Spatially-resolved Debris Disk Studies: Present and Future

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thanks to John Krist for some of this material

Talk Overview

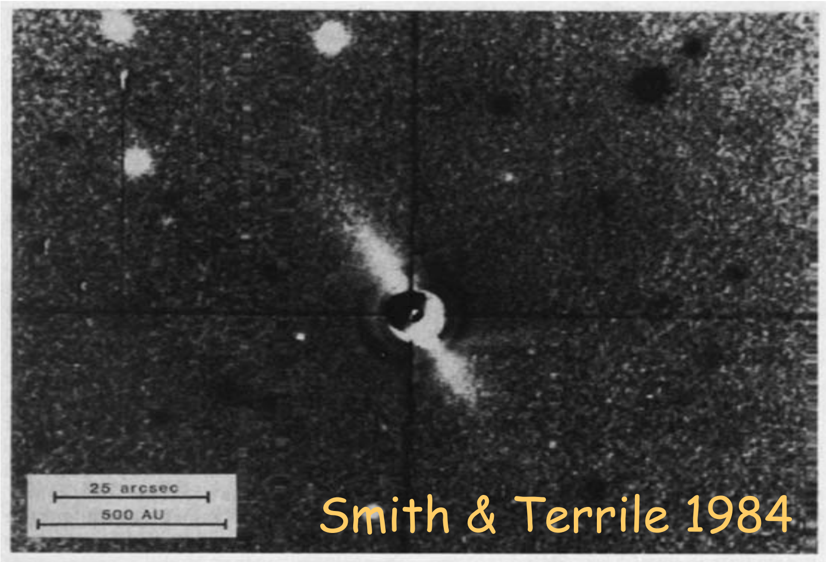
- History and inventory of resolved debris disks
- Scattered light imaging (HST)
- Thermal IR imaging, ground+Spitzer
- The case of epsilon Eridani
- Searches for planetary perturbers
- Debris disk imaging with upcoming facilities

What is Learned from High Resolution Debris Disk Imaging?

- Confirms basic disk morphology of dust distribution
  - position angle
  - major and minor axes (outer radius of disk)
- Measurable disk parameters
  - Radial disk structure (gaps, rings)
  - Azimuthal disk structure (asymmetries)
  - Vertical density structure (warping)
- Derivable disk parameters via modeling scattered light (thermal emission)
  - Inclination
  - Radial surface brightness profile → radial density (x temperature) profile
  - Vertical disk structure if nearly edge-on → scale height
  - Dust mass-opacity product, phase function, polarizability, their λ dependence
  - Dust grainsizes with thermal emission resolved at 2 or more wavelengths
- Some of the derivable properties are degenerate

It all started with β Pictoris

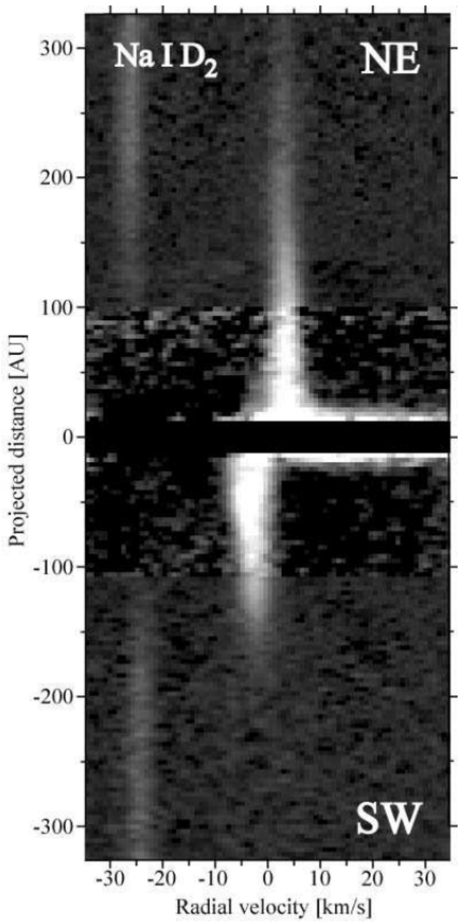
- Coronagraphic detection of edge-on disk around a bright, nearby IRAS source
- No other robust scattered light disk detections in surveys of IRAS excess stars
- Further progress was prevented by seeing-limited image quality



β Pictoris imaging today

Na I velocity map

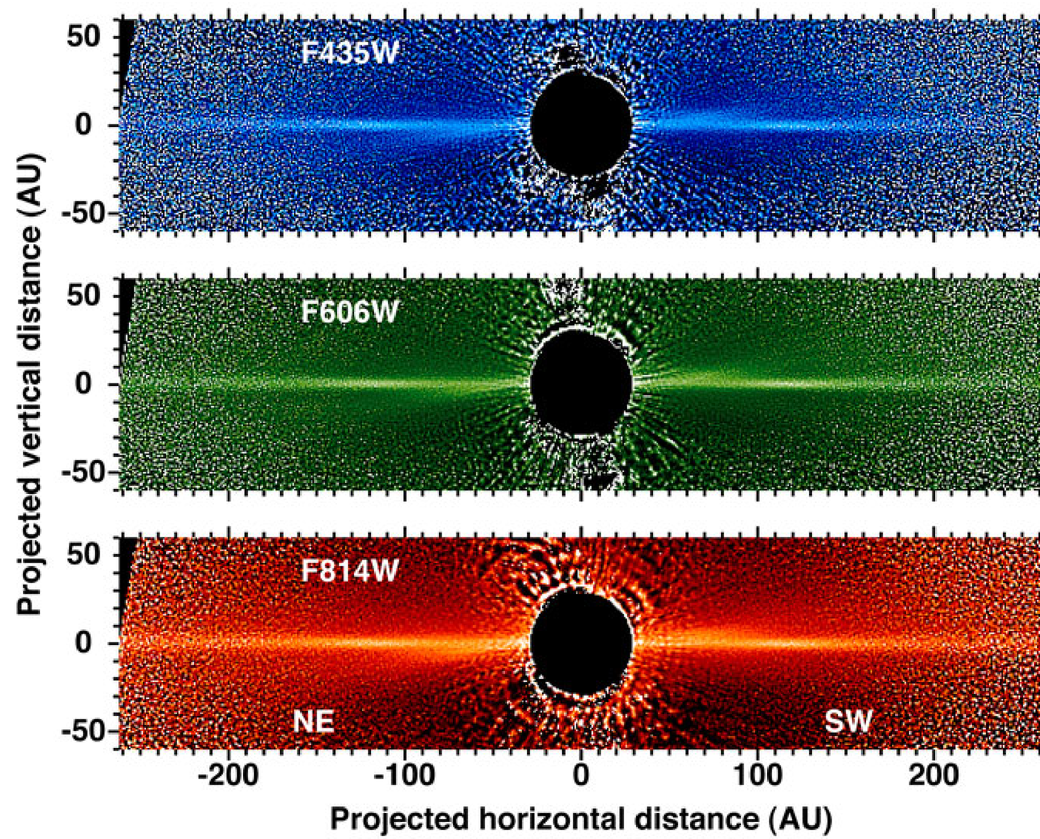
Brandeker et al. 2004



HST multicolor coronagraphy

Inner disk warp

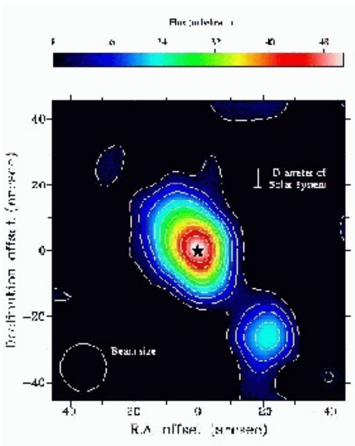
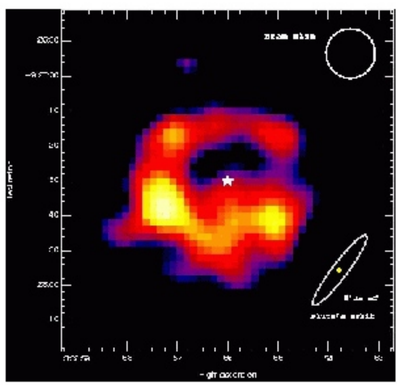
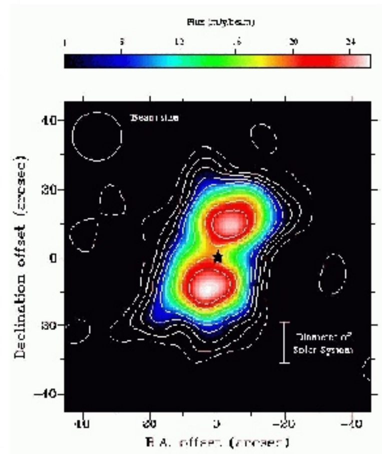
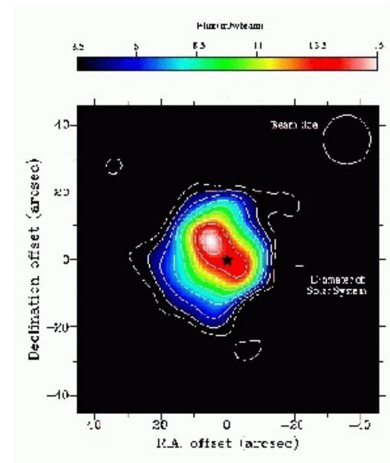
Slightly red disk color, peaking at r> 120 AU



Golimowski et al. 2006

JCMT Resolves the Fabulous Four Debris Disks at 850 μm

Holland et al. 1998, Greaves et al. 1998

β Pictoris	ε Eridani	Fomalhaut	Vega
			
A5 V d= 19 pc	K2 V d= 3 pc	A3 V d= 7 pc	A0 V d= 7 pc

Inventory of Resolved Debris Disks

(Objects with at least 1 refereed publication)

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

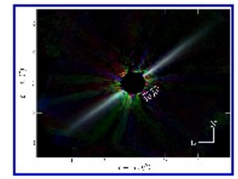
File Edit View History Bookmarks Tools Help

http://circumstellardisks.org/

PRESTO Spitzer Timecard ADS Simbad Webdisks LAsat Google

Catalog of Resolved Circumstellar Disks

Last updated: October 16 2008; maintained by Caer McCabe (Caltech)



- What's new...
- Description of Catalog
- Contributing to the database
- List of refuted or withdrawn disks
- Search the website

Total number of disks: 113 (Pre-Main Sequence disks: 95, Debris Disks: 18)

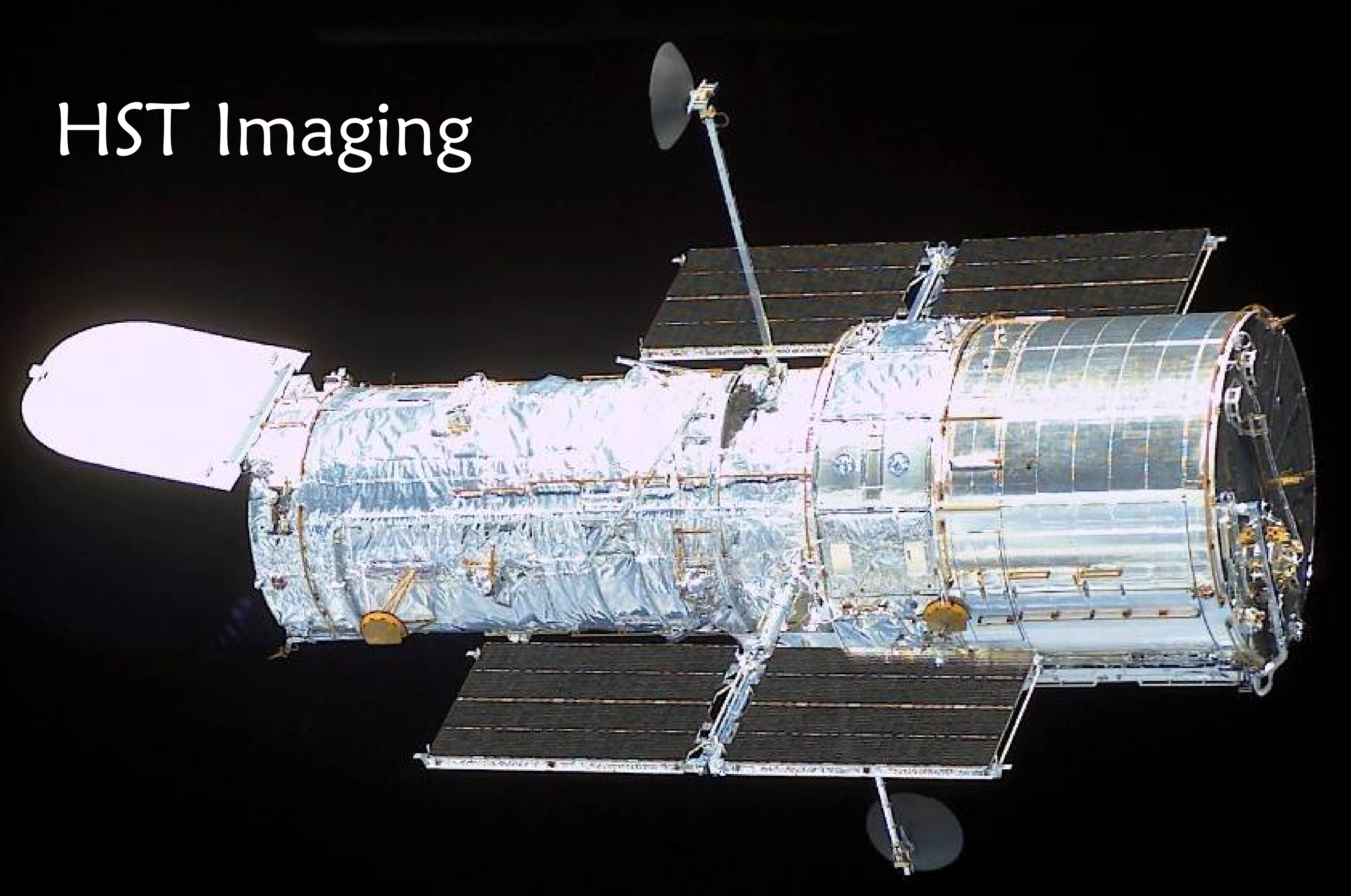
Object	SpTy	Category	Distance (pc)	R band (mag)	Disk Diameter ('')	Disk Diameter (AU)	Inclination	How well Resolved	At ref. wavelength (micron)
Epsilon Eridani	K2	MS	3.22	3.8	66	212	25	5.6	850
Tau Ceti	G8 V	MS	3.6	3.5	37	133	60	3.2	850
Fomalhaut	A3	MS	7.2	1.2	36	259	66	698.1	0.6
Vega	A0	MS	7.8	0.1	140	1092	0	8.2	70
AU Mic	M1	MS	9.94	8.9	29.25	290	90	567.2	0.6
HD 139664	F5 IV	MS	17.5	4.7	5.5	96	87	106.7	0.6
Eta Corvi	F2 V	MS	18.2	4.4	11.3	205	45	1.0	850
HD 53143	K1	MS	18.4	6.9	6	110	45	116.4	0.6
Beta Pic	A5	MS	19.28	3.9	26	501	90	504.2	0.6

Done

Your inputs needed !

Talk to Caer McCabe (IPAC)

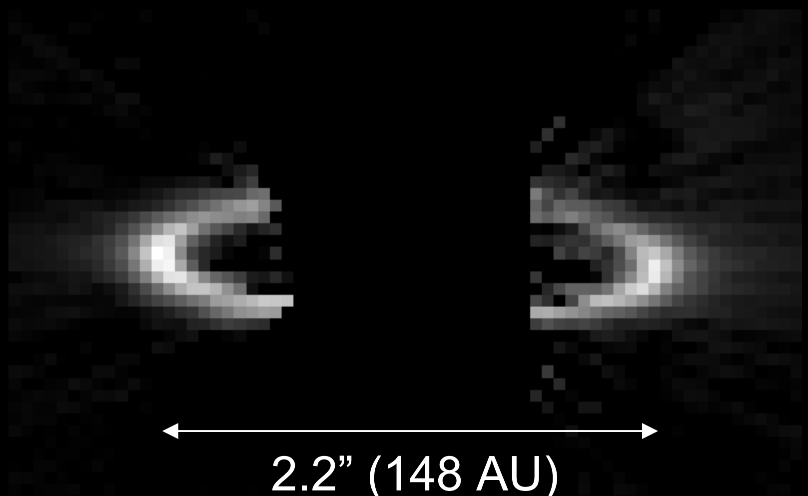
HST Imaging



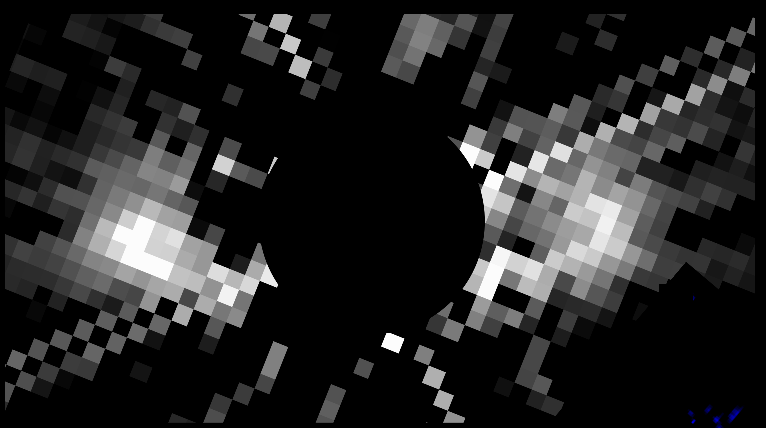
HR 4796A

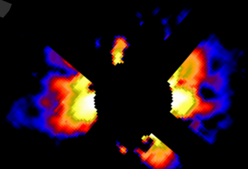
A0V, 67 pc, ~8 Myr, $L_d/L_* = 5 \times 10^{-3}$, with nearby M star

STIS (0.2 – 1 μm)



NICMOS (J band)





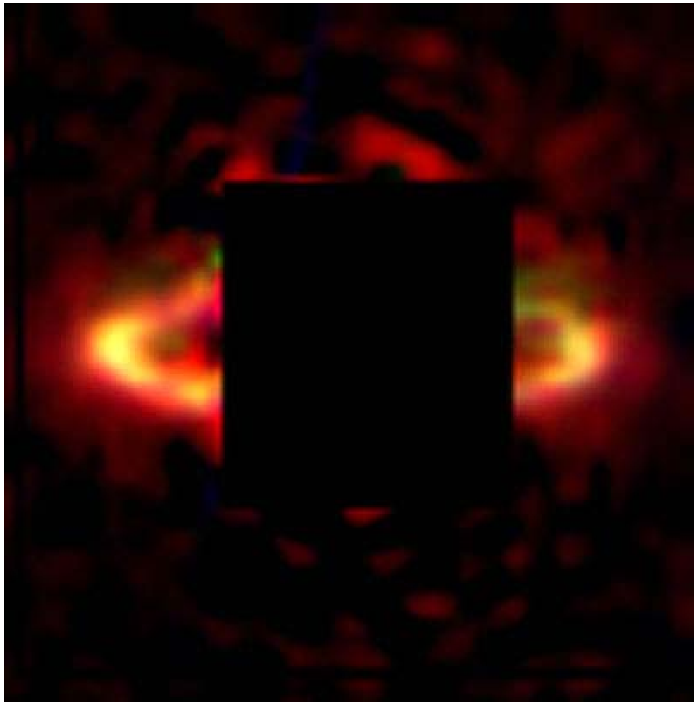
Ground K’
Augereau et al. (1999)

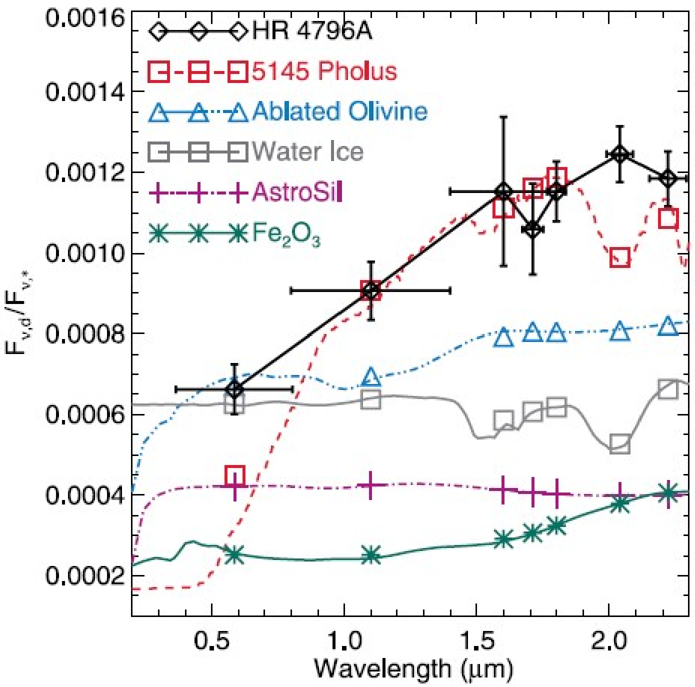
Small Brightness asymmetry; companion star or planet ?
Sharp inner edge.
May be nearly optically thick in radial direction.

Subtractions by John Krist.
Science results in *Schneider et al. (1999, and arXiv0810.0286)*

Red color of HR 4796A ring; organics ?

Debes et al. 2008 argue for this

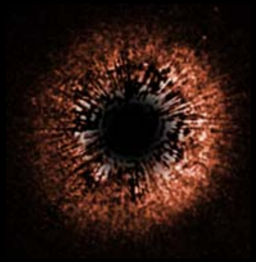


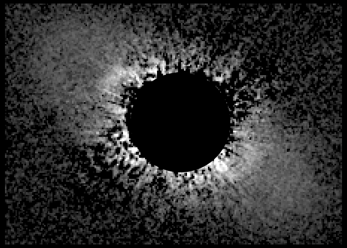


Koehler, Mann & Li et al. 2008 argue instead for porous grains with silicate, C, and H_20 ice

Known Colors of Debris Disks

Relative to Star

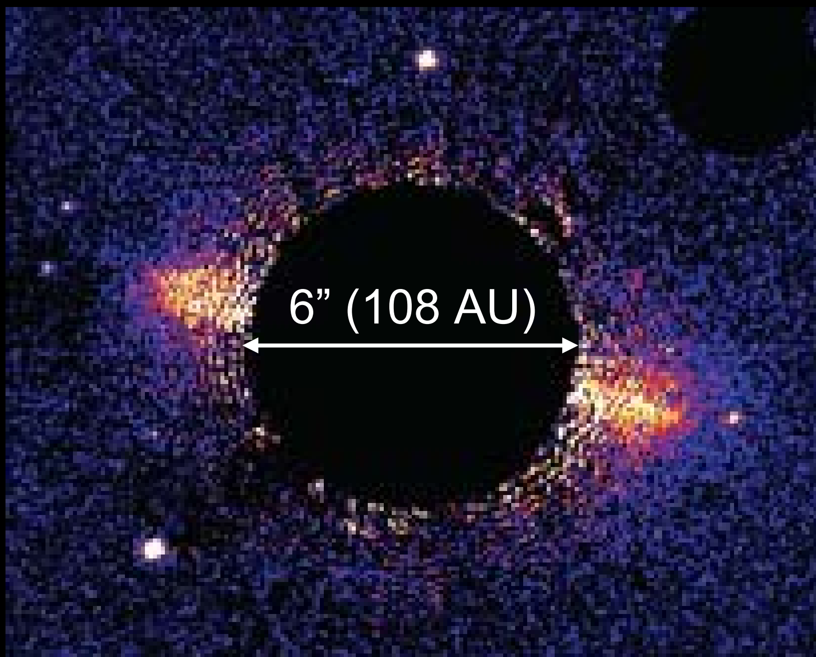




Red	**Neutral**	**Blue**
HD 141569A	HD 92945	HD 32297 (?)
HD 4796A		HD 15115
Beta Pic		AU Mic
HD 181327		
HD 107146		

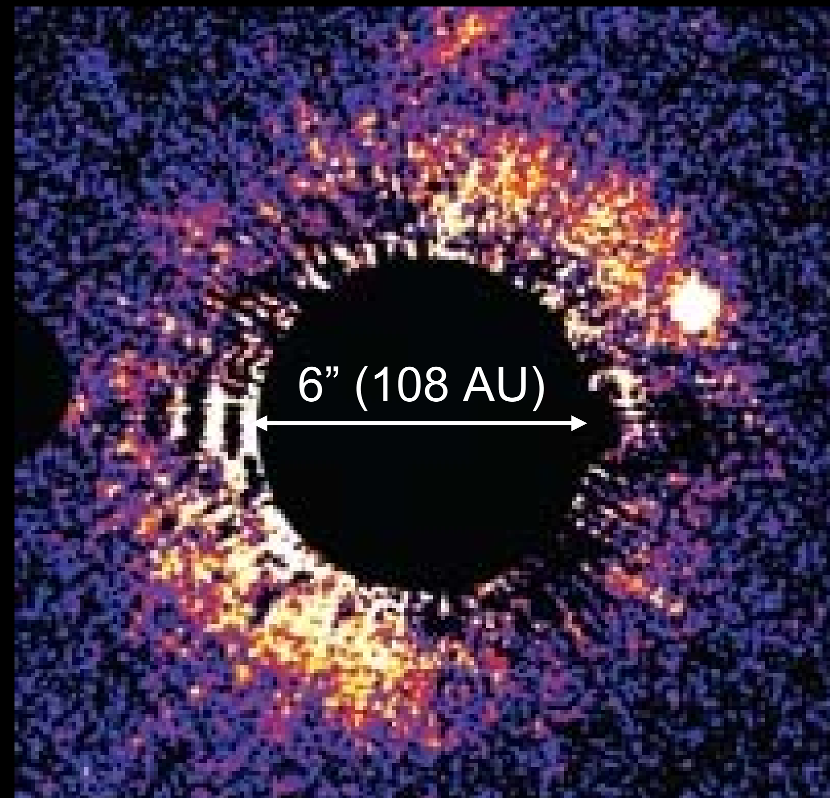
HD 139664

F5V, 18 pc, 100-1000 Myr,
$L_d/L_*=1 \times 10^{-4}$



HD 53143

K1V, 18 pc, ~1 Gyr,
$L_d/L_*=3 \times 10^{-4}$

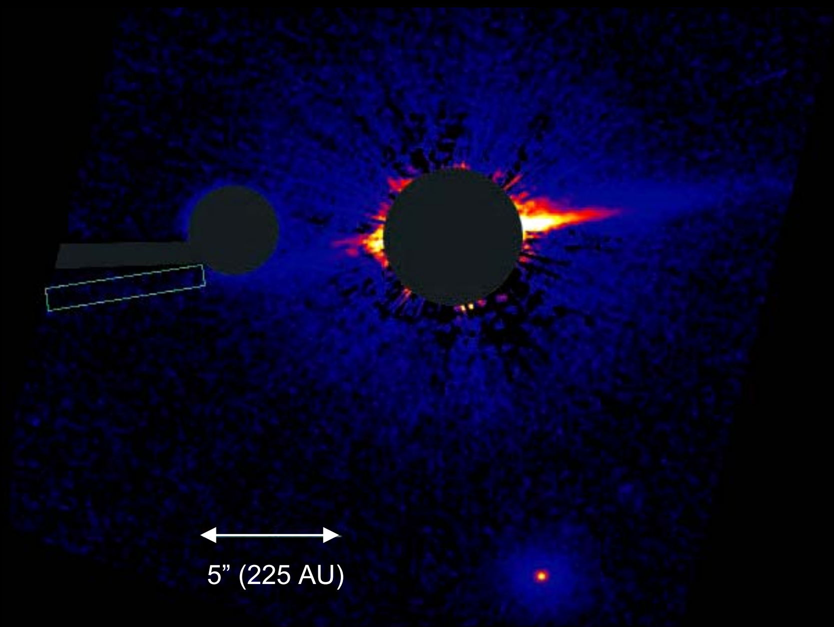


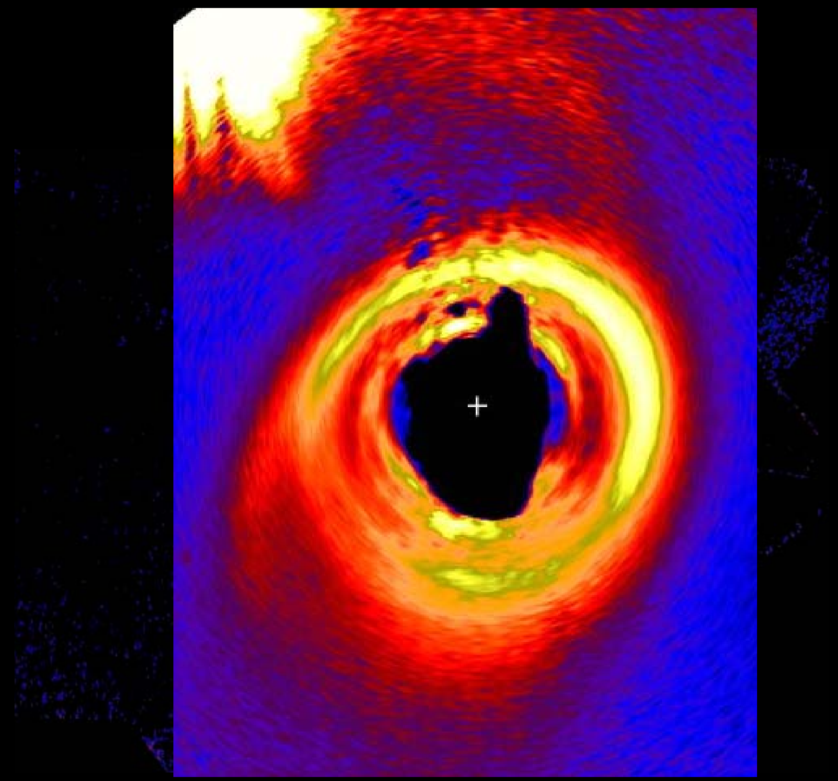
Both ACS Wide V band, Kalas et al. (2006)

HD 15115

F2V, 45 pc, ~12 Myr?, $L_d/L_* = \sim 5 \times 10^{-4}$

ACS (Wide V band)





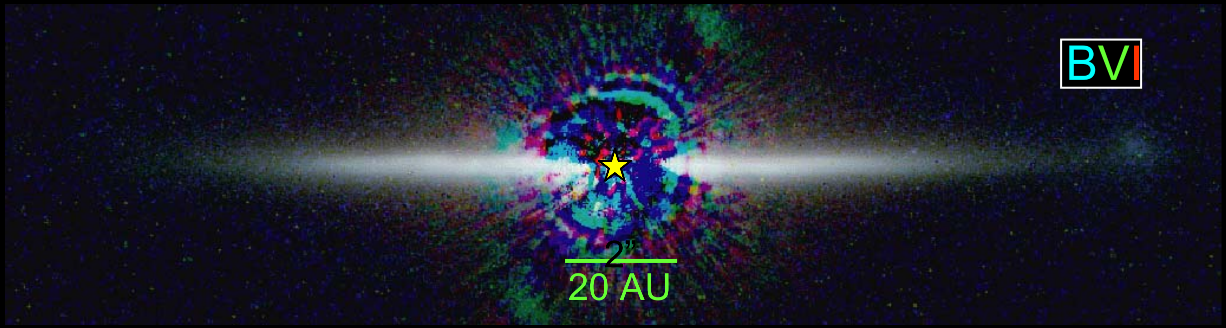
Kalas et al. (2007)

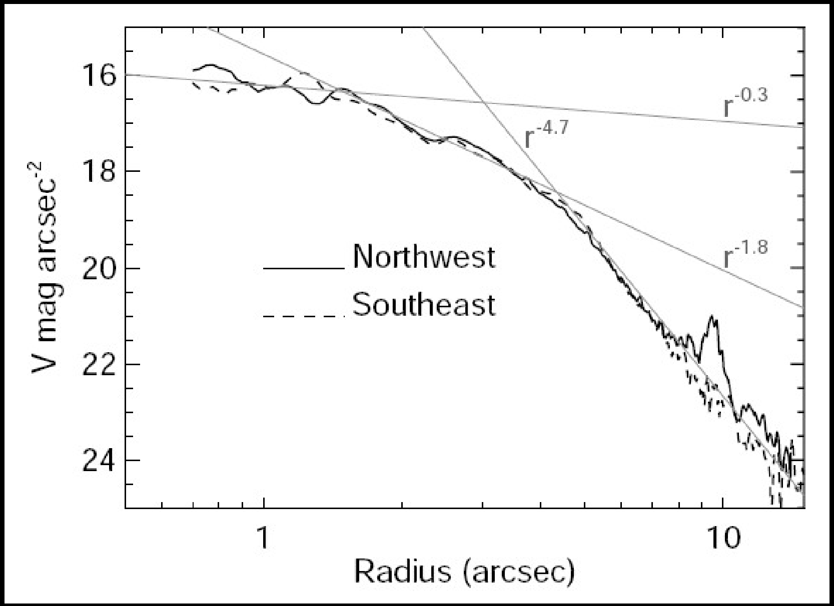
Very asymmetric edge-on disk. Possible fly-by candidate identified Disk is blue relative to star based on V-H colors, and becomes more blue at larger radii

AU Mic

M1V, 10 pc, 12 Myr, $L_d/L_* = 4 \times 10^{-4}$

ACS (B,V,I)





Cleared inner hole < 12 AU

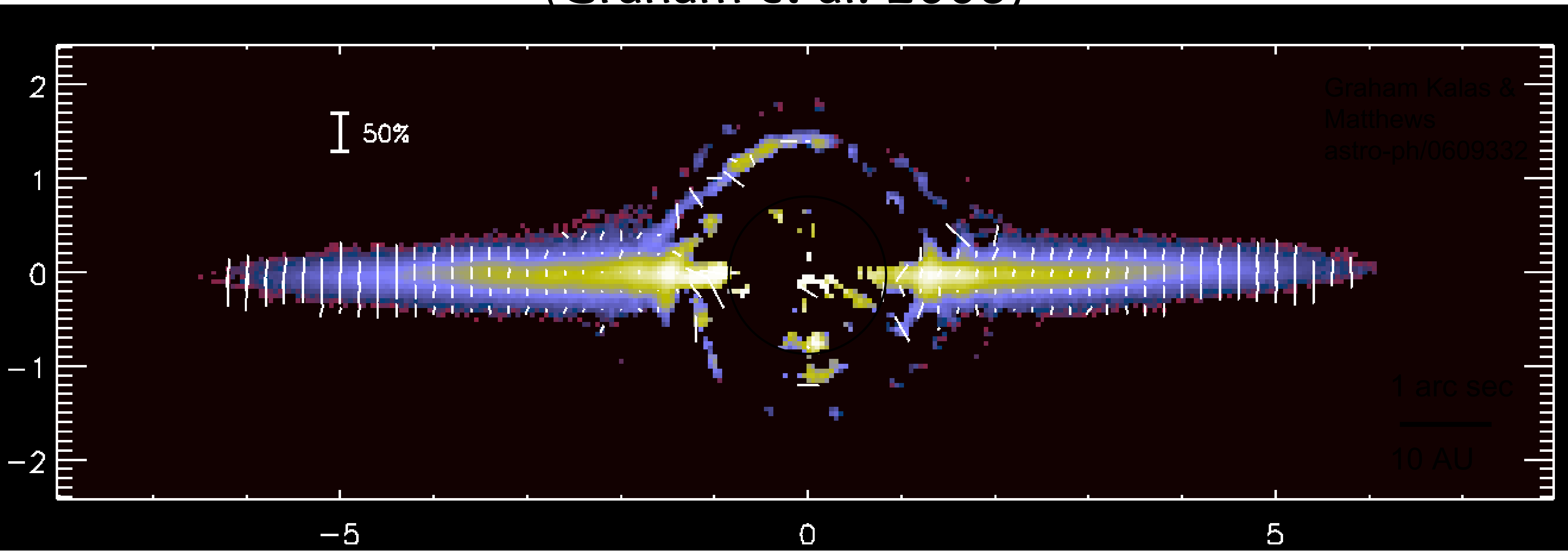
Flat surface density 12 < r < 49 AU

$\Sigma \propto r^{-(2.2 \text{ to } 2.7)}$ beyond 49 AU

Krist et al. (2005)

AU Mic in Polarized Light

(Graham et al. 2006)



- HST R band coronagraphic imaging polarimetry
- Peak polarization of 41% indicates single scattering by sub-micron size particles
- Consistent with highly porous, micron-sized dust aggregates

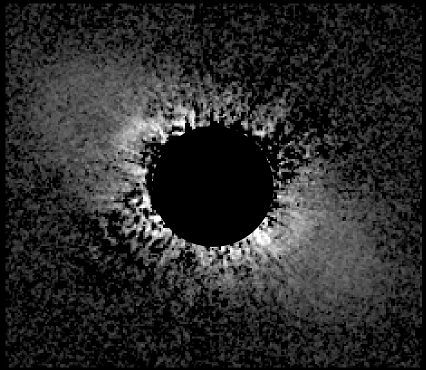
Degree of Forward Scattering

g = 0 Isotropic

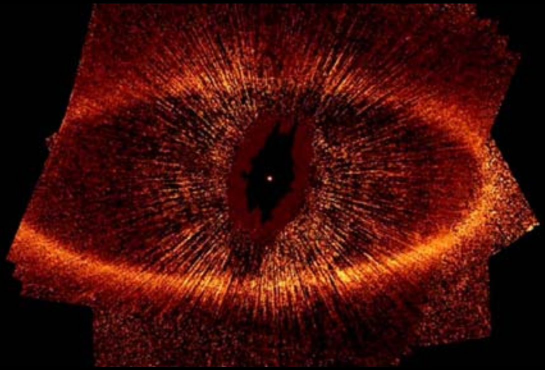
g = 1 Full forward scattering

g = -1 Full backward scattering

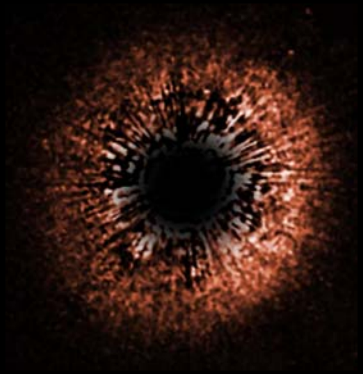
g = 0



g = 0.2



g = 0.3

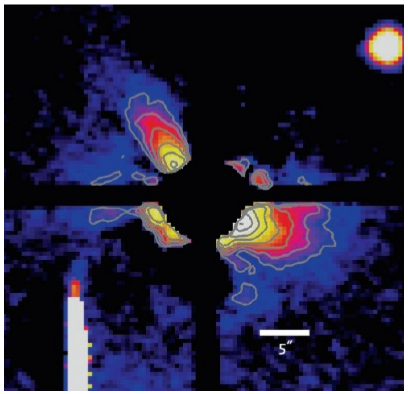


g = 0.4 (0.7?)

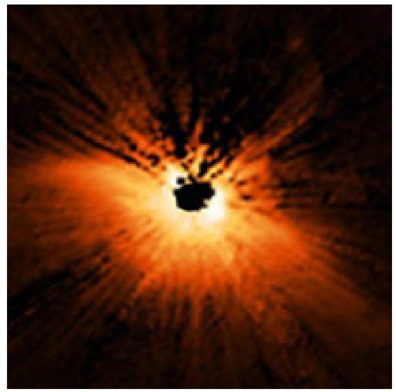
Strong forward scattering suggests smaller particles

Disks with ISM interactions

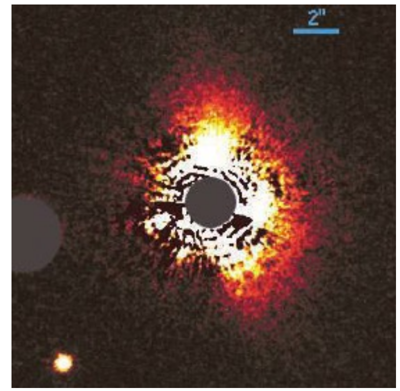
Morphologies swept-back from star's proper motion



HD 32297
Kalas et al.
2005
R band
Mauna Kea

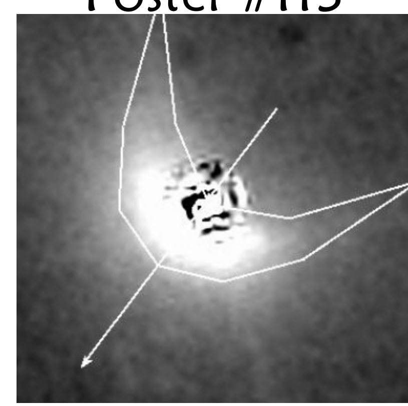


HD 61005
Hines et al.
2007
J band
HST/NICMOS



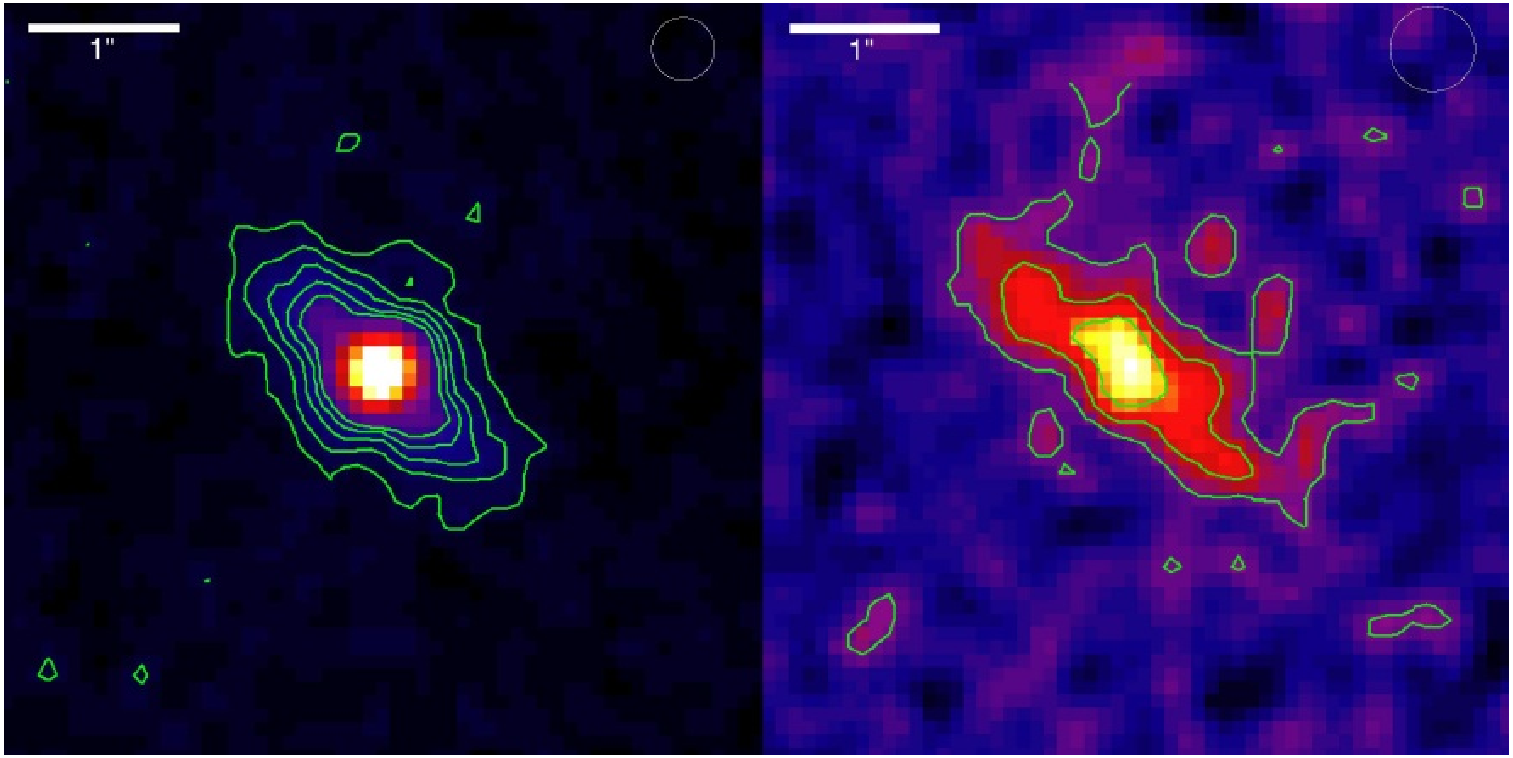
HD 15745
Kalas et al.
2007
R band
HST/ACS

δ Vela
Gáspár et al.
2007
24 μm
Spitzer/MIPS
<u>bowshock,
not disk</u>
See also
Poster #113



Groundbased Thermal IR I. HD 32297

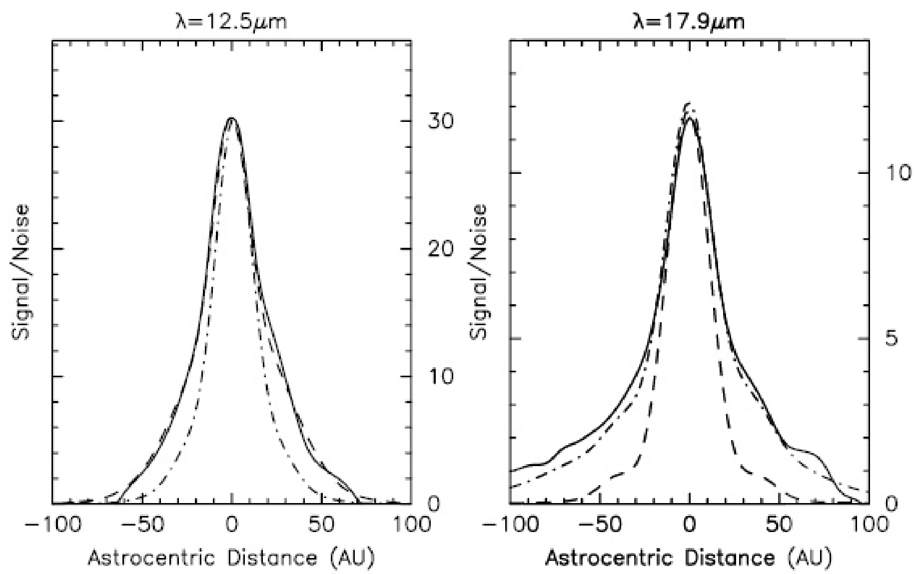
Moerchen et al. 2007.



12 μm 18 μm

See also Fitzgerald et al. 2007

Groundbased Thermal Infrared II. Profile Fitting



49 Ceti
Wahhaj et al. 2007

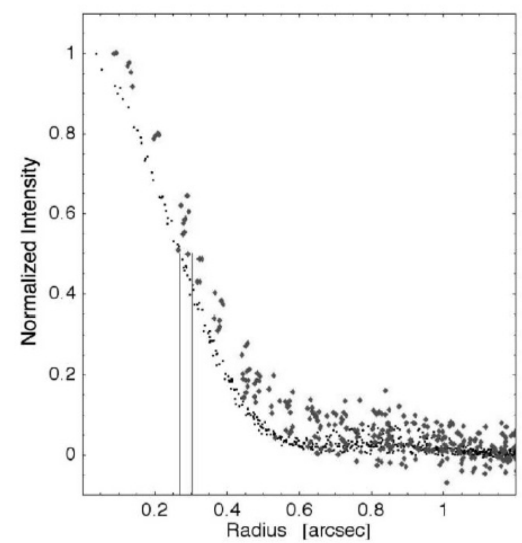
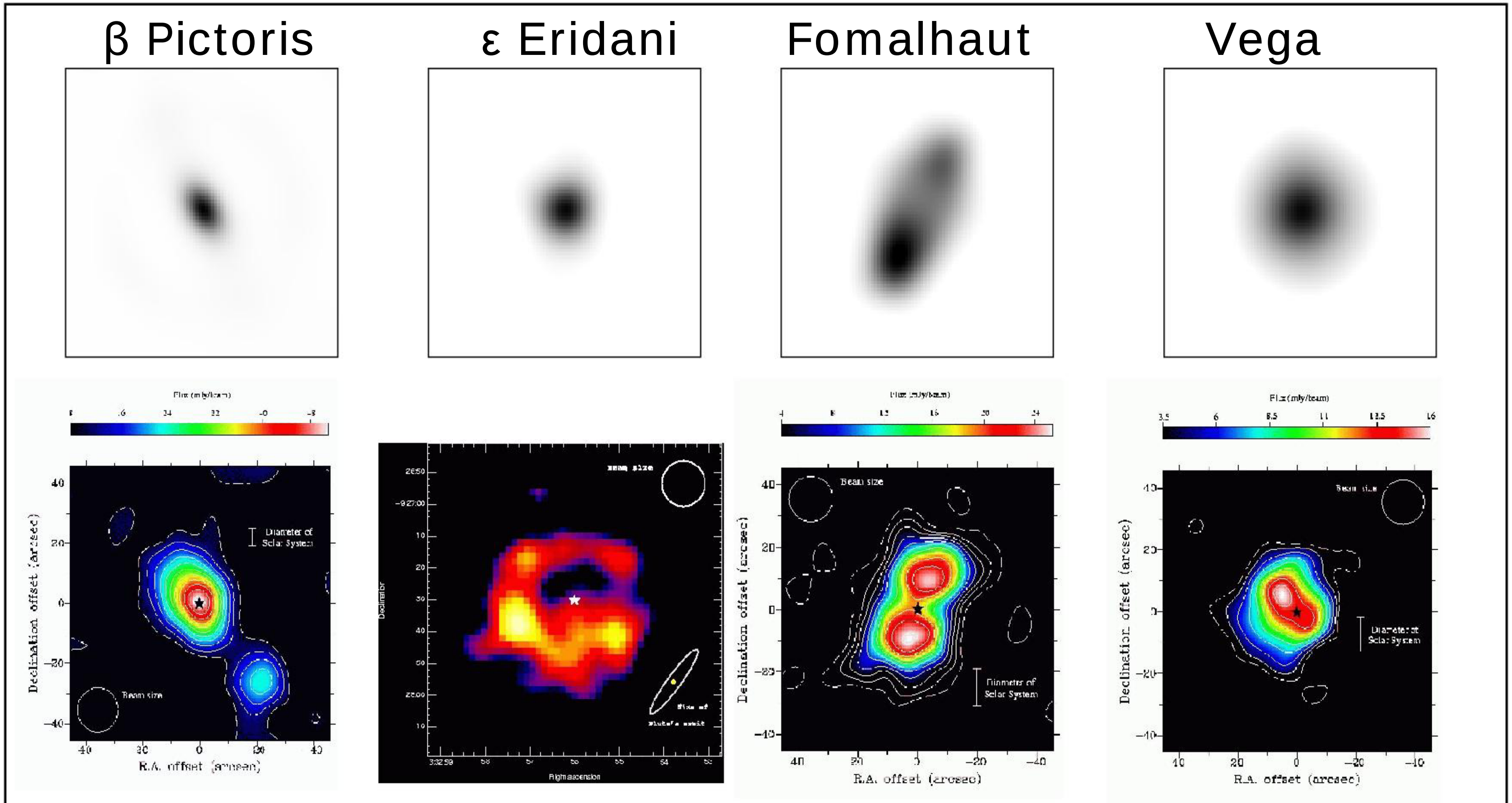


FIG. 1.—Profiles of azimuthally averaged normalized intensity for ζ Lep (*diamonds*) and reference PSF star (*dots*); vertical lines indicate the FWHM values of profile fits to the PSF star and ζ Lep. [*See the electronic edition of the Journal for a color version of this figure.*]

Zeta Lep
Moerchen et al. 2007

The Fabulous Four Debris Disks: Spitzer/MIPS 70 μm vs. JCMT 850 μm



Holland et al. 1998, Greaves et al. 1998

Spitzer/MIPS Radial Profiles of Vega

Su et al. 2005

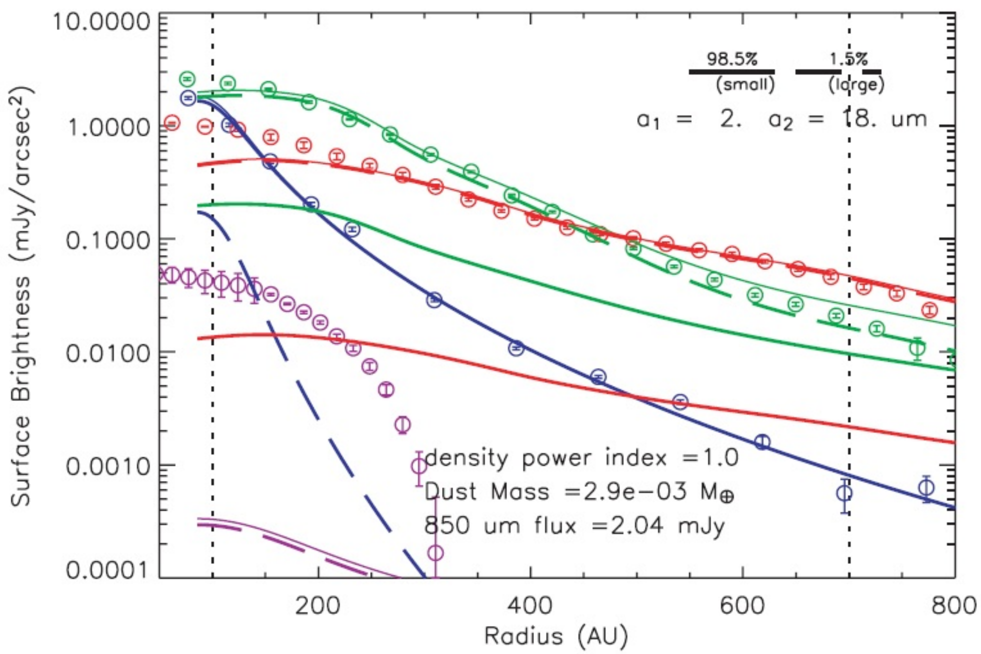


FIG. 12.—Observed radial surface brightness profiles for the Vega debris disk are plotted as open circles, with colors representing different bands (24 μm, *blue*; 70 μm, *green*; and 160 μm, *red*). Model profiles from the large grain

Face-on disk
a ~ 2 μm grains needed to reproduce observed F_{24}/F_{70}

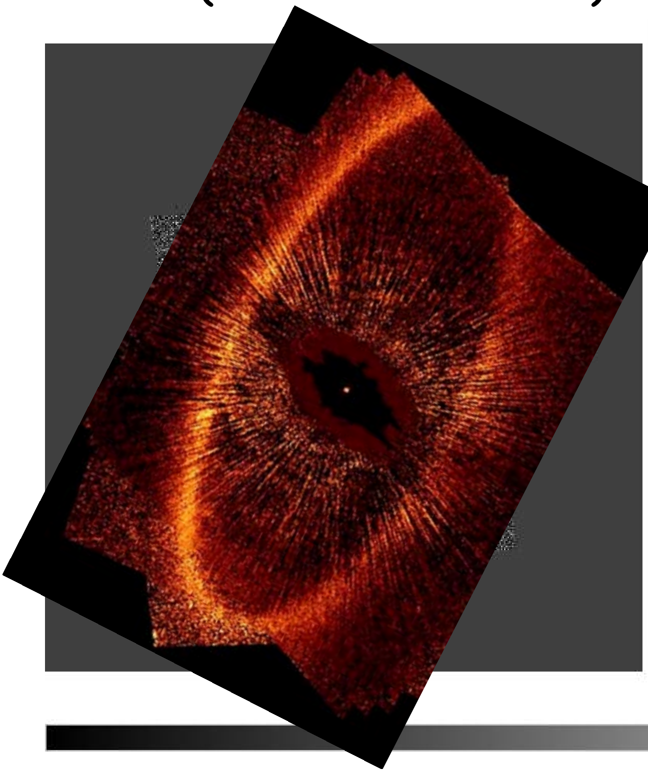
$\Sigma \propto r^{-1}$ to match radial brightness profiles:

⇒ Blowout dust population

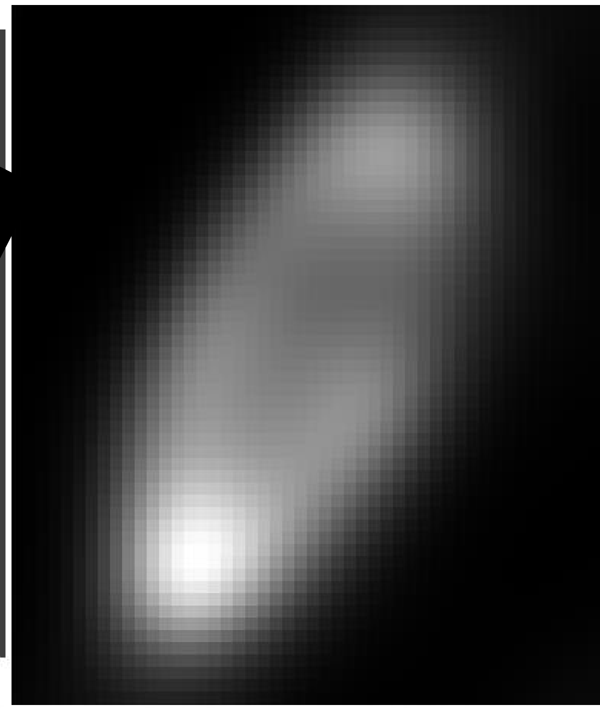
Fomalhaut's Eccentric Ring

A3V star, age 200 Myrs, distance 8 pc

HST (Kalas et al. 2005)

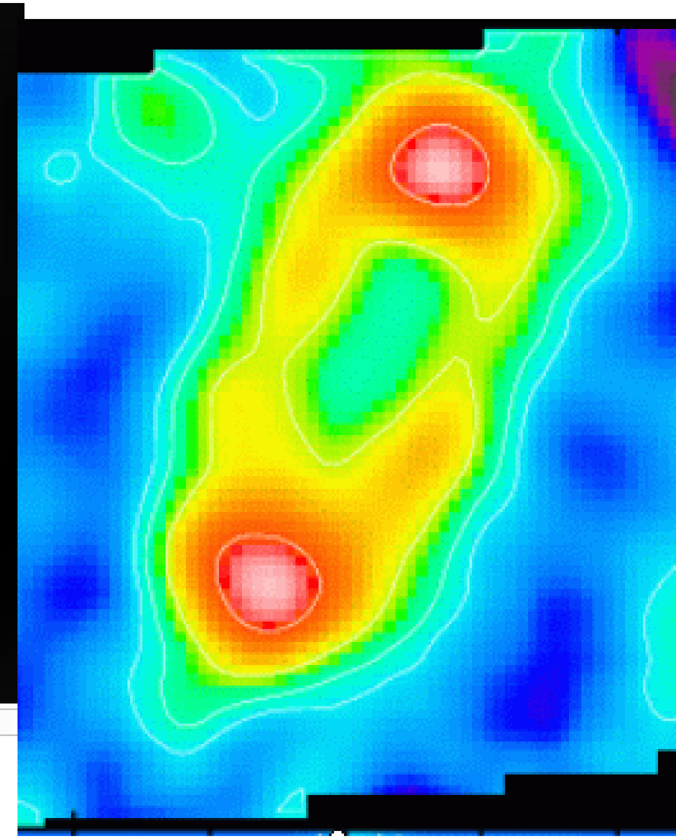


0.6 μm



MIPS 70 μm deconvolved

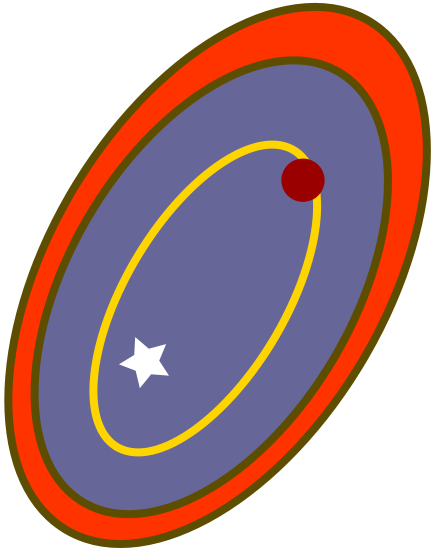
CSO (Marsh et al. 2005)



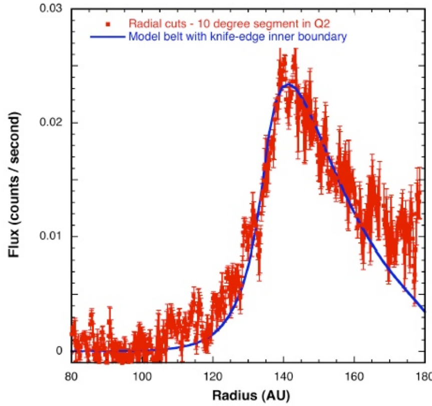
350 μm

Eccentric ring model (Wyatt et al. 1999)

- Outer ring is perturbed by eccentric interior planet
- Produces brightness asymmetry in thermal emission from the Fomalhaut disk
- Models predict mass of perturber:
  - 0.06 to 0.3 M_J, if located at ring inner edge (Quillen 2006)
  - Higher planet mass required if it is located well inside ring
- Planetary perturbations in Mark Wyatt's talk, posters by Stark #122 and Moro-Martin #119



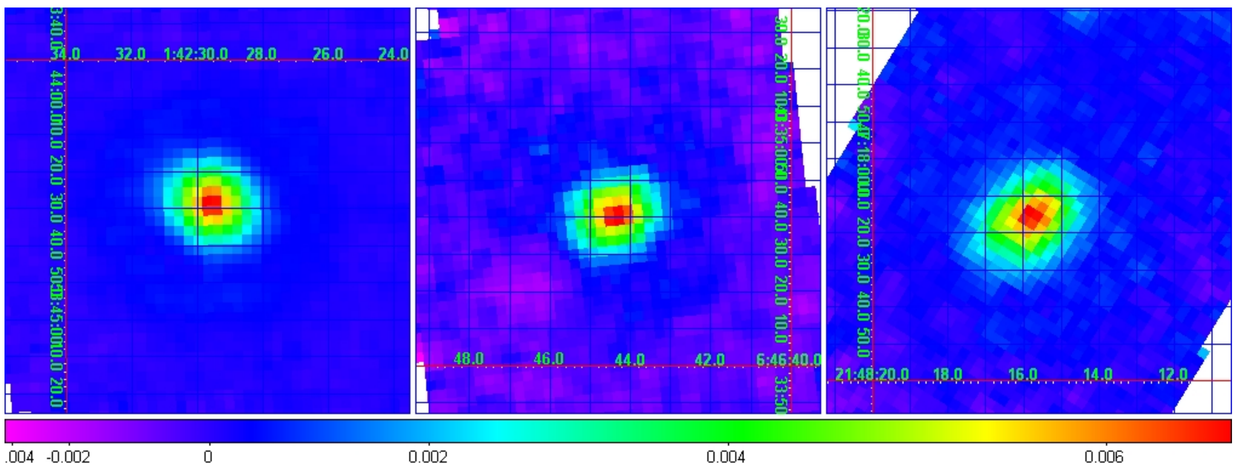
Sharpness of ring inner edge
Kalas et al. 2005



Solar-type stars with Debris Disks Spatially Resolved at 70 μm

Bryden et al; see poster #105

Smaller grain blowout sizes allows larger resolved disks ?



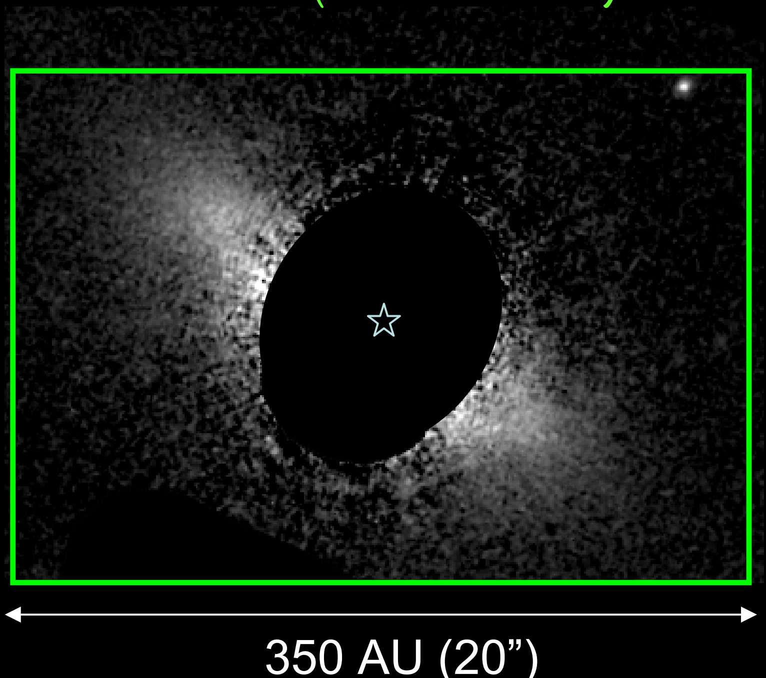
HD 10647	HD 48682	HD 207129
F9 V	G0 V	G0 V
17 pc	17 pc	16 pc

HD 10647 (HR 506, q[1] Eri)

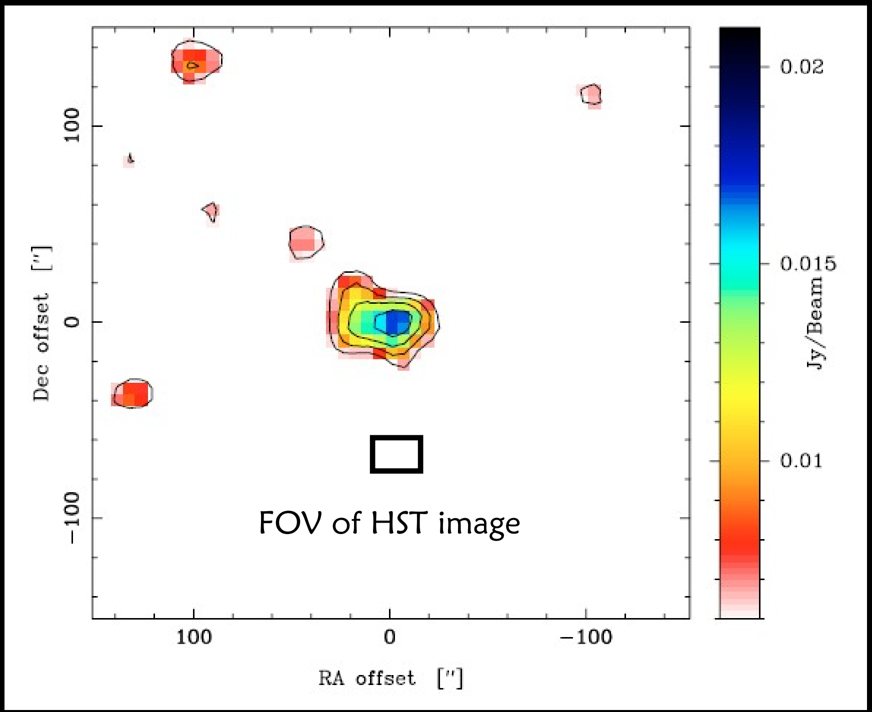
F9V, 17 pc, 0.3-7 Gyr, $L_d/L_* = 3 \times 10^{-4}$

Has R-V planet: a = 2 AU, M*sin*i = 0.91 M_{Jup}

HST ACS (Wide V band)



APEX/LABOCA 870 micron



Inclined ring, r= 80-120 AU
Slight asymmetry

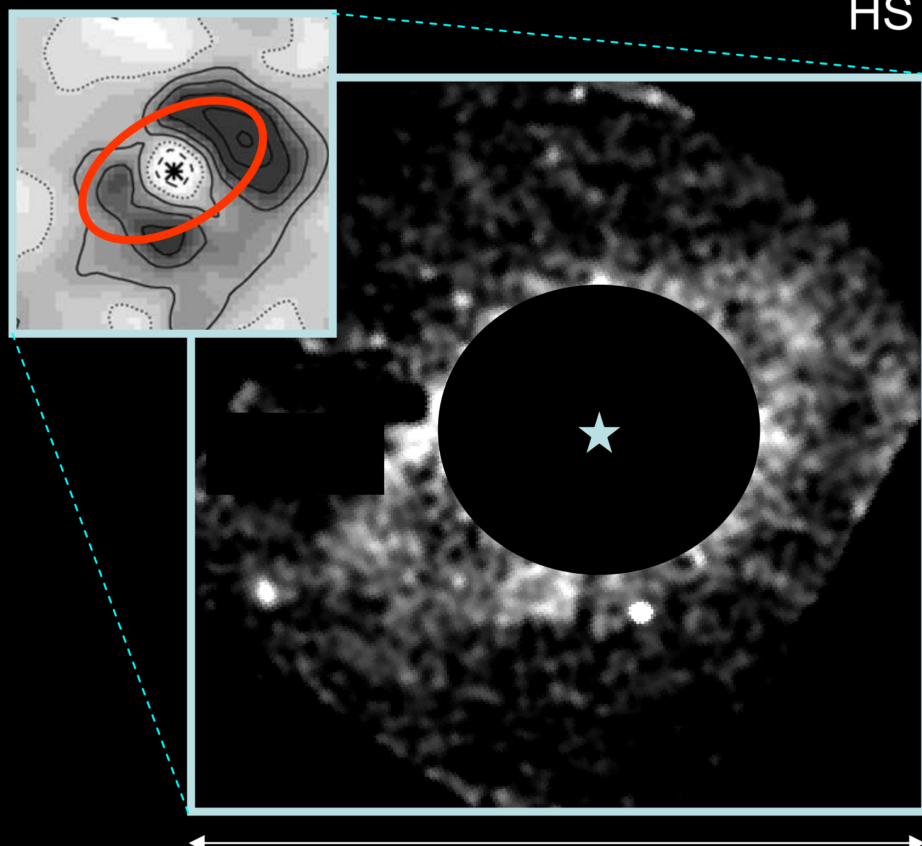
Stapelfeldt et al. (in prep)

Gaussian source
HWHM= 275 AU
Liseau et al. 2008

Cold material extending to 2x radius of scattered light & 70 μm emission !

HD 207129

G0V, 16 pc, ~6 Gyr, $L_d/L_*=1 \times 10^{-4}$

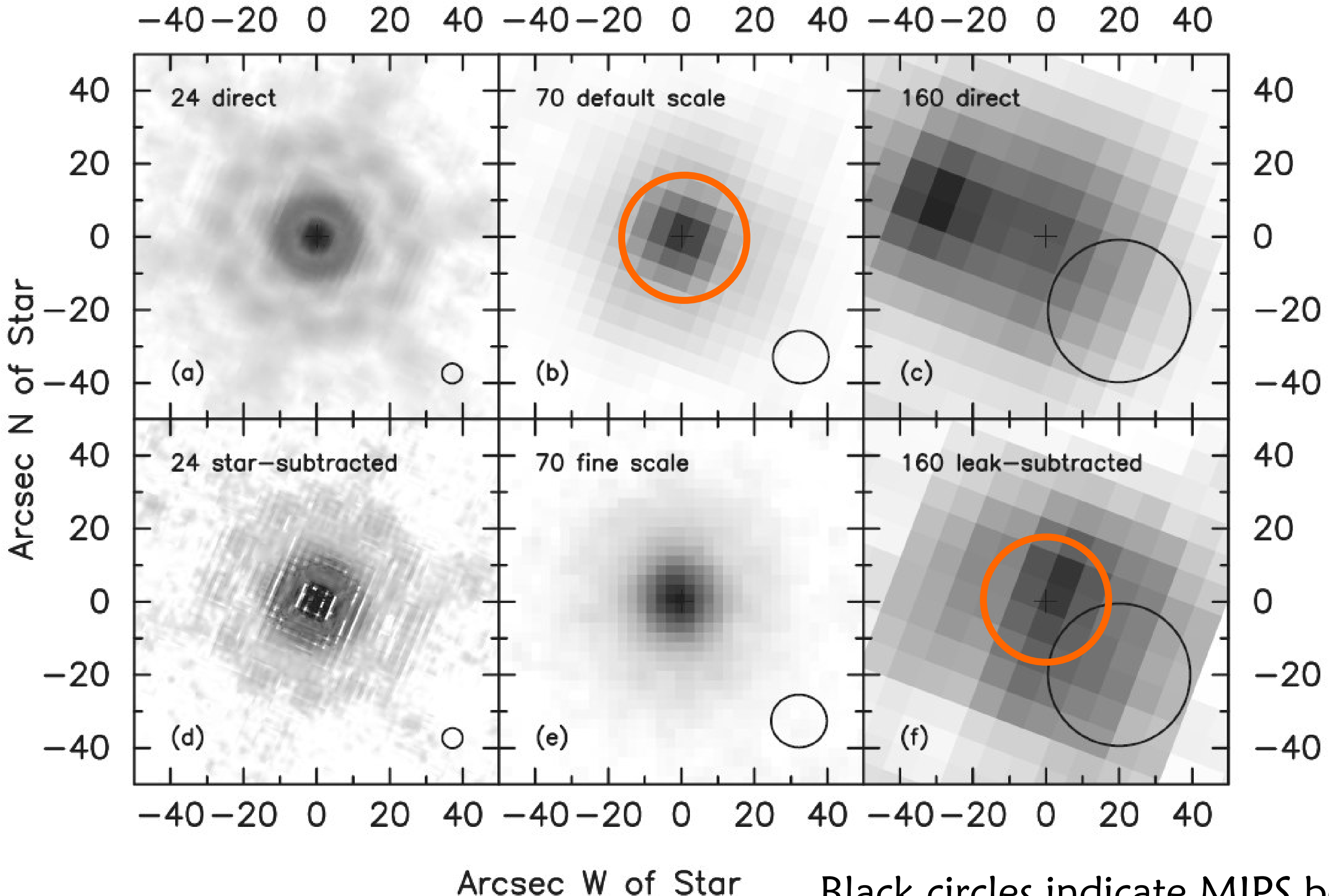


- *Seen only in roll self-subtractions*
- *Faintest disk yet seen*
  V = 24 mag / arcsec²

ε Eridani Spitzer/MIPS

Backman et al. 2009, arXiv/0810.4564

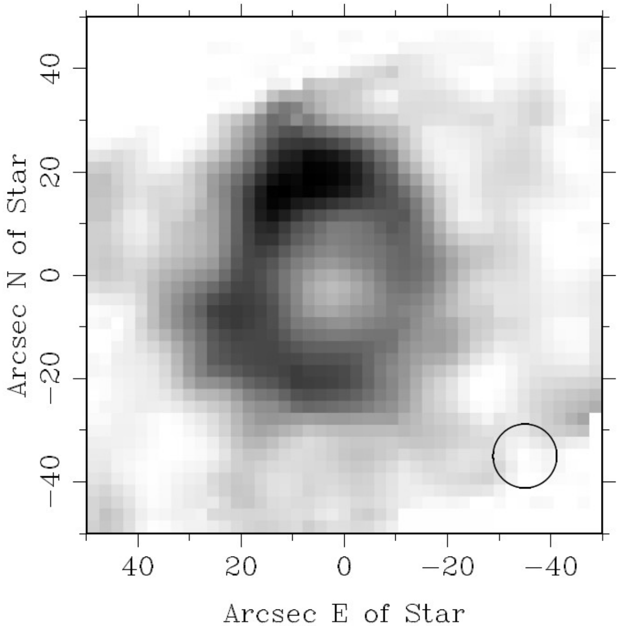
Submm ring size



Black circles indicate MIPS beam size

ε Eridani's perplexing submm face

CSO/Sharc II 350 μm

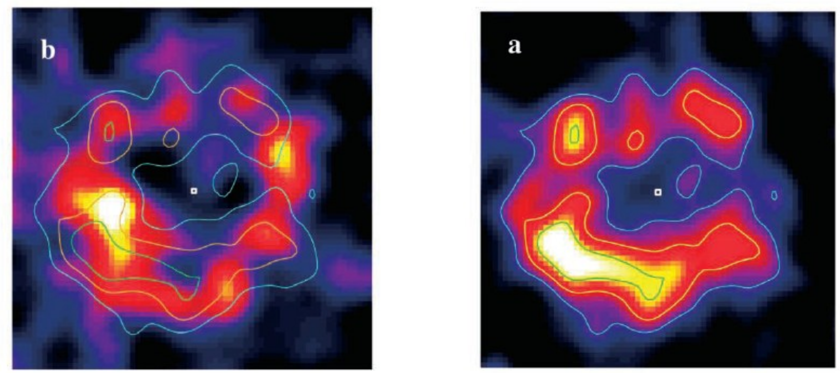


Backman et al. 2009

JCMT/SCUBA

450 μm

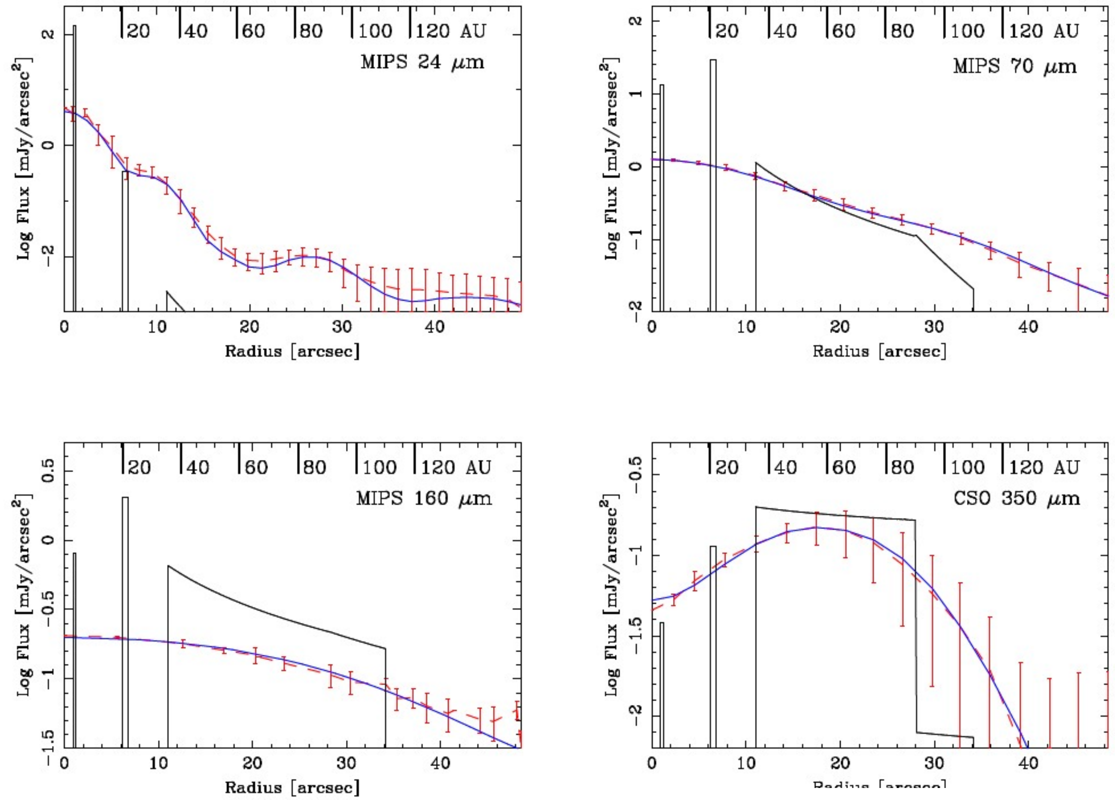
850 μm



Greaves et al. 2005

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

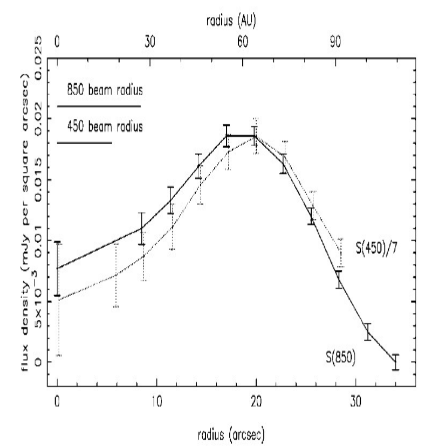
ε Eridani radial bright-ness profiles



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

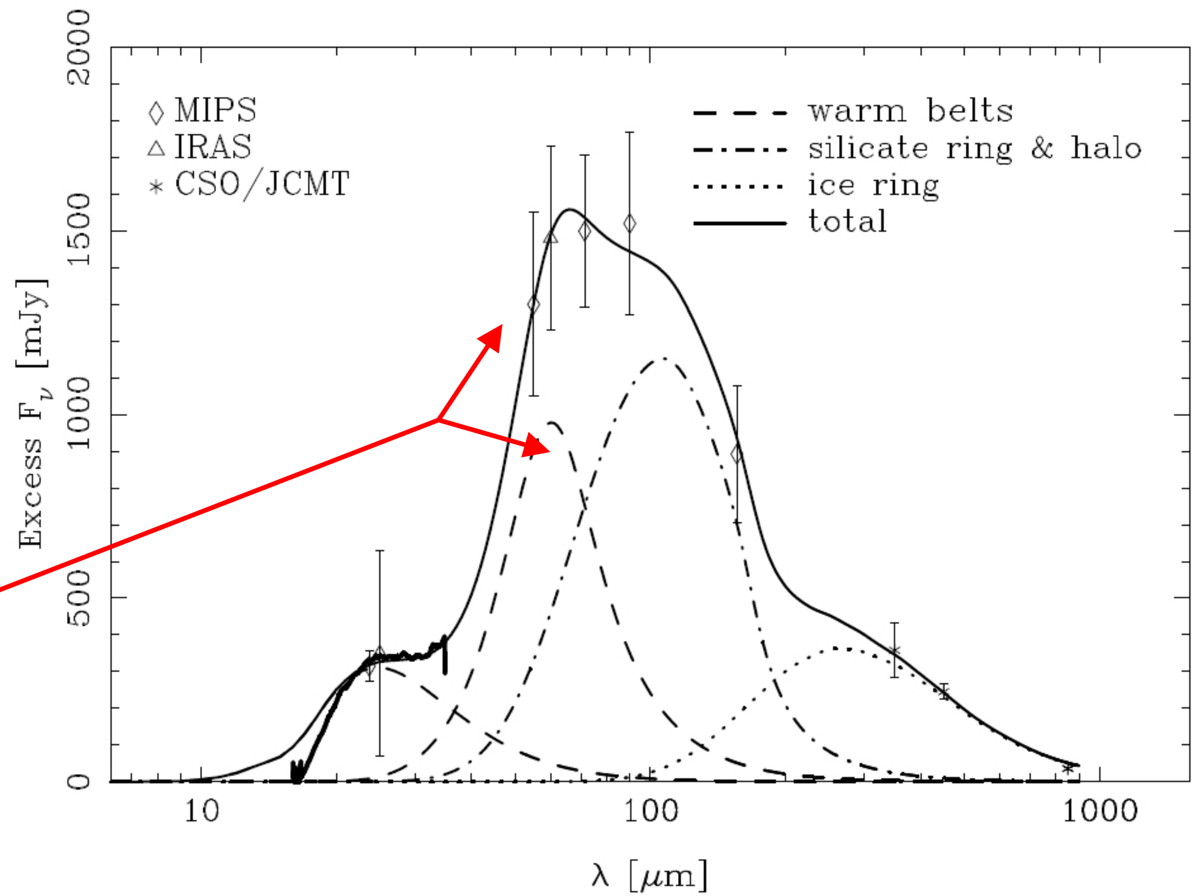
Right: JCMT 450 & 850 μm profiles (Greaves et al, 2005)



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

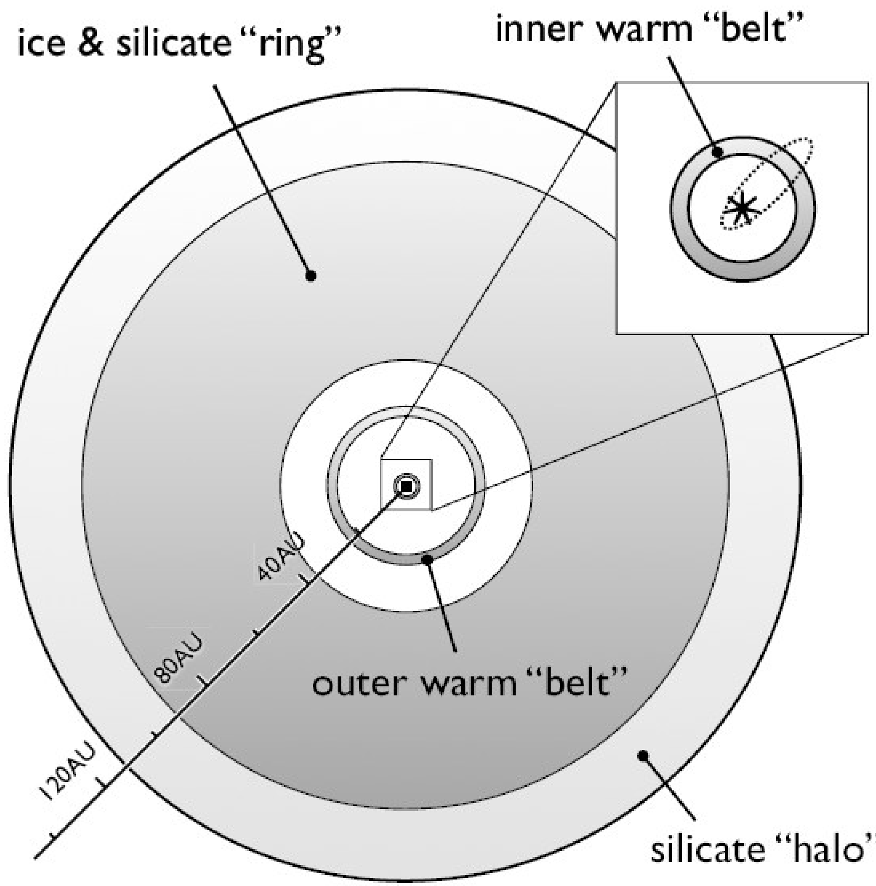


55 μm flux density measured in MIPS SED mode requires 5th component: a ring near 20 AU

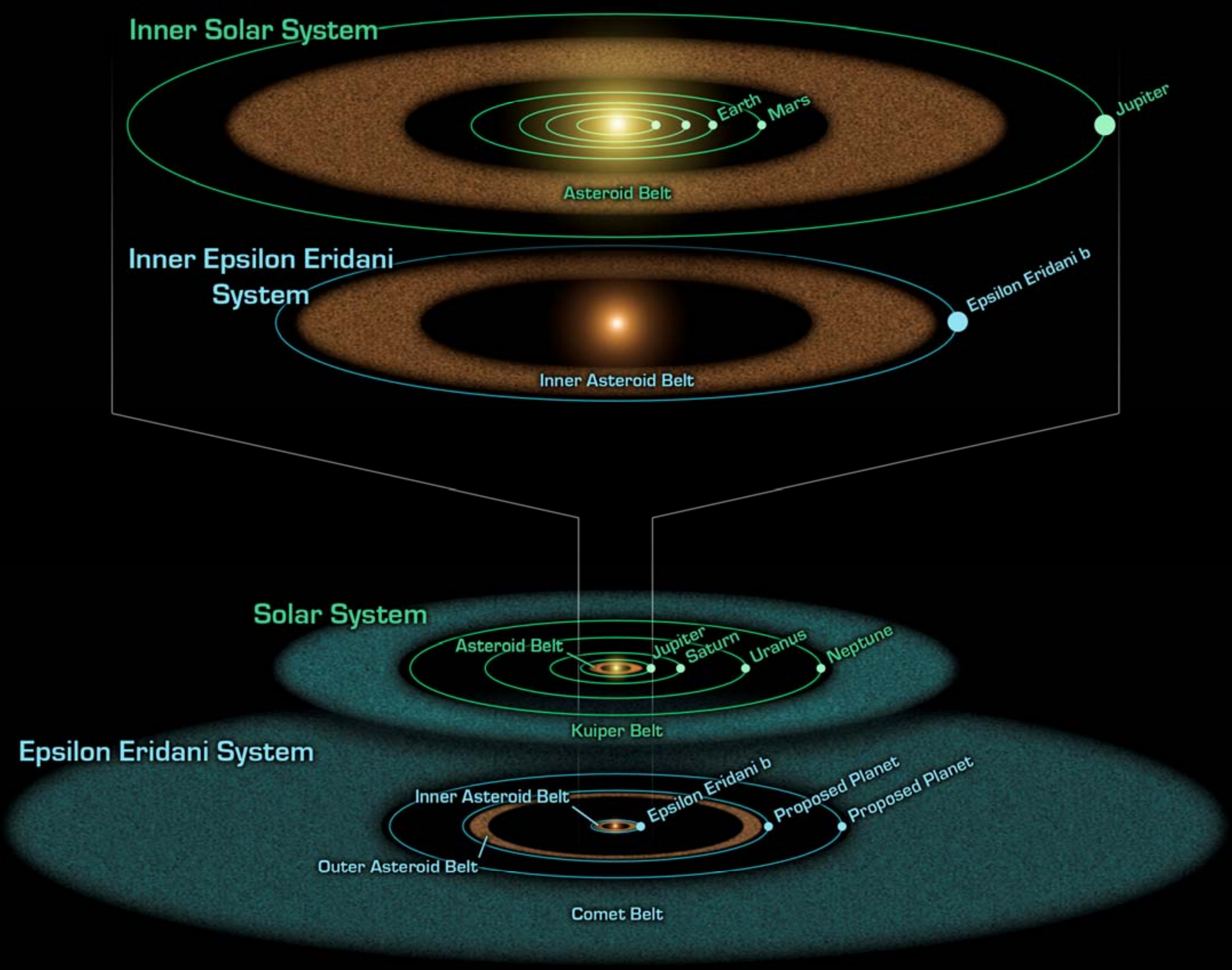
New View of the ε Eri debris disk

graphic by Massimo Marengo

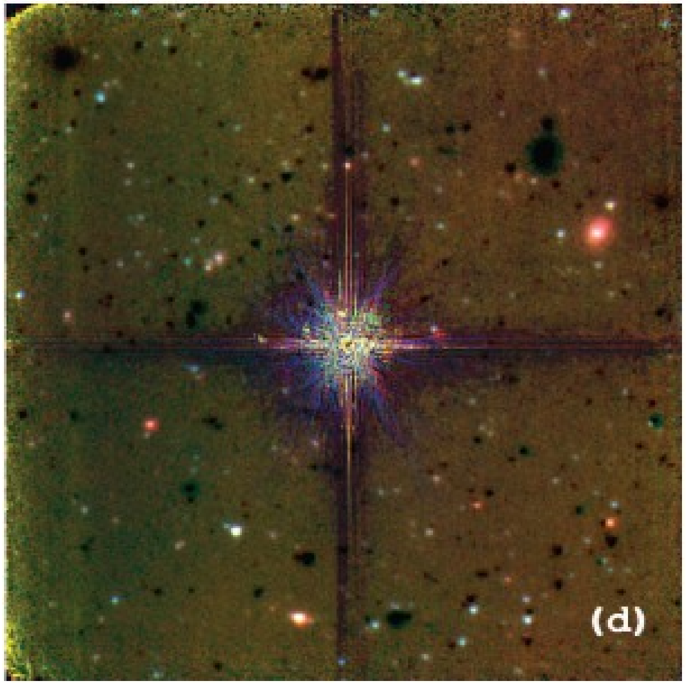
- Three disconnected debris belts
- Inner belt at 2-3 AU is close to RV planet ε Eri b (a= 3.4 AU)
- Eccentricity of the RV planet is unlikely to be 0.7 (Benedict et al. 2006). 0.25 (Butler et al. 2006) is more consistent with Spitzer results.



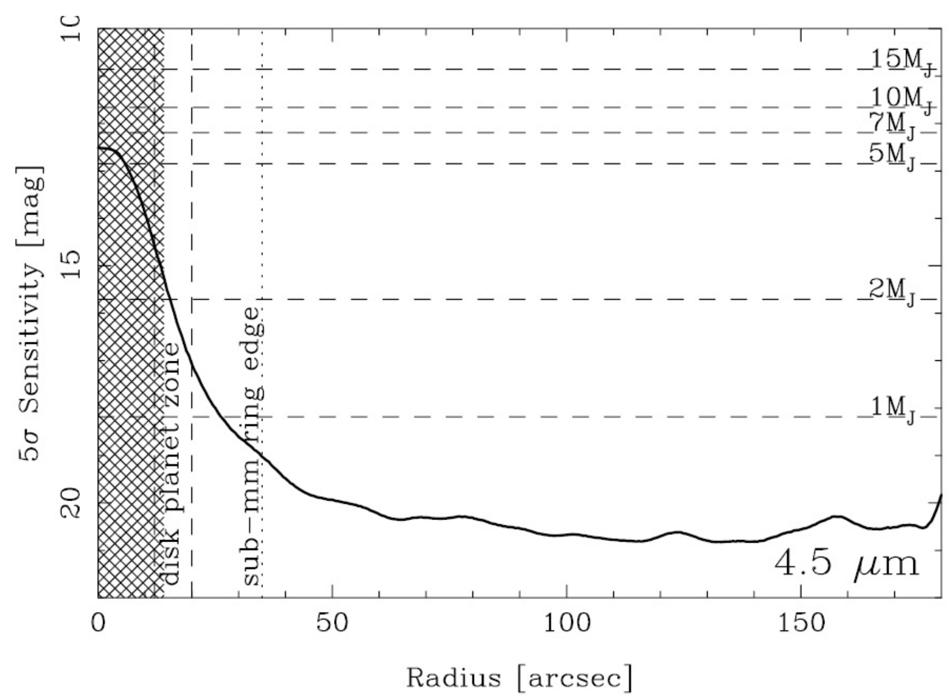
ε Eridani vs. our solar system



Spitzer/IRAC eps Eri companion search



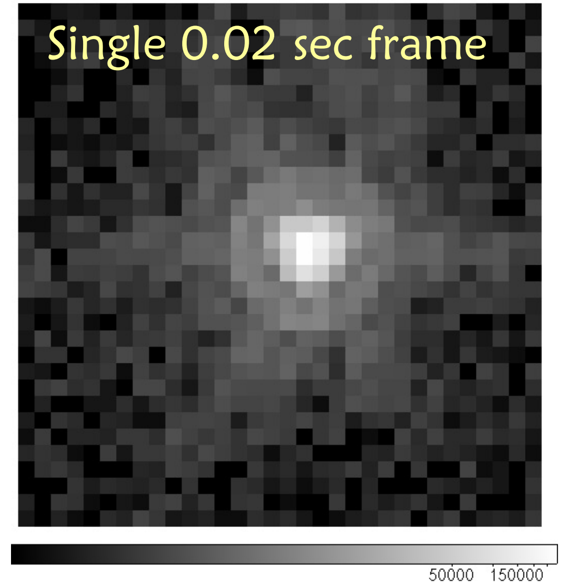
Marengo et al. 2006
IRAC full array search to 500 AU radius
324 x 12 sec exposures
Central 50 AU obscured by saturation.

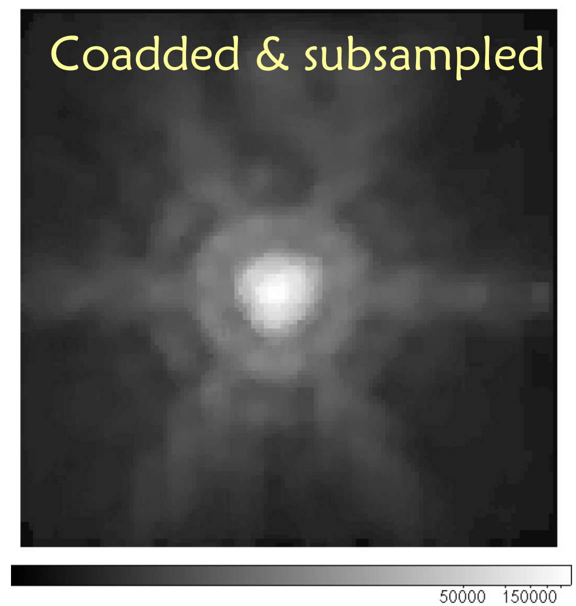


Result: Any planet outside the ring constrained to < 1 Jupiter mass (Burrows et al. models).
<u>What about inside the ring ?</u>

Next Step: Deep IRAC subarray imaging

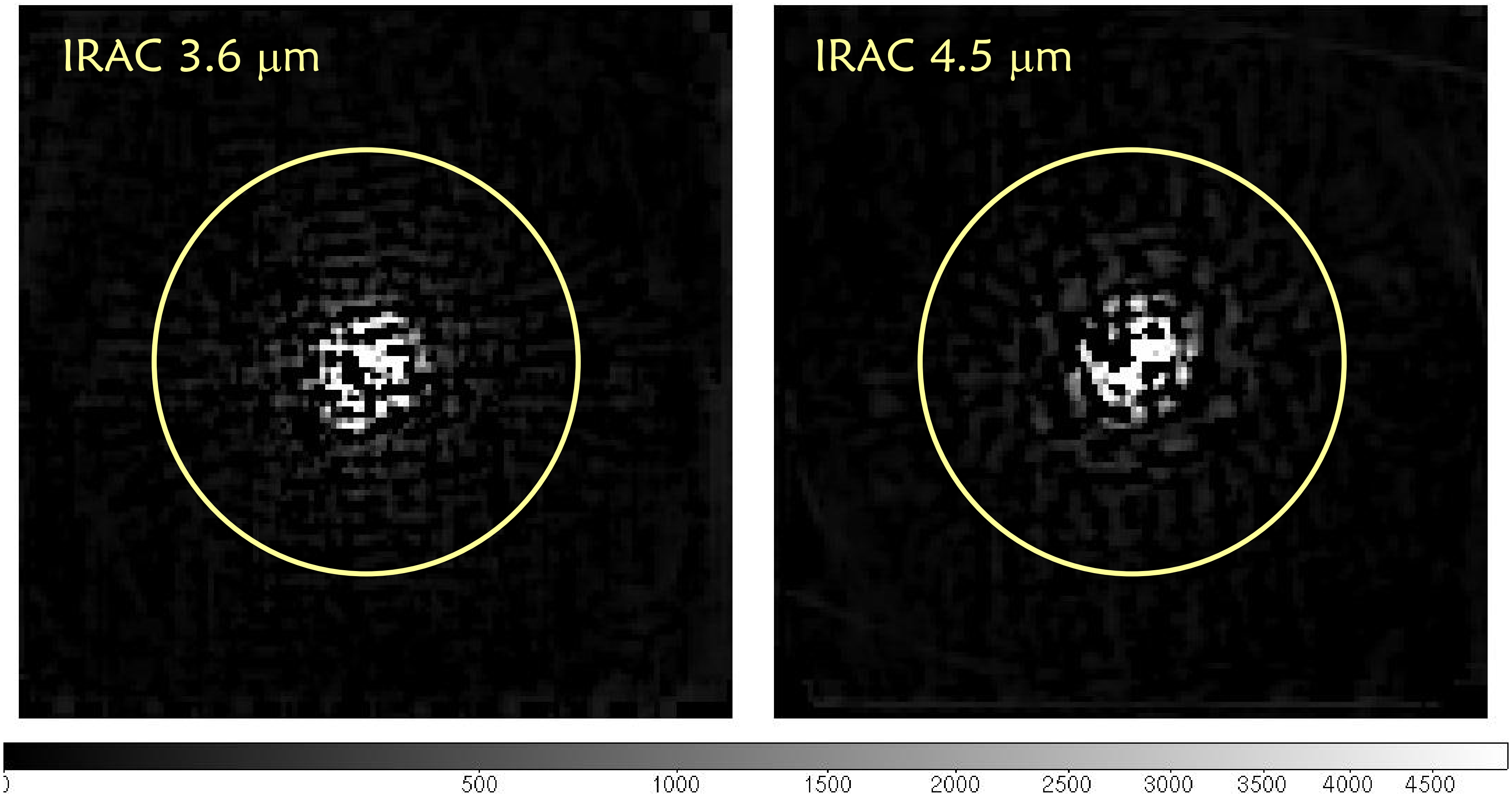
- No coronagraph aboard Spitzer
- Use the IRAC subarray with <u>0.02 sec frame time</u> to mitigate saturation. 32x32 pixels.
- Covers r< 19″ (60 AU) region interior to the submm ring
- 146,880 exposures (!) at each of two roll angles in bands 1&2.
- Use roll subtraction to remove the bright stellar PSF



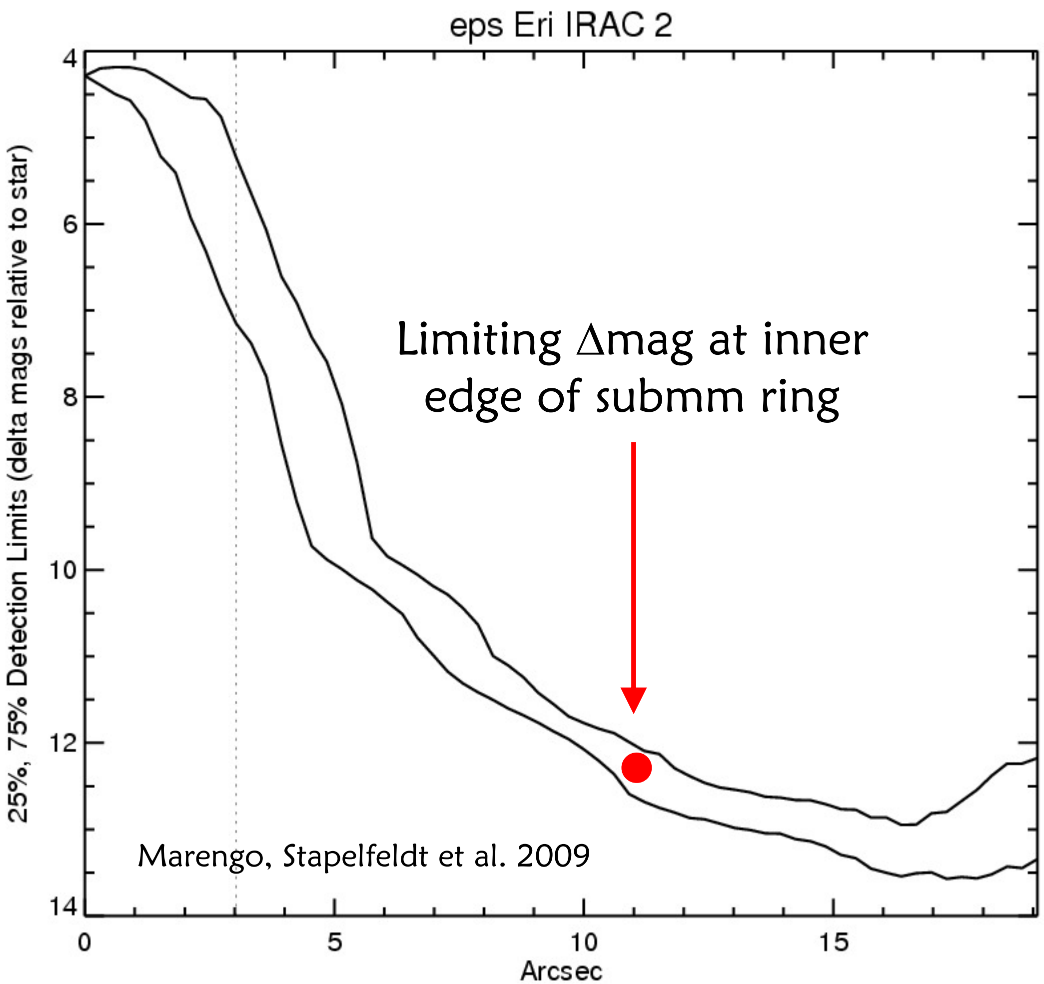


Eps Eri PSF subtraction

38" Subarray field of view; circle shows inner radius of submm ring



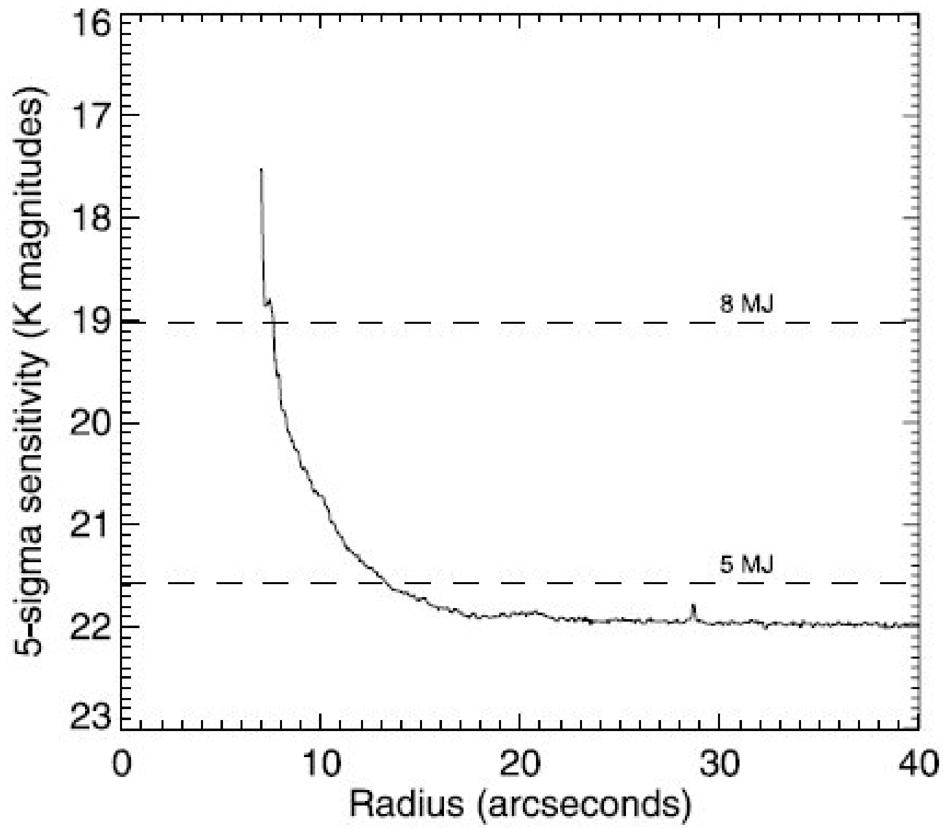
No Eps Eri companion detected. Upper limits from subarray data:



- Limiting mag is 13.9 at 4.5 μm; Fν= 0.5 mJy
- This corresponds to a <u>3 Jupiter mass object</u> at 1 Gyr age (Burrows, Sudarsky & Hubeny 2004)
- The above model predicts this object would have H= 22.9, K= 25.2: below AO detection limits.
- Spitzer/IRAC provides strongest constraint yet on mass of possible planet near submm ring

Perturber searches with Adaptive Optics in the Near-IR

- Eps Eri: Macintosh et al. 2003
- Vega: Macintosh et al. 2003, Hinkley et al. 2007
- Spitzer/FEPS debris disks: Apai et al. 2007
- Spitzer/GTO debris disks: Palomar (Tanner et al. ongoing)
- Will be an important thrust for upcoming AO instruments: Palomar 1640 (Hinkley poster #94), Subaru, GPI, Sphere



K band limits for eps Eri
Macintosh et al. 2003

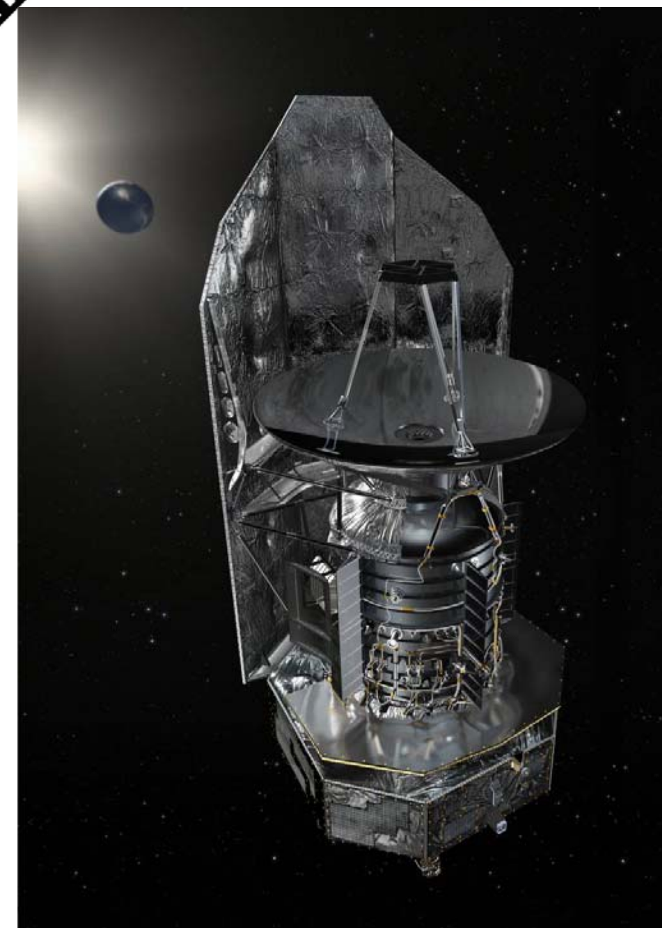
2008 Keck Interferometer 10 μm Nulling Campaign

See also Liu Poster #115 on MMT nulling

- Goal: Detect extended exozodiacal dust clouds around nearby stars
  - Screen stars for future terrestrial exoplanet searches
  - Sensitivity of a few hundred times our zodiacal cloud
- 45 targets being observed for 3 PI teams
  - 5 runs so far, decent weather; 2 more to come
- Serabyn team preliminary results to date:
  - From 16 targets observed, 1 clear detection and 1 probable detection of dust in the 0.5-1 AU region

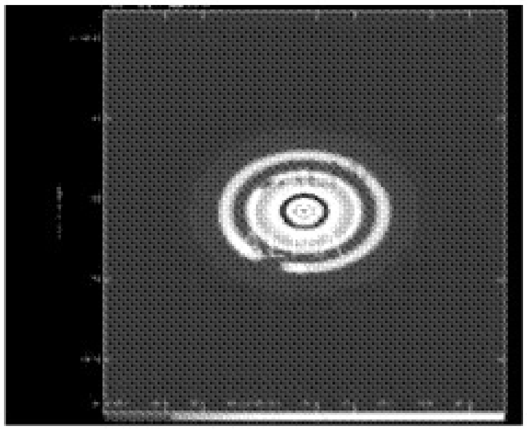
Herschel

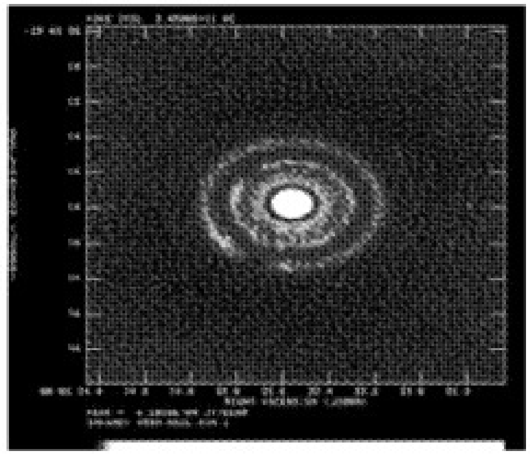
- 2009 launch
- 70 μm imaging resolution 4x sharper than Spitzer/MIPS; resolving central holes & disk asymmetries
- Sensitivity to lower levels of L_{IR}/L_{star} at 100 & 160 μm
- 400 nearby targets to be surveyed by DUNES and DEBRIS key programmes (see Eiroa poster #121, Phillips #118, Sibthorpe #104, Rodmann #102)



ALMA continuum imaging

Wooten, Mangum & Holdaway 2004





Left: Model disk image at 850 μm, 125 AU radius, d= 15 pc, $L_{IR}/L_{star} \approx 3\times10^{-5}$ (F_ν= 10 mJy)

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

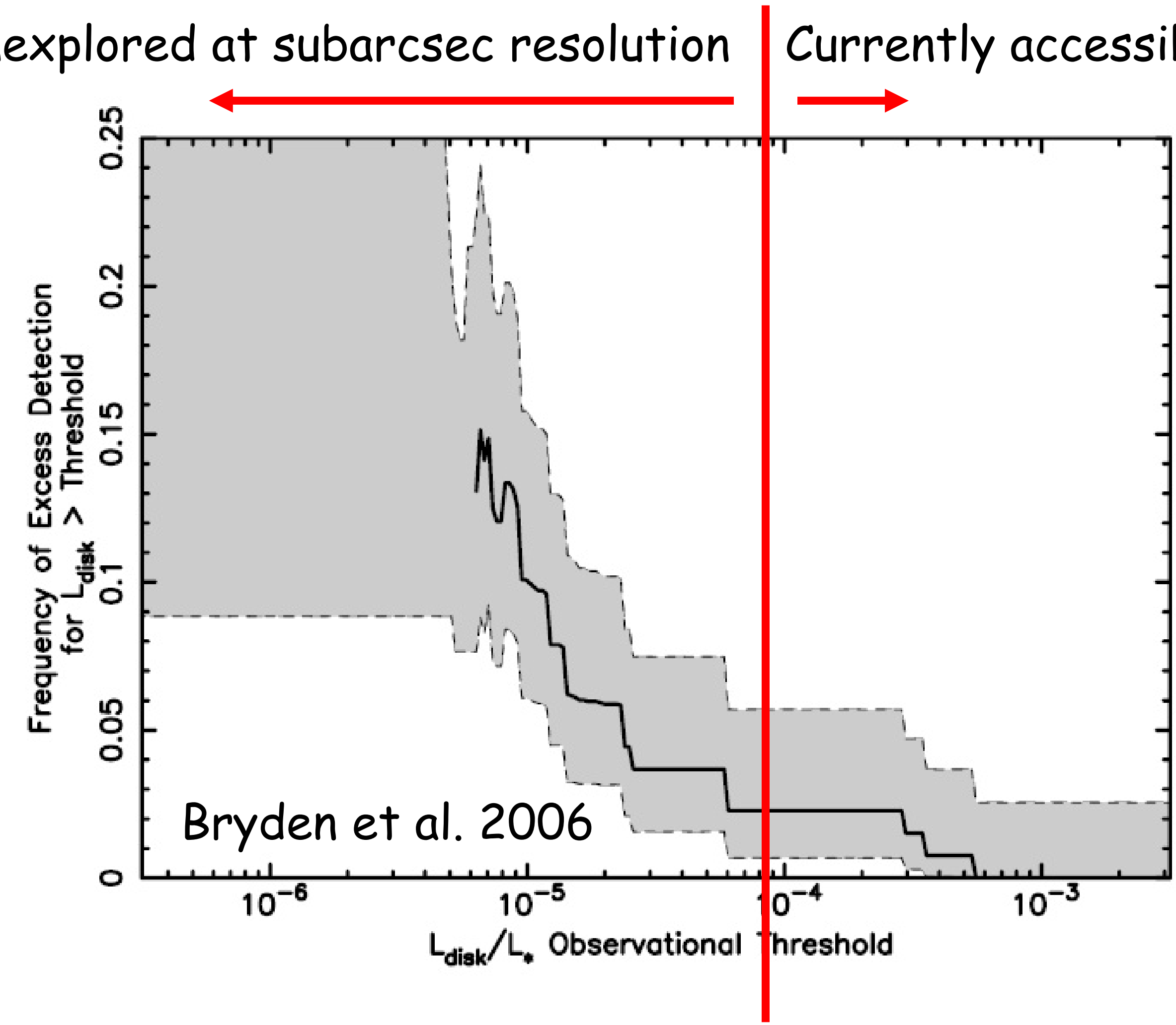
Numerous targets should be accessible for mapping at subarcsec resolution

Very few debris disk systems are bright enough for mapping at 0.1″ resolution

(small F_ν. large sizes)

Scattered Light Imaging accesses only high LIR/Lstar debris disks

Unexplored at subarcsec resolution | Currently accessible in scattered light

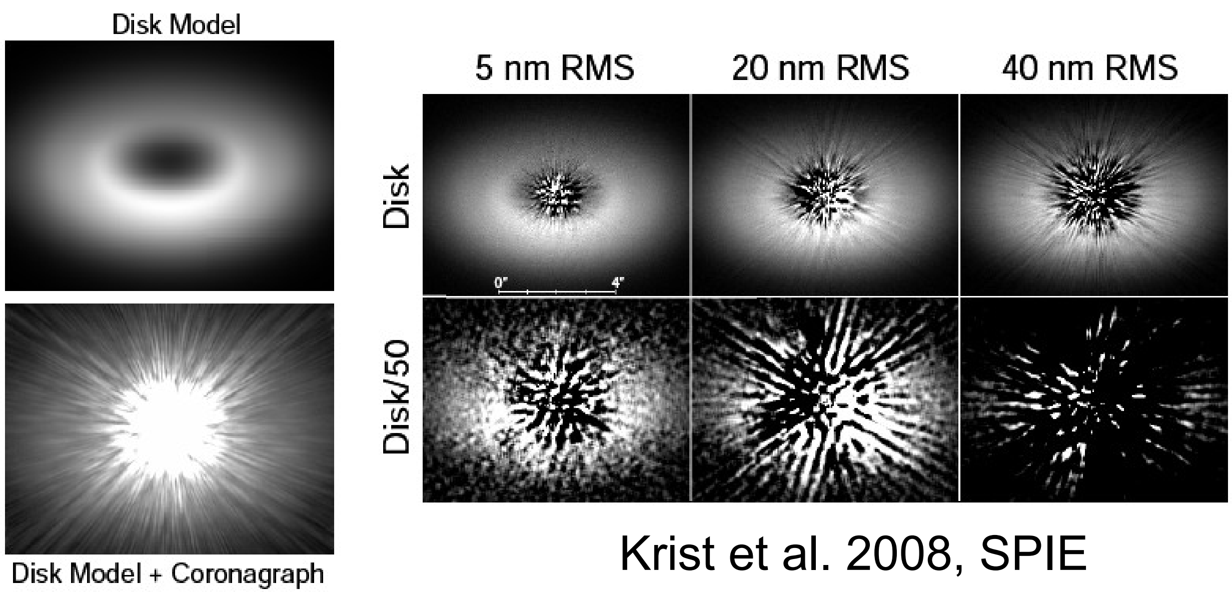


Future progress:

- Complete surveys of high LIR/Lstar targets with existing facilities
- Develop & deploy new capabilties to image at higher contrasts: ExAO.
- Polarimetry of younger / later type objects with smaller grains

JWST & disk scattered light

Simulated NIRCAM coronagraph K band images of an LIR/Lstar = 0.008 disk vs. primary mirror wavefront stability



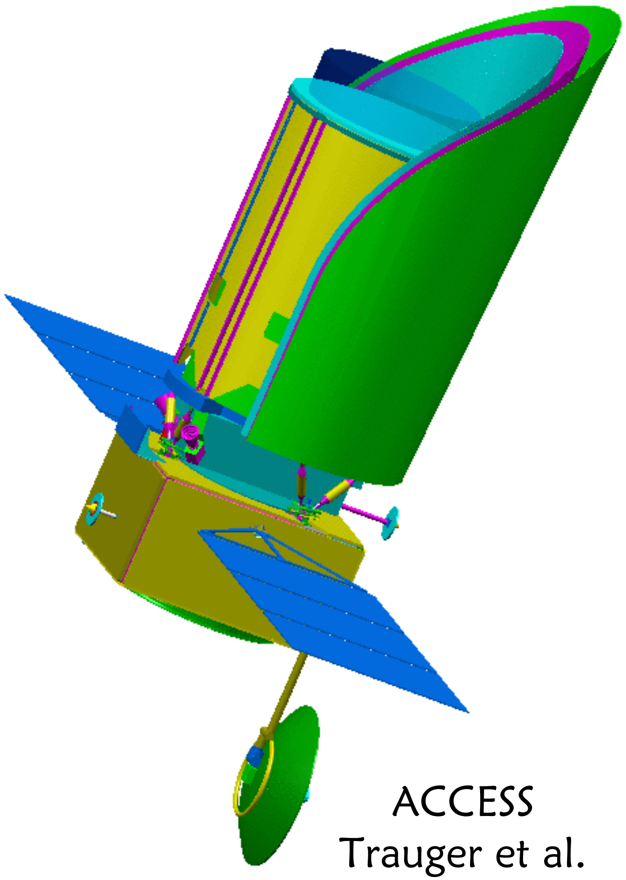
Krist et al. 2008, SPIE

<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

Small coronagraph mission concepts

- 10^9 contrast at 3 λ/D separation demonstrated in JPL lab tests
- Active optical wavefront control with deformable mirrors
- Mission based on ~1.5 m telescope under study by several groups
- Multiple coronagraph options
- Debris disk & exozodi imaging down to 10 zodi level in nearby sunlike stars; RV planet spectra
- Candidate for NASA exoplanet probe mission selection in 1-2 years



ACCESS
Trauger et al.

Summary

1. Debris disk imaging provides essential information on dust spatial distributions and particle properties. No single wavelength tells the whole story.
2. Only about 2 dozen debris disks are spatially resolved today. This won't change greatly until future instrument developments expand our ability to image more tenuous systems.
3. Searches for companions perturbing the disk structures will become increasingly important.
4. Spitzer debris disk surveys have given us the target list for imaging studies over the next 1-2 decades.