Debris Disk Clues to Nearby Exoplanets

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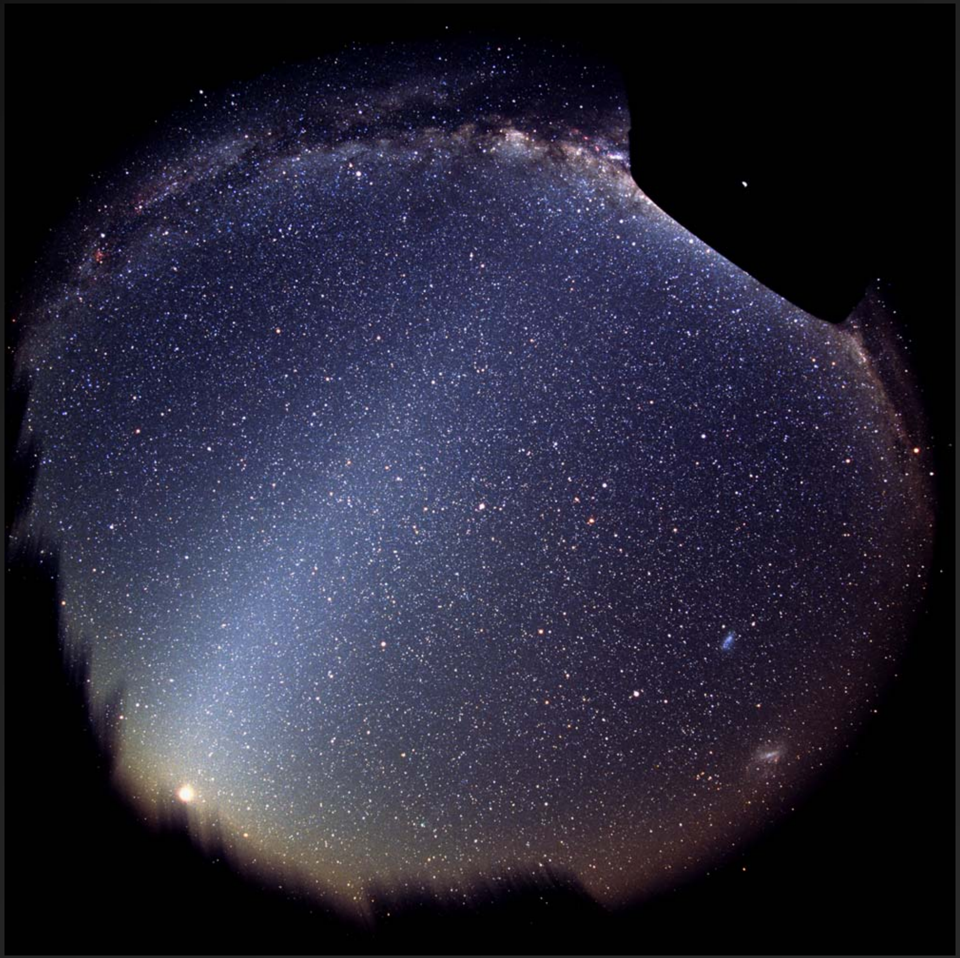
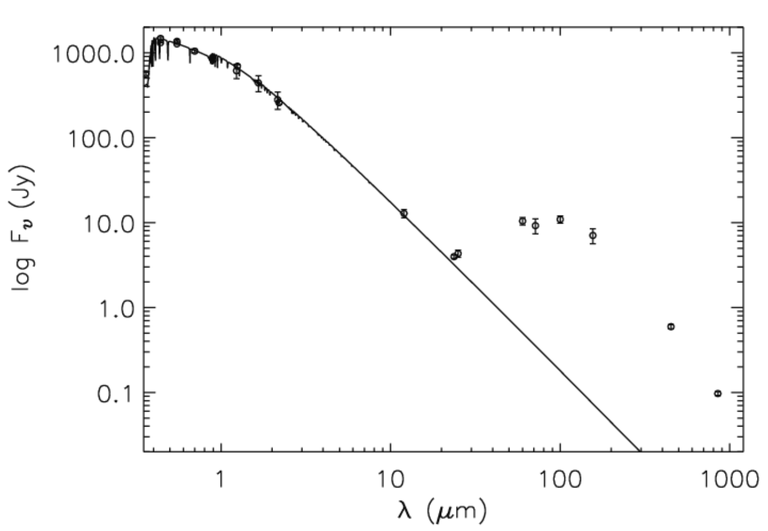
Zodiacal Light: Our Sun's Inner Debris Disk

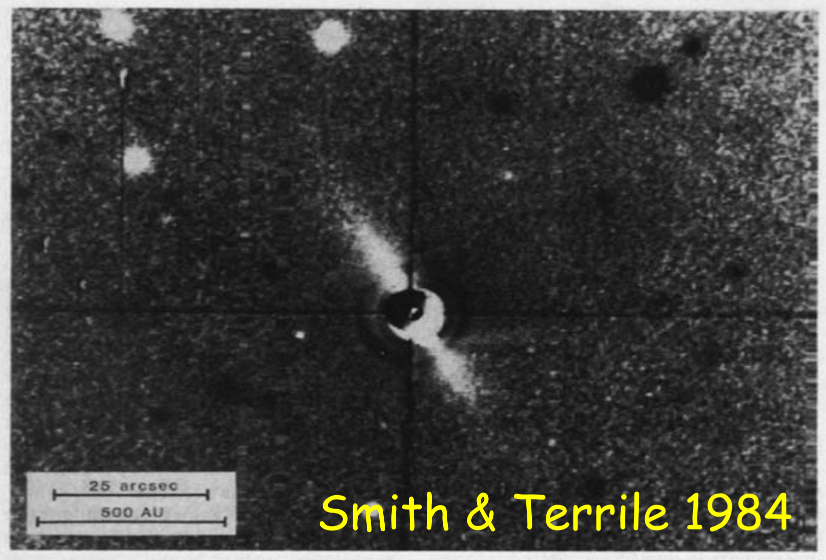
- Interplanetary dust particles are released by asteroid collisions & cometary passages
- Particle concentration in the ecliptic plane causes zodiacal light
- Median particle size is 30 μm, but a wide size range is seen
- Particles interior to main asteroid belt
- Even though its fractional luminosity is just 10^{-7} of the Sun, the zodiacal light is the most luminous component of our planetary system



Extrasolar debris disks were discovered by their far-infrared excess: IRAS satellite, 1984

- Optically thin, gas-poor particle disks with optical depths from 30- 20,000 times Sun's "zodi"
- Disk masses very small, < few lunar masses. NOT protoplanetary disks.
- 10-100s of AU scales: Kuiper Belts
- Dust removal timescale much shorter than stellar ages: grains can't be primordial. Continuing replenishment of small particles from larger parent bodies is required.
- The best evidence for extrasolar planetary systems prior to 1995





Smith & Terrile 1984

A statistical correlation between debris disks and planets ?

Bryden et al. 2009

- Early Spitzer results suggested debris disks were more common in RV planet systems (Beichman et al. 2005)
- Later work on larger samples finds <u>no correlation</u>. IR excess frequencies in sample of 305 stars are
  - 14±3% no RV planet
  - 9±3% with RV planet
- Corresponding lack of correlation between disk frequency and stellar metallicity
- Weak tendency for planet-bearing stars to have brighter disks

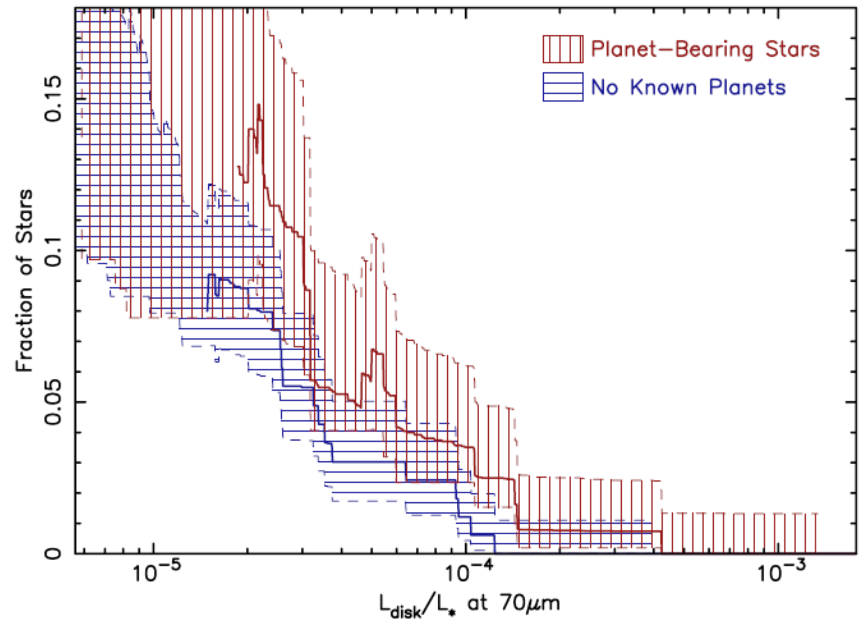
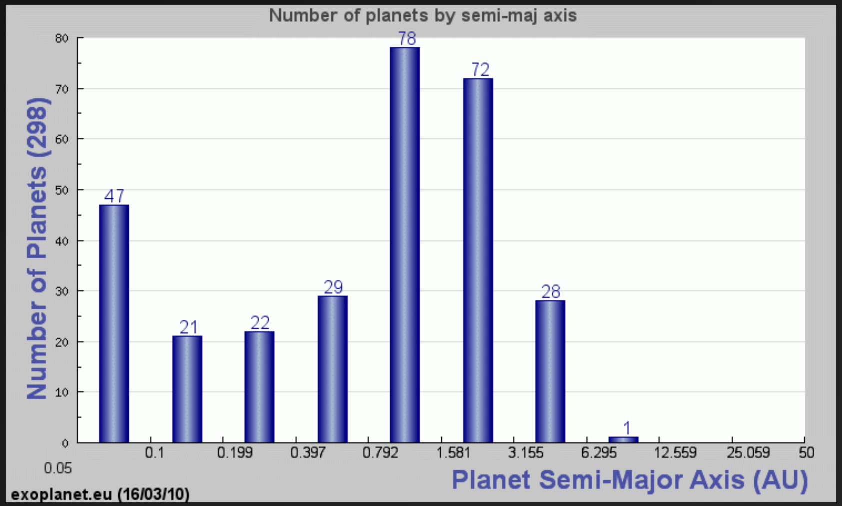


Figure 3. Cumulative fraction of stars with 70 μm excess as a function of disk luminosity for the planet and non-planet samples. As in Figure 1, the dust's fractional luminosity, $L_{\rm dust}/L_\star$, is derived from the strength of the 70 μm emission relative to the stellar photosphere (Equation (2)). For both the planet and non-planet samples, dust disks with $L_{\rm dust}/L_\star > 10^{-4}$ are rare, with $L_{\rm dust}/L_\star \approx 10^{-5}$ disks detected much more frequently. The 1σ uncertainties in the underlying distributions of $L_{\rm dust}/L_\star$ are indicated by the shaded regions. While the dust around planet-bearing stars is nominally brighter than for the non-planet stars (i.e., the red line lies above the blue line), the difference is not statistically significant.

Why no disk/planet correlation ?

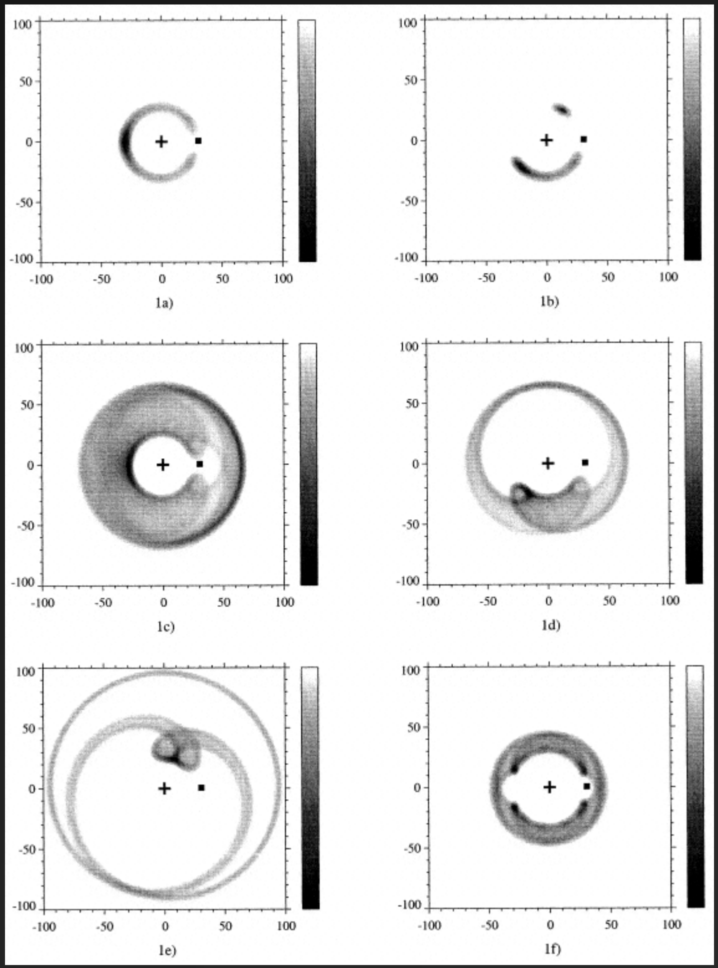
- Most debris disks have inner holes suggestive of planets
- Seems doubtful that planet formation would produce system of small bodies & dust debris at 10s of AU, but not larger objects closer in



- INCOMPLETENESS: RV studies currently probe only to ~5 AU distances.
- Spitzer most sensitive to IR excess beyond 10 AU, and Kuiper disks ≥50x that of the Sun
- Can expect correlations to appear when both techniques advance to probe common radial region

Connecting Individual Planets & Disks

- Disk images can provide the system inclination
- Dust provides a field of test particles that respond to dynamical influence of planet
- Disk structures (rings, central clearings, and asymmetries) point to nearby planets and allow theoretical constraints on their masses & orbital elements

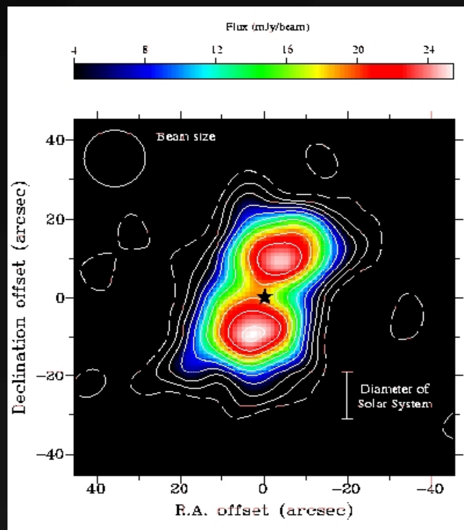


Ozernoy et al. 1999

19 Systems with both Planets and Debris Disks

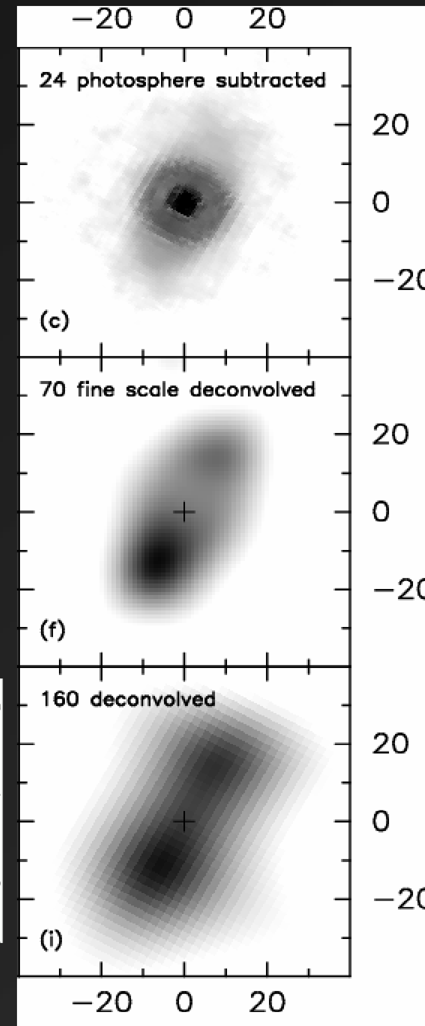
Star	Planet orbital semi-major axes (AU)	Outer planet Eccentricity	Approx. Disk Inner Radius	Disk Resolved ?
Fomalhaut	115	probably 0.11	133 AU	HST, Spitzer, submm
HR 8799	24, 38, 68	?	95 AU	Spitzer
HD 69830	0.08, 0.19, 0.63	0.07	1.0 AU	
Epsilon Eridani	3.4	0.3-0.7 ??	2 AU, 35 AU	Spitzer, submm
Gl 581	0.03, 0.04, 0.07, 0.22	0.38	4 AU	
HD 142	1.0	0.37	> 28 AU	
HD 10647	2.0	0.1	10 AU	HST, Spitzer
HD 19994	1.4	0.3	> 7 AU	
HD 38529	0.12, 3.70	0.36	> 103 AU	
HD 50554	2.38	0.42	> 58 AU	
HD 52265	1.13	0.29	> 40 AU	
HD 82943	0.75, 1.19	0.22	> 65 AU	
61 Vir	0.05, 0.22, 0.48	0.35	4 AU	
70 Vir	0.48	0.4	> 5 AU	
HD 128311	1.10, 1.76	0.25	> 11 AU	
HD 150706	0.82	0.38	110 AU	
HD 178911 B	0.32	0.12	> 28 AU	
HD 202206	0.83, 2.55	0.27	> 50 AU	
HD 216435	2.56	0.07	> 13 AU	

Fomalhaut disk: far-IR and submm images of an asymmetric ring with radius ~130 AU



JCMT/SCUBA 850 μm (Holland 1998)

CSO / Sharc II 350 μm (Marsh 2005)

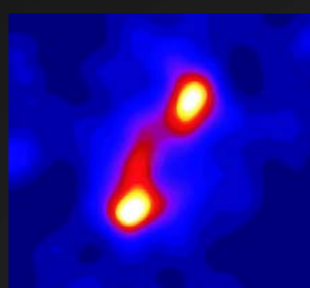


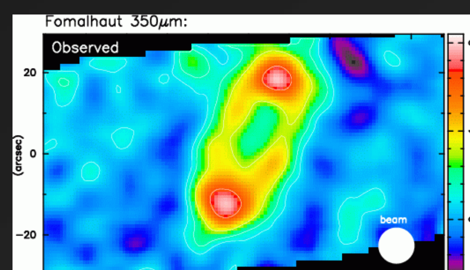
MIPS 24 μm (PSF-subtracted)

MIPS 70 μm

MIPS 160 μm

JCMT/ SCUBA 450 μm (Wyatt 2002, Holland 2003)

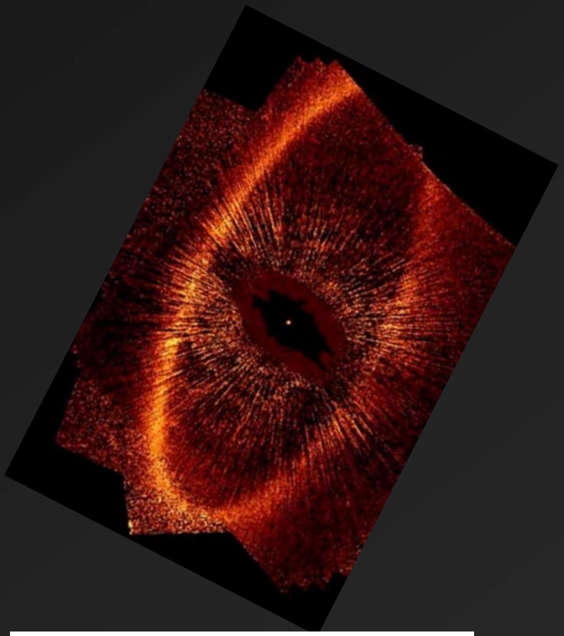




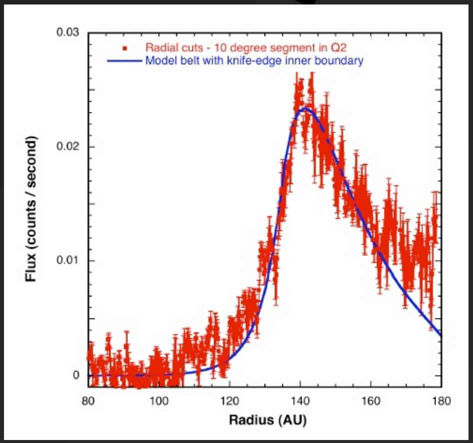
Stapelfeldt et al. 2004

Eccentric Ring Confirmed by HST

(Kalas et al. 2005)



- Detected in 0.6 μm scattered light
- Ring geometry: center is offset 2″ from the star; shape fit with $e = 0.11$
- Ring has sharp inner edge, as if dynamically sculpted
- Brighter on E side, consistent with modest forward scattering



Mon. Not. R. Astron. Soc. **372**, L14–L18 (2006) doi:10.1111/j.1745-3933.2006.00216.x

Predictions for a planet just inside Fomalhaut's eccentric ring

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ABSTRACT
We propose that the eccentricity and sharpness of the edge of Fomalhaut's disc are due to a planet just interior to the ring edge. The collision time-scale consistent with the disc opacity is long enough that spiral density waves cannot be driven near the planet. The ring edge is likely to be located at the boundary of a chaotic zone in the corotation region of the planet. We find that this zone can open a gap in a particle disc as long as the collision time-scale exceeds the removal or ejection time-scale in the zone. We use the slope measured from the ring edge surface brightness profile to place an upper limit on the planet mass. The removal time-scale in the chaotic zone is used to estimate a lower limit. The ring edge has eccentricity caused by secular perturbations from the planet. These arguments imply that the planet has a mass between that of Neptune and that of Saturn, a semi-major axis of approximately 119 au and longitude of periastron and eccentricity, 0.1, the same as that of the ring edge.

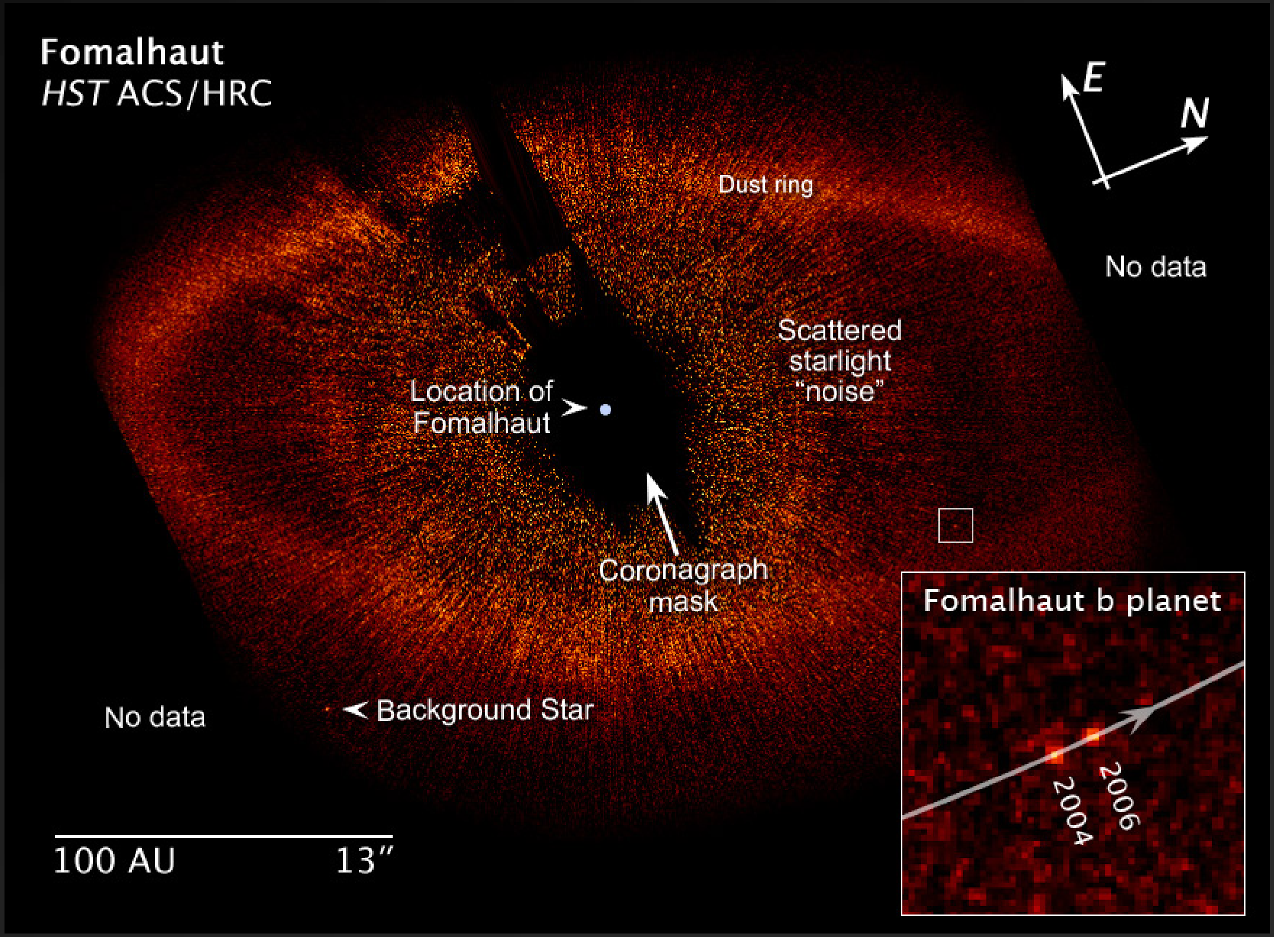
Key words: stars: individual: Fomalhaut – planetary systems – planetary systems: protoplanetary discs.

Planet seen in 2008
Kalas et al.

Deprojected orbit semi-major axis of 115 AU:
4x Sun-Neptune distance

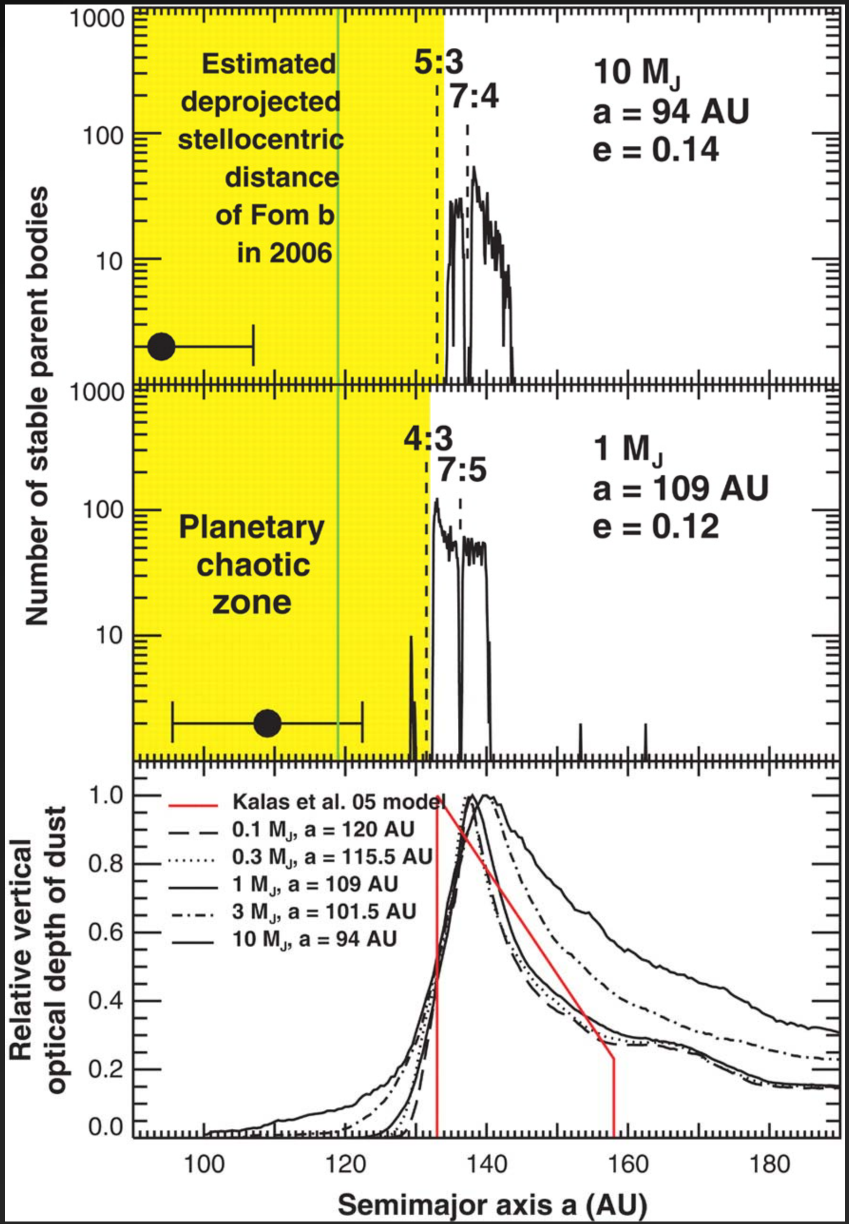
Common proper motion with star: not a background object

Orbital motion seen parallel to ring inner edge; consistent with Kepler's law



Parent body stability to planetary perturbations

- Chiang et al. 2009 refine Quillen 2006 result
- Planet with a= 115 AU must have mass < 3 M_J in order for ring to be stable

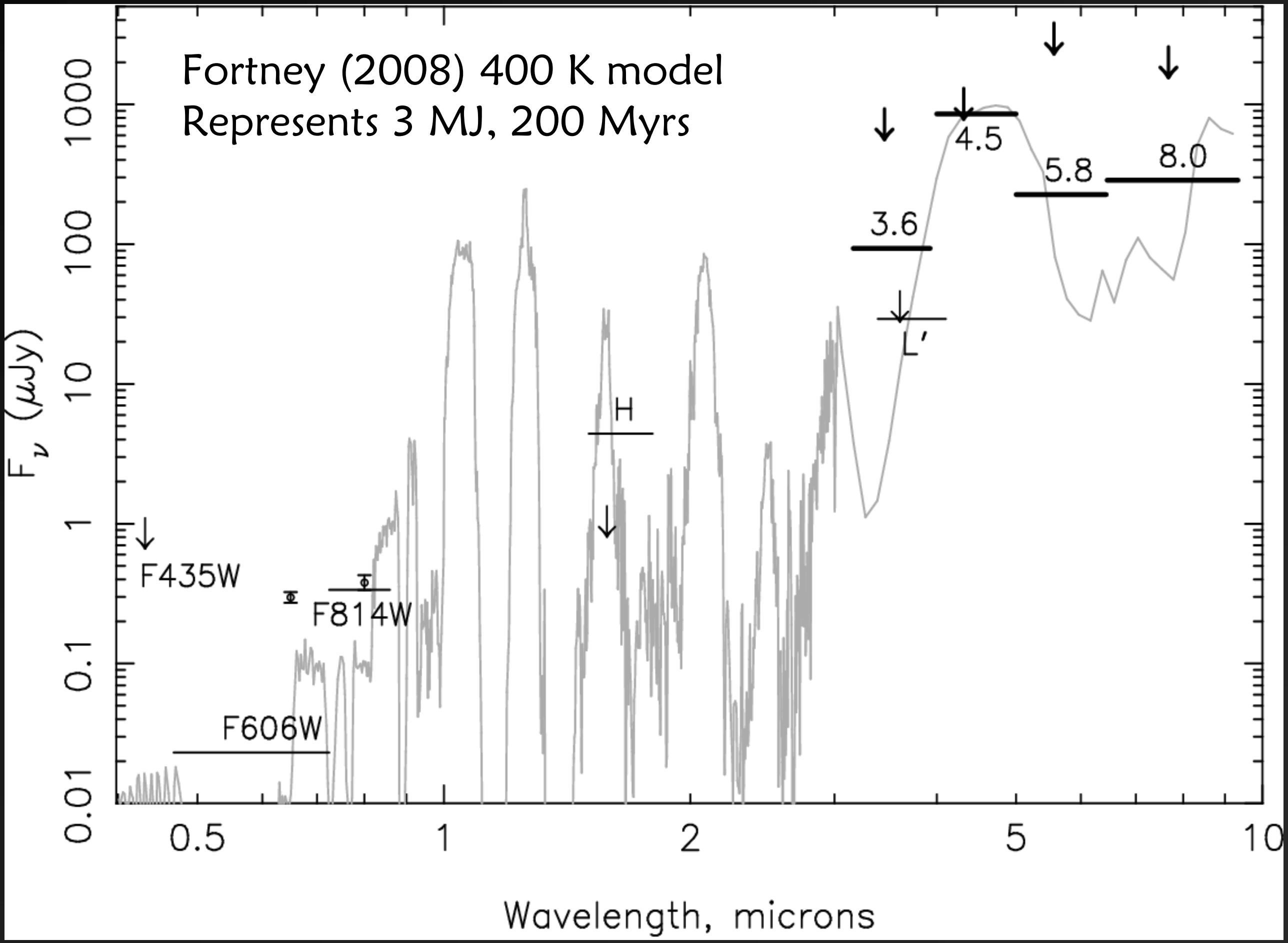


Kalas et al. 2008 photometry

Table S2: Photometry on Fomalhaut b

UT Date	Filter	Magnitude	Error (mag)
2004-10-25	F606W	24.43	0.08
2004-10-26	F606W	24.29	0.09
2005-07-21	H (1.6 μm)	$>$22.9	3σ limit
2005-10-21	CH_4	$>$20.6	3σ limit
2006-07-14/20	F606W	25.13	0.09
...	F814W	24.55	0.13
...	F435W	$>$24.7	3σ limit
2008-09-17/18	L' (3.8 μm)	$>$16.6	3σ limit

Fomalhaut b from 0.4-8 μm

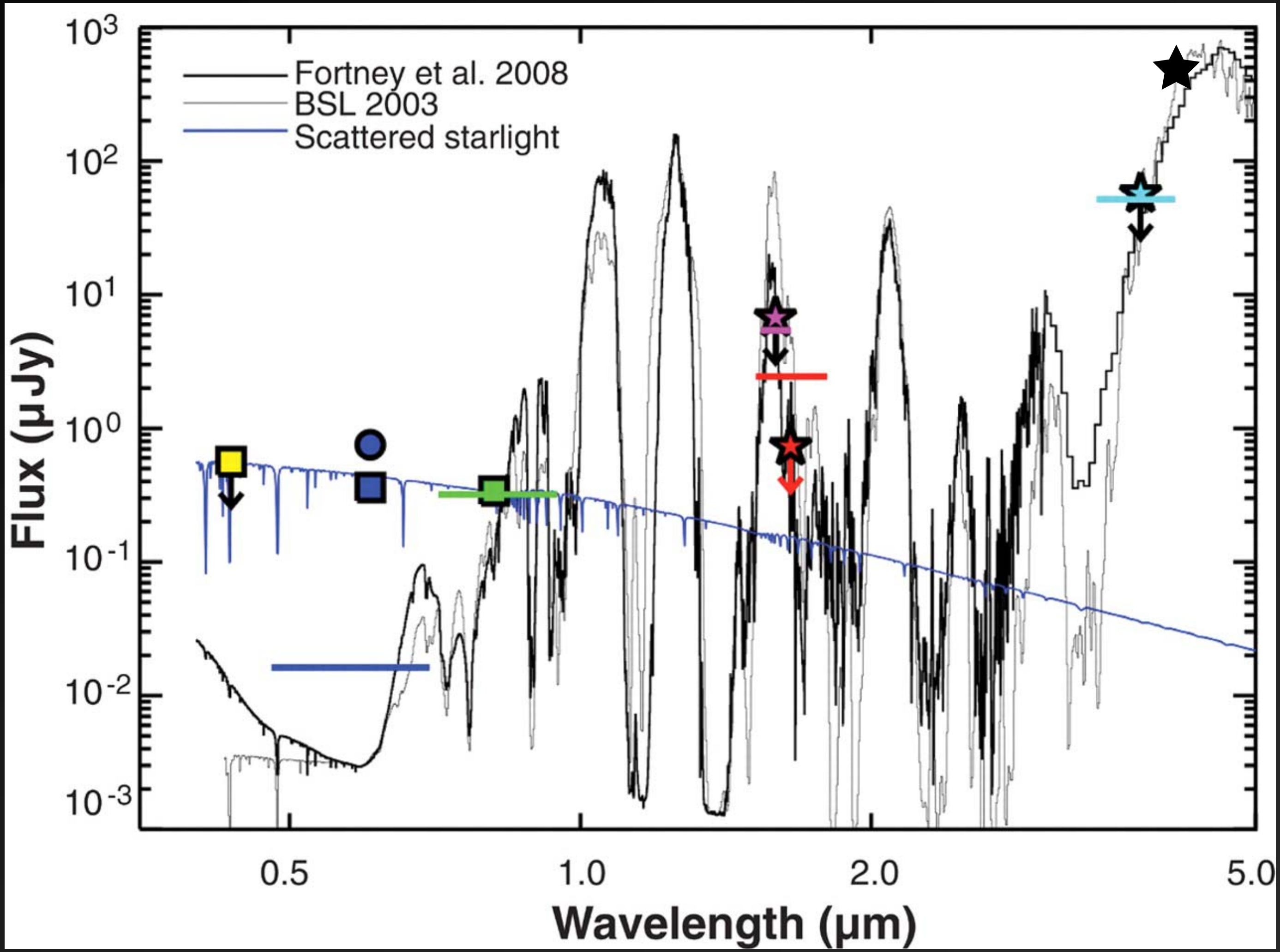


Spitzer/IRAC limits from Marengo et al. 2009
HST + Keck/Gemini from Kalas et al. 2008

Thermal emission from Fomalhaut b: 3 MJ object, age 200 Myrs ?

- Assume HST sees this at 0.8 μm ; Teff 400 K
- Pro: Consistent with 3.6 & 4.5 μm limits
- Con: Model emission is 3x the observed upper limit at 1.6 μm band (Keck), and should have been detected at 4.5 μm
- Con: Model emission is ~50x fainter than the measured brightness at R band (HST)
- Need model atmospheres to be wrong (composition? Water clouds ?), and major extra source of R band flux (Halpha emission ?)

Fomalhaut b photometry vs. model thermal emission (3 MJ, 200 Myrs)



Kalas et al. 2008

Reflected light from Fomalhaut b?

- Pro: Consistent with all the observed colors and upper limits
- Con: Object is 6 mag brighter than our Jupiter would appear at 119 AU
- Need reflecting area of ~20 Jupiter radii, comparable to ring system spanning orbits of the Galilean satellites. Even larger if not optically thick.
- A protosatellite disk of this size is expected during first few Myrs, but not at 200 Myr age of Fomalhaut.
- Alternative: huge planetary ring system. Breakup of 30 km object could produce the needed dust reflecting area. Or, ring system accretes debris escaping from stellar debris ring. Theorist needed !

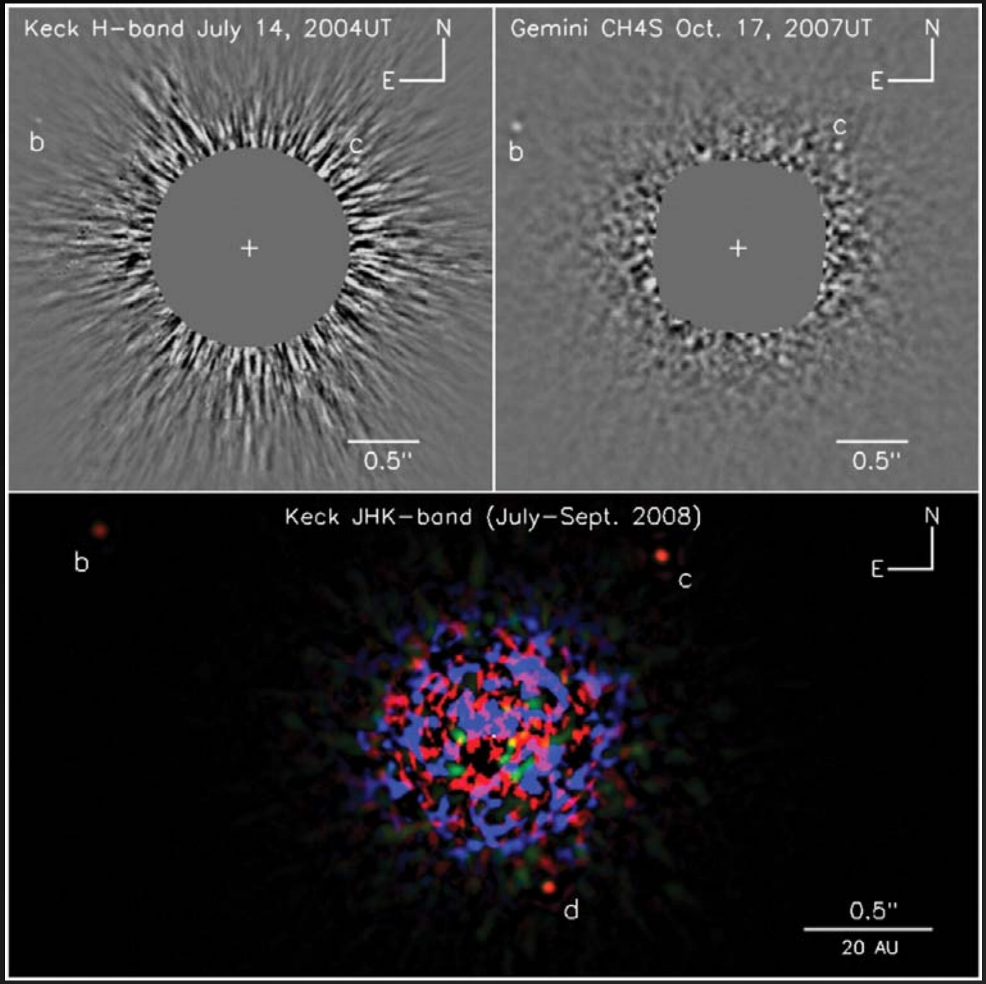
Mystery of Fomalhaut b will persist

- More groundbased work unlikely to help;
  Keck, Gemini, VLT don't detect the object
- HST Servicing Mission didn't help:
  - Repair of Advanced Camera coronagraph failed. No new optical spectrophotometry can be obtained for Fom b; orbit tracking will be tried with STIS coronagraph.
  - New WFC3 IR channel J band observations didn't achieve useful depth.
  - NICMOS coronagraph images would do better, but revival of this instrument is in doubt
- JWST measurements in 2014+ should be definitive.

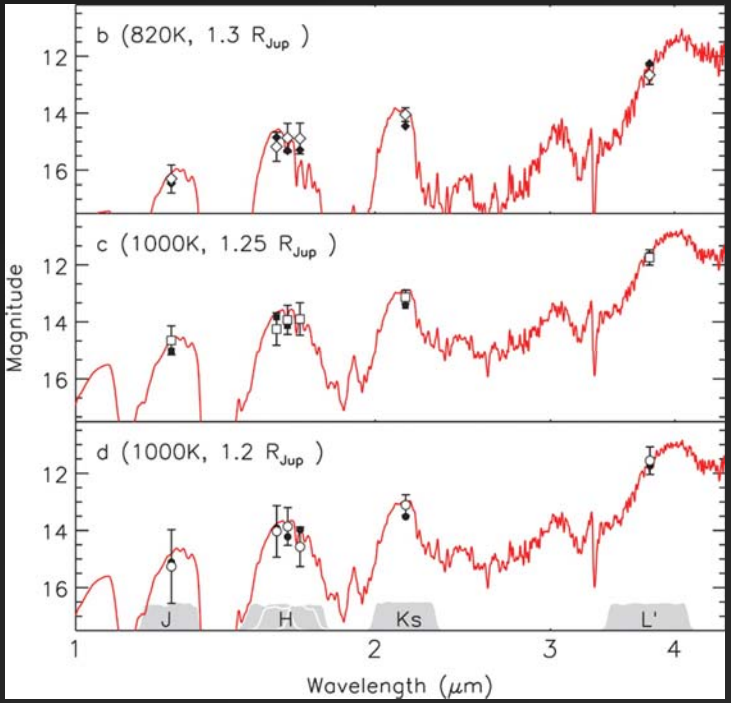
- Two inner dust belts indicated by modeling of Spitzer data: one near 7 AU, another at perhaps 50 AU. (Stapelfeldt in prep)

Three planets orbiting HR 8799

Marois et al. 2008

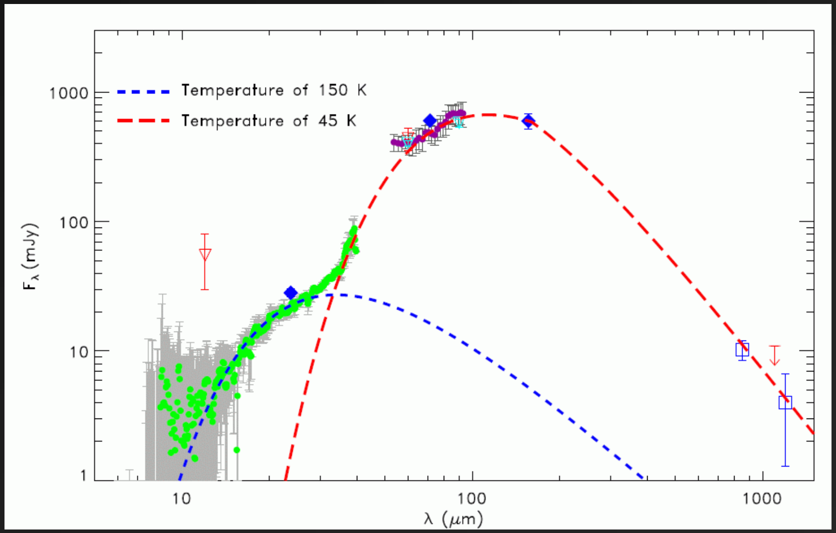


A0 star at 40 pc distance
Young system age ~60 Myrs
"Easy" contrast of 10^5



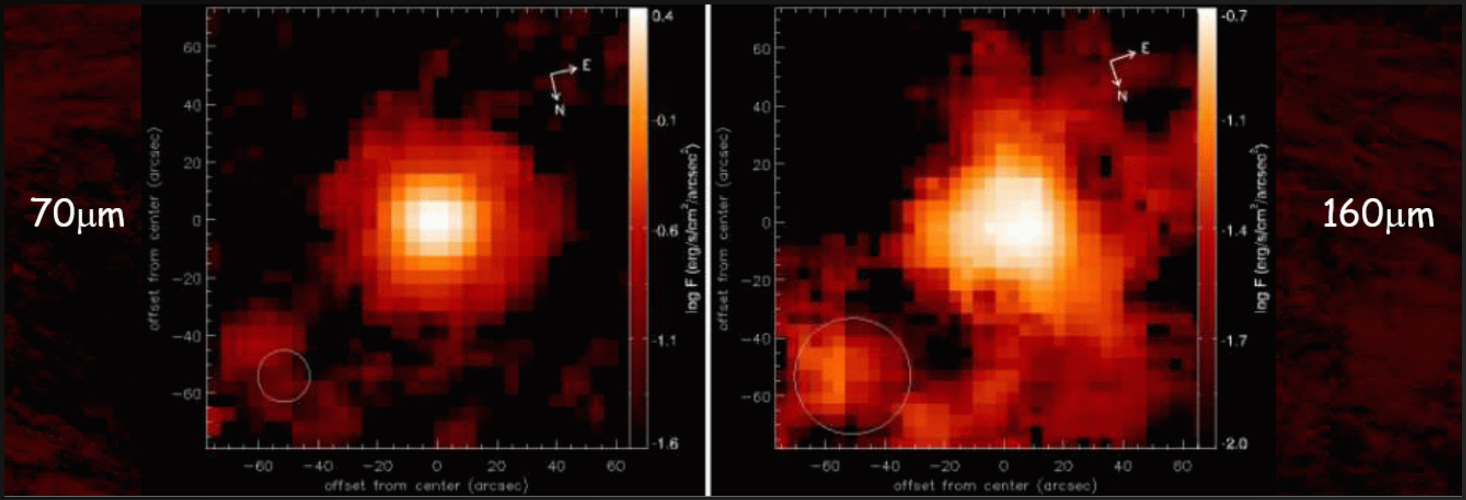
The HR 8799 Debris Disk

- Infrared excess shows two blackbody-like components
- Simple blackbody grains would produce this if located in belts at
  - 9 AU (T= 150 K)
  - 95 AU (T= 45 K)
- Dynamically viable: This would place the dust interior and exterior to the planets imaged at 24, 38, 68 AU



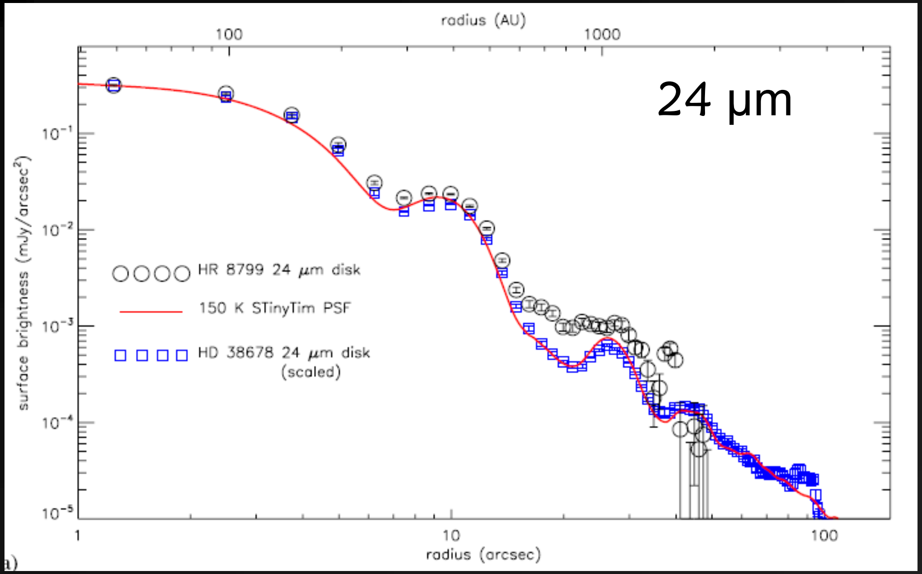
(Su et al. 2009)
see also
Chen et al. 2009,
Reidemeister et al. 2009

Disk is spatially resolved at 70 µm

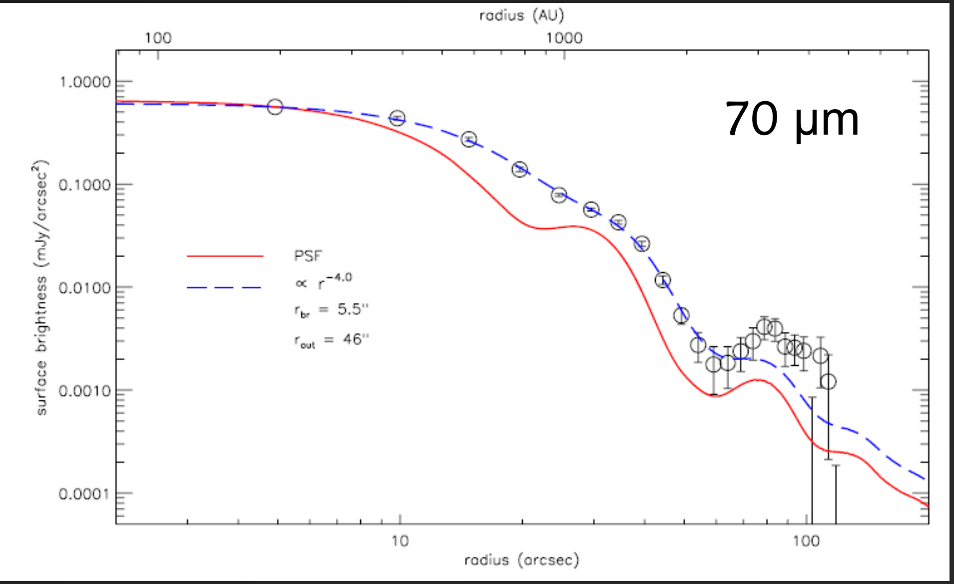


- Two cold components seen: Unresolved image core, plus halo extending to 1000 AU radius. But halo is barely resolved (MIPS 70 µm beamsize = 700 AU)
- Azimuthal symmetry suggests disk is viewed to within 25° of face-on, in agreement with inferences from orbital motion of HR 8799b, orbit stability analyses, and stellar vsini.

1-D radial profiles vs. instrument PSF

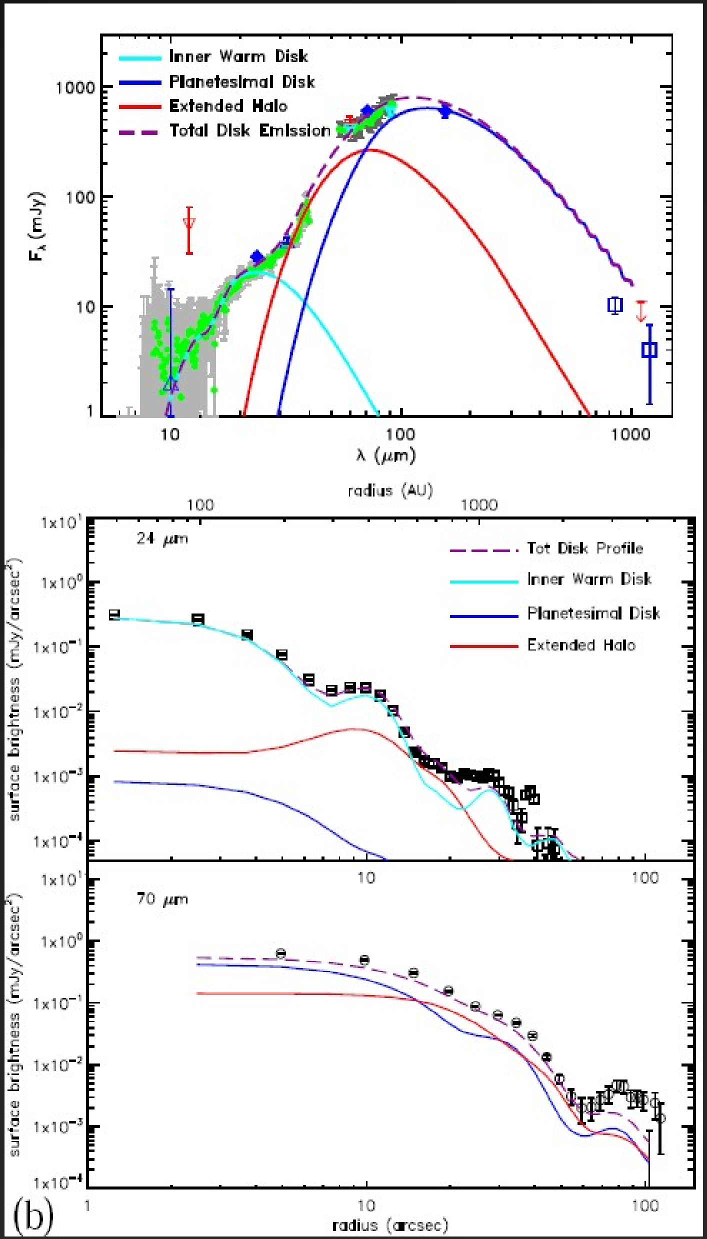


- Ratio of 24/70 surface brightness establishes the local disk temperature and thus the grainsize

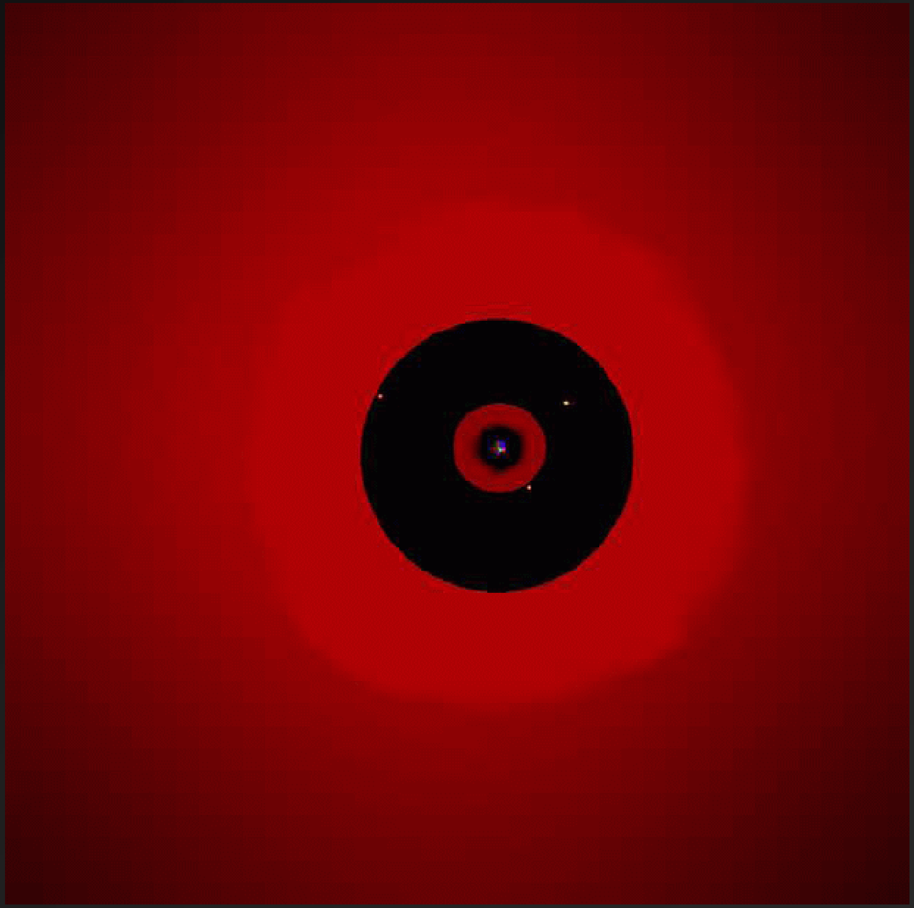


Preferred model for HR 8799 disk

- Inner warm disk belt
  r= 6-15 AU, 1-5 μm grains
- Planetesimal parent belt
  between r= 90-300? AU,
  grainsizes 10-1000 μm
- Halo extending from
  r= 300?-1000 AU with small
  1-10 μm grains
- Halo has 50% of IR luminosity



Disk/planet arrangement in HR 8799



Graphic courtesy George Rieke

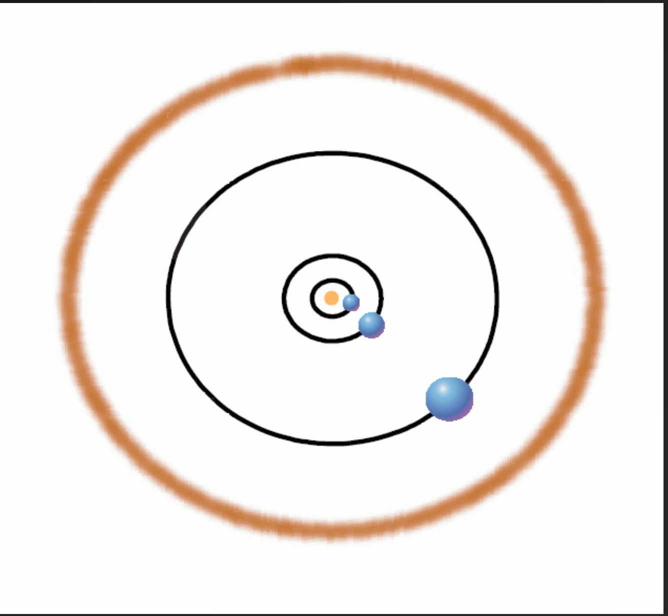
HR 8799 Disk Halo

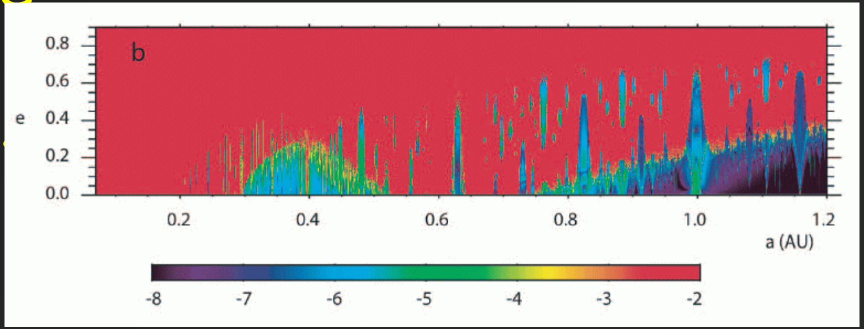
- Radial density profile consistent with a radiation pressure driven particle outflow as for Vega disk (Su et al. 2005). Weakly bound grains may play a role.
- Mass of escaping dust (relative to parent bodies) would be ~15x that expected in normal collisional equilibrium (Wyatt 2007).
- Major recent collision; dynamical stirring by the observed giant planets ?

HD 69830 triple Neptune System

(Lisse et al. 2007)

- Old K0 star, d= 13 pc
- Unusual population of small/warm dust particles; major recent collision ? (Beichman et al. 2005)
- Planets at 0.08, 0.19, 0.63 AU (Lovis et al. 2006)
- Detailed dust size/composition analysis & radiative balance places the dust belt at ~1 AU, exterior to planets.
- Parent bodies would be dynamically stable there.

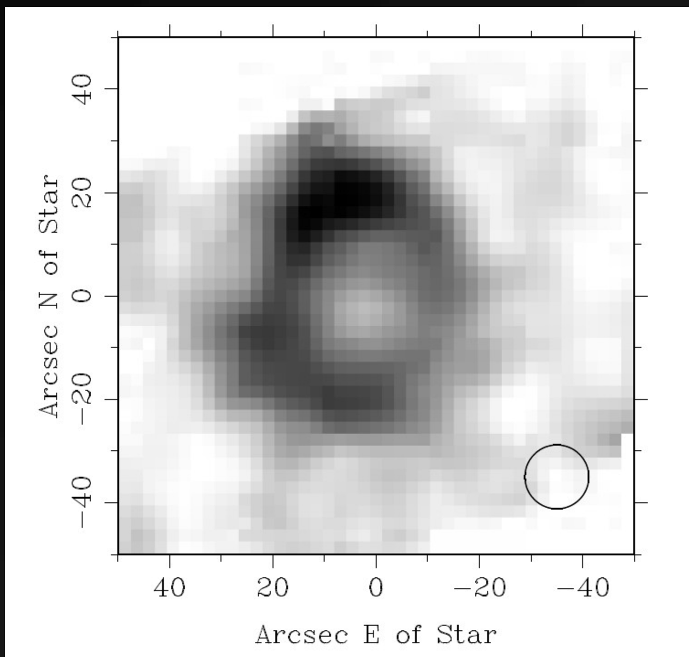




ε Eridani's perplexing submm face

K2 star only 3.3 pc distant

CSO/Sharc II 350 μm

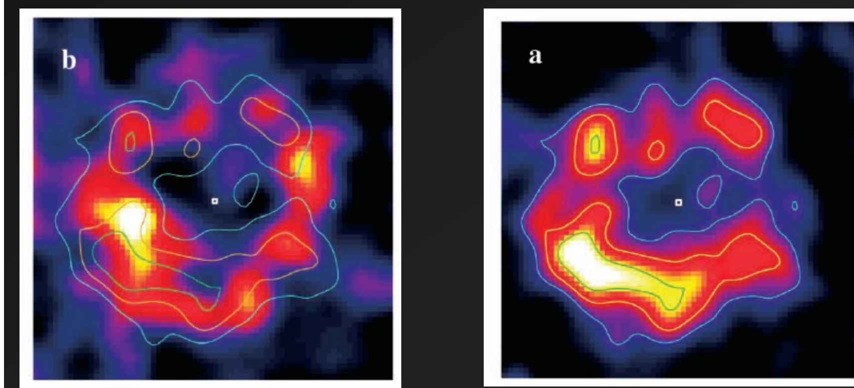


Backman et al. 2009

JCMT/SCUBA

450 μm

850 μm



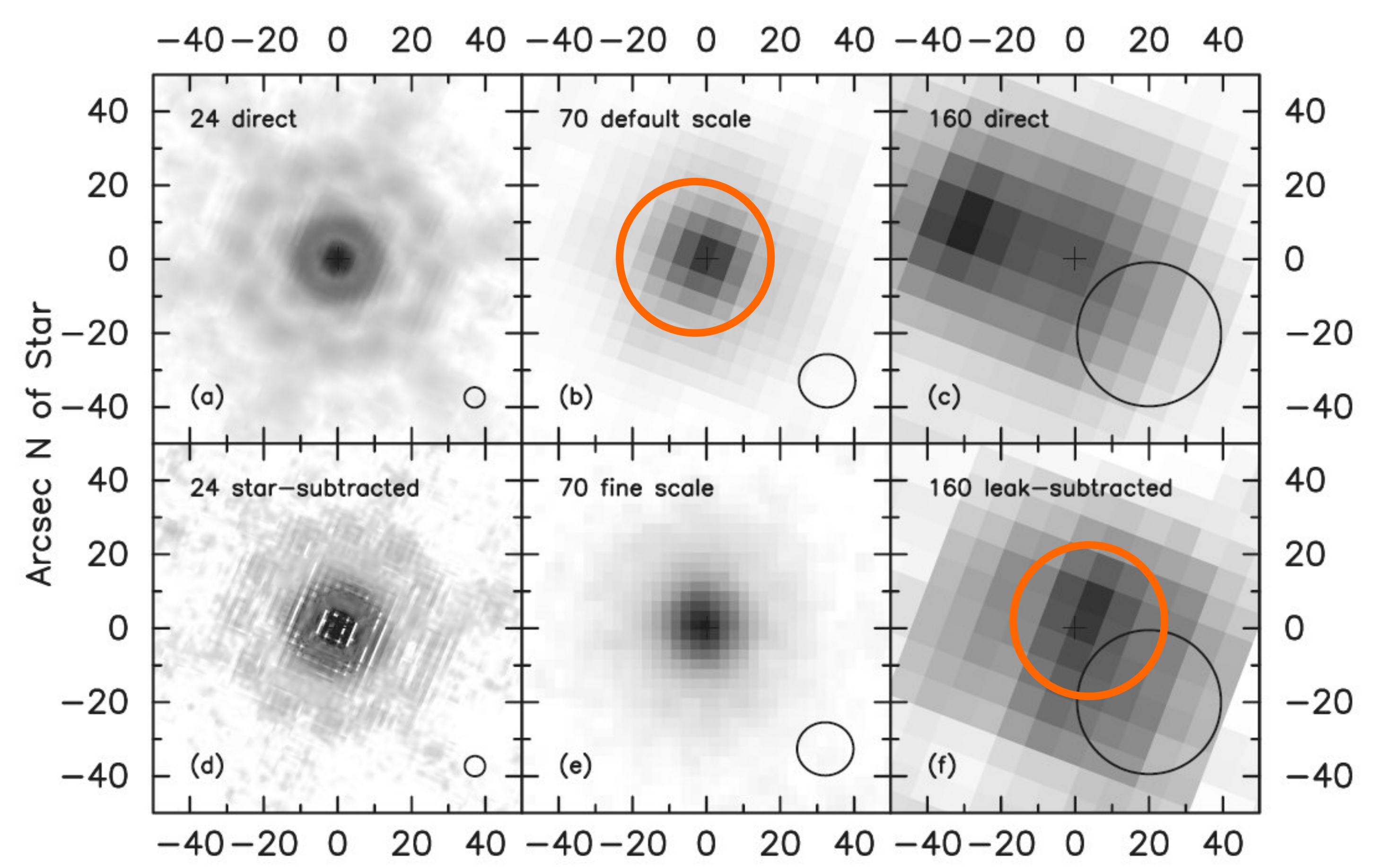
Greaves et al. 2005

Ring is confirmed in multiple datasets, but azimuthal clumps show no consistent pattern

ε Eridani seen by Spitzer/MIPS

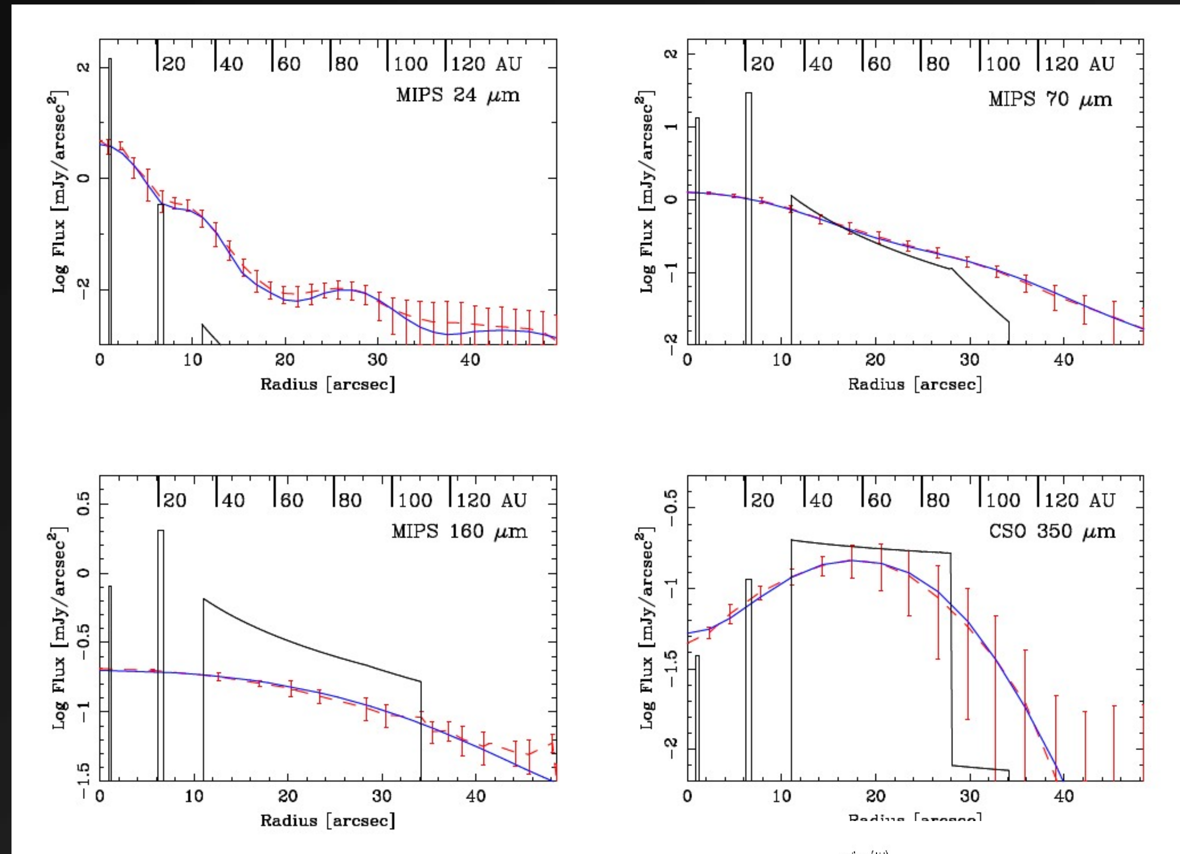
Backman et al. 2009

Submm ring size



Black circles indicate MIPS beamsize

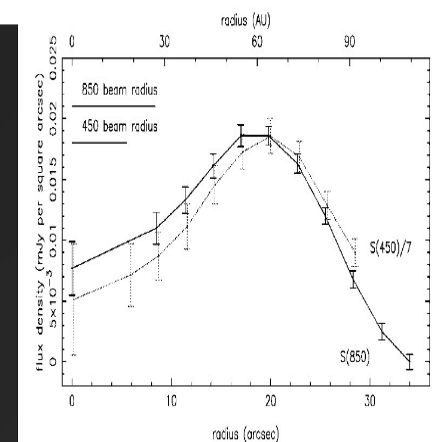
ε Eridani radial brightness profiles



Spitzer+CSO results from Backman et al. 2009. Red dashed line & error bars show observations. Black lines show model emission profiles before & after PSF convolution

Separate inner belt, outer ring required by 24 and 350 μm profiles. Extended halo of outer ring required by 70, 160 μm profiles

Right: JCMT 450 & 850 μm profiles (Greaves et al, 2005)

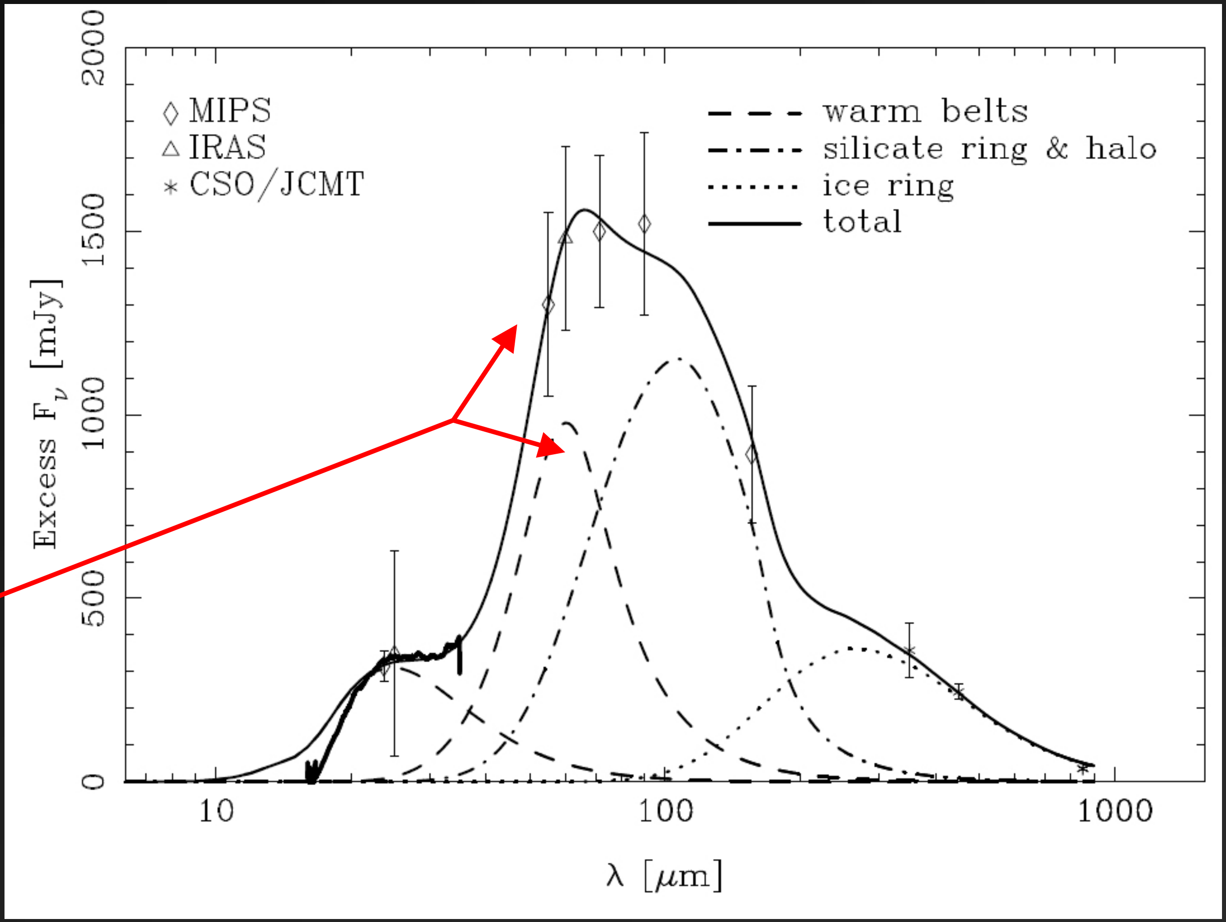


ε Eridani excess spectrum model

Backman et al. 2009

Outer ring must contain both large grains to make the submm emission, and smaller grains for the co-spatial 70/160 μm emission

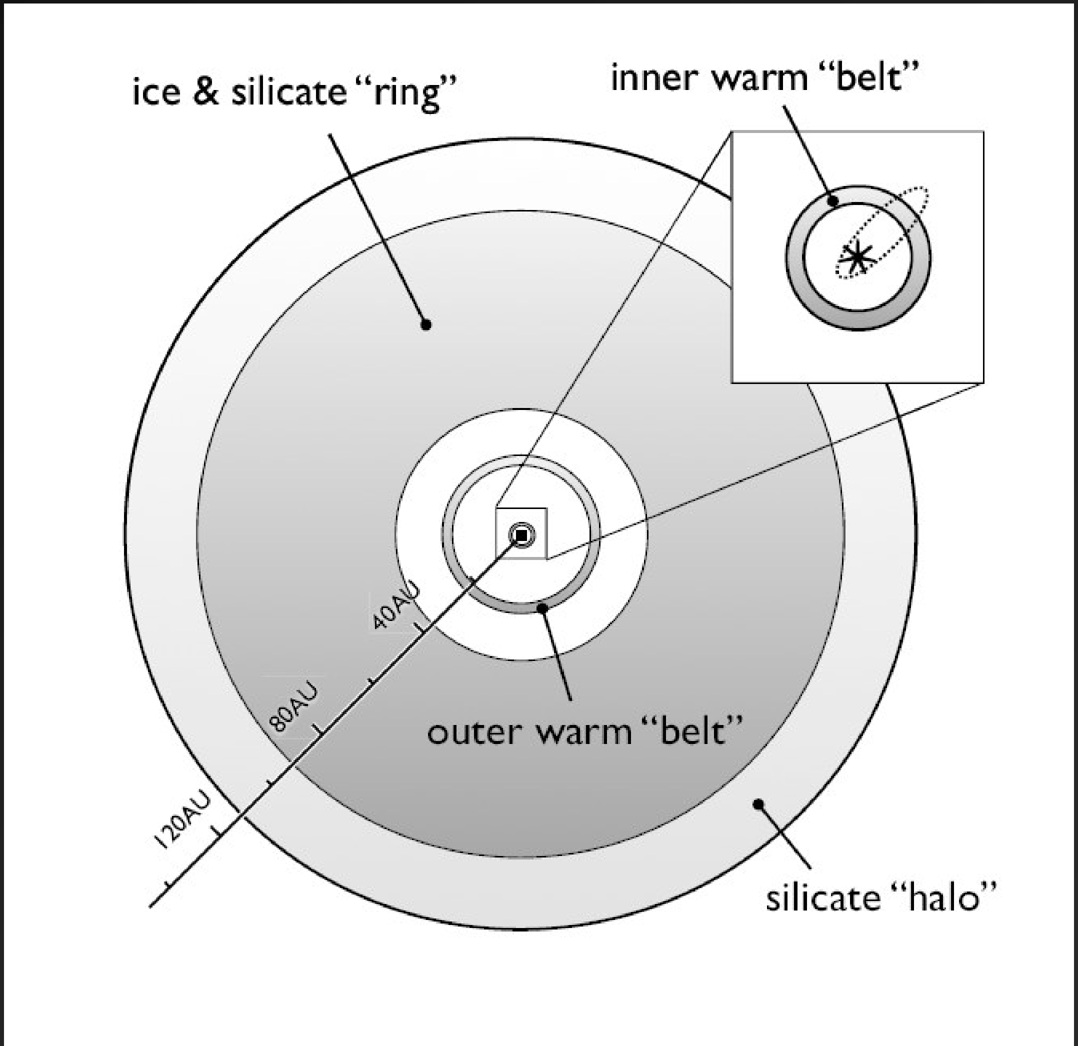
55 μm flux density measured in MIPS SED mode requires 5th component: a ring near 20 AU



New View of the ε Eri debris disk

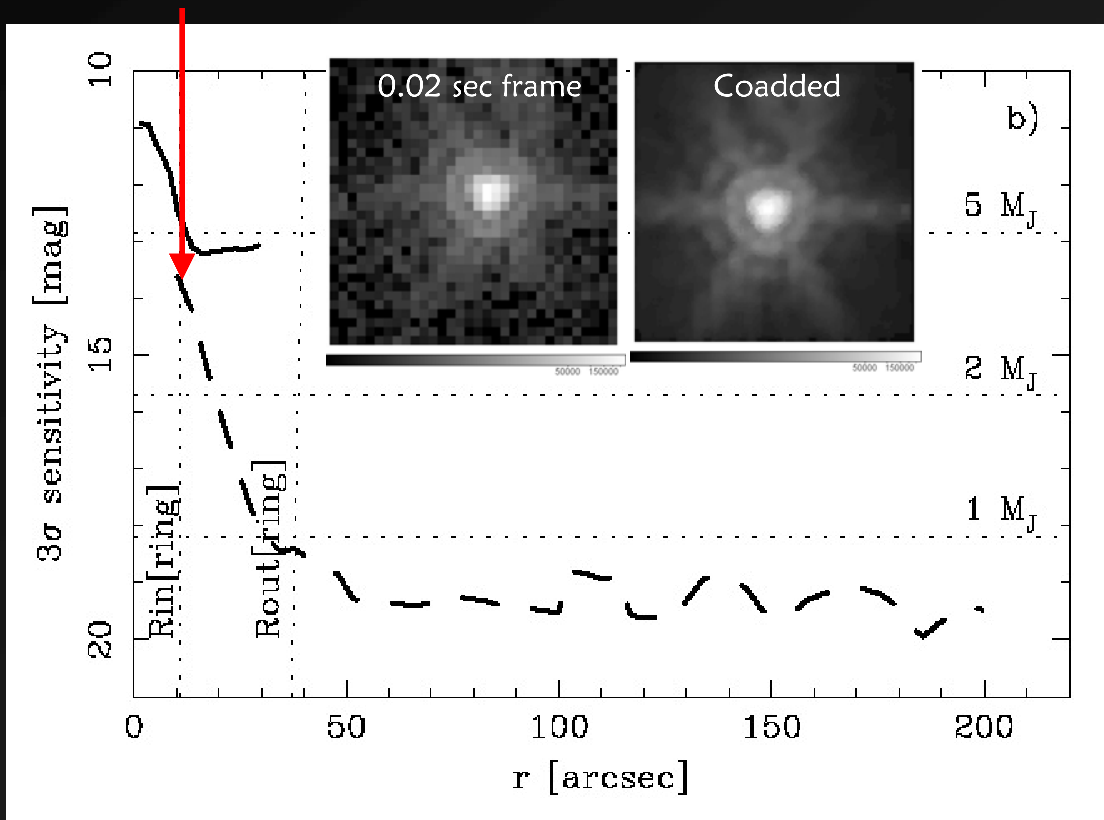
graphic by Massimo Marengo

- Three disconnected debris belts
- Inner belt at 2-3 AU is close to RV planet ε Eri b (a= 3.4 AU)
- Eccentricity of the RV planet is unlikely to be 0.7 (Benedict et al. 2006), as this would disrupt the inner belt.
- e= 0.3 +/- 0.23 is current value on exoplanets.org ; much more consistent with Spitzer results.



No Eps Eri companion detected
Upper limits from IRAC subarray data:

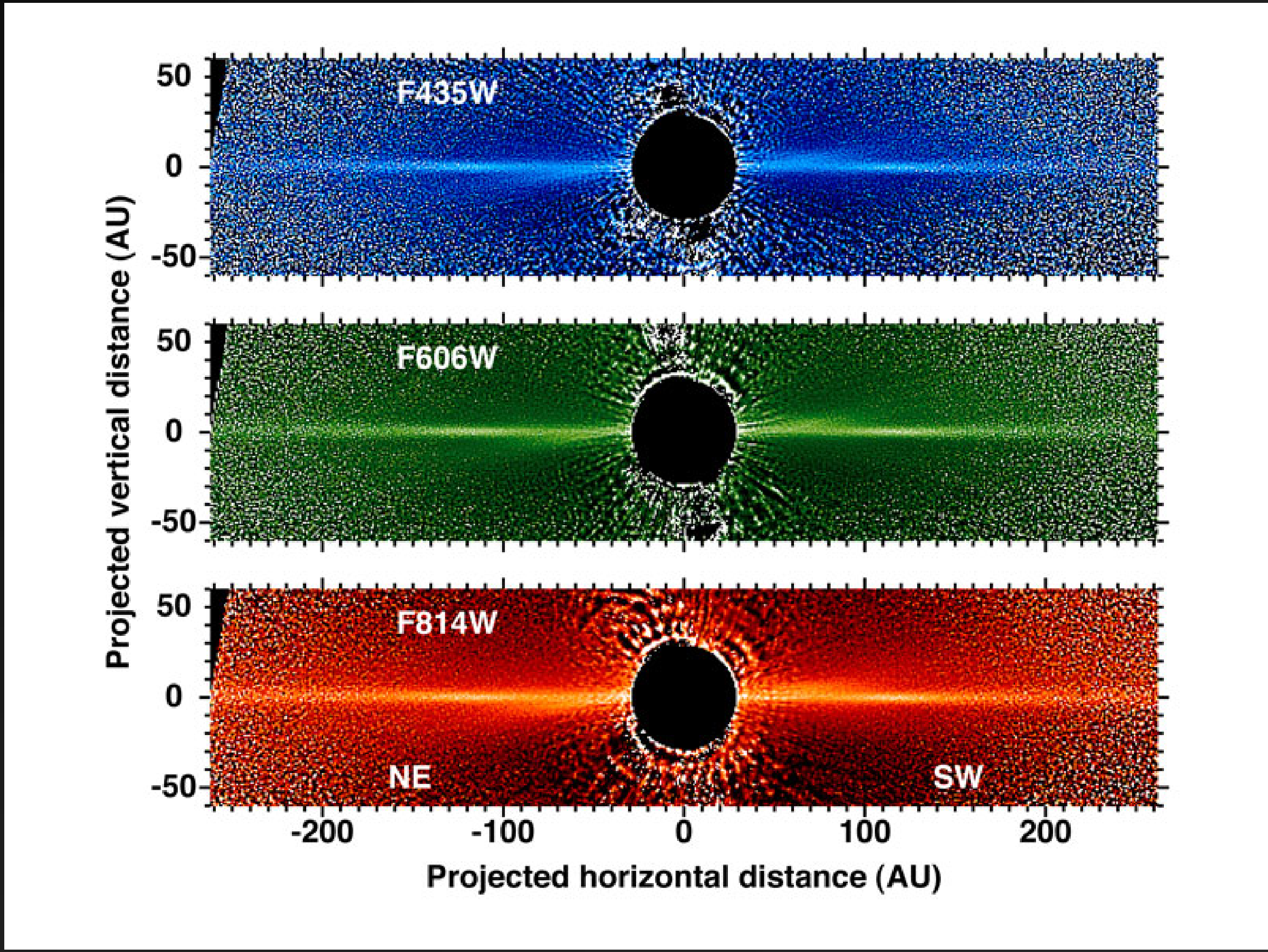
Marengo et al. 2009



- 146,880 frames taken at two roll angles
- Limiting mag is 13.9 at 4.5 μm (0.5 mJy)
- This corresponds to a 3 Jupiter mass object at 1 Gyr age (Burrows, Sudarsky & Hubeny 2004)
- No real evidence for outer ring clumps or associated planet in the system

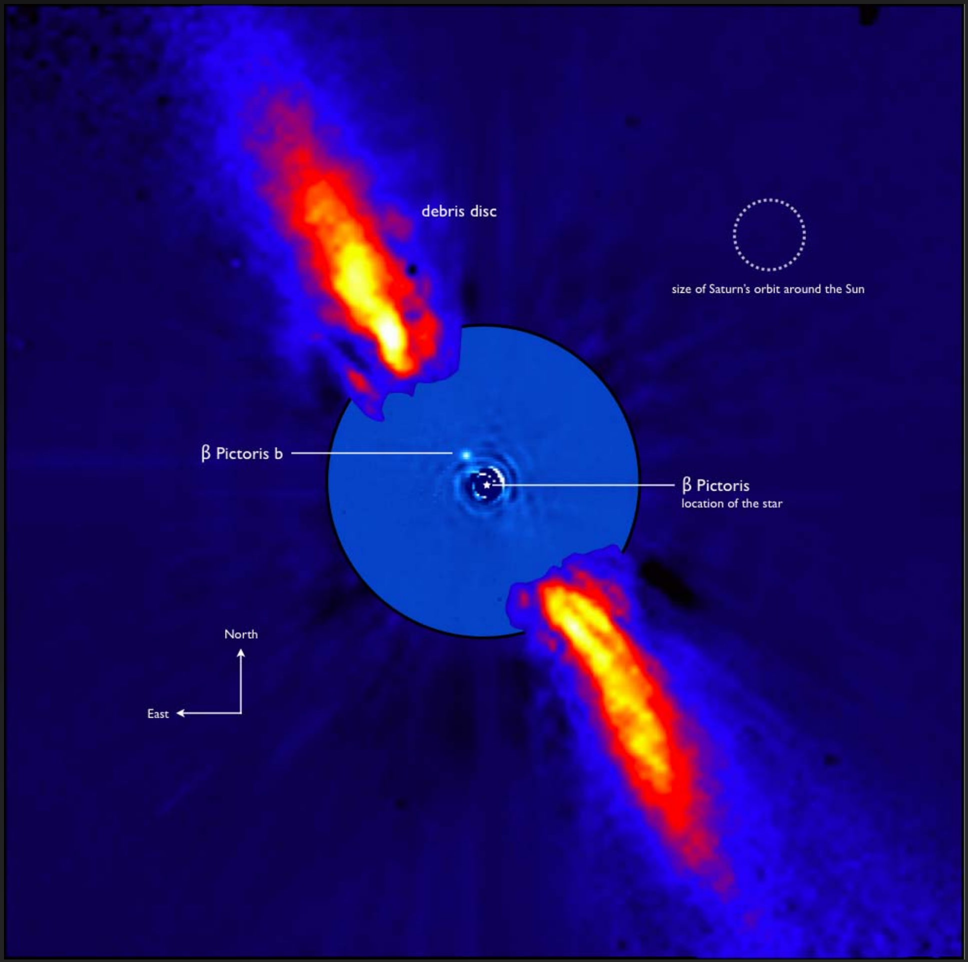
β Pictoris warped inner disk

HST coronagraphy Golimowski et al. 2006



Beta Pictoris: Perturbing planet found ?

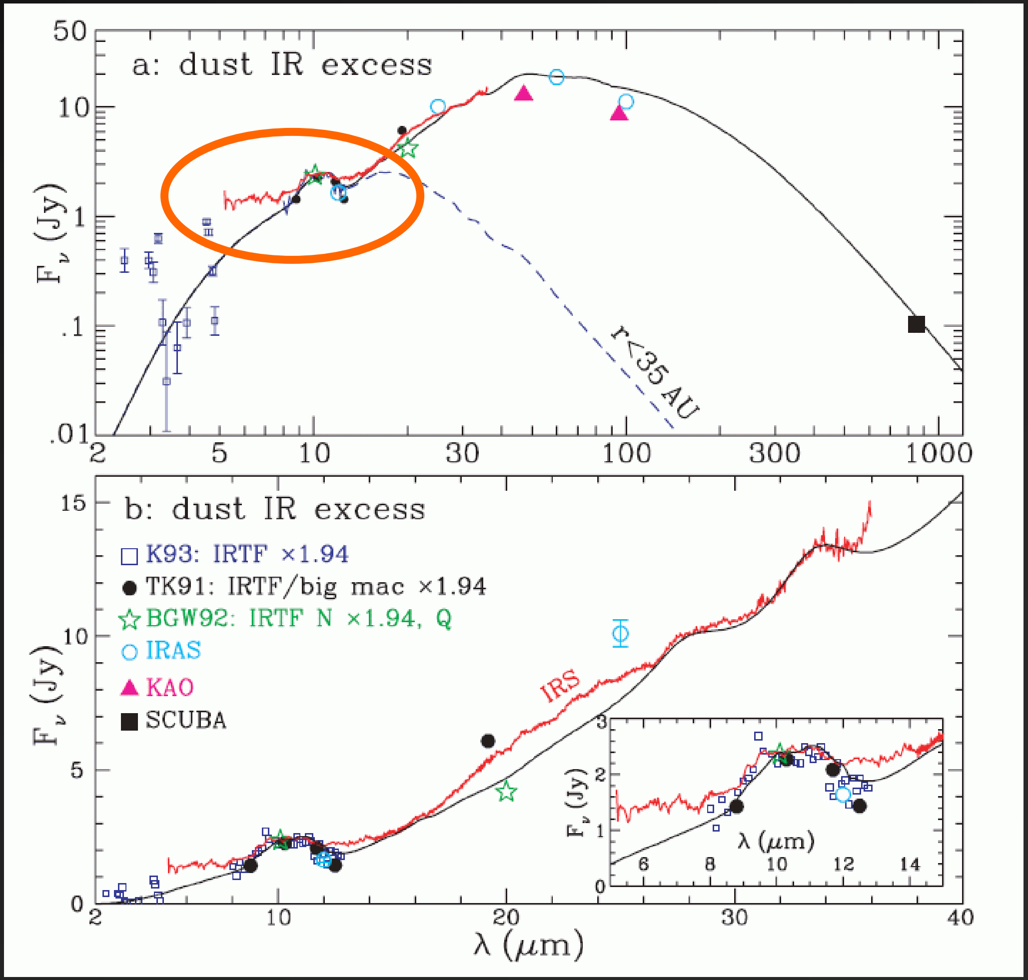
- 2003 VLT 3.4 μm image published by Lagrange et al. 2009.
- No confirmation by proper motion or photometry at other wavelengths
- <u>Not detected in 2009 images by several groups</u>
- If real, a >= 8 AU and mass= 8 $M_{Jupiter}$
- Stellar proper motion is northward; would move a BG source within 0.1" of the star in 2010



Region of β Pic planet candidate is not cleared of dust

Spitzer/IRS results of Chen et al. (2007)

- Dust excess emission seen down to λ= 5μm
- Silicate emission indicates minimum grainsize ~1 μm.
- Modeled as continuous disk 0.2 < r < 2000 AU, peak density at 100 AU
- How to maintain dust cloud that spans planet's orbit ?



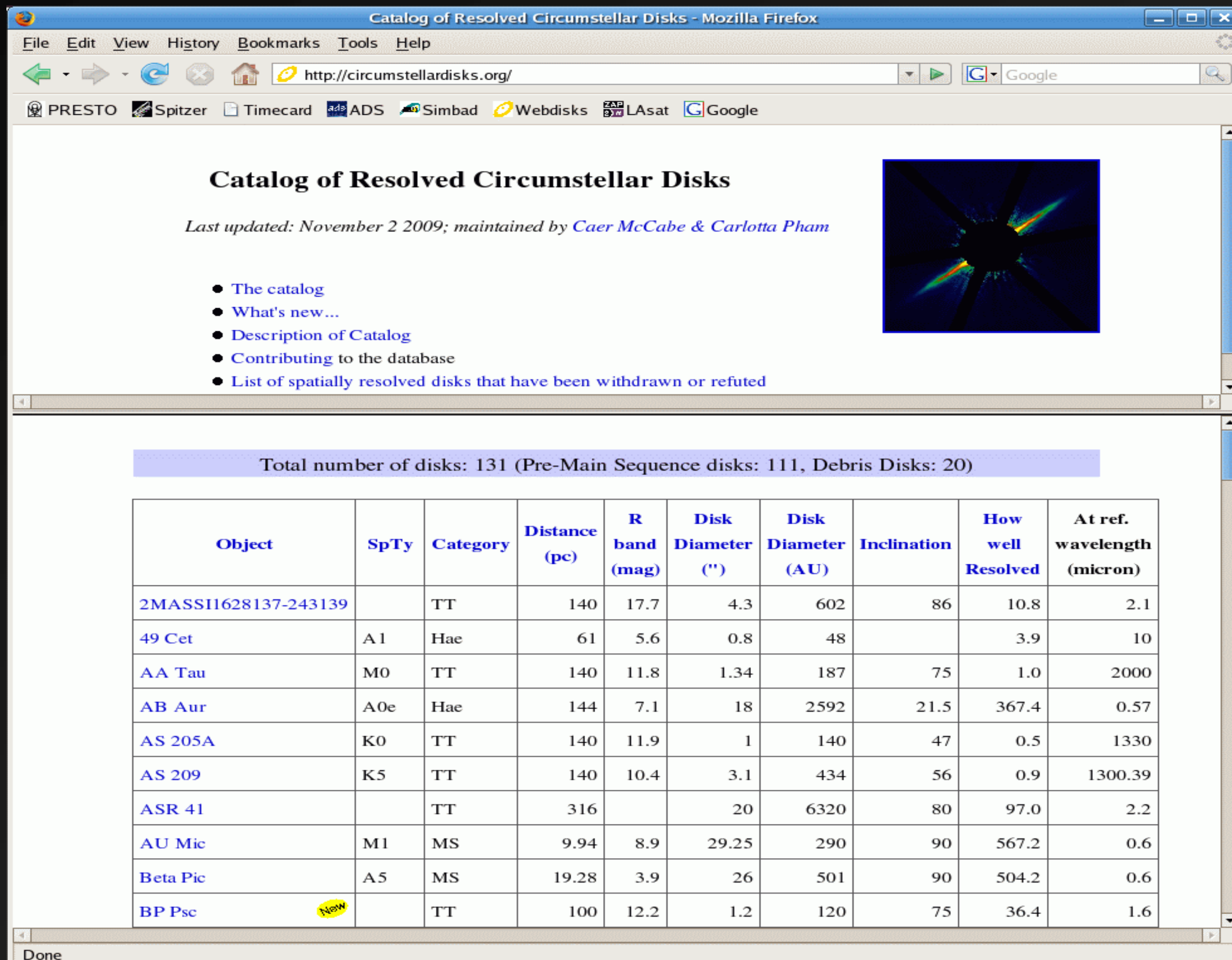
Inventory of Resolved Debris Disks

20 today, 14 at 0.1″ resolution

Star Name	Spectral Type	Lir/Lstar	Scattered Light ground	Scattered Light space	Thermal IR ground	Far-IR space	Millimeter/ submillimeter
HD 141569A	B9	8.00E-03	Y	Y	Y	N	
HD 32297	A0	3.00E-03	Y	Y	Y		Y
HD 181327	F5	2.00E-03		Y	Y		Y
HD 61005	G8	2.00E-03		Y			
HD 15745	F2	2.00E-03		Y			
beta Pic	A5	2.00E-03	Y	Y	Y	Y	Y
HR 4796A	A0	1.00E-03	Y	Y	Y	N	
HD 107146	G2	1.00E-03		Y		Y	Y
49 Ceti	A1	9.00E-04		N	Y	Y	Y
HD 15115	F2	5.00E-04		Y			
AU Mic	M0	5.00E-04	Y	Y	N	?	N
HD 53143	K1	3.00E-04		Y			
HD 10647	F9	3.00E-04	?	Y		Y	Y
HD 139664	F5	1.00E-04		Y		Y	
eps Eri	K2	1.00E-04	N	N	N	Y	Y
gamma Oph	A0	9.00E-05		N		Y	N
Fomalhaut	A3	8.00E-05	N	Y	N	Y	Y
eta Corvi	F2	3.00E-05		N		Y	Y
Vega	A0	2.00E-05	N	N	N	Y	Y
tau Ceti	G8	1.00E-05		N		N	Y

Track disk imaging at

http://circumstellardisks.org



Catalog of Resolved Circumstellar Disks - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://circumstellardisks.org/

PRESTO Spitzer Timecard ADS Simbad Webdisks LAsat Google

Catalog of Resolved Circumstellar Disks

Last updated: November 2 2009; maintained by Caer McCabe & Carlotta Pham

- The catalog
- What's new...
- Description of Catalog
- Contributing to the database
- List of spatially resolved disks that have been withdrawn or refuted

Total number of disks: 131 (Pre-Main Sequence disks: 111, Debris Disks: 20)

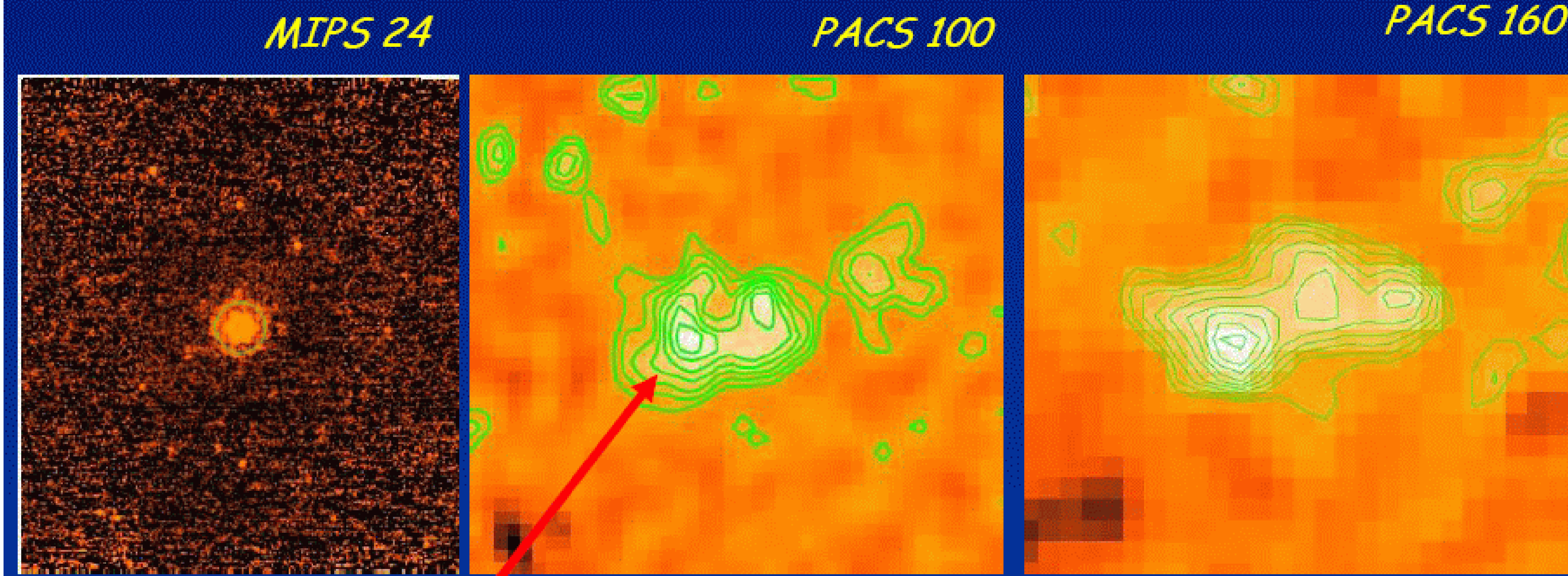
Object	SpTy	Category	Distance (pc)	R band (mag)	Disk Diameter ('')	Disk Diameter (AU)	Inclination	How well Resolved	At ref. wavelength (micron)
2MASSI1628137-243139		TT	140	17.7	4.3	602	86	10.8	2.1
49 Cet	A1	Hae	61	5.6	0.8	48		3.9	10
AA Tau	M0	TT	140	11.8	1.34	187	75	1.0	2000
AB Aur	A0e	Hae	144	7.1	18	2592	21.5	367.4	0.57
AS 205A	K0	TT	140	11.9	1	140	47	0.5	1330
AS 209	K5	TT	140	10.4	3.1	434	56	0.9	1300.39
ASR 41		TT	316		20	6320	80	97.0	2.2
AU Mic	M1	MS	9.94	8.9	29.25	290	90	567.2	0.6
Beta Pic	A5	MS	19.28	3.9	26	501	90	504.2	0.6
BP Psc New		TT	100	12.2	1.2	120	75	36.4	1.6

Done

Future I. Herschel

- Launch May 14 2009 !
- 70 μm imaging resolution of 4″, 4x sharper than Spitzer/MIPS; resolving central holes & disk asymmetries
- Sensitivity to lower dust levels at 100 & 160 μm
- 400 nearby targets to be surveyed by DUNES and DEBRIS key programmes

HIP 15371



30 – 60 AU; Kuiper Belt ~ 30 – 50 AU !!!

HIP 113357 (51 peg)

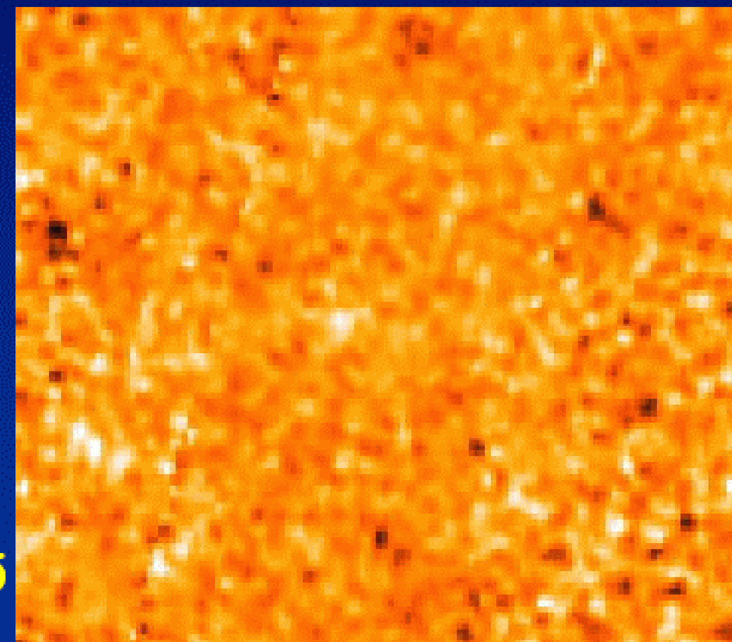
G2IV

D = 15.60 pc

Age ~ 4 Gyr

F(Spitzer, 70 μm)	28.1 mJy
F(predicted, 100 μm)	10.8 mJy
Point-source	
Total int. time	1989 sec
On-source time	1364 sec
STD background	5E-5 Jy
F(observed, 100 μm)	12 mJy

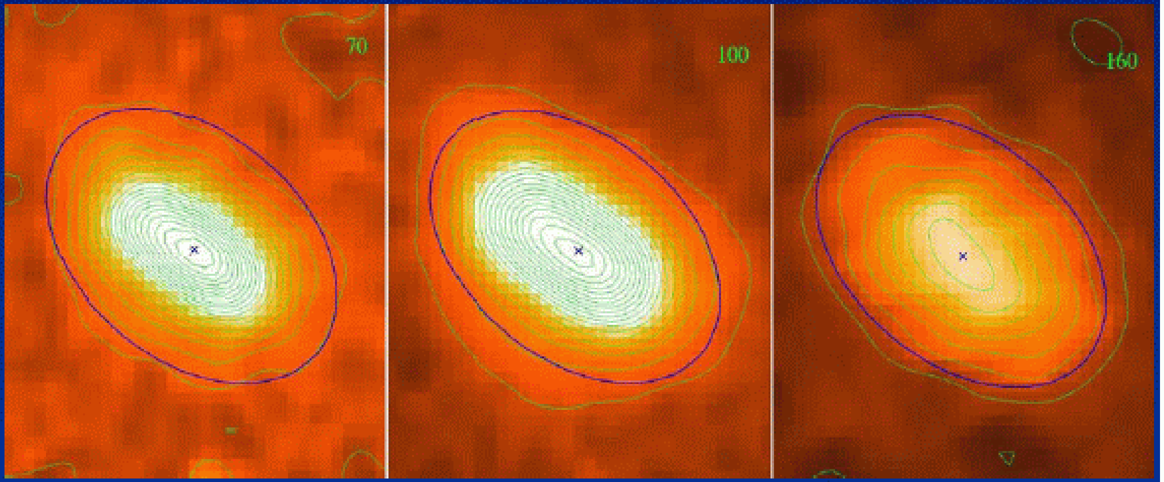
PACS 100



HIP 7978 (q1 Eri)

F8-9V
D = 17.35 pc
Age > 2 Gyr

PACS 70 *PACS 100* *PACS 160* *LABOCA 870*



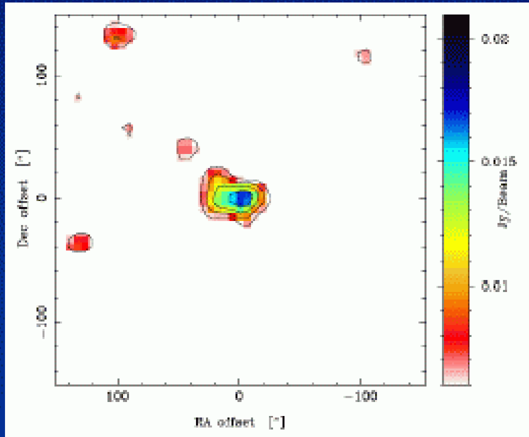


Fig. 1. q[1] Eri observed at 870 μm with the submm camera LABOCA at the APEX telescope (HPBW~18"). Within the

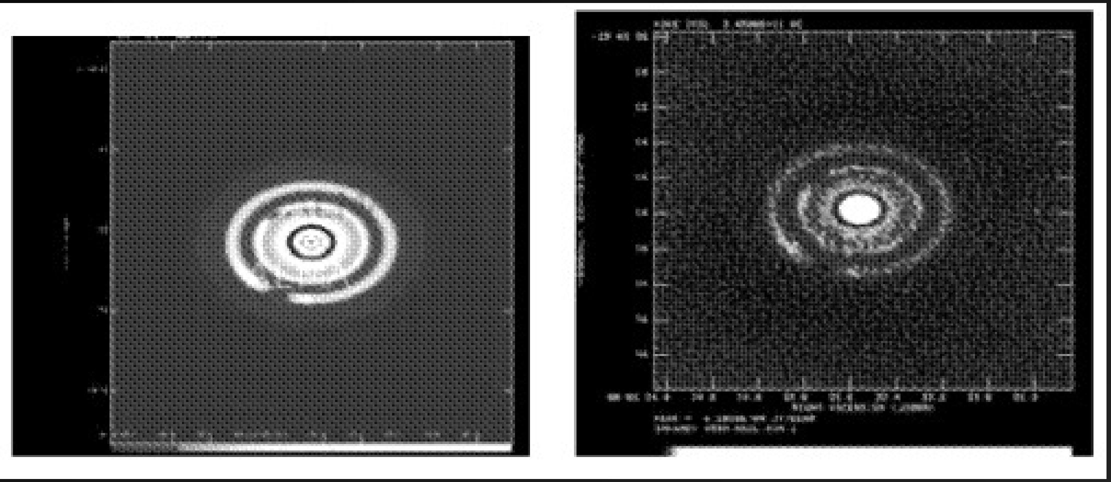
$R_{870} > R_{100,160} > R_{70}$

$R_{max} \sim 300$ AU

Liseau '08

Future II. ALMA continuum imaging

Wooten, Mangum & Holdaway 2004



Left: Model disk image at 850 μm, 125 AU radius, d= 15 pc, (about ¼ surface brightness of Fomalhaut disk)

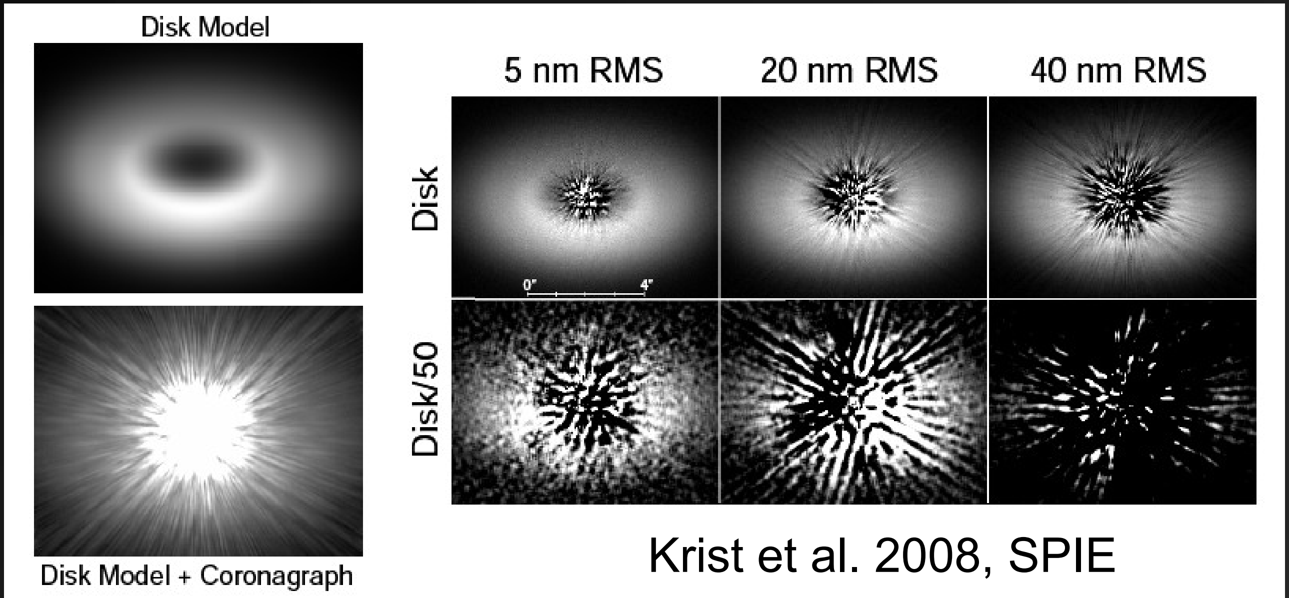
Right: Simulation of 4 hour ALMA observation, 0.4″ synthesized beam

Only a handful of debris disk systems are bright enough in the submm for this sort of mapping

(small fluxes. large sizes)

Future III. JWST & disk scattered light

Simulated NIRCAM coronagraph K band images of disk with 3x beta Pic dust, vs. primary mirror wavefront stability



<u>Conclusion: In the near-IR, JWST disk imaging won't probe a new contrast domain.</u> 3-5 μm scattered light will be a unique niche.

25 µm thermal imaging should resolve 1-2 dozen debris disks

There is a large unexplored parameter space for debris disk scattered light imaging

- Only 2% of nearby stars have debris disks bright enough for current high contrast imaging systems
- Improve high contrast imaging 10x would raise the frequency of highly resolved disks to 10%: comparable to RV planet frequency.
- Path to indirect detection of cool, Neptune-like planets beyond 5 AU separations
- <u>Explore planetary systems through dust structures</u>

Bryden et al. 2009

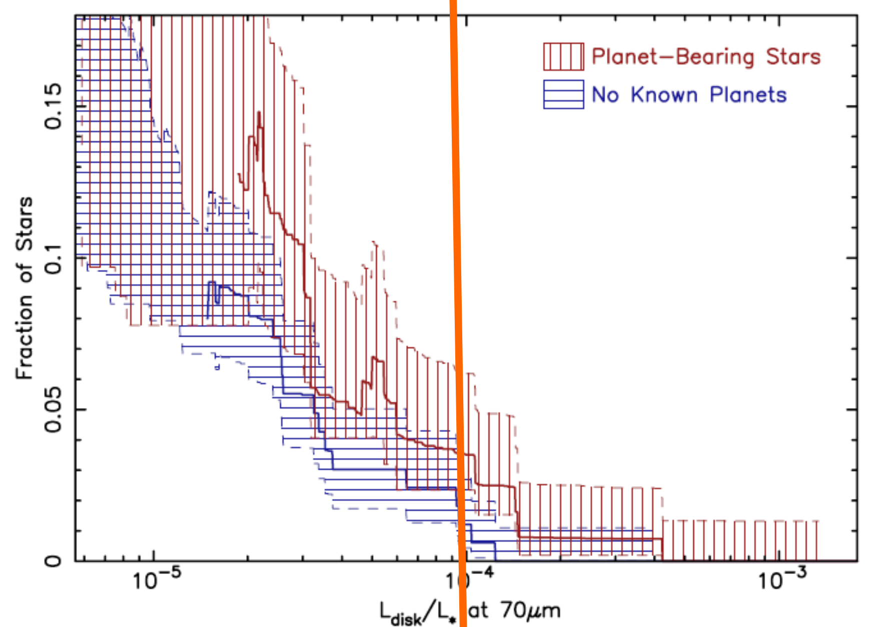
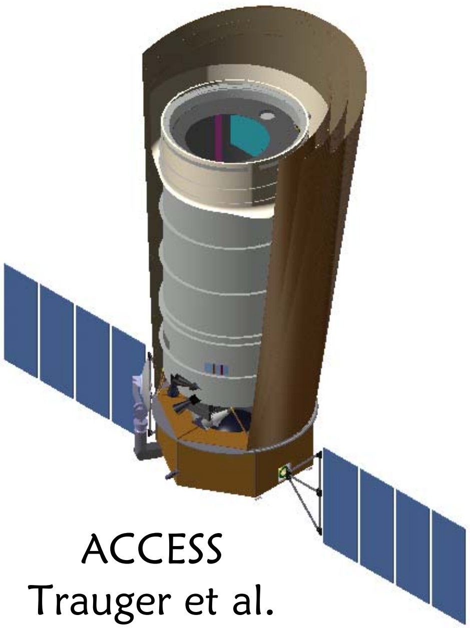


Figure 3. Cumulative fraction of stars with 70 μm excess as a function of disk luminosity for the planet and non-planet samples. As in Figure 1, the dust's fractional luminosity, $L_{\rm dust}/L_\star$, is derived from the strength of the 70 μm emission relative to the stellar photosphere (Equation (2)). For both the planet and non-planet samples, dust disks with $L_{\rm dust}/L_\star > 10^{-4}$ are rare, with $L_{\rm dust}/L_\star \approx 10^{-5}$ disks detected much more frequently. The 1σ uncertainties in the underlying distributions of $L_{\rm dust}/L_\star$ are indicated by the shaded regions. While the dust around planet-bearing stars is nominally brighter than for the non-planet stars (i.e., the red line lies above the blue line), the difference is not statistically significant.

Next steps in coronagraphy

- 10^{-9} contrast at 3 λ/D separation demonstrated in JPL lab tests
- Mission based on ~1.5 m telescope studied by several groups
- Multiple coronagraph options
- Debris disk & exozodi imaging down to 10 zodi level in nearby sunlike stars; RV planet spectra
- NASA exoplanet probe mission TBD years from now ?



ACCESS
Trauger et al.

- Ground AO imaging offers a partial, near-term step toward this capability, maybe to 10^{-7} contrast
- Stratospheric balloon above atmospheric turbulence offers a near-term option to work to 10^{-8} contrast on debris disk targets (Wes Traub et al.)