

# Protoplanetary Disks at High Angular Resolution

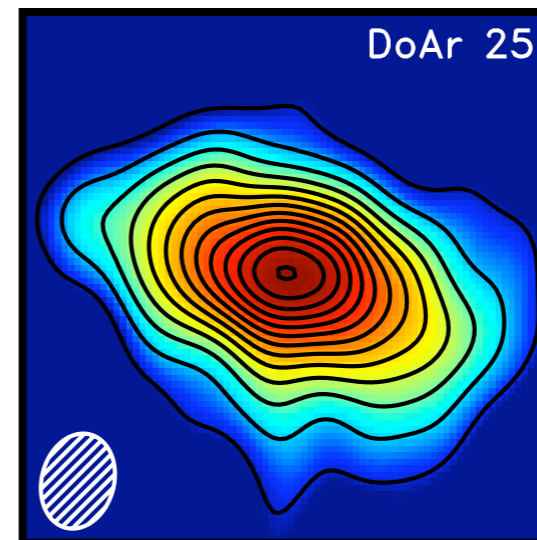
*results from the SMA at 870 microns*

Sean Andrews

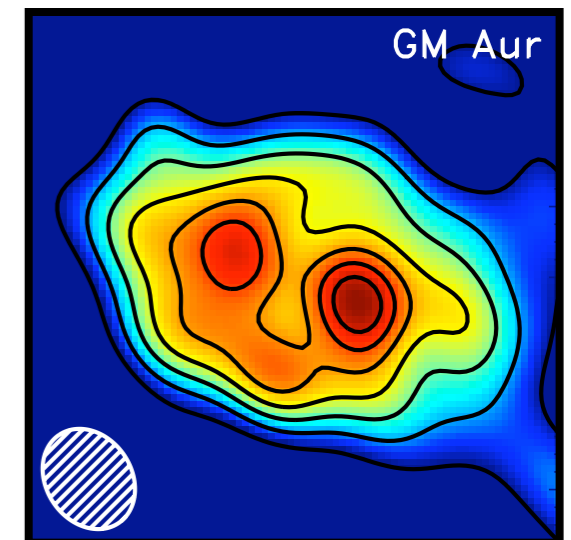
Hubble Fellow, Harvard/SAO



*courtesy of N. Patel*



Andrews et al. 2008



Hughes et al. 2009

*in collaboration with:*

- David Wilner (Harvard/SAO)
- Meredith Hughes (Harvard/SAO)
- Kees Dullemond (MPIA Heidelberg)
- Charlie Qi (Harvard/SAO)
- Catherine Espaillat (Harvard/SAO)

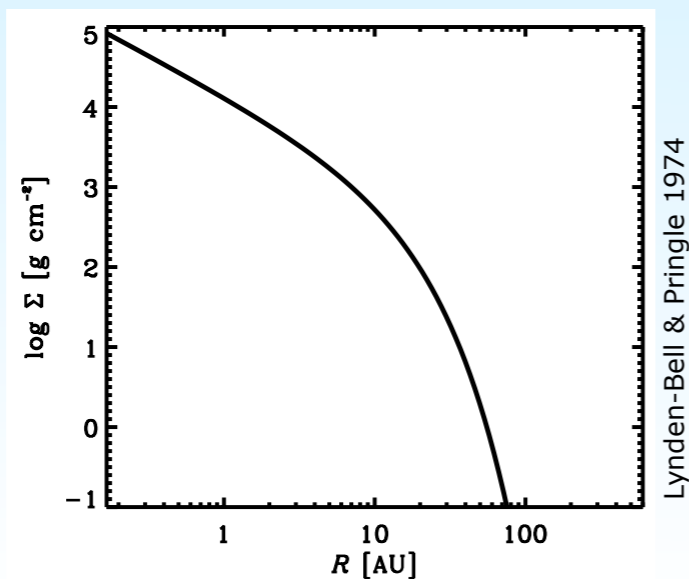
# *evolution of disk material*

## ***viscous evolution***

“friction” + orbital shear

***M*** flows in, ***L*** out

accretion + spreading



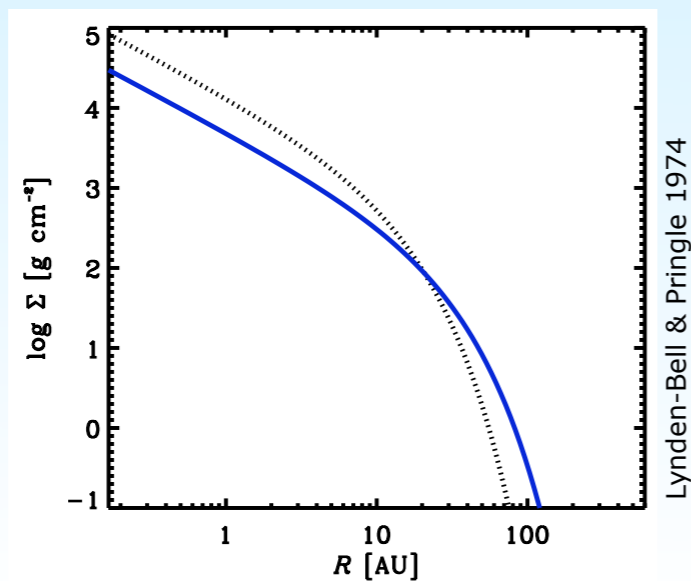
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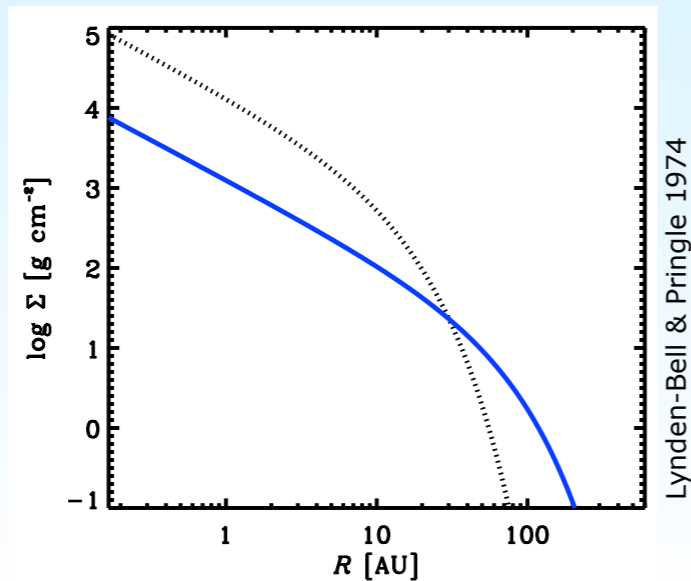
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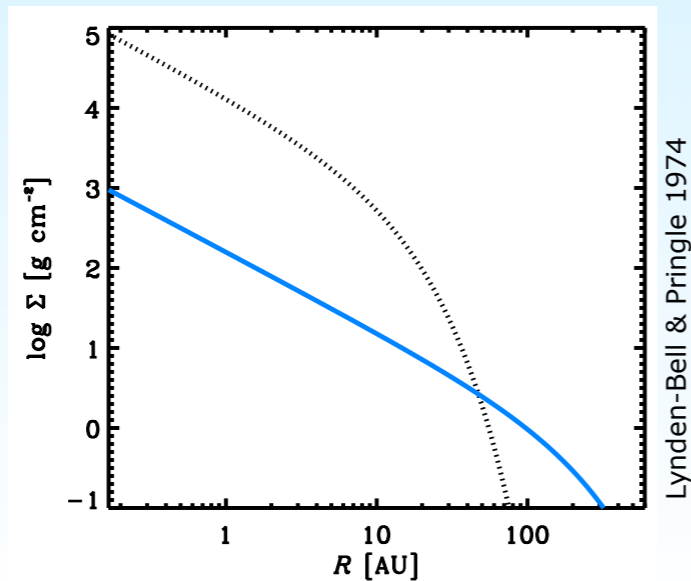
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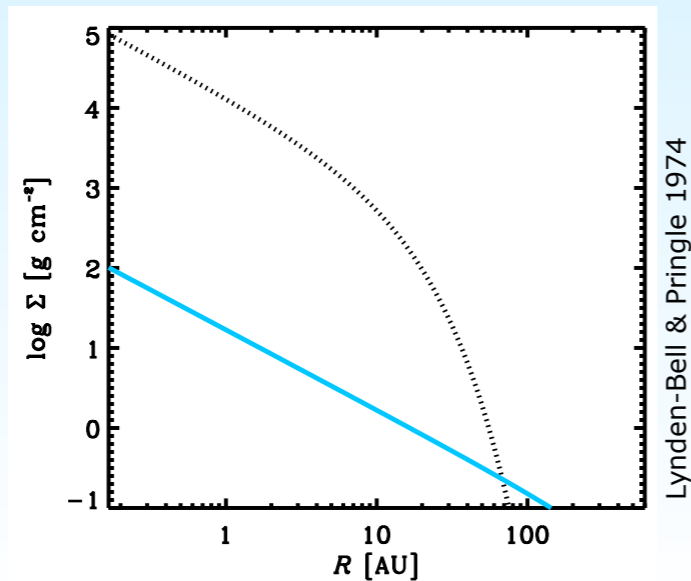
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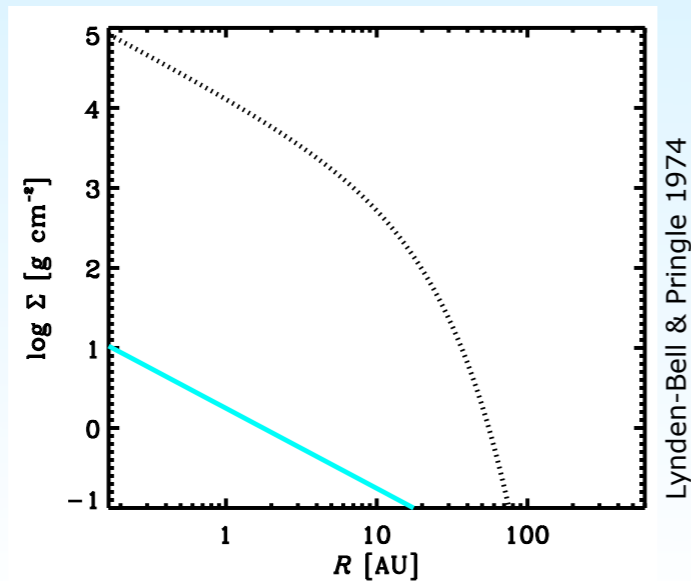
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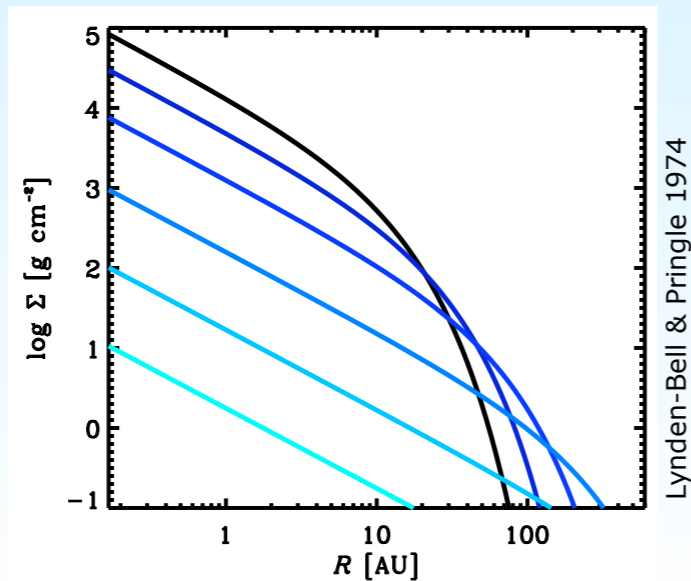
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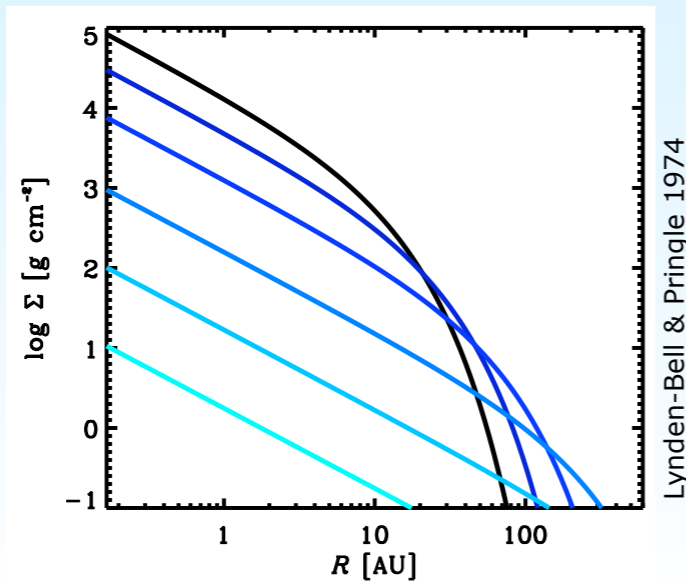
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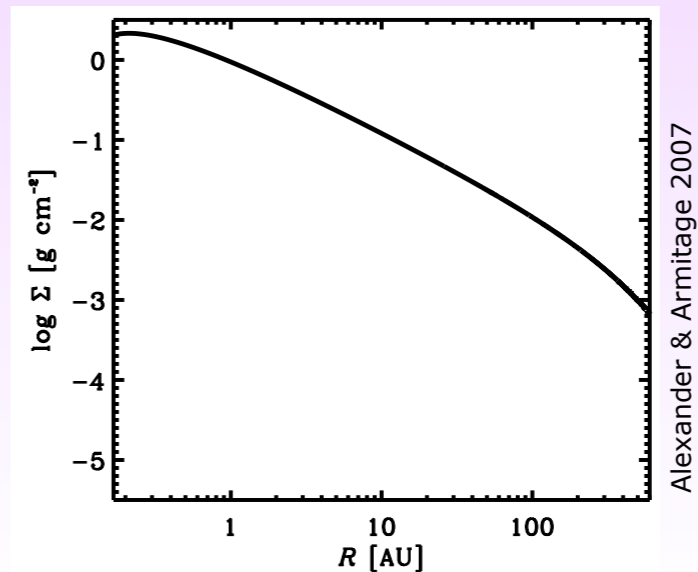


## “clean-up”

photoevaporative wind

or tidal interactions

low-density gap/cavity



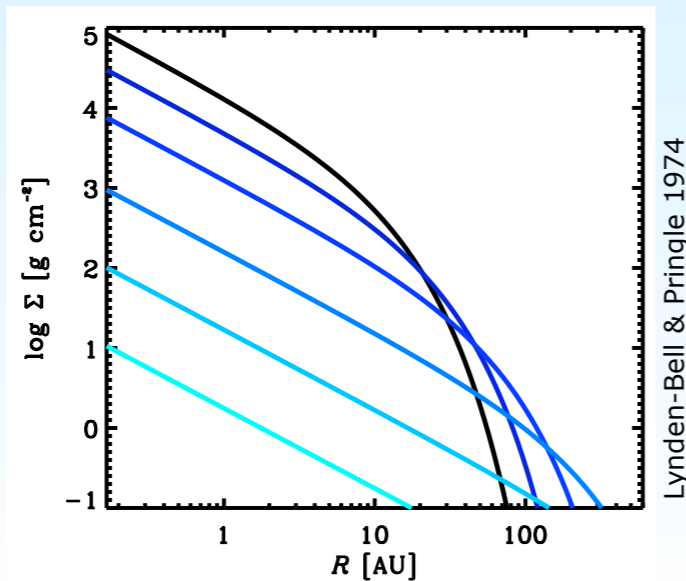
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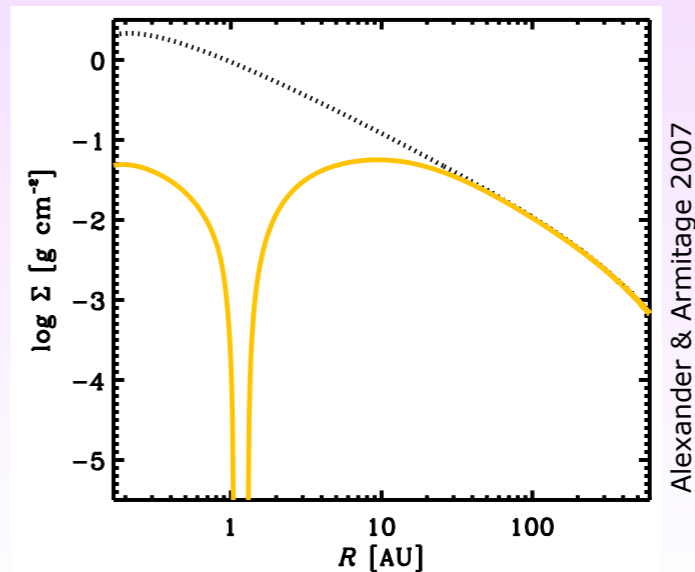


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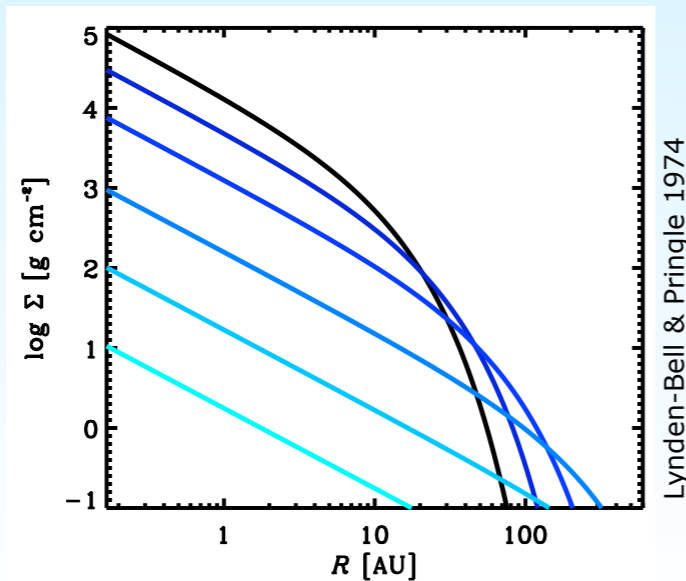
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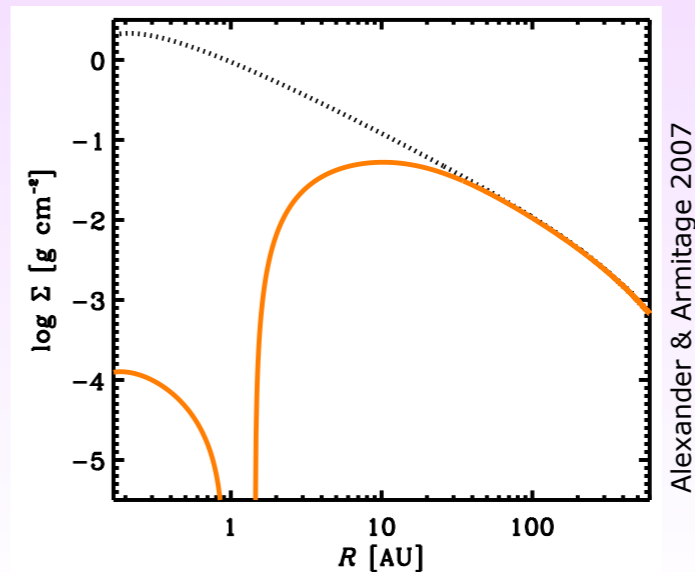


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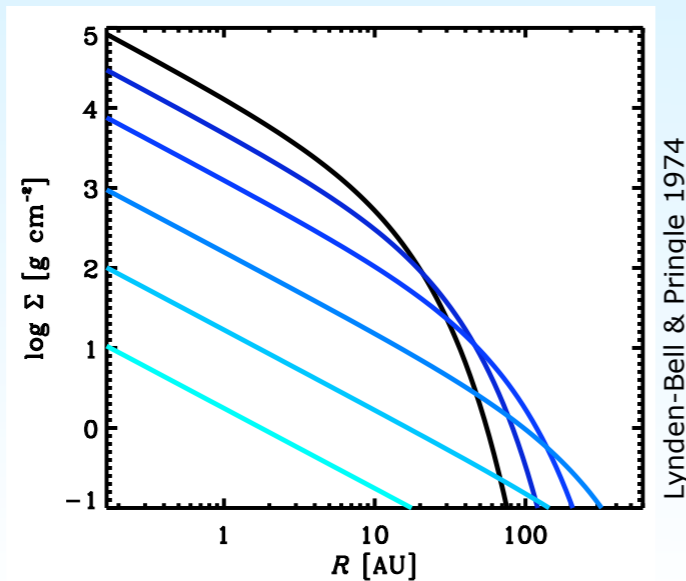
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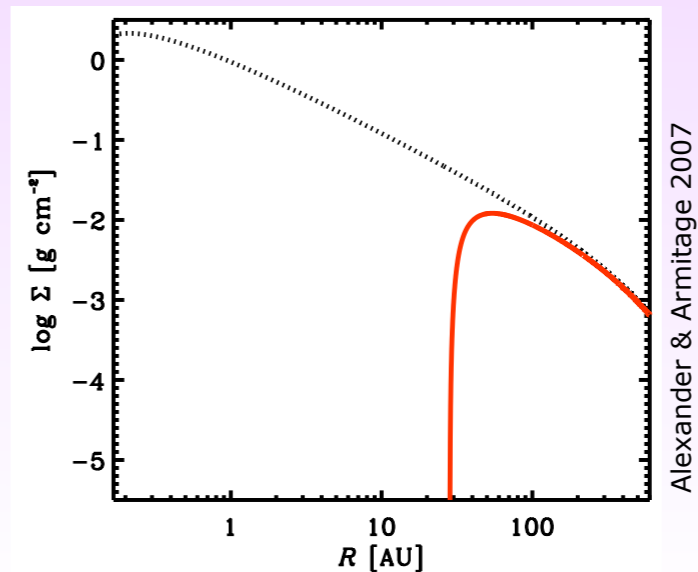


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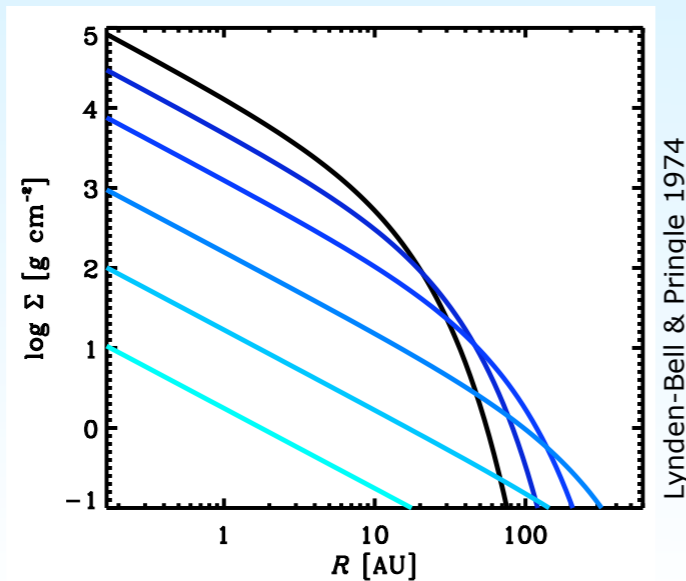
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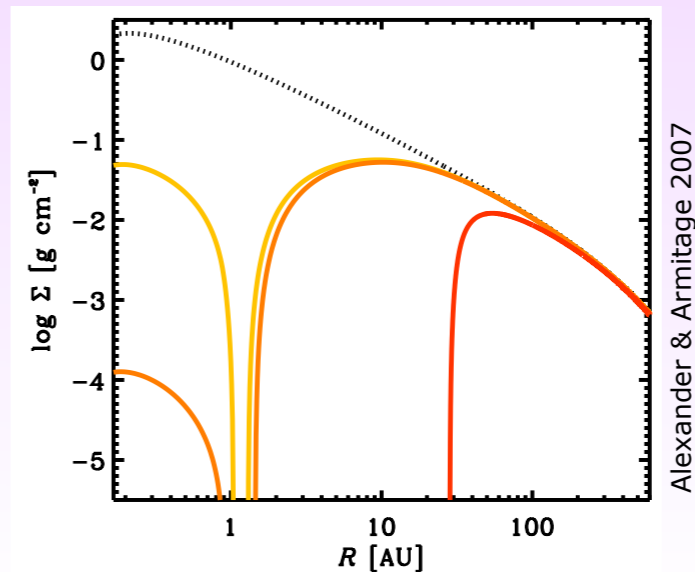


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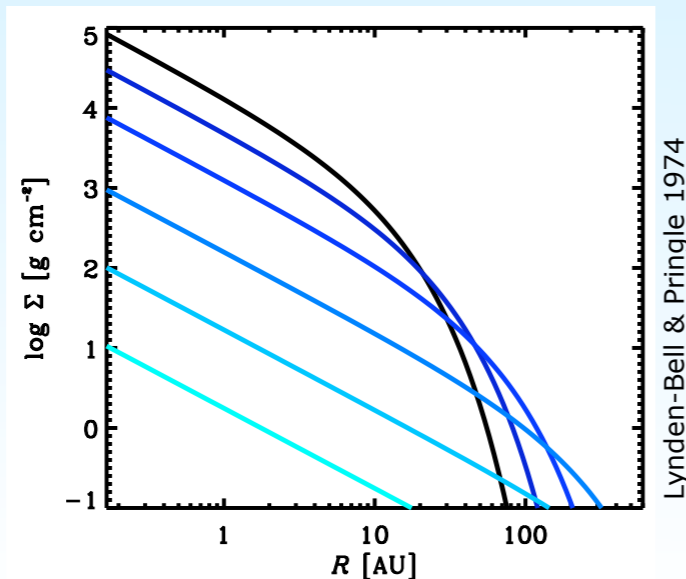
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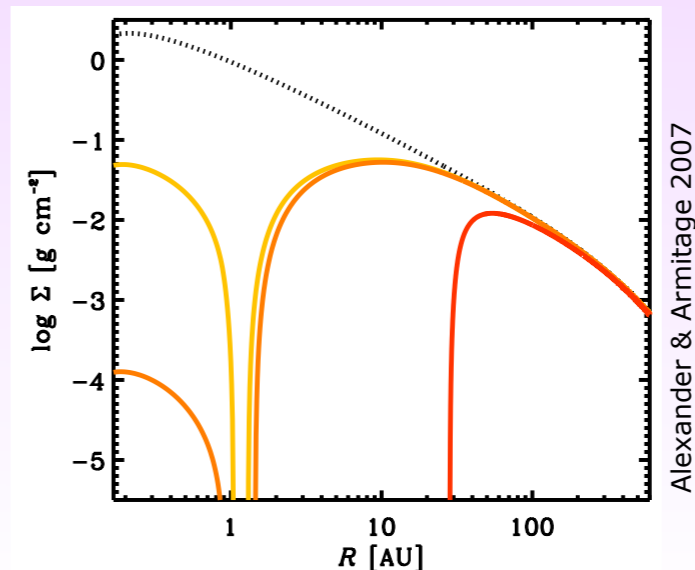


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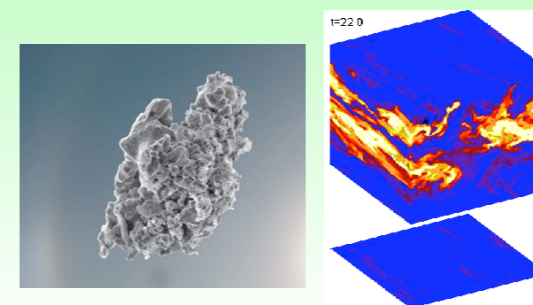
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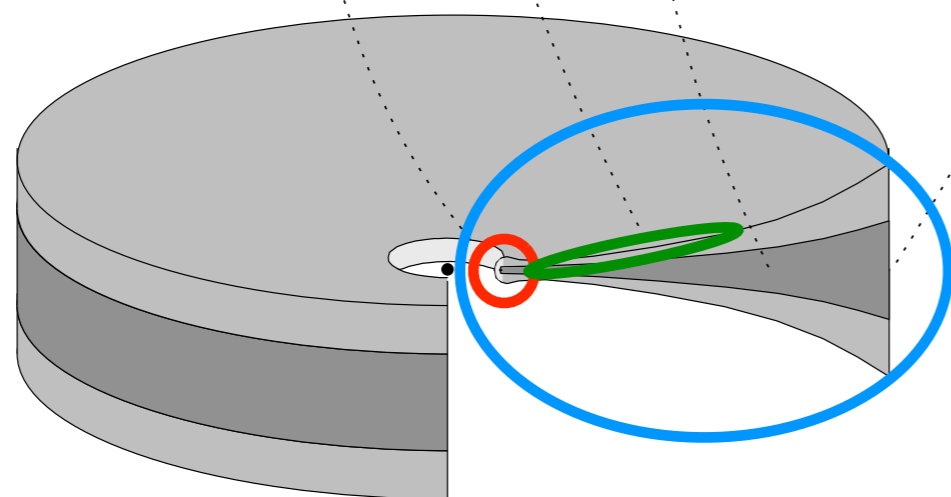
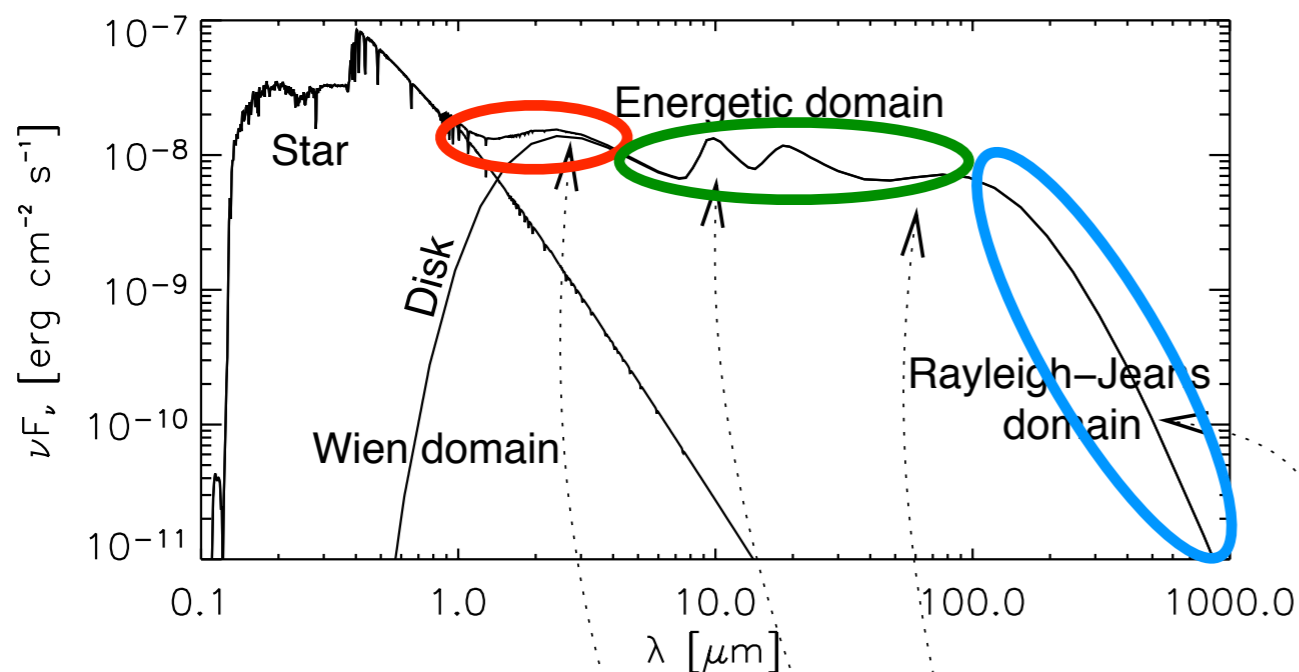
## grain growth

aggregation/settling/turbulence

opacity/color evolution



# key tool: sub-mm continuum emission



Dullemond et al. 2007

- bright emission from dust
- no stellar contamination
- unique tracer of midplane (for now...)
- high spatial resolution

$$R \approx 10 \left( \frac{1 \text{ km}}{b} \right) \left( \frac{d}{100 \text{ pc}} \right) \text{ AU}$$

- *optically thin emission*

$$S_\nu \propto \kappa_\nu \Sigma T$$

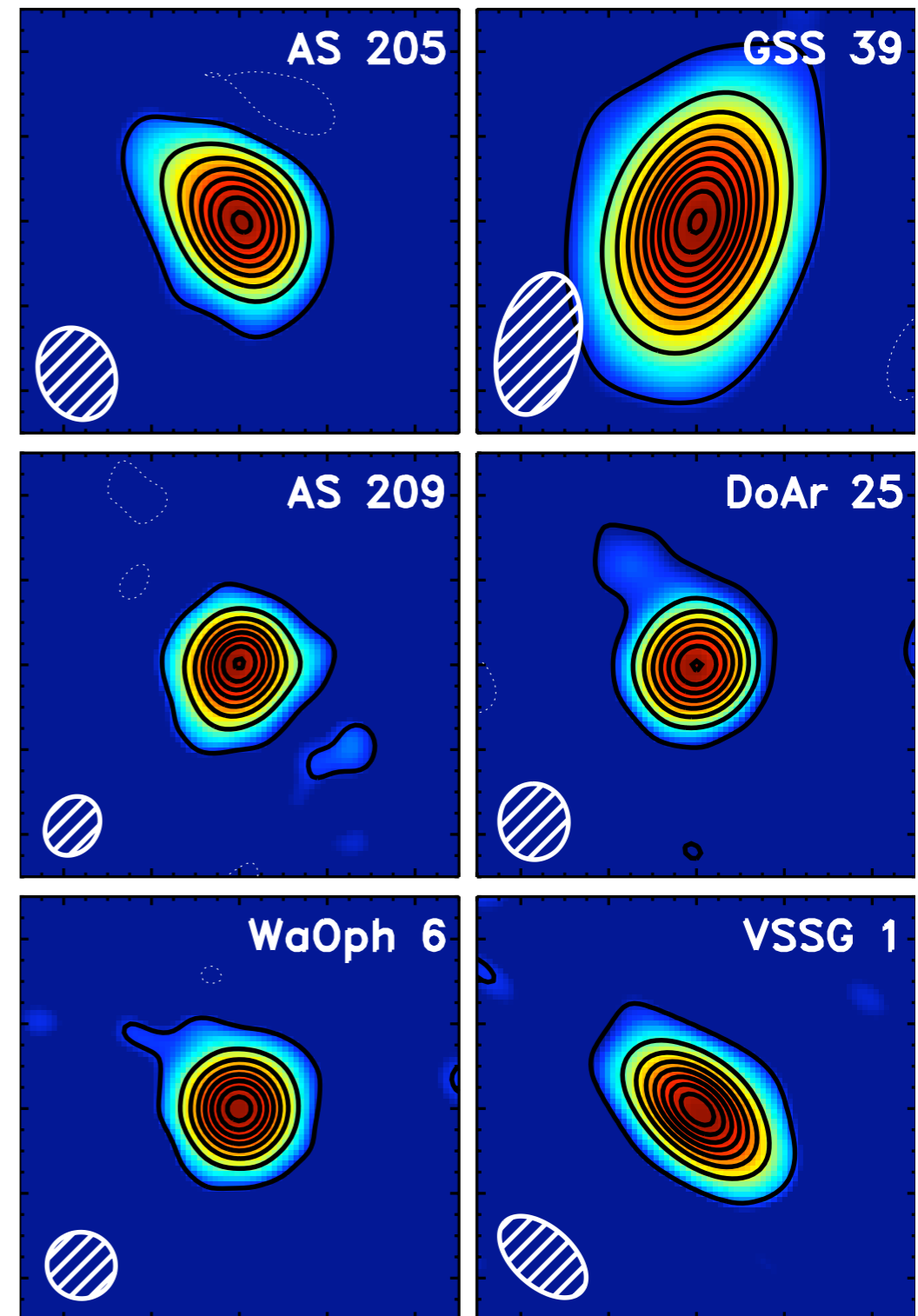
Beckwith et al. 1990

# high resolution disk survey in Oph

1 Myr-old low-mass star formation  
nearby:  $d \sim 125$  pc  
major target region for ALMA



L. E. Allen



Andrews &amp; Williams 2007a

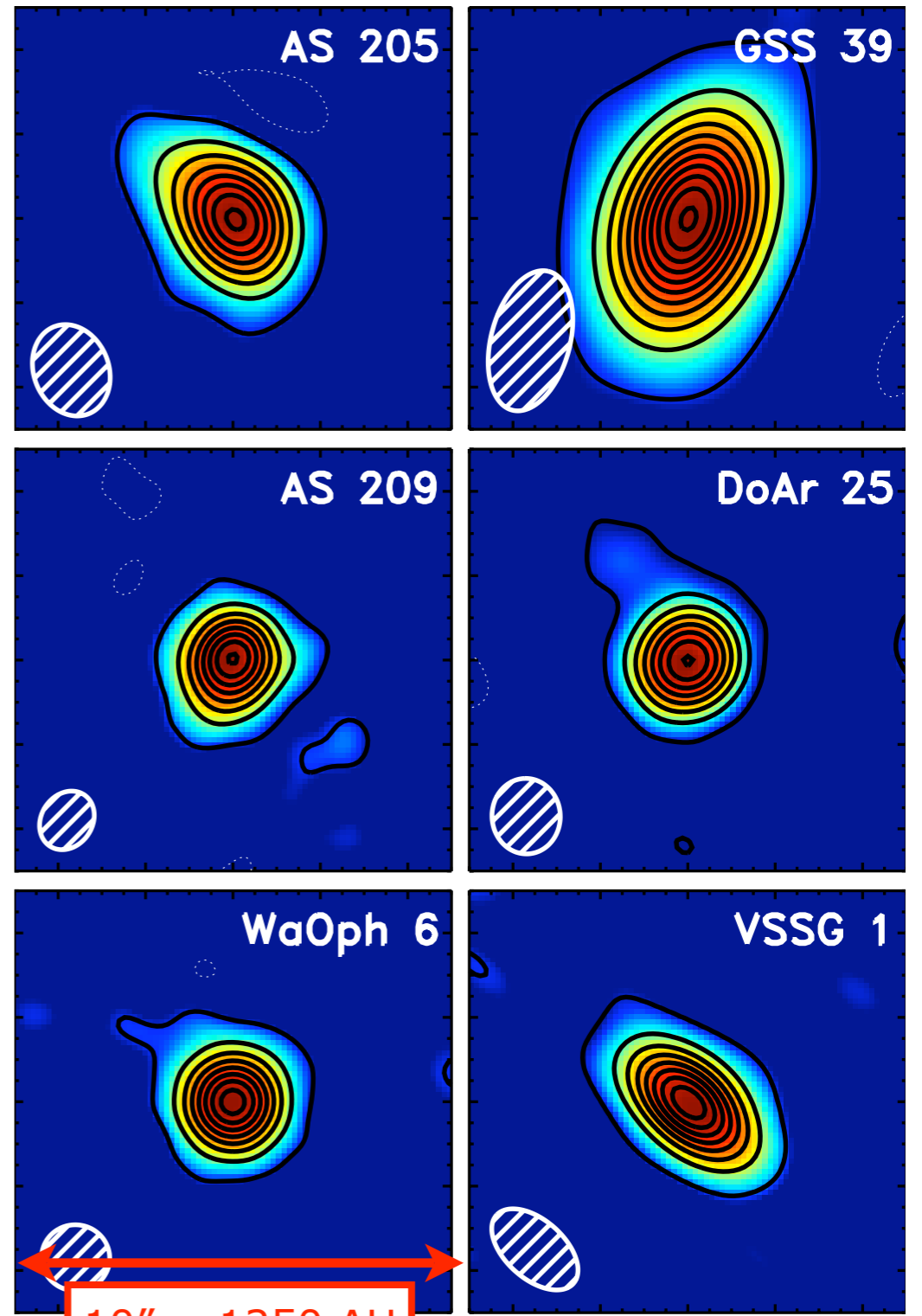


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10" = 1250 AU

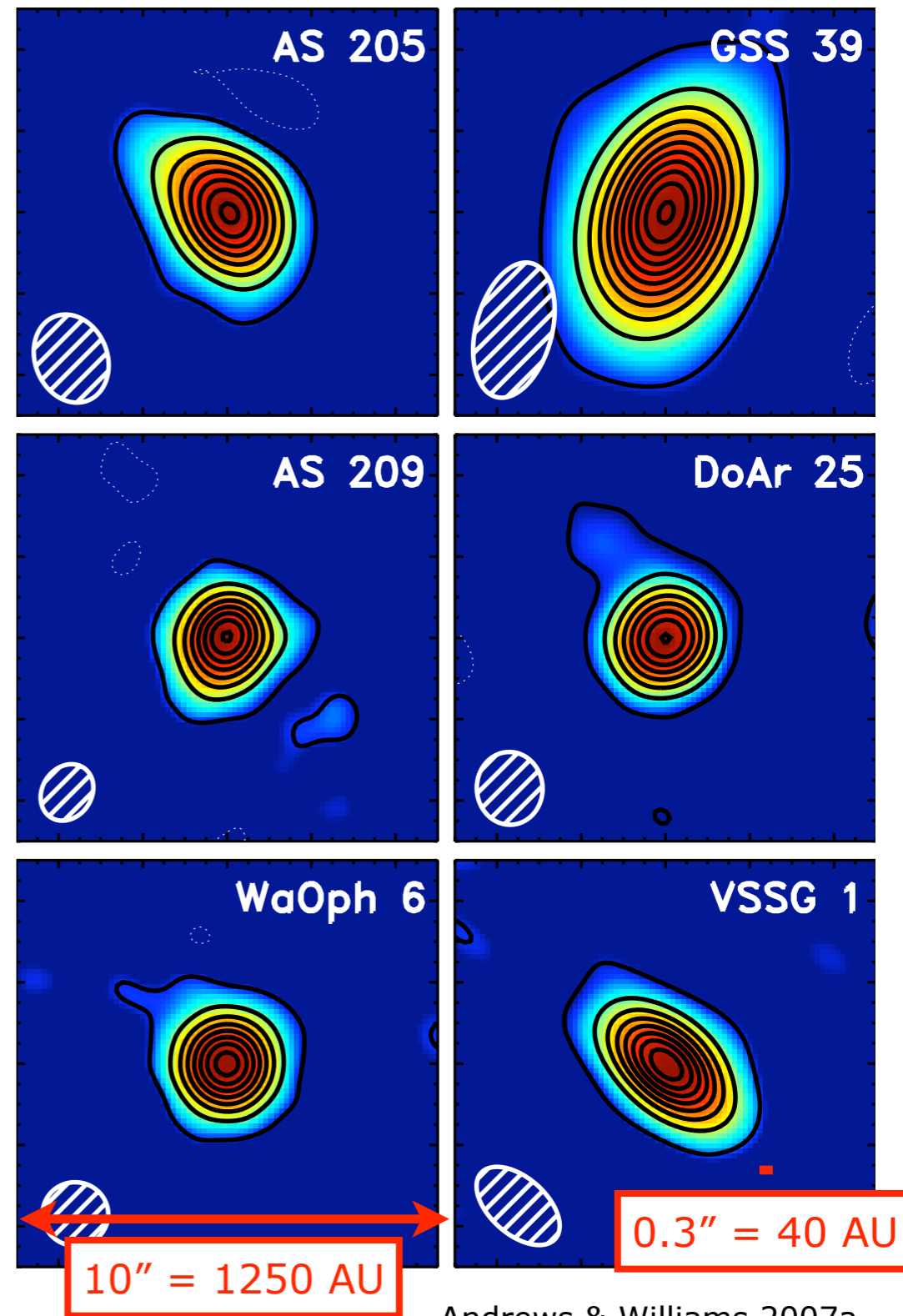
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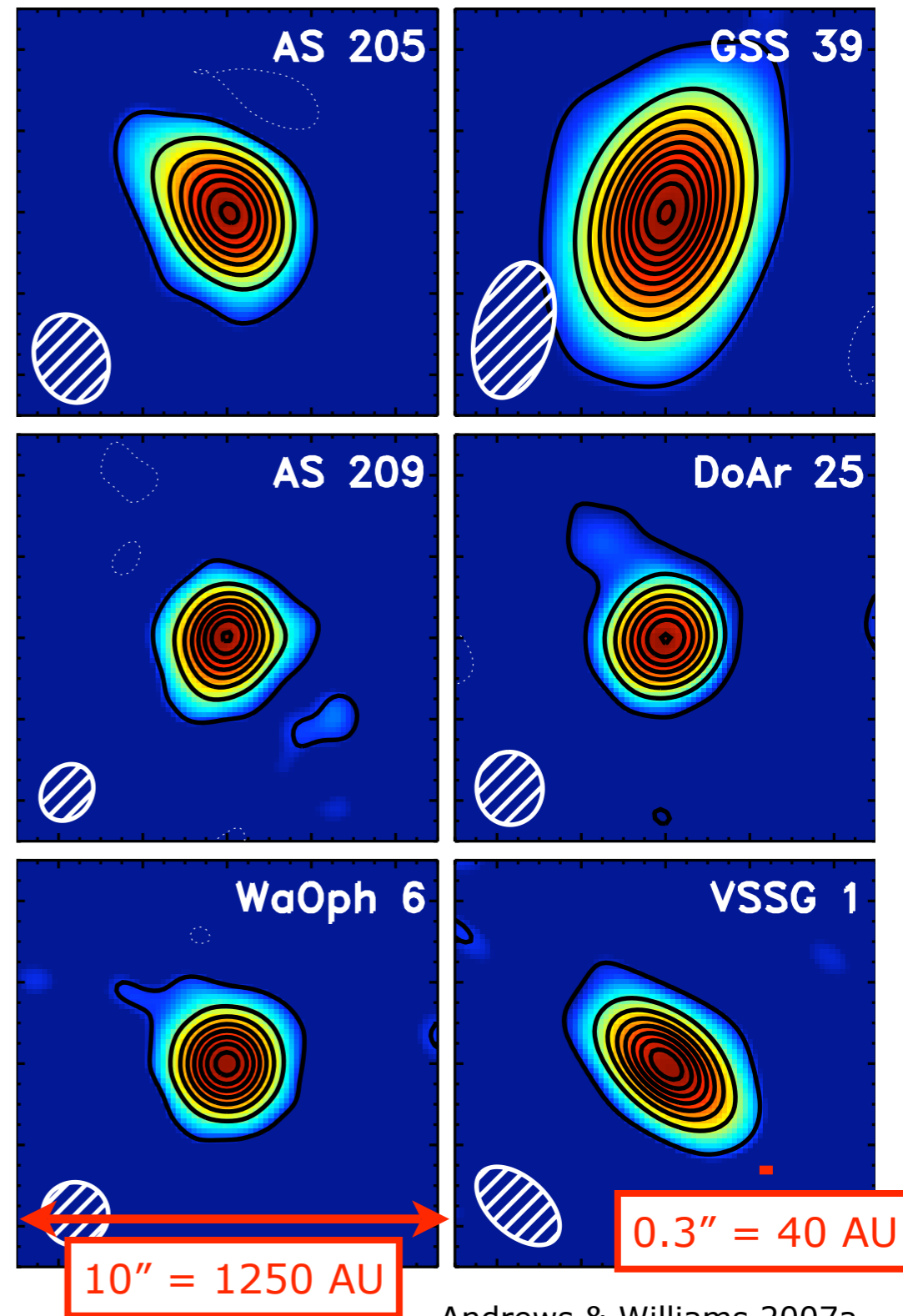
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870 microns + 0.5 km baselines  
 $0.3'' = 40$  AU resolution



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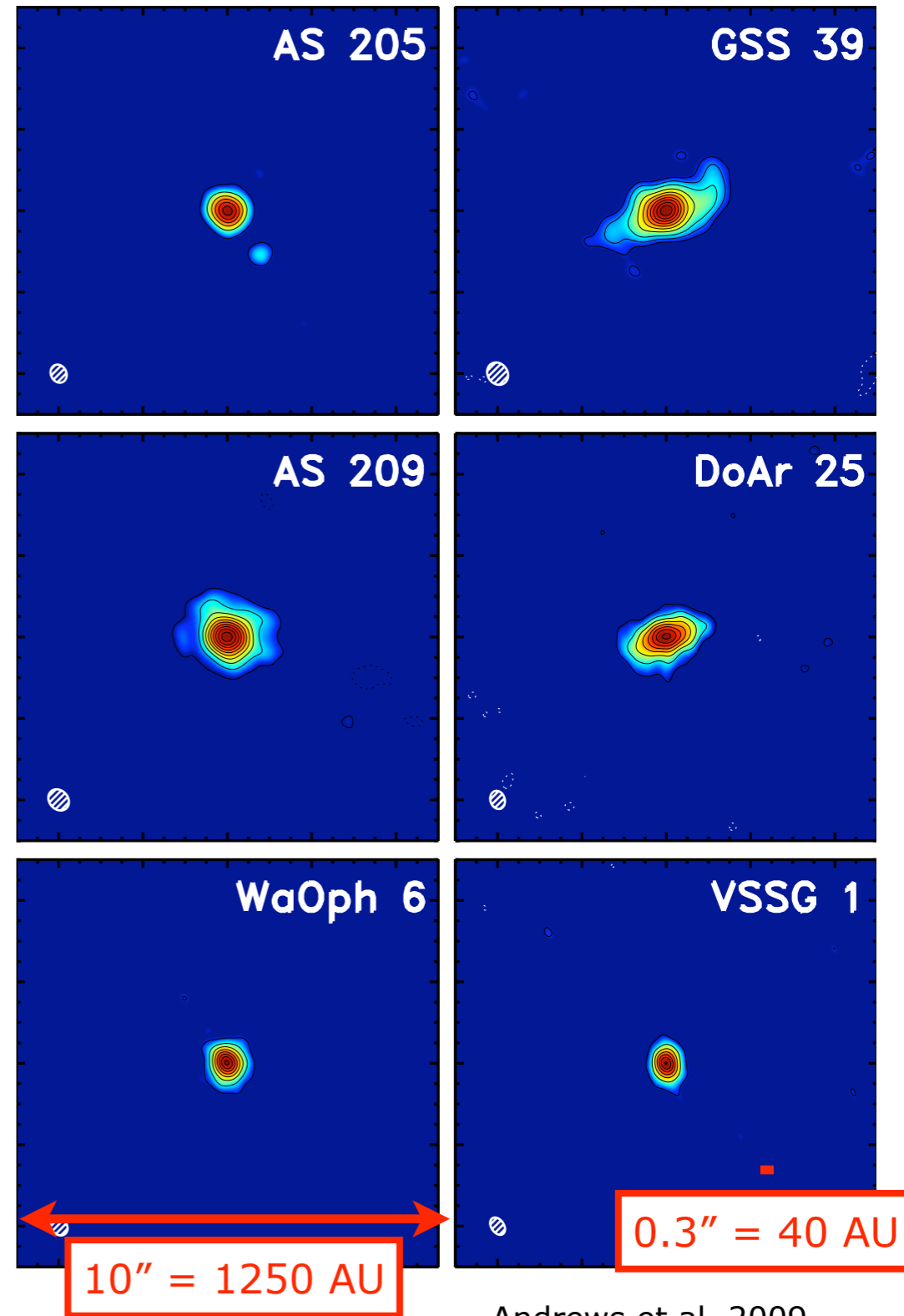
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Andrews et al. 2009

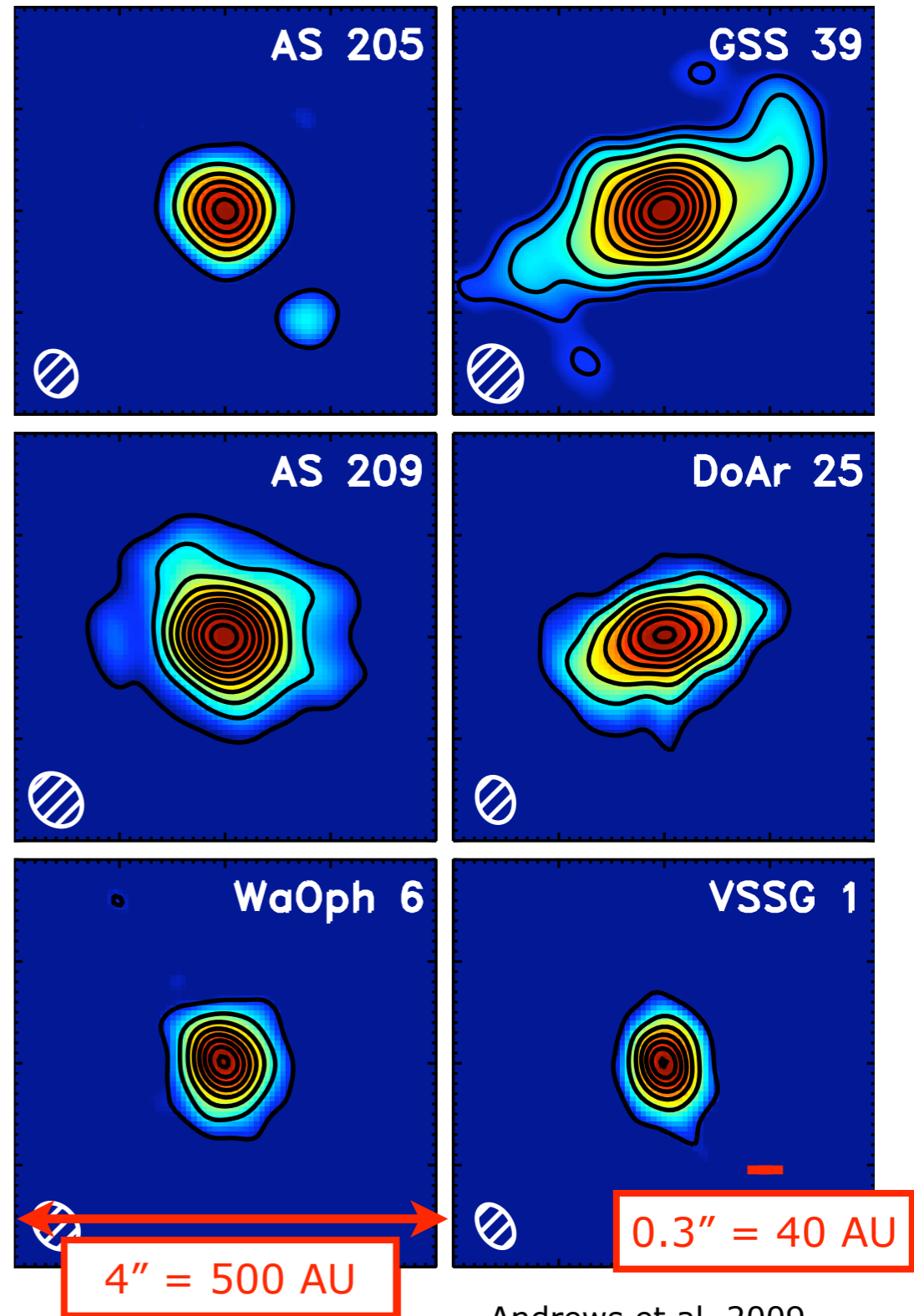
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Andrews et al. 2009

# *modeling disk structure*

parametric density structure

$$\rho(R, Z) = \frac{\Sigma}{\sqrt{2\pi}H} \exp \left[ -\frac{1}{2} \left( \frac{Z}{H} \right)^2 \right]$$

$$\Sigma(R) \propto \left( \frac{R}{R_c} \right)^{-\gamma} \exp \left[ - \left( \frac{R}{R_c} \right)^{2-\gamma} \right]$$

$$H(R) \propto R^\psi$$

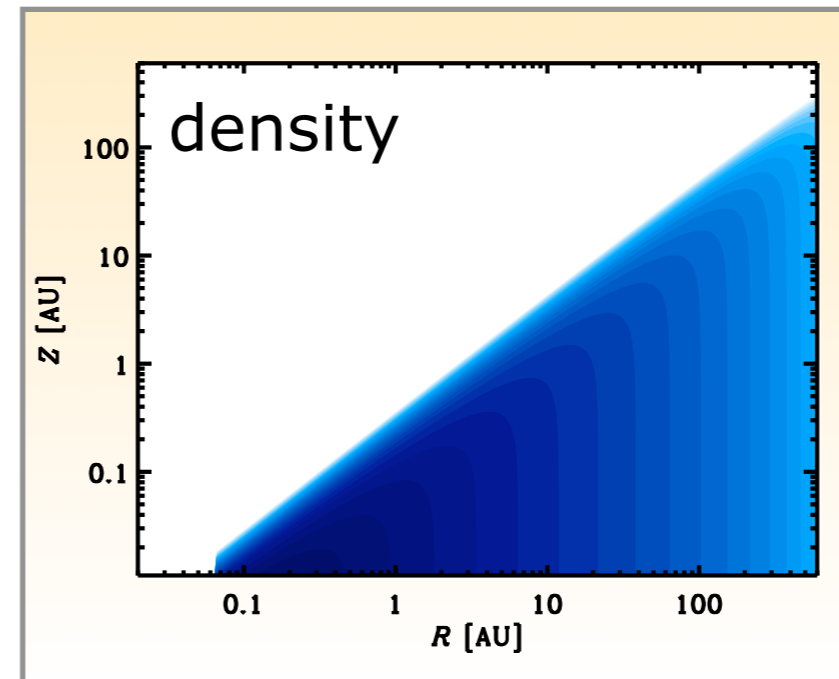
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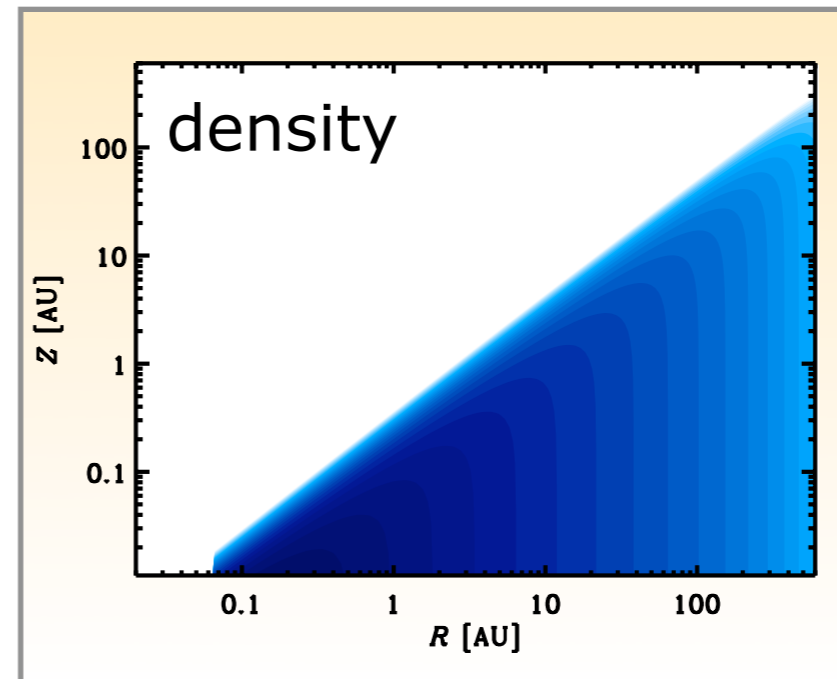
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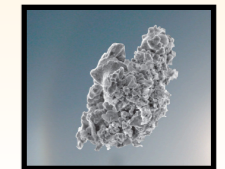
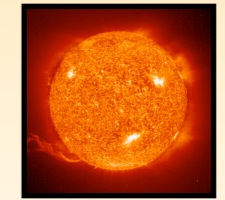
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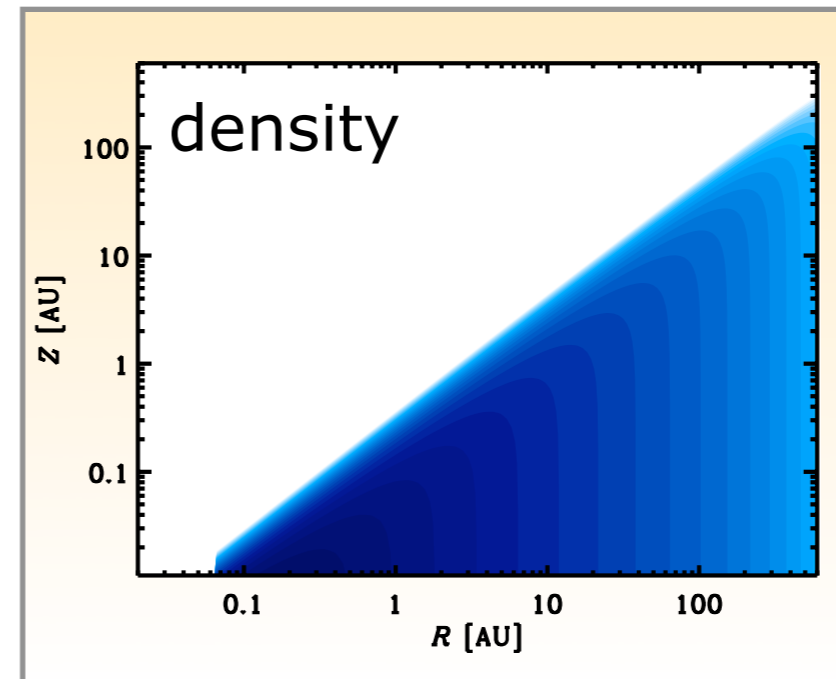
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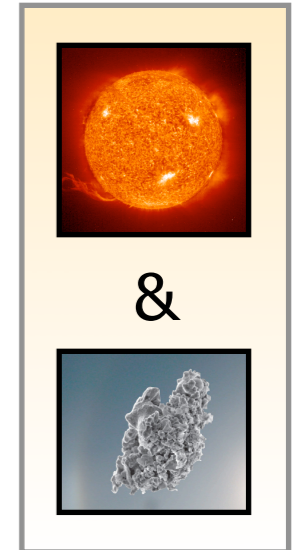
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+



2-D Monte Carlo radiative transfer

Dullemond & Dominik 2004

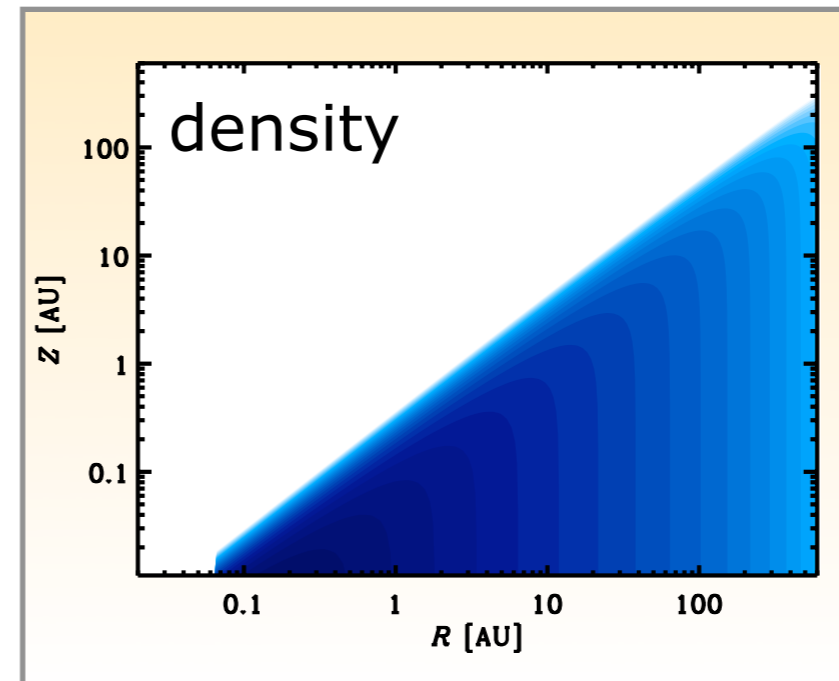
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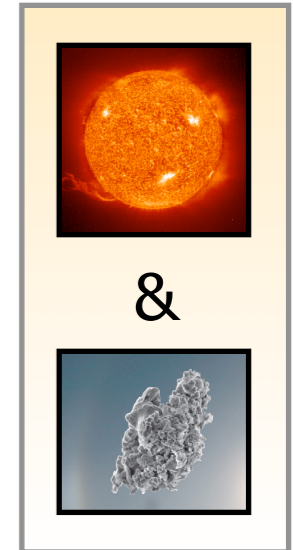
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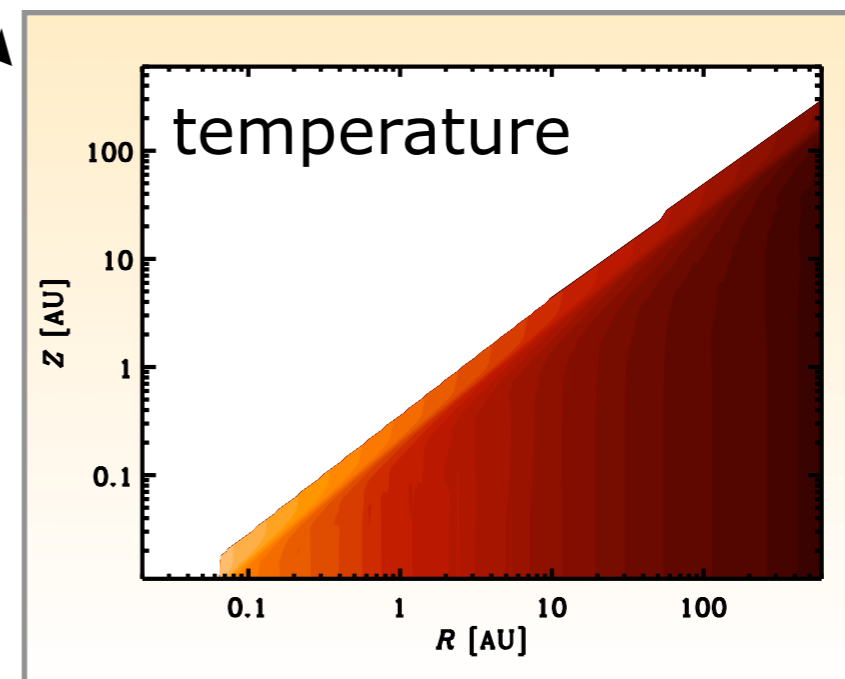


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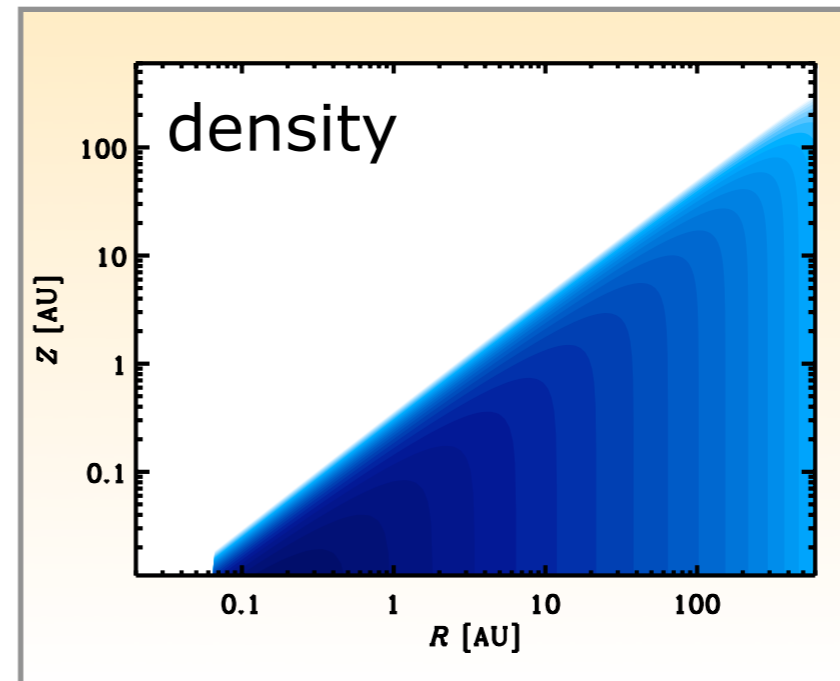
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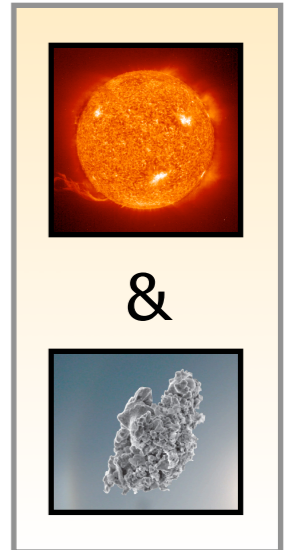
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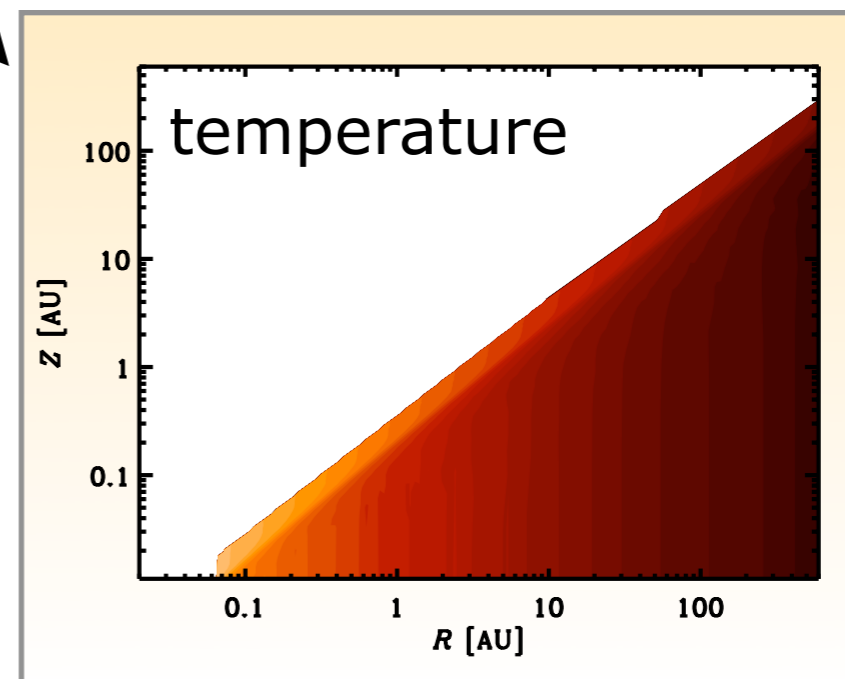
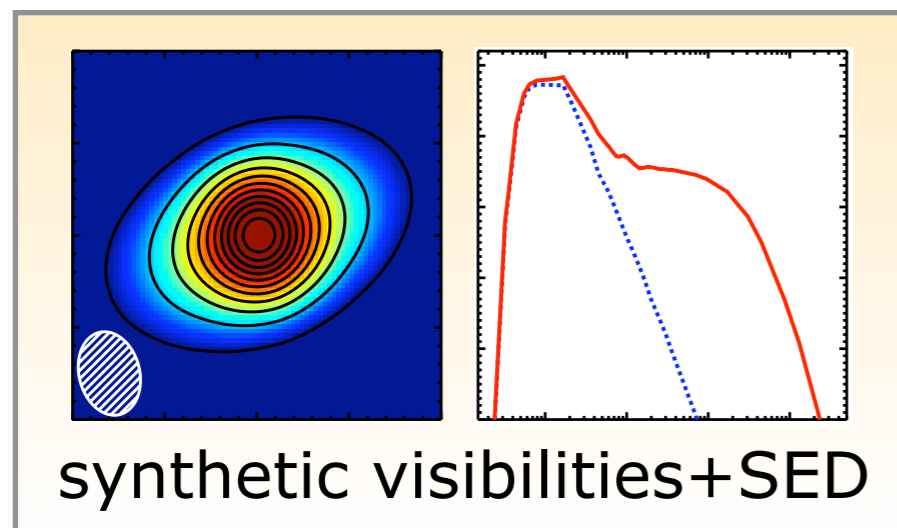
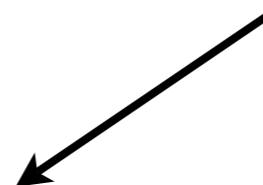


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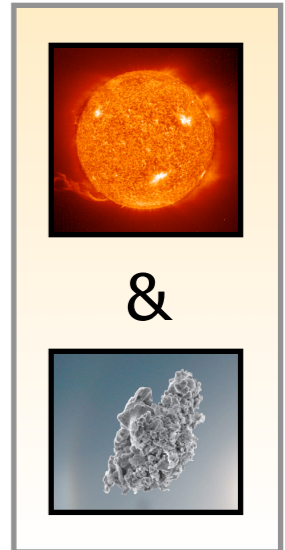
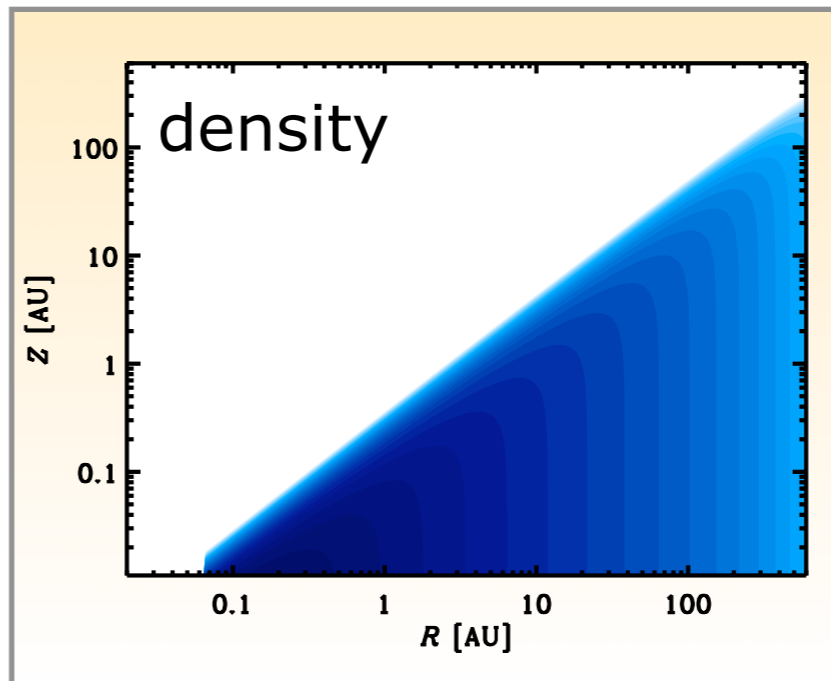
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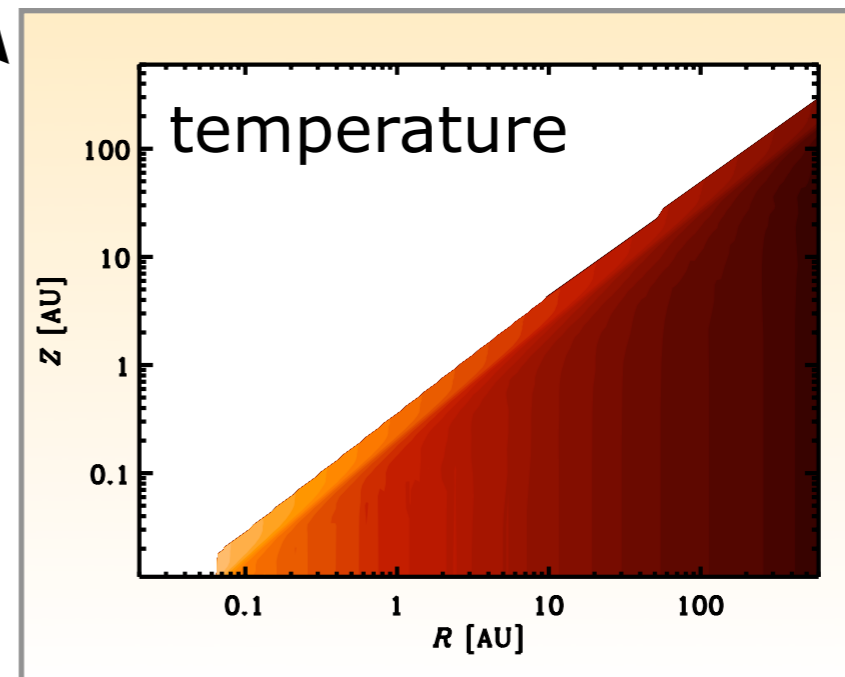
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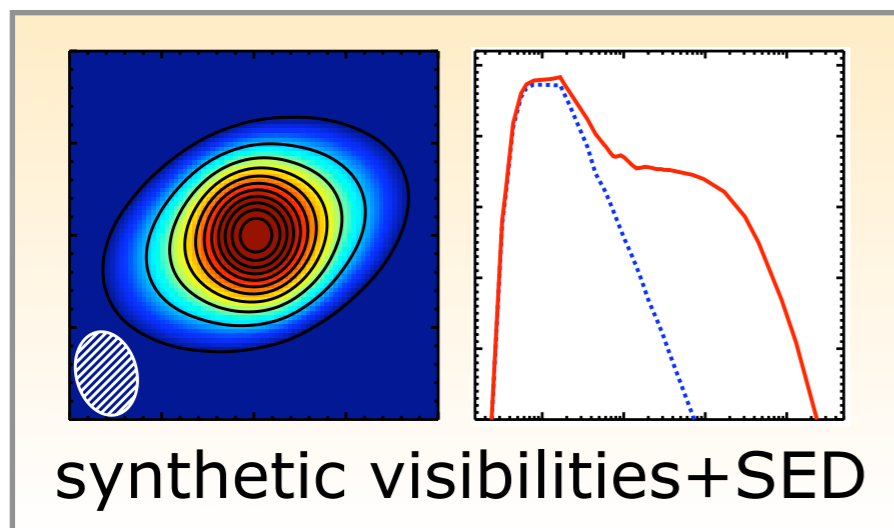


2-D Monte Carlo radiative transfer

Dullemond & Dominik 2004



compare with data

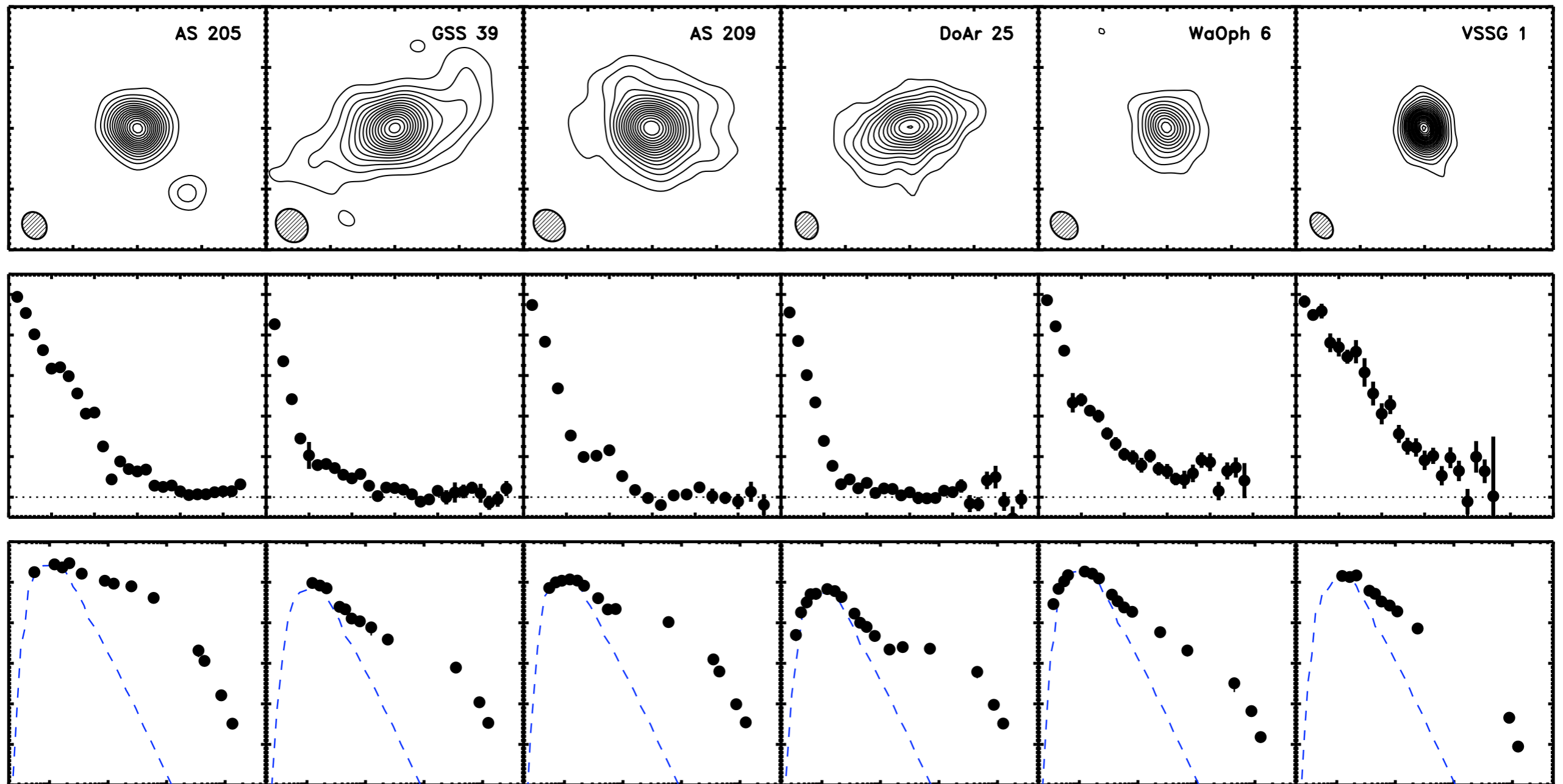


# modeling results

*points = data*

*blue curve = star*

*contours = data*



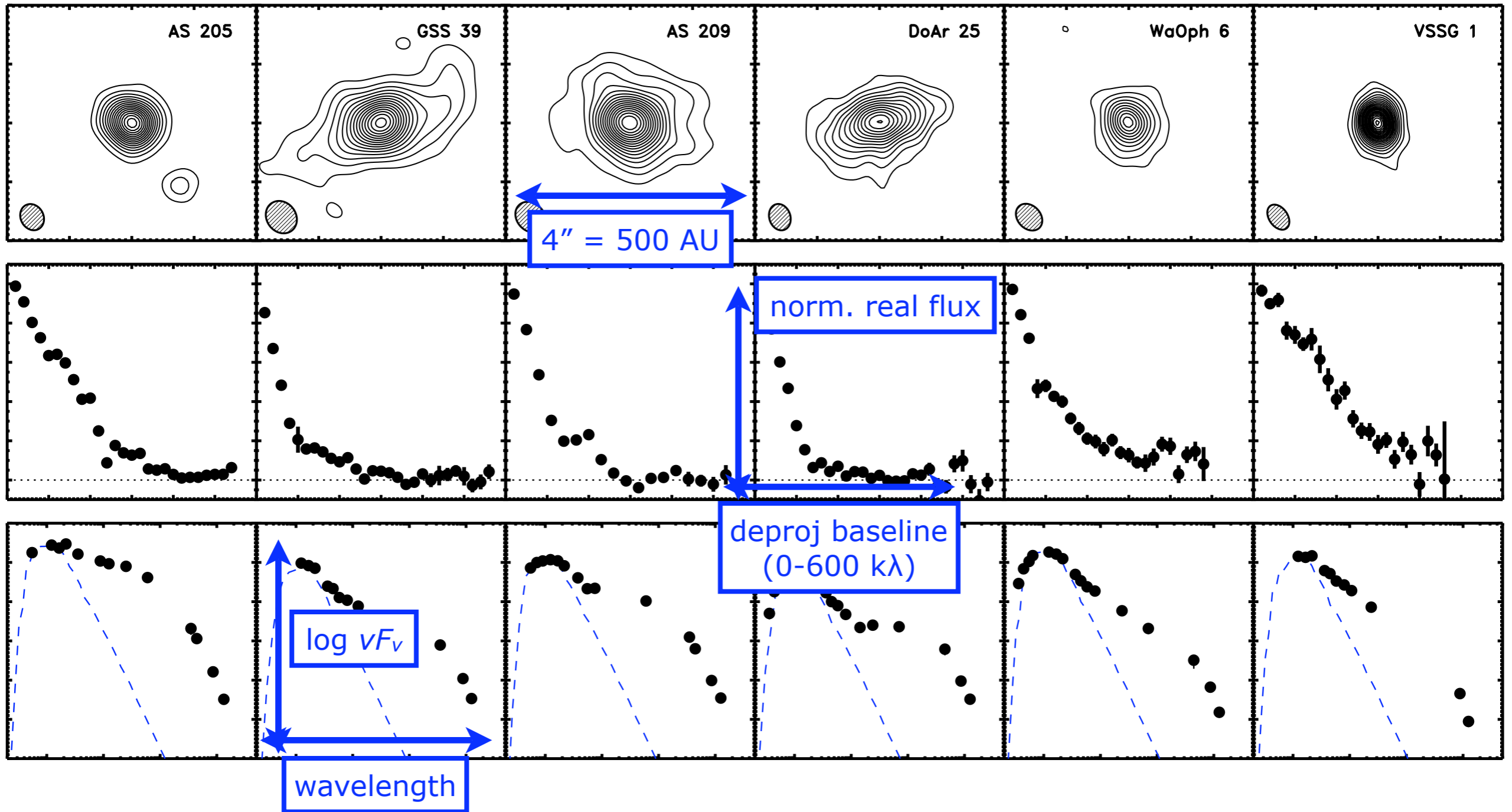
Andrews et al. 2009

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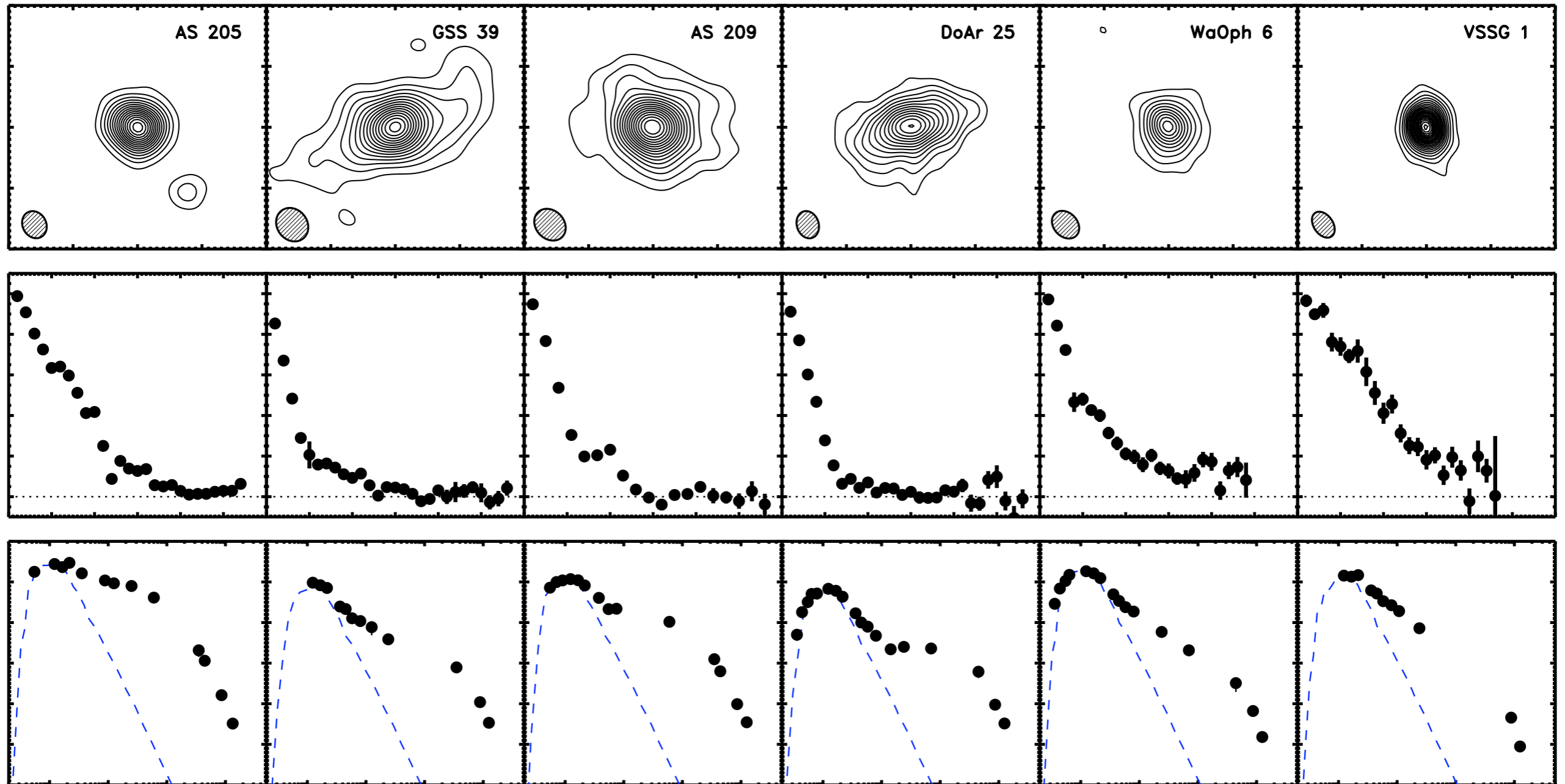
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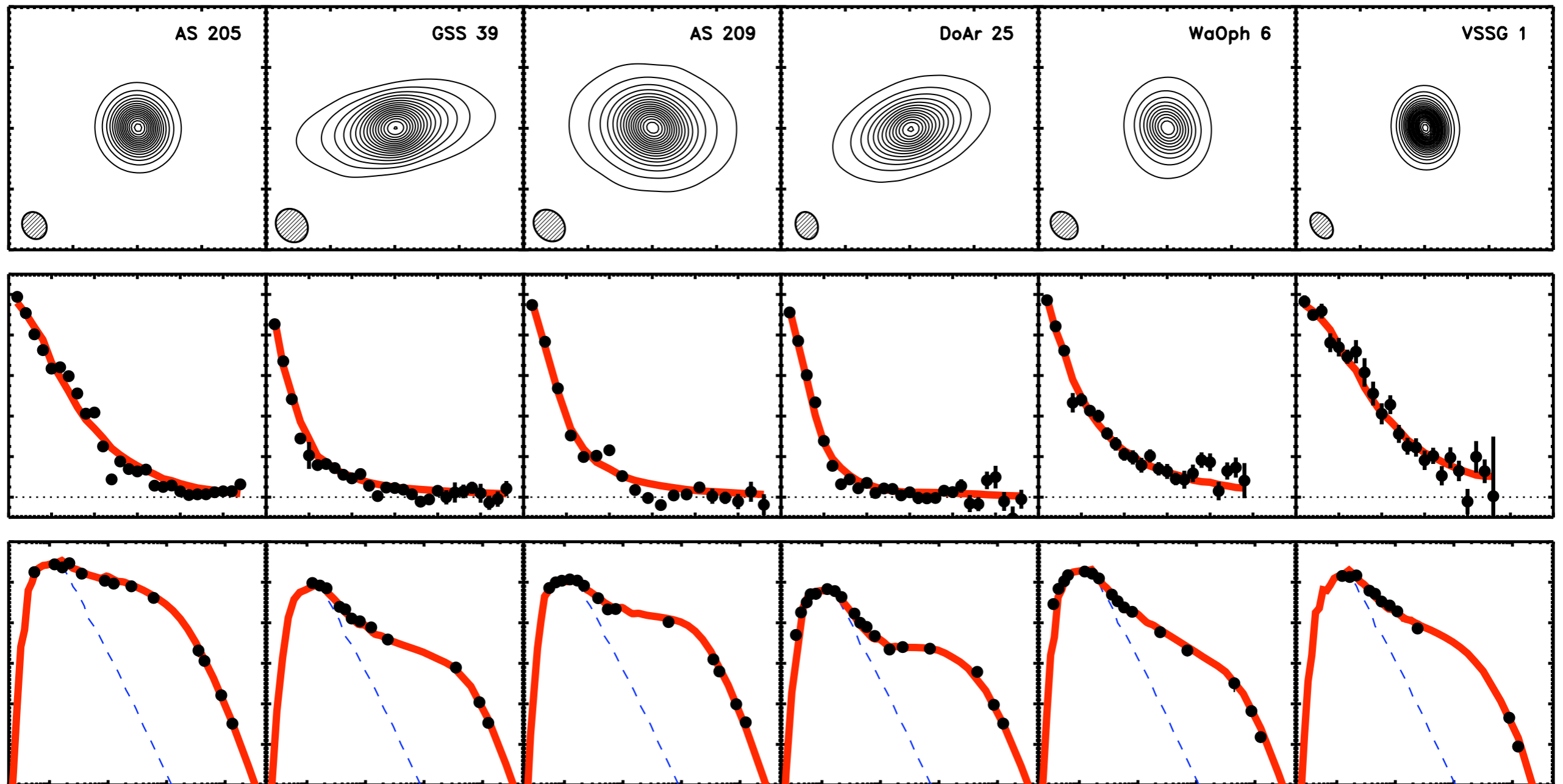
# modeling results

points = data

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contours = model

red curve = model



Andrews et al. 2009



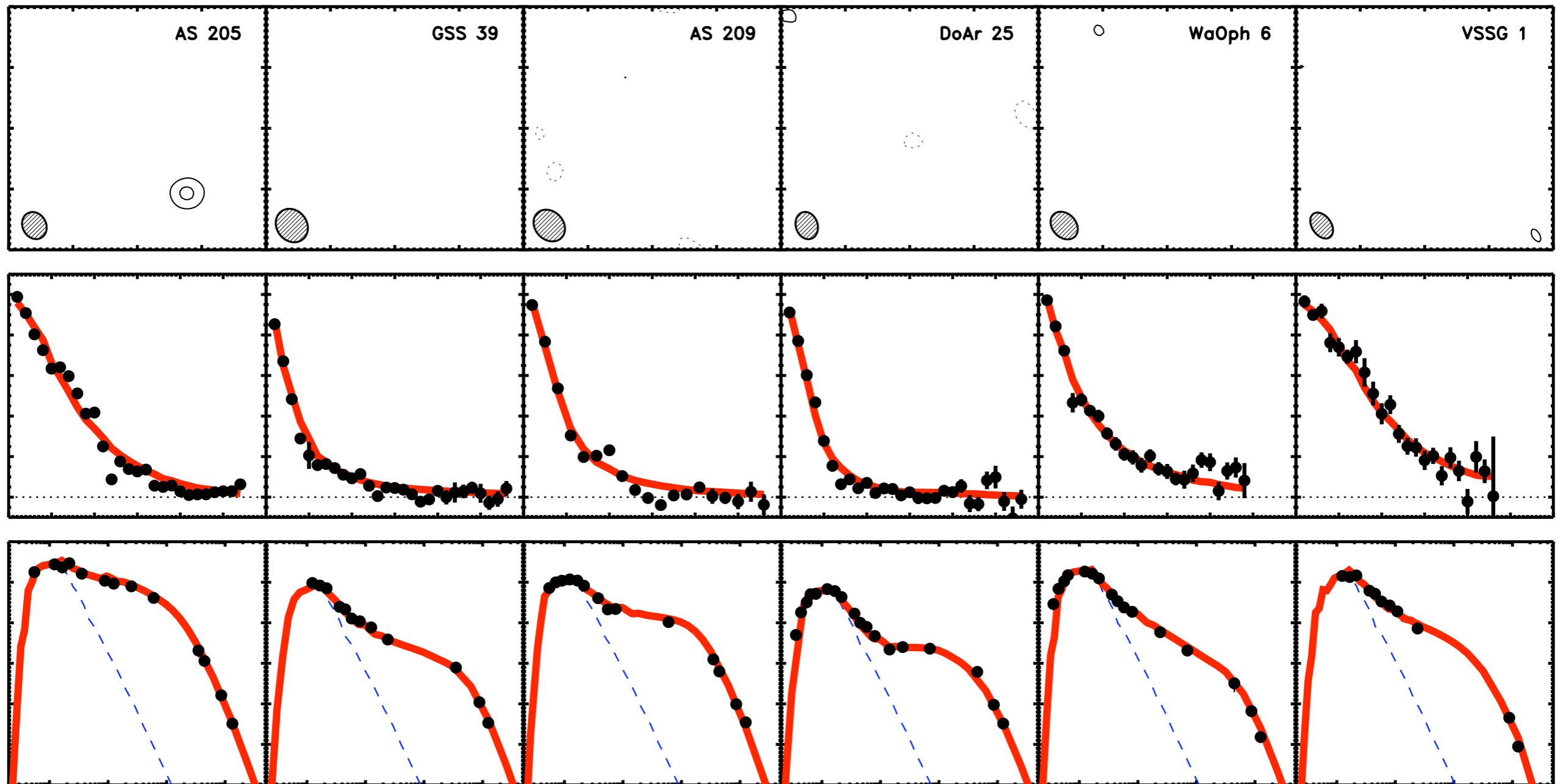
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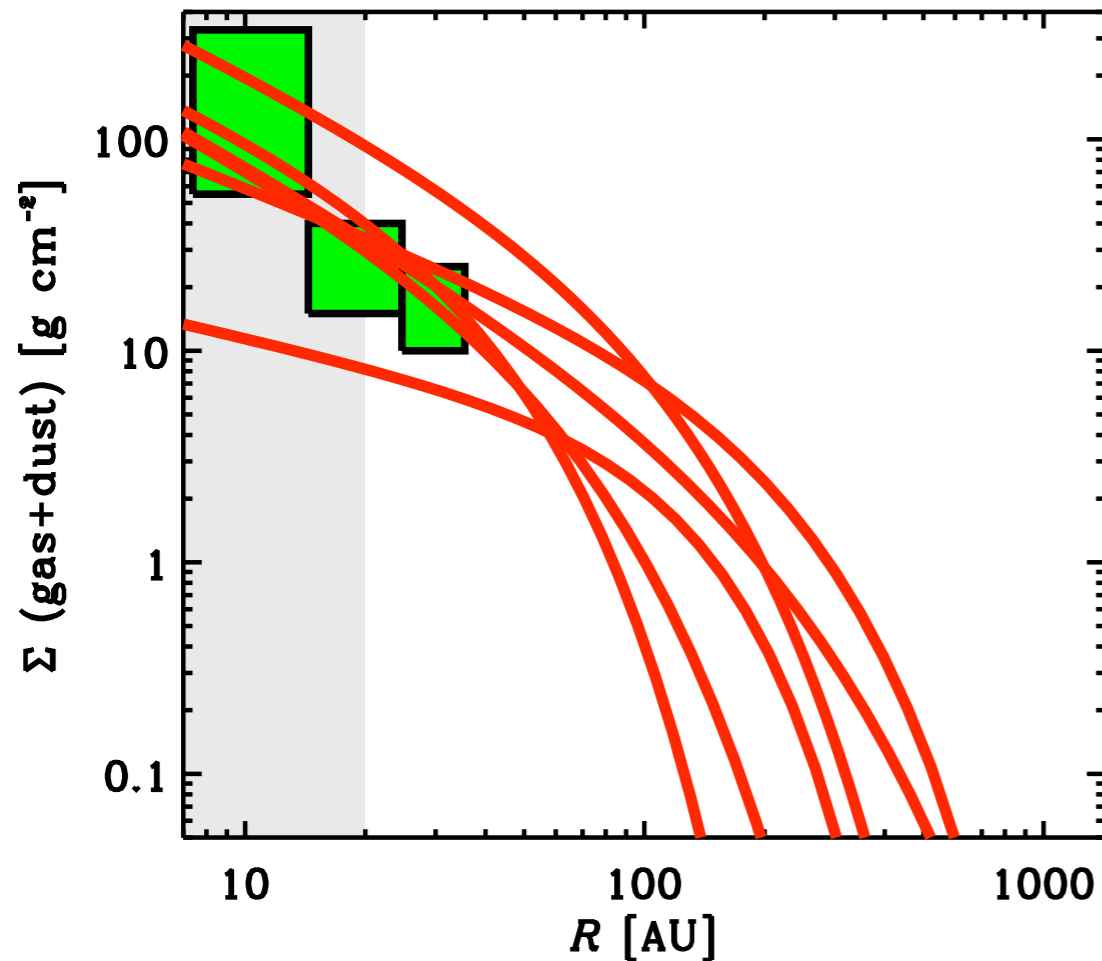
contours = residuals

red curve = model



Andrews et al. 2009

# implications: viscous evolution/planet formation



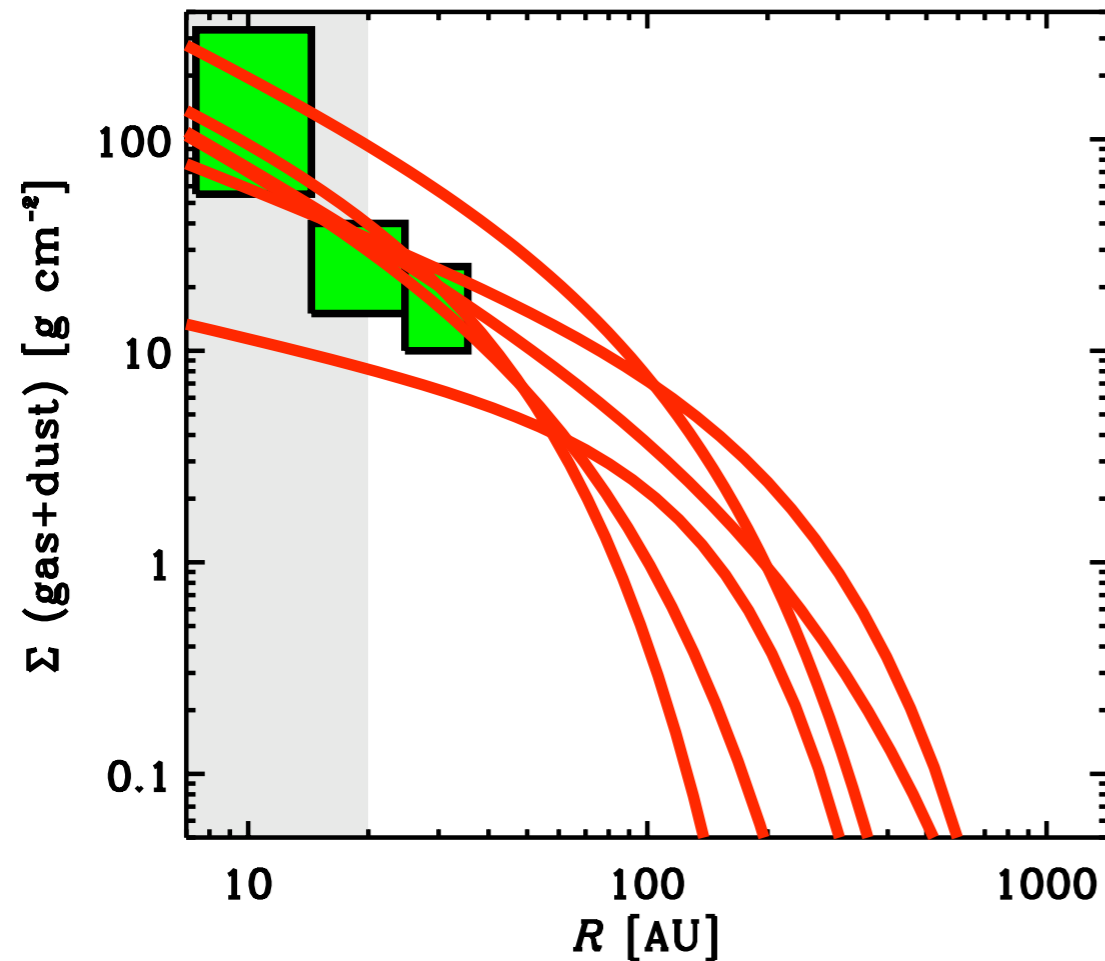
surface densities:

$$\Sigma(R) \propto \left(\frac{R}{R_c}\right)^{-\gamma} \exp\left[-\left(\frac{R}{R_c}\right)^{2-\gamma}\right]$$

$$\gamma \sim 0.4-1.0; \text{ median } \gamma = 0.9$$

Andrews et al. 2009

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## viscous evolution:

structure set by viscous torques  
*not* large-scale grav. instabilities

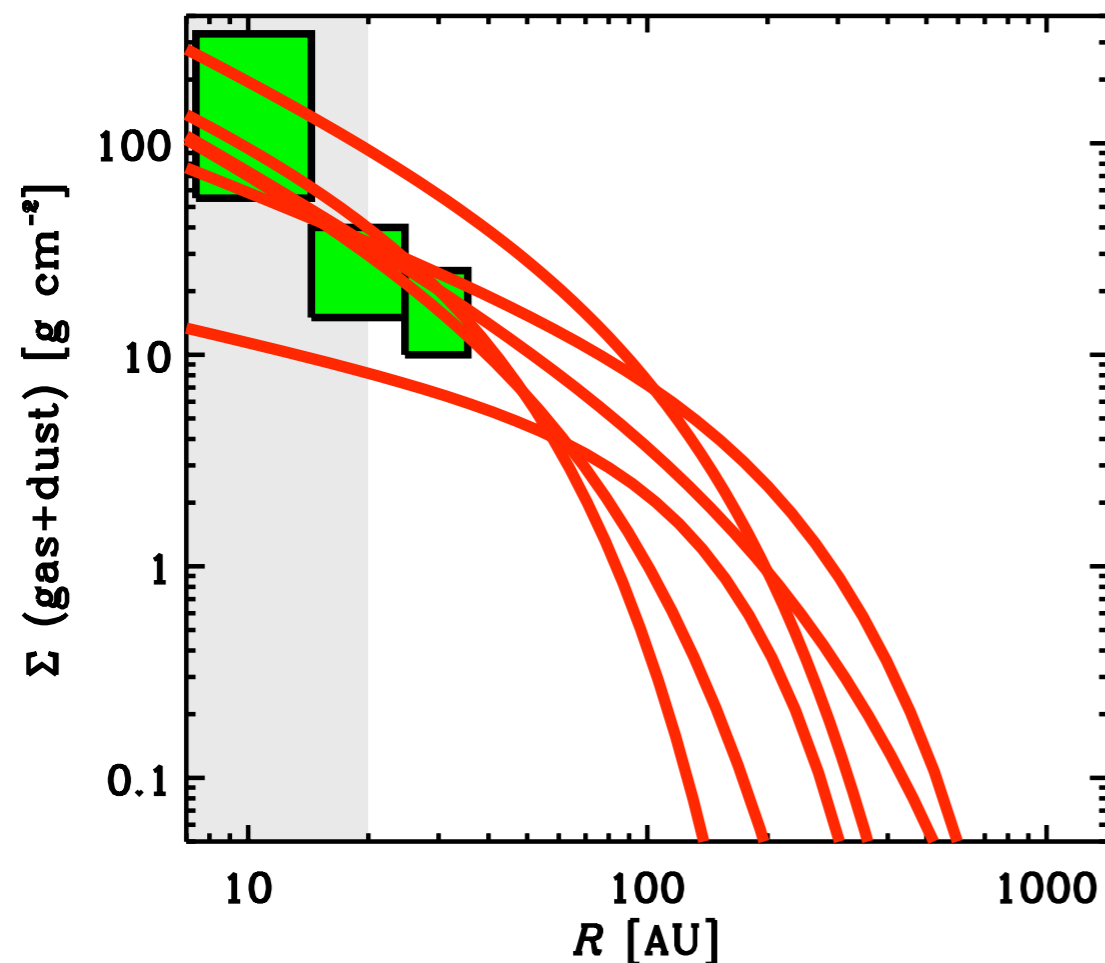
link with  $\dot{M}$  to quantify viscosity  
 $\alpha \sim 0.0005-0.08$ ;  $\sim$ MRI values

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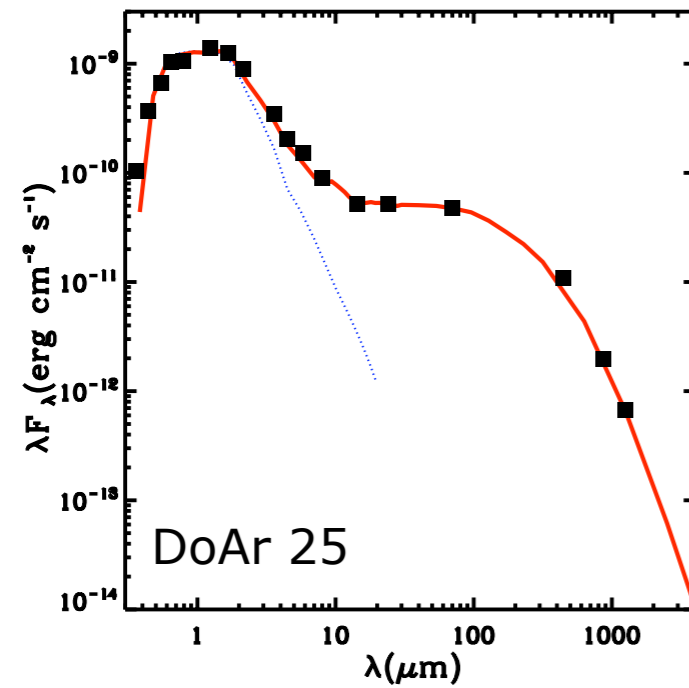
## planet formation:

densities comparable to MMSN  
in the  $R \sim 10-40$  AU range

plenty of mass at large radii  
*grav. stable* at all locations

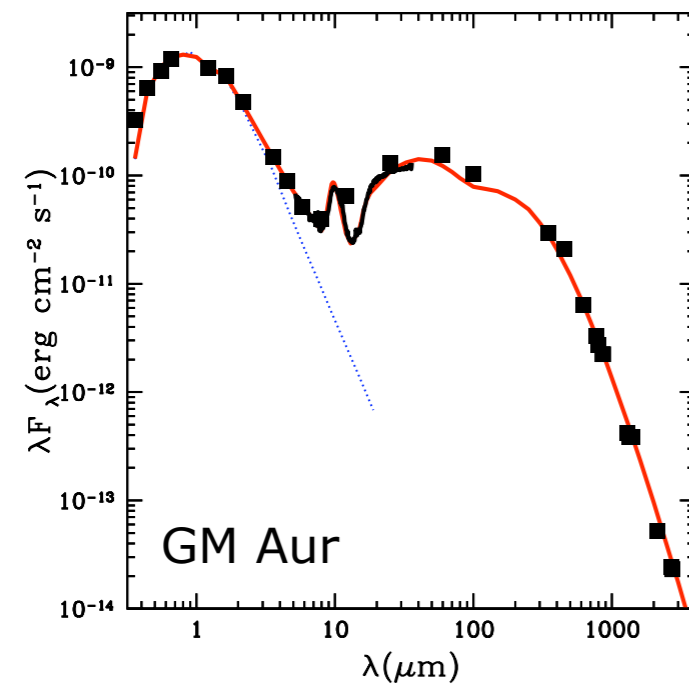
*disk evolution: transition disks*

normal



Andrews et al. 2008

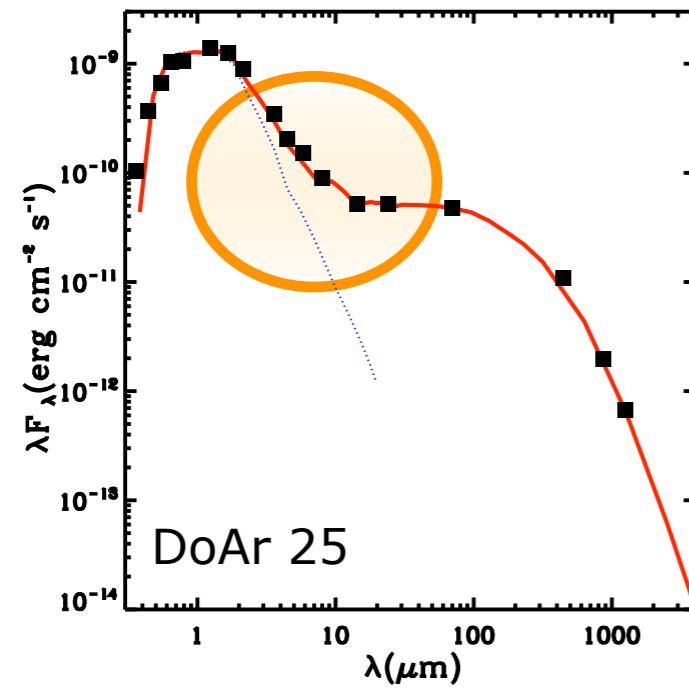
transition



Hughes, Andrews et al. 2009

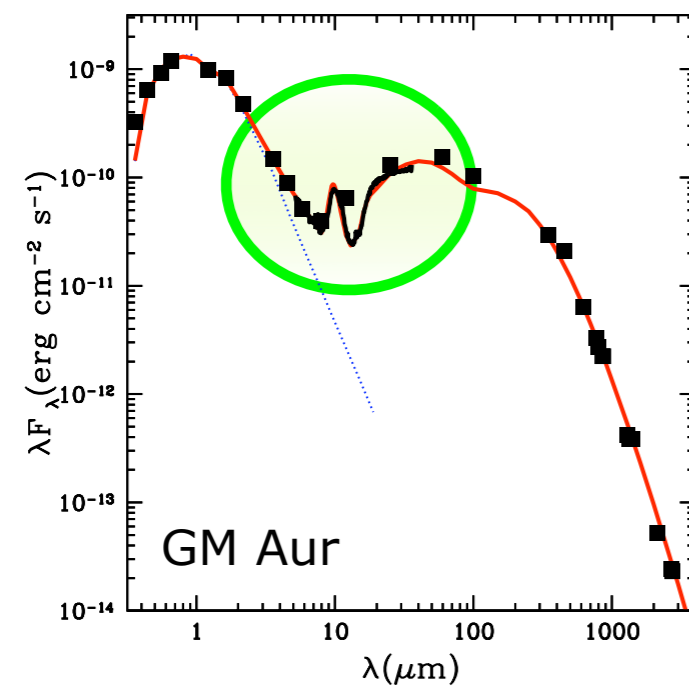
# *disk evolution: transition disks*

normal



Andrews et al. 2008

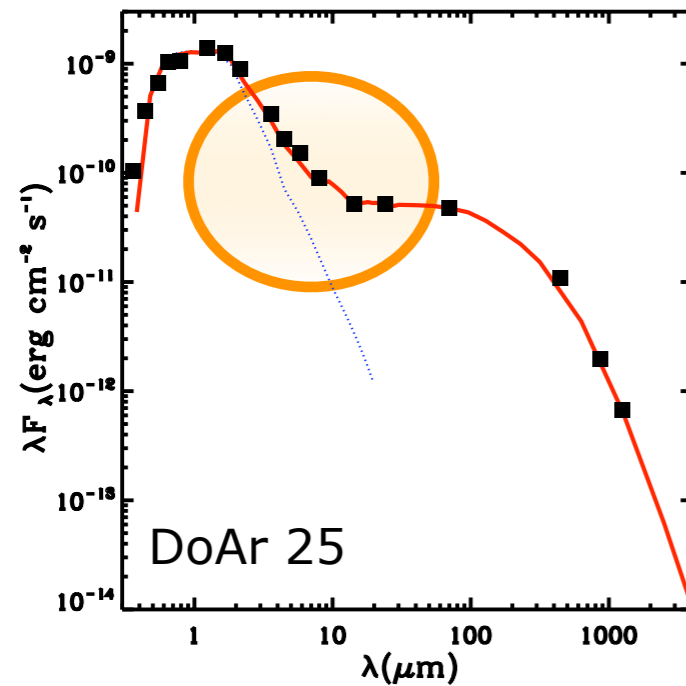
transition



Hughes, Andrews et al. 2009

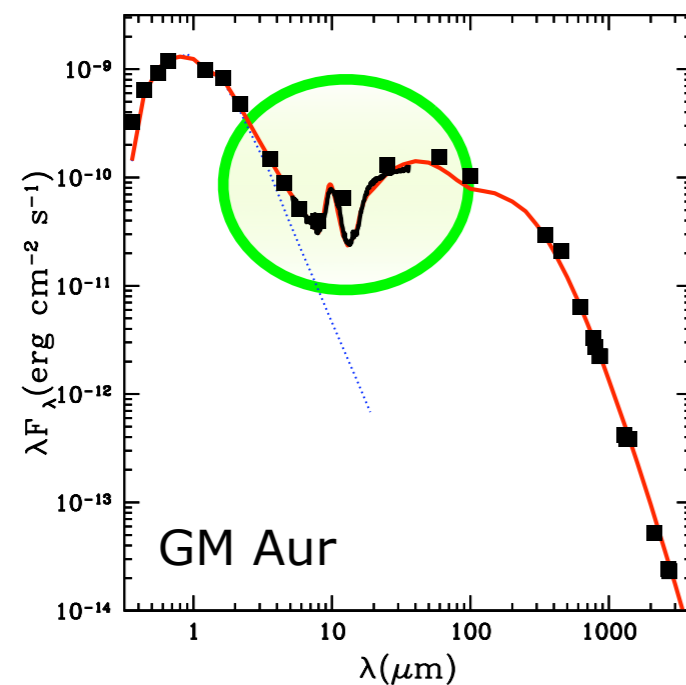
# disk evolution: transition disks

normal



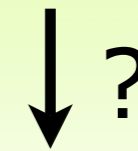
Andrews et al. 2008

transition



Hughes, Andrews et al. 2009

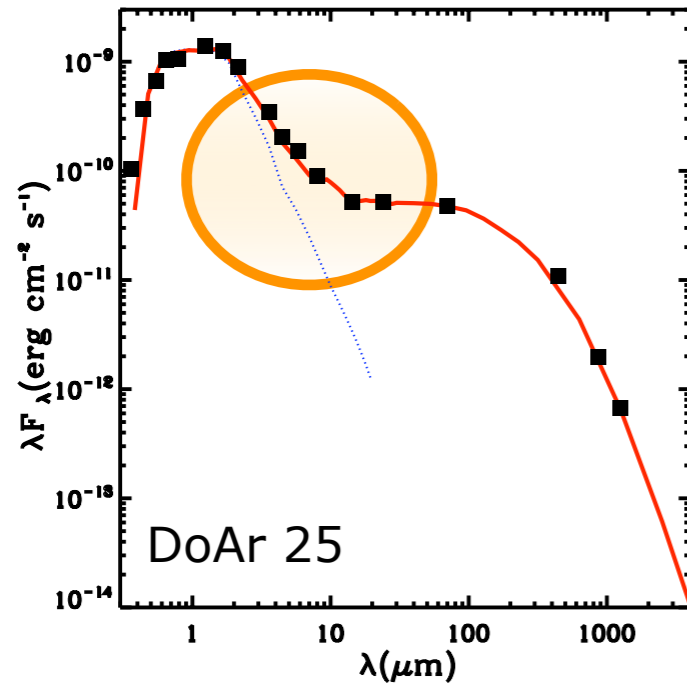
missing infrared excess



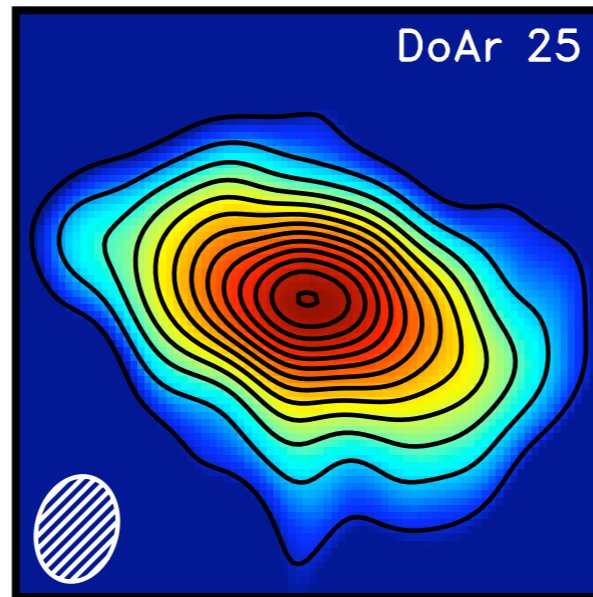
missing warm dust

# disk evolution: transition disks

normal



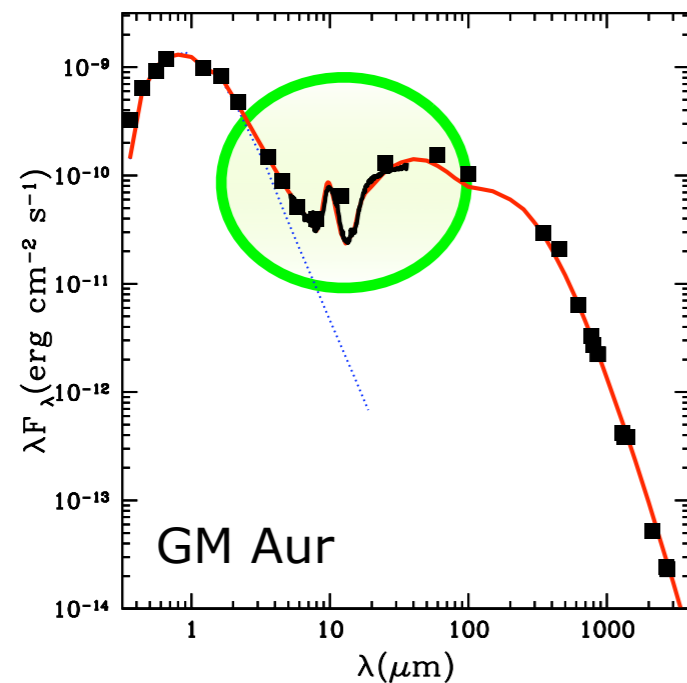
Andrews et al. 2008



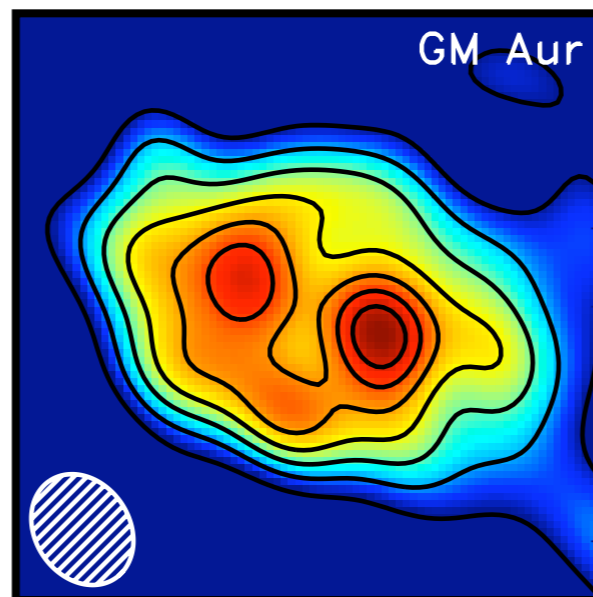
$R \sim 20$  AU orbit 

missing infrared excess  
↓ ?  
missing warm dust

transition



Hughes, Andrews et al. 2009

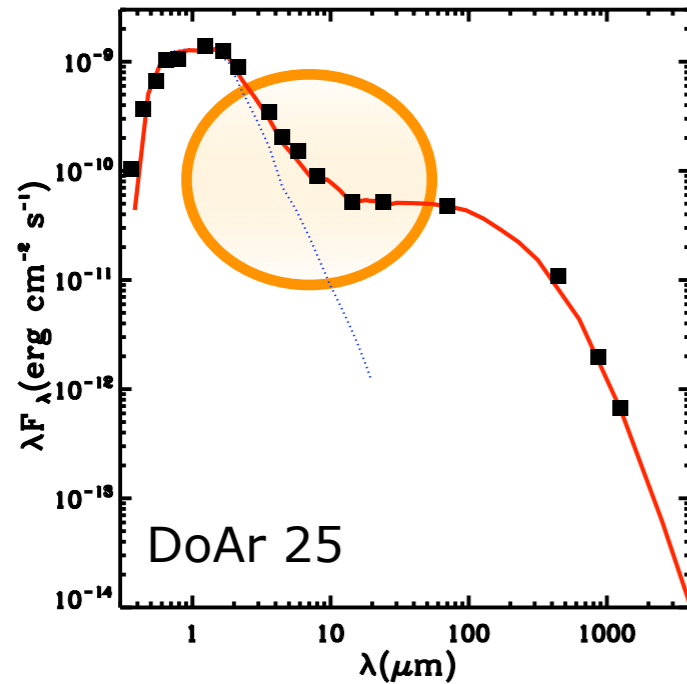


direct submm imaging:  
*yes!*  
optical depth "cavities"

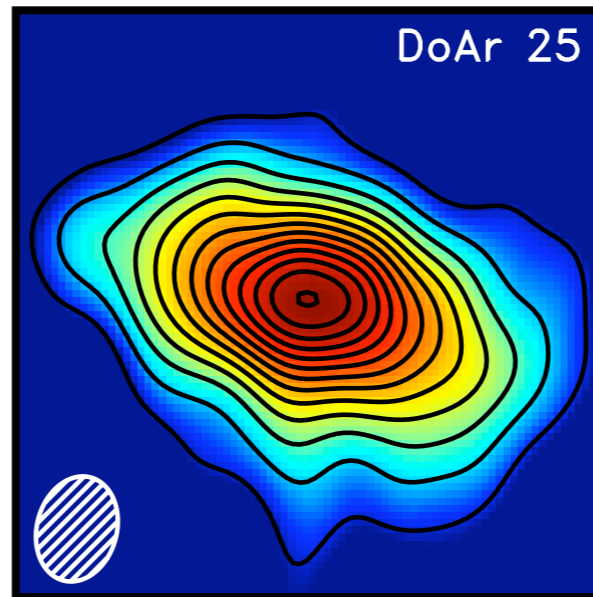


# disk evolution: transition disks

normal



Andrews et al. 2008

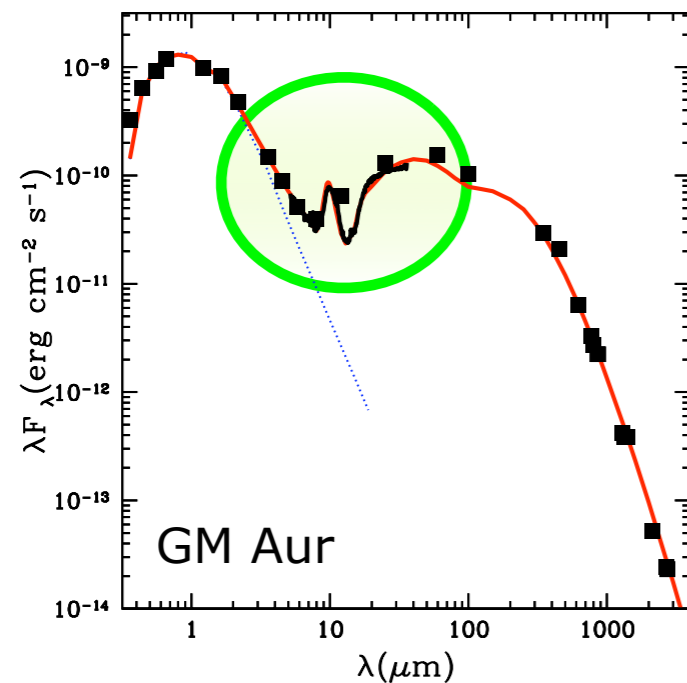


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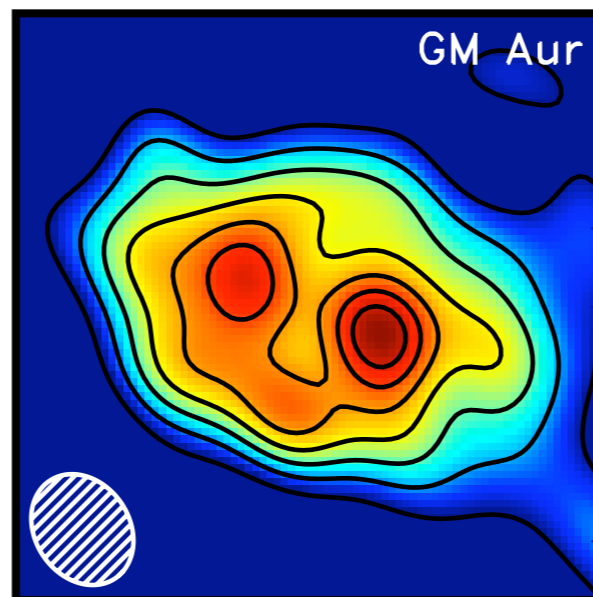
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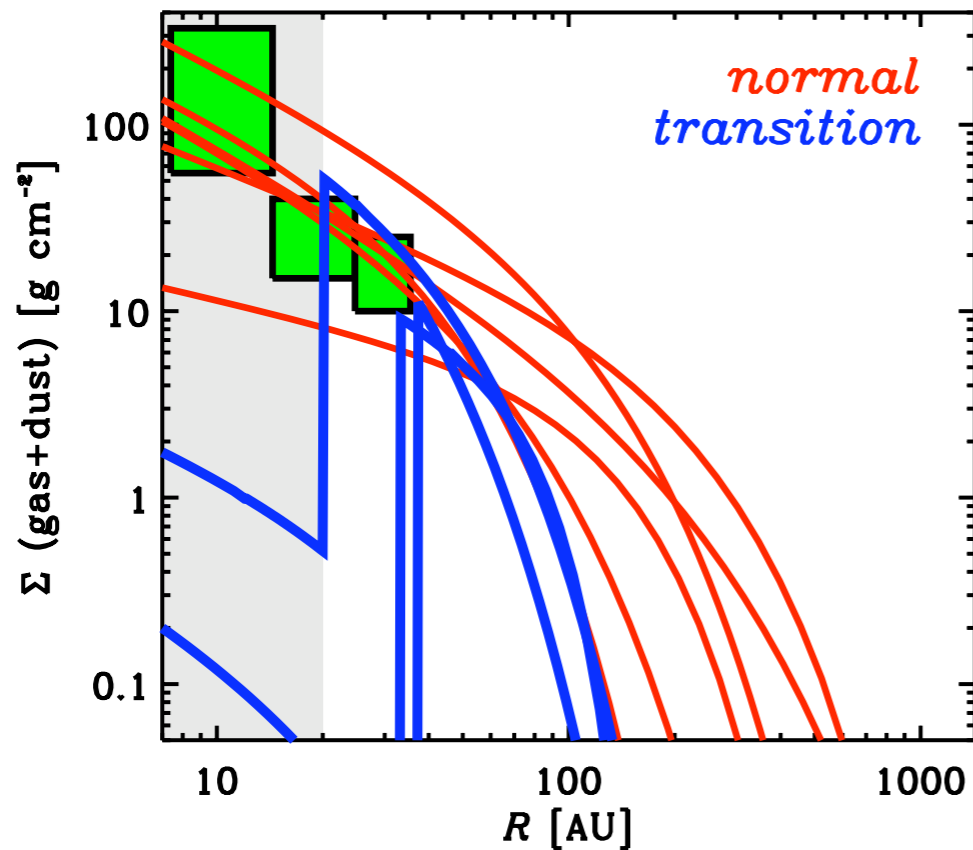


Hughes, Andrews et al. 2009

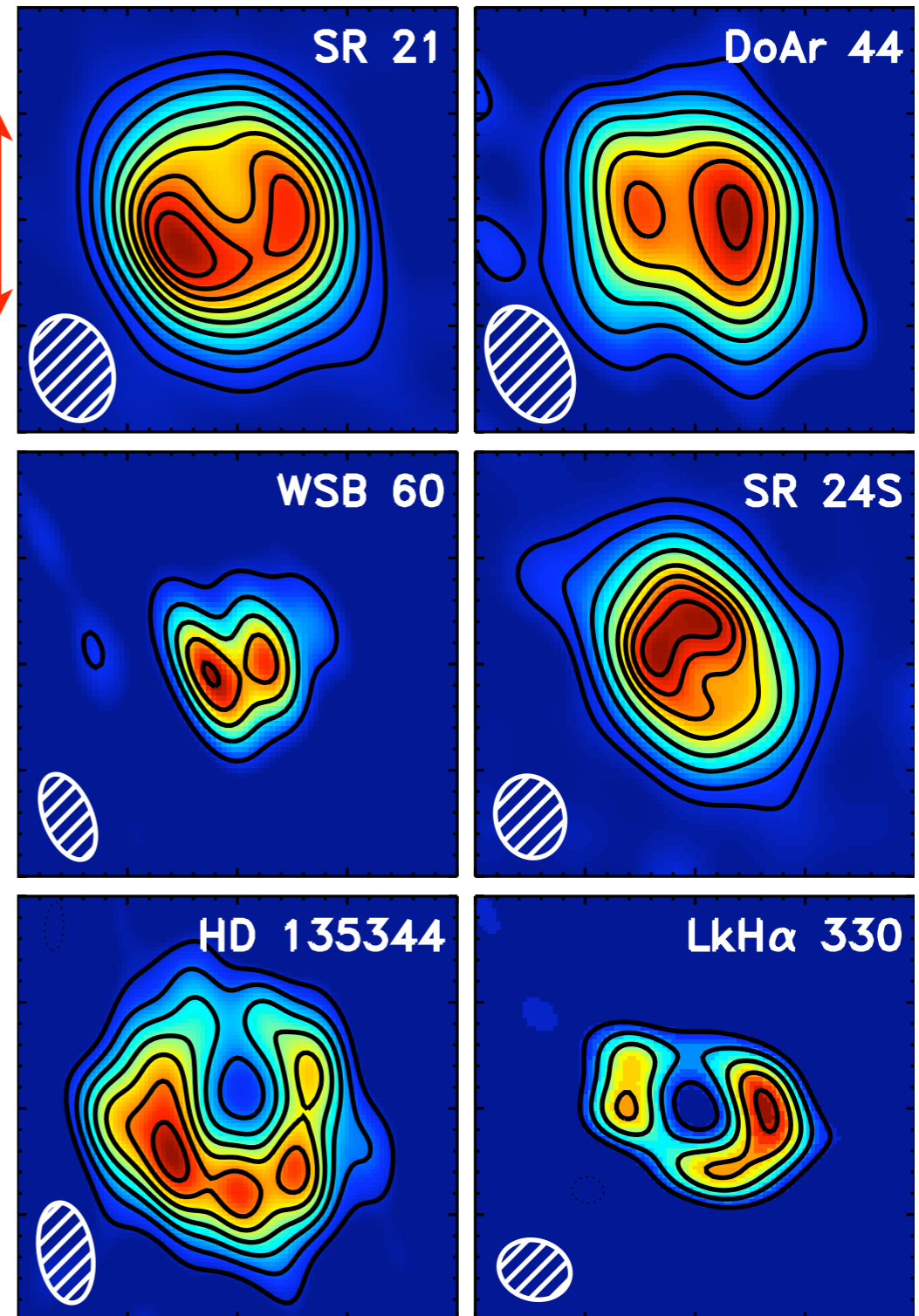


how are they made?  
- photoevaporation  
- particle growth  
- tidal interactions  
• star or BD  
• giant planet

# implications for planet formation

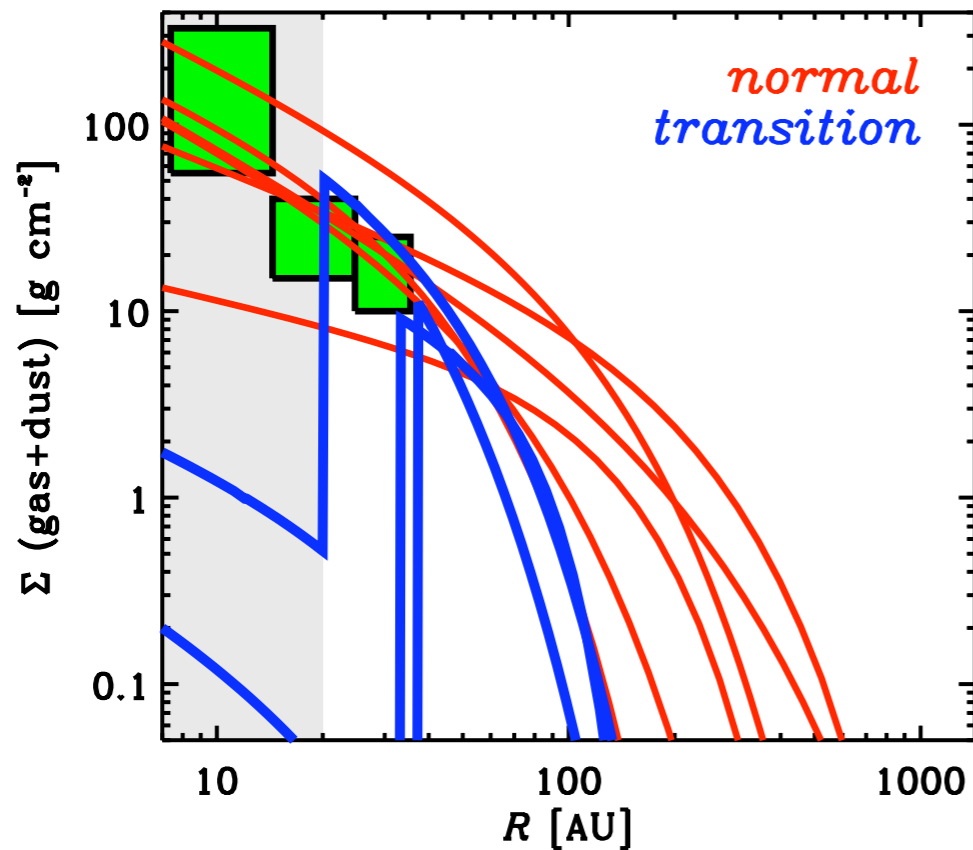


compare to MMSN/normal disks  
cavity radii  $R_{cav} \sim 20-40$  AU



Andrews et al. 2009; Brown et al. 2007, 2009

# implications for planet formation



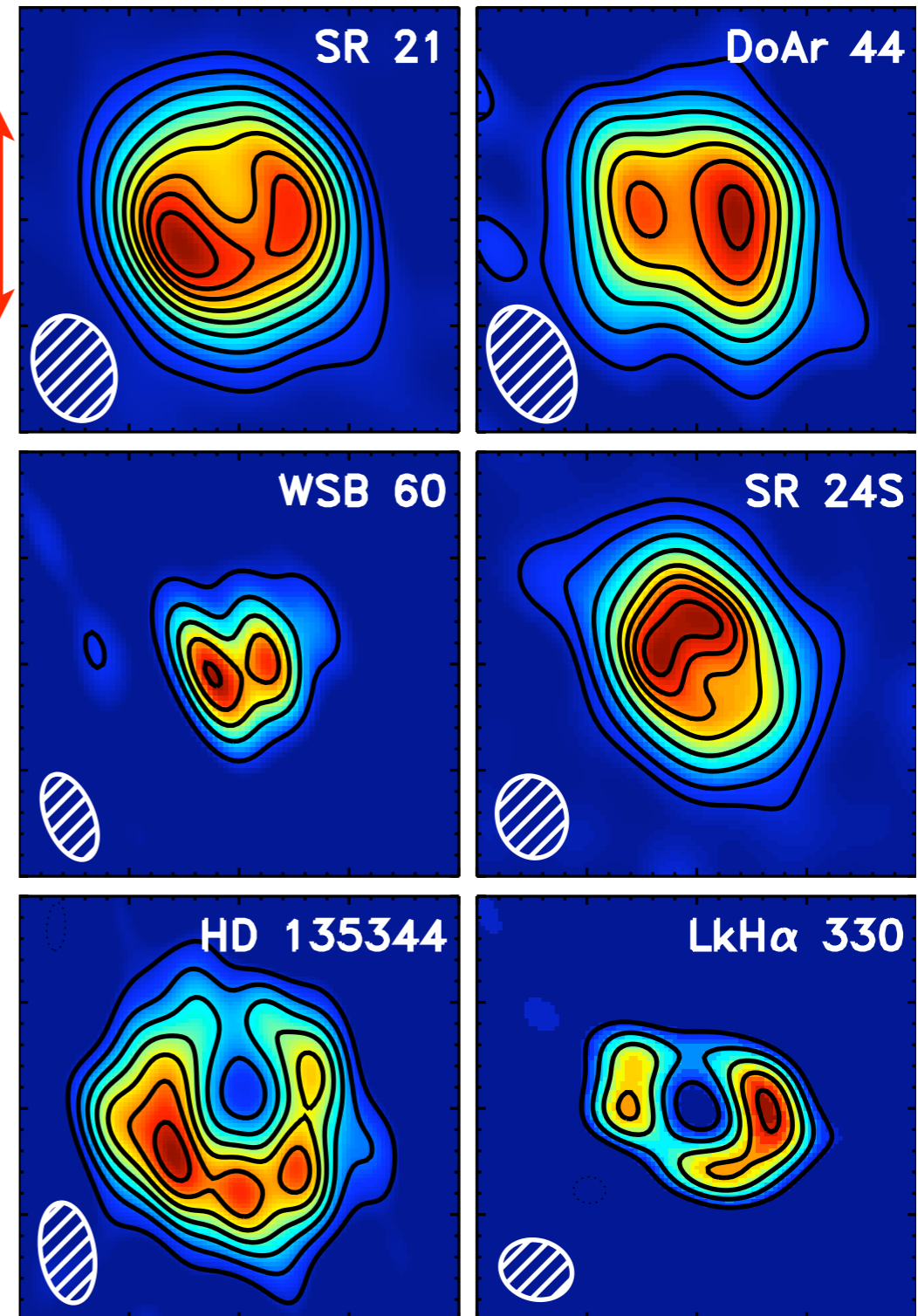
compare to MMSN/normal disks  
cavity radii  $R_{cav} \sim 20\text{-}40$  AU

*but why these disks?*

tidal interactions with unseen  
companion star/BD/planets?

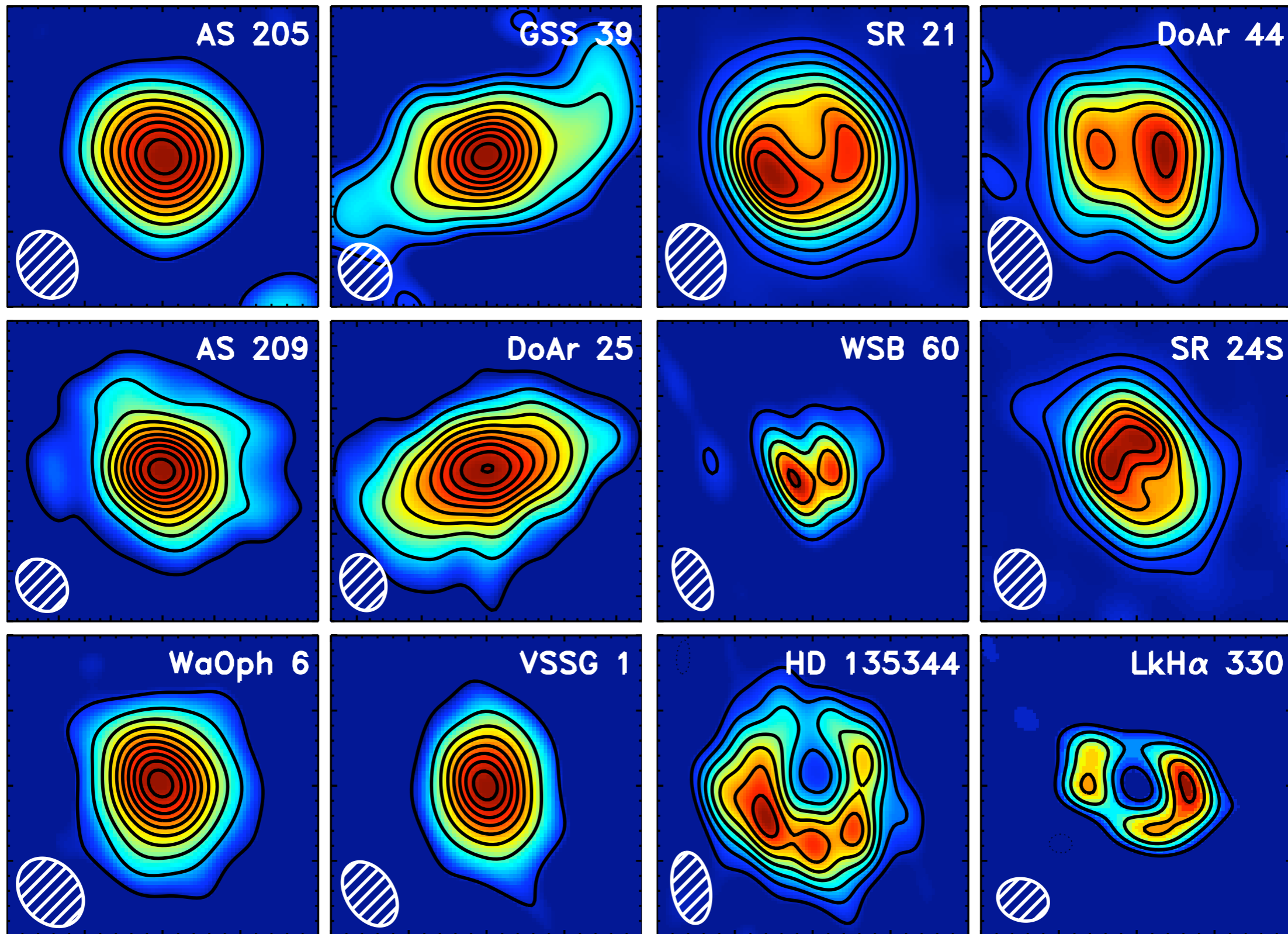
**a hint:** the stars seem *older*

0.5"  
 $\sim 60$  AU



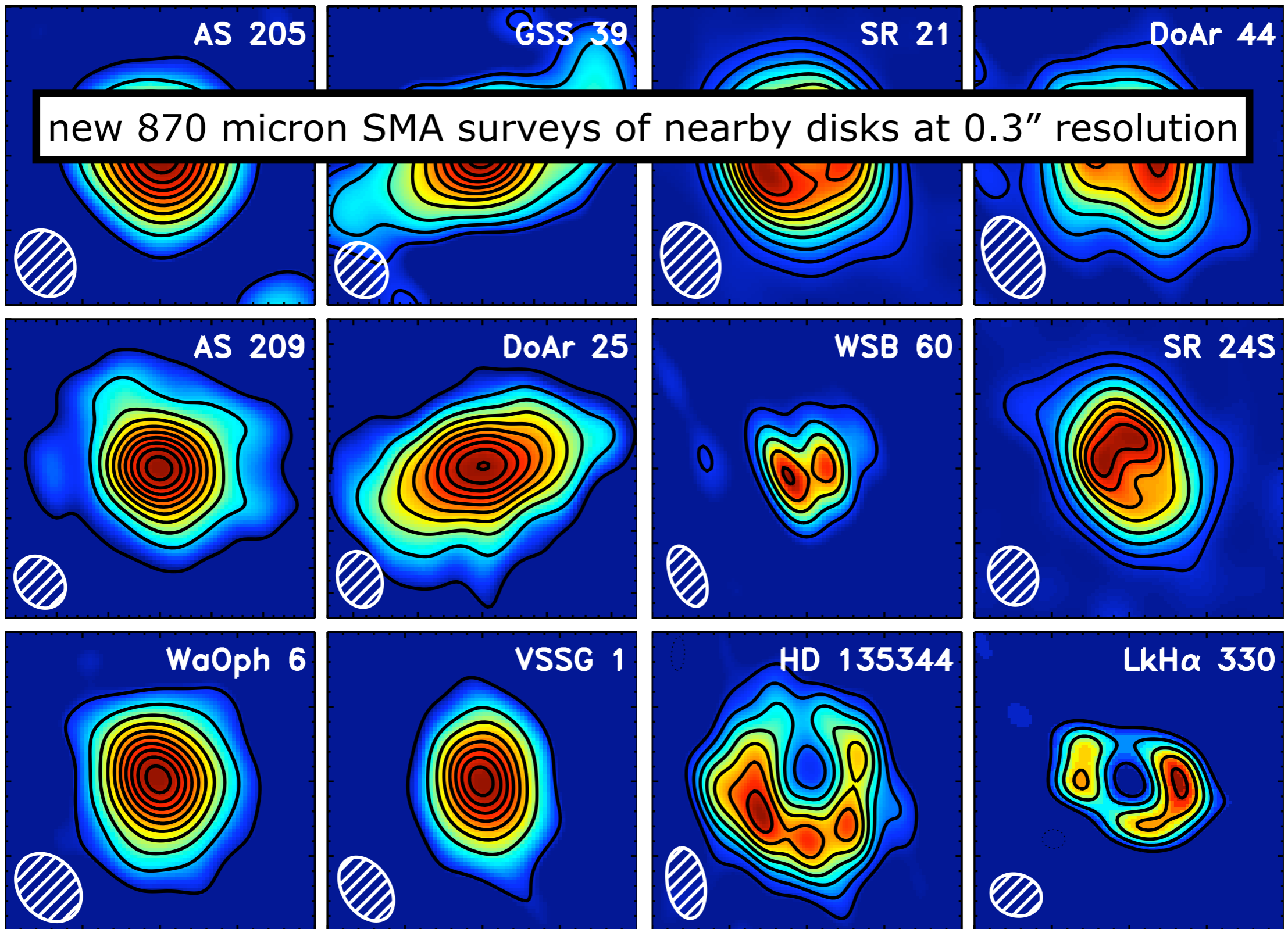
Andrews et al. 2009; Brown et al. 2007, 2009

# summary



# summary

new 870 micron SMA surveys of nearby disks at 0.3" resolution

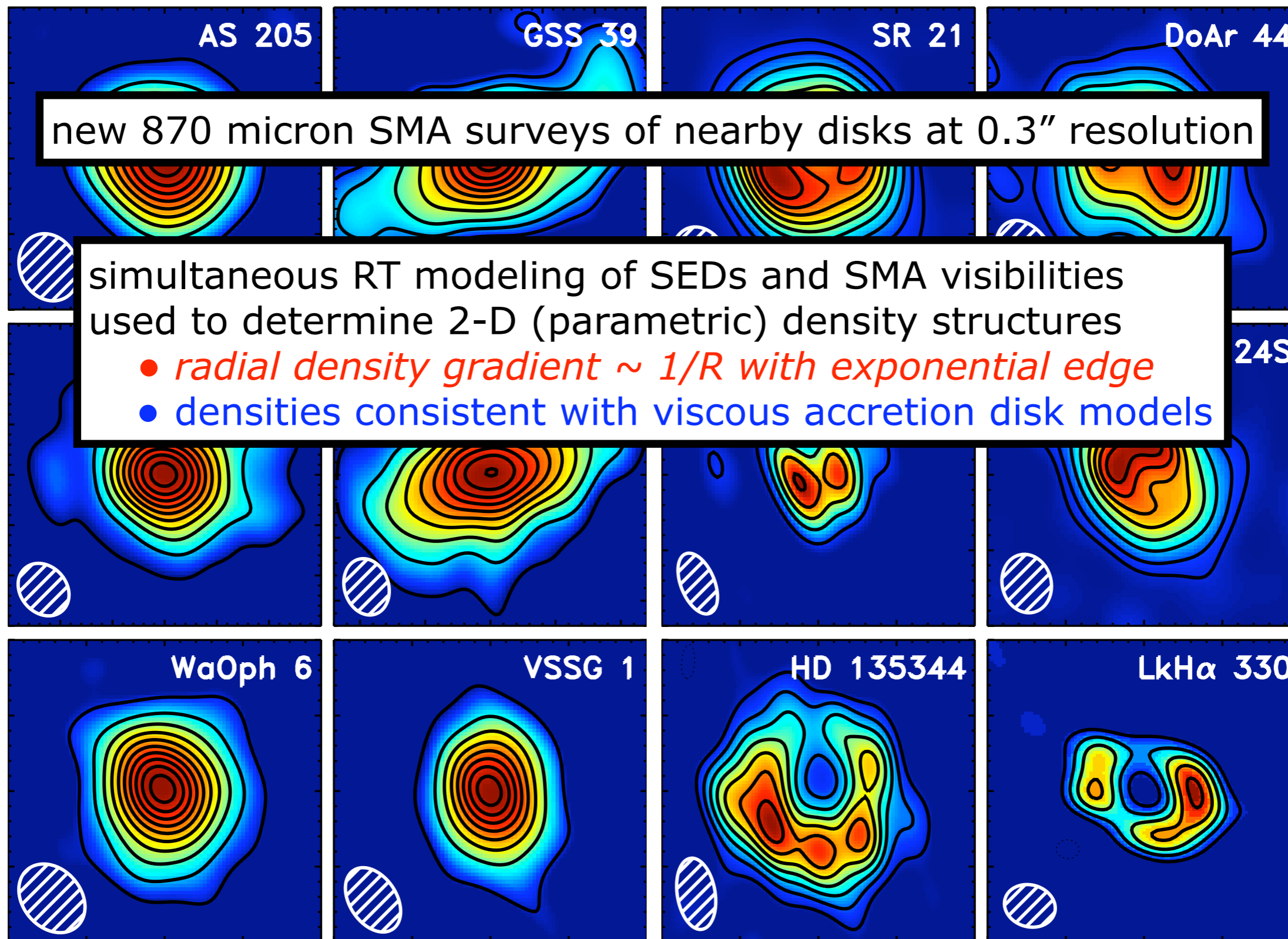


## summary

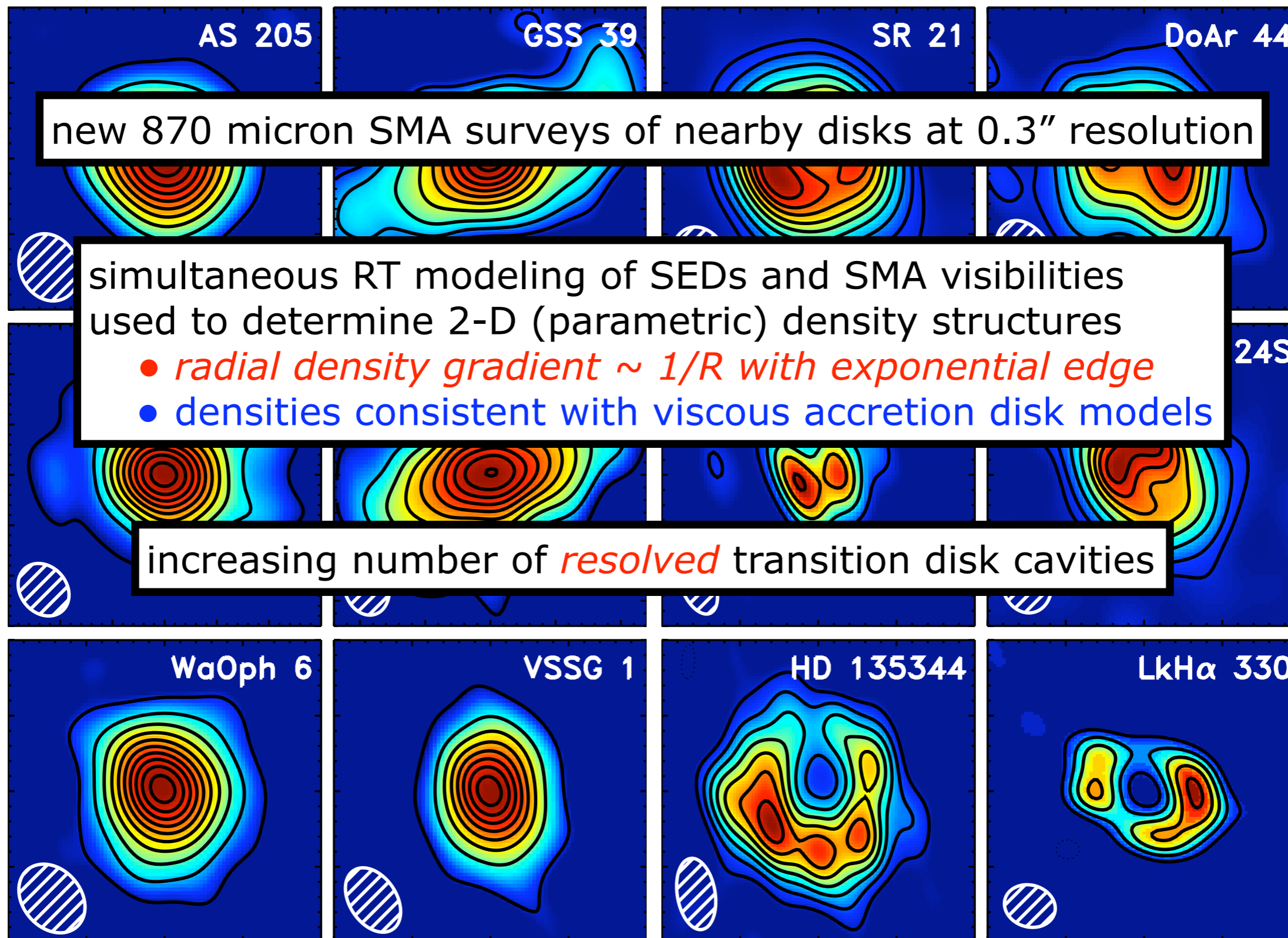
new 870 micron SMA surveys of nearby disks at 0.3'' resolution

simultaneous RT modeling of SEDs and SMA visibilities used to determine 2-D (parametric) density structures

- *radial density gradient  $\sim 1/R$  with exponential edge*
- densities consistent with viscous accretion disk models



## summary



## summary

AS 205

GSS 39

SR 21

DoAr 44

new 870 micron SMA surveys of nearby disks at 0.3" resolution

simultaneous RT modeling of SEDs and SMA visibilities  
used to determine 2-D (parametric) density structures

- *radial density gradient*  $\sim 1/R$  with *exponential edge*
- densities consistent with viscous accretion disk models

24S

increasing number of *resolved* transition disk cavities

WdOph 6

VSSG 1

HD 135344

1 kH $\alpha$  330

**NEXT:** bandwidth-doublers installed on SMA (2 GHz  $\rightarrow$  4 GHz)

- double Oph sample, down to median disk mass
- new survey in Lupus