デブリ円盤におけるダスト特性

Dust properties in debris disks

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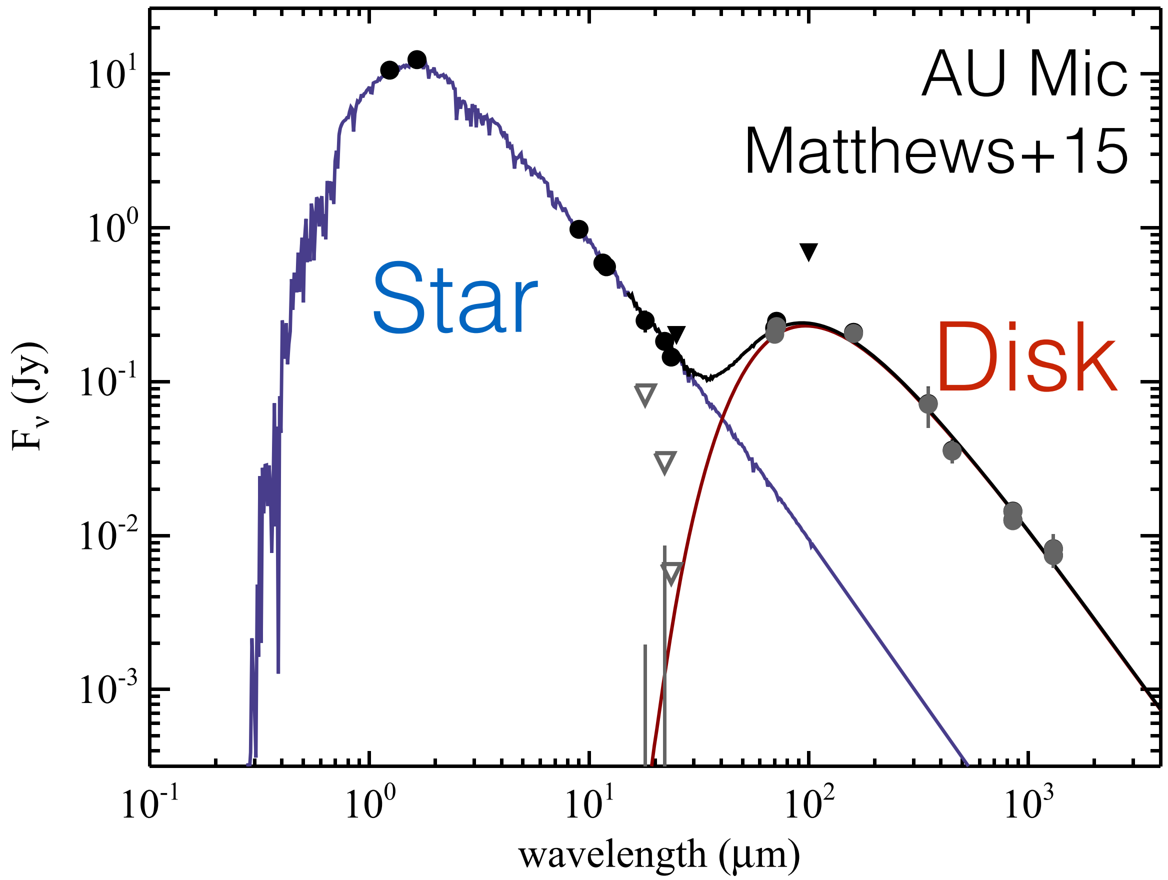
1. Introduction
2. Dust characterization by observations
3. Dust opacity in millimeter-wavelengths
4. Summary

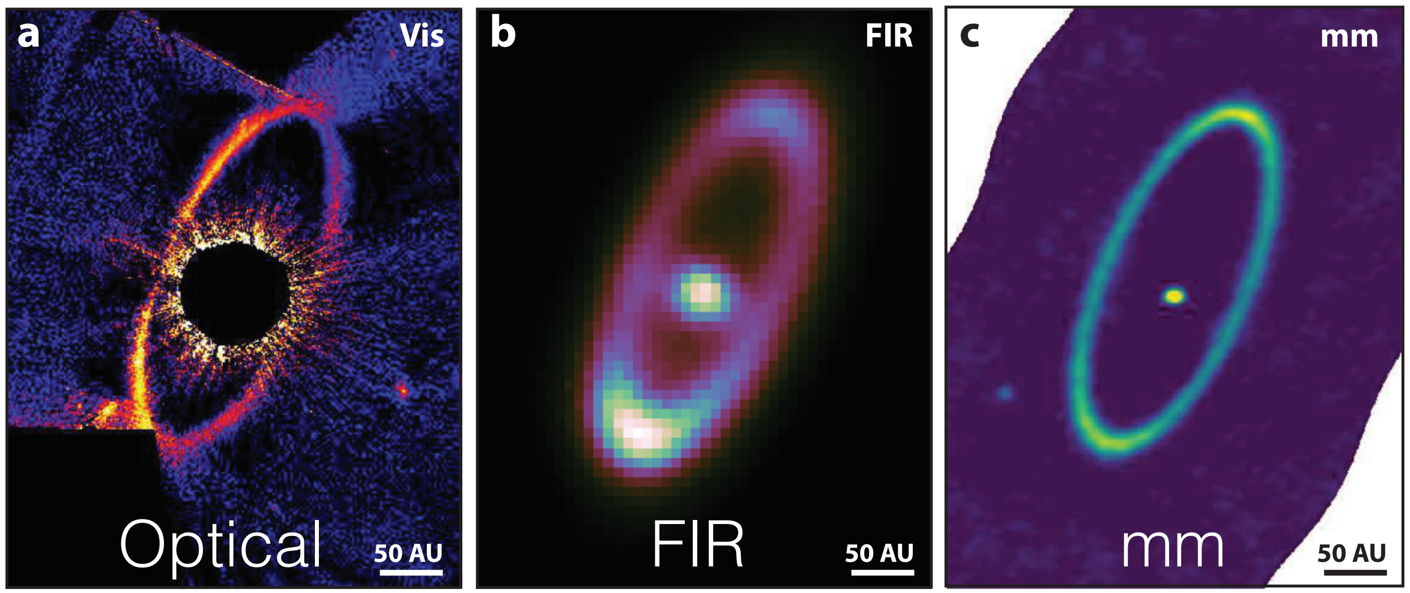
What are debris disks?

- Dusty disks around main-sequence stars
  - descendant of protoplanetary disks
- SED typically shows excess emission in infrared wavelengths.
- High-resolution imaging is now available

SED



High-resolution imaging



Fomalhaut, Hughes et al. (2018)

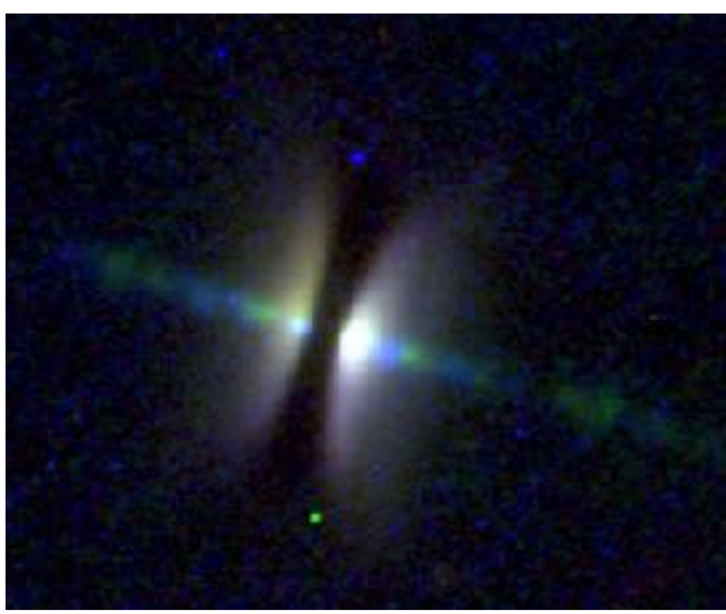
PPDs and debris disks

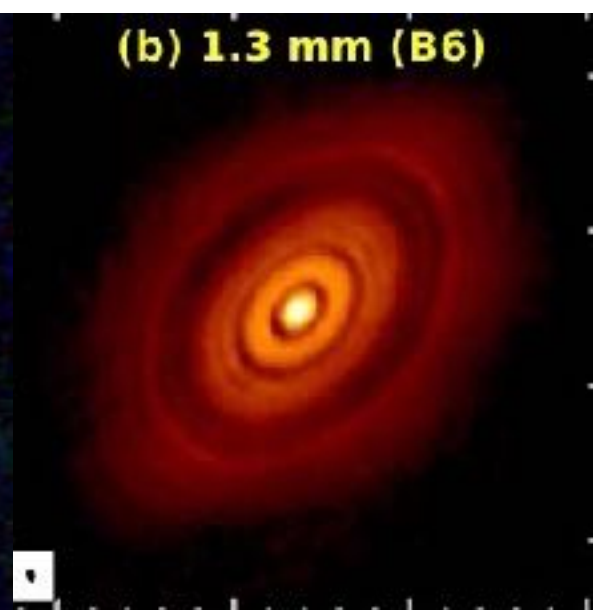
Protoplanetary disks

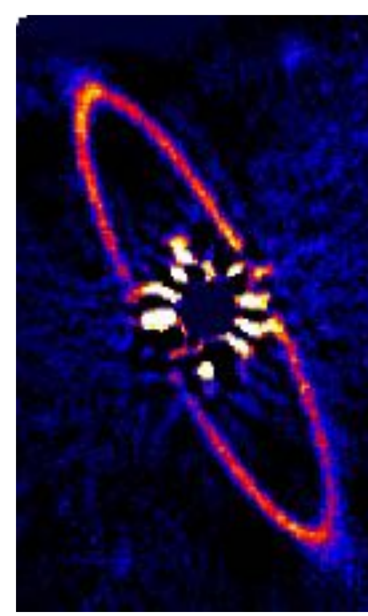
- Young (< 1-10 Myr)
  → Host star: PMS
- Optically thick
- Gas rich
- Primordial dust

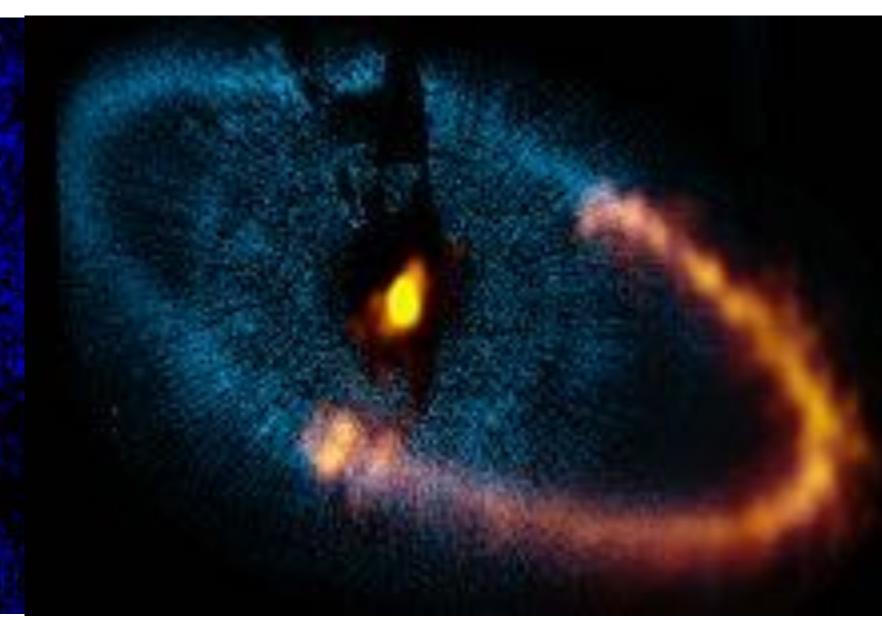
Debris disks

- Old (> 1-10 Myr)
  → Host star: MS
- Optically thin
- Dust rich (& gas)
- **Secondly dust**



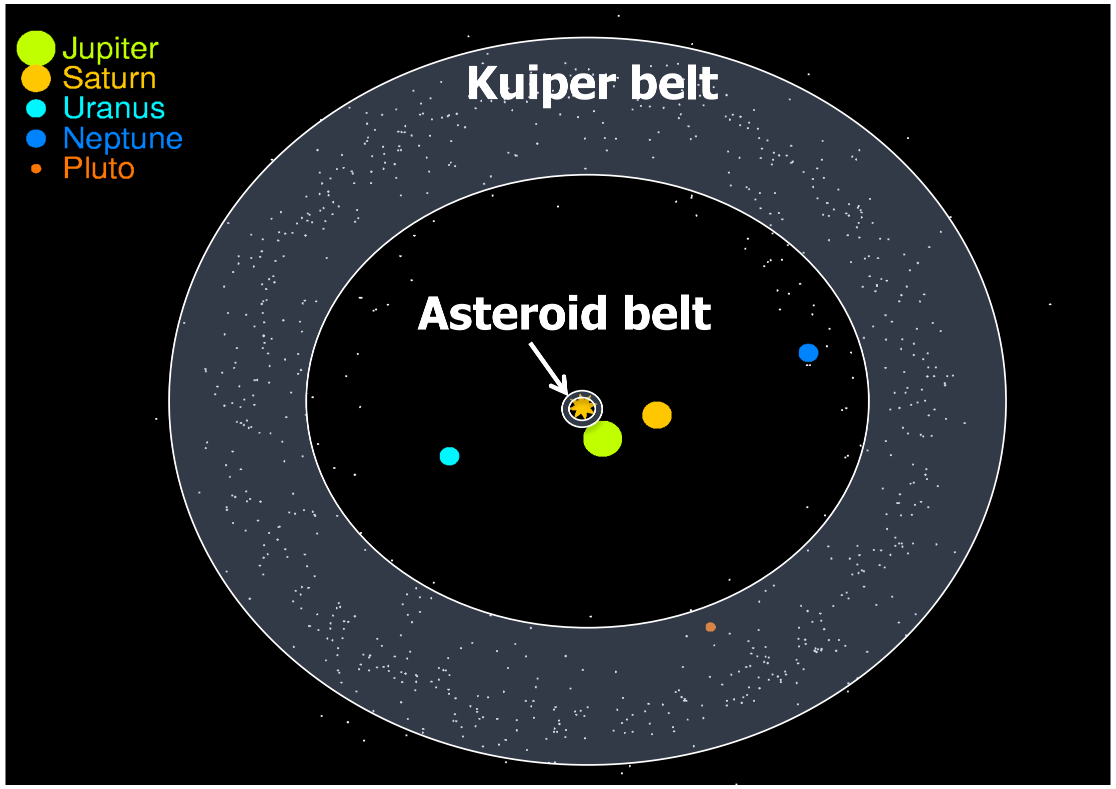




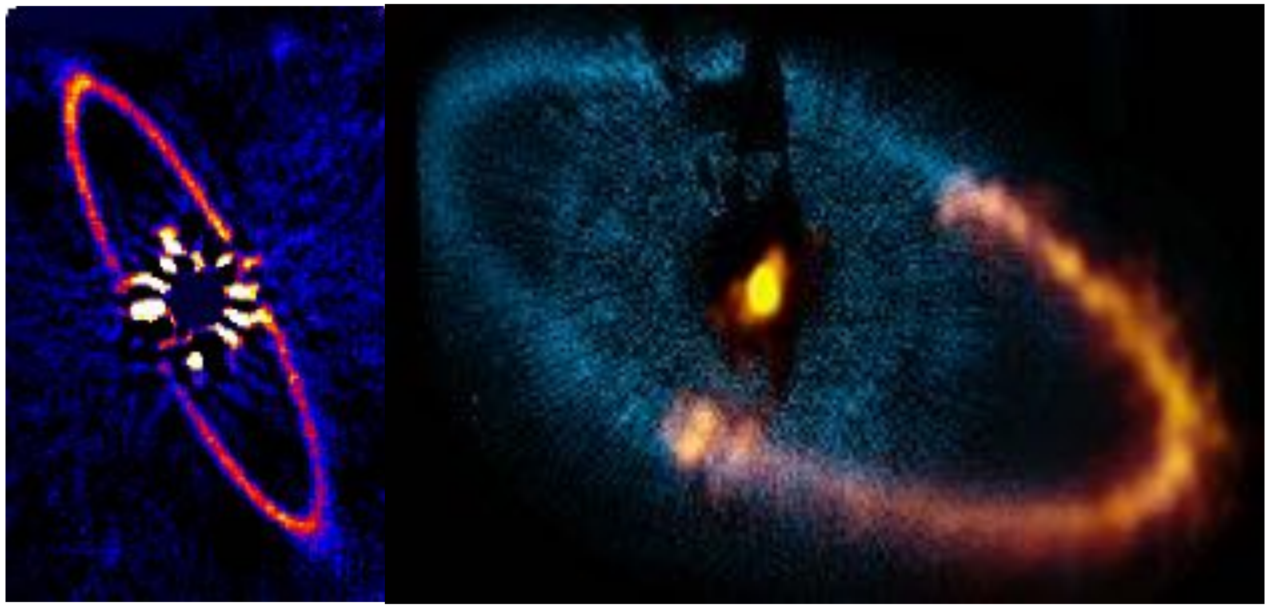


Solar System and Debris disks

- The solar system contains debris disk components:
  - Asteroid belt (e.g., zodiacal light)
  - Kuiper belt
- Debris disk structure indicates planetary architecture!



Debris disks
= analog of young Solar System



Although asteroid belt and Kuiper belt are much fainter than those seen in debris disks…

What can we learn from debris dust?

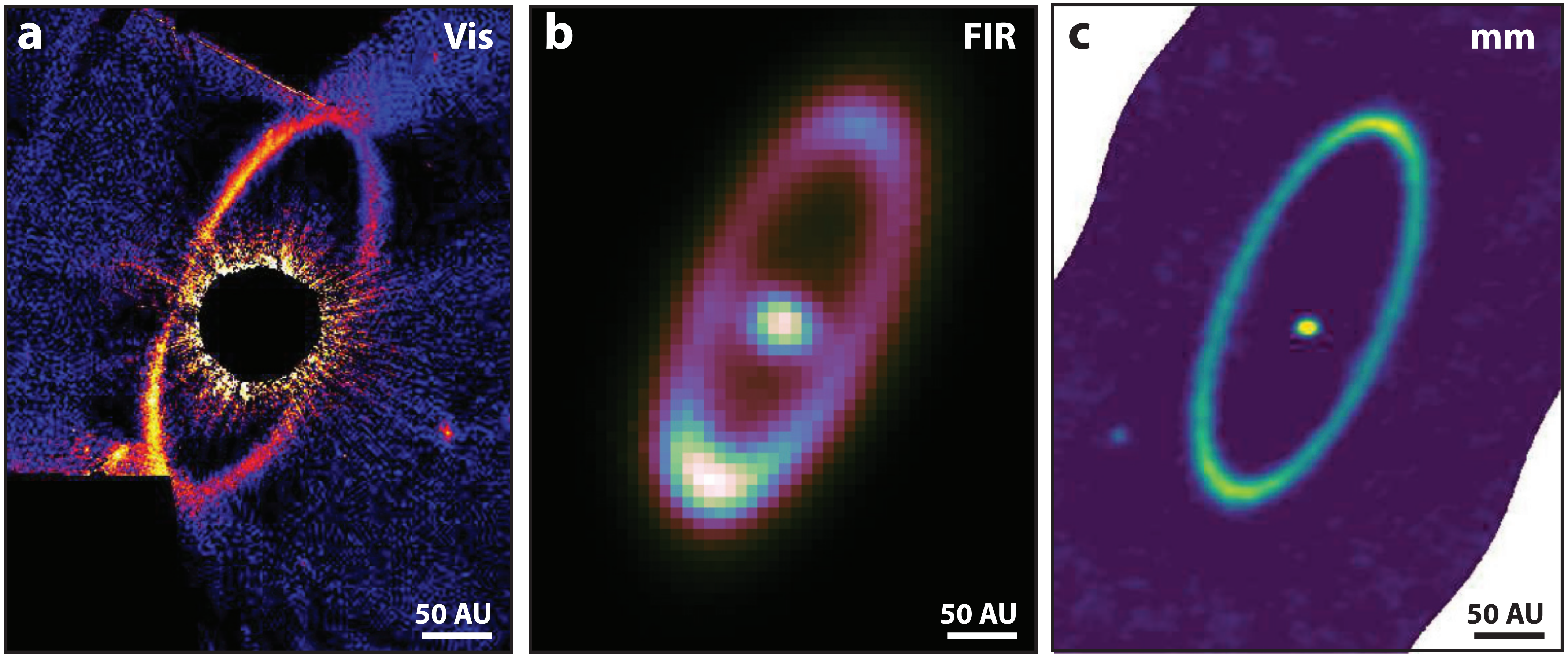
- Properties of Parent bodies
  - dust composition
  - dust shape, structure, and porosity

- Fragmentation process
  - grain size distribution
  - minimum/maximum grain radius

- System dependences
  - stellar type? age?
  - How does it differ from our Solar System?

How can we know their properties?

- Thermal emission (MIR - mm) & Scattered light (Opt - NIR)
- Optically thin for all wavelengths!
  → Much more simple than protoplanetary disks
- Combined analysis of scattering and thermal is a powerful tool.



Fomalhaut, Hughes et al. (2018)

Dust characterization

§2.1 Dust Composition
§2.2 Grain size distribution
§2.3 Dust shape & structure

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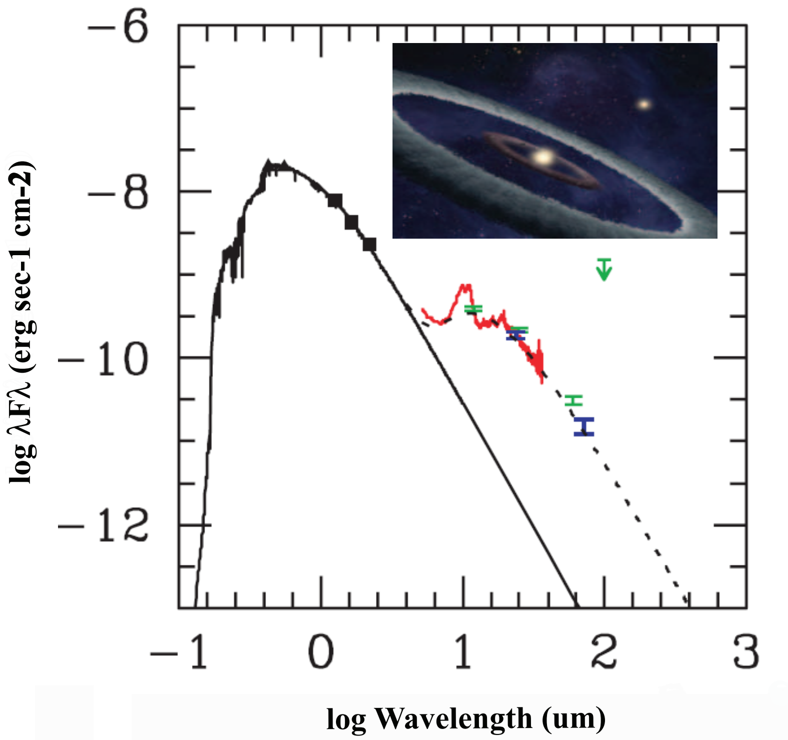
Dust composition

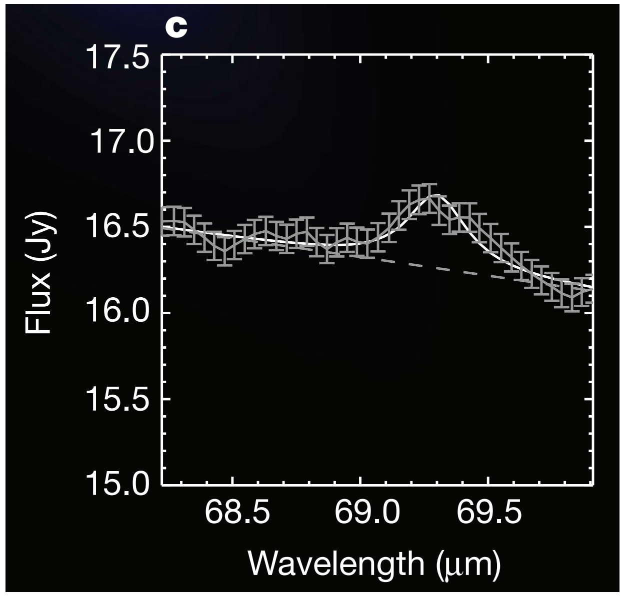
- Direct evidence of composition: **solid-state feature**
  - silicate features: λ =10 μm, 20 μm, 69 μm
- 10 and/or 20 μm silicate emission from debris disks
  - 120 targets/571 sources ≈ 20% (Chen+14, Mittal+15)
  - biased for warm and small grains (<~10 μm/2π ~1.6 μm)
- 69 μm feature can be seen in more lower temp.

HD 113766

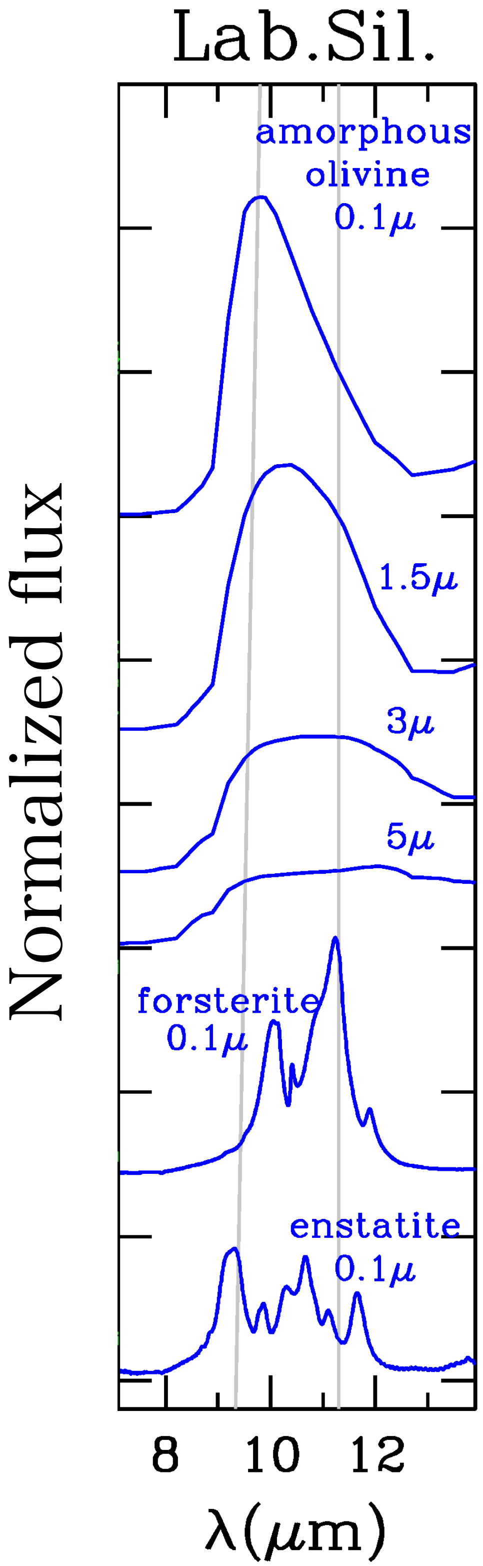


Lisse+2008

β-pic



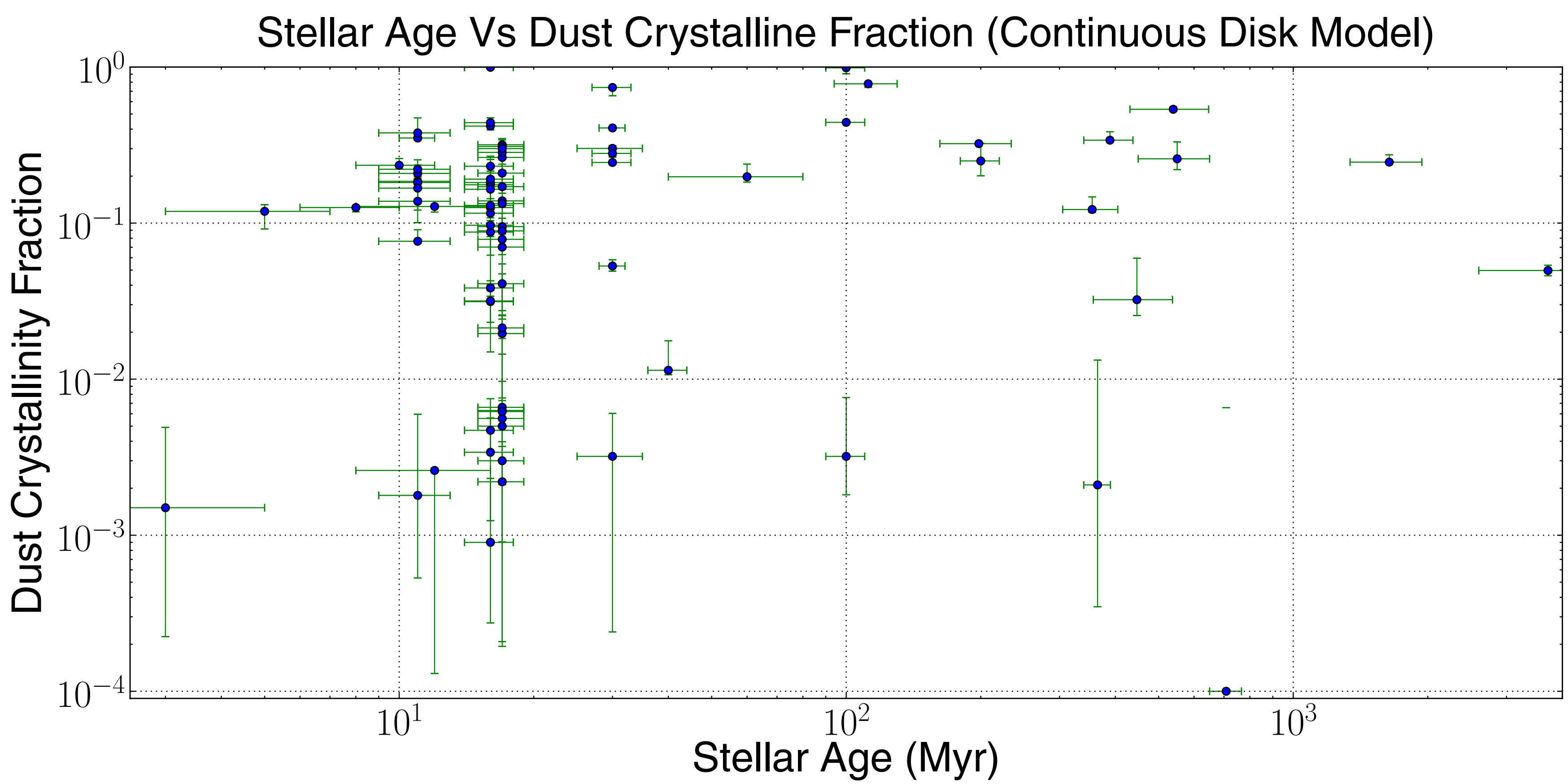
de Vries+2012



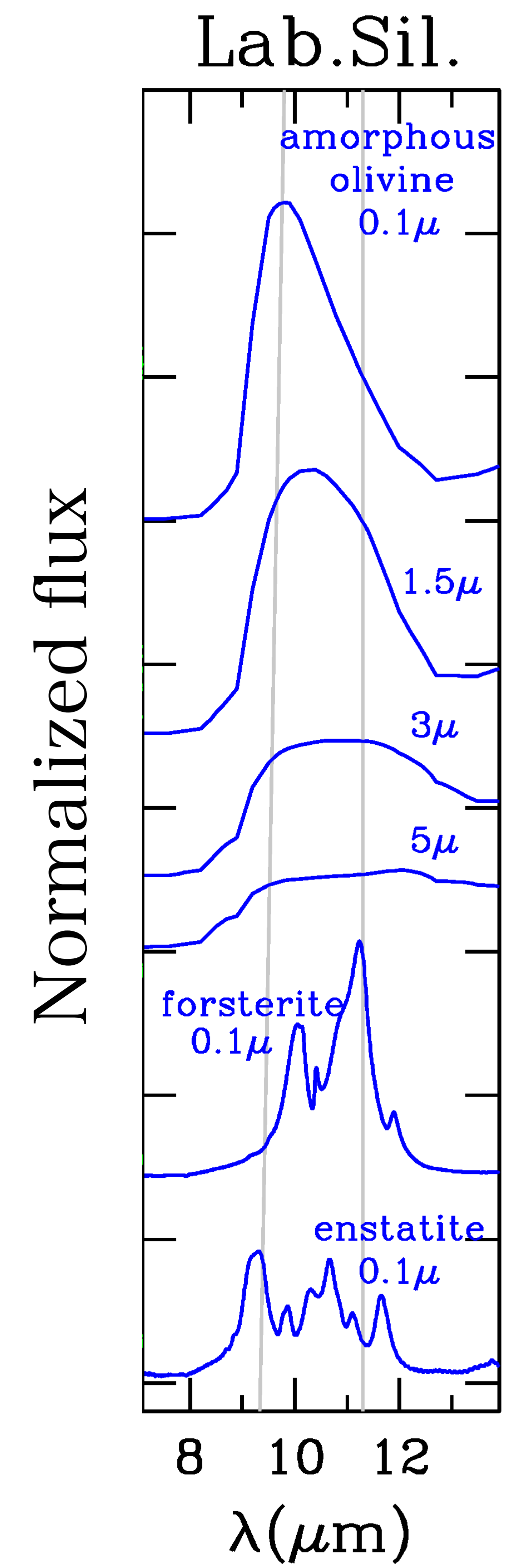
Natta+2007

Crystallinity of silicate

- Interstellar silicate: >99% amorphous (Kemper+04)
- Crystallinity of silicate in debris disk (Mittal+15)
  - show a wide variety : <1 - 95%
  - no clear correlation with stellar age



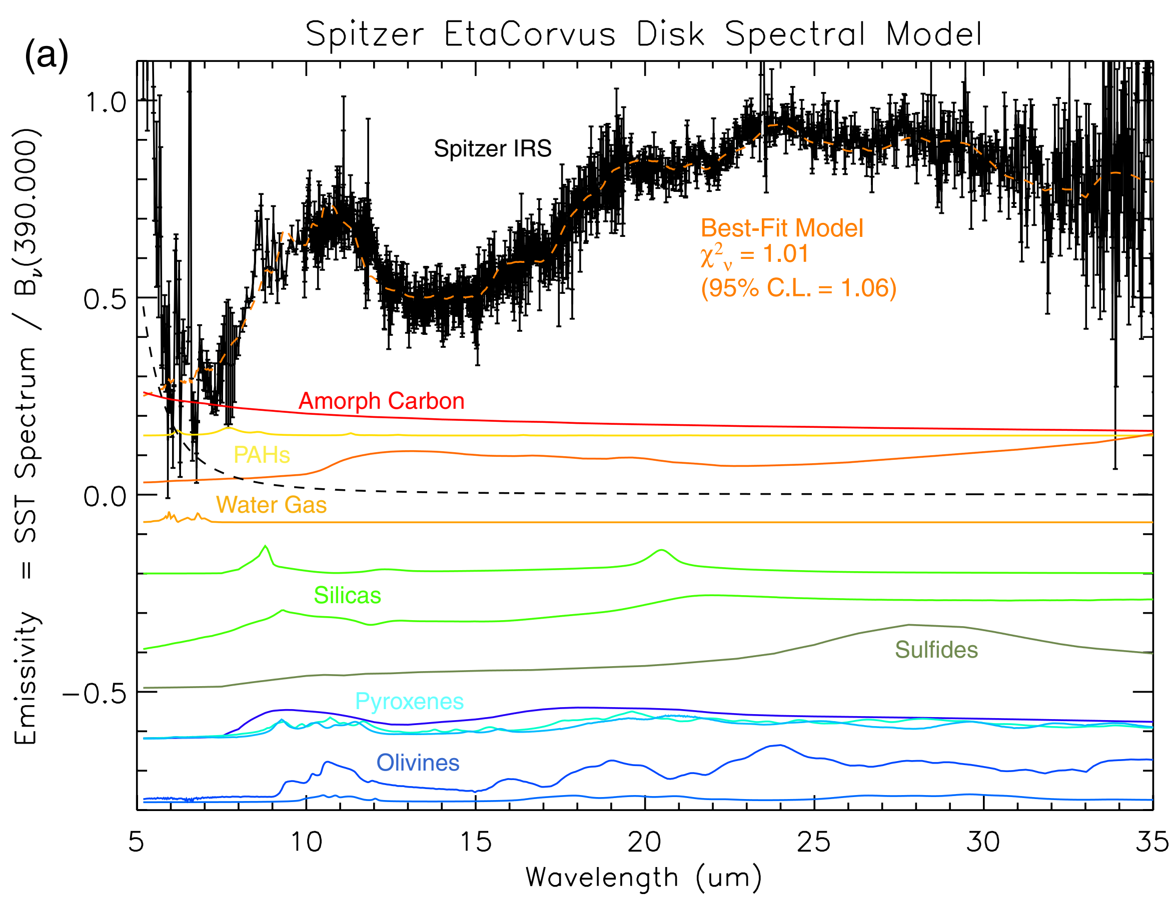
Mittal+2015



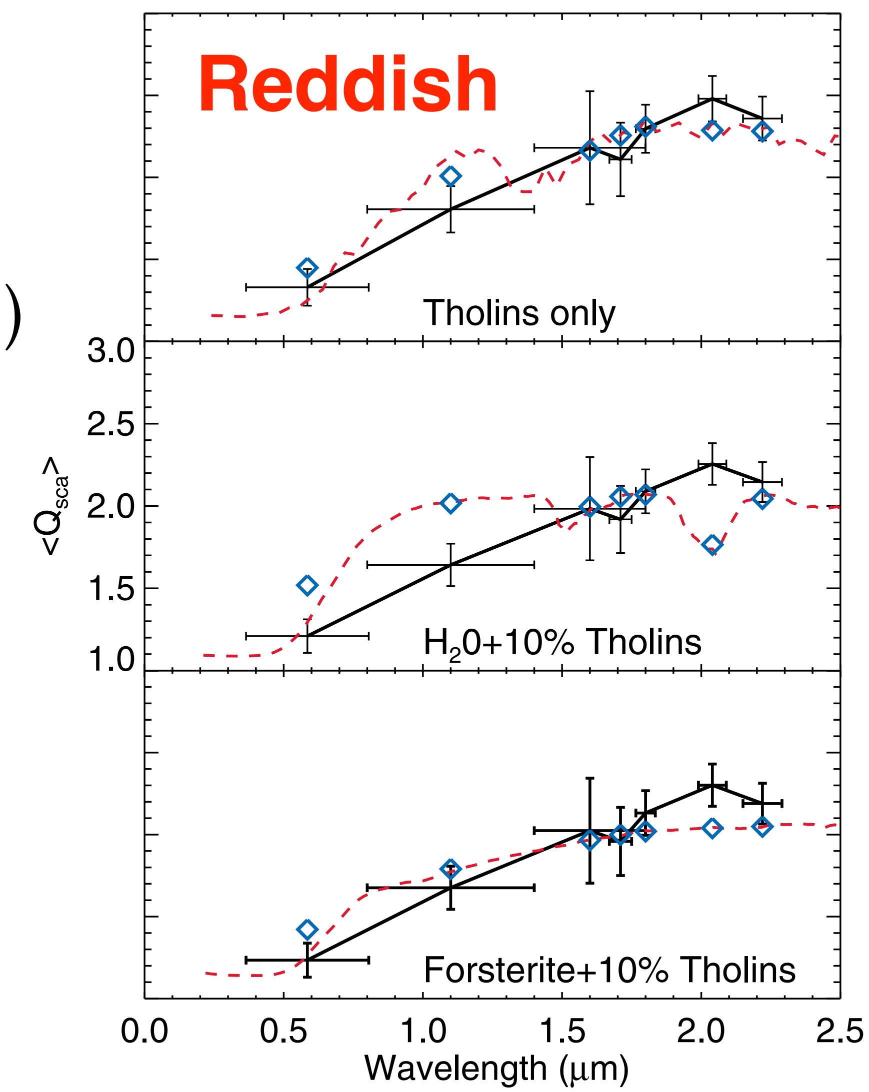
Natta+2007

Other material signature?

- High SNR Spectral decomposition @ MIR
  - Sulfide, amorphous carbon, water (Lisse+12)
  - Still fitting is <u>model dependent</u> (Lebreton+16)
- Reddish NIR Scattered light
  - Reddish colors due to organics (Debes+2008)
  - Solution is not unique because colors can be affected by grain size & structure (Koehler+08)



Lisse+2012



HR 4796, Debes+2008

Dust characterization

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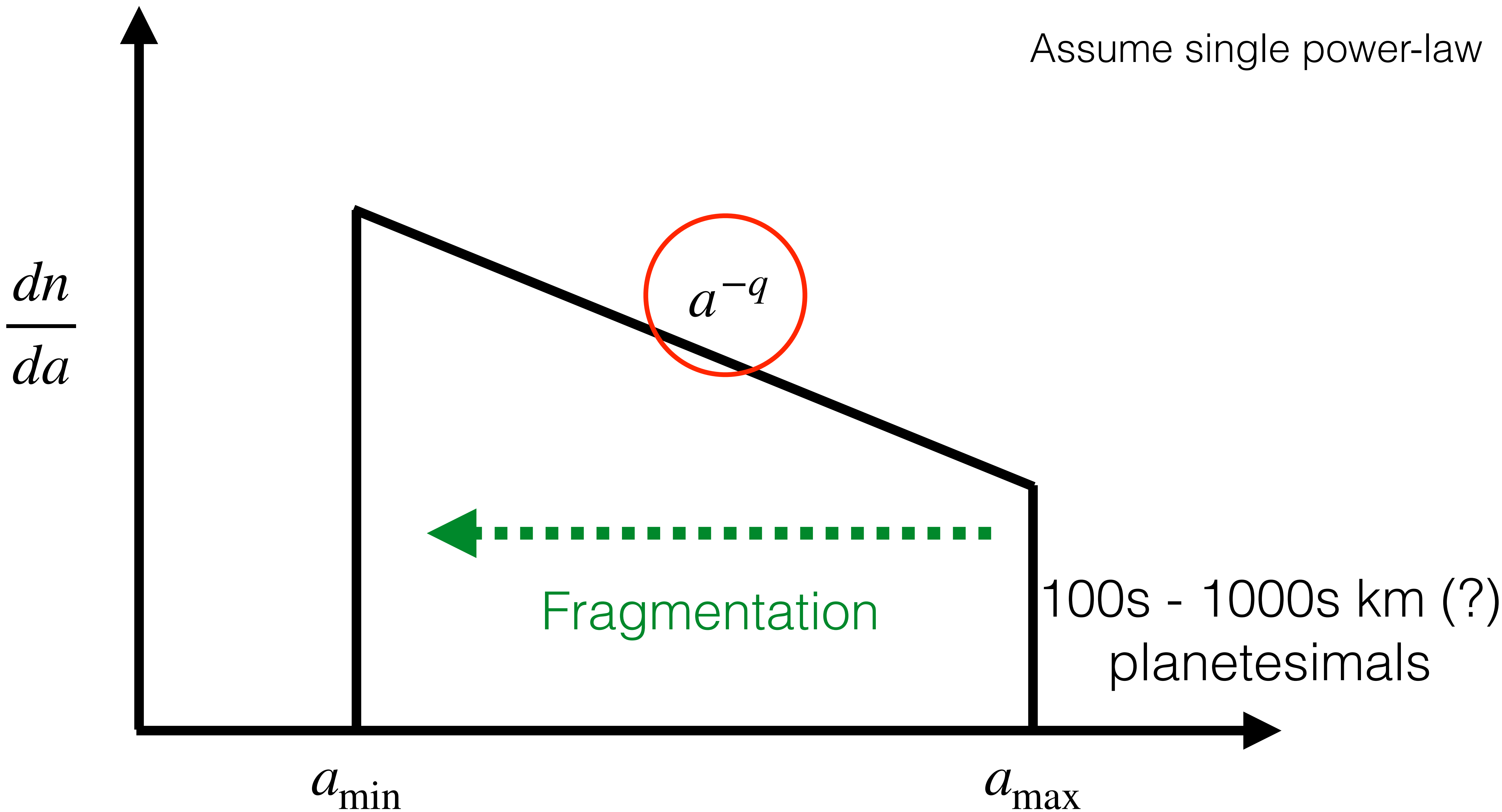
Grain size distribution in debris disk



Question: $a_{\rm min}$ and q in debris disk?

Grain size distribution power-law index q

- mm-wave flux (thermal) from debris dust (optically thin)

$$F_\nu = \kappa_\nu B_\nu(T_d) M_{\rm dust} d^{-2} \propto \nu^{\beta+2} \propto \nu^{\alpha_{\rm mm}}$$

Dust opacity: $\kappa_\nu \propto \nu^\beta$

Observed flux slope $\alpha_{\rm mm}$ depends on dust property β!

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- Approximate relation exists ($a_{max} >> \lambda$) (Draine 2006)

Observed mm-wave flux slope

$$q = \frac{\alpha_{\rm mm} - 2}{\beta_s} + 3$$

Power-law index q of grain size distribution

Opacity index at Rayleigh limit (Intrinsic material property)

$\beta_s \approx 1.7$ @ ISM

Opacity index in Rayleigh limit β_s

☑ 星間ダスト (a_{max}~0.1μm << mm波)

- 分子ガスが卓越するline of sightでβ=1.66

  (Planck Collaboration Int. XIV , 2014, A&A, 564, A45)

☑ **β_s := β in Rayleigh limit (x<<1)**

(a) 結晶質の絶縁体 (結晶質silicate/H_2O iceなど)

赤外線の格子振動のdamping wingによる吸収 (Lorentz model)

$\beta_s = 2$

(b) 導体/半導体 (graphiteなど)

自由電子によるエネルギー散逸 (Drude model)

$\beta_s = 2$

(c) 非晶質の絶縁体 (非晶質silicate/H_2O iceなど)

モデル化は発展途上, 主に室内実験で調べられている (e.g., Demyk+17')

性質) ・結晶質よりも大きな吸収係数

・温度依存性がある

No unique β

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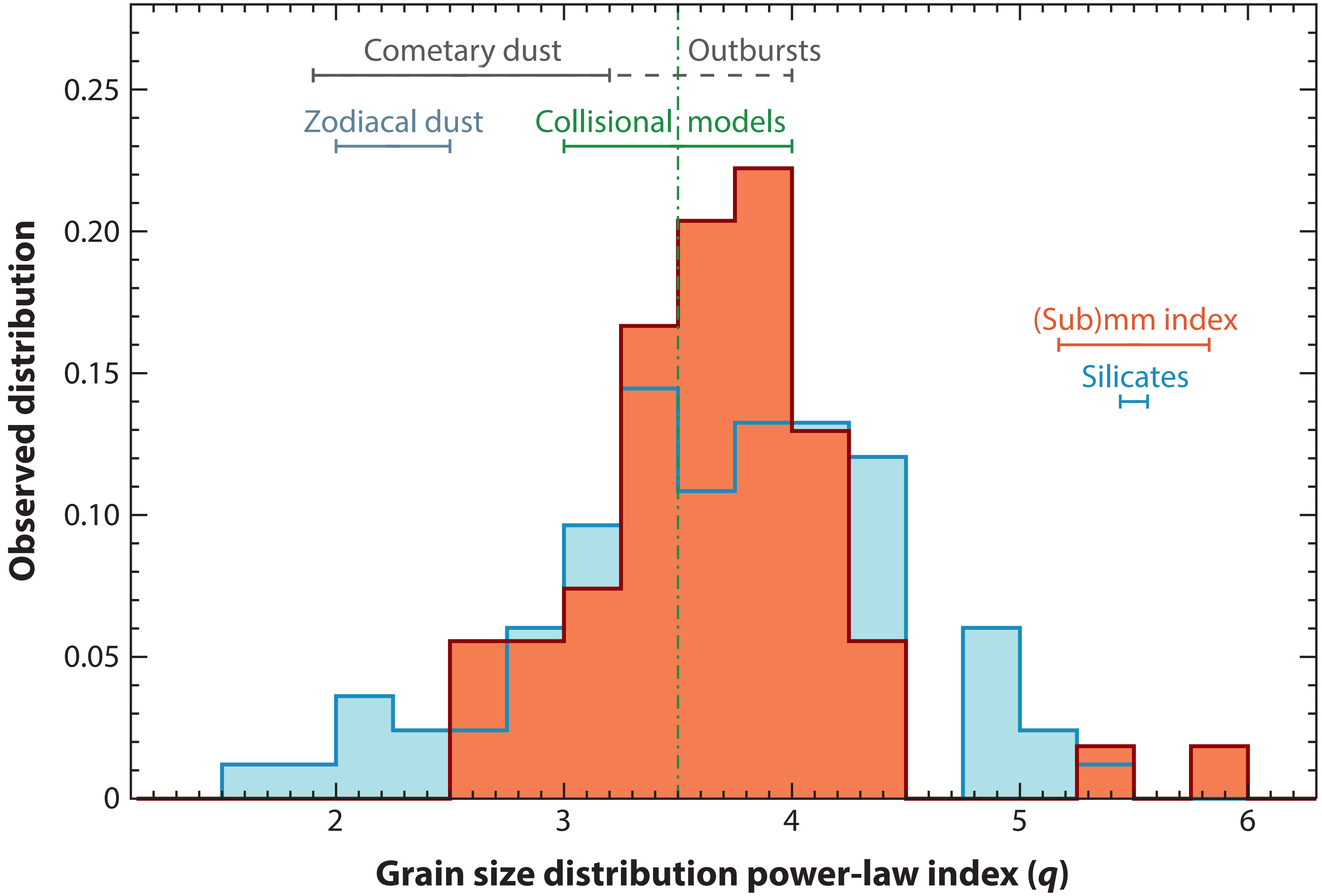
⇒ No unique β

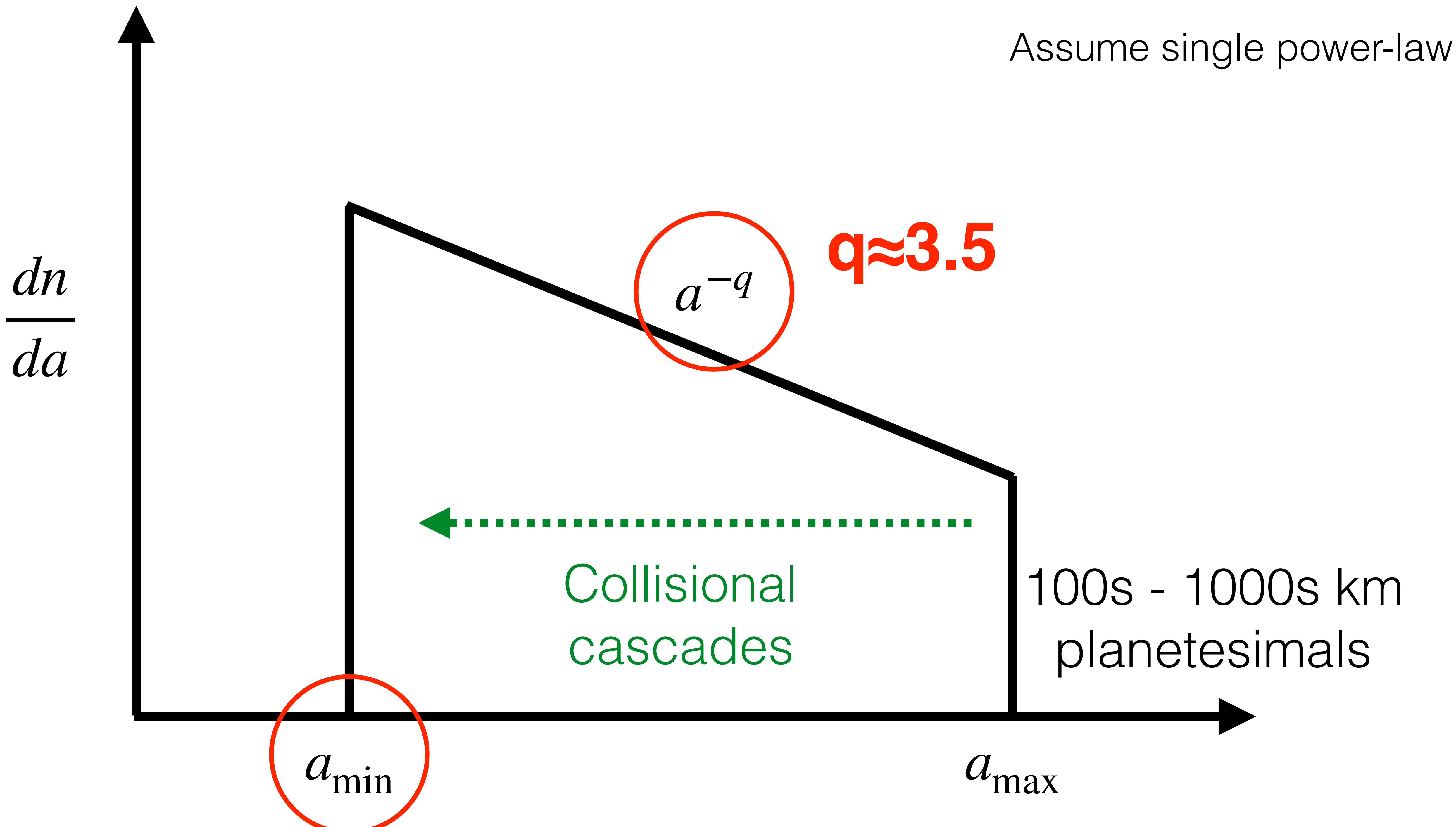
Grain size distribution power-law index

- Inferred power-law index q approximately coincides with collisional cascade models, which predicts q ≈ 3 - 4. (q=3.5: Dohnanyi+69, Tanaka+96)



Hughes et al. (2018) references therein

Grain size distribution in debris disk



Question: $a_{\min}$ and q in debris disk?

Minimum size: blown-out size by stellar radiation pressure

- Specific orbital energy of a particle (circular orbit)

$$\frac{v^2}{2} - (1-\beta)\frac{GM}{r} \geq 0, \quad \beta = \frac{F_{\rm RP}}{F_{\rm grav}} \;\Rightarrow\; \beta \geq 0.5$$

unbound

- Ratio of radiation pressure and stellar gravity (both ∝ r^{-2})

$$\beta \simeq 0.2\langle Q_{\rm pr}\rangle_\star \left(\frac{a}{1\ \mu{\rm m}}\right)^{-1}\left(\frac{L_\star/M_\star}{L_\odot/M_\odot}\right)$$

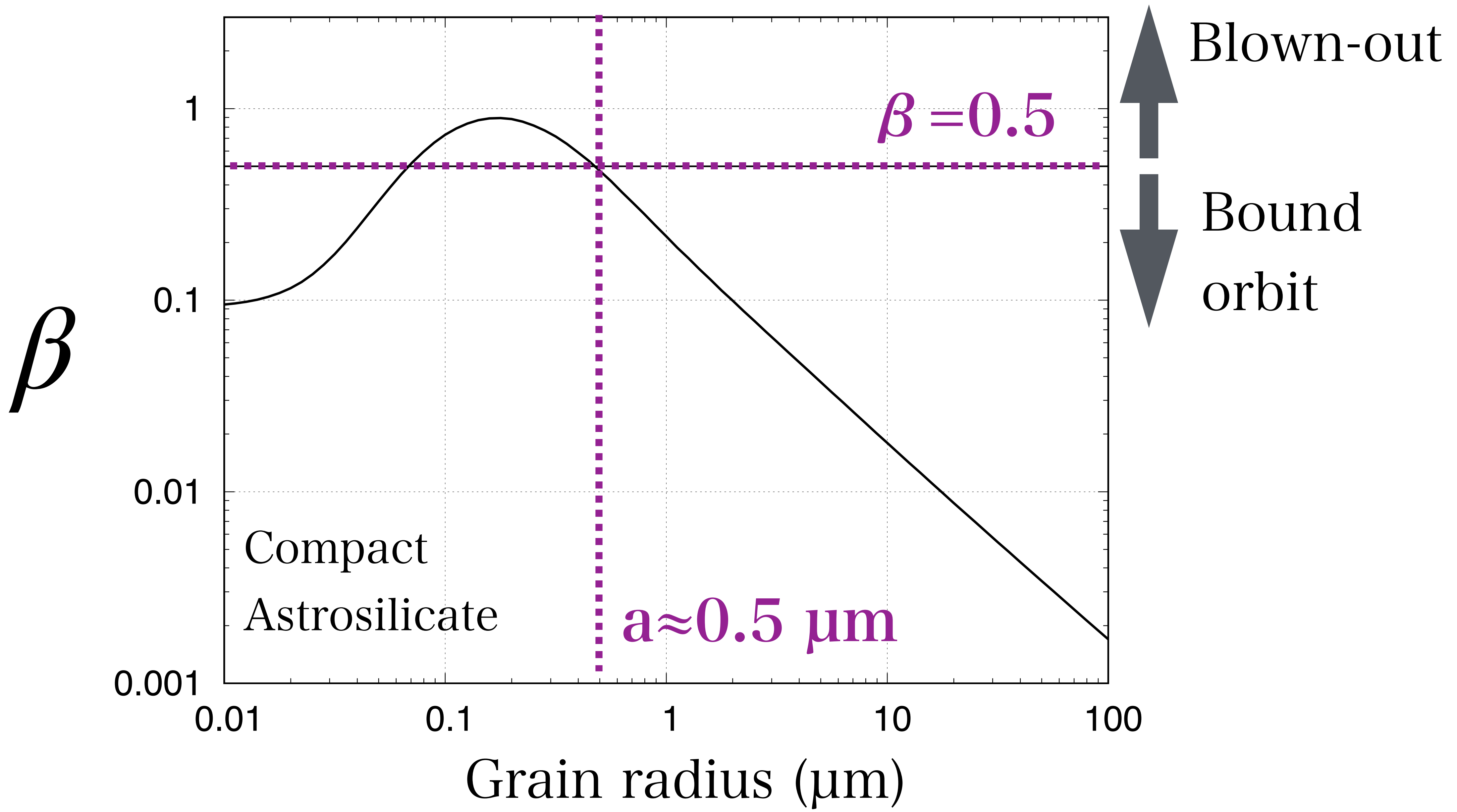
$$\Rightarrow\; a_{\rm min} \simeq 0.4\ \mu{\rm m}\langle Q_{\rm pr}\rangle_\star \left(\frac{L_\star/M_\star}{L_\odot/M_\odot}\right) \quad \text{with } \beta = 0.5$$

$$a_{\rm min} \propto L_\star^{3/4} \quad \text{with } L_\star \propto M_\star^4$$

Small grains are blown out from the system

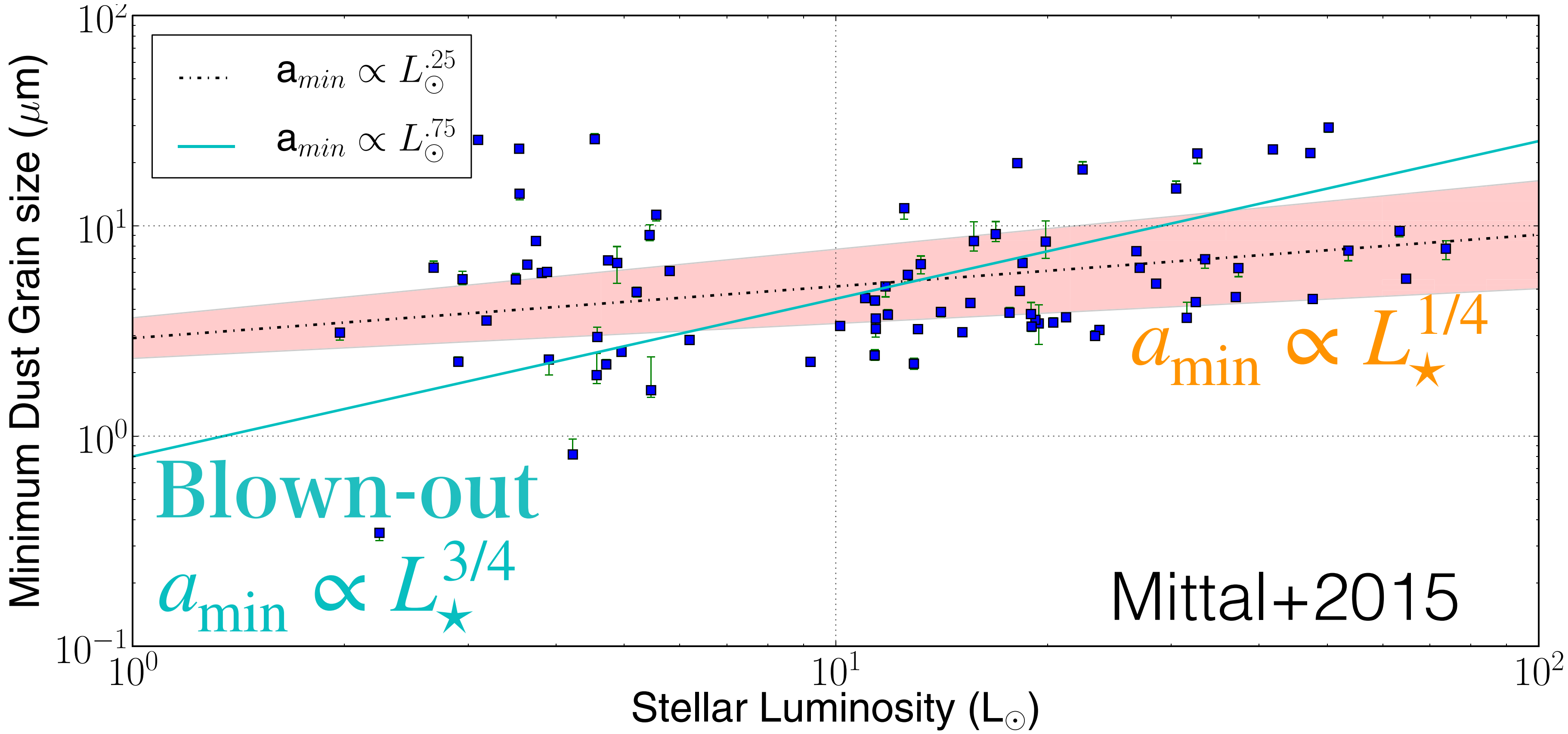
Example of the β-value

- <Qpr> (and then β) drops in the Rayleigh domain
- β-value depends on optical constant and dust structure (e.g., Mukai et al. 1992)



Minimum size of dust: observations

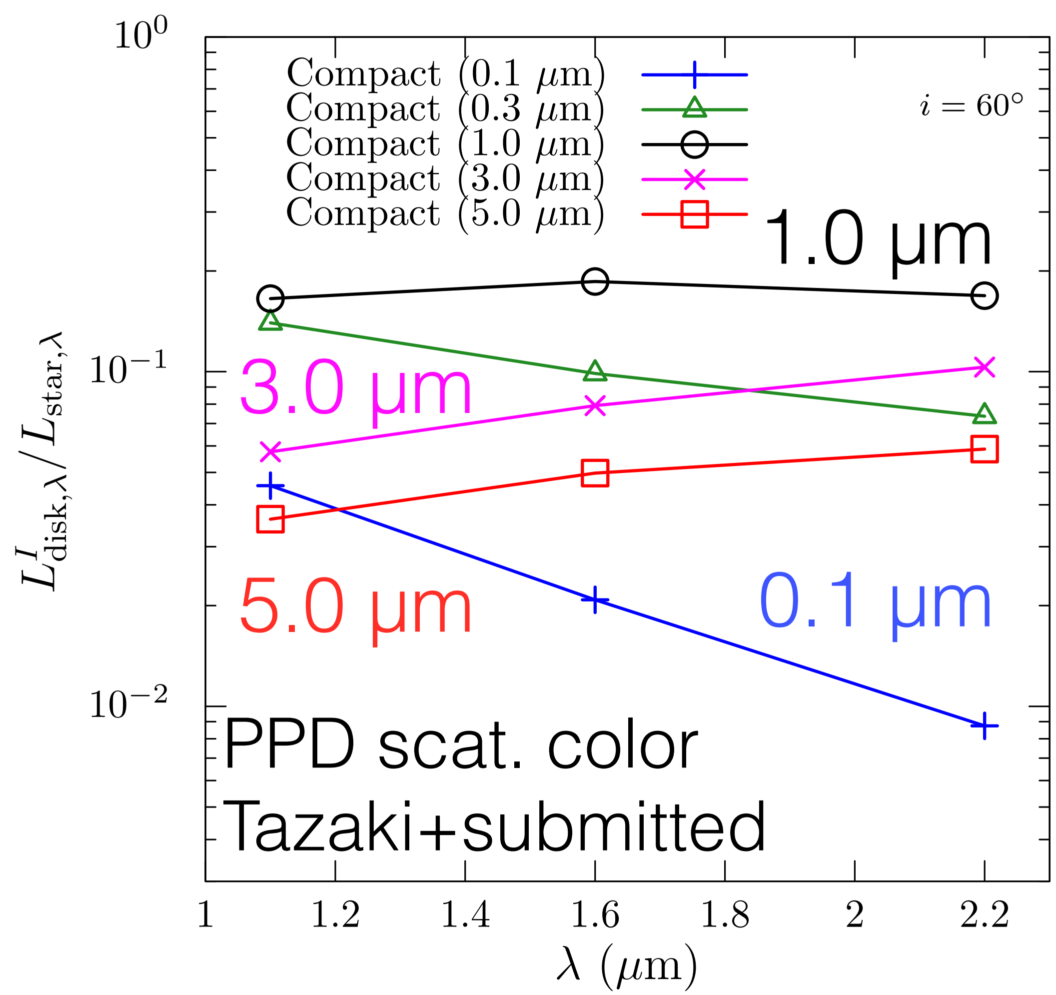
- MIR silicate feature constrains minimum dust grains
- Derived minimum size: ≈ 0.3 μm - 40 μm (Mittal+15)
- Positive correlation between a_{min} & stellar luminosity
- But dependence is shallower than that of blown-out size

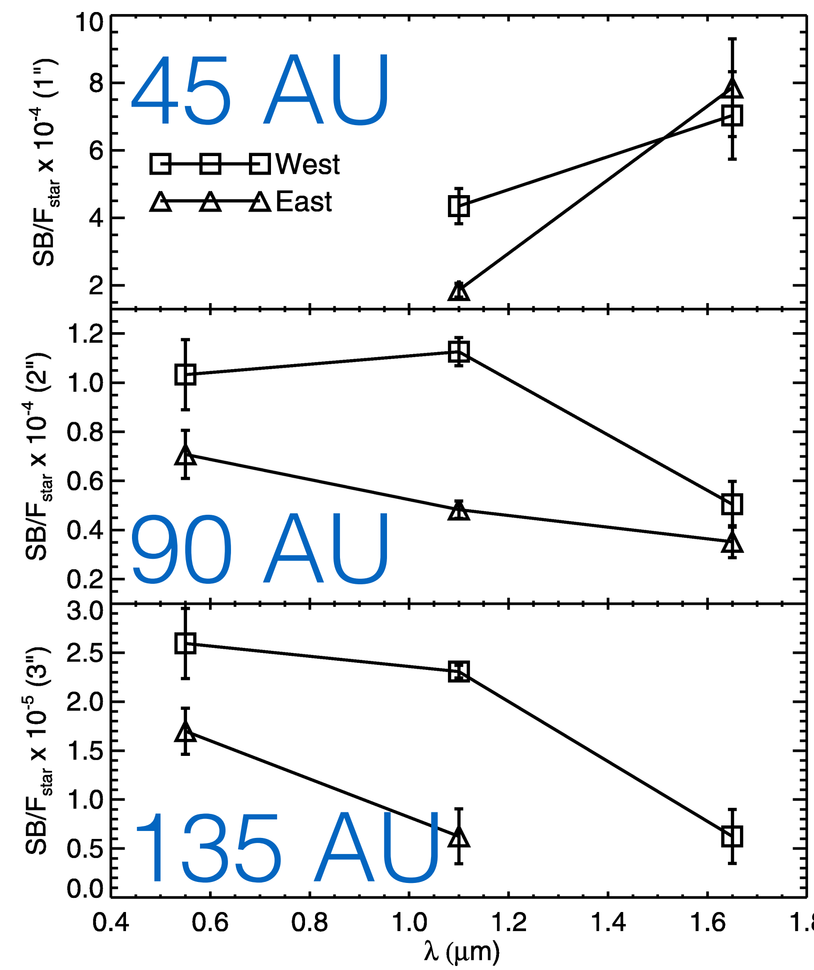


Inconsistent with radiation pressure prediction!

Blown-out small grains: halo component

- Outer debris disk show blue colors (Debes+08)
  = “halo of small grains”
- Small grains (compared to λ)
  show blue colors (Rayleigh scatt.)





Debes+2008

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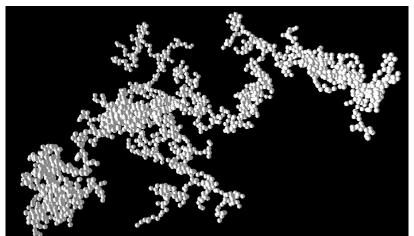
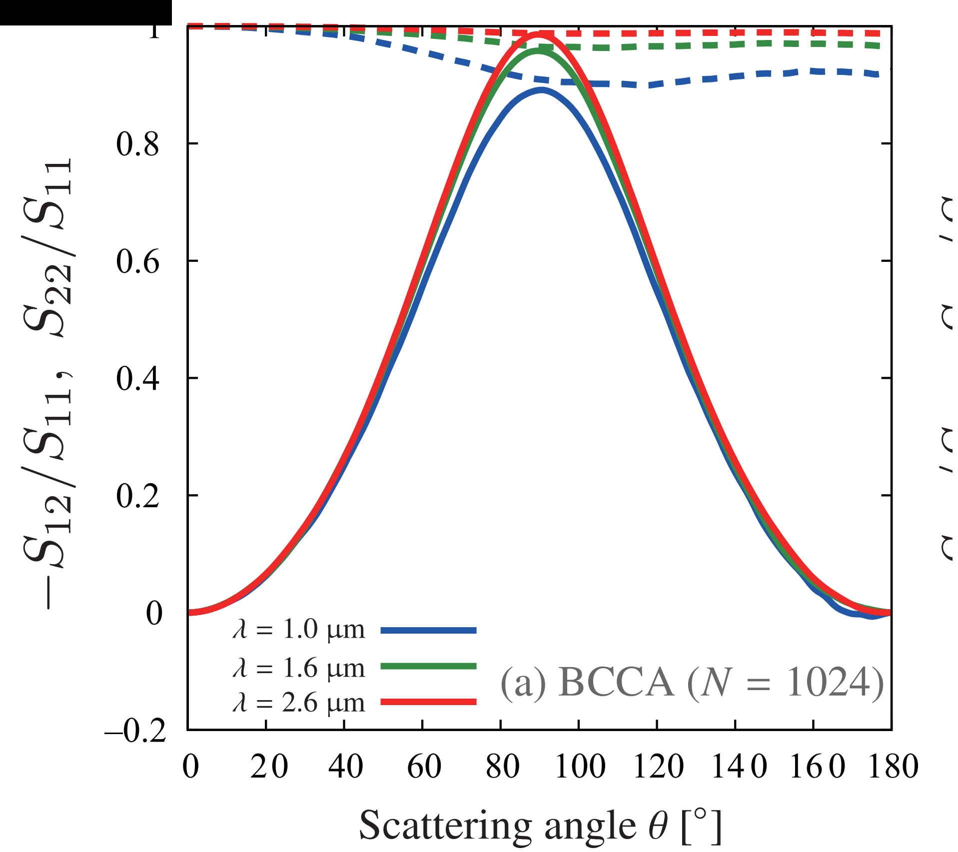
Probing dust structure: linear polarization

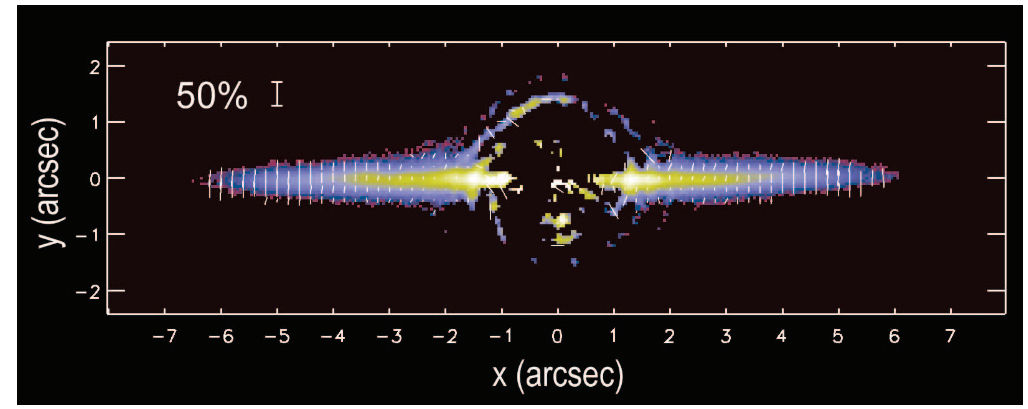
fluffy aggregate (df=1.9)
2πR/λ~ 23, P(θ=90°) ~ 80%

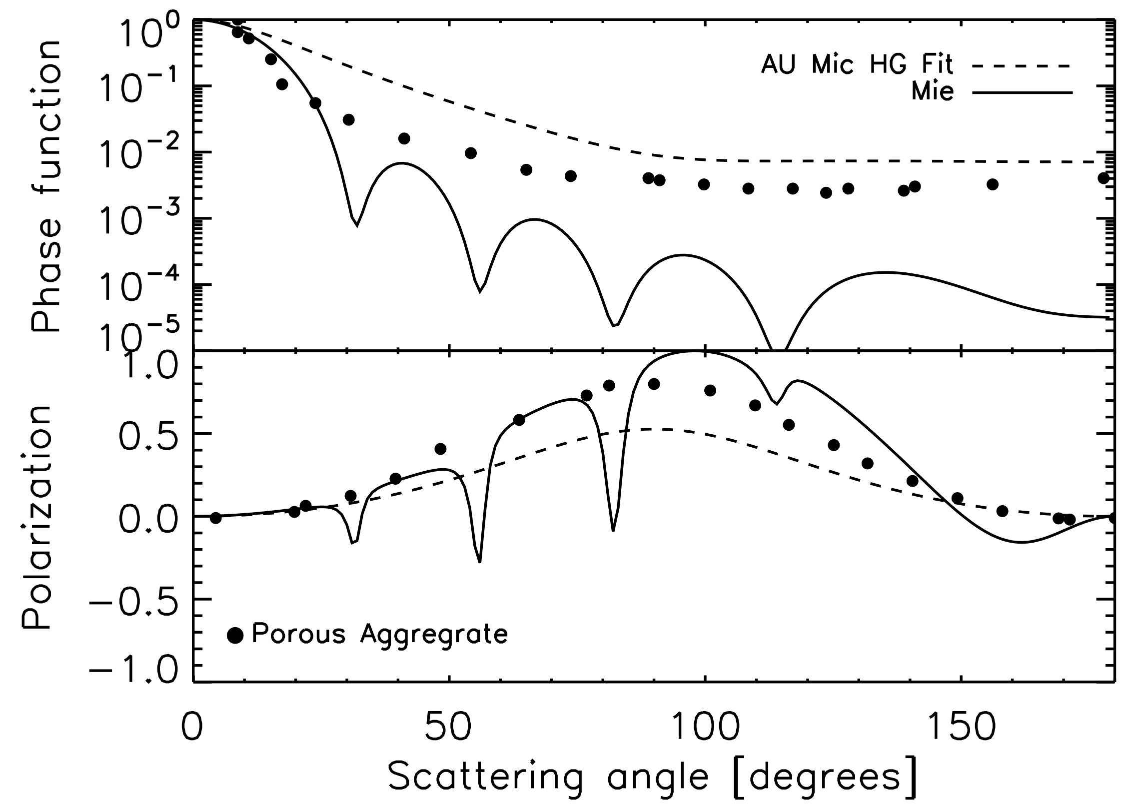


Tazaki+2016



Graham+2007



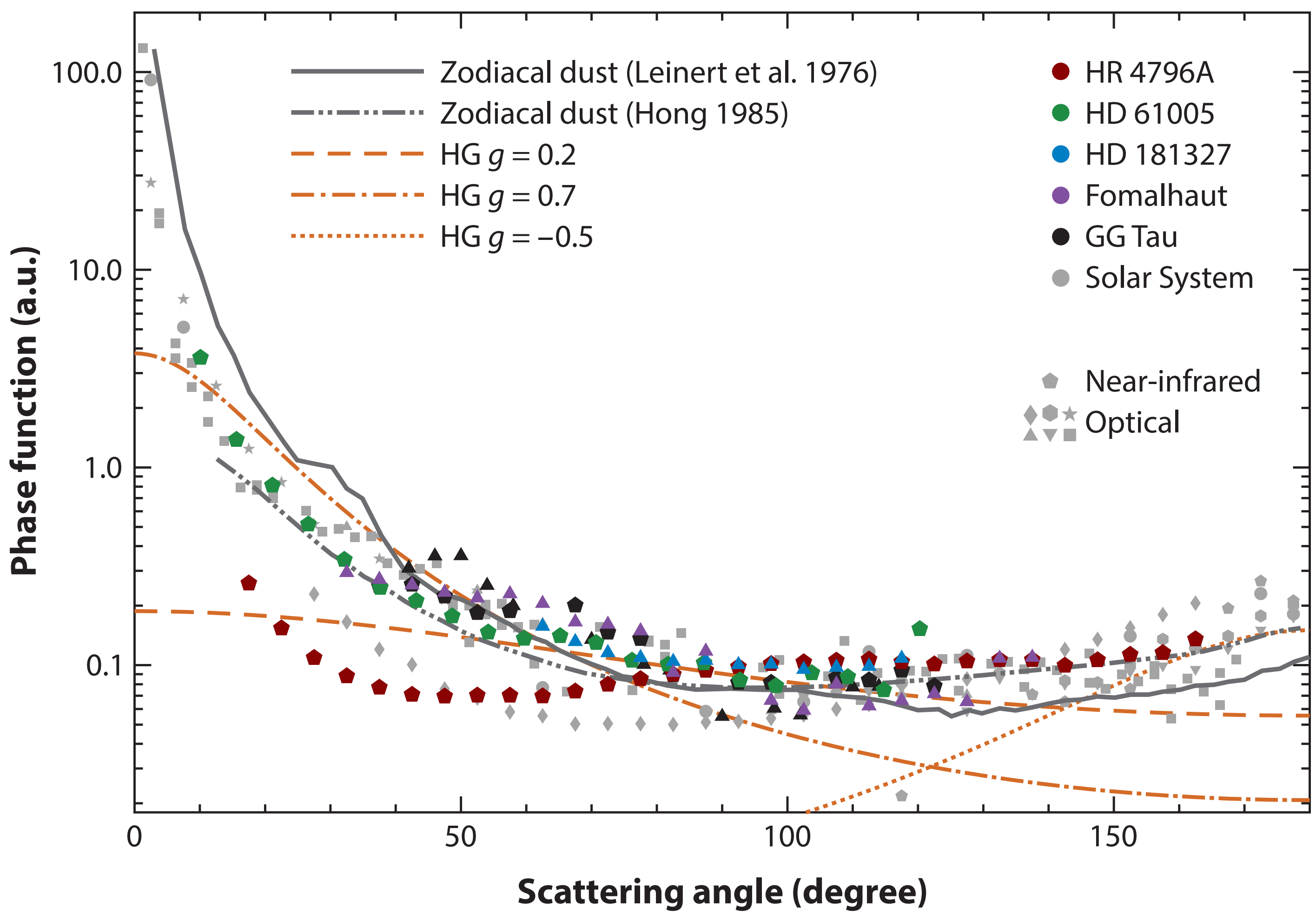


High polarization fraction of AU Mic indicates the presence of fluffy aggregates

Phase function of debris dust

- Most disk show similar phase function
- Phase function becomes almost flat at side and back scattering.
  - Henyey-Greenstein function cannot reproduce this trend.

Hughes et al. (2018)



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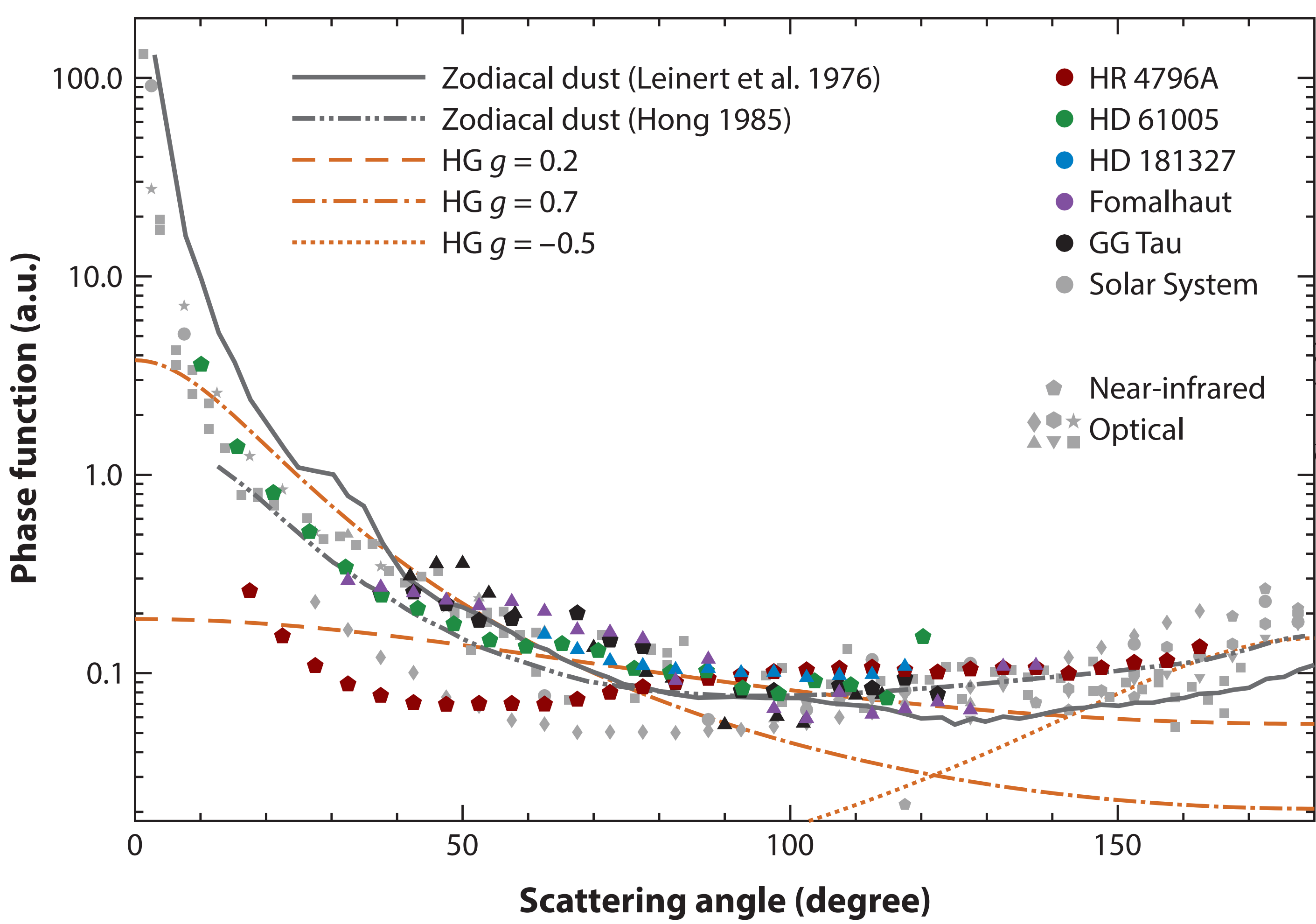
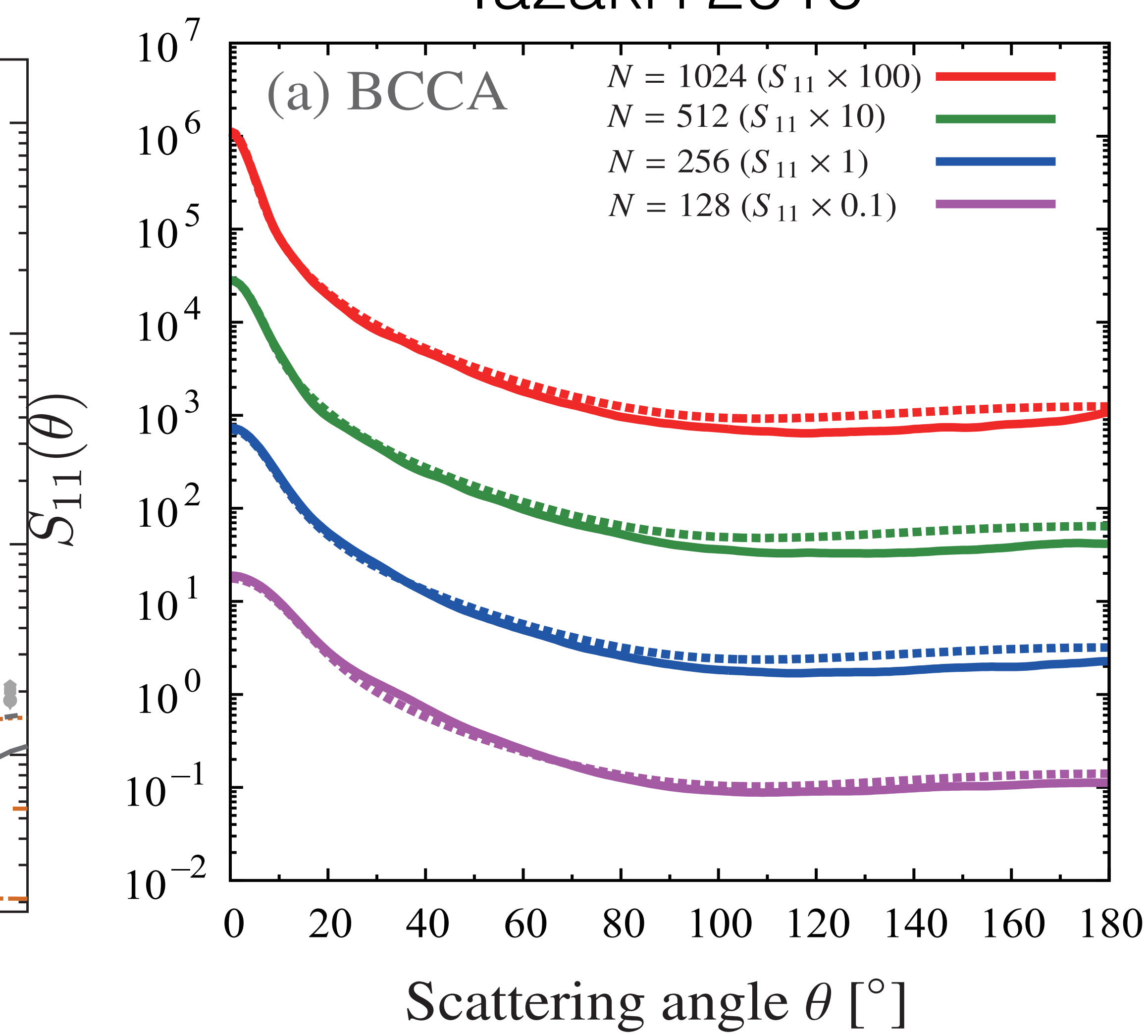


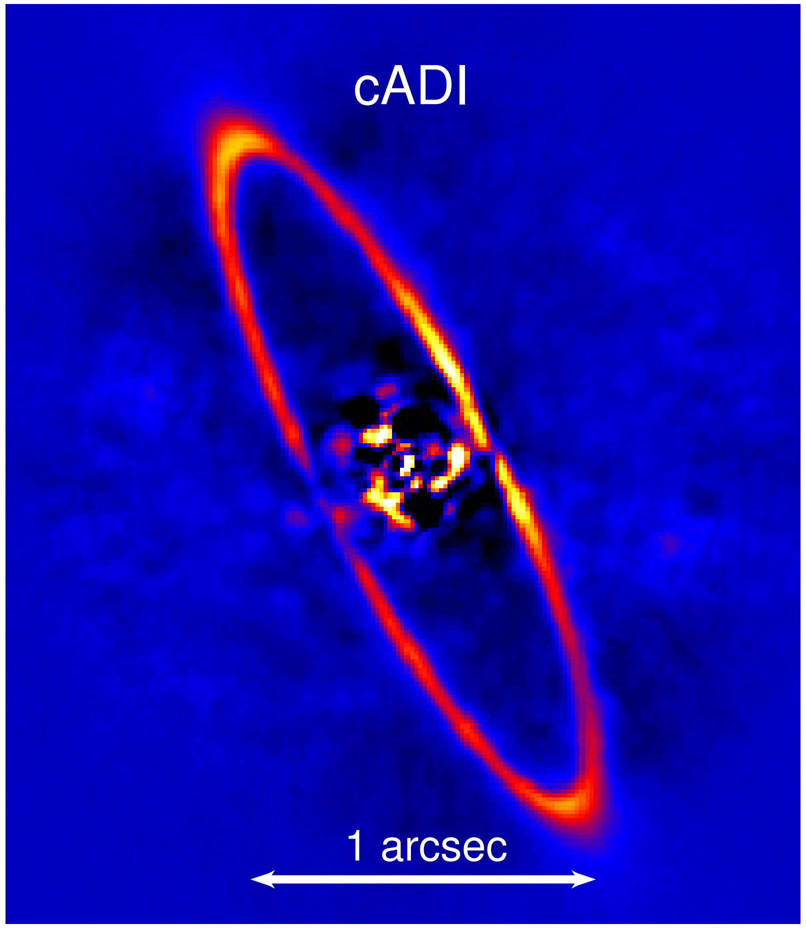
Tazaki+2016

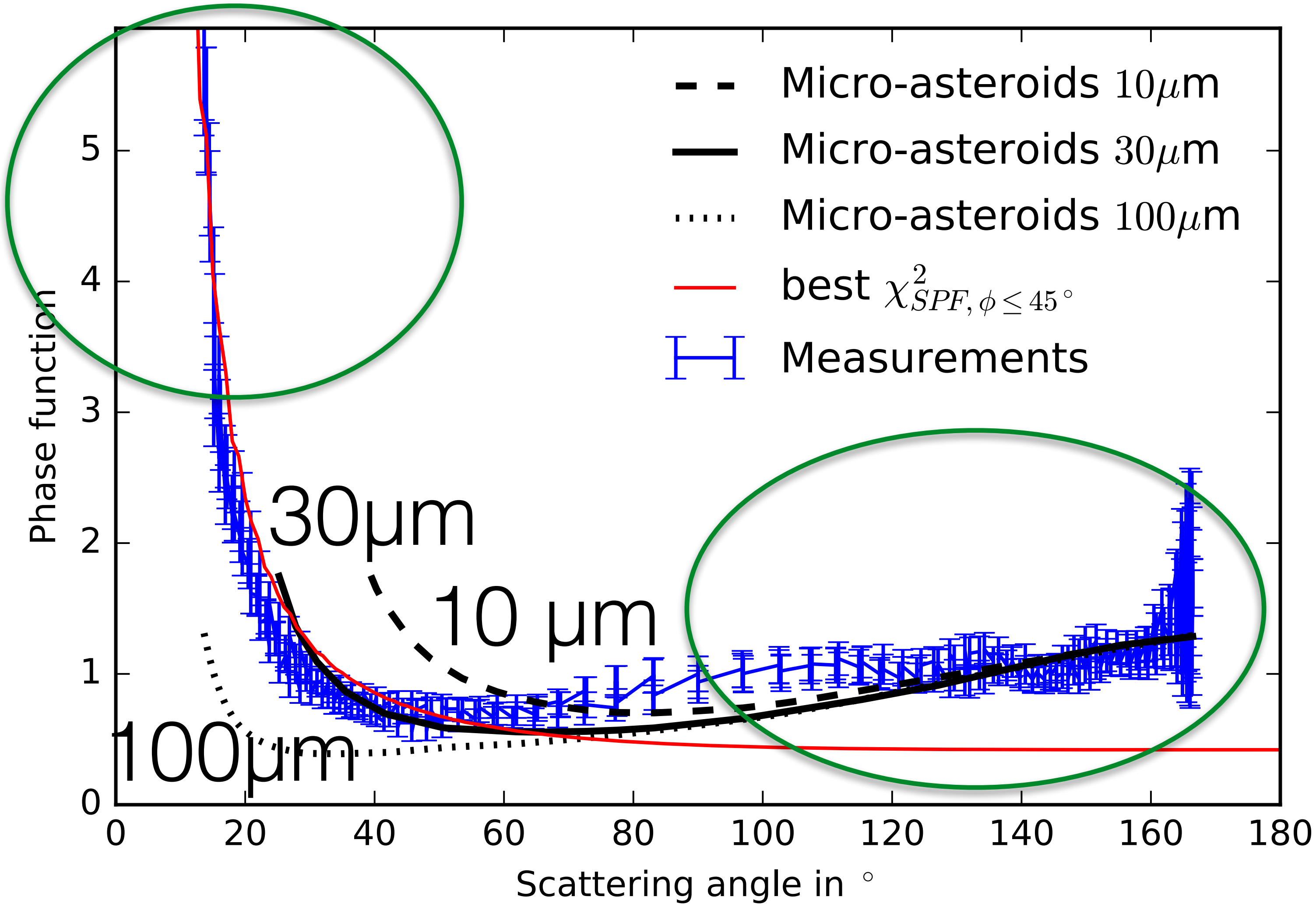


Fluffy aggregates show flat phase function!

Exception: HR 4796A

Milli+2017

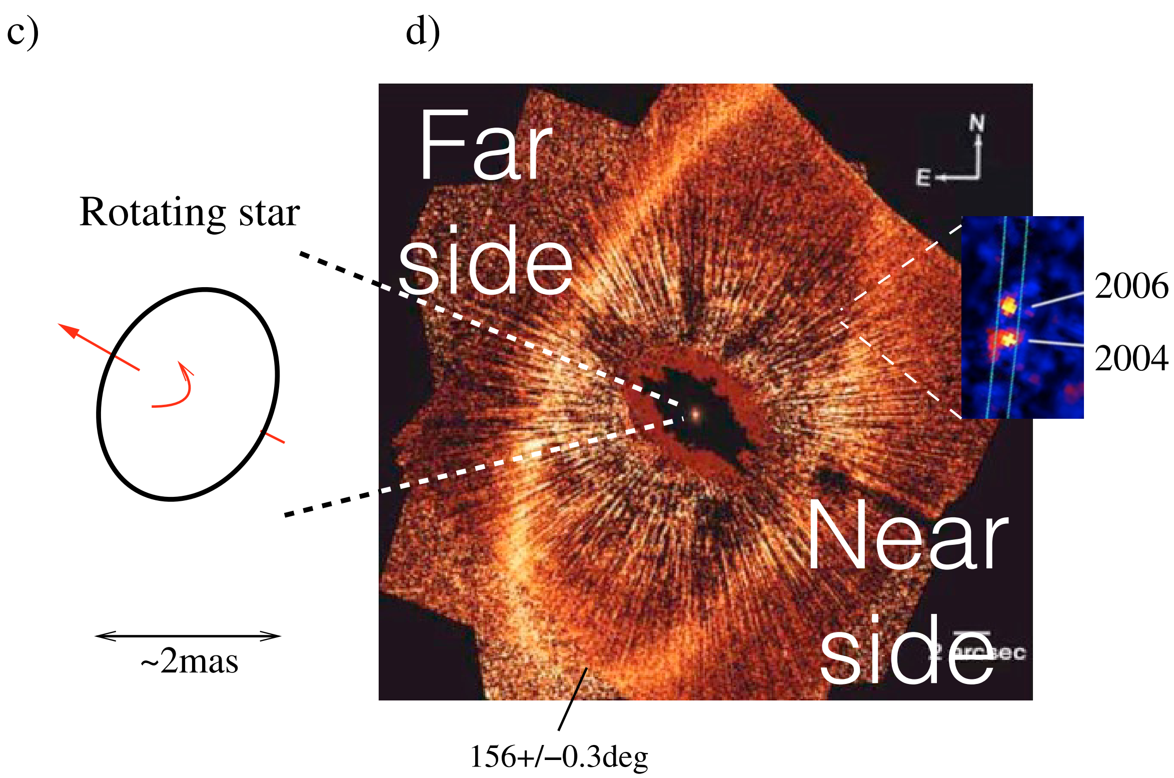




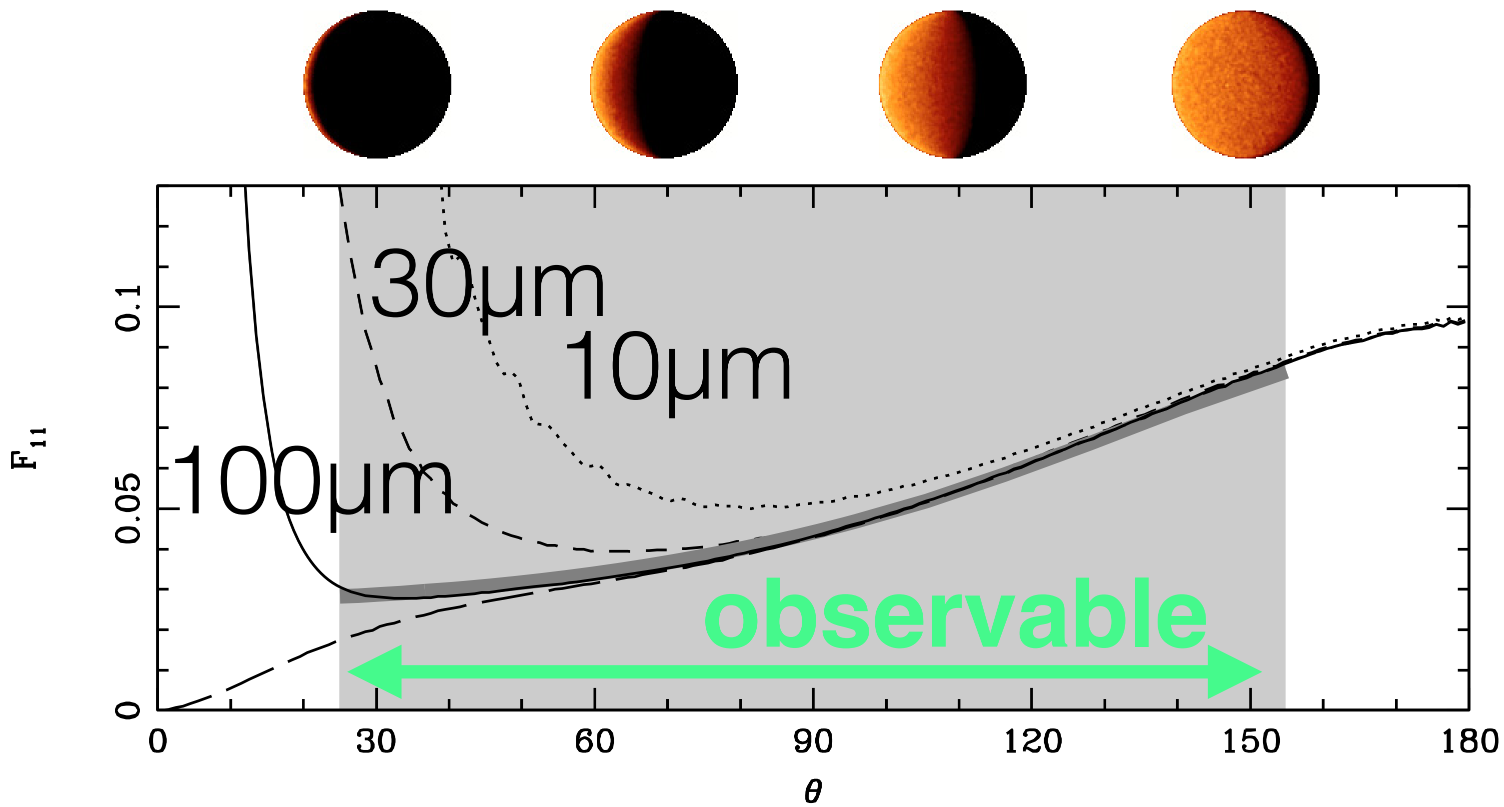
- Phase function with strong forward scattering AND continuous increase at side- and back-scattering are detected.
  → consistent with phase function of 30 μm-sized grains

Enhanced backscattering: Fomalhaut

Le Bouquin+2009



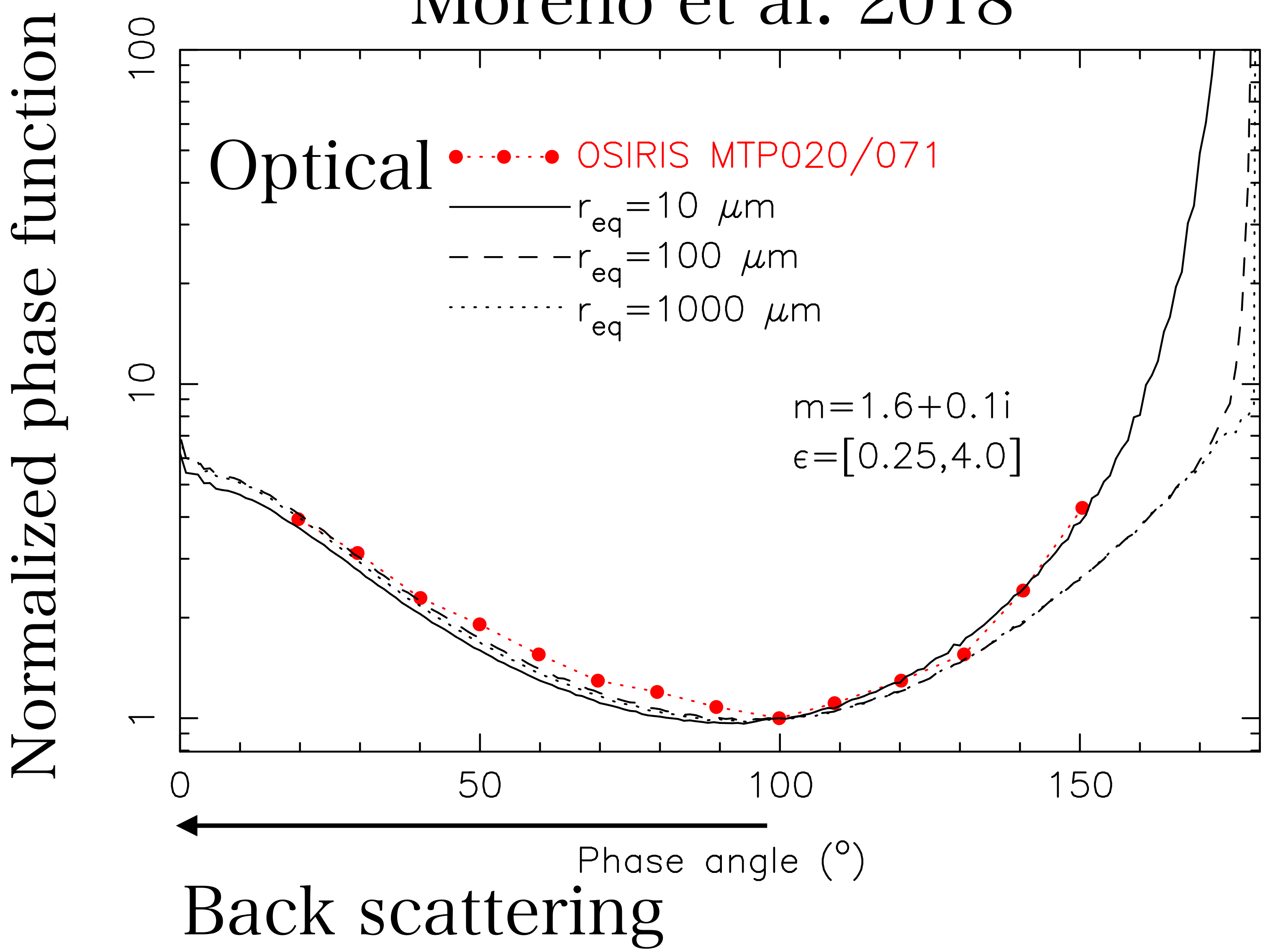
Min+2010

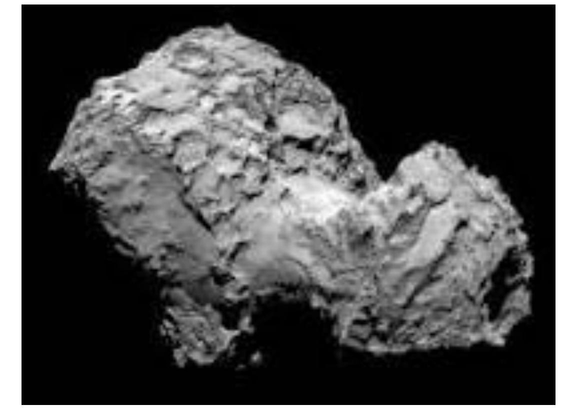


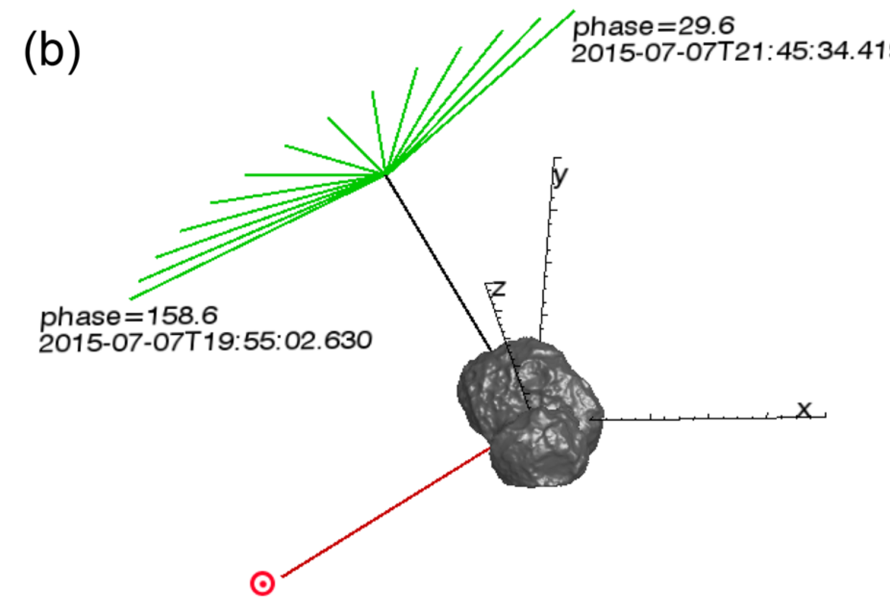
- The bright side might be <u>the far side</u> of Fomalhaut (Le Bouquin+2009)
- <u>Suppose this is true</u>, large grains (>100 μm) can explain a continuous increase of phase function at side- and back-scattering region (Min+2010) (like lunar phase!).

Phase function of dust coma of comet 67P: Rosetta/OSIRIS observations

Moreno et al. 2018







Bertini et al. 2017

Large (>10 μm) elongated particles aligned their long axes perpendicular to the solar radiation can reproduce OSIRIS obs.

§3.millimeter-wave dust opacity

“Standard value” of mm-wave opacity

- Beckwith et al. (1990)
  - mm波における原始惑星系円盤のダスト連続光サーベイ観測論文
  - ダスト不透明度として以下の値を採用 (“**業界標準値**”)

$$\kappa_\nu = 2\ \mathrm{cm}^2\ \mathrm{g}^{-1} \left(\frac{\lambda}{1.3\ \mathrm{mm}} \right)^{-\beta},\ \beta = 1$$

  - 観測的には大きな矛盾はない(と思われる, e.g., SED, disk mass)
  - なんらかの具体的なダスト・モデルに基づいた値ではない
- cf.) Beckwith+90のopacity値は星間ダストの値よりも約１桁大きい

$$\kappa_\nu = 0.21\ \mathrm{cm}^2\ \mathrm{g}^{-1} \left(\frac{\lambda}{1.3\ \mathrm{mm}} \right)^{-\beta},\ \beta = 1.68$$

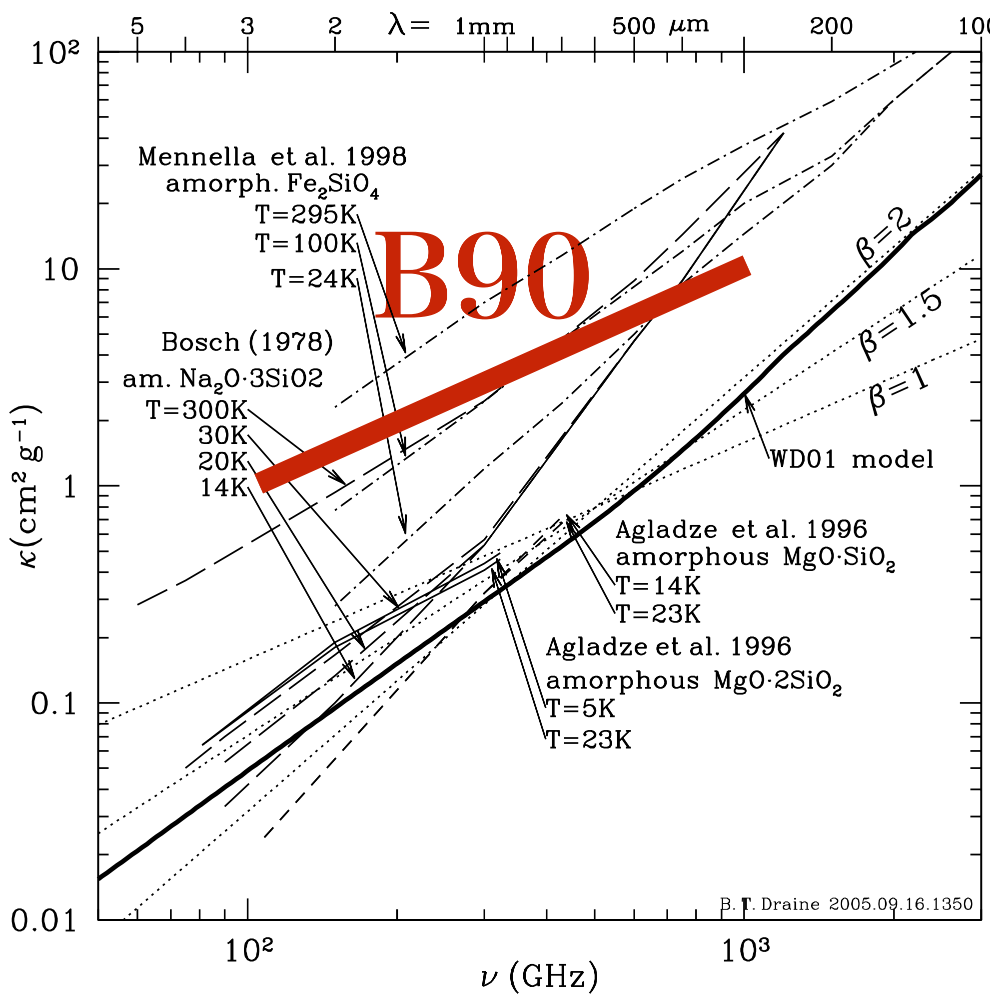
Li & Draine (2001)

Opacity: Amorphous silicate

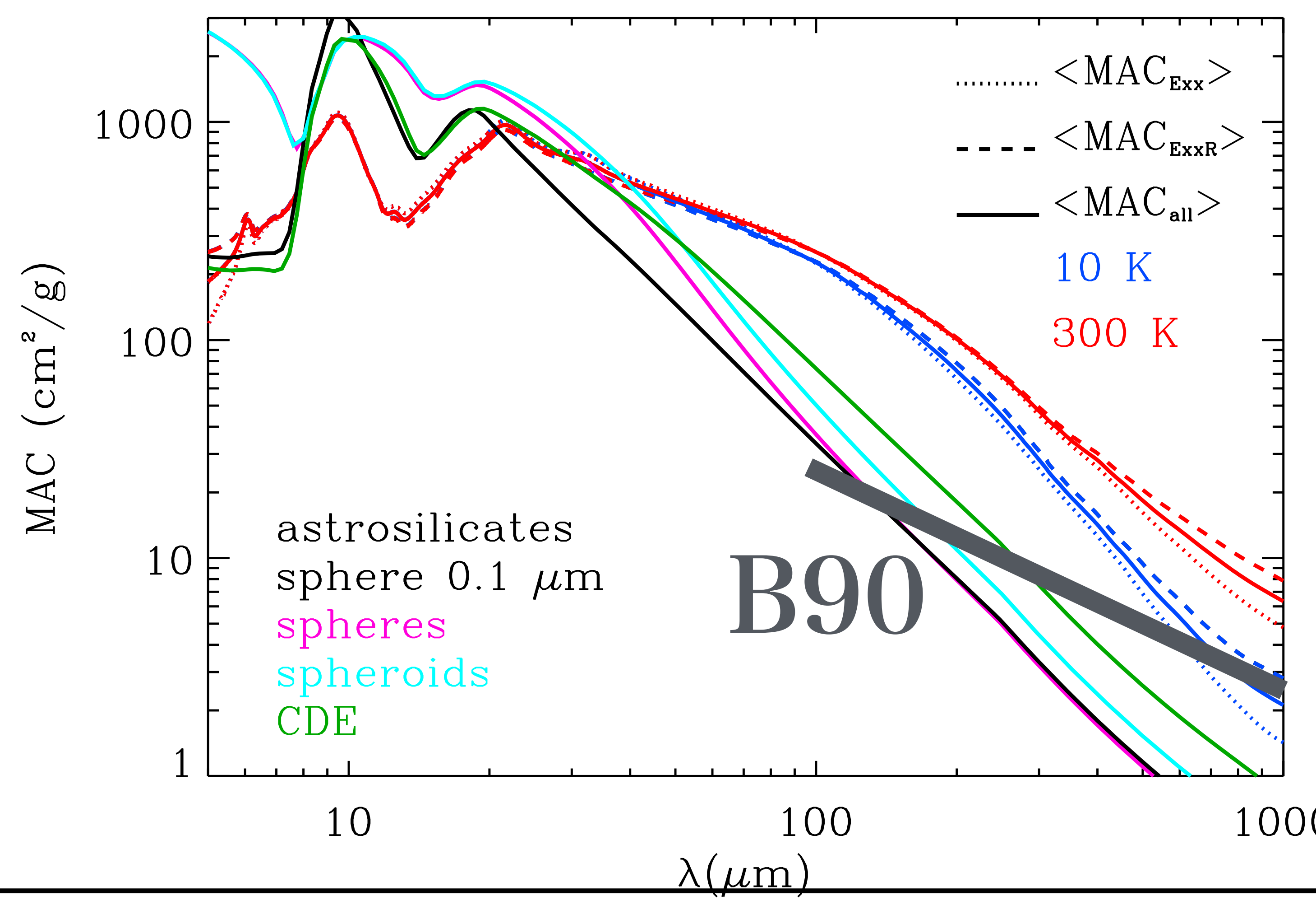
- Lab. measurement: $0.2\ \mathrm{cm^2\ g^{-1}} \lesssim \kappa_{\rm abs} \lesssim 10\ \mathrm{cm^2\ g^{-1}}$ @ $\lambda = 1$ mm
- Beckwith+90: $\kappa_{\rm abs} = 2.6\ \mathrm{cm^2\ g^{-1}}$ @ $\lambda = 1$ mm

B90 opacity: Within the range of Lab. measured opacity

Draine 2006



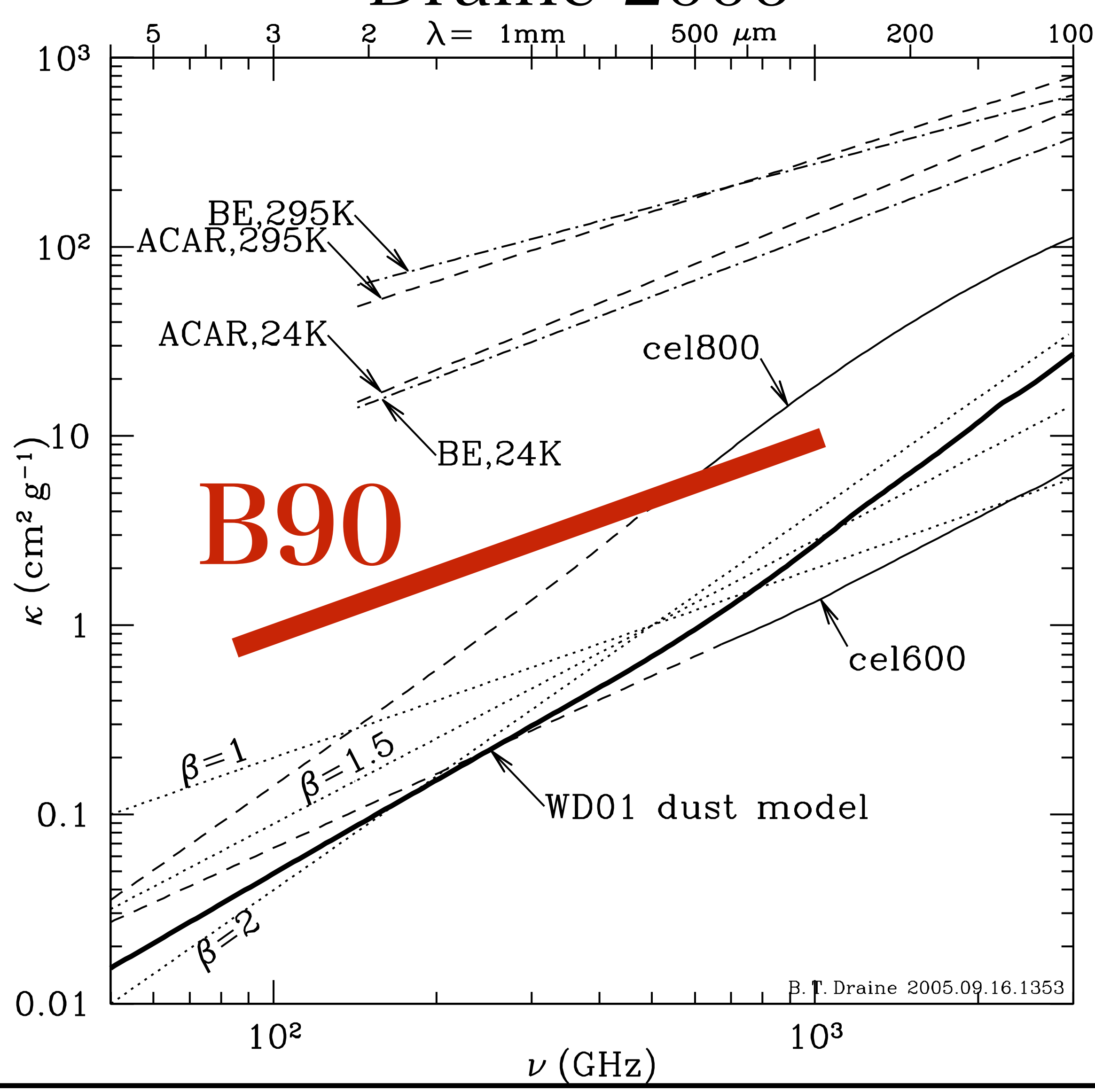
Demyk et al. 2017



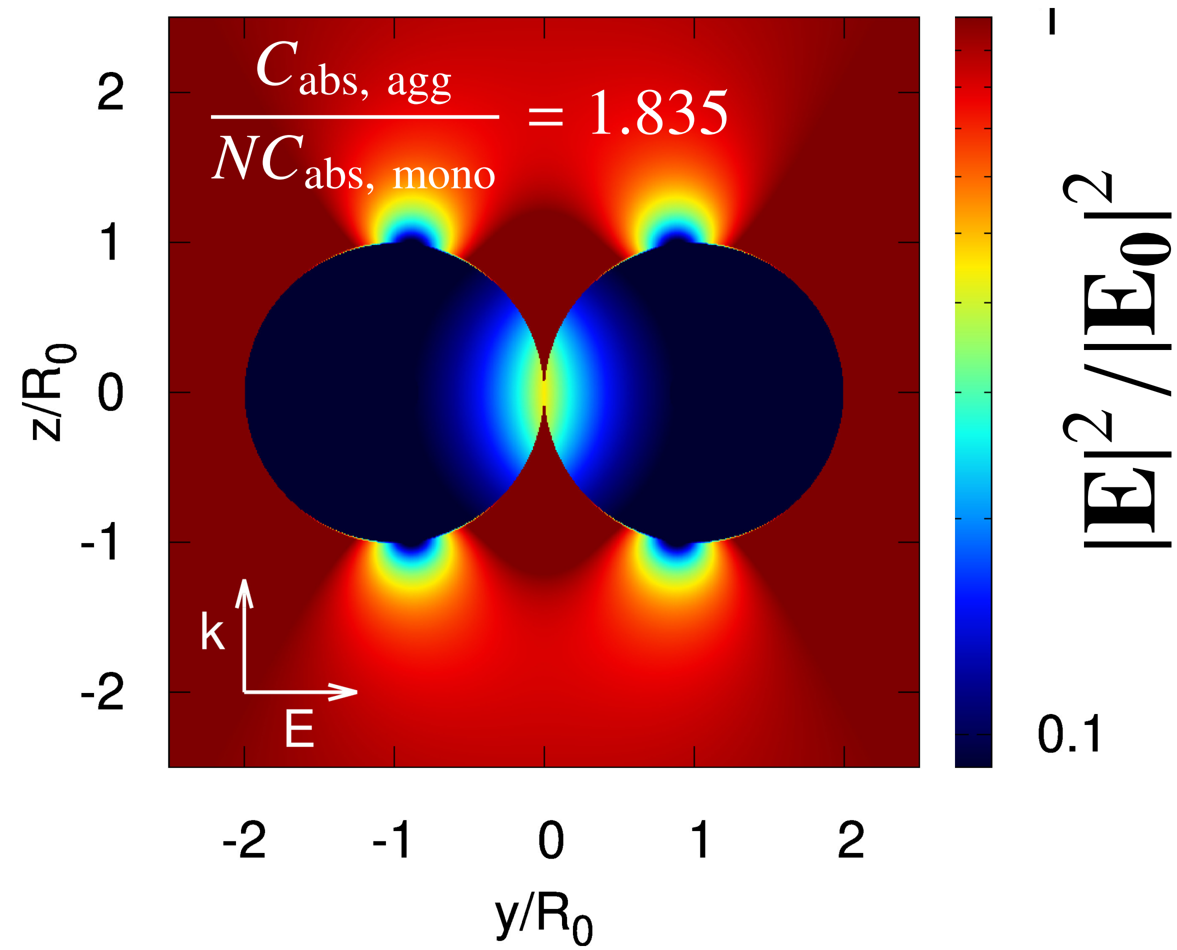
Opacity: Carbonaceous material

- Lab. measurement: $\kappa_{abs} \approx 25 - 30 \text{ cm}^2 \text{ g}^{-1}$
- ≈10 times larger larger than Beckwith's opacity value
- Presumably due to connection effect (Tazaki & Tanaka 18', references therein).

Draine 2006

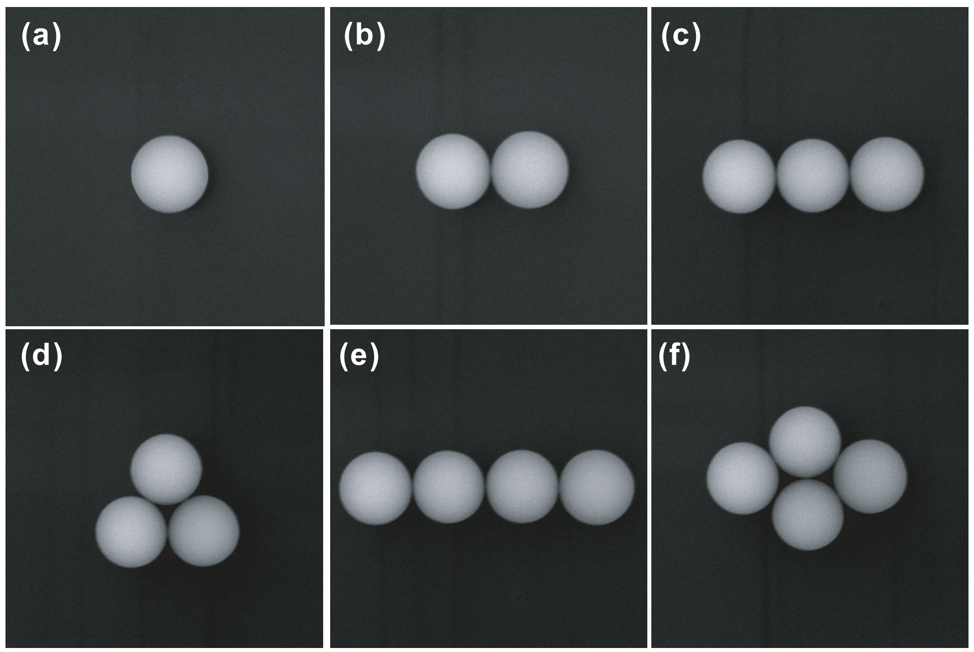


Tazaki & Tanaka 2018

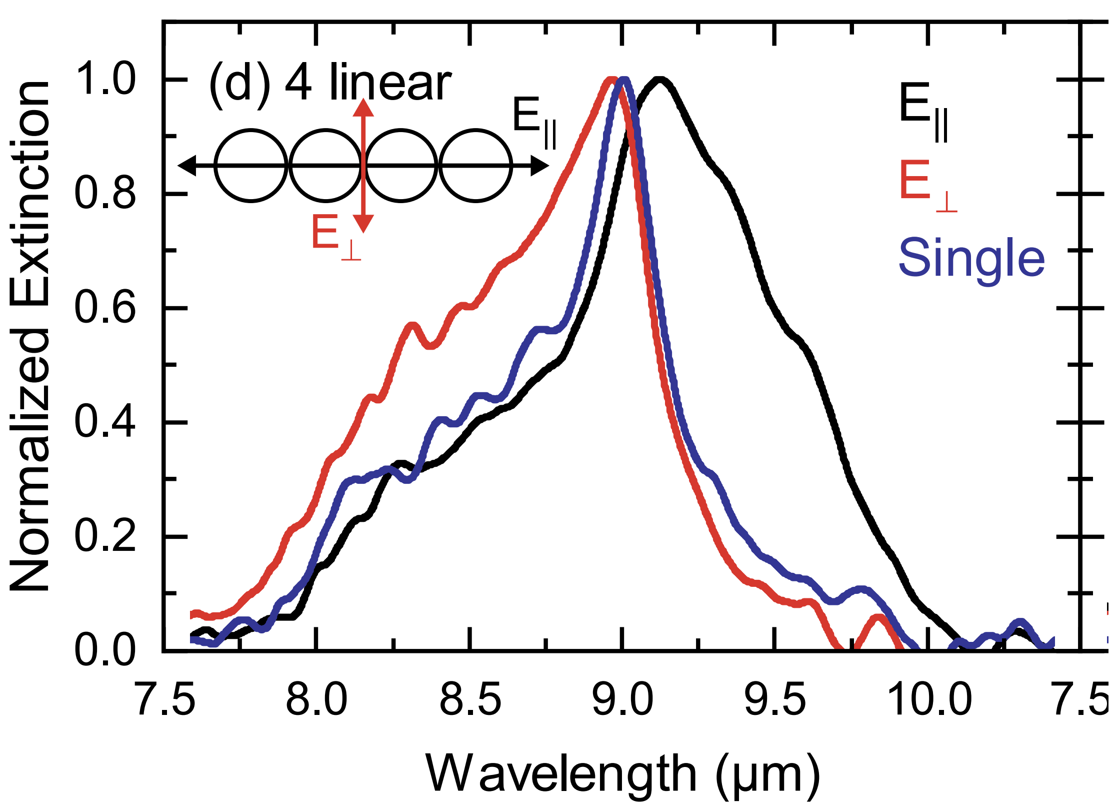


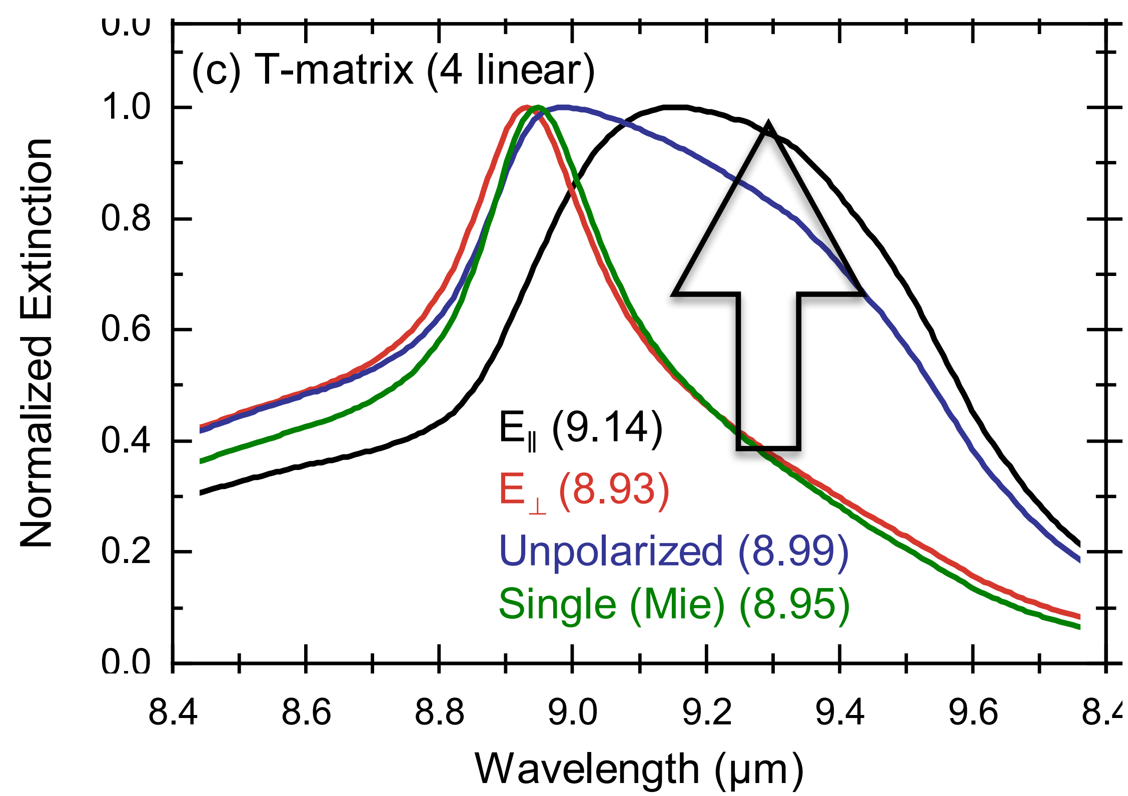
Effect of aggregation: silicate feature

Tamanai, …, Tazaki et al. 2018, A&A, 619, A110



- Lorentz-model : dielectric function becomes large at $\lambda > \lambda_c$
- Connection (proximity) effect makes "shoulder" in the feature





Summary

- Dust grains in debris disks contain amo/cry silicate, although constraints on other species are still weak.
- Grain size distribution power-law index seems to be consistent with collisional cascade models ($q \approx 3$-4)
- Minimum grain size in debris disk is not determined only by stellar radiation pressure. Importance of gas??
- Scattering phase function looks similar for some debris disks, indicating that porous structure of debris dust might be common.
- Beckwith+90's millimeter-wave opacity ("standard value") seems to be comparable to the opacity of amorphous silicate, but roughly 10 times smaller for carbonaceous composition.