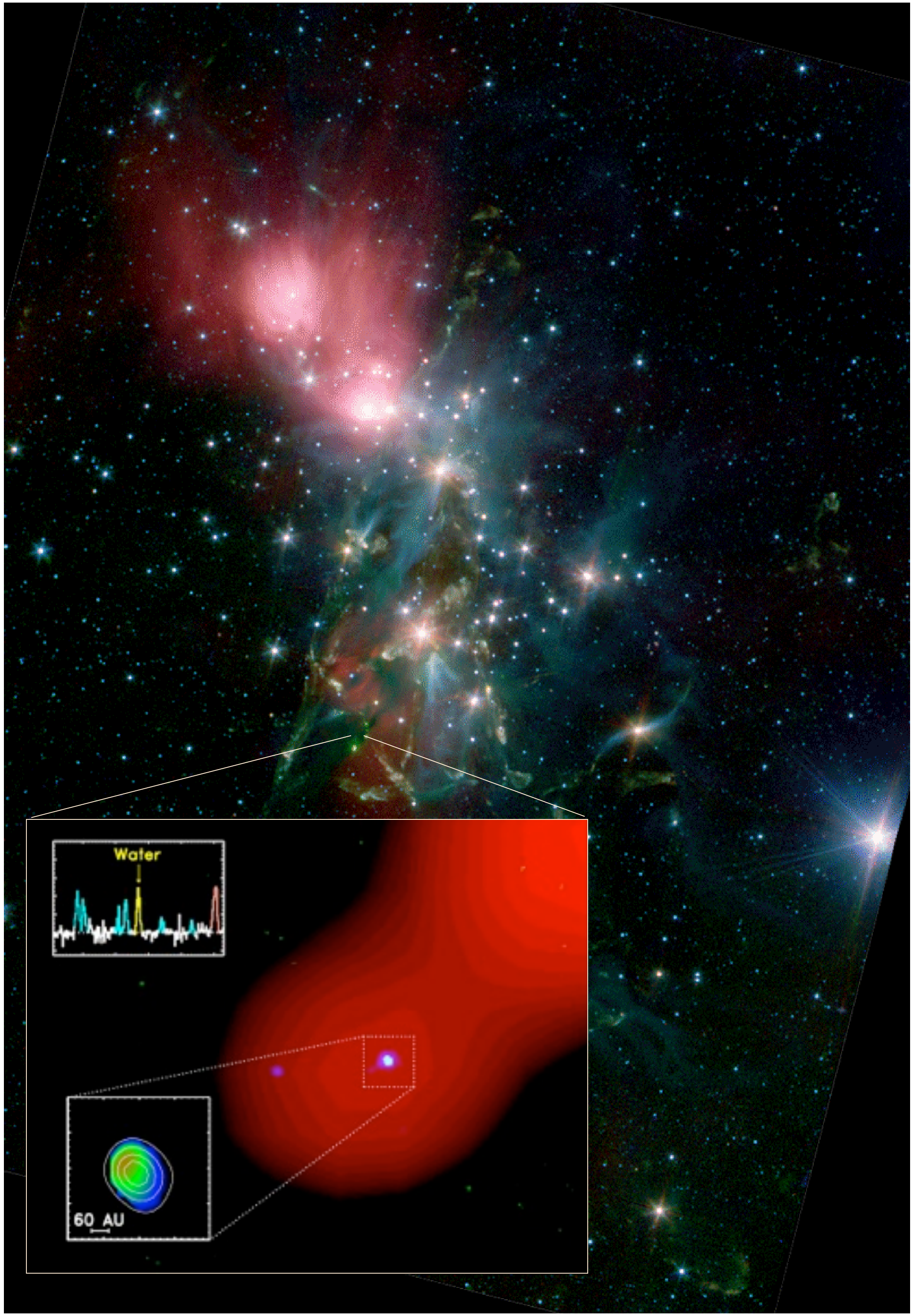


The formation and early evolution of circumstellar disks

Jes Jørgensen

Centre for Star and Planet Formation
& Niels Bohr Institute
University of Copenhagen

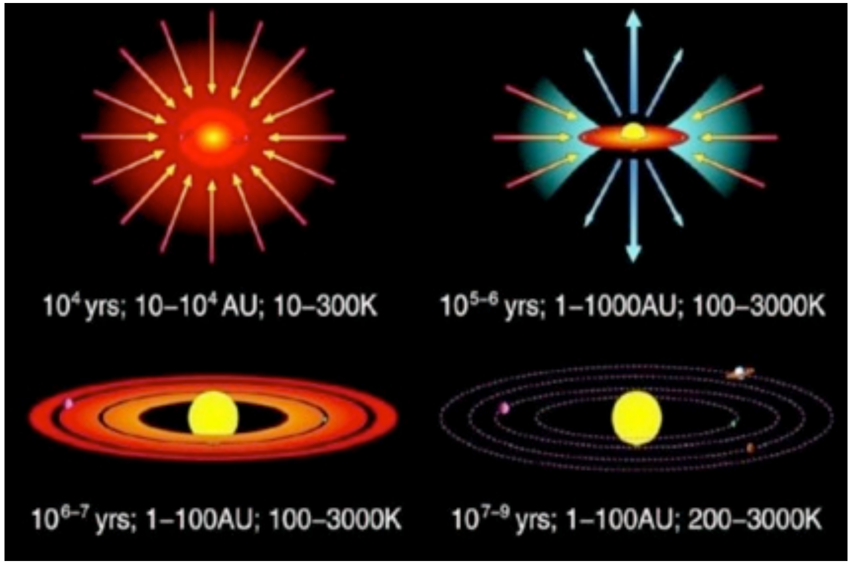
STARPLAN

LUNDBECK**FONDEN**

Outline

- Protostars and their environments (the things we thought we knew)
- Continuum studies of the small-scale structure of embedded “disks”
  - Disks or no disks?
  - Mass and evolution
  - All the complications: dust opacity/grain growth and temperature
- Line observations
  - Dynamics: Keplerian rotation (or not) in embedded disks/envelopes
  - Just a word on chemistry

The evolution of low-mass YSOs



after Shu et al. 1987

Low-mass stars formed from gravitational collapse of cores (or filaments).

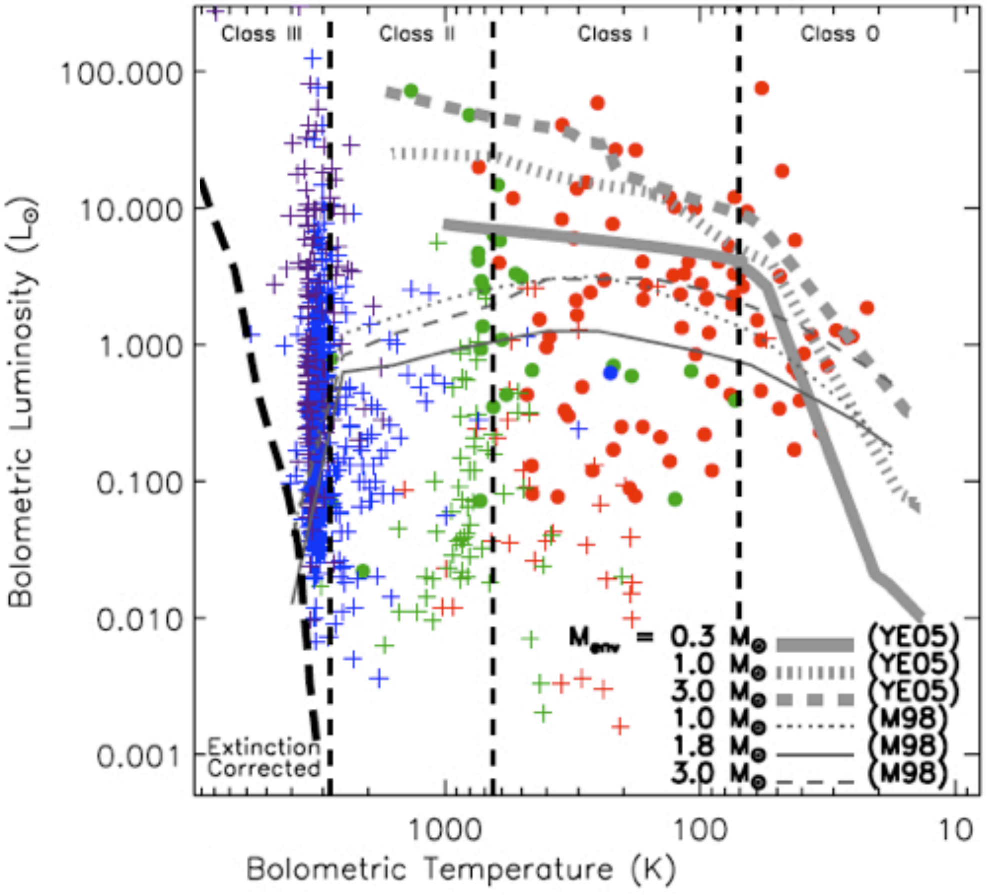
Gradual dispersal of circumstellar material (envelope) through disk accretion; outflow action.

Eventually left with star + (Keplerian) disk system.

How and when do circumstellar disks form? How rapidly is matter accreted onto the central star? What is the physical/chemical evolution of the dust +gas?

A few statements about protostars

- From numbers of Class 0 vs. I objects the Spitzer/c2d results show that the Class 0 phase lasts longer than previously thought (10^5 vs. 10^4 years).



Evans et al. (2009)

A few statements about protostars

- From numbers of Class 0 vs. I objects the Spitzer/c2d results show that the Class 0 phase lasts longer than previously thought (10^5 vs. 10^4 years).
- Combined with SCUBA observations give that protostars loose most of their “envelopes” in a few 10^5 years.

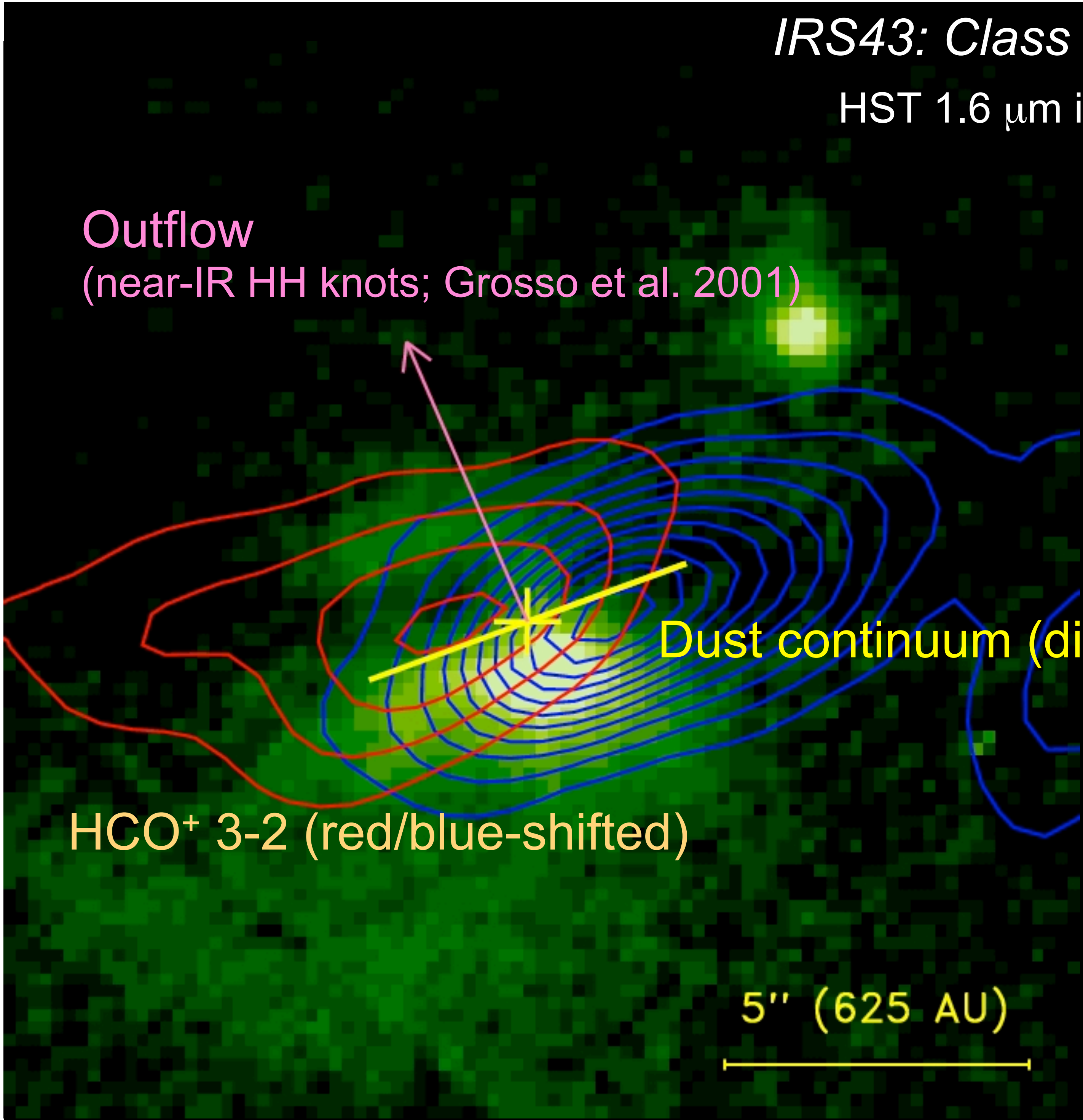
Fraction of c2d YSOs within 15” of a SCUBA core ($M_{\mathrm{env}} \gtrsim 0.1\, M_\odot$).

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

Jørgensen et al. (2008)

IRS43: Class I YSO in Ophiuchus

HST 1.6 μm image (Allen et al. 2002)



Outflow
(near-IR HH knots; Grosso et al. 2001)

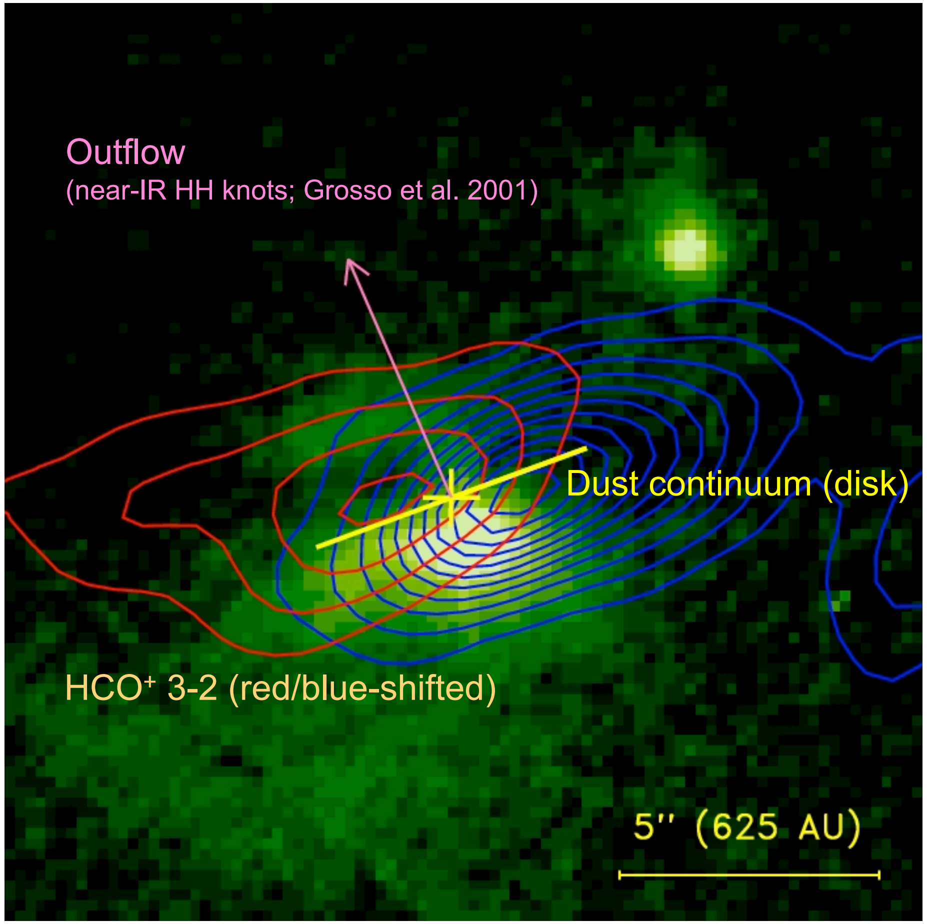
Dust continuum (disk)

HCO$^+$ 3-2 (red/blue-shifted)

Jørgensen et al. 2009

A few statements about protostars

- From numbers of Class 0 vs. I objects the Spitzer/c2d results show that the Class 0 phase lasts longer than previously thought (10^5 vs. 10^4 years).
- Combined with SCUBA observations give that protostars loose most of their “envelopes” in a few 10^5 years.
- In the late Class I phase clear evidence for (Keplerian) disk-like structures are seen.



Jørgensen et al. 2009

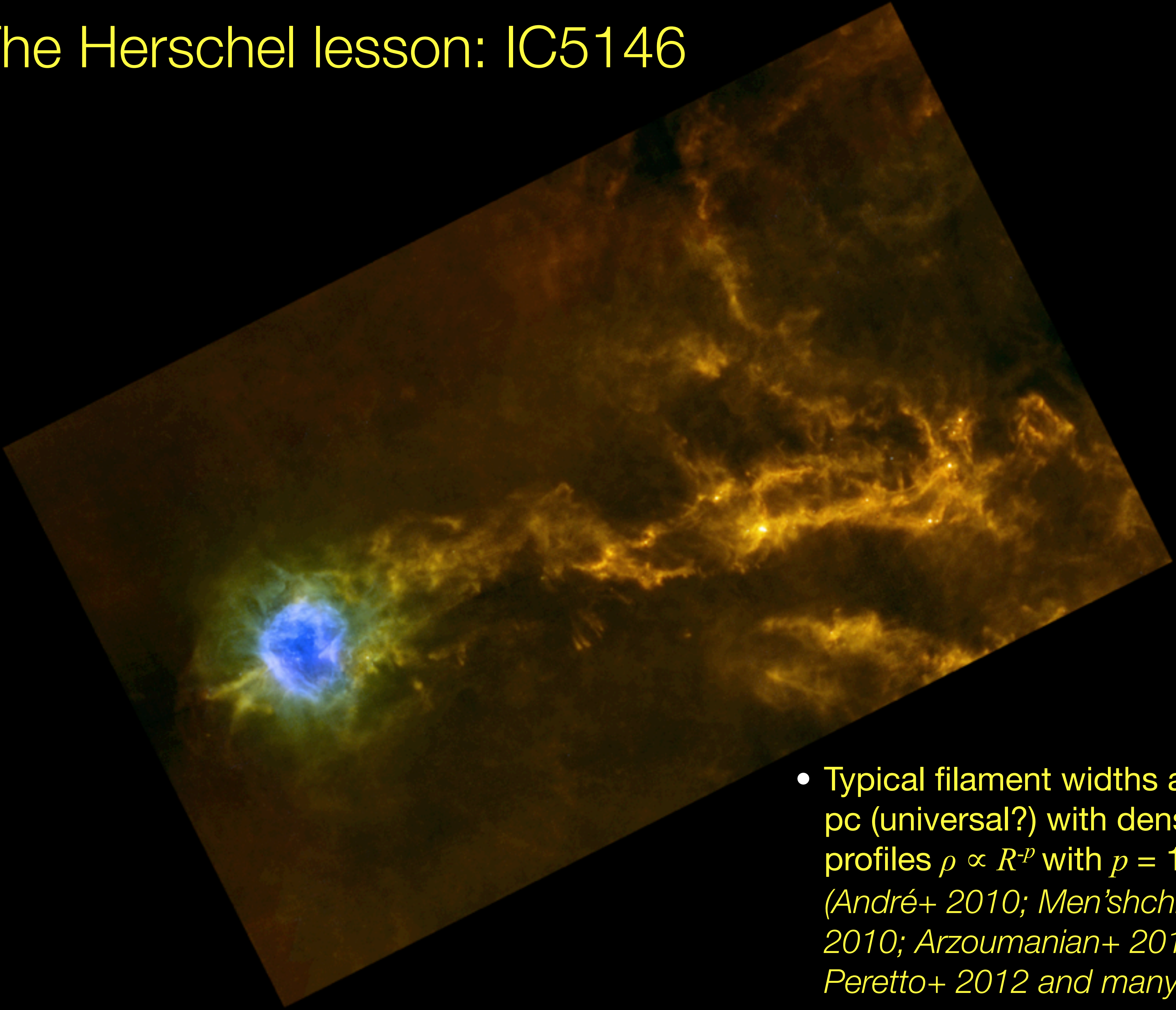
Observations of embedded protostars

- Mid-infrared (Spitzer): limited sensitivity to earliest protostars (although *do* scrap the statement that Class 0 objects are not detected at wavelengths shorter than 10 μm).

- Far-infrared (Herschel): sensitive to peak of SEDs (luminosity of protostar) or distribution of low surface brightness cold dust (prestellar cores/filaments)

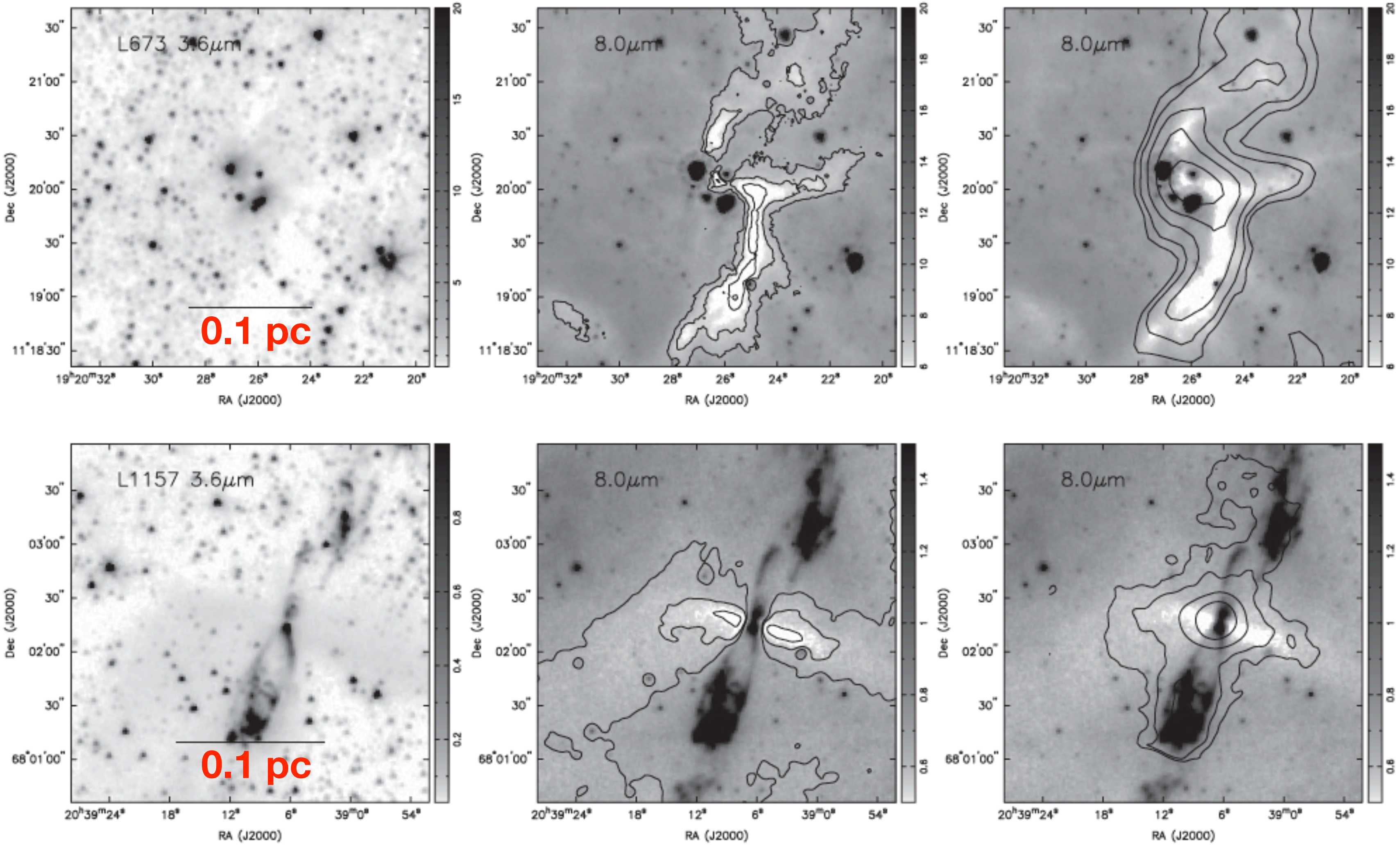
- Submillimeter: cold (10-20 K) dust - i.e., dust on large scales.

The Herschel lesson: IC5146



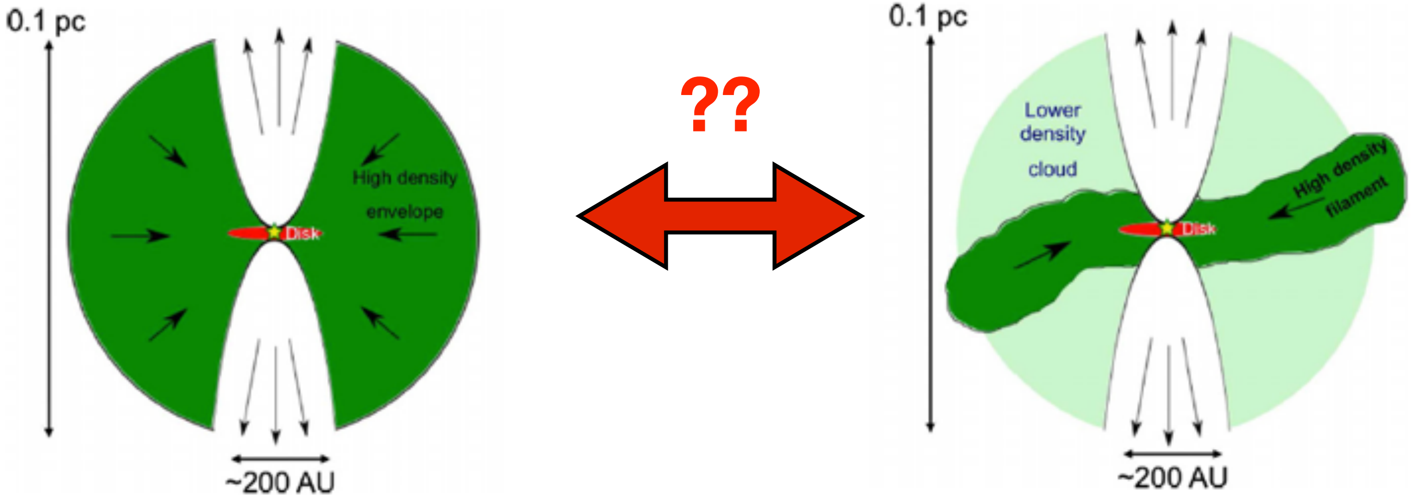
- Typical filament widths about 0.1 pc (universal?) with density profiles $\rho \propto R^{-p}$ with p = 1.5-2.0. *(André+ 2010; Men'shchikov+ 2010; Arzoumanian+ 2011, Peretto+ 2012 and many more).*

Complex structures of embedded protostars

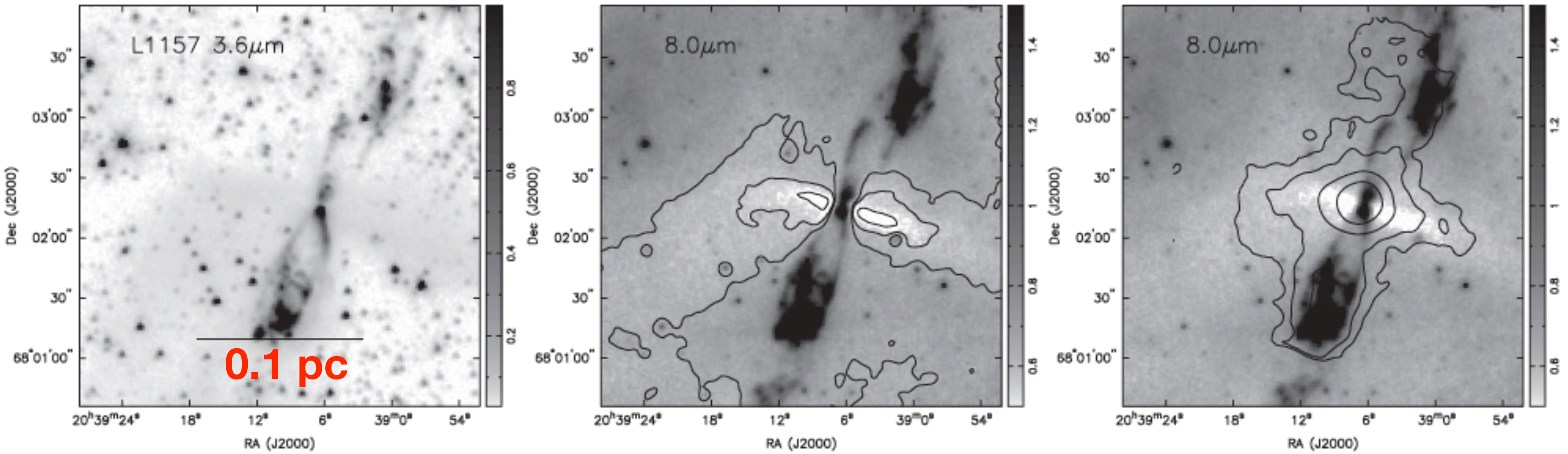


Tobin et al. (2010)

Complex structures of embedded protostars



Lee et al. (2012)



Tobin et al. (2010)

A small back of the slide calculation...

Envelope density profile $n \propto r^{-p}$ with $p \sim 1.5 - 2.0$

$$N = \int_{r_i}^{r_o} n(r)dr \propto \int_{r_i}^{r_o} r^{-p} dr$$

[line of sight column density]

$$= \frac{1}{1-p}(r_o^{1-p} - r_i^{1-p}) \sim \boxed{r_i^{1-p}} \qquad r_o \gg r_i$$

$$M = \int_{r_i}^{r_o} 4\pi \underline{r^2 n(r)} \mu m_{\mathrm{H}} dr \propto \int_{r_i}^{r_o} r^{2-p} dr$$

[mass]

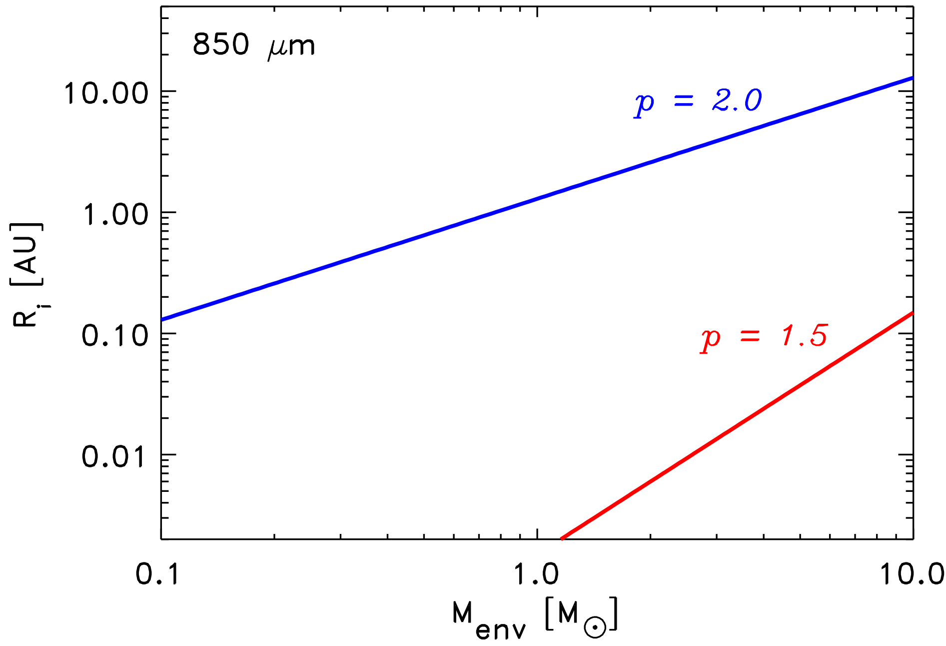
$$= \frac{1}{3-p}(r_o^{3-p} - r_i^{3-p}) \sim \boxed{r_o^{3-p}} \qquad r_o \gg r_i$$

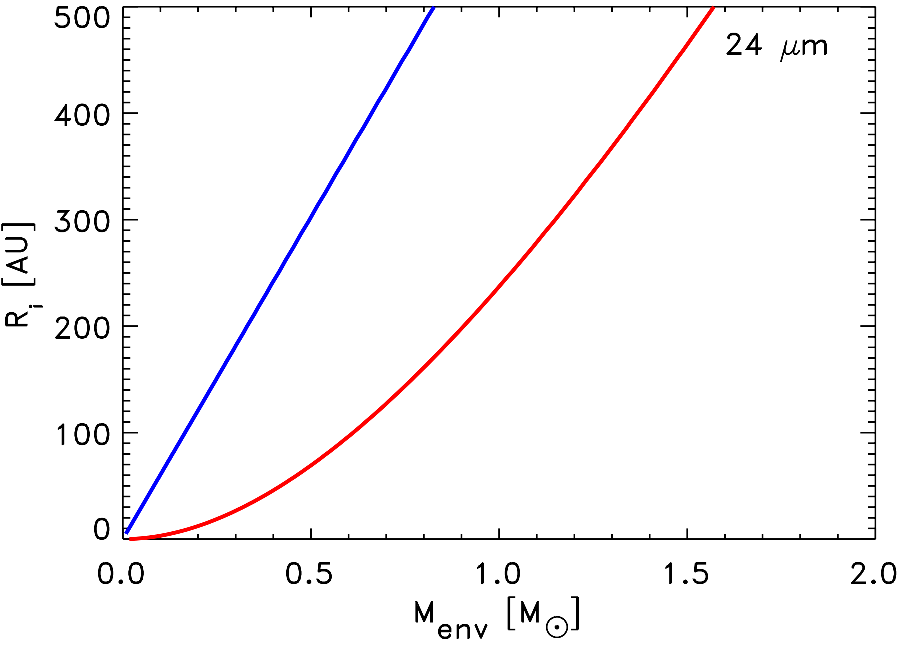
The line-of-sight column density (or related extinction) is "determined" by the envelope inner radius, whereas the mass (or beam avg. column) is "determined" by the outer radius. A more filamentary structure (flatter in one projected direction) will only strengthen this.

Column density and mass

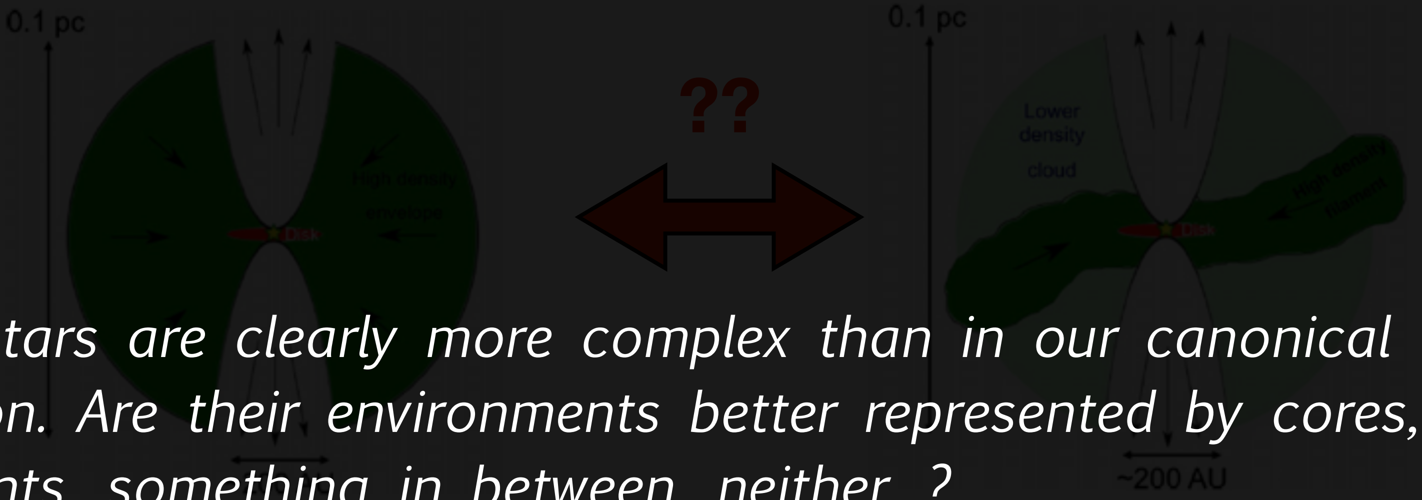
- The mass is on large scales whereas the line of sight column density/extinction is on small scales.

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



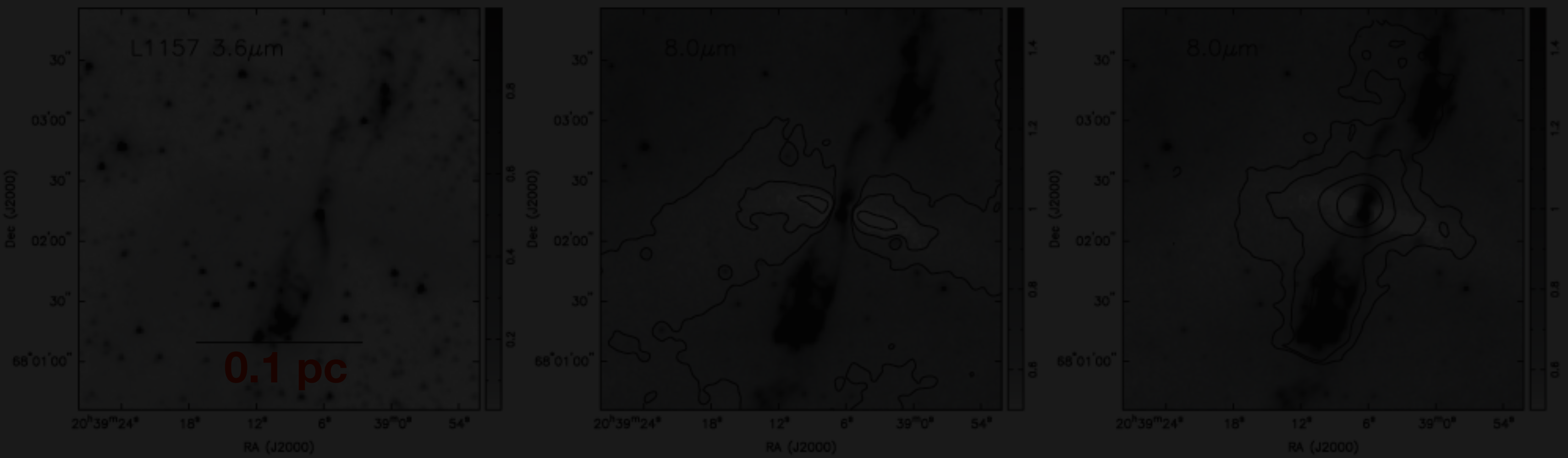


Complex structures of embedded protostars



Lee et al. (2012)

Protostars are clearly more complex than in our canonical cartoon. Are their environments better represented by cores, filaments, something in between, neither…?



Tobin et al. (2010)

Continuum observations

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*$_\mathrm{d}$

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.

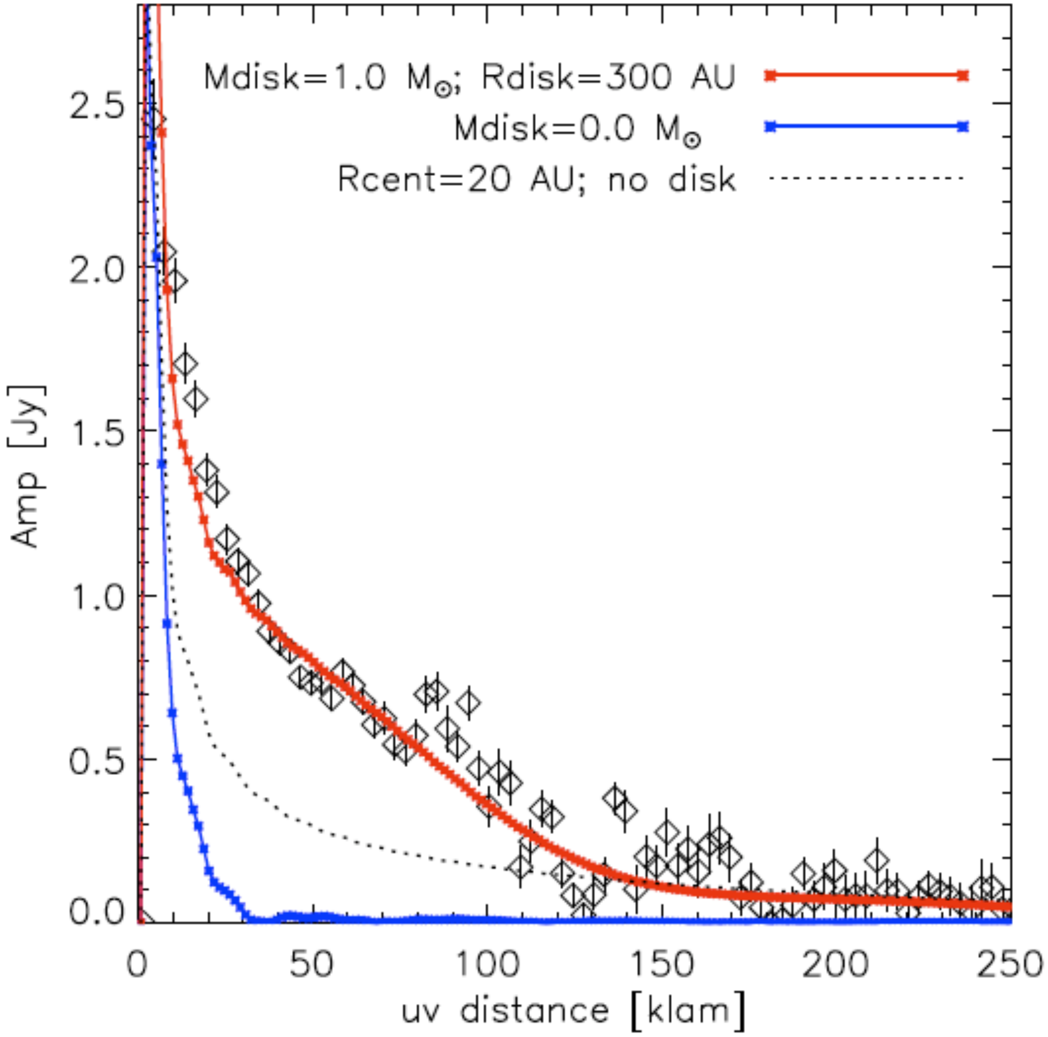
Looney et al. (2000, 2003): BIMA survey of Class 0 and I sources, multiplicity, and analytic fits. Low disk/envelope mass ratios → fast processing of material (>85% of continuum flux ~ envelope).

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.

- Jørgensen et al. (2005): SMA observations of NGC1333-IRAS2A coupled with radiative transfer model of SCUBA envelope ⇒ 300 AU diameter disk.

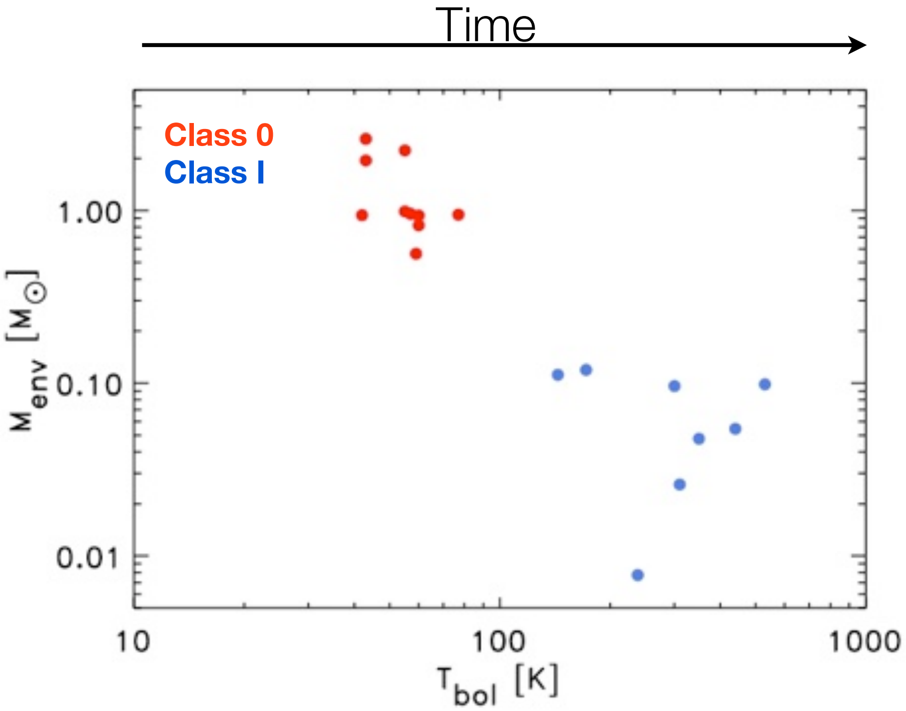
- Enoch et al. (2009): CARMA observations of Serpens SMM1: massive (1.0 $M_\odot$; 300 AU radius disk. A steep envelope density profile remove the need for such a disk, but not consistent with SED (i.p., mid-IR).

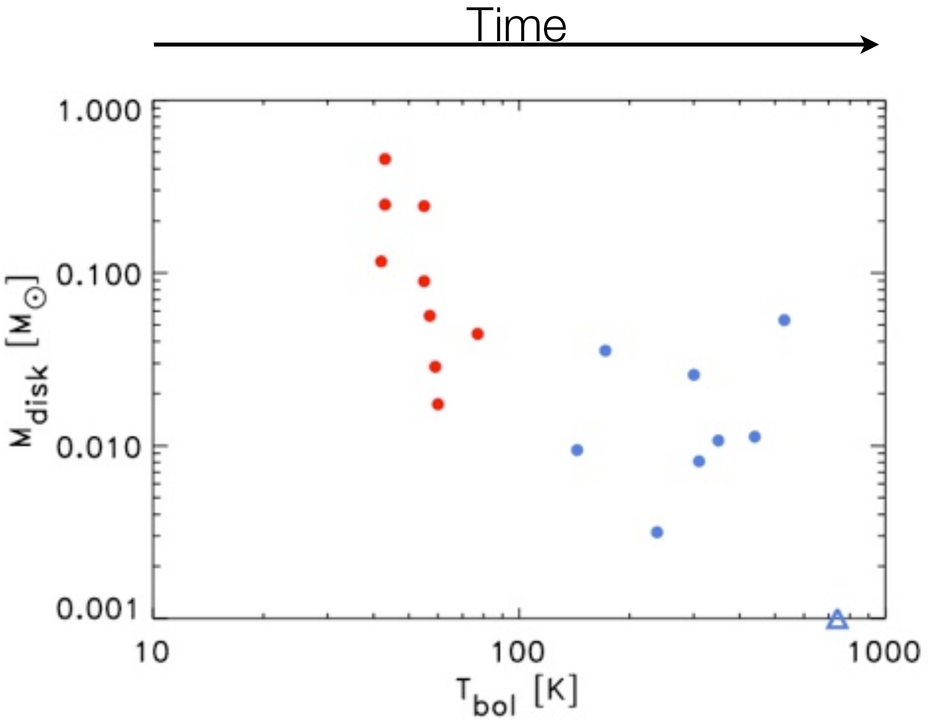


Enoch et al. (2009)

Mass evolution of low-mass stars?

- Jørgensen et al. (2009) survey of 20 embedded protostars with the SMA. Utilize fit of envelope structures on larger scales (1000+ AU) and extrapolate to smaller scales. I.e., subtraction of envelope contributions - what is left is attributed to a “disk”.

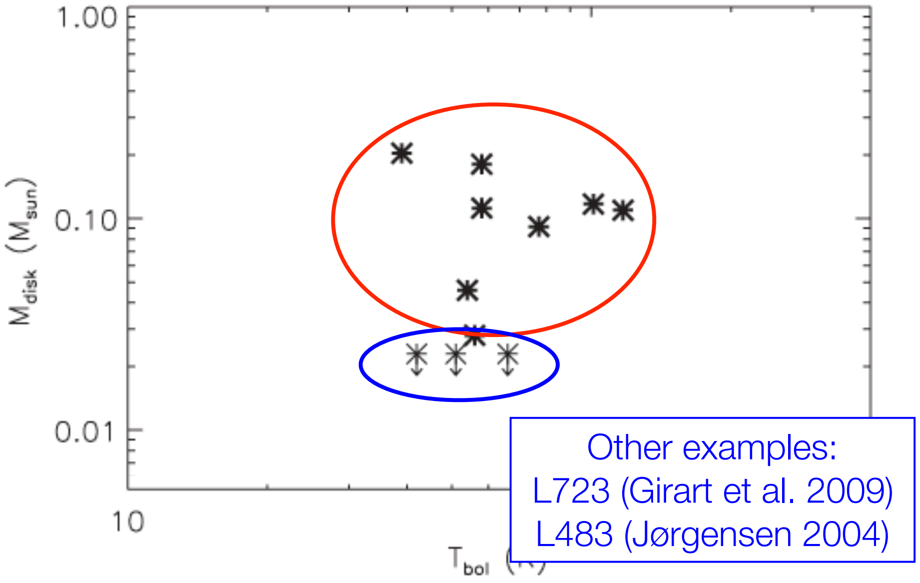




“Disks” around Class I sources are not more massive than those around the younger Class 0’s ⇒ rapid “disk” formation and growth.

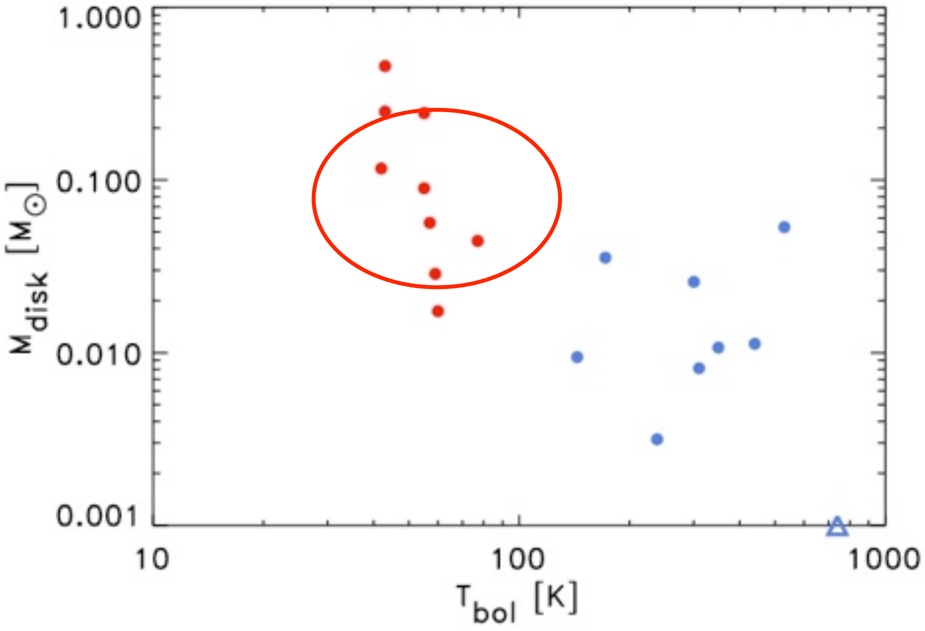
Mass evolution of low-mass stars?

- Enoch et al. (2011) independent survey of 9 embedded protostars in Serpens with CARMA. Similar result as in Jørgensen et al. study - presence of compact continuum emission (“disks”).



Other examples:
L723 (Girart et al. 2009)
L483 (Jørgensen 2004)

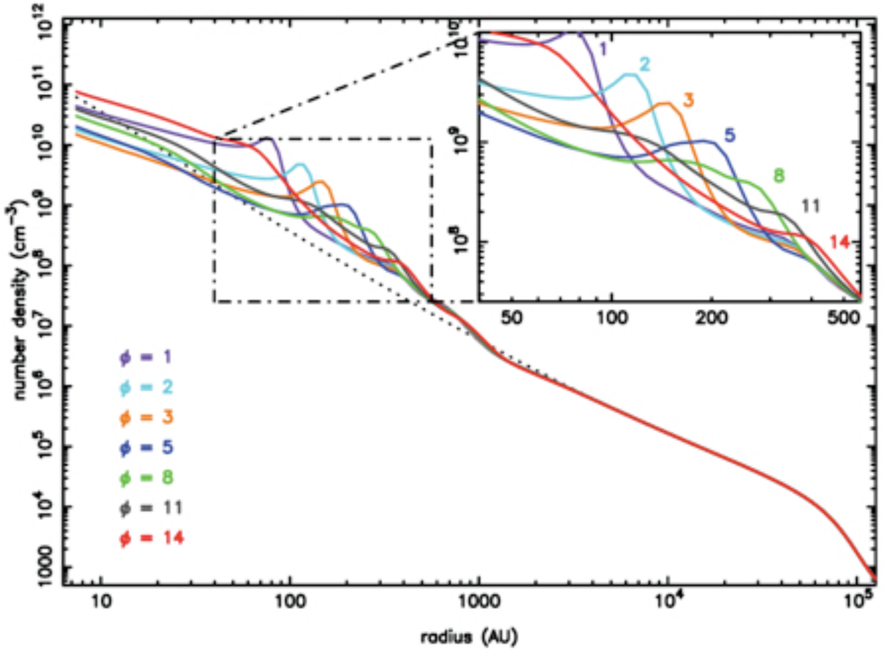
Enoch et al. (2011)

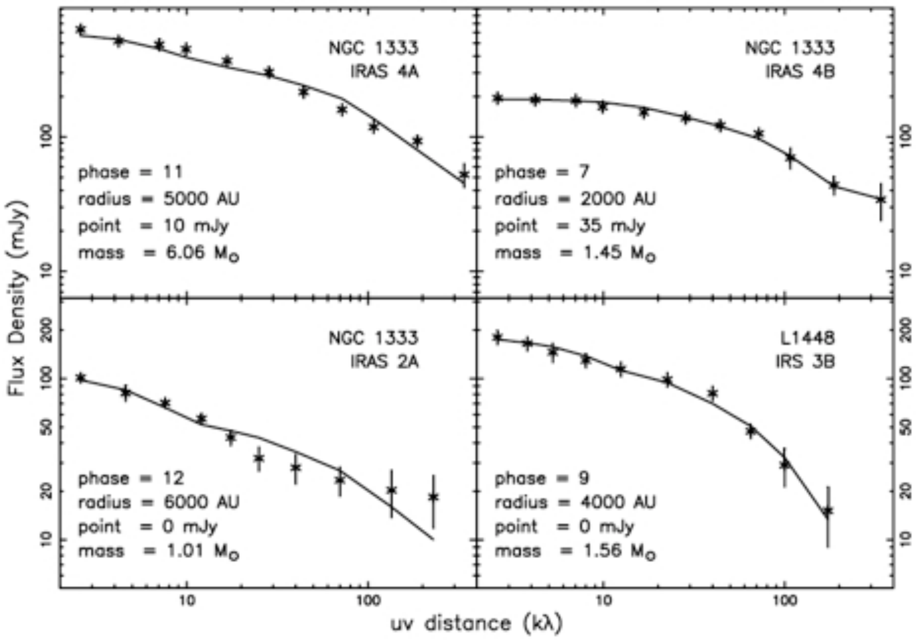


Jørgensen et al. (2009)

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. The density enhancement on small scales to some degree replaces the need for a central unresolved component.

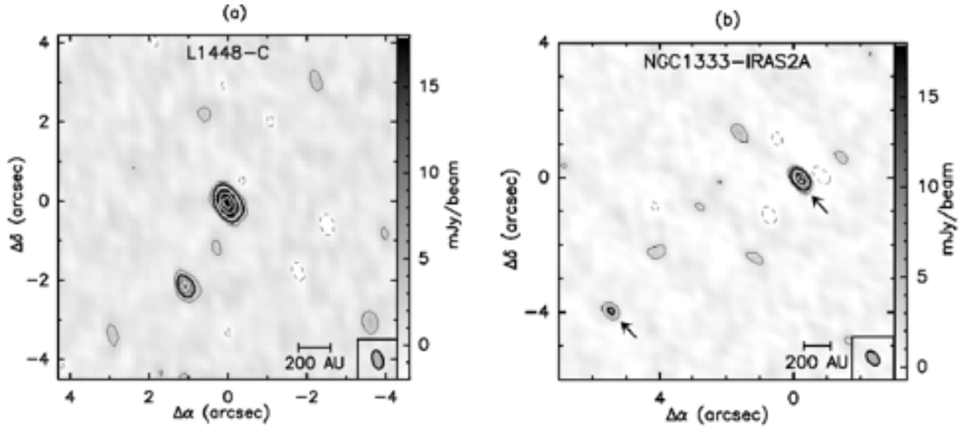


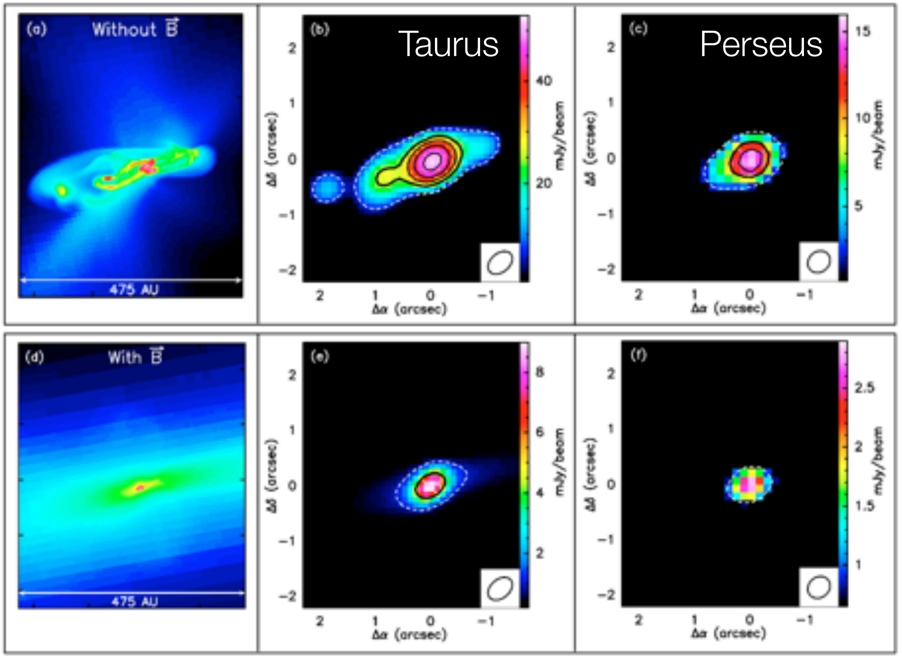


Chiang et al. (2008)

Comparison between models for disk formation

- Maury et al. (2010) comparison of models to IRAM PdBI “A config.” observations.
  - *Stamatellos & Whitworth (2009): massive ~ 0.7 $M_\odot$ (fragmenting) disks and no envelope.*
  - *Bate (2009): hydrodyn. simulation of cloud collapse, disk formation - incl. radiative feedback suppressing fragmentation*
  - *Hennebelle & Teyssier (2008): MHD simulations of collapse and fragmentation*
- From these three set of models, the latter simulation of magnetized cores can best reproduce obs. compact (< 300 AU) structures.





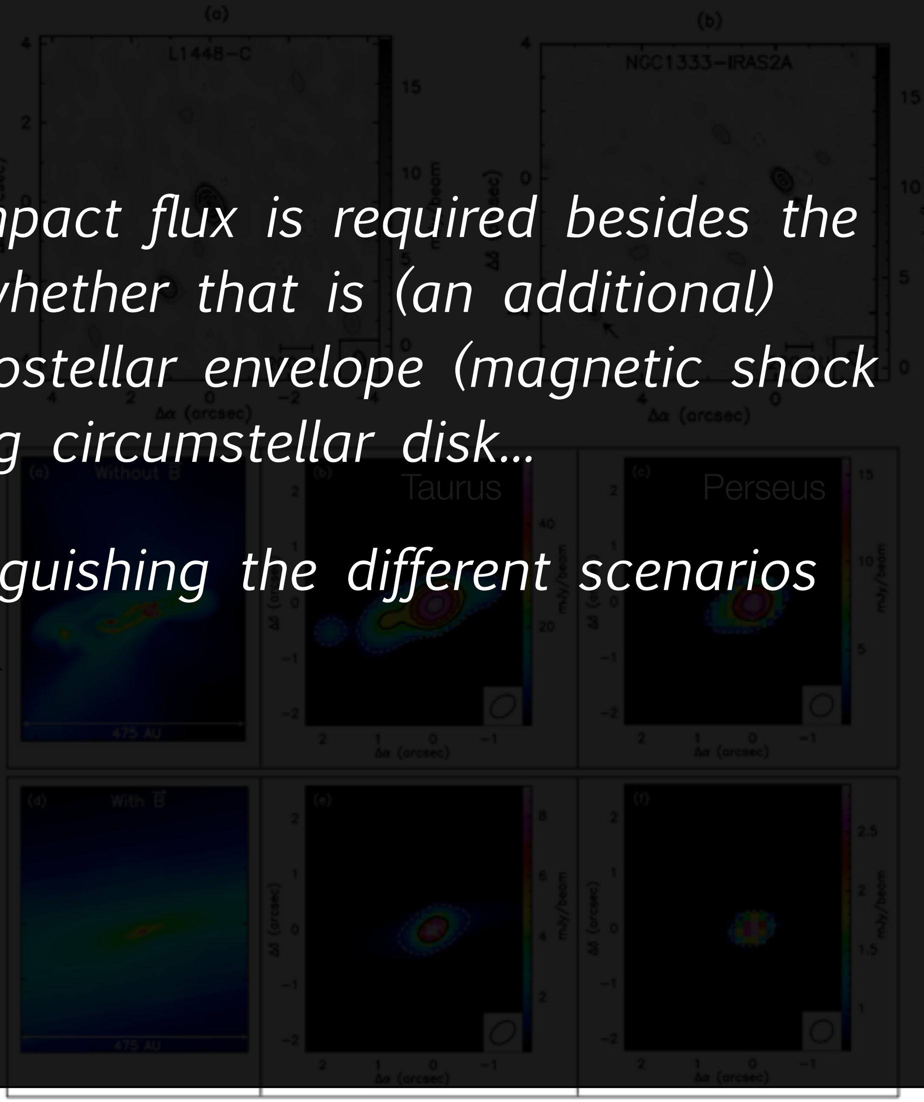
Maury et al. (2010)

Comparison between models for disk formation

- Maury et al. (2010) comparison of models to IRAM PdBI “A config.” observations.
  - Stamatellos & Whitworth (2009): massive 0.7 $M_\odot$ (fragmenting) disks and no envelope.
  - Bate (2009): hydrodyn. simulation of cloud collapse, disk formation - incl. radiative feedback suppressing fragmentation.
  - Hennebelle & Teyssier (2008): MHD simulations of collapse and fragmentation
- From these three set of models, the latter simulation of magnetized cores can best reproduce obs. compact (< 300 AU) structures.

An additional component of compact flux is required besides the centrally condensed envelope - whether that is (an additional) density enhancement in the protostellar envelope (magnetic shock wall), a pseudo-disk or a rotating circumstellar disk…

…but clearly other ways of distinguishing the different scenarios are required.



Maury et al. (2010)

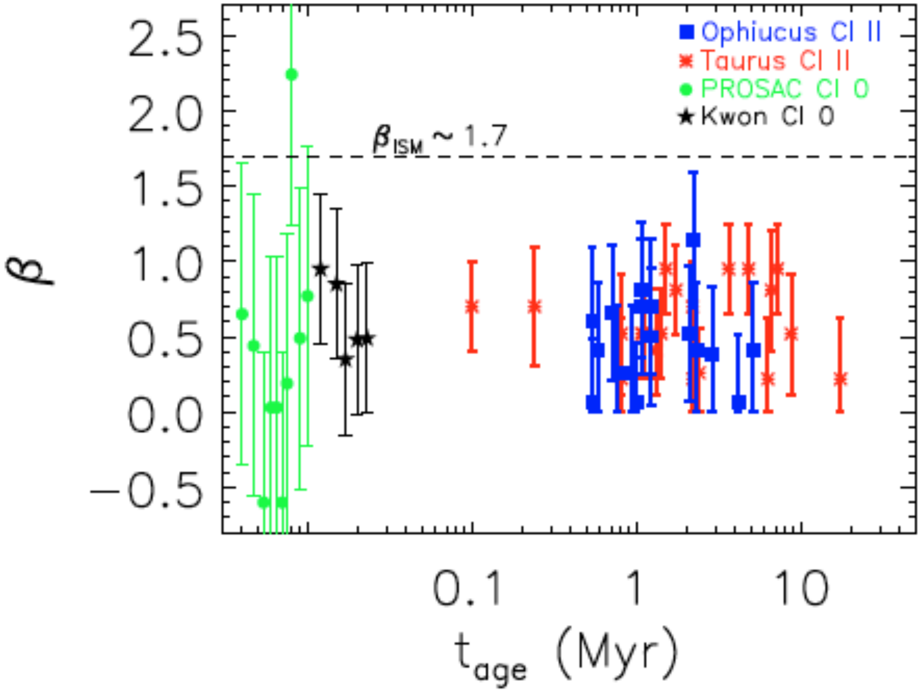
Do we understand dust?

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

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

- 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).

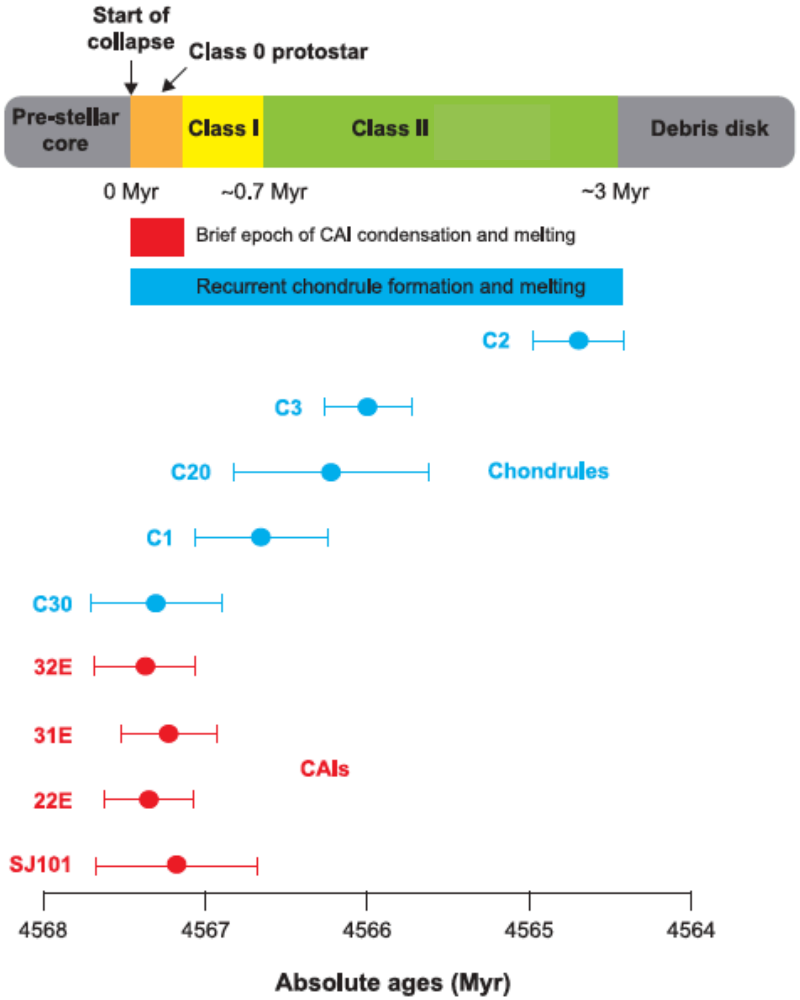
- Possibly radial variation in β in extended emission in CARMA observations of Class 0 protostars (Kwon et al. 2009; Chiang et al. 2013)



Ricci et al. (2010)

A small digression...

- Recent (re)investigation of CAI and chondrule ages in primitive meteorites using Pb-dating (contrasting previous measurements from short-lived radio isotope systems).
- The previous inferred discrepancy between CAI and chondrules ages does not appear to hold any more.
- Does the CAI formation event correspond to the earliest protostellar stages (chondrule formation perhaps linked to episodic accretion events)?

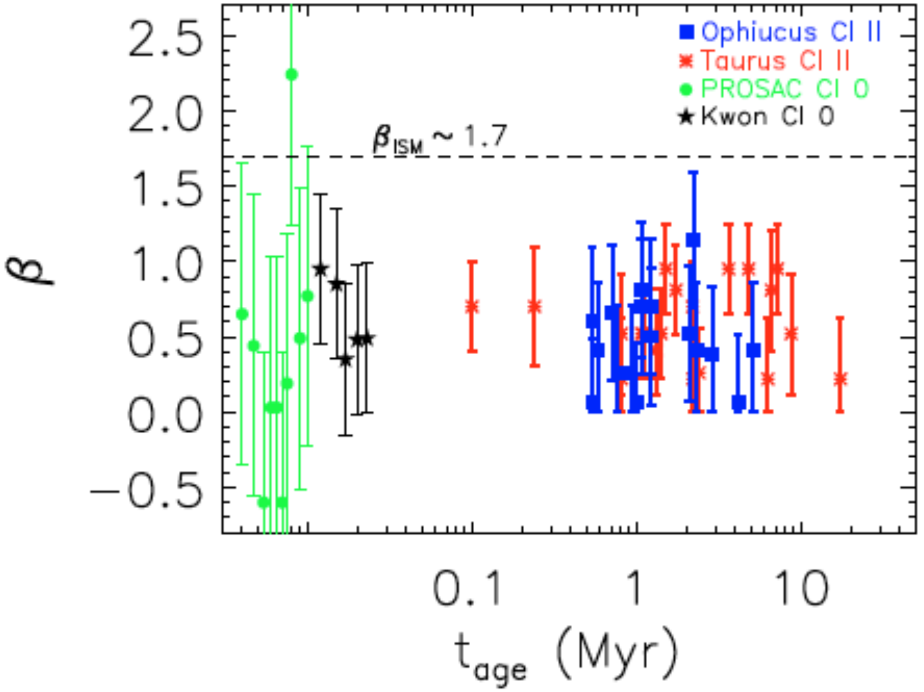


Connelly et al. (2012)

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.
- 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).
- Possibly radial variation in β in extended emission in CARMA observations of Class 0 protostars (Kwon et al. 2009; Chiang et al. 2013)



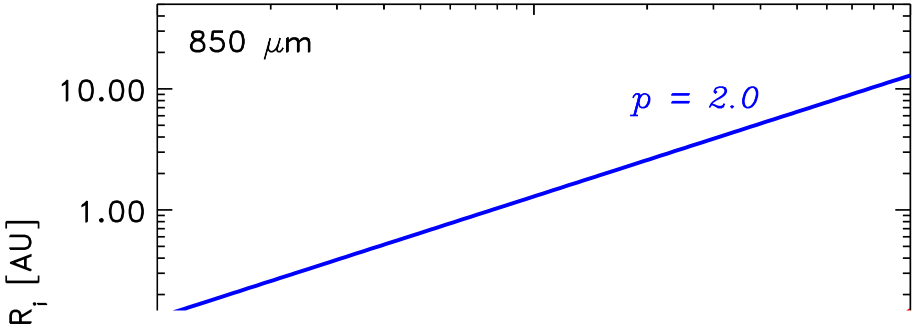
Ricci et al. (2010)

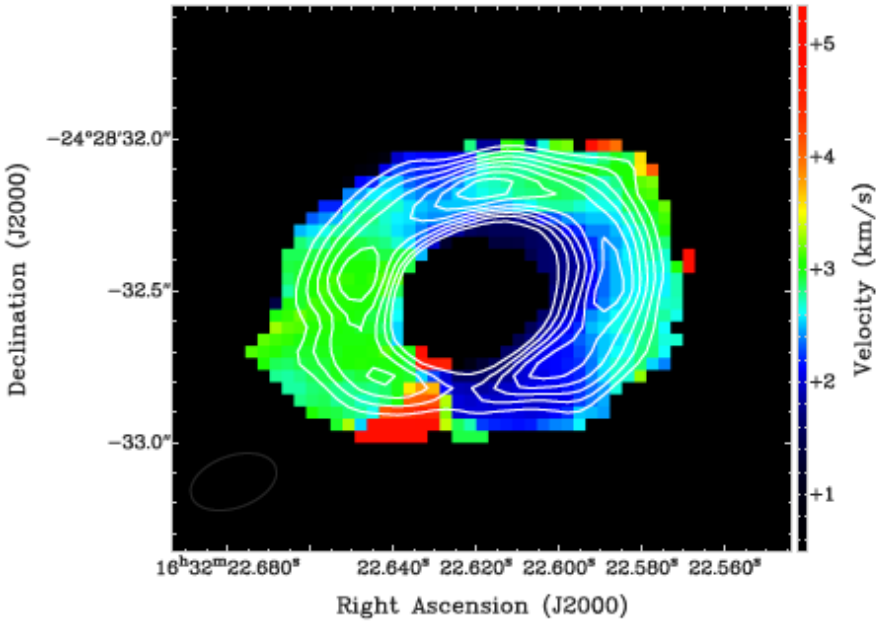
Optically thick dust?

- The envelope itself is unlikely to be strongly optically thick in the submm.
- Any disk-like components might. The most massive “disks” around the Class 0’s in the PROSAC sample are becoming marginally optically thick *(Jørgensen et a al. 2007)*:

$$\langle \tau_{870} \rangle = \left(\frac{0.5}{\cos\theta}\right)\left(\frac{M_D}{0.1\ M_\odot}\right)\left(\frac{R_D}{100\ \mathrm{AU}}\right)^{-2}.$$

- IRAS 162923-2422(b) shows clear depression of molecular emission at continuum peaks indicative of optically thick dust. Another way of showing that deeply embedded “disks” are present?



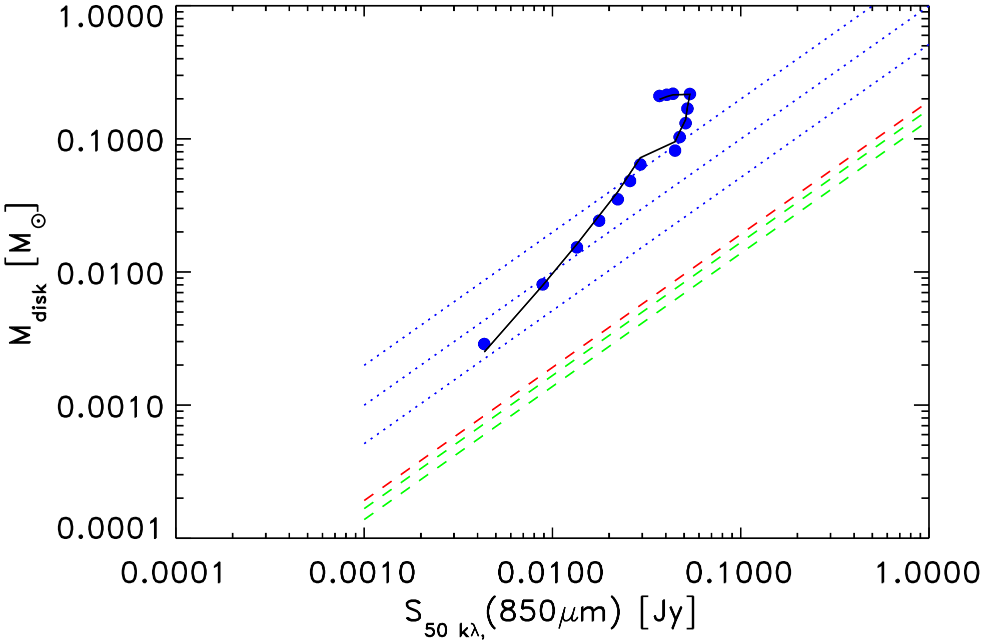


Zapata et al. (2013)

Do we understand temperatures?

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

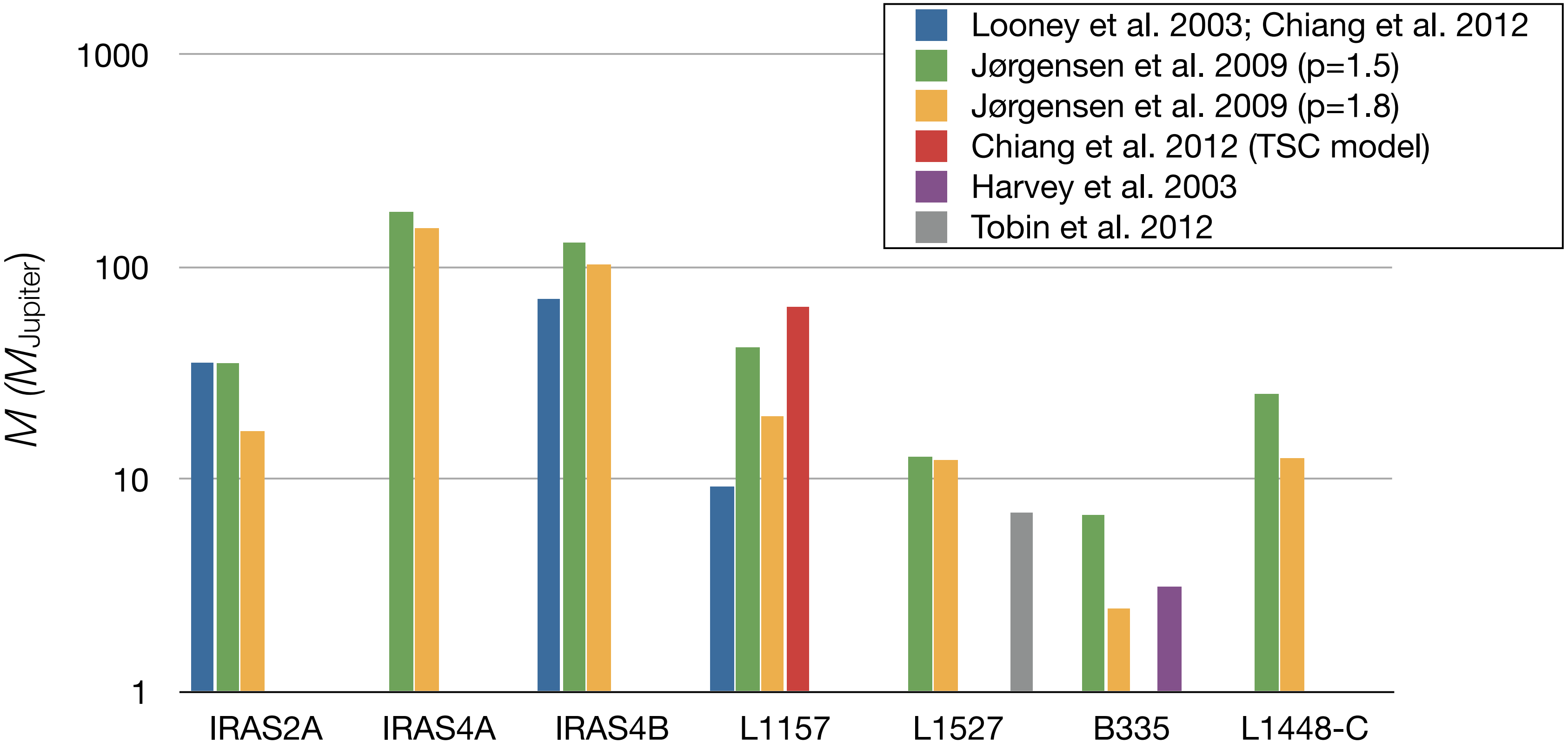
- Changes in disk temperatures as they grow in size or mass may also introduce systematic uncertainties in dust derived masses.



- 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. *Figure from Jørgensen et al. (2009)*

“Disk” masses for embedded protostars

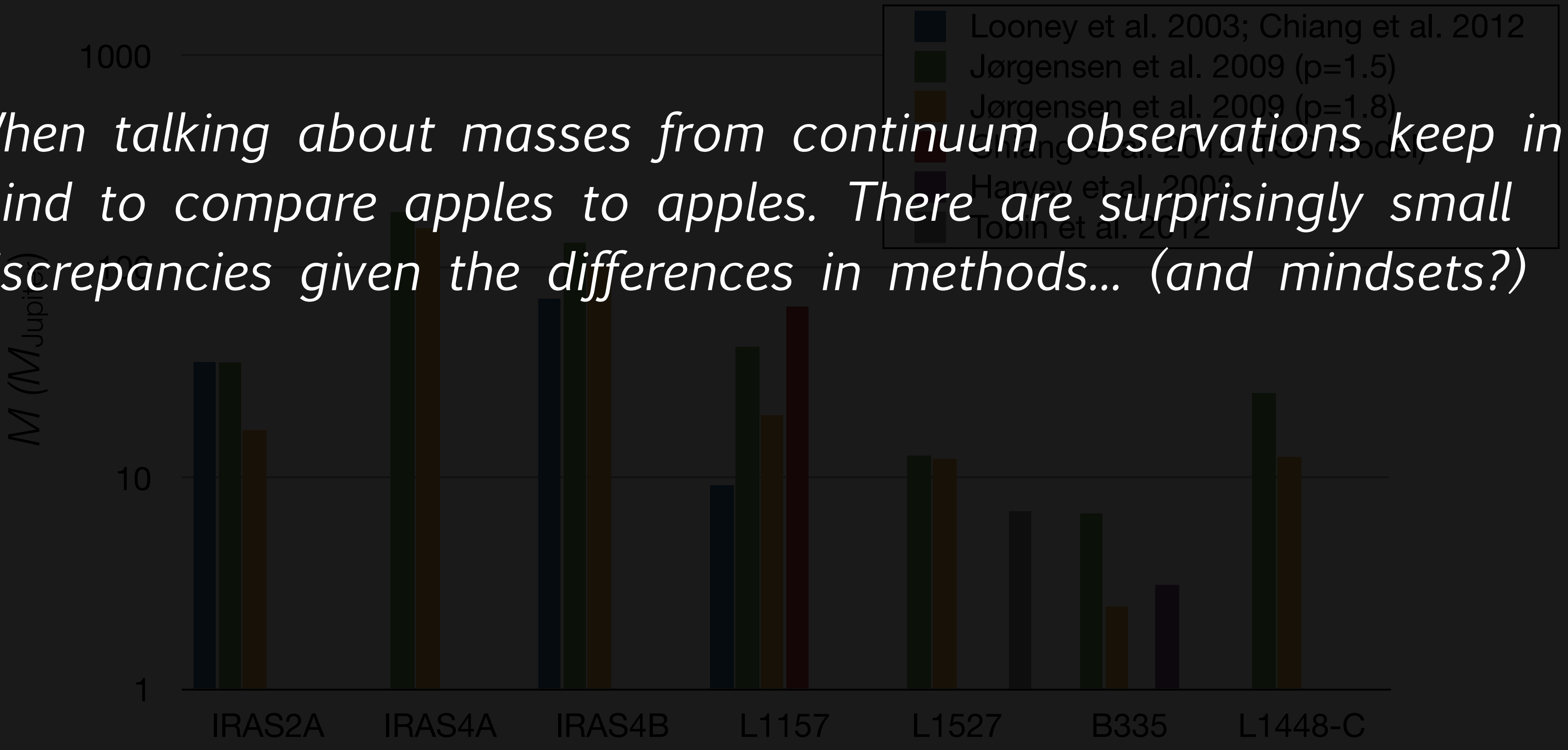
- Taking into account different assumptions about millimeter wavelength dust opacities and temperatures - surprisingly “small” differences in “disk” masses.



“Disk” masses for Class 0 objects studied by multiple authors - adopting HL Tau as a standard.

“Disk” masses for embedded protostars

- Taking into account different assumptions about millimeter wavelength dust opacities and temperatures - surprisingly “small” differences in “disk” masses.



“Disk” masses for Class 0 objects studied by multiple authors - adopting HL Tau as a standard.

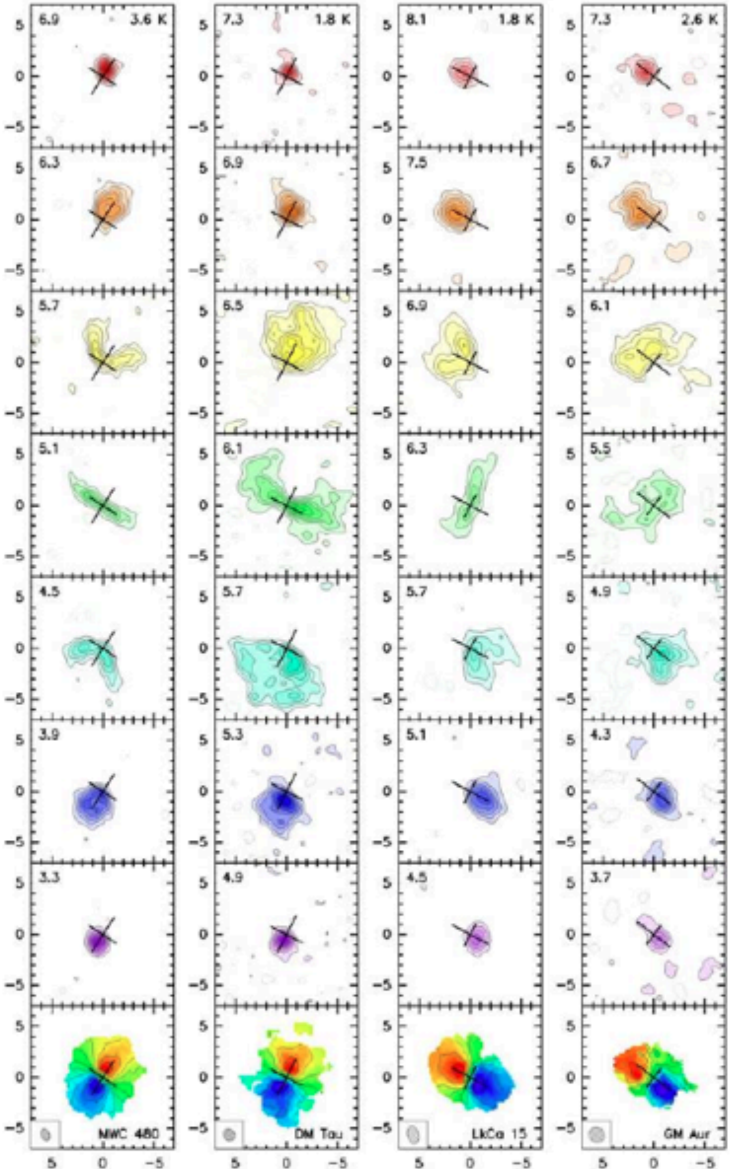
When talking about masses from continuum observations keep in mind to compare apples to apples. There are surprisingly small discrepancies given the differences in methods… (and mindsets?)

Dynamics

Gas: dynamics in disks around Class II sources

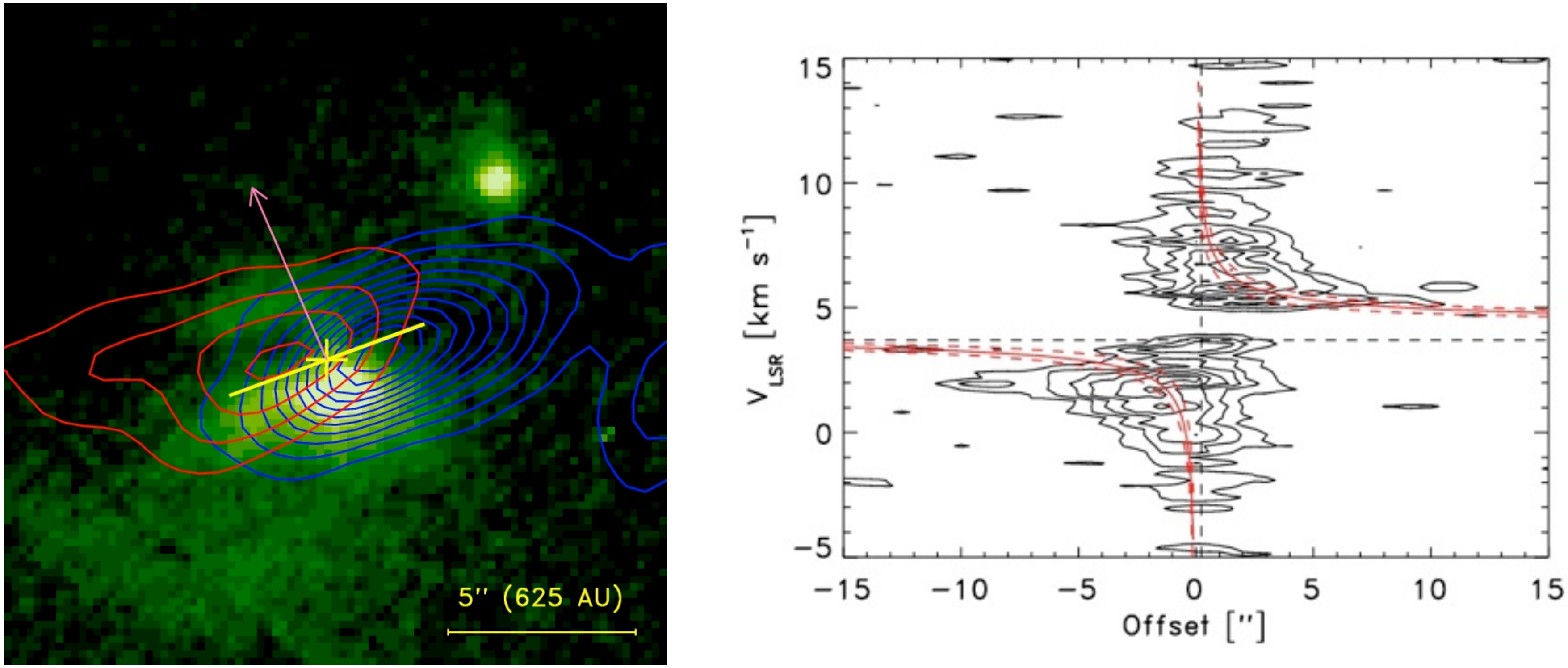
- We know the end-product by the Class II stage... namely Keplerian rotating disks

- Clearly needed to confirm structure of embedded disks as well.



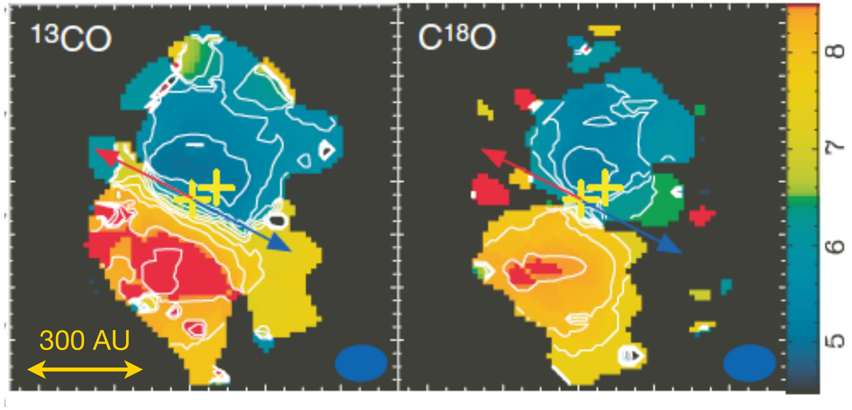
From Dutrey et al. (PPV); based on Simon et al. (2000)

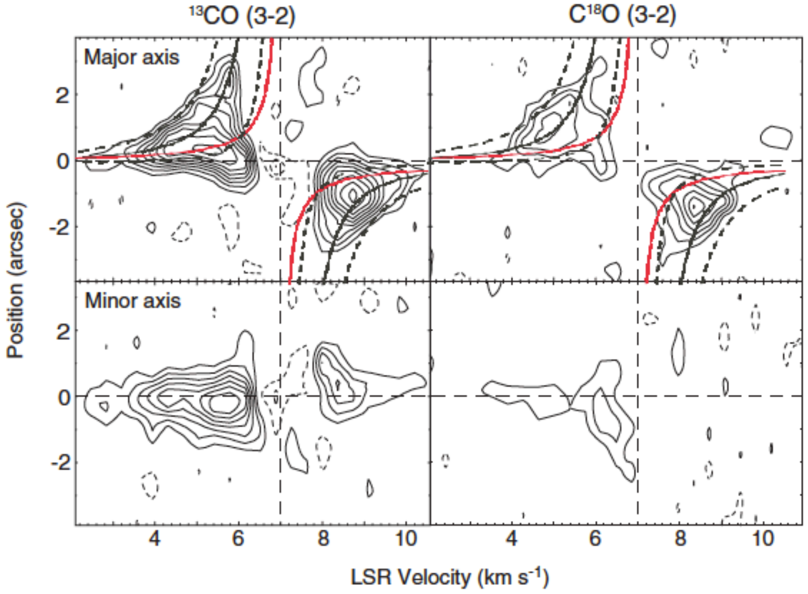
Gas: dynamics in disks around Class I sources



Keplerian rot. patterns in HCO$^+$ 3-2 in Class I sources confirm disk structure and allow estimate of dynamical masses.

A couple of other examples from the next talks

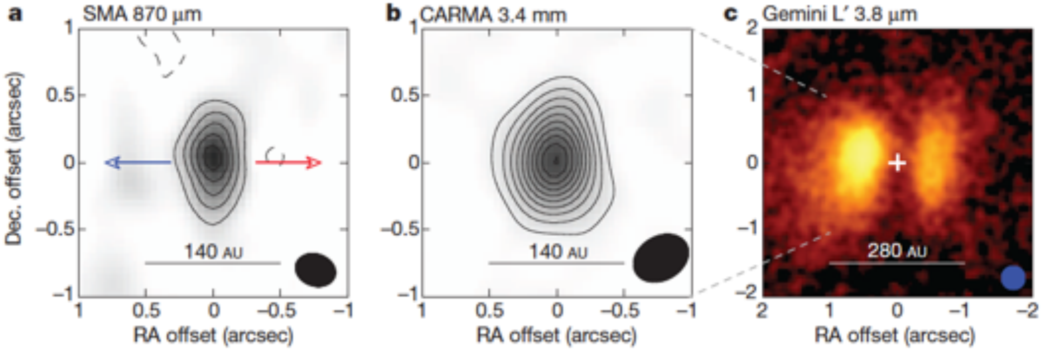


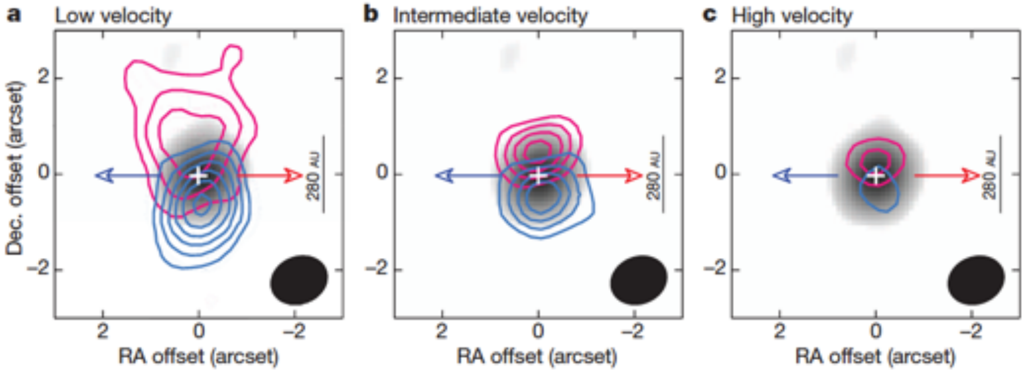


- L1551-NE protobinary system.

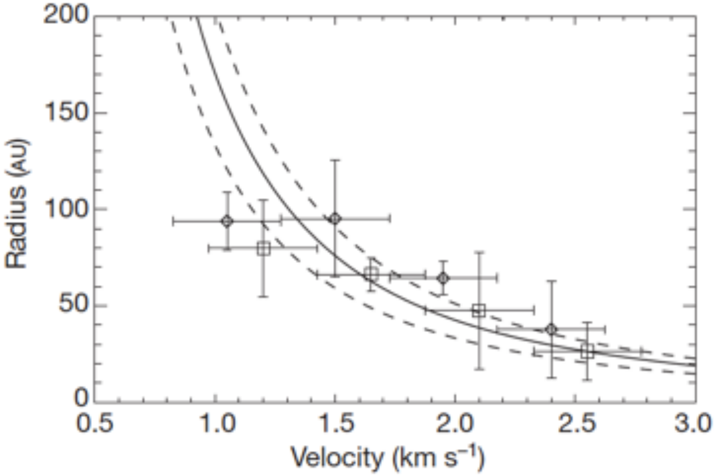
Takakuwa et al. (2012)

A couple of other examples from the next talks





- L1527 - the youngest protostar with Keplerian rotation?

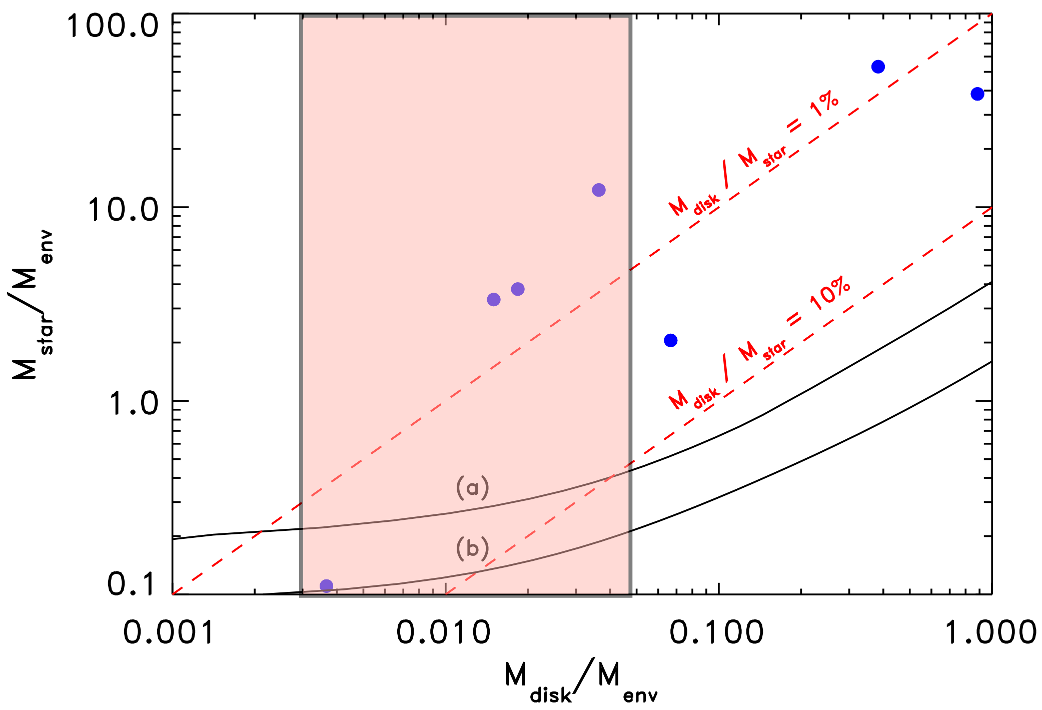


Tobin et al. (2012)

Protostellar disks with Keplerian rotation

	T_{bol} [K]	L_{bol} [$L_\odot$]	M_{star} [$M_\odot$]	M_{disk} [$M_\odot$]	M_{env} [$M_\odot$]
L1527	59	2.6	0.19	0.0063	1.72
L1551-NE	91	4.2	0.8	0.026	0.39
TMC1A	172	2.2	0.4	0.0018	0.12
L1489-IRS	238	3.7	1.35	0.004	0.11
IRS43	310	6.0	1.0	0.023	0.026
IRS63	351	0.79	0.37	0.0018	0.098
Elias 29	391	13.6	2.5	0.018	0.047

Protostellar disks with Keplerian rotation

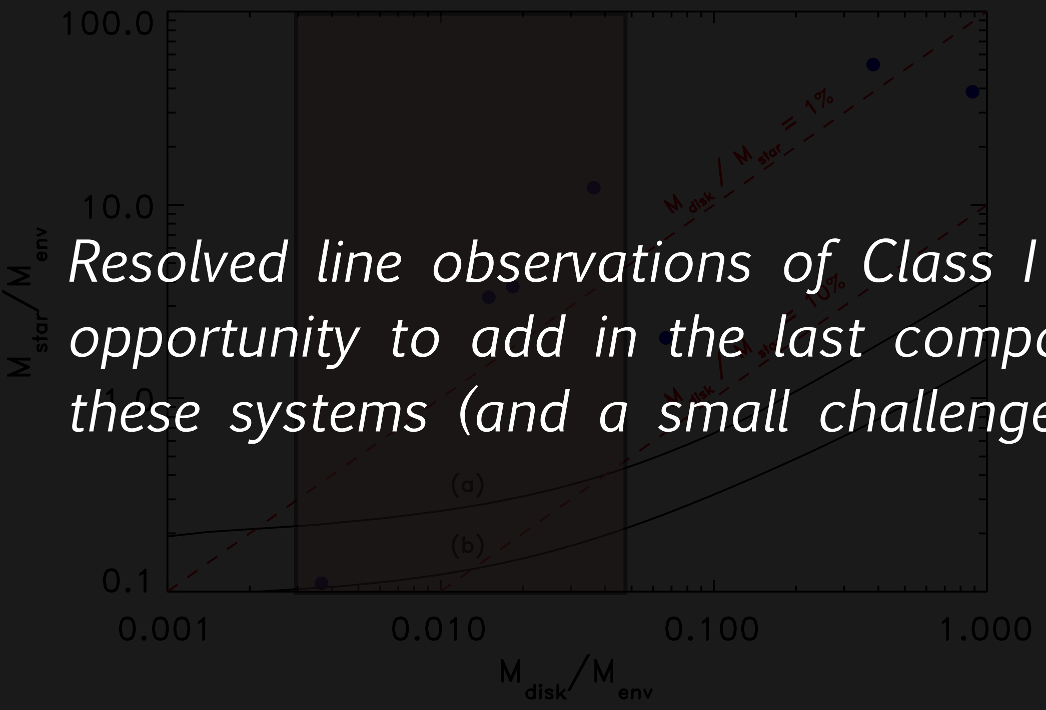


- Comparison to evolutionary models from Visser et al. 2009. Generally much less massive disks relative to central stars than predicted from models in later stages

- Possibly an indication of rapid processing of material from envelope through disk. Jørgensen et al. (2009).

Predicted stellar and disk mass measured relative to the envelope mass in the models of Visser et al. (2009). Both models with $\Omega_0 = 10^{-14}$ *s*$^{-1}$ *and* c_s *of either 0.19 km s*$^{-1}$ *(a) and 0.26 km s*$^{-1}$ *(b). Updated version of figure from Jørgensen et al. (2009)*

Protostellar disks with Keplerian rotation



- Comparison to evolutionary models from Visser et al. 2009. Generally much less massive disks relative to central stars than predicted from models in later stages
- Possibly an indication of rapid processing of material from envelope through disk. Jørgensen et al. (2009).

Predicted stellar and disk mass measured relative to the envelope mass in the models of Visser et al. (2009). Both models with $\Omega_0 = 10^{-14}$ s^{-1} and c_s of either 0.19 km s^{-1} (a) and 0.26 km s^{-1} (b). Updated version of figure from Jørgensen et al. (2009)

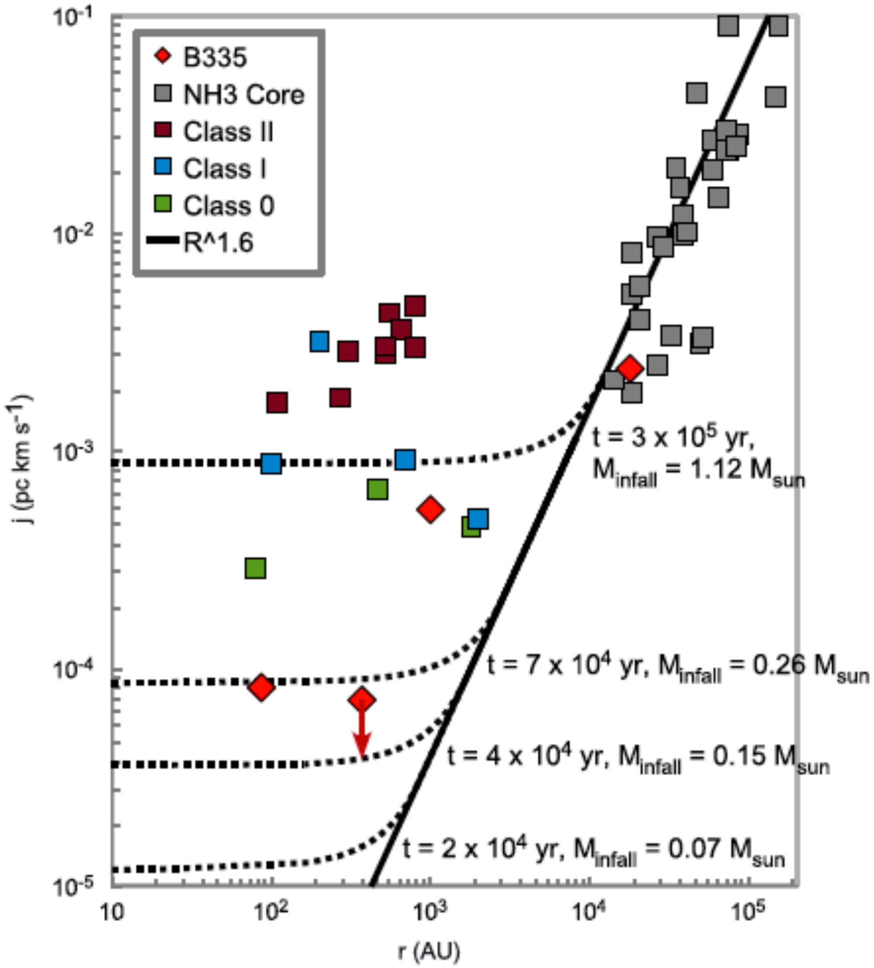
Resolved line observations of Class I YSOs provide good opportunity to add in the last component in tracing the mass in these systems (and a small challenge to modelers)...

Angular momentum regimes

- How are these different regimes related. Ohashi et al. (1997) suggests transition from sharply declining specific angular momentum on larger scales to inner region where specific angular momentum is conserved $(v \propto r^{-1})$.

- Example is seen in combined single-dish and interferometric observations of B335 (Yen et al. 2011).

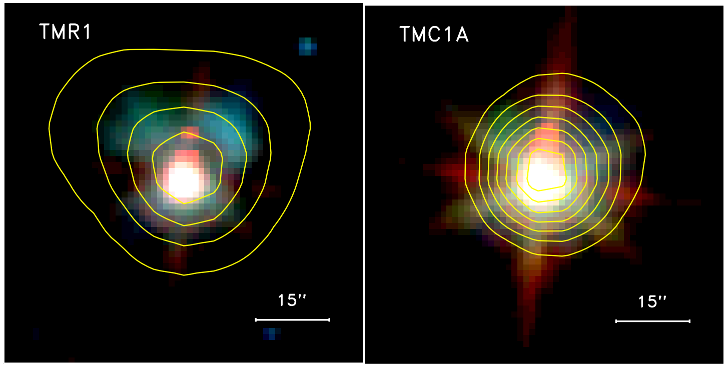
- Still, how to get from profile with conserved specific angular momentum to Keplerian rotation?

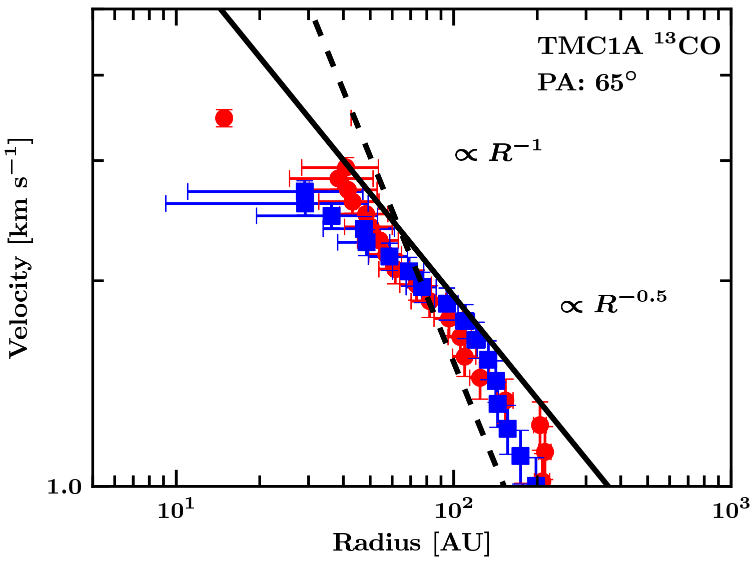


Yen et al. (2011)

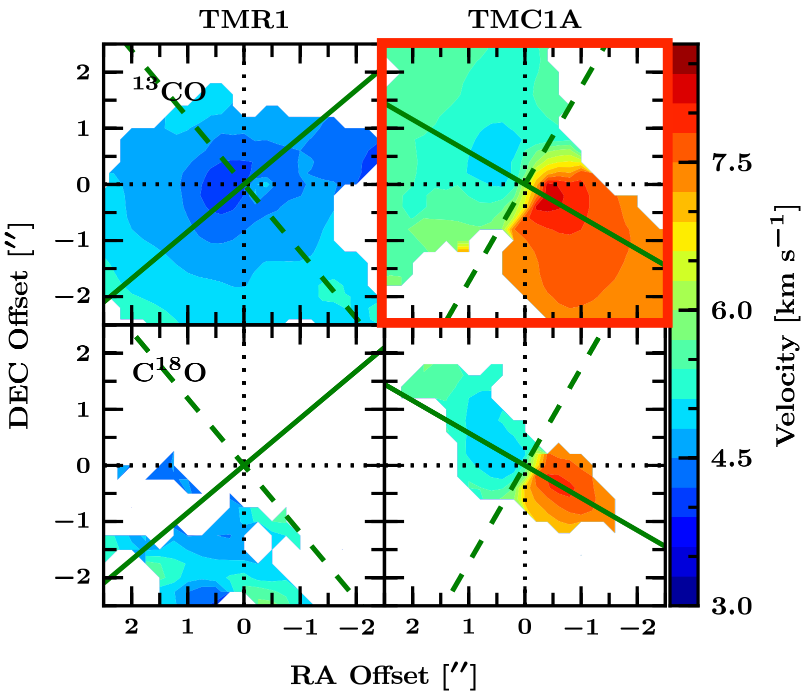
Dynamics in disks around Class I sources

- IRAM PdBI subarcsecond observations of ^{13}CO and C^{18}O 2-1 toward two Class I protostars in Taurus (*Harsono et al. 2013*).
- Velocity profile shows clear break at 100 AU consistent with inside-out formation of Keplerian disk.





Harsono, JKJ et al. 2013

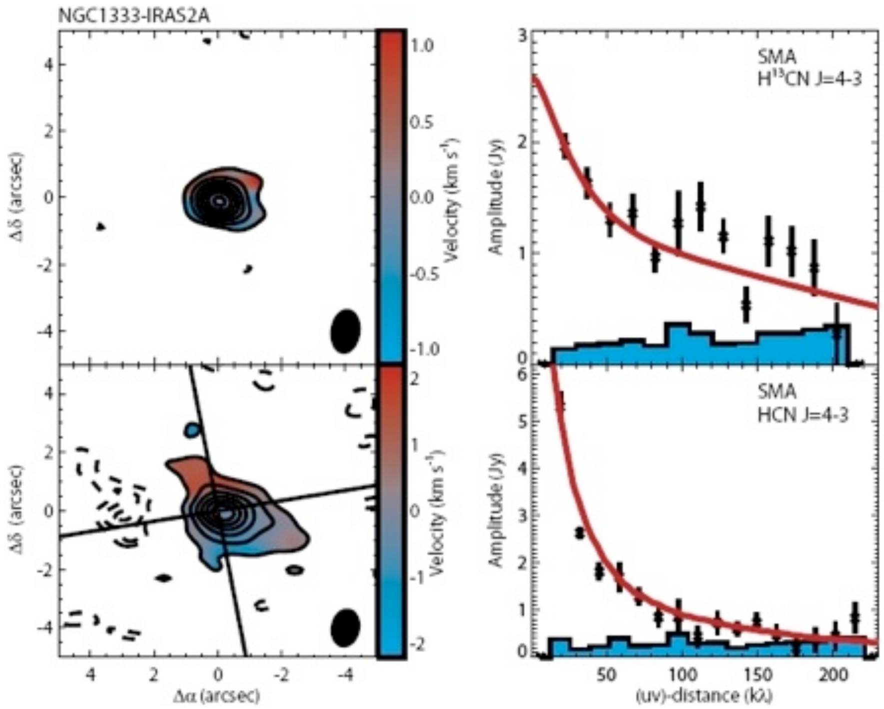


(Lack of) dynamical structure in the Class 0 stage?

- Common submillimeter line tracers such as HCO^+, HCN become optically thick on few hundred AU scales for envelopes more massive than ~0.1 $M_\odot$ (i.e., Class 0 sources).

- Optically thin species show the requirement of compact components, but chemistry may play a role in interpretation.

- NGC1333-IRAS2A: Kinematics on small scales dominated by infall rather than rotation.



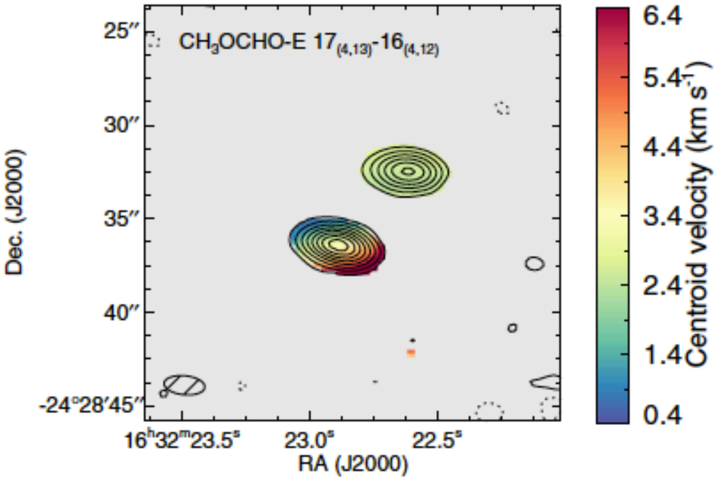
Brinch et al. (2009)

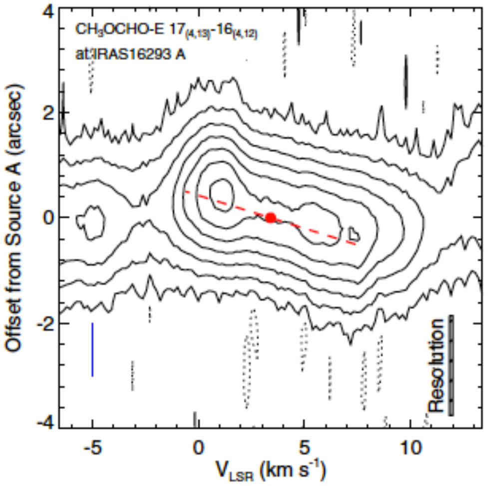
IRAS 16293-2422 with ALMA

- Other example: IRAS 16293-2422 (ALMA-SV) data: clear velocity gradient seen toward one component of binary (*Pineda et al. 2012*).

- However, also no clear indication of rotation velocity fields there (not all velocity gradients indicate rotation; see also *Tobin et al. 2012*).

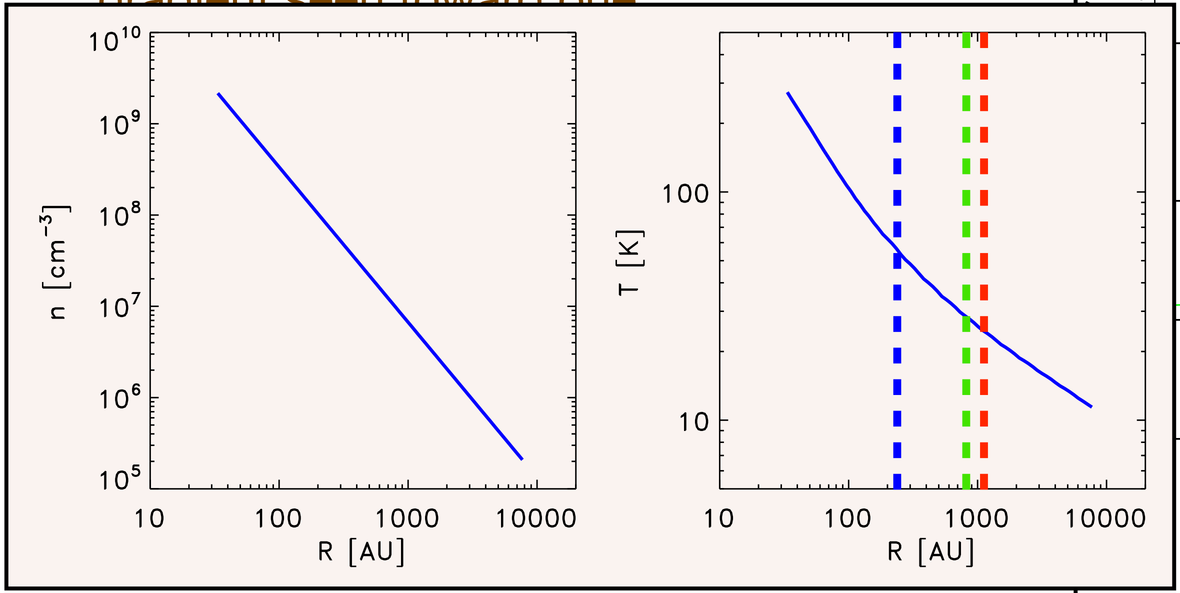
- Differences to velocity field in less dense gas (but similar angular scales) in eSMA data (*Favre et al., 2013 to be submitted*).

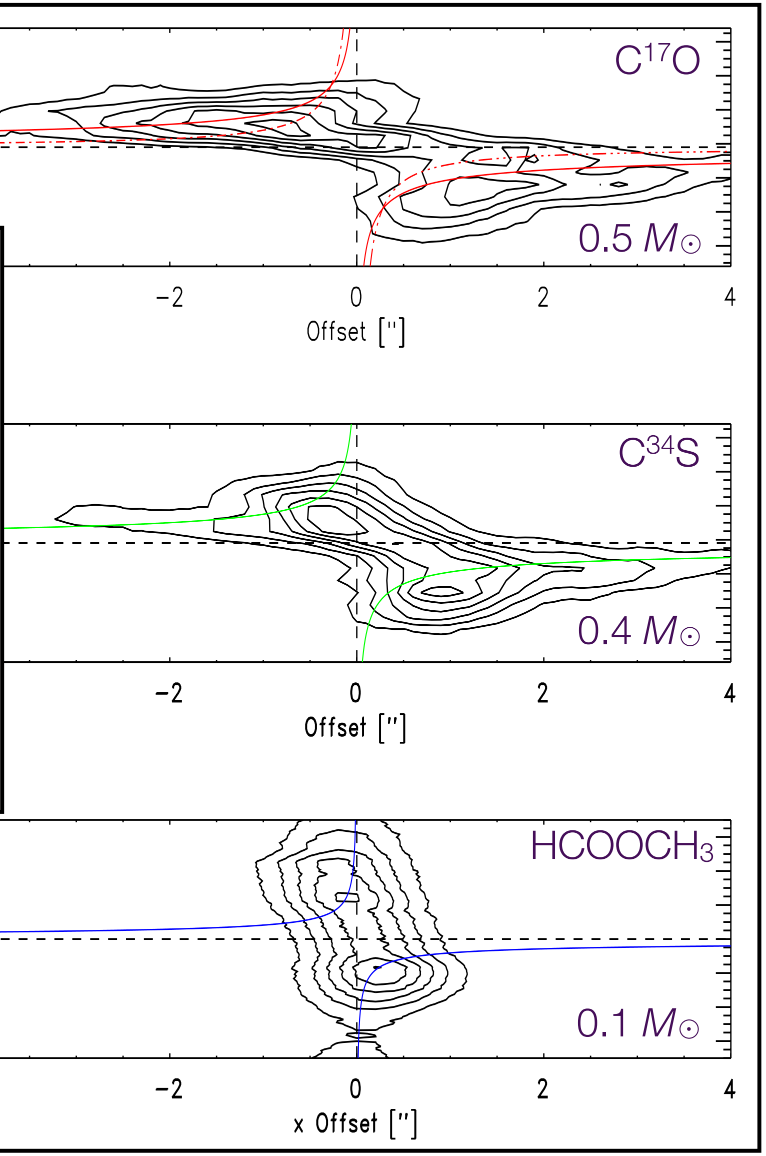




IRAS 16293-2422 with ALMA

- Other example: IRAS 16293-2422 (ALMA-SV) data: clear velocity gradient seen toward one

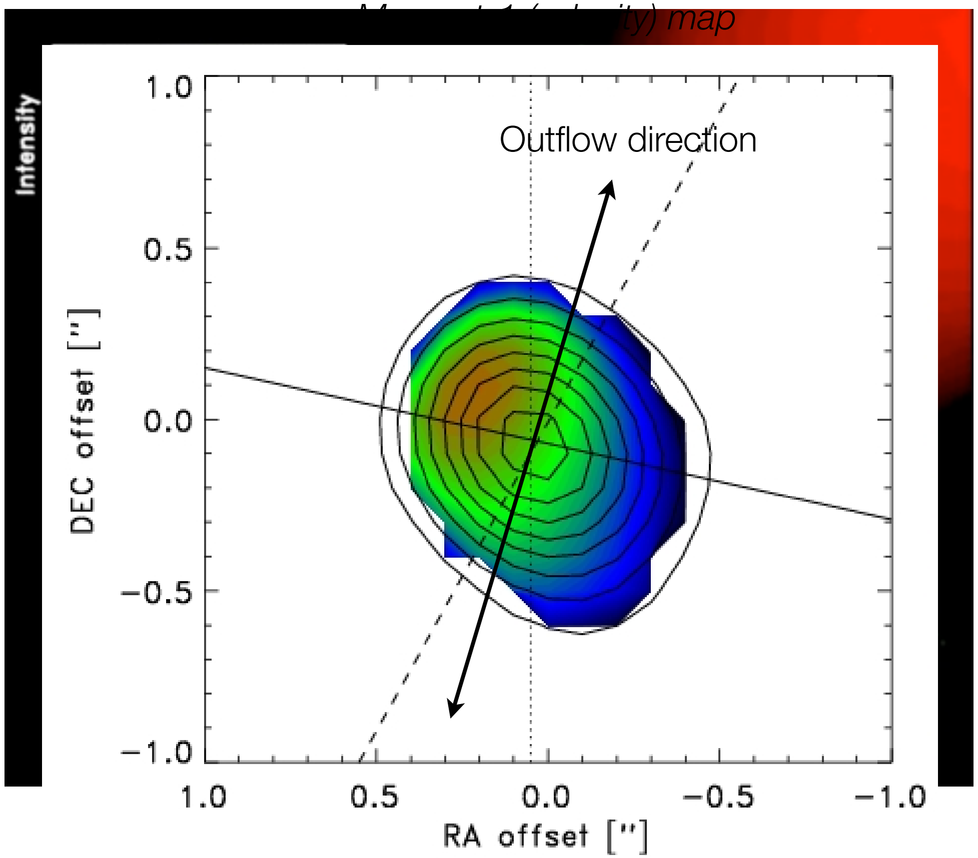




- Differences to velocity field in less dense gas (but similar angular scales) in eSMA data (*Favre et al., 2013 to be submitted*).

Water in the inner regions of NGC1333-IRAS4B

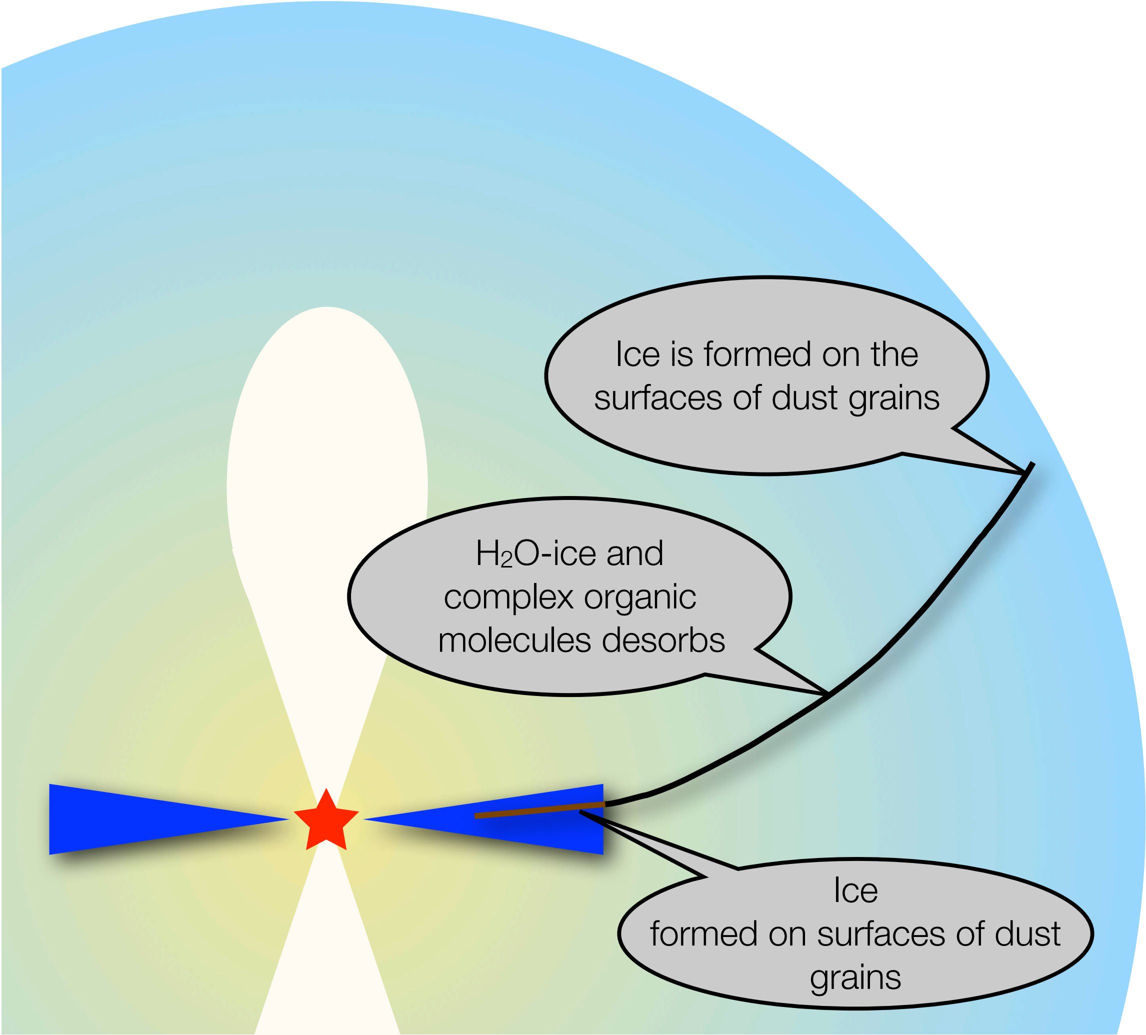
IRAM PdBI imaging of $H_2^{18}O$ emission from NGC1333-IRAS4B



- Warm H_2O detected with Spitzer suggested to have its origin in an accretion shock in the circumstellar disk *(Watson et al. 2007)*.
- Imaged at 0.5” (125 AU) resolution with the PdBI targeting the $H_2^{18}O$ line at 203 GHz.
- Velocity gradient consistent with origin in disk.

Jørgensen & van Dishoeck (2010)

Importance *for* and *of* chemistry...



- Water Tracing the composition of ices (water, complex organics)

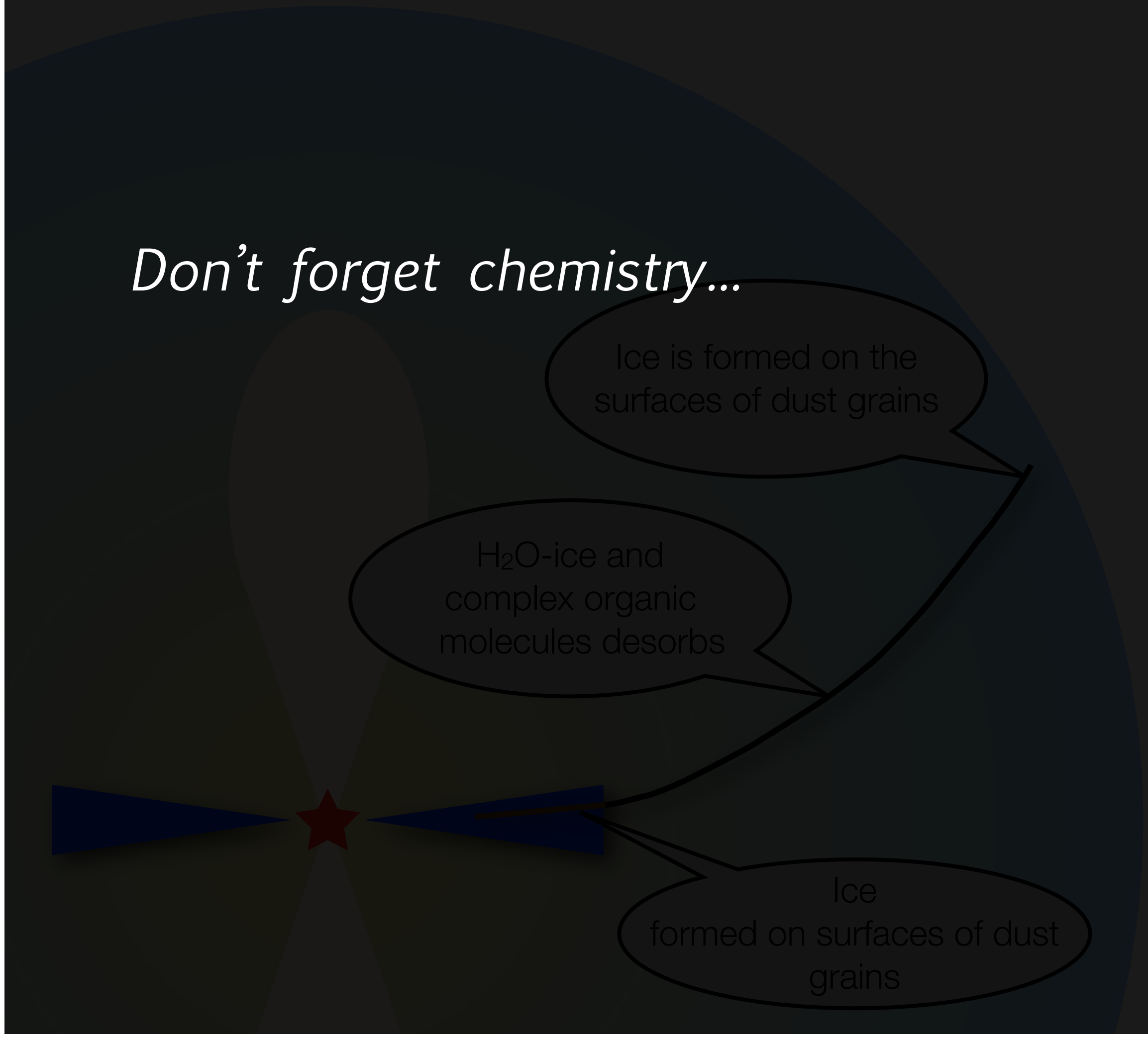
- Origin: in the hot inner region of the protostellar envelope?
  - ➡ PdBI: “Low” $[H_2O]_{in} \sim 10^{-7}$

- ...or circumstellar disk?
  - ➡ H_2O emission from thin layer (0.03% of disk mass)

- Clearly accurate physical structure critical - but if you believe that the water abundance is well-understood a cold reservoir and gas and dust is needed.

Importance *for* and *of* chemistry...

Don't forget chemistry...



Ice is formed on the surfaces of dust grains

H_2O-ice and complex organic molecules desorbs

Ice formed on surfaces of dust grains

- Water Tracing the composition of ices (water, complex organics)
- Origin: in the hot inner region of the protostellar envelope?
  - ➡ PdBI: "Low" $[H_2O]_{in} \sim 10^{-7}$
- ...or circumstellar disk?
  - ➡ H_2O emission from thin layer (0.03% of disk mass)
- Clearly accurate physical structure critical - but if you believe that the water abundance is well-understood a cold reservoir and gas and dust is needed.

Summary

- High-angular resolution (sub)millimeter wavelength and mid-infrared observations, coupled with detailed radiative transfer models the structure of protostars from 10,000 to ~100 AU scales and beyond (*the better the data - the more complex the picture*).
  - *Density enhancements in protostars on few hundred AU scales: either presence of disks, i.e., rapid formation and growth, or alternative explanations including pseudo-disks, enhancements due to magnetic shocks, ...*
  - *Possible systematic errors due to temperature and/or dust evolution - but overall approaches to problem lead to similar results.*
- Resolved line observations provide means to break model degeneracies and address the systematic uncertainties.
  - *Keplerian disks seen around an increasing number of Class I (and even a few Class 0/I borderline) objects.*
  - *Where does the break between the infalling/rotating envelope and Keplerian disk occur? Important task for ALMA.*
  - *Absence of Keplerian rotation in Class 0 disks significant - or a result of "tools"?*
  - *Important link between chemical and disk formation studies.*