# Collisional Evolution of Debris Disks

## Unraveling planetesimals and planets

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**Collaborators:**
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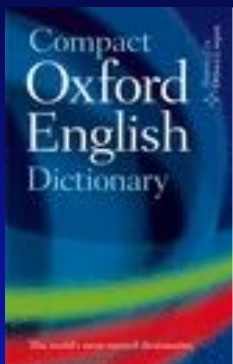
# Do we understand what a debris disk is?

# I think so:




**debris**

/**deb**ree, **day**bree/

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

— ORIGIN French, from *débriser* 'break down'.


**disc, disk**

**/dɪsk/**

- **noun** a thin circular plate of any material

## ... but do we understand debris disks?

# Outline

- Introduction
- Basic physics and modeling methods
- Steady-state evolution: theory
- Steady-state evolution: observations
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- Long-term evolution
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# Fragmentation is ubiquitous

| Time | 0.1 | 1 | 10 | 100 Myr |
| --- | --- | --- | --- | --- |
| From dust to pl/simals | Growth of embryos | Gas planet formation | Terrestrial planet formation | Planetary system evolution |
| e.g. Brauer et al. (2008) | e.g. Kobayashi & Tanaka (2009) | e.g. Pollack (1996) | e.g. Kenyon & Bromley (2005) | |

*Growth is accompanied by fragmentation*

*Fragmentation dominates*

# That’s all about planetary systems

Dust distributions and properties

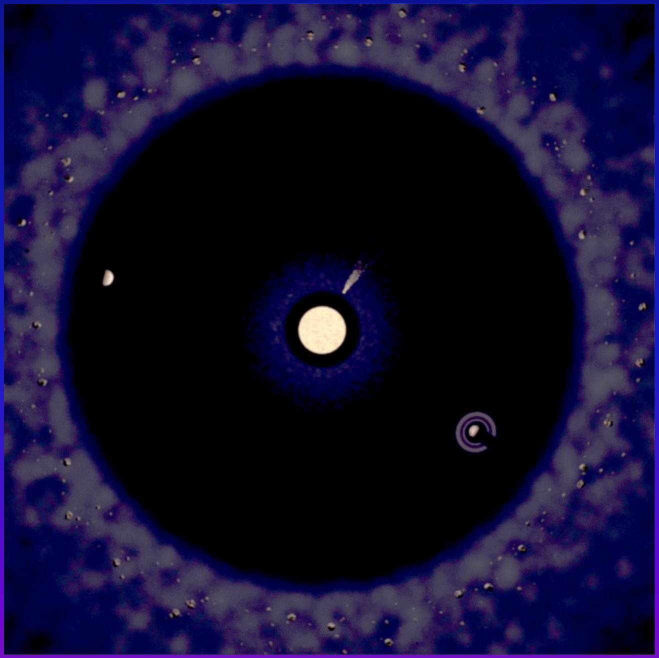
*Compute* ←

*Infer* →

Planetesimals and planets

*Compute* ↓ *Infer* ↑

*Infer* ↓ *Compute* ↑



Dust observations

Formation history

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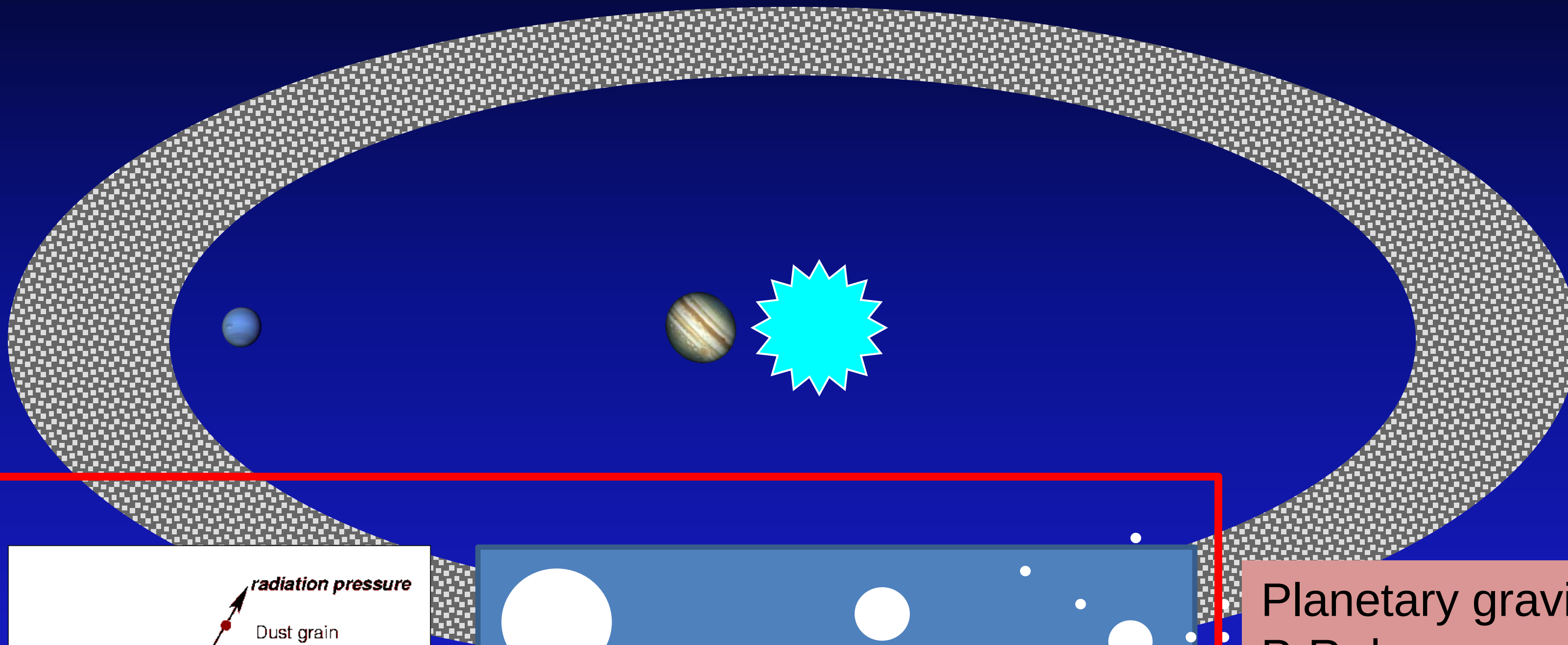
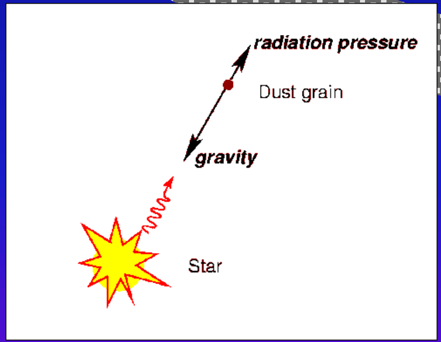
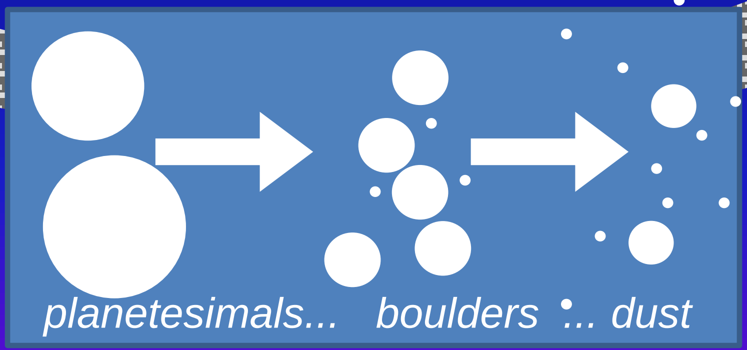
# Basic physics






Planetary gravity
P-R drag
Gas drag
Lorentz force
…

Stellar (photo)gravity

Collisional cascade

Other forces

# Modeling methods

*Talk by Marc Kuchner*

## ❑ N-body simulations

- ✓ Inflated spheres", local PiaB, "collisional grooming", ...
- Accurate dynamics
- Inaccurate collisions


## ❑ Statistical codes

- ✓ Multiannulus PiaB, kinetics in orbital elements, …
- Accurate collisions
- Simplified dynamics

## ❑ Hybrid methods

- ✓ Combinations of both above, "superparticles",...
- Share (dis)advantages of two previous methods

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

# ACE (Analysis of Collisional Evolution)

Initial planetesimal belt → 

→ Debris disk at subsequent time instants

Features:
- statistical code in an (m,q,e)-mesh
- accurate photogravitational dynamics
- collisions (mergers, cratering, disruption)
- diffusion by P-R, stellar wind, gas drag
- distributed parallel computing

Krivov & Sremčević (2003-2004), Löhne (2005-2009)

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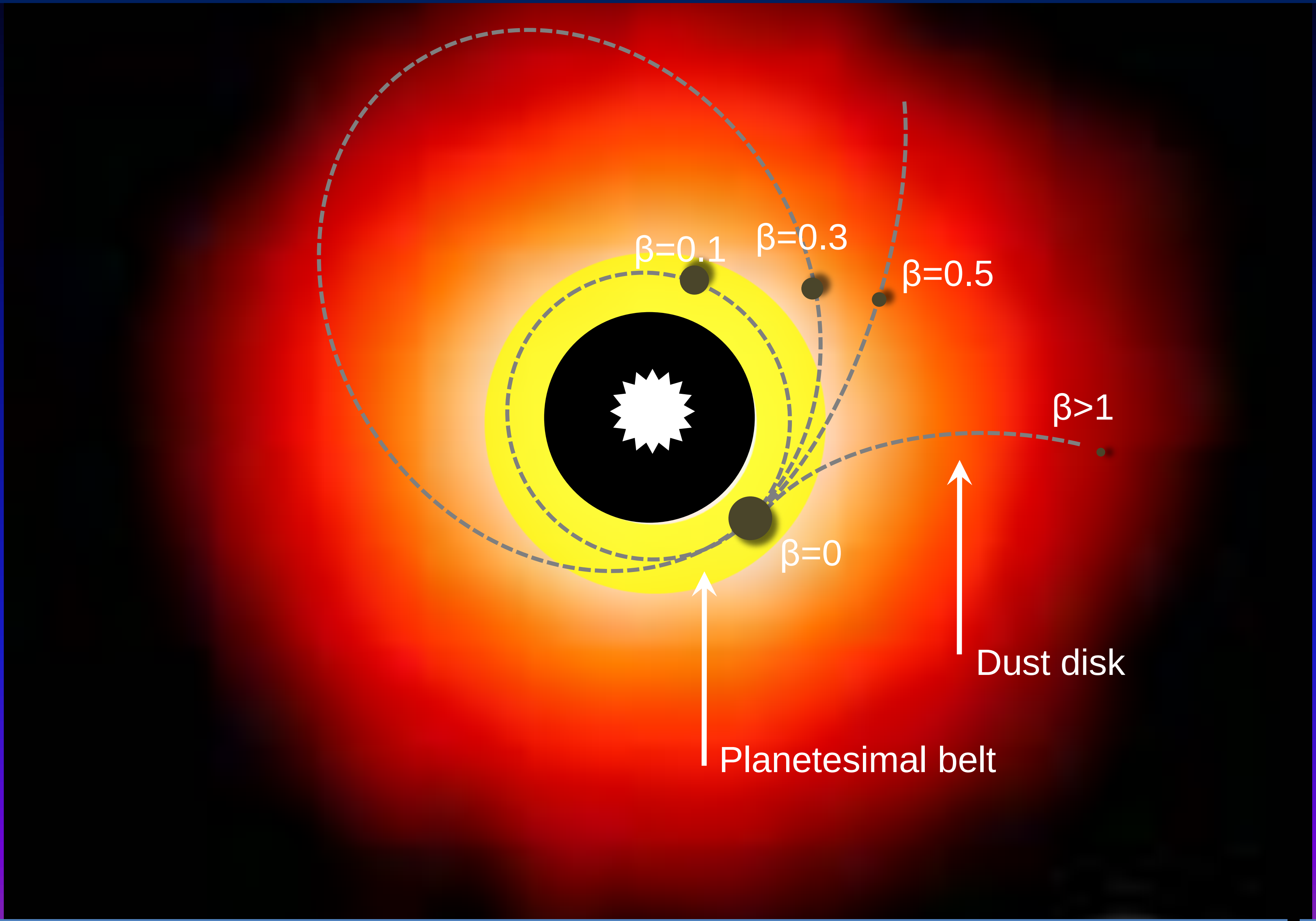
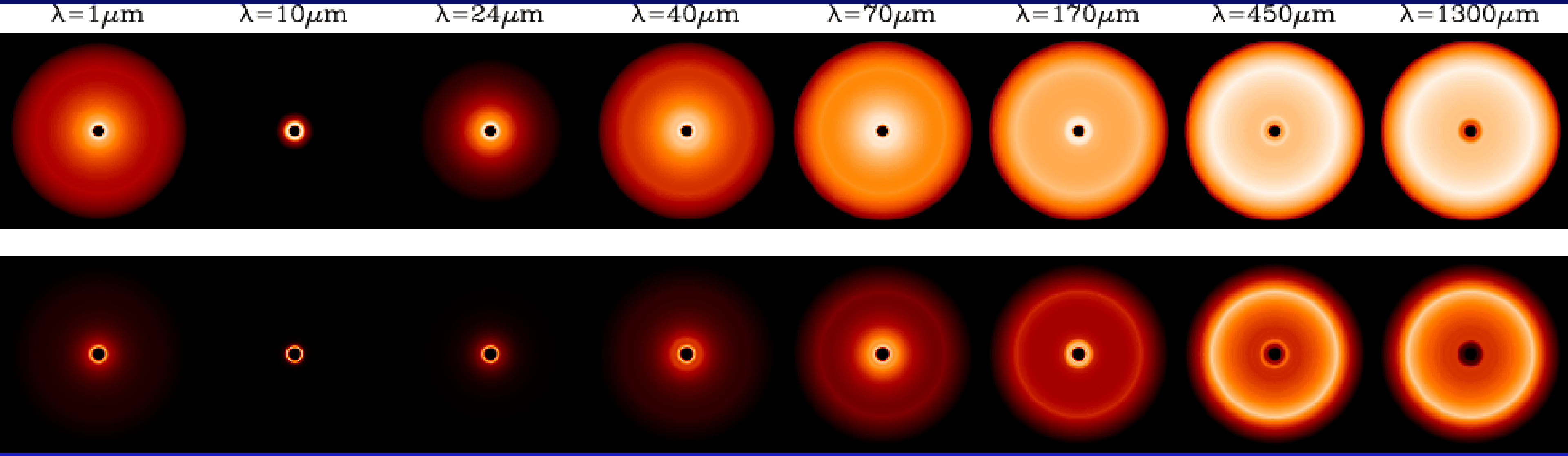
# A typical debris disk



# Disk appearance at different wavelengths




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

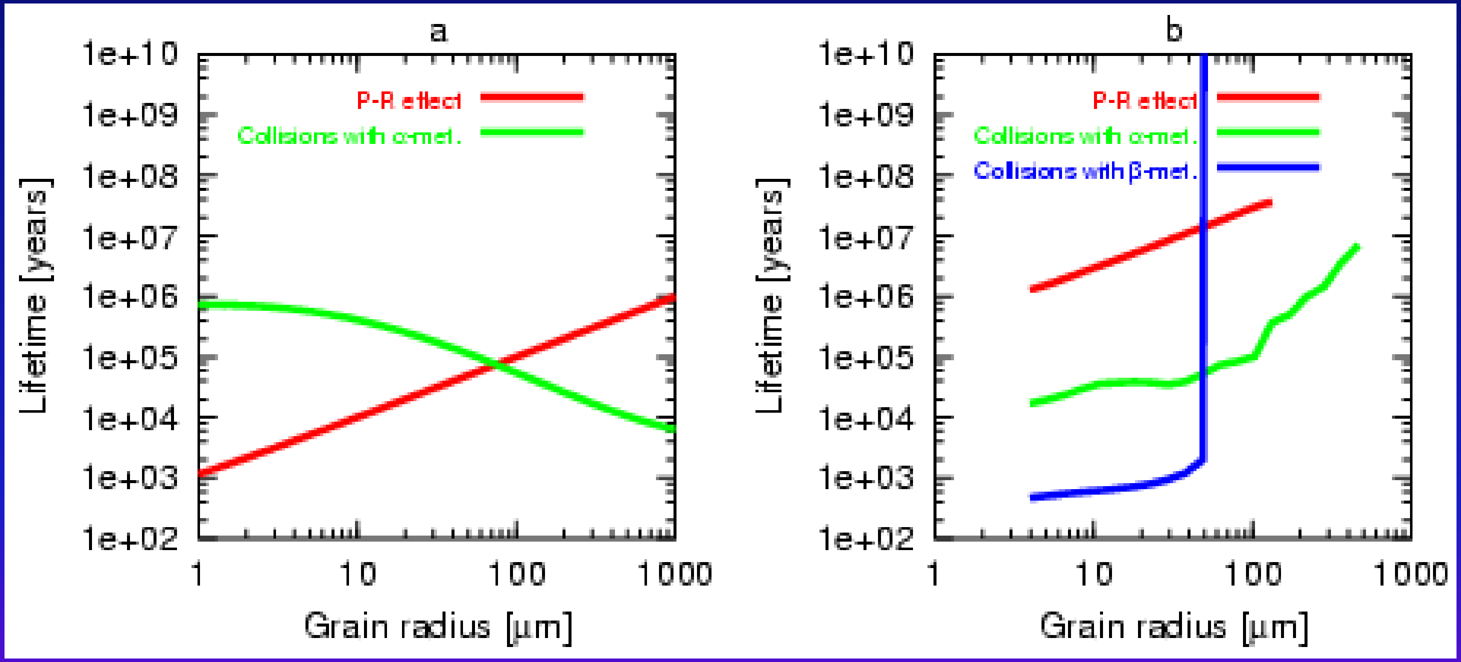
# Collision-dominated vs transport-dominated disks

Disks with low optical depth, especially around late-type stars (here: our Zodi)

Leinert & Grün, In Phys. Inner Heliosphere (1990)

Dustier disks (here: β Pic)

Krivov et al., AAp **362,** 1127 (2000)




All debris disks detected so far are collision-dominated (Wyatt, ApJ **598**, 1007-1012, 2005), but we should be able to enter the world of transport-dominated disks soon

# Collision-dominated disks: scaling rules

F=any quantity proportional to amount of material in any size regime
Exact rule for collision-dominated disks:

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

F=any quantity proportional to amount of material in any size regime
Approximate rule for disks with a fixed relative width and height:

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

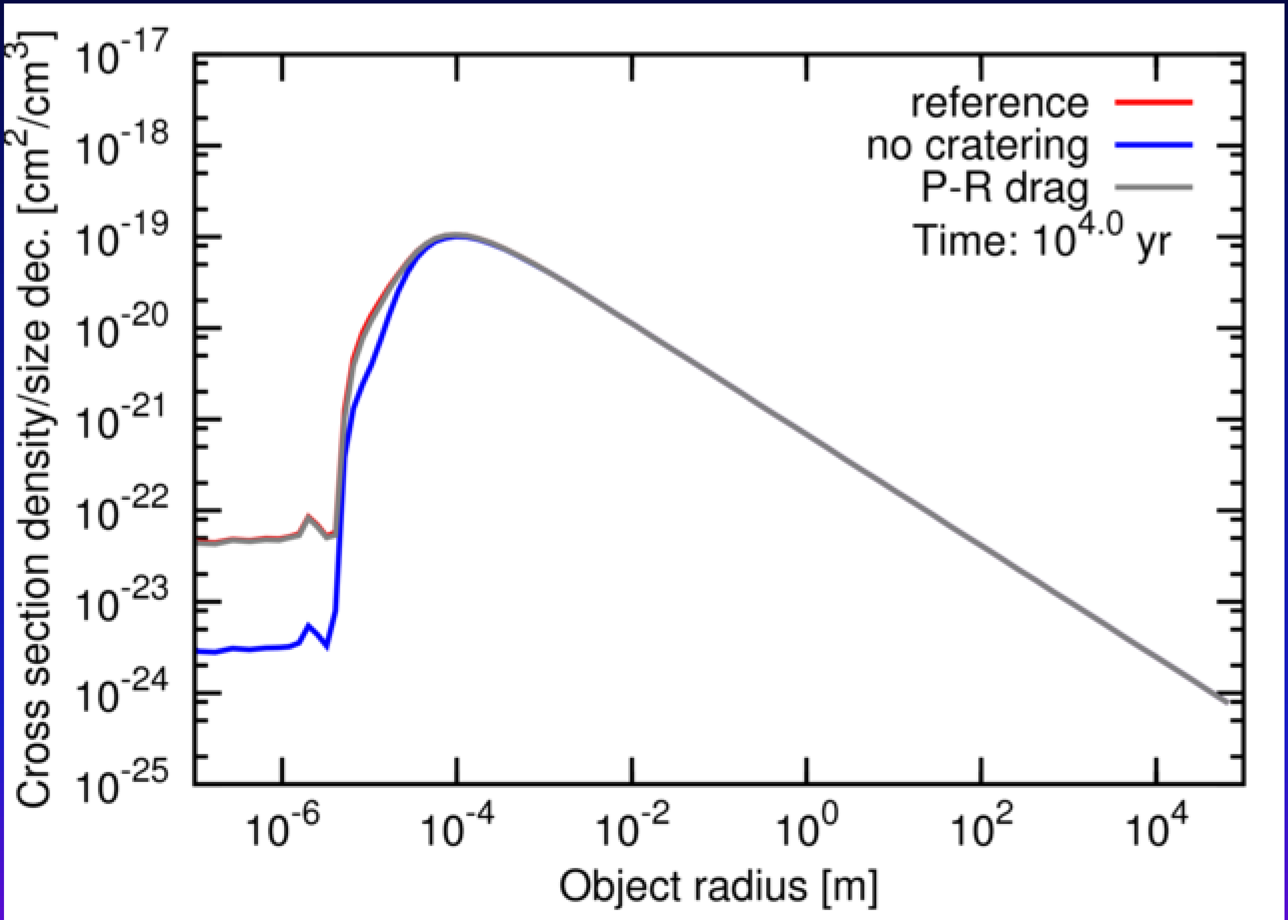
F=any quantity proportional to amount of "dust" (objects in strength regime)
Approximate rule for collision-dominated disks:

$$F(M_o, r, zt) \approx z^{-\xi} F(M_o, r, t), \quad \xi \sim 0.3 \ldots 0.4$$

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

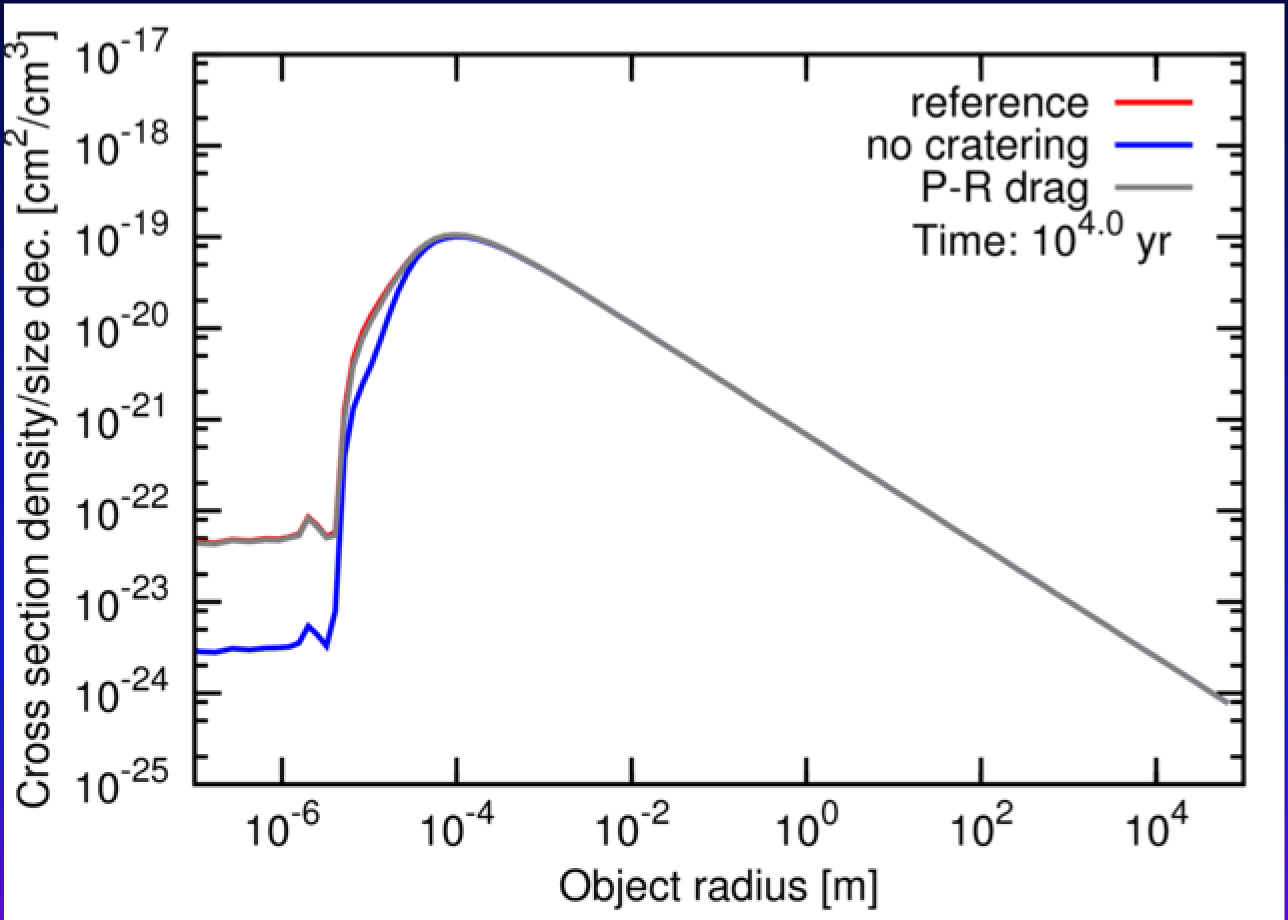
Löhne, Krivov, & Rodmann, ApJ **673**, 1123-1137 (2008)

# Collision-dominated disks: size distribution




Animation: Torsten Löhne

# Collision-dominated disks: size distribution




Animation: Torsten Löhne

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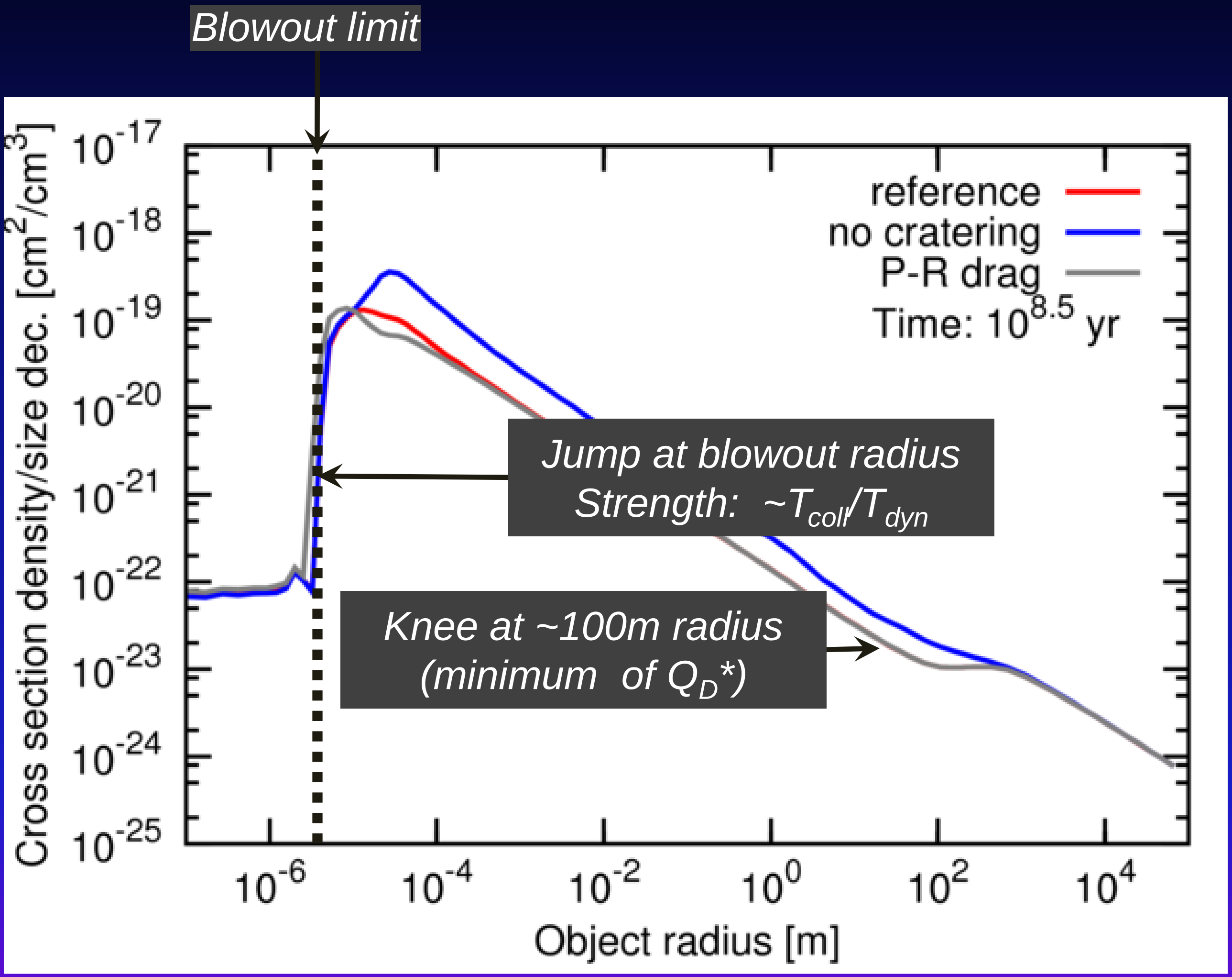
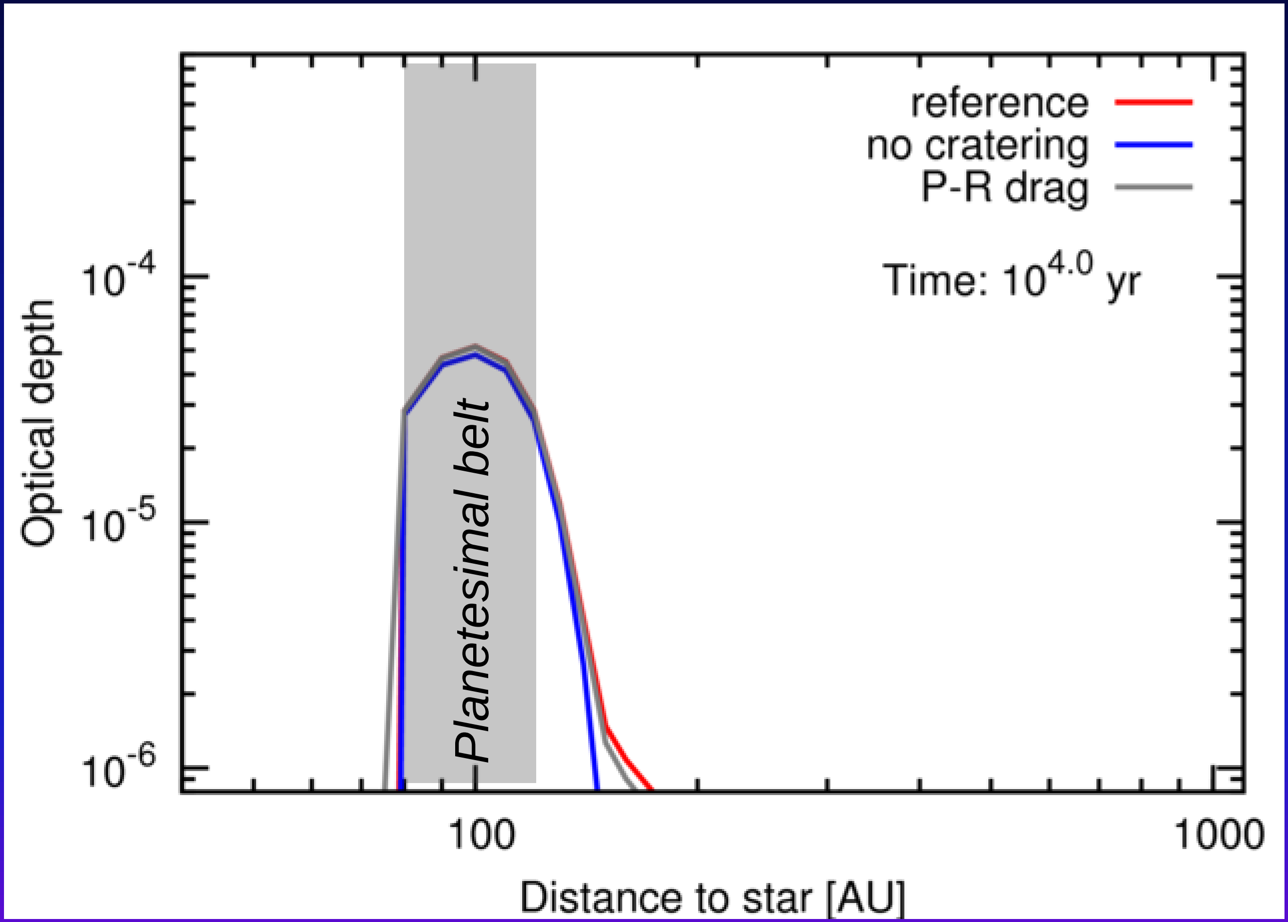


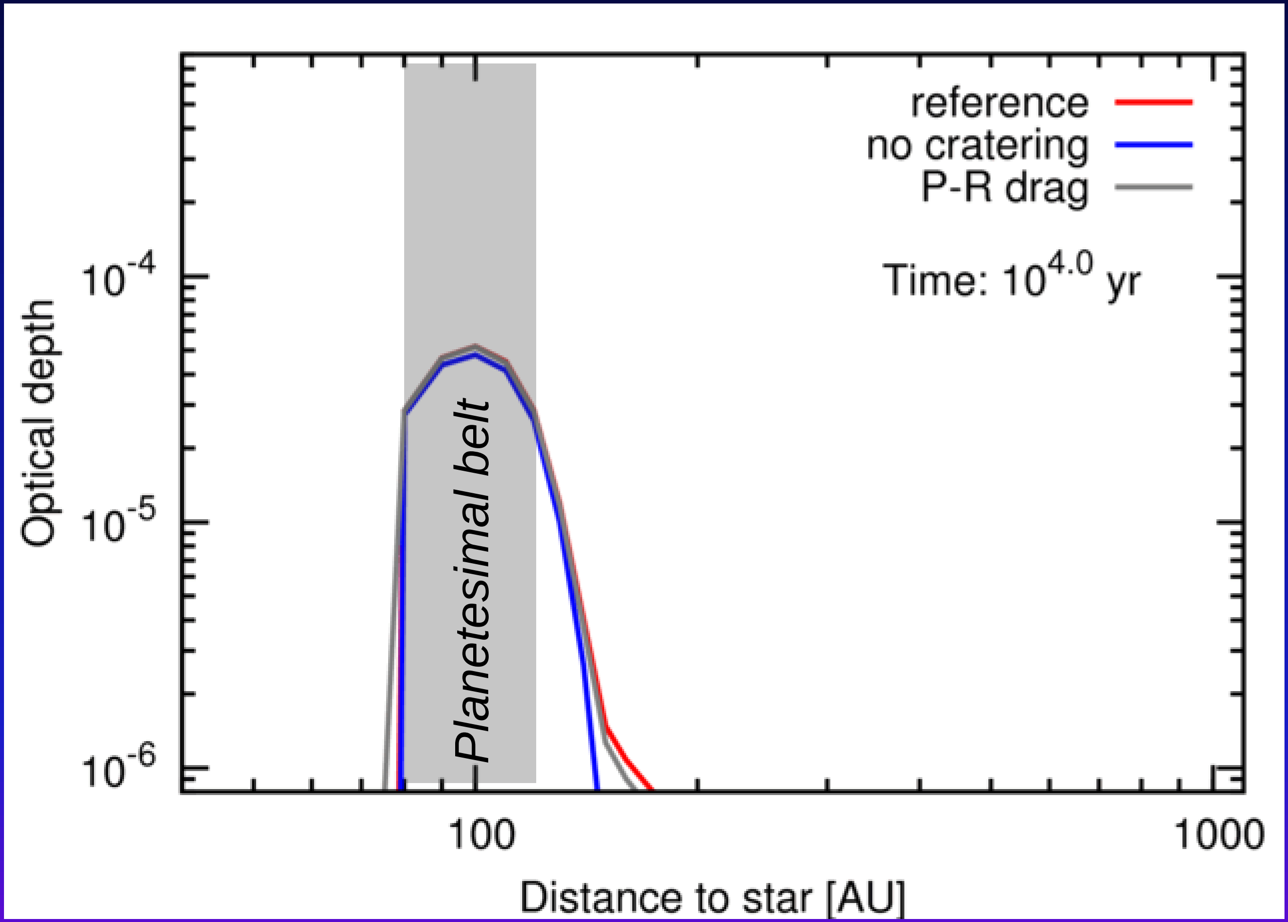

Animation: Torsten Löhne

# Collision-dominated disks: radial distribution




Animation: Torsten Löhne

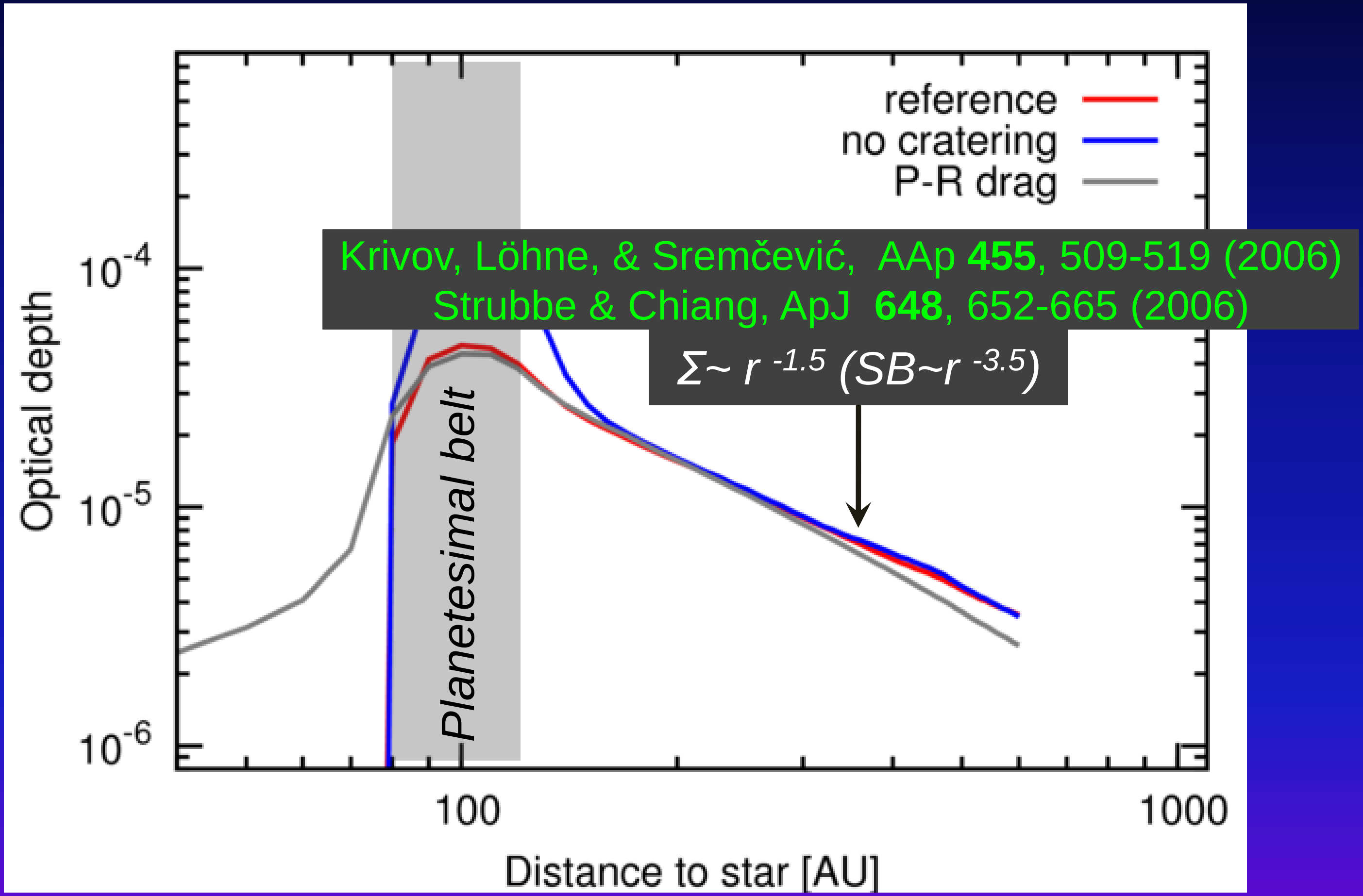
# Collision-dominated disks: radial distribution




Animation: Torsten Löhne

# Collision-dominated disks: radial distribution

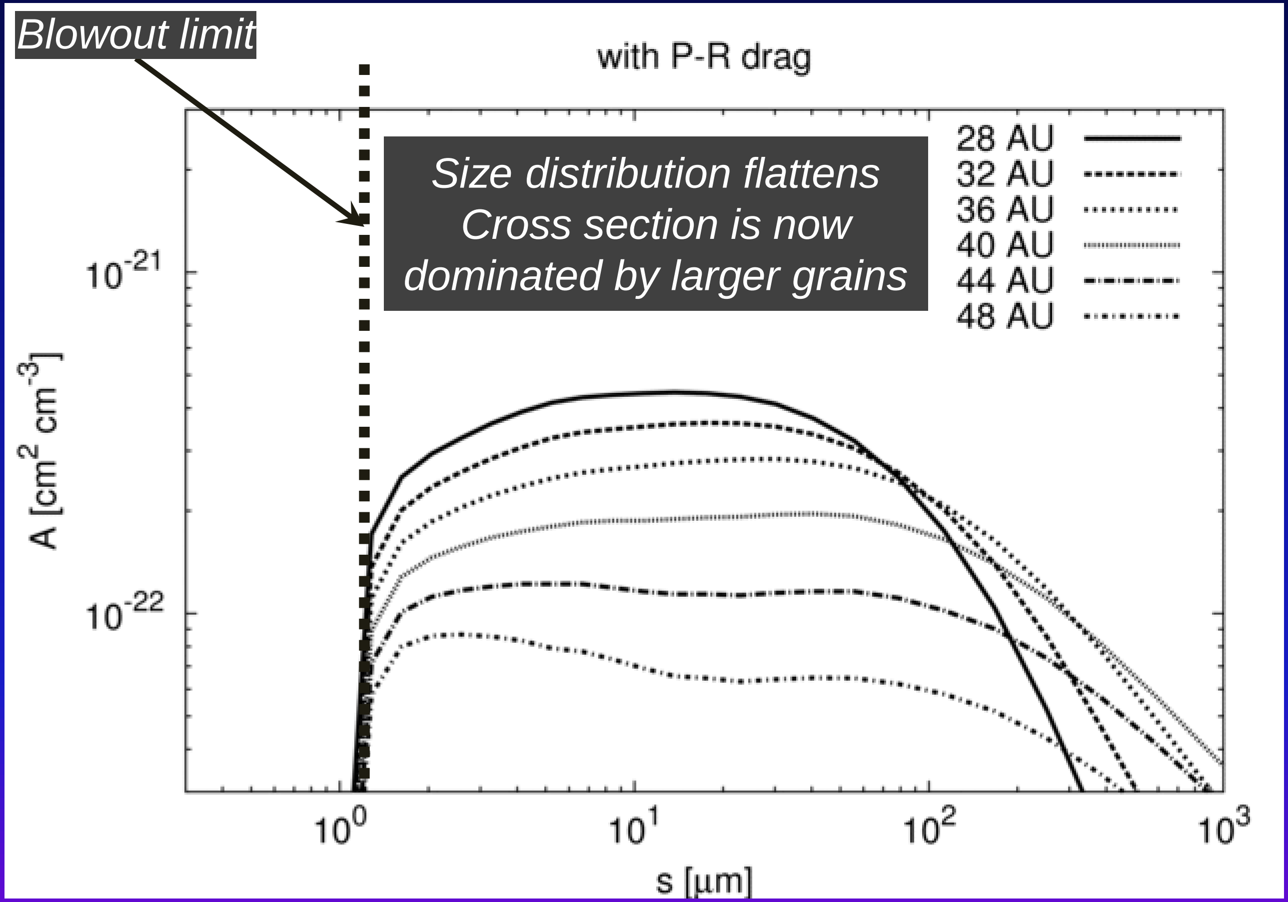
→ ***Talk by Eugene Chiang***




Animation: Torsten Löhne

# Transport-dominated disks: size distribution

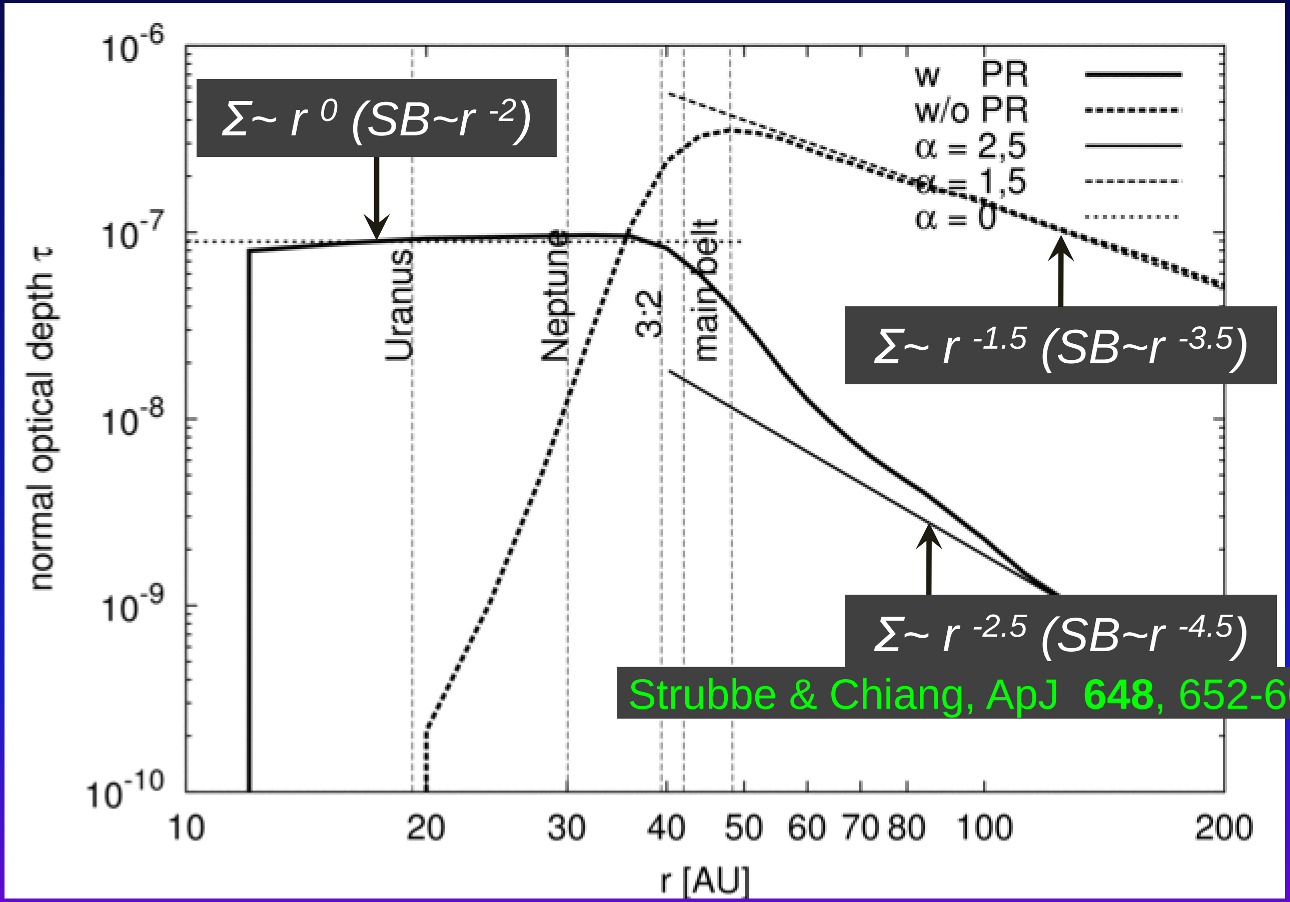
Edgeworth-Kuiper belt dust disk




Vitense, Krivov, & Löhne (in prep.)

# Transport-dominated disks: radial distribution

Edgeworth-Kuiper belt dust disk

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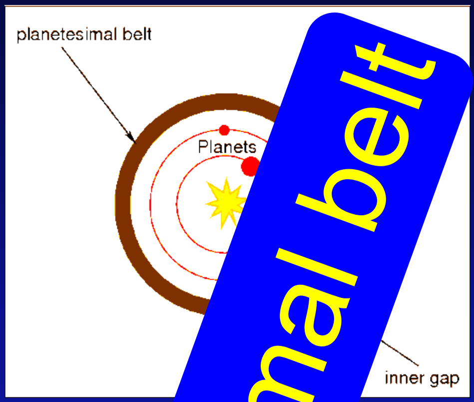
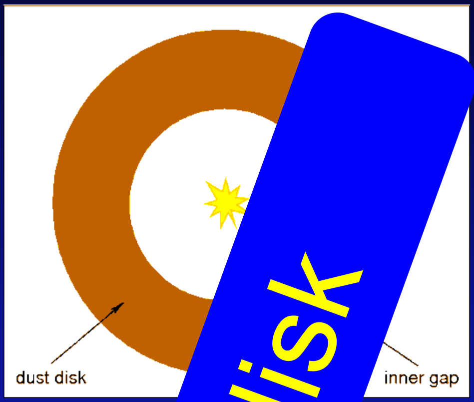
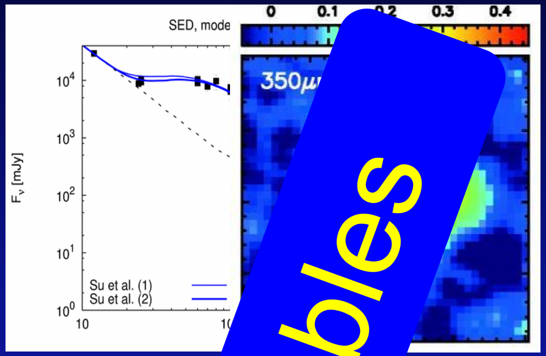
# Two approaches to data analysis

Traditional approach

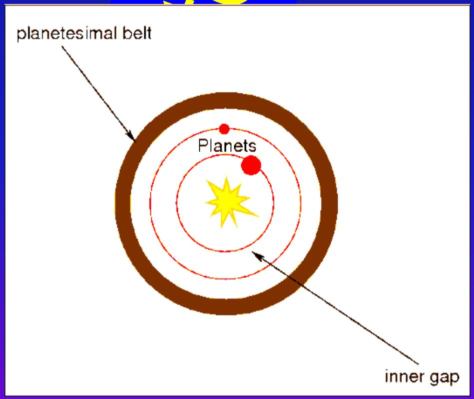



?

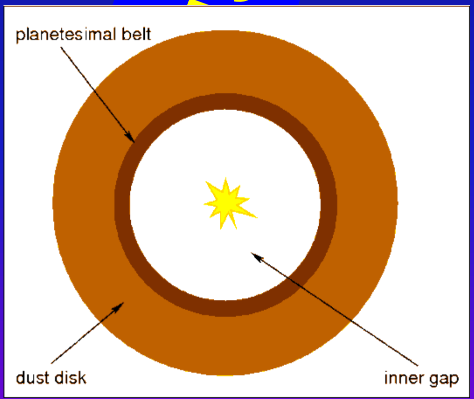


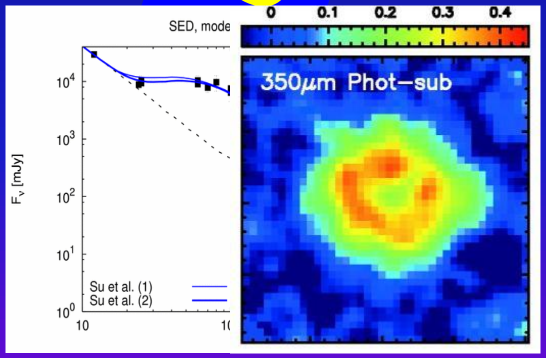

Collisional approach




Collisional model




Thermal emission model




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

# 1984

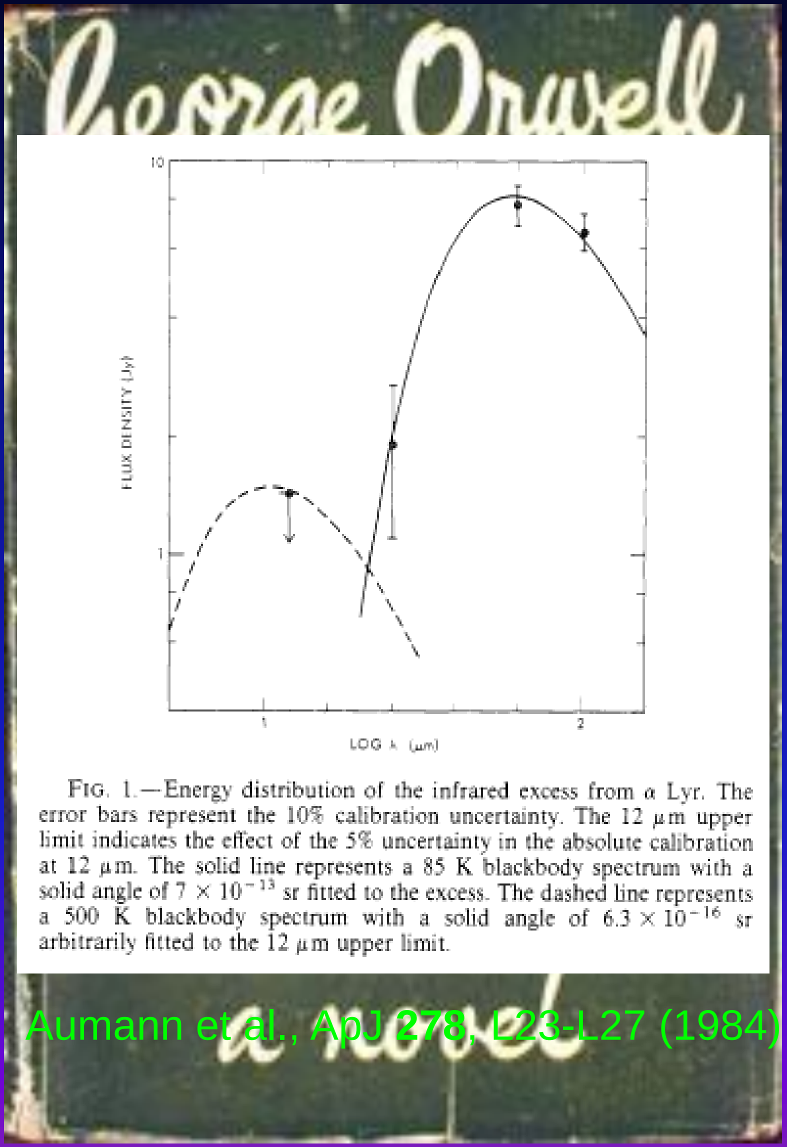
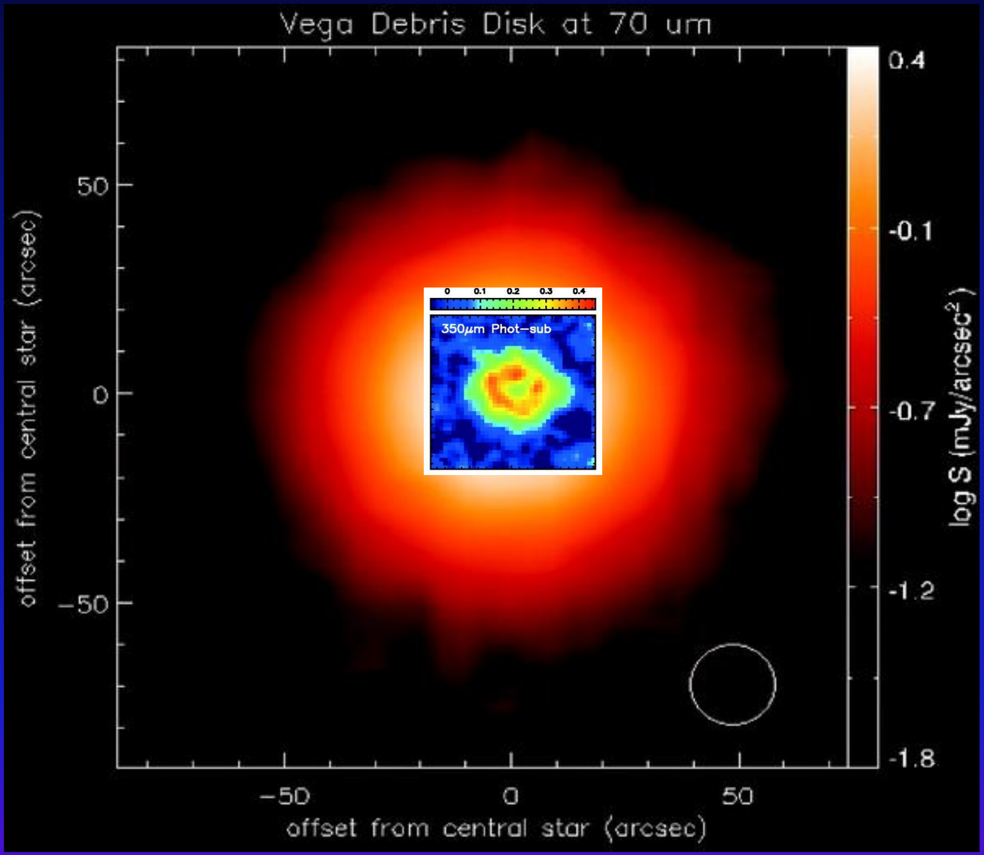



FIG. 1.—Energy distribution of the infrared excess from α Lyr. The error bars represent the 10% calibration uncertainty. The 12 μm upper limit indicates the effect of the 5% uncertainty in the absolute calibration at 12 μm. The solid line represents a 85 K blackbody spectrum with a solid angle of $7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

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

# The Vega disk: huge and short-lived?




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

Sub-mm observations:
a clumpy ring at ~100 AU

Spitzer/MIPS mid- to far-IR:
an extended disk ~800 AU

Fitted SED & profiles with
1… 50 μm & ~200 μm grains

- Blowout ~ 8…50 μm (if porous)
- SB~r $^{-3...4}$ looked like blowout

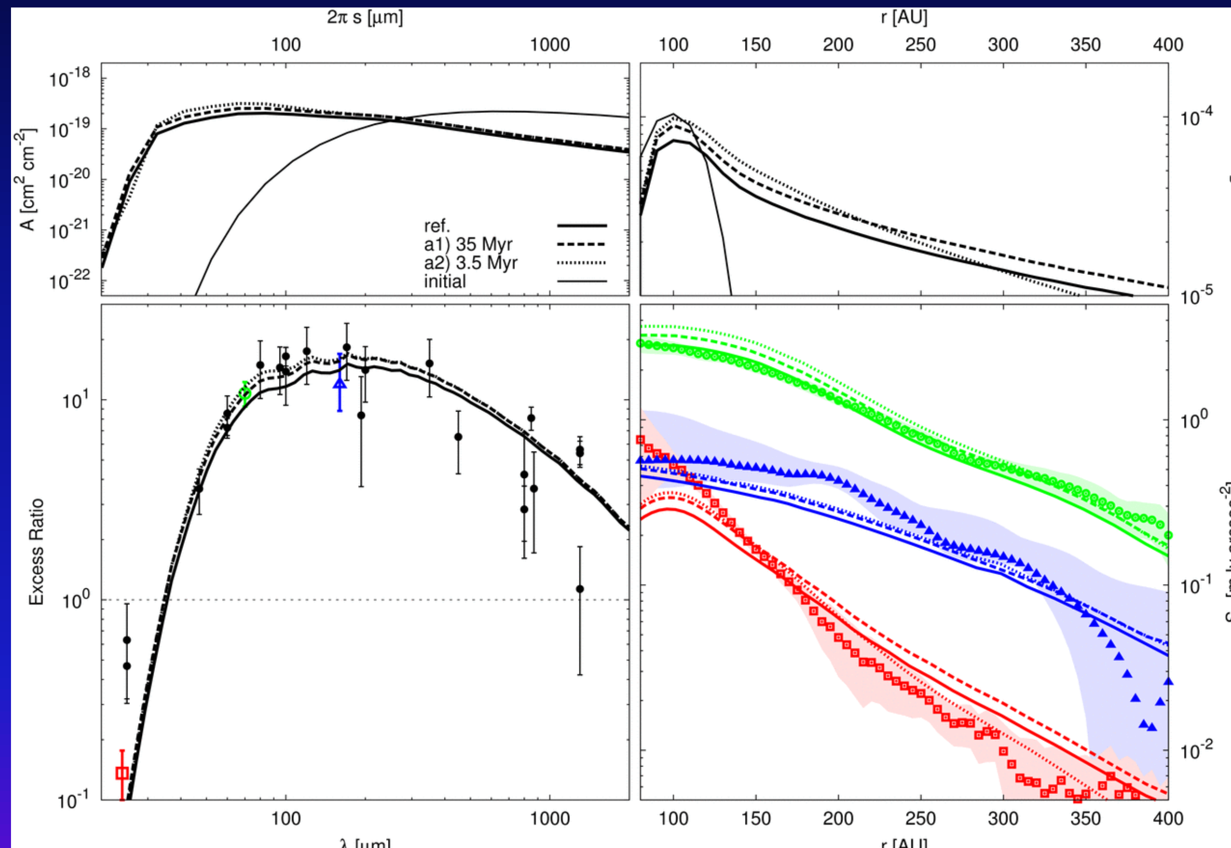
=> extended disk = “dust wind”

Consequence:
Huge mass loss ~3 Mjup
Recent major collision?

# The Vega disk: steady-state, naturally

➡ ***Poster by Torsten Löhne***

- First-guess model
- "Collisional age"
- Stellar luminosity
- Location of belt
- Extension of belt
- Dynam. excitation
- Dust composition
- Cratering yes/no
- $Q_D^*$ (strong/weak)
- Fragment distrib
- PR effect yes/no




Müller, Löhne, & Krivov, ApJ (submitted)

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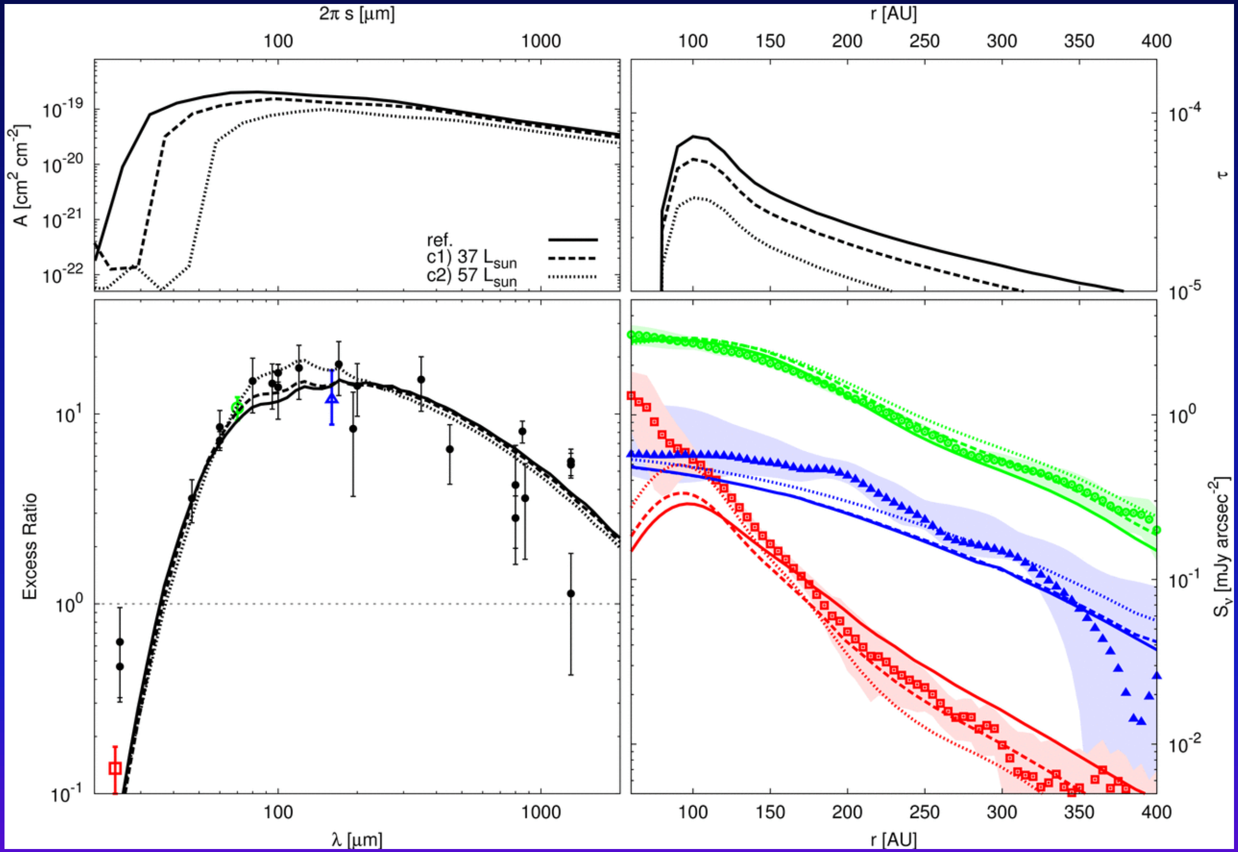


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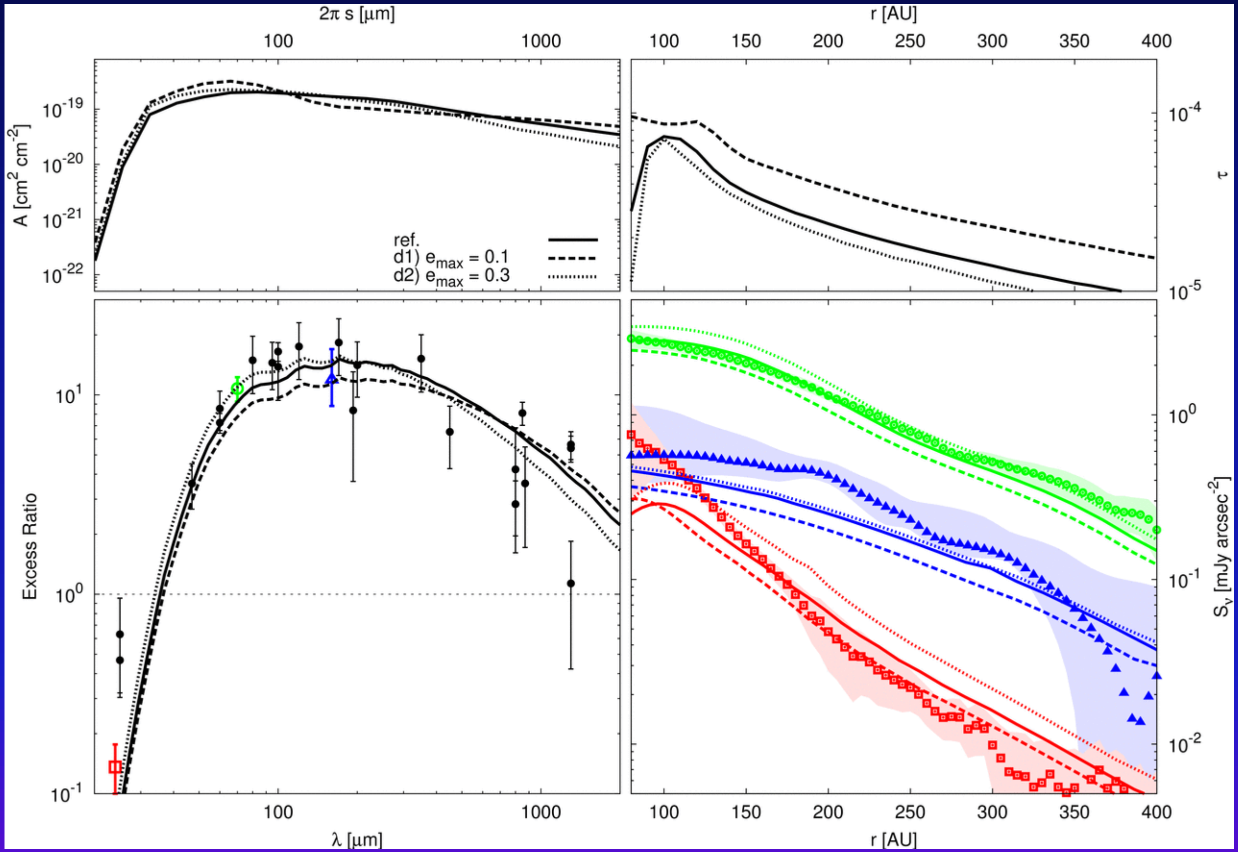


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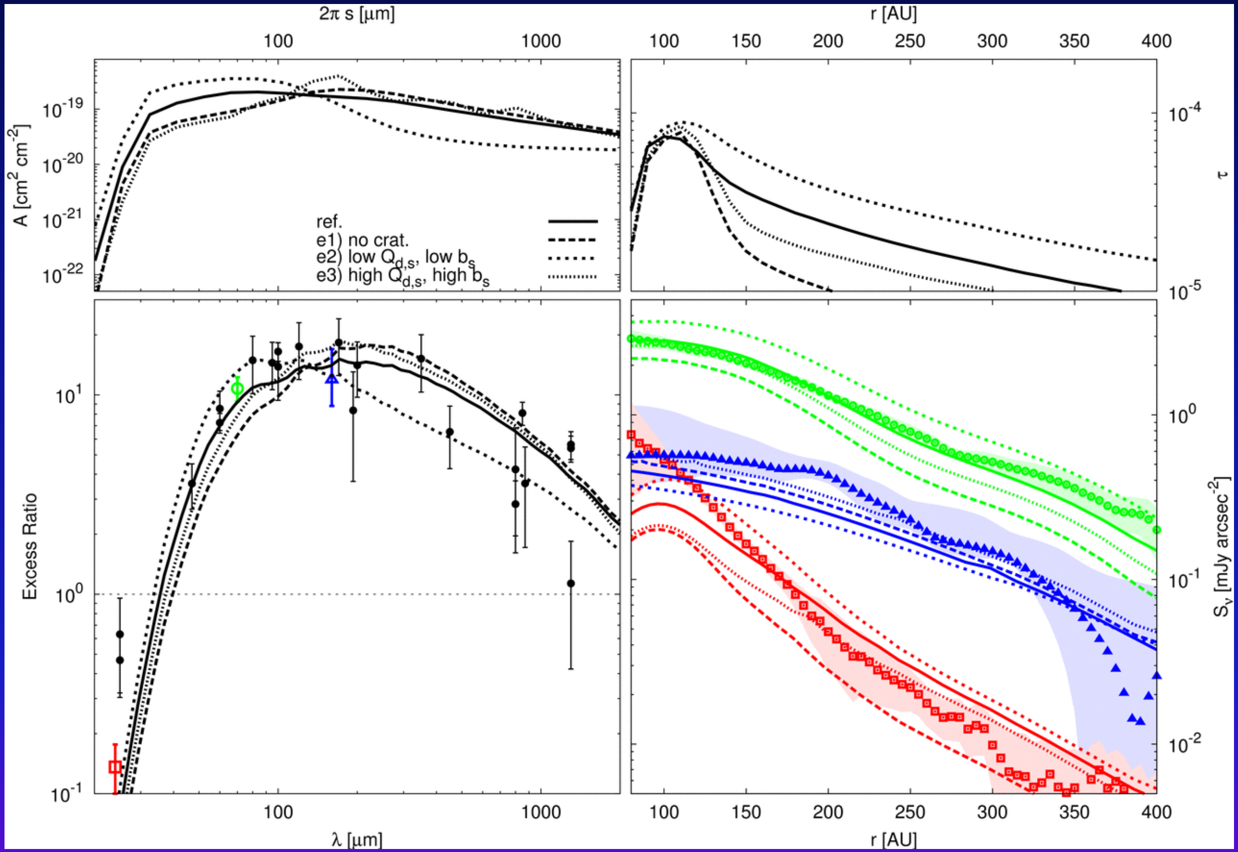


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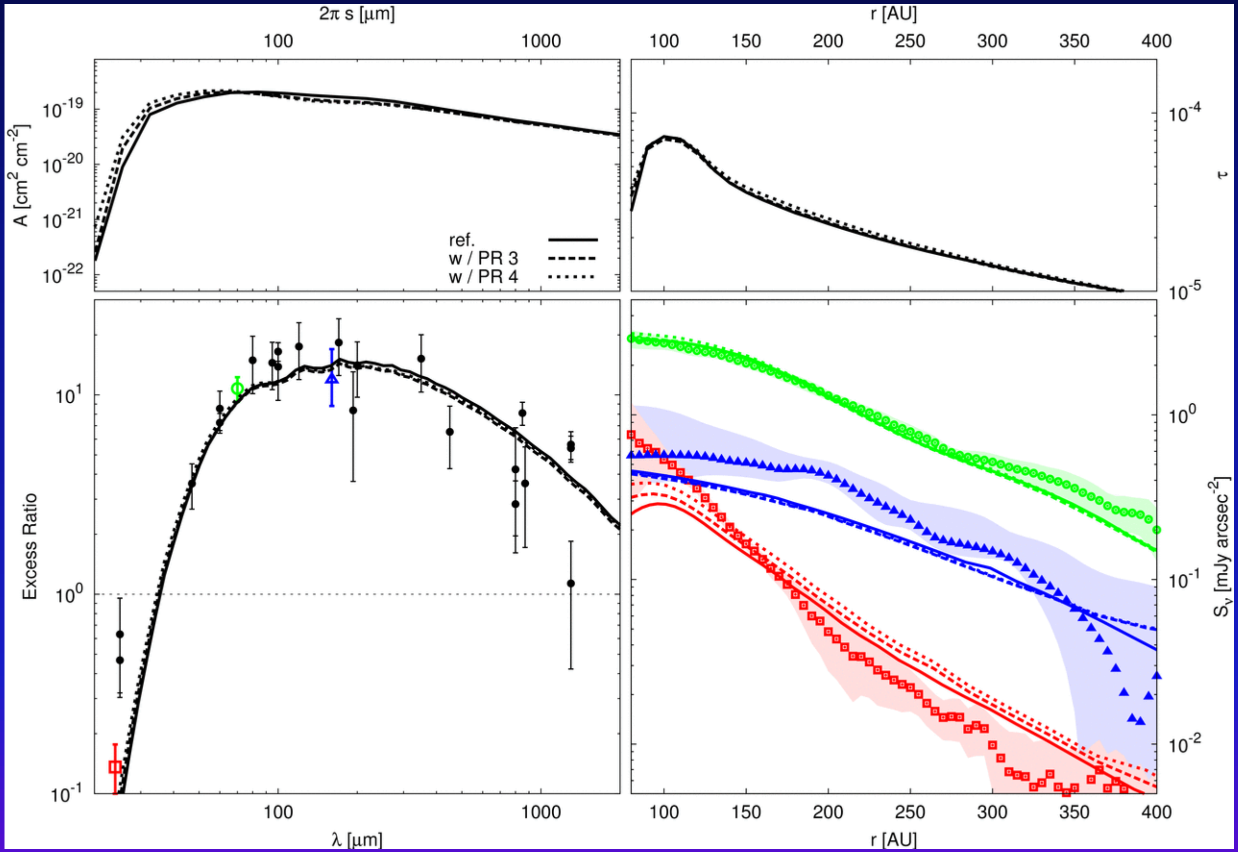



Müller, Löhne, & Krivov, ApJ (submitted)

# The Vega disk: steady-state, naturally

➡ ***Poster by Torsten Löhne***

Summary of the steady-state scenario

- Collisional cascade probably ignited early in the system's history
- Narrow planetesimal ring at ~80…120 AU
  Extended dust disk up to ~500 AU or more (small grains in ell orbits)
- Dynamical excitation probably ~0.1…0.3, origin unconstrained
- Total disk mass ~10 Mearth (in bodies with s<100 km)
- Total mass loss ~2…3 Mearth
- Consistent with reduced stellar luminosity
- Cratering collisions mandatory

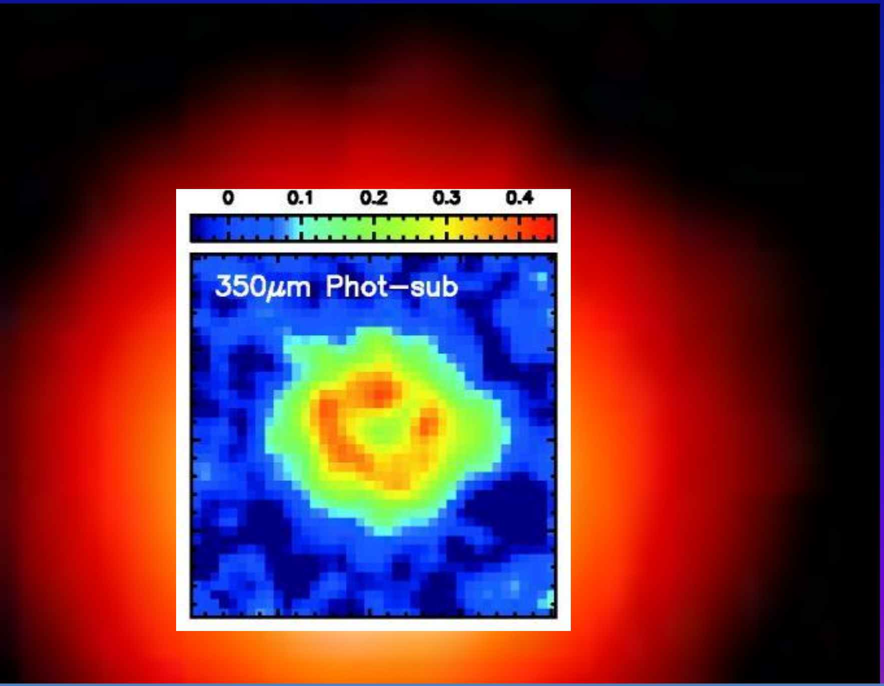
Müller, Löhne, & Krivov, ApJ (submitted)

# Extended disks vs narrow disks

***Yesterday's discussion***

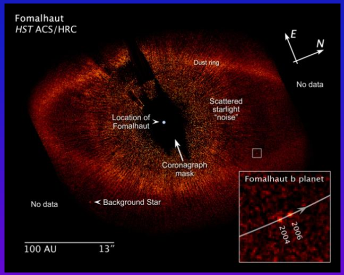
## Extended disks:

- Vega
- β Pic
- HR8799
  (Su et al., ApJ , in press)



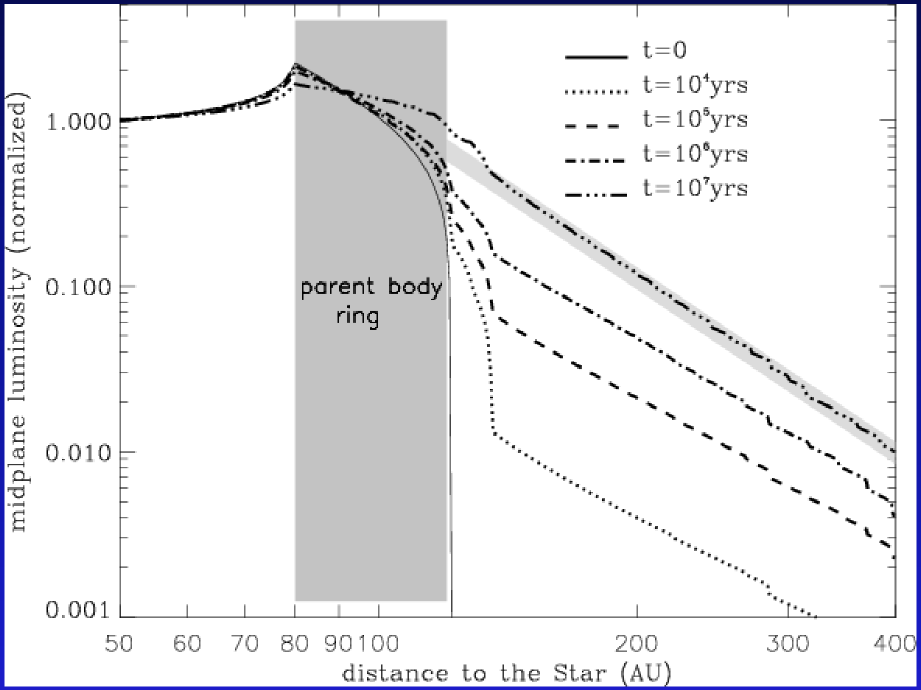

## Narrow disks:

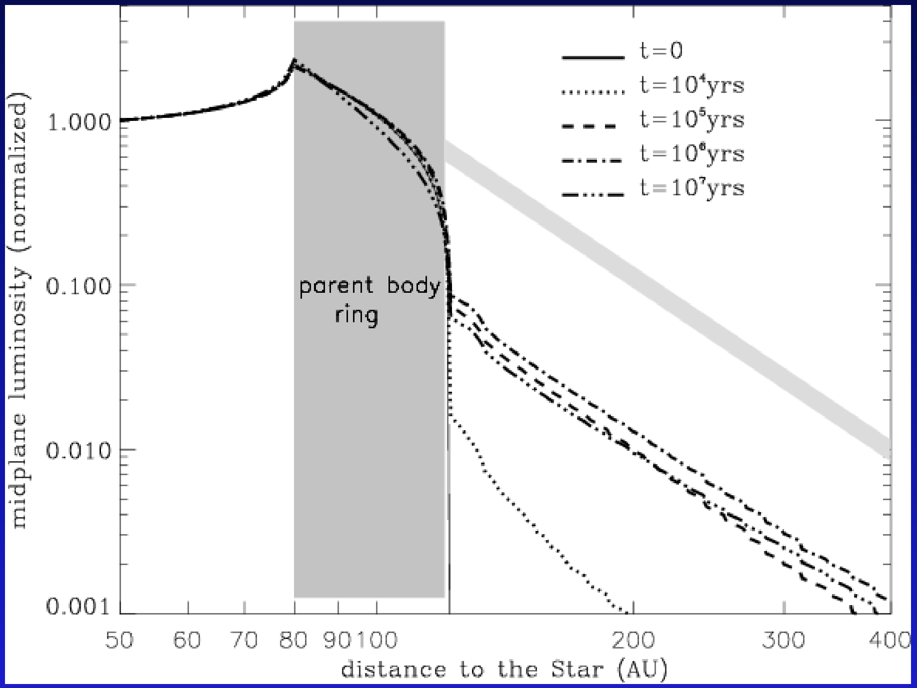
- Fomalhaut
  (Stapelfeldt et al., ApJSS **154**, 458-462, 2004)
- β Leo
  (Stock et al., in prep.)




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

# Radially thick disks and dynamically cold disks




Thébault & Wu, AAp **481**, 713-724 (2008)

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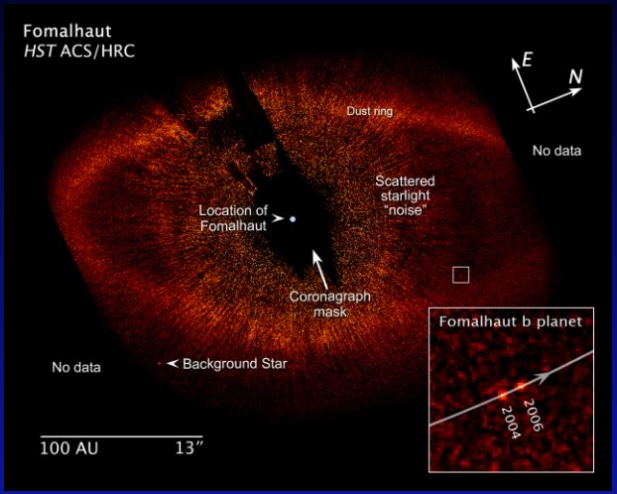
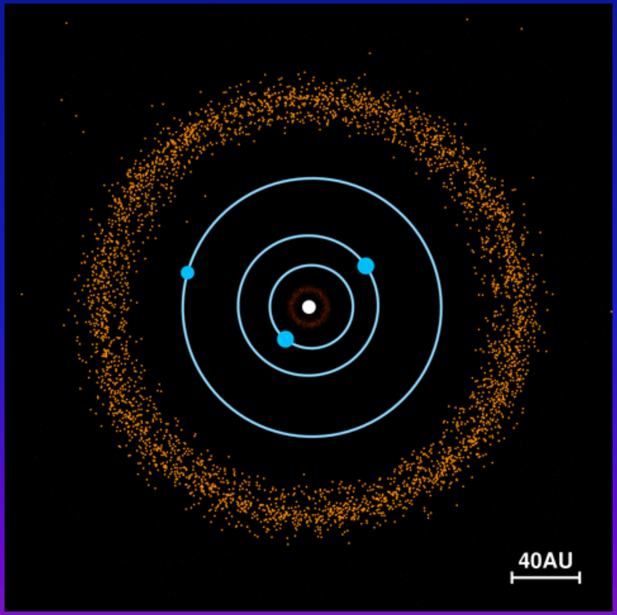
# Planets as a reason for inner gaps in debris disks

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




Marois et al., Science **322**, 1348 (2008)

Reidemeister et al., AAp **503**, 247 (2009)




***Talk by Paul Kalas, yesterday's discussions***

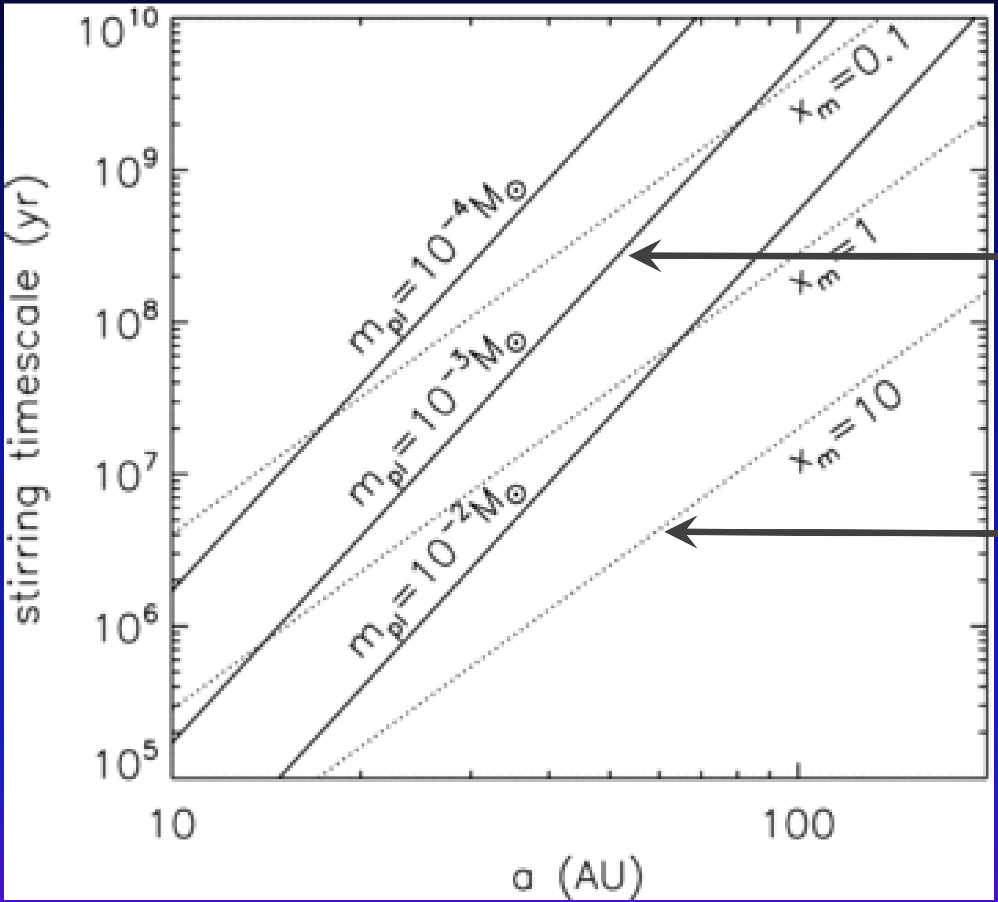
Resolved disks all show inner gaps

SEDs of unresolved disks imply inner gaps, too (lack of warm emission)

Planets are expected in the gap (e.g. Quillen, MNRAS **377**, 1287-1294, 2007), and some were found (Fom, HR8799)

# Secular stirring by planets vs self-stirring

➡ ***Talk by Alex Mustill***

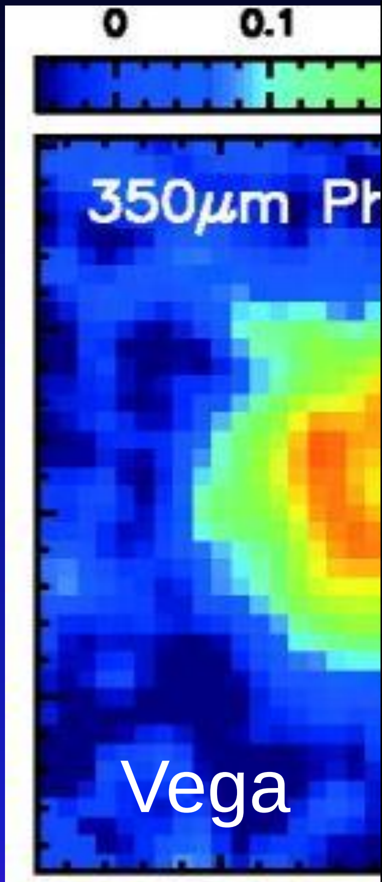



*Secular stirring by a planet*
*with a=5 AU, e=0.1*

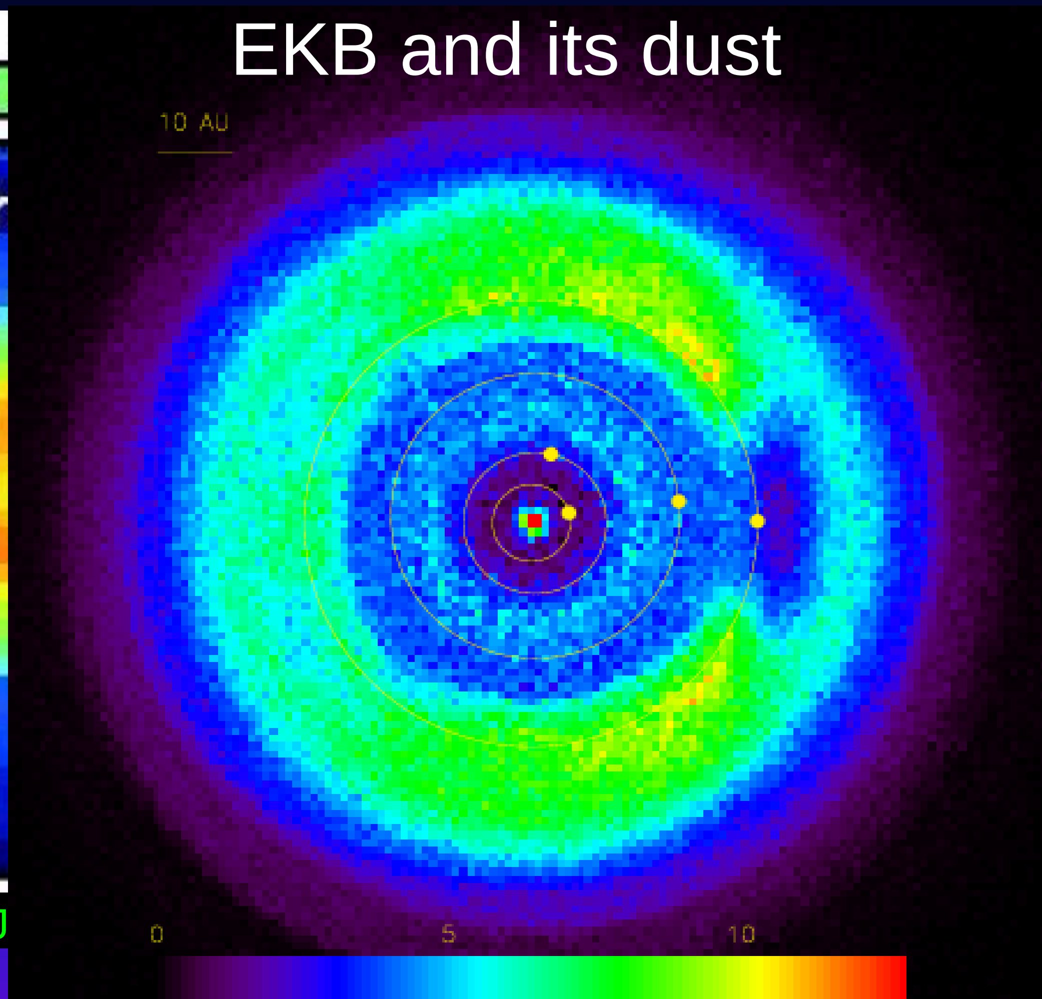
*Self-stirring :*
*time to form Pluto-sized bodies in an ~$x_m$ x MMSN disk*
(Kenyon & Bromley, ApJS **179**, 451, 2008)

Mustill & Wyatt, MNRAS (in press)

# Resonant stirring and clumps




Marsh et al., ApJ




Liou & Zook, AJ **118**, 580 (1999)

Moro-Martín & Malhotra, AJ **124**, 2305 (2002)


L87-L190 (2005)

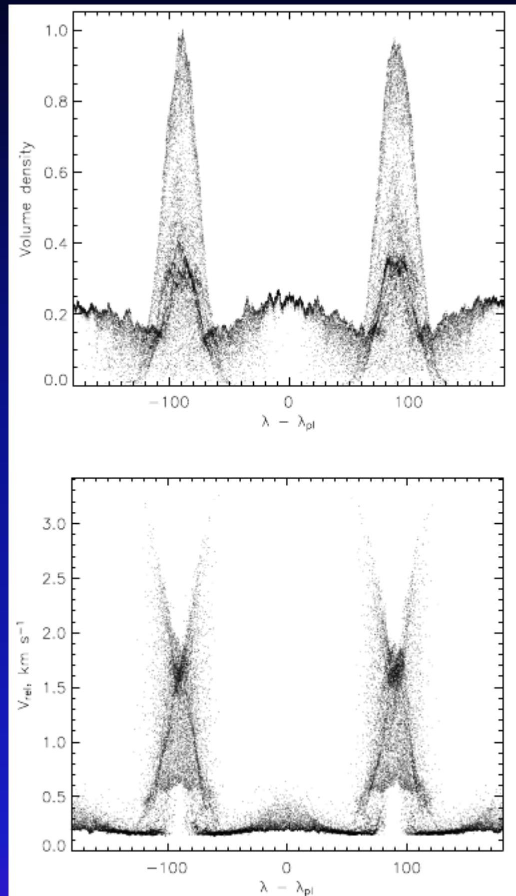
Interpretation: a

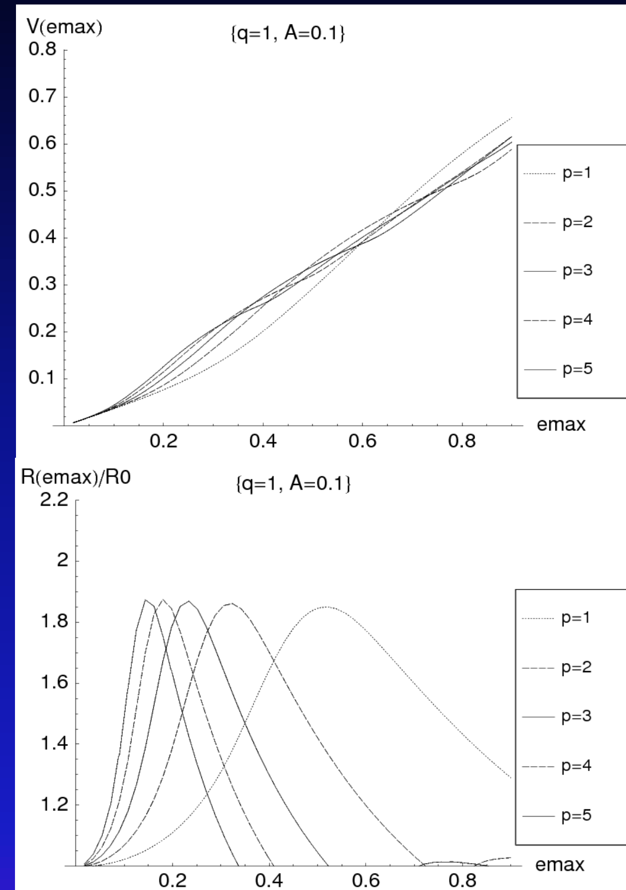
in resonances

# Resonant stirring and clumps

*Collisional velocities*

*Collisional rates*




*in the clumps:*
*substantially higher*

*in the entire belt:*
*only slightly higher*

Wyatt, ApJ **639**, 1153-1165 (2003)

Queck et al., Cel.Mech. **99**, 169-196 (2007)

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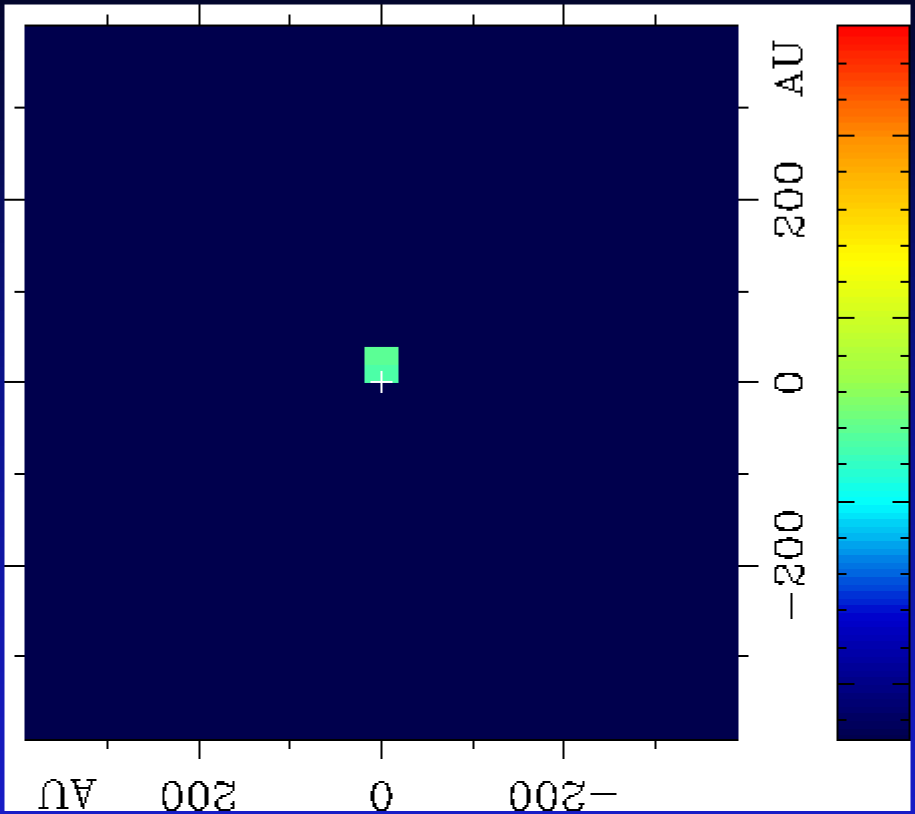
# Intrinsic stochasticity, major breakups, avalanches



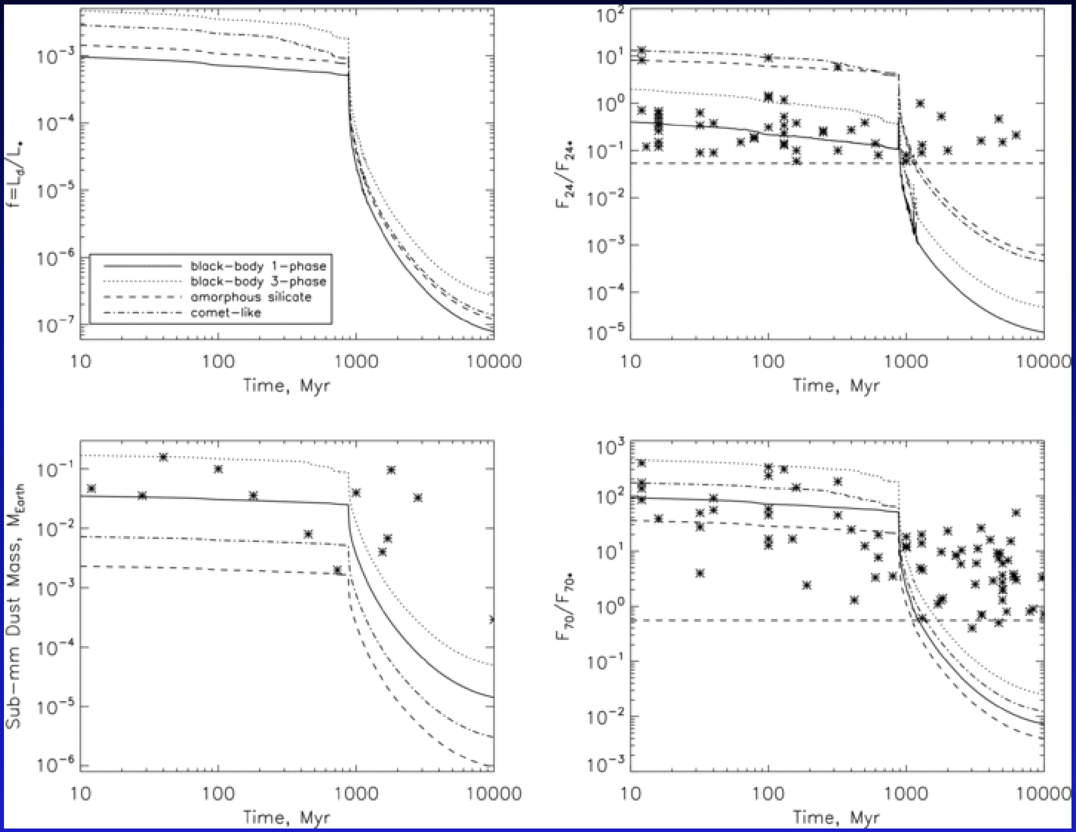

Grigorieva,Thébault, & Artymowicz,
AAp **461,** 537-549 (2007)

Major collisions are rare

Their effect is just a short-lasting pertubation of a steady-state evolution

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

# Planetary shake-downs




Booth et al., MNRAS **399,** 385-398 (2009)

***Talk by Mark Booth***

Apart from a short-lasting rise of warm emission, an LHB-like event is effectively a transition from one steady state to another

- Modeled the solar system debris disk in the Nice model
- A pre-LHB solar system ‘s debris disk would be among the brightest sources
- A post-LHB disk is far below the detection limits

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- Steady-state evolution: link to planets
- Short-term evolution
- Long-term evolution
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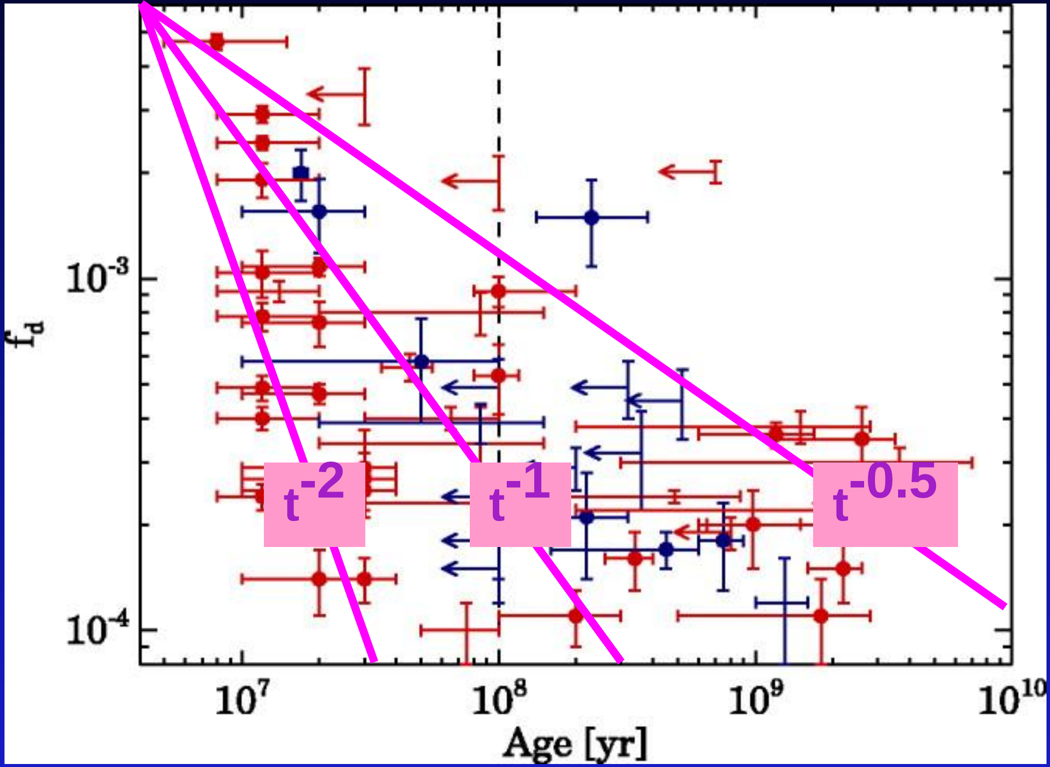
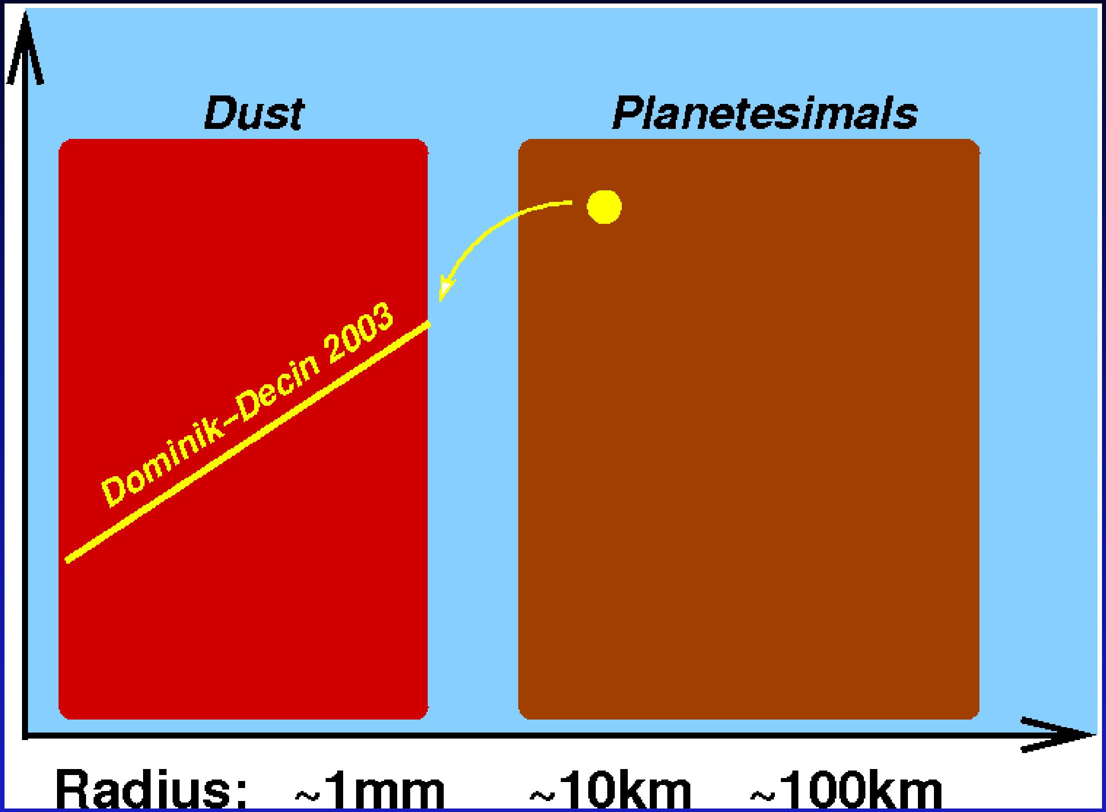
# Statistics of debris disks: a long-term decay




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

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

# Steady-state models




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

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

# Steady-state models

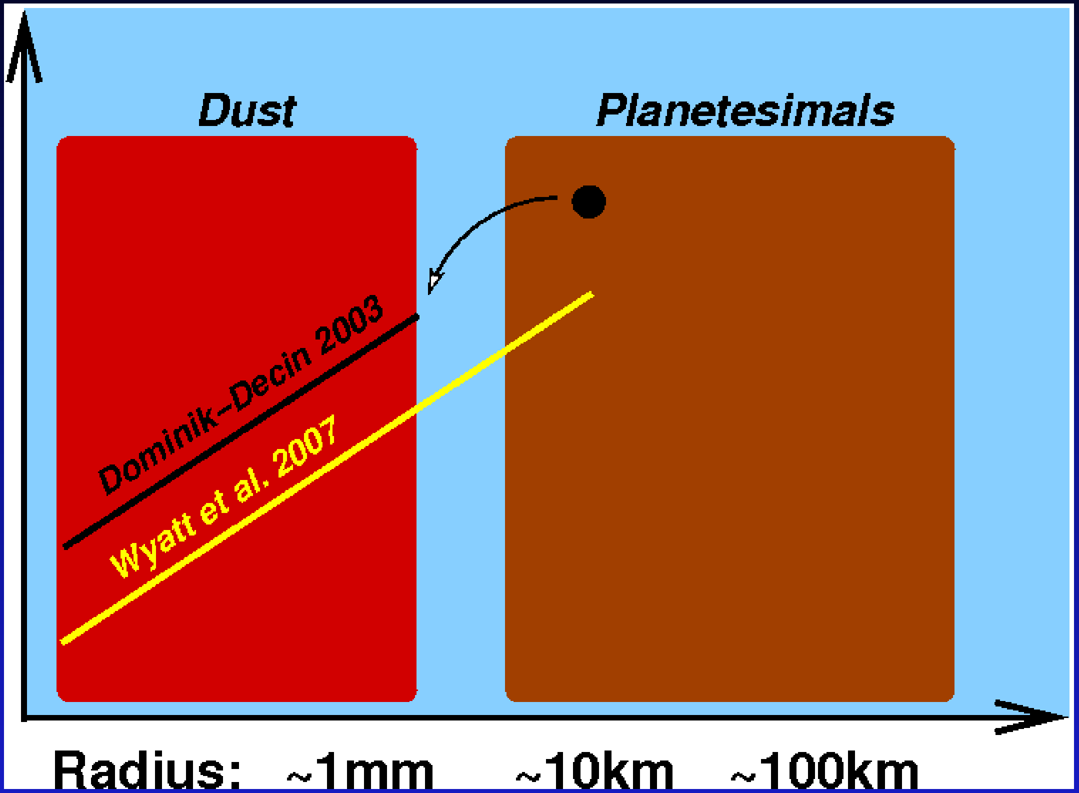
$$\frac{dM_{\rm disk}}{dt} = -\frac{M_{\rm disk}^2}{M_0 \tau}$$

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

- For collision-dominated disks, total disk mass ~ dust mass ~ t $^{-1}$
- For transport-dominated disks, total disk mass ~ dust mass ~ t $^{-2}$

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

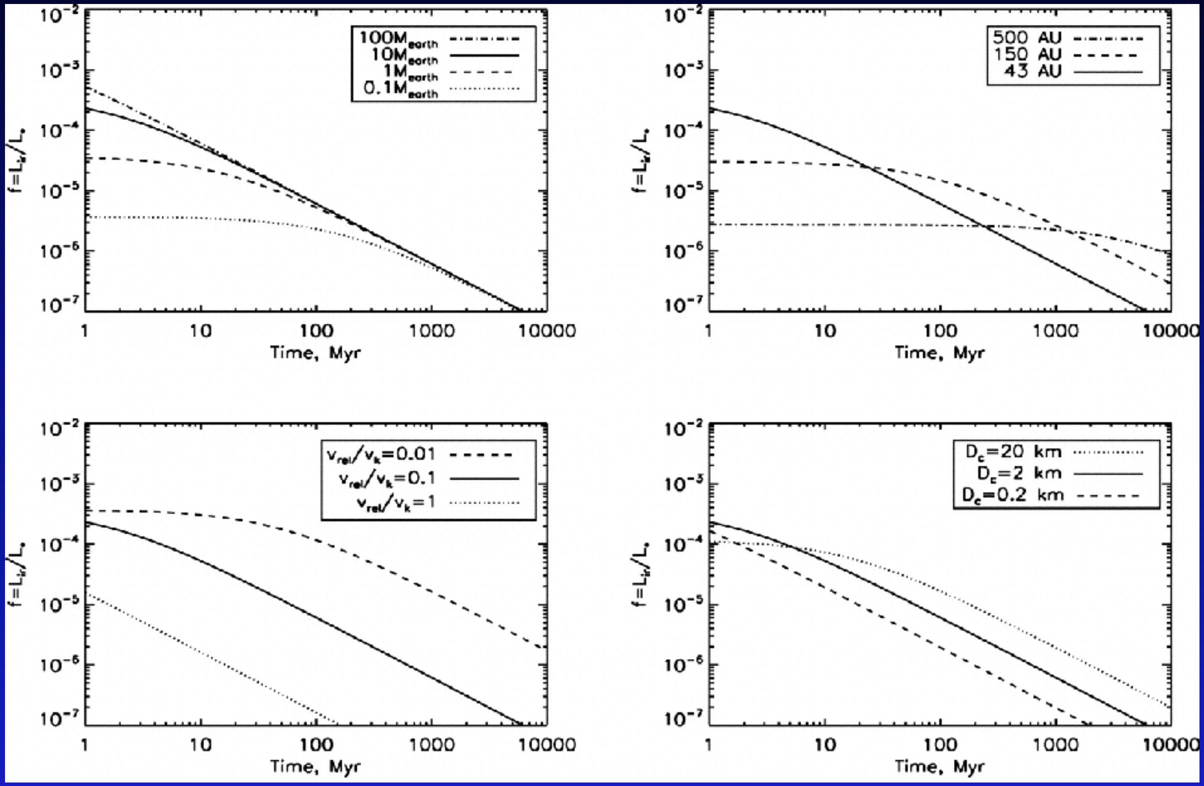
# Steady-state models




$Q_D$* assumed to be a single power-law
Collisional equilibrium assumed at all sizes

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

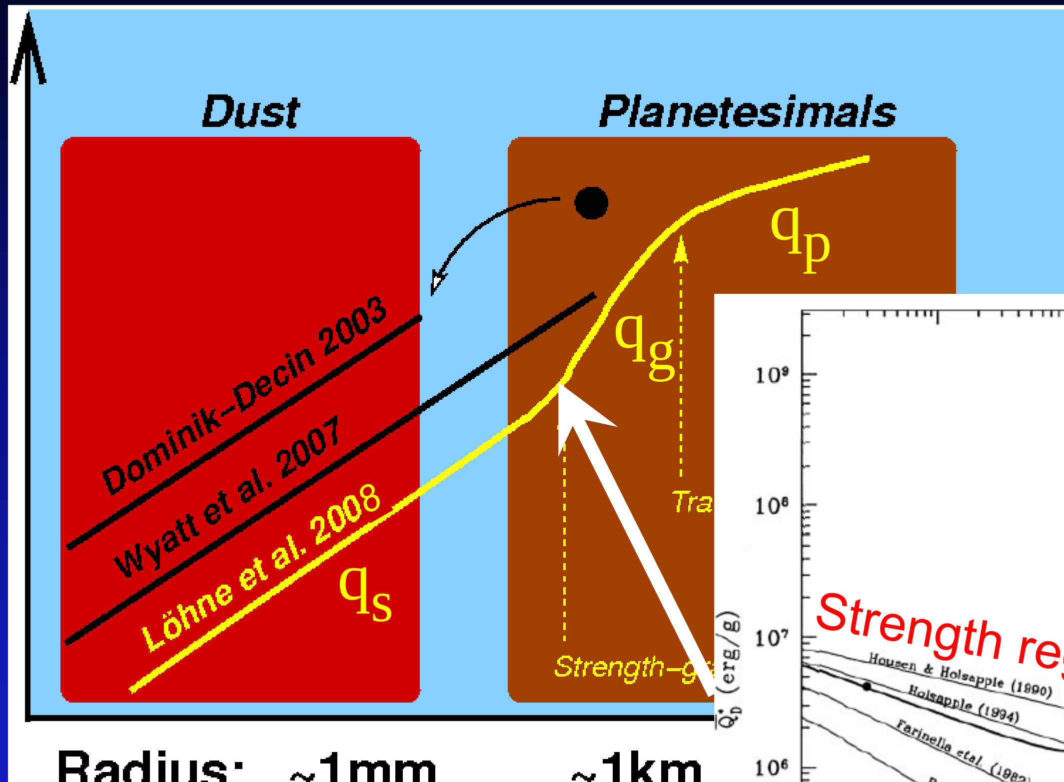
# Steady-state models

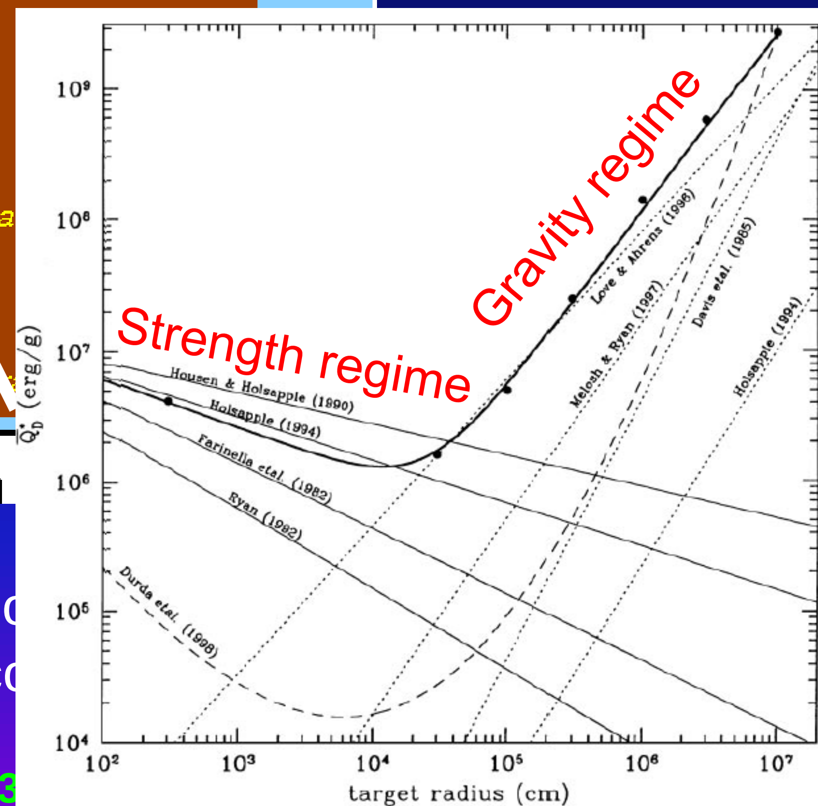



- For any given age, there is a maximum possible amount of dust
- Disk evolution depends on r, e, I, $D_c$

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

# Non-steady-state models




Strength-gravity transitio

Large planetesimals are not in co

Löhne, Krivov, & Rodmann, ApJ **673**

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

# Non-steady-state models

**Total disk mass**

$$M_{\rm disk}(t) \approx \frac{M_0}{1+t/\tau_{\rm max}} \left[1 - \left(\frac{s_{\rm min}}{s_{\rm max}}\right)^{6-3q_{\rm p}}\right]^{-1} \times \left[1 - \left(\frac{s_{\rm b}}{s_{\rm max}}\right)^{6-3q_{\rm p}} \cdot \left(\frac{t}{\tau_{\rm b}}\right)^{\frac{2-q_{\rm p}}{q_{\rm p}-5/3+(q_{\rm p}-1)b}} \times \left(1 - \frac{2-q_{\rm p}}{2-q_{\rm g}}\right)\right]$$

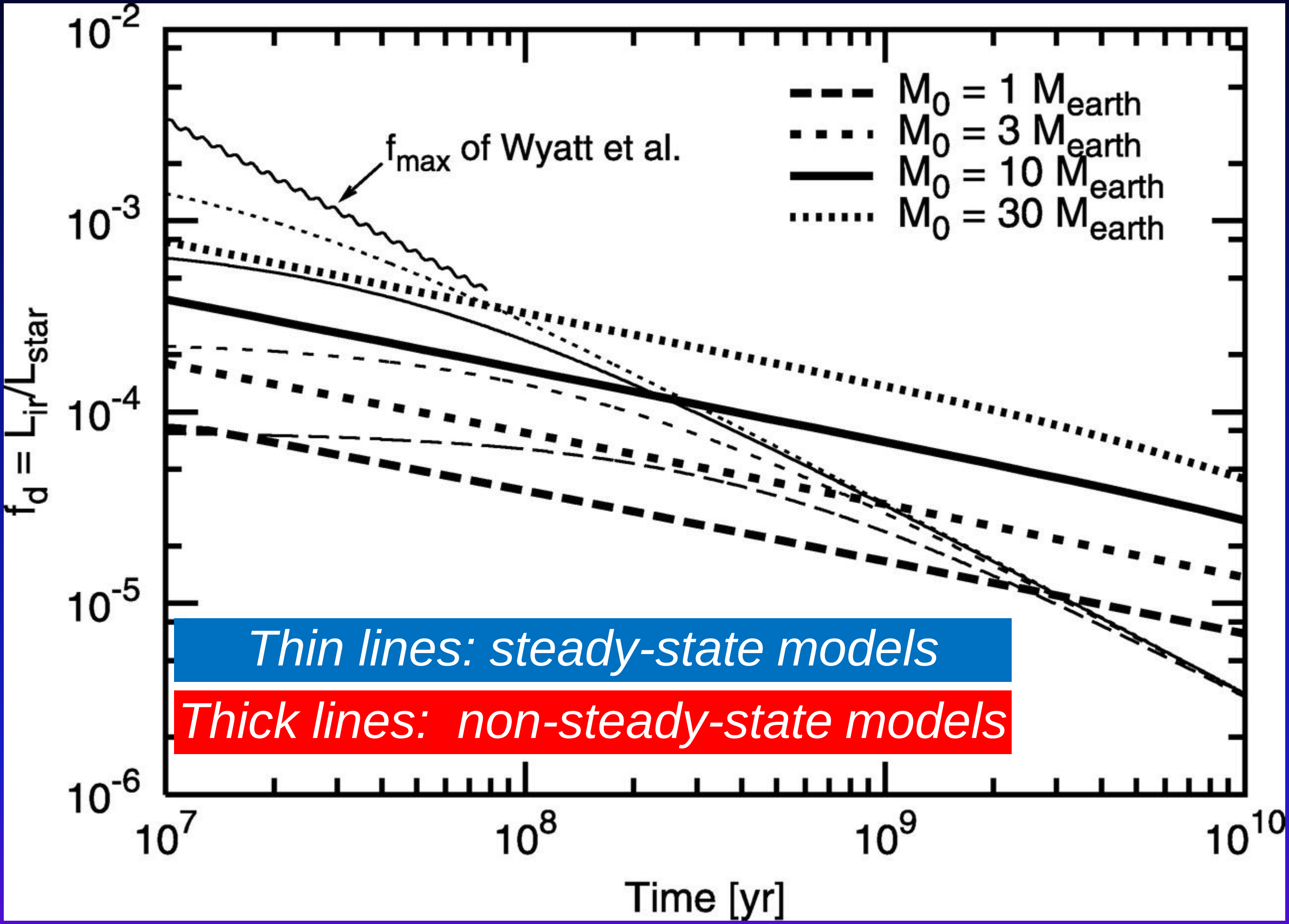
*Steady-state models*

**Dust mass**

$$M_{\rm dust}(t) = \frac{M_0}{1+t/\tau_{\rm max}} \cdot \left(\frac{t}{\tau_{\rm b}}\right)^{\frac{q_{\rm g}-q_{\rm p}}{q_{\rm p}-5/3+(q_{\rm p}-1)b_{\rm g}}} \cdot \frac{2-q_{\rm p}}{2-q_{\rm s}} \times \left(\frac{s_{\rm b}}{s_{\rm max}}\right)^{2-q_{\rm p}} \left[\left(\frac{s_{\rm d}}{s_{\rm b}}\right)^{2-q_{\rm s}} - \left(\frac{s_{\rm min}}{s_{\rm b}}\right)^{2-q_{\rm s}}\right]^{-1}$$

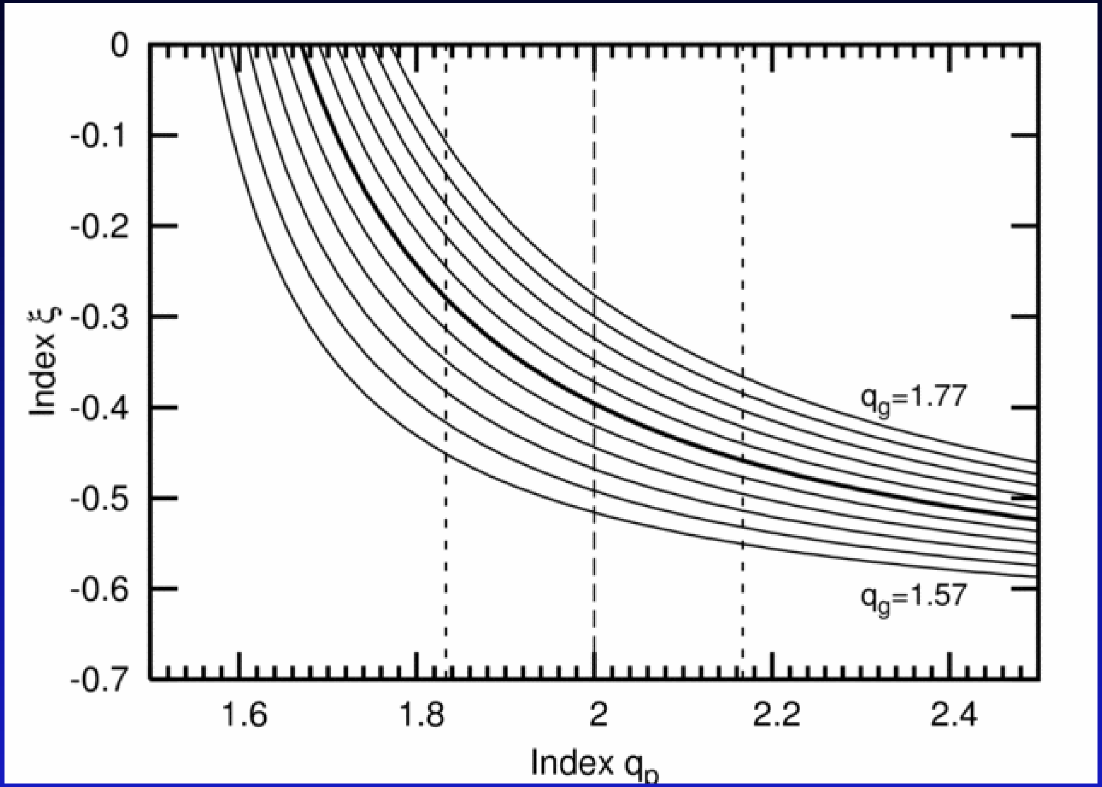
The total disk mass and the dust mass follow different laws

# Non-steady-state models




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

# Non-steady-state models




• The dust mass decays as ~**t** $^{\xi}$

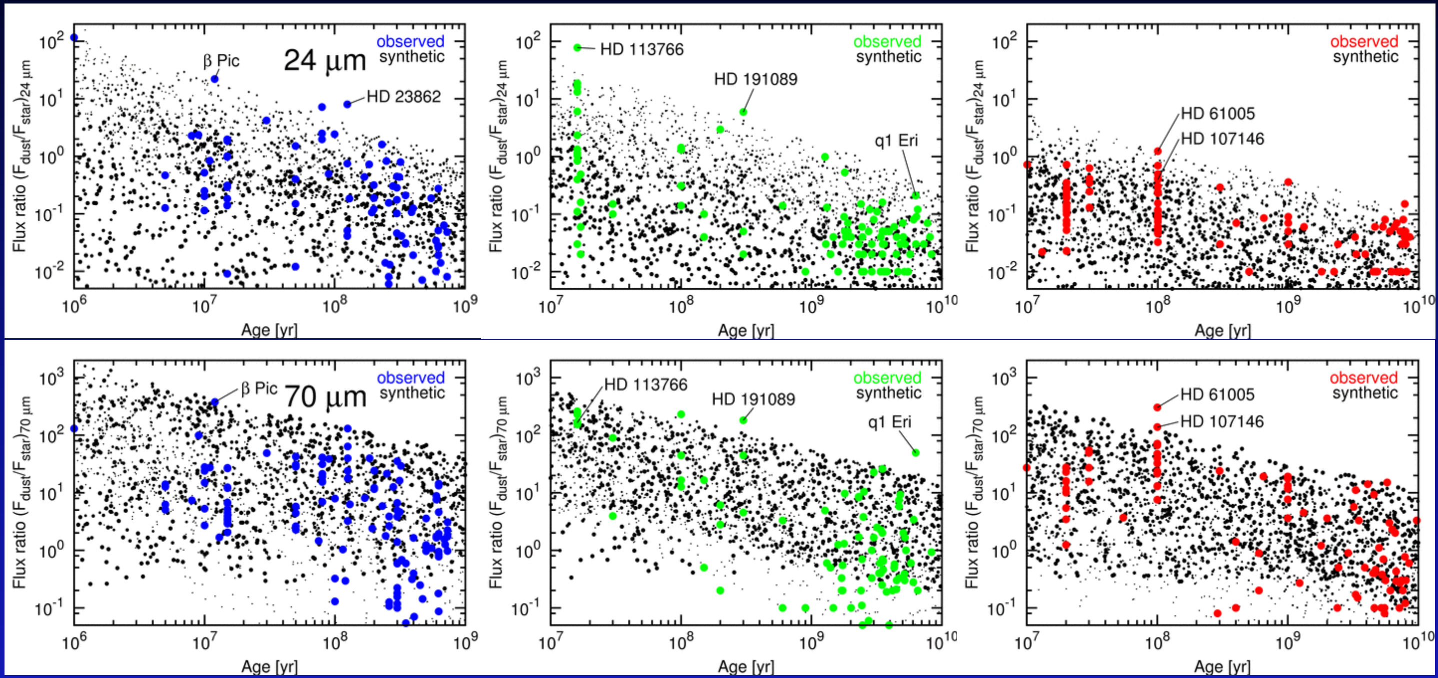
• Index $\xi$ depends on the "primordial" size distribution of planetesimals

•Typical values: $\xi$ ~ -0.3...-0.4 and not -1

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

# Synthetic populations vs observations

Löhne et al.
(in prep.)




| | | | |
|---|---|---|---|
| Min radius, AU | 5 | 5 | 5 |
| Max radius, AU | 180 | 140 | 130 |
| Min mass, $M_{earth}$ | 0.03 | 0.03 | 0.03 |
| Max mass, $M_{earth}$ | 25 | 250 | 250 |
| Largest body, km | 25 | 150 | 300 |

# Outline

- Introduction
- Basic physics and modeling methods
- Steady-state evolution: theory
- Steady-state evolution: observations
- Steady-state evolution: link to planets
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# Summary

- Debris disks consist  of solids from planetesimals to dust. All solids are subject to stellar gravity and collisions. At  dust sizes, also radiation pressure is important
- Steady-state evolution of debris disks is well understood, and is consistent with many debris disks currently observed
- Short-term evolution may be determined by one-time events (major breakups, planetary shake-downs, …) that may interrupt or re-shape steady-state evolution
- Long-term evolution is determined by collisional equilibrium at smaller sizes (<10…100km) and a lack thereof at larger sizes
- Debris disks can (and should!)  be used to constrain properties of  planetesimals and their accretion history
- Debris disks can serve as tracers of planets and place constraints on their formation and migration history