Observations of debris disks before Herschel

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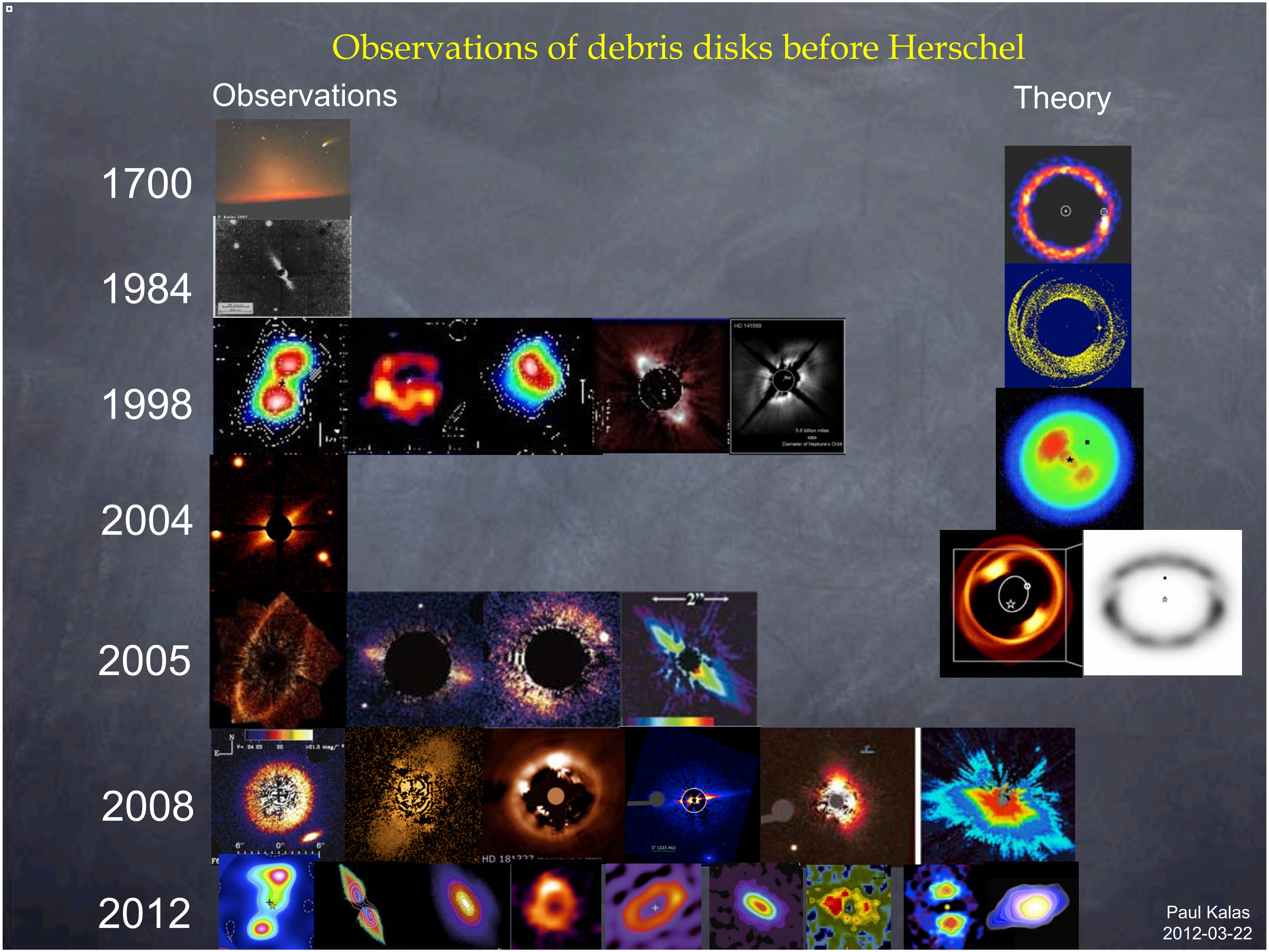
UC Berkeley & SETI Institute

"From Atoms to Pebbles: Herschel's view of Star and Planet Formation" Symposium

CNES HERSCHEL 2012
March 22, 2012
Grenoble, France

Observations of debris disks before Herschel

Paul Kalas
2012-03-22



Observations of debris disks before Herschel
Observations
Theory
1700
1984
1998
2004
2005
2008
2012
HD 141569
2"
Paul Kalas
2012-03-22

Pre-Herschel Observations of Debris Disks

1) IRAS 12, 25, 60, 100 μm (1984 -)
2) Scattered light imaging, ground and space (1984 -)
3) Resolved emission 10 μm – 850 μm (1997-)
4) Hipparchos Mission - ages (1997-)
5) ISO (1998 - 2003) debris disk evolution given age information.
6) Spitzer Space Telescope (2004 -)

Solar System Debris Disk: Zodiacal Light

Hale-Bopp
Dust loss?
10^8 kg s^{-1}

"The light at its brightest was considerably fainter than the brighter portions of the milky way... The outline generally appeared of a parabolic or probably elliptical form, and it would seem excentric as regards the sun, and also inclined, though but slightly to the ecliptic."
-- Captain Jacob 1859

Parent bodies: comets and asteroids

New title for Herschel Symposium:
”From atoms to pebbles to planets, but back to pebbles again.”

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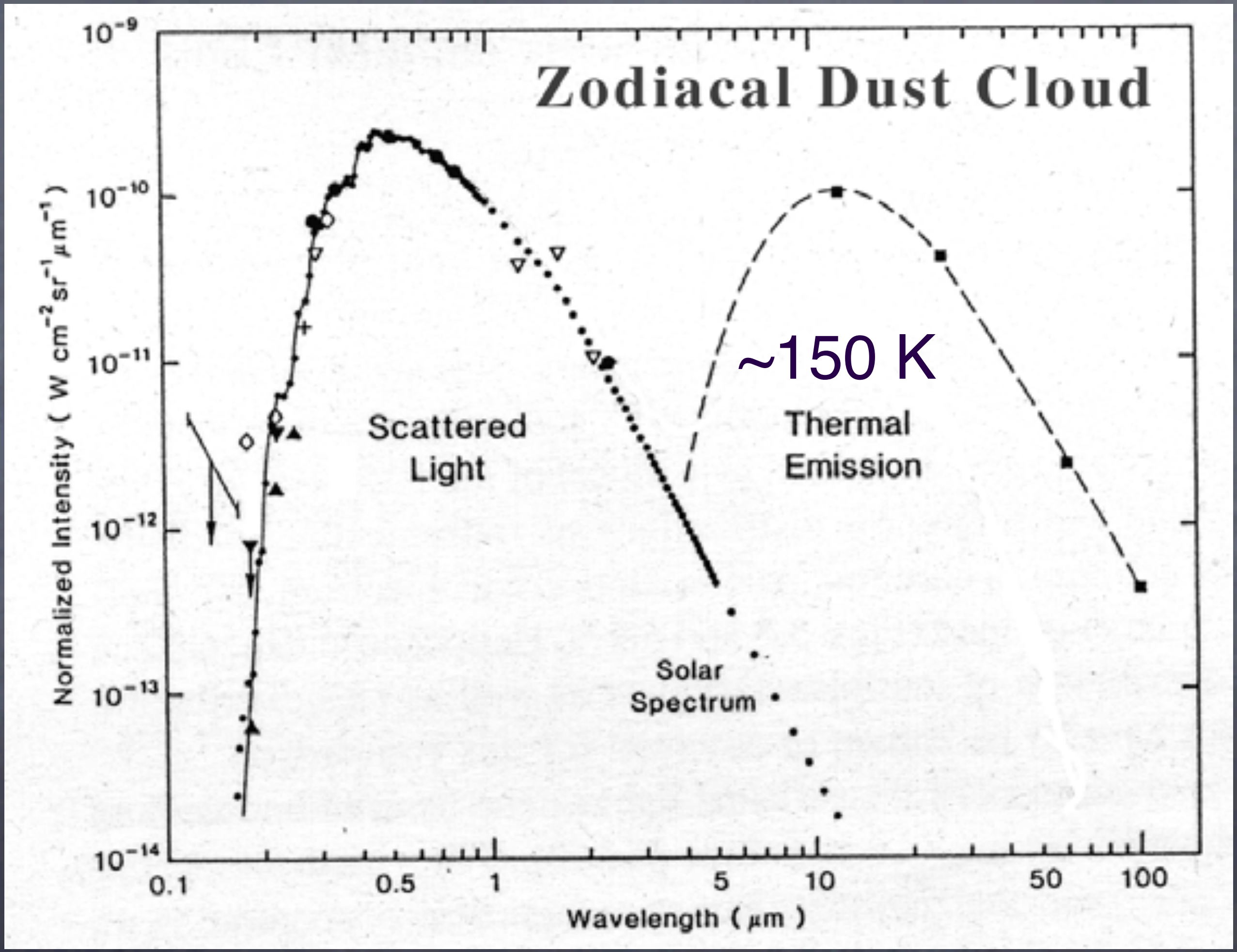
Zodiacal Dust also prominent in the infrared due to thermal emission



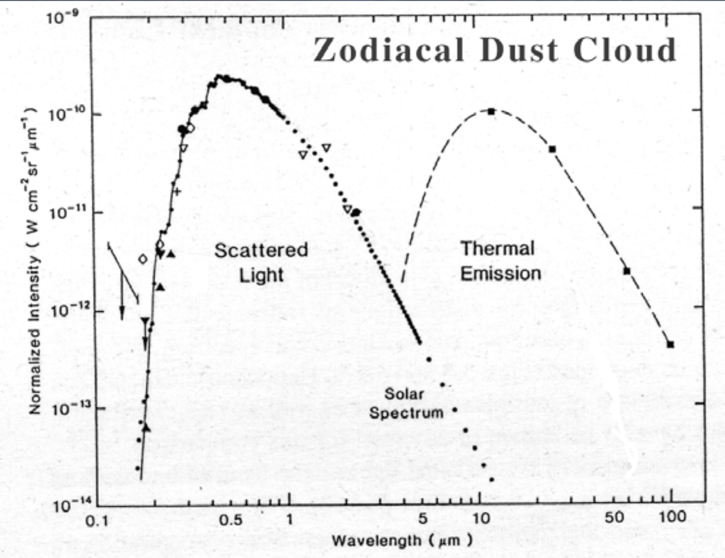
Leinert & Gruen 1990

IRAS Mission

All-sky survey

1983 (Feb. - Nov.)

Center Wavelength	# working detectors	FOV (arcmin)	Bandpass (μm)	Detector Material	Average 10-sigma Sensitivity (Jy)
12	16	.75 x 4.5	8.5 - 15	Si:As	0.7
25	13	.75 x 4.6	19 - 30	Si:Sb	0.65
60	15	1.5 x 4.7	40 - 80	Ge:Ga	0.85
100	13	3.0 x 5.0	83 - 120	Ge:Ga	3.0



Detectable around other stars?

At 10-20 μm,

$F_{dust} = 10^{-7}\ L_{\odot}$

2×10^{-4} Jy !

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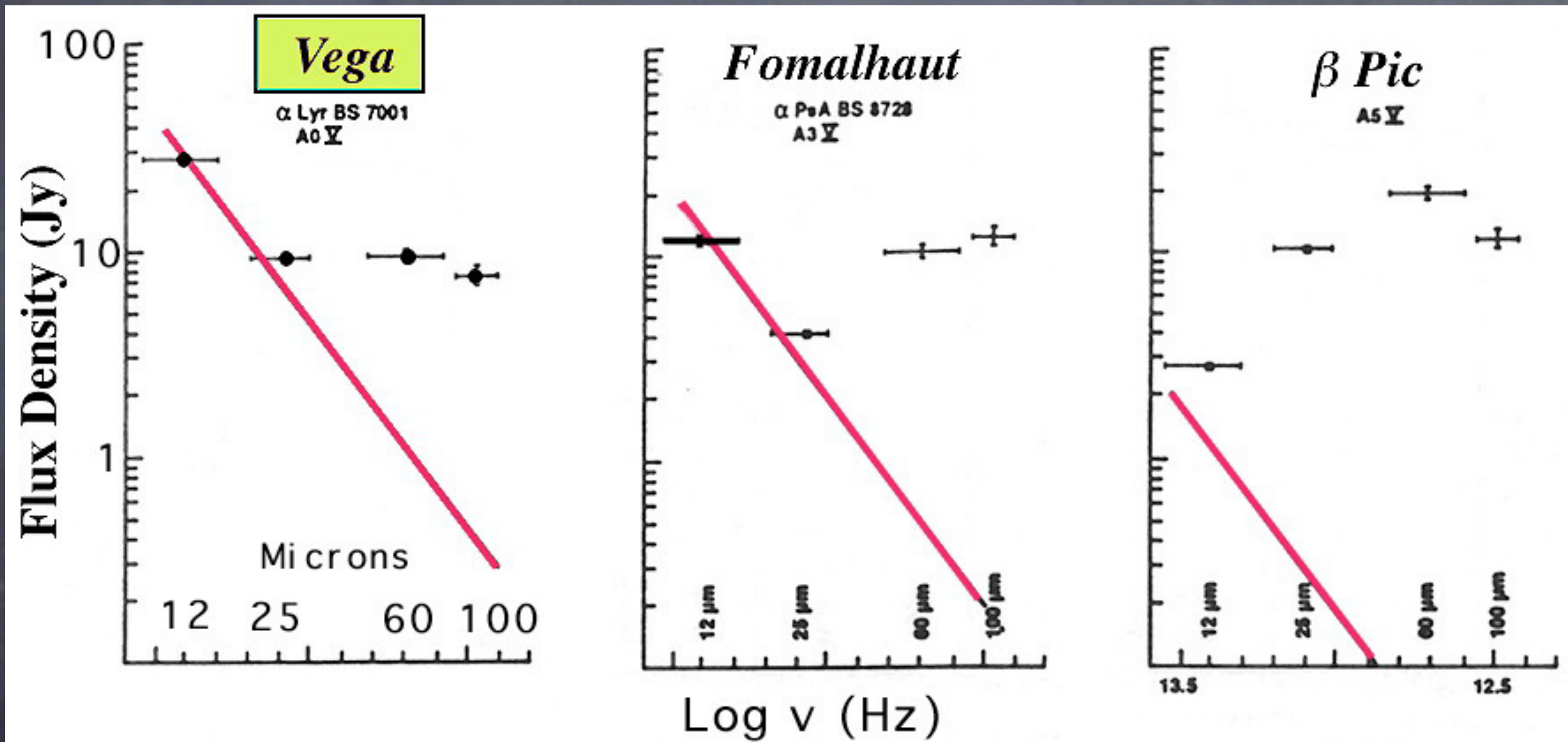
1984: The Vega Phenomenon

The discovery of excess emission from main sequence stars at IRAS wavelengths (Aumann et al. 1984).



Backman & Paresce 1993
"The Big Three"

1984: The Vega Phenomenon

The discovery of excess emission from main sequence stars at IRAS wavelengths (Aumann et al. 1984).

Grain temperature gives radius from star where most of the dust resides, but distinguishing a shell versus disk architecture requires resolved imaging.

THE ASTROPHYSICAL JOURNAL, **278**:L23–L27, 1984 March 1

DISCOVERY OF A SHELL AROUND ALPHA LYRAE[1]

H. H. AUMANN, F. C. GILLETT, C. A. BEICHMAN, T. DE JONG, J. R. HOUCK, F. J. LOW,
G. NEUGEBAUER, R. G. WALKER, AND P. R. WESSELIUS
Received 1983 September 22; accepted 1983 November 18

ABSTRACT

IRAS observations of α Lyrae reveal a large infrared excess beyond 12 μm. The excess over an extrapolation of a 10,000 K blackbody is a factor of 1.3 at 25 μm, 7 at 60 μm, and 16 at 100 μm. The source of 60 μm emission has a diameter of about 20″. This is the first detection of a large infrared excess from a main-sequence star without significant mass loss. The most likely origin of the excess is thermal radiation from solid particles more than a millimeter in radius, located approximately 85 AU from α Lyr and heated by the star to an equilibrium temperature of 85 K. These results provide the first direct evidence outside of the solar system for the growth of large particles from the residual of the prenatal cloud of gas and dust.

Not a 150K exozody that was discovered, but a cold exo Kuiper Belt/Shell, before the Kuiper Belt was detected in 1992.

Important Parallel Developments

Solar Astronomy: First detection of the solar corona without a lunar eclipse (1932)

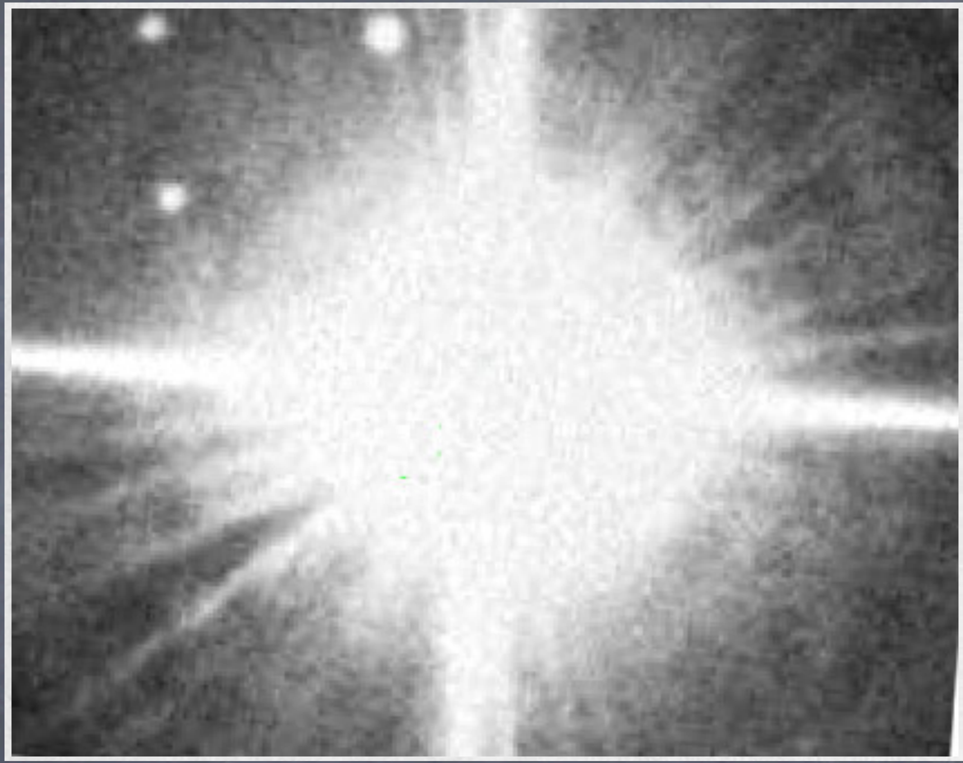
Bernard Lyot (1897-1952)

Solar System Science: Voyager 2 reaches Saturn (1981)

Brad Smith (head of Voyager imaging team)

Direct Image of the β Pic Dust Disk

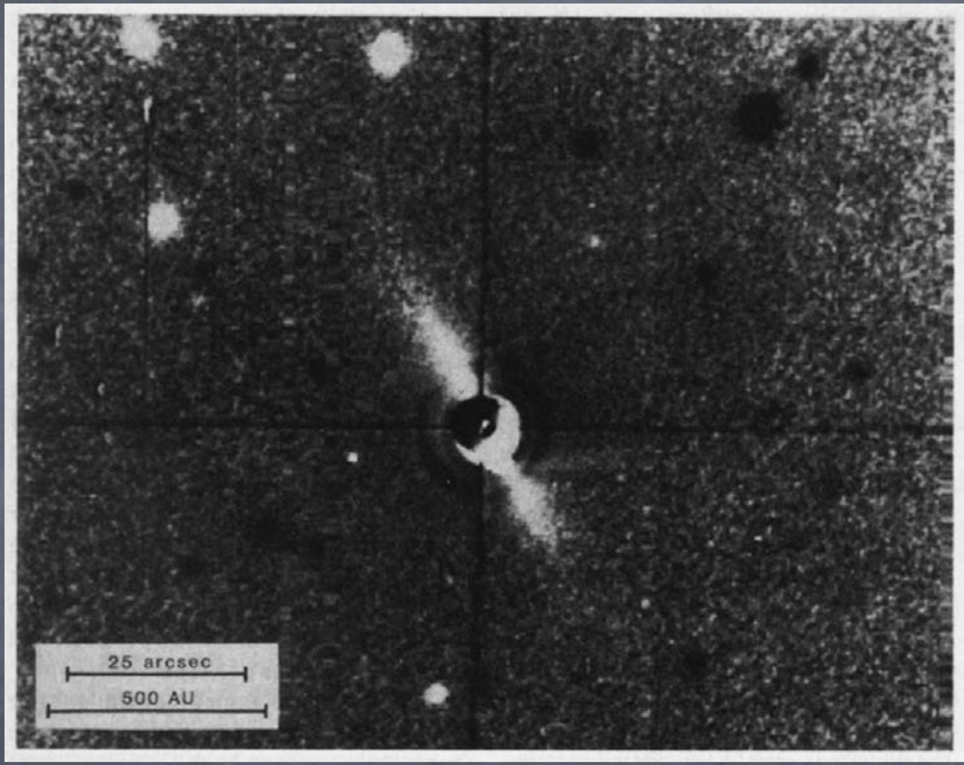
as early as 1983



Smith & Terrile 1984

Beta Pic was the Rosetta Stone Debris Disk for 15 years
>300 refereed papers

Direct Image of the β Pic Dust Disk
not a shell of dust, but a disk of dust



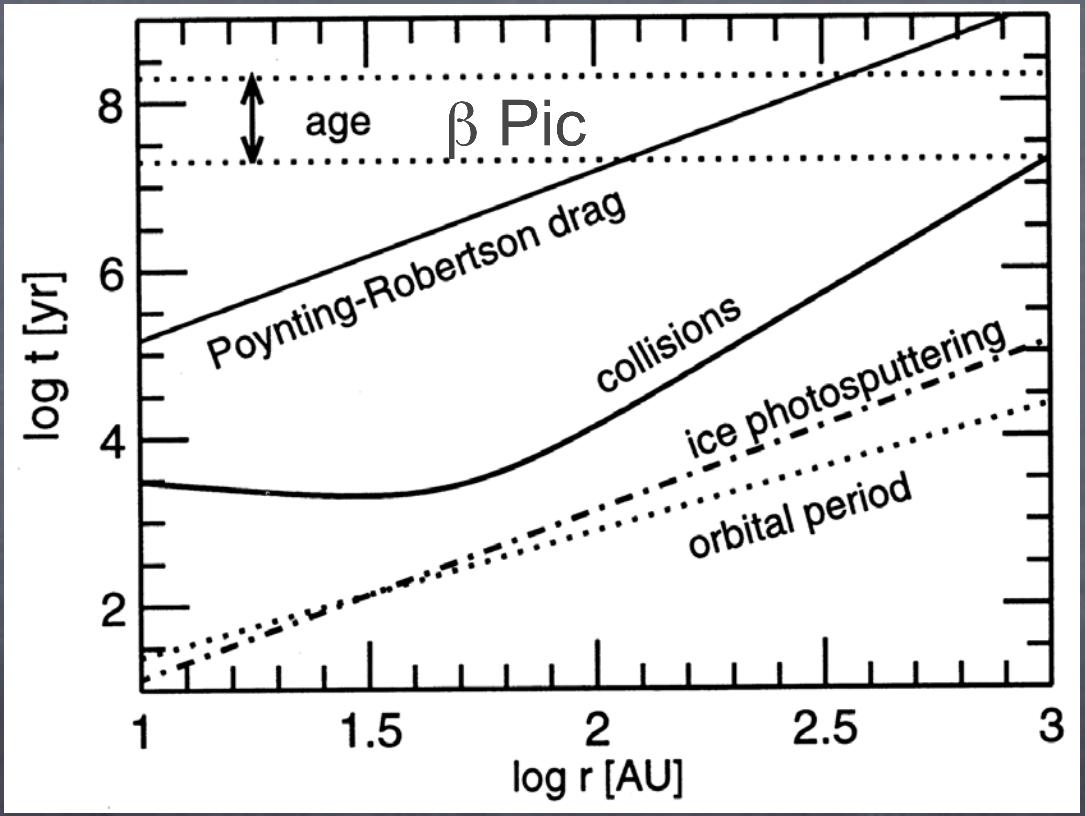
Smith & Terrile 1984

Beta Pic was the Rosetta Stone Debris Disk for 15 years
>300 refereed papers

What is the origin of dust?

The Dust Must be Replenished

Age of system >> lifetime of dust



Artymowicz 1997

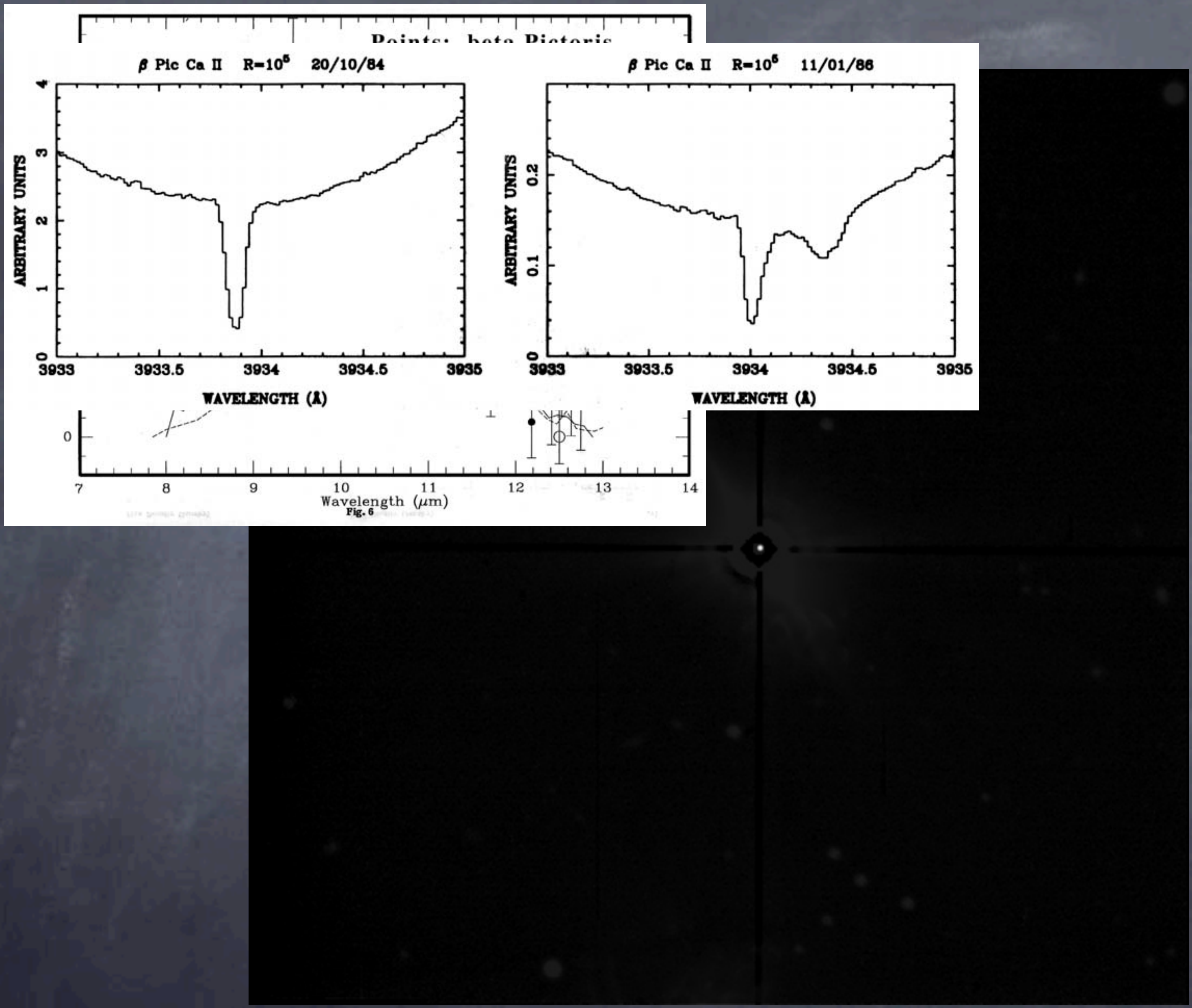
From 1984 to 1998:

Debris disk science was mostly concerned with:

(1) The detailed study of Beta Pic

(2) Mining the IRAS catalogs for more debris disk candidate stars

β Pic Detailed Studies



β Pic
< 0.4 AU
1900 - 1999

SpT = A5V

d = 19.3 pc

Beust
Deleuil
Ferlet
Knacke
Lagrange
Lamers
Lecavelier des Etangs
Morbidelli
Vidal Madjar

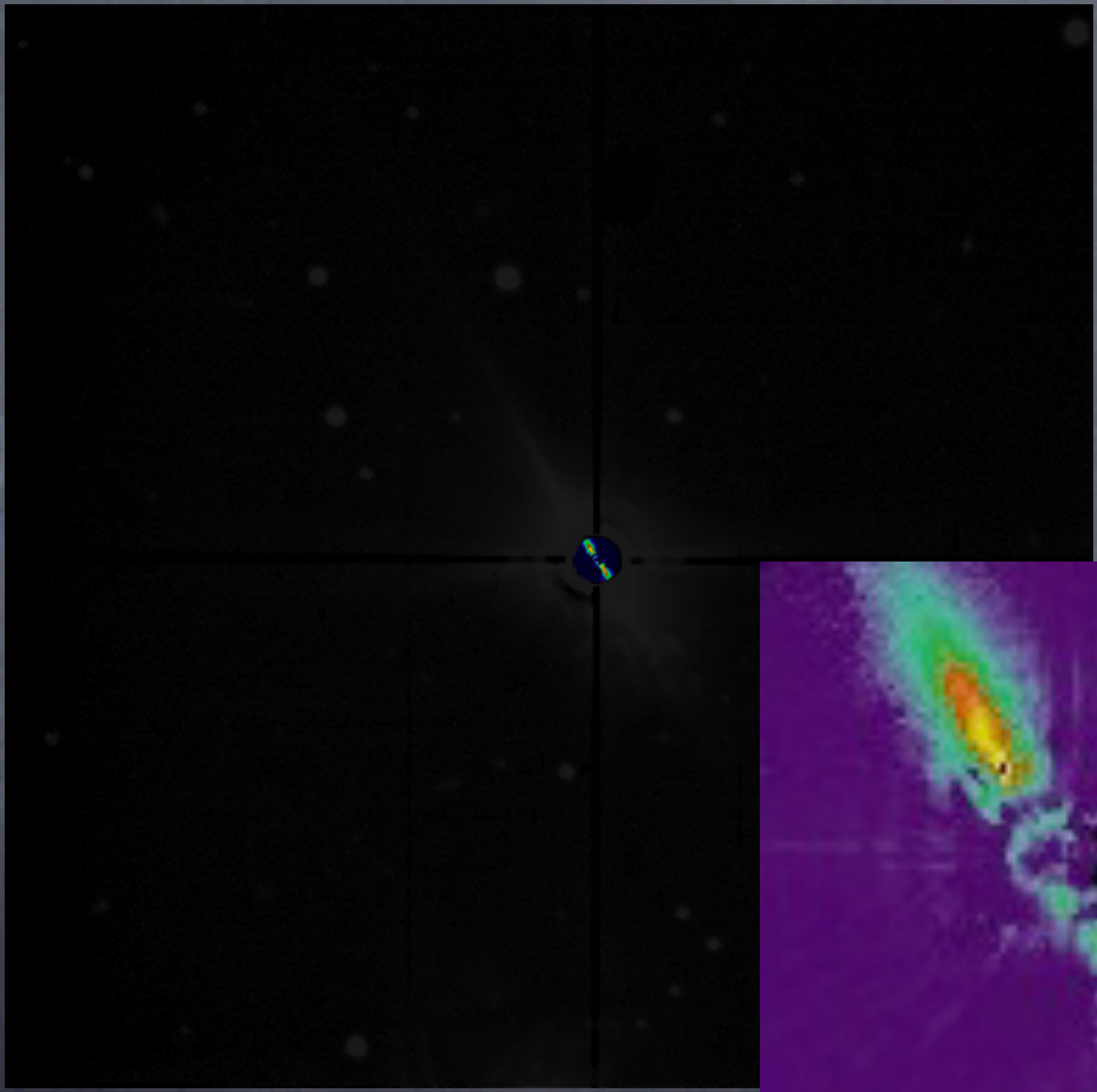
β Pic Detailed Studies

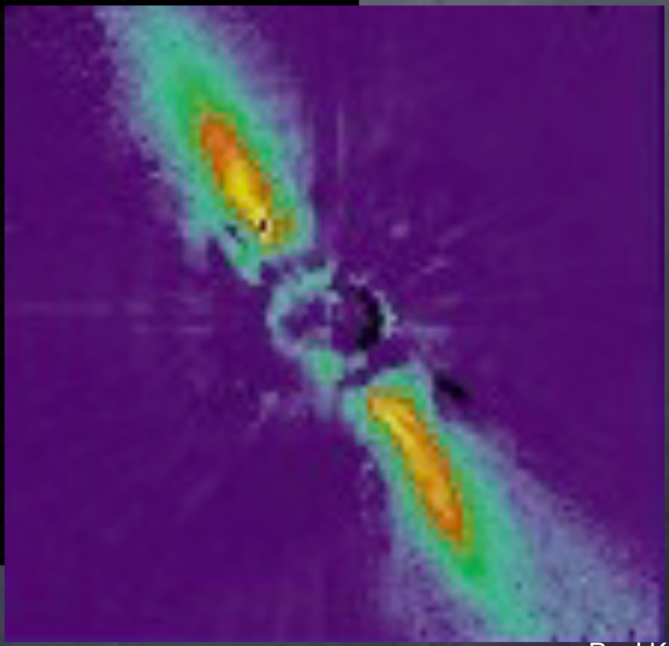
0.5 - 2.2 μm

β Pic

5" = 100 AU

1995 - 1997





Burrows et al. 1995
Beuzit et al. 1996
Mouillet et al. 1997
Heap et al. 2000

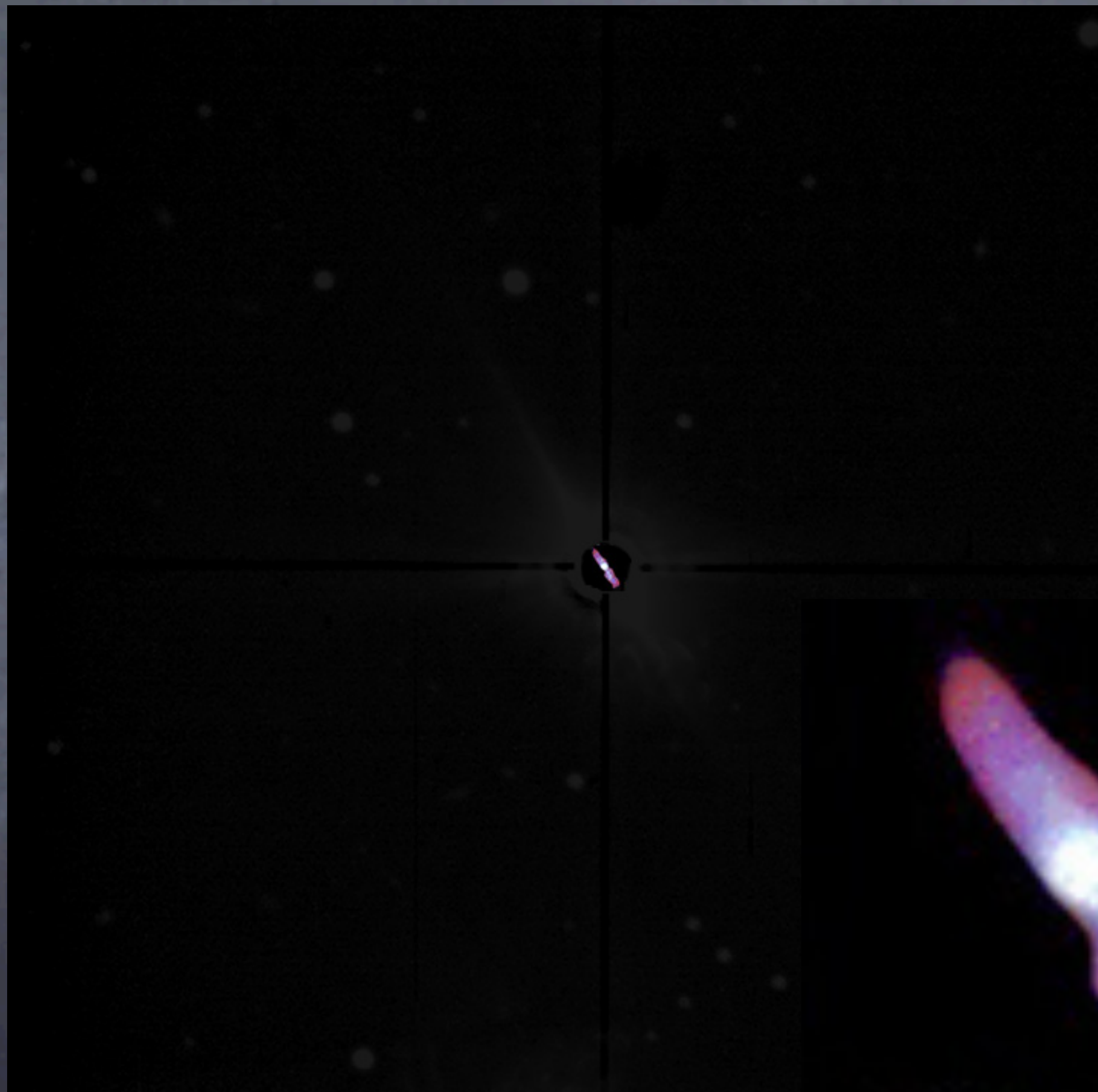
β Pic Detailed Studies

10 - 20 μm

β Pic

5" = 100 AU

1994-1997



Lagage & Pantin 1994
Roques et al. 1994
Pantin et al. 1997

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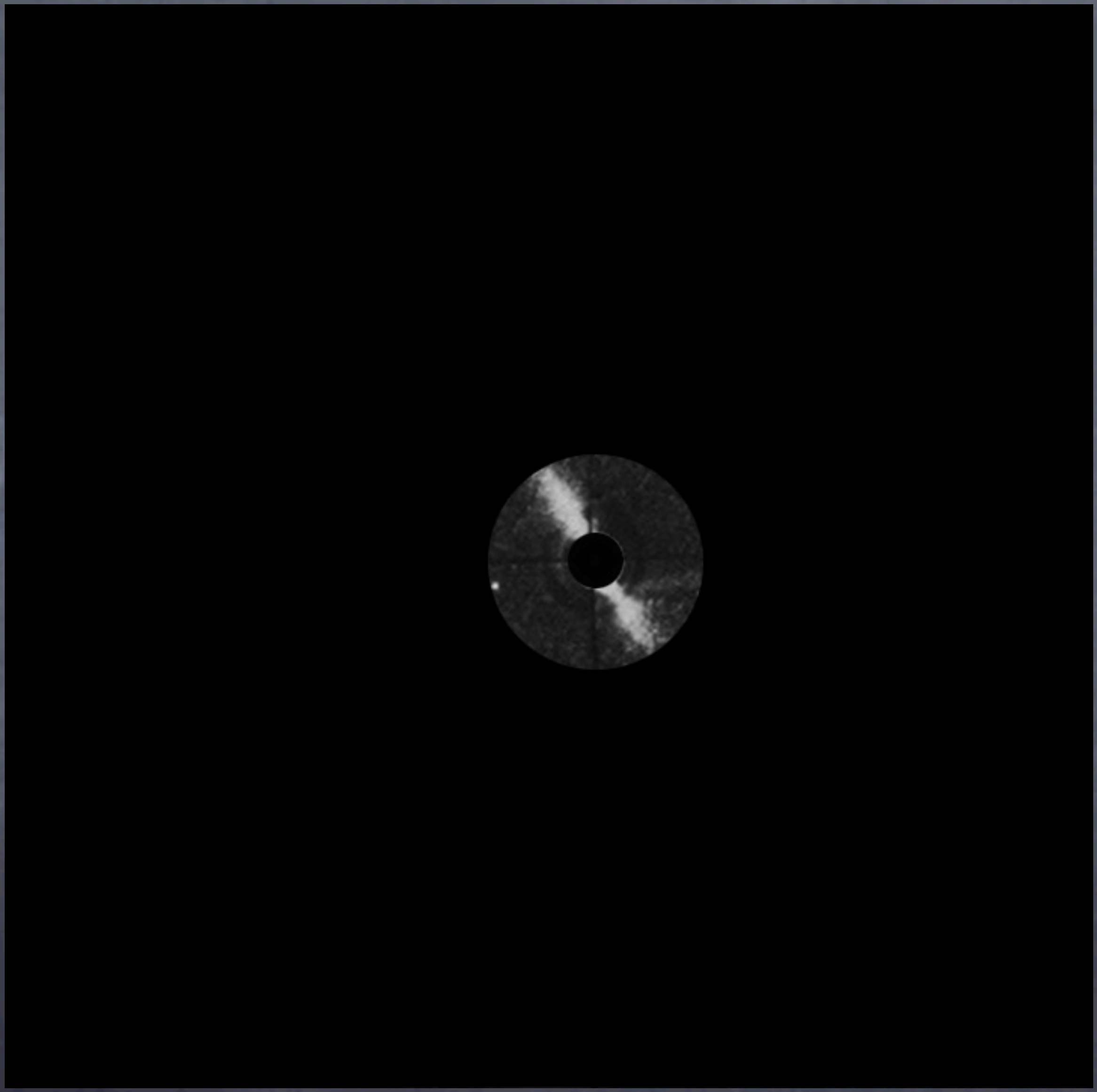
0.5 - 0.8 μm



β Pic

25" = 500 AU

1984

Smith & Terrile 1984

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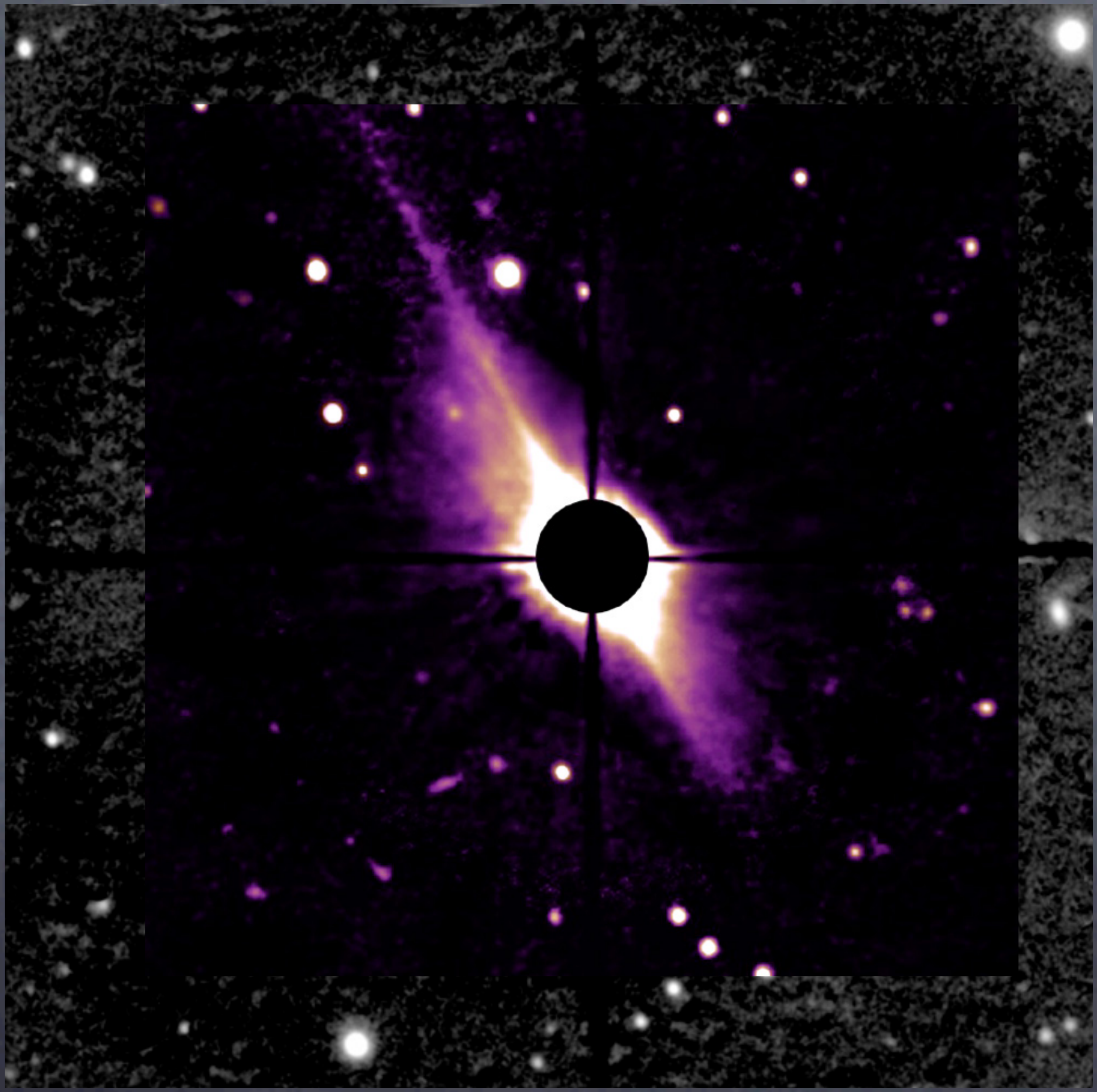
0.5 - 0.8 μm



β Pic

100" = 2000 AU

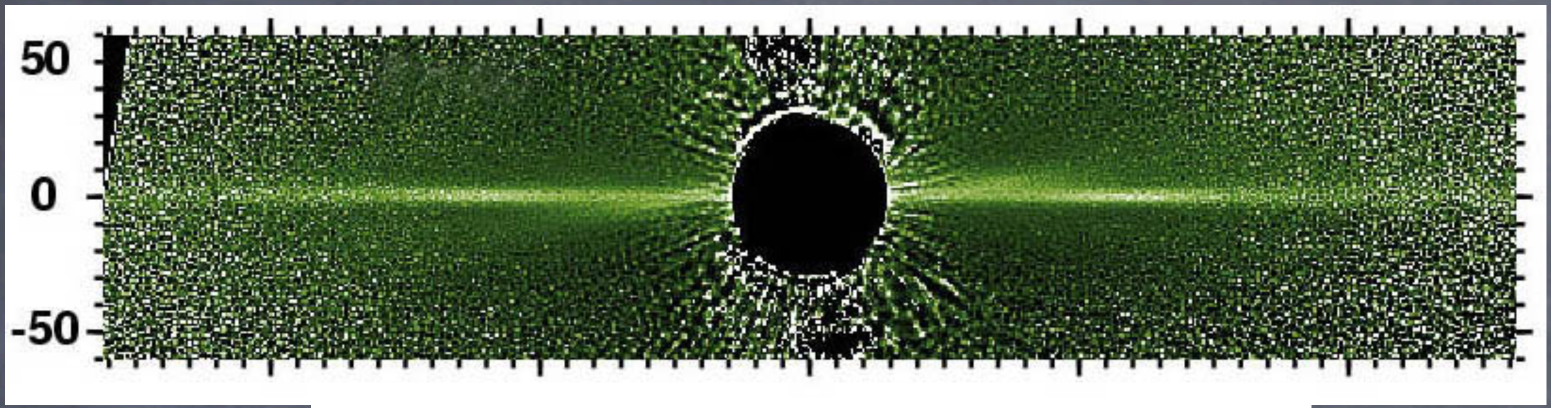
2000 A.D.

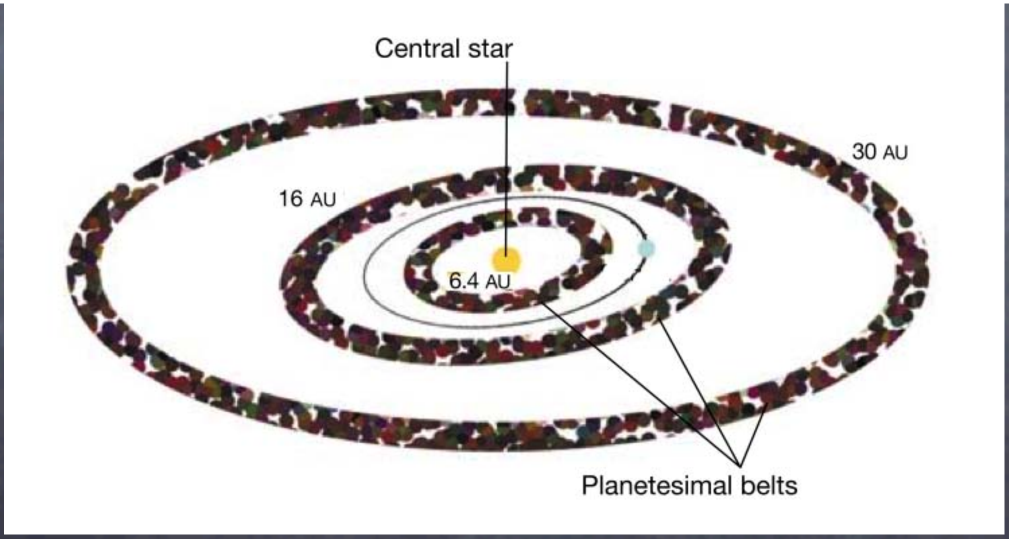
Very COLD material

Kalas & Jewitt 1995, Discovery that Debris Disks can be Asymmetric, Dynamically Complex

Beta Pic's Double Disk

The Latest Optical Image with Hubble (ACS/HRC)
Golimowski et al. 2006





Okamoto et al. 2005

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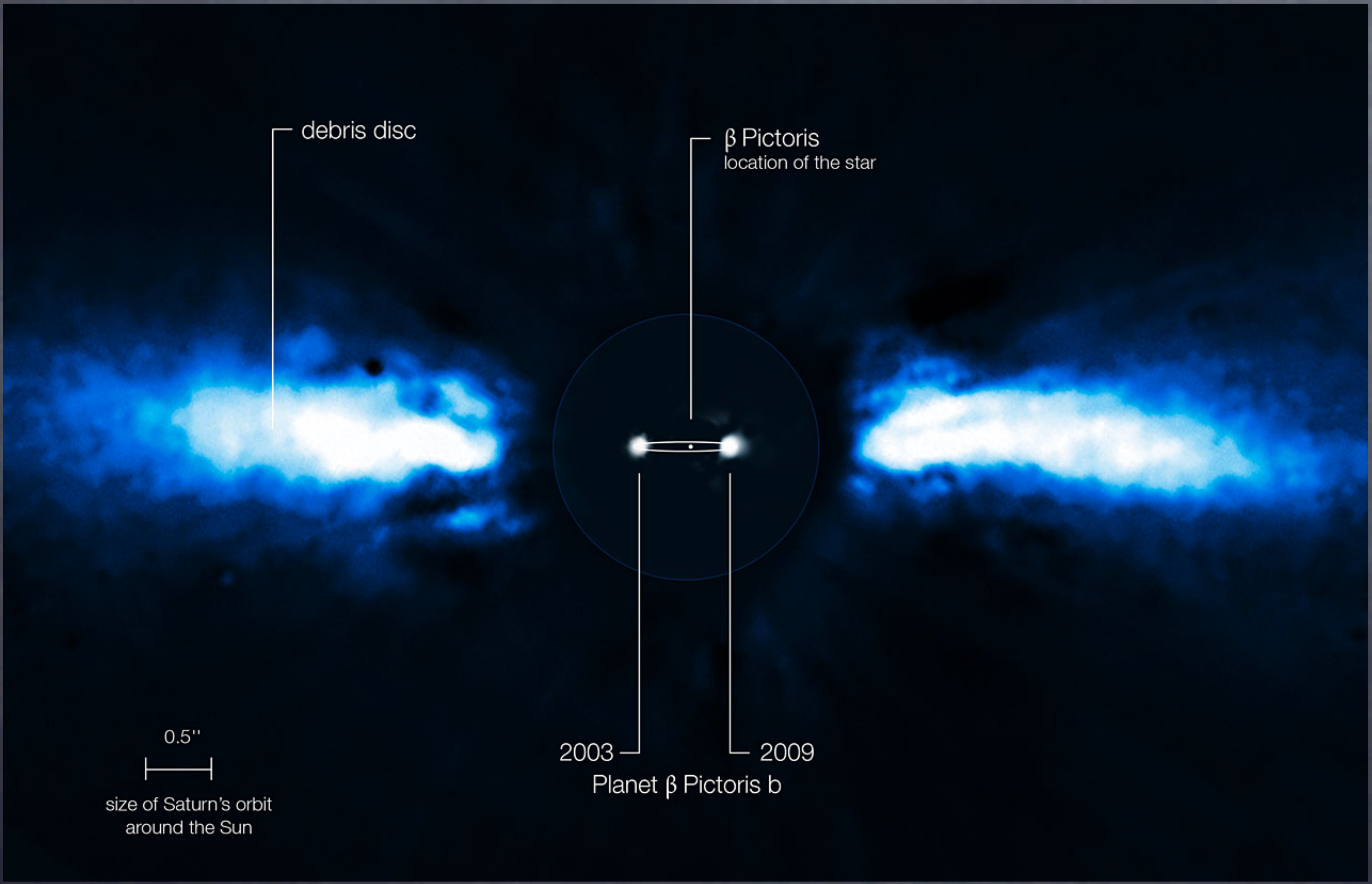
Grenoble's Exoplanet (Beta Pic b)



Dynamics (astrometry) can now be used to estimate exoplanet masses, independently from the luminosity-evolution models (photometry).

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2012-03-22

Mining the the IRAS catalog for new candidate debris disks:

Cross correlate positions of FIR point sources with optical catalogs of stars. Approximately ~15% (±5%) of main-sequence stars have debris disks.

IRAS PSC v.2

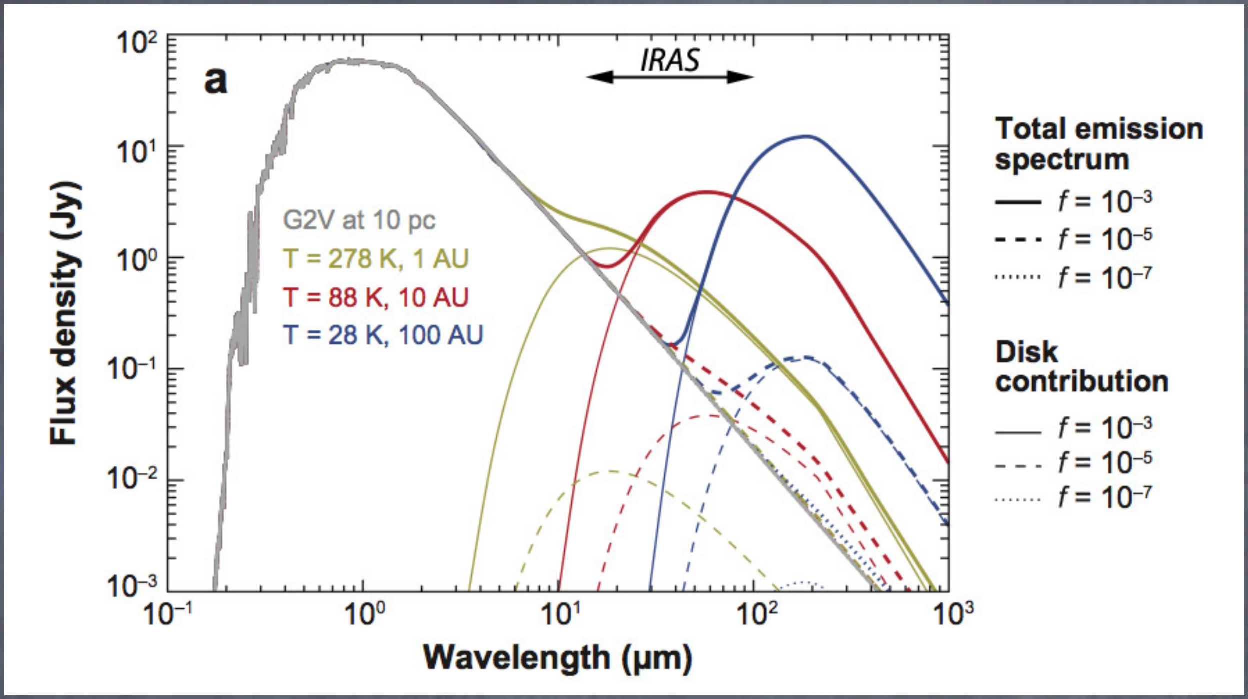
IRAS FSC

- Gliese
- Bright Star Catalog
- SAO
- Michigan Spectral

Aumann 85	12
Backman & Gillett 87	25
Walker & Wolstencroft 88	30
Backman & Paresce 93	75
Mannings & Barlow 98	193; 60 new

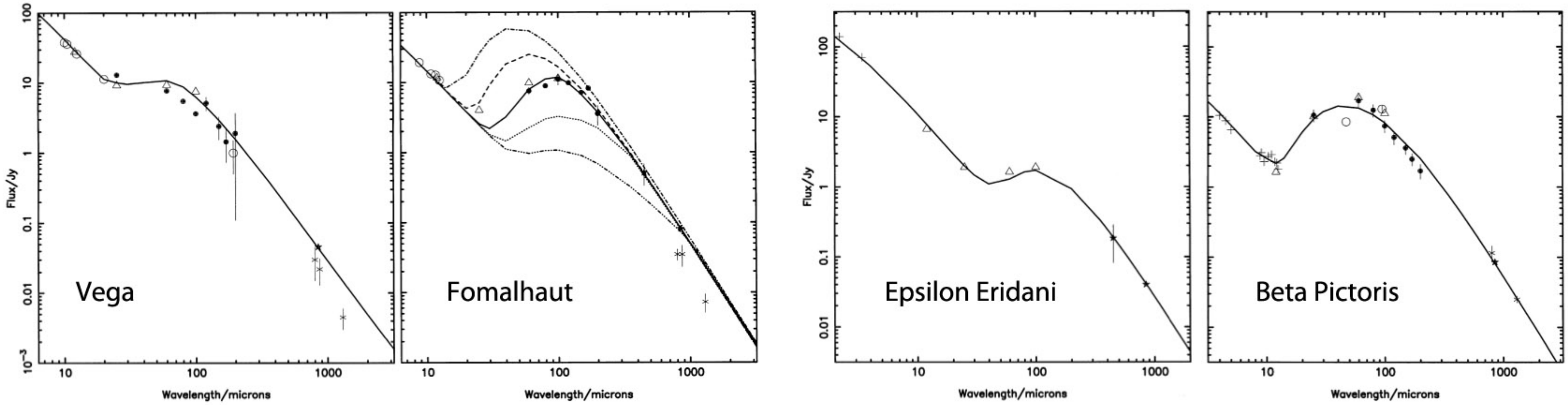
IRAS continues to yield valuable science; e.g. Zuckerman & Song 2004, Moor et al. 2006, Rhee et al. 2007.

From IRAS data can infer the structure of debris disks because temperature gives dust location – all debris disks have central depletions



Mark Wyatt 2008 ARAA

Dent et al 2000



IRAS key results (1984 - 2004 – present day):

(1) Frequency of debris disks: ~15% of A – K stars have debris disks (what about the M stars?)

(2) Temperature -> Location -> Structure of debris disks (central holes - evidence for planetary systems)

This early paper sums up the core findings from IRAS

EXPLOITING THE INFRARED: IRAS OBSERVATIONS OF THE MAIN SEQUENCE

D. E. Backman and F. C. Gillett

ABSTRACT. We examined coadded IRAS survey data on samples of nearby main sequence stars in search of far-IR excesses similar to examples attributed to clouds of orbiting grains. Of 134 systems, 25 (19%) show significant excesses at 25, 60, or 100 μm with color temperatures greater than 35 K.

Frequency

Approximately 15% of the stars have excess more luminous than 2×10^{-5} L_*, roughly independent of spectral type. Several stars with excesses appear to be older than 2×10^9 yrs, indicating that the particle cloud phenomenon is not solely a feature of young objects.

Diversity

Models of three prominent clouds that have been spatially resolved (β Pic, α PsA, and α Lyr) imply central depleted regions with radii of order 20 AU. One possible explanation for maintenance of the depleted regions is that a planet orbits at and defines each cloud's inner boundary, sweeping up particles entering that region.

Planet connection

The sun could have a cloud with similar geometry and somewhat smaller optical depth than these examples which would be difficult to detect from earth because of bright zodiacal and galactic emission.

Kuiper Belt should exist

Backman & Gillett 1987

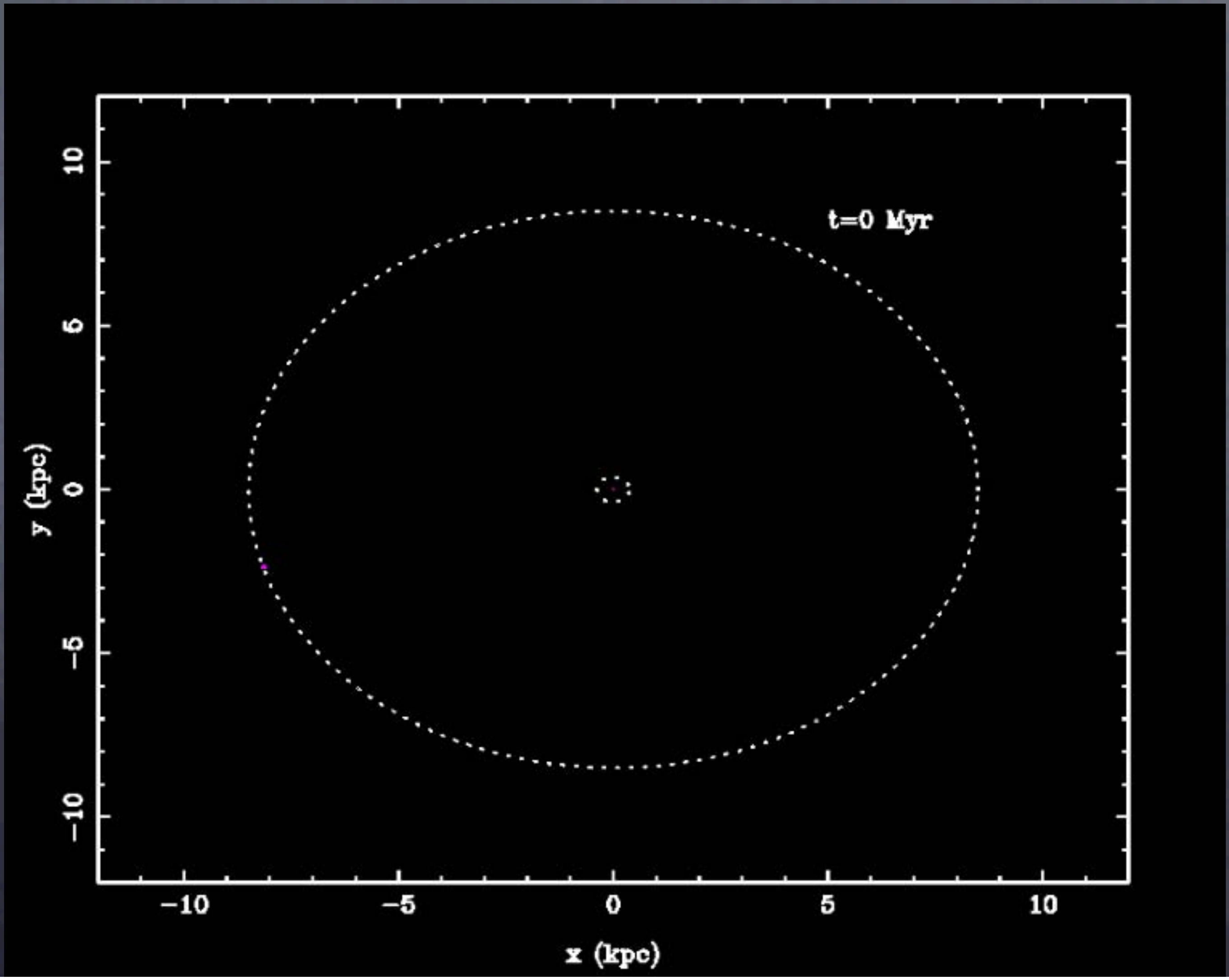
After IRAS, we wanted to explore:

Why do some stars have debris disks and others do not?

What is the evolution over time?

Need ages – central importance of the Hipparchos Mission

1. Find moving groups (i.e. derive U,V,W using Hipparcos and RV from ground)



Need ages – central importance of the Hipparchos Mission

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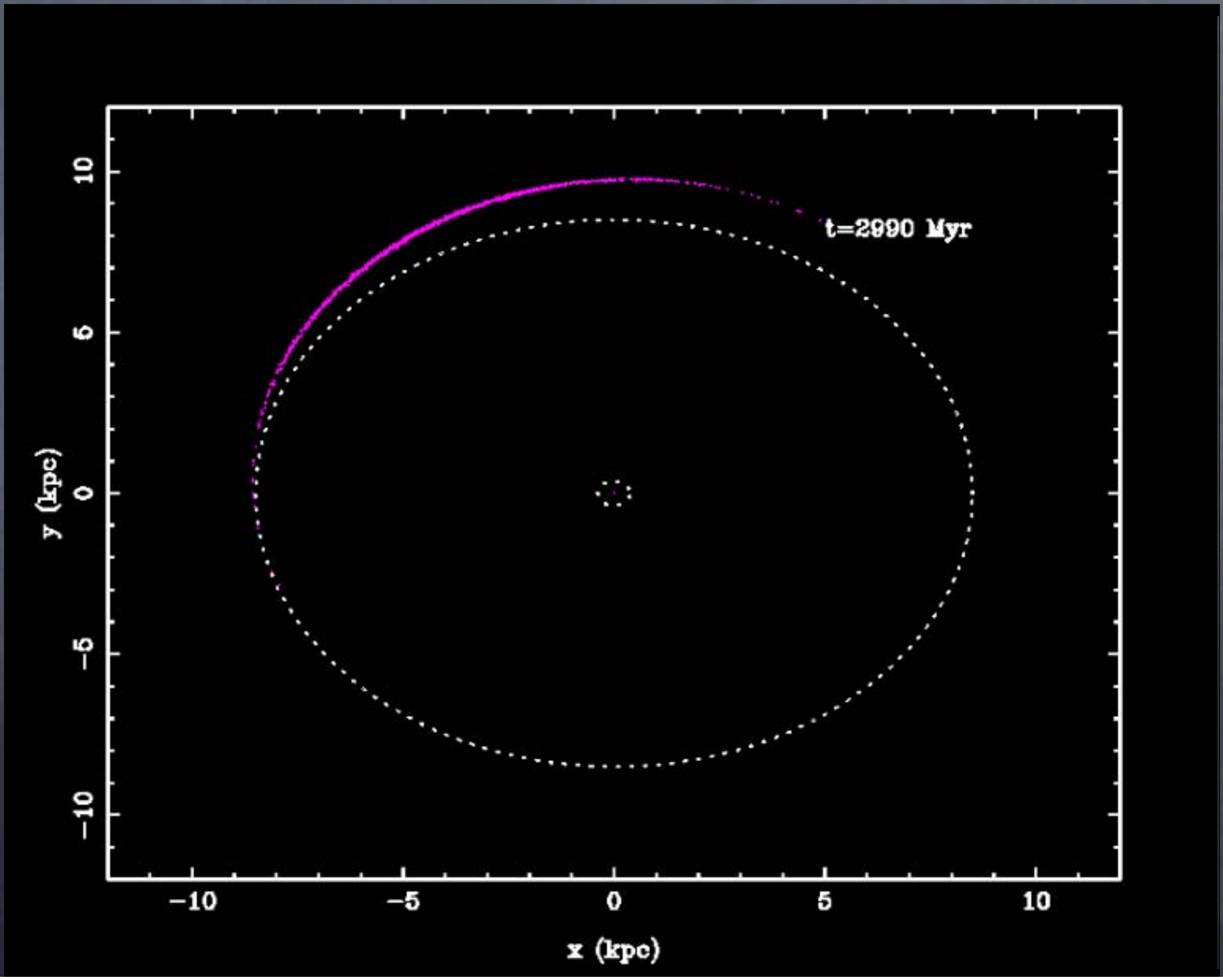


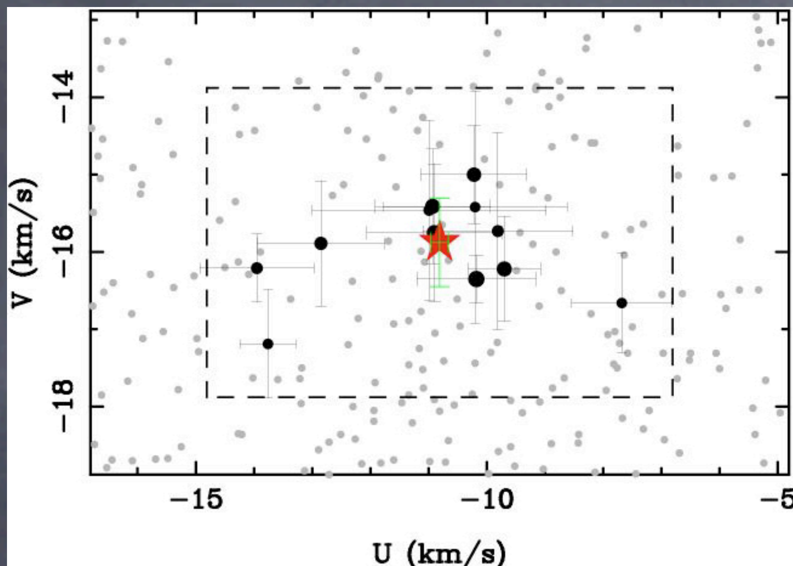
For example: The Beta Pic Moving Group

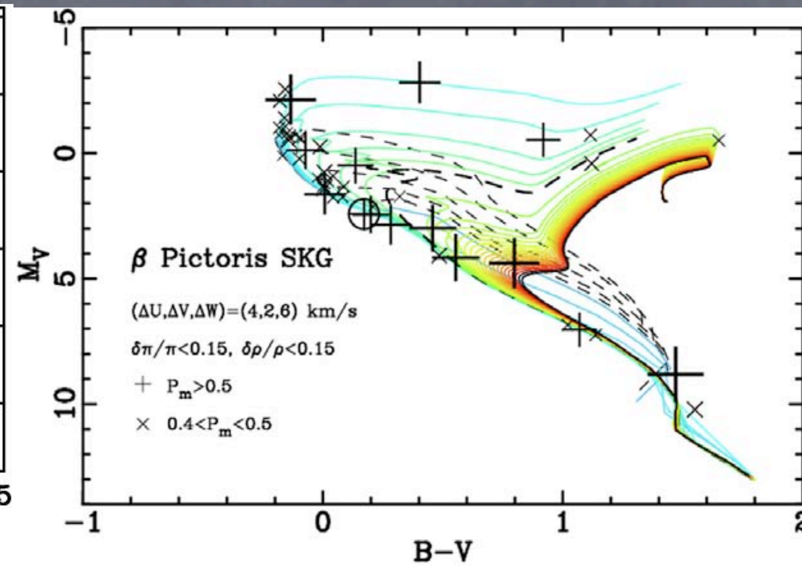
Observables: α, δ, μ_α, μ_δ, π, R_v ----> l, b, U, V, W

Hipparcos Catalog: 118,218 stars

Barbier-Brossat & Figon (2000): 36,145 stars

Determine U, V, W for 21,497 stars





Follow-up with spectroscopy and search for age indicators:

see papers by Zuckerman, Song, Bessel, Webb, Barrado y Navascues, Stauffer, et al.

THE ASTROPHYSICAL JOURNAL, 562:L87–L90, 2001 November 20

THE β PICTORIS MOVING GROUP

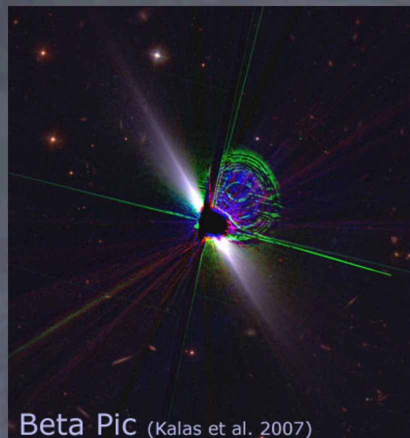
B. ZUCKERMAN AND INSEOK SONG

M. S. BESSELL R. A. WEBB

Beta Pic moving group

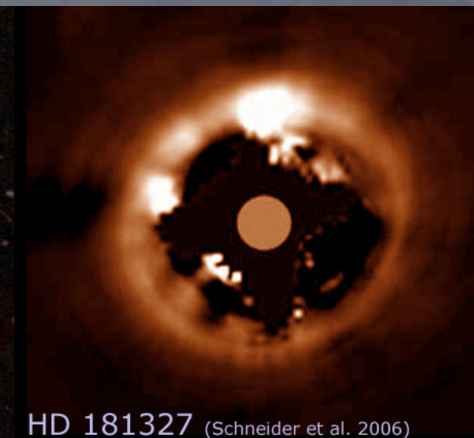
Age ~ 12 Myr, d < 50 pc

Sister Disks: The Beta Pic Moving Group (age ~ 12 Myr)

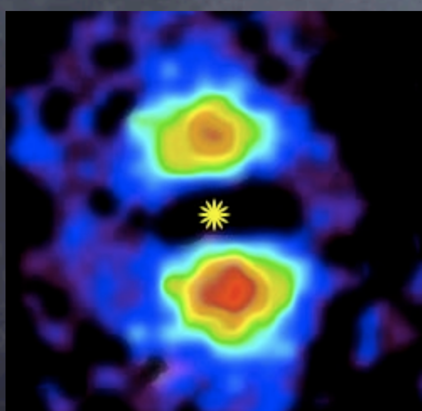


Beta Pic (A5V)

AU Mic (M2V)

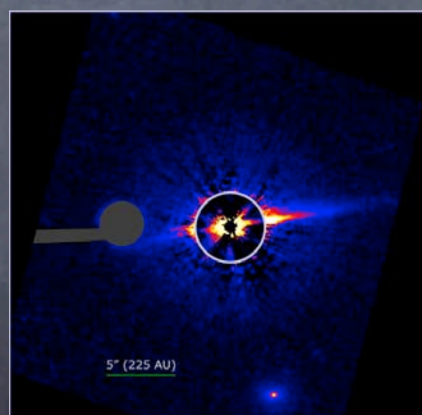


HD 181327 (F5.5V)



Eta Tel (A0V)

Smith et al. 2009



HD 15115 (F2V)

Kalas et al. 2007

Vexing unanswered question: Stars with a common origin, yet their circumstellar material organized differently?

Star	SpT	Optical depth
Beta Pic	A5V	24.3+/-1.1
HD 15115	F2V	4.9 +/- 0.4
HD 181327	F5.5V	29.3+/-1.6
AU Mic	M2V	4.0 +/- 0.3

Dust depletion

Paul Kalas
2012-03-22

After IRAS, we wanted to explore:

Why do some stars have debris disks and others do not?

Some nearby stars were discovered to be young, and debris disks are detectable at early ages.

Nevertheless, there is significant diversity – not all 10 Myr old stars have debris disks, and there is diversity in the debris disks that are detected.

What is the evolution over time?

ISO (1999 –)

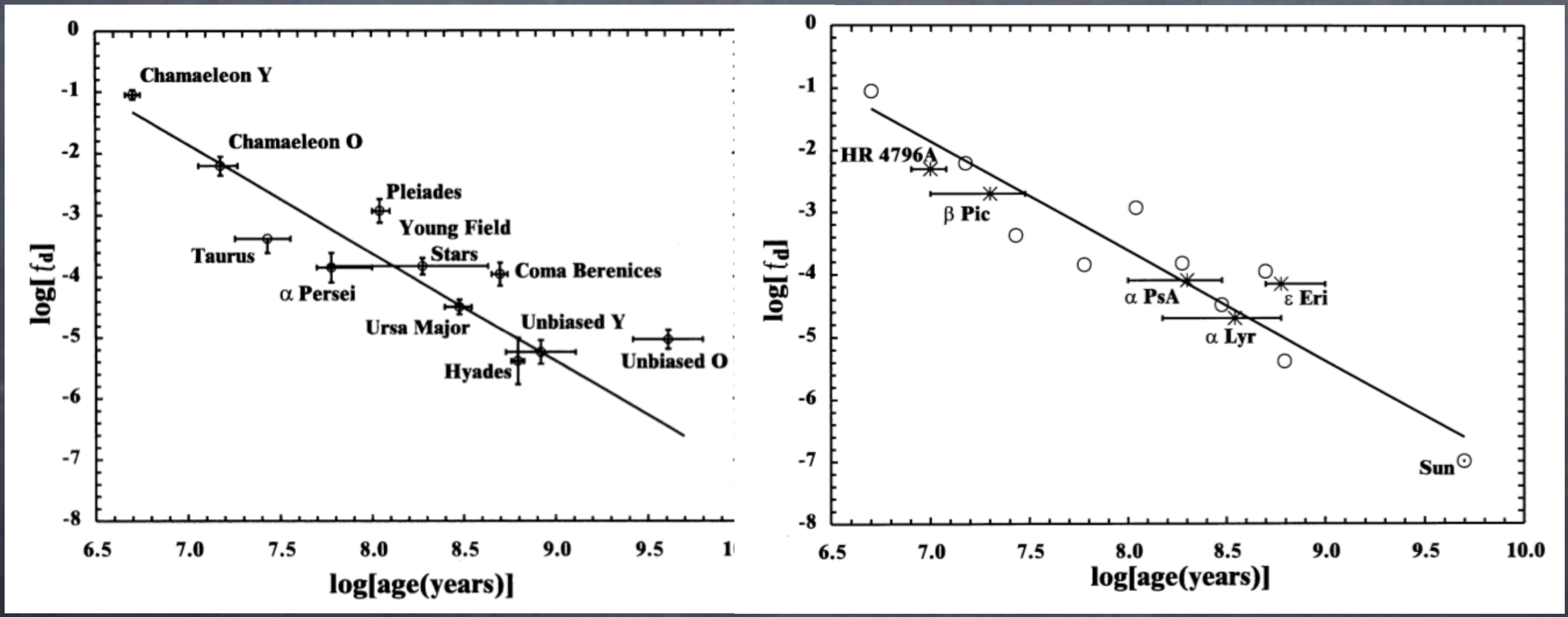
“*Disappearance* of stellar debris disks around main-sequence stars after *400 million years*” Habing et al., 1999

“The Vega Phenomenon around *G dwarfs*” Decin et al. 2000

“Dusty debris around *solar-type stars*: *Temporal* disk evolution” Spangler et al., 2001

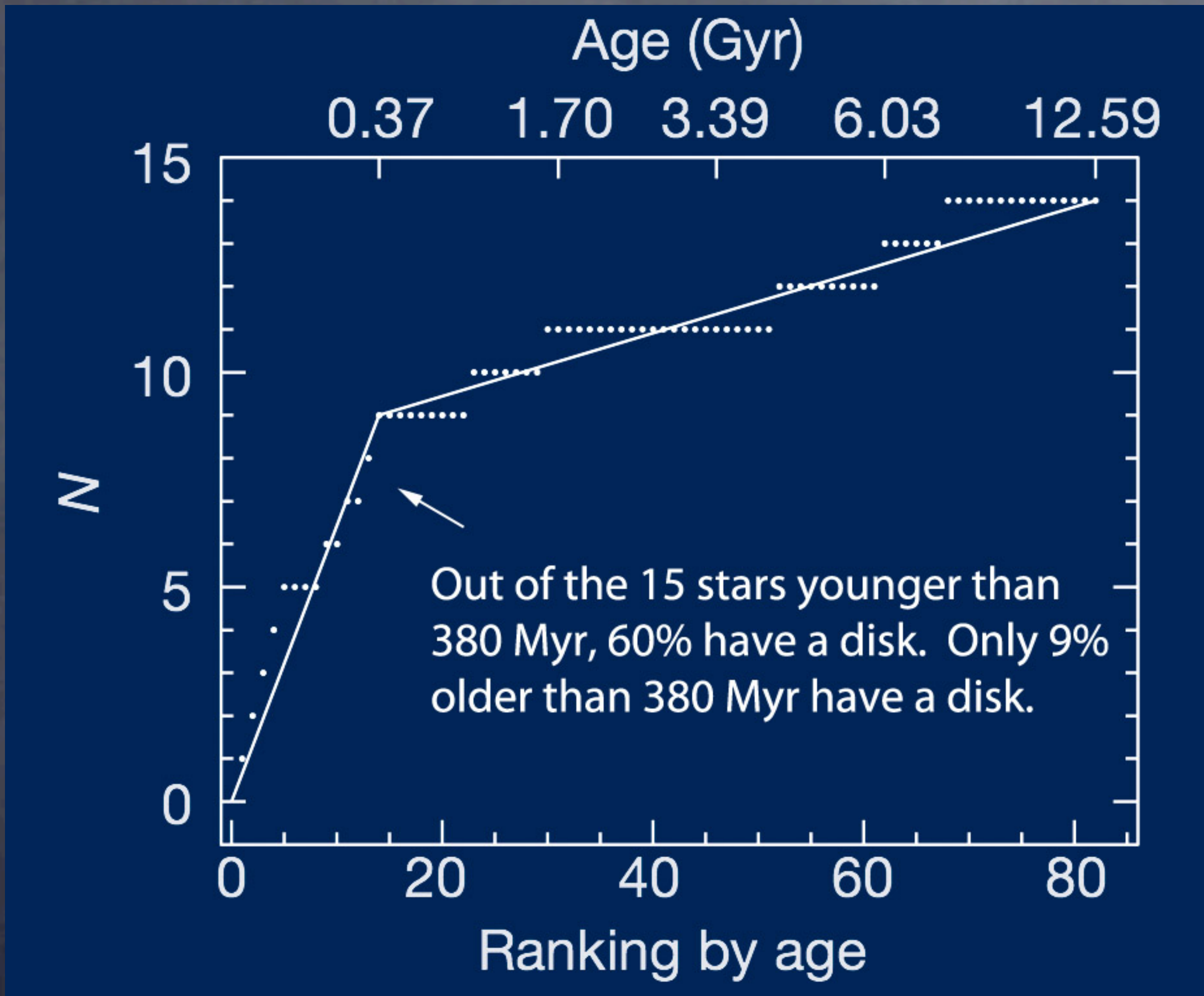
“Incidence and *survival* of remnant disks around main-sequence stars” Habing et al. 2001

“The *age dependence* of the Vega Phenomenon: Observations” Decin et al. 2003



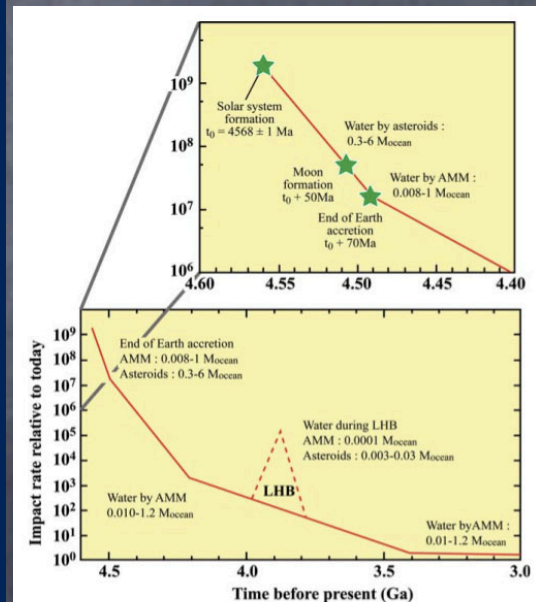
Spangler et al. 2001, solid line fit shows age$^{-1.76}$ dependence

ISO (1999 –)



Habing et al. 1999 (see also Habing et al. 2001)

Inner solar system



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2012-03-22

After IRAS, we wanted to explore:

Why do some stars have debris disks and others do not?

Some nearby stars were discovered to be young, and debris disks are detectable at early ages.

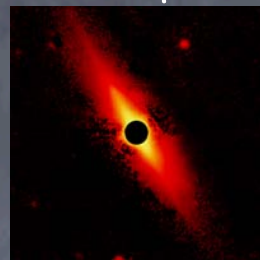
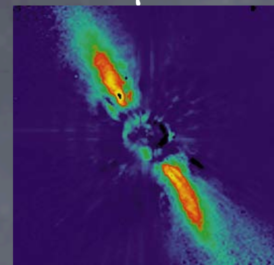
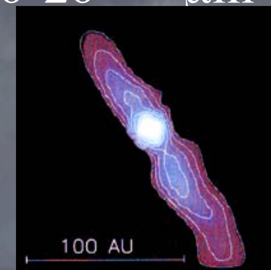
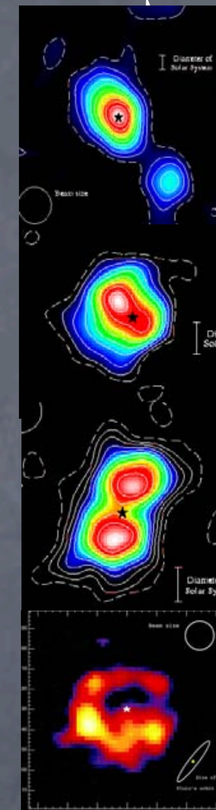
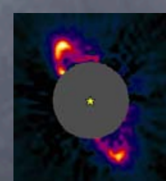
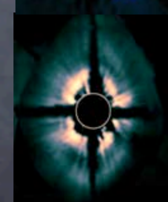
Nevertheless, there is significant diversity – not all 10 Myr old stars have debris disks, and there is diversity in the debris disks that are detected.

What is the evolution over time?

ISO results suggest t^{-2}, but with significant differences at any given age.

Delayed stirring (late planet formation far from star) could cause rapid evolution overall, and older stars could have prominent debris disks (Dominik & Decin 2003, Kenyon & Bromley models).

In general, the frequency of debris disks drops significantly to <10% at around 400 Myr. Need a larger sample.

	0.5 µm	2.2 µm	10-20 µm	850 µm
β Pic			 	
Vega				
Fomalhaut				
ε Eri				
HR 4796A		HST/NICMOS 		JCMT/SCUBA
HD 141569				

1998-1999 HST/NICMOS & JCMT SCUBA2
New resolved Images &
connection to planetary dynamics

Resolved images of dust
structure linked to unseen planets

11:10 - 11:50 *Modeling/theory review:* Debris Discs: Modeling/theory review — *P. THEBAULT, Observatoire de Paris*

See the Image Gallery in the Circumstellar Disk Learning Site for citation information on each image shown above:
http://www.disksite.com

Paul Kalas
2012-03-22

HST Advanced Camera & Spitzer

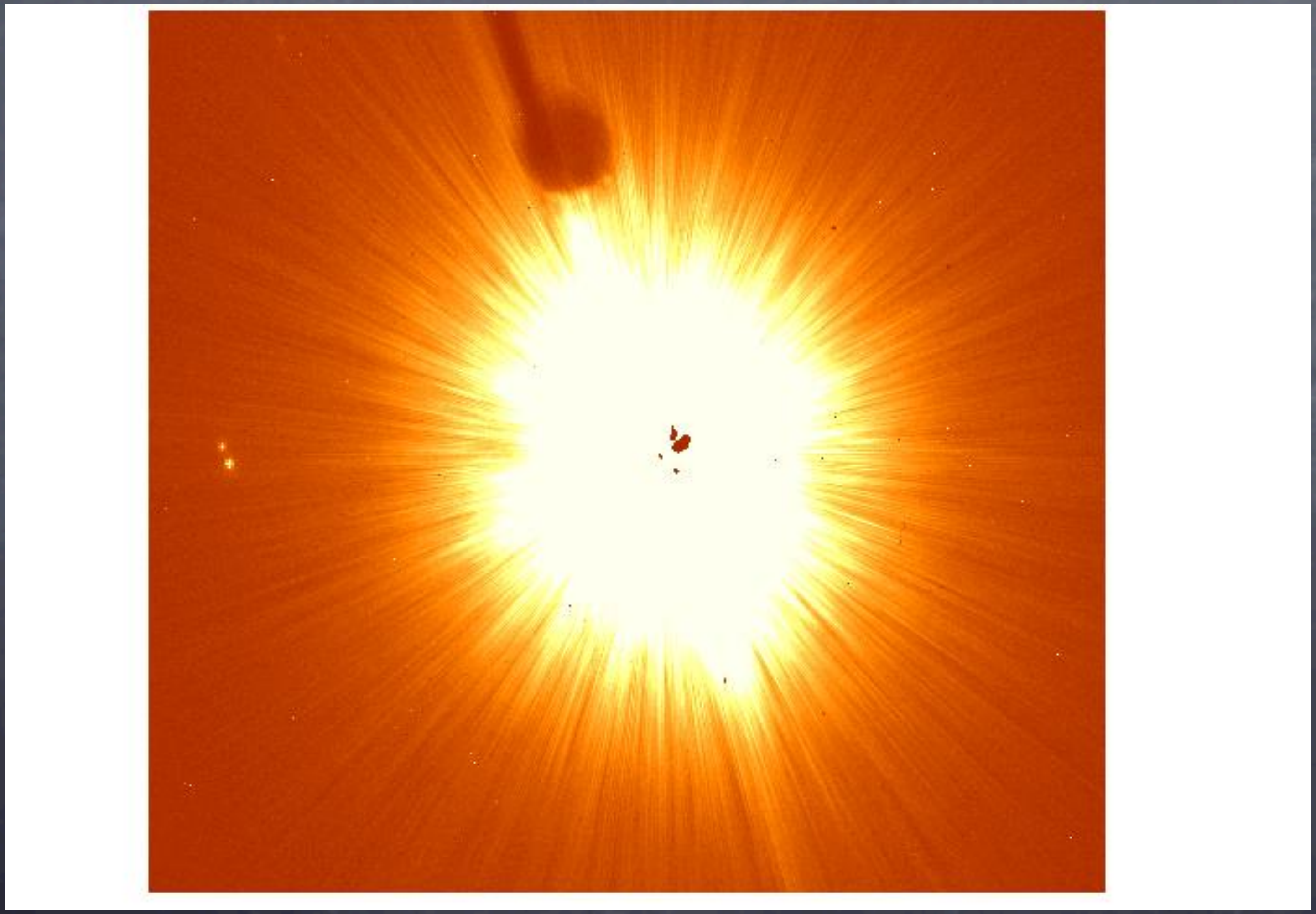
March, 2002

August, 2003

Paul Kalas
2012-03-22

ACS High Resolution Channel Coronagraph

ζ Lep, V=3.5, SpT=A2V, d = 22 pc, τ_{IR} = 0.1 x β Pic



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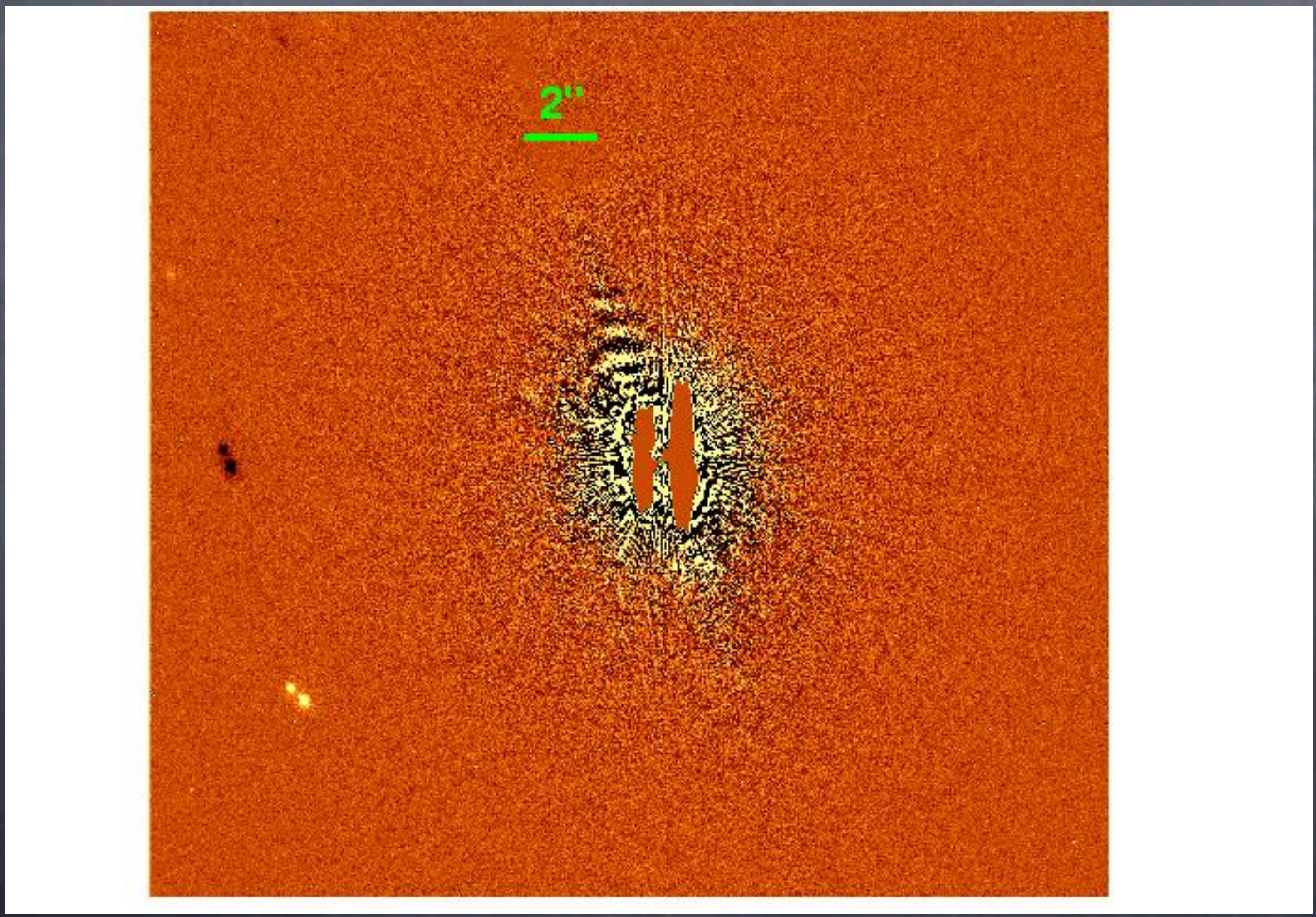
2012-03-22

Telescope Roll with PSF Self Subtraction

ζ Lep, V=3.5, SpT=A2V, d = 22 pc, τ_{IR} = 0.1 x β Pic



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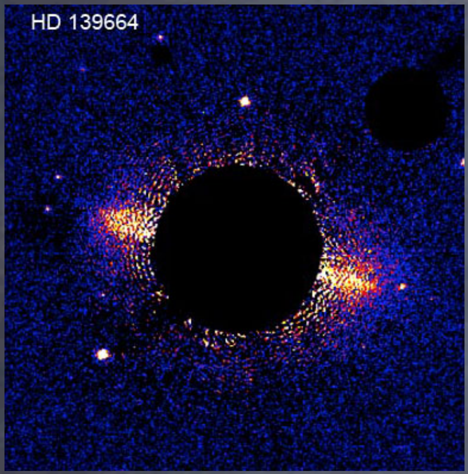
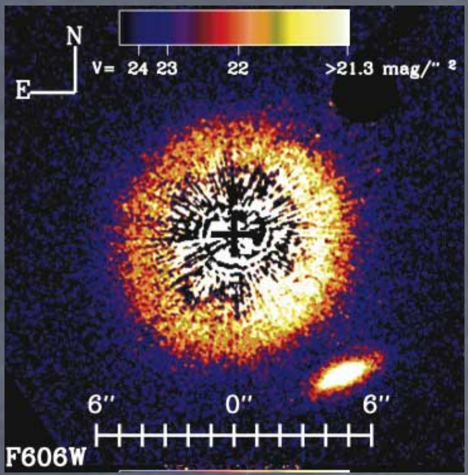
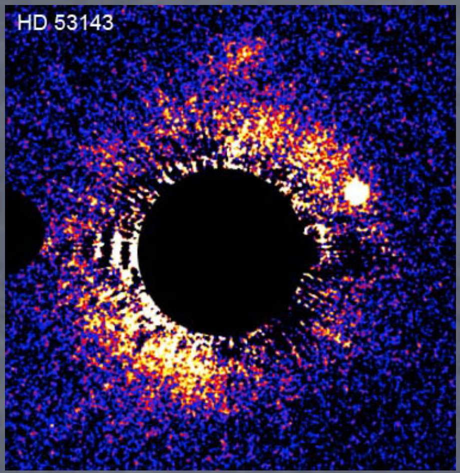
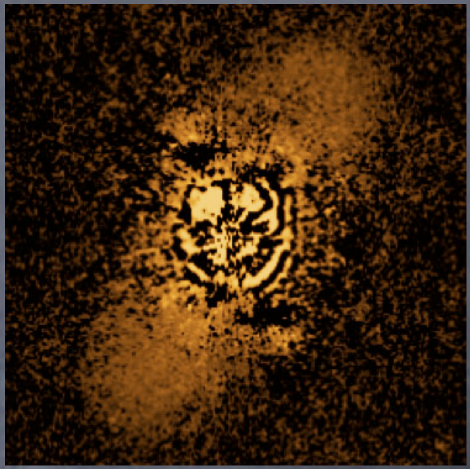
Finally have sensitivity to image debris disks around solar type stars









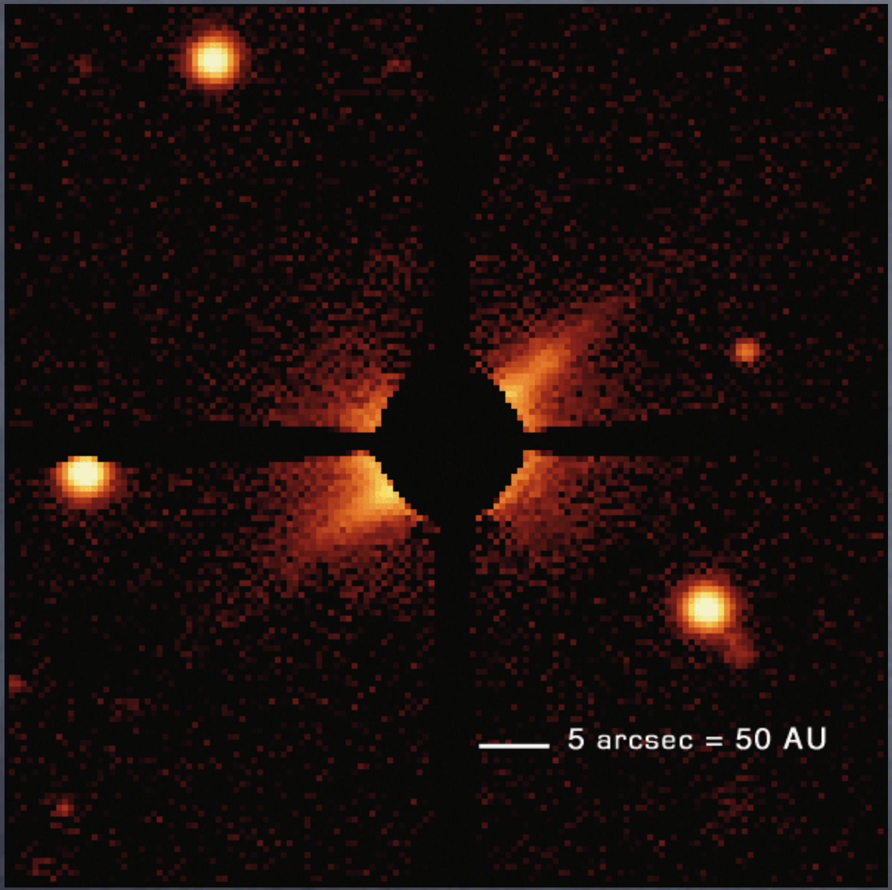
HD 139664
SpT=F5V
d=17.5 pc
age = 300 Myr
60 - 109 AU
Kalas et al. 2006

HD 107146
SpT=G2V
d=28.5 pc
age = 100 Myr
60 - 185 AU
Ardila et al. 2004

HD 53143
SpT=K1V
d=18.4 pc
age = 1.0 Gyr
>110 AU
Kalas et al. 2006

HD 92945
SpT=K1V
d = 22 pc
age = 100 Myr
>146 AU
Clampin et al. 2006

AU Mic Discovery Image: Kalas, Liu, & Matthews 2004



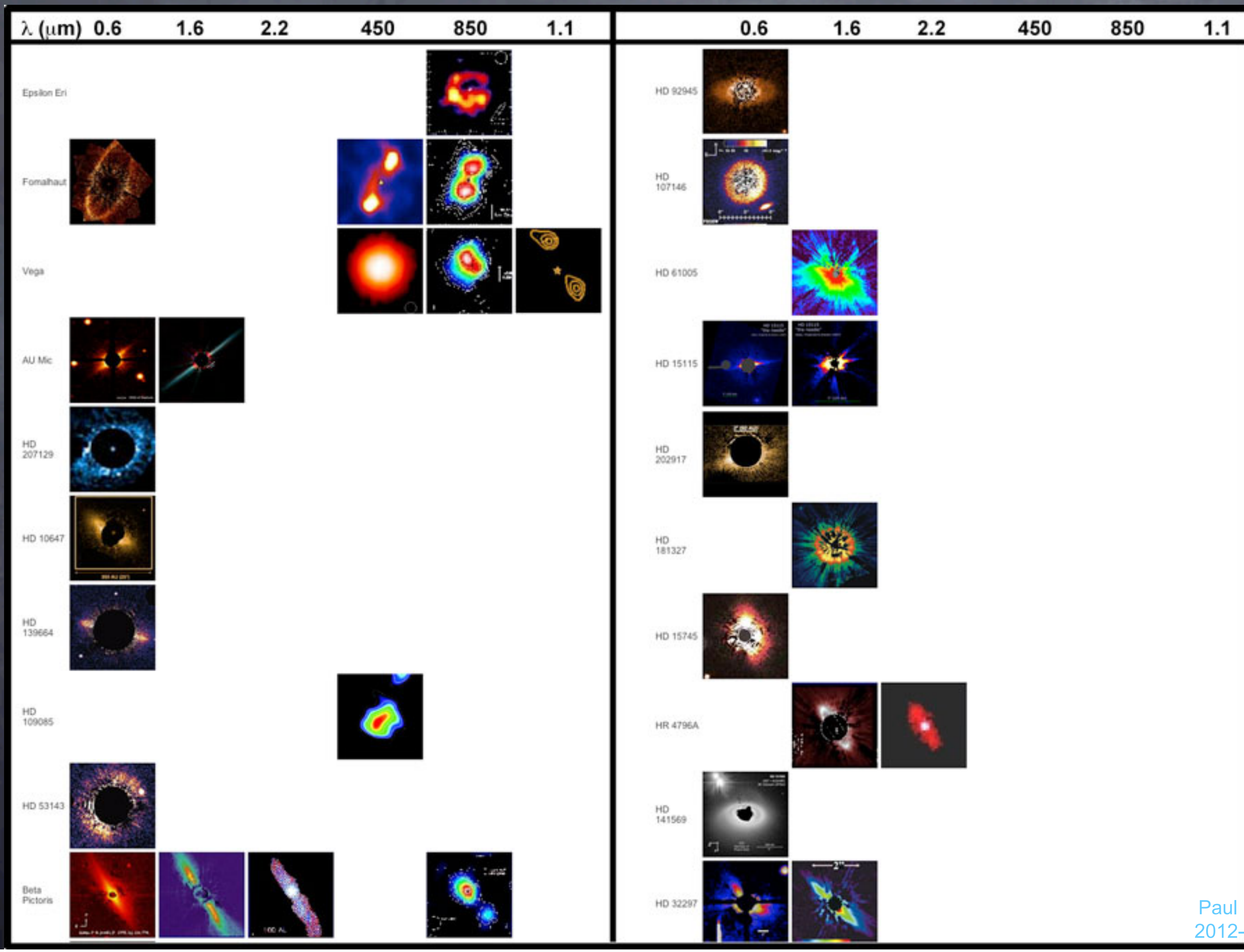
M star at 10 pc
1 arcsec = 10 AU

One of the closest flare stars:
Distance = 9.9 pc
SpT = M1Ve
Mass = 0.5 M_{sun}
Radius = 0.56 R_{sun}
T_{eff} = 3500 K
Luminosity = 0.1 L_{sun}
M_v = 8.8 mag
Period = 4.865 d
Avg. Mag. Field: B = 4000 G
Hα Equivalent Width = 8.70
Quiescent X-ray flux:
$\log_{10}(L_x)$ = 29.8 erg/s
Age: Young

R-band, UH 2.2 m telescope, 0.4"/pix, 900 s, seeing FWHM = 1.1"

Debris Disk Snapshot: 2008

http://www.disksite.com/



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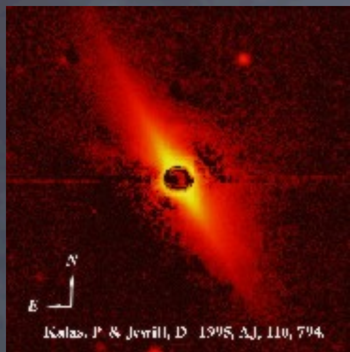
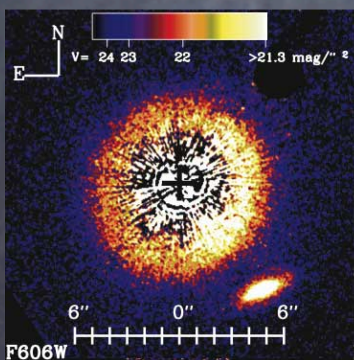
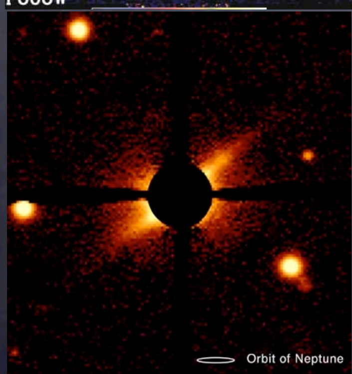
Possible disk “types”:

1. Do these trace fundamentally different distributions of underlying planetesimal population?
2. Are these different stages of debris disk evolution, or fundamentally different, long lived architectures?
3. Where does the solar system fit in?

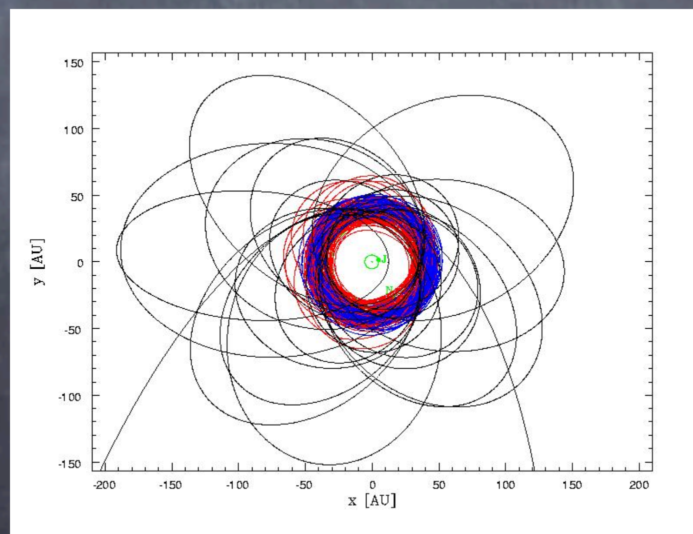
Wide Disks (>55 AU extent)



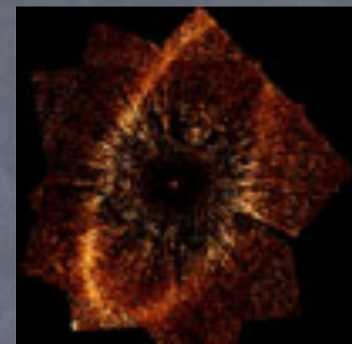


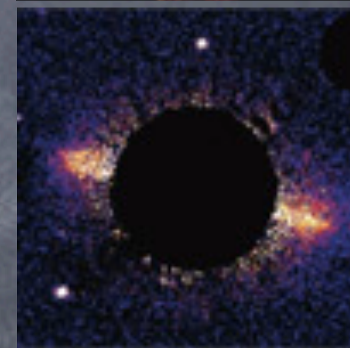


Solar system



Narrow Belts (20-30 AU extent)





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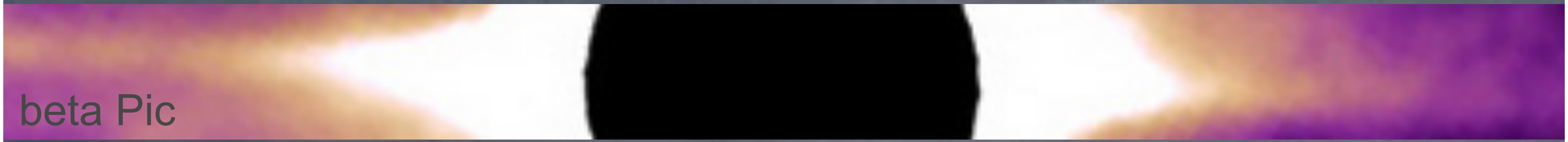
Architectures: Physical extent

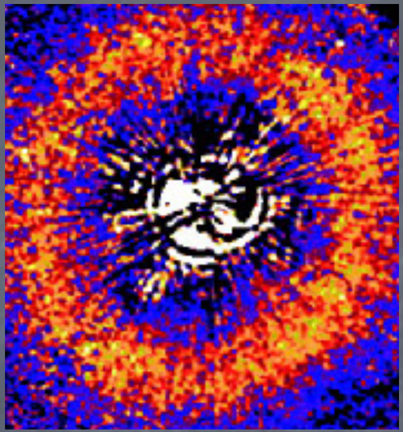
>>800 AU



AU Mic

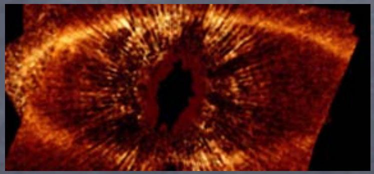
>200 AU

HD 107146



170 AU

Fomalhaut

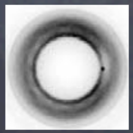


140 AU

HR 4796A

70 AU

Sun



50 AU

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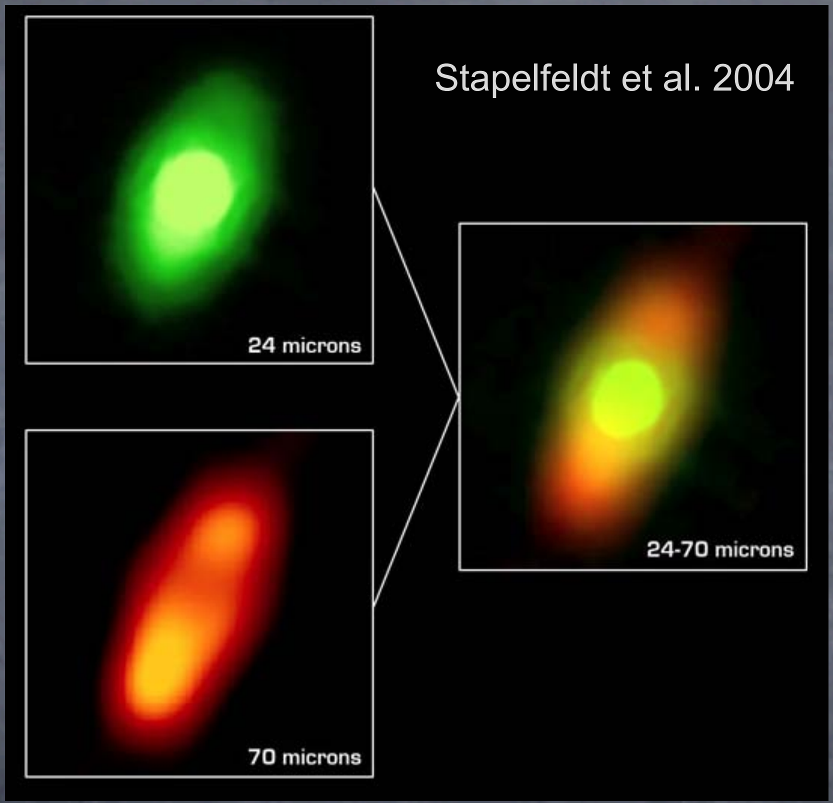
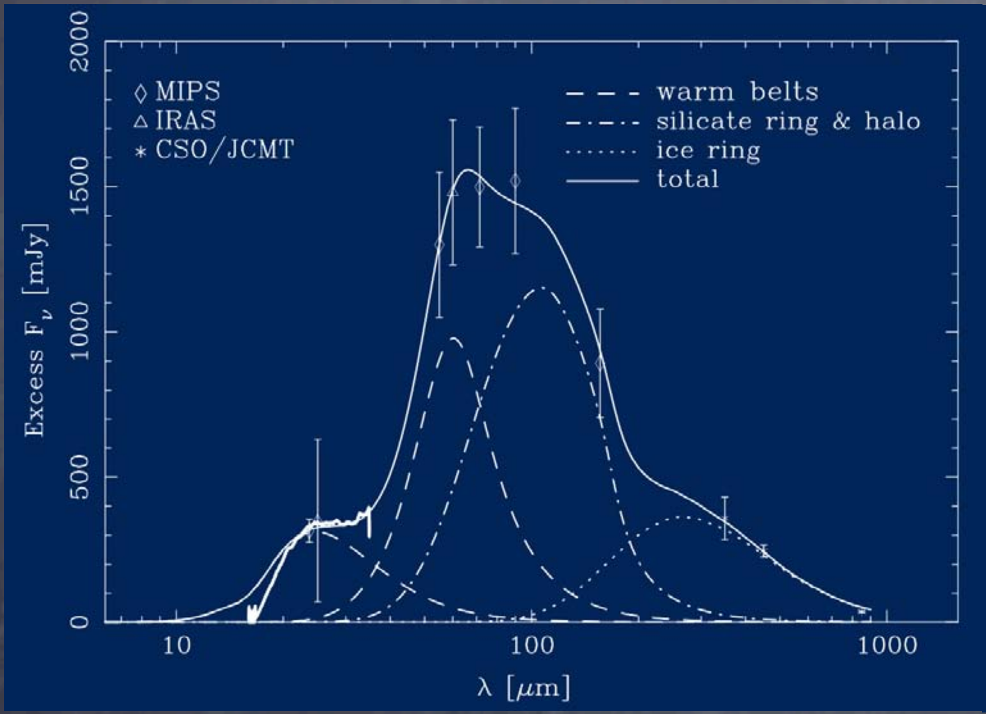
Spitzer also produced resolved images of debris disks

Fomalhaut at 24 & 70 micron imaging

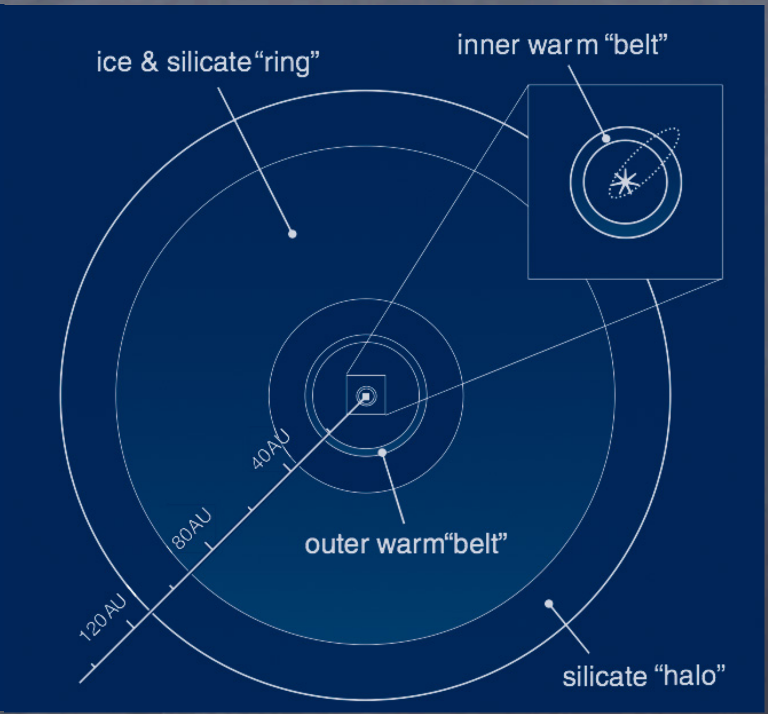


Spatially resolved at 24, 70 & 160 μm
Asymmetry could be due to a secular perturbation of a planet at 40 AU.
(see also Marsh et al. 2005, planet at 86 AU)

Spitzer observations of Epsilon Eridani (Backman et al. 2009)



Eps Eri SED after subtracting the stellar photosphere



Planet between the warm & cold dust belts? Planets produce both the ring edges and the clumpy azimuthal features seen in sub-mm maps?

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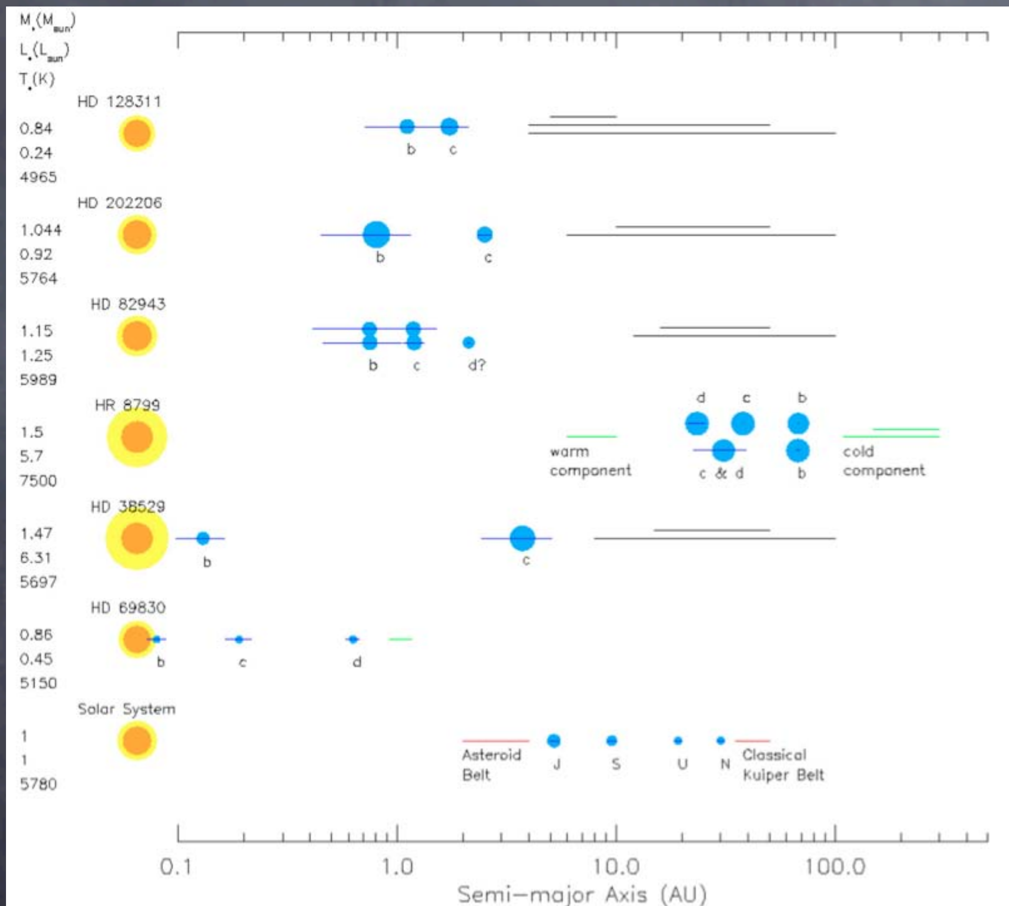
Spitzer: Debris Disk / Planet connexion

Multiple planet systems that also have debris disks (Moro-Martin et al. 2010)



Gray lines are the locations of planetesimal belts that could be inferred from Spitzer data, but need spatially *resolved* images to pin down the correct inner and outer belt boundaries.

Greaves 2004, Beichman et al. 2005, Bryden et al. 2009 also explore whether or not the frequency of debris disks differs between samples of stars that have detected planets, or do not have detected planets.

09:00 - 09:40	*Herschel overview:* Debris Discs and Connection to Exoplanets: Herschel Overview	*J. GREAVES, University of St Andrews*
11:50 - 12:10	• Study of debris disks in planet-host stars: are planets and debris correlated? Results from the DEBRIS and DUNES Herschel surveys	*A. MORO-MARTIN, Centro de Astrobiología (INTA-CSIC), Madrid* & Mark Wyatt

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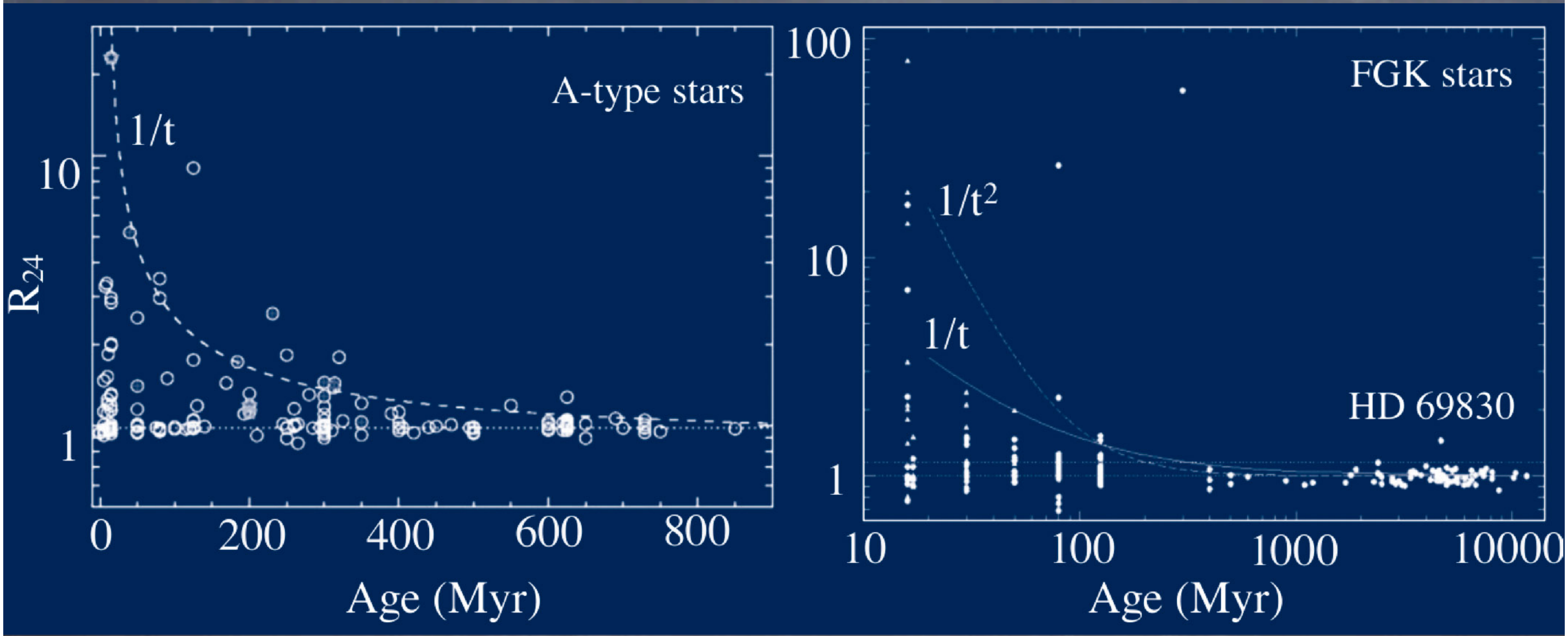
Spitzer: Evolution over time



Plots show 24 μm dust emission divided by stellar emission for A stars (Su et al. 2006) and FGK stars (Siegler et al. 2007)

Significant diversity at any given age, but evolution as t $^{-1}$ seems to describe the 24 μm (warm dust) data instead of t $^{-2}$

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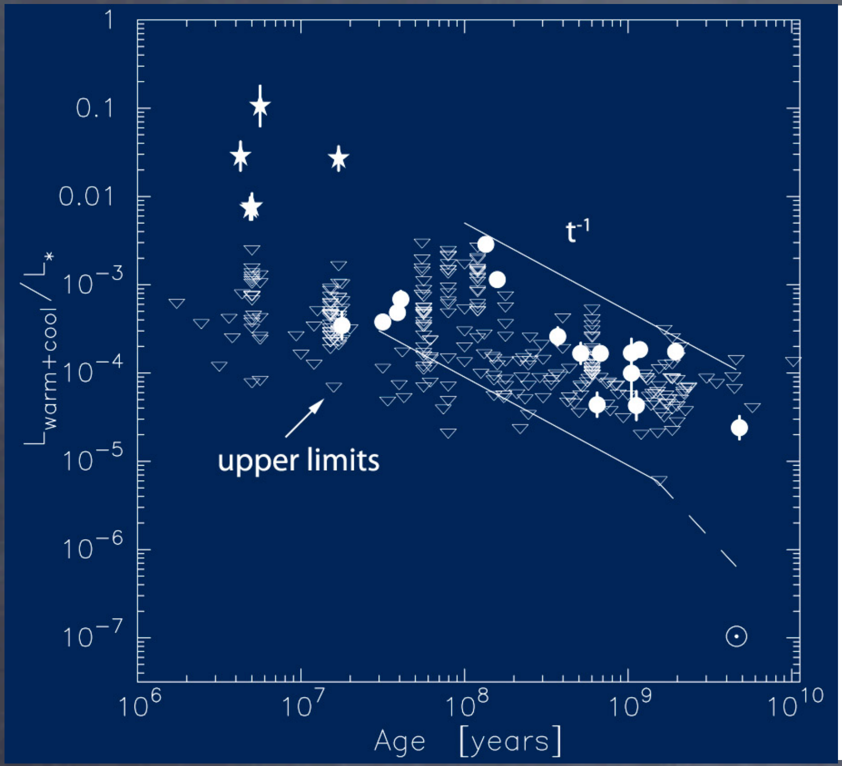
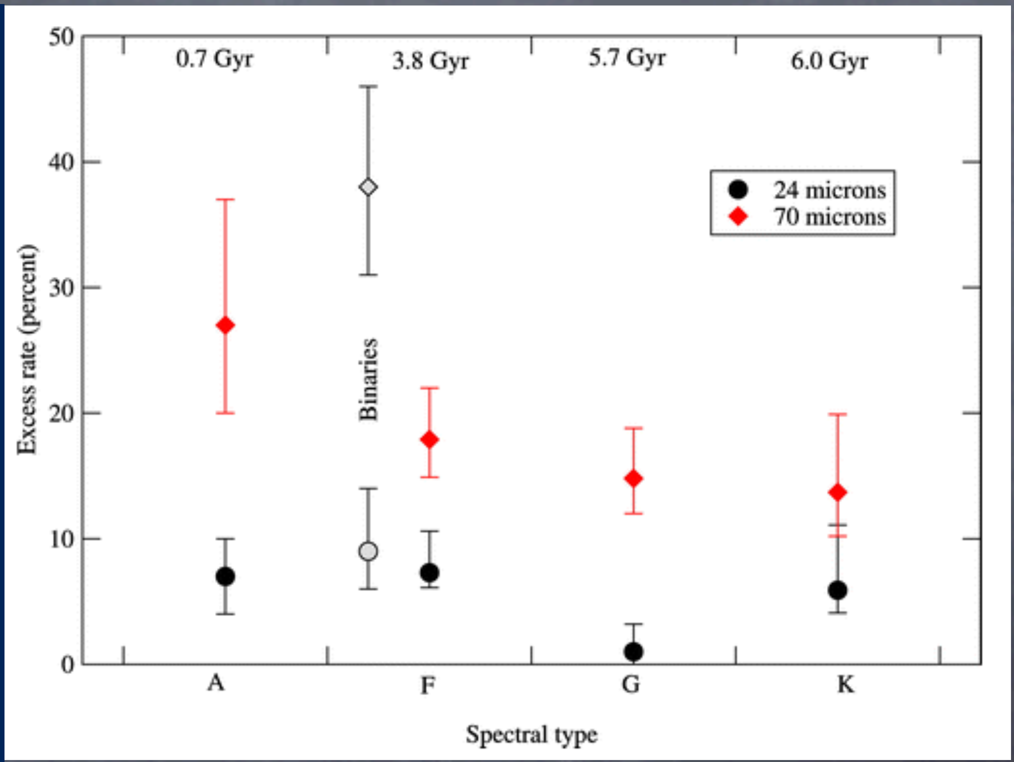
Spitzer: Frequency of Debris Disks

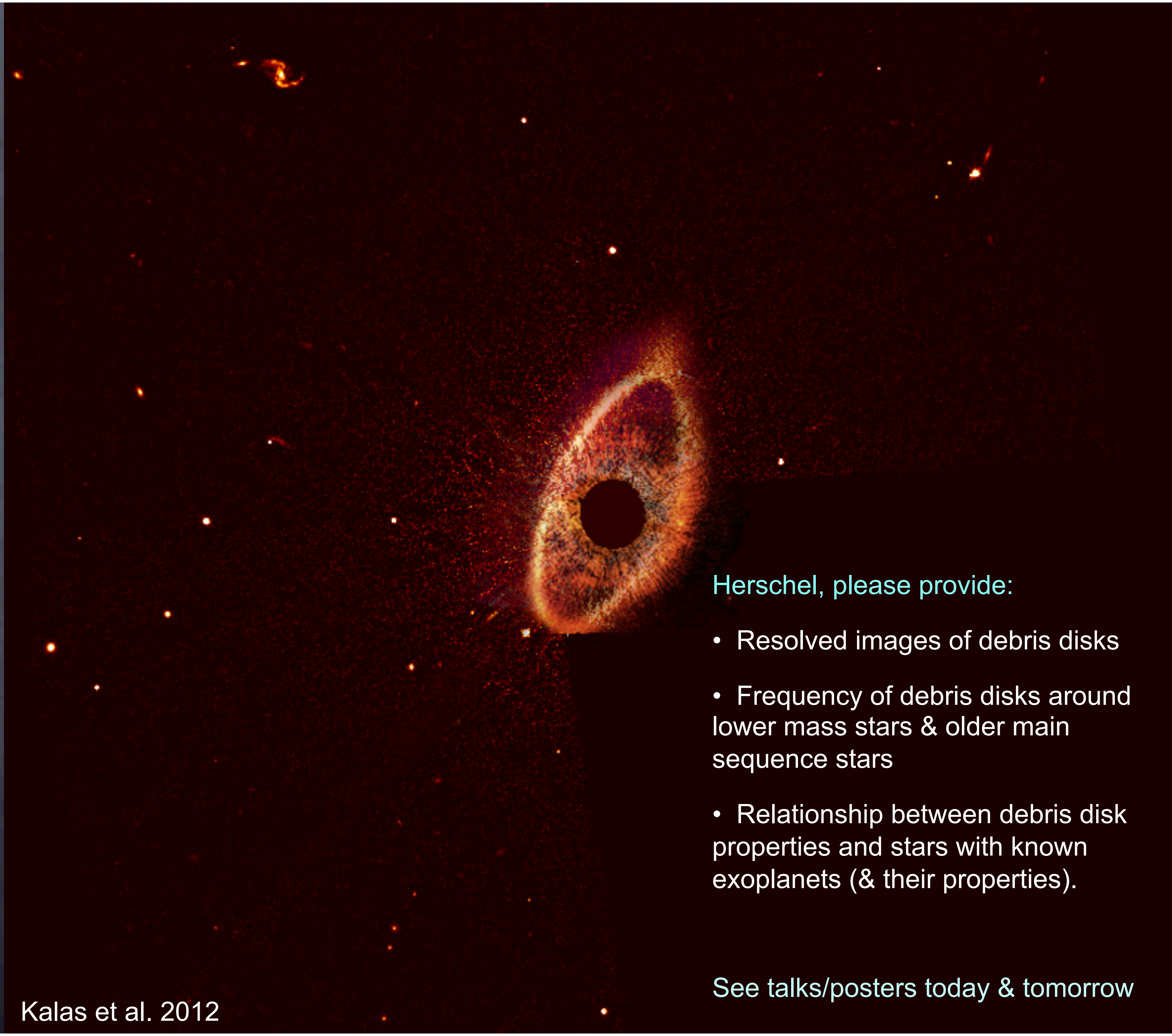


Carpenter et al. 2009



Trilling et al. 2008: For ages >0.6 Gyr

See also: Bryden et al. 2006, Meyer et al. 2008, Hillenbrand et al. 2008, Moor et al. 2011



Kalas et al. 2012

Herschel, please provide:

- Resolved images of debris disks
- Frequency of debris disks around lower mass stars & older main sequence stars
- Relationship between debris disk properties and stars with known exoplanets (& their properties).

See talks/posters today & tomorrow