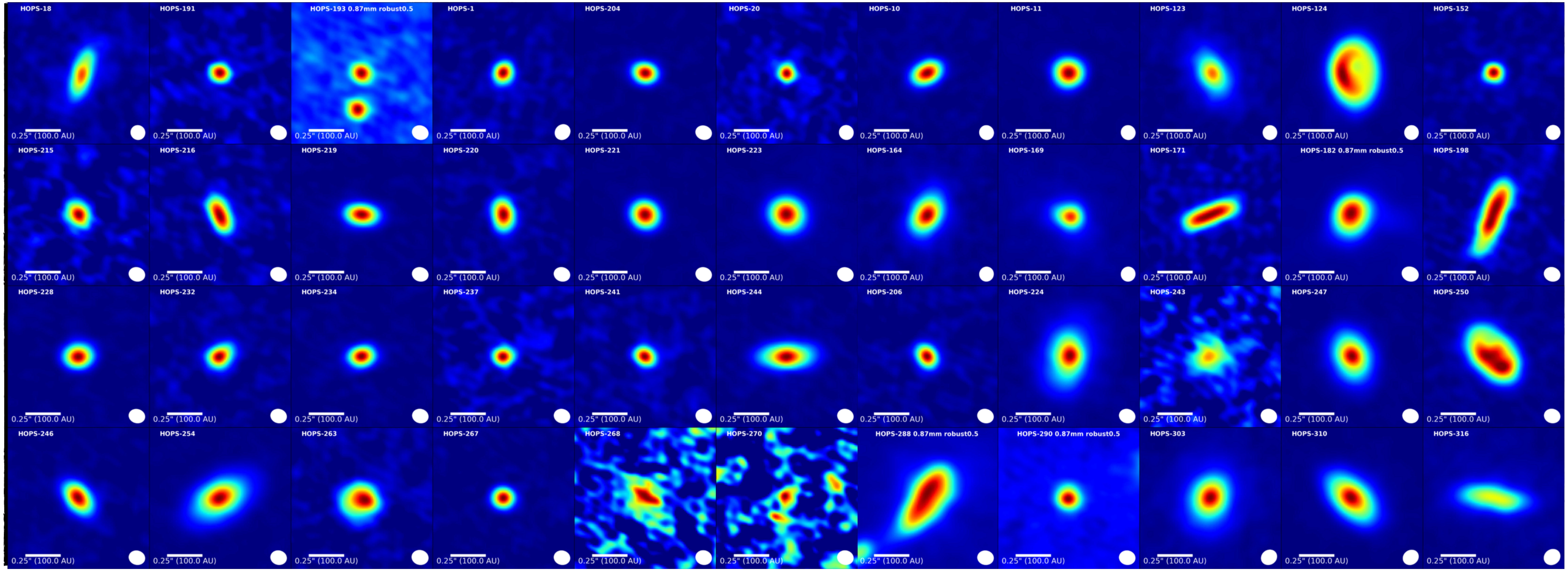
Image credit: Tobin et al. 2020

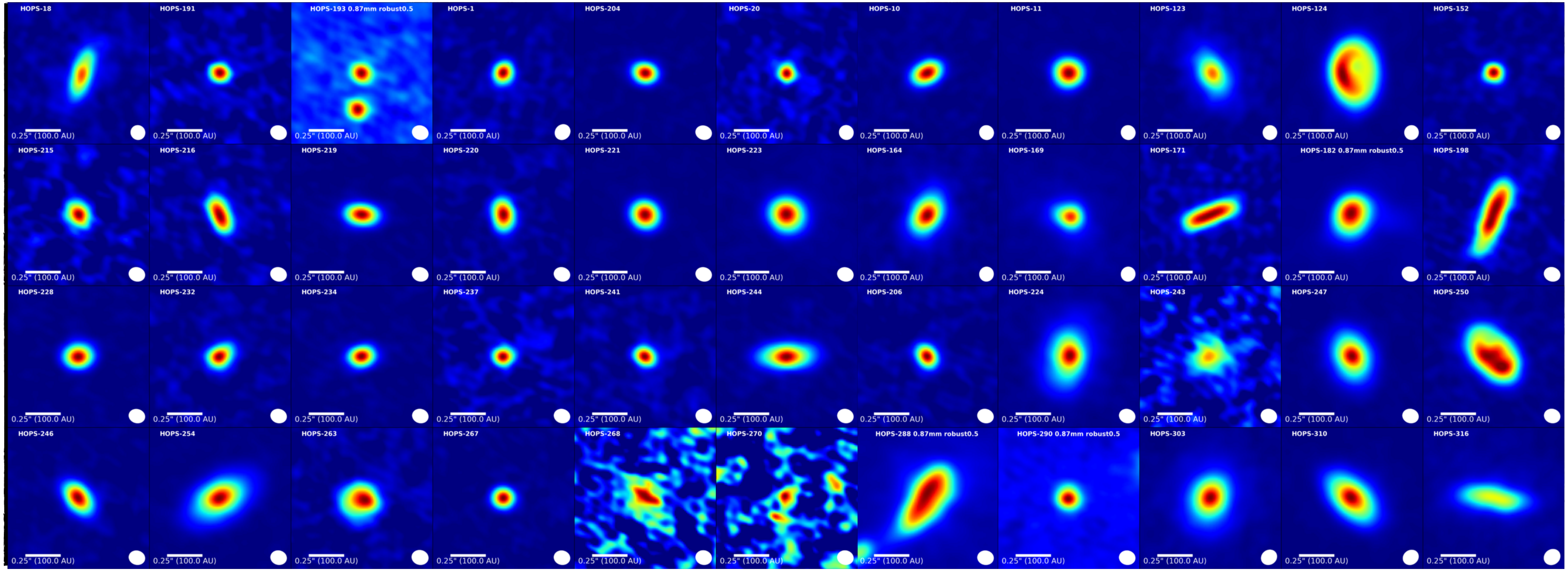


Substructures in Embedded Disks: Insights from the VANDAM Orion Survey

Patrick Sheehan
NSF Astronomy & Astrophysics Fellow

MIAPP Program: Gaps, Rings, Spirals, and Vortices
October 26, 2021

Image credit: Tobin et al. 2020



~~Substructures~~ Planet Formation in Embedded Disks: Insights from the VANDAM Orion Survey

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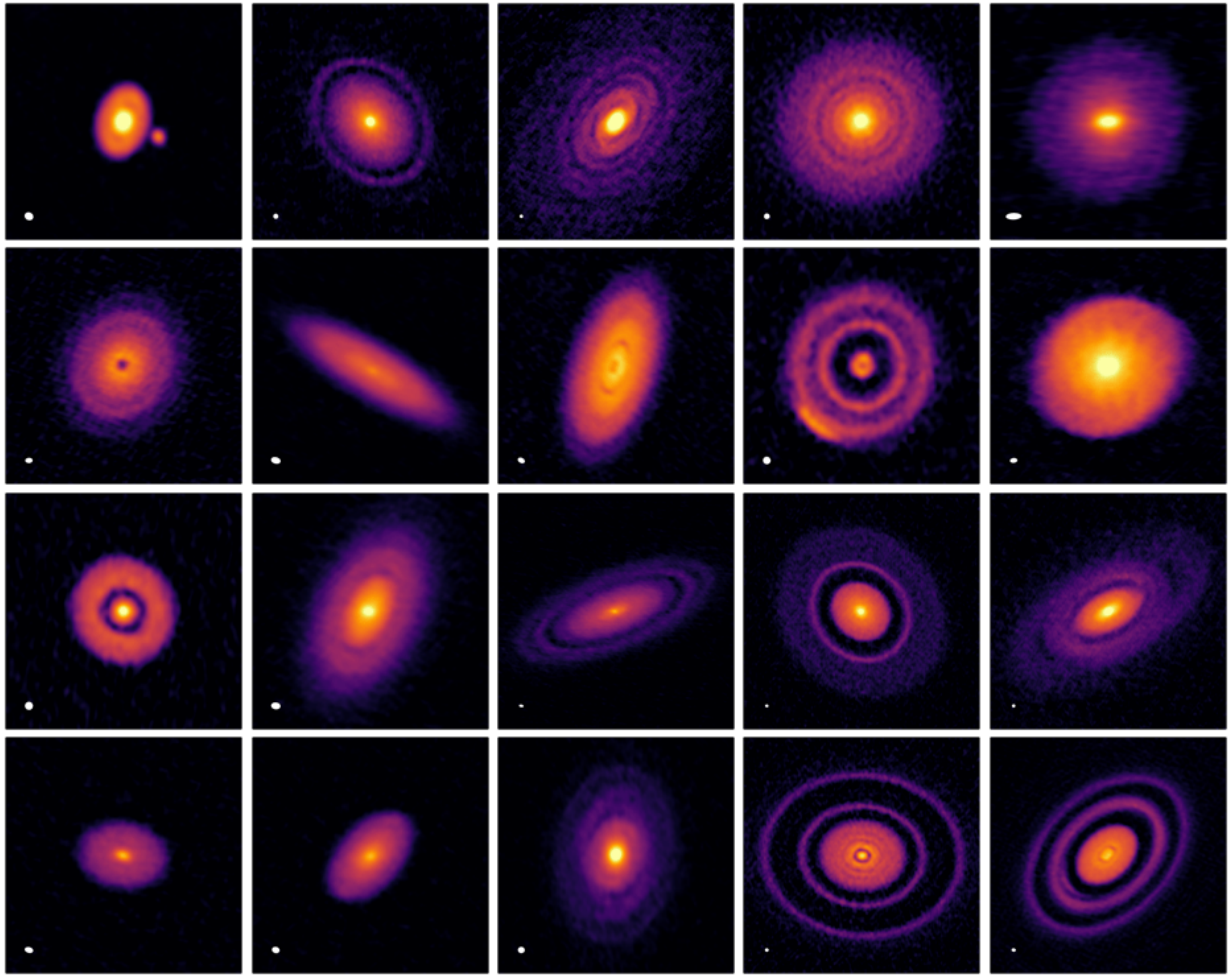
Substructures in protoplanetary disks

I. Why Embedded Disks?



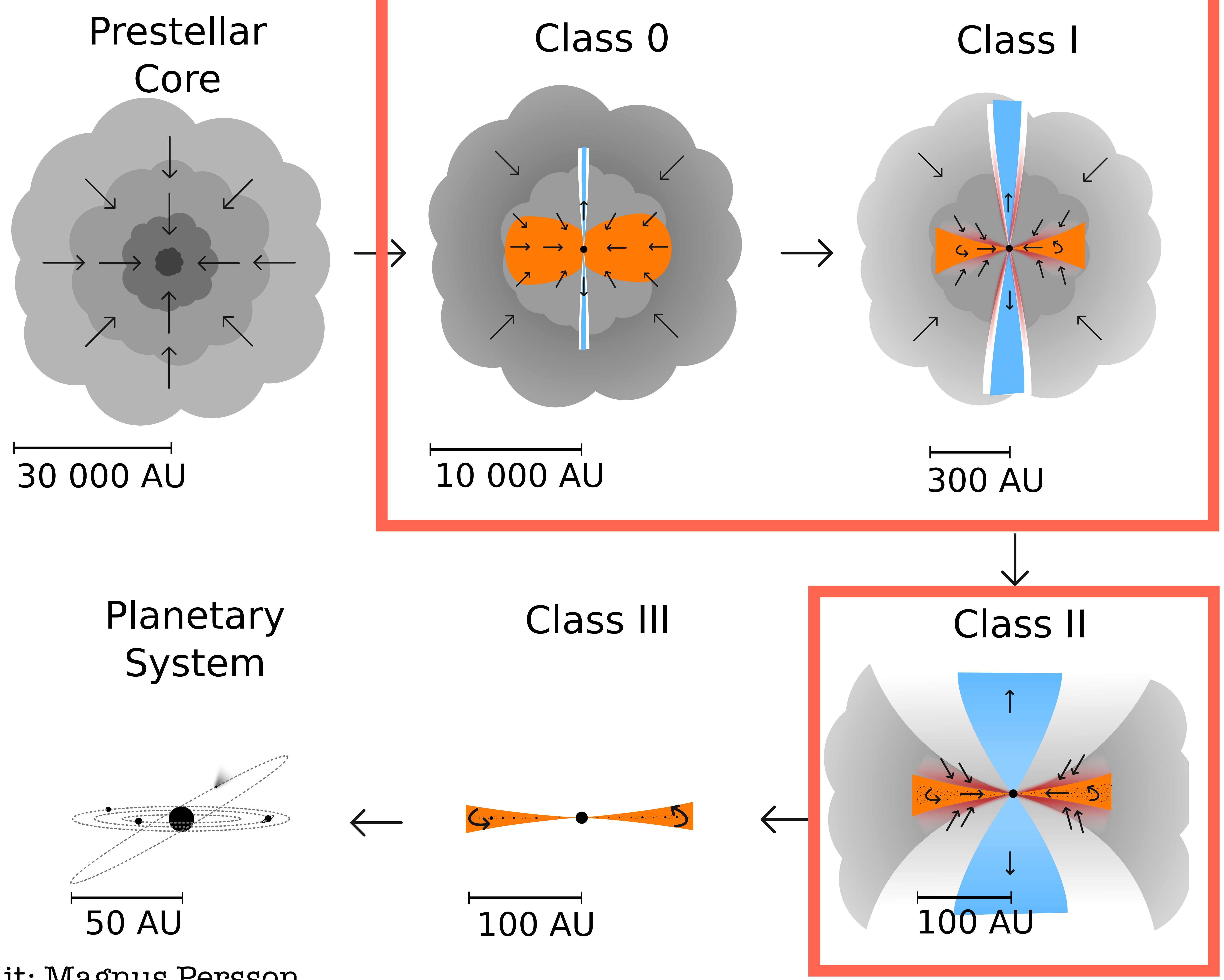
DSHARP, 2018

Substructures appear to be ubiquitous

Protoplanetary disk structures are not primordial

Stages of Star Formation

I. Why Embedded Disks?



"Embedded" disks

- The earliest stages of disks ($t < 0.5$ Myr)
- Disk size a tracer of envelope collapse?
- Set the stage for disk evolution and planet formation

"Protoplanetary" disks

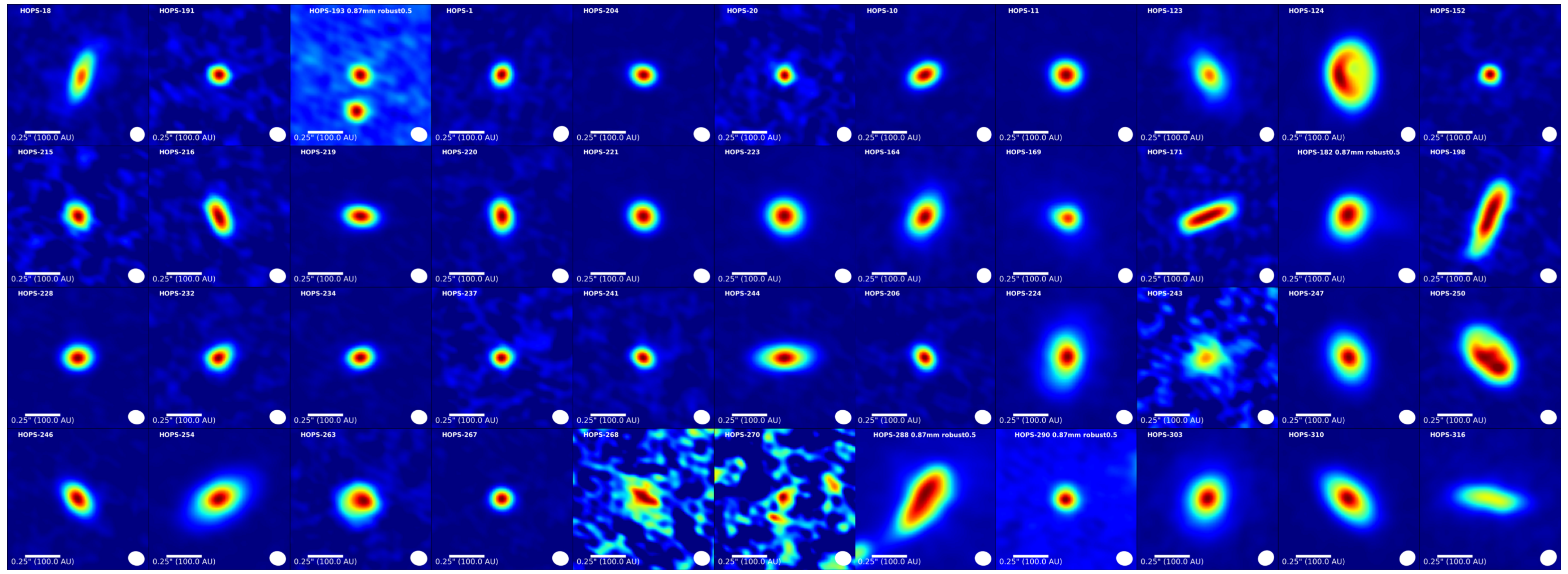
- Ages of 1-10 Myr
- Where planets are forming?

Image credit: Magnus Persson

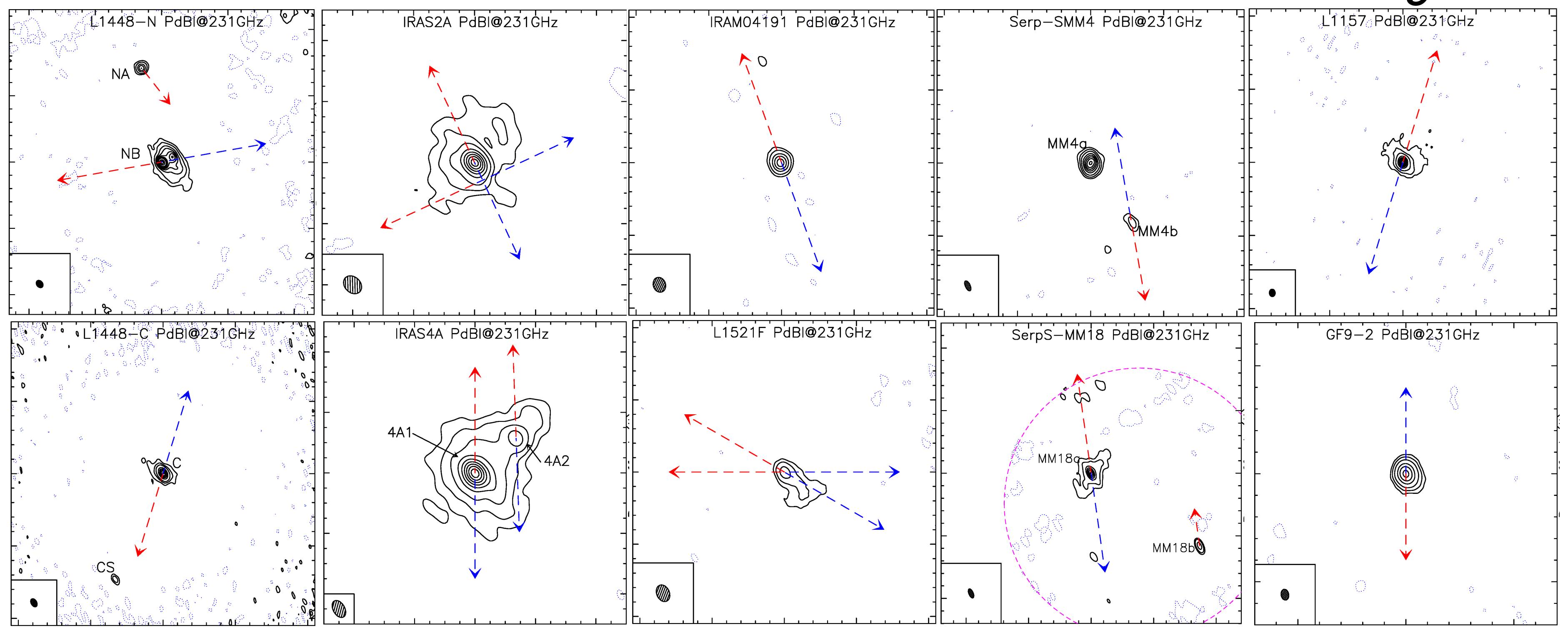
A New Era of Protostellar Disk Surveys

I. Why Embedded Disks?

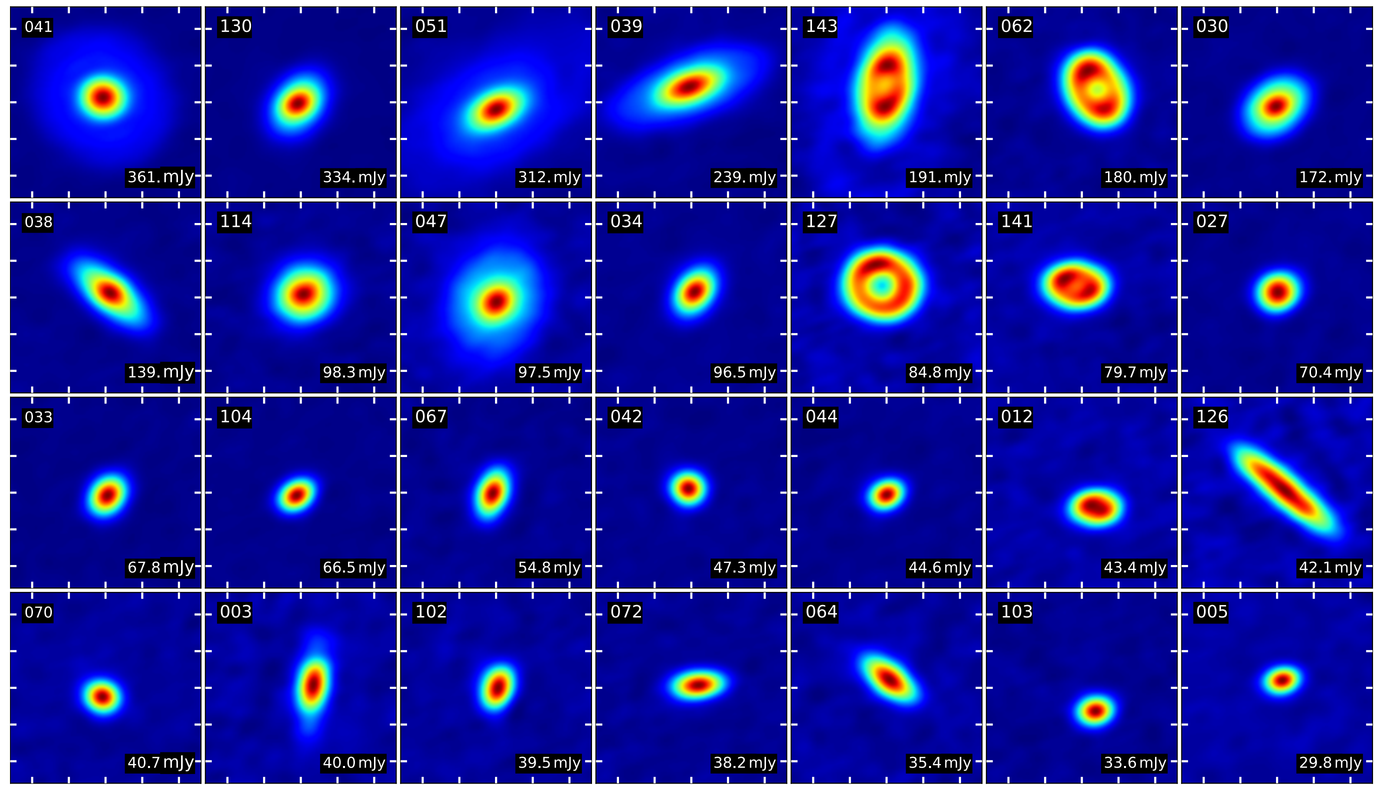
VANDAM: Orion
300 Embedded Disks Tobin et al. 2020



CALYPSO (PdBI)
16 Embedded Disks
Maury et al. 2019

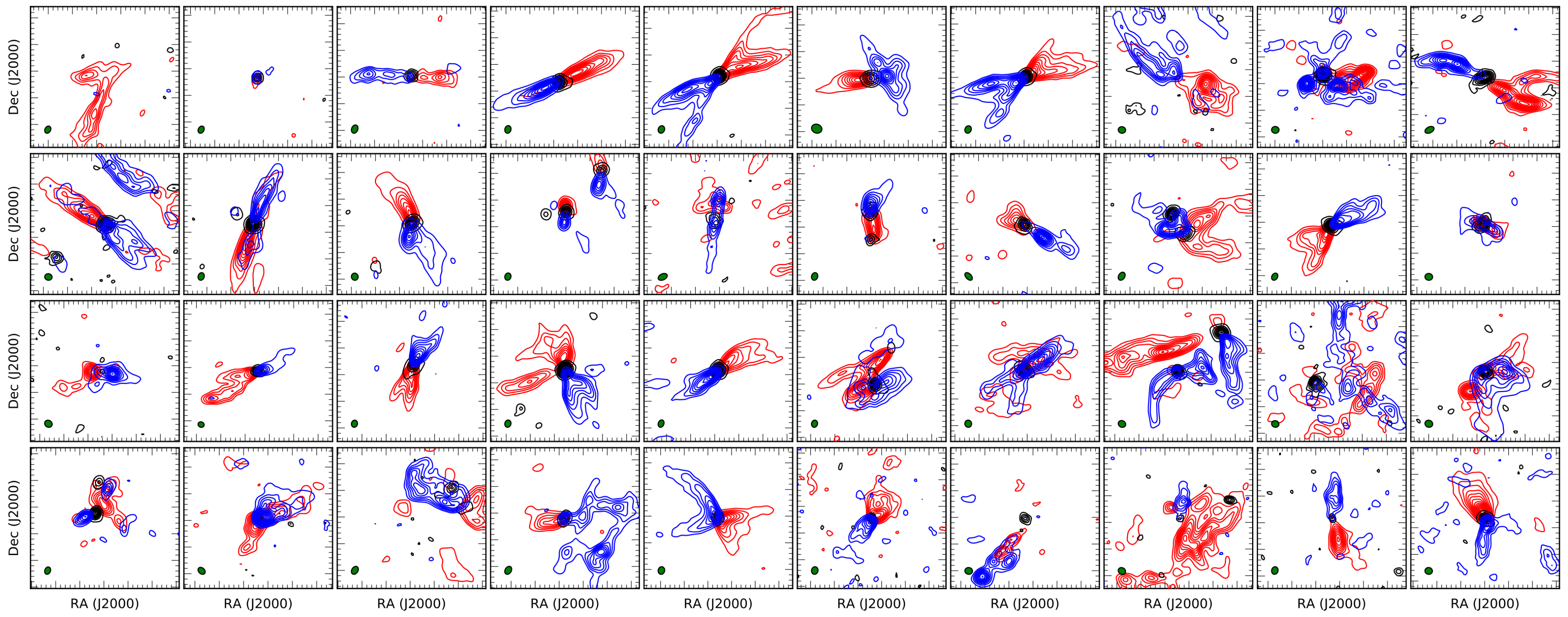


ODISEA: Ophiuchus
78 Embedded Disks

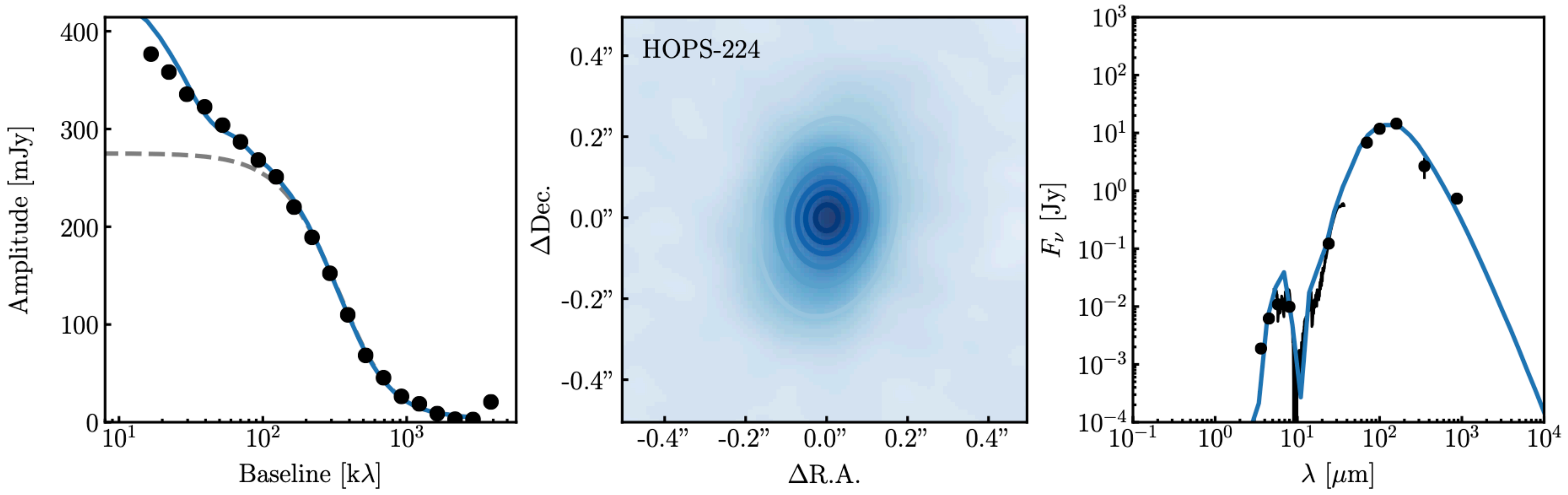


Cieza et al. 2018

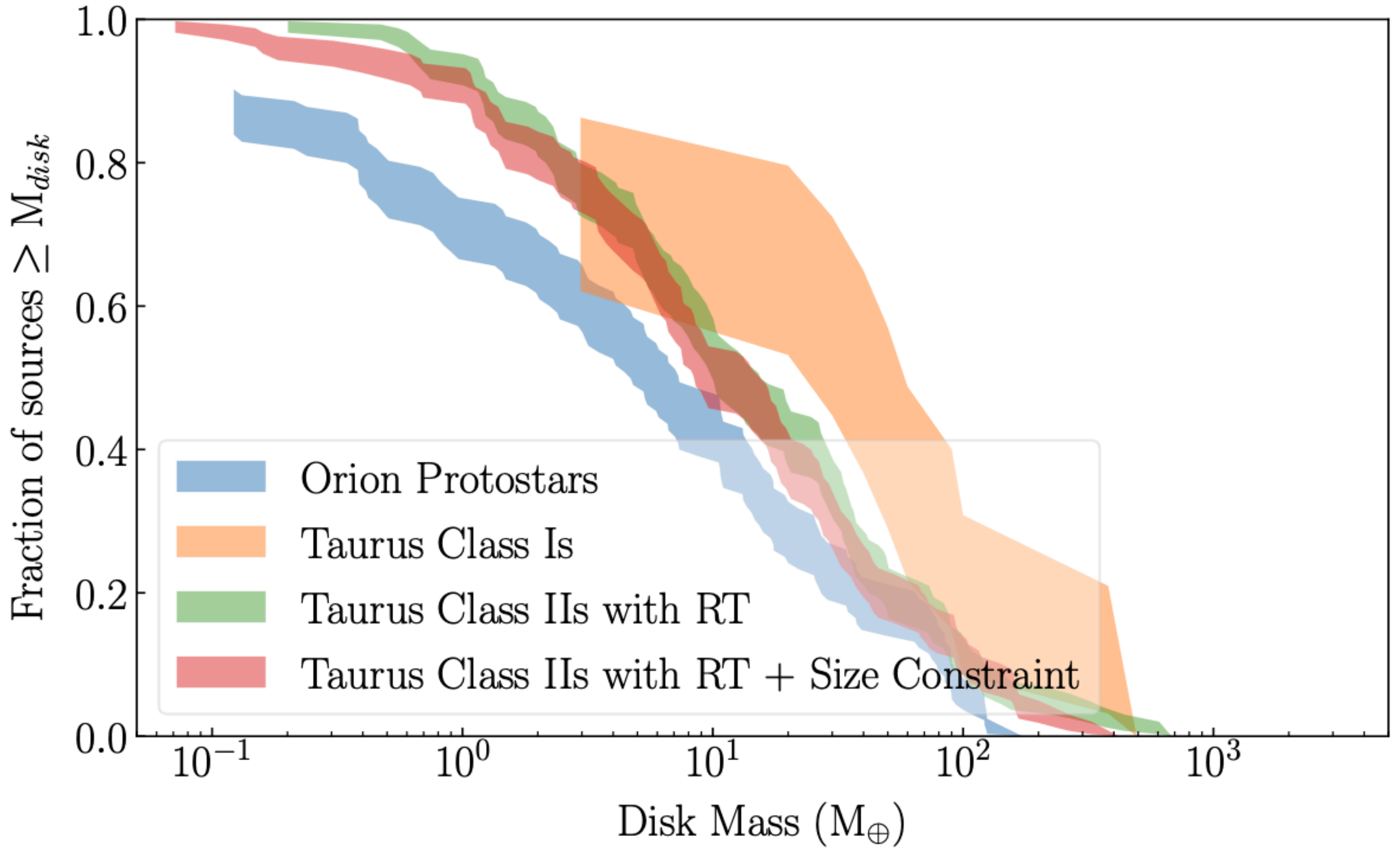
MASSES (SMA) - Perseus
74 Embedded Disks
Stephens et al. 2019



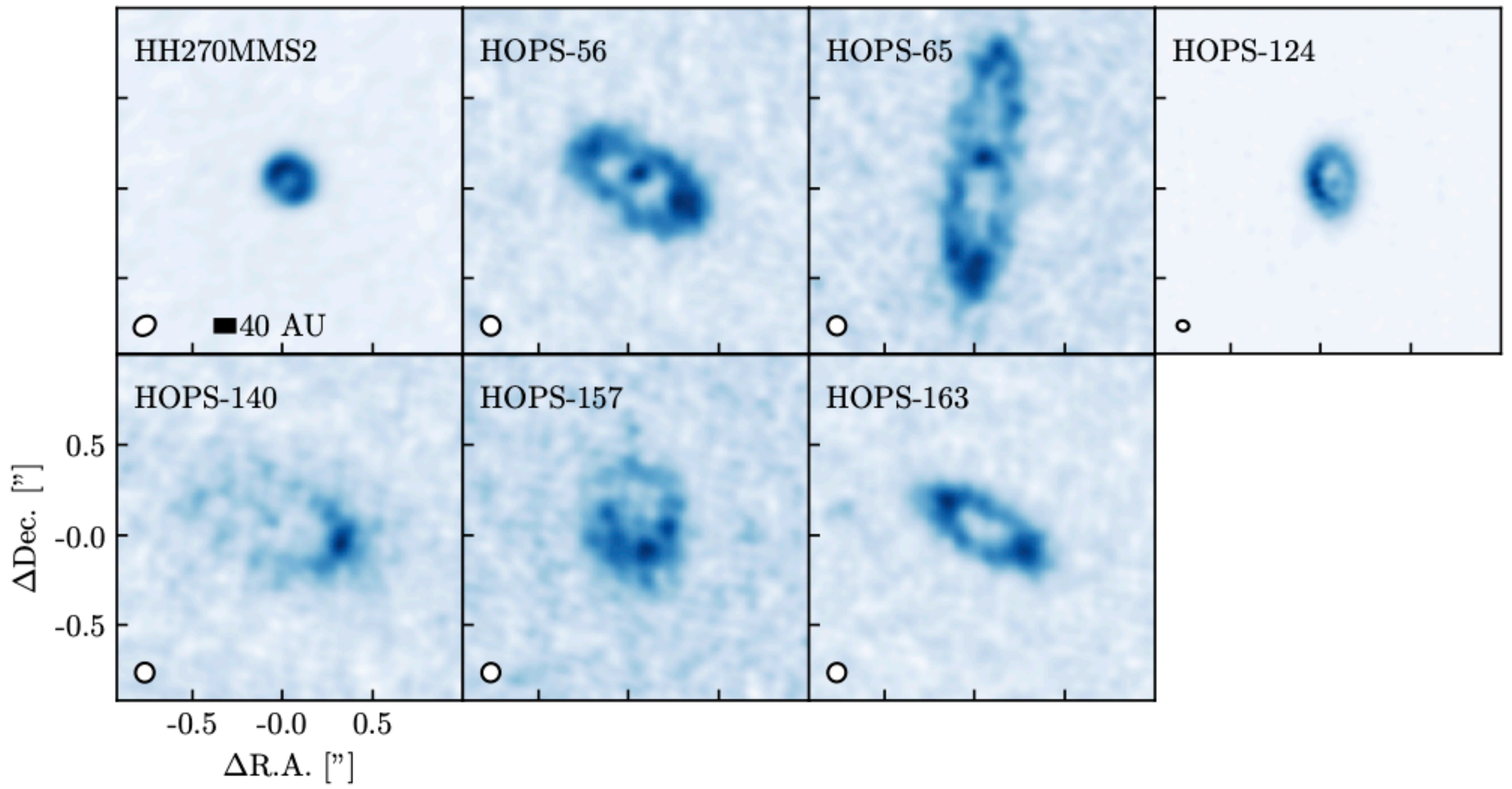
I. Why Radiative Transfer Modeling?



II. Disk Demographics: The Environment of Planet Formation



III. Substructures: Witnessing Planet Formation in Embedded Disks?



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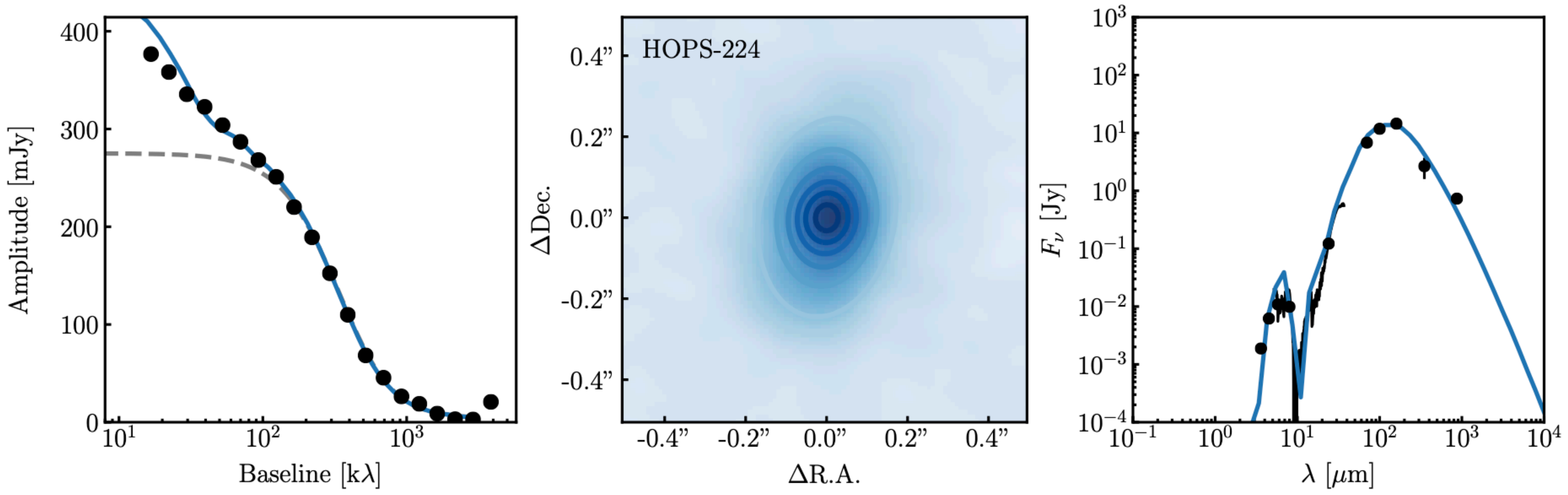

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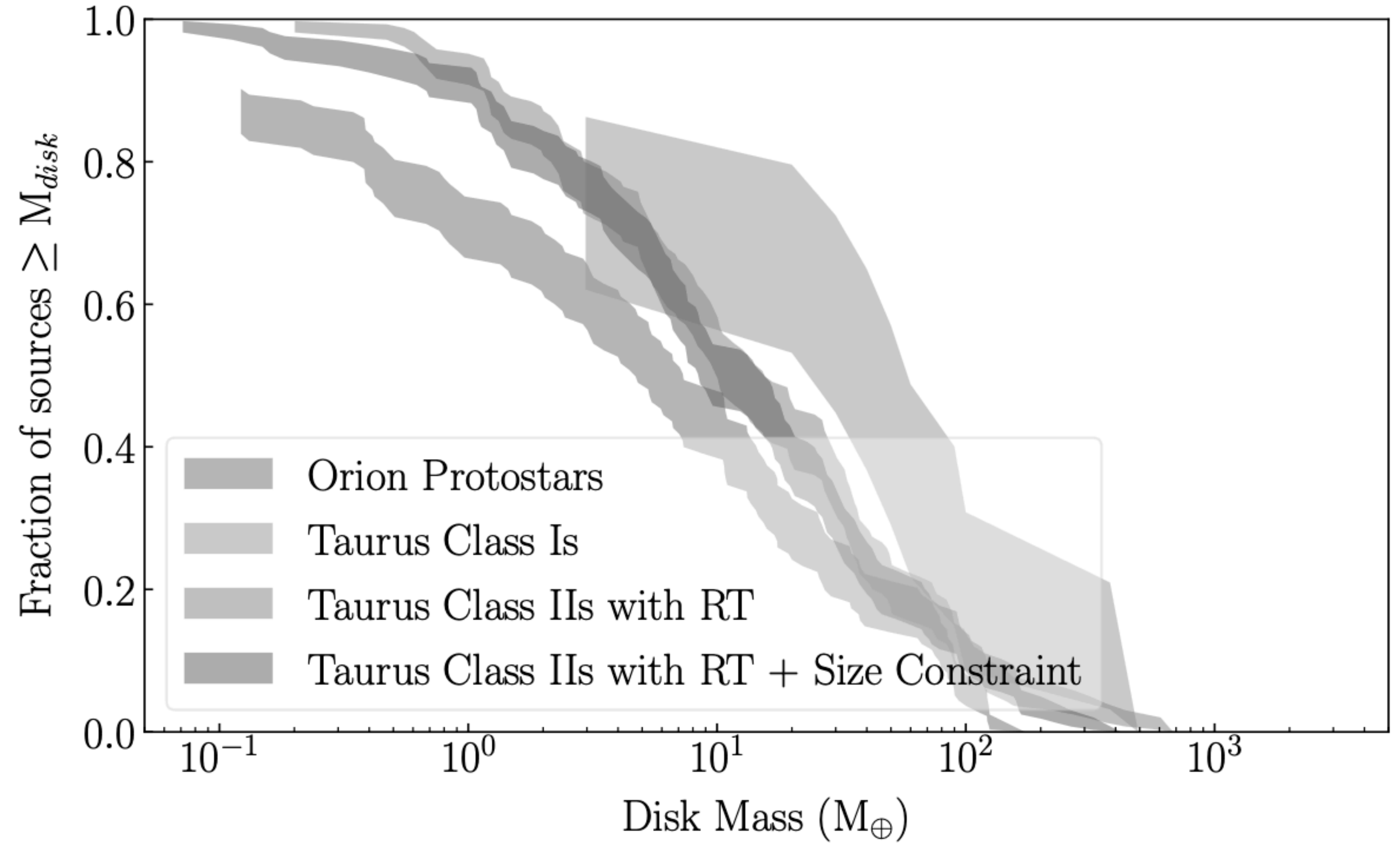

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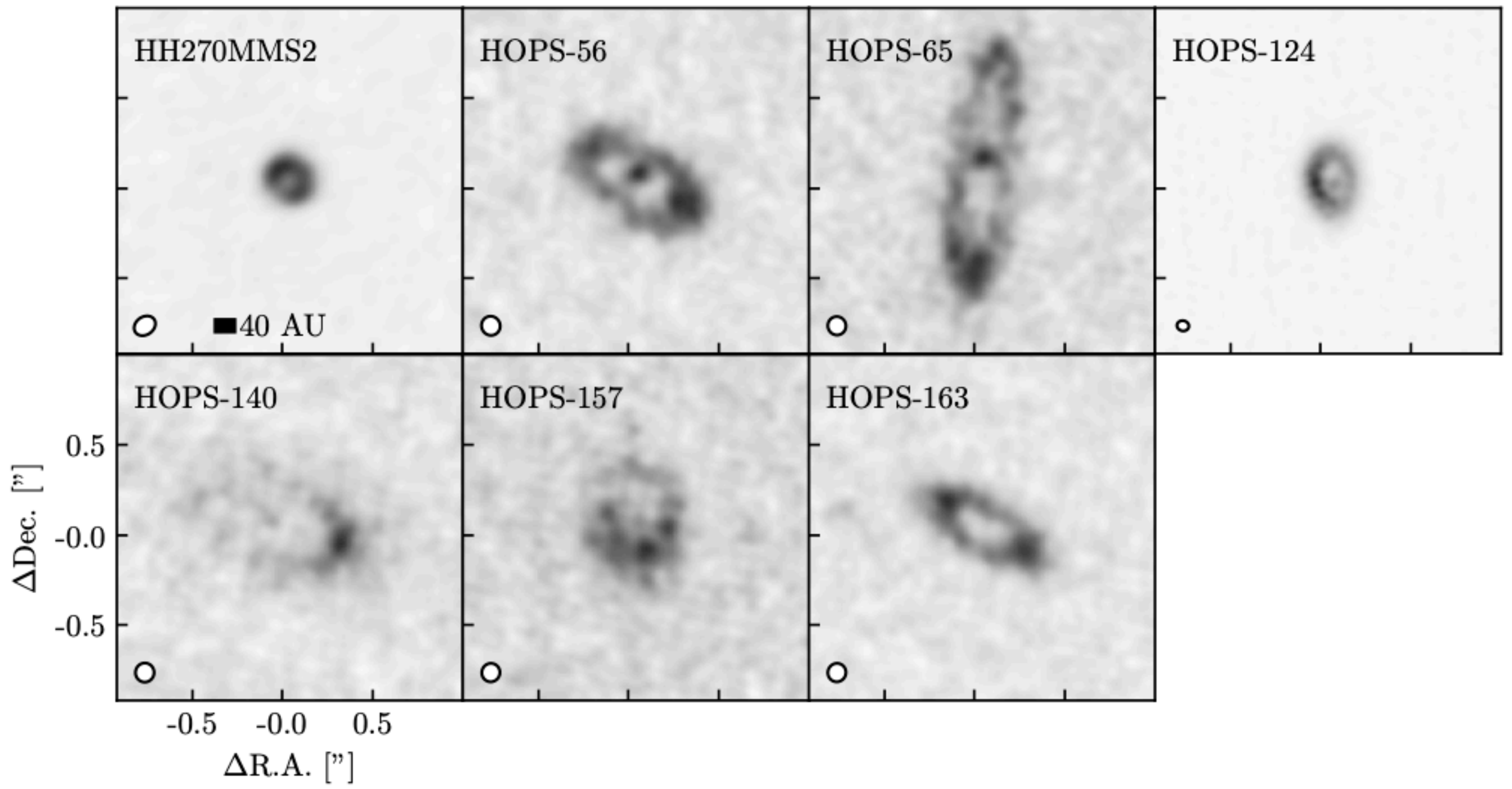


Radio Brightness is a Proxy for Disk Mass and Size

I. Why Radiative Transfer Modeling?

Source distance

(sub)millimeter flux

$$M_d = \frac{d^2 F_\nu}{\kappa_\nu B_\nu(T_c)} \times 100$$

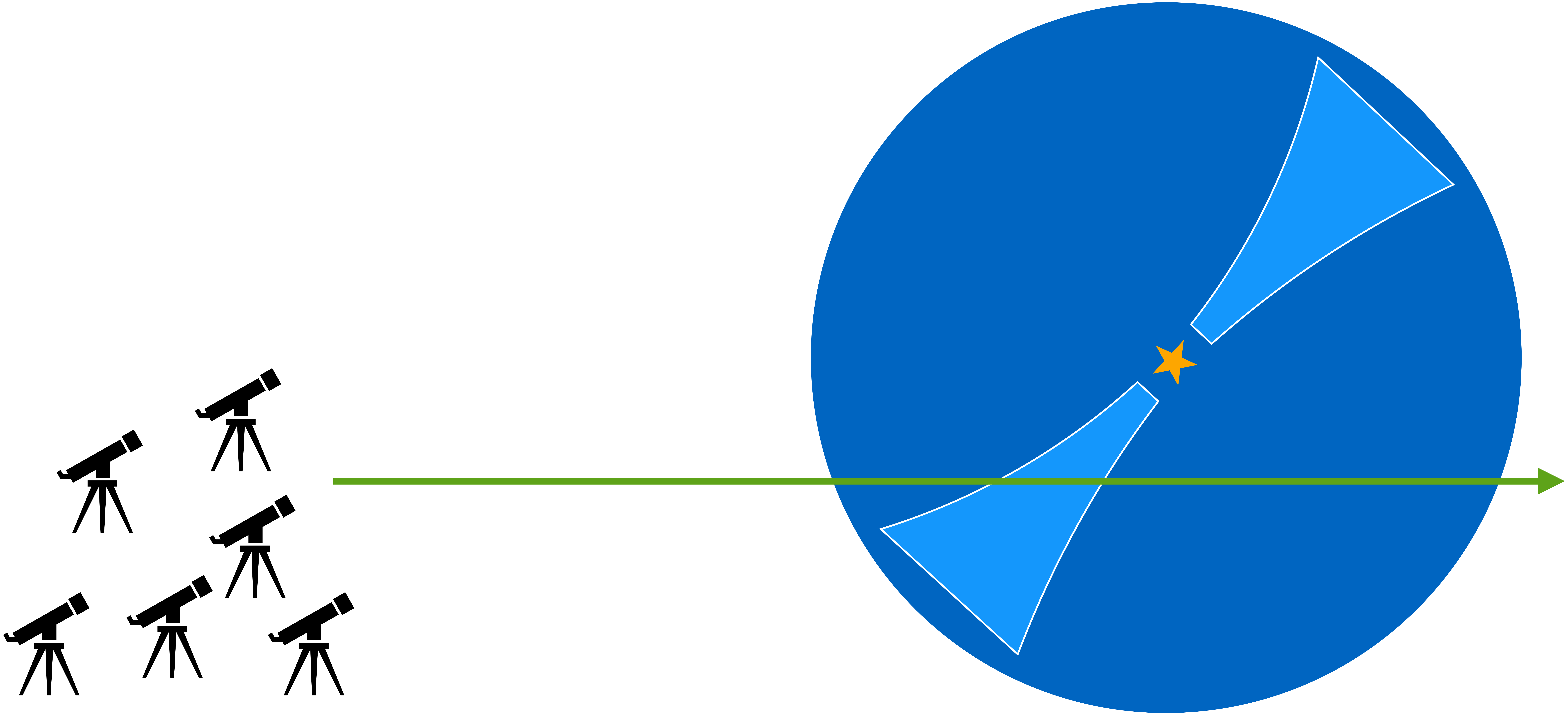
Gas-to-dust ratio

Opacity

Disk temperature

For Embedded Disks, Envelope Matters

I. Why Radiative Transfer Modeling?



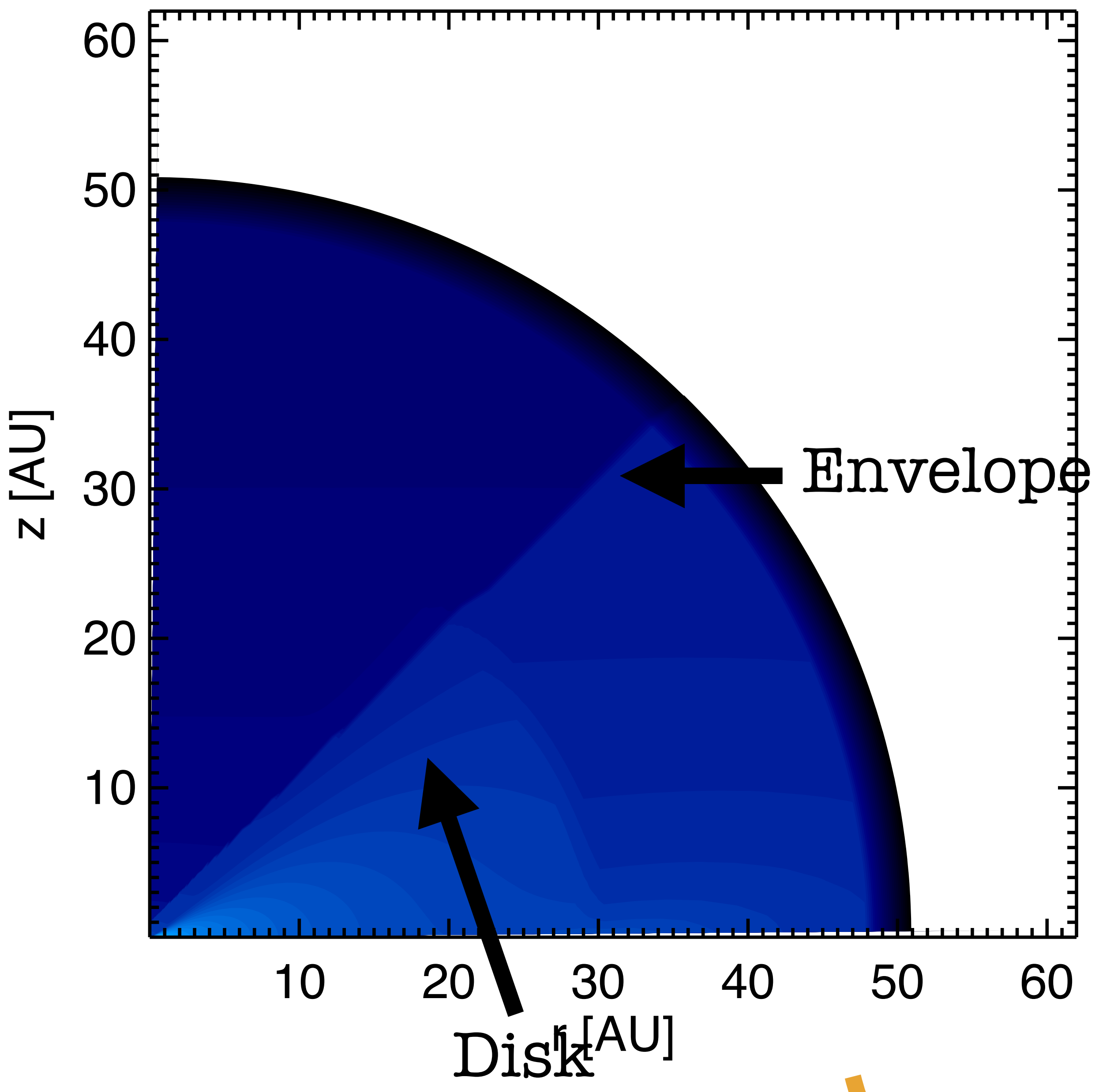
Radiative Transfer Forward Modeling

I. Why Radiative Transfer Modeling?

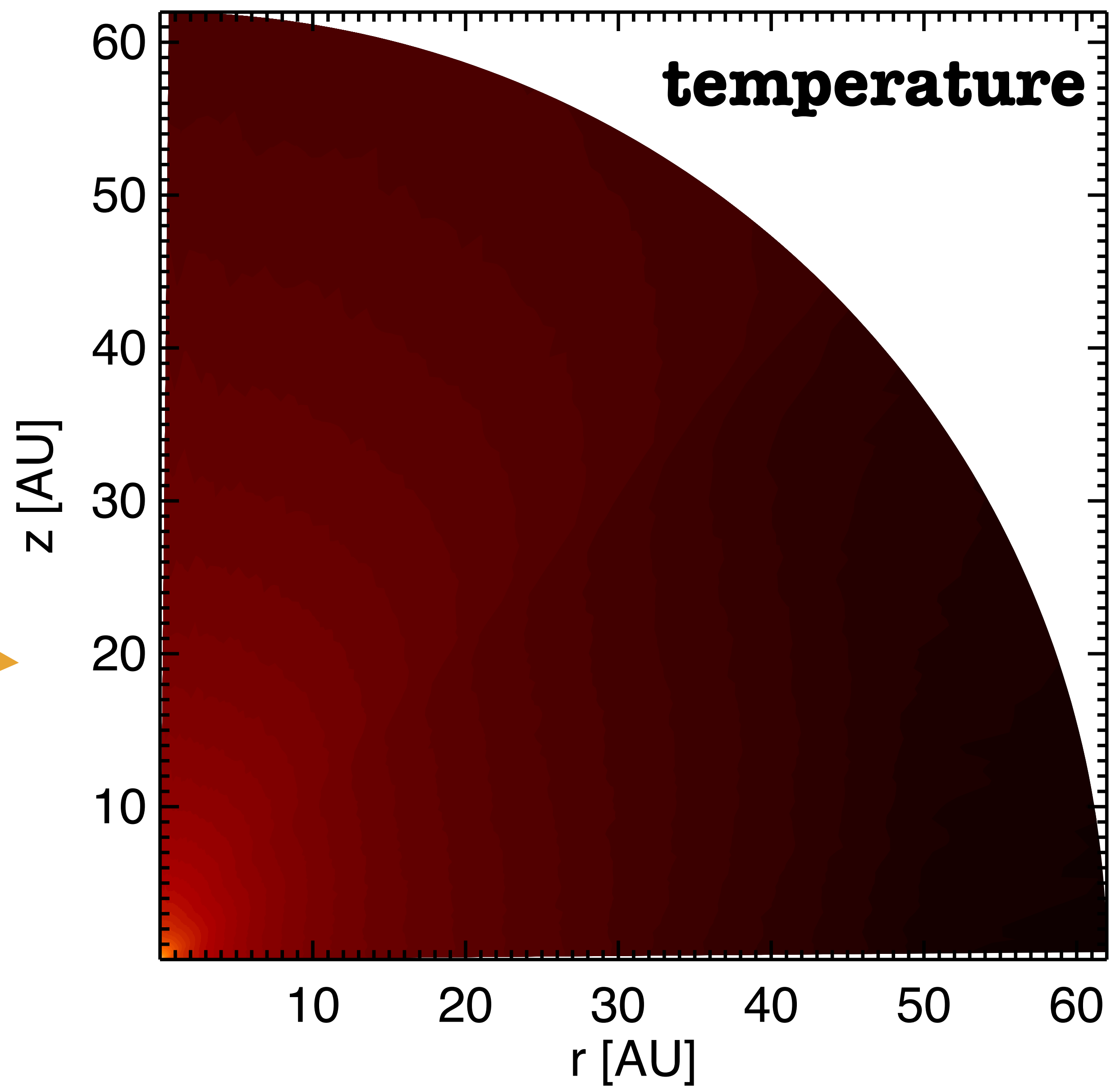
pdspy.readthedocs.io

parametric density distribution

disk + envelope + outflow cavity

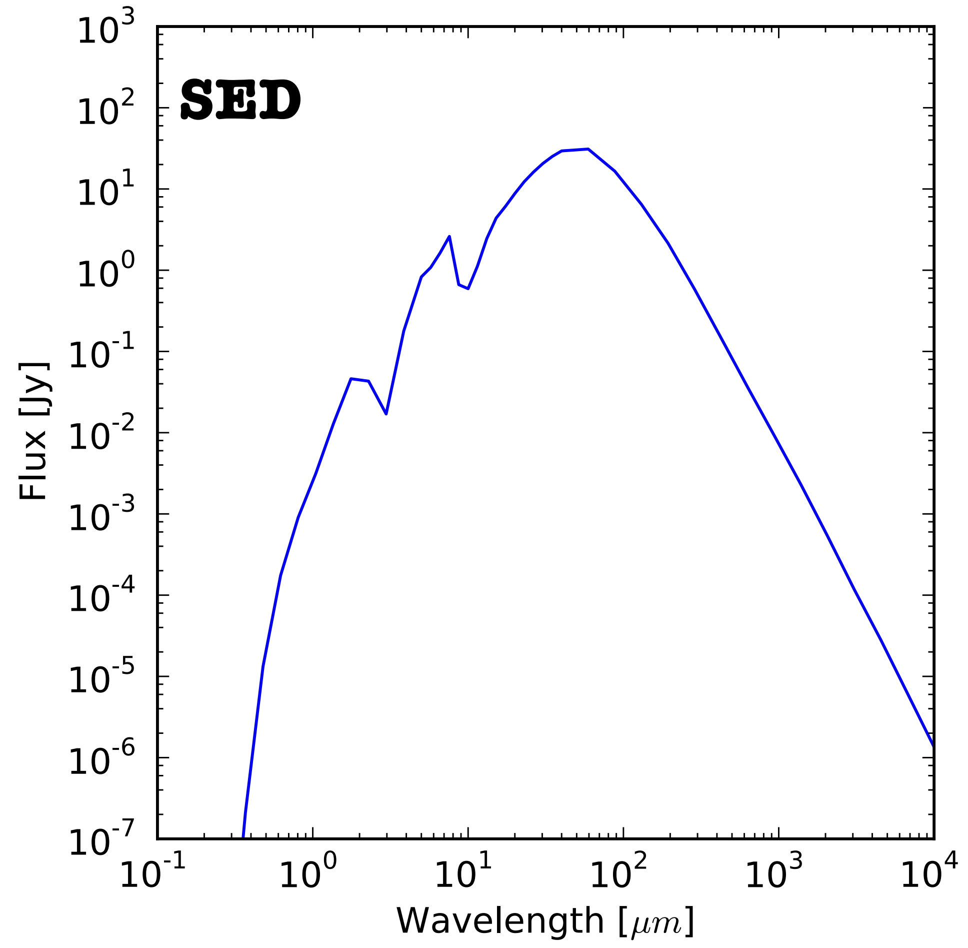


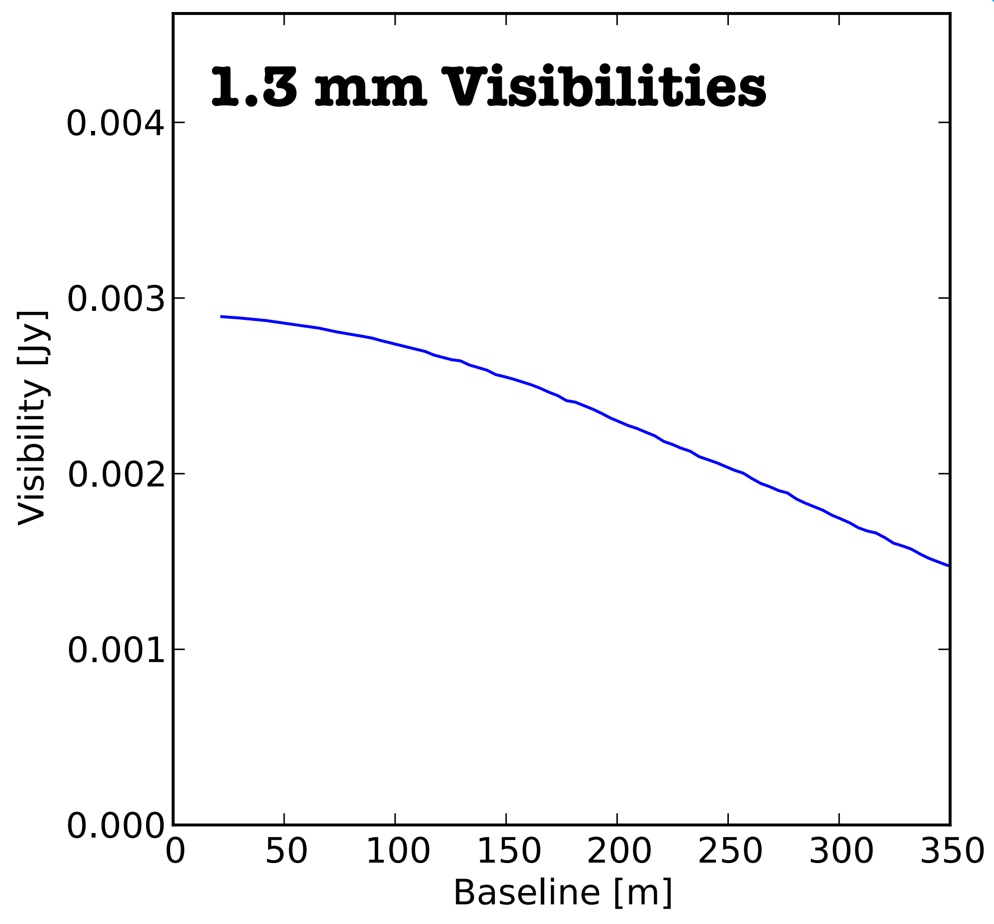
Radiative Equilibrium with RADMC-3D



Raytracing with RADMC-3D

synthetic observations

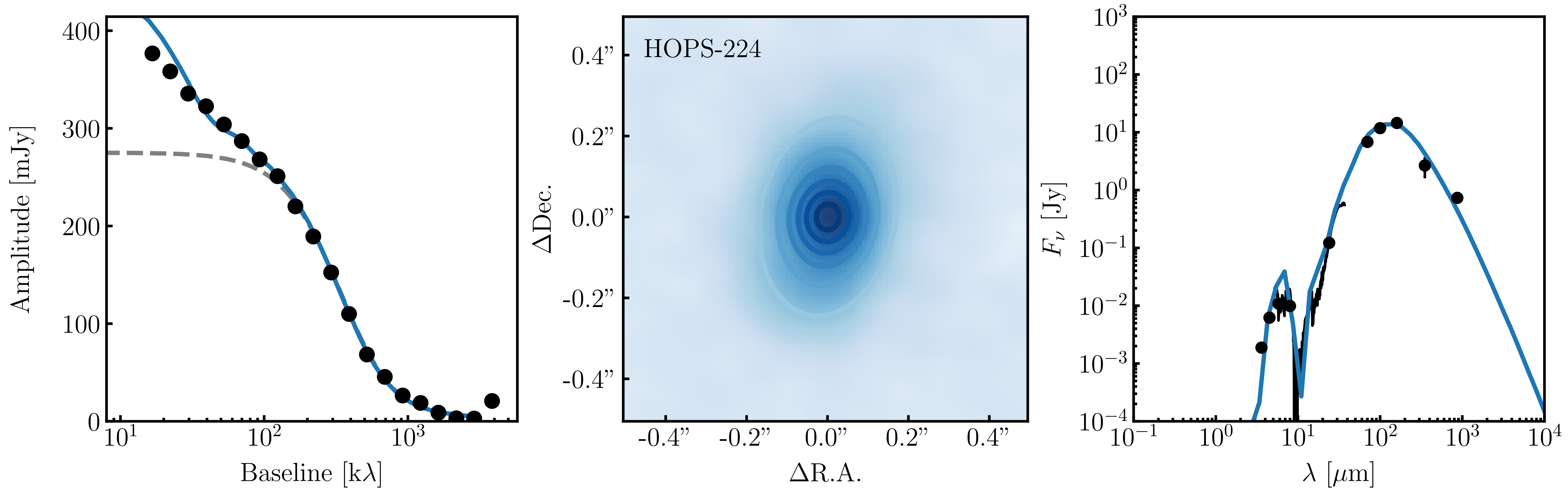




Historically:
By-eye/-hand or
Large, poorly sampled grids

pdspy:
MCMC
Nested Sampling

best fit model



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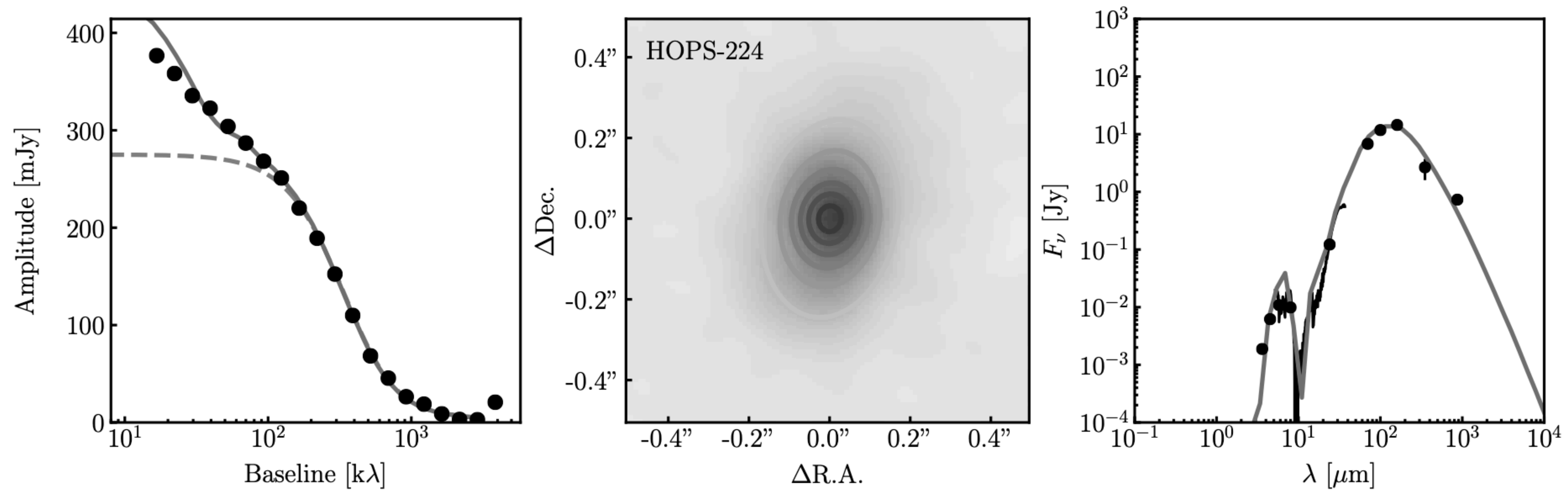
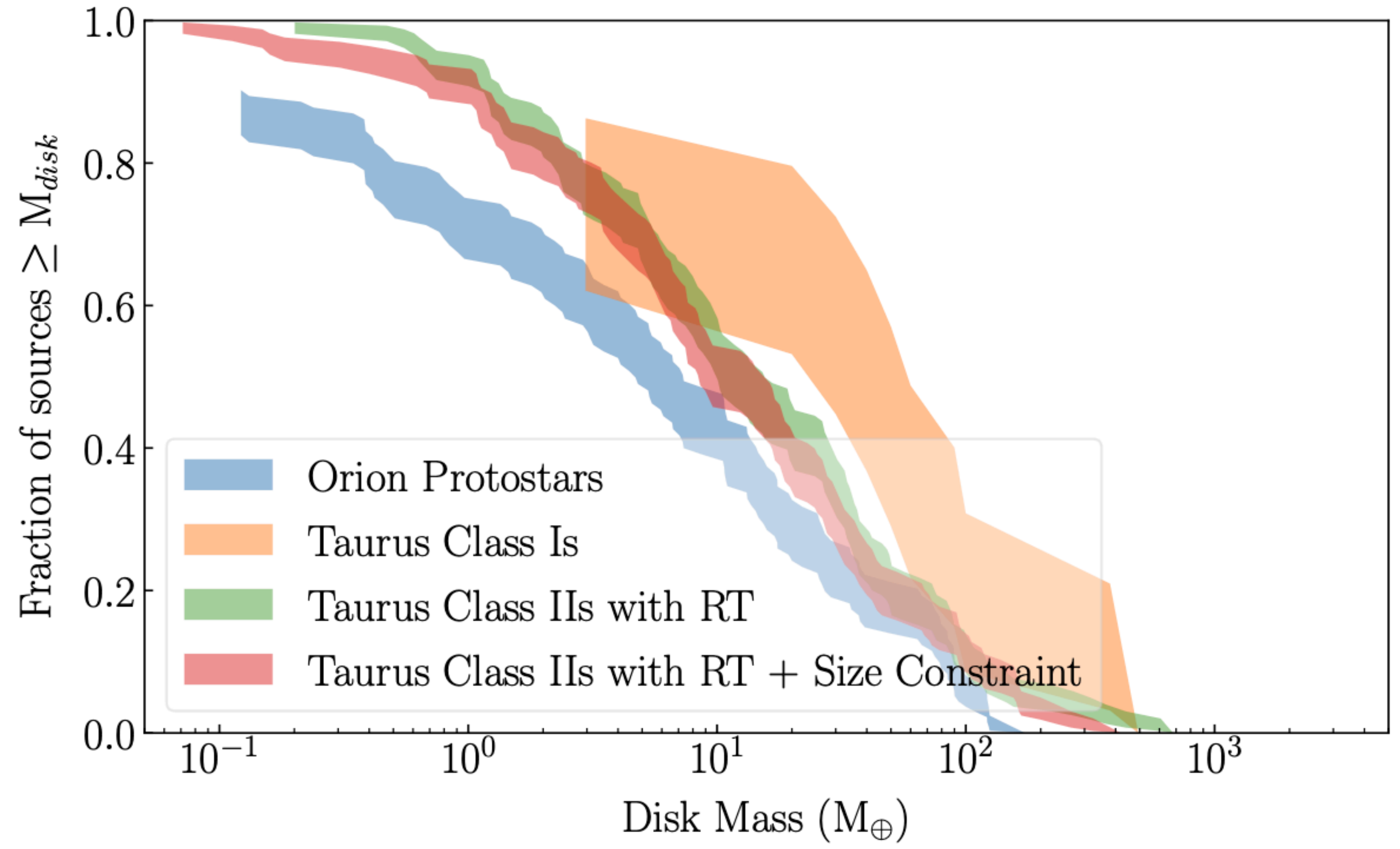
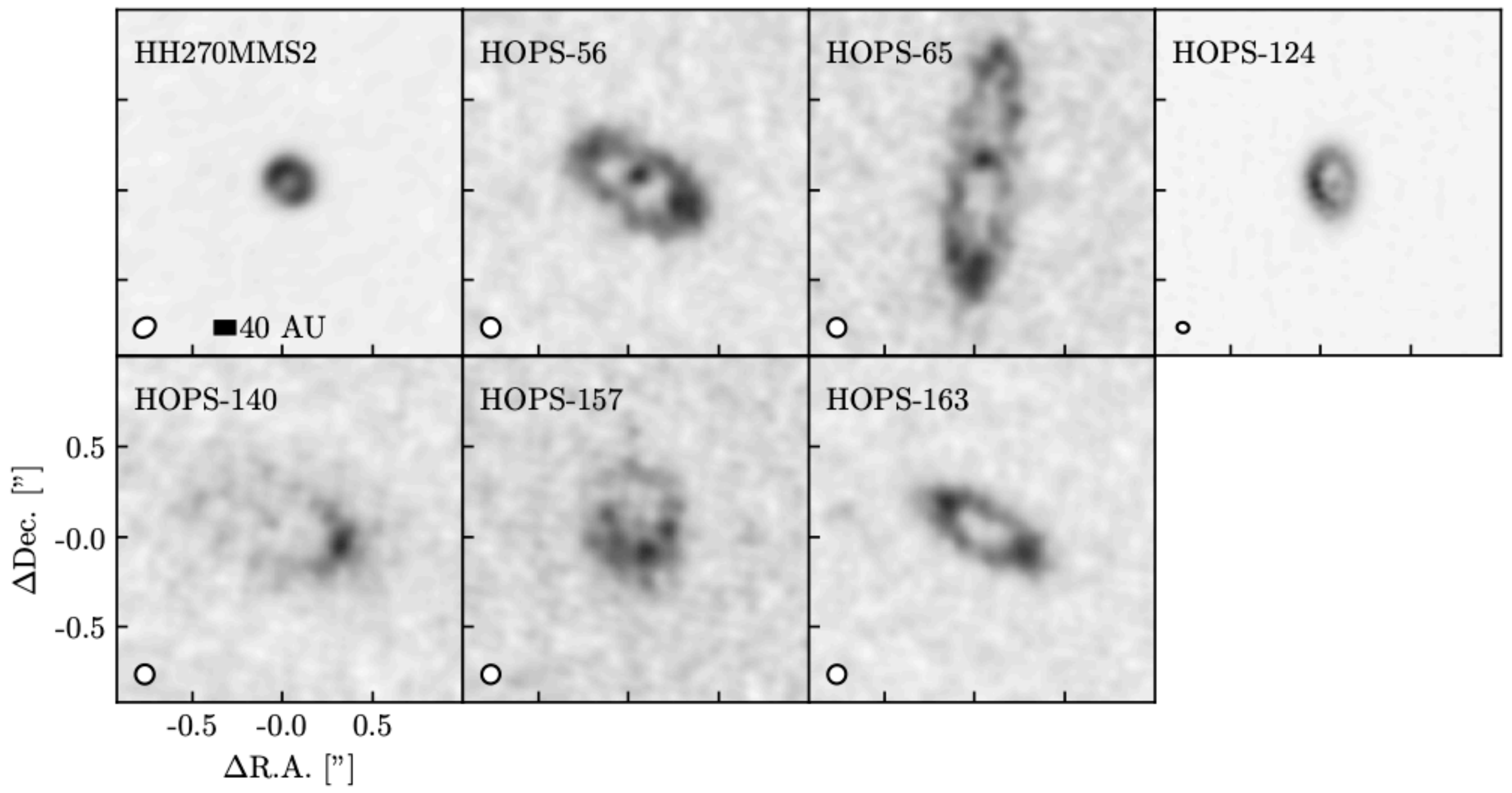


II. Disk Demographics: The Environment of Planet Formation



III. Substructures: Witnessing Planet Formation in Embedded Disks?

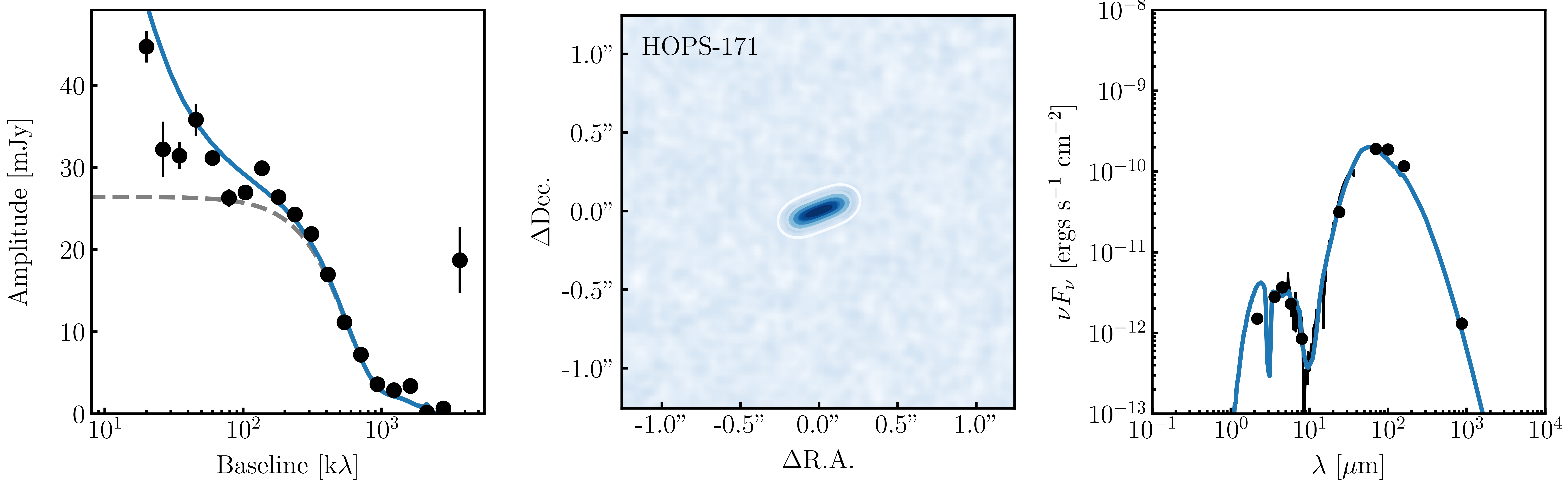


Modeling Embedded Disks in Orion

II. Disk Demographics: The Environment of Planet Formation

- PI of 5,000,000 core-hour allocation to model 100 single protostars in the VANDAM: Orion survey with NSF XSEDE supercomputers
    - Largest full radiative transfer modeling sample, to-date

Sheehan et al, in prep.

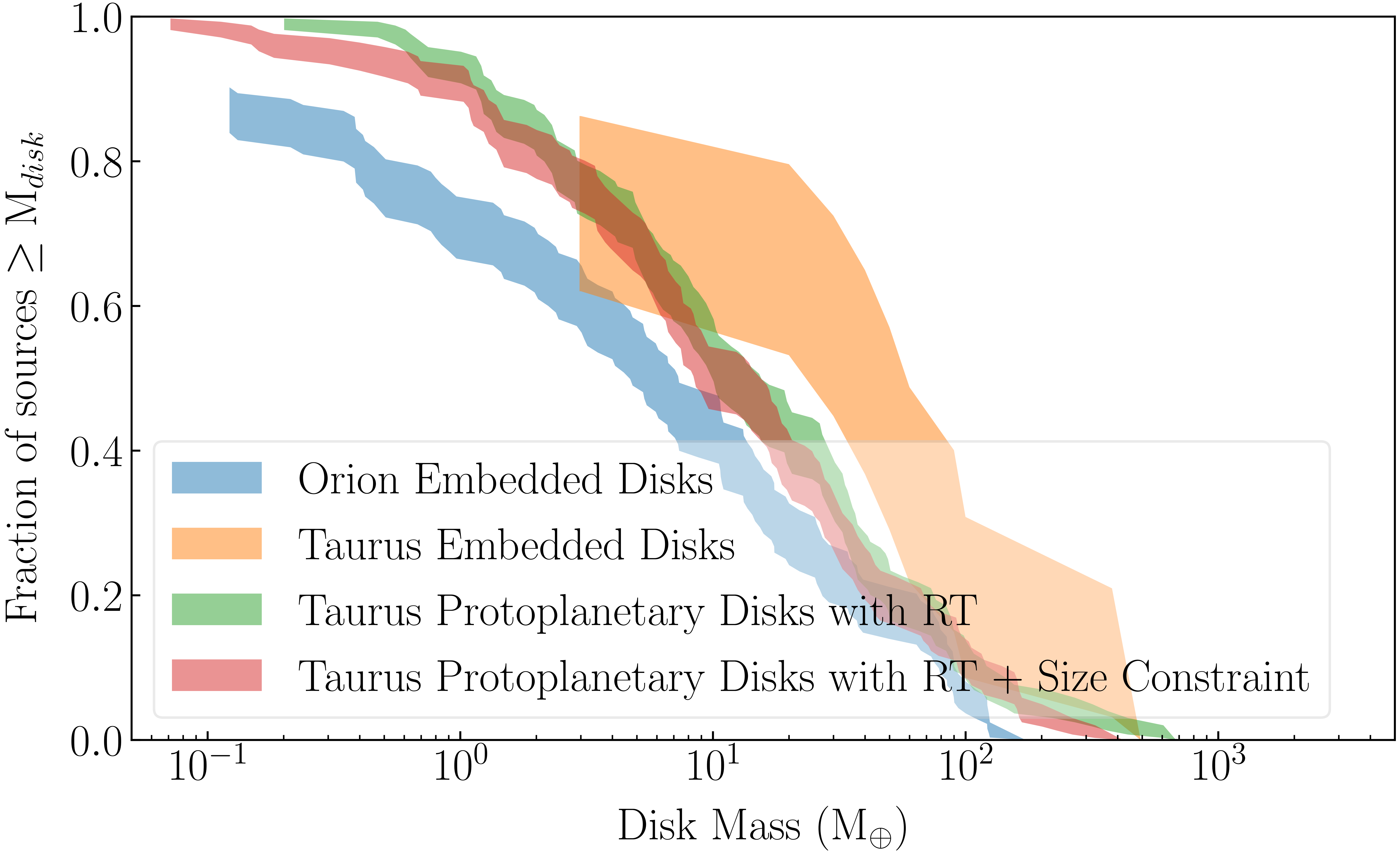


The Initial Mass Budget for Planet Formation

II. Disk Demographics: The Environment of Planet Formation

embedded disks are more massive than protoplanetary disks

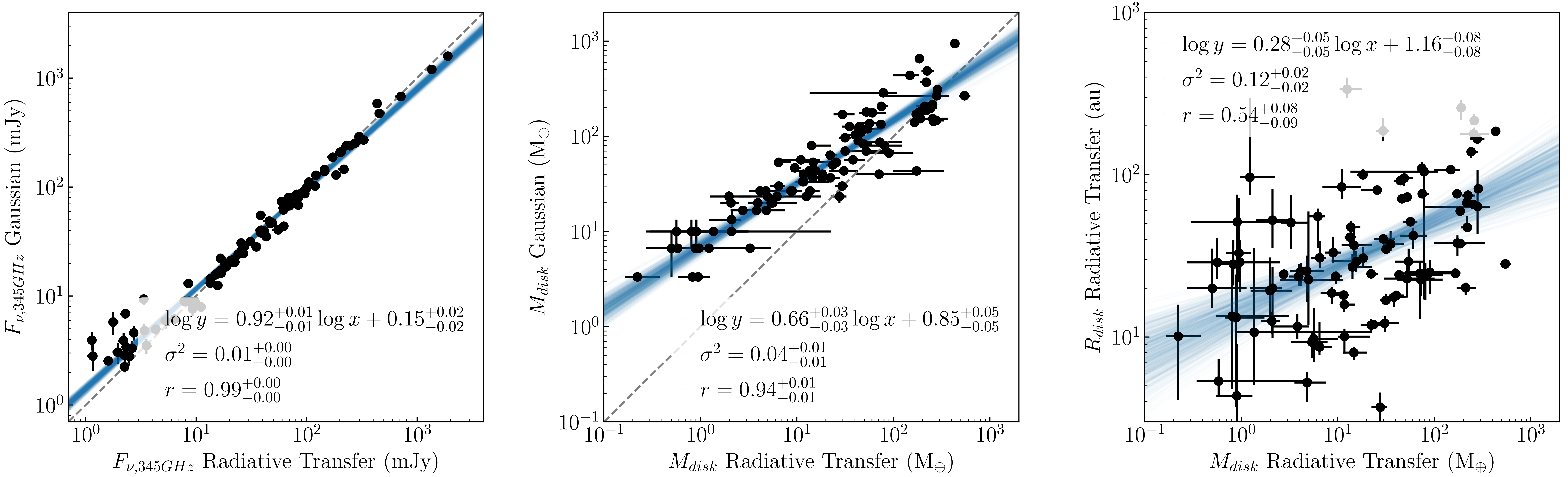
Sheehan et al. in prep.



Tobin, Sheehan et al., 2020

Why the difference in disk masses?

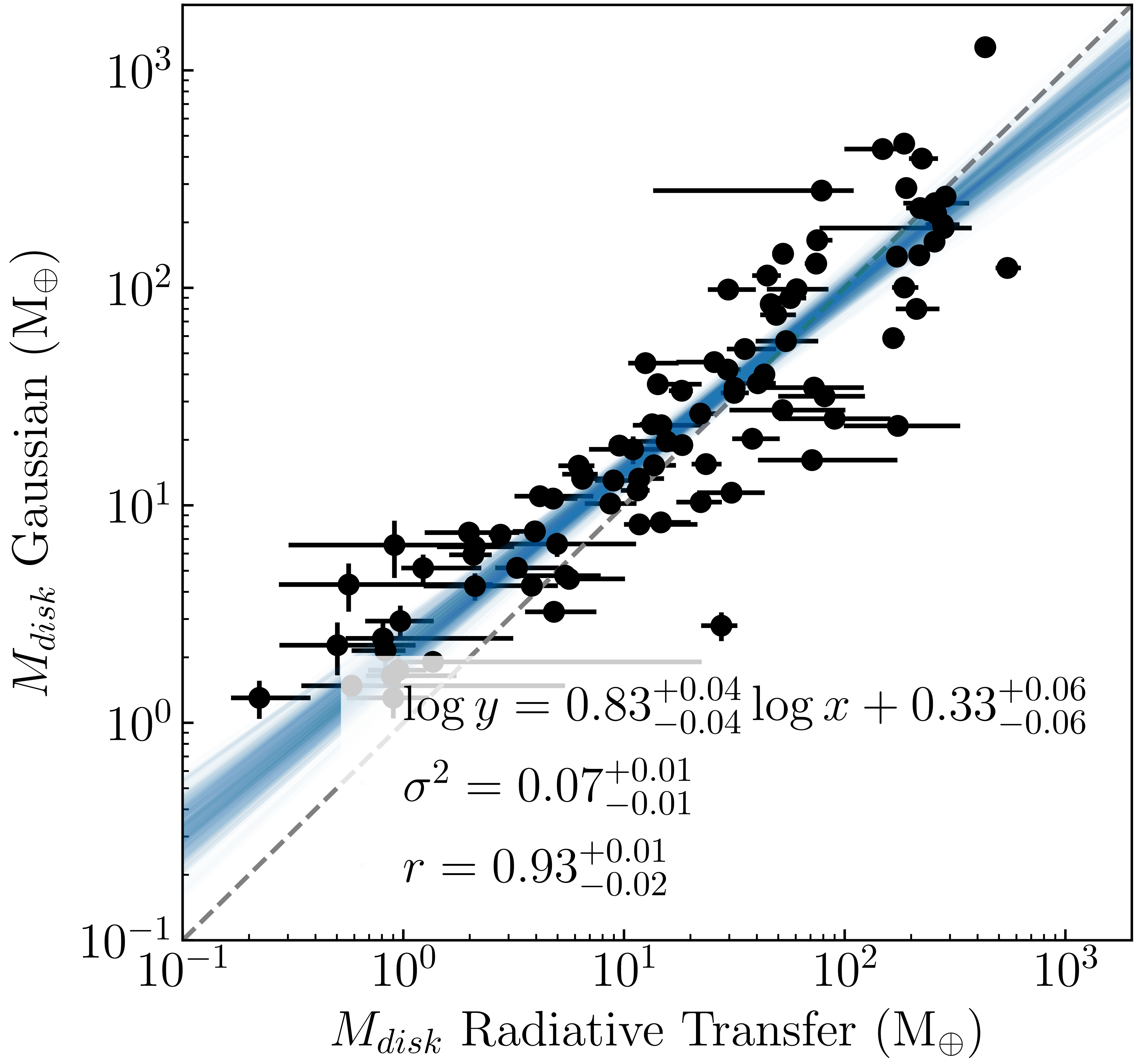
II. Disk Demographics: The Environment of Planet Formation



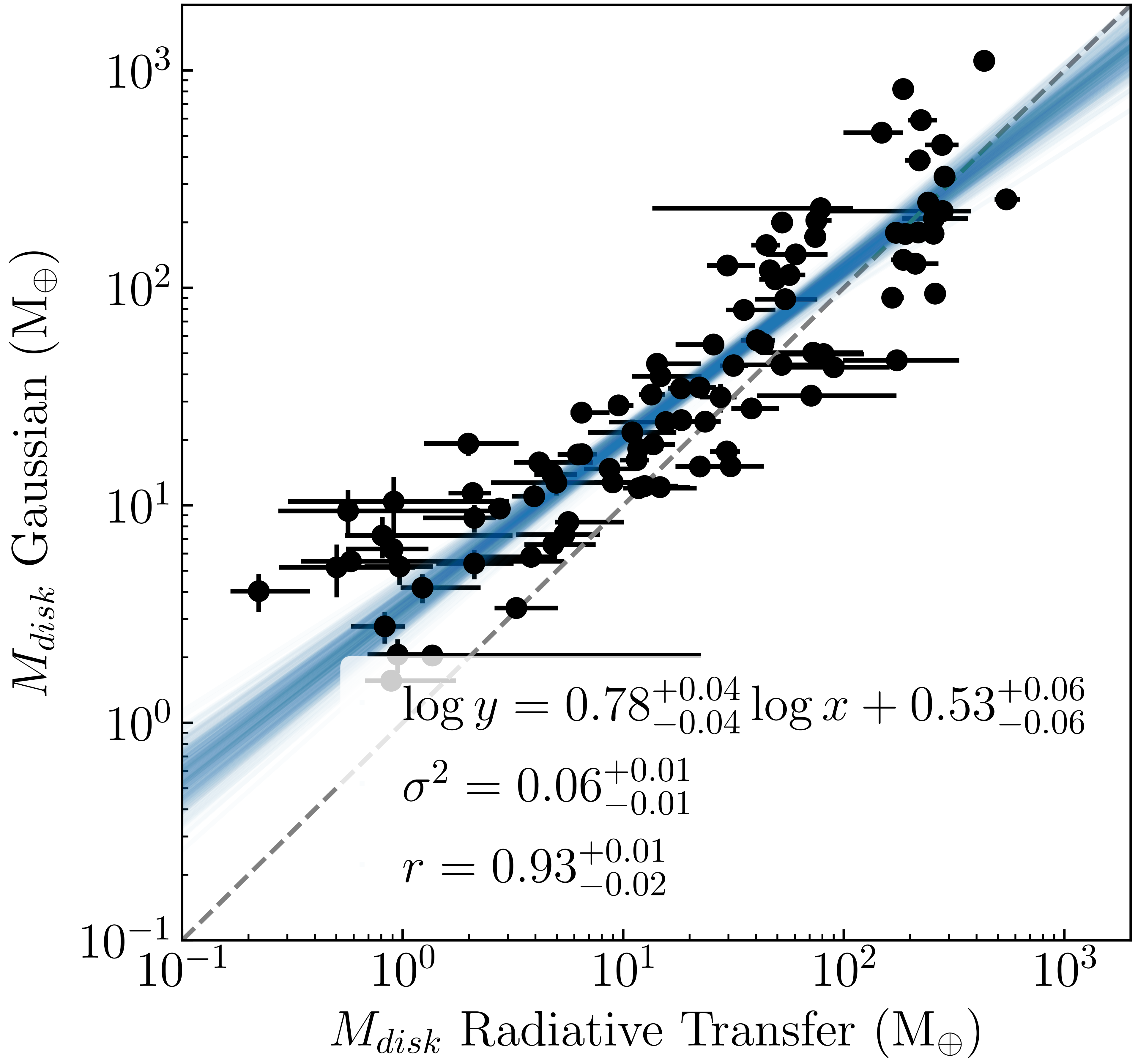
Disk temperature is proportional to R_{disk}

Why the difference in disk masses?

II. Disk Demographics: The Environment of Planet Formation



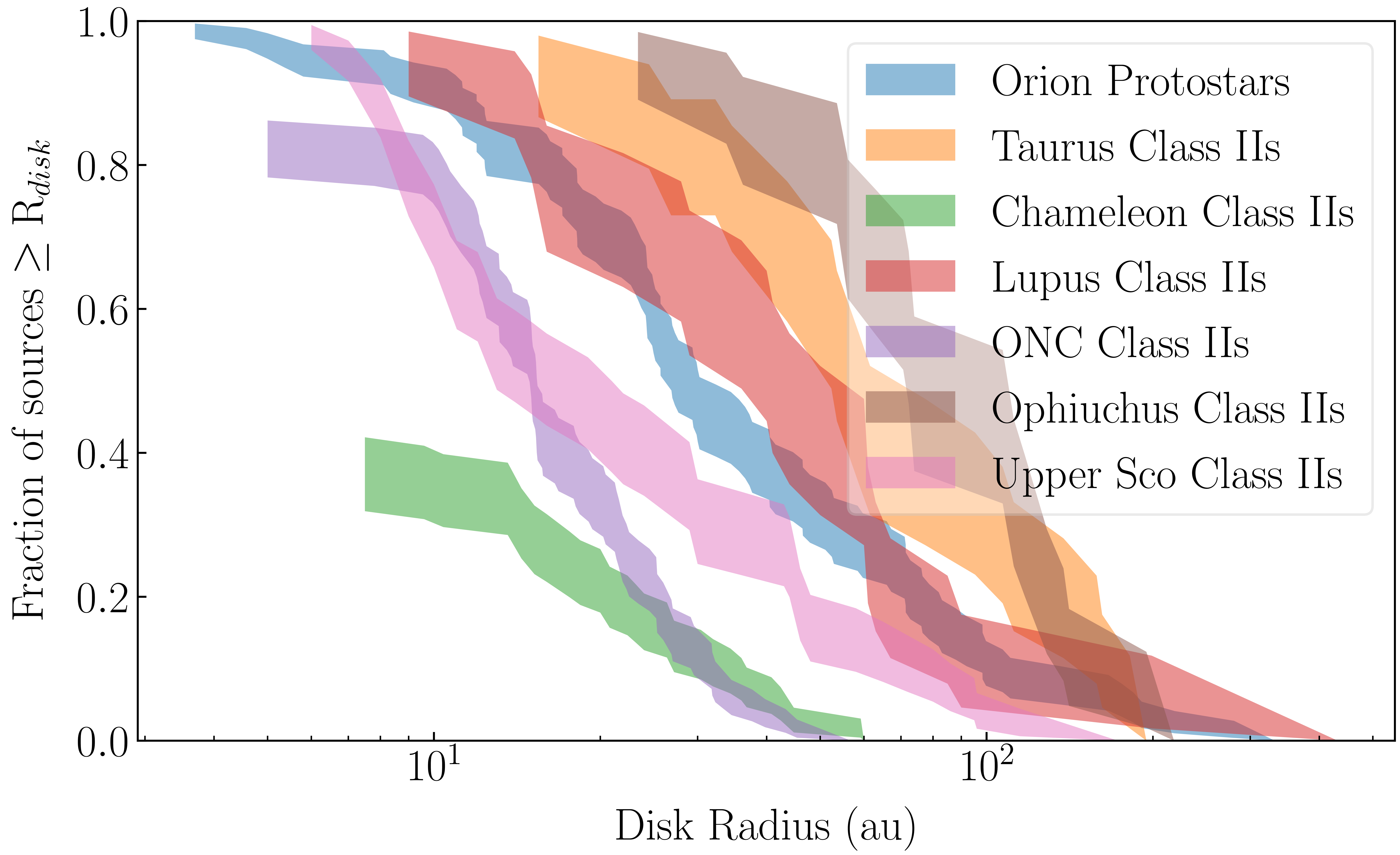
Corrected using radiative transfer R_{disk}



Corrected using Gaussian R_{disk}

How large are protostellar disks?

II. Disk Demographics: The Environment of Planet Formation



Warning!

Not all disk radii measured in the same way.

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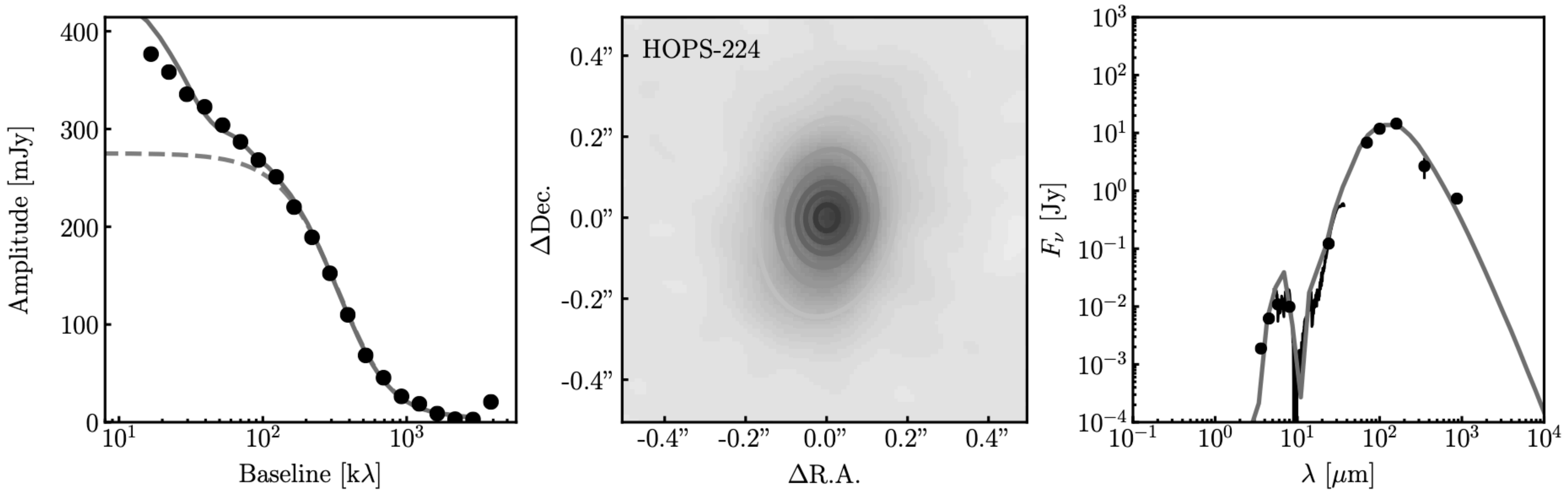

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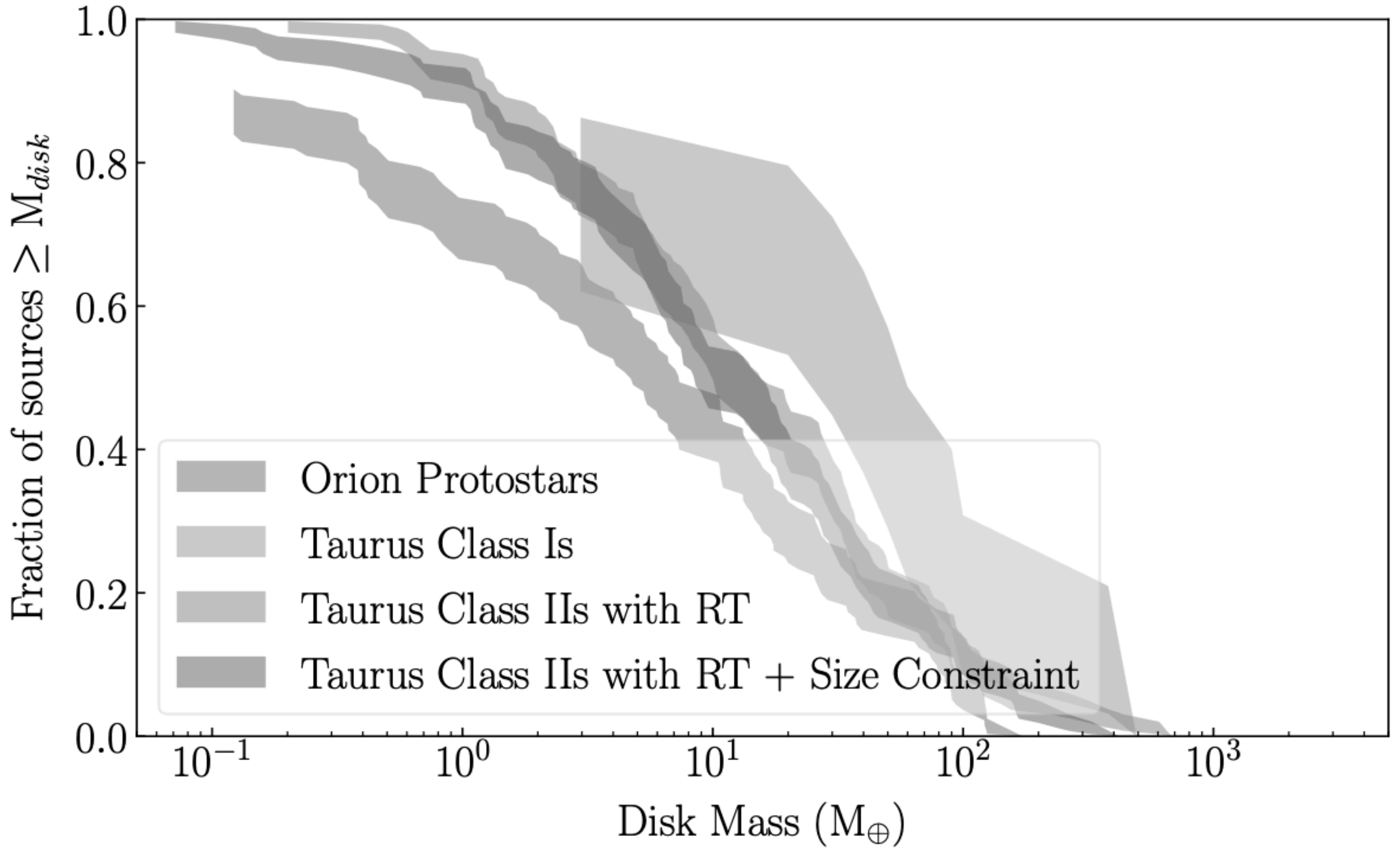
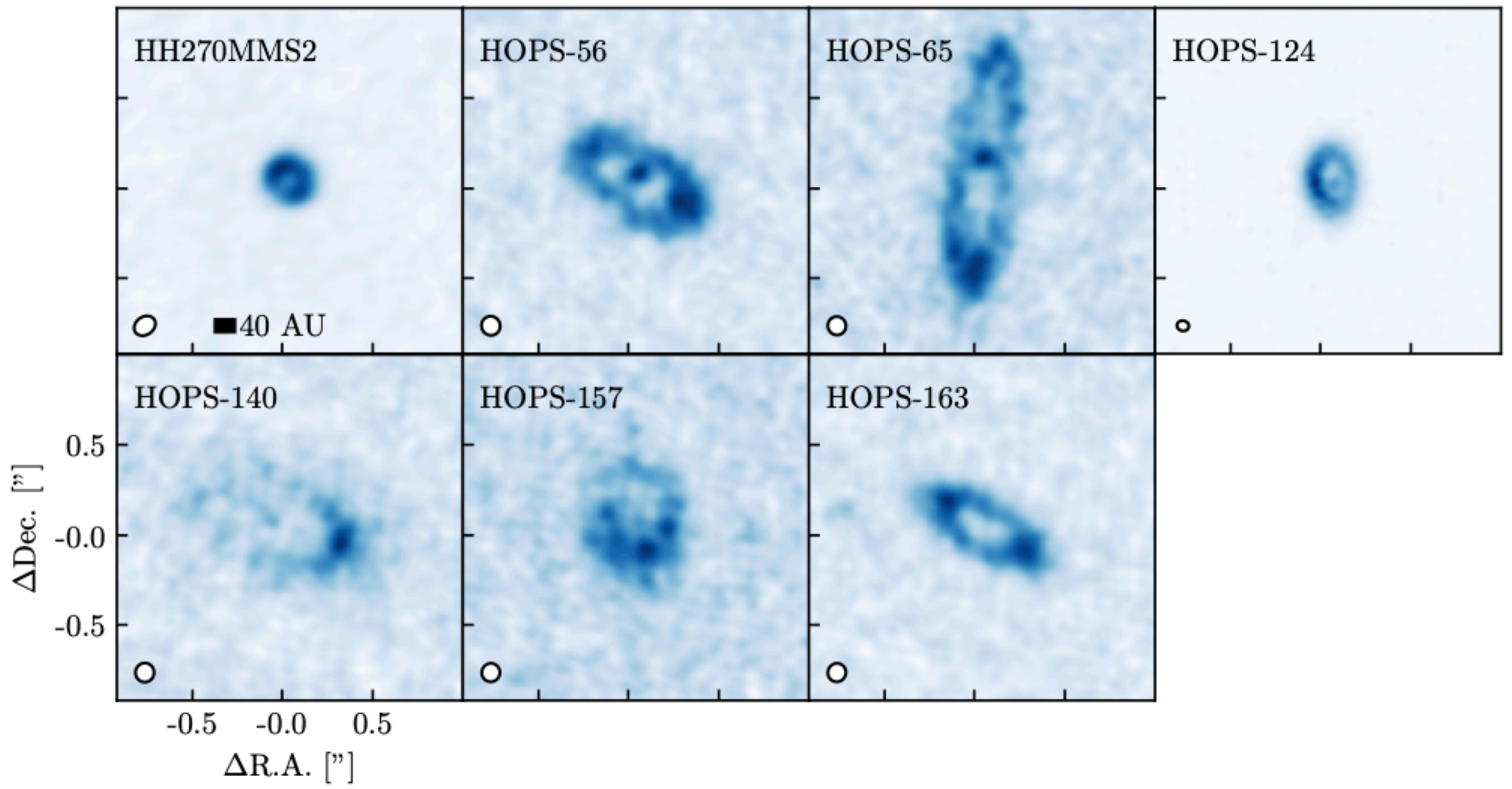


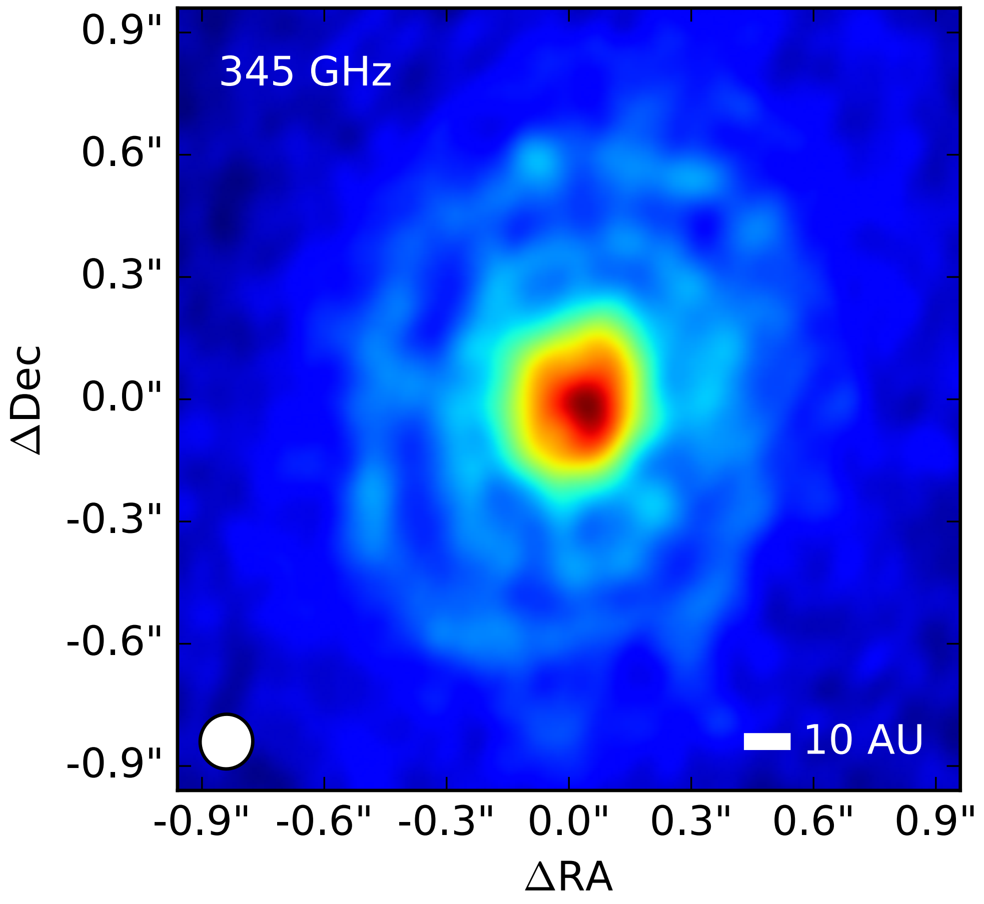
III. Substructures: Witnessing Planet Formation in Embedded Disks?



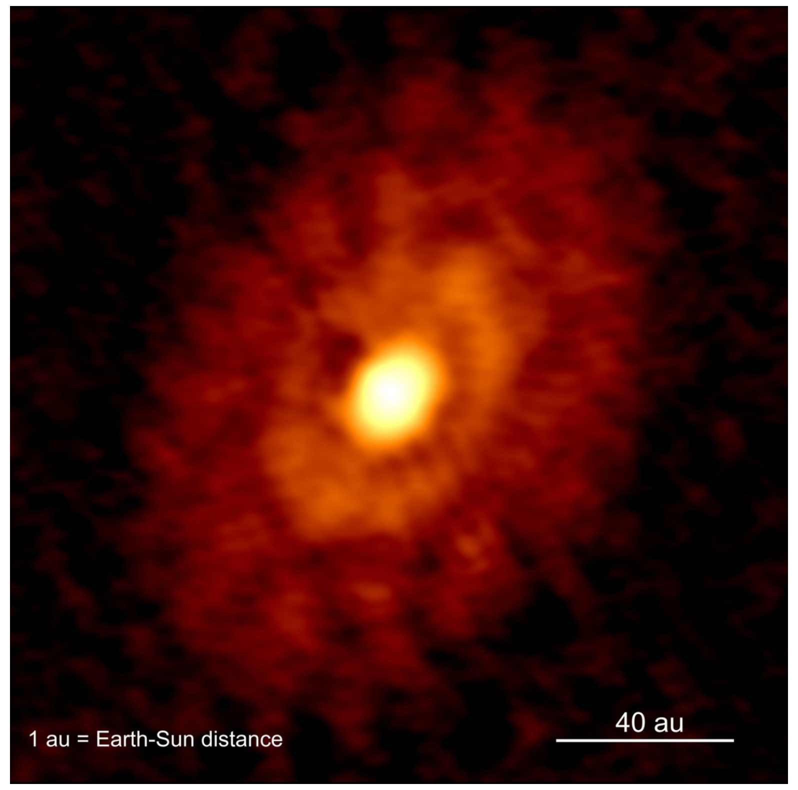
A Diversity of Substructures

III. Substructures: Witnessing Planet Formation in Embedded Disks?

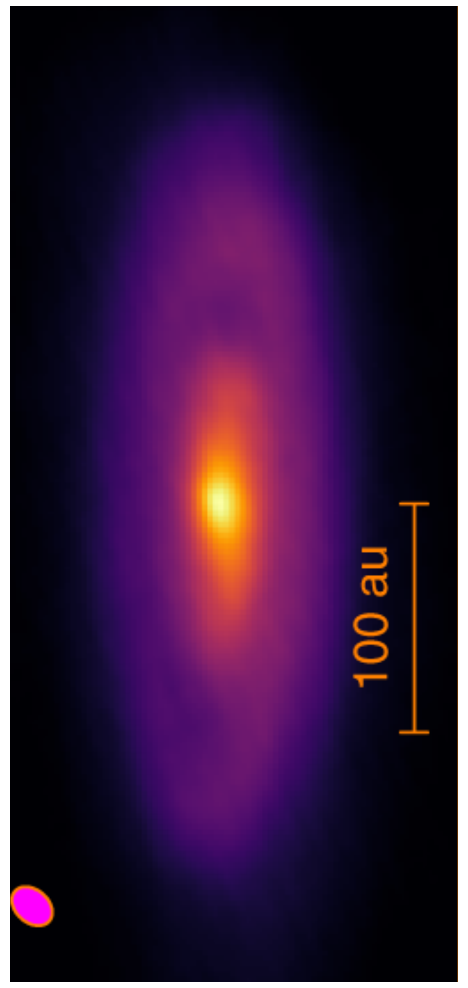
Sheehan & Eisner 2018



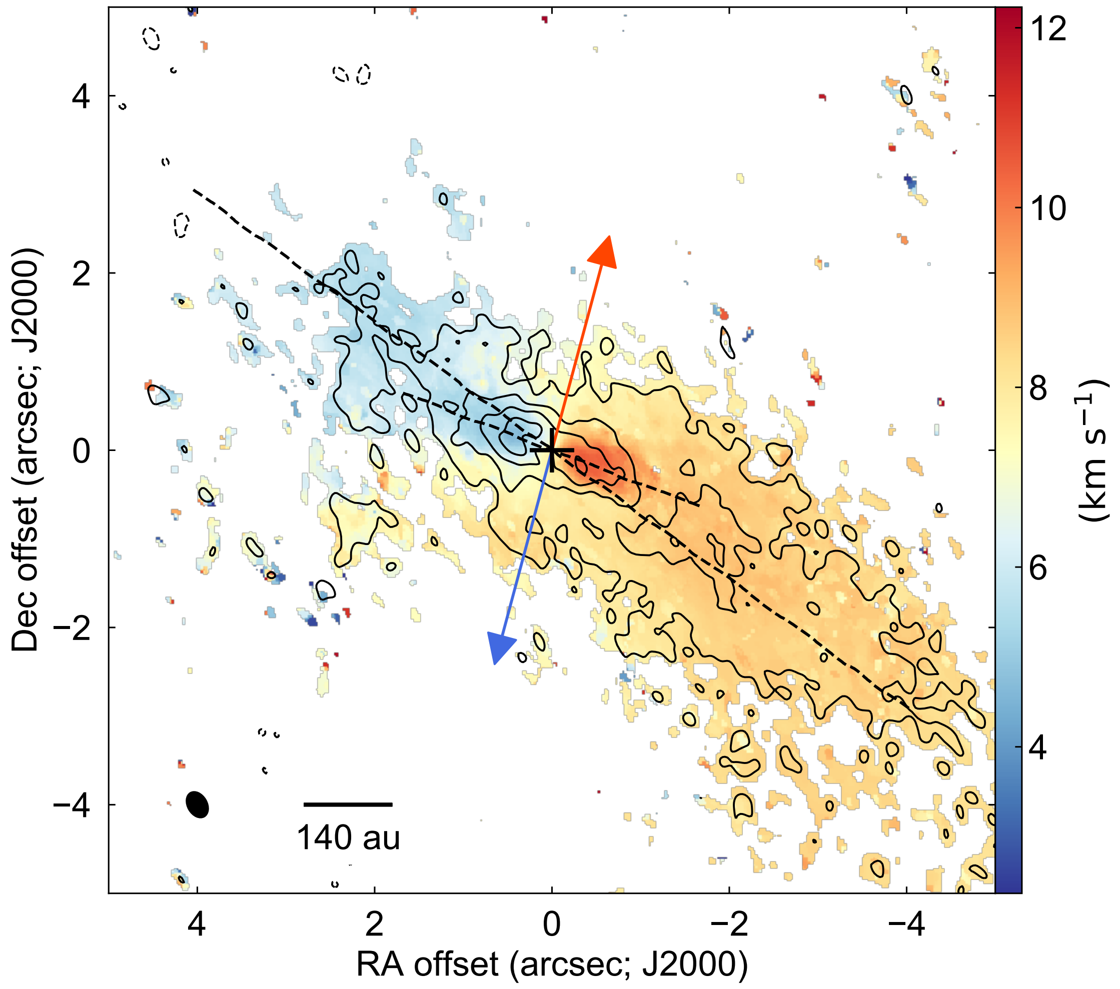
Segura-Cox et al. 2020



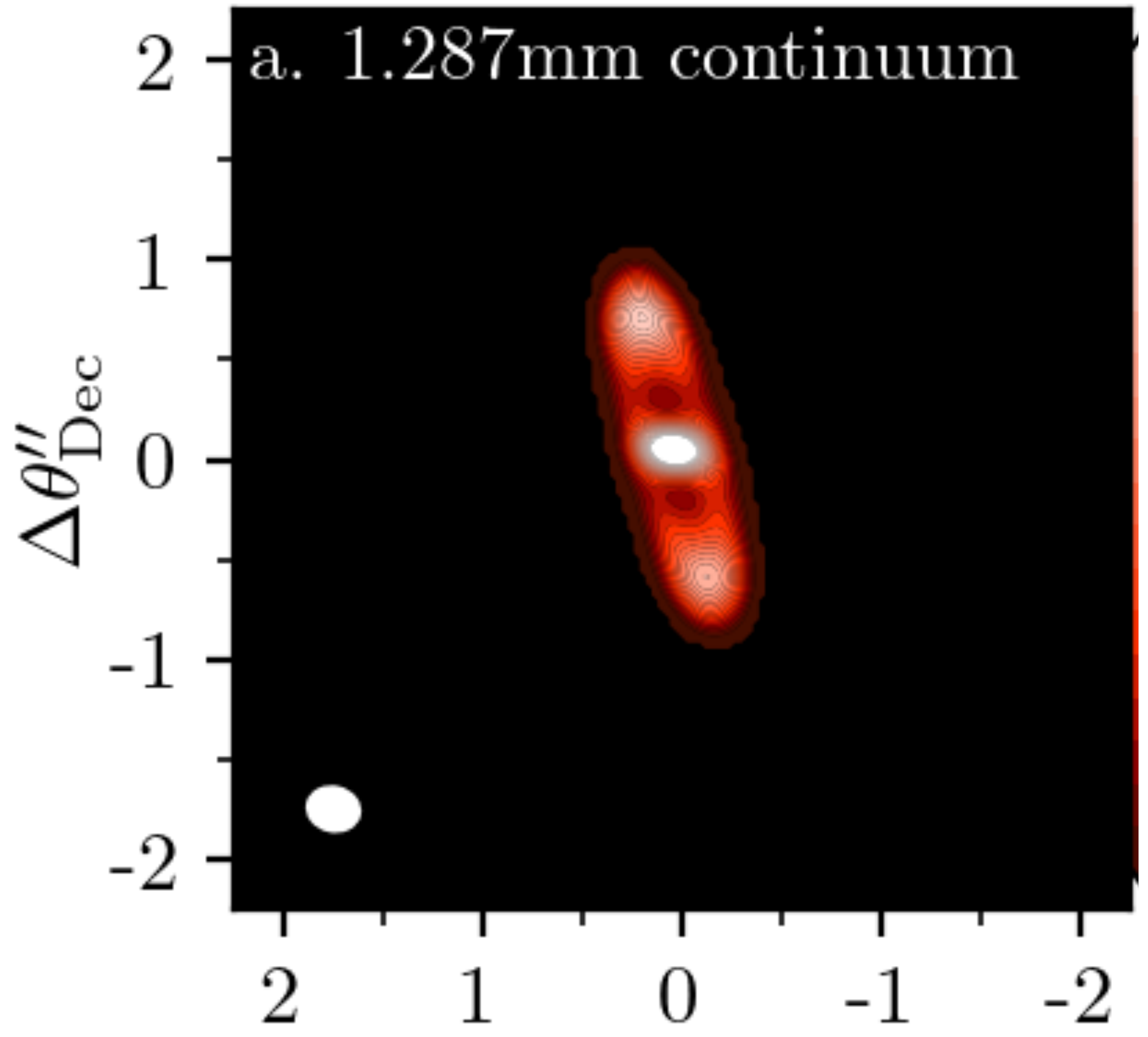
Lee et al. 2019



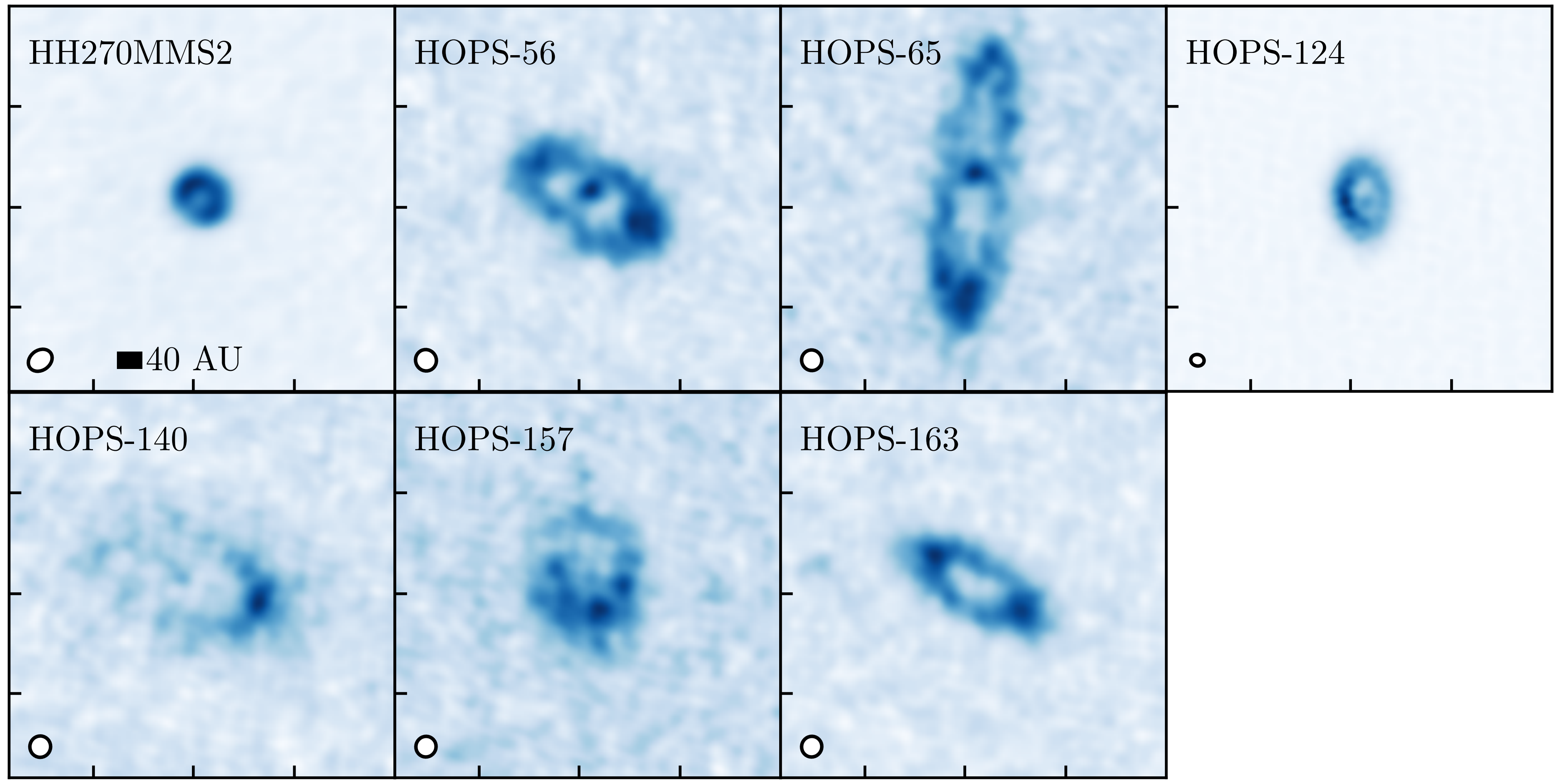
Sai et al. 2020



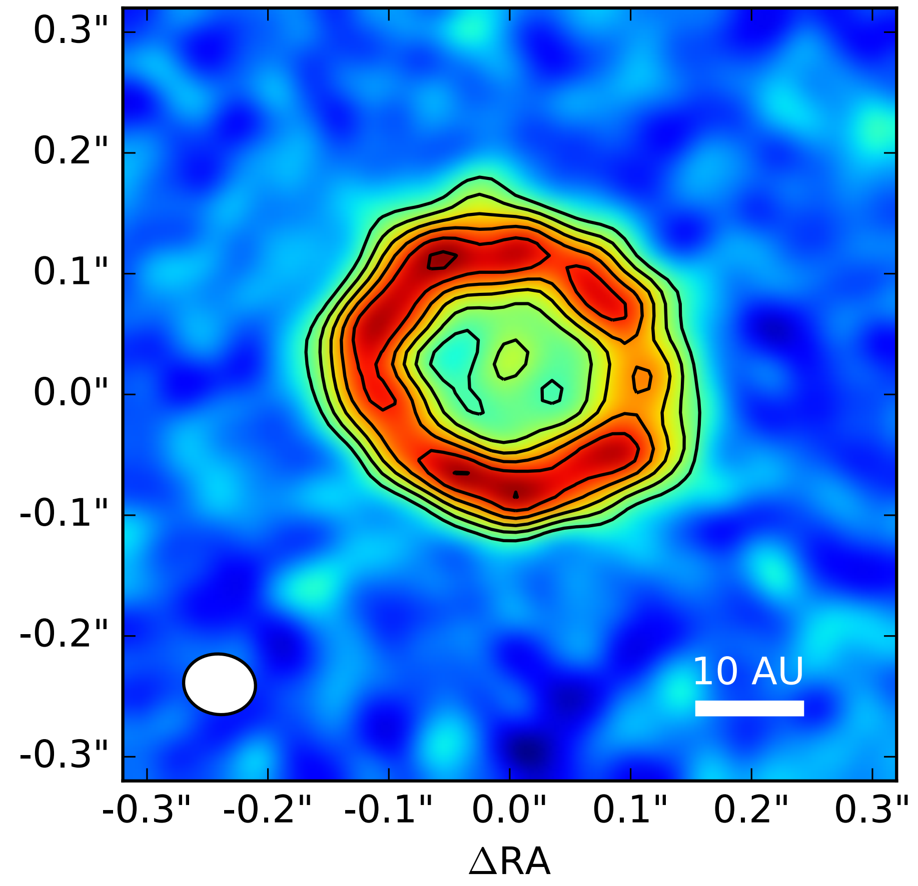
Alves et al. 2020



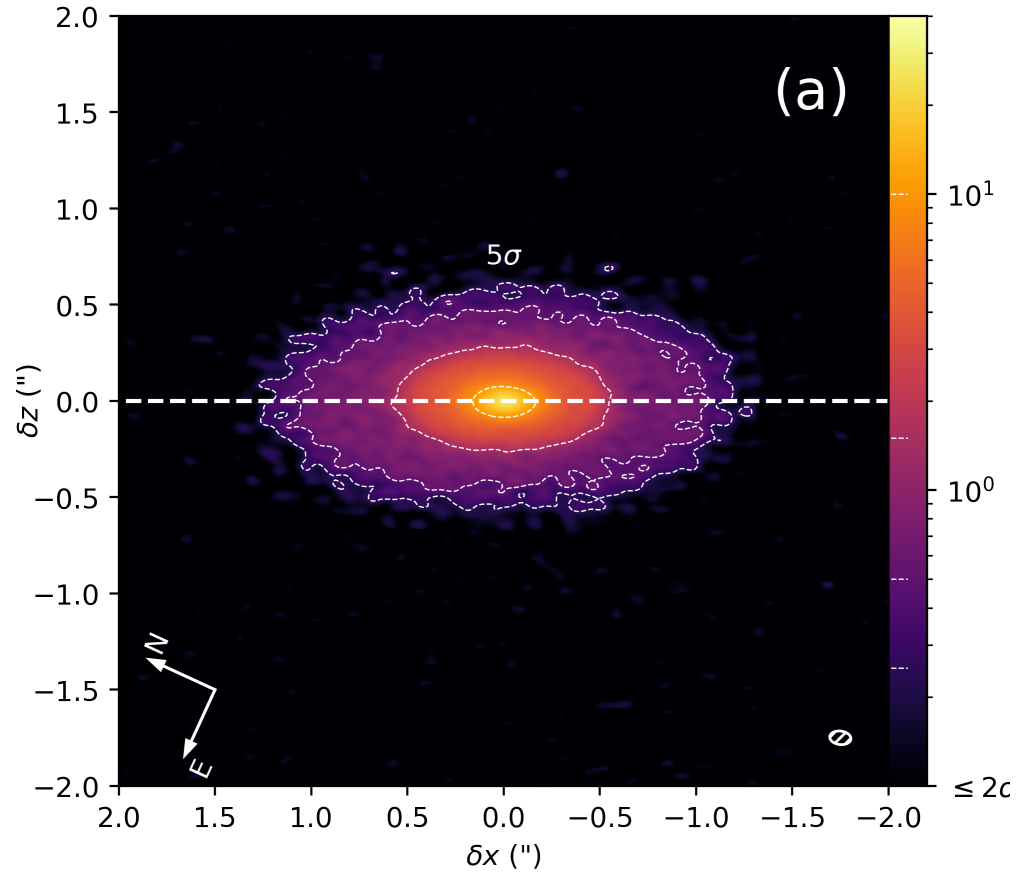
Sheehan, et al. 2020



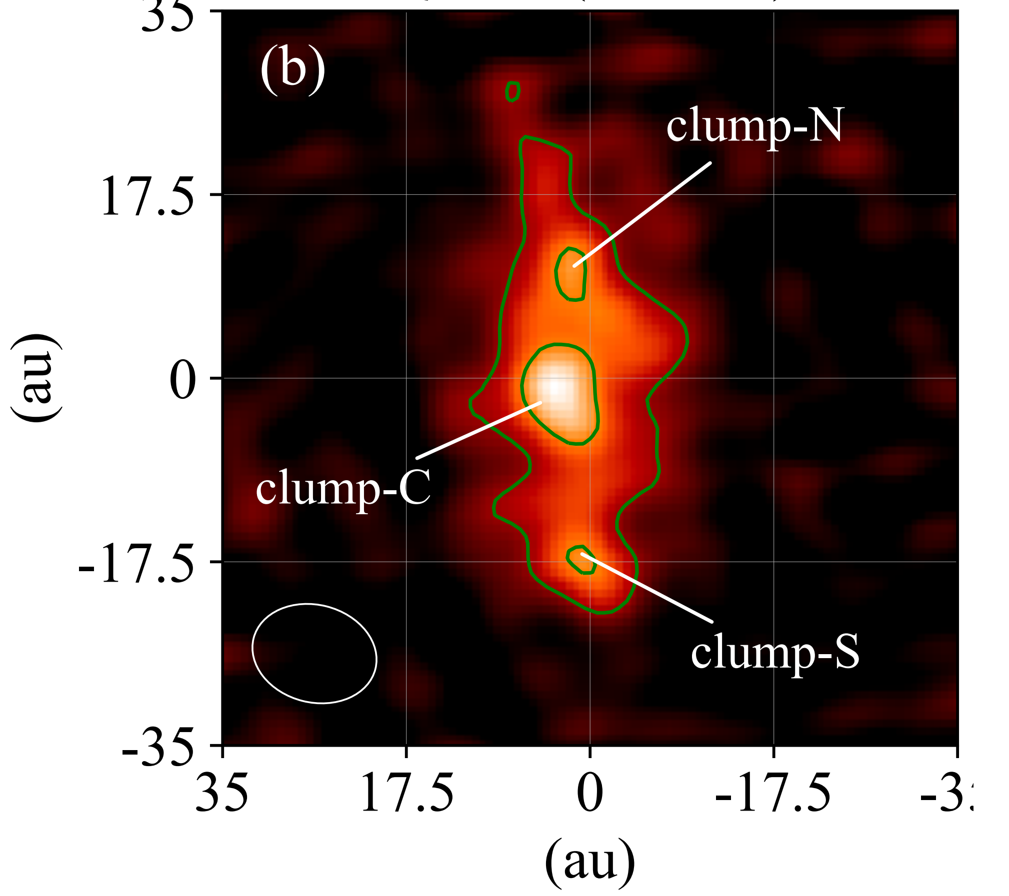
Sheehan & Eisner 2017a



de Valon et al. 2020

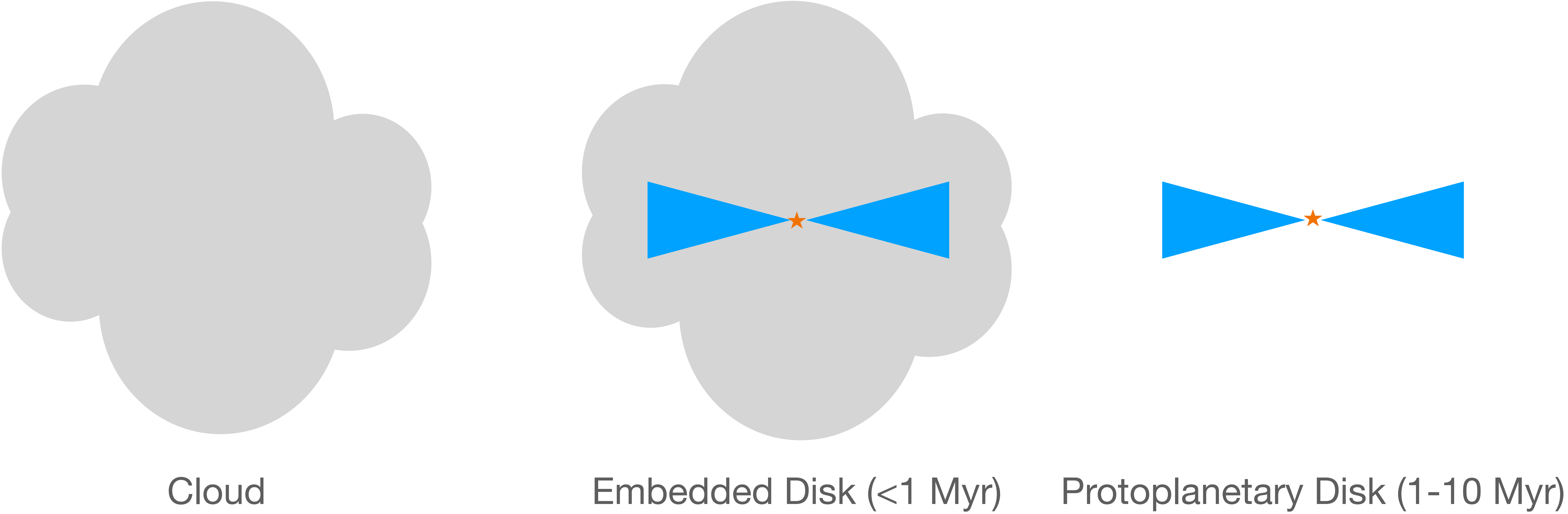


Nakatani et al. 2020



When Do Substructures Form?

III. Substructures: Witnessing Planet Formation in Embedded Disks?



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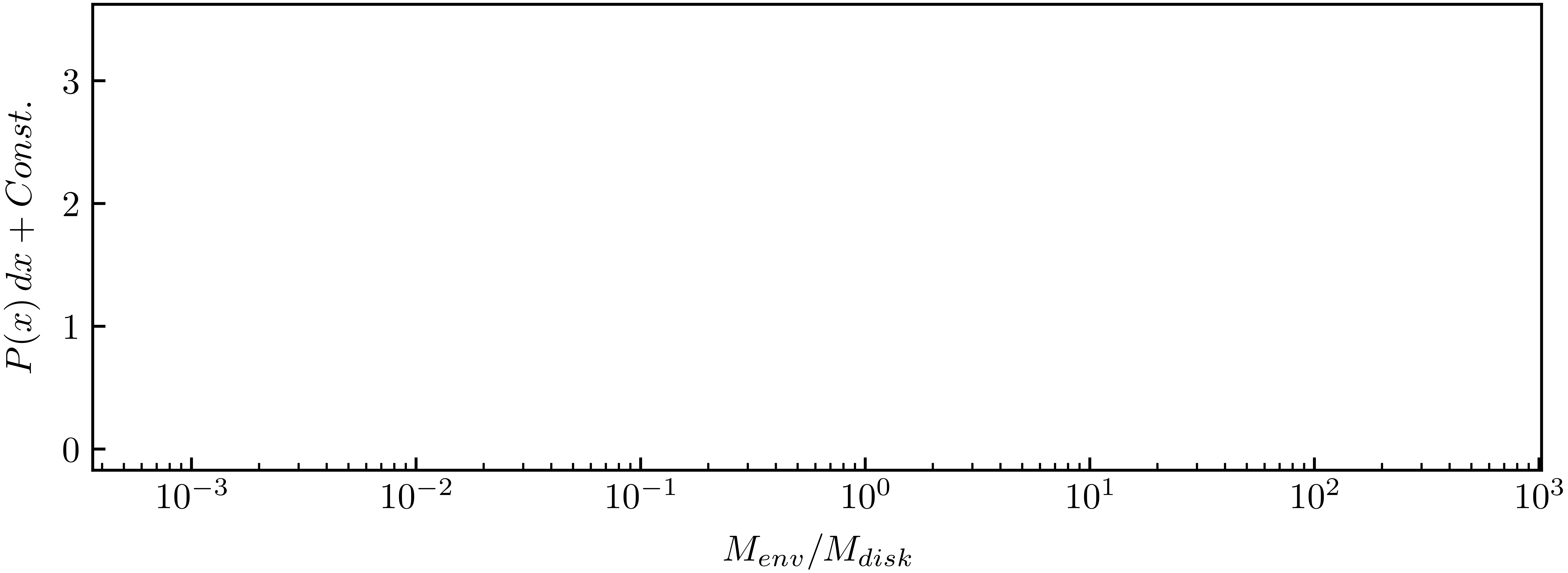
Sheehan et al. 2020



Older ⟷ **Younger**

When Do Substructures Form?

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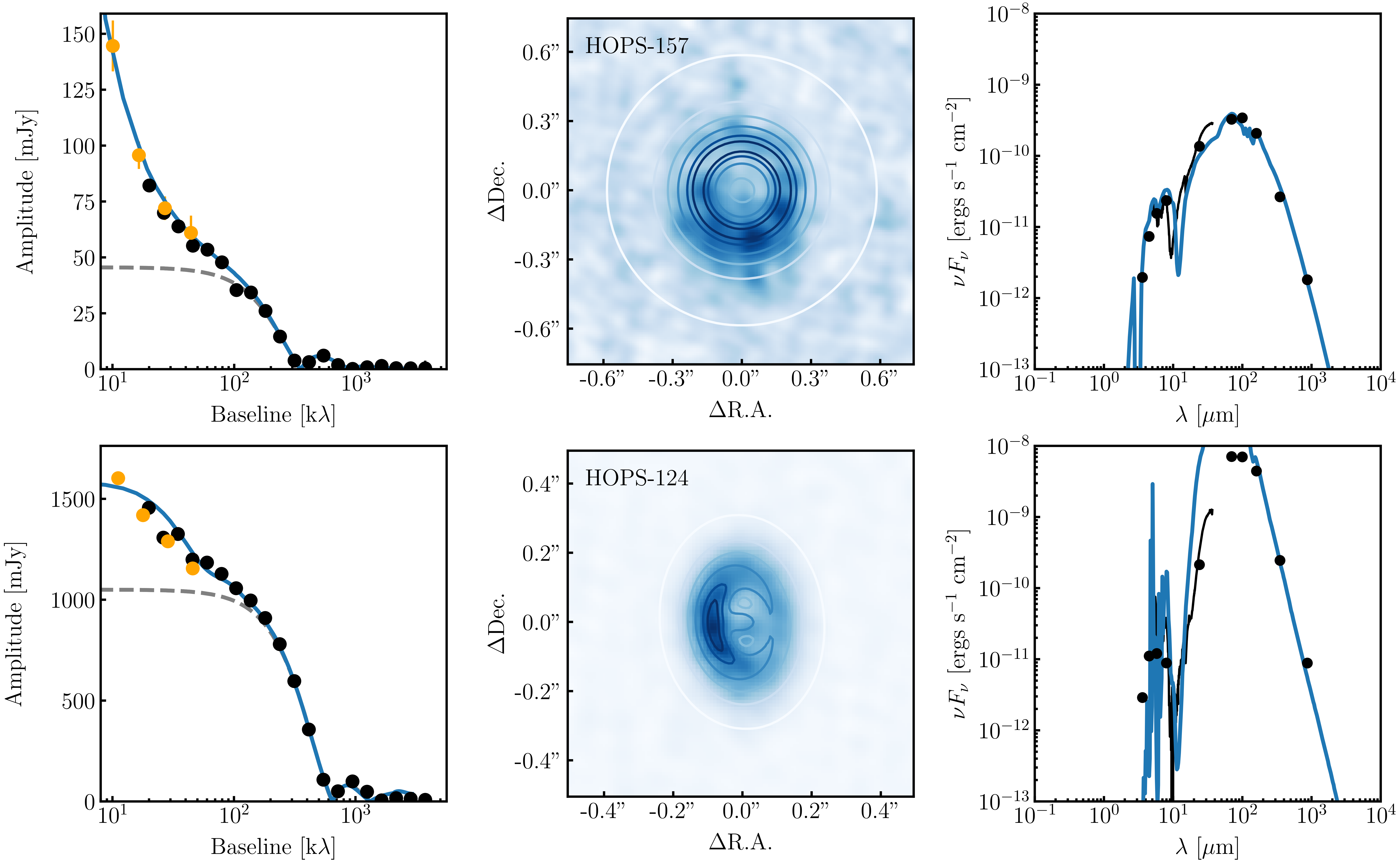

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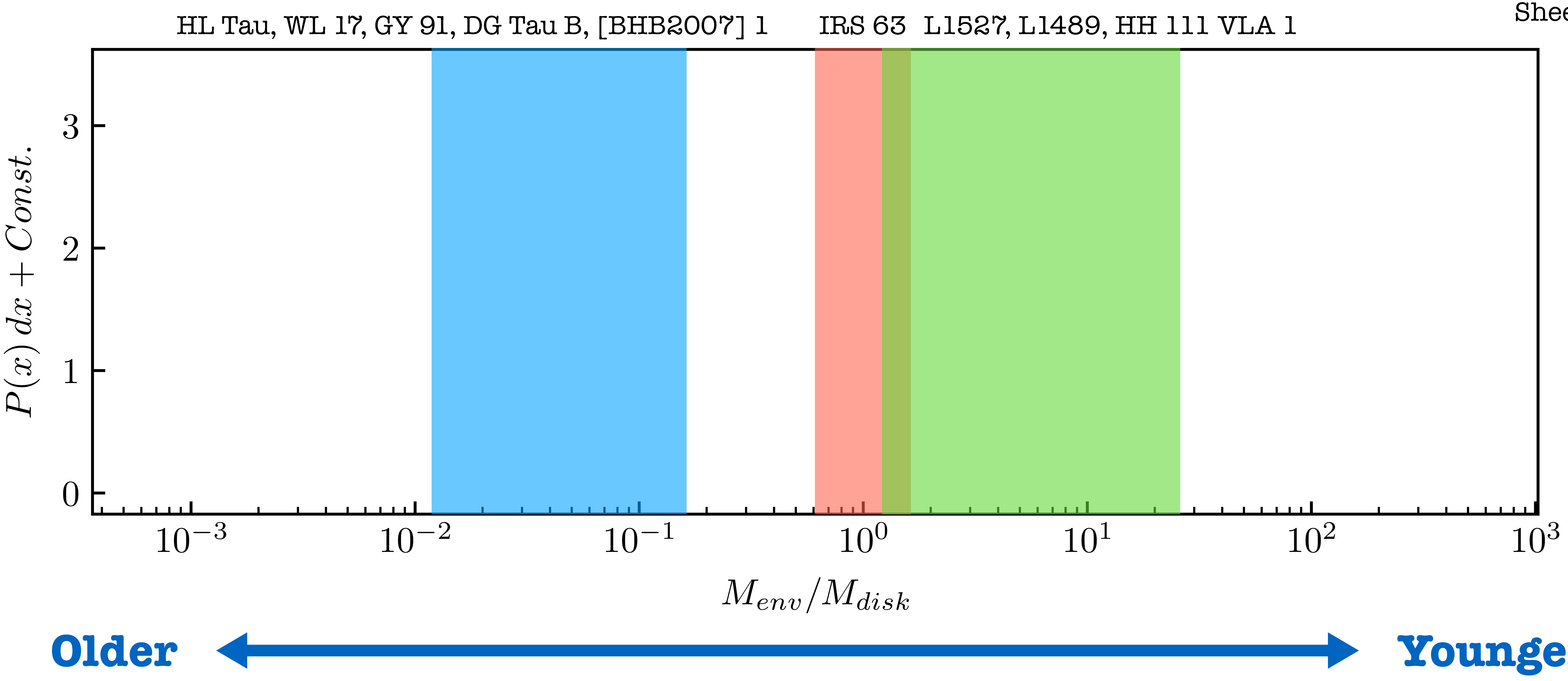

Large Cavities = Young Binaries?

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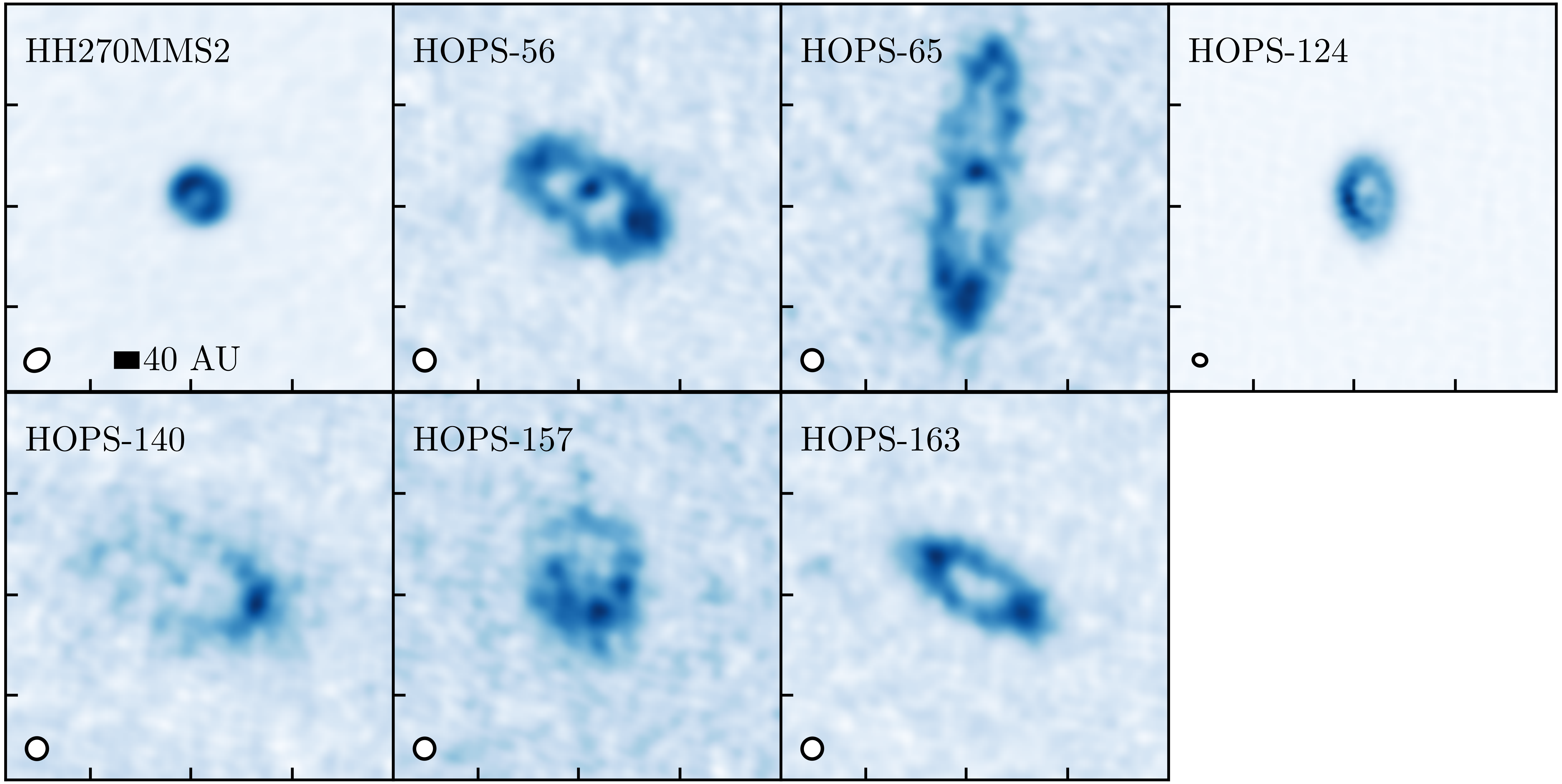
Sheehan, et al. 2020



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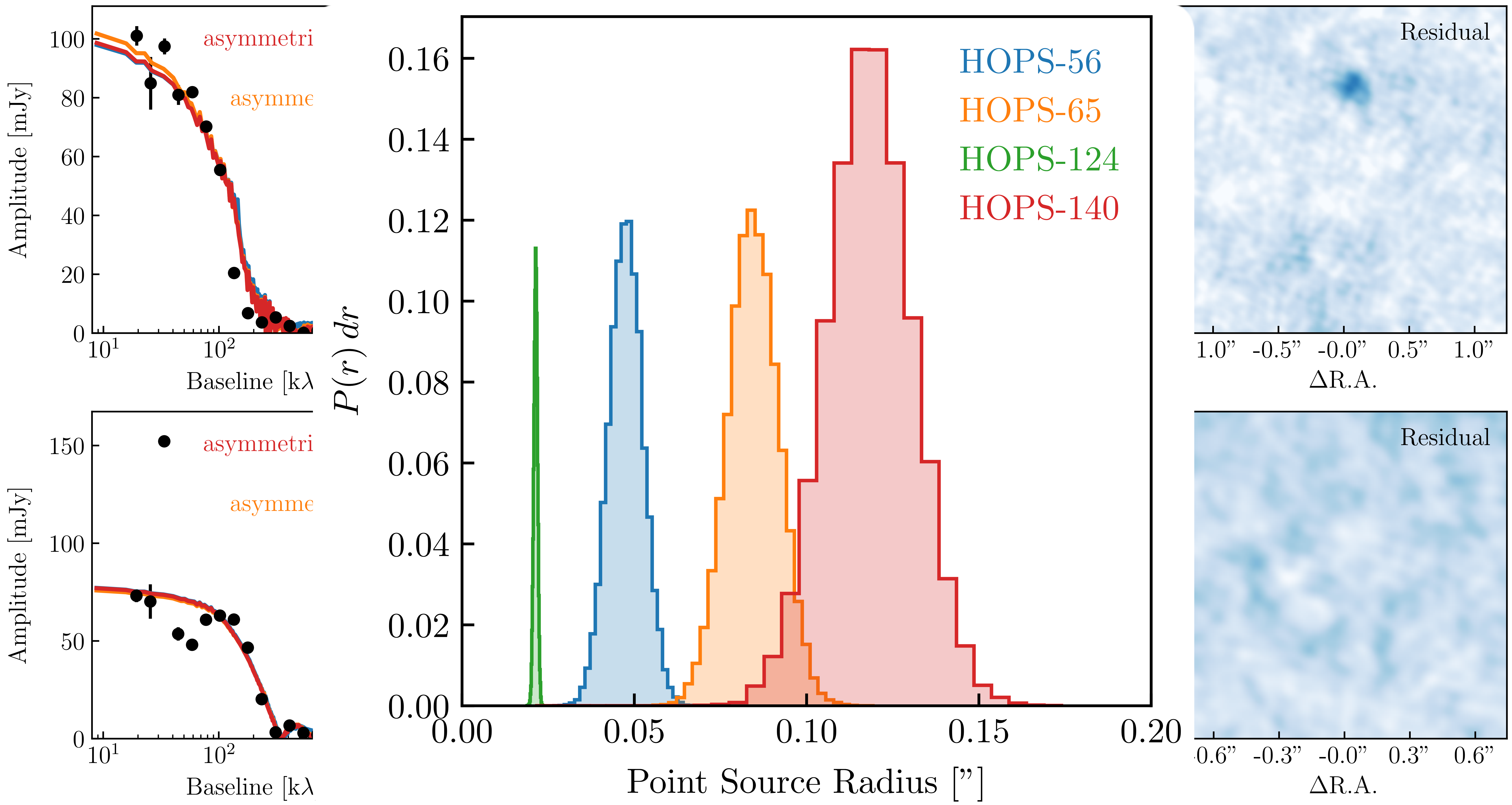

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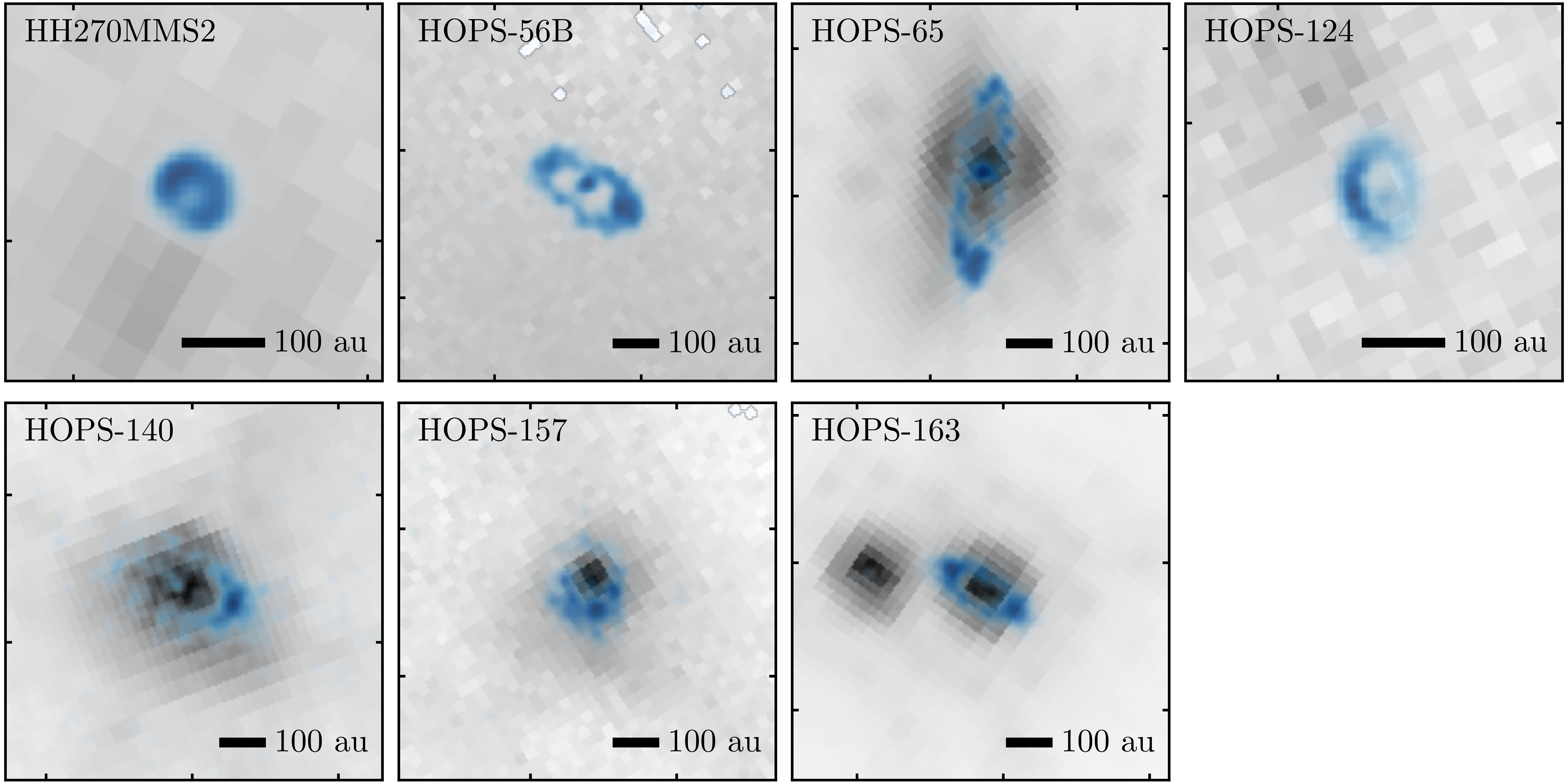
Sheehan et al. 2020



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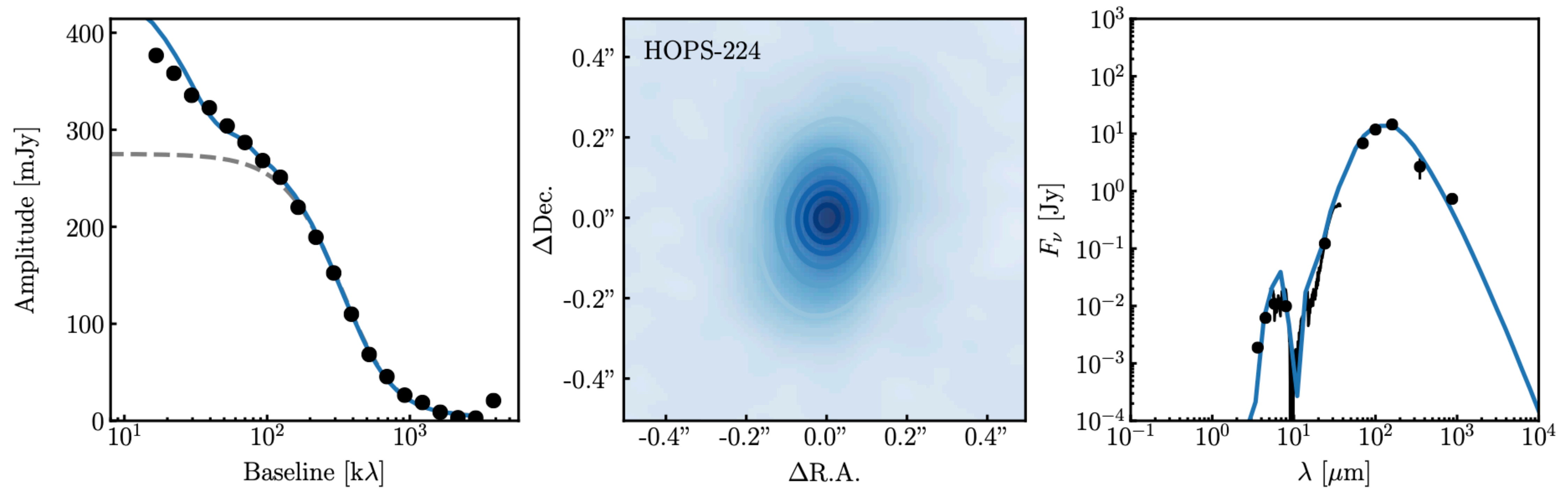

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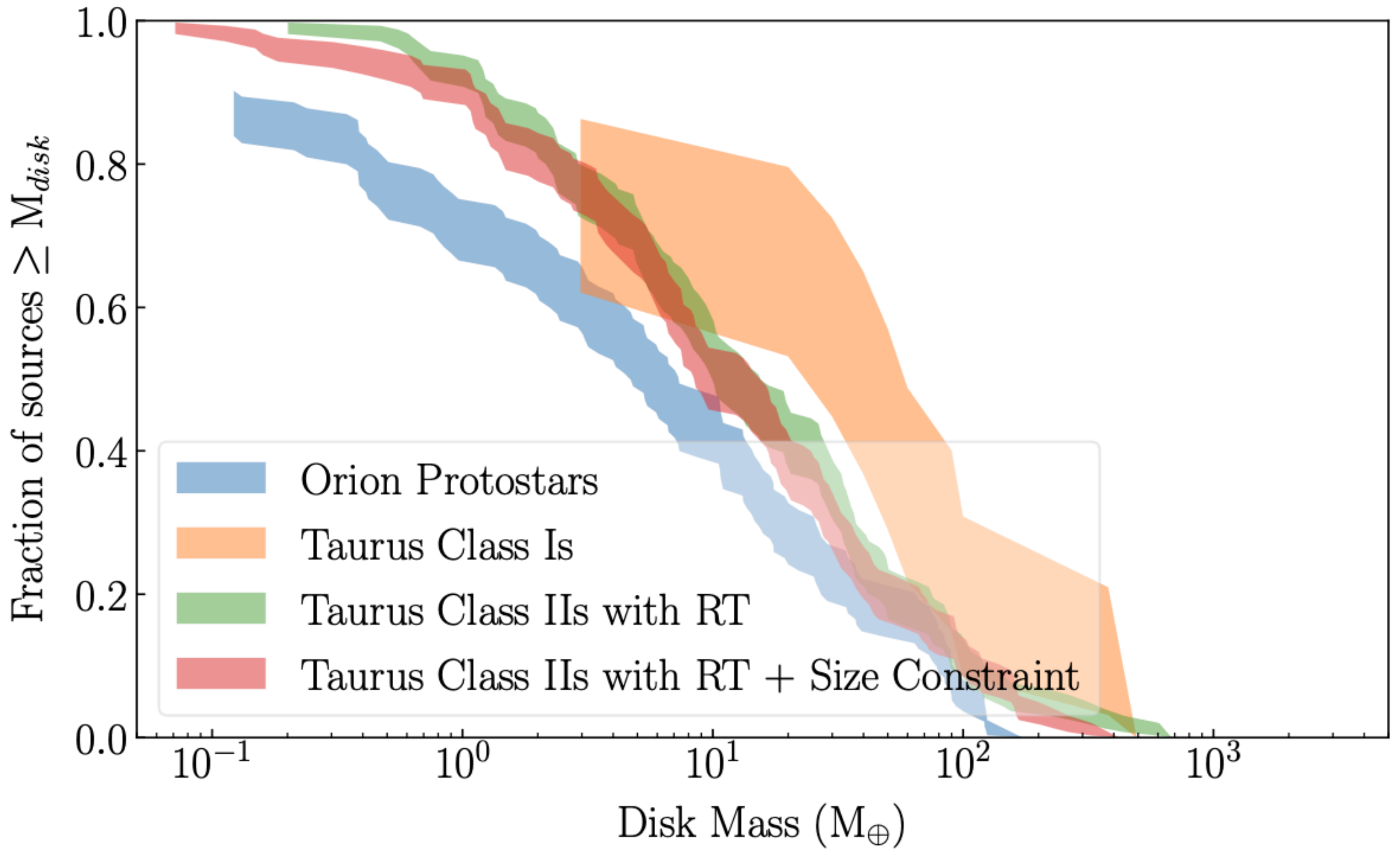

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