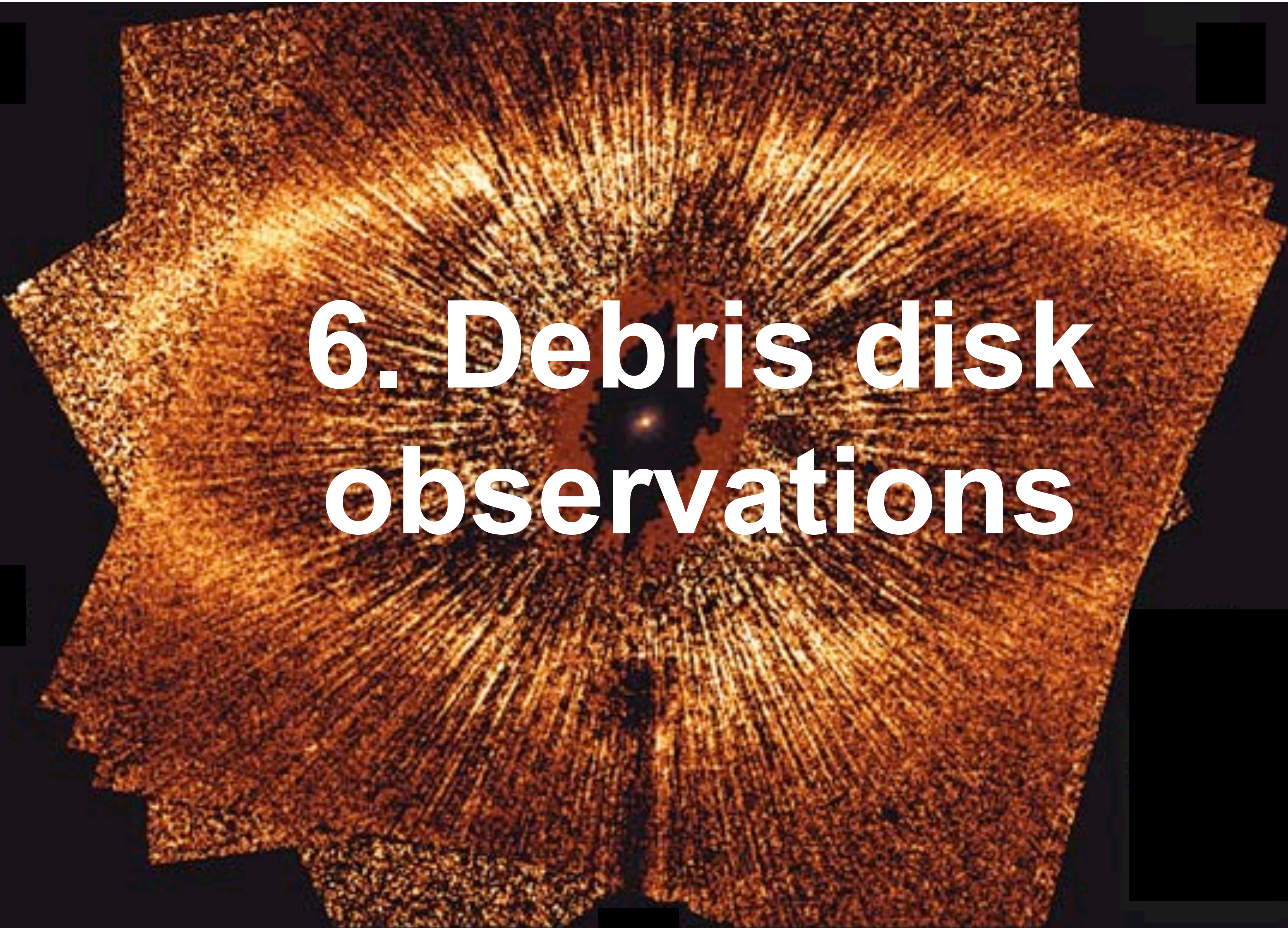
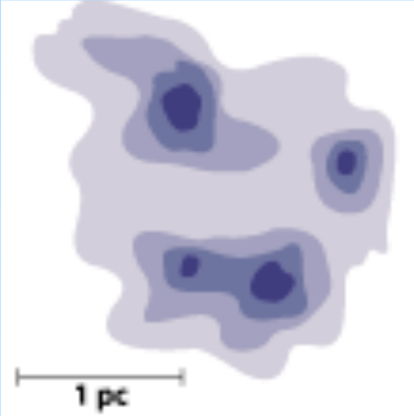
6. Debris disk observations

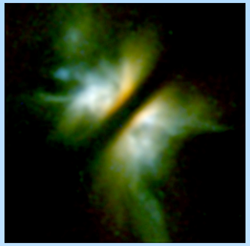


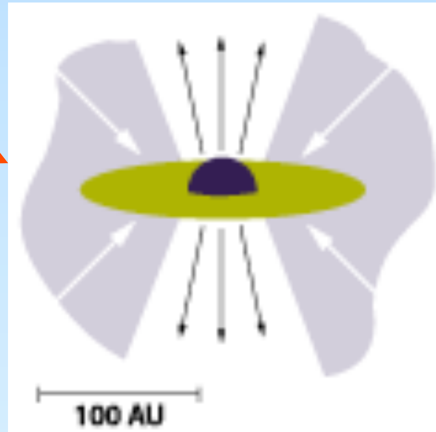
Overview of star and planet formation



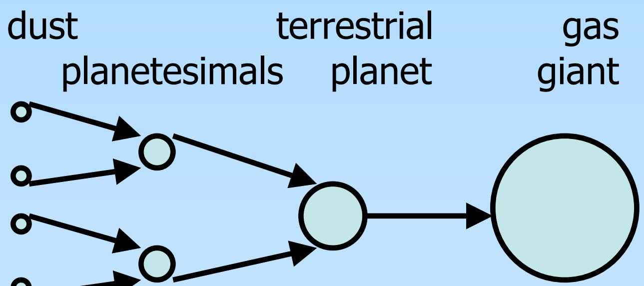
molecular cloud
0Myr

star formation



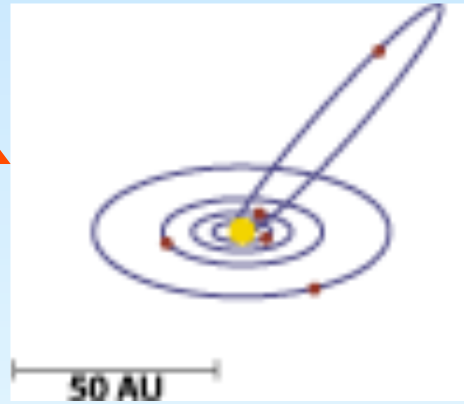


pre-main sequence star
+ protoplanetary disk
1-10Myr



?

planet formation

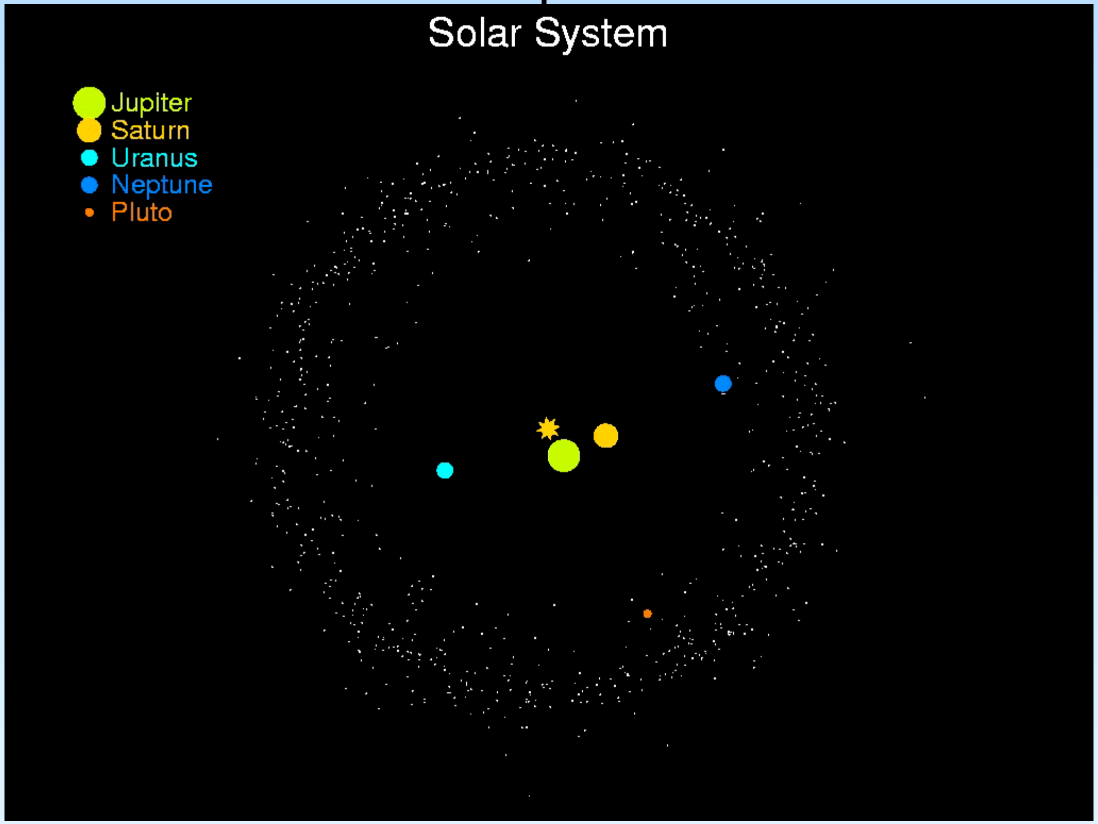


main sequence star
+ planetary system
and/or debris disk
10Myr-10Gyr

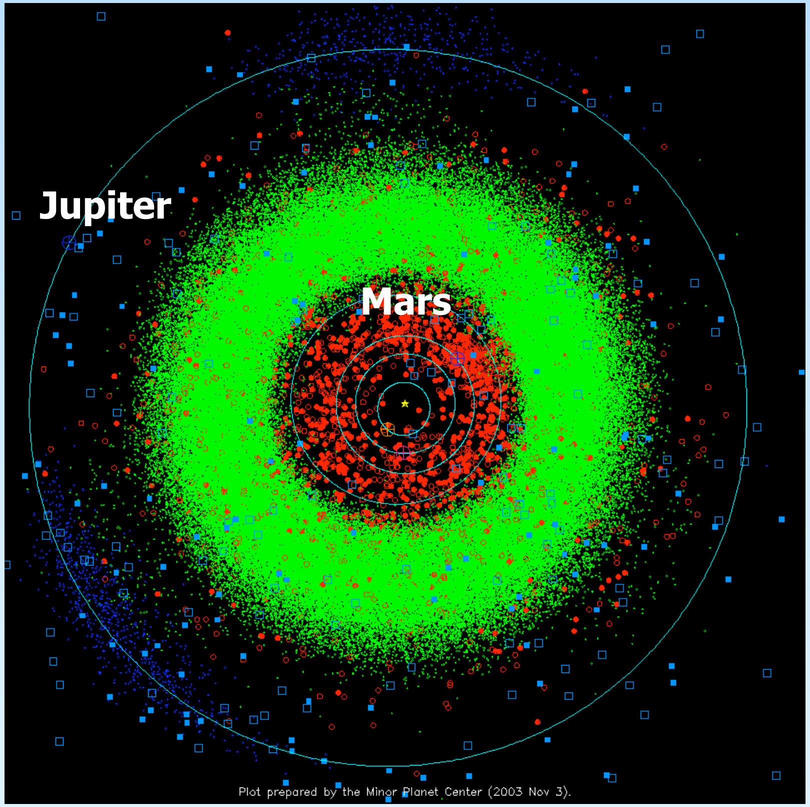
The debris disk of the Solar System

The debris disk of the Solar System is comprised of:

The Kuiper belt



The Asteroid belt

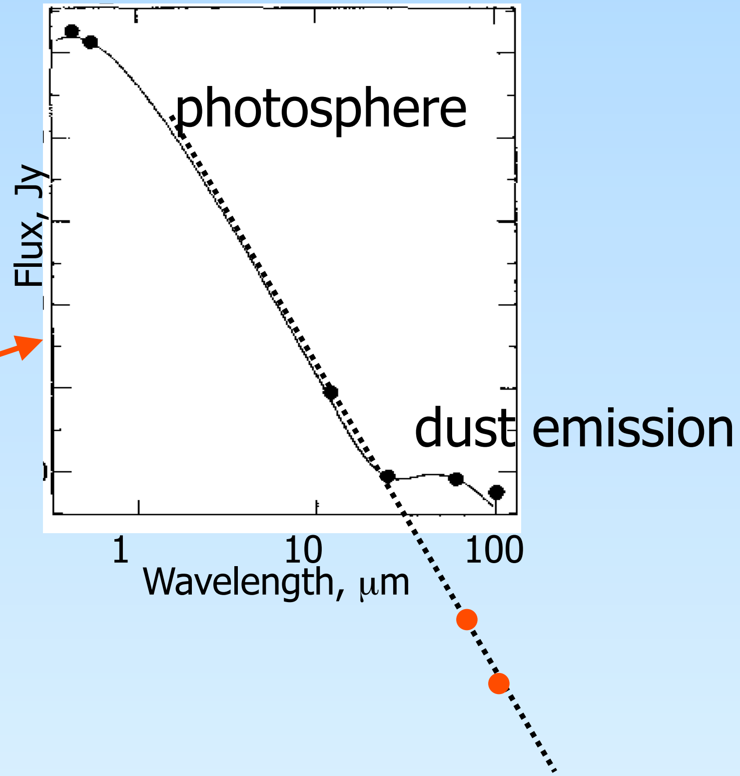


Debris disks are the remnants of the planet formation process, planetesimals which failed to grow into planets.

Discovery of extrasolar debris disks

• IR satellite IRAS detected "**excess**" infrared emission from the nearby 7.8pc main sequence A0V star Vega during routine calibration observations (Aumann et al. 1984)

Excess = more emission than expected from the star alone
SED = Spectral Energy Distribution



• Excess spectrum fitted by black body at ~85K, interpreted as dust emission in shell with luminosity $f=L_{ir}/L_{*}=2.5\times10^{-5}$

• Emission marginally resolved at 60μm: FWHM=34″ whereas point source would be 25″ implying source size of 23″ = 180AU at 7.8pc

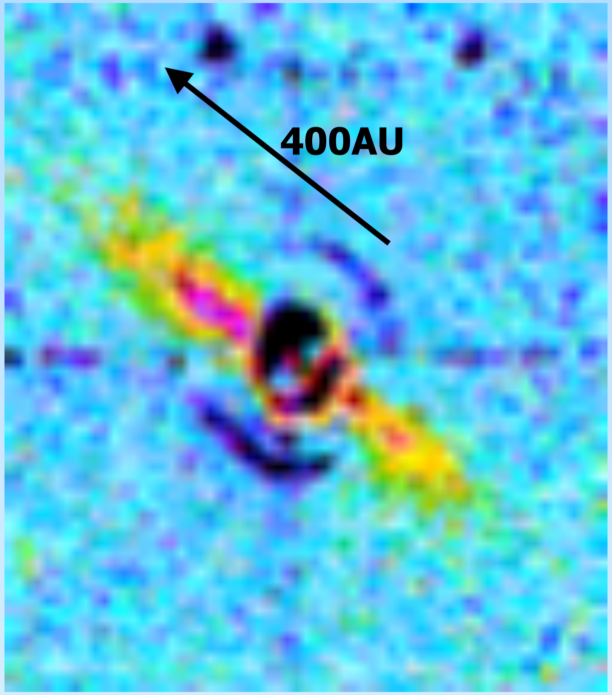
• This fits with dust heated by star, since $T_{bb} = 278.3\ L_{*}^{0.25}\ r^{-0.5}$ and so 85K and $L_{*}=54L_{sun}$ imply radius of ~10″ and source size of 20″

The “big four”

Main sequence stars with excess infrared emission are called “**Vega-like**”

Vega soon joined by 3 more nearby main sequence stars (Gillett 1985):

β Pictoris (A5V at 19.2pc)
Fomalhaut (A3V at 7.8pc)
ε Eridani (K2V at 3.2pc)

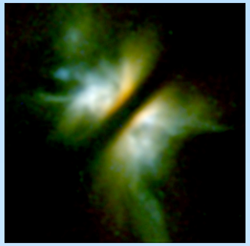


Next big step was when β Pic was imaged using optical coronagraphy showing the dust is in a disk seen edge-on out to 400AU (20”) (Smith & Terrile 1984)

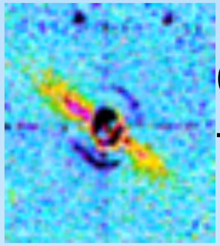
Proto-planetary vs debris disks

Proto-planetary disk <10Myr

Optically thick

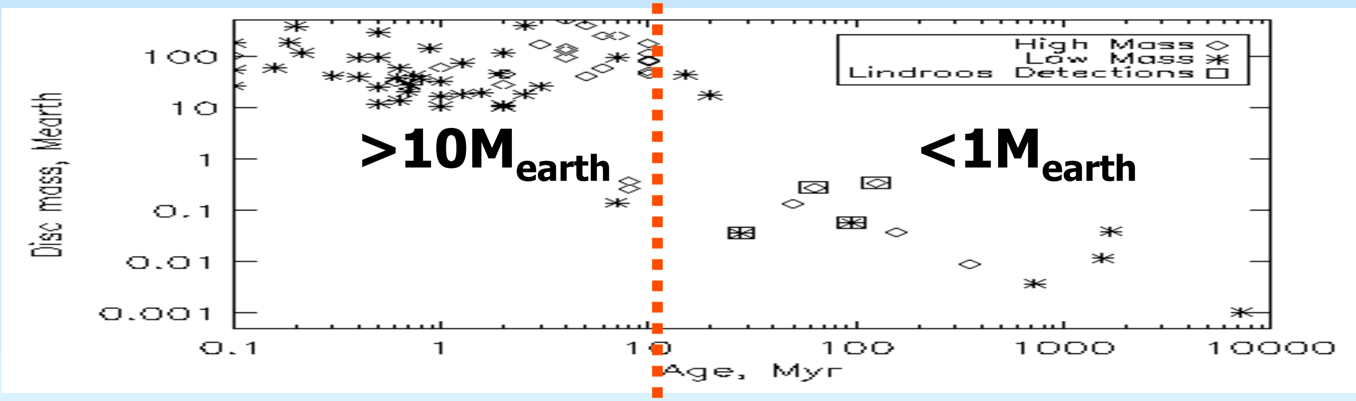


Debris disk >10Myr



Optically thin

Proto-planetary and debris disks are significantly different



Dust from 0.1-100AU	Dust at one radius ~30AU
Massive gas disk	No gas
Accretion onto star	No accretion

Debris disk dust not primordial

Debris disks cannot be remnants of the proto-planetary disks of pre-main sequence stars because (Backman & Paresce 1993):

(1) The stars are old, e.g., Vega is **350Myr**

(2) The dust is small (<100μm) (Harper et al. 1984; Parsesce & Burrows 1987; Knacke et al. 1993)

(3) Small grains have short lifetimes due to P-R drag

$t_{pr} = 400\ r^2 / (M_* \beta)$ years,

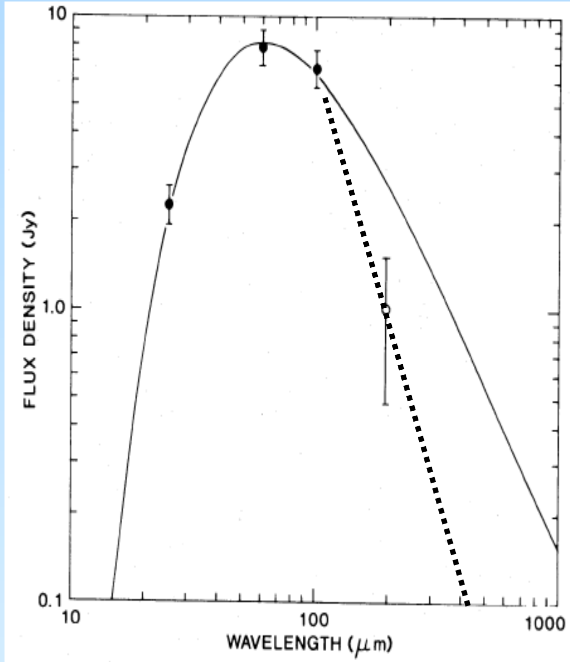
where $\beta \approx (1100/\rho D)(L_*/M_*)$

e.g., for Vega ($54L_{sun}$, $2.5M_{sun}$, r=90AU, D=100μm, ρ=2700kg/m^3): **t_{pr}=15Myr**

(4) They also have short lifetimes due to collisions

$t_{coll} = r^{1.5} / 12\ M_{star}^{0.5}\ \tau$ years

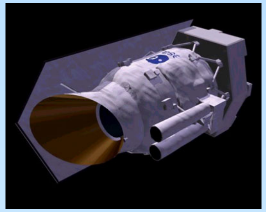
e.g., for Vega ($\tau \approx f = 2.5\times10^{-5}$): **$t_{coll}$=2Myr**



Dust is replenished by the break-up of larger debris with longer P-R drag and collision lifetimes

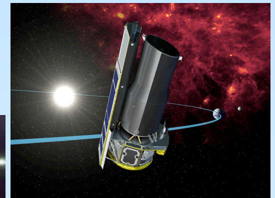
Discovering debris disks

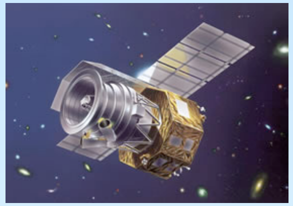
- Dust is cold, typically 50-120K, meaning it peaks at ~60μm
- Star is hot meaning emission falls off $\propto \lambda^{-2}$
- So most debris disks are discovered in far-IR

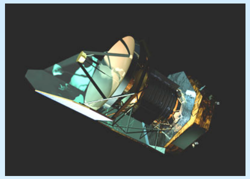


<u>Far-IR (space)</u>

- **IRAS (1983)** did all-sky survey at 12,25,60,100μm
- **ISO (1996)** did observations at 25,60,170μm of nearby stars
- **Spitzer (2003-)** was observing nearby stars at 24,70,160μm
- **Akari (2006-)** currently doing all-sky survey 2-180μm
- **Herschel (2009-)** observations at 60-670μm
- **Spica (2017+)** planned 5-200μm

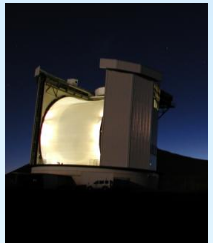






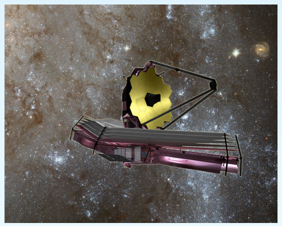
<u>Sub-mm (ground)</u>

- **JCMT, SCUBA2 (2009+)** survey of 500 nearest stars at 850μm
- **ALMA (2010+)** high resolution sub-mm



<u>Mid-IR (space)</u>

- **JWST (2013+),**



DARWIN/TPF (2020+)

Surveys for debris disks

Survey strategy:

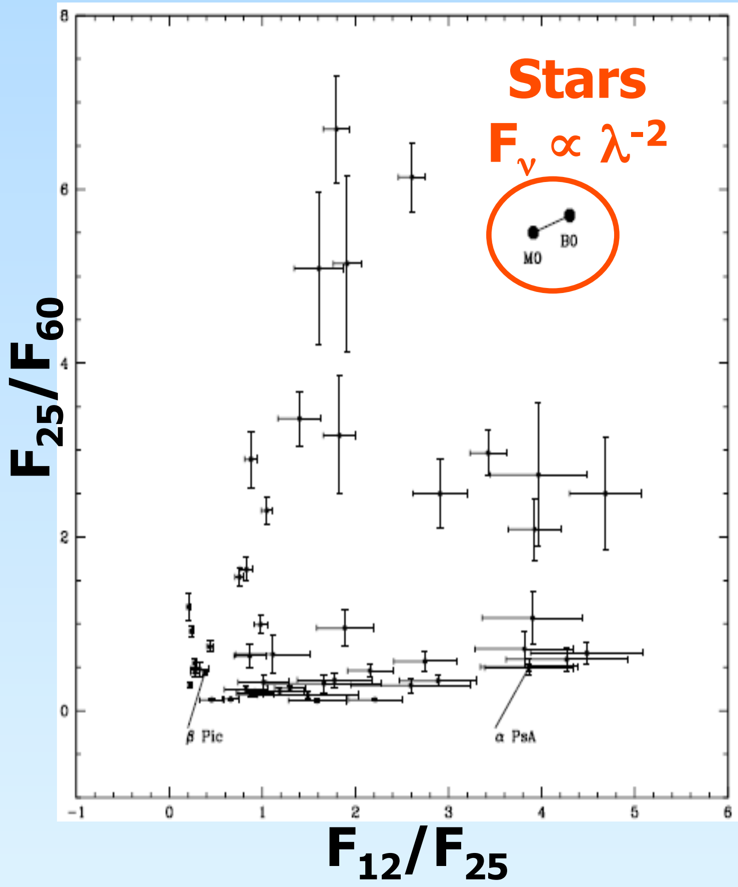
(1) take list of main sequence stars and their positions (e.g., HD catalogue)

(2) look for nearby infrared source (e.g., <60″) and get IR flux (e.g., IRAS FSC)

(3) estimate stellar contribution in far-IR (from IRAS F_{12}, or V or B, or 2MASS)

(4) find stars with significant excess

$$\sigma = \frac{[(F_{25}/F_{12})(F_{12*}/F_{25*}) - 1]}{[(\delta F_{12}/F_{12})^2 + (\delta F_{25}/F_{25})^2]^{0.5}} > 3$$



Many papers did this in different ways and there are >901 candidates

What do all these disks tell us?

There are two things observations tell us:

(1) Statistics

How do **debris parameters** correlate with **stellar parameters**?

debris parameters	stellar parameters
disk / diskless	spectral type (M_* or L_*),
dust mass (M_{dust})	age (t_*),
or dust luminosity ($f=L_{ir}/L_*$)	metallicity (Z),
dust temperature (T)	presence of planets
or radius (r)	

(2) Detail of individual objects

Images = structure

Spectroscopy = mineralogical features, gas

Dependence on age and spectral type

IRAS:

• 15% of stars have debris (Plets & Vynckier 1999)

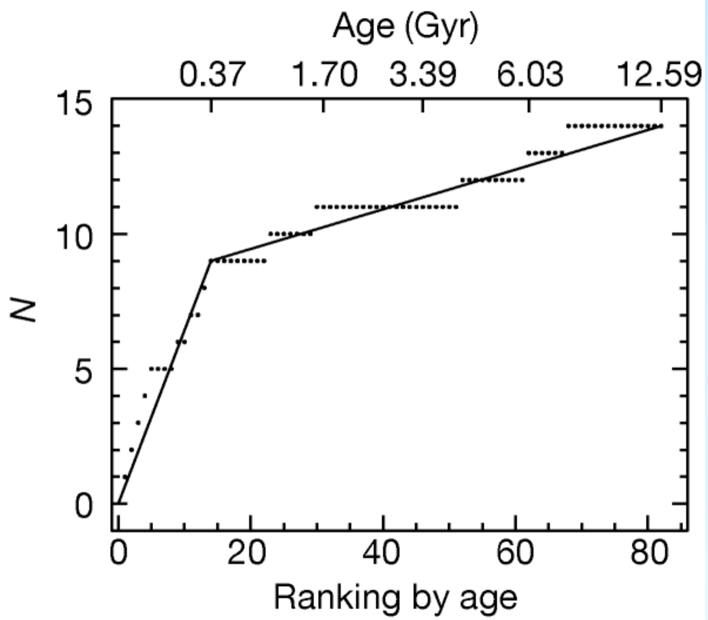
ISO:

• Study of 81 main sequence stars within 25pc gave 17% with debris (Habing et al. 2001):

• Dependence on spectral type: A (40%), F (9%), G (19%), K (8%)

• Dependence on age with disk detection rate going up for younger stars, possibly abrupt decline >400Myr (Habing et al. 1999)

	< 400 Myr		400–1000 Myr		1.0–5.0 Gyr		> 5.00 Gyr	
	tot	disk	tot	disk	tot	disk	tot	disk
A**	10	6	4	0	1	0	0	0
F**	0	0	1	0	17	2	5	0
G**	2	1	0	0	7	0	12	3
K**	3	2	2	0	5	0	12	0
total	15	9	7	0	30	2	29	3



Debris disks are more common around early type stars and around young stars

Problem of detection bias

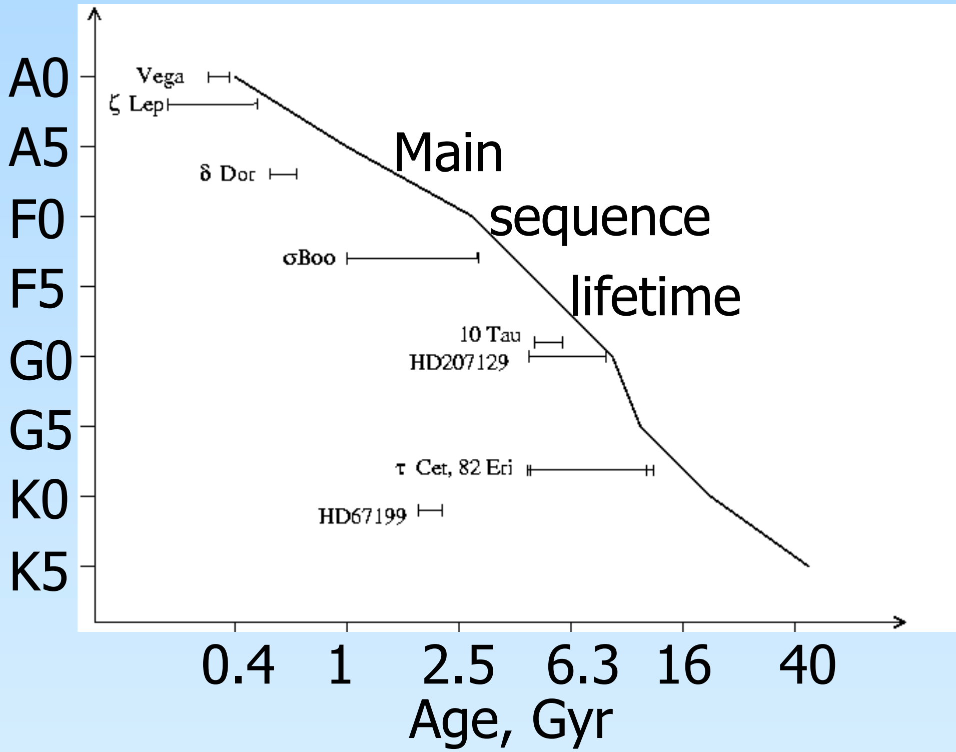
Greaves & Wyatt (2003)

Earlier-type stars have shorter main sequence lives

Disks are found at all ages on the main sequence

No abrupt decline at 400Myr

Solution 1: split samples by spectral type (A stars, FGK stars, M stars)

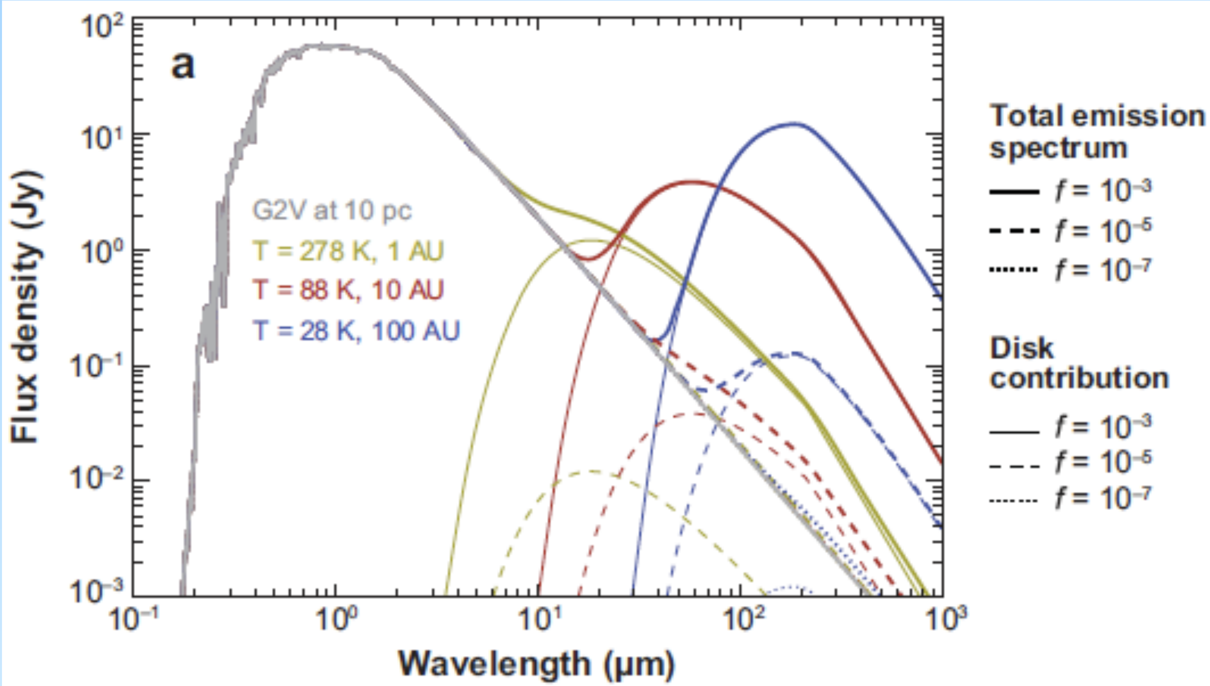


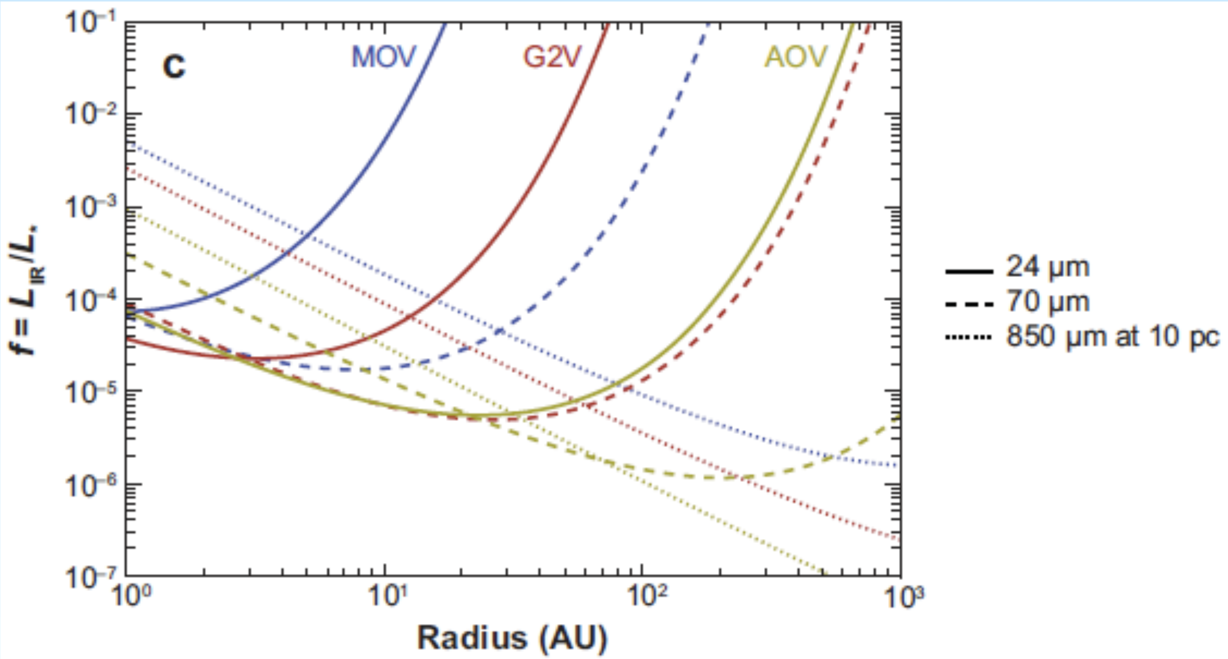
Early-type stars are also more luminous, and it is easier to detect dust around them (remember $T_{bb} = 278.3\ L_*^{0.25}\ r^{-0.5}$); i.e., surveys are sensitive to different disk masses depending on r and L_* as well as λ and threshold sensitivity

Solution 2: survey statistics need well defined thresholds and always need to consider bias

Detection threshold

To first order debris disks have two parameters: $f=L_{ir}/L_{*}$ and T, and their emission spectrum looks like on right

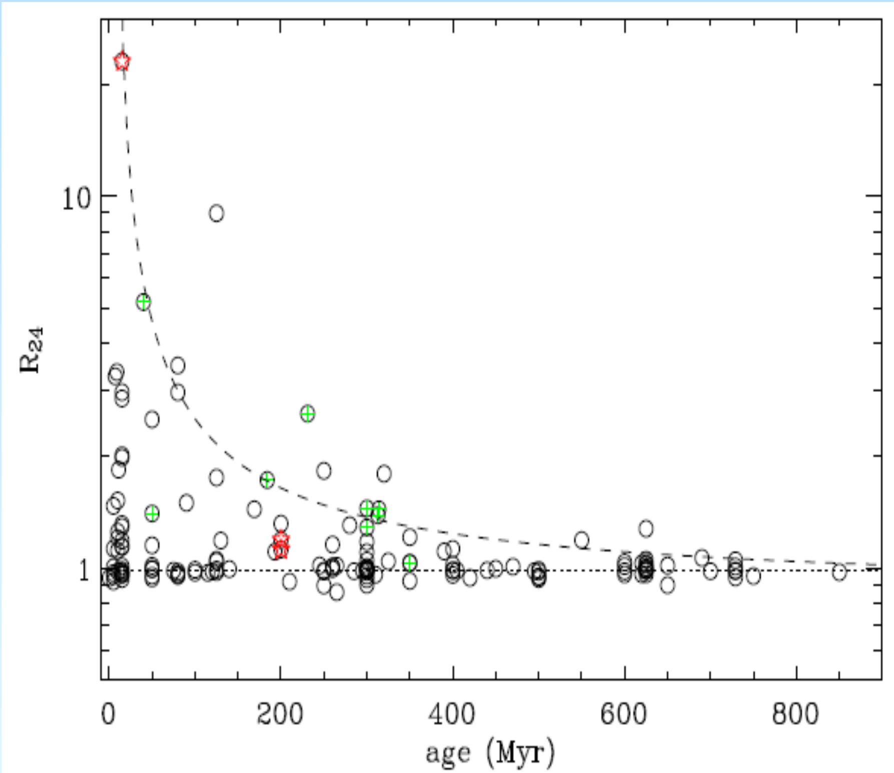


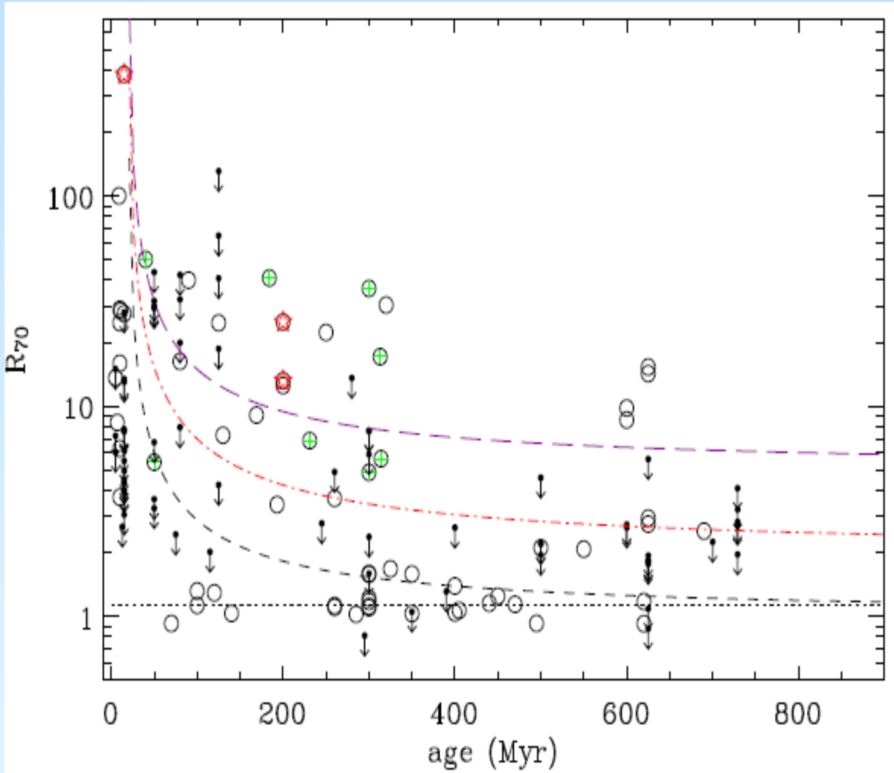


Spitzer calibration limited surveys detected excesses of >0.1 and >0.55 times the stellar flux at 24 and 70μm meaning that f vs T space probed looked like left: M star disks are hard to detect!

Dust excess evolution: down with age

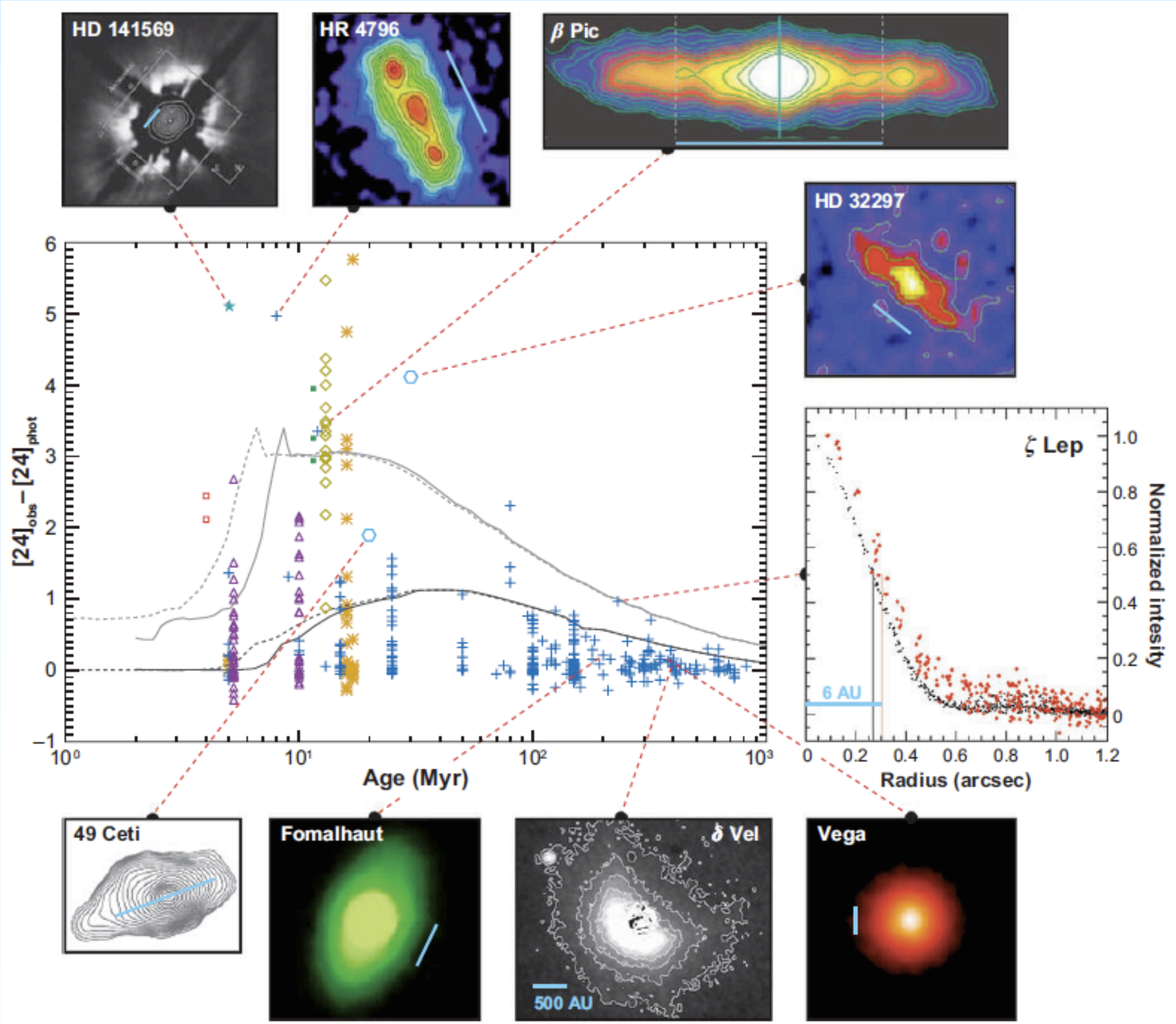
Large Spitzer studies of the 24 and 70μm excesses (F_{tot}/F_*) of A stars found a $\propto t^{-1}$ decline in the upper envelope on timescale of 150Myr at 24μm (Rieke et al. 2005) but longer at 70μm (Su et al. 2007)





Presence of excess depends on wavelength! Or rather on disk radius

Peak at 10-15Myr?



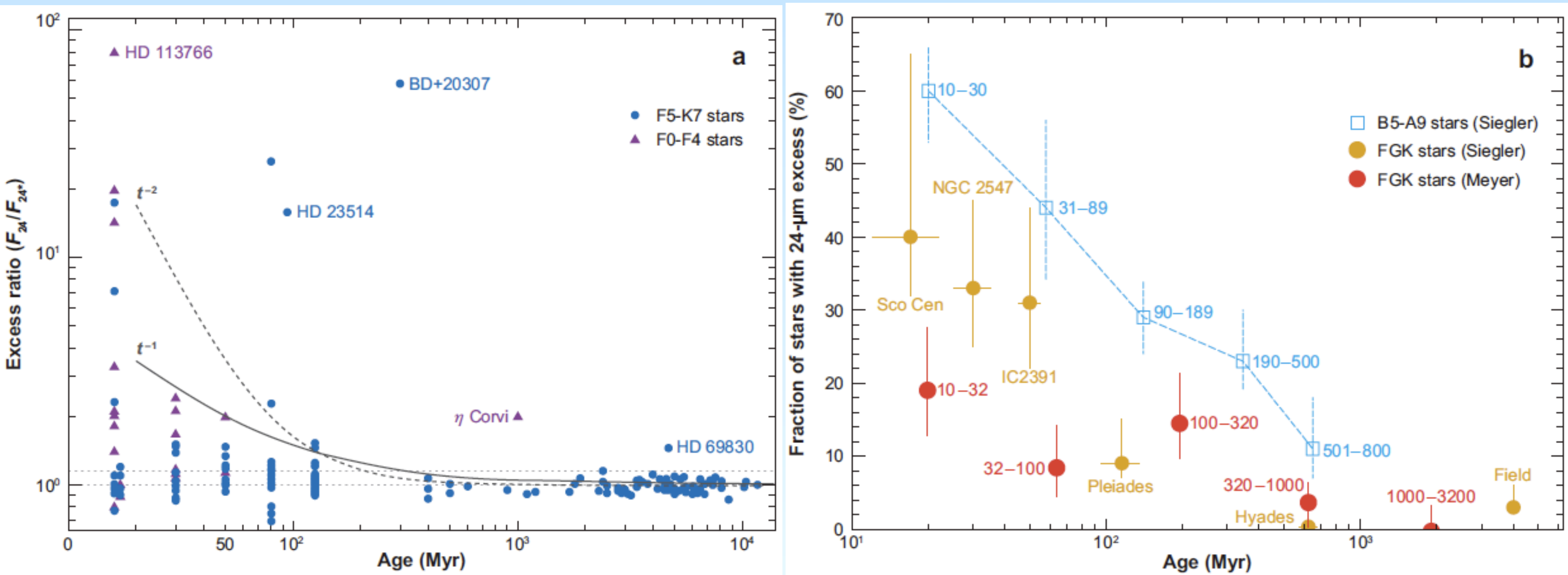
Surveys of young clusters at 24μm suggest that excesses for A stars increase with time to peak at 10-15Myr (Hernandez et al. 2007; Currie et al. 2007)

The statistics are poor, but it is clear that this transition period is key to understanding how debris disks are born; no peak seen for Sun-like stars

Sun-like stars at 24μm

Excesses for sun-like stars at 24μm fall-off much faster than for A stars, having disappeared by a few 100Myr for all but a few exceptionally bright sources around 2-4% of stars (Siegler et al. 2006; Wyatt 2008; Zuckerman et al. 2008)

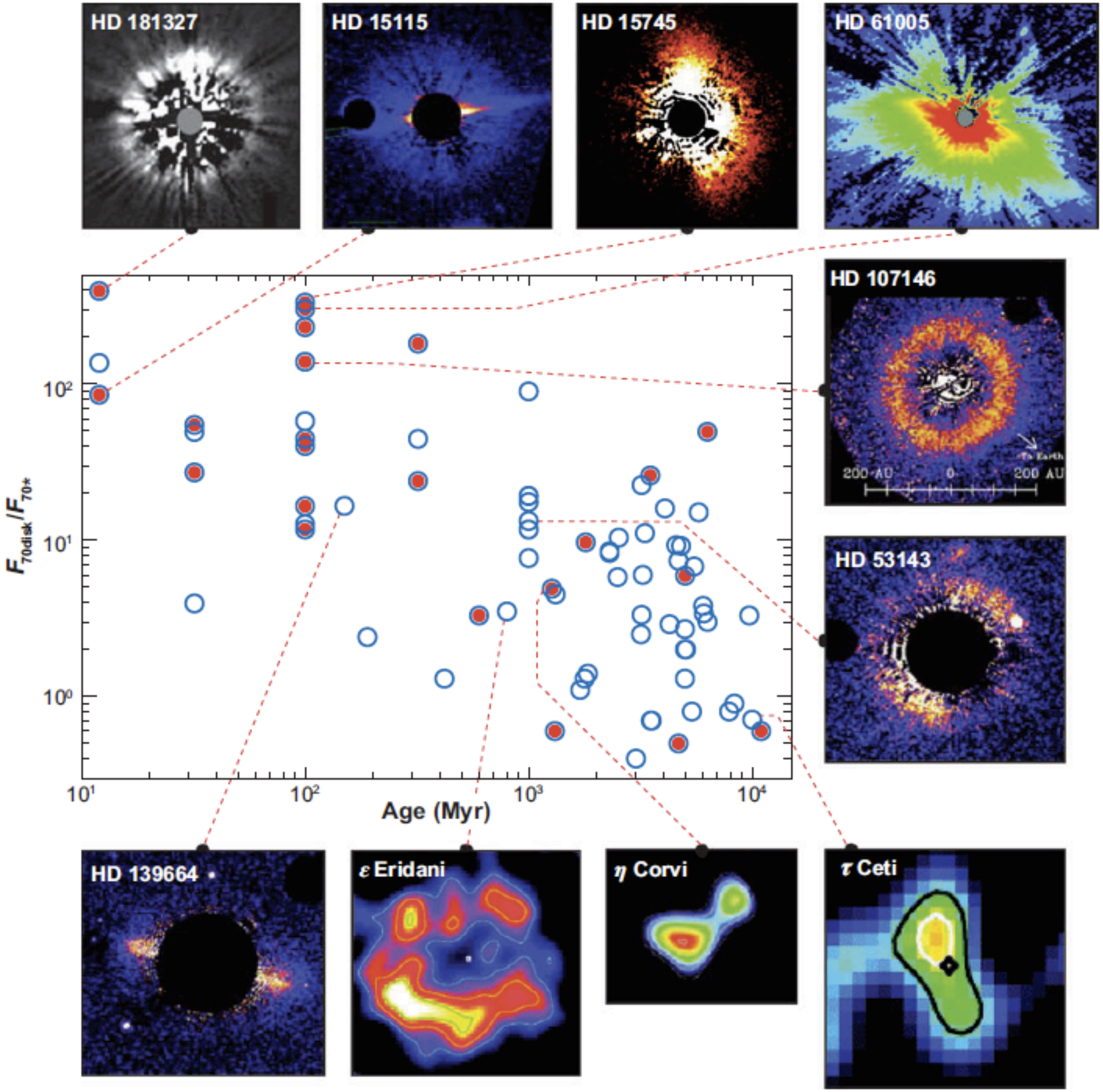
It is not clear if the 24μm excesses are from planetesimal belts or ongoing terrestrial planet formation, or the origin of the exceptionally bright sources



Sun-like stars at 70μm

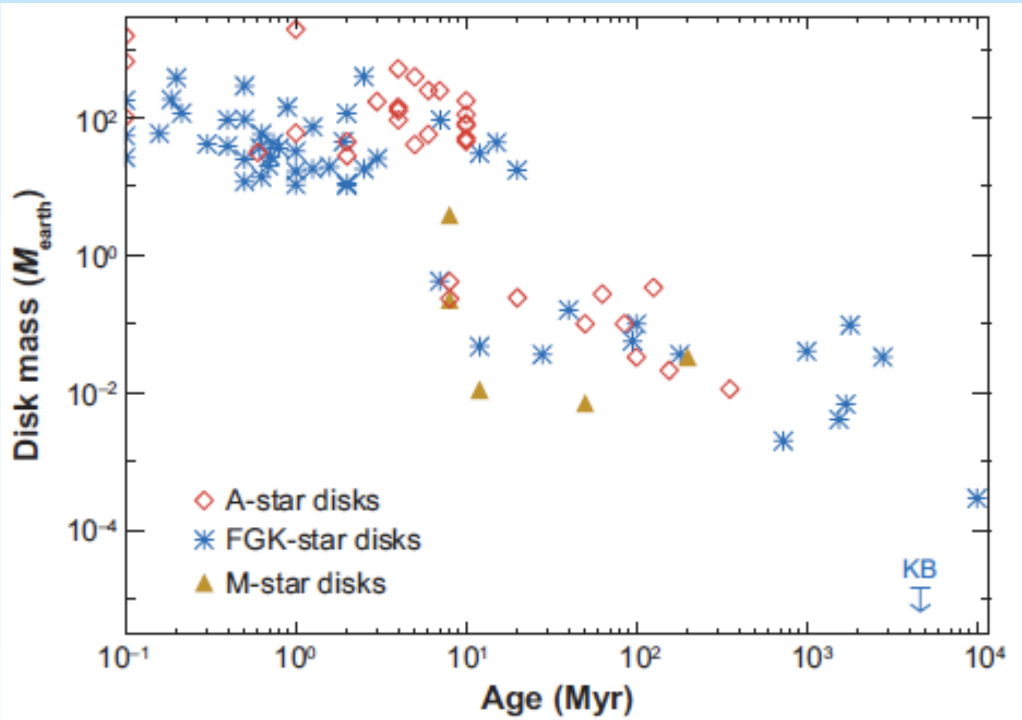
Surveys Sun-like stars at 70μm find a slow decline in excess with age (Beichman et al. 2006; Bryden et al. 2006; Trilling et al. 2008; Hillenbrand et al. 2008)

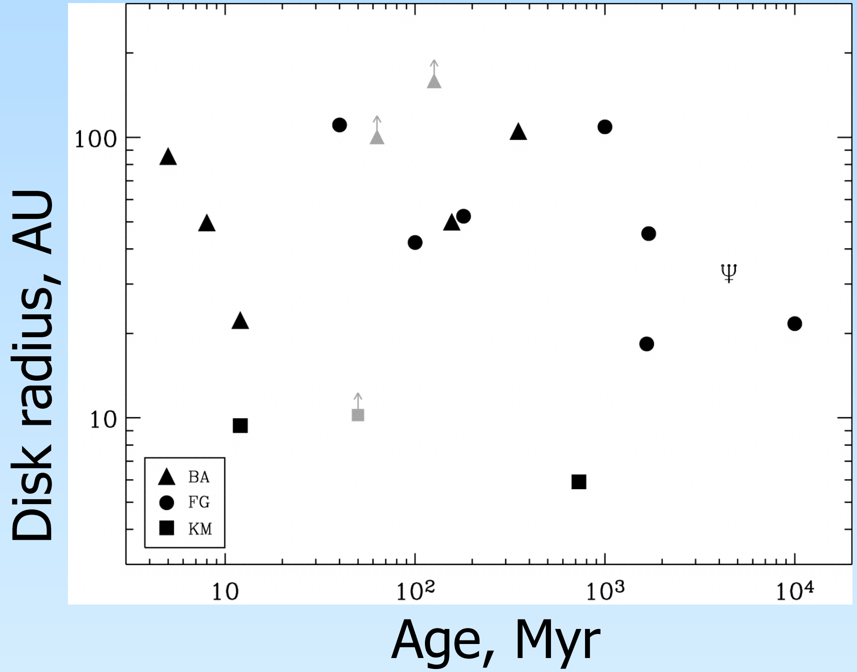
Fall-off in lower envelope is due to fewer young nearby stars meaning that such observations are sensitivity limited



Disk mass and radius evolution

Sub-mm fluxes provide the best measure of disk mass, and show that mass falls off $\propto t^{-1}$ with a large spread of 2 orders of magnitude at any age
(Najita & Williams 2005; Wyatt 2008)





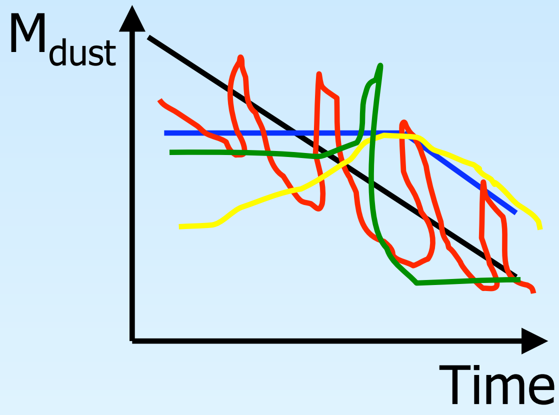
Combined with far-IR fluxes, sub-mm measurements constrain temperature and so radius, showing that there is a large spread in disk radii 5-200 AU at all ages (Najita & Williams 2005)

What is the evolution of individual disks?

We do not know the evolution of individual disks

The bulk observable properties which may evolve with time are: M_{dust} and r
- the population samples suggest that r is constant
- the mass certainly falls, but how?

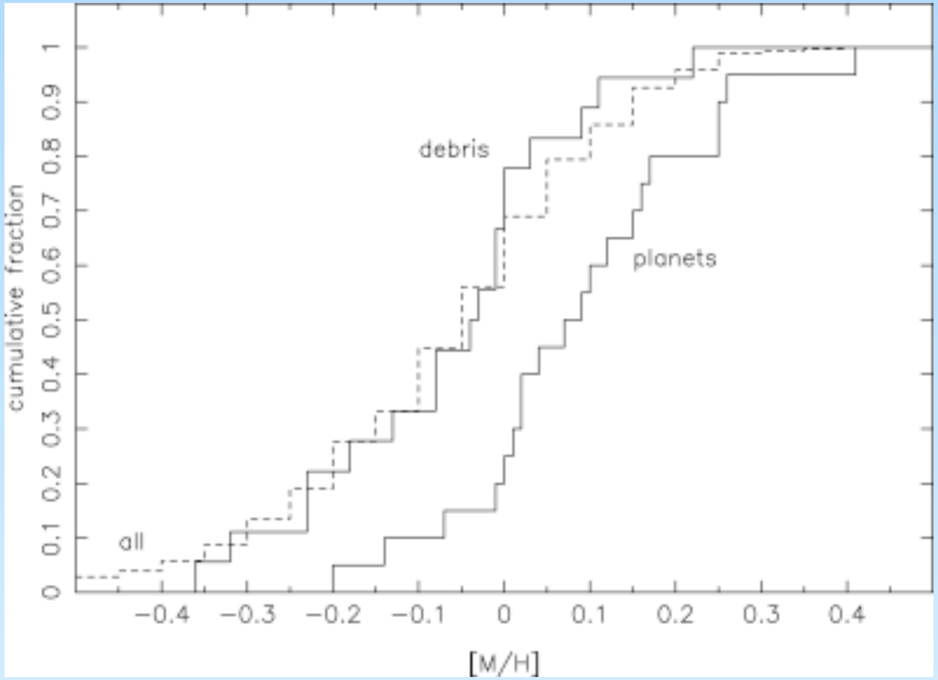
Models proposed in the literature include:
- steady-state collisional processing,
- stochastic evolution,
- delayed stirring ,
- Late Heavy Bombardment



Dependence on metallicity and planets

Of 310 FGK stars <25pc all searched for planets and debris disks (Greaves, Fischer & Wyatt 2006):

- 20 have planets
- 18 have debris detected with IRAS
- 1 has both
- stars with planets are metal-rich (Fischer & Valenti 2005)
- stars with debris disks have same metallicity distribution as all stars



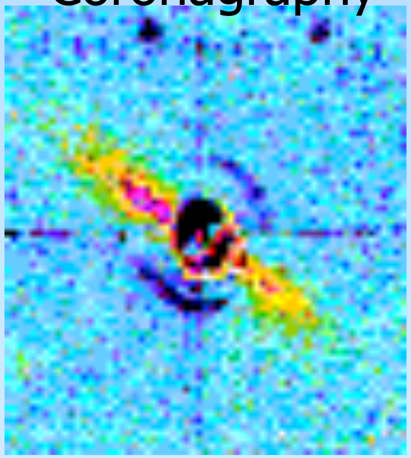
First thought planets and debris could be mutually exclusive (Greaves et al. 2004)

More recent studies with Spitzer show (Beichman et al. 2005):

- 6/26 planet host stars have debris
- Of 84 stars, 4/5 high excess stars have planets
- Planets of debris-planet systems are representative of extrasolar planet sample, though none at <0.25AU

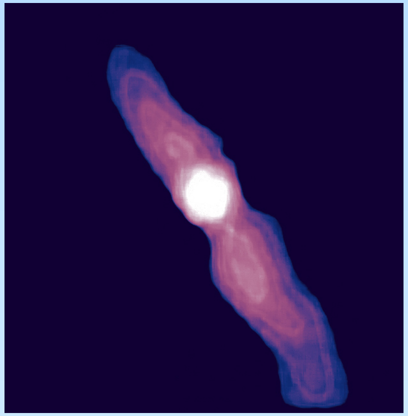
How to Image Debris Disks?

Scattered Light
Optical/Near-IR
Coronagraphy

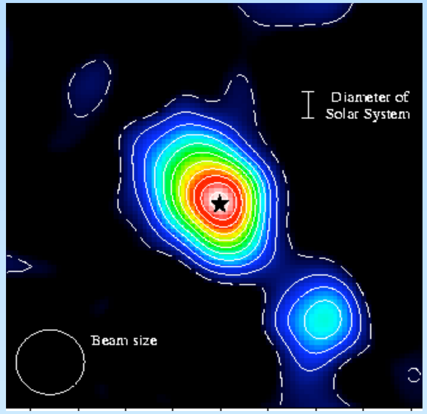


Thermal Emission

Mid-IR



Sub-mm



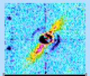
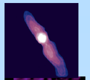
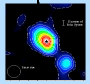
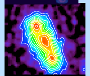
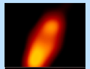
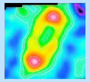
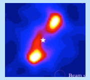
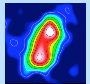
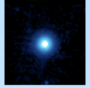
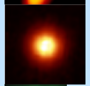
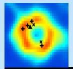
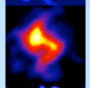
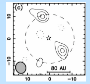
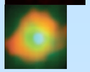
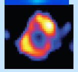
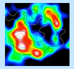
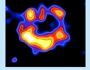
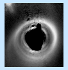
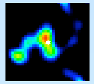
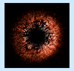
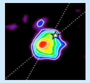
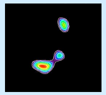
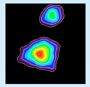
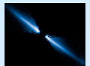
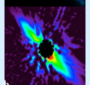
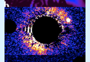
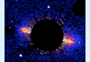
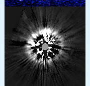
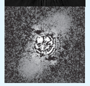
Each technique has its benefits and drawbacks:
e.g., shorter wavelength = higher resolution, but more flux from star

NB in diffraction limit FWHM ≈ λ/D so that disks of radius r (AU) can be resolved on a telescope D (m) in diameter at wavelength λ (μm) out to

$d_{lim} = 10rD/\lambda$ pc

e.g., 100AU disks can be resolved to 18pc with JCMT
50AU disks to 270pc with Gemini/VLT (more like 100pc with stellar flux)

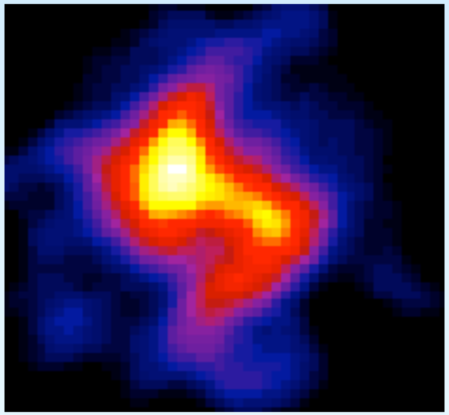
Debris Disk Image Gallery

Year	Star	Optical/NIR <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	η Corvi							
2005	AU Mic							
2005	HD32297							
2006	HD53143							
2006	HD139664							
2006	HD181396							
2006+	HD92945							

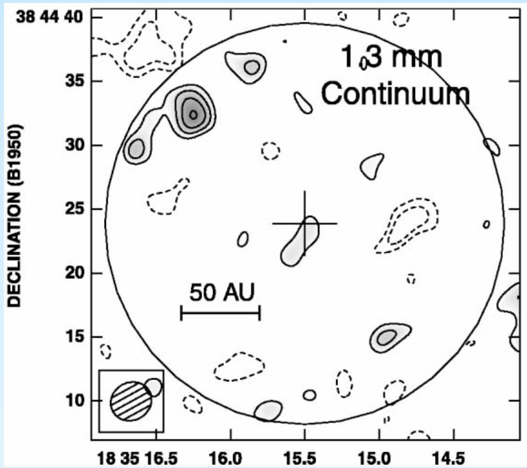
Images of the archetype Vega

Vega is a **350 Myr**-old **A0V** star at **7.8 pc**, and while disk marginally resolved by IRAS, was not until sub-mm images of 1998 that structure seen

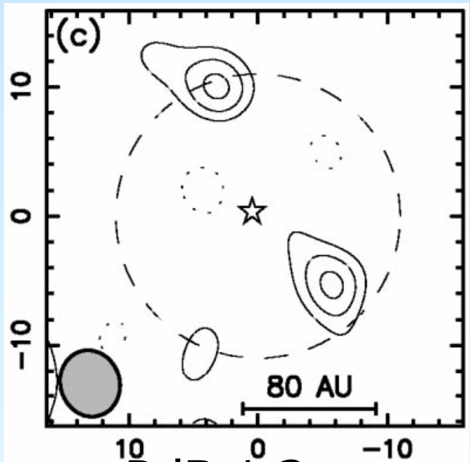
850 μm image shows symmetrical **face-on** structure at ~**90 AU** with a mass of **0.01** $\mathbf{M_{earth}}$ (Holland et al. 1998); dust emission dominated by **two clumps** at ~9 arcsec (70 AU)



Mm interferometry is sensitive to **small scale** structure, so different resolutions see slightly different structures, but clumps are confirmed



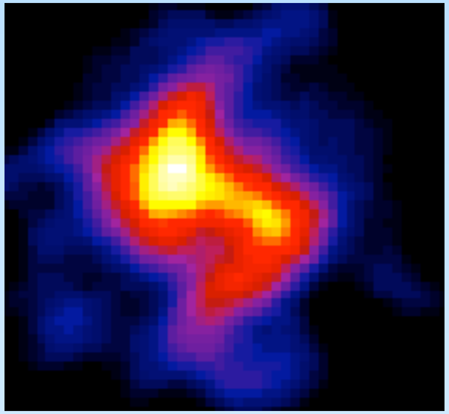
OVRO 1.3 mm
15 nights
(Koerner et al. 2001)



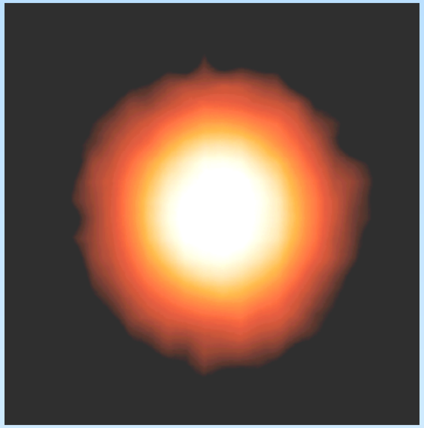
PdB 1.3 mm
23 hours
(Wilner et al. 2001)

Structure is wavelength dependent!

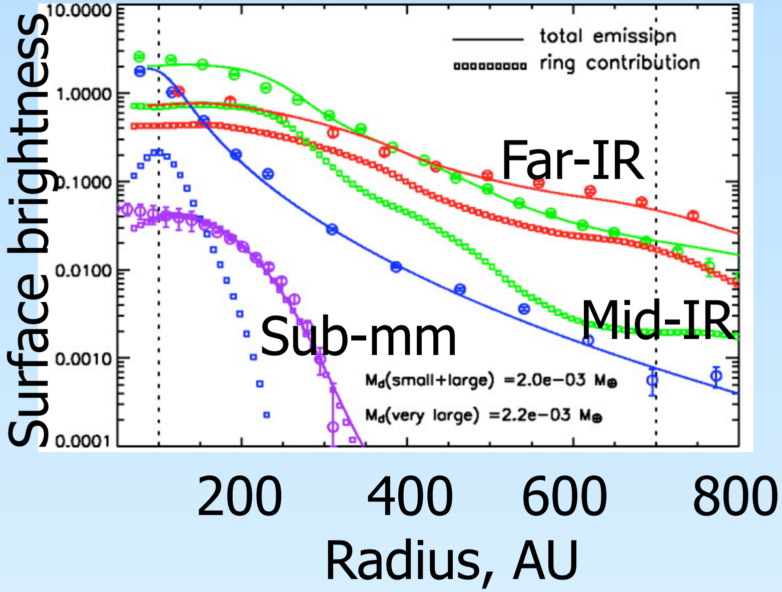
850μm
(Holland et al. 2006)



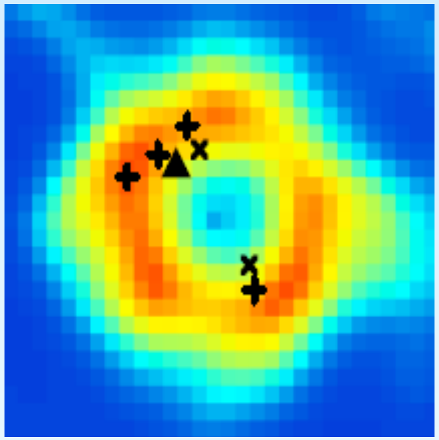
24 and 70μm
(Su et al. 2005)



Surface brightness distribution (Su et al. 2005)



350μm (Marsh et al. 2006)

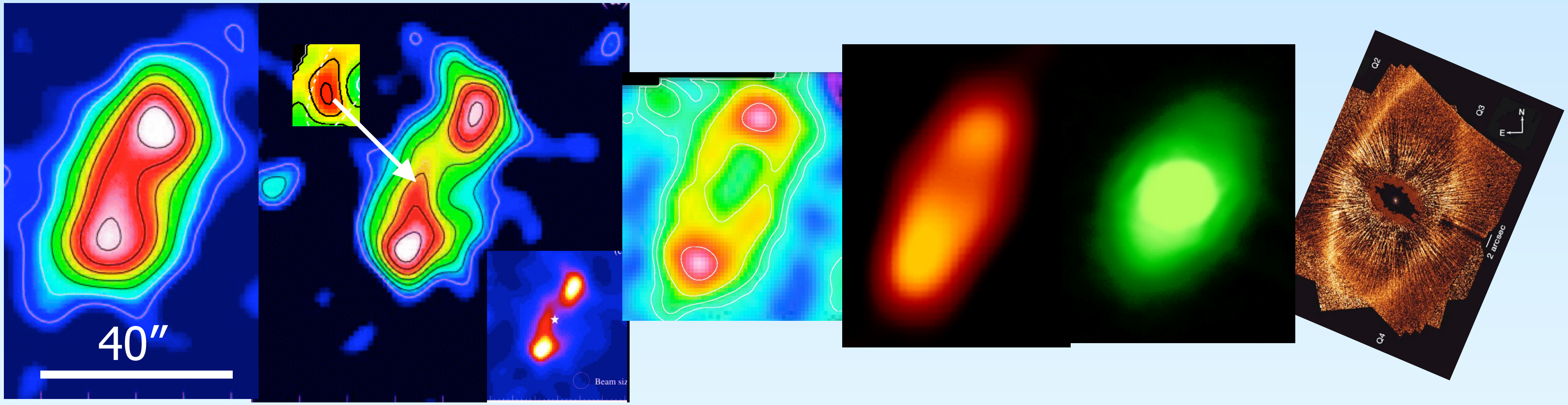


- At 850μm the disk extends to 200AU
- At 24 and 70μm the disk extends to 1000AU
- Dust seen in far-IR implies mass loss of ~2$M_\oplus$/Myr and must be transient
- Clumpiness at 350μm is different to 850μm

Fomalhaut's Dust Disk

Because of similar age, spectral type and distance, Vega and Fomalhaut are often compared: Fomalhaut is a **200 Myr**-old **A3V** star at **7.7 pc**

- Sub-mm SCUBA = edge-on **135 AU ring** with mass **0.02** $\mathbf{M_{earth}}$, clump to SE
- Sub-mm SHARCII = no evidence of clump
- Far-IR = SE ansa brighter
- Mid-IR = some emission from closer to star
- Optical = sharp inner edge, star not at centre of ring



850 μm 450 μm — Holland et al. (2003)

350μm — Marsh et al. (2004)

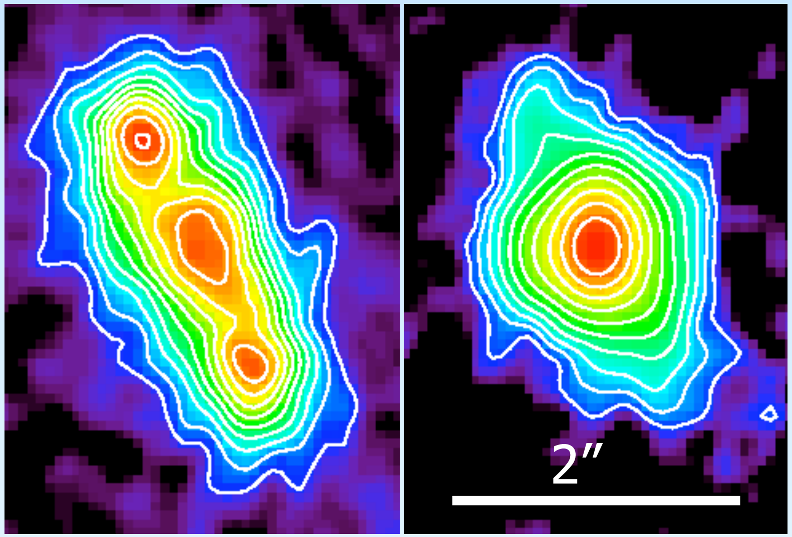
70μm 24μm — Stapelfeldt et al. (2005)

optical — Kalas et al. (2005)

The HR4796 Dust Disk

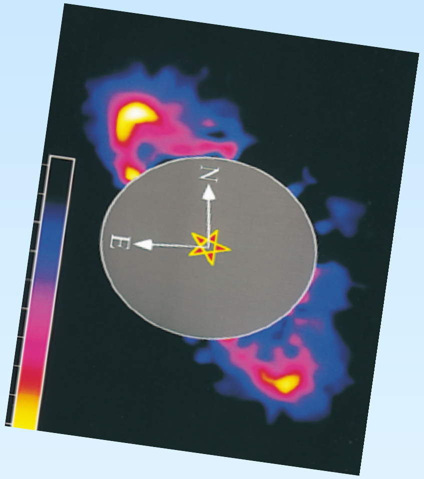
Debris disks around young stars are brighter and so easier to image
HR4796A (**10 Myr**-old **A0V** star at **67 pc**) is a disk in the TWHydra association

- Mid-IR = edge-on dust ring at **70 AU**, NE brighter than SW
- Near-IR = ring also imaged
- Sub-mm = ring contains **>0.25 M_{earth}** of dust (Greaves et al. 2000)
- Most flux at star is photospheric, but additional dust at 9 AU (Augereau et al. 1999)



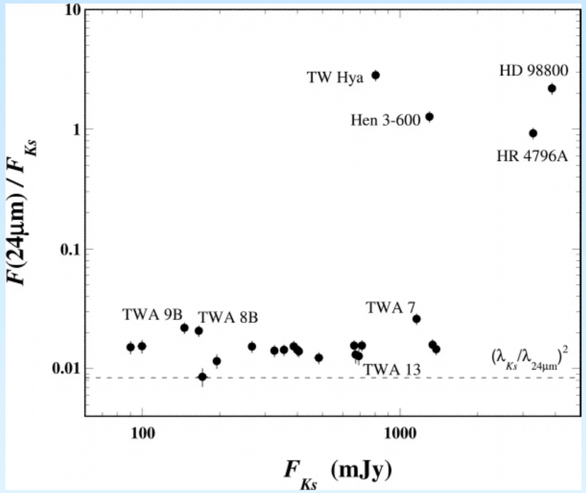
18 μm 10 μm

Telesco et al. (2000)



1.1 μm

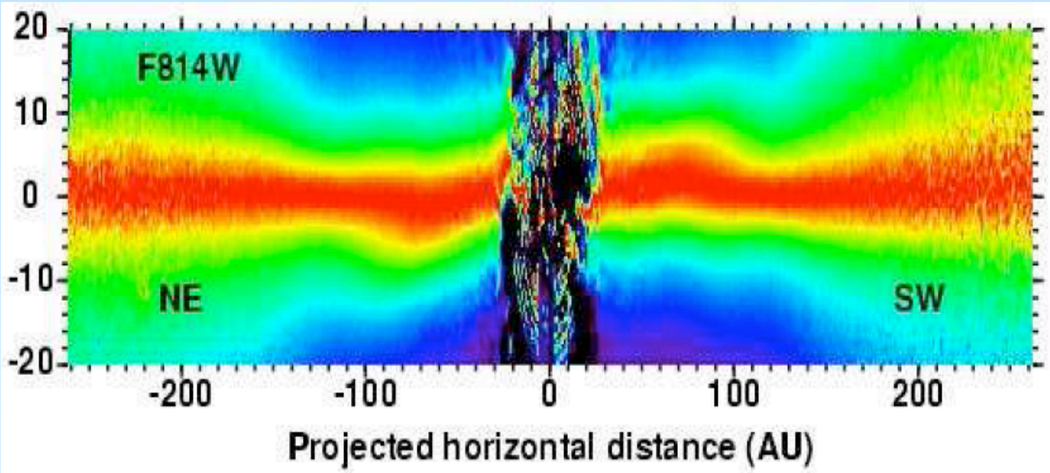
Schneider et al. (1999)



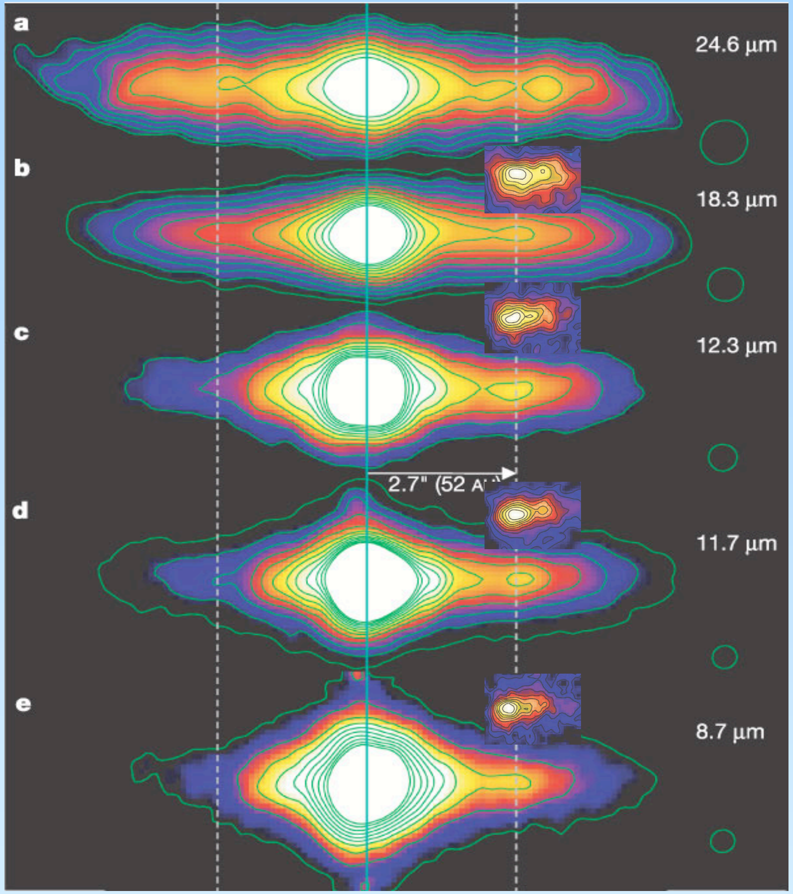
Low et al. (2005)

The inner β Pictoris disk

β Pic is a ~12 Myr A5V star with edge-on disk extending to 1000s of AU and has been imaged in optical to sub-mm



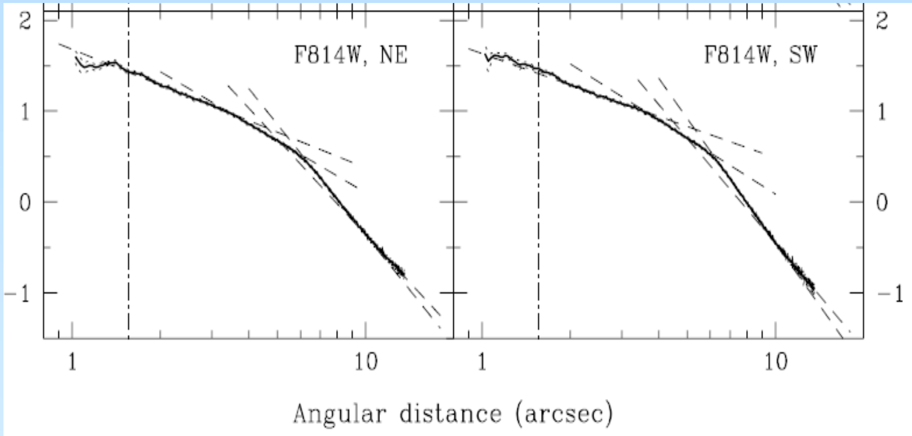
Optical images of inner region show warp at ~100AU (Heap et al. 2000; Krist et al. 2006)



Mid-IR images show a clump of material 52 AU from the star, with temperature indicating grains in the process of radiation pressure blow-out (Telesco et al. 2005)

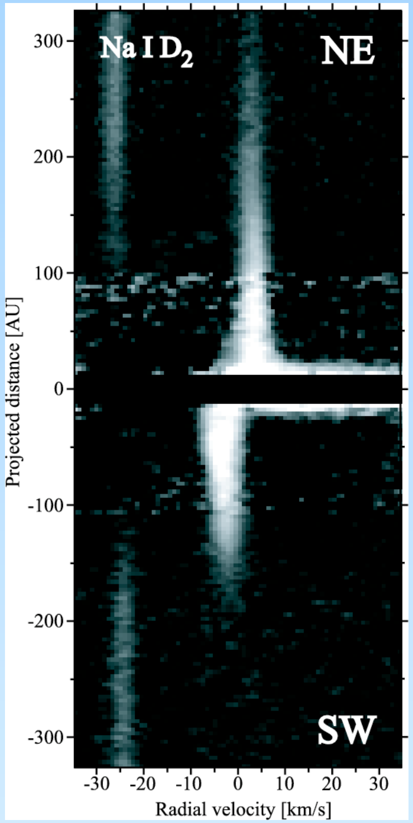
The outer β Pictoris disk

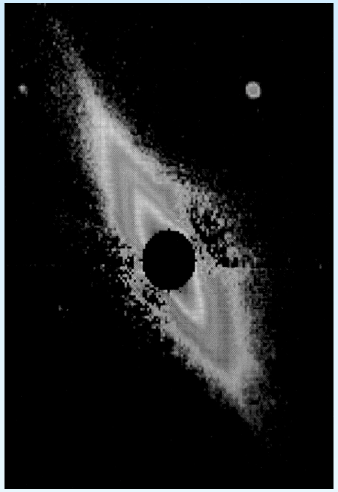
There is a break in the surface brightness profile at ~7" (130 AU)

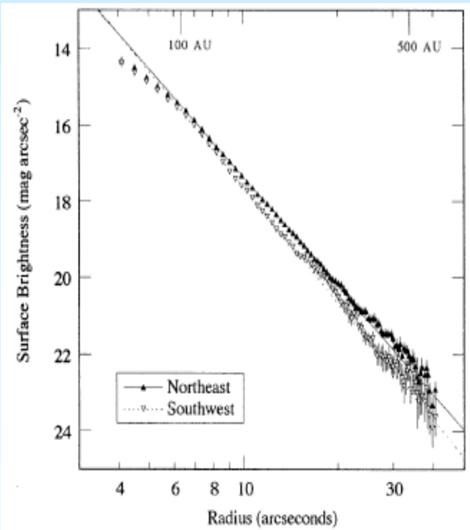


Gas is also detected in β Pic (at low levels, ~gas/dust=0.1) showing keplerian rotation and a similar break in profile indicating this is coincident with the dust

(Brandeker et al. 2004)

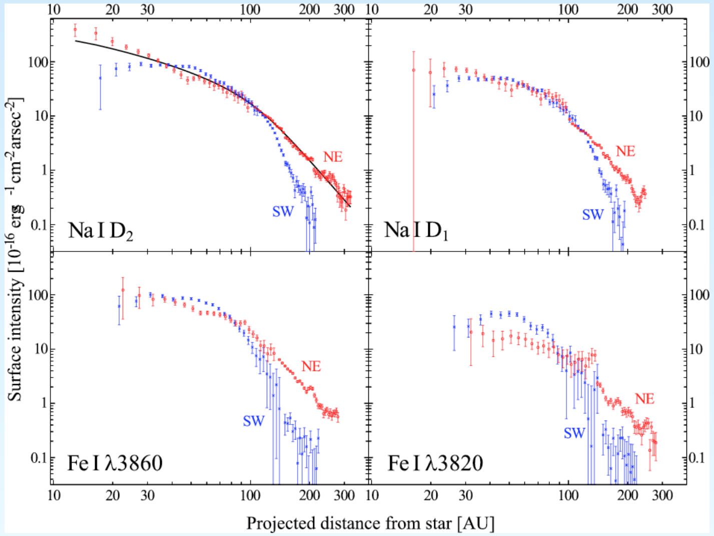






Dust is seen out to 800AU

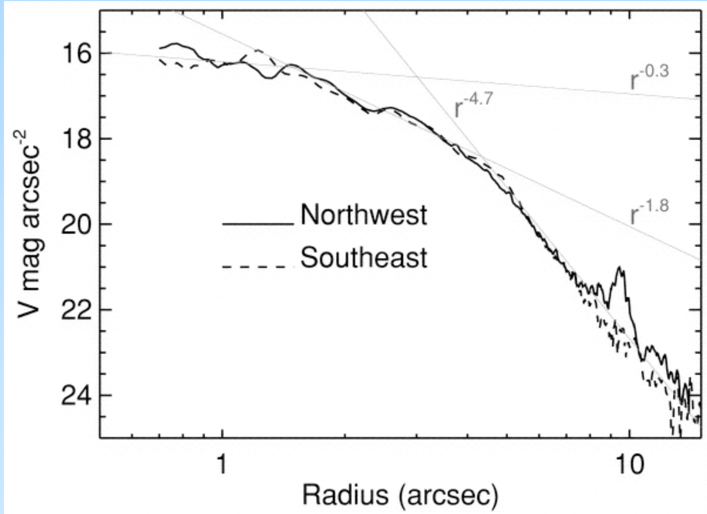
(e.g., Kalas & Jewitt 1995)

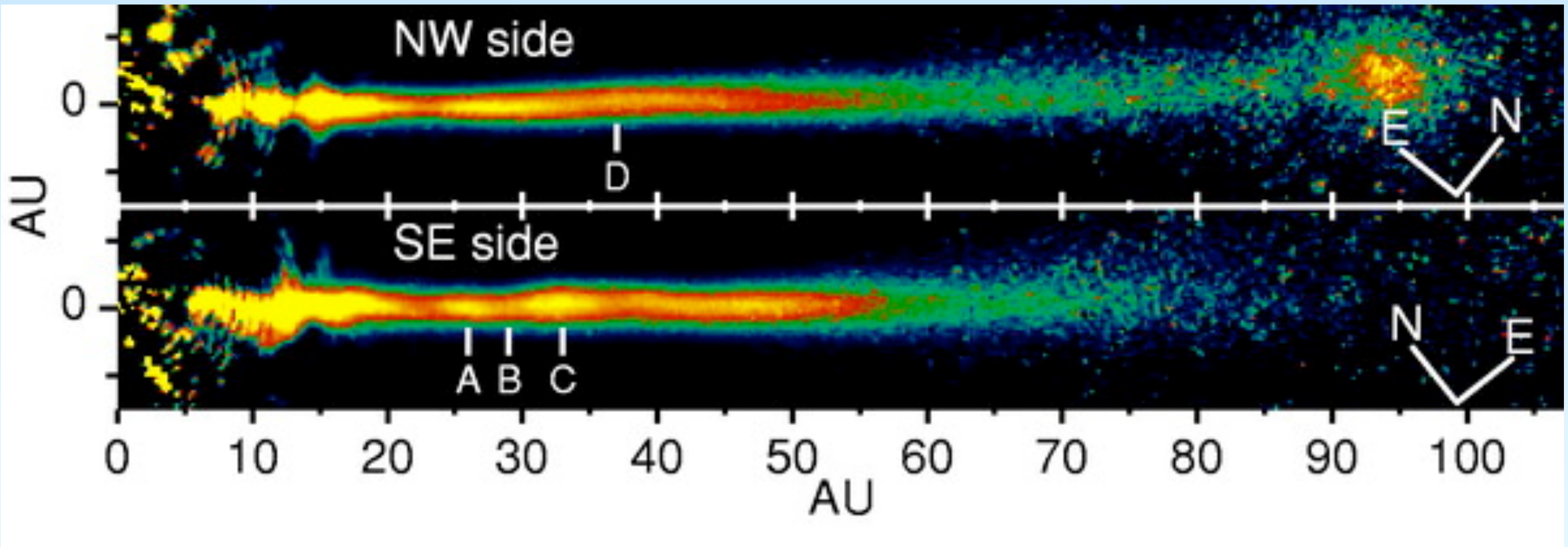


β Pic association (AU Mic)

AU Mic is an M0V star at 10pc in the β Pic association and so is ~12 Myr

It also has an imaged disk which looks remarkably similar to β Pic, since it is:
- edge-on and has a
- turn-over in surface brightness profile

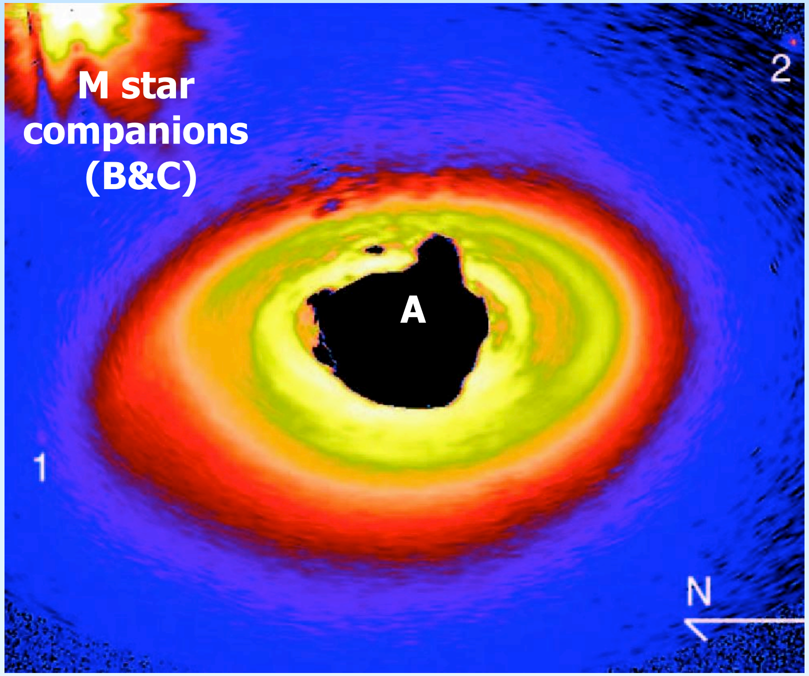




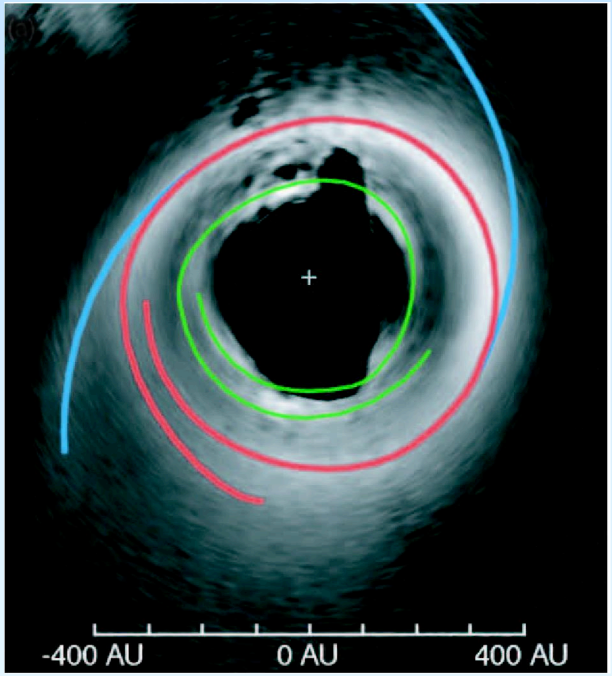
Isolated young stars: HD141569A

- HD141569A is a **5 Myr**-old **B9.5V** star at **99 pc**
- HD141569B and C are M star companions at 1200 AU separation
- Optical coronagraphic imaging from HST shows dust out to 1200 AU, dense rings at 200 and 325 AU with tightly wound spiral structure (Clampin et al. 2003)
- Disk at <200AU marginally resolved mid-IR (Fisher et al. 2000; Marsh et al. 2002)

V band surface brightness



Deprojected surface density

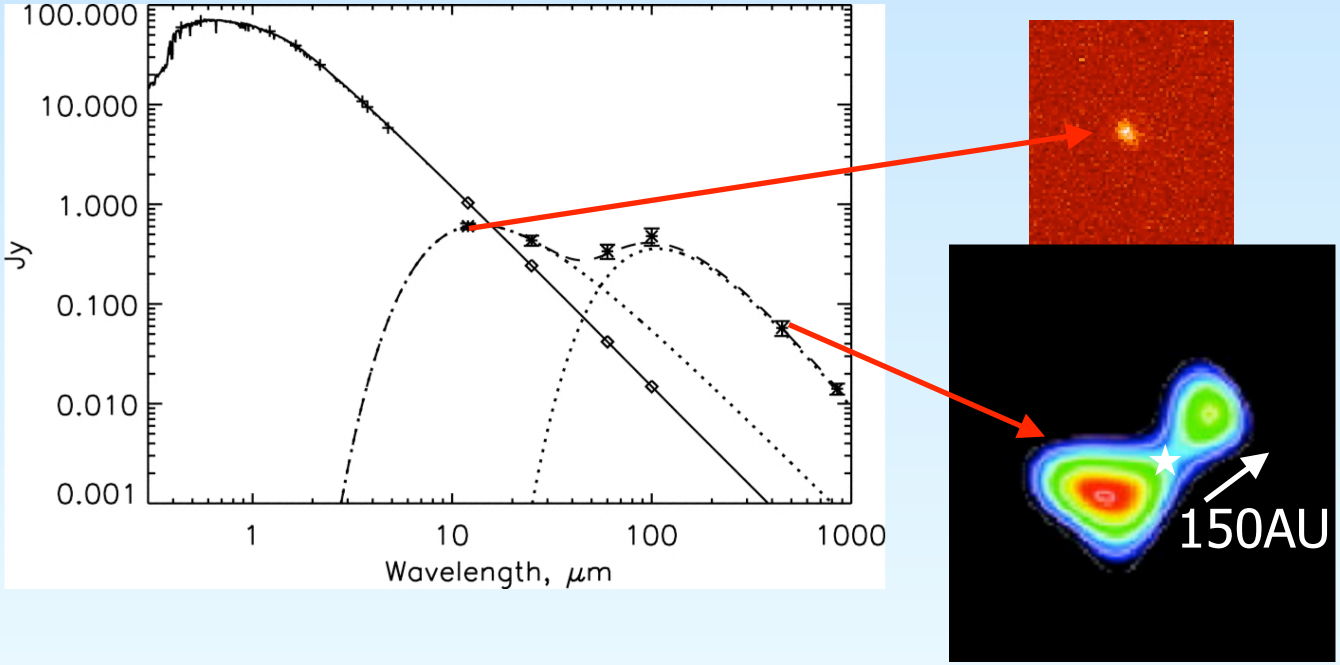


Clampin et al. (2003)

Hot and cold dust around old F star

The 1Gyr old F2V star η Corvi is most notable for its resolved Kuiper Belt, which SCUBA imaging at 450μm shows is near edge-on with a radius of ~100AU and central cavity (Wyatt et al. 2005)

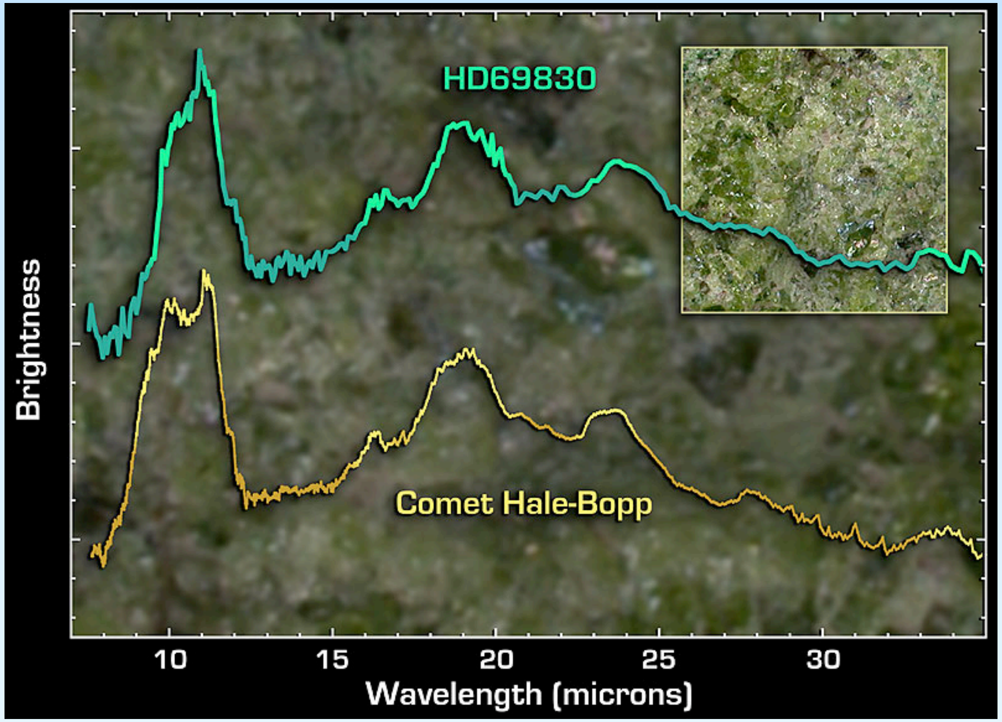
The SED shows presence of hot dust, which mid-IR imaging confirms placing location at <10AU

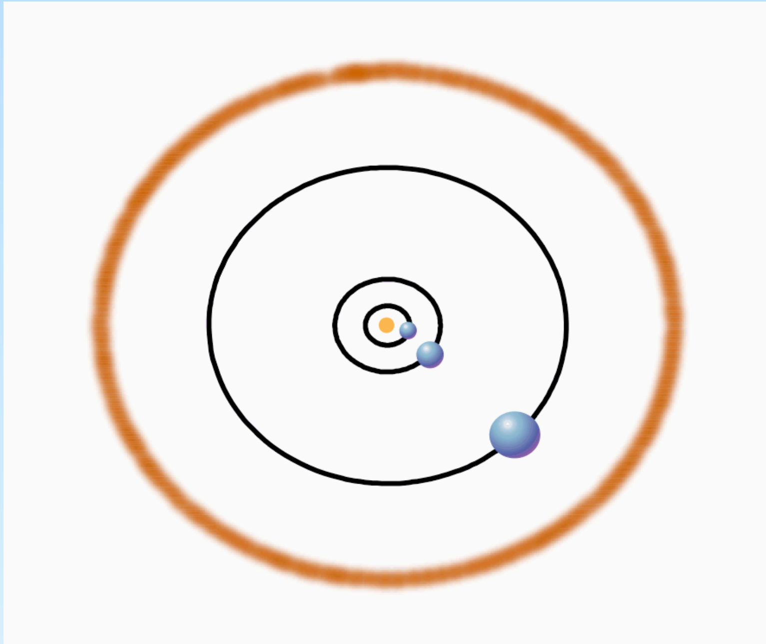


The "Hale-Bopp" star HD69830

Only 2% of stars have hot dust <10AU (Bryden et al. 2006), one of which is 2Gyr old K0V star HD69830

A mid-IR spectrum similar to that of Hale-Bopp with a temperature of ~400K, shows dust is concentrated at 1AU (Beichman et al. 2005)





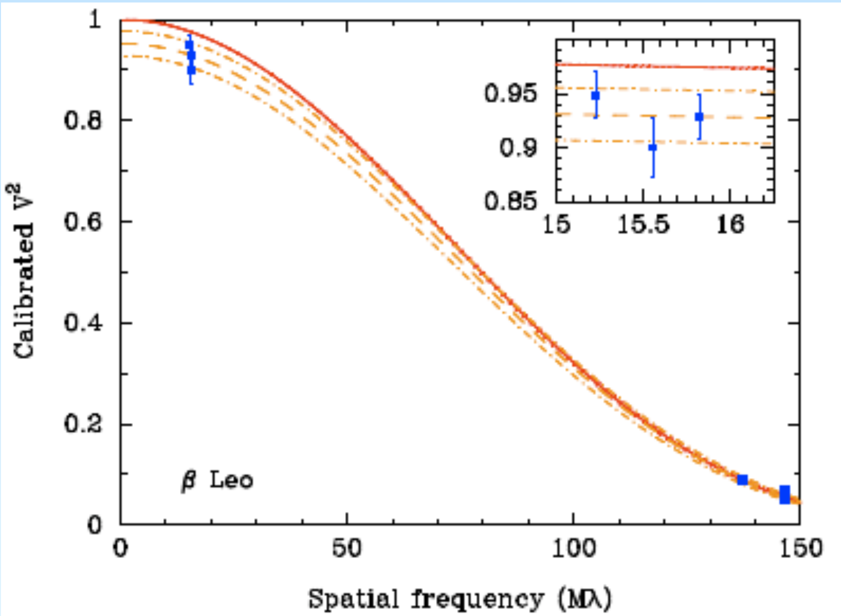
It was also recently found to have 3 Neptune mass planets orbiting at 0.08, 0.16 and 0.63 AU on nearly circular orbits (Lovis et al. 2006)

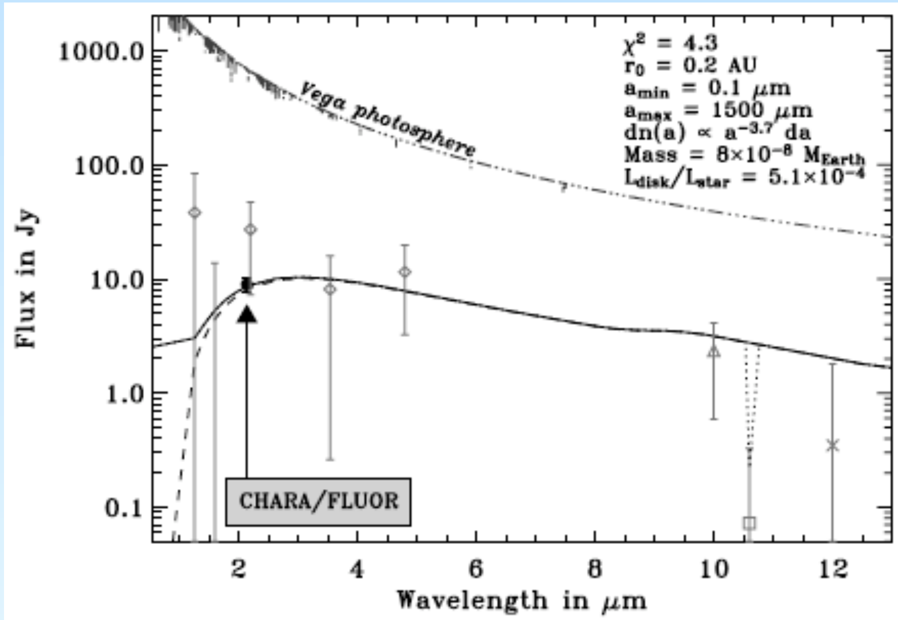
Very unusual to have dust at 1AU at 2Gyr implying it is transient (Wyatt et al. 2007)

Very hot dust from interferometry

CHARA/FLUOR interferometric observations are providing evidence for dust very close, <<1AU, to their stars (di Folco et al. 2006, 2007; Absil et al. 2008; Akeson et al. 2008)

Detections currently for Vega, τ Ceti and β Leo



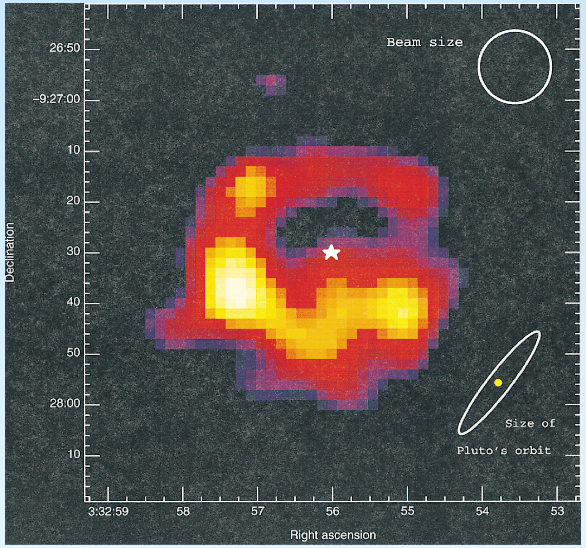


The proximity of the dust to the star implies it is transient (Wyatt et al. 2007)

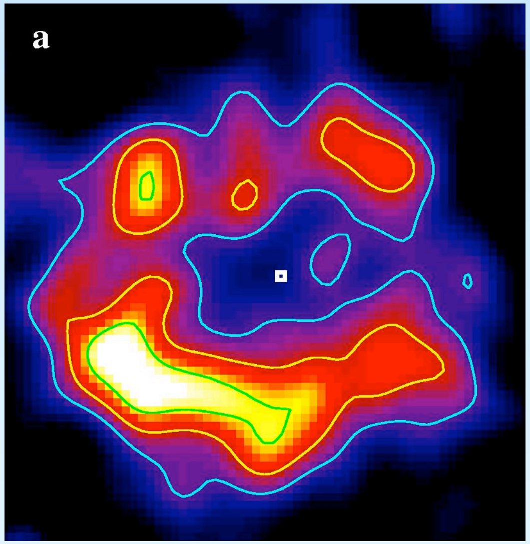
Old debris disks: ε Eridani

- ε Eridani is an **800 Myr**-old **K2V** star at **3.2 pc**
- 850 μm image (**30hr**) shows 25° from face-on, slightly offset, dust ring at **60 AU** with a mass of **0.01 M_{earth}** (Greaves et al. 1998; 2005)
- Emission dominated by **3 clumps** of asymmetric brightness
- 1"/yr proper motion detected, possible rotation of structure (Poulton et al. 2006)
- planet at 3.4 AU with e=0.6 (Hatzes et al. 2000)

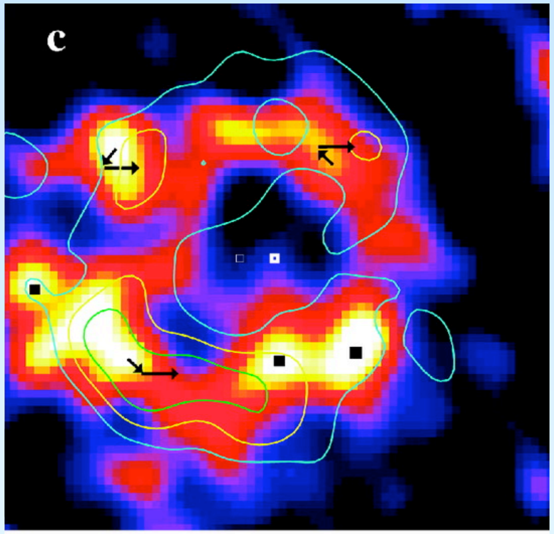
1997



1997-2003



1997 (col), 2003 (cont)

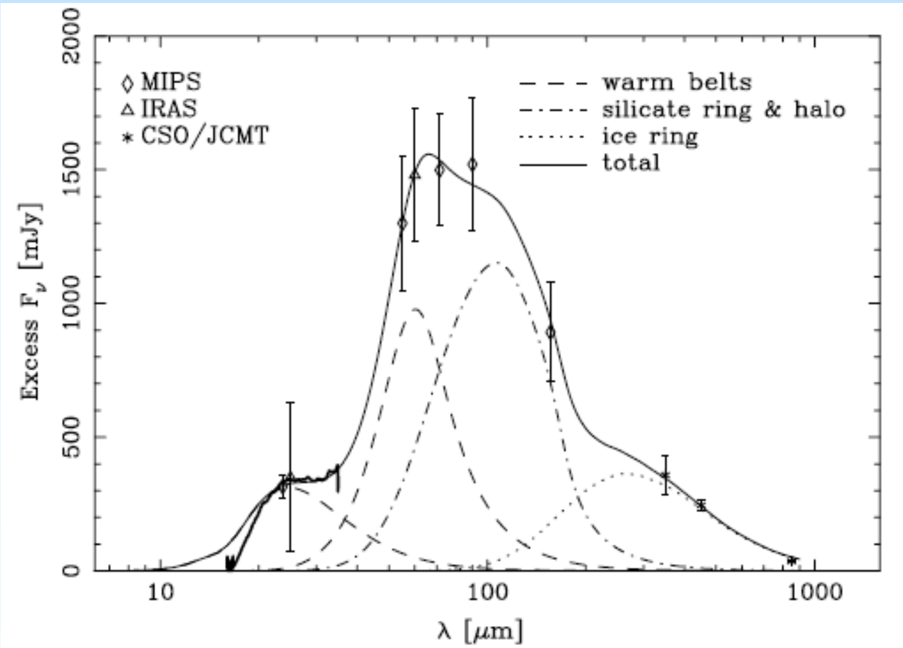


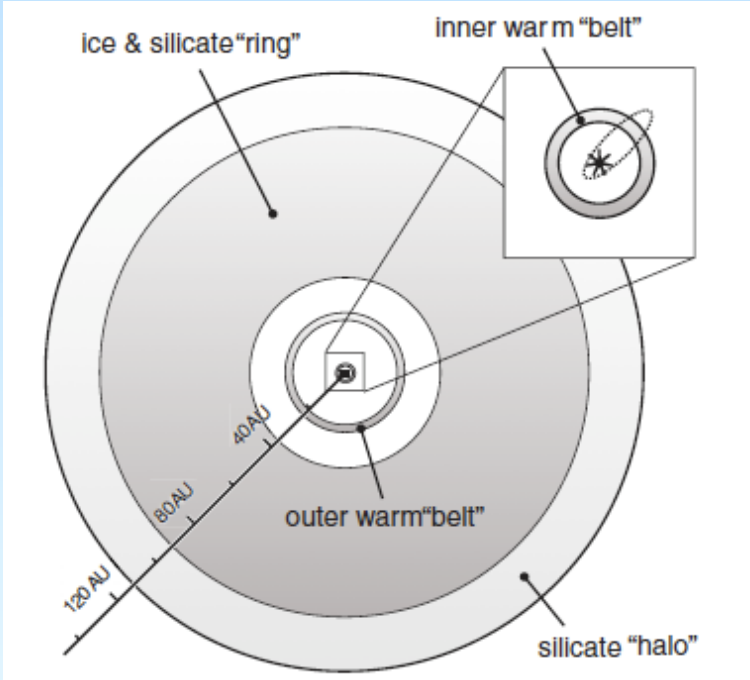
Greaves et al. (1998)

Greaves et al. (2005)

ε Eridani: dust in inner regions

Spitzer imaging and spectroscopy found evidence for dust within the main ring seen in the sub-mm (Backman et al. 2009)

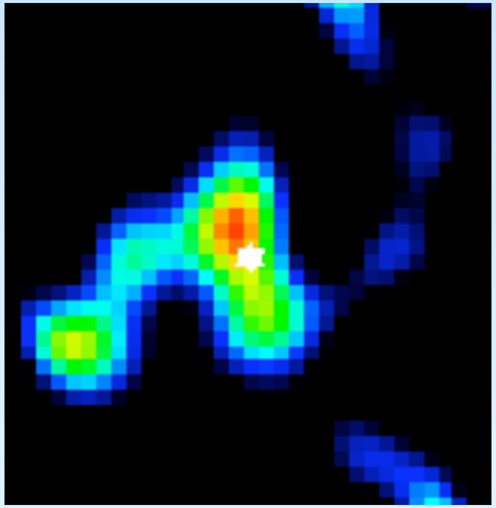


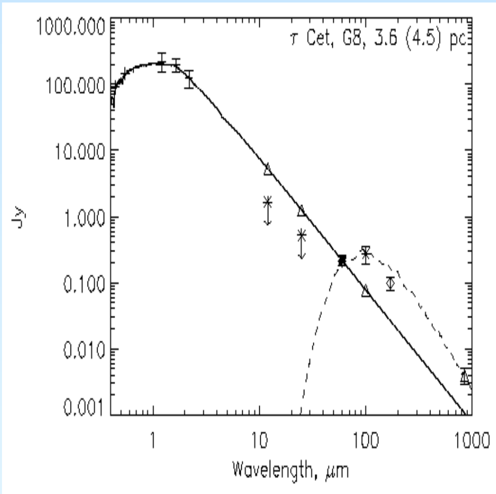


Old Debris Disks: τ Ceti

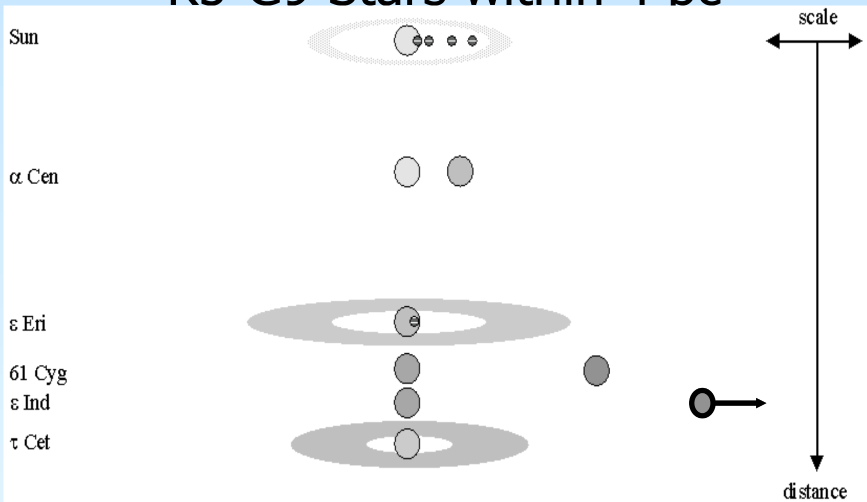
- τ Ceti is a 7.2 Gyr G8V star at 3.6 pc
- Imaging at 850 μm has confirmed the presence of an inclined debris disk with a radius ~55 AU, and a dust mass 5×10^{-4} M_{earth}
- Thus it has at least ten times more mass than the Kuiper Belt ~10^{-5} M_{earth}
- The only solar-type (age and spectral type) star with confirmed debris disk

850 μm (Greaves et al. 2004)





K5-G9 Stars within 4 pc

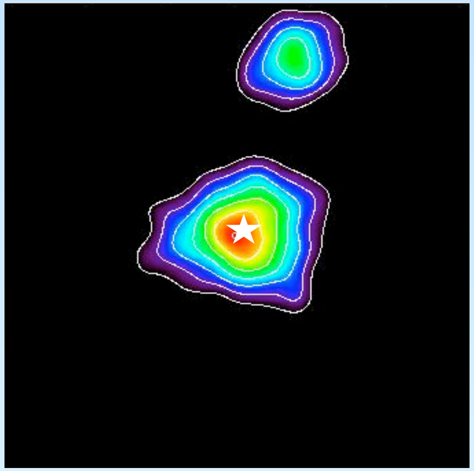


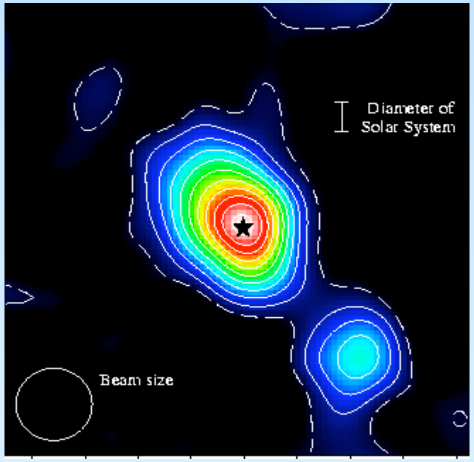
Of the six nearest K5-G9 stars, three are binary systems, two have massive debris disks, and one, the Sun, has a tenuous debris disk

Background galaxies in sub-mm

Clumps in sub-mm images are ubiquitous, and are usually assumed to be background galaxies (aka SCUBA galaxies), which have number counts from blank field surveys:

620 $F_{850\mu m}$>5mJy sources per square degree (Scott et al. 2002)
2000 $F_{450\mu m}$>10mJy sources per square degree (Smail et al. 2002)





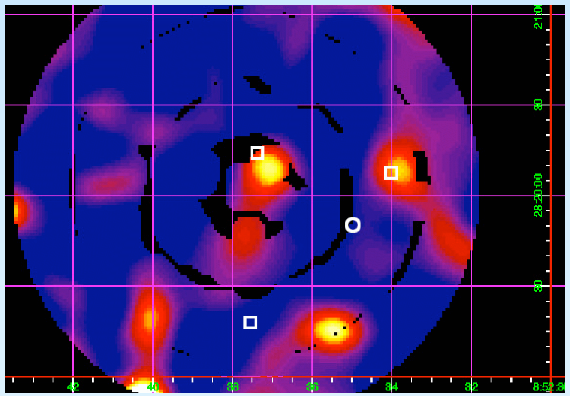
However they appear so often near debris disks (especially 19mJy source near β Pic) that perhaps some are related objects

Debris disk studies provide deep surveys for background galaxies in relatively unbiased way (all sky), and candidates can be easily followed up with AO imaging because of proximity to guide/reference star

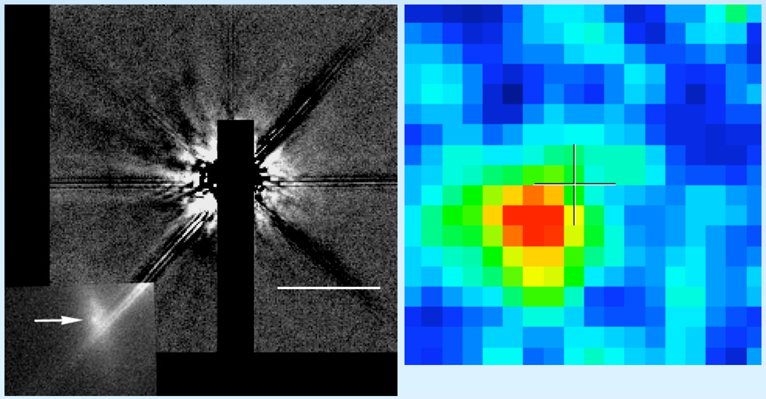
Bogus debris disks

Imaging weeded out bogus debris disks, stars with IRAS excesses that come from background objects (Spitzer is much less prone):

- 55 Cancri - bounded by three galaxies (Jayawardhana et al. 2002)
- HD123160 - giant star with nearby galaxy (Kalas et al. 2002; Sheret, Dent & Wyatt 2003)
- HD155826 - background carbon star (Lisse et al. 2002)

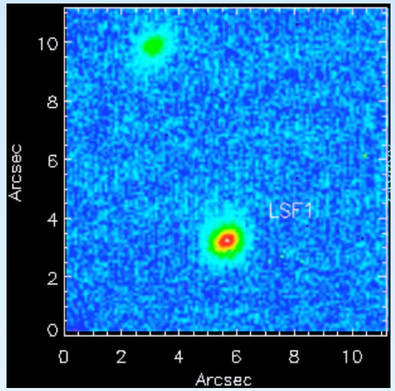


55 Cancri at 850 μm (and R)
(Jayawardhana et al. 2002)



HD123160 at K and 850 μm
(Kalas et al. 2002) (Sheret, Dent & Wyatt 2003)

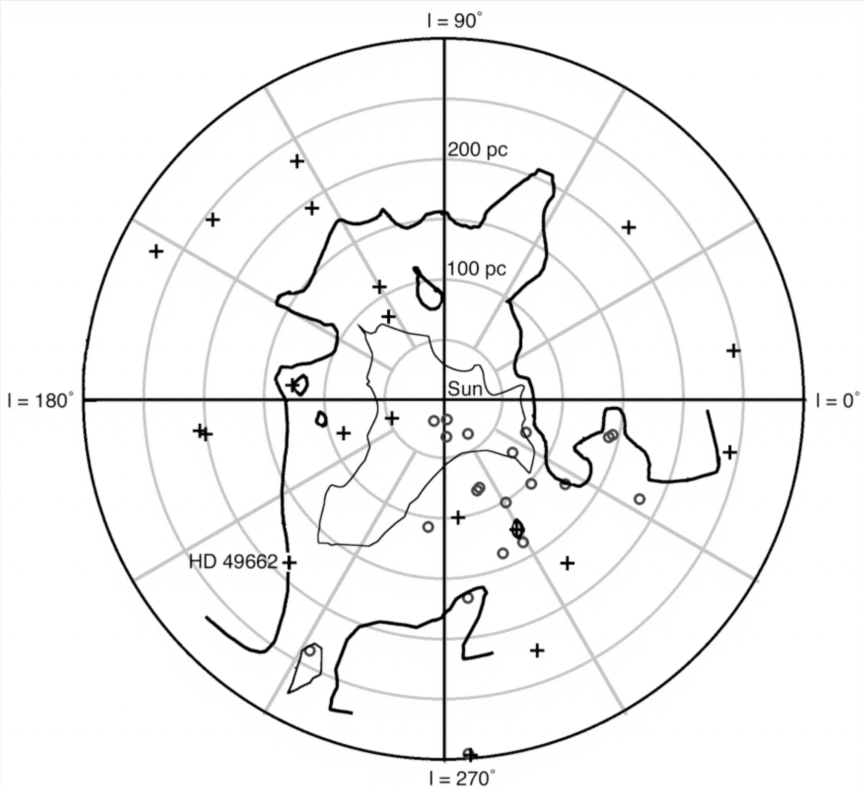
HD155826
at 11.7 μm
(Lisse et al. 2002)



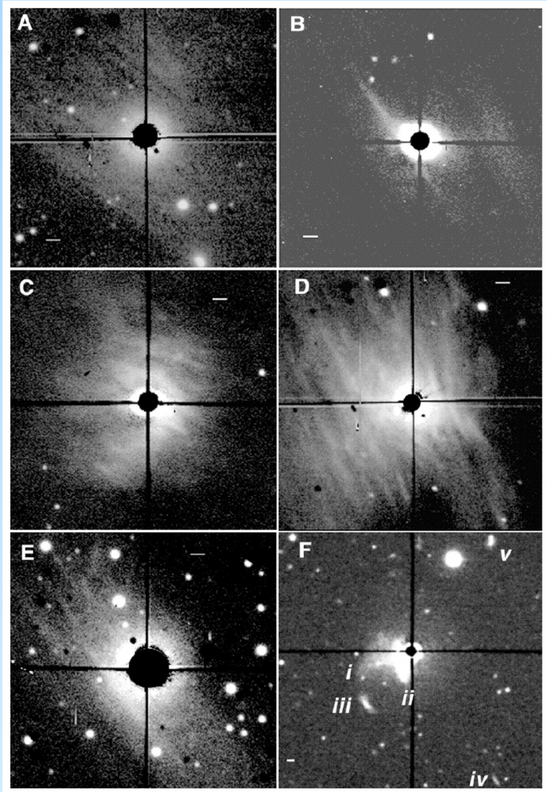
Nearby cirrus

Some stars are interacting with nearby cirrus

Optical images show diffuse nebulosity around the stars with a stripy pattern reminiscent of structure in cirrus seen in the Pleiades



Kalas et al. (2002)

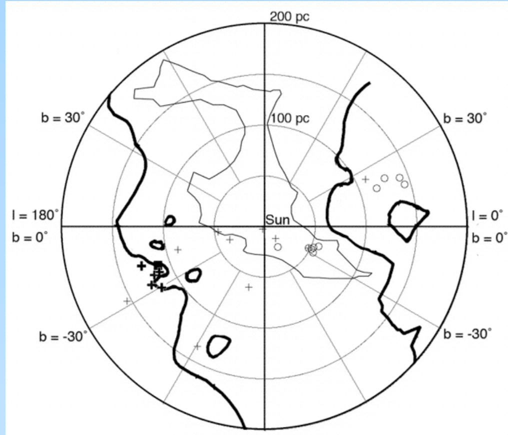


The Sun is situated in the local bubble (<100pc, see NaD absorption contours) meaning the local ISM is too diffuse for this kind of interaction, but more distant debris disk candidates may be bogus

HD32297

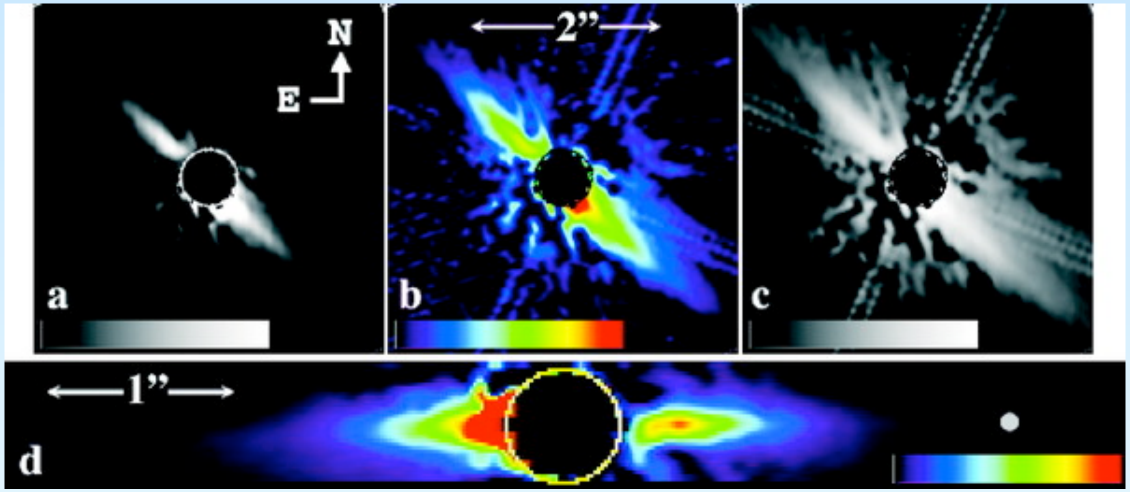
One of the imaged debris disks is associated with a wall of interstellar gas

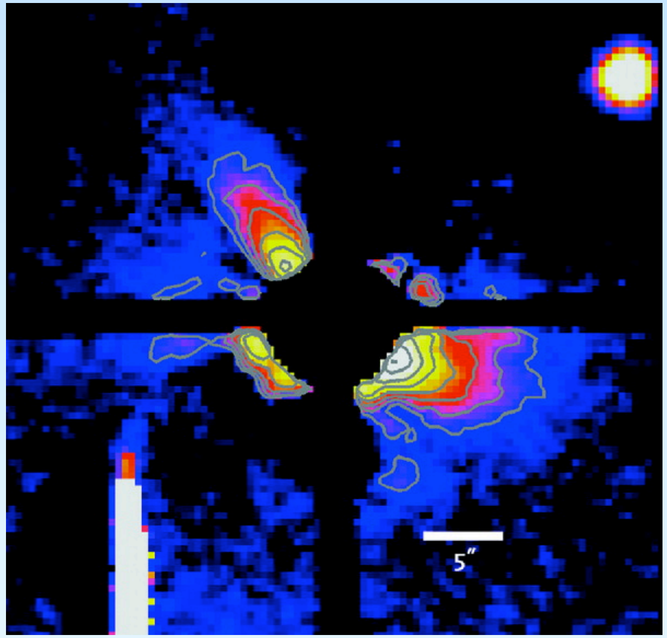
This is an 8Myr A0V star at 113pc with a $L_{ir}/L_{*}=2.7\times10^{-3}$ disk to 400AU imaged in near-IR, with distinct asymmetry in nebulosity to 1680 AU at slightly different position angle (15^{o}) in optical



Optical R band image
(Kalas et al. 2005)

NICMOS near-IR image (Schneider et al. 2005)





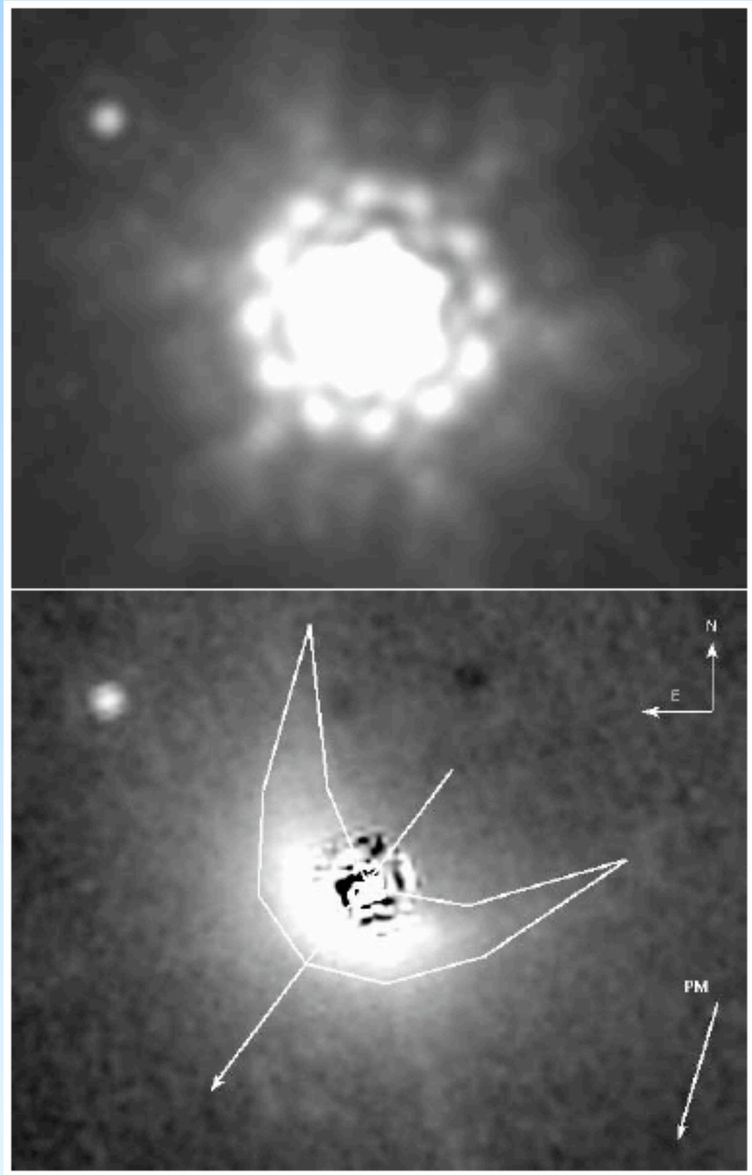
The interaction of ISM on the disk (eg., sandblasting) is still unknown

δ Velorum

Some stars show bow shock structure expected if they are interacting with interstellar dust (Gaspar et al. 2008)

This is a multiple system: A1V+A5V eclipsing binary (10mas) + G star companion at 0.6”

Imaging at 24μm shows a bow shock in the direction of relative motion



Models have to explain...

(1) Radial structure (2) Asymmetric structure (3) Evolution