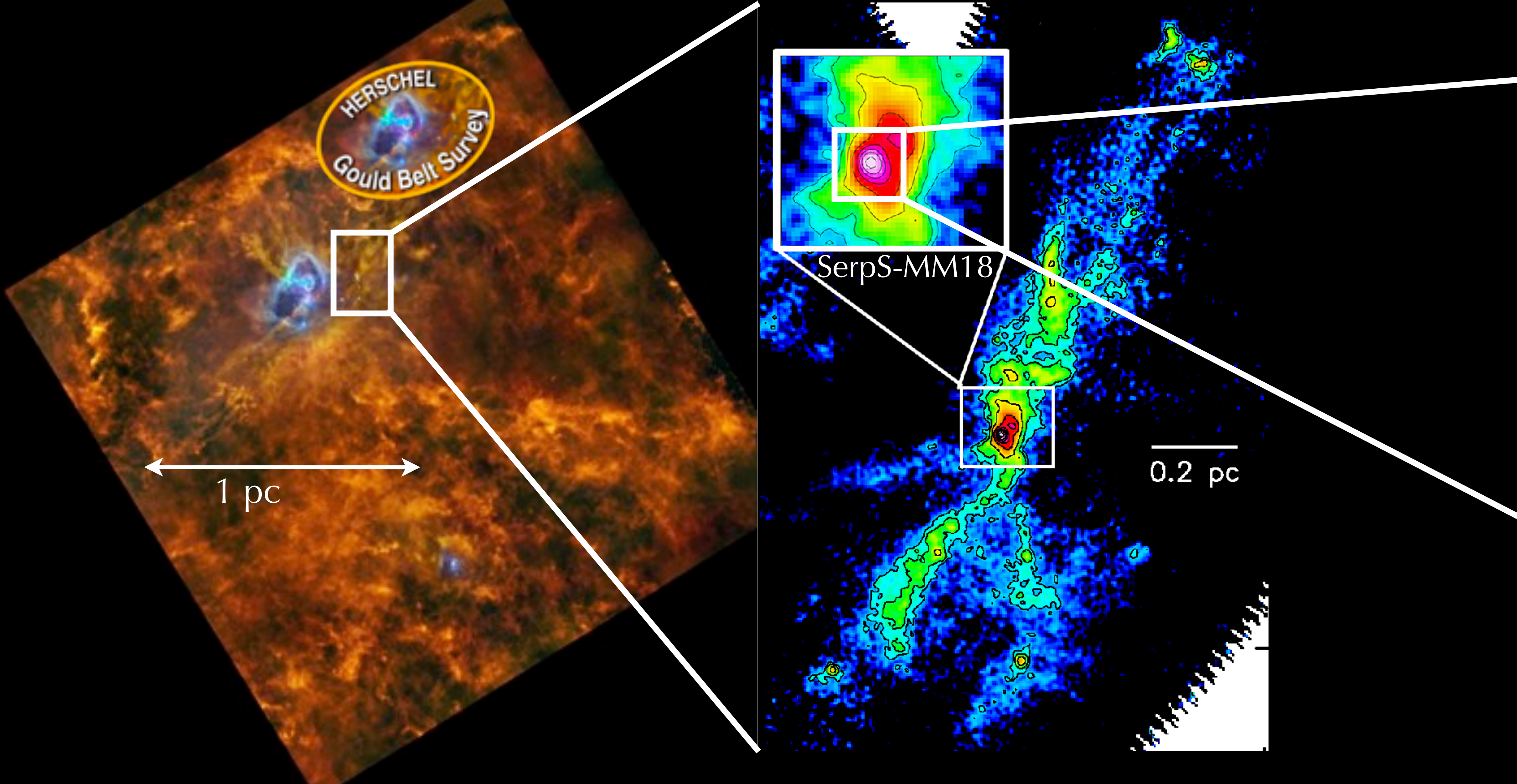
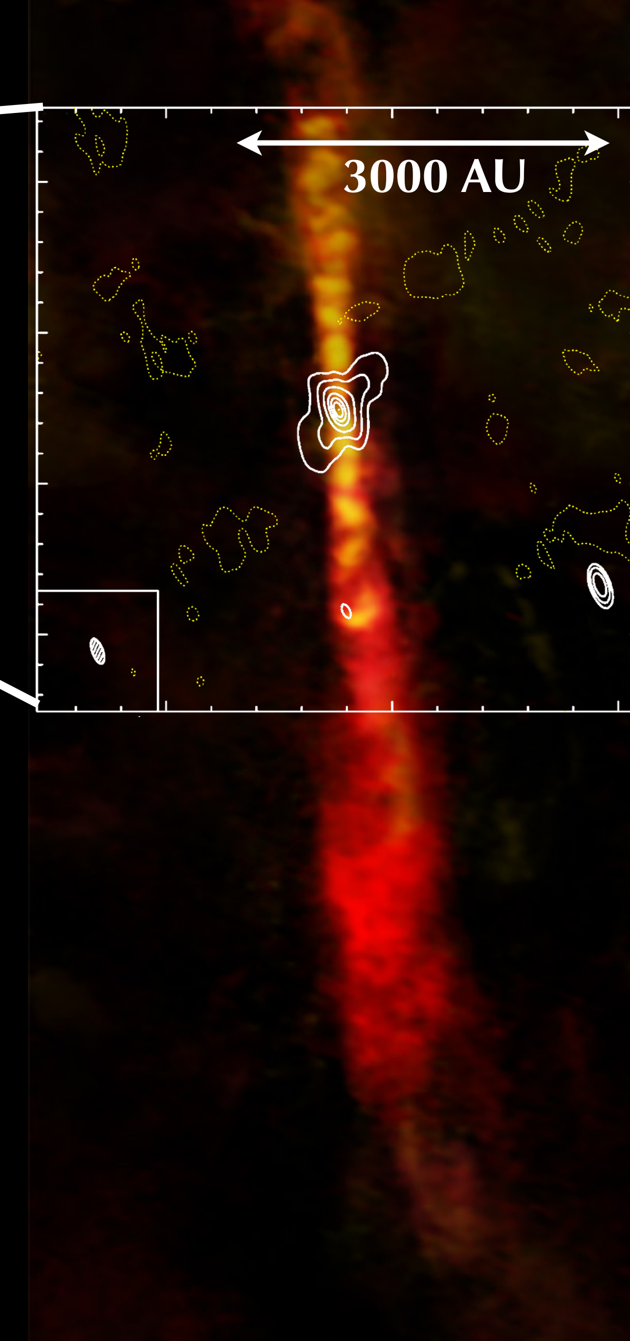




The Chronology of the Formation of the Solar System

Chapter I: From molecular clouds to protostellar cores

Chapter II: The formation of protostellar discs

A. Maury & B. Commercon - Les Houches 2017

Today:
Chapter II

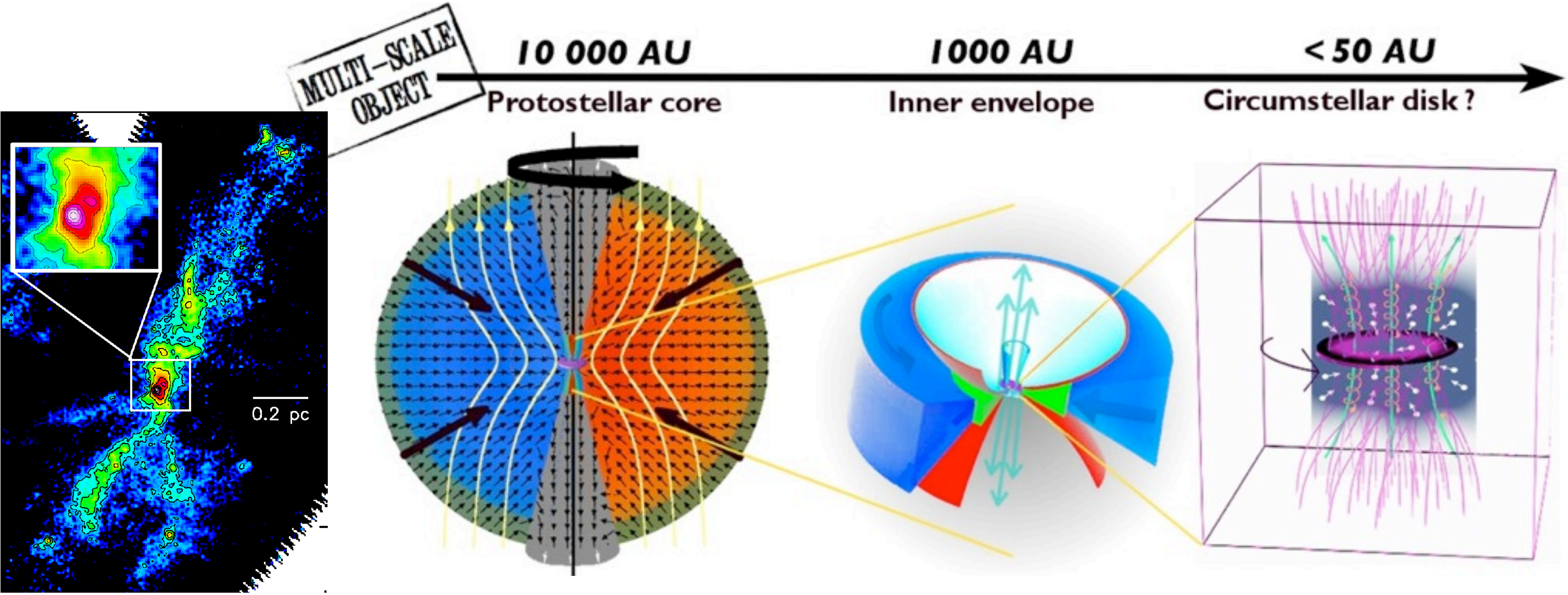
Small-scale properties of low-mass Class 0 protostars: constraints on the formation of protoplanetary discs

Questions addressed in this lecture

How does the accretion proceeds onto the central protostellar object ?
What are the properties of pristine circumstellar discs ?

Recap

Anatomy of a typical protostar

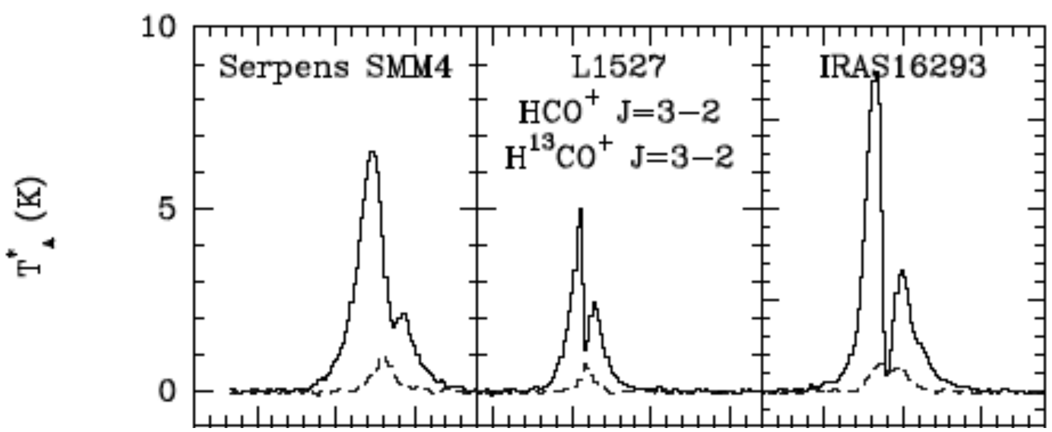


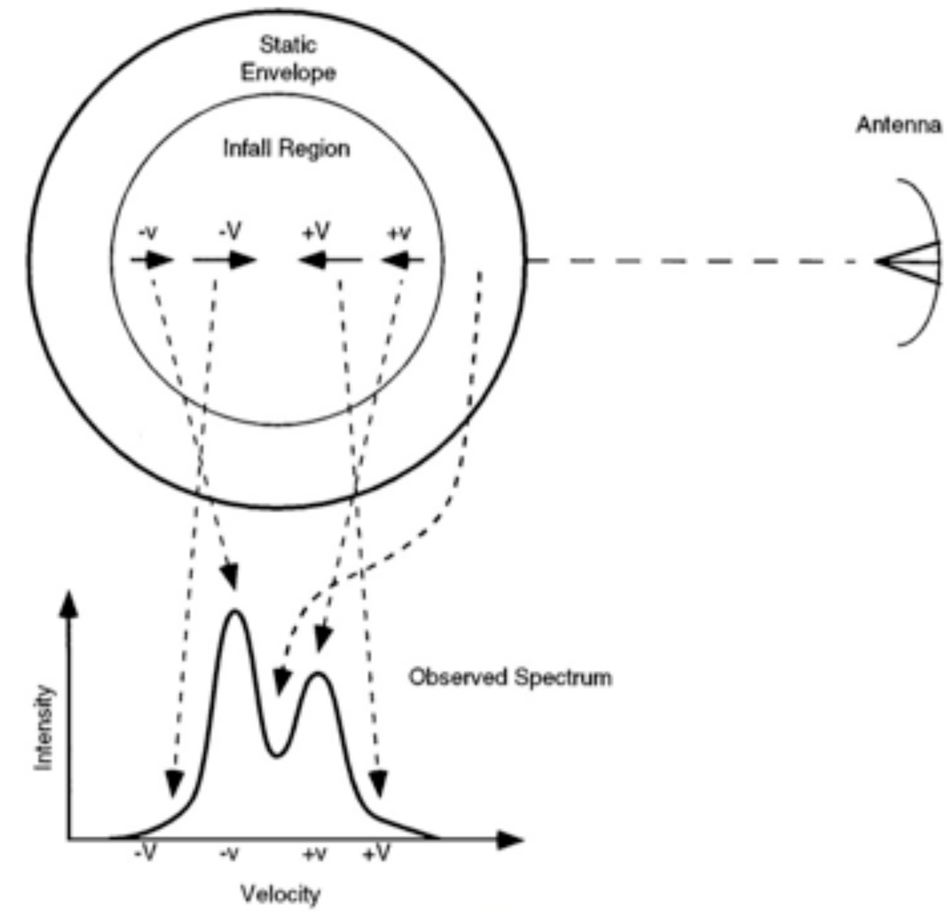
Column density:	10^{21} N_{H2}/cm^2	--	10^{23} N_{H2}/cm^2
Temperature:	5K	--	500 K
Gas mass:	1-5 M_o	--	< 0.01 M_o

Observing the infall

- Identified through asymmetric line profiles

  Commonly used: HCO+, CS, H2CO, N2H+

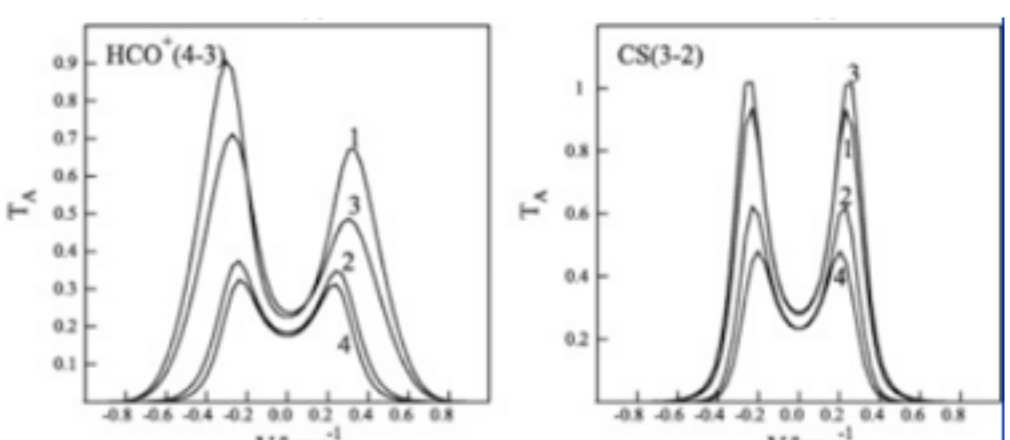


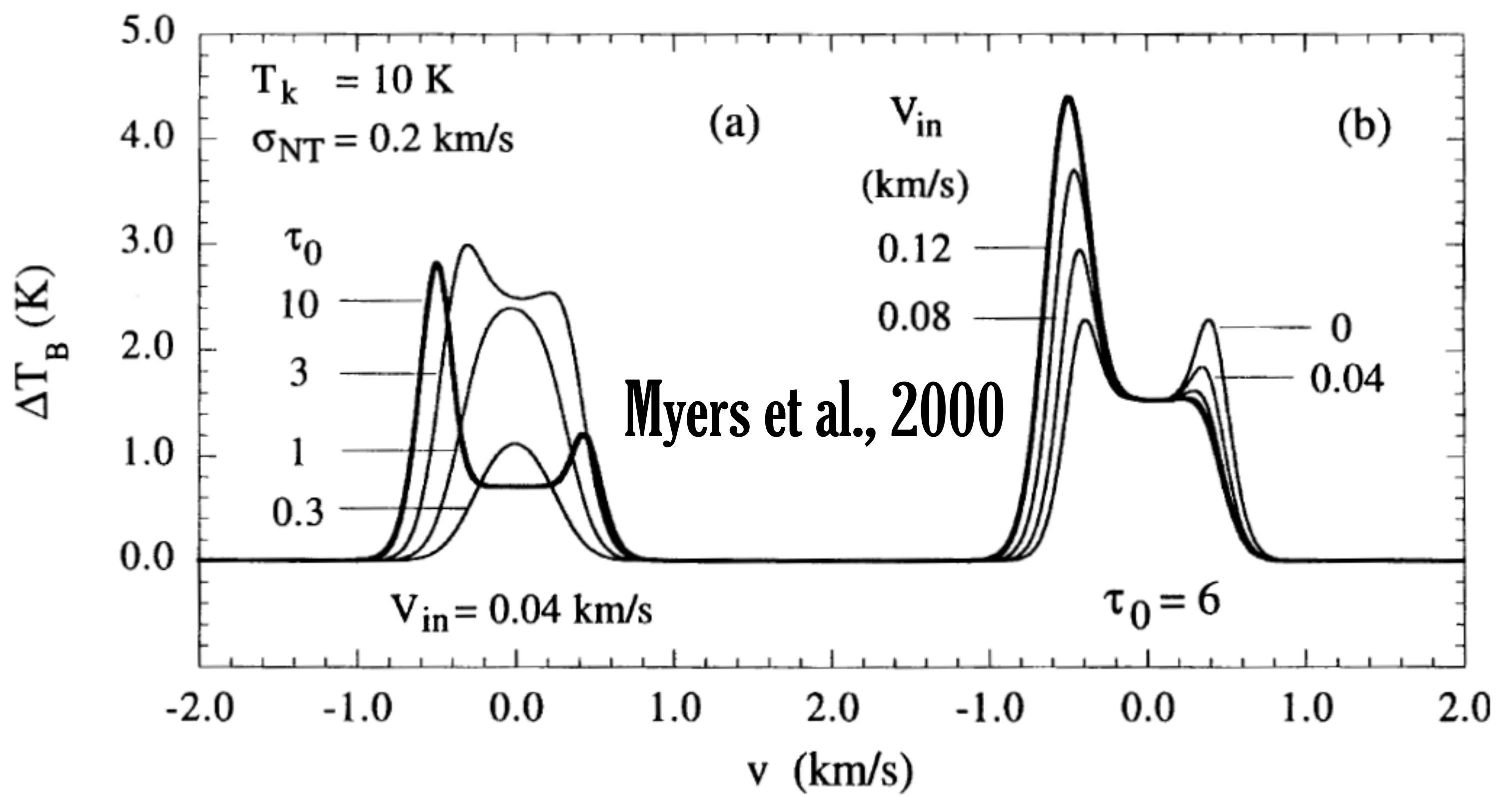


- Caution!

  Depletion can affect line profiles

  and infall signature !

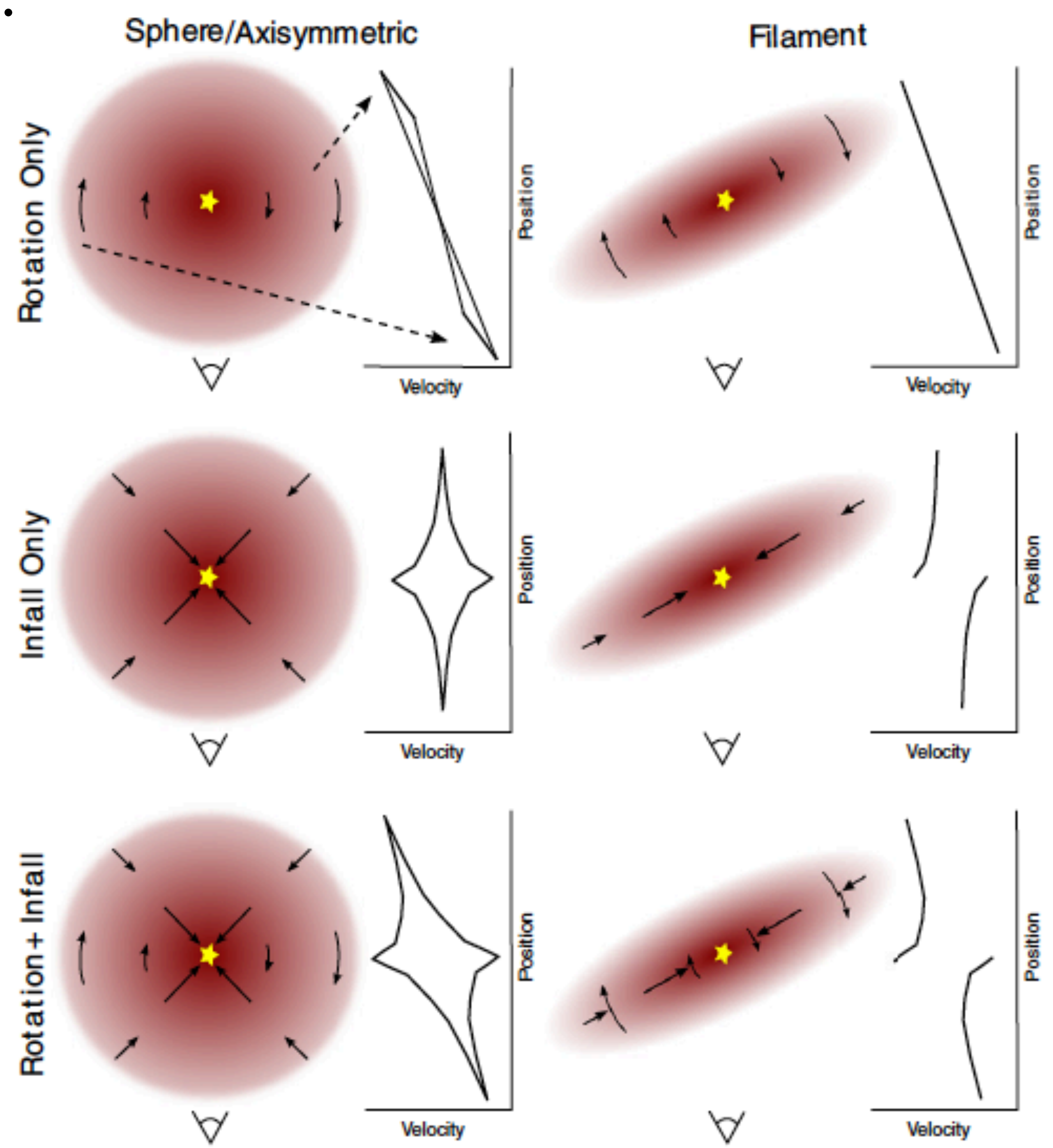




Measuring the infall

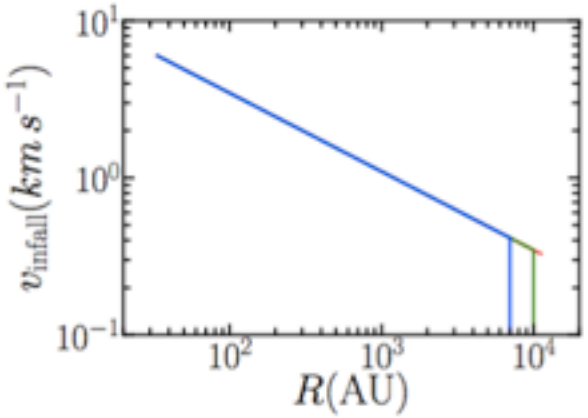
- Skewness/asymmetry (e.g. Gregersen+ 97, Mardonnes+ 97) : doesn't measure infall rate but can identify infall candidates. No model required.

- PV diagram (e.g. Tobin+ 12, Yen+ 14) : use analytical/RT model and observed PV to constrain balance of infall and other motions

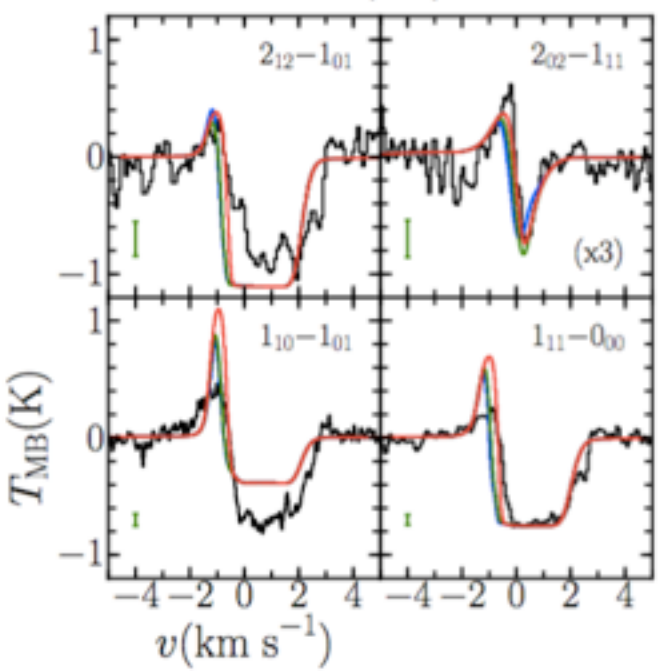


- 1-D RT model to fit line profiles from multiple lines (e.g. Hogerheijde & Sandell 00, Belloche+ 06, Mottram+ 13) => self-consistently constrain fit to 1-D model using line shape and intensity

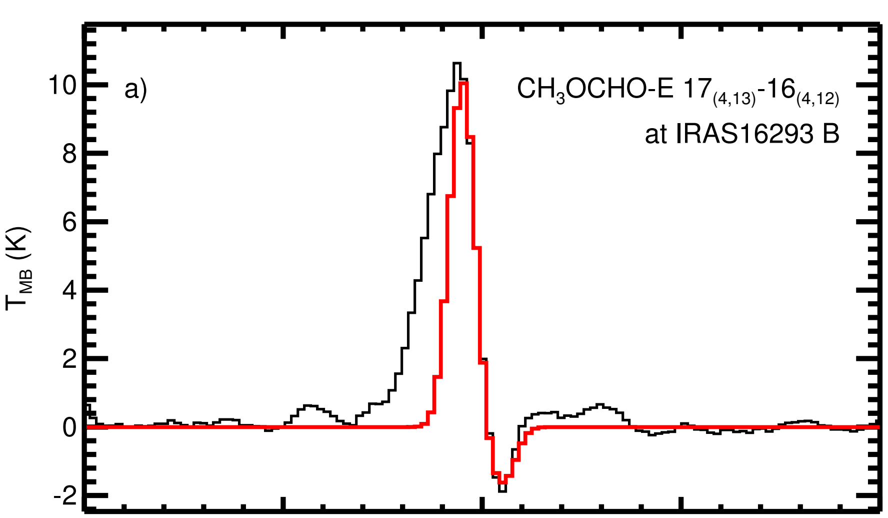
Measuring the infall

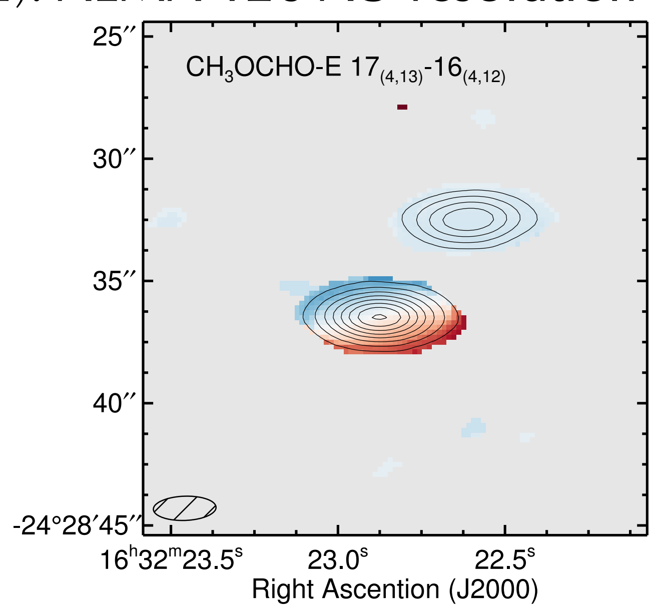


IRAS4A (Mottram+ 2013): water lines
Herschel WISH



IRAS 16293B (Pineda+ 2012): ALMA 120 AU resolution

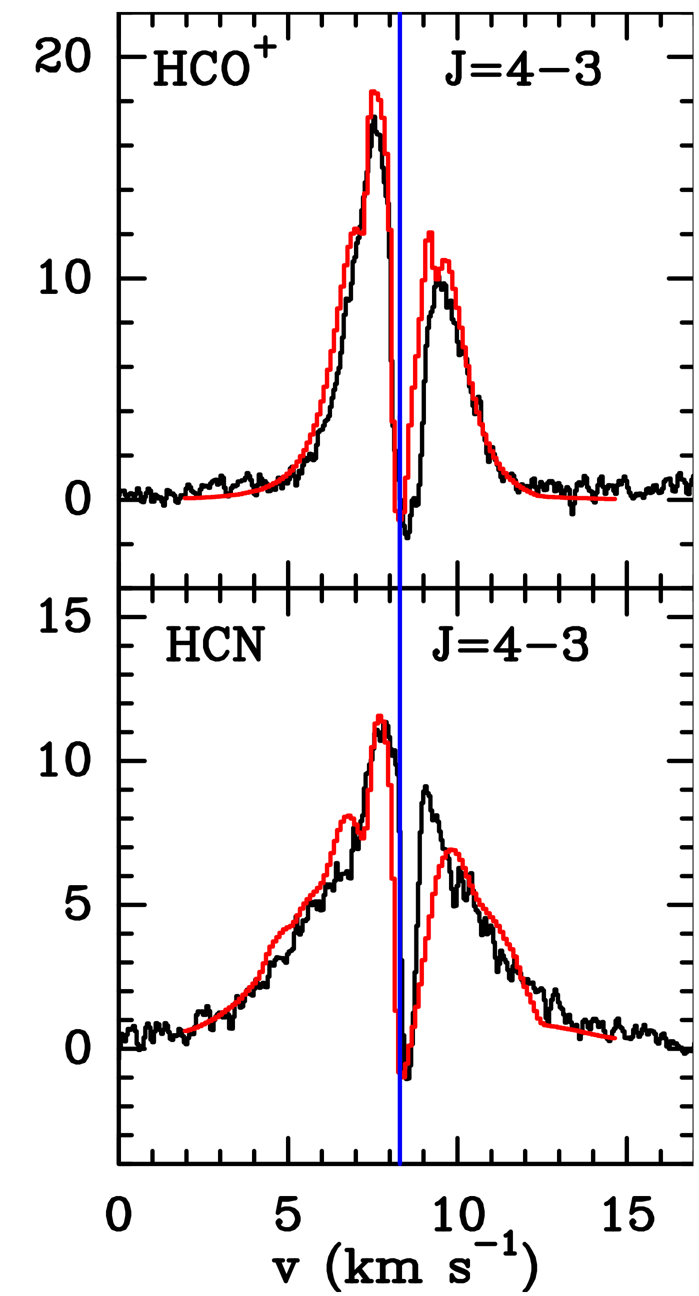




infall speed 0.5-0.7 km/s

mass infall rate 4x10^{-5} M$_o$/yr

B335 (Evans+ 2015):
ALMA 50 AU resolution



mass infall rate 3x10^{-6} M$_o$/yr

accretion rate 9.6x10^{-7} M$_o$/yr

age 5x10^4 yrs

$$\dot{M}_{\rm acc} = \frac{L_\star R_\star}{G M_\star f_{\rm acc}},$$

Luminosity problem:

Protostars have luminosities < than would be expected for the accretion rate determined from the IMF + observed star formation rate (Kenyon & Hartmann 1990, Dunham+ 2010).

Total protostellar luminosity

Photospheric luminosity

0.25 M_{SUN}

10^{-5} M_{SUN} yr^{-1}

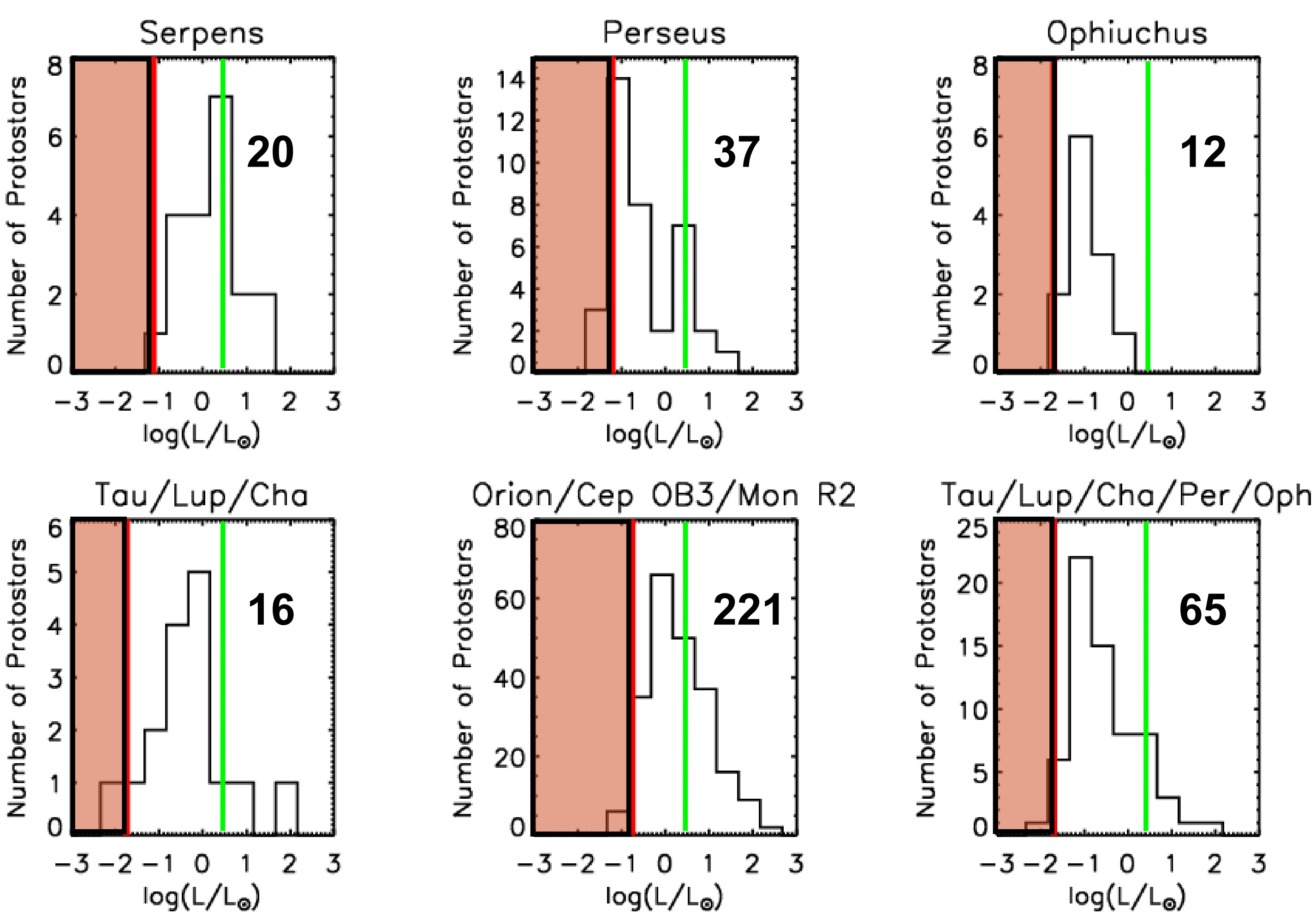
3 R_{SUN}

$$L_p = L_{\rm phot} + f_{\rm acc}\frac{Gm\dot{m}}{r}$$

$\lesssim 1$

$L_{ACC} \sim 25$ L_{SUN}

Median observed luminosity = 1.2 - 1.3 L_{SUN}

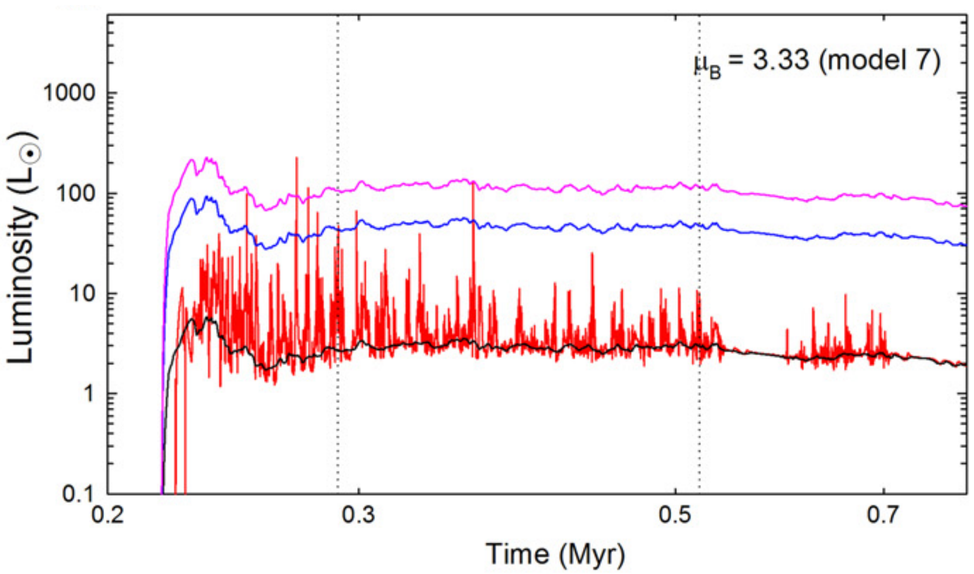


Spitzer surveys: luminosities < than expected for continuous accretion over 5 x 10^5 years ($L_{acc} \sim 5$ L_{sun}), particularly for low mass regions (Kryukova+ 2012)

Caution: improved the coverage of the low luminosity tail by extrapolating bolometric luminosity from a well sampled SED in the MIR but lacks FIR data points

Infall and accretion in protostars

Episodic Accretion ?



Offner+ 2011, Dunham+ 2014, Vorobyov+ 2015

Embedded protostars: difficult to observe the accretion bursts directly

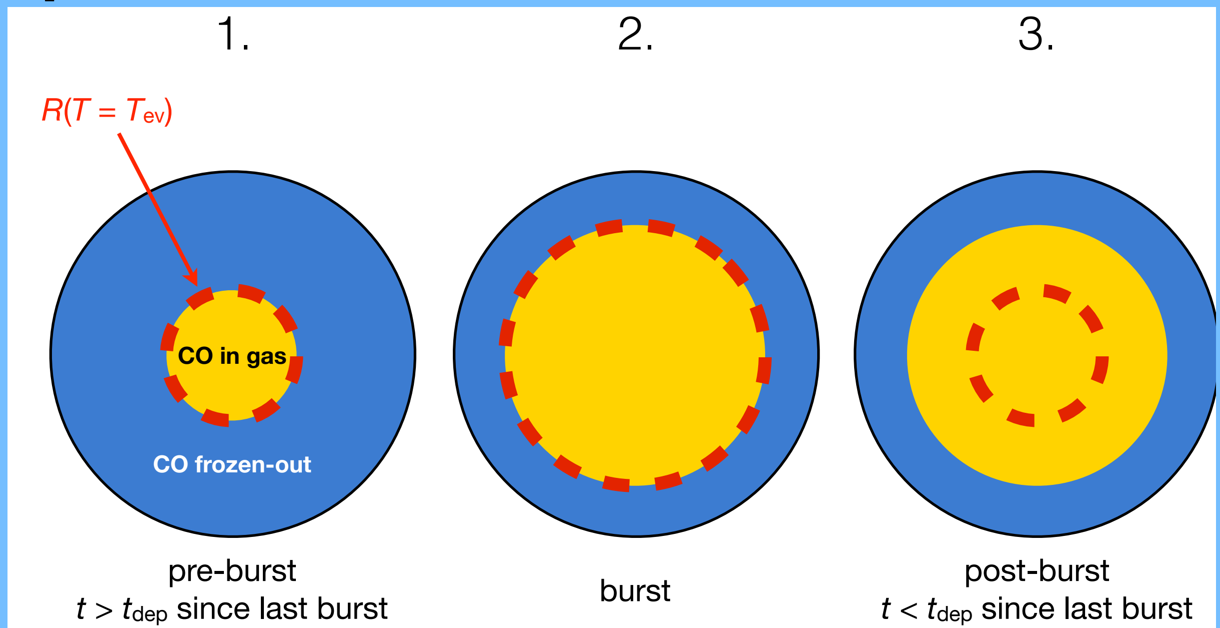
Some indirect clues:
- periodic shocks observed in protostellar jets
- chemical probes of temperature variations

Jorgensen+ (2015), Anderl+ (2015): extent of C18O emission in protostellar envelopes does not follow the expectations from the temperature profile

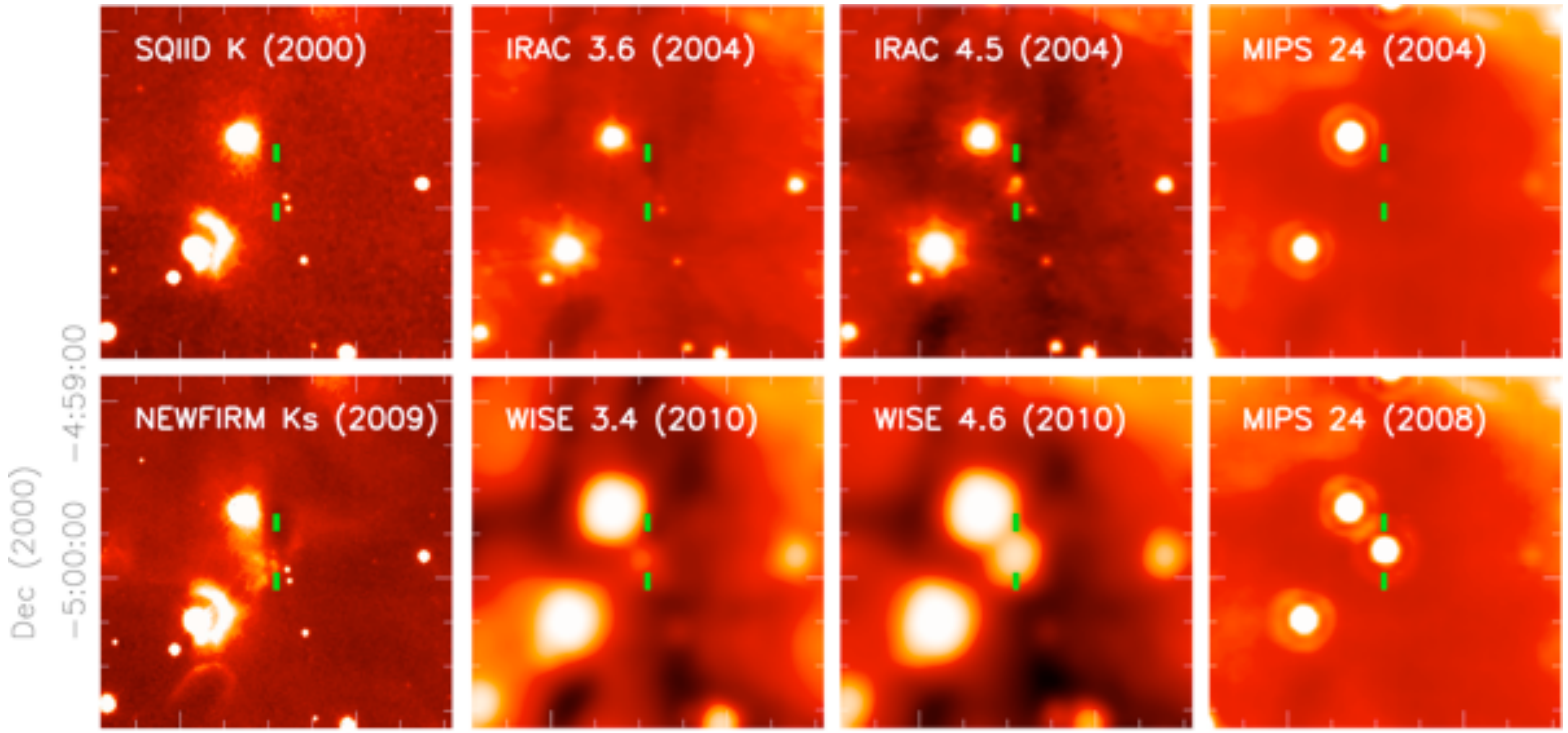
=> suggests a recent increase in temperature that allowed CO in the gaz phase at larger radii in the recent past

chemistry timescale > cooling down timescale of the gaz would explain why CO is observed where the current temperature is <30K

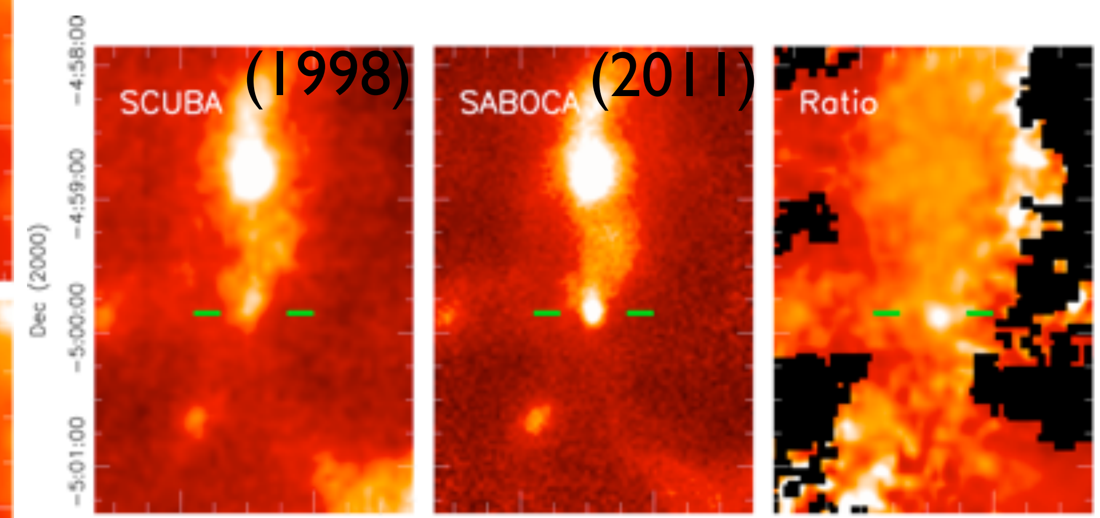
=> interpreted as a clue for accretion burst



HOPS 383

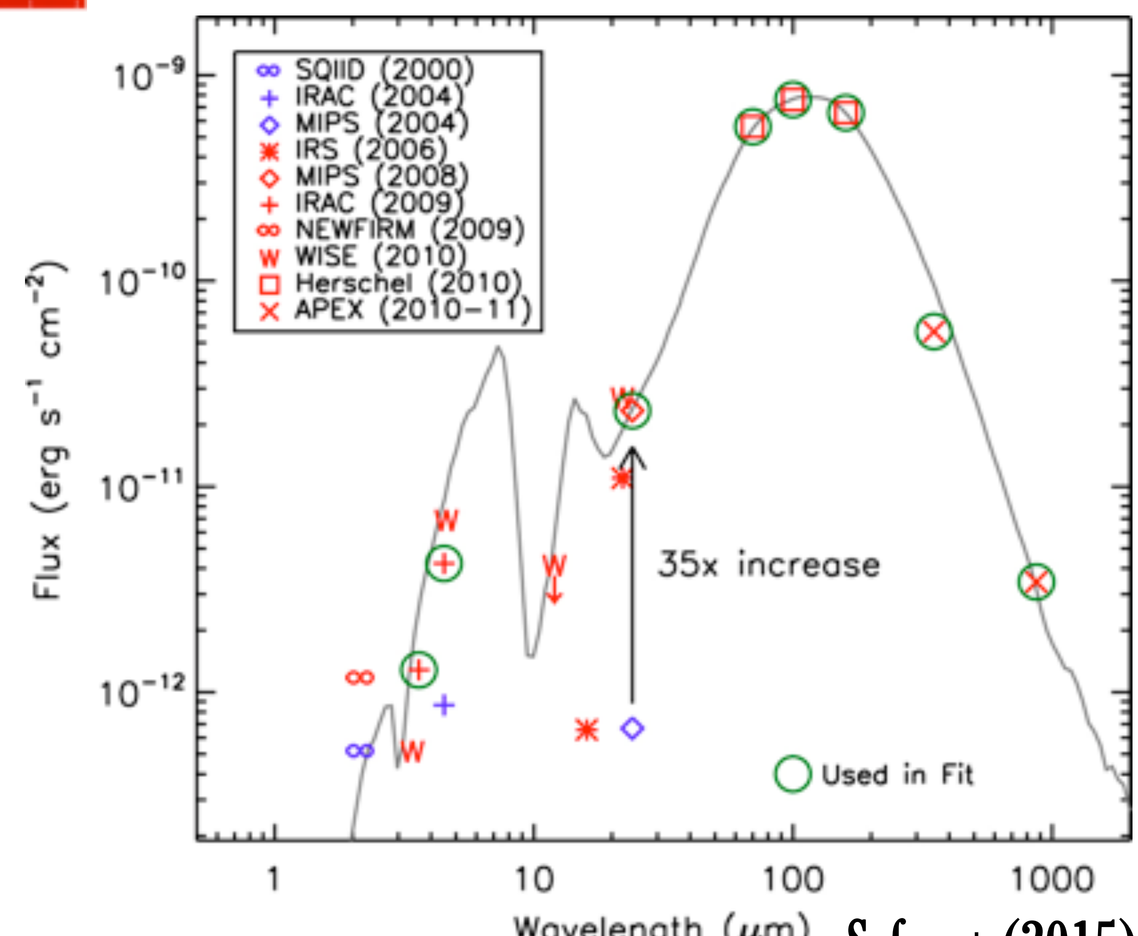


Spitzer vs WISE at <24µm



SCUBA vs SABOCA at 0.8mm

x35 in bolometric luminosity ?

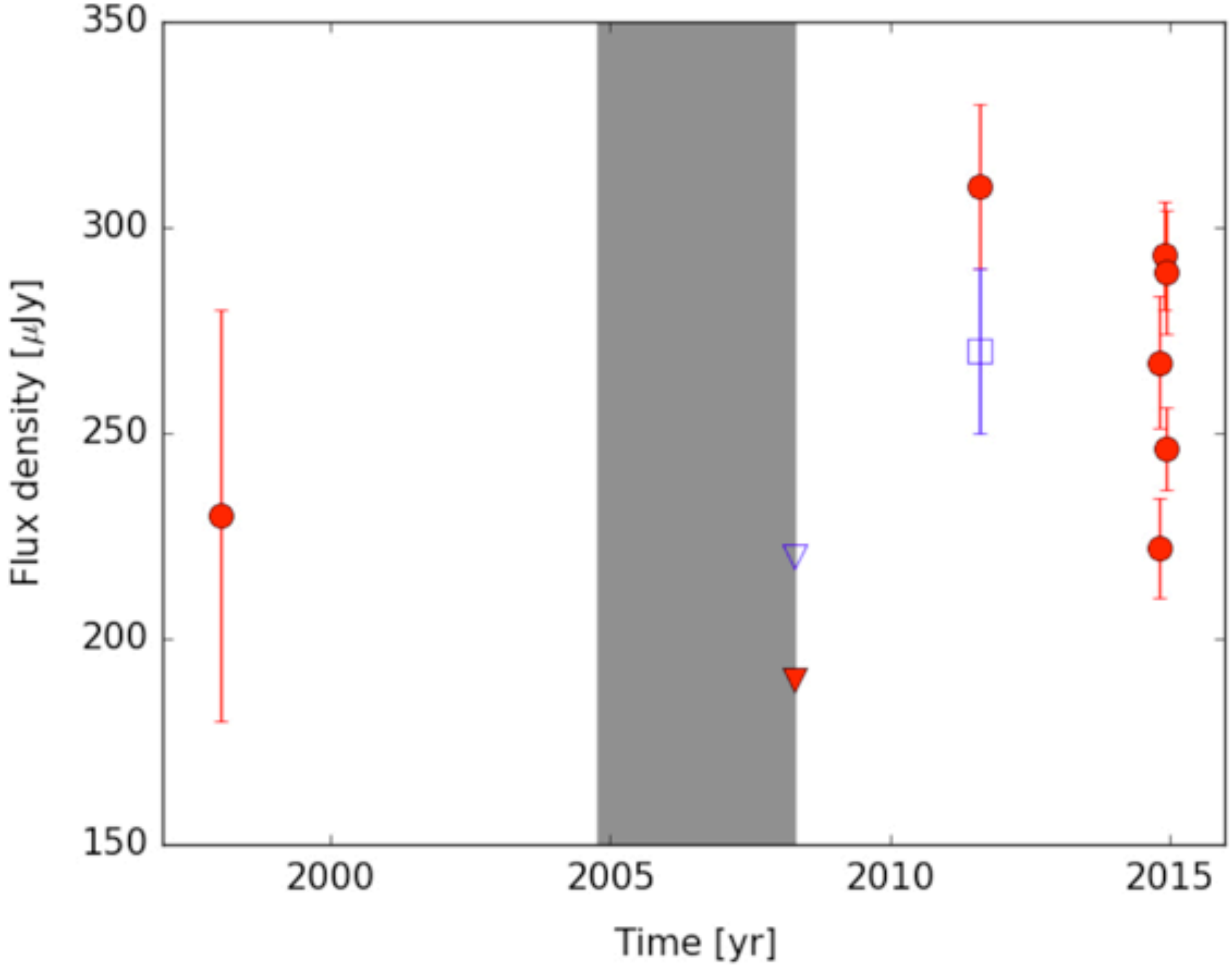


Safron+ (2015)

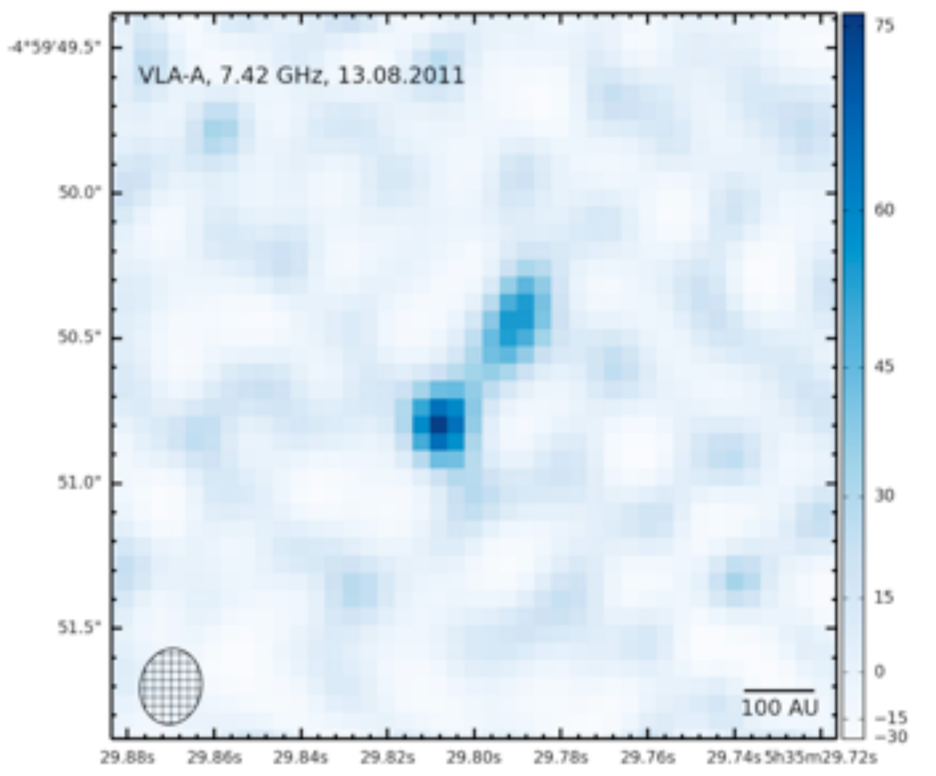
Infall and accretion in protostars

HOPS 383 x35 in bolometric luminosity

BUT no large increase in the radio flux :



Galvan-Madrid+ 2015: VLA@9GHz



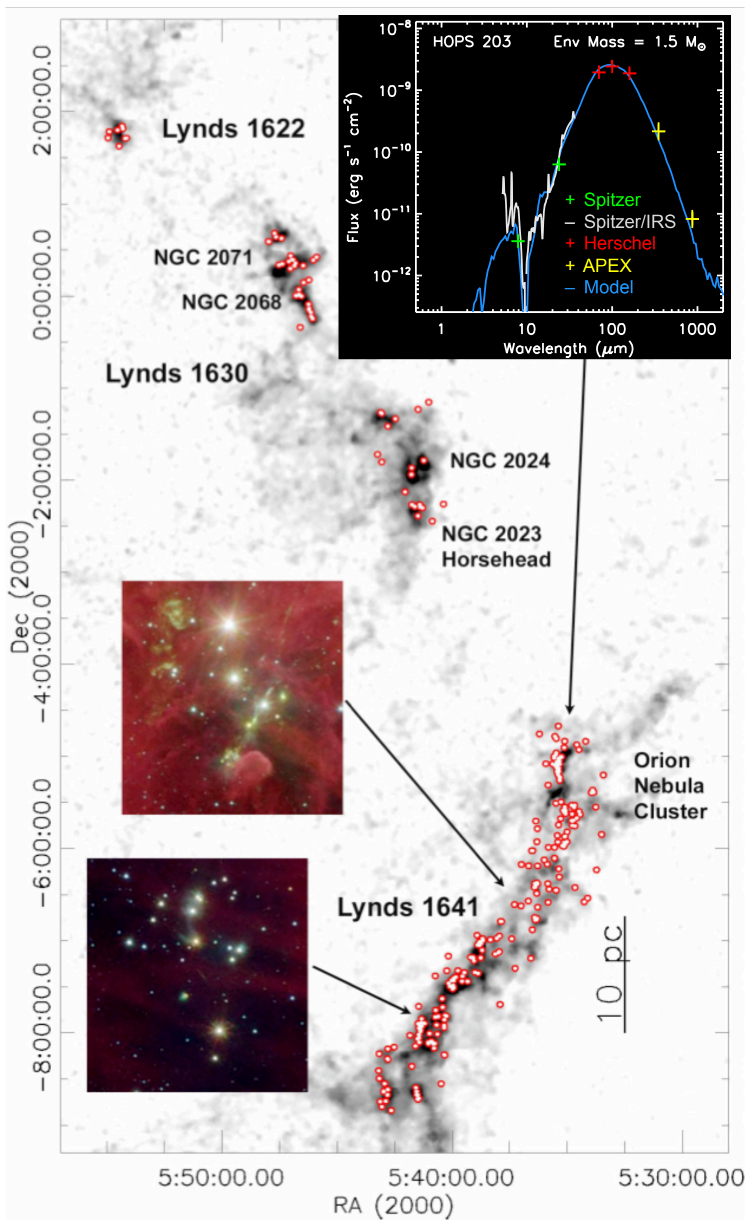
Possible explanation if the increase in submm luminosity is due to an accretion burst:

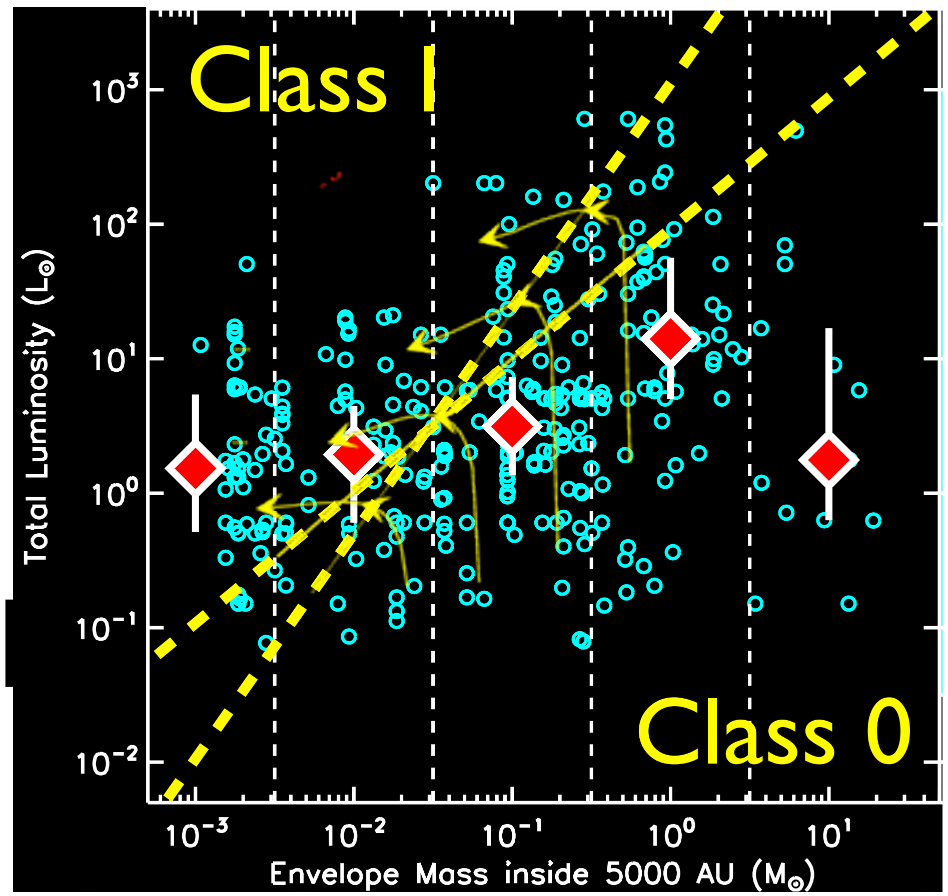
- no correlation accretion/ejection ?
- the ionized material recombines quickly (dense material -> shadowed from the ionizing source) ?

Infall and accretion in protostars

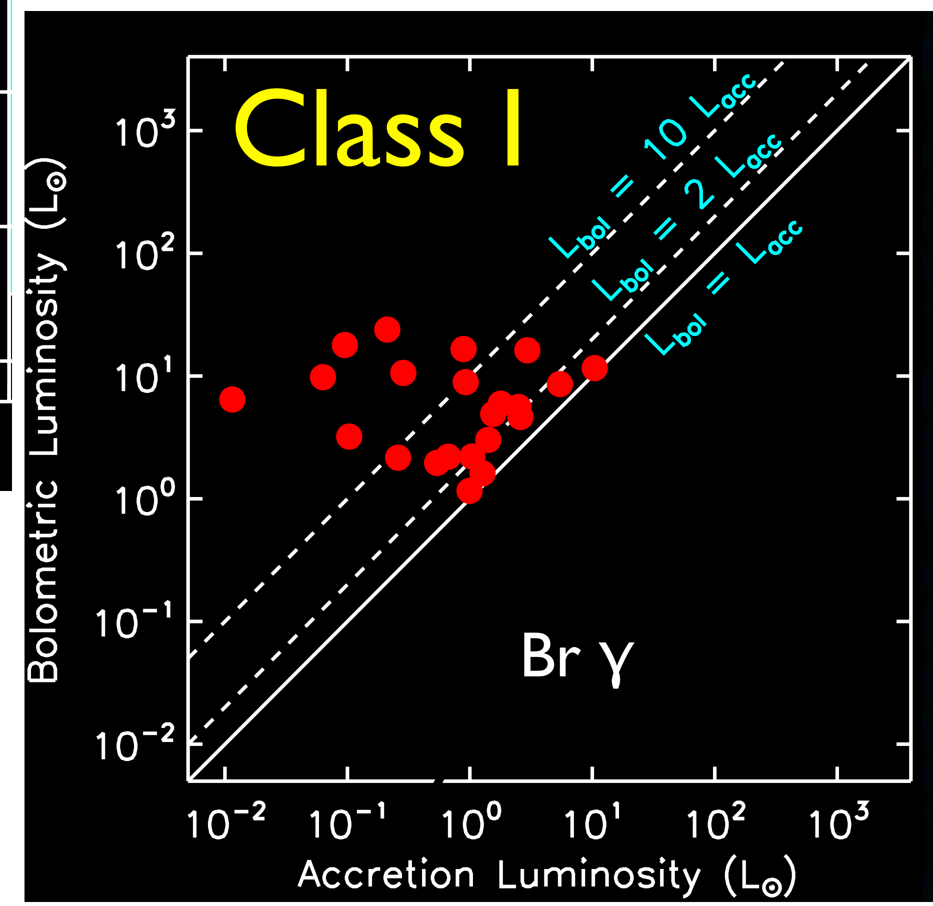
HOPS survey of Orion protostars (PI Megeath)

HERSCHEL ORION PROTOSTAR SURVEY





Furlan+ (2016)
Stutz+ (2013)
Fischer+ (in prep)



Accretion luminosities for late Class I objects are typically a small fraction of their bolometric luminosities + no clear relationship Lbol-Lacc ?

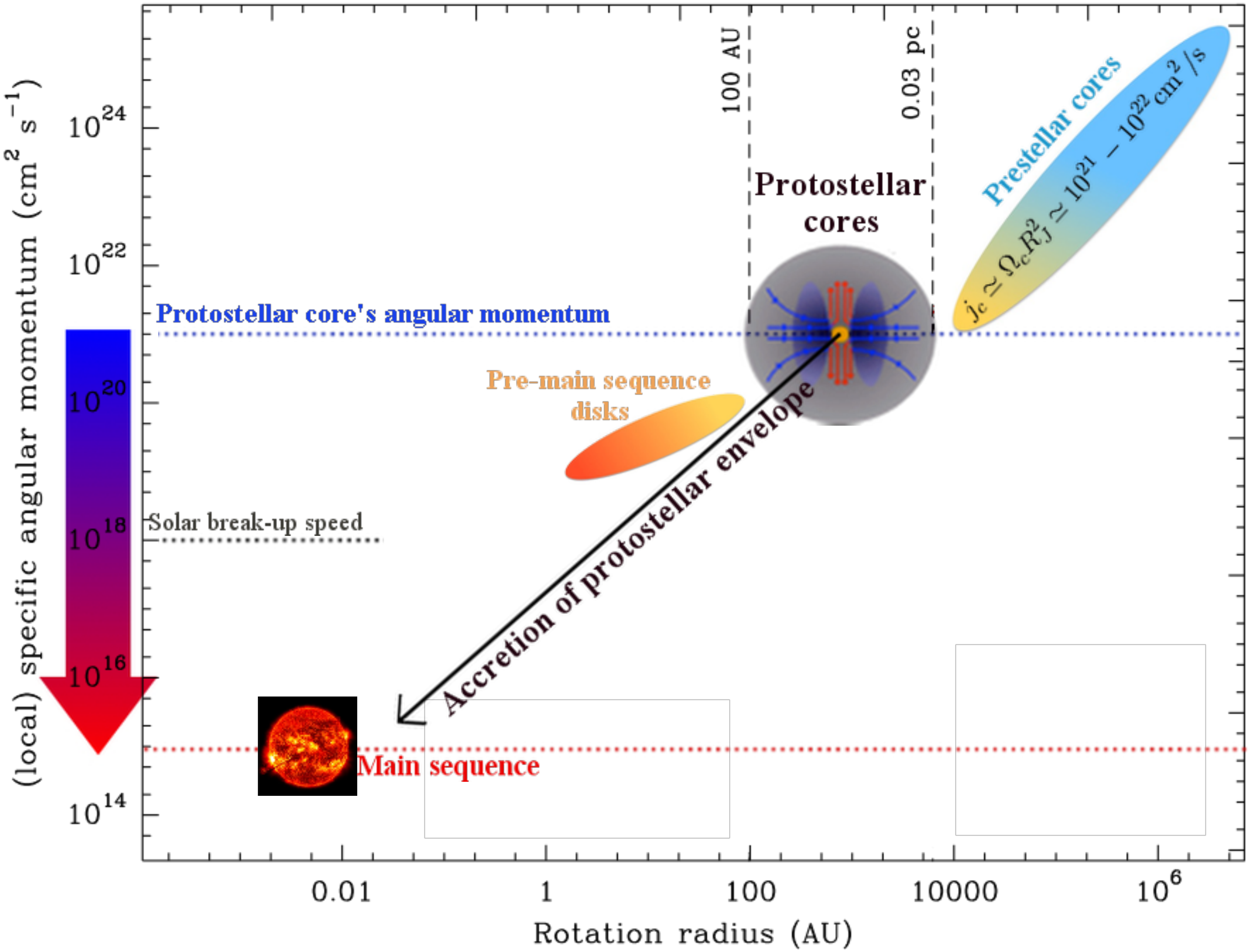
Problem ? ALMA needed to derive accretion rates from embedded objects at small scales !

Angular momentum in protostars

L = m v r

core collapses -> rotation amplified by $(r_2/r_1)^2$

from 0.1 pc core's diameter to the Sun's size : factor of 4 x 10^6 in angular momentum



Belloche 2013
(Adapted from Ohashi 1999)

Solved by formation of discs, jets and fragmentation ?

Why a disc?

Historically, the existence of discs has been suggested by the existence of the solar system (planar)
Nebular hypothesis (Kant, Laplace)

Centrifugal radius

Where the gravitational acceleration is balanced by the centrifugal force.

$$L = I\omega \sim MR^2\omega$$

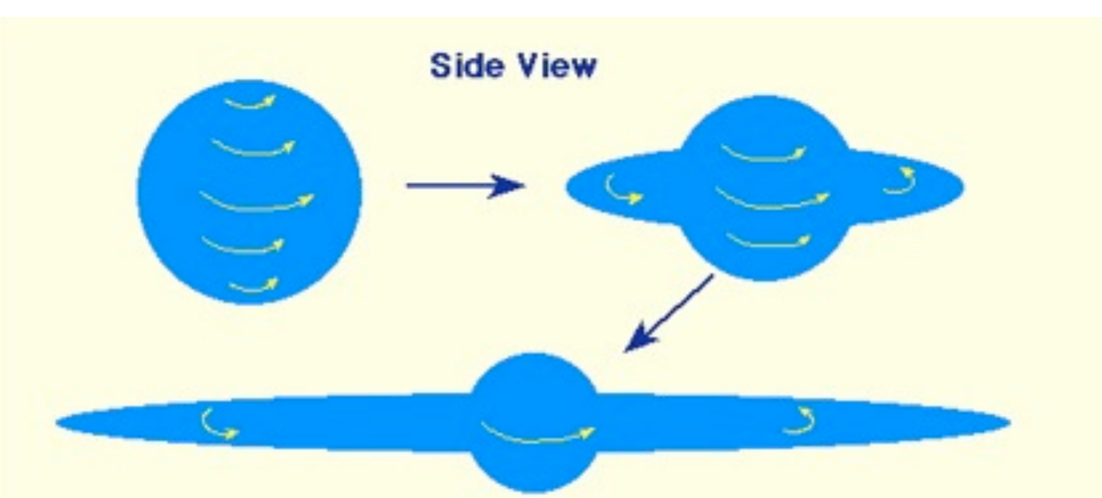
initial size $R \sim 1\text{pc}$, initial spin ω

$$L = Mr^2\Omega \quad \text{final size } r, \text{ final spin } \Omega$$

$$\Omega = \sqrt{\frac{GM}{r^3}} \quad \text{for a Keplerian rotation}$$

$$\sqrt{GMr} = R^2\omega$$

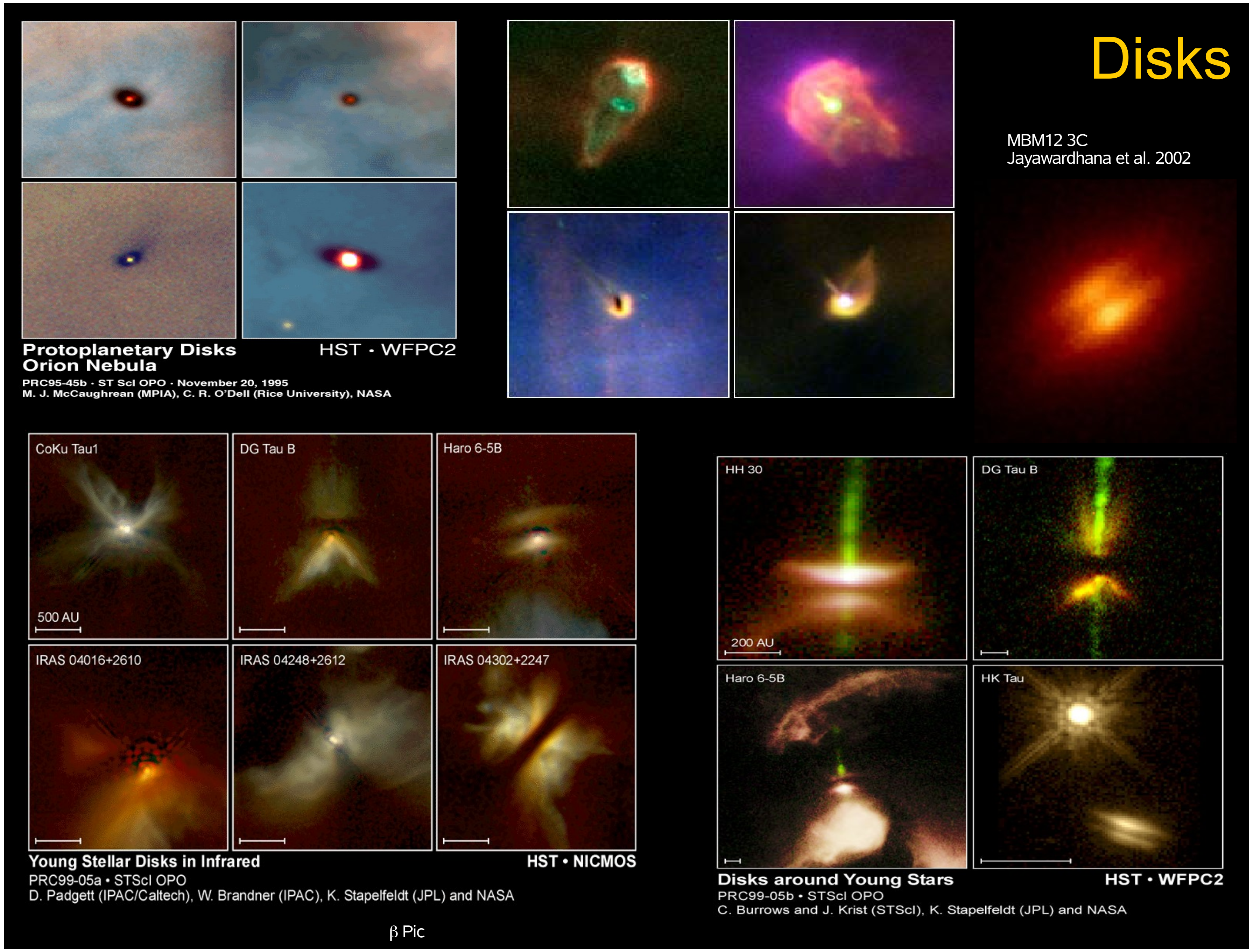
$$\boxed{r_c = \frac{R^4\omega^2}{GM}} \text{ is known as the centrifugal radius.}$$

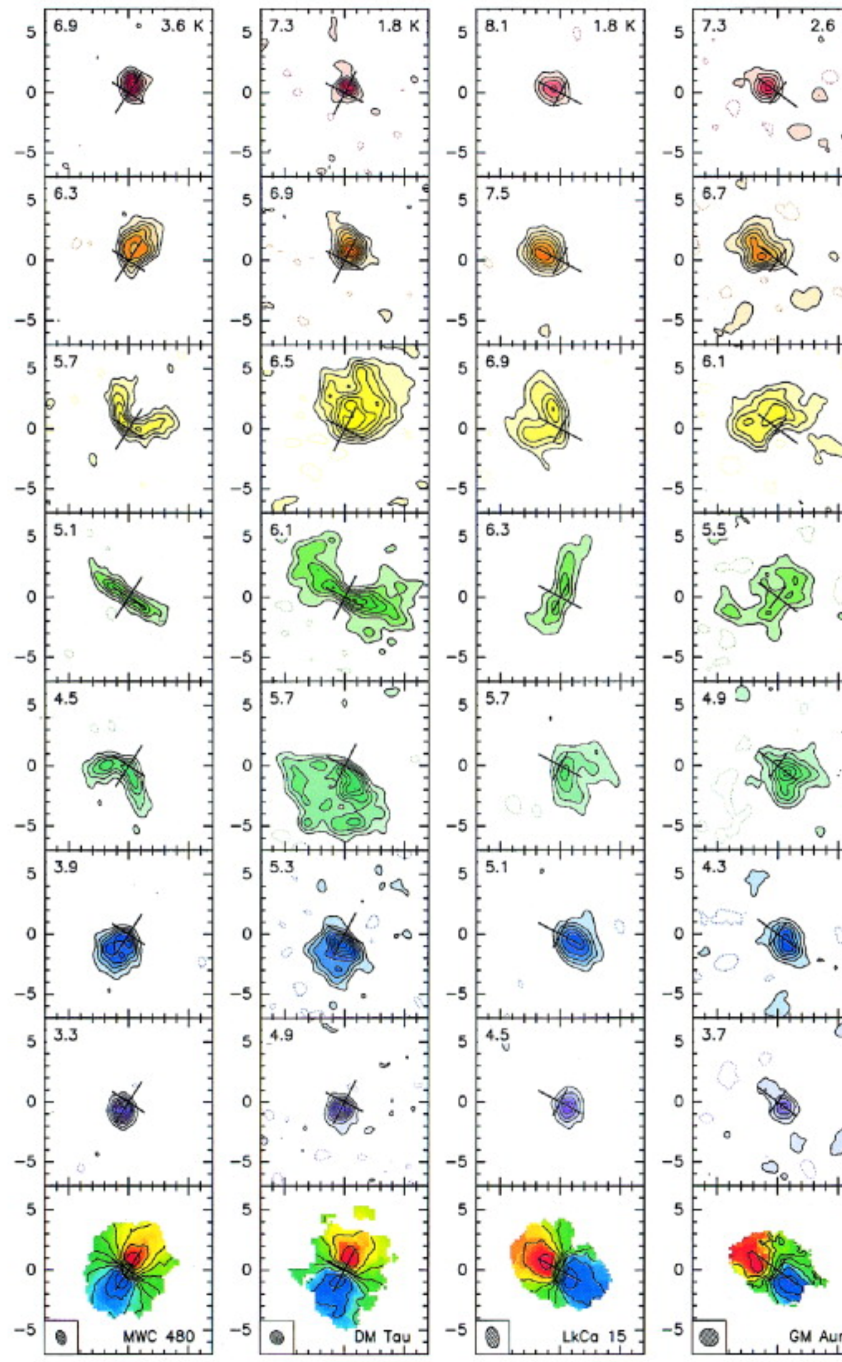


Initial core angular momentum + angular momentum conservation in protostellar collapse
→ centrifugal radius R_c → material piles up in disc

- $R_c \sim c_s \Omega_0^2 t^3/16$ in traditionally inside-out collapsing core with solid body rotation (Terebey, Shu & Cassen, 1984): increasing with time because in inside-out collapse rarefaction wave moves out.
- $R_c \sim t$ in magnetized cores (Basu 1997)

Discs are indeed observed towards Class I / T-Tauri young stars

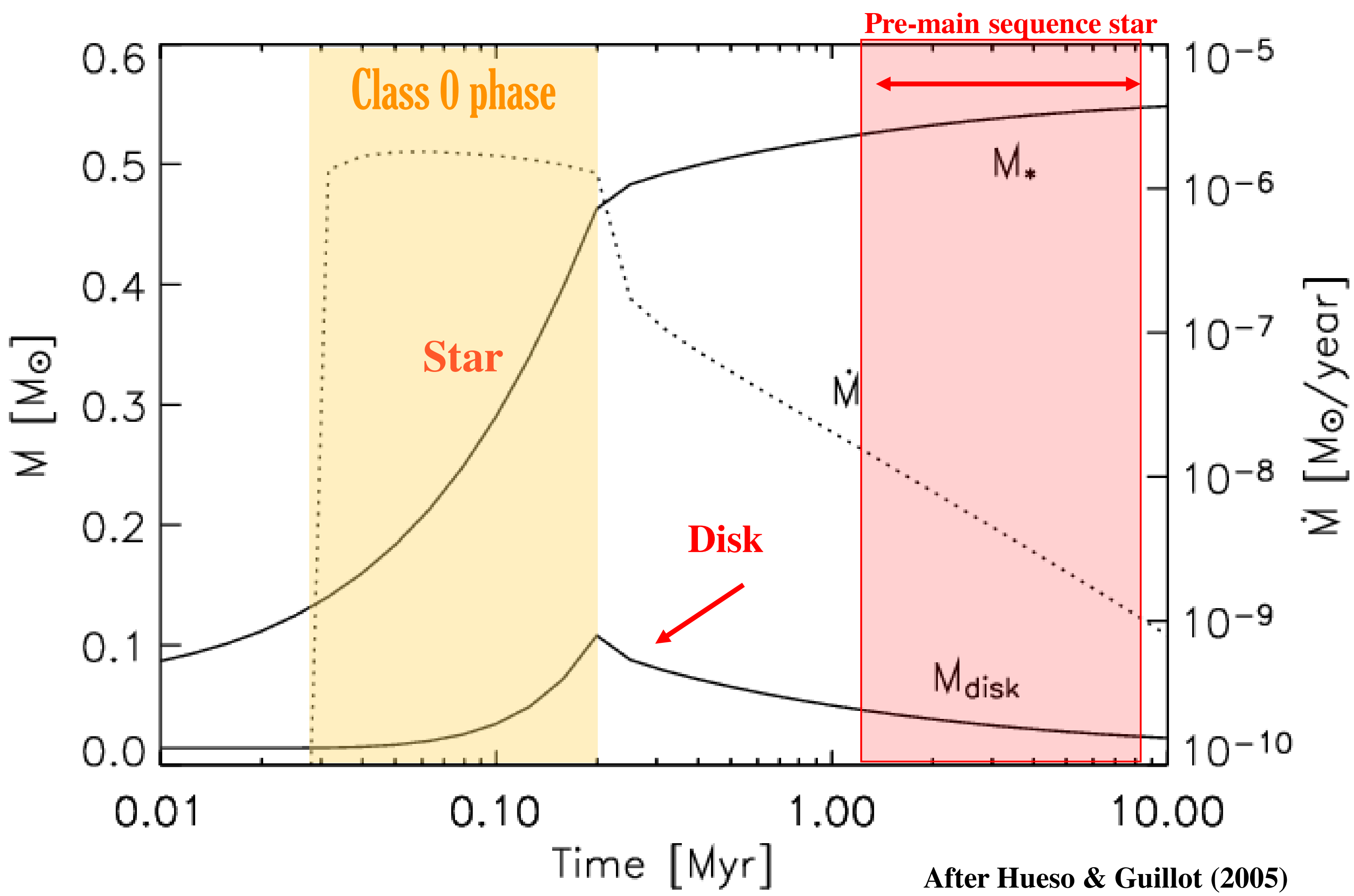




Simon, Dutrey, Guilloteau 2000

How early do we expect discs to form ?

The conservation of angular momentum is effective since the earliest stages of collapse, and a disc should form very quickly (a few 10^3 years) after the beginning of collapse.



After Hueso & Guillot (2005)

Simple hydrodynamics predicts the existence of ≥100 AU discs at the beginning of the Class 0 phase (10^4 yrs after beginning of collapse).

How big do we expect discs to be ?

Interferometric measurements of the dust continuum emission at mm wavelengths (Eisner+ 2005, 2012, Jorgensen+ 2009) and mid-IR observations (modeling SEDs: Wolfe+ 2008, Gräfe+ 2013) :

median size 250 AU and masses ranging from 0.01 to 0.5 $M_{\star}$ at Class I stage

Taurus Ophiuchus

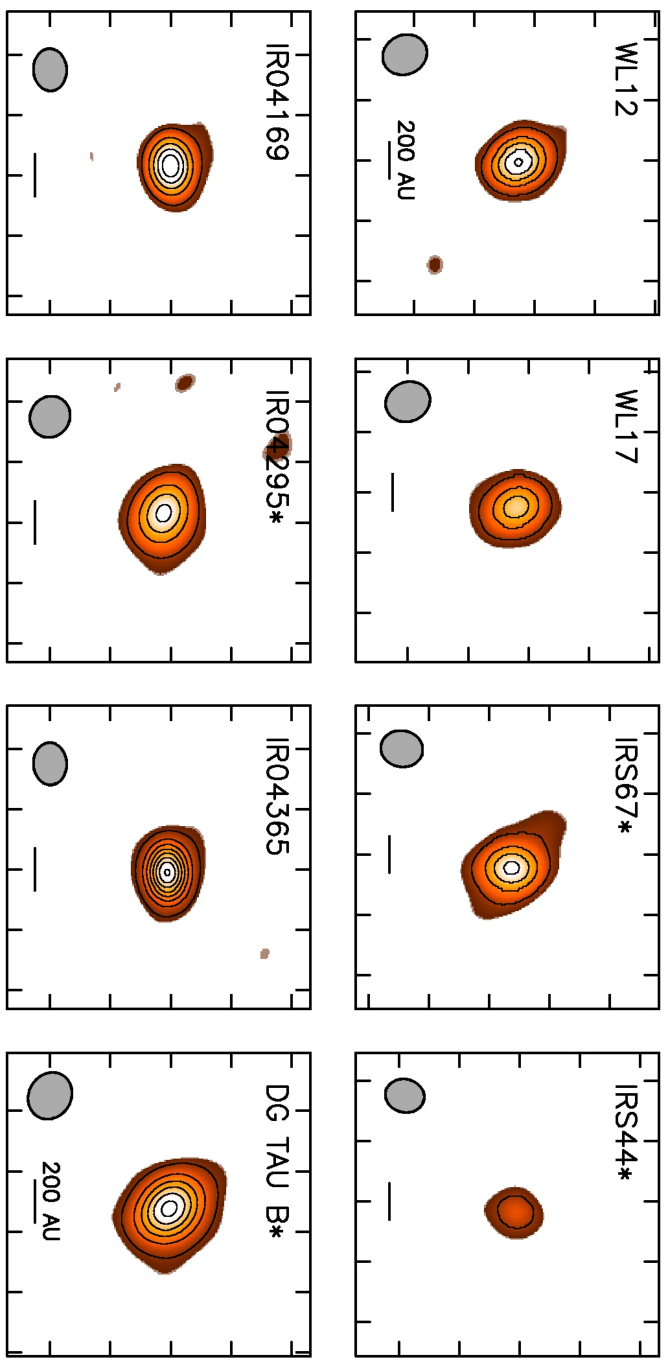
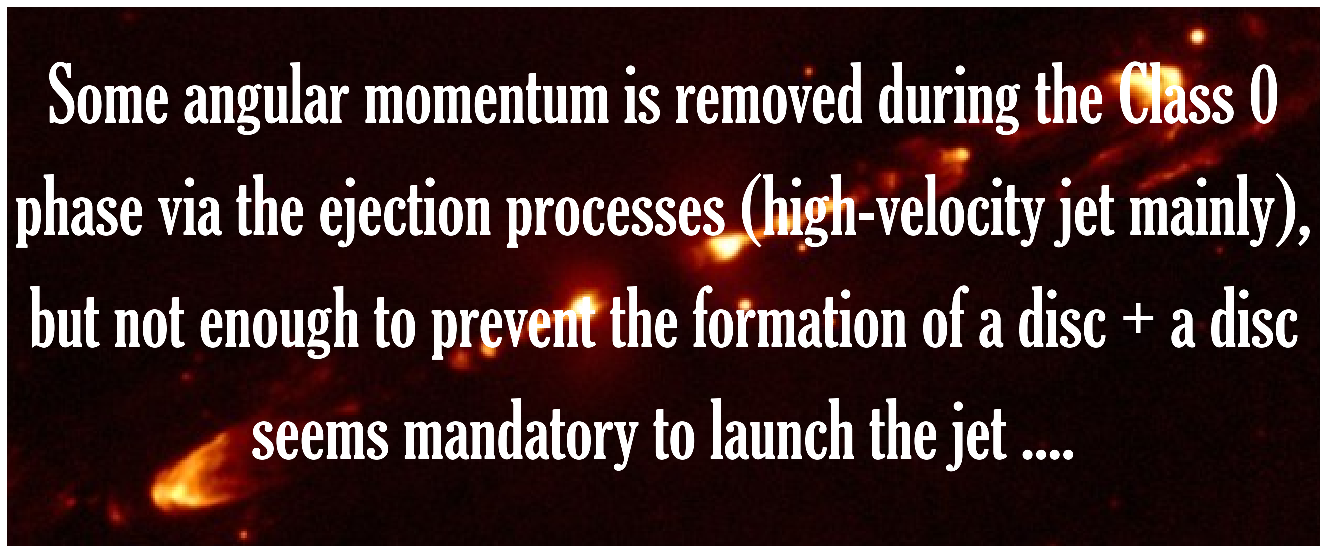


Table 4
Best-fit Disk+Envelope Models

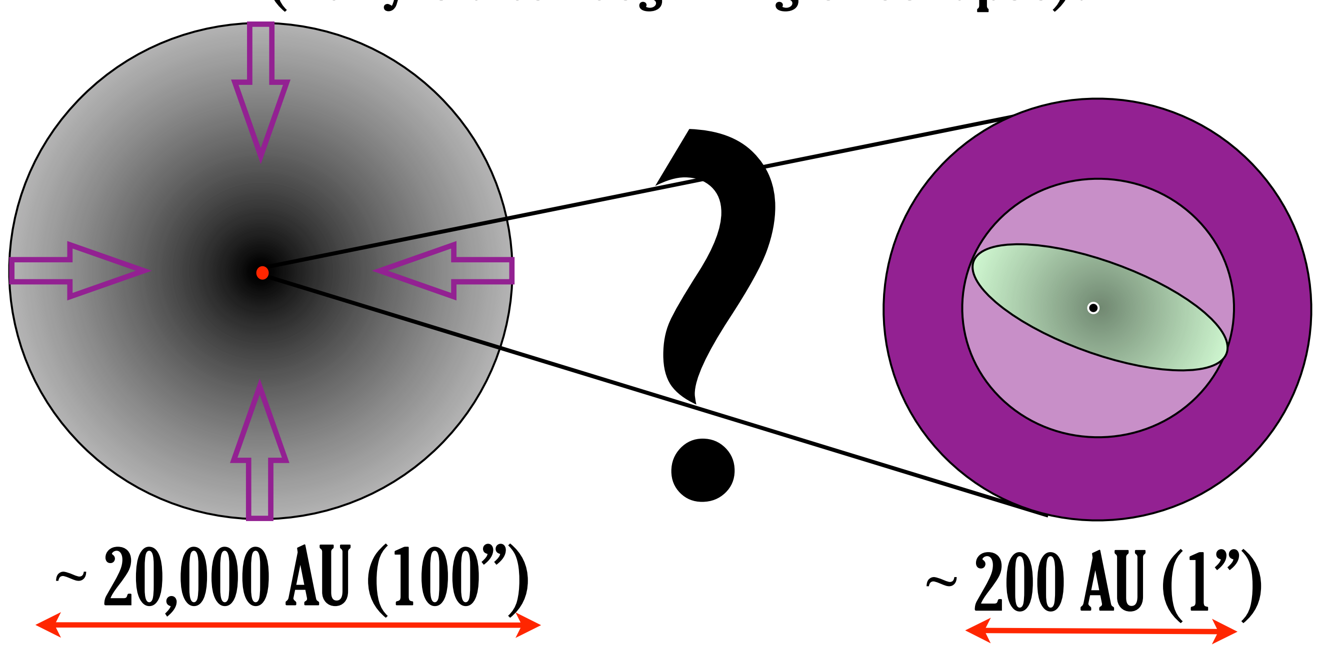
Source		$w_{\rm mm}$	$w_{I\ \rm band}$	$w_{\rm SED}$	χ_r^2 ($M_\odot$)	$M_{\rm disk}$ (AU)	$R_{\rm disk}$ (AU)	$h_{1\ \rm AU}$ ($M_\odot$)	$M_{\rm env}$ (AU)	$R_{\rm out}$	$f_{\rm cav}$ ($L_\odot$)	L_* (°)	i (°)	P.A.
IRAS 04016+2610	A	1	1	1	5.0	0.005	250	0.05	0.10	2000	1	3	35	60
IRAS 04016+2610	B	10	1	1	3.0	0.005	250	0.05	0.10	2000	1	3	40	60
IRAS 04016+2610	C	1	10	1	3.9	0.005	450	0.05	0.05	1000	0.2	10	65	60
IRAS 04016+2610	D	1	1	10	2.8	0.005	450	0.15	0.05	500	0.2	3	35	60
IRAS 04166+2706	A	1	1	1	1.6	0.01	450	0.15	0.10	1000	0.2	1	55	210
IRAS 04166+2706	B	10	1	1	1.4	0.01	450	0.05	0.10	500	0.2	1	50	120
IRAS 04166+2706	C	1	10	1	1.2	0.0	30	...	0.05	500	0.02	3	60	140
IRAS 04166+2706	D	1	1	10	1.9	0.01	450	0.15	0.10	2000	0.2	1	65	240
IRAS 04169+2702	A	1	1	1	2.1	0.01	450	0.15	0.10	2000	1	1	30	90
IRAS 04169+2702	B	10	1	1	1.6	0.01	250	0.05	0.10	500	0.2	1	35	90
IRAS 04169+2702	C	1	10	1	1.4	0.01	450	0.15	0.10	2000	1	1	30	90
IRAS 04169+2702	D	1	1	10	2.4	0.0	100	...	0.05	500	0.02	1	55	90
IRAS 04287+1801	A	0.1	1	1	6.6	0.10	250	0.05	0.05	1000	1	10	40	160
IRAS 04287+1801	B	0.5	1	1	8.1	0.50	450	0.05	0.10	1000	0.2	3	40	180
IRAS 04287+1801	C	0.1	10	1	2.8	0.10	100	0.05	0.10	2000	0.2	10	50	160
IRAS 04287+1801[a]	D	1	1	10	9.0	0.50	450	0.05	0.01	2000	0.2	10	50	160
IRAS 04295+2251	A	1	1	1	3.3	0.01	100	0.05	0.05	1000	0.2	1	45	300
IRAS 04295+2251	B	10	1	1	2.2	0.01	100	0.05	0.05	500	0.2	1	45	300
IRAS 04295+2251	C	1	10	1	1.9	0.01	30	0.05	0.005	500	0.2	1	50	300
IRAS 04295+2251	D	1	1	10	1.9	0.01	30	0.05	0.005	500	1	1	55	300
IRAS 04302+2247	A	1	1	1	3.8	0.01	250	0.05	0.05	500	0.2	1	70	10
IRAS 04302+2247	B	10	1	1	3.0	0.01	250	0.05	0.10	500	0.2	1	75	10
IRAS 04302+2247	C	1	10	1	2.2	0.005	100	0.15	0.005	500	1	1	89	10
IRAS 04302+2247	D	1	1	10	3.7	0.01	250	0.15	0.05	2000	0.2	1	70	10
IRAS 04361+2547	A	1	1	1	4.8	0.005	30	0.15	0.005	500	1	3	55	310
IRAS 04361+2547	B	10	1	1	2.6	0.01	450	0.15	0.01	500	1	3	45	280
IRAS 04361+2547	C	1	10	1	2.1	0.005	100	0.15	0.01	500	1	3	45	280
IRAS 04361+2547	D	1	1	10	5.5	0.005	30	0.15	0.005	500	1	3	55	310
IRAS 04365+2535	A	1	1	1	1.3	0.005	100	0.05	0.05	500	0.2	1	25	310
IRAS 04365+2535	B	10	1	1	1.3	0.005	100	0.15	0.10	1000	1	1	25	310
IRAS 04365+2535	C	1	10	1	1.1	0.005	100	0.05	0.05	500	0.2	1	25	310
IRAS 04365+2535	D	1	1	10	1.5	0.005	100	0.05	0.05	500	0.2	1	25	310

Discs at the Class 0 stage ?

The conservation of angular momentum is effective since the earliest stages of collapse, and a disc should form very quickly (a few 10^3 years) after the beginning of collapse.



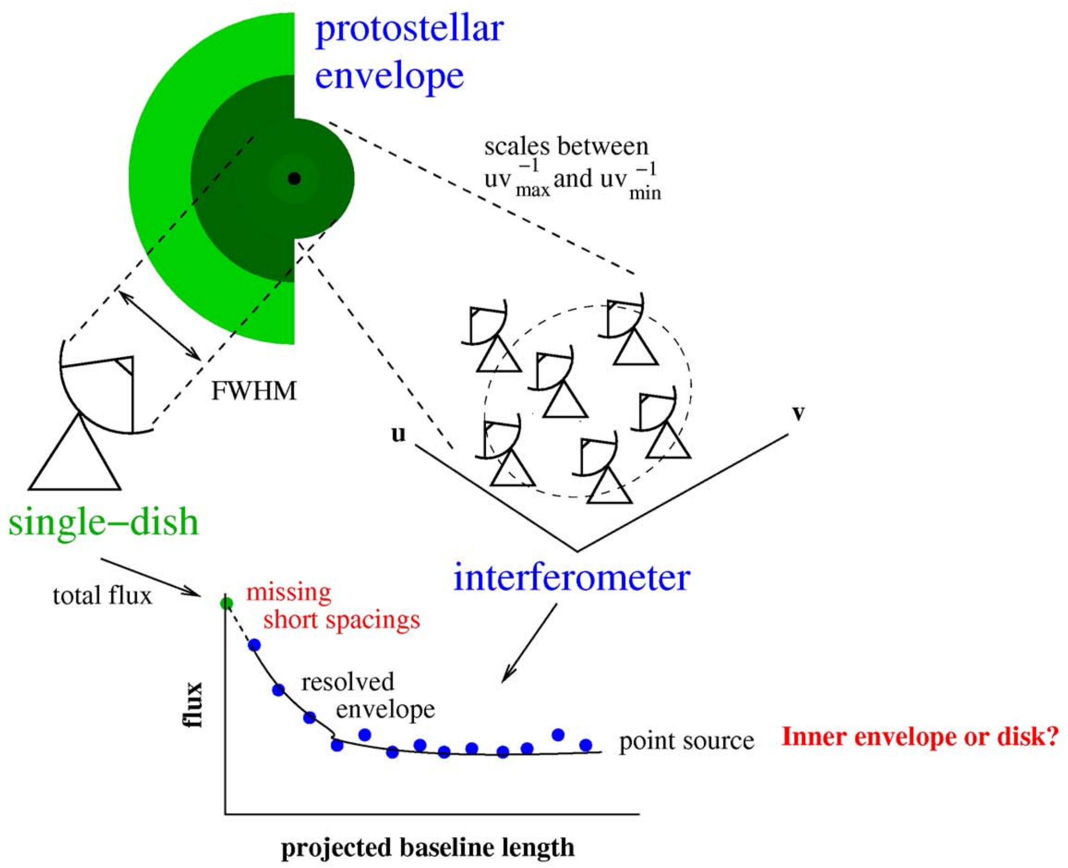
Simple hydrodynamics predicts the existence of ≥100 AU discs at the beginning of the Class 0 phase (10^4 yrs after beginning of collapse).



How to seek for discs at the Class 0 stage ?

Class 0 protostars: d ≥ 150 pc + emit most of radiation in the submm/mm range + envelope sizes of ~10.000AU

⇒Need for interferometry to dig into the envelope and search for the predicted ~ 100–500 AU discs.

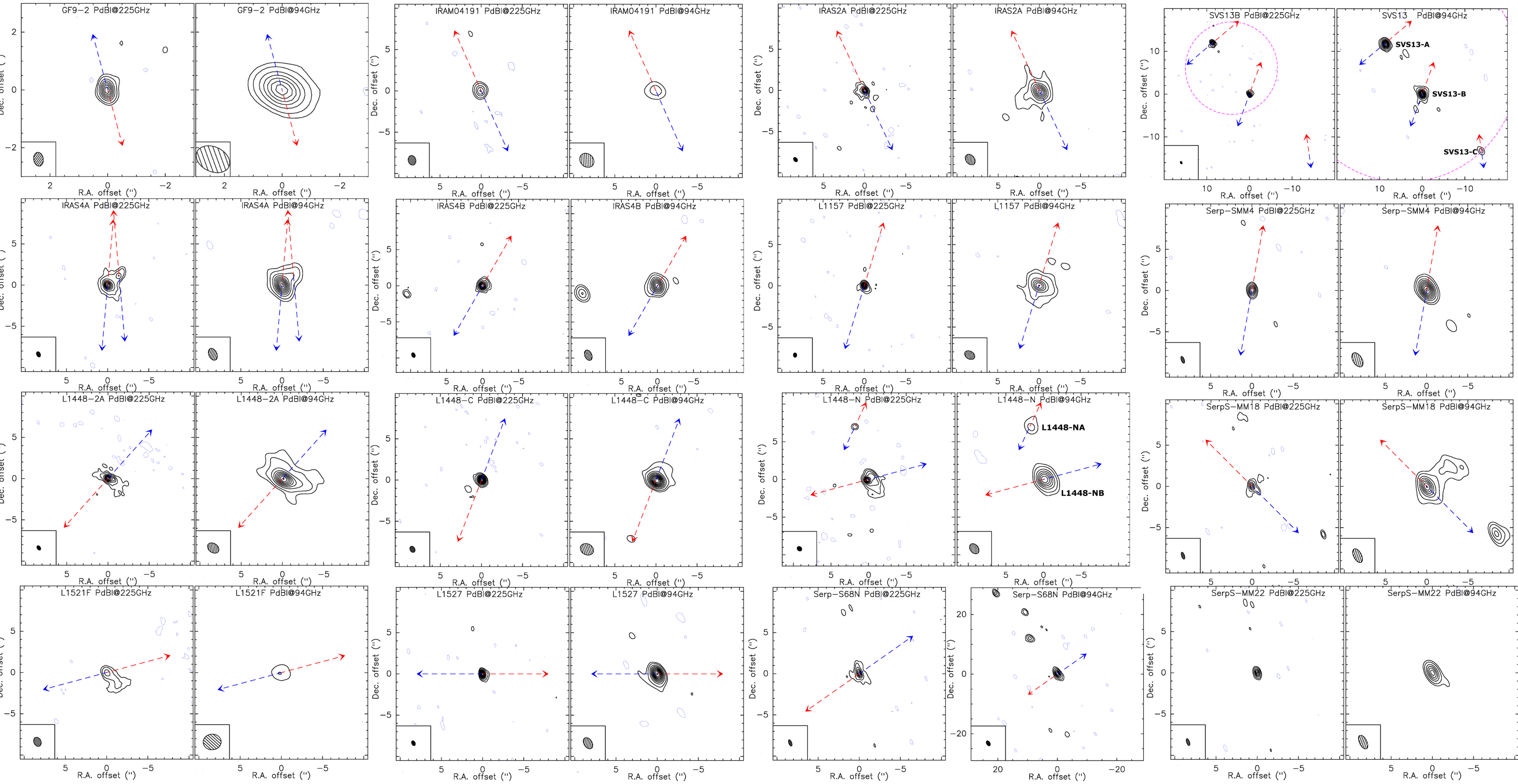


Pb: massive, cold envelope overwhelms the disc ➞ how to differentiate the embedded disc from its cocoon ?

1. looking at longest baselines (interferometric filtering + FT)
2. using line emission for rotation signature: kinematic proof of rotationally supported disc

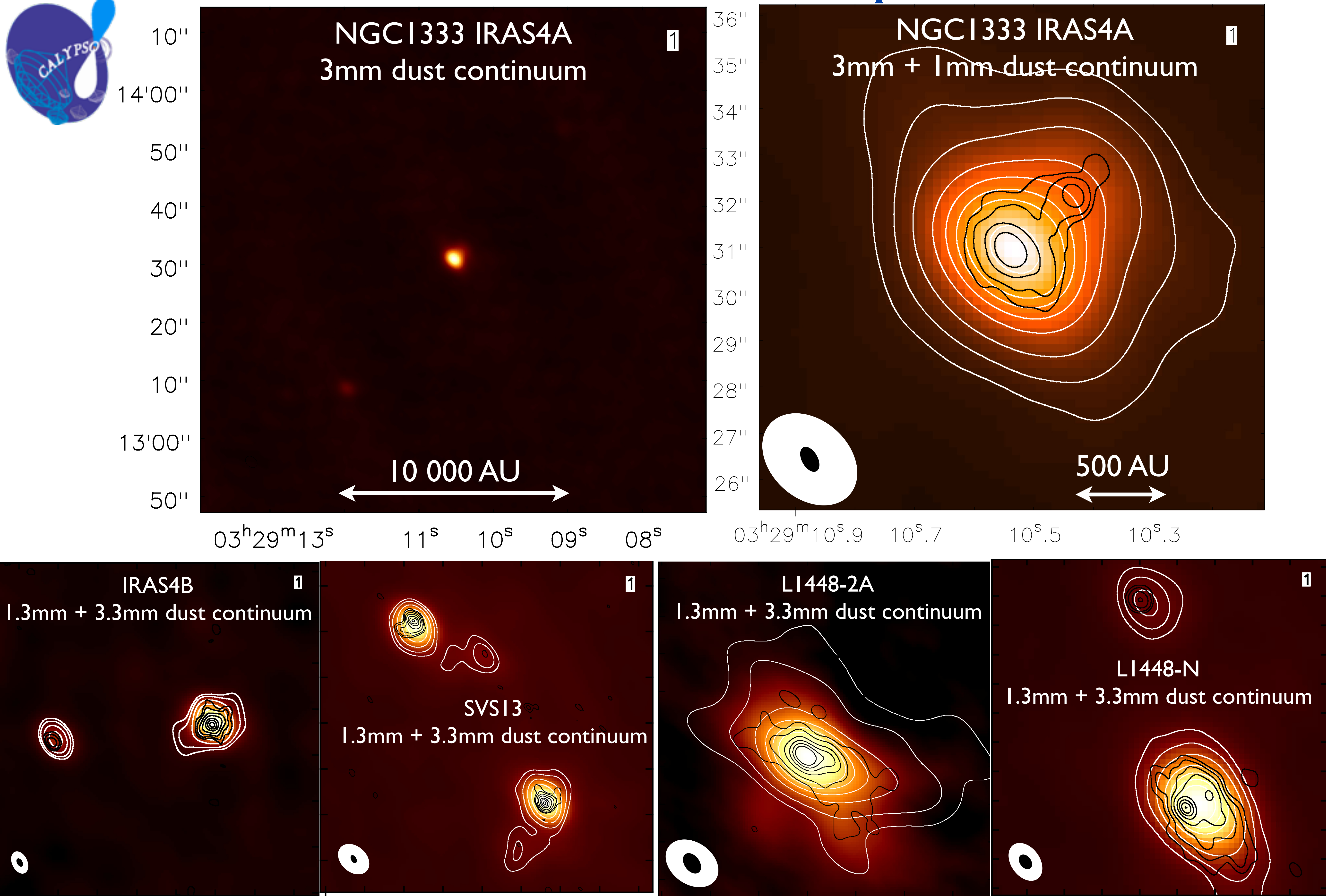
Discs around Class 0 protostars

CALYPSO IRAM-PdBI survey:
16 Class 0 protostars



Maury et al (2010, 2014, in prep.) Maret et al. (2014) Codella et al. (2014)
Santangelo et al. (2015) Anderl et al. (2016) Podio et al. (2016)

CALYPSO: dust continuum maps



CALYPSO: dust continuum analysis

Envelope description in the spatial domain

$$\rho(r) = \rho_{\rm flat}\left[\frac{R_{\rm flat}}{\left(R_{\rm flat}^2 + r^2\right)^{1/2}}\right]^p \equiv \frac{\rho_{\rm flat}}{\left(1+(r/R_{\rm flat})^2\right)^{p/2}}$$

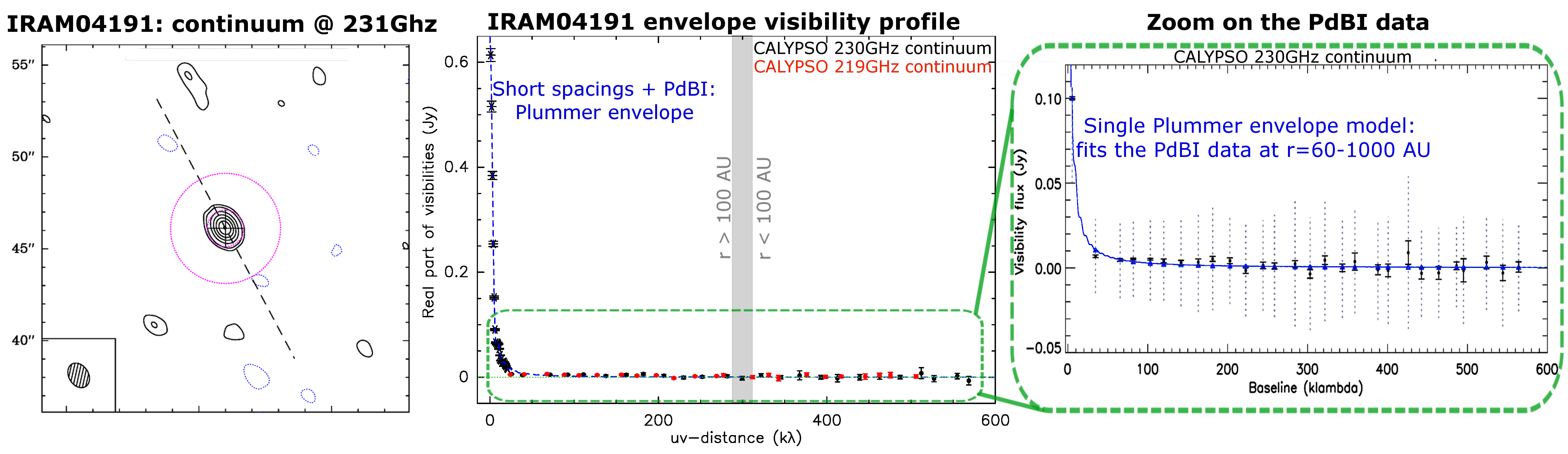
$$T(r) = 60\left(\frac{r}{2\times10^{15}\ {\rm m}}\right)^{-q}\left(\frac{L_{\rm bol}}{10^5\ {\rm L_\odot}}\right)^{q/2}\ {\rm K}$$

$$\rightarrow I(r) \propto r^{-(p+q-1)}$$

Envelope description in the Fourier domain with interferometric baseline $b = \sqrt{u^2+v^2}$,

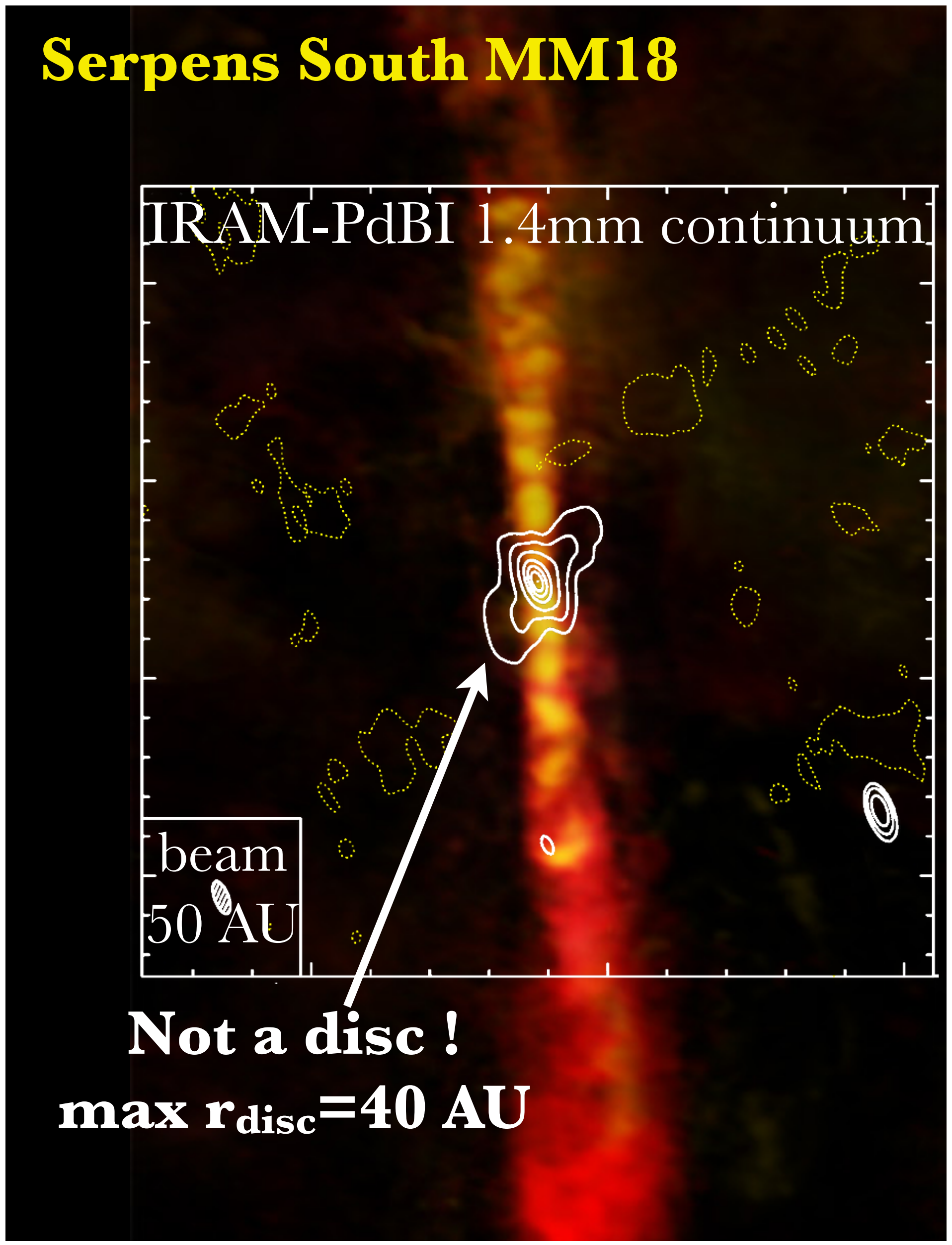
$$V(b) = 2\pi\int_0^\infty I_\nu(r_{\rm b})J_0\left(2\pi r_{\rm b} b\right) r_{\rm b}\,dr_{\rm b} \quad \text{with} \quad J_0(z) = \frac{1}{2\pi}\int_0^\infty \exp\left(-iz\cos\theta\right)$$

$$\rightarrow V(b) \propto b^{p+q-3}$$

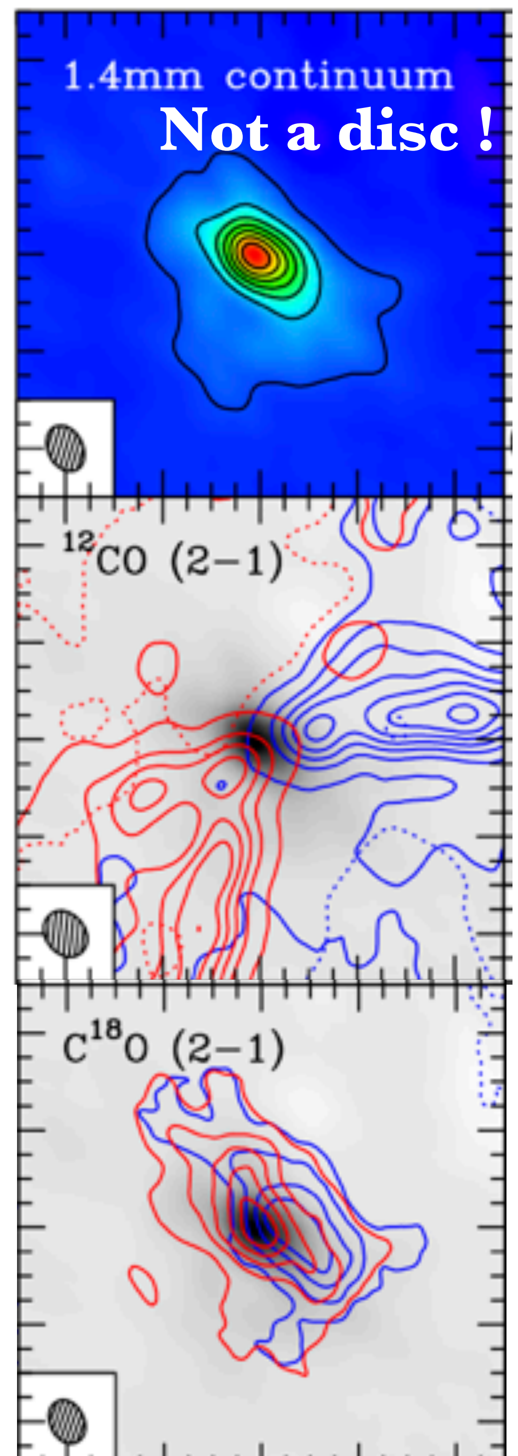


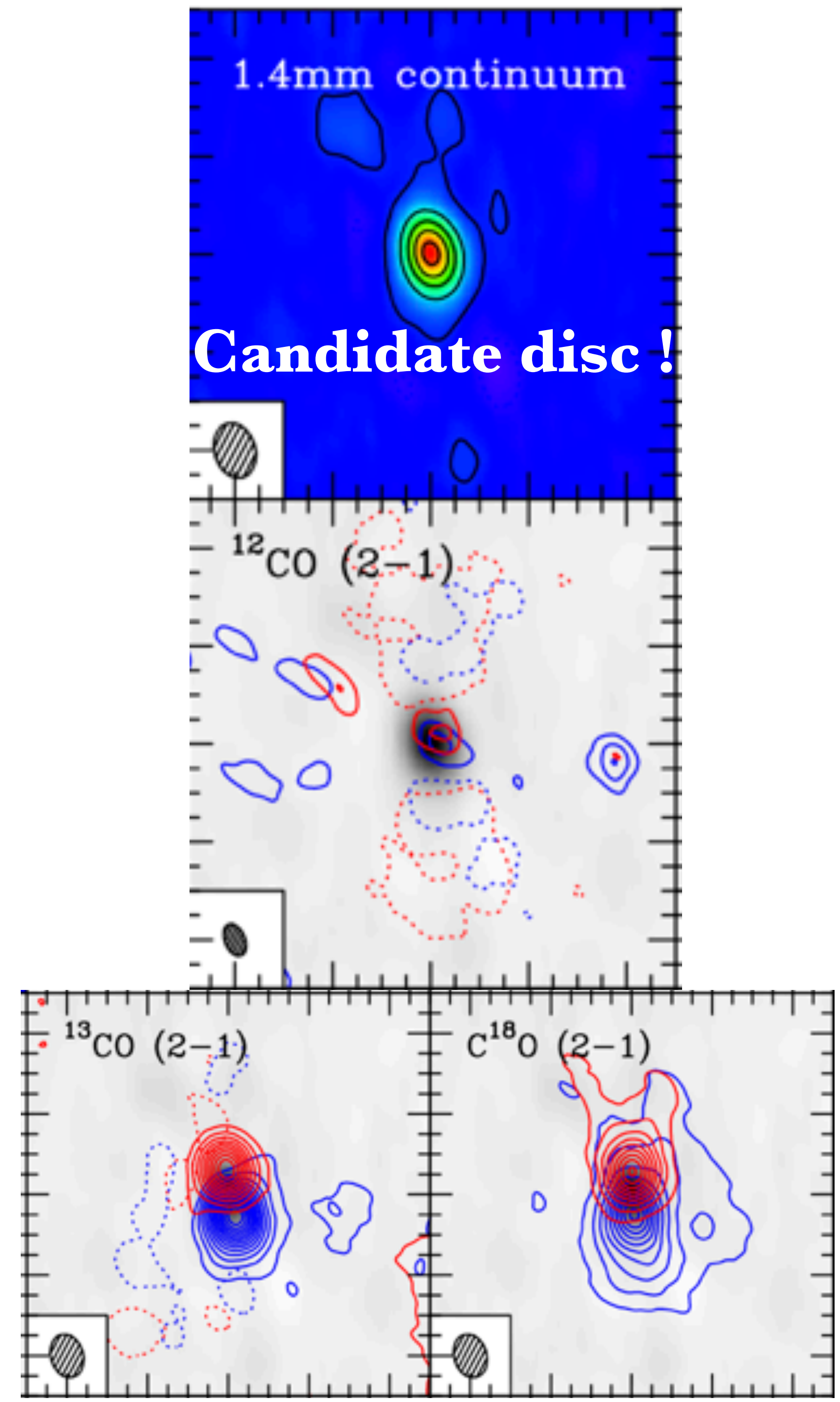
CALYPSO: dust continuum analysis

Why bother with analytical description of envelope and disc ?



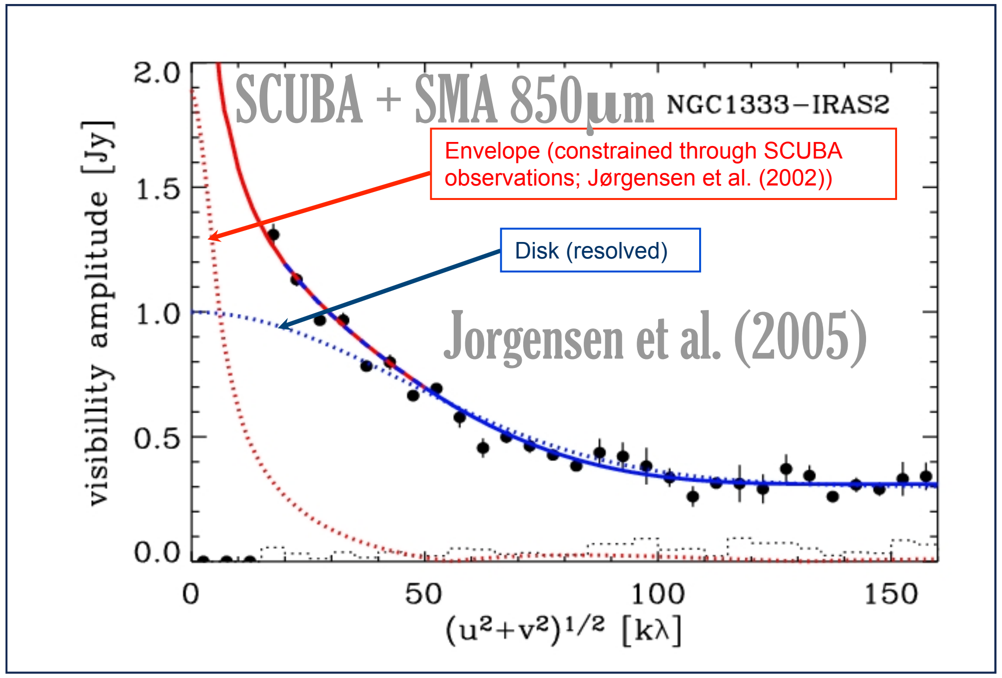
Because what looks like a disc
is not always a disc





... And what looks like envelope
can sometimes be disc emission ...

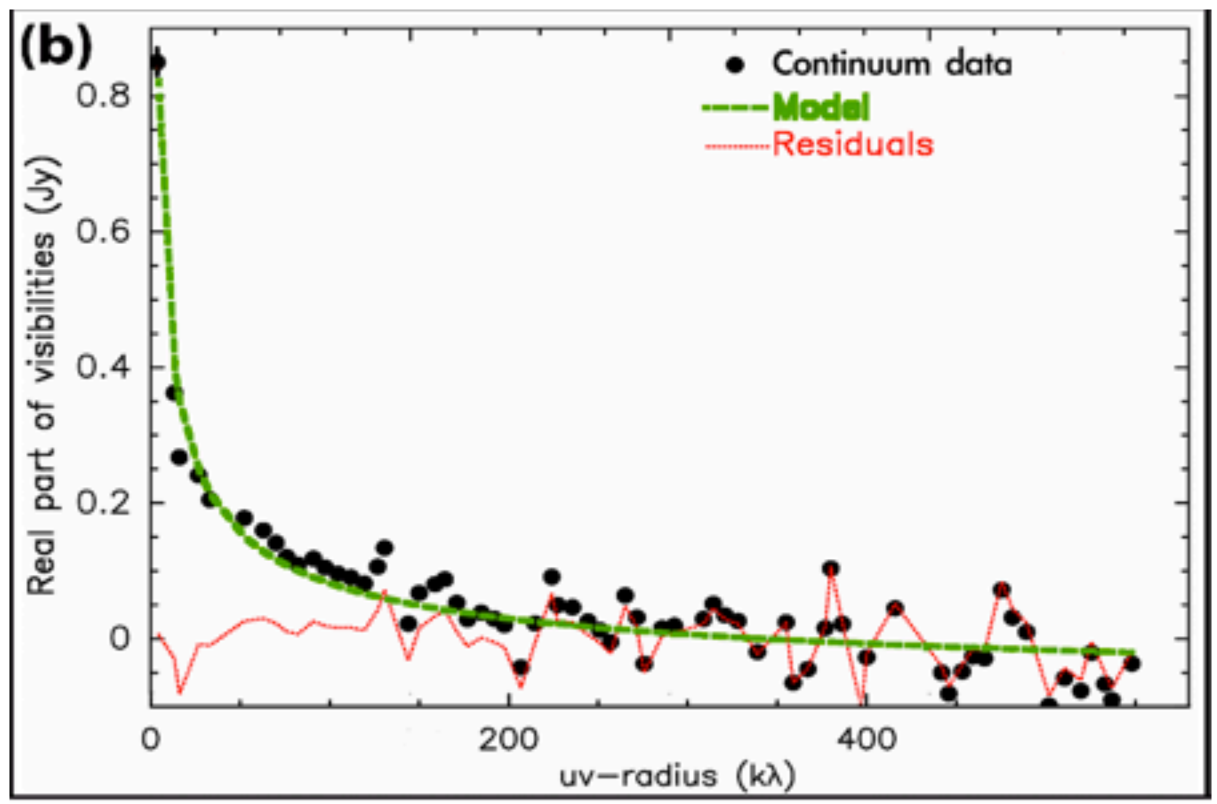
The CALYPSO view of IRAS2A



PROSAC : a survey with SMA

Jorgensen et al. (2007, 2009)

Disc is invoked to explain flux observed at scales ~1-3″- which is higher than what expected from classical envelope models



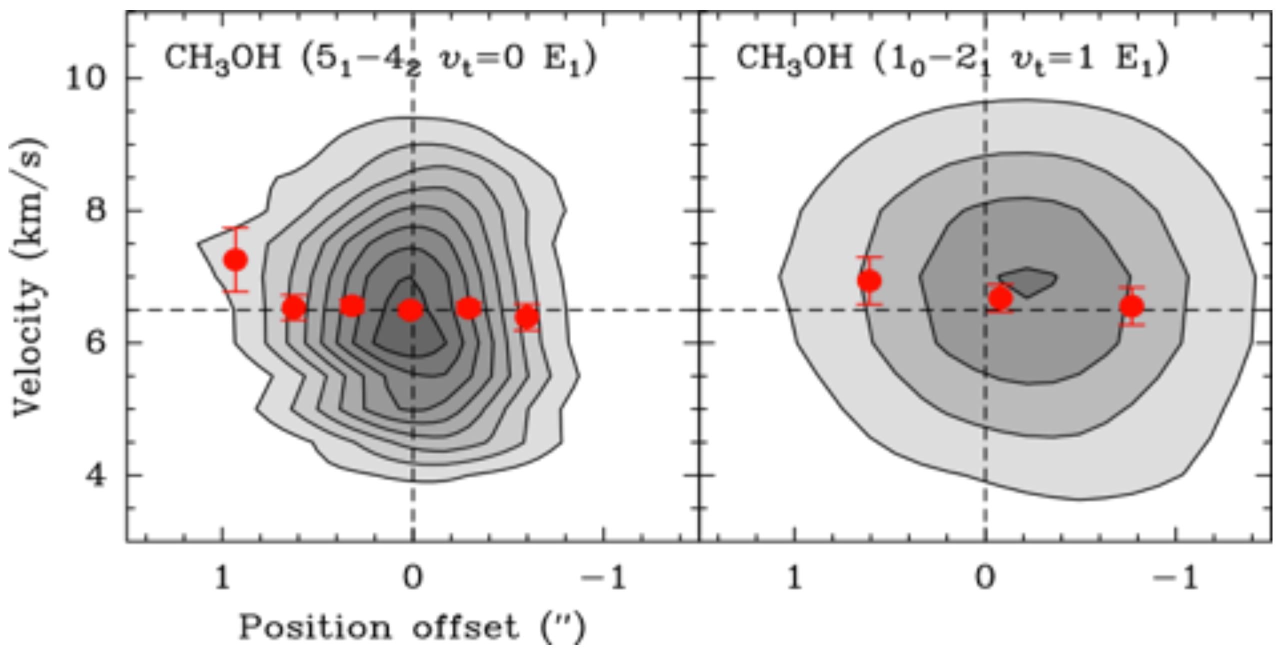
Maury et al. (2014)

1mm dust continuum emission:

well reproduced by power-law envelope profile

if present the disc component is <40 AU

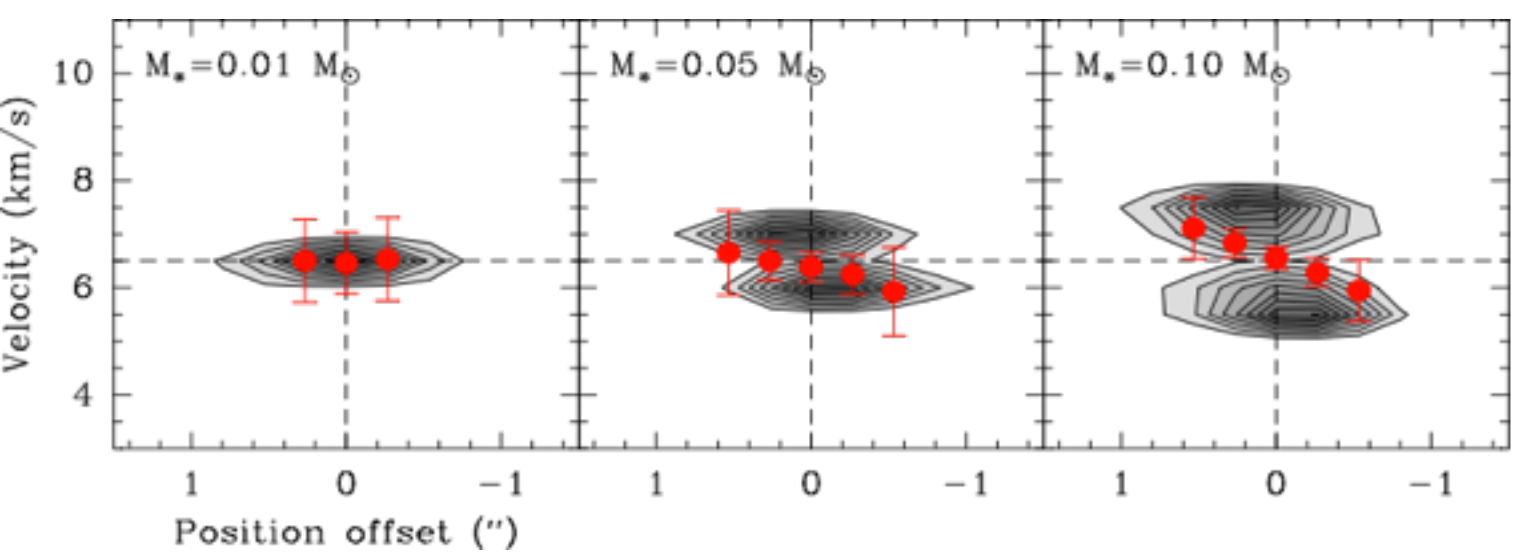
The CALYPSO view of IRAS2A



PV diagrams along axis PA 107°:
no clear signature of rotation.

But first order moment (red points)
suggests presence of a velocity gradient

Observed methanol velocity dispersion
at r~45 AU:
can be reproduced by
infalling, slowly rotating envelope
around a central protostar ~ 0.1 - 0.2 M☉

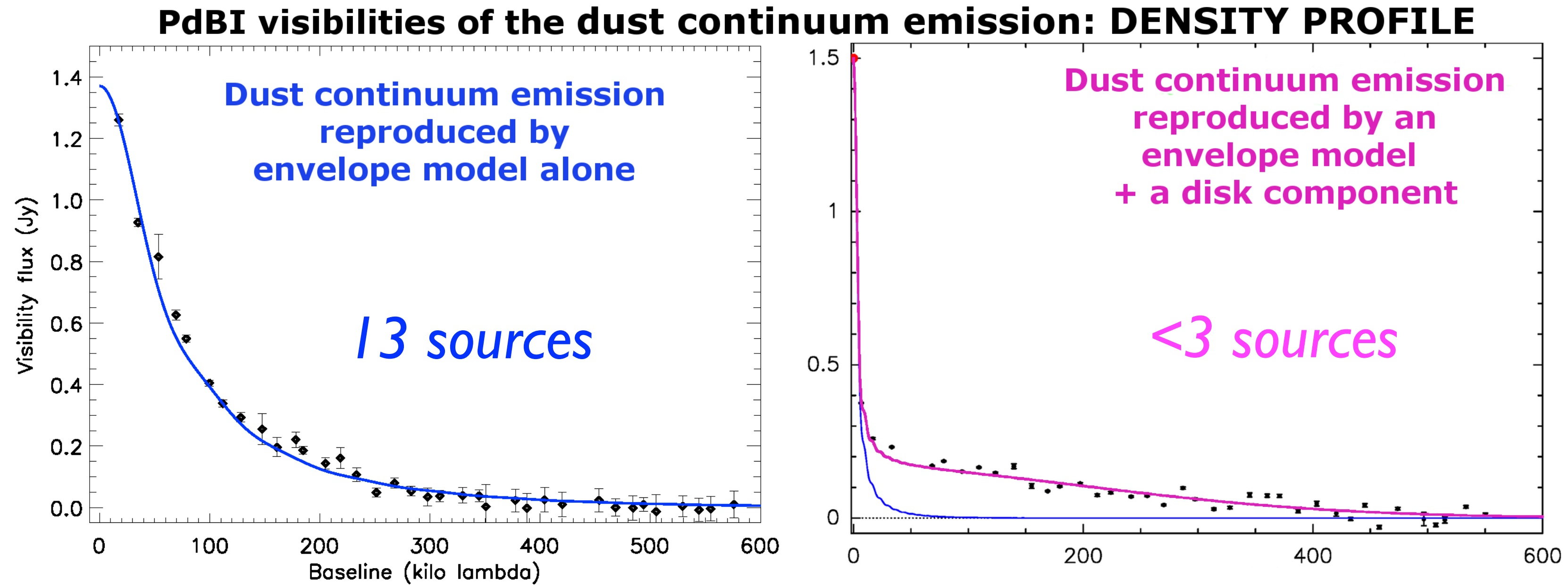


Synthetic PV for dynamic masses of 0.01M☉, 0.05M☉ and 0.1M☉ in keplerian rotation.
PV diagram and linewidths: not consistent with a model of a keplerian disc

If a disc is present it must have r<45 AU

Maret et al. 2014 - Maury et al. 2014

The CALYPSO view on Class 0 discs: statistics



16 Class 0 sources observed with PdBI: maps of the 1.3mm
+
3mm dust continuum emission

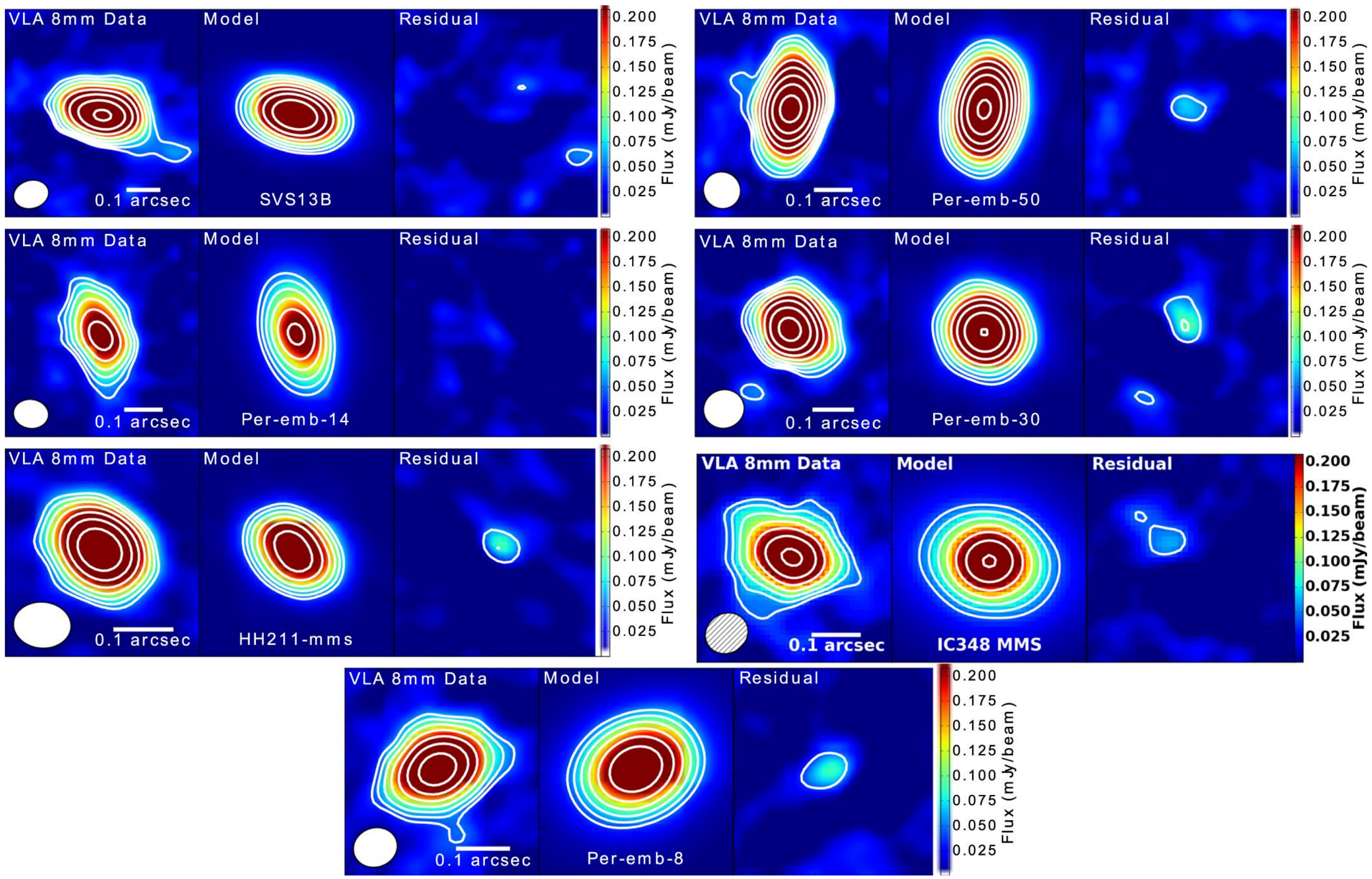
Among 14 Class 0 protostars at d<300 pc:
1 detection of r>100 AU disc-candidate structure
2 sources w/ additional continuum emission at ~50 AU

i.e. at most 25% of Class 0 protostars
with continuum disc-like structures at r>50-100 AU

Maury & CALYPSO collab. (in prep)

Discs around Class 0 protostars

VANDAM VLA survey



6 Class 0 protostars: all with r_{disc} < 15-30 AU

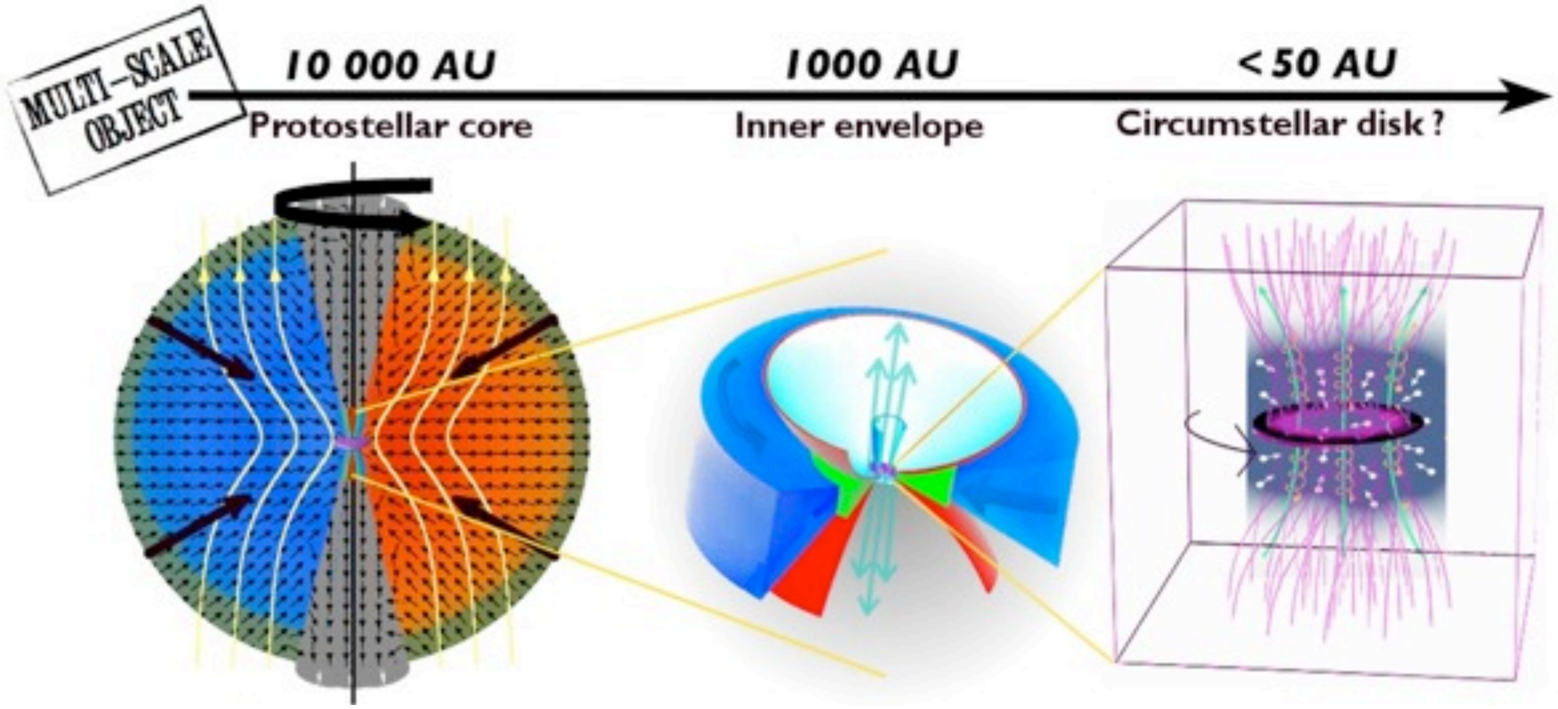
Source	q	γ	R_c (AU)	$\chi^2_{\mathrm{reduced}}$
SVS13B	0.25	$0.21^{+0.23}_{-0.20}$	$24.28^{+2.1}_{-1.7}$	2.194
	0.50	$0.42^{+0.25}_{-0.21}$	$25.50^{+1.9}_{-1.5}$	2.185
	0.75	$0.63^{+0.24}_{-0.22}$	$26.46^{+1.6}_{-1.4}$	2.175
	1.00	$0.85^{+0.26}_{-0.23}$	$27.28^{+1.4}_{-1.2}$	2.164
Per-emb-50	0.25	$0.08^{+0.02}_{-0.16}$	$21.9^{+0.8}_{-0.9}$	1.556
	0.50	$0.26^{+0.15}_{-0.17}$	$23.3^{+1.1}_{-1.0}$	1.558
	0.75	$0.44^{+0.16}_{-0.17}$	$24.6^{+1.4}_{-1.1}$	1.560
	1.00	$0.64^{+0.16}_{-0.18}$	$25.7^{+1.4}_{-1.3}$	1.563
Per-emb-14	0.25	$-0.11^{+0.16}_{-0.00}$	$28.5^{+2.3}_{-2.1}$	1.110
	0.50	$0.09^{+0.08}_{-0.21}$	$30.6^{+2.8}_{-2.3}$	1.114
	0.75	$0.27^{+0.17}_{-0.24}$	$32.5^{+2.2}_{-2.8}$	1.119
	1.00	$0.48^{+0.19}_{-0.23}$	$33.9^{+3.6}_{-3.1}$	1.123
Per-emb-30	0.25	$0.02^{+0.18}_{-0.31}$	$14.0^{+1.0}_{-0.9}$	1.100
	0.50	$0.20^{+0.04}_{-0.32}$	$14.9^{+1.9}_{-1.1}$	1.102
	0.75	$0.39^{+0.30}_{-0.34}$	$15.8^{+1.9}_{-1.3}$	1.104
	1.00	$0.59^{+0.14}_{-0.33}$	$16.5^{+31.3}_{-1.6}$	1.107
HH211-mms	0.25	$0.48^{+0.40}_{-0.78}$	$10.5^{+0.8}_{-0.8}$	1.009
	0.50	$0.65^{+0.43}_{-0.82}$	$11.0^{+1.0}_{-0.9}$	1.009
	0.75	$0.81^{+0.42}_{-0.79}$	$11.5^{+1.2}_{-1.2}$	1.009
	1.00	$1.01^{+0.44}_{-0.81}$	$11.9^{+1.4}_{-1.3}$	1.009
IC348 MMS	0.25	$-0.58^{+0.11}_{-0.11}$	$25.7^{+2.8}_{-2.2}$	1.085
	0.50	$-0.39^{+0.19}_{-0.11}$	$29.0^{+3.2}_{-2.6}$	1.096
	0.75	$-0.19^{+0.11}_{-0.27}$	$31.6^{+4.1}_{-2.9}$	1.107
	1.00	$0.02^{+0.07}_{-0.11}$	$33.7^{+4.3}_{-3.1}$	1.118
Per-emb-8	0.25	$0.01^{+0.16}_{-0.19}$	$19.0^{+1.2}_{-1.1}$	1.099
	0.50	$0.20^{+0.17}_{-0.20}$	$20.2^{+1.4}_{-1.3}$	1.107
	0.75	$0.40^{+0.17}_{-0.21}$	$21.2^{+1.6}_{-1.4}$	1.114
	1.00	$0.61^{+0.17}_{-0.20}$	$22.1^{+1.8}_{-1.6}$	1.122

Segura-Cox+ (2016)

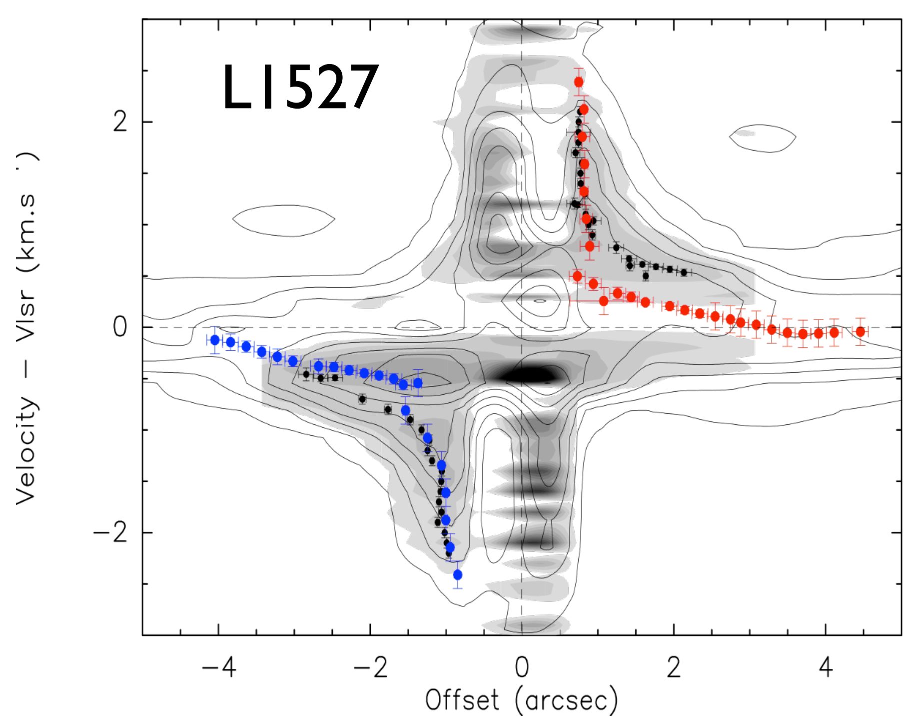
And several other individual studies find also small upper-limit for disc sizes in the youngest protostars ....

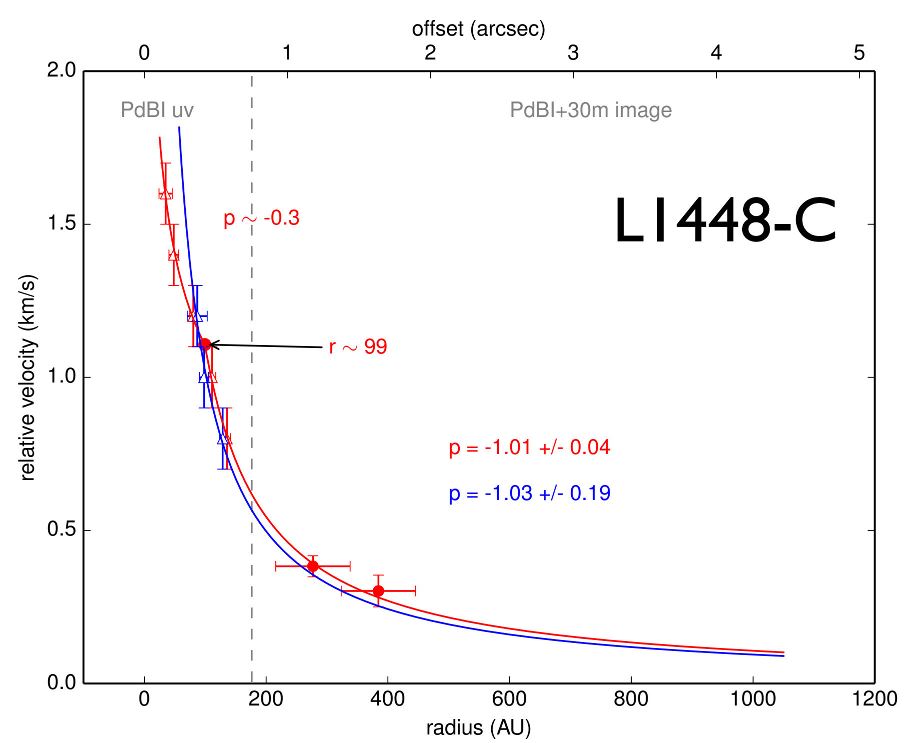
CALYPSO: angular momentum conservation in Class 0 protostars ?

< 25% of Class 0 might harbor continuum disc-like structures at r>50-100 AU



To disentangle envelope kinematics from disc kinematics:
a multi-scale approach is necessary to analyze correctly the rotation and infall patterns

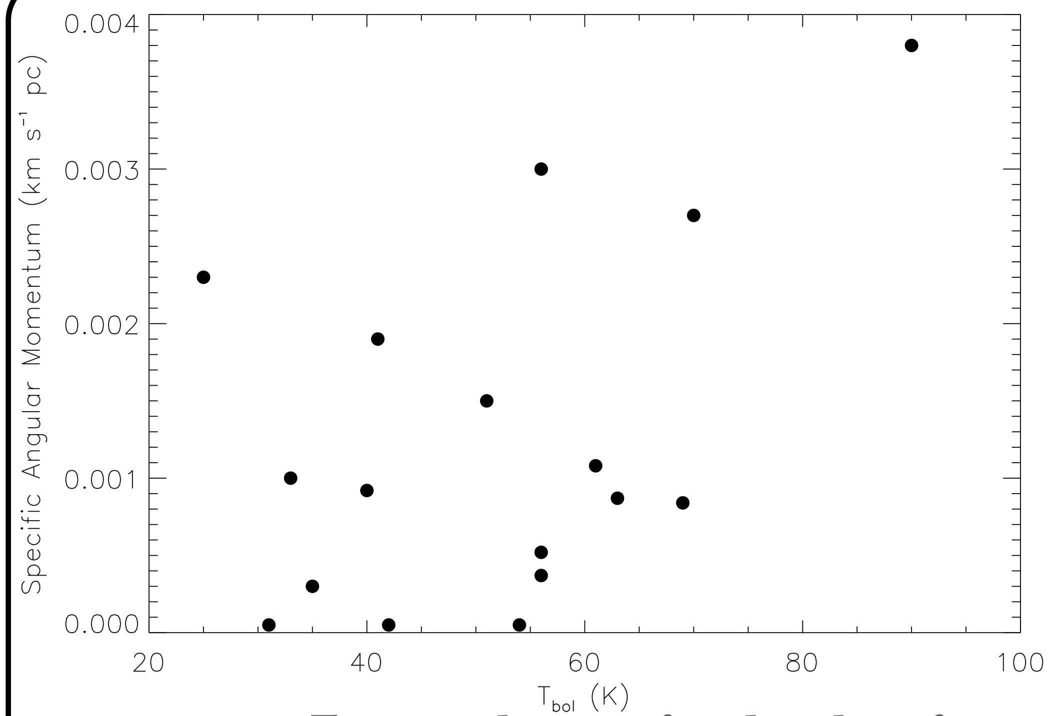


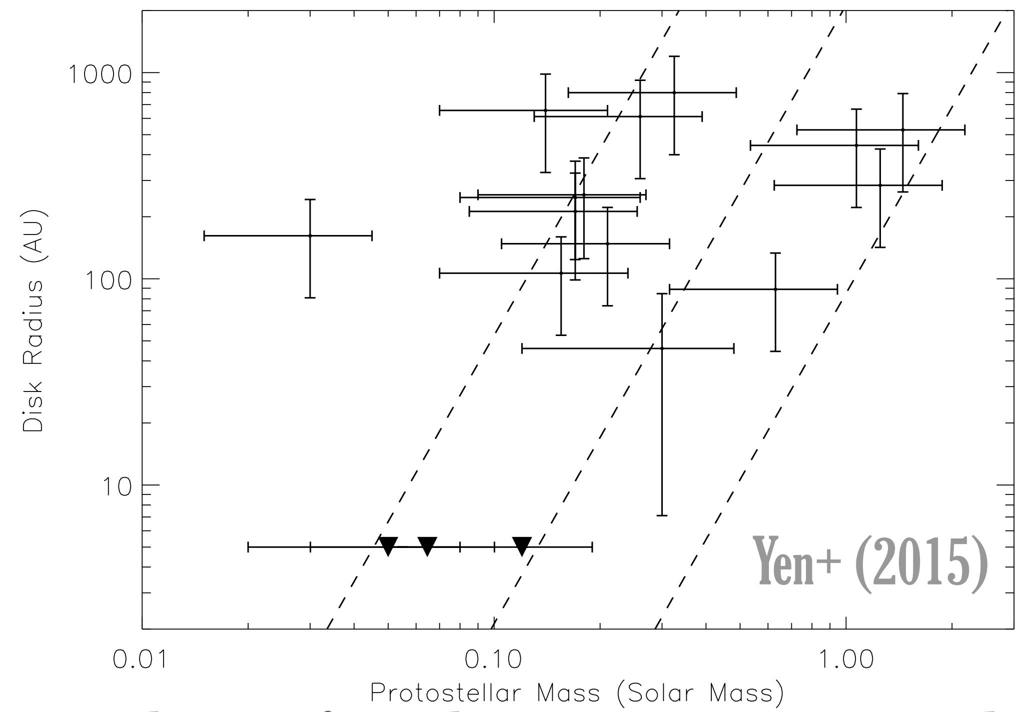


Combined analysis of molecular tracers
from the IRAM-30m (500 - 50000 AU scales)
and the IRAM-PdBI CALYPSO survey (50-1000 AU scales)

Gaudel, Maury, Belloche (in prep.)

CALYPSO: disc statistics





Source	R_d (AU)
L1448 IRS 2	130–390
L1448 IRS 3B	330–720
L1448-mm	140–160
NGC 1333 IRAS 4A	630–720
NGC 1333 IRAS 4B	<5
L1527 IRS	70–150
B335	<5
L1157	<5

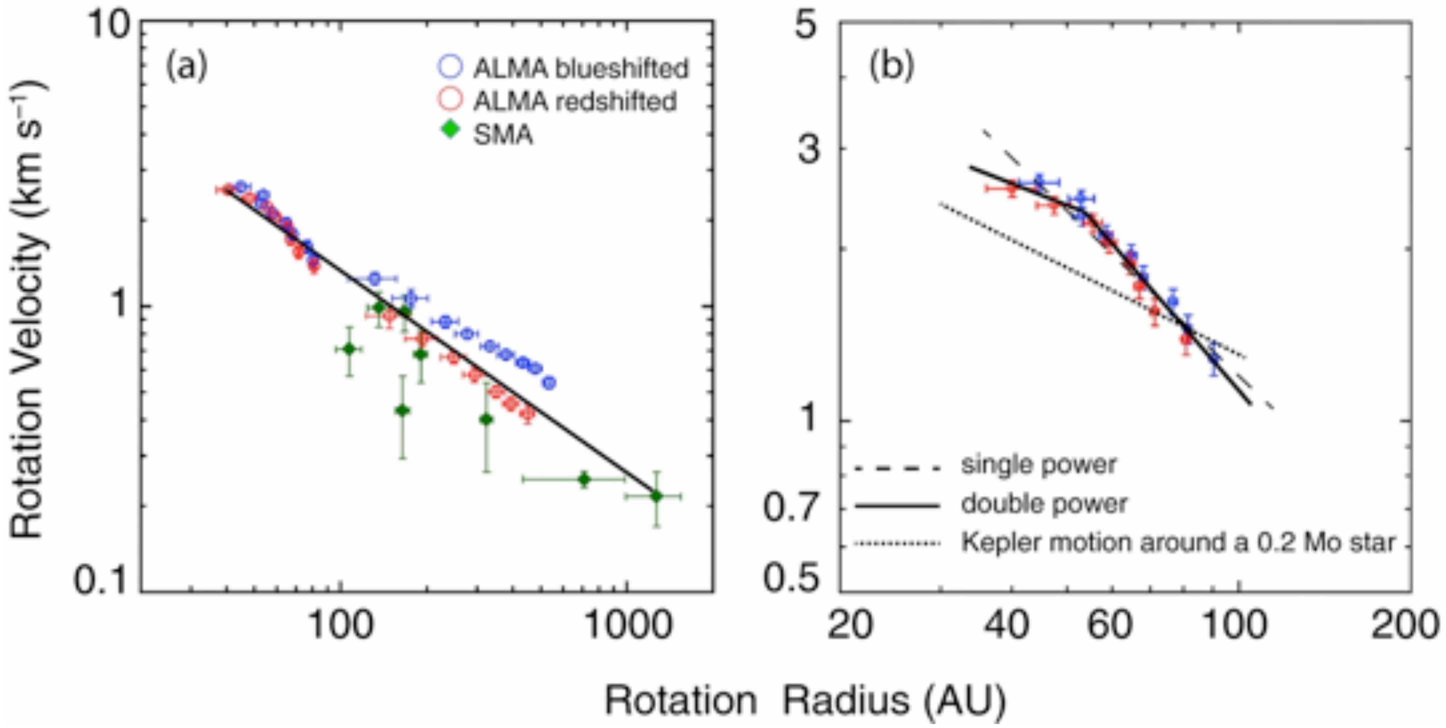
Expected centrifugal radius from extrapolation of angular momentum measured at 1000 AU radius

Upper-limits on disc radii
as measured from CALYPSO continuum observations are
smaller by at least 50 %
than disc sizes expected from angular momentum conservation

==> Hydro discs are excluded in >75% of the CALYPSO sample

Challenging the long-standing solution for AM problem
& the standard star/disc formation scenario

Do we detect keplerian rotation inside Class 0 envelopes ?



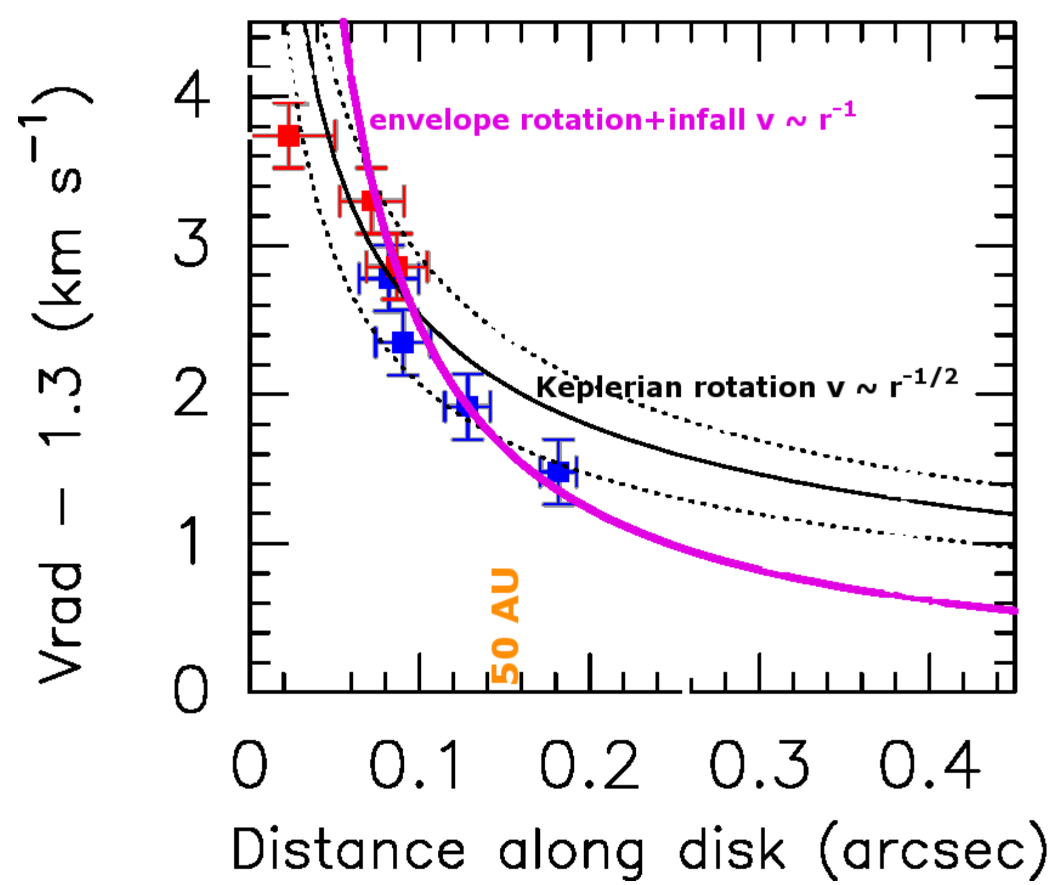
L1527 :

ALMA C18O data (Ohashi+ 2014)
shows velocity
consistent with rotating-infalling envelope
down to r~50 AU

+ possible transition to Keplerian regime
at r<50 AU ?

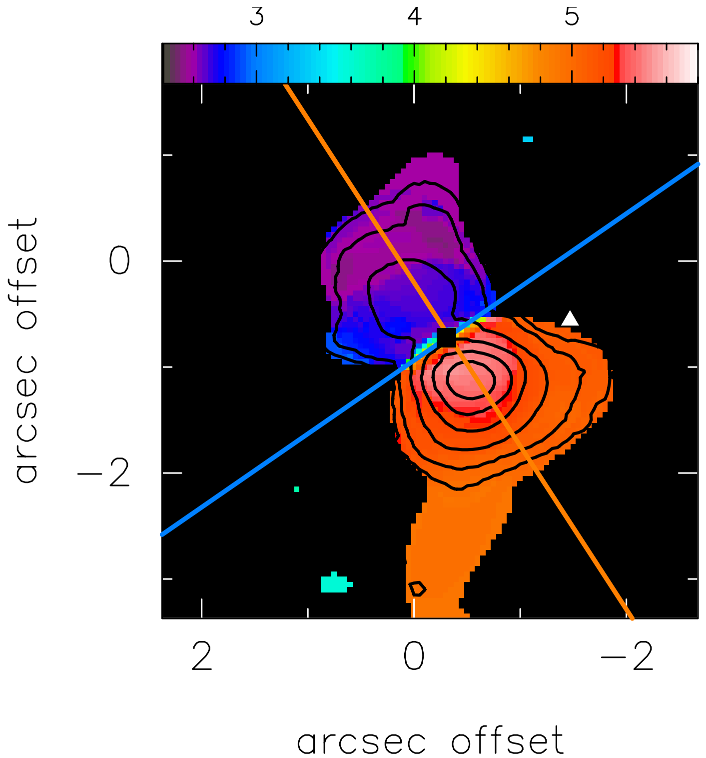
HH212:

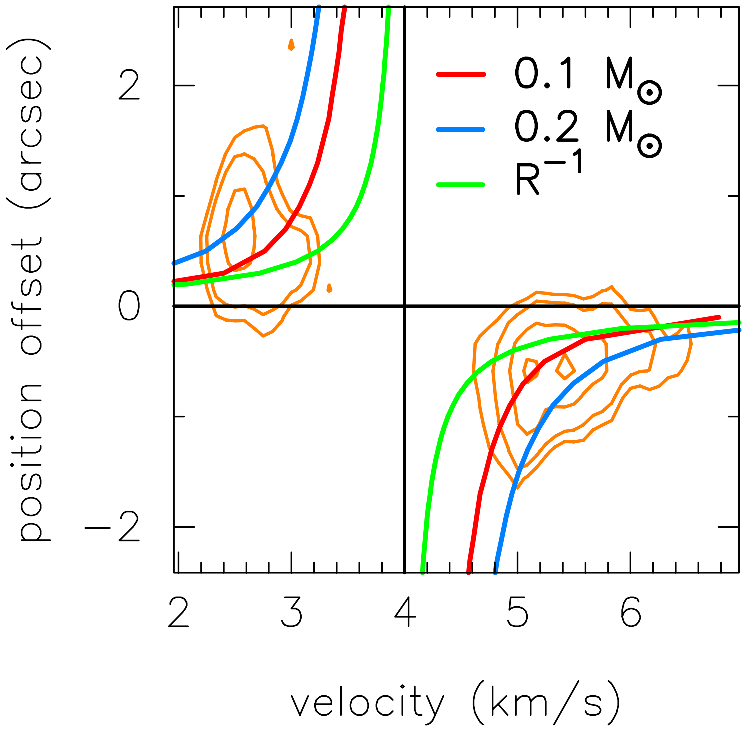
rotation detected in C17O (Codella+ 2014, ALMA)
consistent with both envelope rotation or Keplerian rotation



Do we detect keplerian rotation inside Class 0 envelopes ?

VLA 1623

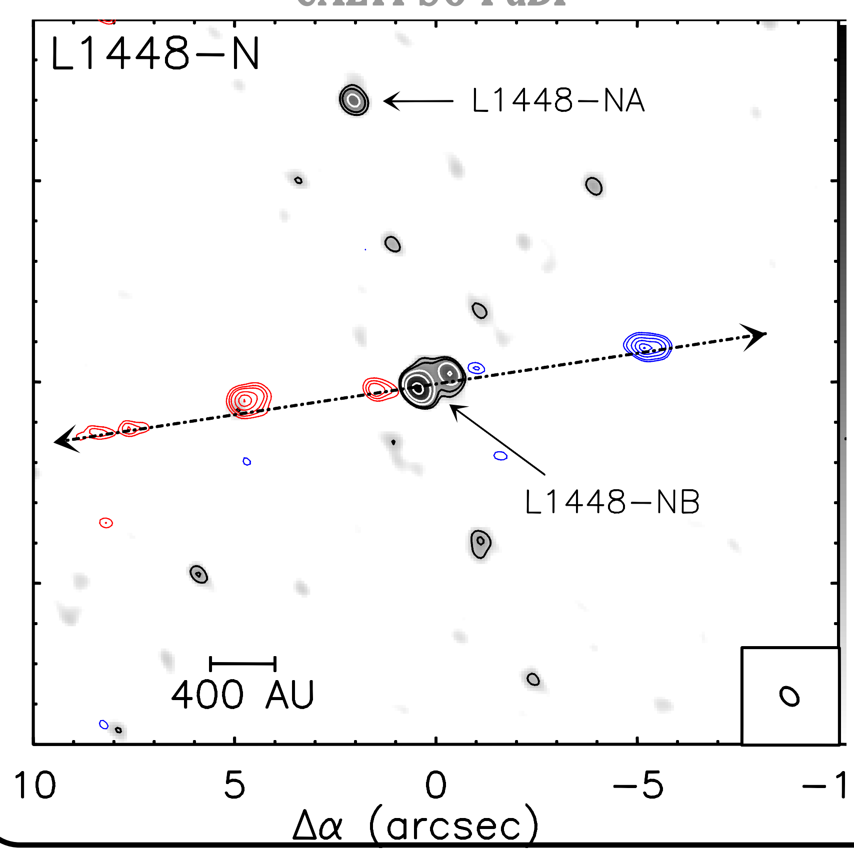


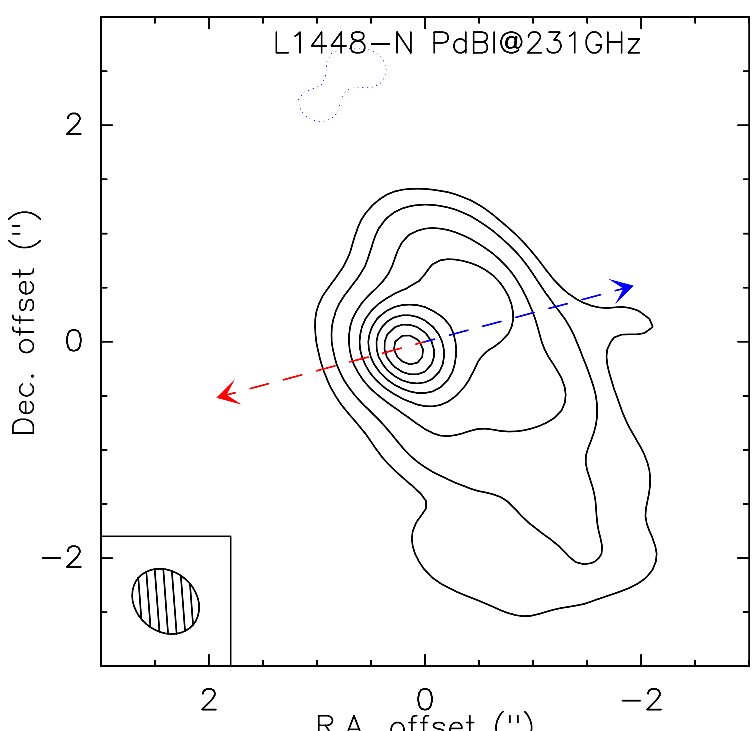


Murillo+ (2012) :
argue Keplerian rotation is
detected in C18O ALMA map
and propose it traces a r~150 AU disc
=> probably not constrained enough ?

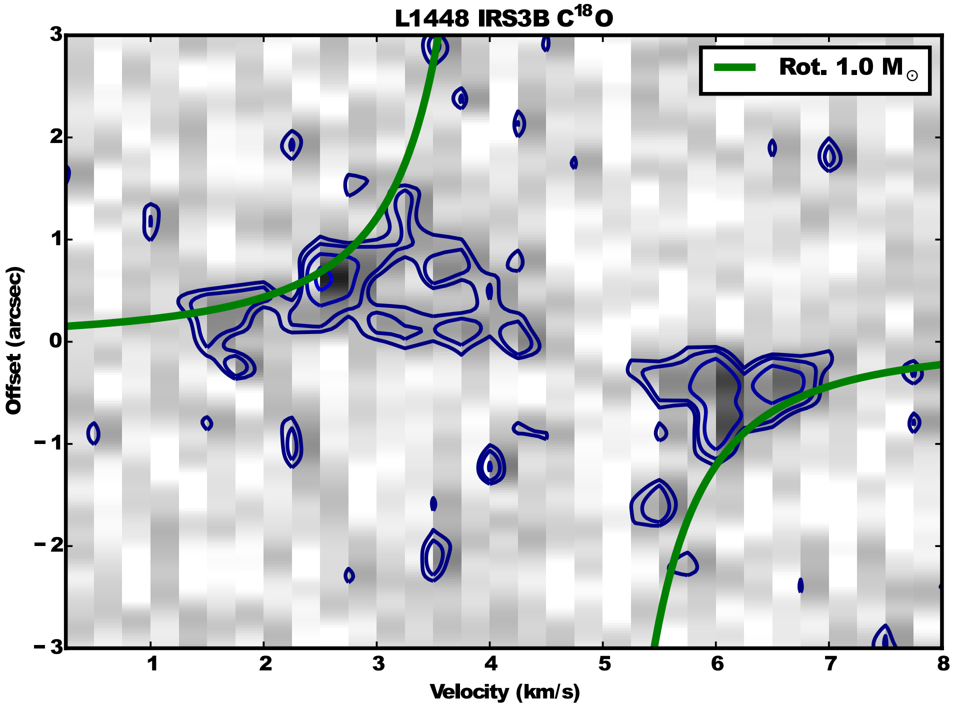
L1448-NB

CALYPSO PdBI



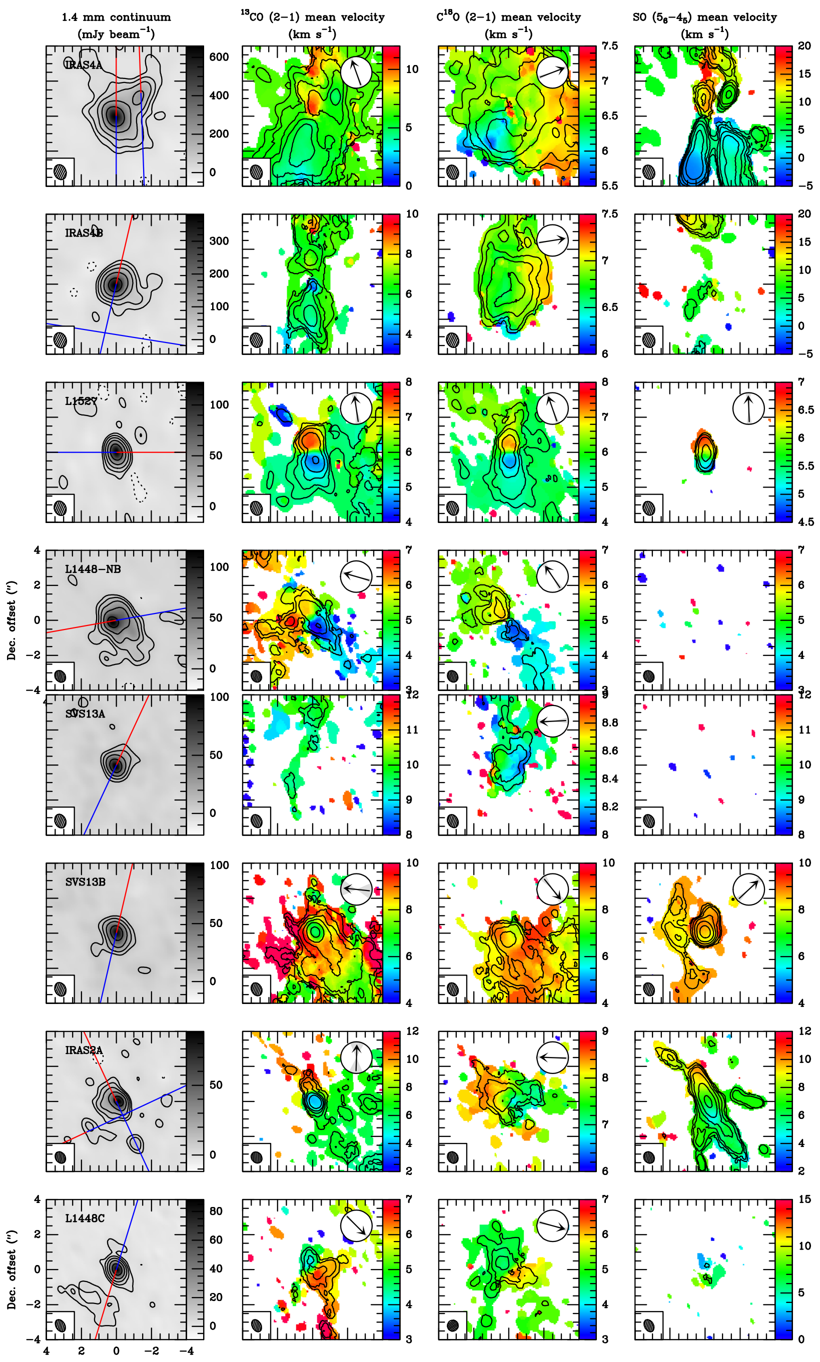


Maury & CALYPSO collab. (in prep)



Tobin+ (2016) claim keplerian rotation
and disc fragmentation

Do we detect keplerian rotation inside Class 0 envelopes ?



CALYPSO sample of 16 Class 0 protostars:

1 clear keplerian detection at r~60 AU

+

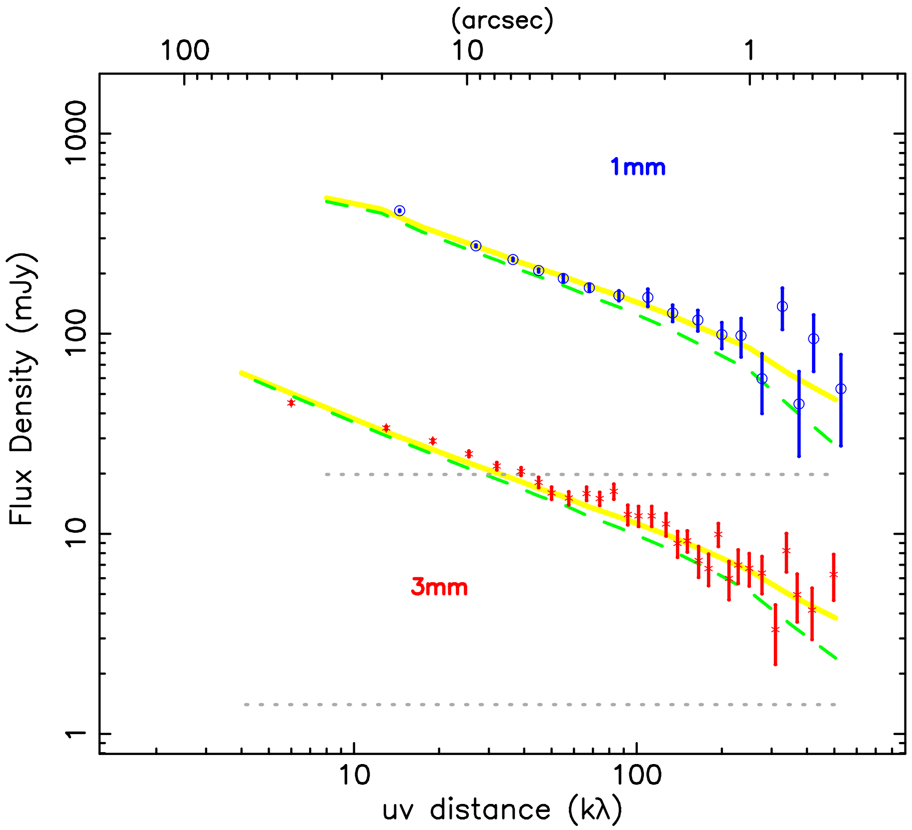
2 velocity gradients consistent with keplerian rotation at r~40 AU
(also disk candidates from the continuum analysis)

+

13 Class 0 without detected keplerian motions at radii>50 AU

(Maret et CALYPSO in prep.) preliminary results

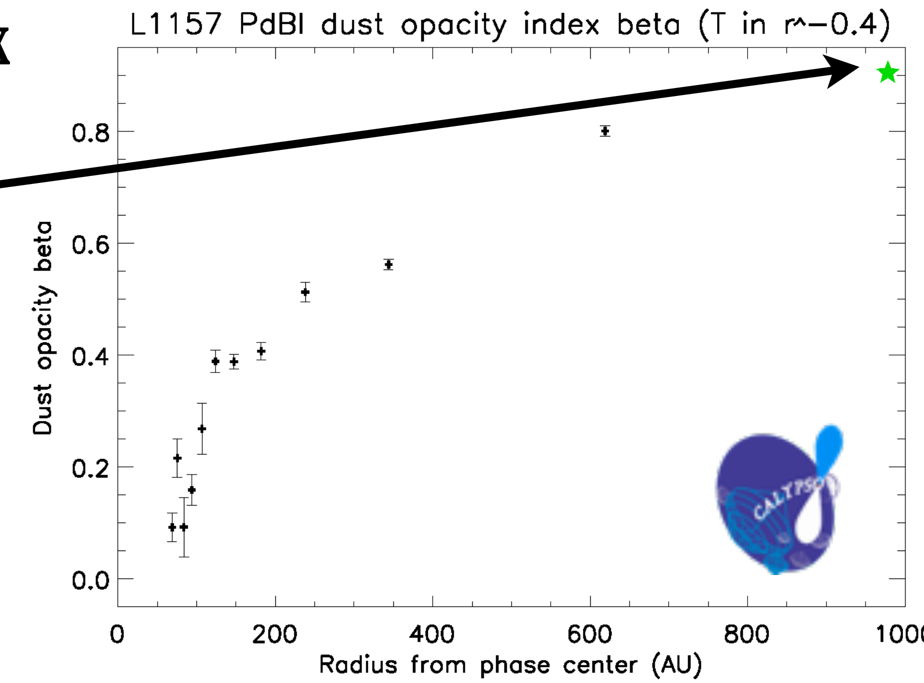
Class 0 discs/ inner envelope properties: grain growth already !

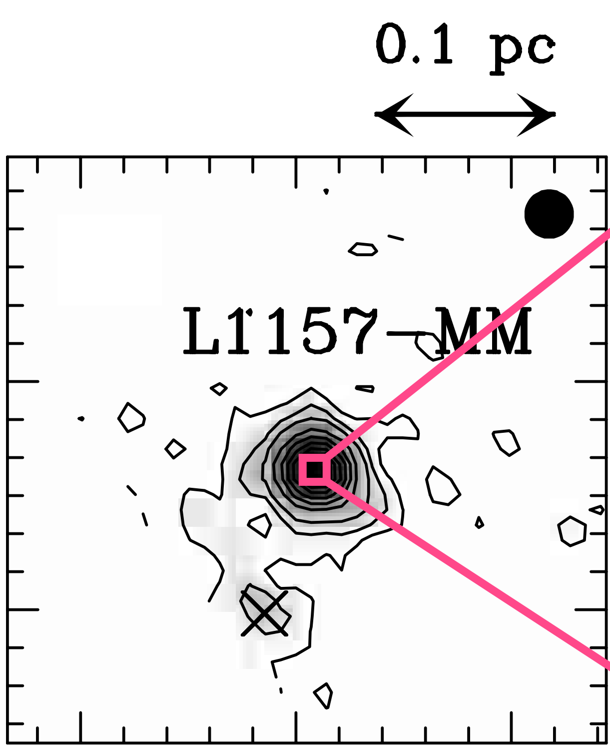


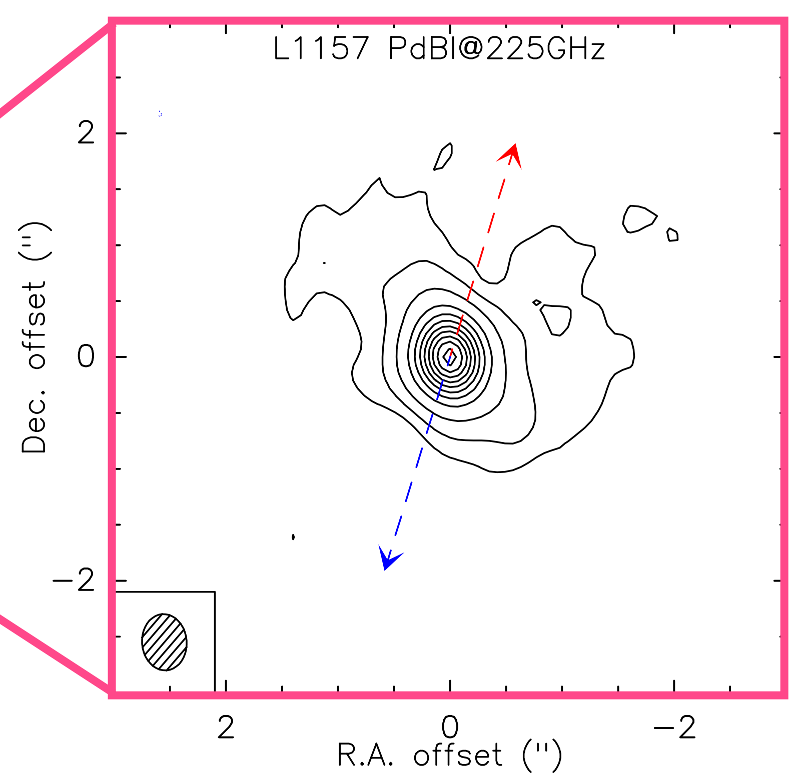
Class 0 protostar L1157
dust opacity spectral index

$\beta \sim 0.9$
at r 1000 AU
(Chiang+ 2012)

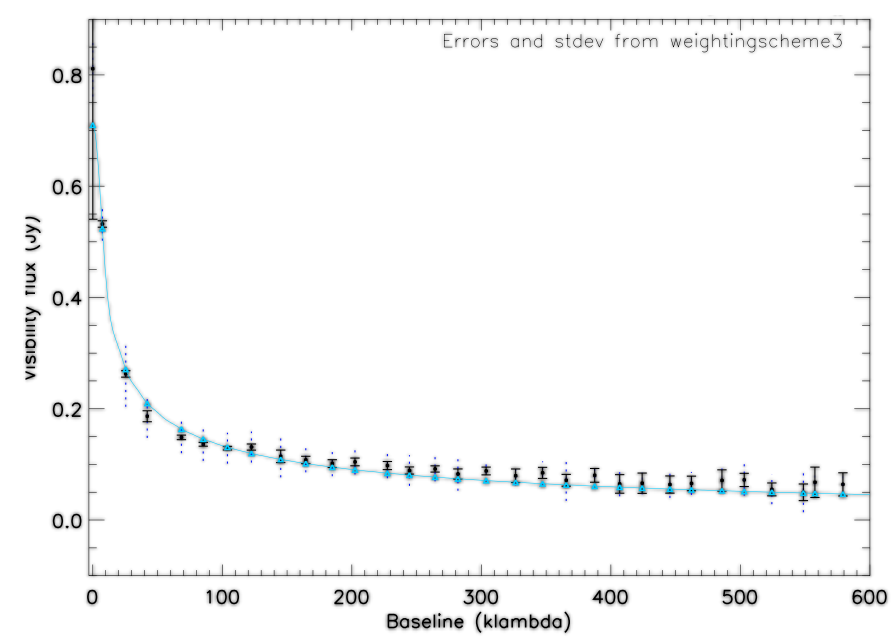
$\beta \sim r^{-1.5}$
at r ~50-1000 AU
(Maury+ 2017)







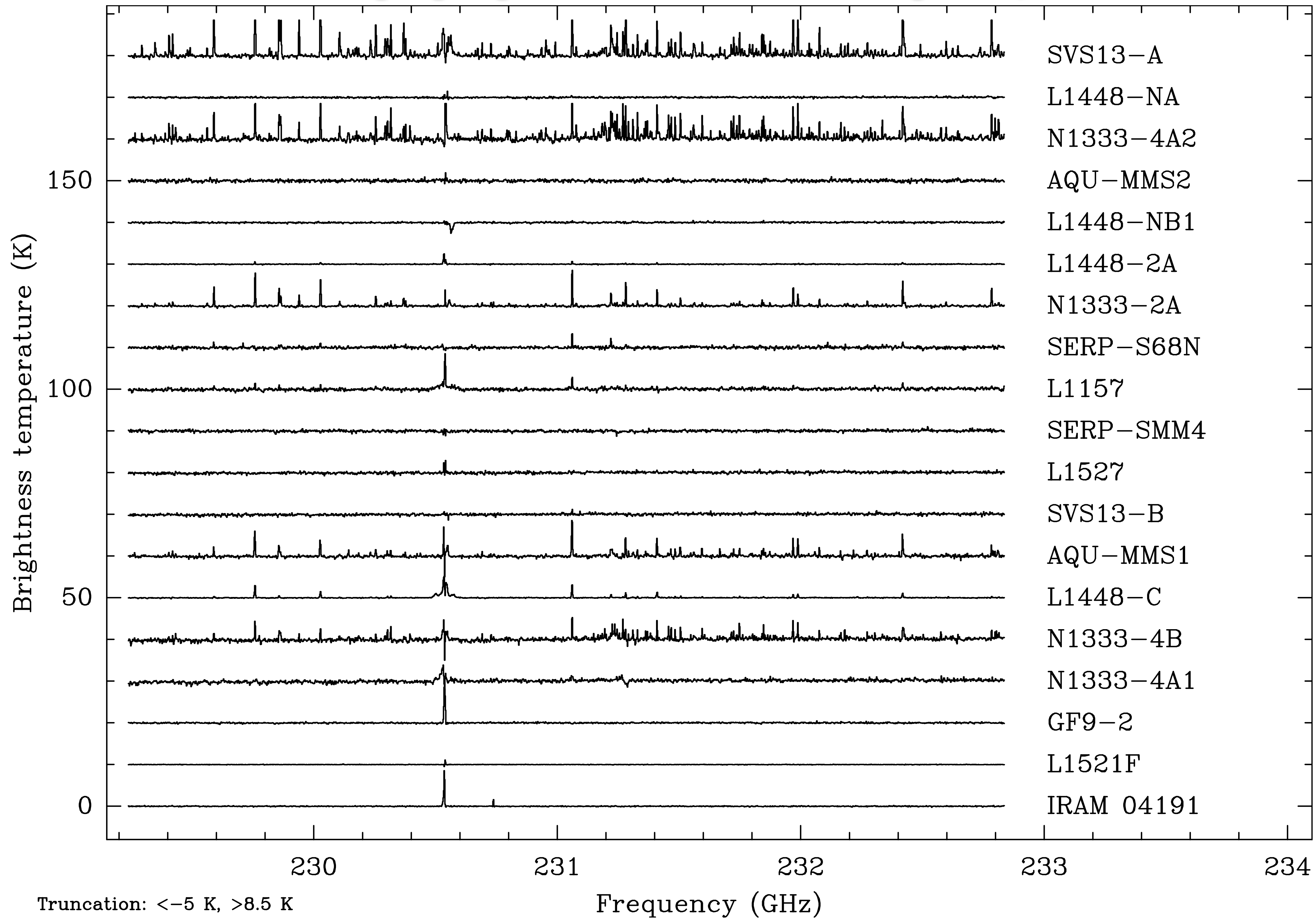
CALYPSO: disc<40 AU !



Class 0 discs/ inner envelope properties: chemical complexity !

See also, eg:

Maret+ (2005)
Jorgensen+ (2015,2016)
Caseli & Ceccarelli review (2012)



Complex organic chemistry primarily found in region r < 50 AU (Maury+ 2014): mostly consistent with snow-line from protostellar luminosity but still some misfits ....

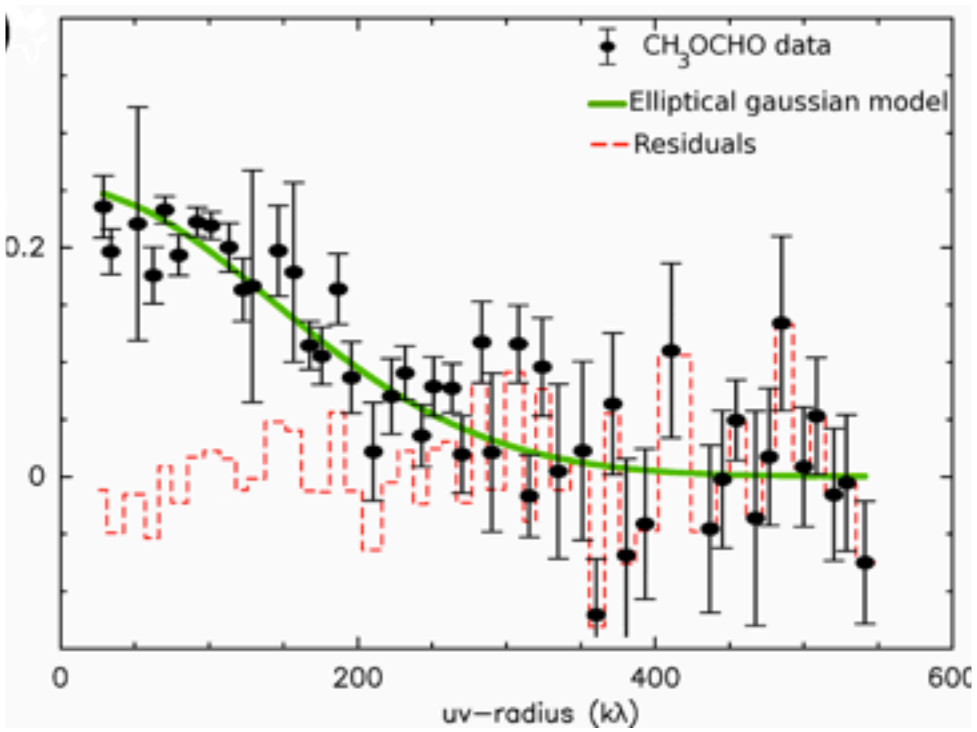
Belloche+ 2017 (in prep) : some hint of evolutionary trend (most rich in more evolved sources with young discs developed)

Class 0 discs/ inner envelope properties: chemical complexity !

CO snow line in protostars
(cf Pierre Hily Blant lecture this morning)

see also Oberg+ (2016)

NGC1333 IRAS2A



COMs: emitting sizes resolved <100 AU

No preferential elongation along the jet axis

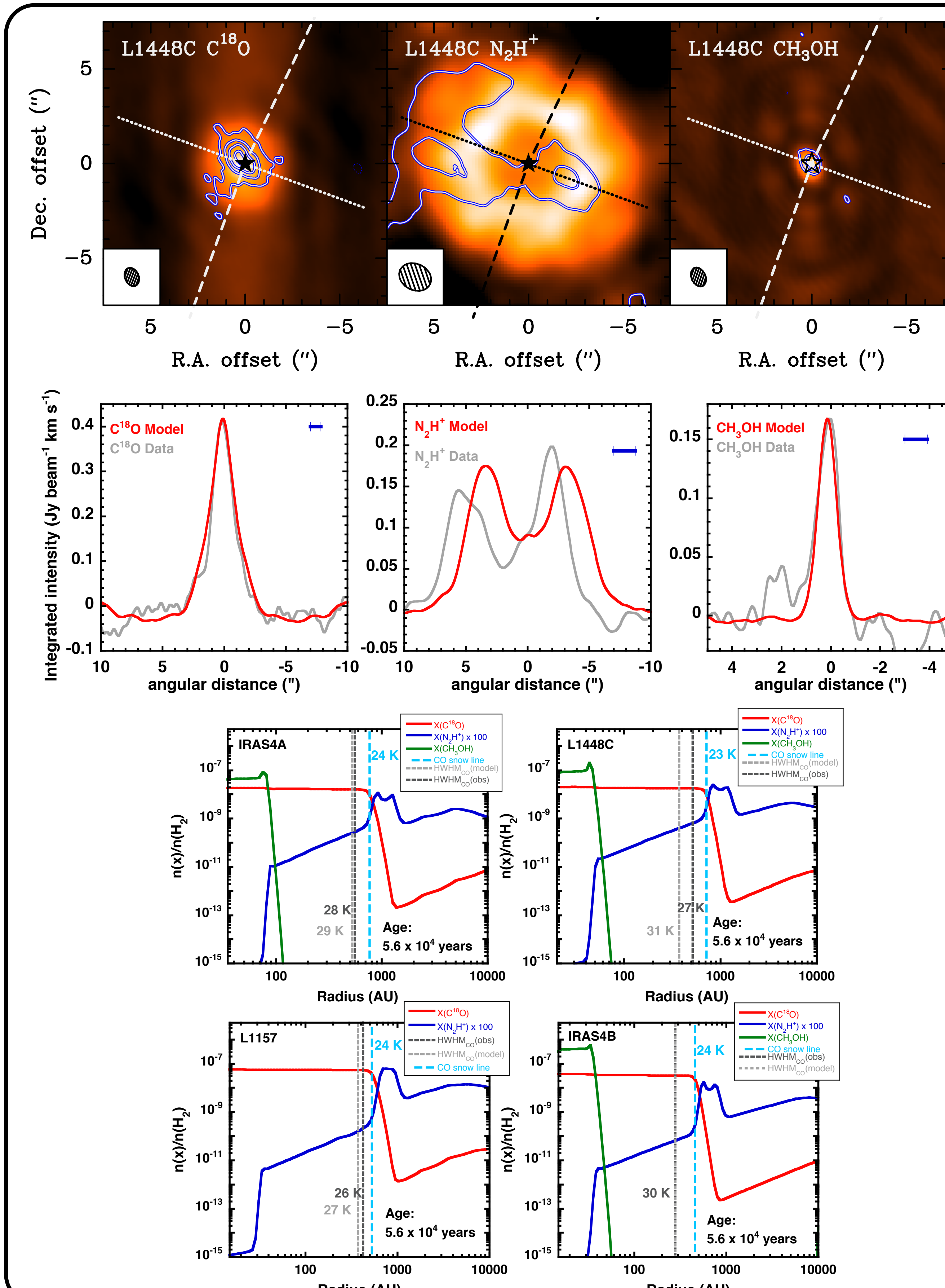
COMs emission is resolved spatially with > 10's of COMs lines

(Maury+ 2014)

Episodic accretion ?

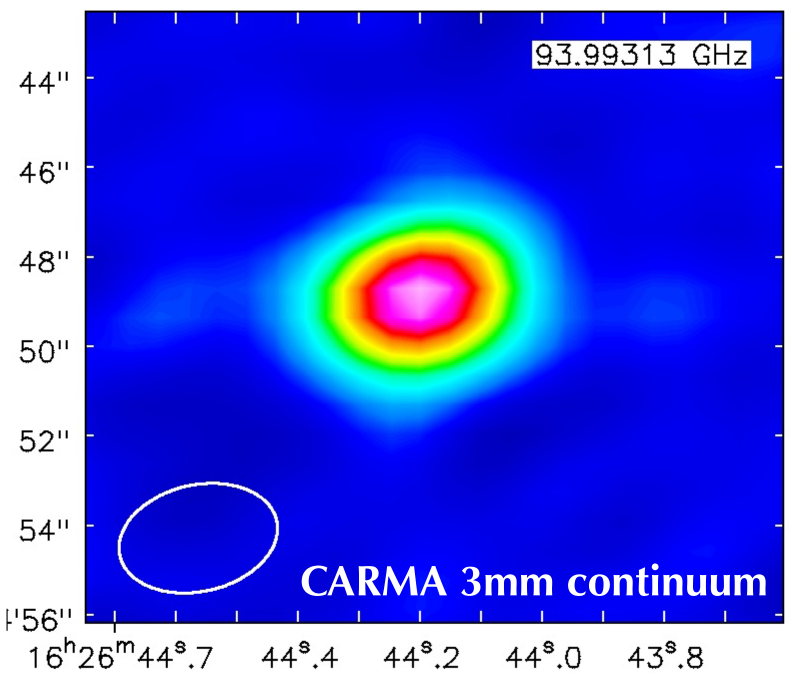
Anderl+ (2015):

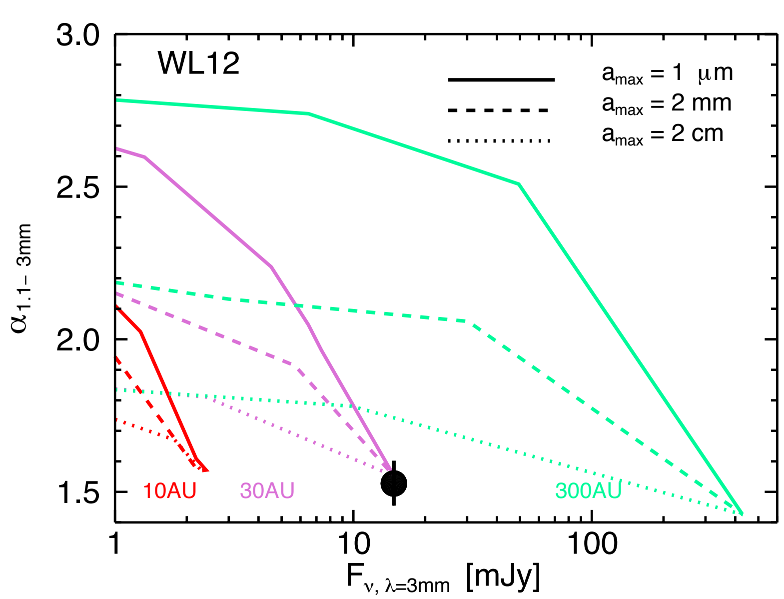
chemical abundances in a sample of Class 0 protostars down to radii 50 AU



Discs around Class I protostars

Miotello+ (2012)

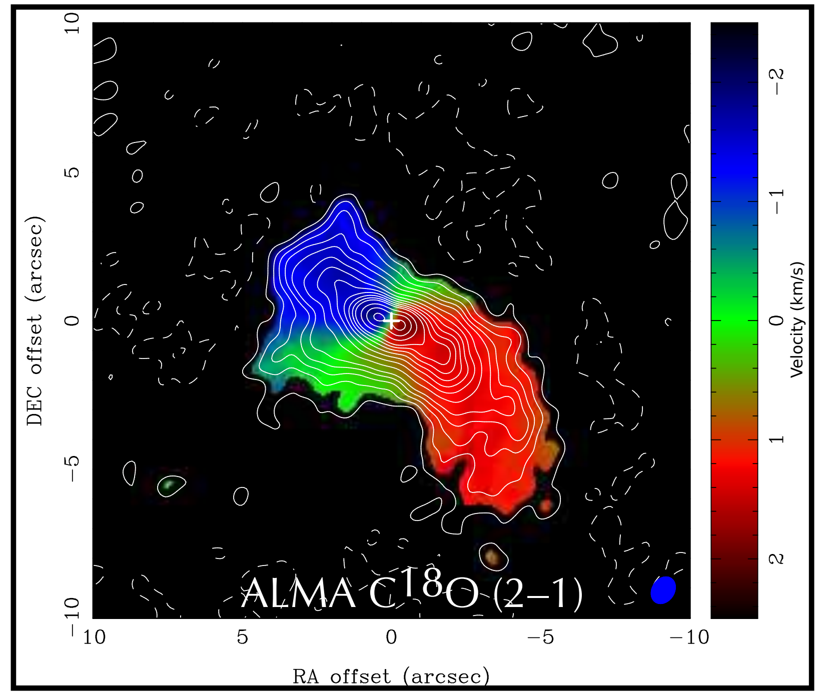


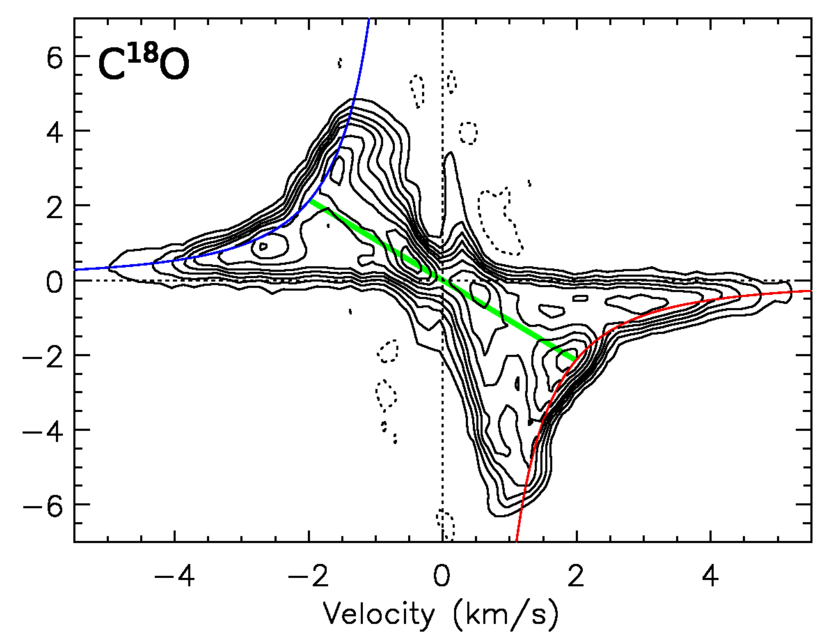


2 Ophiuchus Class I protostars

mm-size grains

Yen+ (2014)

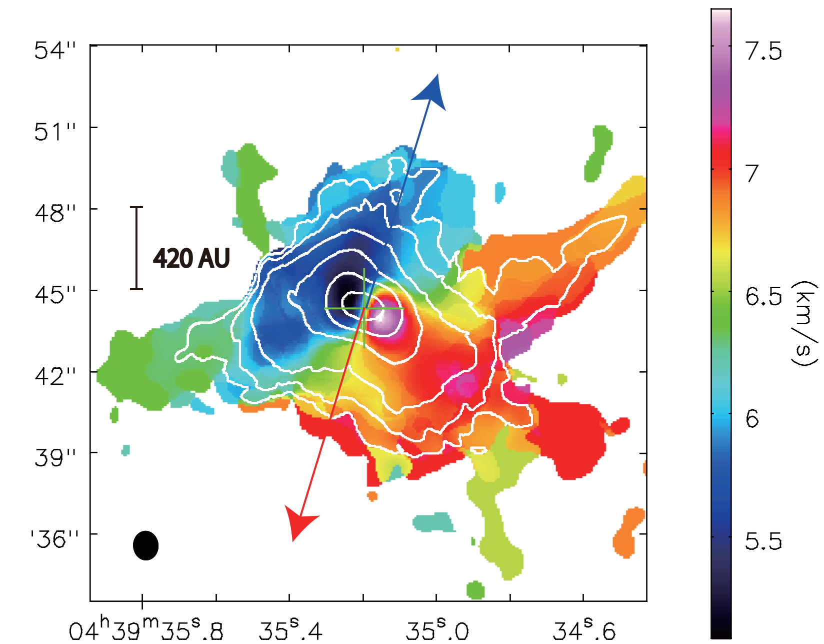


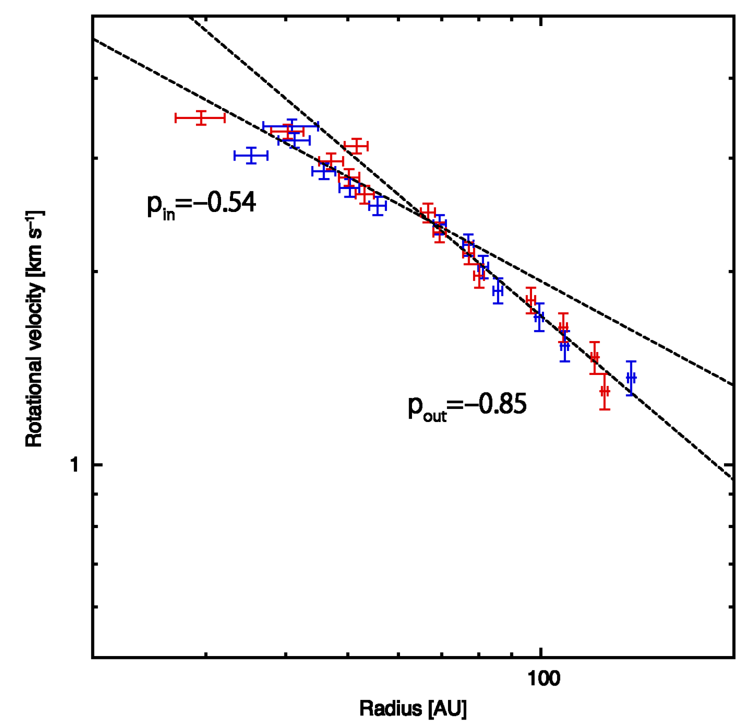


L1489 IRS1

disc radius 300-500 AU

Aso+ (2015)





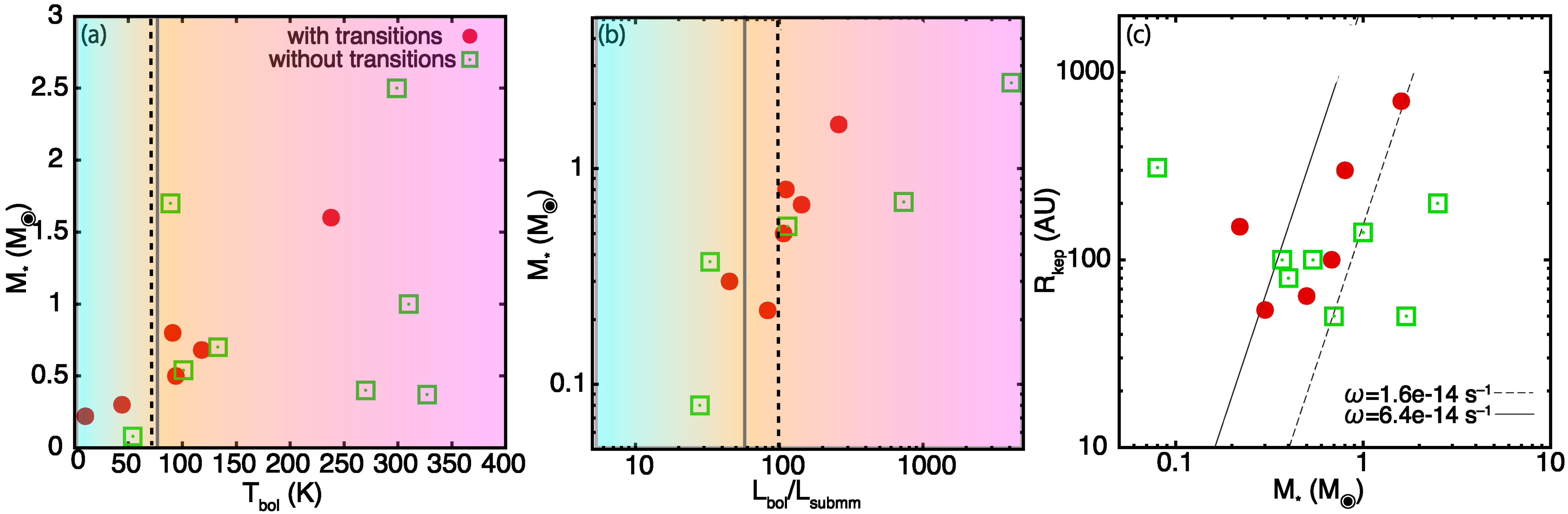
TMC-1A

disc radius 60-90 AU

$M_* \sin^2 i = 0.56\ M_\odot$

Note the recent ALMA survey of disks in Lupus (Ansdell+ 2016, Manara+ 2016, Miotello+ 2017): a population of small / low mass disks ...

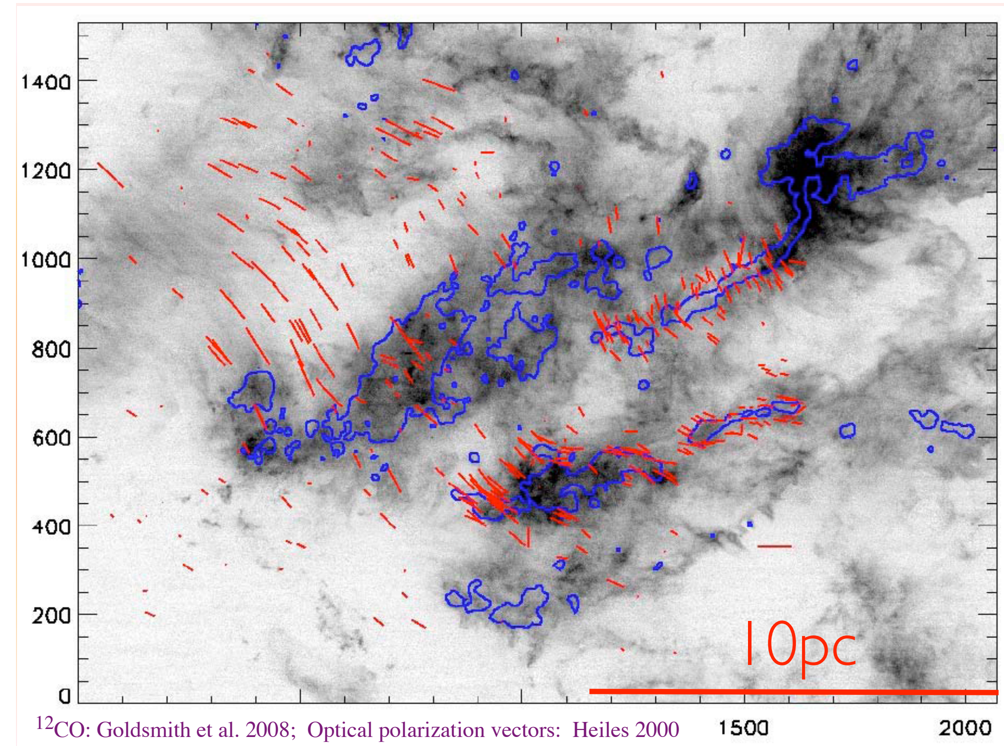
Discs around Class I protostars



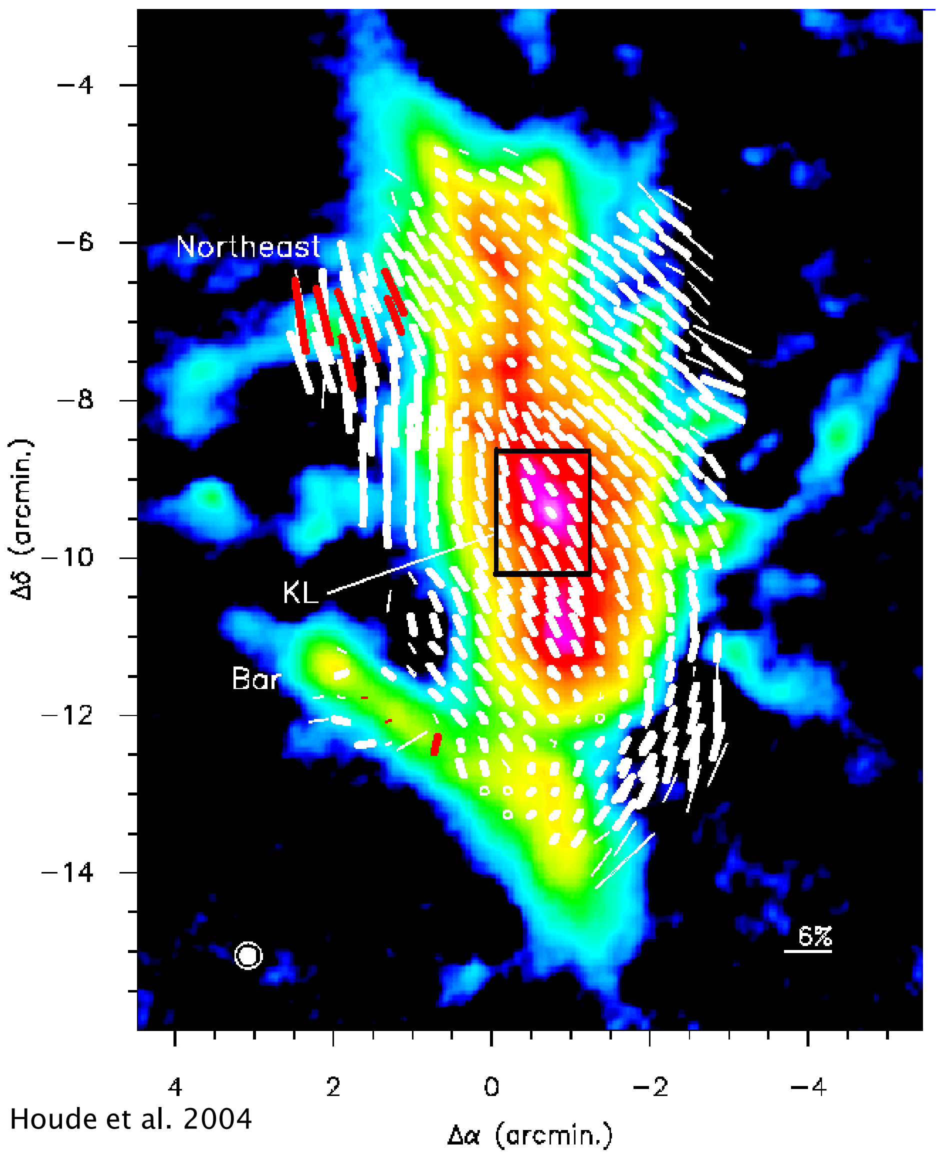
Source	L_{bol} ($L_\odot$)	T_{bol} (K)	$L_{bol}/L_{\rm submm}$[a]	$R_{\rm kep}$ (AU)[b]	M_* ($M_\odot$)[c]	$M_{\rm disk}$ ($M_\odot$)[d]	Class		
R CrA IRS7B	4.6	89	...	50	1.7	0.024	I	no	4
L1551 NE	4.2	91	111	300	0.8	0.026	I	yes	5,14,17
L1551 IRS 5	22.1	94	107	64	0.5	0.07	I	yes	6,12,16
TMC1	0.9	101	114	100[i]	0.54	0.025-0.06	I	no	7,12,16
TMC-1A	2.7	118	143	100	0.68	2.5×10^{-3}	I	yes	8,12,16
TMR1	2.6	140	734	50	0.7	0.01-0.015	I	no	7,16
L1489 IRS	3.7	238	259	700	1.6	$3\text{-}7 \times 10^{-3}$	I	yes	9,15,16
L1536	0.4	270	...	80	0.4	0.07-0.024	I	no	7,12
Elias 29	14.1	299	4215	200	2.5	$\lesssim 7 \times 10^{-3}$	I	no	10,12,16
IRS 43	6.0	310	...	140	1.0	8.1×10^{-3}	I	no	11,15
IRS 63	1.0	327	33	100	0.37	0.055	I	no	10,12,16

Aso+ (2015)

The ISM is magnetized



Measurements of polarized dust emission toward the low-mass star-forming region Taurus. Goldsmith et al. (2008)



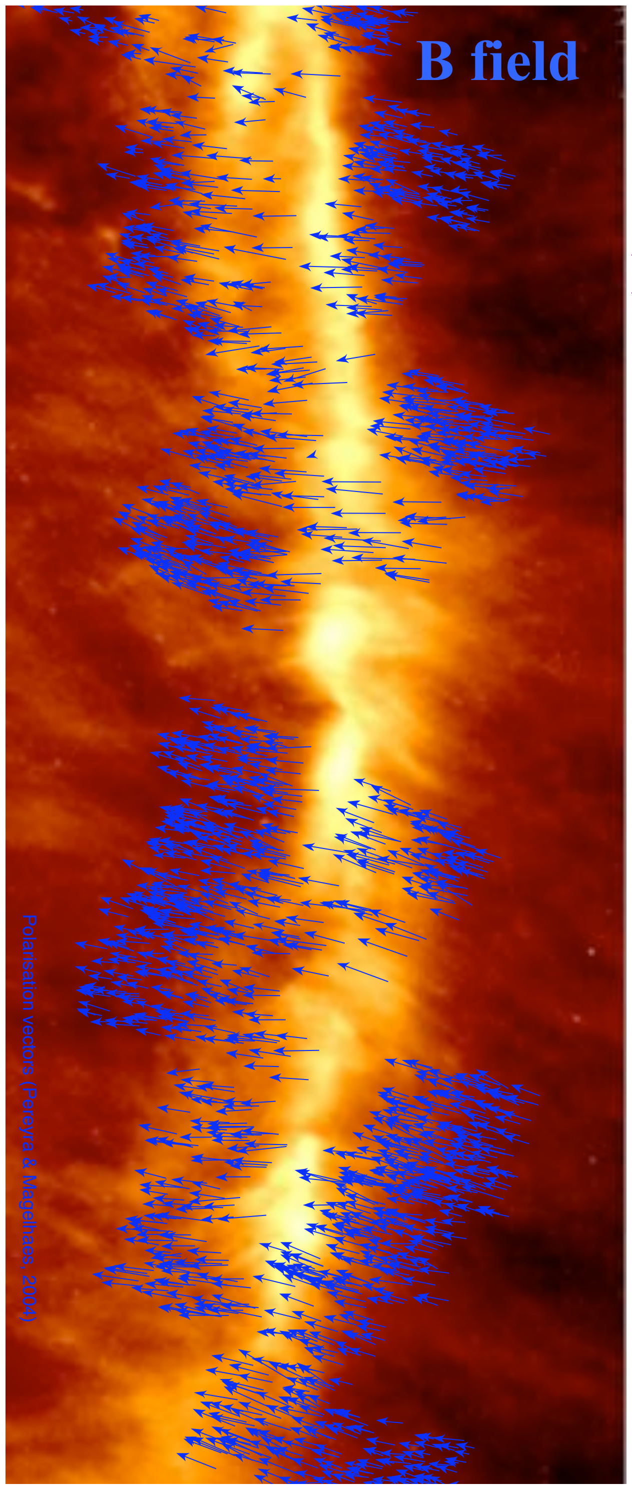
Measurements of polarized dust emission toward the high-mass star-forming region Orion. Houde et al. (2004)

ISM Component	B_{total} (μG)
diffuse ionized medium (synchrotron equipartition, RMs)	7 ± 3
H I clouds (H I Zeeman)	6.0±1.8 (λ ~ 0.1)
molecular clouds (OH, CN Zeeman)	10 – 3,000+ (λ_C ~ 1)

See also Falgarone et al. (2008) for Zeeman measurements in star-forming dense cores.

Role of magnetic fields ?

➢ **Bimodal distribution of filament vs. B-field orientations** (see also H.-b. Li+2013 + Planck polar. results J. Soler et al.)



Musca filament:
M/L ~ 20 $M_\odot$/pc

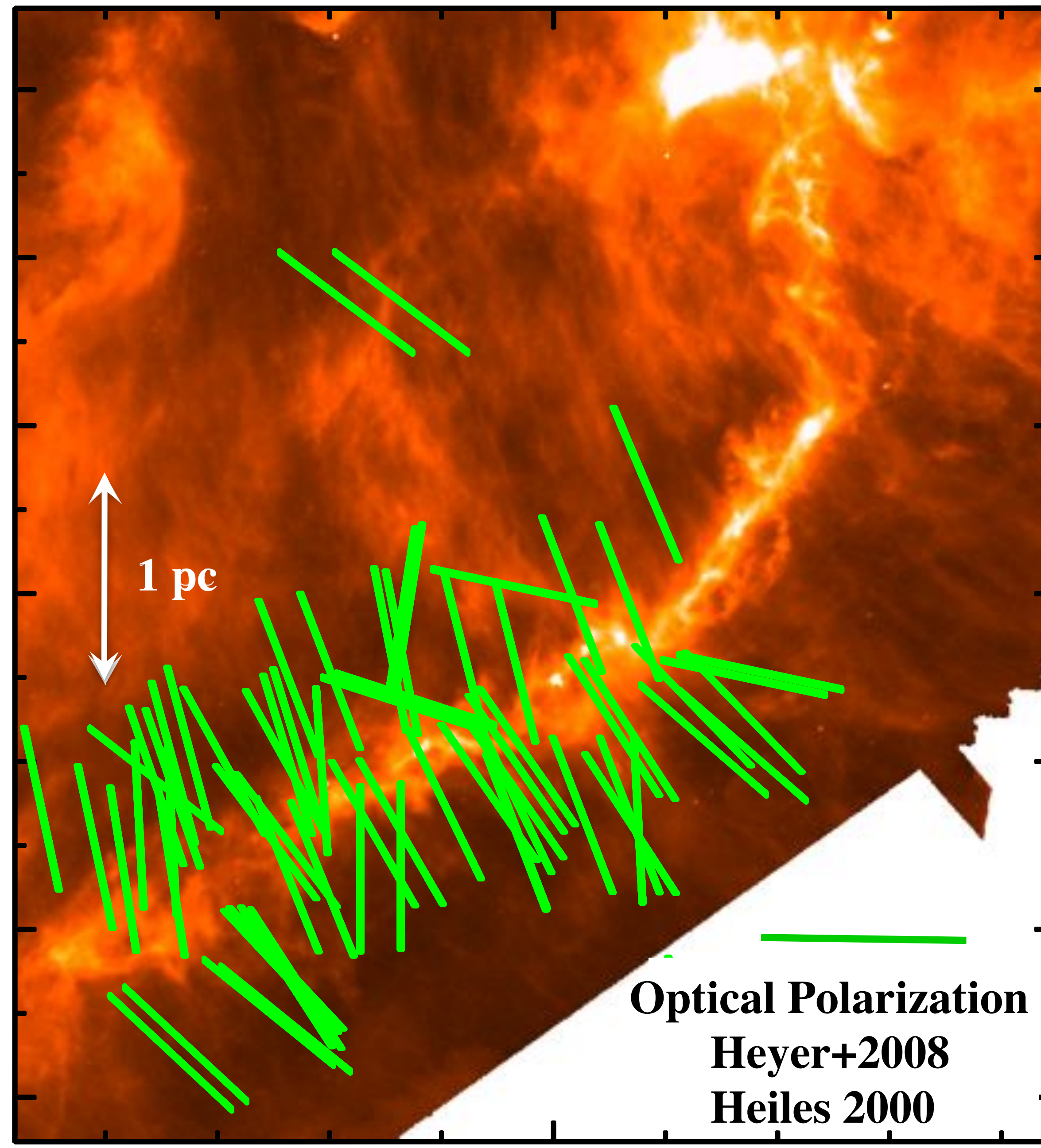
N. Cox et al. 2015

Polarization vectors overlaid on *Herschel* images

Pereyra & Magelhaes 2004

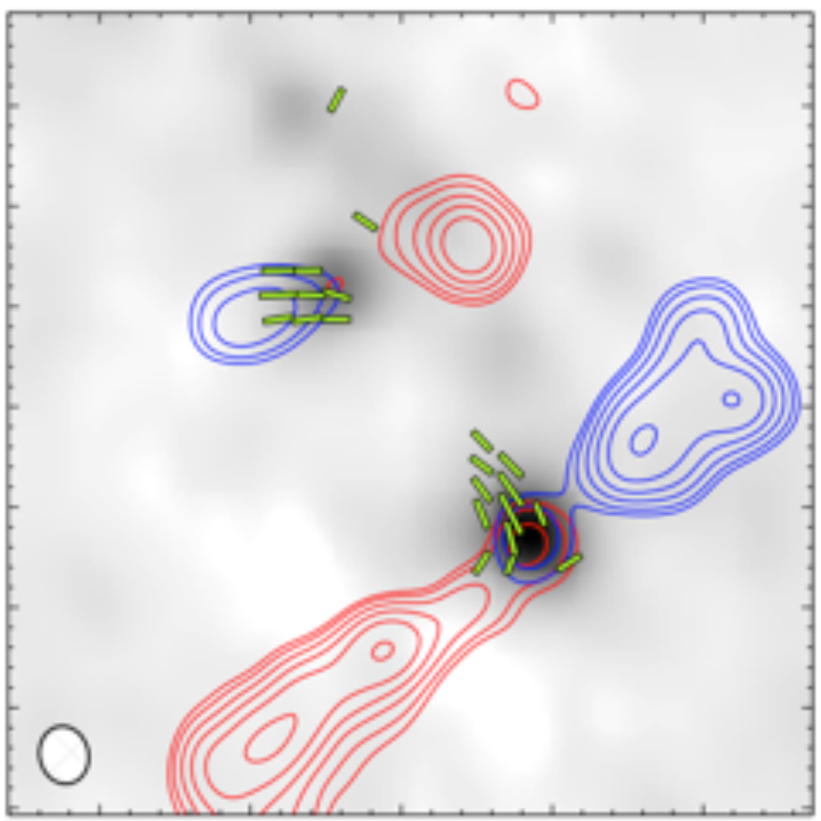
Taurus B211 filament: M/L ~ 50 $M_\odot$/pc

P. Palmeirim et al. 2013



Protostars are often embedded in MC magnetic fields

TADPOL survey

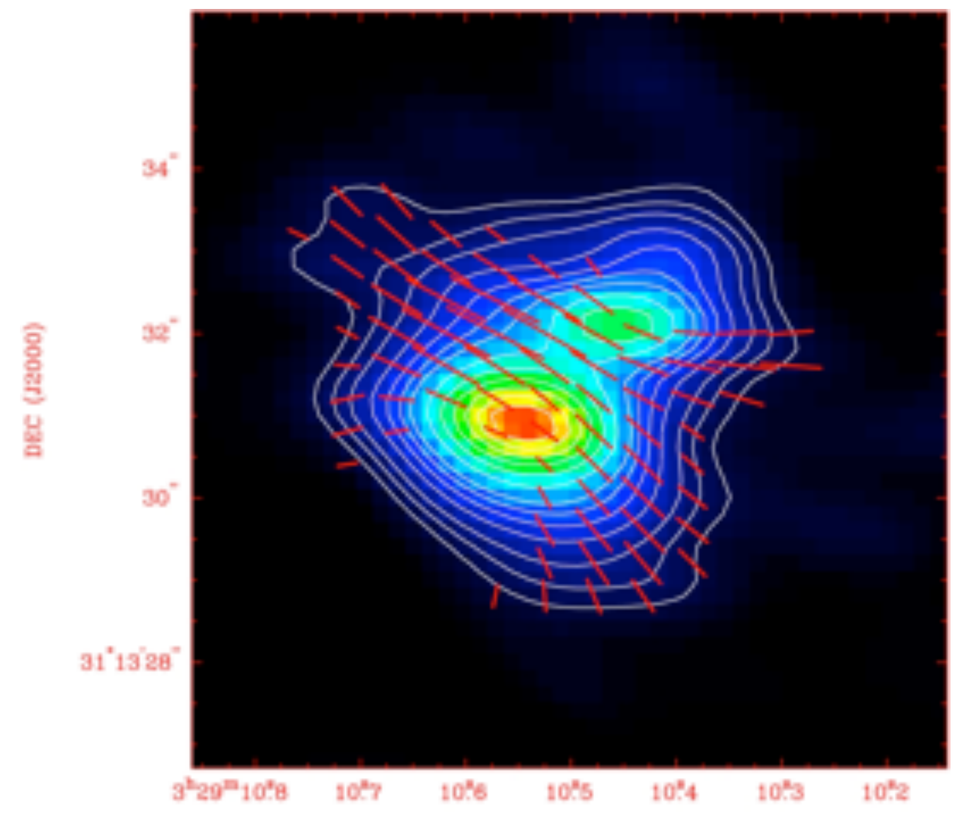


1 mm polarization at CARMA in 13 Class 0 protostars.

Dust polarization maps with ∼ 0.005pc angular resolution

Hull et al. (2013, 2014)

SMA studies



0.8 mm polarization at SMA in IRAS16293.

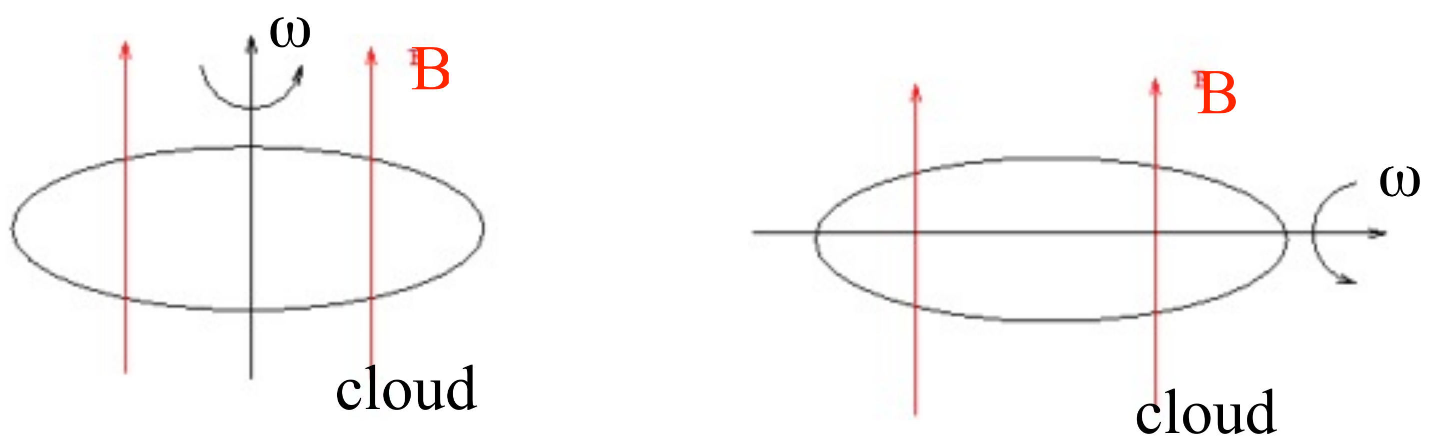
Dust polarization map with ∼ 200AU angular resolution

Girart, Rao, Marrone Science (2006)
Rao et al. (2014)

What is magnetic braking ?

Rotation motions generate Alfven torsional waves that can transport the angular momentum to the outer parts of the contracting cloud.

Magnetic braking is more effective perpendicular to field lines



Magnetic braking happens when the field is sufficiently twisted due to the different rotation velocities between the infalling envelope and the central «disc» region.

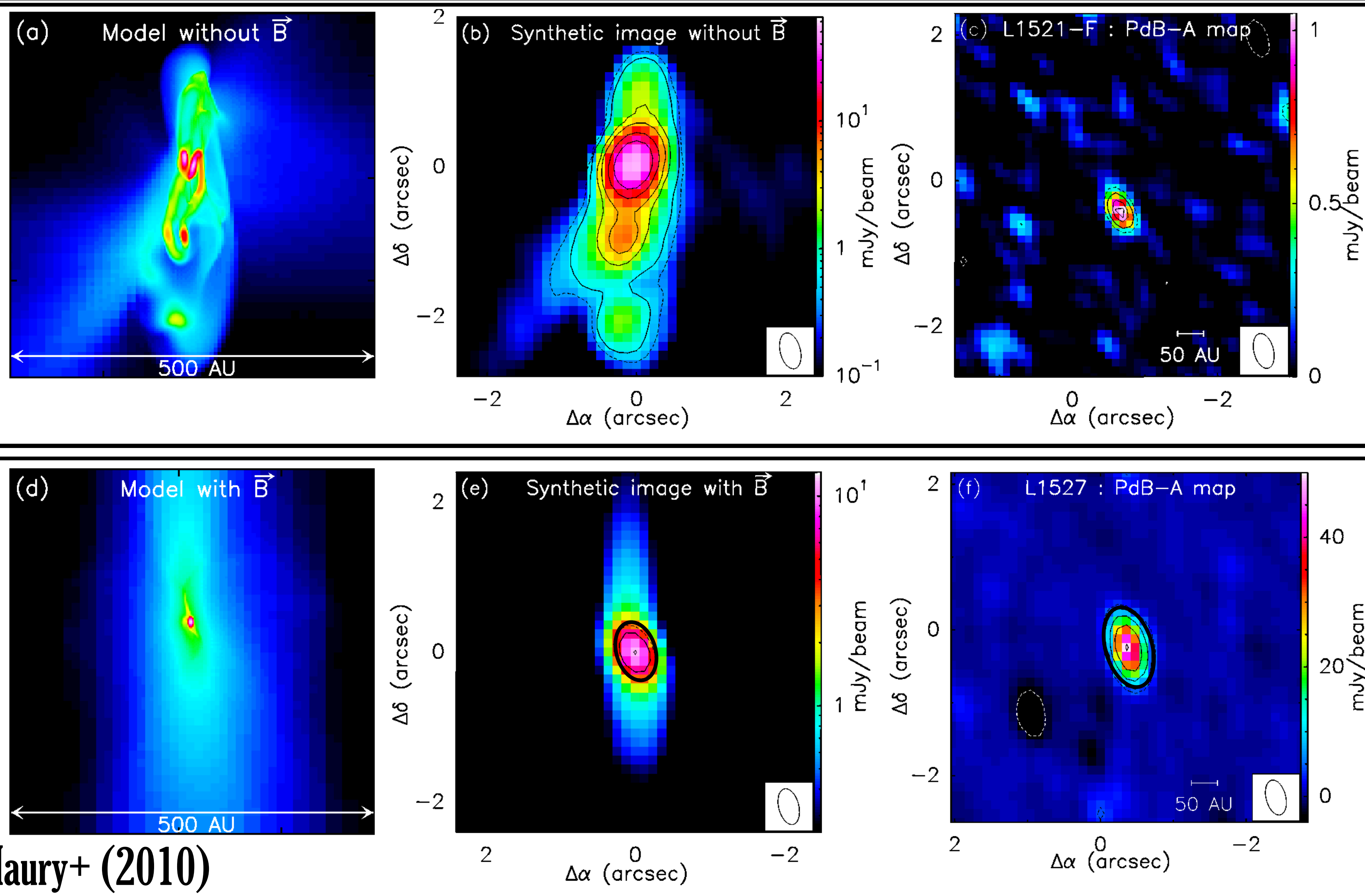
This happens only if the envelope is a lot more massive than the central «disc» region (centrifugal radius, remember!).

Magnetic braking allows to redistribute the angular momentum from the inner infalling envelope to the outer parts of the envelope, and therefore delays the formation of a large rotationally-supported disc.

(Gillis et al. 74,79, Mouschovias & Paleologou 79,80, Basu & Mouschovias 95)

Comparison of Class 0 observations to numerical simulations of star formation

Column density maps from numerical simulations	Synthetic images put at Taurus distance	Observed PdB-A maps of Taurus sources



Maury+ (2010)

Comparison with numerical simulations of SF :

- favor magnetic models of protostellar formation because no large rotationally-supported structure.
- note the presence of a pseudo-disc in the magnetized model ...

A summary

- ## Protostellar classes & lifetimes

  Herschel statistics : a fast main accretion phase (consistent with André+ 2000) < 10^5 yrs

- ## Envelope Infall & Accretion Rates

  Possibly luminosity problem could be reduced by new Herschel statistics and/or ALMA providing us direct constraints on kinematics in the accretion zone
  Episodic accretion proposed as a solution to luminositty problem - and to be tested further

- ## Conservation of angular momentum ?

  Multi-scale analysis over 3 orders of magnitude are needed to assess protostar's angular momentum
  Problem still unsolved: maybe magnetized collapse will help ?

- ## The quest for the youngest disks

  Class I discs: some good constraints reveal larger scatter in properties than previously thought
  Class 0 discs are mostly small (<50 au) : low-end of size distribution still to be probed

- ## Protostellar multiplicity fraction

  Large surveys are coming showing some fragmentation at large (and small?) scales
  Problem of source nature at subarcsecond scales: more versatile ALMA observations will help

- ## Magnetized core collapse ?

  Lack of large disk and need to solve angular momentum problem + observations of magnetized cores
  role of magnetic field to regulate the protostellar accretion has to be investigated

Testing the magnetically regulated scenario:

Probe magnetic fields

Search for small MHD discs : density and kinematics at 10-50 AU scales

Investigate kinematics in young protostars: what about angular momentum ?

NOEMA & ALMA !

ALMA

ALMA Specifications

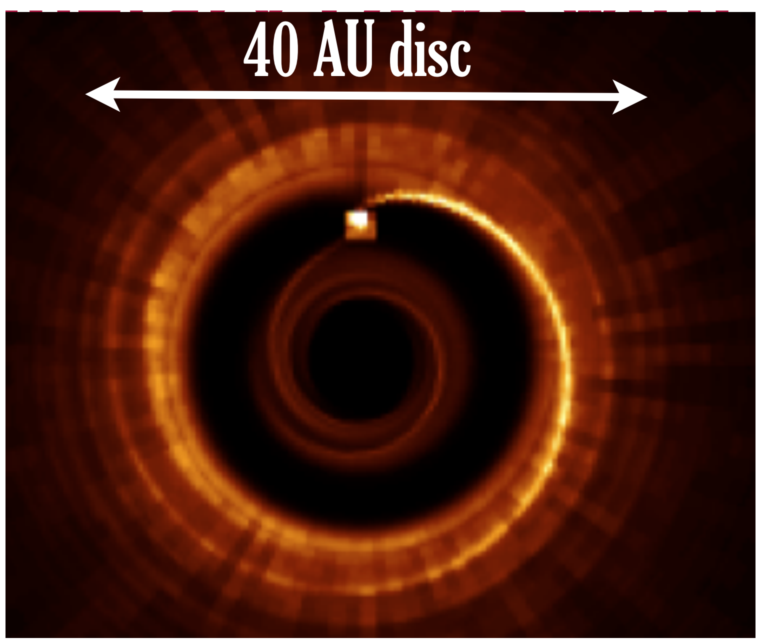
- 54 12-m antennas, 12 7-m antennas, at 5000m site
- Surface accuracy <25 μm, 0.6” reference pointing in 9m/s wind,
  2” absolute pointing all-sky
- Array configurations between 150m and ~15-18km
- Angular resolutions ~40mas at 100 GHz (5mas at 900GHz)
- 10 bands in 31-950 GHz + 183 GHz WVR.
- 8 GHz BW, dual polarization.
- Interferometry, mosaicing & total-power observing.
- Correlator: 4096 channels/IF (multi-IF), full Stokes.
- Data rate: 6MB/s average; peak 64 MB/s.
- All data archived (raw + images), pipeline processing.

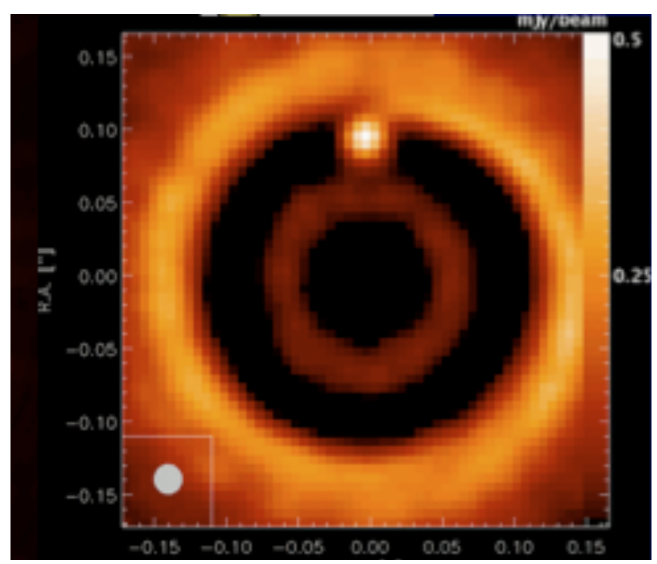
- ALMA improves
  - Sensitivity: 100x
  - Spatial Resolution: up to 100x
  - Wavelength Coverage: ~2x
  - Bandwidth: ~2x
    - Scientific discovery parameter space is greatly expanded!

DV01 makes the climb from the OSF to the AOS (2009)

The Atacama Large Millimeter Array

- A fast instrument ⇨ surveys become possible
- A sensitive instrument ⇨ weak lines, faint objects become accessible
- High angular resolution ⇨ details of star formation
- Wide field imaging with ACA ⇨ from large to small scales
- Wide frequency coverage ⇨ wide range of physical conditions can be adressed
- Polarisation
- But a large survey, at high angular resolution, in full polarisation, over arcmin scales, in several lines, would take forever ⇨ Choices will have to be made





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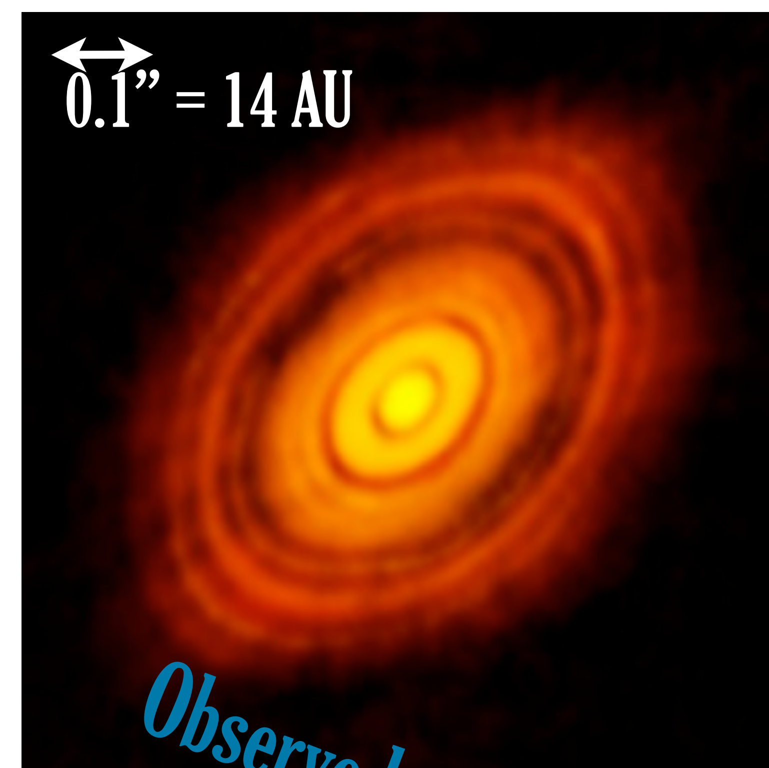

Model → Predictions (2010) → Observed with ALMA (2015)

The Atacama Large Millimeter Array

ALMA is perfect to study the formation of stars

- Initial mass function from large scale surveys (gas + dust images)
- Polarization: the role of magnetic fields
- Complete samples in several types of star-forming regions
- Velocity field (accretion) in envelopes of Class 0 protostars
- (non)-Keplerian discs around YSOs:
  - Star masses from disc kinematics
  - Evolutionary tracks of proto / PMS stars
  - Evolutionary status of discs
  - Planet formation
- Binarity (70 %): gas + dust distribution, tidal truncation of inner / outer disc