Origins of Stars and Planets in the VLT Era

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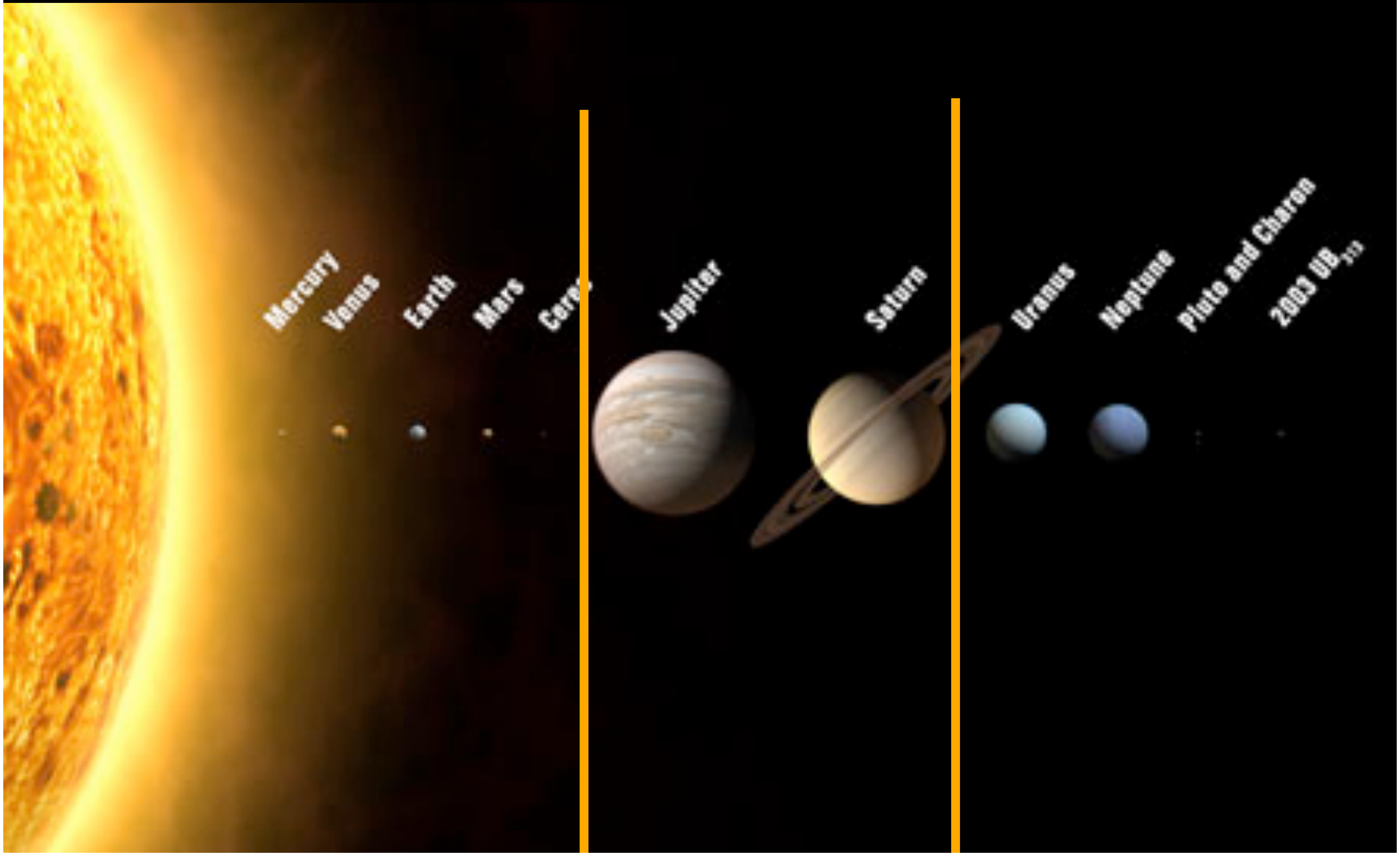
From Circumstellar Disks to Planets
5 November 2009, ESO/MPE Garching

Planet Formation = Saving the Solids



Are planetary systems like our own are common or rare among sun-like stars in the Milky Way galaxy?

Q: What is the history of planetesimal collisions vs. radius?

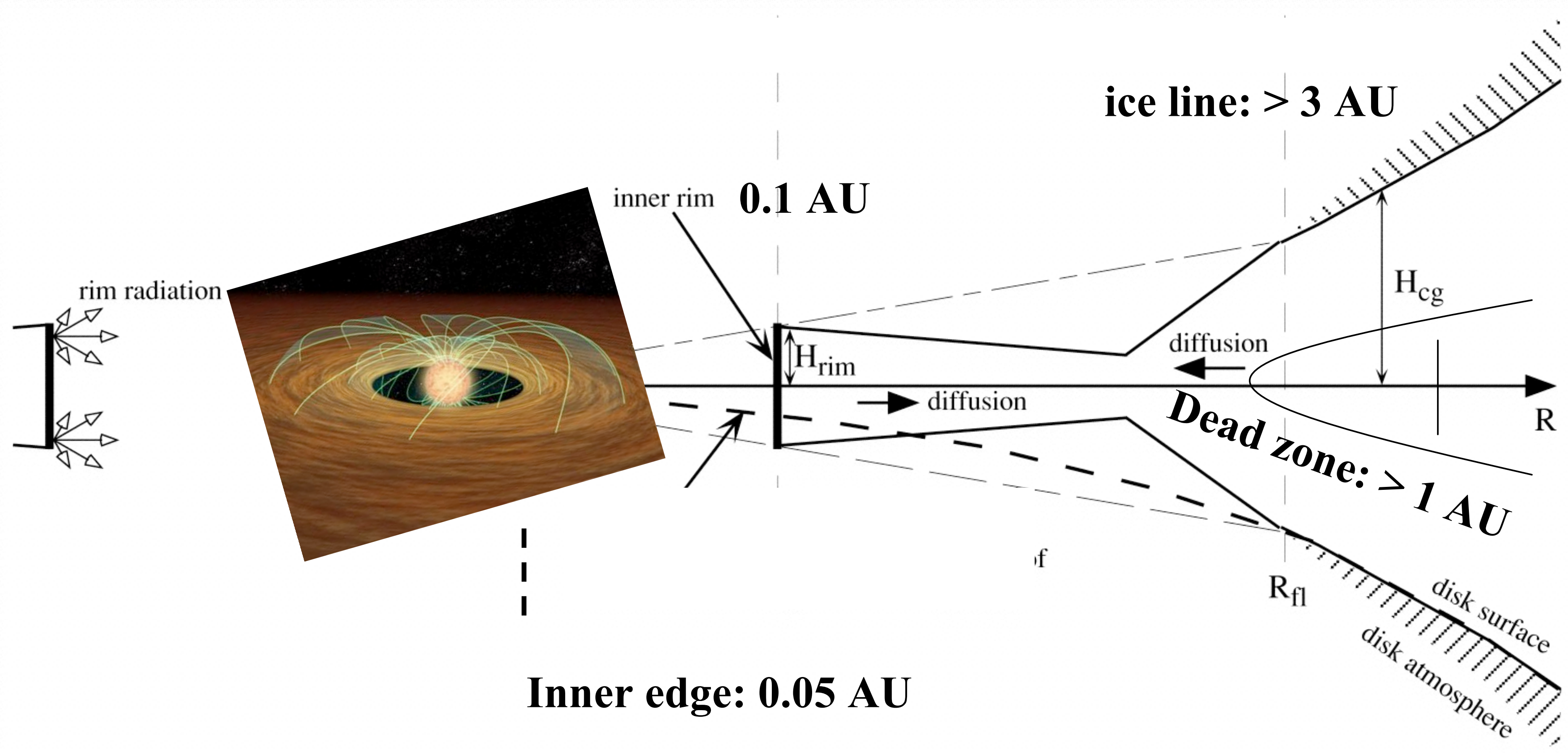
Q: How does this vary with stellar properties?

Q: Can we see evidence for terrestrial planet formation?

Q: Is there a connection between giant planets and debris?

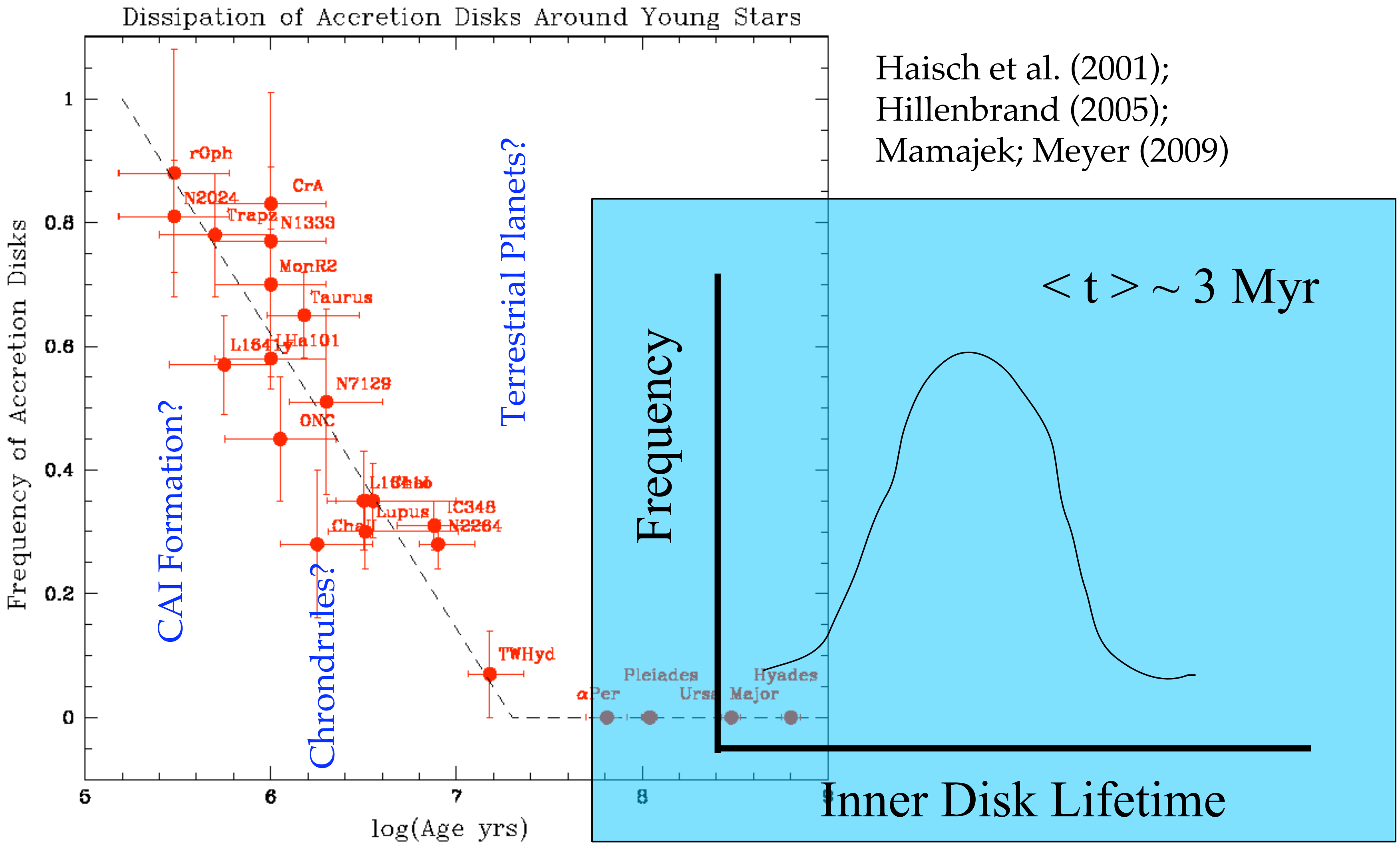
Because the answers are subtle,
need large samples over a wide range of ages.

Initial Conditions in Protostellar Disks.



Inner (< 0.1 AU) Accretion Disk Evolution 0.1-10 Myr

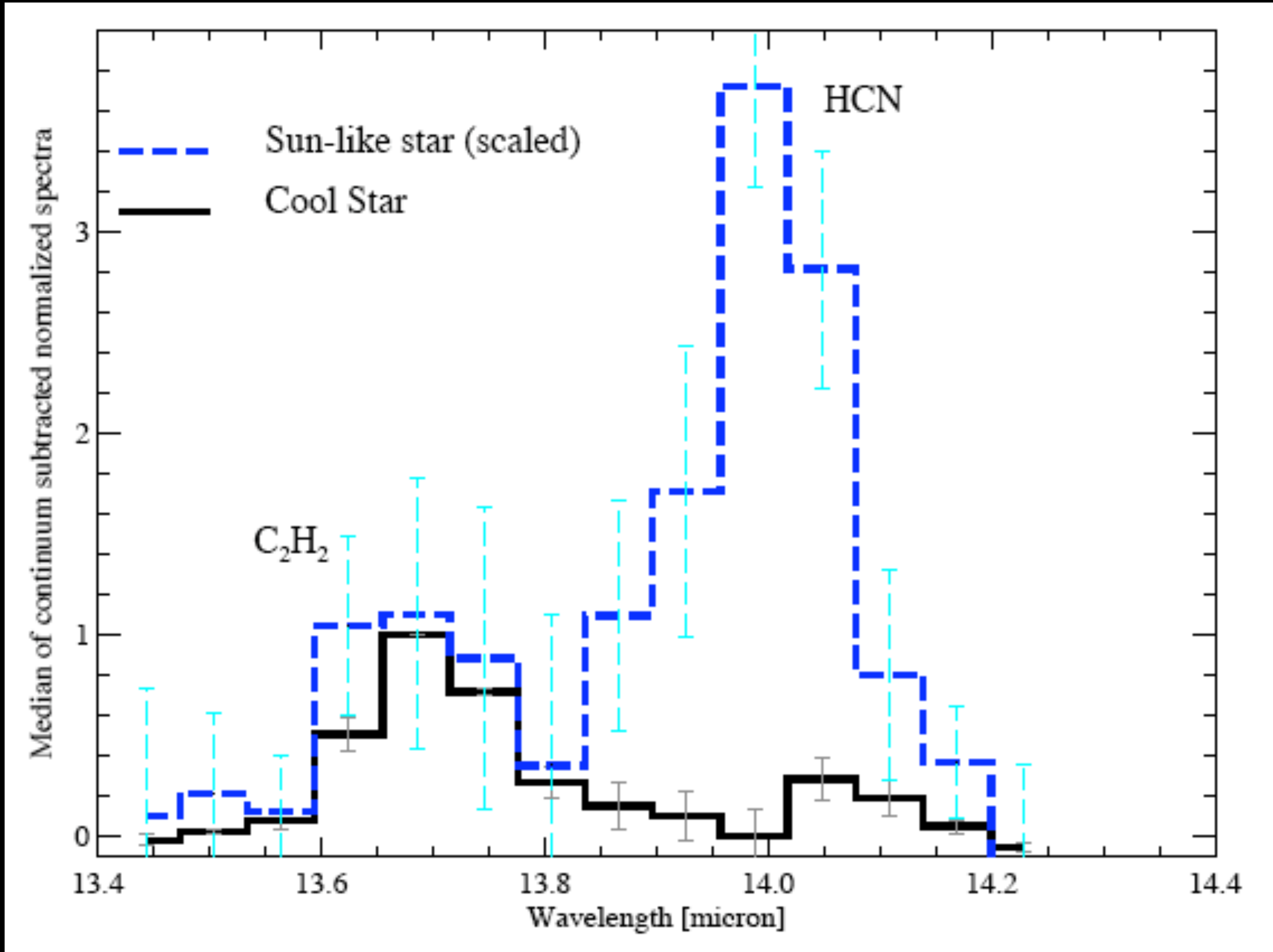
Haisch et al. (2001);
Hillenbrand (2005);
Mamajek; Meyer (2009)



Properties Influencing Disk Evolution

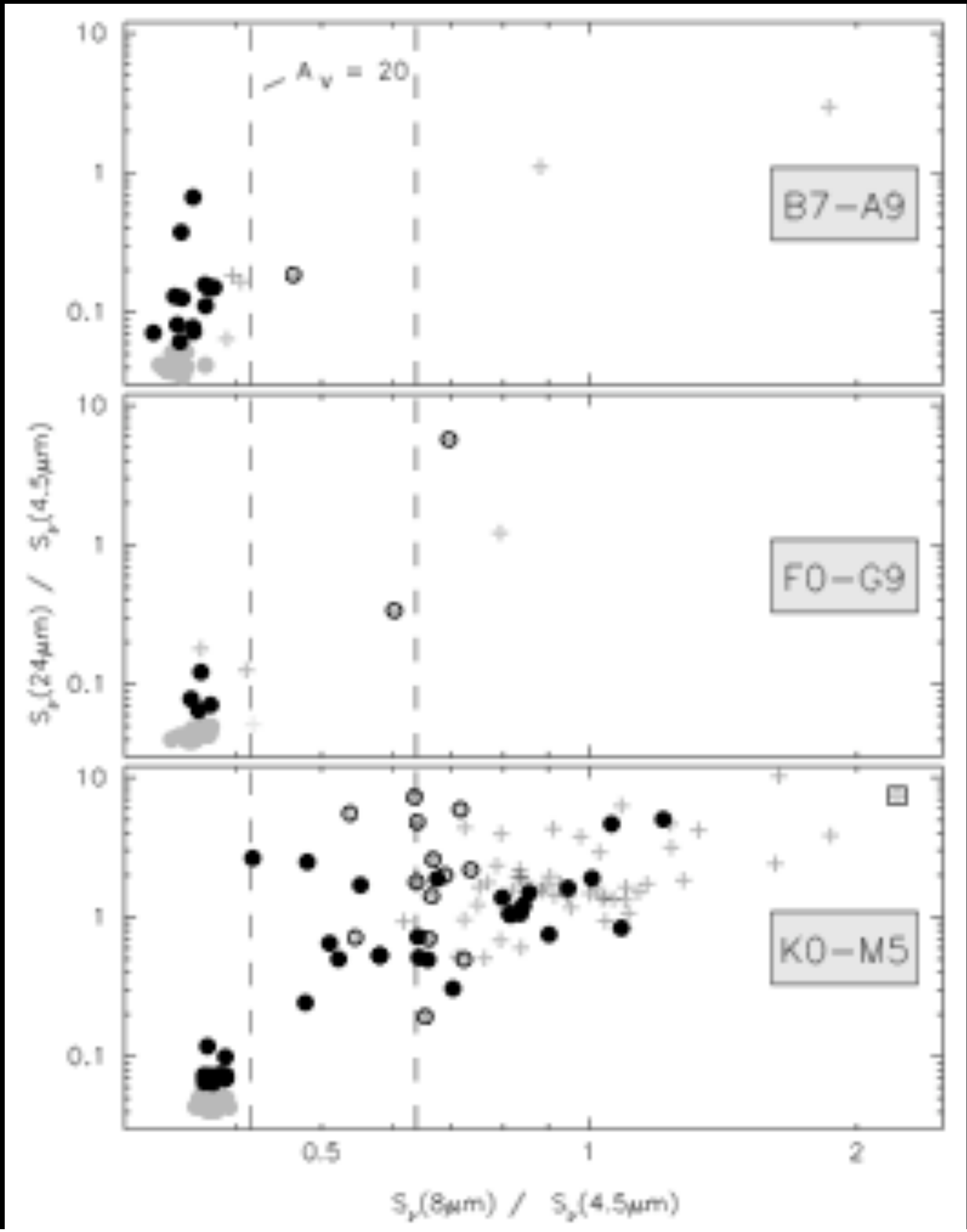
- **Stellar Mass:**
- **Luminosity & Incident Spectra:**
- **Initial cloud core angular momentum:**
- **Composition:**
- **Companions versus Mass and Orbital Radius:**
- **Formation environment:**

Disk chemistry may vary with stellar mass (and time).



Pascucci et al. (2009); cf. Carr & Najita (2008); Pontoppidan et al. (2008)

Disk Evolution in Upper Sco at 5 Myr: 220 Stars



=> Primordial disks last longer around lower mass stars.

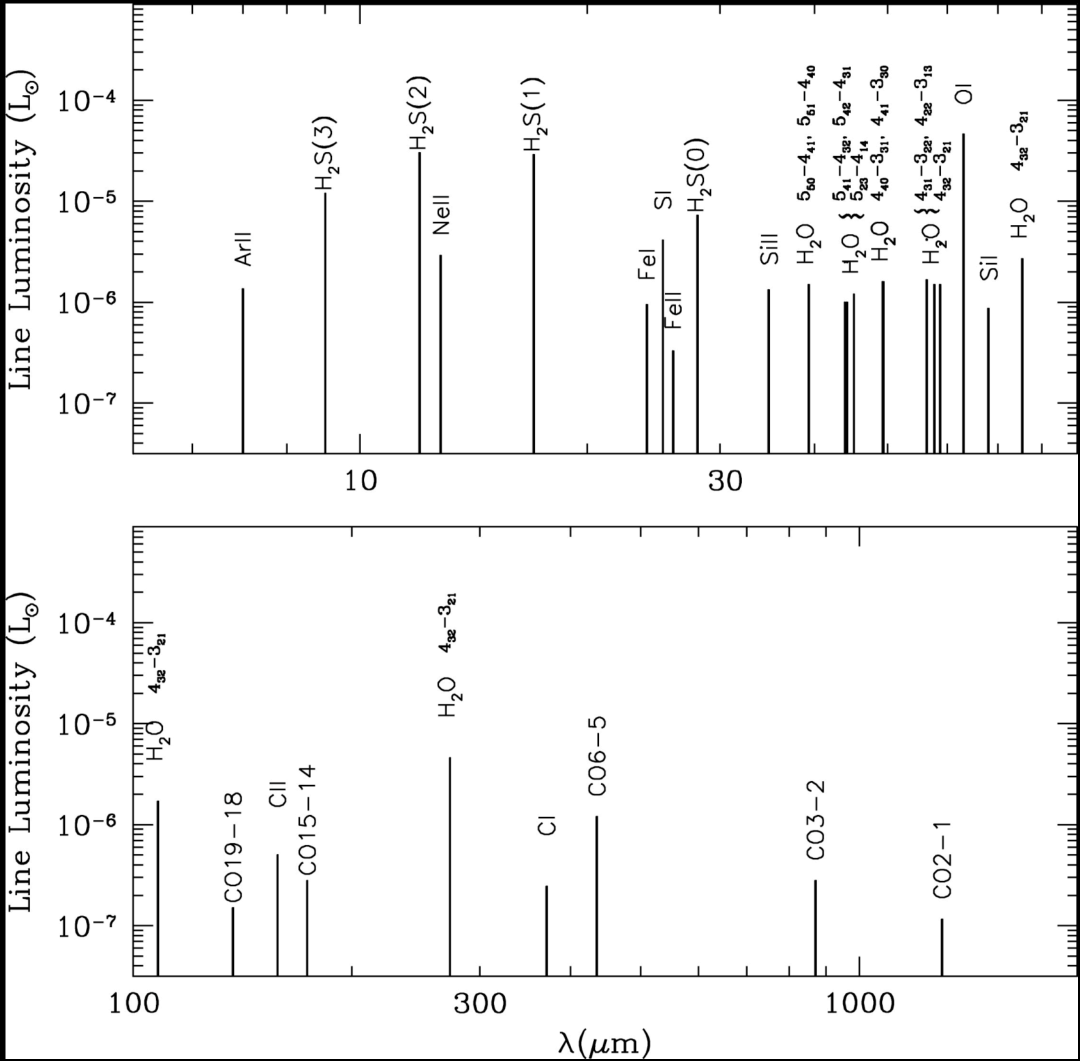
=> Duration of the "transition" ~10^5 yrs.

Carpenter et al. (2010)
And many others…

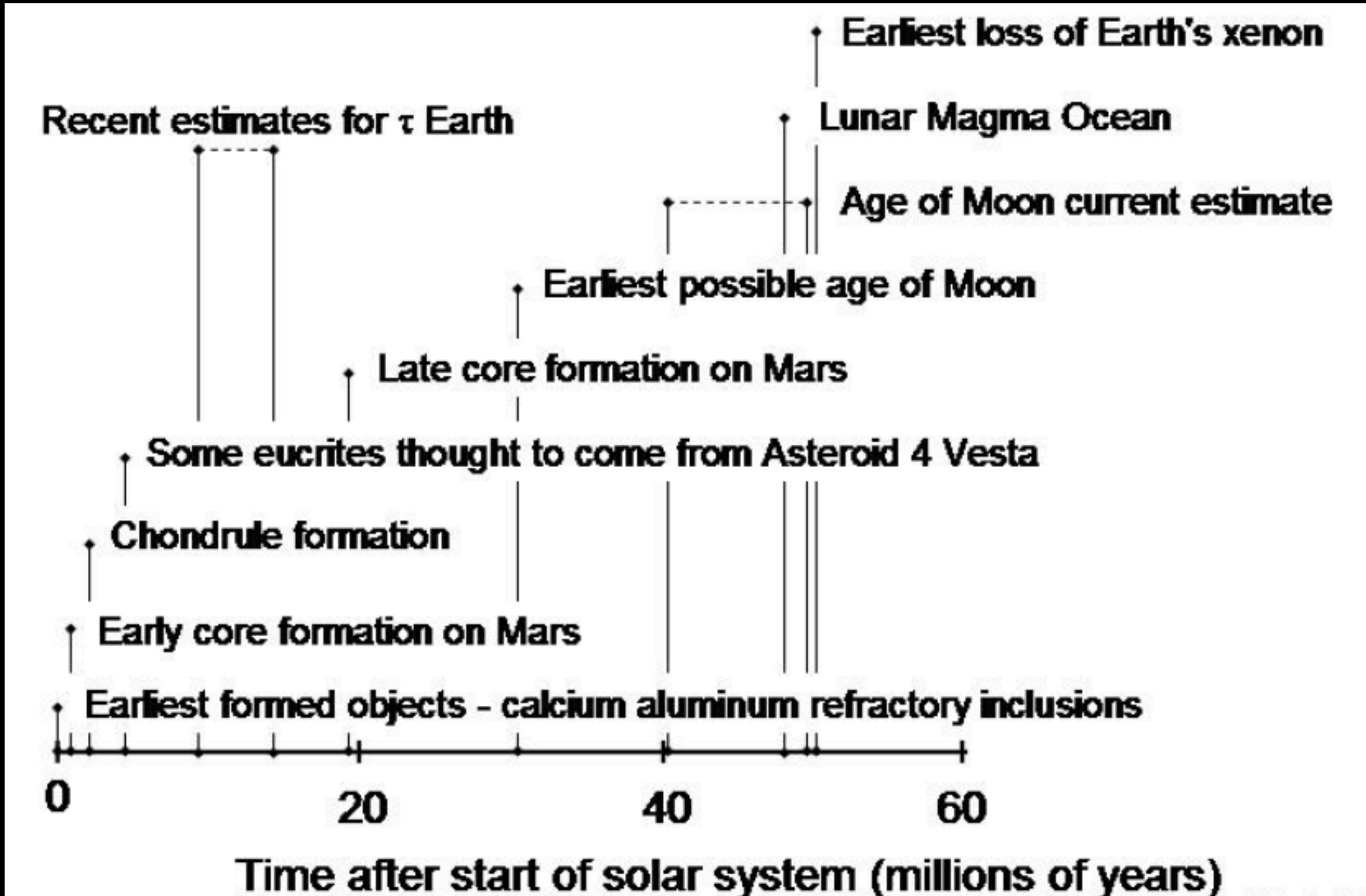
- Primordial (Gas Rich) Disks:
  - Required for gas giant planet formation (Pascucci et al. 2006).
- Debris (Dusty) Disks:
  - Trace evolution of planetesimal swarms: collisions of parent bodies then dust removal. (M. Wyatt)
- How can you tell the difference?
  - Absence of gas (Gas/Dust < 0.1).
  - Dust processing through mineralogy (silica?).

Debris dust may be generated early on in gas rich disks and could dominate opacity before gas dissipates!

Herschel will be powerful probe of the final stages of gas dissipation (ice giant formation).



Gorti & Hollenbach (2008); GASPS and DIGIT Open Time Key Programs


Earliest loss of Earth's xenon
Recent estimates for τ Earth
Lunar Magma Ocean
Age of Moon current estimate
Earliest possible age of Moon
Late core formation on Mars
Some eucrites thought to come from Asteroid 4 Vesta
Chondrule formation
Early core formation on Mars
Earliest formed objects - calcium aluminum refractory inclusions
0
20
40
60
Time after start of solar system (millions of years)

Planet Formation Timescale as a Function of Stellar Mass and Orbital Radius:

$$t_p \sim \rho_p \times R_p / [\sigma_d \times \Omega_d]$$

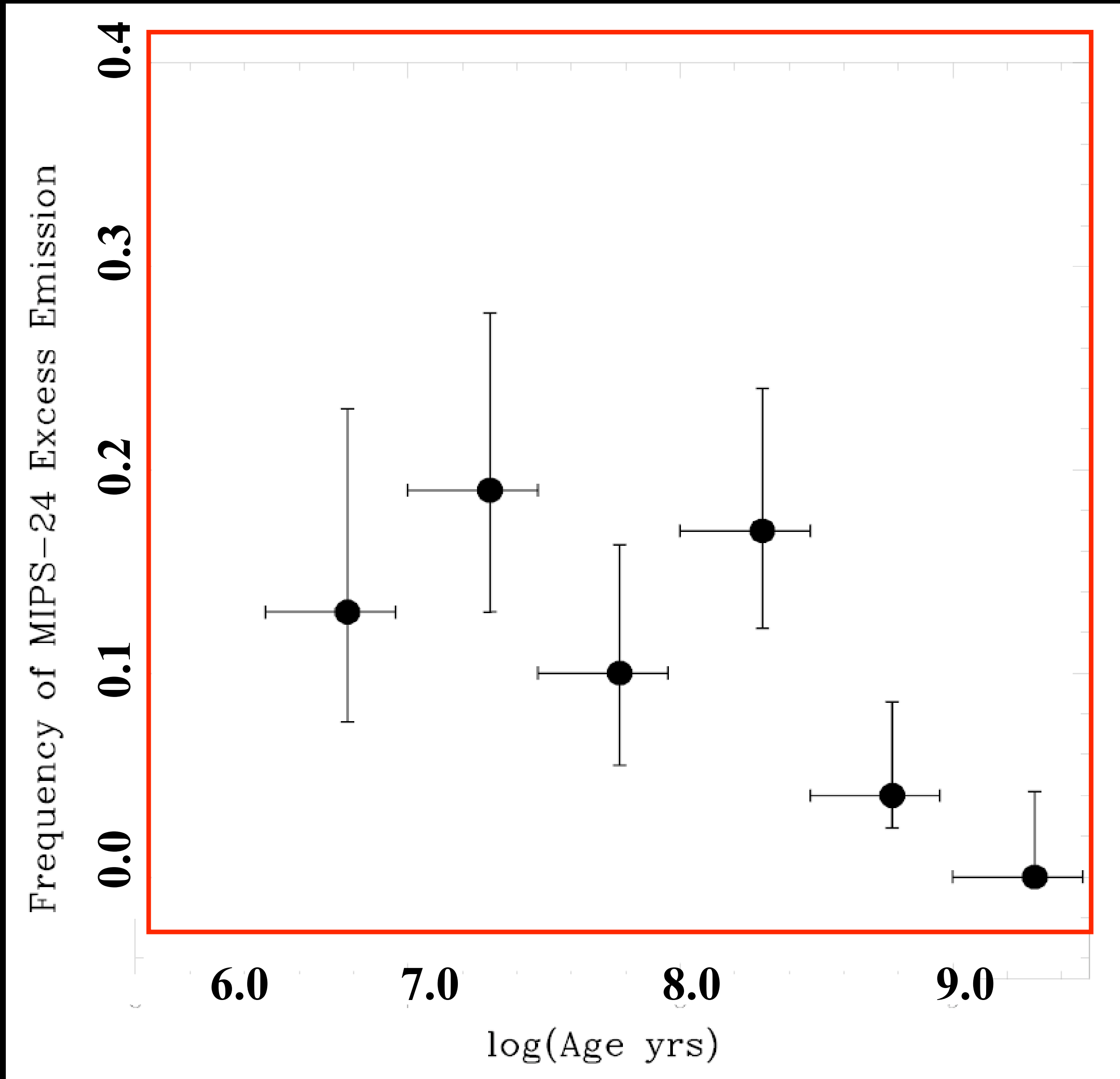
with $\sigma_d \sim M_* / a$ and $\Omega_d \sim \mathrm{sqrt}(M_* / a^3)$

$$t_p \sim [\rho_p \times R_p \times a^{5/2}] / [M_*^{3/2}].$$

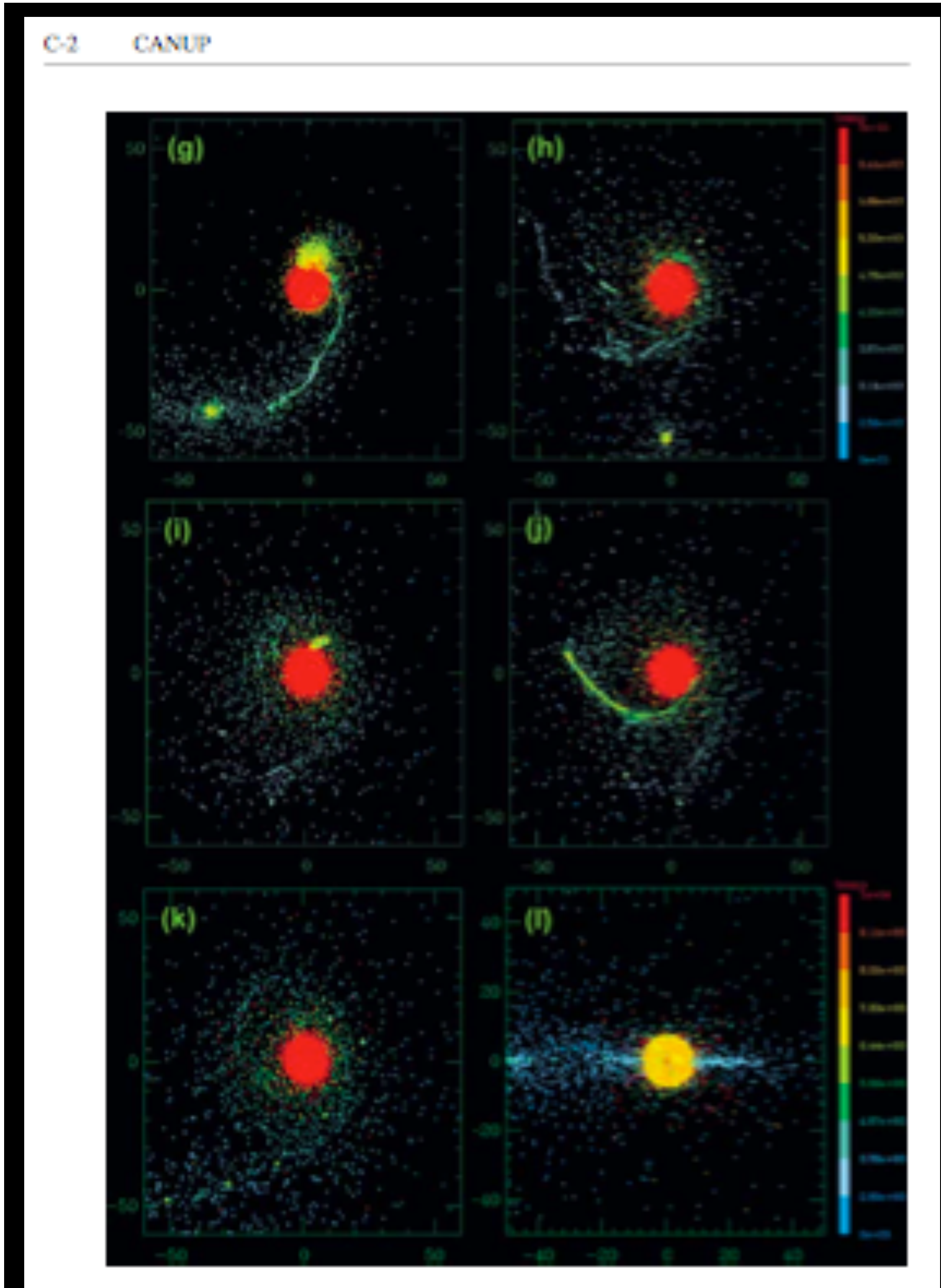
Massive planets farther out around stars of higher mass.

Yet disks last longer around stars of lower mass!

Warm Dust Around Sun-like Stars:
Tracing Evidence of Terrestrial Planet Formation?



Meyer et al. (2008); Kenyon & Bromley (2004; 2006


C-2 CANUP
(g)
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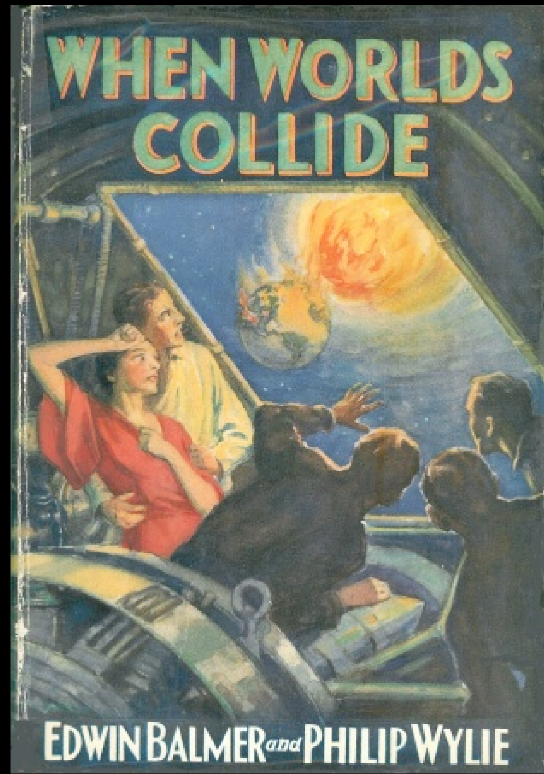
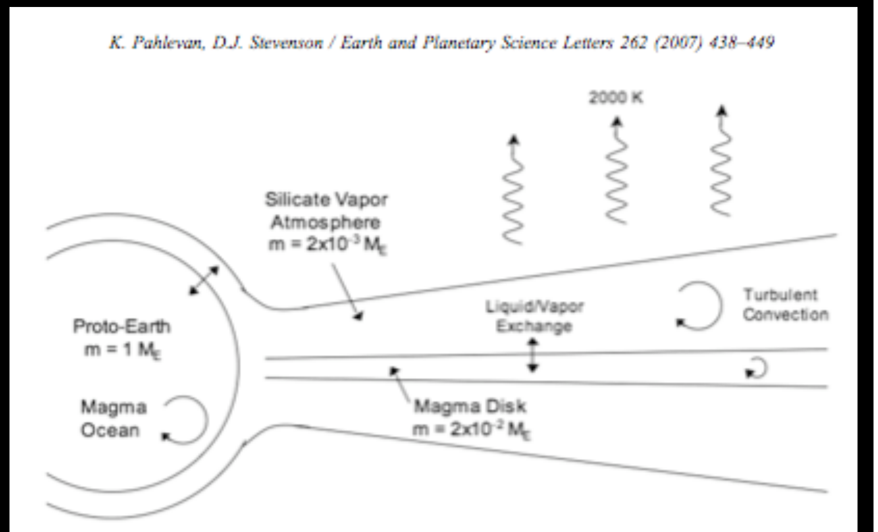
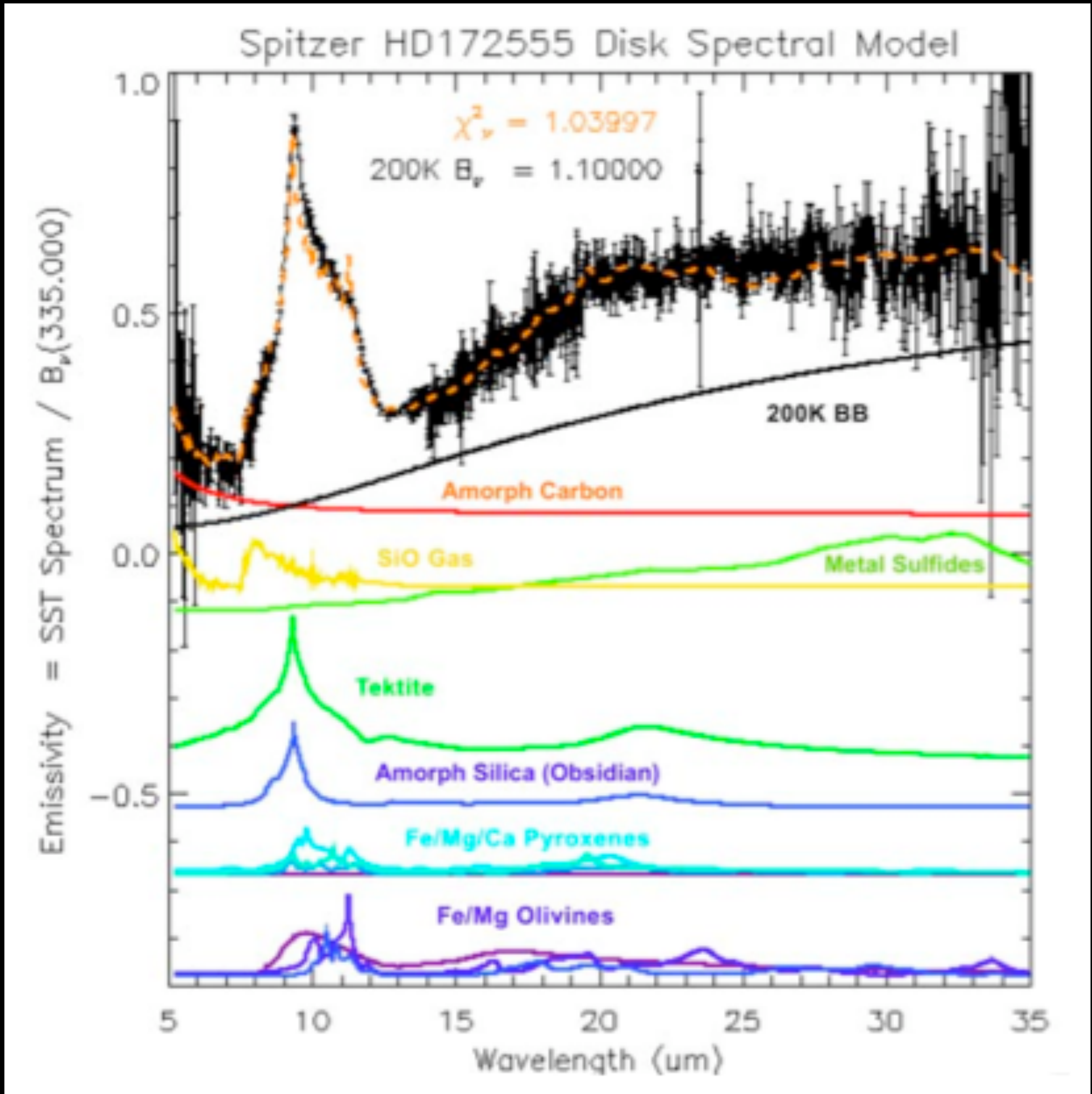

WHEN WORLDS COLLIDE
EDWIN BALMER and PHILIP WYLIE


K. Pahlevan, D.J. Stevenson / Earth and Planetary Science Letters 262 (2007) 438–449
2000 K
Silicate Vapor
Atmosphere
m = 2x10^-3 M_E
Liquid/Vapor
Exchange
Turbulent
Convection
Proto-Earth
m = 1 M_E
Magma
Ocean
Magma Disk
m = 2x10^-2 M_E



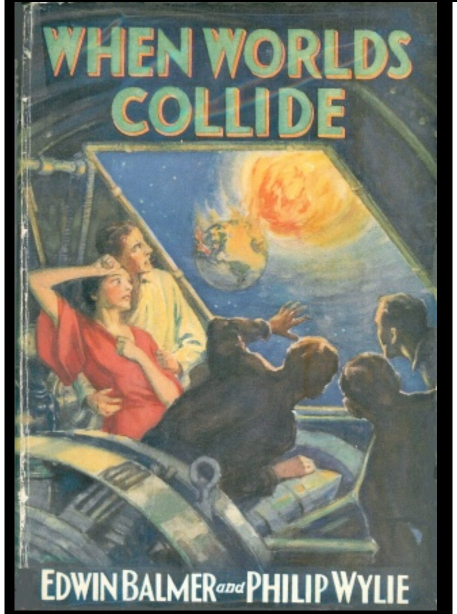
Earth-Moon collision released 5 x10^{-3} Mearth in hot gas.

If condensed to micron sized dust, more than 100x above detection limits.

Lifetime of such dust ~ 10^3 years over timescale of 10^7 yrs.

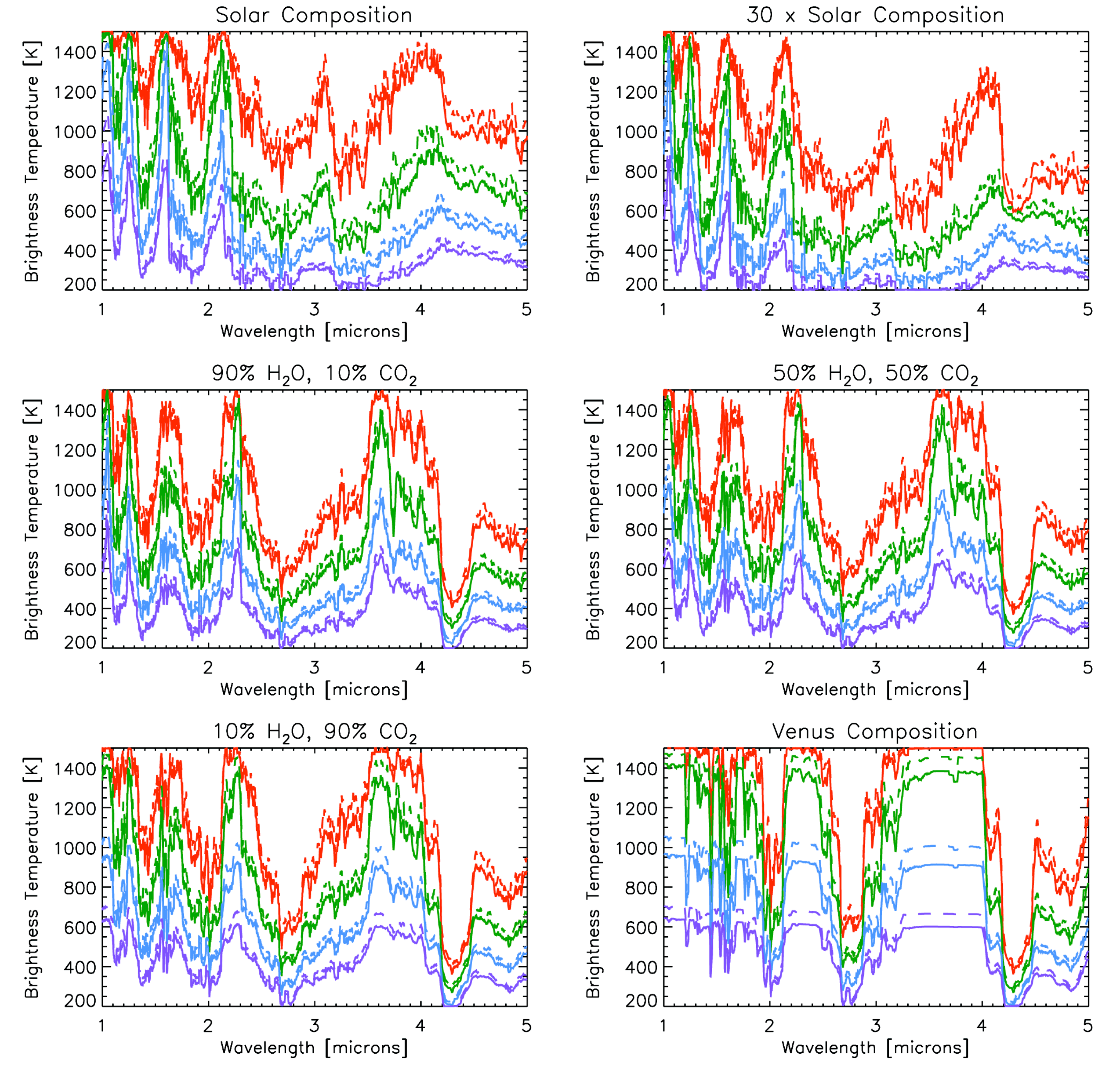
Such collisions are *rare* in Spitzer samples.

Lisse et al. (2009)

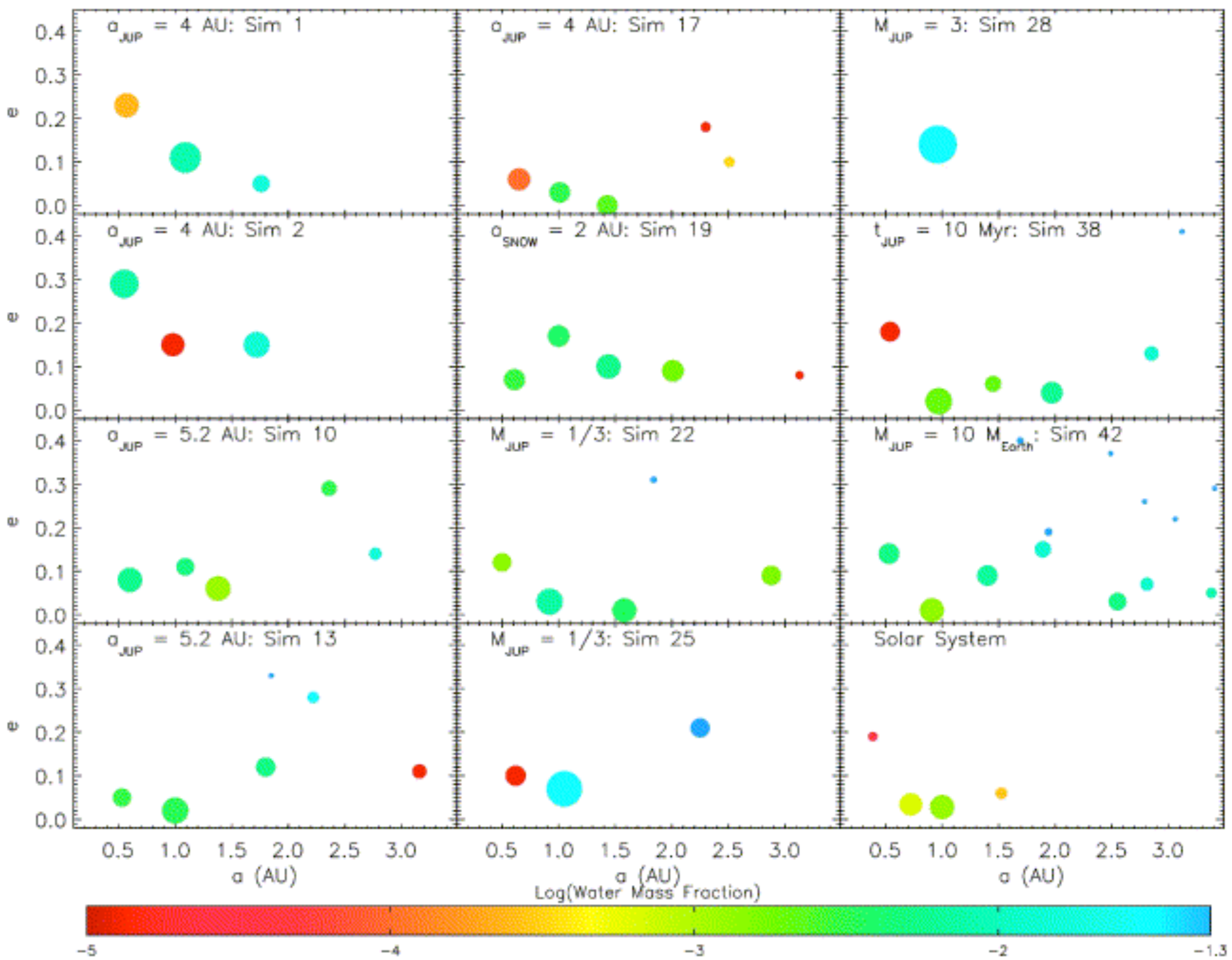


…you can see them with next generation instruments!

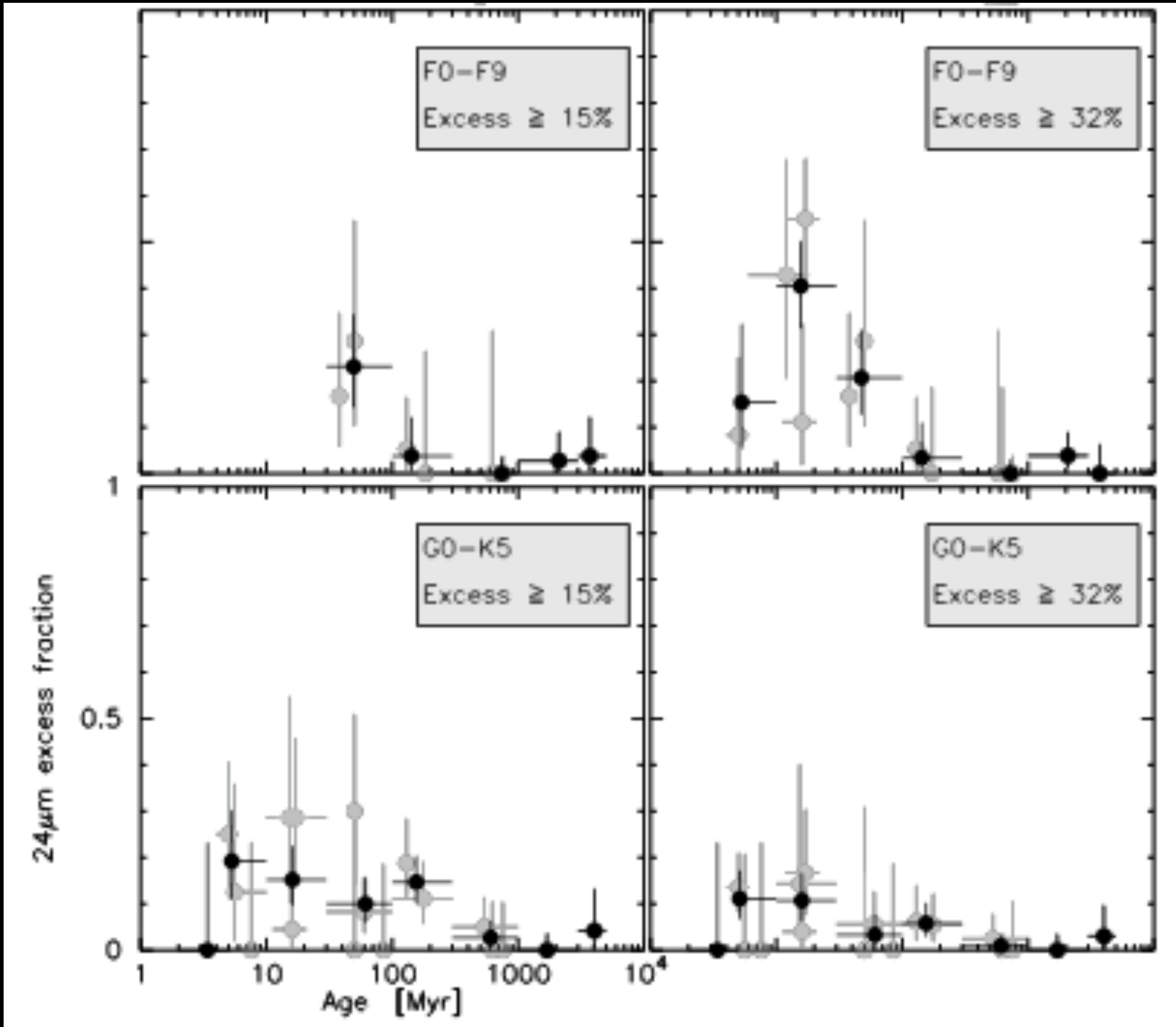
Miller-Ricci, Meyer, Seager, Elkins-Tanton (2009)



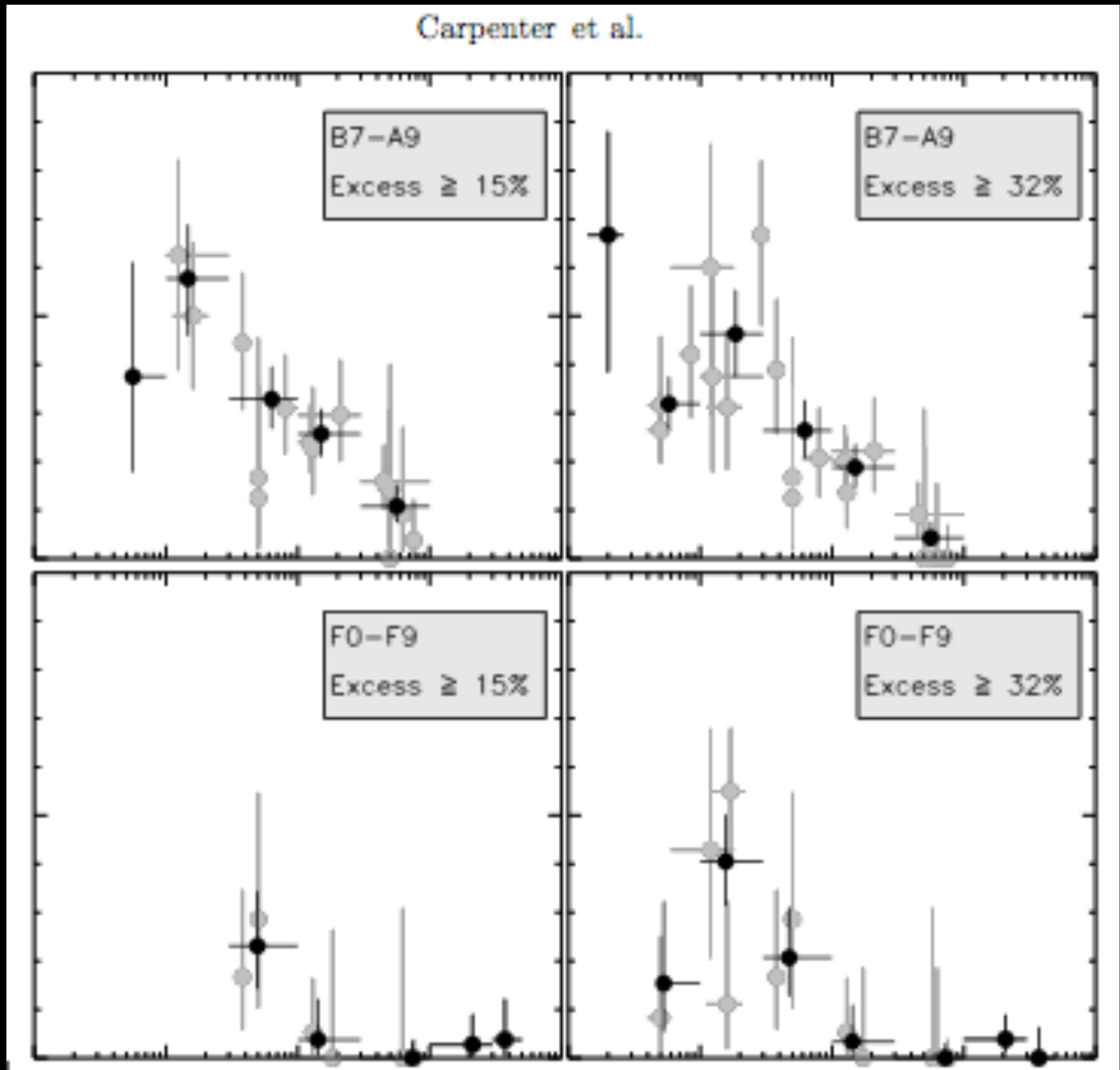
Planetesimal Dynamics = Compositional Differences



Raymond et al. (2004; 2006); Bond et al. (2009); others…



Carpenter et al. (2010)



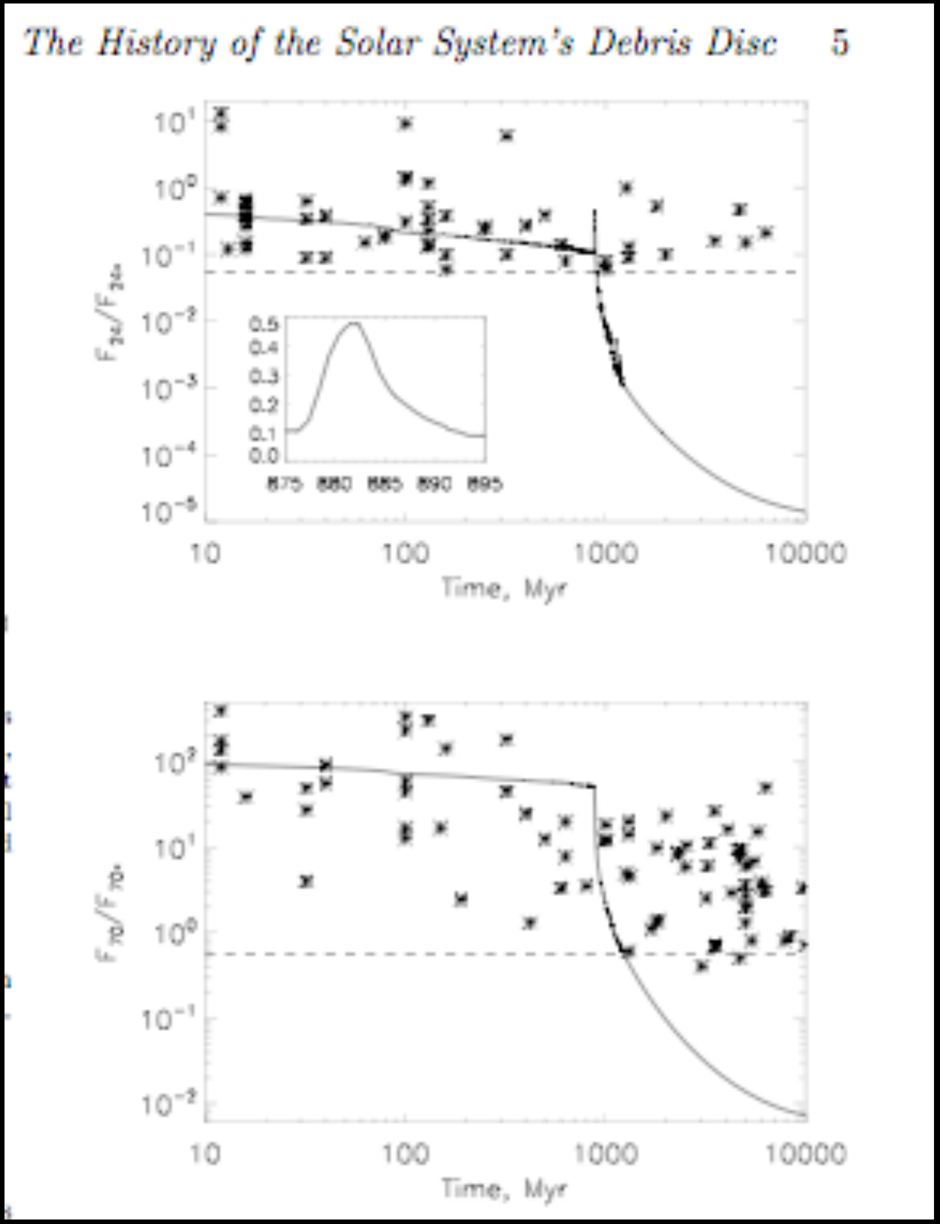
Carpenter et al. (2010)

Late Heave Bombardments Around Sun-like stars…

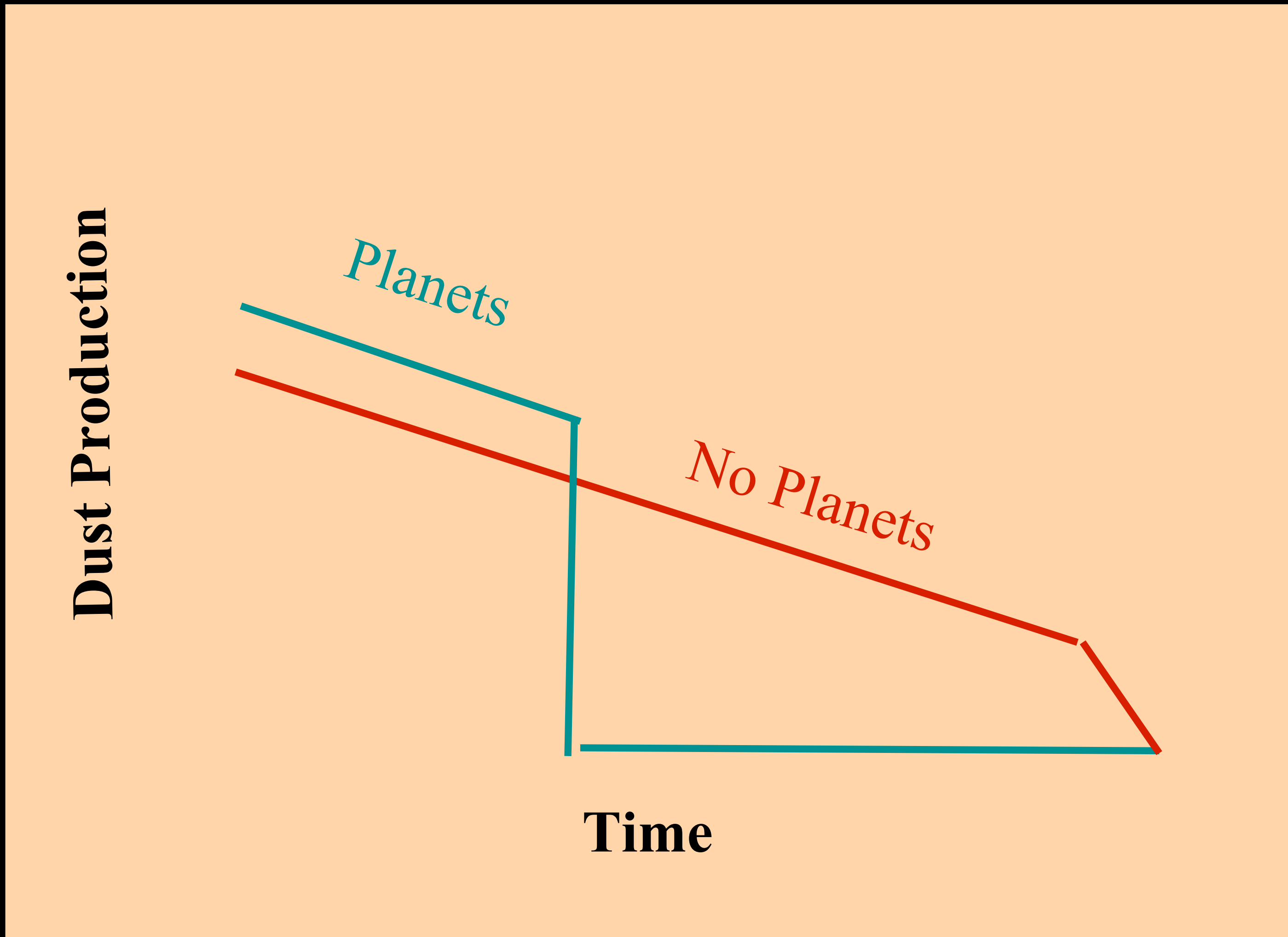
are rather special events!

Was our system unusually bright from 8 to 24 microns at early times?

Booth et al. (2009)
Cf. Greaves et al. (2009)
& Meyer et al. (2007)



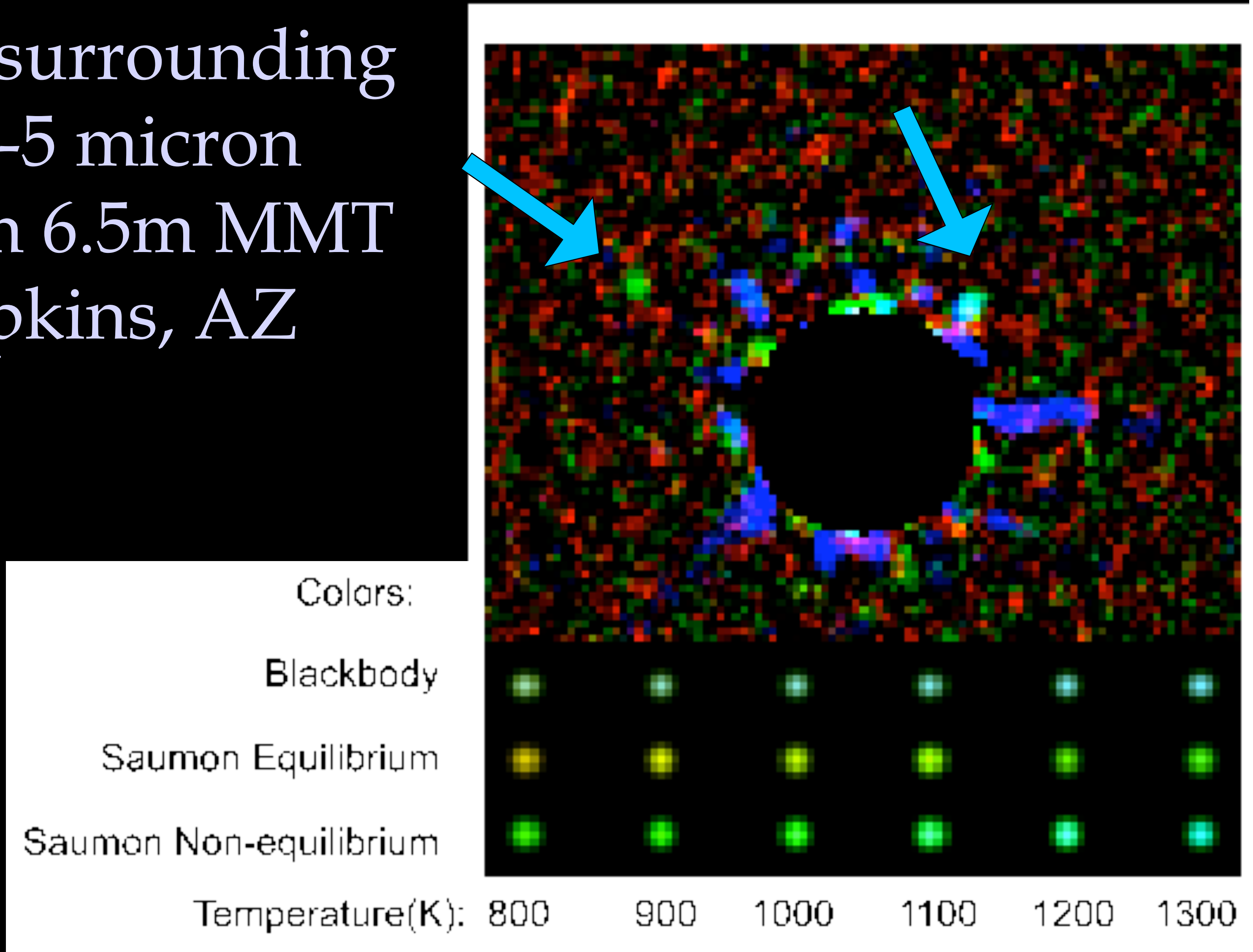
The connection between planetesimal belts and presence/absence of giant planets is not clear.



No link between debris and RV planets found! Could debris disks be more common than Gas Giants?

Moro-Martin et al. (2007a; 2007b), Kospal et al. (2009), Bryden et al. (2006)
Notable Exceptions: HD 69830, HR 8799, Fomalhaut, Beta Pic, eps Eri…

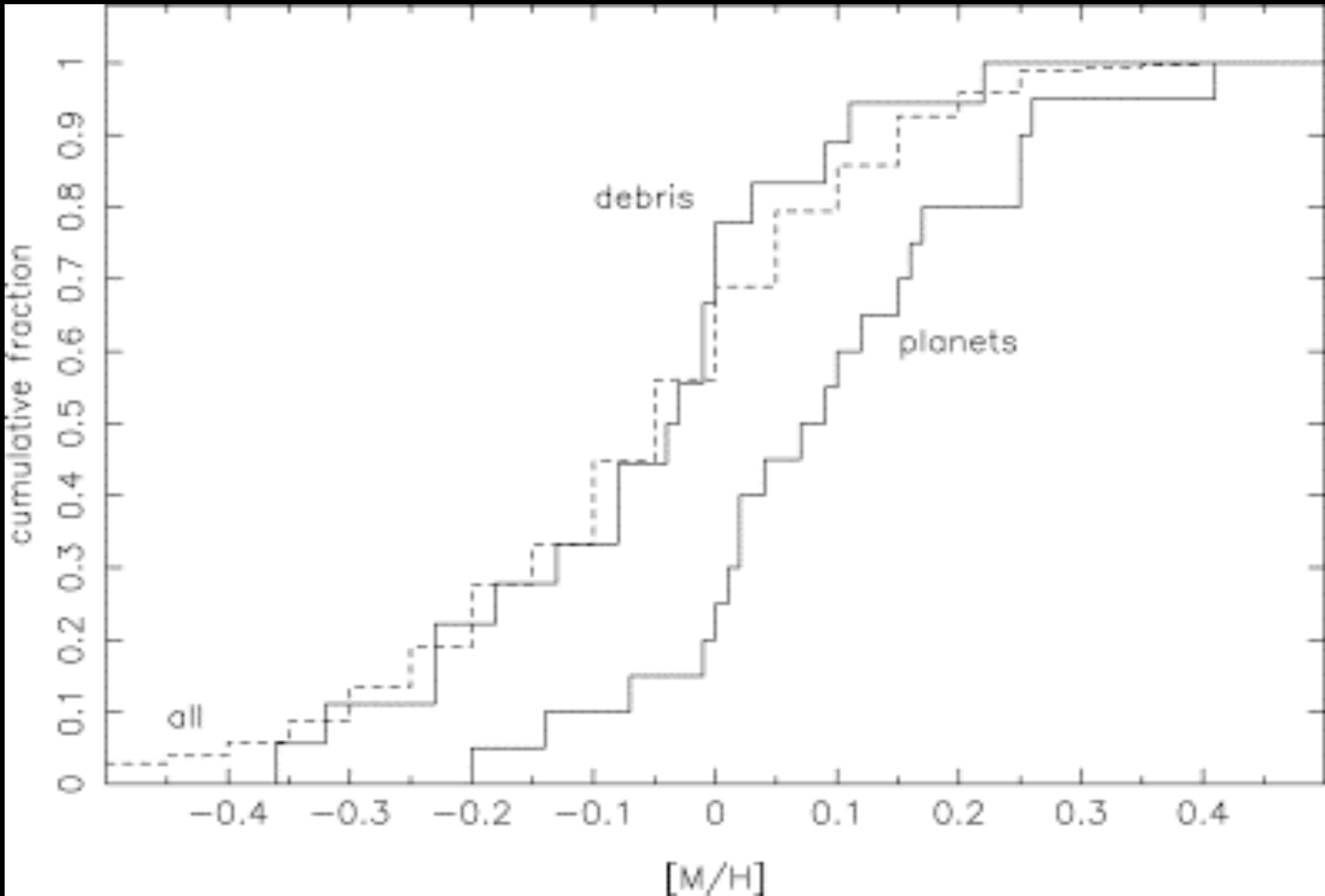
Exoplanet surrounding HR 8799: 3-5 micron image from 6.5m MMT on Mt. Hopkins, AZ



Planets are bluer than expected in L'-M (Hinz et al. submitted).

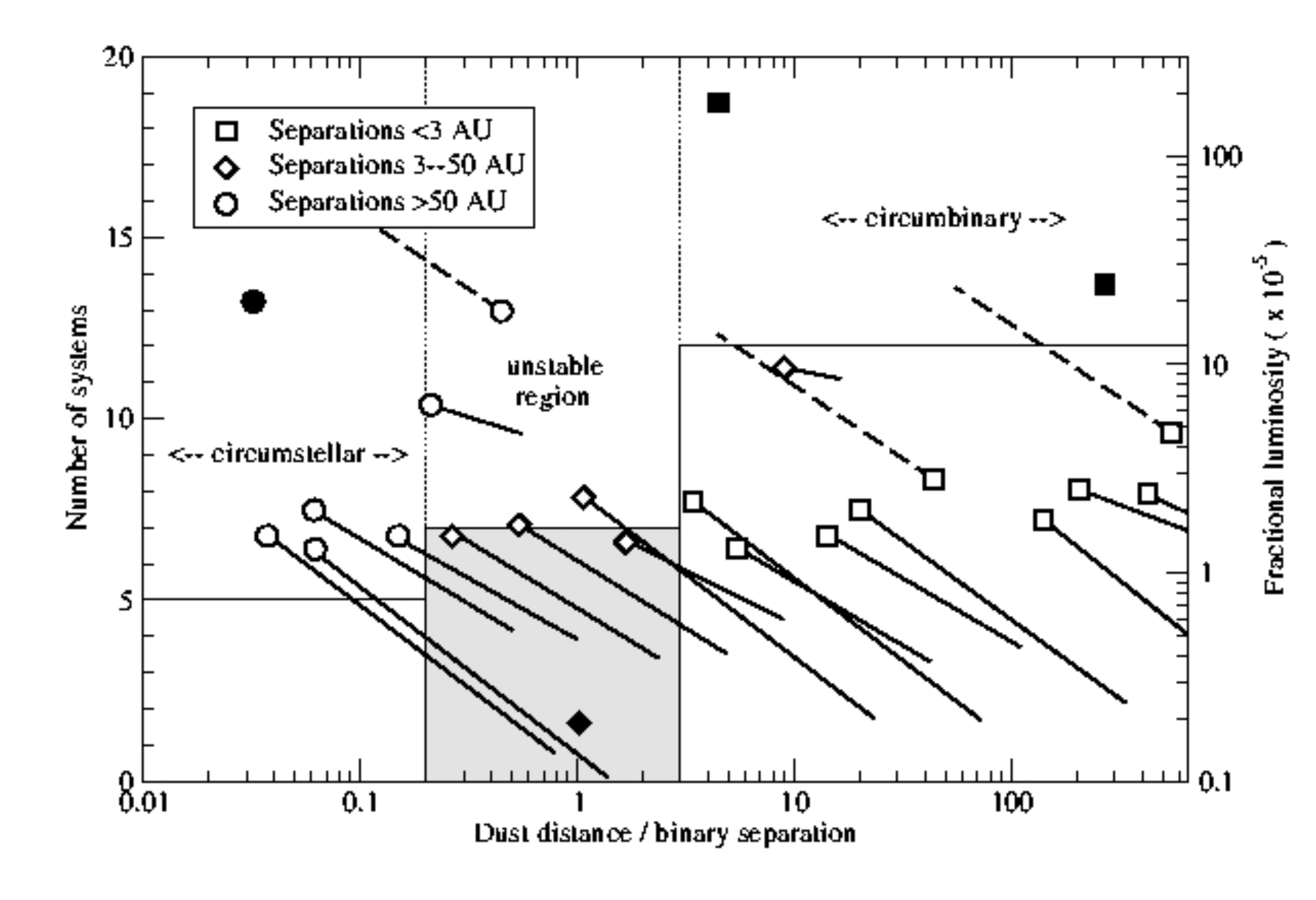
Cf. Su et al. (2009) - inner and outer debris belts.

Debris Disks vs. Metallicity:
More "diverse" than RV planet systems?



Greaves et al. '06; Bryden et al. '06; Najita et al. (in preparation).

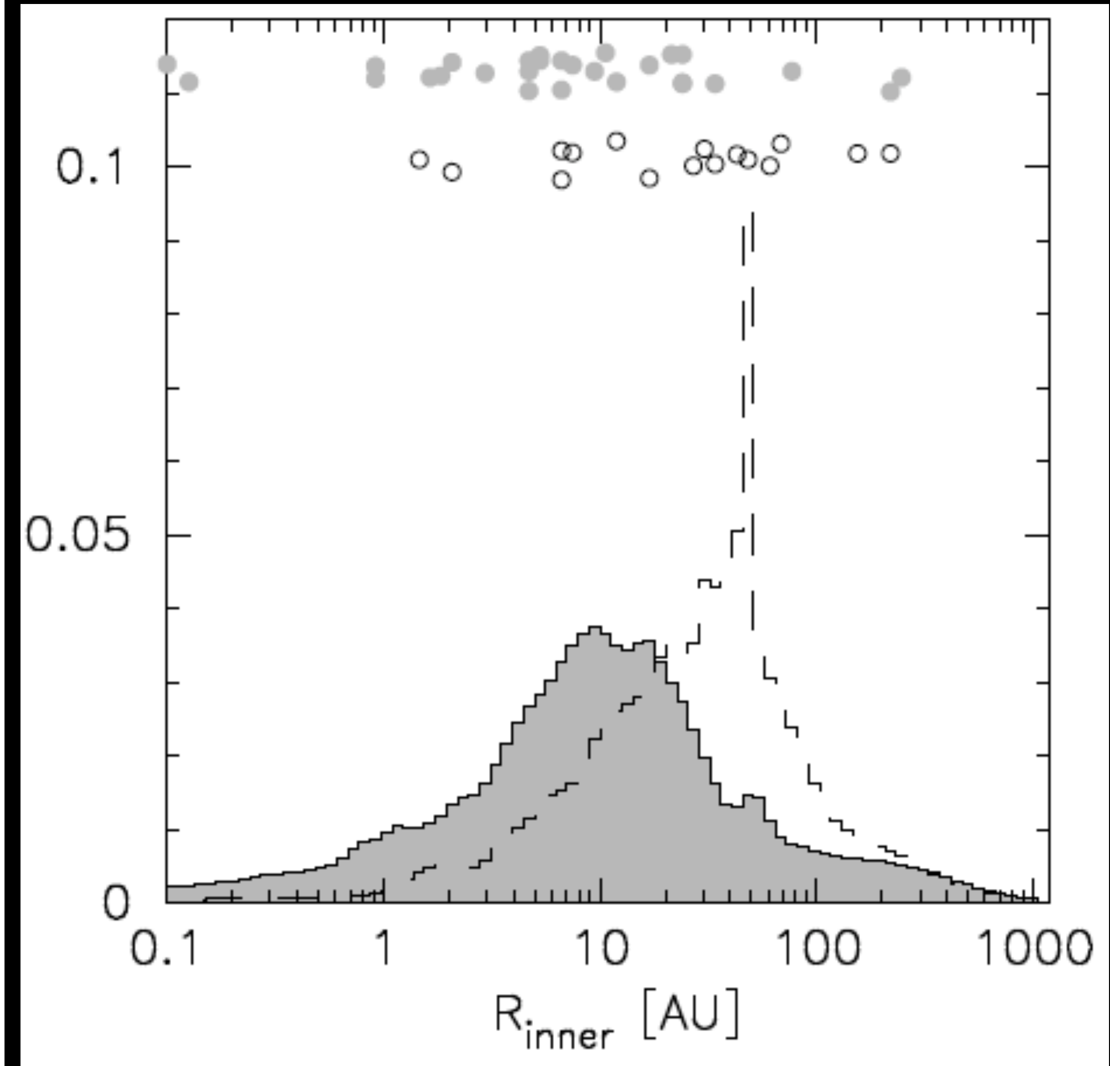
Debris Disk Evolution and Multiplicity:

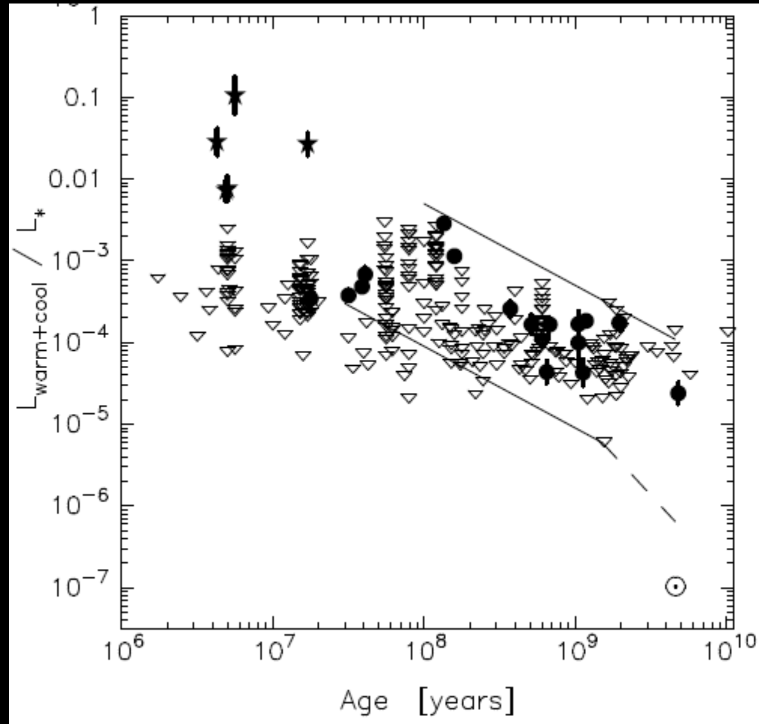


Debris Disks not inhibited by companions.

Trilling et al. (2007) cf. Wyatt et al. (2003)

Spitzer/FEPS (Meyer et al. 2006)
The Last Word:
Carpenter et al. (2009)

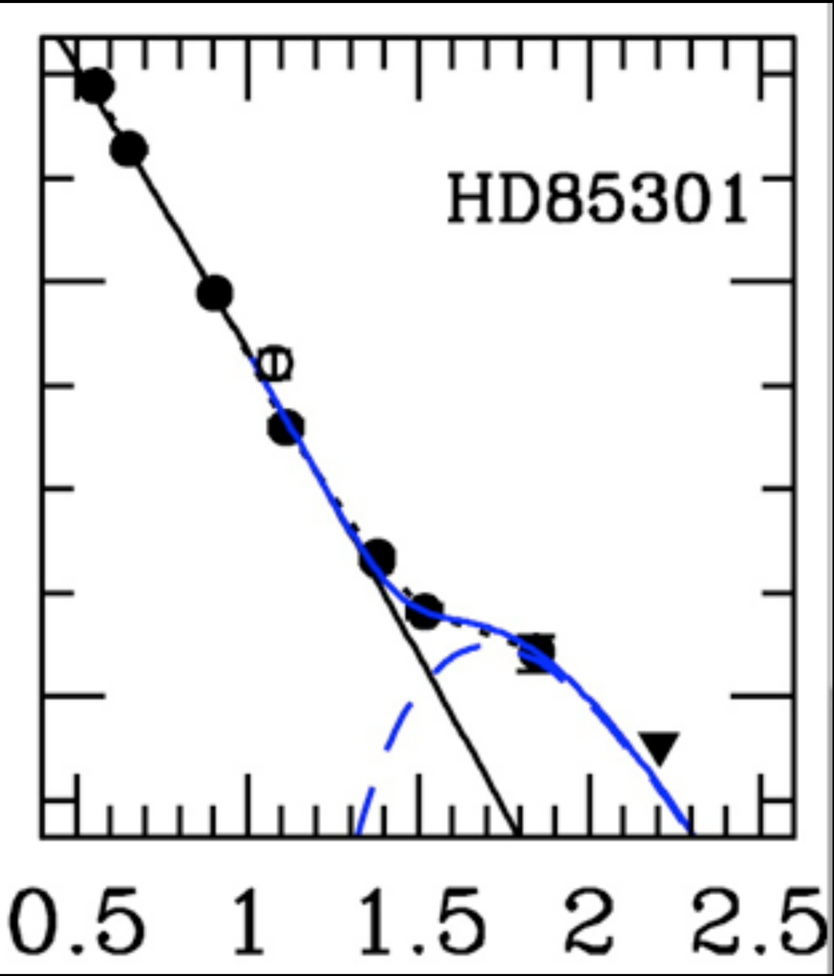


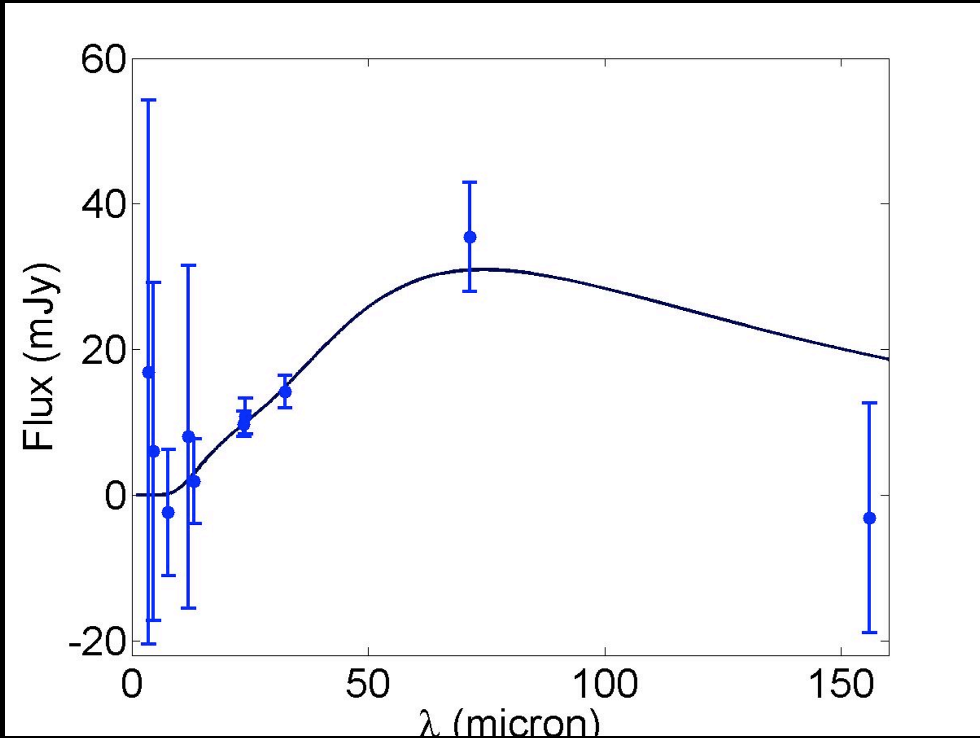


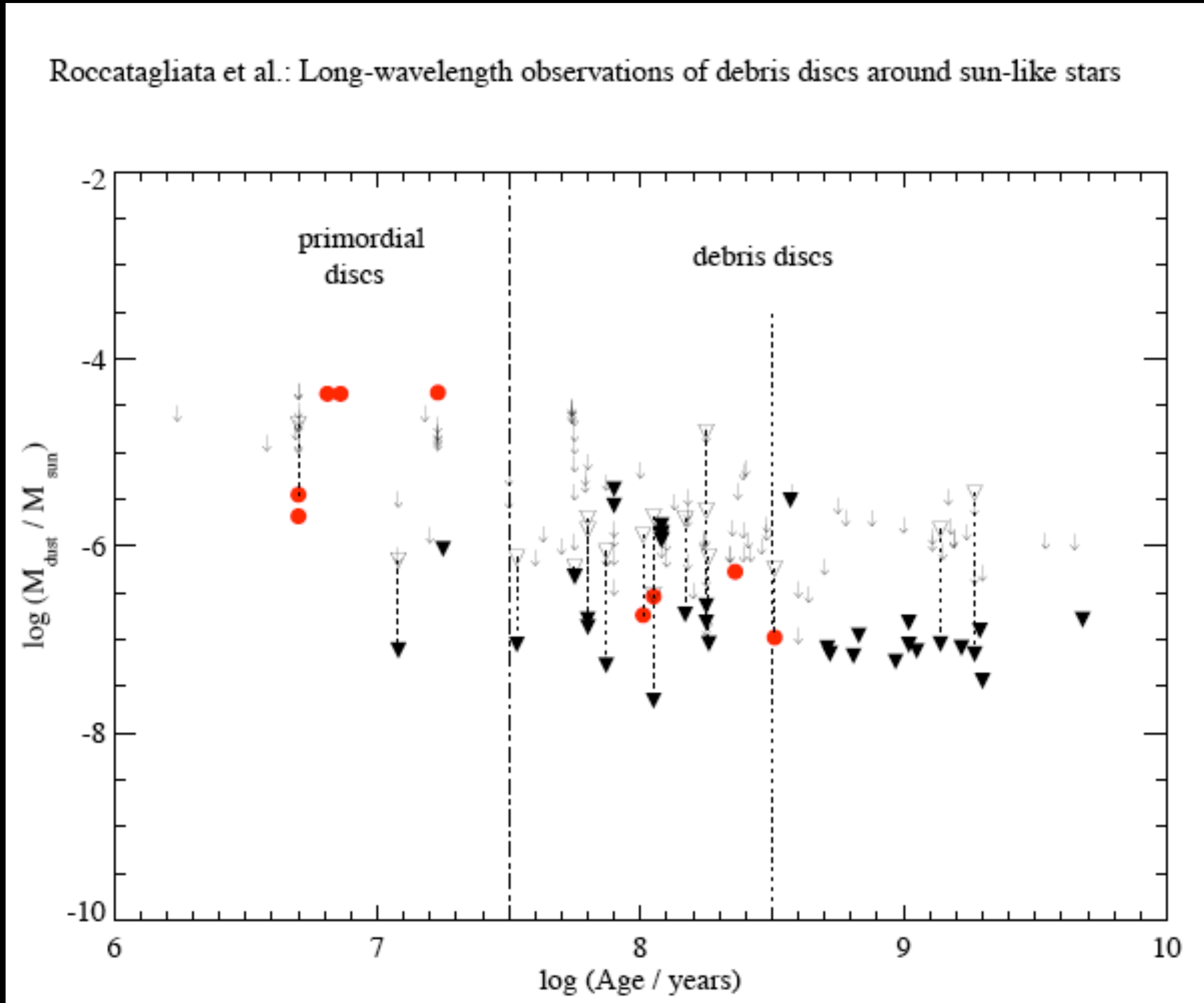
Evolution in Disk Luminosity:
A stars: Su et al. (2006)
G stars: Bryden et al. (2006)
M stars: Gautier et al. (2007)

Distribution of Inner Hole Sizes: cf. Morales et al. (2009)

About 30 % of debris systems are Multi-Temperature Debris Disks: Bands or Rings?







Sub-mm Observations of Debris Disks:
Carpenter et al. (2005); Greaves et al. (2006; 2008); Liu et al. (2004)
Greaves et al. (2009); Lestrade et al. (2009); SCUBA-2 coming…

Are planetary systems like our own are common or rare among sun-like stars in the Milky Way galaxy?

Primordial Disk Evolution:

- disks around lower mass stars are less massive but live longer than their more massive counterparts.

- large dispersion in evolutionary times could indicate dispersion in initial conditions.

Are planetary systems like our own are common or rare among sun-like stars in the Milky Way galaxy?

- *transition time from primordial to debris is 0.1 Myr.*

- *planetesimal belts evolve quickly out to 3-30 AU.*

- *any difference between evolution in field versus clusters?*

Debris Disk Evolution:

- currently detectable systems are collision-dominated.

- more common (and massive) around stars of higher mass.

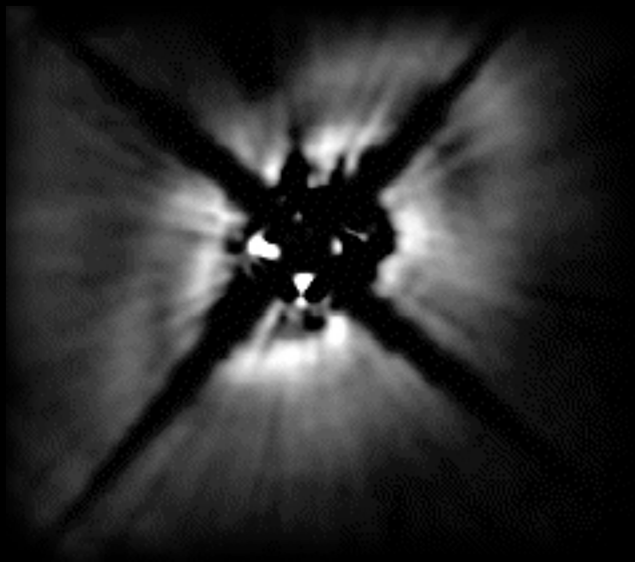
- evolutionary paths are diverse.

- "consistent with" initial conditions, and current state of solar system being common.

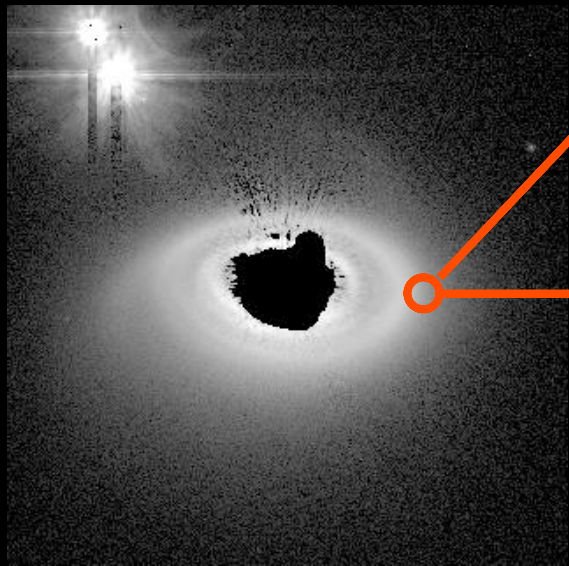
- connection to planetary systems unclear.

Are systems without debris those with dynamically full planetary systems, or those without any planets?

Can SPHERE discern the ice-line in scattered light?

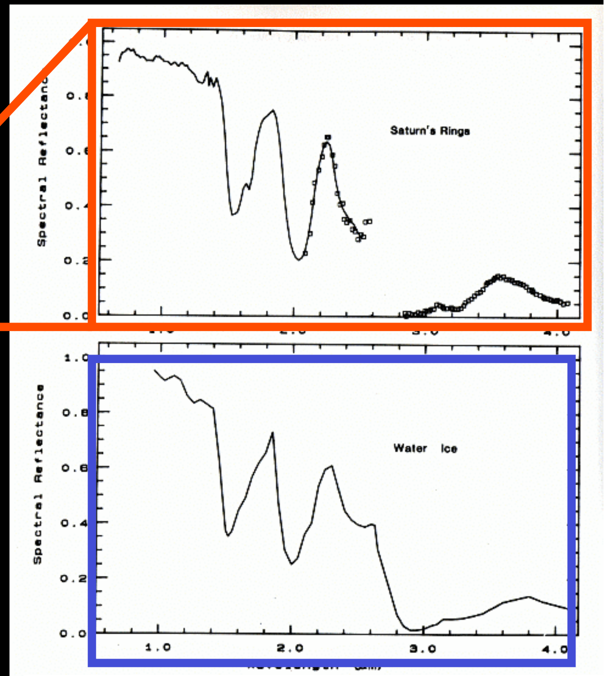


(Weinberger et al. 1999)



(Clampin et al. 2003)

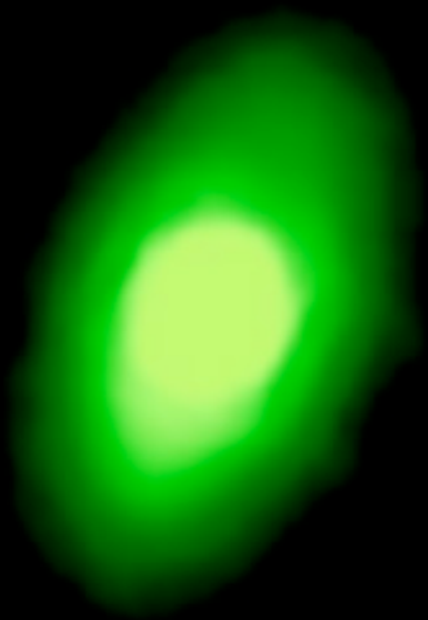
Saturn's Rings



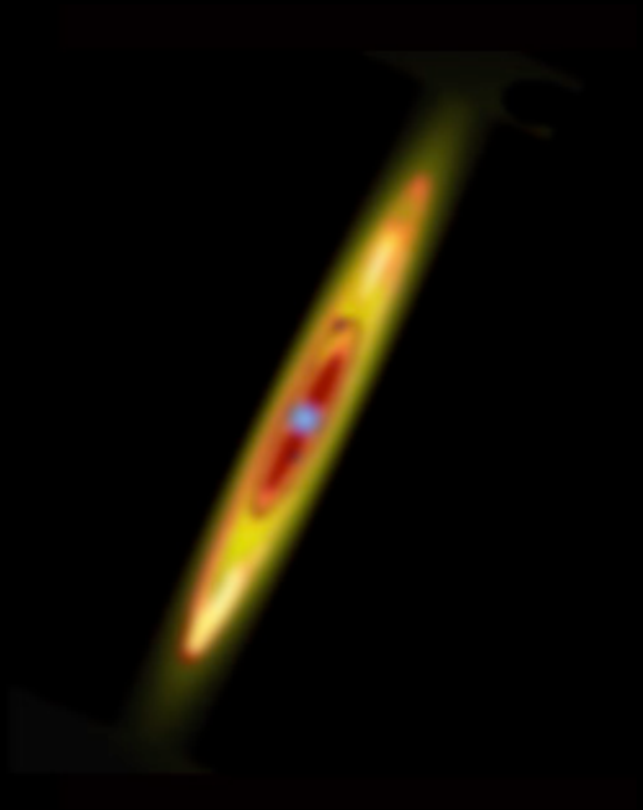
Water Ice

Disk structure, dust particle size, and composition from multi-color imagery (cf. Debes et al. 2007).

A Picture is Worth 1024 x 1024 Points on an SED…



Spitzer @ MIPS-24



JWST-MIRI

Embargo until after launch

Herschel

Context for E-ELT in 2020:

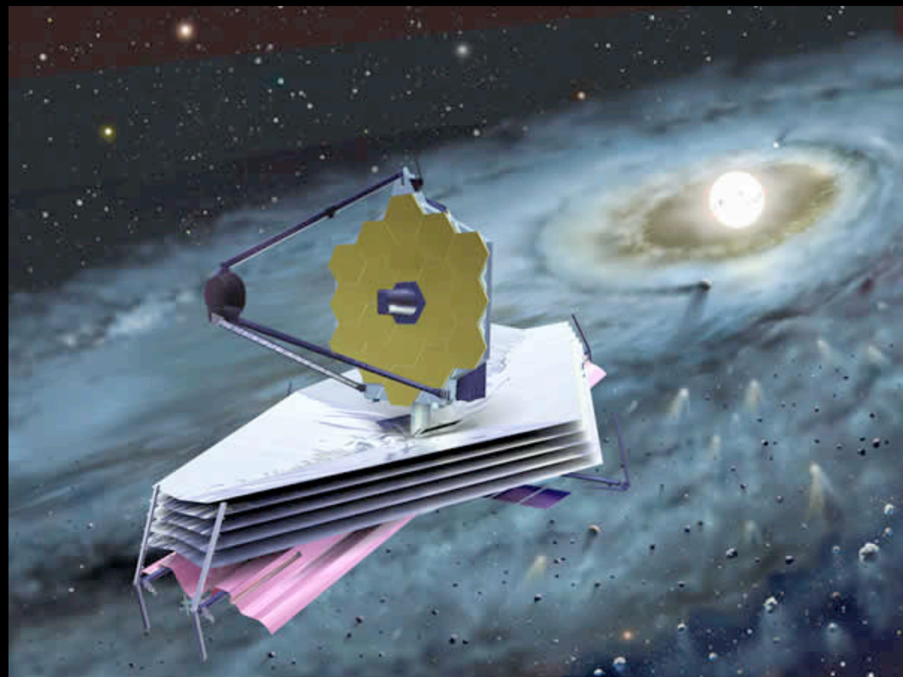
COROT/Kepler results known.

SPHERE/GPI surveys complete.

SOFIA/ALMA normal operations.

Five years of JWST observations.

NASA/ESA Probe/“M” Class Missions launched.



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