Debris Disks:

Seeing Dust,

Thinking of Planetesimals and Planets

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Outline

Part I

- Concept of debris disks
- Observations of debris disks
- Basic theory of debris disks

Part II

- Debris disks: seeing dust
- Debris disks: thinking of planetesimals
- Debris disks: thinking of planets
- Debris disks: thinking of planetary systems

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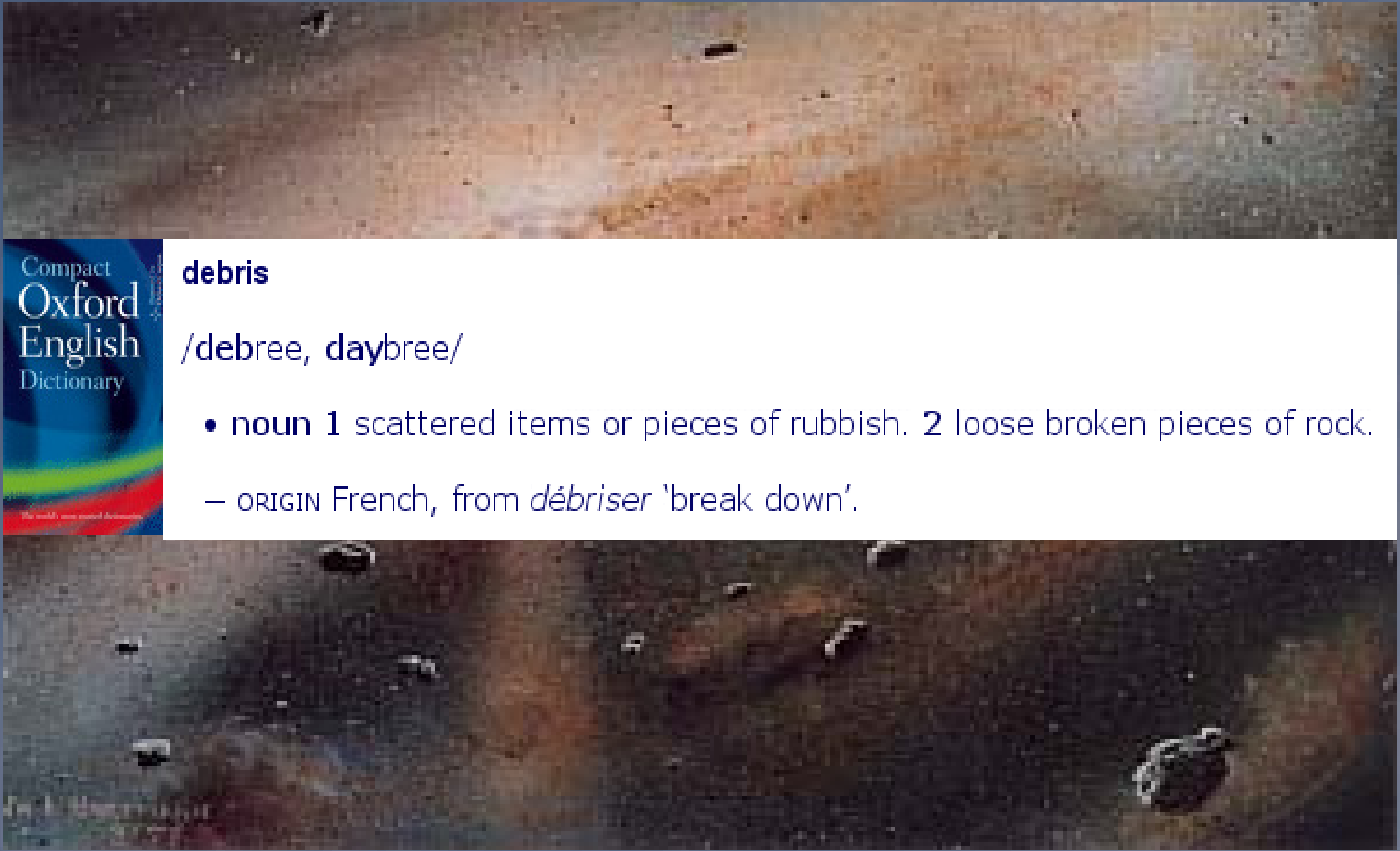
The name of the game



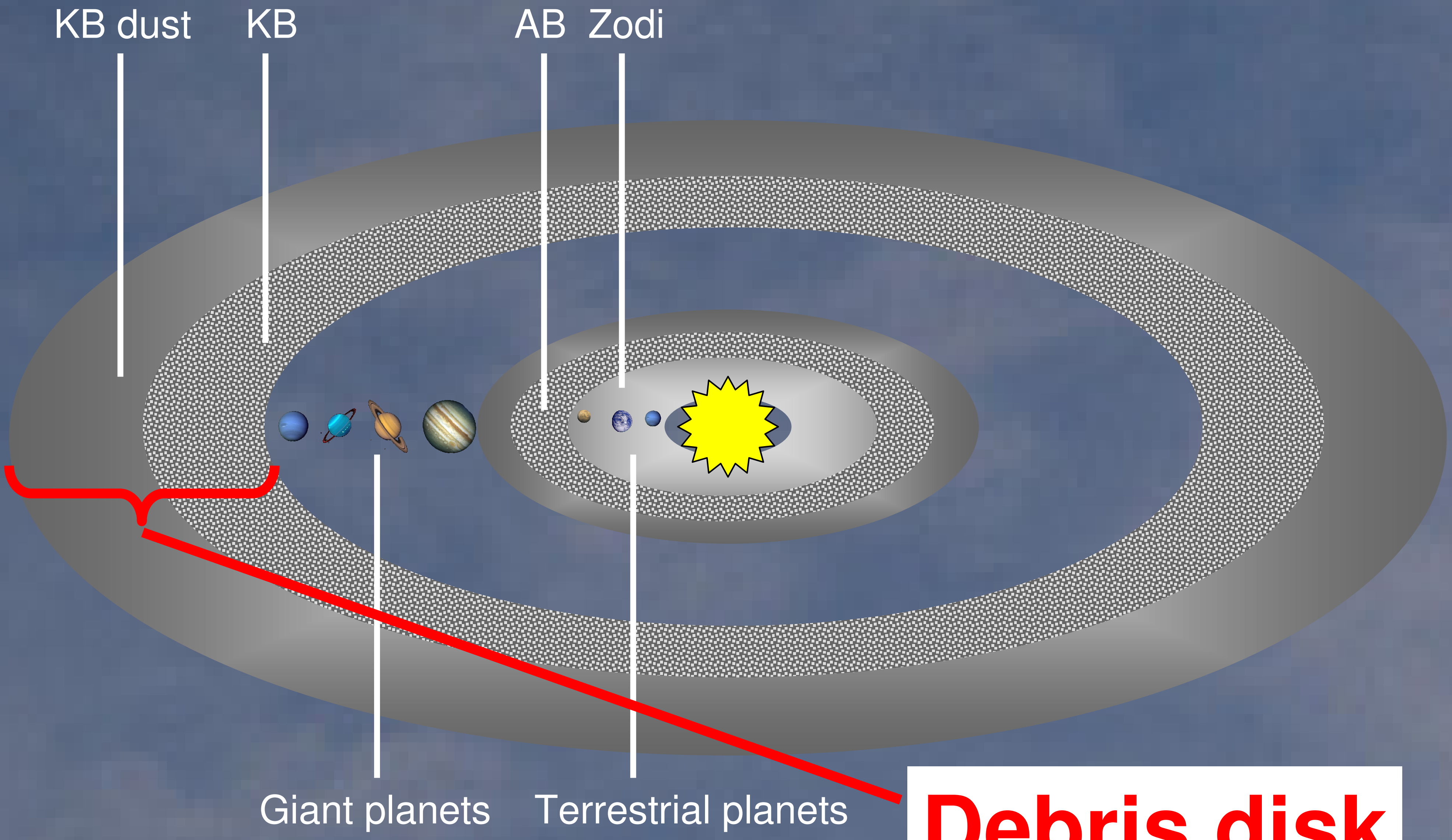
debris

/**de**bree, **day**bree/

- **noun 1** scattered items or pieces of rubbish. **2** loose broken pieces of rock.

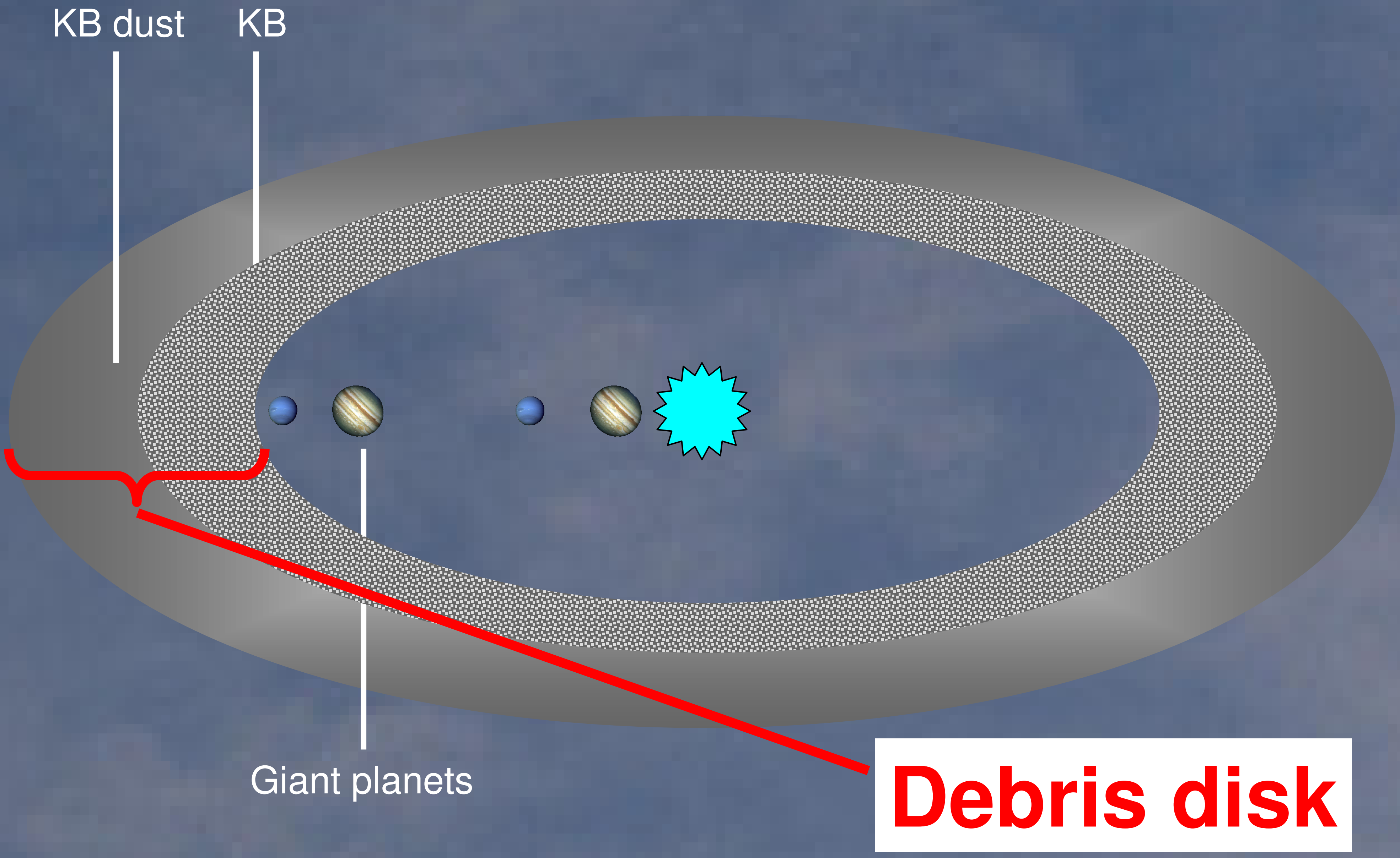
— ORIGIN French, from *débriser* ‘break down’.

Our solar system



Debris disk

Other planetary systems



Protoplanetary phase and debris disk phase

Standard formation scenario:

- A disk of gas and dust
- From dust to planetesimals
- From planetesimals to embryos (~1Myr)
  (closer to the star, otherwise takes too long)
- Gas accretion onto large embryos (< 10 Myr)
- Disk clearing
- Formation of terrestrial planets (~100 Myr)
- A planetesimal belt on the periphery (KB), producing dust

Evolutionary phases of planetary systems

10Myr

10Gyr

Debris disk phase

PP phase

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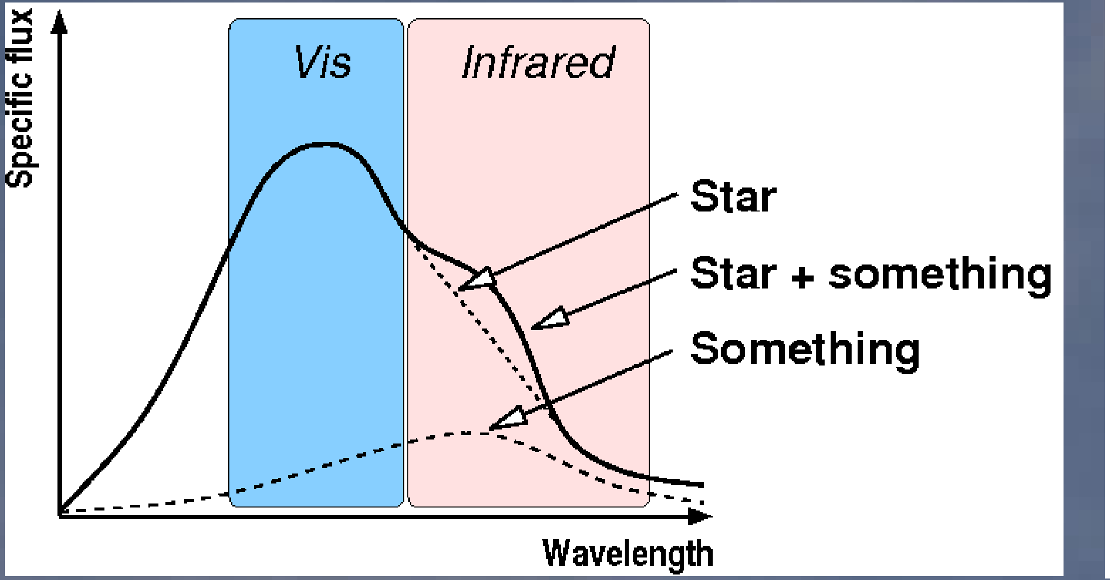
(1) Infrared excesses ("Vega phenomenon")

The first discovery of an infrared excess over stellar photospheric emission of a main-sequence star: Vega. Evidence for dust!



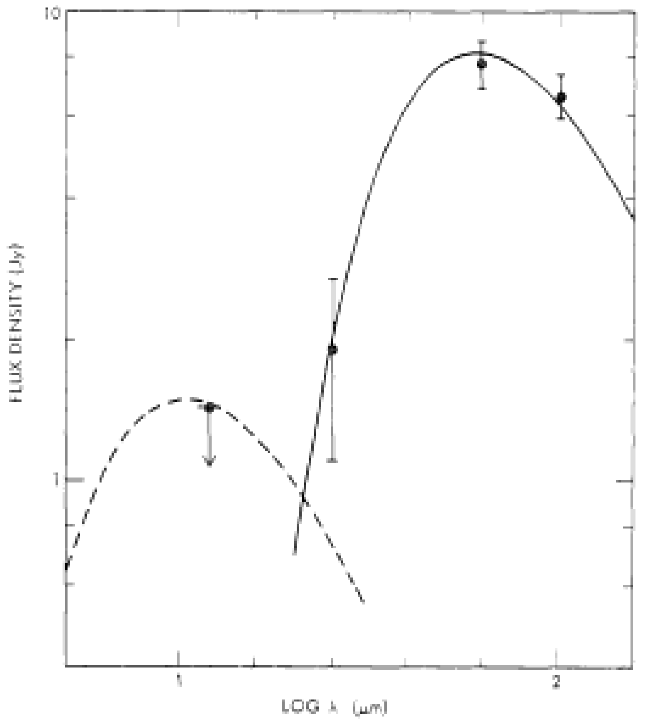


FIG. 1.—Energy distribution of the infrared excess from α Lyr. The error bars represent the 10% calibration uncertainty. The 12 μm upper limit indicates the effect of the 5% uncertainty in the absolute calibration at 12 μm. The solid line represents a 85 K blackbody spectrum with a solid angle of 7×10^{-13} sr fitted to the excess. The dashed line represents a 500 K blackbody spectrum with a solid angle of 6.3×10^{-16} sr arbitrarily fitted to the 12 μm upper limit.

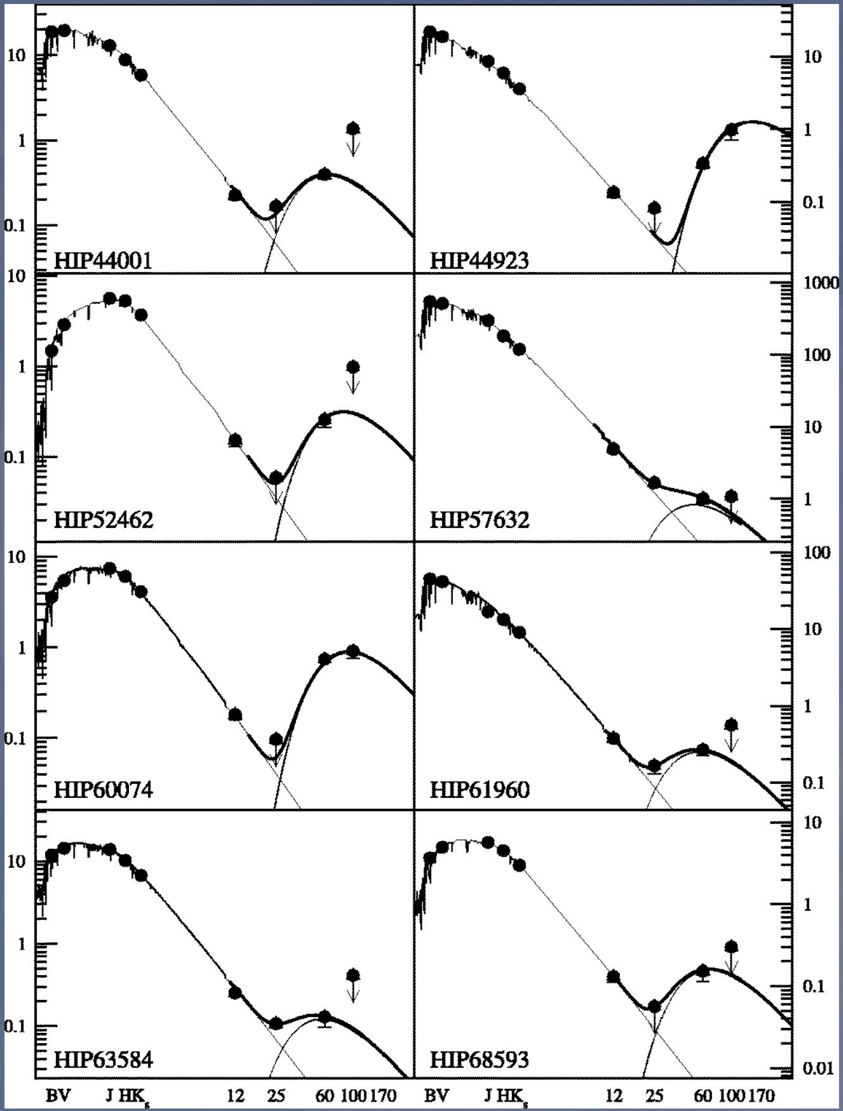
Aumann et al., ApJ ***278****, L23-L27 (1984)*

(1) Infrared excesses ("Vega phenomenon")

Since then:
thanks to IRAS, ISO, ..., Spitzer,
the Vega phenomenon has been
observed around ~1000 nearby
stars

About 15% of main-sequence stars have dust around them. Almost the same incidence around AFGK stars, may be slightly higher for early types, M unclear

Near future: Herschel
-> poster by Jens Rodmann

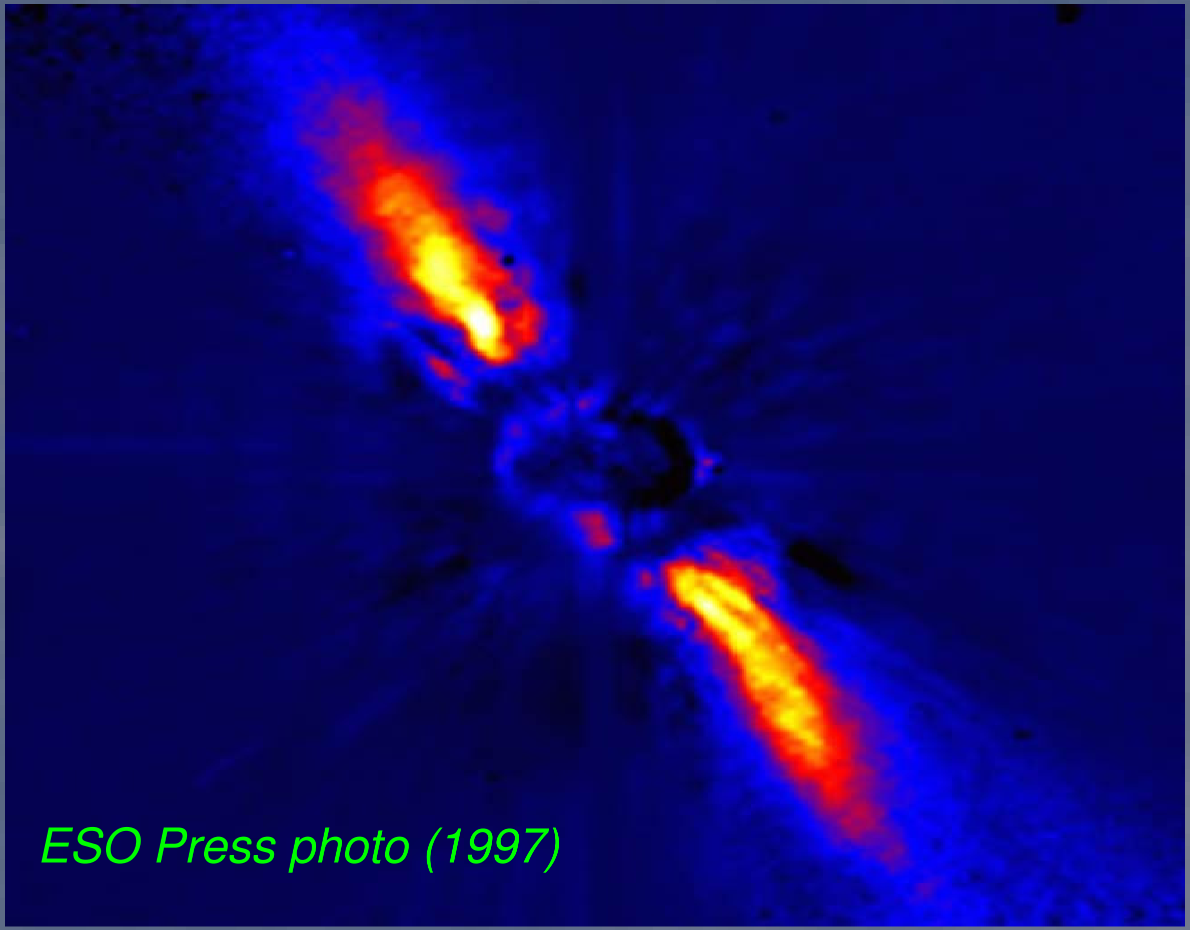


Zuckerman & Song, ApJ ***603****, 738-743 (2004)*

(2) Images

The first image of a dust disk around a main-sequence star: β Pictoris

Dust is present in the form of a structured disk

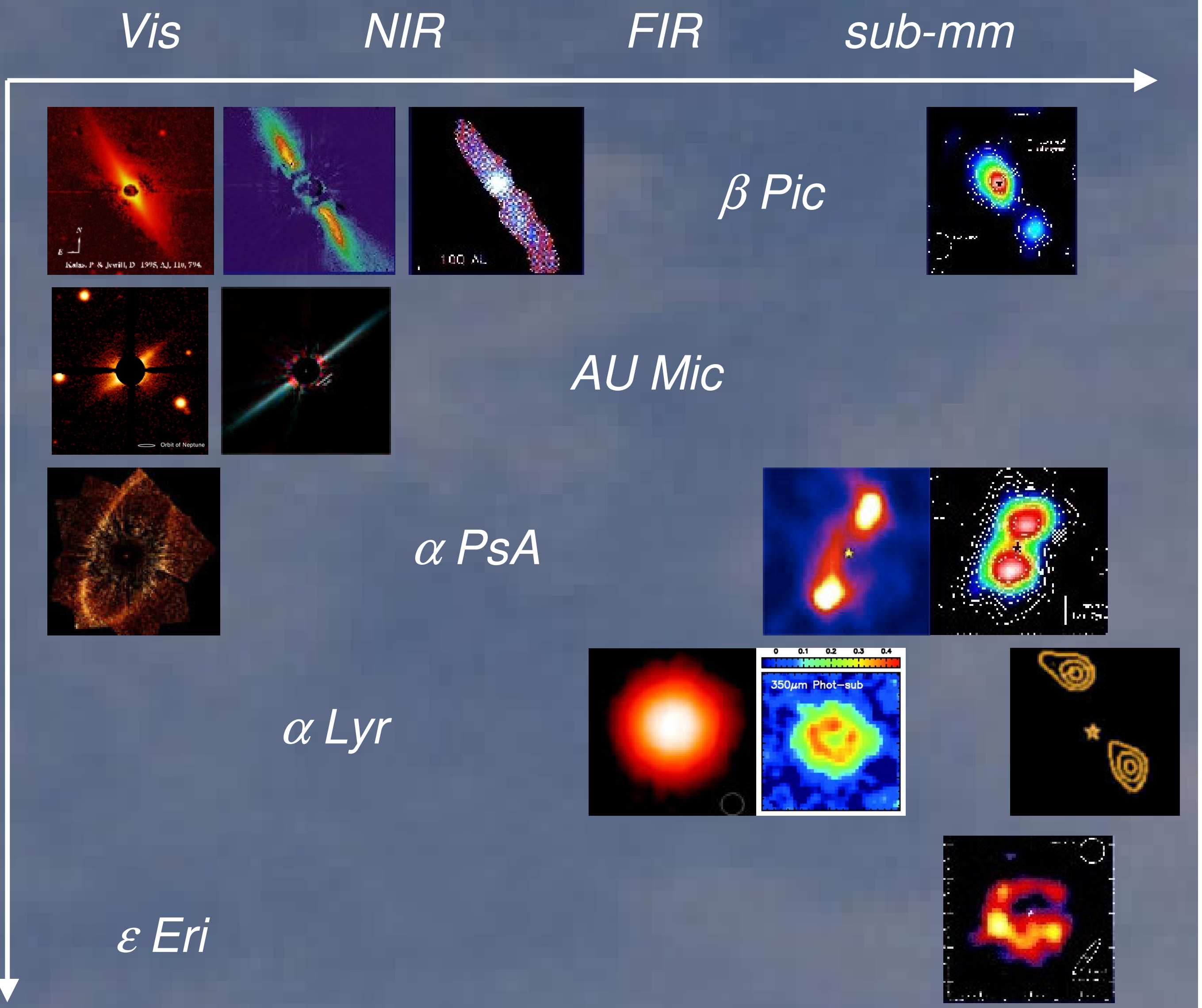

ESO Press photo (1997)

(2) Images

Since then: imaging with many ground-based instruments and HST, both in scattered light and thermal emission

By now, about 20 disks imaged

~10 Myr age



~1 Gyr age

Observed dust is evidence for planetesimals

Ages of systems: 10 Myr ... 10 Gyr
But: estimated lifetime of dust particles: < 1Myr

↓

Dust cannot be primordial and
needs continuous replenishment

↓

As growth is impossible,
dust must stem from parent bodies, planetesimals

↓

A conceivable mechanism:
collisions of planetesimals

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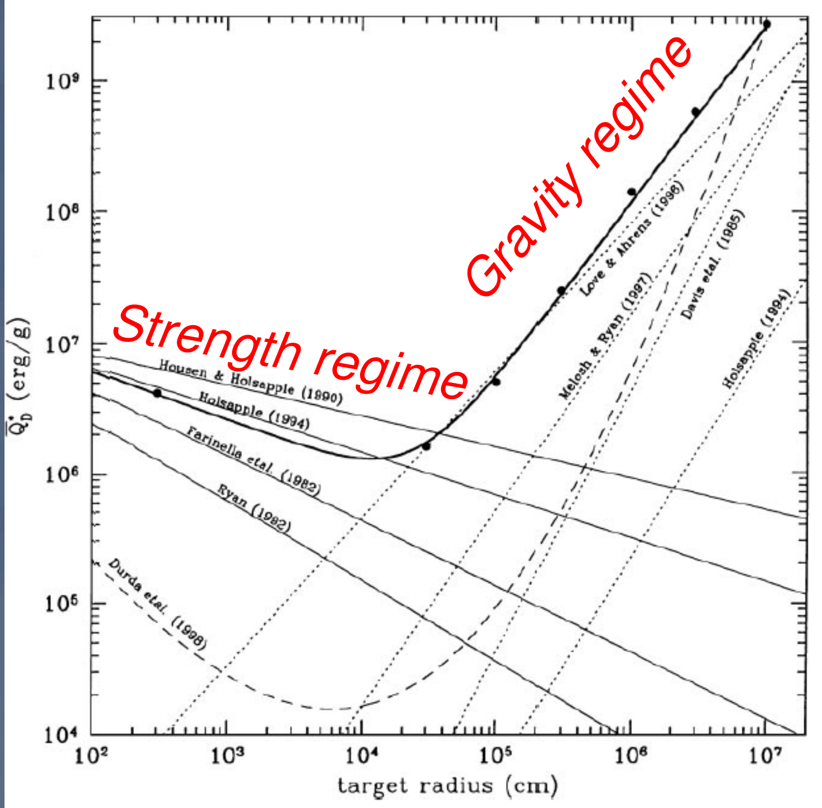
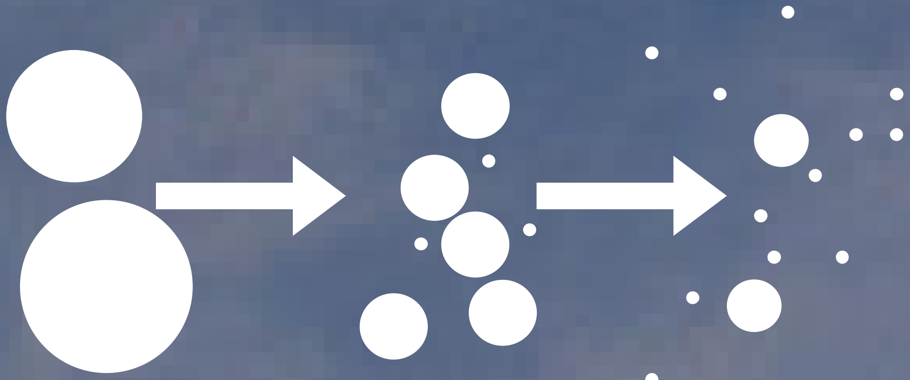
Physical processes: (a) collisions

Individual collisions



Benz & Asphaug, Icarus **142,** *5-20 (1999)*

Collisional cascade



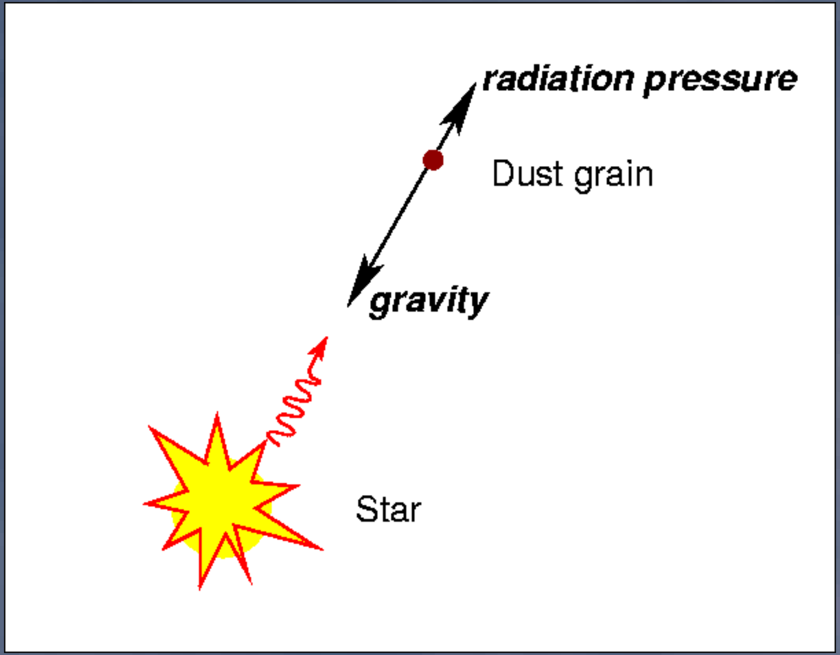
planetesimals...   boulders   ... dust

Under debris disk conditions:
- Disruptive collisions
- Cratering collisions

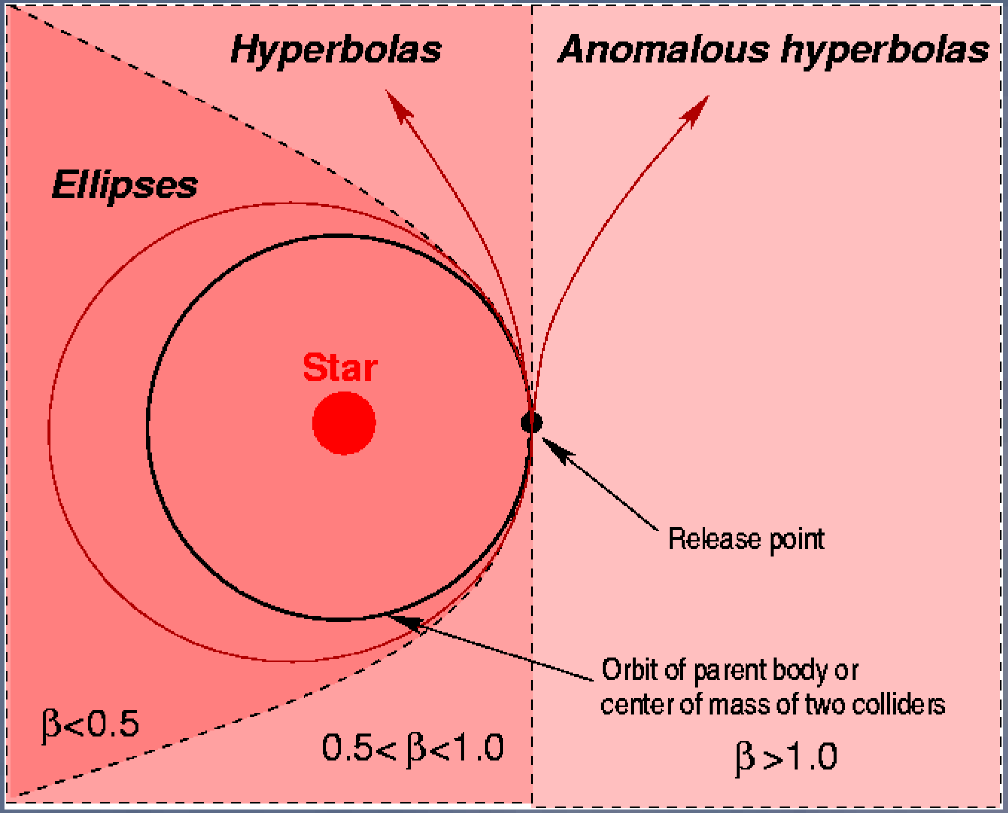
Collisional cascade grinds planetesimals to ever-smaller fragments, down to dust sizes.

Physical processes: (b) stellar "photogravity"

Stellar "photogravity"



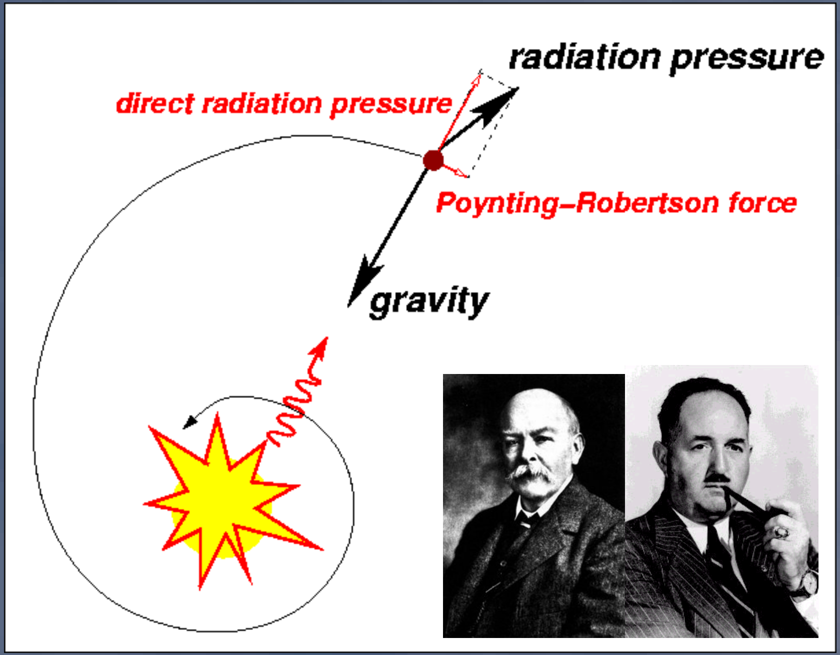
planetesimals in nearly-circular orbits,
dust grains in elliptic ones,
fine dust leave the system in hyperbolas



Krivov et al., Icarus **445,** 509-519 (2006)

Physical processes: (c) drag forces

Poynting-Robertson force



dust orbits slowly circularize
and shrink toward the star

Wyatt & Whipple, ApJ **111,** *134 (1950)*
Breiter & Jackson, MNRAS **299,** *237 (1998)*

Stellar wind drag force

“corpuscular analog” to the P-R effect
(strong for late-type stars)

Burns et al. (1979), Plavchan et al. (2005)

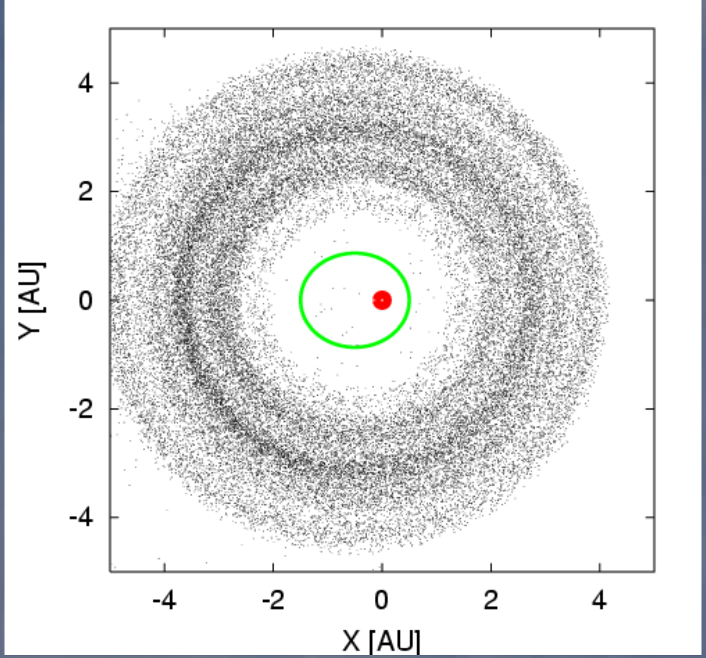
Physical processes: (d) planetary perturbations

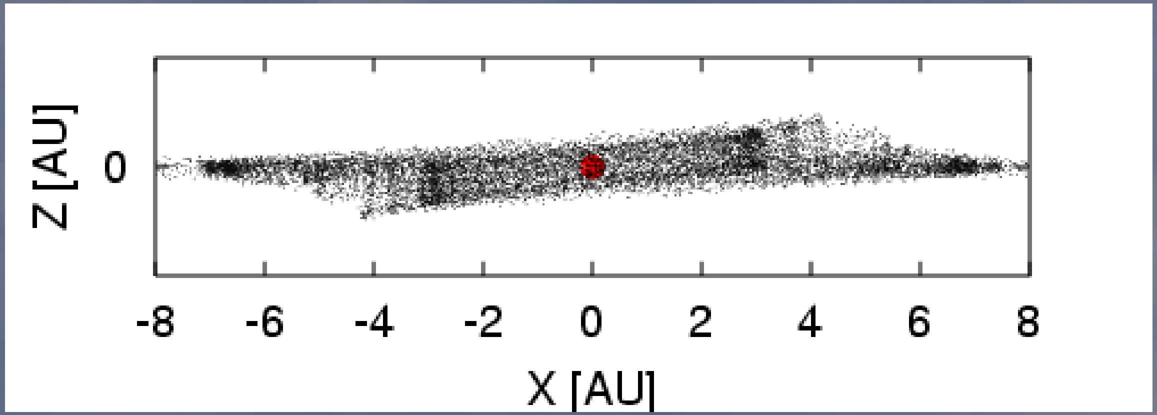
Gravity of planets

confines planetesimals,
stirs them up,
exerts secular and resonant perturbations on them

secular offset (e, ϖ)

secular warp (i, Ω)





Original Schematics

Physical processes: (e) others

Sublimation and sputtering	eliminate dust close to the star, gradually reduce their size (important for early-type stars)
Lorentz force	important for small grains only and only if appreciable MF is present

... and many others
that are usually not included in debris disk models,
but may be important...

Modeling methods

- **Celestial mechanics / N-body simulations**

  - N-body + "inflated spheres" + local PiaB *(Thébault, Wyatt)*

  Accurate dynamics but inaccurate collisions (if any)

- **Kinetic theory / Statistical codes**

  - Multiannulus PiaB *(Kenyon & Bromley, Thébault)*
  - Kinetics in orbital elements *(Dell'Oro, Krivov)* ← ACE

  Accurate collisions but simplified dynamics

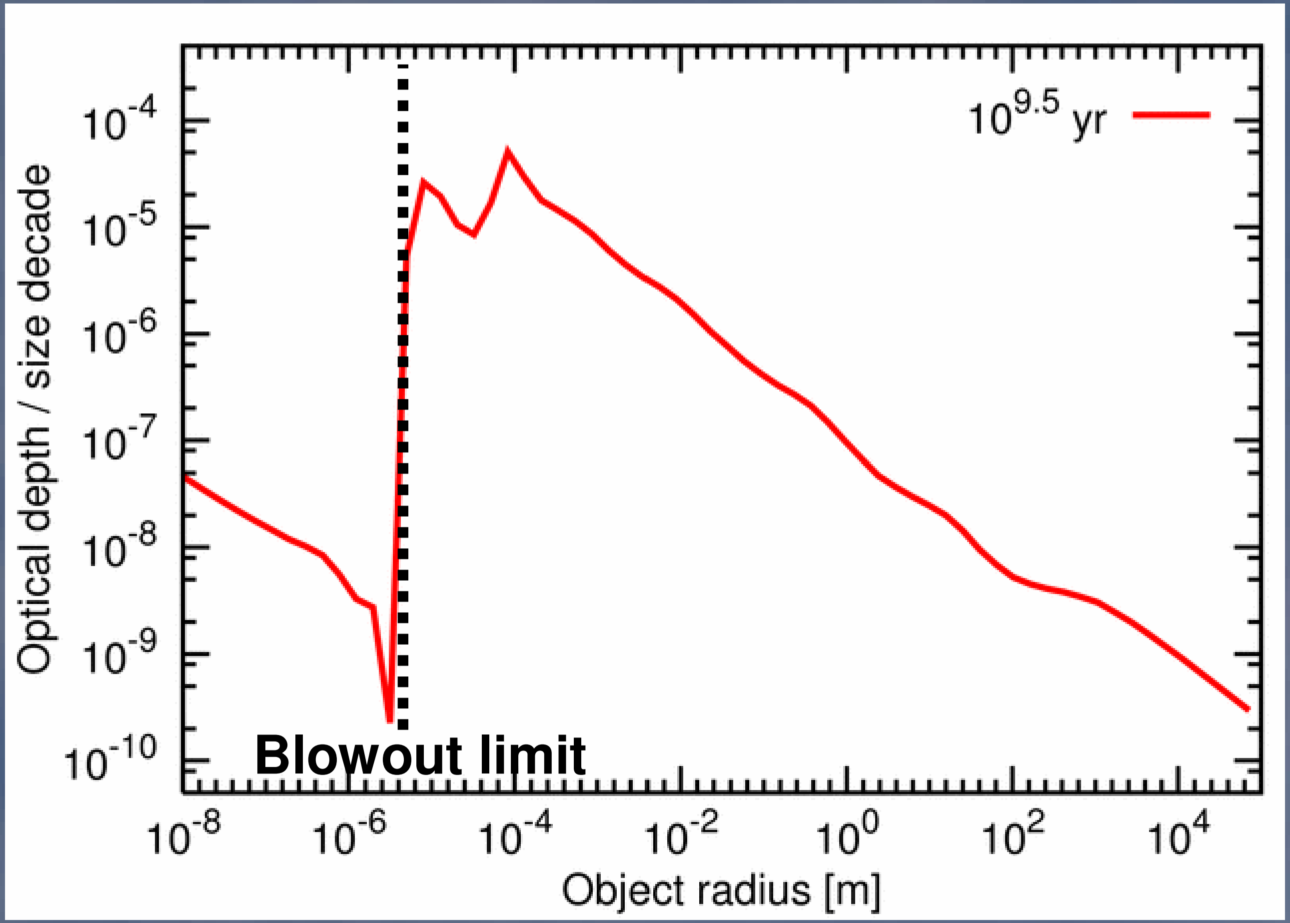
- **Hybrid methods**

  - "Superparticles" *(Grigorieva)*

  Share (dis)advantages of two previous methods

Main challenge: how to combine accurate dynamics with accurate collisions?

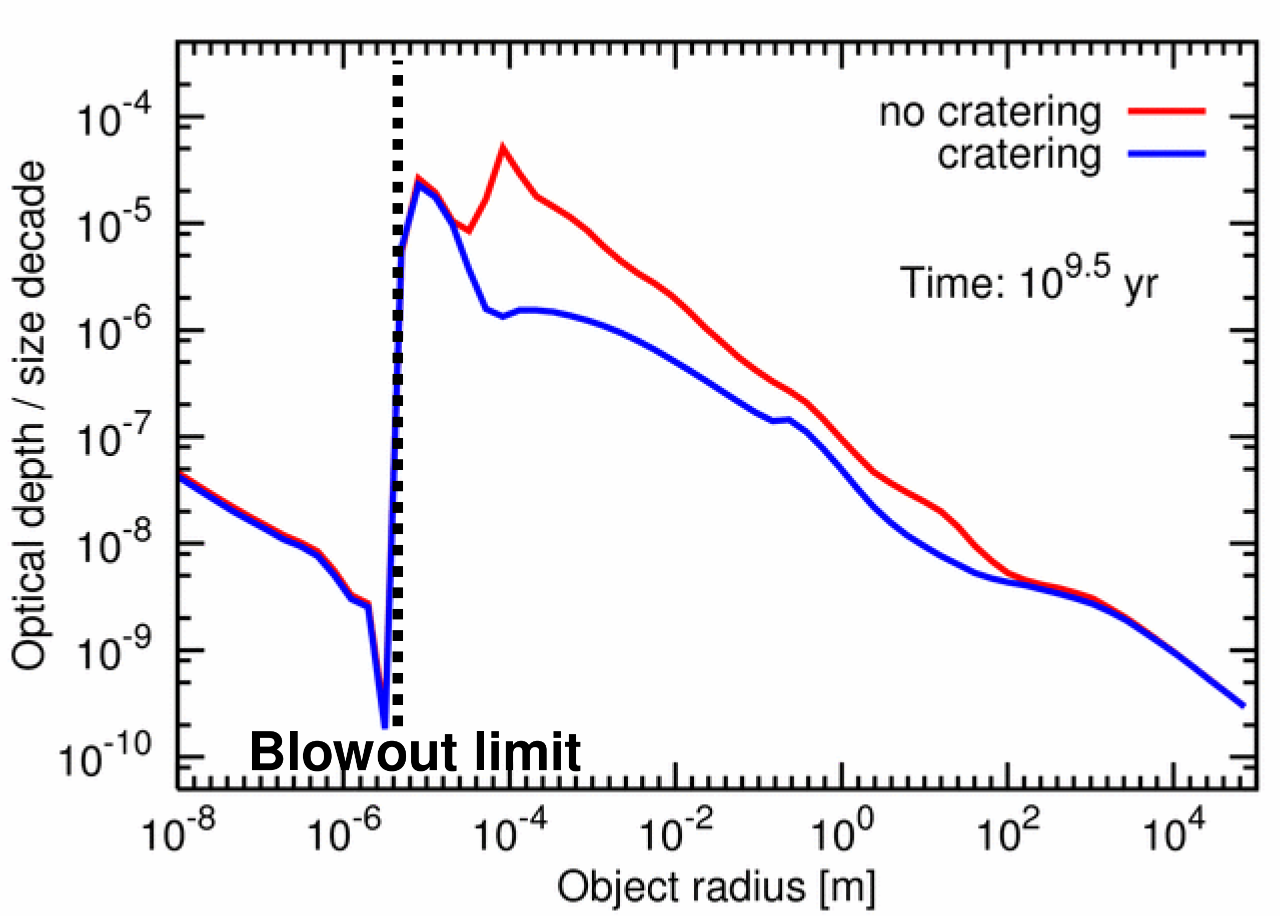
Collisions and photogravity at work: size distribution



Krivov, Löhne, & Sremčević, AAp ***455****, 509 (2006)*

- Tiny blowout grains are present, but in smaller amounts
- Grains just above blowout limit dominate cross section
- Size distribution is wavy

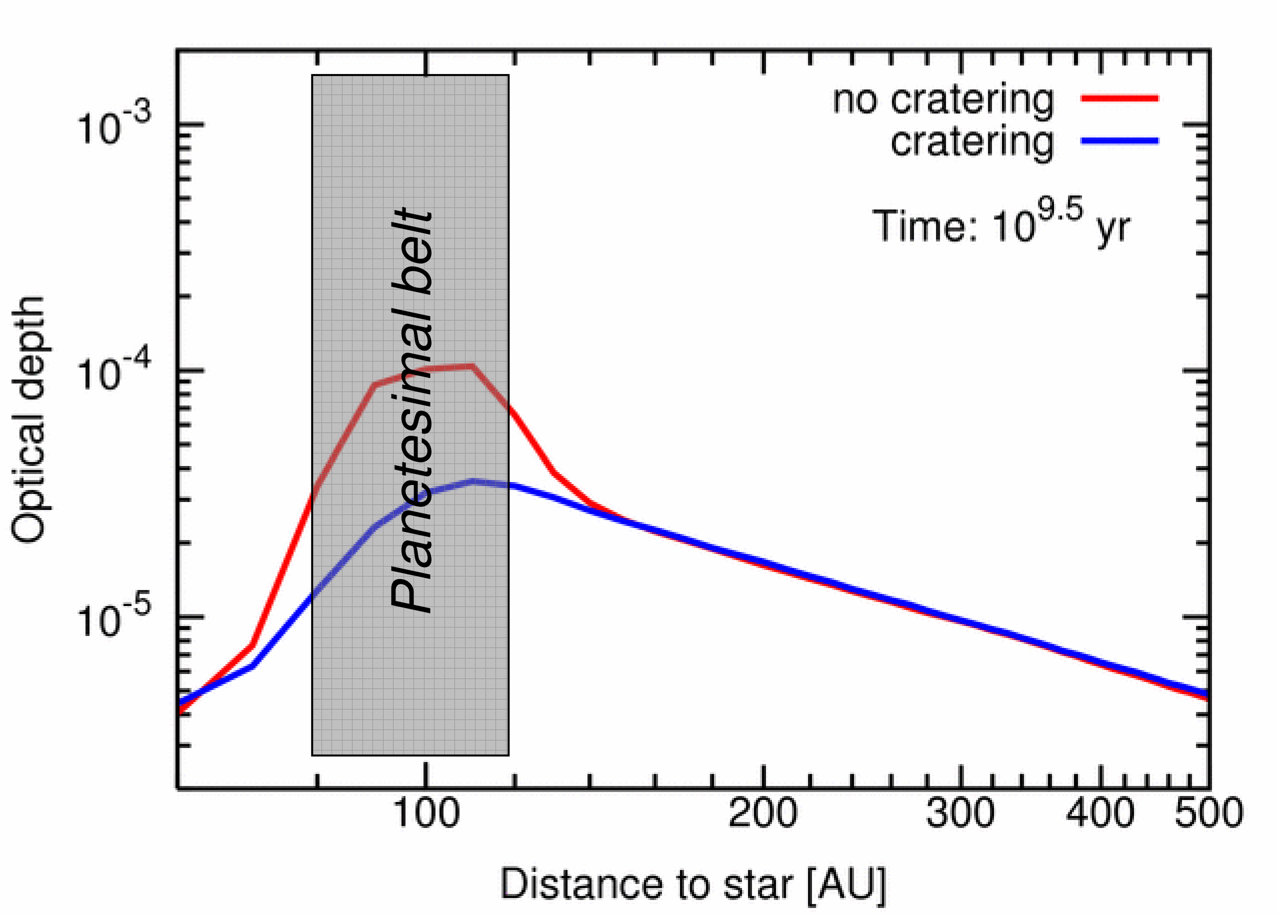
Collisions and photogravity at work: size distribution



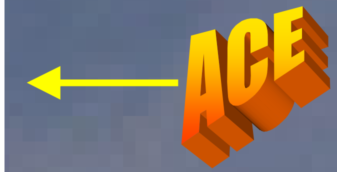
Thébault & Augereau, AAp ***472****, 169 (2007)*

- Cratering collisions are important
- They substantially enhance the “main” maximum

Collisions and photogravity at work: radial profiles



Krivov, Löhne, & Sremčević, AAp ***455****, 509-519 (2006)*



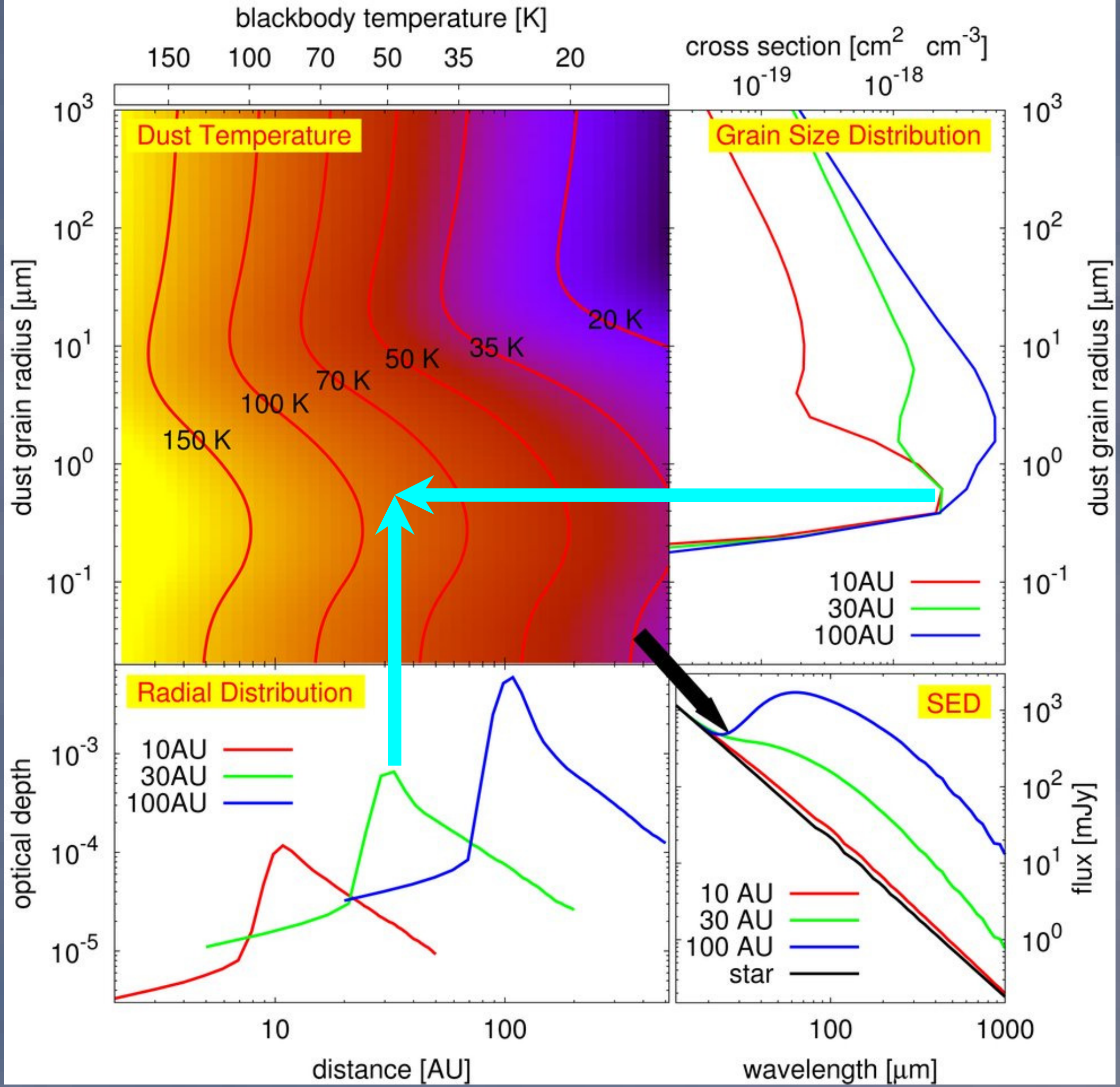
Surface density index ~-1.5, brightness index ~-3.5

From dust distributions to observables

Need to calculate light scattering and thermal emission of dust

The thermal emission example

Krivov, Müller, Löhne,& Mutschke, ApJ ***687*** *(2008)*



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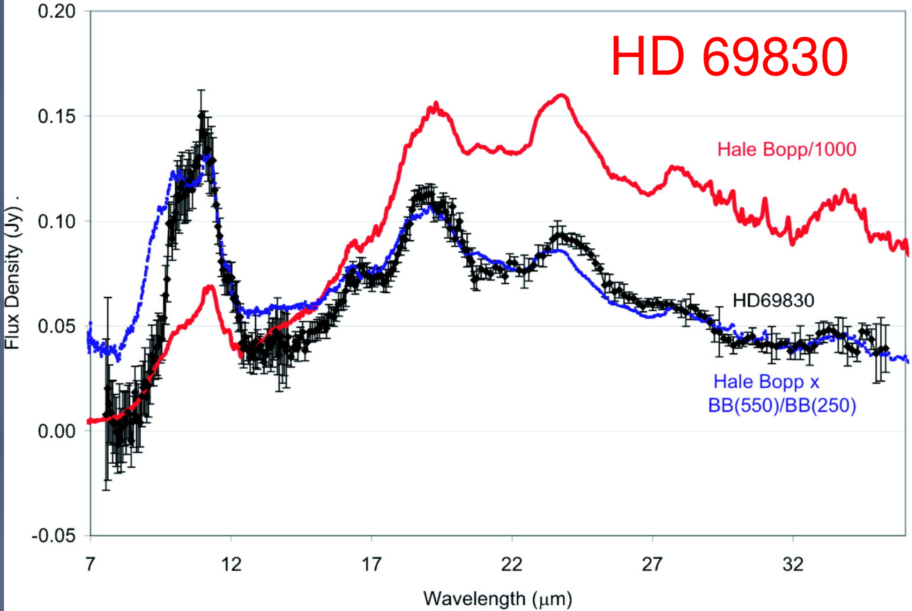
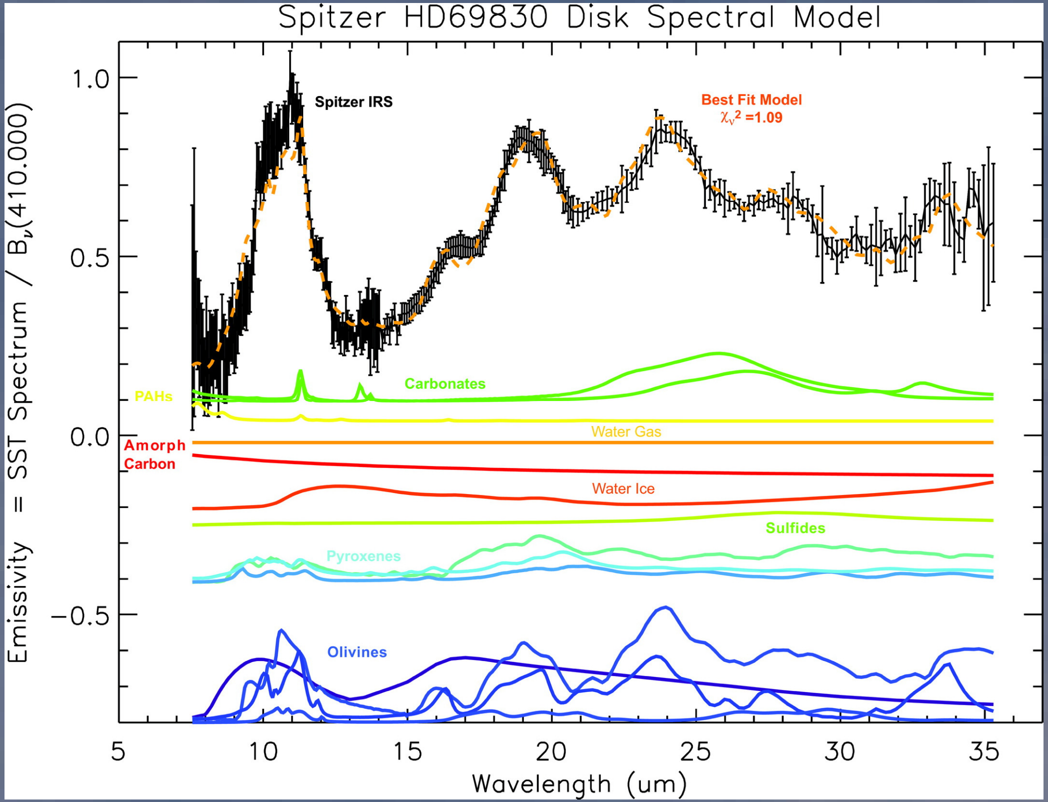
What do infrared spectra tell us about dust grain properties?



Beichman et al.,
ApJ ***626,*** *1061-1069 (2005)*


Spitzer HD69830 Disk Spectral Model

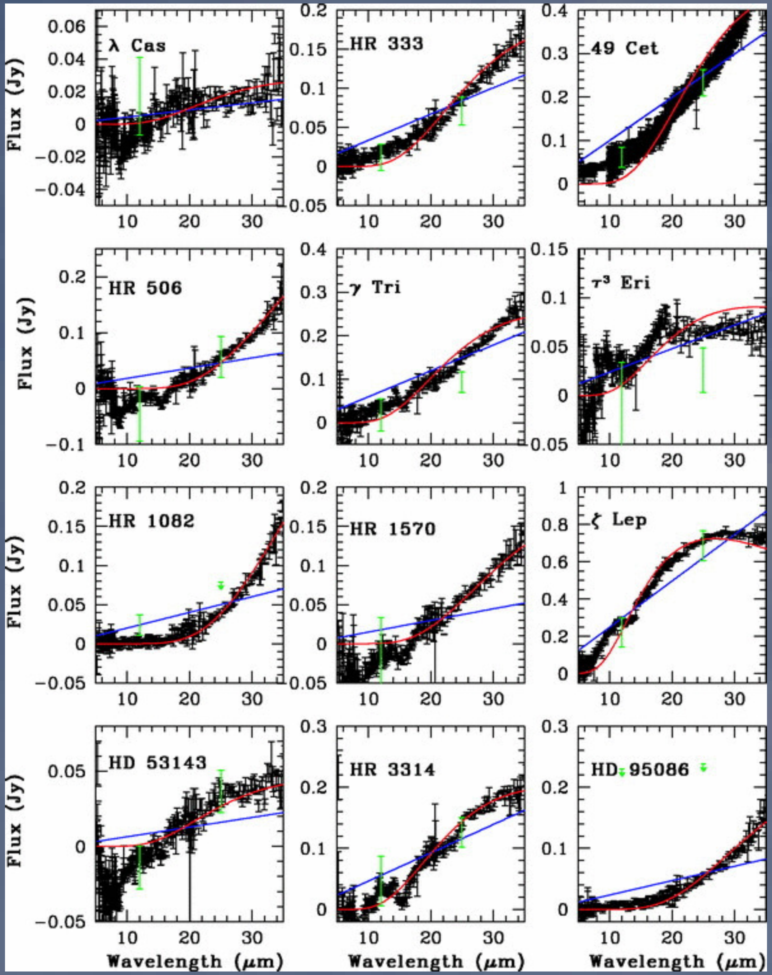
Lisse et al., ApJ ***658****, 584-592 (2007)*

At a first glance:
looks like cometary dust!

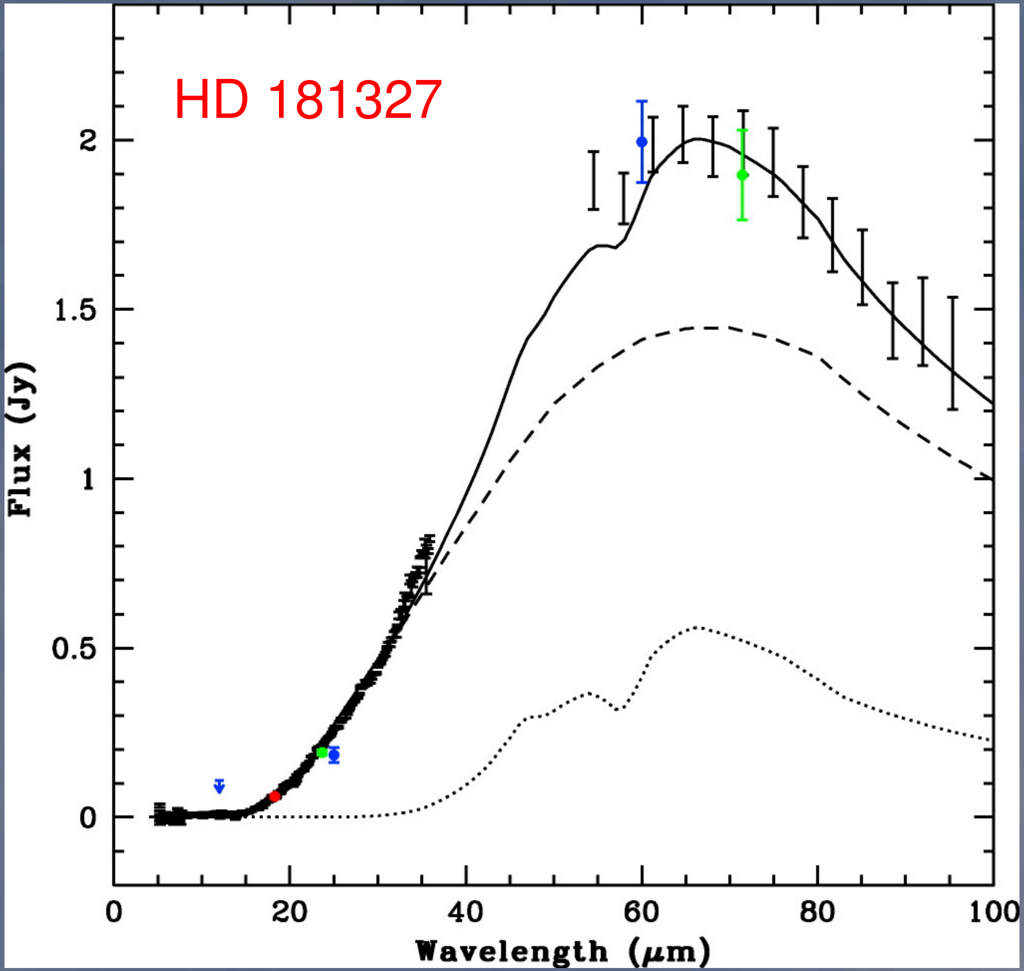
A closer look: HD69830 50% crystalline, Hale-Bopp only 7-30%. Asteroidal dust?

-> many posters!

What do infrared spectra tell us about dust grain properties?



Chen et al., ApJS ***166,*** *351-377 (2006)*



Chen et al.,ApJ ***689,*** *539-544 (2008)*

10 mu Si feature is often observed.
When not, no Si? Or large grains?
-> many posters!

Water ice around at 90 AU from
an F5 star despite photodesorption?

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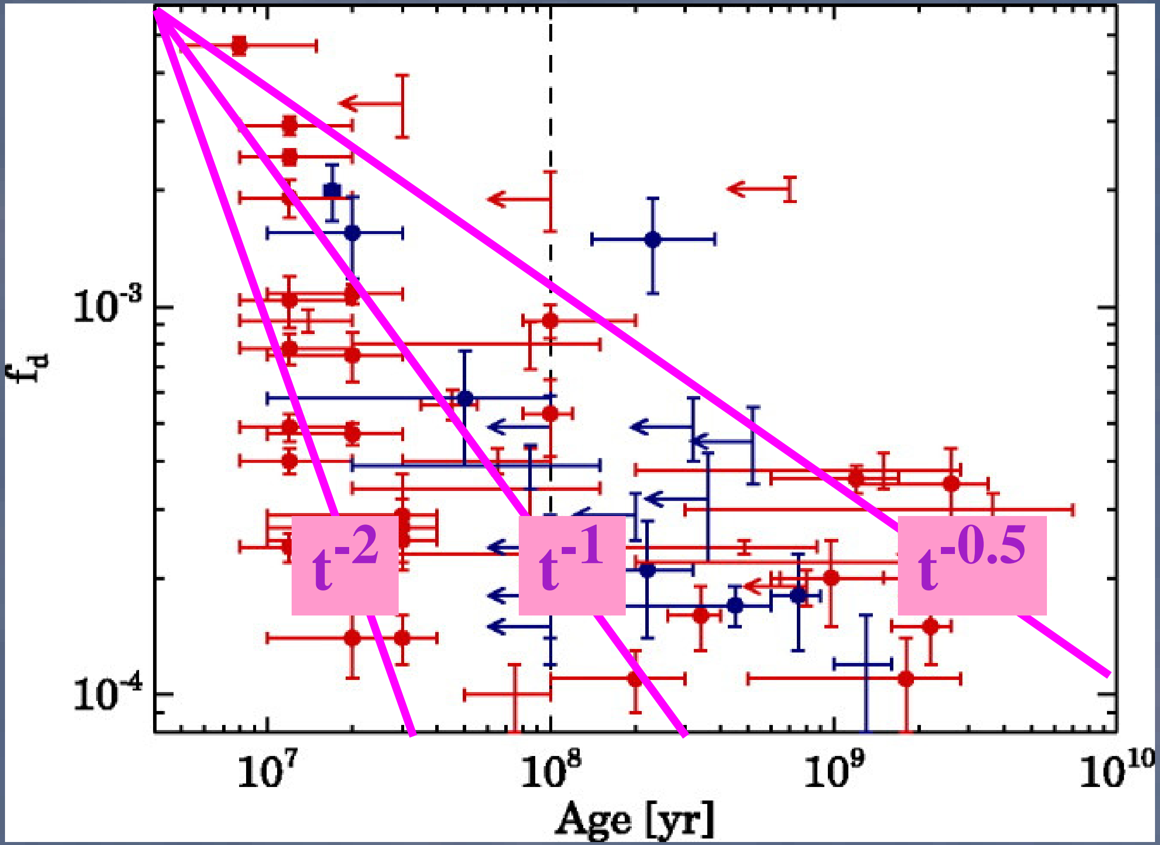
Seeing kids, thinking of parents

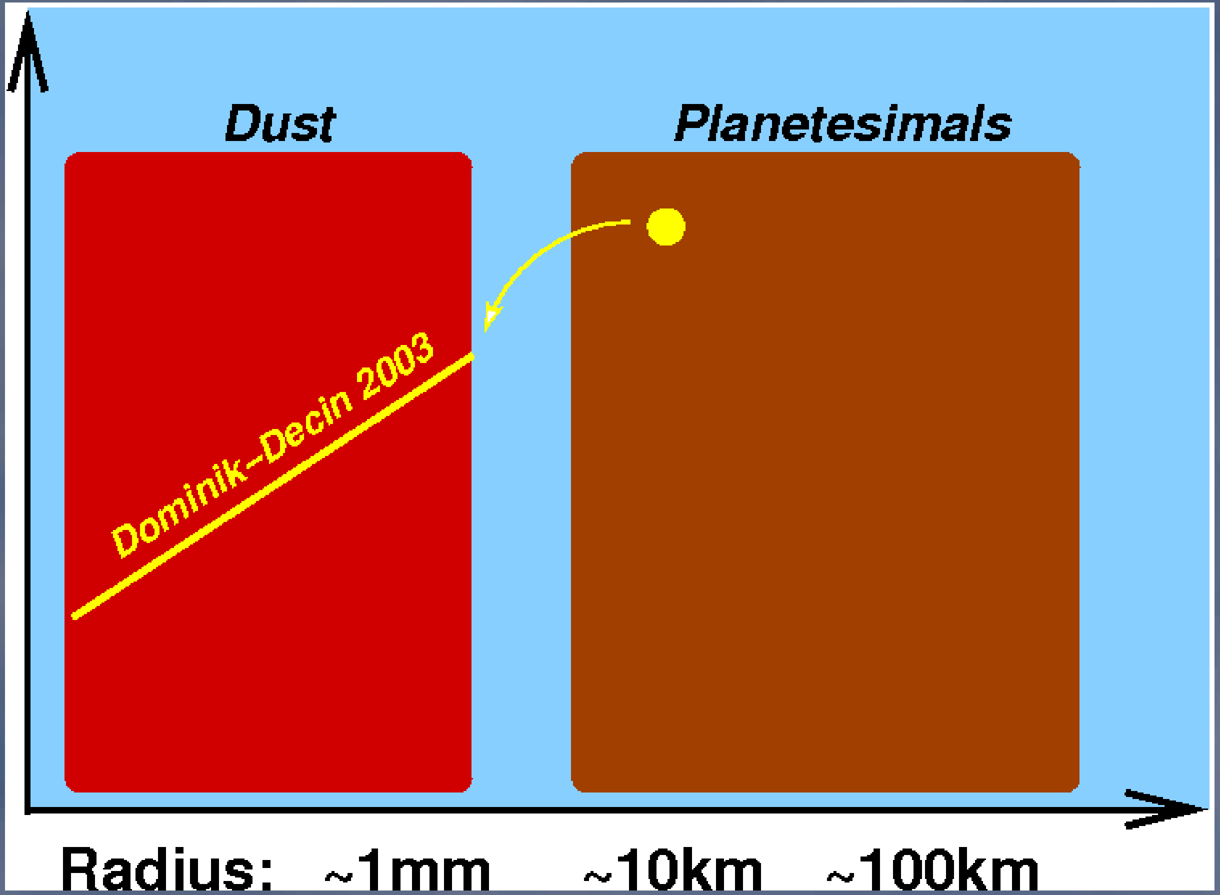
Statistics of debris disks: a long-term decay



Moór et al. ApJ ***644,*** *525-542 (2006)*

- Dust luminosity decay with system's age, albeit with a large scatter
- Reason: collisional depletion of a planetesimal belt

Dominik-Decin (2003) model



- Equal-sized planetesimals “feed” dust
- Dust has a single power-law size distribution

Dominik & Decin, AAp **598,** *626-635 (2003)*

Dominik-Decin (2003) model

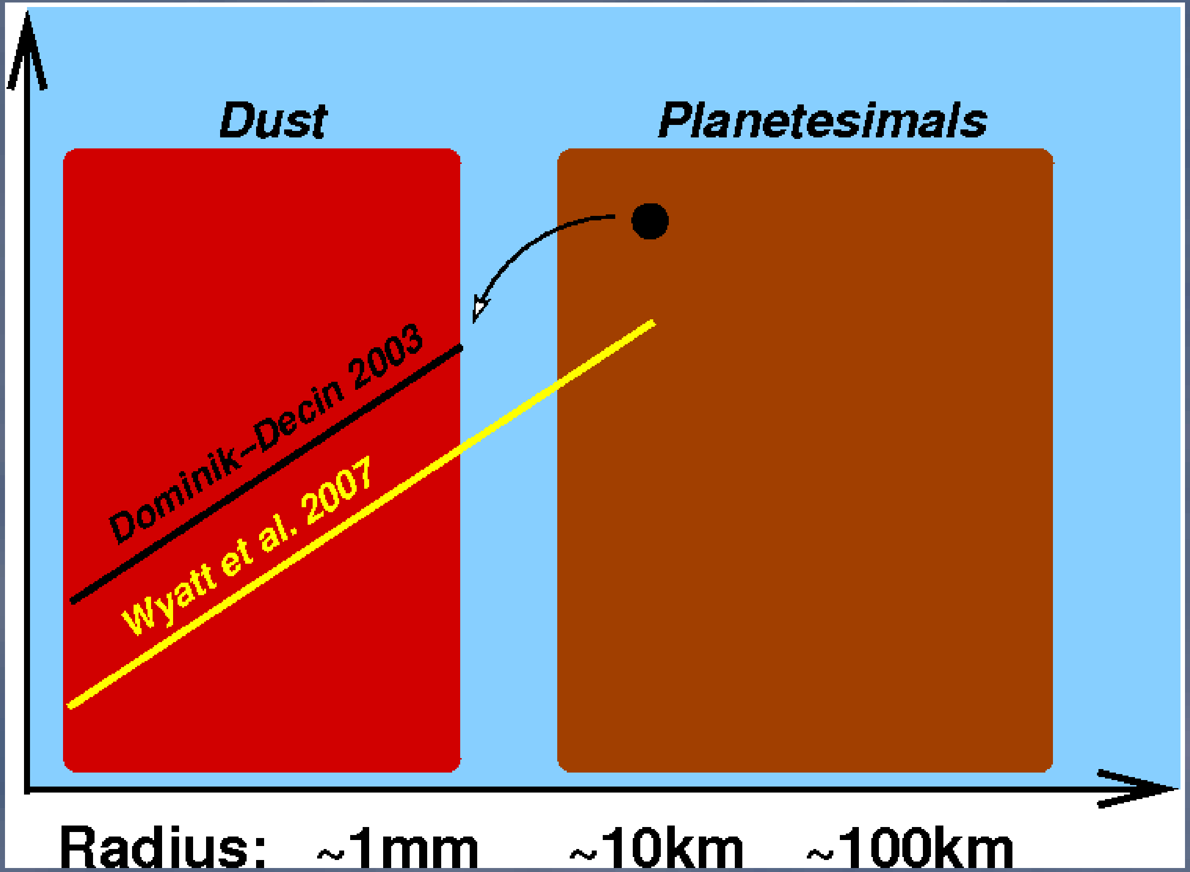
$$\frac{dM_{\text{disk}}}{dt} = -\frac{M_{\text{disk}}^2}{M_0 \tau}$$

$$M_{\text{disk}}(t) \approx \frac{M_0}{1 + t/\tau} \approx M_0 \frac{\tau}{t}$$

- For collision-dominated disks (usually the case), total disk mass ~ dust mass ~ t^{-1}
- *"Delayed stirring"* suggested to explain high luminosity in some of the old systems

Dominik & Decin, AAp **598,** *626-635 (2003)*

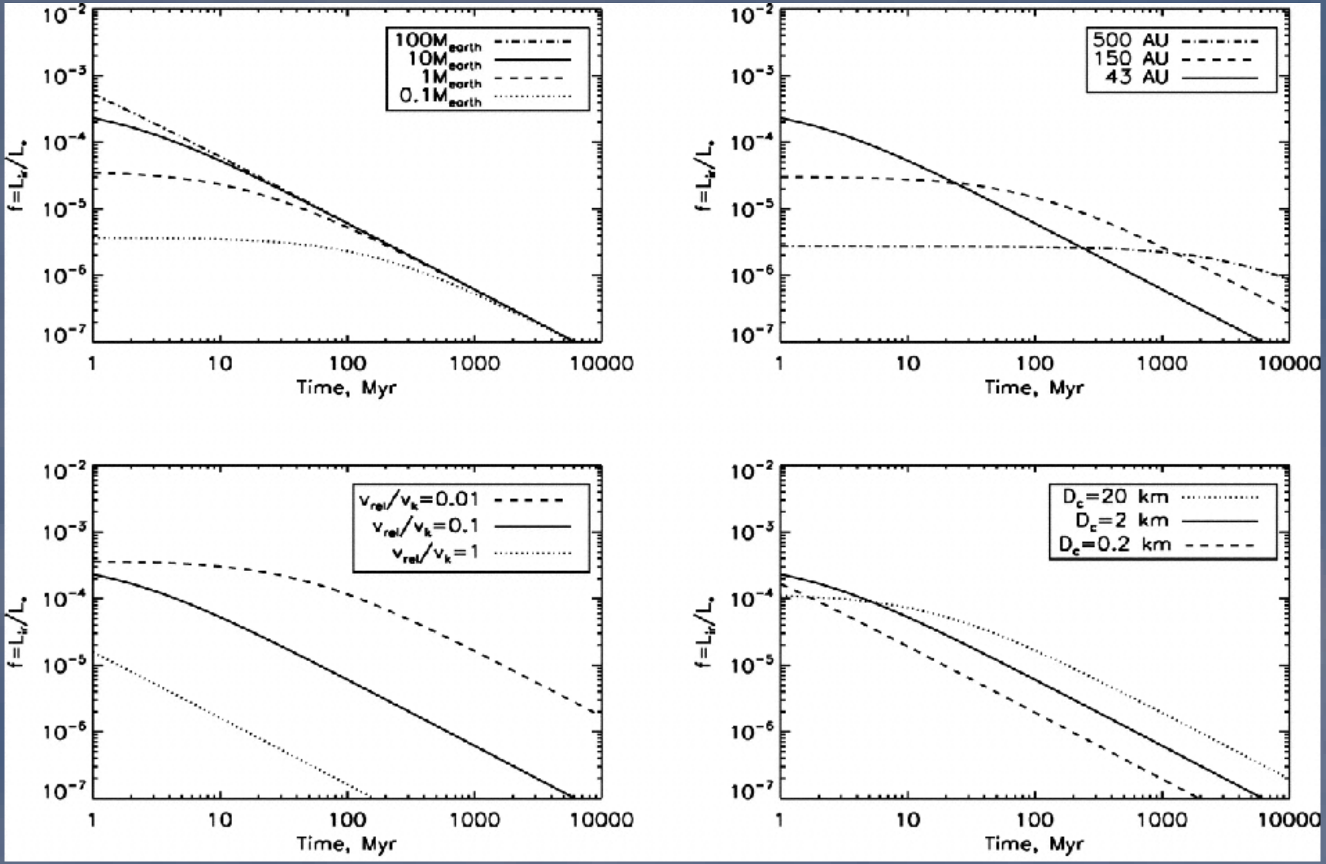
Wyatt et al. (2007) model



Still, an assumption of a quasi-steady state
(a single power-law size distribution)

Wyatt et al., ApJ **658,** *569-583 (2007)*

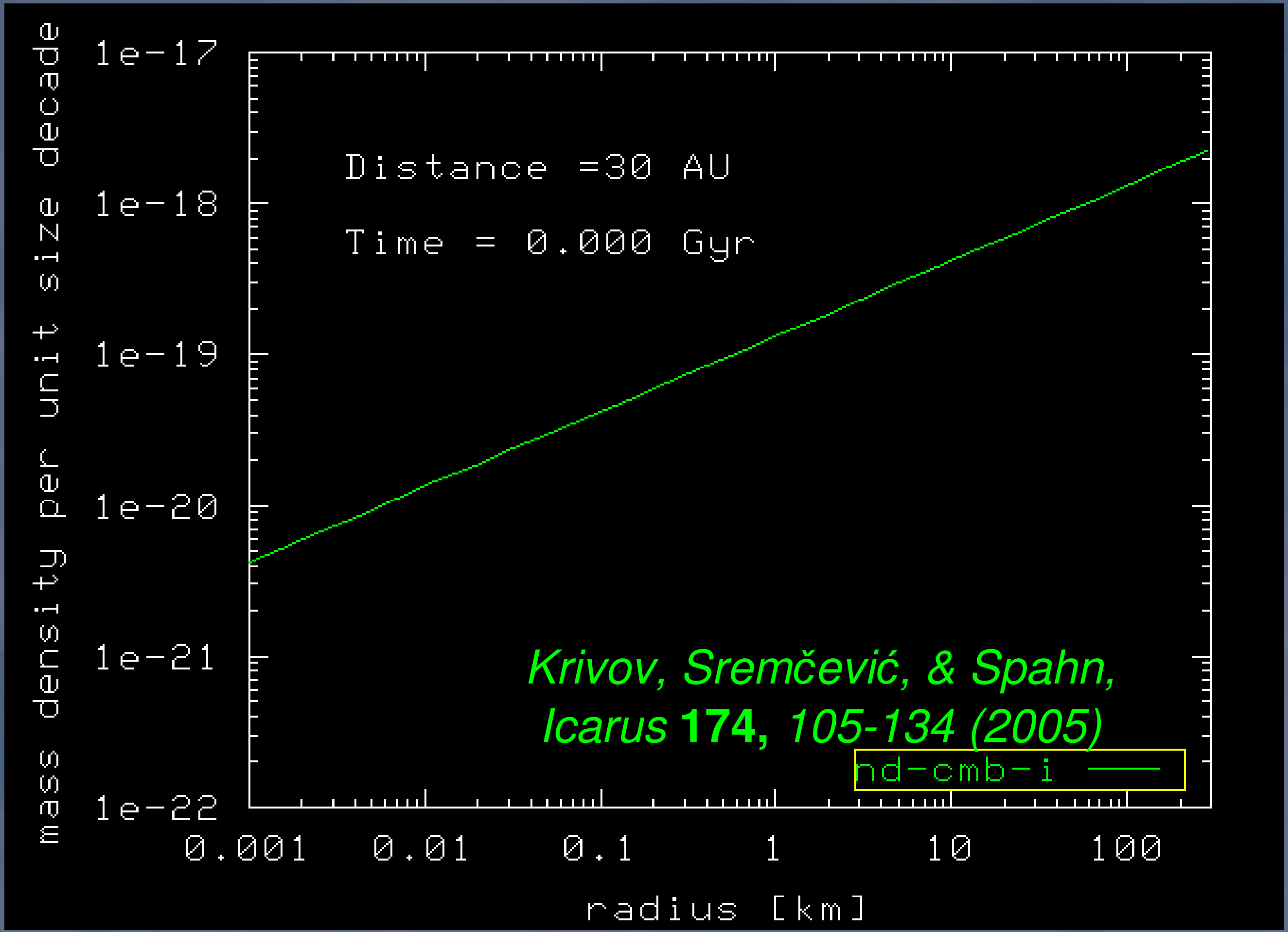
Wyatt et al. (2007) model



- For any given age, there is a maximum possible amount of dust
- Disk evolution depends on *r, e, I,* D_c

Wyatt et al., ApJ **658,** *569-583 (2007)*

Löhne et al. (2008) model



Krivov, Sremčević, & Spahn, Icarus ***174,*** *105-134 (2005)*

← ACE

- Large planetesimals are not in collisional equilibrium
- Strength-gravity transition plays a major role

Löhne, Krivov, & Rodmann, ApJ ***673****, 1123-1137 (2008)*

Löhne et al. (2008) model

Scaling rules

$$F(xM_o, r, t) = x\,F(M_o, r, xt)$$

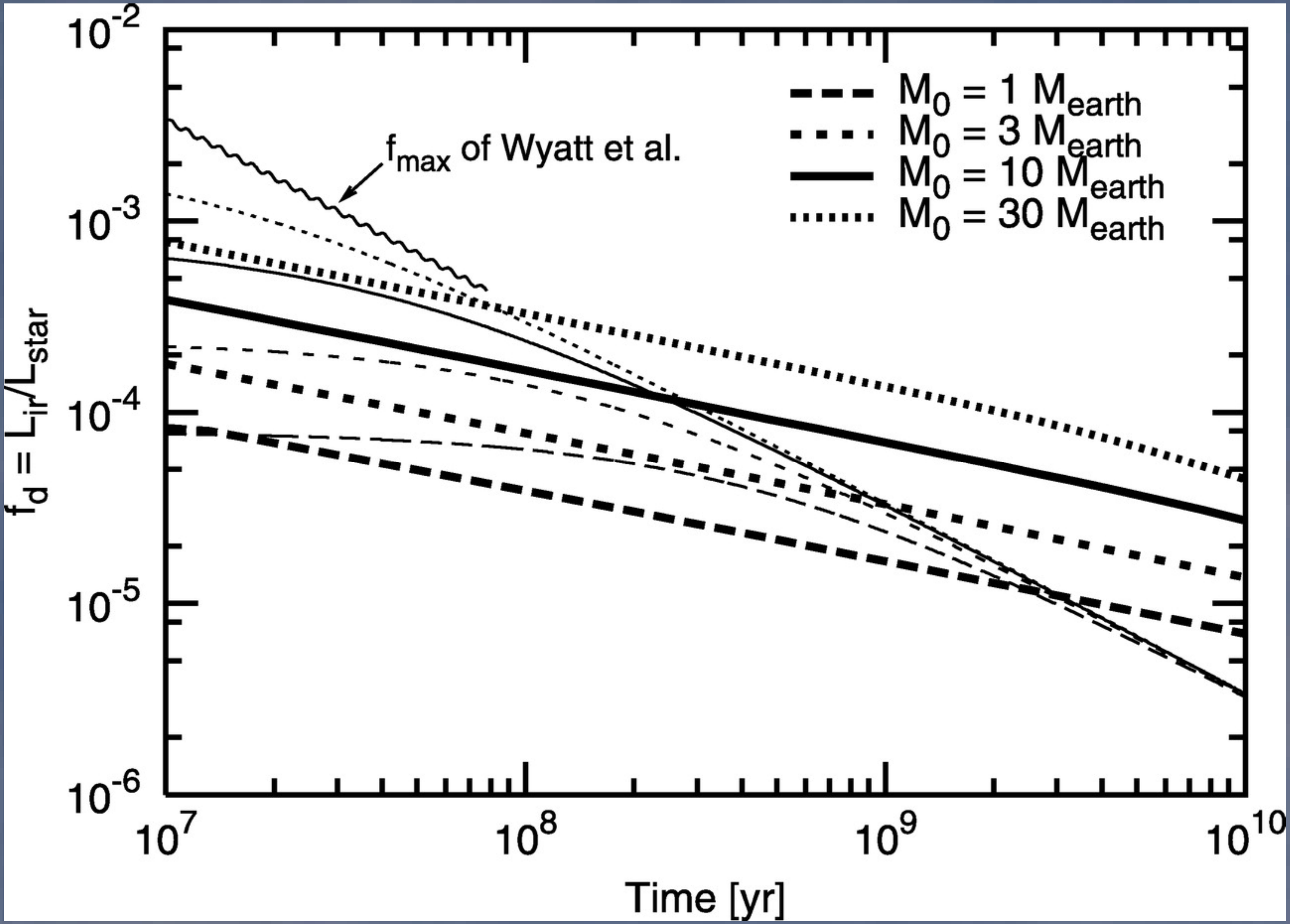
$$F(M_o, yr, t) \approx F(M_o, r, y^{-4.3}t)$$

$$F(M_o, r, zt) \approx z^{-\xi}F(M_o, r, t),$$

$$\xi \sim 0.3 \ldots 0.4$$

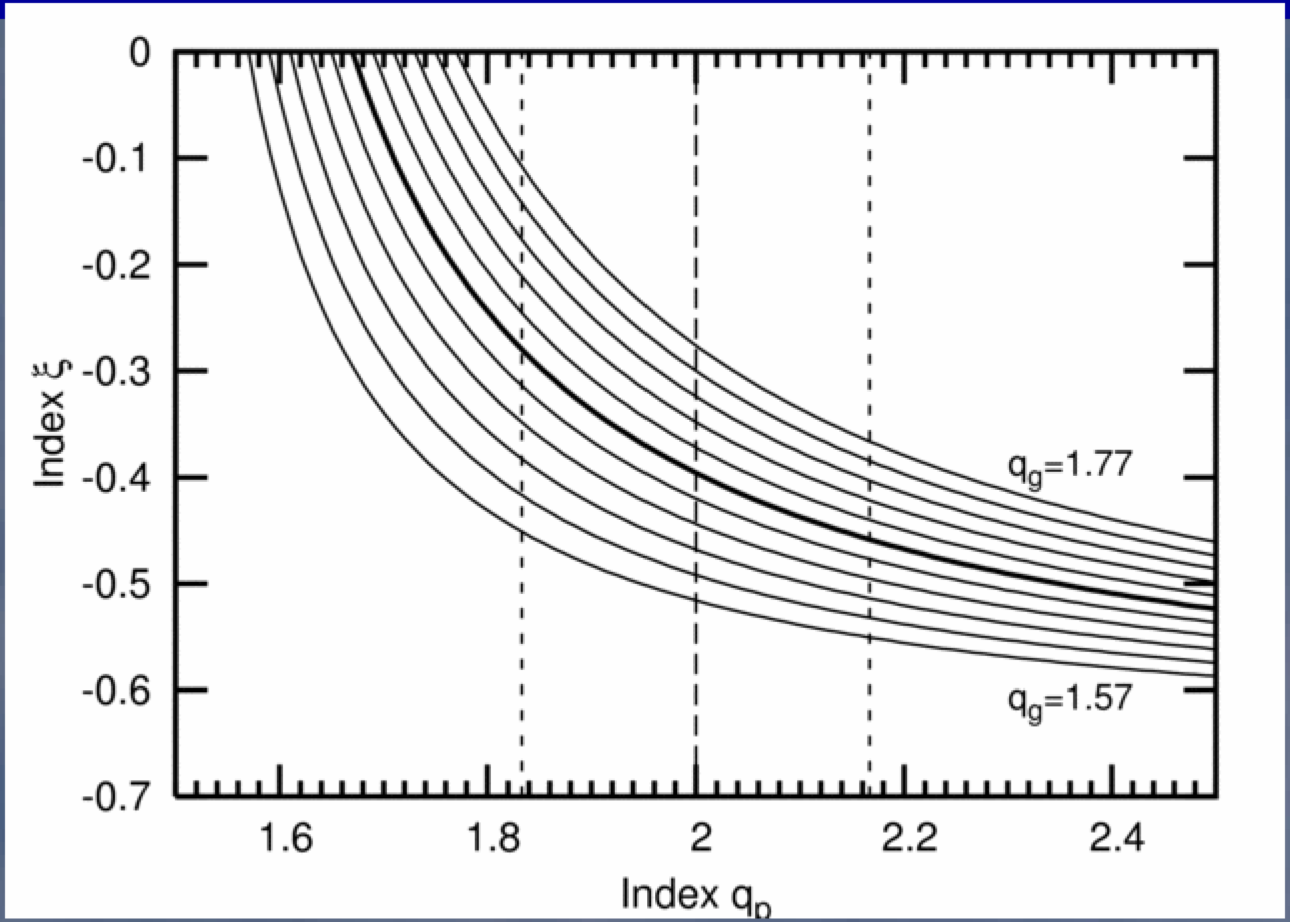
Löhne, Krivov, & Rodmann, ApJ ***673****, 1123-1137 (2008)*

Löhne et al. (2008) model



Löhne, Krivov, & Rodmann, ApJ ***673****, 1123-1137 (2008)*

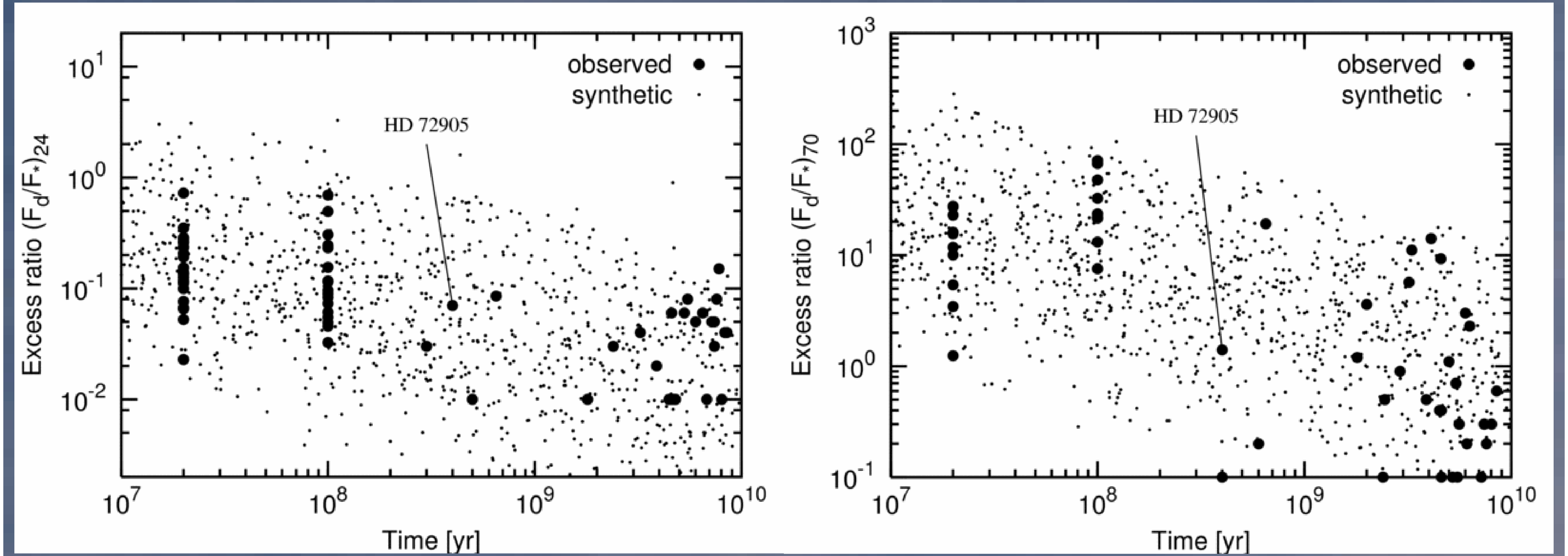
Löhne et al. (2008) model



- The dust mass decays as ~*t* $^{\xi}$
- Index ξ depends on the "primordial" size distribution of planetesimals
- Typical values: ξ ~ -0.3...-0.4 and not -1

Löhne, Krivov, & Rodmann, ApJ **673**, *1123-1137 (2008)*

Löhne et al. (2008) model

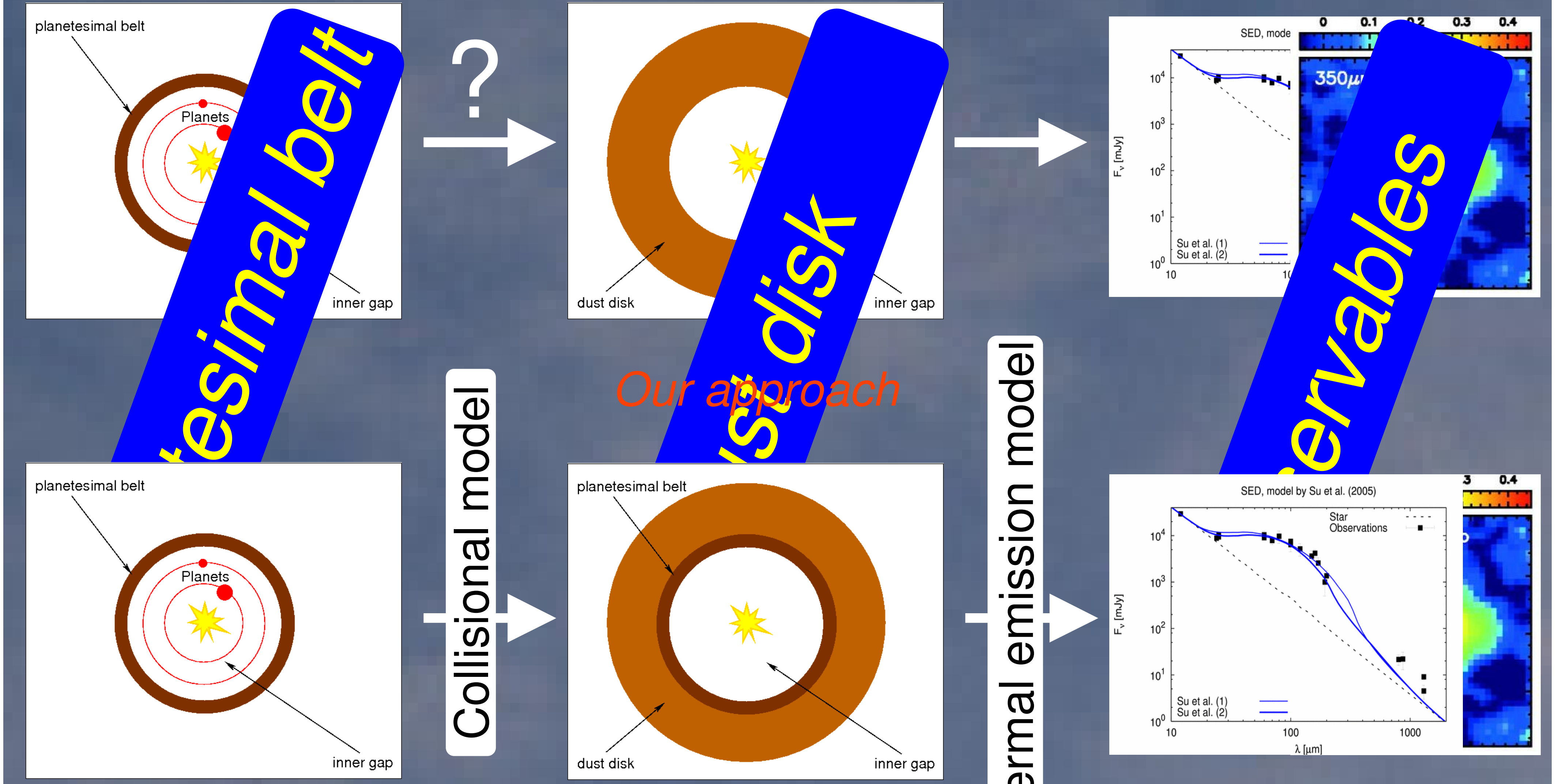


A synthetic population of debris disks calculated with the model is in a good agreement with the Spitzer 24 and 70μm statistics

Löhne, Krivov, & Rodmann, ApJ ***673****, 1123-1137 (2008)*

Individual systems: two approaches

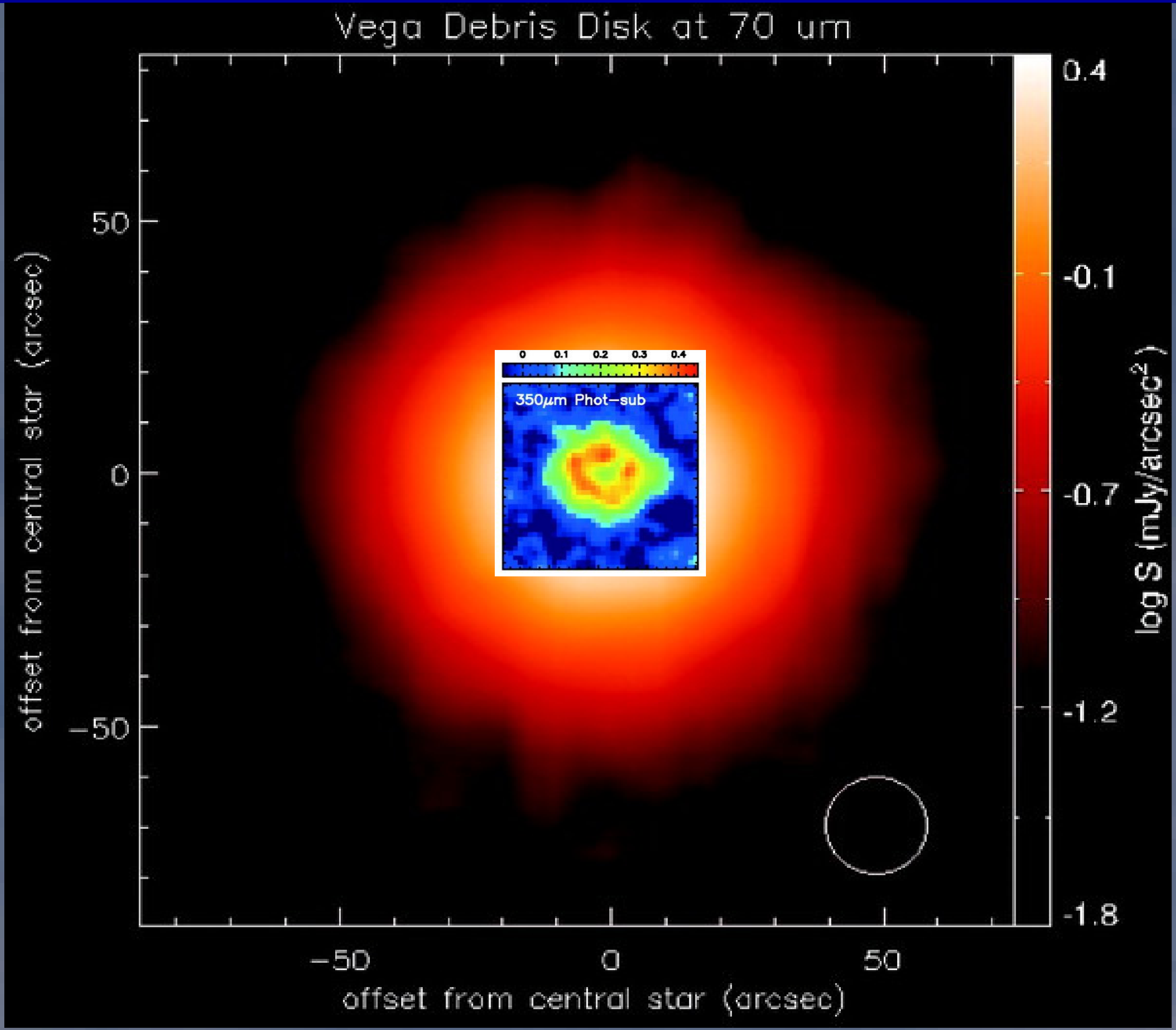
Traditional approach



Our approach

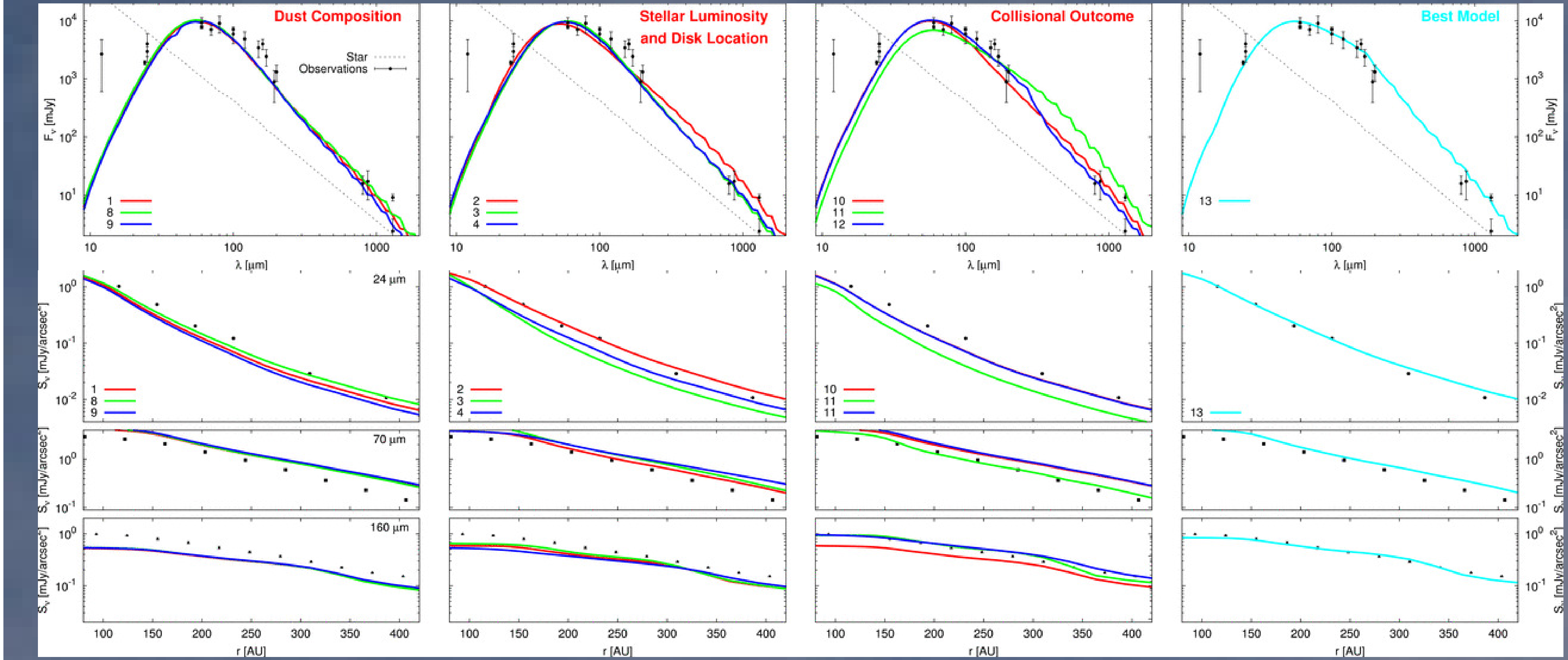
Krivov, Müller, Löhne, & Mutschke, ApJ ***687*** *(2008)*

Individual systems: the Vega disk



Su et al., ApJ (2005); Marsh et al., ApJ (2006)

Individual systems: the Vega disk



Müller, Löhne, & Krivov, in prep. ***-> poster by Sebastian Müller***

Collisional + thermal emission modeling
Parameters: stellar luminosity; disk location, extension, excitation;
dust composition; collisional outcome prescription

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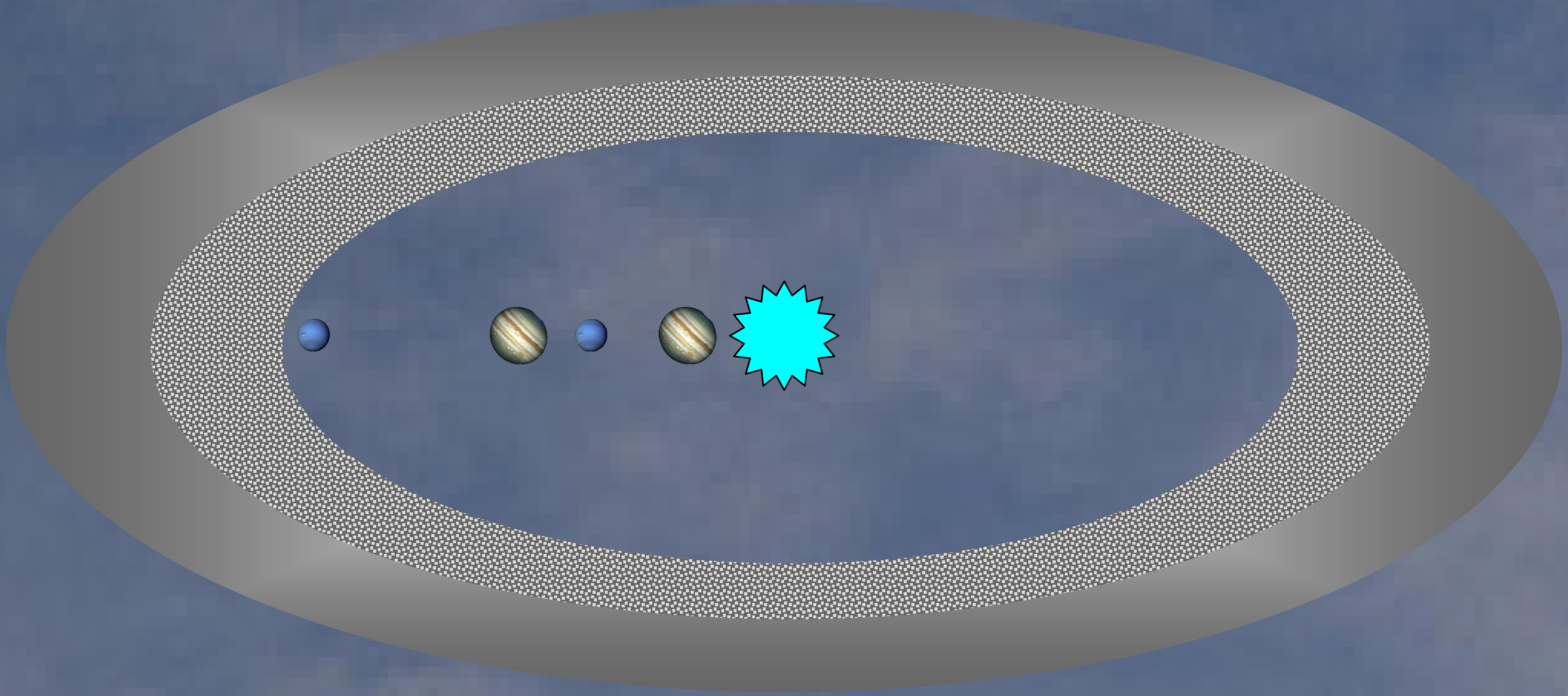
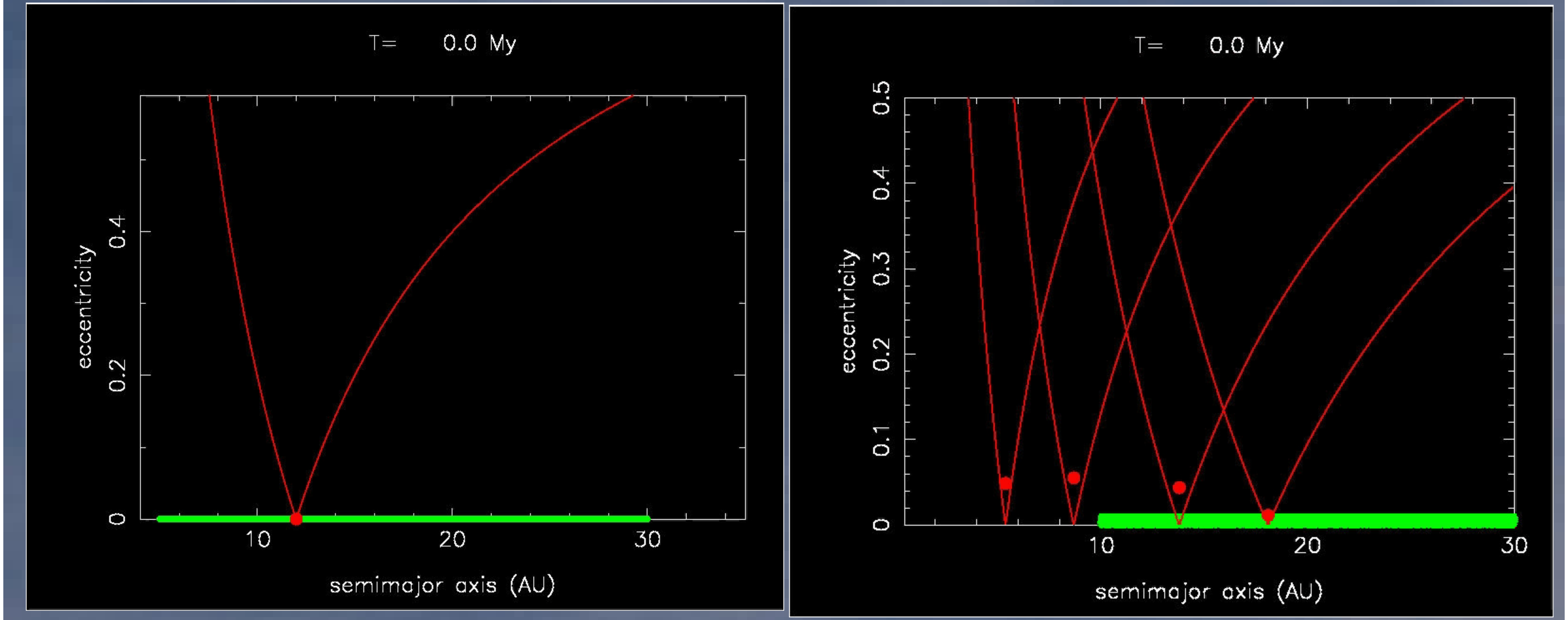
Inner gaps: footprints of planets?



Infrared excesses and images reveal EKB-sized disks, extending from several tens AU outward, with inner gaps

Inner gaps: footprints of planets?



Simulations and animations: Alessandro Morbidelli

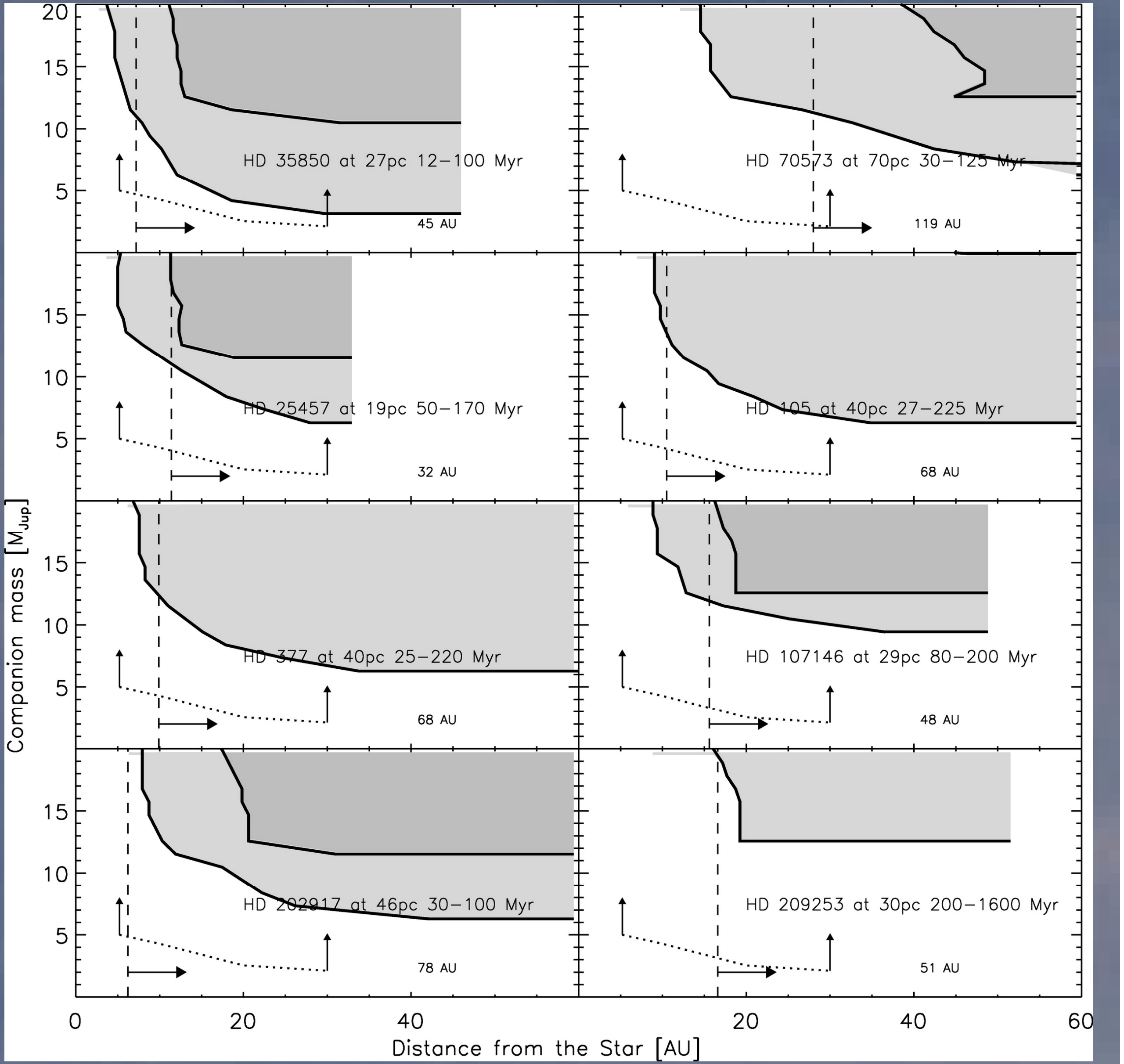
Inner gaps can be naturally explained with two or more migrated planets
Alternatively, with two or more planets after encounters

First attempts to find these planets

8 young systems with cold excesses searched with VLT/NACO

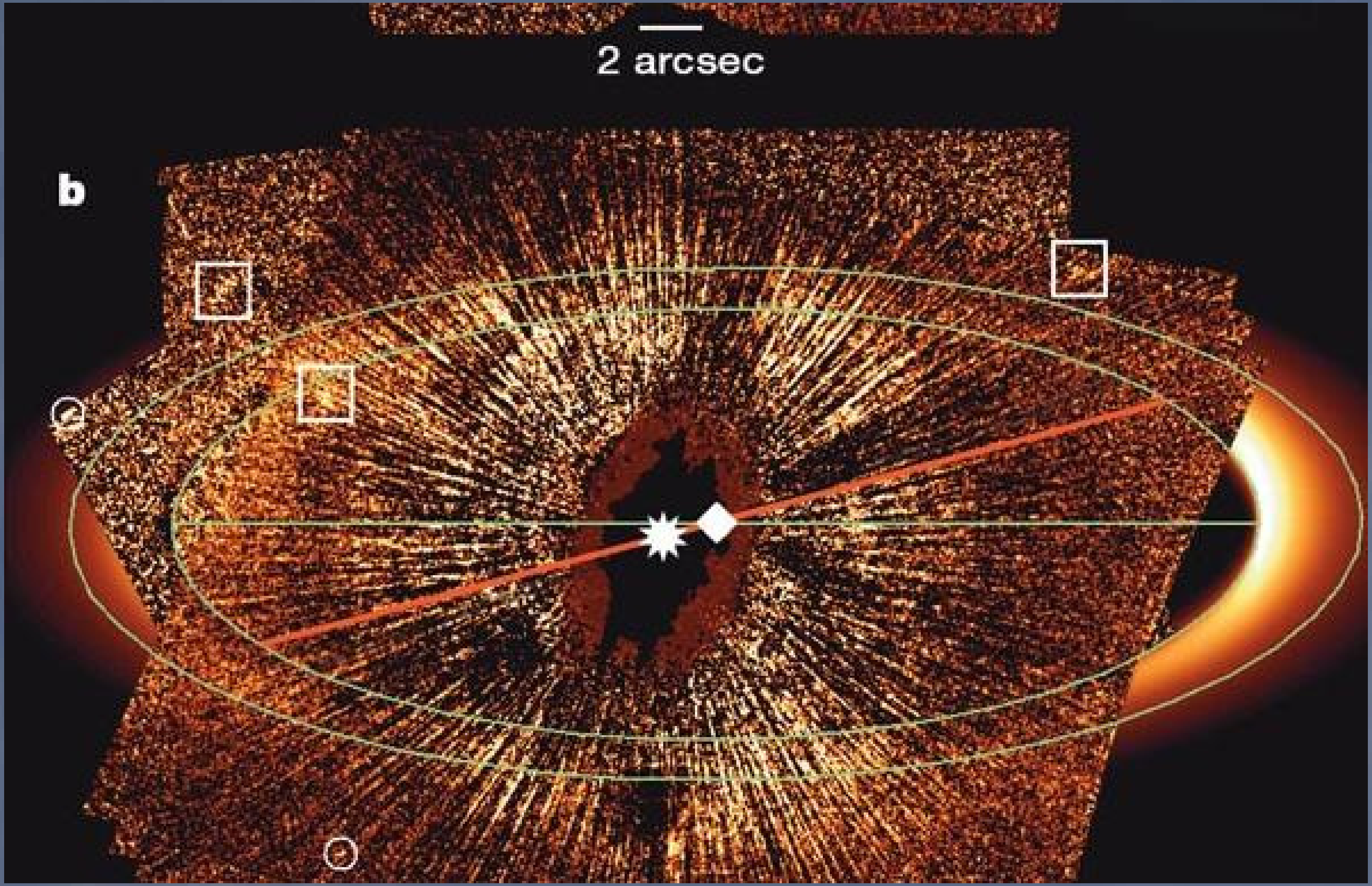
no planets found

Apai et al.,ApJ ***672****,1196-1201 (2008)*



Another attempt: Fomalhaut

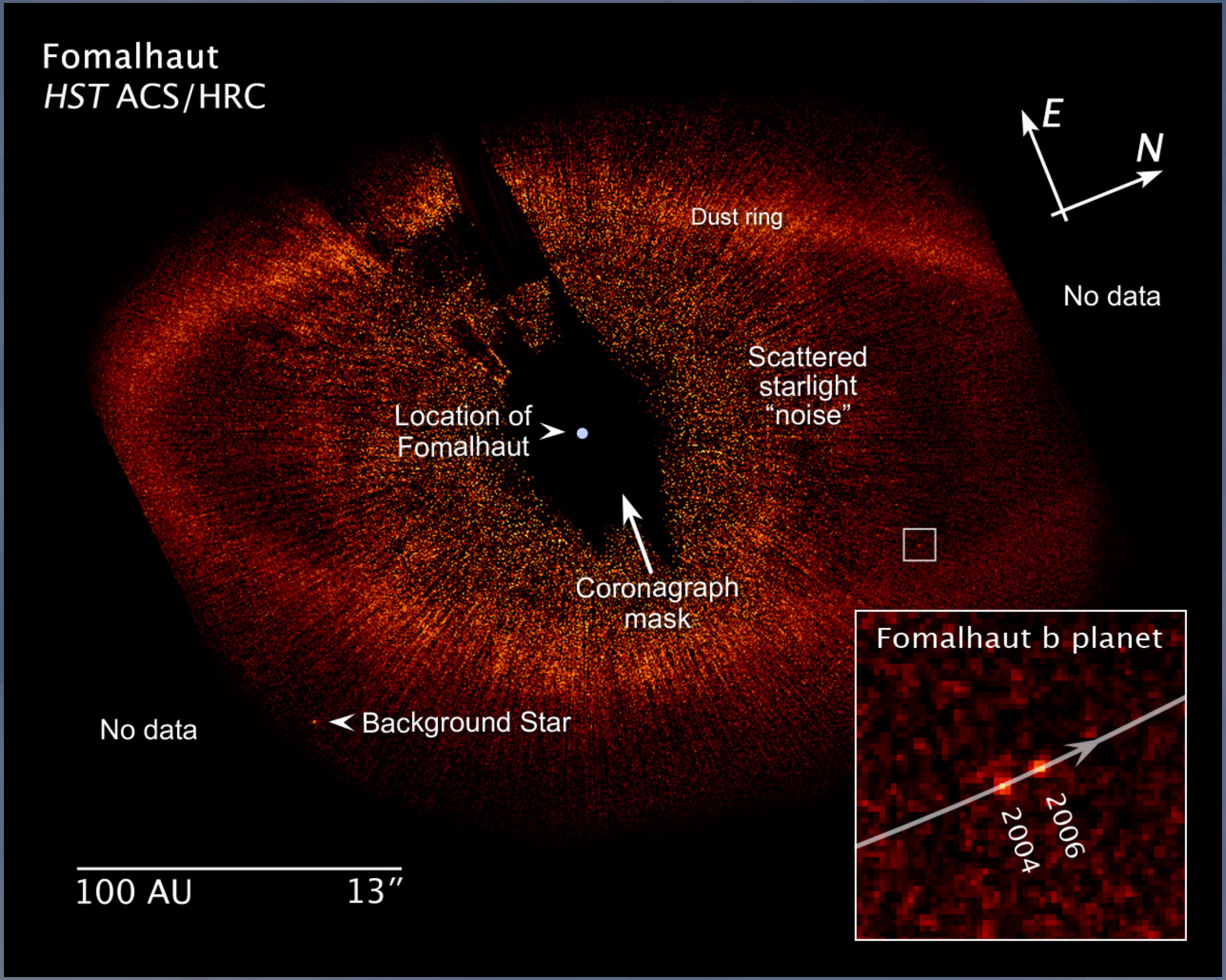
Elliptic ring with inner gap: a planet was expected...



Kalas et al., Nature (2005)

Another attempt: Fomalhaut

...and is now discovered



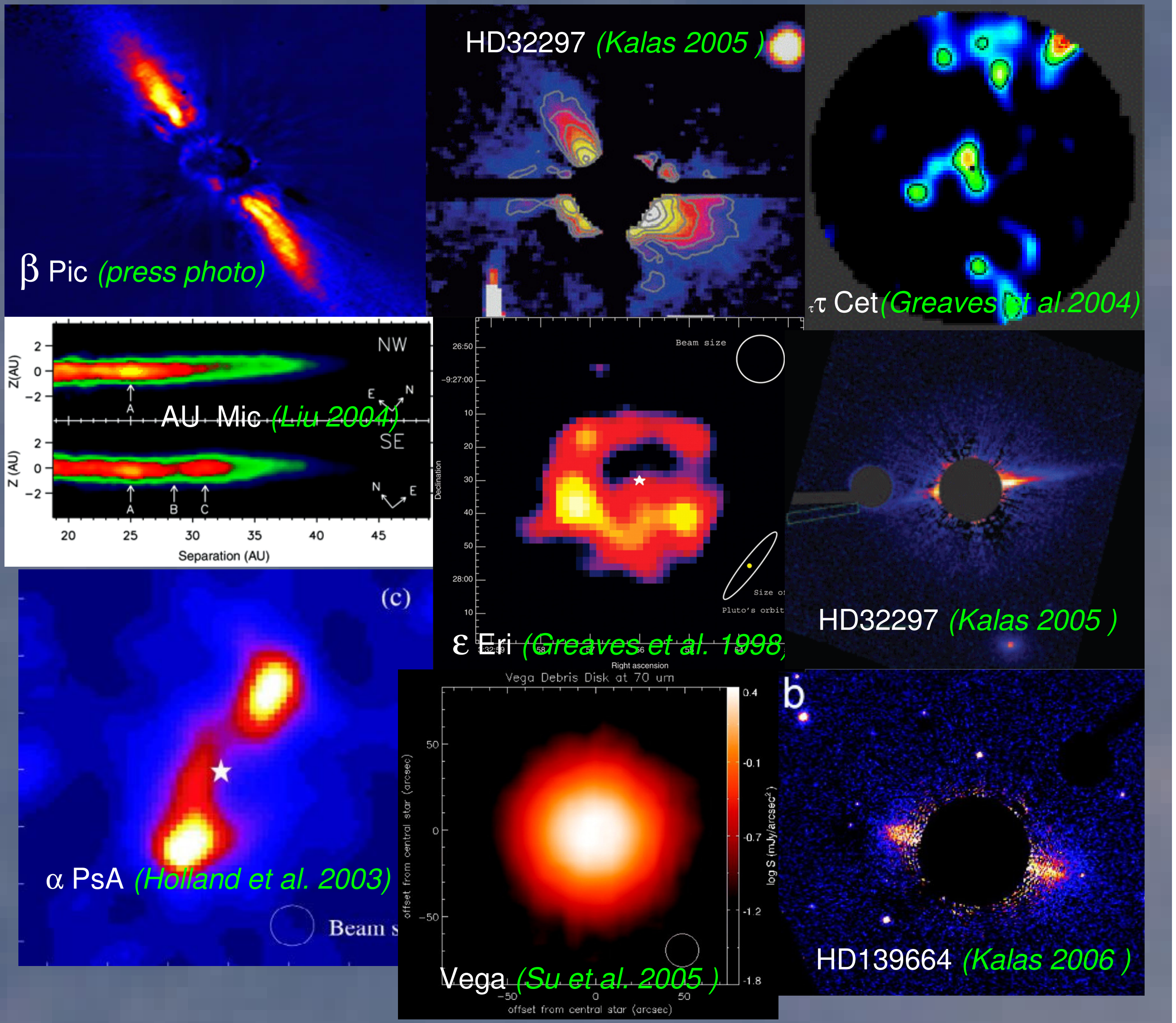
Kalas et al., Science ***322****, 1345 (2008)*

There is more structure in resolved disks

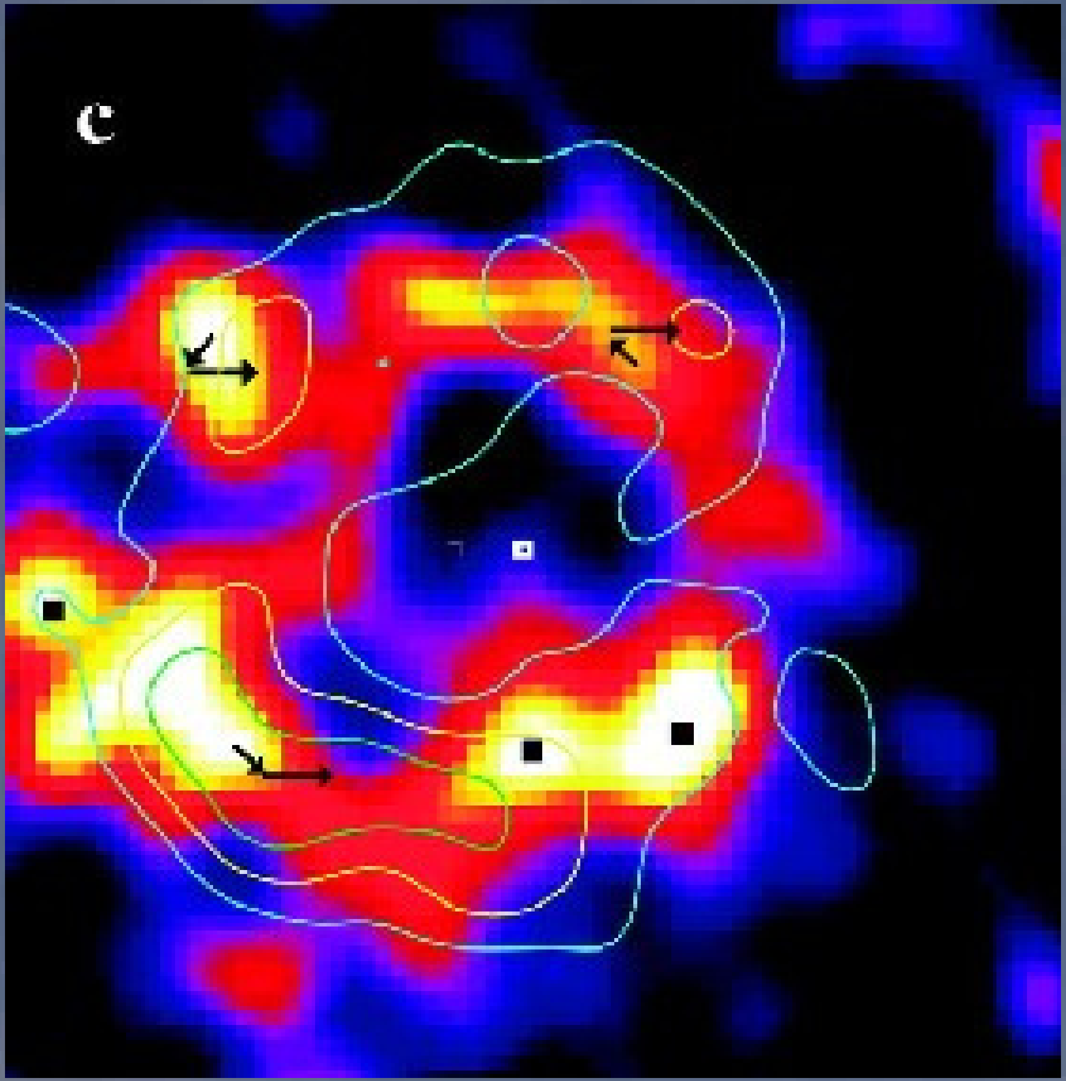
Radial,
azimuthal,
vertical
structure:

- rings,
- gaps
- clumps
- spirals
- offsets
- warps

...

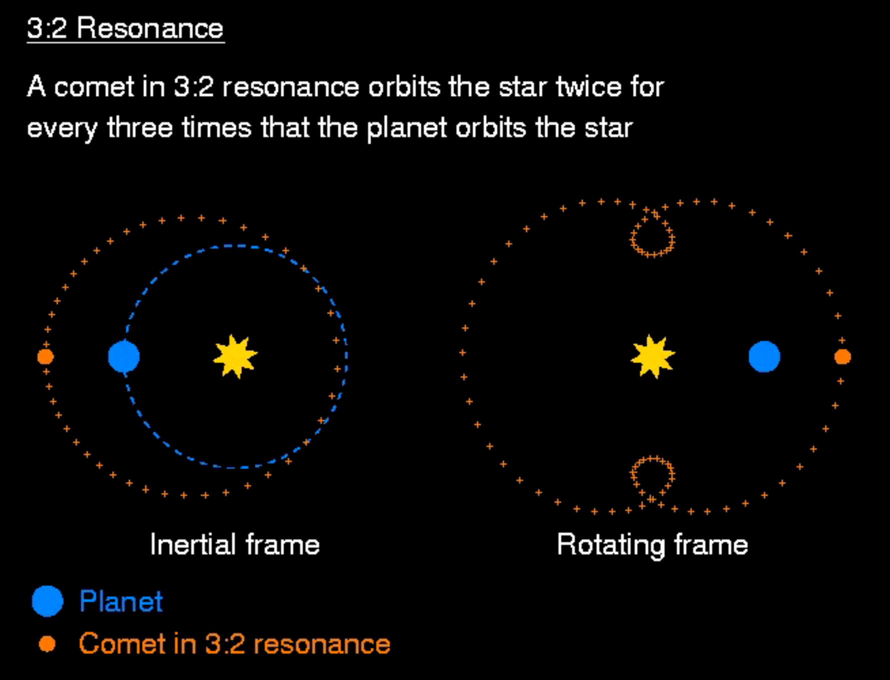


Clumps of ε Eri



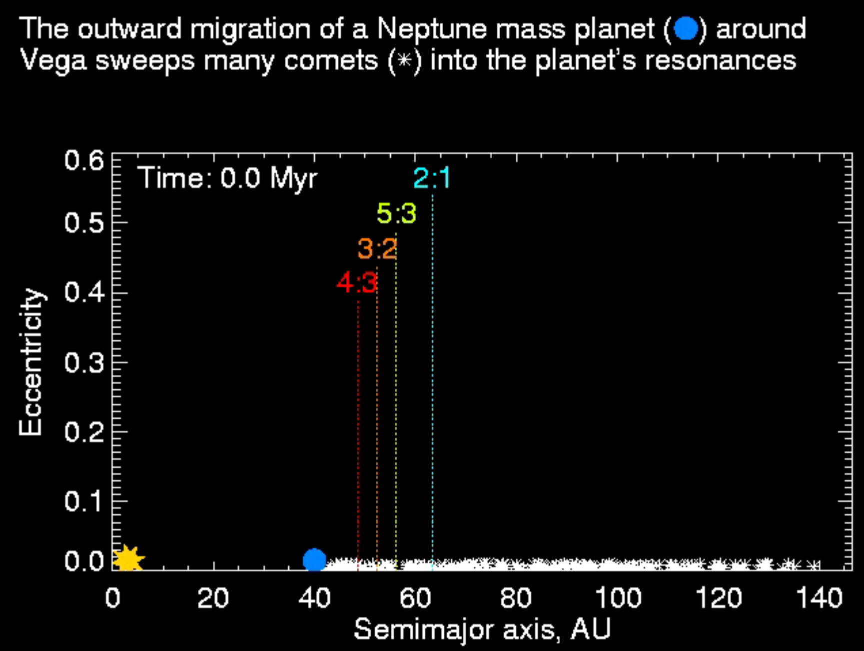
Greaves et al., ApJ **619**, *L187-L190 (2005)*

Clumps due to resonances with a planet



3:2 Resonance

A comet in 3:2 resonance orbits the star twice for every three times that the planet orbits the star



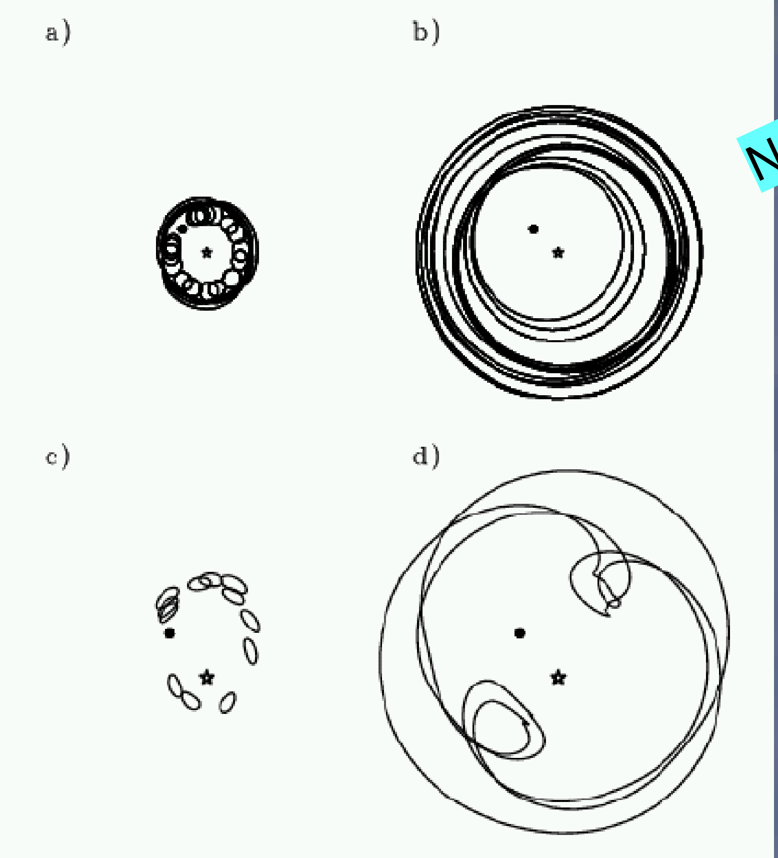
The outward migration of a Neptune mass planet (●) around Vega sweeps many comets (*) into the planet's resonances

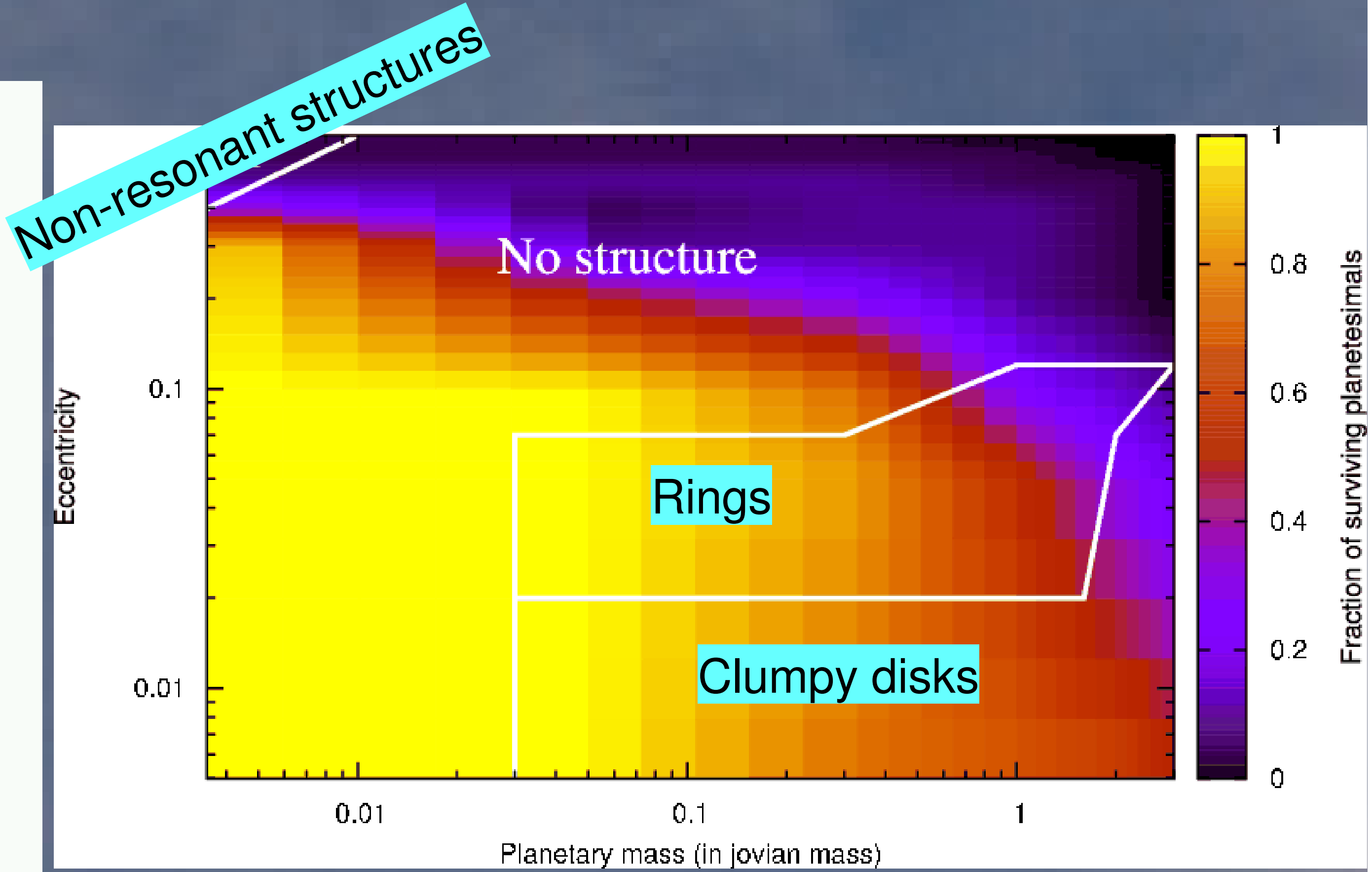
Simulations and animations: Mark Wyatt

Wyatt, ApJ (2003); Wyatt, ApJ (2006);
Krivov, Queck, Löhne, & Sremcevic, AAp (2007);
Reche, Beust, Augereau, & Absil, AAp (2008)

Not only clumps, but also rings

Dependence on planetary mass and eccentricity



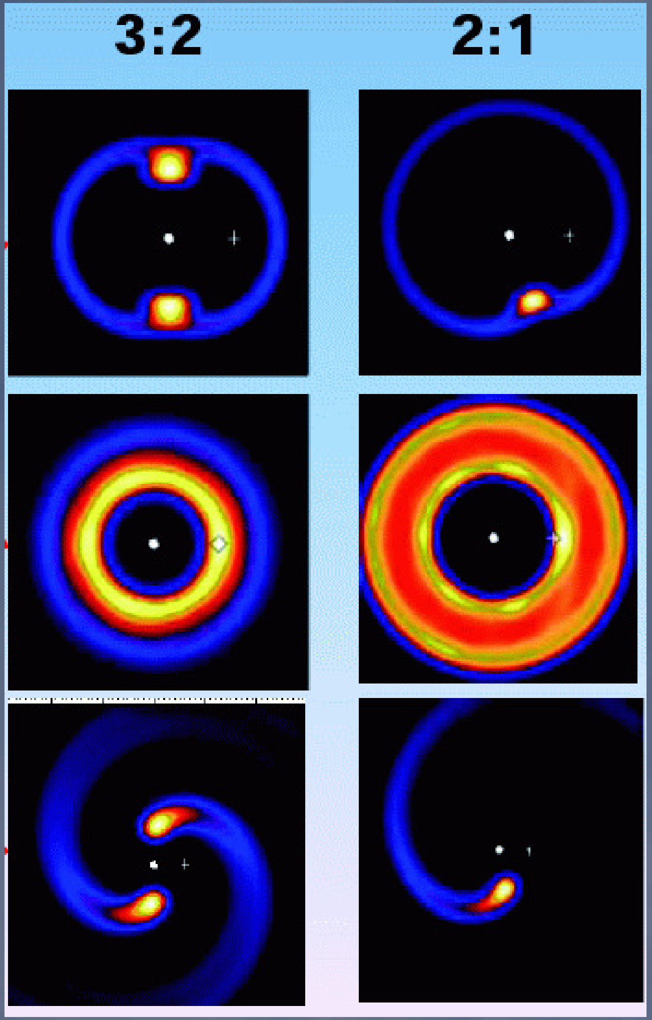


Kuchner & Holman, ApJ ***588****, 1110-1120 (2003)*

Reche et al., AAp ***480****, 551-561 (2008)*

Dust can also form spirals

Wyatt, ApJ **639**, *1153-1165 (2006)*



Large grains:
stay in clumps

Medium-sized grains:
form a ring

Small grains:
spirals emanating
from clumps

Caution: alternative explanations for clumps and spirals

- Major collision between planetesimals
- “Supercomet”
- Passage of a nearby star

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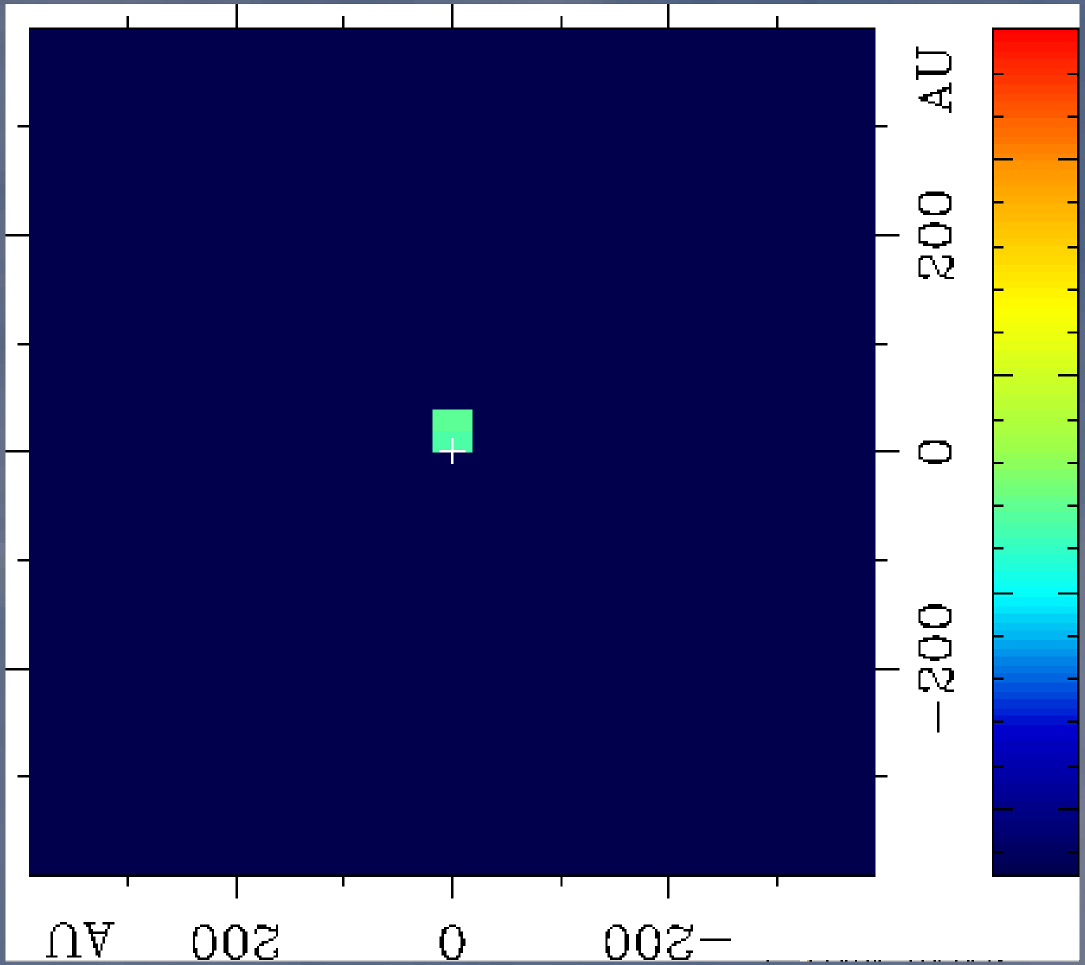


Grigorieva,Thébault, & Artymowicz, AAp **461,** *537-549 (2007)*

- A spiral-ilke pattern for ~1000 yrs
- Avalanches possible, but only for dustiest disks

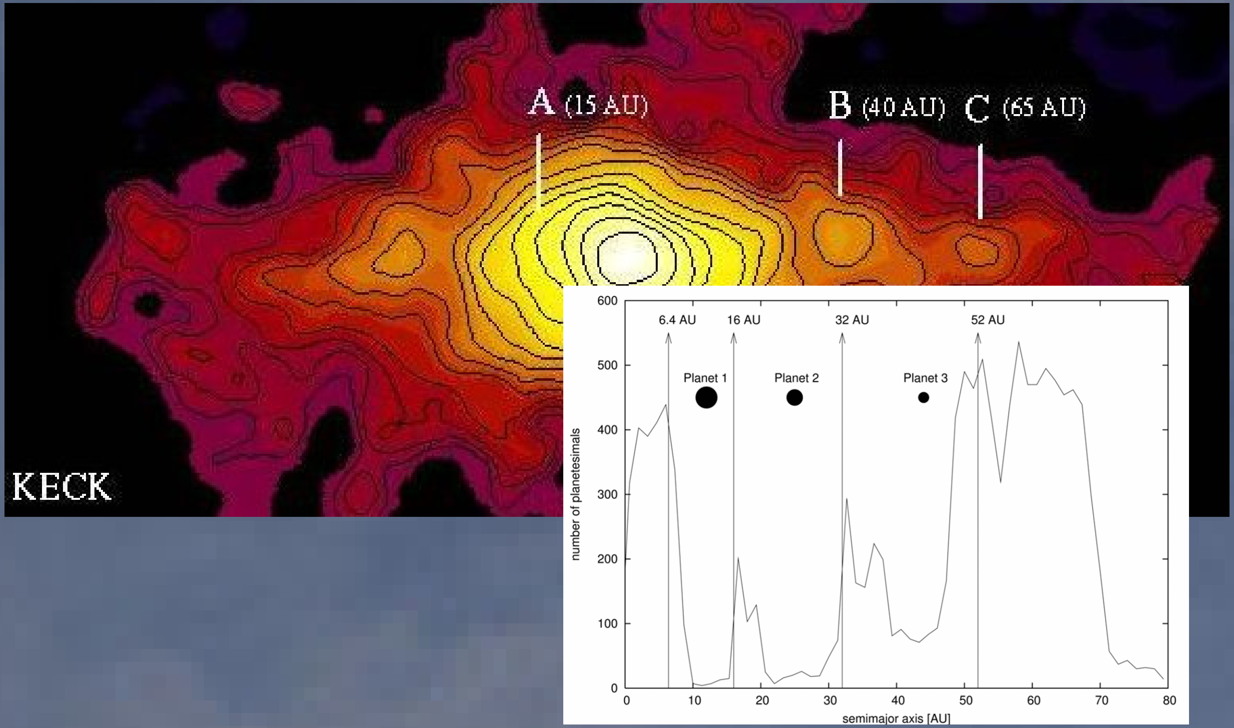
β Pic

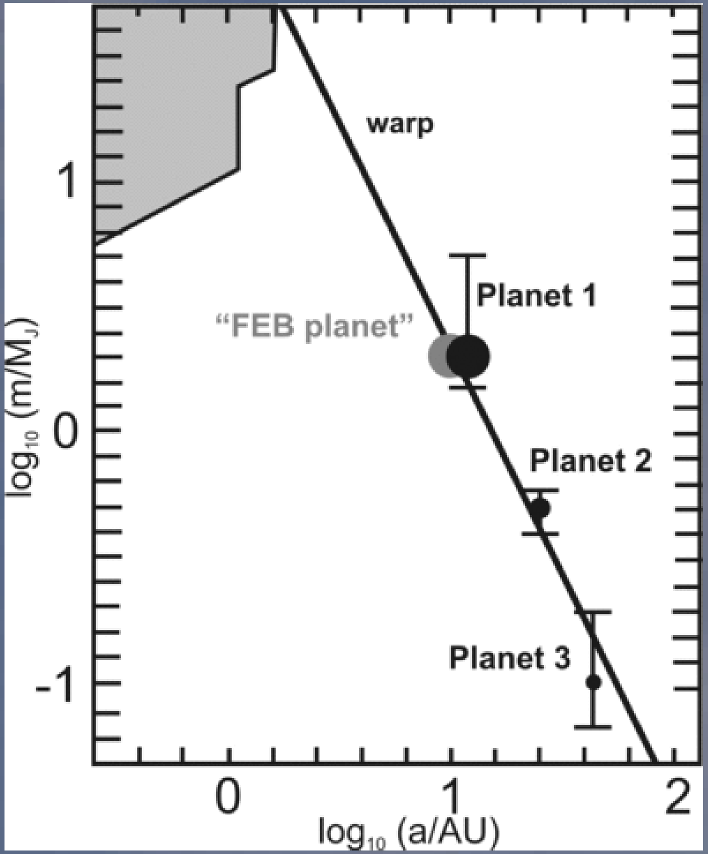
Planets were expected:

(1) offset (2) warp (3) FEBs *(tens of papers)*

(4) several rings *(Okamoto et al., Nature 2005)*

(5) "stream" *(Baggaley, JGR 1999; Krivov et al., AAp 2004)*

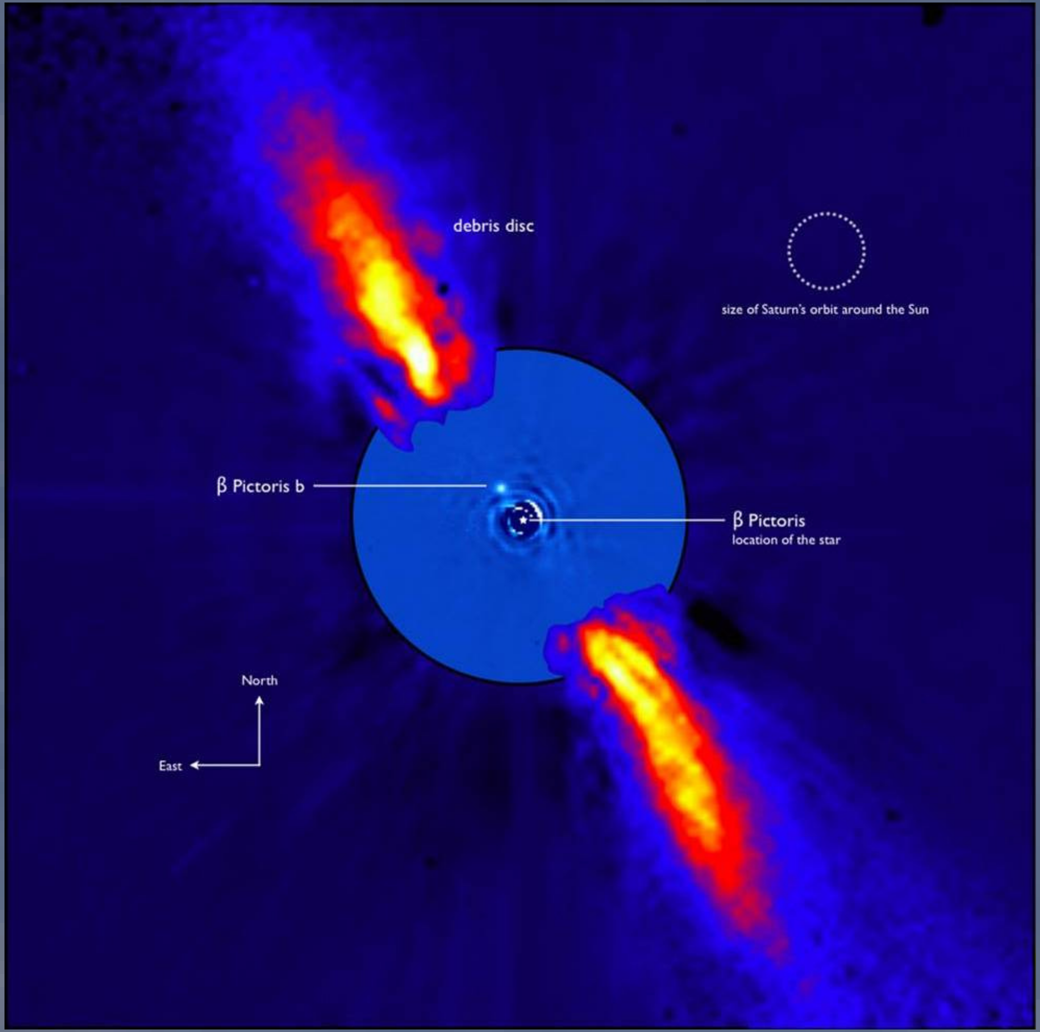




Freistetter, Krivov, & Löhne, AAp ***466****, 389-393 (2007)*

β Pic

...and “planet 1” now seems to have been discovered



Lagrange et al., A&A (in press)

Outline

Part I

- Concept of debris disks
- Observations of debris disks
- Basic theory of debris disks

Part II

- Debris disks: seeing dust
- Debris disks: thinking of planetesimals
- Debris disks: thinking of planets
- Debris disks: thinking of planetary systems

- Summary

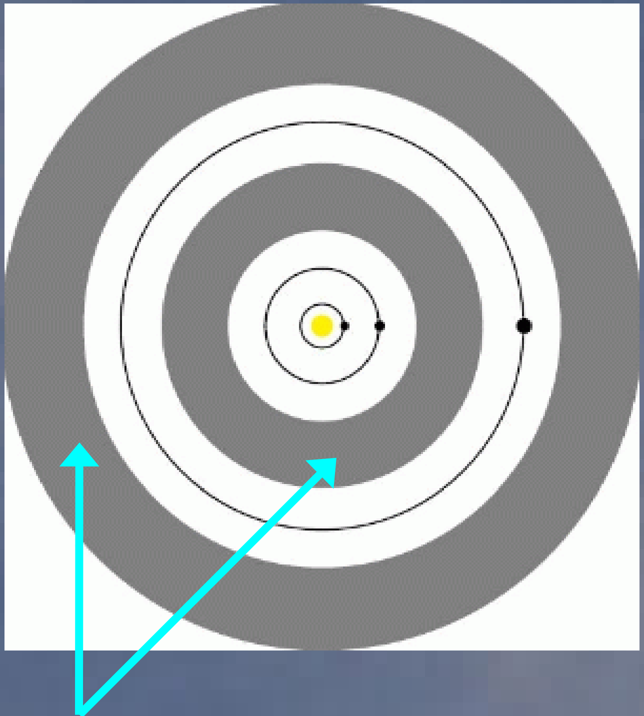
The hot dust problem

Only 2% of FGK stars exhibit hot dust detections (< 24 µm or < 10 AU)

Most of these systems with hot dust (4 / 7) have dust luminosities larger than “maximum for a given age” allowed by stationary collisional models

Wyatt et al., ApJ ***658,*** *569-583 (2007)*

Example:
HD 69830

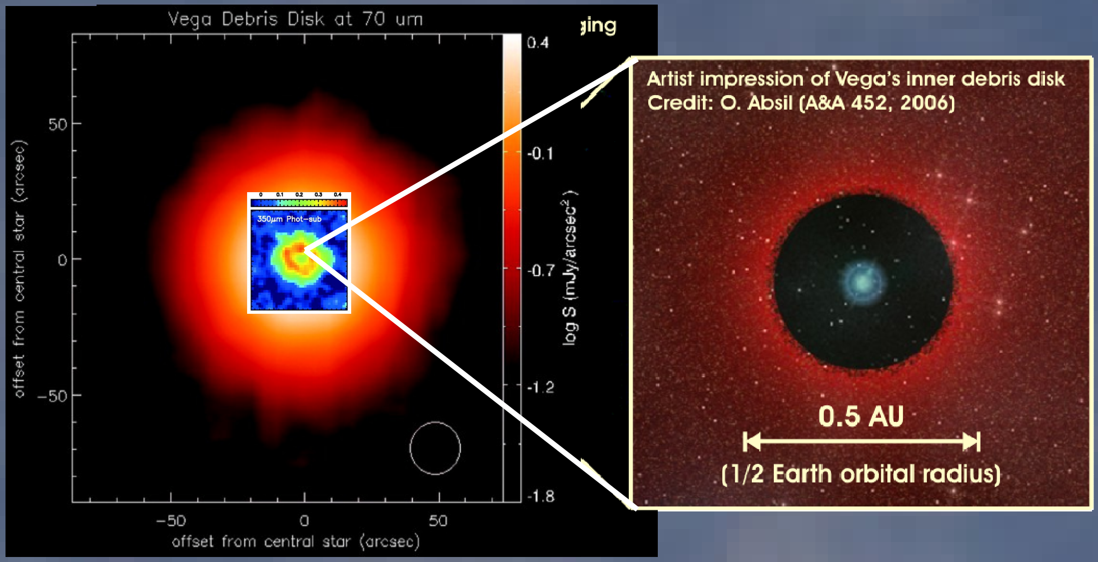


Possible parent body locations

1AU

Beichman et al., ApJ ***626,*** *1061-1069 (2005),*
Lovis et al., Nature ***441,*** *305-309 (2006)*

The hot dust problem: exozodis



Vega system:

Discovered a "zodiacal cloud" within 1 AU from the star

Derived 10^{-7} Mearth in small dust grains

Requires dust production rate of ~0.01 Mearth / Myr

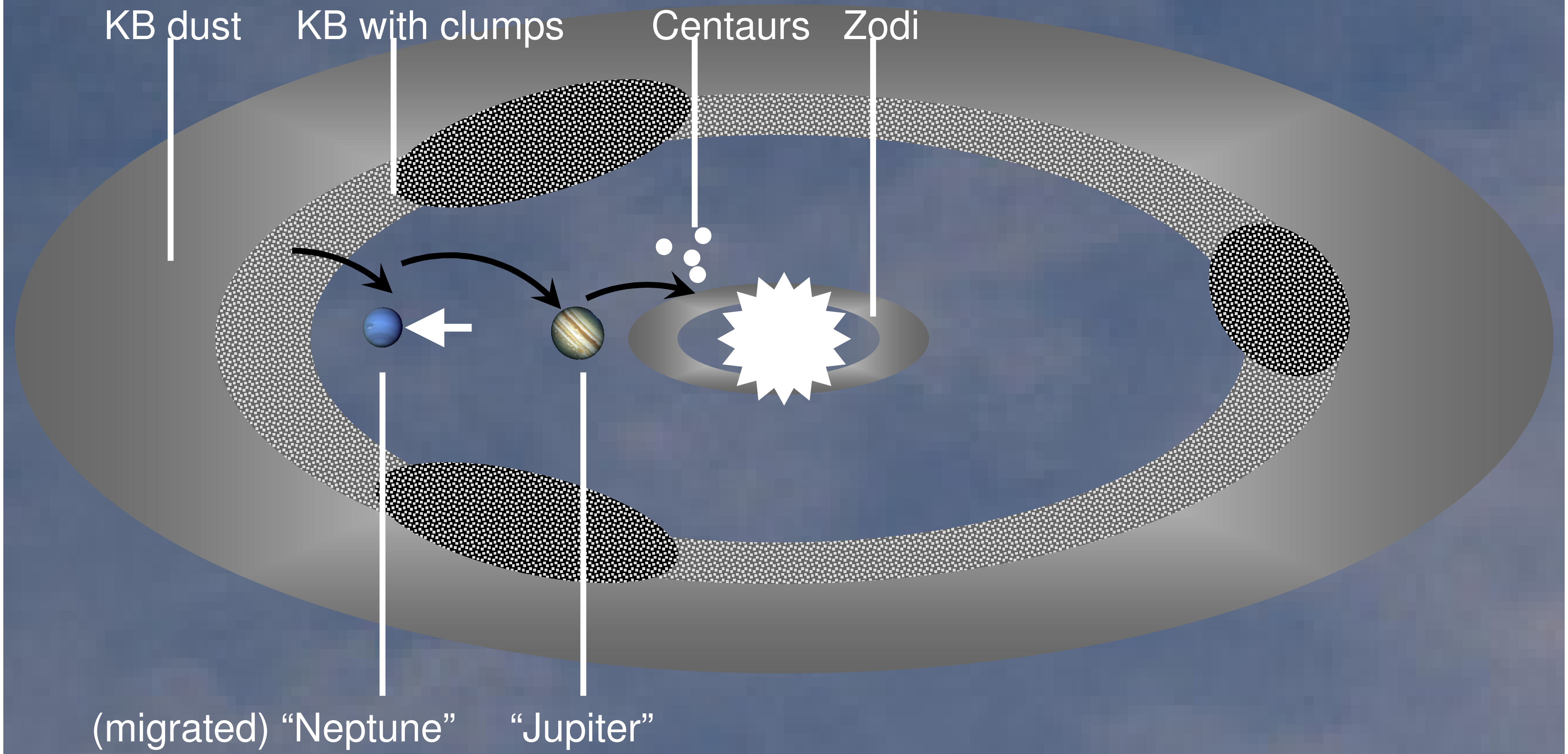
Incompatible with steady-state evolution: an unrealistically large mass of the "asteroid belt"

Absil et al., AAp ***452****, 237-244 (2006)*

Later on, several other exozodis with similar problems

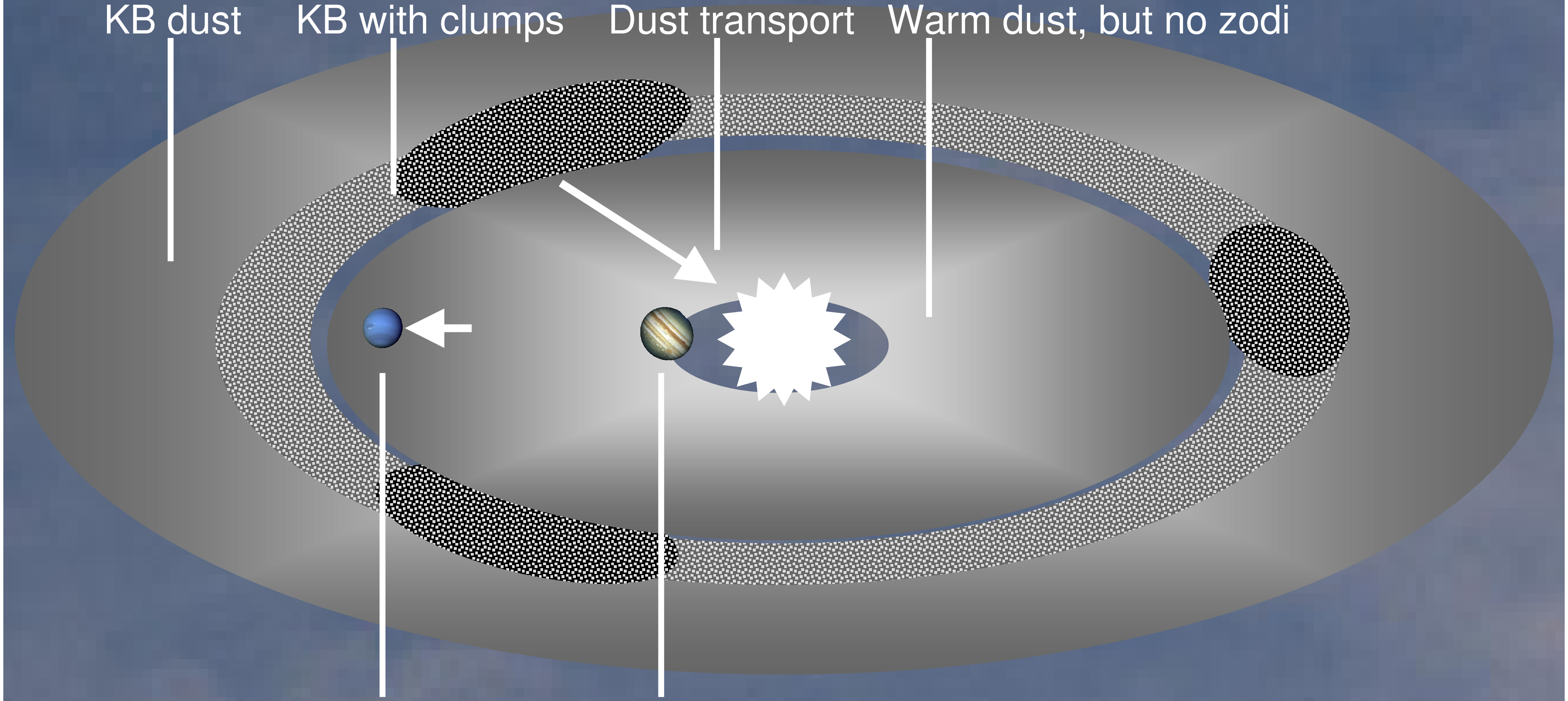
Di Folco et al., AAp ***475****, 243-250 (2007); Absil et al., ApJ, in press (2008)*

The planetary system of Vega: transport of planetesimals?



Absil, Beust, Reche, Augereau, Krivov, Müller, & Löhne (in prep.)

The planetary system of ε Eri: transport of dust?



KB dust

KB with clumps

Dust transport

Warm dust, but no zodi

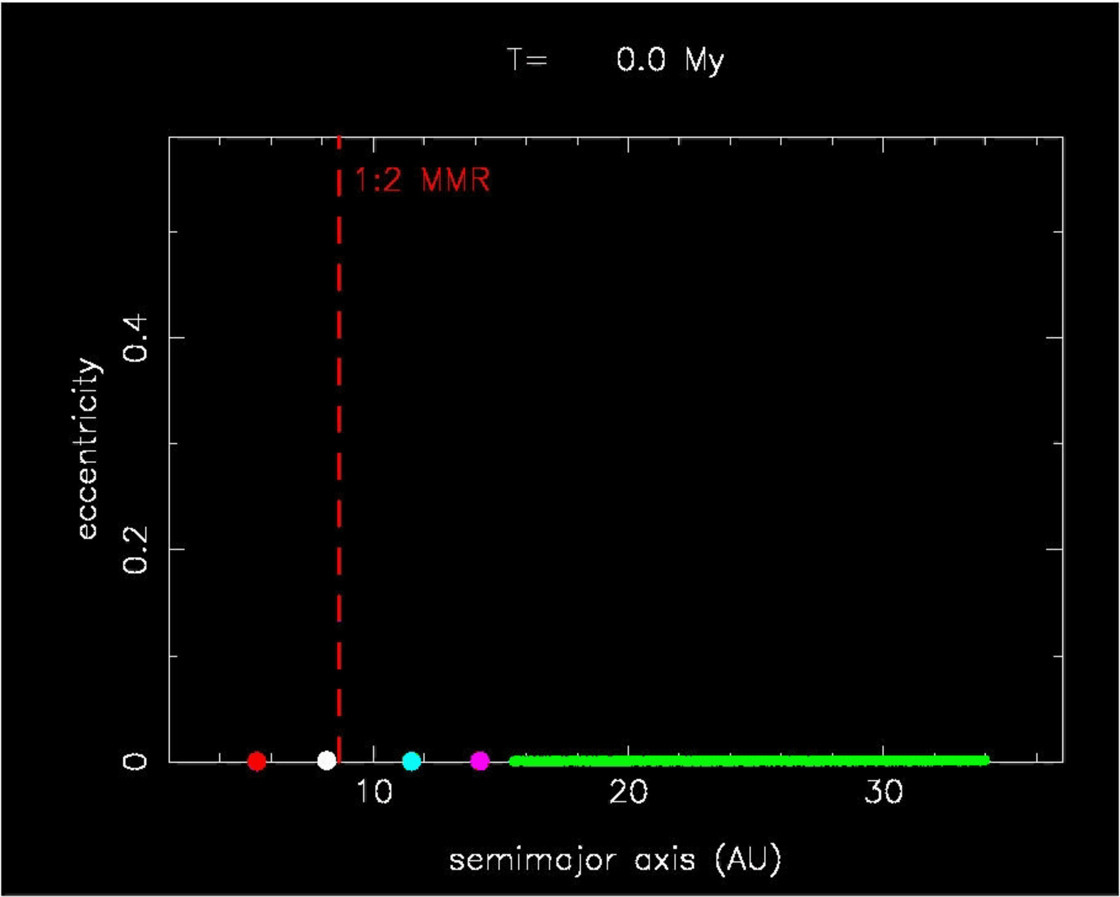
(migrated) “Neptune”

a known RV planet

Reidemeister, Krivov, Müller, Löhne, Augereau, & Absil (in prep.)

Alternatively, transport by dynamical instabilities?

Late Heavy Bombardment in the solar system 3.8 Gyr ago



Simulation and animation: Alessandro Morbidelli

Nobody knows whether LHB-type events are common

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Summary

- Debris disks are optically-thin, dusty, gas-poor disks around main-sequence stars
- Debris disks are common around those stars
- Debris disk observations reveal emission of dust
- Debris disks are direct evidence for planetesimals
- Debris disks are indirect evidence for planets
- Debris disks give clues to the formation, evolution, and architecture of planetary systems

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- Su et al., ApJ 628, 487 (2005)
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