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With thanks to
M. Wyatt,
P. Kalas,
L. Churcher,
G. Duchene,
B. Sibthorpe,
A. Roberge

Debris Disks: the first 30 years
Where will Herschel take us?

Brenda Matthews

Herzberg Institute of Astrophysics
& University of Victoria

CSA ASC

National Research Council Canada
Conseil national de recherches Canada

Canada

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Outline

- Debris disk: definition and discovery
- Incidence and evolution
- Characterizing debris disks
- Disks around low-mass stars (AU Mic)
- Planetary connection
- Herschel surveys

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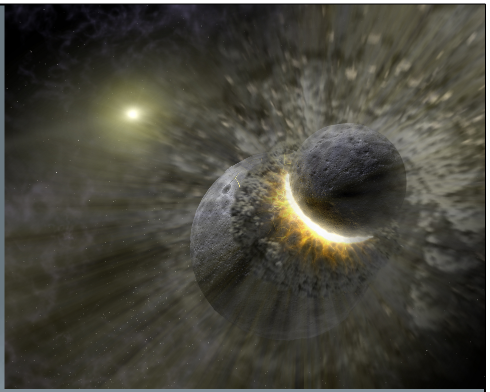
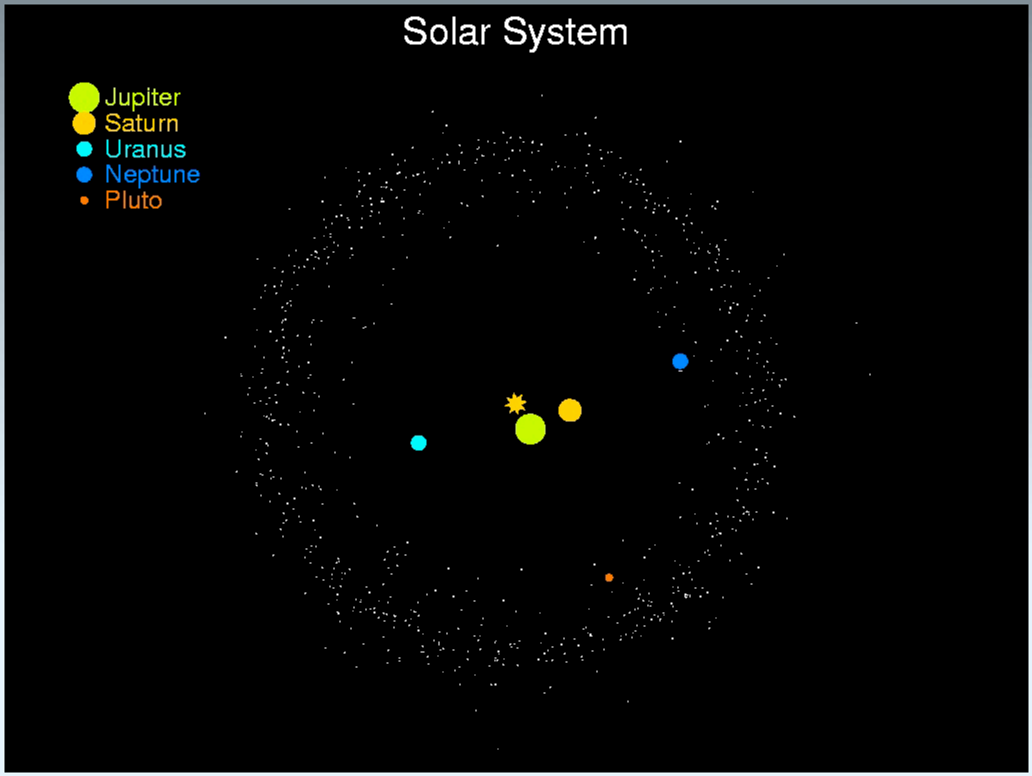
"Debris" Disks



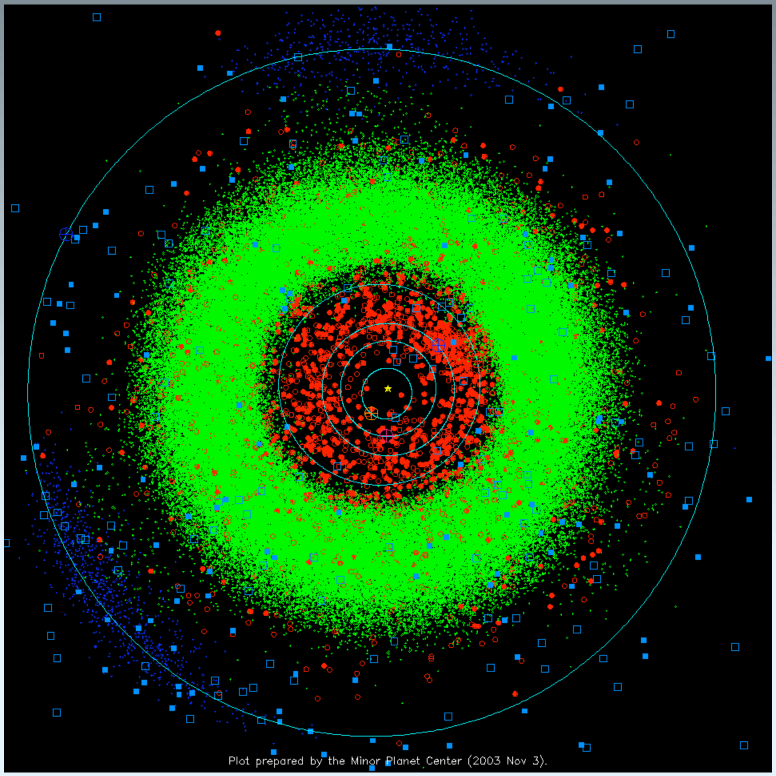
- Debris disks are produced from the remnants of the planet formation process

- Second generation dust is produced through collisional processes
- The debris disk can include
  - Planetesimal population (though not directly observable)
  - Dust produced (detectable from optical → centimetre)
    - Dust may lie in belts at various radii from the star

Solar System Debris Disk



Kuiper Belt



Asteroid Belt

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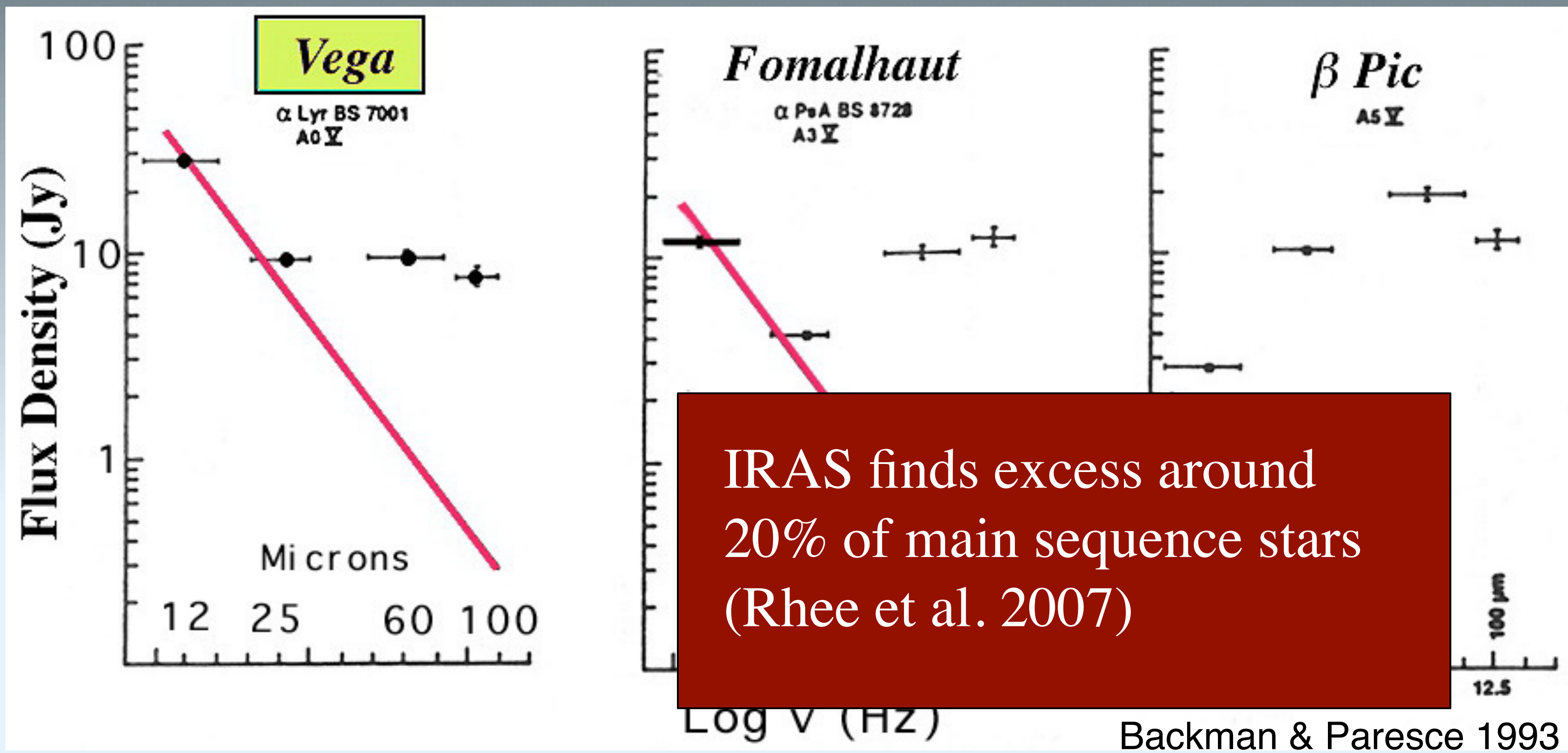
Debris Disk Snapshot: Zodiacal Light

Photo: Stefan Binnewies

"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

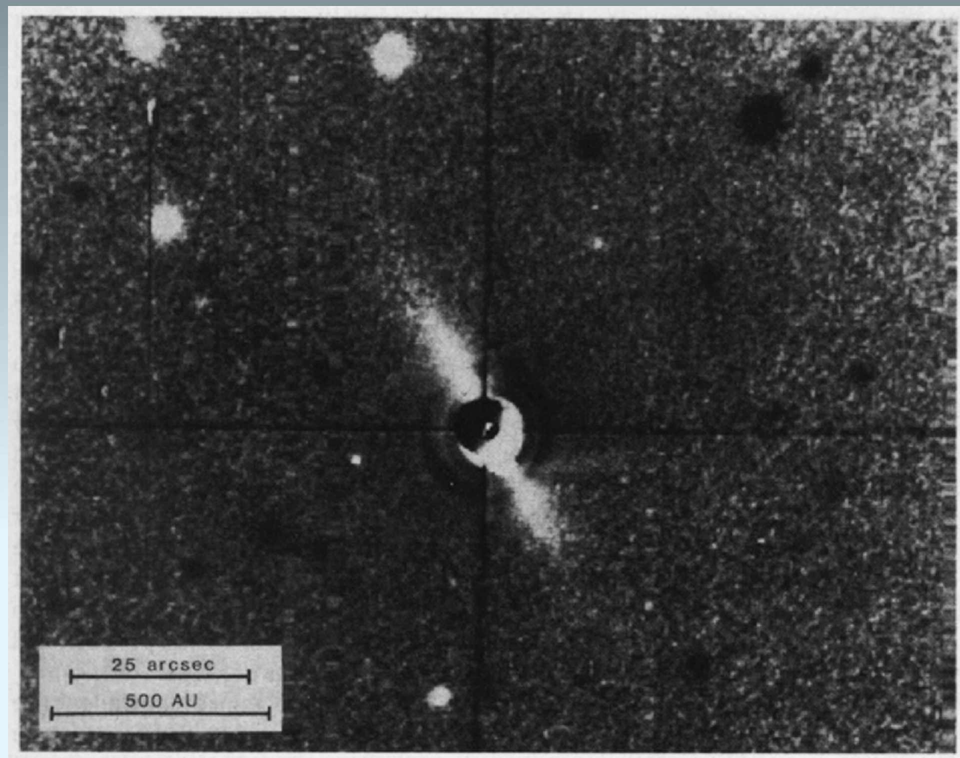
Discovery: Vega Phenomenon



Backman & Paresce 1993
"The Big Three"

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

Circumstellar Dust Disks



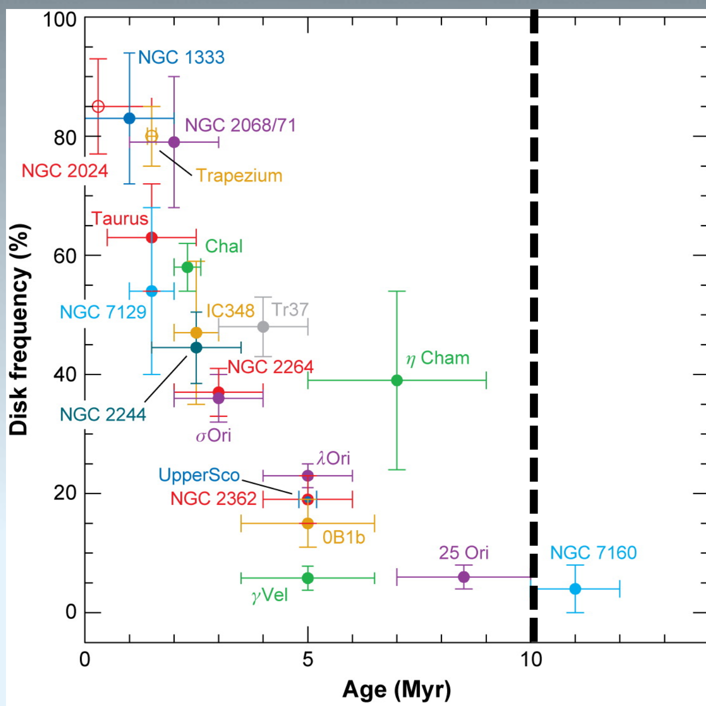
Smith & Terrile 1984

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

Dust must be second generation

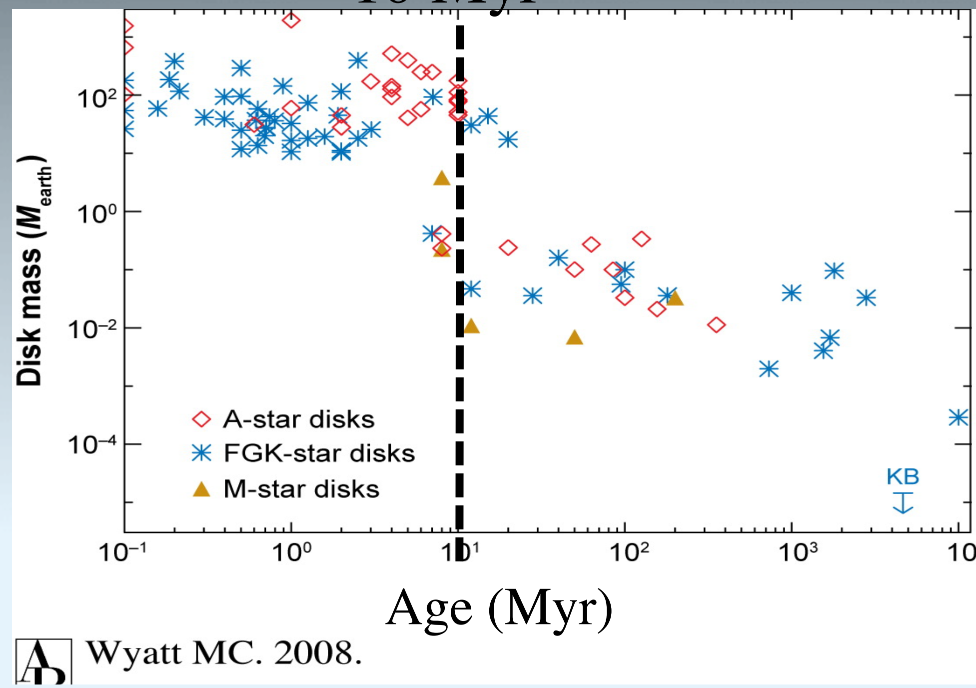
- Debris disks cannot be the remnants of the protoplanetary disks found around pre-main sequence stars (Backman & Paresce 1993):
  - The stars are old (e.g., up to 100s of Myr, even Gyr)
  - The dust is small (< 100 micron) (Harper et al. 1984; Parsesce & Burrows 1987, Knacke et al. 1993) and would be lost to the system on timescales < age of the stars
  - Small grains have short lifetimes due to PR drag
    - e.g., for Vega, t_{pr} = 15 Myr
  - Lifetimes are also short due to collisions
    - e.g. for Vega, t_{coll} = 2 Myr

Transitions from “Primoridial Disks”



Hernandez et al. 2008
Wyatt 2008

10 Myr



Dust from 0.1 – 100 AU	Dust in belts
Massive gas disk	No gas
Accretion onto star	No accretion
Optically thick	Optically thin

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Disk Thermal Emission

- Dust is cold (50-150 K), meaning it peaks in the far-IR where stellar emission is falling off as λ^{-2}
- Far-IR (space)
    - IRAS (1983) all sky survey at 12, 25, 60 100 micron
    - ISO (1996) obs at 25, 60, 170 micron of nearby stars
    - Spitzer (2003) several large programs surveying for debris disks at 24 and 70 micron (+ spectroscopy & 160 micron)
    - Akari (2006) all-sky survey 2-180 micron
    - Herschel (2009) four surveys with debris disk targets 70-500 micron
- Sub-mm/mm (ground)
    - JCMT (1997) 5-25%
    - APEX, IRAM 30 m

15% (Plets & Vynckier 99)

17% (Habing et al. 01)

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Debris dependences

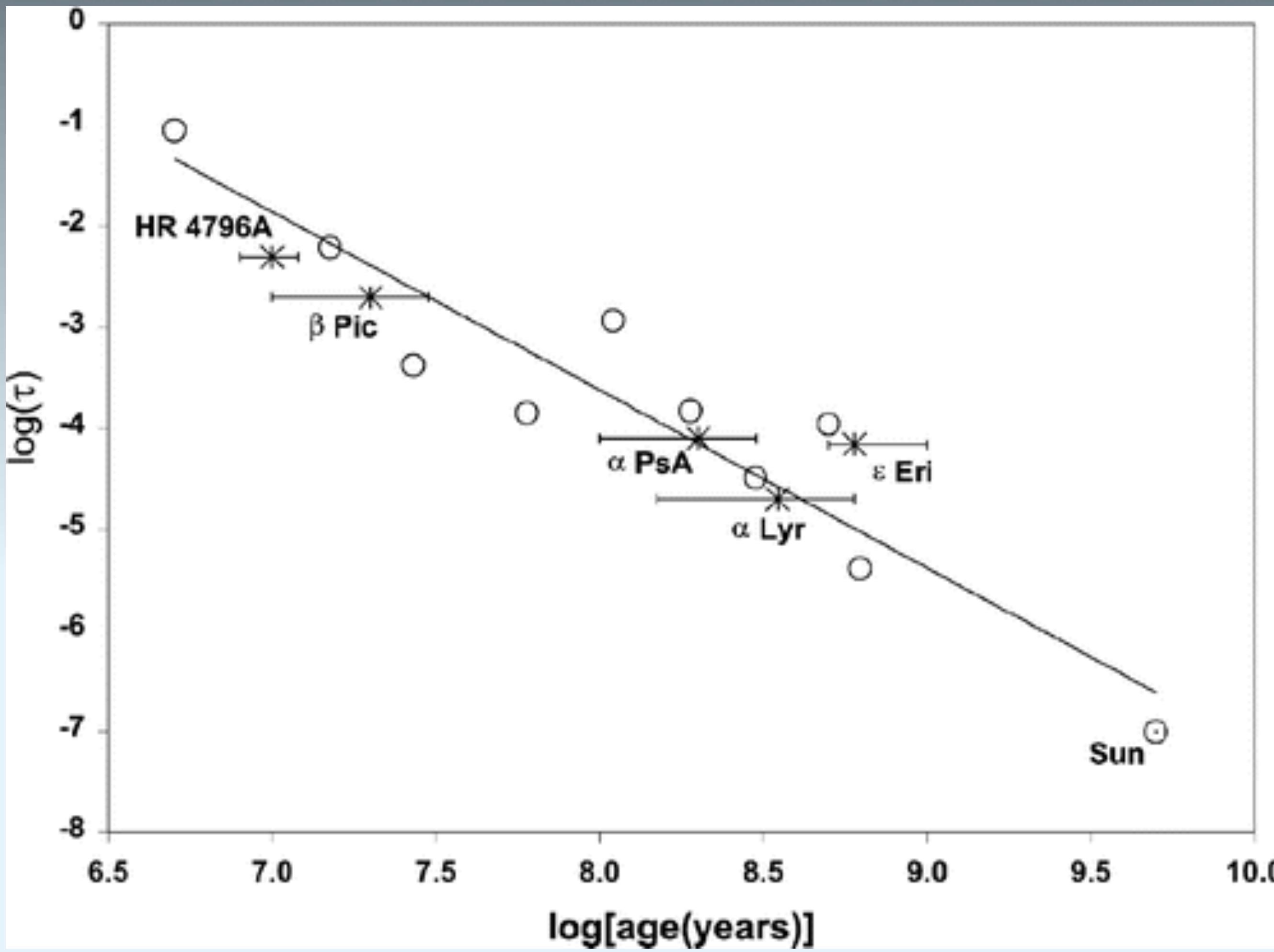
- Suggestion that the fraction of stars with detectable disks is a function of
  - Stellar age (Spangler et al. 2001)
  - Spectral type (Habing et al. 2001)
  - Wavelength (Laureijs et al. 2002)
  - Presence of known giant planets (Beichman et al. 2005)
    - or not (Beichman et al. 2006)

See Maldonado poster P17.2 for nice study of kinematics & age-related properties of debris/non-debris hosts

Disks over time

- 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 (more in Mark Wyatt's talk)

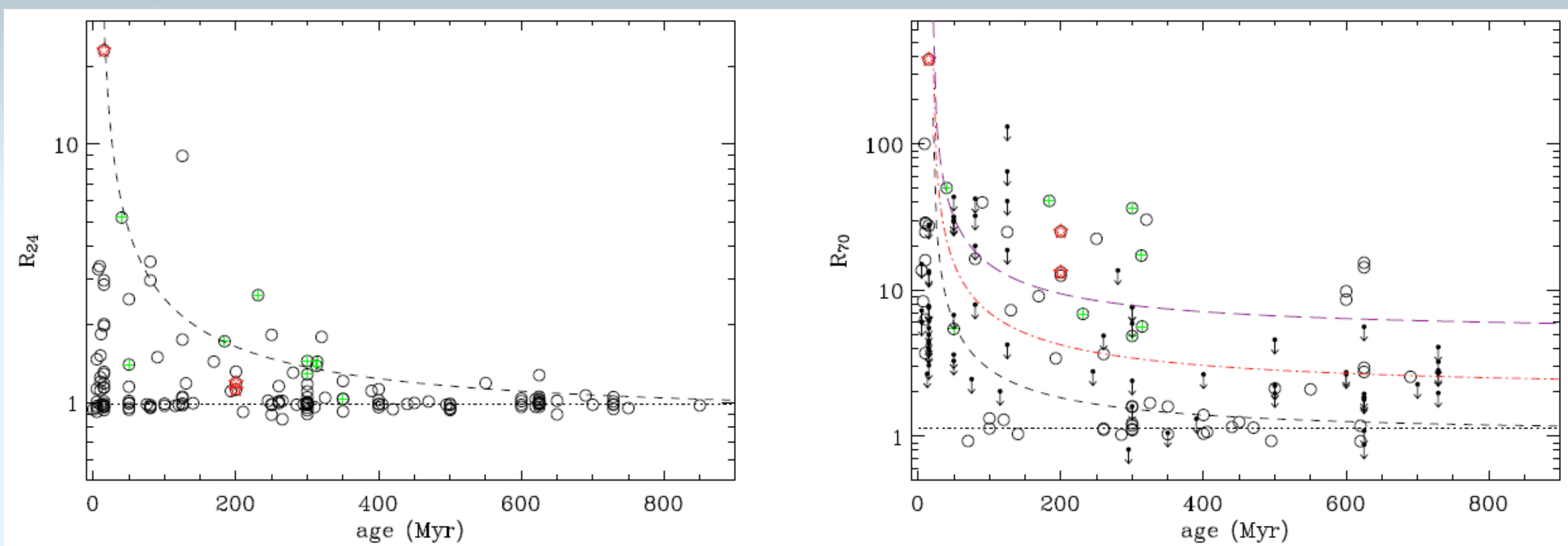
Luminosity v. age



Zuckerman 2001 ARA&A

Dust excess evolution A stars

- 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 decay timescale of 150 Myr at 24 μm but longer (~400 Myr) at 70 μm



Rieke et al. 2005, Su et al. 2006

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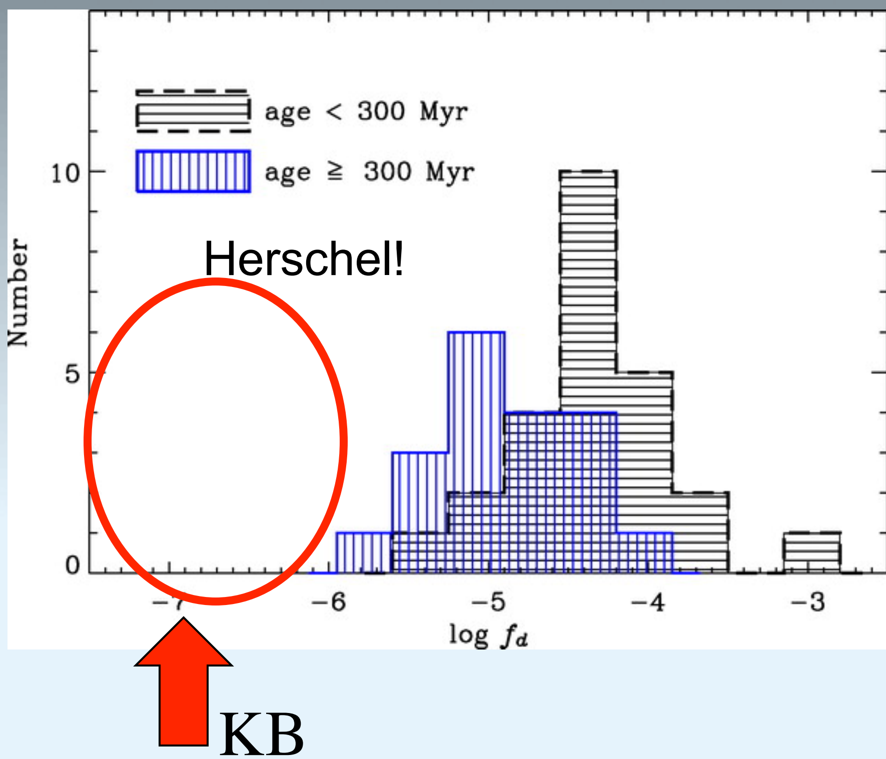
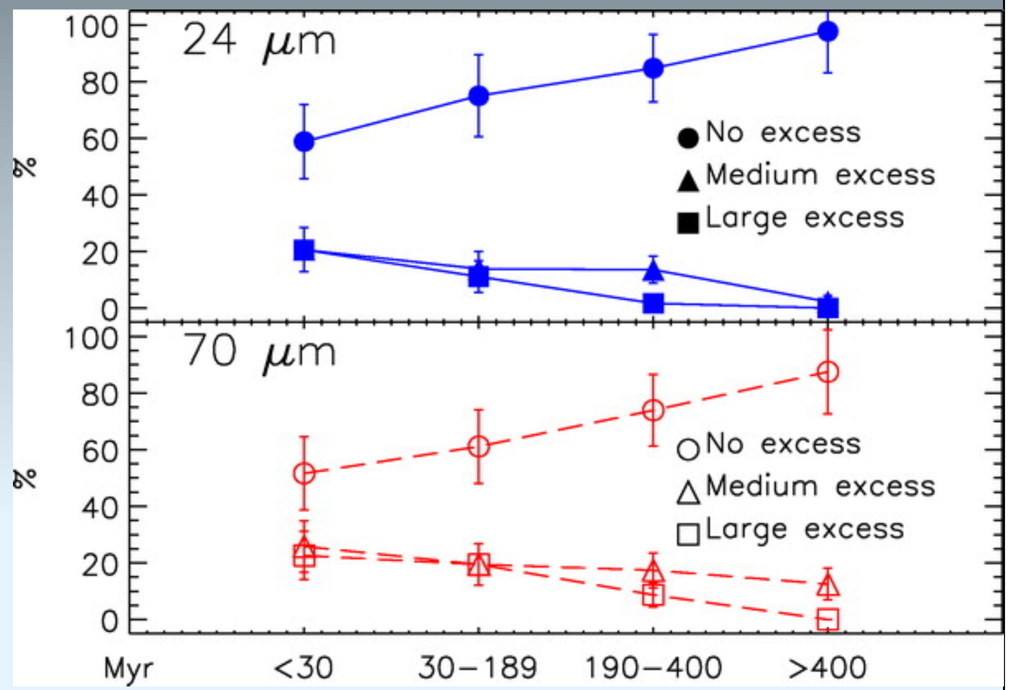
Spitzer
A stars

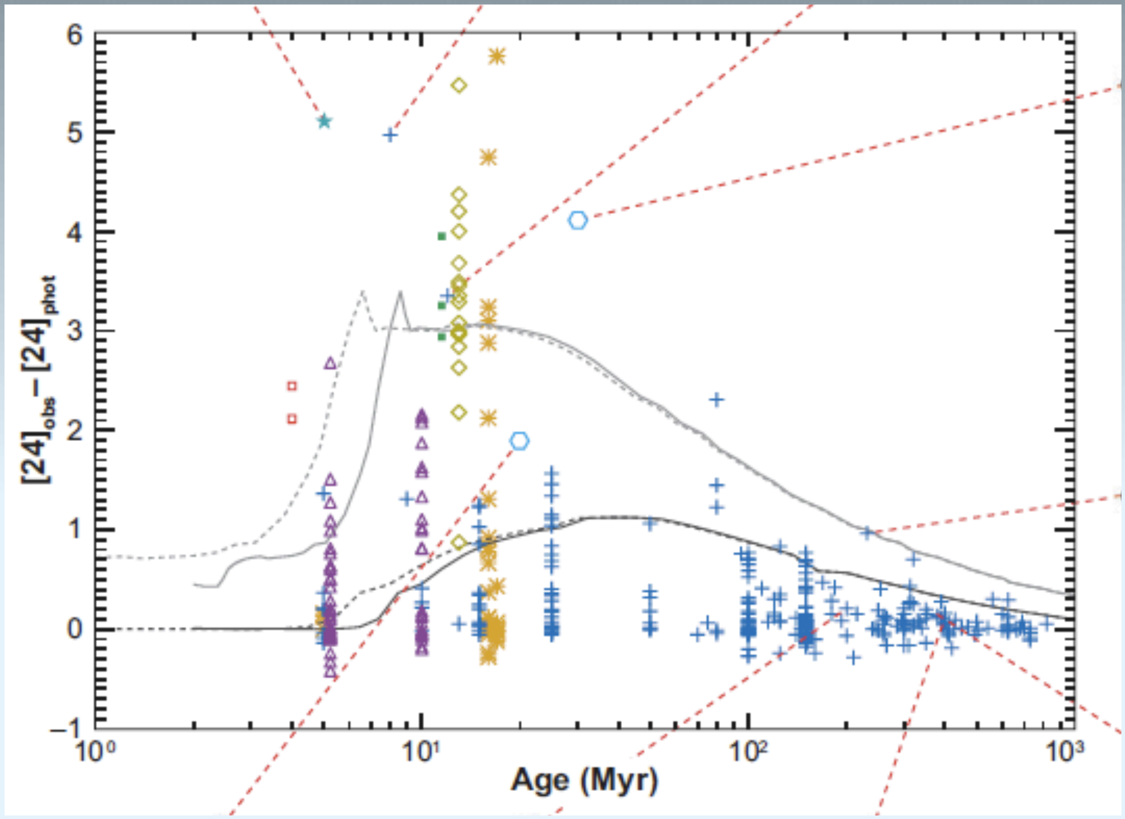




- Luminosity decline relative to the star is evident
- 24 micron excess declines fastest (~0 by 400 Myr)

Su et al. 2006

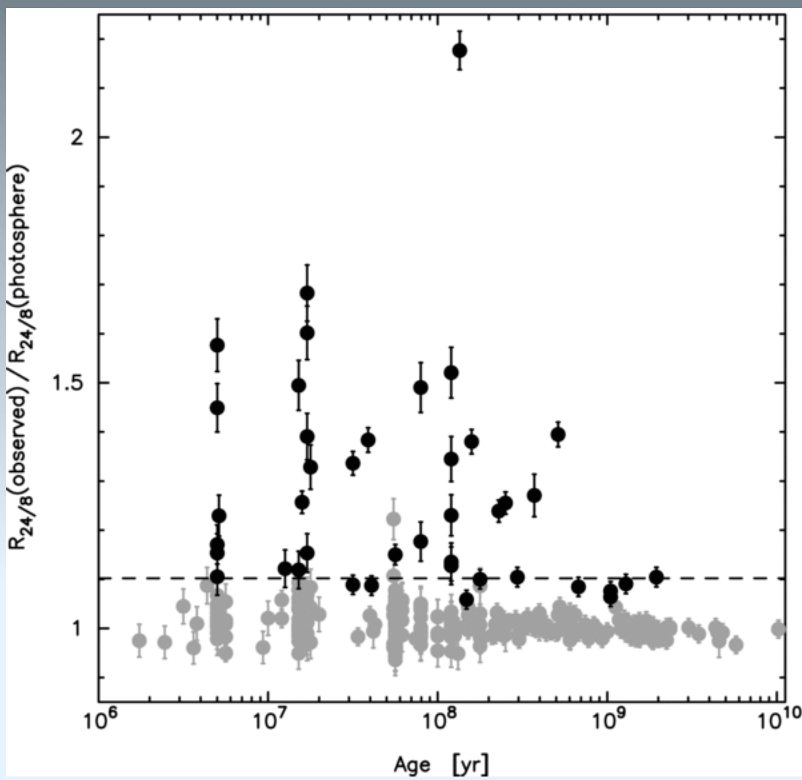
Excess Peak at 10-15 Myr?

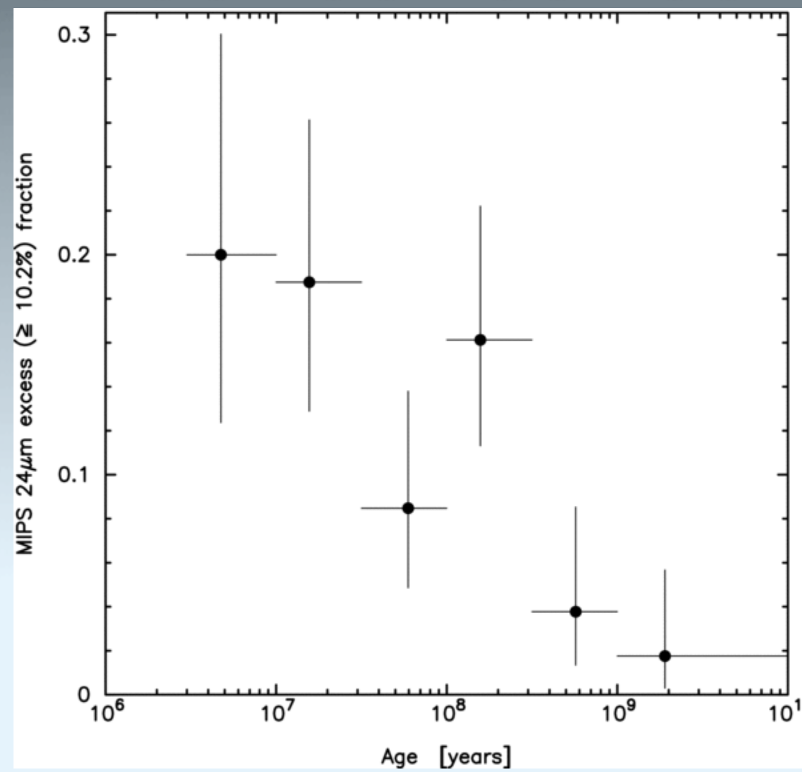


- Young cluster surveys at 24 micron suggest that A star excesses increase to a peak at 10-15 Myr (Hernandez et al. 2007; Currie et a. 2007)
- Stats are poor, but this period is key to understanding the origins of debris disks
- No similar peak is seen for Sun-like (FGK) stars

Wyatt 2008

FEPS: Sun-like Stars (FGK)





- Decline in strong (>10.2%) excess at 24 micron is even more pronounced

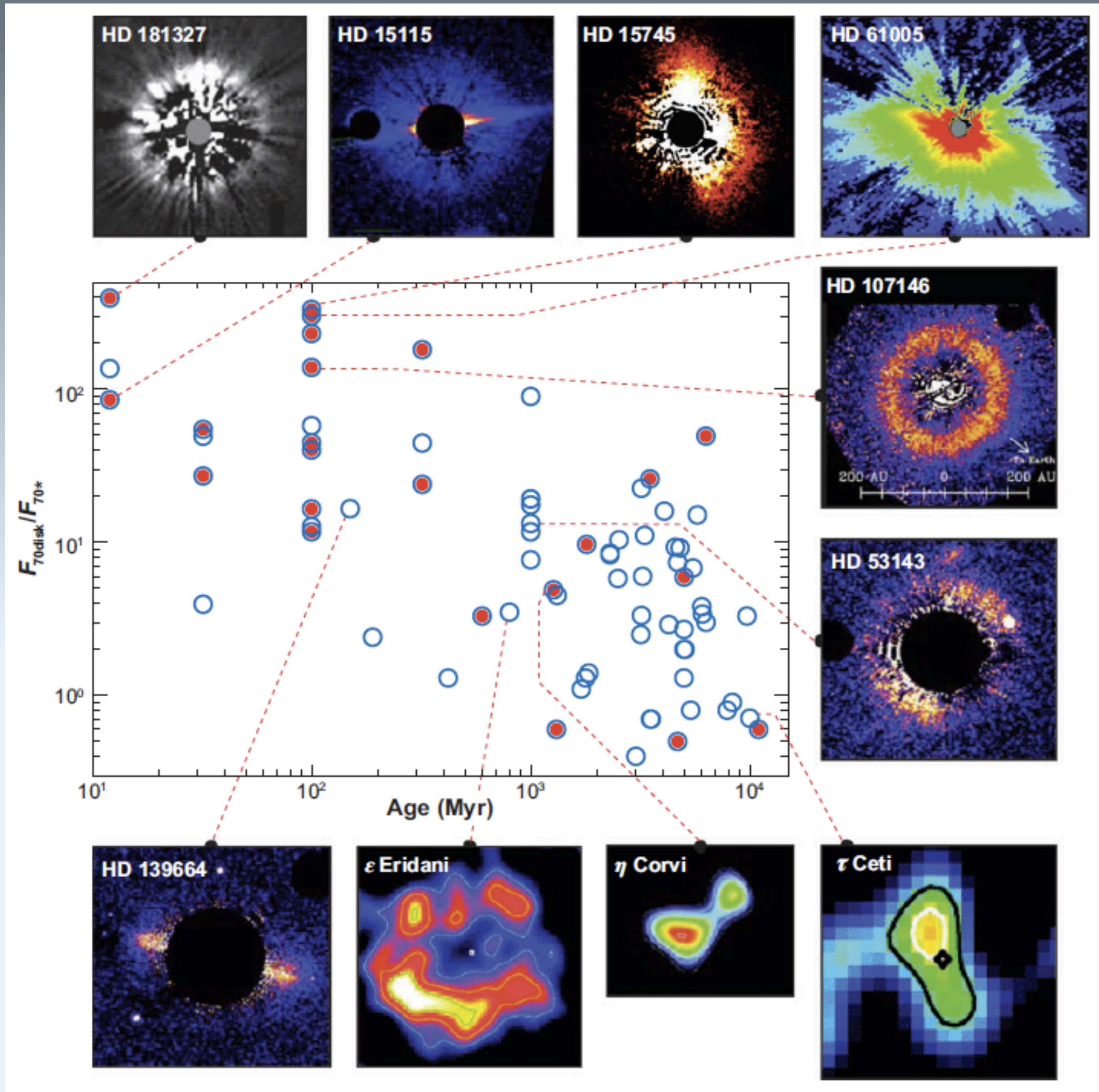
Carpenter et al. 2009

Sun-like Stars

- Surveys of Sun-like stars at 70 μm 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



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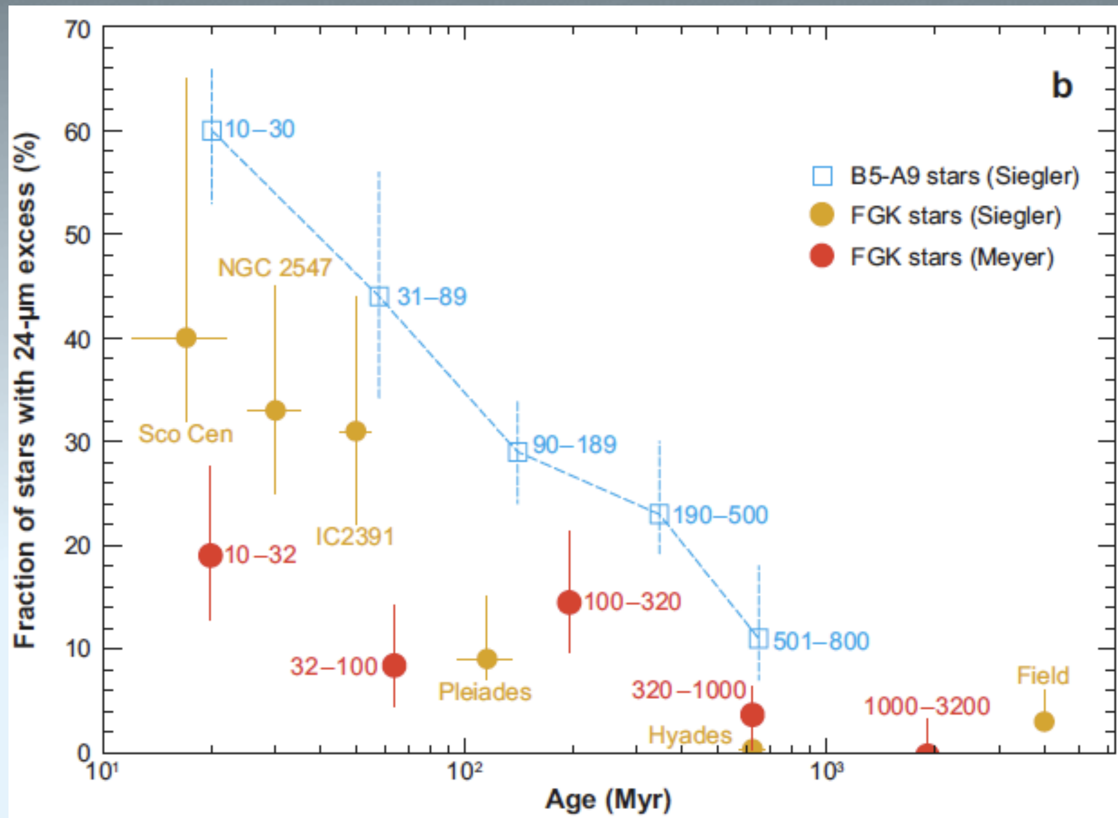
Excesses across spectral type

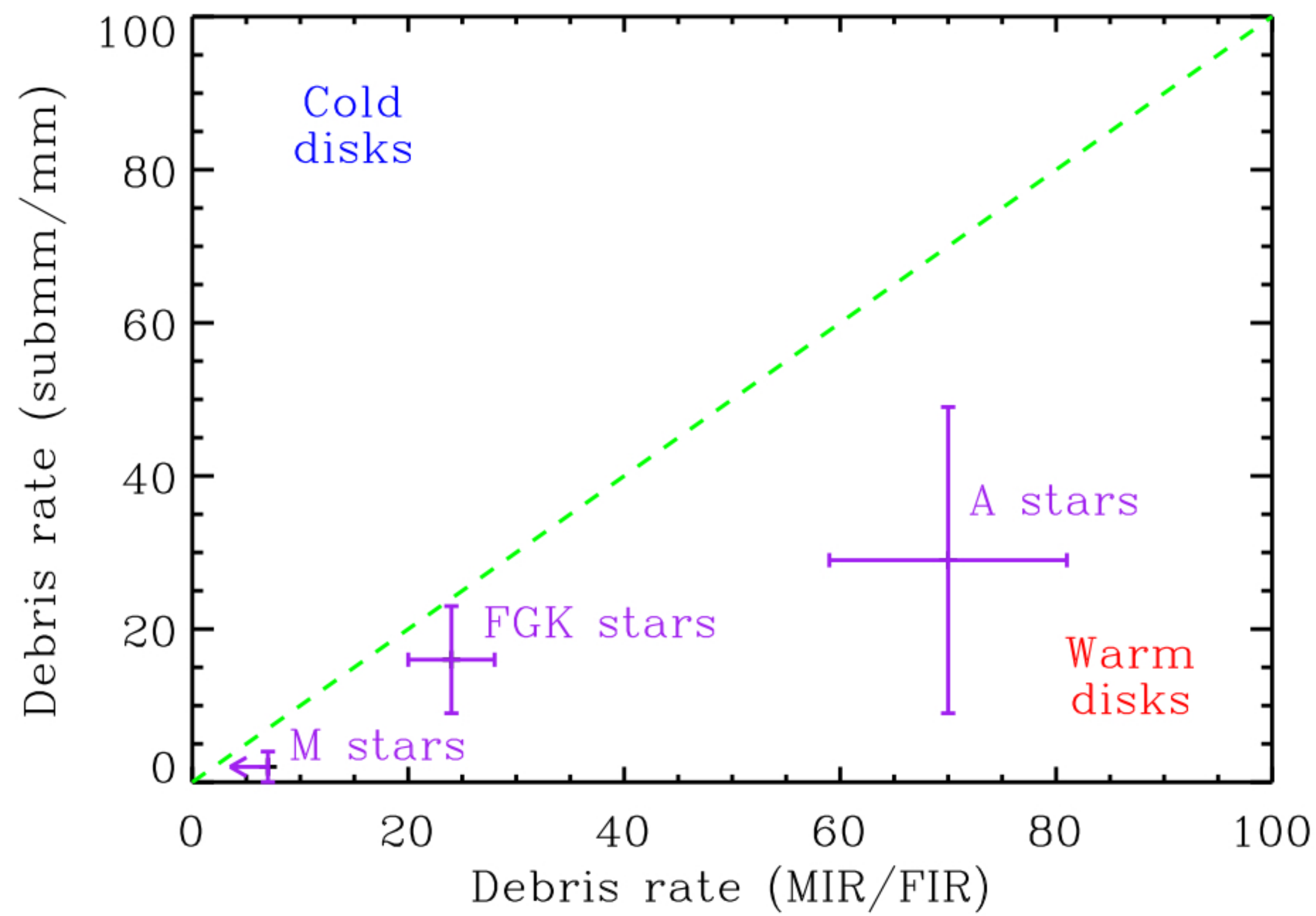
- 24 micron FGK excesses fall-off much faster than for A stars
  - Few 100 Myr
  - Only exceptional bright excesses remain for 2-4% of stars
  - planetesimal belts or ongoing terrestrial planet formation?
  - Could also just be exceptional bright disks



Seigler et al. 2006 Wyatt 2008 Zuckerman et al. 2008

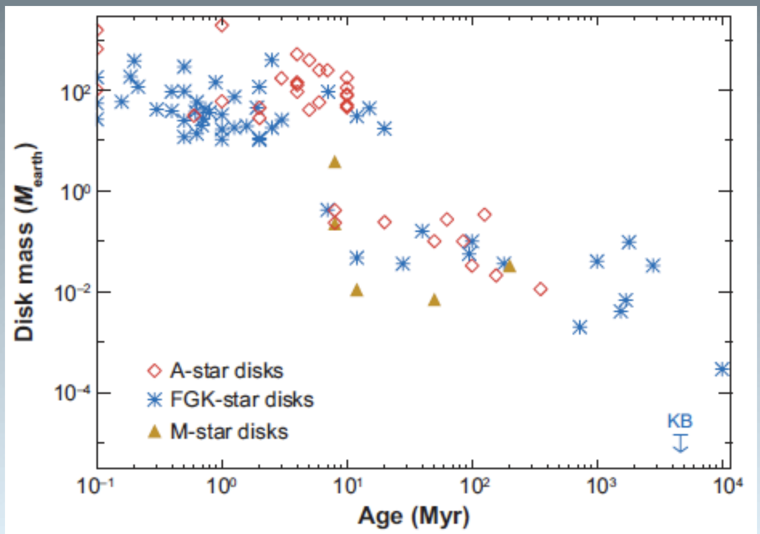
Dependence on Spectral Type

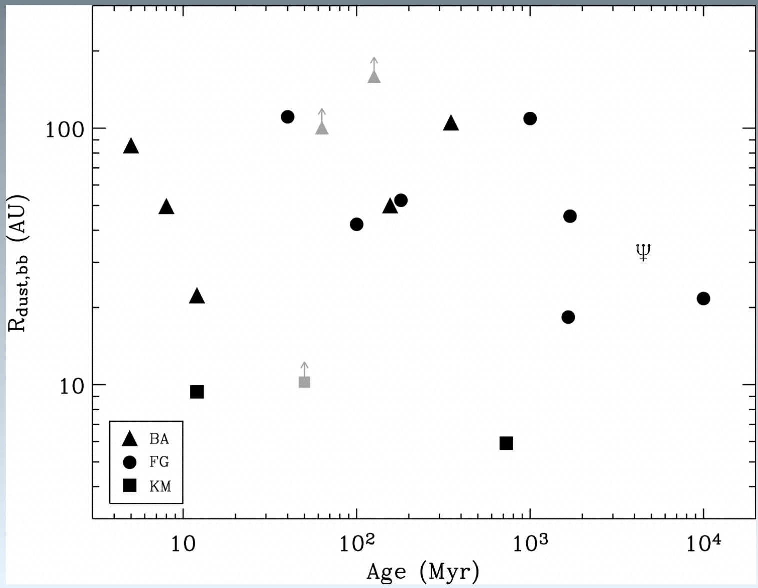
IRAS+
Spitzer +
submm



Disk Mass and Radius

Observable



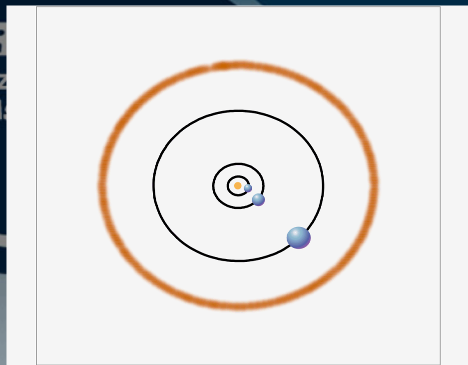


- mass falls off ∝ t^{-1} with a large spread of 2 orders of magnitude at any age (Najita & Williams 2005; Wyatt 2008)

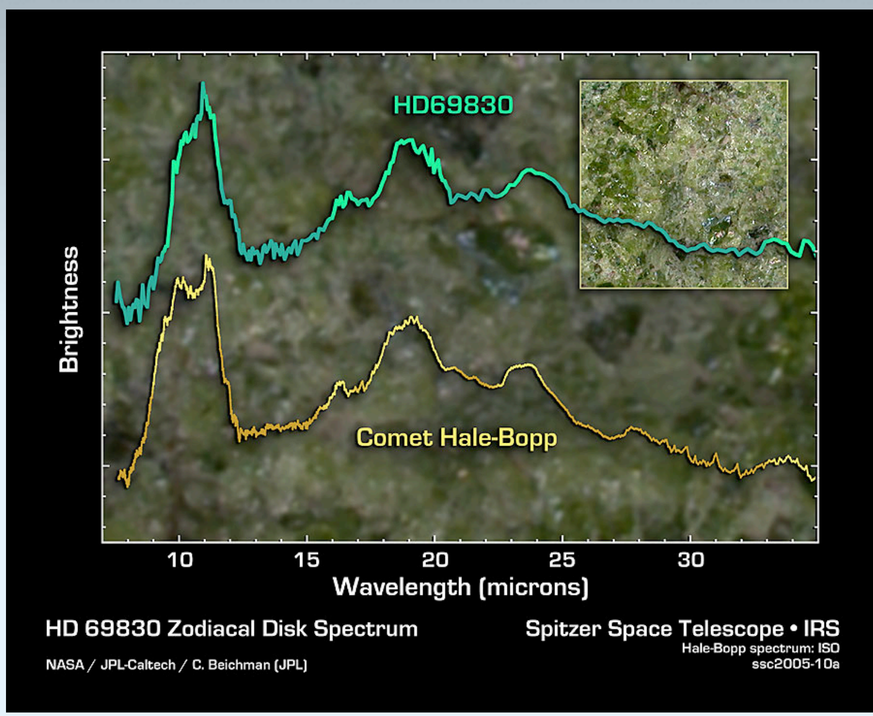
- large spread in disk radii 5-200 AU at all ages (Najita & Williams 2005)

Wyatt 2008

Debris disks can be transient



The “hale-bopp” star HD 69830

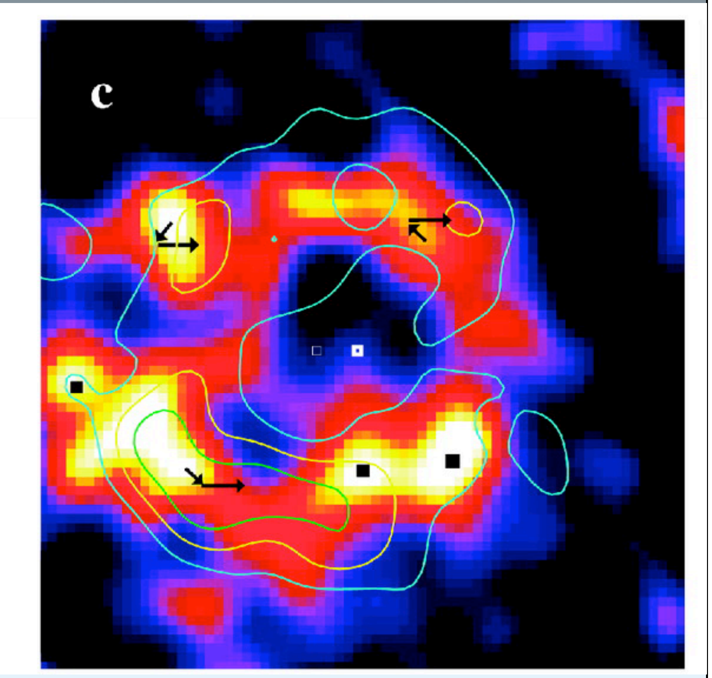


- Only 2% of stars have hot dust < 10AU (Bryden et al. 2006)
  - E.g. K0V star HD 69830
  - 2 Gyr
- A similar mid-IR spectrum
  - T=400 K
  - → 1 AU (Beichman et al. 05)
- 3 Neptune mass planets orbiting at 0.08, 0.16 and 0.63 AU on nearly circular orbits (Lovis et al. 2006)

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

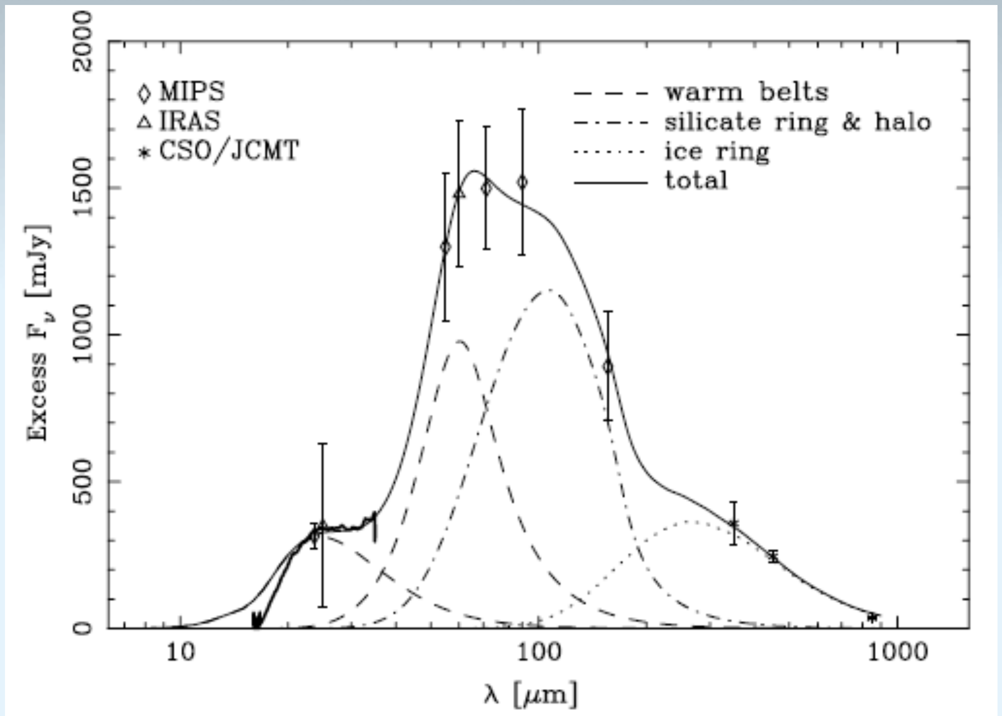
Old debris disks: Epsilon Eridani

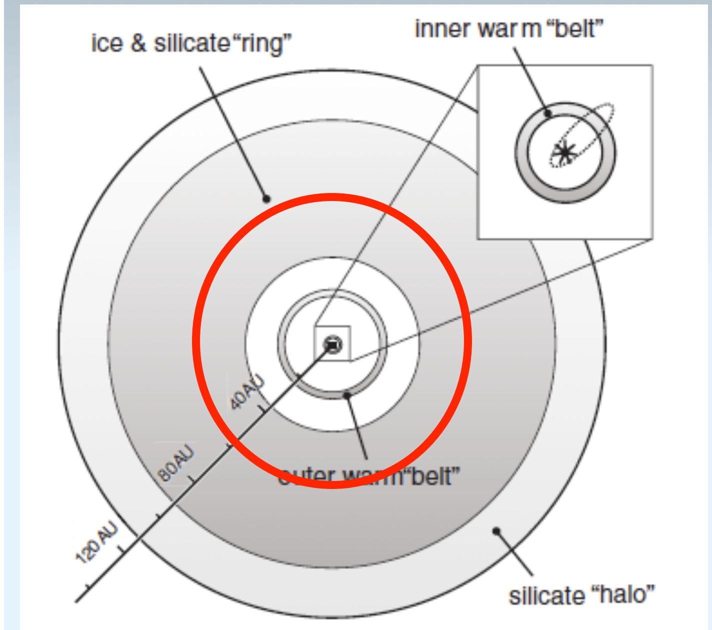
- older, fainter disks need very sensitive cameras and high resolution to minimize confusion with background galaxies
- ε Eridani
  - 800 Myr-old K2V star at 3.2 pc
  - planet at 3.4 AU with e=0.6 (Hatzes et al. 2000)
  - 850 µm image shows face-on, slightly offset, dust ring at 60 AU with a mass of 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)



Old debris disks: More on Eps Eri

- Spitzer imaging and spectroscopy found evidence for dust within the main ring seen in the sub-mm

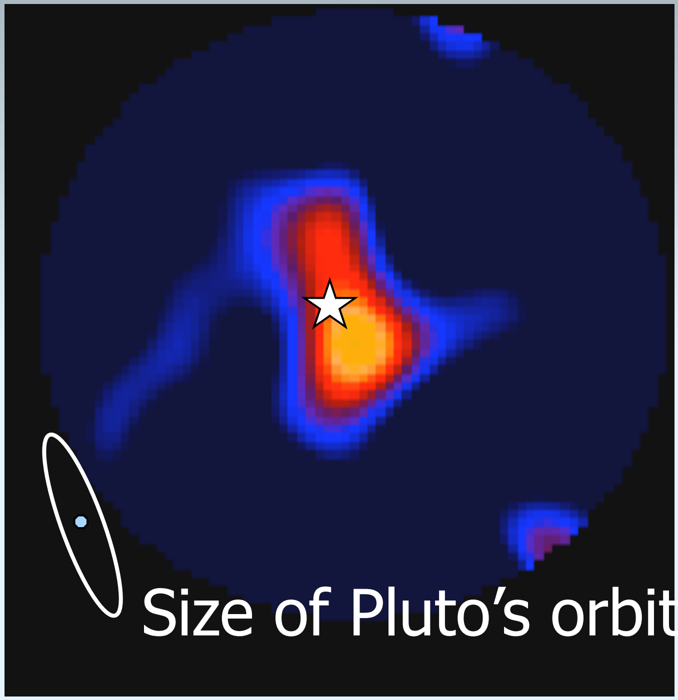




Backman et al. 2009

Old debris disks: only solar analogue

- only tau Ceti (7.2 Gyr old G8V star at 3.6 pc) has a well-imaged debris disc that has outlived the Sun
- inclined debris disk with a radius ~55 AU
- dust mass 5 x 10^{-4} M_{earth}
- only solar-type (age and spectral type) star with confirmed debris disk
  - no Jupiter or Saturn analogue
  - need more analogues for insights to first Galactic planetary systems



Greaves et al. 2004

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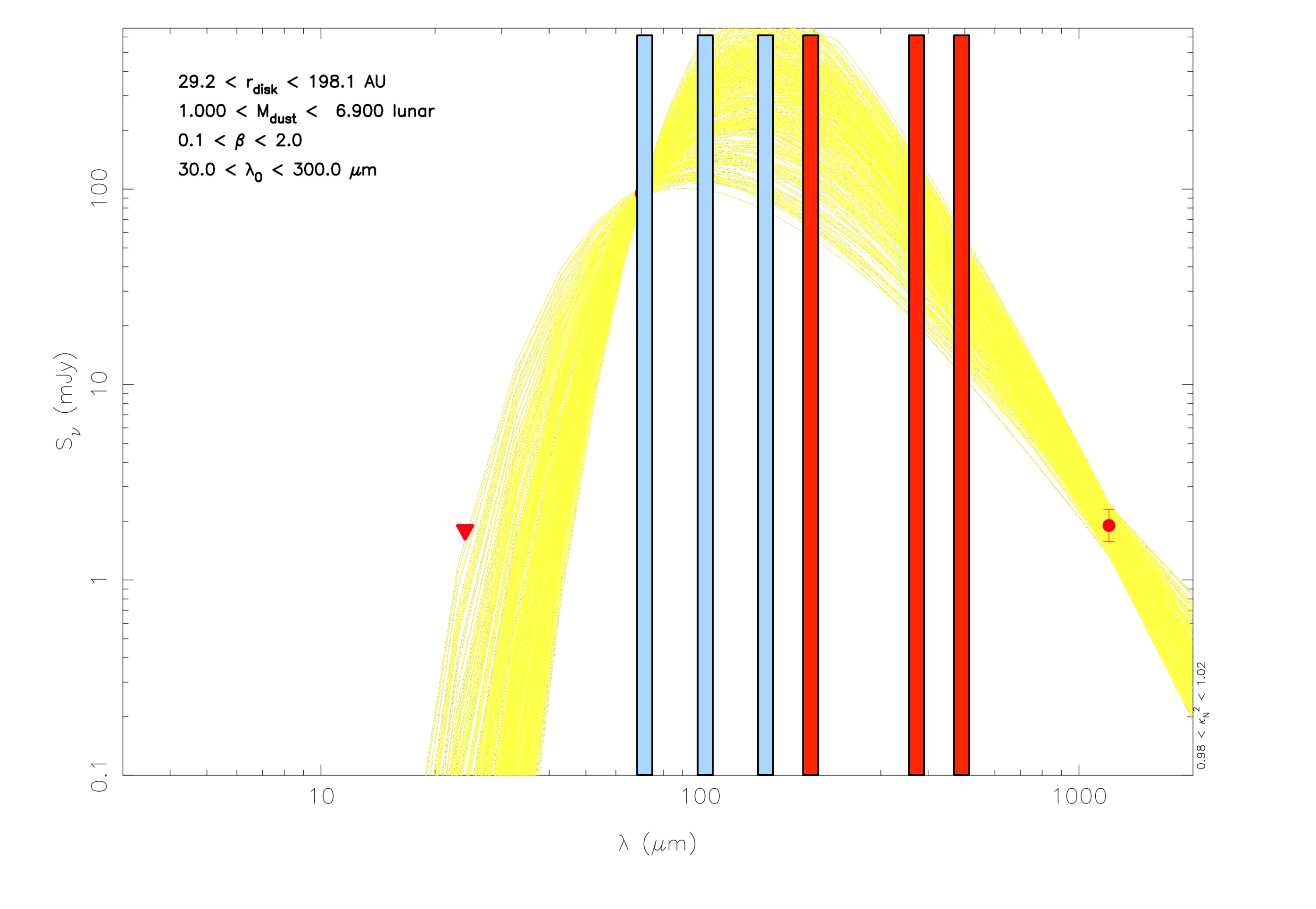
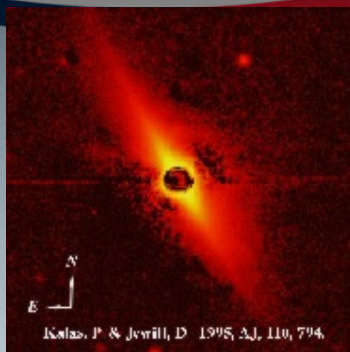
Spectral Energy Distributions

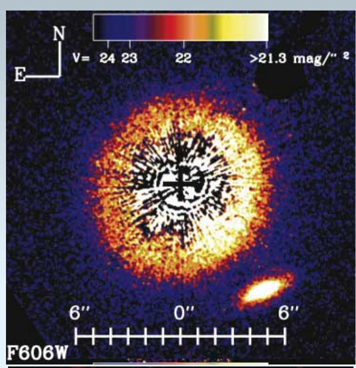


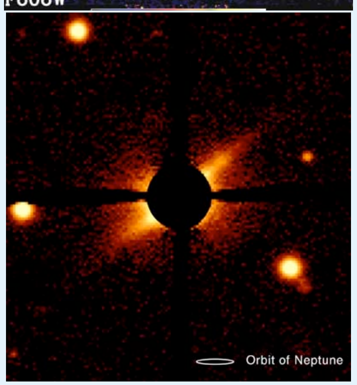
J.-F. Lestrade

Disk Morphologies

Wide Disks
(>55 AU extent)

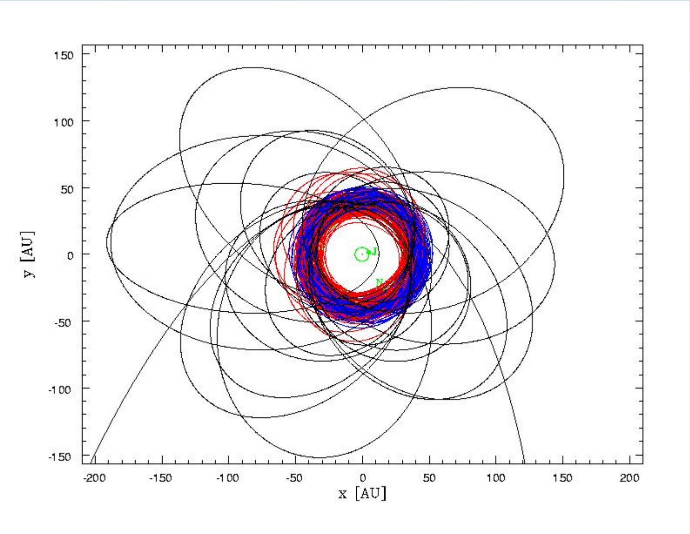




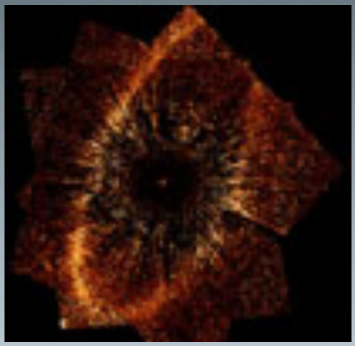


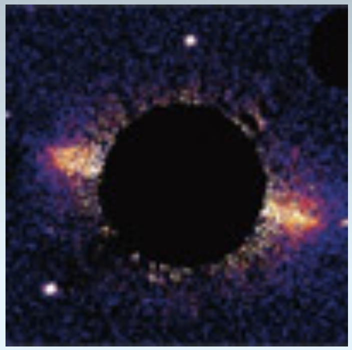
Possible disk "types":

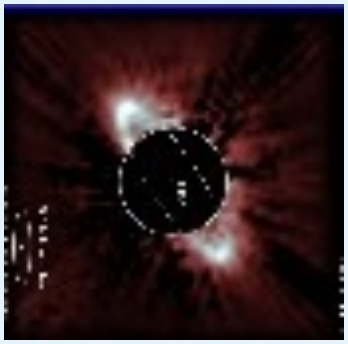
1. Do these trace fundamentally different distributions of underlying planetesimal population?
2. Are these different stages of debris disk evolution, or fundamentally different, long lived architectures?
3. Where does the solar system fit in?



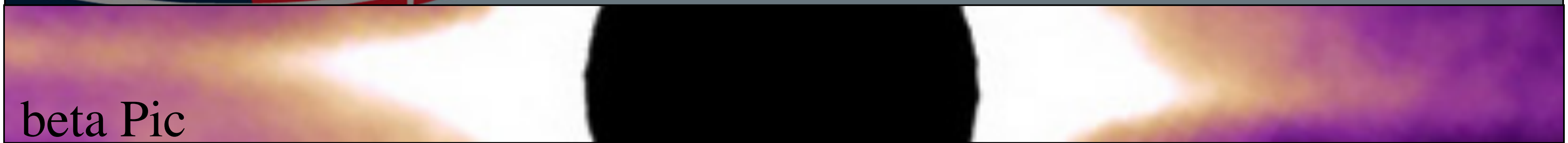
Narrow Belts
(20-30 AU extent)

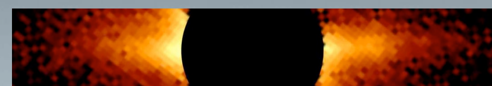


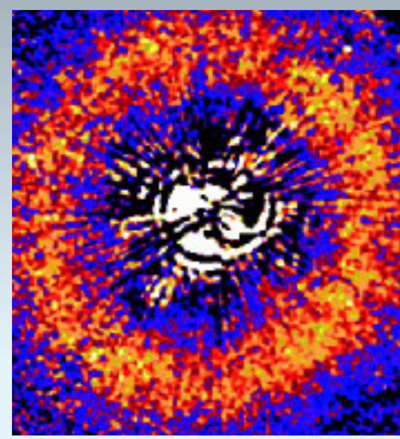


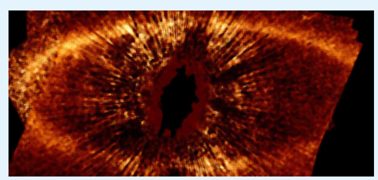


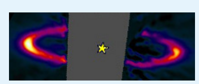
Physical Extent



AU Mic  >200 AU

HD 107146  170 AU

Fomalhaut  140 AU

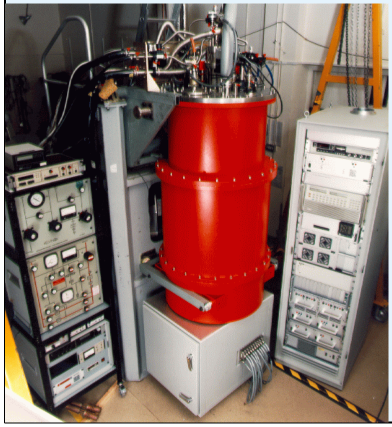
HR 4796A  70 AU

Sun  50 AU

Cold submm disks 1997-2005

- Any star can be observed (star is negligible)
  - Don’t need to go to space
- Best method to measure the mass of the disk
- Only means to search for very cold disks (T_{disk} < 40 K)

- SCUBA added significantly to the number of resolved disks
  - 7/10 when SCUBA retired in 2005



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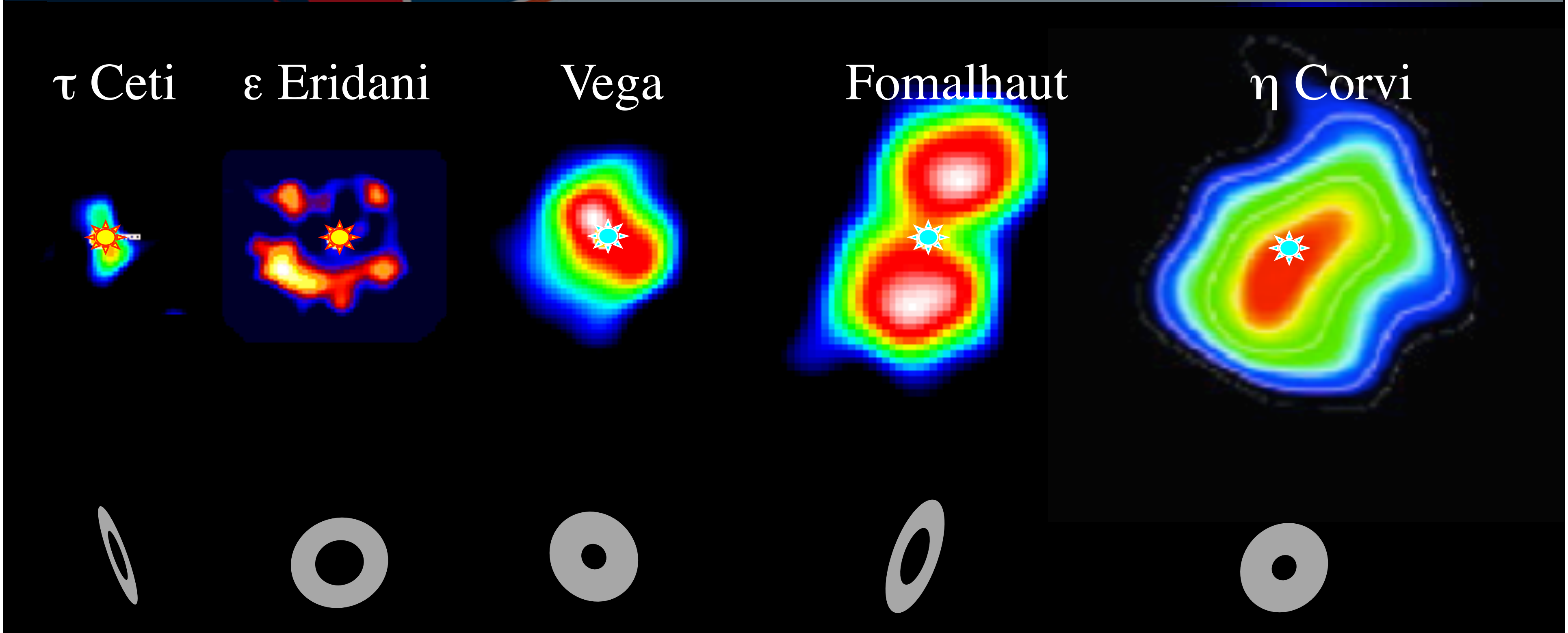
A SCUBA Gallery

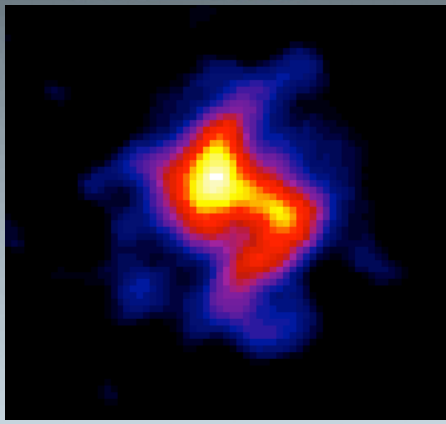


G8V	K2V	A0V	A3V	F2V
10 Gyr	0.85 Gyr	~0.4 Gyr	0.3 Gyr	~ 1 Gyr

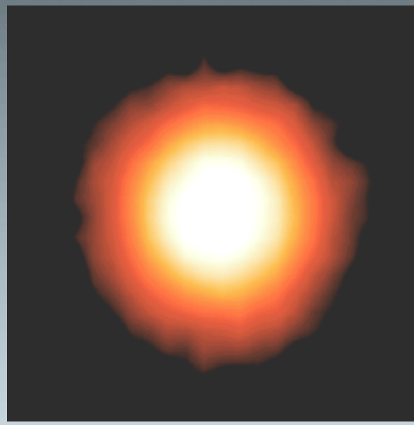
The disks are shown to the same physical scale, i.e. as if all at one distance; actual distances are 3 to 18 pc.

P1 9.2: dust ring around Vega

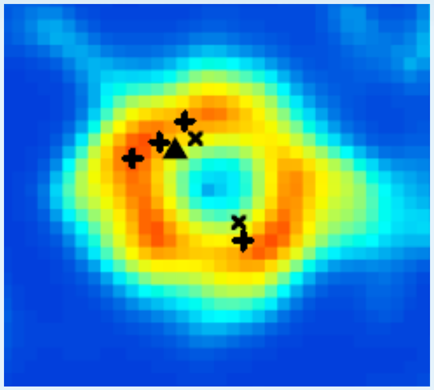
Variation with wavelength: Vega



850 micron
(Holland et al. 2006)



24 & 70 micron
(Su et al. 2005)

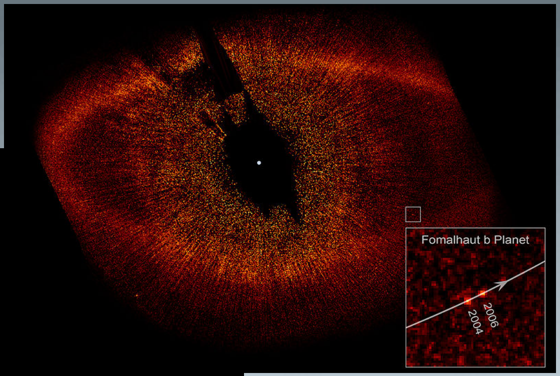


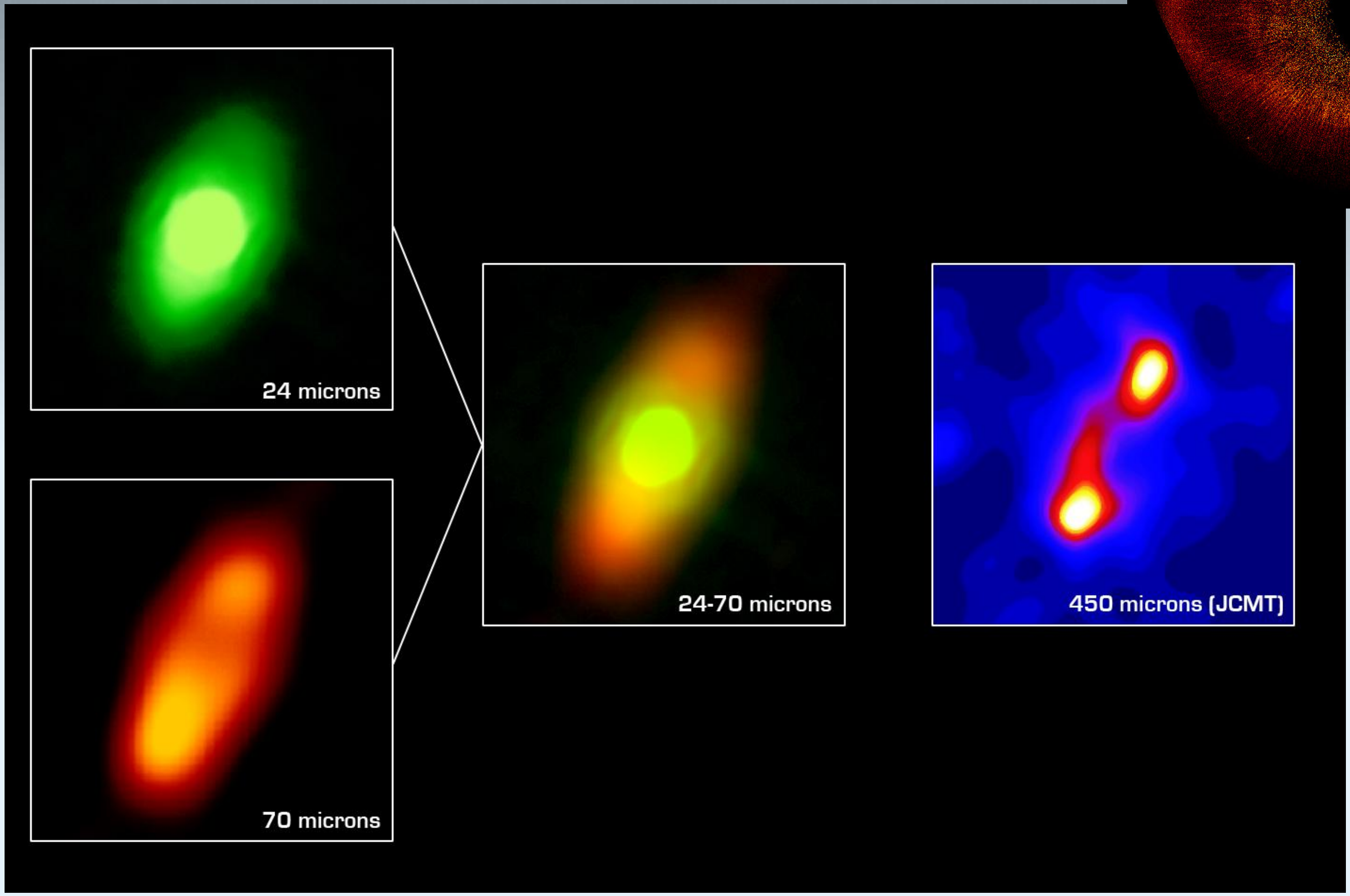
350 micron
(Marsh et al. 2006)

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

The Fomalhaut Disk

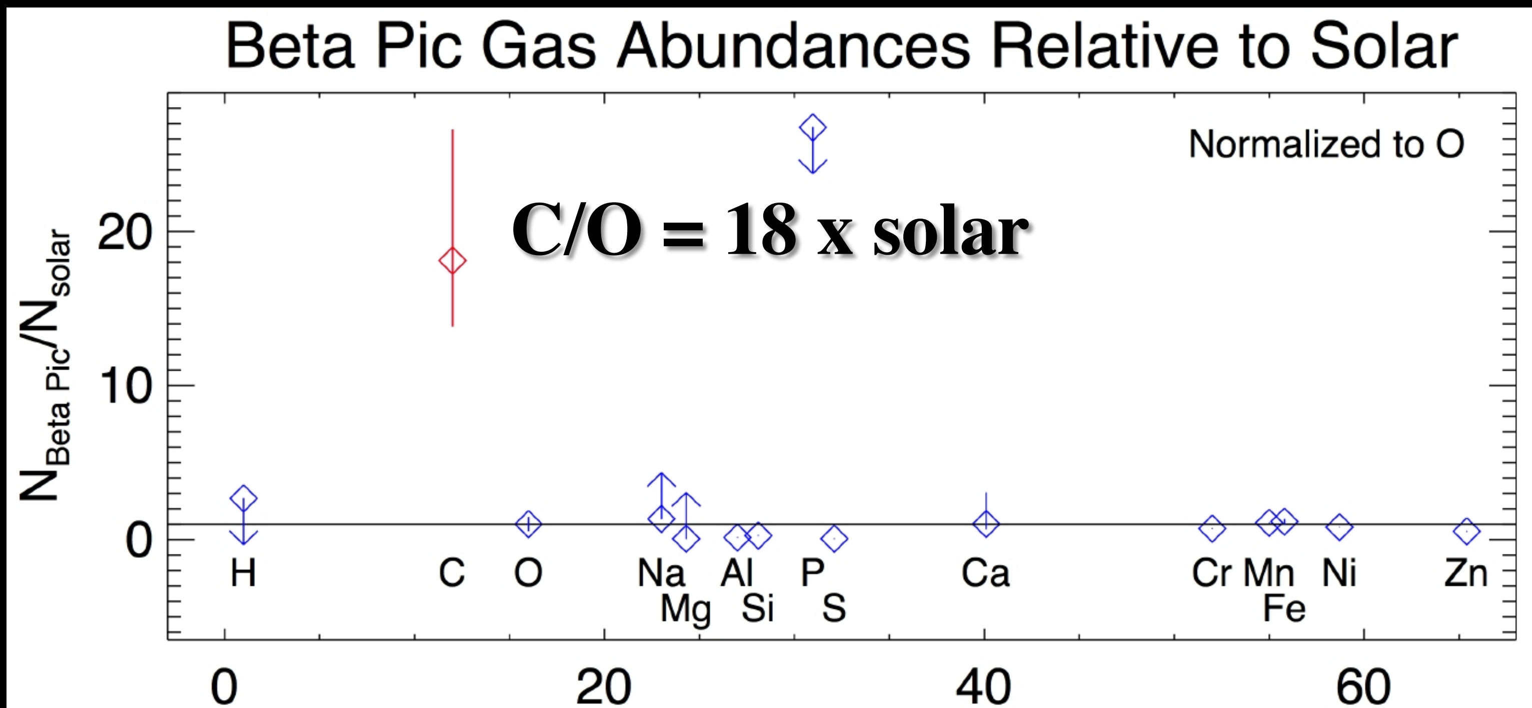
More in Amaya's talk!





Gas in beta Pic

See poster P14:2 by Alexis Brandeker!

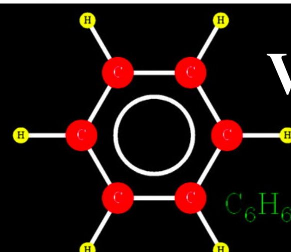


Roberge et al. (2006)

Comet Halley Dust

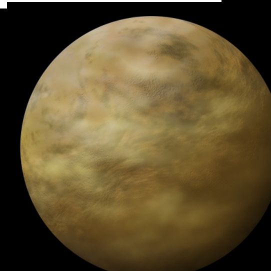
C/O ~ 1.8 x solar

(Jessberger et al. 1988)



Volatile organics?

Carbon-rich planetesimals?



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Disks around Low-mass stars

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- – Disk lifetimes could be extended by low radiation field of M stars
- – Potentially planet-forming over a longer timescale than more massive stars
- – Ms ~85% of all main sequence stars by population
- – M stars can form planets
  - GL 876 has detected planets at 0.13 and 0.21 AU (Marcy et al. 2001)
  - GL 436 has a Neptune-sized planet at 0.03 AU (Butler et al. 2004)

Frequency of M star disks ~ frequency of debris disks

Low-mass star Disk Searches

- Not historically targeted by optical/near-IR studies (weak scattered light)
- No favored stellar mass unless the mass of the disk is correlated with the mass of the star
- Not a lot of detections
  - SCUBA
    - Liu, Matthews, Williams & Kalas (2004) [25% - 8 targets]
    - Lestrade et al. (2006) [13^{+6}_{-8}% - 32 targets]
  - Spitzer
    - Gautier et al. 2007 [0% - 62 targets]
    - Several in Low et al. (2003) for young stars in TWA (one not genuine (Plavchan et al. 2009)
  - Lestrade: IRAM 30 m searches

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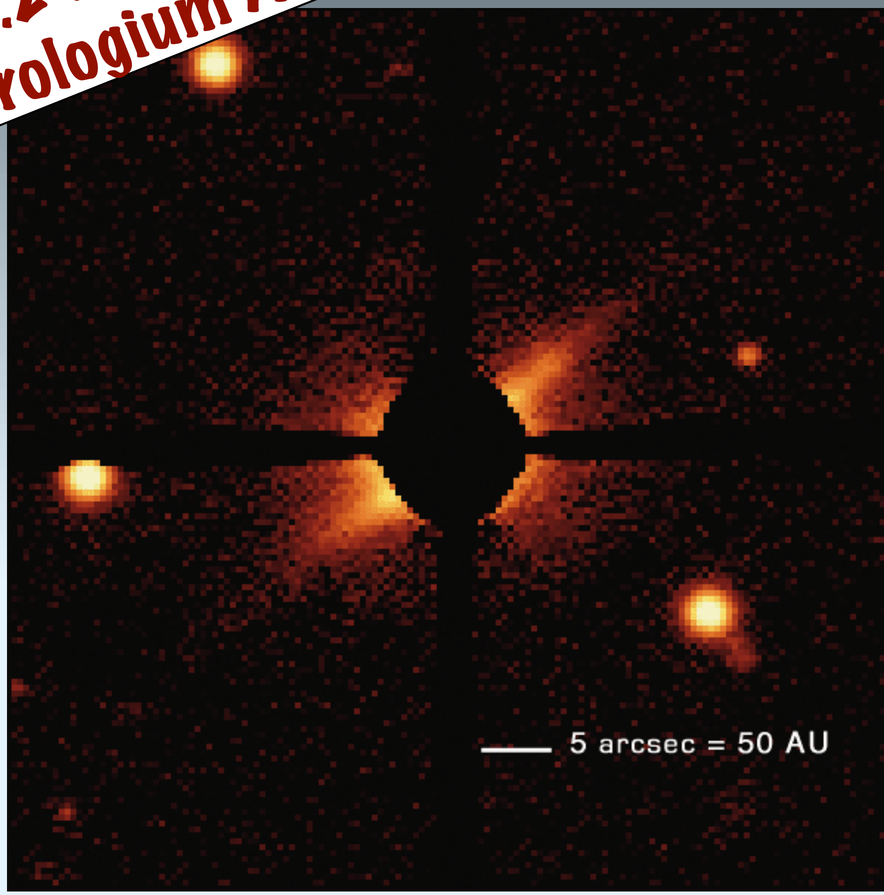
See Donaldson poster, P1 6.2 about the Tucana-Horologium Association

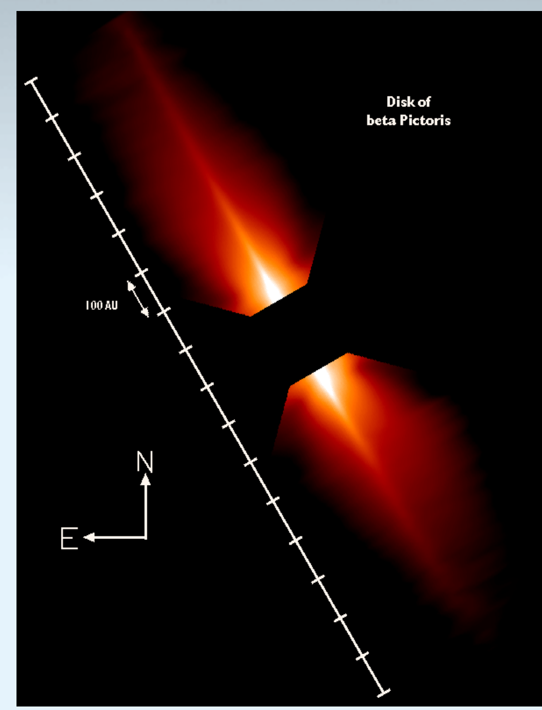
AU Mic Discovery Image

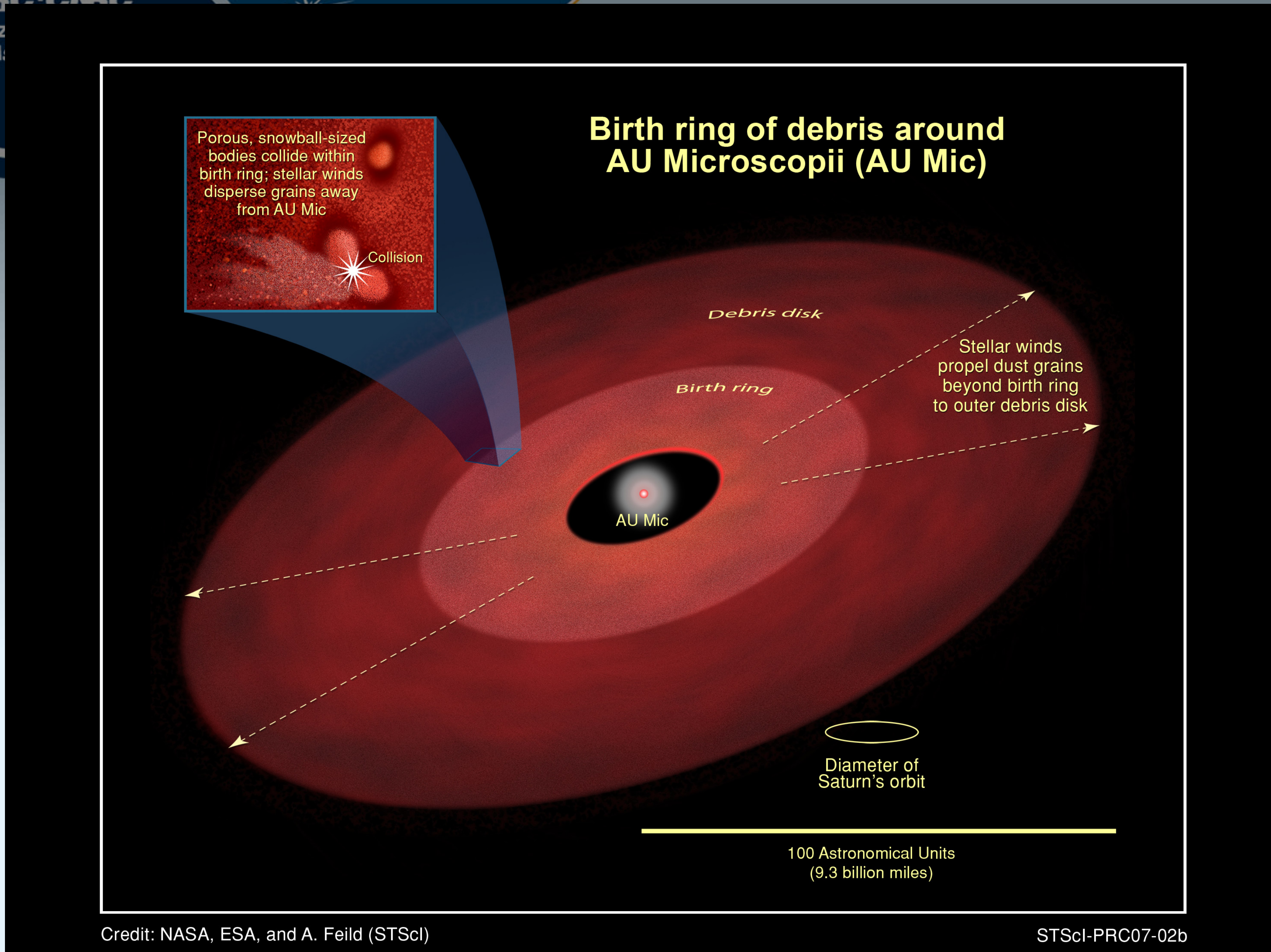


R-band, UH 2.2 m telescope, 0.4"/pix, 900 s, seeing FWHM = 1.1"

Kalas, Liu, & Matthews 2004

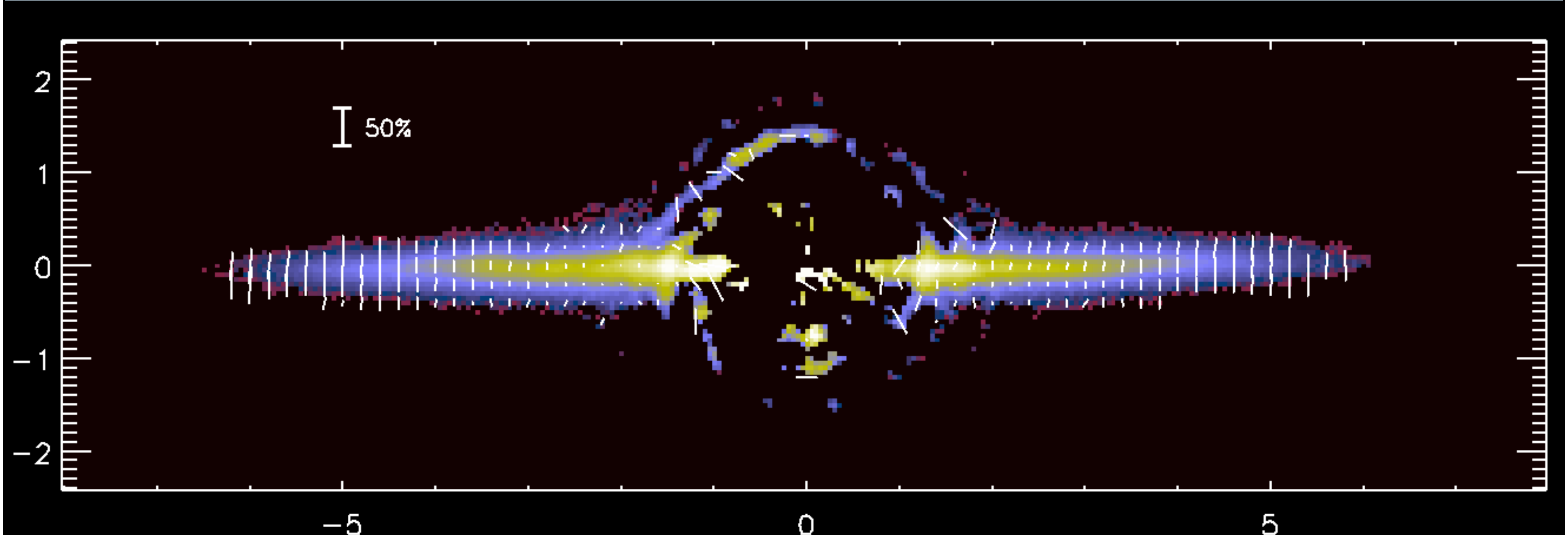
M star at 10 pc
1 arcsec = 10 AU





Strubbe & Chiang (2006)

Dust Properties of AU Mic



For edge-on disks polarimetry is essential

- Information about the scattering phase function is lost because of averaging along the line of sight.
- This information is recovered if *Q* and *U* are available because of the different angular dependence of the matrix elements of the complex amplitude scattering function.
- We find polarization 5% at 20 AU, rising to 40% beyond 50 AU.

HST ACS: HRC Polarization

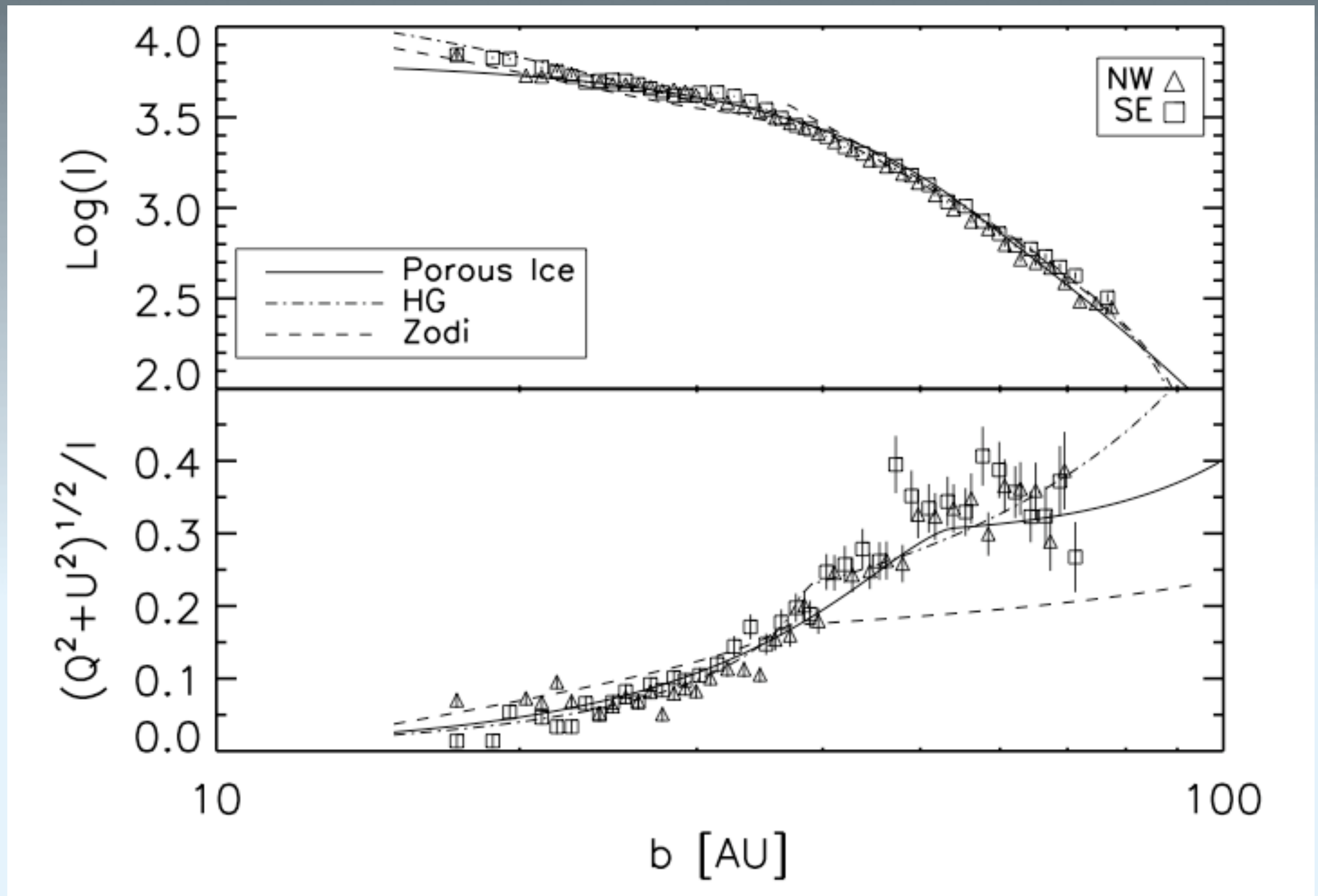
J. R. Graham, P. Kalas, & Matthews 2007

Models of Dust

Simultaneous fit of surface brightness & polarization constrains <cosθ> and p_{max}

Porous (91%) water ice grains 0.6 micron in size

Zodiacal dust model CANNOT produce high polarization, nor does cometary dust.

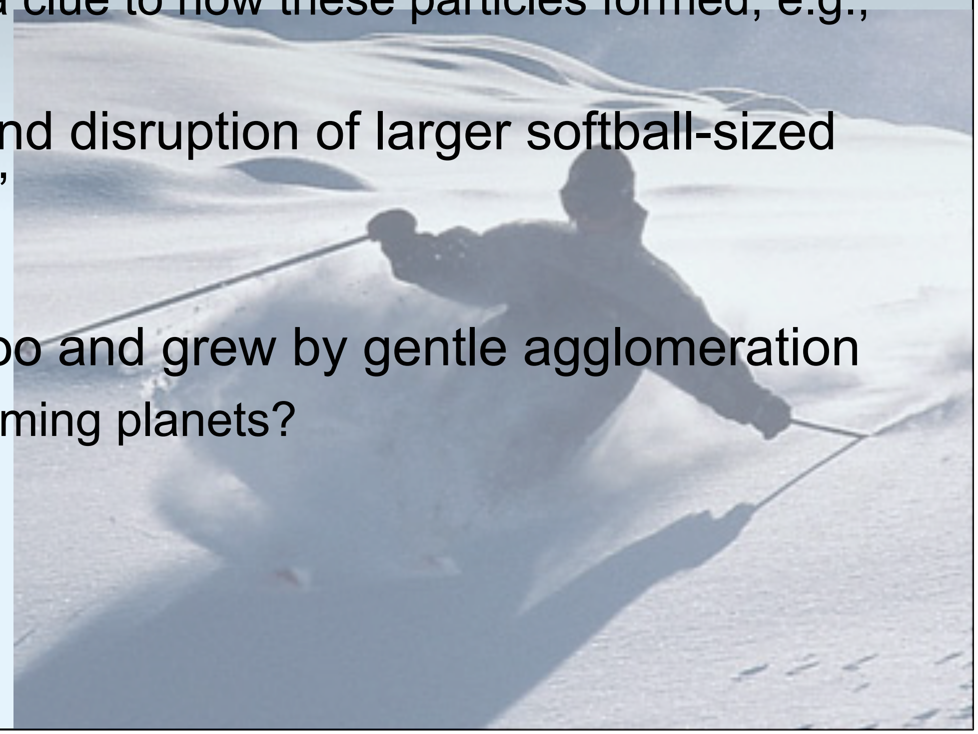


Graham, Kalas & Matthews 2007

HST ACS: HRC Polarization

Implications

- Discovery of fluffy dust grains in the AU Mic debris disk
  - Dust is fluffy/porous like fresh powder snow (97% air, 3% ice)
    - The fluffiness or “porosity” is a clue to how these particles formed, e.g., snow flakes vs. hail stones
  - Dust is released by collision and disruption of larger softball-sized (10 cm/4-inch) “parent bodies”
  - Parent bodies must be fluffy too and grew by gentle agglomeration
    - Key clue in the first step to forming planets?



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Outline

- Debris disk: definition and discovery
- Incidence and evolution
- Characterizing debris disks
- Disks around low-mass stars (AU Mic)
- Planetary connection
- Herschel surveys

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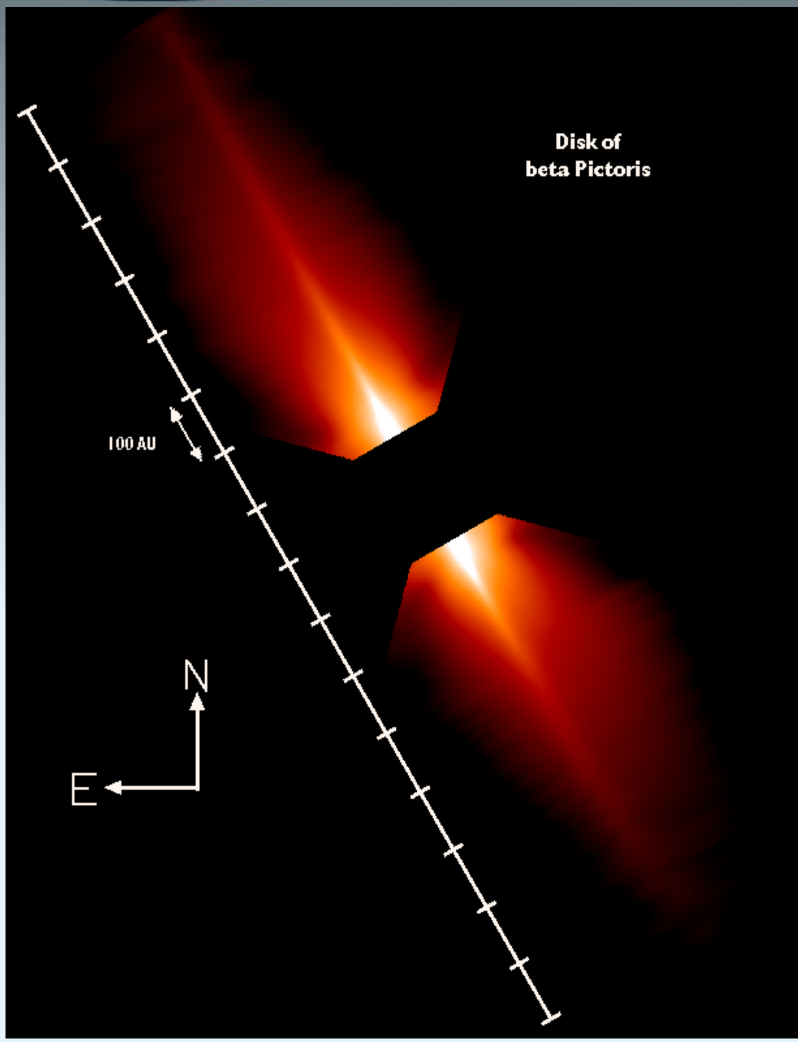
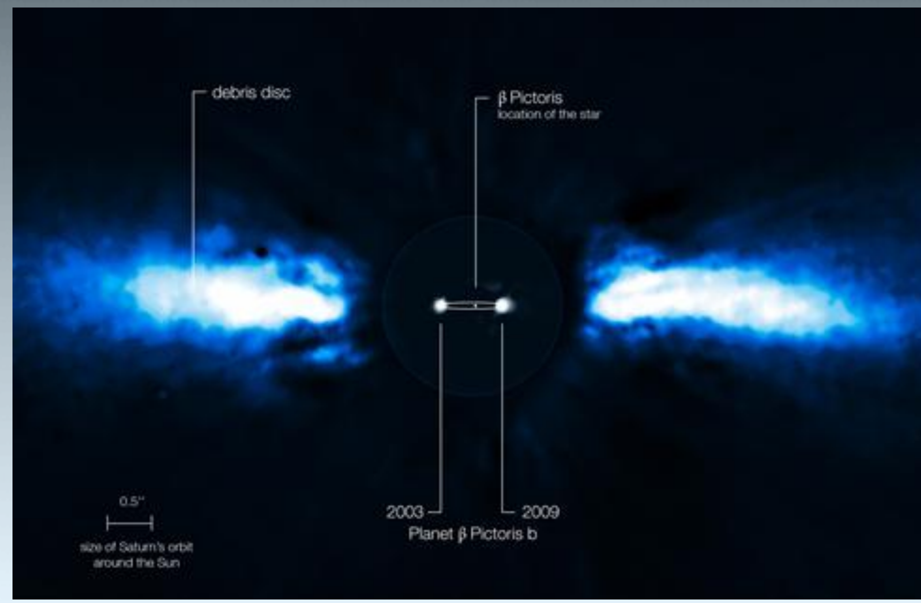
The Beta Pictoris Disk





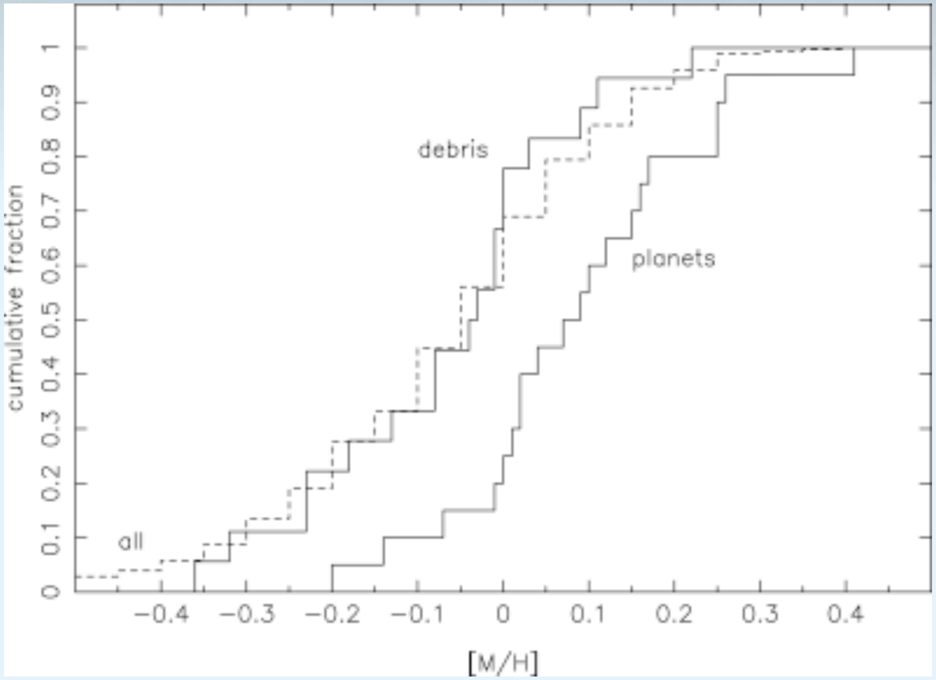
Lagrange et al. 2010

Beta Pictoris b
~ 8 M_J at 8 AU

P20:2 Maddison:
mm obs of beta Pic

The Planetary Connection: Correlation with Metallicity

- Of 310 FGK stars < 25 pc 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

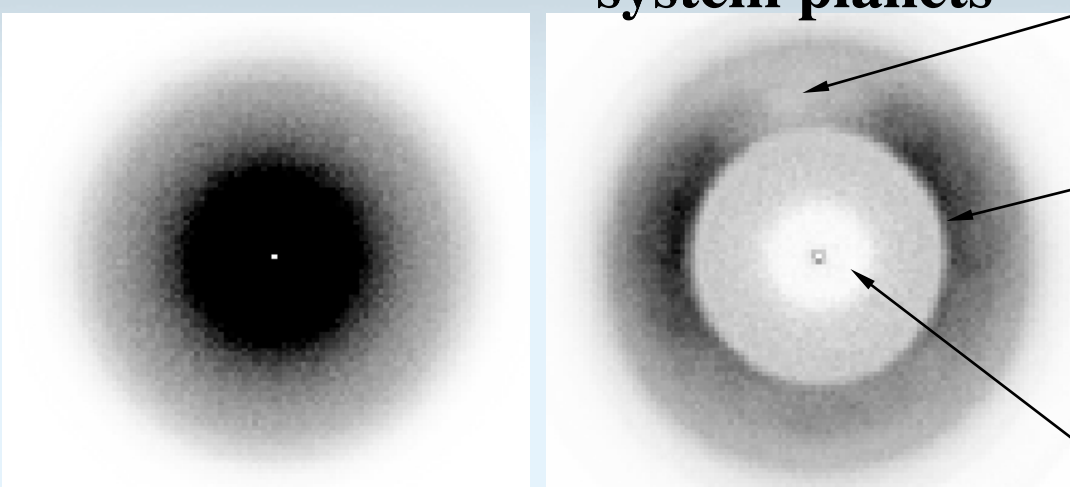


The Planetary Connection: Indirect evidence in debris

- Planets within debris disks sculpt the dust distribution

Dust—no planets

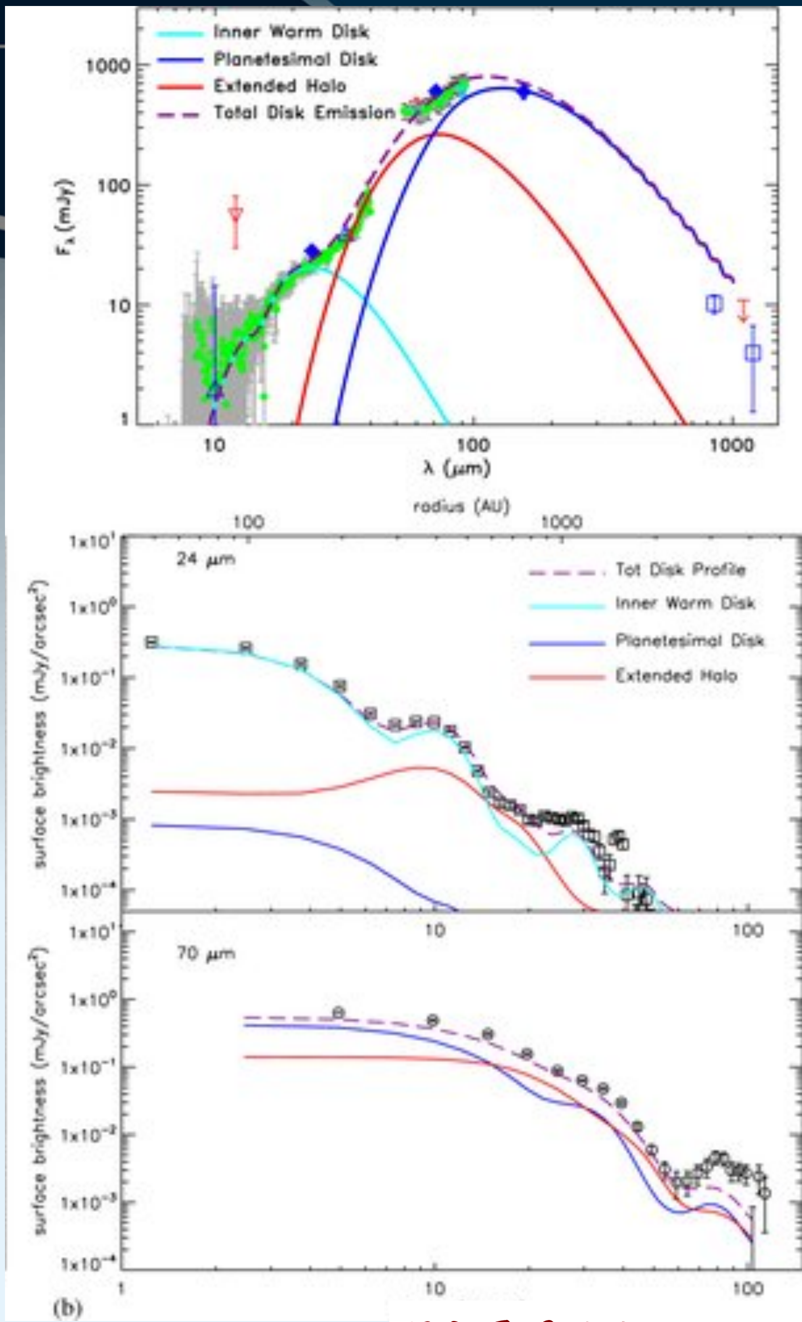
Dust—solar system planets



Minimum at Neptune's position (to avoid planet)

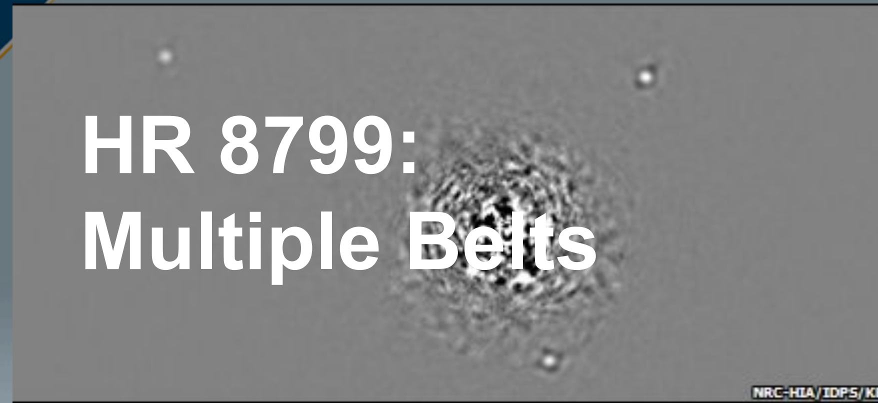
Ring-like structure along Neptune's orbit (trapping into mean motion resonances)

Clearing of dust < 10 AU (gravitational scattering by Jupiter & Saturn)

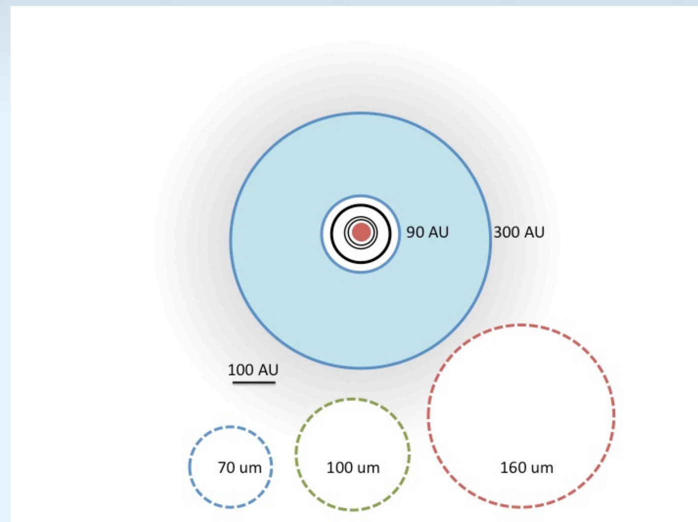


Su et al. 2009

HR 8799: Multiple Belts



- Spitzer data reveal evidence for three components within the HR 8799 debris disk
- Su et al. 2009 call these the inner warm disk, the planetesimal disk and the extended halo



P15:2 Moya re: HR8799 primary

Outline

- Debris disk: definition and discovery
- Incidence and evolution
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- Herschel surveys

Herschel debris disc surveys

- need to continue to go beyond individual systems to the origins of evolution of debris discs in general
  - where does the Solar System's comet belt fit in the population?
  - what is the relation to planetary systems?
    - a signpost, or indicator of failed planet formation?
  - can there be massive comet belts to many-Gyr ages?
    - possibly very prolonged planetary bombardment?

Herschel debris disk surveys

- GTKP (SAG 6) (Vandenbussche et al. 2010; Sibthorpe et al. 2010)
  - PI: Olofsson P19.2
  - Photometry and spectroscopy of “Big Six” debris disks
- OTKP DUNES (Eiroa et al. 2010; Liseau et al. 2010)
  - PI: Eiroa ← next talk! + P18.2, P21.2, P22.2
- OTKP DEBRIS (Phillips et al. 2010; Matthews et al. 2010)
  - PI: Matthews
- OTKP GASPS (Mathews et al. 2010, Pinte et al. 2010, Thi et al. 2010, Meeus et al. 2010) P16.2
  - PI: Dent

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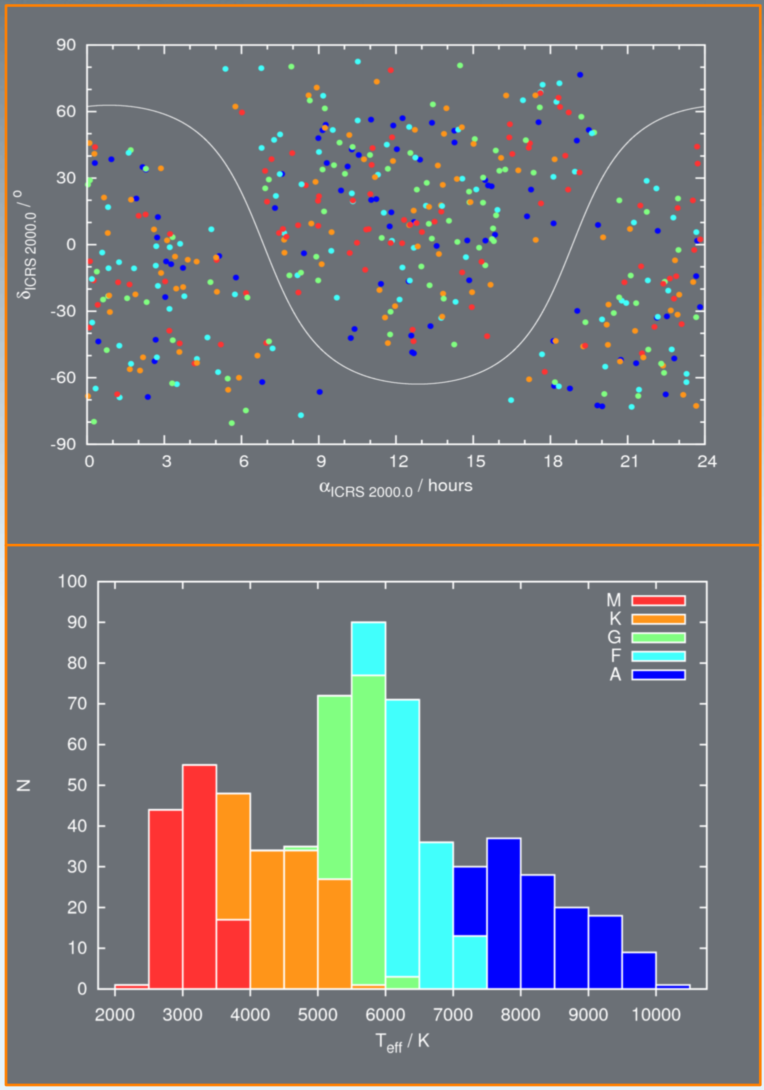
The DEBRIS Survey: Science Goals

- Disc Emission via a Bias-free Reconnaissance in the Infrared/Submillimetre

- Four primary science goals:
  - To establish what factors affect having a debris disc – planets, multiplicity, stellar mass etc
  - To place the solar system in context (common or unusual?)
  - To characterize the debris disc population
  - To resolve discs and model their structure

DEBRIS

The DEBRIS Survey: Sample



- Targets drawn from Unbiased Nearby Stars sample (Phillips et al. 2010)
- ~90 each of A, F, G, K and M type primaries (446)
- Sp. Type samples volume-limited, with confusion cut
- Volume limits: 46, 24, 21, 16, 8.6 (A-M)

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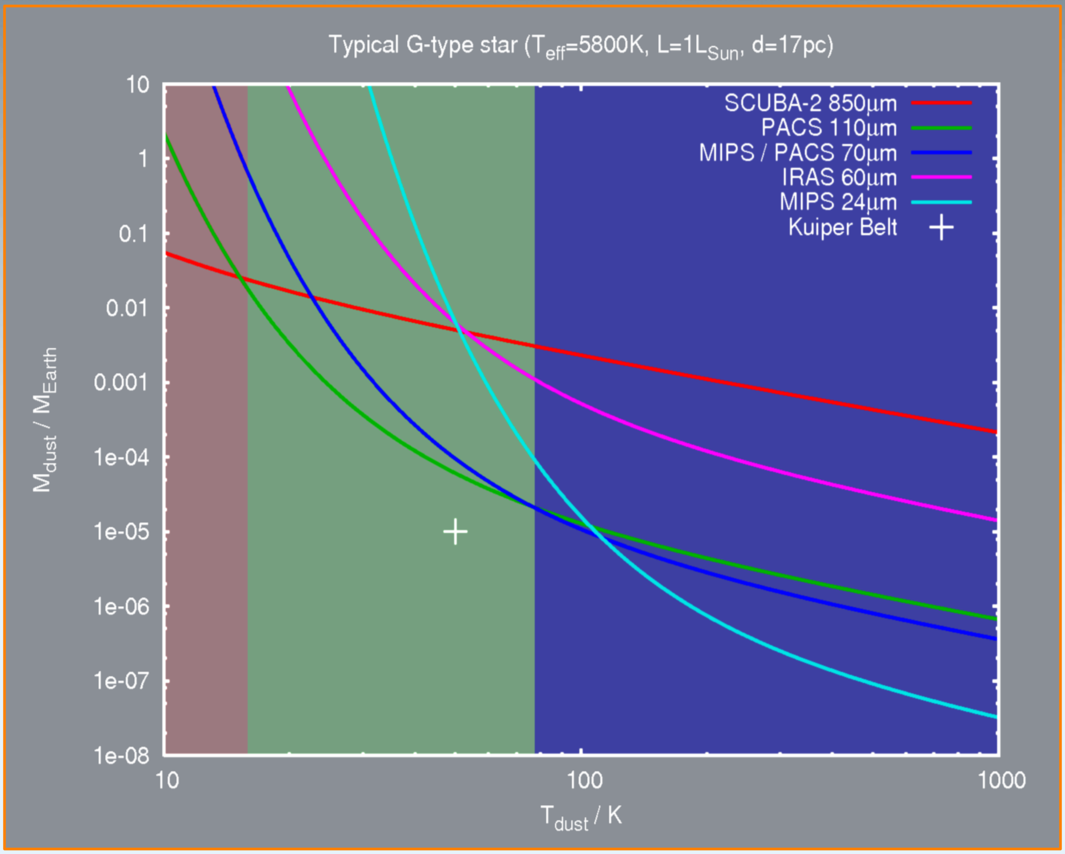
The DEBRIS Survey: Sensitivity



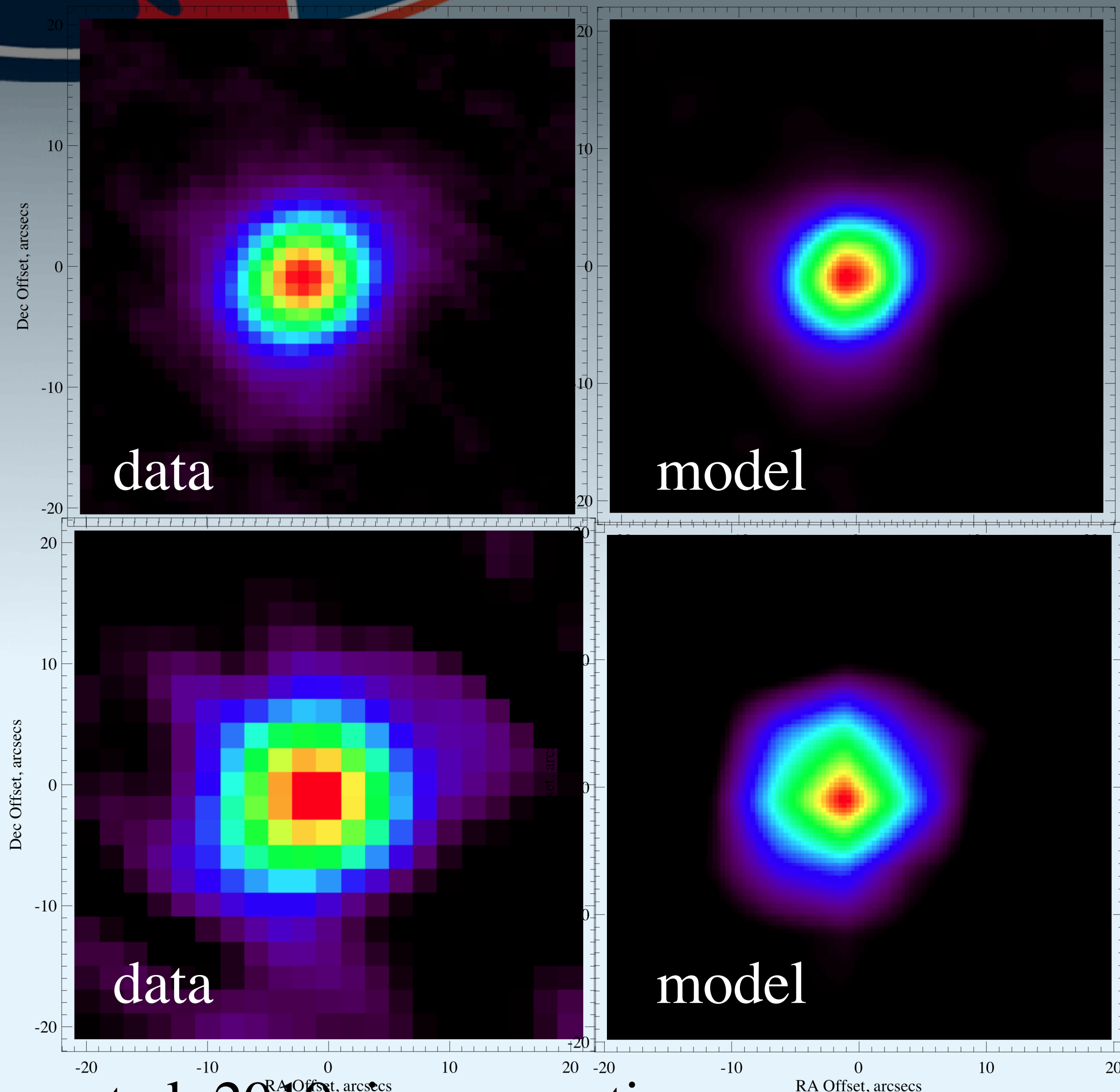
- Flux-limited, uniform depth
- Driven by 100 micron sensitivity
  - 1 sigma rms = 1.5 mJy
- PACS 100/160
- SPIRE follow-up for 110 targets (confusion limited)

DEBRIS

The DEBRIS Survey: Observations to date

- SDP observations
  - 7 targets observed with PACS 100/160
  - Six known disks detected
  - SPIRE data toward 3 targets
- 133 targets to date with PACS
  - 98 observed by DEBRIS (excess ~10%, 20% for As)
    - 50% of detected disks are resolved
  - 35 observed by DUNES
- First SPIRE followup now scheduled

Beta Leo Modeling

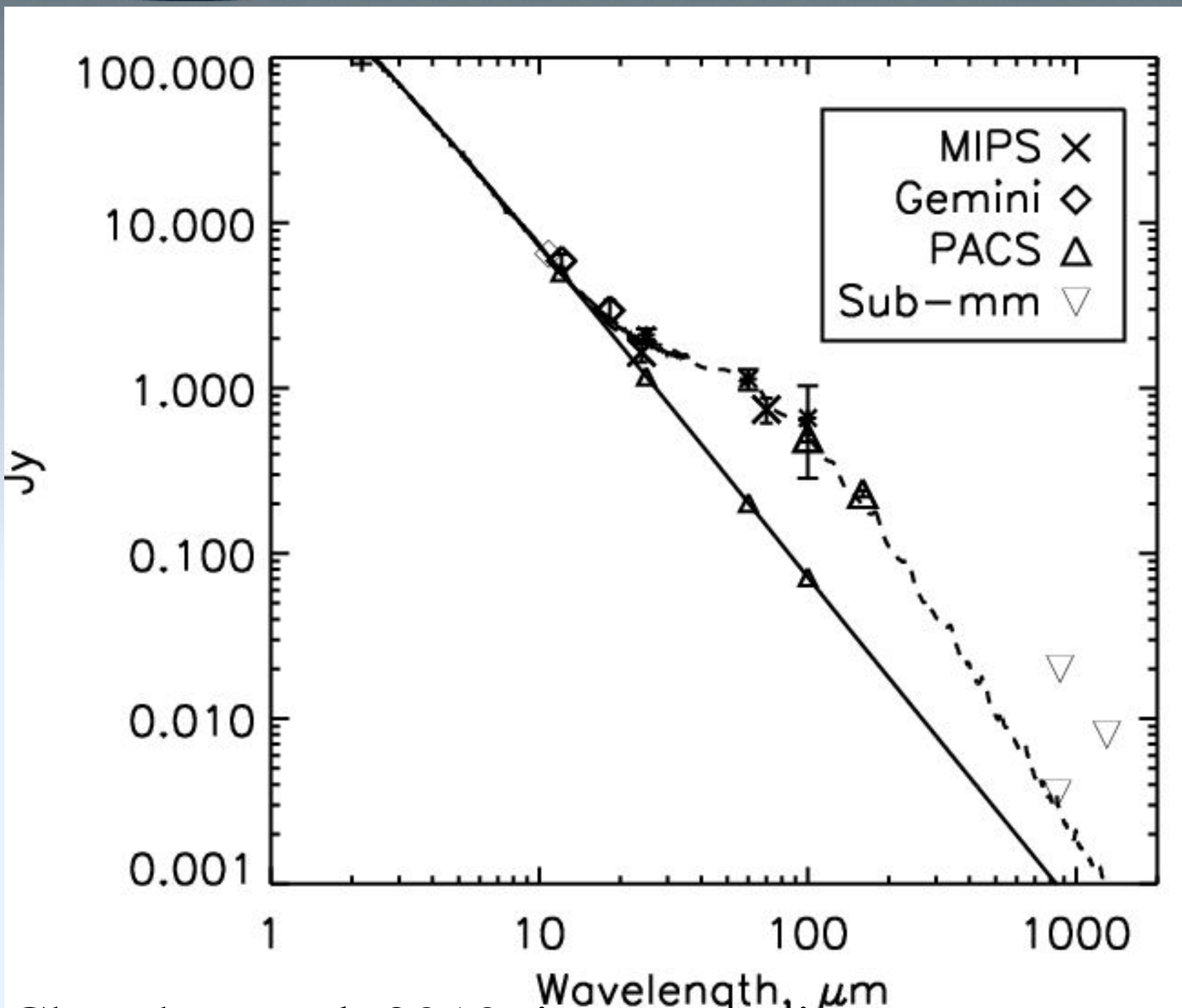


100 micron

160 micron

Churcher et al. 2010, in preparation

Beta Leo
Current best-fit model



r(in) 15+/-5 AU

r(out) 70+/-10 AU

$\Sigma \alpha r^{-1+/-0.5}$

i=55+/-10° (from edge on)

a(min) =5.8 micron

Porosity 20%

Churcher et al. 2010, in preparation

The DEBRIS Survey: Summary

- Resolution impact is immediate
  - A&A SE: beta Leo and beta UMa resolved for the first time
  - Disk sizes are comparable to the KB (40-50 AU)
    - Among smallest disks yet resolved
  - More detailed beta Leo modeling yields $15 < r < 70$ AU
  - Components of eta Corvi disk (see Mark Wyatt’s talk)

- Early excess ratios ~10% for 98 observed targets
  - 20% among A stars
- 50% detected disks resolved by PACS 100

Summary

- Debris disks are most common around young, early stars
- Spitzer provides evidence that warm disk components are lost faster than the colder, outer disks
- Excesses decline faster around A stars than FGK stars
- Detection of late K and M excesses are significantly fewer than around Sun-like or A stars
- Significant disks are detected around old stars, but rare (transient)

- Herschel's sensitivity will allow us to detect fractional luminosities comparable to our own KB
- Resolution is CRITICAL for effective disk characterization
- Herschel is very effective at resolving debris disks on the scale of the KB!

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Lots more to come on debris disks!

(today and from Herschel!)