Signatures of Planets in Debris Disks

Amaya Moro-Martin
Princeton University

In collaboration with Sebastian Wolf and Renu Malhotra

Outline

- Introduction:
  - What is a debris disk?
  - How its structure is created?
  - What can it tell us about massive planets?
- If disk is spatially unresolved...
  - SEDs are sensitive to the presence, location and mass of massive planets.
  - But SEDs are degenerated!
    ⇨ Need spatially-resolved observations.
- Modeling of brightness density distributions

Introduction

- Many (>15%) MS stars are surrounded by debris disks: cold far-IR emitting dust (1-10$M_{☾}$) that reprocesses star light and emits at longer λ's.

KB dust disk = 10^{-4} $M_{☾}$

- Debris disks are indirect evidence of planetary formation:

Dust Removal Time Scales:
Poynting-Robertson drag ~ 10^5 yrs

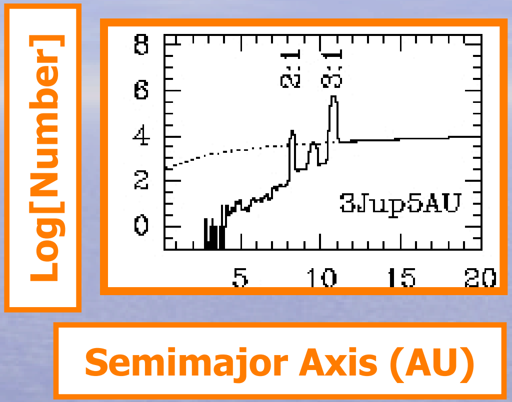
<<

Age of Star
> 10^7 yrs

- Dust is not primordial but must be "continuously" (?) replenished by a reservoir of undetected planetesimals (of unknown mass) producing dust by mutual collisions

Do debris disks harbor massive planets?

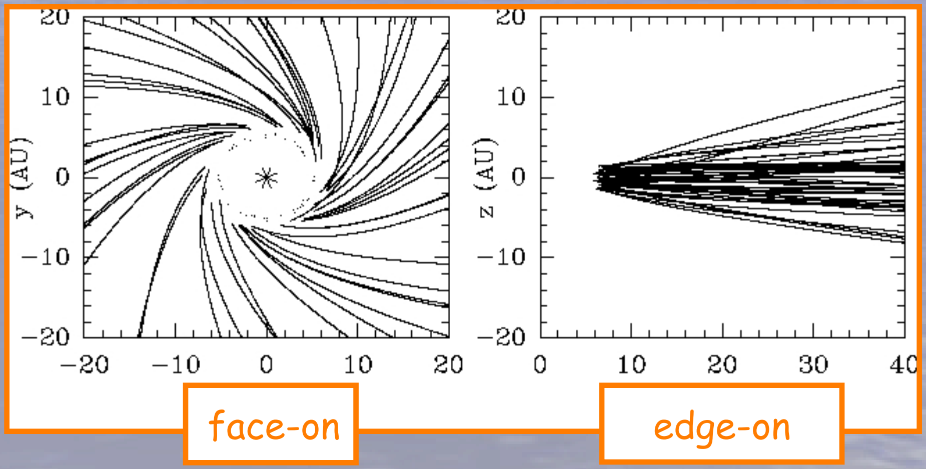
- As dust particles spiral inward (due to PR drag), they can get trapped in Mean Motion Resonances with the planets. I.e. massive planets shepherds the dust grains in the disks.



⇨ Radial and azimuthal structure

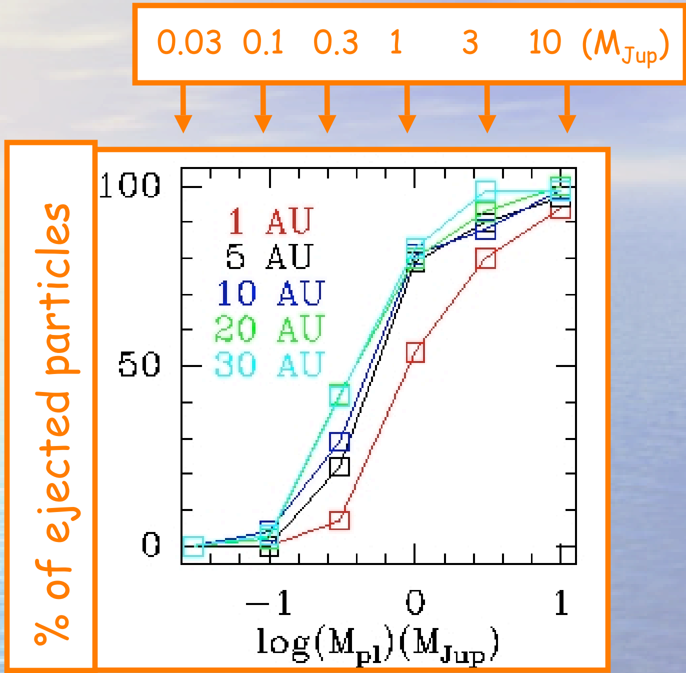
- Massive planets may eject dust particles out of a planetary system via grav. scattering

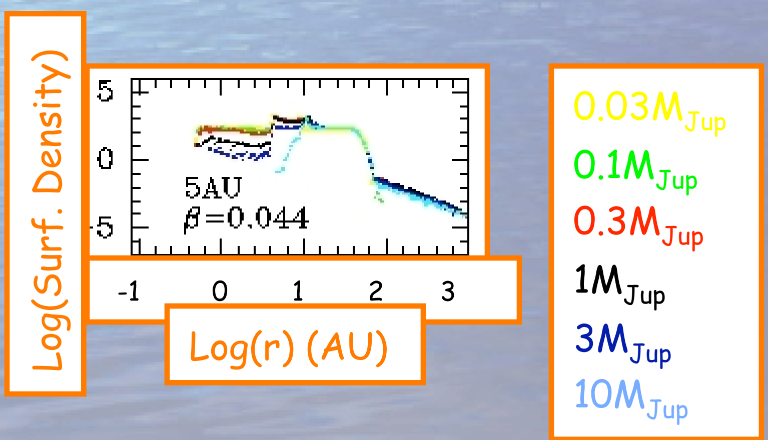
⇨ Gaps



Trajectories of KB dust particles ejected by Jupiter

How empty the gap is depends strongly on the planet mass



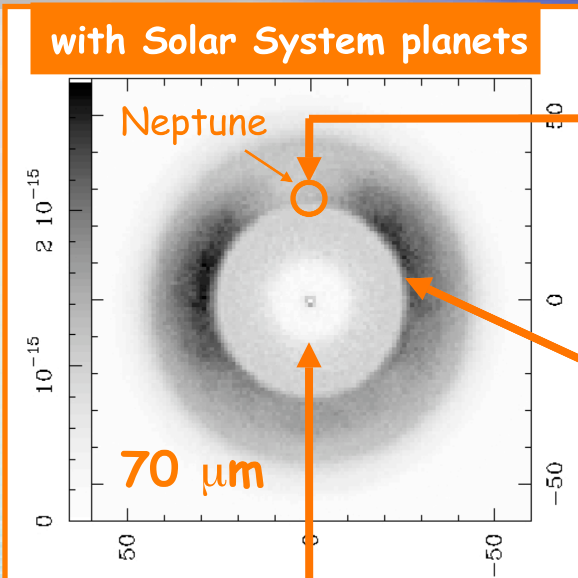


M_{planet}	a_{planet}	Ejection effic.
< $0.1M_{Jup}$		0 %
$1M_{Jup}$	5-30 AU 1 AU	80 % 50 %
> $3M_{Jup}$	5-30 AU 1 AU	> 90 % > 80 %

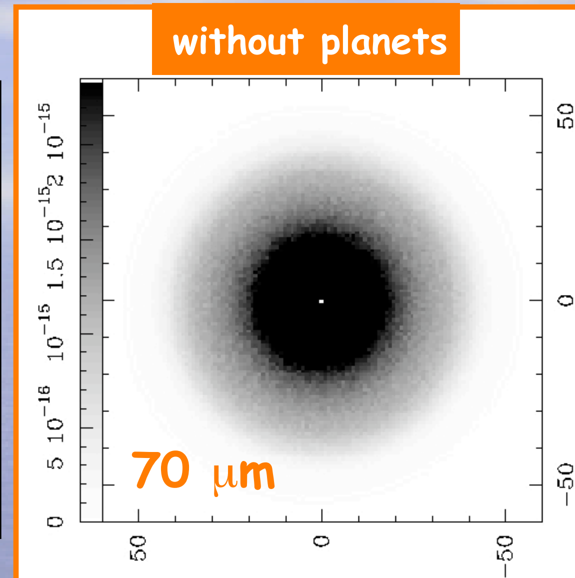
In the Solar System, 80-90% of KB dust particles are ejected by Jupiter and Saturn

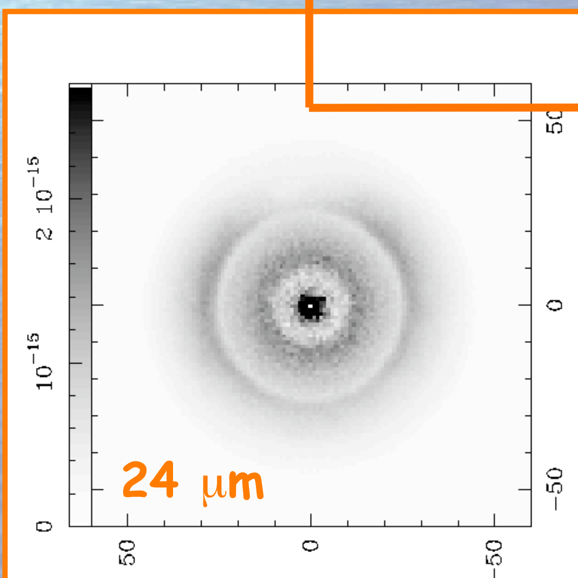
We will see how this gap is the most prominent feature in the SED of spatially unresolved disks.

Example of debris disks with embedded planets: KB Dust Disk



- minimum at Neptune's position (avoid resonant planet)
- ring-like structure along Neptune's orbit (MMRs)





clearing of dust from inner 10 AU (due to grav. scattering by Jupiter and Saturn)

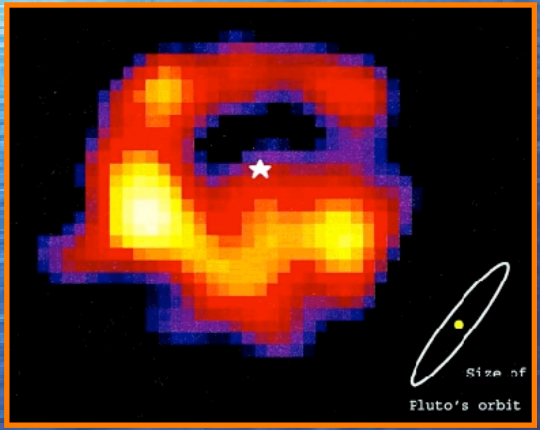
Has the KB dust disk been detected? Landgraf et al. (2002) claimed Pioneer 10 and 11 detected KB dust beyond 10AU.

- Gaps and asymmetries observed in high-resolution observations suggest giant planets may be present.
- Structure is sensitive to long period planets ⇒ Affects stability of orbits in habitable zones (TPF)

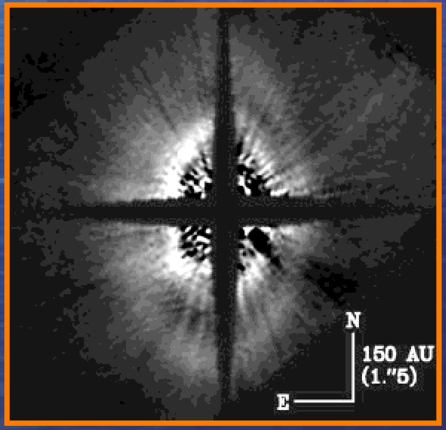
  ⇒ complementary to radial velocity and transit surveys.

We can learn about the diversity of planetary systems from the study of debris disks structure!

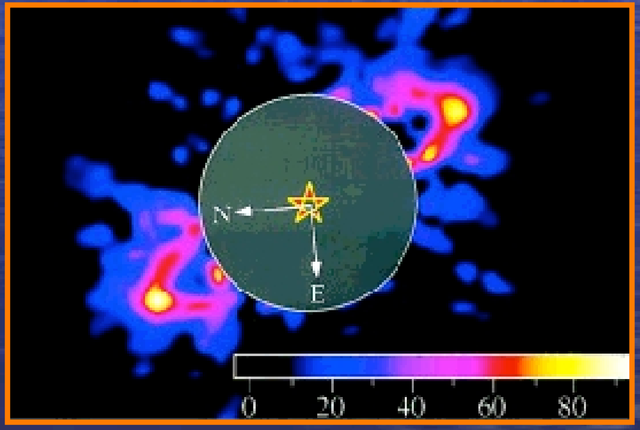
Dust has a larger total surface area: easier to observe than planets.



ε-Eri 850μm (emitted light; Greaves et al. 98)



H141569 1.1μm (scattered light; Weinberger et al. 99)



HR4796A 1.6 μm (scattered light; Schneider et al. 99)

SEDs of spatially unresolved disks

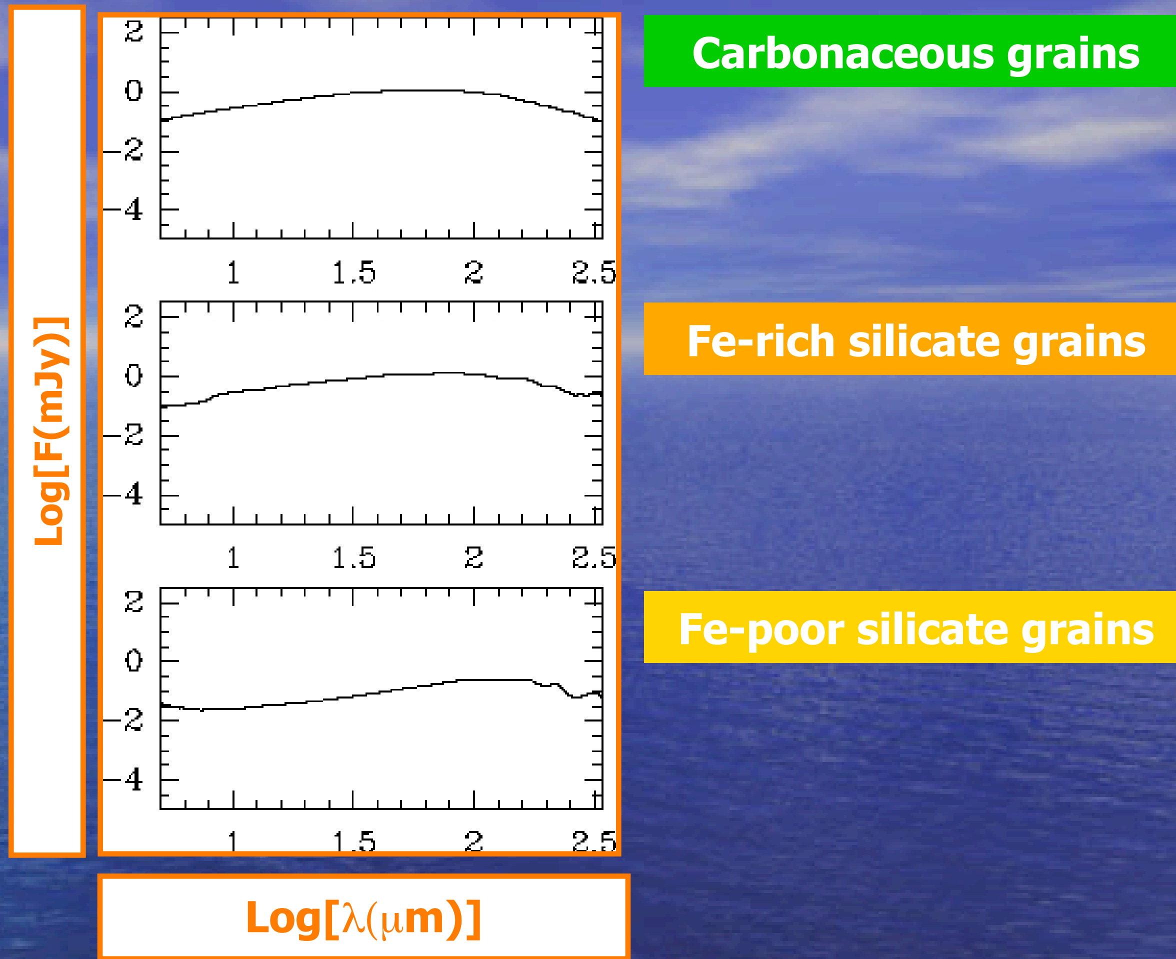
- Very few systems are be spatially resolved with current telescopes ⇨ in most cases we cannot look for planets by studying debris disk structure directly.

- But the structure carved by the planets affects the shape of the Spectral Energy Distribution (SED) of the disk ⇨ we can study the debris disk structure indirectly

This is one of the goals of the Spitzer FEPS Legacy Project

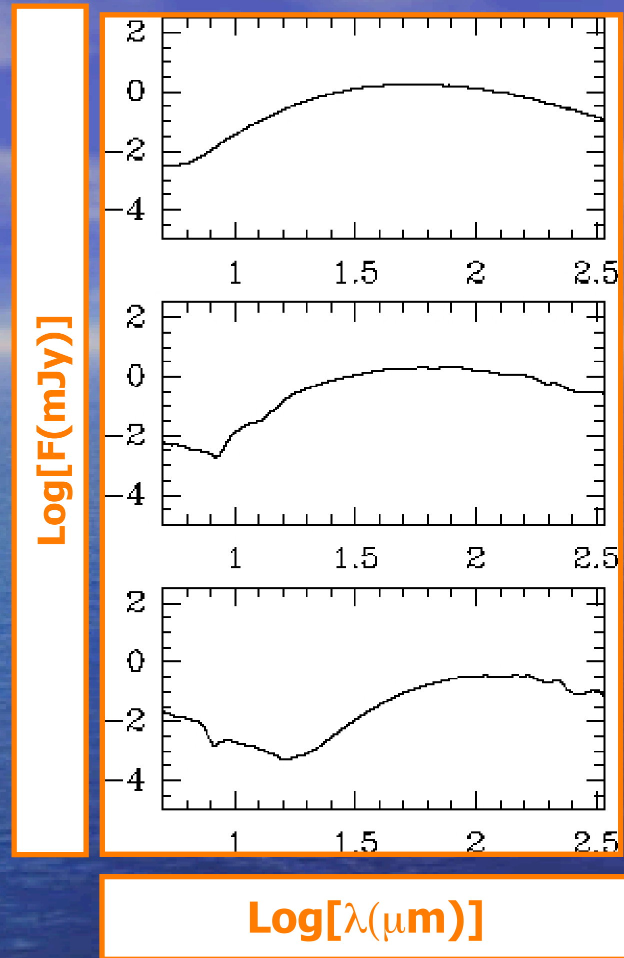
Let's see some modeled SEDs of debris disks with embedded planets in different configurations.

No planet


Log[F(mJy)]
Log[λ(μm)]
2
0
−2
−4
1
1.5
2
2.5
Carbonaceous grains
Fe-rich silicate grains
Fe-poor silicate grains


planetesimals
star
1AU 5AU
30AU
50AU

1 M_{Jup} at 5 AU

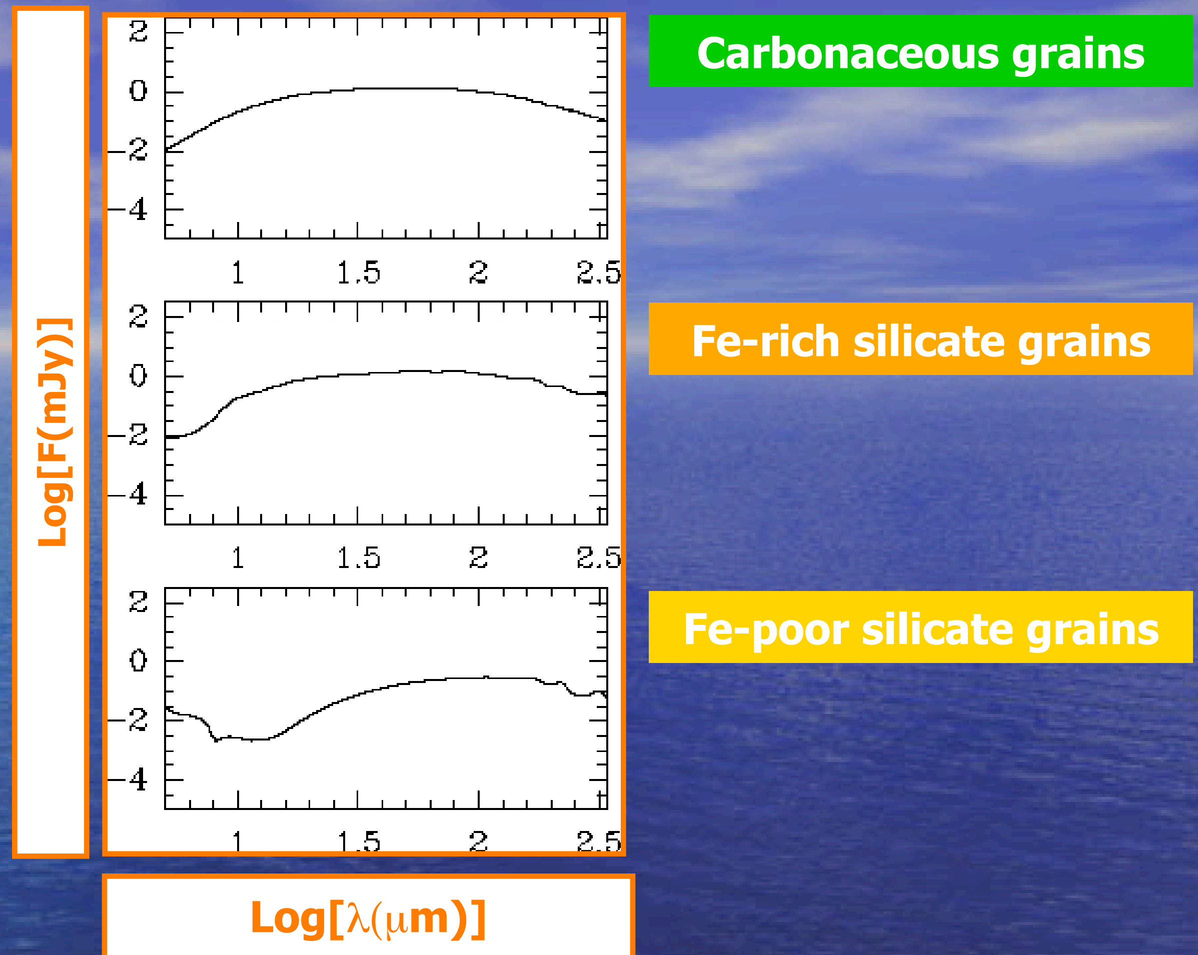


Carbonaceous grains

Fe-rich silicate grains

Fe-poor silicate grains

3 M_{Jup} at 1 AU



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planetesimals
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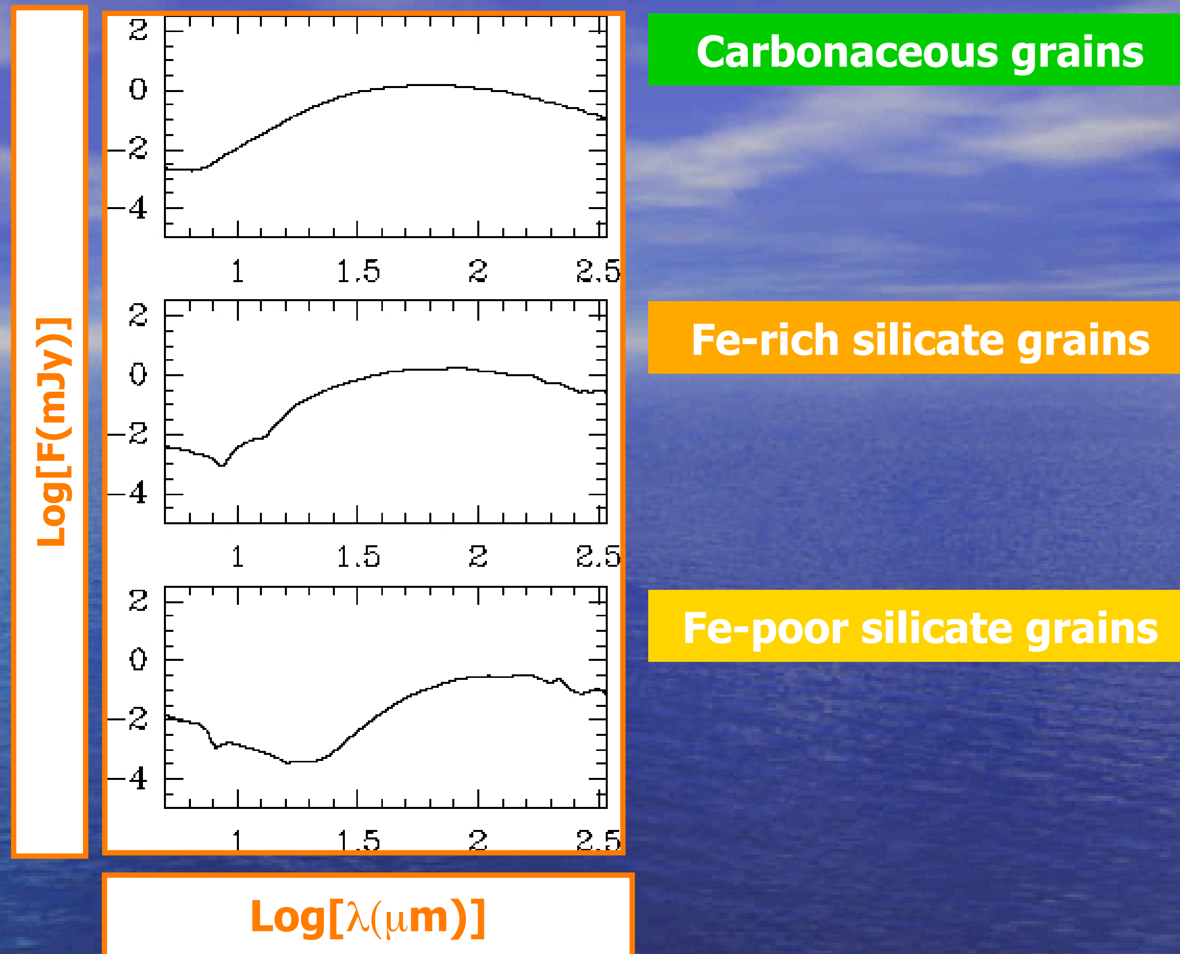
3 M_{Jup} at 5 AU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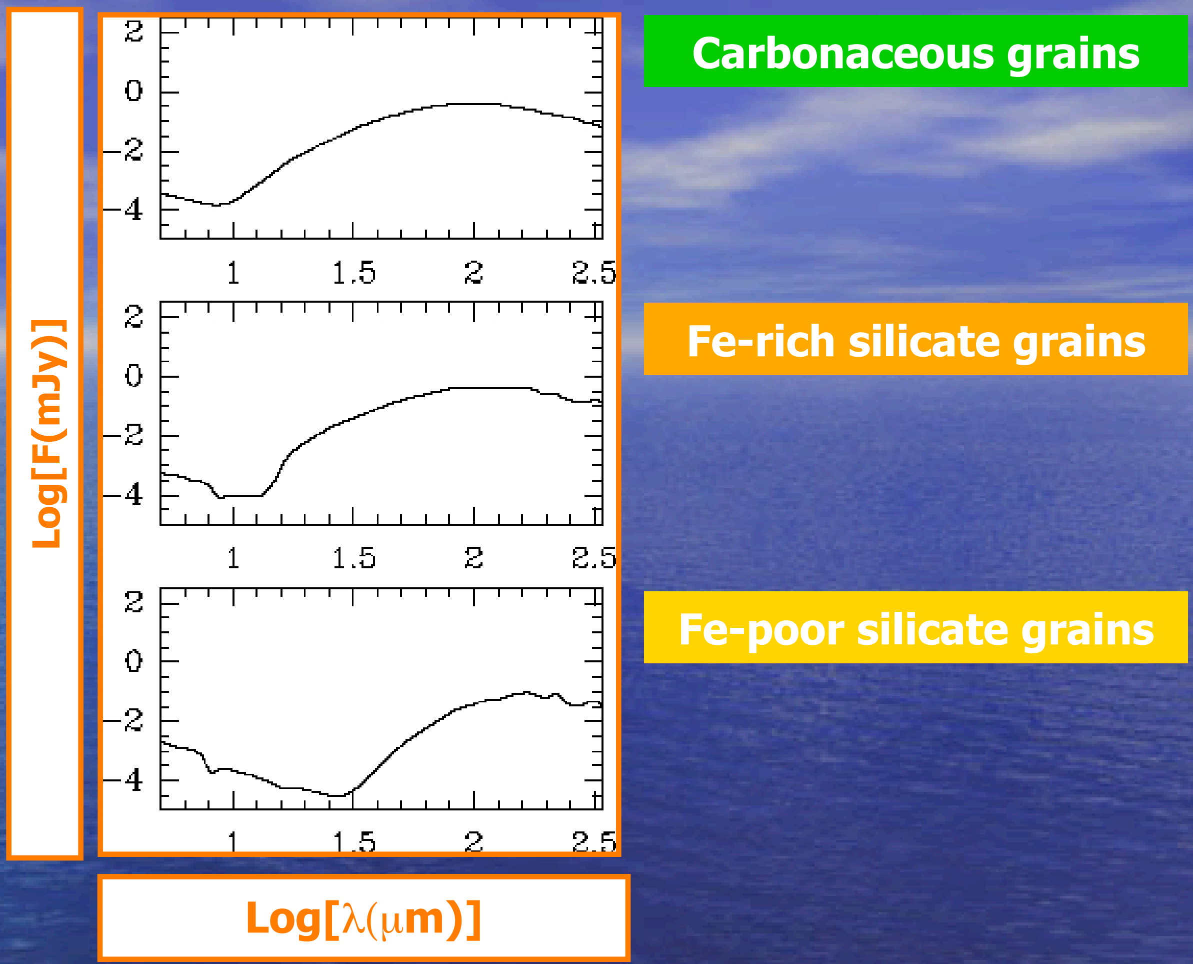
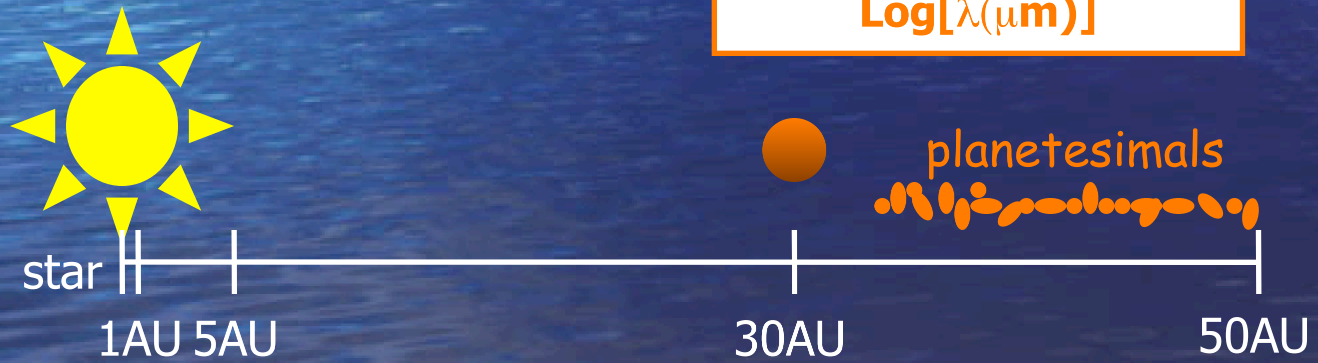
1.5
2
2.5

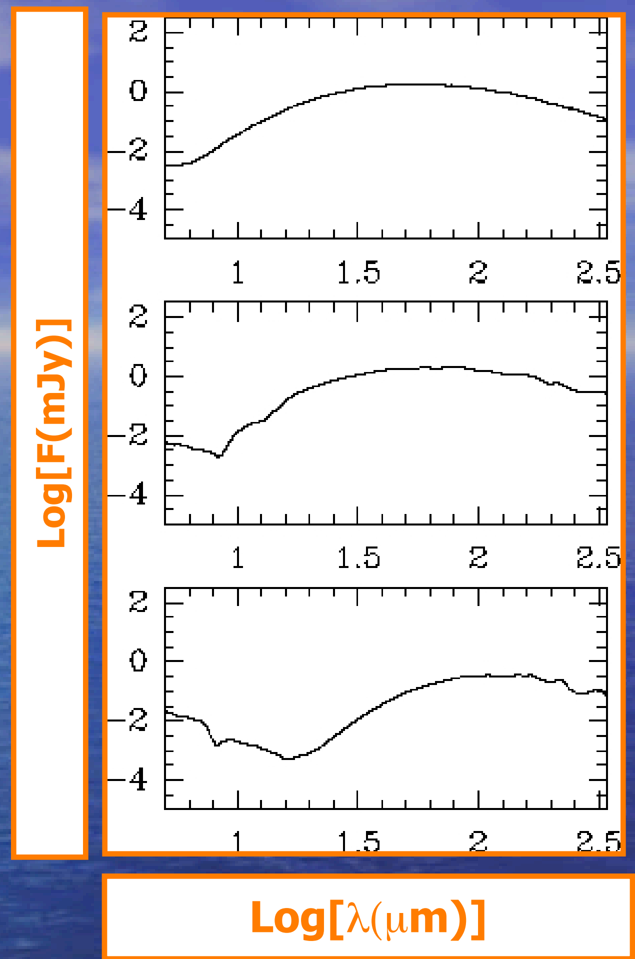

planetesimals
star
1AU 5AU
30AU
50AU

3 M_{Jup} at 30AU





1 M_{Jup} at 5 AU

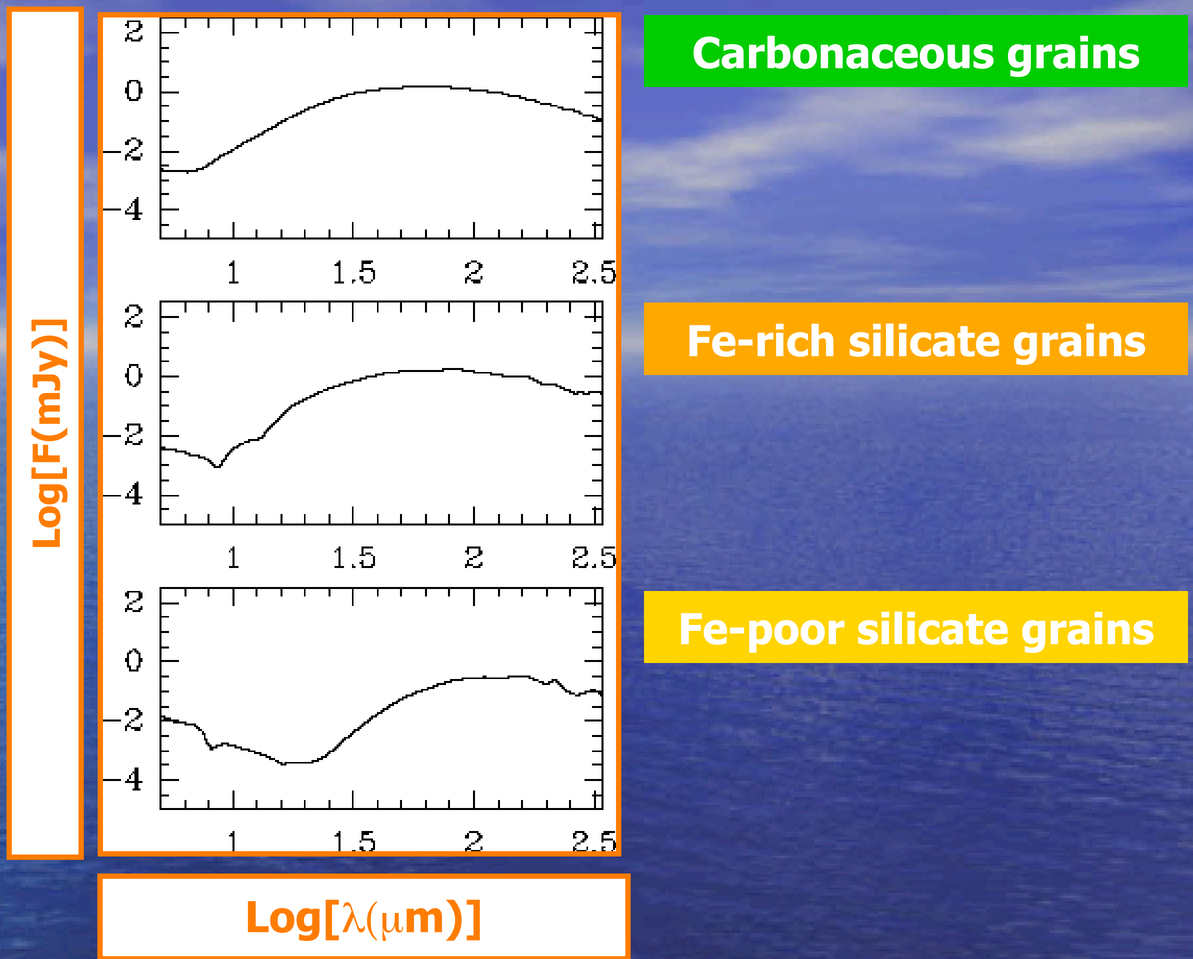


Carbonaceous grains

Fe-rich silicate grains

Fe-poor silicate grains

3 M_{Jup} at 5 AU



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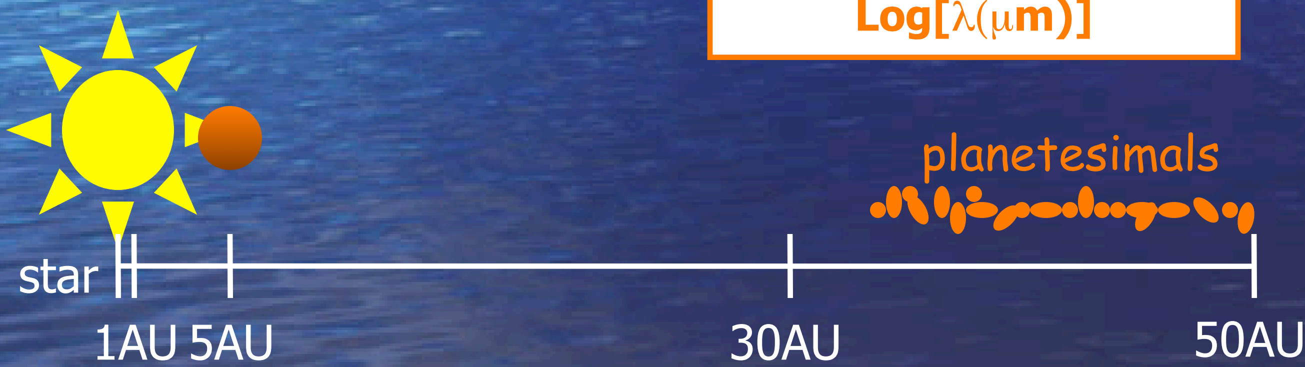
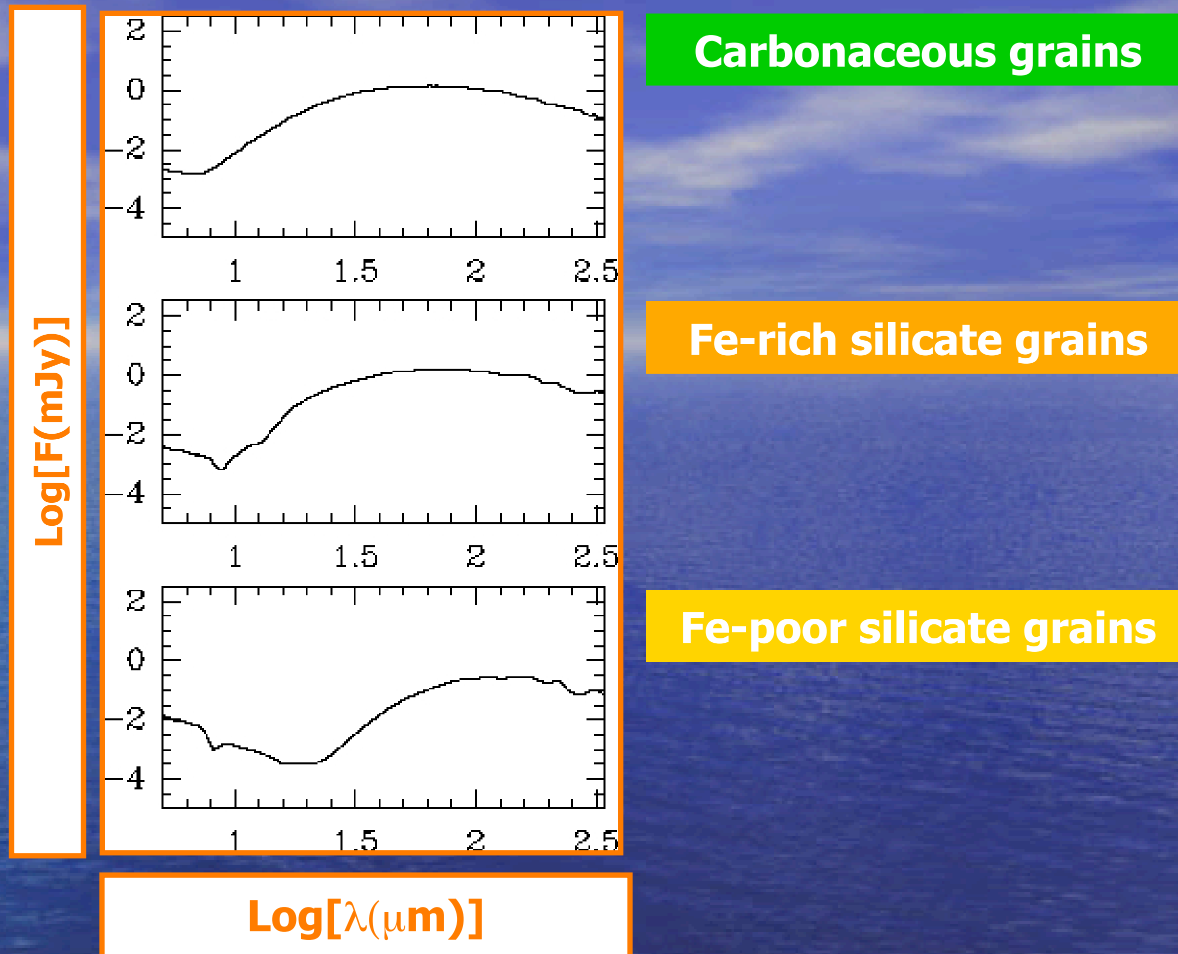


planetesimals
star
1AU 5AU
30AU
50AU

$10 M_{Jup}$ at 5 AU



What can we learn from the SEDs?

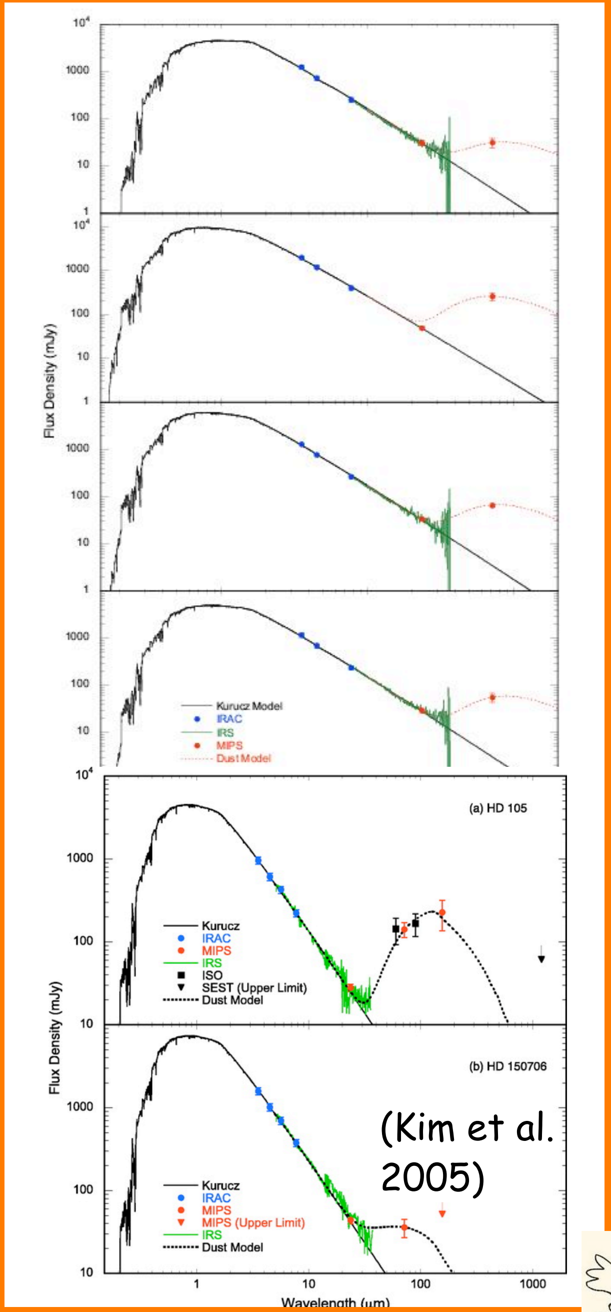
- The SED of a dust disk with embedded planets is fundamentally different from that of the disk without planets.
- Significant decrease of the near/mid-IR flux due to the clearing of dust inside the planet's orbit.
- It may be possible to diagnose the location of the planet and the absence/presence of planets.
- Based on how empty the gap is we could set lower limits to the mass of the planet.

Inner gaps appear to be common in cold KB-like disks

(Kim et al. 2005, Meyer et al. 2004)

- 70 μm excesses: T_{max} < 100K, R_{in}>10AU
- No 24 μm excesses: Upper limit of warm dust inside R_{in} ~ 10^{-6}-$10^{-6.5}$ M_{Earth}
  2-3 orders of magnitude below the lower limits for the masses in the cold disk.
  ⇨ Large depletion inside R_{in}
- Lifetimes (due to PR) ~ 10^6 yr
  - Replenishment of dust
  - PR would erase the density contrast inside and outside R_{in}

What is stopping the particles from drifting all the way toward the star?



- Sublimation of icy grains? No, T<100K.
- Blowout by radiation pressure? No, dust grains are large enough to be on bound orbits.
- Could be destruction of the grains due to mutual collisions, or/and
- Gravitational scattering by a massive planet. If the planet is in a circular orbit the models predict the planet to be located (0.8-1.25)xR_{in}, with a mass significantly larger that Neptune and probably larger than Jupiter.

Source	Grain size (μm)	Gap Radius (AU)	Dust Mass (M solar)	Dust Temp. (K)	Spectral Type
HD 6963	10	18	4E-11	57	G0
HD 8907	10	33	1E-9	58	F8
HD 13974	10	> 28	< 1E-11	< 55	G0V
HD 122652	10	31	1E-10	56	F8
HD 145229	10	24	1E-10	56	G0
HD 206374	10	> 20	< 6E-11	< 57	G6.5
HD 105	5 - 1000	45	1E-7		G0
HD 107146	10	26	3E-9	55	G2
HD 150706	1	20	7E-8		G3
eps-Eri	10	7	9E-11	80	K2
tau-Ceti	10	11	2E-11	71	G8

(Kim et al. 2005)

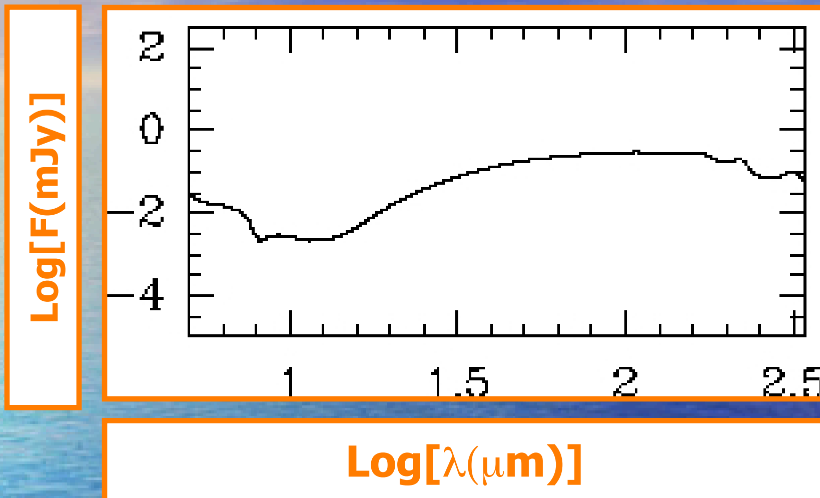
Inner gaps appear to be common; if produced by gravitational scattering of dust by massive planets, this would imply that...

- "Planetary outflows" may contribute significantly to the clearing of circumstellar debris in planetary systems.
- They can contaminate the immediate vicinity of the star-forming regions affecting the particle size distribution of their local ISM
- Maybe we have already detected such an outflow from beta-Pic!

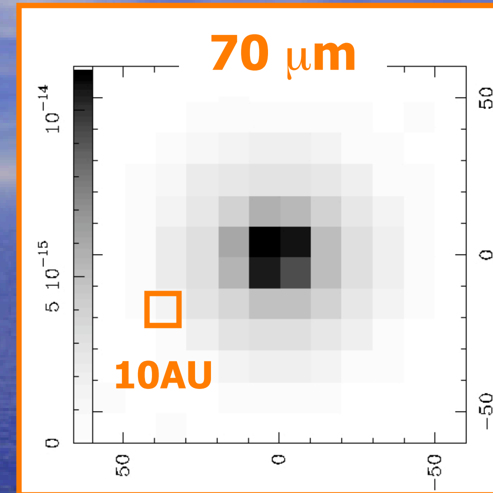
3 M_{Jup} at 1 AU

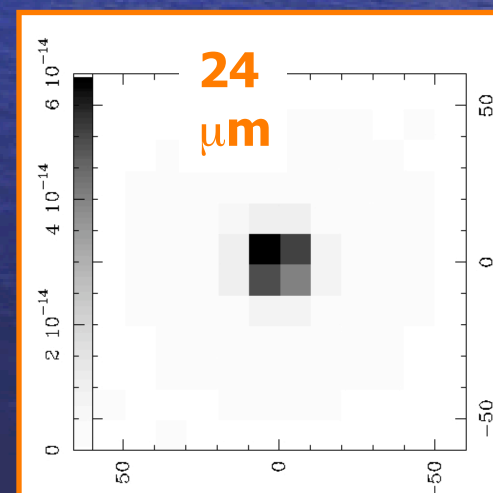
There are degeneracies that can only be solved with high-resolution observations…

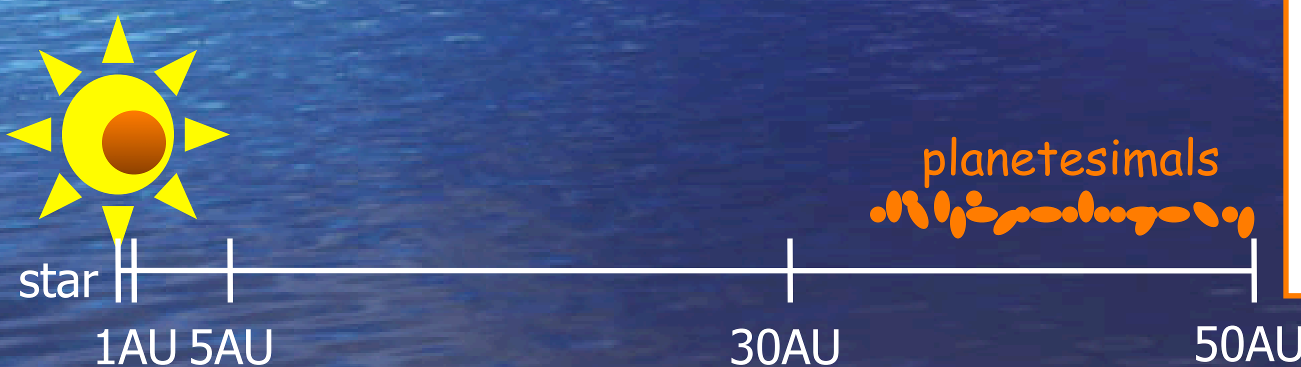
1'' at 10 pc



Fe-poor silicate grains

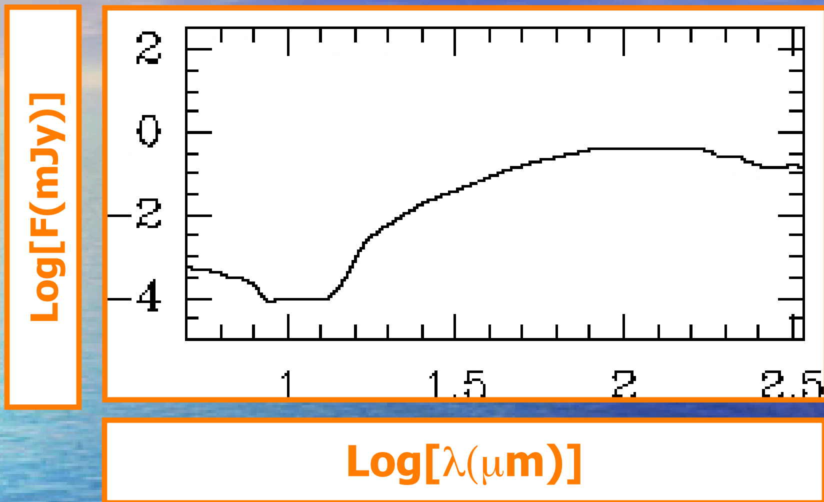






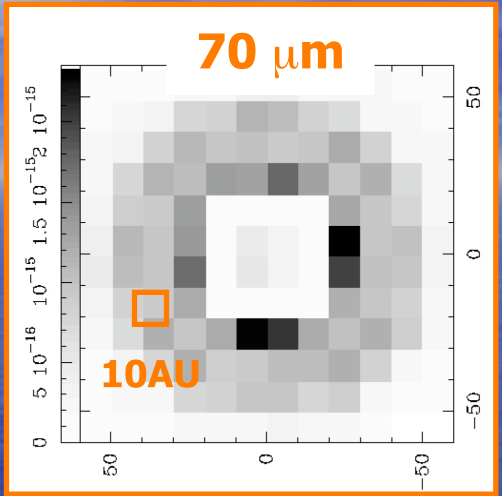
3 M_{Jup} at 30AU

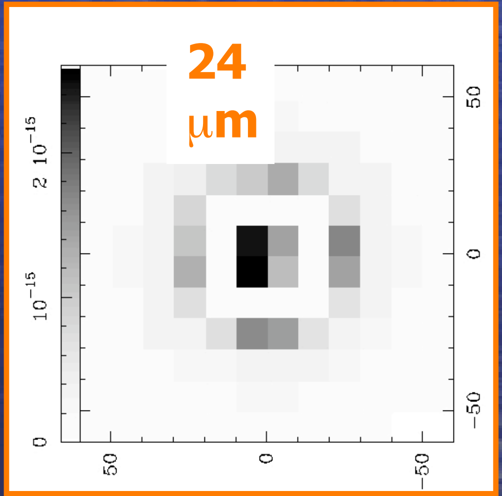
There are **degeneracies** that can only be solved with high-resolution observations…

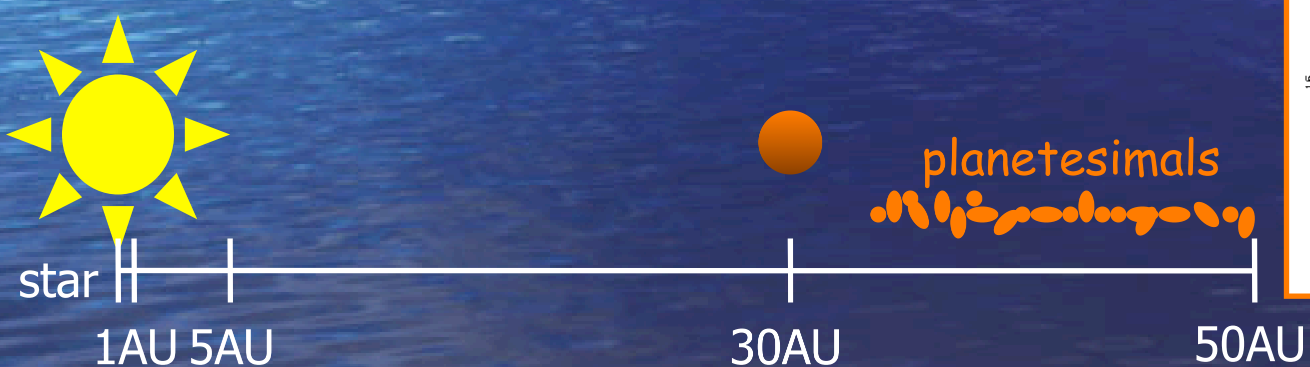


Fe-rich silicate grains

1" at 10 pc



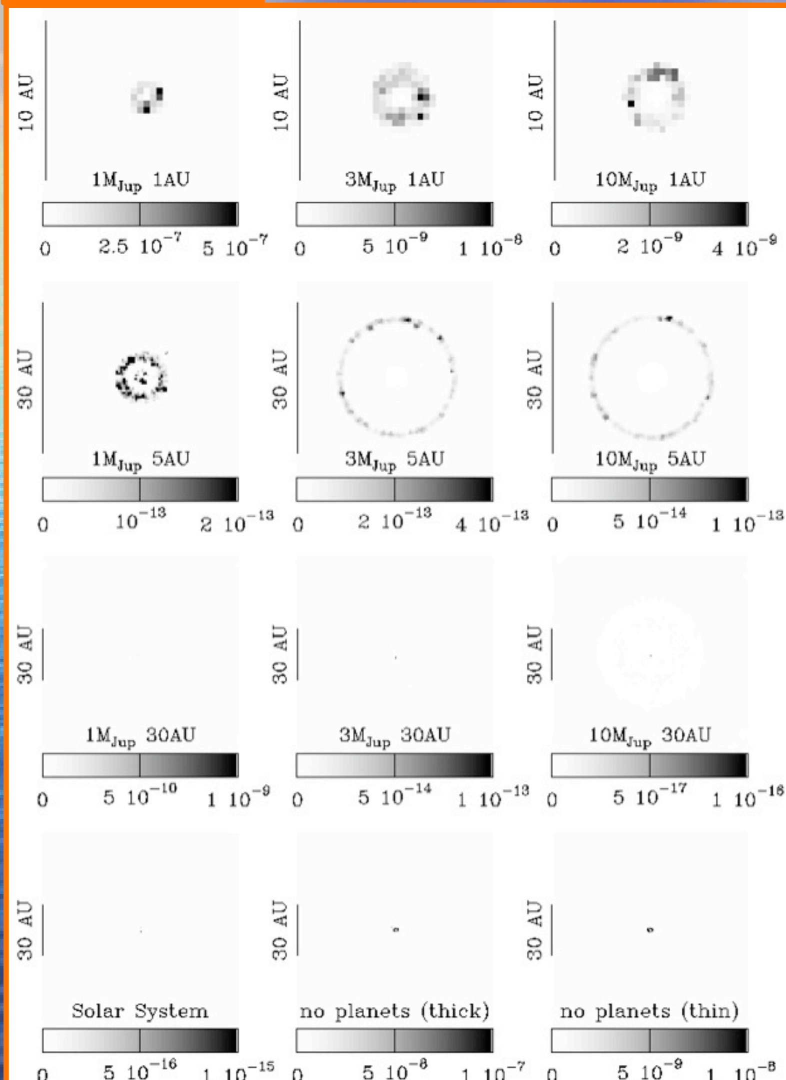




Modeling the Brightness Density Distributions

3 μm

Thermal Emission



- Astronomical Silicates
- Dust Mass: 10^{-10} M_{Sun}

  (Kuiper-Belt dust = 4×10^{-11} M_{Sun})
- Particle size distribution:

  $n(a) \sim a^{-3.5}$ (at production)

  0.7μm - 135μm
- Distance = 140pc
- Units: Jy/pixel

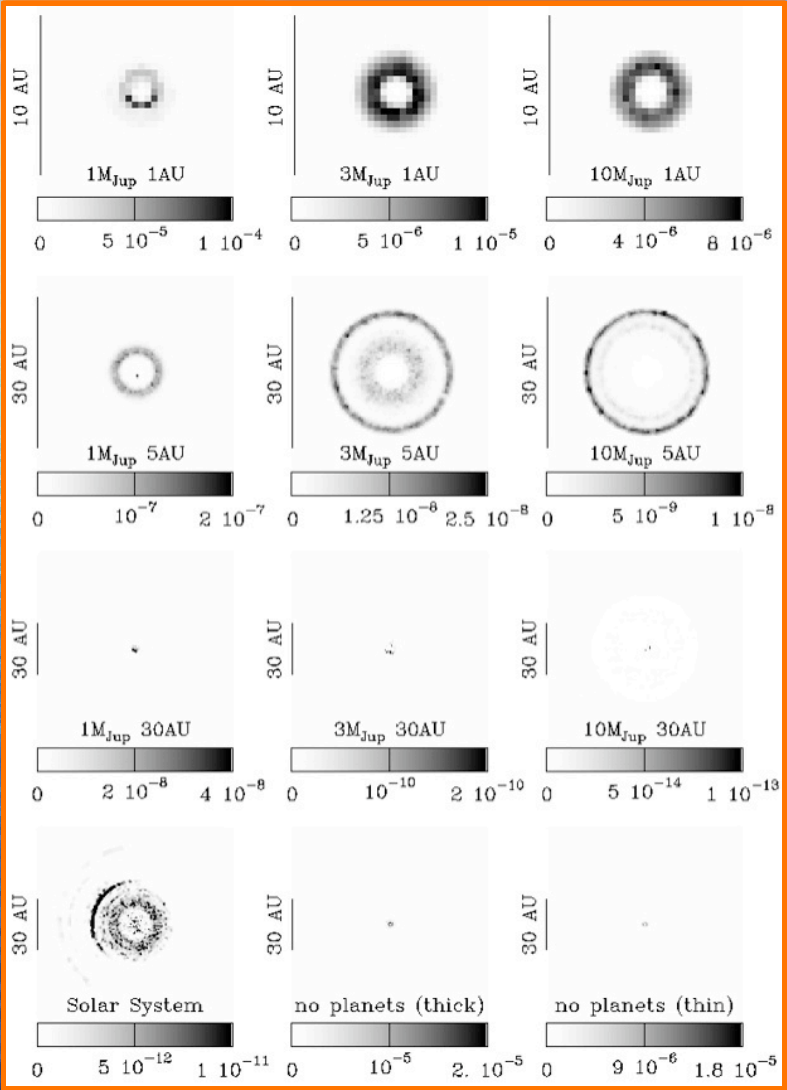
  512x521=200AUx200AU

  0.39 AU/pixel

Modeling the Brightness Density Distributions

10 μm

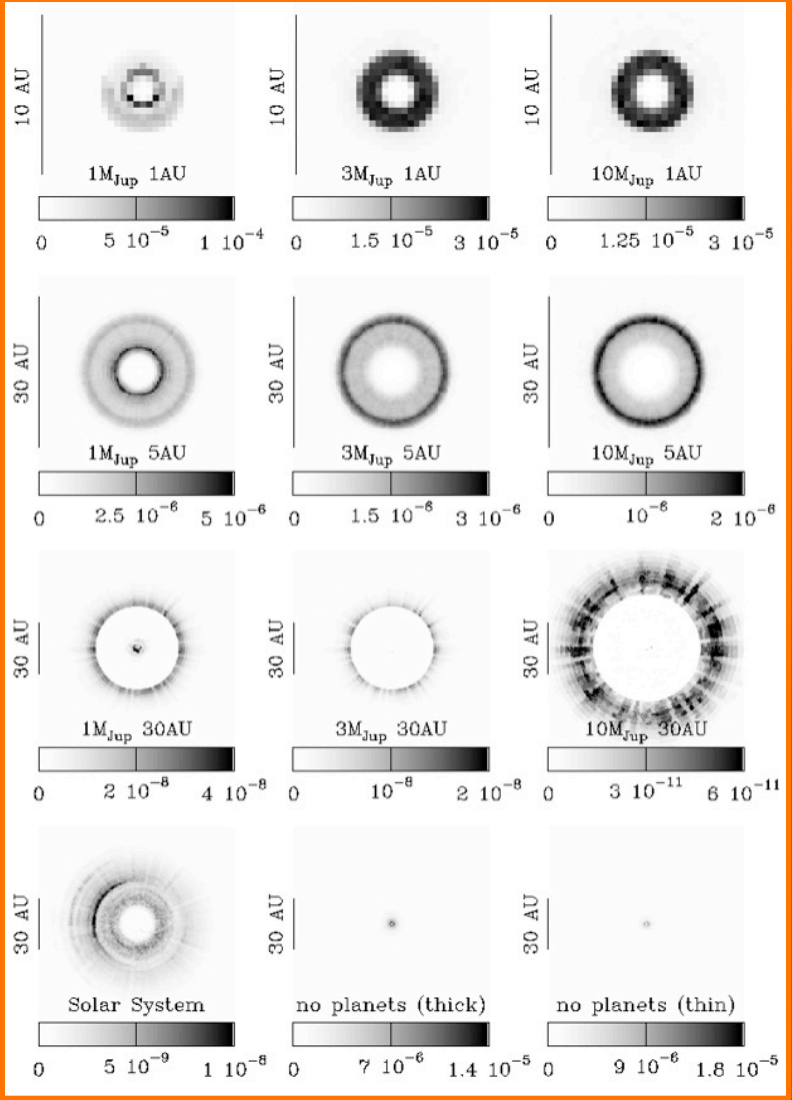
Thermal Emission



Modeling the Brightness Density Distributions

30 μm

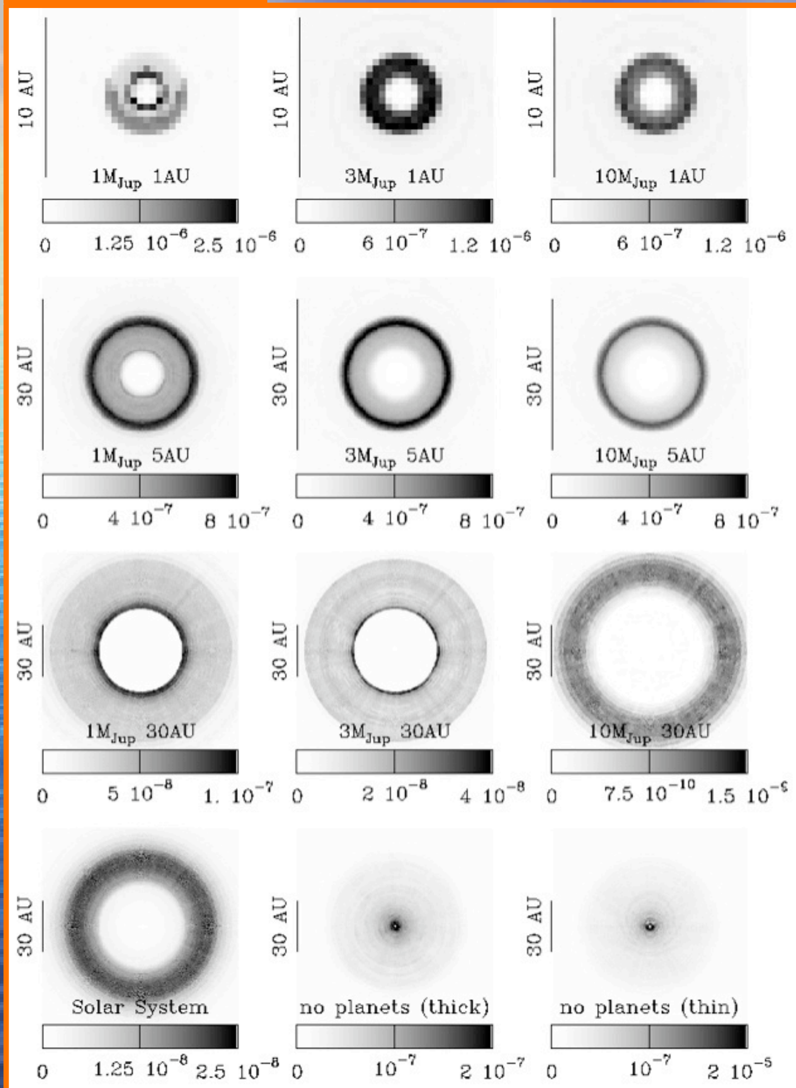
Thermal Emission



Modeling the Brightness Density Distributions

333 μm

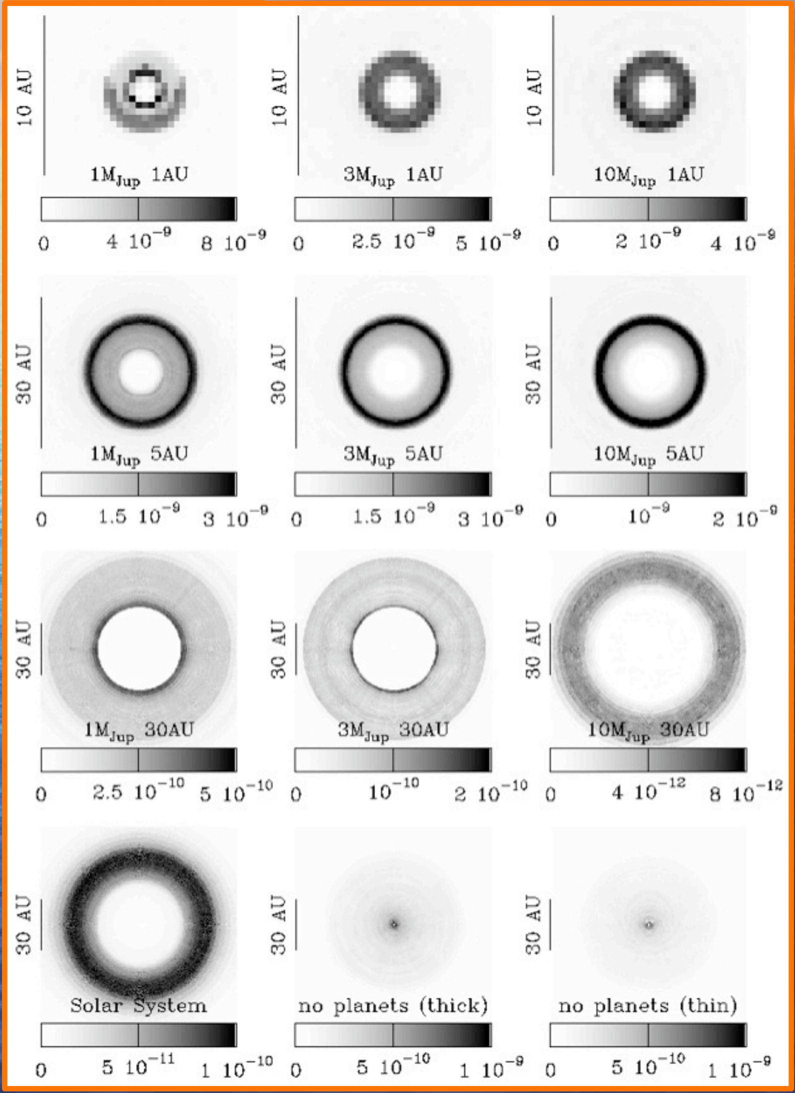
Thermal Emission



Modeling the Brightness Density Distributions

1300 μm

Thermal Emission



- Inner edge: determined by location of the planet.
- Outer edge:
    - 1-5 AU: determined by 3:1 MMR.
    - 30 AU: determined by the location of planetesimals.
- Model with planet at 5AU: outer-most enhanced brightness region created by 3:1 MMR.
- Some inner ring-like features are not determined by MMR but to a combination of increasing grain temperature and sharp decrease of dust number density.
- Azimuthal asymmetries from MMRs are smoothed out when combining different particle sizes.

Conclusions

- Massive planets create structure in debris disks.
- Structure is sensitive to long period planets, complementing radial velocity and transit surveys.
  - ⇨ Debris disk help us learn about diversity of planetary systems.
- The clearing of dust inside the planet's orbit has a clear signature in the disk SED ⇨ SEDs are sensitive to the presence and location of massive planets.
- Inner gaps appear to be common in cold KB-like disks
  - ⇨ Gravitational scattering by massive planets may be common:
    - Clearing of circumstellar dust.
    - Enrichment of local ISM with large dust grains.
- SEDs are degenerated ⇨ Need spatially resolved observations.
- We are working on simulating the brightness density distributions (in scattered light and thermal emission) for exotrasolar Kuiper-Belt dust disks with embedded planets in circular orbits.

Additional slides

What are we learning from Spitzer observations of debris disks?

1. Debris Disks and planets co-exist! (Beichman et al. 2005)

Spitzer has identify the first stars with well-confirmed planetary systems and well-confirmed IR excess!!

Study of 26 FGK stars with confirmed radial velocity planets (average age ~ 1Gyr):

- 6/26 show 70 μm excess (average age ~ 4Gyr).
- none with 24 μm excess: upper limit of warm dust L_{dust}/L_{star} ~5x10^{-5} (compared to L_{dust}/L_{sun} ~10^{-7} for AB).

⇨ KB analogs: T<100K; >10AU; 100 x surface emitting area of the solar system's dust.

- Potential correlation of planets with IR excess

2. Cold KB-like disks appear to be more common than AB-like disks (Hines et al. 2005)

Only 1 out of 33 stars (with ages between 10 Myr and 2 Gyr) have warm excesses:

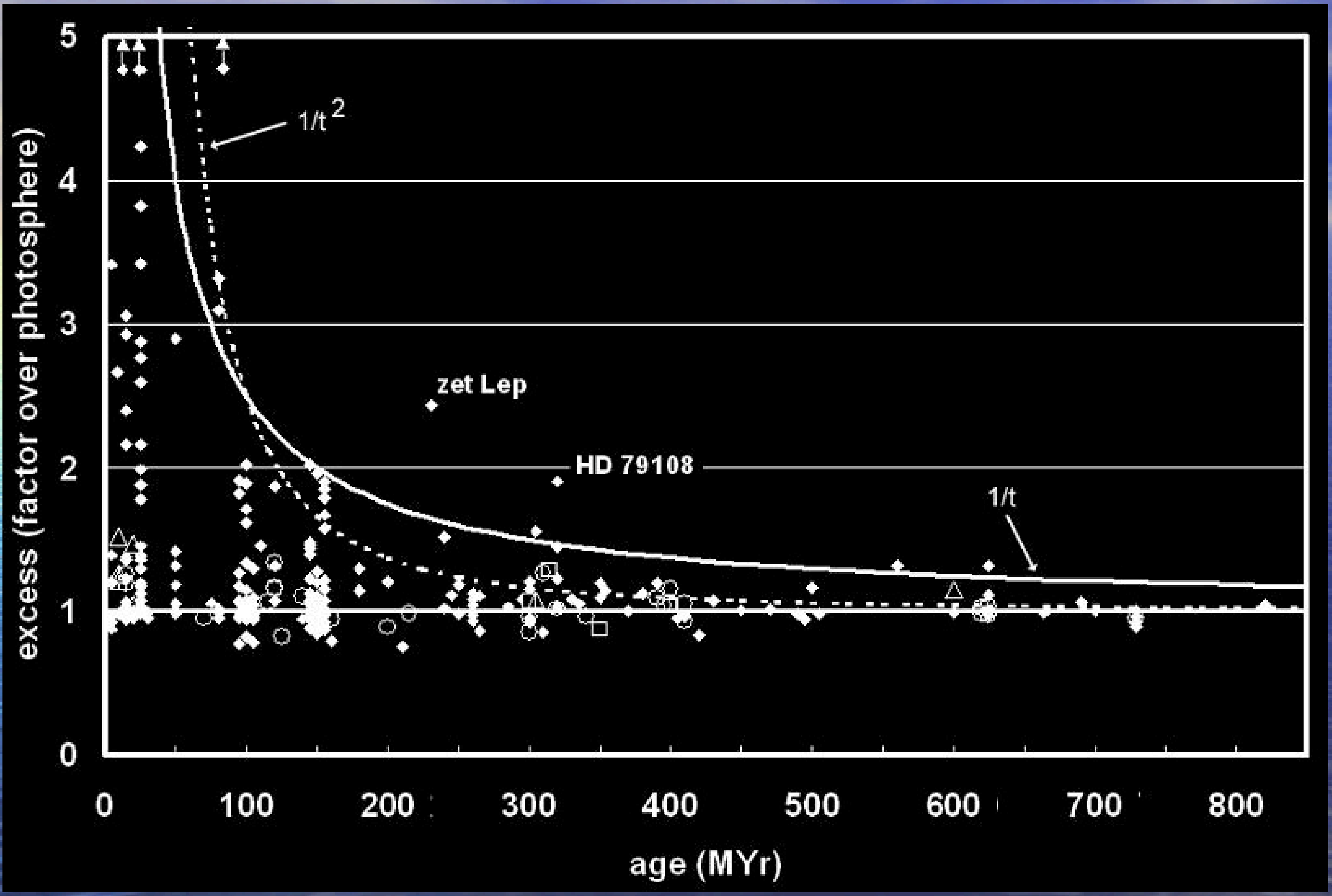
- Are these excesses short lived events connected with the formation of terrestrial planets? or...
- Is the dust production rate in the terrestrial planet-building zone rare?

3. Individual collisional events can dominate the properties of debris disks over Myr timescales (A-star survey: Rieke et al. 2005, Su et al. 2005).

⇨ Debris disk sub-structure could be due to a recent collision

4. There is a large range of initial planetary systems structures (A-star survey)

⇨ Stars of a similar age show substantial differences in the amount of dust!



excess (factor over photosphere)
age (MYr)
1/t 2
1/t
zet Lep
HD 79108
0
1
2
3
4
5
0
100
200
300
400
500
600
700
800

5. Inner gaps appear to be common in cold KB-like disks

(Kim et al. 2005, Meyer et al. 2004)

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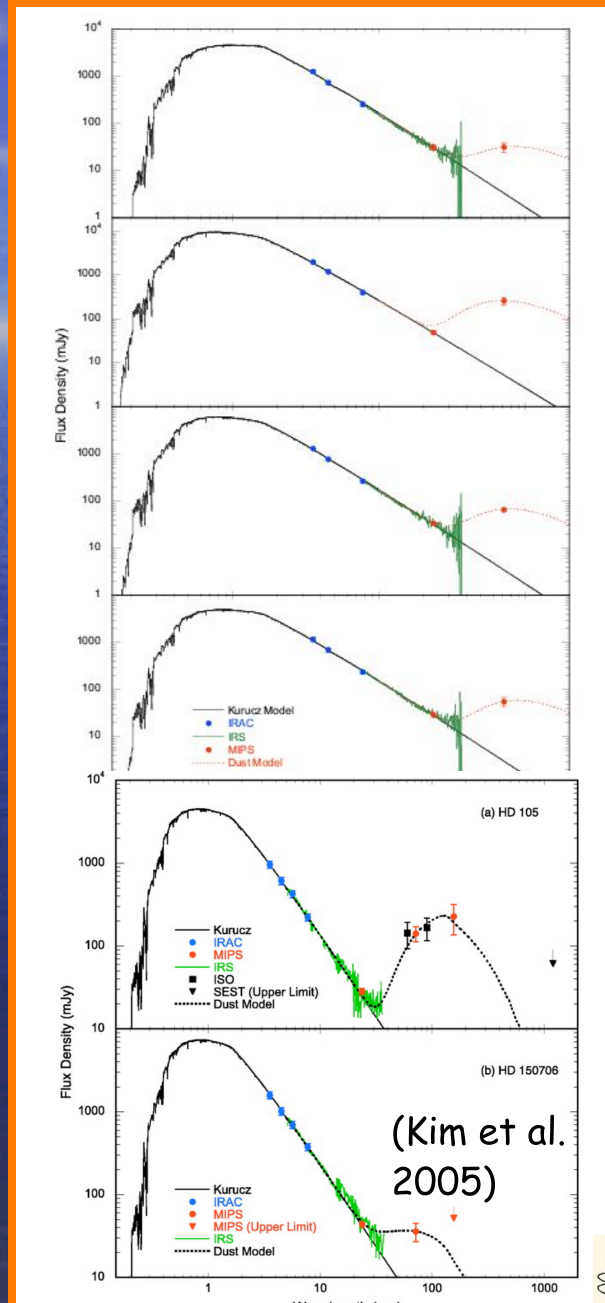

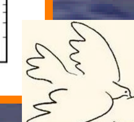

- Sublimation of icy grains? No, T<100K.
- Blowout by radiation pressure? No, dust grains > blowout size.
- An interesting possibility: scattering by a massive planet.

If the planet is in a circular orbit the models predict the planet to be located (0.8-1.25)xR_{gap}, with a mass similar or larger than Jupiter.

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- They can contaminate the immediate vicinity of the star-forming regions affecting the particle size distribution of their local ISM
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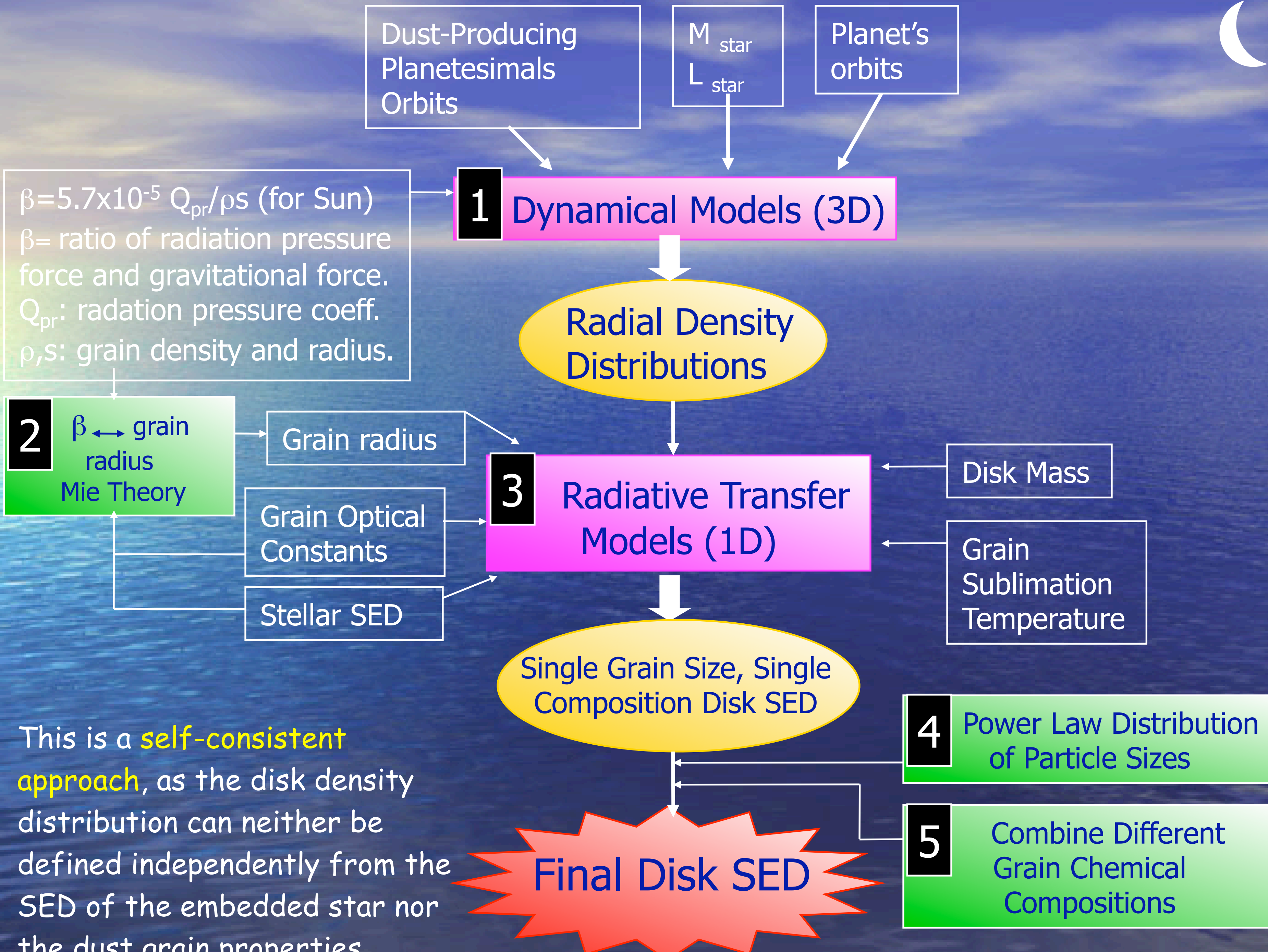
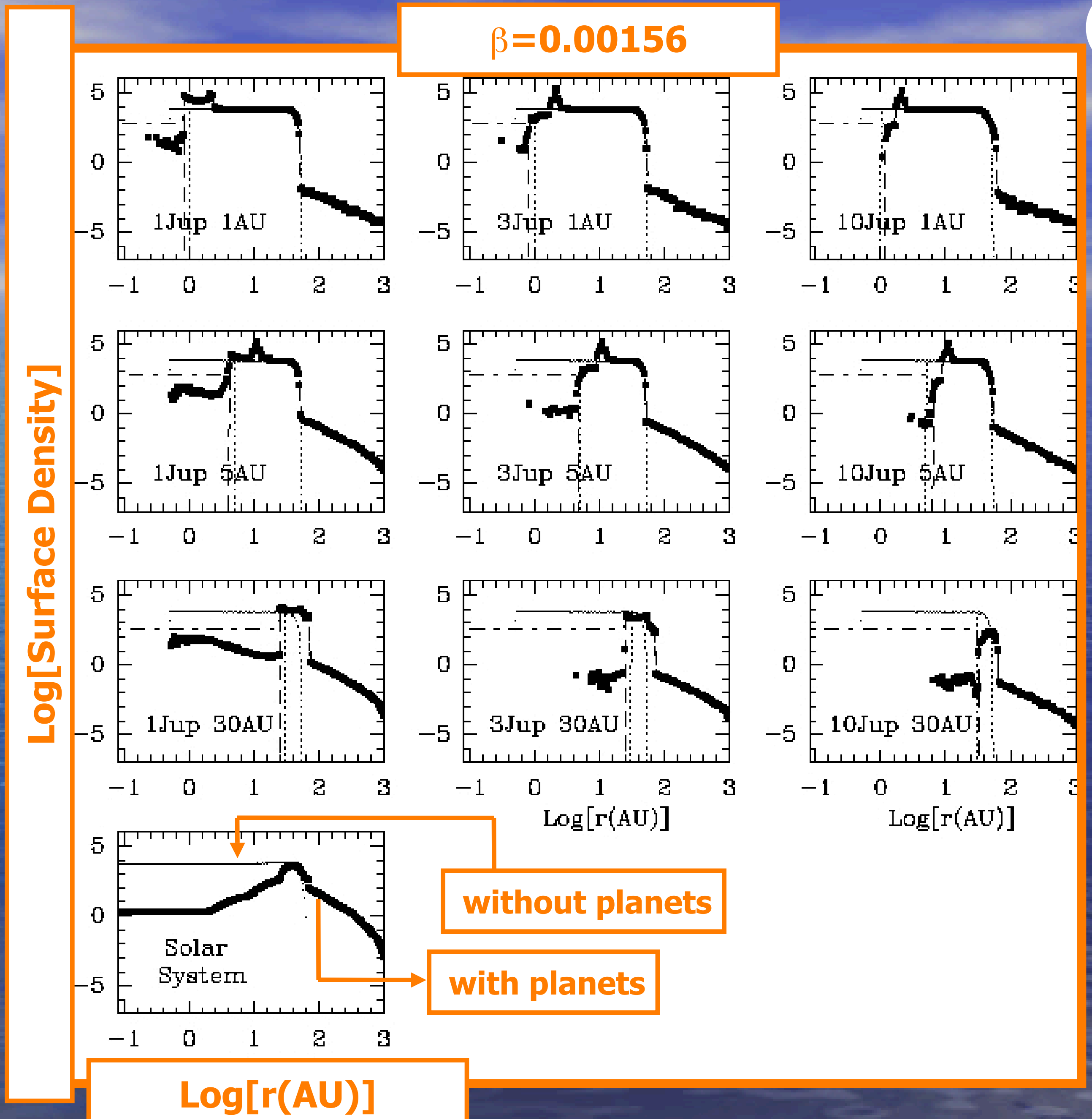
For details about the modeling:

- "Study of the Dynamics of Dust from the Kuiper Belt: Spatial Distribution and Spectral Energy Distribution", Moro-Martin & Malhotra, 2002, AJ, 124, 2305
- "Dynamical models of KB Dust in the Inner and Outer Solar System", Moro-Martin & Malhotra, 2003, AJ, 125, 2255
- "Signature of planets in spatially unresolved debris disks", Moro-Martin, Wolf & Malhotra, 2005, ApJ, 621, 1079
- "Dust outflows and inner gaps generated by massive planets in debris disks", 2005, ApJ, in press.

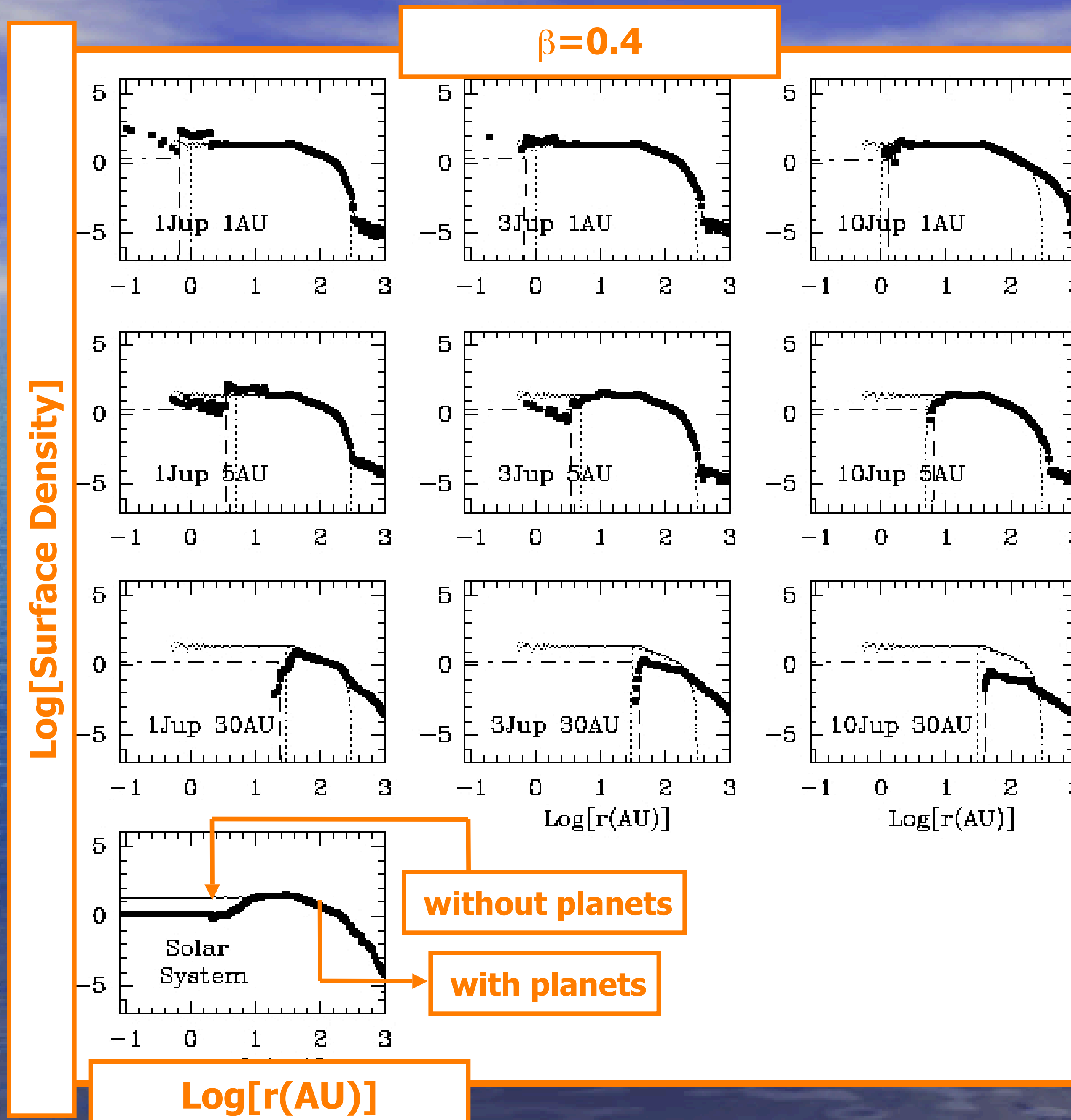
Pre-prints at: http://www.astro.princeton.edu/~amaya



This is a *self-consistent approach*, as the disk density distribution can neither be defined independently from the SED of the embedded star nor the dust grain properties



Radial Density Distributions



Radial Density Distributions

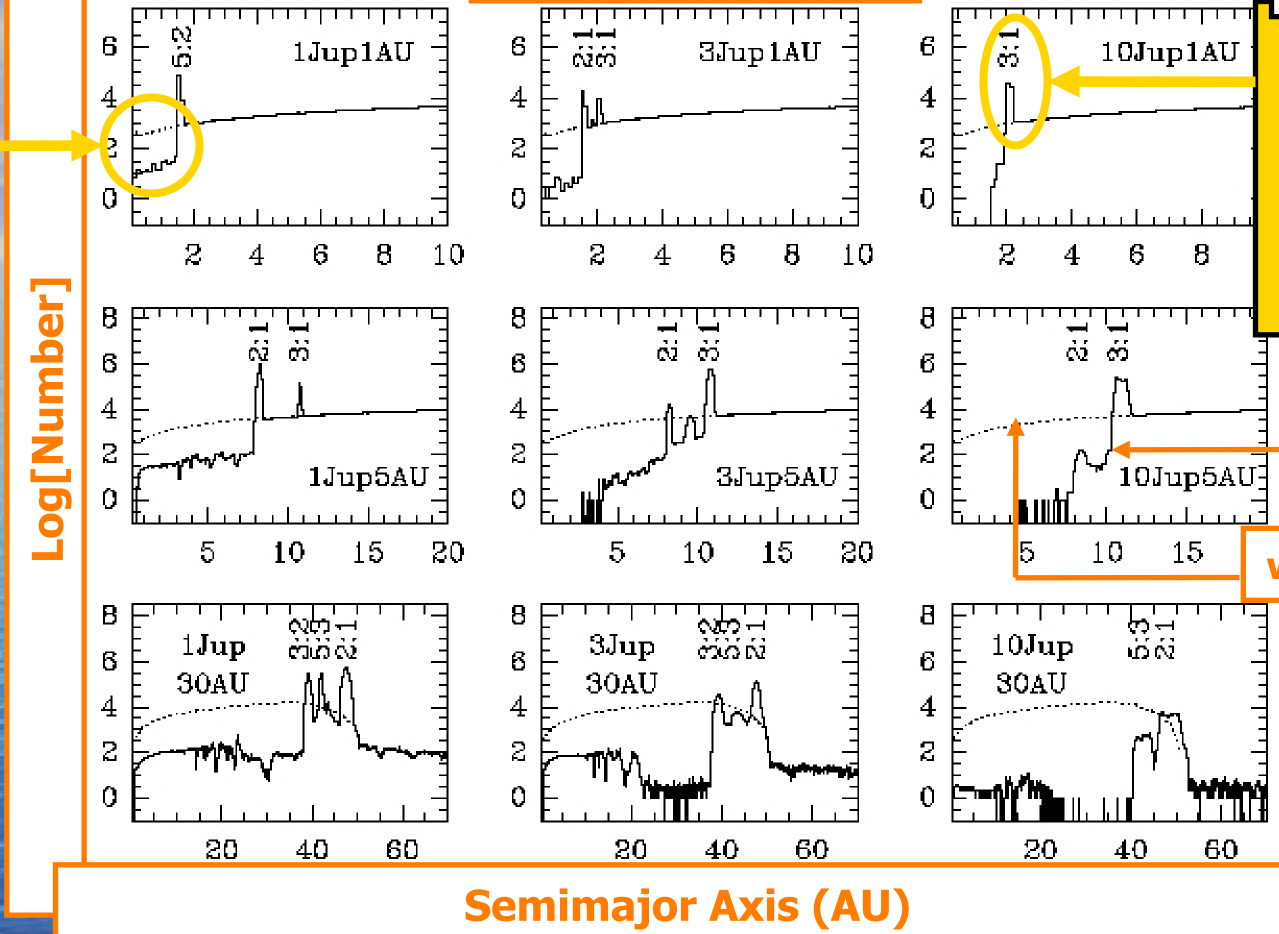
Effect 2

Clearing inside the planet's orbit

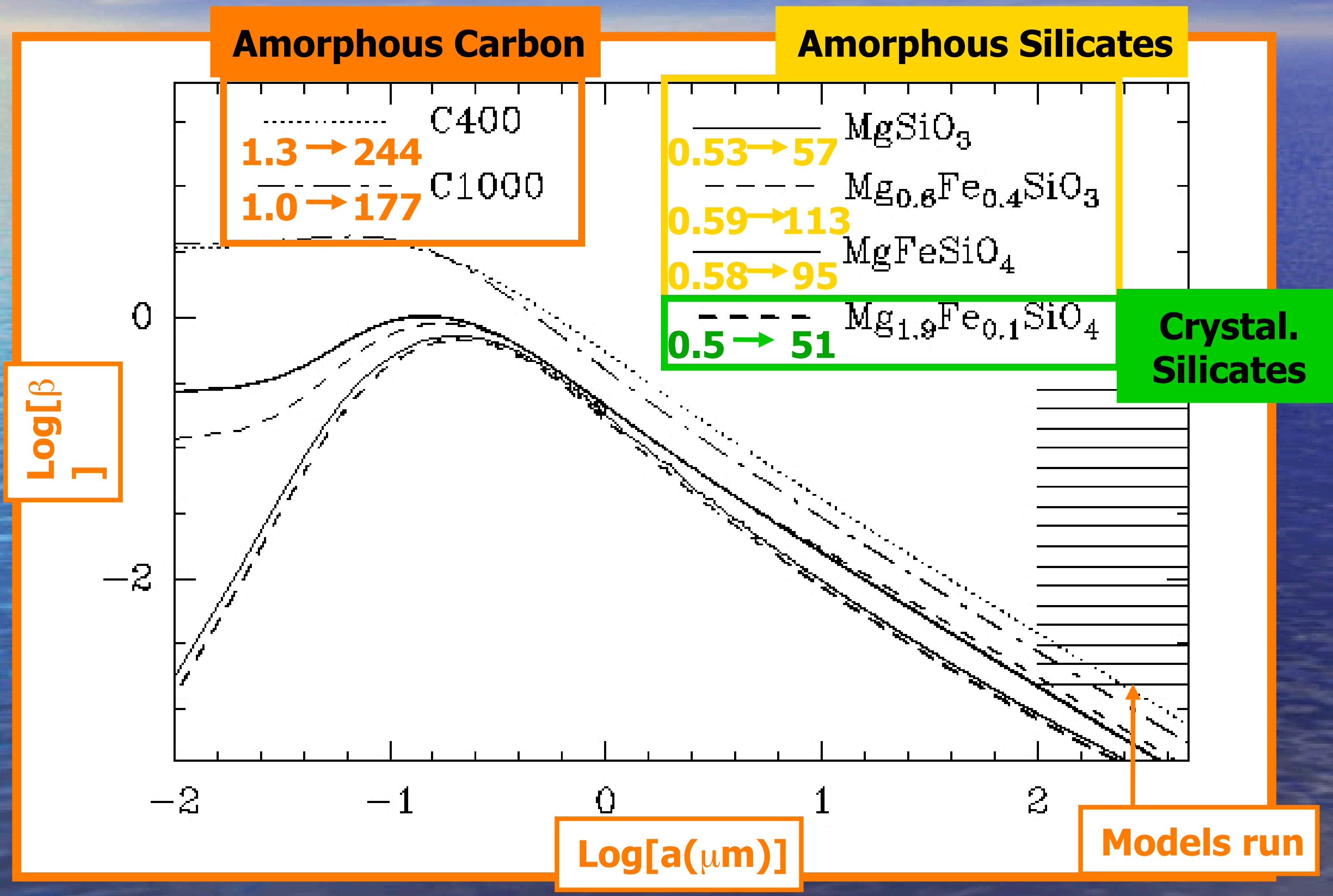
Effect 1

Accumulation of particles in exterior MMRs with planet

β=0.0125



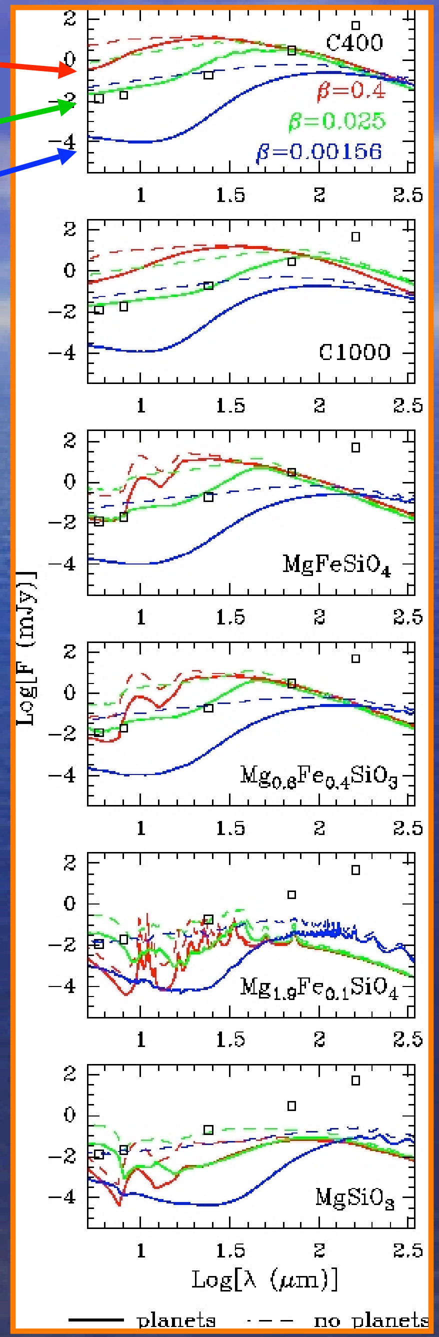
2 $\beta \longleftrightarrow$ Grain Radius Relation



Small grains

Intermediate grains

Large grains



C400

C1000

$MgFeSiO_4$

$Mg_{0.6}Fe_{0.4}SiO_3$

$Mg_{1.9}Fe_{0.1}SiO_4$

$MgSiO_3$

Single Grain Size, Single Composition Disk SED