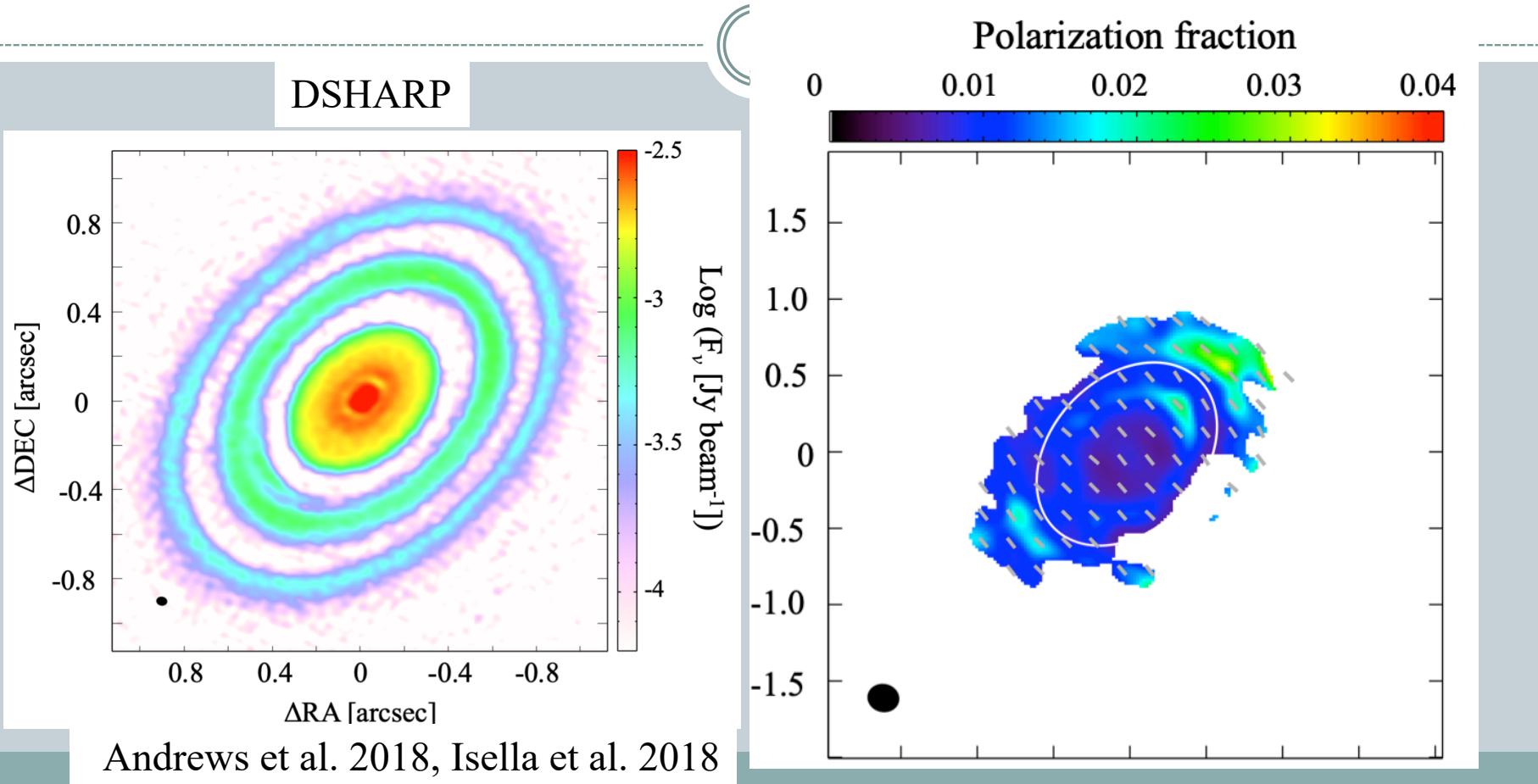


Radial variations of grain sizes and dust scale heights on the protoplanetary disk of HD 163296

Satoshi Ohashi
(RIKEN SPDR)

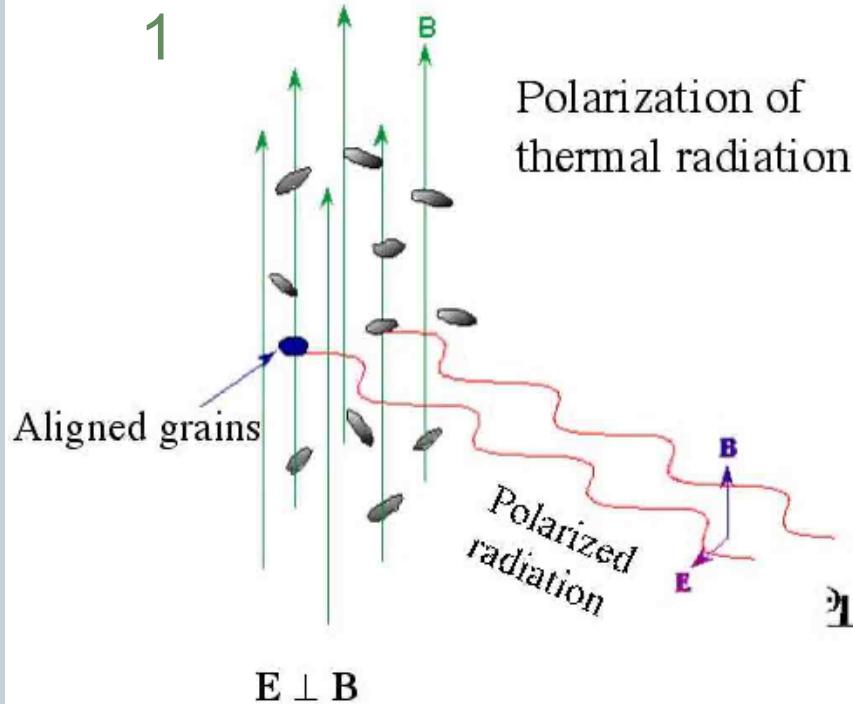


Main mechanisms of polarization

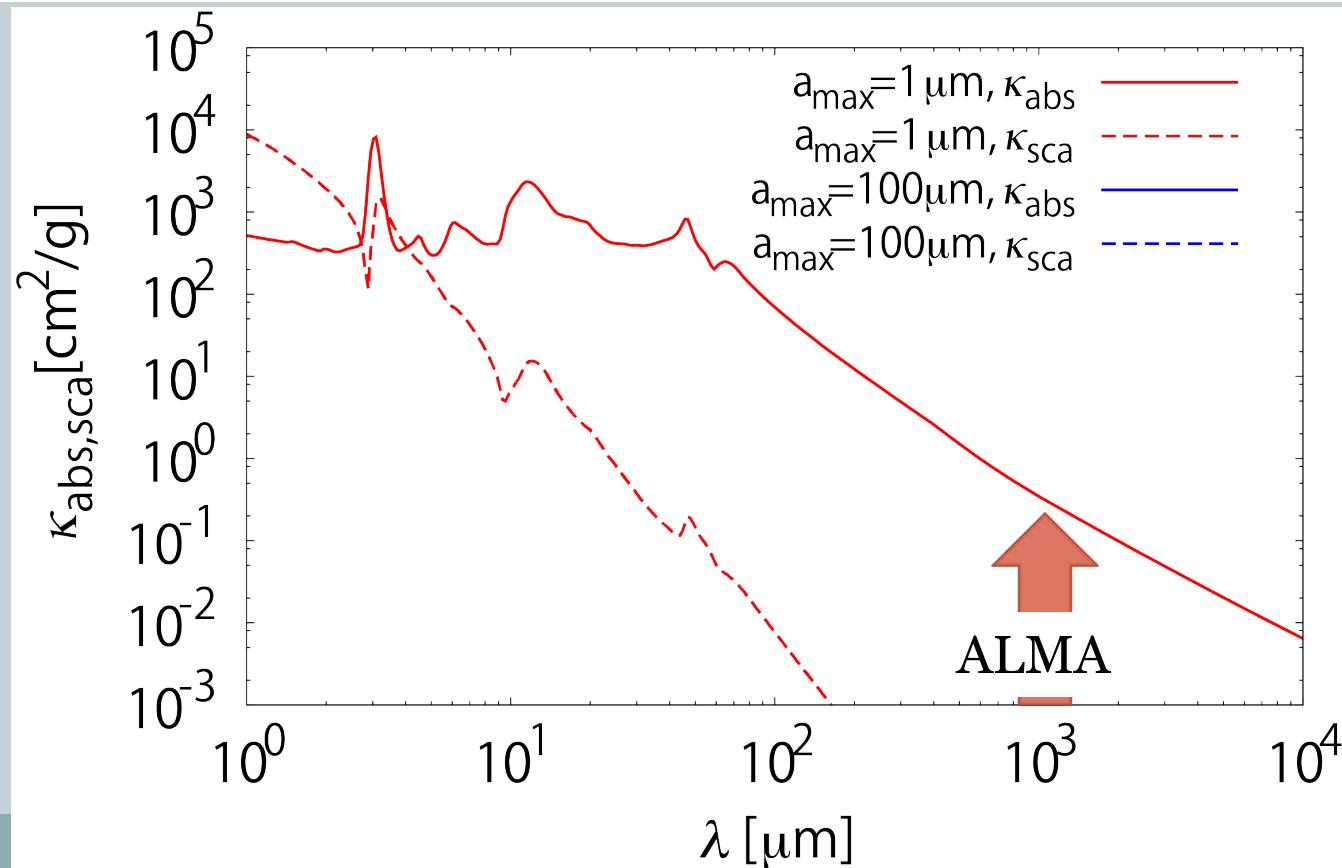
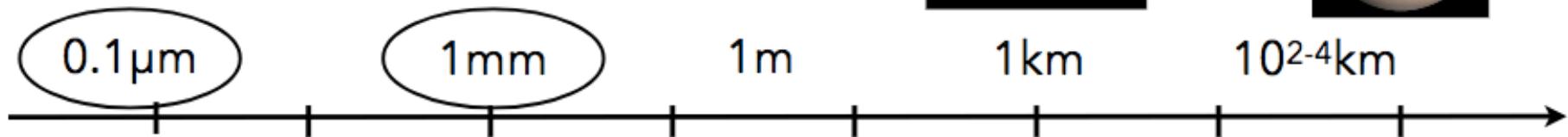
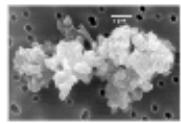


The elongated dust grains are aligned

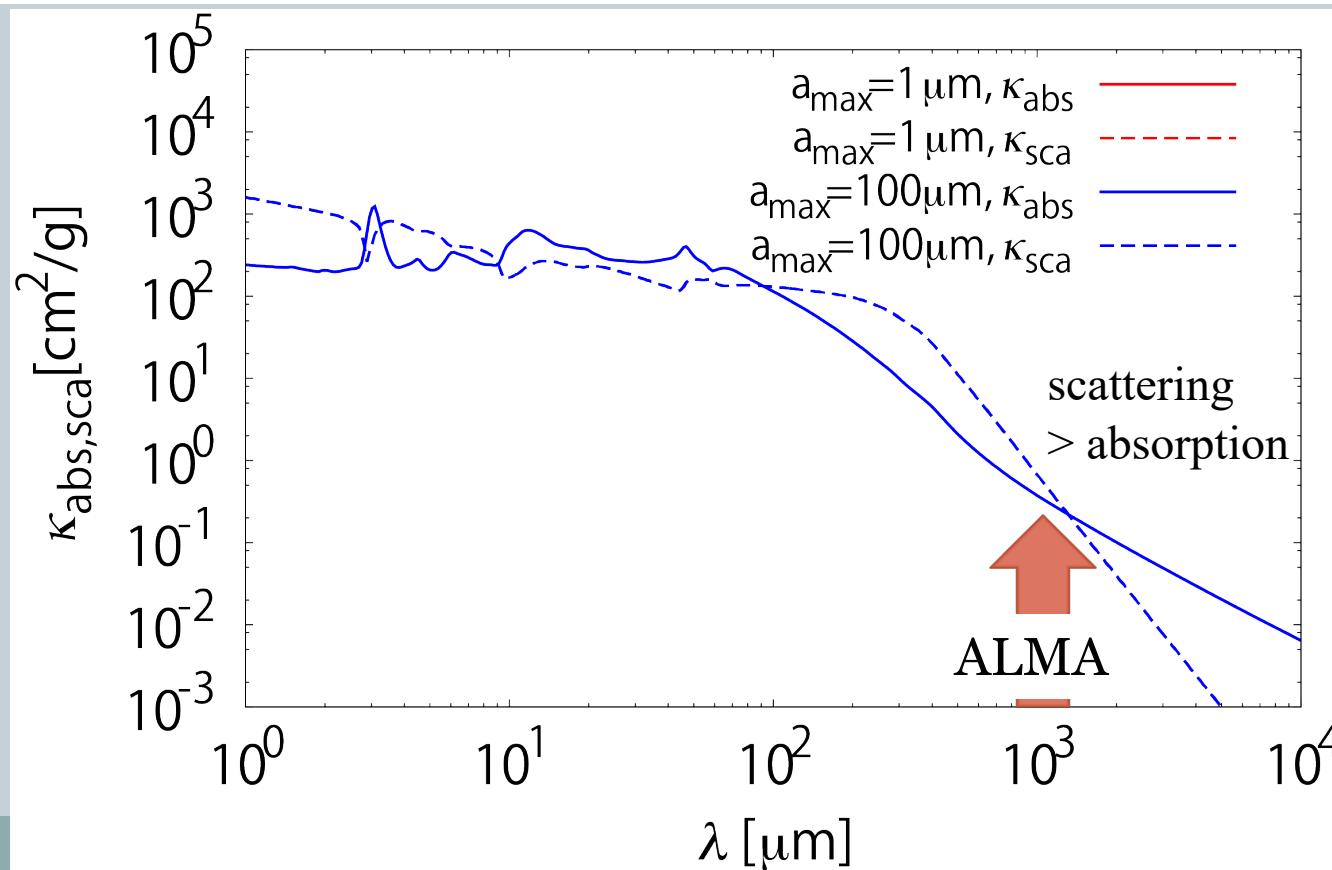
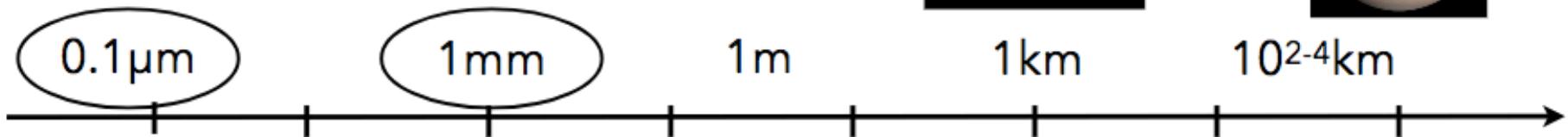
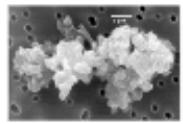
with 1. magnetic fields
in star forming region



Dust is big in disks



Dust is big in disks



Main mechanisms of polarization



The elongated dust grains are aligned with

1, 2, 3

Polarization of
thermal radiation

Aligned grains

Polarized
radiation

$E \perp B$

1. magnetic fields
 - or 2. radiation gradients
 - or 3. gas flows
- in PPDs

Main mechanisms of dust polarization



Dust alignment
at millimeter wave
In PPDs

with 1. magnetic fields
or 2. radiation gradients
or 3. gas flows
in PPDs

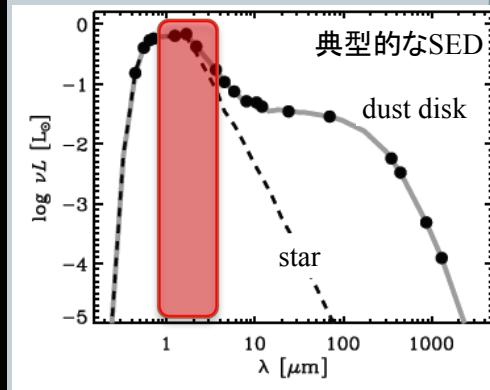
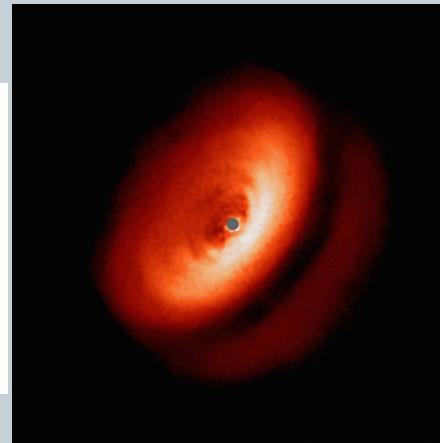
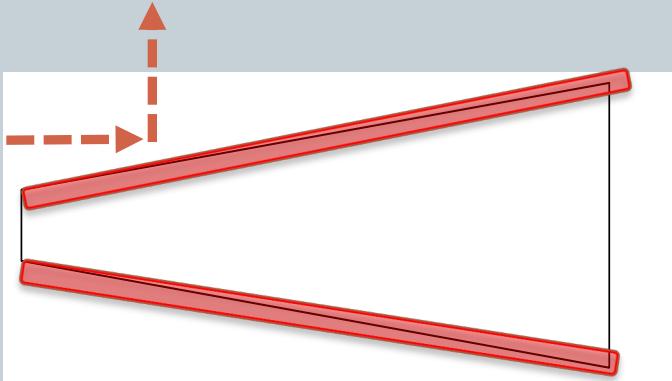
Scattering
at millimeter wave
In PPDs



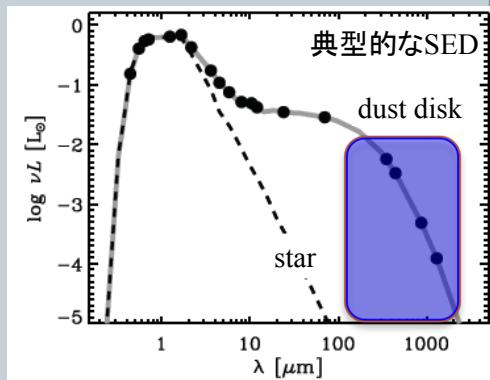
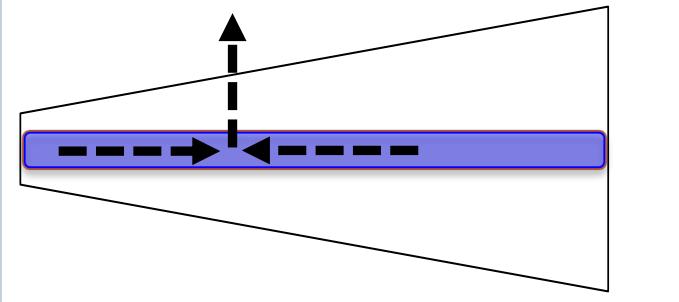
Scattering at millimeter



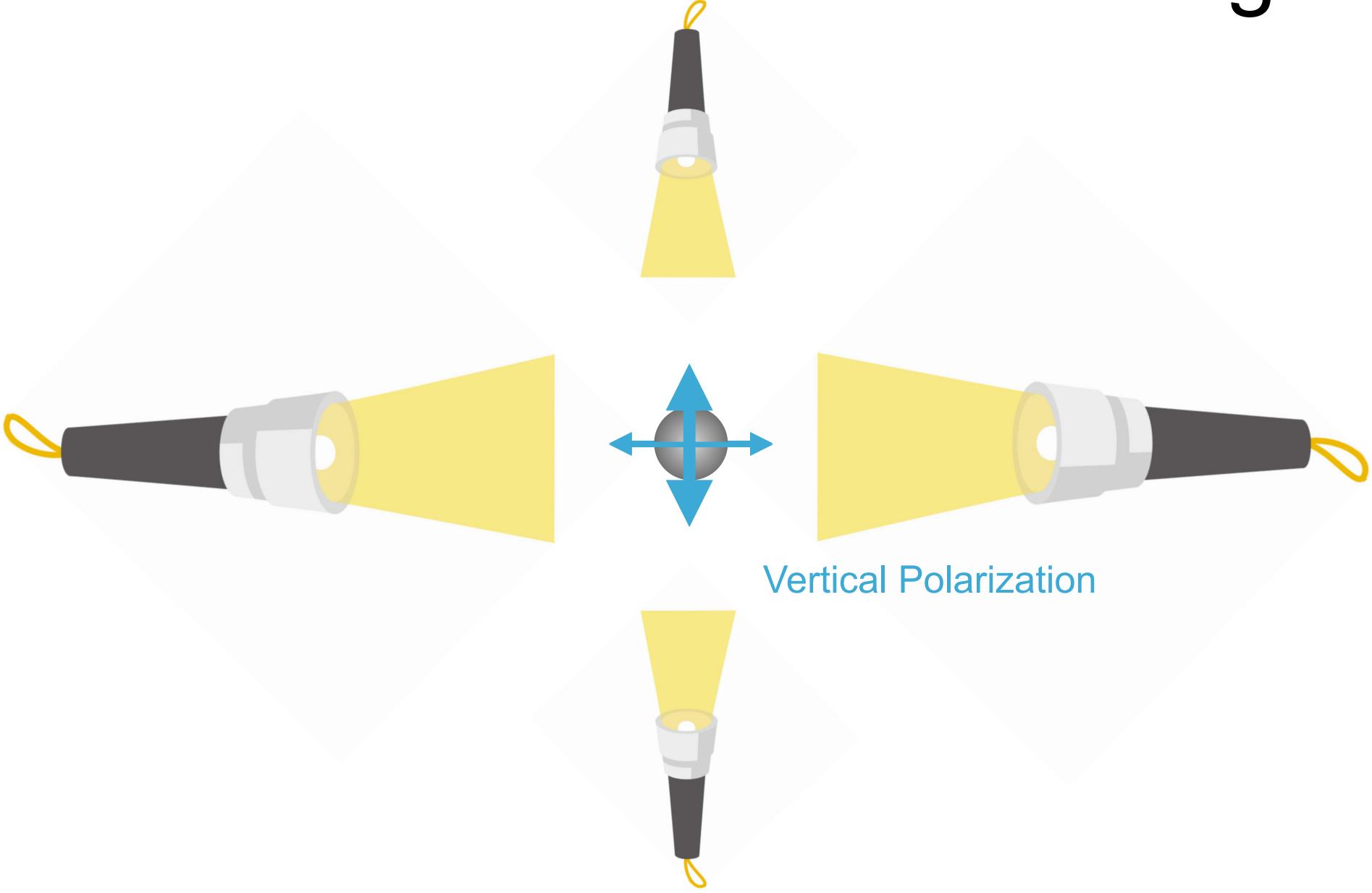
Infrared



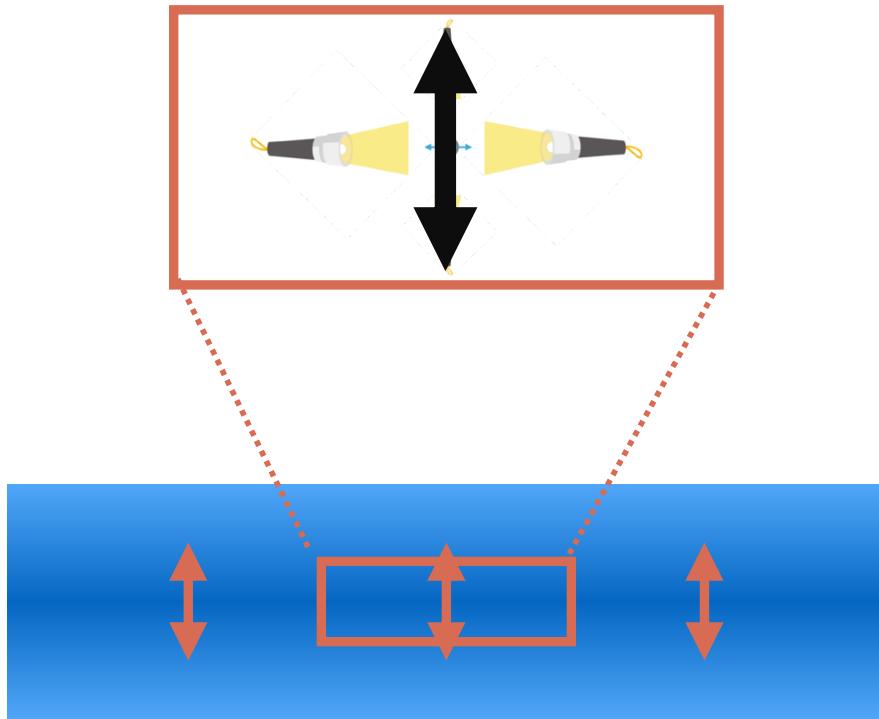
Millimeter



Polarization due to scattering

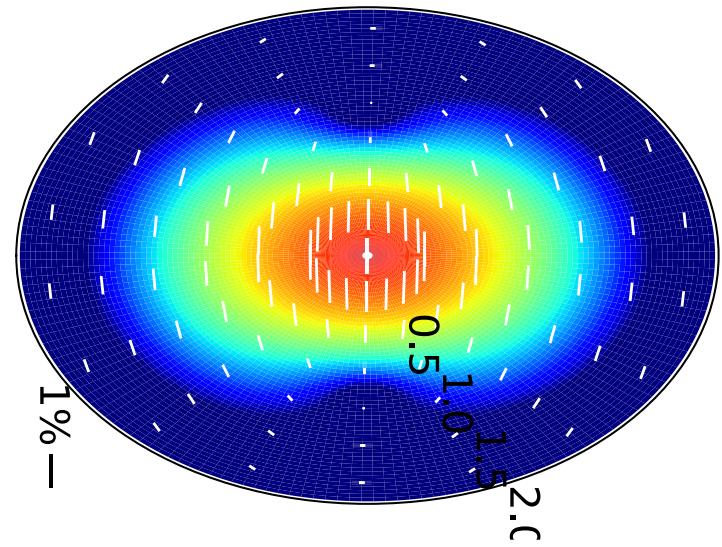


Self-scattering in inclined disks



(disk, edge-on view)

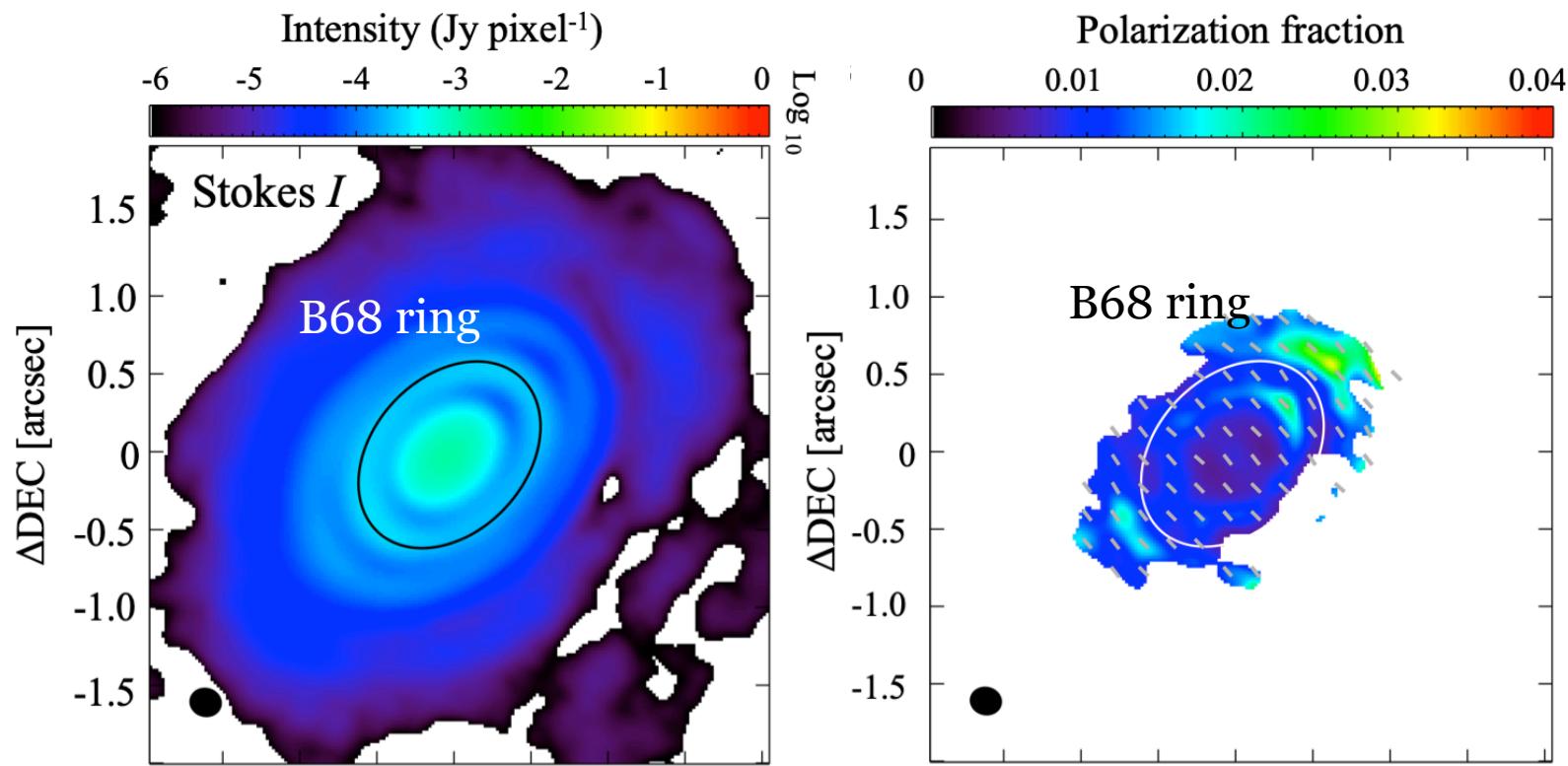
$i=45^\circ$



Yang, Li, et al. 2016

See also [Kataoka et al. 2016a](#)

The ideal target of HD 163296 reported by Dent et al. 2019



Dent et al. (2019) have shown the polarization morphology
within the disk

Can we model these observed features?

Radiative transfer calculations (RADMC-3D)



- Dependence on grain size

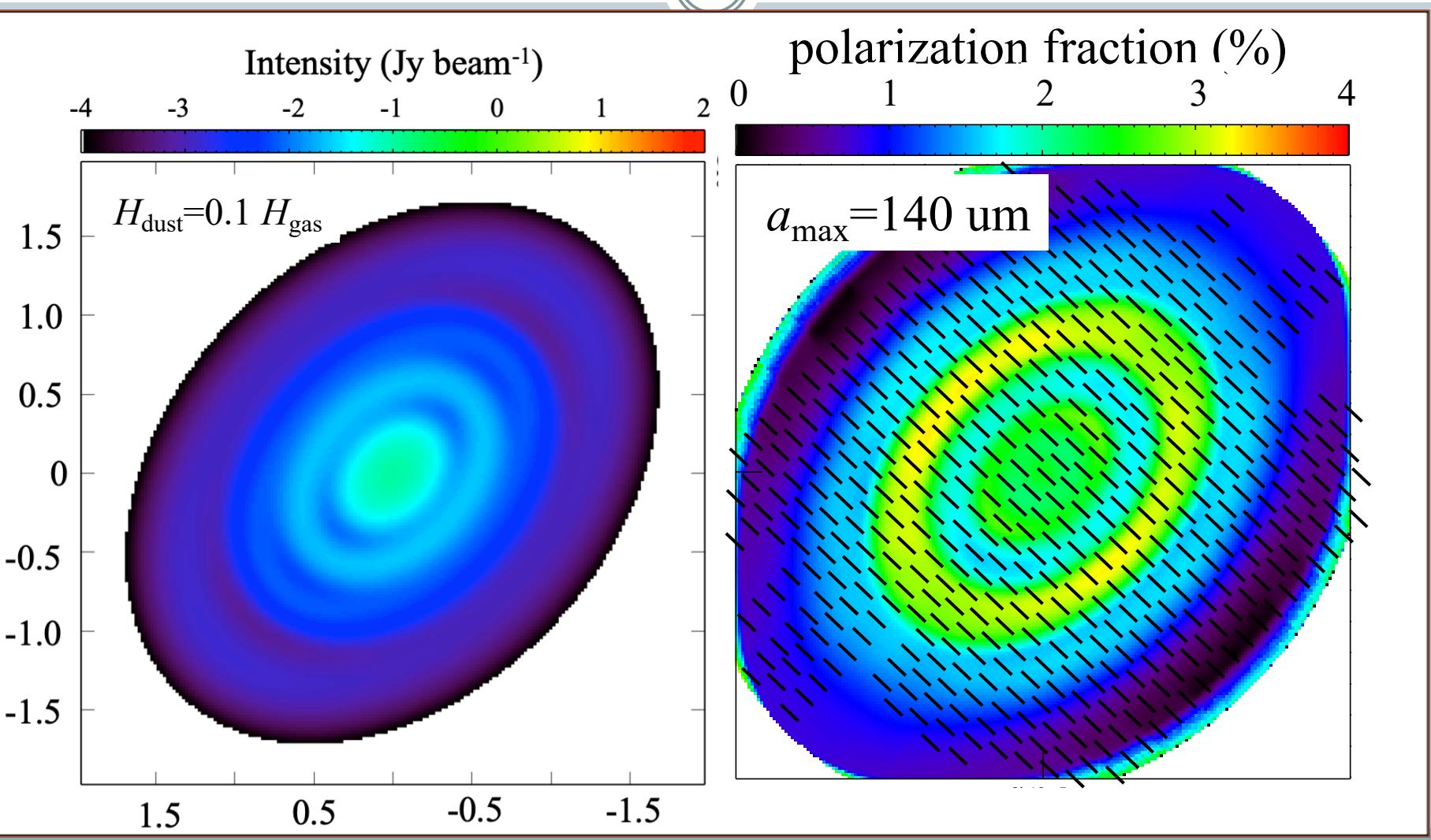
*Polarization fraction depends on a size of grains,
but polarization patterns are independent*

- Dependence on scale height

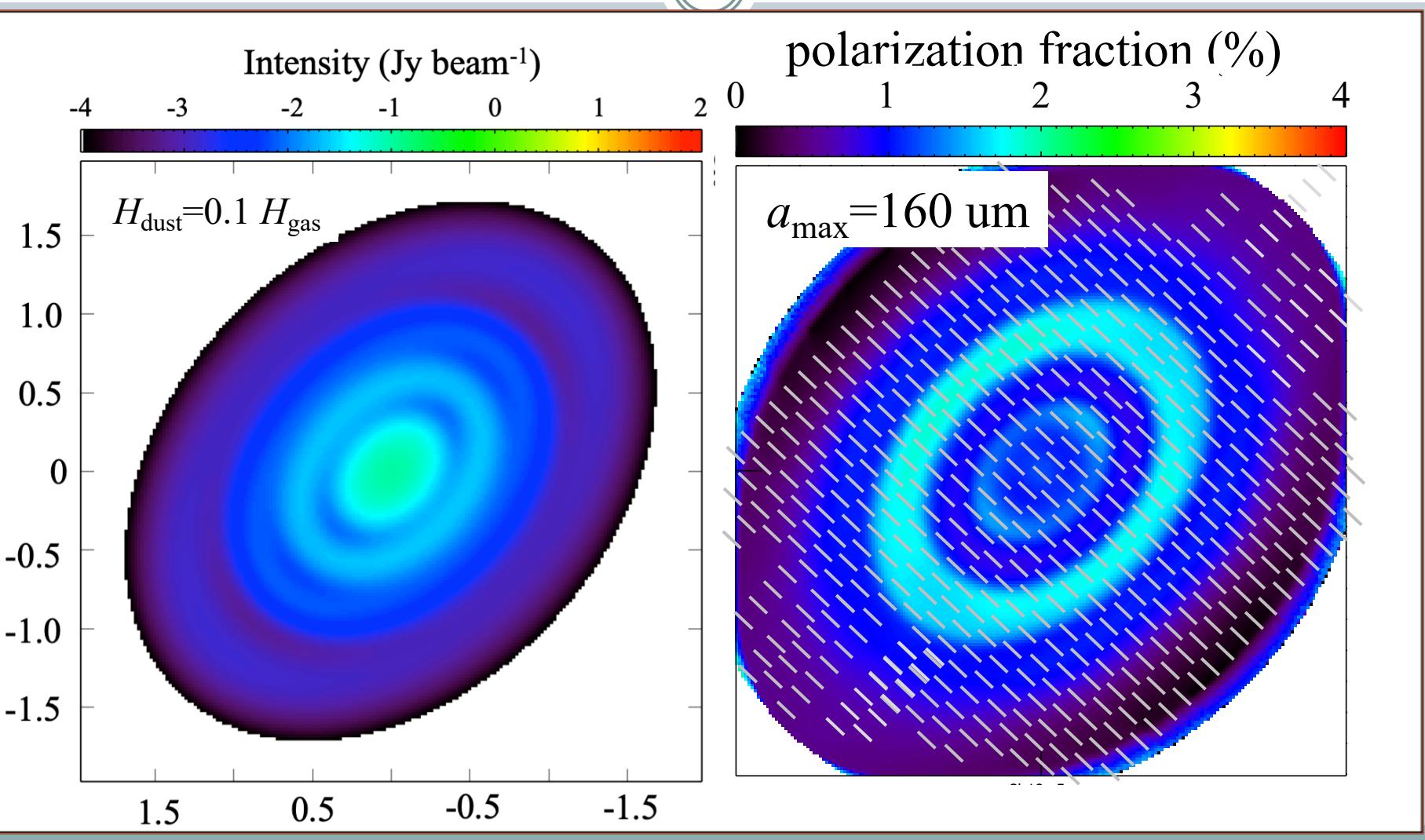
Azimuthal variation is enhanced by scale height

- Best model

Effect of grain size



Effect of grain size



Conditions of dust grains for polarization

- For efficient scattering

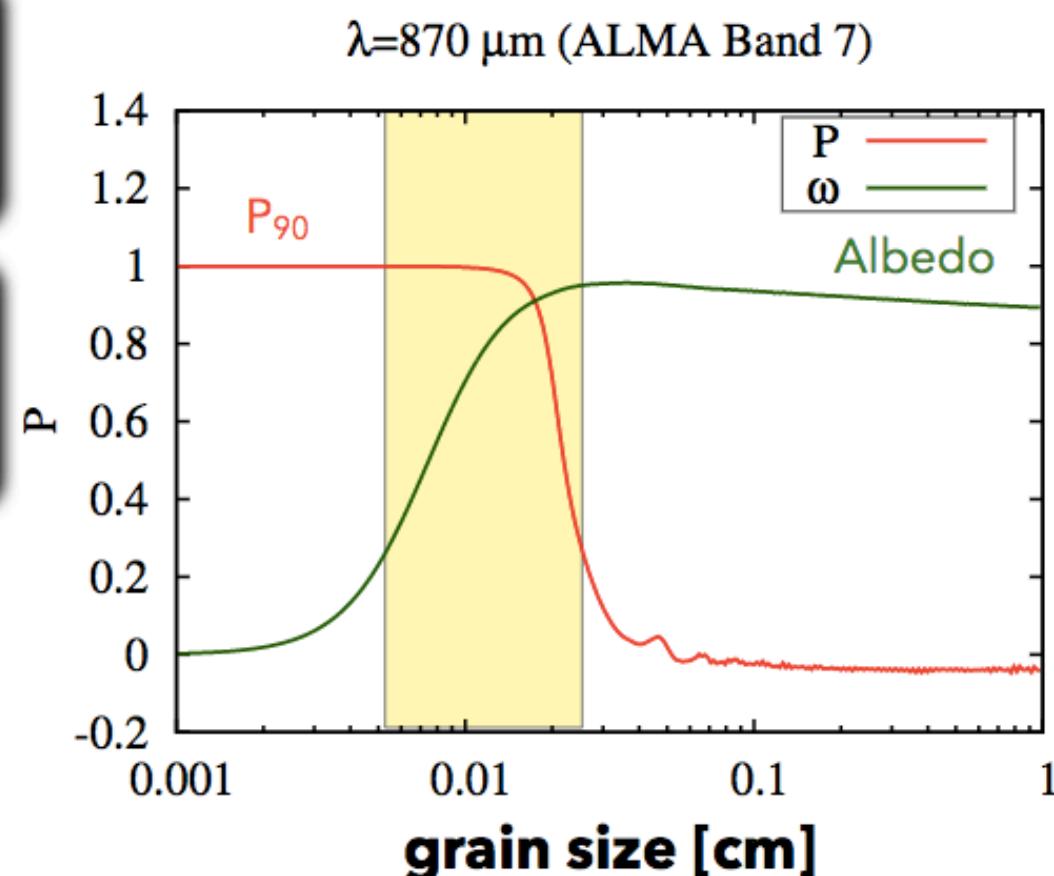
(grain size) $> \sim \lambda$

- For efficient polarization

(grain size) $< \sim \lambda$

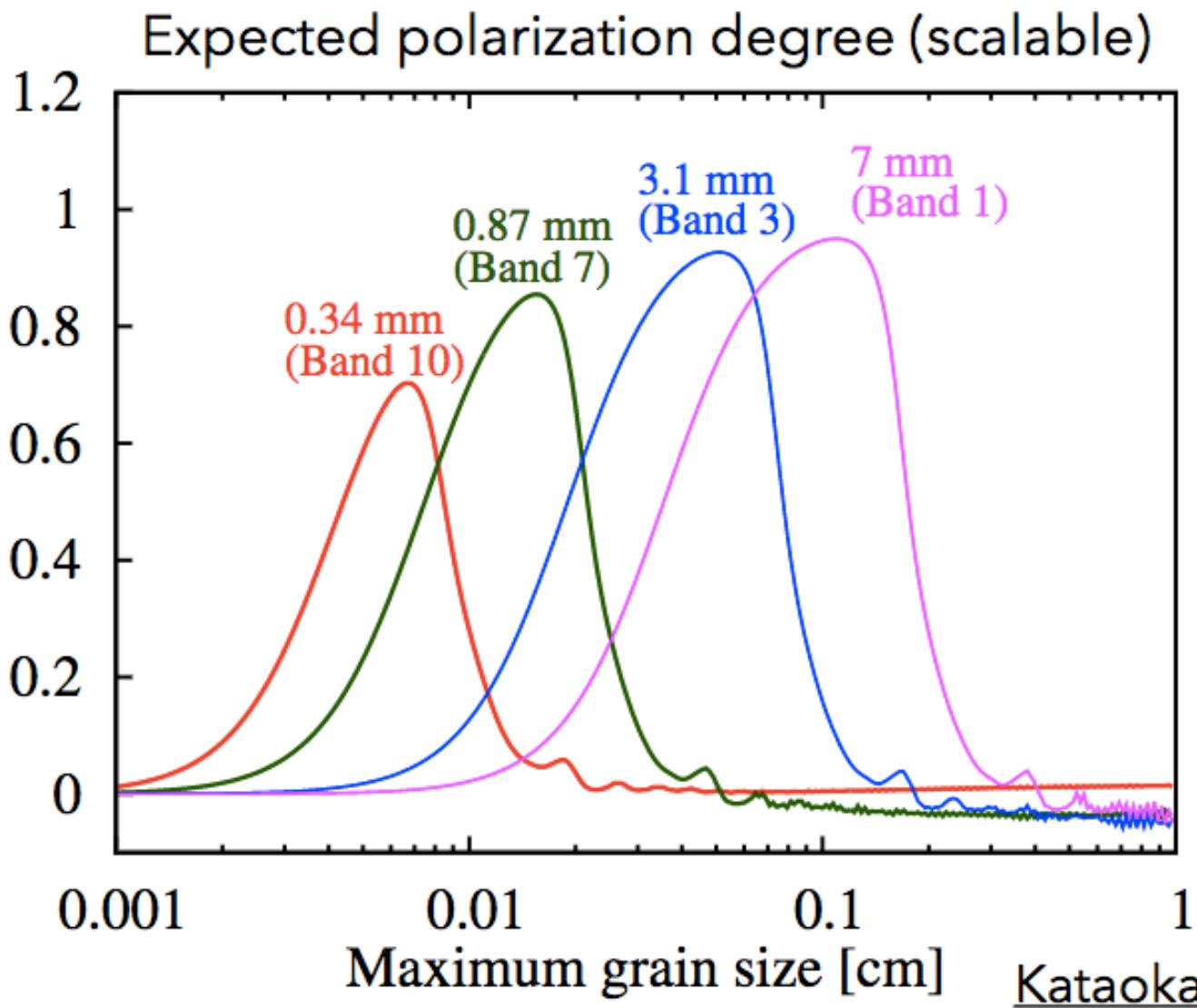


There is a grain size which contributes most to the polarized emission



If $(\text{grain size}) \sim \lambda/2\pi$, the polarized emission due to dust scattering is the strongest

Grain size constraints by polarization



Multi-wave polarization → constraints on the grain size

Radiative transfer calculations (RADMC-3)



- Dependence on grain size

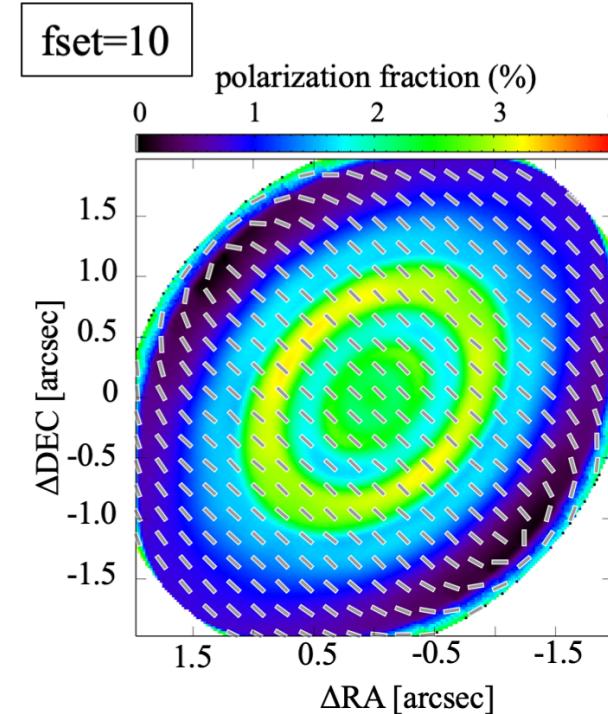
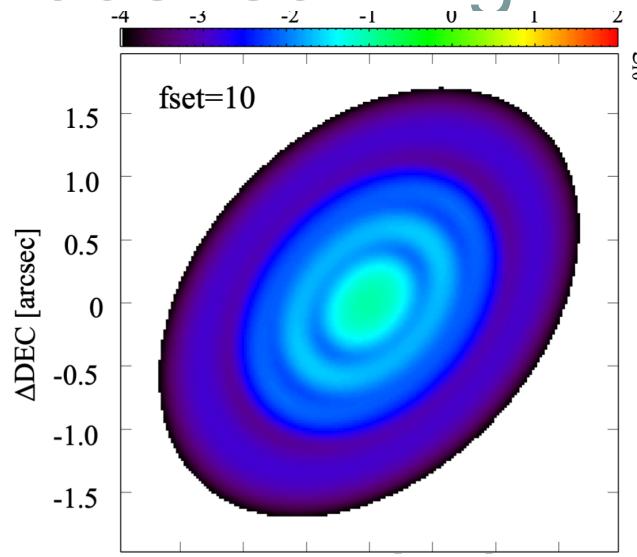
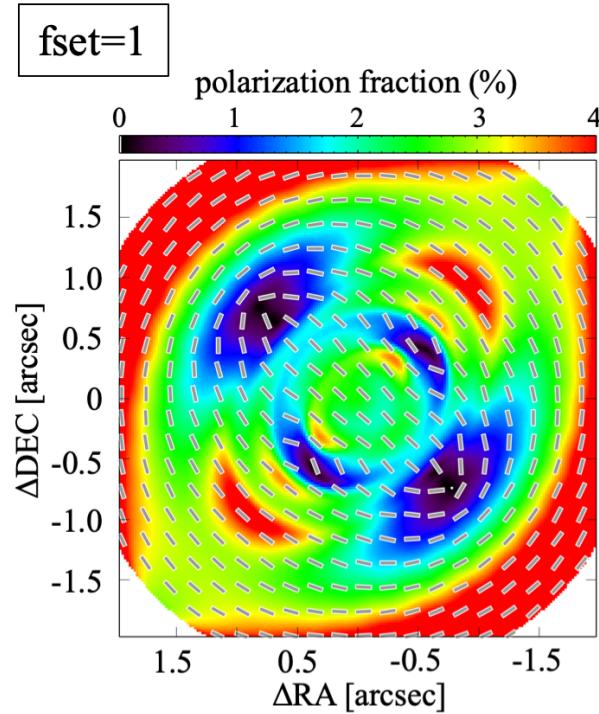
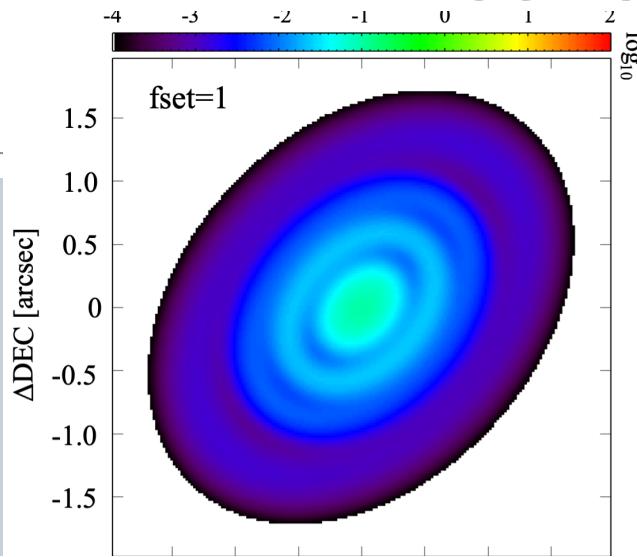
*Polarization fraction depends on a size of grains,
but polarization patterns are independent*

- Dependence on scale height

Azimuthal variation is enhanced by scale height

- Best model

Effect of dust settling



$$H_{\text{dust}} = \frac{H_{\text{gas}}}{f_{\text{set}}}$$

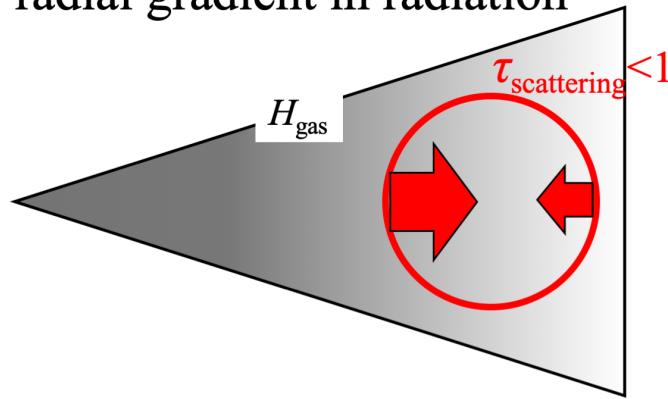
Scale height is also important for scattering



Incoming flux along the radial direction increases with scale height
→ Azimuthal polarization is produced,

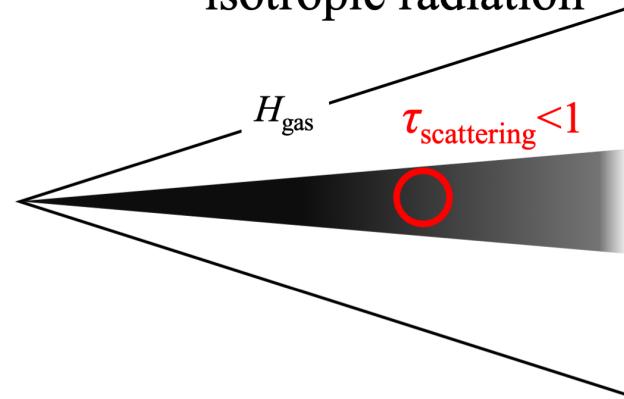
$$H_{\text{dust}} = H_{\text{gas}}$$

radial gradient in radiation



$$H_{\text{dust}} < H_{\text{gas}}$$

isotropic radiation



Radiative transfer calculations (RADMC-3)



- Dependence on grain size

*Polarization fraction depends on a size of grains,
but polarization patterns are independent*

- Dependence on scale height

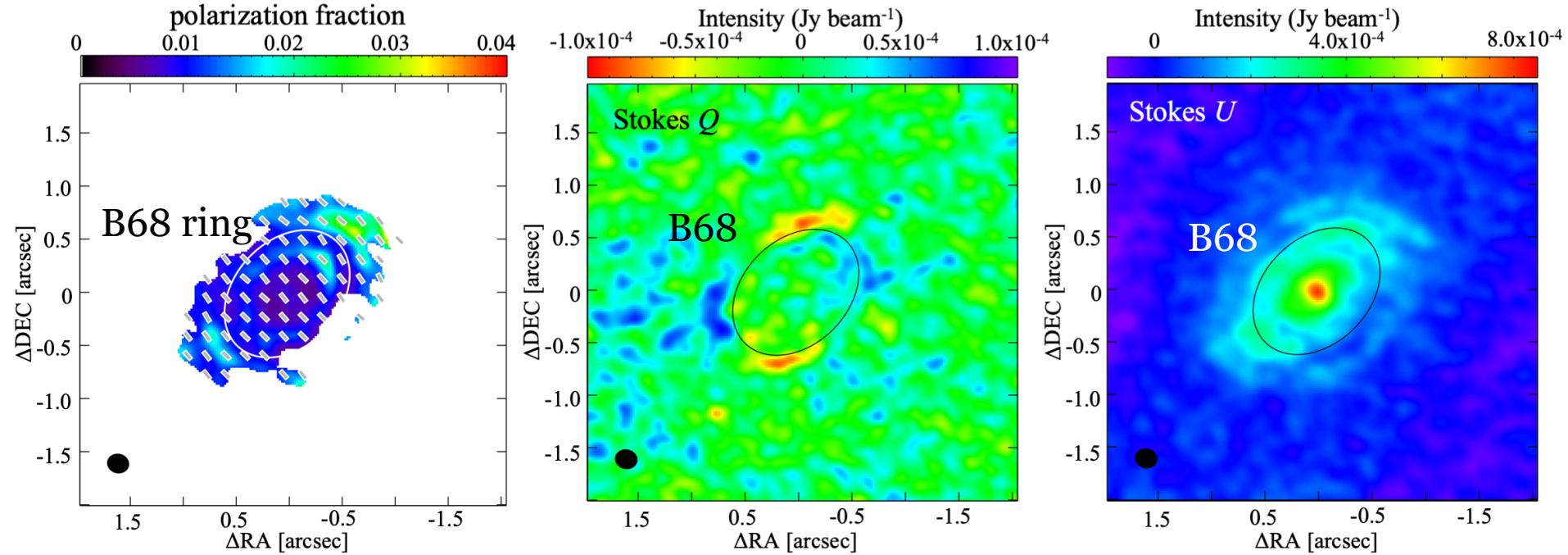
Azimuthal variation is enhanced by scale height

- Best model

Comparisons with observation



- polarization vectors may be difficult to compare between model and observation.
- We discuss Stokes Q and U images.



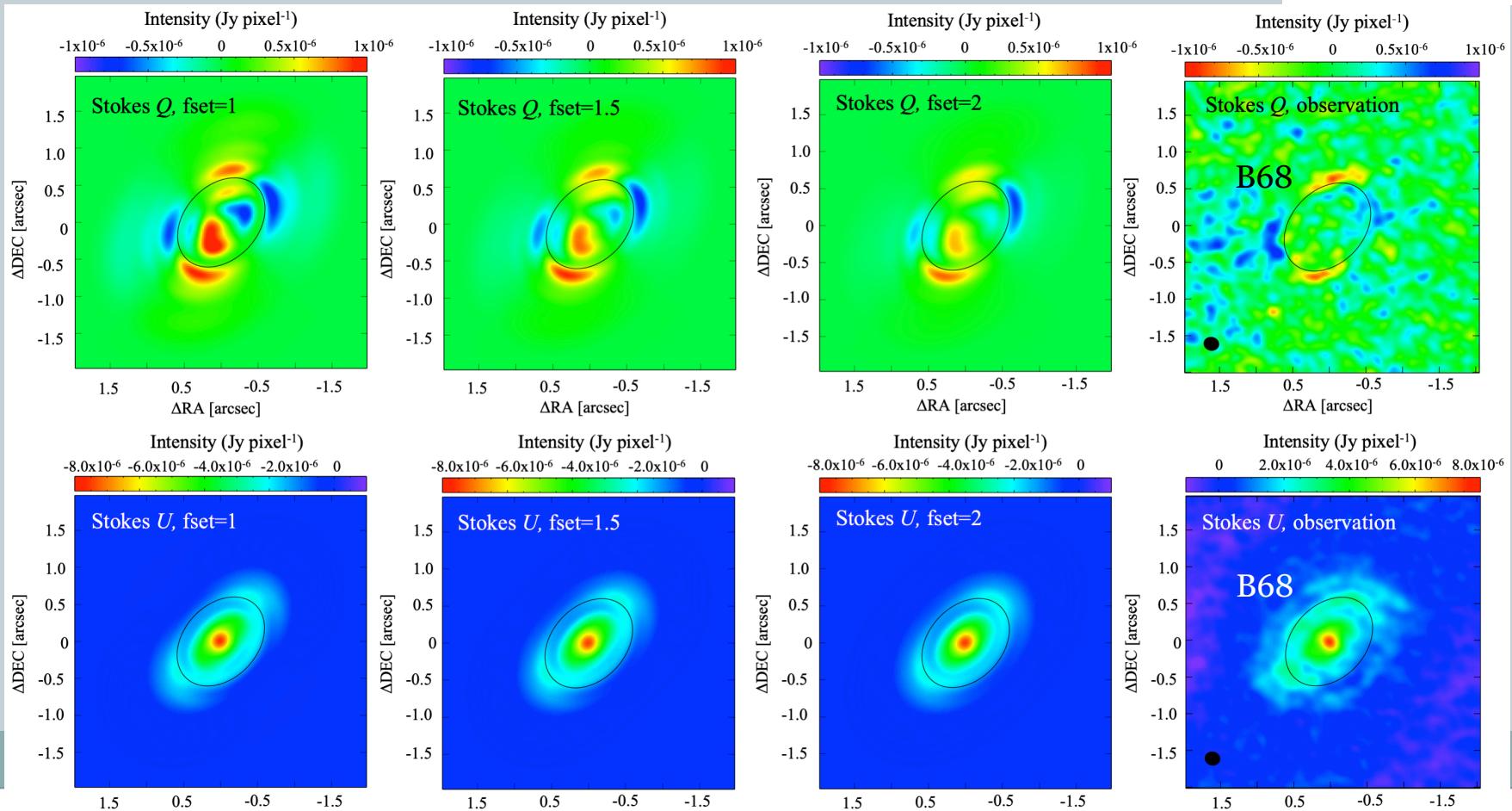
Note: grain sizes set to be 1 mm at the rings and 140 micron at the gaps to match the observed polarization

Radial variations of scale height



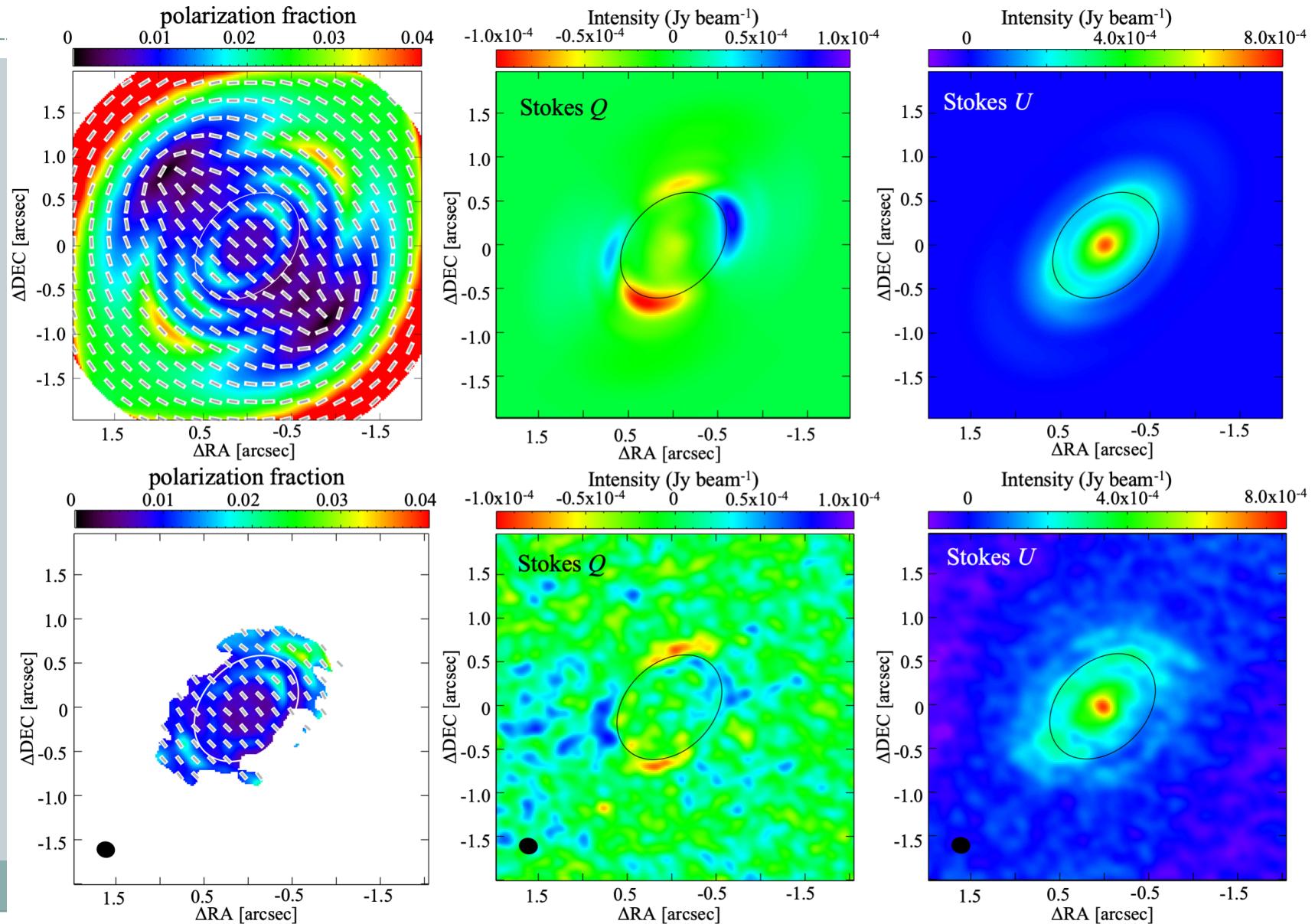
Stokes Q emission increases by increasing scale height
The observation shows no Stoke Q emission $r < 70$ au,
indicating the scale height is low $r < 70$ au and high $r > 70$ au

$$H_{\text{dust}} = \frac{H_{\text{gas}}}{\text{fset}}$$



Best model

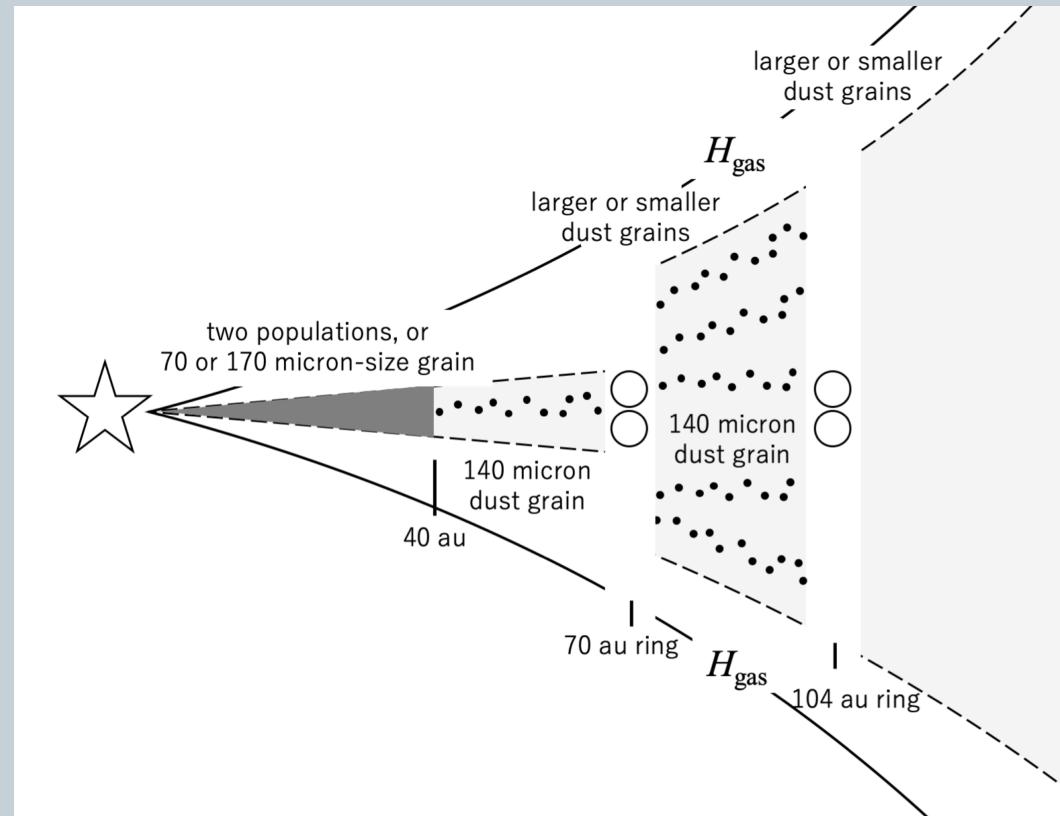
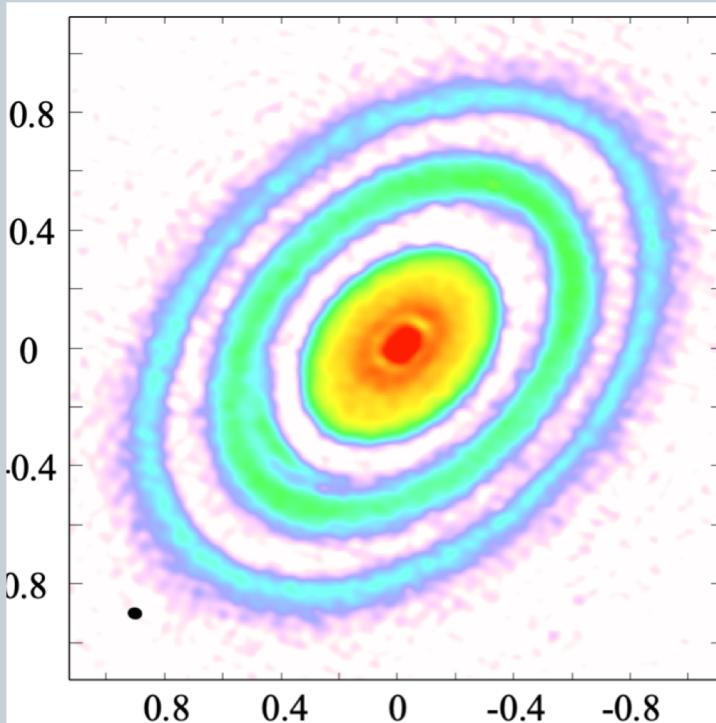
140um and 1mm model: scale height $H_d=0.1 H_{\text{gas}}$ ($r < 68$ au) and $0.7 H_{\text{gas}}$ ($r > 68$ au)



Radial variations of grains and scale height



Based on the model, the possible dust size and scale height distributions are shown

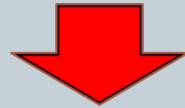


Radial variations of grains and scale height

Dust scale height

$$H_{\text{dust}} \sim \sqrt{\frac{\alpha}{\text{St}}} H_{\text{gas}}$$

$$\text{St} = \frac{\pi \rho a}{2 \Sigma_{\text{gas}}}$$

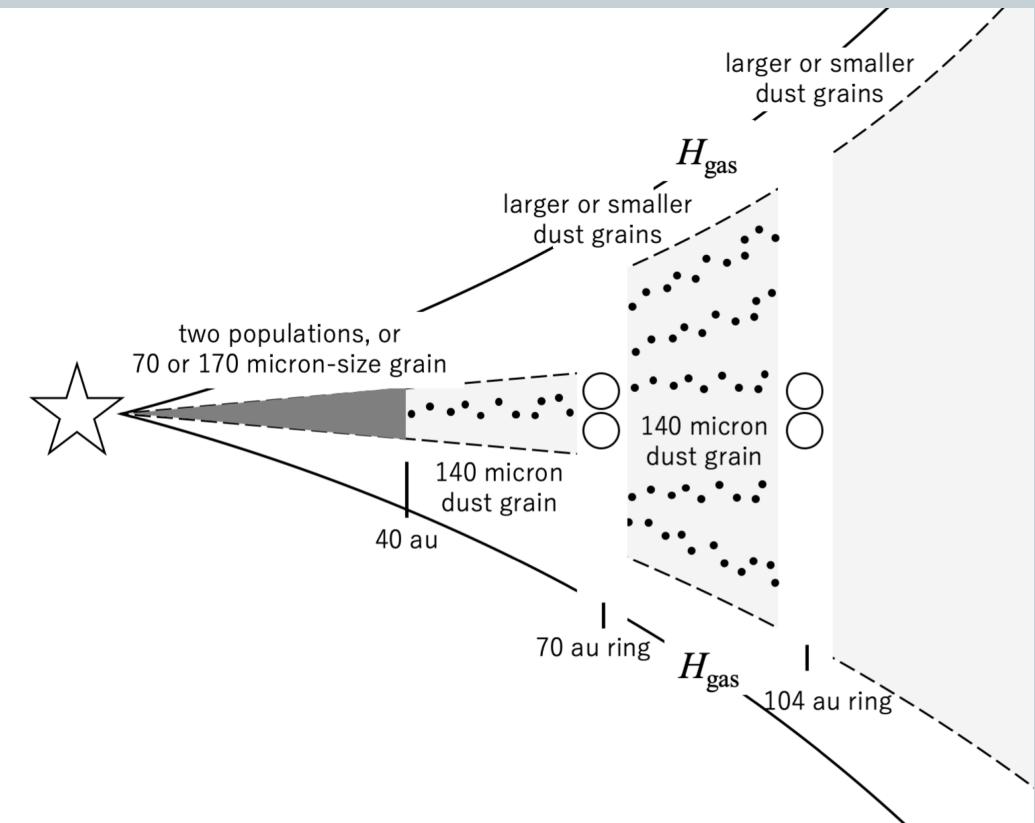


Scattering allow us to investigate not only grain size but also dust scale height

turbulence a will be different between 50 and 90 au

$$\alpha \lesssim 1.5 \times 10^{-3} \quad \text{at 50 au}$$

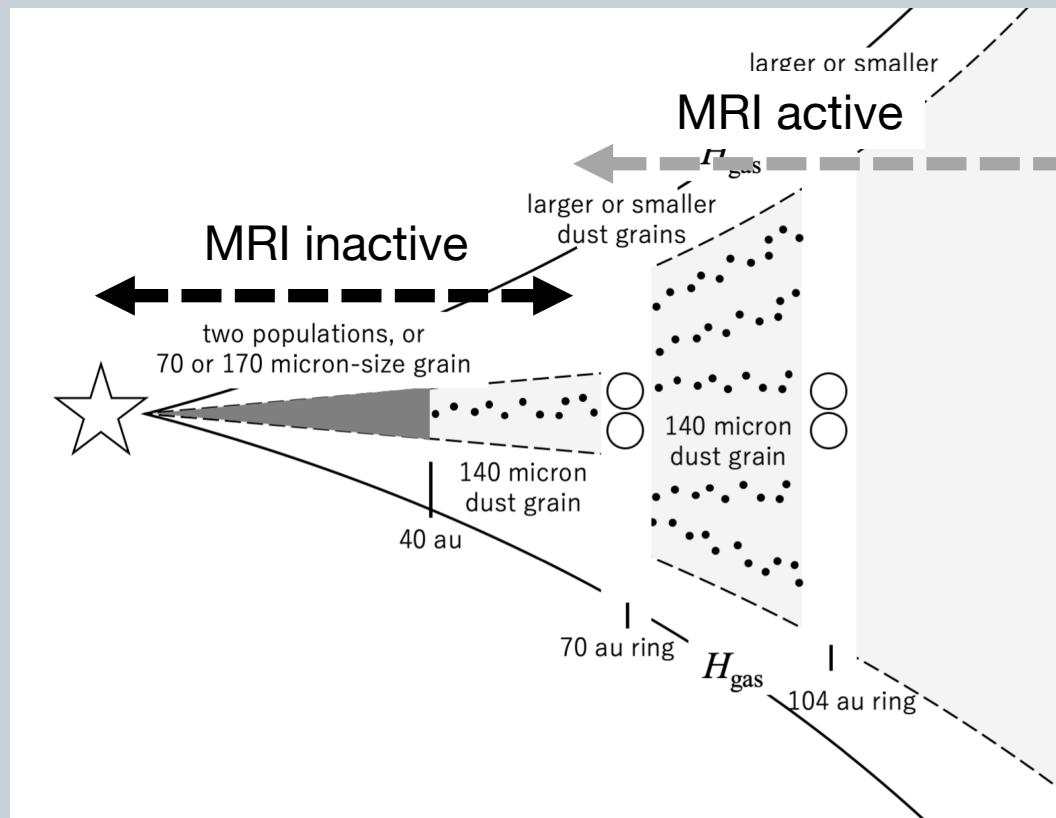
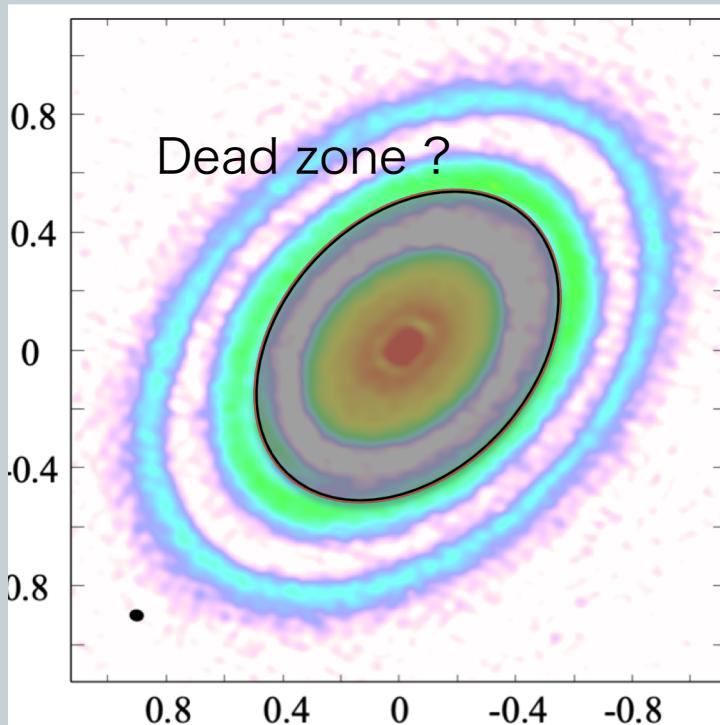
$$\alpha \sim 0.015 - 0.3 \quad \text{at 90 au}$$



Radial variations of grains and scale height



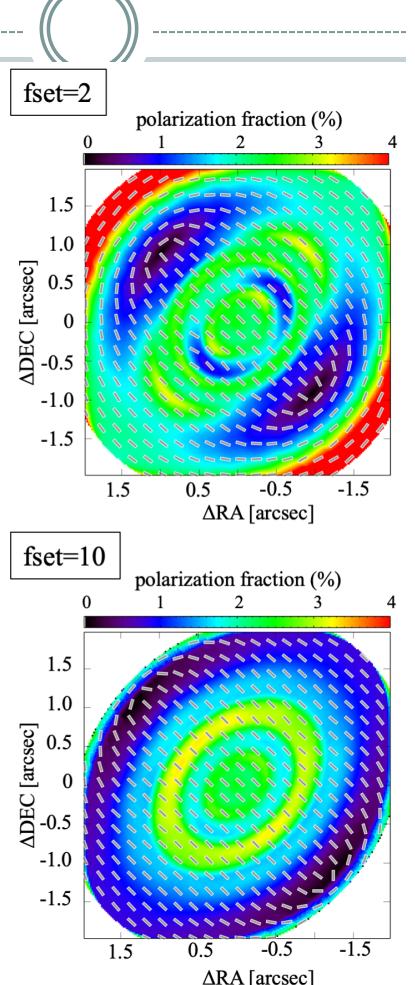
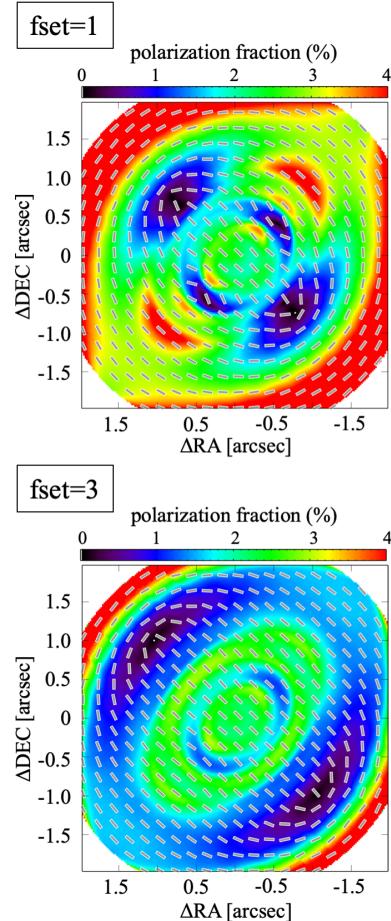
Scattering allow us to investigate not only grain size but also dust scale height

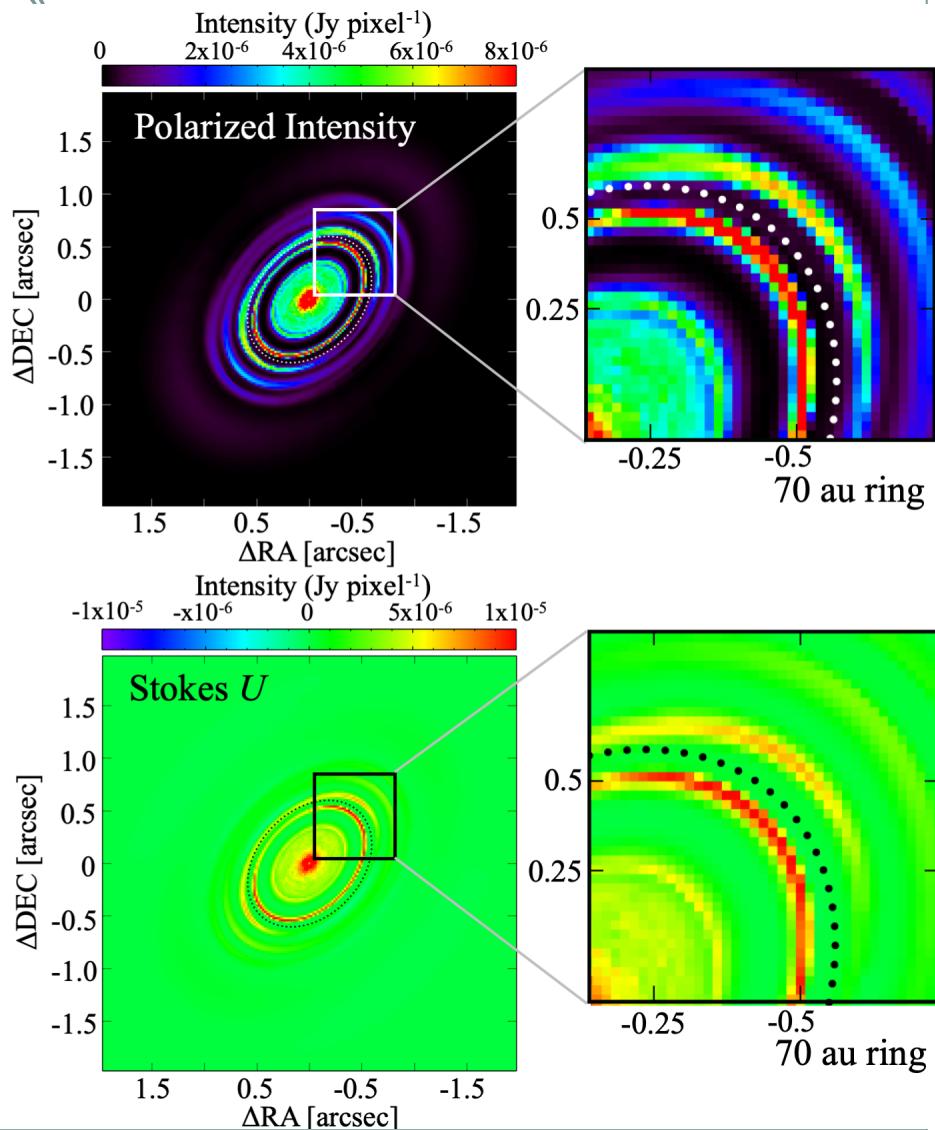
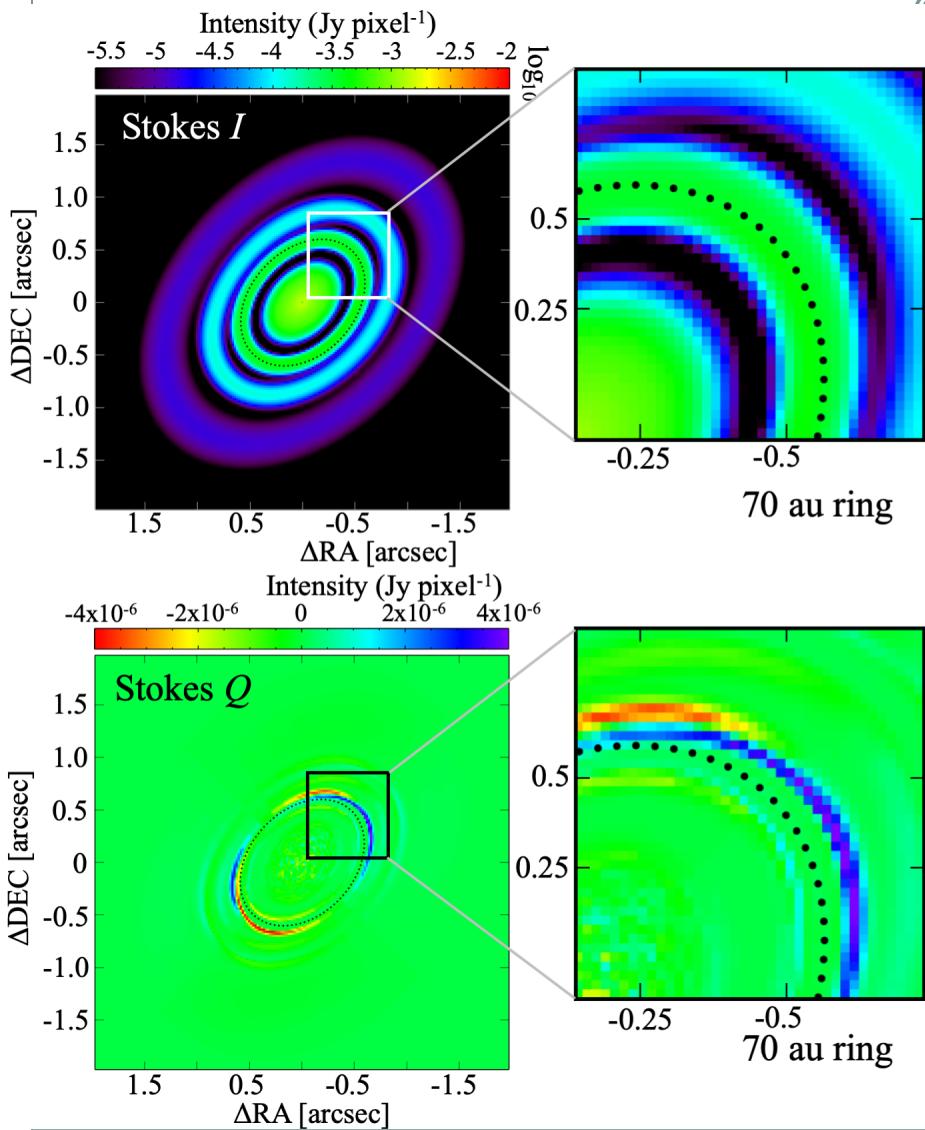


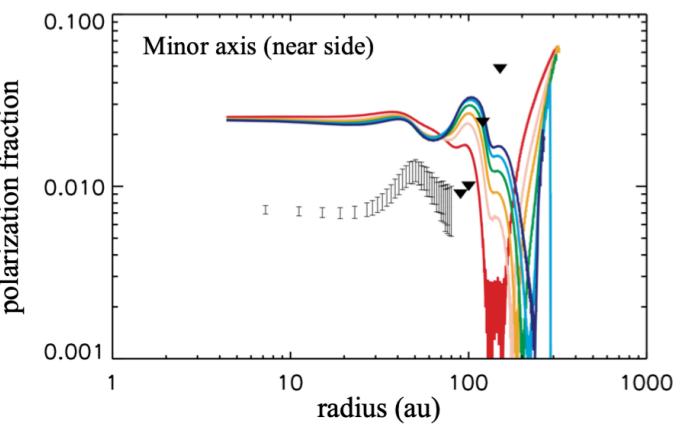
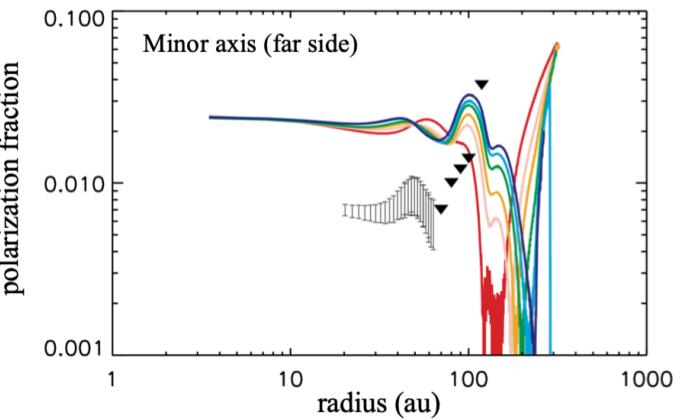
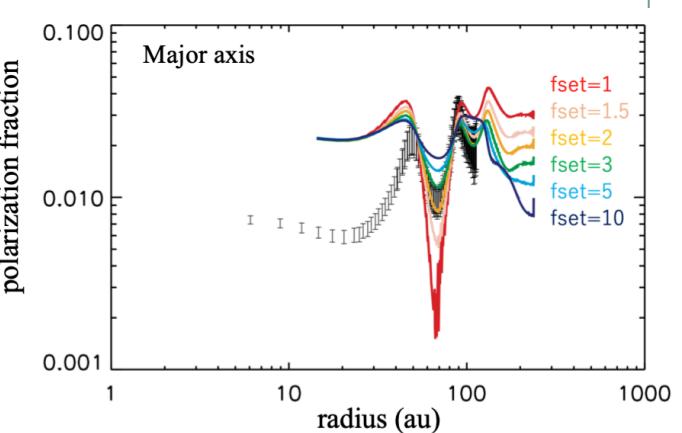
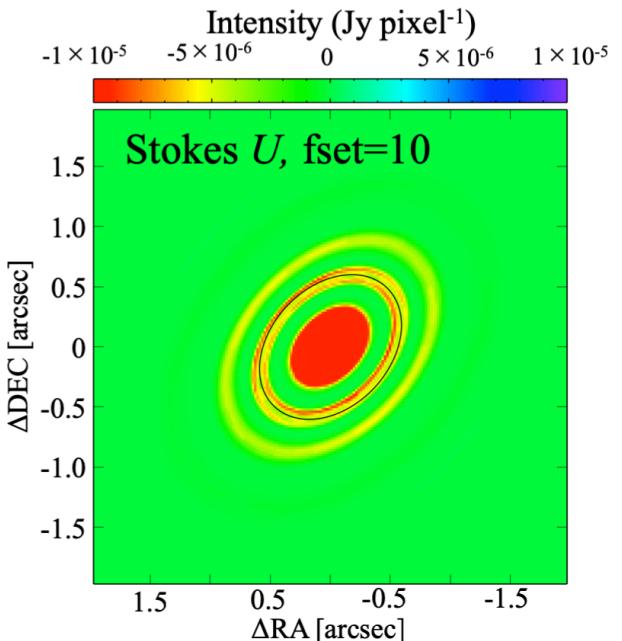
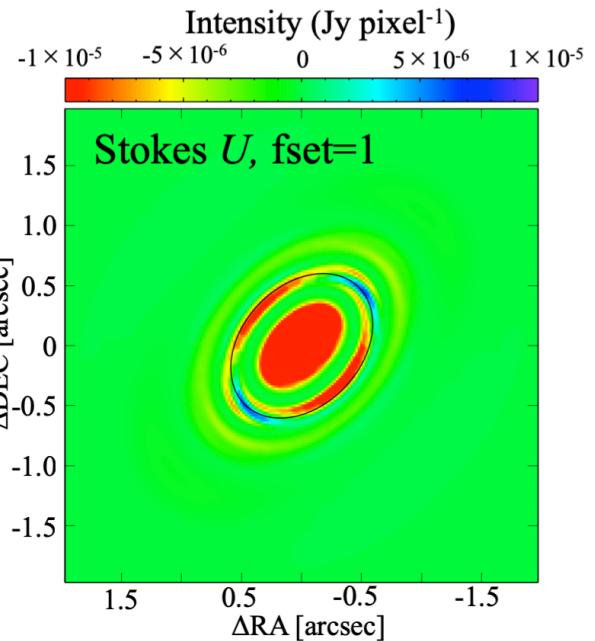
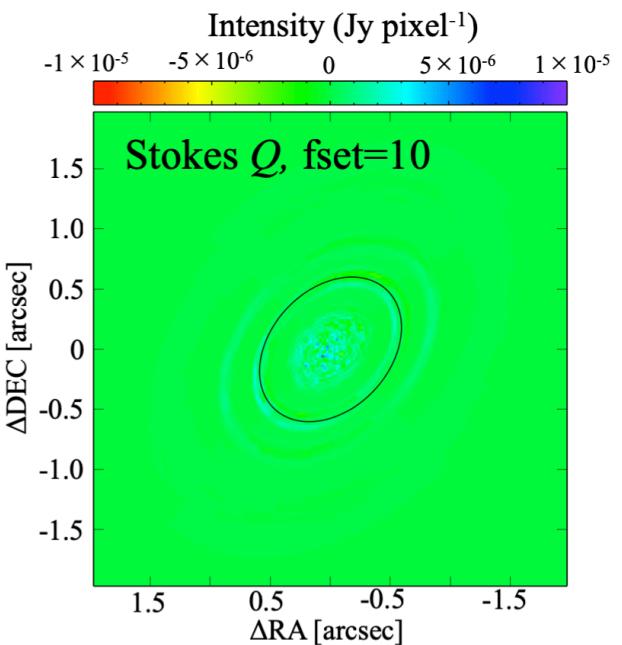
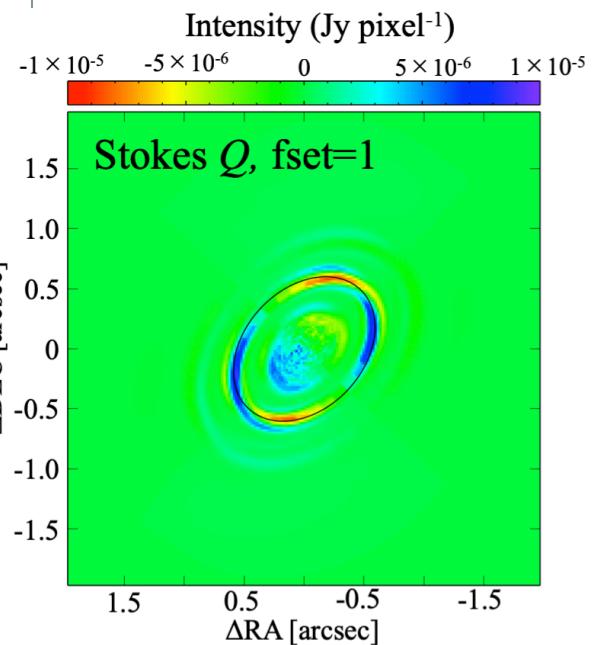




Singe grain population model



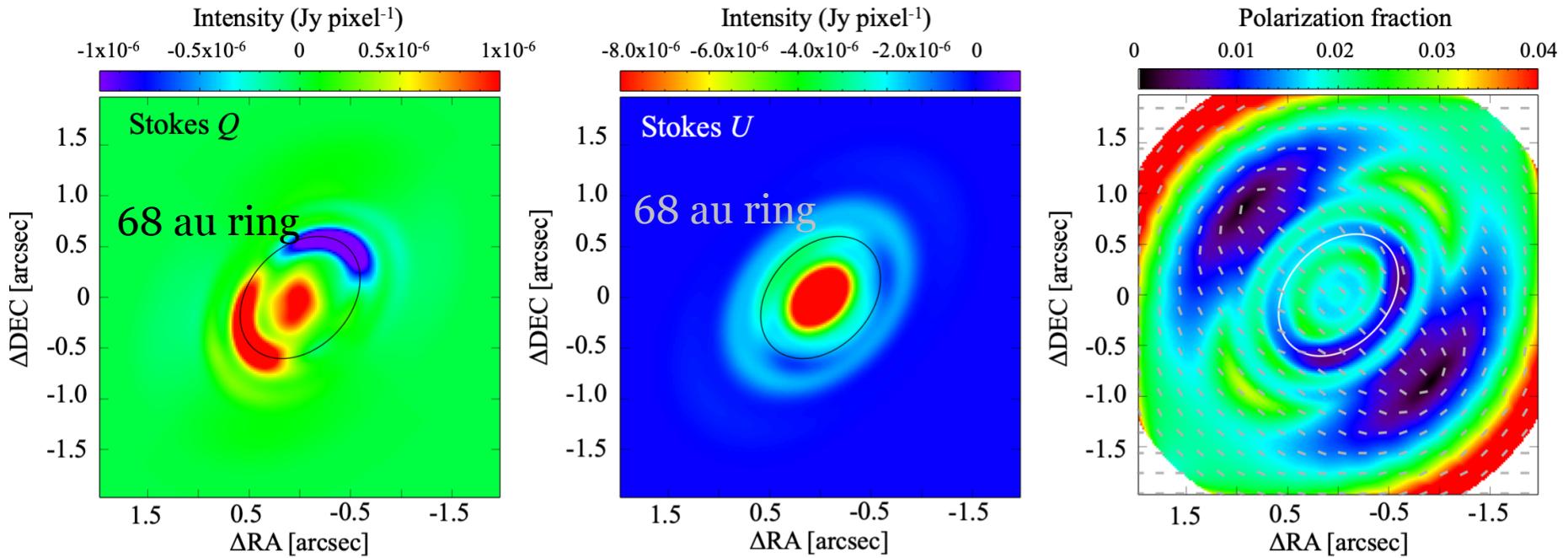




Radial variations of grains and scale height



150 um single grain size with changing fset at 68 au from 1.5 to 10



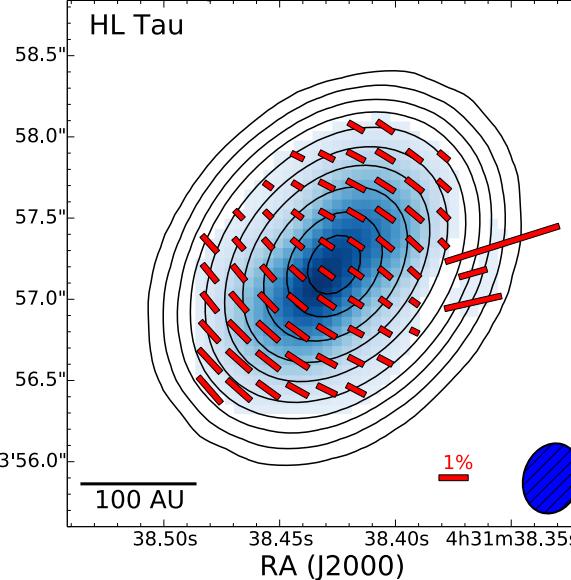


Self-scattering

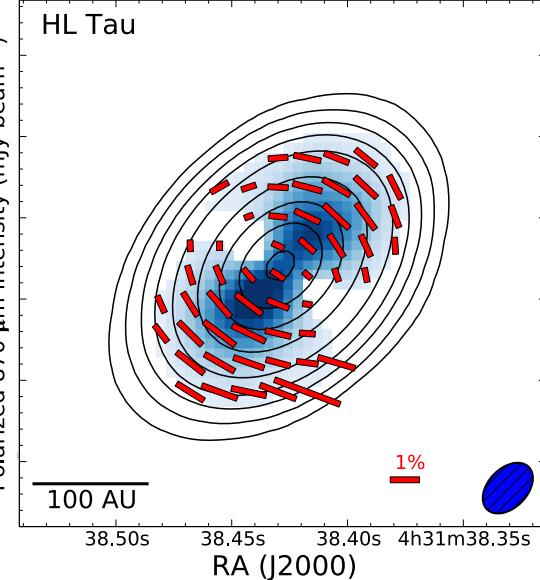
Self-scattering + dust alignment

dust alignment

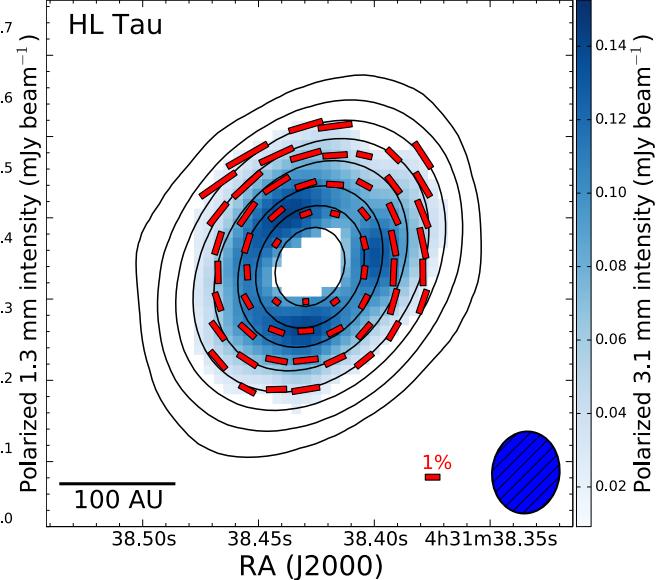
870 μm (ALMA Band 7)



1.3 mm (ALMA Band 6)

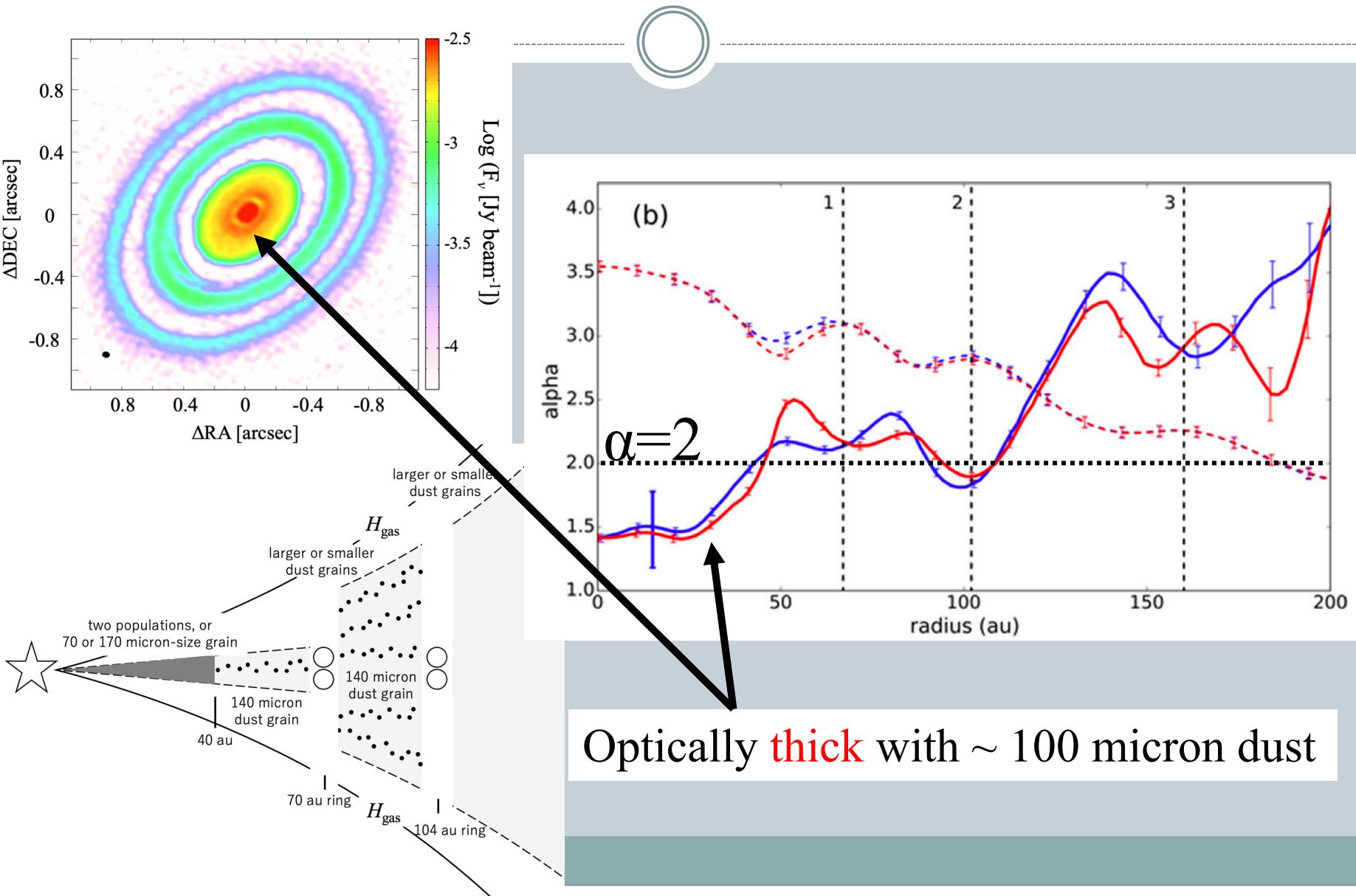


3.1 mm (ALMA Band 3)

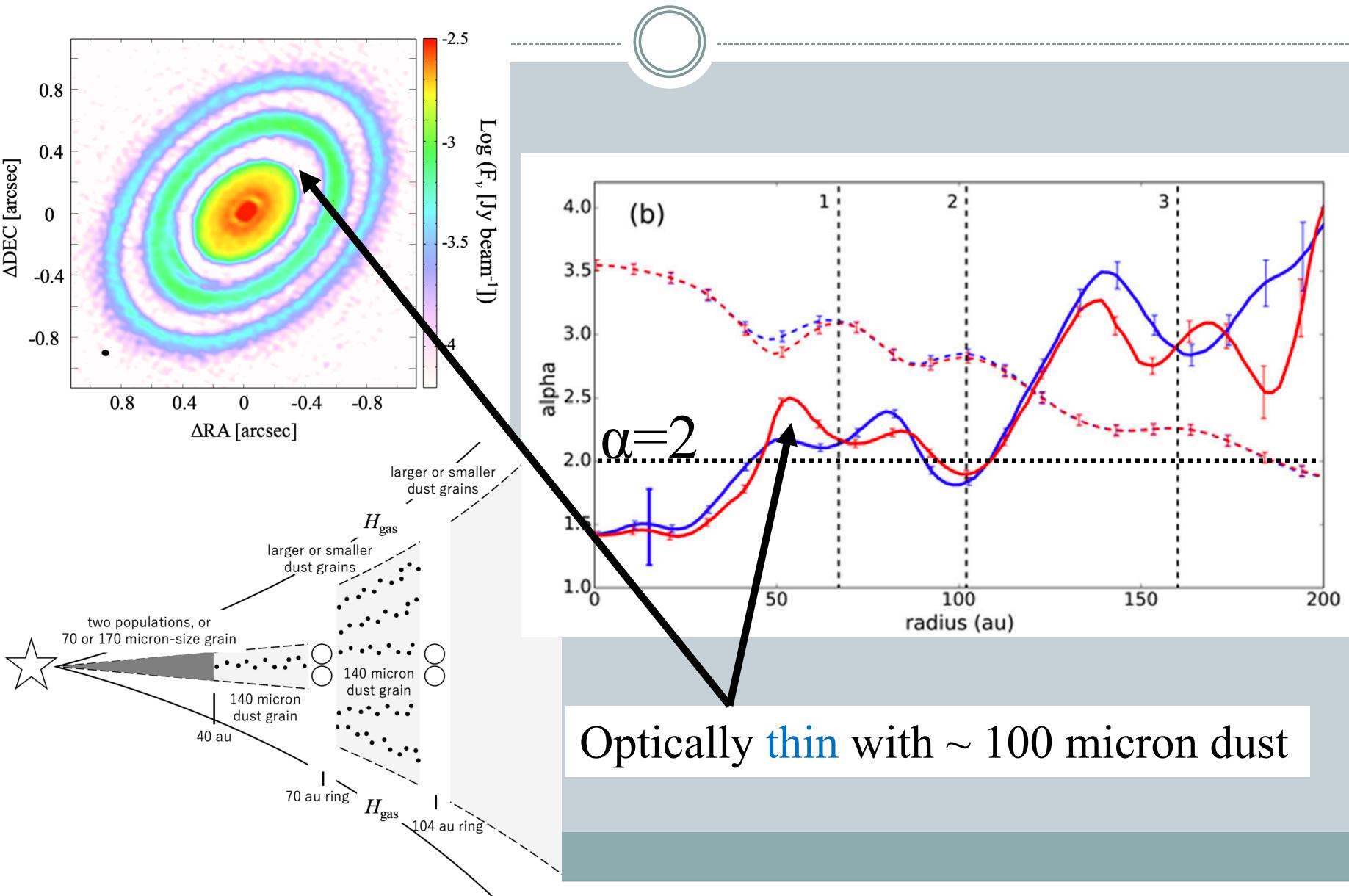


Stephens et al. 2017

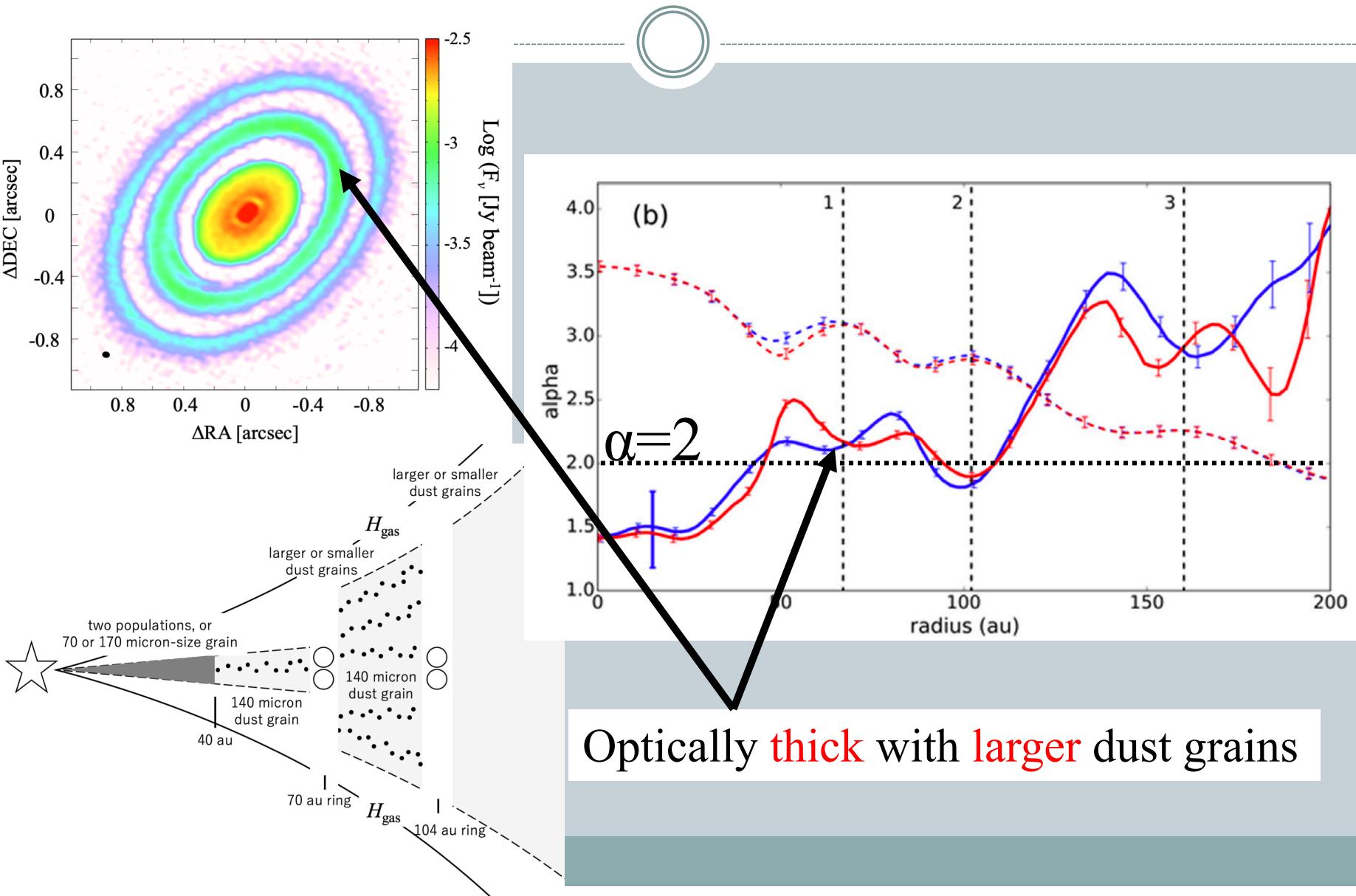
Consistency between scattering and spectral index



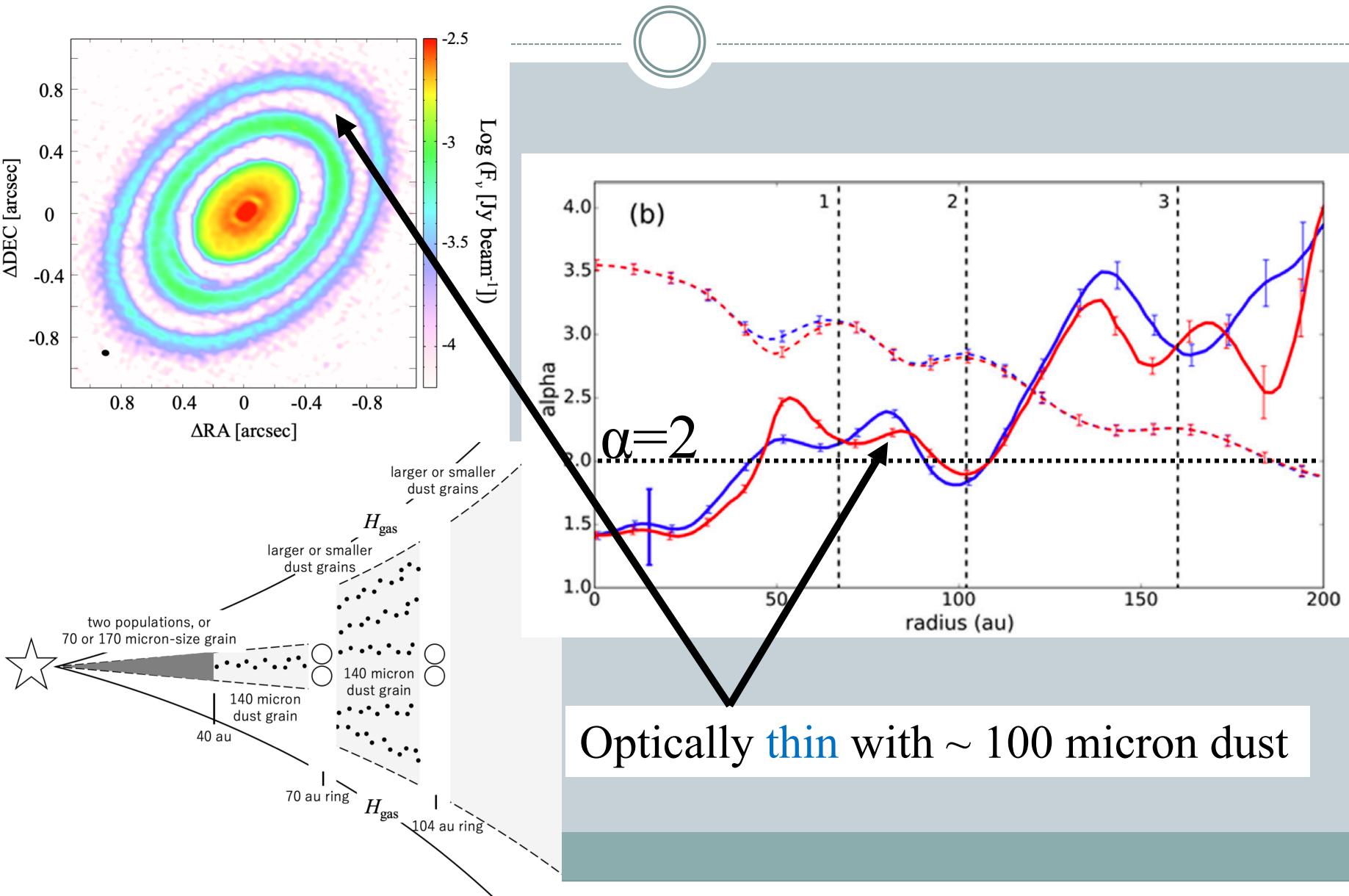
Consistency between scattering and spectral index



Consistency between scattering and spectral index



Consistency between scattering and spectral index



Consistency between scattering and spectral index

