Detecting the earliest stages of giant planet formation in scattered light

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Outline

- Motivation
- Intro about the basics of disk imaging
- Preliminary results
  – The code, and the psf
  – Disk without gaps – the effects of disk depletion factor and disk mass (and envelope)
  – Disk with gaps – the effects of gap position, width, and depth.
- Summary

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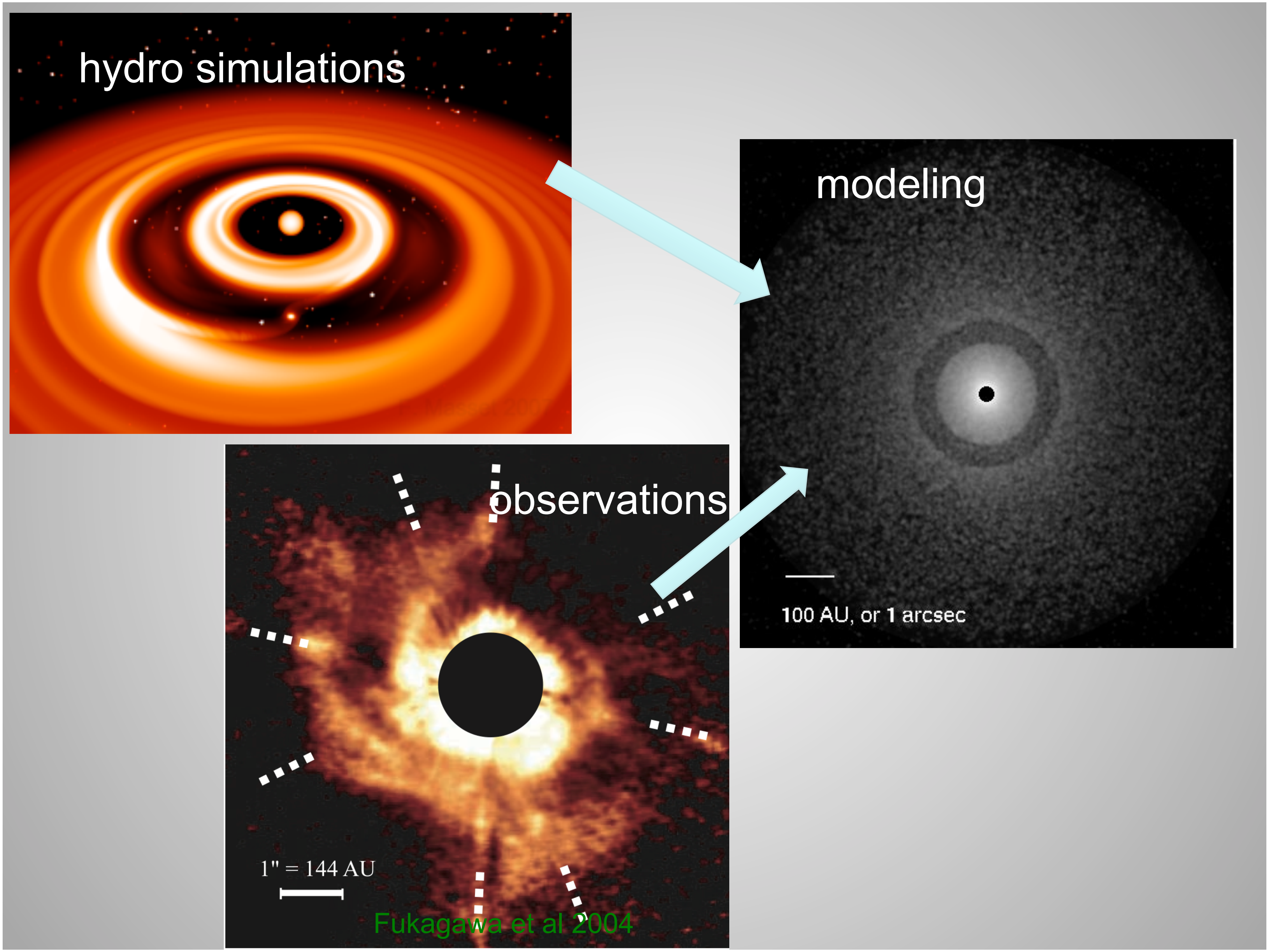
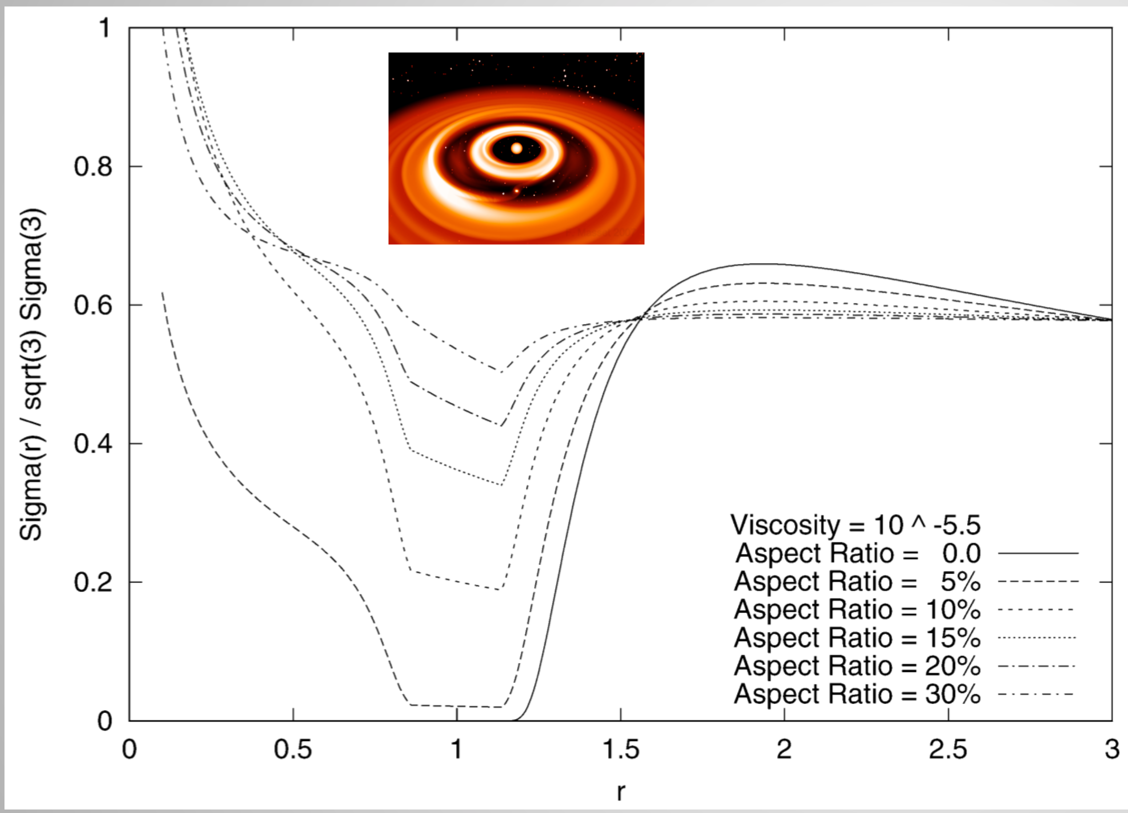

hydro simulations
modeling
100 AU, or 1 arcsec
observations
1" = 144 AU
Fukagawa et al 2004

Motivation: theory side



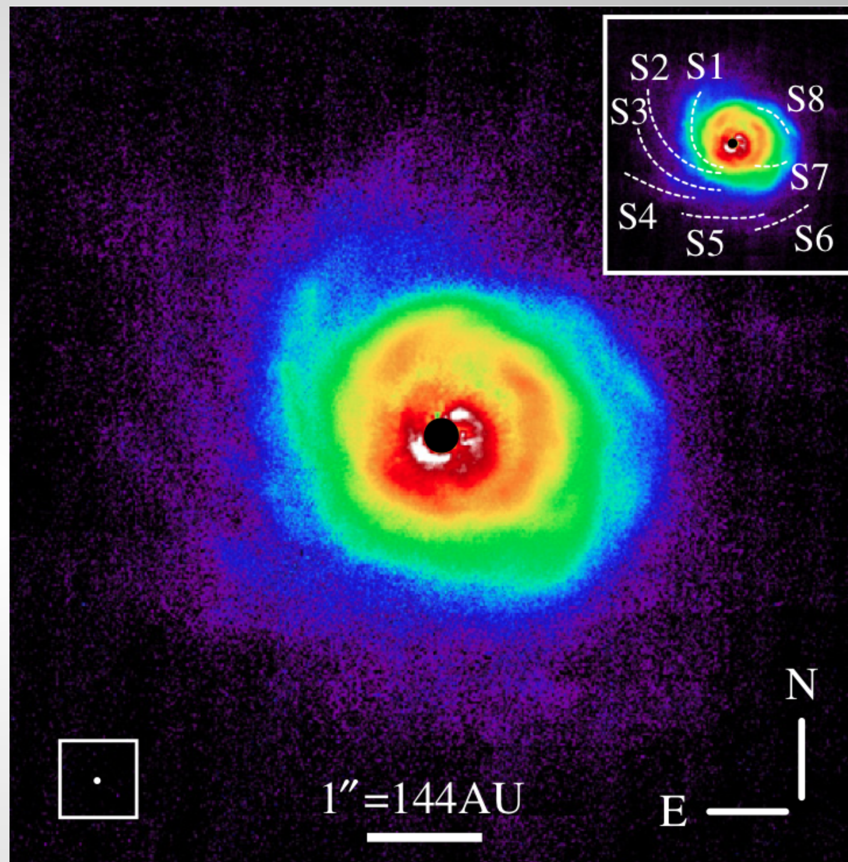
Crida et al. 2006

We have theoretical gap models from hydro simulations, but what would they look like in NIR scattered light?

Basically, you give a theorist a planet, he returns you a gap.

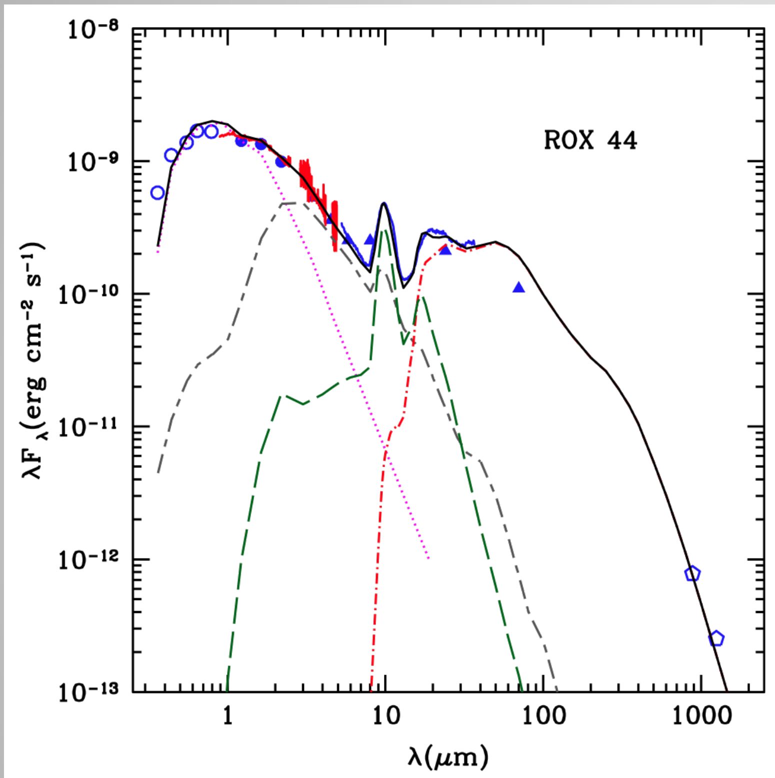
Motivation: observation side

With excellent AO system, coronagraph, and speckle remove techniques, largest grounded based optical-IR (J, H and K band) telescopes (i.e., Subaru and Gemini) are undergoing projects to take near IR images of nearby star forming regions.

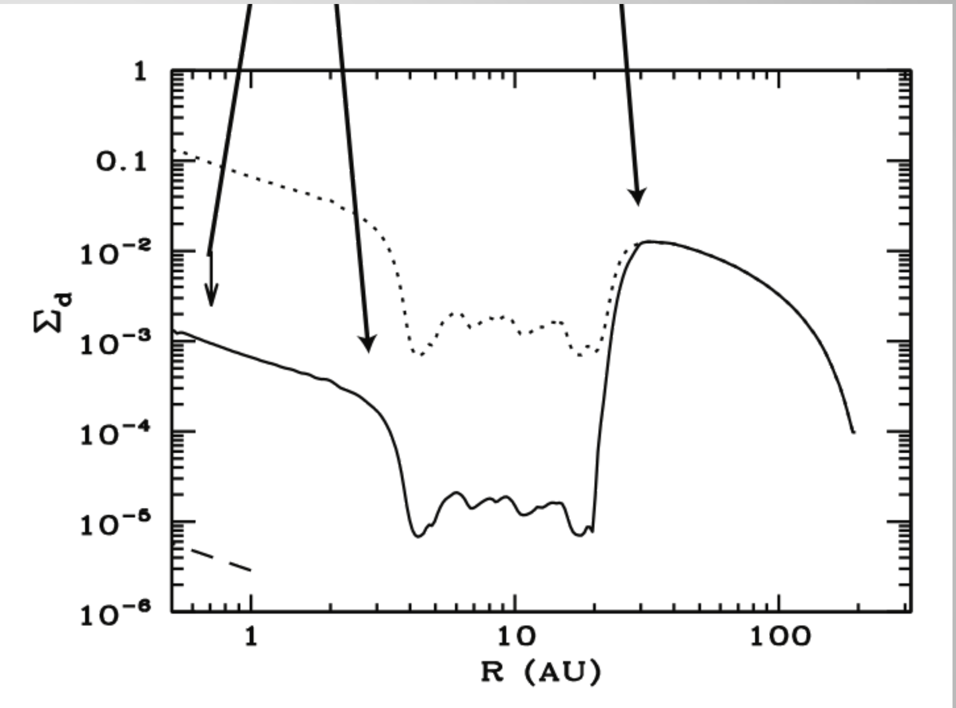


AB Aur, Hashimuto 2011, Subaru H band (1.6μm)
Diffraction limit is achieved on a 8m class telescope → ***spatial resolution 5AU*** *for the nearest star forming region.*

Motivation: observation side



Espaillat et al. 2010



Zhu et al. 2011

For (pre) transitional disk,
SED → disk depletion factor

and theorist are trying
very hard to explain it.

But what can we learn from the direct disk imaging?

Motivation: observation side

There is increasing evidence for previously-unresolved large gaps in T Tauri disks (Andrews et al 2010). It is likely that many T Tauri/ Herbig Ae/Be systems are actively forming planets (and gaps), even at ages of 10 Myr.

One track for detecting small gaps - ALMA/ EVLA, submm/mm emission.

The other – scattered light NIR images – what can be learned from these? what are the limitations on detection?

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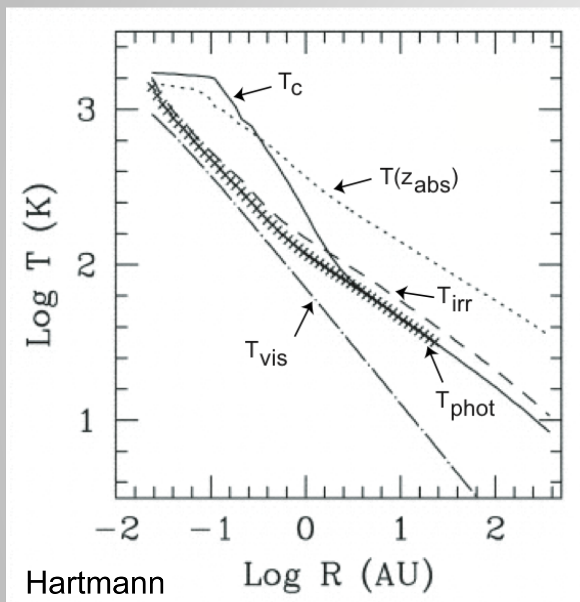
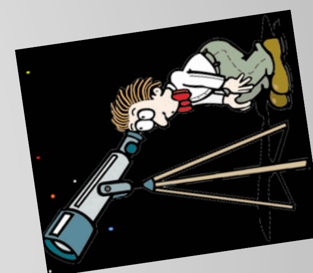
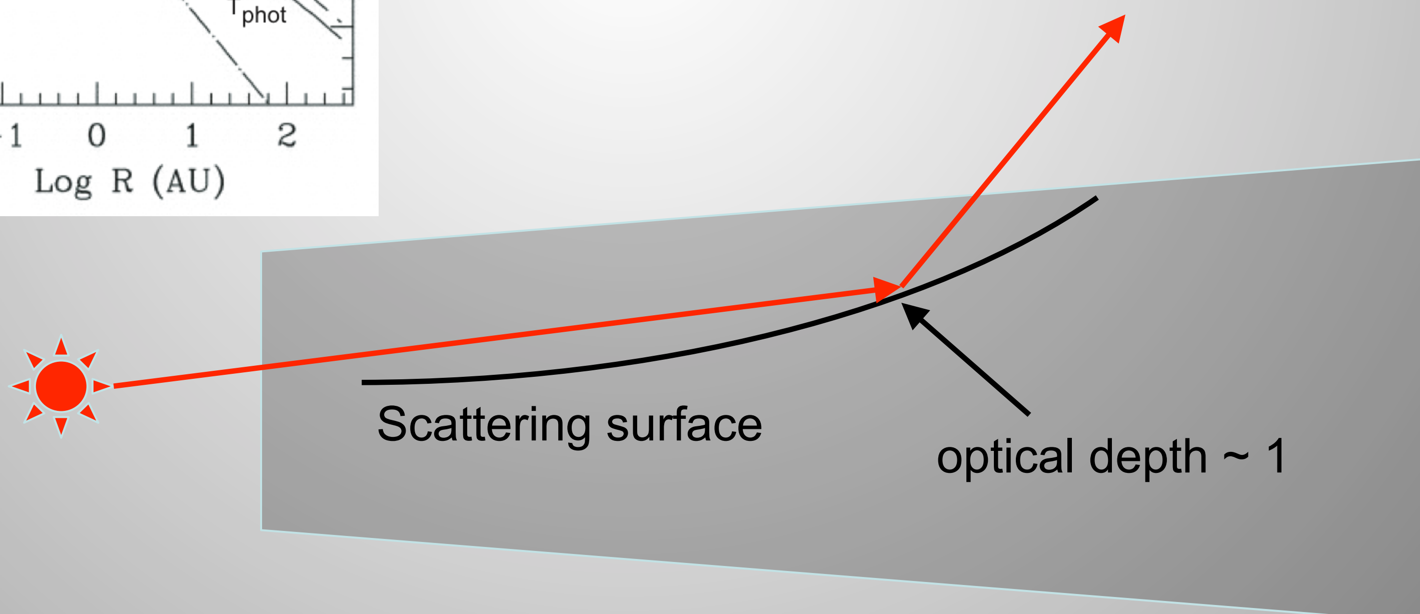
What does a NIR disk image tell us?



Disk emission contributes little at J, H, and K bands, especially when the central part is blocked by the coronagraph.





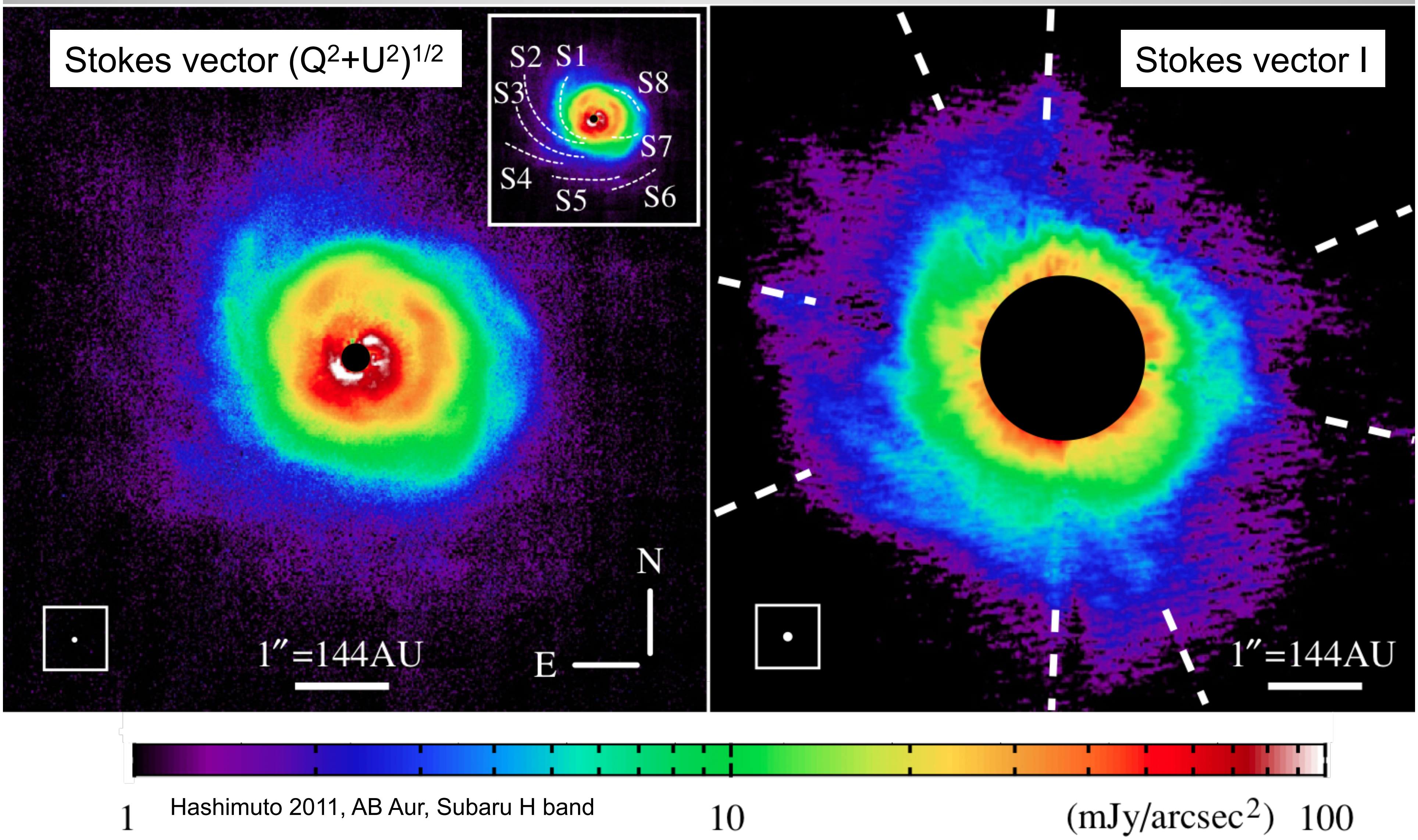
Polarized Intensity

When it comes to direct imaging of the disk, there are three things which the observers want to achieve:

1. Better Spatial resolution.
2. Suppress the star light, so the disk structure could be seen.
3. Smaller inner working angle (smaller mask), to probe the inner disk.

Polarization: a fundamental difference between disk light and stellar light. So the subtraction of one polarization angle from another largely suppresses the stellar light.

Polarized Intensity



Hashimuto 2011, AB Aur, Subaru H band

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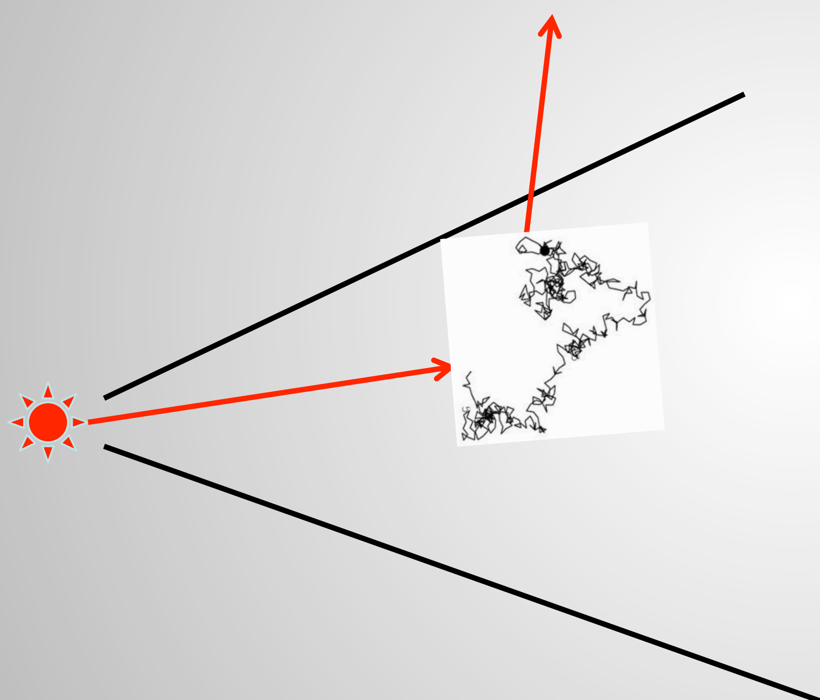
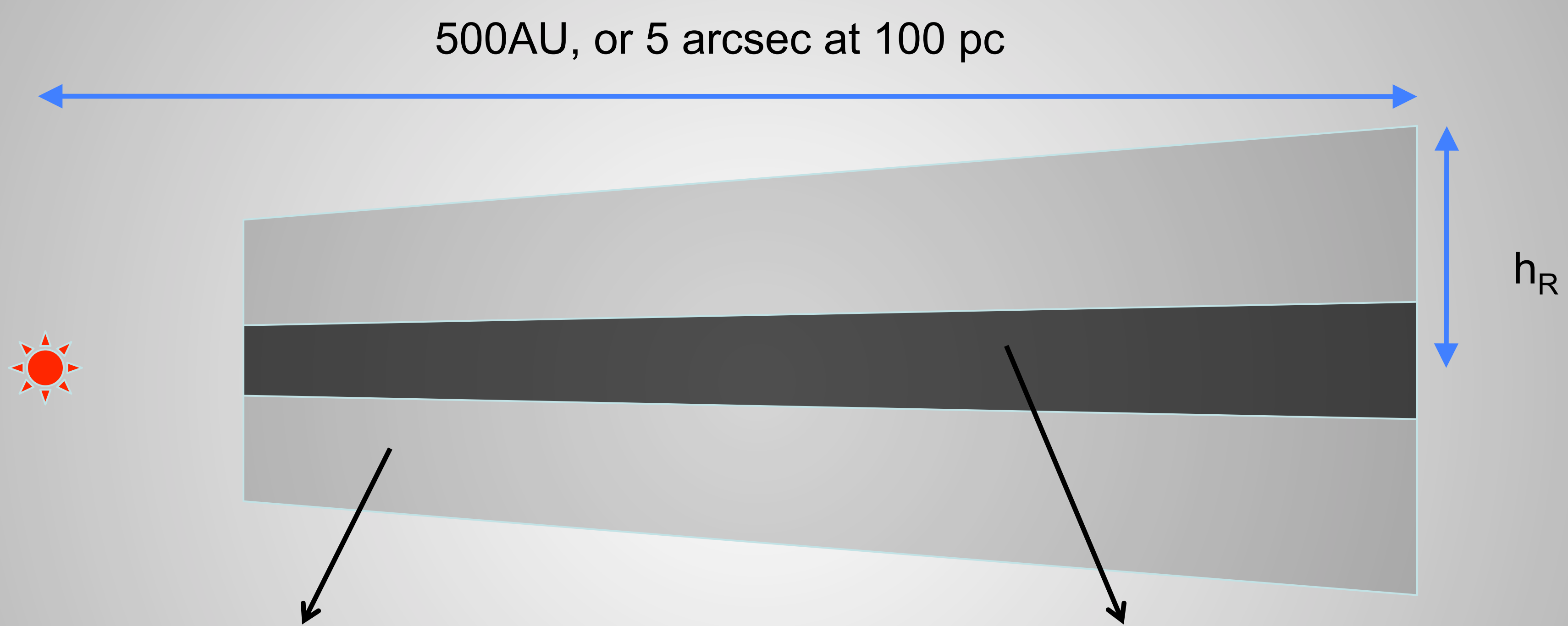
Tool: Barbara Whitney's Monte Carlo Radiative Transfer code



The fiducial model



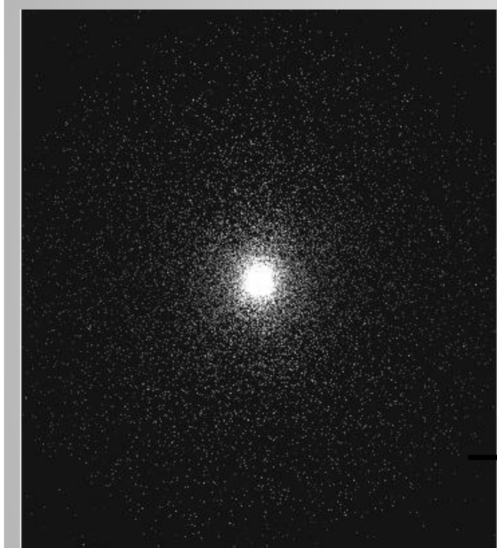
Normal dust disk (m_{d1}), basically ISM grains, scale height h_R ($h_R/R=0.05$ at 10 AU)

Settled disk (m_{d2}), larger grains, scale height $0.1h_R$

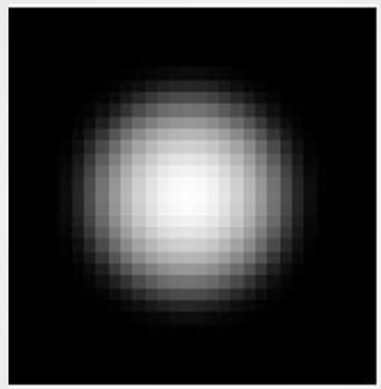
Total disk mass is 0.01 solar mass, which is distributed into two components ($m_{d1}/(m_{d1}+m_{d2})$ is the depletion factor).

PSF and coronagraph: disk

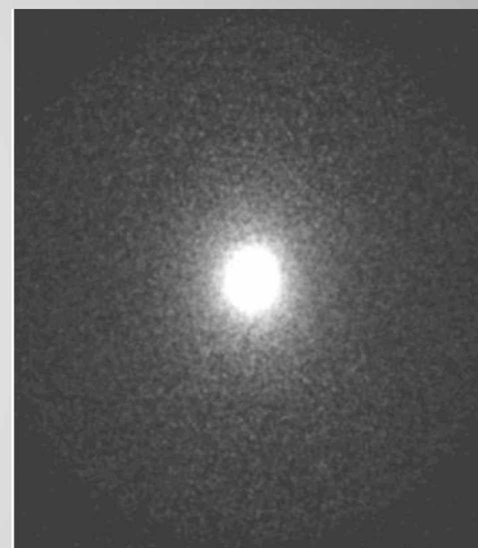
raw disk



disk psf



convolved disk

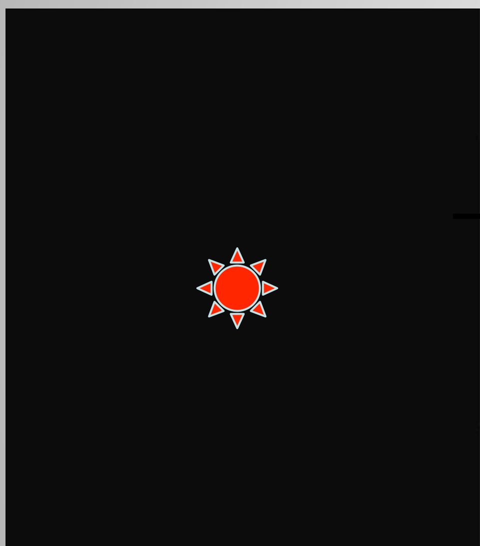


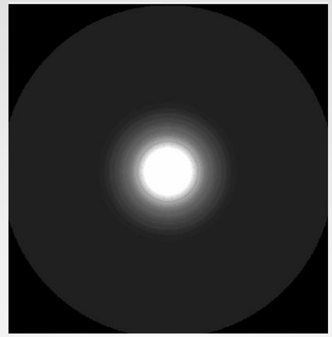
We are still working on to get a 2D more realistic psf from the instrument team

For the disk, we use a diffraction-limited PSF (results of an excellent AO system) for an 8m telescope at 1.6 microns (FWHM 0.06 arcsec, Hashimuto 2011) to smear out the image

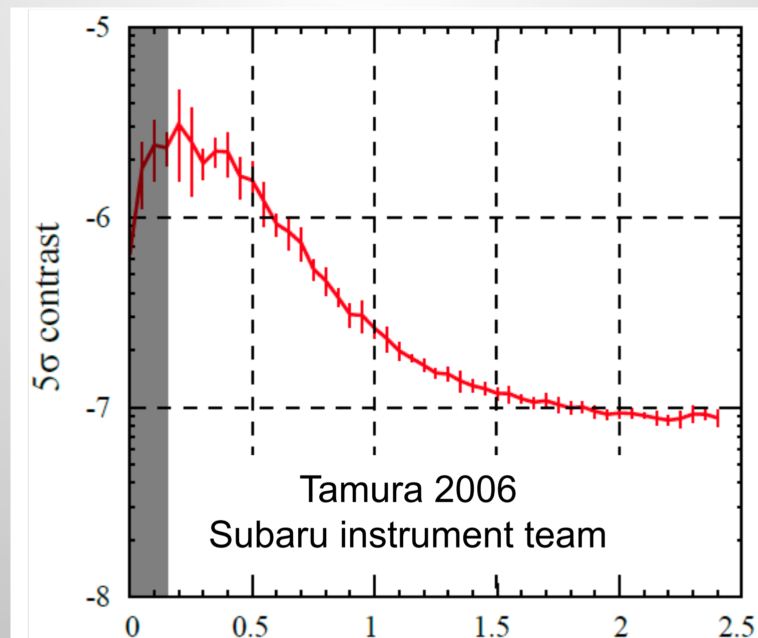
PSF and coronagraph: star

raw image of the star (single pixel)

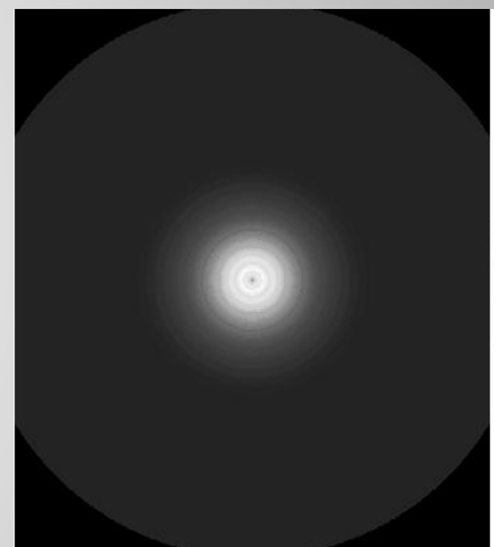




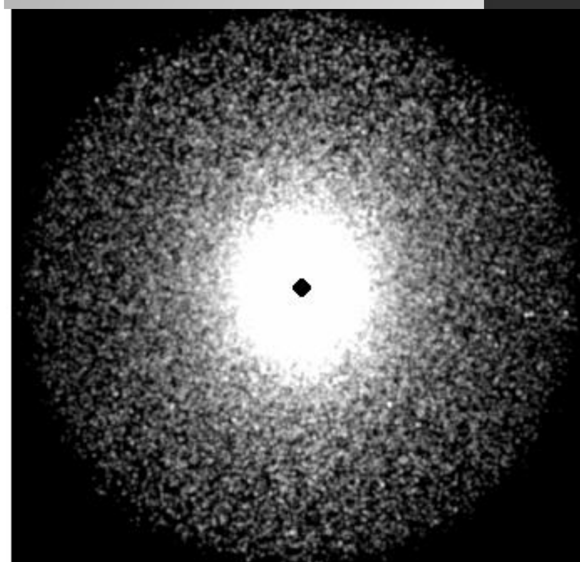
convolve with the coronagraph PSF

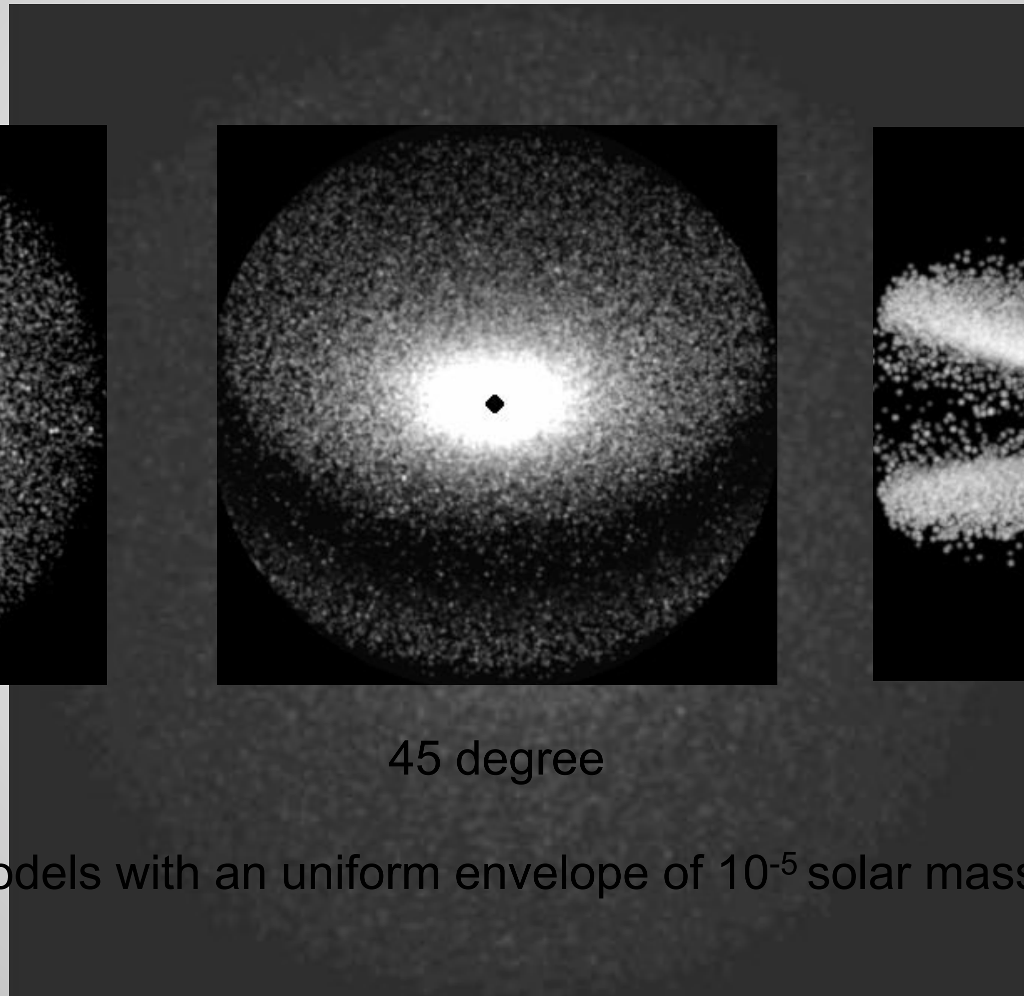


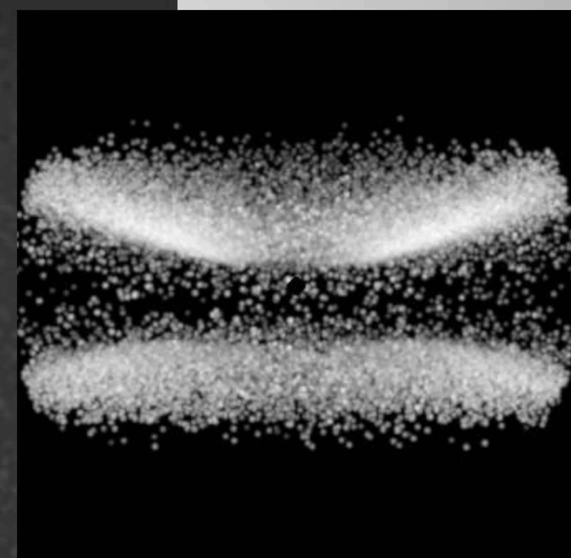
convolved star



Finally, disk+star, with corresponding PSF …







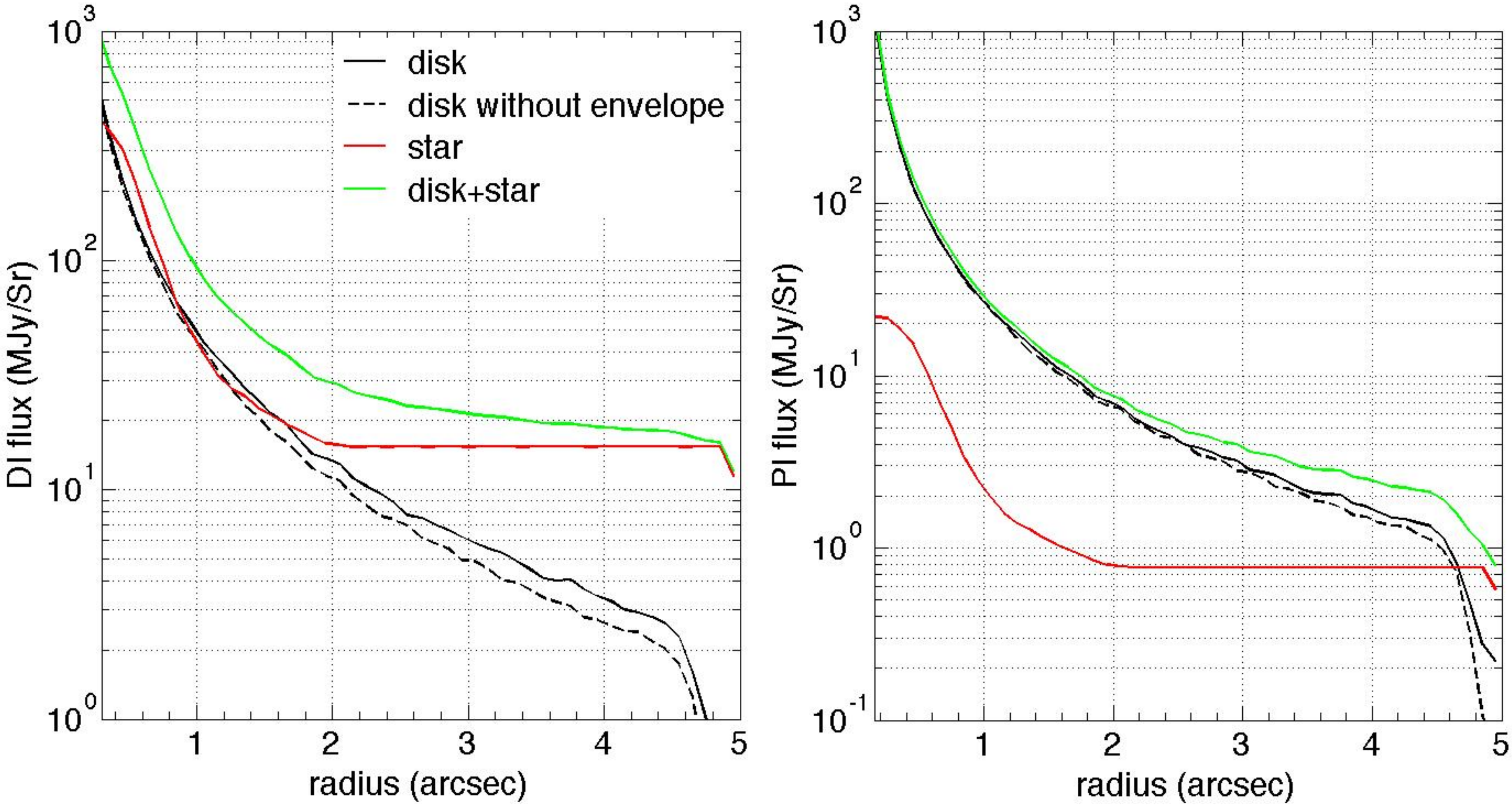
face on

45 degree

edge on

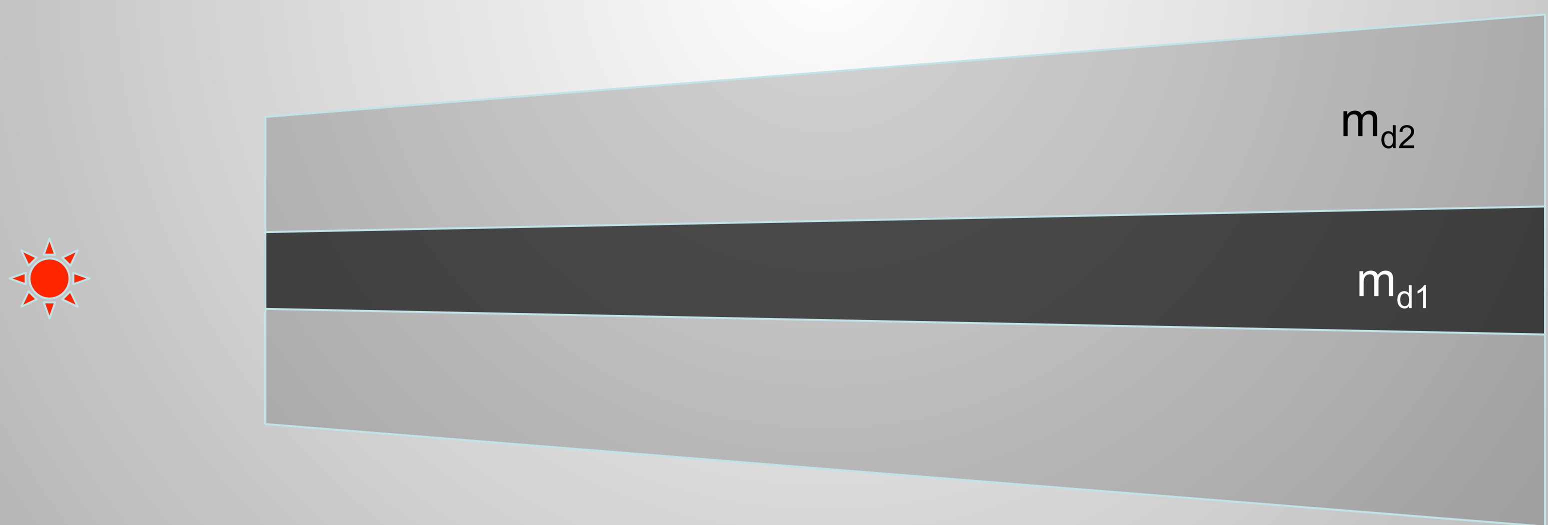
We tried models with an uniform envelope of 10^{-5} solar mass as well

radial profile of the surface brightness: face on



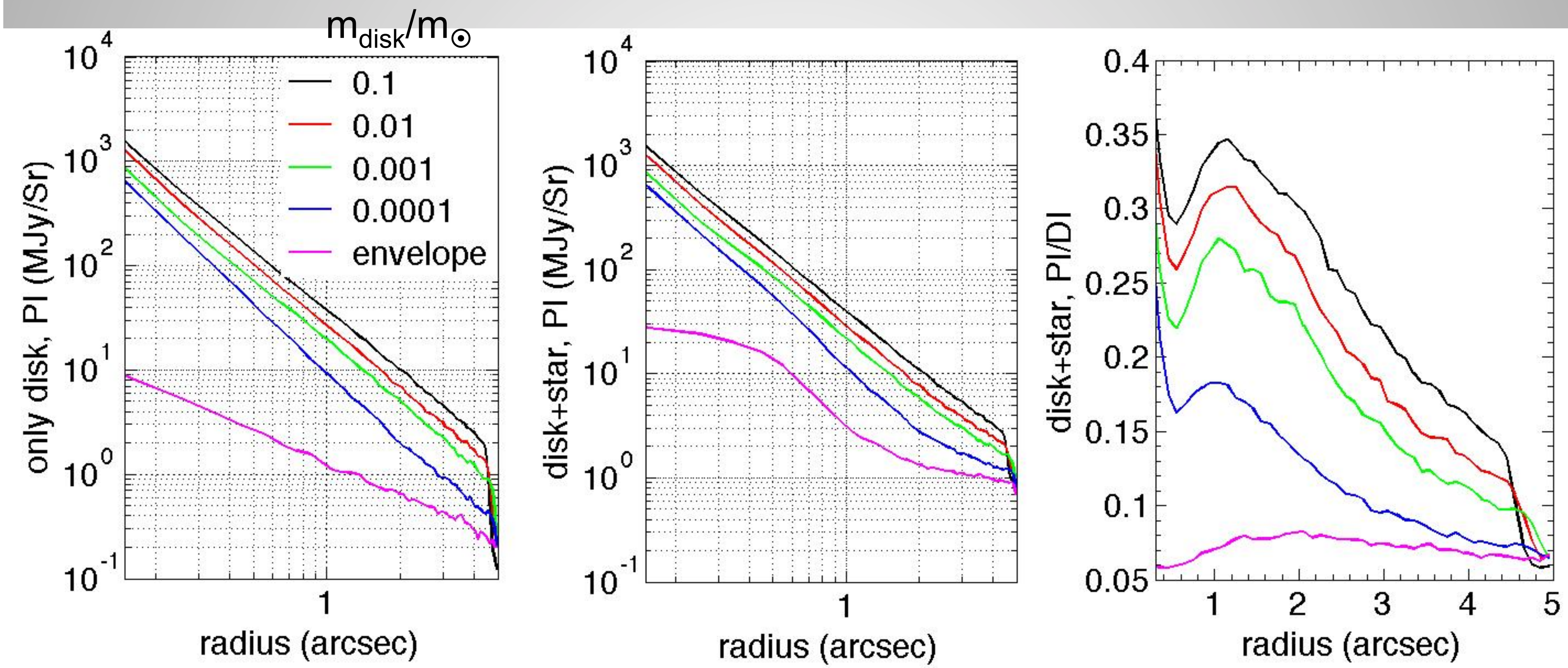
The coronagraph curve is not exactly accurate beyond 2.5 arcsec, but we still see why polarized intensity is the key.

Disk without gaps, to check the effect of disk mass and disk depletion factor



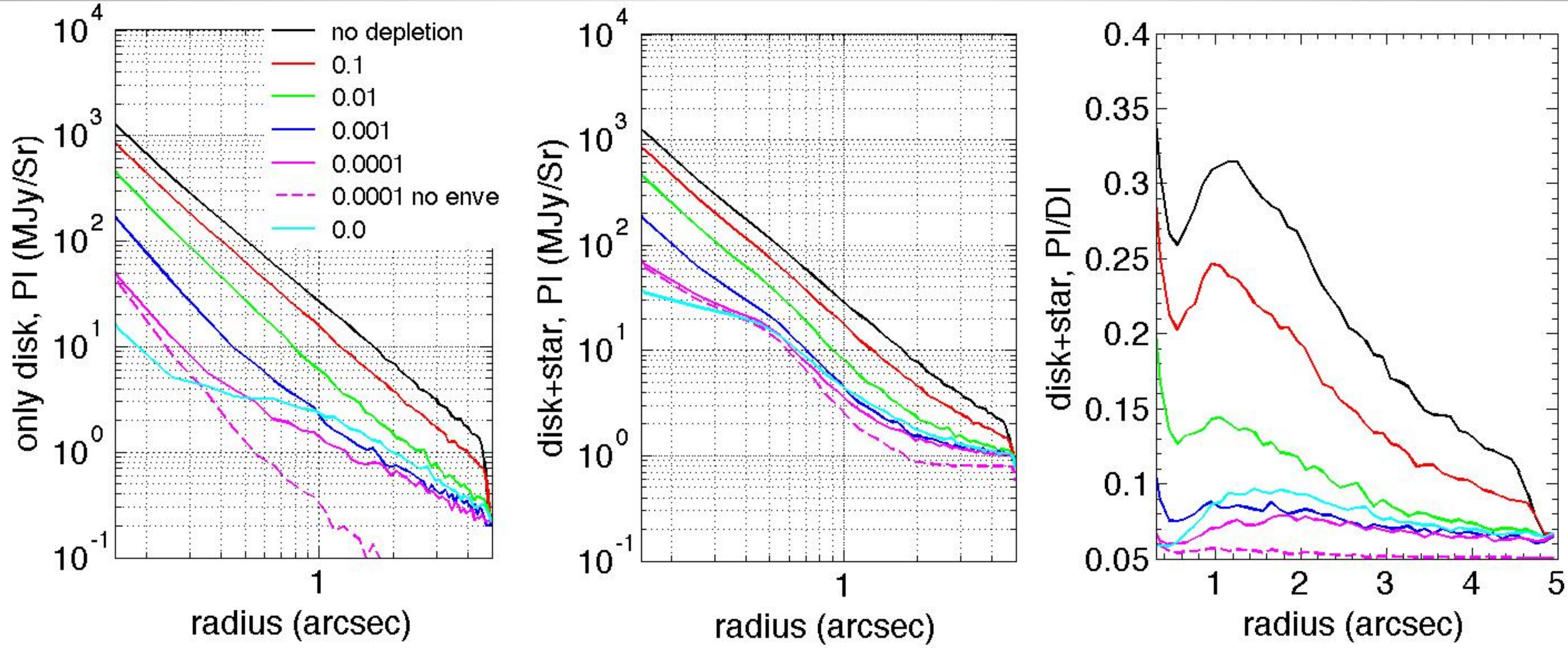
depletion factor: $m_{d2}/(m_{d1}+m_{d2})$

Radial profiles for different disk masses (no depletion in these cases)



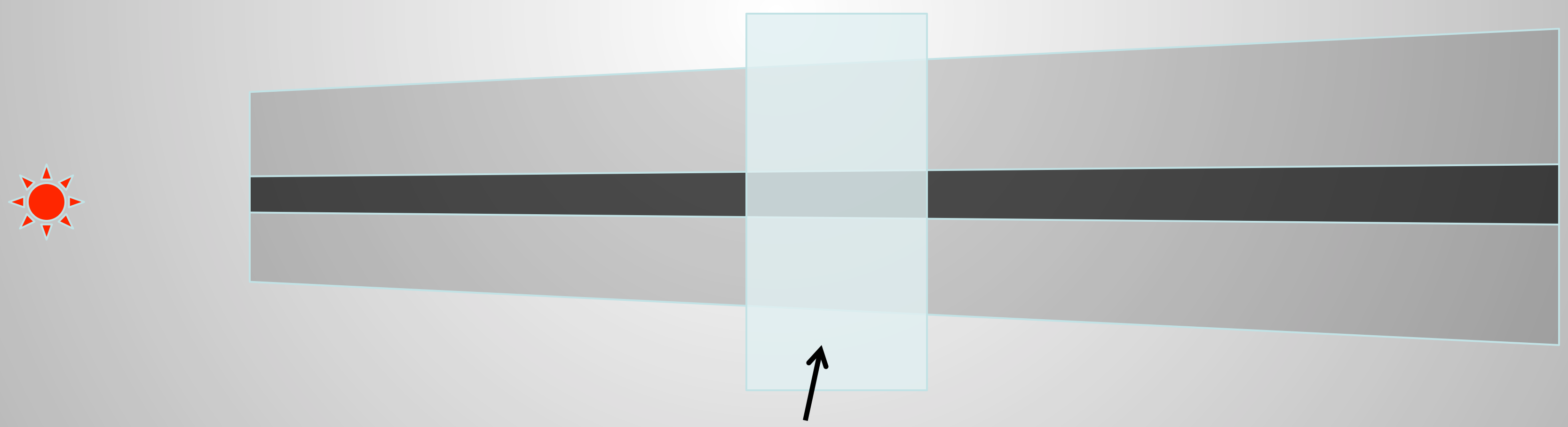
disks with different masses have different flux amplitude, but the slope is basically the same

Radial profiles for different disk masses (total disk mass 0.01 solar mass)



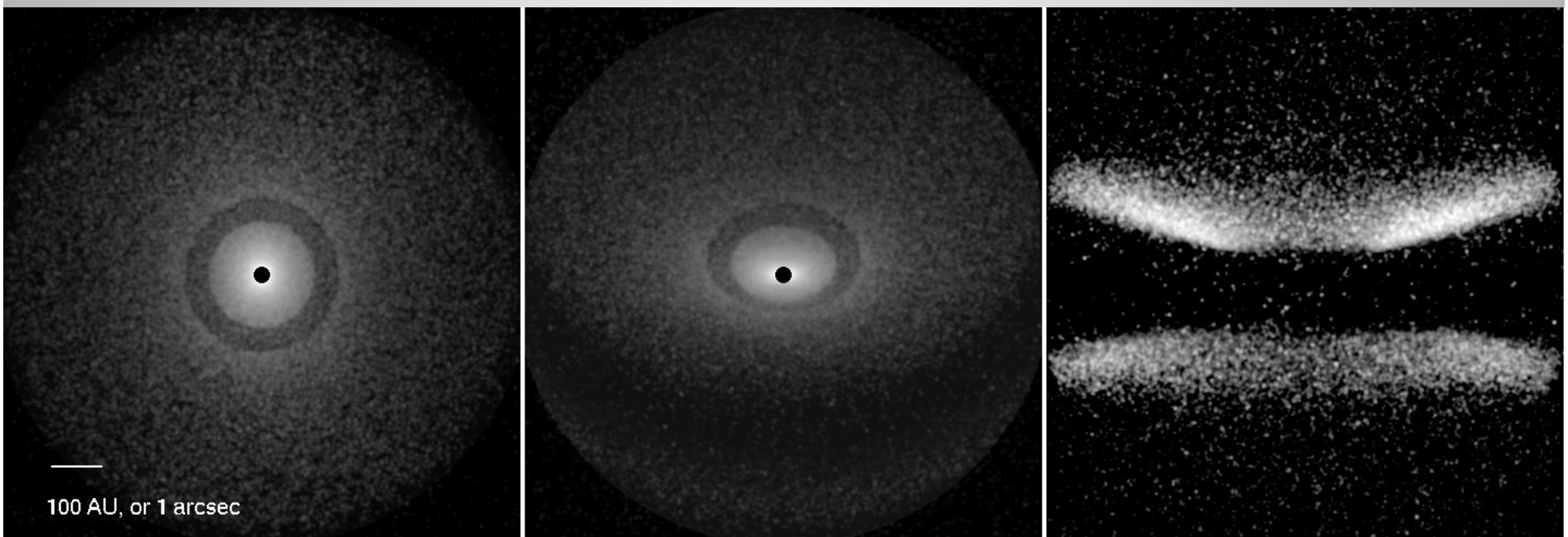
profile is determined by the mass in the normal disk (when optically thick), so transition from (for the normal disk) optically thick to optically thin?

so now, gaps…

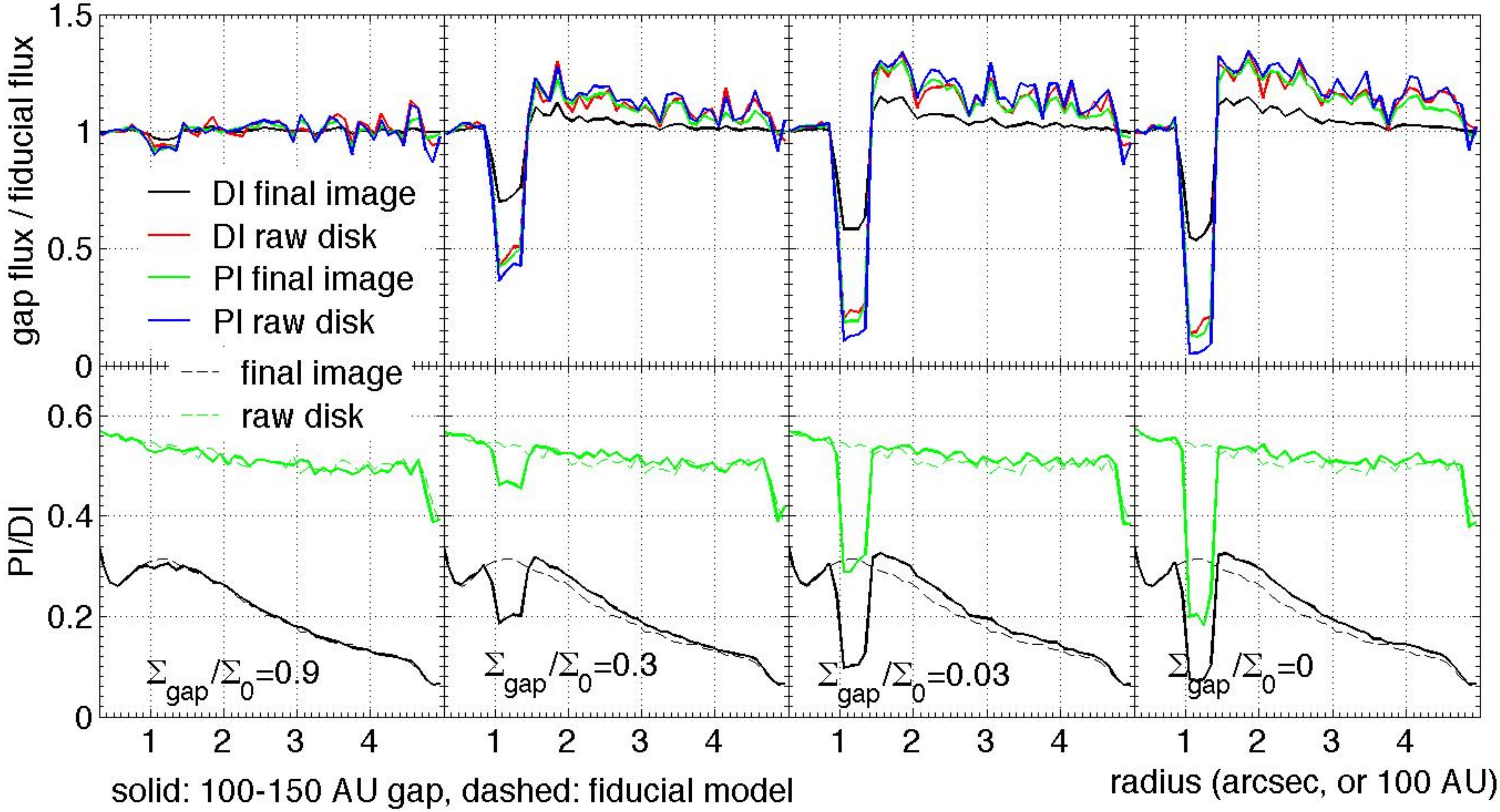


density in this region is depleted by a factor of (1 - depletion factor)

Example: 100-150 gap, depletion factor 0.3

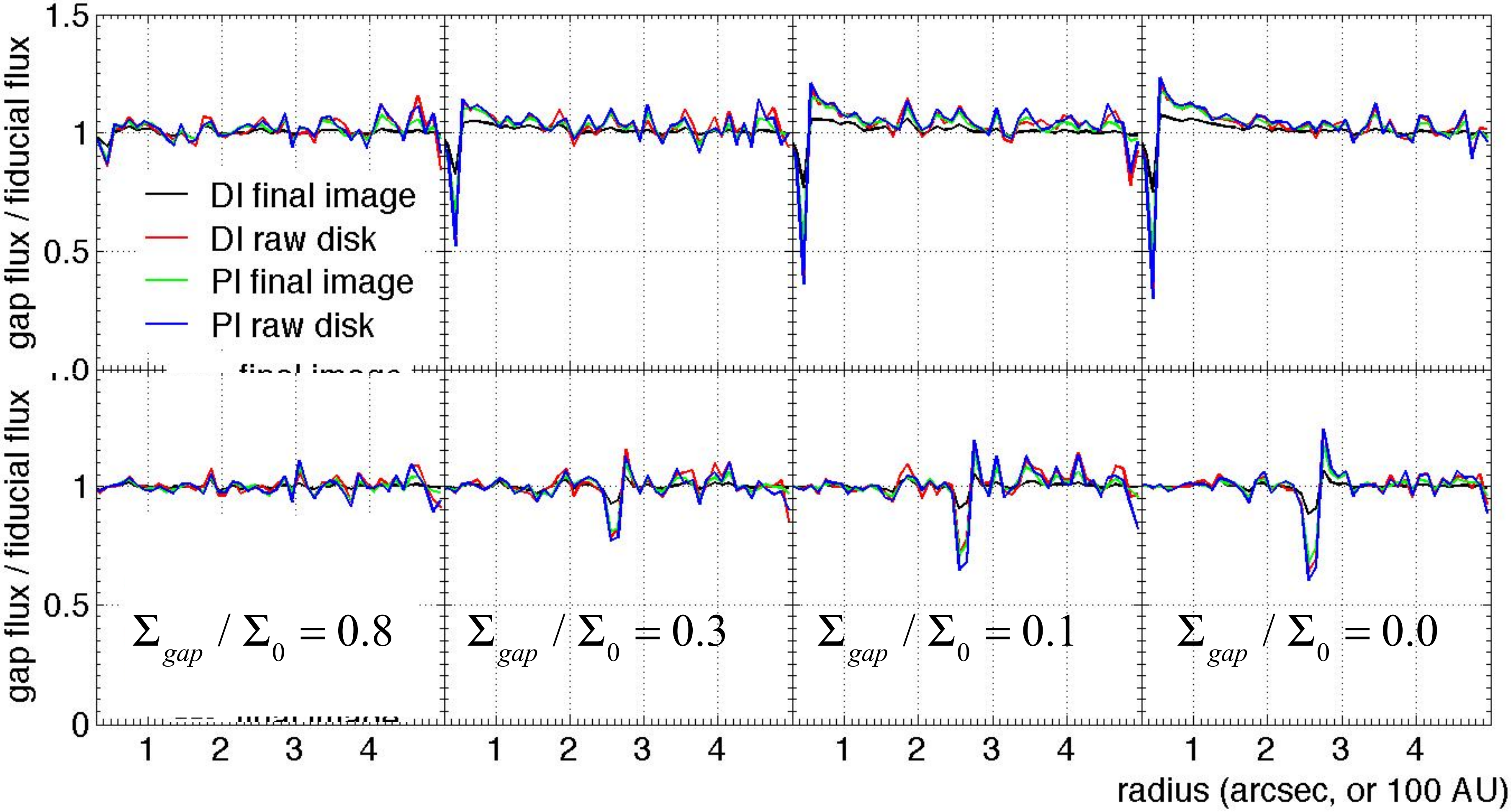


100-150 gap, face on view



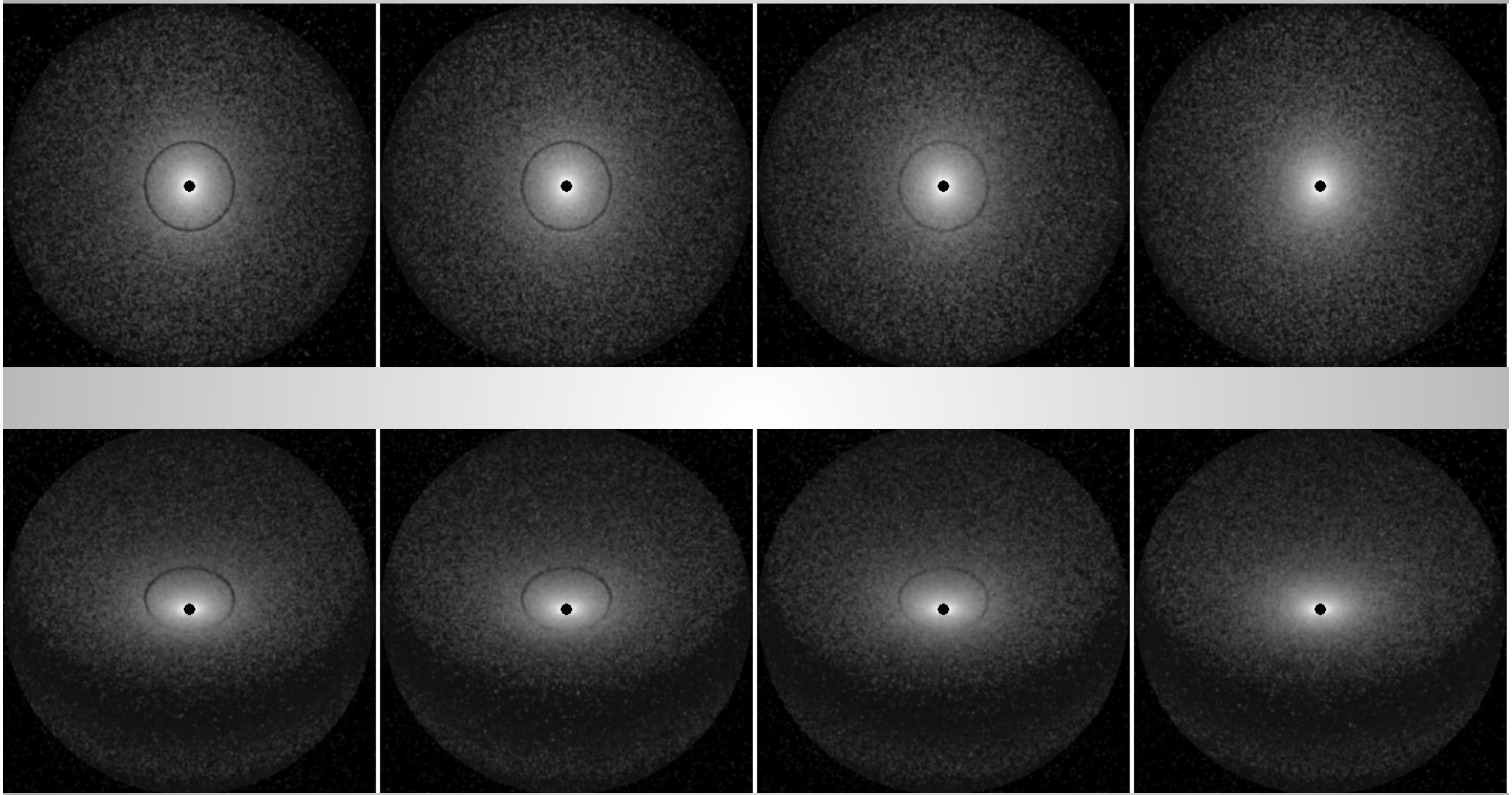
Surface brightness dip – gap depth

40-50 AU and 270-280AU gap, face on view



inner gaps makes narrower but deeper dip than outer gaps

A 120-130 AU gap



$\Sigma_{gap} / \Sigma_0 = 0.0$ $\Sigma_{gap} / \Sigma_0 = 0.1$ $\Sigma_{gap} / \Sigma_0 = 0.3$ $\Sigma_{gap} / \Sigma_0 = 0.8$

Depletion factor – where is the *detection limit?*

Next step

1. Get a more realistic 2D psf (for both the disk and the star) from the instrument team.
2. Quantify the results on the limit of detectability on gap size and depth.
3. Infer the scattering surface from the observations using our modeling, based on which to *translate* imaging info into disk properties, such as the depletion factor.
4. Some disks are more flared than others (from SED), and that will help in seeing gaps because the disks will be brighter; in a truly flat disk, can we really see gaps?
5. Make predictions of what kind of observable signal one can get from various physics, such as GI, MRI, and planets. Build a bridge between numerical hydro simulations and observations.

Summary

- We simulated the NIR scattered light images for the protoplanetary disks, using a Monte Carlo radiative transfer code.
- We have explored the parameter spaces to check the effects depletion factor and disk mass for the no gap disks, and gap position, width, and depth for the gapped cases.
- The future plan.

THANK YOU