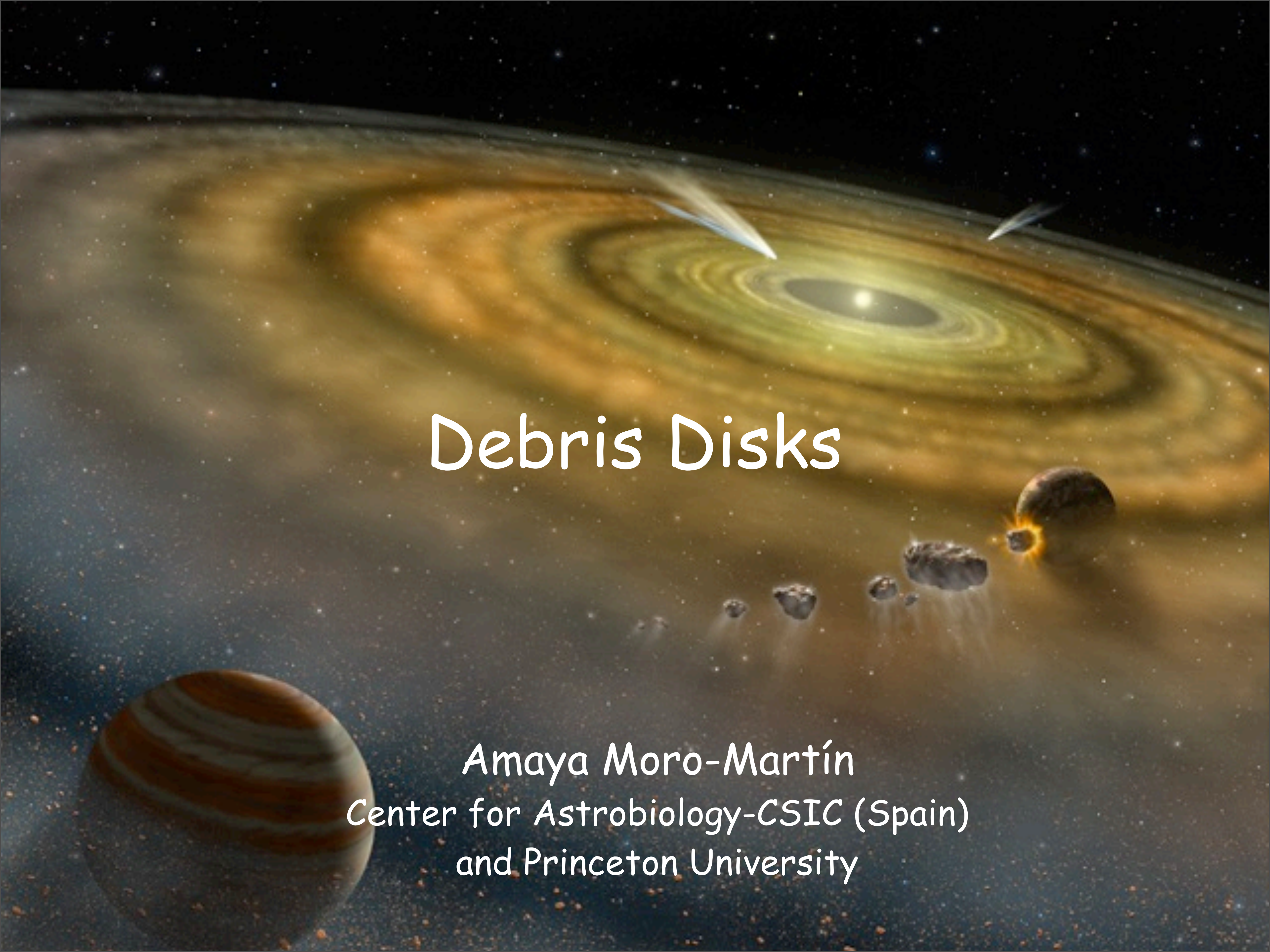


Debris Disks

Amaya Moro-Martín
Center for Astrobiology-CSIC (Spain)
and Princeton University

Outline

Part I

What is a debris disks

Part II

Why are debris disks interesting

Part III

Future prospects in debris disks studies

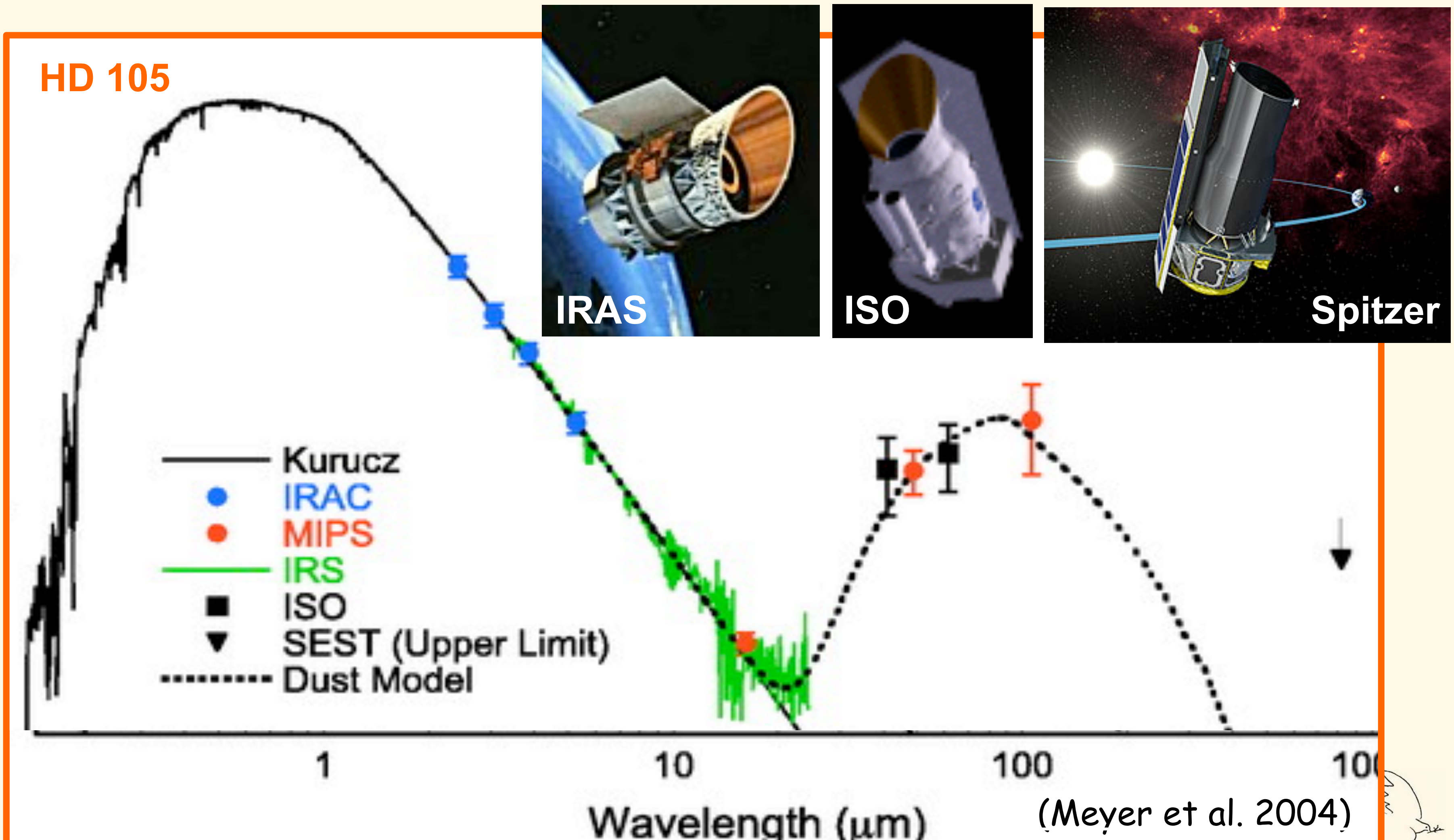
(of particular relevance to the Japanese community)

What is a debris disk

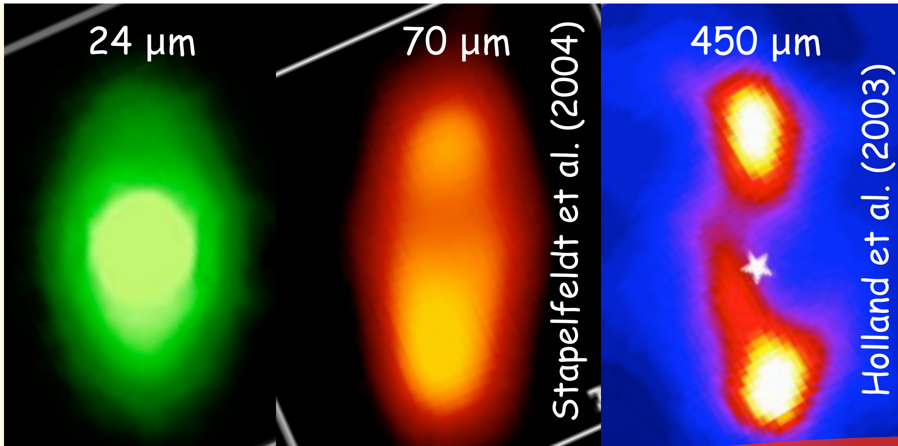
Debris disks main properties

- Disks of dust around mature (0.01-10 Gyr) main sequence stars (generally K2-A, i.e. 0.8-3 M_{sun})
- Sizes: 10s-100s AU (Solar System size)
- Low gas-to-dust ratio (primordial gas dissipates in < 10 Myr)
- There are ~300 known debris disks, mostly detected by IRAS and Spitzer from their IR excesses; some also detected in scattered light
- Mostly spatially unresolved

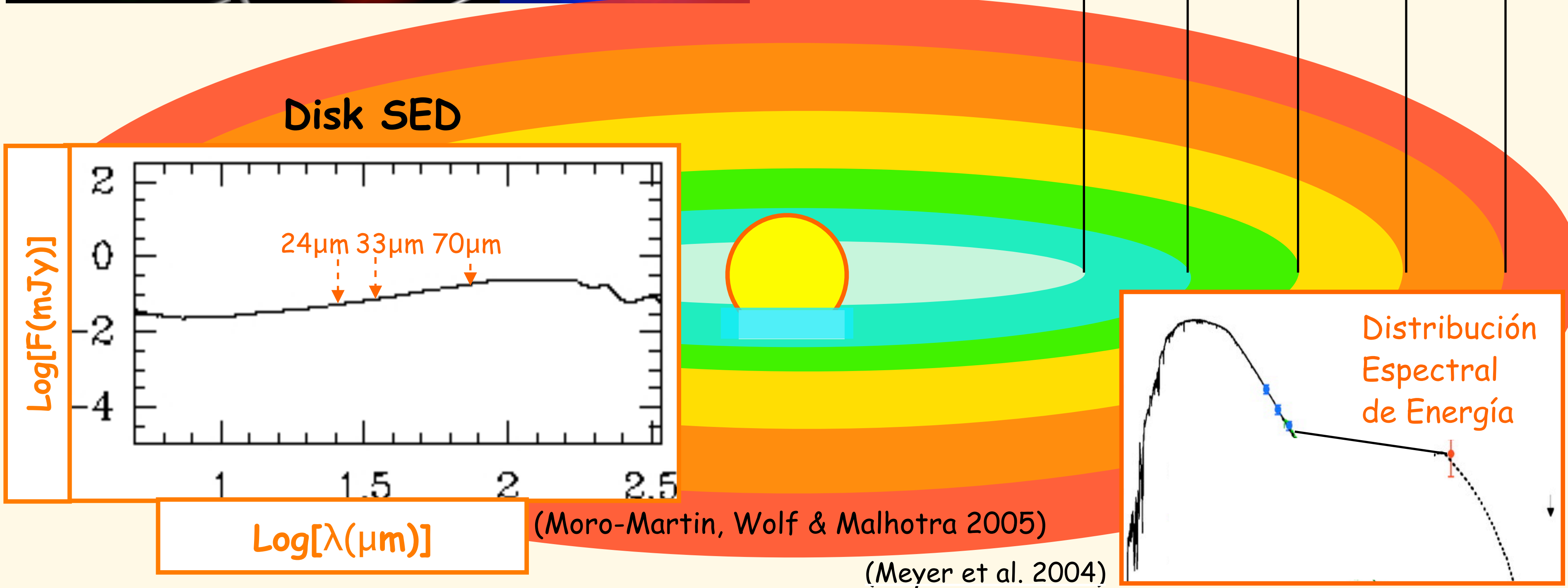
Debris disks main properties



Debris disks main properties



Disks are generally spatially unresolved.
Can constrain dust location from SED.



Debris disks main properties

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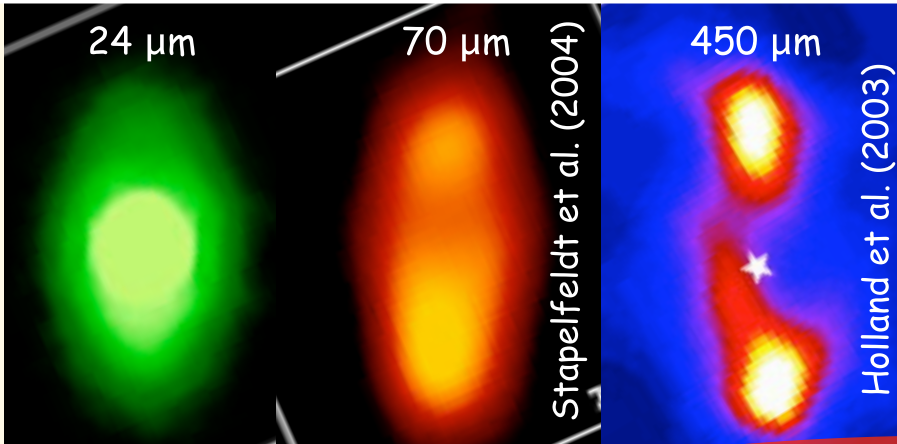
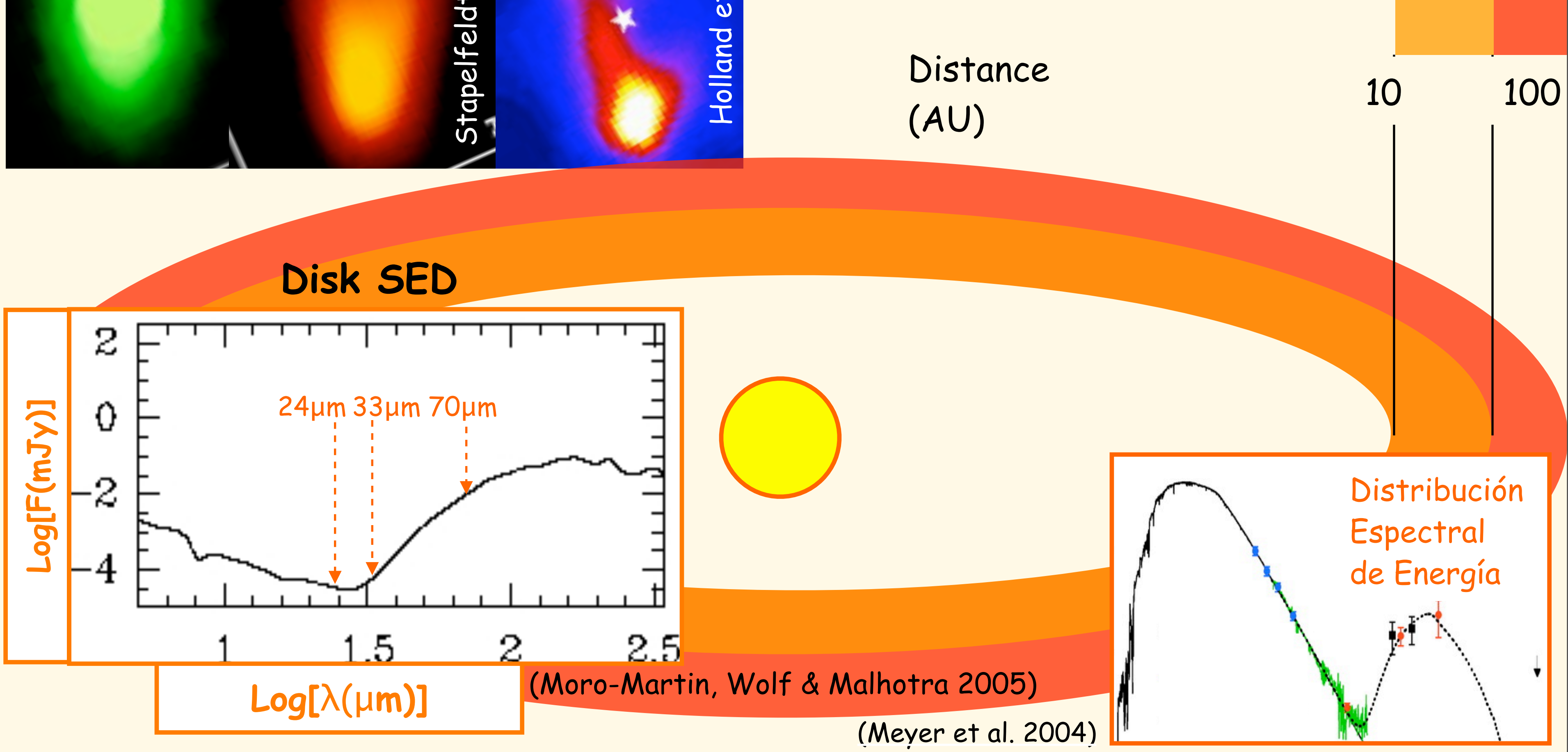




Debris disks main properties

- Frequency of debris disks from Spitzer surveys:
  - FEPS Legacy survey: 328 FGK stars (0.7-1.4M_{sun}) >3 Myr.; 5-70 μm.
    Detection rates: 15% at 24 μm (<300 Myr), 3% at 24 μm (>300 Myr), 7% at 70 μm.
  - FGK GTO Survey: 150 FGK stars; 8-70 μm.
    Detection rates: 13+/-3% at 70 μm.
  - MIPS GTO Binary Survey: 69 A3-F8 binaries.
    Detection rates: 9+/-4% at 24 μm and 40+/-7% at 70μm (1/2 circumbinary and 1/3 circumstellar)
  - MIPS GTO A-star Survey: 160 A stars, 5-850 Myr.
    Detection rates: 32+/-5% at 24 μm and 33+/-5 at 70μm.

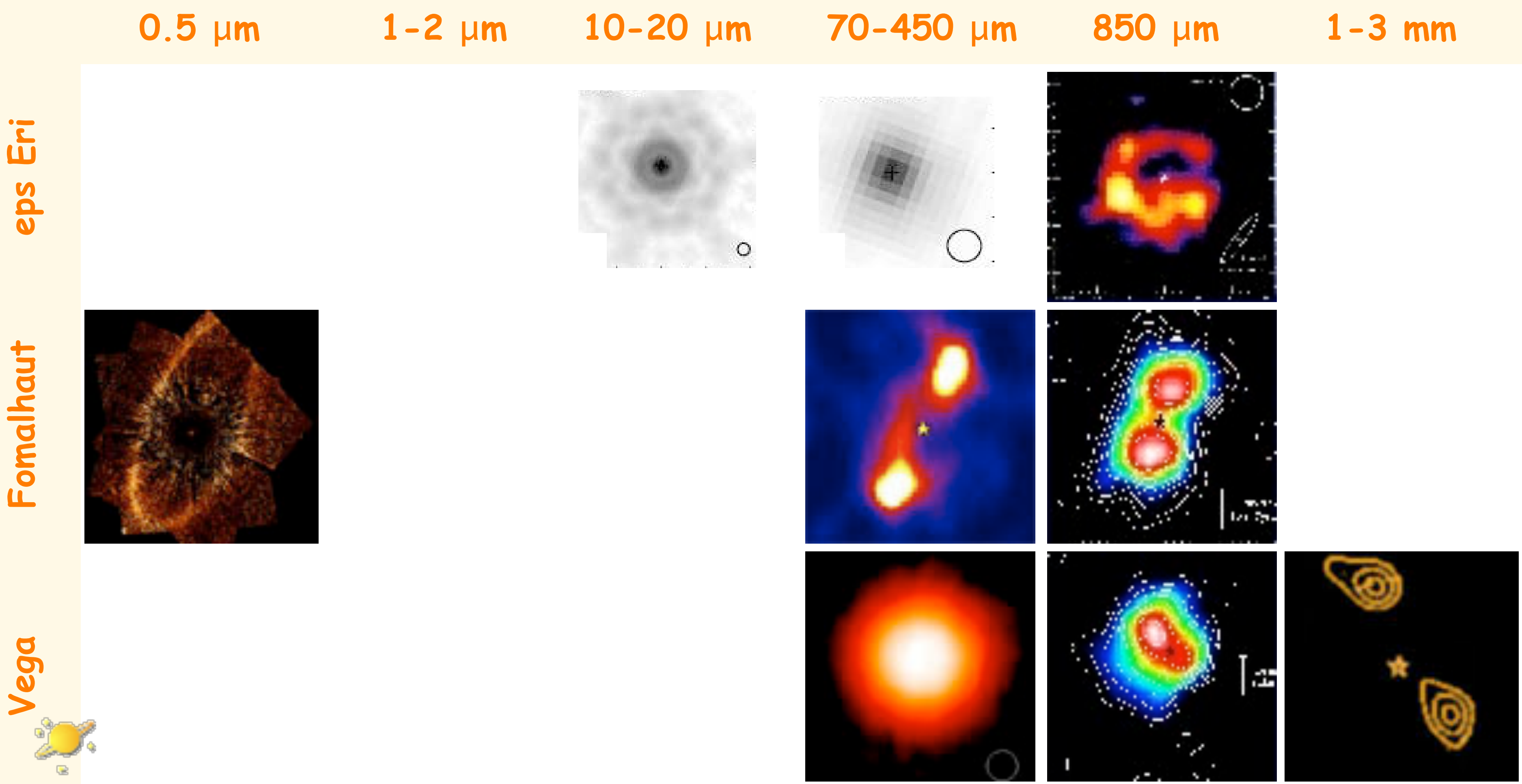
  Surveys limited to $L_{dust}/L_* \sim 10^{-5}$

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

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

- 22 spatially resolved; showing a complex morphology (warps , spirals, offsets, brightness asymmetries, cumply rings, sharp inner edges...)

Gallery of spatially resolved debris disks

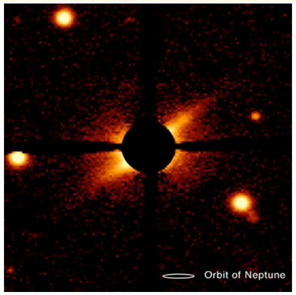


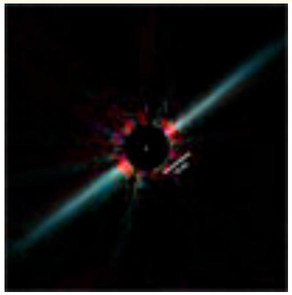
See individual references in http://astro.berkeley.edu/~kalas/disksite/pages/gallery.html#

Gallery of spatially resolved debris disks

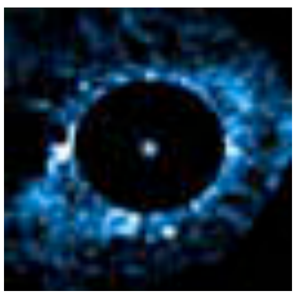
0.5 µm | 1-2 µm | 10-20 µm | 70-450 µm | 850 µm | 1-3 mm

AU Mic

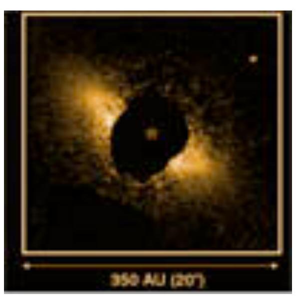




HD 207129



HD 10647



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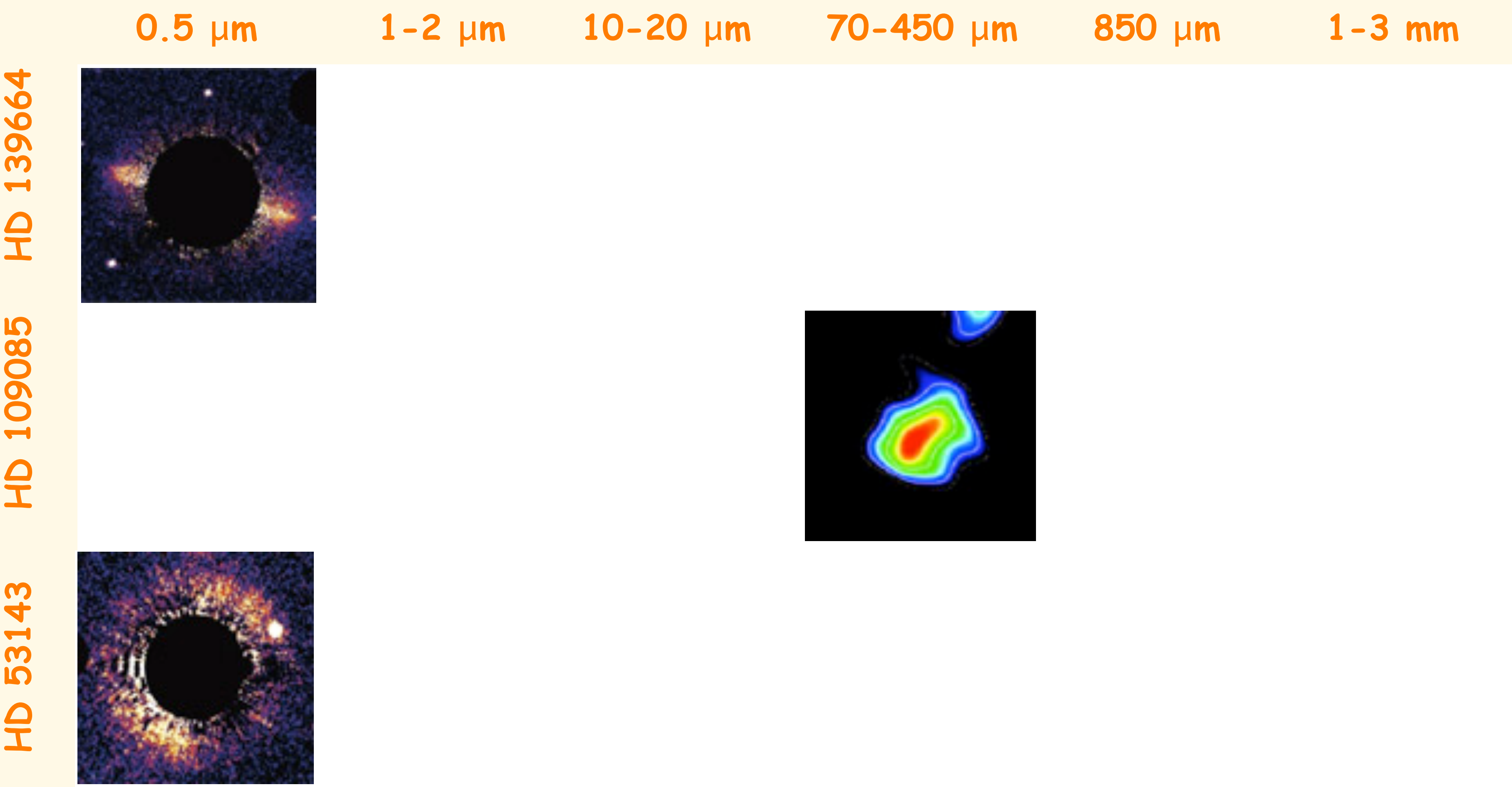
Gallery of spatially resolved debris disks



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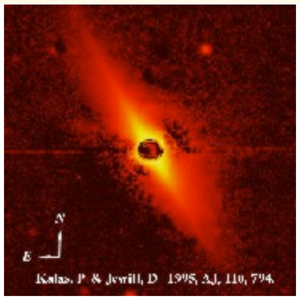
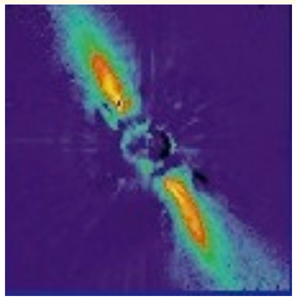
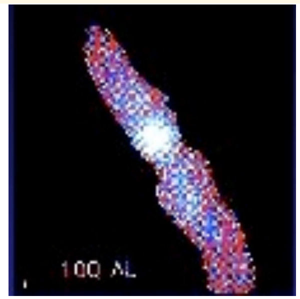
Gallery of spatially resolved debris disks

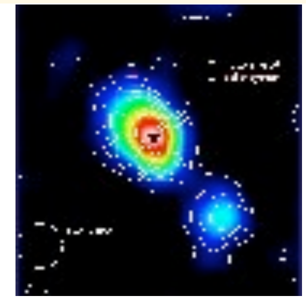
0.5 µm | 1-2 µm | 10-20 µm | 70-450 µm | 850 µm | 1-3 mm

beta Pic

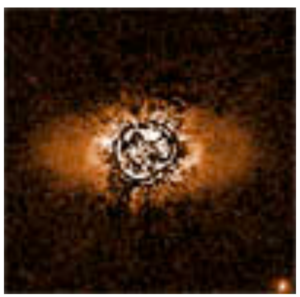




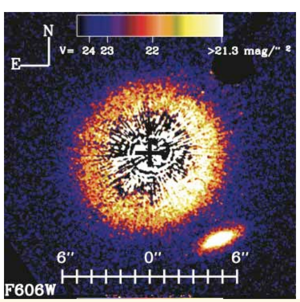




HD 92945



HD 107146



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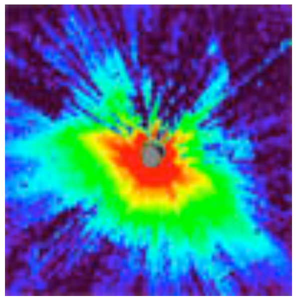
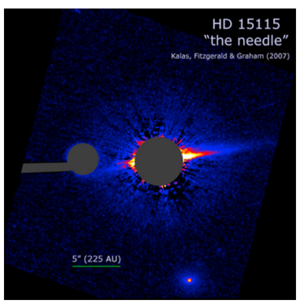
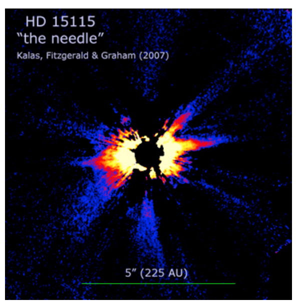
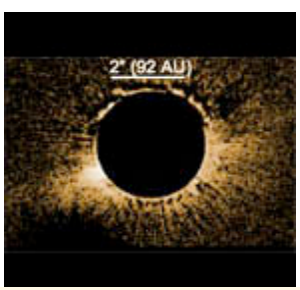
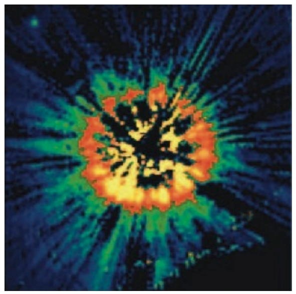
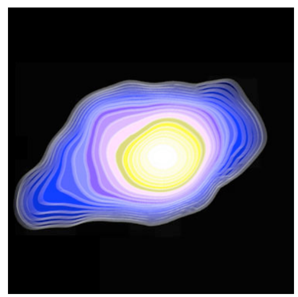
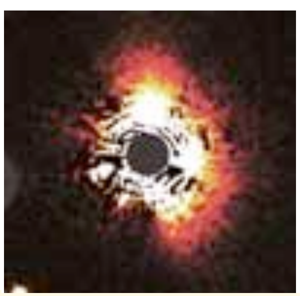
Gallery of spatially resolved debris disks

	0.5 μm	1-2 μm	10-20 μm	70-450 μm	850 μm	1-3 mm
HD 61005						
HD 15115						
HD 202917						

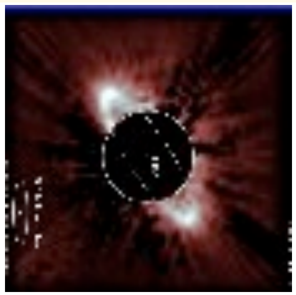
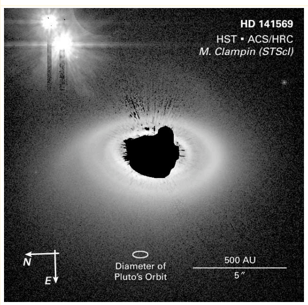
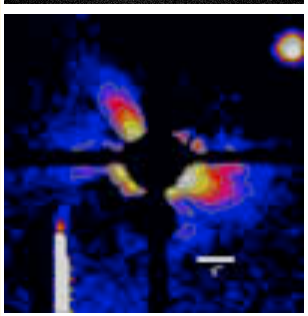
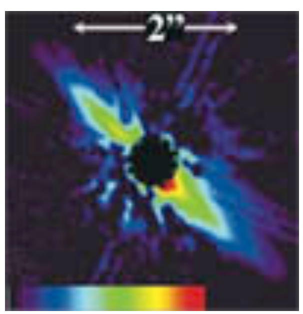
See individual references in http://astro.berkeley.edu/~kalas/disksite/pages/gallery.html#

Gallery of spatially resolved debris disks

	0.5 µm	1-2 µm	10-20 µm	70-450 µm	850 µm	1-3 mm
HD 181327						
49 Cet						
HD 15745						

See individual references in http://astro.berkeley.edu/~kalas/disksite/pages/gallery.html#

Gallery of spatially resolved debris disks

	0.5 µm	1-2 µm	10-20 µm	70-450 µm	850 µm	1-3 mm
HR 4796A						
HD 141569						
HD 32297						

See individual references in http://astro.berkeley.edu/~kalas/disksite/pages/gallery.html#

Why are debris disks interesting

Debris disks are evidence of the presence of planetesimals

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

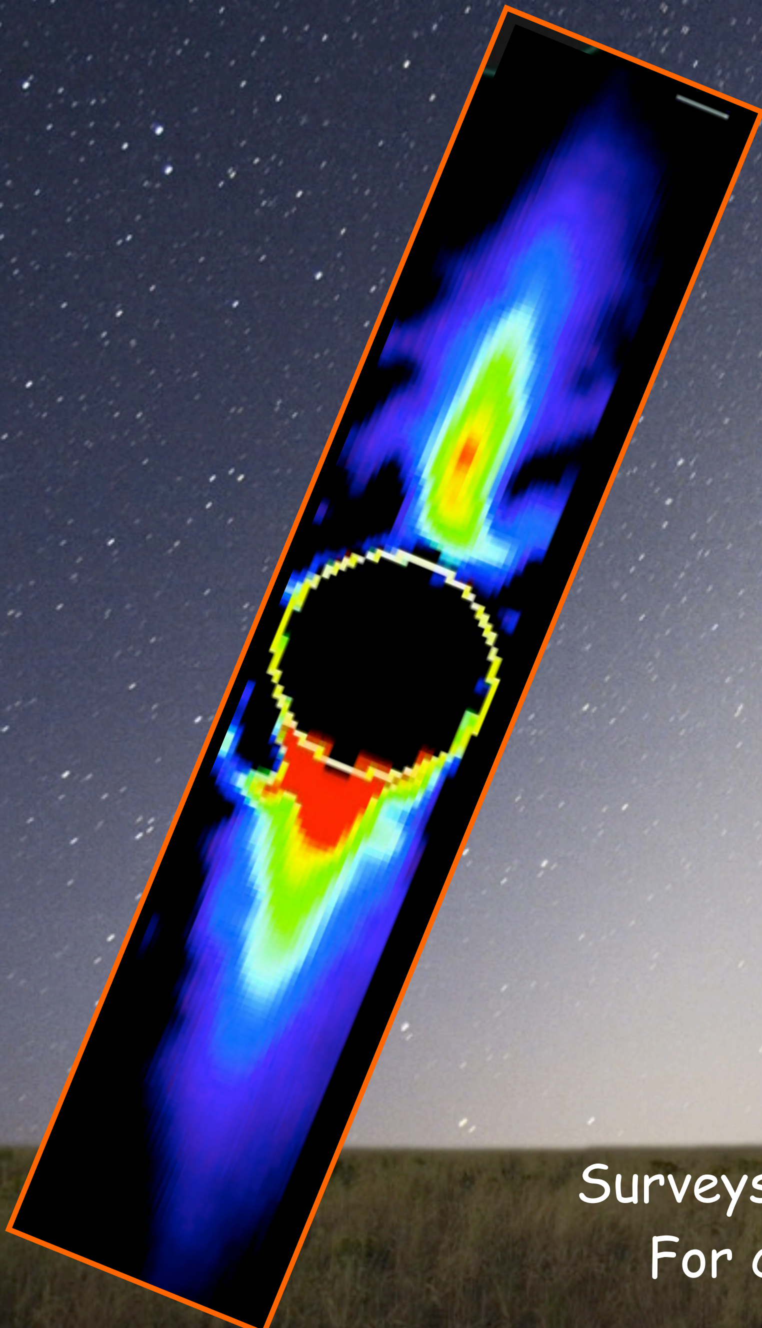
Radiation Pressure: $\frac{\tau_{blowout}}{yr} = 0.5\sqrt{\frac{(R/AU)^3}{(M_*/M_\odot)}}.$

<< Stellar age > 10^7 yrs

Dust is not primordial but is replenished by planetesimals (like asteroids, comets and KBOs). Indirect evidence that the first steps of planet formation have taken place.

Debris disks are planetary systems.


Interplanetary Dust
Particle (15 μm)

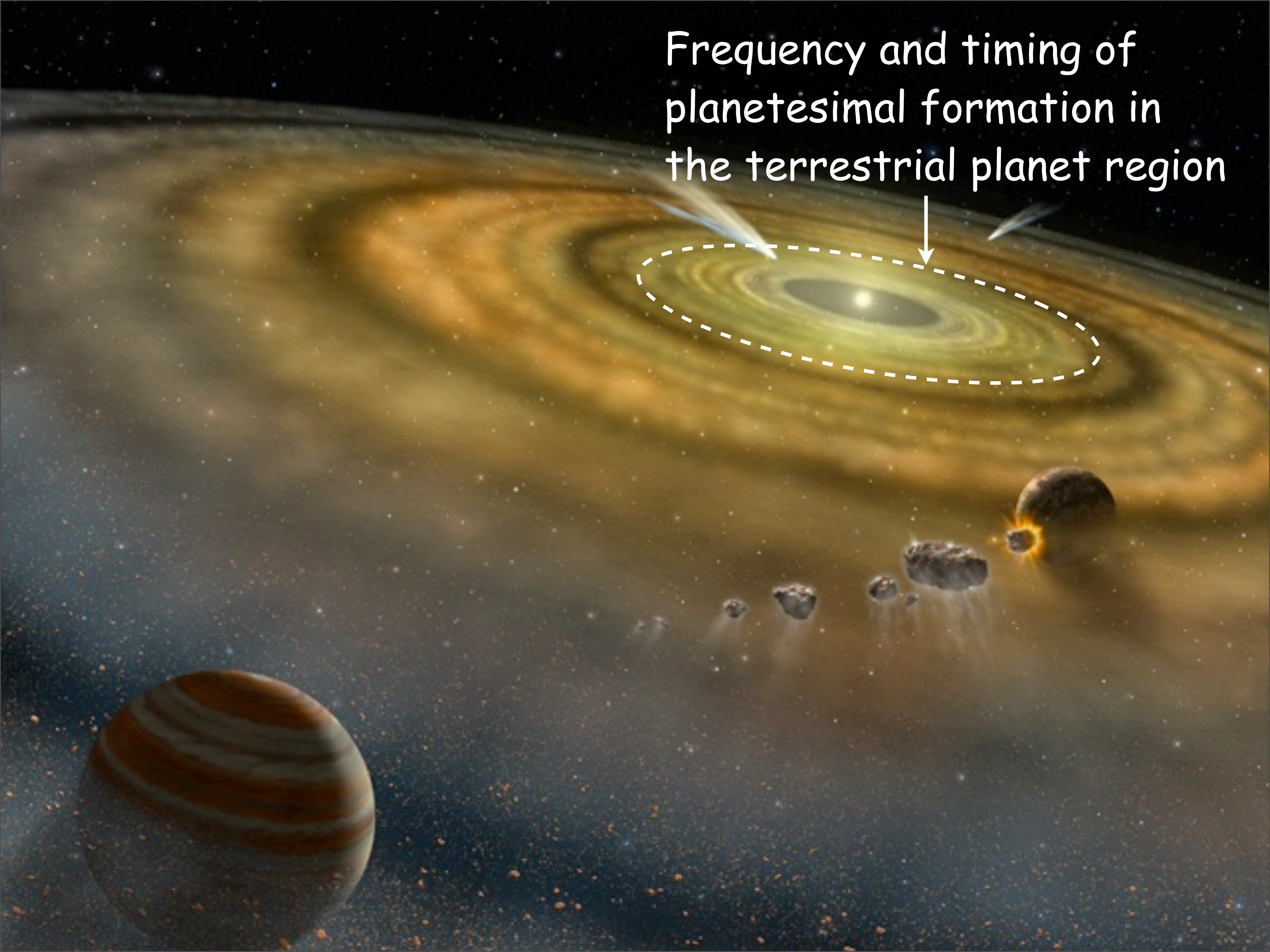


The study of debris disks can shed light on the diversity of planetary systems, helping us place our Solar System into context

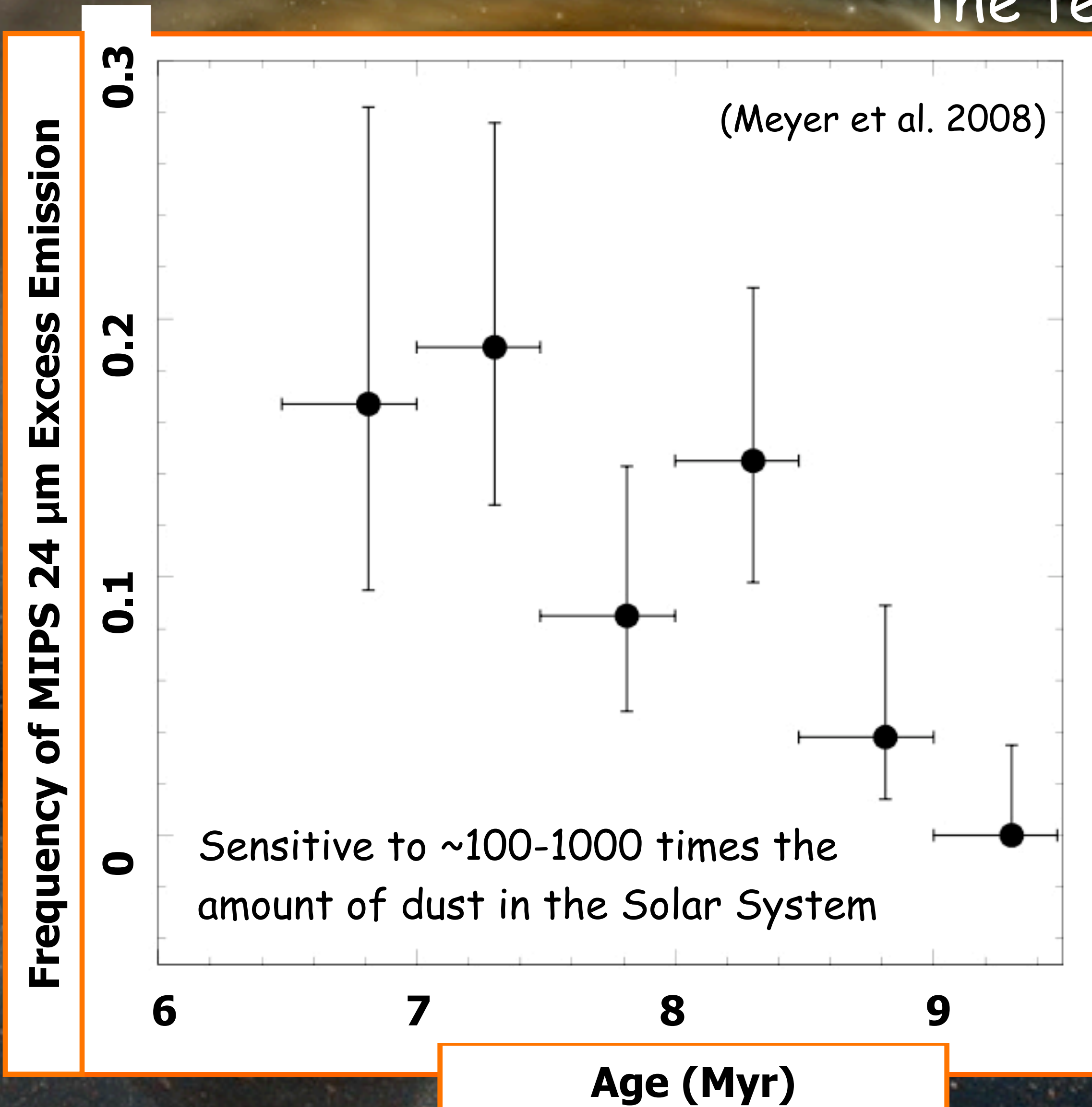
Surveys limited to $L_{dust}/L_* \sim 10^{-5}$

For comparison: $L_{dust}/L_* \sim 10^{-7}$-$10^{-6}$ for the KB

$L_{dust}/L_* \sim 10^{-8}$-$10^{-7}$ for the AB

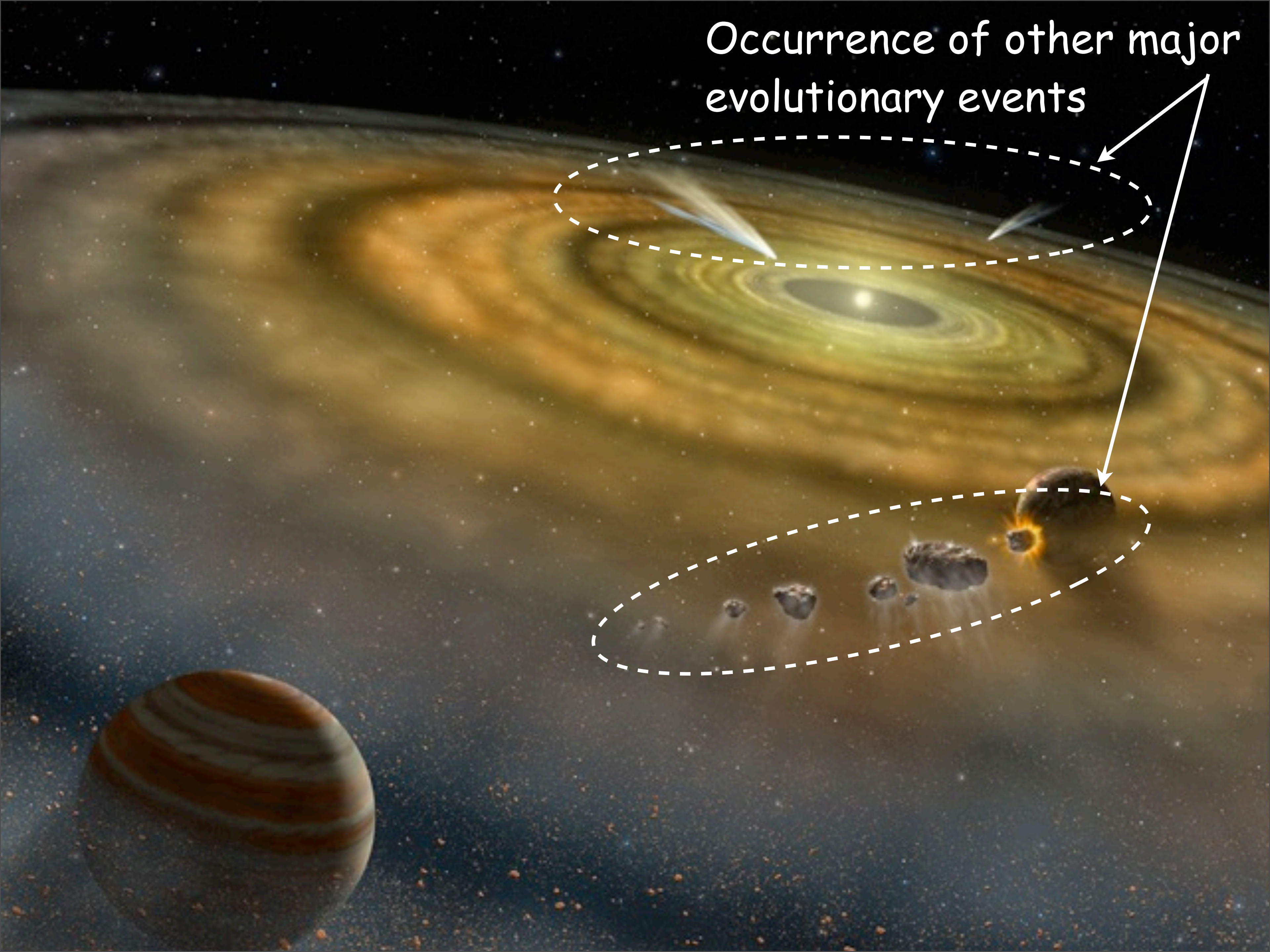

Frequency and timing of planetesimal formation in the terrestrial planet region

Frequency and timing of planetesimal formation in the terrestrial planet region

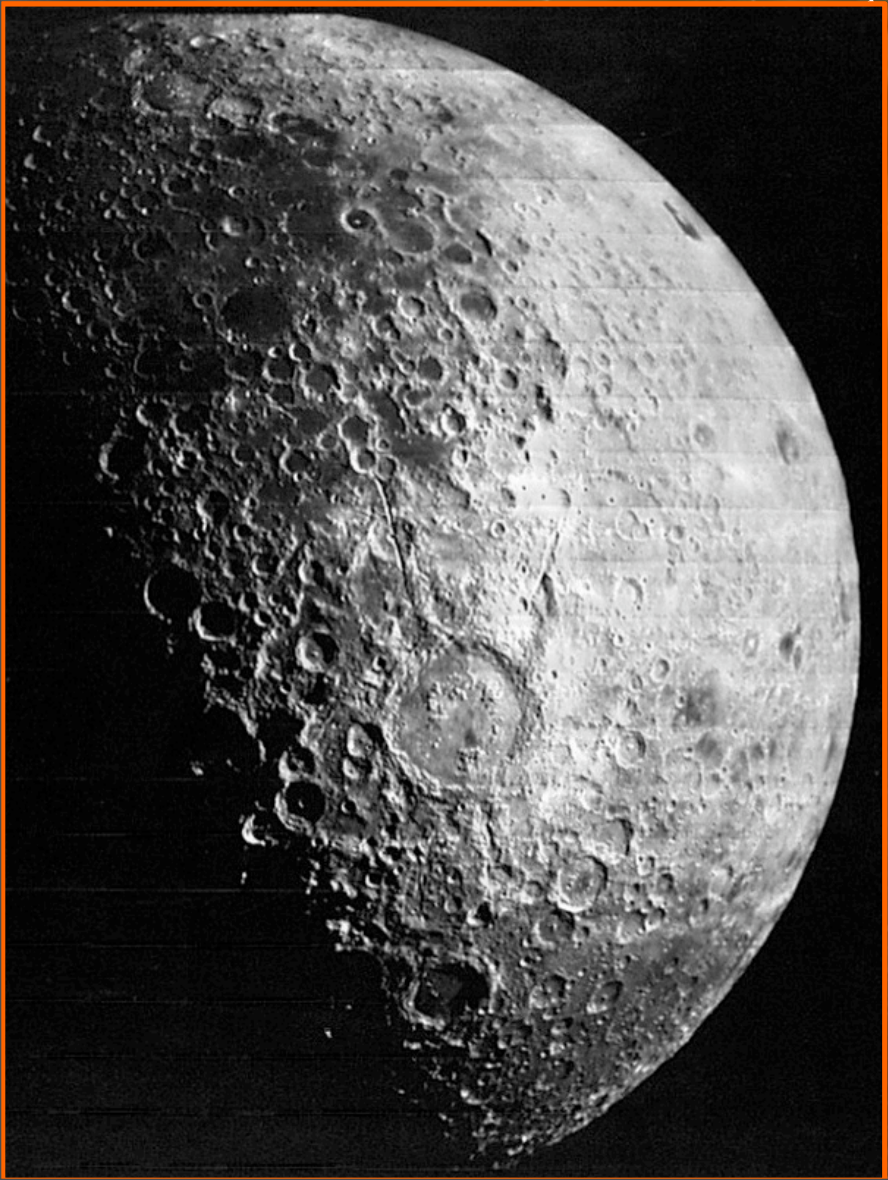


If epoch of 24 µm excess emission lasts < x10 the age bins, at least 32% of sun- like stars exhibit evidence of planetesimal formation in the terrestrial planet region.

If epoch lasts < age bins, frequency is > 60%.

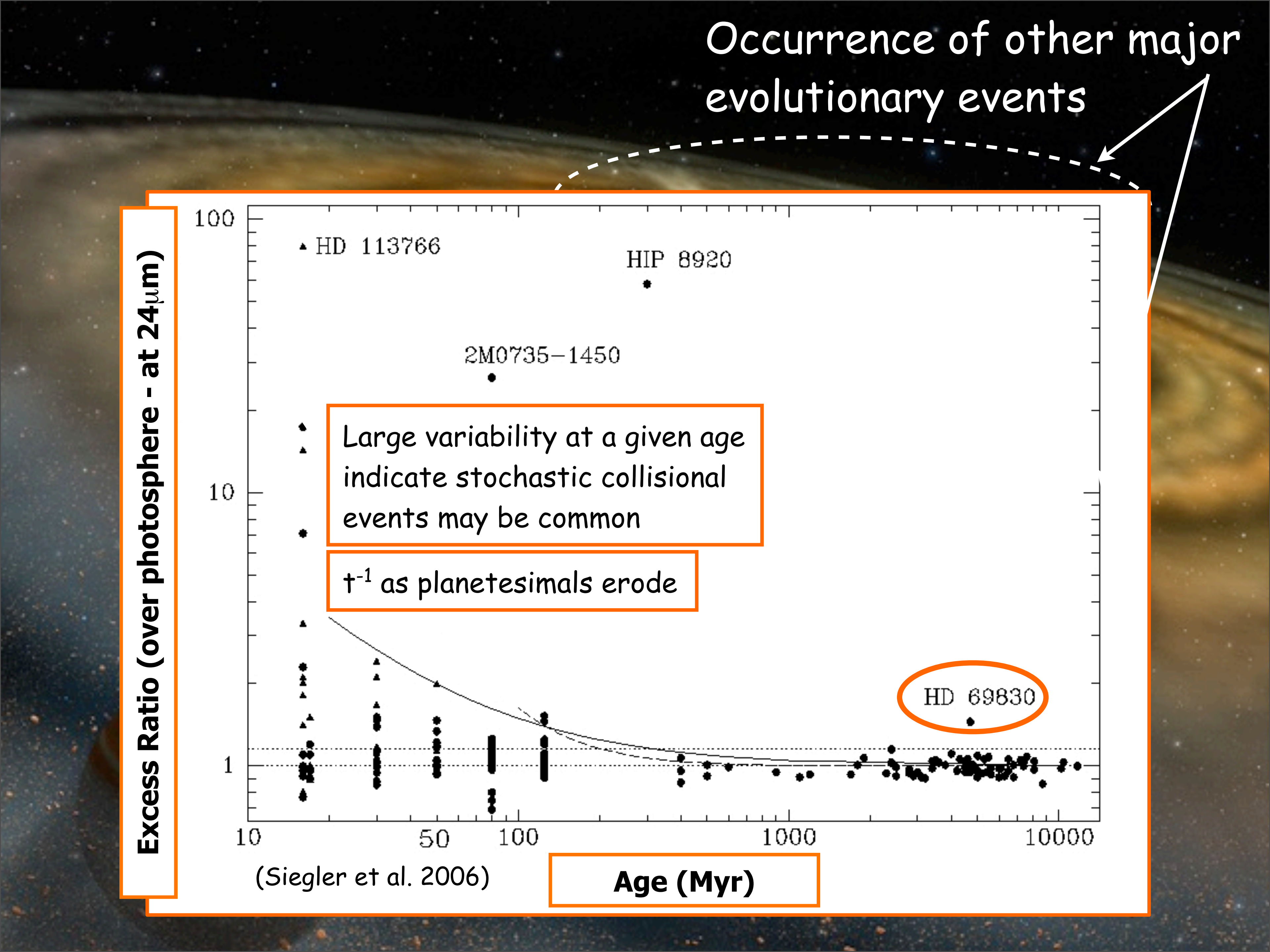

Occurrence of other major evolutionary events

Occurrence of other major evolutionary events



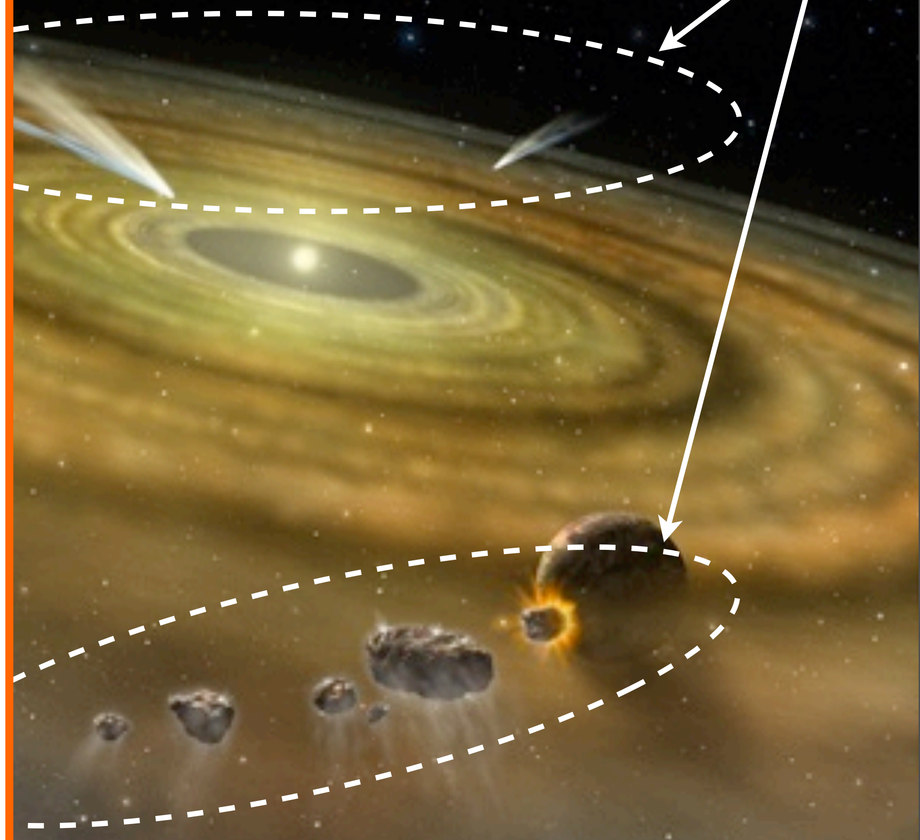
...e.g. the Late Heavy Bombardment in the early Solar system

- Narrow period of time (3.8-4.1 Gya)
- Large number of impact crater created in the Moon and the terrestrial planets (D_{crater} ~ 100 km $D_{impactor}$ ~ 10 km).
- Source of impactors: main asteroid belt.
- Triggered by orbital migration of giant planets; sweeping of secular resonances through AB; ejection of asteroids into planet-crossing orbits.
- Unique event in Solar system's history
- High rate of asteroid collisions and dust production
- Large spike in the warm dust luminosity of the young Solar System well after the planets were formed.



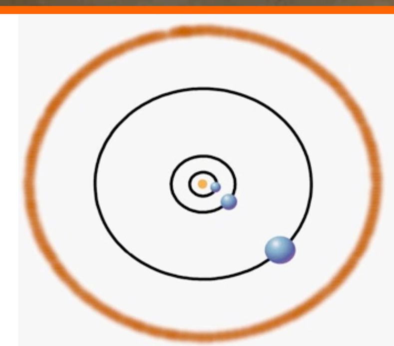
Occurrence of other major evolutionary events
Excess Ratio (over photosphere - at 24μm)
100
10
1
HD 113766
HIP 8920
2M0735−1450
HD 69830
Large variability at a given age indicate stochastic collisional events may be common
t⁻¹ as planetesimals erode
10
50
100
1000
10000
(Siegler et al. 2006)
Age (Myr)

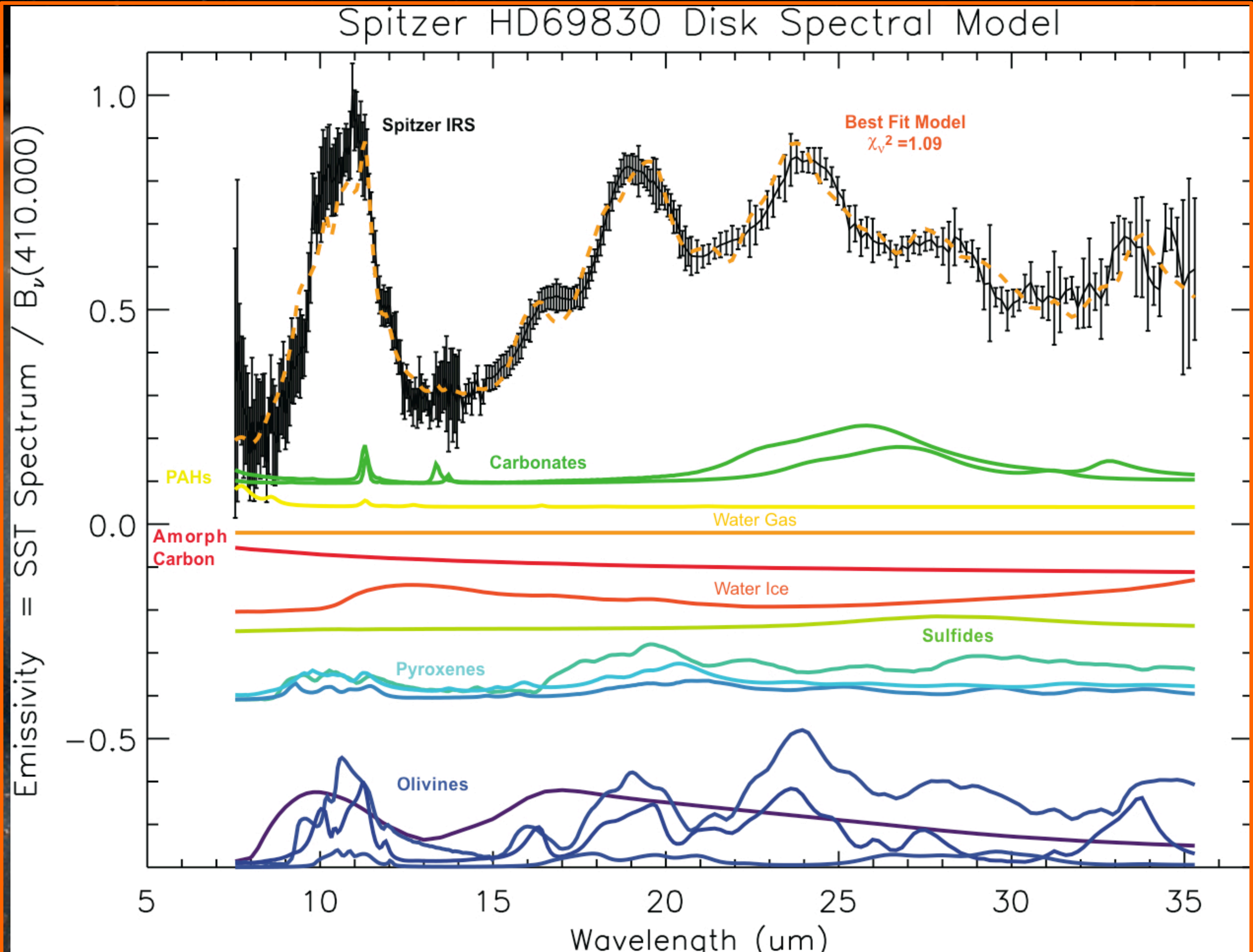
Occurrence of other major evolutionary events



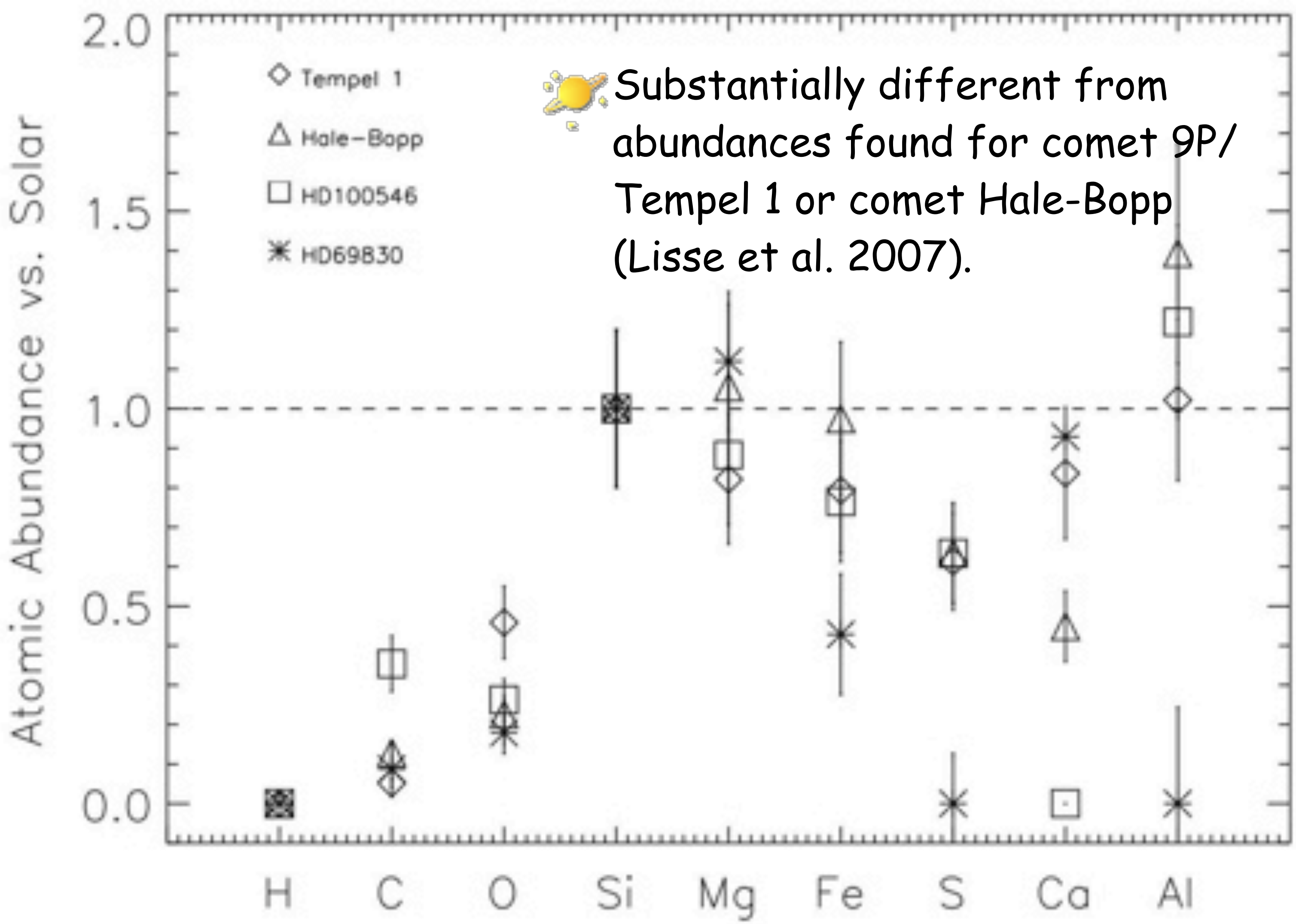
HD 69830 (K0V, 0.8M_{sun}, 0.45L_{sun}, 2 Gyr)

- 3 Neptune-like planets: ≥ 10.2 $M_\oplus$ at 0.0785 AU, ≥ 11.8 $M_\oplus$ at 0.186 AU and ≥ 18.1 $M_\oplus$ at 0.63 AU (Lovis et al. 2006)
- Spitzer shows a strong 24 μm excess (warm dust) but no 70 μm excess (no cold dust) (Beichman et al. 2005)
- Possibly a transient event, because...
  - The observed levels of dust production is too high to be sustained for the star's lifetime.
  - There are strong emission features implying small grains with short lifetimes.
- Could be an AB at ~ 1 AU (~2:1 and 5:2 MMRs of outermost planet - Lisse et al. 2007)
- ...or it could be a LBH-type of event where icy planetesimals are scattered into the inner system (Wyatt et al. 2006)



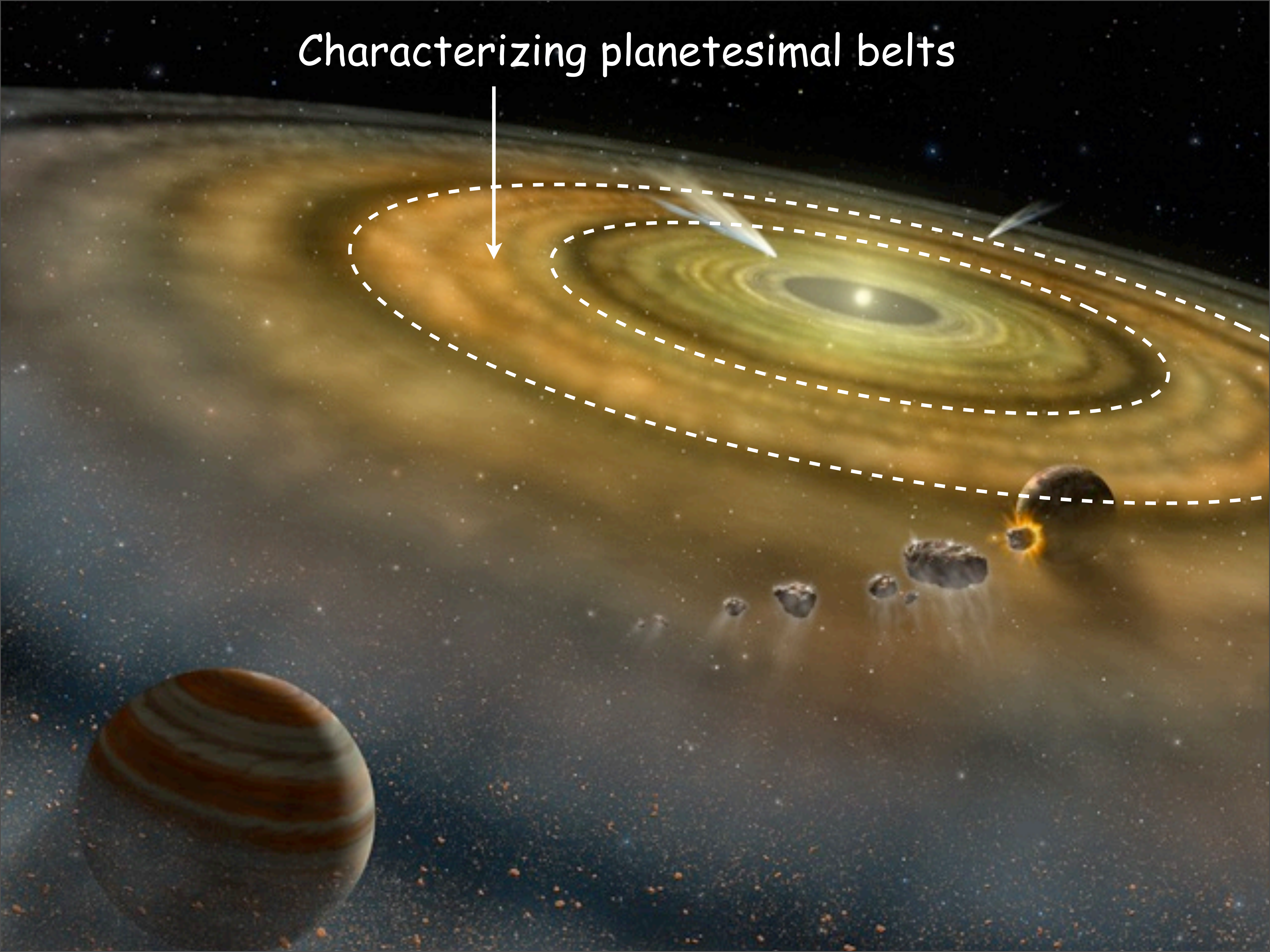


Spitzer HD69830 Disk Spectral Model
Spitzer IRS
Best Fit Model
χ_ν^2 =1.09
Carbonates
PAHs
Water Gas
Amorph Carbon
Water Ice
Sulfides
Pyroxenes
Olivines
Emissivity = SST Spectrum / B_ν(410.000)
Wavelength (um)
1.0
0.5
0.0
−0.5
5
10
15
20
25
30
35

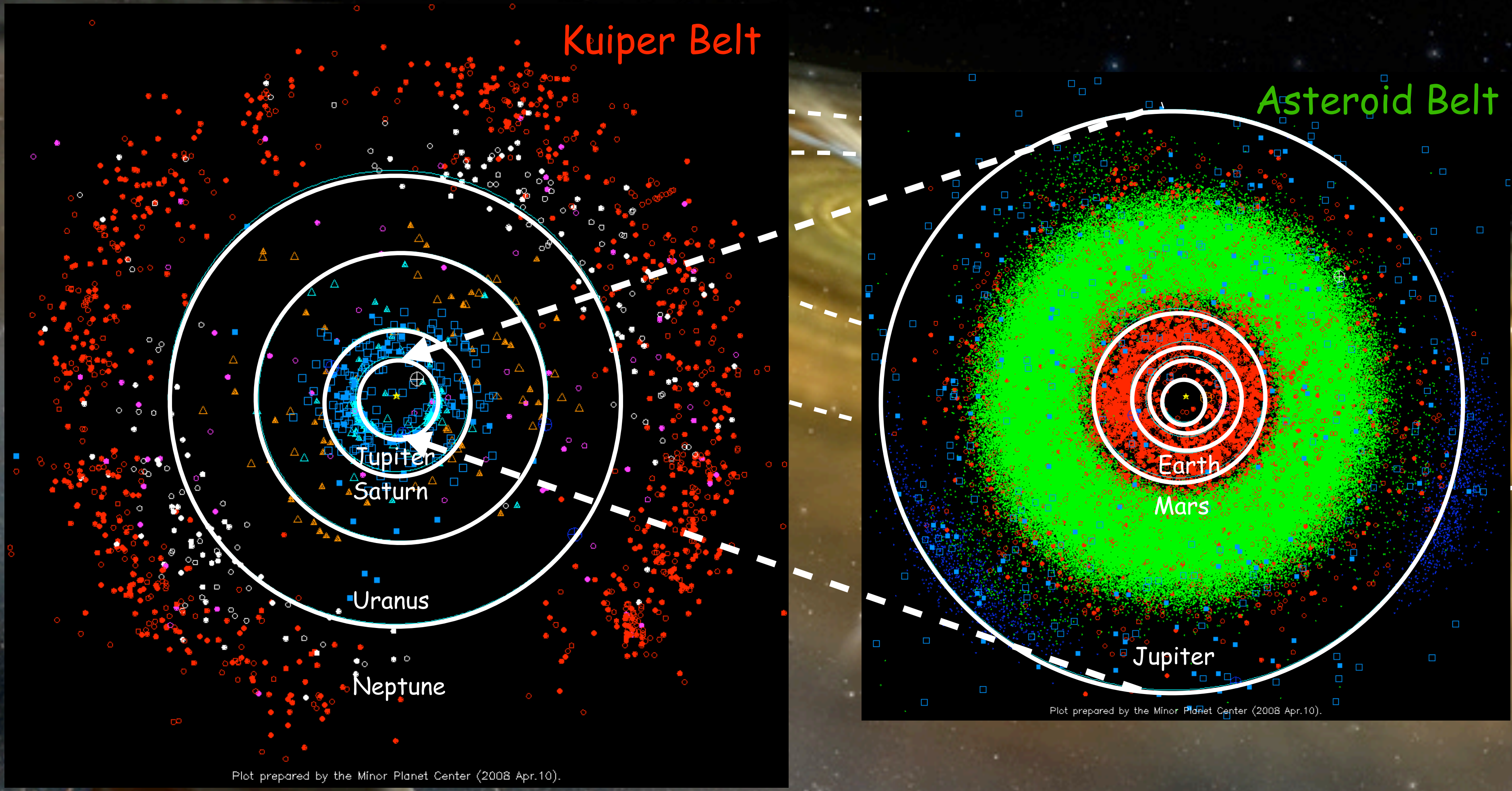


Substantially different from abundances found for comet 9P/Tempel 1 or comet Hale-Bopp (Lisse et al. 2007).

Similar to P- or D-type asteroidal body. Analogous to the fragmentation material that accompanied the formation of the Karin and Veritas families in the Solar system.


Characterizing planetesimal belts

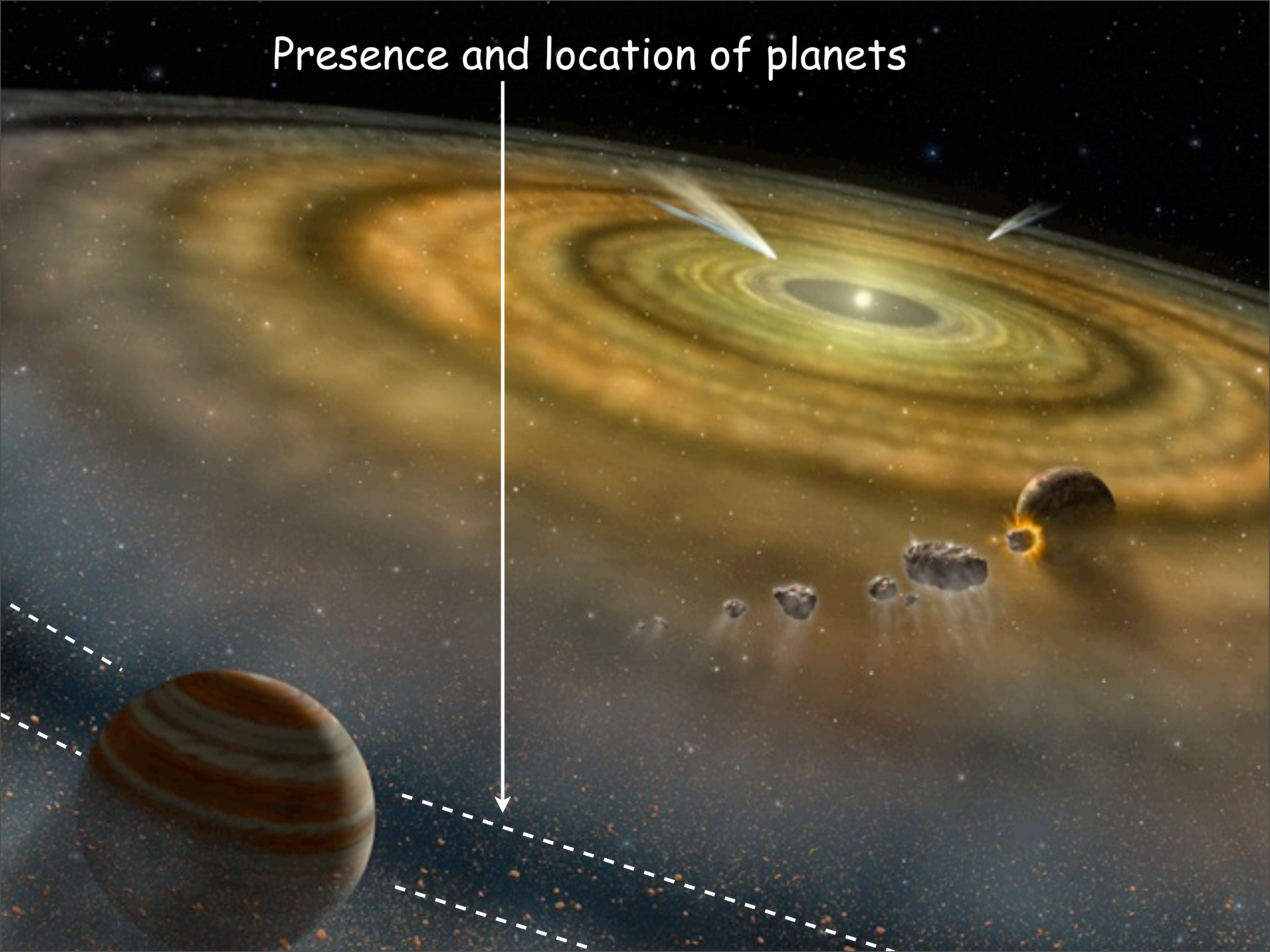
Characterizing planetesimal belts



Frequency of cold debris disks (KB-type): ~10%
(Bryden et al. 2006, Hillenbrand et al. 2008, Carpenter et al. 2008.)

Frequency of giant planets (<20 AU): ~12%
(extrapolating from RV surveys; Marcy et al. 2005).

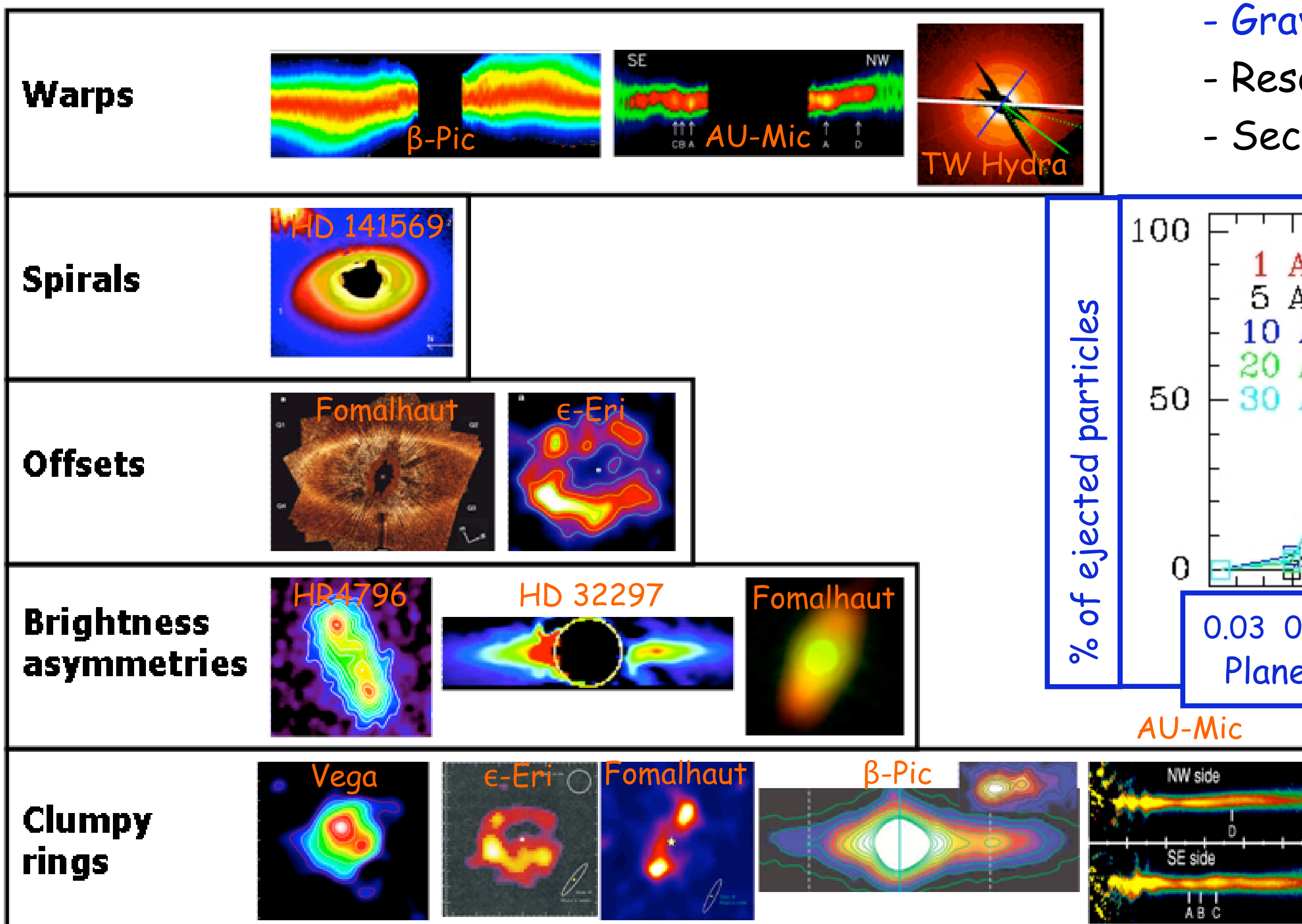
➡ But results are sensitivity limited to > 100x KB dust. Debris disks at the Solar System level may be common

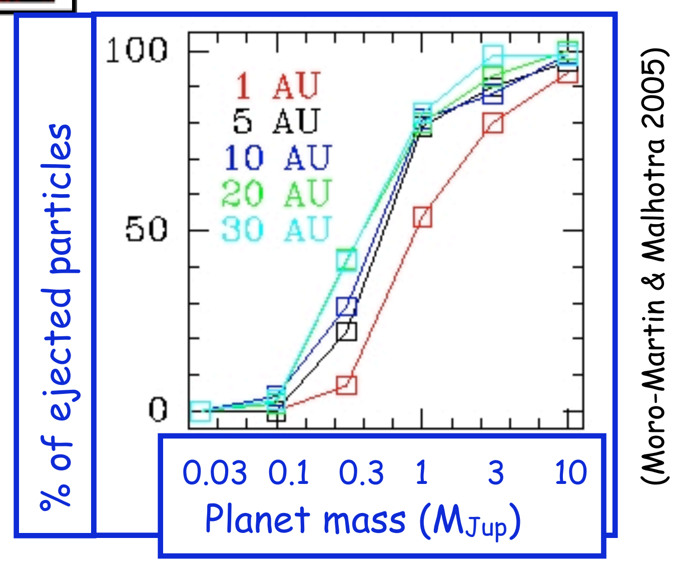

Presence and location of planets

Presence and location of planets

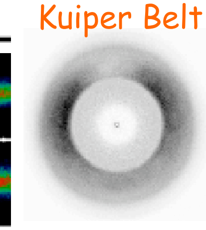
High resolution observations show complex morphology that could result from gravitational perturbations by planets via:

- Gravitational scattering
- Resonant perturbations
- Secular perturbations





Kuiper Belt



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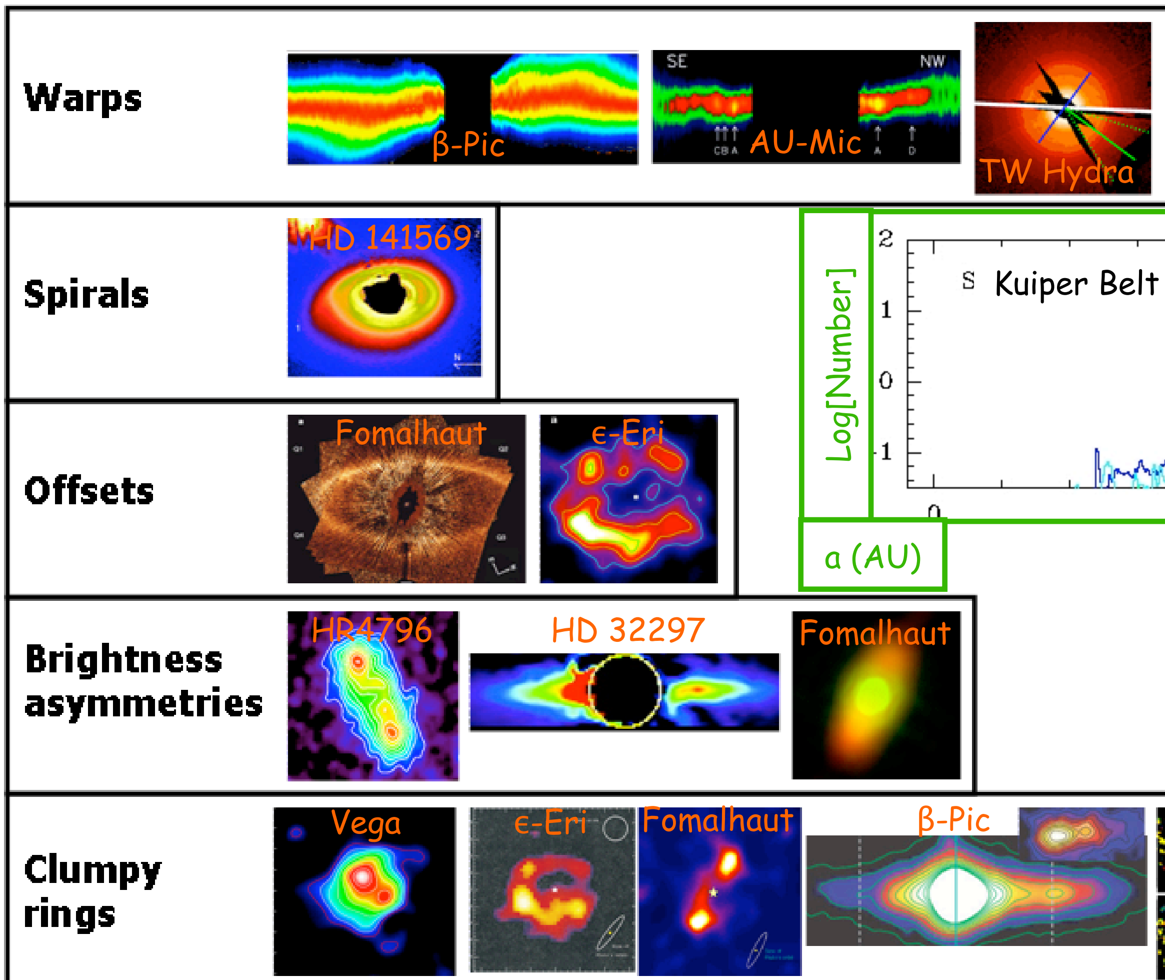
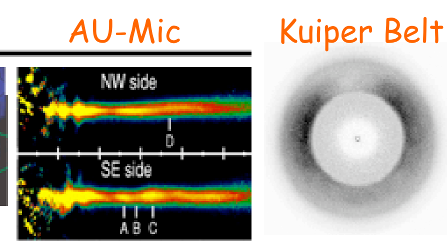
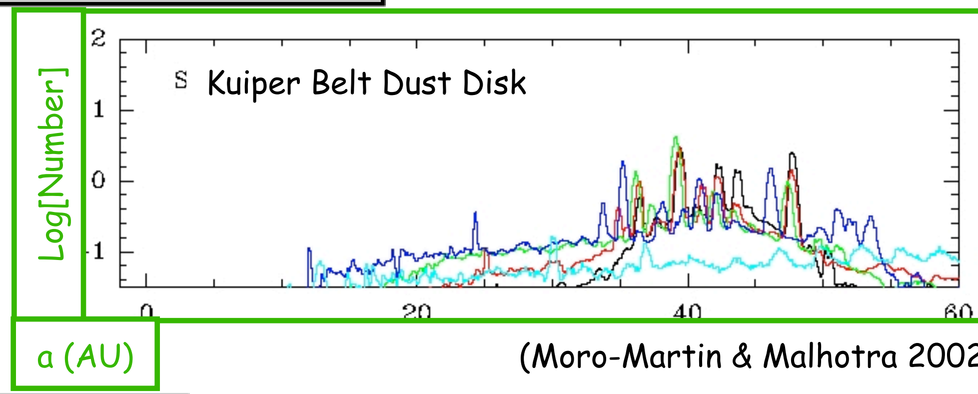
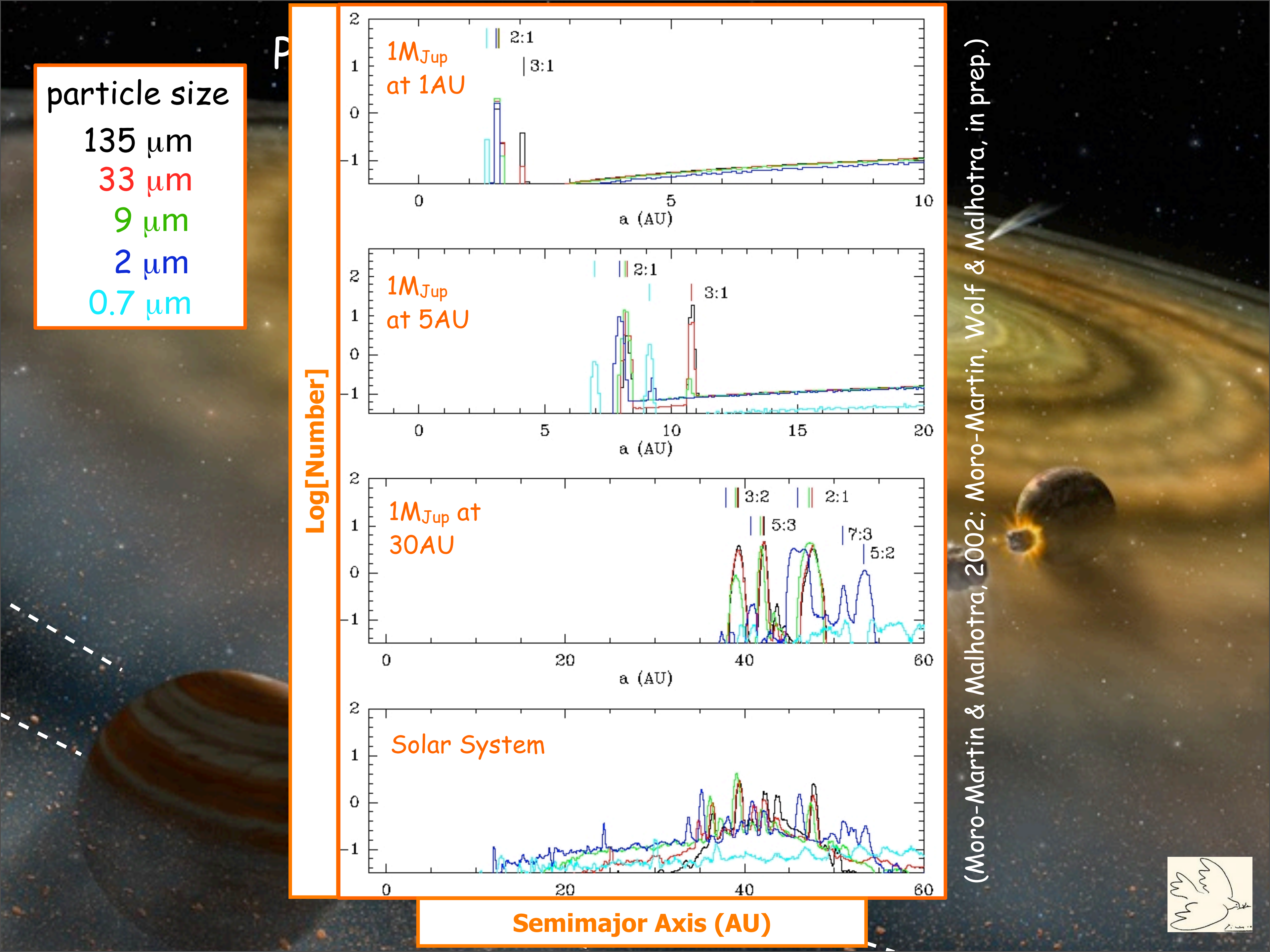






(Moro-Martin & Malhotra 2002)


particle size
135 μm
33 μm
9 μm
2 μm
0.7 μm
Log[Number]
1MJup at 1AU
2:1
3:1
a (AU)
1MJup at 5AU
2:1
3:1
a (AU)
1MJup at 30AU
3:2
2:1
5:3
7:3
5:2
a (AU)
Solar System
Semimajor Axis (AU)
(Moro-Martin & Malhotra, 2002; Moro-Martin, Wolf & Malhotra, in prep.)

Presence and location of planets

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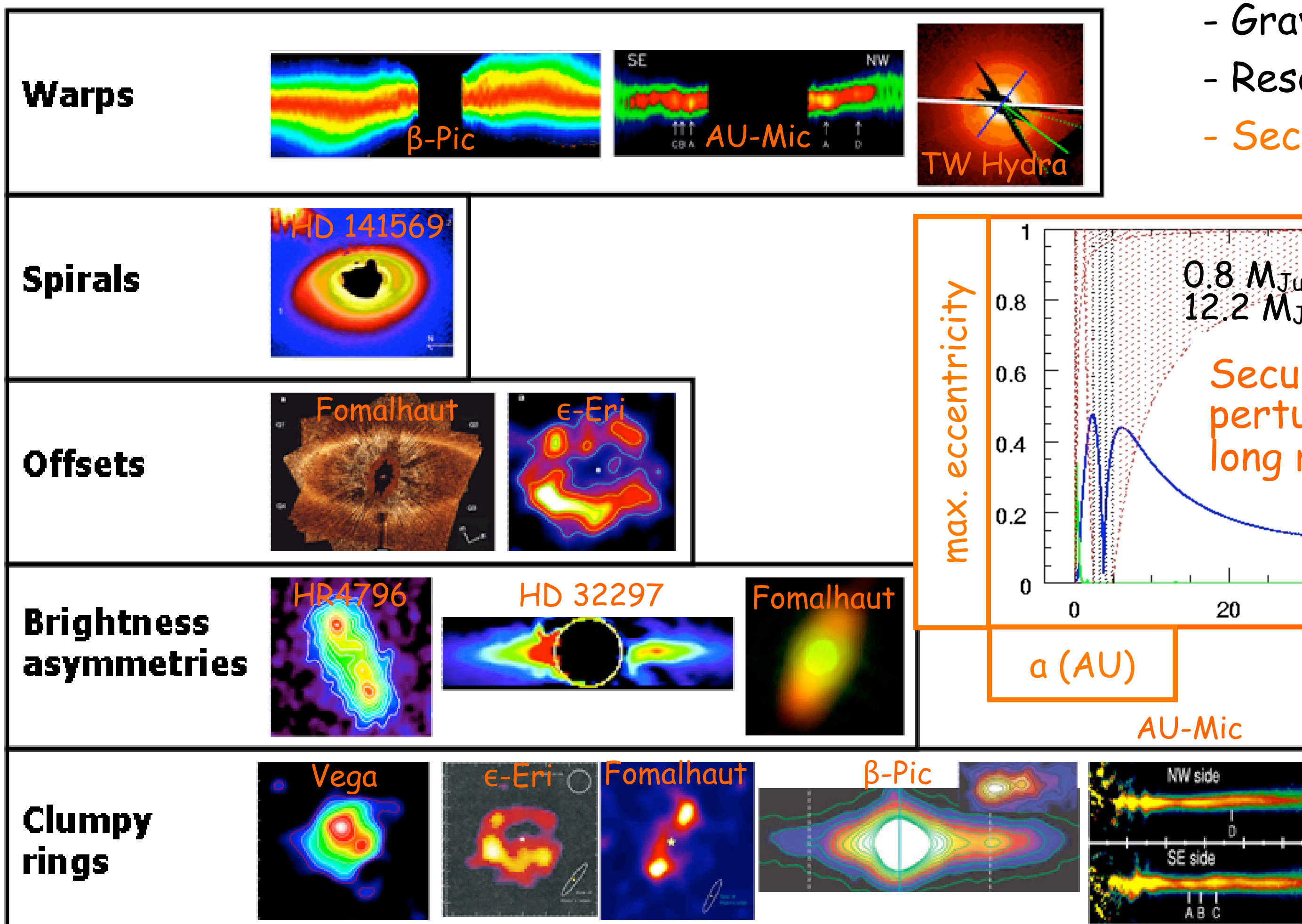
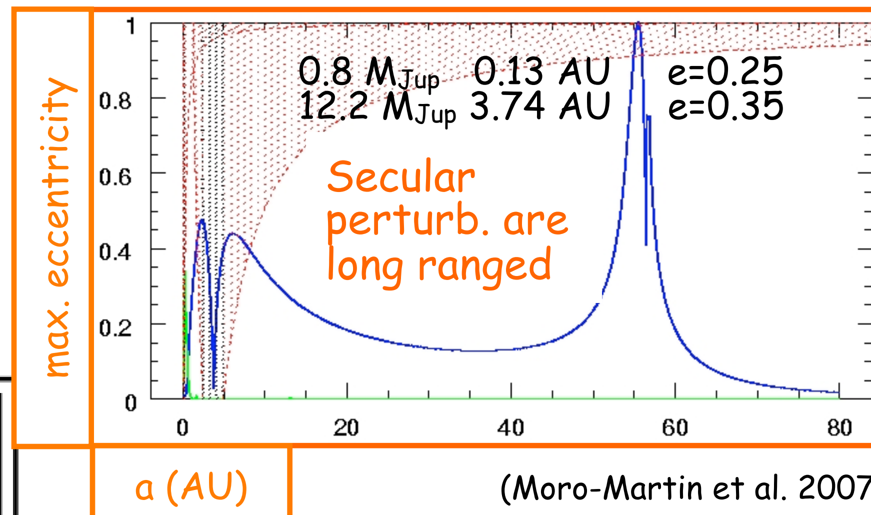
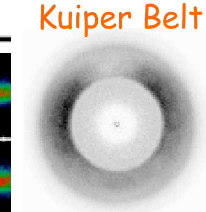




(Moro-Martin et al. 2007)

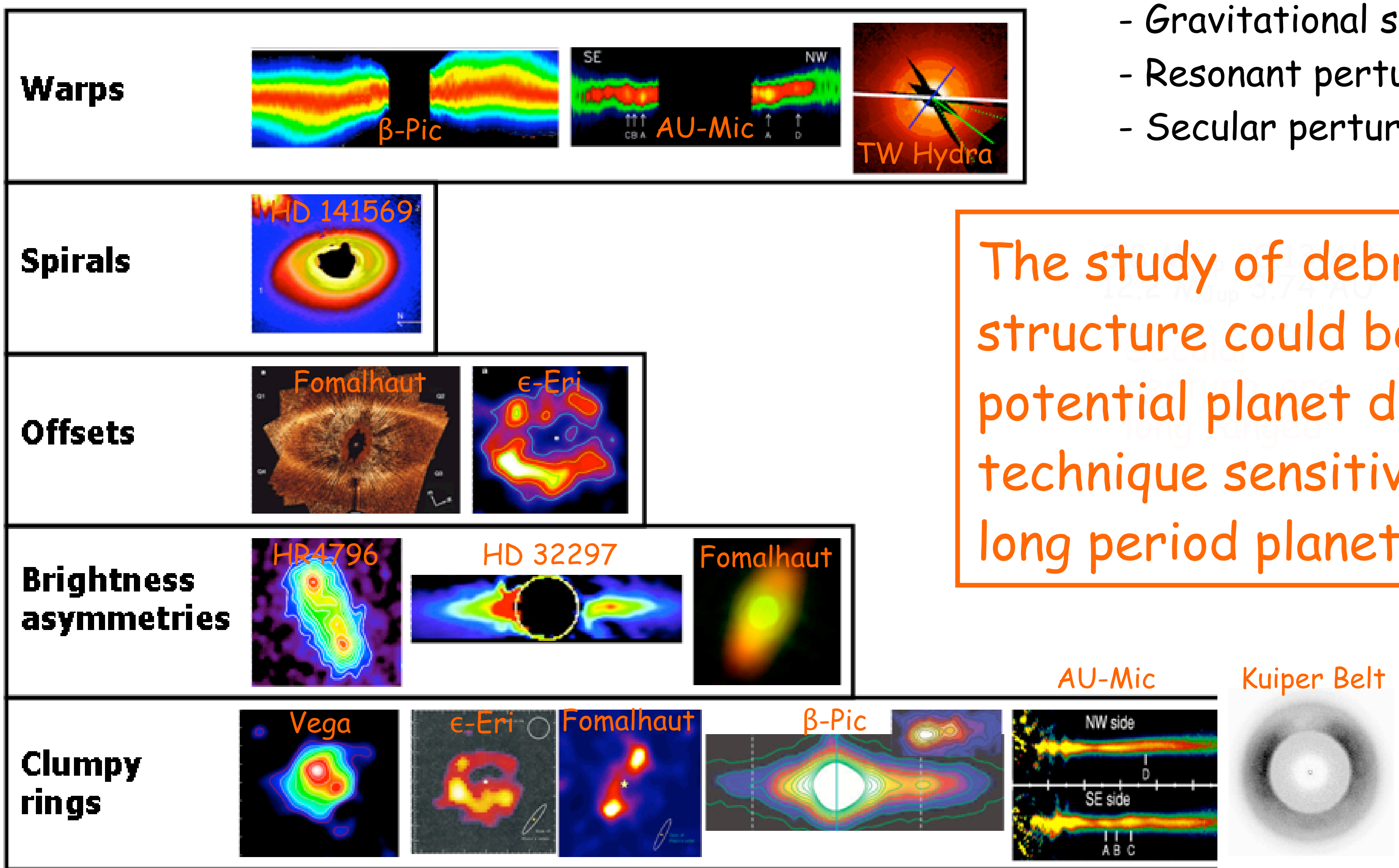
Kuiper Belt



Presence and location of planets

High resolution observations show complex morphology that could result from gravitational perturbations by planets via:

- Gravitational scattering
- Resonant perturbations
- Secular perturbations



The study of debris disk structure could be a potential planet detection technique sensitive to long period planets.

Future prospects in debris disks studies

(of particular relevance to the Japanese astronomical community)

SUBARU 種 S E E D S

2009-2014

Subaru Strategic Exploration of Exoplanets and Disks with HiCIAO/AO188

Goal: To address the following key issues in exoplanet/disk science

- The detection and census of exoplanets in the outer circumstellar regions around solar-mass stars and massive stars (test for planet formation models).
- The evolution of protoplanetary and debris disks including their morphological diversity.
- The direct link between exoplanets and circumstellar disks from a few AU to 10s of AU.

SUBARU 種 S E E D S

2009-2014

- 1st Subaru Legacy Survey.
- 1st project under the newly approved N-PAC
- 120 nights awarded for 5 years.
- 500 targets (focus on solar-mass) (including ~100 debris disks targets)

  Most extensive imaging survey so far.
- 3 years ahead of other next generation 8-m instruments
  - Gemini Planet Imager (GPI)
  - Spectro-Polarimetric High-contrast Exoplanet Reseach (SPHERE - VLT)
- Search for protoplanetary and debris disks and for young self-luminous planets >1 M_{Jup} from few AU to 10s of AU
- Only imaging. Spectroscopy should follow
- Observations start late 2009. Proprietary time: 18 months.

SUBARU 種 SEEDS

2009-2014

- **21 institutes 83 members (18 foreigners).**
- Principal Investigator (PI): 田村元秀（国立天文台）
- Co-PI: 臼田知史（国立天文台）、高見英樹（国立天文台）
- Co-I: （国立天文台） 家正則、石井未来、浮田信治、臼田知史、臼田-佐藤功美子、川辺良平、神鳥亮、Olivier Guyon、小久保英一郎、鈴木竜二、周藤浩士、高遠徳尚、高見英樹、竹田洋一、Alexander Tavrov、田村元秀、寺田宏、西川淳、早野裕、藤吉拓哉、Tae-Soo Pyo、観山正見、村上尚史、森野潤一、渡邉誠；（総合研究大学院大学）工藤智幸、塚越崇、橋本淳、眞山聡；（放送大学）海部宣男；（北海道大学）馬場直志；（東北大学）北村美佐絵、山田亨；（茨城大学）岡本美子、百瀬宗武；（東京大学）上野宗孝、葛原昌幸、成田憲保；（東京工業大学）井田茂、佐藤文衛；（宇宙科学研究本部）塩谷圭吾、片坐宏一、中川貴雄；（神奈川大学）本田充彦；（名古屋大学）大坪貴文、加藤恵理、叶哲生、芝井広、住貴宏、深川美里、中島亜紗美、松尾太郎、森下裕乃、山本広大；（名古屋市立大学）杉谷光司；（京都大学）犬塚修一郎、武藤恭之、福江翼；（神戸大学）伊藤洋一、大朝由美子、Ingrid Mann、日置智紀；（米国 プリンストン大学）Jeremy Kasdin、Jill Knapp、Michael McElwain、Amaya Moro-Martin、David Spergel、Ed Turner、Robert Vanderbei；（米国 ハワイ大学）Klaus Hodapp；（米国 JPL）Gene Serabyn；（台湾 中央研究院天文及天文物理研究所）大橋永芳、高見道弘、Jennifer Karr；（ドイツ マックスプランク研究所）後藤美和、Wolfgang Brandner、Thomas Henning、Markus Janson、Joseph Carson；（フランス ニース大学）Lyu Abe；（イギリス ハートフォードシャー大学）Tim Gledhill、James Hough、Philip Lucas

- HiCIAO can obtain spatially resolved observations at high resolution with unexplored dynamical range and inner working angle.
- HiCIAO can obtain polarimetry observations useful to study dust grain properties (size and composition).
- HiCIAO can substantially expand the sample of spatially resolved debris disks and in favorable cases do a **simultaneous search for long-period planets (same spatial scale as the dust).**

What is the connection between debris disks and planets?

SUBARU 種 S E E D S 2009-2014

Focus	IR Nasmyth (w/ AO188)
Wavelength	0.85 – 2.50 microns
Observation modes	DI, PDI, SDI (w/ coronagraph)
Resolution	0.03" (J), 0.04" (H), 0.055" (K)
Strehl ratio	0.3 (J), 0.5 (H), 0.7 (K) with AO
Field of view	20"x20" (DI), 20"x10" (PDI), 5"x5" (SDI)
Contrast	10^4 at 0.1", $10^{5.5}$ at 1.0" (SDI w/ coronagraph)
Pixel scale	0.010 "/pix
Occulting masks	0."15, 0."20, 0."26 (4.6 l/D @J,H,Ks), 0."6 dia.

SUBARU 種 SEEDS

2009-2014

Spectral Differential Imaging (SDI) mode:

FOV : 5″ x 5″

Filters : CH_4, [FeII], H_2

Four images are generated simultaneously with different narrowband filters

Enhance contrast for self-luminous gas planets

Contrast : 10^4 @ 0.″1 separation, $10^{5.5}$ @ 1″ separation

Direct Imaging (DI) mode:

FOV: 20″x20″

Filters: Y, J, H, K_s

Polarimetric Differential Imaging (PDI) mode:

FOV : 20″ x 10″

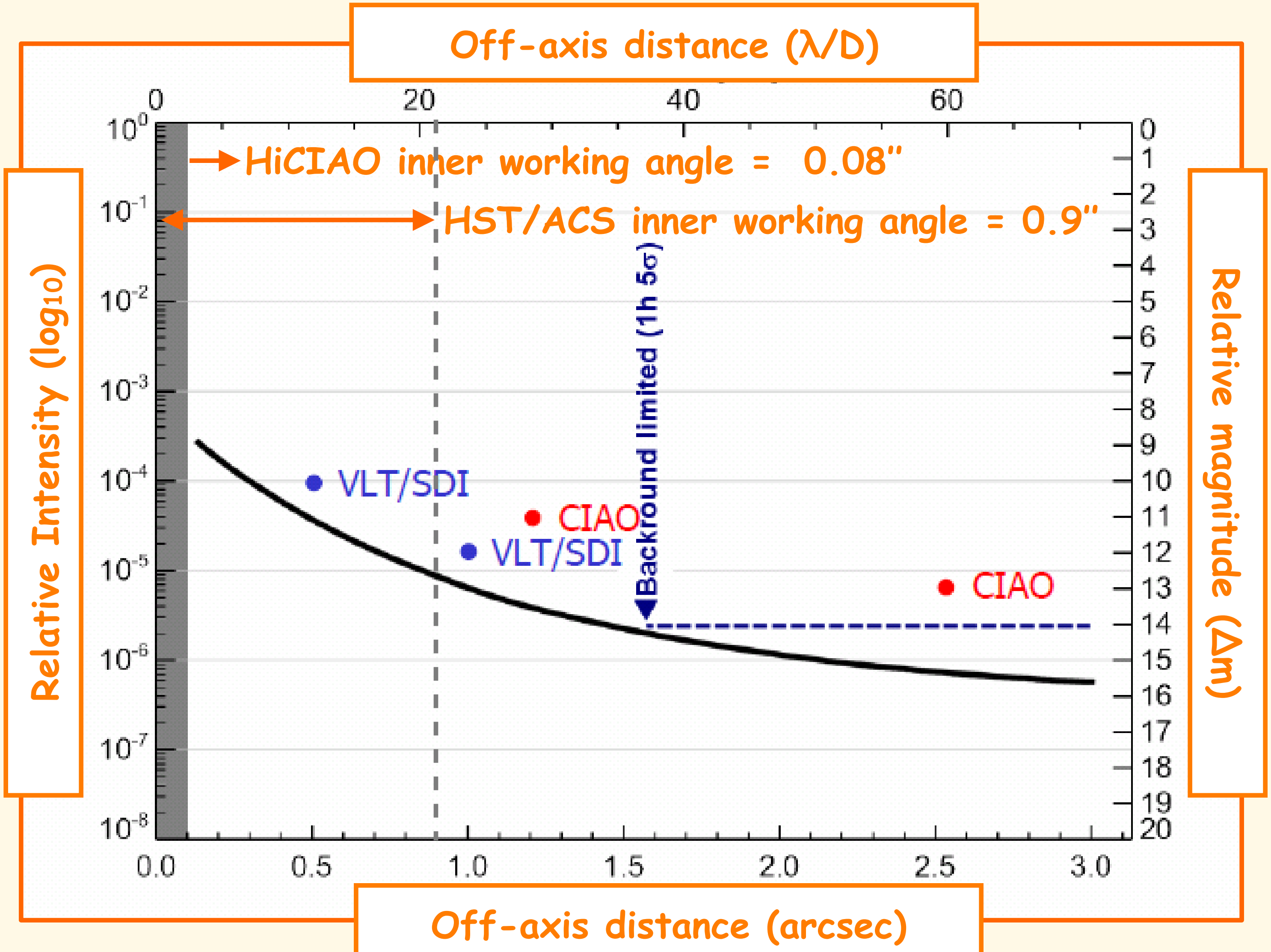
Filters : Y, J, H, Ks

Two images (o-ray/eo-ray) are generated simultaneously

Enhance contrast for proto-planetary/debris disks

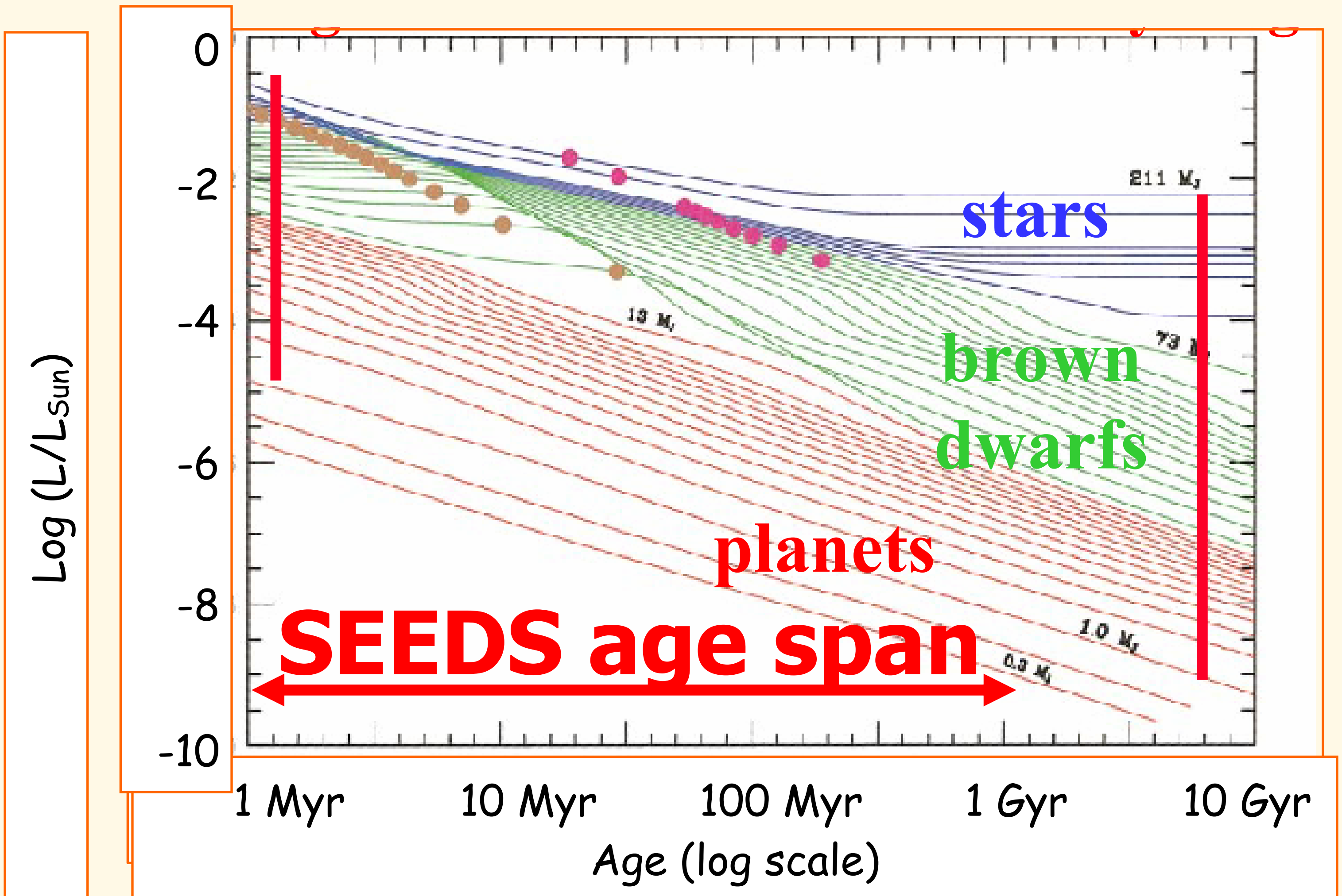
SUBARU 種 S E E D S

2009-2014



SUBARU 種 S E E D S

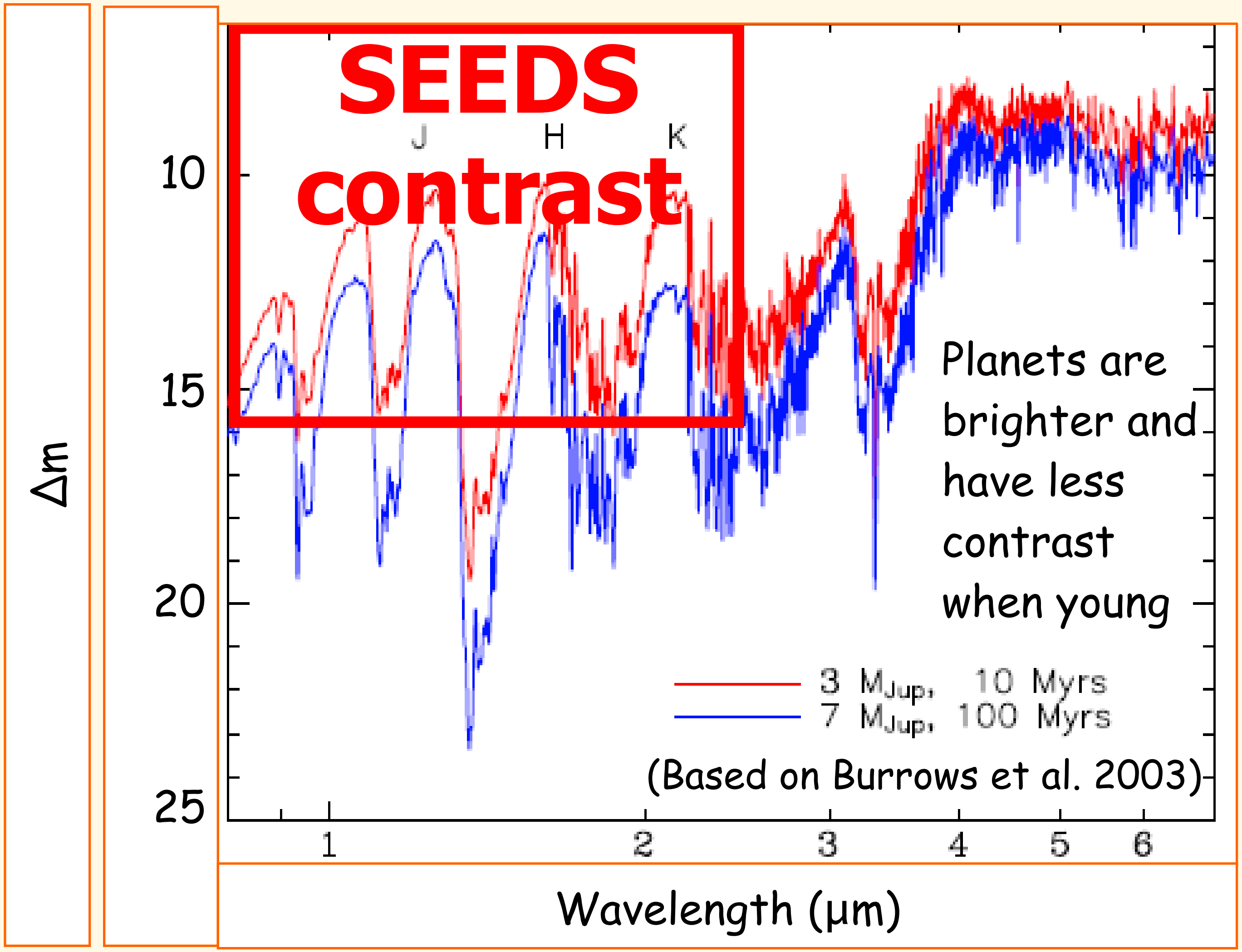
2009-2014



(Based on Burrows et al. 2003)

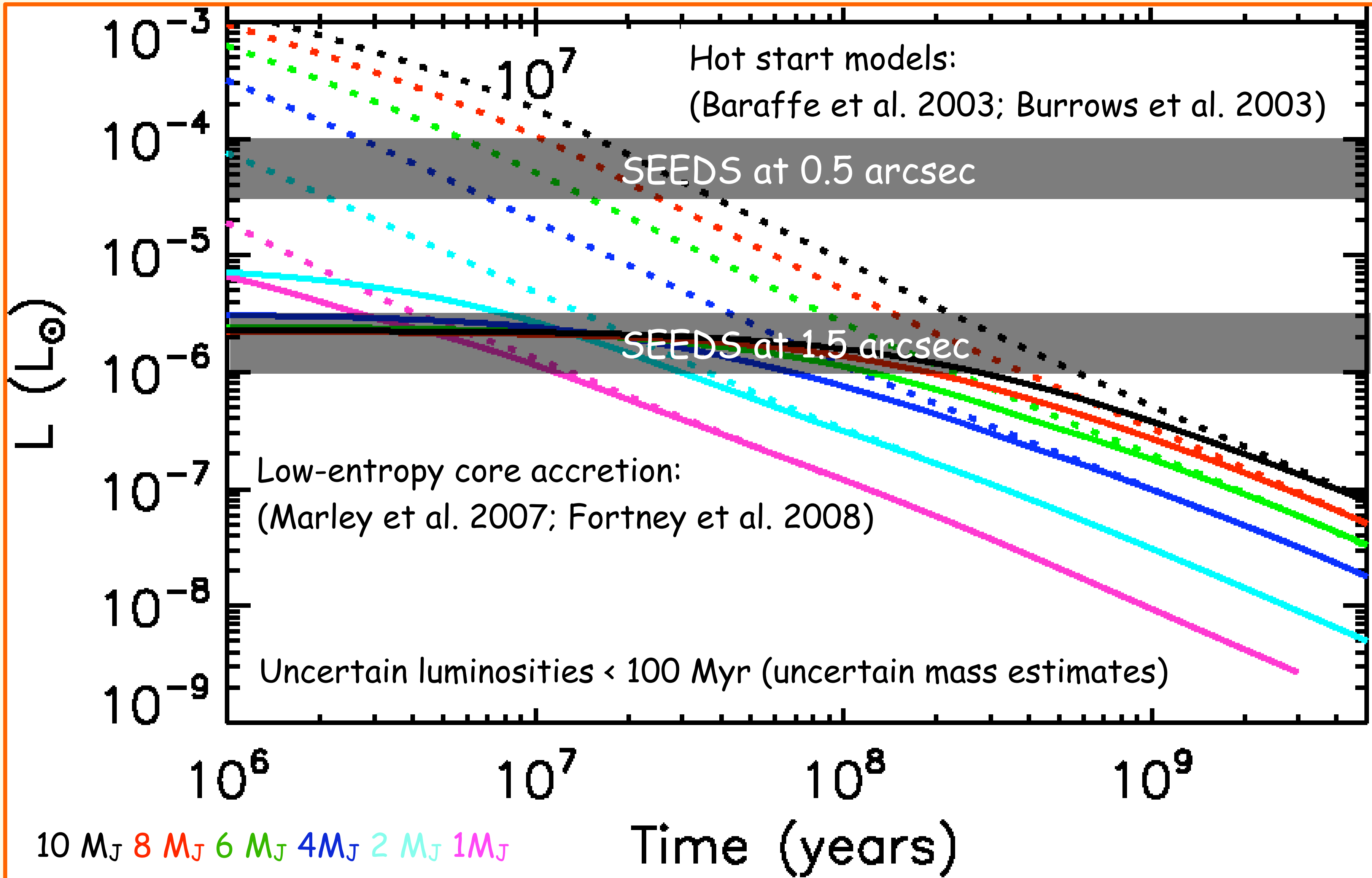
SUBARU 種 SEEDS 2009-2014

Direct imaging of young, self-luminous planets from few-10s of AU



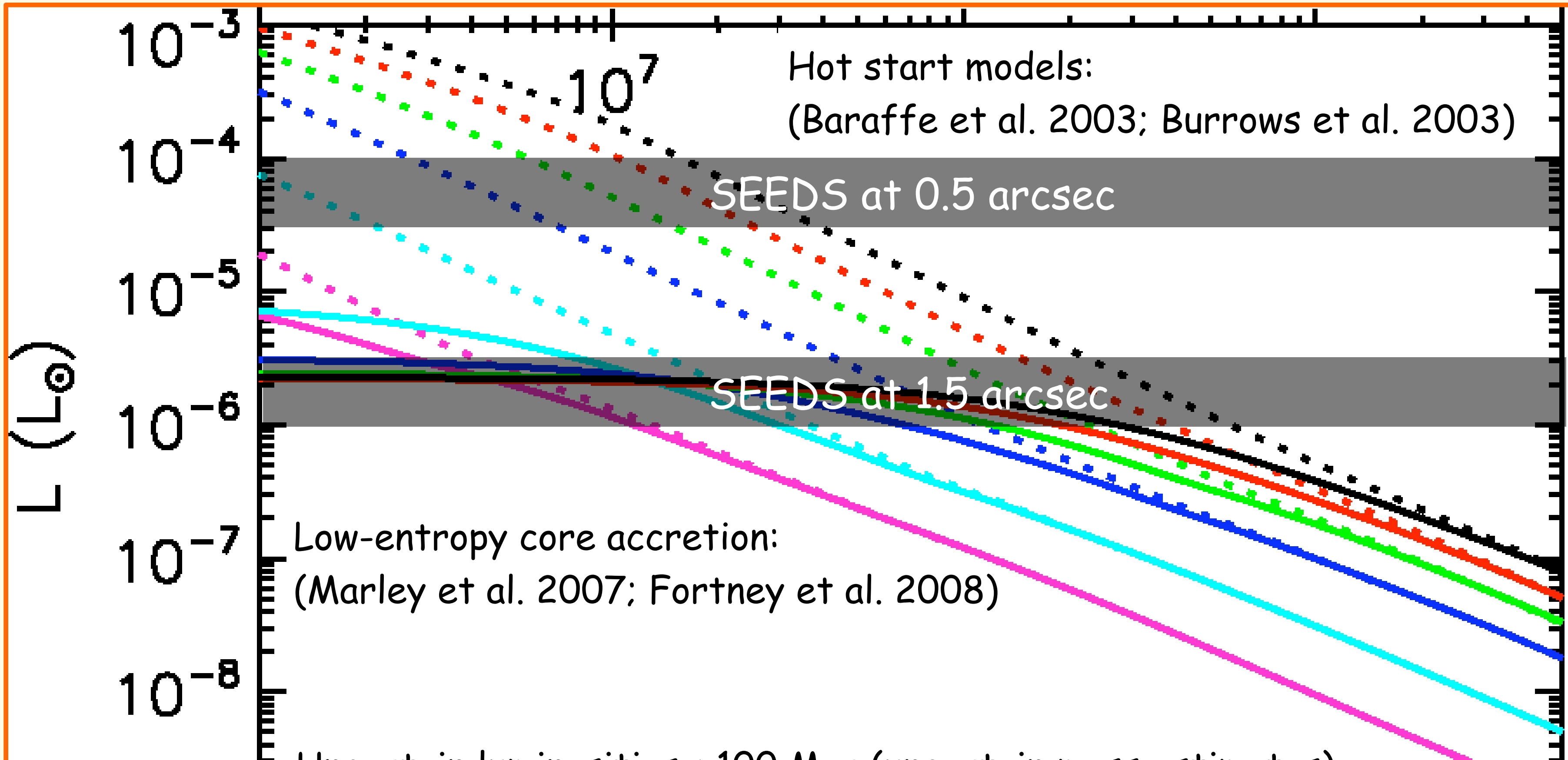
SUBARU 種 SEEDS

2009-2014



SUBARU 種 SEEDS

2009-2014



Distance	Category	Expected Planet Detection Performance	
< 200 pc	YSOs	>2 M_J for >15 AU	>0.5 M_J for >100 AU
125 pc	Open Clusters	>5 M_J for >12 AU	>3 M_J for >30 AU
< 30 pc	Nearby Stars	>10 M_J for a few AU	>1 M_J for >25 AU

ALMA

- High sensitivity: large unbiased surveys sensitive the level of dust found in the Solar System. Improve statistics.

  - Are KB-like disks common? The presence of icy planetesimals can shed light on the possiblity of water delivery in the terrestrial planet region.

ALMA

- Unprecedented spatially resolution (a few milliarcseconds for the longest baselines and highest frequencies - better than HST in the optical) In some cases, ALMA will spatially resolve the debris disks.

- Spatially resolved observations of debris disks around stars with planets will help us understand how planets affect the disk structure.

- Because debris disk structure is sensitive to long period planets, its study could be used as a planet detection technique complementary to radial velocity and transit surveys (preferentially sensitive to planets close to the star), and to direct imaging (preferentially sensitive to young planets).

SPICA

~ 2018 ?

- 3.5 meter telescope (similar to Herschel) but cooled to < 5K. Sensitivity in FIR is 100 times better than Herschel.

- Monolithic mirror (unlike the segmented JWST) will deliver diffraction limited performance at 5µm with a clean point spread function.

- SAFARI instrument: FIR imaging spectrometer from 30-120 µm with a large field-of-view of 2′x2′ and angular resolutions from 2′′ to 15′′ (or 20 to 150AU at 10 pc).

SPICA

~ 2018 ?

SPICA's high-photometric sensitivity would be able to detect dust at 90 K down to a dust mass of 0.01 M_{Moon} around Solar-type stars out to 180 pc (compared to 18 pc for Herschel), increasing the number of detections to 10^5 (compared to 10^2) and allowing for better statistics of disk frequencies and properties as a function of stellar type, age and environment.

- Are LHB-type of events common? This can set constraints on the frequency of planet migration and have consequences for the habitability of these systems.

SPICA

~ 2018 ?

- For distant systems, SPICA's spectroscopy would be able to study the mineralogy or 100s of spatially unresolved debris disks and the coronograph would allow to image and take spectra of the inner disks.

- For nearby systems, SPICA' spectroscopy would be able trace the variation in dust mineral content and grain size distribution as a function of radius; compare to composition of asteroids and KBOs, also studied by SPICA (the large FOV would allow for KBO detections that could be fully characterized with SPICA).

SPICA

~ 2018 ?

- In nearby systems, SPICA would be able to spatially resolved the disks allowing to study their structure; Vega has taught us that multi-λ's studies are critical for the correct interpretation of the systems.

- SPICA's coronography would allow to search for planets and dust on similar spatial scales, shedding light on the planet-disk interaction.