

Characterization of planetesimal belts through the study of debris disks

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Debris disks host planetary systems

Protoplanetary disks dissipate in about 6 Myr, but there is evidence of dust around 7-15% of mature stars (10-10,000 Myr) of a wide range of stellar masses (0.5-3 M_{sun}).

Dust lifetime < 0.01-1 Ma

Poynting-Robertson: $t_{PR} = 710 \left(\frac{s}{\mu m} \right) \left(\frac{\rho}{g/cm^3} \right) \left(\frac{R}{AU} \right)^2 \left(\frac{L_{\odot}}{L_*} \right) \frac{1}{1+albedo}$ years

Grain-grain collisions: $t_{col} = 1.26 \cdot 10^4 \left(\frac{R}{AU} \right)^{3/2} \left(\frac{M_{\odot}}{M_*} \right)^{1/2} \left(\frac{10^{-5}}{L_{dust}/L_*} \right)$ years

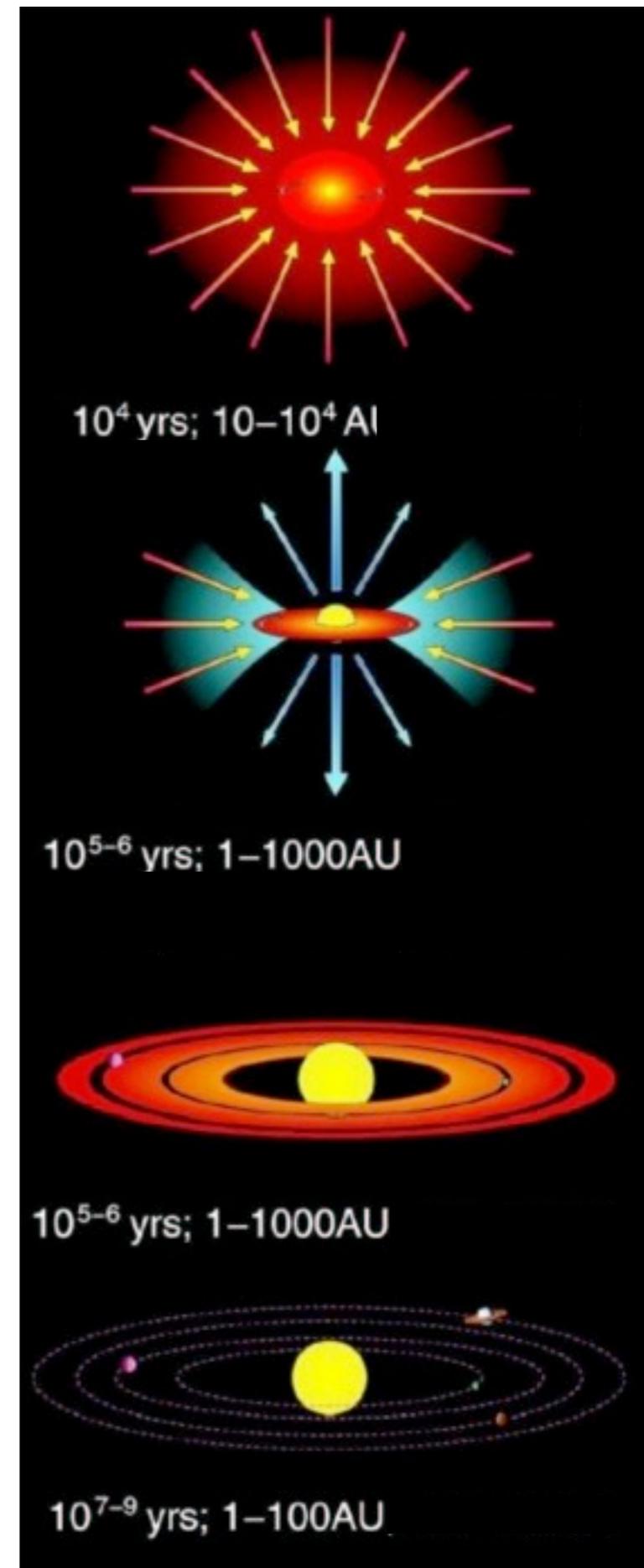
Radiation Pressure: $t_{blow} = \frac{1}{2} \left(\frac{(R/AU)^3}{M_*/M_{\odot}} \right)^{1/2}$ years

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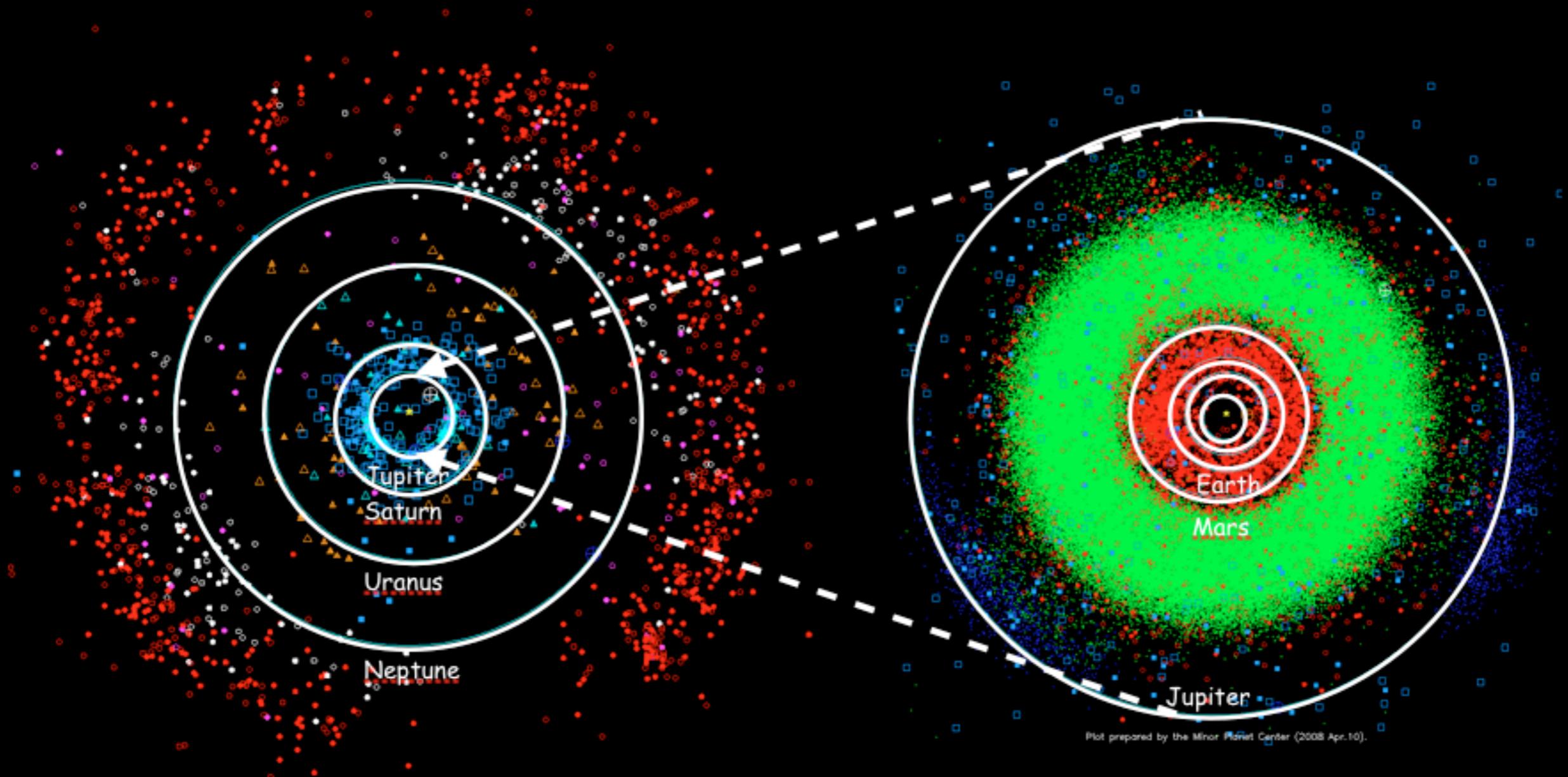
stellar age > 10 Ma



Debris dust cannot be primordial; it must be generated by planetesimals (like asteroids, comets and KBOs)



Sources of Solar System Dust



Plot prepared by the Minor Planet Center (2008 Apr.10).

Plot prepared by the Minor Planet Center (2008 Apr.10).

Kuiper Belt

Asteroid Belt

Minor Planet Center

Comet-like Asteroid P/2010 A2 • January 29, 2010

Hubble Space Telescope • WFC3/UVIS



(Jewitt 2010)

NASA, ESA, and D. Jewitt (UCLA)

STScI-PRC10-07

Solar System debris disk



extra-solar debris disk



β -Pictoris
(Schultz, HST)

extra-solar debris disk

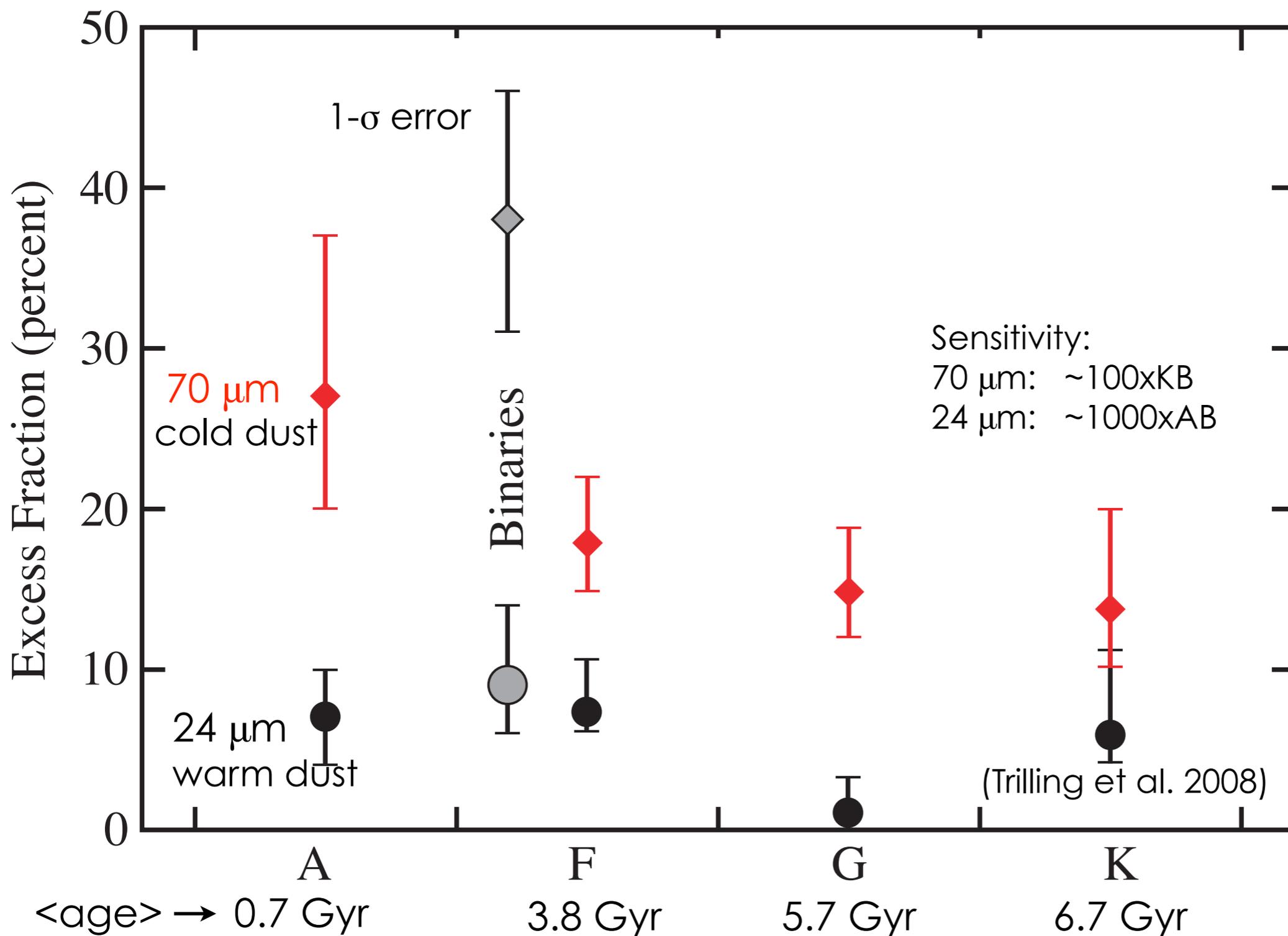
Debris disks...

- are indirect evidence of planetesimal formation.
- help characterize the planetesimals (location, composition...).

β -Pictoris
(Schultz, HST)

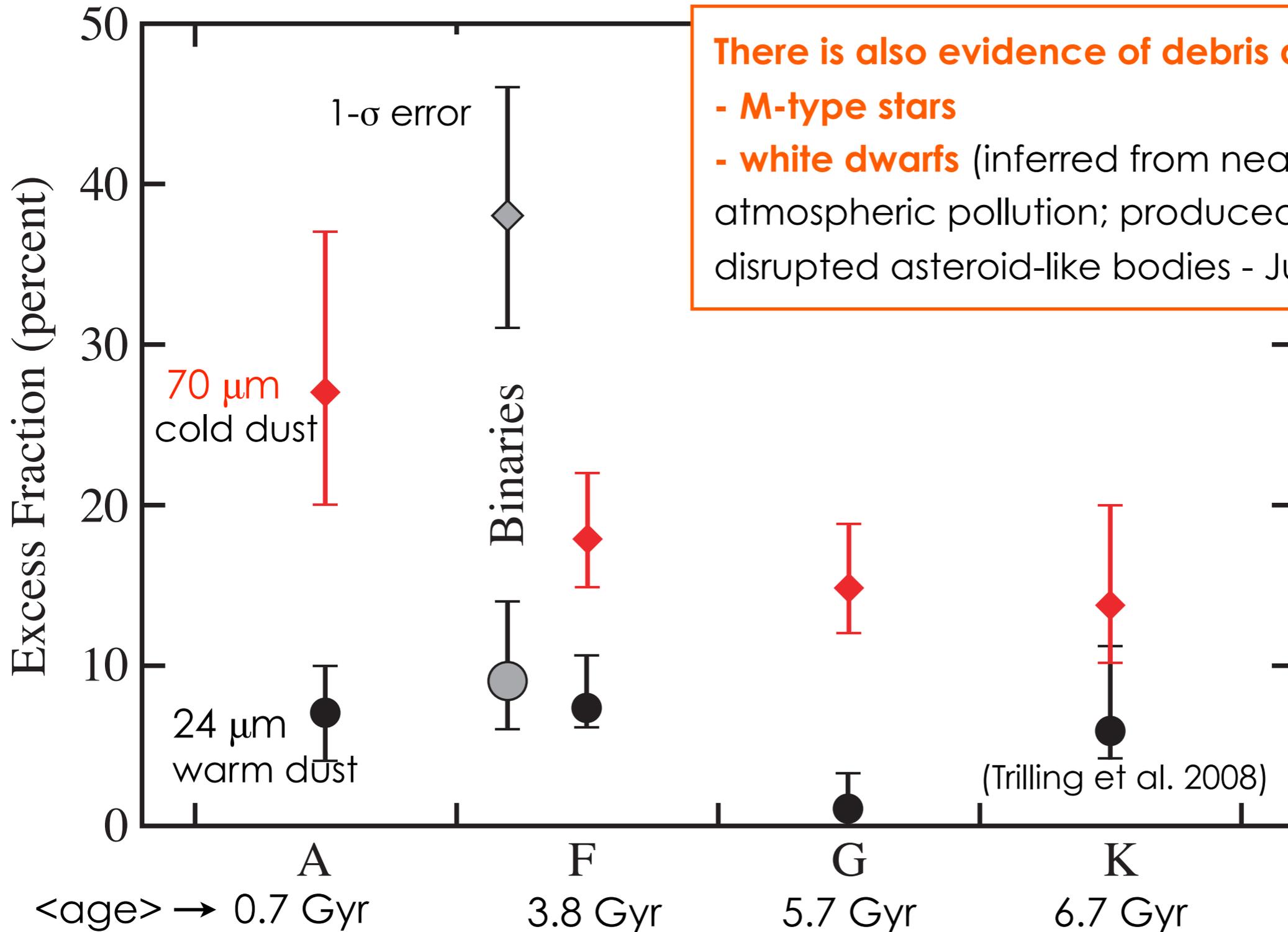
debris disks are found around stars with a wide range of stellar properties

$(M^*, L^*, [M/H]^*)$



debris disks are found around stars with
a wide range of stellar properties

$(M^*, L^*, [M/H]^*)$



There is also evidence of debris disks around...

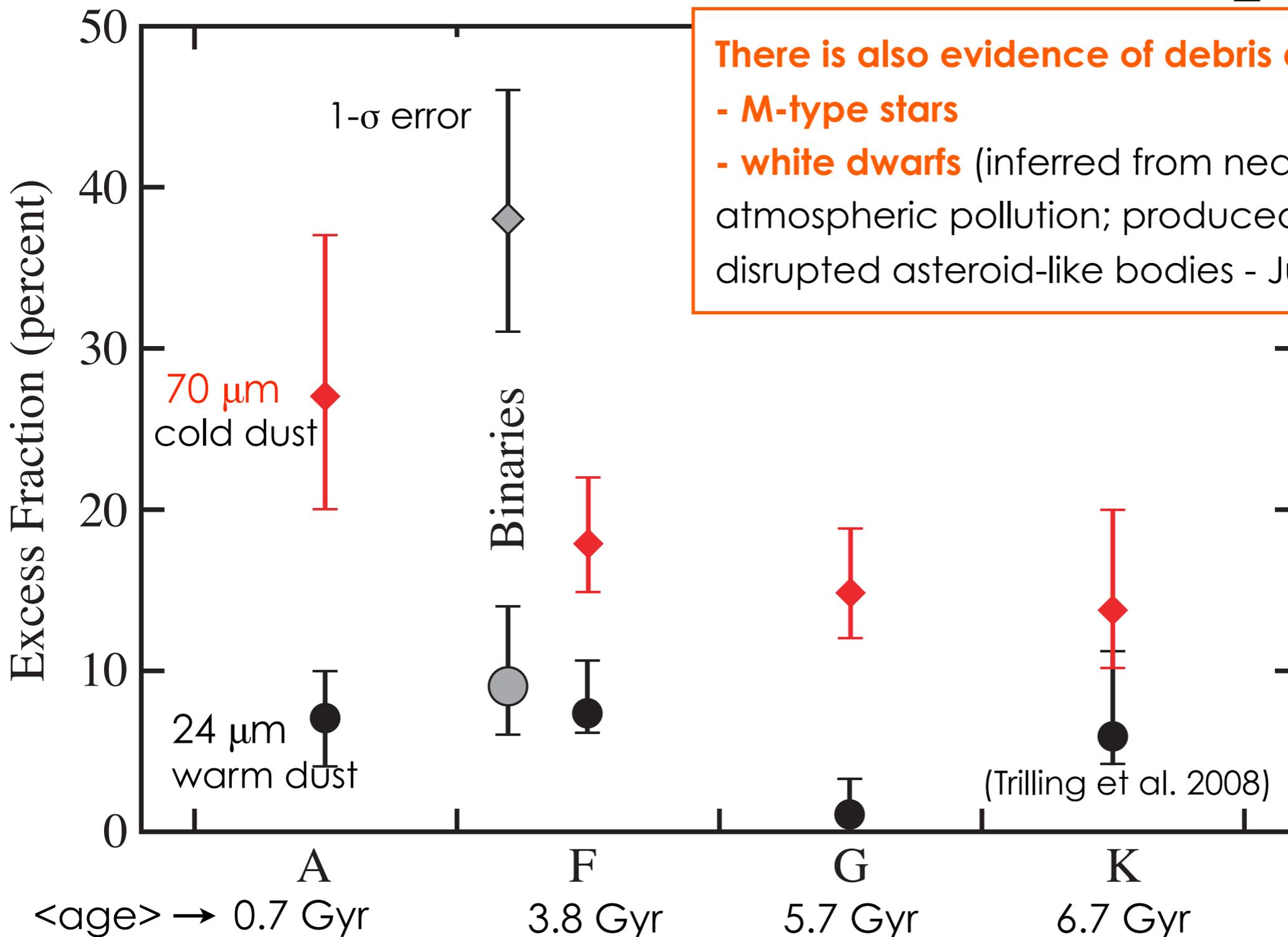
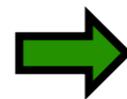
- M-type stars

- white dwarfs (inferred from near IR excess + atmospheric pollution; produced by tidally disrupted asteroid-like bodies - Jura, 2006, 2007).

debris disks are found around stars with a wide range of stellar properties

$(M^*, L^*, [M/H]^*)$

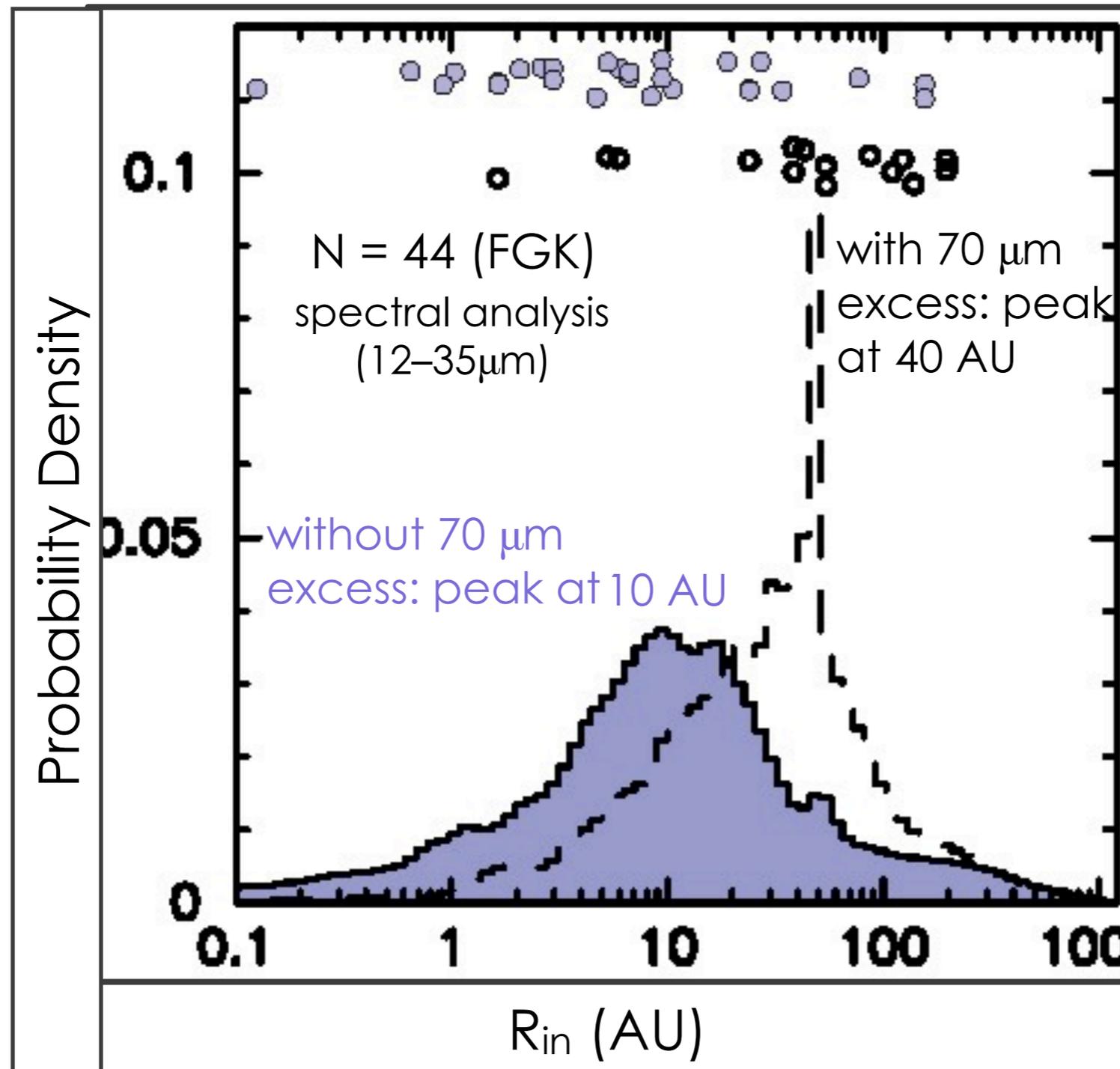
Planetesimal formation takes places under a wide range of conditions.



There is also evidence of debris disks around...

- **M-type stars**
- **white dwarfs** (inferred from near IR excess + atmospheric pollution; produced by tidally disrupted asteroid-like bodies - Jura, 2006, 2007).

**Cold dust is more common:
the SEDs indicate the presence of large inner gaps (KB-like)**

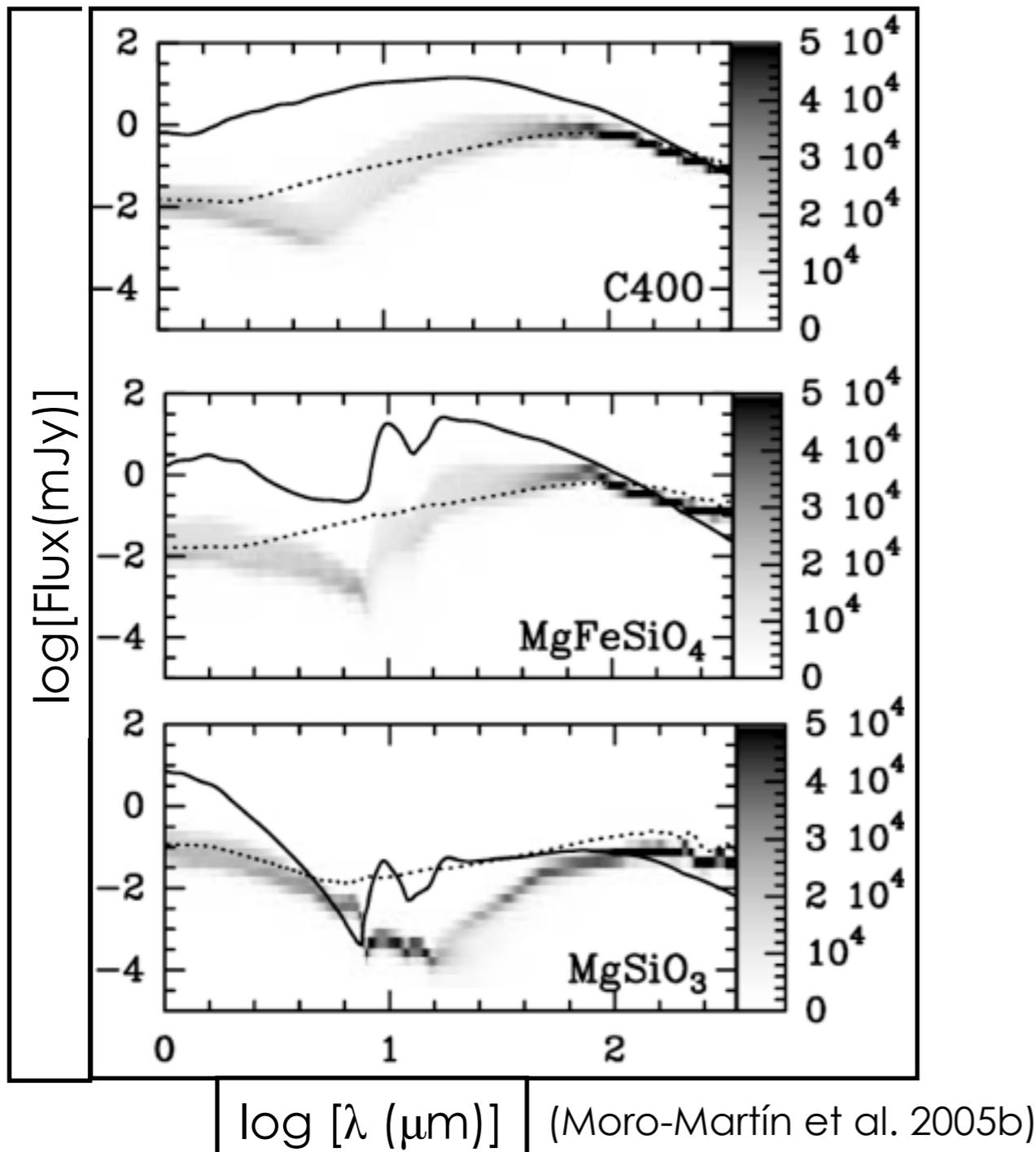


(Carpenter et al. 2009)

Massive planets may be responsible for the formation of the inner gaps in disks

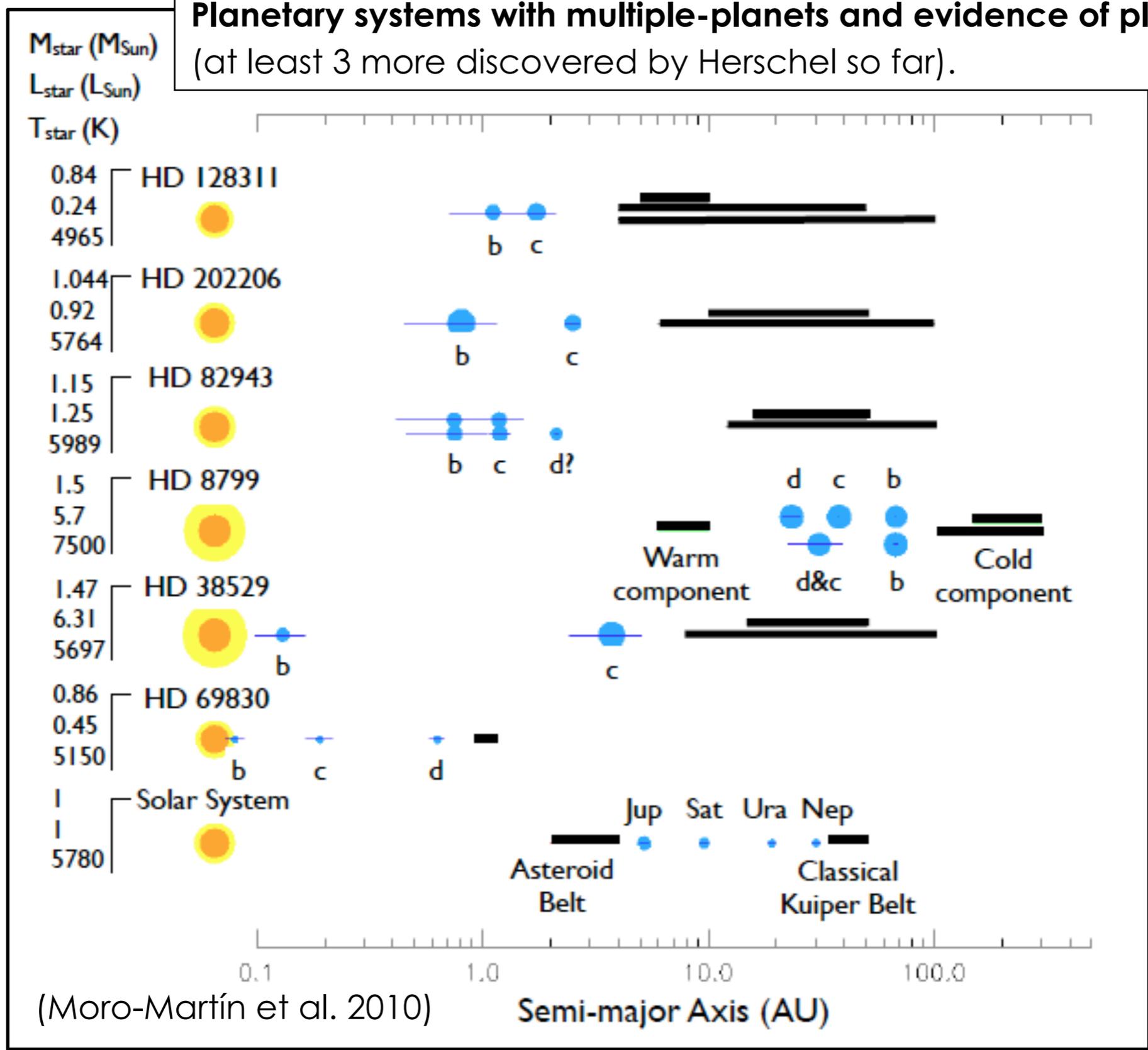
lines: disk w/o planets (no gap) — 135 μm
 0.7 μm

grey scale: disk with planets at 1-30 AU (with gap) and dust grain with a power-law distribution.



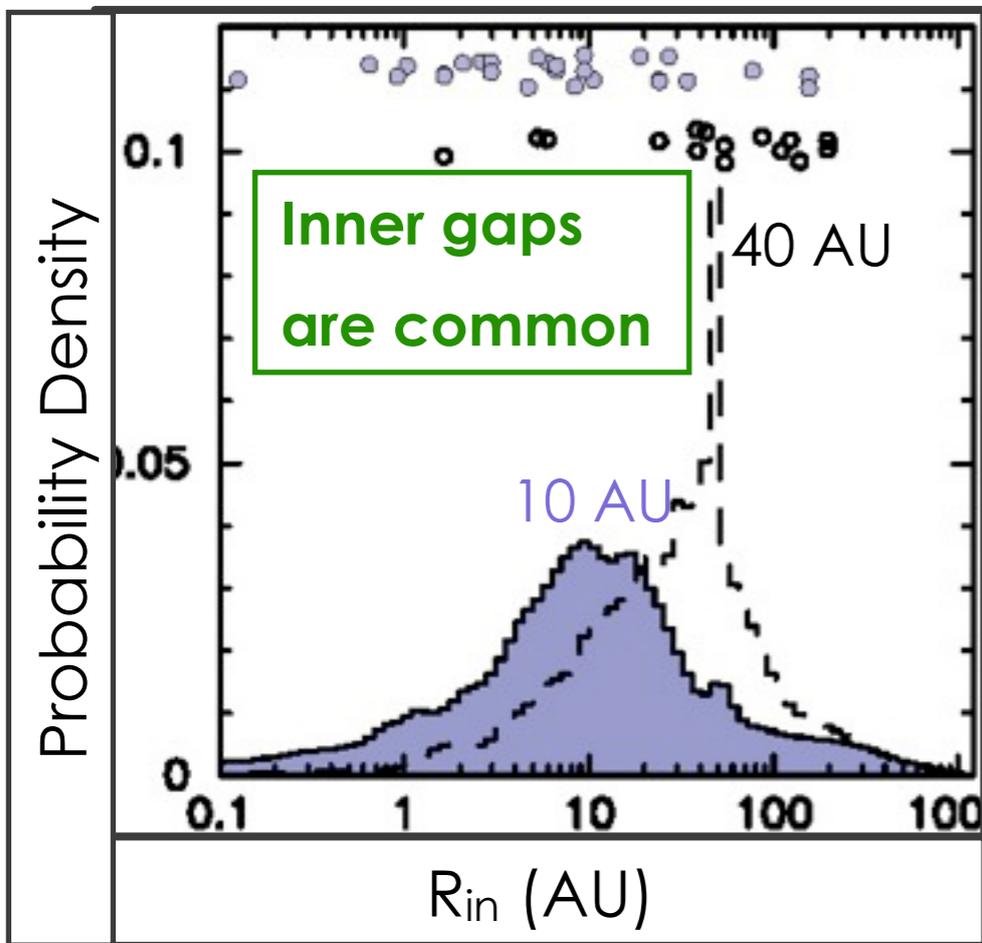
Need of spatially resolved observations....

Planetary systems with multiple-planets and evidence of planetesimals
 (at least 3 more discovered by Herschel so far).



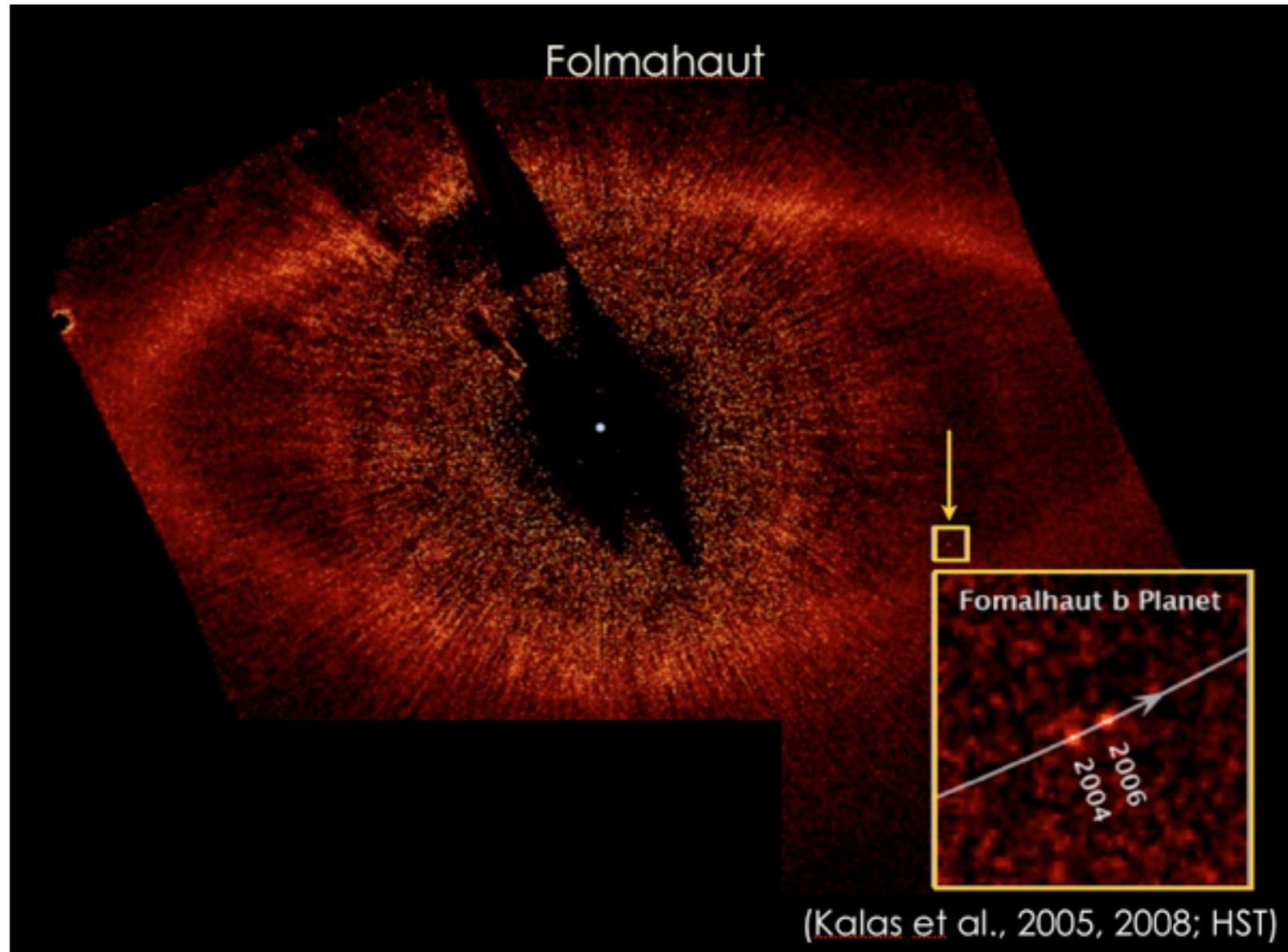
(Moro-Martín et al. 2010)

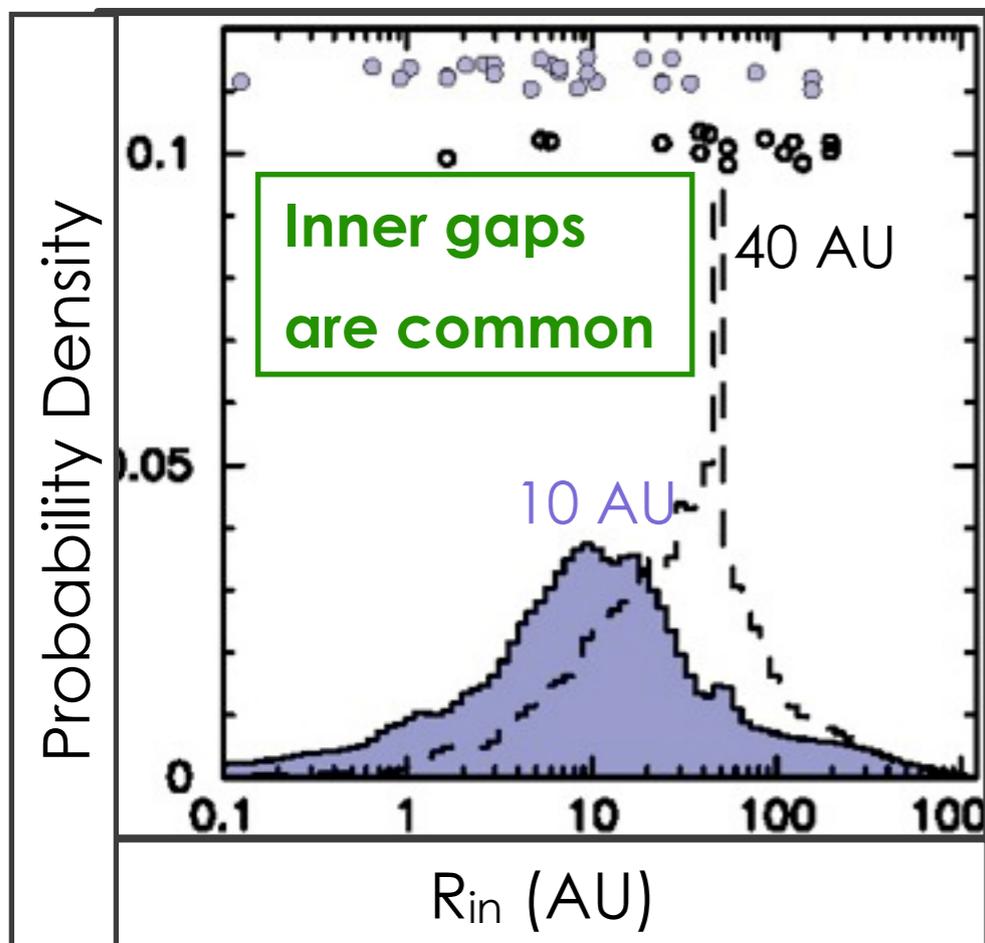
**Need
Rout**



(Carpenter et al. 2009)

...and massive planets may be responsible for the formation of some of these inner gaps.





(Carpenter et al. 2009)

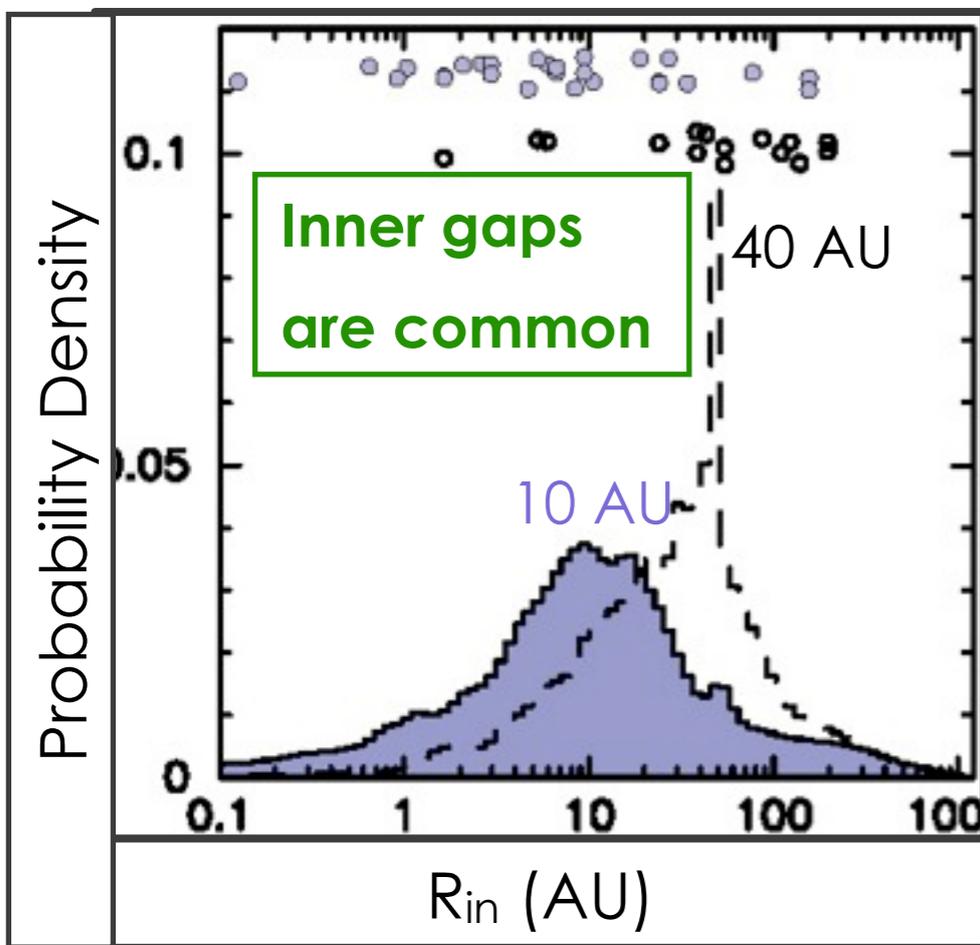
...and massive planets may be responsible for the formation of some of these inner gaps.



Search for giant planets in debris disks with large inner gaps (inferred from spatially resolved images or from SEDs).

Subaru program "SEEDS" (Strategic Exploration of Exoplanets and Disks with HiCIAO/AO188) (P.I. M. Tamura)

- high resolution imaging
- large dynamic range
- small inner working angle (0.08'')



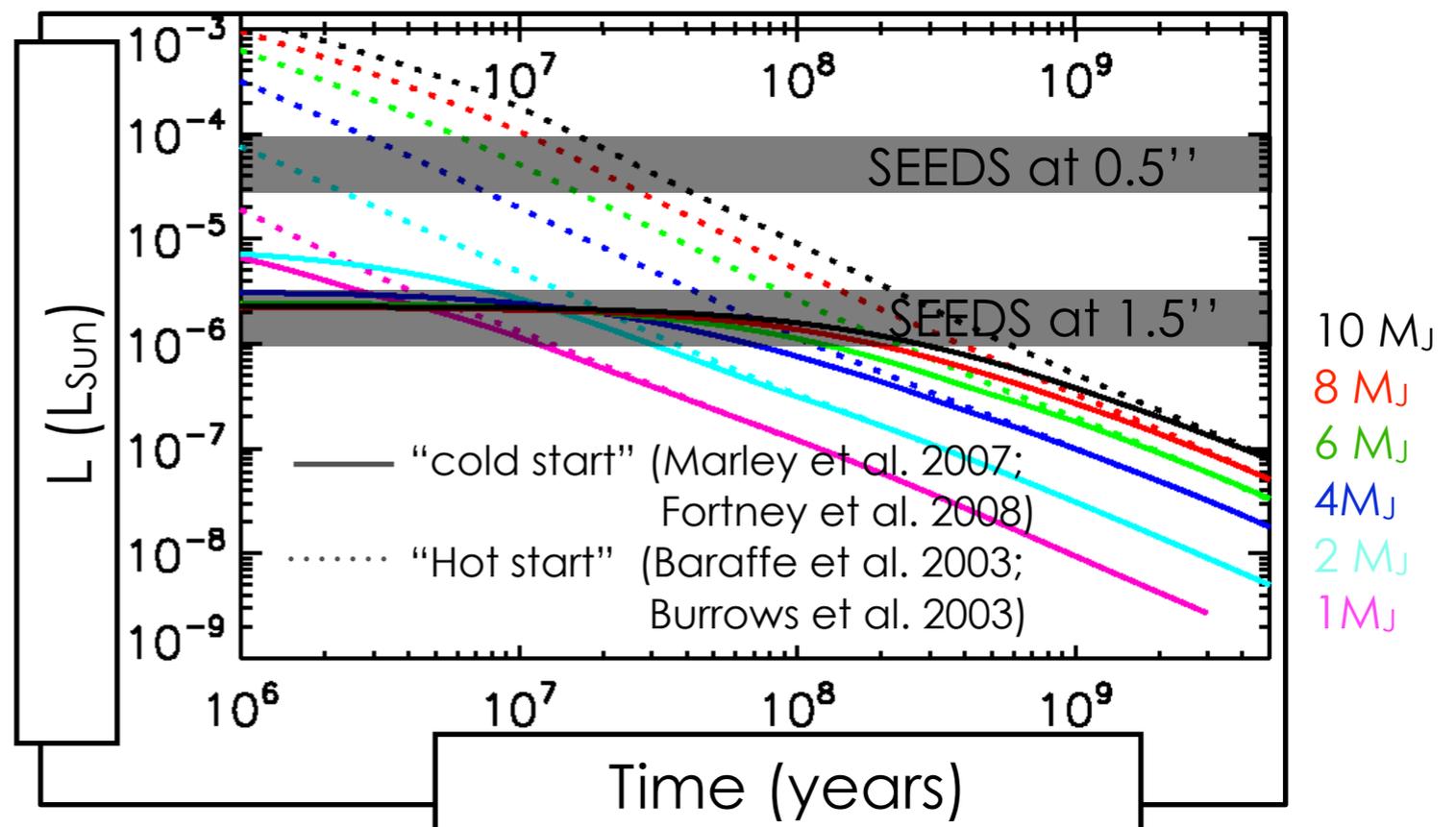
(Carpenter et al. 2009)

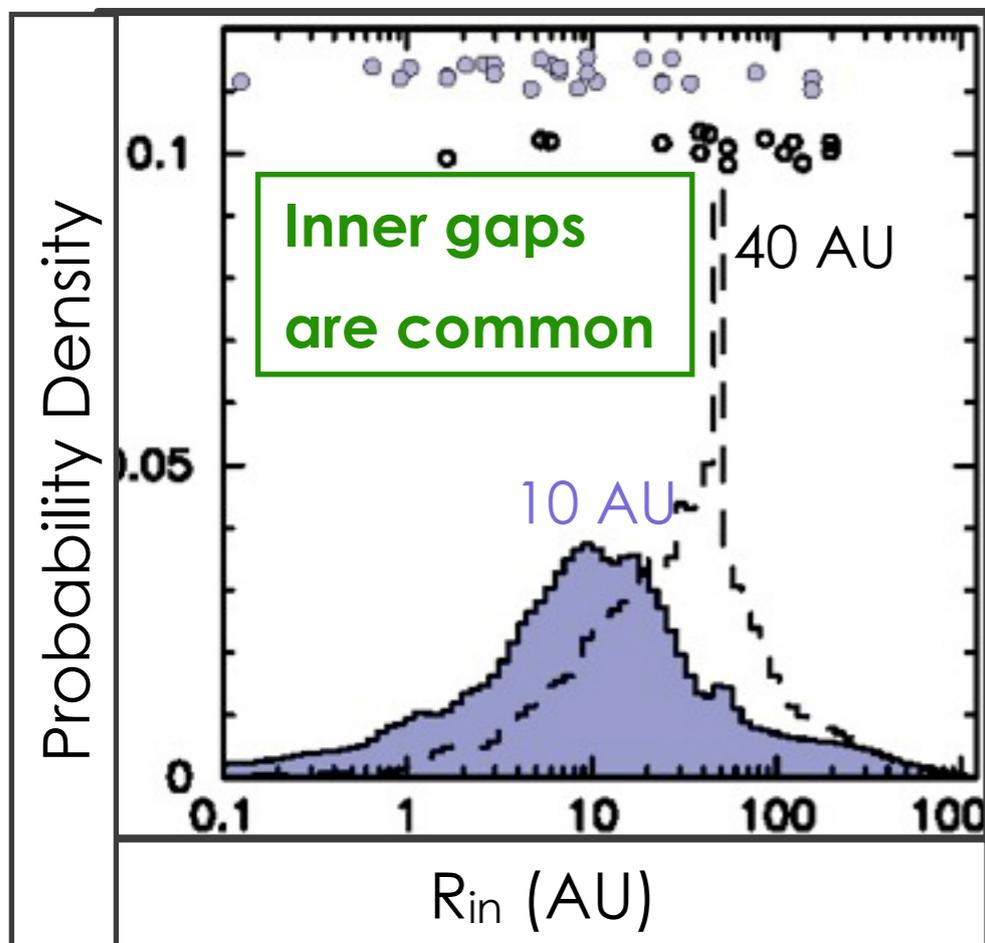
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Subaru program "SEEDS" (Strategic Exploration of Exoplanets and Disks with HiCIAO/AO188 (P.I. M. Tamura))





(Carpenter et al. 2009)

SEEDS-DD targets:

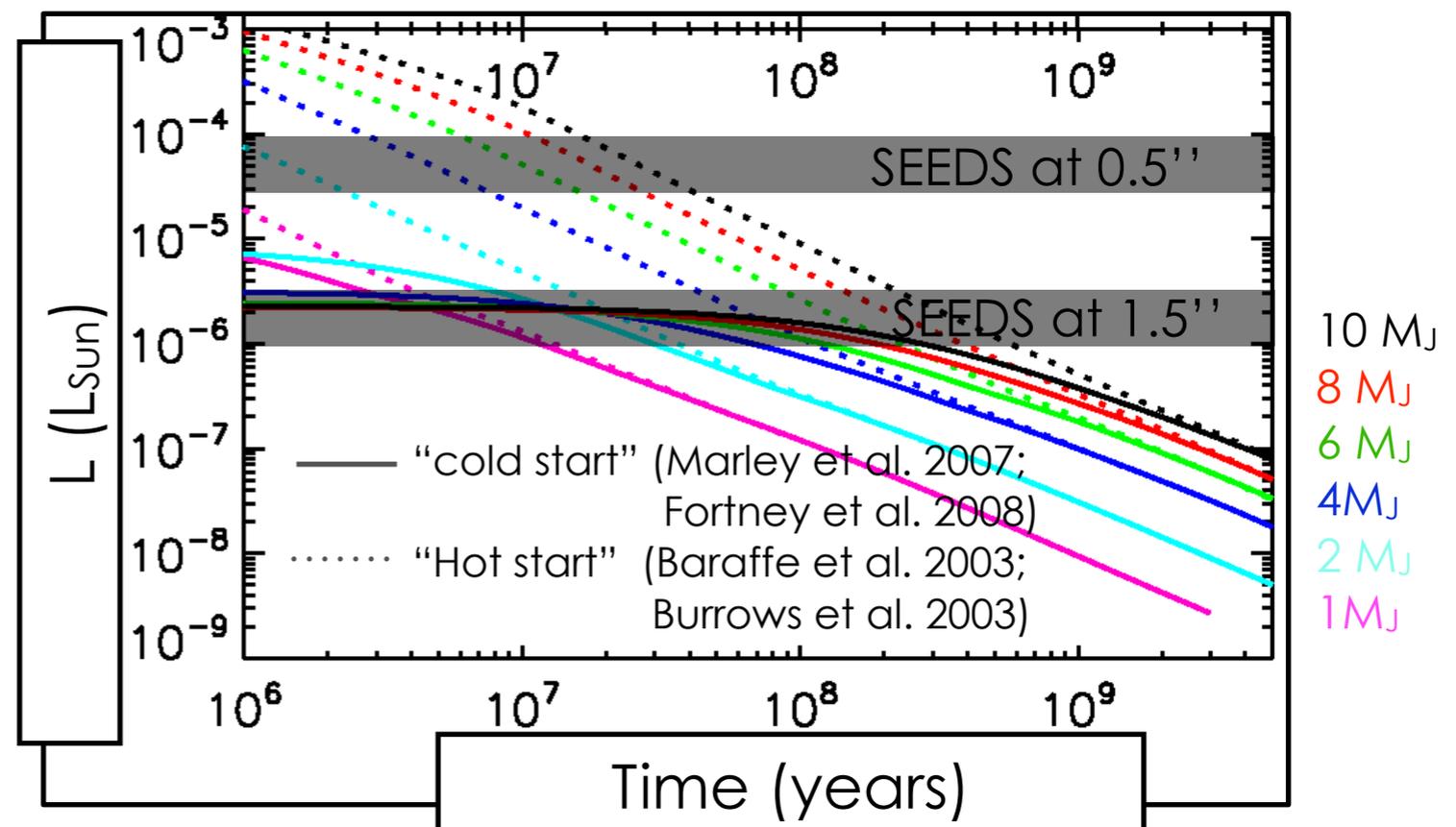
- approx. 80 debris disks studied by Spitzer.
- mostly systems with inferred large inner gaps.
- few systems with warm dust (uncommon).

...and massive planets may be responsible for the formation of some of these inner gaps.



Search for giant planets in debris disks with large inner gaps (inferred from spatially resolved images or from SEDs).

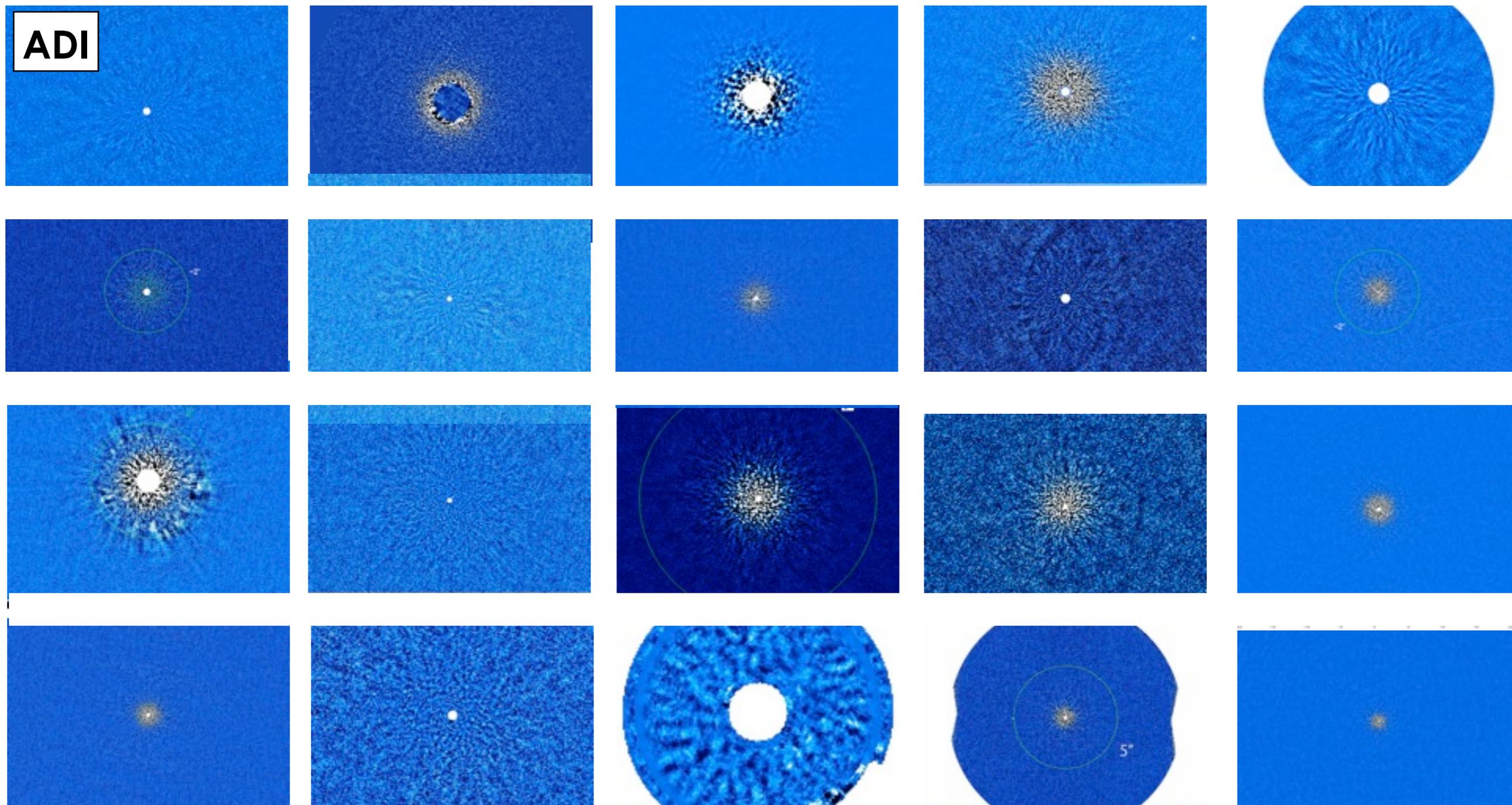
Subaru program "SEEDS" (Strategic Exploration of Exoplanets and Disks with HiCIAO/AO188 (P.I. M. Tamura)



On-going survey.

27 targets observed up to date.

No new planetary companions found (...so far)

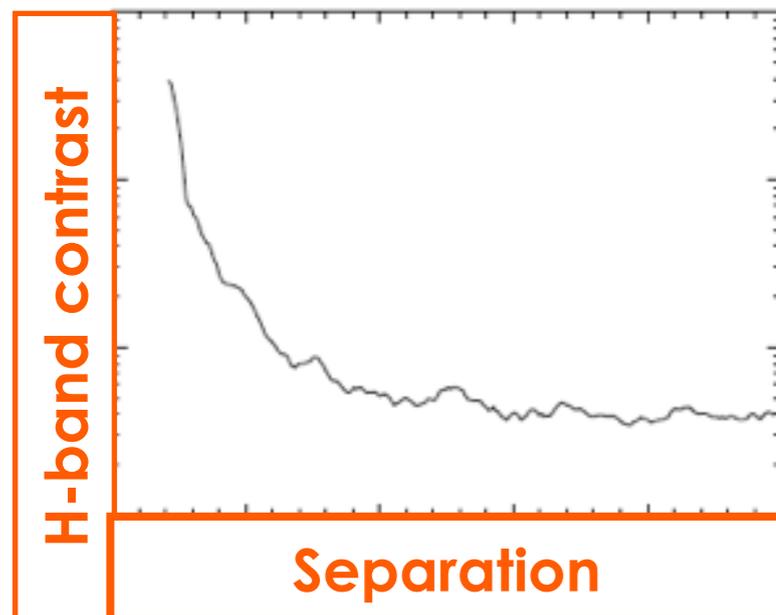


On-going survey.

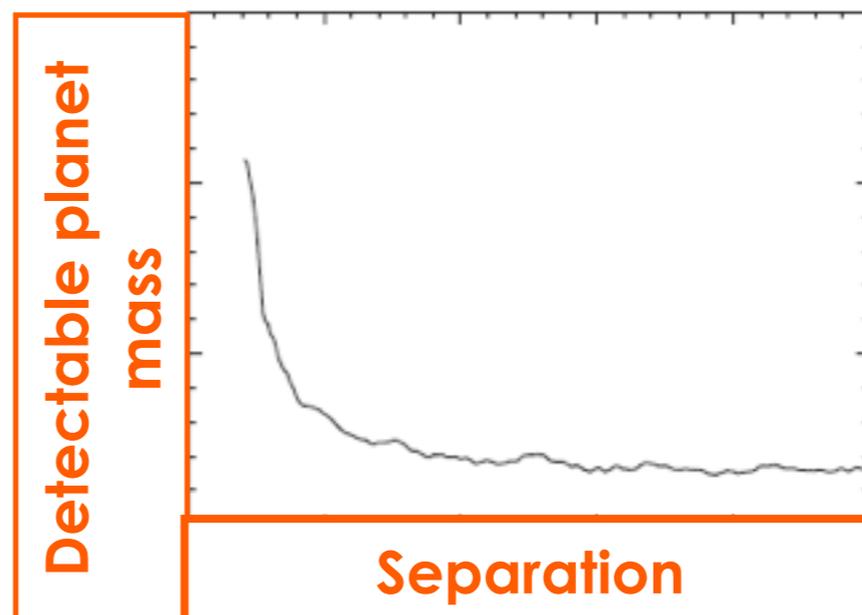
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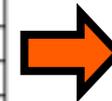
AO188 → SCExAO



stellar age
+ cooling
models



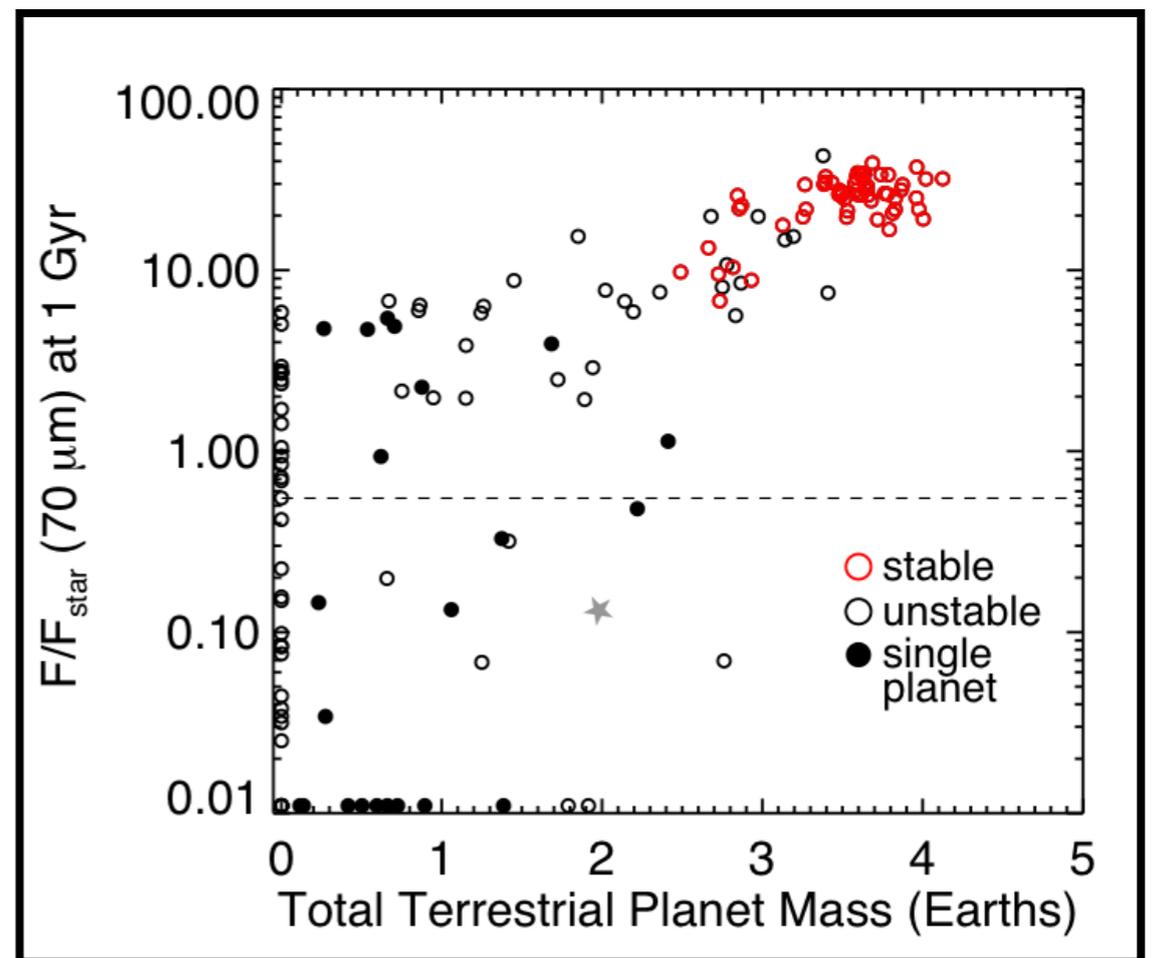
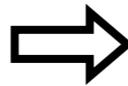
Compare to
inferred disk
inner radius
and dust
depletion
factor



Search for warm dust at small inner working angles:

Non-detections are important because cold disks without warm dust are good candidates for the search of terrestrial planets because...

- Low zodi (contaminant) light.
- The presence of cold dust seems to be correlated with the presence of terrestrial planets (because the former implies the system has undergone mild dynamical evolution with moderate gravitational instabilities).



(Raymond et al. 2011)

Herschel-DEBRIS Key Program

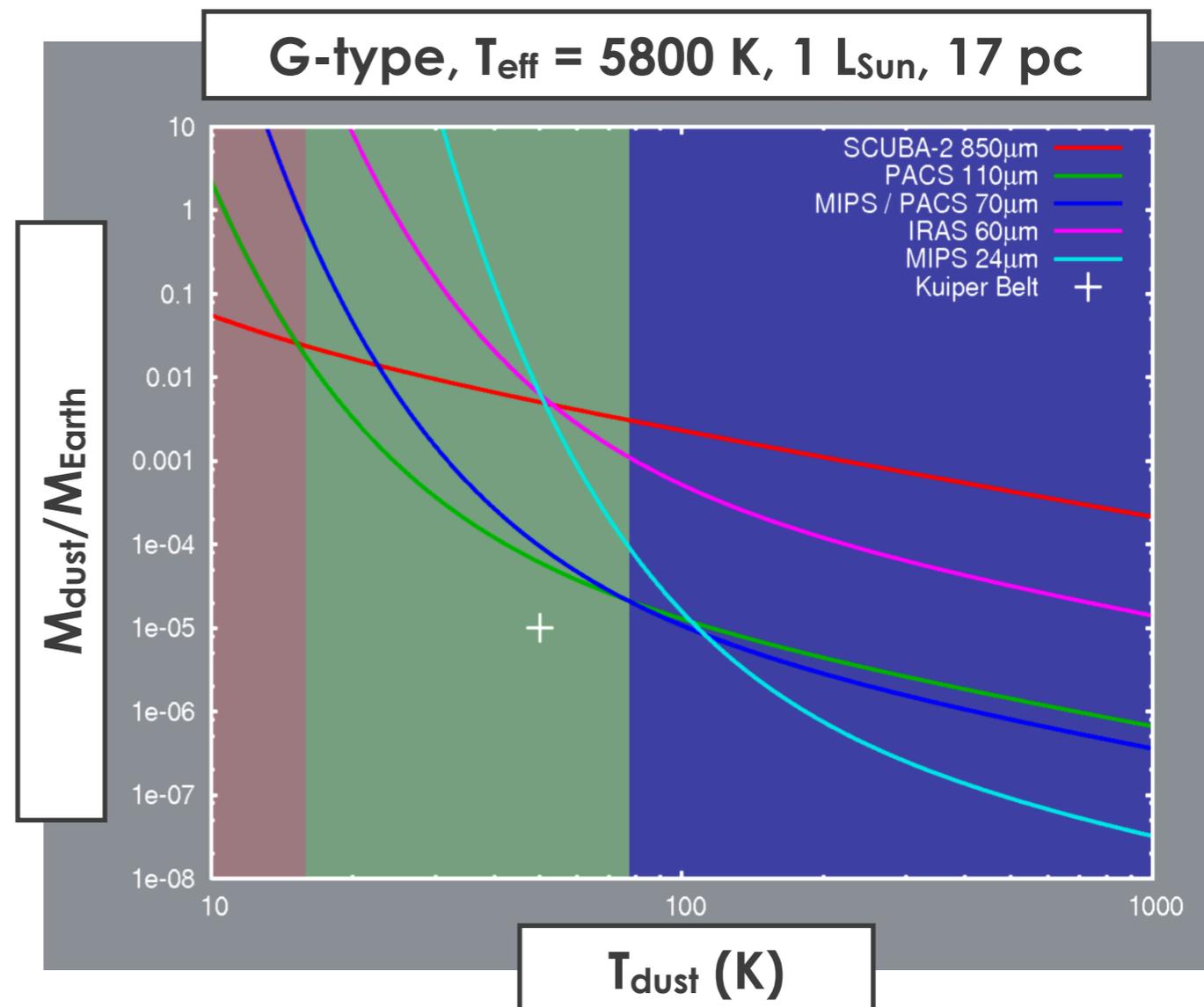
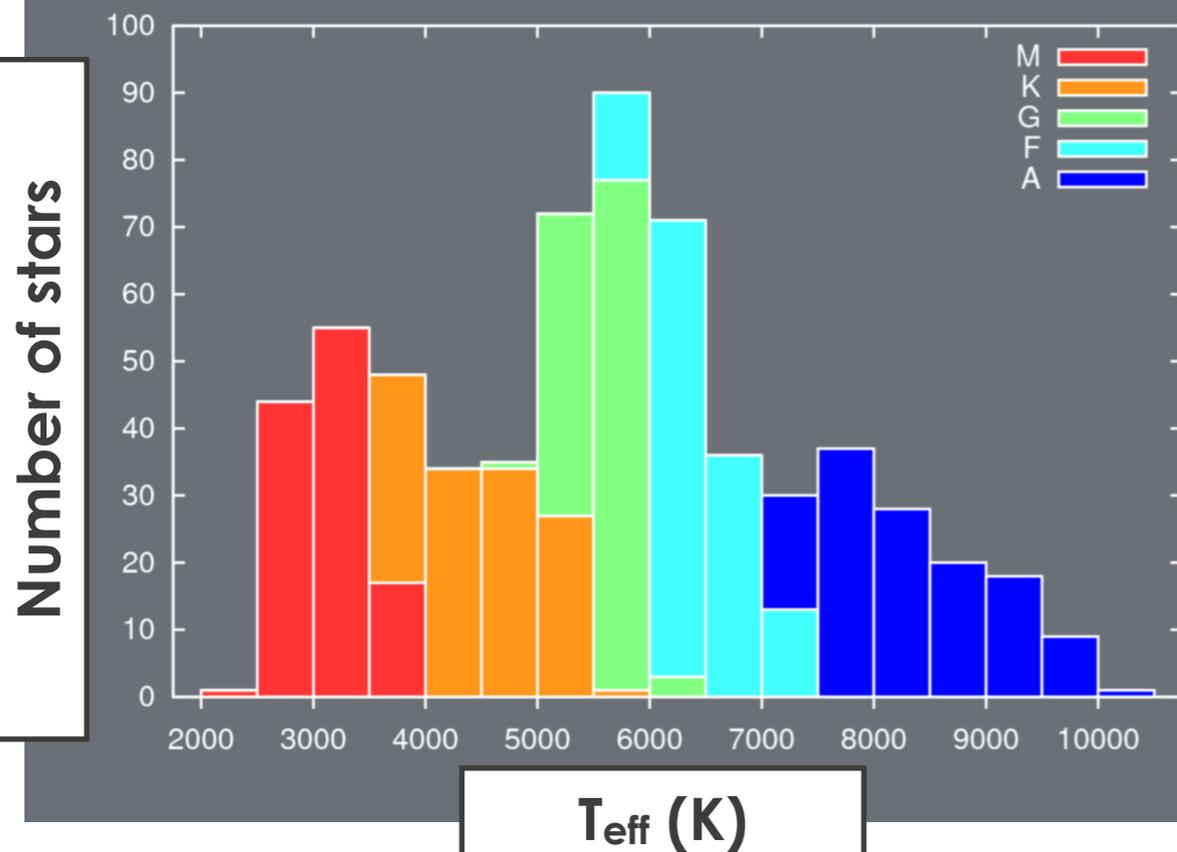
(P.I. Brenda Mathews)

Survey at 100 and 160 μm to search and characterize debris disks around 446 nearby stars.

- Targets from the Unbiased Nearby Stars sample in Phillips et al. (2010)
- ~90 stars of each type: A, F, G, K, M
- Sp.Type samples volume-limited w. confusion cut.
- Follow-up of 110 stars @250,350,500 μm
- Flux-limited, uniform depth, driven by 100 μm sensitivity (1σ rms = 1.5 mJy).

Volume limits (pc):

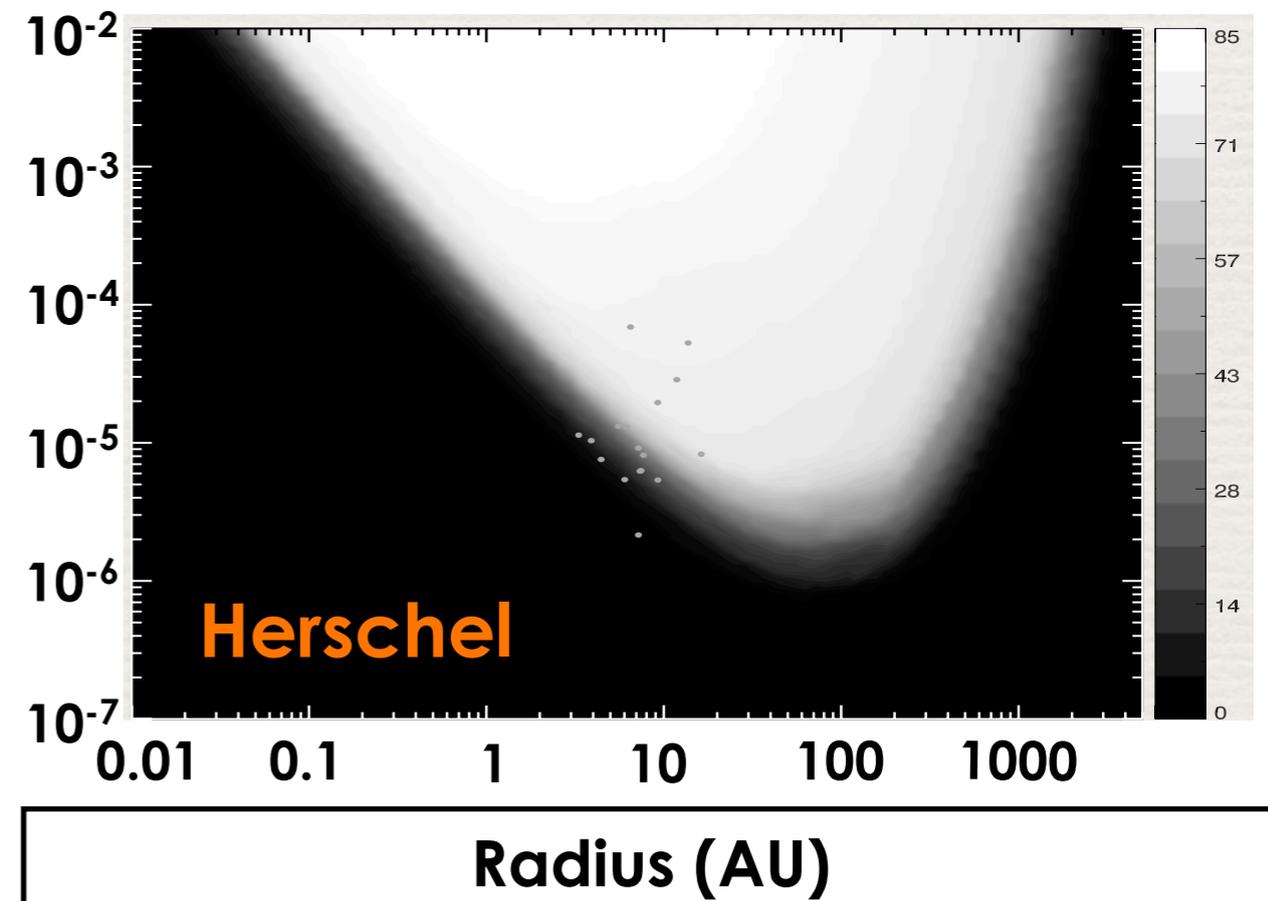
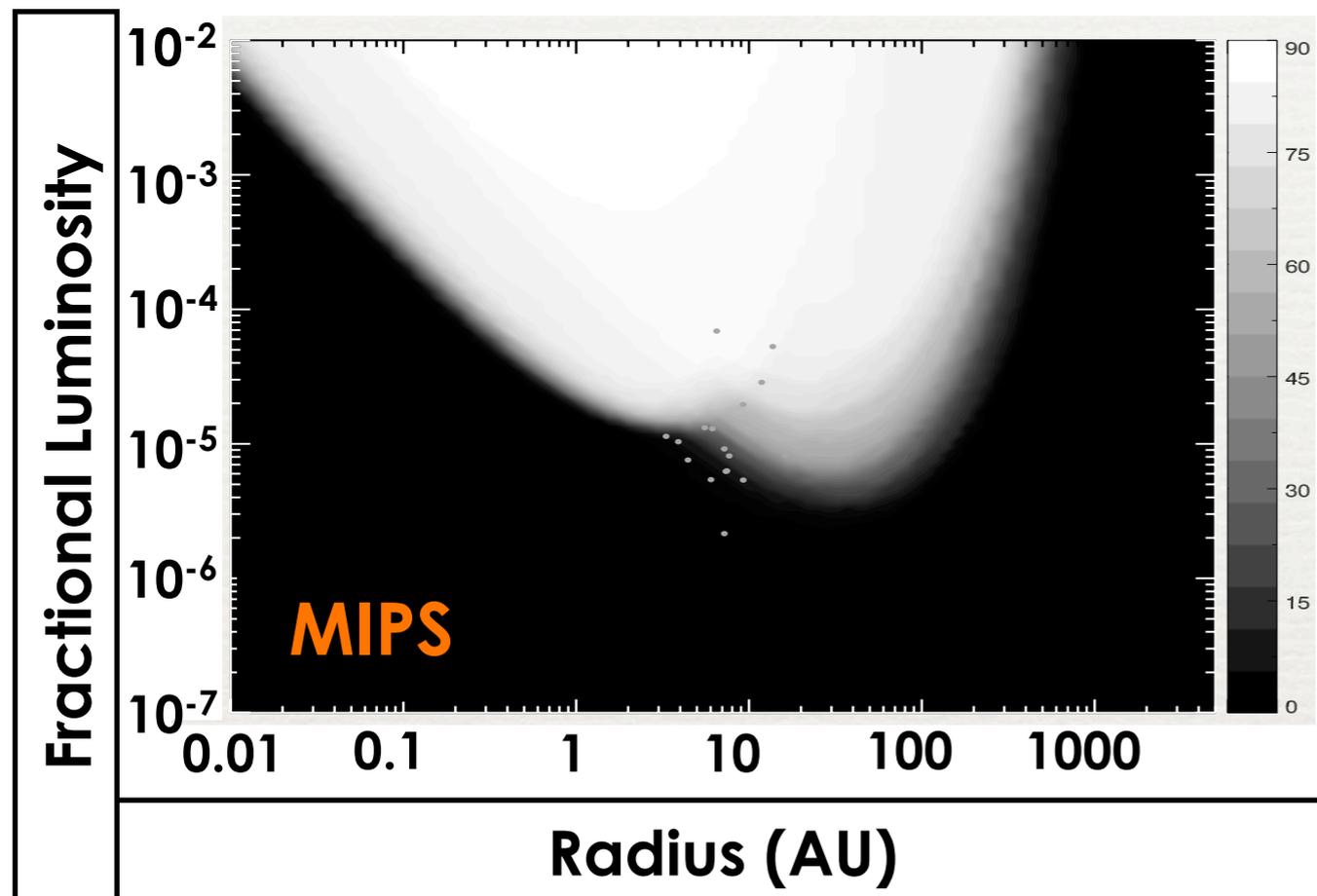
Sp. Type	A	F	G	K	M
Volume limits (pc)	46	24	21	16	8.6



Herschel-DEBRIS Key Program

Preliminary Results

Disk parameter space G-type



(Kennedy in prep.)

Herschel-DEBRIS Key Program

Preliminary Results

- Herschel is identifying new debris disks. **Increasing the debris disk frequencies around cold late-type stars.** Most of the other debris disks had been detected previously by Spitzer.

Sp. Type	A	F	G	K	M
Frec.	26%	24%	19%	9.5%	1.3%

(Kennedy in prep.)



decreased wrt Spitzer
(identification of
background sources)

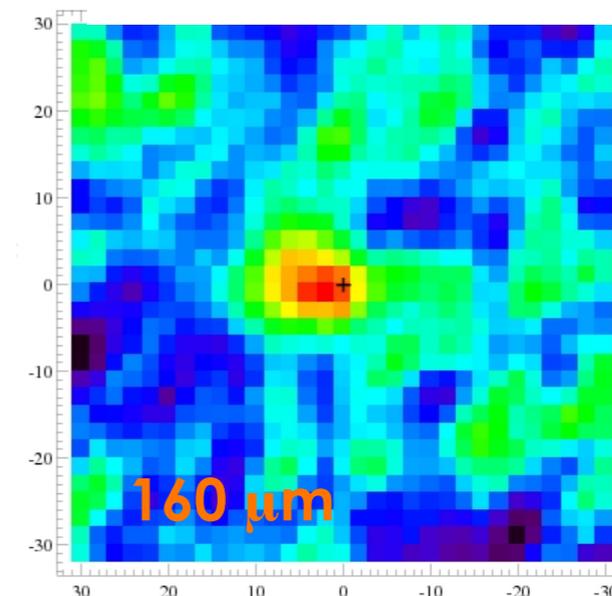
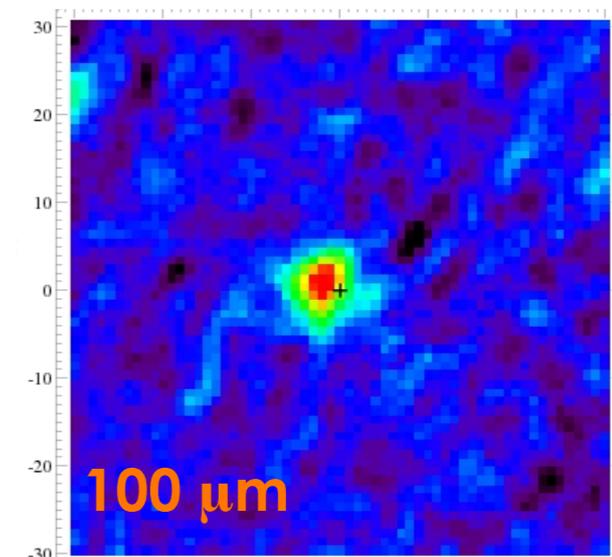
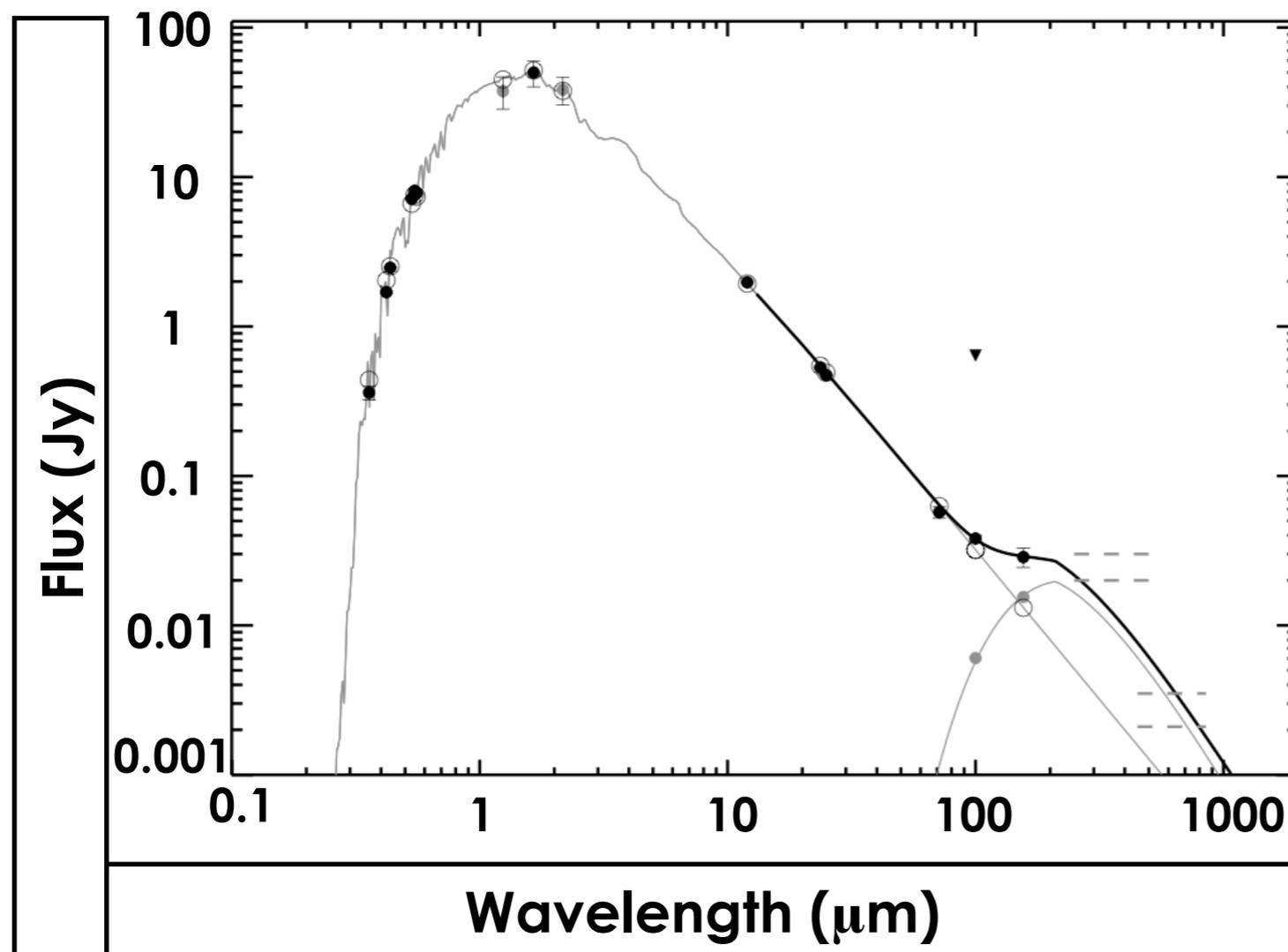


increased wrt Spitzer

Herschel-DEBRIS Key Program

Preliminary Results

- **New type of debris disks found: very cold disks**, with excesses $> 160 \mu\text{m}$, $T_{\text{dust}} < 30 \text{ K}$, very faint, more common around late-type stars (difficult to account for the lack of warm dust).



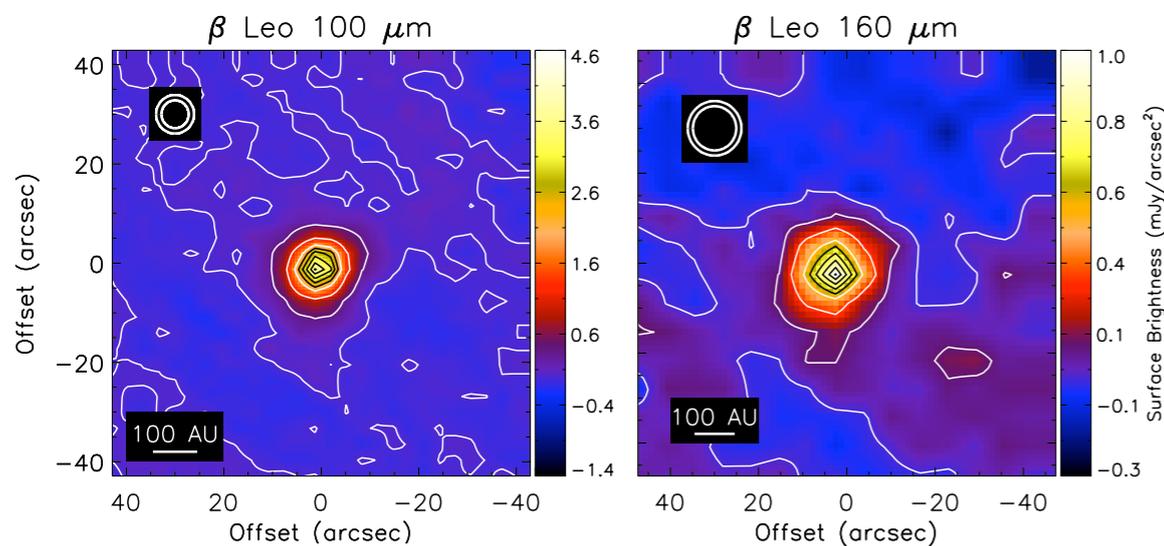
Herschel-DEBRIS Key Program

Preliminary Results

- Increasing the number of spatially resolved disks; some very compact (e.g. a 40 AU disk, smaller than the solar system debris disk).

- $R_{\text{disk (resolved)}}/R_{\text{bb (sed)}} \sim 1-4$

implies a range of composition and/or grain sizes.

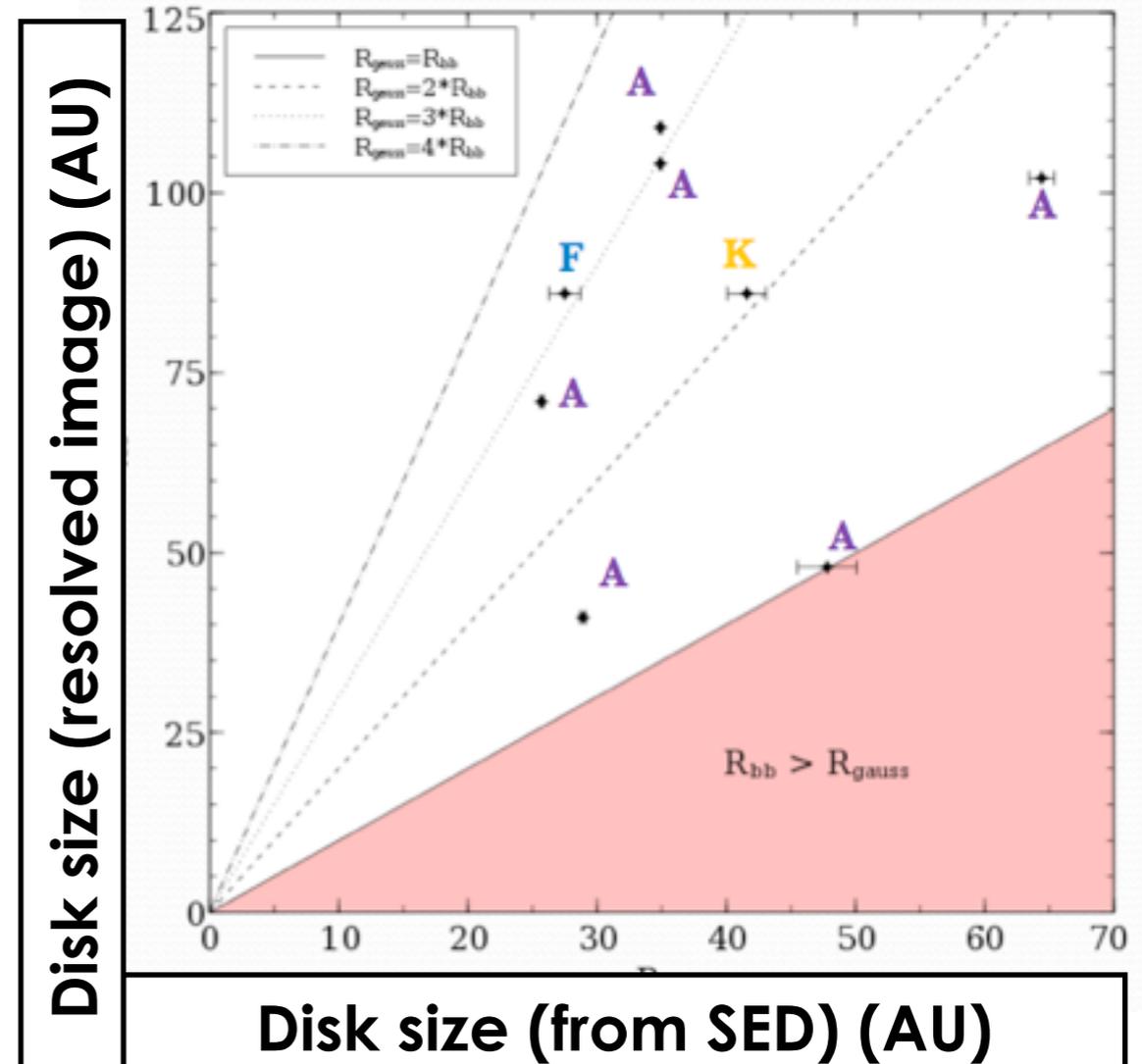


A-type

11 pc

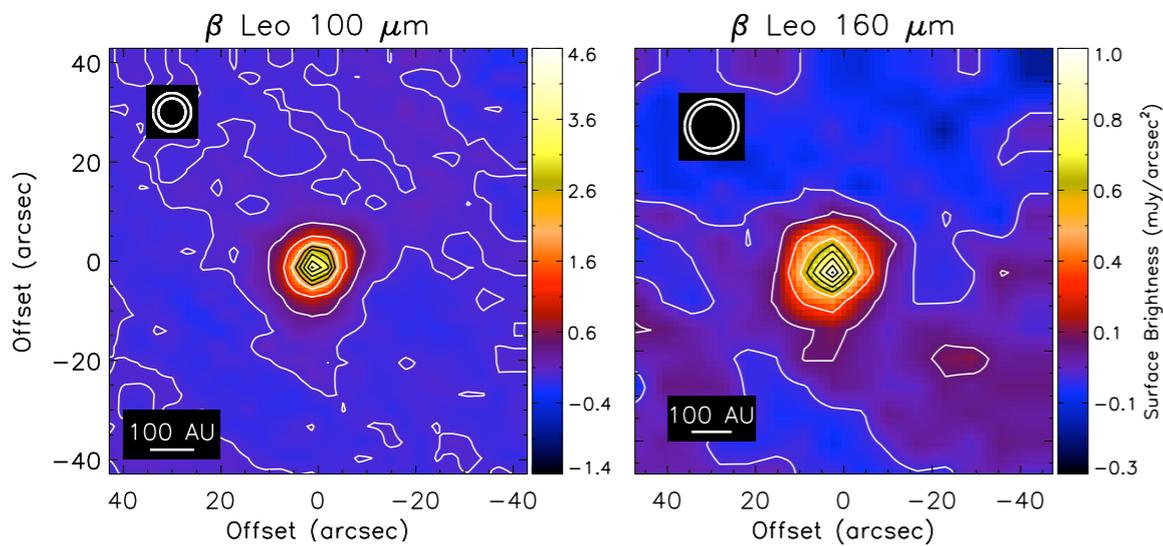
SED: $T_{\text{dust}} \sim 112$ KImages: $R_{\text{disk}} \sim 39$ AU

(Matthews et al. 2010)



See Mark Booth's poster

Increasing the number of spatially resolved disks; some very compact (e.g. a 40 AU disk, smaller than the solar system debris disk).



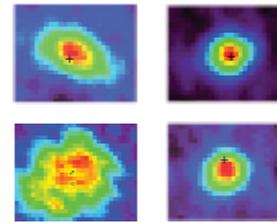
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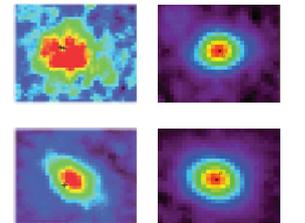


Using the DEBRIS Survey to Constrain Disc Properties
M. Booth^{1,2} and the DEBRIS Team

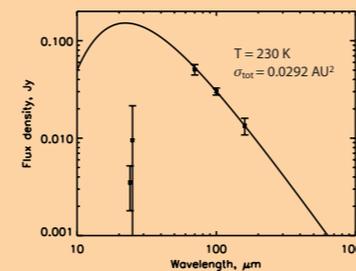
¹Dept. of Physics & Astronomy, University of Victoria, Elliott Building, 3800 Finnerty Rd, Victoria, BC, V8P 5C2 Canada
²Herzberg Institute of Astrophysics, National Research Council of Canada, 5071 West Saanich Road, Victoria, BC, V9E 2E7 Canada
E-mail: markbooth@cantab.net



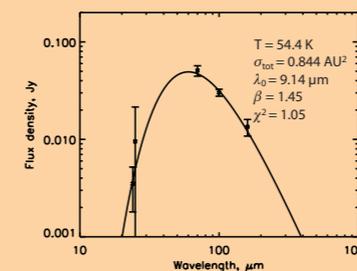
1. DEBRIS Survey
DEBRIS (Disc Emission via a Bias-free Reconnaissance in the Infrared/Sub-millimetre) is an open time key project (PI: Brenda Matthews) on the Herschel Space Observatory. The aim of the project is to conduct an unbiased, flux limited survey of the nearest stars for debris discs (Phillips et al. 2010). It is in the process of observing 446 systems (of spectral types A, F, G, K and M) at wavelengths of 100 and 160 μ m with the PACS instrument and many of these systems will be followed up with SPIRE at 250, 350 and 500 μ m (Matthews et al. 2010). Many of the targets are also shared with (and some observed by) the DUNES team (Eiroa et al. 2010).



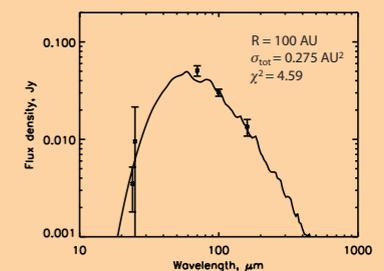
2. SED Modelling



These plots show the photosphere subtracted data from IRAS, MIPS and PACS for one of the stars in our sample. In the above plot a black-body curve has been fit to the two PACS fluxes. This fit gives a radius of 10.8 AU. This fit clearly gives a flux far too high for the 24 and 25 μ m wavelengths.

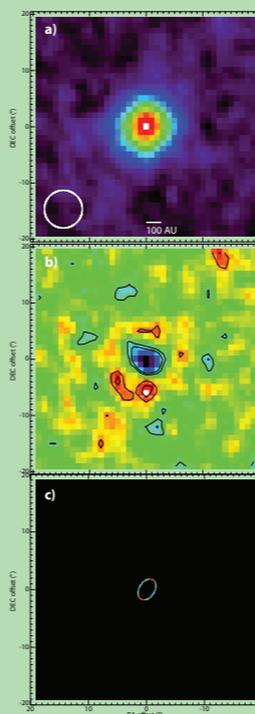


Here a modified black-body is used to fit to all the points. The black-body is modified by a factor $(\lambda_0/\lambda)^\beta$. For this star the λ_0 value is unusually low (values around 210 μ m are more common e.g. Wyatt 2008) however, without any sub-mm data this parameter is poorly constrained by the fitting process.



In this plot realistic grain properties have been used. We use optical properties from the Li and Greenberg (1997) core mantle model. In this case amorphous silicate grains have been used with a silicate to organics ratio of 1:2. A Dohnanyi (1969) size distribution has been used with a minimum grain size equal to the blowout grain size (18 μ m).

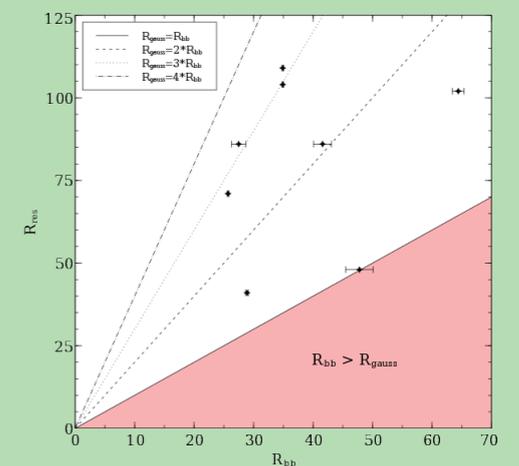
3. Resolved Modelling



The superior resolving power of Herschel has allowed us to view debris discs like never before. Over 20 discs from the DEBRIS survey have now been resolved with Herschel, some at more than one wavelength. One of these discs is shown to the left (a). Subtracting a PSF scaled to the total flux leaves us with some clear residuals as shown in (b) where the contours highlight 2 and 3- σ residuals. The PSF is clearly oversubtracting at the centre and leaving evidence for a ring.

Resolved modelling of these discs provides us with a secondary method of inferring the radius. One method of fitting the disc parameters is by creating models of the spatial distribution of the dust and using realistic optical properties. A range of models can then be created and a best fit found as has been done with β Leo (Churcher et al. 2011). This method is used in (c) which shows a ring of 71 AU and 43°. This has then been combined with the stellar flux and convolved with the PSF (d). Subtracting this from the image leaves us with much cleaner residuals than just fitting a PSF (e).

A plot of R_{res} vs. R_{bb} is shown to the right. This shows a preliminary look at eight of our resolved systems, which we have attempted to fit with narrow rings. It can be seen that there is a wide dispersion in the results with some stars showing a resolved radii more than 3 times larger than that given by a black-body fit, but no obvious correlation that applies to all stars. This implies that dust properties vary between systems.



References

Backman, D. E., & Paresce, F. 1993, Protostars and Planets III, 1253
Churcher, L. J., et al. 2011, arXiv:1107.0316
Dohnanyi, J. S. 1969, JGR, 74, 2531
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This research is funded through a Space Science Enhancement Program grant from the Canadian Space Agency.

Herschel-DEBRIS Key Program

Preliminary Results

- **Characterization of the first debris disks around mature M-type stars.**
- Identification of **new debris disks around planet-host stars** (including multiple-planet systems; characterization of planetary systems: planets + planetesimals).
- Approaching **KB dust disk flux level for nearest targets.**

Exchange of debris between planetary systems

Exchange of debris between planetary systems

- Debris disk frequency indicate that planetesimal formation is common.
- ~20% of stars harbor giant planets < 20 AU.
- Giant planets eject planetesimals efficiently.

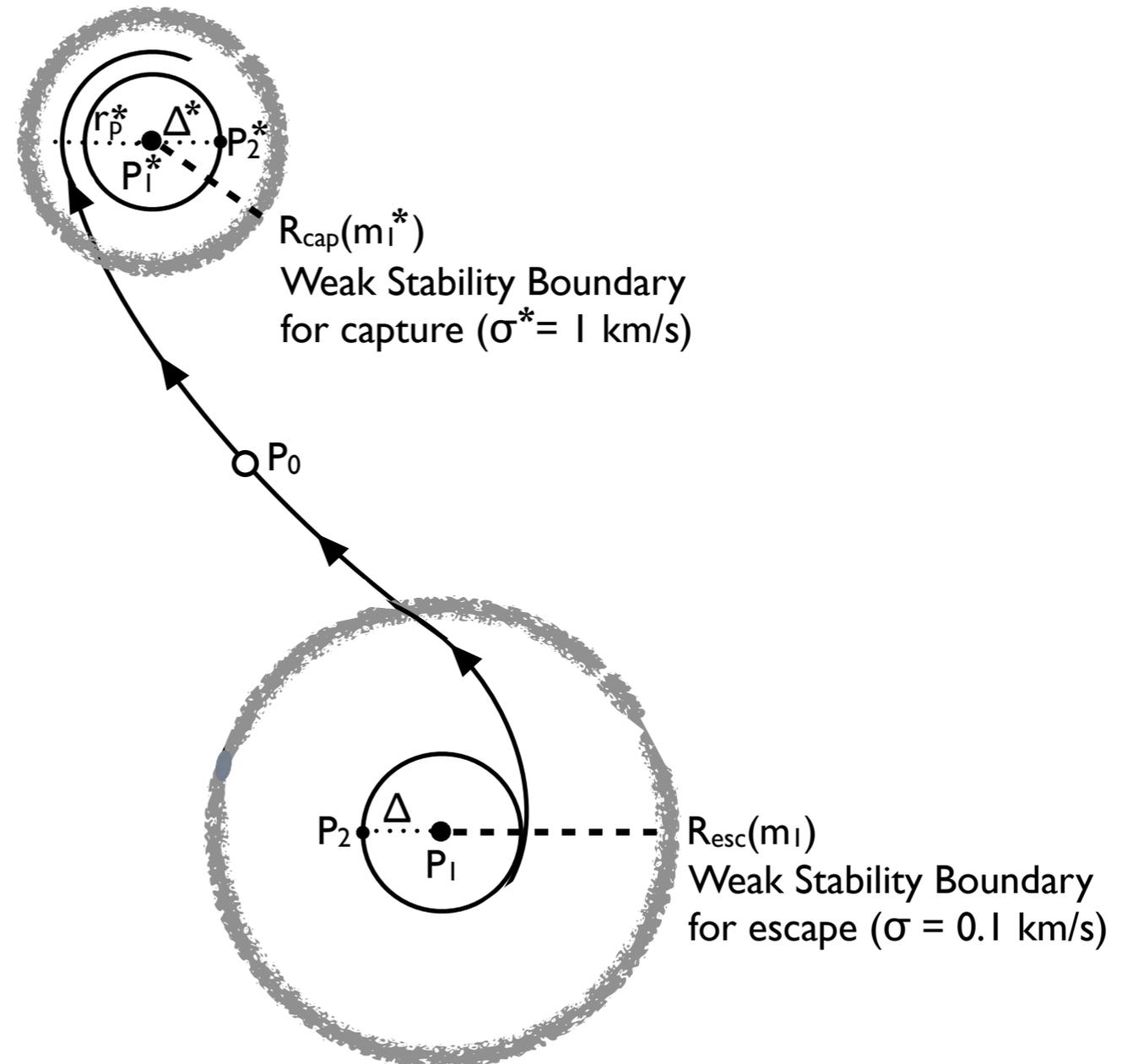


The interstellar medium must be filled with planetesimals

**Is the exchange of solid material
possible between planetary systems?**

Exchange of debris between planetary systems

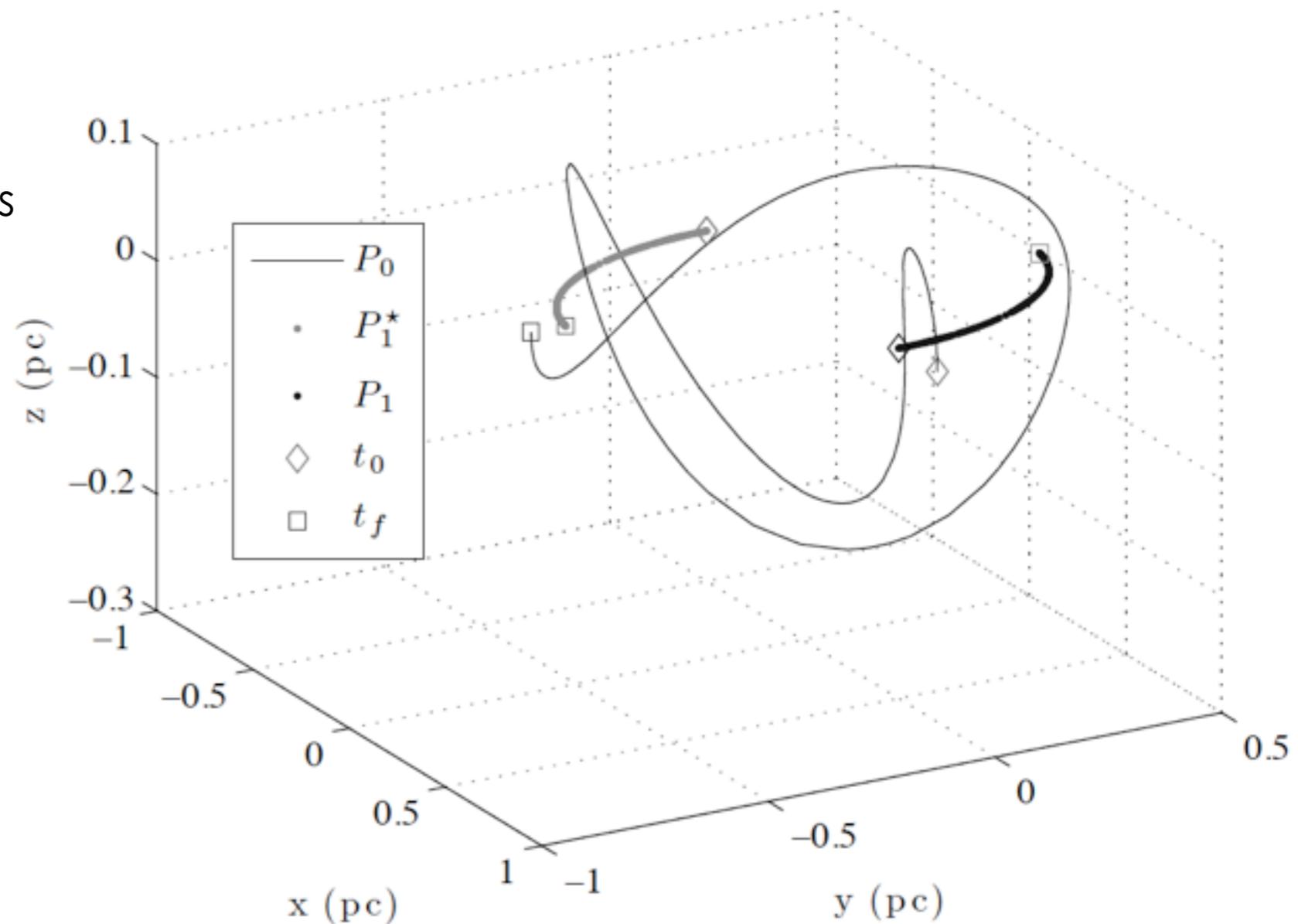
- There is a minimum energy transfer mechanism that allows and maximizes the capture of debris by other planetary systems (quasi-parabolic orbits).



(Belbruno, Moro-Martín, Malhotra, Savransky, submitted)

Exchange of debris between planetary systems

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(Belbruno, Moro-Martín, Malhotra, Savransky, submitted)

Exchange of debris between planetary systems

Properties of solar birth cluster (Adams 2010)

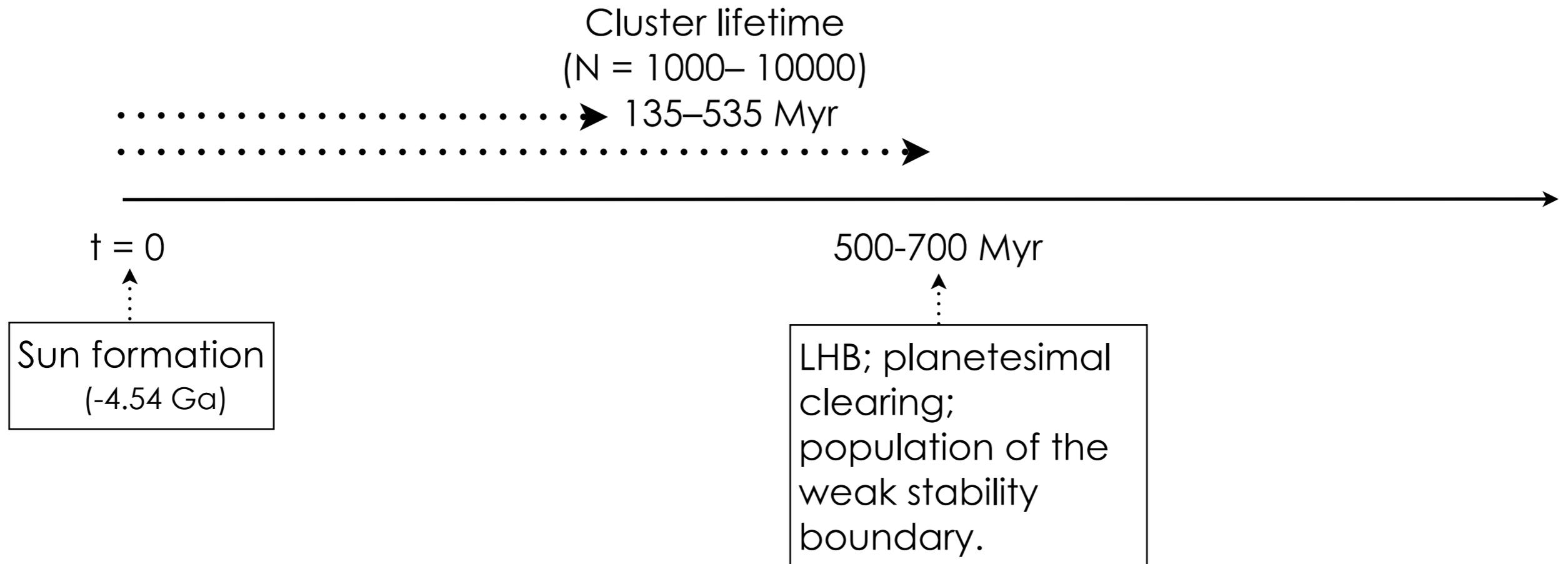
- $N = 4300$ ($N=1000-10000$)
- $M_{\text{total}} = \langle m_{\text{star}} \rangle N \sim 0.88N = 3784 M_{\text{sun}}$ (IMF; ignoring the gas).
- Cluster size: $R \sim 1 \text{ pc} (N/300)^{0.5}$
- Average distance between stars: $D = n^{-1/3} = 19 \text{ pc}^{-3} \rightarrow D = 0.375 \text{ pc}$
- Cluster lifetime: $t = 2.3 \text{ Myr} M^{0.6} = 322.5 \text{ Myr}$

$M^*_{\text{source}} (M_{\text{sun}})$	$M^*_{\text{target}} (M_{\text{sun}})$	Capture probab.
1.0	1.0	0.15%
1.0	0.5	0.05%
0.5	1.0	0.12%

Using this mechanism, a large number of debris could have been transferred to the nearest planetary system (of the order of 10^{14} - 10^{17} with masses $> 10 \text{ kg}$).

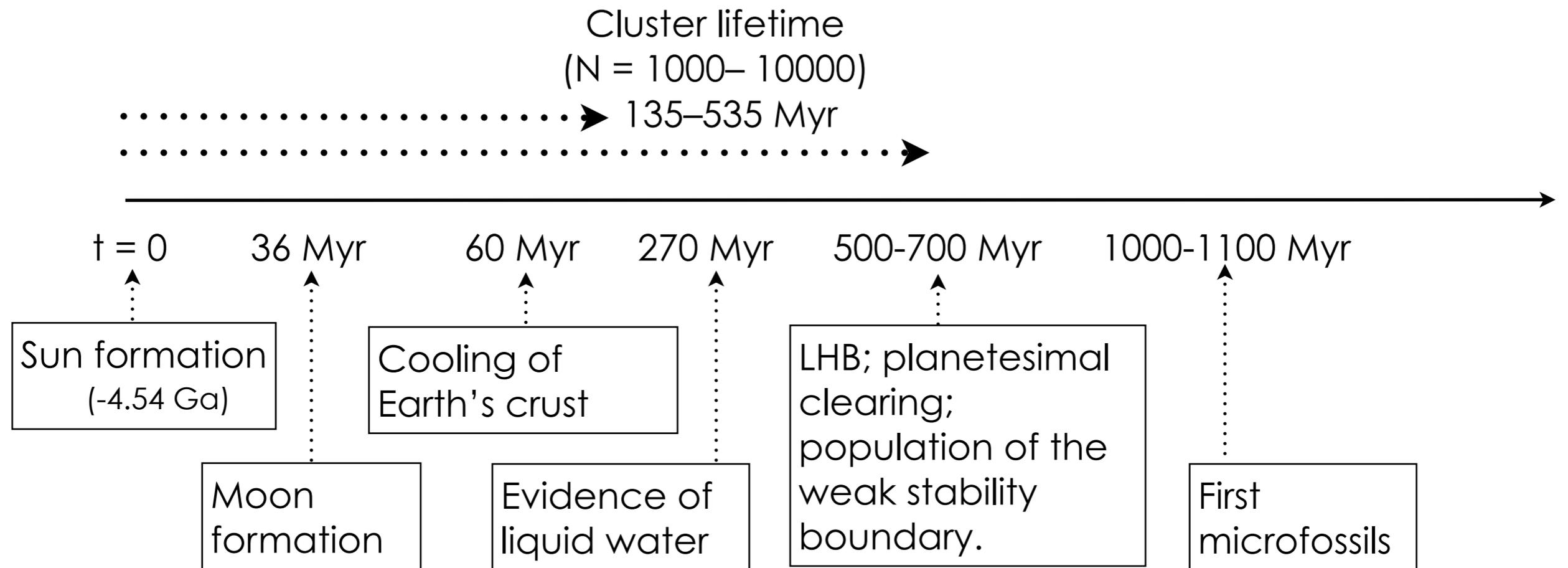
(Belbruno, Moro-Martín, Malhotra, Savransky, submitted)

Exchange of debris between planetary systems



The characteristic timescale for populating the weak stability boundary with debris overlaps marginally with the expected cluster lifetime.

Exchange of debris between planetary systems



Lithopanspermia from the Solar System to the nearest neighbor in the cluster is a possibility if life on Earth had an early start.

Can microorganisms survive long interstellar journeys?

Characteristic time

- ~ 6 Myr: transfer timescale to nearest planetary system.
- ~ 10s Myr: to land on a terrestrial planet.

