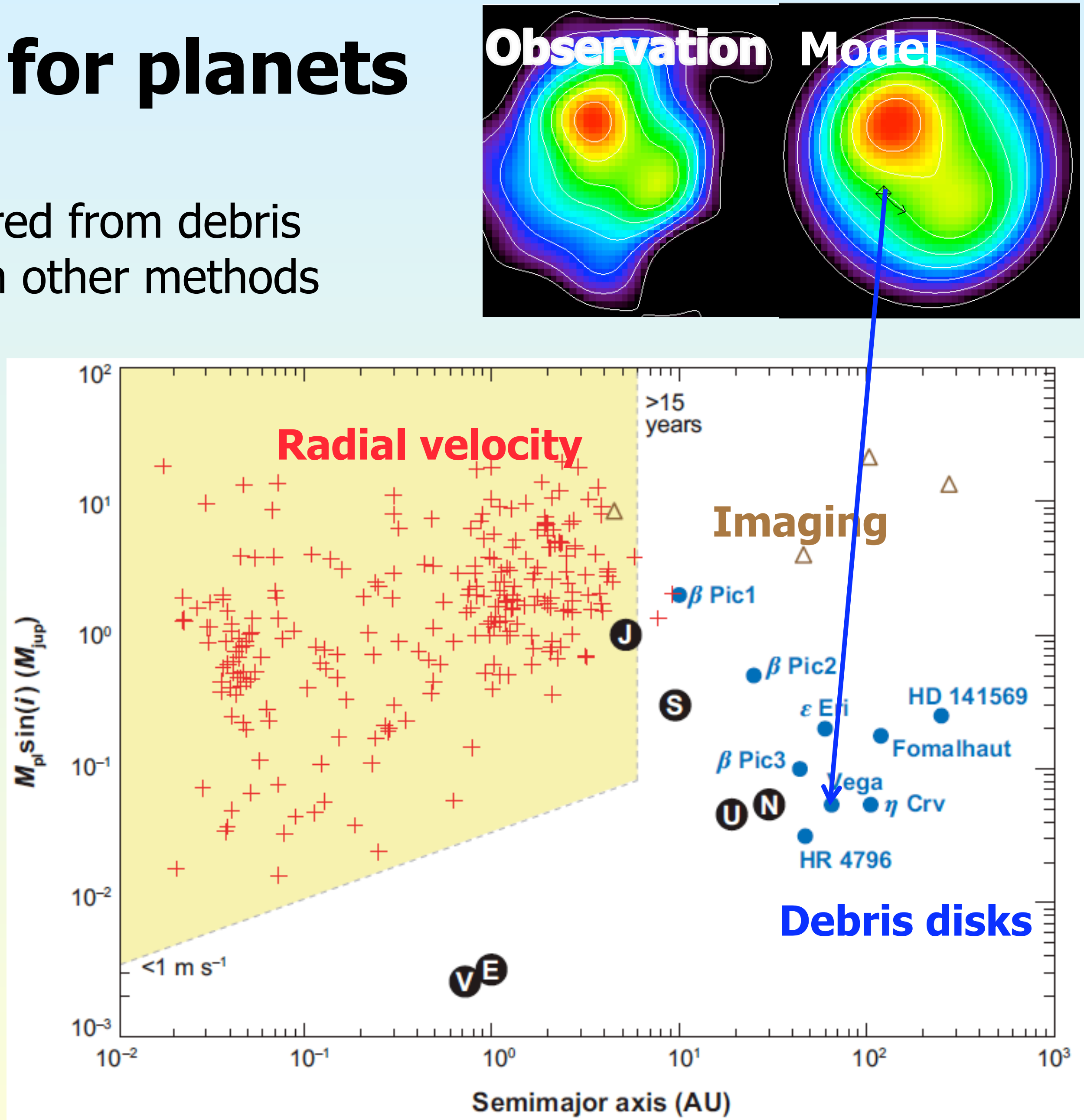
Time: 0.0 Myr



# Indirect evidence for planets

Comparison of planets inferred from debris disks with those found from other methods

**Debris disk structures reveal planets in a region of parameter space inaccessible to other techniques**



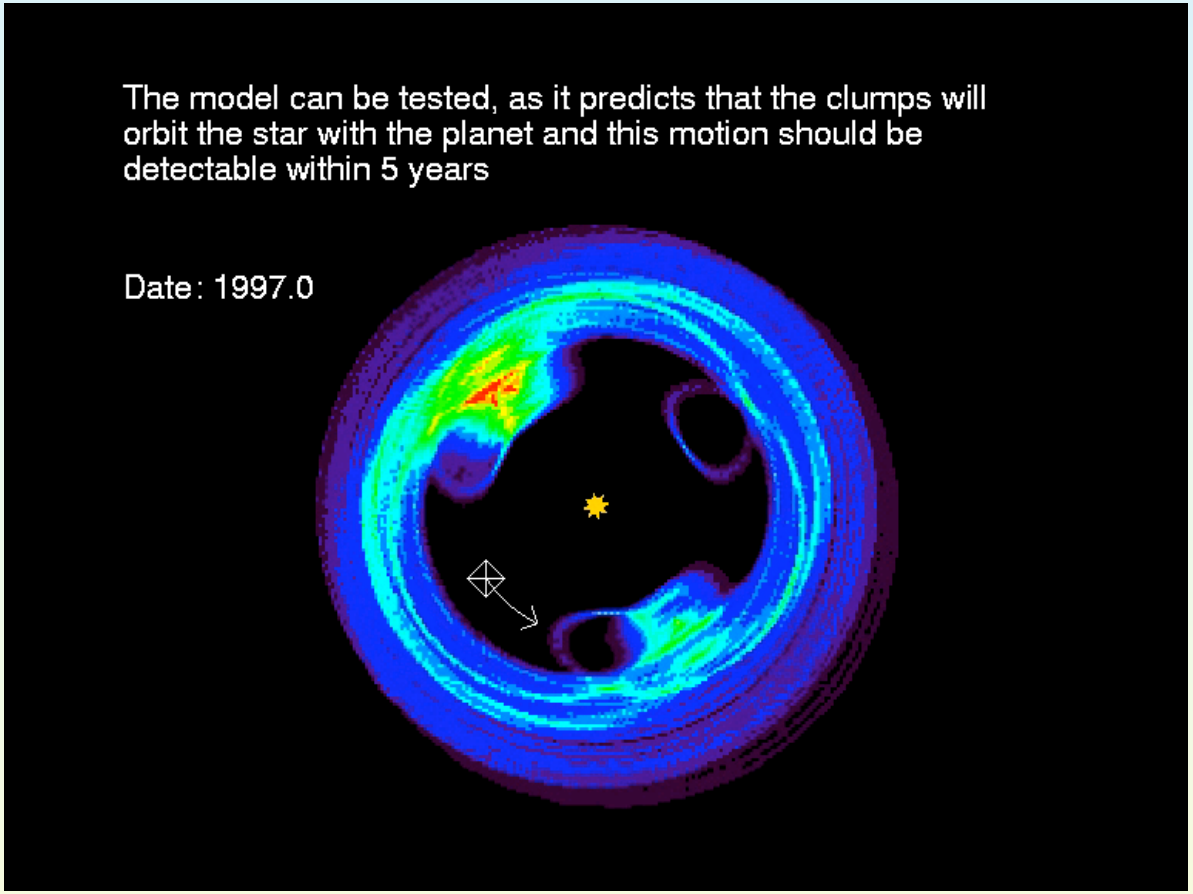
# Proof 1,2: disk structure varies with time

Just because these are the only models that explain the observed structure does not make them right

Need to confirm one of the predictions of the model:

0) Detect planet!
• Hard!

1) High resolution structure

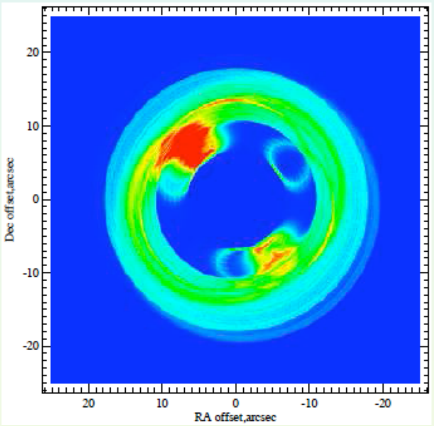



2) Clumpy resonant structure orbits star with planet
• Tentative detection over 5 years for ε Eri (Poulton et al. 2006)

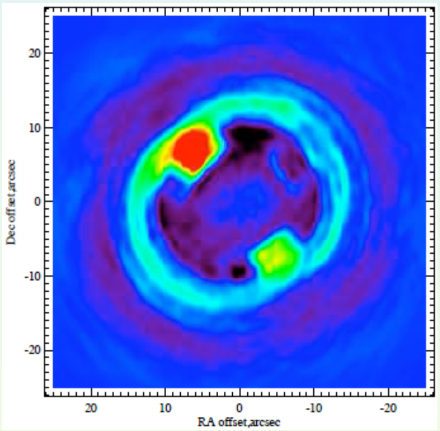
# Simulation of Vega disk (no noise)

Q: What baselines are needed to constrain the models?
A: Use CASA with no noise to simulate images of Vega

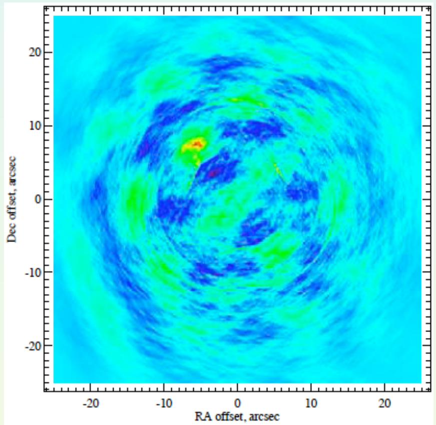
Input model



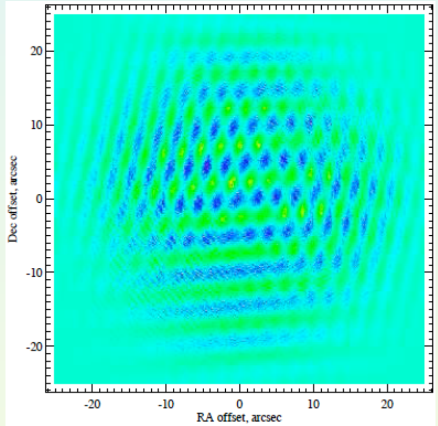

$B_{max}$=200m




$B_{max}$=1.8km




$B_{max}$=16.1km



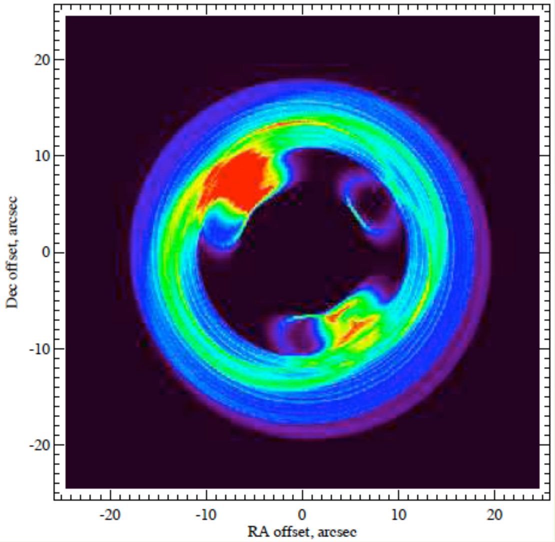

Fraction of flux retained is just 52% for $B_{max}$=1.8km and 3% for $B_{max}$=16.1km

For this over-resolved disk the shortest baselines are required, although higher resolution structure than present in the model is possible

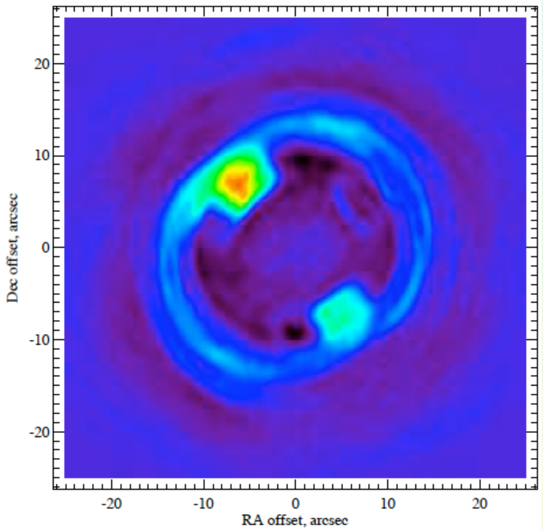
# Simulation of Vega disk (with noise)

Q: How long observations are needed to constrain the models?
A: Use CASA with noise to simulate images

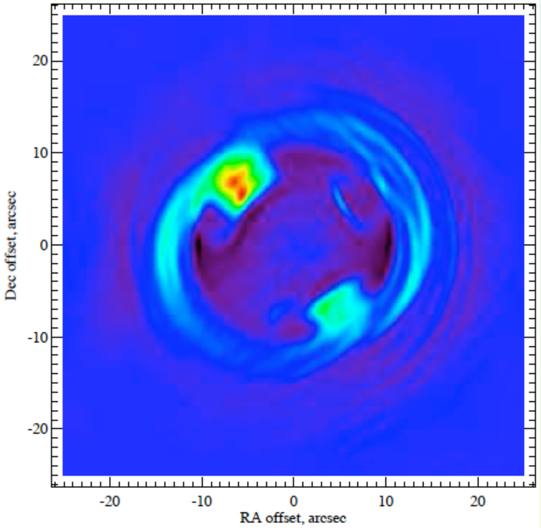
Input model




$B_{max}$=200m, 0.5hr




$B_{max}$=200m, 8hr



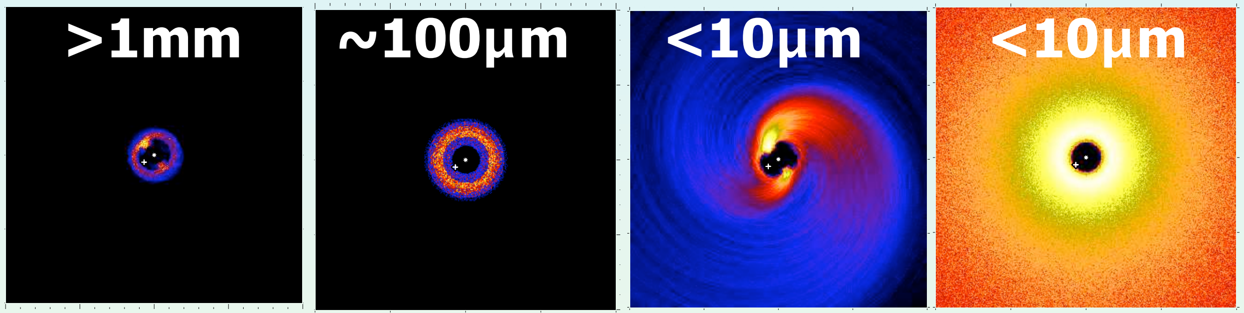

The clumpy structure is clearly visible even on short integrations

Issue: Including noise in CASA (in this simulation thermal noise was adjusted to achieve appropriate mJy/beam)

# Proof 3: disk structure varies with wavelength

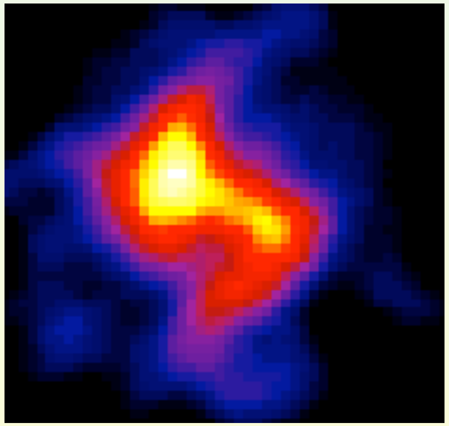
Model predicts structure changes with grain size (due to radiation pressure) and so wavelength of observation (Wyatt 2006)

Dust size and wavelength

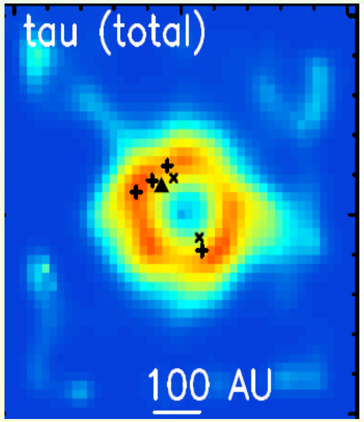



Observations agree, BUT mass loss is 100 times prediction at $2M_\oplus$/Myr

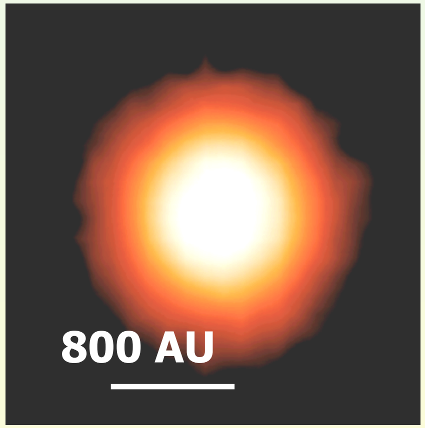
850μm
(Holland et al. 2008)



350μm
(Marsh et al. 2006)




24-70μm
(Su et al. 2005)



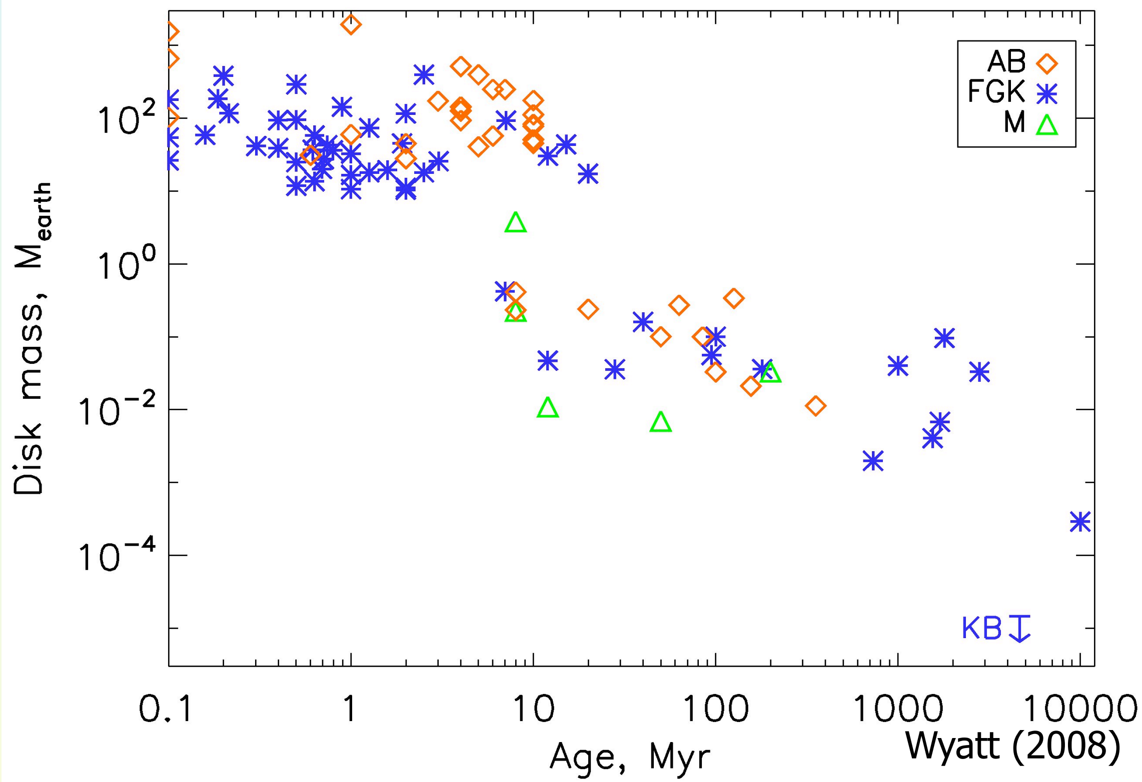

ALMA covers transition at which structure changes setting vital constraints

# Sub-mm/far-IR debris disk surveys

Surveys of (unresolved) debris disks show how disk mass evolves, how disk incidence varies with stellar mass, binarity, metallicity, exoplanet parameters

Sub-mm surveys measure
- disk mass
- spectral slope (dust size)
- cold disks

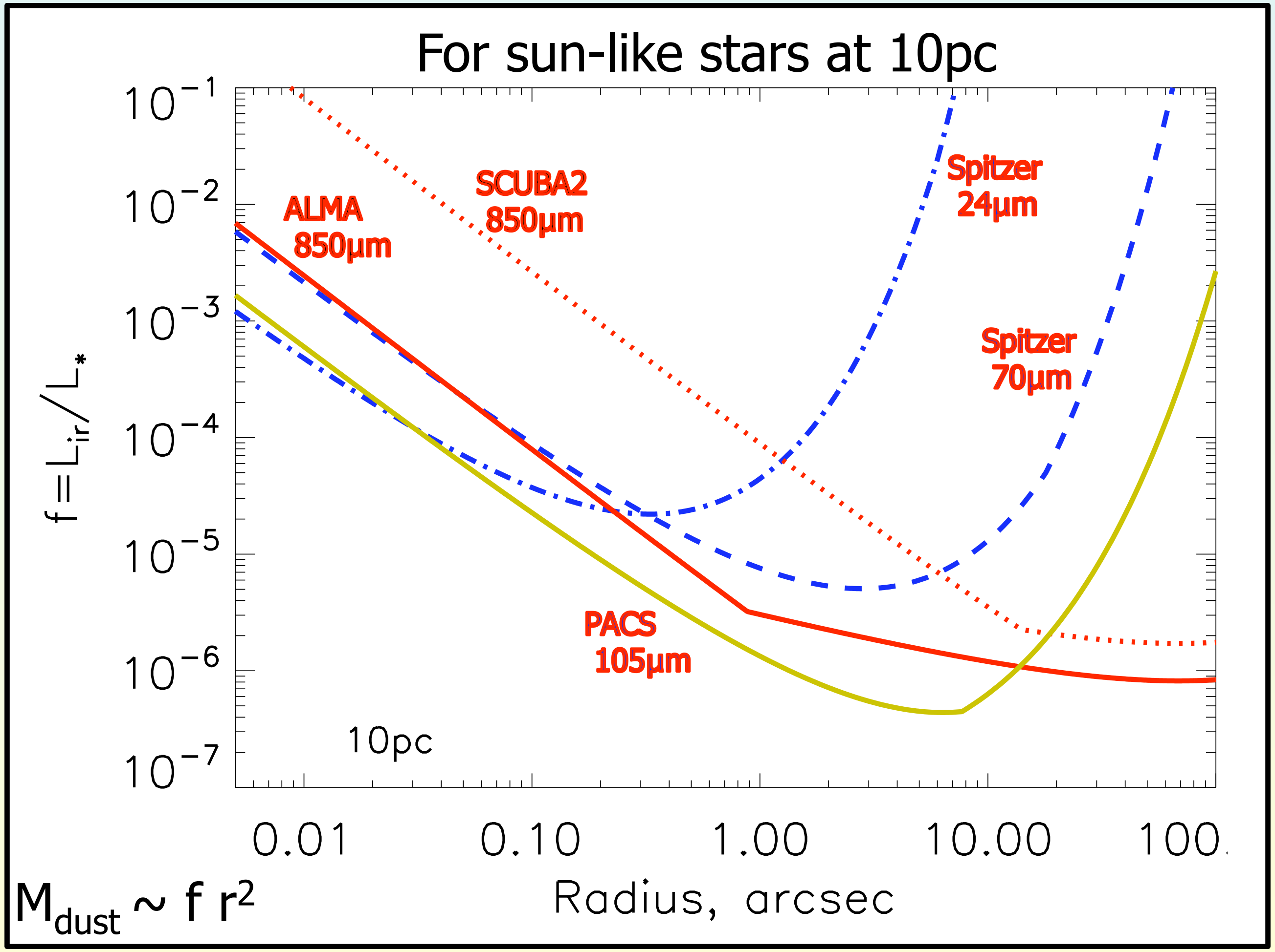
Far-IR surveys measure
- temperature (radius)
- warm disks




From 2009:
- SUNS survey with SCUBA2 on JCMT of nearest 500 stars to 2mJy at 850µm (nearest 100 of spectral types A,F,G,K,M)
- DEBRIS survey with PACS on Herschel to 1-2mJy at 105,160µm of same

# ALMA sensitivity compared to other facilities

Q: How does ALMA's sensitivity to debris disks compare with SCUBA2 and PACS?
A: Map out the region of f vs r parameter space detectable by each facility



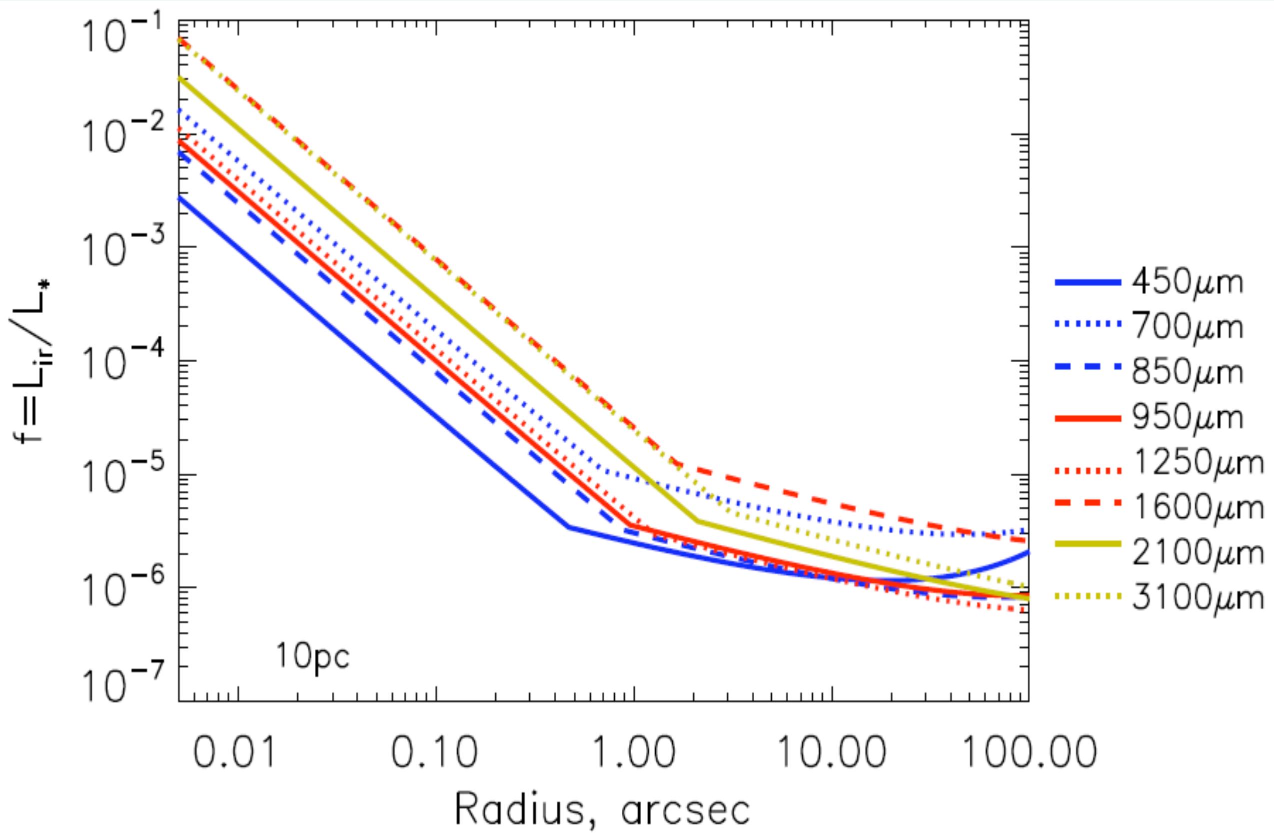

ALMA will detect all disks detected by SCUBA2 and most by Herschel

ALMA can measure
- dust mass
- temperature (radius)
- spectral slope (dust size)

for all ~200 known disks, and those discovered by SUNS and DEBRIS

# Observing strategy: wavelength

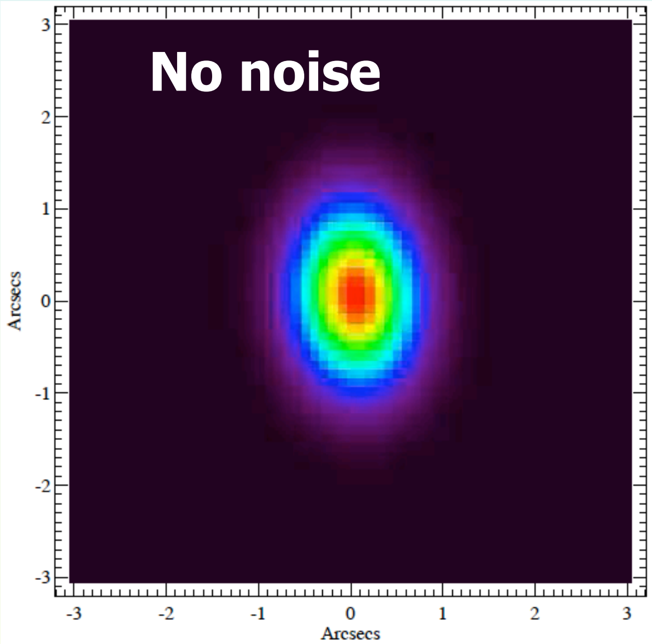
Q: What waveband is most sensitive to debris disks?
A: Use sensitivity estimate and assumptions about spectral slope ($F_\nu \sim \lambda^{-3}$)

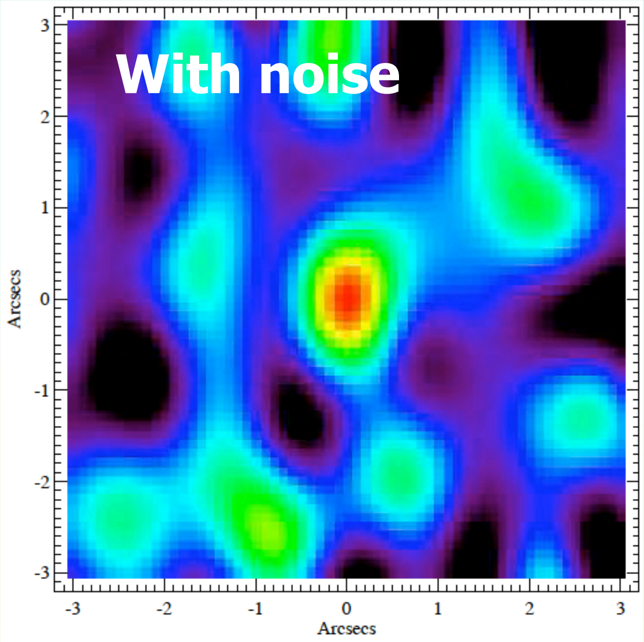



- Except for largest disks (>100AU), 450μm then 850μm are most sensitive
- NB lower sensitivity if resolved ($r>2.1\times10^{-4}\lambda/B_{max}$) so $B_{max}$=0.2km used

# Simulation at limit of detectability

Q: Can ALMA really detect disks at that limit?
A: Use CASA to simulate an observation of a faint disk + noise



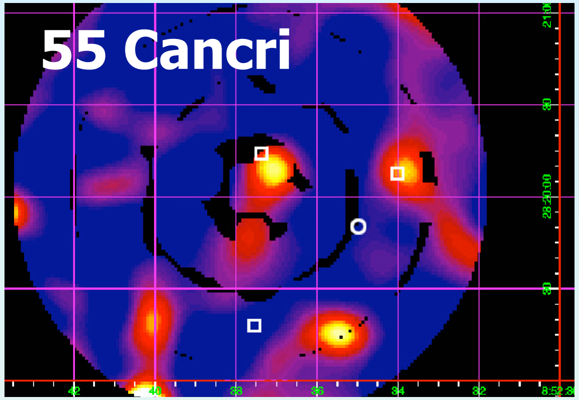



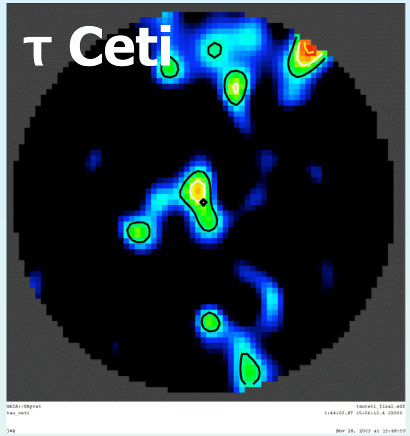

0.12mJy disk observed for 0.5hr at 850µm with $B_{max}$=200m (0.04mJy/beam)

The disk is clearly detected with above the noise…

… however, full simulation with thermal and phase noise required

# Is ALMA confused?

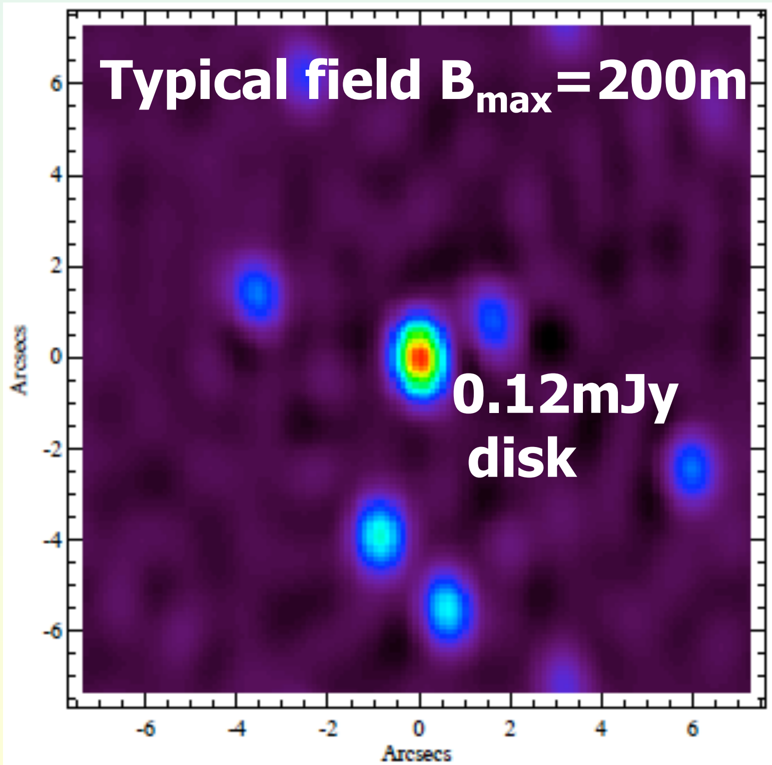



Q: SCUBA(2) imaging of debris disks is confusion limited, how about ALMA?
A: Simulate image of debris disks with model galaxy population

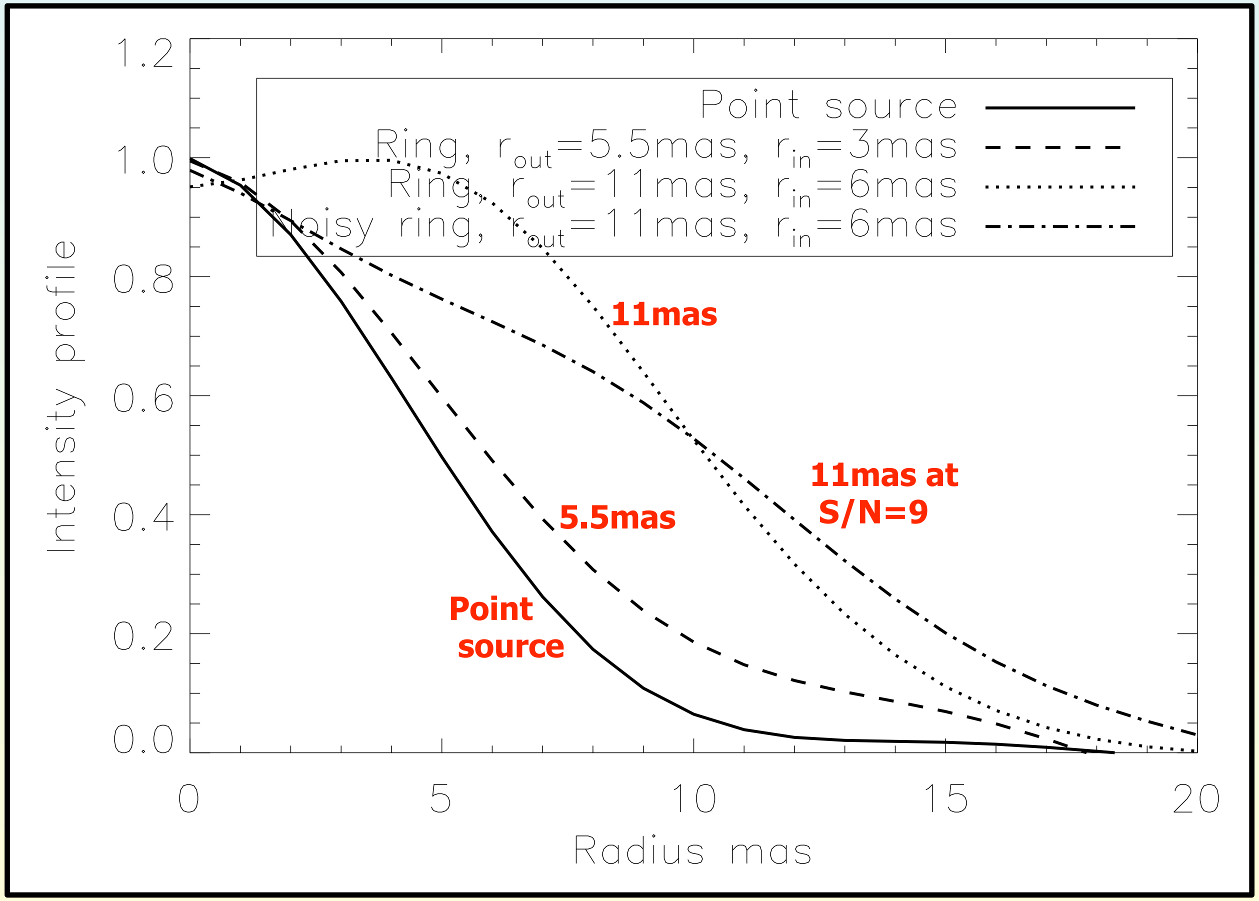
Model background galaxy population:
$N(>S) = (10^5/1.8)\,[(S/1.8)+(S/1.8)^{3.3}]^{-1}$
per square deg (S in mJy)

- Depends on $B_{max}$ (longer $B_{max}$ less affected)
- For $B_{max}$=200m confusion important for >8hr observations (<0.01mJy/beam) with 5% false detection rate for 0.03mJy disks



# Sensitivity required to resolve disks

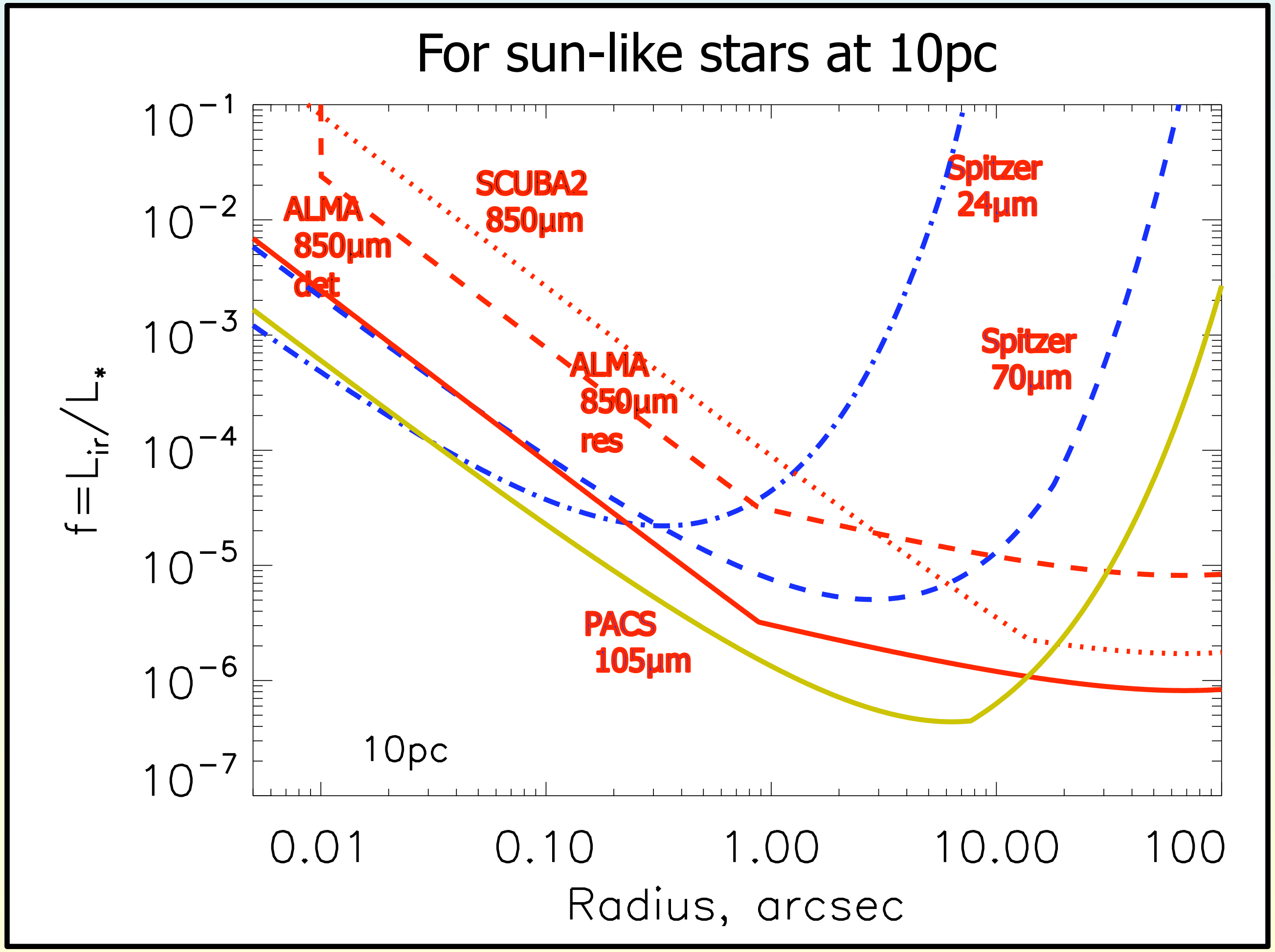
Q: What angular size will ALMA be able to resolve for a given sensitivity?
A: Use CASA to simulate a disk with radius close to FWHM




- For $B_{max}$=16.1km disks with r>11mas (i.e., r>FWHM) are easily resolved
- Also need S/N > 30 for a reliable resolution and radius determination

# Parameter space for resolving disks

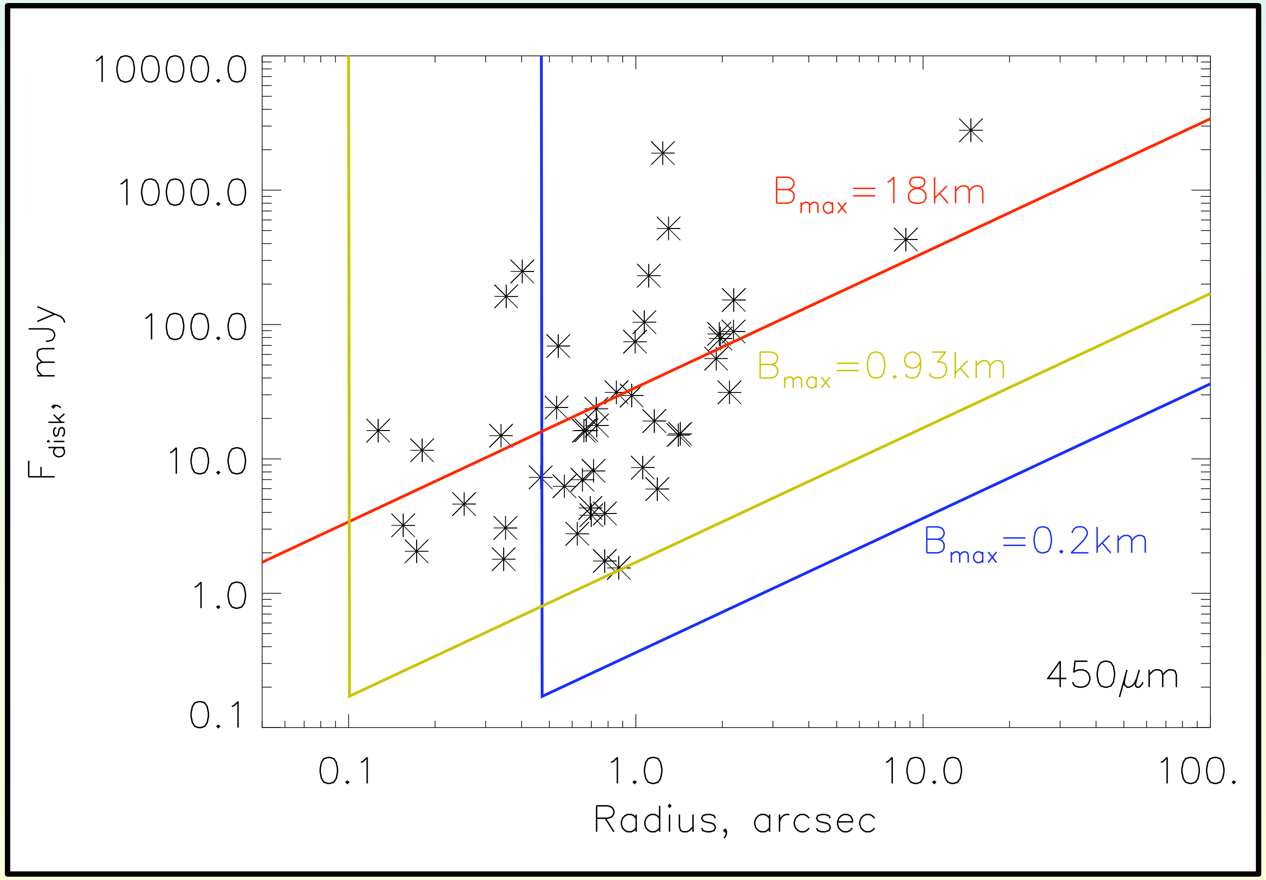
Q: What parameter space will ALMA be able to resolve disks?
A: Same plot of parameter space




Not only will ALMA measure dust mass, temperature (radius), spectral slope (dust size) for hundreds of disks, it will also directly measure most of their radii and search for asymmetries

# Resolving known nearby A star disks

Q: How many of known A star disks will ALMA resolve?
A: Plot known A stars on $F_{disk}$ vs predicted radius (from temperature)



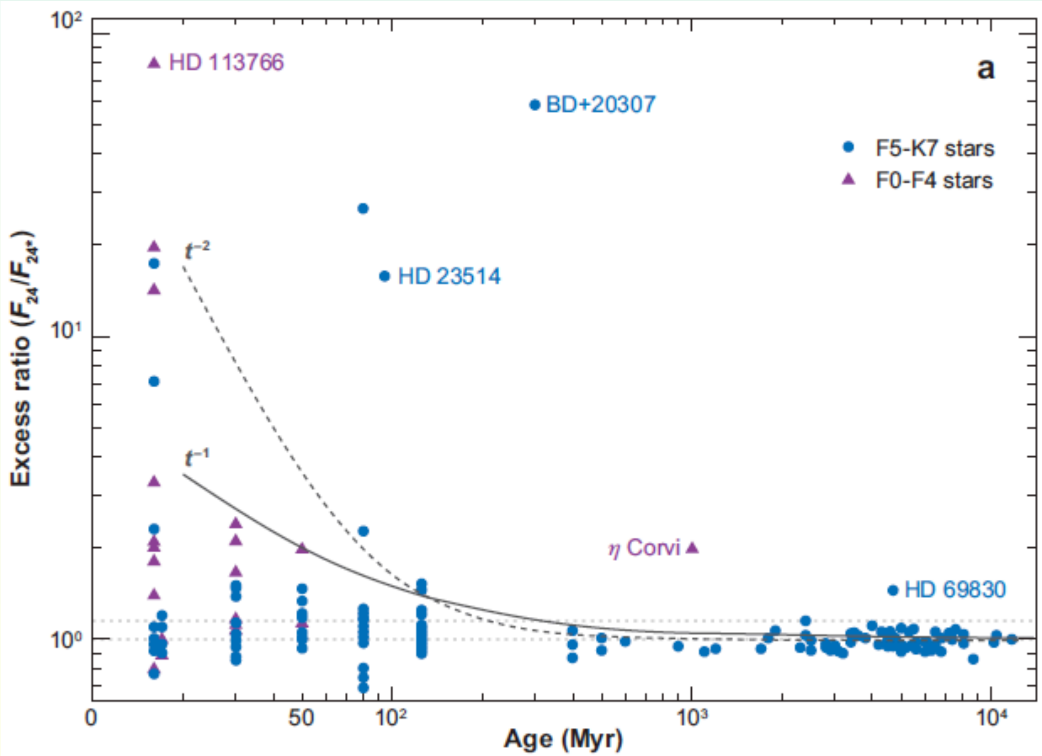

All known A stars disks are resolvable with ALMA!

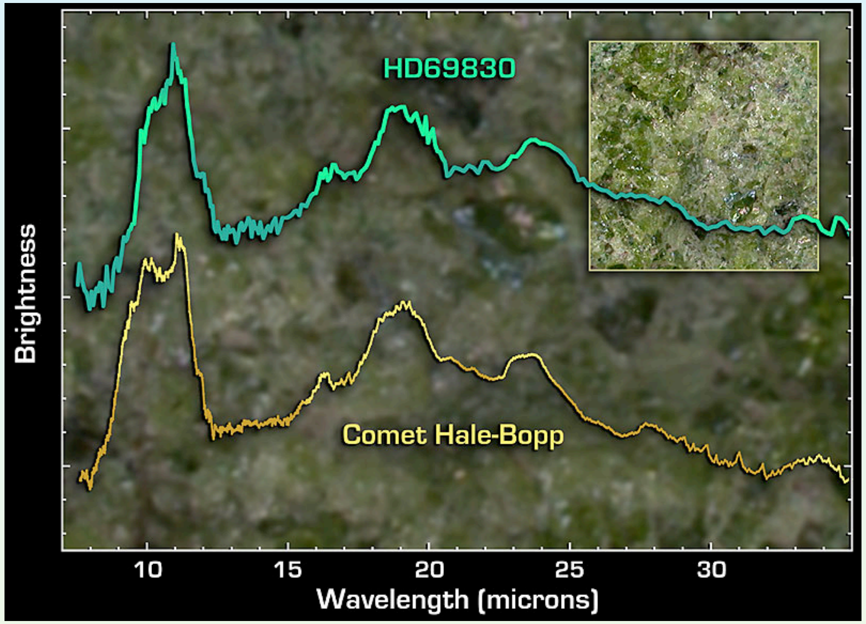
Optimal baseline is that which just resolves the disk

But temperature is not always a good predictor for radius

# The terrestrial planet region

The majority of sun-like stars have no 24μm excess indicating the inner 30AU are relatively clear of dust



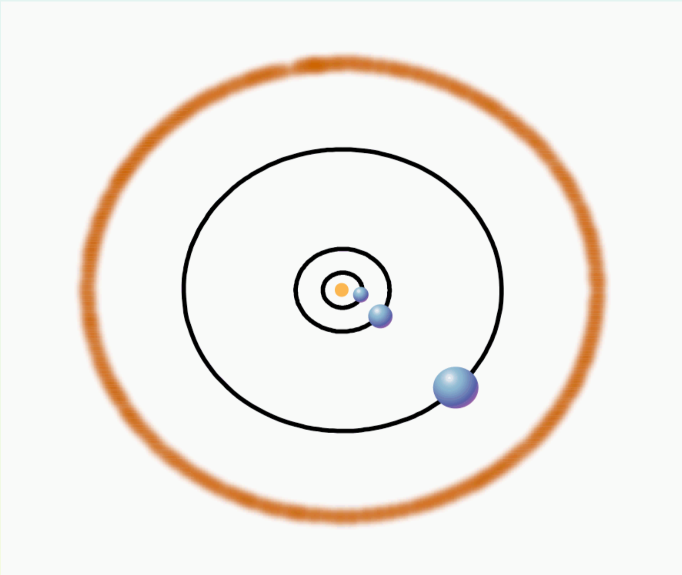



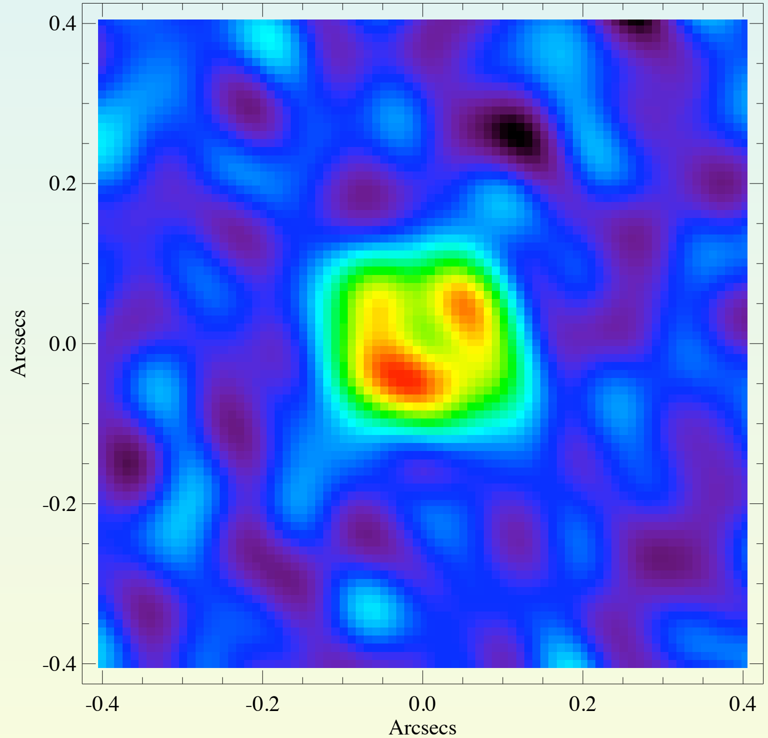

But some, like HD69830 have dust at 1AU (Beichman et al. 2005)

The dust is outside 3 Neptune mass planets discovered in radial velocity studies (Lovis et al. 2006) and appears to be transient (Wyatt et al. 2007)

# Resolving terrestrial region of HD69830

Q: Can ALMA resolve the terrestrial regions of HD69830?
A: Use CASA to simulate a 1AU (80mas) ring with 0.3mJy at 450µm in 12 hour observation and $B_{max}$=900m





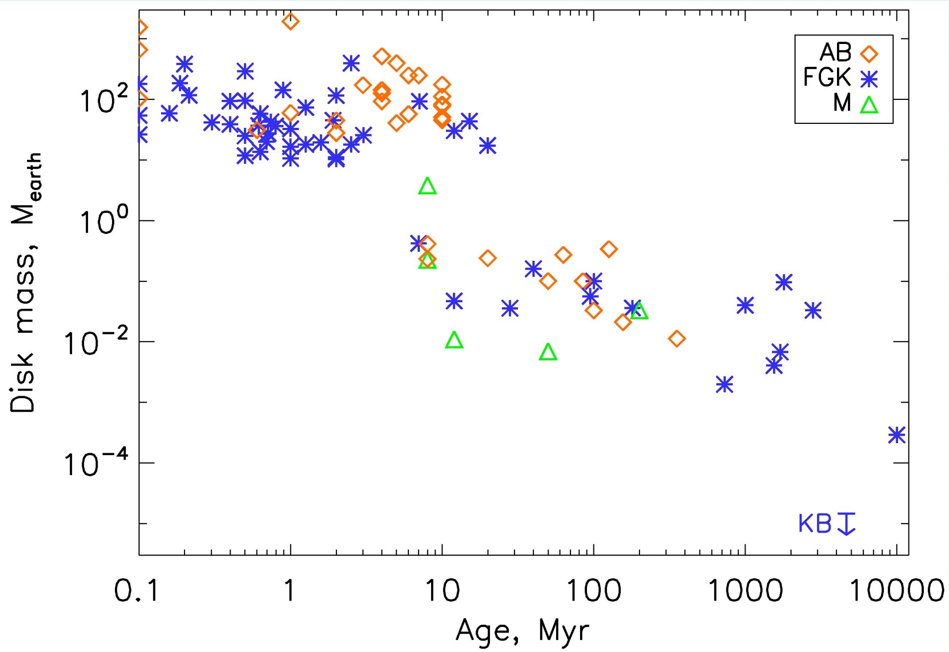

This disk is resolvable, allowing us to

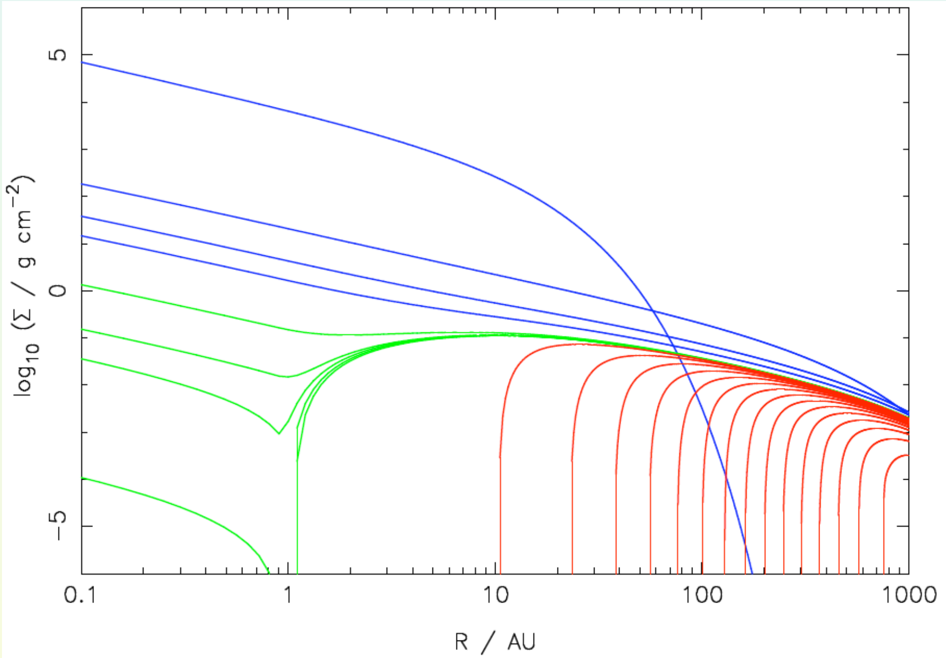
- determine inclination = planet masses
- pinpoint the location of the ring and assess radial extension = test models
- look for non-axisymmetric structure and time dependence = planet interaction

# Protoplanetary disk dispersal

Rapid mass loss at 10Myr from protoplanetary disks is inferred

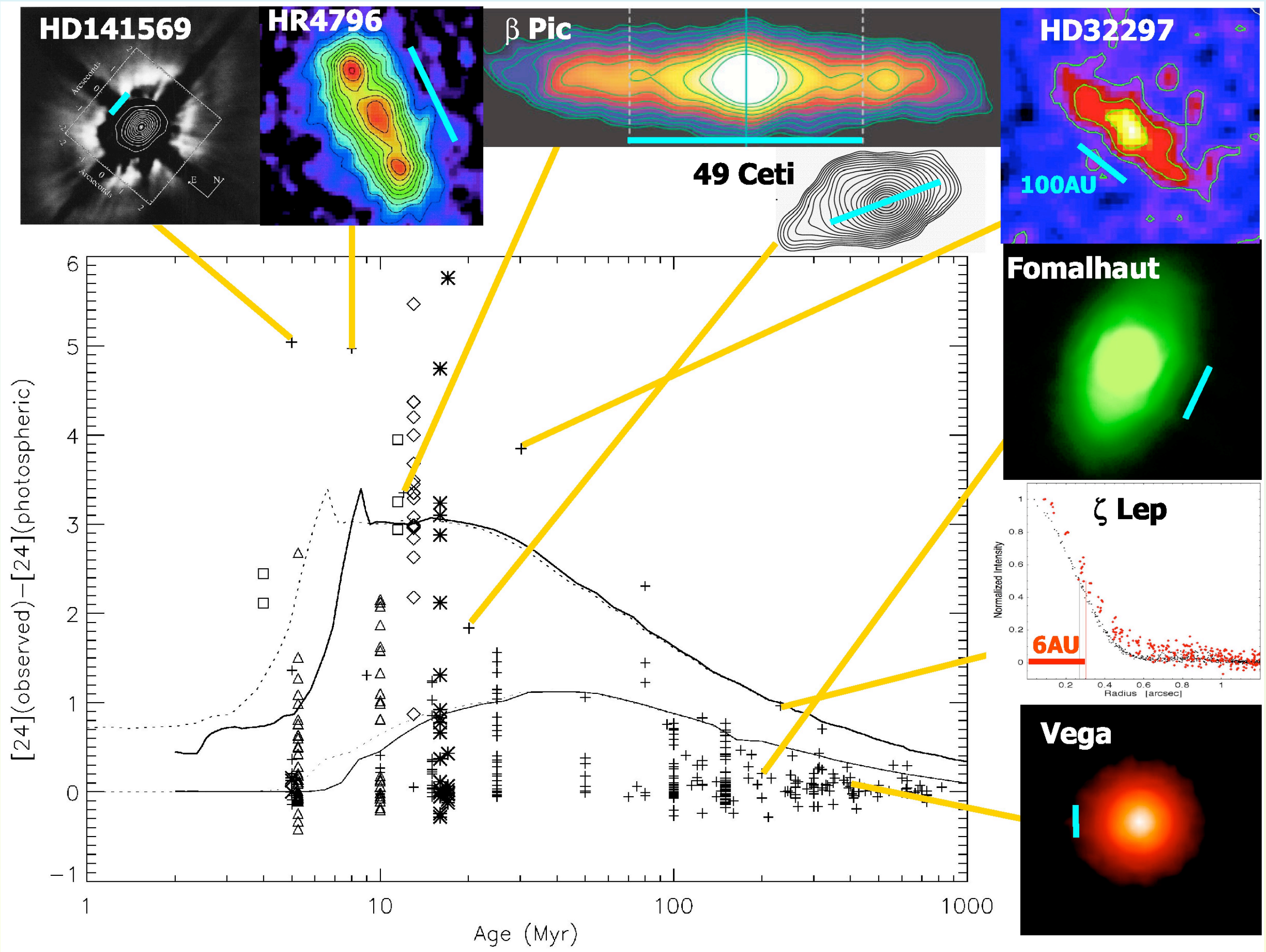
Models for disk evolution due to viscosity and photevaporation predict inside-out dispersal(Alexander et al. 2006)




Need direct evidence for inside-out evolution by resolving inner hole

# The birth of debris disks




Debris disks increase in brightness following protoplanetary disks dispersal

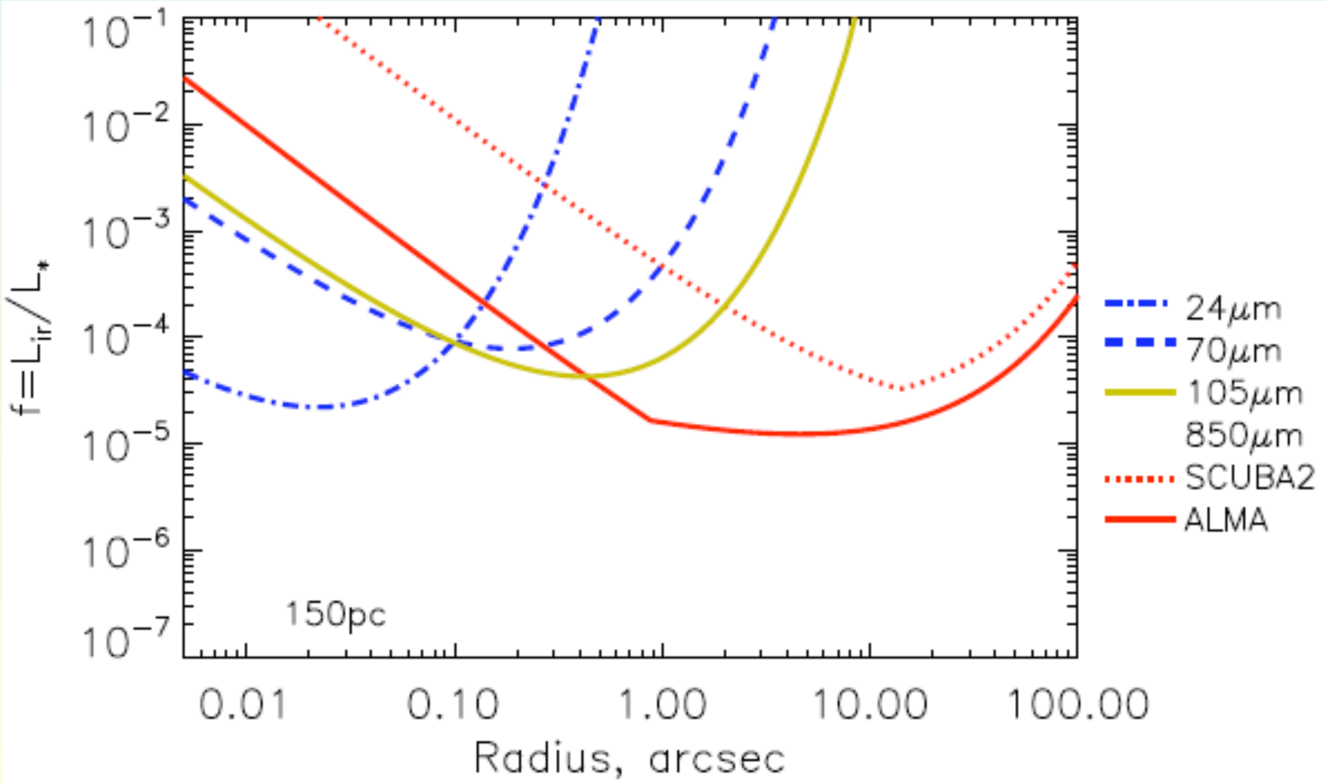
Inferred to be caused by ongoing planet formation (of Plutos in outer regions)

To understand transition need to image many young systems (i.e., at 150pc)

# Resolving protoplanetary disks

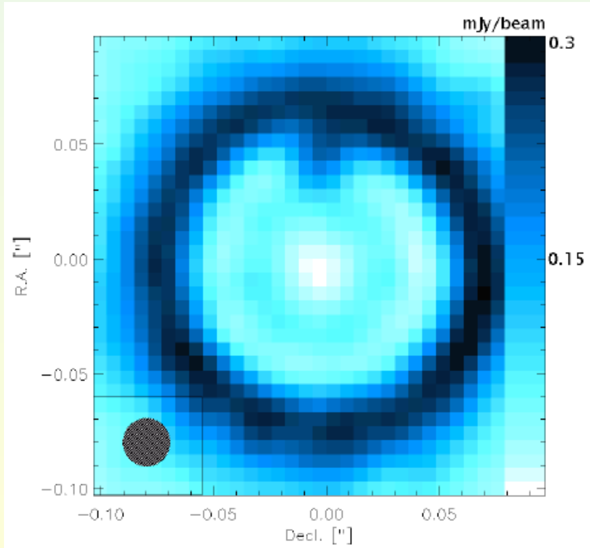
Q: Can ALMA resolve the transition disks?
A: Resolvability plot for sun-like stars at 150pc

As protoplanetary disks have f >> 0.01 (by definition), these will be resolvable by ALMA down to smallest scales of around 1AU



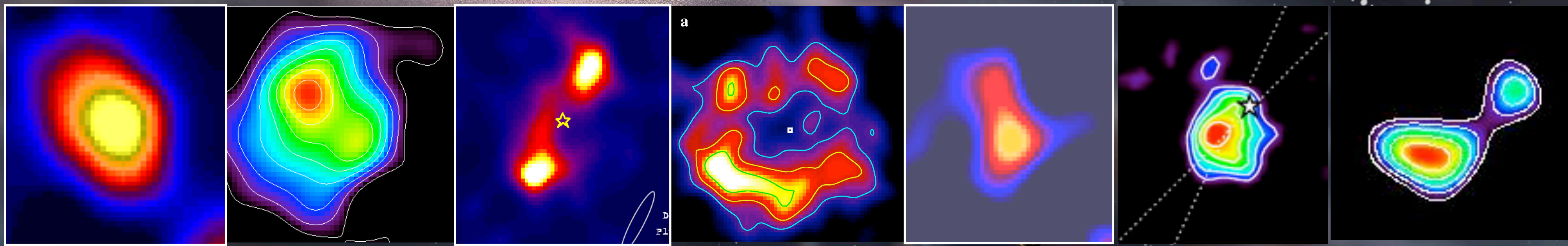

Can also look for gaps carved by planets

(e.g., Wolf & D'Angelo 2004)



# Conclusions

Number of sub-mm images of debris disks will increase from 7 now…



… to ~40 after SUNS survey… and several hundred with ALMA

This leads to exciting possibilities of indirectly detecting hundreds of Neptune-like planets, constraining disk mass and radius evolution, exploring link with giant planets, probing terrestrial planet regions

Plus exciting science in protoplanetary disks (disk dispersal; planet detection)