Coronagraphy and Debris Disk Imaging

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Exoplanet observing techniques: What's new, cheap, and near-term?

- Microlensing: Global networks
  Planetary mission imagers ?
- Radial Velocity: New telescopes, spectrographs
- Combined light: Ground & space telescopes
  Planetary mission instruments ?
- Astrometry: VLTI instrument
- High Contrast Imaging:

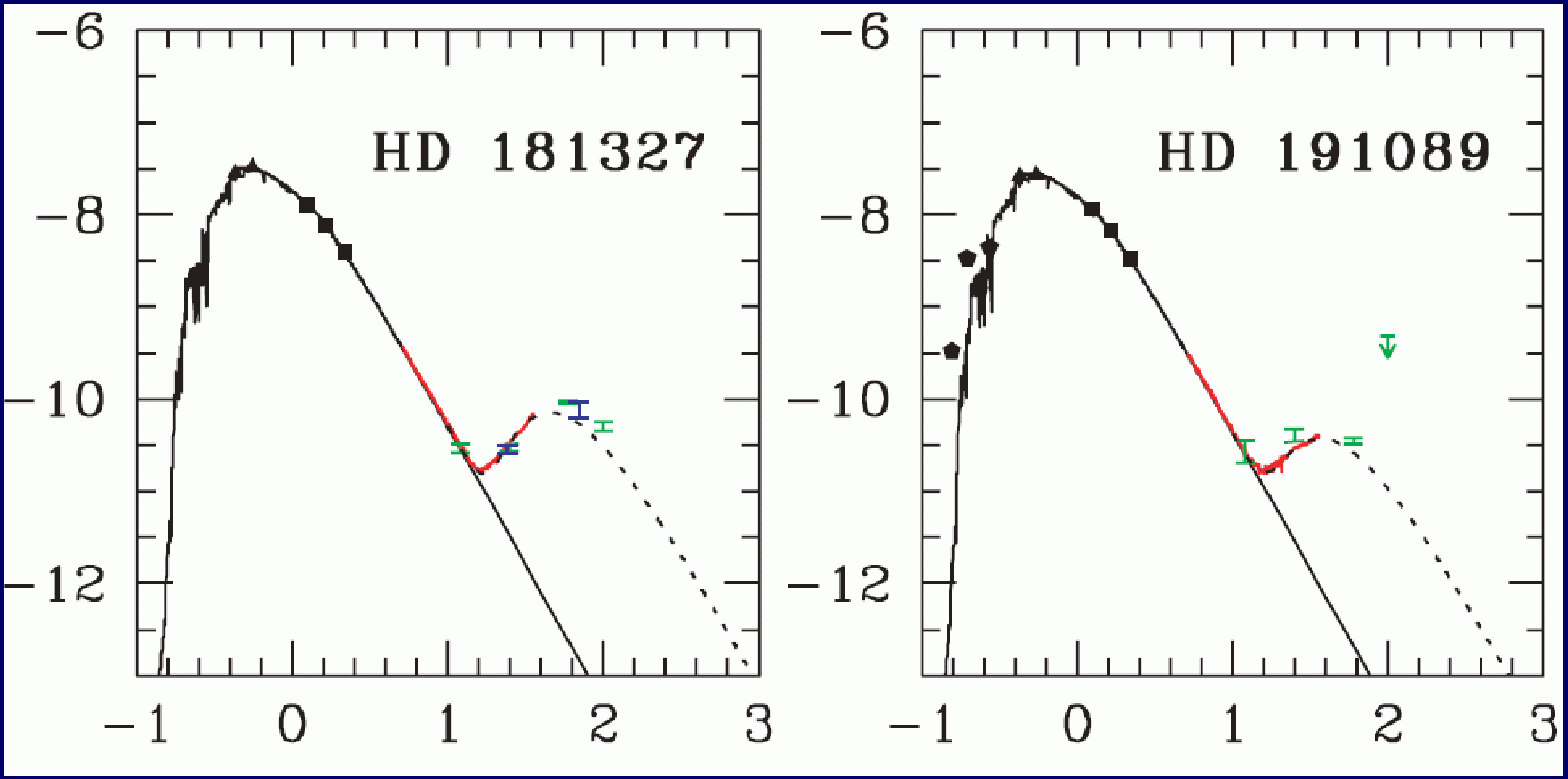
  Near-infrared coronagraphs on the ground (Palomar, Gemini, VLT, Subaru) and in space (JWST) to contrasts of $\sim 10^{-6}$ or 10^{-7}

Exoplanetary system at 10 pc

Scattered light Contrast to Star	10^{-10}	10^{-8}	10^{-9}	10^{-7} to 10^{-5}	
Star	Terrestrial	Zodi	Jovian	Kuiper Dust (debris disk)	
Linear Scale	1 AU	3 AU	5 AU	40 AU	
Angular Scale	0.1″	0.3″	0.5″	4″	
Telescope Size to Resolve	8 m	2.5 m	1.5 m	0.2 m	Optical
	24 m	8 m	4.5 m	0.6 m	Near-IR

~1000 Debris disks known. Most look like this.

Chen et al. 2006



Far-IR excess emission provides dust infrared luminosity and a characteristic temperature.

Relationship of disk temperature to orbital radius depends on dust properties

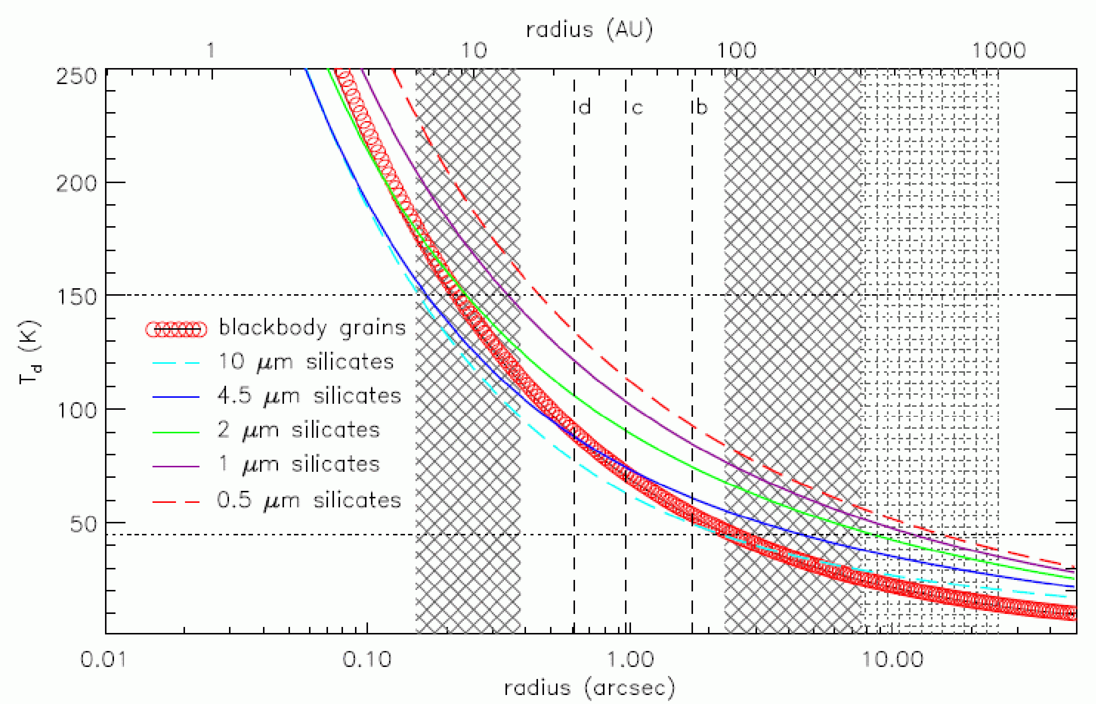


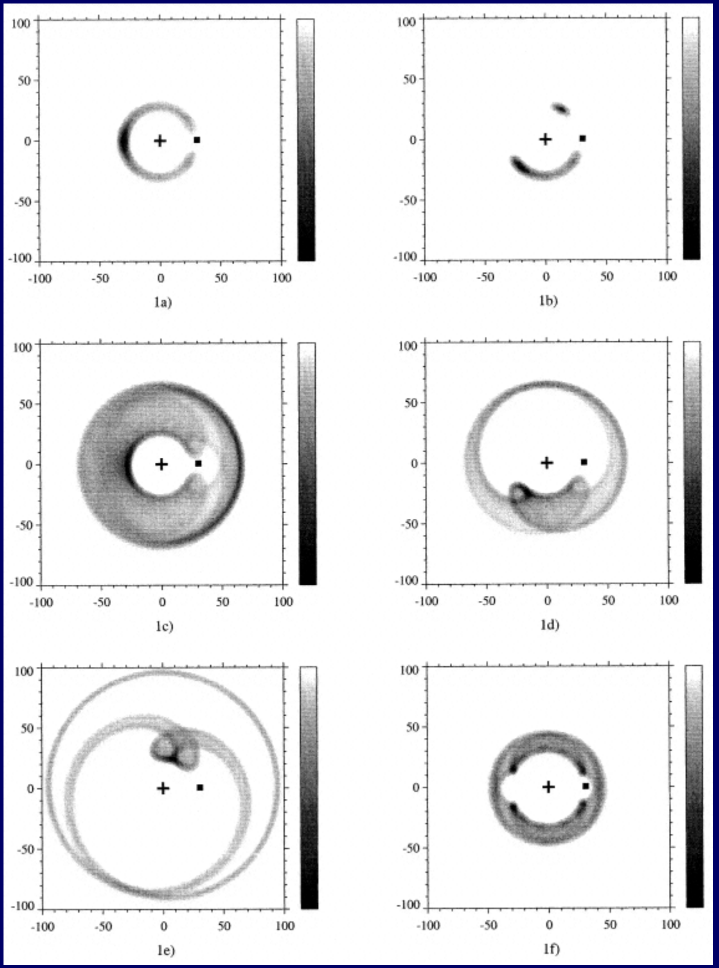
FIG. 4.— Thermal equilibrium dust temperature in the HR 8799 system computed based on various grain sizes of astronomical silicates. The two

Su et al. 2009

- Imaging detection establishes disk size & density profile, and then (through modeling) the dust properties.
- Enables comparative understanding vs our Kuiper Belt

Disk structures can trace planetary perturbations

- 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

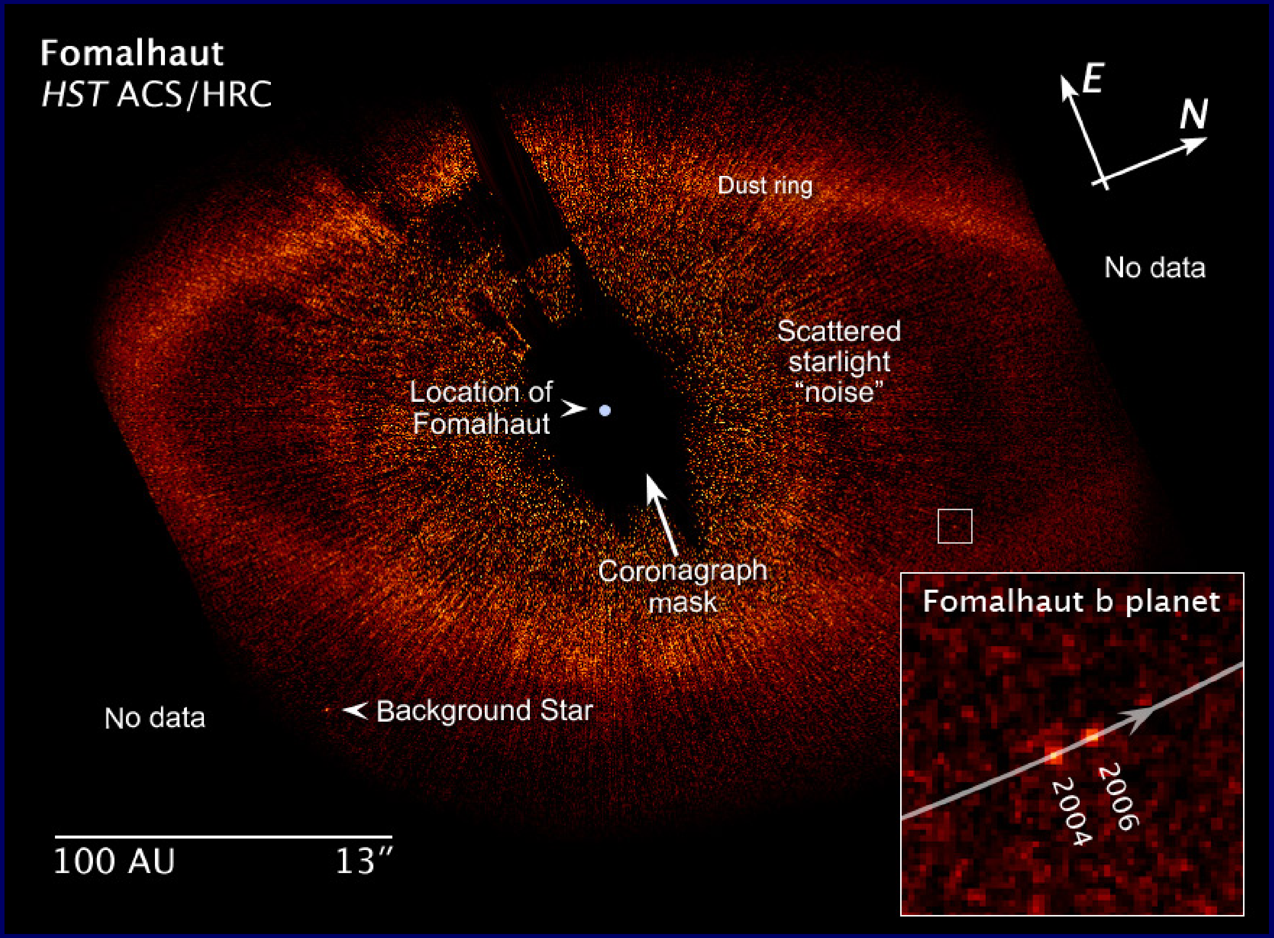
Planet seen in 2008

Kalas et al.

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

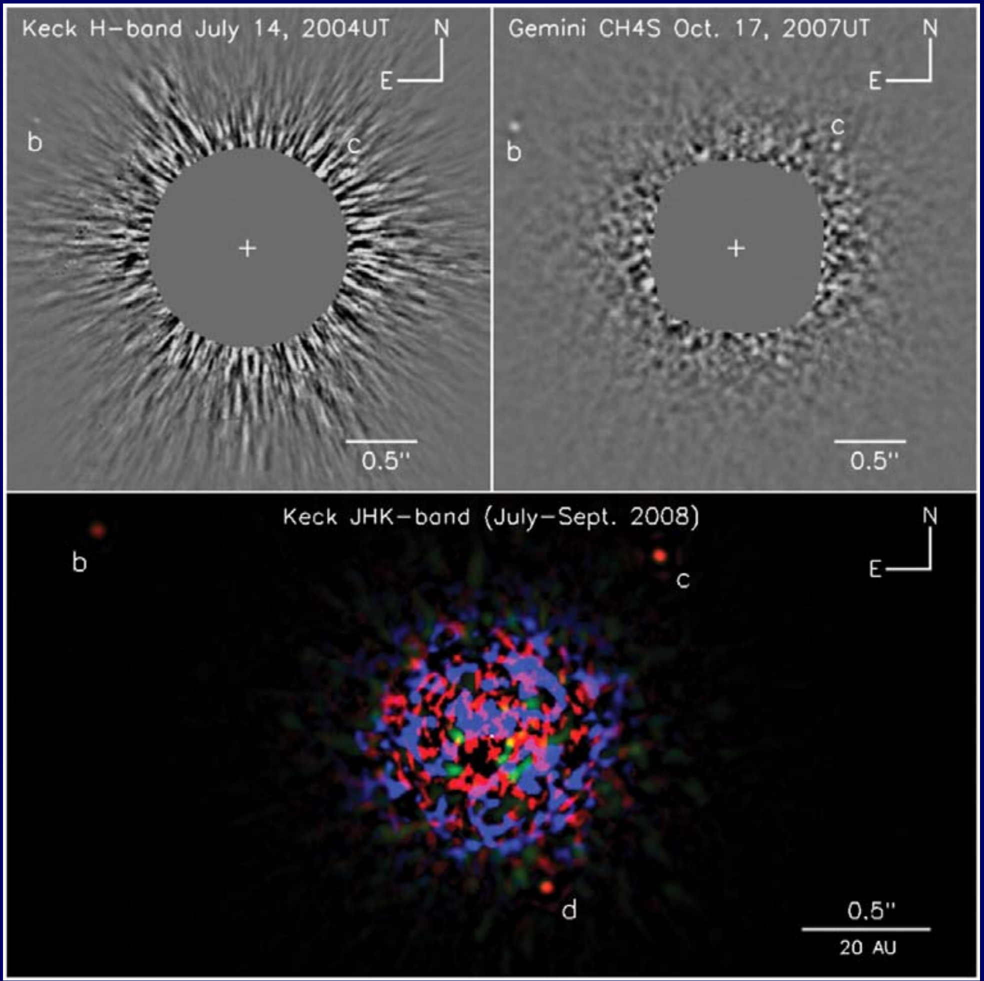
Common proper motion with star: not a background object

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

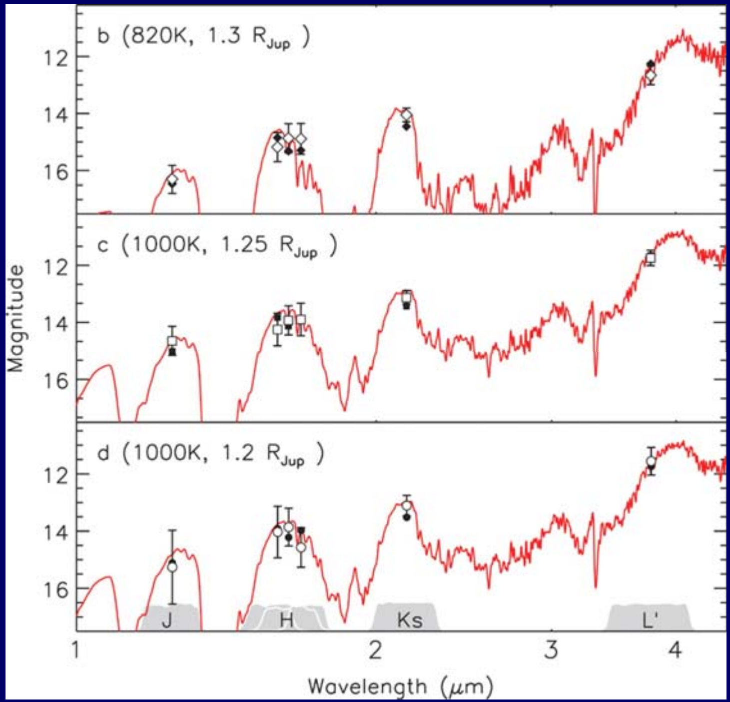


Three planets orbiting HR 8799

Marois et al. 2008

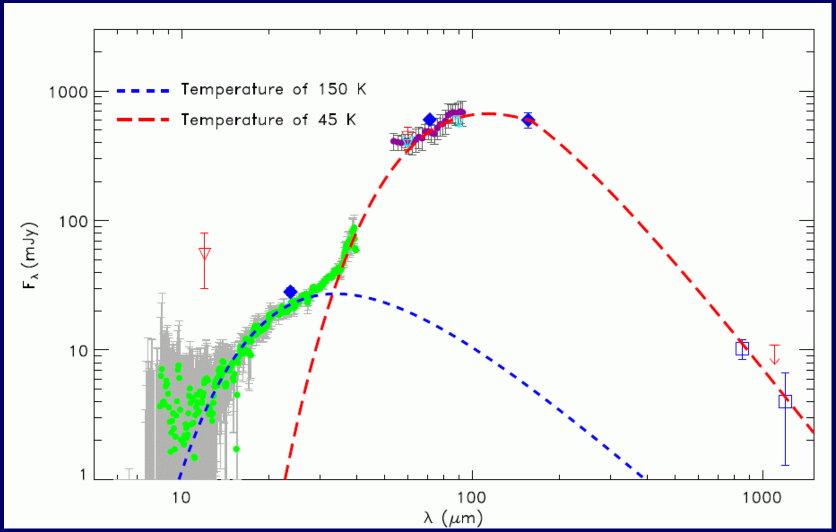


A0 star at 40 pc distance
Young system age ~60 Myrs
"Easy" contrast of 10^5



The HR 8799 Debris Disk

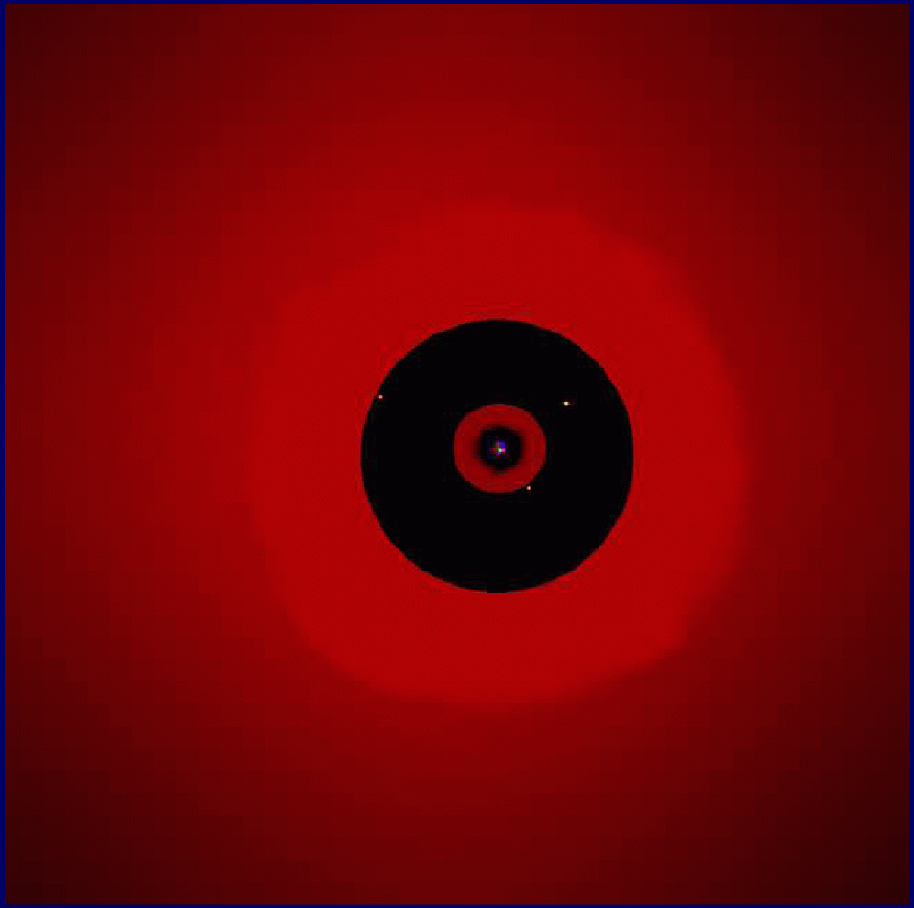
- Infrared excess shows two blackbody-like components
- Simple blackbody grains would produce this if located in belts at
  - 9 AU (T= 150 K)
  - 95 AU (T= 45 K)
- Dynamically viable: This would place the dust interior and exterior to the planets imaged at 24, 38, 68 AU



(Su et al. 2009)

see also
Chen et al. 2009,
Reidemeister et al. 2009

Disk/planet arrangement in HR 8799

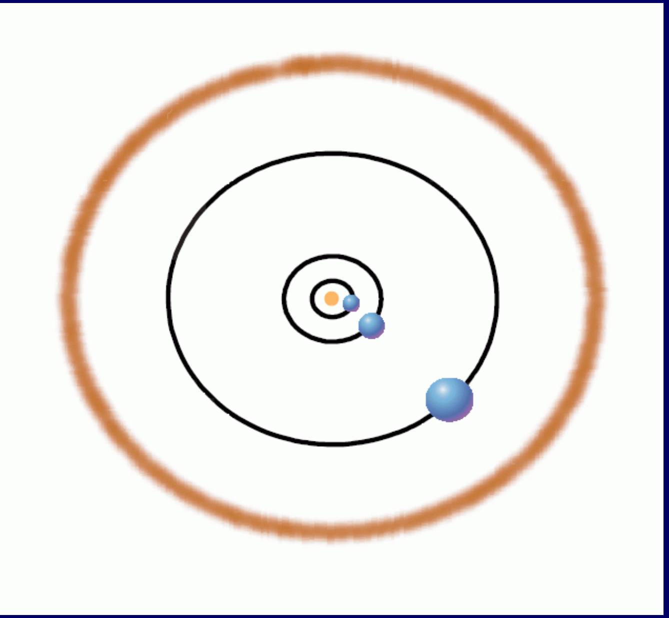


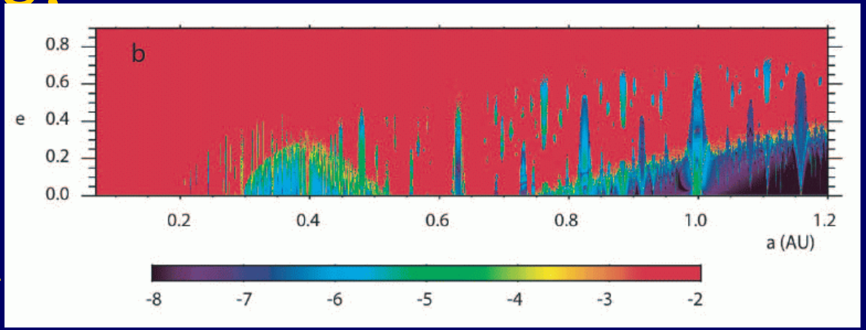
Graphic courtesy George Rieke

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.
- No image of disk to confirm

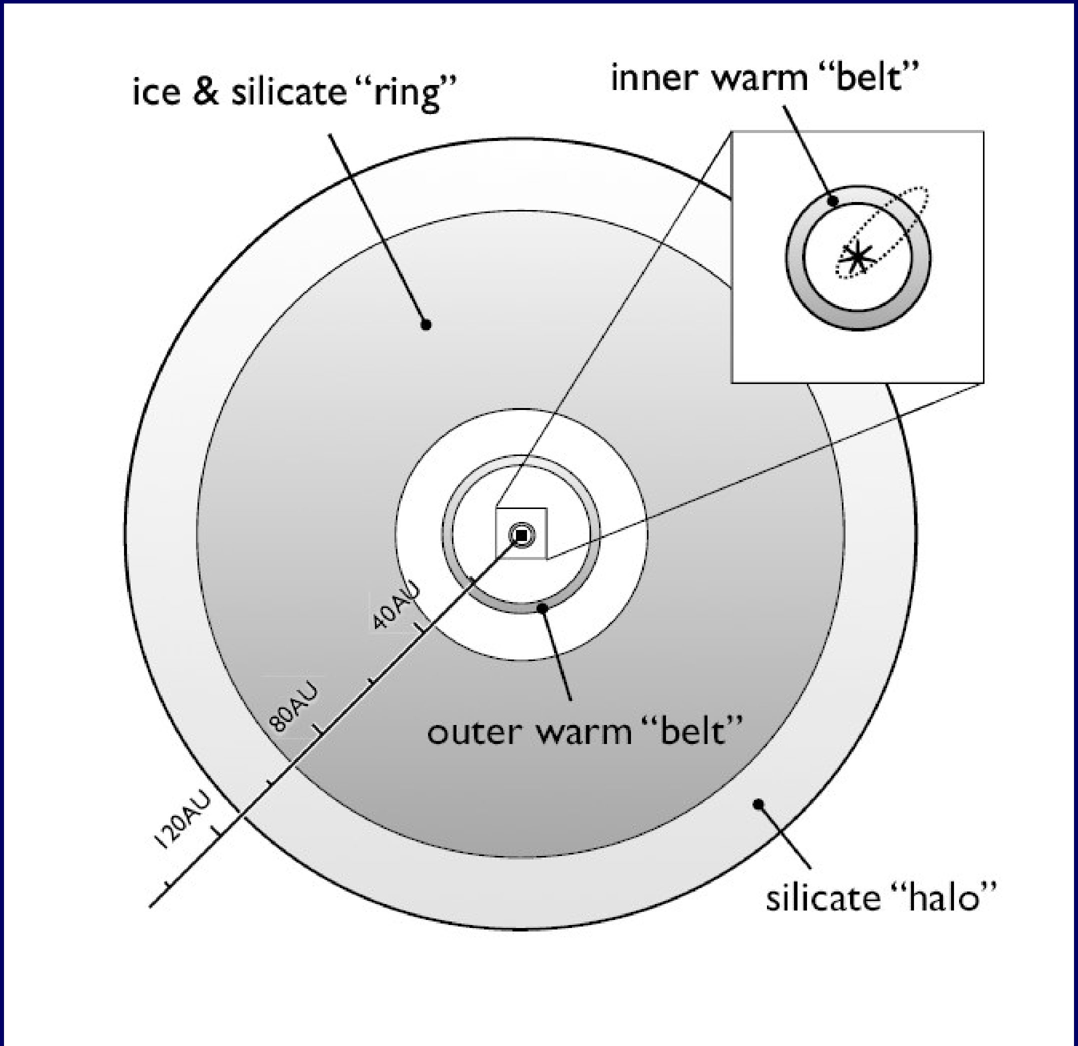




New View of the ε Eri debris disk

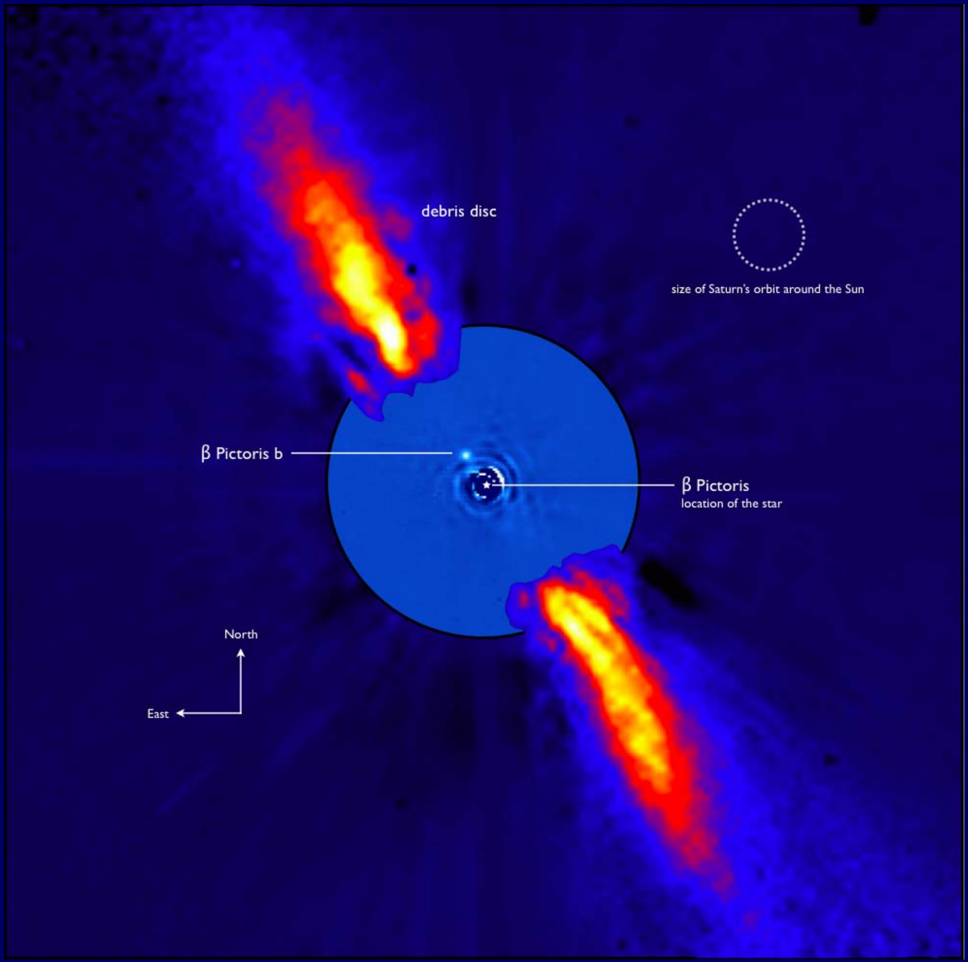
graphic by Massimo Marengo

- 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.
- This picture only approximate: system imaged to date only at 8″ (25 AU) resolution.

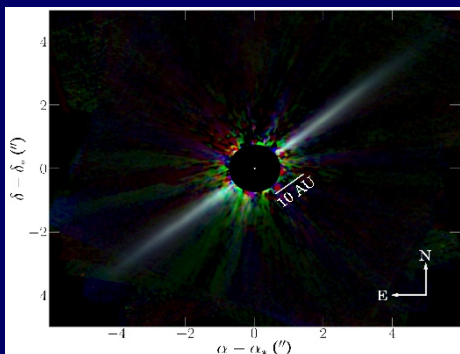


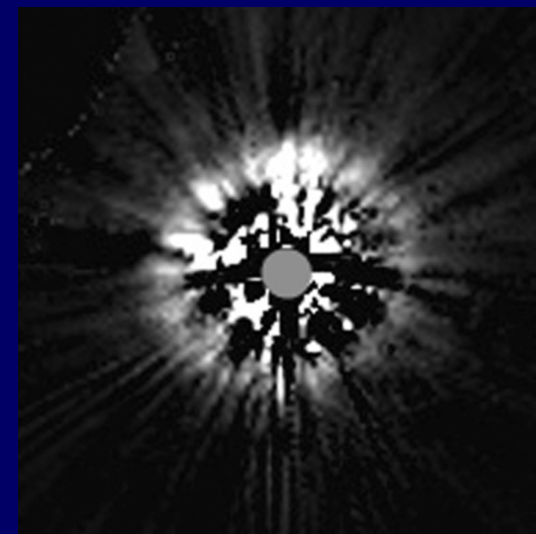
Beta Pictoris: Perturbing planet found ?

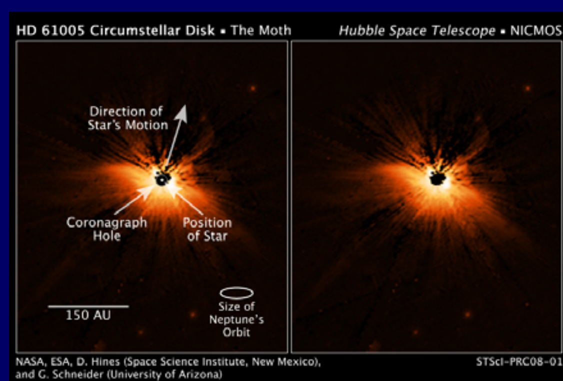
- 2003 VLT 3.4 μm image published by Lagrange et al. 2009.
- No confirmation by proper motion or photometry at other wavelengths
- Not detected in 2009 images by several groups
- If real, a >= 8 AU and mass= 8 $M_{Jupiter}$
- Stellar proper motion is northward; would move a BG source within 0.1" of the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

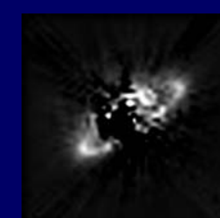


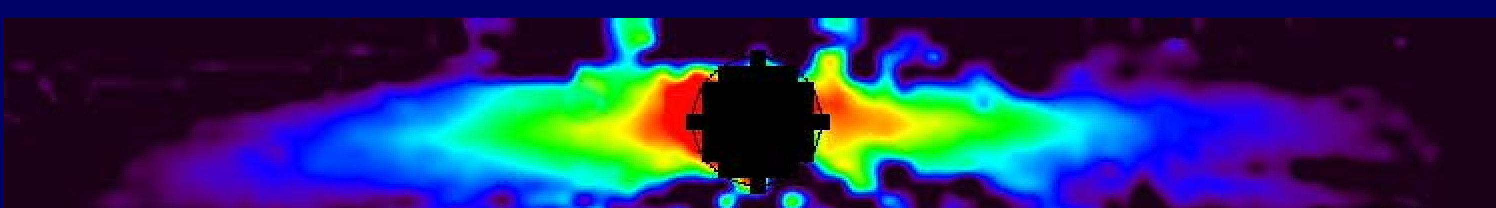
Other Scattered Light Images

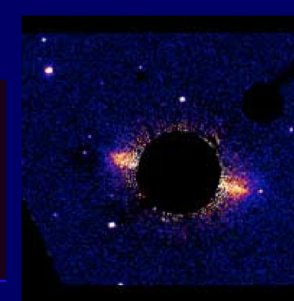












Inventory of Resolved Debris Disks

21 today, 14 at 0.1″ resolution. How to expand ?

Star	Spectral	Lir/Lstar	Scattered Light	Scattered Light	Thermal IR	Far-IR	Millimeter/
Name	Type		ground	space	ground	space	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

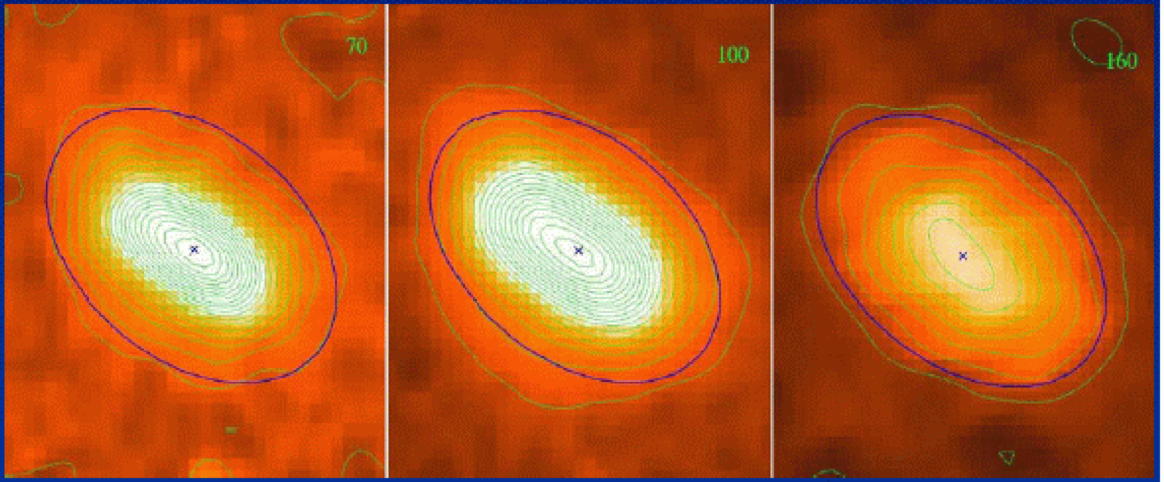
Herschel

- Launched 1 year ago 5/14/09
- 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
- 3 newly resolved debris disks in Herschel first results

HIP 7978 (q1 Eri)

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

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



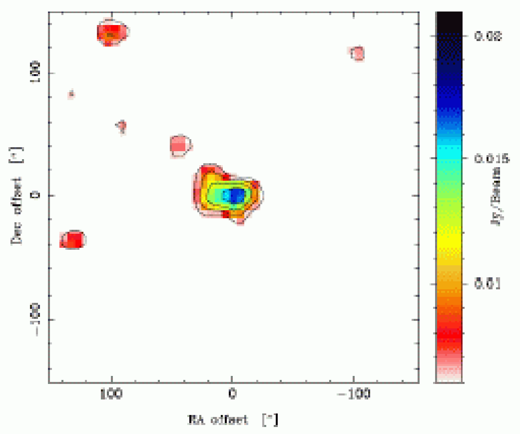


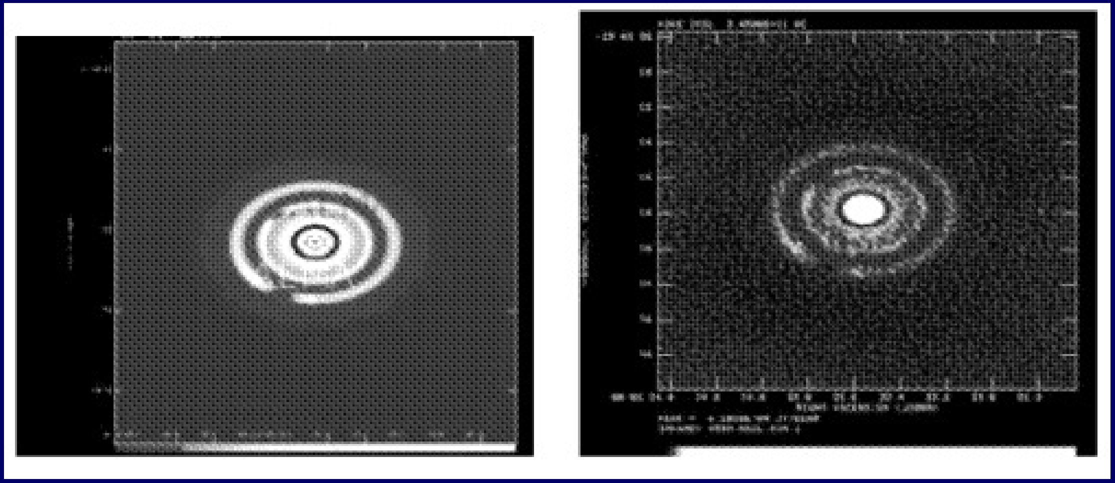
Fig. 1. q[1] Eri observed at 870 μm with the submm camera LABOCA at the APEX telescope (HPBW~18″). Within the

$R_{870} > R_{100,160} > R_{70}$
$R_{max} \sim 300$ AU

Liseau '08

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)

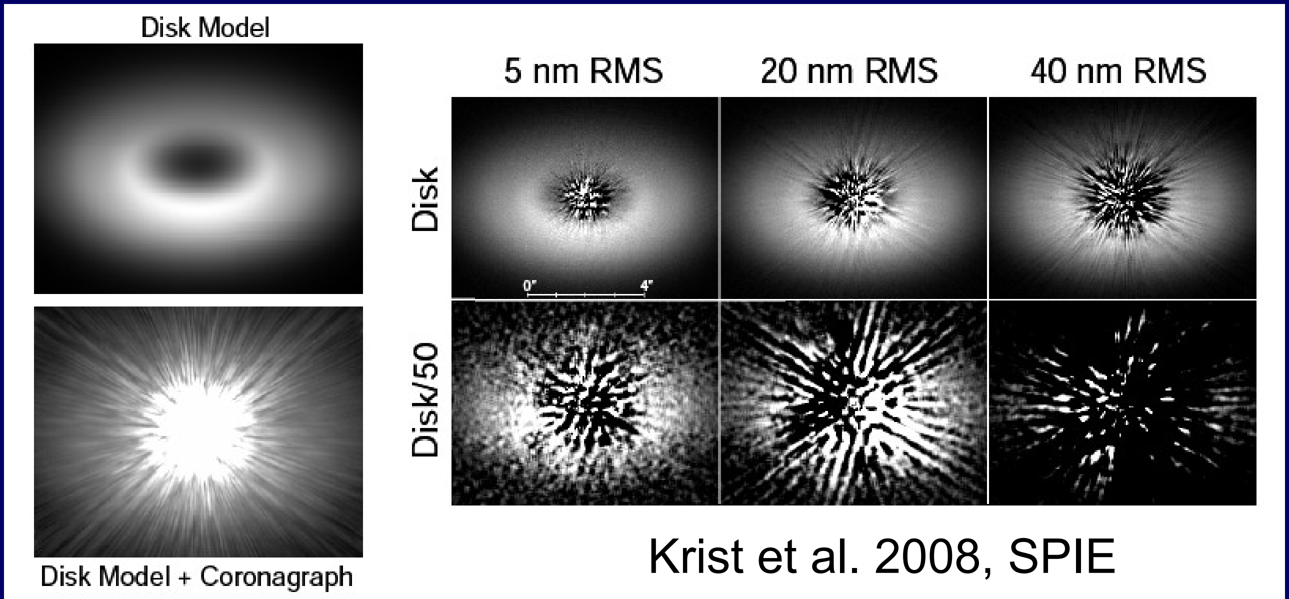
Right: Simulation of 4 hour ALMA observation, 0.4″ synthesized beam

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

(small fluxes. large sizes)

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 with 0.8″ beamsize

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

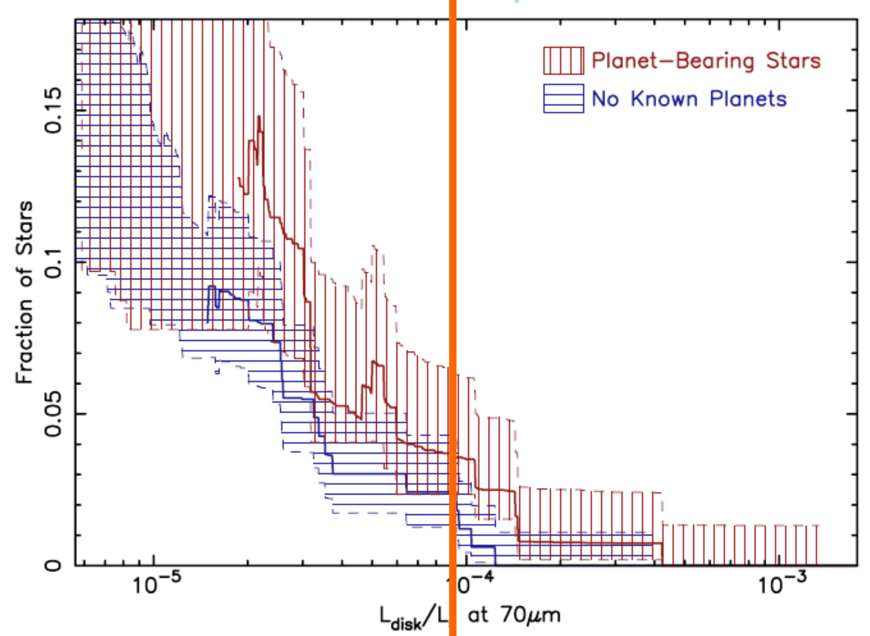
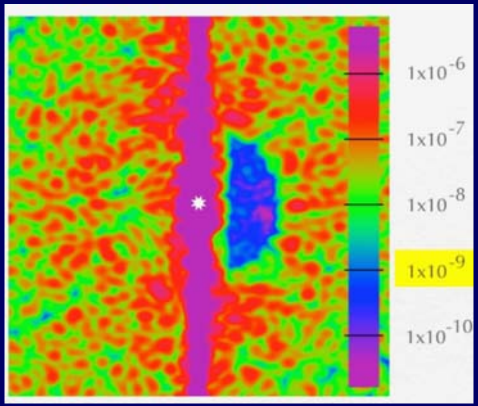
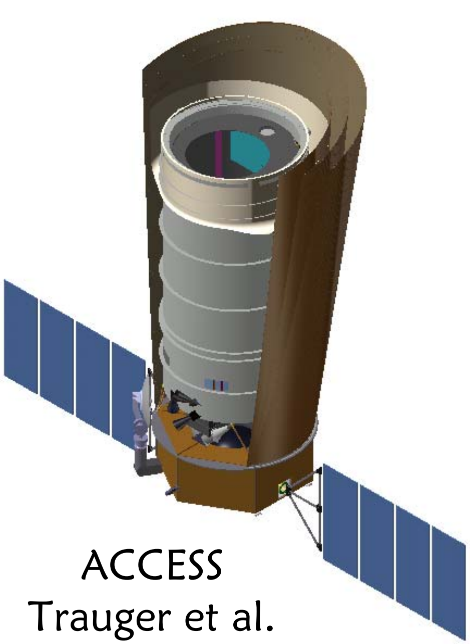


Figure 3. Cumulative fraction of stars with 70 μm excess as a function of disk luminosity for the planet and non-planet samples. As in Figure 1, the dust's fractional luminosity, $L_{dust}/L_\star$, is derived from the strength of the 70 μm emission relative to the stellar photosphere (Equation (2)). For both the planet and non-planet samples, dust disks with $L_{dust}/L_\star > 10^{-4}$ are rare, with $L_{dust}/L_\star \approx 10^{-5}$ disks detected much more frequently. The 1σ uncertainties in the underlying distributions of $L_{dust}/L_\star$ 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 using this system on ~1.5 m telescope studied by several groups
- Multiple coronagraph options
- Direct detection & spectroscopy of giant planets in reflected light
- Would also do debris disk & exozodi imaging down to 10 zodi level in nearby sunlike stars
- Possible NASA exoplanet probe mission TBD years from now. How to do something sooner ?

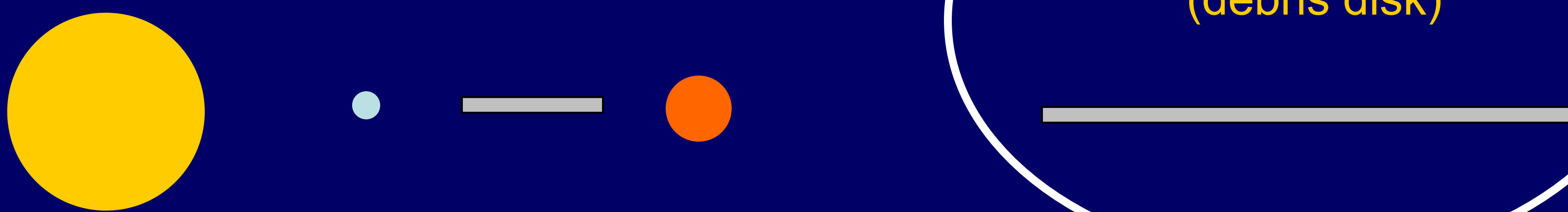




ACCESS
Trauger et al.

Exoplanetary system at 10 pc

Scattered light Contrast to Star	10^{-10}	10^{-8}	10^{-9}	10^{-7} to 10^{-5}	
Star	Terrestrial	Zodi	Jovian	Kuiper Dust (debris disk)	



	1 AU	3 AU	5 AU	40 AU	
Linear Scale					
	0.1″	0.3″	0.5″	4″	
Angular Scale					
Telescope Size to Resolve	8 m	2.5 m	1.5 m	0.2 m	Optical
	24 m	8 m	4.5 m	0.6 m	Near-IR

Zodiac: Coronagraph aboard a Stratospheric Balloon

- Above atmospheric turbulence, should achieve contrast performance better than ground AO and approaching that of a space platform
- Operate at visible wavelengths with 1-m telescope, deploy coronagraph with precision wavefront control
- Small telescope can still be very sensitive to extended surface brightness
- Debris disk targets a good match to the contrast, inner working angle, and observing time available
- Proposal submitted to NASA APRA, PI Wes Traub

Assessing Debris disk targets

- 108 cataloged by Spitzer around stars within 40 pc of the Sun.
- Their integrated scattered light brightness can be directly estimated from the observed infrared luminosity and an assumed albedo (we choose 10%).
- Disk size is unknown, but assume smallest dust particles are a few x the radiation pressure blowout size, and estimate size for thermal equilibrium
- Radial dust distribution is unknown, but rings are suggested by the adequacy of blackbody fits to the far-IR SEDs. Adopt deltaR/R~ 0.2.
- Disk inclination is unknown; pick median value 30° from edge-on
- From above assumptions, compute scattered light brightness and contrast to the star in telescope beamsize

Tabulation of nearby debris disks

NearbyDD2.3a - OpenOffice.org Calc

File Edit View Insert Format Tools Data Window Help

Arial 12

Q36 ACS yes, NIC no

	A	B	C	D	E	F	G	H	I	J	K	L	N
1													
2	Star	HIP	V	SpT	RA	Dec	Dis (pc)	Spitzer Ref	Lir/L*	Dust T	Disk type	Disk radius	Disk rad "
3	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
4	Eps Eri	16537	3.7	K2V	03 32	-09 27	3.2	Backman 2	1.0E-04		MIPS+IRS	and 35-9	28.13
5	Tau Ceti	8102	3.5	G8V	01 44	-15 56	3.6	Stapelfeldt	1.5E-05	590 K	MIPS	> 0.5 AU	0.14
6	Gl 581	74995	10.6	M3V	15 19	-07 43	6.3	Kospal 200	1.2E-05	< 104	70 um only	> 4 AU	0.63
7	Fomalhaut	113368	1.2	A3V	22 57	-29 37	7.7	Stapelfeldt	8.0E-05		MIPS+IRS	14, 120-14	18.18
8	Vega	91262	0.0	A0Vv	18 36	+38 47	7.8	Su 2005	2.0E-05	72 K	MIPS+IRS	800	102.56
9	61 Vir	64924	4.7	G5V	13 18	-18 18	8.5	Trilling 200	2.0E-05	< 97	70 um only	> 20 AU	2.35
10	HD 1581	1599	4.2	F9V	00 20	-64 52	8.6	Trilling 200	1.0E-05	< 218	70 um only	> 4 AU	0.47
11	AU Mic	102409	8.9	M1	20 45	-31 20	9.9	Rebull 200	2.0E-04	50 K	70+160	**145 AU**	14.65
12	EP Eri	13402	6.0	K1V	02 52	-12 46	10.4	Trilling 200	3.0E-05	< 103	70 um only	> 12 AU	1.15
13	Beta Leo	57632	2.1	A3Vv	11 49	+14 34	11.1	Su 2006	2.0E-05	123 K	MIPS+IRS	30 AU	2.70
14	HD 76151	43726	6.0	G2V	08 54	-05 26	11.3	Trilling 200	1.2E-05	< 120	IRS + 70 u	> 14 AU	1.24
15	HD 33262	23693	4.7	F7V	05 05	-57 28	11.7	Trilling 200	5.0E-06	< 158	70 um only	> 9 AU	0.77
16	HD 20807	15371	5.2	G1V	03 18	-62 30	12.1	Trilling 200	1.0E-05	< 150	70 um only	> 8 AU	0.66
17	HD 69830	40693	6.0	K0V	08 18	-12 37	12.6	Trilling 200	1.0E-04	400 K	24+IRS	.0 AU (est	0.08
18	HD 30495	22263	5.5	G3V	04 47	-16 56	13.3	Trilling 200	2.5E-05	< 88	70 um only	> 30 AU	2.26
19	10 Tau	16852	4.3	F9V	03 36	+00 24	13.7	Trilling 200	1.0E-05	< 144	70 um only	> 11 AU	0.80
20	HD 166	544	6.1	K0V	00 06	+29 01	13.7	Trilling 200	5.9E-05	87 K	MIPS	20 AU	1.46
21	HD 72905	42438	5.6	G1.5V	08 39	+65 01	13.9	Trilling 200	3.0E-05	< 123	IRS + 70 u	> 14 AU	1.01
22	GJ 42	4148	7.2	K3V	00 53	-30 21	14.1	Koerner 20	4.0E-05	< 85	70 um only	> 18 AU	1.28
23	GJ 14	1368	8.9	K7V	00 17	+40 56	15.0	Koerner 20	1.1E-04	< 83	70 um only	> 12 AU	0.80

Sheet1 Sheet3

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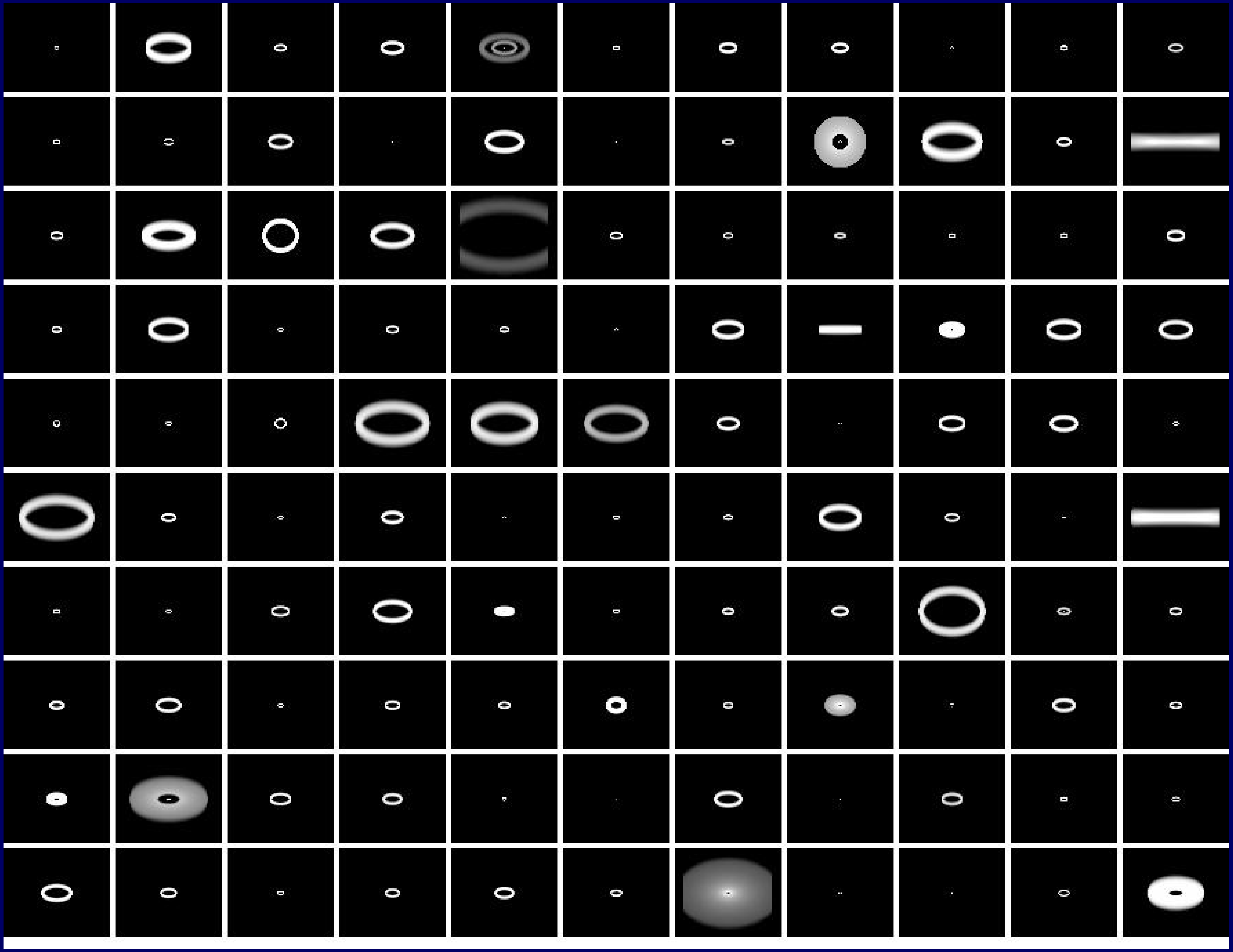
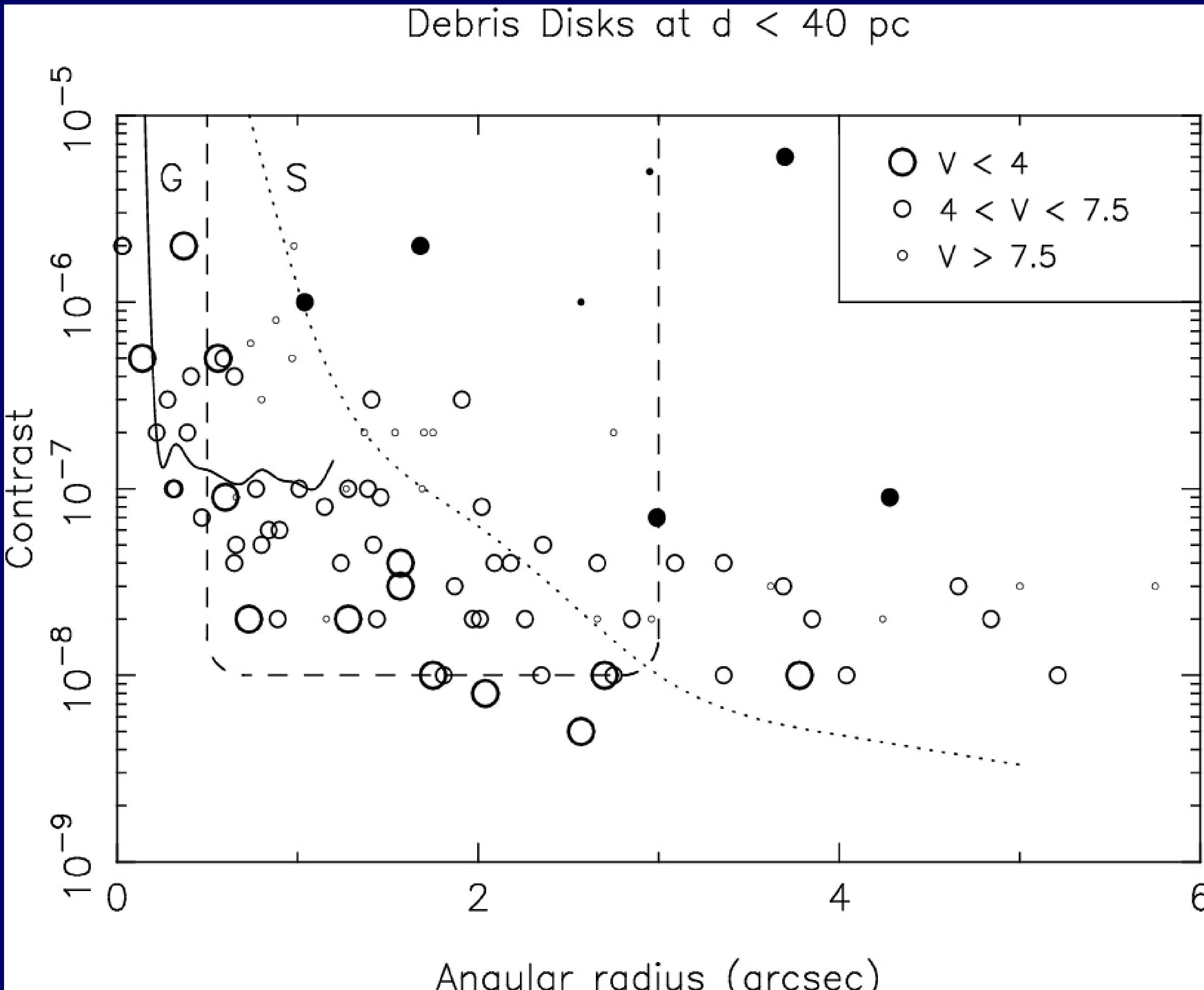


Target properties vs. Zodiac predicted performance



Dashed line: Zodiac coronagraph sensitivity

Solid line: Gemini/GPI sensitivity

Dotted line: HST/ACS Former sensitivity

Summary Points

- Debris disks are an important element of exoplanet science
- Unique high-contrast observations of DD are possible from a balloon platform, in the near-term, at modest cost.
- Realization of this opportunity depends on increased awareness in the advisory panels, NASA HQ, and the NASA scientific balloon program