Formation and early evolution of disks

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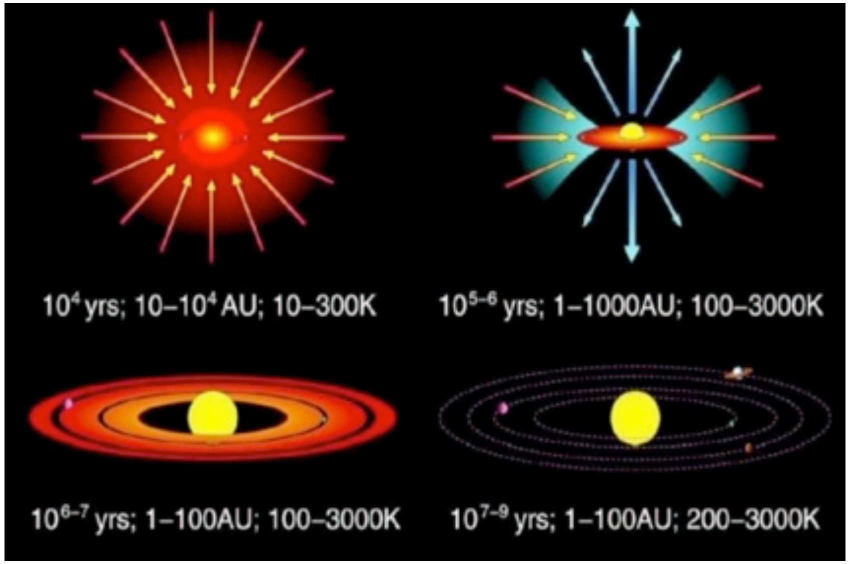
The evolution of low-mass YSOs



after Shu et al. 1987

Low-mass stars formed from gravitational collapse of dense cloud cores.

Gradual dispersal of protostellar envelope (disk accretion; outflow action).

When do circumstellar disks form? How rapidly is material accreted onto the central star?

Deep mid-infrared and/or high angular resolution (sub)mm wavelength observations required to disentangle/probe emission on disk scales

NGC 1333

JCMT/SCUBA 850 μm

Sandell & Knee 2001
H. Kirk e.a. 2006

Spitzer 3.6, 4.5 and 8 μm

J.K. Jørgensen e.a. 2006
R.A. Gutermuth e.a. 2008

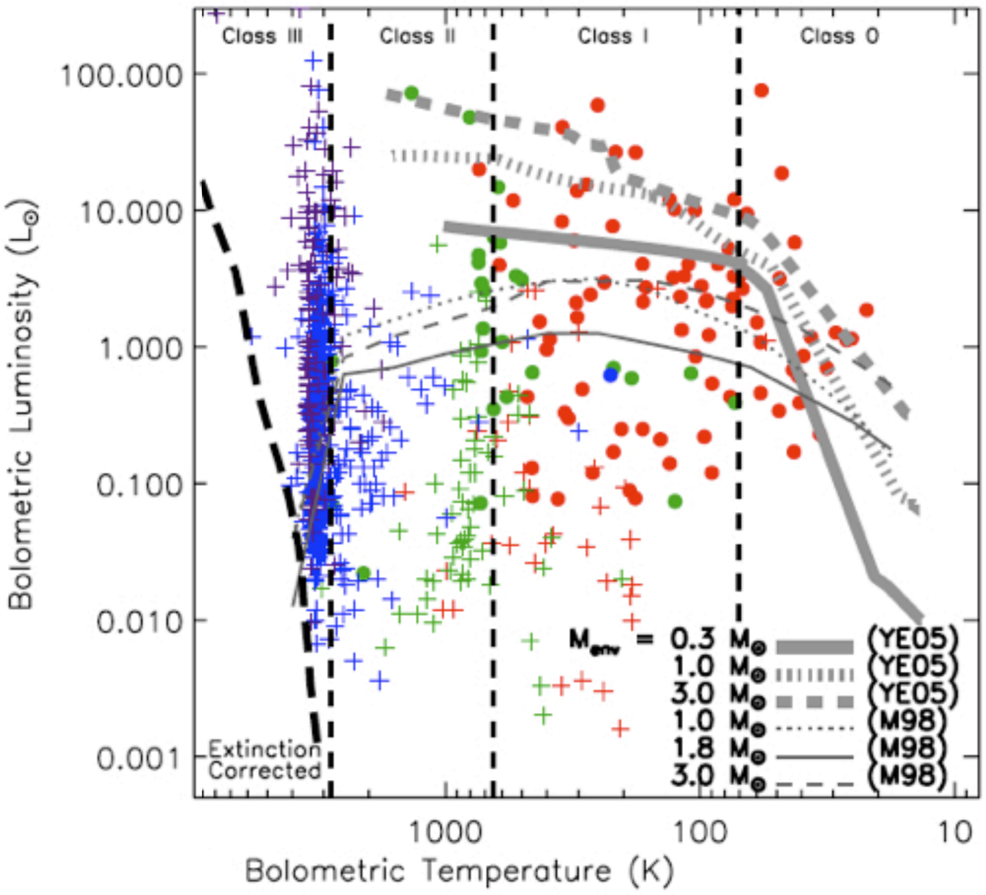
B, V, I and Hα (visible)

T.A. Rector/University of Alaska Anchorage, H. Schweiker/WIYN and NOAO/AURA/NSF

A few statements about protostars

- Protostars are under-luminous compared to accretion of the large-scale envelope directly onto a central star (episodic accretion important?)

- The Class 0 stage last longer than previously thought (10^5 vs. 10^4 years).



Evans et al. (2009)

A few statements about protostars

- Protostars are under-luminous compared to accretion of the large-scale envelope directly onto a central star (episodic accretion important?)
- The Class 0 stage last longer than previously thought (10^5 vs. 10^4 years).
- Protostars loose their envelopes in a few 10^5 years.
- Protostars drive outflows.

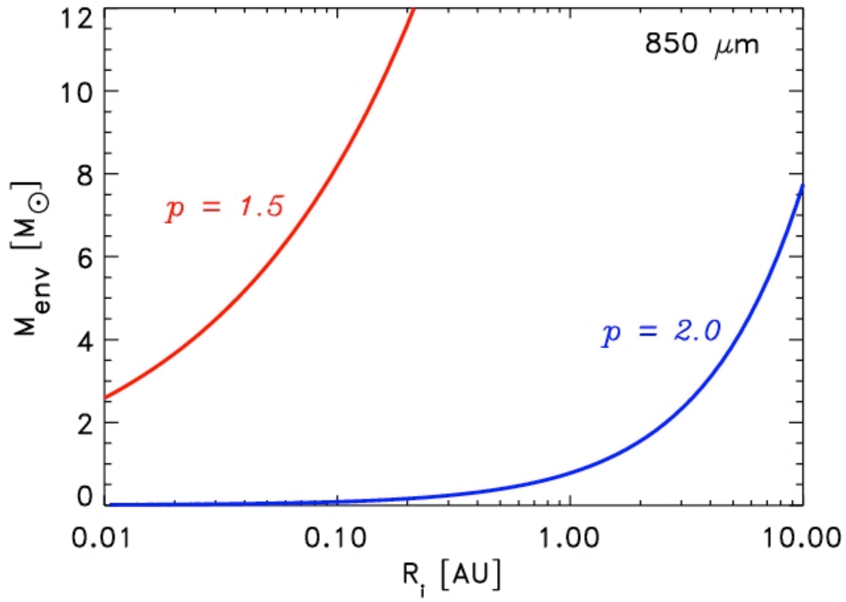
Fraction of c2d YSOs within 15” of a SCUBA core ($M_{env} \gtrsim 0.1\ M_\odot$).
Jørgensen et al. (2008)

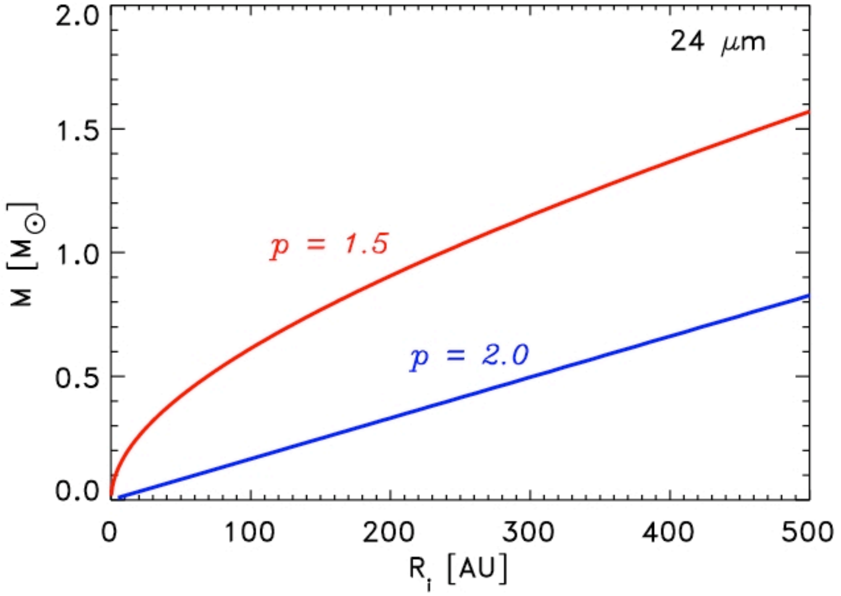
	Perseus	*Ophiuchus*
0	*100% (def.)*	*100% (def.)*
I	*58%*	*47%*
Flat	*10%*	*9%*
II	*1%*	*3%*

Column density and mass

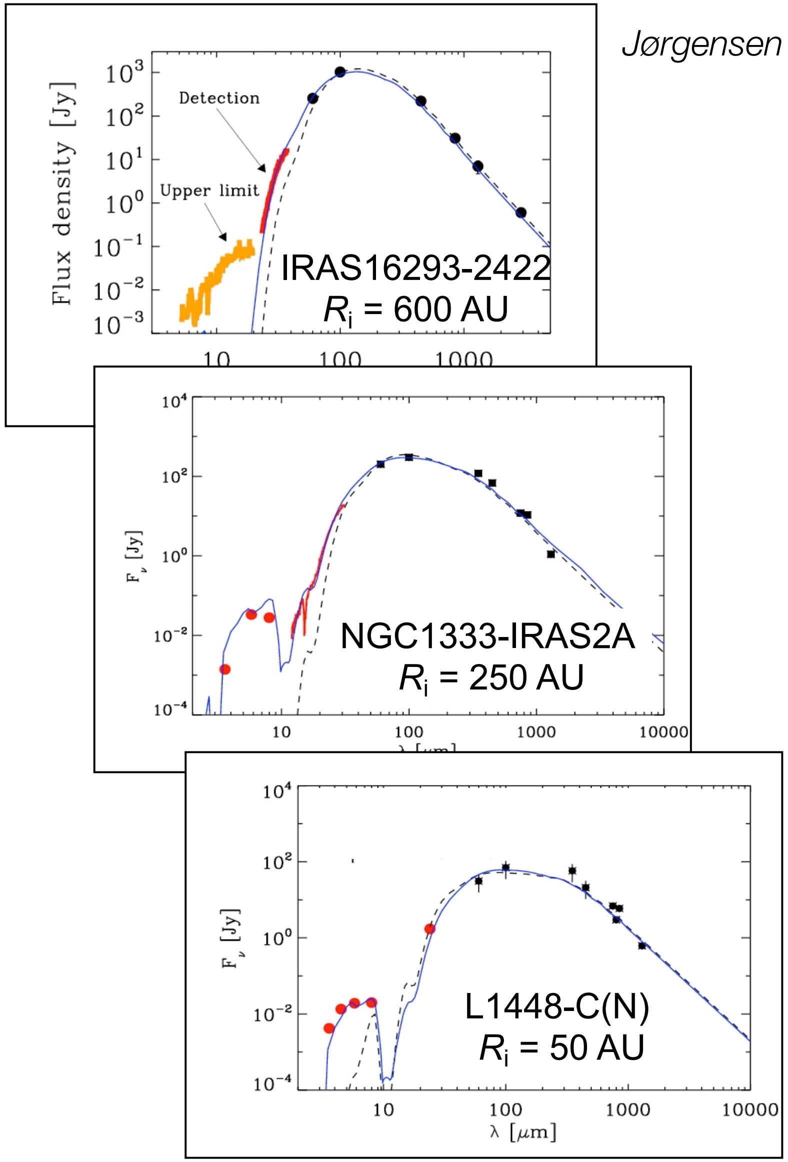
- Typical envelopes have $n \propto r^{-p}$ with $p \approx 1.5$-2.0.
- The mass is on large scales (single-dish beam) whereas the line of sight column density/extinction is on small scales (IR pencil-beam).

When looking inwards, at what radius do envelopes become optically thick?

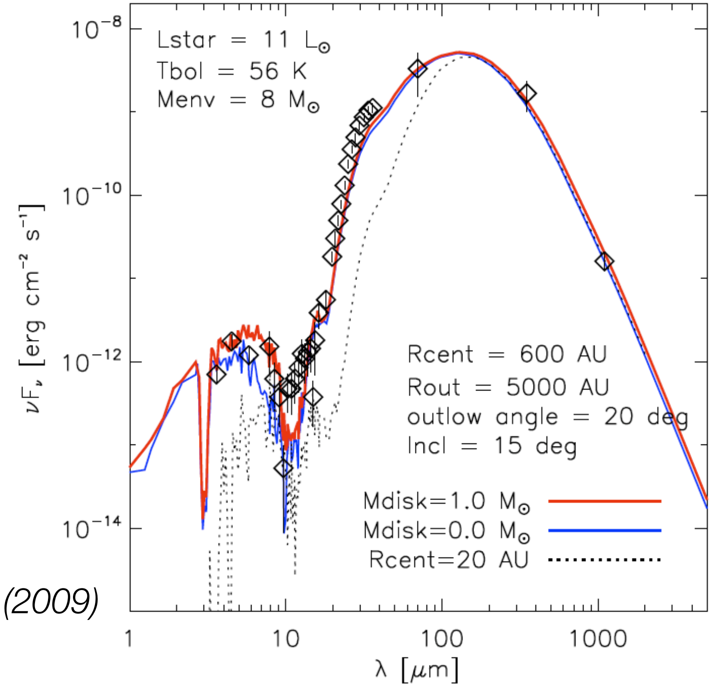




Mid-infrared “excesses” generally seen



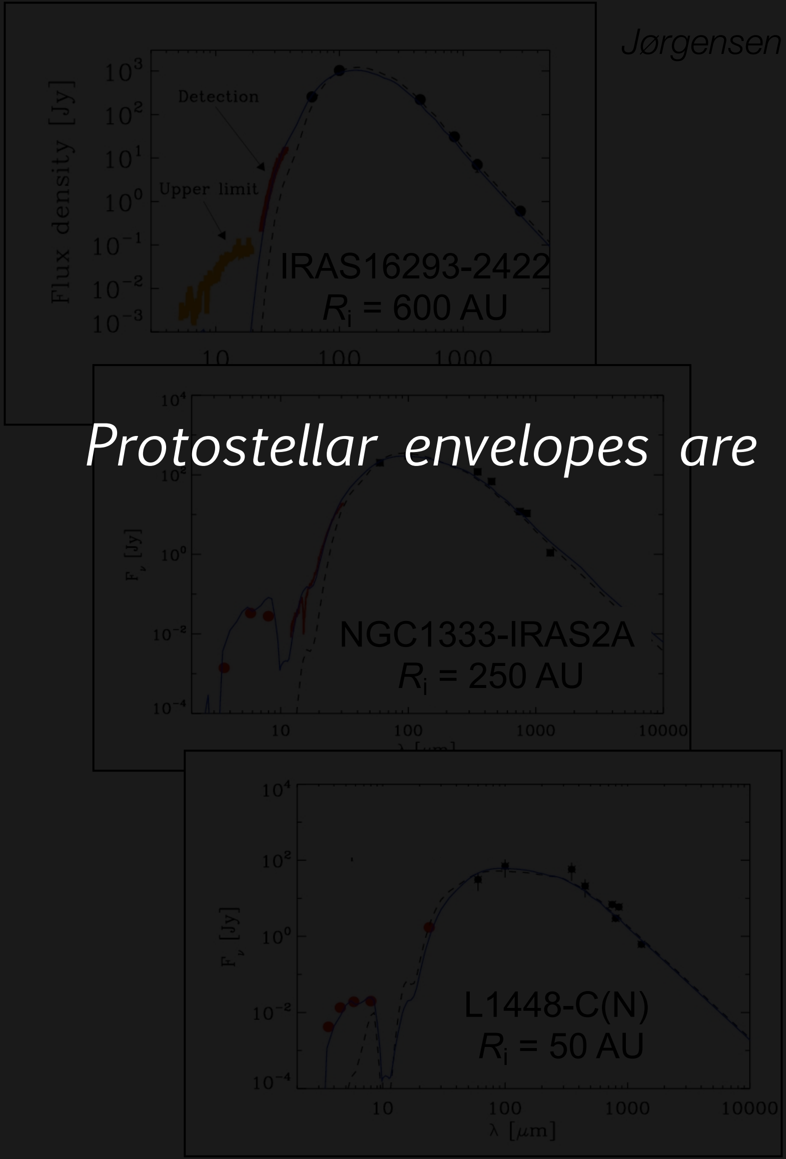
Jørgensen et al. (2005)



Enoch et al. (2009)

If “inner cavity” is introduced (i.e., inner radius wherein envelope profile flattens), the SED is well-reproduced. Otherwise envelope severely optically thick at mid-IR wavelengths; not enough emission escapes from the central source(s). Radii correspond well to size of binary/disk structures.

Mid-infrared “excesses” generally seen



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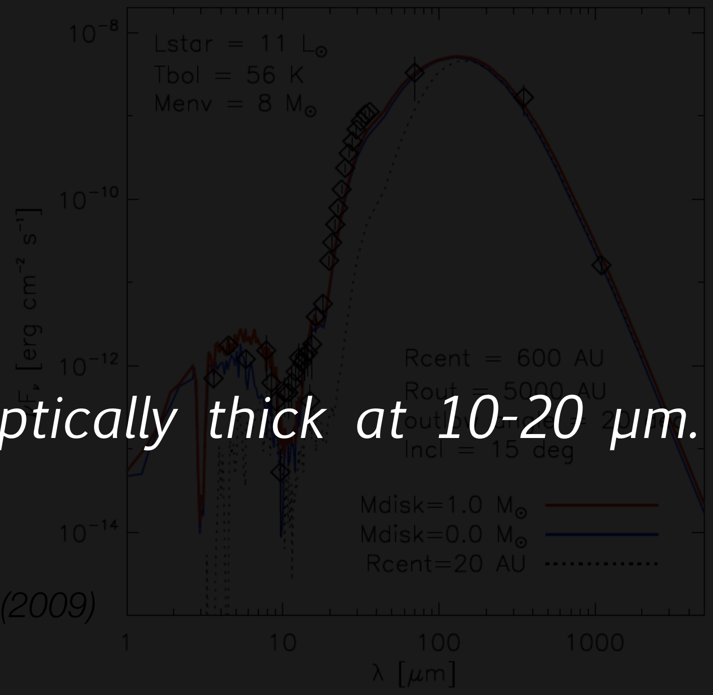

Enoch et al. (2009)

Protostellar envelopes are not (even) optically thick at 10-20 μm.

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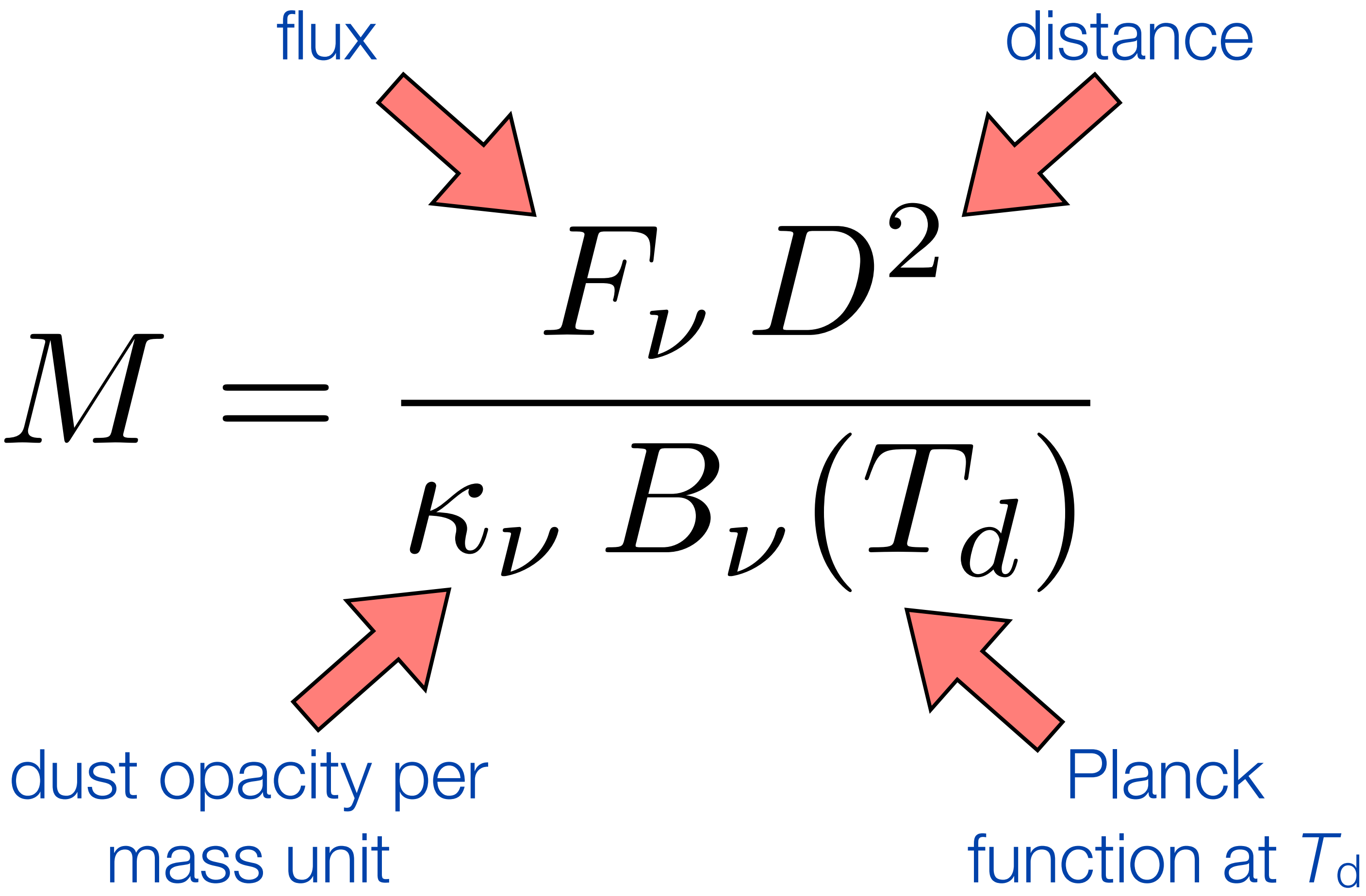
Mass of circumstellar disks from continuum obs.



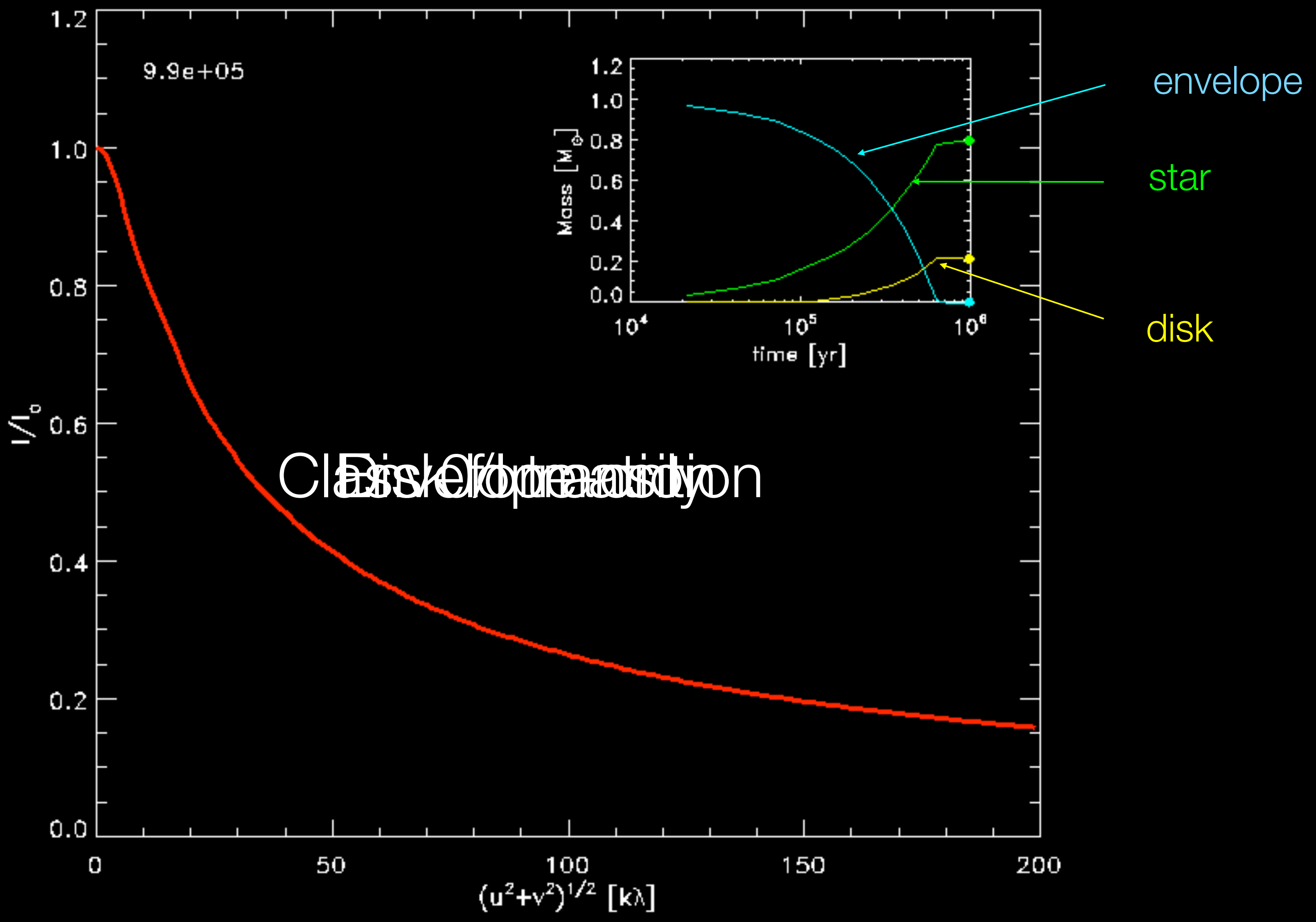
flux

distance

$$M = \frac{F_\nu \, D^2}{\kappa_\nu \, B_\nu(T_d)}$$

dust opacity per
mass unit

Planck
function at *T*d



Evolution of interferometric continuum flux for collapsing model (Visser et al., 2009; Cassen & Moosman 1981; Terebey et al. 1984)

Millimeter continuum searches for embedded disks

- a few studies -

Keene & Masson (1990): Detection of excess emission at long baselines in the embedded protostar L1551-IRS5.

Terebey et al. (1993): 10 low-mass low-mass YSOs observed with OVRO at about 7” resolution combined with IRAM 30 m 1.3 mm data; analysis within Terebey, Shu & Cassen (1984) model for collapsing, rotating core. Massive ($M > 0.5$ $M_{\odot}$) circumstellar structures rare, but OVRO emission usually dominated by spatially unresolved component.

Hogerheijde+ (2000, 2001): Radiative transfer modeling of SCUBA envelopes, inferring the presence of disks from OVRO obs.

Looney et al. (2000, 2003): BIMA survey of Class 0 and I sources, multiplicity, and analytic fits. Low disk/envelope mass ratios → fast processing of material (>85% of continuum flux ~ envelope).

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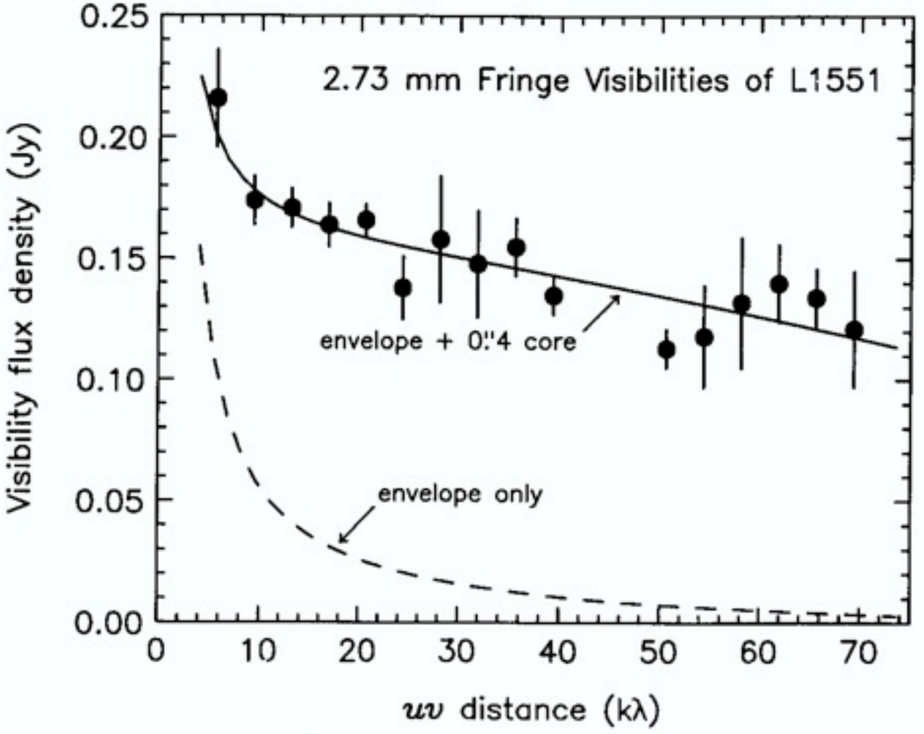
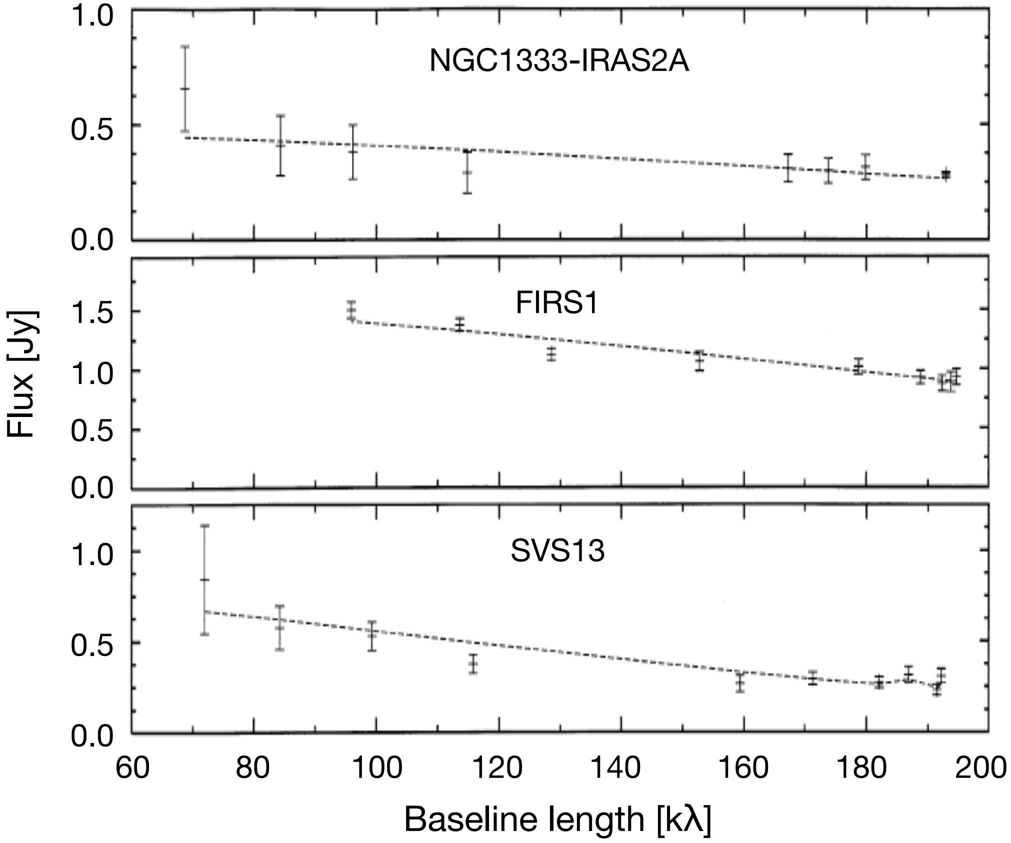


FIG. 3.—The observed 2.73 mm visibilities. The dashed line shows the visibilities resulting from an envelope with 0.29 Jy total flux and with a volume emissivity $\propto r^{-2}$. The solid line shows the visibilities resulting from a similar envelope with a flux of 0.14 Jy plus a compact Gaussian source with a flux of 0.15 Jy (for a total flux of 0.29 Jy) and a half-power radius of 0.″4. It is obvious that the two-component model fits the data much better than a simple power-law source.

Resolved disks...?

- Brown et al. (2000): survey of 0.8 mm continuum emission from embedded YSOs with the JCMT +CSO interferometer. Resolved 1” structures in 3 Class 0 protostars.



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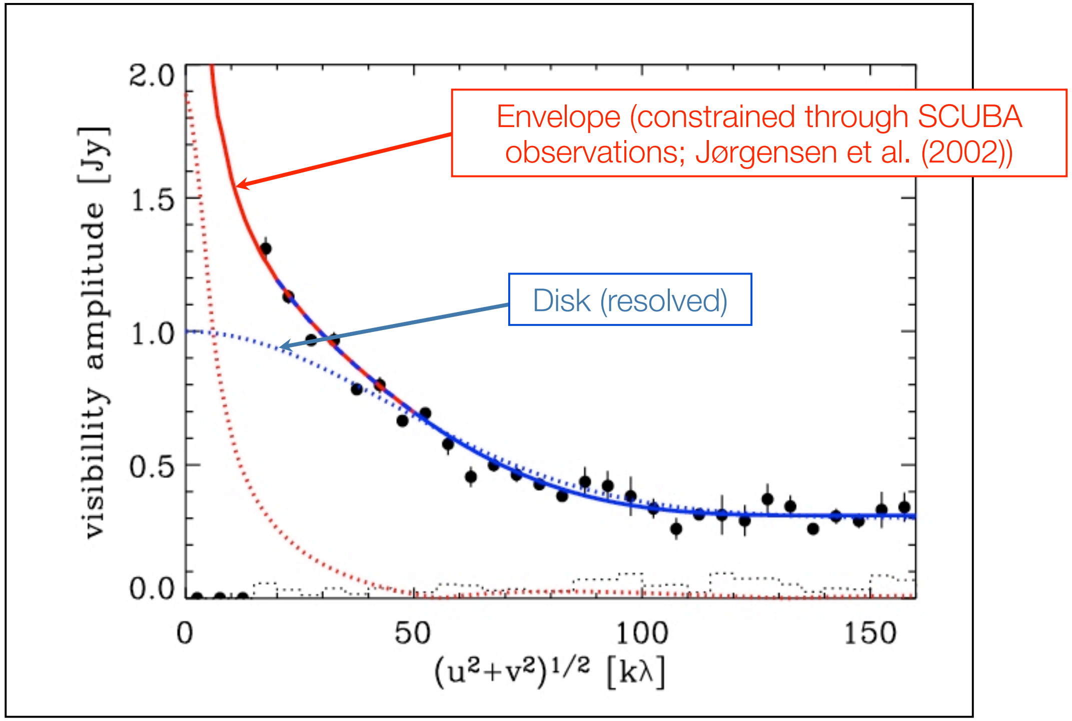

Envelope (constrained through SCUBA observations; Jørgensen et al. (2002))

Disk (resolved)

Jørgensen et al. (2005)

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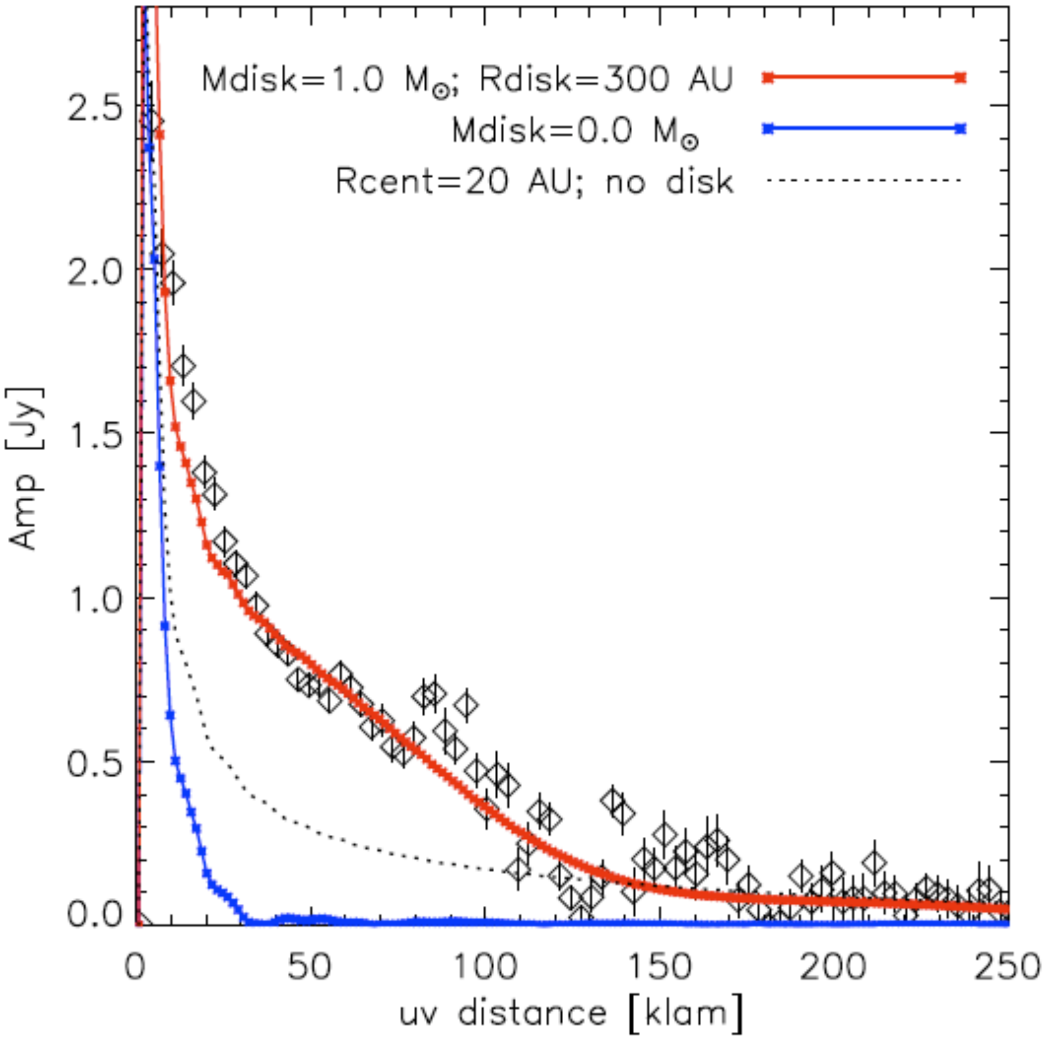
- **Enoch et al., in press.:** CARMA observations of Serpens SMM1: massive (1.0 $M_\odot$; 300 AU radius disk. A steep envelope density profile remove the need for such a disk, but not consistent with SED (i.p., mid-IR).



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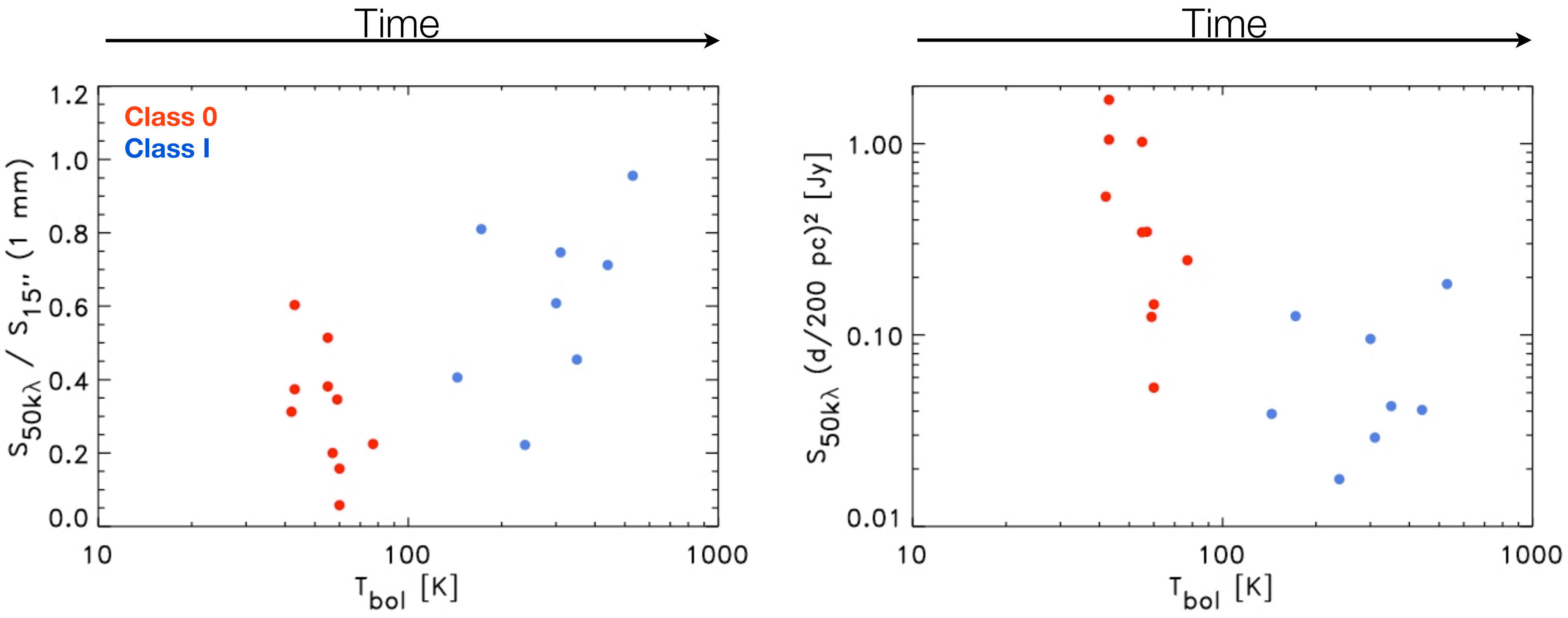
Mass evolution of low-mass stars

SMA survey of emission (~1”) from 20 embedded YSOs (Jørgensen et al. 2009)



Disks around Class I sources are not more massive than those around the younger Class 0’s ⇒ rapid disk formation and growth.

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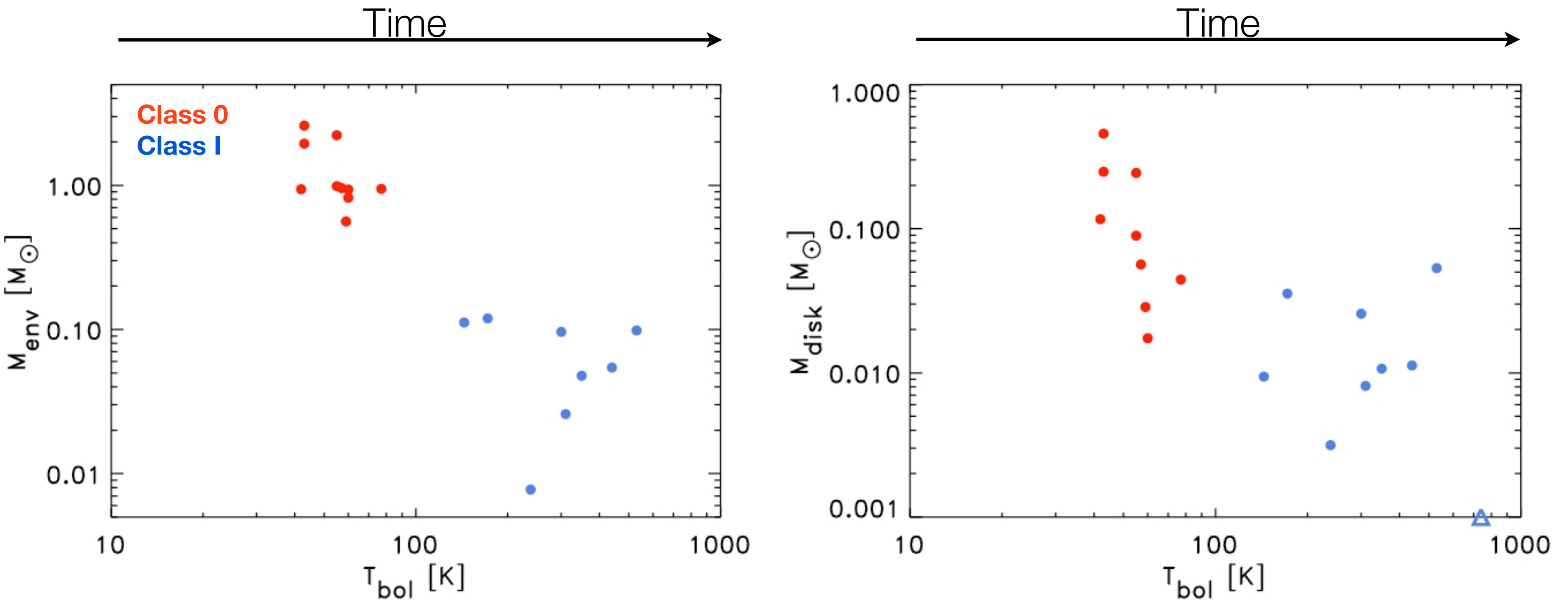

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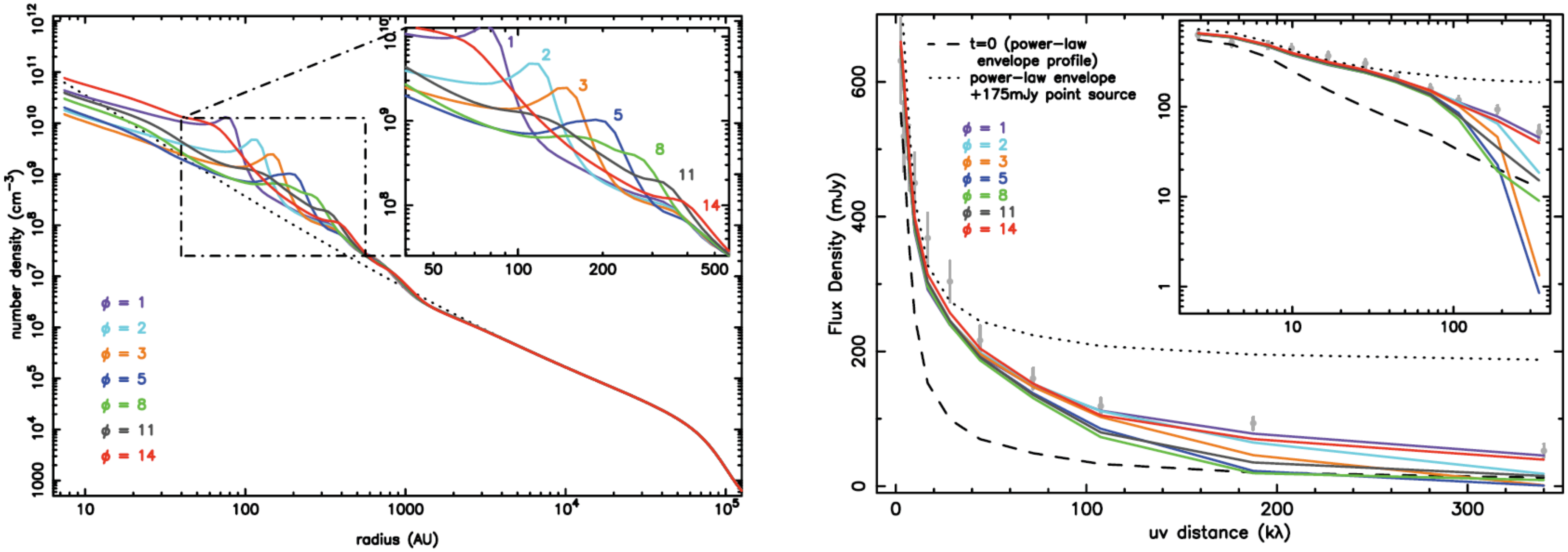
...or other density enhancement on small scales?

- Magnetic collapse models by Tassis & Mouschovias (2005). Formation of enhanced magnetic field, resulting in a shock progressing outwards. Accretion/formation of magnetic shock wall proceeds sequentially.
- Modeling of 4 YSOs from sample of Looney et al.; remove the need of central accretion disks (or place upper limits on their masses, 0.1 $M_{\odot}$)



Chiang et al. (2008)

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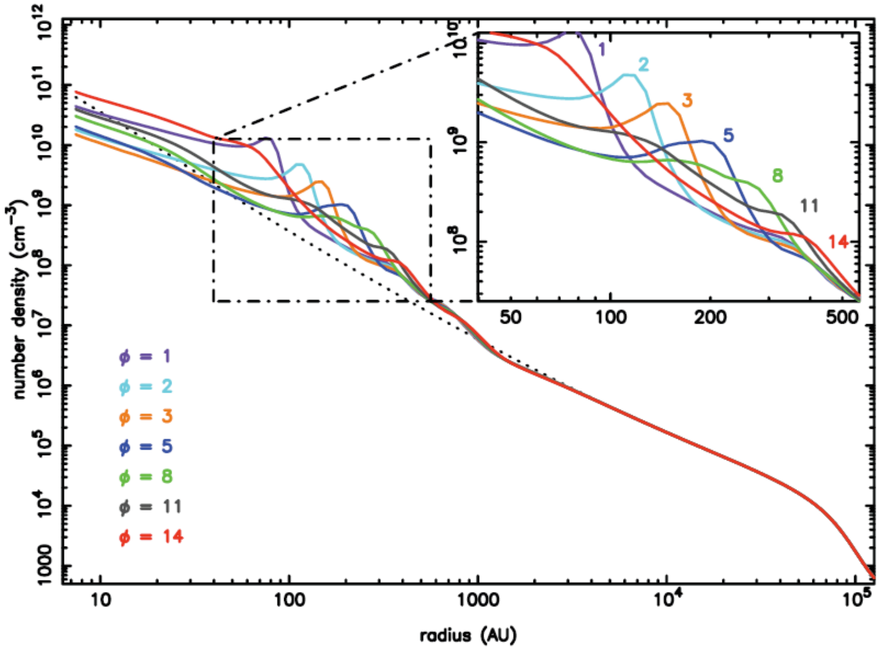
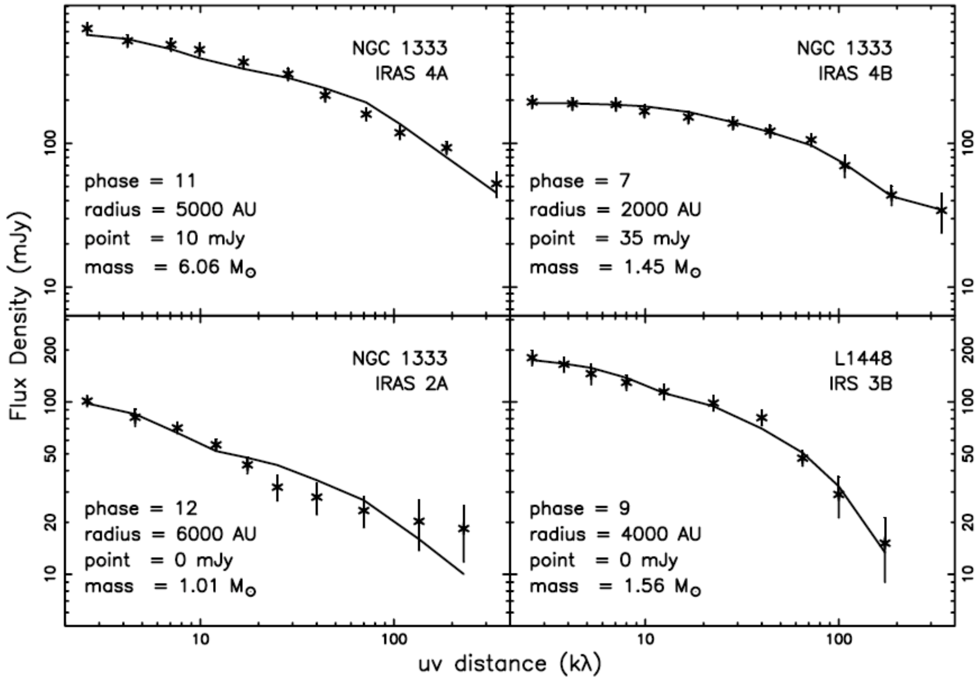


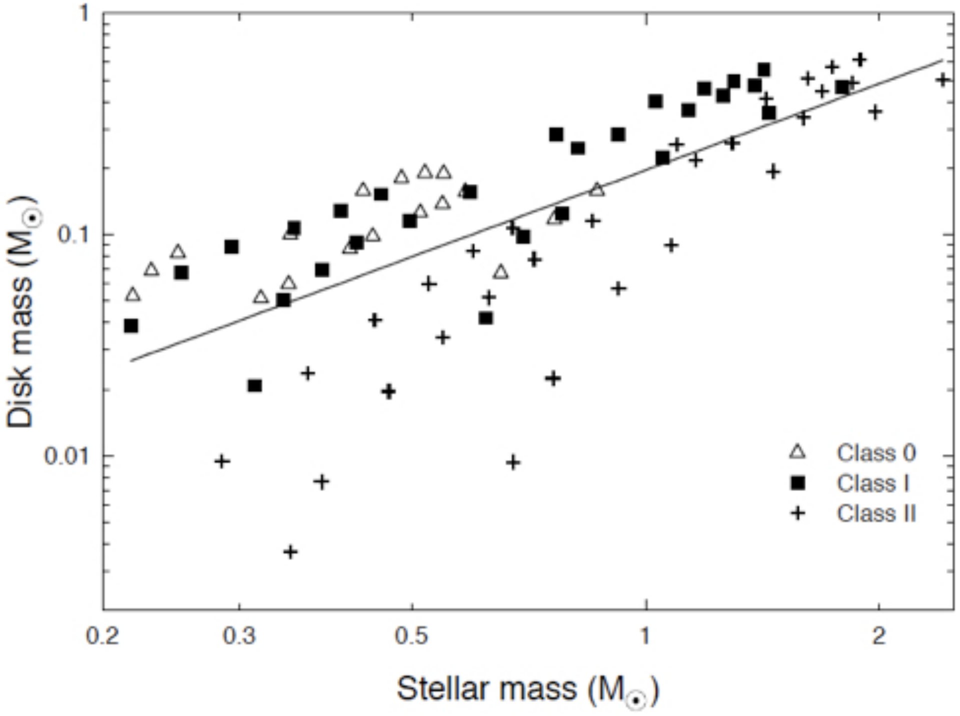


Chiang et al. (2008)

Other model descriptions?

- Vorobyov et al. (2009): models of self-gravitating and viscous disks in hydrodynamical simulations (“burst accretion”). Little difference between Class 0 and I disk masses; significant decline in disk masses toward Class II stage in viscous models.

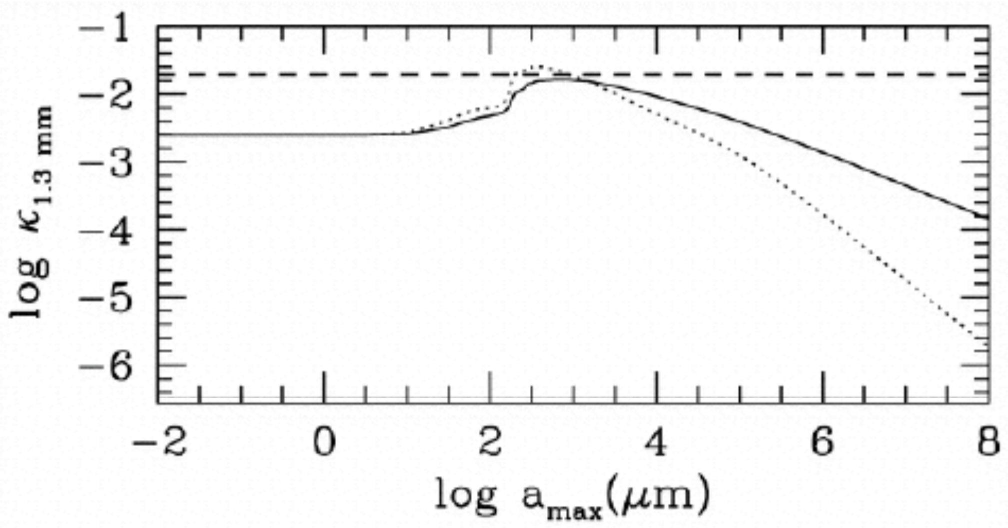
- Clearly other discriminators necessary to separate models.



Do we understand dust?

$$M = \frac{F_\nu \, D^2}{\kappa_\nu \, B_\nu(T_d)}$$

- Grain-growth in dense envelope/disk material could change the mm dust opacity systematically.



Hartmann (2008)
see also d'Alessio et al. (2001)

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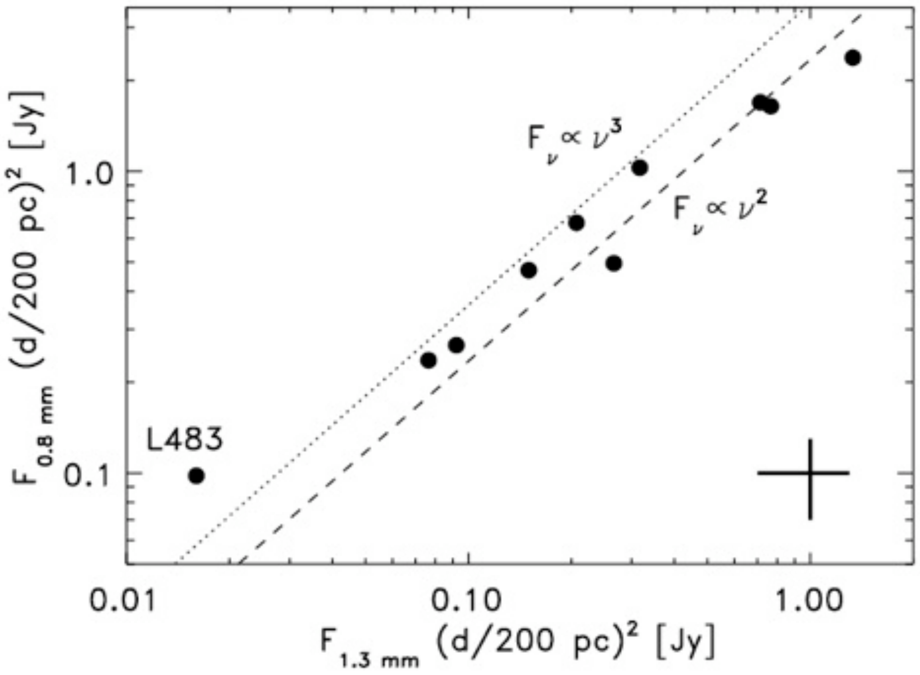
- Evidence for “non-ISM” spectral indices on small-scales in the disks of Class 0 protostars surveyed in the PROSAC SMA data (Jørgensen et al. 2007).



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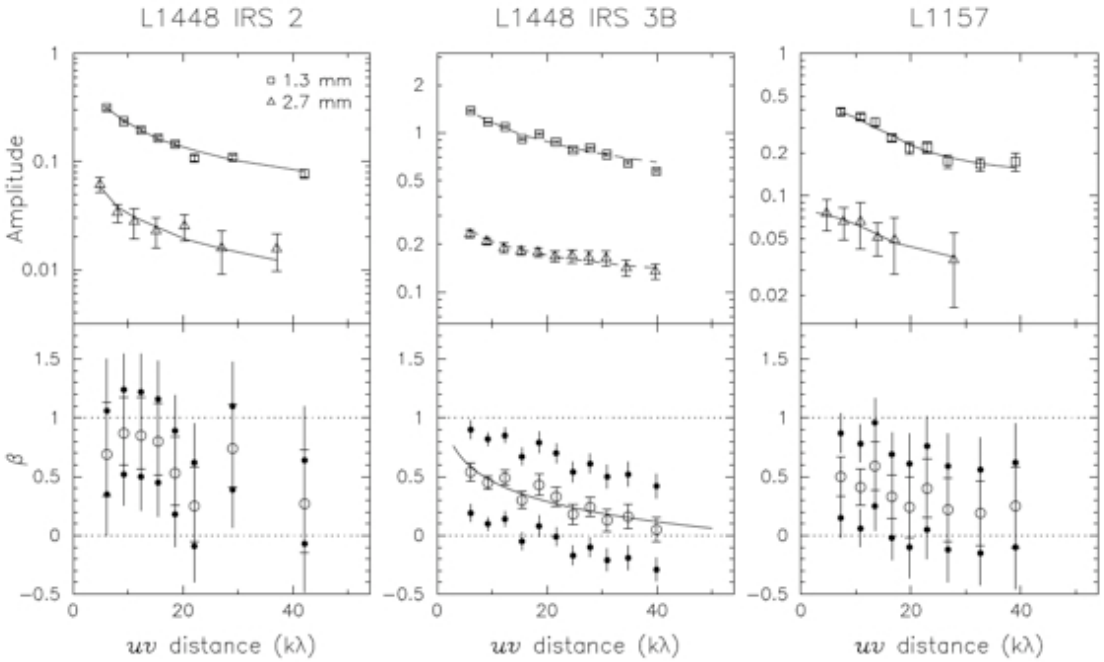
- Possibly radial variation in β in extended emission in CARMA observations of 3 Class 0 protostars (Kwon et al. 2009)

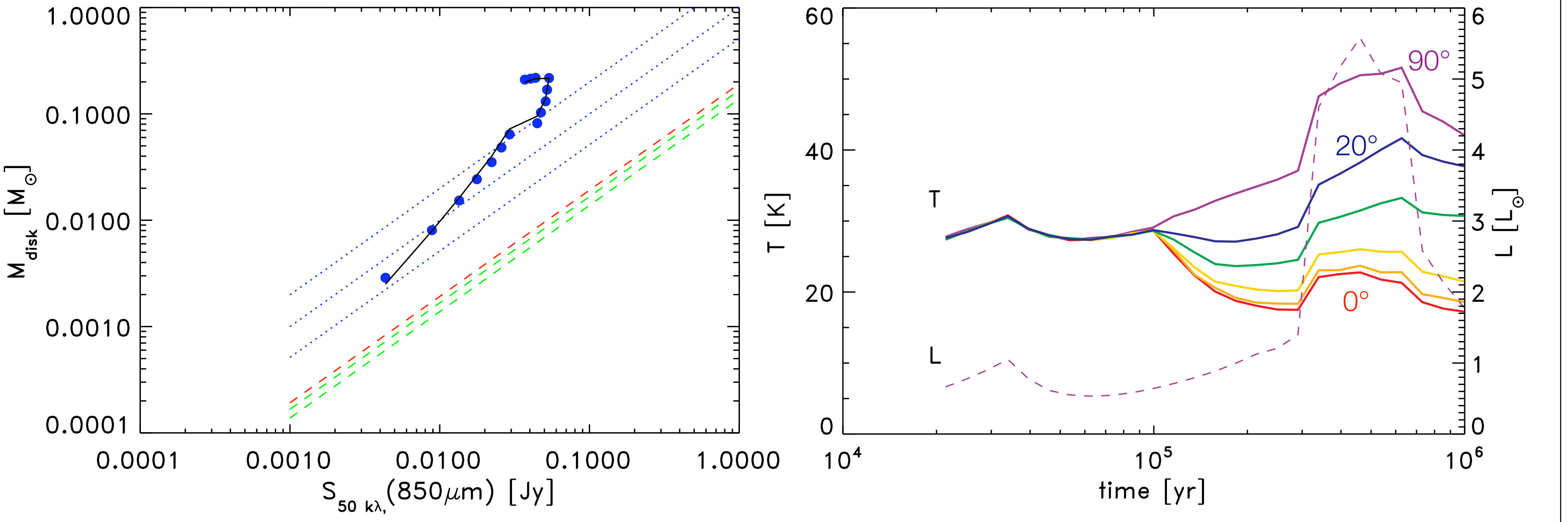


Kwon et al. (2009)

Do we understand temperatures?

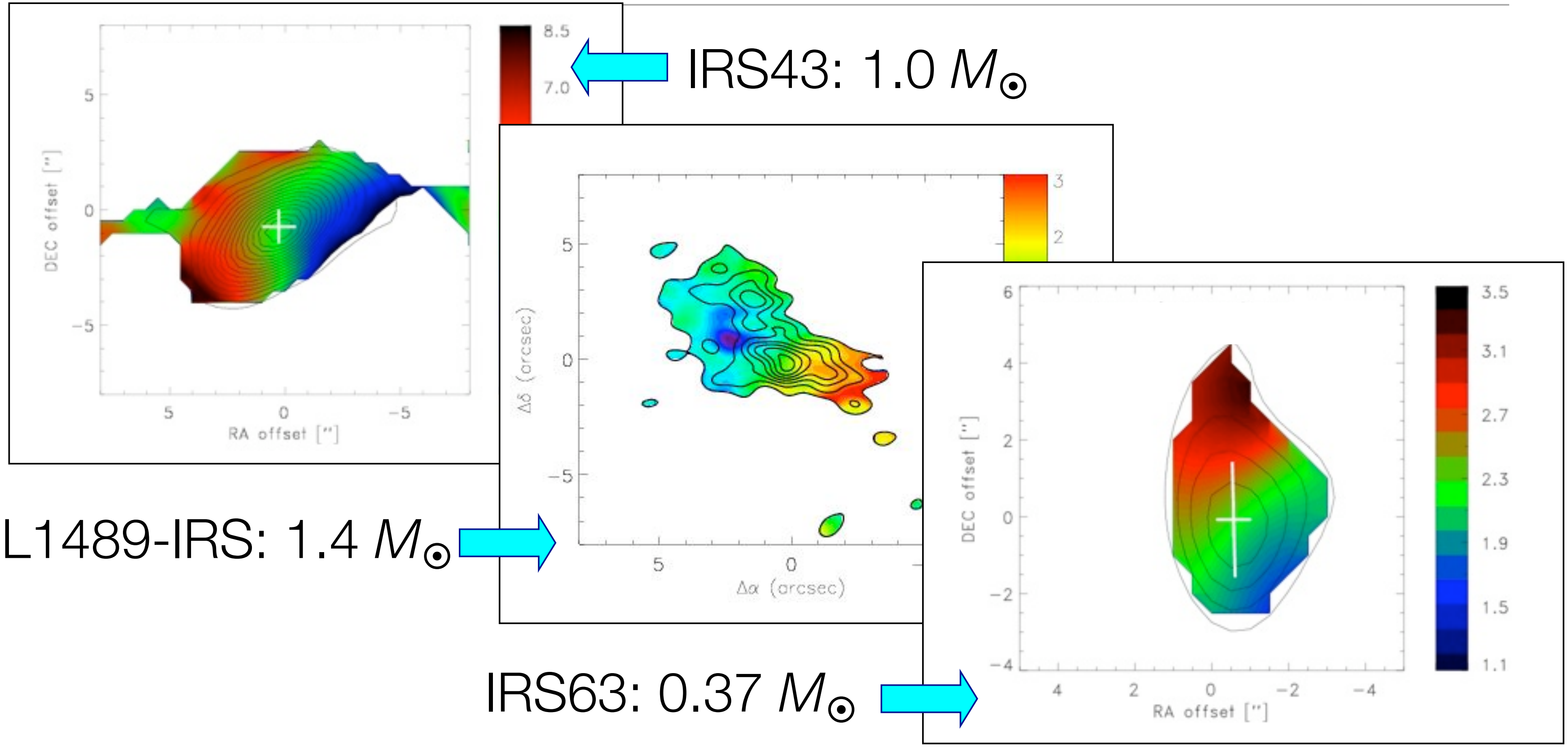
$$M = \frac{F_\nu \, D^2}{\kappa_\nu \, B_\nu(T_d)}$$

- Changes in disk temperatures as they grow in size or mass may also introduce systematic uncertainties in dust derived masses.



- *Left:* relation between disk masses and submillimeter “interferometric” fluxes in models of Visser et al. (2009; solid lines) as well as in typical adopted observed relations. *Right:* temperature of disk at 200 AU along rays with different inclination angles as function of time. *Figures from Jørgensen et al. (2009)*

Lines: dynamics in disks


IRS43: 1.0 $M_{\odot}$

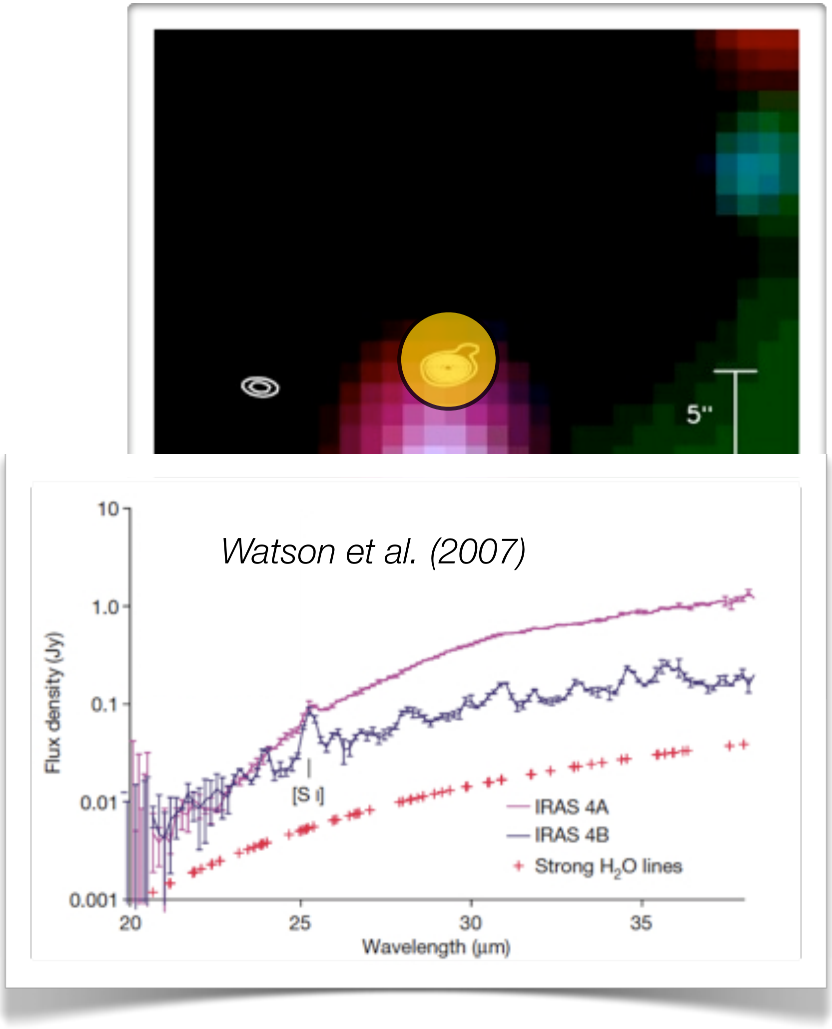
L1489-IRS: 1.4 $M_{\odot}$

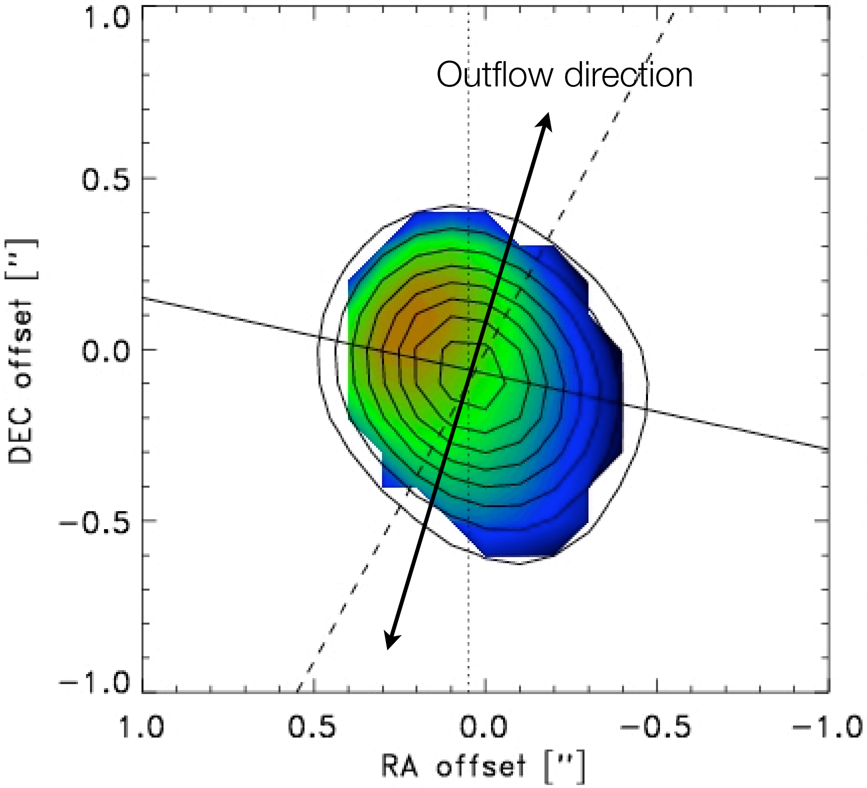
IRS63: 0.37 $M_{\odot}$

Keplerian rot. patterns in HCO^+ 3-2 emission in Class I sources confirm disk structure and allow direct estimate of stellar masses *(examples from Brinch et al. 2007; Lommen et al. 2008; Jørgensen et al. 2009).* Picture for Class 0 sources less clear (lines optically thick in envelopes + time-scale?; *Brinch et al. 2009*).

Lines: dynamics (and chemistry) in disks

NGC1333-IRAS4B in Perseus





Moment-1 (velocity) map

Summary

- High-angular resolution (sub)millimeter wavelength and mid-infrared observations, coupled with detailed radiative transfer models of available multi-wavelength data reveal the structure of protostars from 10,000 to ~100 AU scales.
  - *mid-IR: Inner envelopes (presence of "cavities") possibly reflects the disk formation.*
  - *submm: Density enhancements in protostars on few hundred AU scales: either presence of disks with significant masses (~0.05 $M_\odot$) and sizes (~100 AU), i.e., rapid formation and growth - or enhancements due to "magnetic shocks".*
  - *Note: possible systematic errors due to temperature and/or dust evolution.*
- Resolved line observations provide means to break model degeneracies and address the systematic uncertainties. In addition, such data provide crucial constraints on disk dynamics (stellar masses) and/or chemistry (cf. HCO^+ and H_2O line images of Class I and 0 disks, respectively).