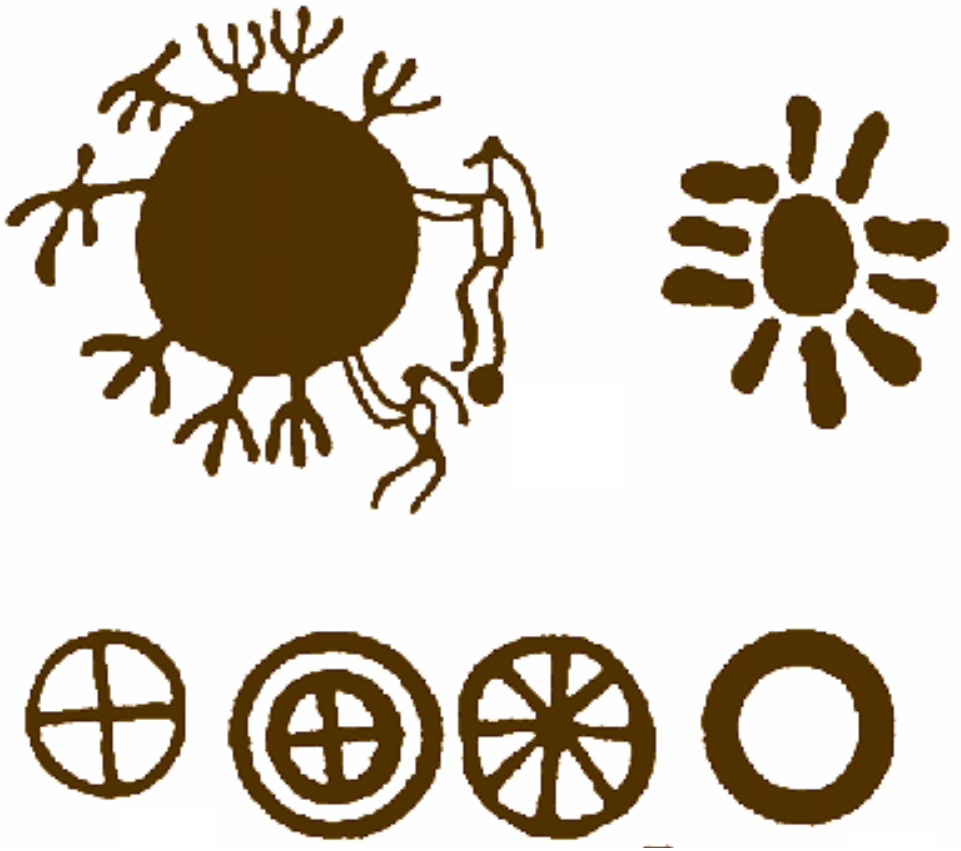
Planets, planetesimals and dust
Lessons from Spitzer



Amaya Moro-Martín
CAB (CSIC-INTA)

These dust disks (a.k.a debris disks) host planetary systems

Dust is not primordial but is replenished by planetesimals (like asteroids, comets and KBOs).

Dust Removal Time Scales $< 10^4$-10^6 yr

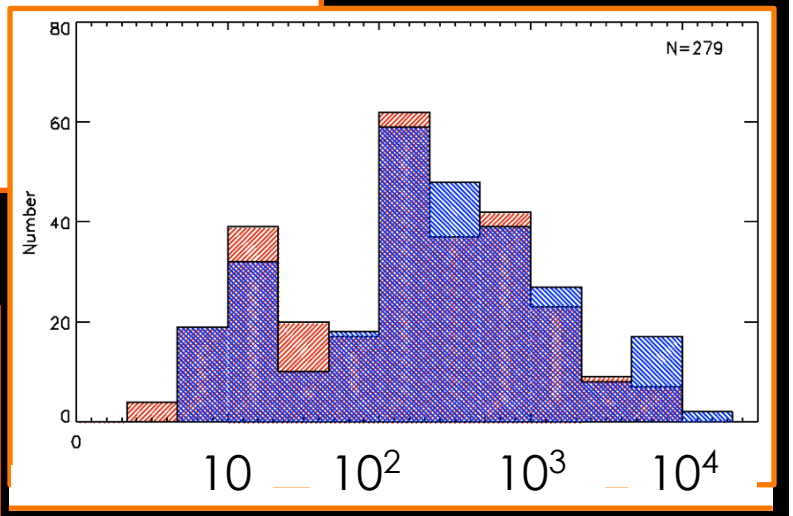
Poynting-Robertson: $t_{PR} = 710(\frac{b}{\mu m})(\frac{\rho}{g/cm^3})(\frac{R}{AU})^2(\frac{L_\odot}{L_*})\frac{1}{1+albedo}\ yr,$

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

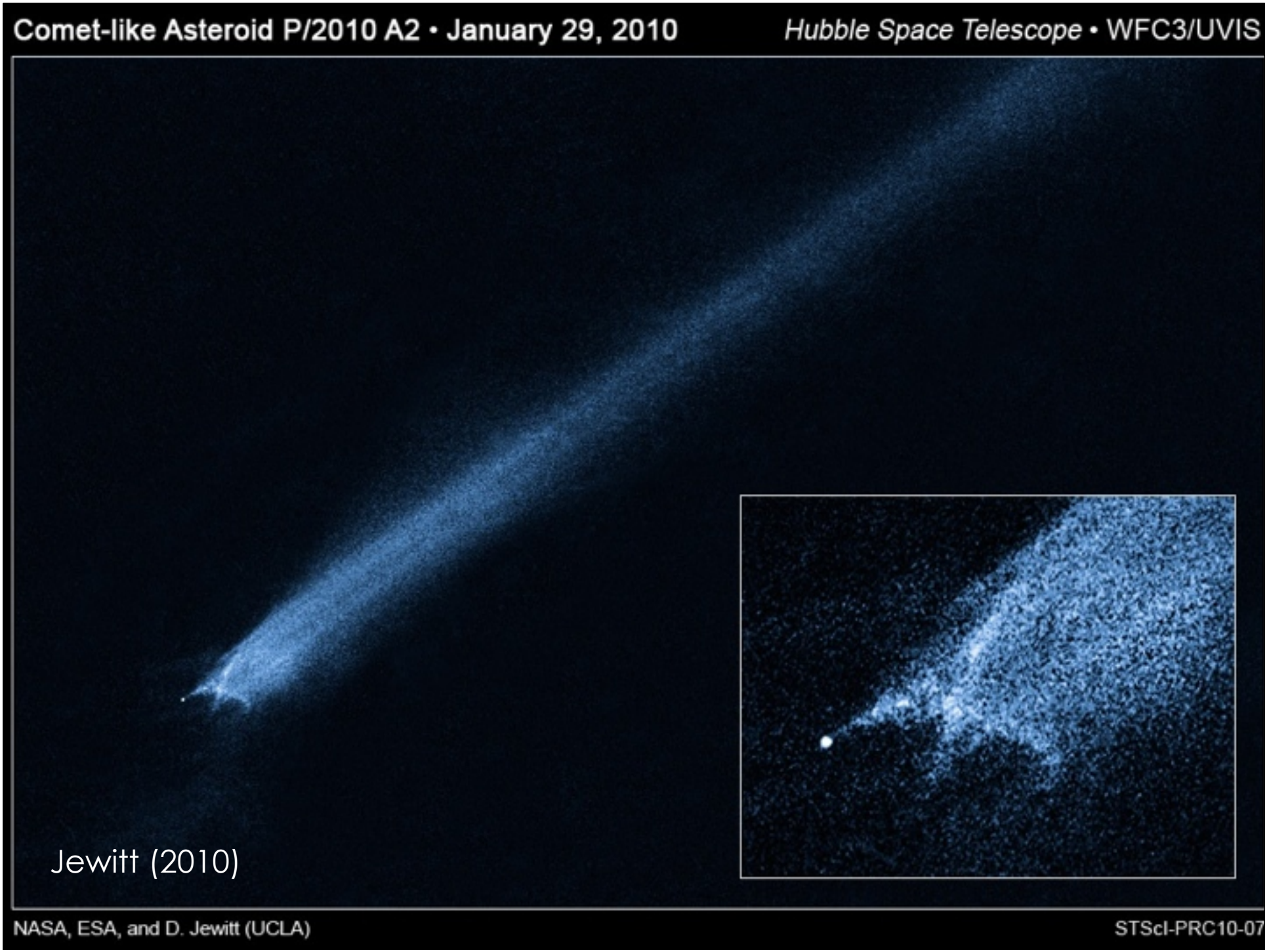
Radiation Pressure: $\frac{\tau_{blowout}}{\mathrm{yr}} = 0.5\sqrt{\frac{(R/AU)^3}{(M_*/M_\odot)}}.$

<< Stellar age > 10^7 yrs

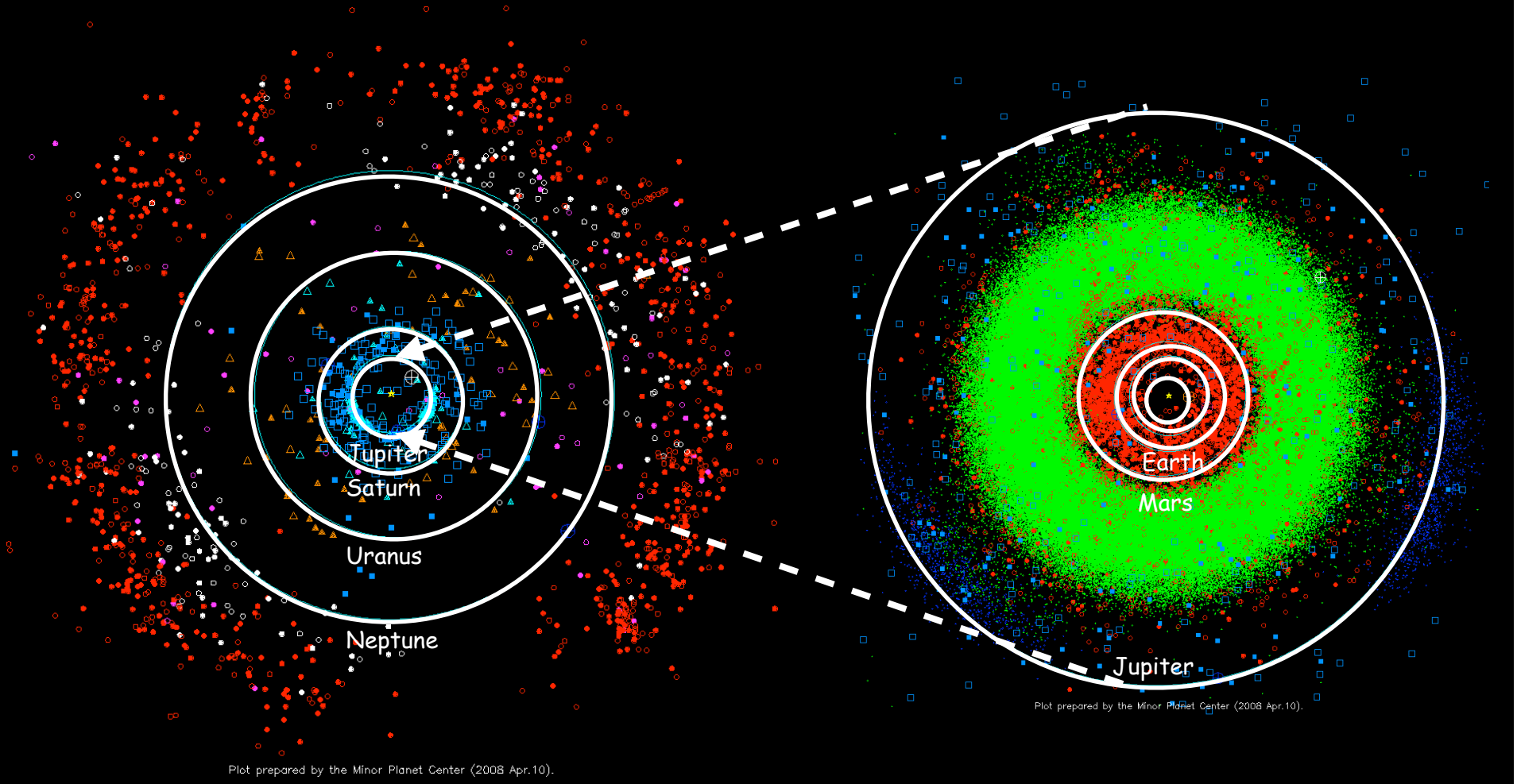
Debris disks are indirect evidence that the first steps of planet formation have taken place



Stellar Age (Myr)


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

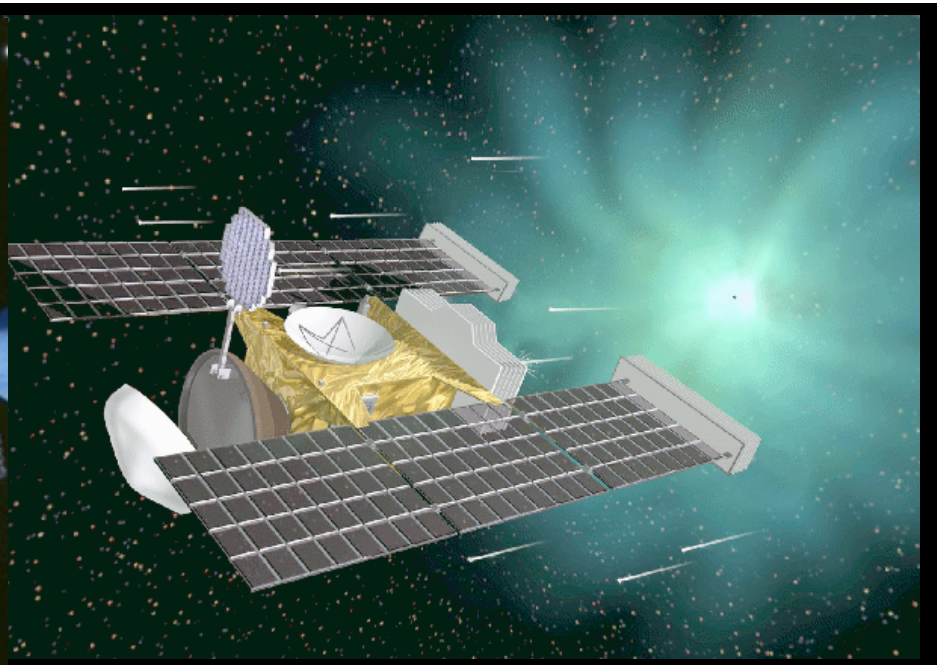
Sources of Solar System Dust



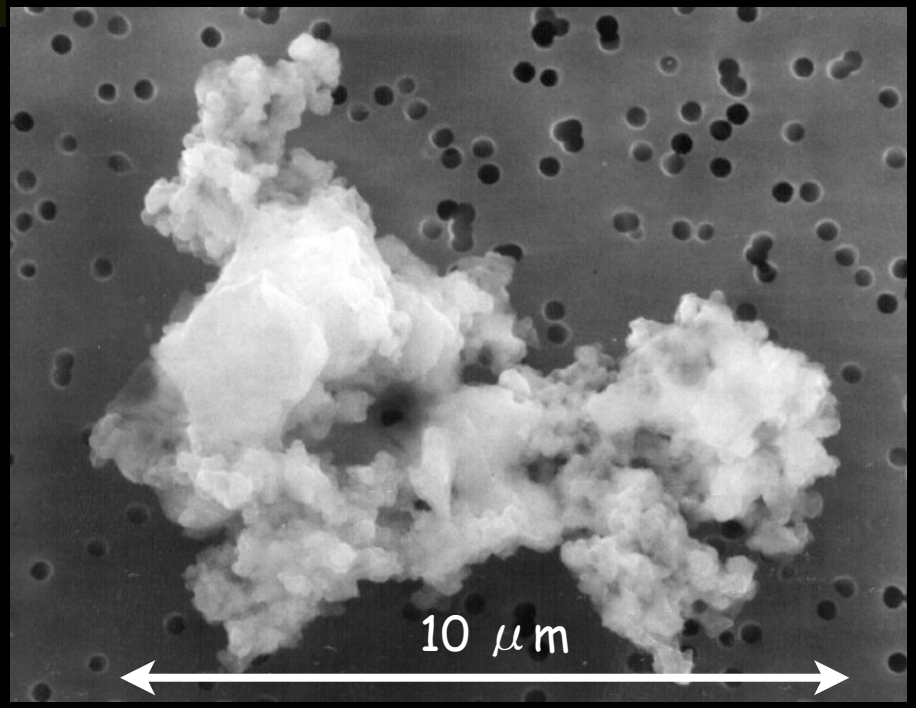
Kuiper Belt

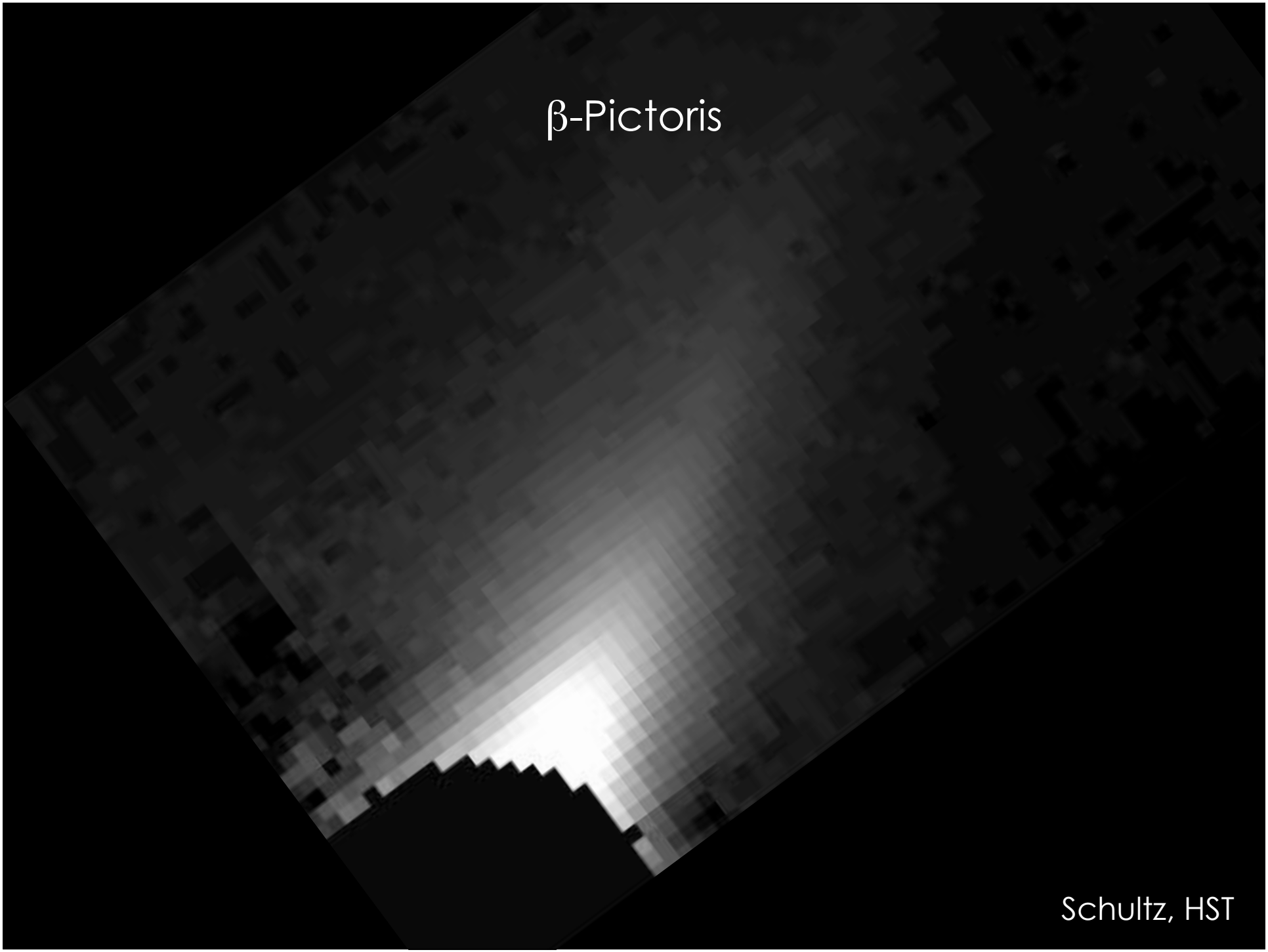
Asteroid Belt

Minor Planet Center

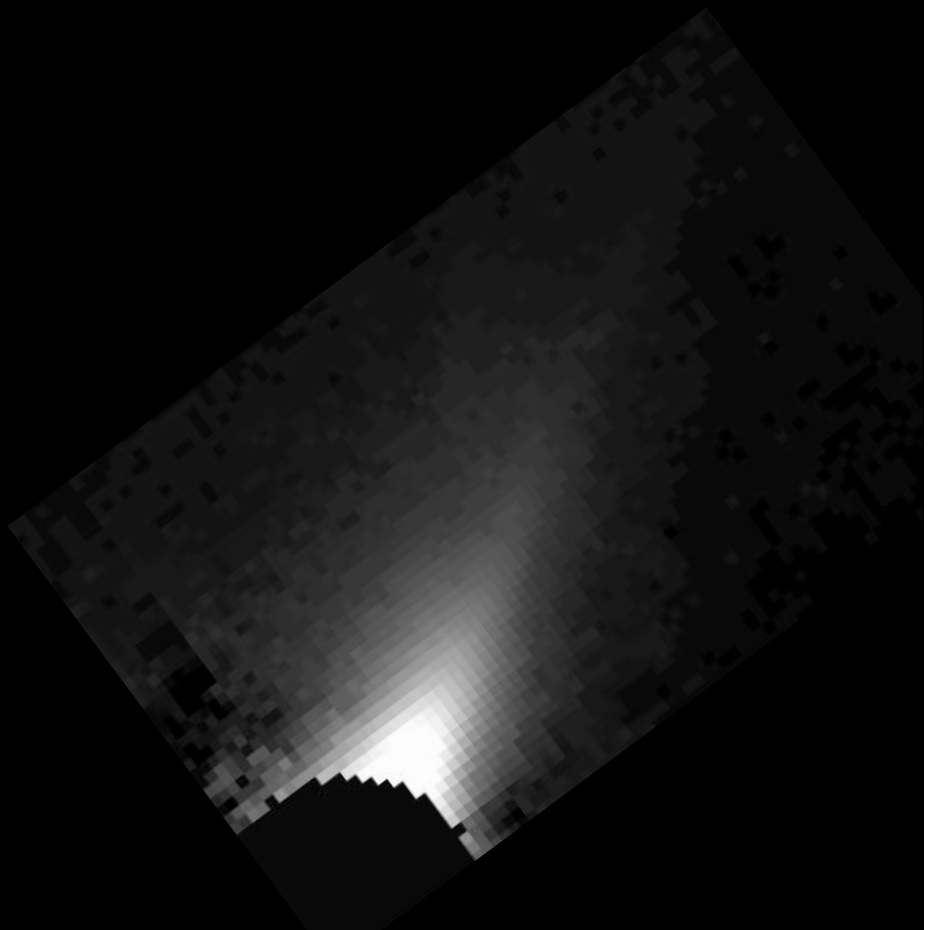



dust
particle


10 μm


β-Pictoris
Schultz, HST

solar



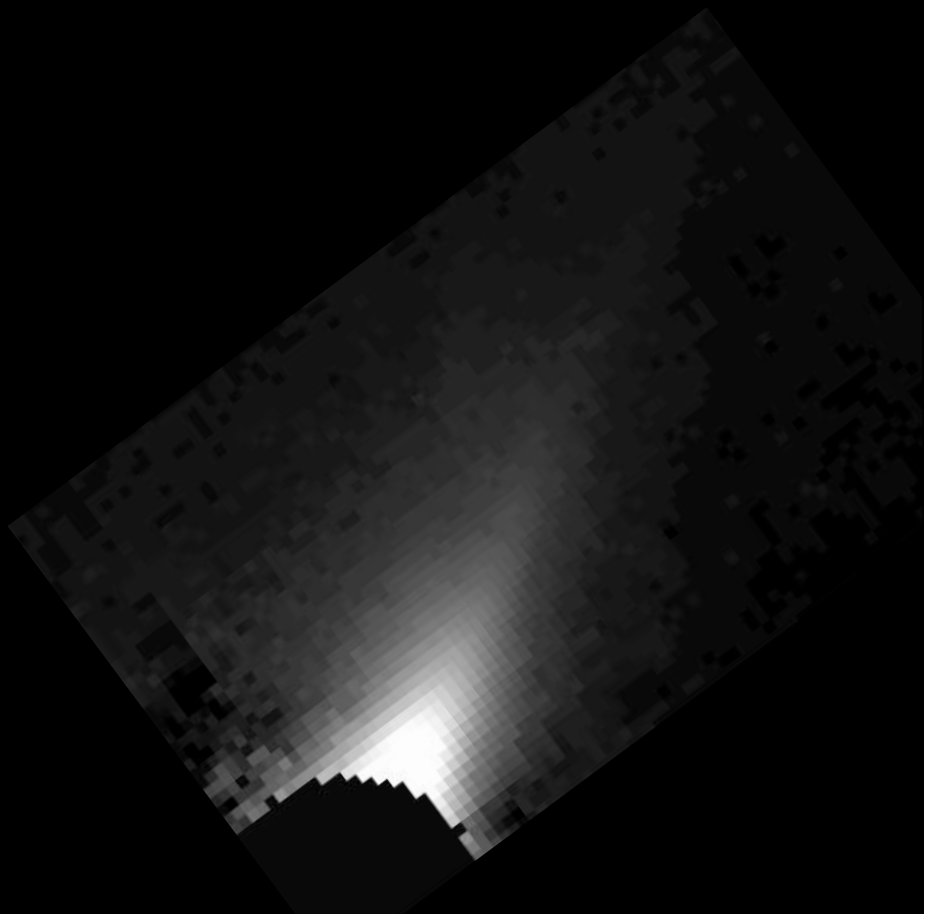
extra- solar

Pre-Herschel...

(1) Most disks have high dust content

(2) Most disks are spatially unresolved

solar



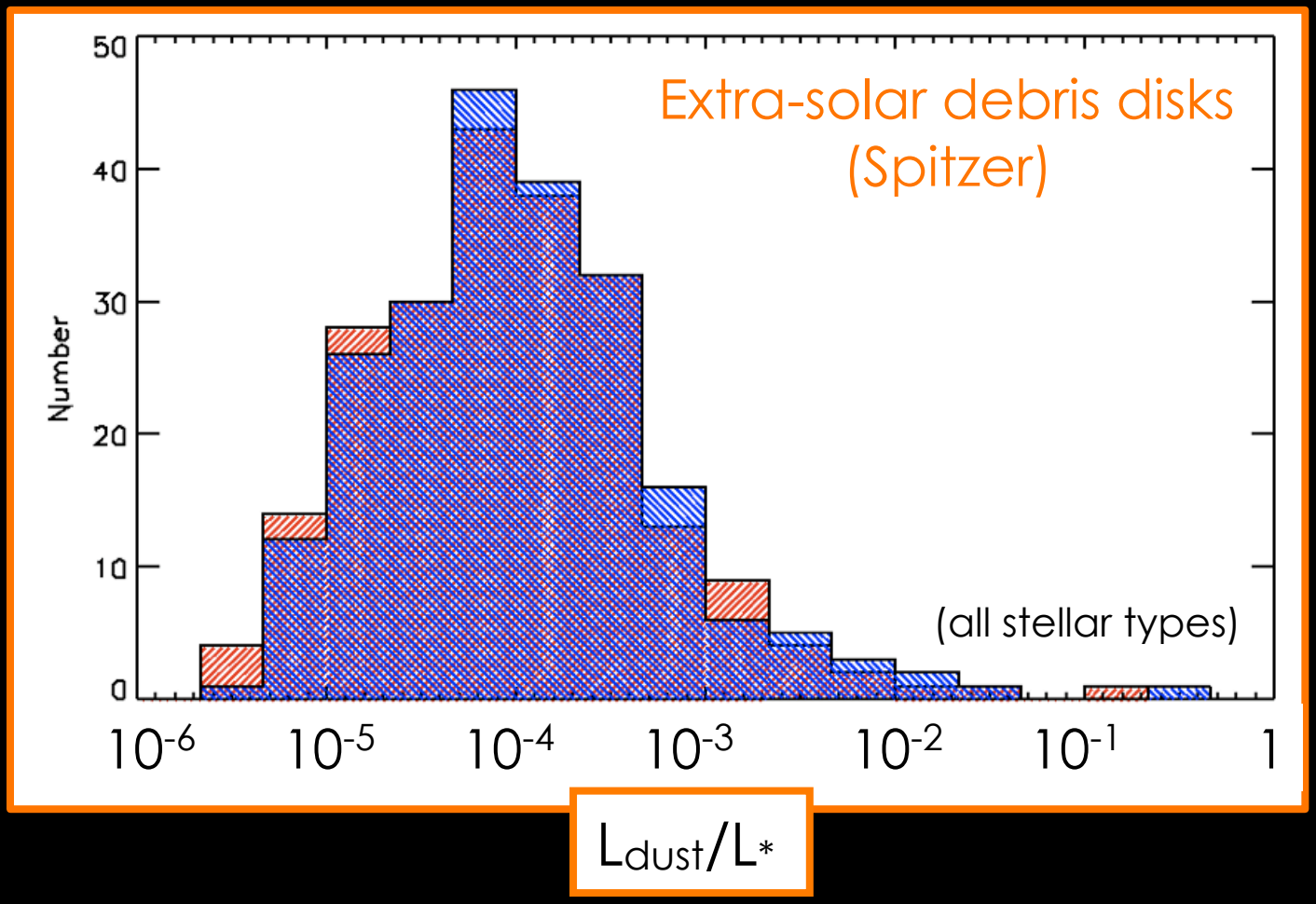
extra- solar

(1) Pre-Herschel: most disks have high dust content

Solar System debris disk:

Kuiper Belt dust: $L_{dust}/L_* \sim 10^{-7}$-$10^{-6}$

Asteroid Belt dust: $L_{dust}/L_* \sim 10^{-8}$-$10^{-7}$



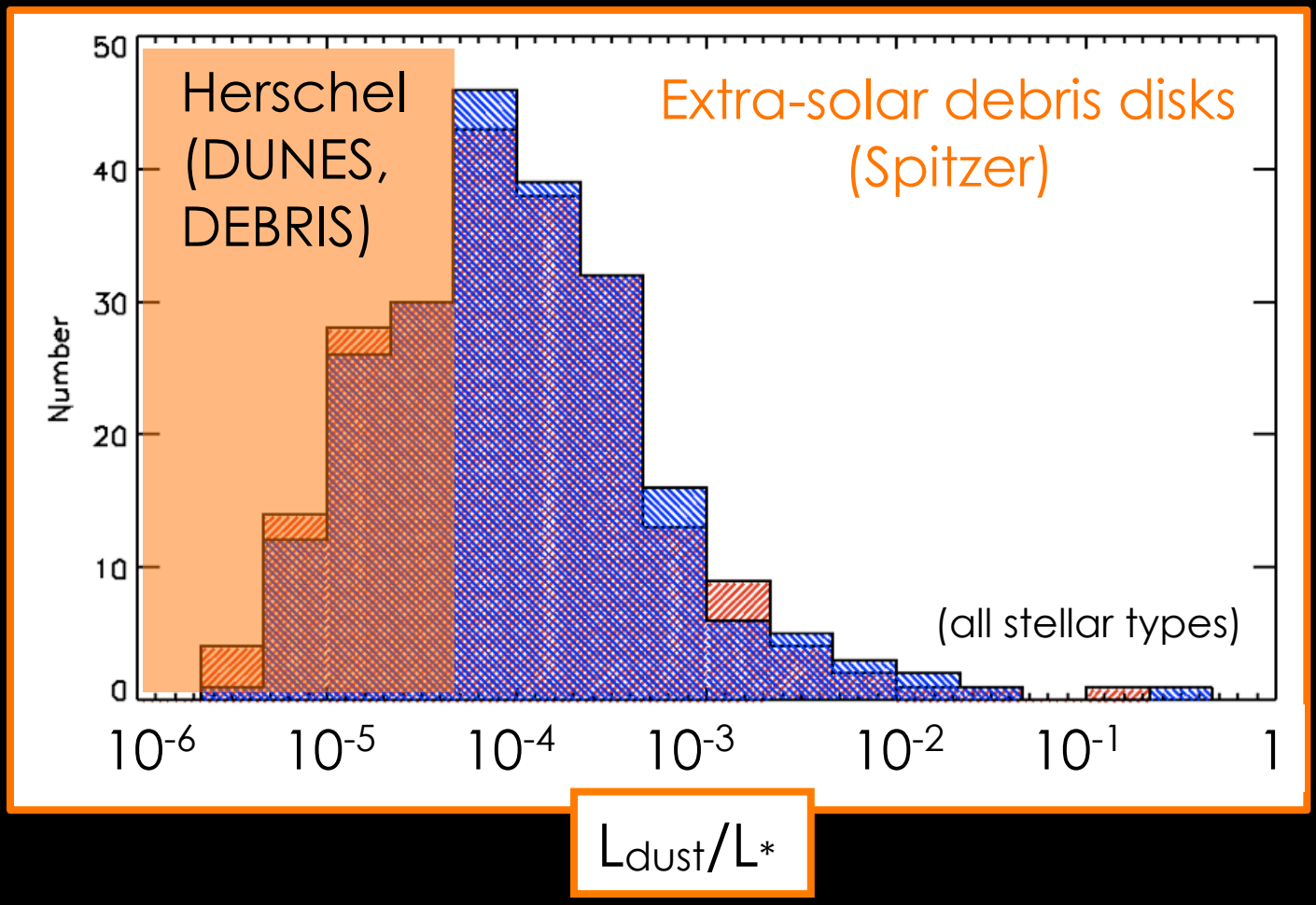
(1) Pre-Herschel: most disks have high dust content

Solar System debris disks:

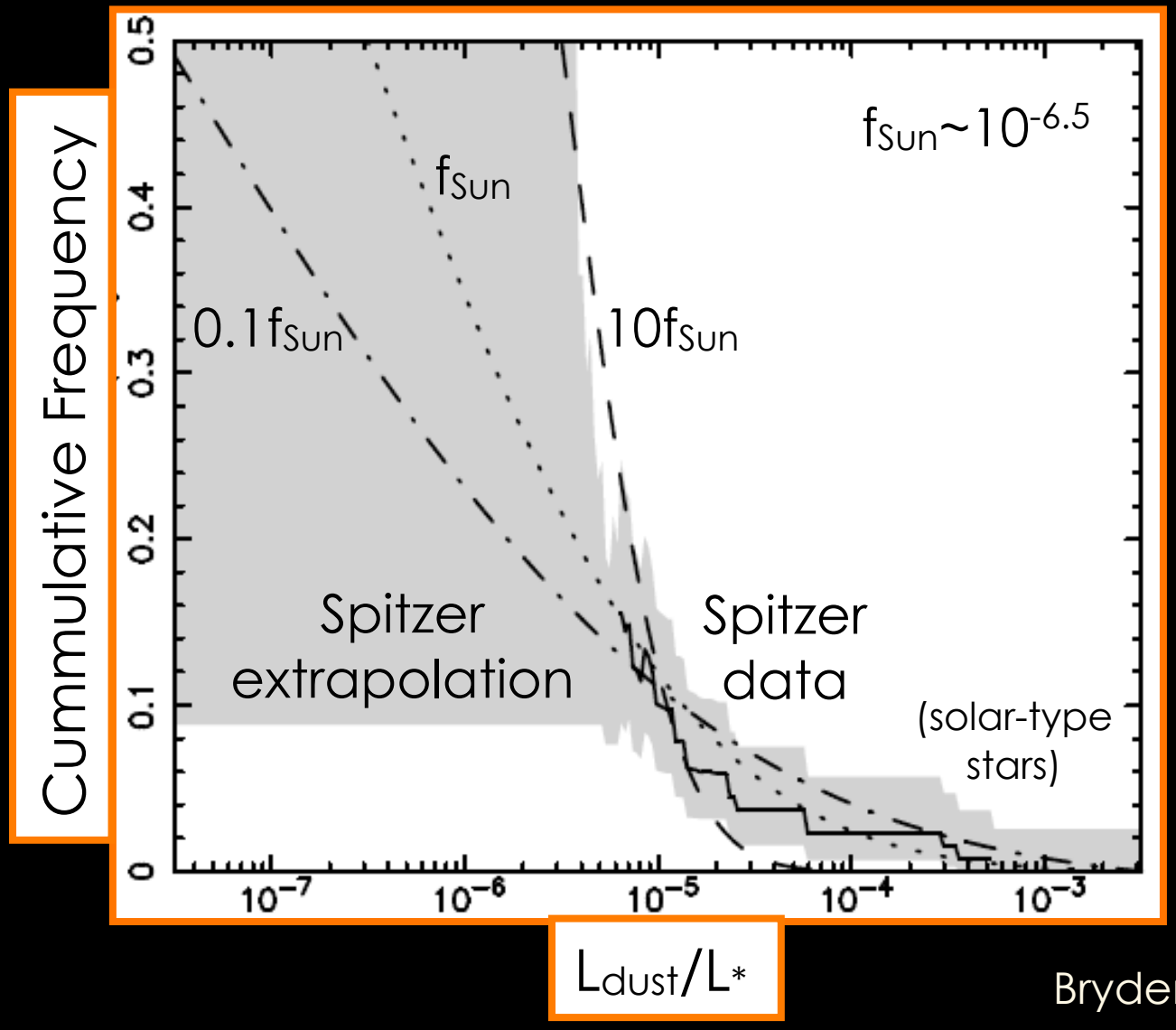
Kuiper Belt dust: $L_{dust}/L_* \sim 10^{-7}$-$10^{-6}$

Asteroid Belt dust: $L_{dust}/L_* \sim 10^{-8}$-$10^{-7}$

Herschel faintest disk:
$L_{dust}/L_* =$ few x 10^{-7}
(DUNES)

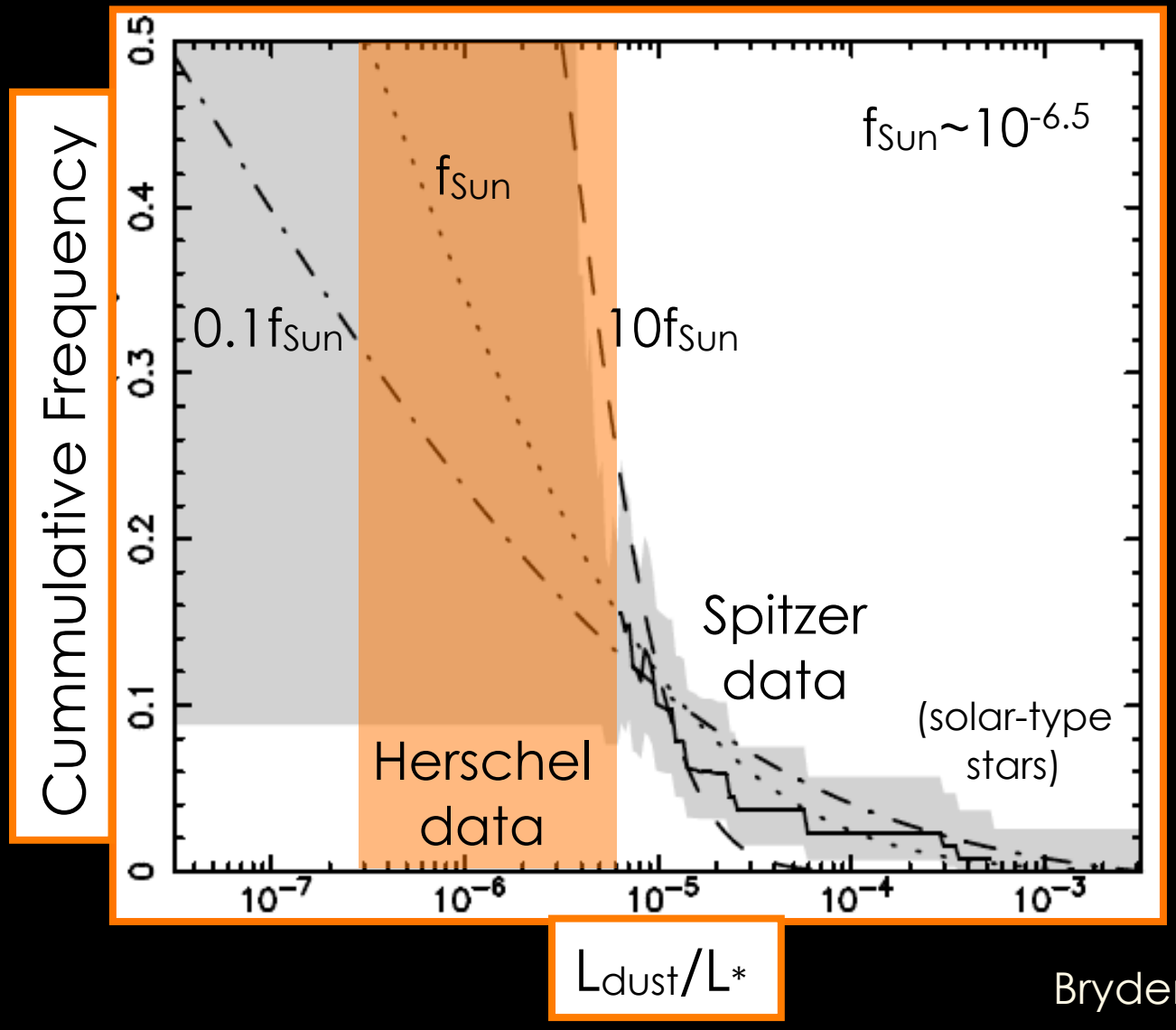


(1) Pre-Herschel: most disks have high dust content



Bryden et al. (2006)

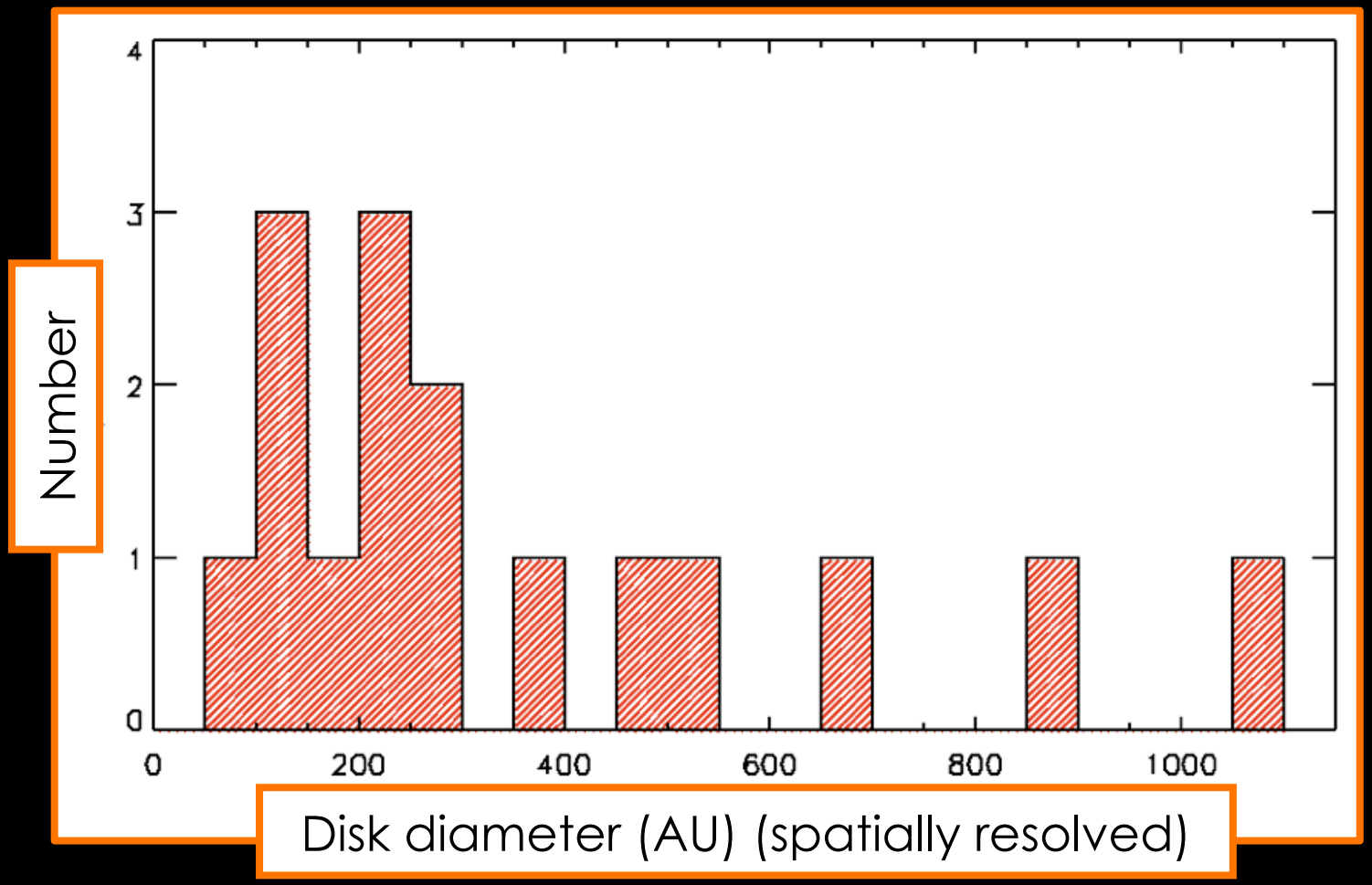
Herschel: Is the dust content of the Solar System average? Are planetesimal-clearing events common?



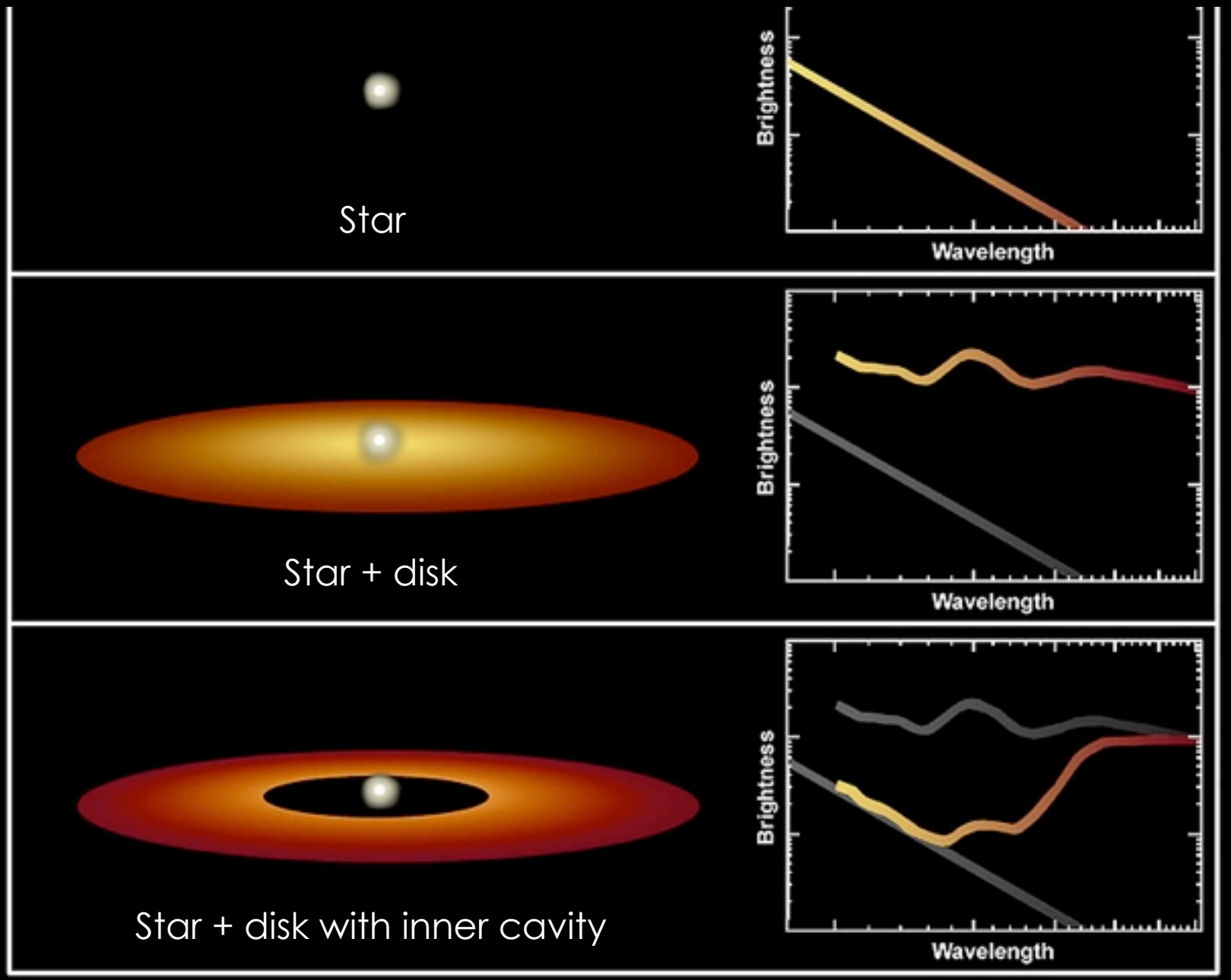
Bryden et al. (2006)

(2) Pre-Herschel: most disks are spatially unresolved

Solar System debris disk:
Classical Kuiper Belt ~ 50 AU
Scattered Kuiper Belt > 1000 AU

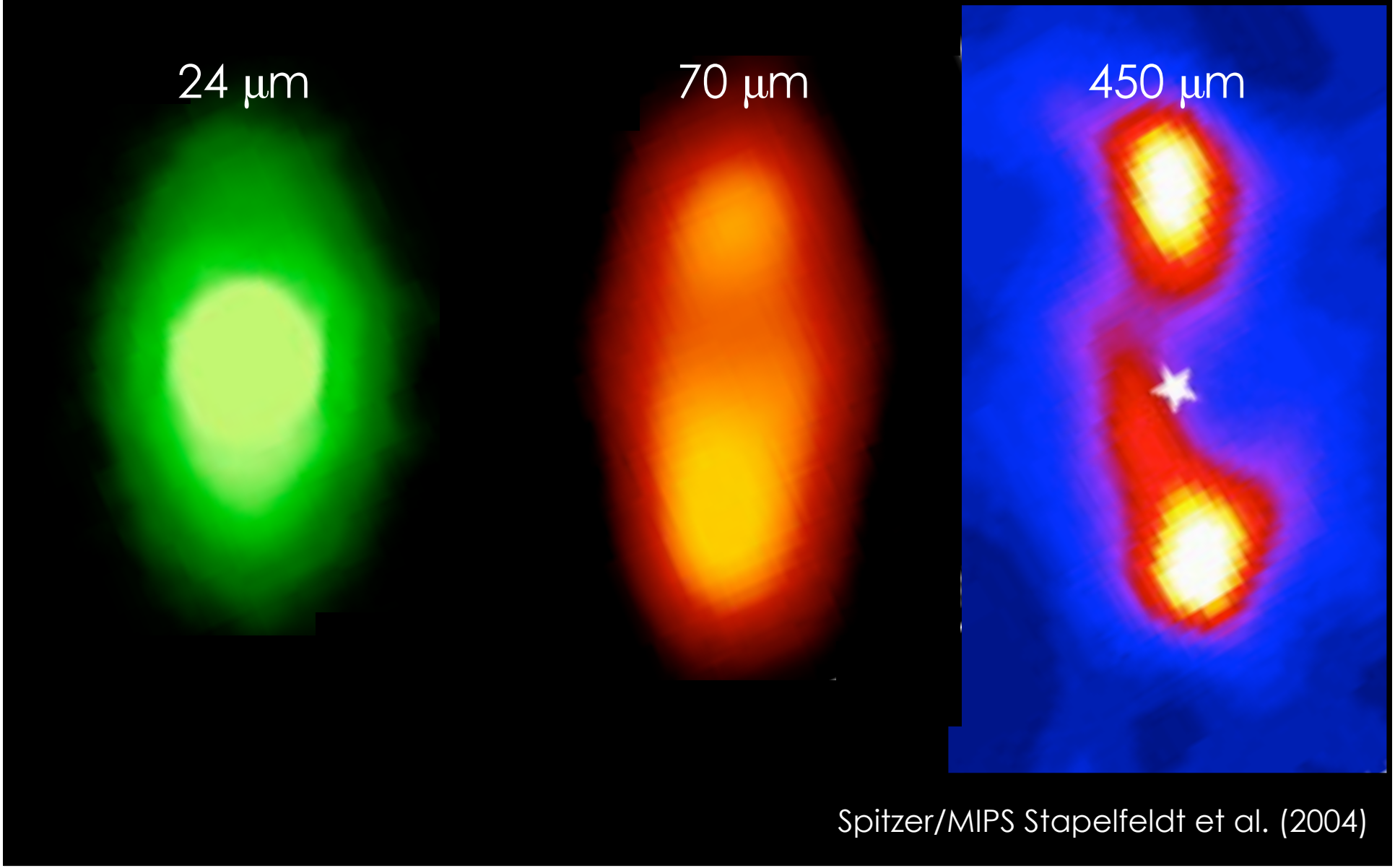


Spectral Energy Distributions

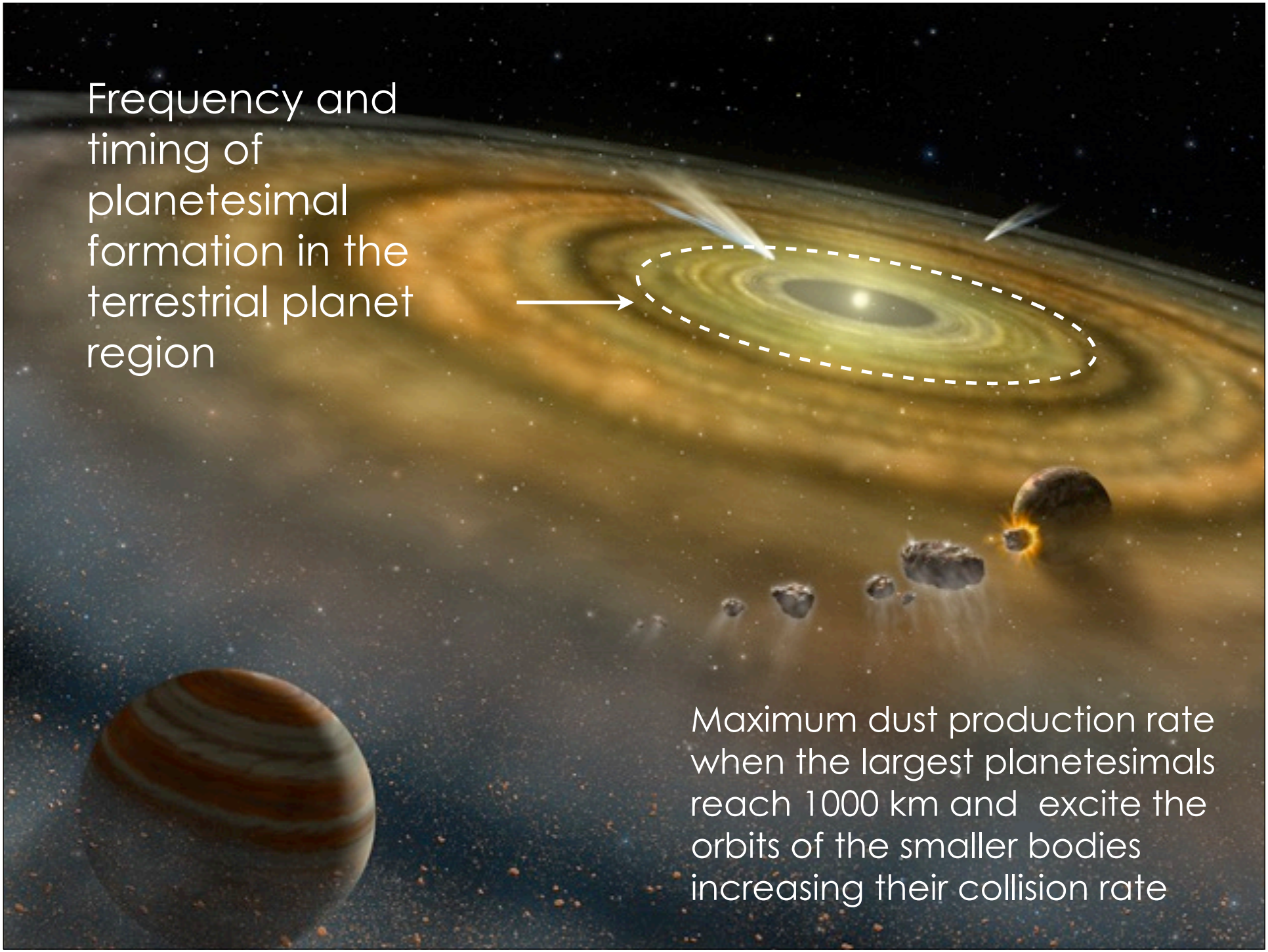


Watson et al., Spitzer

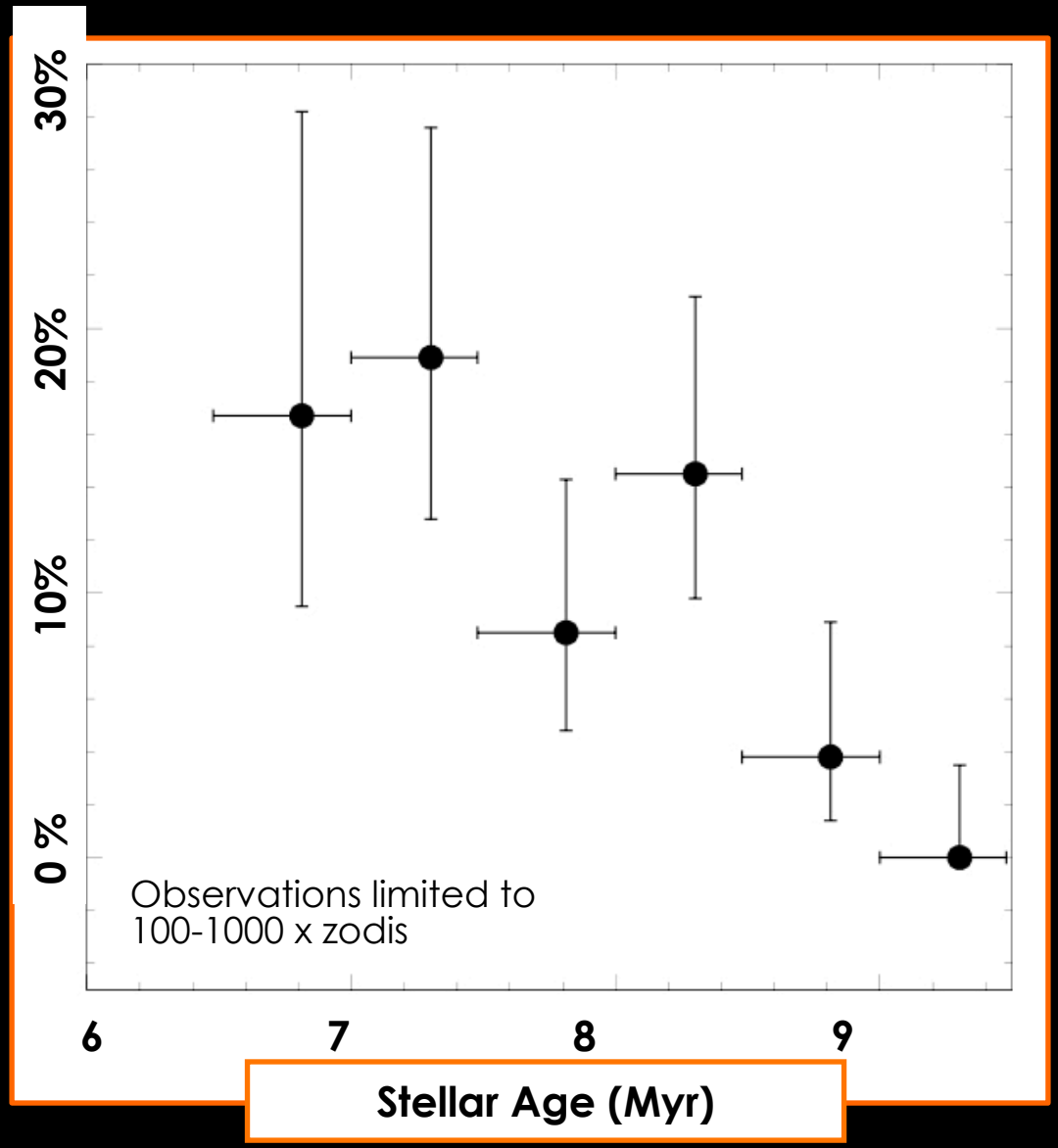
Fomalhaut debris disk



Spitzer/MIPS Stapelfeldt et al. (2004)


Frequency and timing of planetesimal formation in the terrestrial planet region
Maximum dust production rate when the largest planetesimals reach 1000 km and excite the orbits of the smaller bodies increasing their collision rate

Percentage of stars with warm dust emitting at 24 μm



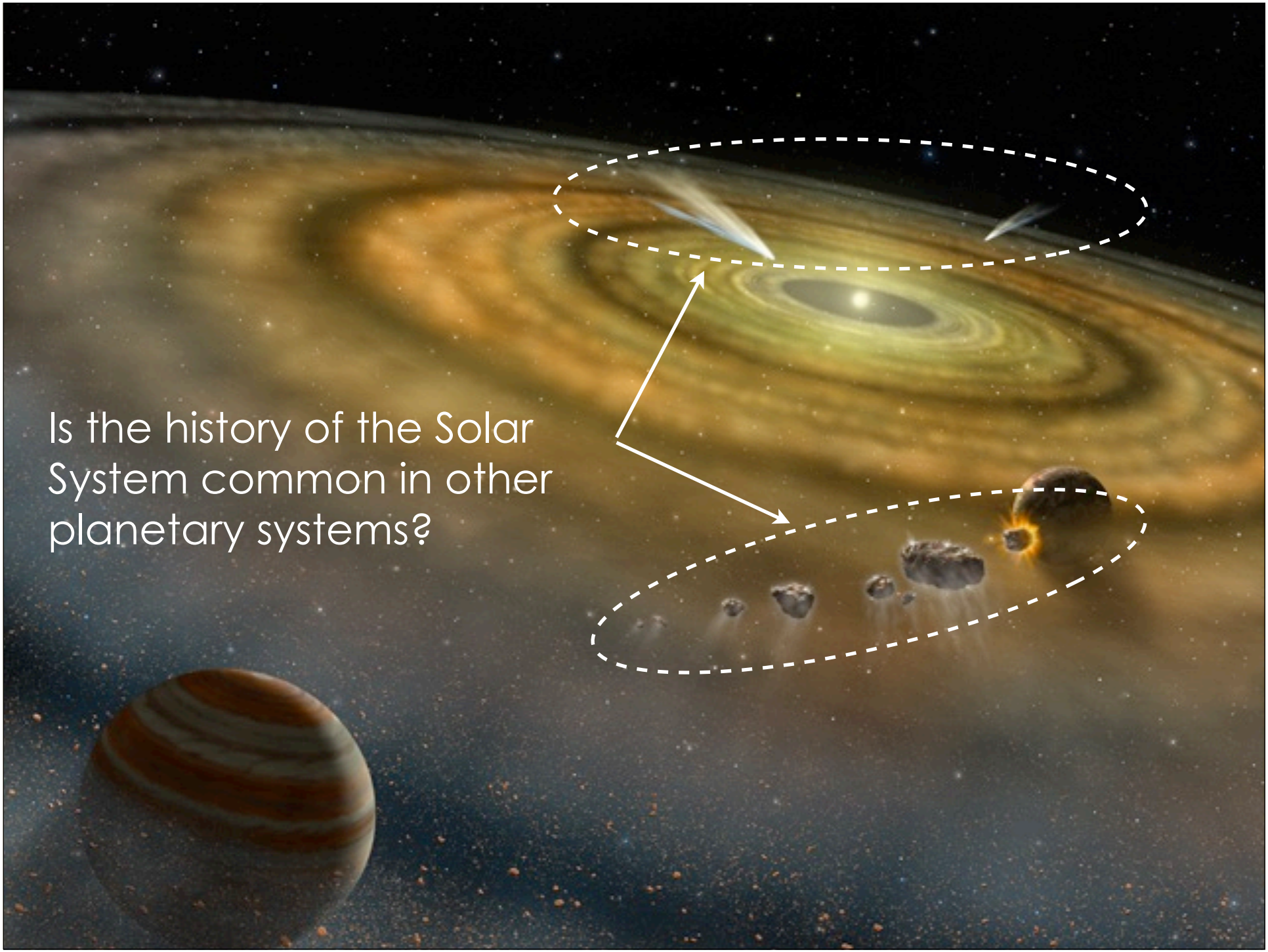
Interpretation depends on duration of dust production epoch, τ_{dpr}:

~32%: if τ_{dpr} < 10 x age bin

> 60%: if τ_{dpr} < age bins

18% 3-30 Myr
12% 30-300 Myr
2% 300-3000 Myr

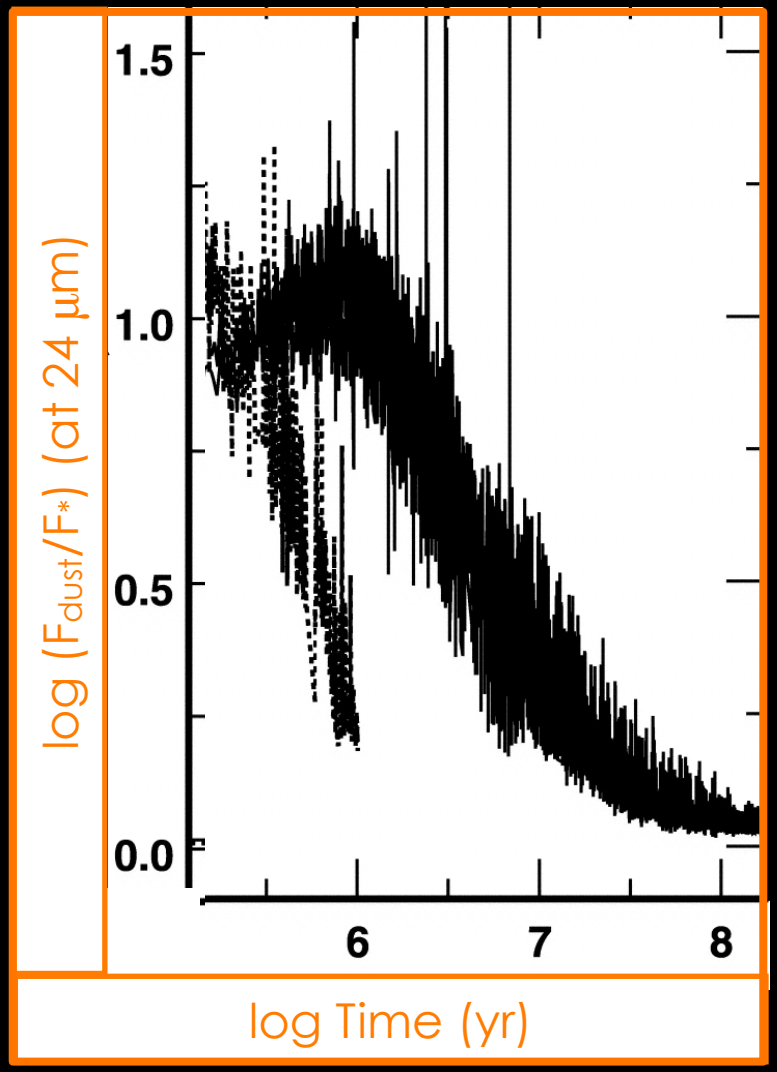
(Meyer et al. 2008)


Is the history of the Solar System common in other planetary systems?

Evolution of dust in the Solar System

- Very high in the past; evidence of massive young planetesimals belts.
- Steady 1/t decrease due to planetesimal erosion.
- Peak due to Late Heavy Bombardment; triggered by orbital migration of giant planets; sweeping of secular resonances through AB; ejection of asteroids into planet-crossing orbits.
- Peaks due to the individual collisions of large bodies.

  (E.g. the formation of the Veritas family 8.3 Myr ago; responsible for 25% of the zodi)



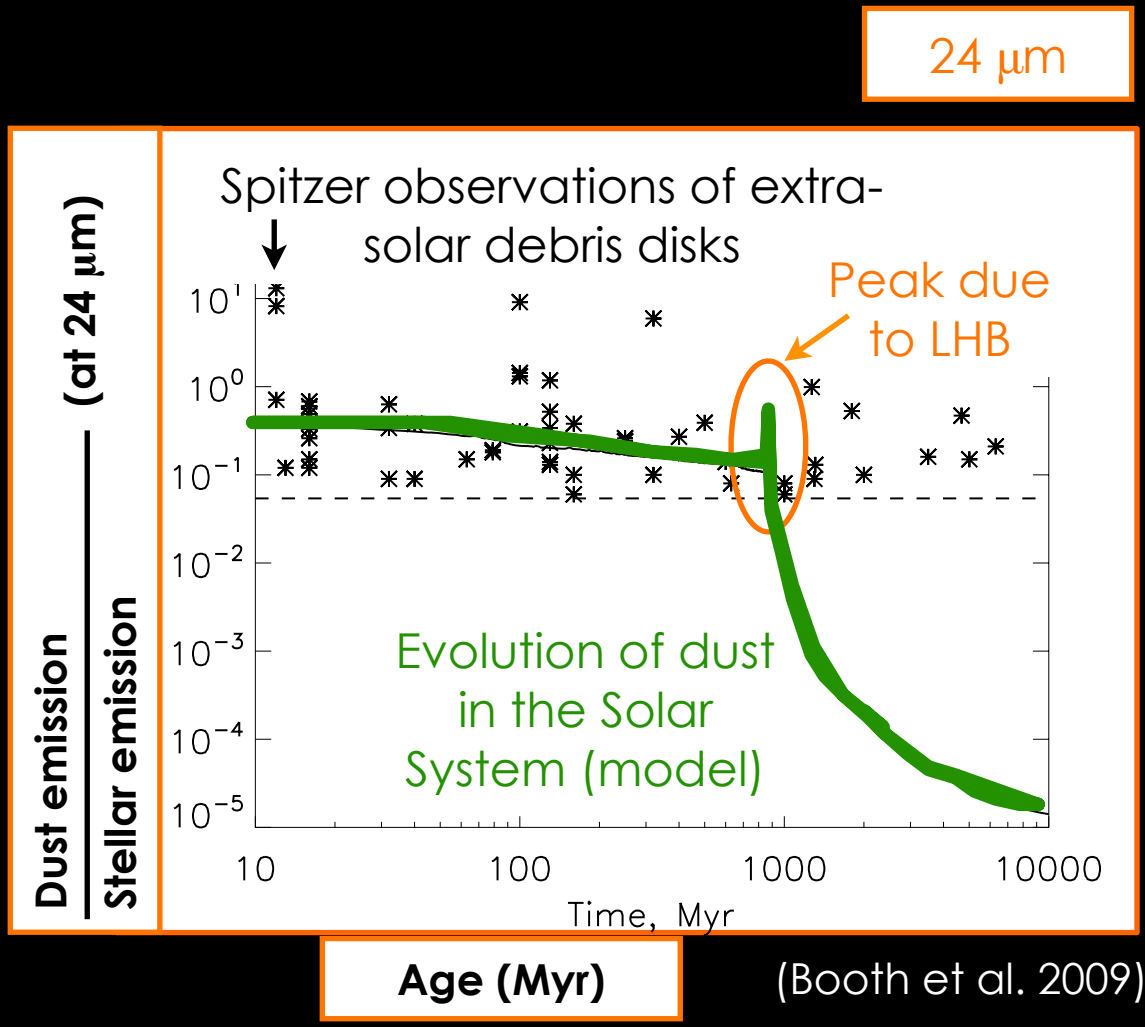
(Kenyon & Bromley 2005)

Are processes like the LHB common in other planetary systems?

Main feature: sharp decrease of the frequecuency of debris disks after the clearing of planetesimals

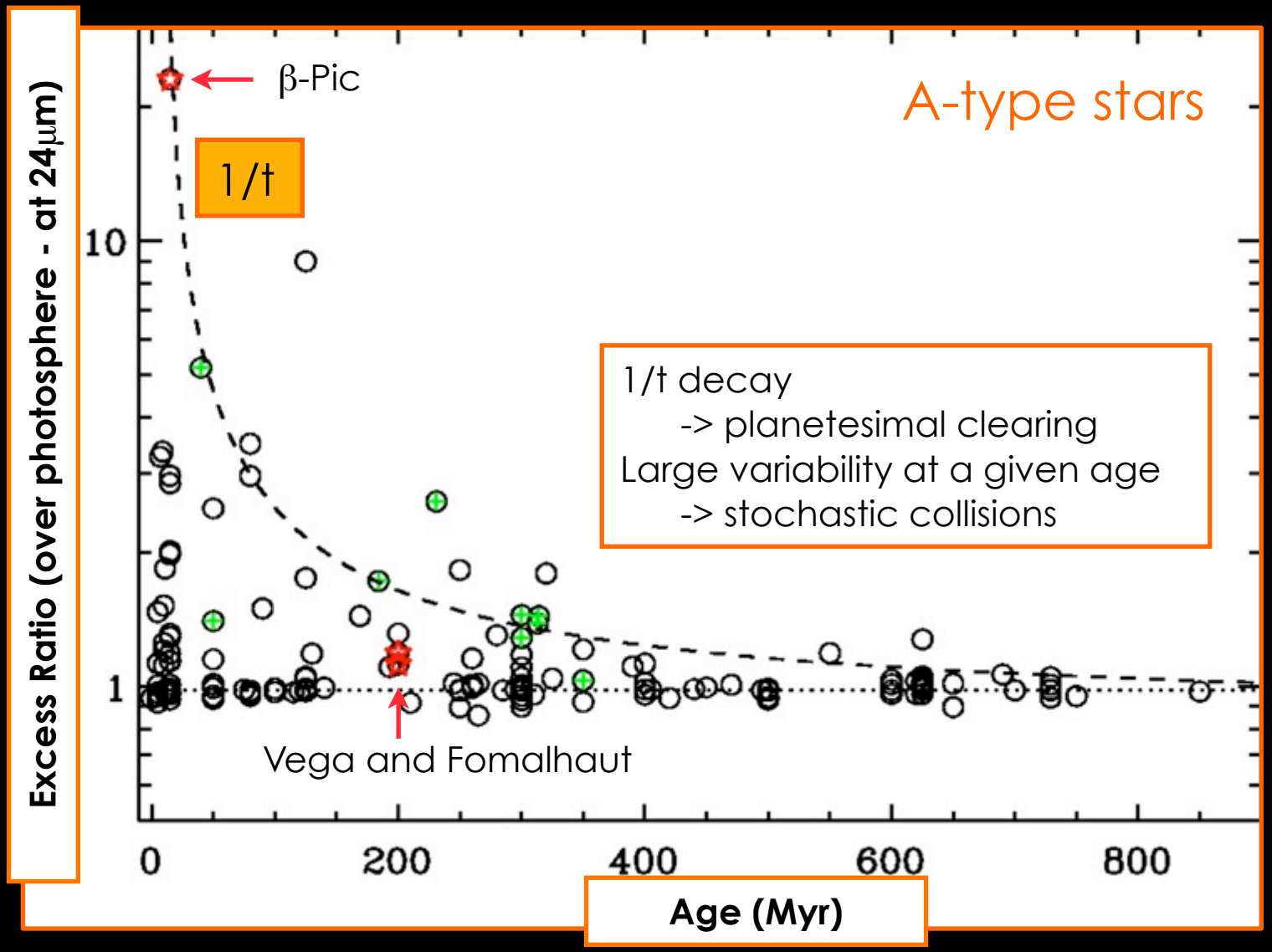
The study of the dust excess emission as a function of stellar age does not show a sharp decline

LHB-type of events don't seem to be common



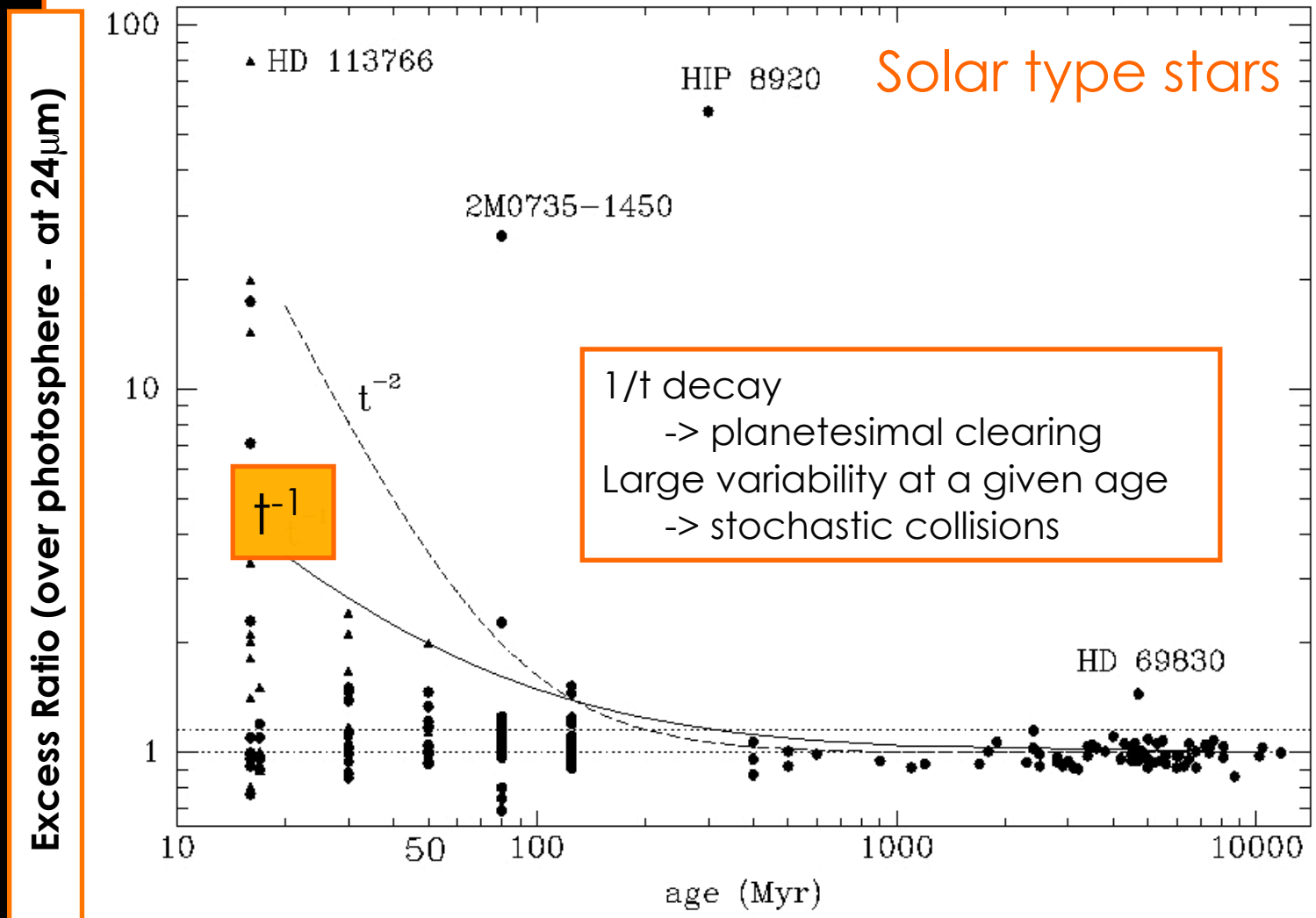
(Booth et al. 2009)

Evolution of dust in extra-solar debris disks (Spitzer)

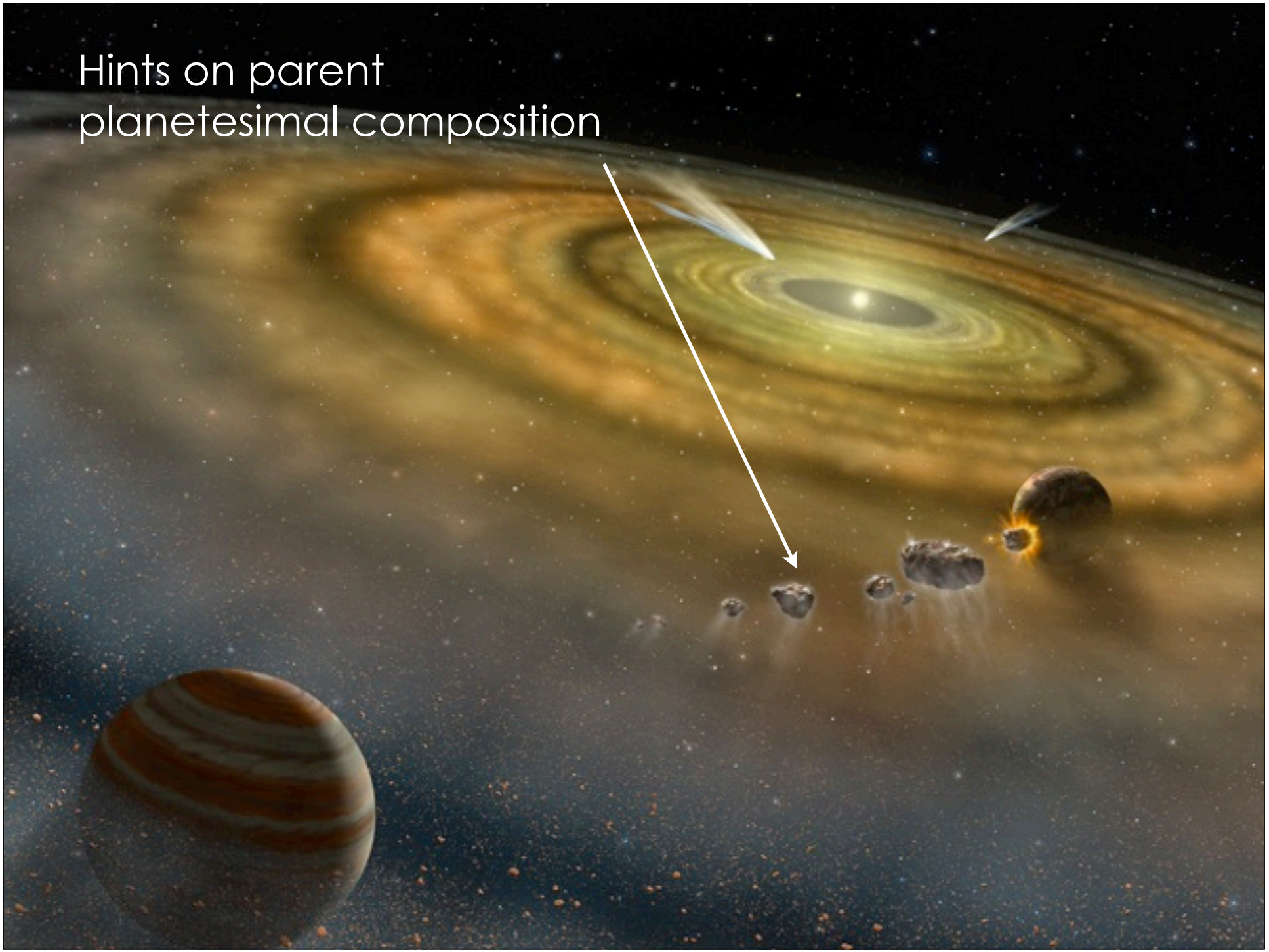


(Su et al. 2006)

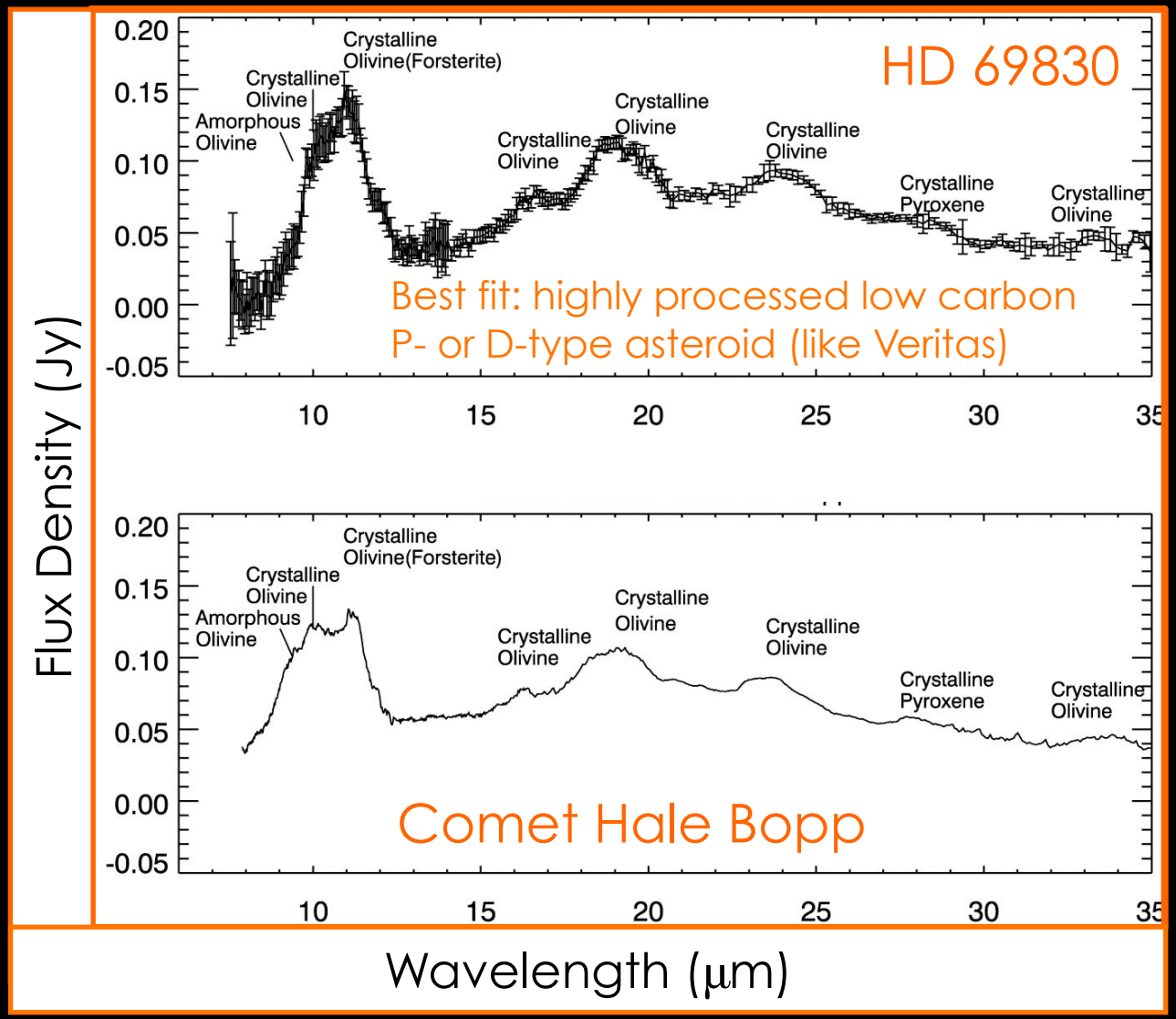
Evolution of dust in extra-solar debris disks (Spitzer)

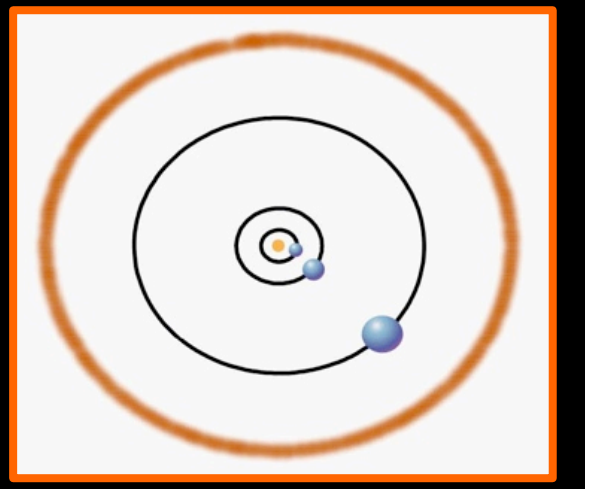


(Siegler et al. 2006)


Hints on parent
planetesimal composition

Hints on parent planetesimal composition





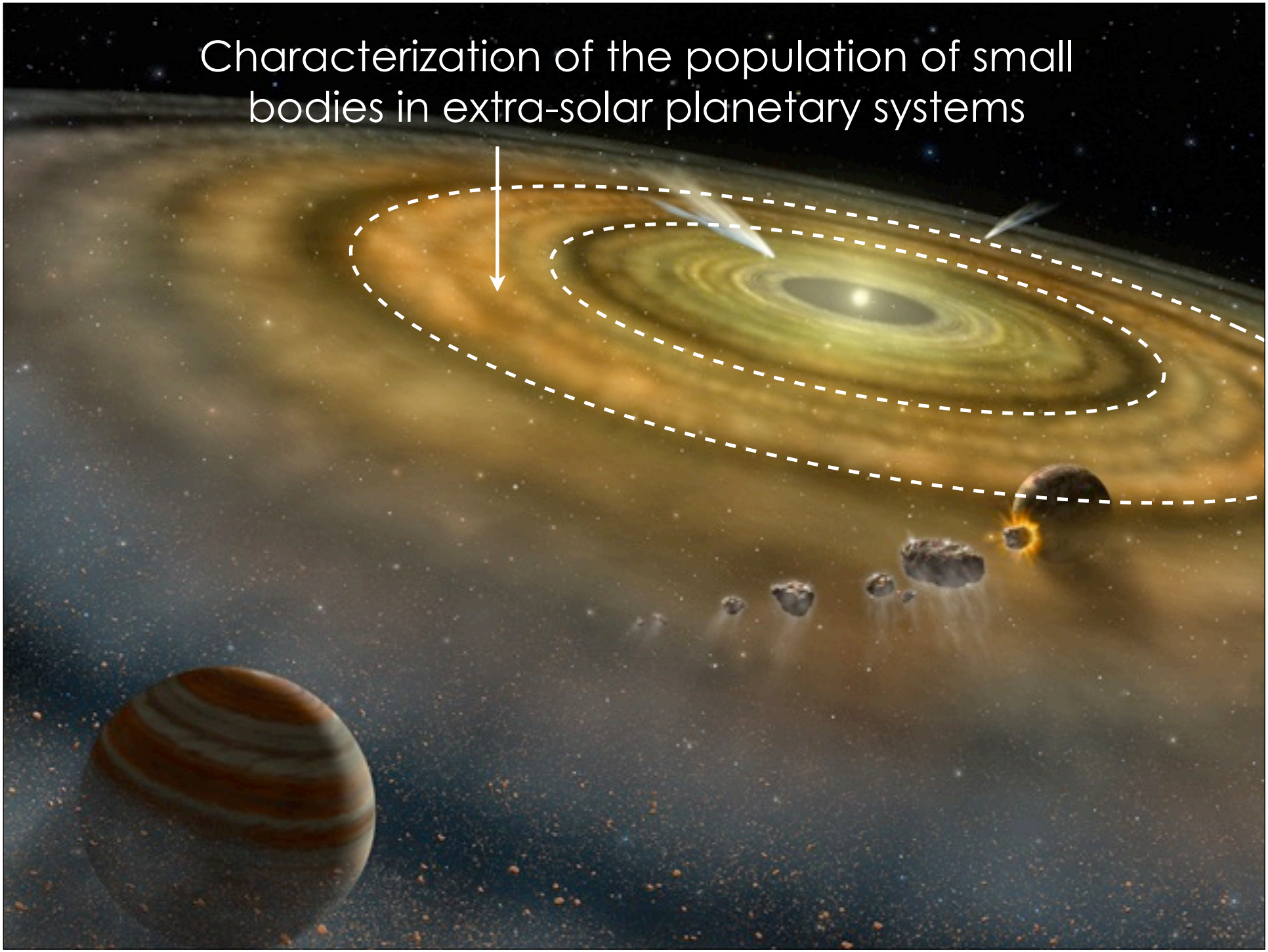
K0V, $0.8M_{sun}$, $0.45L_{sun}$
age: 3000-10000 Myr

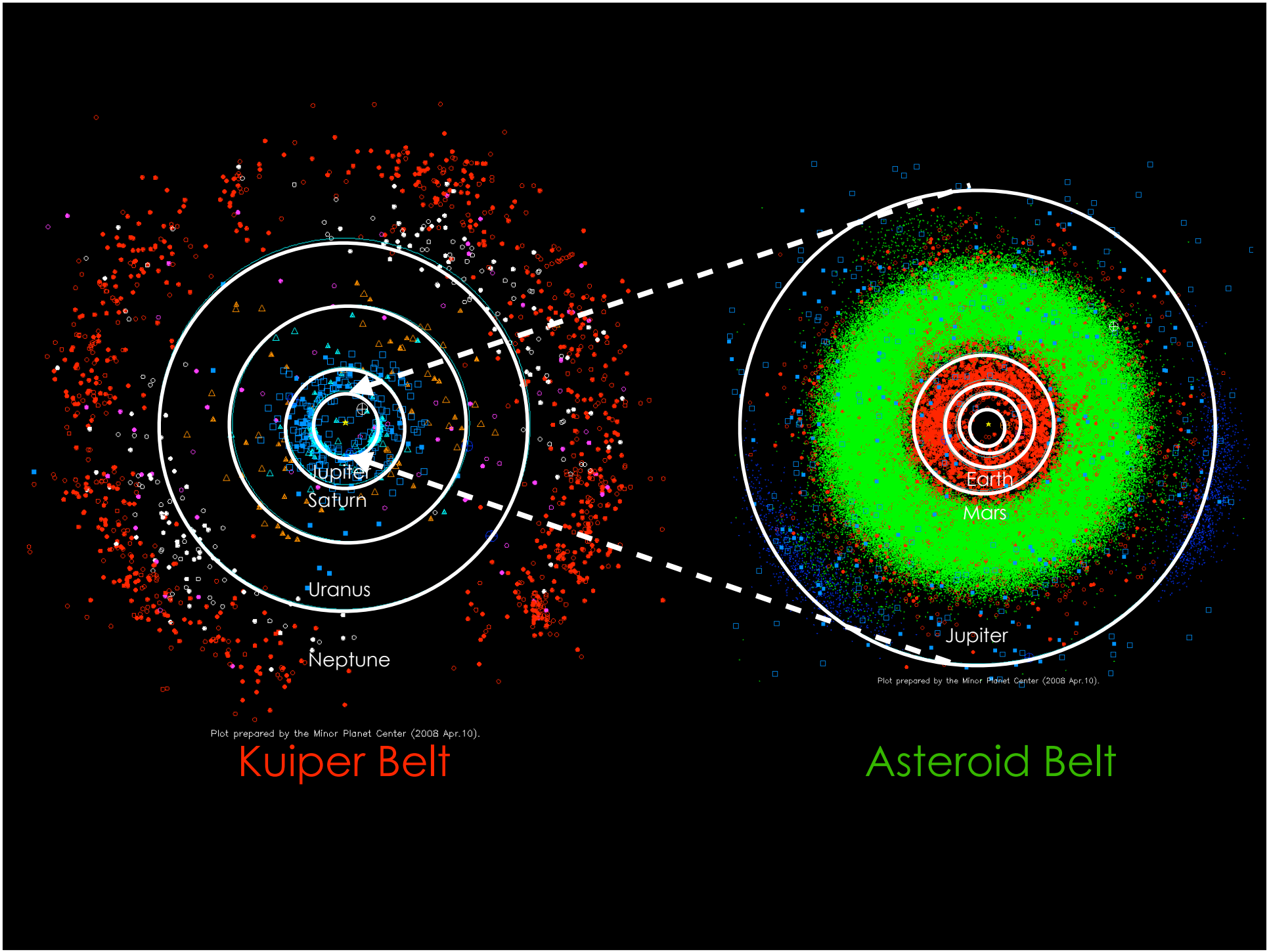
Three planets:
≥ 10.2 $M_{\oplus}$ 0.0785 AU
≥ 11.8 $M_{\oplus}$ 0.186 AU
≥ 18.1 $M_{\oplus}$ 0.63 AU.

Spitzer IR excess:
Strong excess at 24 μm
No excess at 70 μm

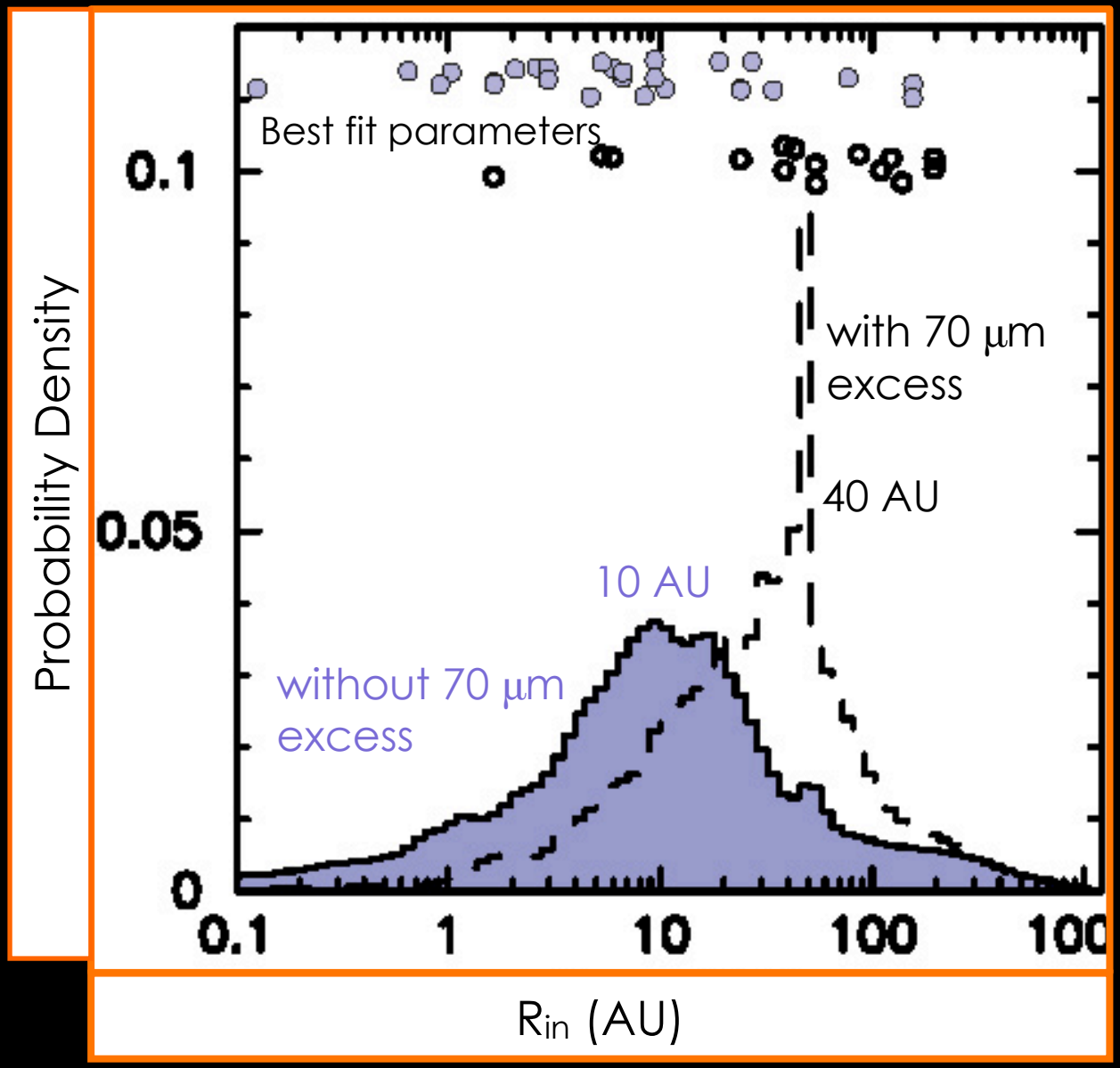
Transient event:
dpr is too high to be sustained (Wyatt et al. 2006)

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


Characterization of the population of small bodies in extra-solar planetary systems


Jupiter
Saturn
Uranus
Neptune
Plot prepared by the Minor Planet Center (2008 Apr.10).
Kuiper Belt
Earth
Mars
Jupiter
Plot prepared by the Minor Planet Center (2008 Apr.10).
Asteroid Belt

Kuiper Belt-like belts are the most common



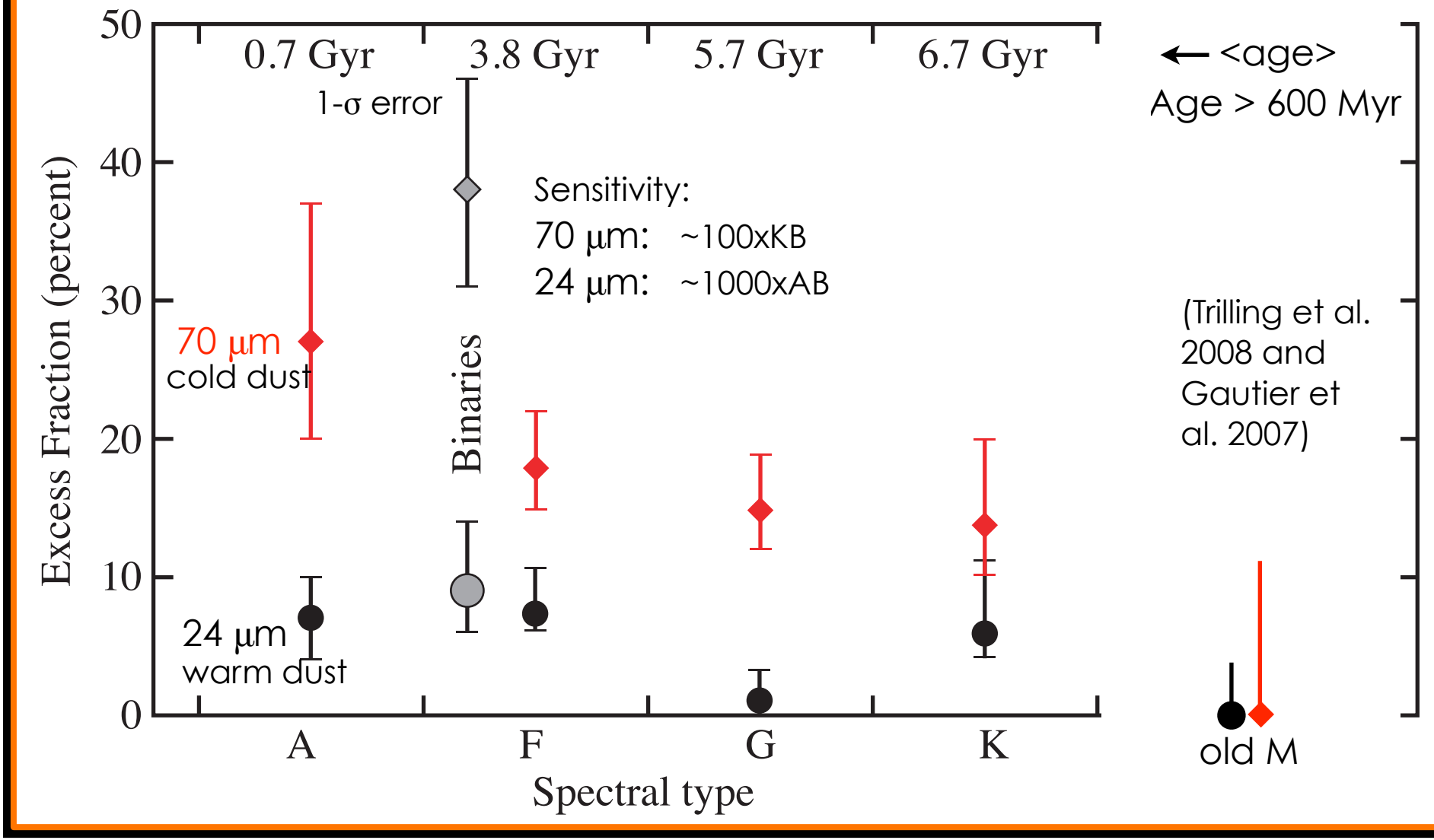
N = 44 (FGK)

From fits to spectra (12–35μm)

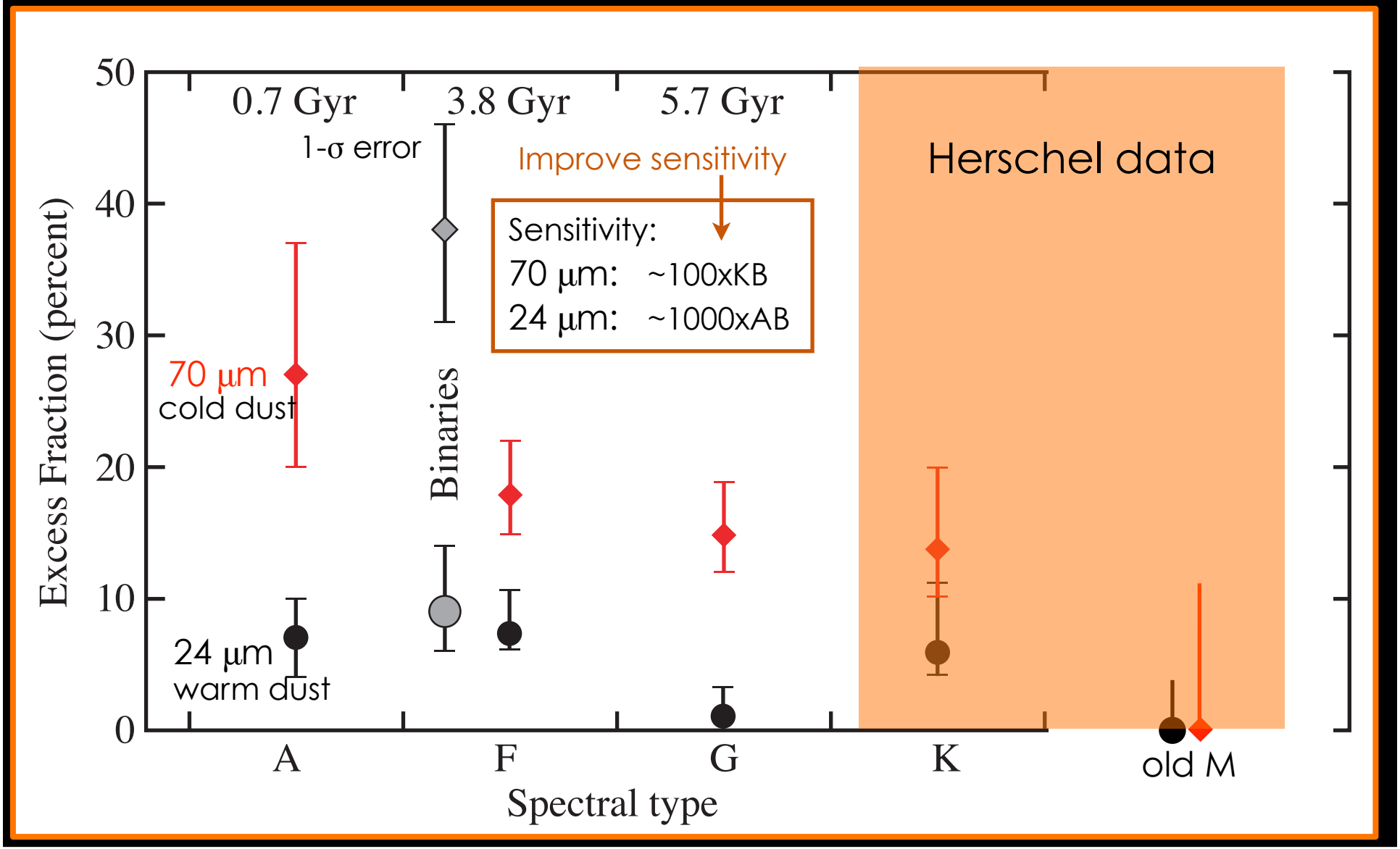
(Carpenter et al. 2009)

Kuiper Belt-like belts are the most common

Frequency of disks is different in old A stars and M stars than in FGK stars.



Kuiper Belt-like belts are the most common



Kuiper Belt-like belts are the most common

no correlation observed

Frequency of cold disks around solar-type stars~6-16% ⟷ Frequency of giant planets (<20 AU): ~17-19%

(Sensitivity: 100 x KB).

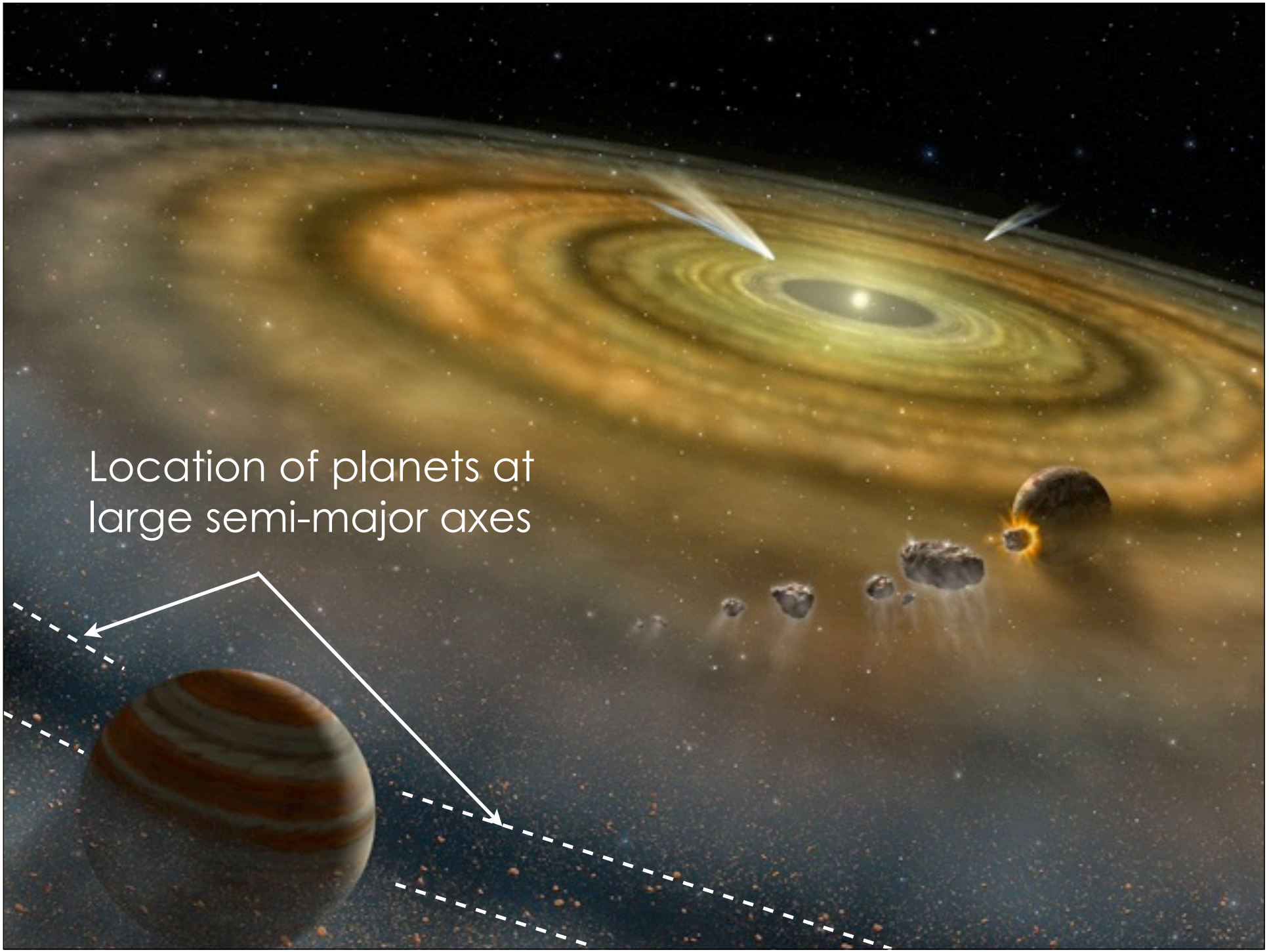
(Sensitivity: Jupiter and Saturn-like planets)

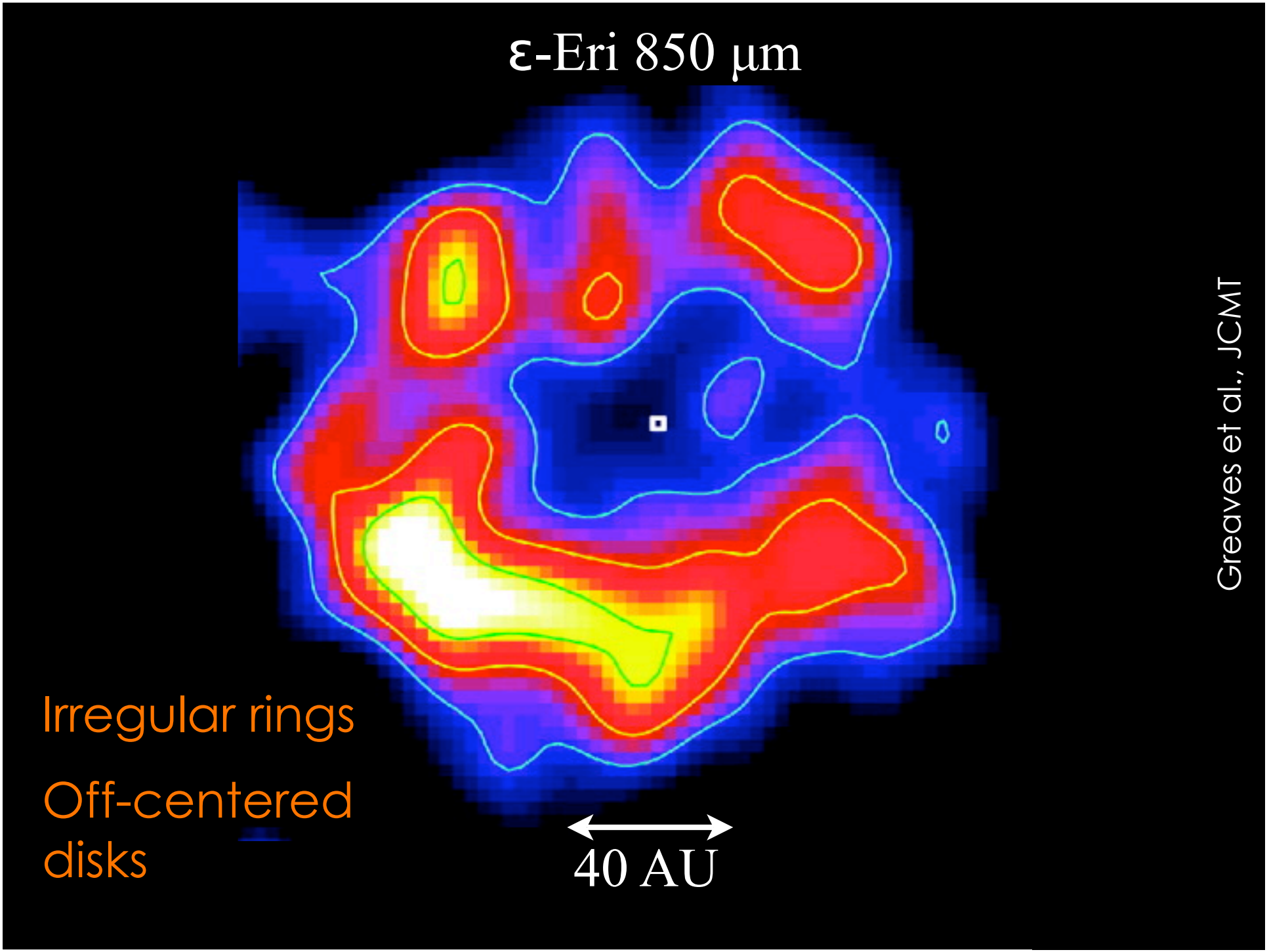
↓

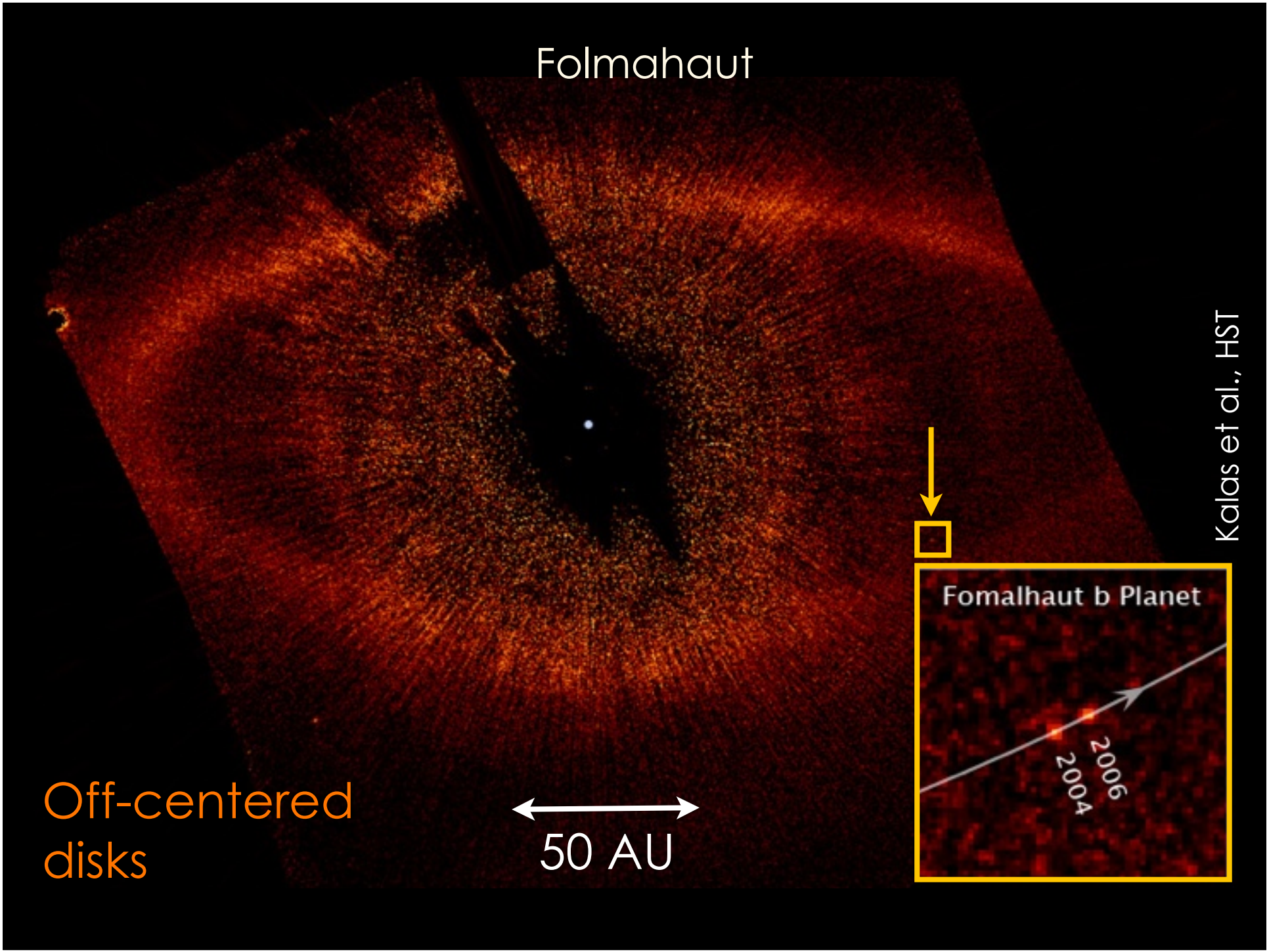
KB-like disks could be very common around solar-type stars

Planetesimal formation...

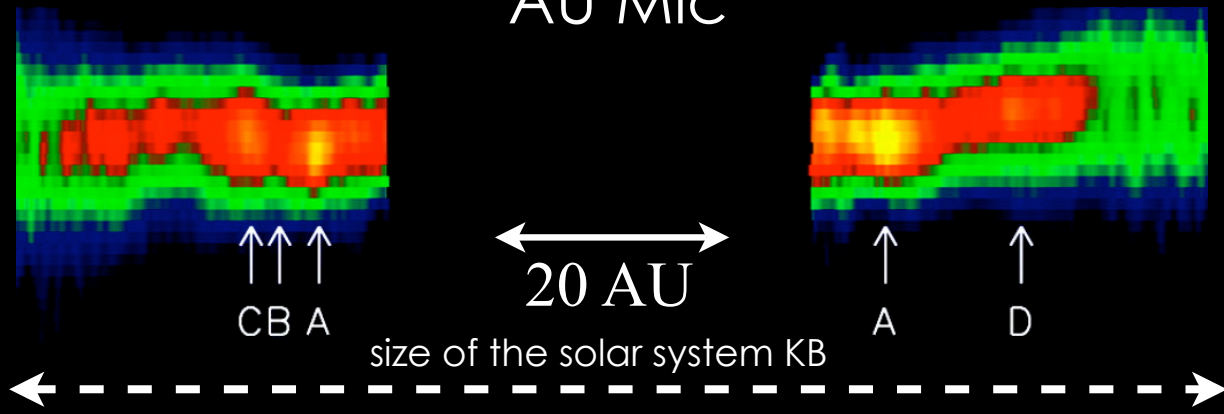
- is a robust process (debris disks are found around stars with a stellar luminosities spanning more than 2 orders of mag).
- is more common than giant planet formation (unlike planets, debris disks are not correlated with high stellar metellicities)


Location of planets at
large semi-major axes


ε-Eri 850 μm
Irregular rings
Off-centered disks
40 AU
Greaves et al., JCMT

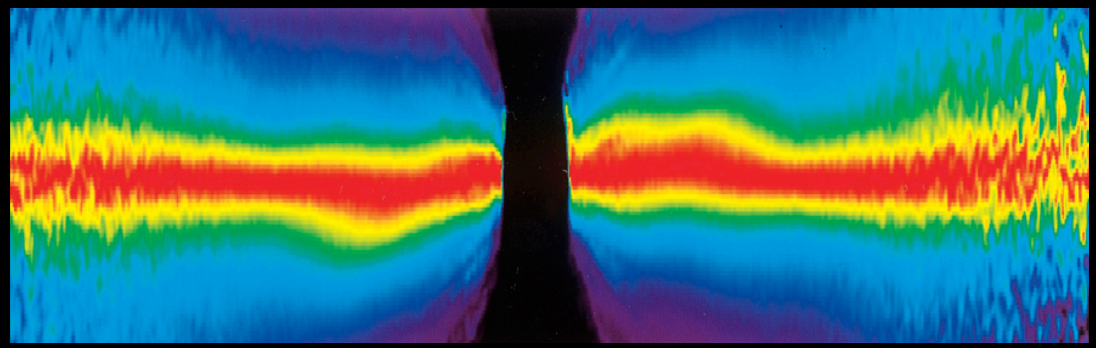

Folmahaut
Kalas et al., HST
Fomalhaut b Planet
2006
2004
Off-centered
disks
50 AU

AU Mic



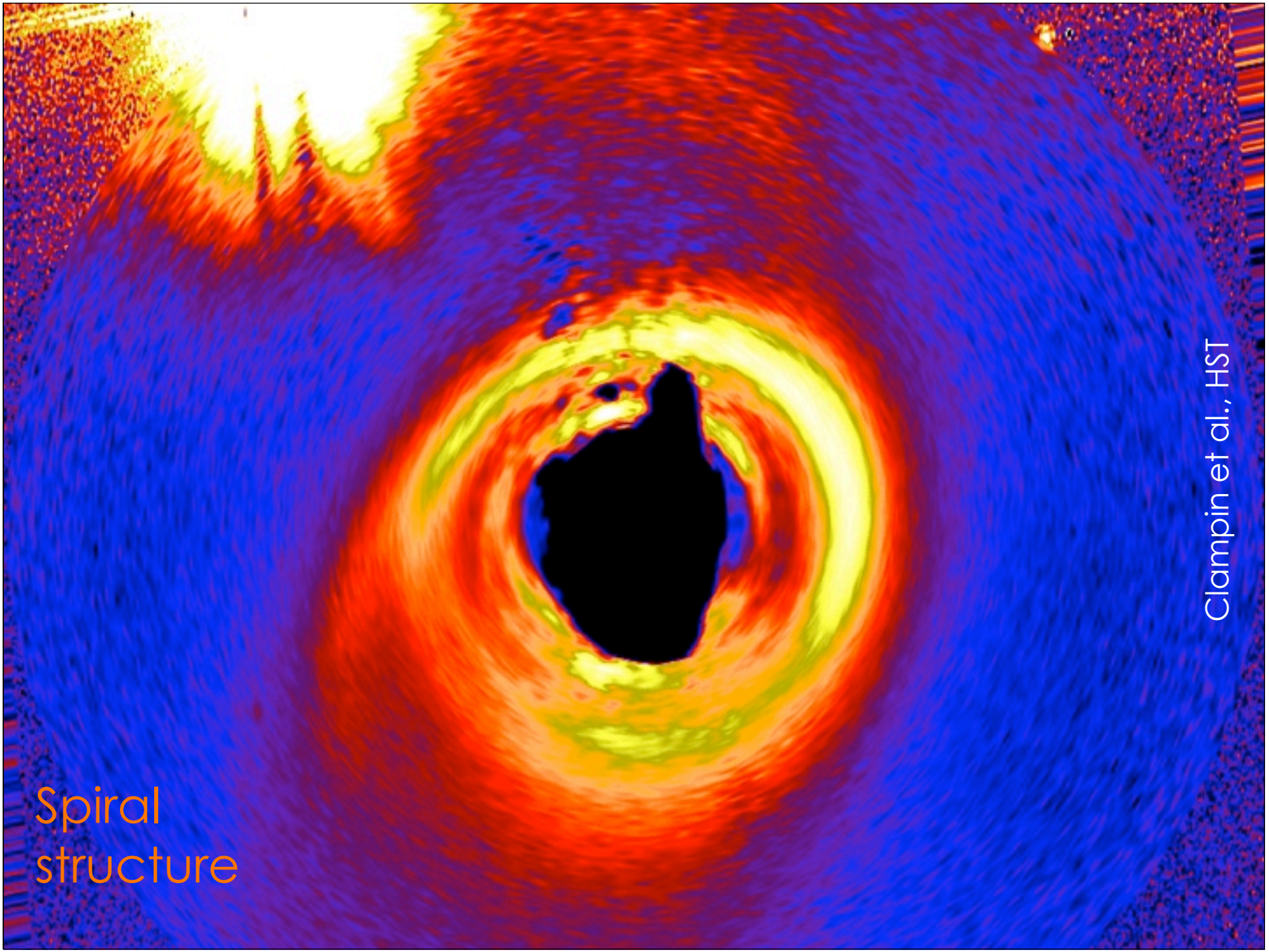
(Liu 2004)

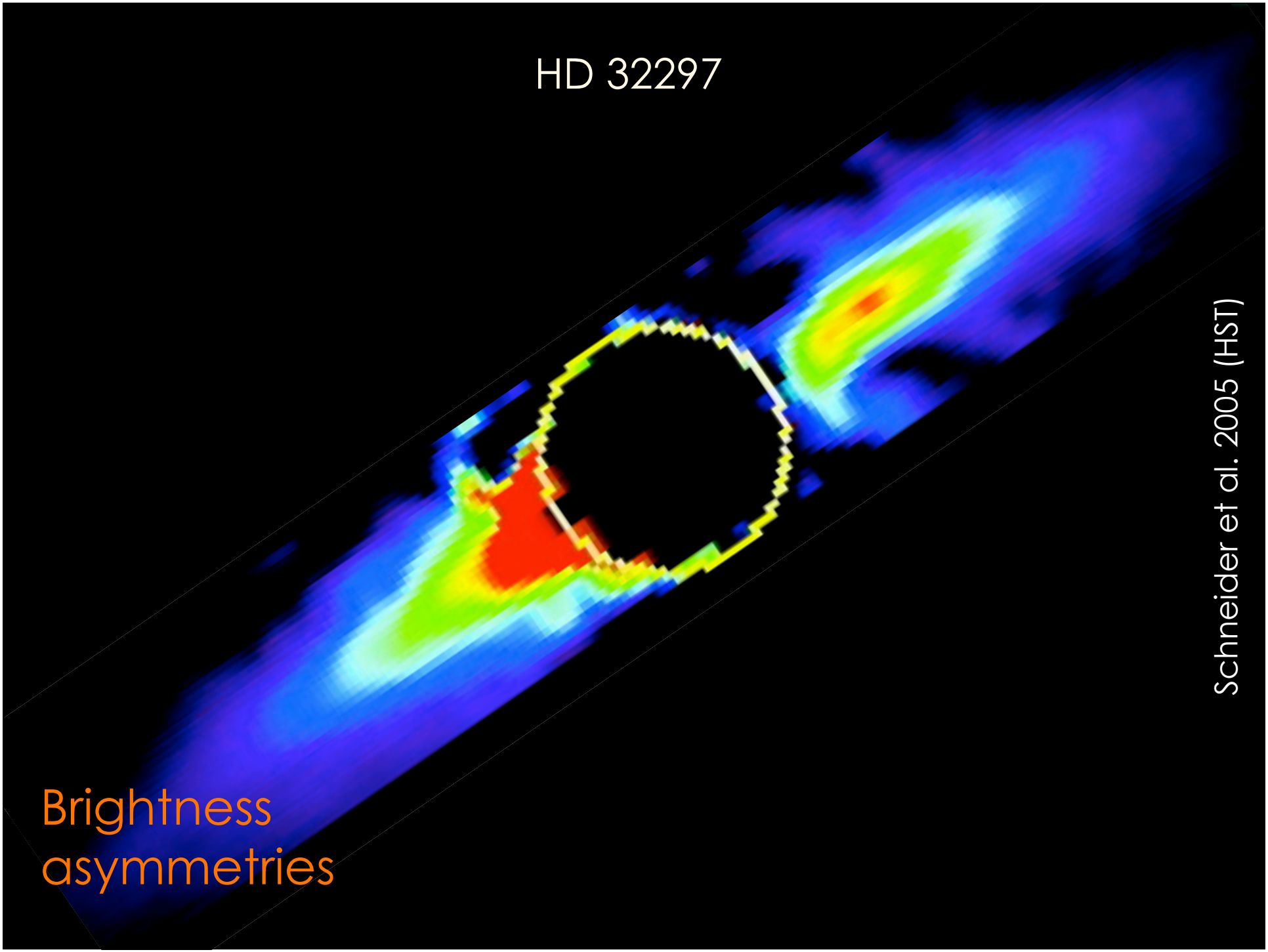
β-Pic 0.2-1 μm



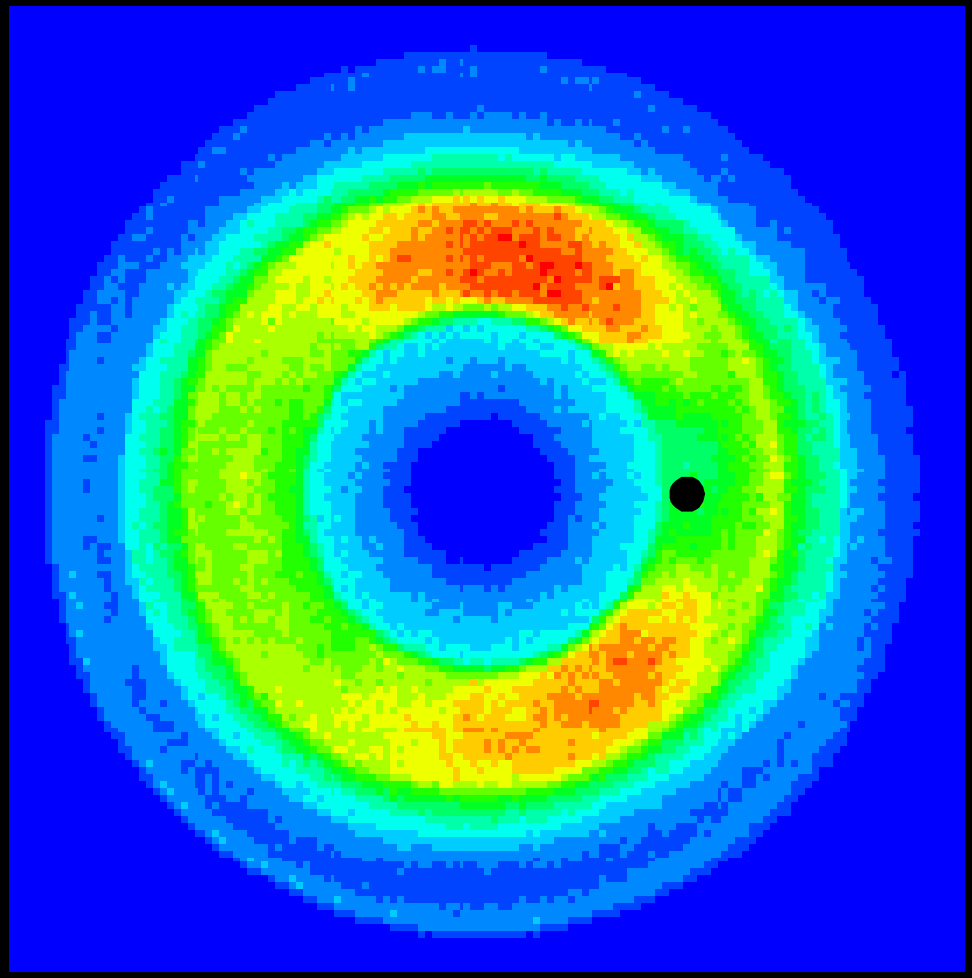
(Heap et al. 2000)

Warped disks


Spiral
structure
Clampin et al., HST


HD 32297
Schneider et al. 2005 (HST)
Brightness asymmetries

Model of Kuiper Belt Dust



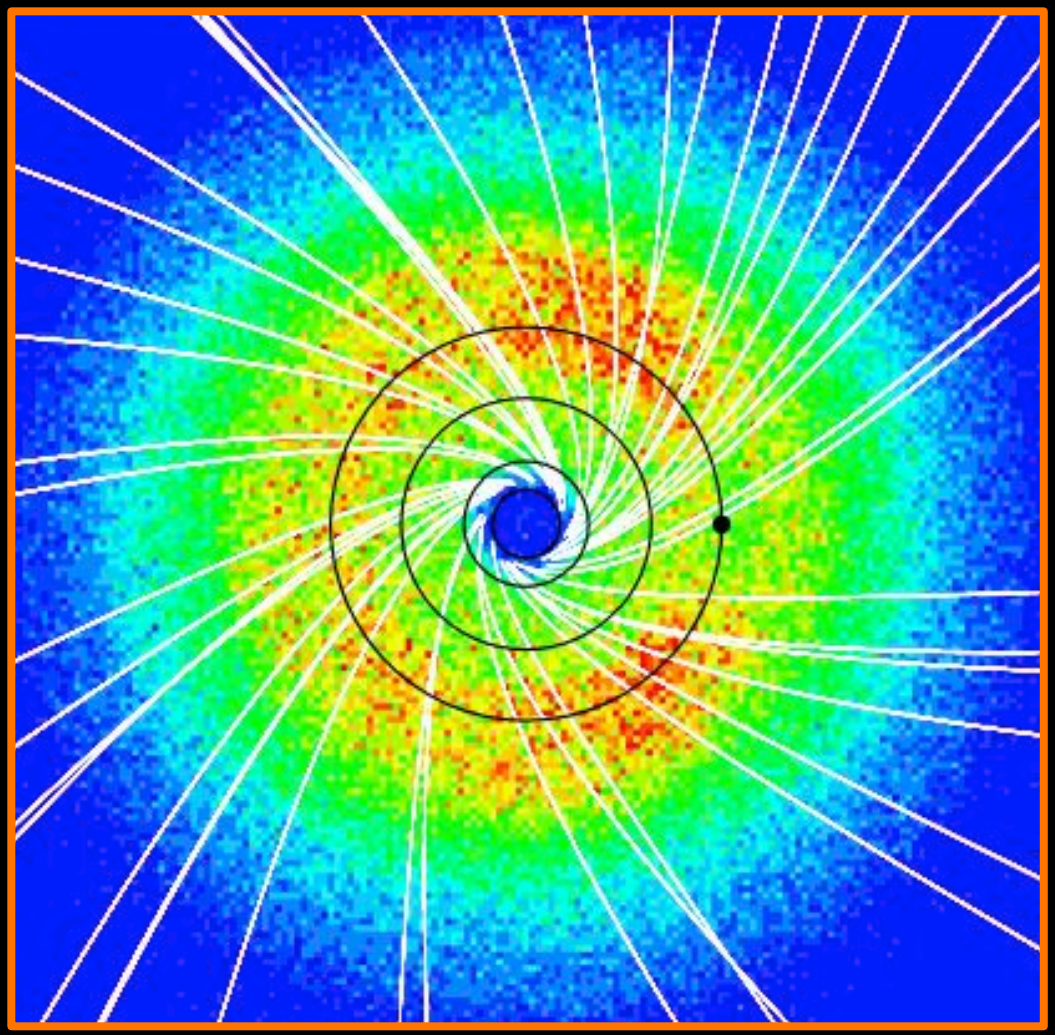
Irregular rings

Brightness asymmetries

Moro-Martín and Malhotra (2002)

Planets can affect the debris disk structure

- Gravitational ejection
- Resonant perturbations
- Secular perturbations



(Moro-Martin & Malhotra 2005)

Planets can affect the debris disk structure

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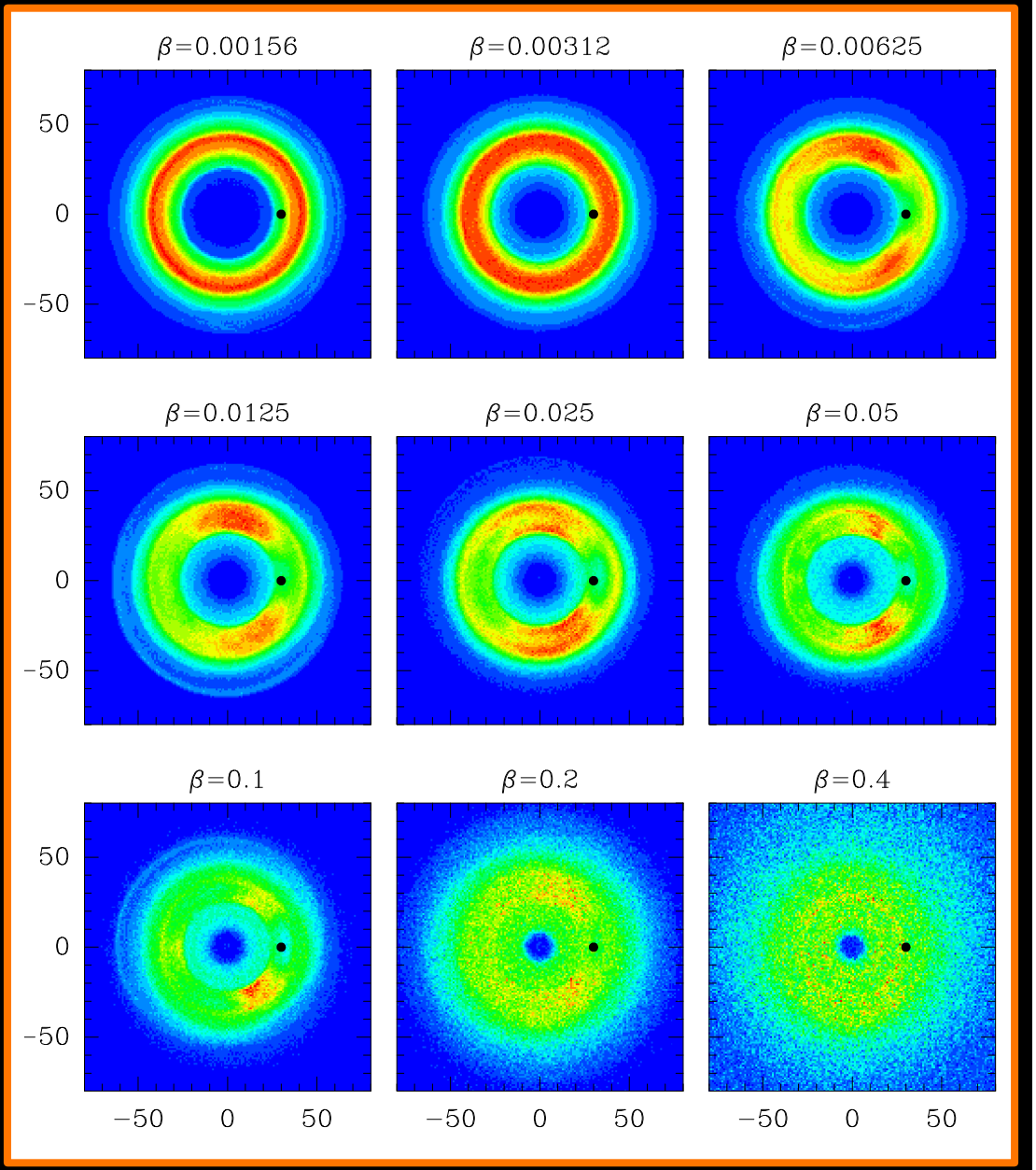

(Moro-Martin & Malhotra 2002)

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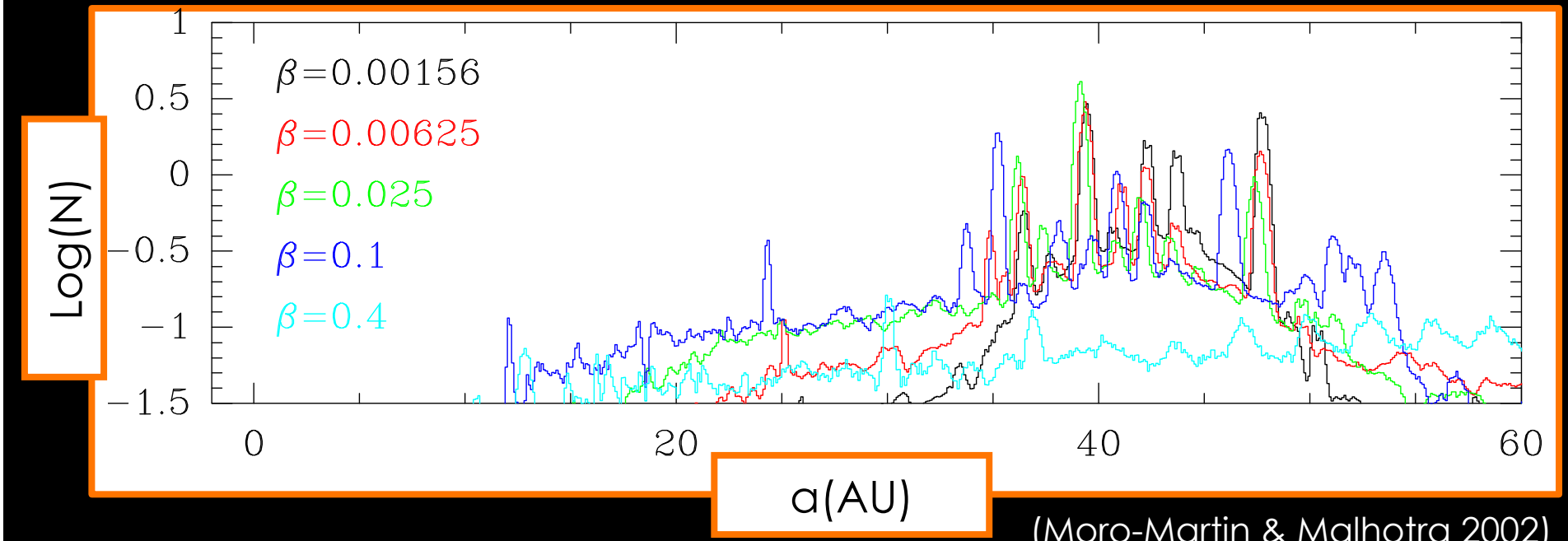

(Moro-Martin & Malhotra 2002)

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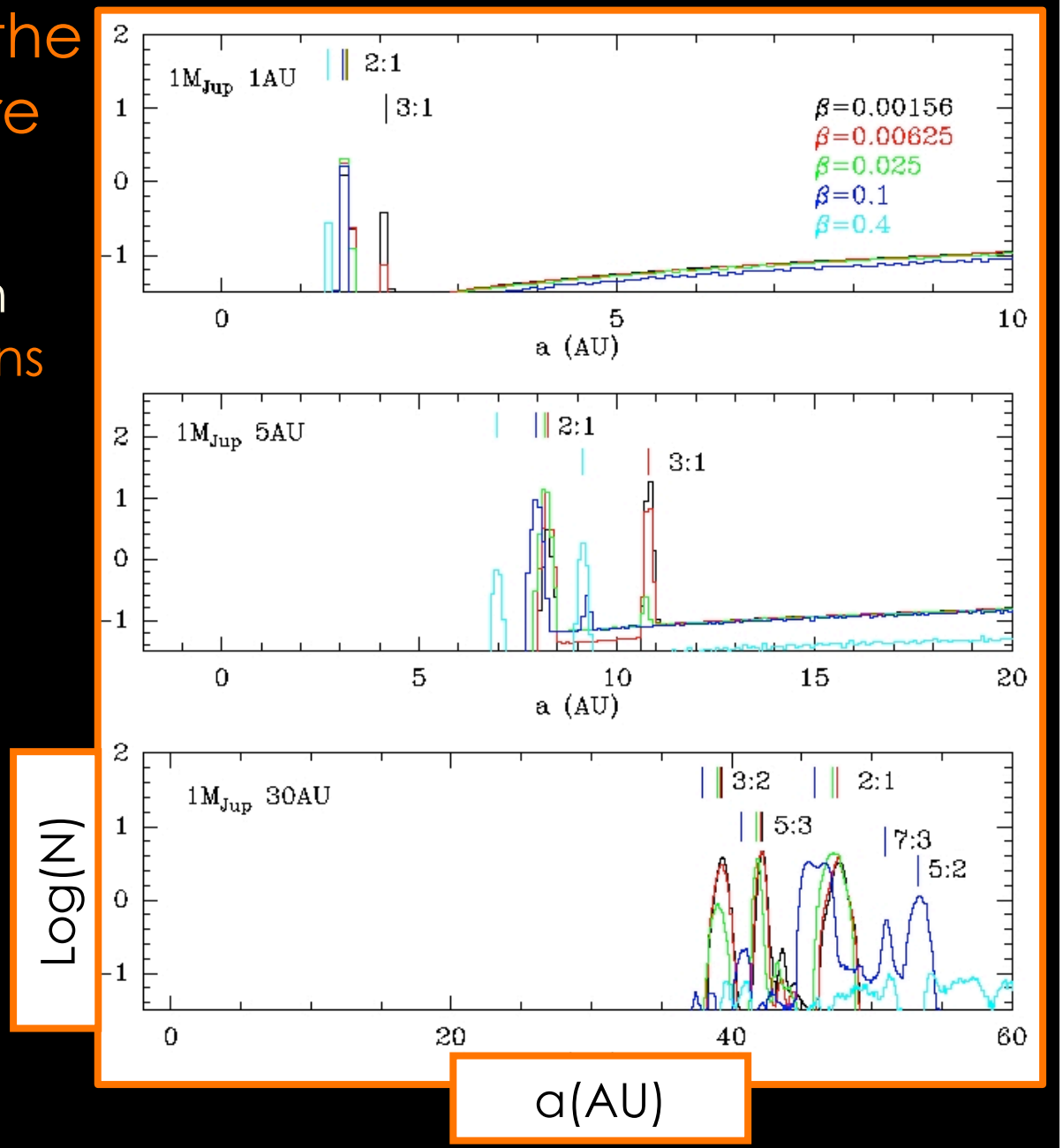

(Moro-Martin & Malhotra 2002)

Planets can affect the debris disk structure

- Gravitational ejection
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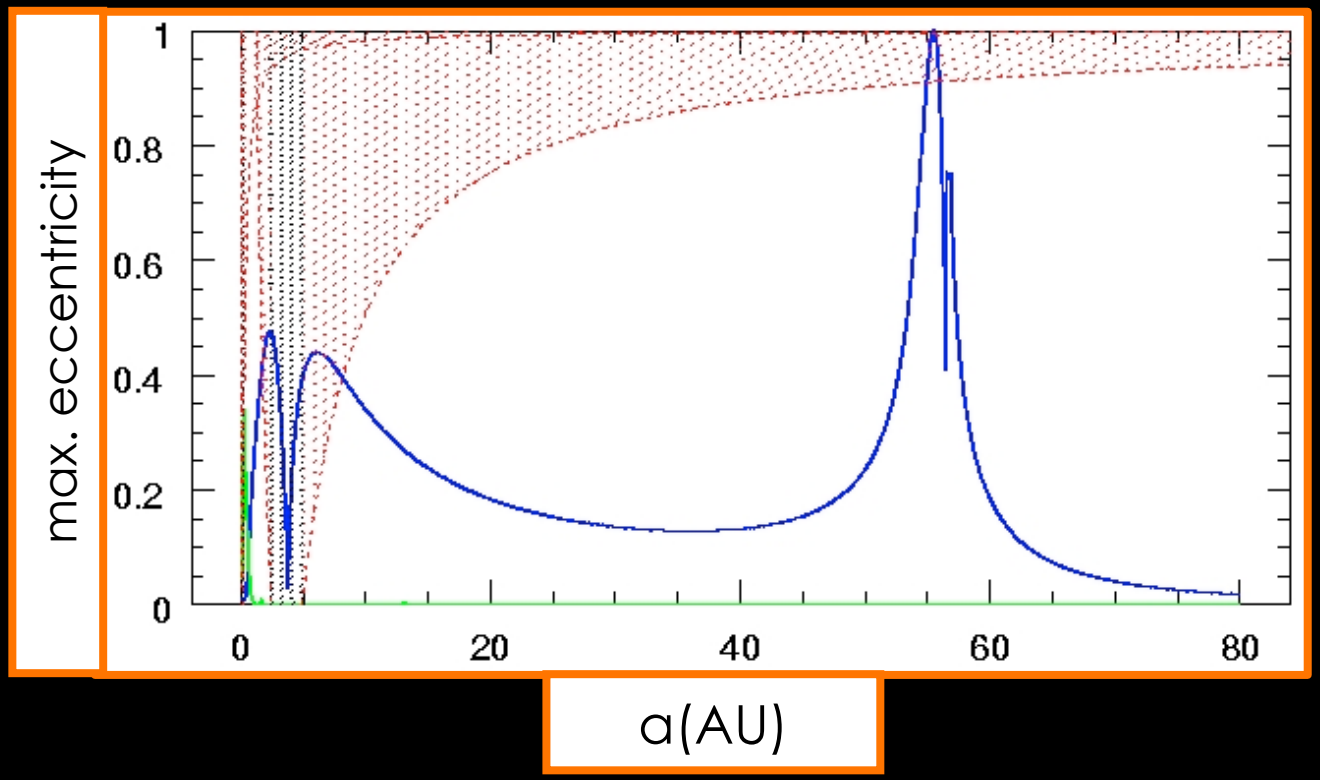
- Secular perturbations



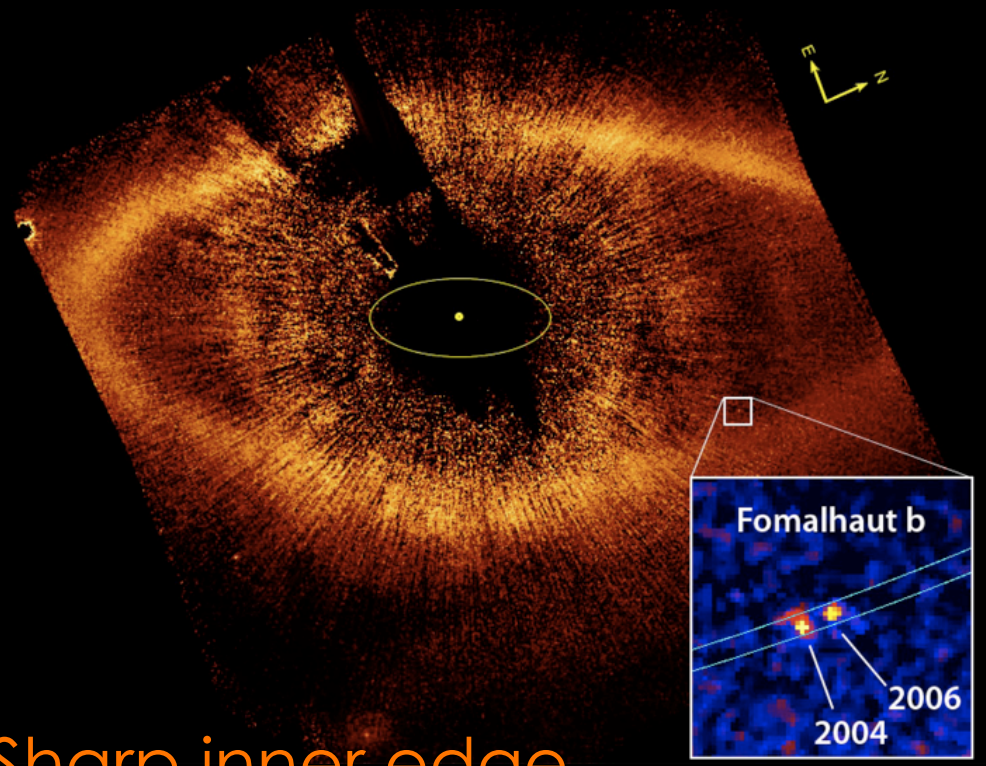
(Moro-Martin et al. 2007)

Planets can affect the debris disk structure

Debris disks structure as a planet detection method

- Sensitive to a wide range of planet masses and semi-major axes.
- Complementary to radial velocity and transit methods (sensitive to planets closer to the star) and to direct imaging (sensitive to young planets)

Planets can affect the debris disk structure

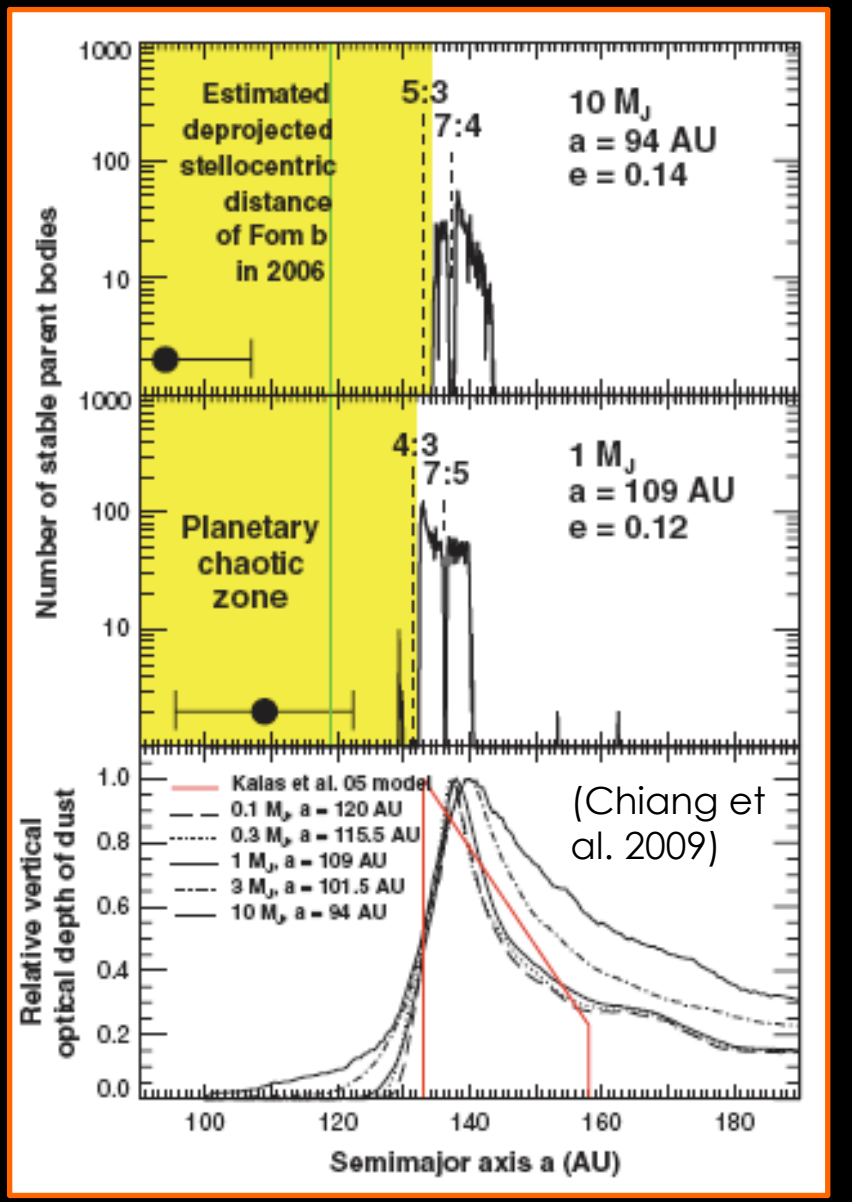


(Kalas et al. 2008)

Sharp inner edge
Off-centered disks

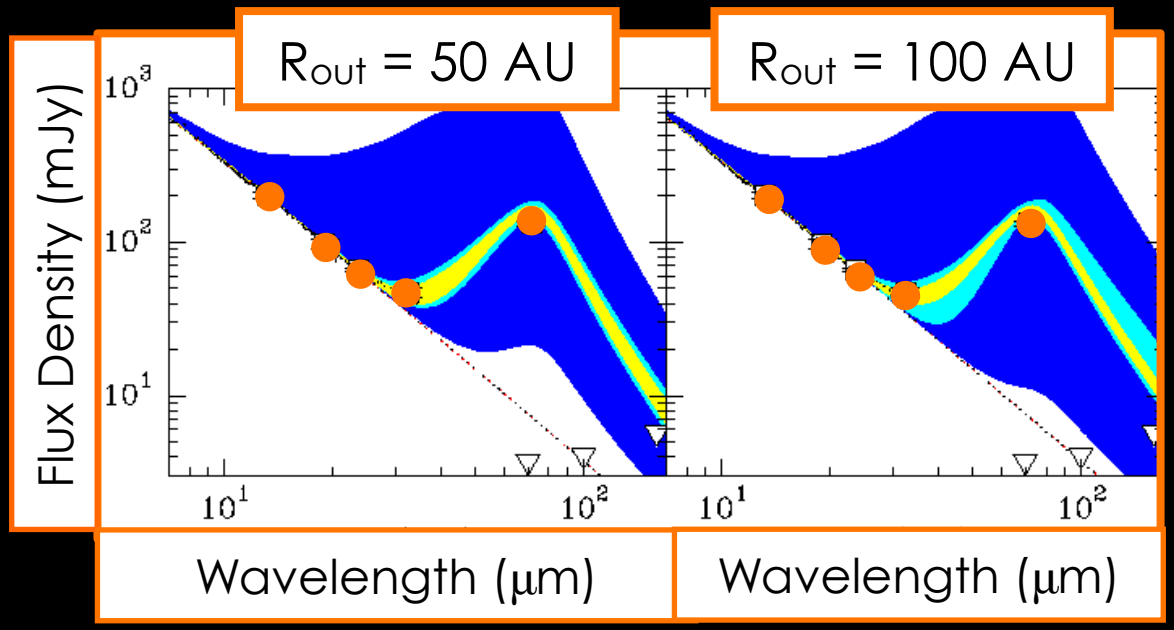
But most disks are unresolved

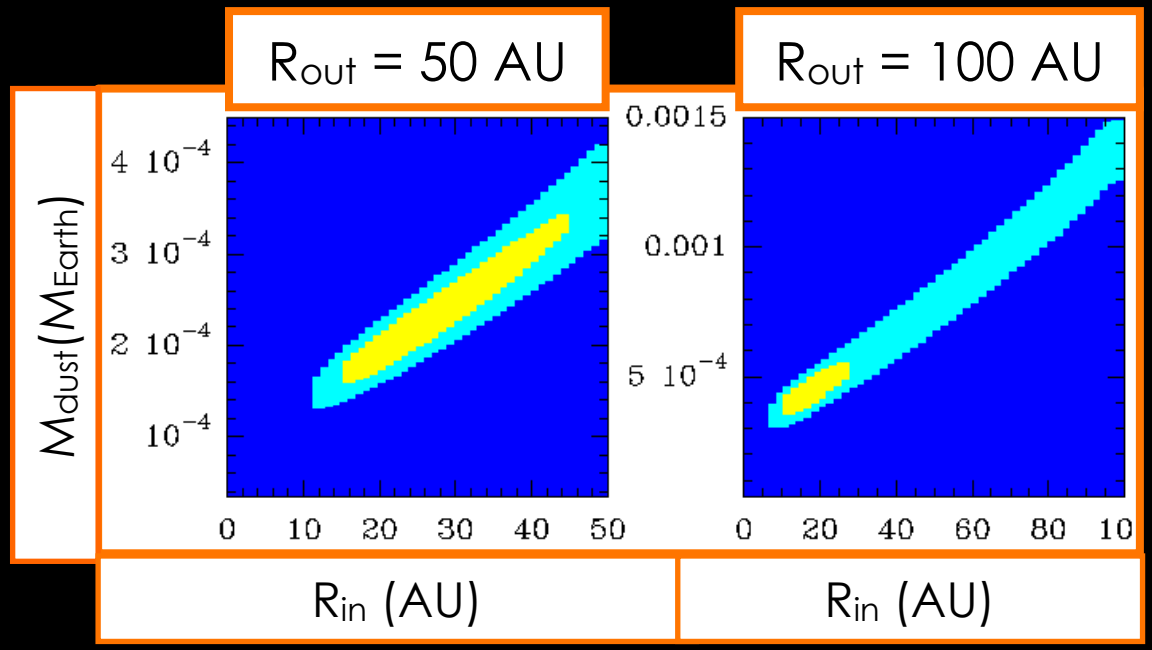
Need spatially resolved observations



(Chiang et al. 2009)

Need spatially resolved observations





HD 82943

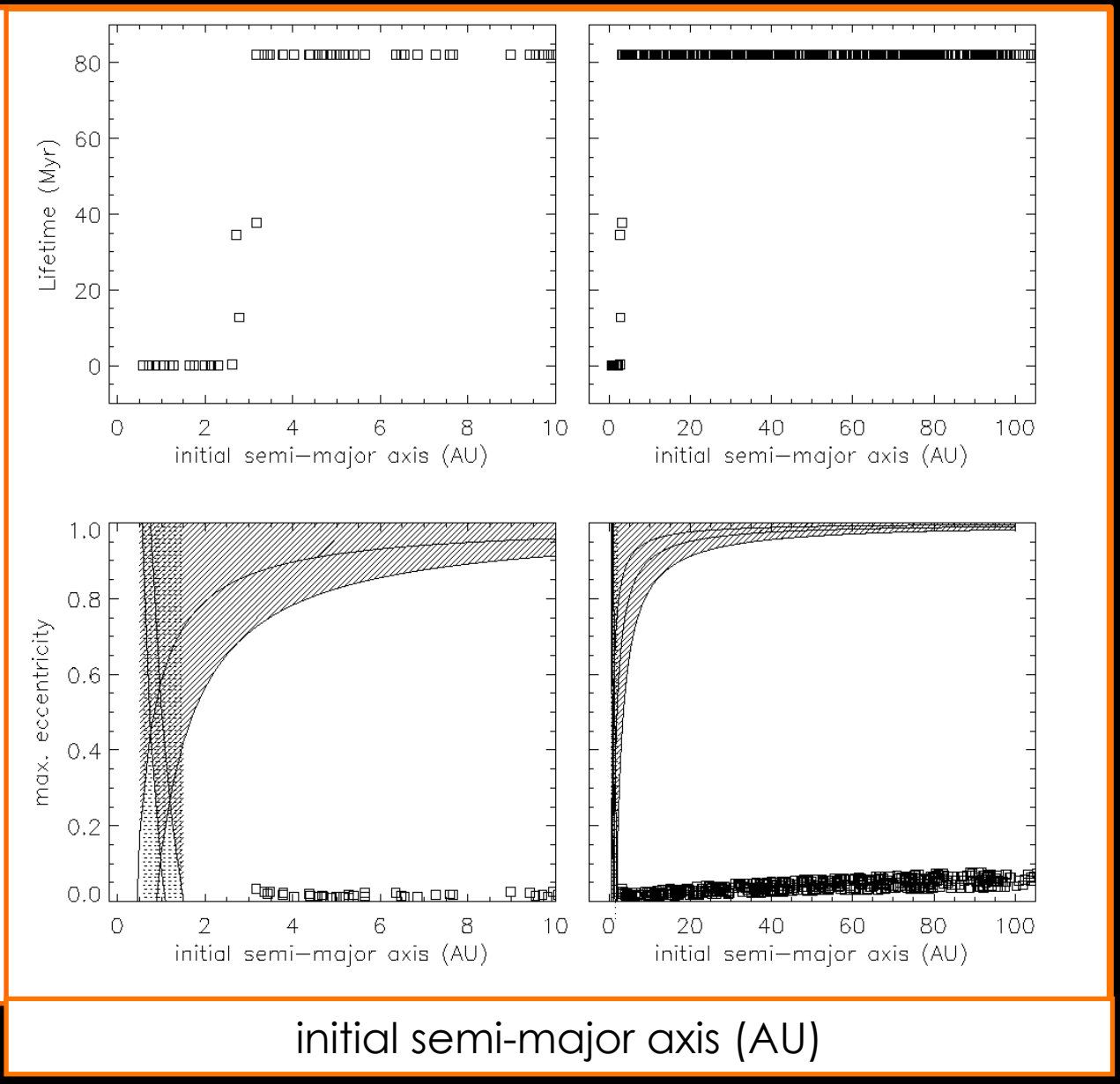
G0 V
age ~ 5 Gyr

Multiple-planet system:
b: M = 1.46 M_{Jup}
a = 0.75 AU
e = 0.45
c: M = 1.73 M_{Jup}
a = 1.19 AU
e = 0.27

(Moro-Martín et al. 2010)

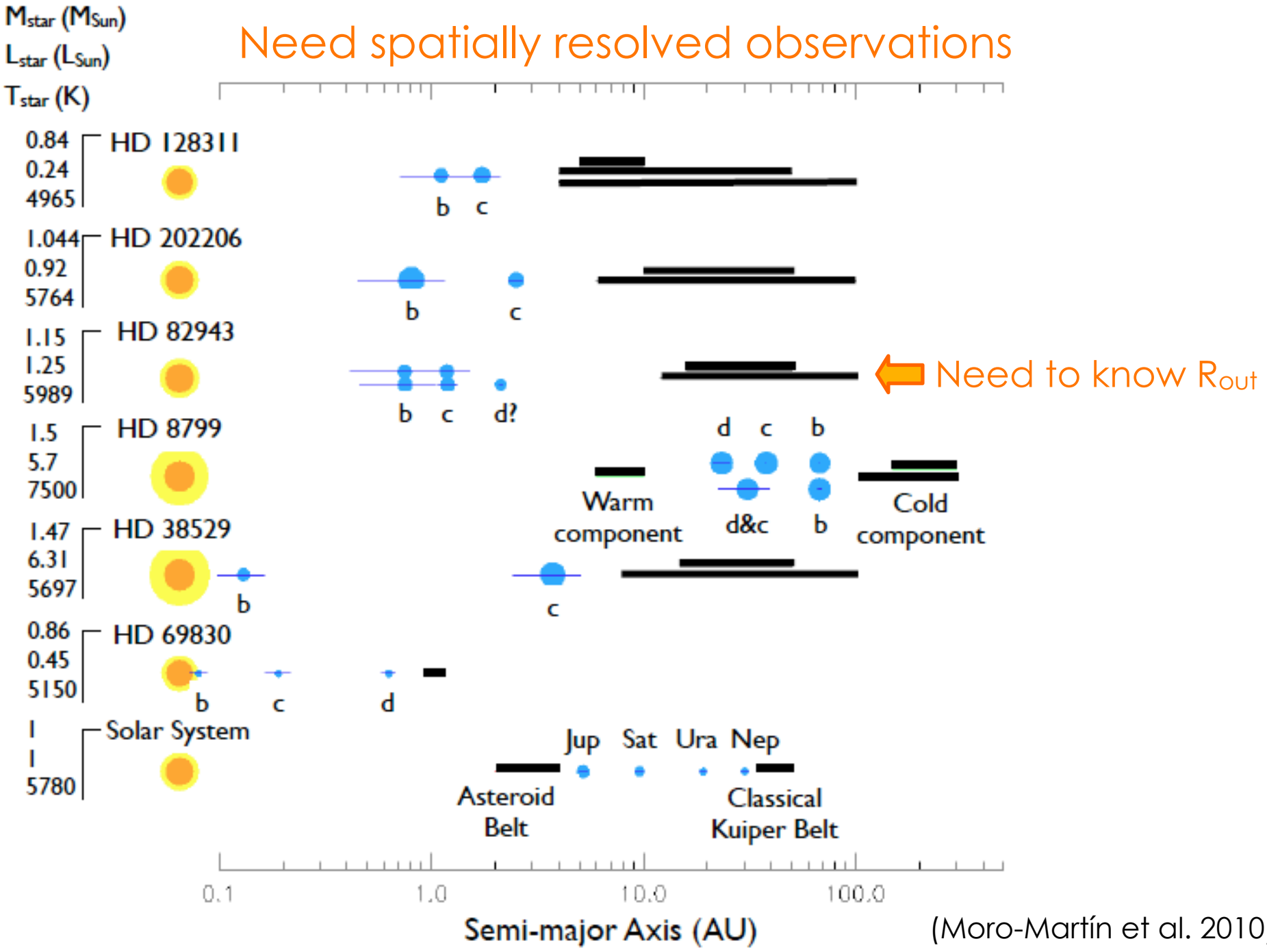
Need spatially resolved observations

HD 82943



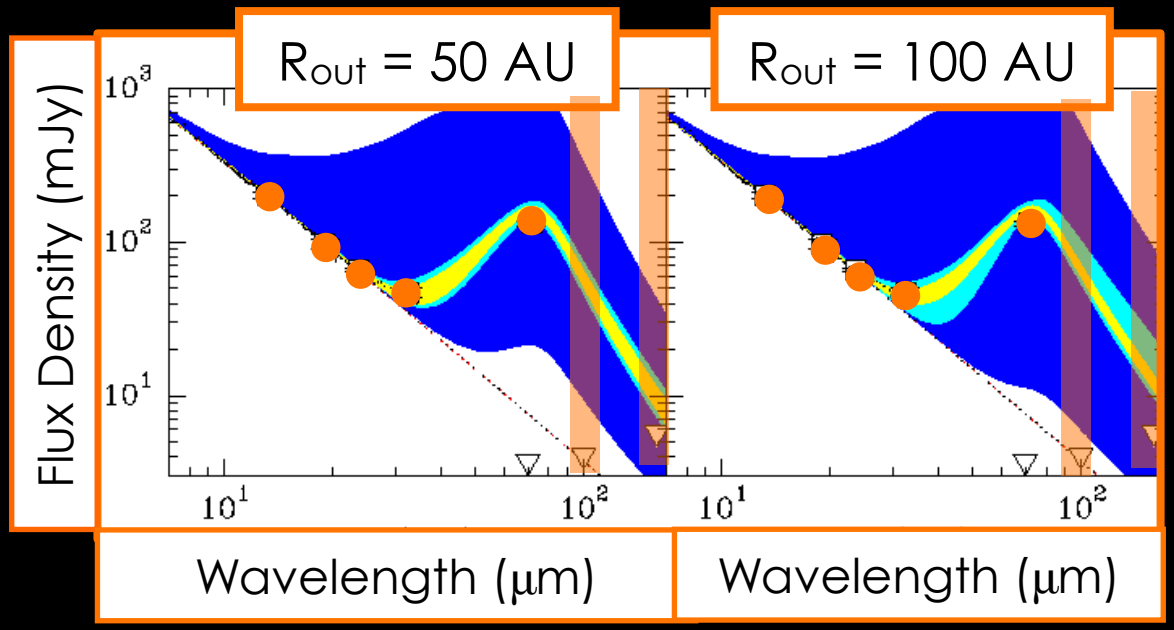
(Moro-Martín et al. 2010)

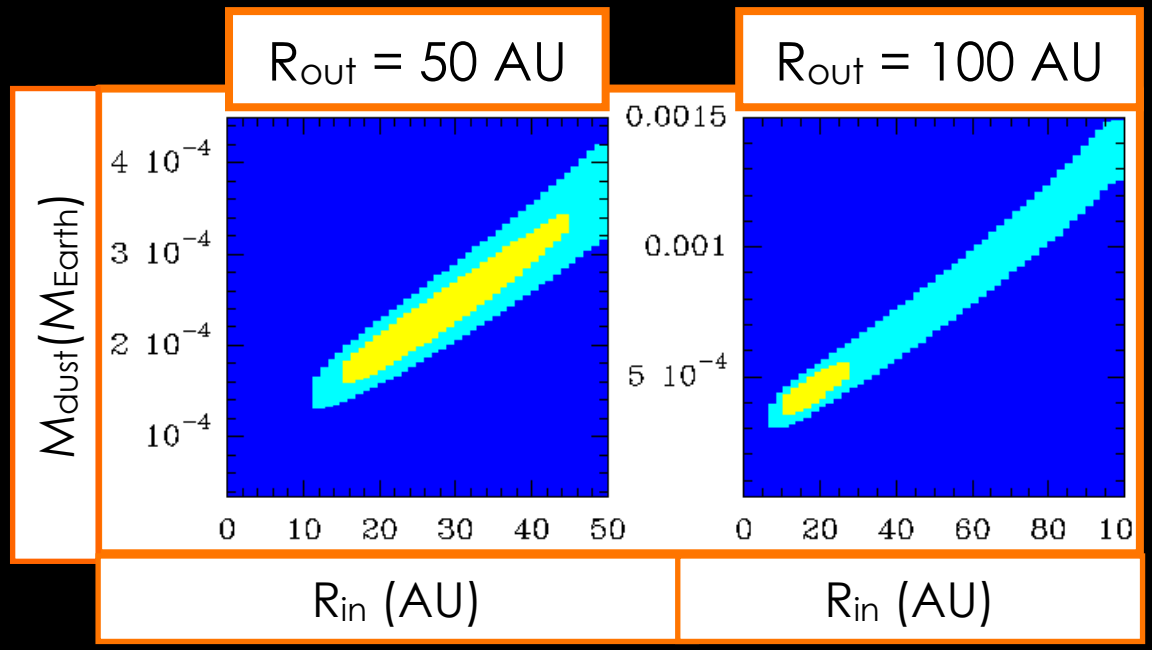
Need spatially resolved observations



(Moro-Martín et al. 2010)

Need spatially resolved observations





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We need spatially resolved observations with Herschel!