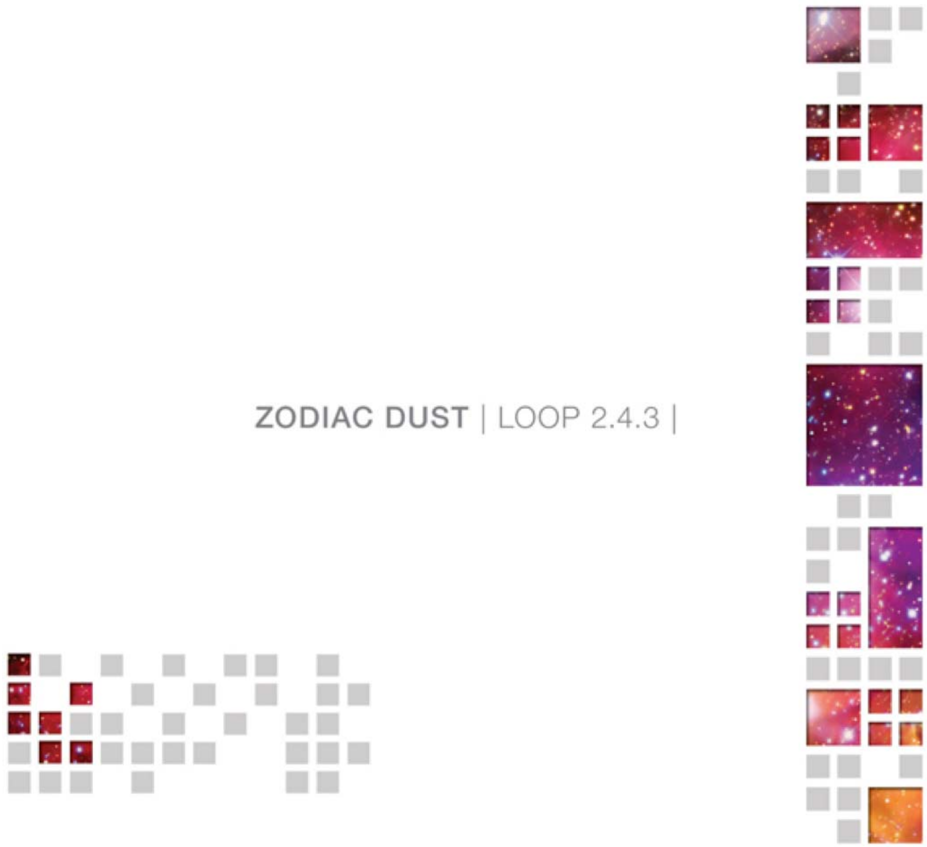


"Zody"

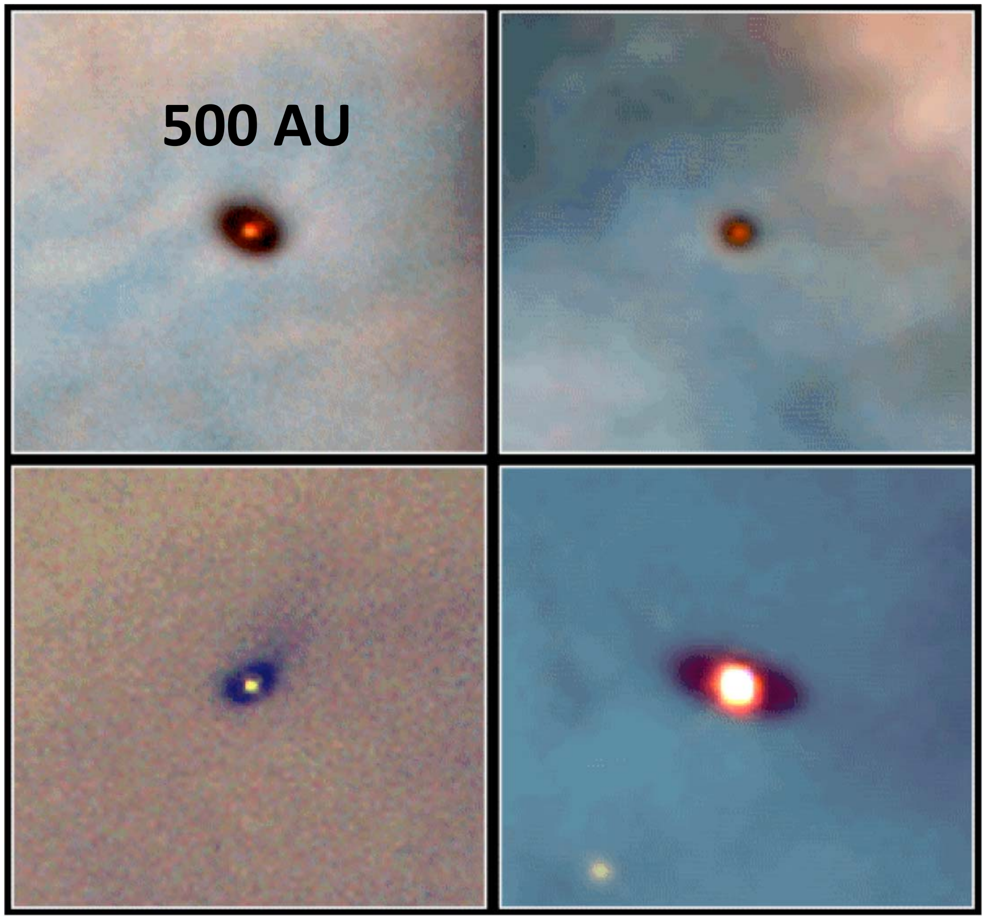
Lynne A. Hillenbrand

Caltech

[some slides courtesy John Carpenter]

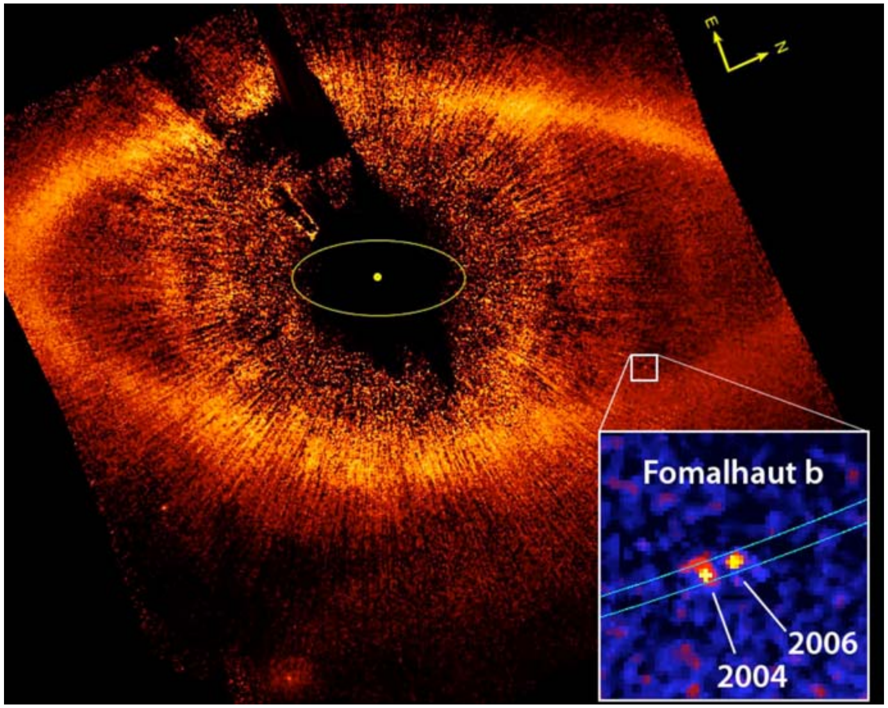
From Primordial Disks to Debris and Planets

Silhouette disks in ~1-2 Myr old Orion

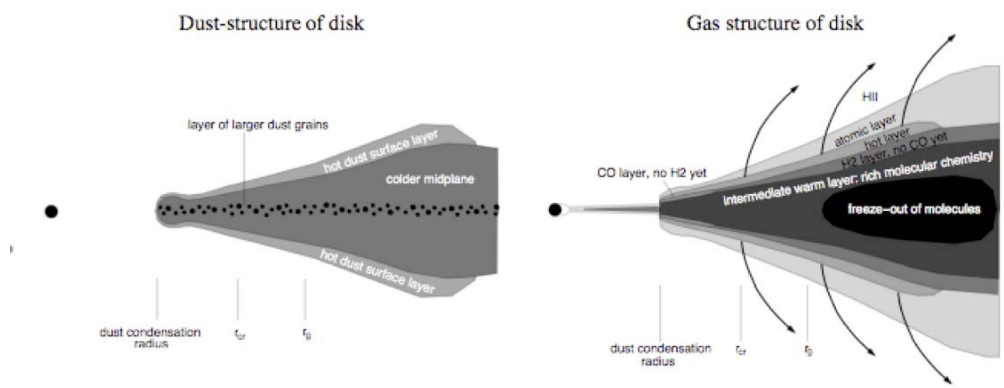


McCaughrean & O'Dell (1996)

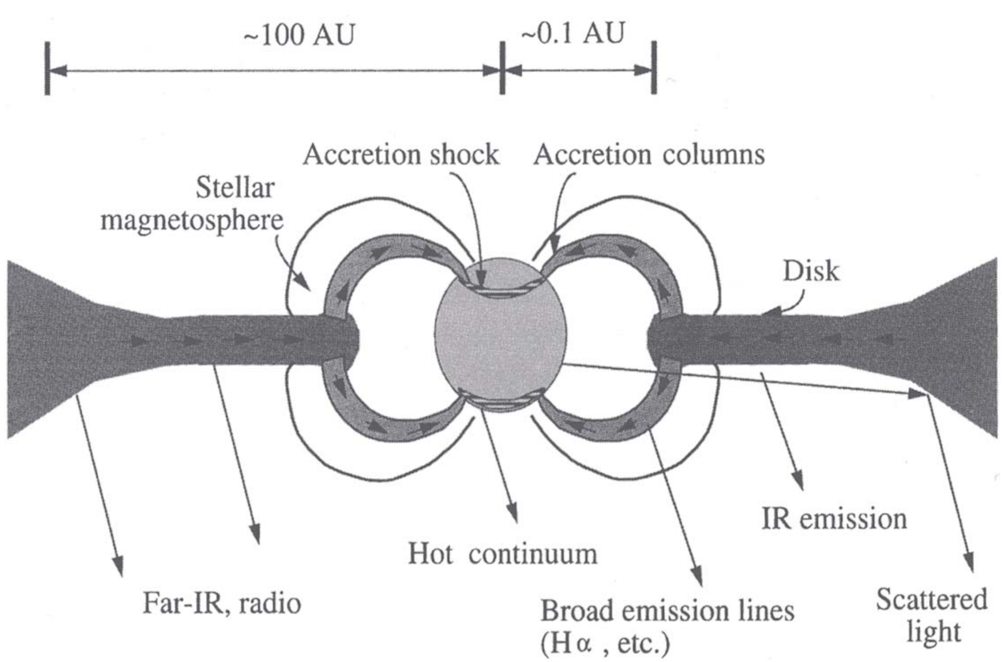
Scattered light debris disk ***AND*** a candidate planet in ~200 Myr old Fomalhaut



Kalas et al. (2008)



[*Dullemond 2001*]



[*Hartmann 1998*]

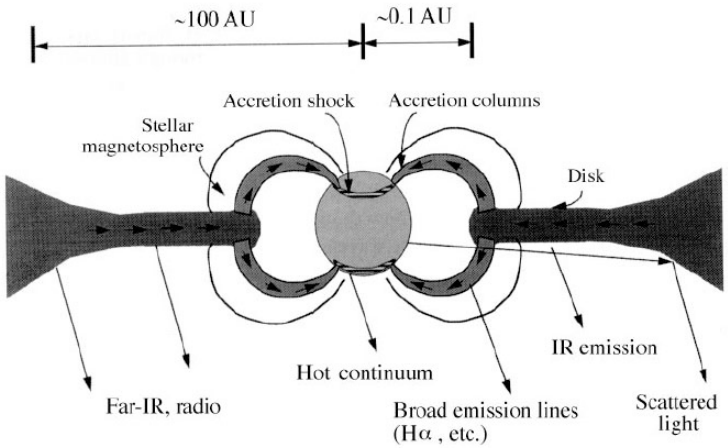
Initial Optically Thick Disk Geometry

- Ultraviolet and blue optical excess from accretion shock and heated photosphere.
- Near- and Mid-infrared excess from hot/warm dust in inner disk. (< 0.1-1 AU)
- Sub- and millimeter emission from cold dust in outer disk. (few to hundreds of AU)

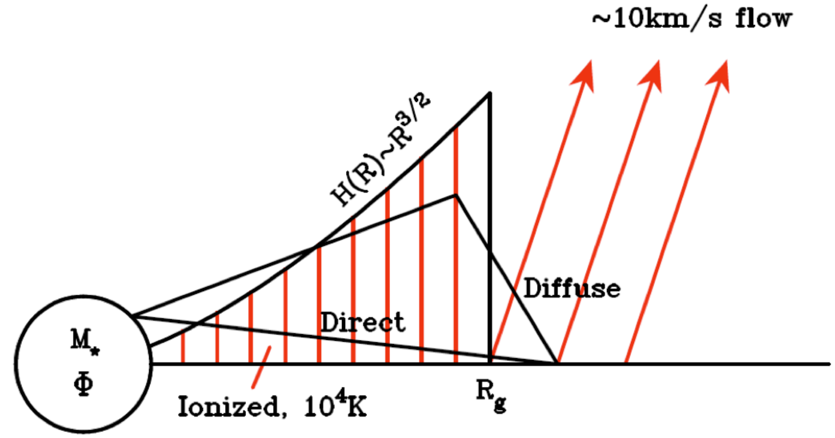
(both continuum and line diagnostics at all wavelengths)

What happens to the gas/dust?

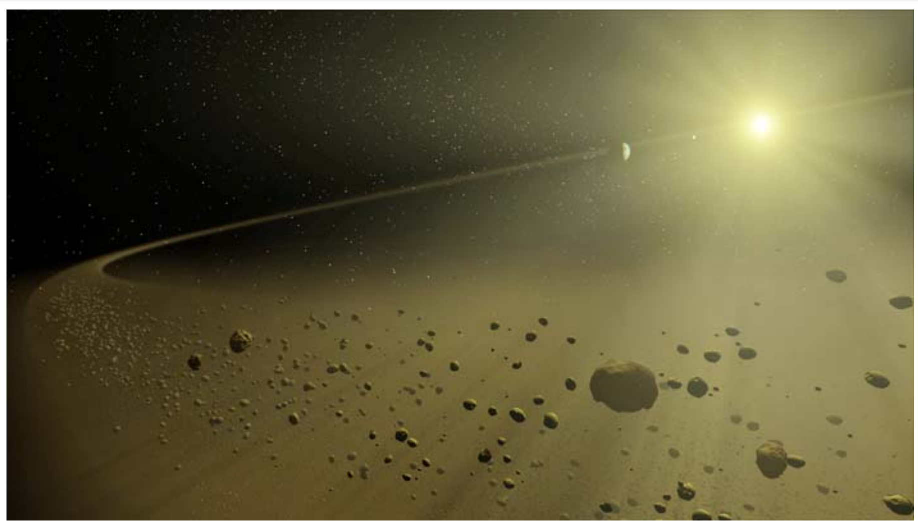
Accretion - also Outflow



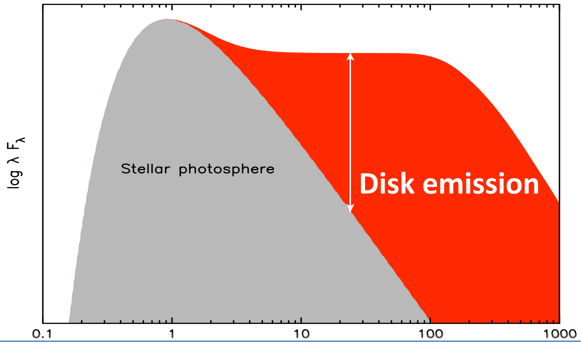
Photoevaporation (UV and Xray)



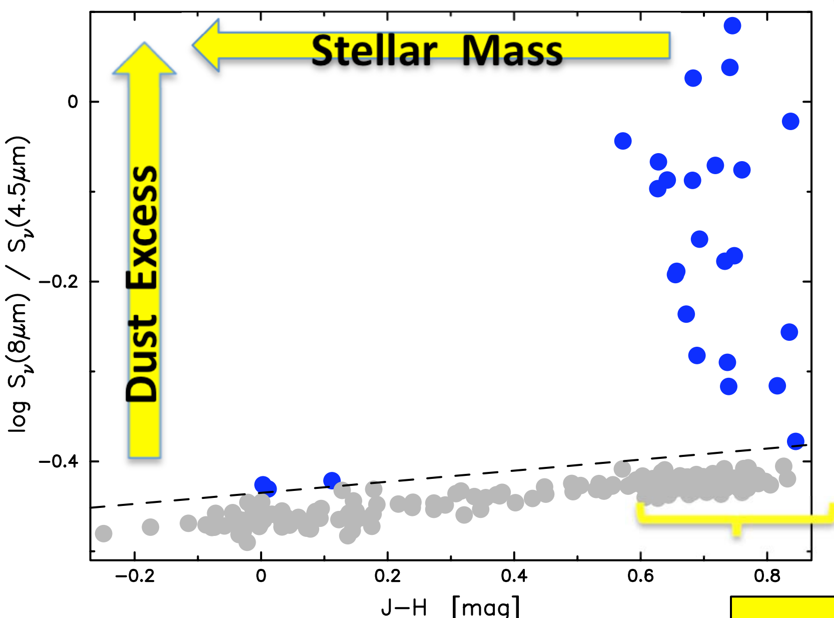
Planetesimals ➡ planets ➡ debris dust



Identifying disks and characterizing timescales for disk dissipation



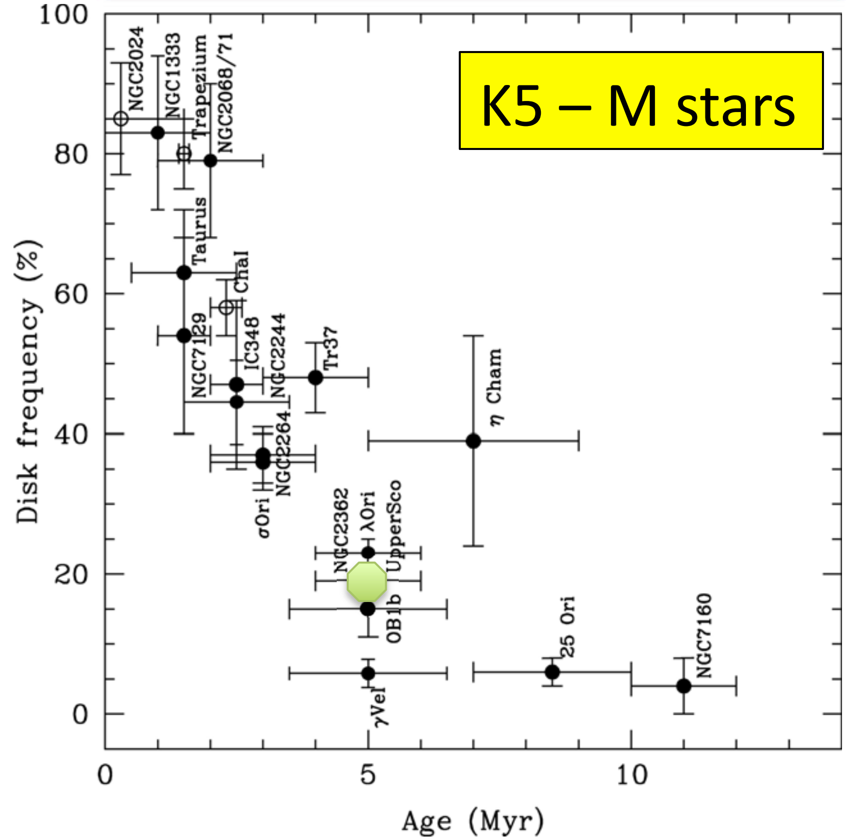
Stellar Mass Dependence



Carpenter et al. (2009)

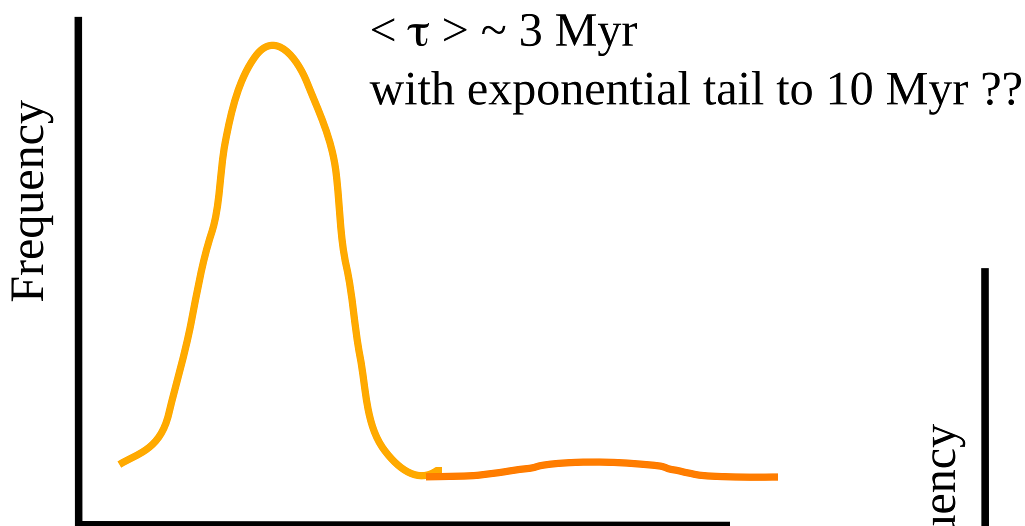
K5 – M stars

Stellar Age Dependence

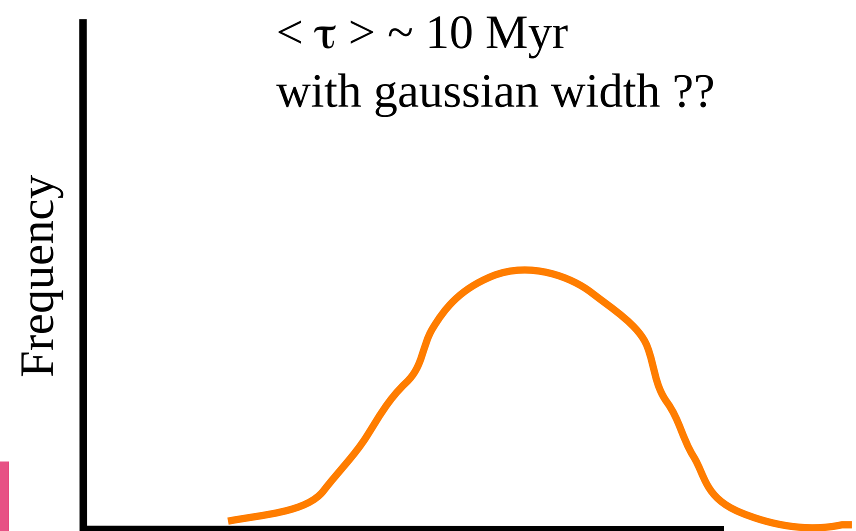


e.g. Hernandez et al. (2008)

Goal to Establish the Frequency Distribution of Disk Lifetimes

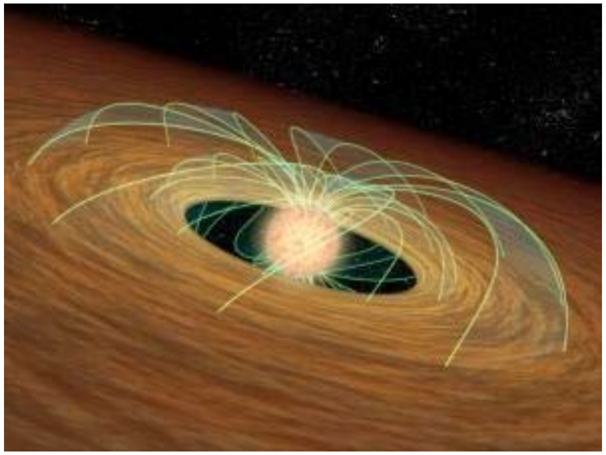


Inner Disk Lifetime
(<0.3 AU) or ~ MVEM zone



Outer Disk Lifetime
(>10 AU) or ~ JSUN zone

⇒ evolution in σ [Σ (r)]
for comparison to models



Gas and Dust to Planets

- Gas dissipation:
  - viscous accretion on to star
  - outflow in winds/jets
  - photo-evaporation
  - gas giant accretion

- Grain evolution:
  – growth from ISM-sized dust to larger solids:
  μm → cm → km → moon/Mars sized "oligarchs" → 1-10 M_{earth} planets

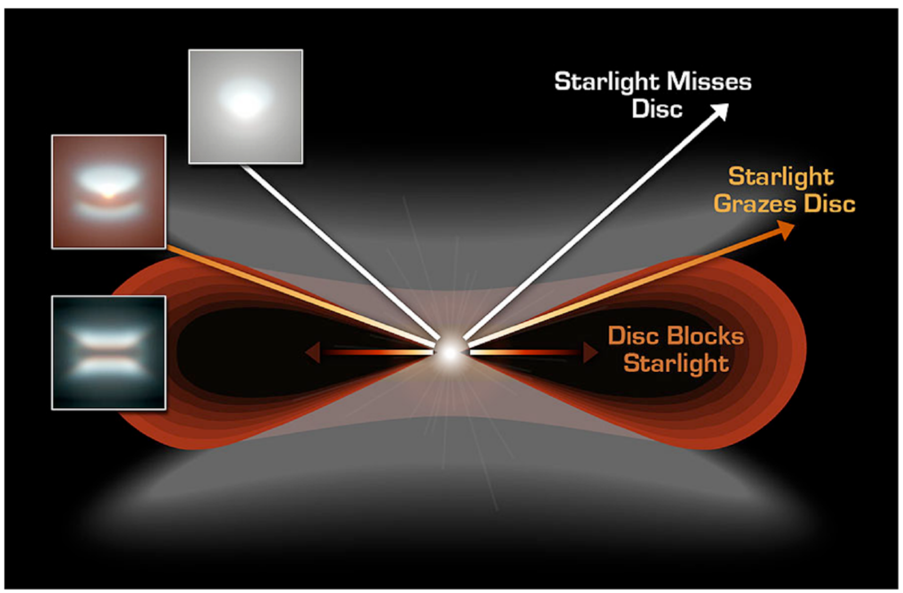
  – rapidly re-generate "debris" dust"

What is the Difference Between "Primordial" and "Debris" Disks?

Primordial

$\tau \geq 1$

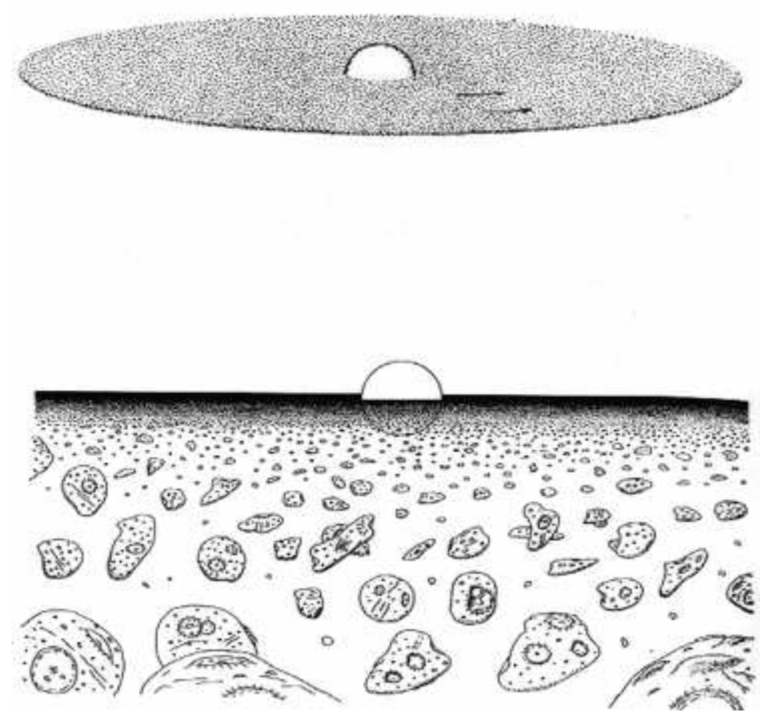
- first generation
- geometry
- radiative transfer



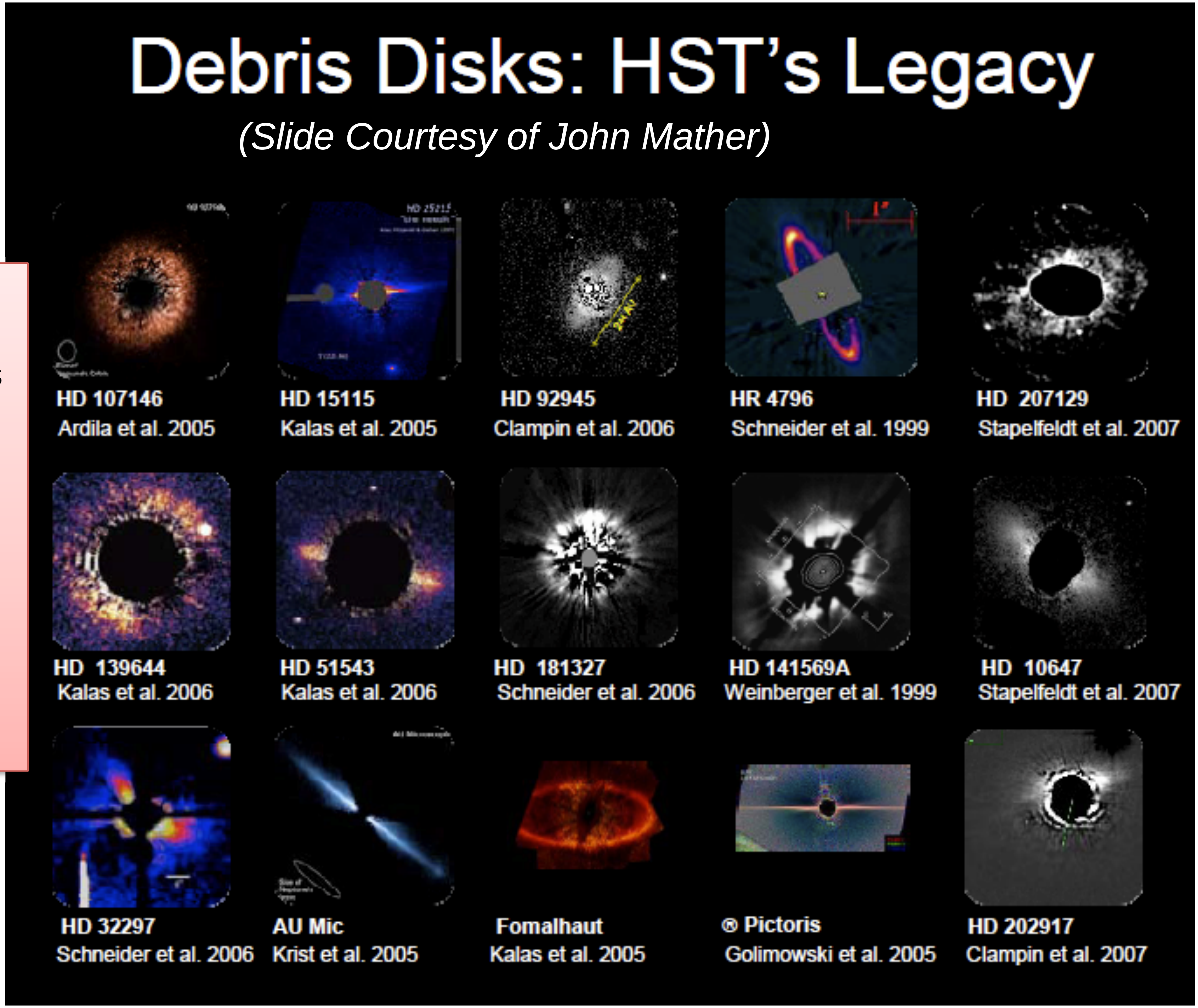
Debris

$\tau << 1$

- second generation
- total mass
- surface area

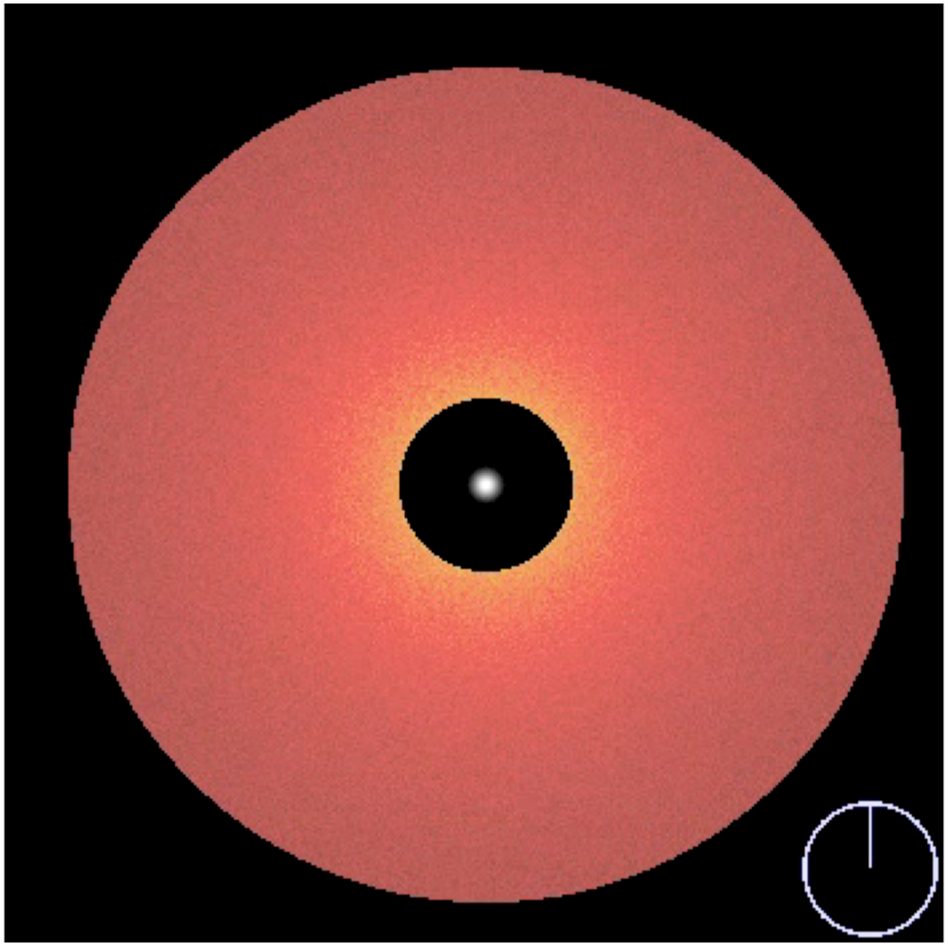


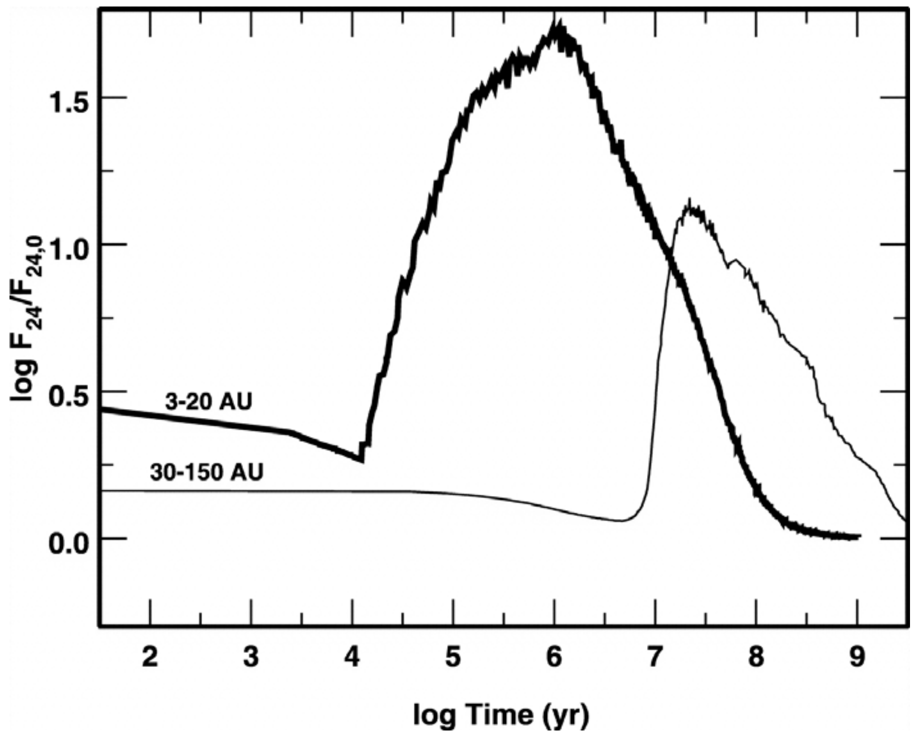
These are mostly young (less than a few hundred million years) and early type (more massive than the Sun) stars!



Evolution of planetesimal belts

Debris luminosity vs. time

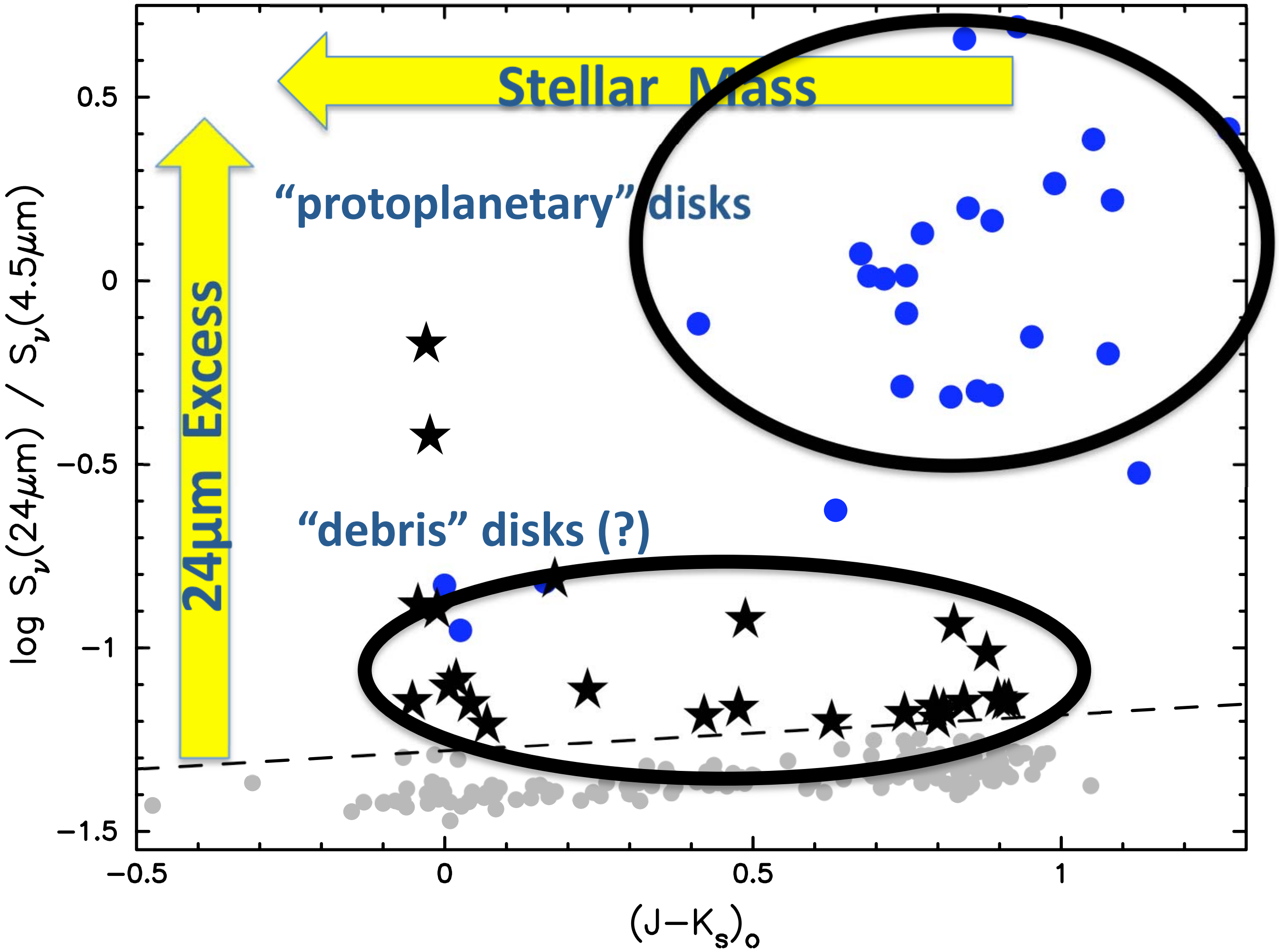




Kenyon & Bromley (2004, 2005)

When does debris production start?

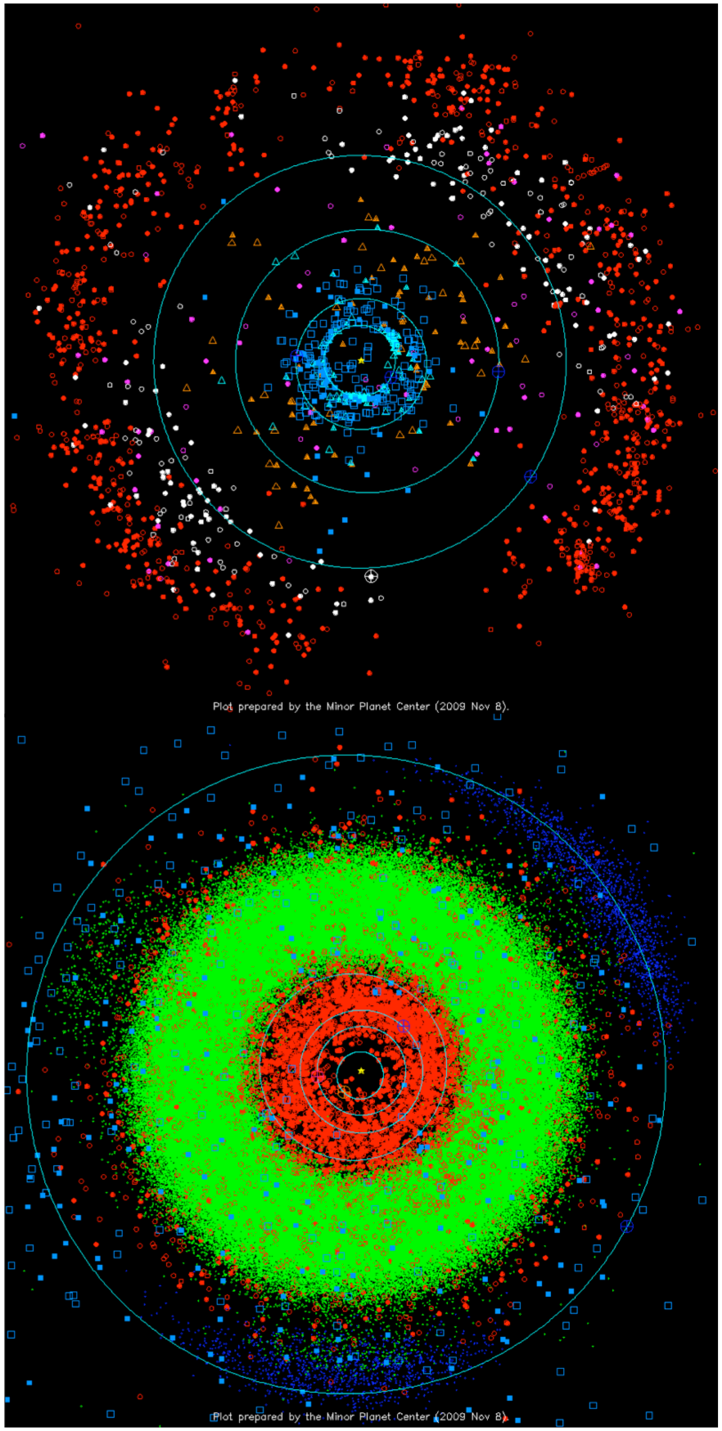
5 Myr old Upper Scorpius OB Association



Carpenter et al. 2009

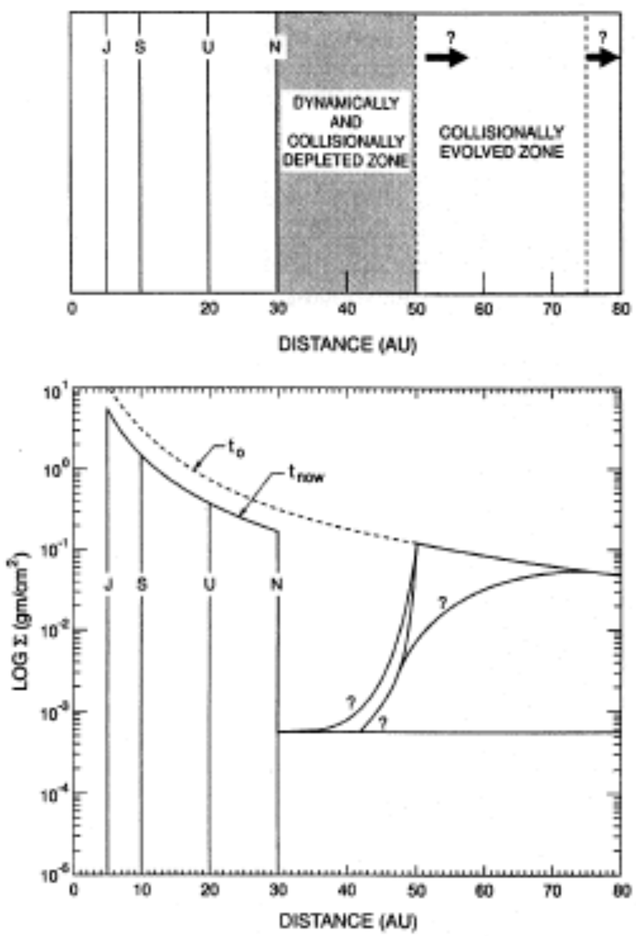
Solar System Minor Planets Provide Ground Truth

- The debris dust that is observed around other stars originates in the collissional cascade of planetesimals that we can not observe.
- Process is induced by giant planets – also mostly as-yet undetected.



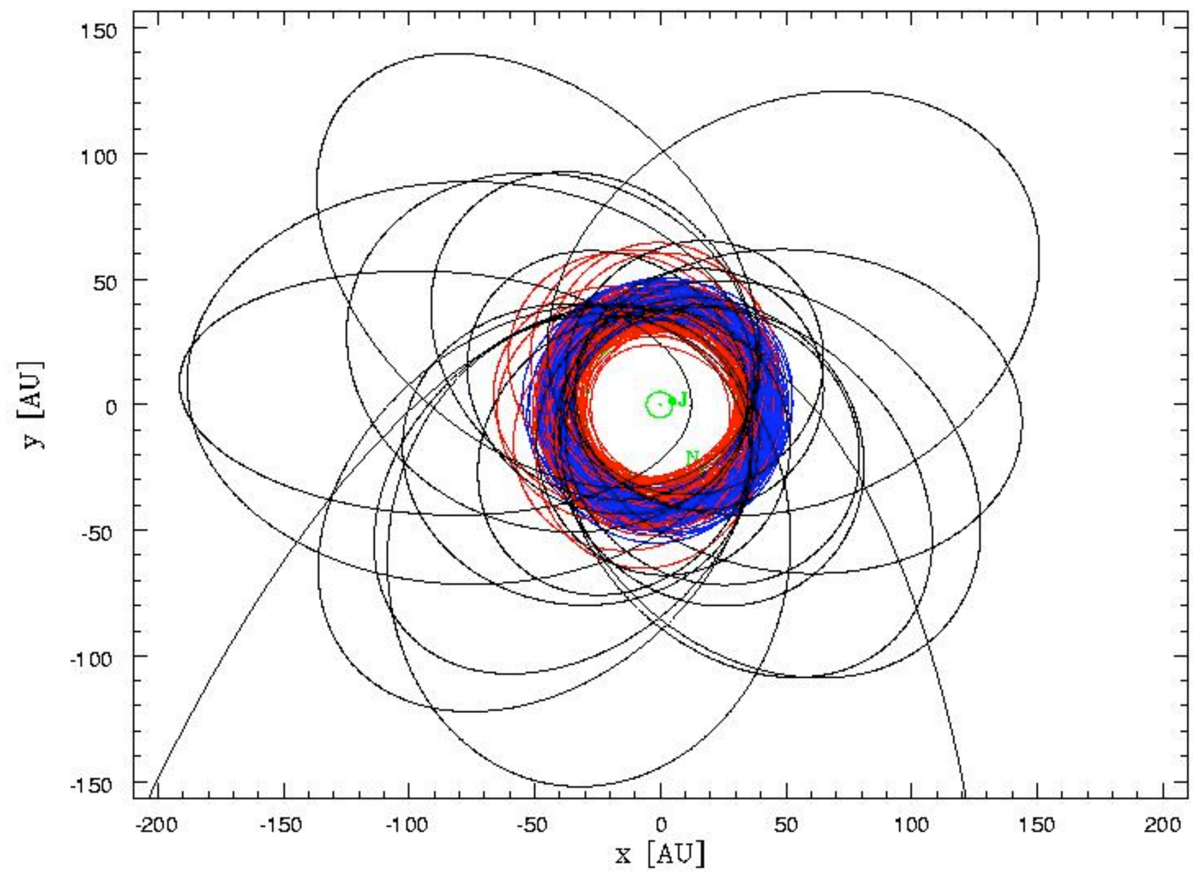
Our Debris Disk: Parent Bodies

Primordial Kuiper Disk



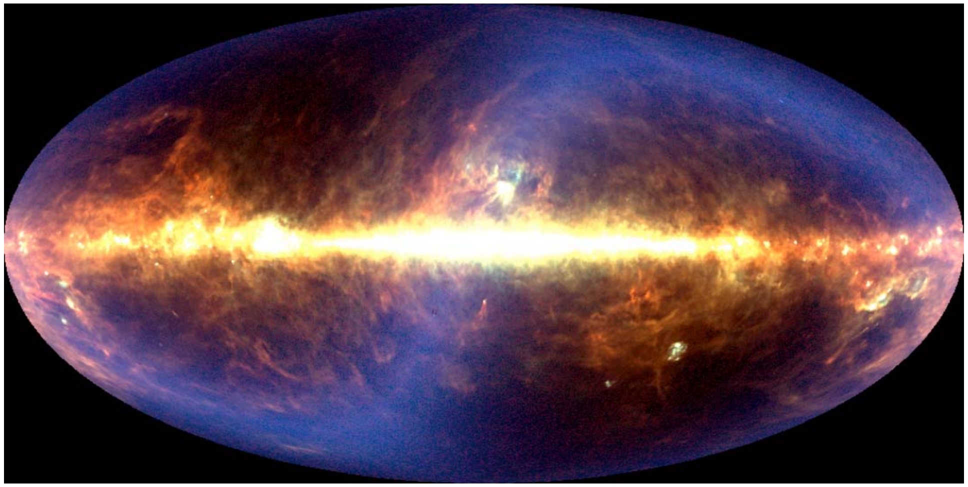
Stern (1996)

Orbits of known Kuiper Belt objects



(Jewitt)

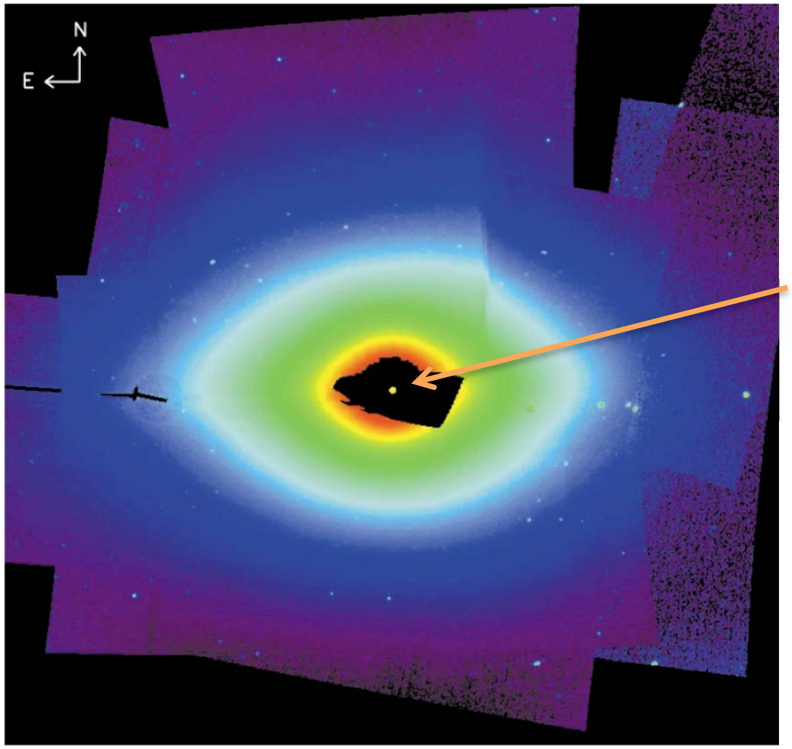
Our Debris Disk



COBE

Photograph from
Mauna Kea showing
the zodiacal light and
also comet Hale-Bopp

[photo courtesy: Paul Kalas]

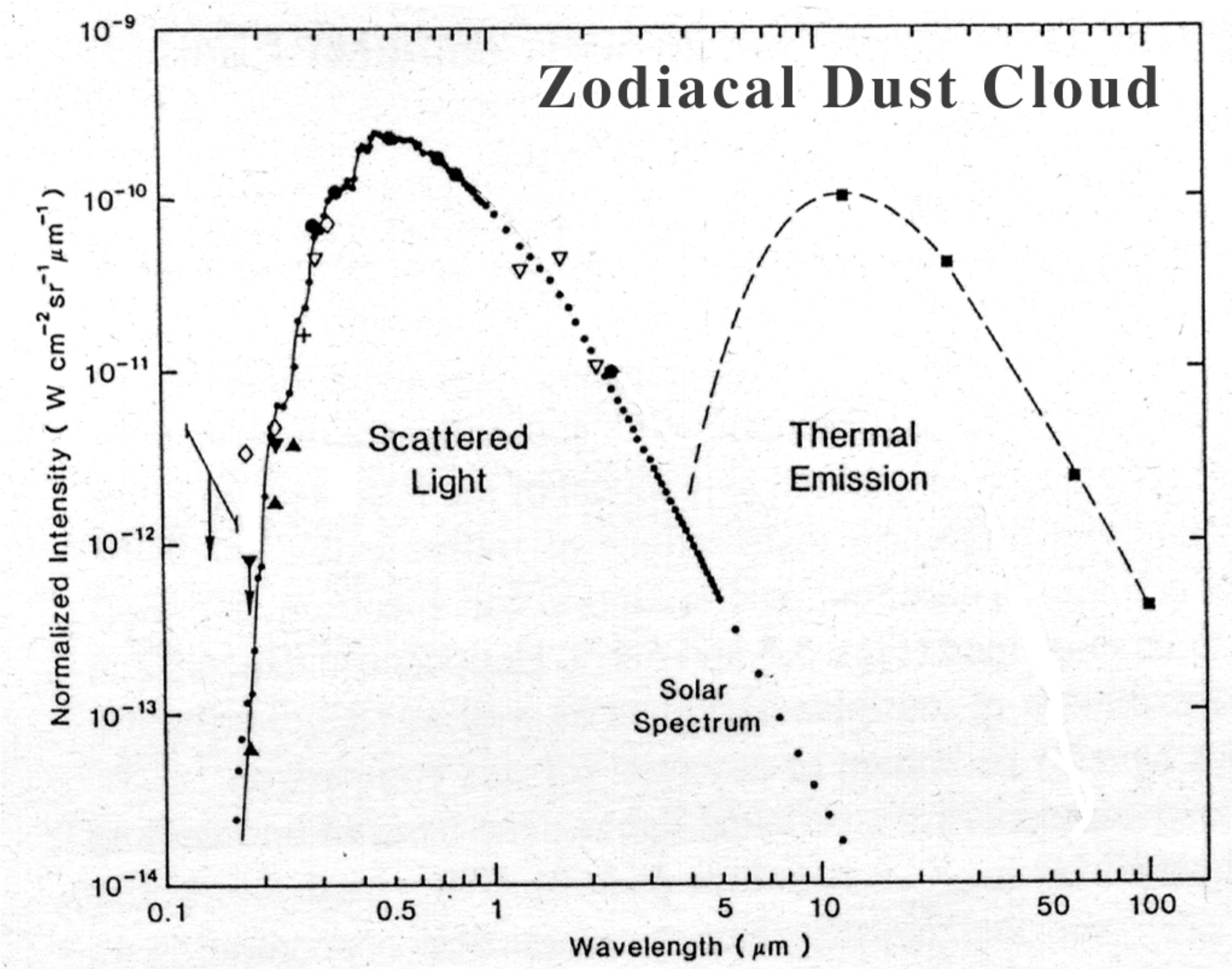


Clementine [Hahn et al. 2002]

Our Debris Disk

- Properties of zody dust:
  - silicate and carbonaceous grains 10-100 um in size
  - mass of 1x10 km body ground up = 10^{-7} m^2/m^2 of dust at 1 AU
- Origin of zody dust:
  - Asteroid Belt [collisions and erosion] -- 70%
  - Comets in inner s.s. [sublimation and ejection] -- 20%
  - Jupiter Trojan Asteroids [collisions and erosion] -- few %
  - Kuiper Belt [collisions and erosion] -- <10%
  - ISM grains [passing through] -- 0.1%

Scattered and Thermal Emission

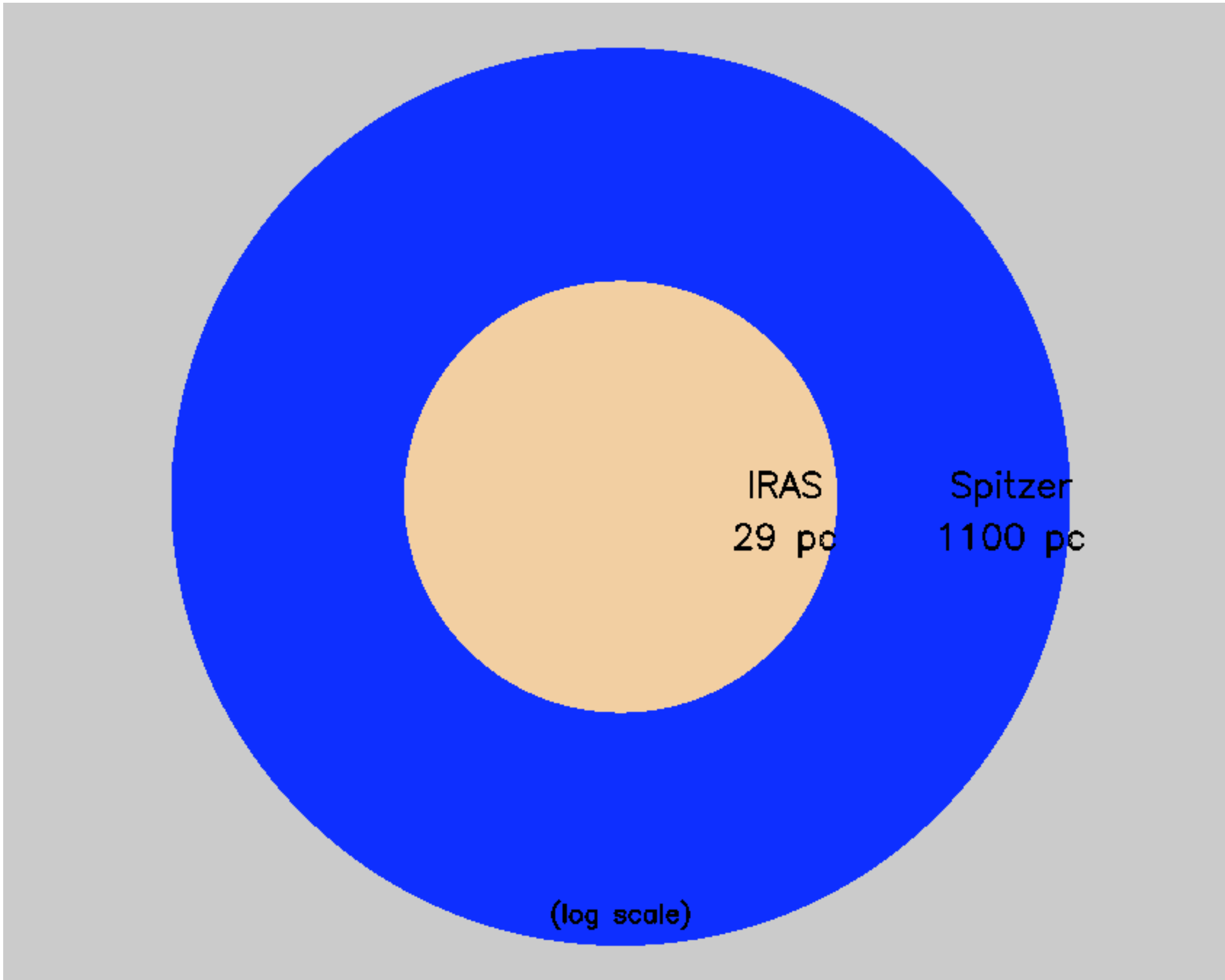


[Leinert & Gruen 1990]

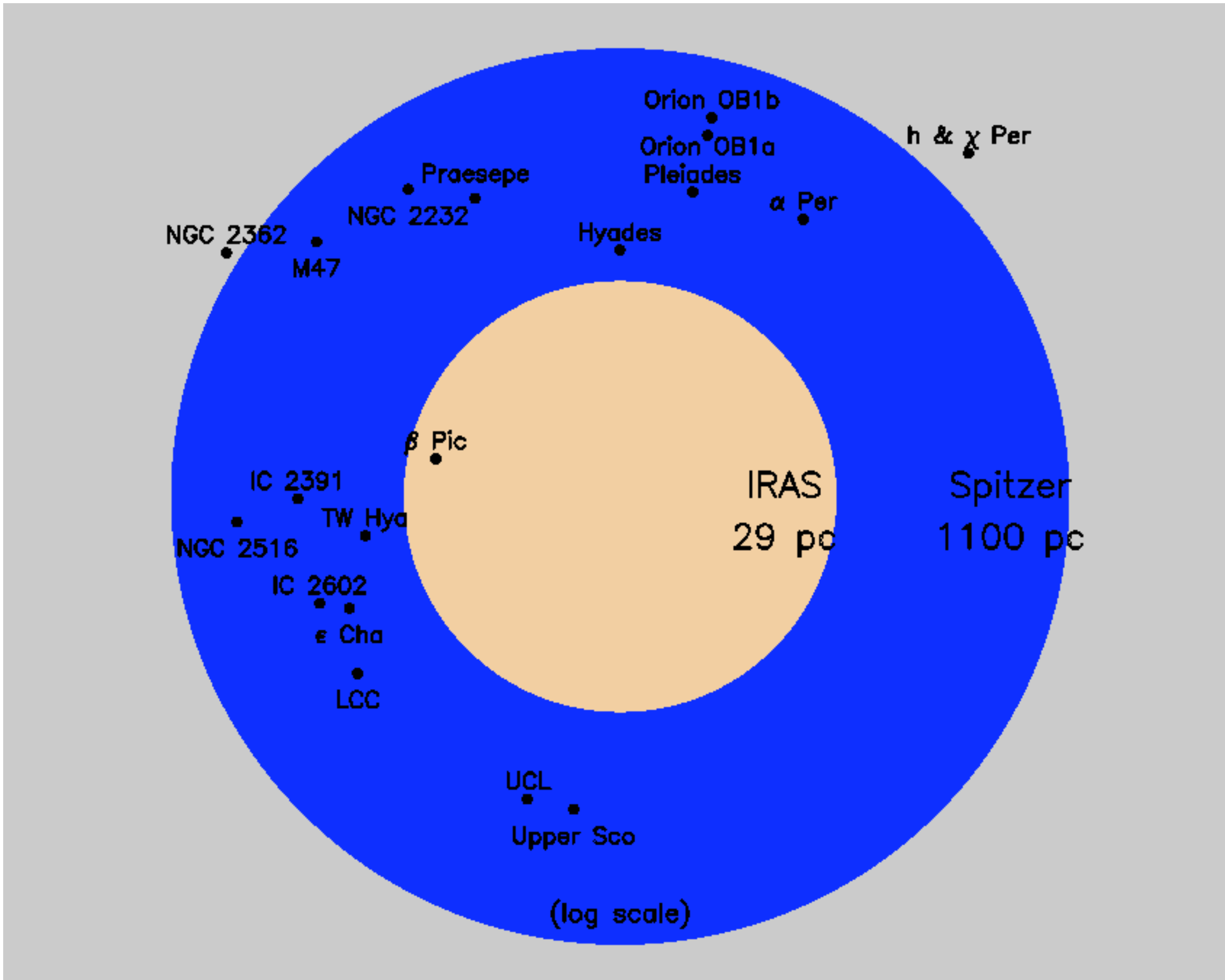
What is Needed from Measurements

- Sensitivity
- Precision as well as Accuracy
- Contrast (i.e. get rid of the central bright star)
- Attention to Stellar Parameters
  - age (not easy at all)
  - mass, luminosity (relatively straightforward)
  - some dependencies:
    - $T_{dust} \propto L_*^{1/4}$
    - $\beta = F_{rad} / F_{grav} \propto L_*(t)/ M_*$
    - grains ejected if $\beta > 0.5$

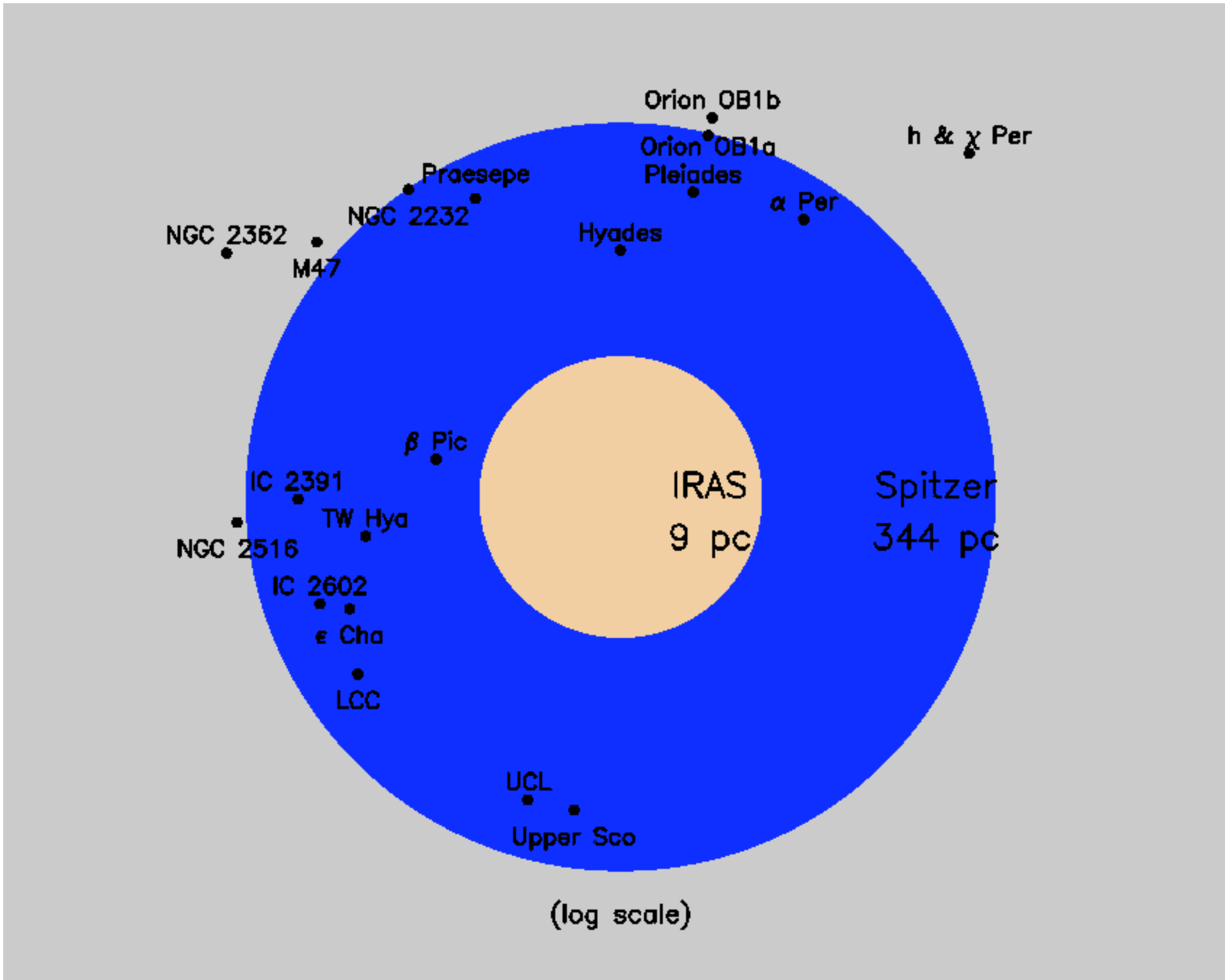
Sensitivity @ 24μm (A0 stars)



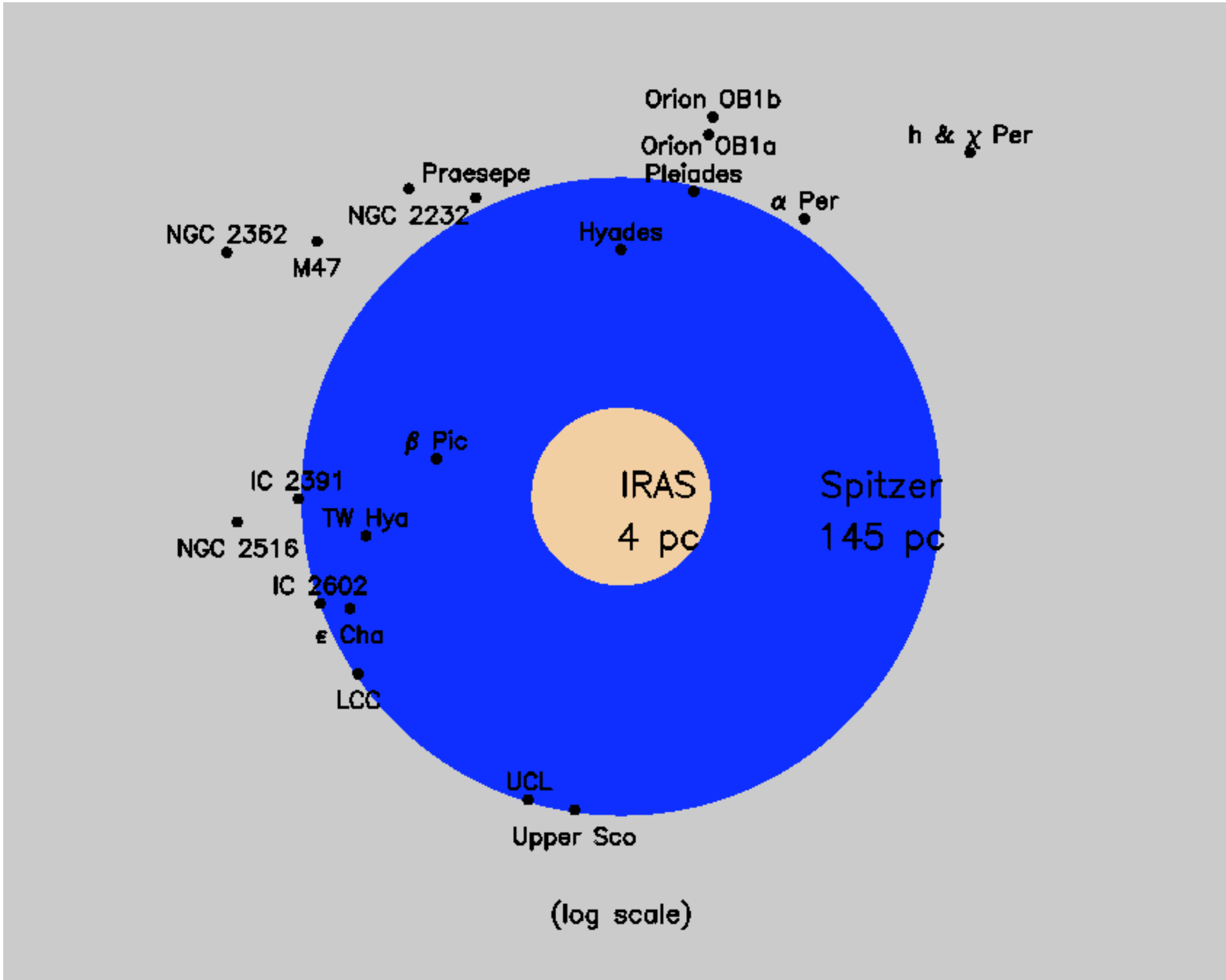
Sensitivity @ 24μm (A0 stars)



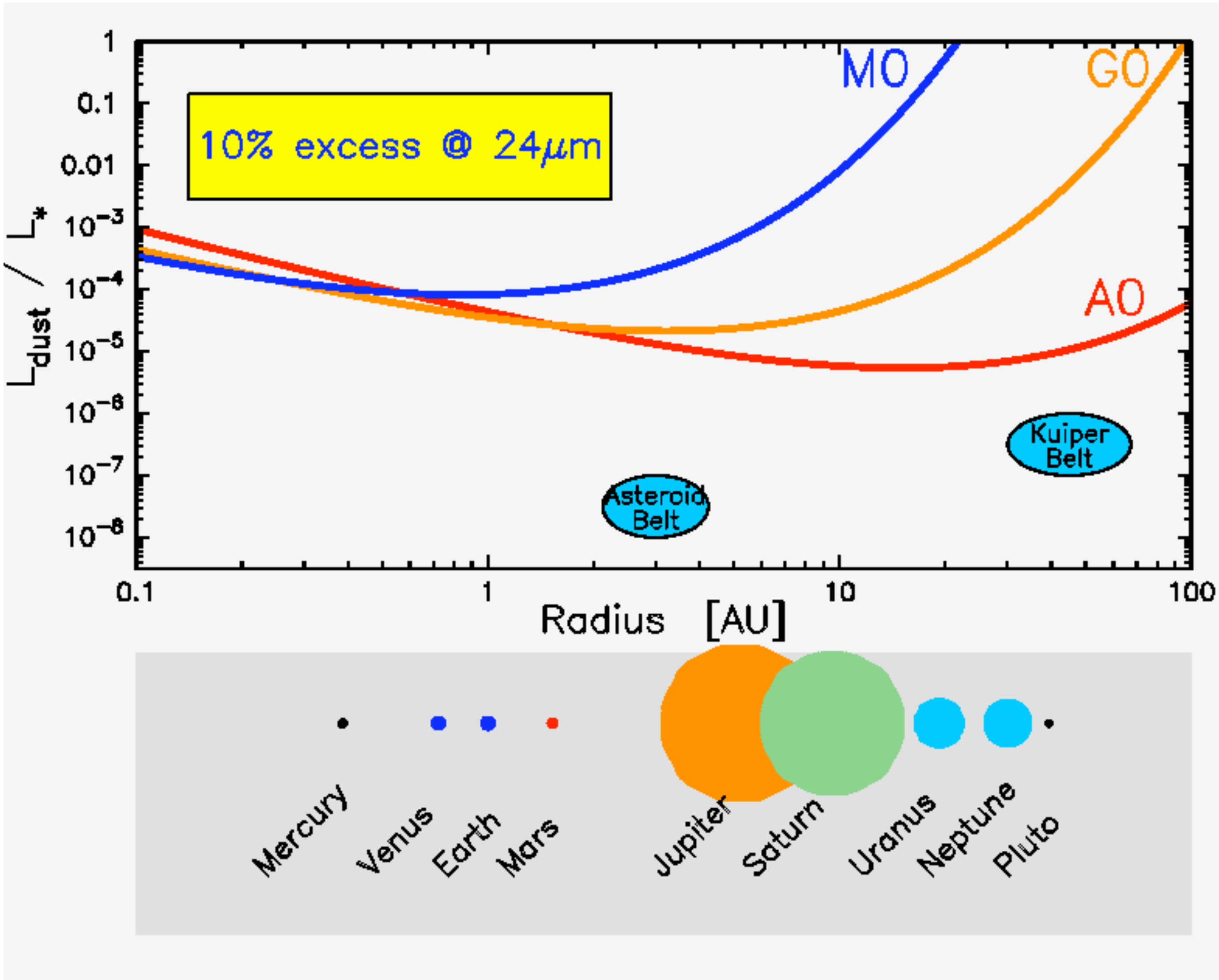
Sensitivity @ 24μm (G0 stars)



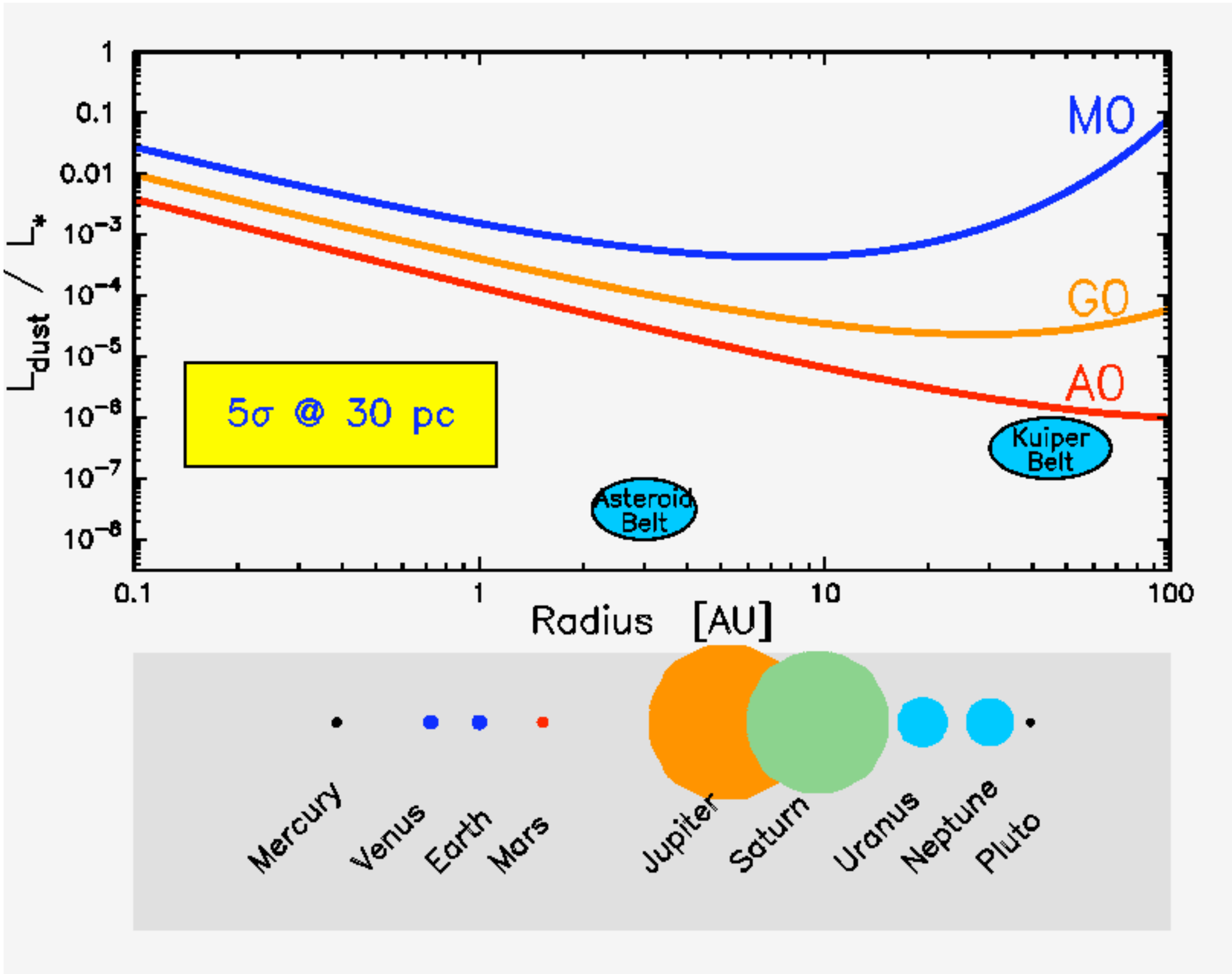
Sensitivity @ 24μm (M0 stars)



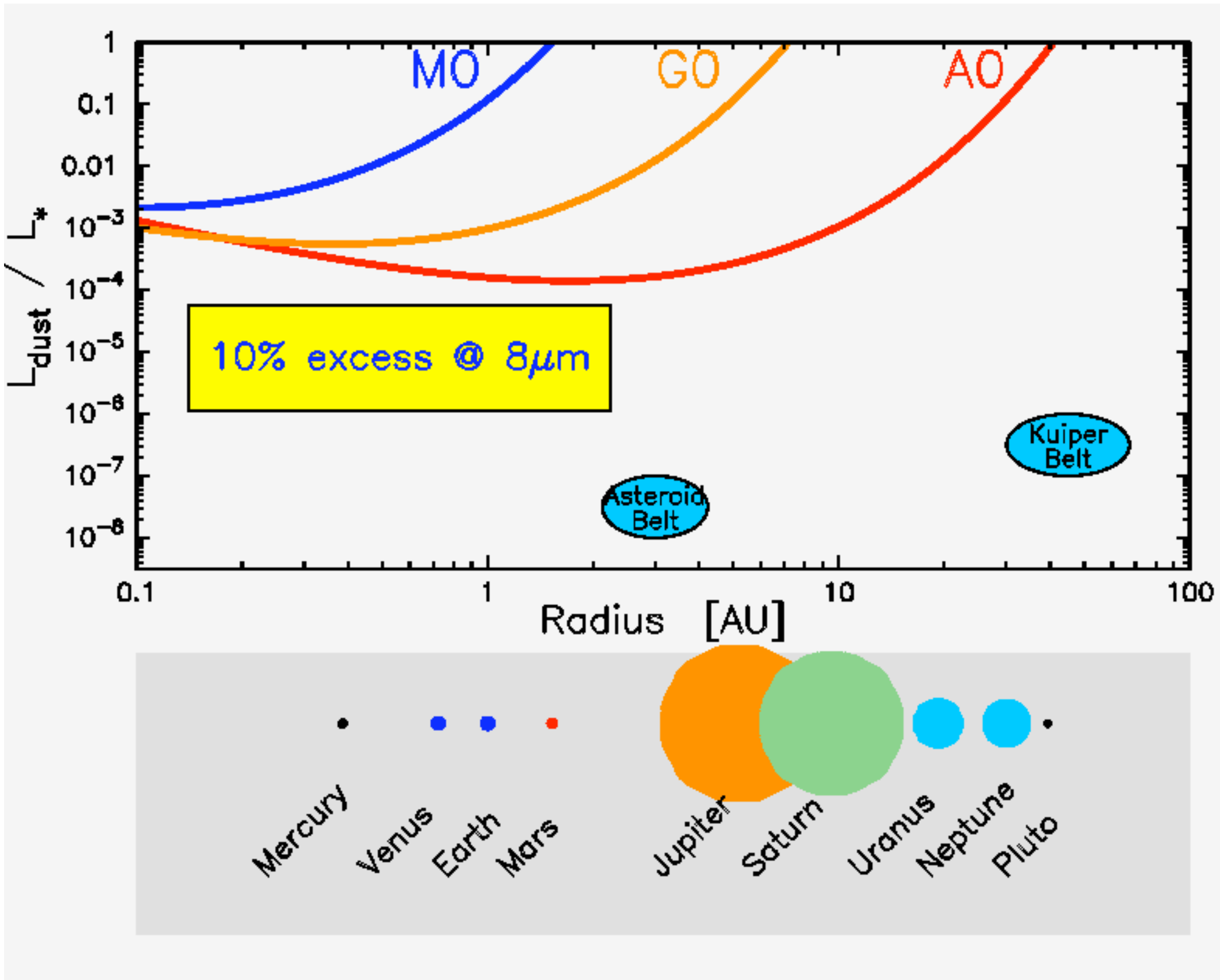
Spitzer Sensitivity to Debris: 24 μm



Spitzer Sensitivity to Debris: 70 μm

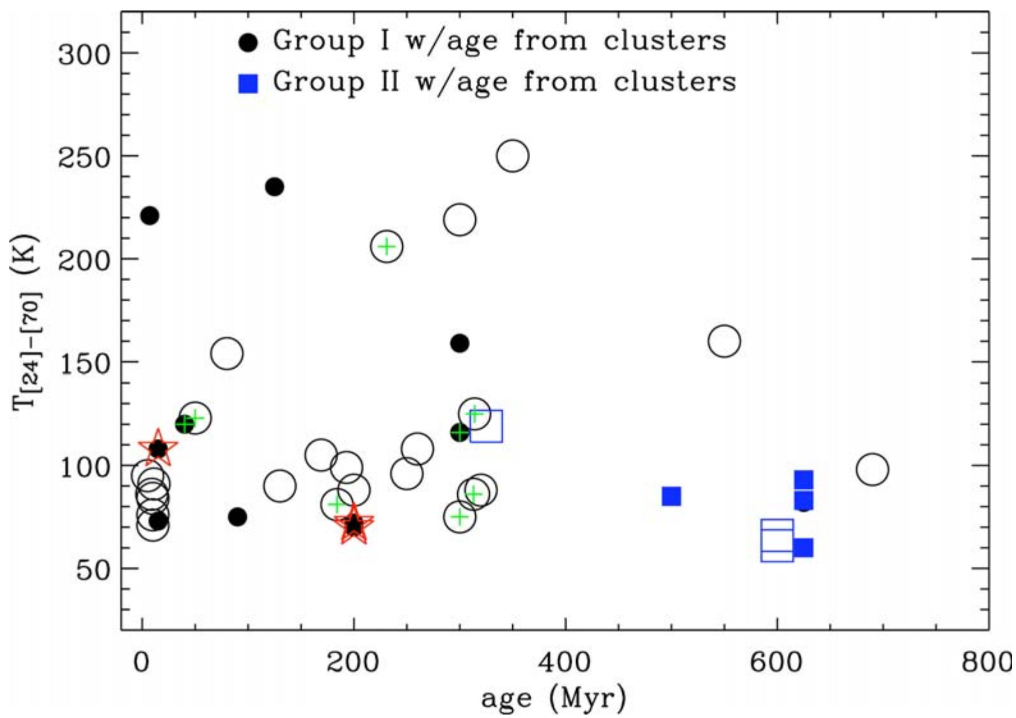


Spitzer Sensitivity to Debris: 8 µm



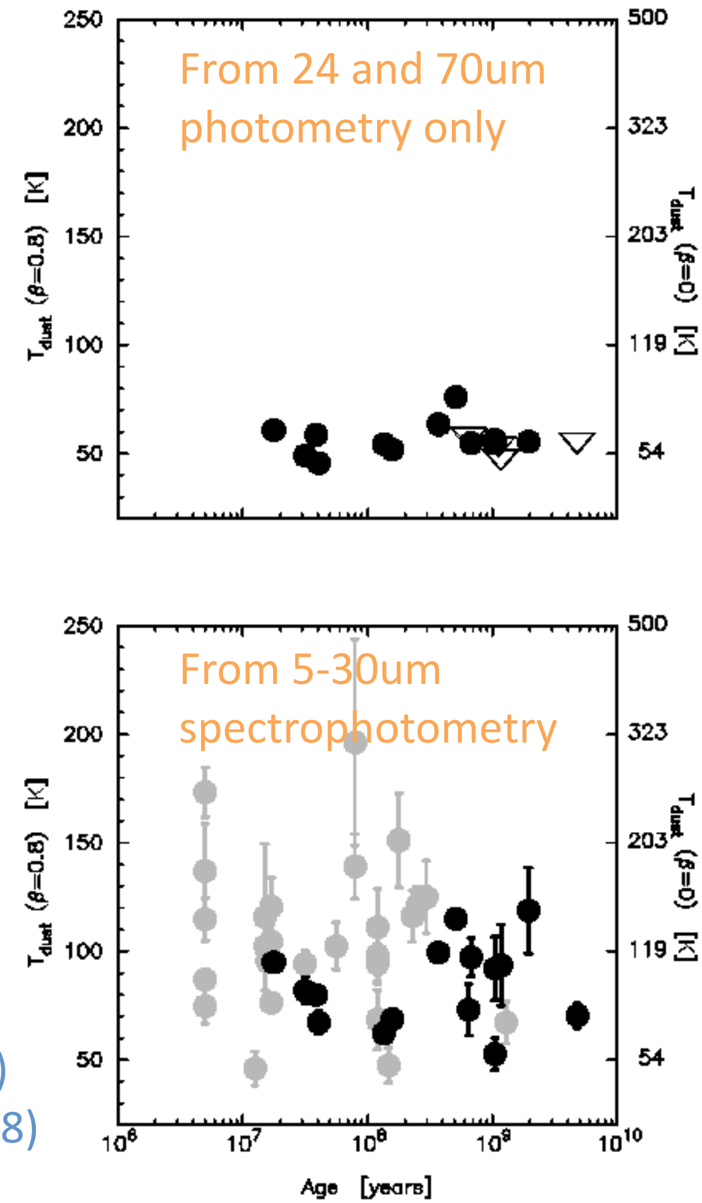
Dust temperatures inferred with Spitzer

A stars



Su et al. (2006)

G stars

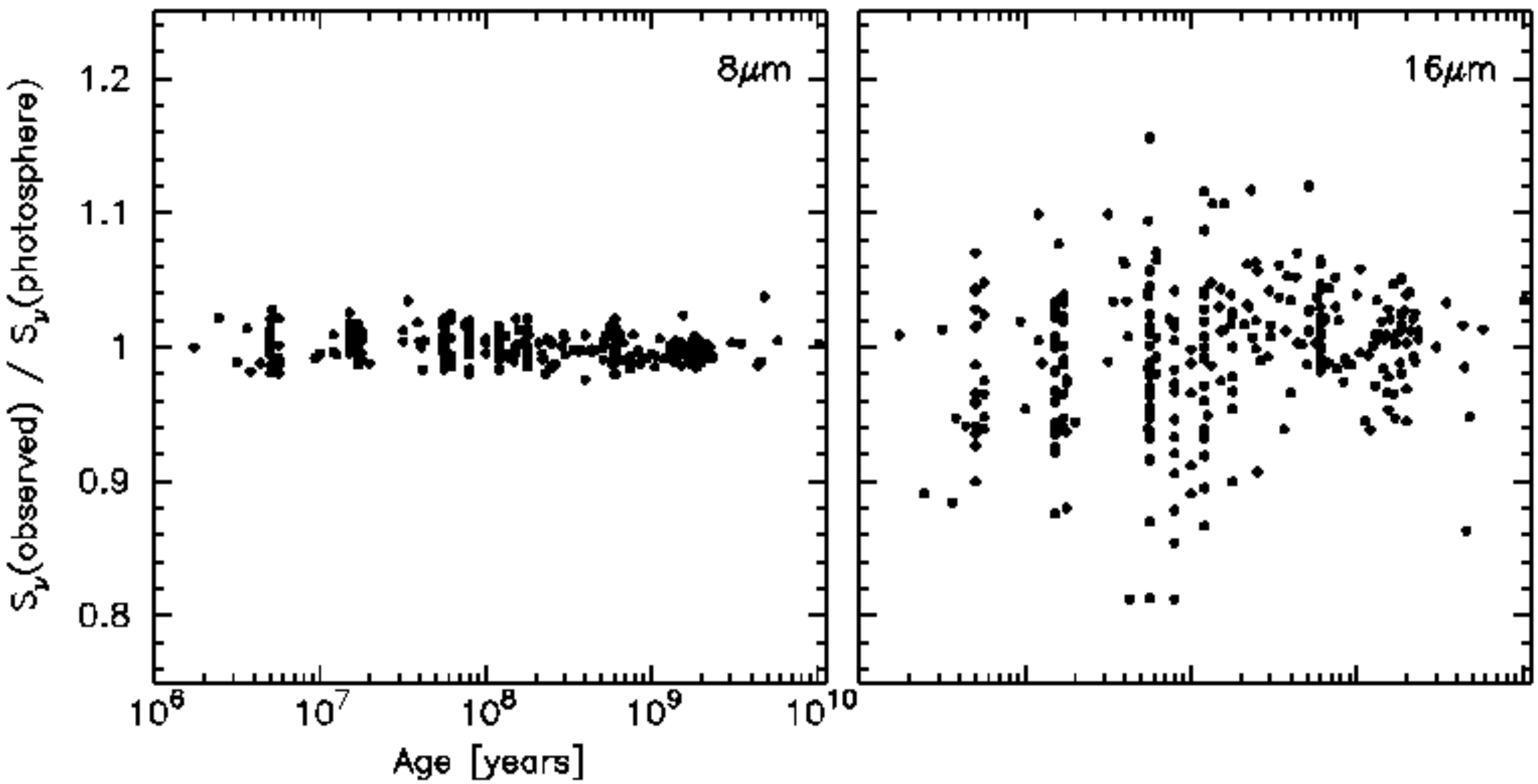


Carpenter et al. (2008)
Hillenbrand et al. (2008)

Warmer debris around solar type stars?

< 3% excess at 8μm

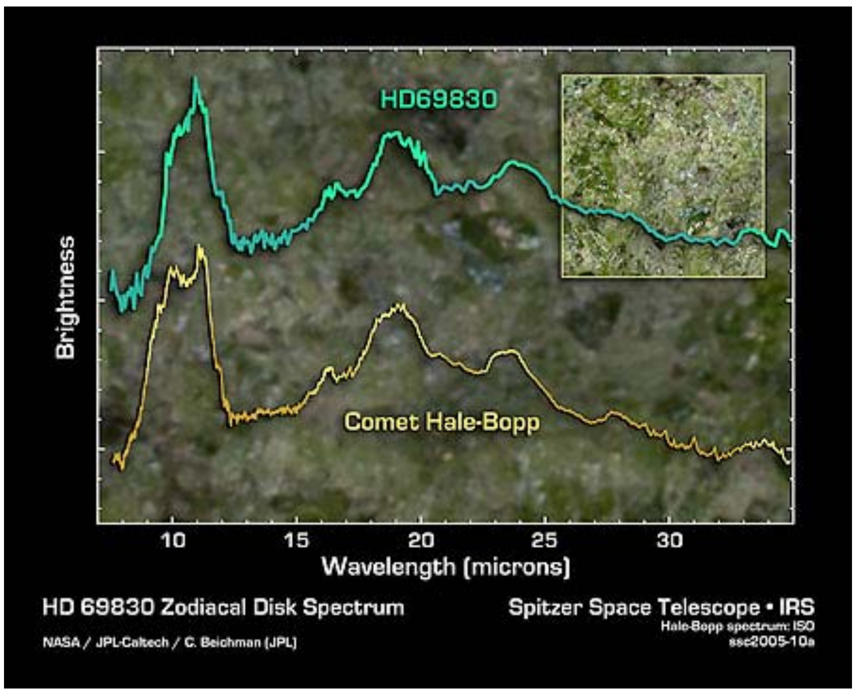
< 15% excess at 16μm



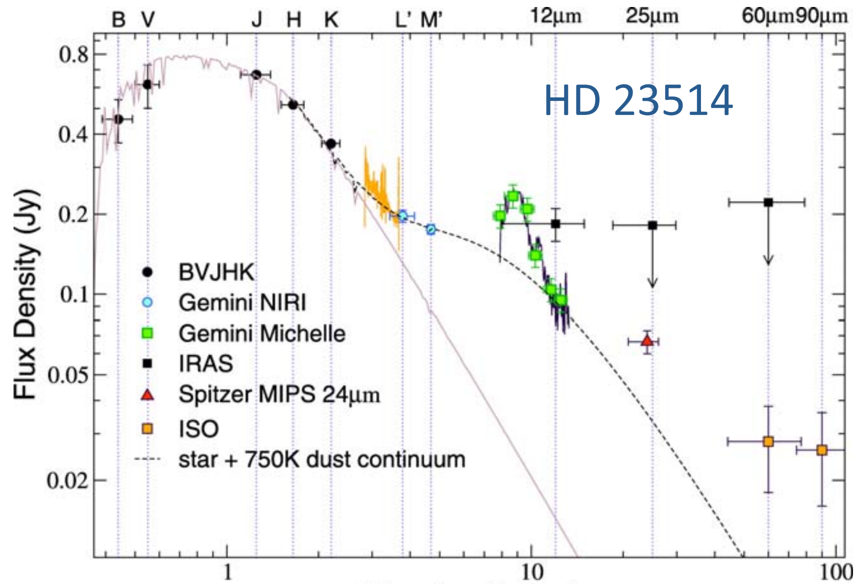
Carpenter et al. (2008)

Yes, indeed a few warm debris disks

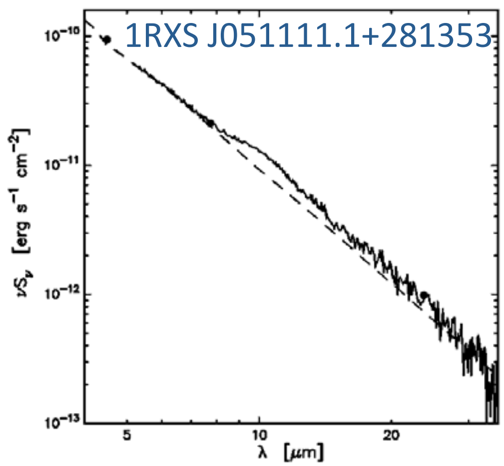
- ~ 300 K equiv to ~1 AU
- ~ 2.5% of > 1 Gyr solar type stars have warm dust
- limits: ~ 1400x zodiacal belt



Beichman et al. (2005)
(see also Lisse et al. 2007)

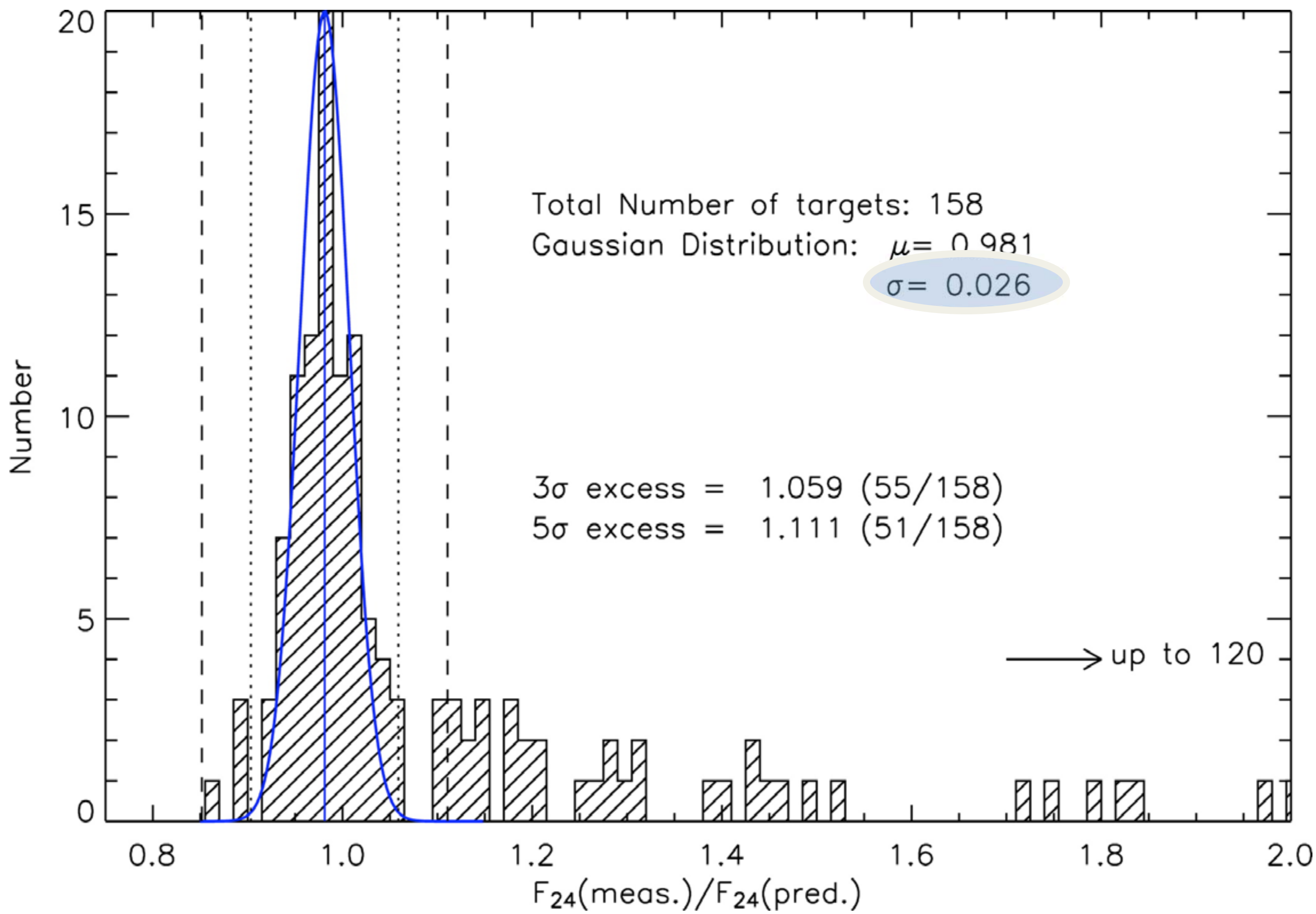


Rhee et al. (2008)



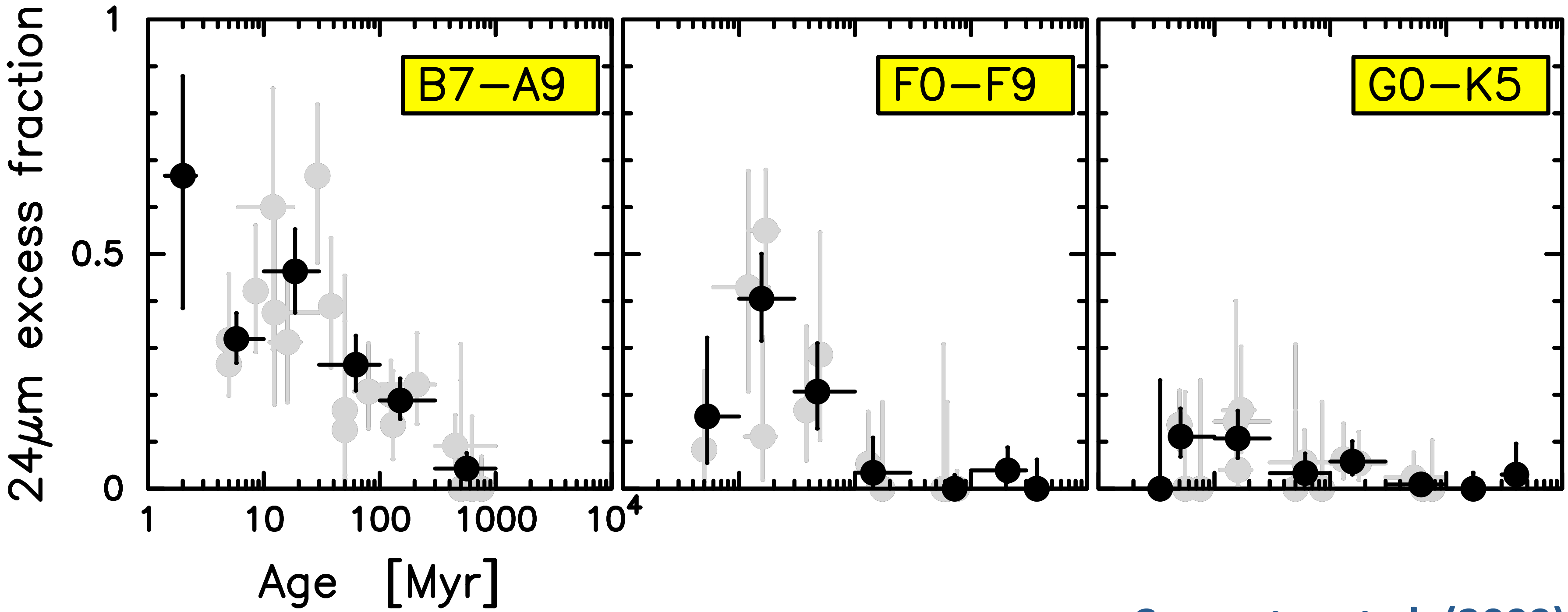
Carpenter et al. (2008)

Photometric Accuracy and Precision



Su et al. (2006)

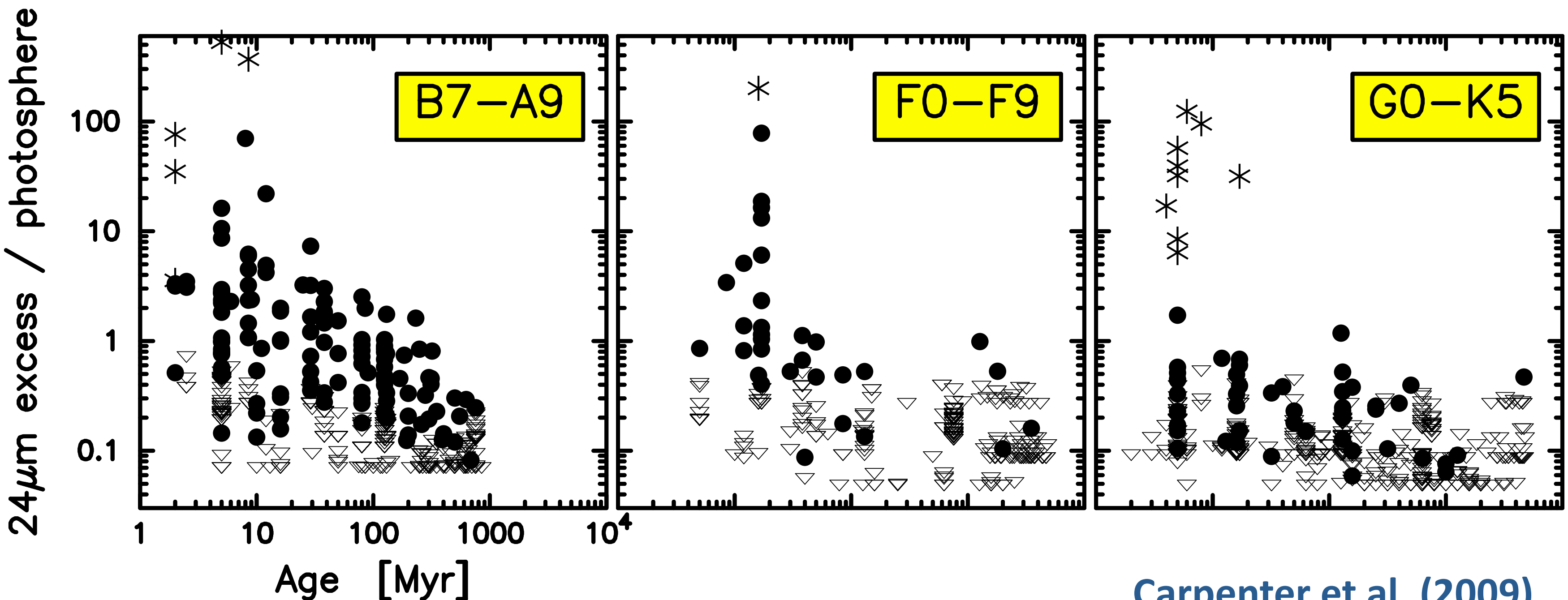
Fraction of stars with debris disks



Carpenter et al. (2009)

- Require > 32% excess
- For ages > 10 Myr disk fraction declines with age
- As for primordial disks, debris decline is mass-dependent

24µm excess vs. stellar age

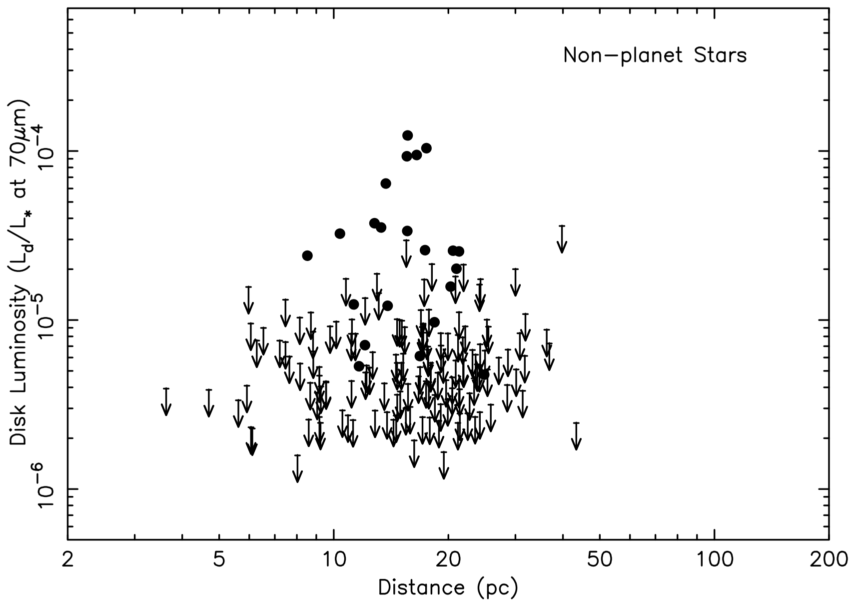


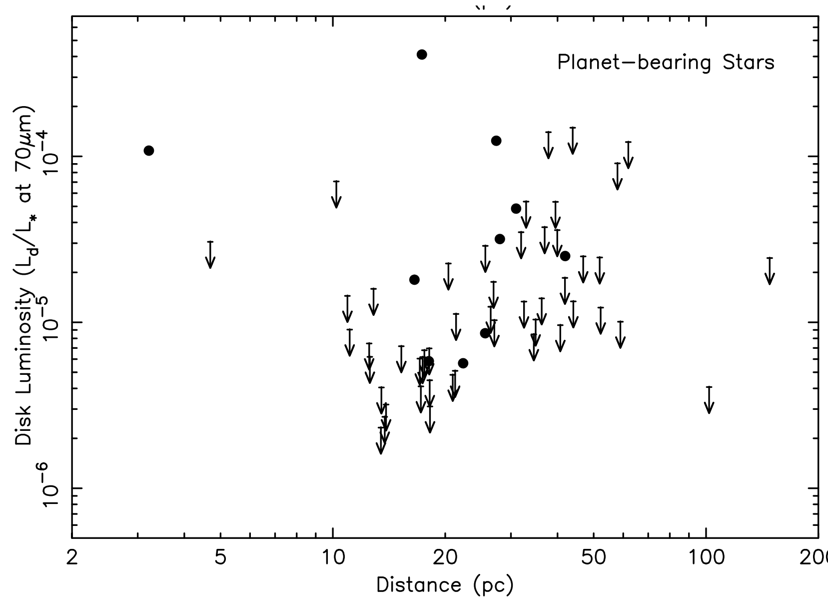
Carpenter et al. (2009)

- 2.6 sigma “peak” in 24um excess for F-type stars
- B/A/F/G stars: any trends < 2 sigma for ages < 20 Myr

=> No conclusive evidence for peak in debris production

Relation of Debris and Planets





Bryden et al. (2006, 2008)
Moro-Martín et al. (2007a,b)

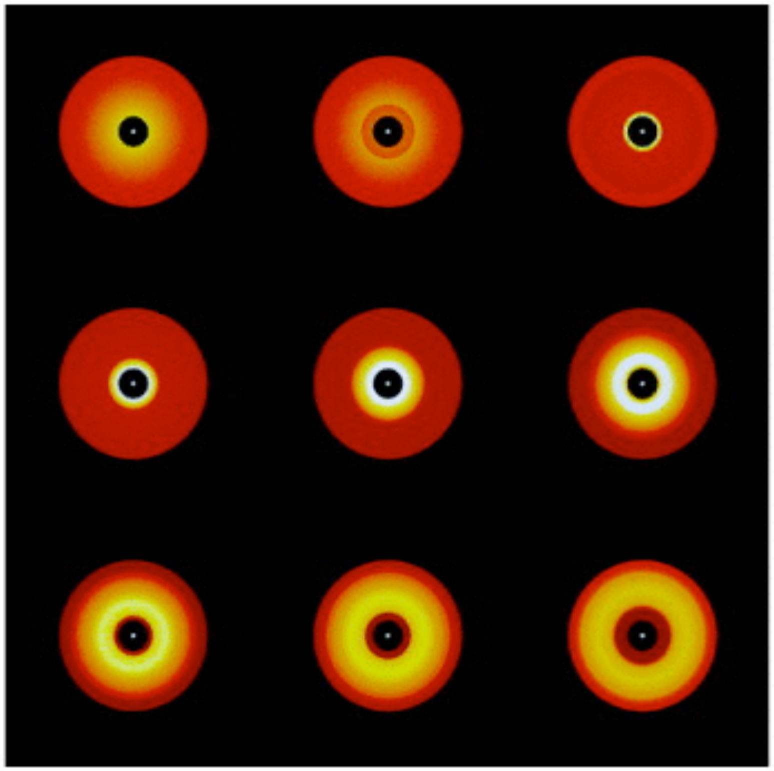
No strong correlation between (known) planets and (known) excess sources
BUT
Incompleteness and bias still dominate.

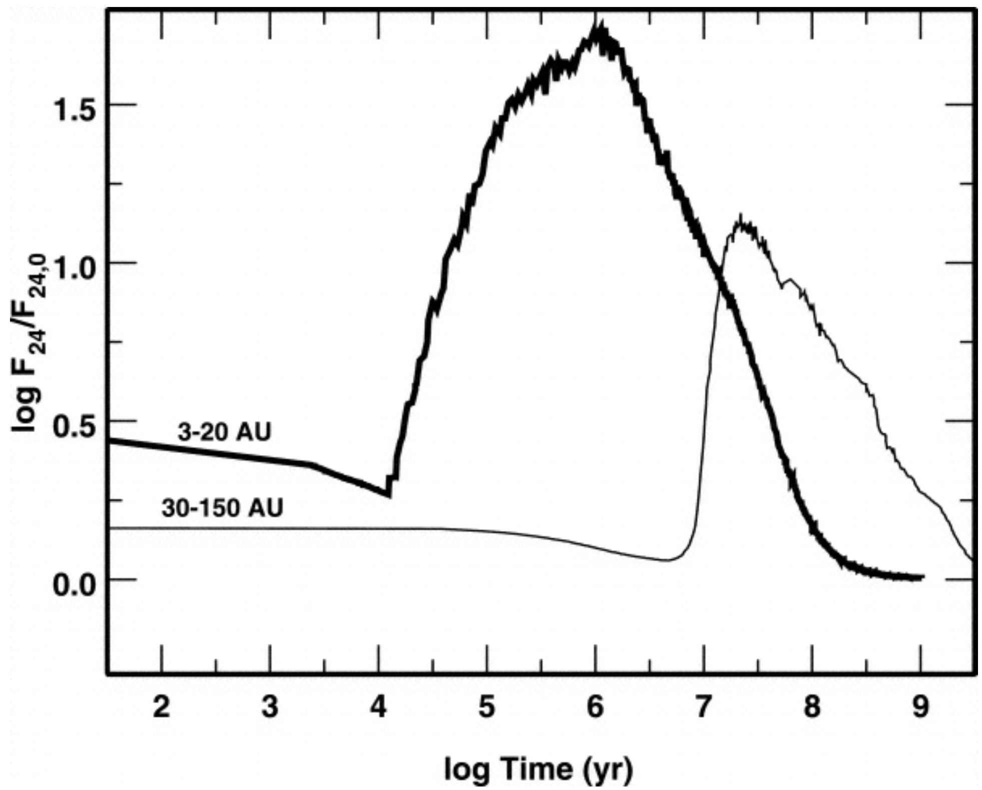
What can we learn from debris disks?

They are the sign posts of planets
(even if we haven't found them yet!)

What can we learn from debris disks?

Formation of planetary systems



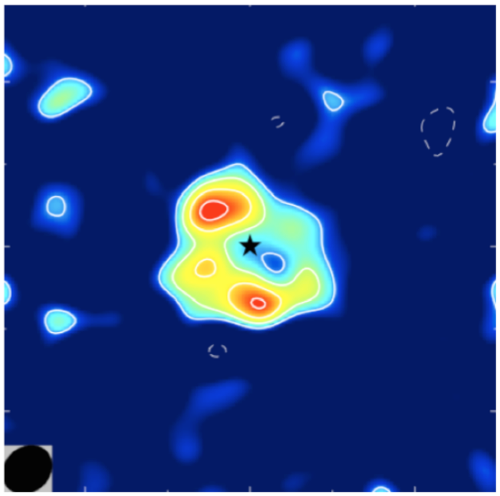
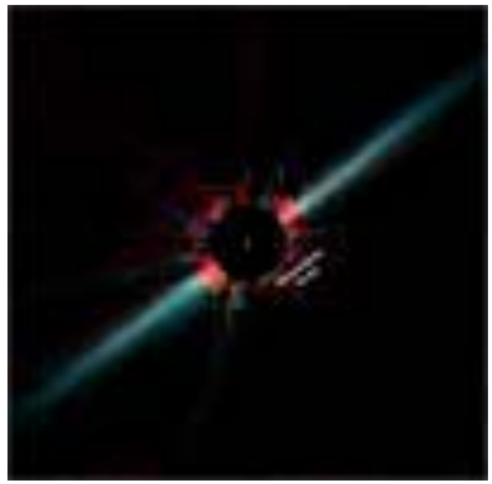
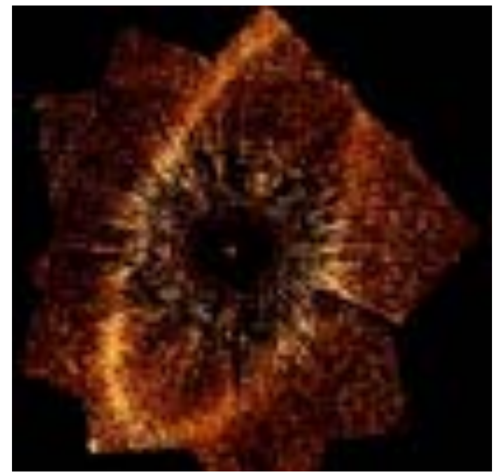
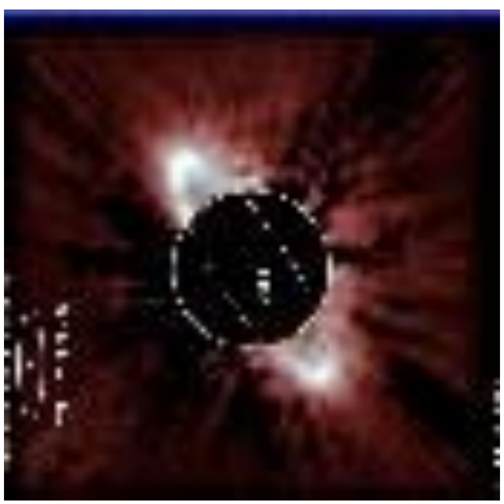
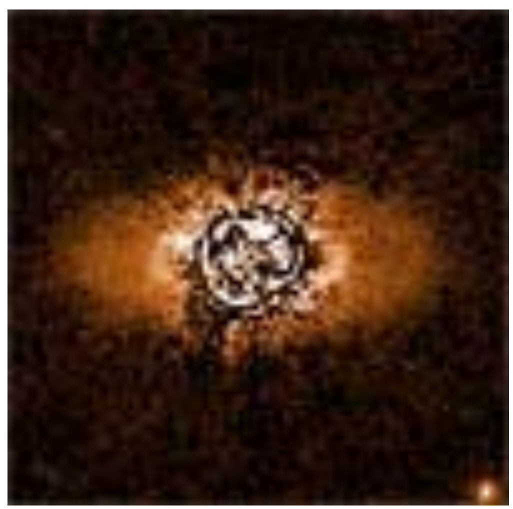
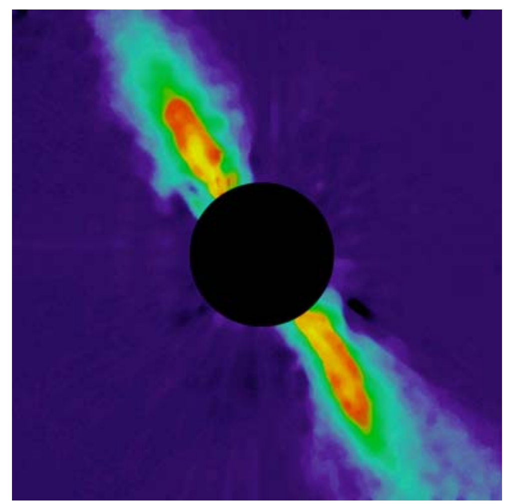


Kenyon & Bromley (2002)

Kenyon & Bromley (2005)

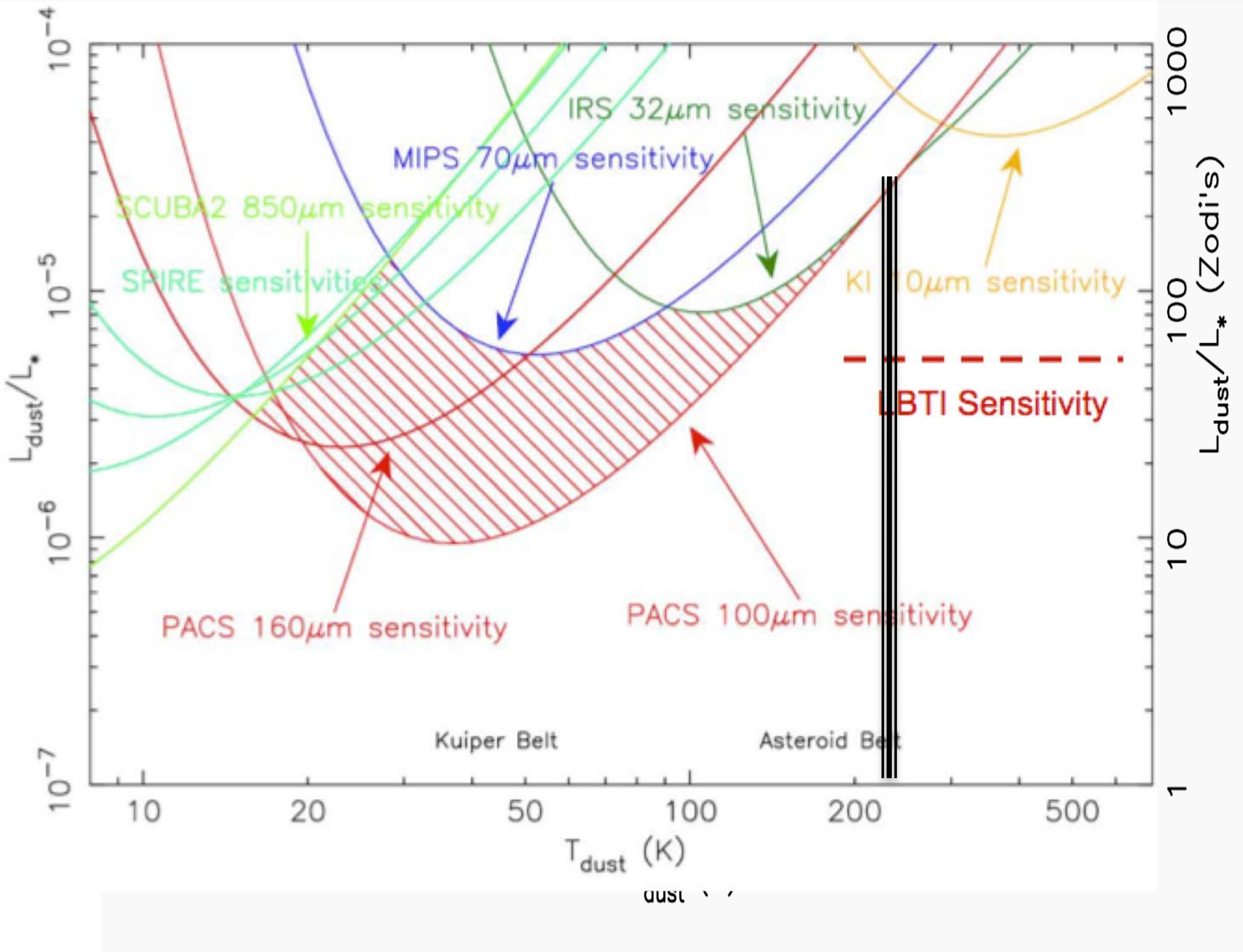
What can we learn from debris disks?

Diversity of mature planetary systems

Comparative Sensitivity Limits

- We are approaching KB dust levels.
- We do not yet know how to detect true zody dust!

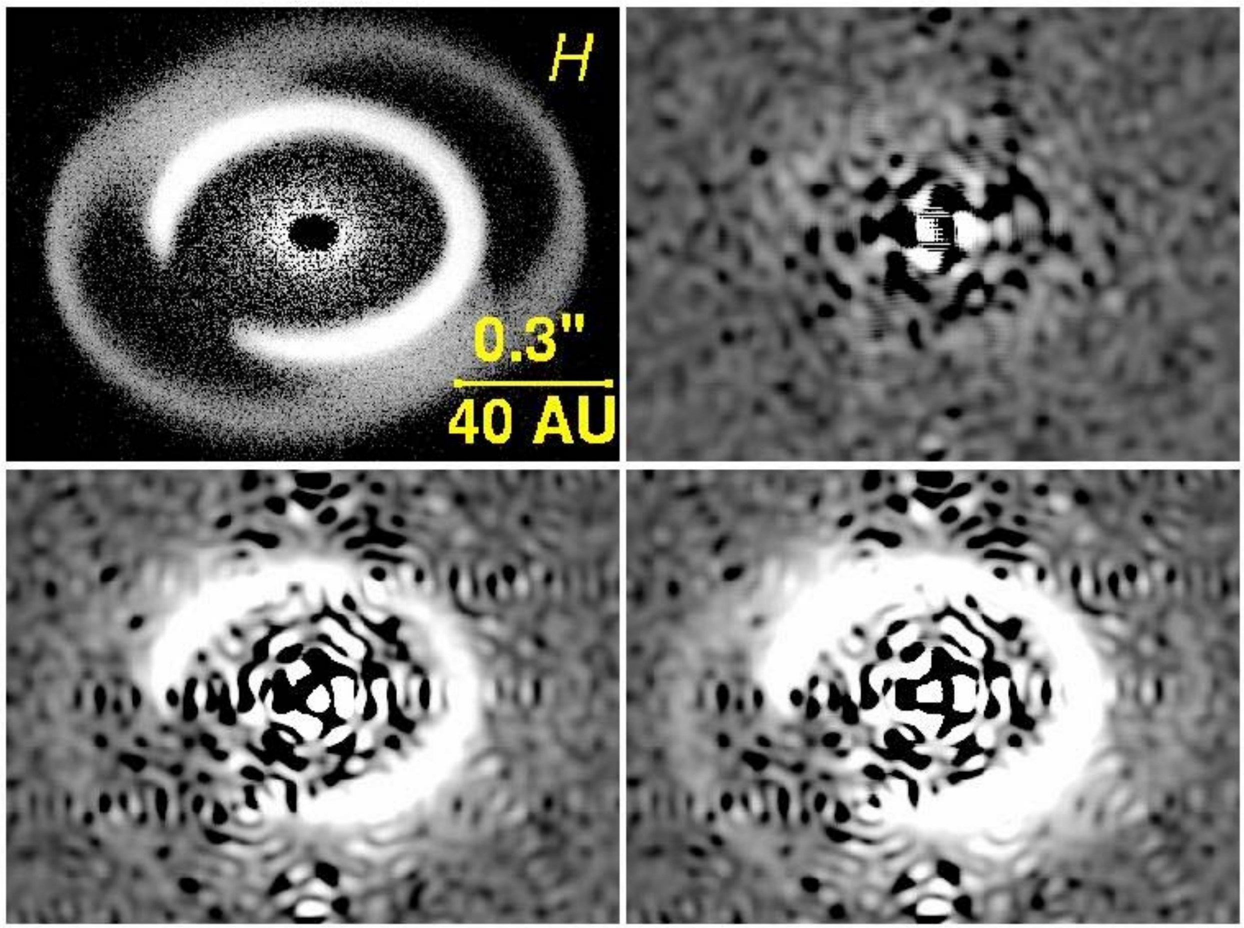


[figure courtesy Geoff Bryden (2007)]

Goal to Detect Forming/Young Planets

Simulations by Sebastian Wolf (2005)

$L_{IR}/L_* = 10^{-4}$ debris disk with embedded planet at $a = 40$ AU



S=27%
300nm r.m.s.
~today

S=82%
120nm r.m.s.

S=90%
90nm r.m.s.

(G2 star in the Pleiades)