Collisional Modeling of Debris Disks

Alexander “Sasha” Krivov,
Torsten Löhne,
Hiroshi Kobayashi,
Sebastian Müller,
Martin Reidemeister,
Christian Vitense,
and the Herschel / DUNES team

Outline

- Ideas, methods, codes
- Application to Vega
- Application to q^1 Eridani
- Application to ε Eridani
- Application to the Kuiper belt
- Application to “cold debris disks”
- Problems and unknowns

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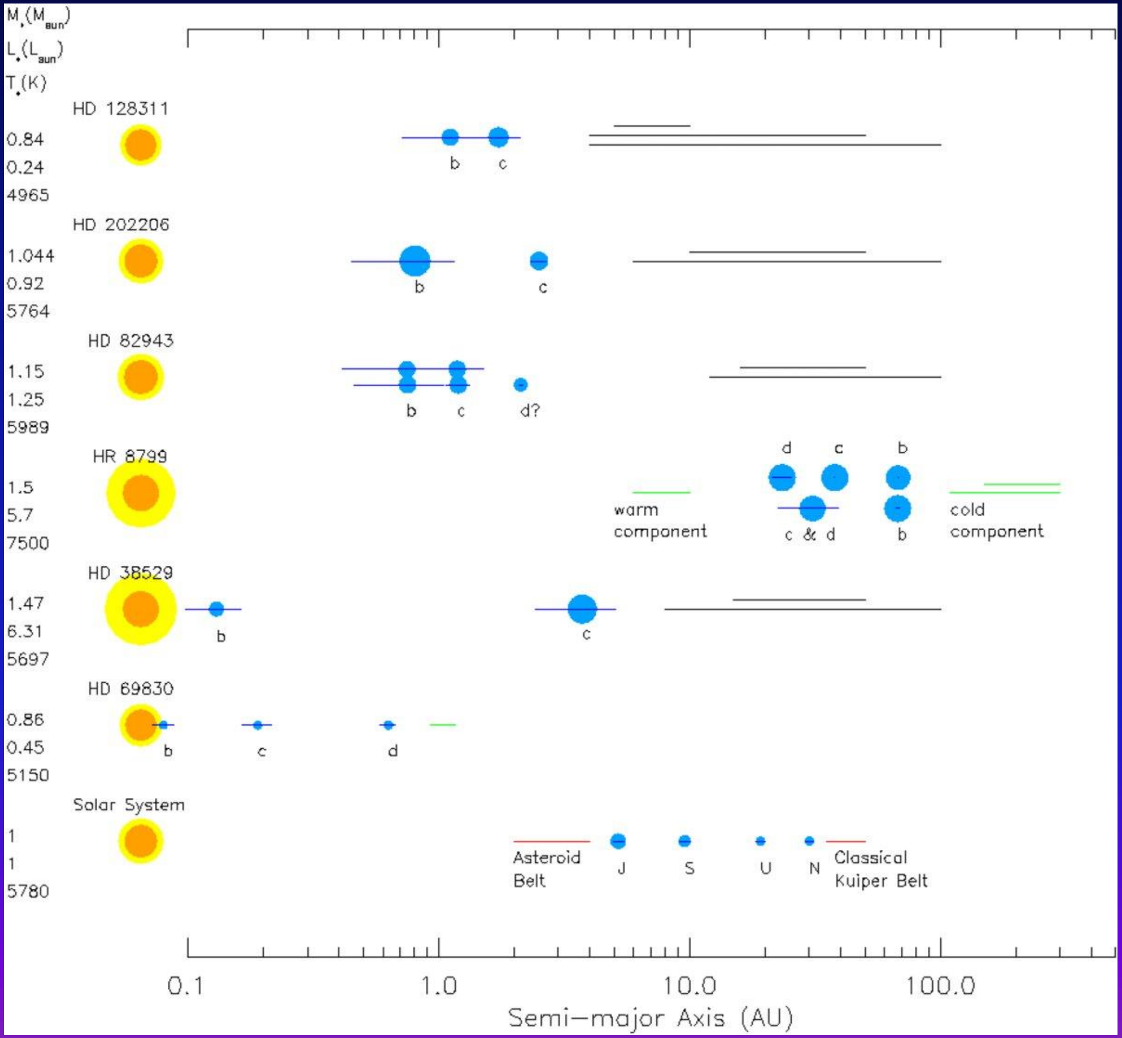
Debris disks in planetary systems

Debris disks co-exist with planets



*Moro-Martín et al., ApJ **717**, 1123-1139 (2010)*

Debris disks in planetary systems

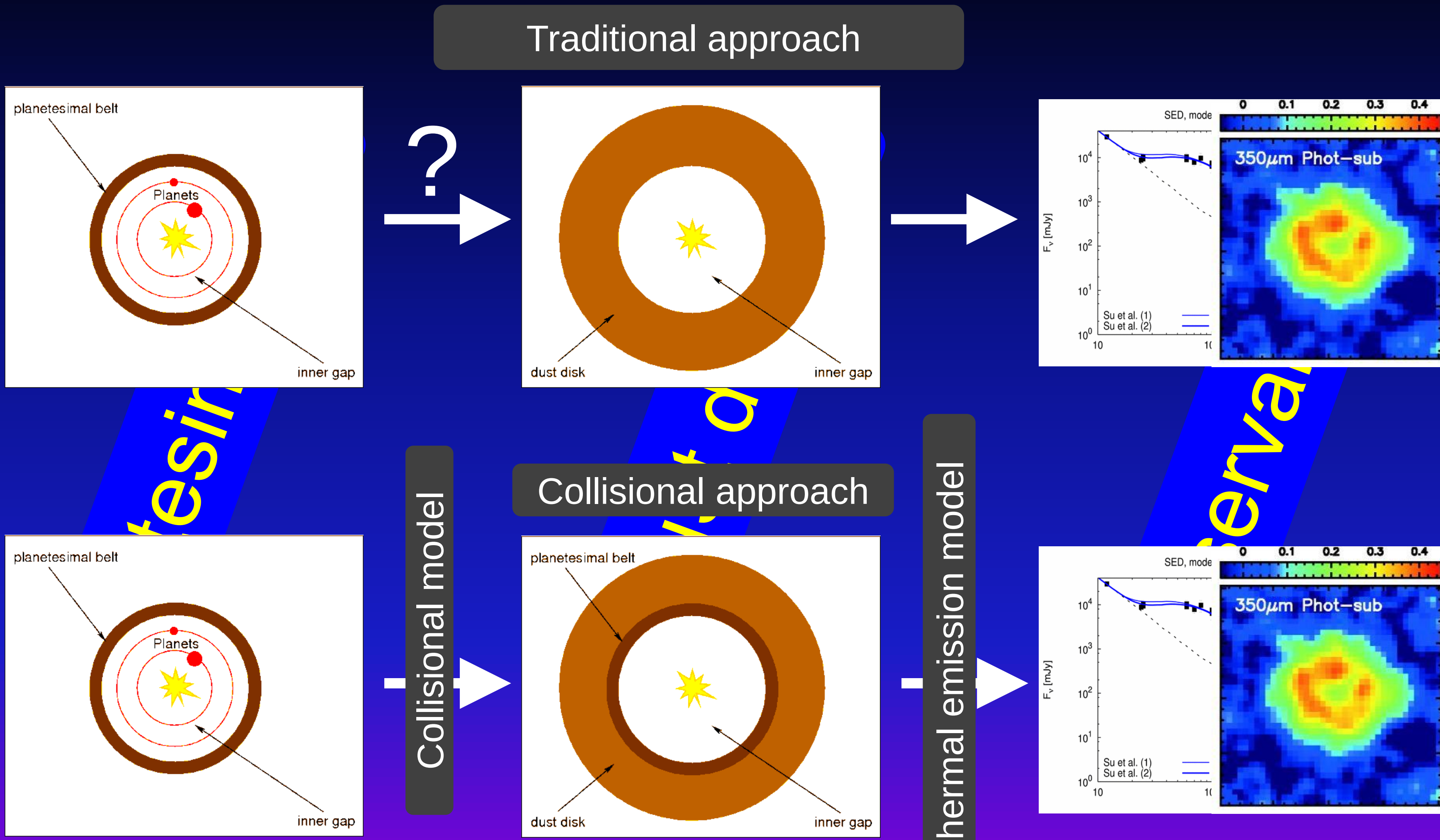
Debris disks are very common

Spitzer: ~15%

Herschel/DUNES: ~30%

	F-type	G-type	K-type	Total
	11	21	18	50
Non-excess	5	13	12	30
Excess (New)	6 (1)	7 (3)	4 (4)	17 (8)
Resolved (New)	3 (2)	4 (3)	1 (1)	8 (6)
Cold discs	1	3	4	8

Two approaches to debris disk modeling



Krivov, Müller, Löhne, & Mutschke, ApJ ***687****, 608-622 (2008)*

Collisional code: ACE

Initial planetesimal belt → 

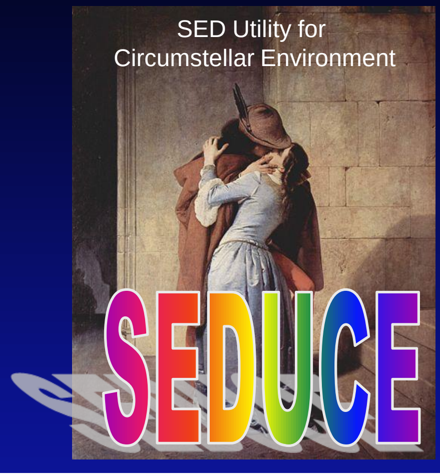
→ Debris disk at subsequent time instants

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

Krivov & Sremčević (2003-2004), Löhne (2005-2010)

Thermal emission codes: SEDUCE & SUBITO

Size and spatial distribution of dust, its optical properties



SED

radial brightness profile

Features:
- NextGen stellar photosphere models
- Mie calculations for arbitrary (n,k)
- Thermal emission (no scattered light)

Müller (2007-2010)

Input and output

Model parameters

Star:	stellar mass	M_*
	stellar luminosity	L_*
	stellar age	t_*
Planetesimal belt:	initial mass	M_0
	location	r
	width	dr
	excitation	$\langle e \rangle, \langle i \rangle$
All solids:	bulk density	
	mechanical properties	
	optical properties	
Collisions:	critical fragmentation energy	
	fragments' size distribution	
	cratering efficiency	

usually known (fixed)
sometimes known
unknown (free)

→

Observables

SED

Brightness profiles in different colors

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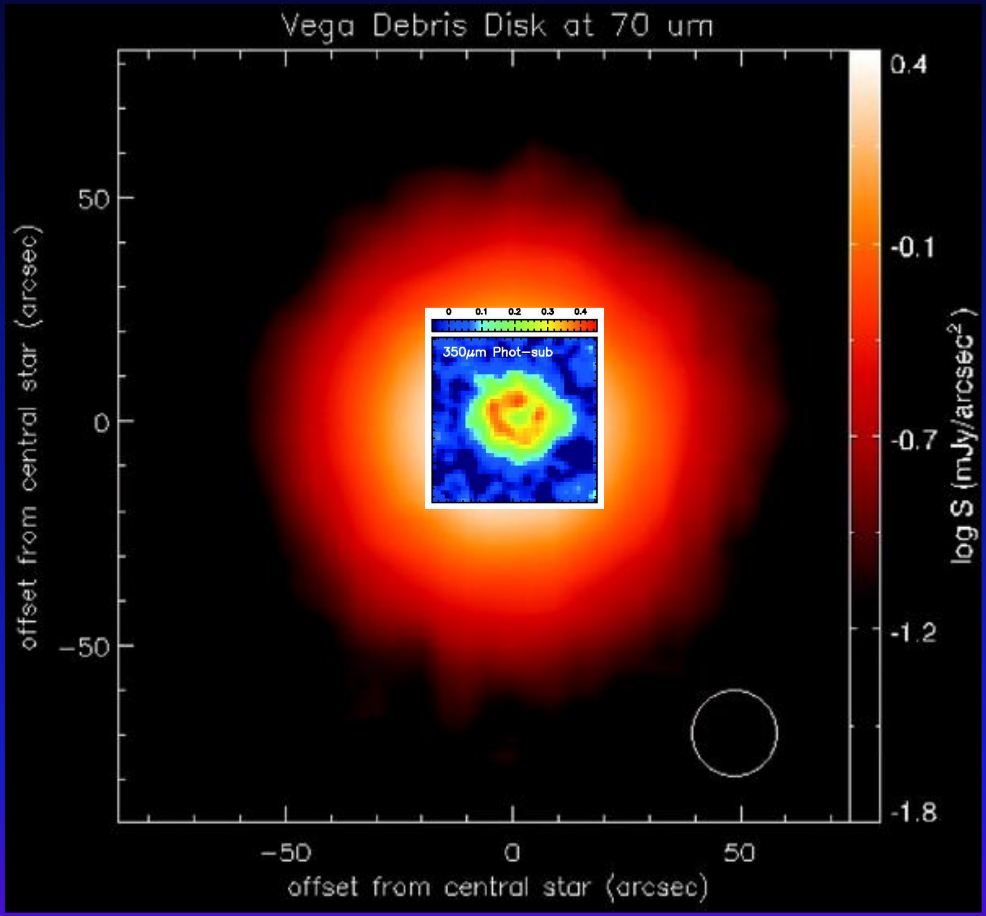
The Vega disk: of transient nature?



Sub-mm observations:
a clumpy ring at ~100 AU
Marsh et al.(2006)

Spitzer/MIPS mid- to far-IR:
an extended disk ~800 AU
Su et al.(2005)

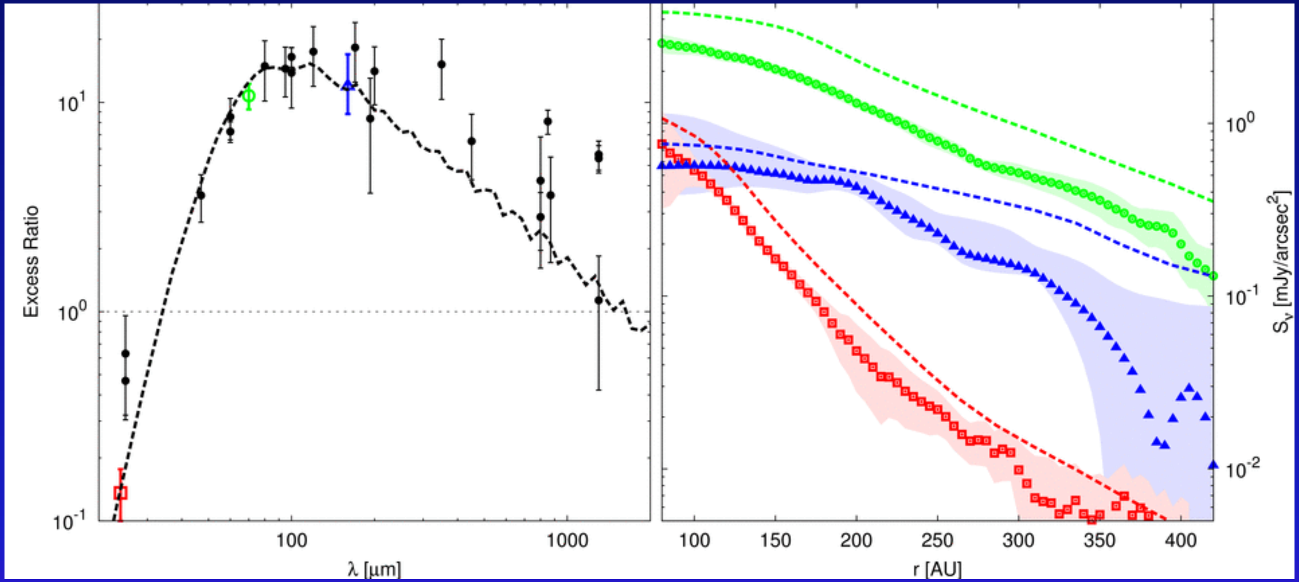
Argued that the disk must be composed of blowout grains and must have an exceptional nature: recent major collision?

Su et al., ApJ **628,** *487-500 (2005)*
Marsh et al., ApJ **646**, *L77-L80 (2006)*

The Vega disk: steady-state, naturally

The first-guess model

- 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 ***708****, 1728-1747 (2010)*

The Vega disk: steady-state, naturally

The best-fit model

- First-guess model
- "Collisional age"
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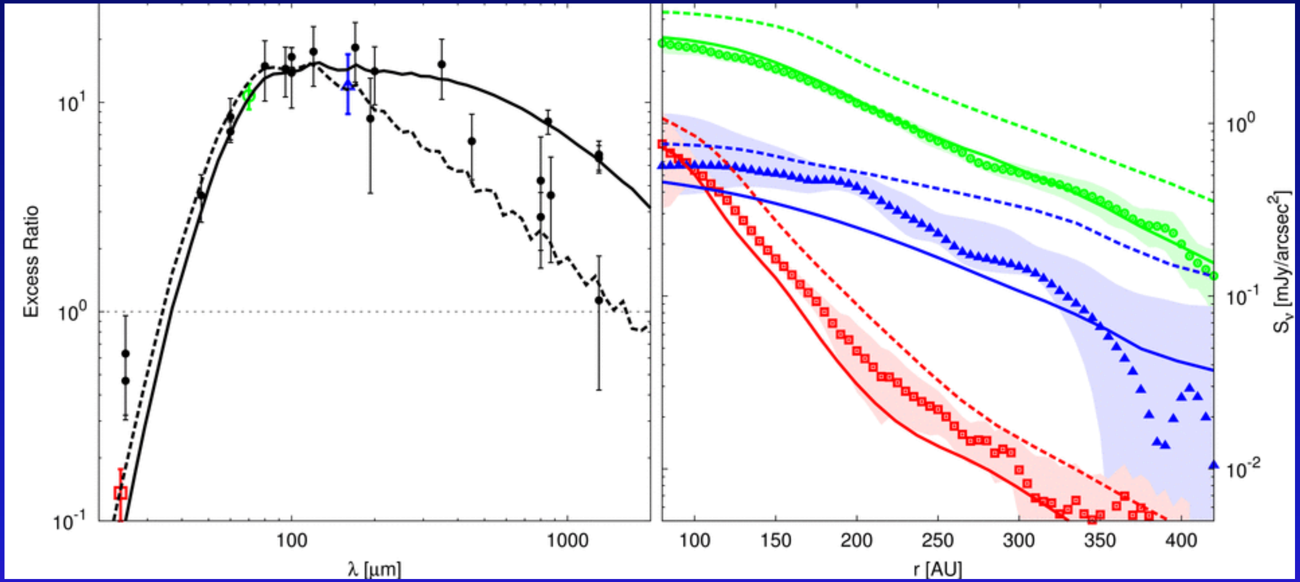

Müller, Löhne, & Krivov, ApJ ***708****, 1728-1747 (2010)*

The Vega disk: conclusions

- **The Vega disk is consistent with a steady-state collisional cascade**
- **Cascade probably ignited early in the system's history**
- **Stems from ring of planetesimals at ~80…120 AU**

  Dynamical excitation probably ~0.1…0.3
- **Total disk mass ~10 $M_{\oplus}$ (in <100 km-sized bodies)**
- **Total mass loss over system's age ~2…3 $M_{\oplus}$**
- **Consistent with reduced stellar luminosity**
- **Cratering collisions mandatory**

Müller, Löhne, & Krivov, ApJ ***708****, 1728-1747 (2010)*

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q^1 Eri before Herschel

STAR

- Spectral type: F8
- Distance: 17.4 pc
- Age : ~ 2 Gyr

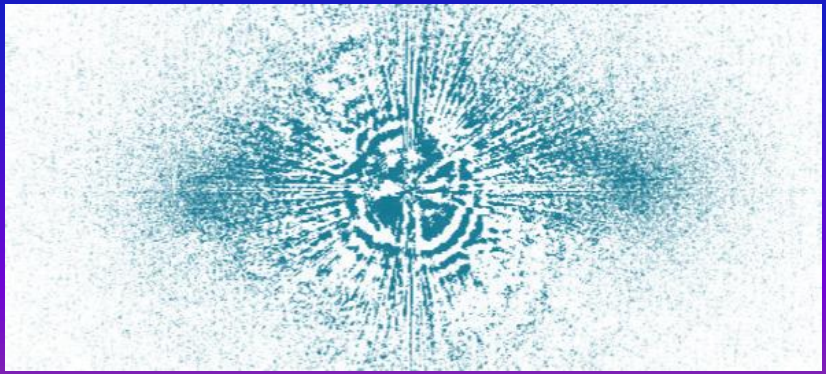
JUPITER-MASS PLANET

- M sin i: 0.9 M_{Jup}
- Semi-major axis: 2.0 AU
- Eccentricity : 0.1

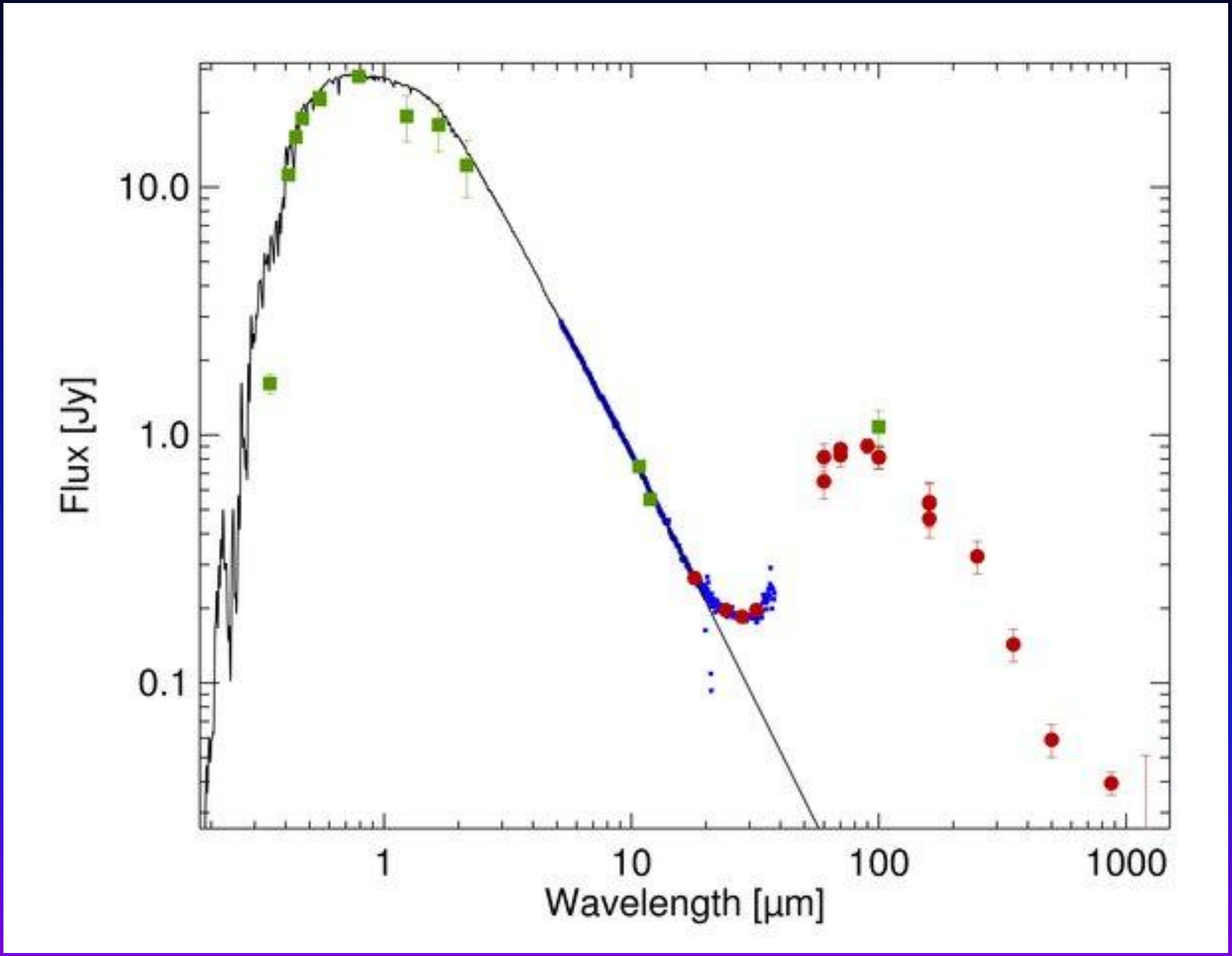
Mayor et al. 2003, Butler et al. 2006

KUIPER-LIKE BELT

- IRAS, ISO, Spitzer, AKARI: cold dust, with a luminosity 1000 times that of the Kuiper Belt
- Sub-mm APEX/LABOCA images: disk extent is up to several tens of arcsec *(Liseau et al. 2008)*
- HST images suggest a peak at 83AU *(Stapelfeldt et al. 2010)*

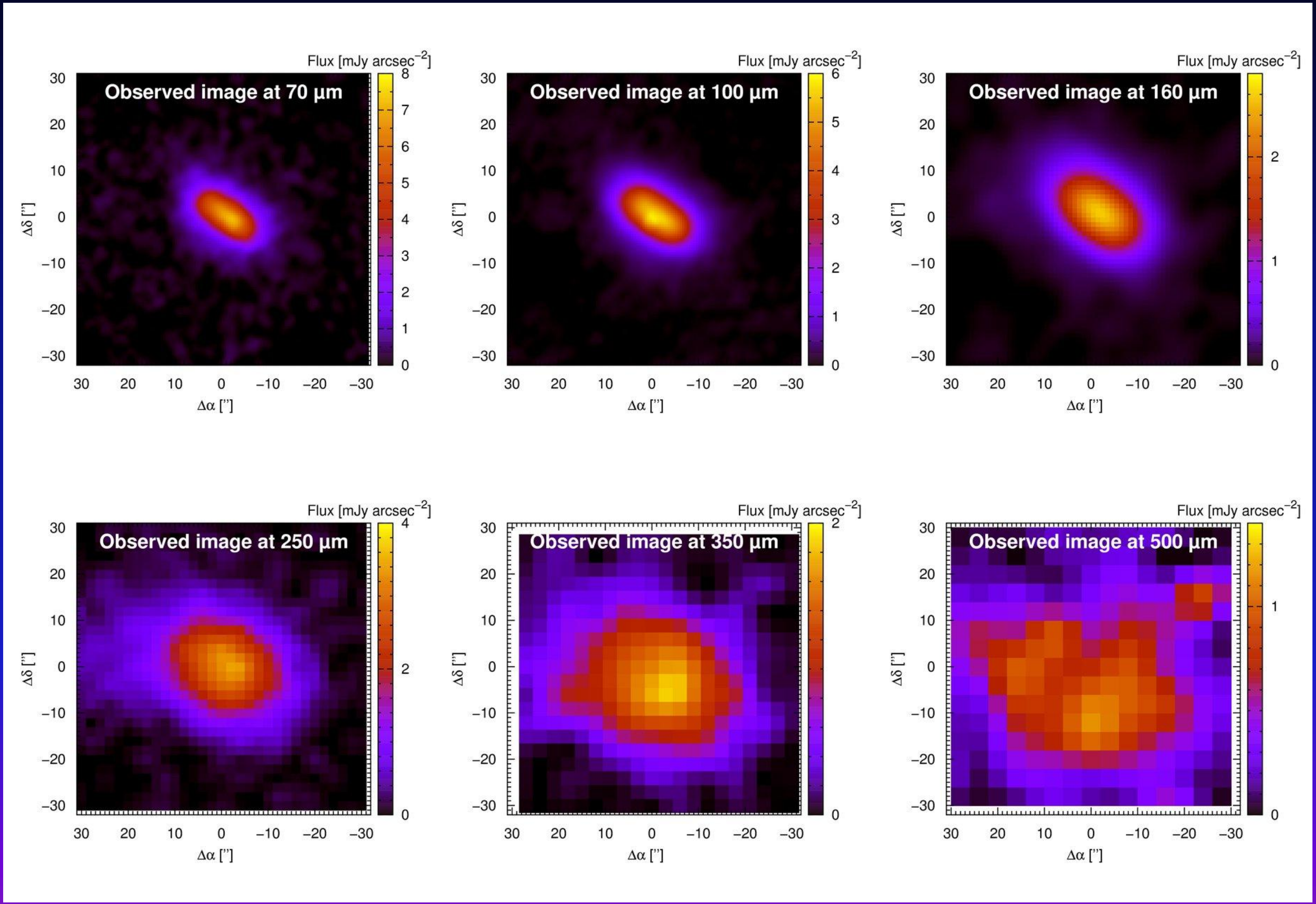


q^1 Eri: Herschel data



Liseau et al., AAp **518,** *L132 (2010)*

q^1 Eri: Herschel data

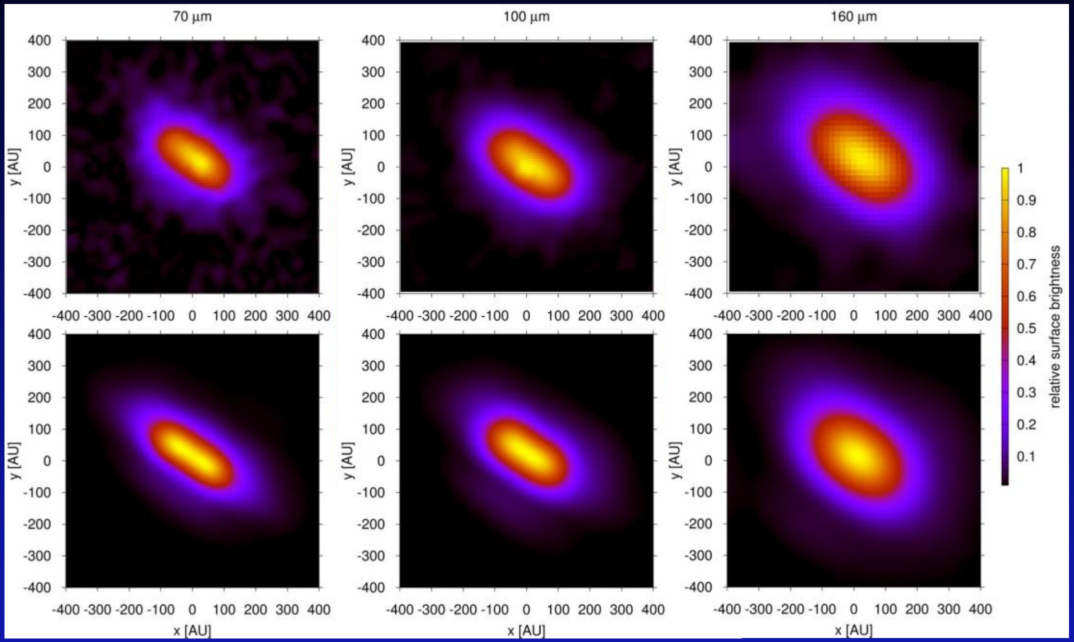


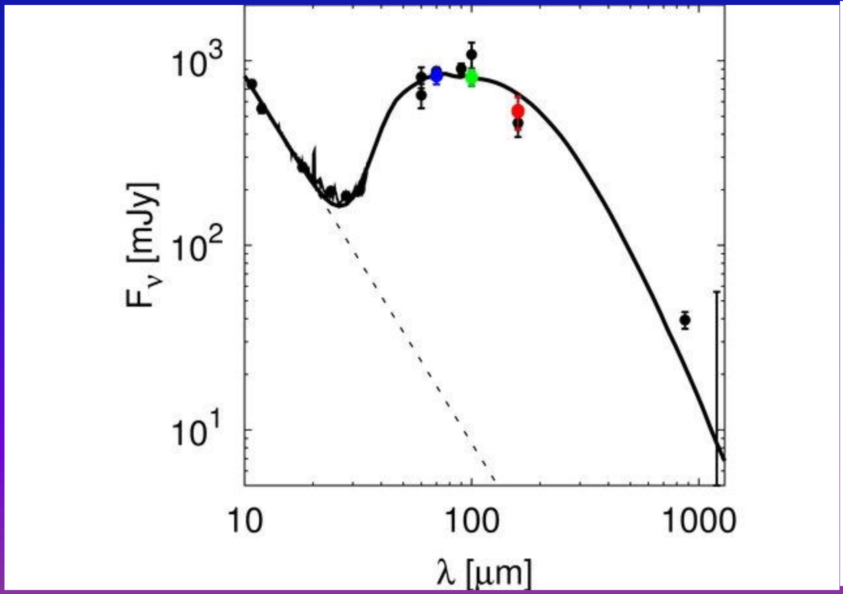
Liseau et al., AAp **518,** *L132 (2010)*

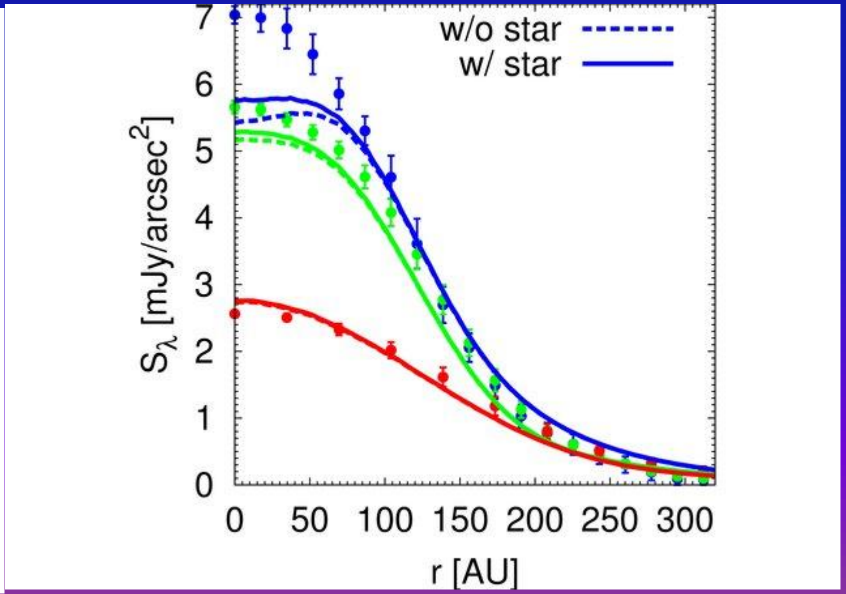
q¹ Eri: modeling results

Observed images

Synthetic images







q^1 Eri: conclusions

Dust disk & grain properties:

- **Mass : 0.02 M_{earth}**
- **Possible hints for ice: best fit with 50-50 silicate-ice mixture**
- **Possible hints for material strength: weaker dust (Q_D*~10^7erg/g)**

Parent belt:

- **Location: 75-125 AU**
- **Eccentricities: 0.0…0.1**
- **Mass : ~1000 M_{earth} (if 2 Gyr), but ~100 M_{earth} (if 0.5Gyr)**
- **Probing collisional history: support to delayed stirring (self-stirring by Plutos, stirring by q^1Eri c, or even q^1Eri b)**

Augereau et al., in prep.

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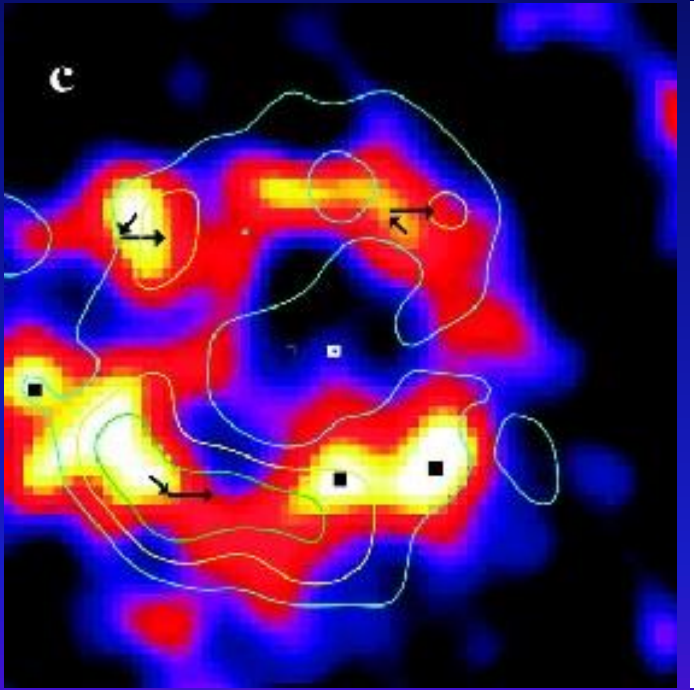
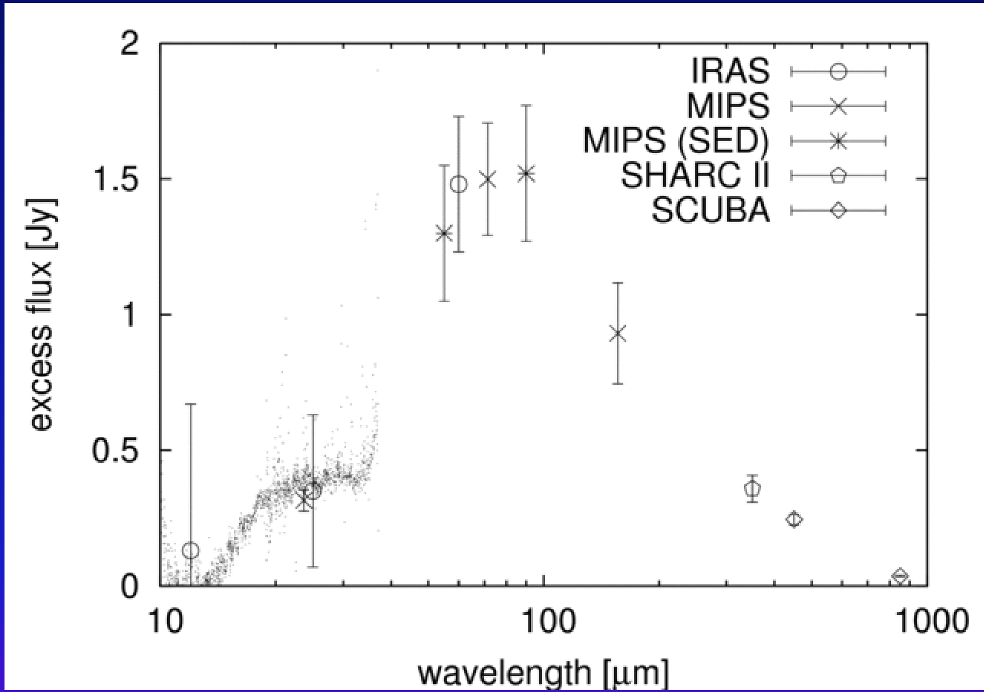
ε Eri system and its puzzling warm dust

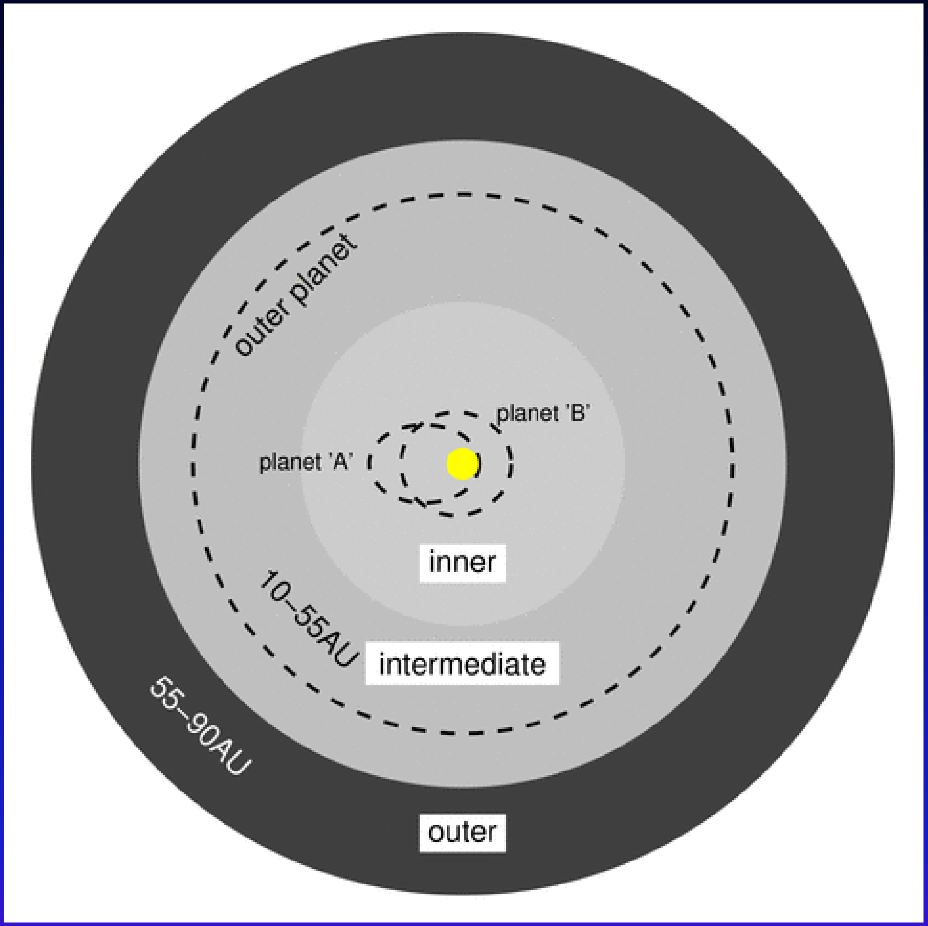
One known RV planet with a=3.4 AU (Hatzes et al. 2000)
One presumed planet at ~40 AU (Liou & Zook 1999)
A "Kuiper belt" at ~60 AU (Gillett 1986, Greaves et al., 1998, 2005)
Warm dust down to a few AU (Backman et al. 2009)





Warm dust that produces the IRS spectrum is located at a few AU
An "asteroid belt" there would be destroyed by the known RV planet

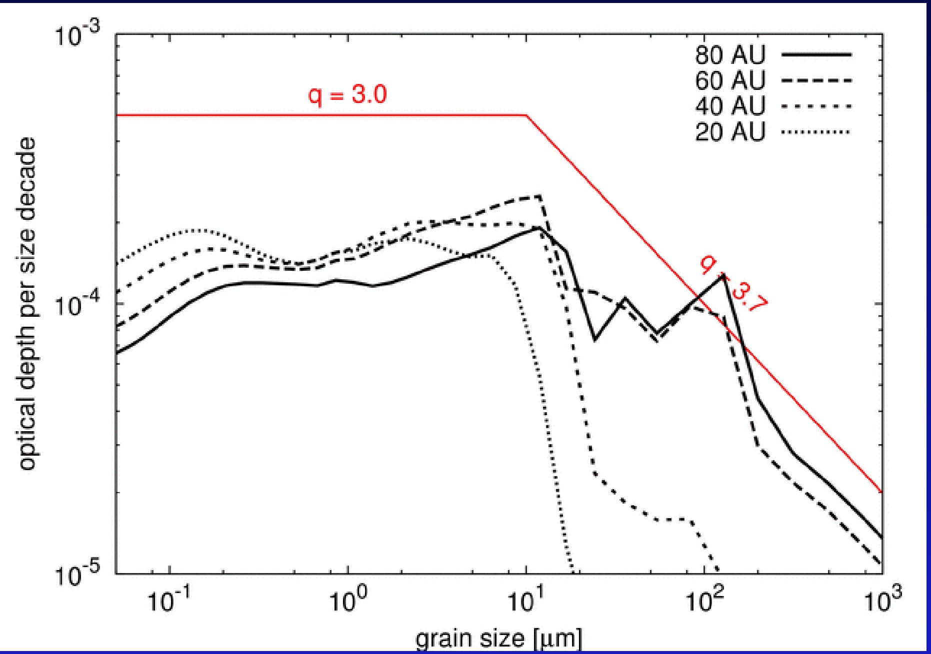
Possible solution

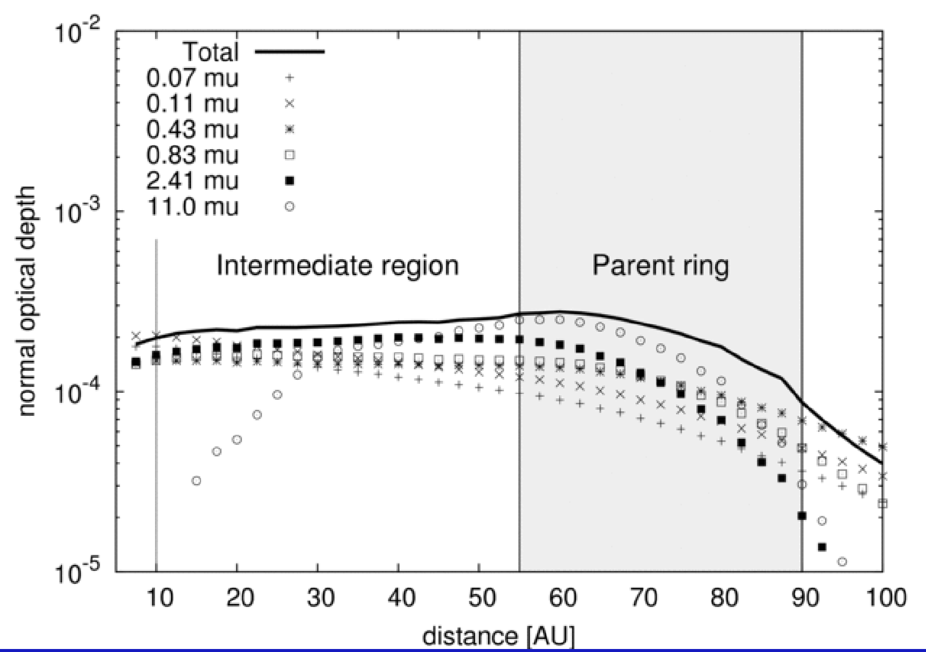


Warm dust could be transported by stellar wind from the "Kuiper belt"

Reidemeister, Krivov, Stark, et al., AAp (submitted)

Modeled size and radial distribution

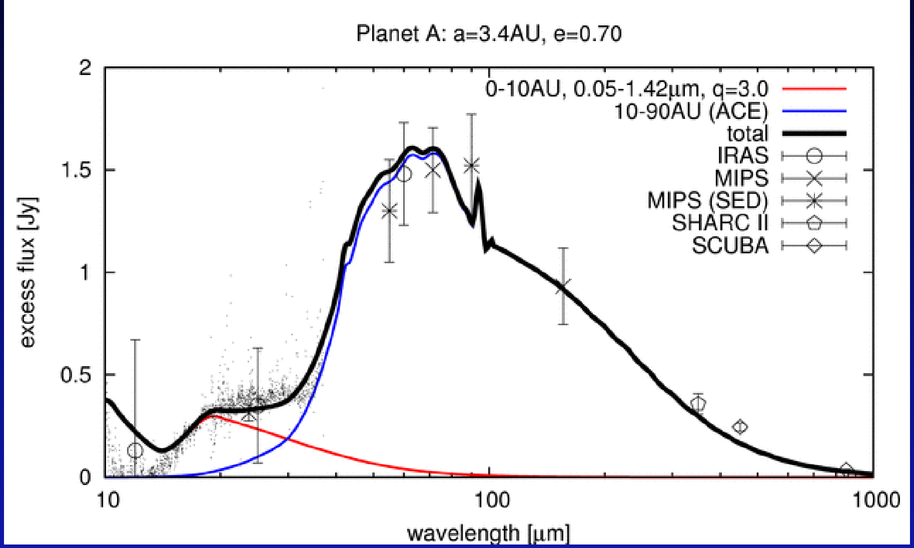




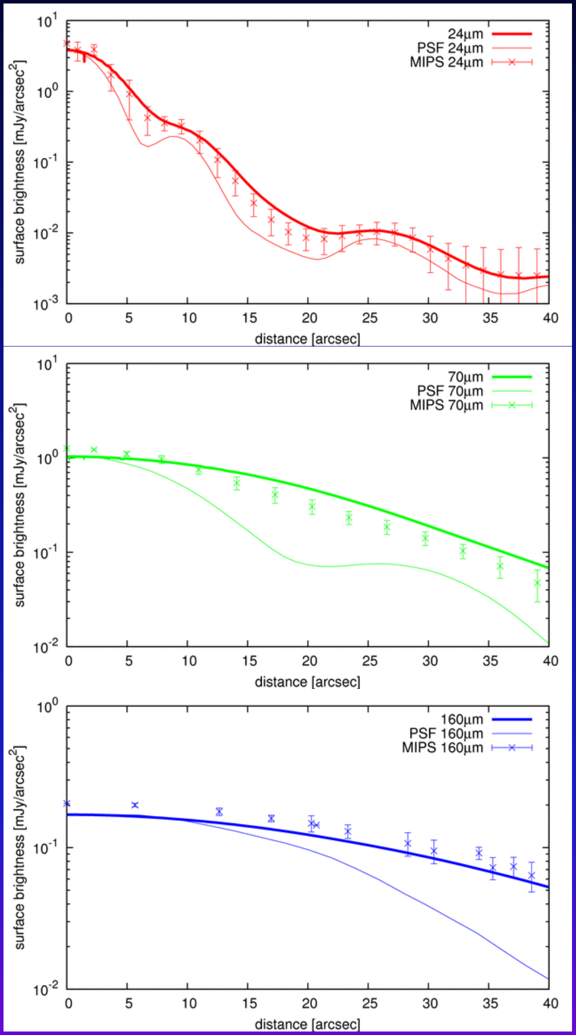
The disk is transport-dominated, despite $\tau \sim 2\times10^{-4}$

Reidemeister, Krivov, Stark, et al., AAp (submitted)

Modeled SED and brightness profiles



The model reproduces all pre-Herschel data: SED from mid-IR to sub-mm, Spitzer/IRS spectrum, Spitzer/MIPS radial profiles. Will it be consistent with Herschel data?



Reidemeister, Krivov, Stark, et al., AAp (submitted)

ε Eri: conclusions

- **The warm dust is produced farther out and is brought inward by stellar wind drag**
- **Possible hints for icy dust**
- **Known inner planet does not affect dust distributions much, so its parameters cannot be further constrained**

Reidemeister, Krivov, Stark, et al., AAp (submitted)

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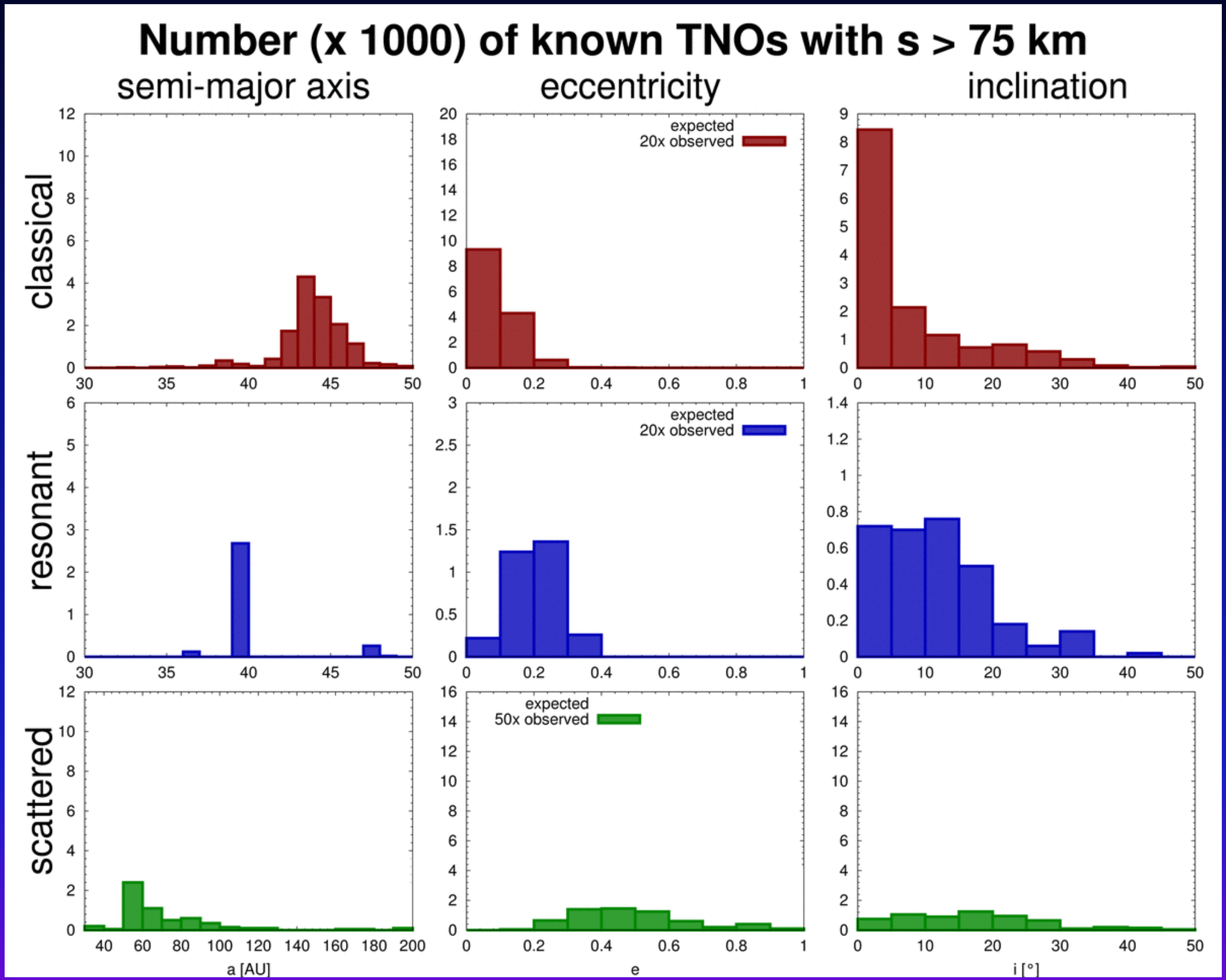
Known EKB…

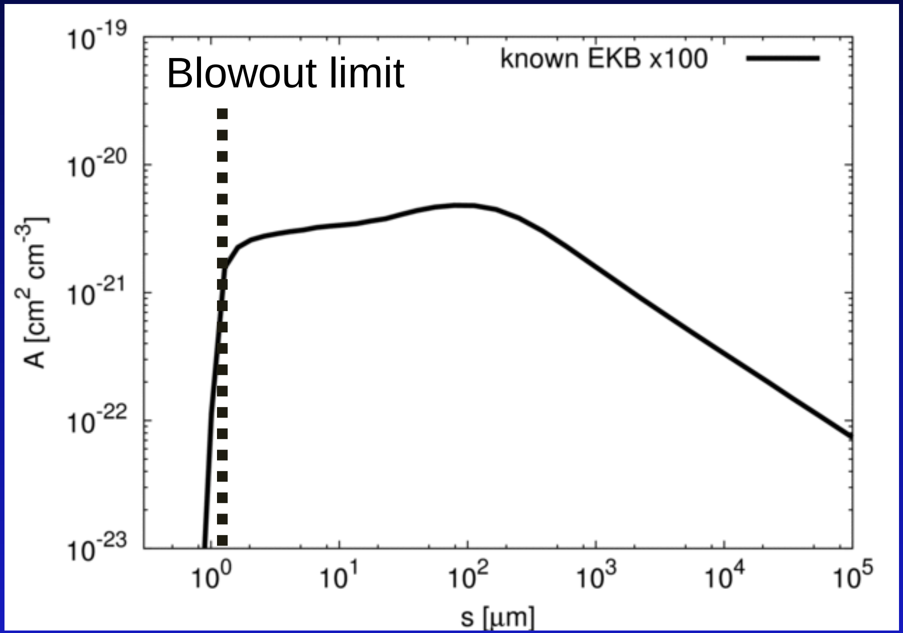


Mass of the known EKB ≈ 0.007 M $_{\oplus}$

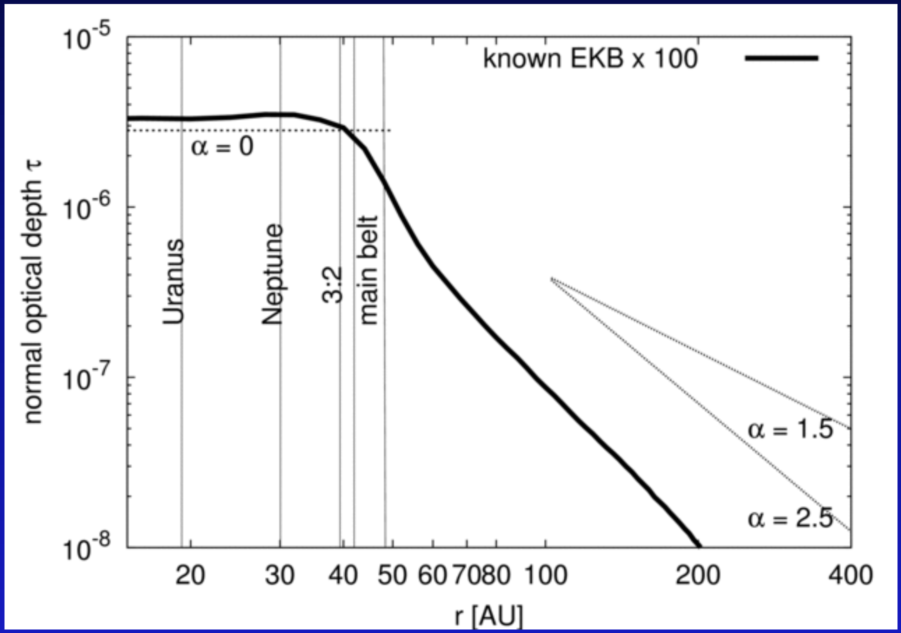
Vitense, Krivov, & Löhne, AAp (in press, astro/ph 1006.2220)

… and its simulated dust disk

Size distribution



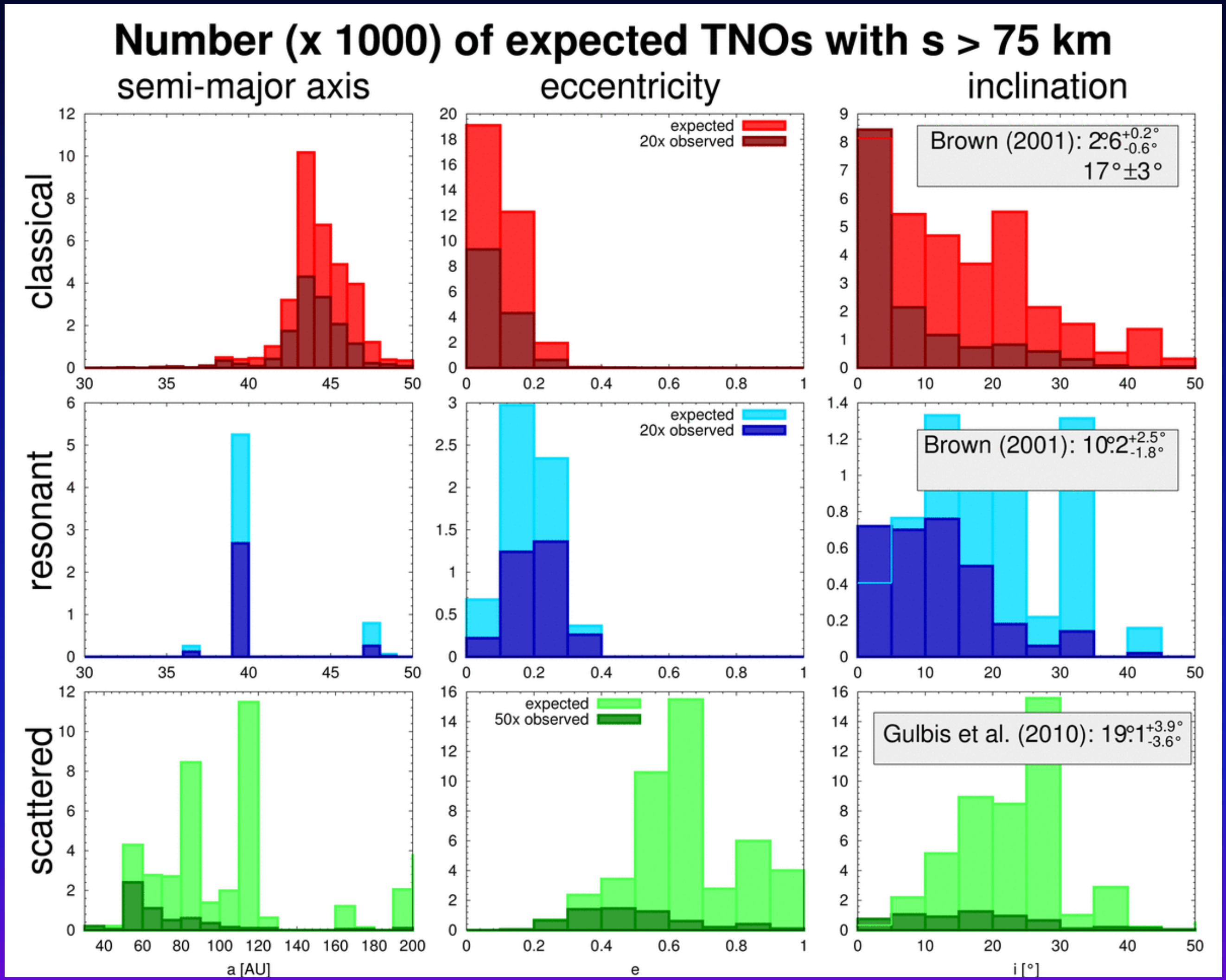
Radial distribution



The dust disk from the known TNOs would have fractional luminosity ~3x10^{-8} and would be transport-dominated

Vitense, Krivov, & Löhne, AAp (in press, astro/ph 1006.2220)

“True” (debiased) EKB…



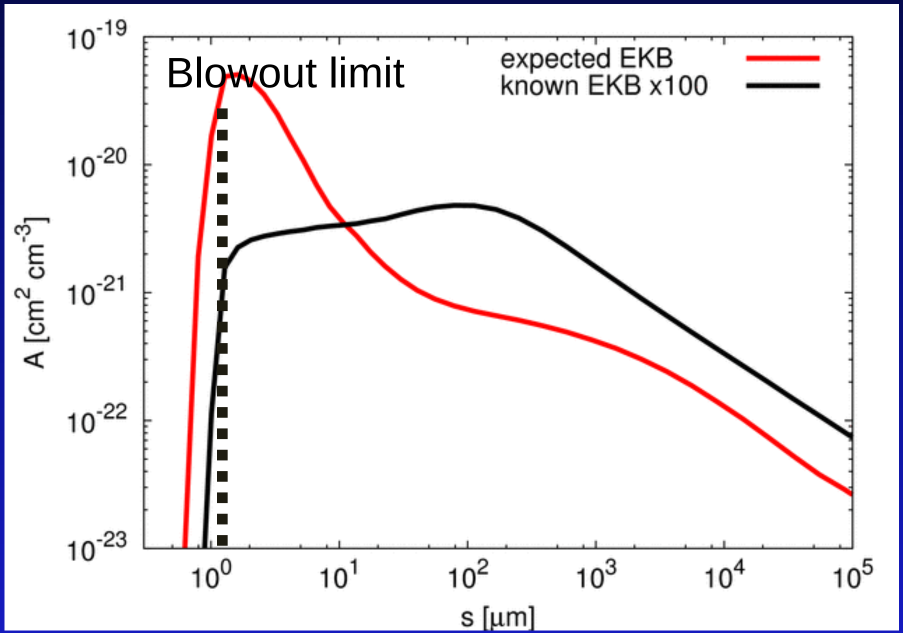
Mass of the known EKB ≈ 0.007 M ⊕

Mass of the “true” EKB ≈ 0.12 M ⊕

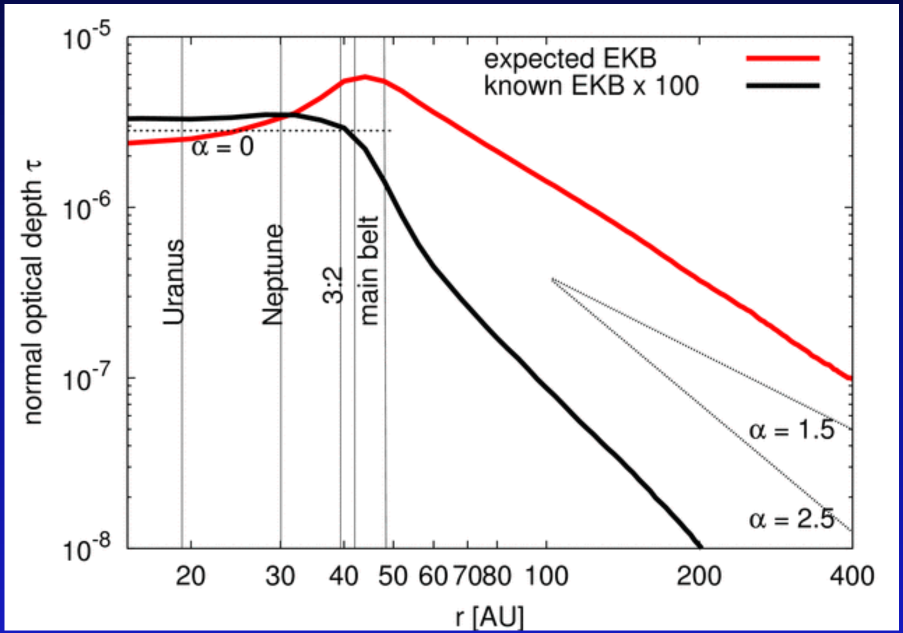
Vitense, Krivov, & Löhne, AAp (in press, astro/ph 1006.2220)

… and its simulated dust disk

Size distribution



Radial distribution



The dust disk of the "true" EKB would have fractional luminosity ~1x10^{-6} and would be collision-dominated

Vitense, Krivov, & Löhne, AAp (in press, astro/ph 1006.2220)

Kuiper Belt: conclusions

- **Estimated mass of the EKB is ~0.1 Earth mass, a half of which is in classical and resonant objects**
- **Estimated fractional luminosity of the EKB dust disk is ~1 x 10^{-6}, close to the Herschel detection limits**

Reidemeister, Krivov, Stark, et al., AAp (submitted)

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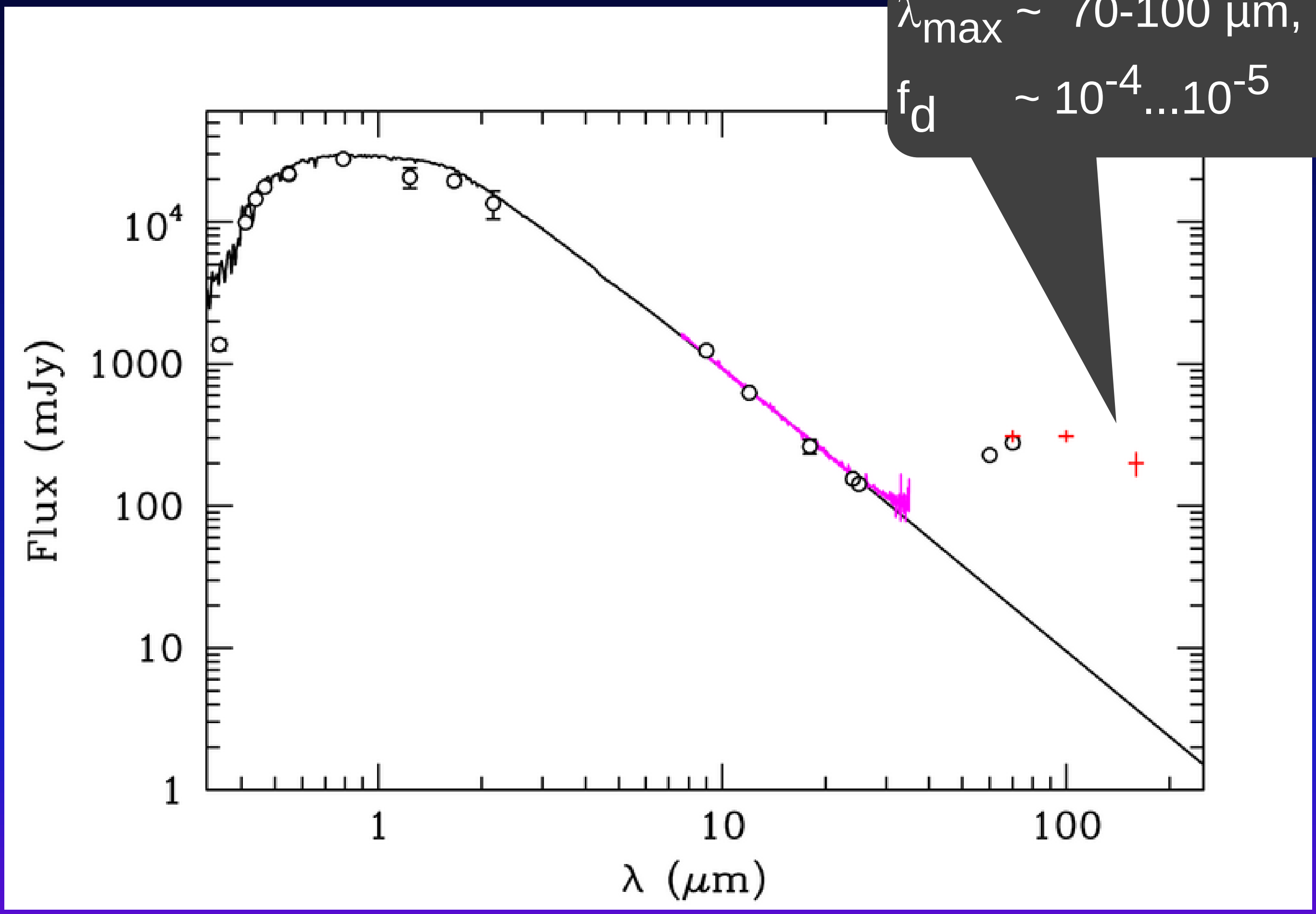
Some of the Herschel/DUNES disks are “normal”…

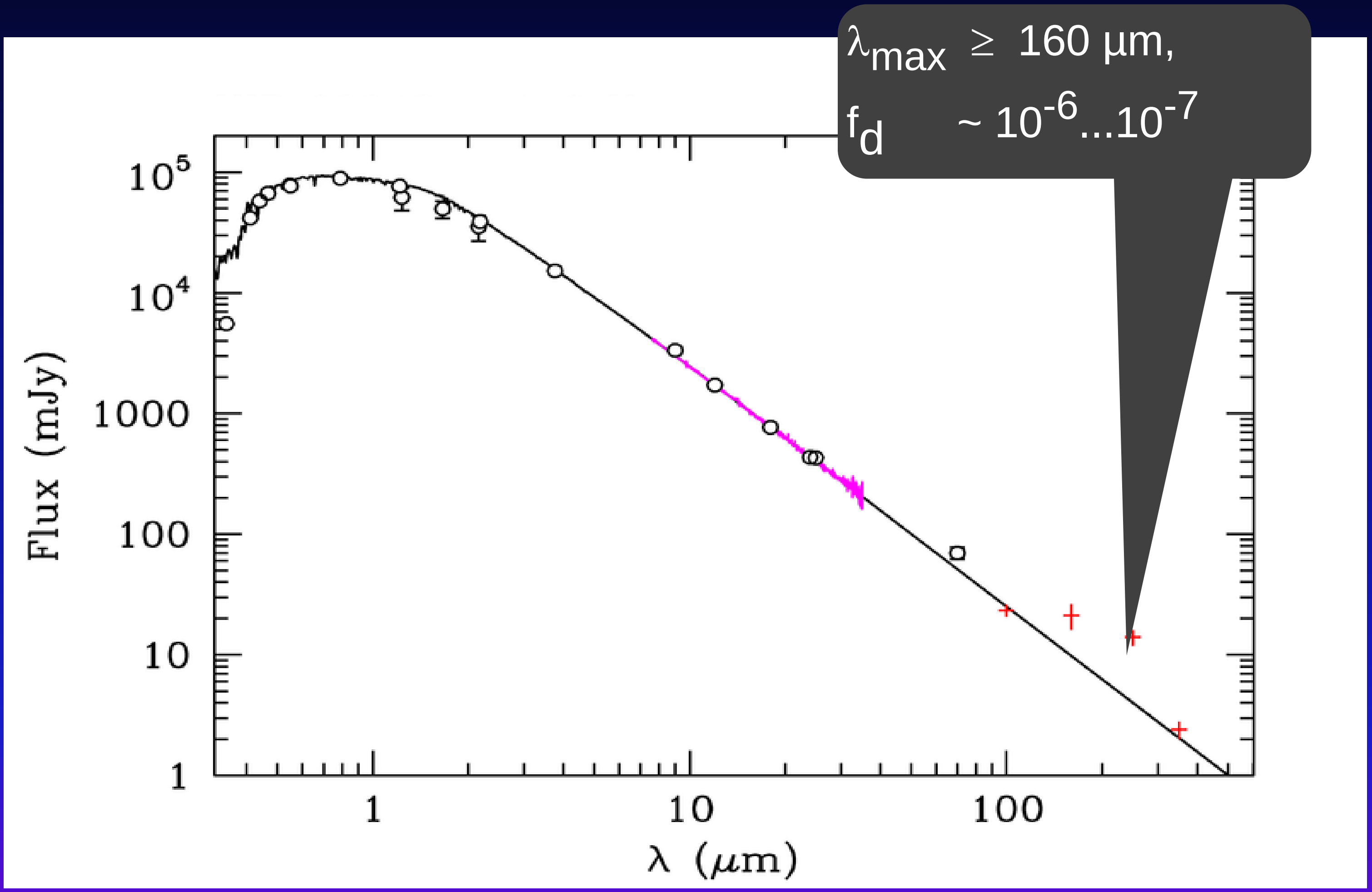


λ_{max} ~ 70-100 μm,

f_d ~ $10^{-4}...10^{-5}$

Marshall et al., in prep.

…but some others are tenuous and astonishingly cold



Marshall et al., in prep.

Challenges of the cold disks

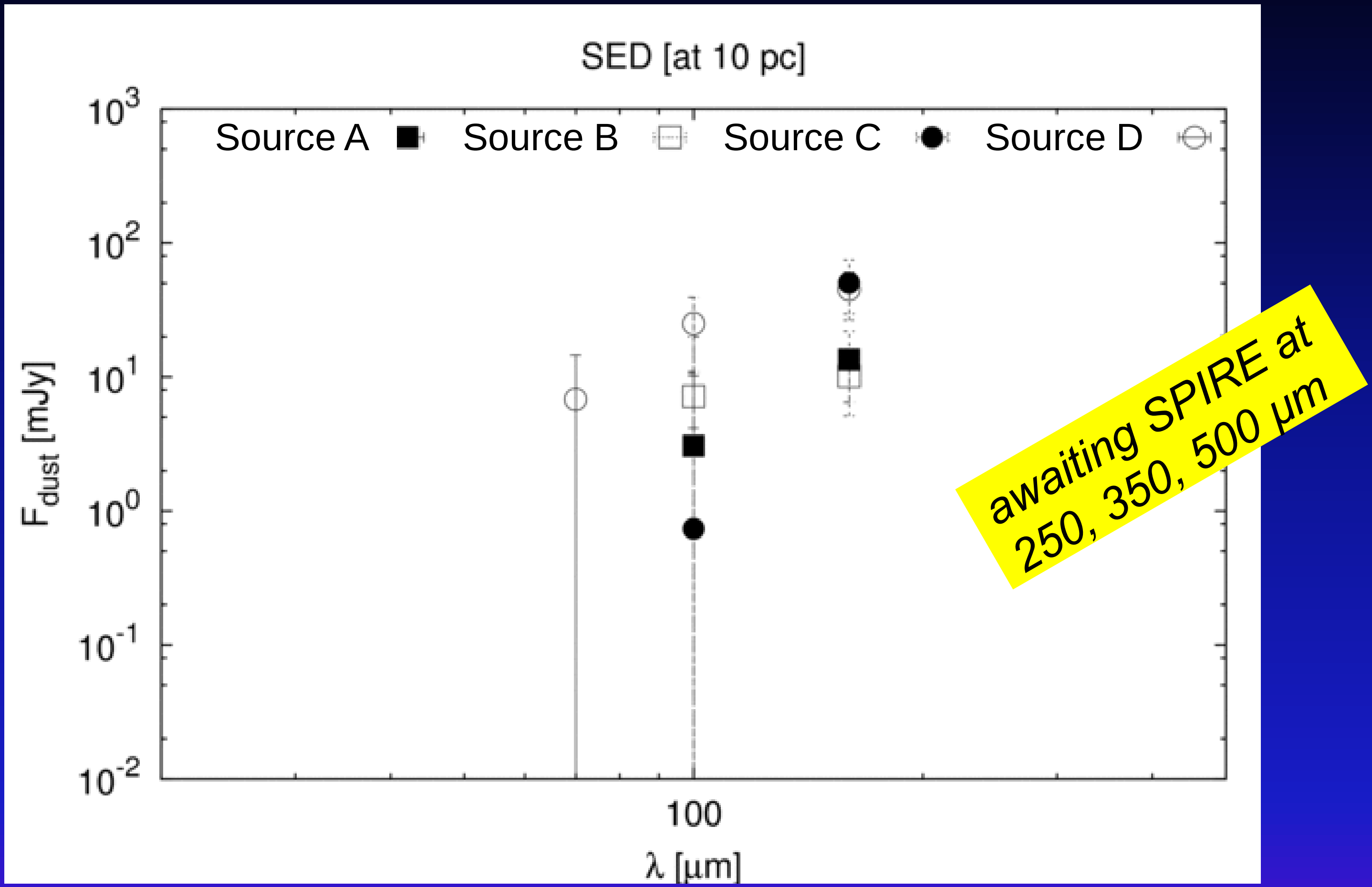
Max at 160 μm would require dust to be typically at distances much larger than 100 AU

But:

Planetesimals can hardly form outside ~100 AU

Resolved images also suggest radii of ~100 AU

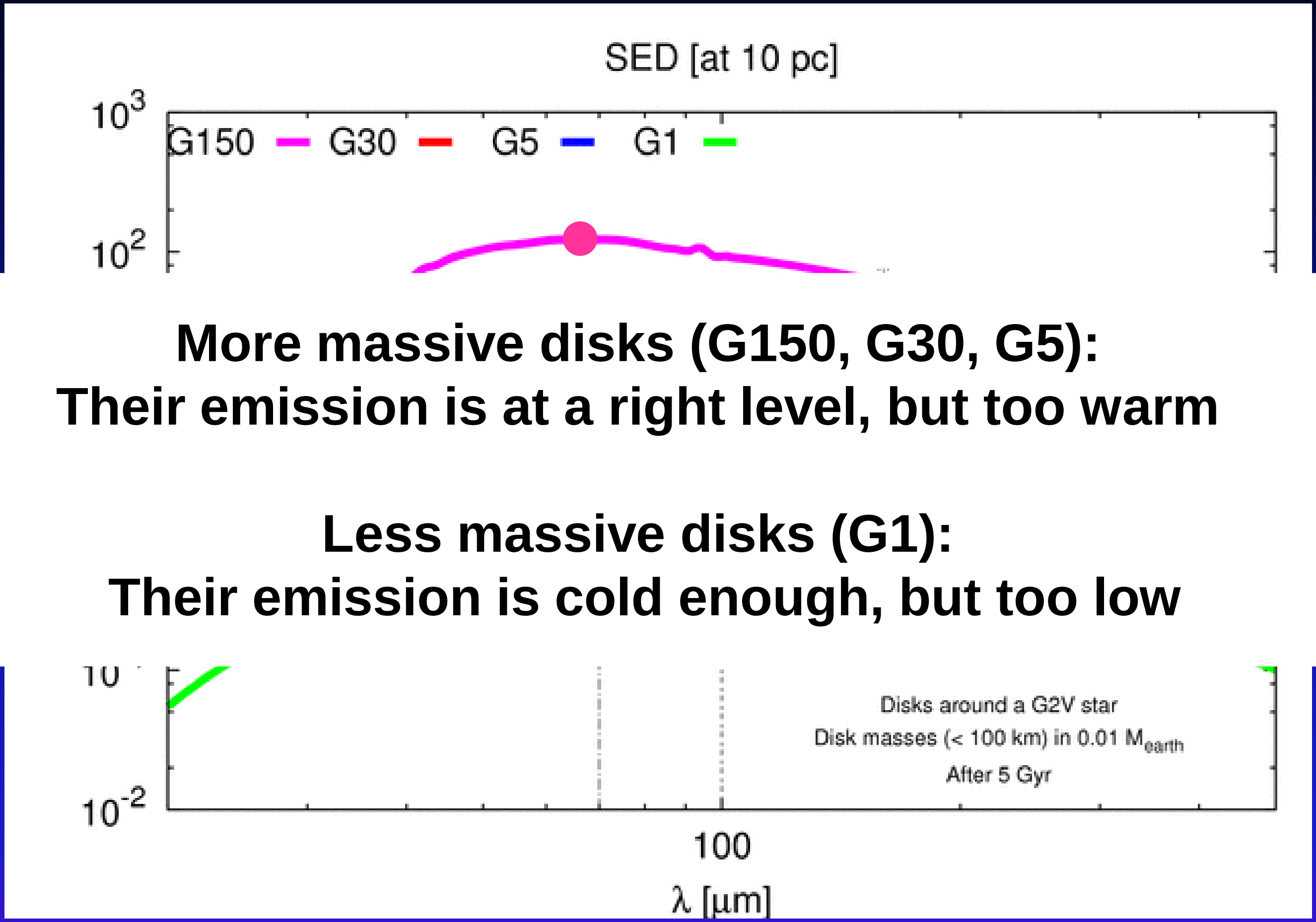
Attempts to understand the cold disks



Excess flux of four most reliable cold disks observed by DUNES

Krivov et al., in prep.

Attempts to understand the cold disks



More massive disks (G150, G30, G5):
Their emission is at a right level, but too warm

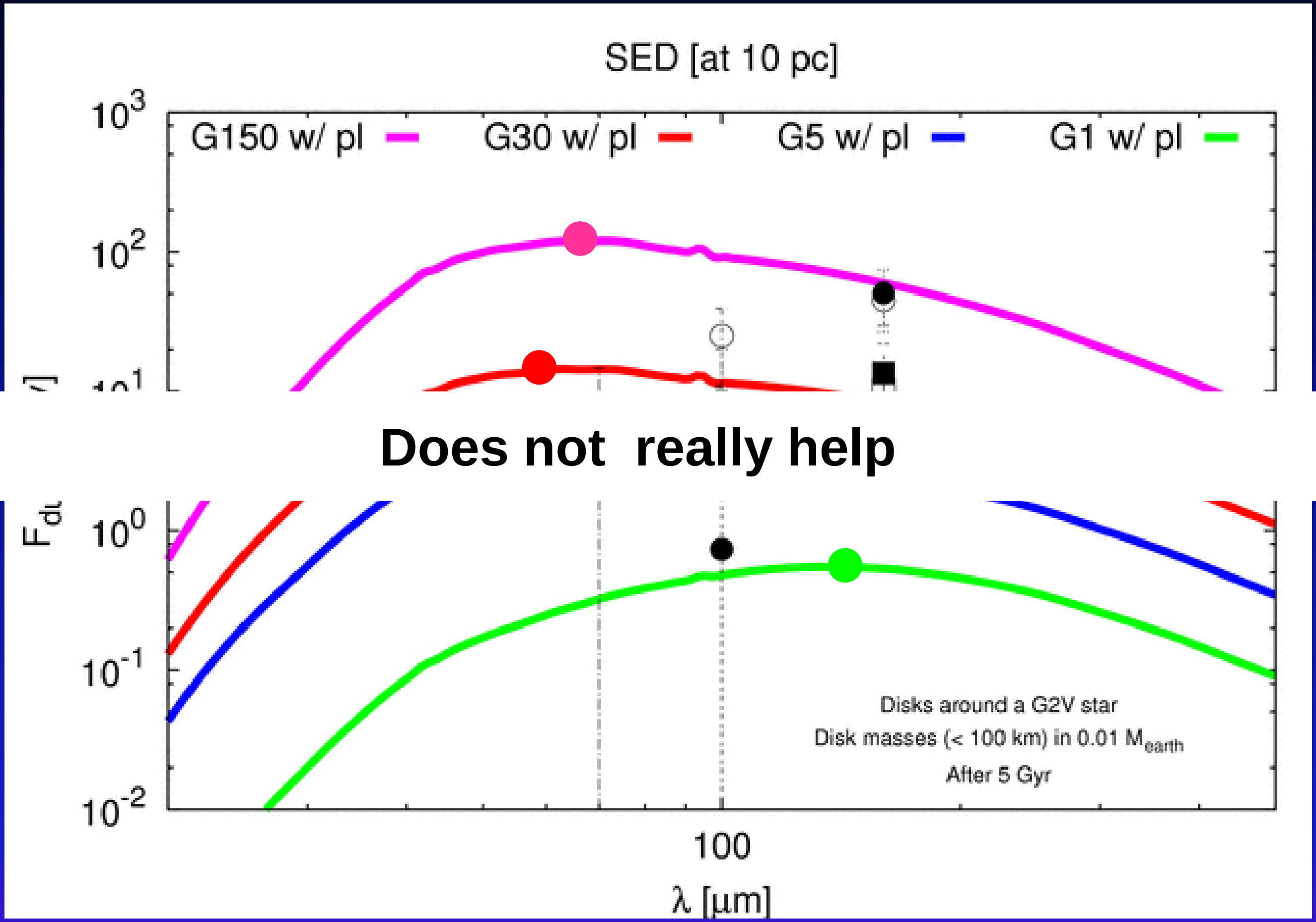
Less massive disks (G1):
Their emission is cold enough, but too low

Tried planetesimal belts at r=100AU, Δr=0.2, e~0.1, 50%ice+50%sil

G150 = 1.50 $M_\oplus$ G30 = 0.30 $M_\oplus$ G5 = 0.05 $M_\oplus$ G1= 0.01 $M_\oplus$

Krivov et al., in prep.

Attempts to understand the cold disks

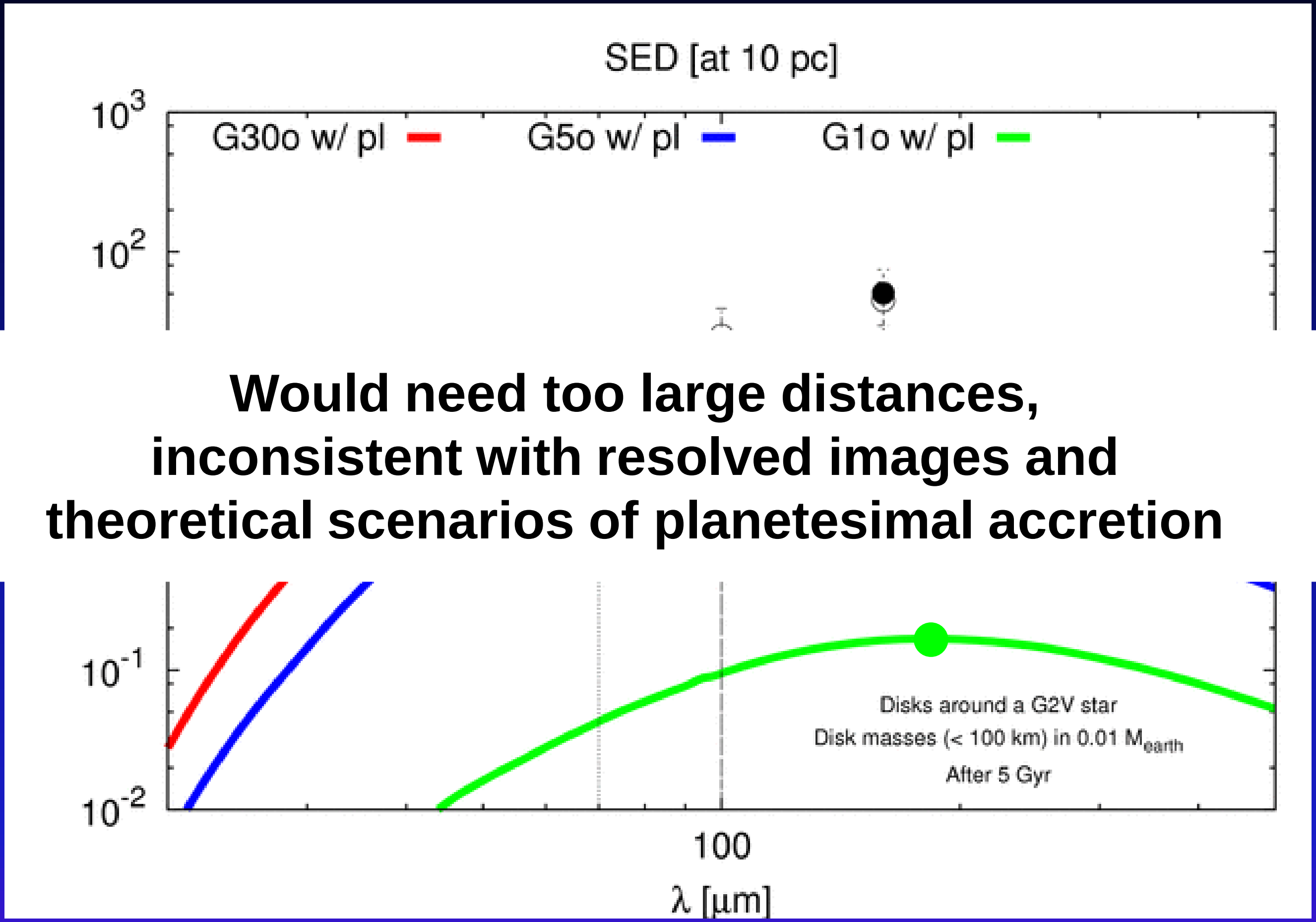


Does not really help

Tried to exclude dust in the inner parts of a dust disk (< 60 AU) assuming that each belt is shaped by a Fomalhaut-like planet

Krivov et al., in prep.

Attempts to understand the cold disks



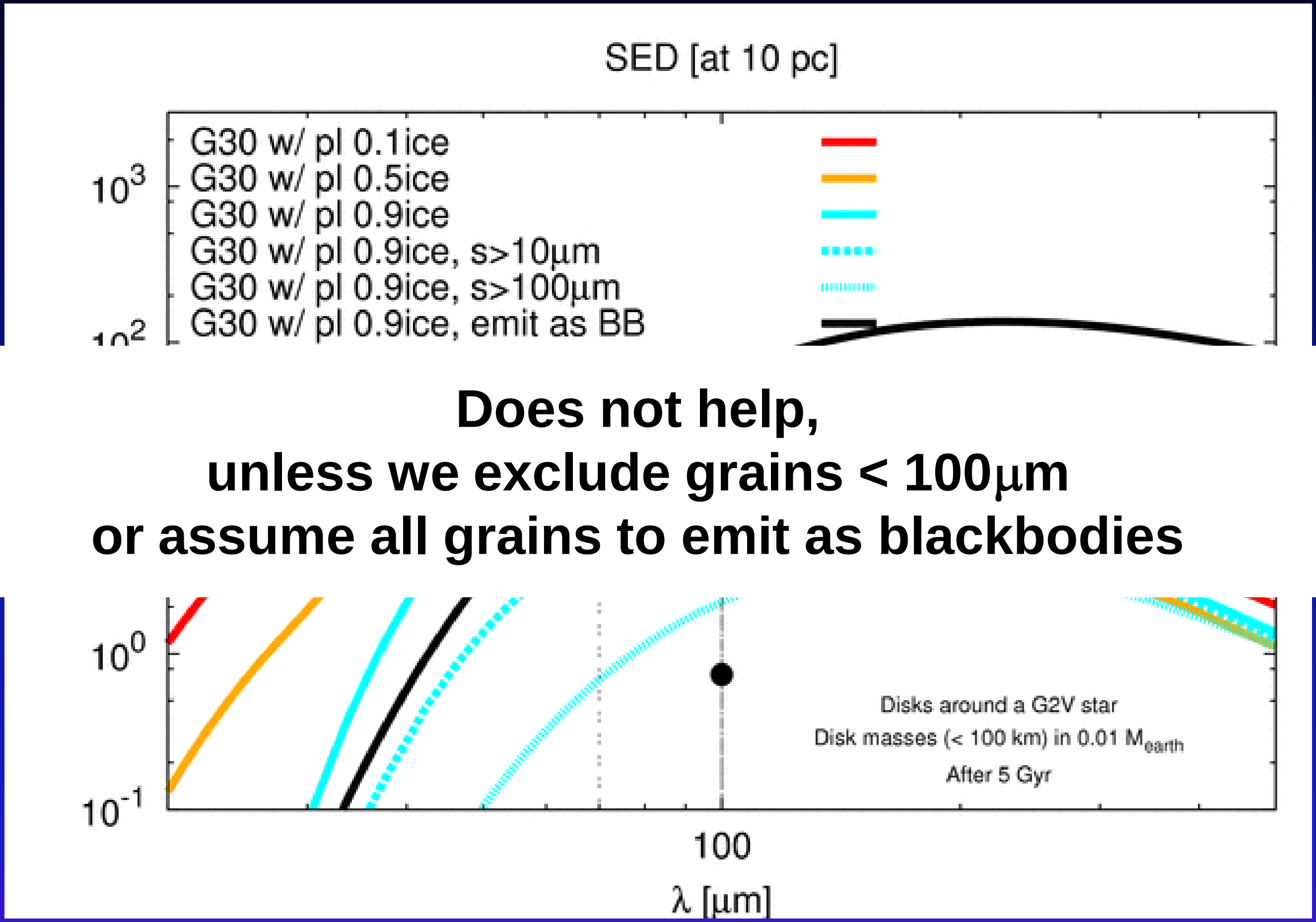
Would need too large distances, inconsistent with resolved images and theoretical scenarios of planetesimal accretion

Tried planetesimal belts at a larger distance: r=150AU

G30o = 0.30 $M_\oplus$ G5o = 0.05 $M_\oplus$ G1o= 0.01 $M_\oplus$

Krivov et al., in prep.

Attempts to understand the cold disks



Does not help,
unless we exclude grains < 100μm
or assume all grains to emit as blackbodies

Tried other dust compositions, large grains only, and blackbody

Krivov et al., in prep.

Cold disks: conclusions

“Cold disks” remain unexplained

Any mechanisms to remove (or depress production) of μm-sized grains?
Or their far-IR emission stronger than expected?

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Problems

Collisional and thermal emission models seem to work and to give reasonable results, but…

- Debris disks of solar-type and late-type stars: modeled SEDs seem to be generally too warm. Why?
- Lack of the modeled 70μm emission in the central parts of DDs around solar-type stars. Modeling problem or indication of “asteroid belts”?
- Cold debris disks remain a mystery!

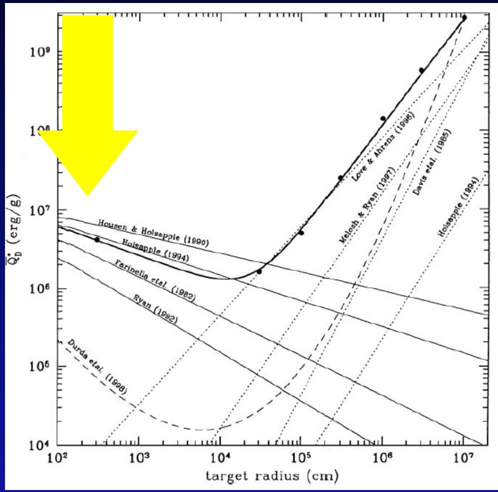
Unknowns

- Are all major physical processes included?

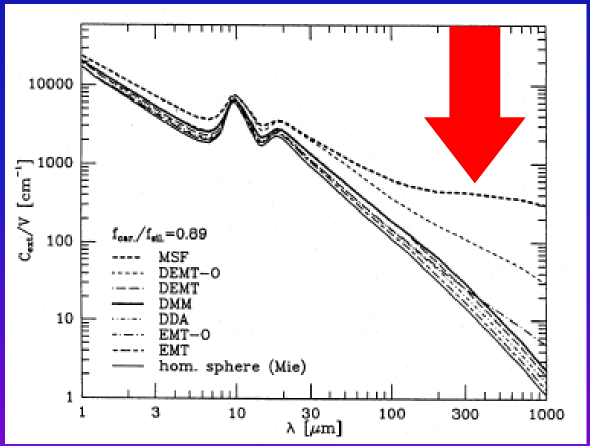
➢ Critical fragmentation energy at dust sizes unknown

- Material composition / optical properties of dust in debris disks largely unknown

➢ Are Mie calculations + assumption of compact grains reasonable?



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



Stognienko et al.
AAp **296,** *797-809 (1995)*