Unveiling Dust in Planet-Forming Disks:
A Multiwavelength Observational and Modeling Perspective

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Why observations of protoplanetary dust?

Evolution from dust to planets is a *very* complicated process, depending on

- dust dynamics (settling & radial drift, turbulence diffusion, trapping…)
- microscopic properties of dust (porosity, chemical composition, …)

Talks by Til Birnstiel, Jürgen Blum

What dust observations can potentially do:

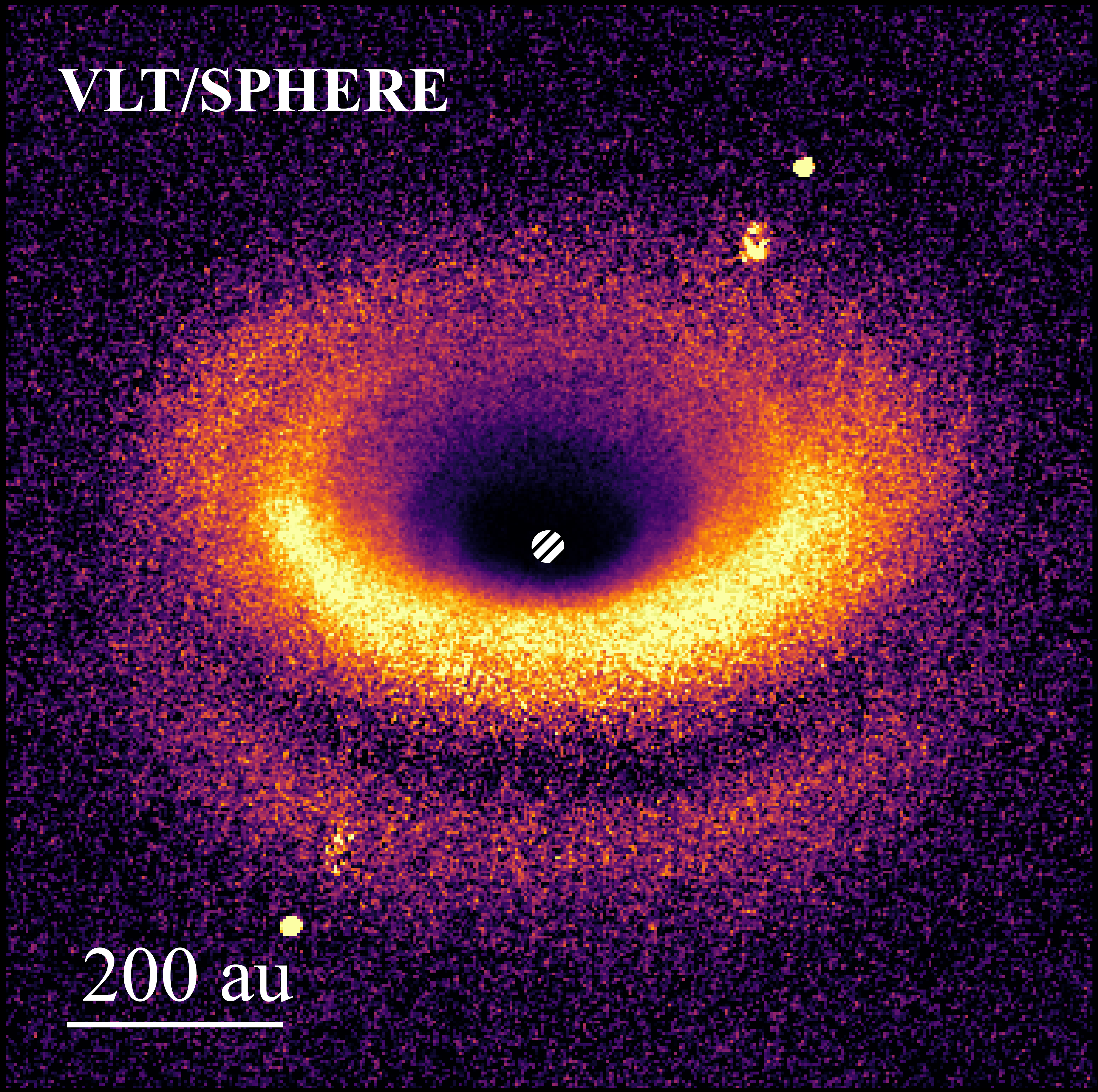
- Testing dust evolution models by measuring (or at least inferring)…
  - dust grain sizes and their spatial distribution
  - dust porosity
  - chemical composition
- Use dust as an indirect tracer of something difficult to measure
  - Grain alignment ⇒ magnetic field

Today’s outline

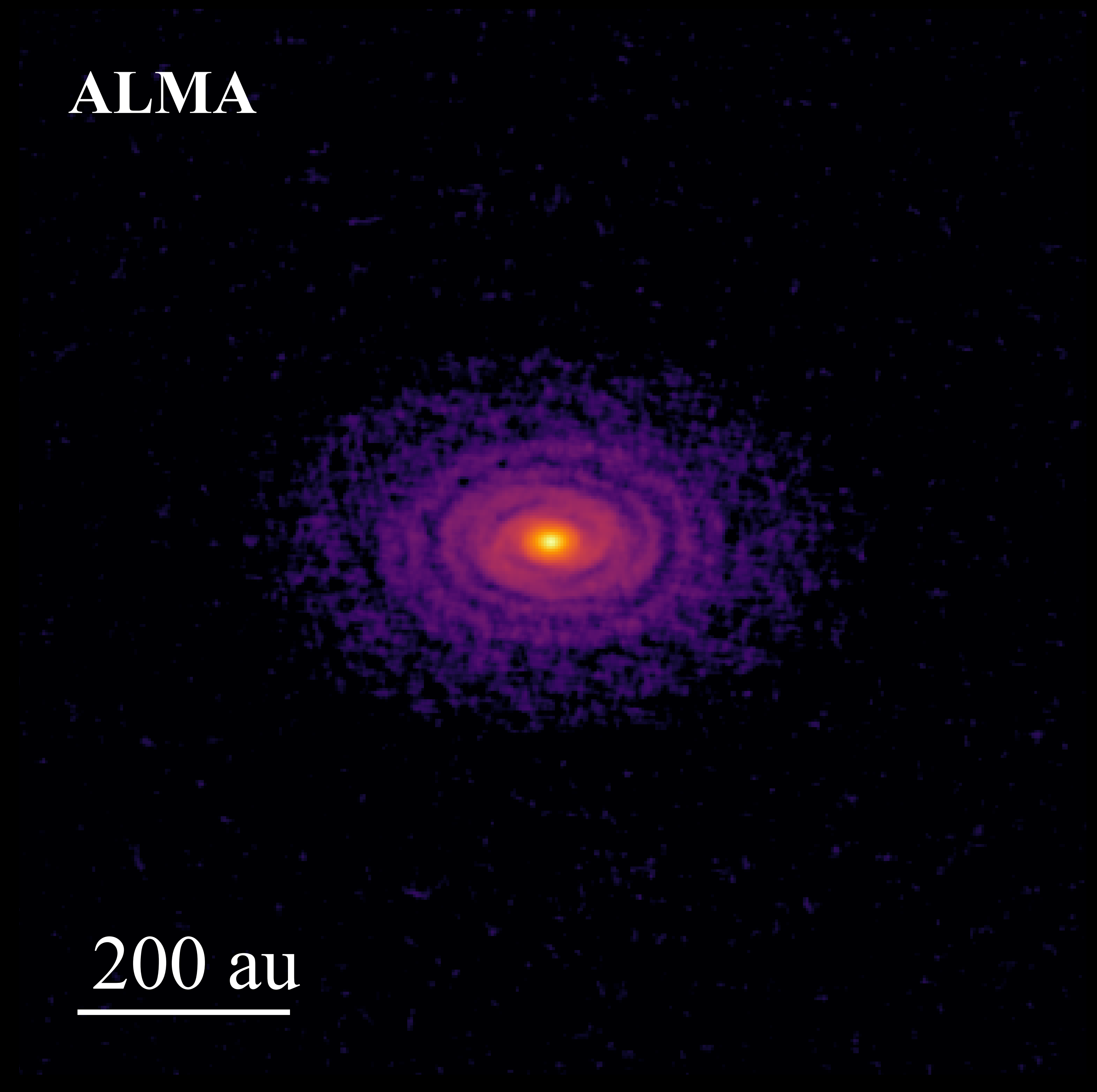
- Recent high resolution imaging observations of disks
- Specific dusty topics (mainly on grain size and porosity constraints):
  - JWST
  - VLT/SPHERE
  - ALMA

High resolution images of the protoplanetary disk around IM Lup

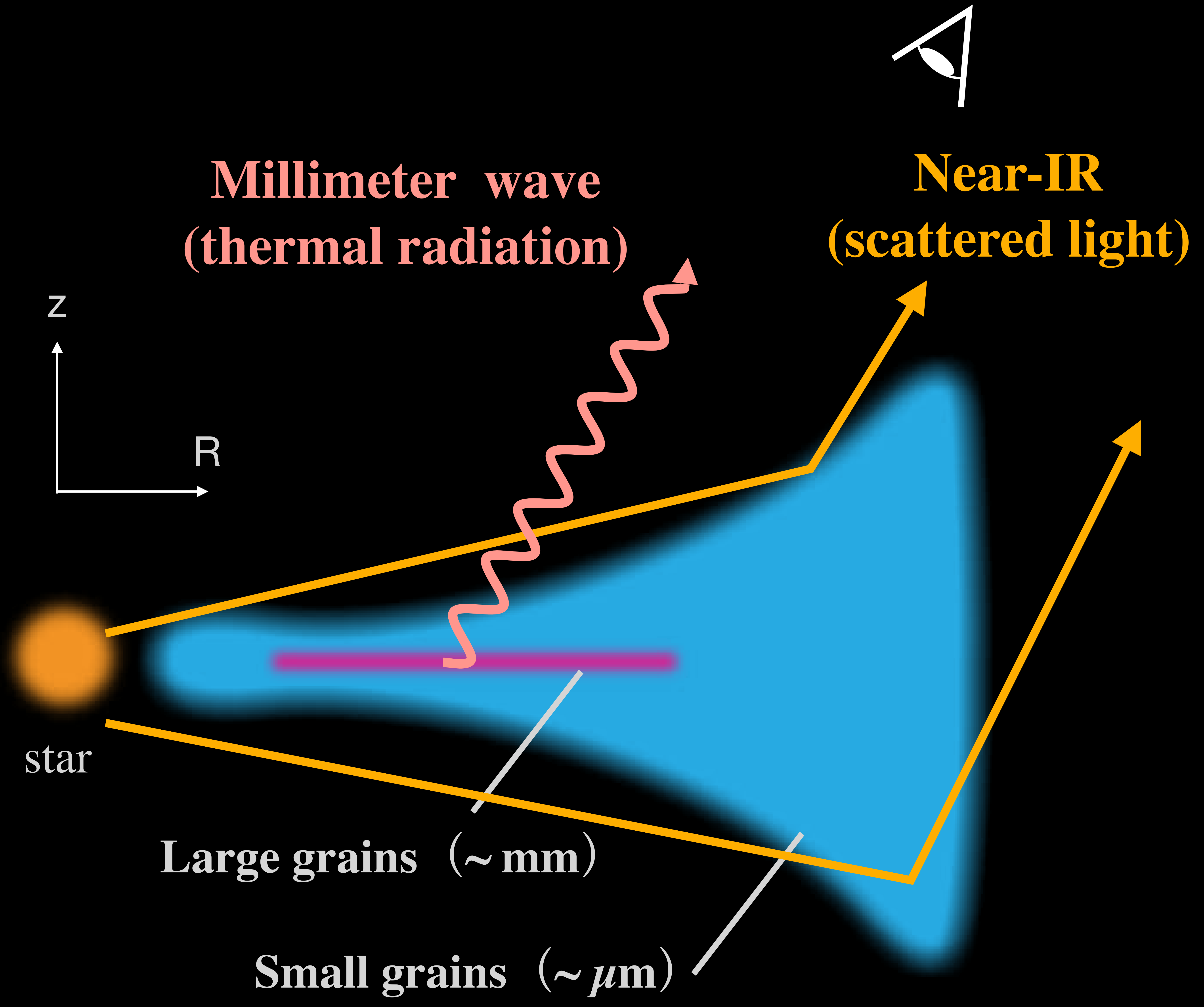
Near-IR

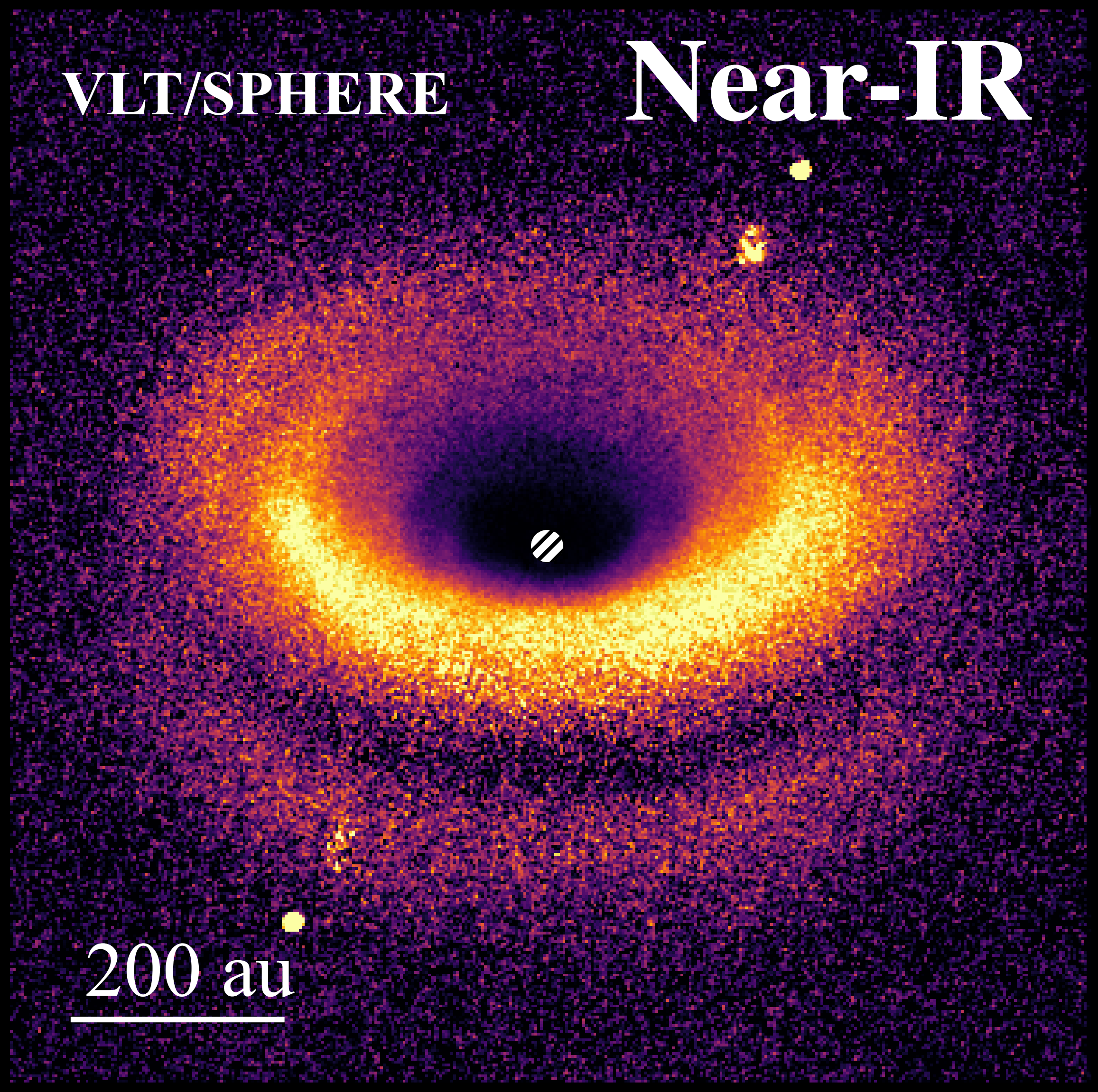


Millimeter wavelength

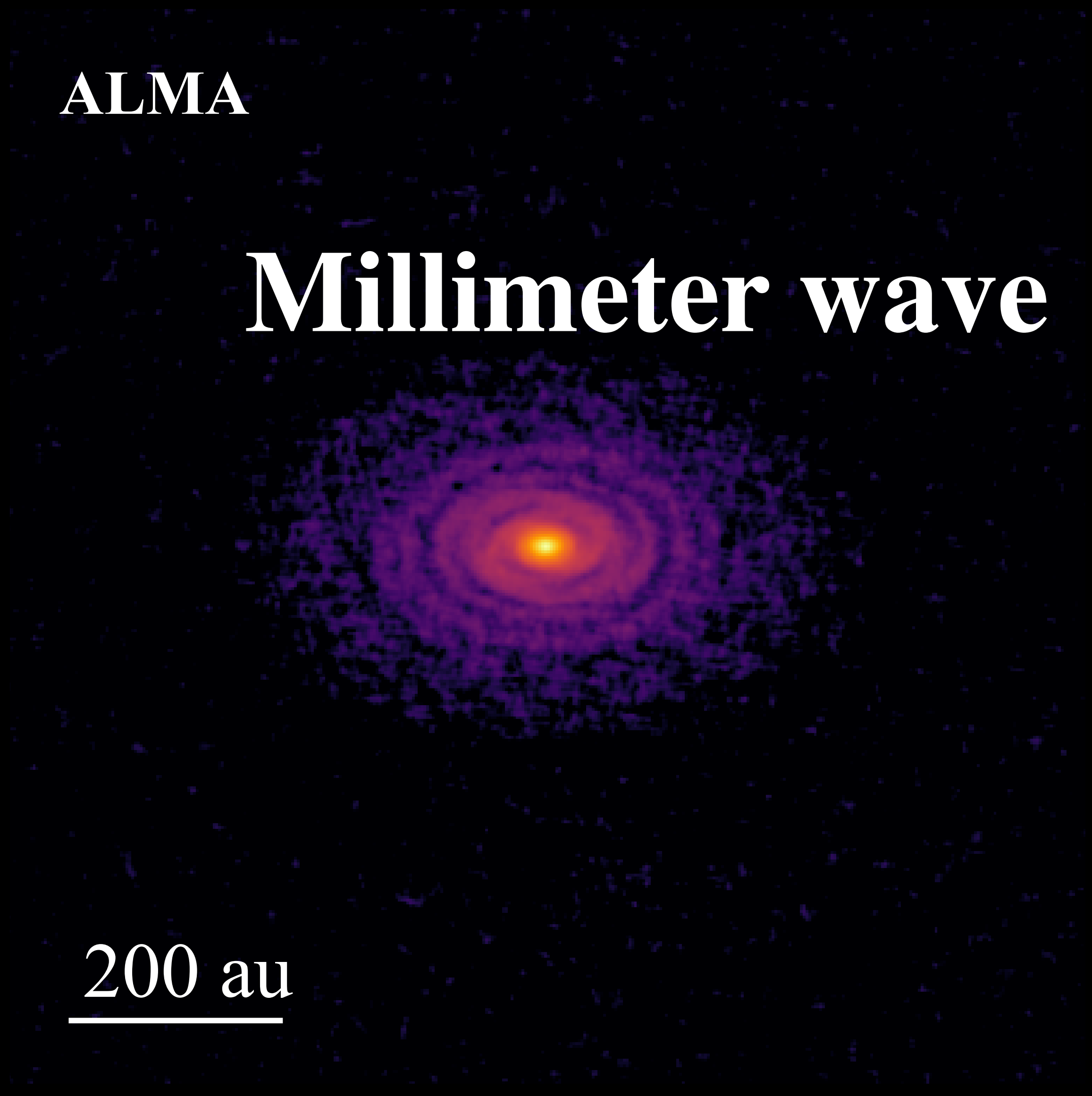


Avenhaus et al. 2018, Andrews et al. 2018, Ginski et al. 2023





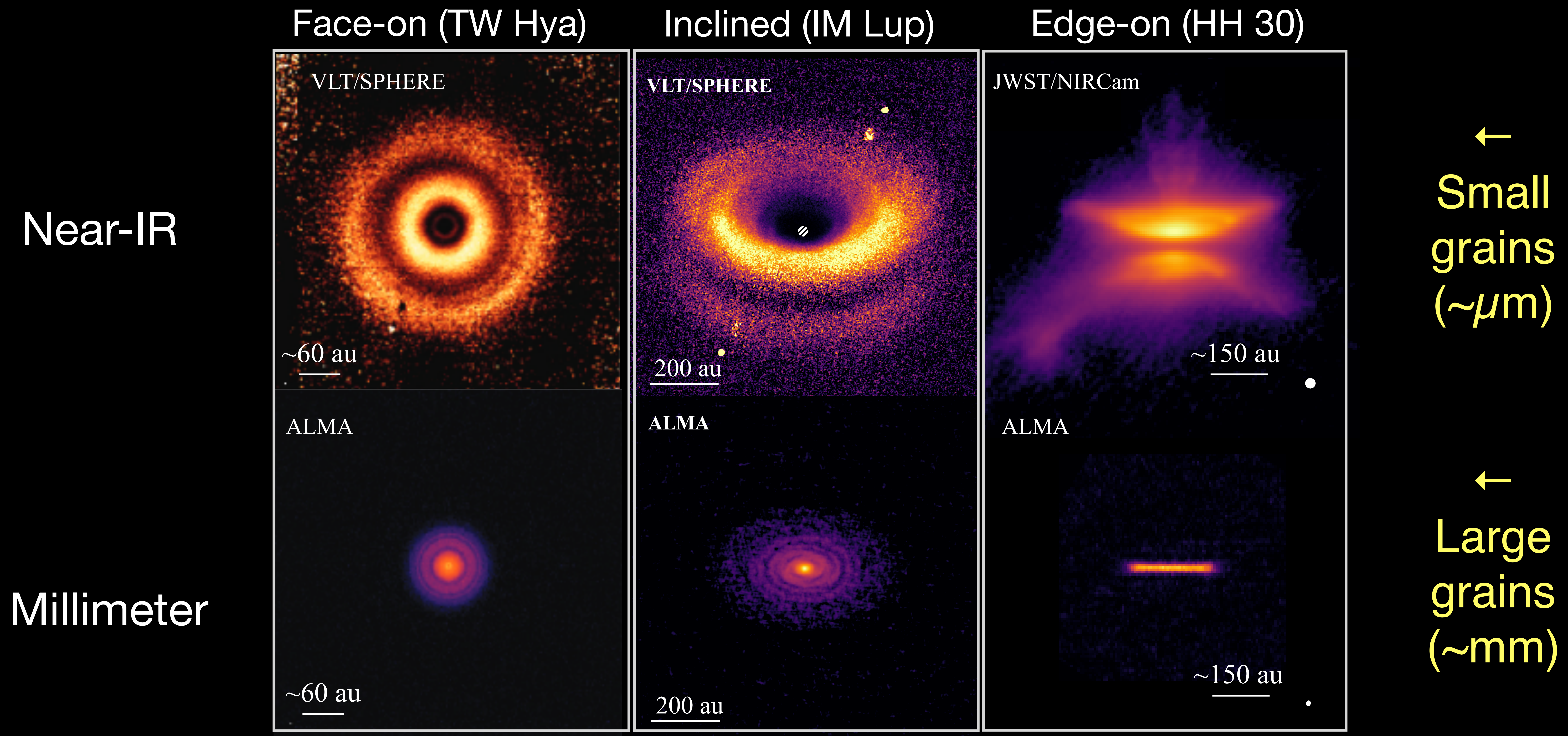
→ small grains (~μm)



→ large grains (~mm)

Avenhaus et al. 2018, Andrews et al. 2018, Ginski et al. 2023

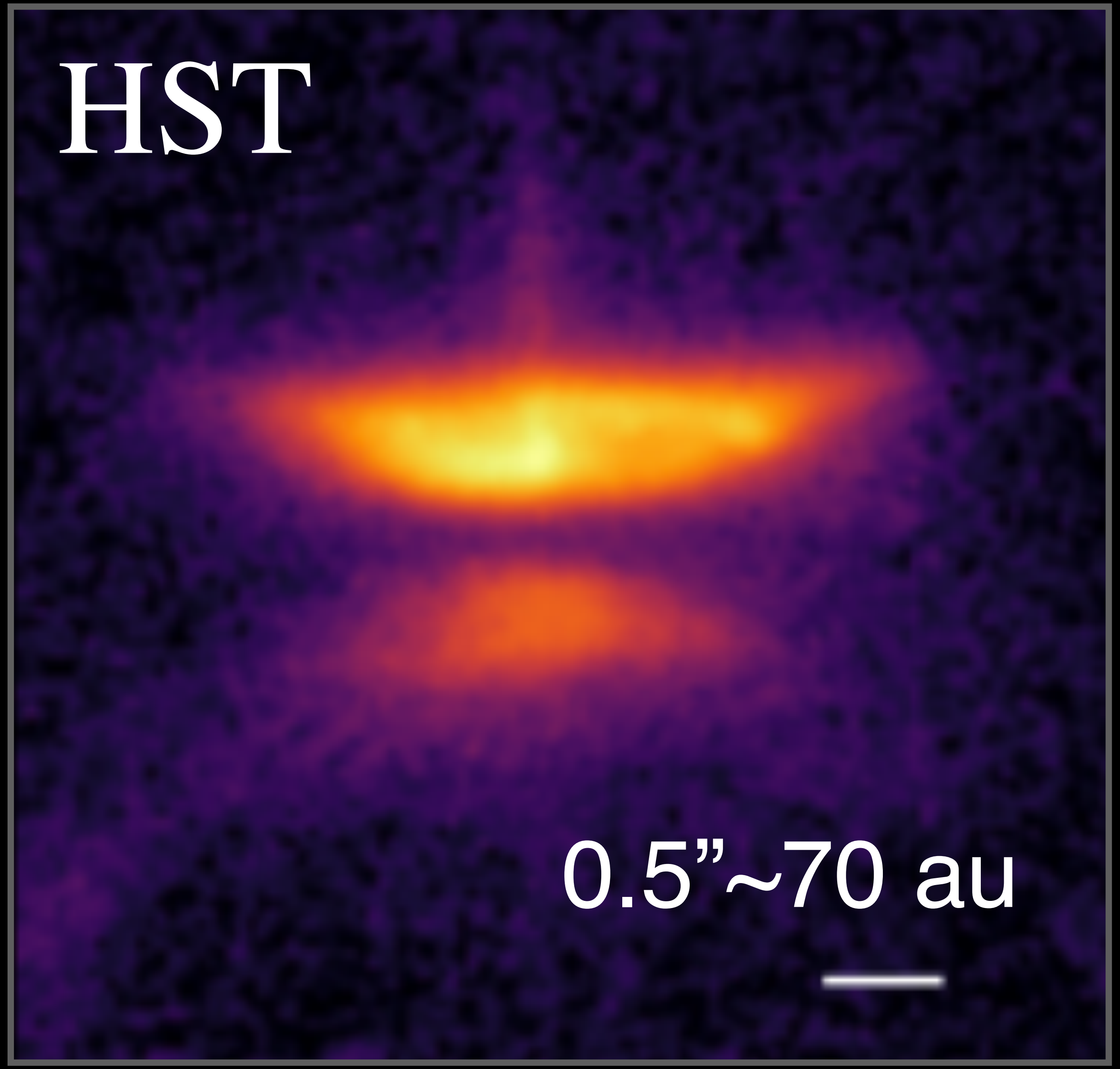
Multiwavelength images of disks



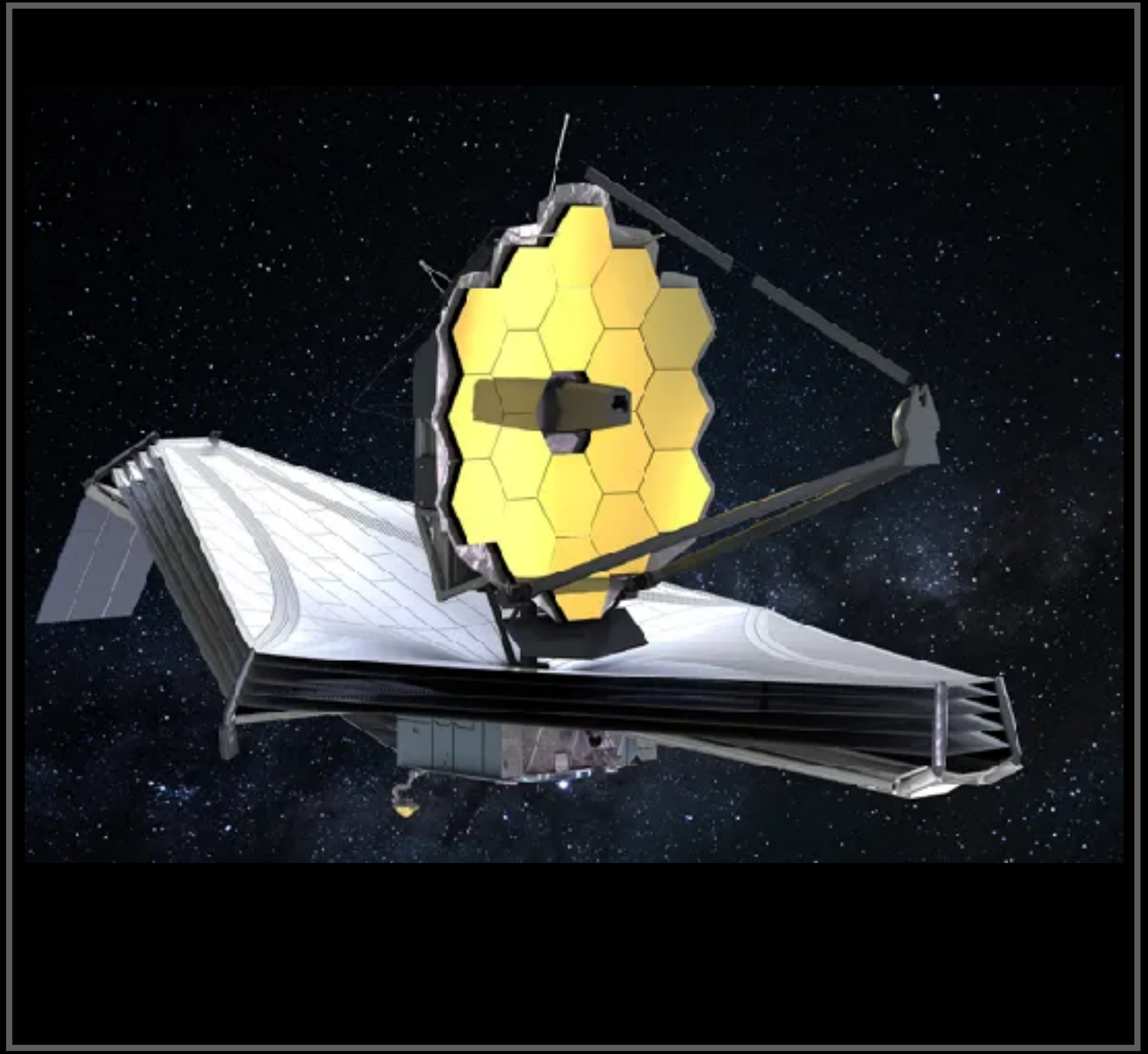
TW Hya: Andrews et al. 2016; van Boekel et al. 2017; Andrews et al. 2020
IM Lup: Avenhaus et al. 2018, Andrews et al. 2018, Ginski et al. 2023, HH 30: Tazaki et al. (2025)

A new game changer: JWST

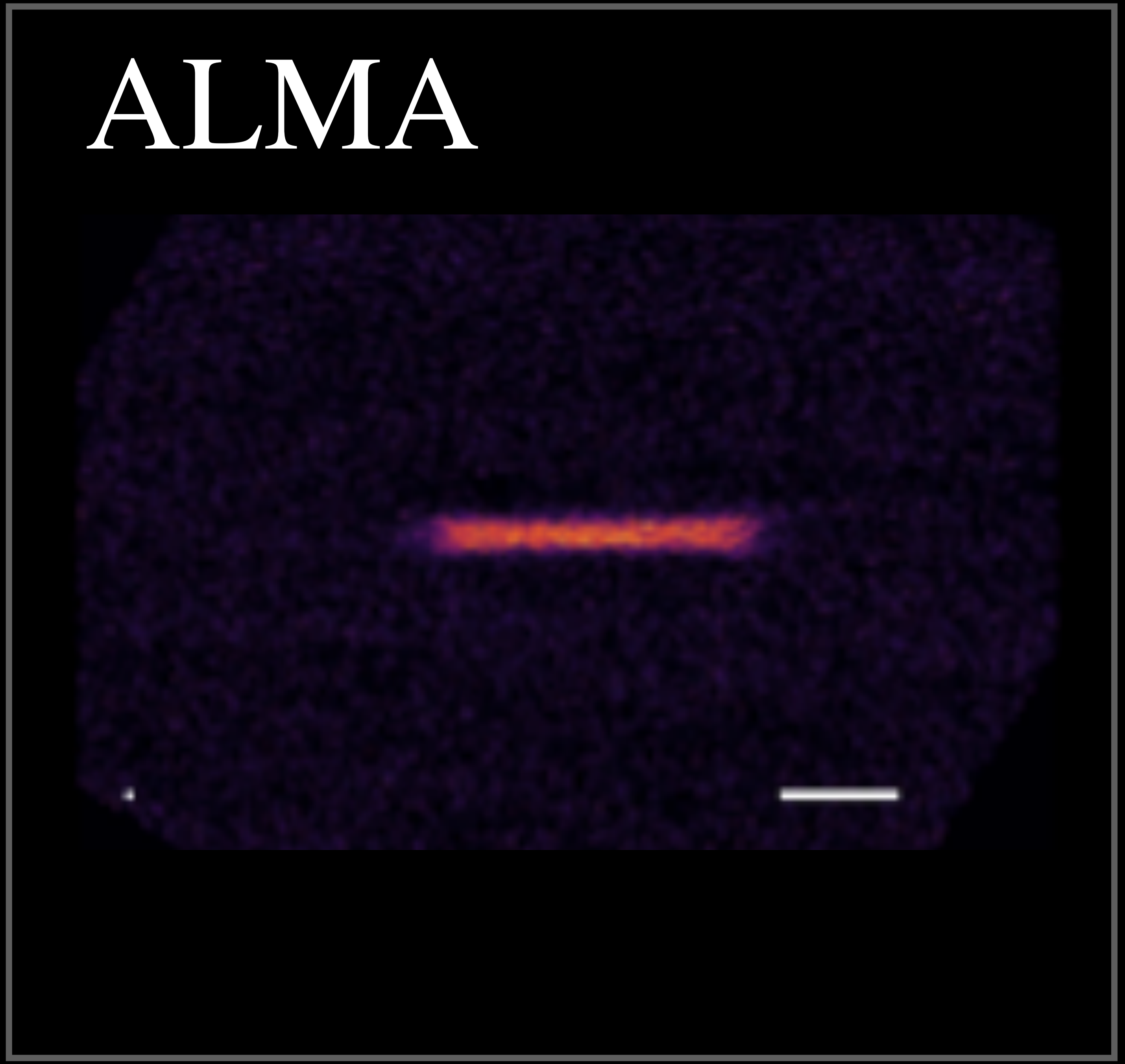
$\lambda_{obs} \sim 1\ \mu m$



Near- / Mid-IR

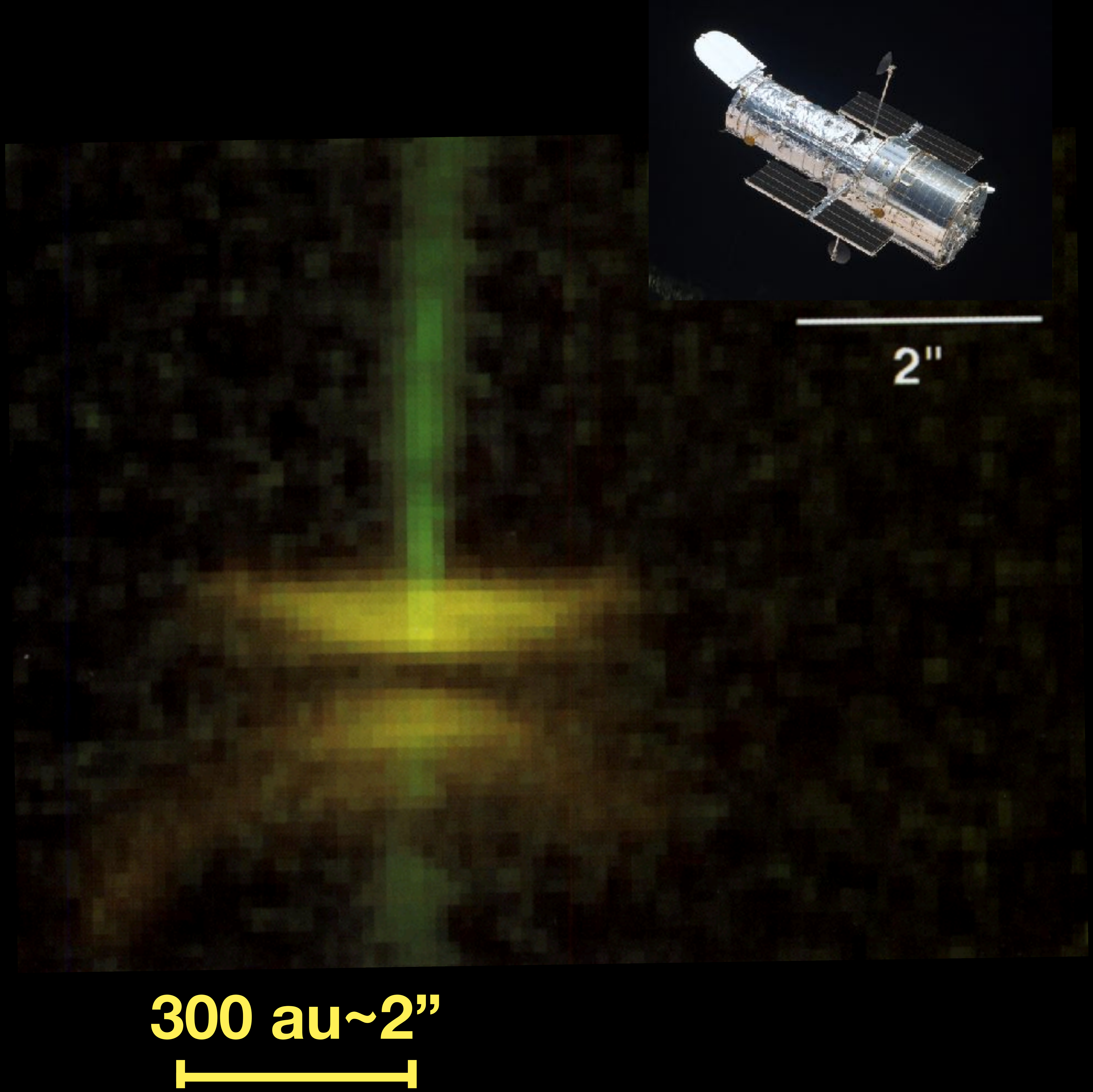


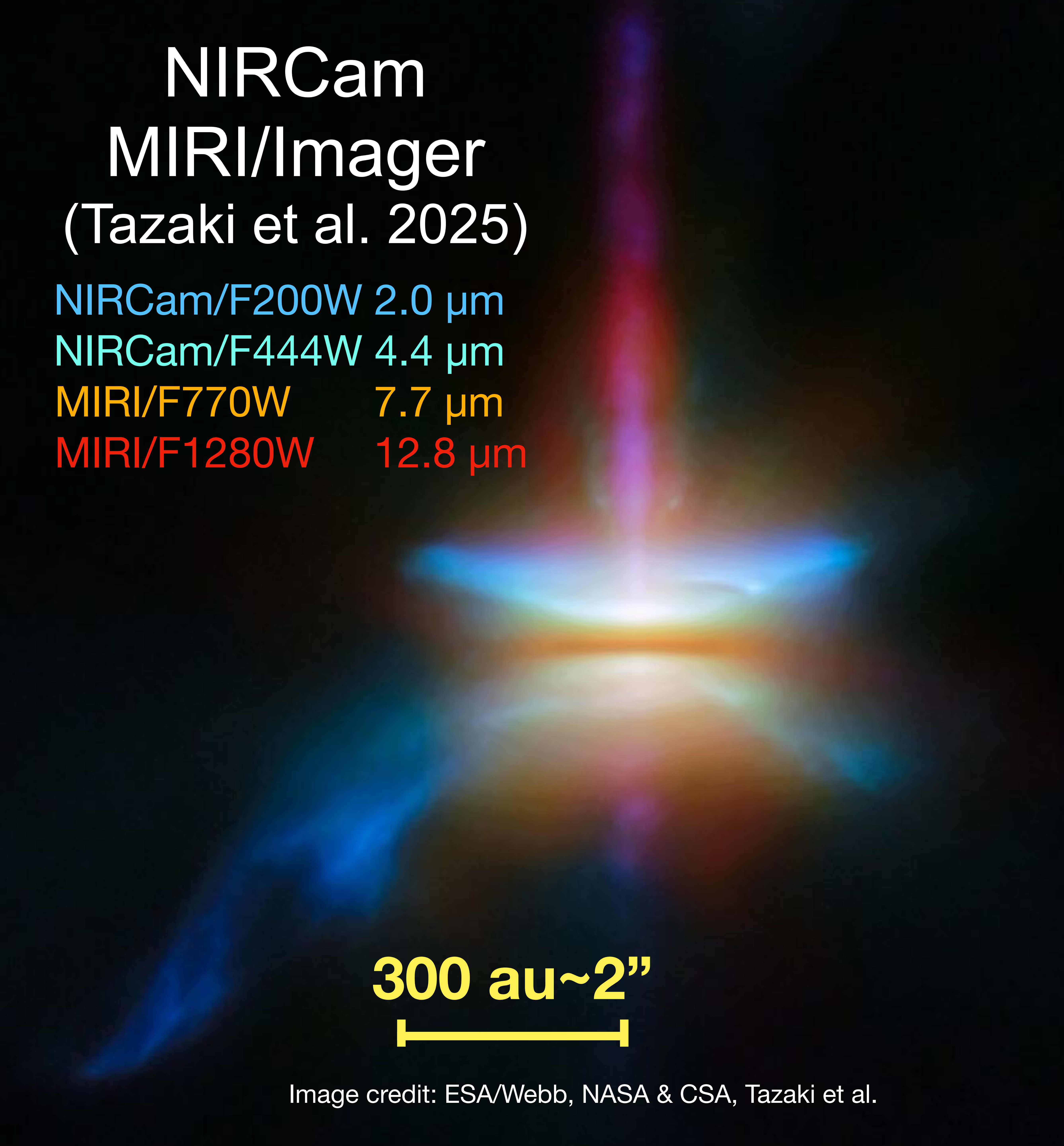
$\lambda_{obs} \sim 1$ mm



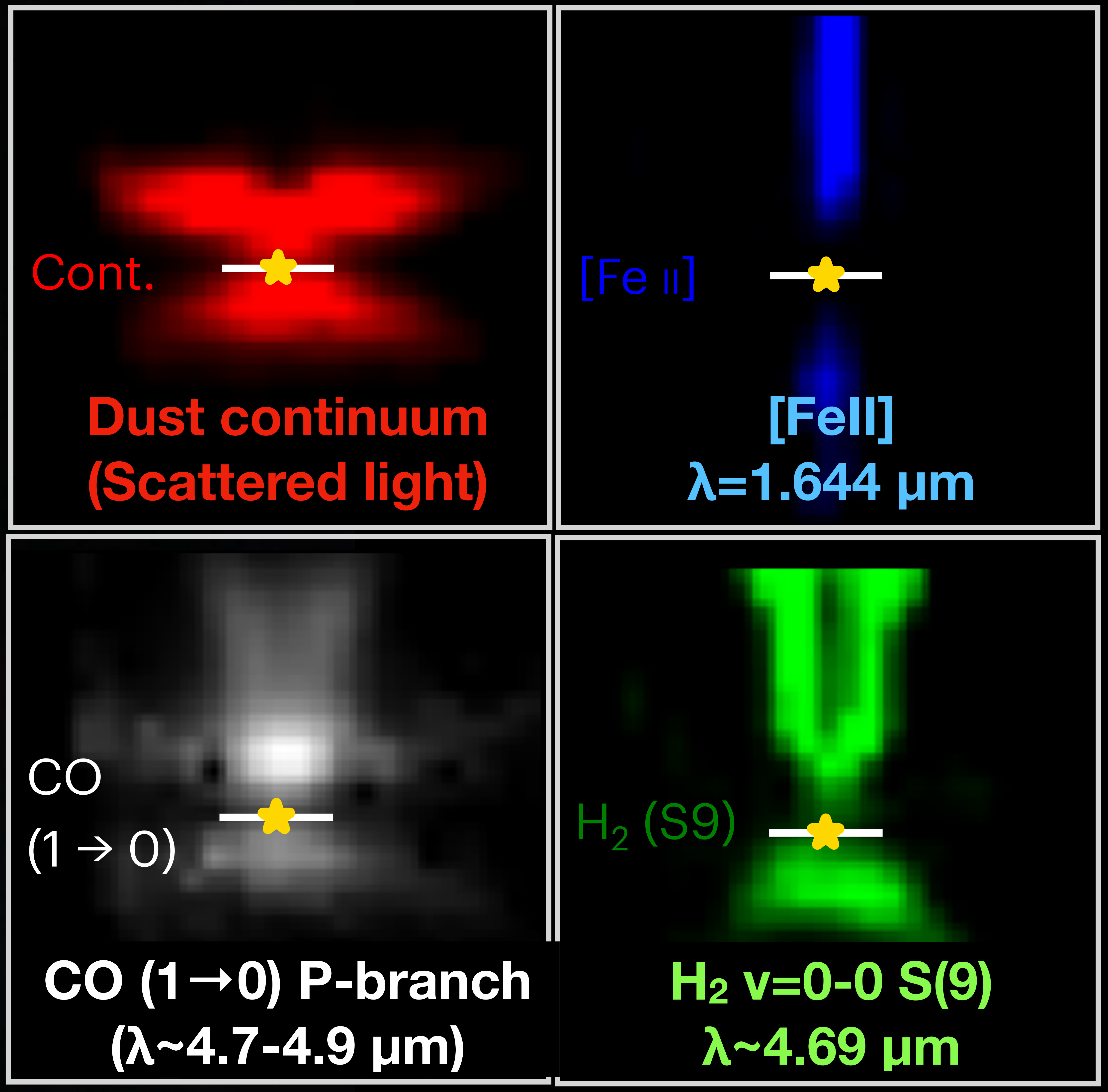
JWST provides spatially resolved images of disks at near- to mid-IR with spectroscopic information

Images: Tazaki et al. 2025


2''
300 au~2”

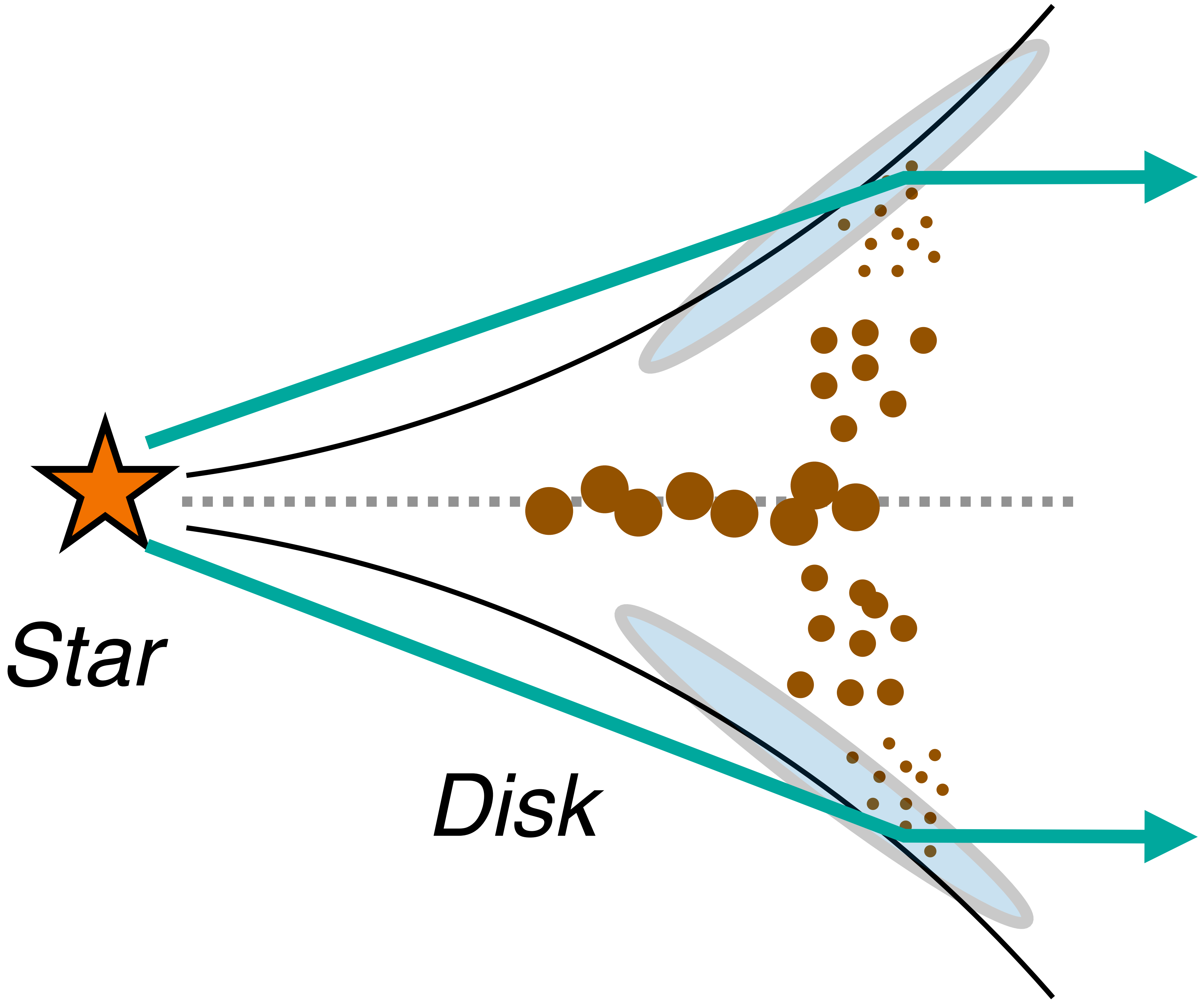


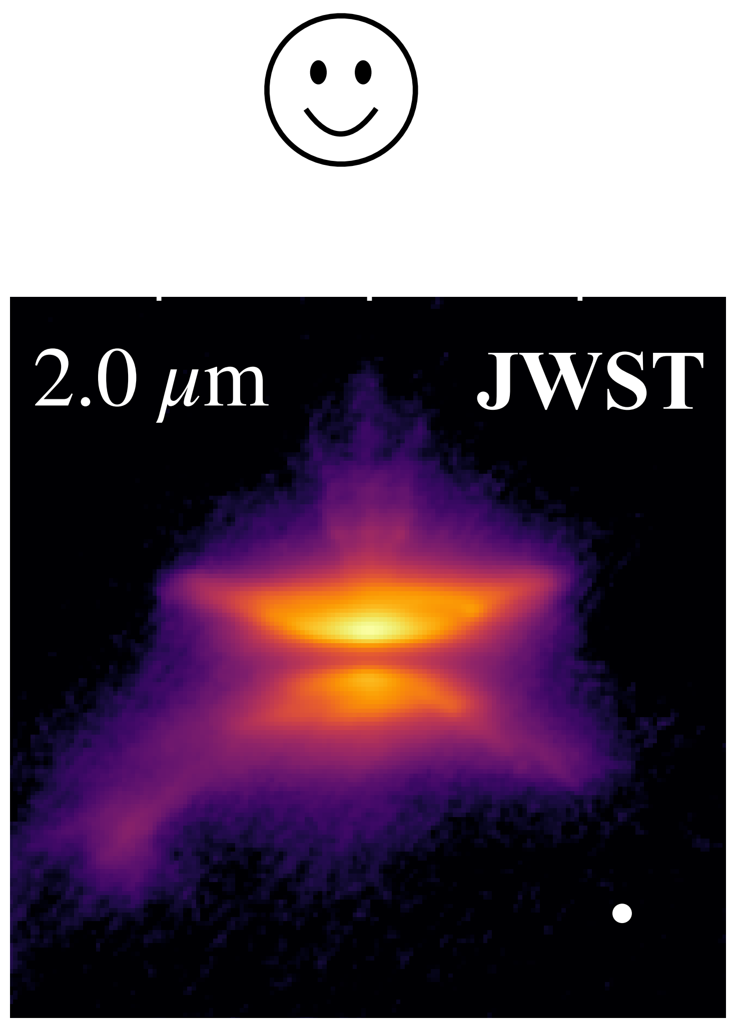
NIRSpec/IFU
(Pascucci et al. 2025)



Today’s outline

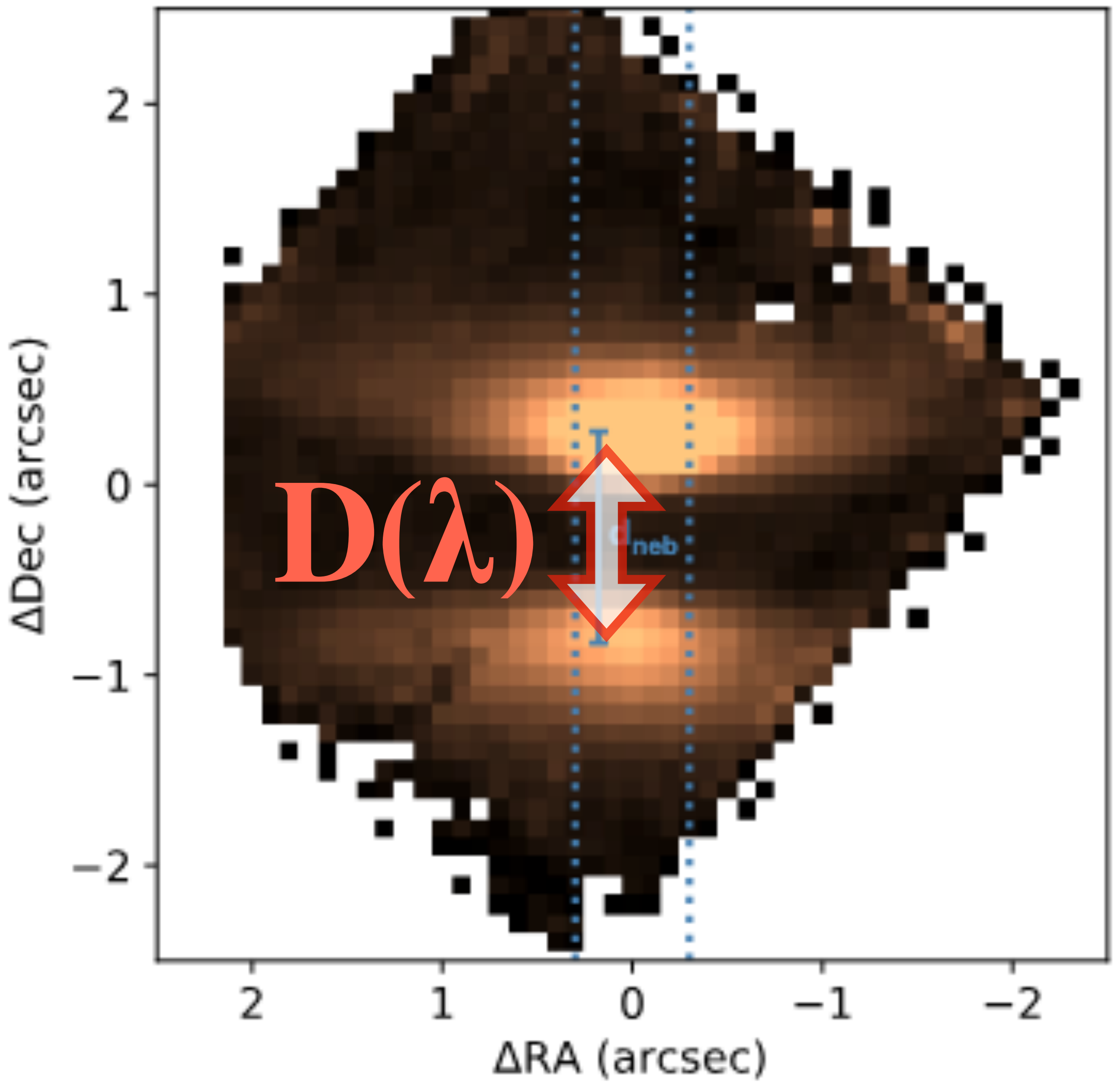
- Recent high resolution imaging observations of disks
- Specific dusty topics (mainly on grain size and porosity constraints):
  - JWST (focusing on edge-on disk observations)
  - VLT/SPHERE
  - ALMA

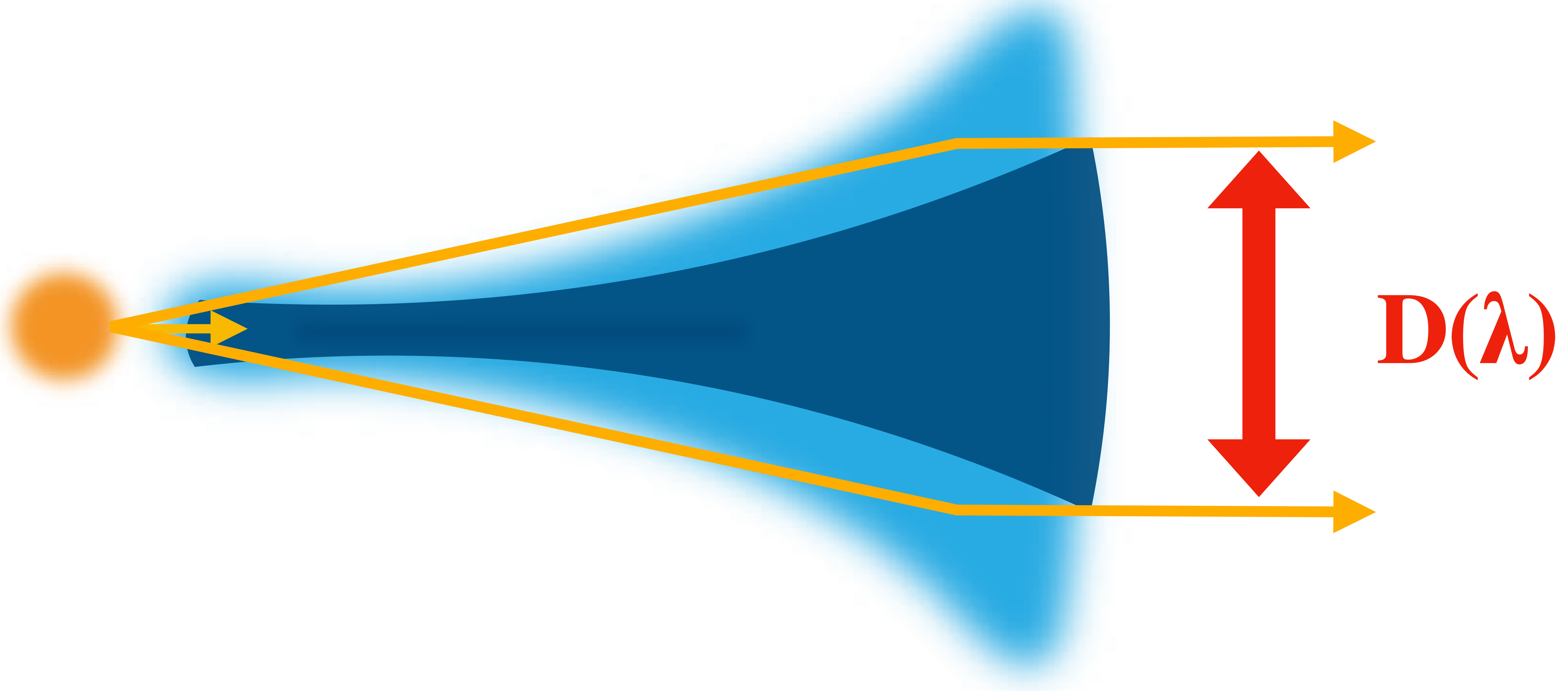




How to measure grain sizes?

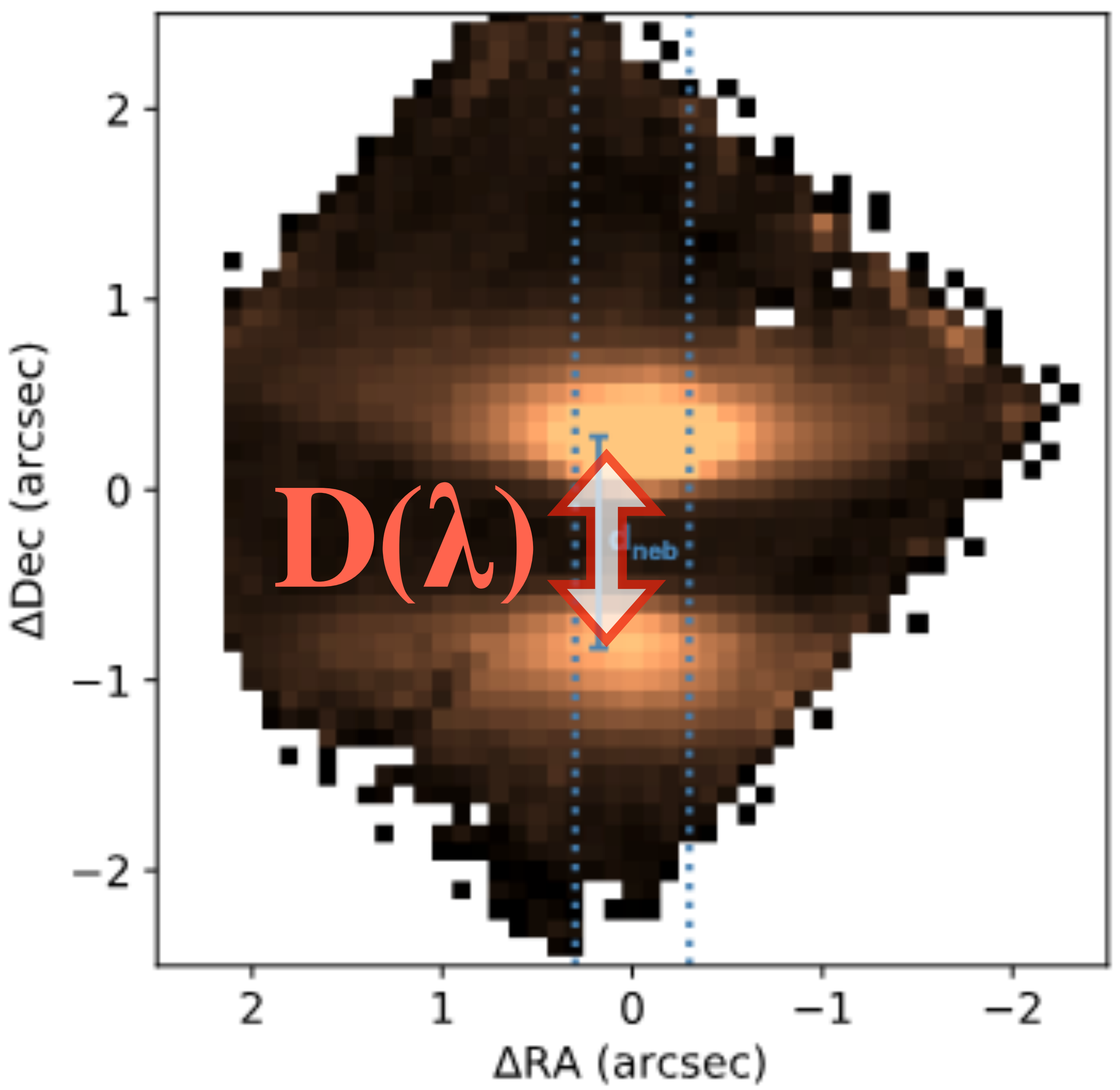
For edge-on disks, **dark lane chromaticity** can constrain grain size.





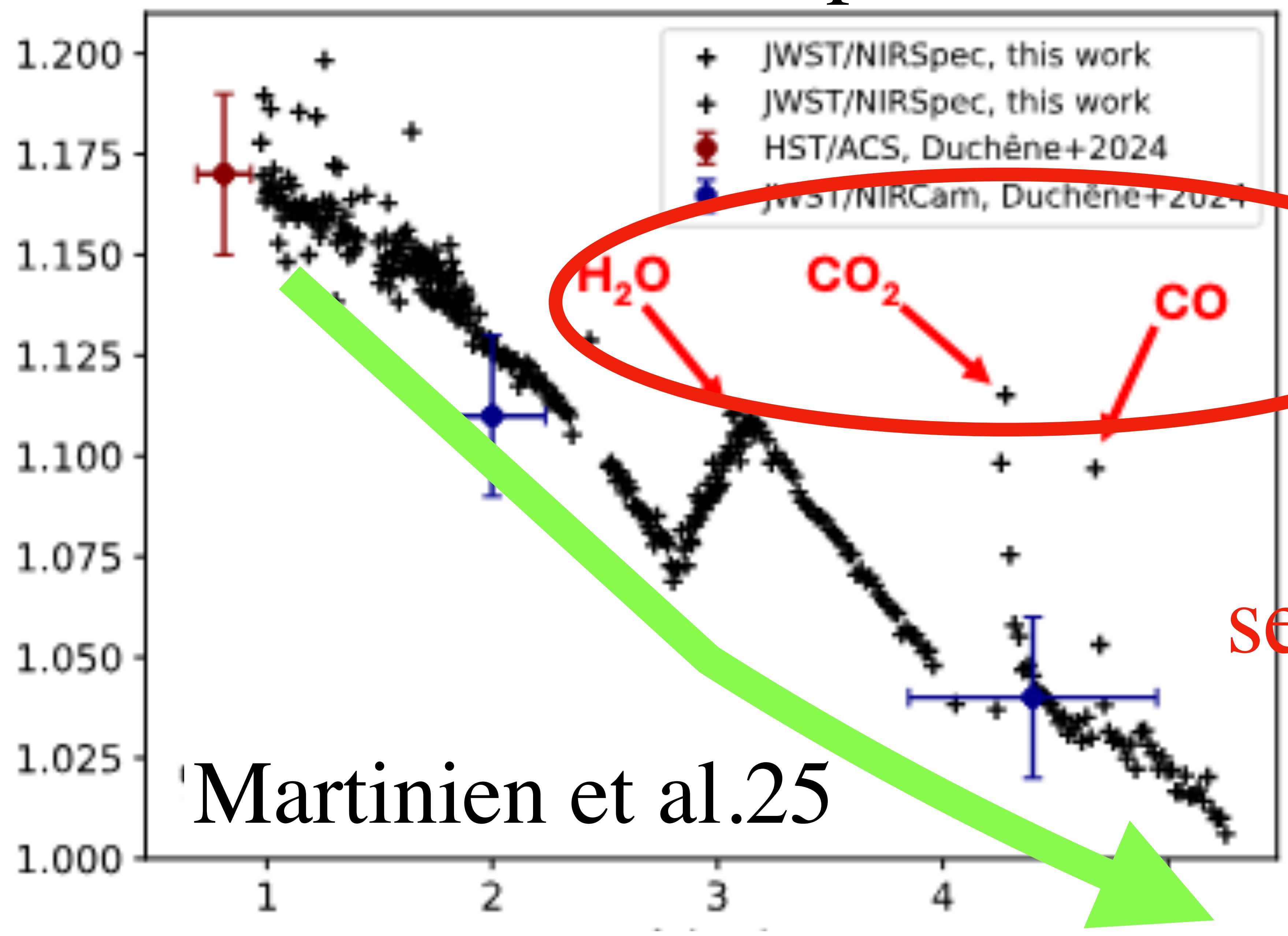
- Dark lane chromaticity D(λ) depends on total disk mass, scale height & dust extinction opacity
- Assuming the scale height and a reference dust opacity $\kappa(\lambda_0)$ (λ_0: ref wavelength)
  - disk mass can be inferred from the observed value of $D(\lambda_0)$
  - and then $D(\lambda)/D(\lambda_0)$ can be link to the extinction opacity of dust grains $\kappa(\lambda)/\kappa(\lambda_0)$

How to measure grain sizes?



D(λ) [arcsec]

JWST/NIRSpec/IFU



Ice features!
see McClure's talk

λ (μm)

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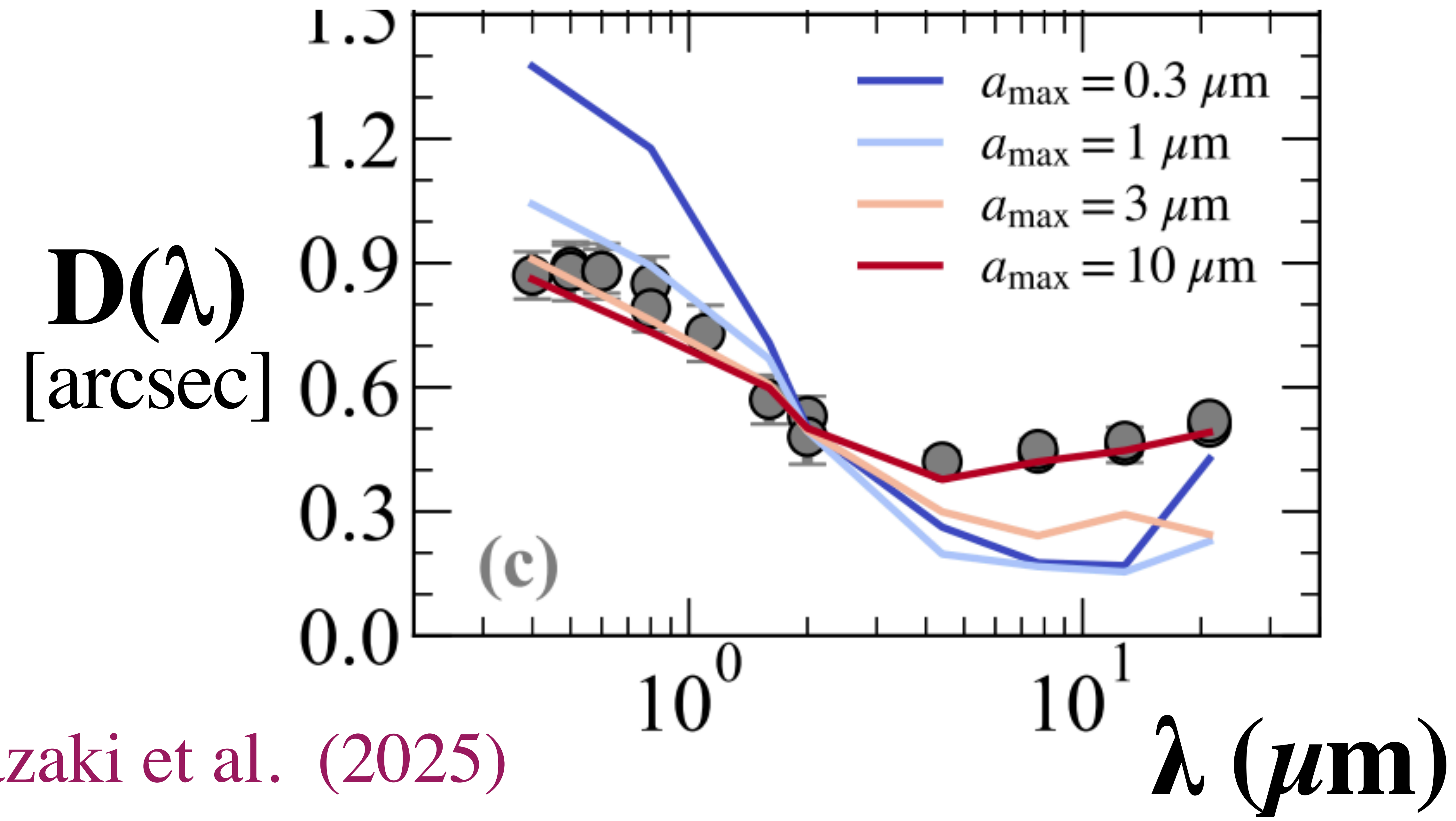
Dark lane chromaticity of the HH 30 disk

HST | JWST

λ=0.6 μm | 0.8 μm | 2 μm | 4 μm | 7.7 μm | 12.8 μm

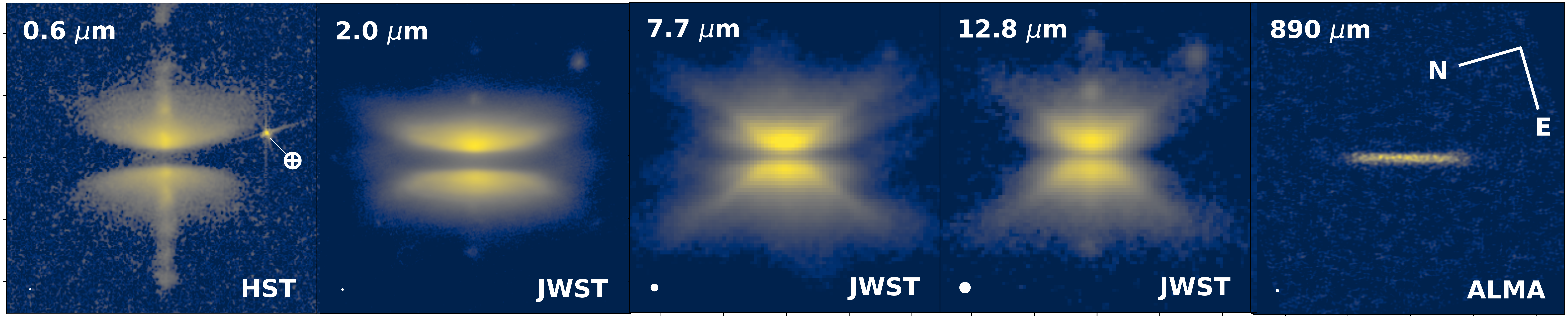
- Dark lane chromaticity D(λ) is best reproduced by the maximum grain size of ~10 μm or lager.
- RT modeling found no evidence for dust settling at least up to grain sizes of ~3-10 μm.



Tazaki et al. (2025)

Unexpected findings: Disk winds?

Duchêne et al. 2024



- X-shaped feature shows up at mid-IR MIRI/F770W and F1280W (Duchêne et al. 2024).
- Likely due to emission from H_2 and AIB carriers (Arulanantham et al. 2024, Dartois et al. 2025)
- AIB in the disk wind?

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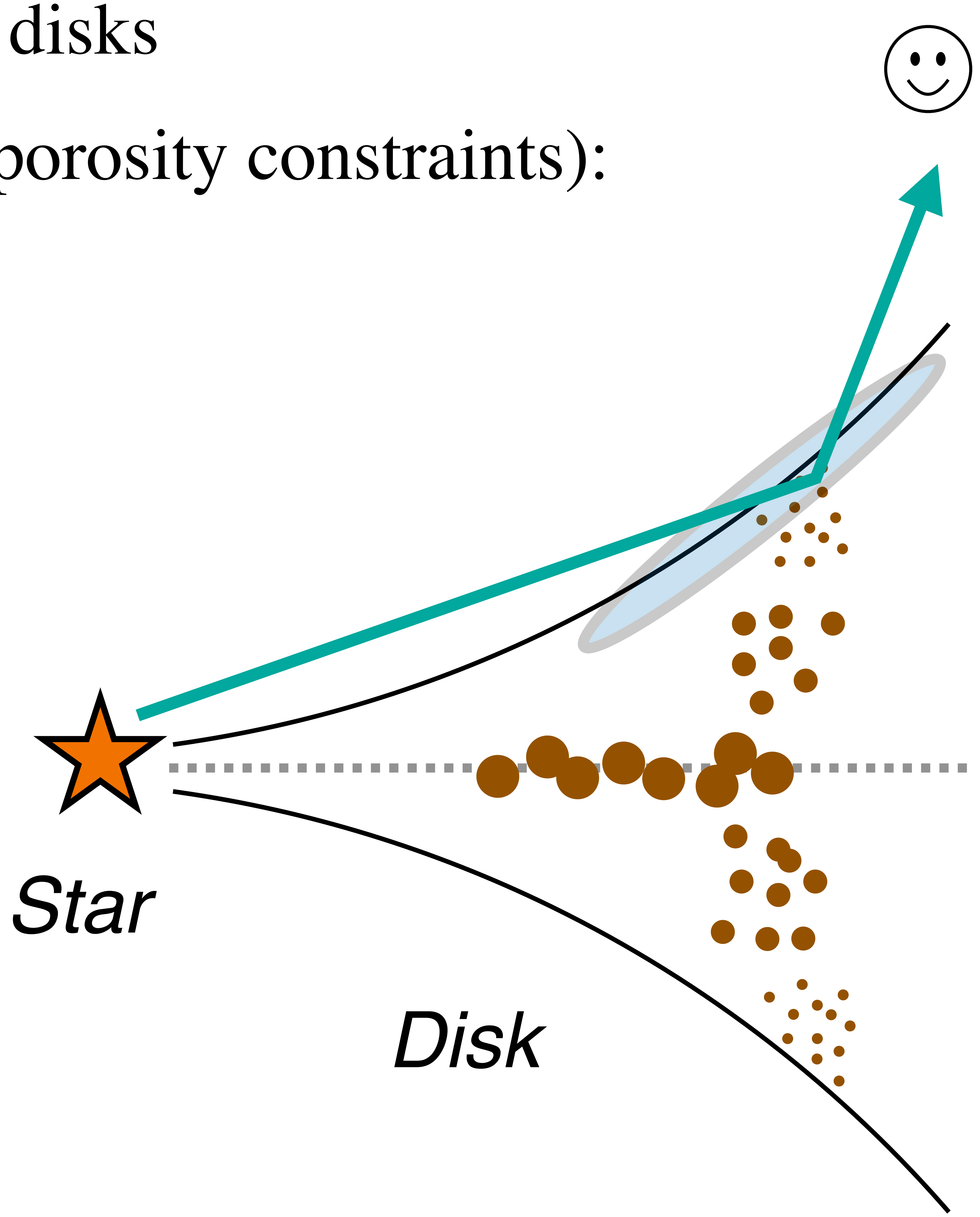
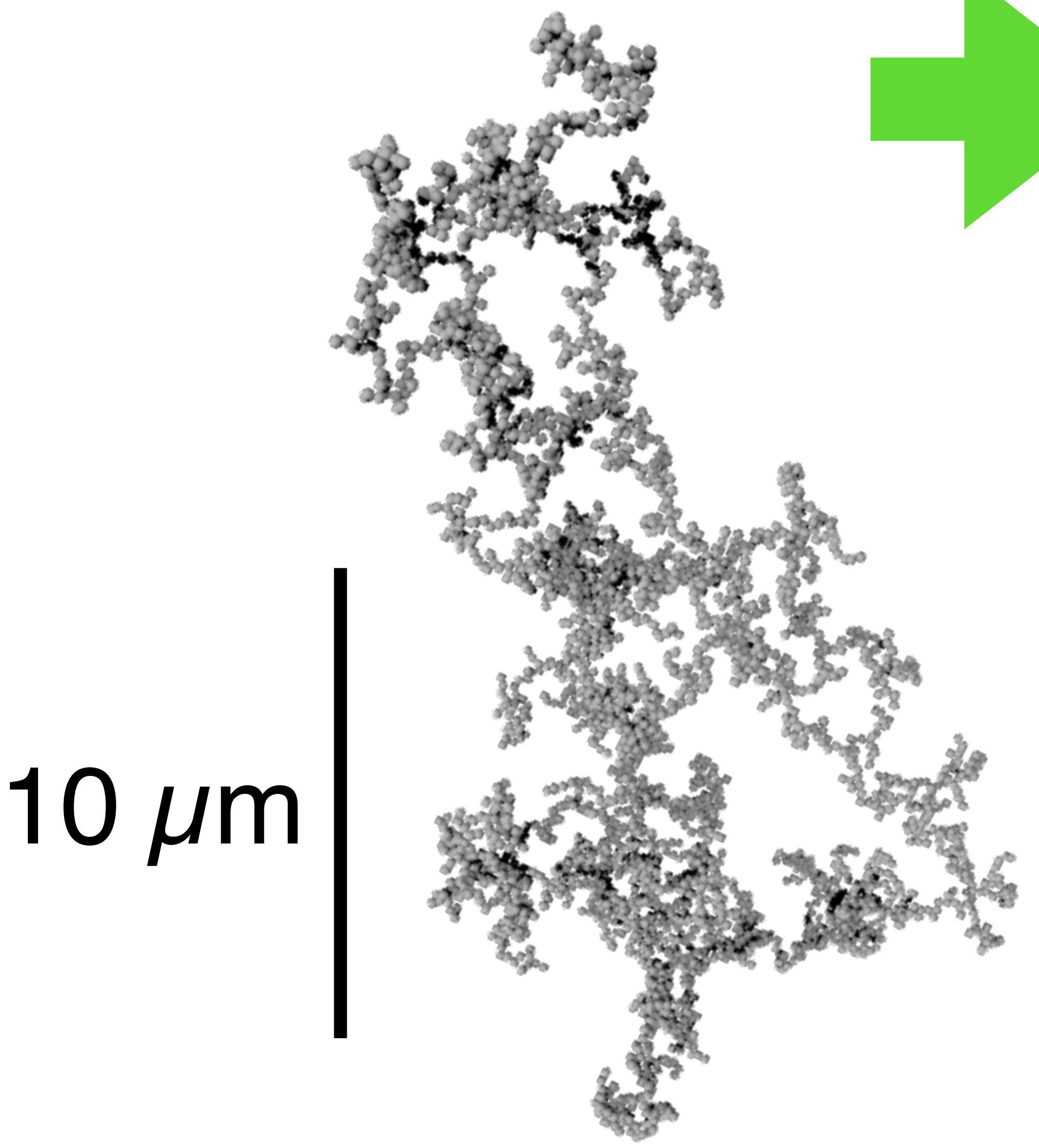


How to study dust porosity at IR?

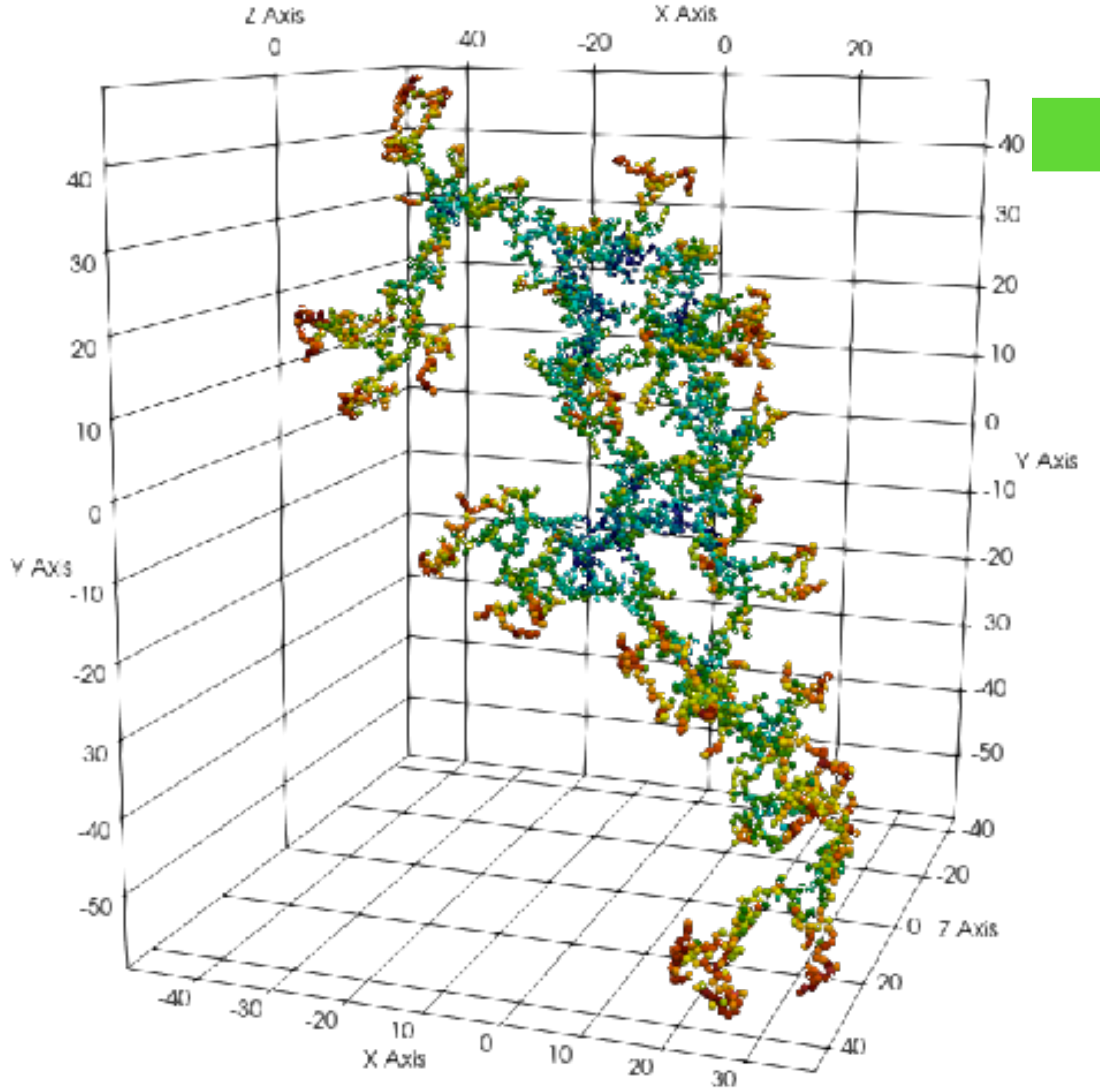
⇒ Still an open question…

We can try some numerical experiments…

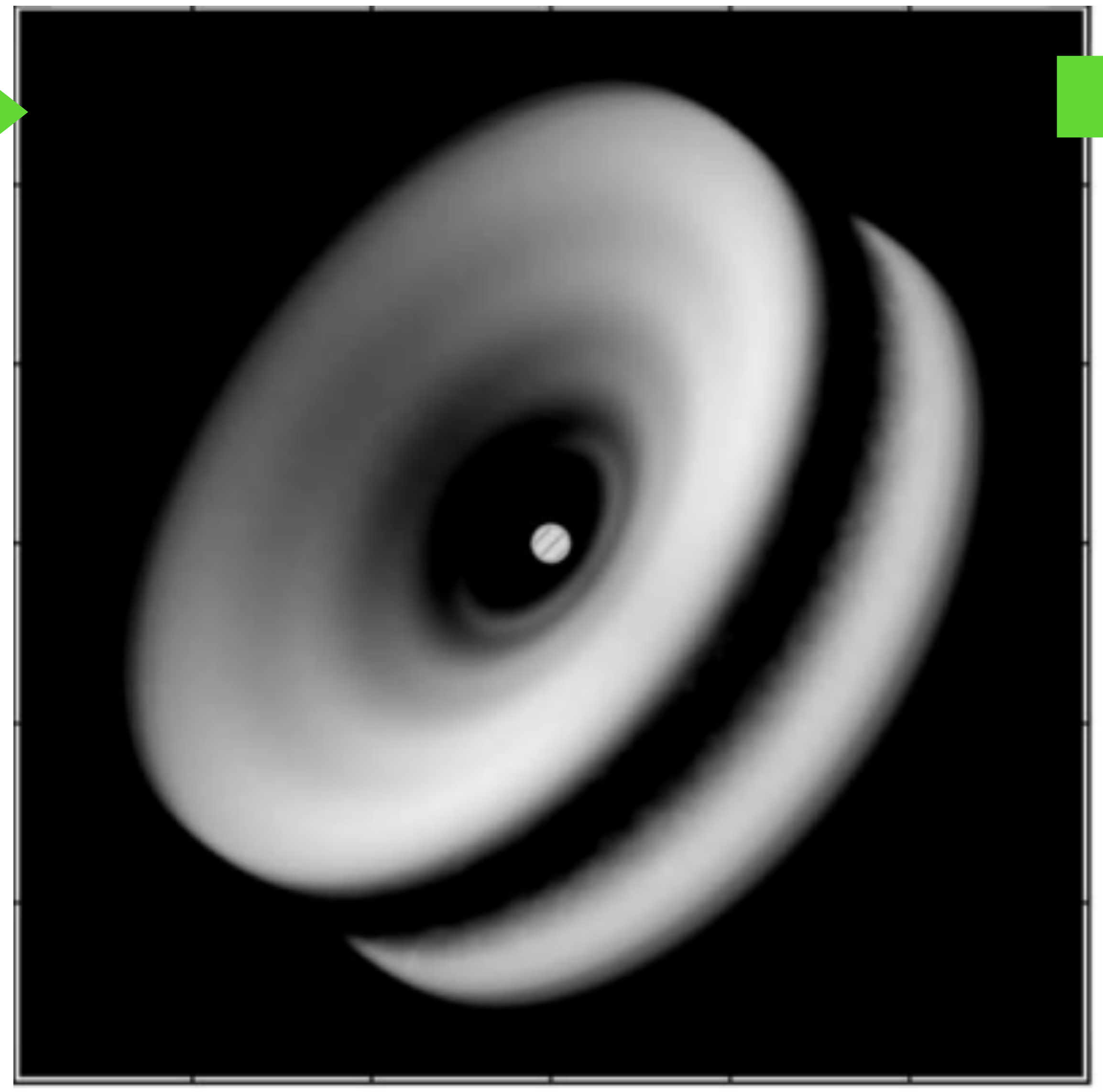
Particle models



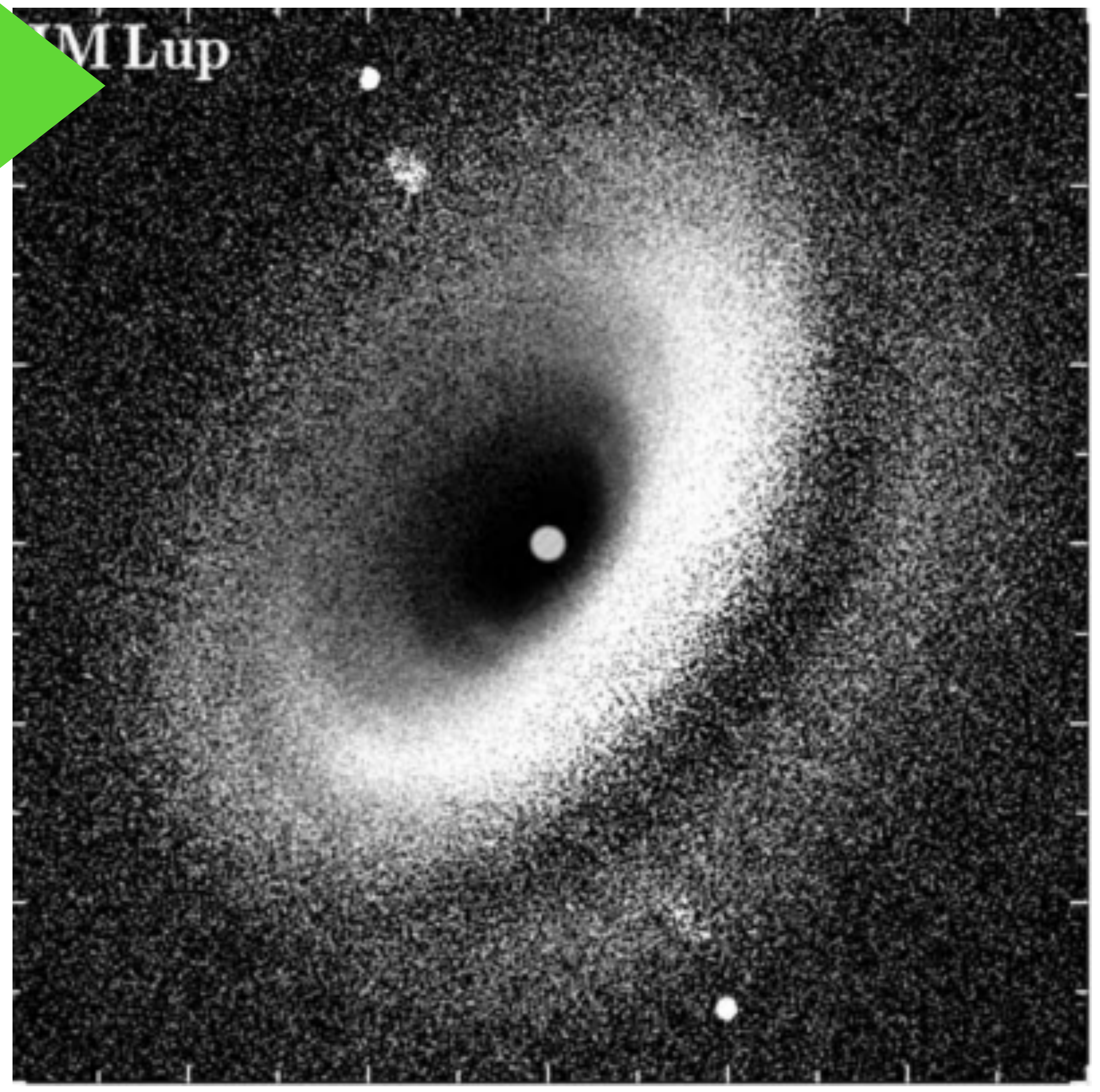
Exact electromagnetic scattering calculation with T-matrix method



Solve disk radiative transfer



Compare to disk observations



Tazaki et al. 2023

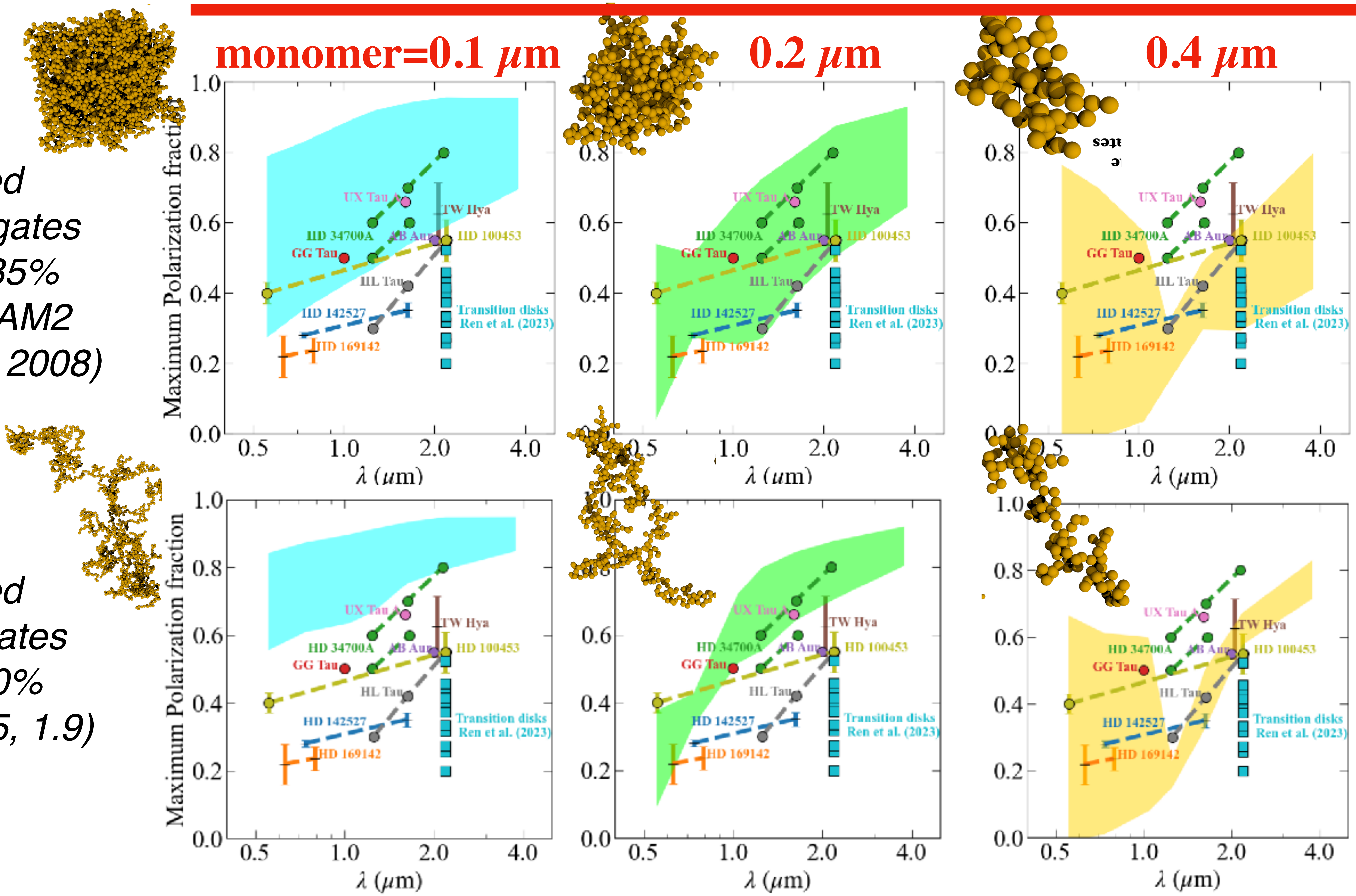
Maximum degree of linear polarization

monomer=0.1 μm 0.2 μm 0.4 μm

Larger monomers

Less porous

Micron-sized Ballistic Aggregates Porosity: 50-85% (BA, BAM1, BAM2 from Shen et al. 2008)



Micron-sized fractal aggregates Porosity: >90% (Df=1.1, 1.3, 1.5, 1.9)

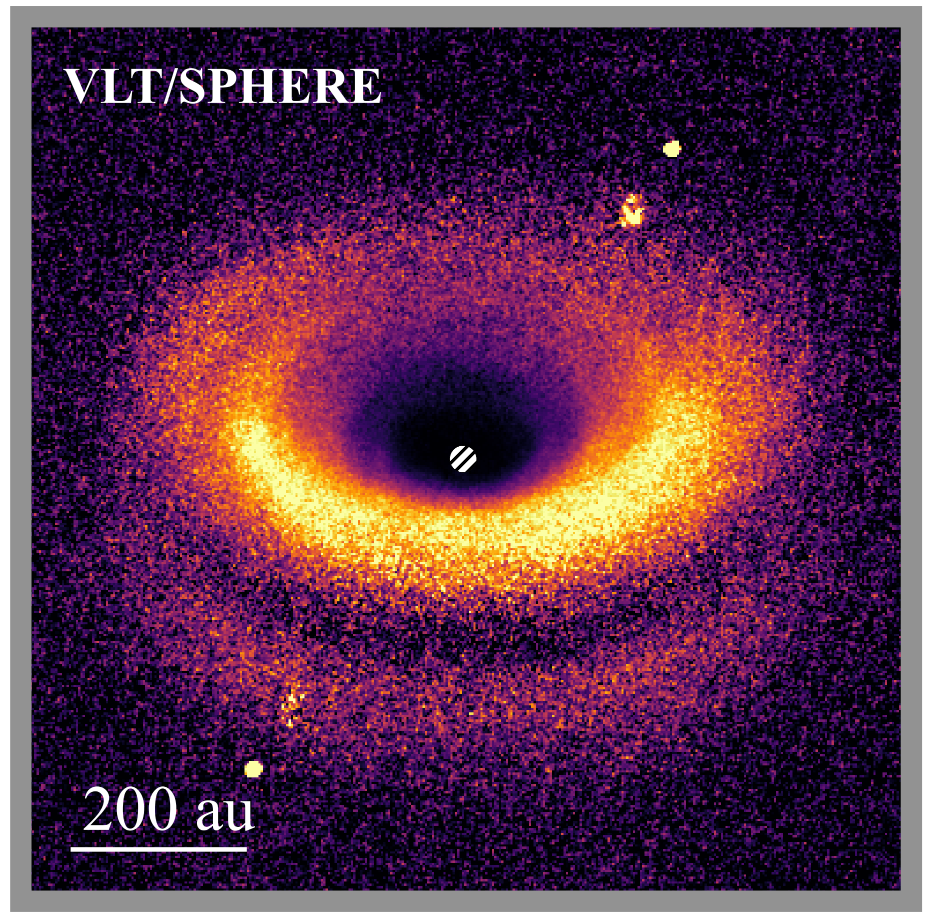
Highly porous

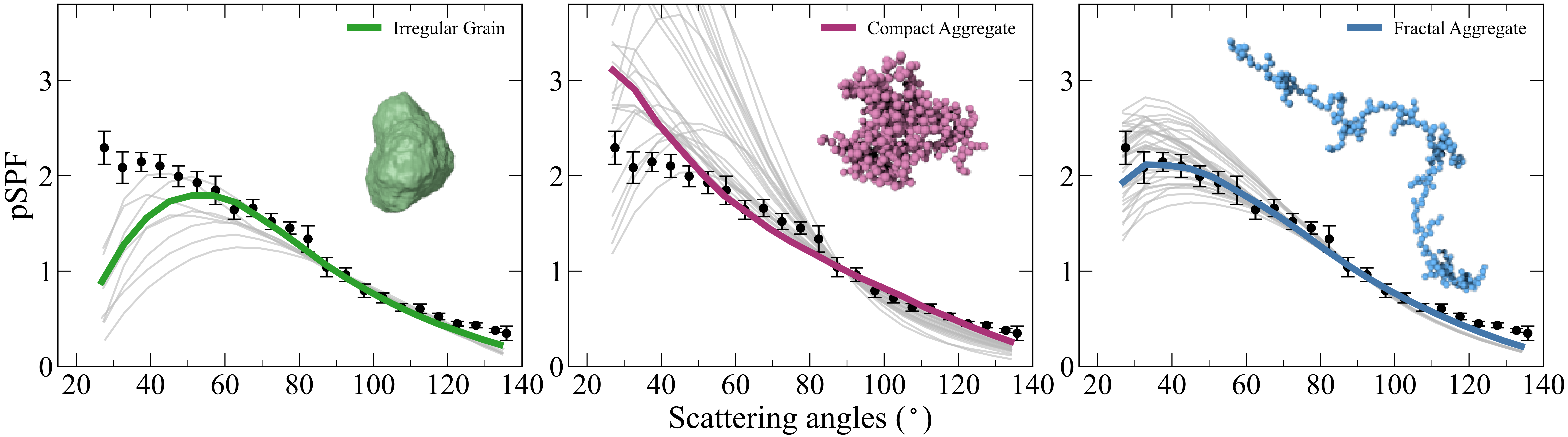
Tazaki & Dominik 2022
Tazaki et al. 2023

DoLP depends not only on porosity, but also strongly on the monomer size

(Polarized) Scattering phase function

- Scattering phase function = angular distribution of scattered light
- Phase functions have been extracted for some disks (e.g., Ginski+23)
- Polarized phase function for the IM Lup disk is best explained by fractal aggregates with a low fractal dimension (< 2).





Tazaki, Ginski and Dominik (2023)

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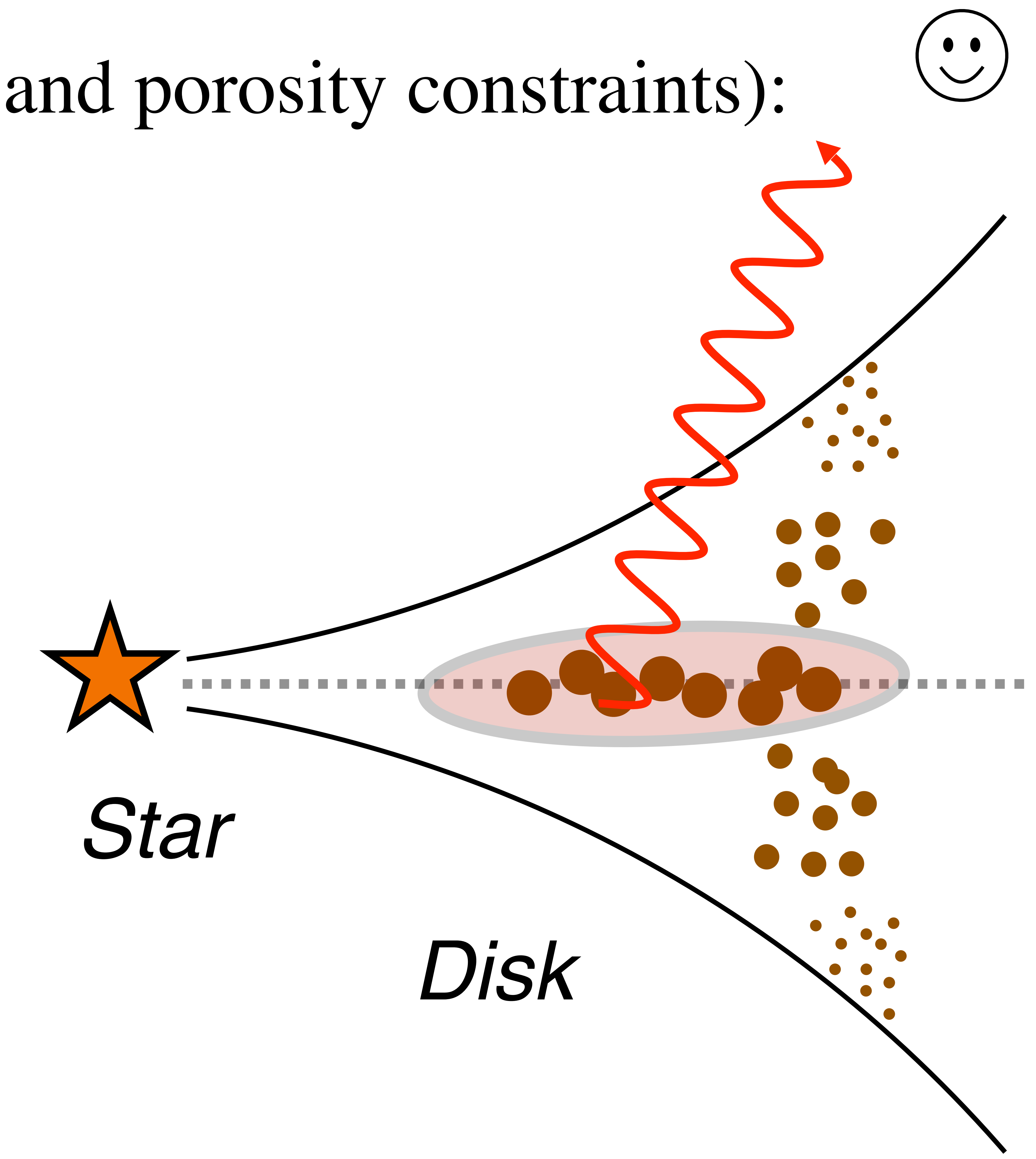
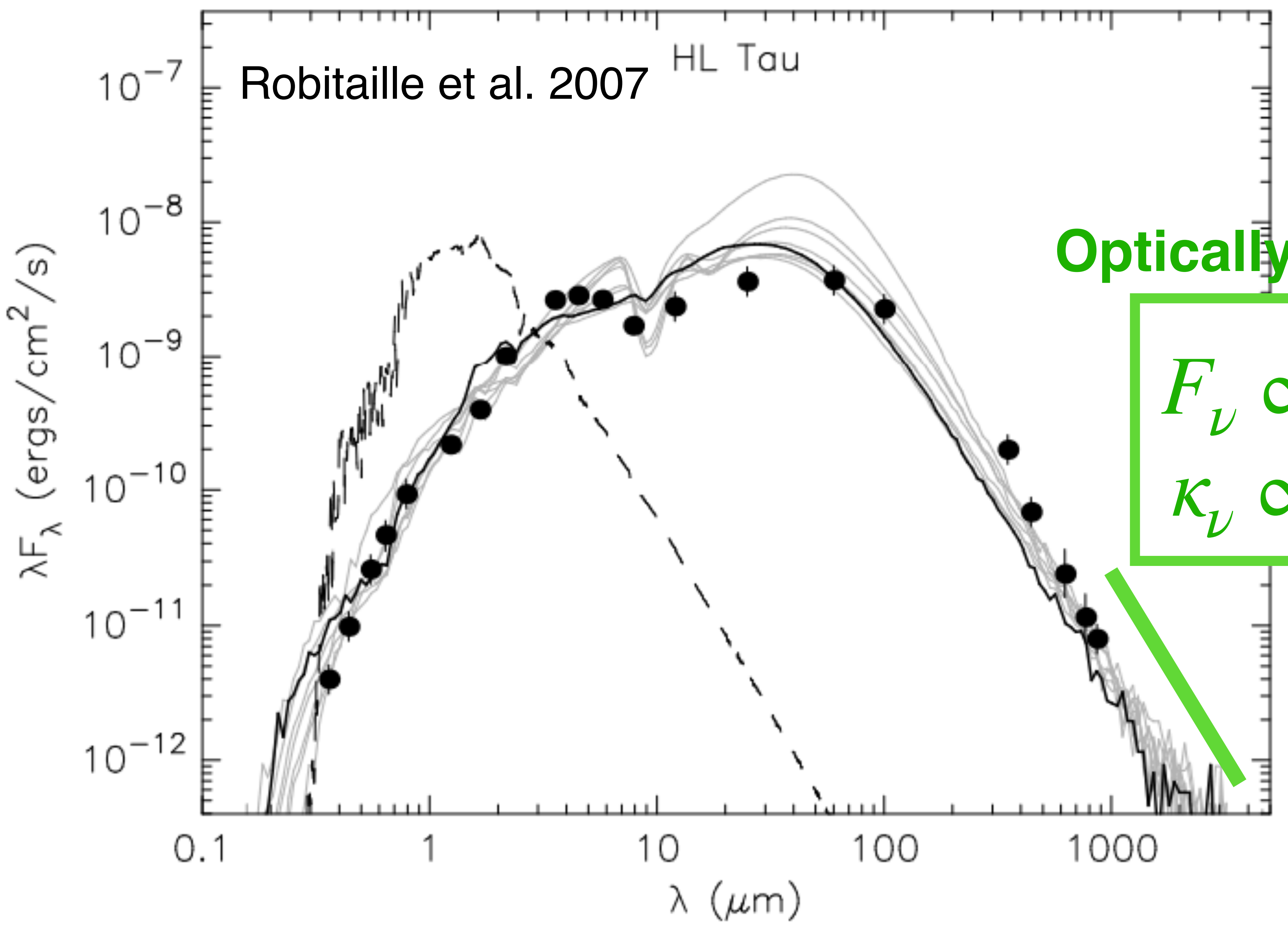


Measuring grain size: SED spectral index

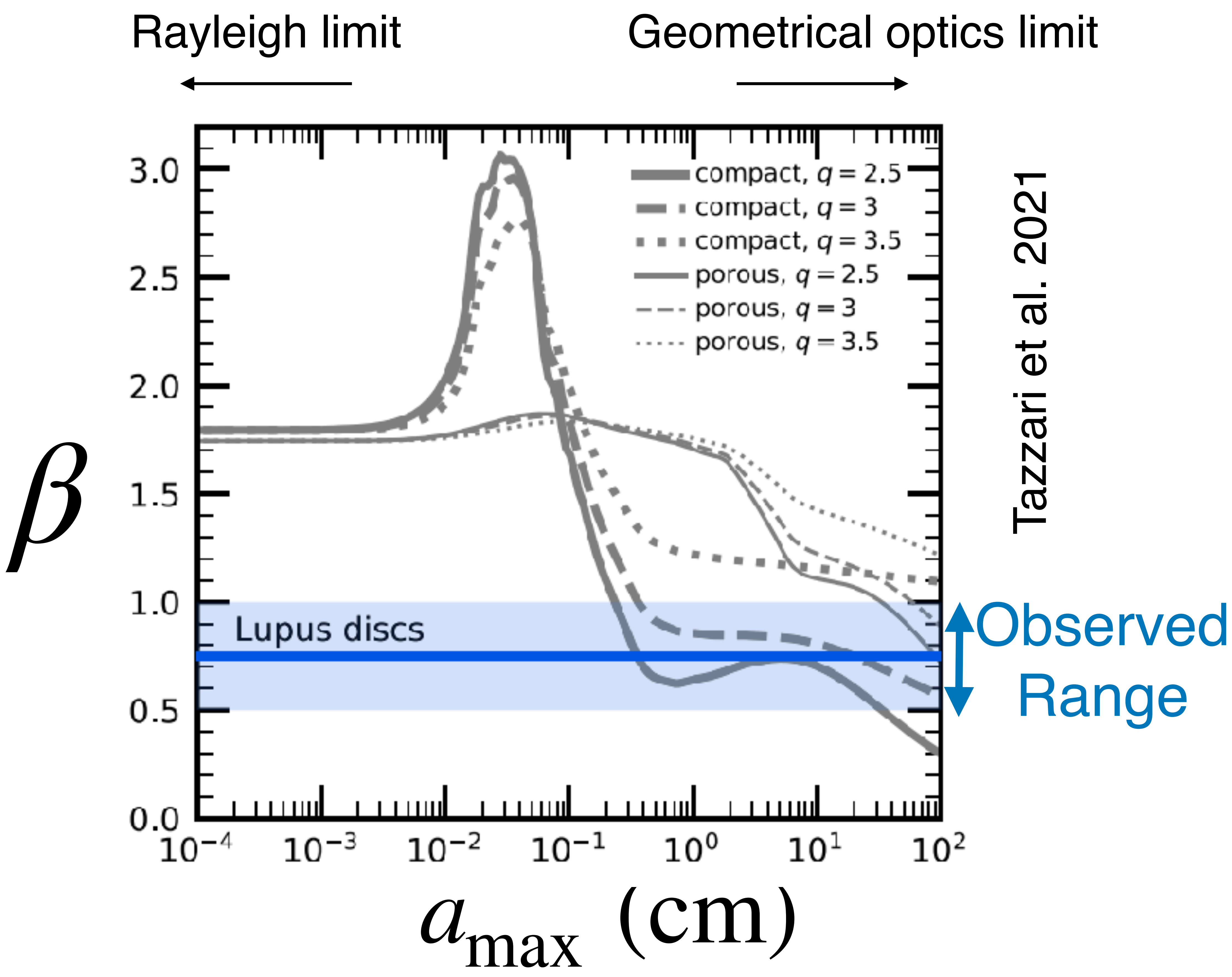
SED



Optically thin limit

$F_\nu \propto \nu^{2+\beta}$

$\kappa_\nu \propto \nu^{\beta}$

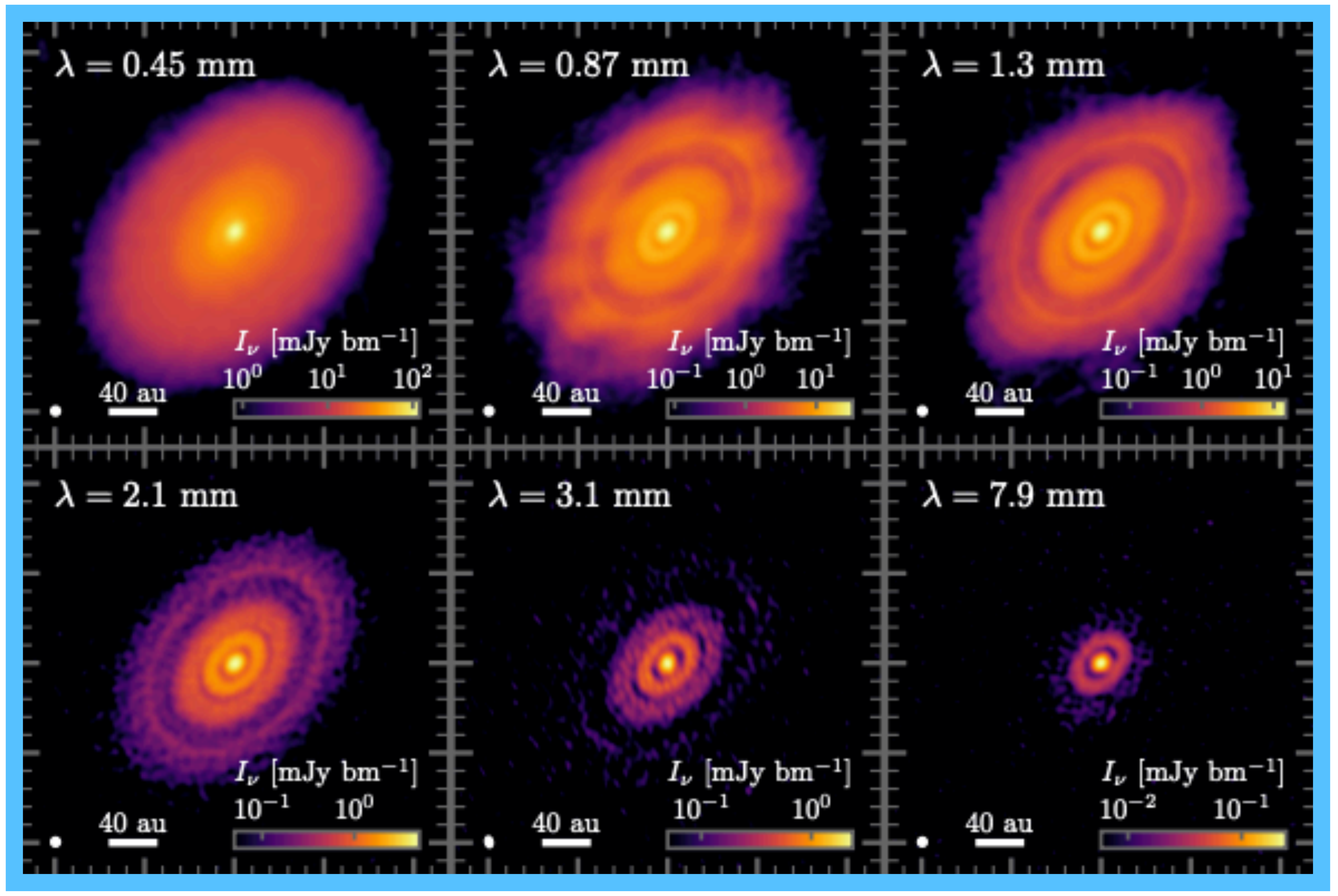


- Under the optically thin assumption and ignoring scattering, $a_{\rm max} \gtrsim 3\lambda \sim 3$ mm (e.g., Beckwith et al. 1990, Draine 2006, Tazzari et al. 2021)
- ⚠️ Disks are often optically thick at sub-millimeter wavelengths and scattering is also often important (e.g., Chung et al. 2025, Garufi et al. 2025, Pinter et al. 2025)

Fitting the data with slab emission models

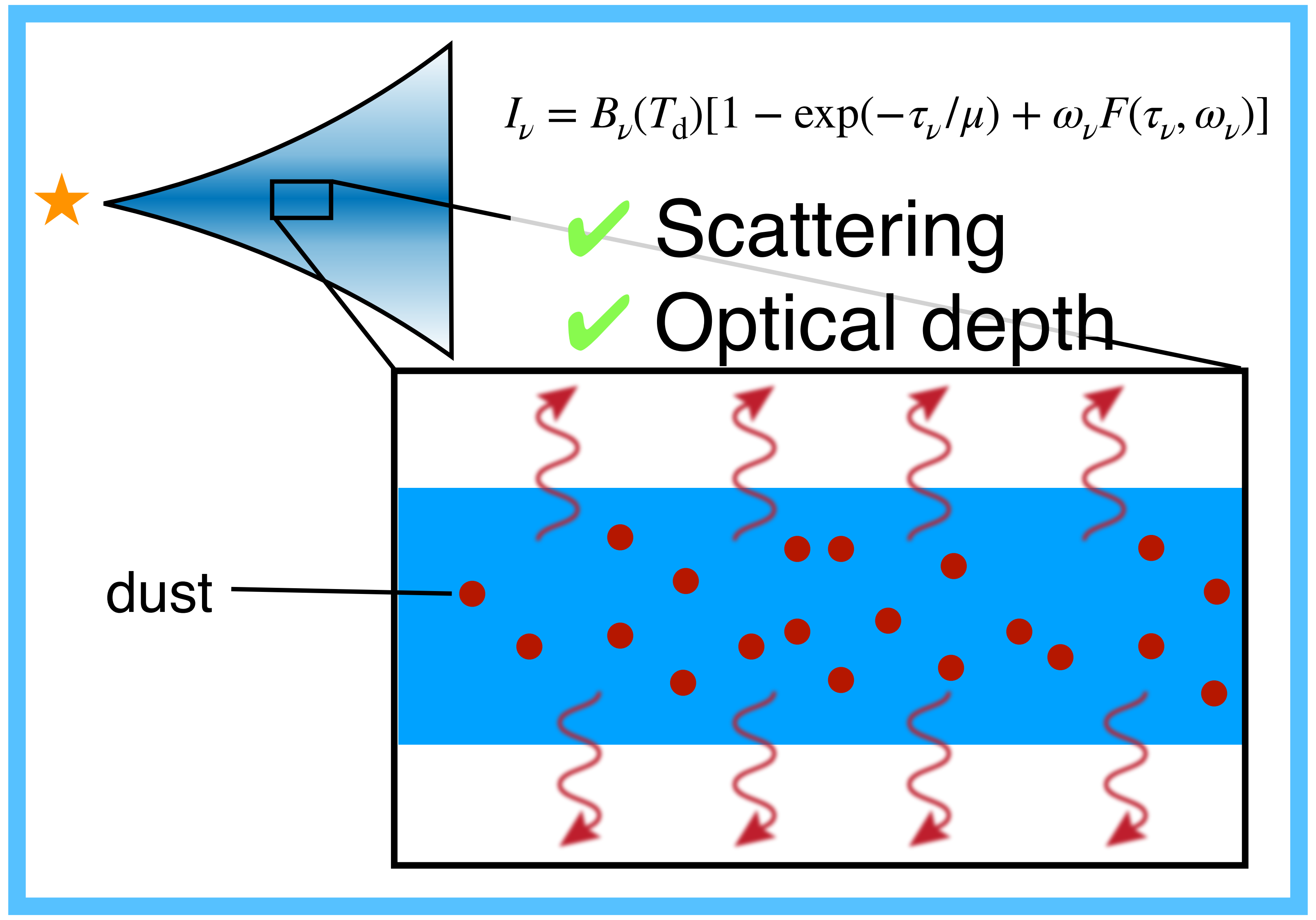
Zhu et al. 2019 Liu 2019; Carrasco-Gonzalez et al. 2019; Ueda et al. 2020; Macias et al. 2021; Sierra et al. 2021; Guidi et al. 2022; Ohashi et al. 2023; Ueda et al. 2025, Zagaria et al. 2025

Muti-band images (Input)



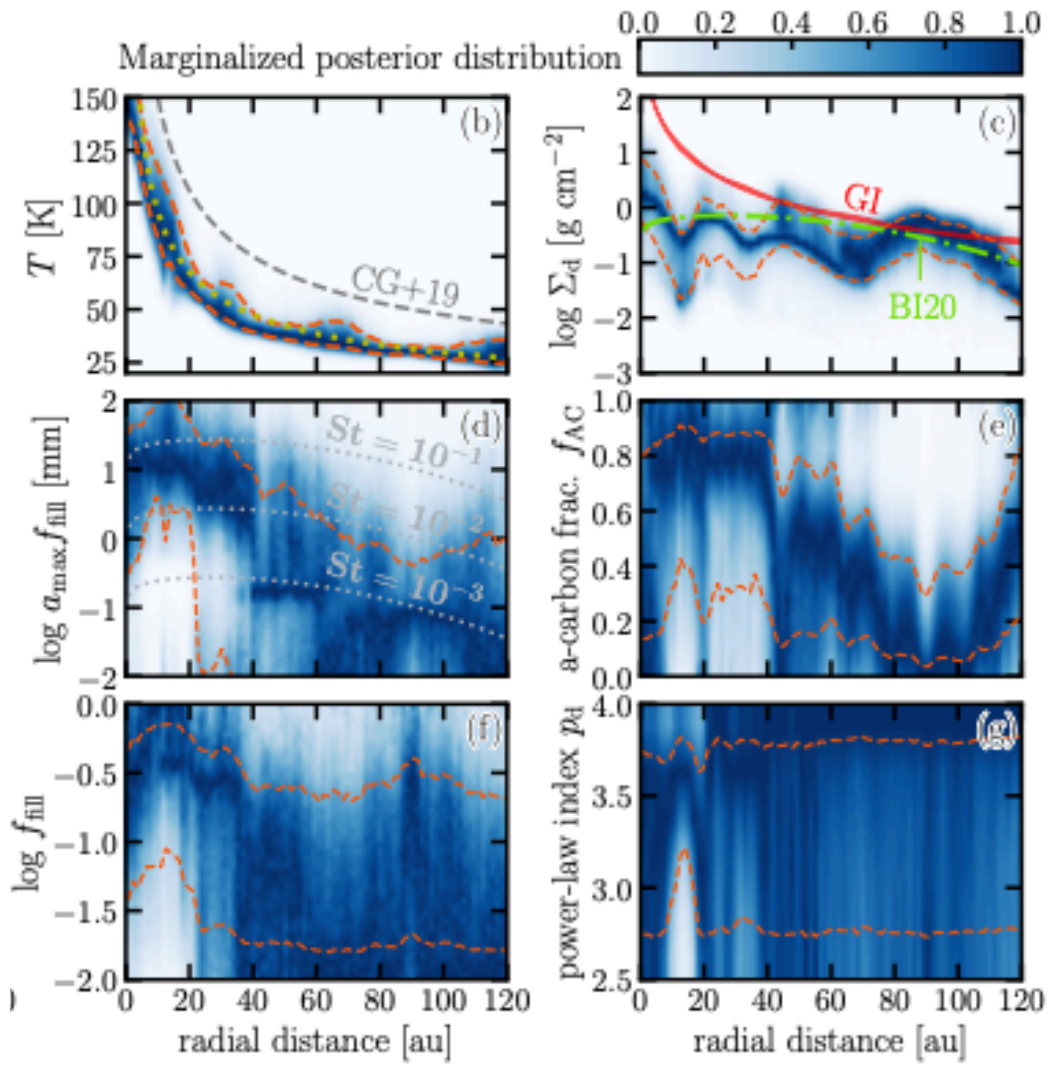
At each r
$I(\lambda)$

Slab model



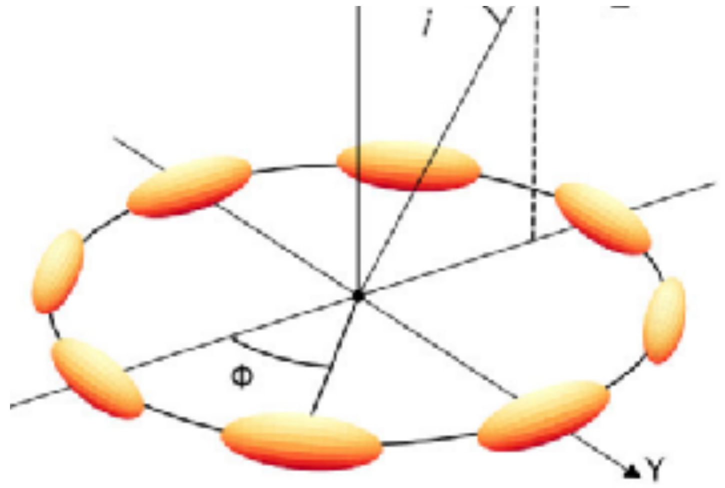
Grid search
MCMC
…

Optimal solution



- $a_{max} \sim 100\ \mu m - 3$ mm for outer (around midplane) regions (i.e.,>50 au) depending on assumed dust composition and porosity.
- Including at least one optically-thin band (a few millimeter wavelength) is crucial, limiting samples for the analysis.

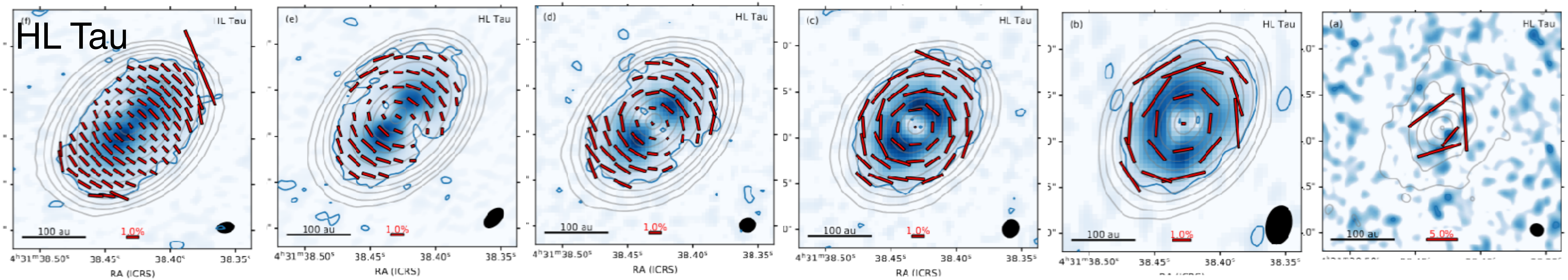
Millimeter-wave polarization



Scattering polarization

Alignment polarization
(w/ azimuthally aligned prolate grains)

λ=0.9 mm | 1.3 mm | 1.5 mm | 2.1 mm | 3.1 mm | 7.0 mm



Daniel Lin et al. 2024

- At least two polarization mechanisms needed: scattering + alignment (e.g., Stephens et al. 2027, Daniel Lin et al. 2022, 2024).
- Scattering polarization is sensitive to the grain size
  - $a_{\rm max} \sim \lambda_{\rm obs}/2\pi \sim 140\ \mu{\rm m}(\lambda_{\rm obs}/0.9\ {\rm mm})$ (Kataoka et al. 2015).

Porosity constraints on (sub)millimeter-sized dust

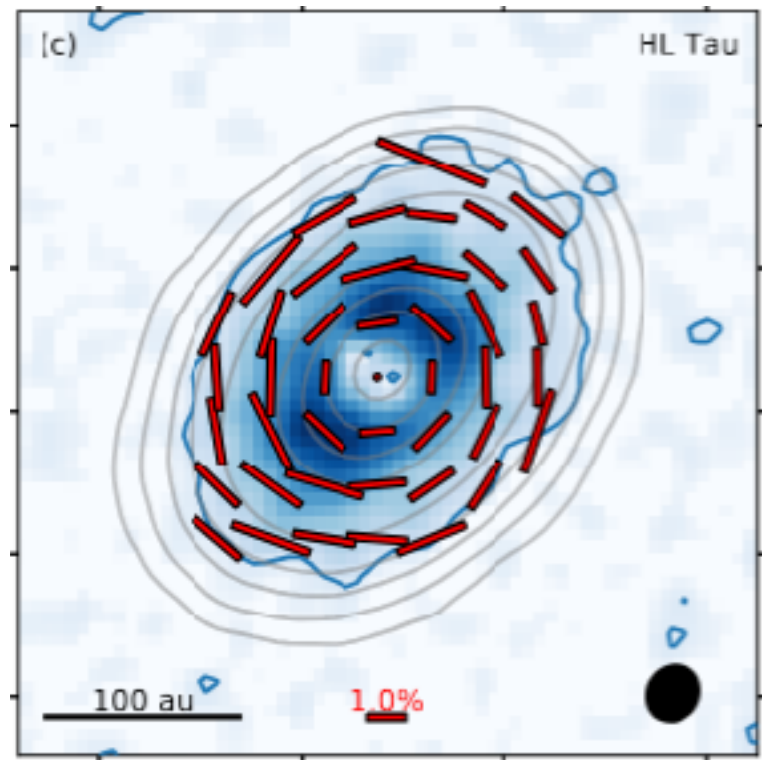
- *Both* scattering and alignment polarization would be *very weak* for extremely high-porosity dust particles (e.g., Tazaki et al. 2019, Kirchschlager et al. 2019).
- Inferred porosity values:
  - Kirchschlager et al. (2019) (for HD 142527; from polarization): $\mathscr{P} < 70\,\%$
  - Zhang et al. (2024) (for HL Tau; from SED+polarization): $\mathscr{P} = 70\% - 97\,\%$
  - Zagaria et al. (2025) (for CI Tau; from SED) : $\mathscr{P} < 70\,\%$
  - Yoshida et al. (2025) (for TW Hya; from scattering albedo) : $\mathscr{P} < 96\,\%$

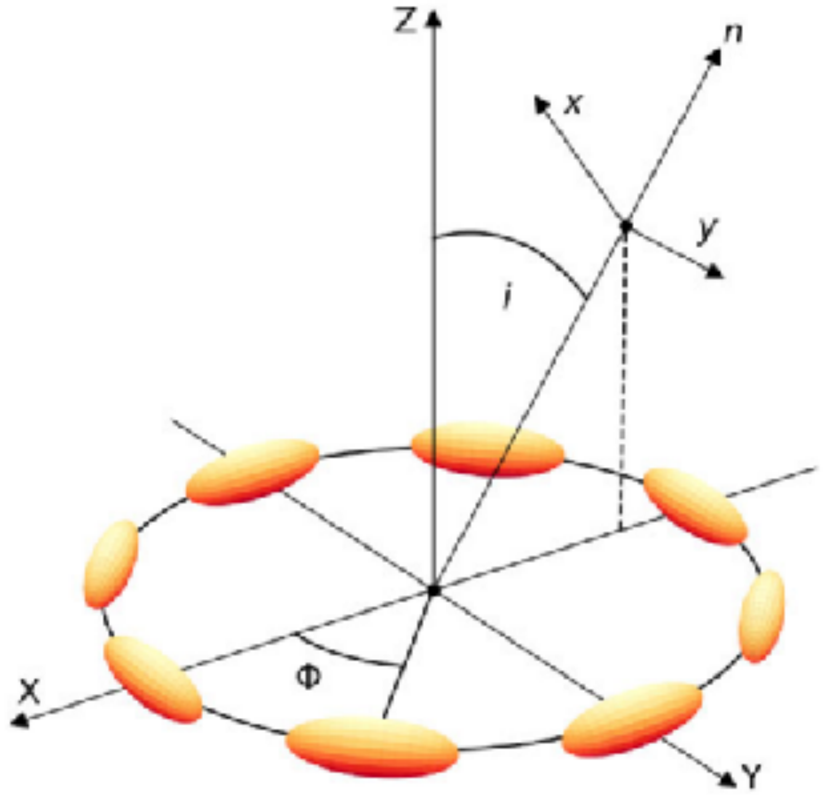
$\Rightarrow$ **Porosity is likely relatively low, i.e.,** $\mathscr{P} < 99\,\%$

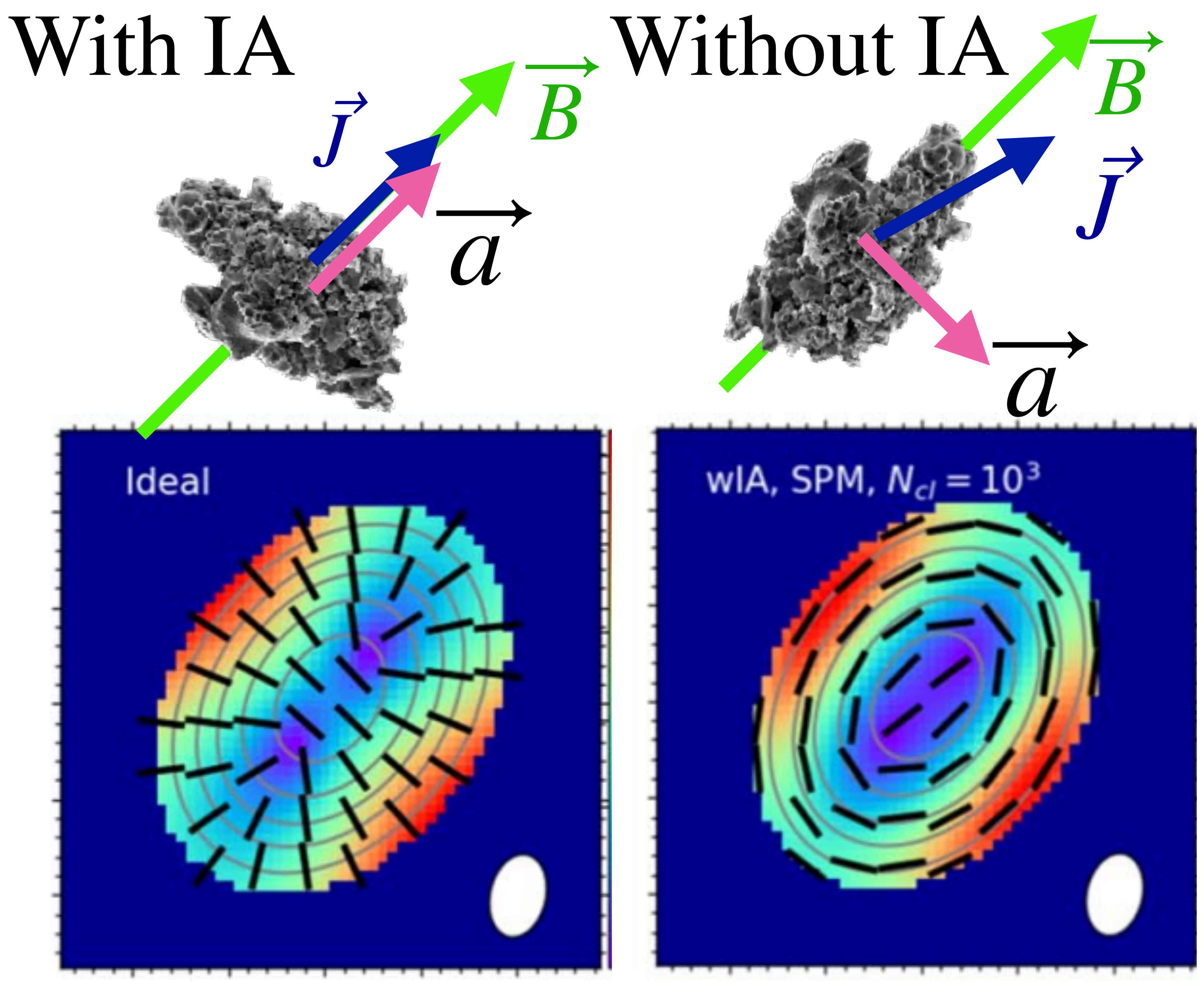
- Formation mechanism of low-porosity pebbles remains being debated. (e.g., Weidling et al. 2009; Tanaka et al 2023; Tatsuuma et al. 2024)
- ⚠️ Further investigation of the effect of light scattering by non-spherical grains needed (e.g., Tazaki et al. 2019, Kirchschlager & Bertrang 2020, Daniel Lin et al. 2023).

Grain alignment in protoplanetary disks

- Alignment-induced polarization is complex
  - B-field, radiation field direction, gas flow, …
    Cho & Lazarian 2007, Bertrang et al. 2017, Tazaki et al. 2017, Yang (Haifeng) et al. 2019, Kataoka et al. 2019, Giang et al. 2023, Lin (Zhe-Yu Daniel) et al. 2022, 2024, Thang et al. 2024, Moritz et al 2025, … etc
  - Polarization reversal and dichroic extinction also complicate the interpretation
    Guillet et al 2019, Lin (Zhe-Yun Daniel) et al. 2022
- Possible origin of the azimuthal polarization for HL Tau
  Thang et al. 2024
  - Grains are aligned with disk toroidal B-field with increased magnetic susceptibility, but without internal alignment (IA).







Thang et al. 2024

Summary

- **Dust sizes**
  - JWST observations reveal ~10-μm sized grains in the outer surface regions of disks.
  - ALMA emission and polarization models favor grains of ~100 μm — ~1 cm (?).
- **Dust porosity**
  - Micron-sized particles may have fluffy structure based on IR scattering phase function.
  - Submillimeter particles should have relatively low porosity, i.e., less than 99%.
- **Origin of millimeter-wave polarization**
  - At least two polarization mechanisms are needed to reproduce the observed mm polarization.
  - B-RAT without internal alignment and with increased magnetic susceptibility may explain the azimuthal polarization pattern of the HL Tau disk.