The *SMA* Perspective on Planet-forming Disks around Young Stars

Sean Andrews

Harvard-Smithsonian CfA

goal: a planet formation model grounded in observations

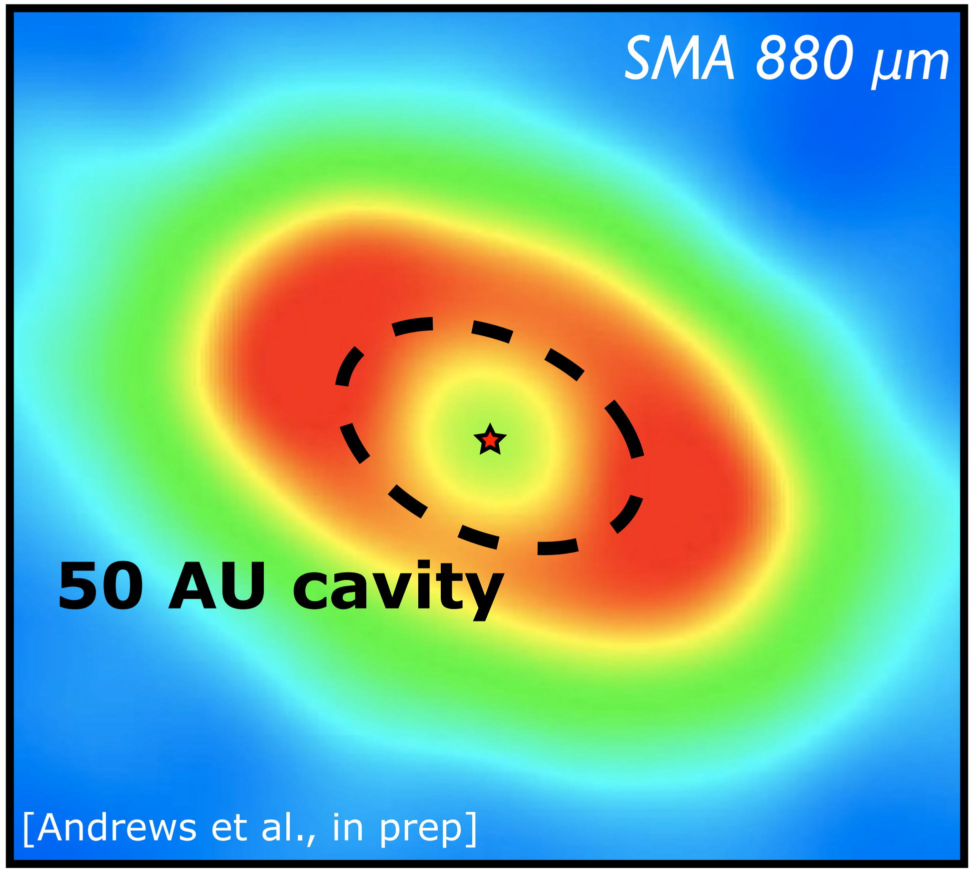
requirements:

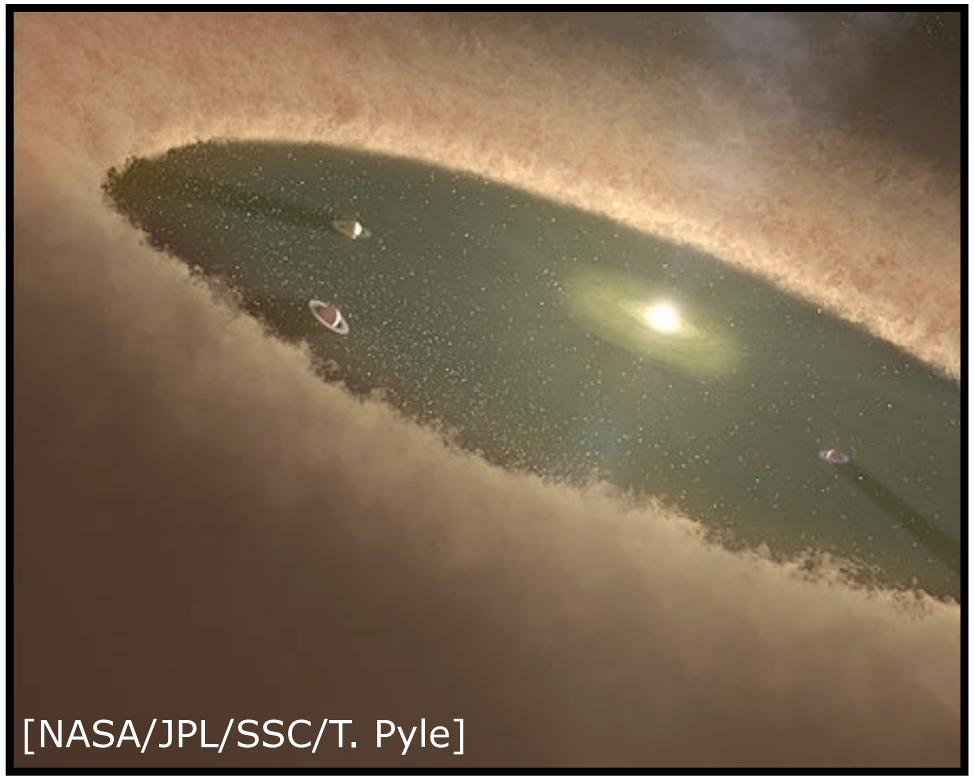
enough stuff + enough time

↓

evolution of mass distribution

- viscous + material evolution
- dissipation/metamorphosis



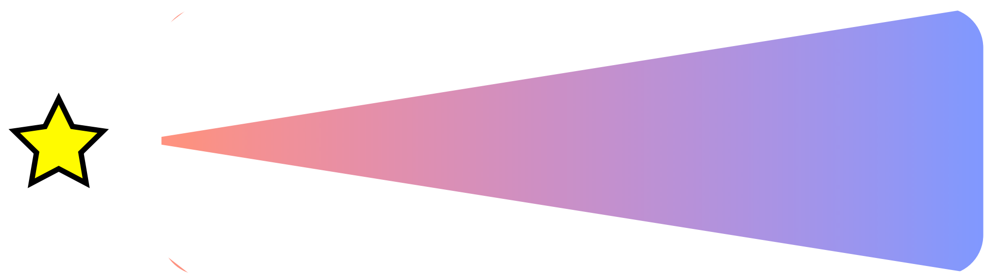


measuring the mass content of a protoplanetary disk

we *assume* most of the mass is cold, molecular gas (H_2)

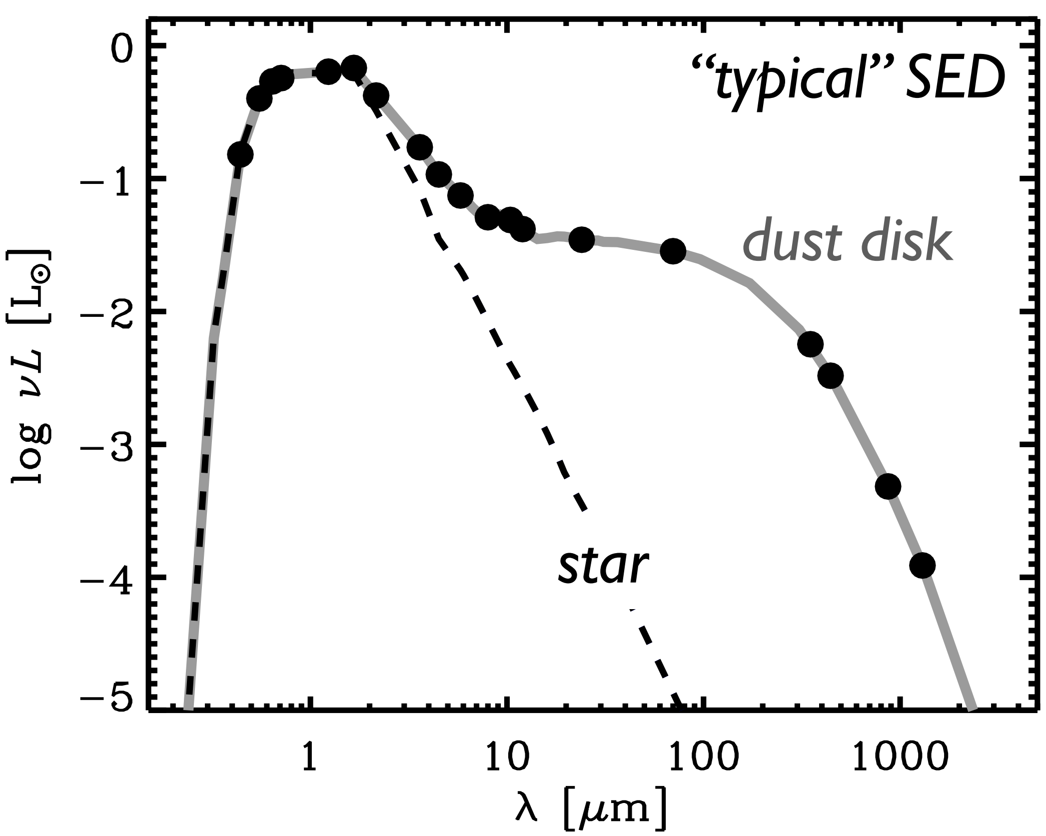
↓

problem: "dark matter"



rely on dust as a tracer

(it dominates the opacity)



measuring the mass content of a protoplanetary disk

we *assume* most of the mass is cold, molecular gas (H_2)

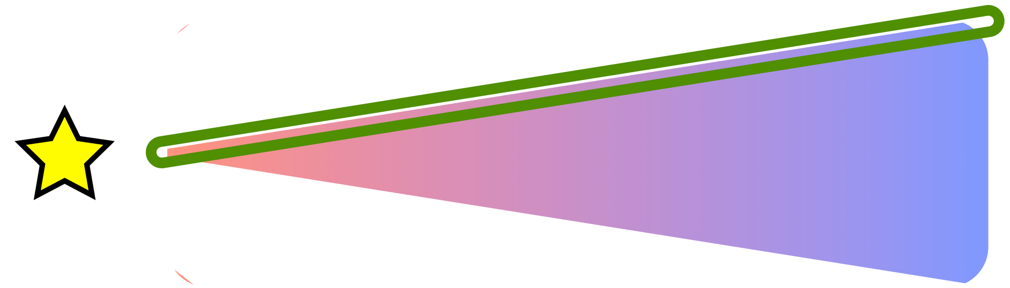
↓

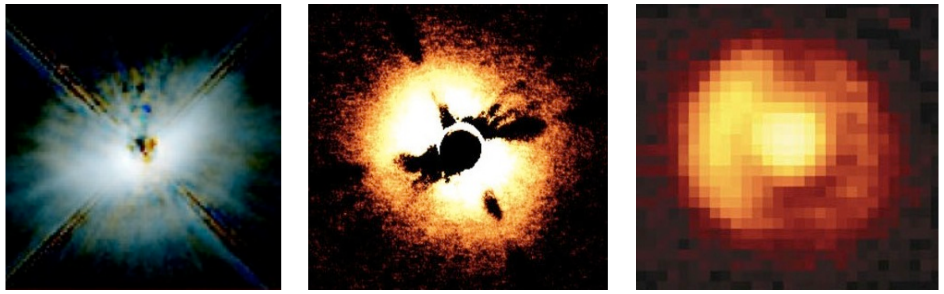
problem: "dark matter"

rely on dust as a tracer

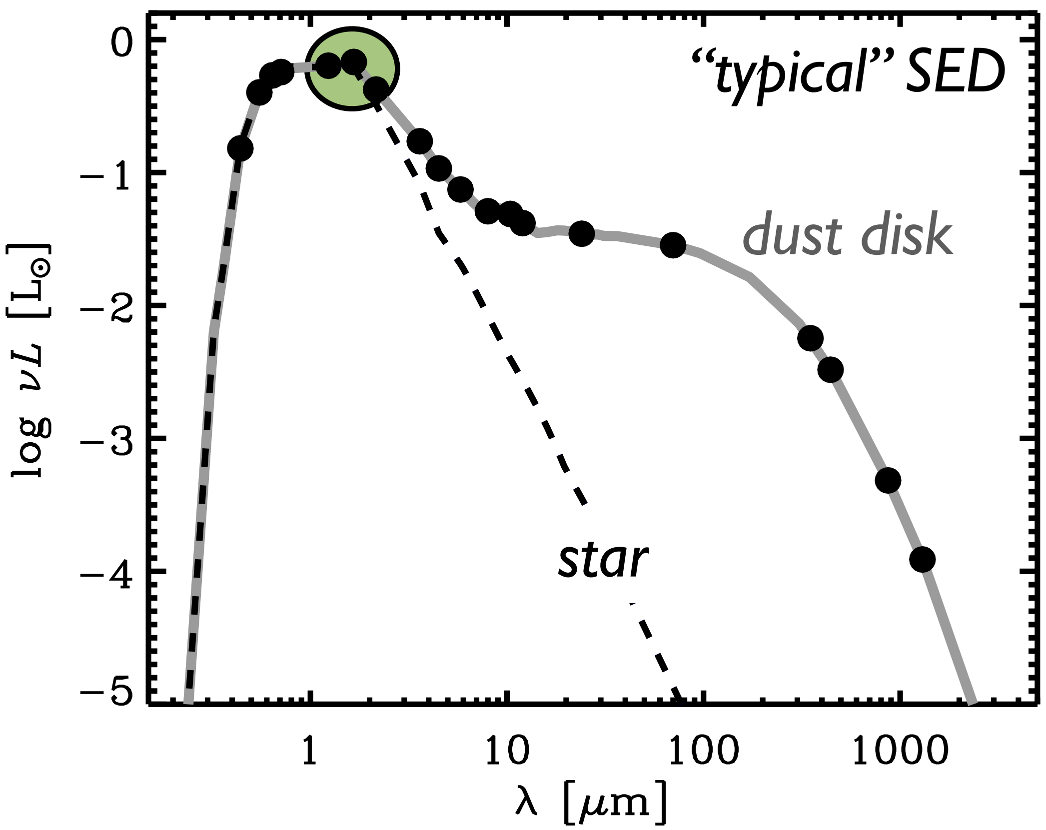
(it dominates the opacity)

- scattered light: flaring/size





[Schneider+ 2003; Kudo+ 2008; Fujiwara+ 2006]



measuring the mass content of a protoplanetary disk

we *assume* most of the mass
is cold, molecular gas (H_2)

↓

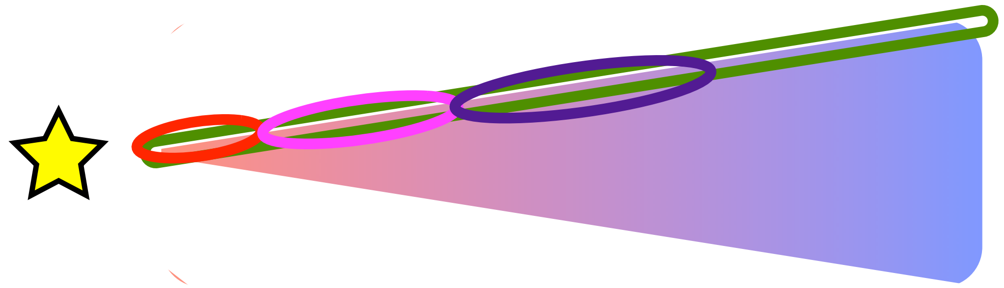
problem: "dark matter"

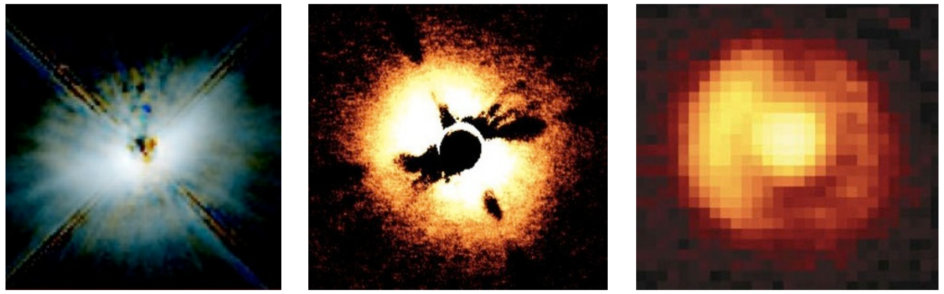
rely on dust as a tracer

(it dominates the opacity)

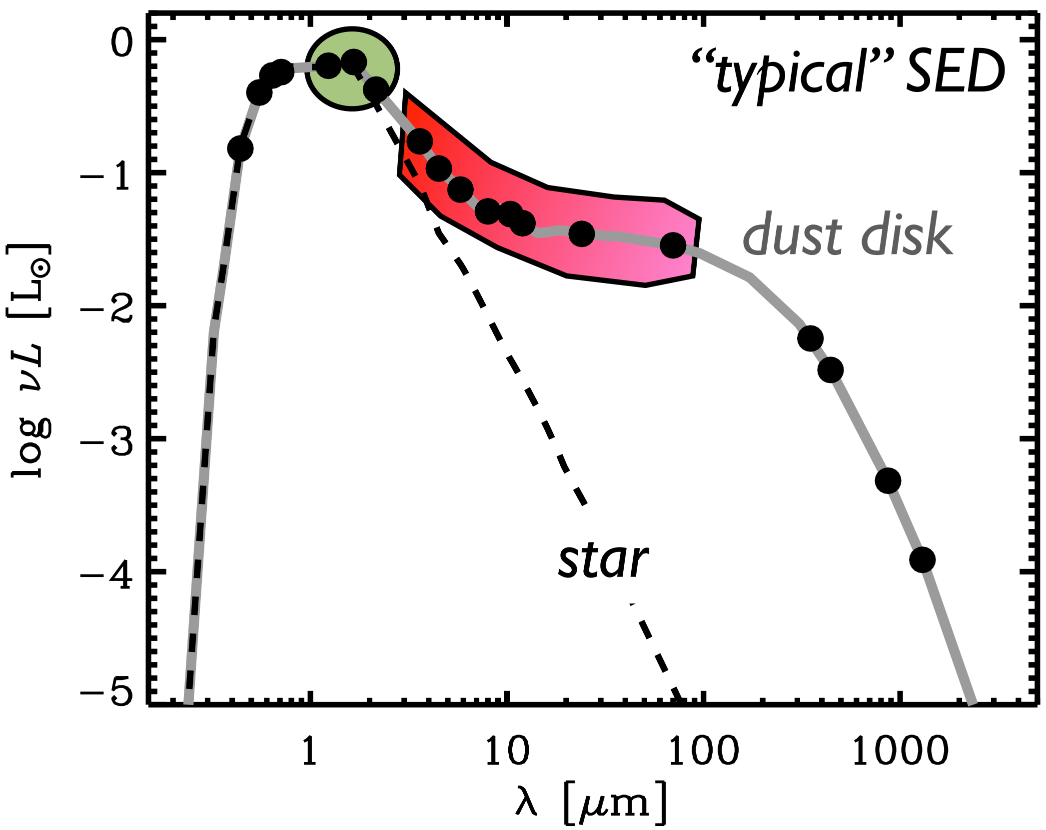
- scattered light: flaring/size

- IR: flared surface/heating





[Schneider+ 2003; Kudo+ 2008; Fujiwara+ 2006]



measuring the mass content of a protoplanetary disk

we *assume* most of the mass is cold, molecular gas (H_2)

↓

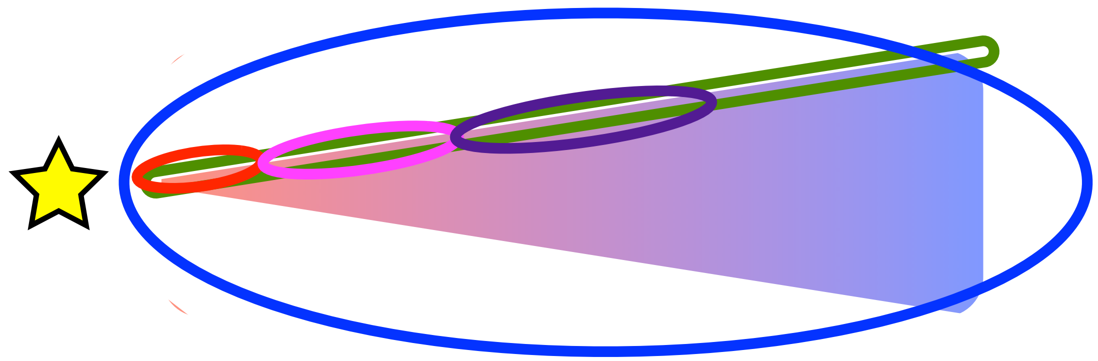
problem: "dark matter"

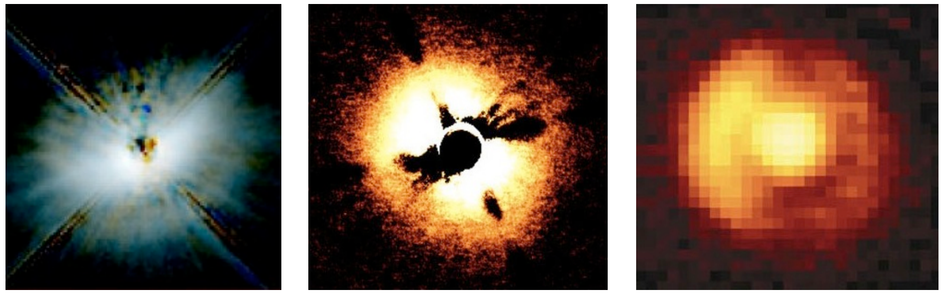
rely on dust as a tracer

(it dominates the opacity)

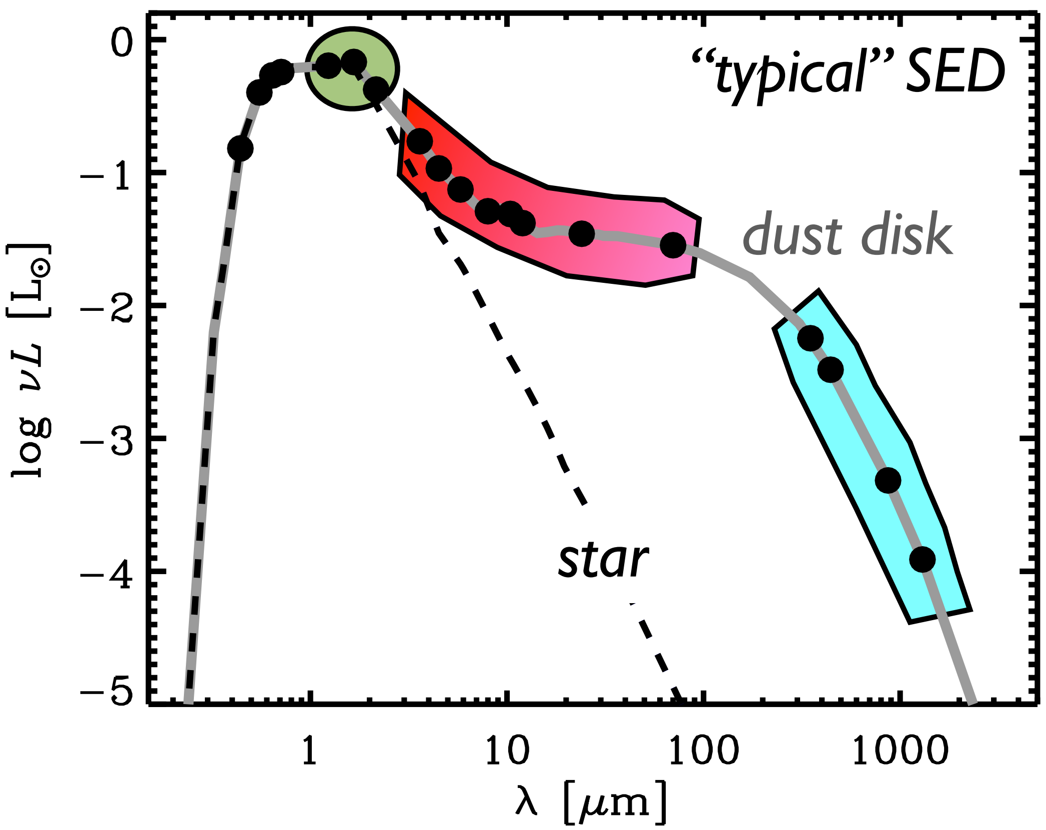
- scattered light: flaring/size
- IR: flared surface/heating
- radio: mass in the midplane

emission $\propto \kappa_\nu \Sigma T$





[Schneider+ 2003; Kudo+ 2008; Fujiwara+ 2006]



measuring the mass content of a protoplanetary disk

we *assume* most of the mass is cold, molecular gas (H_2)

↓

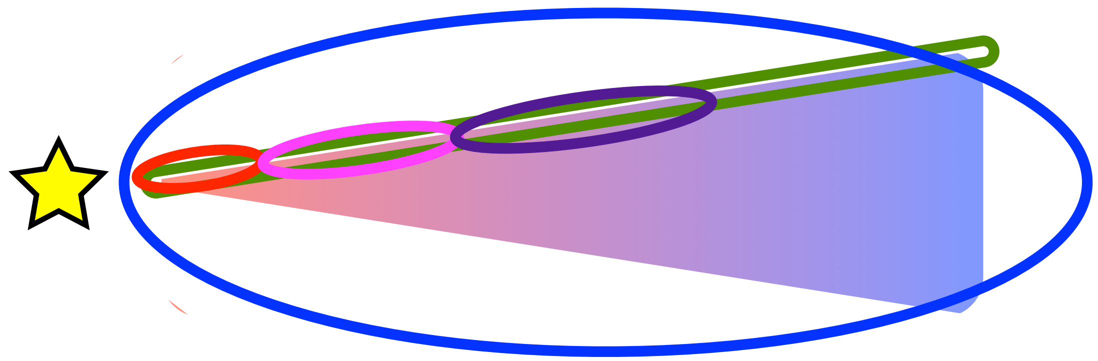
problem: "dark matter"

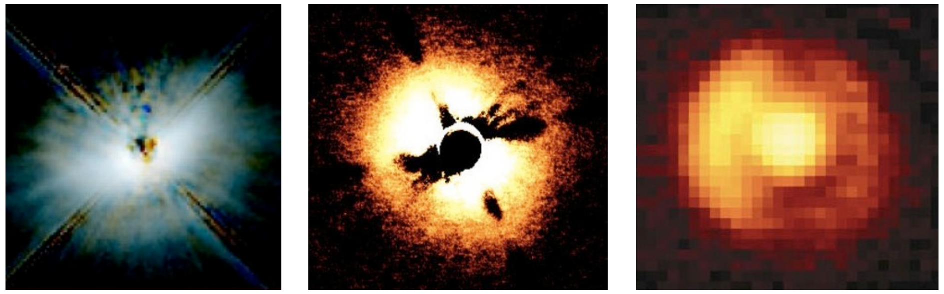
rely on dust as a tracer

(it dominates the opacity)

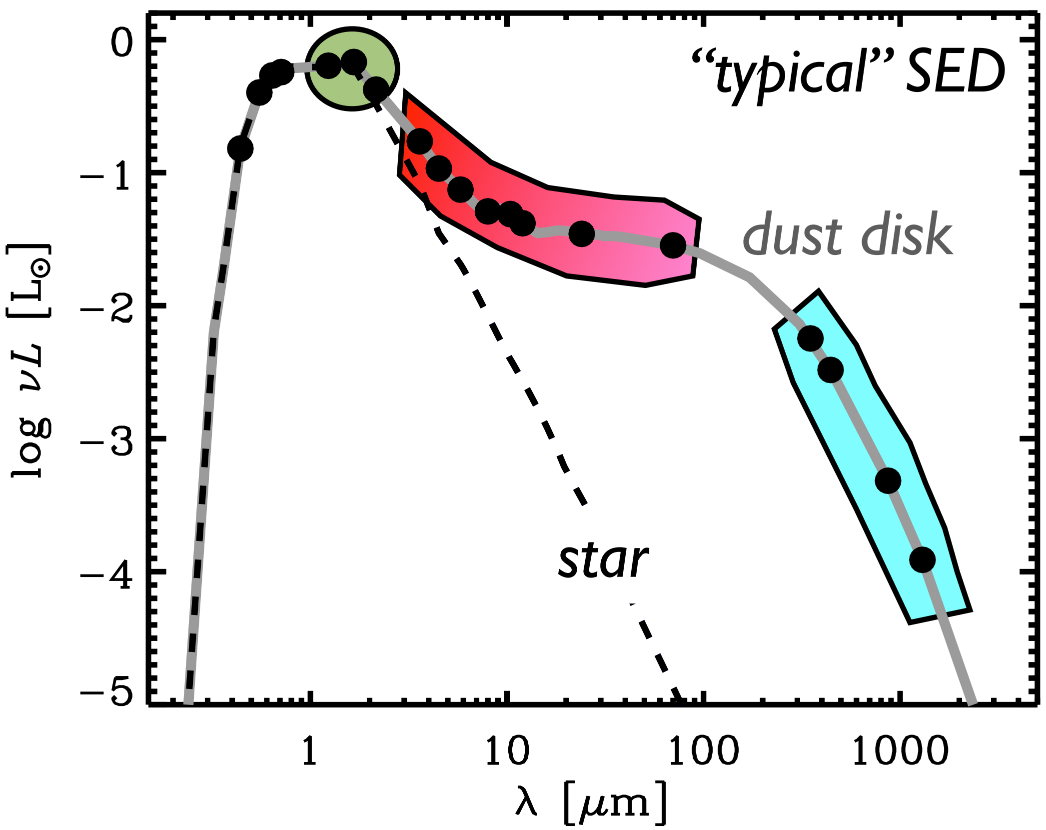
- scattered light: flaring/size
- IR: flared surface/heating
- radio: mass in the midplane

emission $\propto \kappa_\nu \Sigma T$





[Schneider+ 2003; Kudo+ 2008; Fujiwara+ 2006]

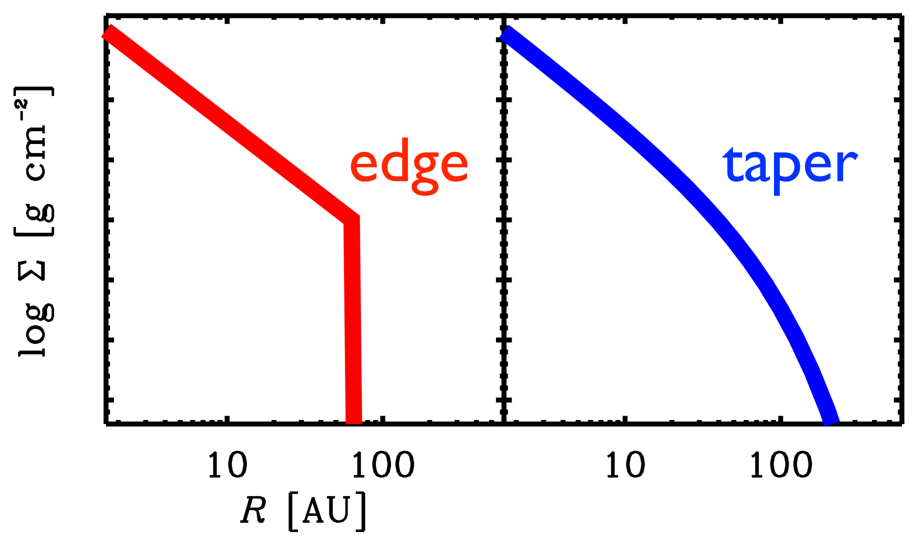


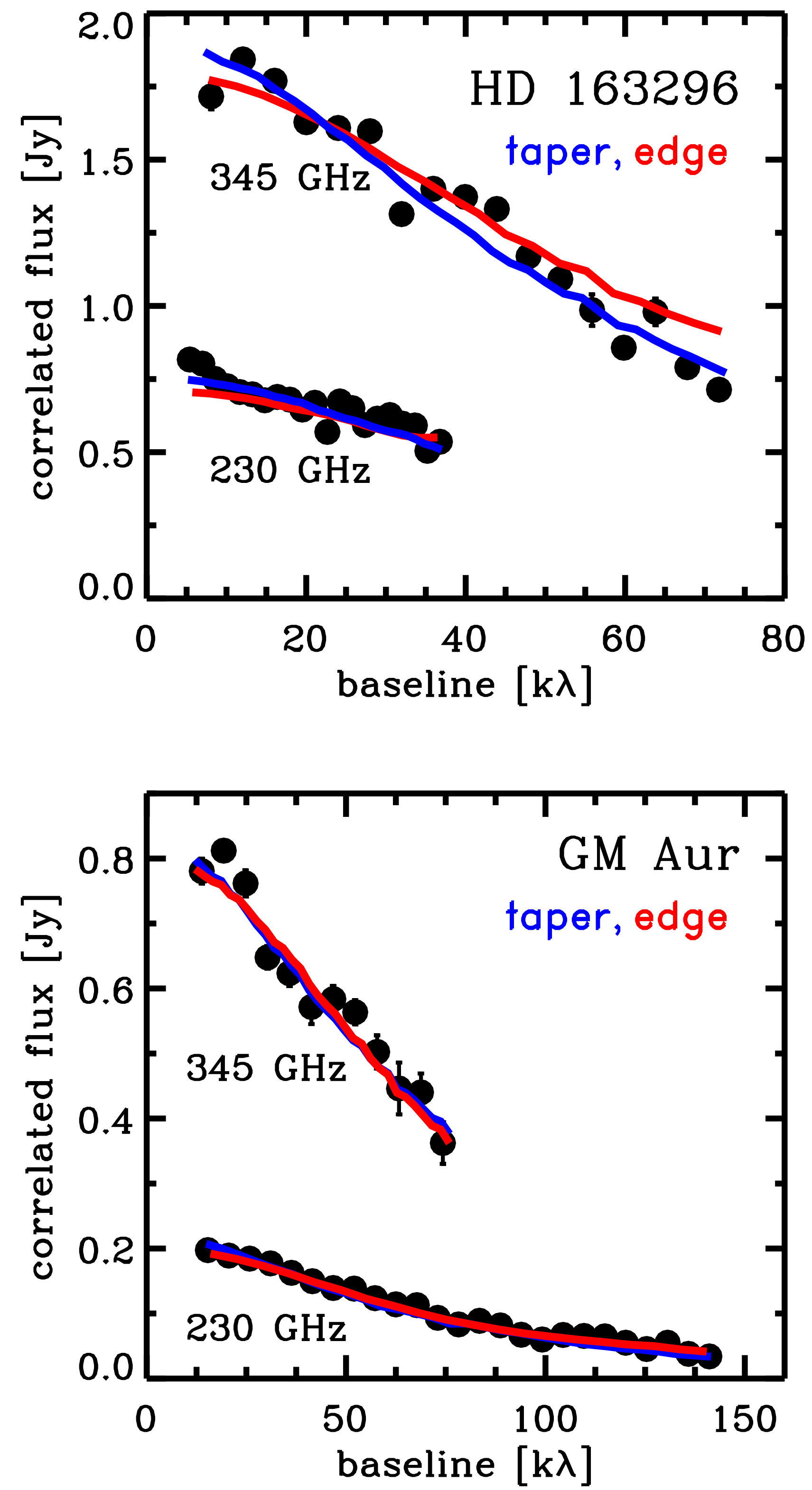
an appropriate model for the density structure?

a density puzzle:

if Σ is a power law+edge,
dust sizes << gas sizes (!)

[Pietu et al. 2005; Isella et al. 2007]



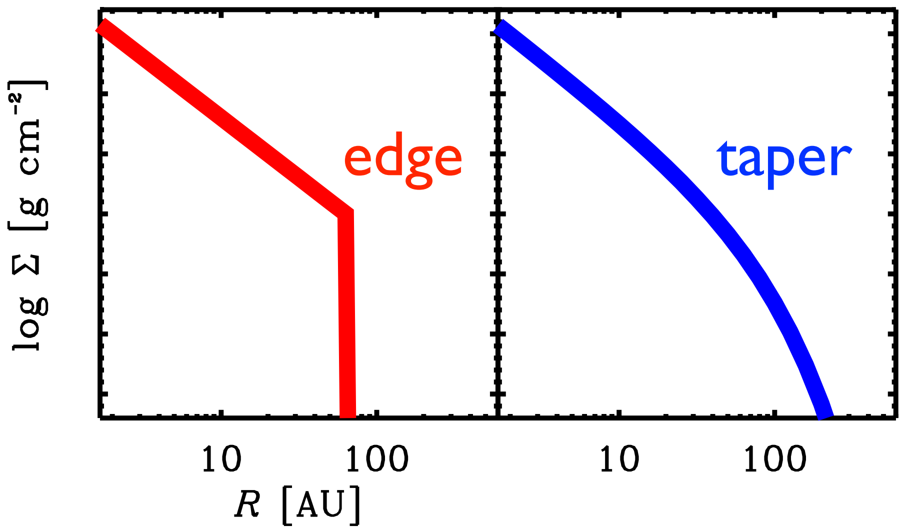


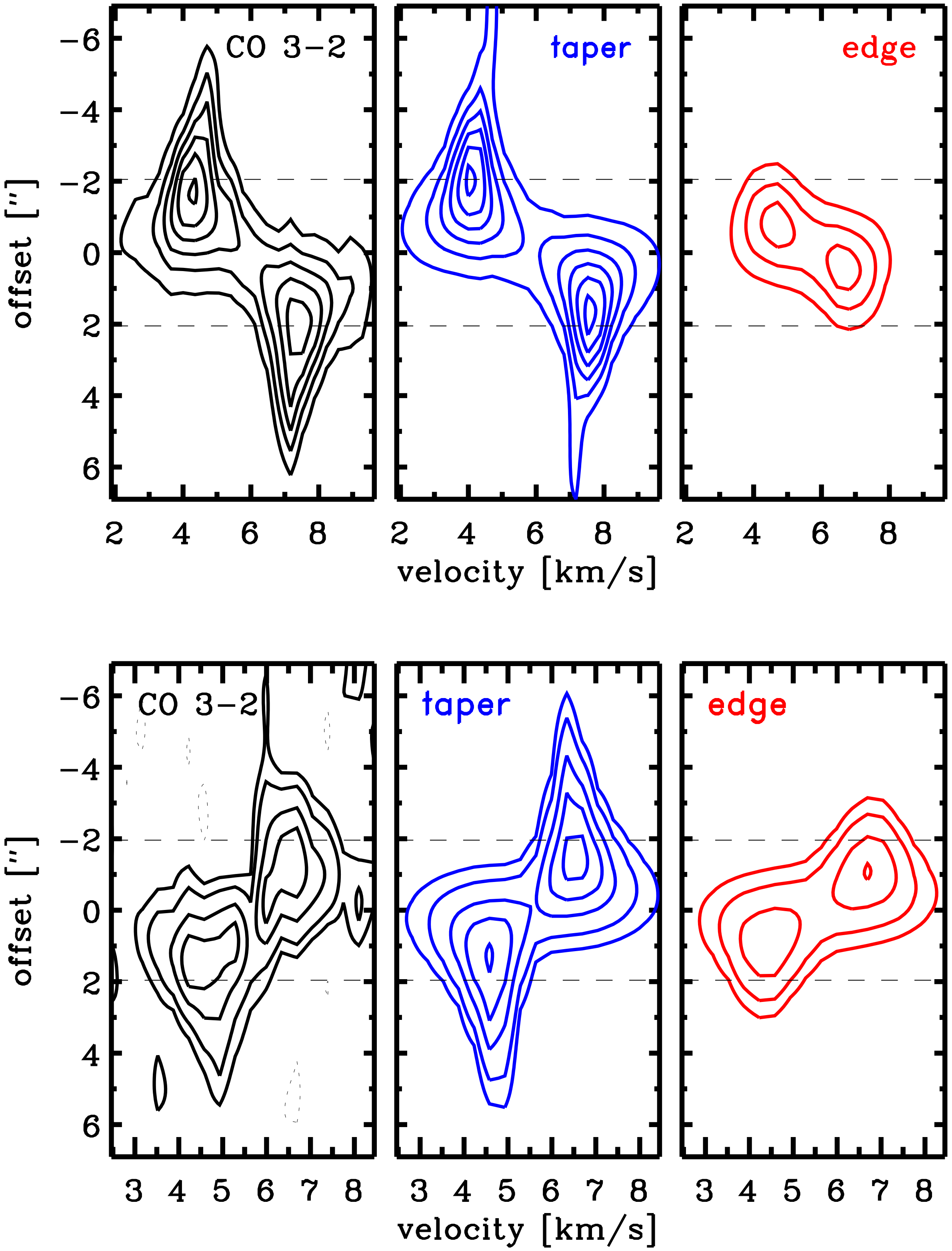
an appropriate model for the density structure?

a density puzzle:

if Σ is a power law+edge,
dust sizes << gas sizes (!)

[Pietu et al. 2005; Isella et al. 2007]



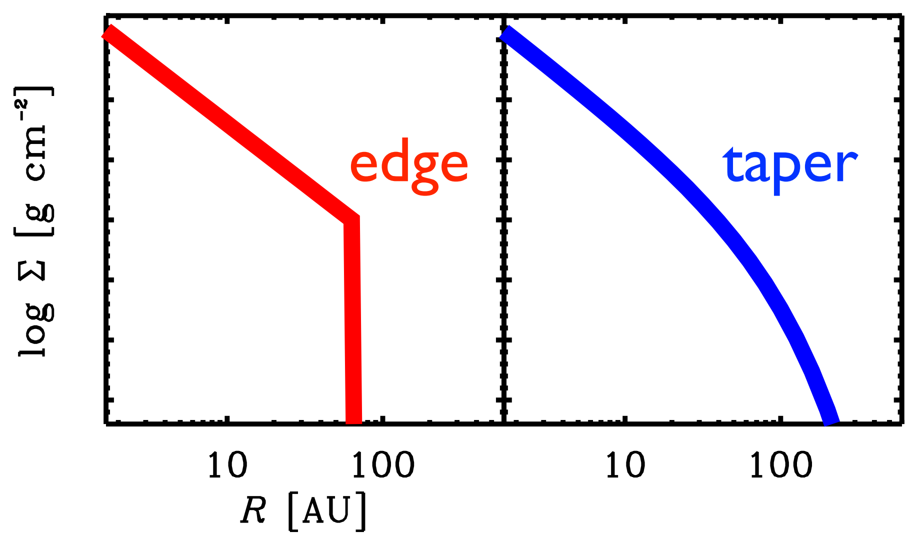


an appropriate model for the density structure?

a density puzzle:

if Σ is a power law+edge,
dust sizes << gas sizes (!)

[Pietu et al. 2005; Isella et al. 2007]

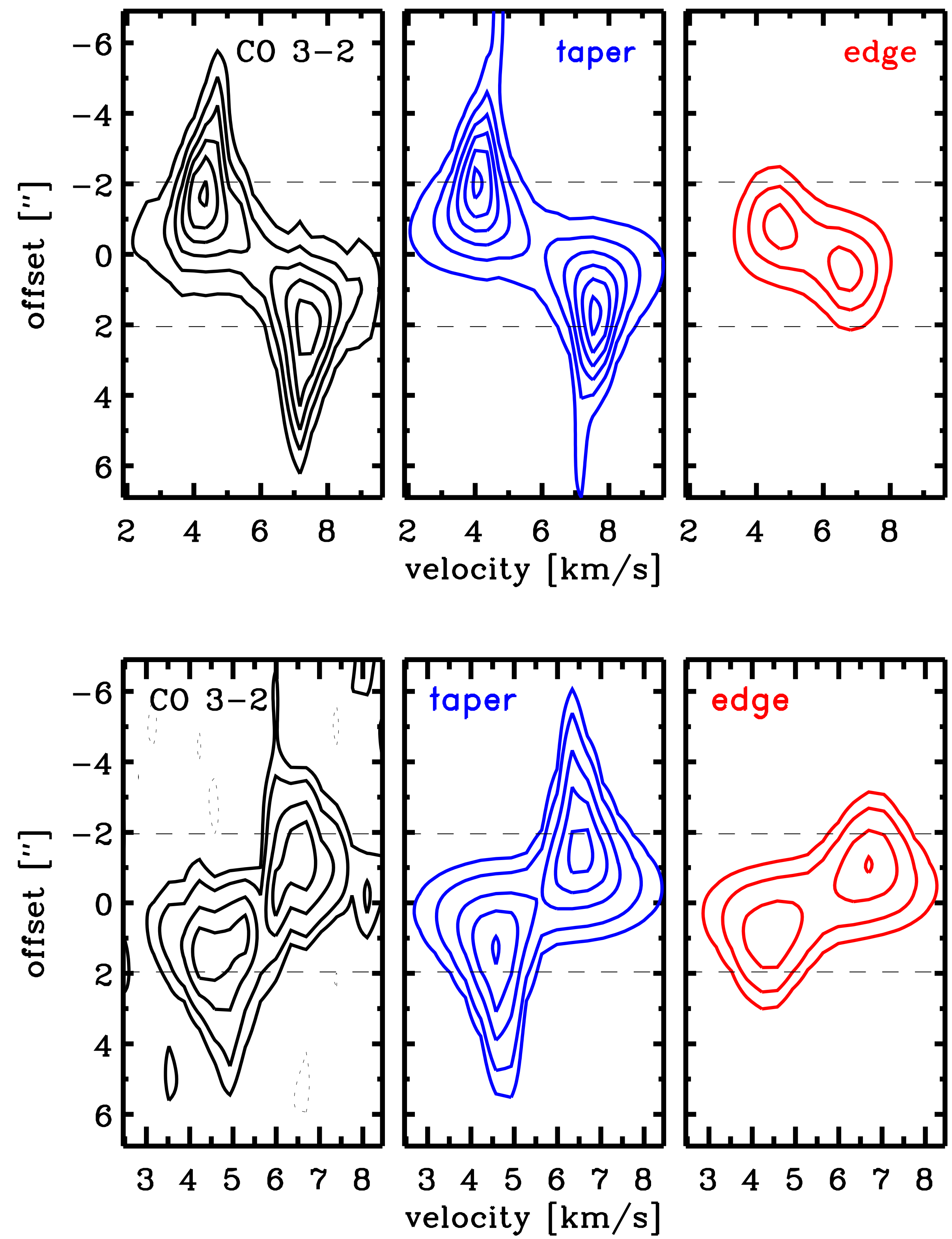


the solution:

Σ has a large-*R* taper;
expected for accretion disks

no sharp (outer) edges!

[Hughes et al. 2008]



disk density structures from radio interferometry data

parametric model:

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

+

starlight, dust population

+

radiative transfer calculations

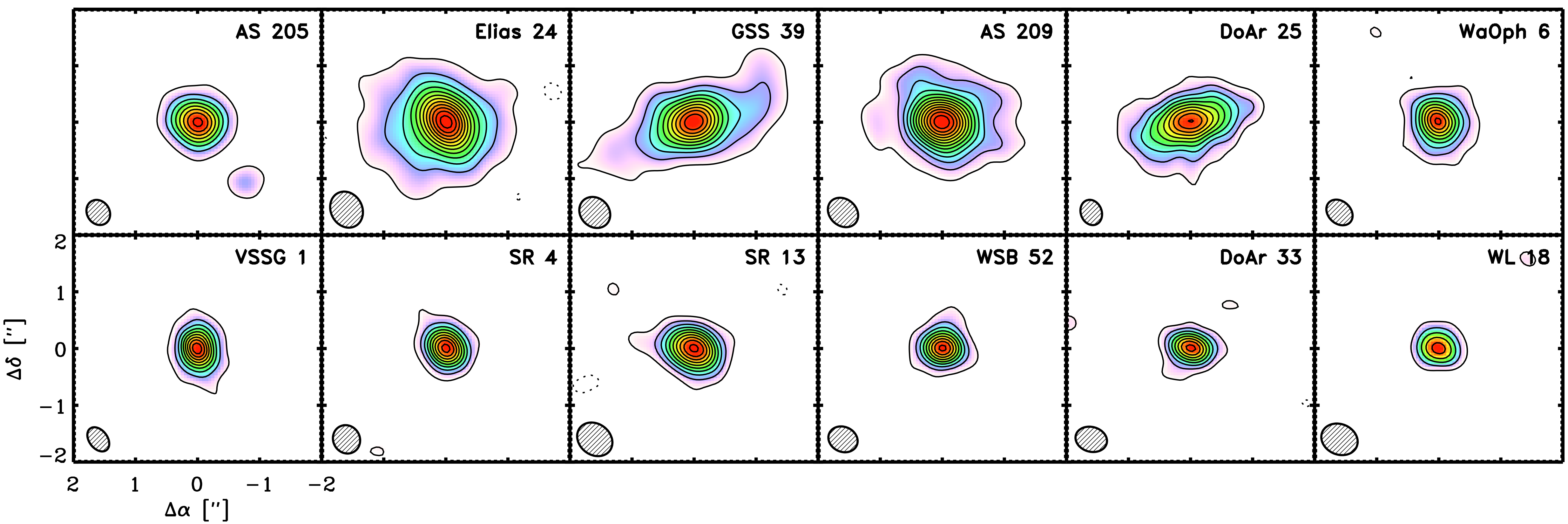
resolved radio emission $\propto \kappa_\nu \Sigma T$

+

IR spectrum/scat. light/CO $\sim T$

[e.g., Kitamura et al. 2002, Pietu et al. 2005, Andrews & Williams 2007, Pinte et al. 2008, Isella et al. 2009]

data



disk density structures from radio interferometry data

parametric model:

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

+

starlight, dust population

+

radiative transfer calculations

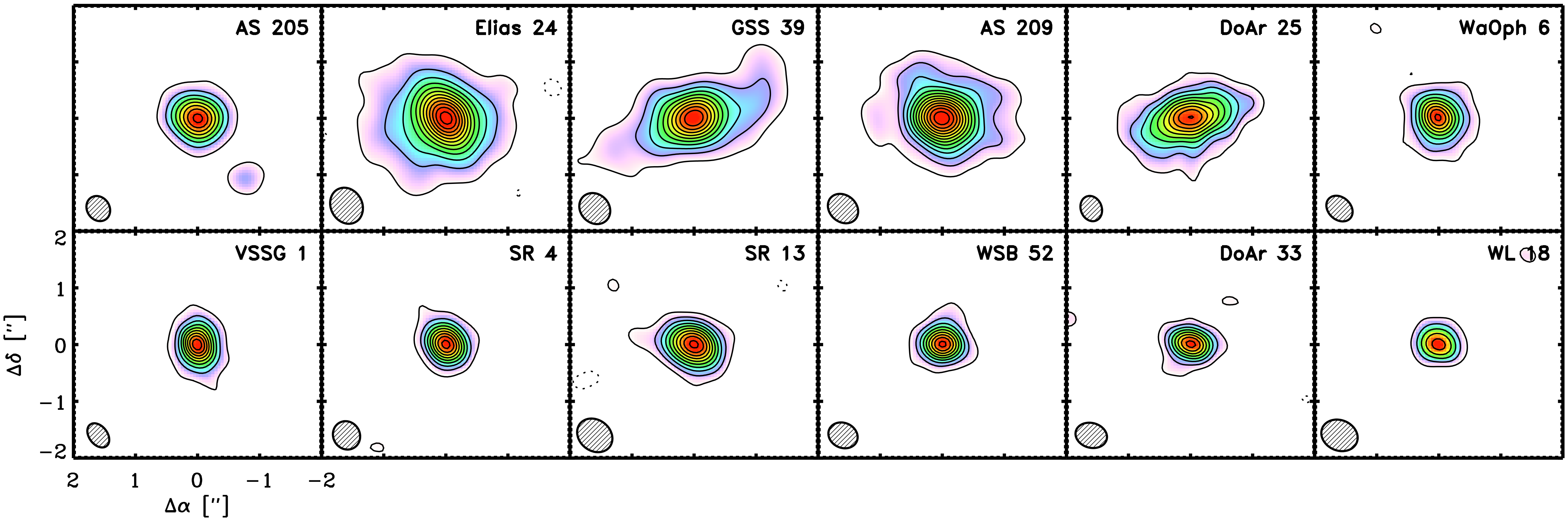
resolved radio emission $\propto \kappa_\nu \Sigma T$

+

IR spectrum/scat. light/CO $\sim T$

[e.g., Kitamura et al. 2002, Pietu et al. 2005, Andrews & Williams 2007, Pinte et al. 2008, Isella et al. 2009]

data



disk density structures from radio interferometry data

parametric model:

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

+

starlight, dust population

+

radiative transfer calculations

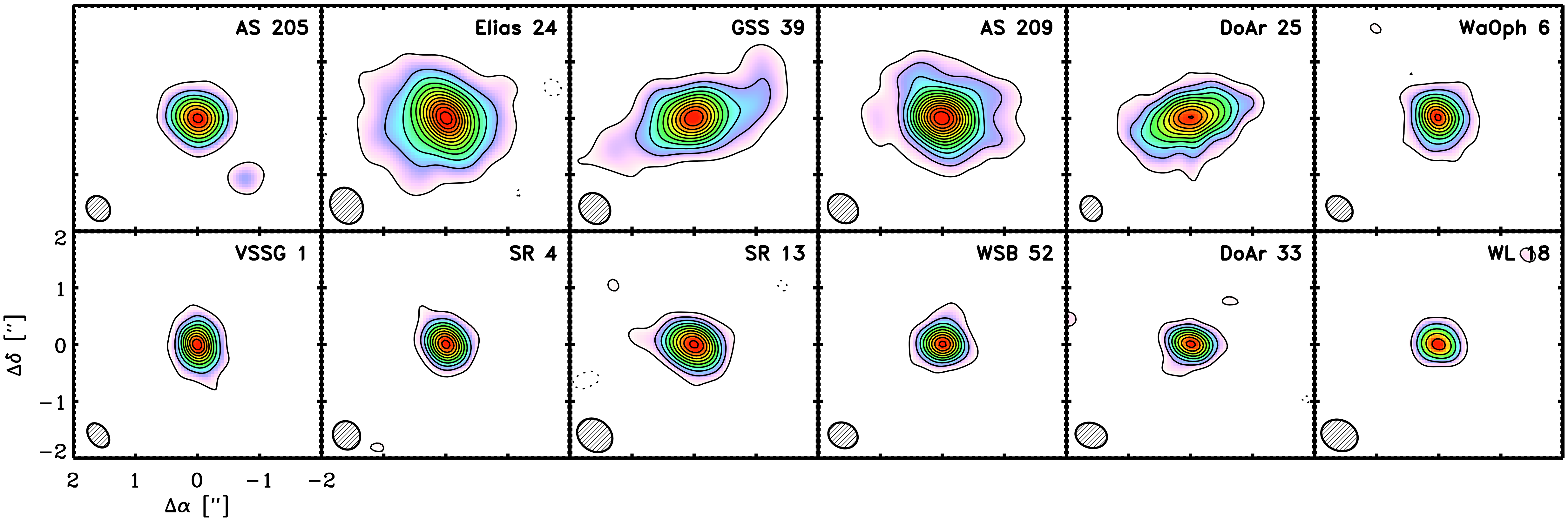
resolved radio emission $\propto \kappa_\nu \Sigma T$

+

IR spectrum/scat. light/CO $\sim T$

[e.g., Kitamura et al. 2002, Pietu et al. 2005, Andrews & Williams 2007, Pinte et al. 2008, Isella et al. 2009]

data



disk density structures from radio interferometry data

parametric model:

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

+

starlight, dust population

+

radiative transfer calculations

resolved radio emission $\propto \kappa_\nu \Sigma T$

+

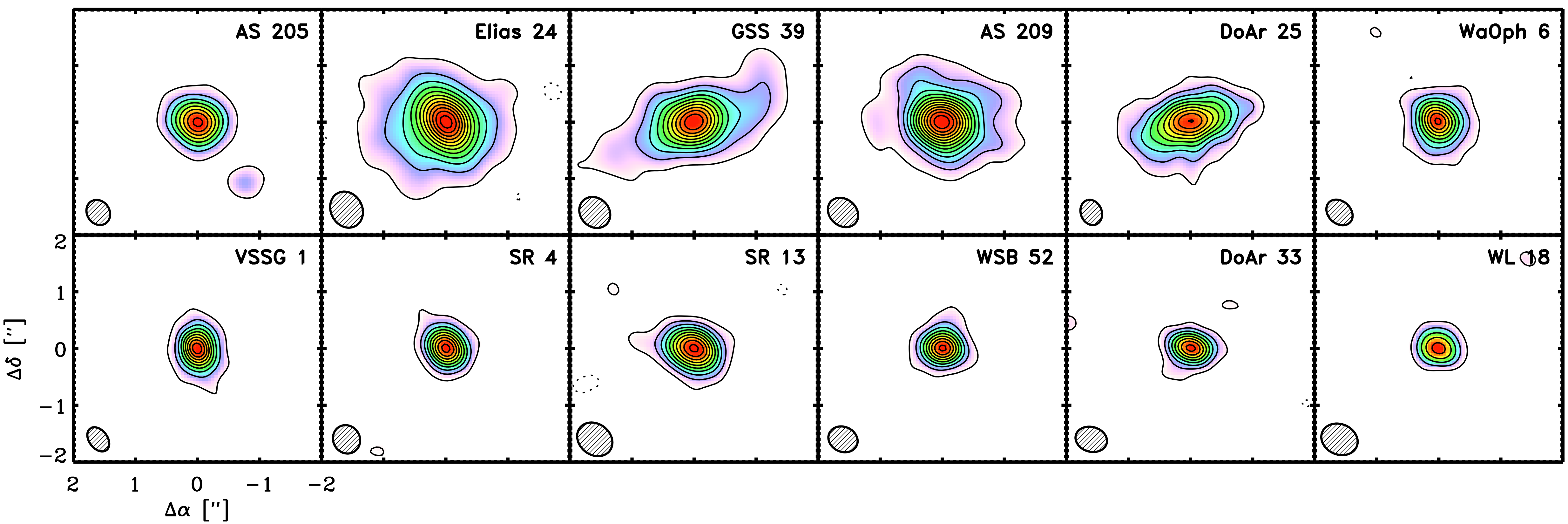
IR spectrum/scat. light/CO $\sim T$

[e.g., Kitamura et al. 2002, Pietu et al. 2005, Andrews & Williams 2007, Pinte et al. 2008, Isella et al. 2009]

new results: SMA disk survey
0.85 mm, 0.3”=20 AU resolution
2-D Monte Carlo RT (RADMC)

[Andrews et al. 2009, 2010]

data



disk density structures from radio interferometry data

parametric model:

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

+

starlight, dust population

+

radiative transfer calculations

resolved radio emission $\propto \kappa_\nu \Sigma T$

+

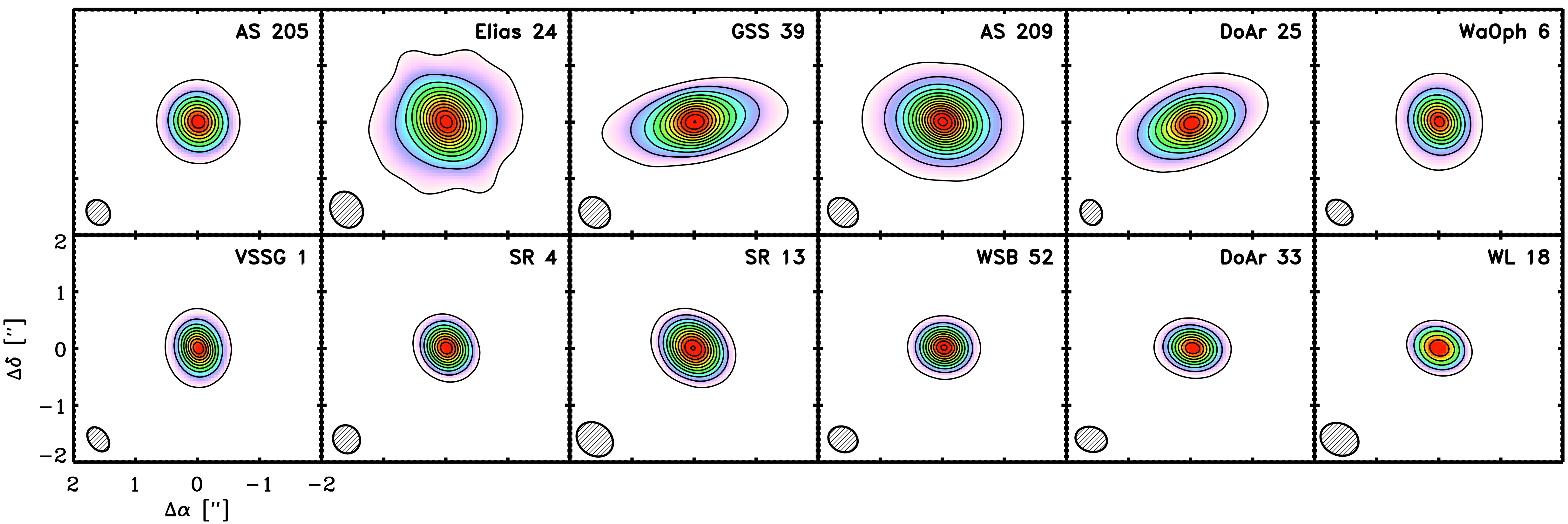
IR spectrum/scat. light/CO $\sim T$

[e.g., Kitamura et al. 2002, Pietu et al. 2005, Andrews & Williams 2007, Pinte et al. 2008, Isella et al. 2009]

new results: SMA disk survey
0.85 mm, 0.3”=20 AU resolution
2-D Monte Carlo RT (RADMC)

[Andrews et al. 2009, 2010]

models



disk density structures from radio interferometry data

parametric model:

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

+

starlight, dust population

+

radiative transfer calculations

resolved radio emission $\propto \kappa_\nu \Sigma T$

+

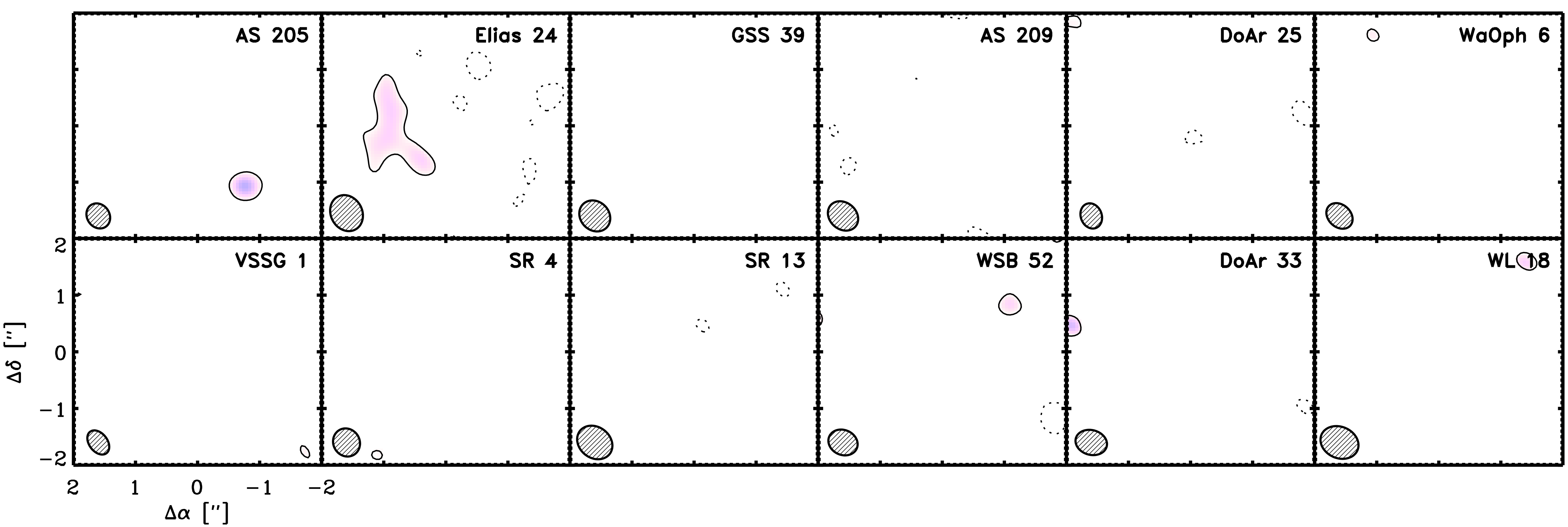
IR spectrum/scat. light/CO $\sim T$

[e.g., Kitamura et al. 2002, Pietu et al. 2005, Andrews & Williams 2007, Pinte et al. 2008, Isella et al. 2009]

new results: SMA disk survey
0.85 mm, 0.3"=20 AU resolution
2-D Monte Carlo RT (RADMC)

[Andrews et al. 2009, 2010]

residuals



disk density structures from radio interferometry data

parametric model:

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

+

starlight, dust population

+

radiative transfer calculations

resolved radio emission $\propto \kappa_\nu \Sigma T$

+

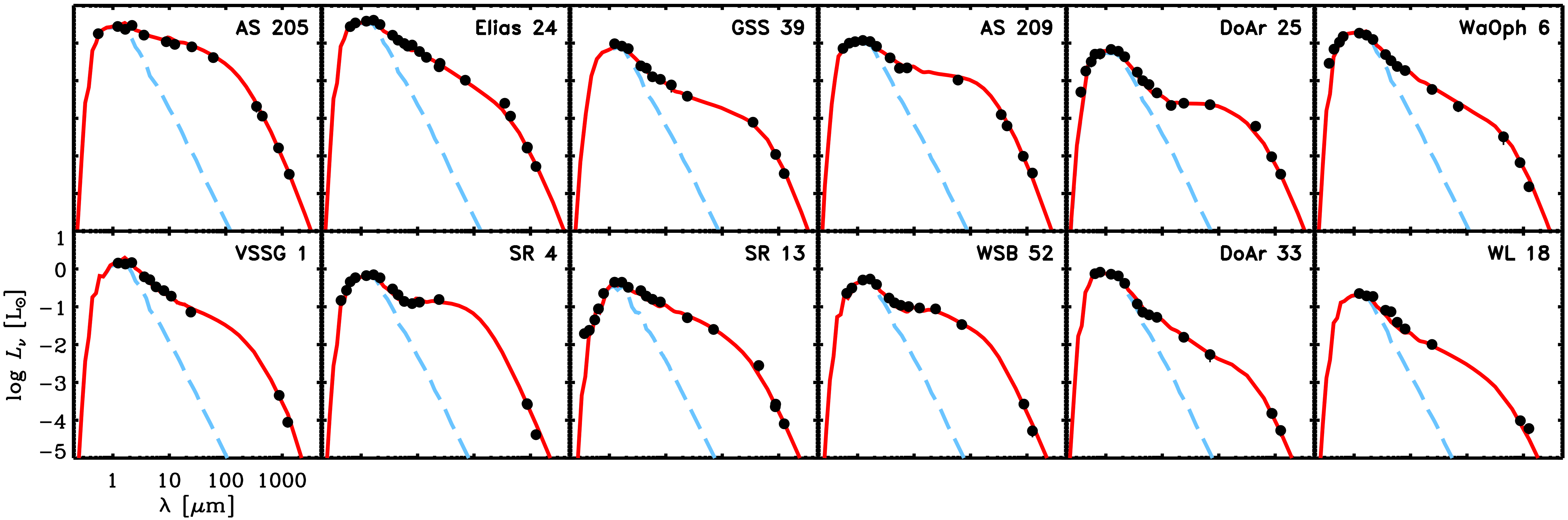
IR spectrum/scat. light/CO $\sim T$

[e.g., Kitamura et al. 2002, Pietu et al. 2005, Andrews & Williams 2007, Pinte et al. 2008, Isella et al. 2009]

new results: SMA disk survey
0.85 mm, 0.3”=20 AU resolution
2-D Monte Carlo RT (RADMC)

[Andrews et al. 2009, 2010]

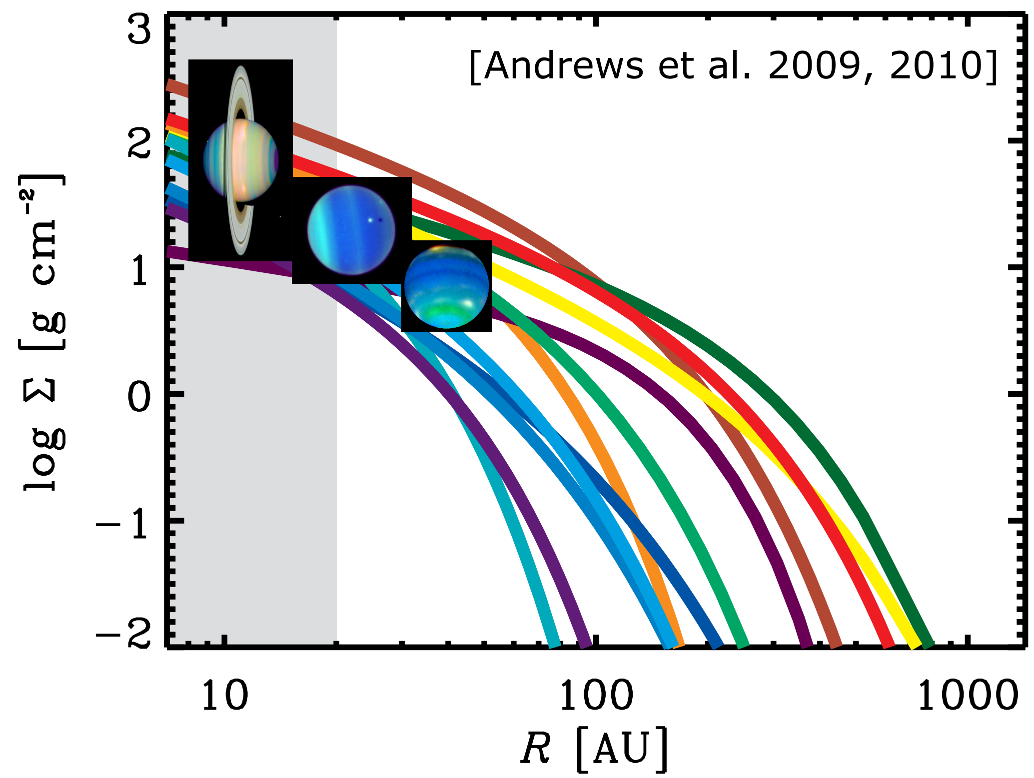
SEDs



can these disks make planets?

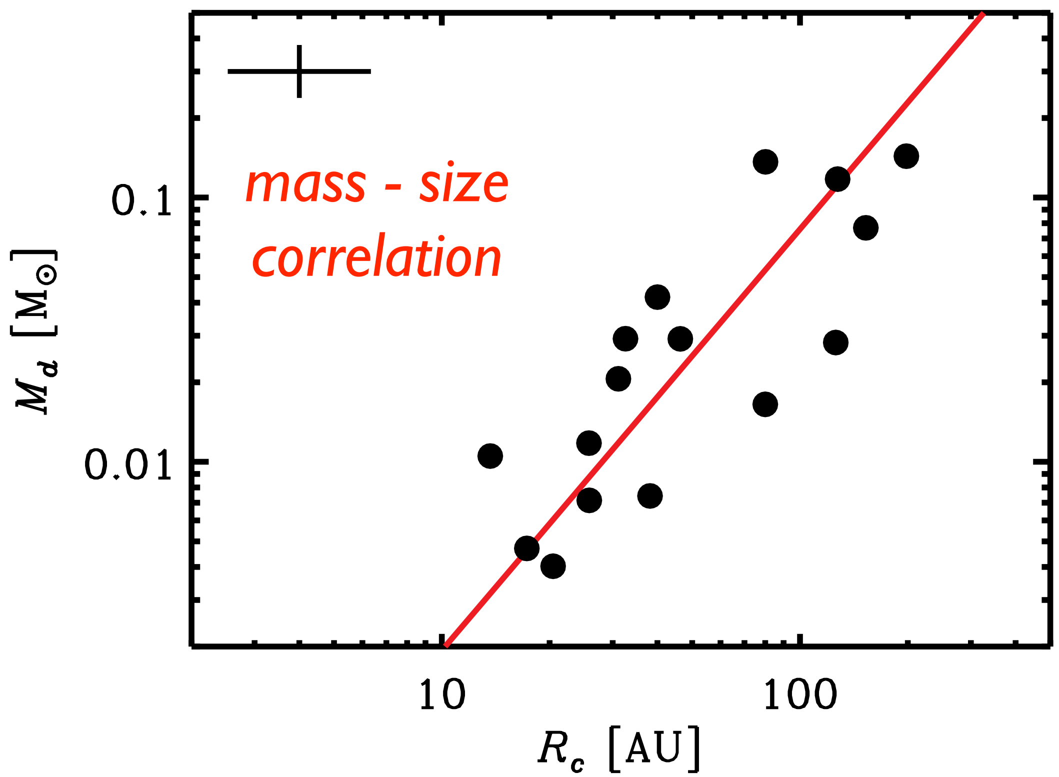
mass distributions:

- Σ ~ solar nebula (10-40 AU)
- Σ ~ 1/*R* (~20-100 AU)
  1/exp(*R*) (larger *R*)
- *mass* ~ 0.01 $M_\odot$ (40-50%)
  0.1 $M_\odot$ (<1%)



disk structure "snapshots":

- viscosity ~ linear in *R*
- + $\dot{M}$ = α ~ 0.001-0.01
- massive disks are larger



the evolution of disk structure: slow, then fast

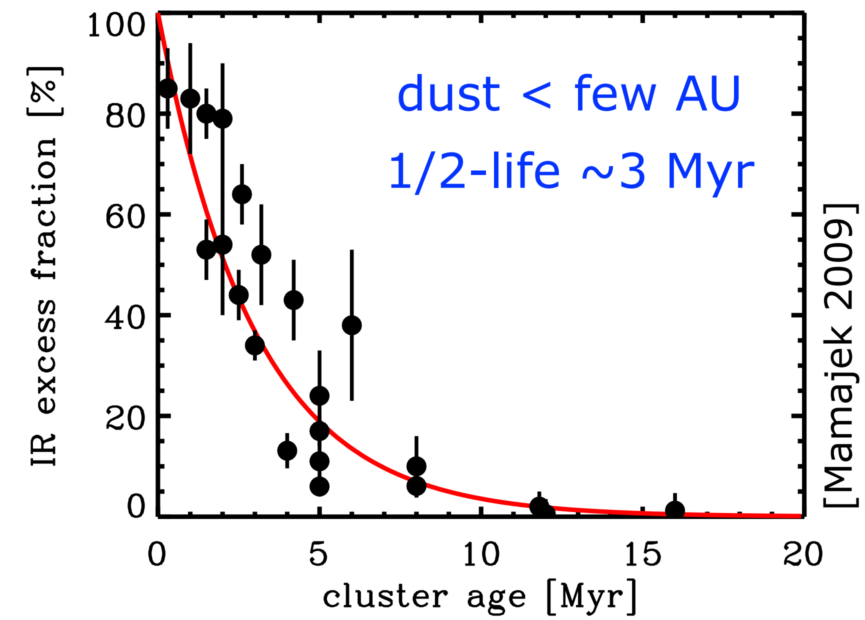
timeline →

formation ↙ ?

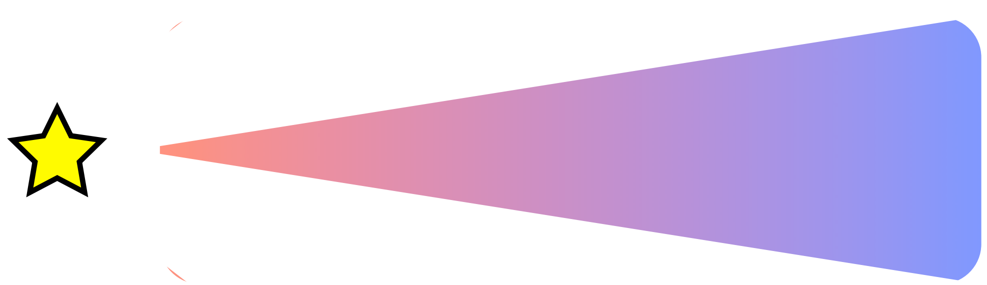
viscous evolution (particle growth?) ↙ accretion + diffusion

dissipation ↙ inside-out clearing (?)

[L-B & P 1974]



[Mamajek 2009]



sedimentation + growth

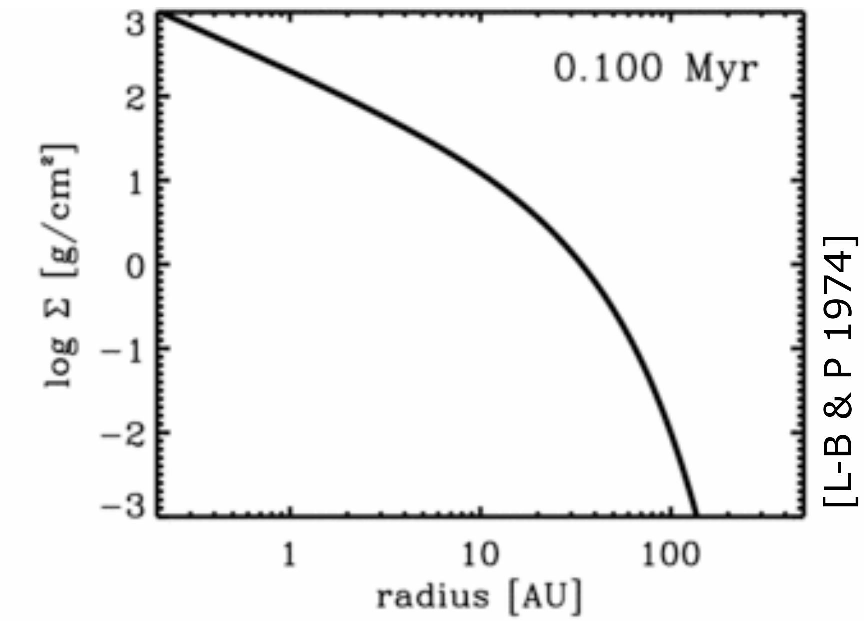
the evolution of disk structure: slow, then fast

timeline →

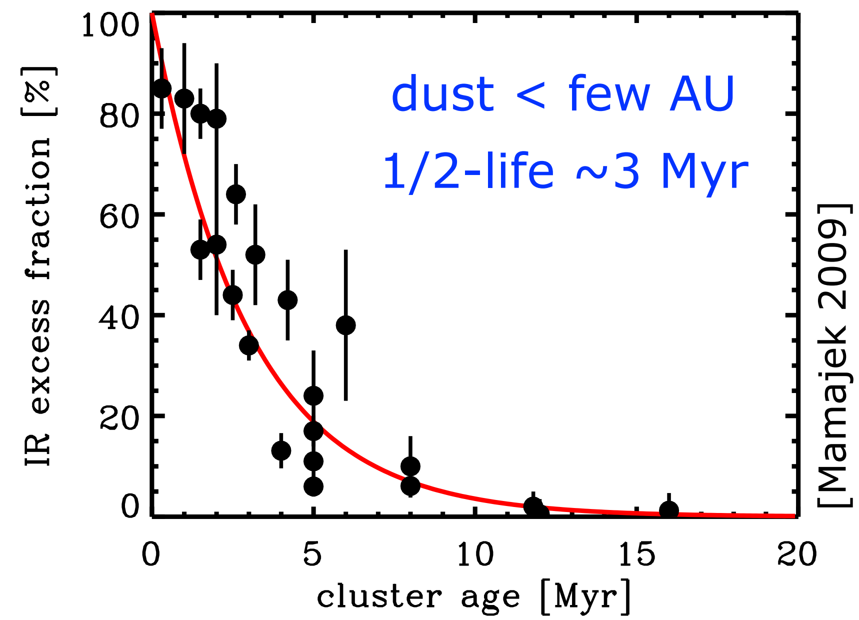
formation — viscous evolution (particle growth?) — dissipation

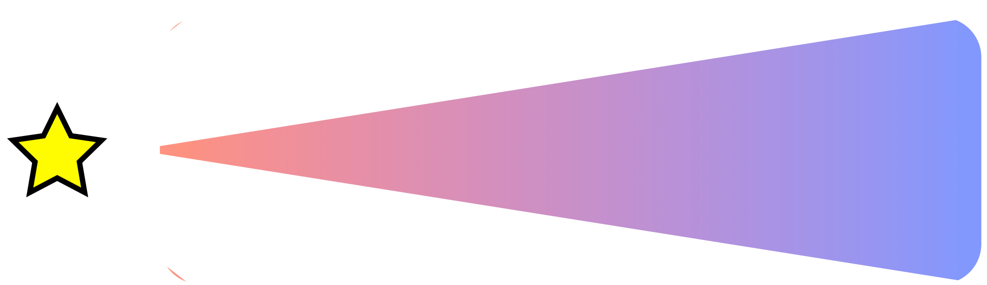
?

accretion + diffusion



inside-out clearing (?)





sedimentation + growth

the evolution of disk structure: slow, then fast

timeline →

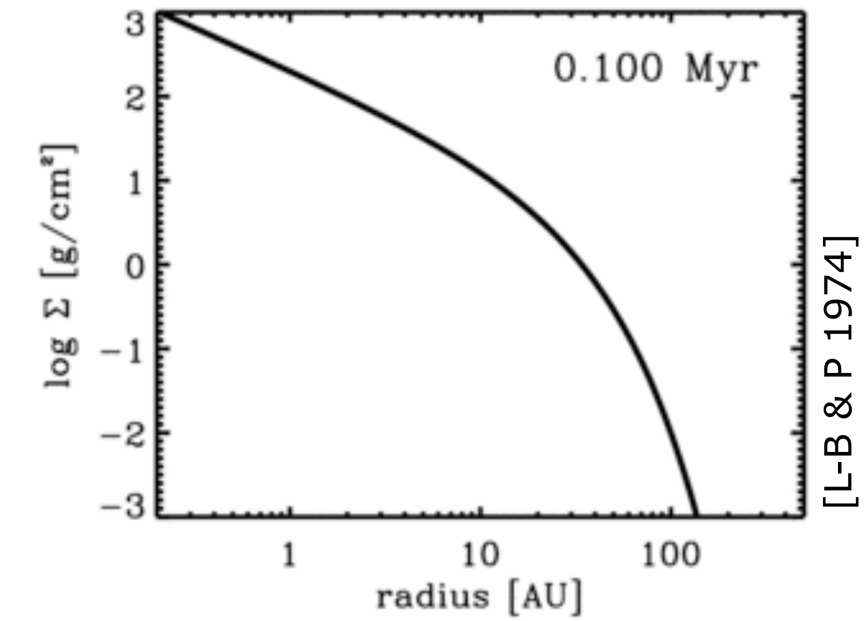
formation

viscous evolution (particle growth?)

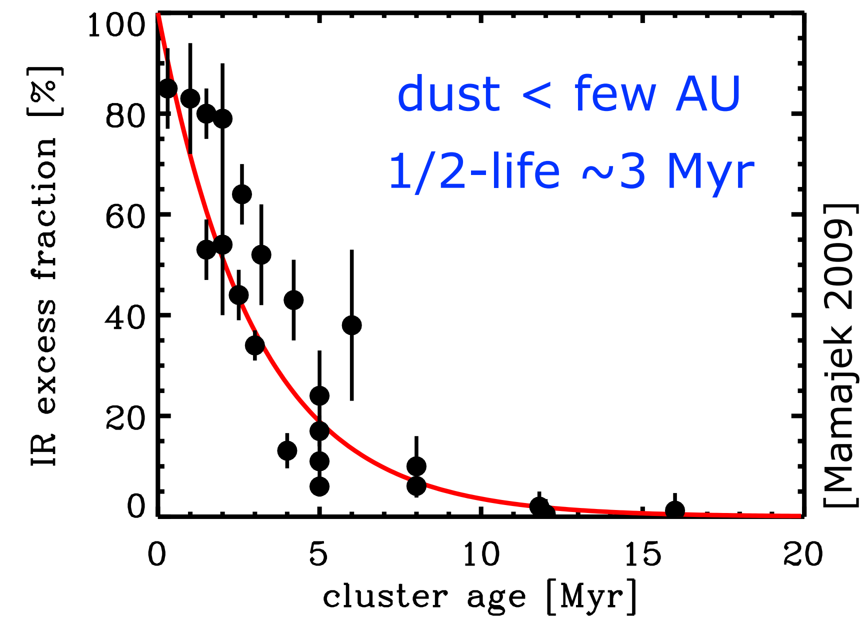
dissipation

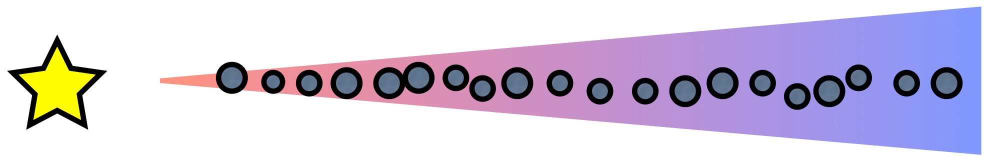
?

accretion + diffusion



inside-out clearing (?)





sedimentation + growth

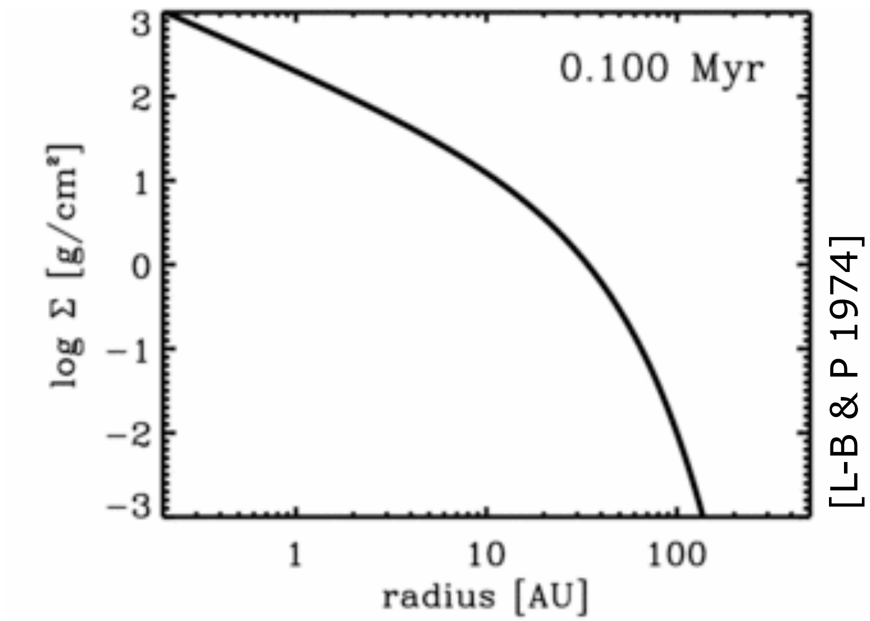
the evolution of disk structure: slow, then fast

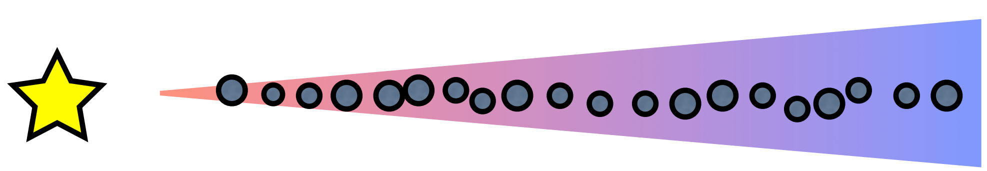
timeline →

formation | viscous evolution (particle growth?) | dissipation

?

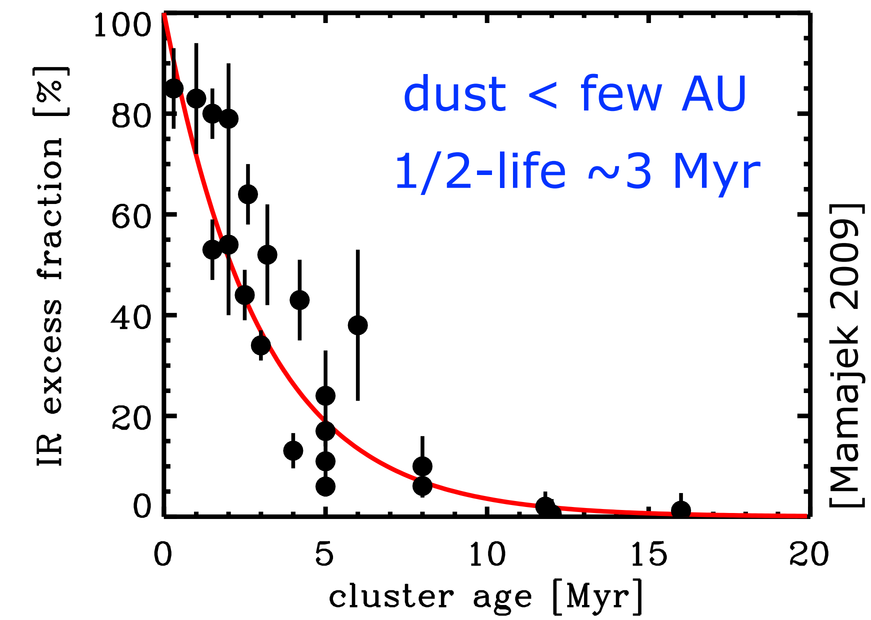
accretion + diffusion

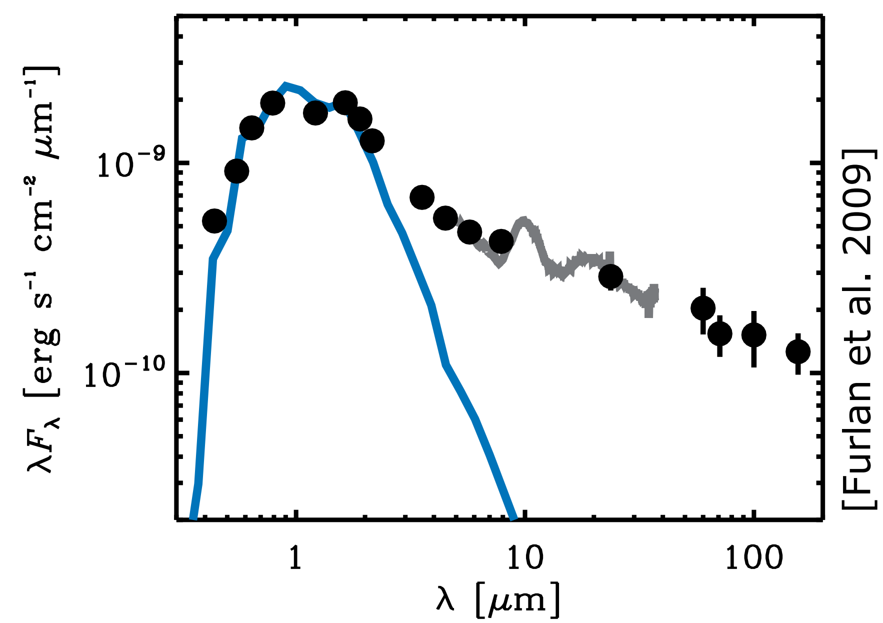




sedimentation + growth

inside-out clearing (?)





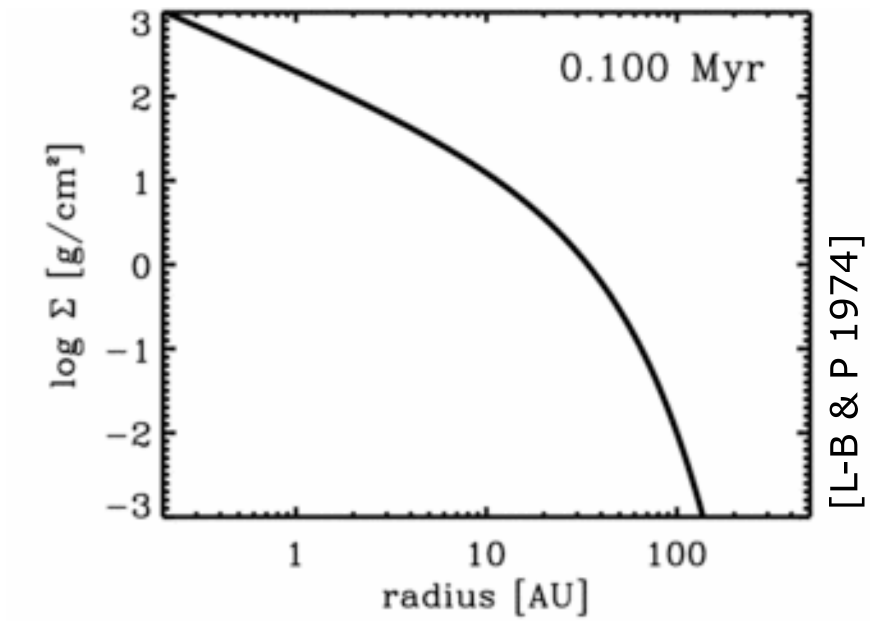
the evolution of disk structure: slow, then fast

timeline →

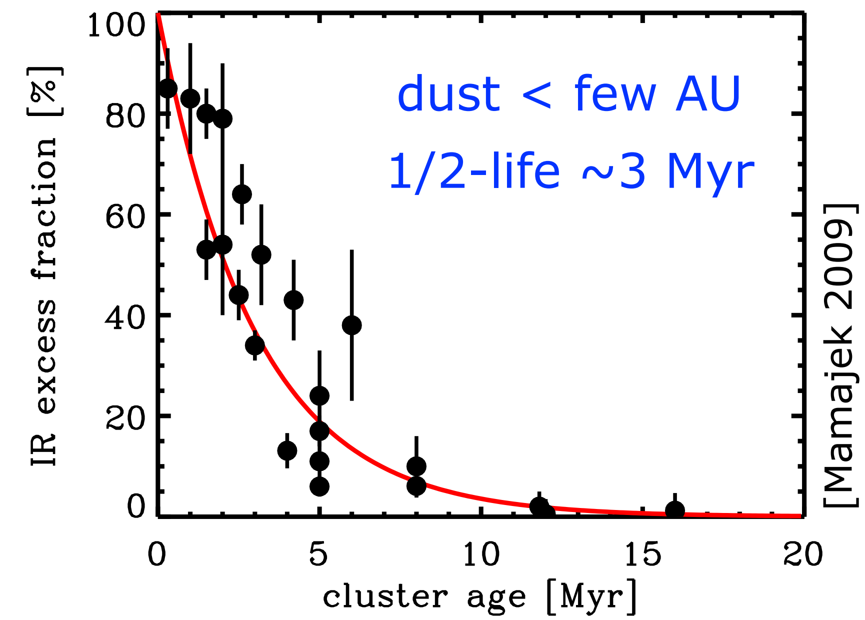
formation — viscous evolution (particle growth?) — dissipation

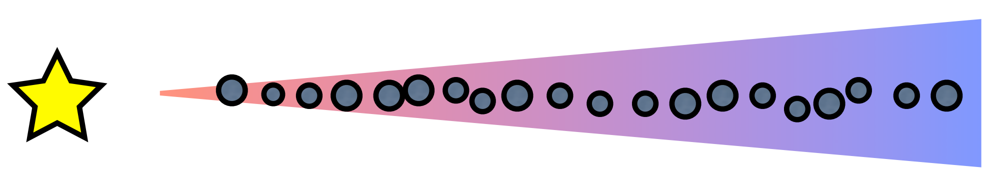
?

accretion + diffusion

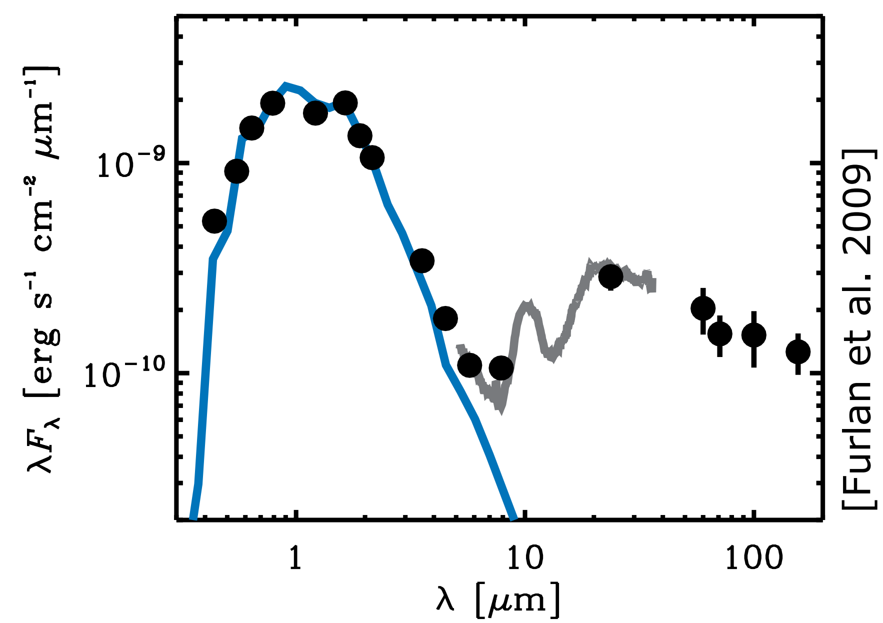


inside-out clearing (?)

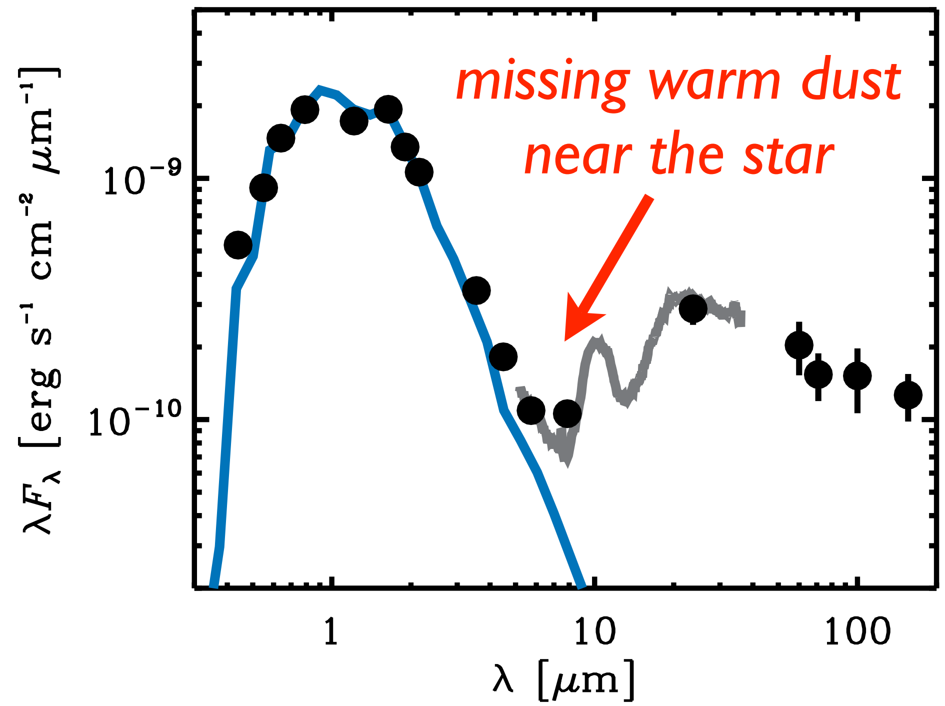


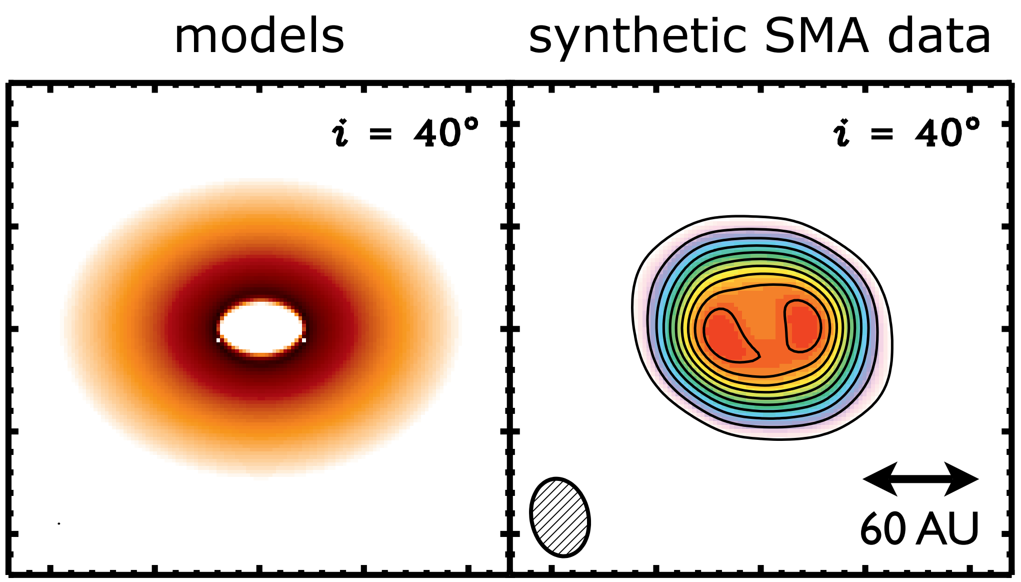


sedimentation + growth



transition disks: rapid clearing of the inner disk

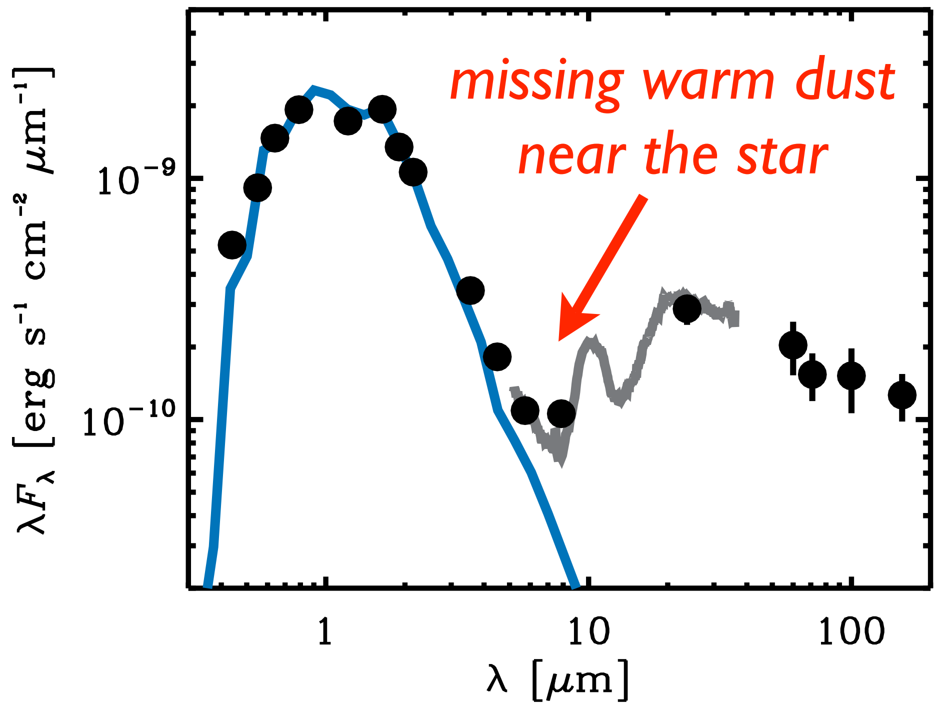


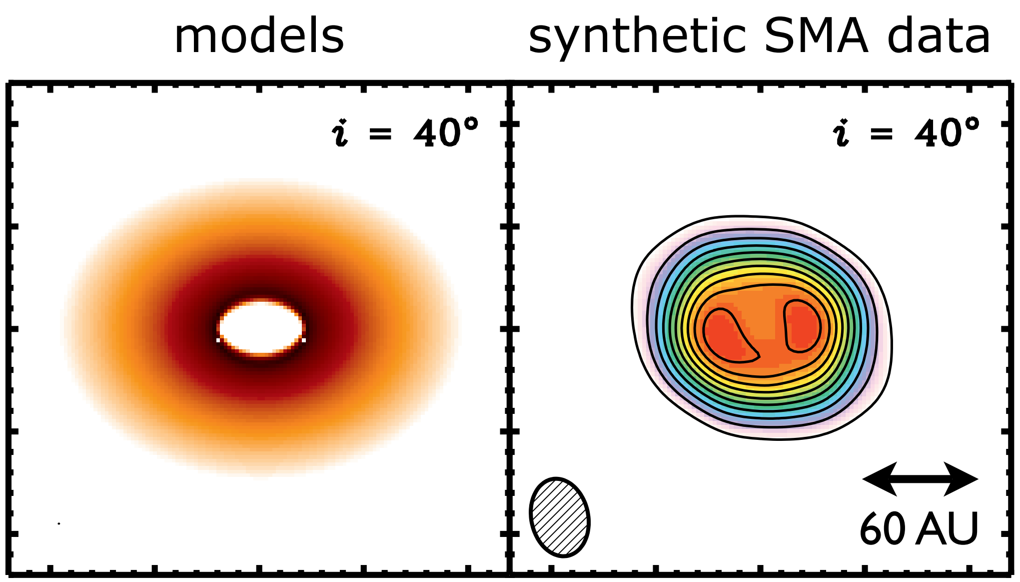


resolving the disk cavity:

- size of cleared region
- properties of remnant disk
- contents of inner disk

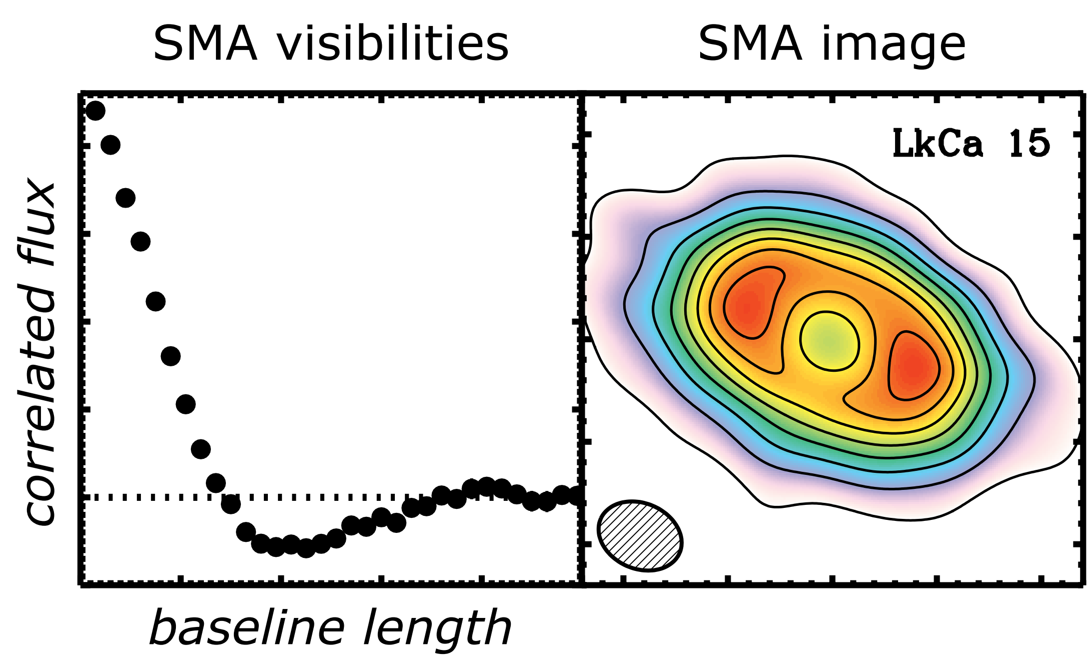
transition disks: rapid clearing of the inner disk





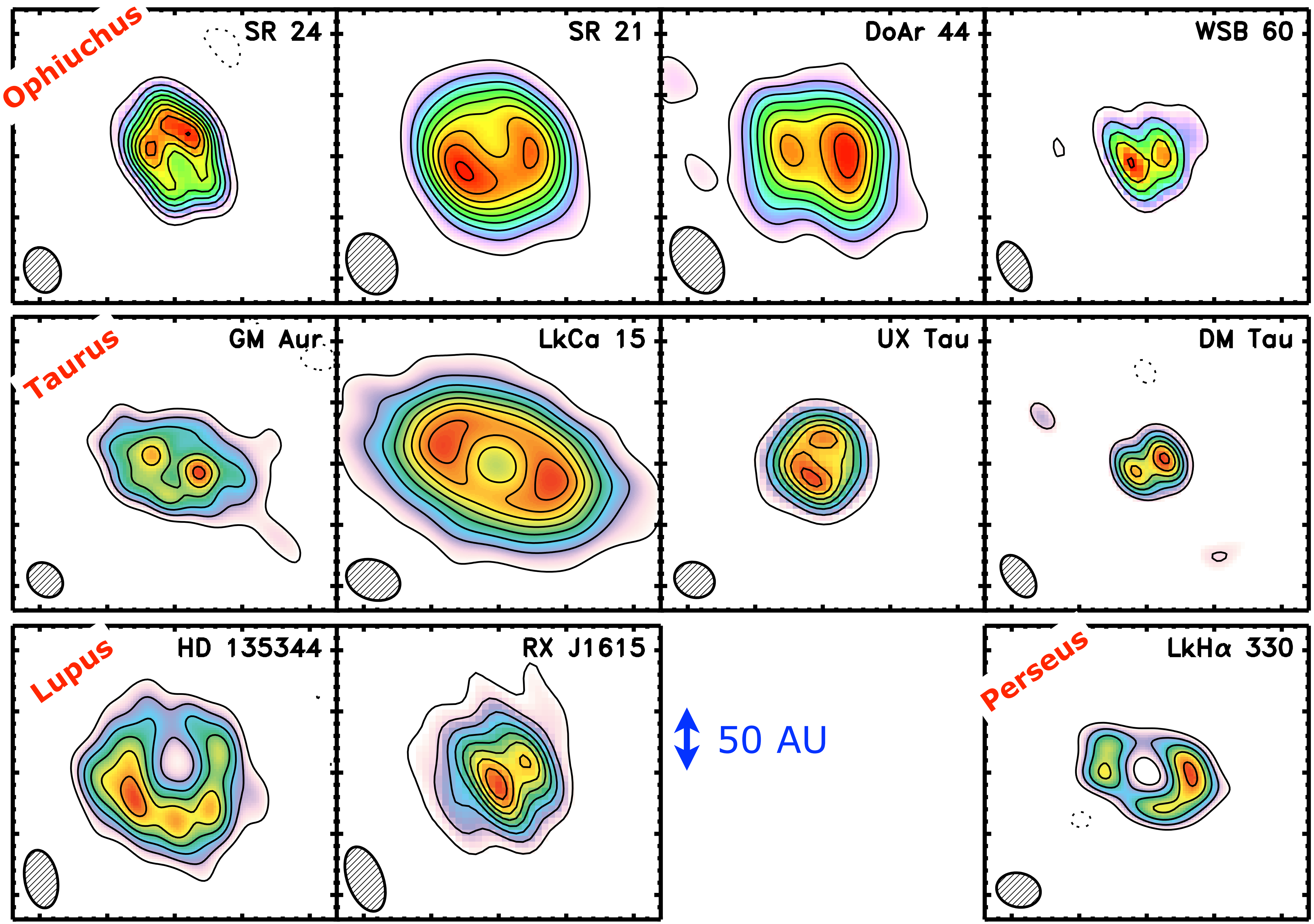
resolving the disk cavity:

- size of cleared region
- properties of remnant disk
- contents of inner disk



[Andrews et al., in prep.]

transition disks: rapid clearing of the inner disk



[Brown et al. 2007, 2008; Hughes et al. 2009; Andrews et al. 2009, 2010+]

transition disks: rapid clearing of the inner disk

- ~1% (1 Myr); ~10% (3 Myr)

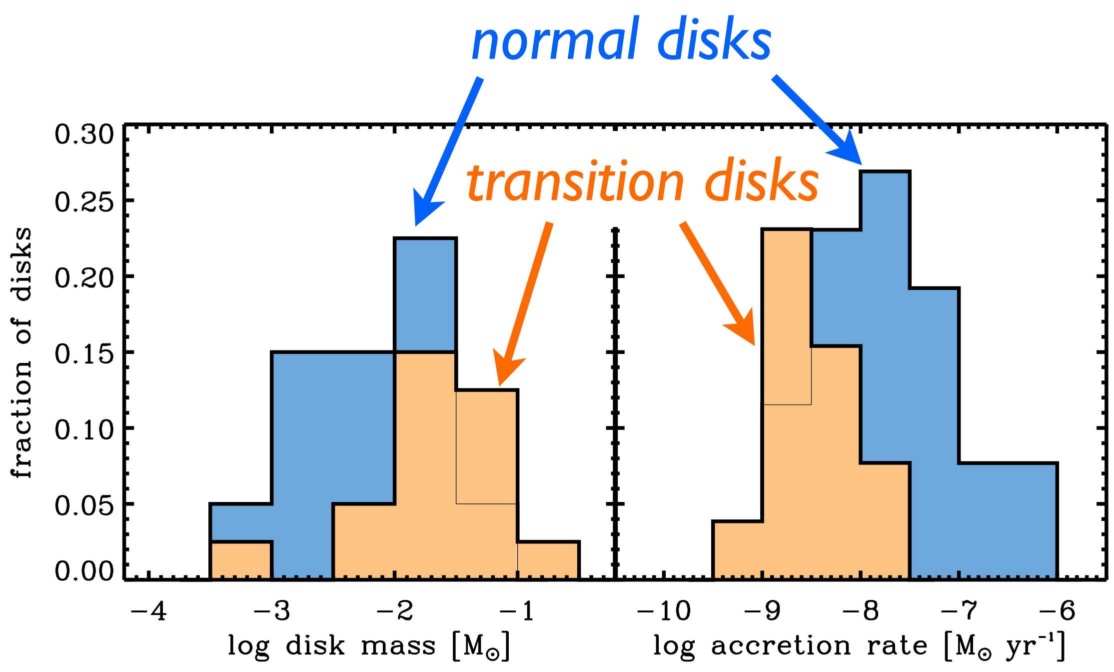
[Strom+ 1989; Muzerolle+ 2010]

- >100x less emission in cavity
- cavity sizes: R~20-40 AU
- massive outer disks (>0.01 $M_\odot$)

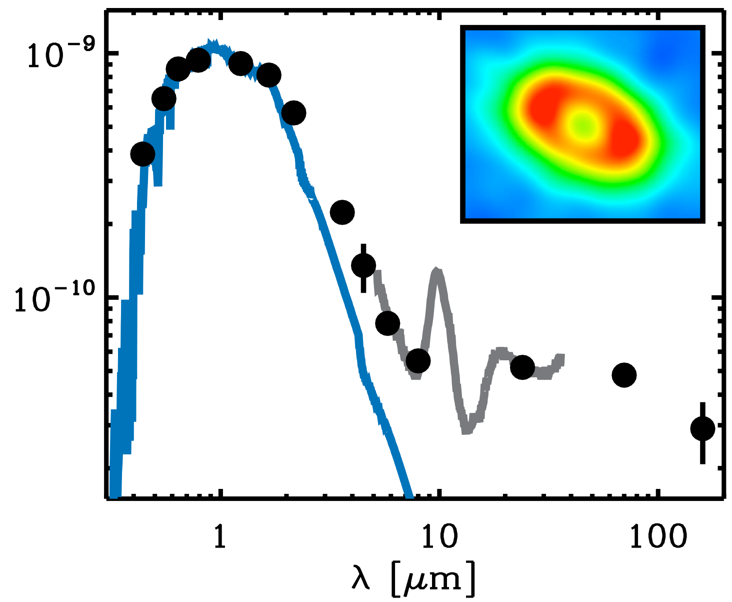
[Pietu; Brown; Hughes; Isella; Andrews]

- lower accretion rates (~10%)
- some material in cavity (gaps?)

[Espaillat+ 2007, 10]



[Najita+ 2007]



[P. Armitage]

transition disks: rapid clearing of the inner disk

- ~1% (1 Myr); ~10% (3 Myr)

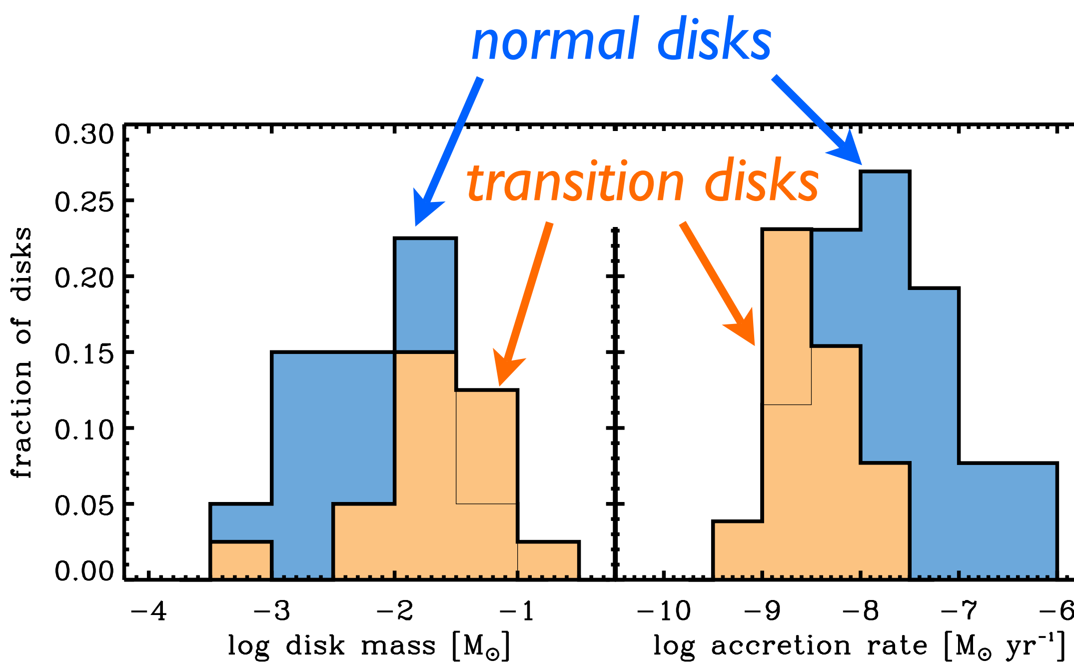
[Strom+ 1989; Muzerolle+ 2010]

- >100x less emission in cavity
- cavity sizes: *R*~20-40 AU
- massive outer disks (>0.01 $M_\odot$)

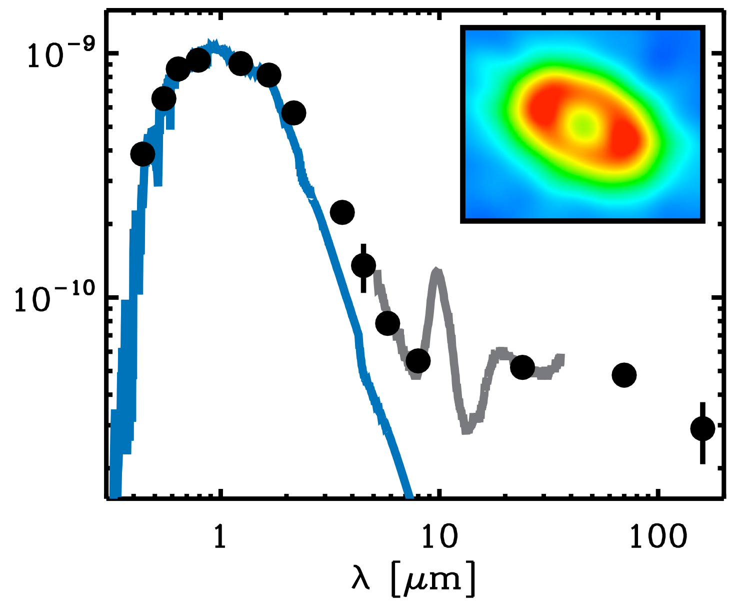
[Pietu; Brown; Hughes; Isella; Andrews]

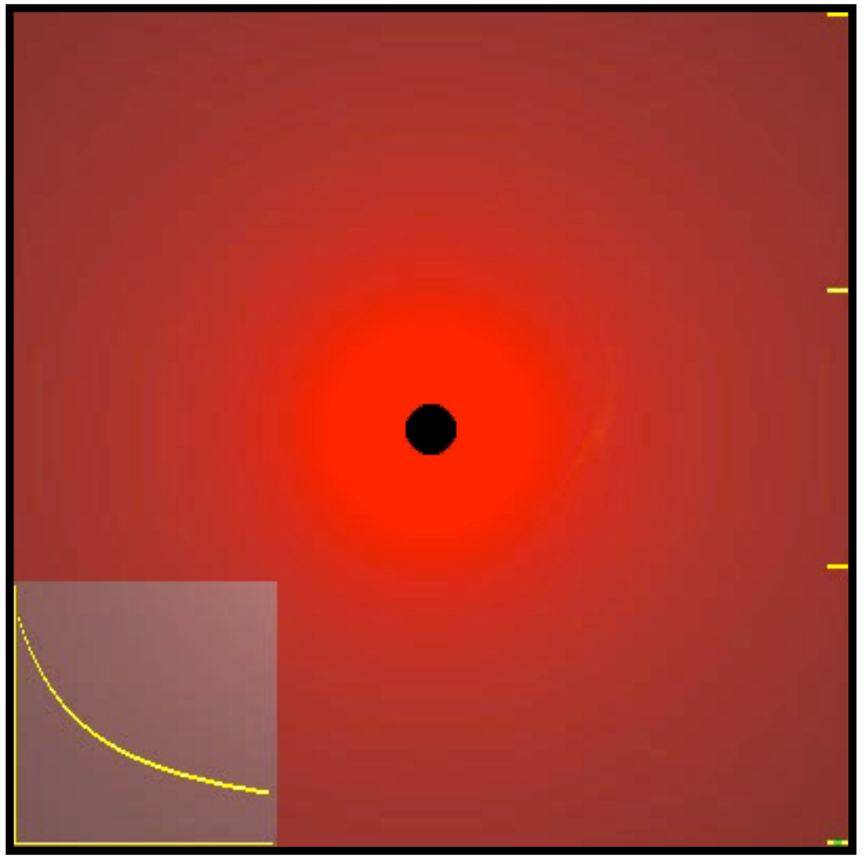
- lower accretion rates (~10%)
- some material in cavity (gaps?)

[Espaillat+ 2007, 10]



[Najita+ 2007]





[P. Armitage]

transition disks: rapid clearing of the inner disk

- ~1% (1 Myr); ~10% (3 Myr)

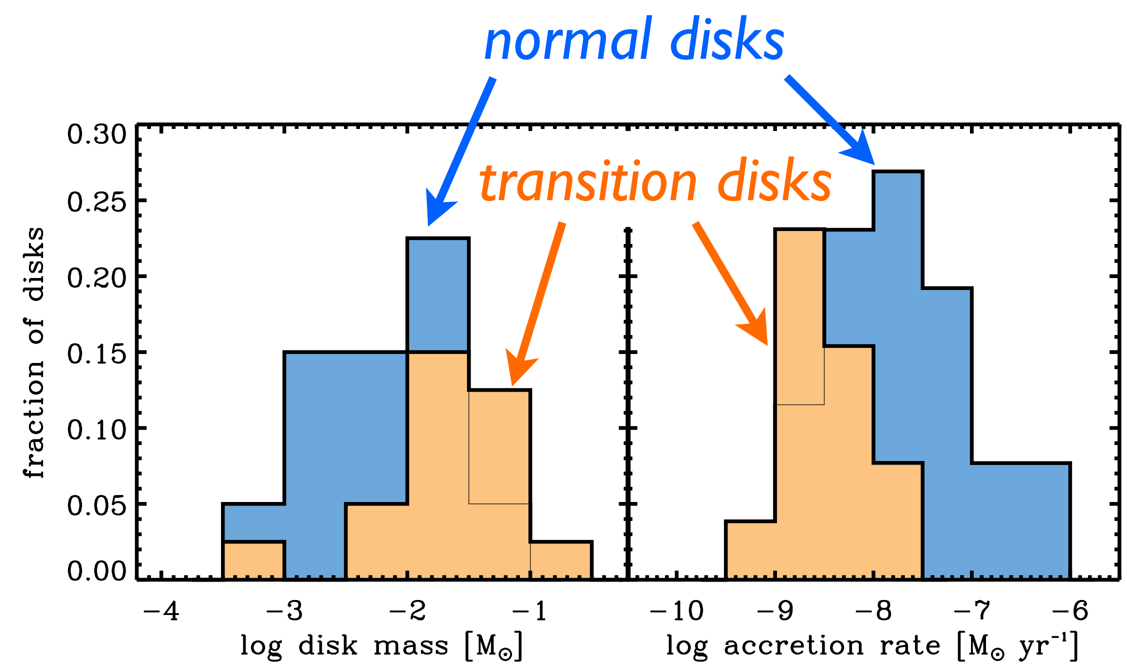
[Strom+ 1989; Muzerolle+ 2010]

- >100x less emission in cavity
- cavity sizes: R~20-40 AU
- massive outer disks (>0.01 $M_\odot$)

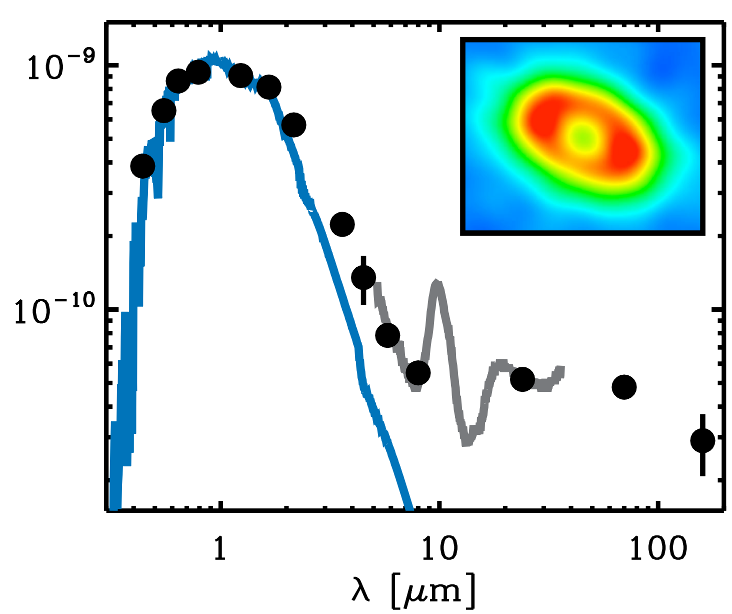
[Pietu; Brown; Hughes; Isella; Andrews]

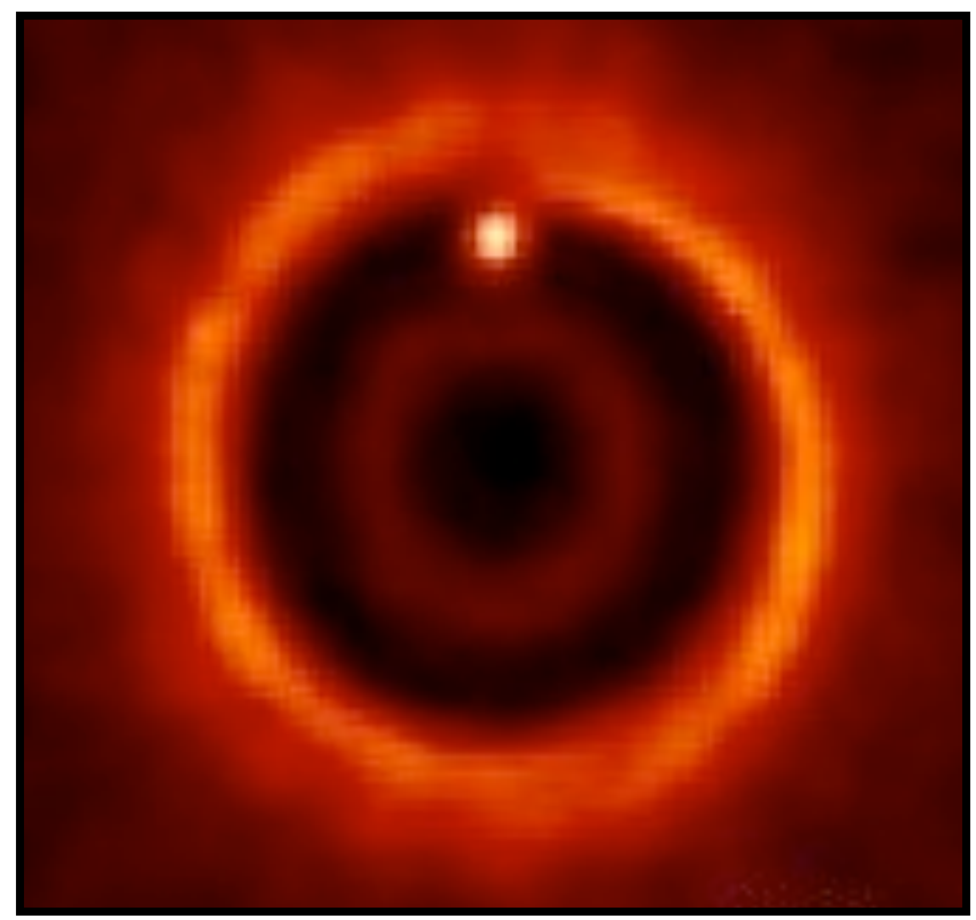
- lower accretion rates (~10%)
- some material in cavity (gaps?)

[Espaillat+ 2007, 10]



[Najita+ 2007]





[Wolf & D'Angelo 2005]

transition disks: rapid clearing of the inner disk

- ~1% (1 Myr); ~10% (3 Myr)

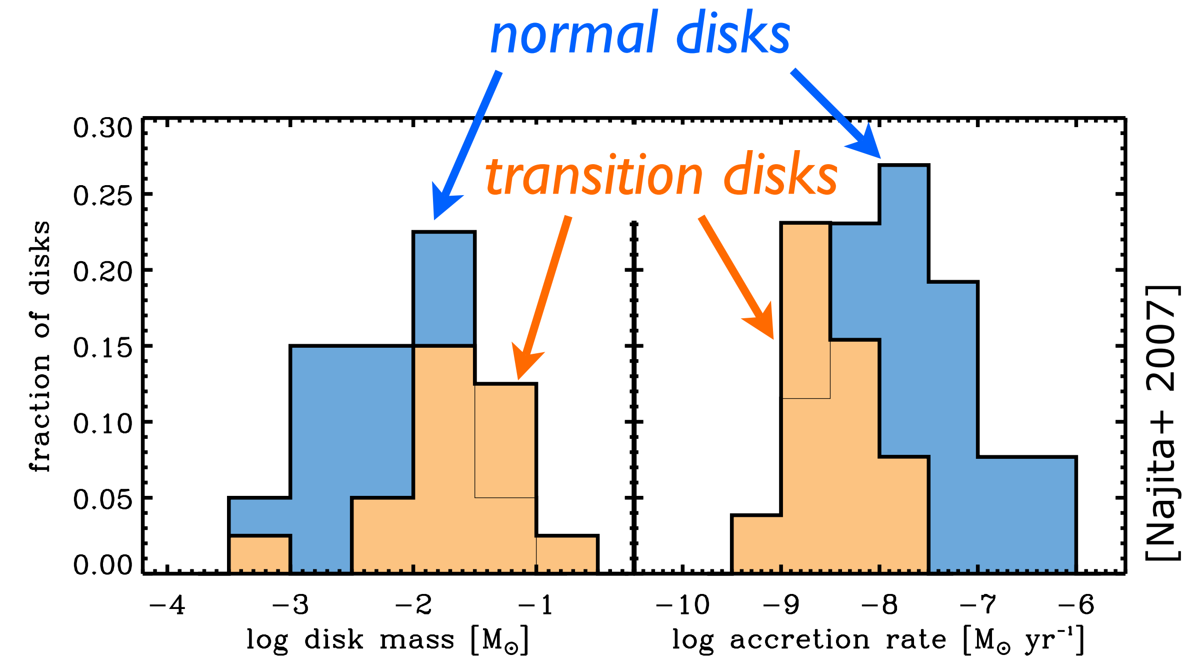
[Strom+ 1989; Muzerolle+ 2010]

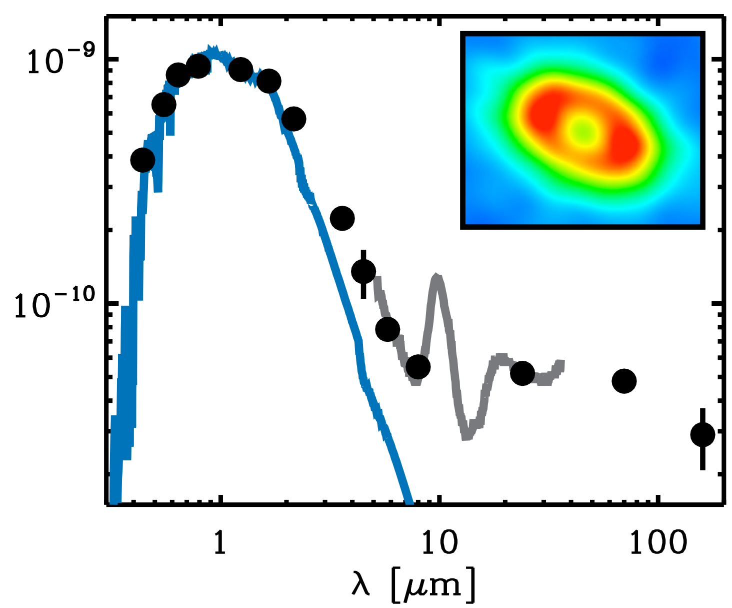
- >100x less emission in cavity
- cavity sizes: R~20-40 AU
- massive outer disks (>0.01 $M_\odot$)

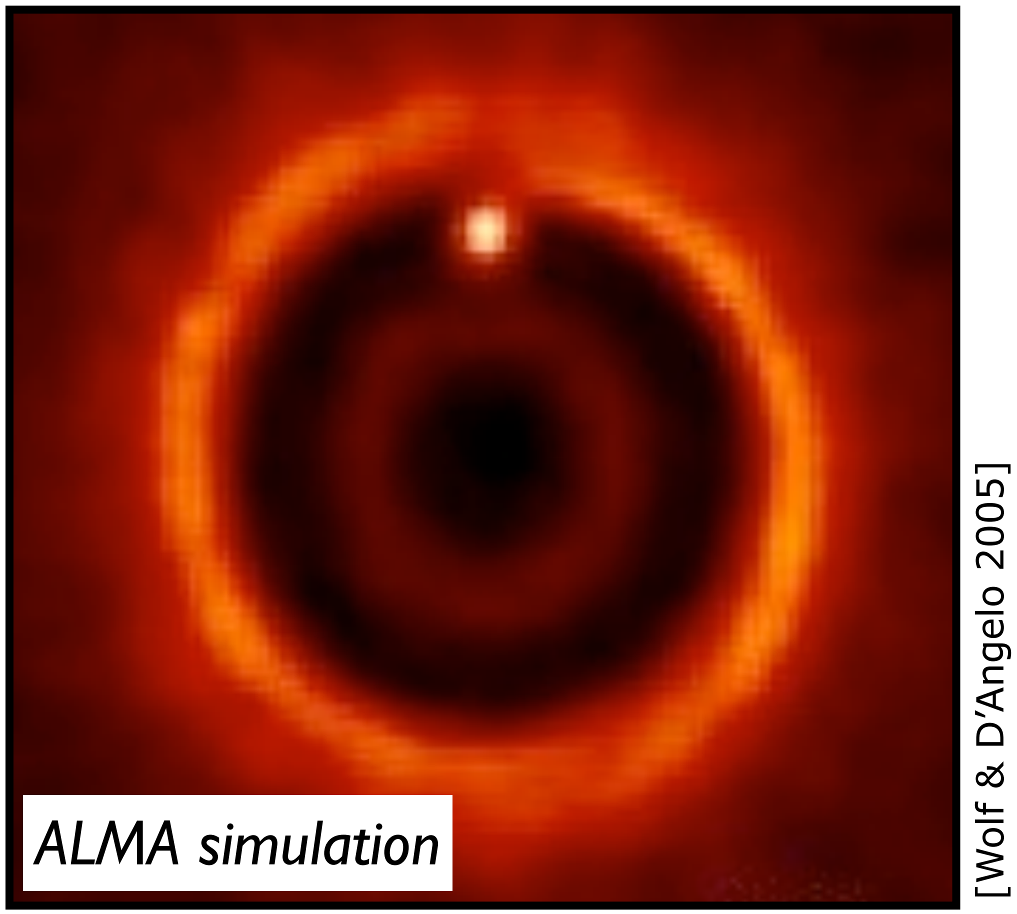
[Pietu; Brown; Hughes; Isella; Andrews]

- lower accretion rates (~10%)
- some material in cavity (gaps?)

[Espaillat+ 2007, 10]





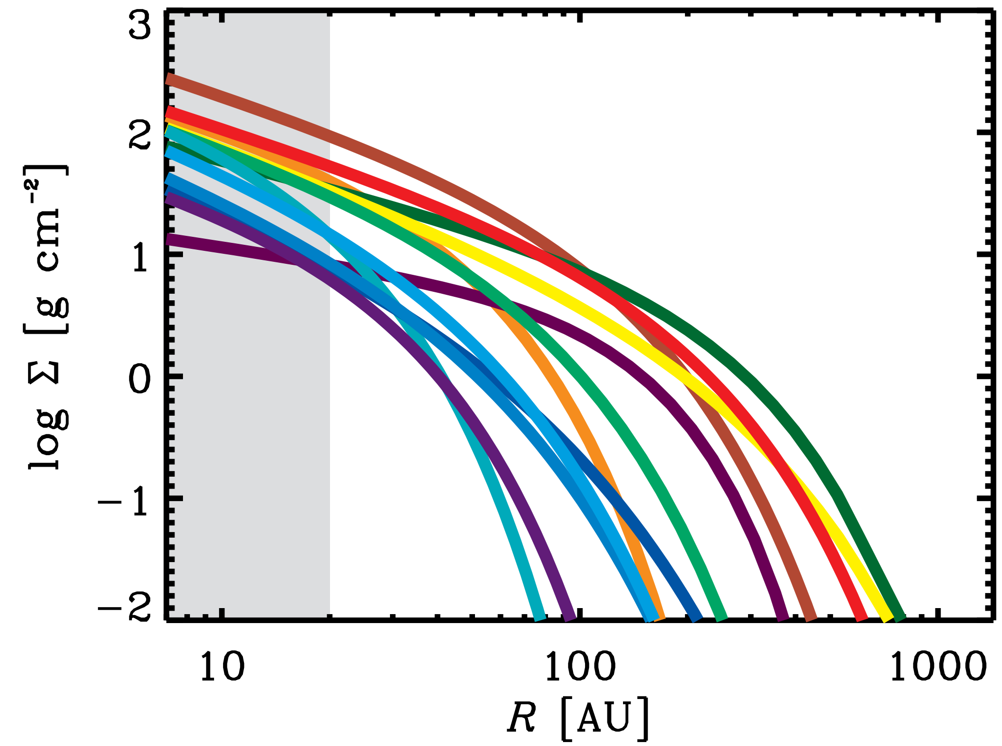


summary: disk structure, evolution, planet formation

SMA: dust sensitivity + angular resolution

↓

"new" field of observational planet formation

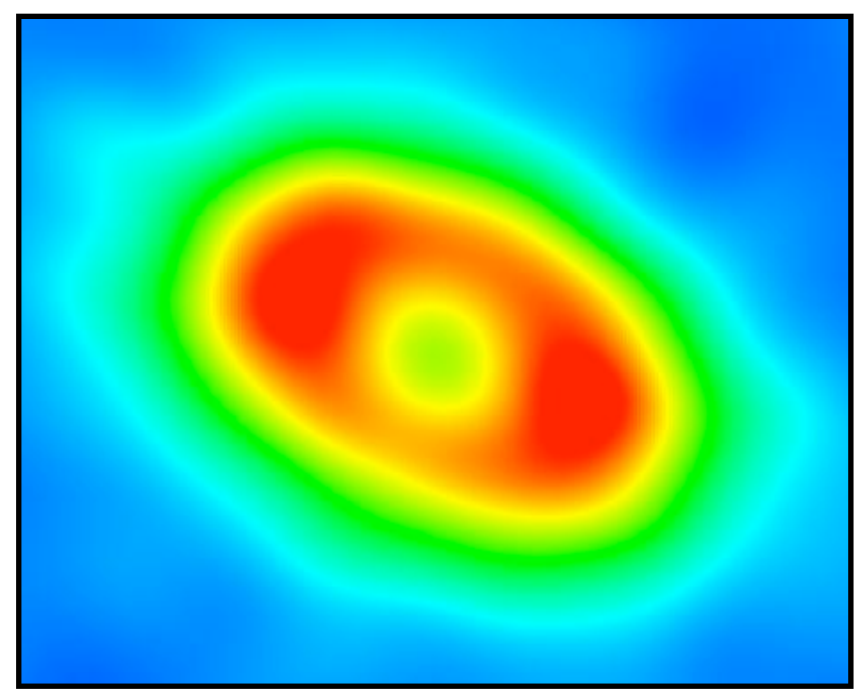


1. disk densities

- resolved radio emission-->Σ
- Σ varies like 1/*R* near star, tapered 1/e^R at large *R*

2. viscous evolution

- viscosity (α) ~ MRI
- mass correlated with size



3. rapid "transitions"

- large, resolved cleared regions
- very young (1 Myr) exoplanets?

thanks to: D Wilner, M Hughes, C Qi, & C Dullemond