Protoplanetary Disks at High Angular Resolution

disk structure, evolution, and
a glimpse at the planet formation process

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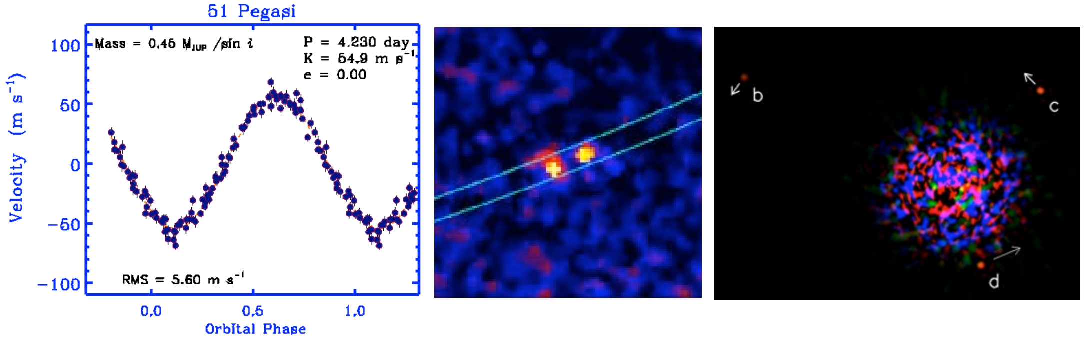
big picture: planet formation

~all young stars have ***disks***

D. E. Potter; McCaughrean et al. 1995; Burrows et al. 1996

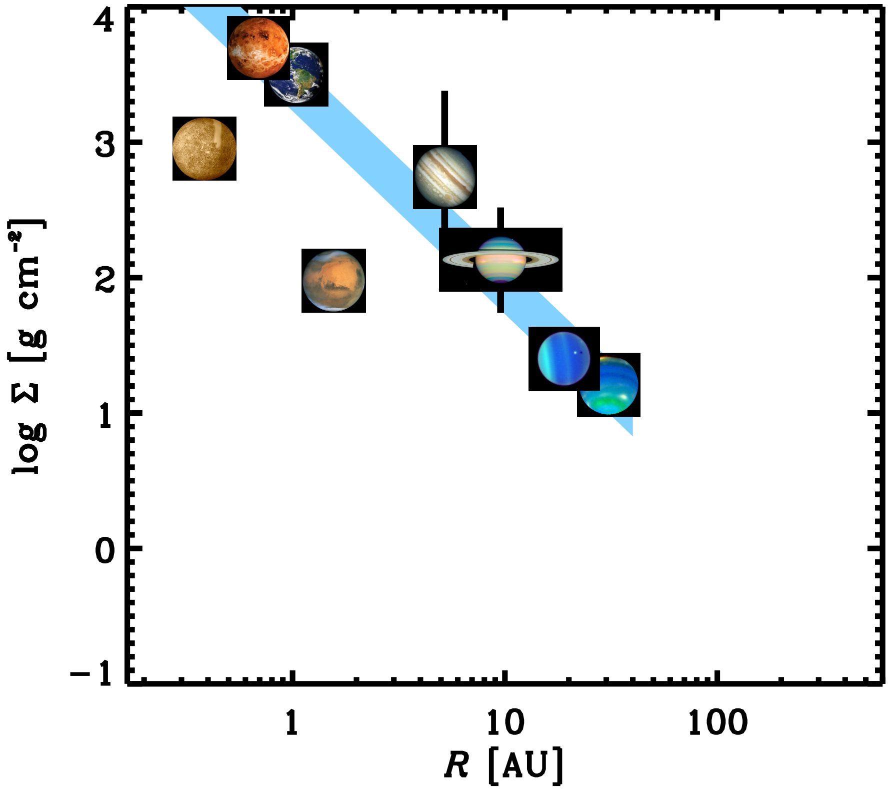
???

>10% of stars have ***planets***

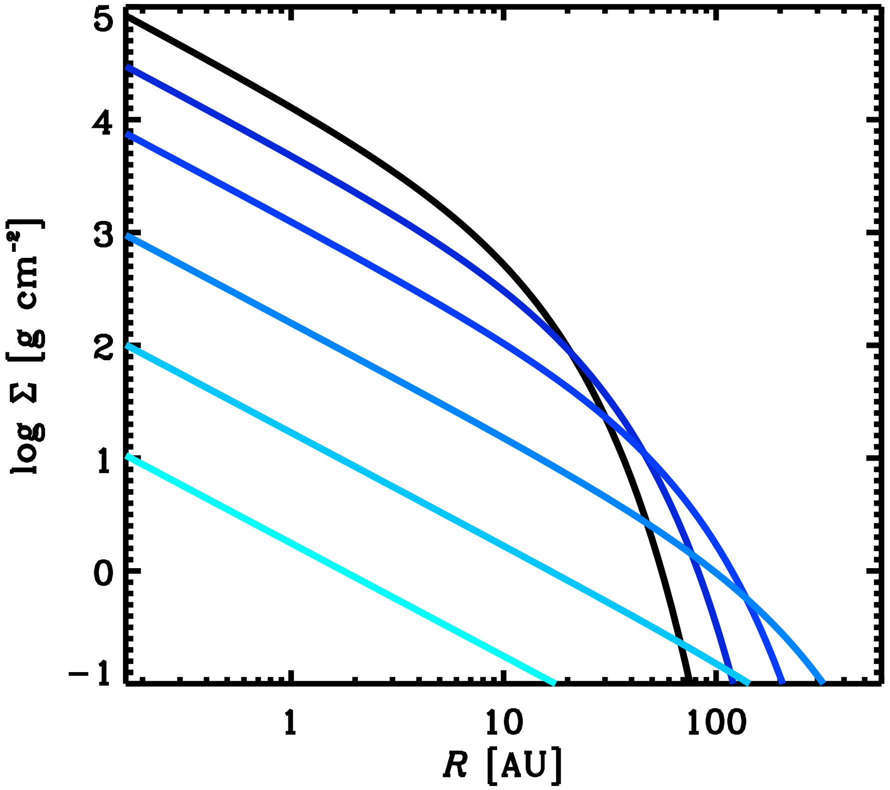


Mayor & Queloz 1995; Kalas et al. 2008; Marois et al. 2008

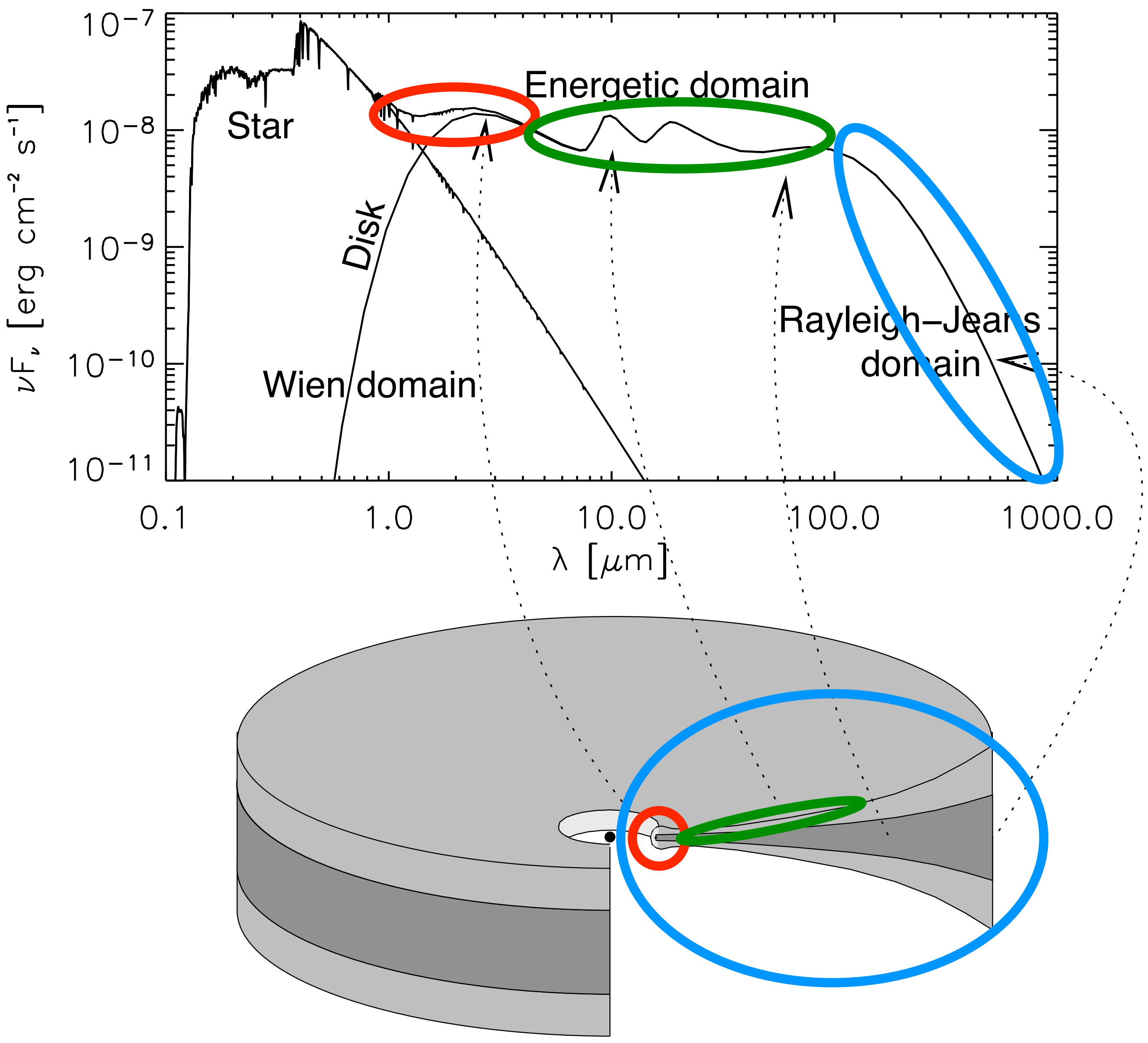
Q1: is there enough stuff in the right places?



Q2: if so, for how long? if not, was there ever?



key tool: sub-mm continuum emission



Dullemond et al. 2007

- bright emission from dust
- *optically thin emission*

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

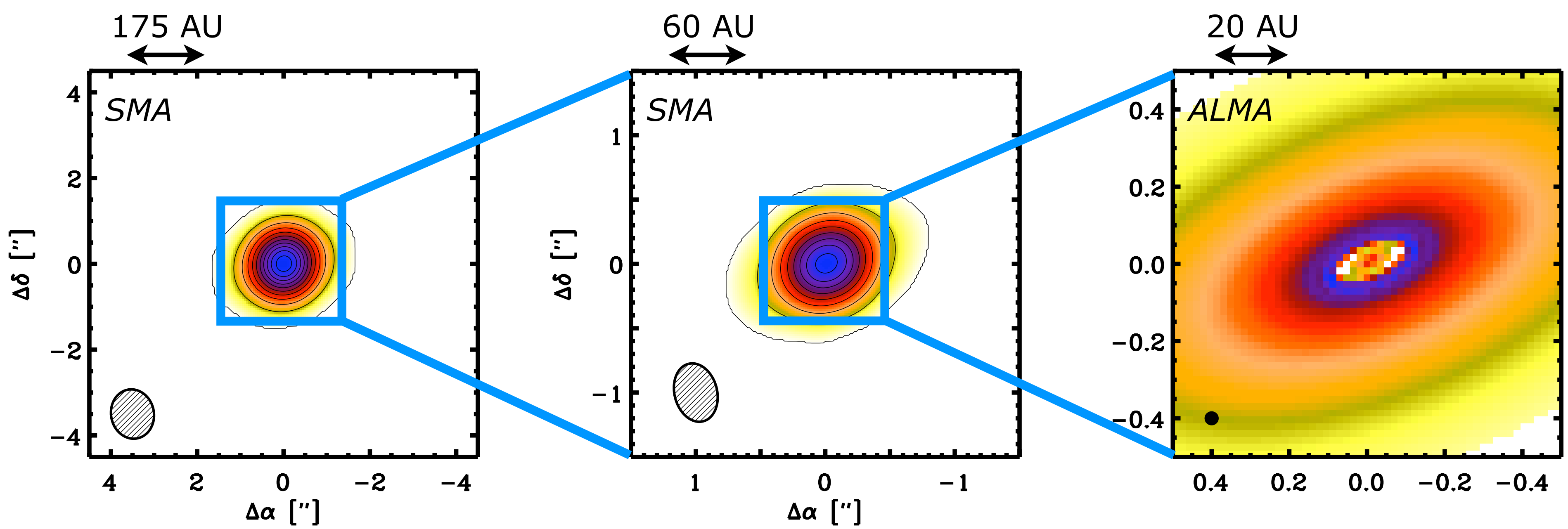
Beckwith et al. 1990

- unique tracer of midplane (for now...)
- spatial resolution

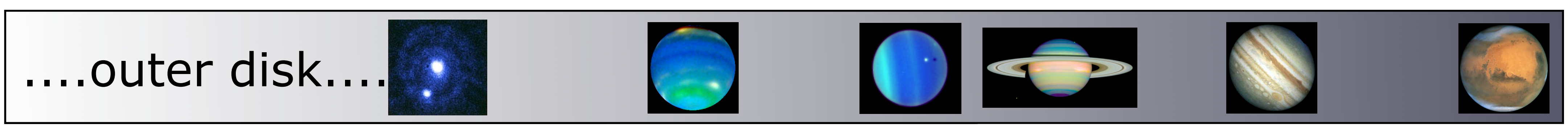
$$R \approx 10 \left(\frac{1\ \mathrm{km}}{b}\right) \left(\frac{d}{100\,\mathrm{pc}}\right)\ \mathrm{AU}$$

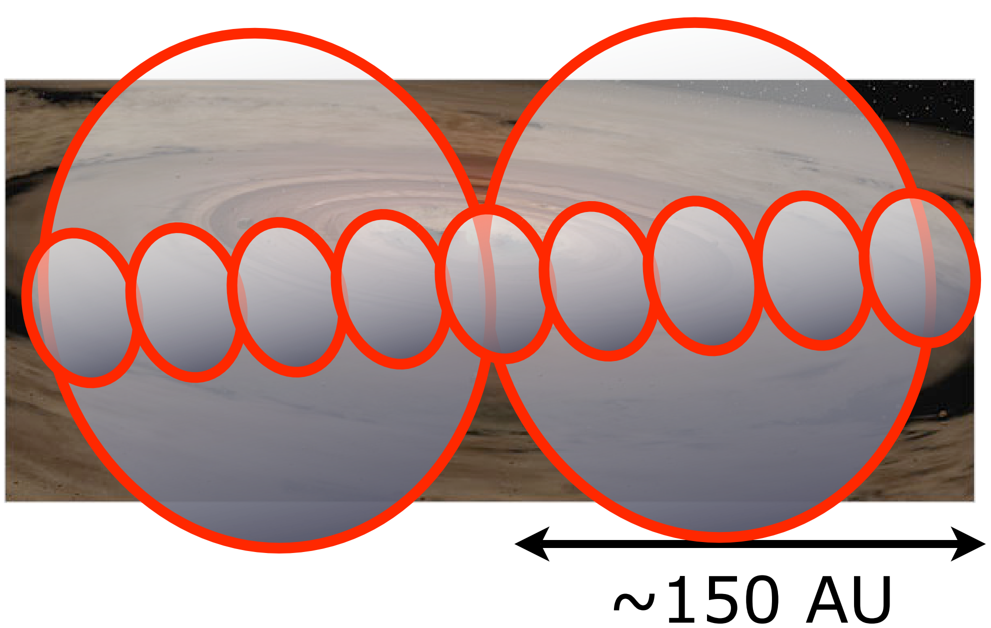
- no stellar contamination

resolution matters



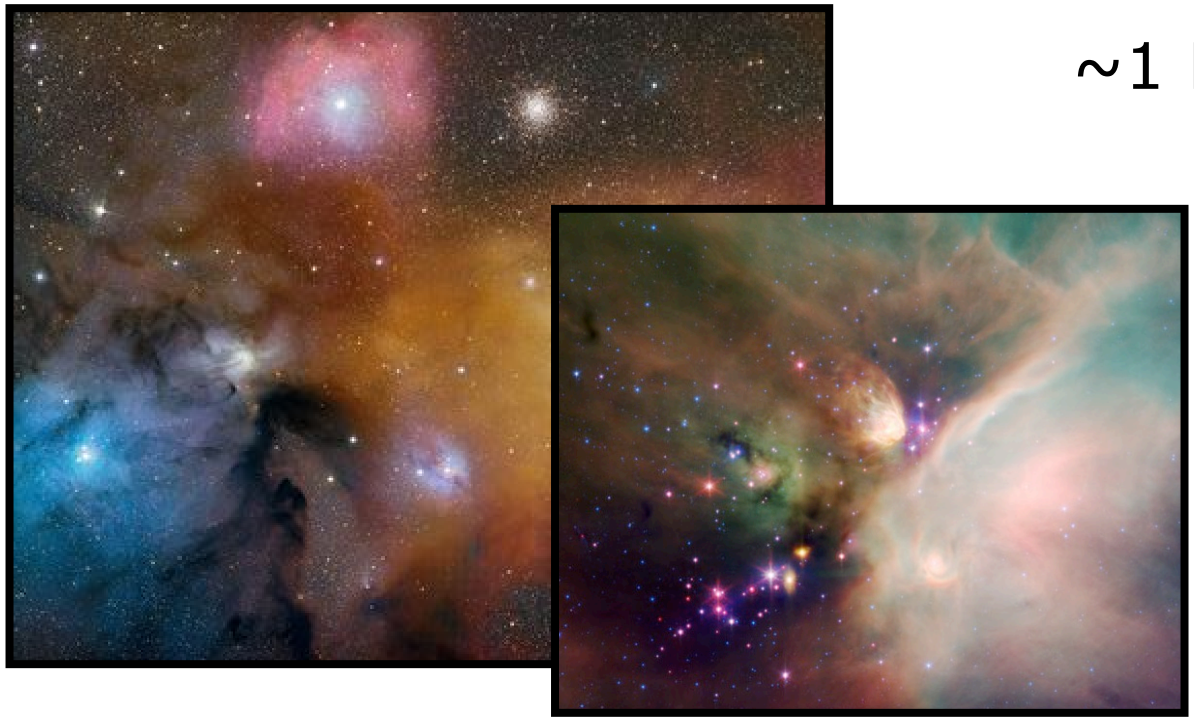
resolution ~1″ ~0.3″ 0.03″





- better leverage on brightness (i.e., density) distribution
- directly probing regions more relevant to planet formation

high resolution disk survey in Oph

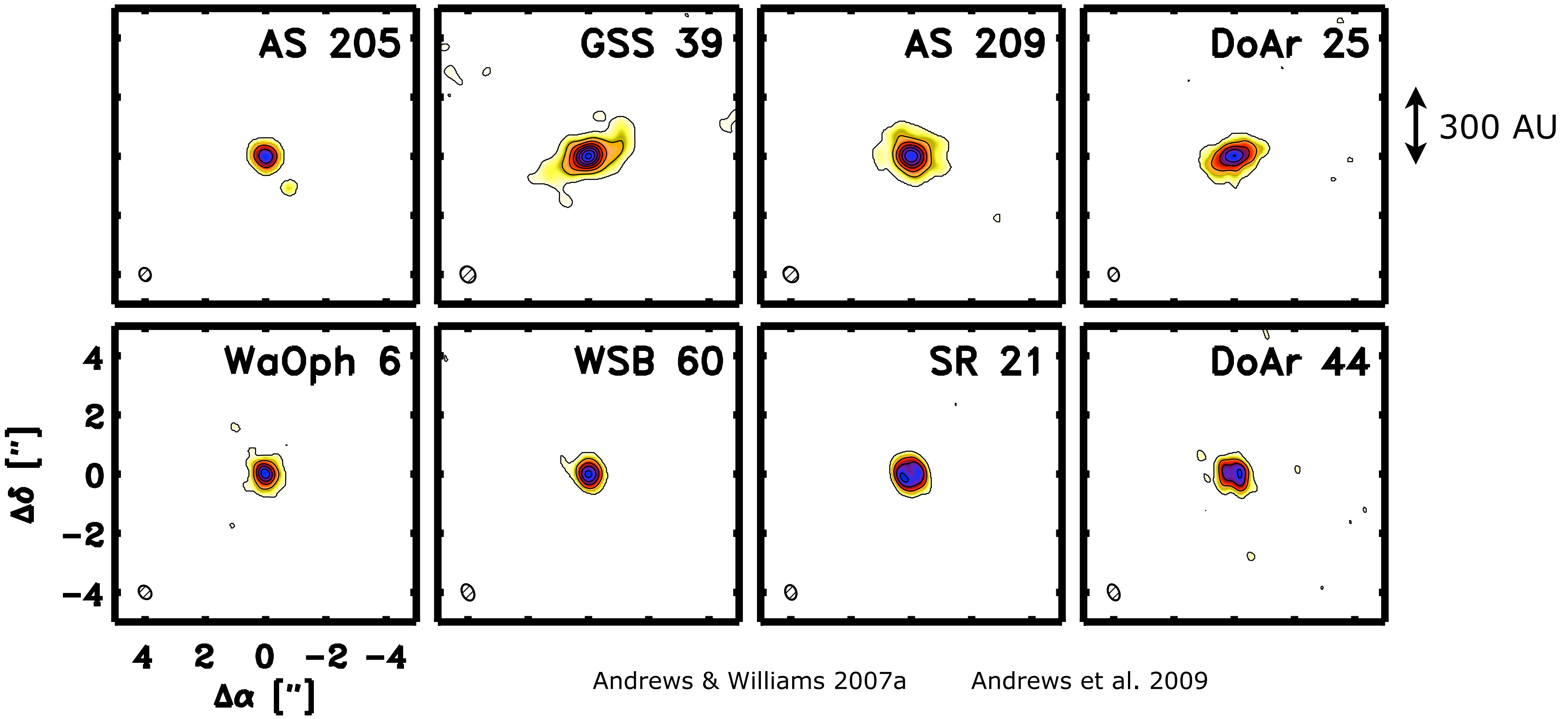


L. E. Allen

~1 Myr-old low-mass star formation

nearby: $d \sim 125$ pc

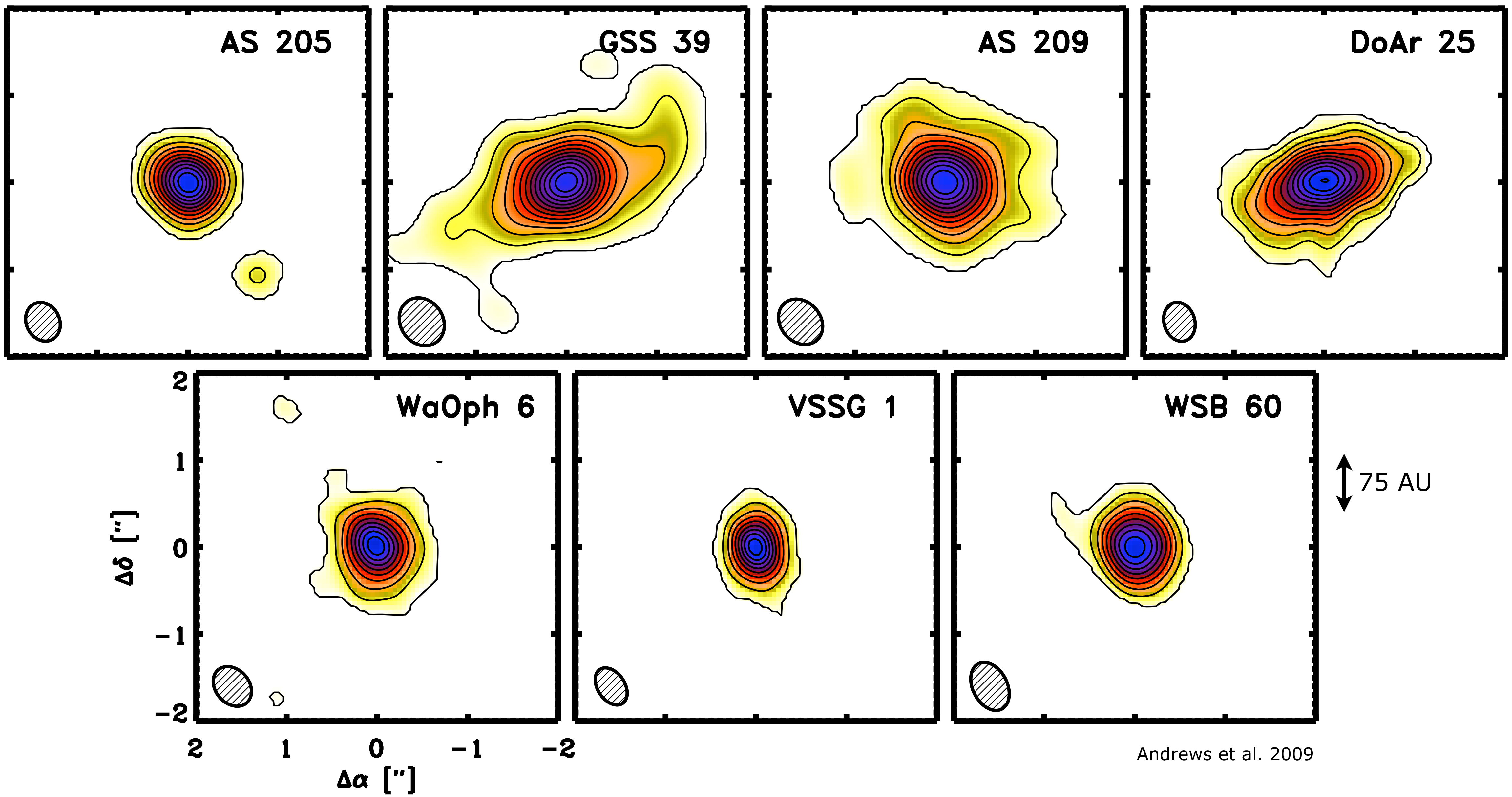
major target region
for ALMA
(Oph is the new Tau)



Andrews & Williams 2007a Andrews et al. 2009

SMA survey of Oph disks

- 0.3" resolution (*R*~20 AU), 870 microns
- 9 of the brightest Class II disks



Andrews et al. 2009

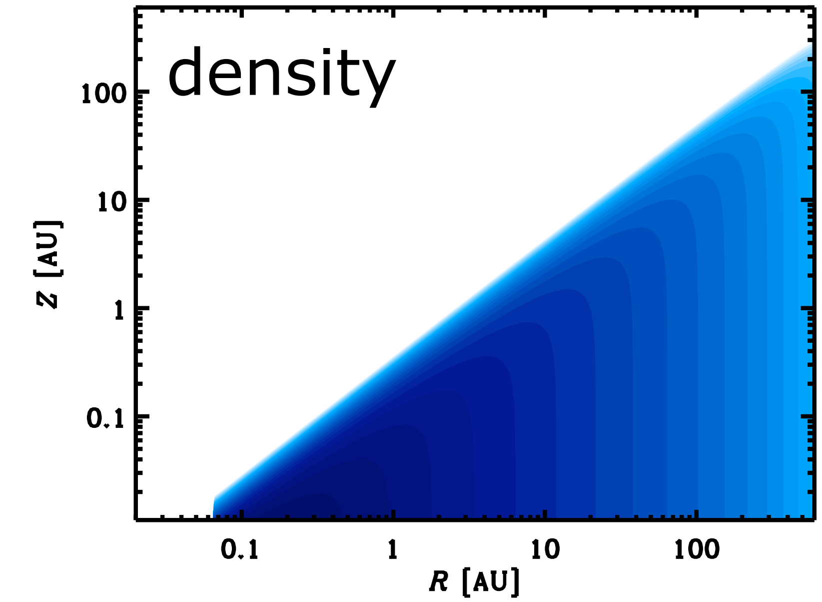
modeling disk structure

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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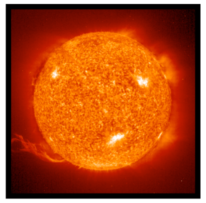

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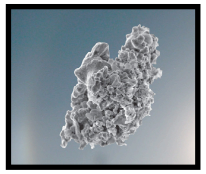
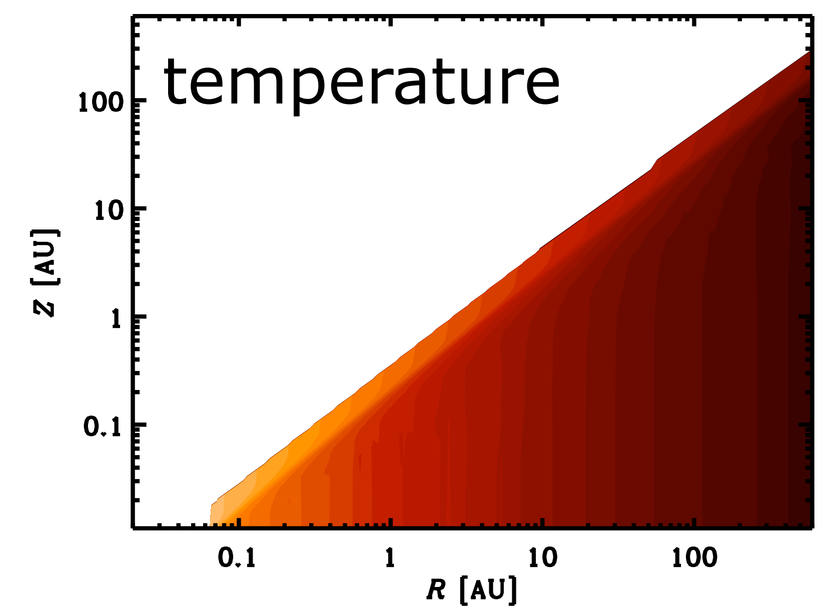
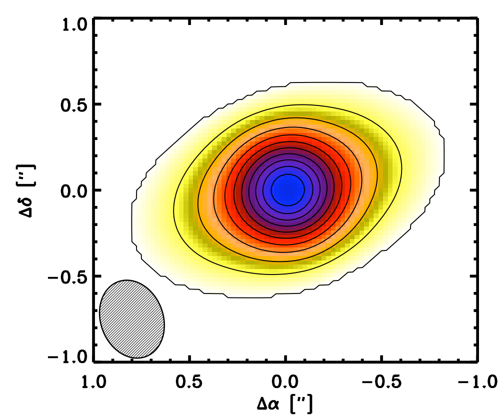
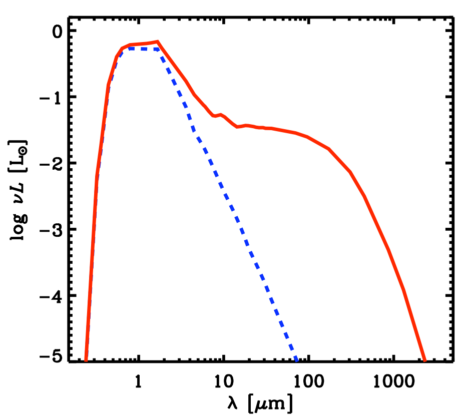


2-D Monte Carlo radiative transfer

Dullemond & Dominik 2004







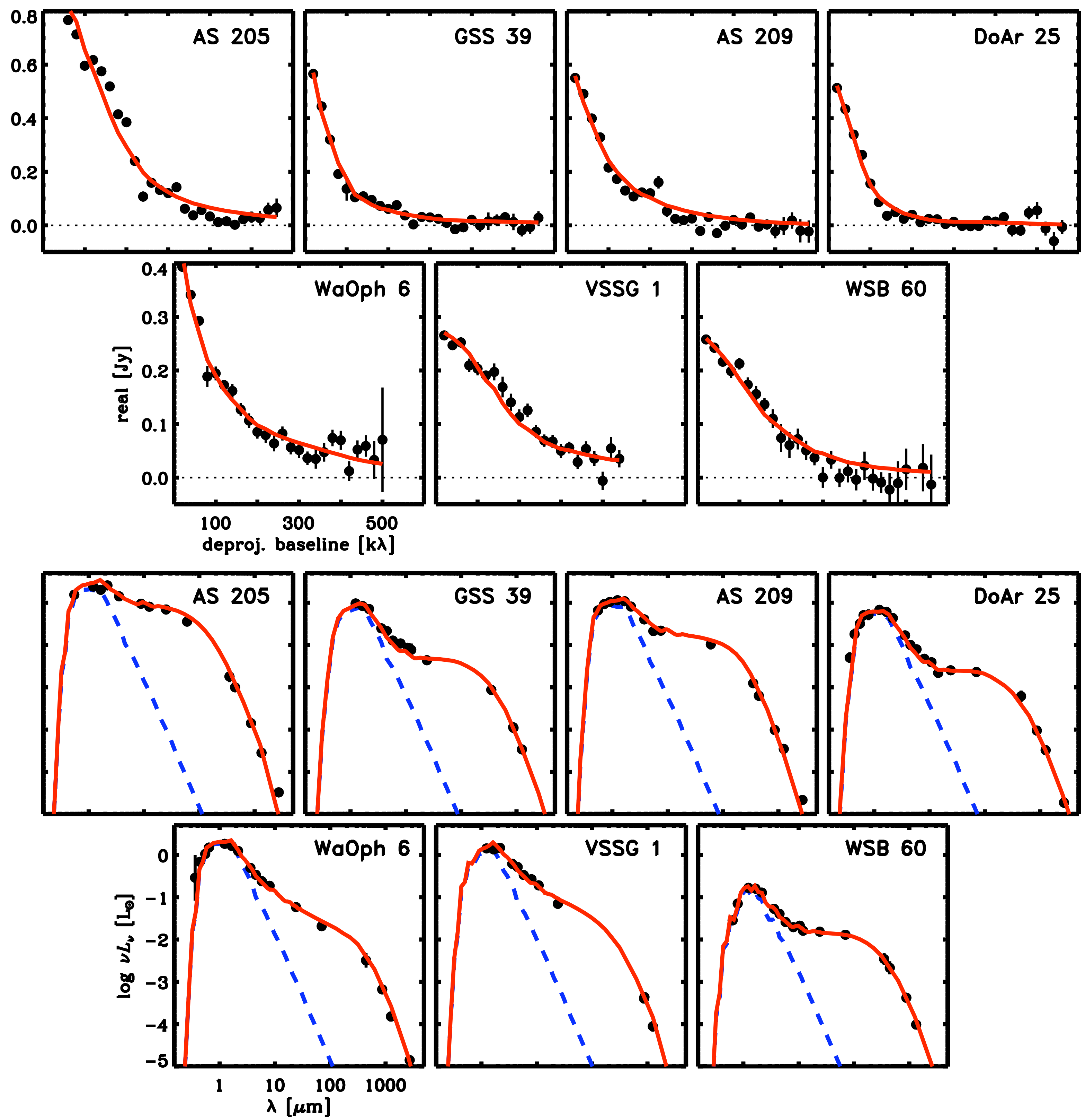
synthetic visibilities + SED

compare with data

modeling results

visibilities

SEDs



modeling results

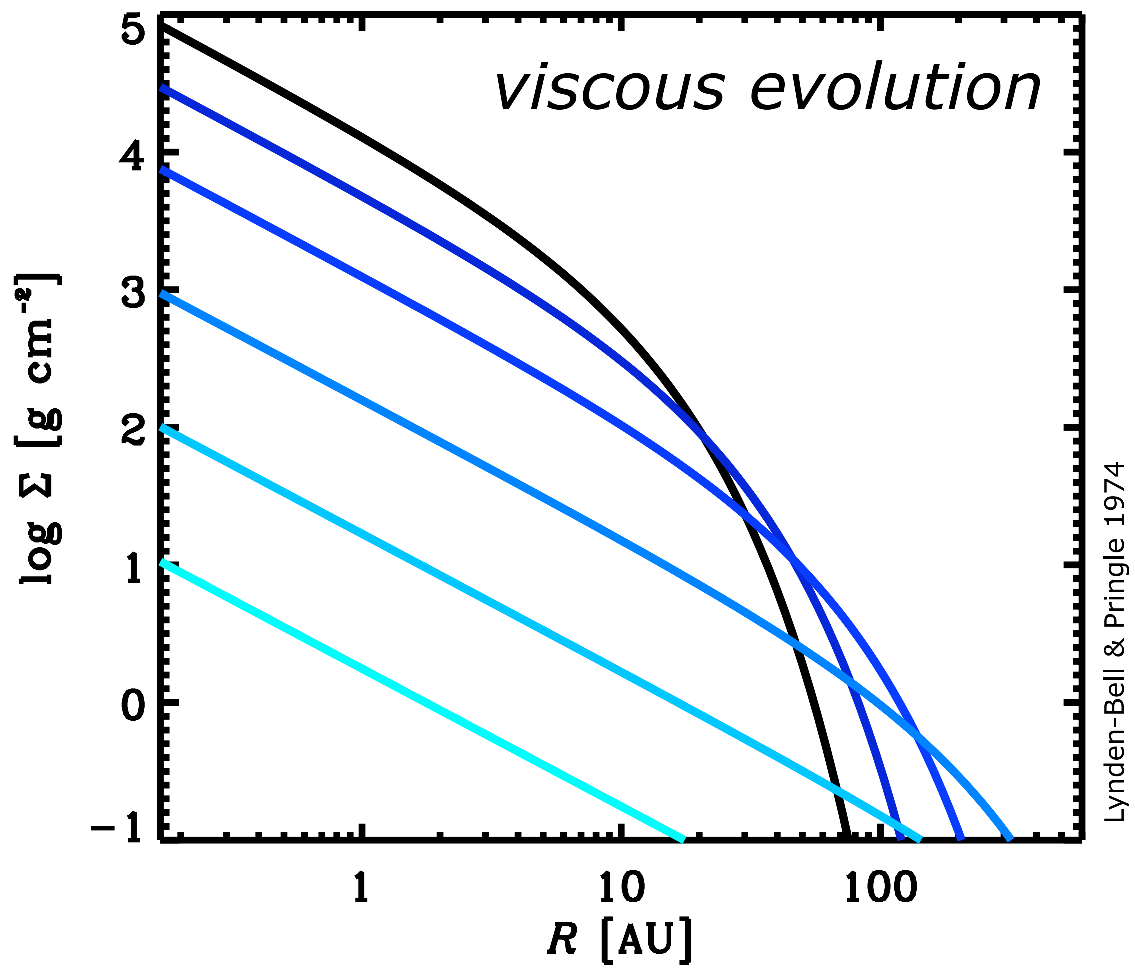
surface density profiles

- comparable to MMSN at ~5-50 AU
- gradients clustered at $\gamma = 1$
  - less steep than MMSN/GI models

    e.g., Vorobyov & Basu 2008

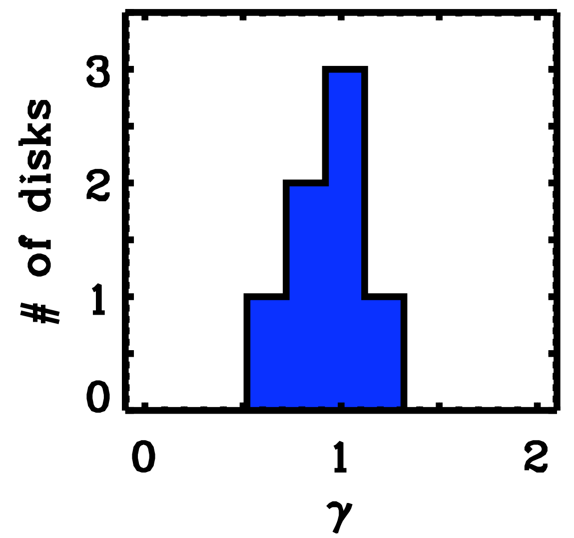
  - "steady" viscous accretion disks

    e.g., Hartmann et al. 1998



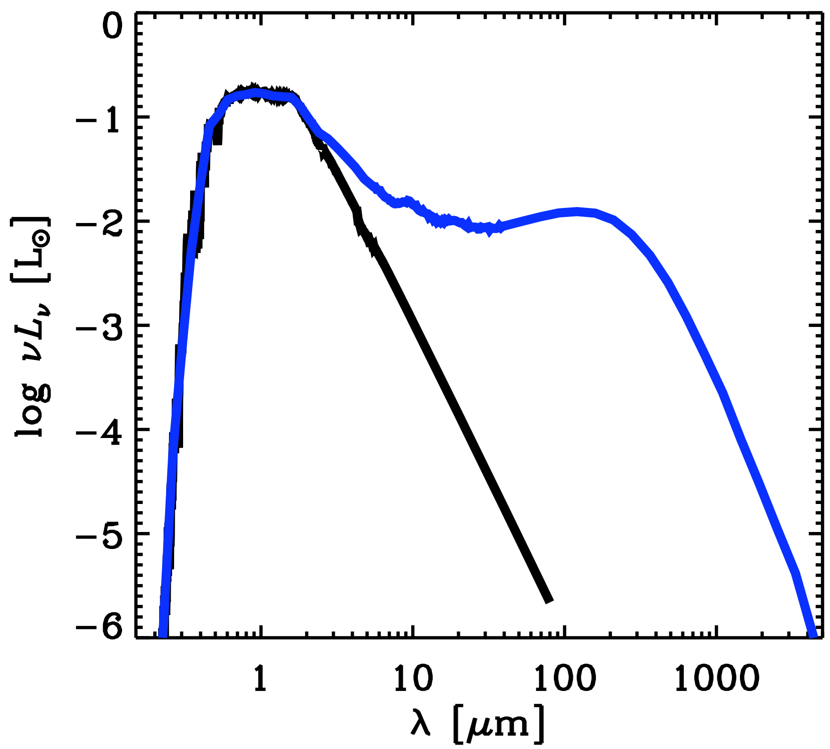
viscous properties

- estimate viscosities: $\nu = \alpha c_s H$
  - structure + accretion rates
  - α ranges from 0.0005-0.06
  - consistent with MRI turbulence

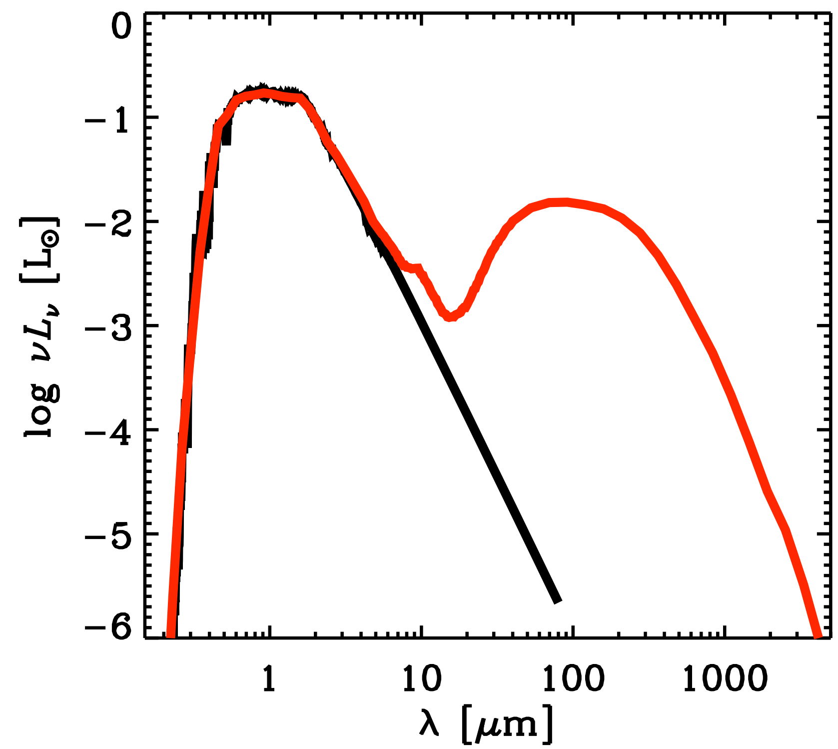


disk evolution: "transition" disks

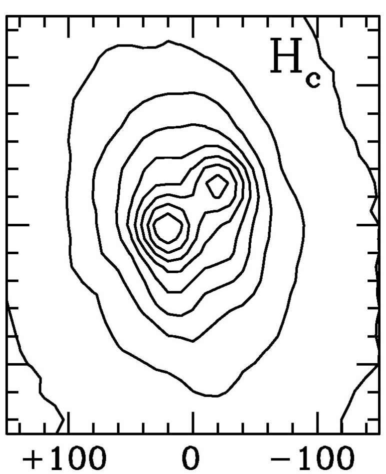
normal



"transition"

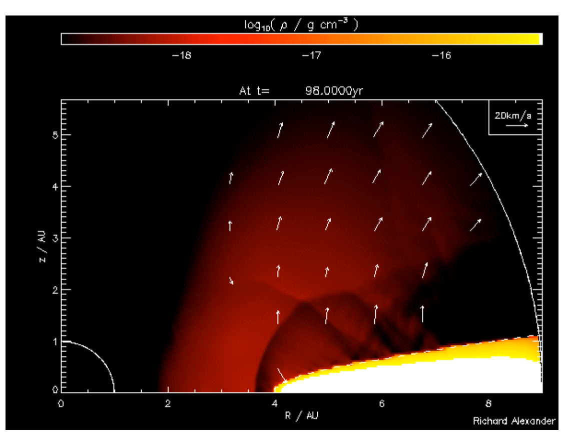


multiplicity



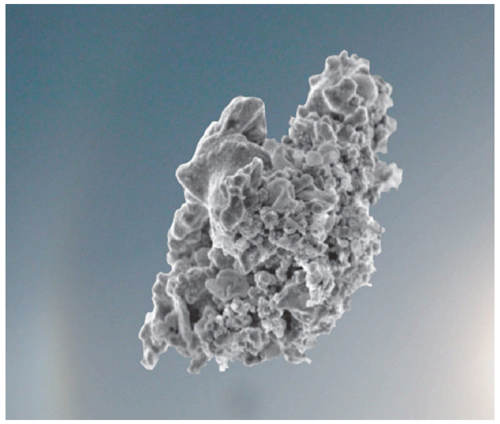
Ireland & Kraus 2008

photoevaporation



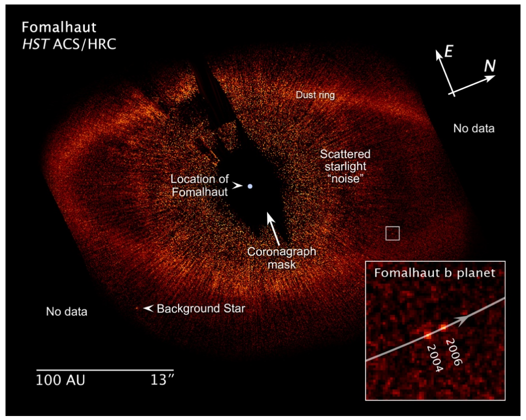
Alexander et al. 2006

grain growth



Dullemond & Dominik 2005

planet interactions

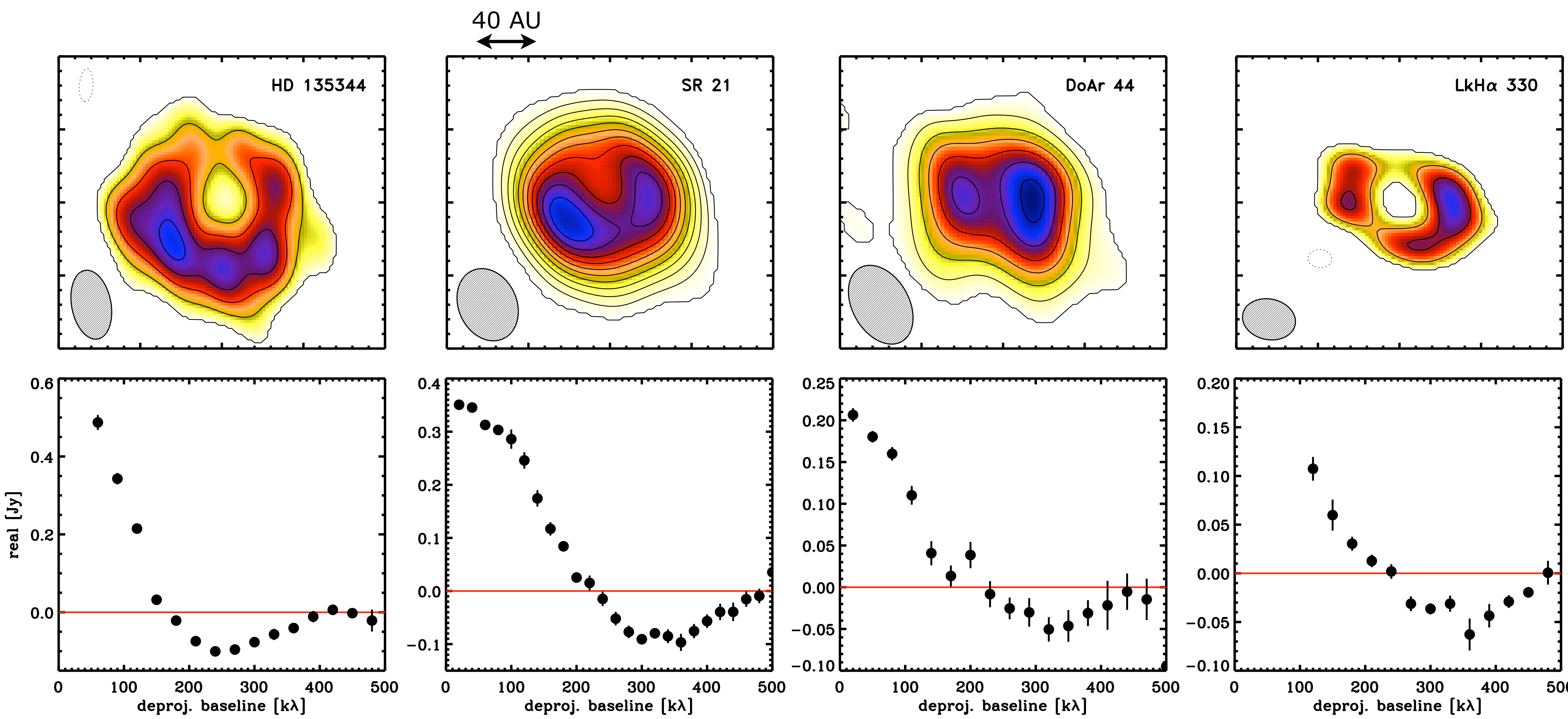


Kalas et al. 2008

direct evidence of central cavities

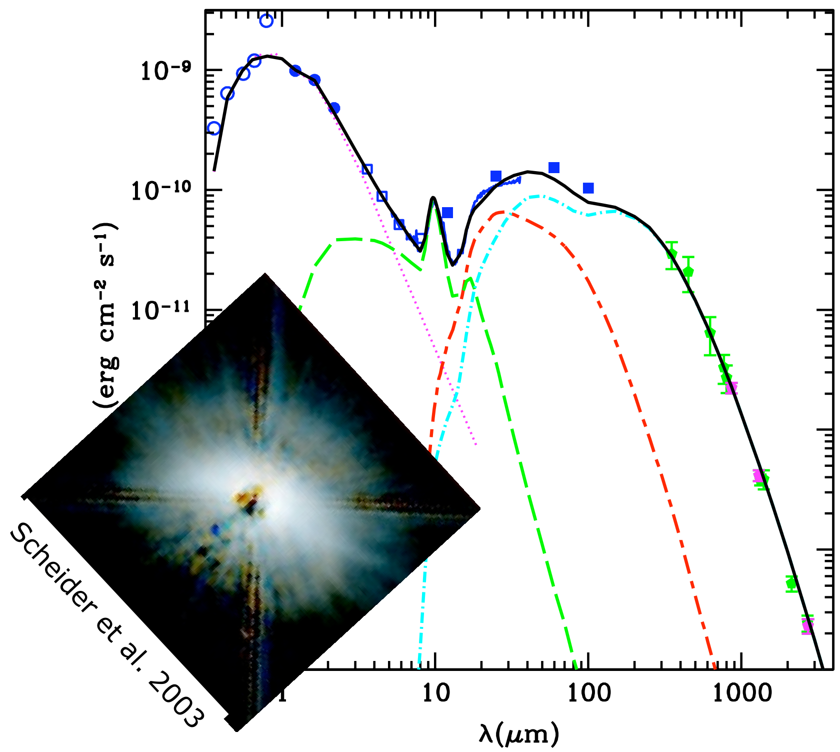
little or no 870 micron emission inside R~20-30 AU

single stars, too much mass for photoevaporation...planets at ~1 Myr?



Brown et al. 2008; Andrews et al. 2009

cavity in the GM Aurigae disk

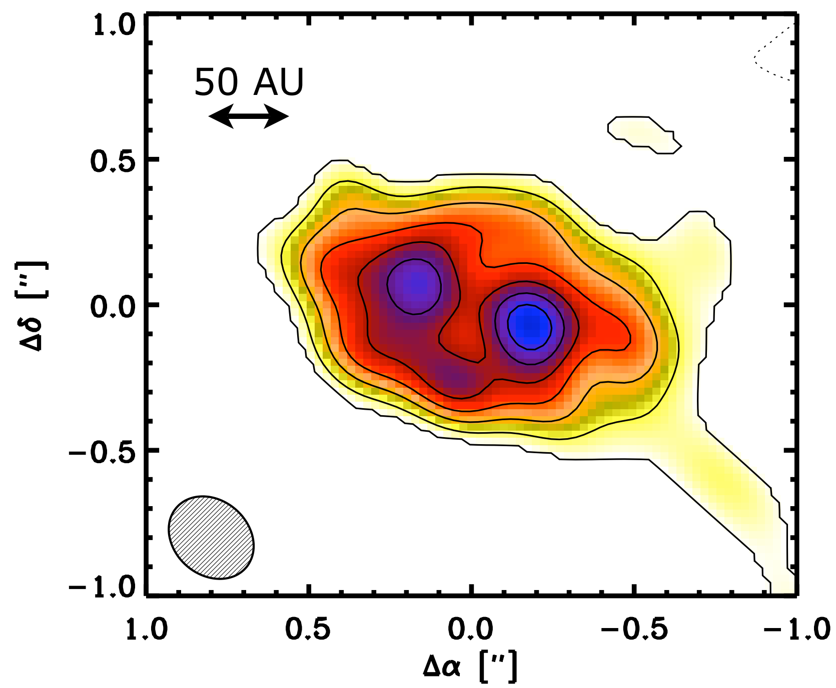


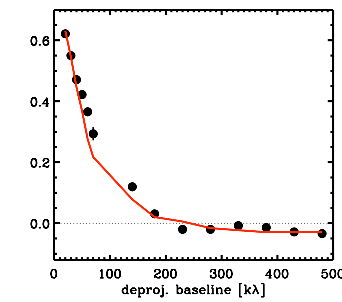
Calvet et al. (2005):
diminished optical depth
for *R*<24 AU

resolved mm image
predictions based solely
on unresolved SED

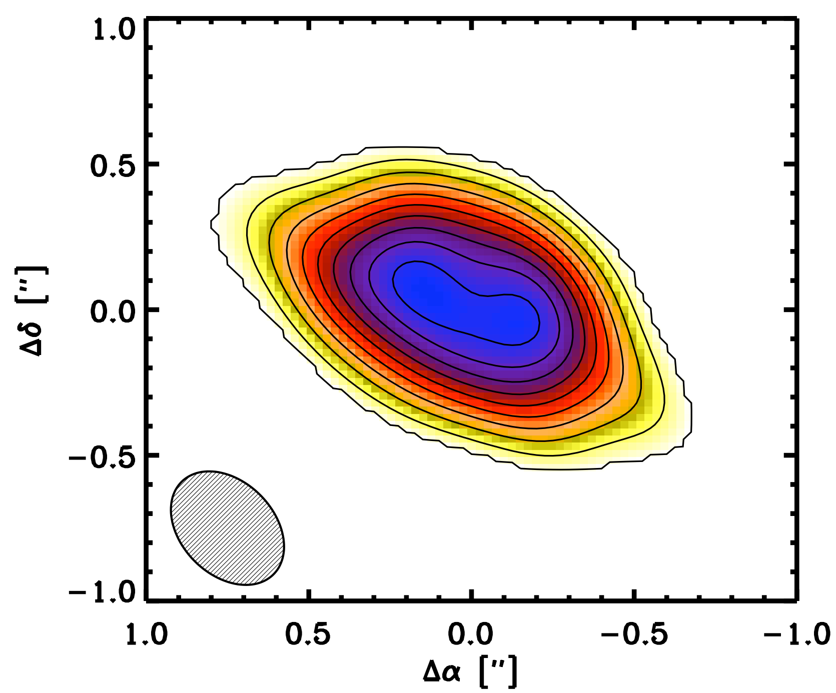
see also D'Alessio et al. 1998; 2001
and Furlan et al. 2006

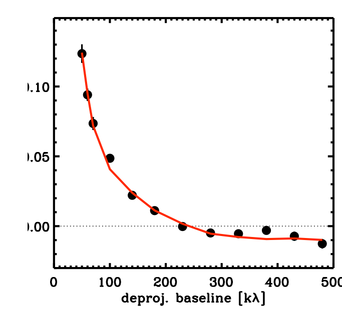
real data





SMA
0.85 mm

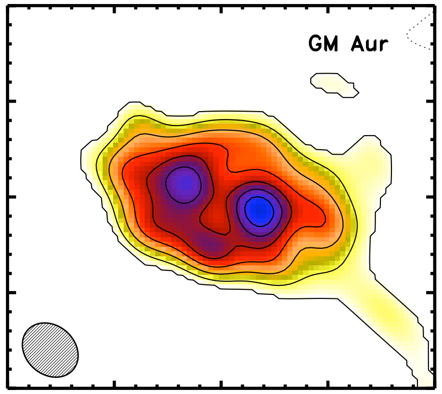


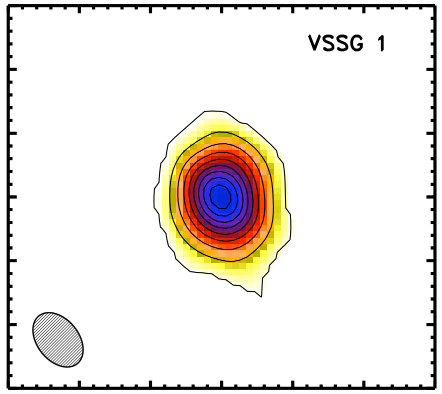


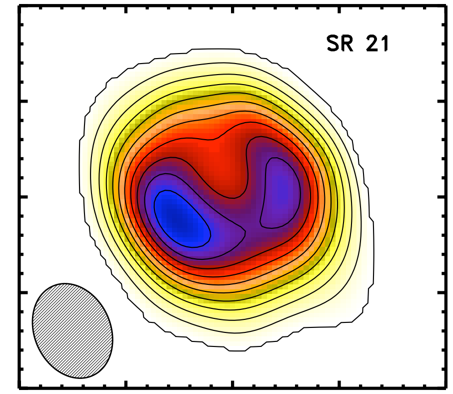
PdBI
1.3 mm

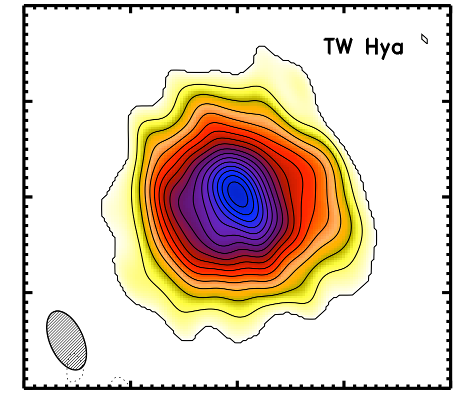
Hughes, Andrews, Espaillat, et al. 2009

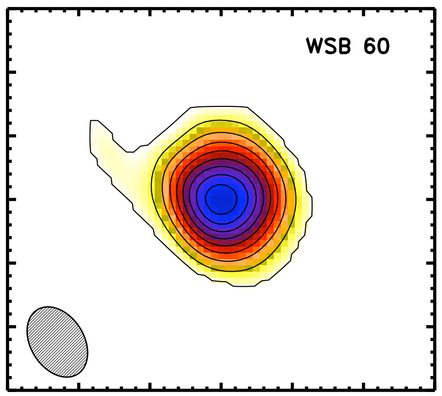
summary

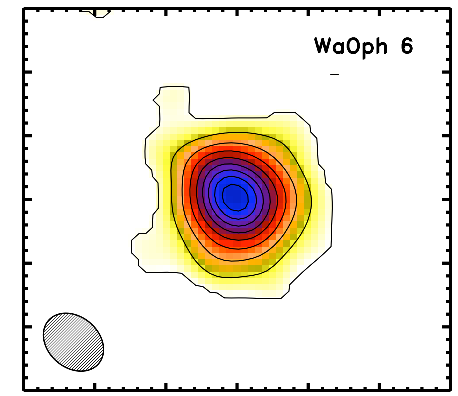


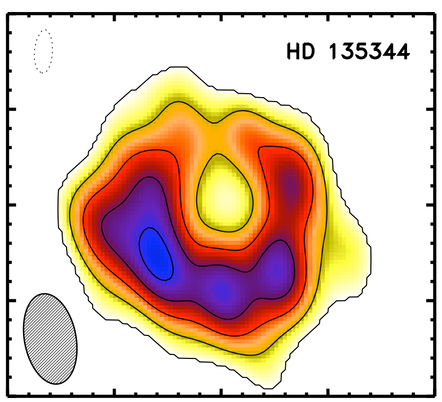


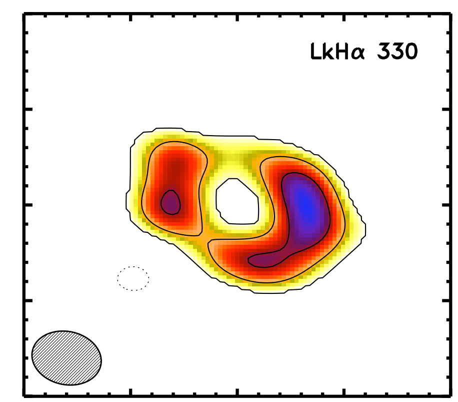












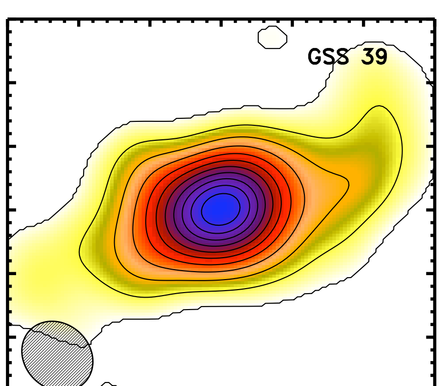
high resolution (0.3”: *R*=20 AU)
870 micron SMA disk survey

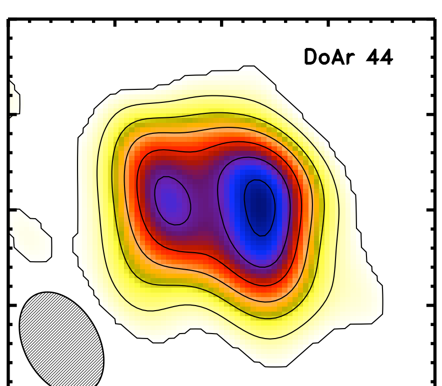
constrain parametric structure models

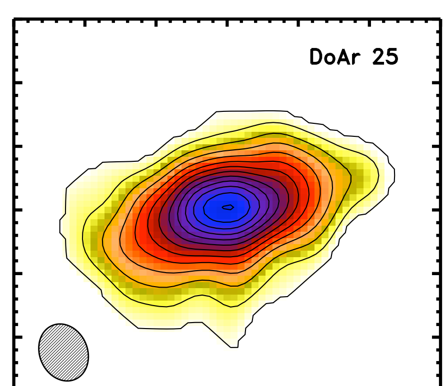
fit SED and SMA visibilities using 2-D RT code

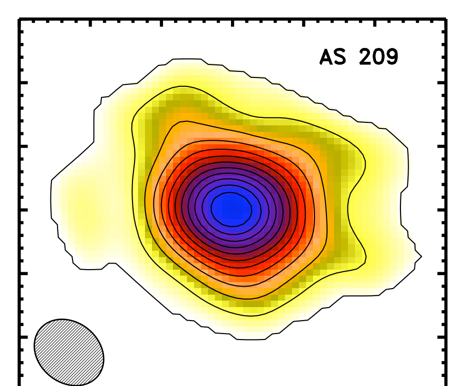
surface densities ~ 1/*R* with exponential edge

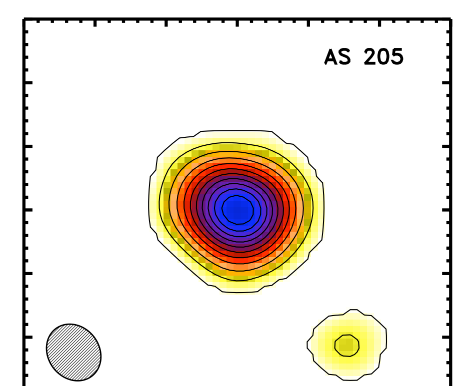
resolved transition disk cavities







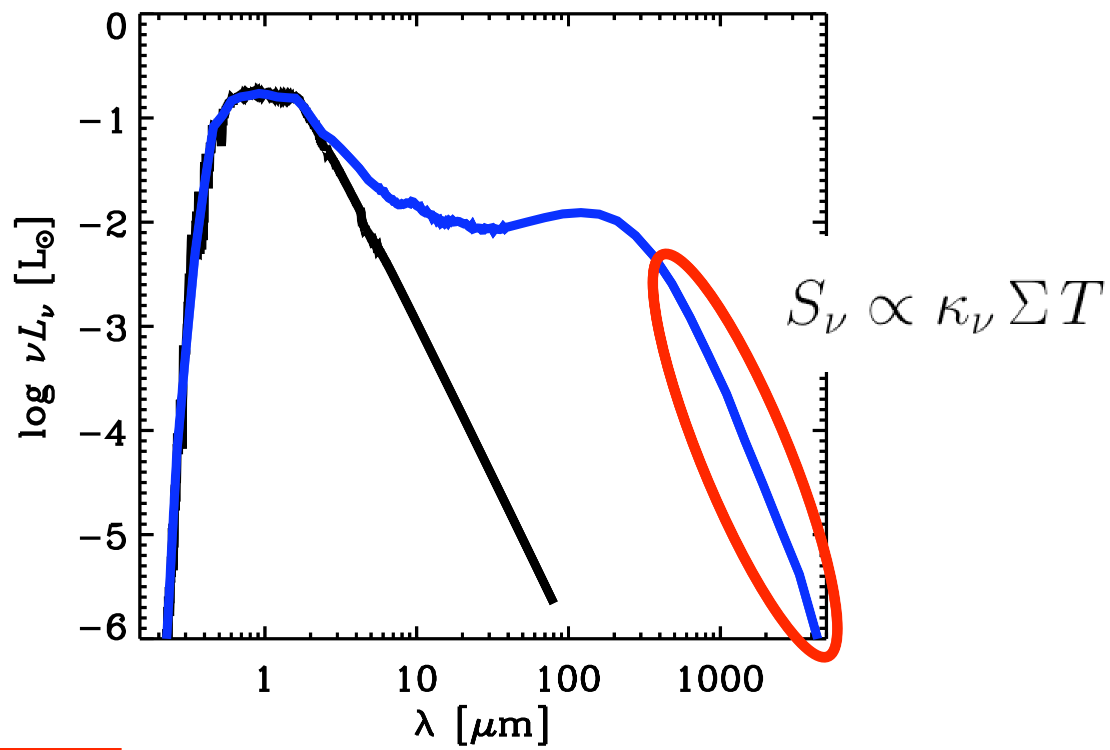




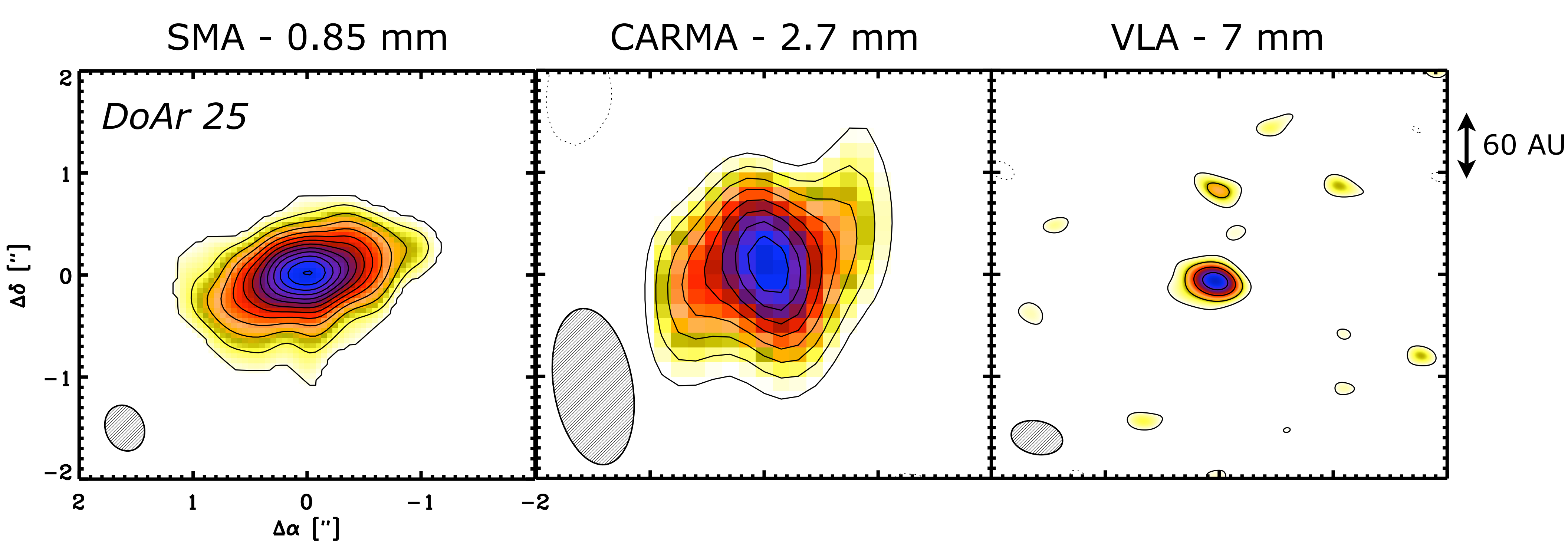
the "catch"

disk structures *linked* to dust emissivities

- some evidence in mm colors
  Beckwith & Sargent 1991
- tend to underestimate densities
  e.g., D'Alessio et al. 2001
- resolved multiwavelength data
  - *helps break degeneracy*
  - *grain growth vs. location*



ALMA + EVLA



a closer look at the TW Hya disk

5-10x older and 3x closer

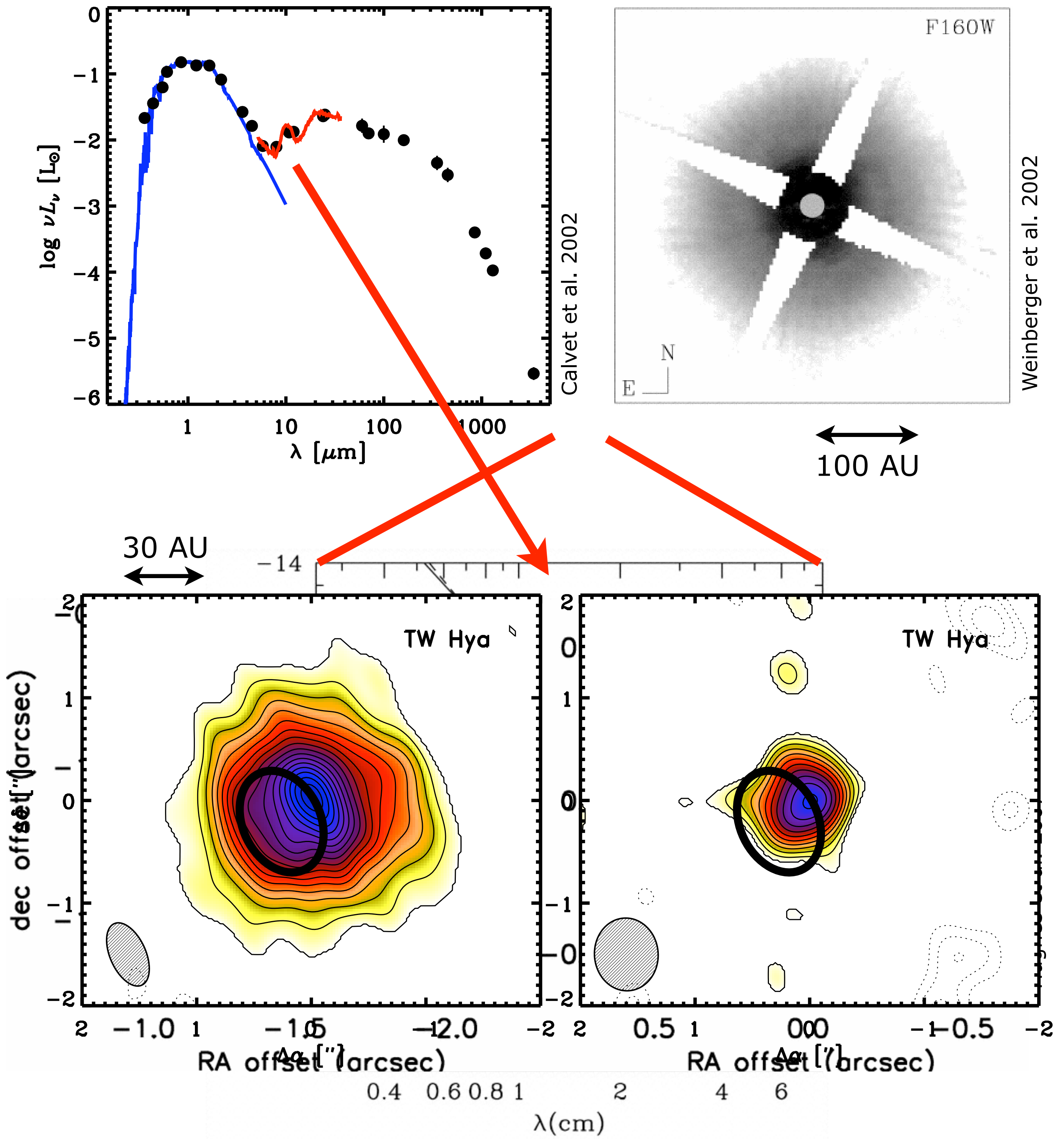
1. SED at cm wavelengths
   - grain growth (pebbles)

   Wilner et al. 2005

2. SED at IR wavelengths
   - hole out to *R* = 4 AU
   - imaged at 7 mm with VLA

   Calvet et al. 2002; Hughes et al. 2007

3. 0.3" at 860 microns
   - structure on 7 AU scales
   - asymmetry at 10 AU
   - 0.5" at 7 mm (VLA)



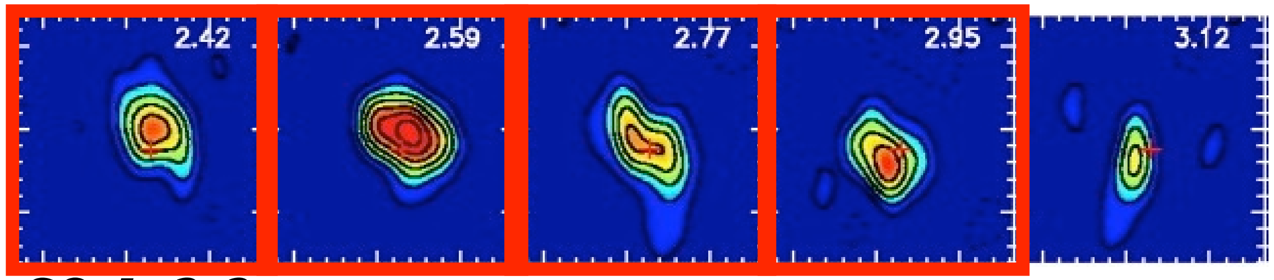
a closer look at the TW Hya disk

5-10x older and 3x closer

1. bright CO line emission
   - isolated from cloud
   - face-on geometry
   - additional heating (x-rays?)

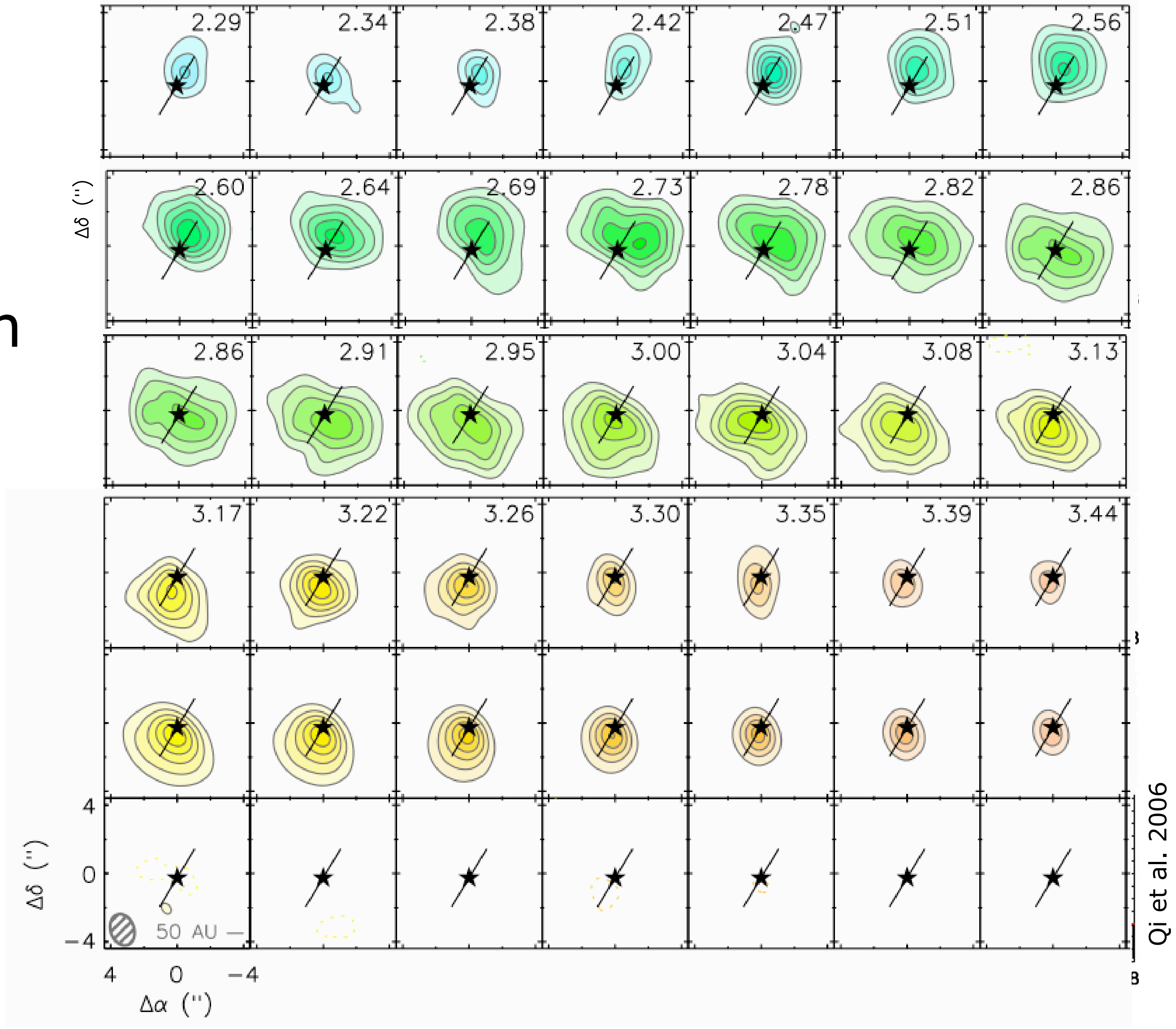
2. detailed kinematics
   - 4x better spectral resolution (44 m/s)
   - Keplerian orbital velocities
   - no supersonic turbulence (unless its laminar)

3. detailed chemistry...
   - isotopes, D-fractionation
   - abundance gradients (!)



CO J=3-2

Qi et al. 2004



Qi et al. 2006