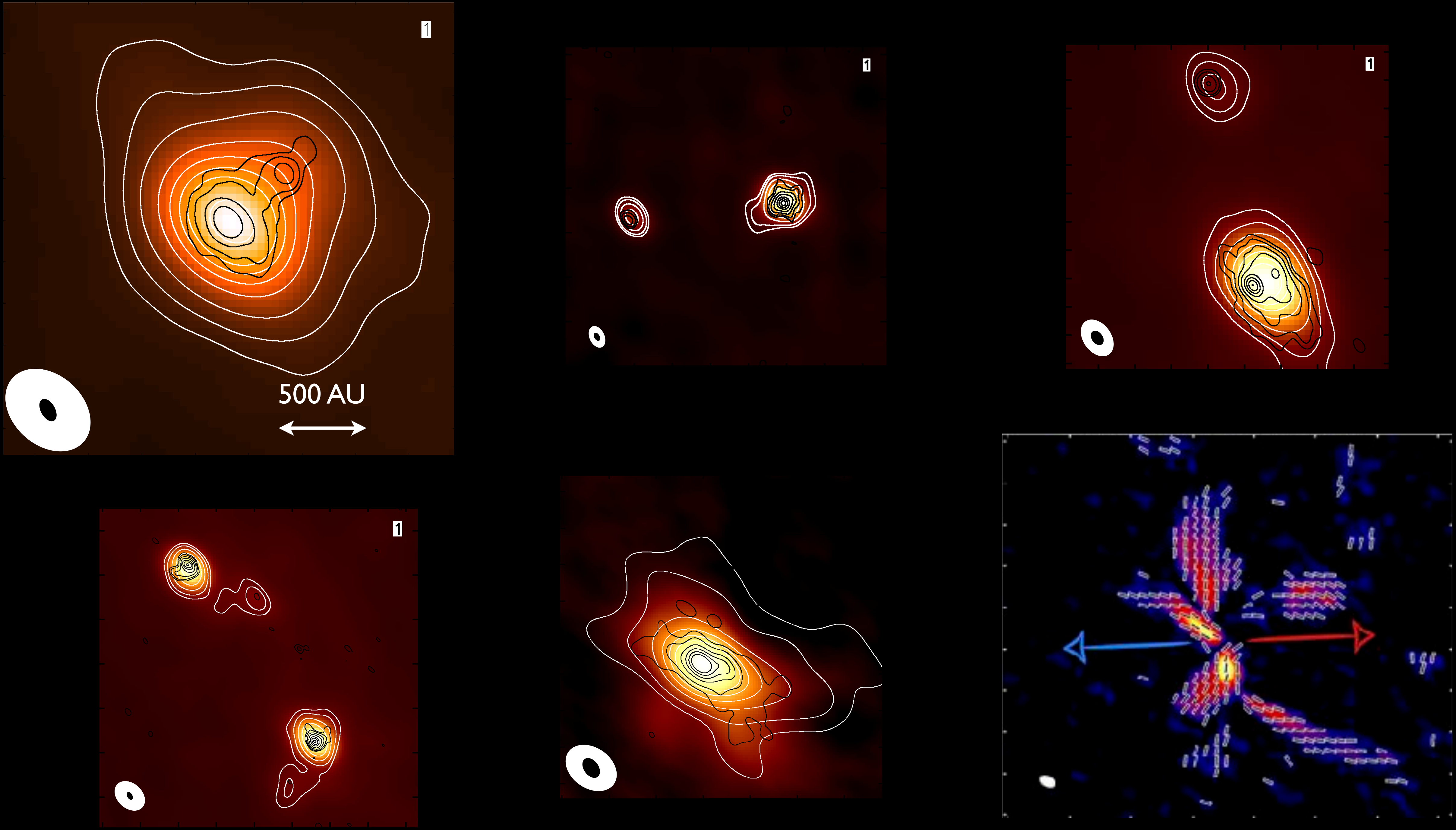
ALMA reveals a magnetically-regulated scenario for protostellar collapse: B335 & future perspectives



ALMA2019 / Anaëlle Maury - CEA Saclay, France

With special thanks to both the CALYPSO and MagneticYSOs collaborators

The angular momentum problem

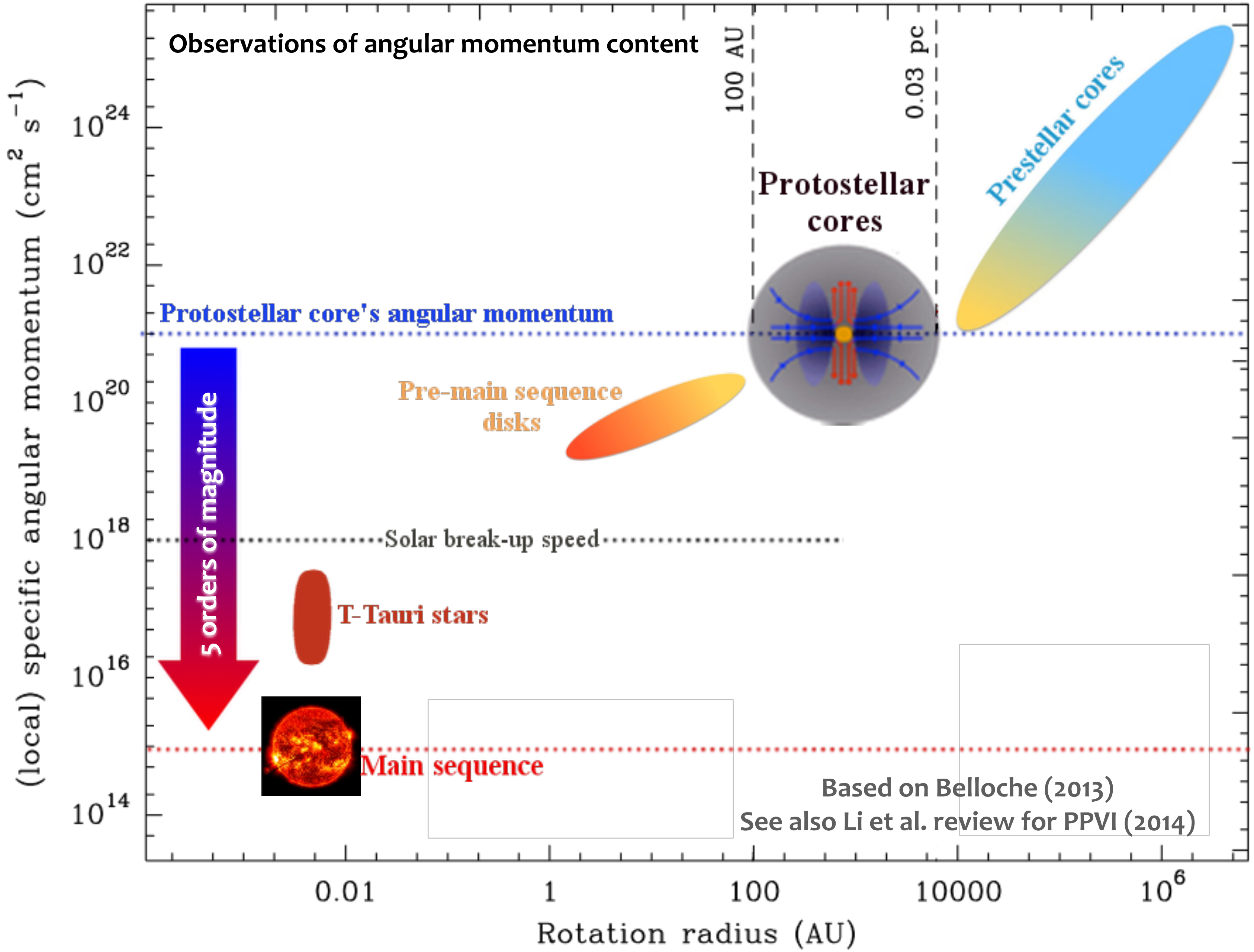
$J = m v r$

core collapses

=> rotation amplified by $(r_2/r_1)^2$

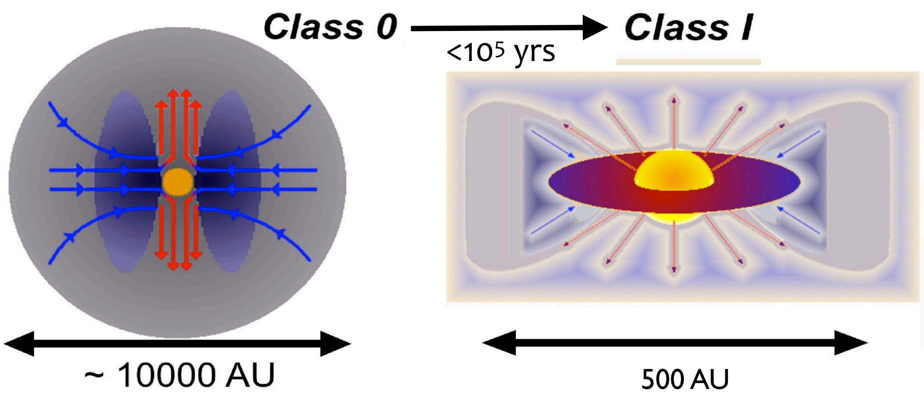
from 0.1 pc core’s diameter to the Sun’s size : factor of 4×10^6 in angular momentum

Protostars must lose >99.99% of their angular momentum prior to entering the T Tauri stage



Based on Belloche (2013)
See also Li et al. review for PPVI (2014)

Class 0 protostars: a key stage for solving the AM problem

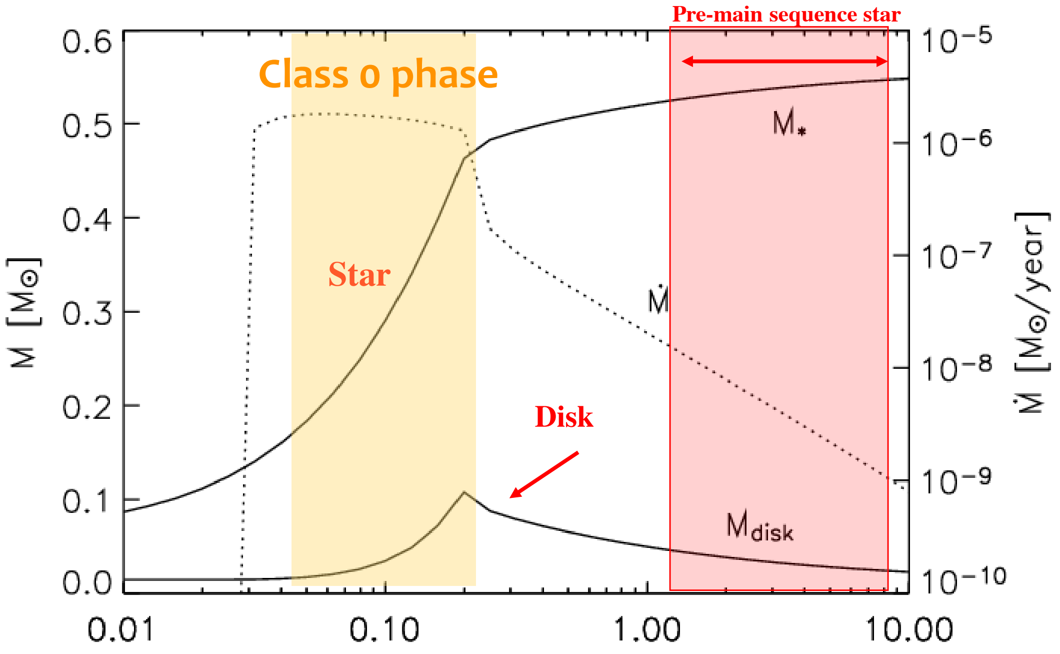


Class 0 phase = main accretion phase

>50% of the final stellar mass is assembled:

need to get rid of the 10.000 AU envelope’s AM during its accretion on 0.1 AU protostellar embryo

Disks as a consequence of AM conservation ?



After Hueso & Guillot (2005)

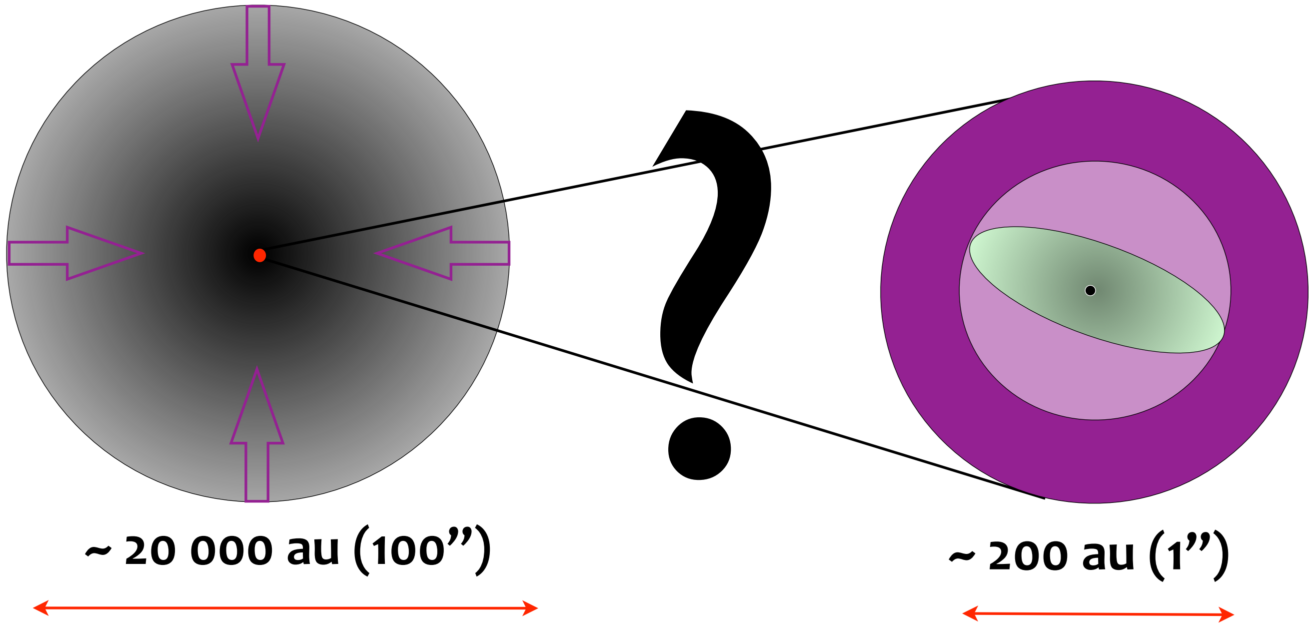
Initial core angular momentum + angular momentum conservation in protostellar collapse

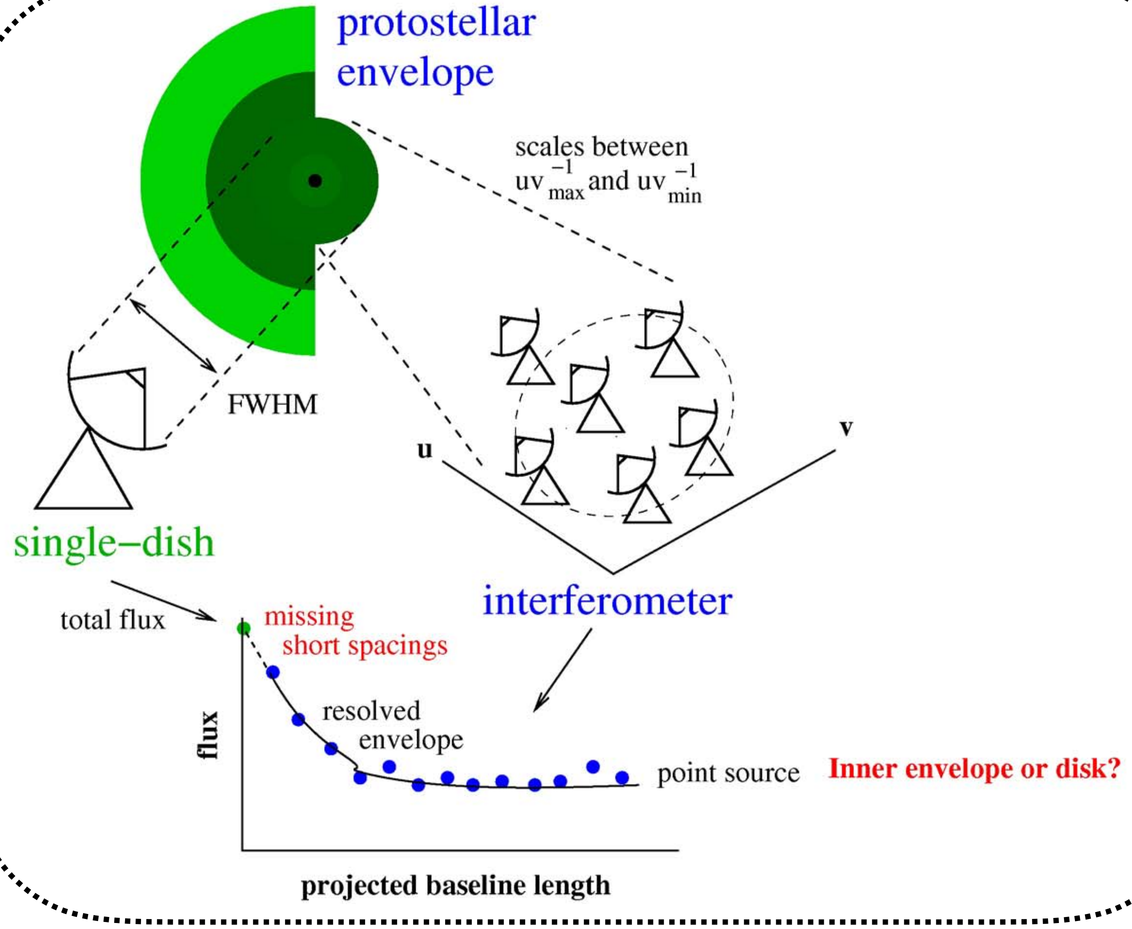
➙ material piles up in disk at centrifugal radius R_c

- $R_c \sim c_s \Omega_0^2 t^3/16$ in traditionally inside-out collapsing core with solid body rotation (Terebey, Shu & Cassen, 1984)
- $R_c \sim t$ in magnetized cores (Basu 1997)

Simple hydrodynamics : ≥100 au disks <10^4 yrs after beginning of collapse.

How to seek for disks in Class 0 protostars ?

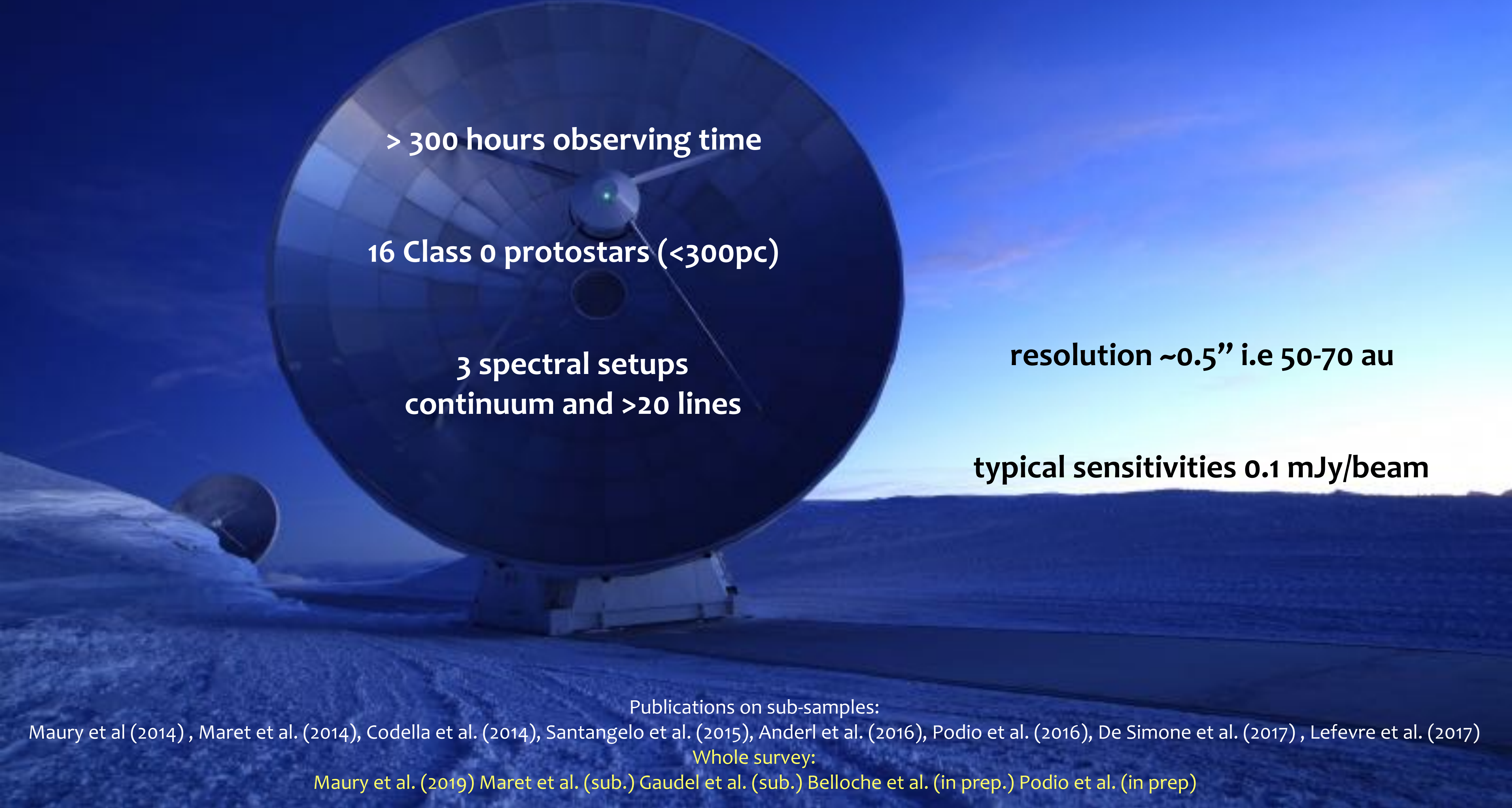




CALYPSO:
the IRAM NOEMA Large Program
to solve the angular momentum problem in Class 0 protostars

A dive into the small-scale physics of the youngest envelopes, disks and outflows.

Ph. André (AIM) - A. Maury (AIM) - C. Codella (INAF) - S. Maret (IPAG); S. Cabrit (LERMA) - F. Gueth (IRAM) - A. Belloche (MPIfR) - L. Testi (ESO / INAF) - B. Lefloch (IPAG) - S. Bontemps (LAB) - P. Hennebelle (AIM) - A. Bacmann (IPAG) - S. Bottinelli (IRAP) - B. Commercon (MPIA) - C. Dullemond (MPIA) - R. Klessen (Heidelberg) - R. Launhardt (MPIA)



> 300 hours observing time

16 Class 0 protostars (<300pc)

3 spectral setups
continuum and >20 lines

resolution ~0.5" i.e 50-70 au

typical sensitivities 0.1 mJy/beam

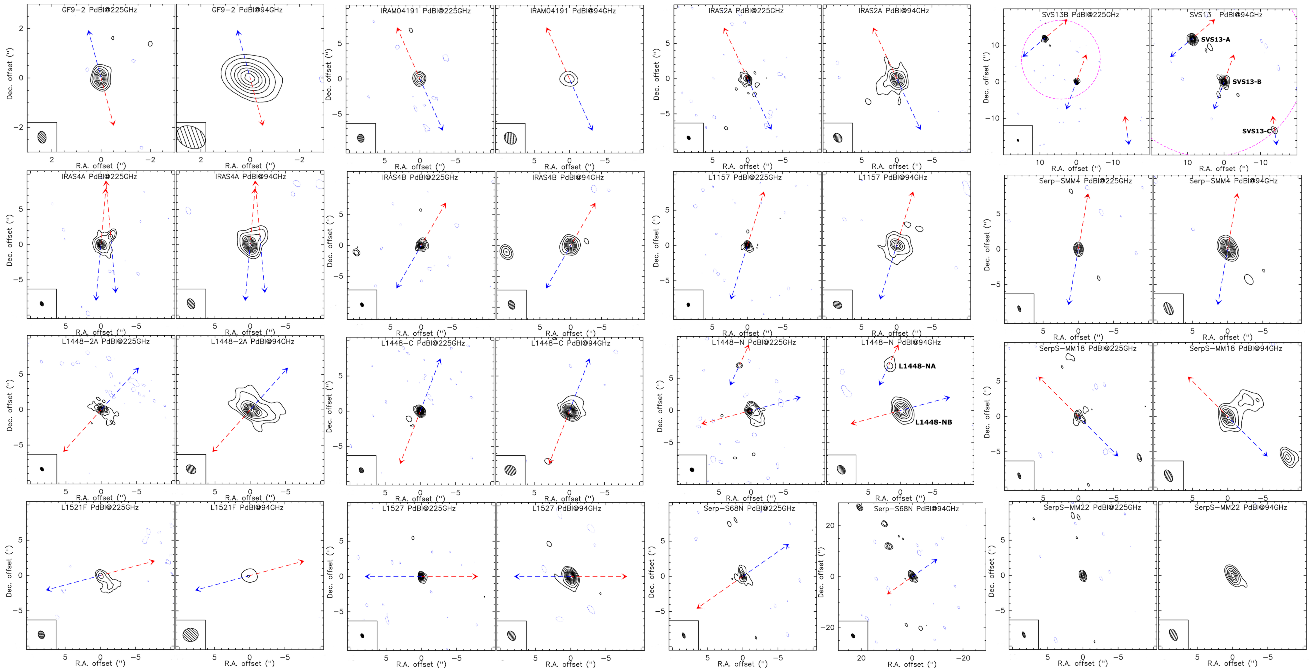
Publications on sub-samples:
Maury et al (2014) , Maret et al. (2014), Codella et al. (2014), Santangelo et al. (2015), Anderl et al. (2016), Podio et al. (2016), De Simone et al. (2017) , Lefevre et al. (2017)

Whole survey:
Maury et al. (2019) Maret et al. (sub.) Gaudel et al. (sub.) Belloche et al. (in prep.) Podio et al. (in prep)

Formation of circumstellar disks during protostellar collapse: young disks are smaller than expected

CALYPSO (IRAM/NOEMA) in 16 Class 0 protostars:

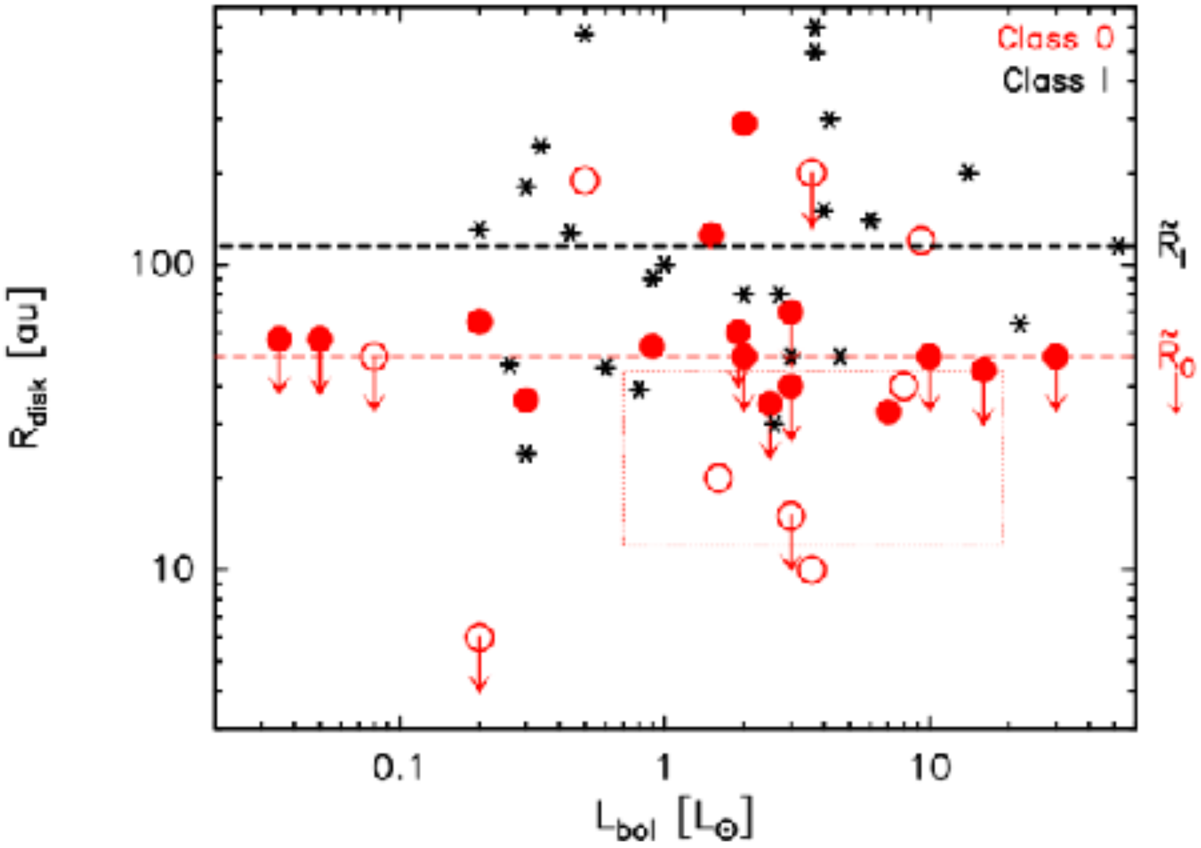
few large disks (20% with $r_{disk} > 60$ au)
median Class 0 disk radius < 40 au



Maury+ (2010, 2014, 2019)

Including the literature (26 Class 0 protostars):

>72% Class 0 disks have $r_{disk} < 60$ au



See Maury, André, Testi & CALYPSO collab (2019)

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

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

$L = Mr^2\Omega$ final size r, final spin Ω

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

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

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

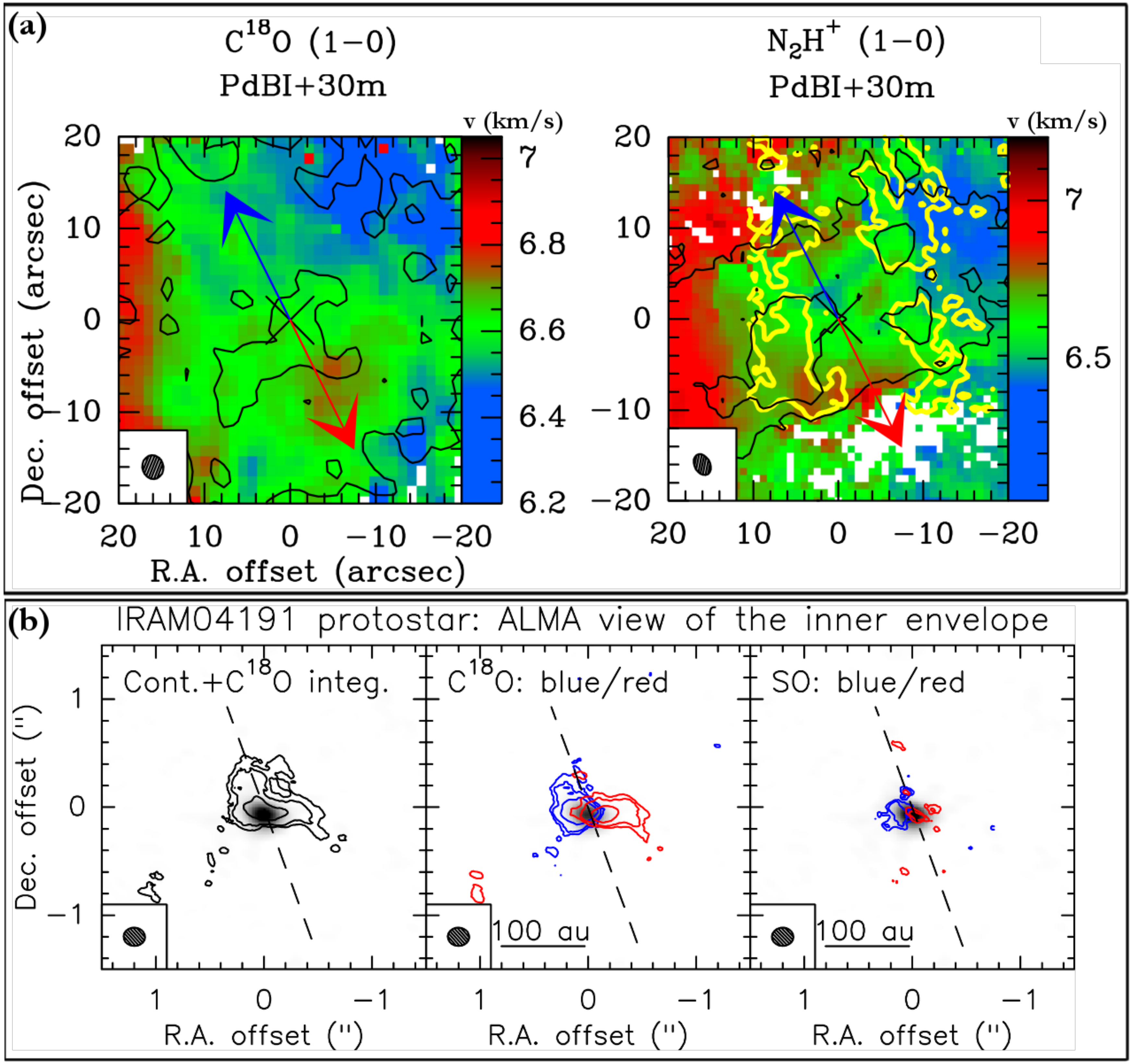
→

Upper-limits on disk radii are smaller by at least 50 % than radii expected from hydrodynamical scenarii

A counter-rotating disk in IRAM04191 ?

Envelope scale

Disk scale

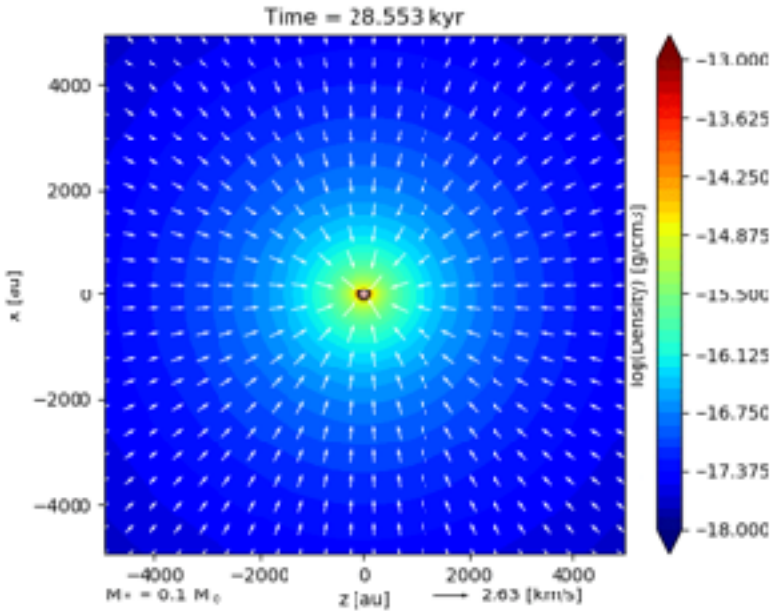


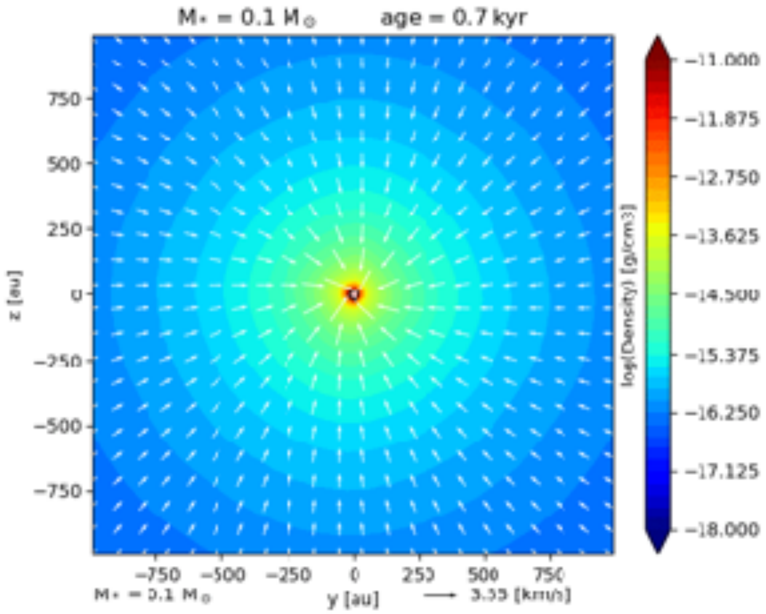
Gaudel, Maury, Belloche & CALYPSO, sub.

Maury et al., IAUS345 & in prep.

The disk is counter-rotating wrt the envelope rotation pattern at 5000 au scales !

Comparison to synthetic observations from numerical simulations of protostellar collapse

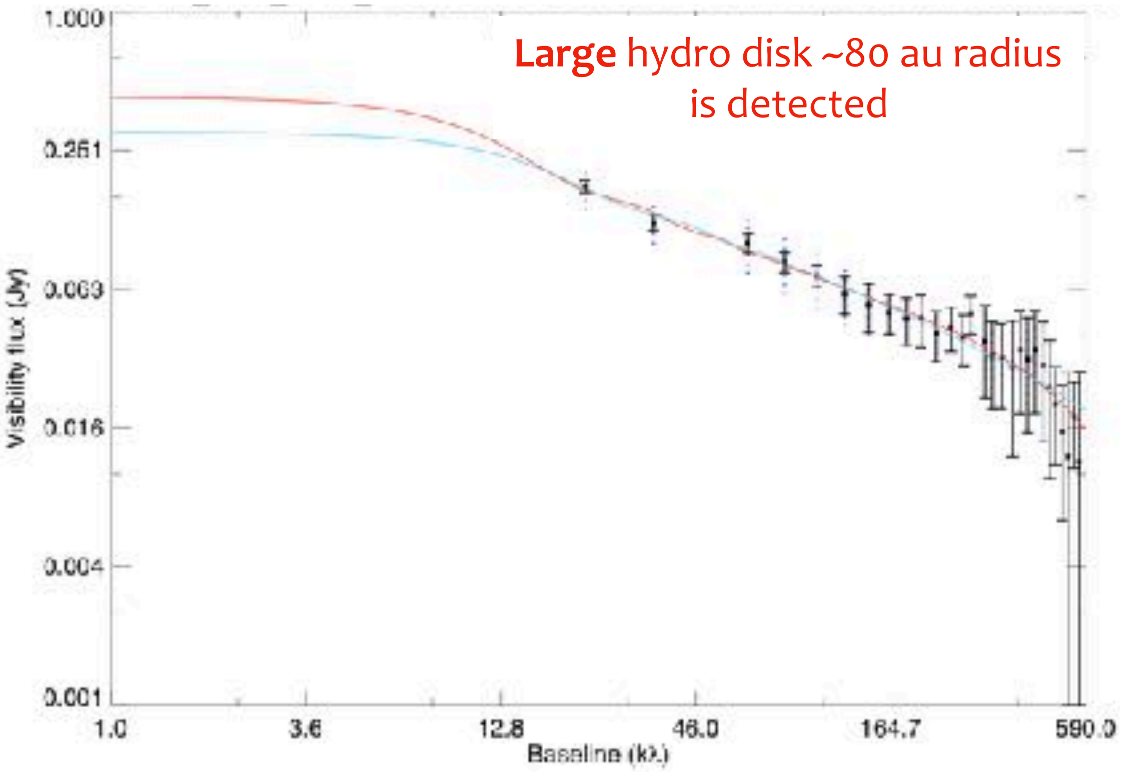




RAMSES MHD simulations by P. Hennebelle & M. Gonzales

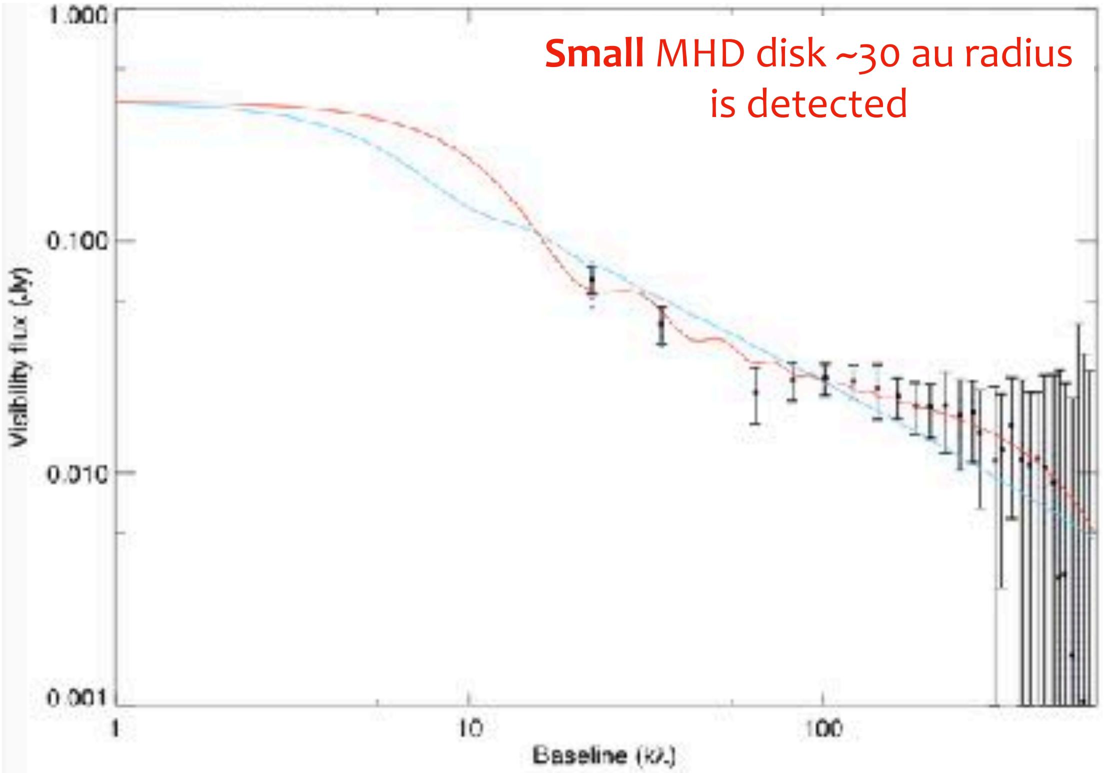
Production of synthetic visibilities
from non-ideal MHD model
=> mm dust continuum emission observed with NOEMA

No magnetic field



Large hydro disk ~80 au radius is detected

Moderate magnetic field



Small MHD disk ~30 au radius is detected

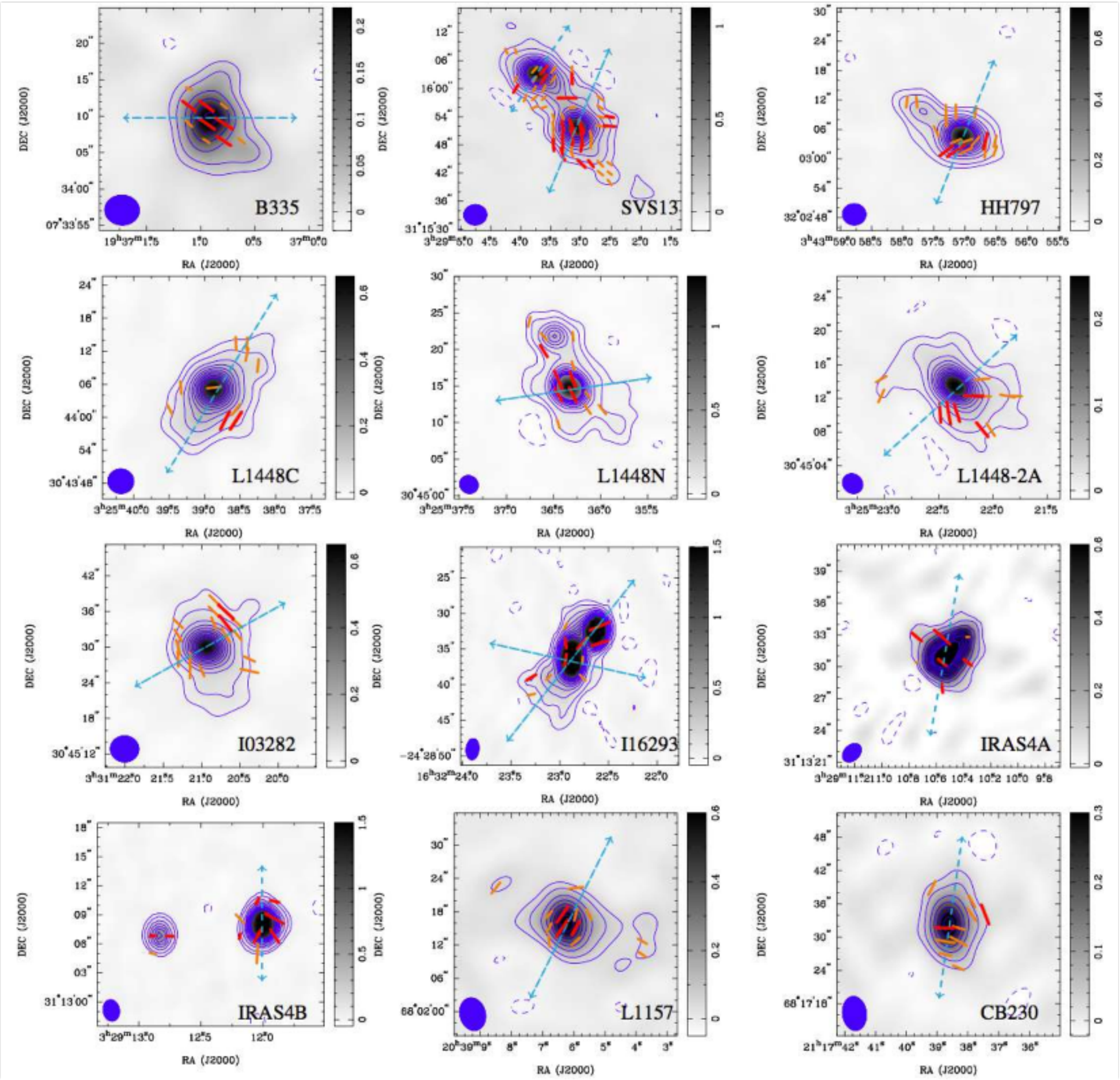
The small disk sizes favor scenarii where the magnetic field is DYNAMICALLY relevant to shape disks

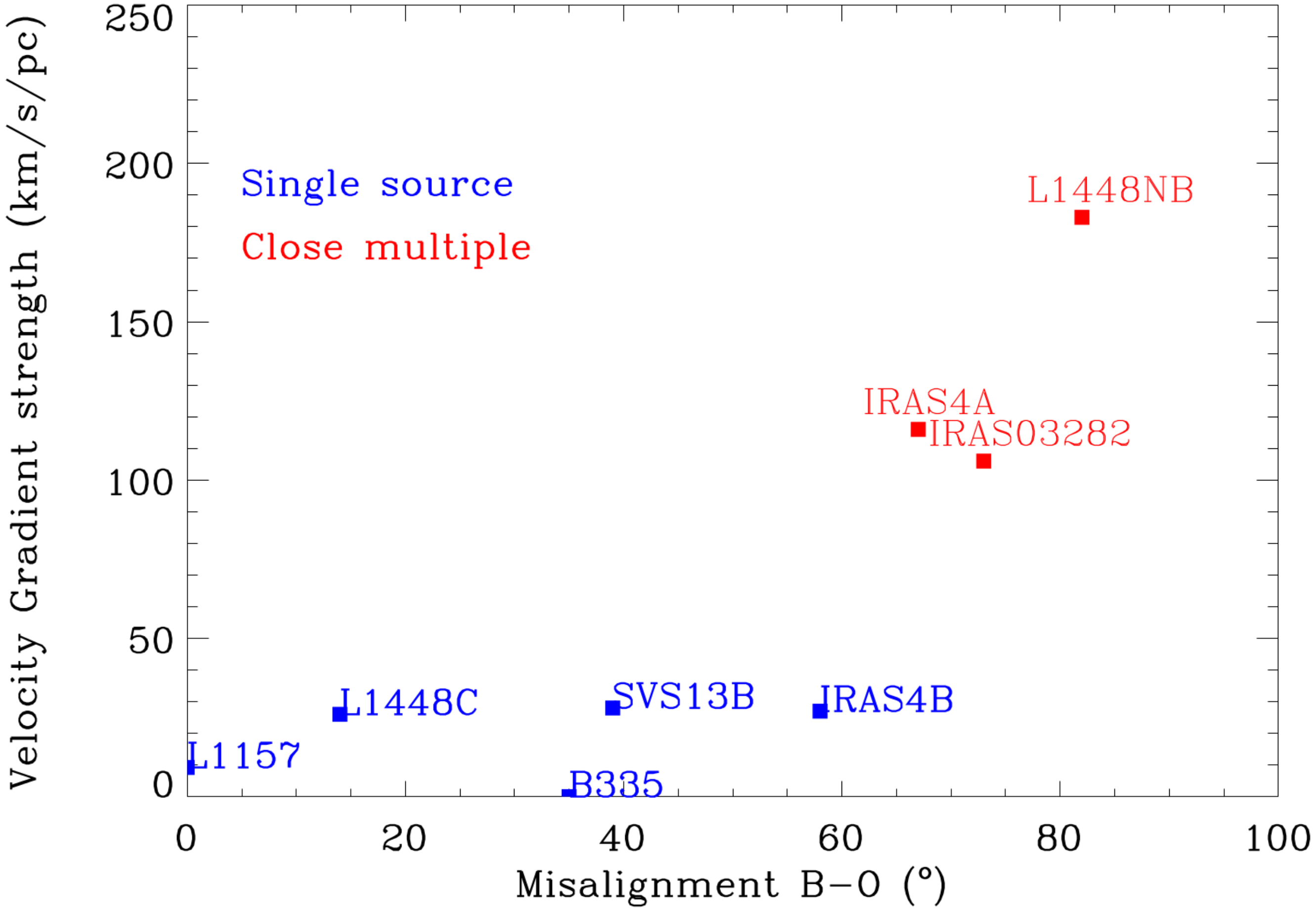
Statistical confirmation of what already suggested in Maury+ (2010), Maury+ (2014), Yen+ (2015) for example

All protostellar envelopes are magnetized to some level: A possible link between B topology and the disk properties ?

12/12 detections with SMA: all low-mass protostars seem to be magnetized at some level

Galametz, Maury, Girart+ (2018)



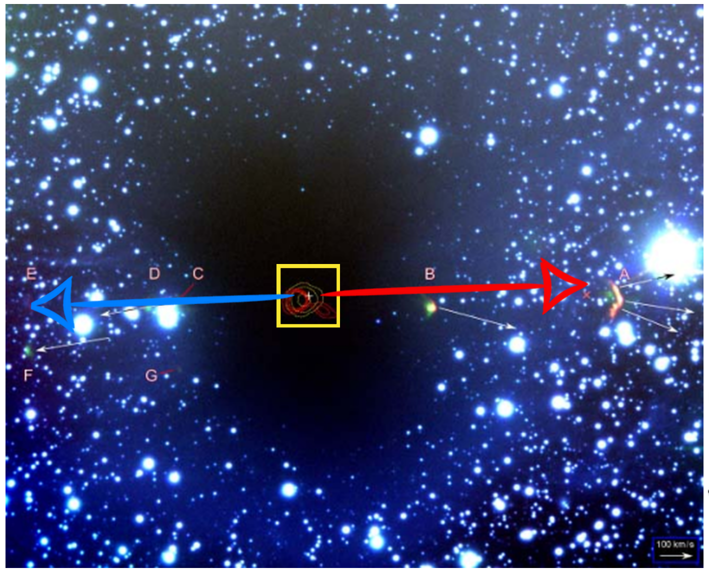


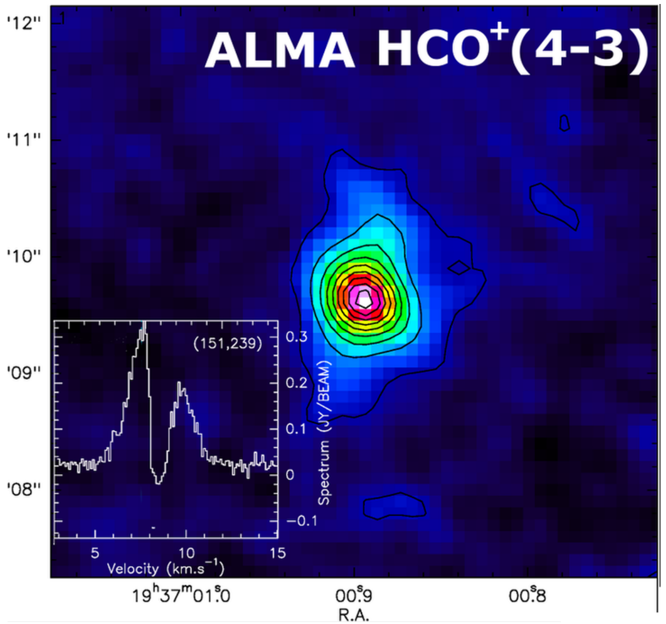
Envelope-scale B-field misalignment is found preferentially in protostars that are close multiple and/or harbor a larger Keplerian disk ?

Current sample: 12 protostars. New study with double sample coming out soon

A magnetically-regulated collapse in B335 ?

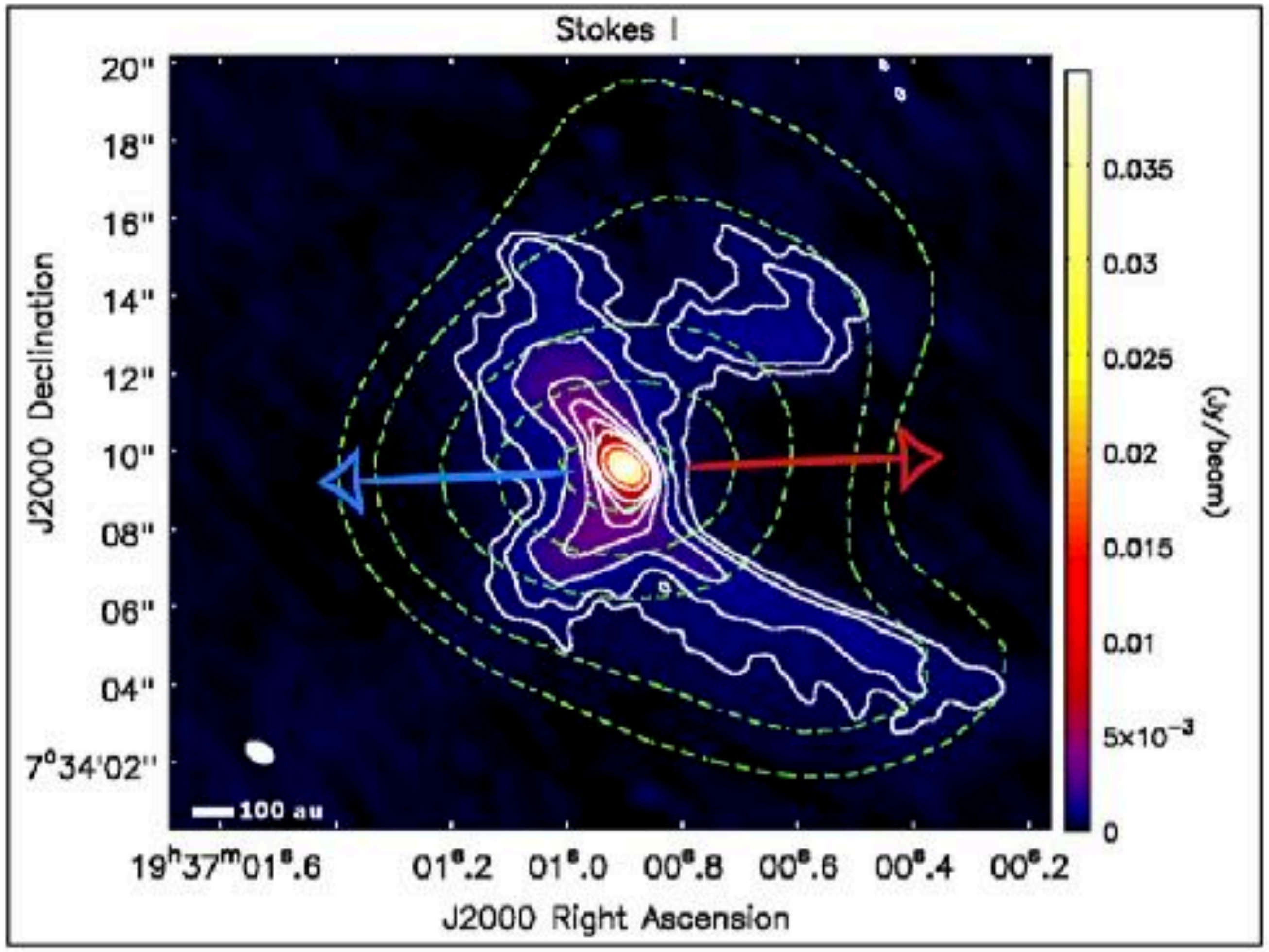
B335 protostar

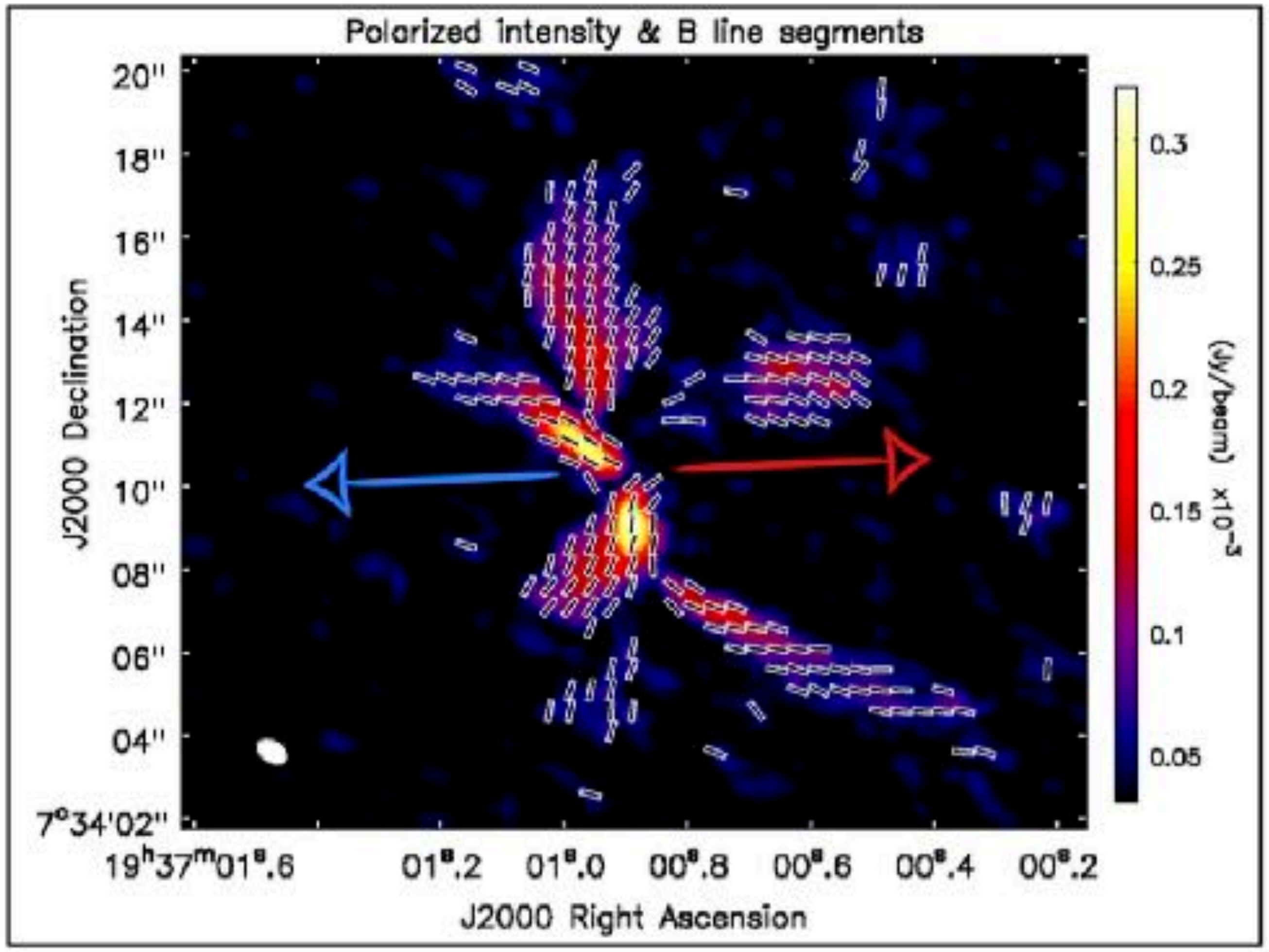




See poster by V. Cabedo

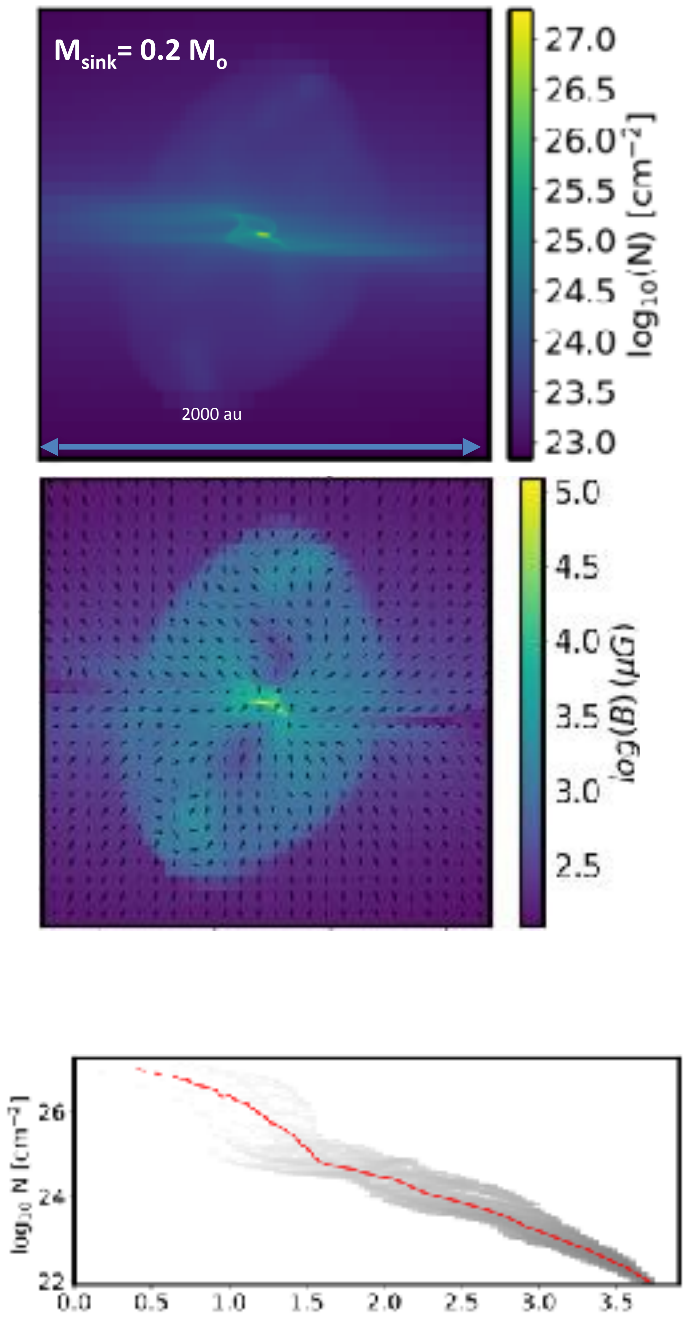
ALMA observations of the 1.3mm dust continuum polarization (Maury, Girart, Zhang + 2018)

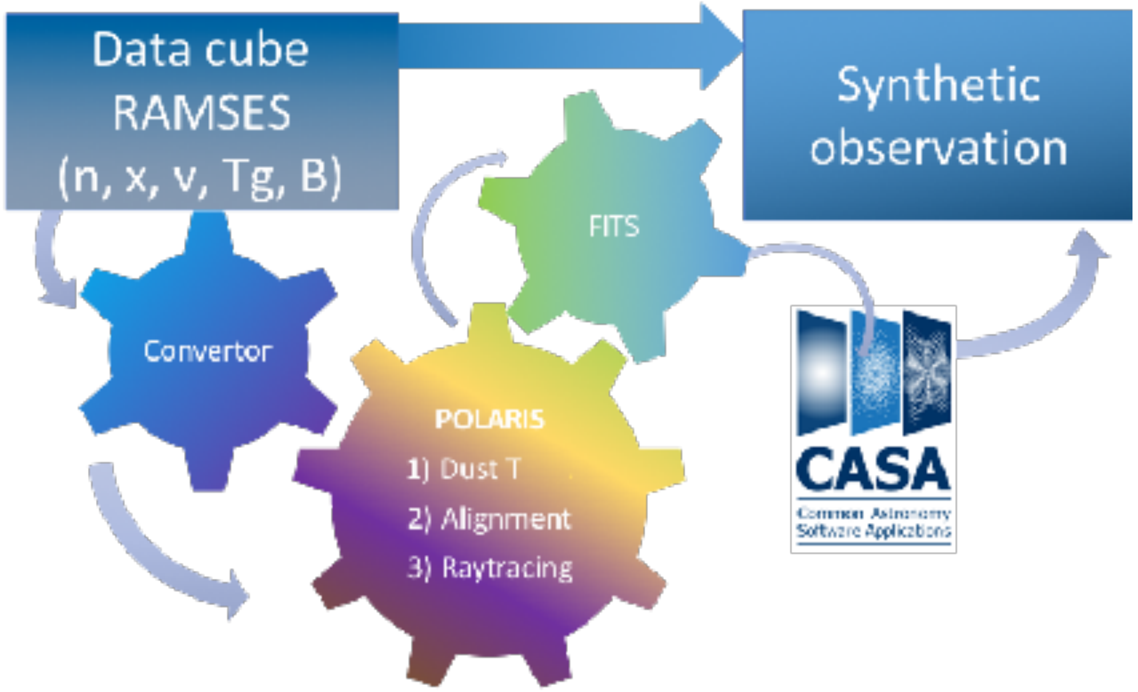




Synthetic observations of protostellar collapse models

Our ALMA synthetic observations of dust (and lines) polarized emission maps, works on MHD simulations outputs developed by V. Valdivia in the framework of the MagneticYSOs ERC





Data cube RAMSES (n, x, v, Tg, B)

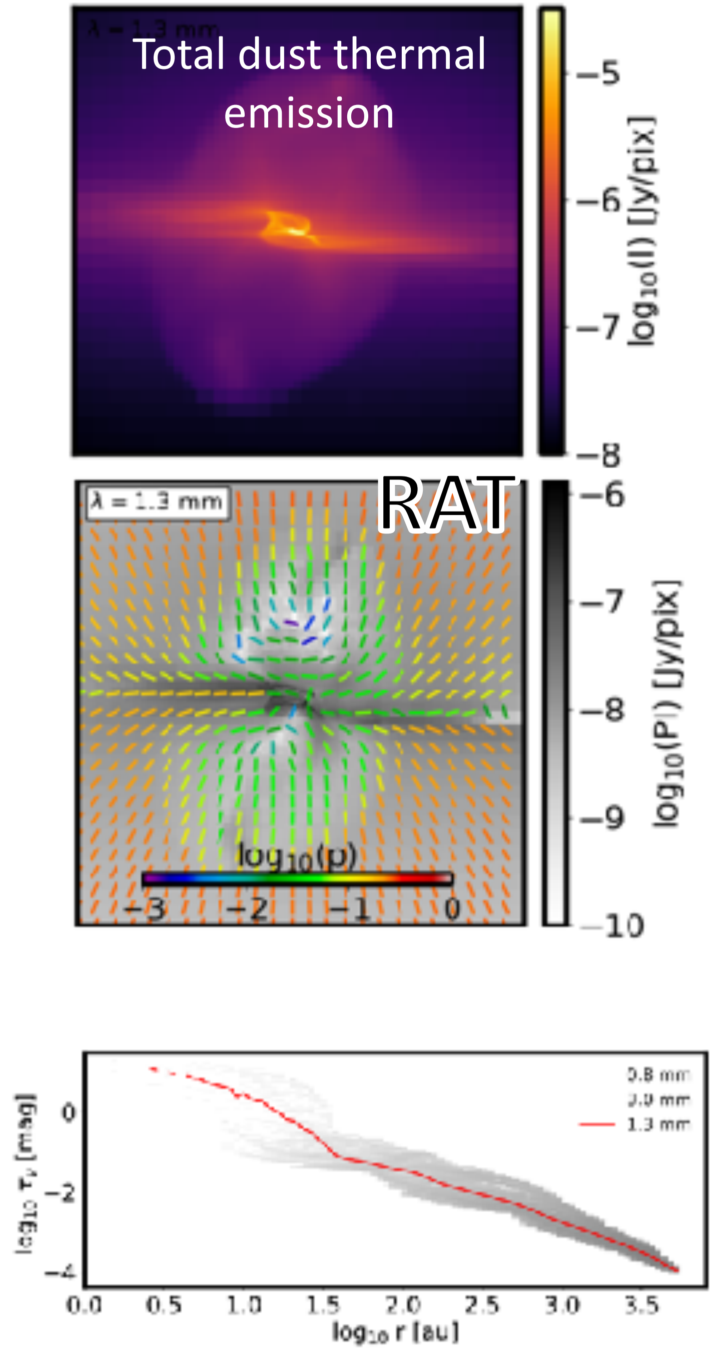
Synthetic observation

FITS

Convertor

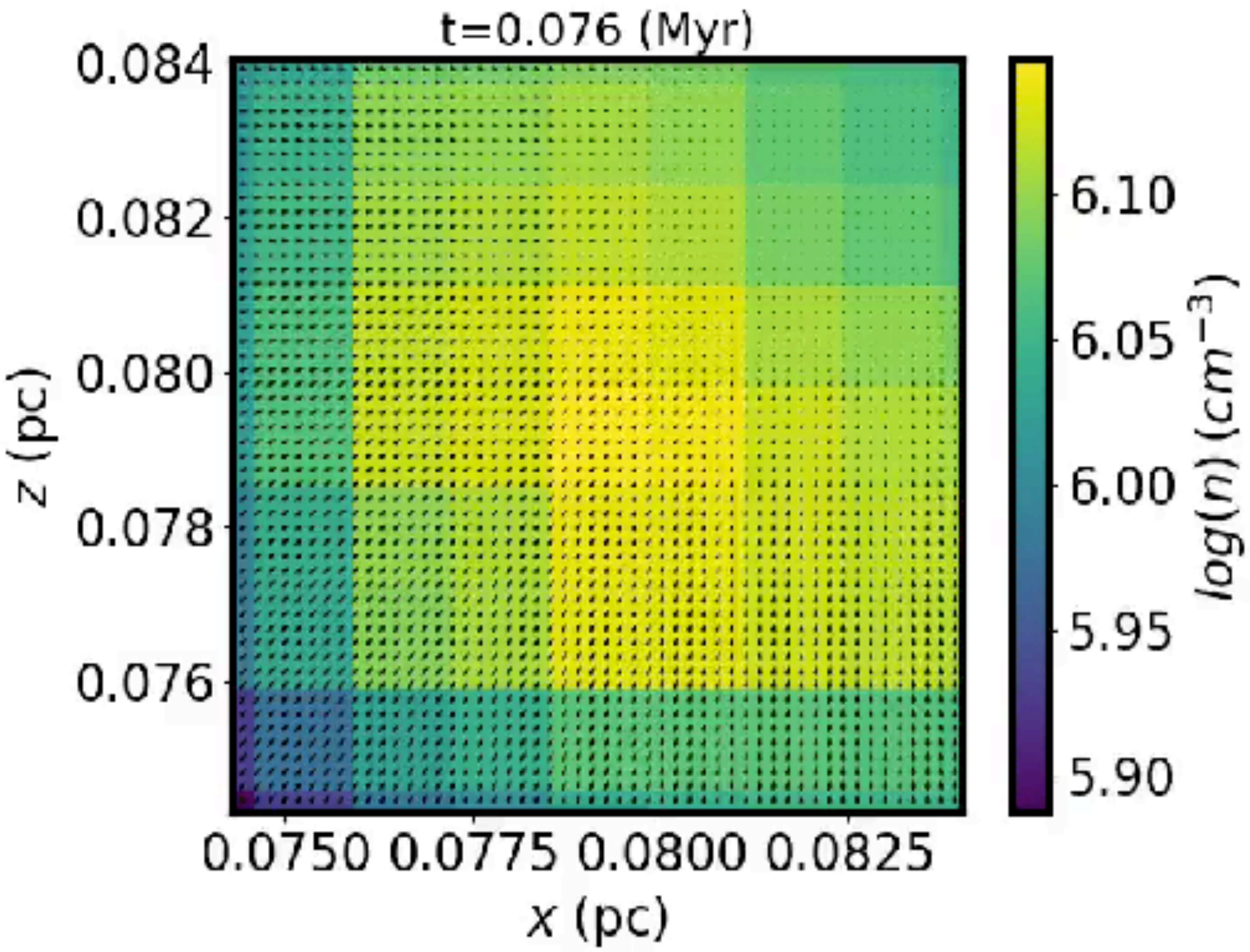
POLARIS
1) Dust T
2) Alignment
3) Raytracing

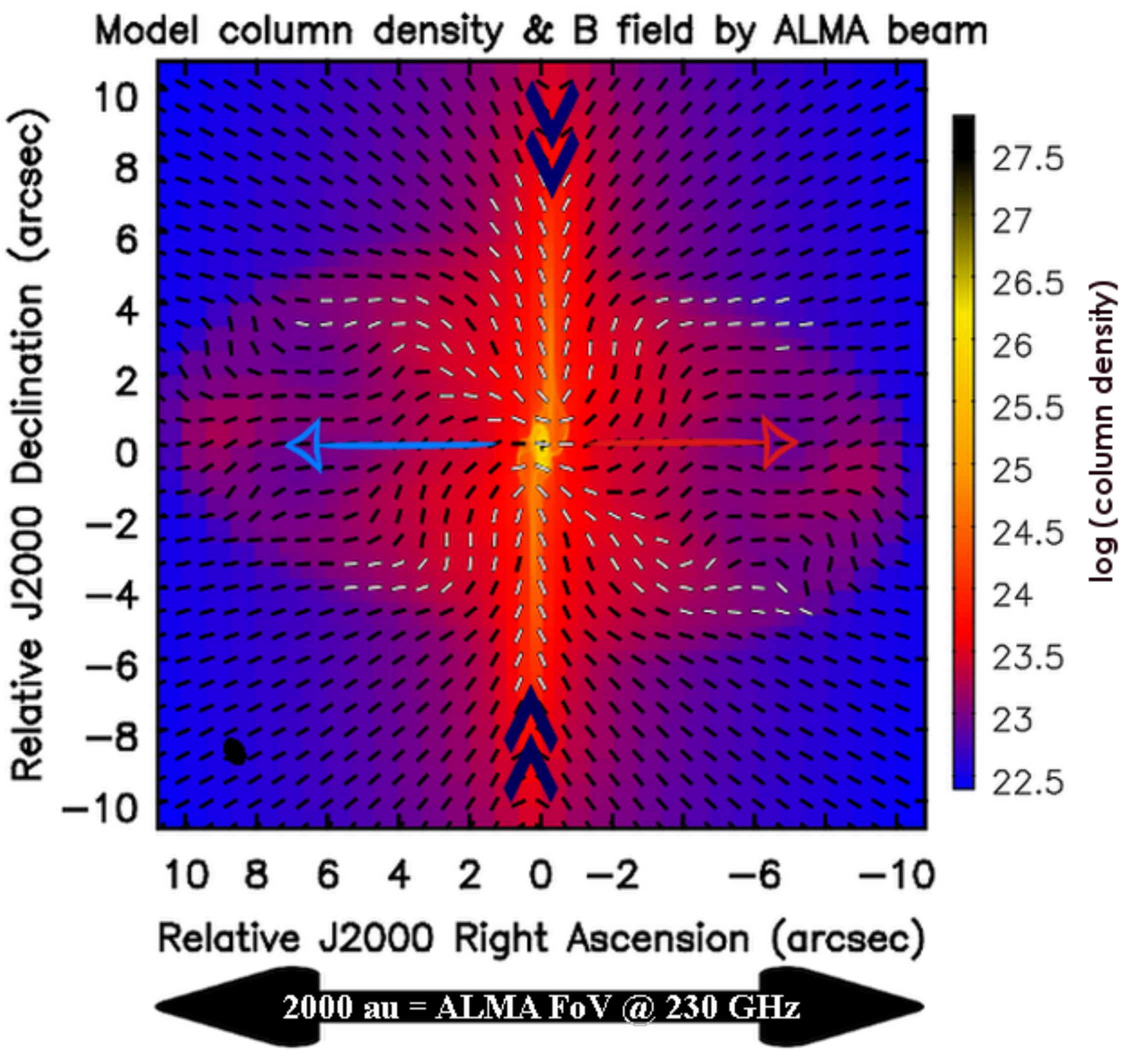
CASA
Common Astronomy Software Applications



A magnetically-regulated collapse in B335 ?

Comparison to synthetic observations of non-ideal MHD models of protostellar collapse





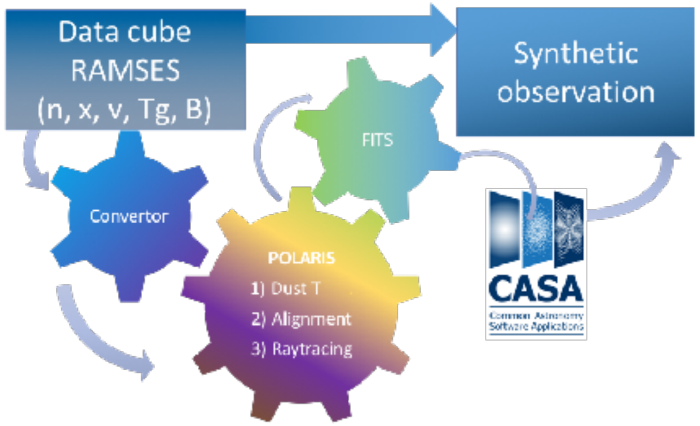
Parameter space:
Core: 2.5 Msun
Times: 0.07, 0.14 and 0.2 Myrs
Mass-to-flux ratio mu : 3, 5, 6, 10
Rotational energy beta 0.1% 1% 10%
Turbulent energy: Mach 0.01 0.2 0.5 1.0

Best model: Egrav/Emag ~ 6

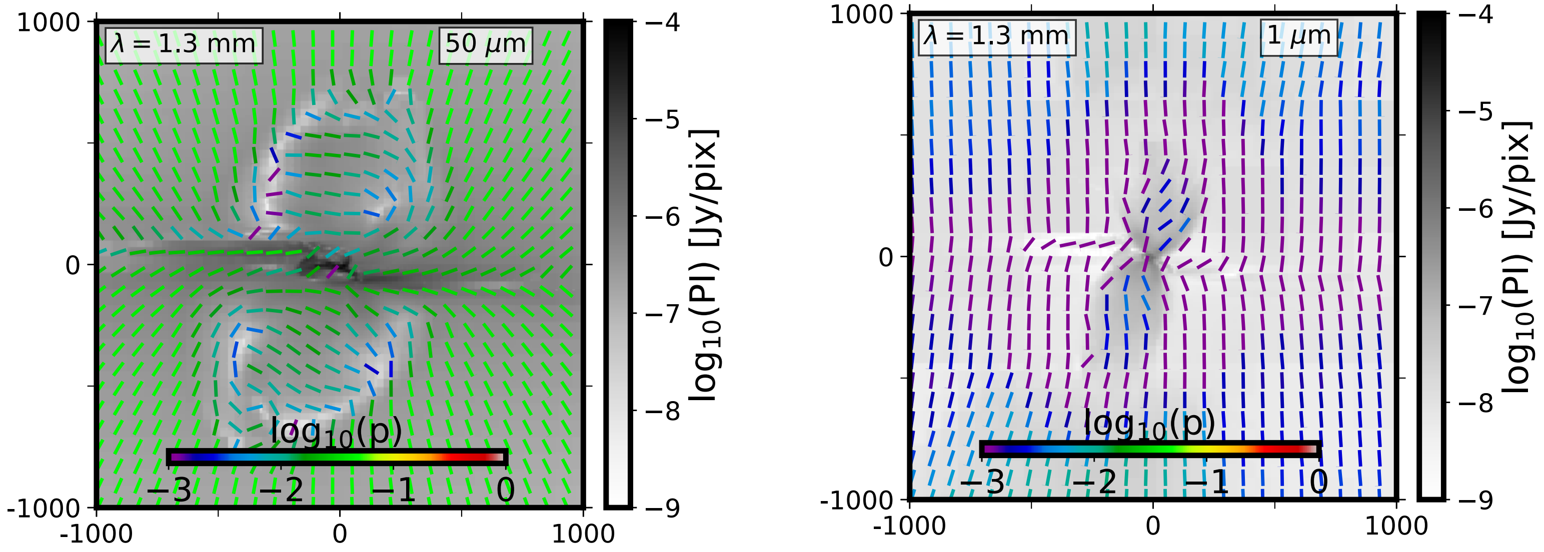
=> B regulates the distribution of angular momentum, and the formation of the protostellar disk

Maury, Girart, Zhang + (2018)

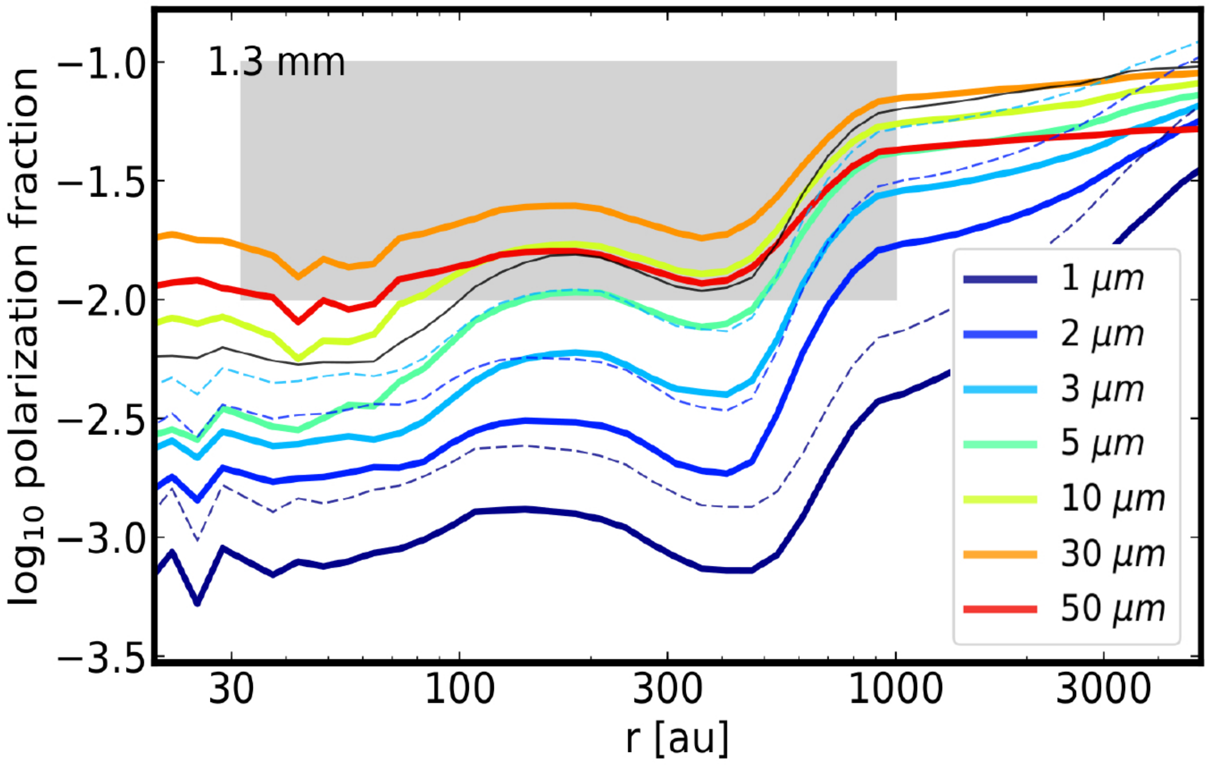
Dust polarization fractions suggest big grains in protostellar cores



Valdivia+ 2019



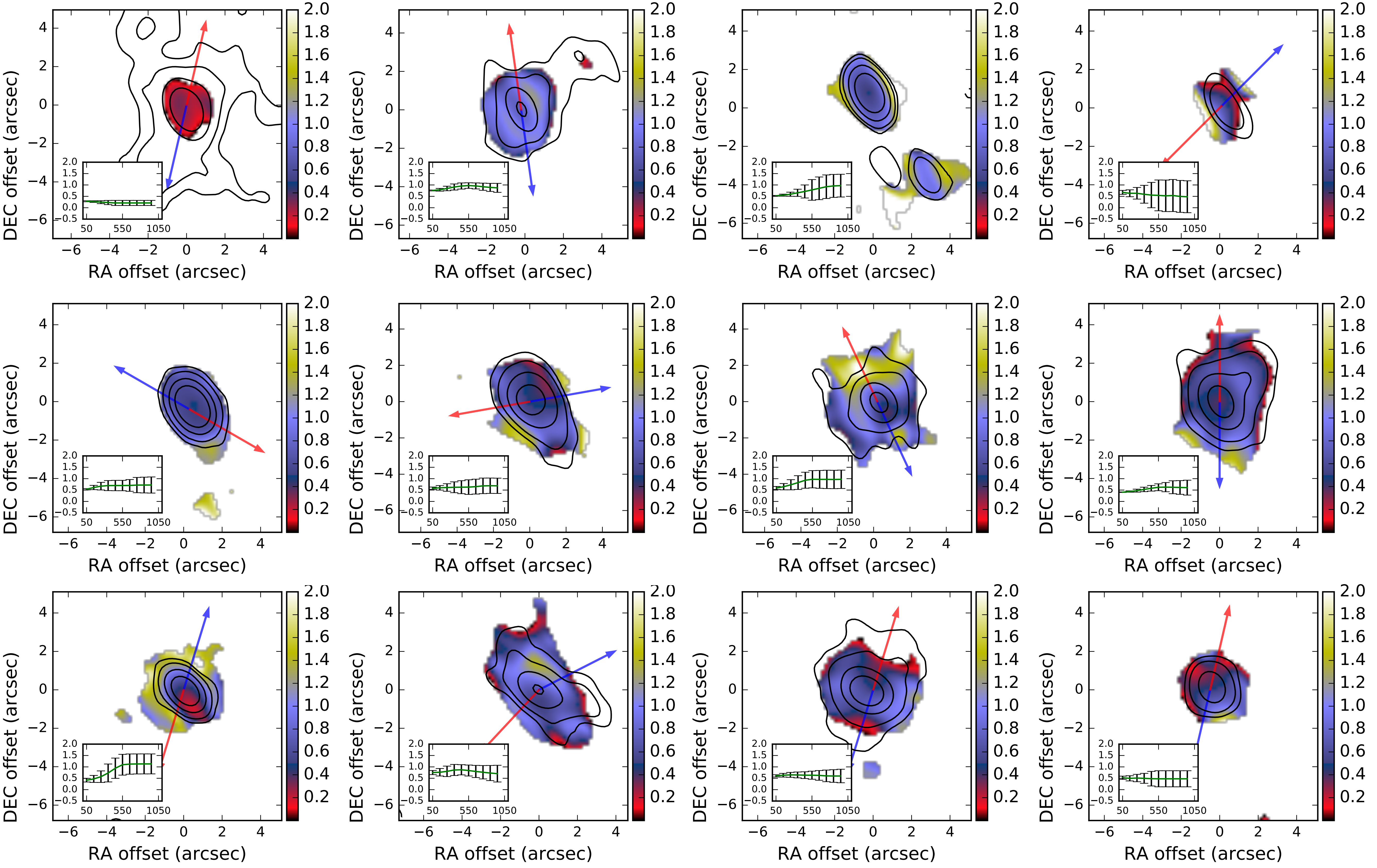
Valdivia, Maury, Brauer + (2019): observed polarization fractions suggest **big grains (> 10 µm) have already grown** at scales 100 – 1000 au in the youngest protostellar objects



See also Le Gouellec, Hull, Maury + (2019)
And Valentin's poster !

Observational signatures of early grain growth in the youngest protostars ?

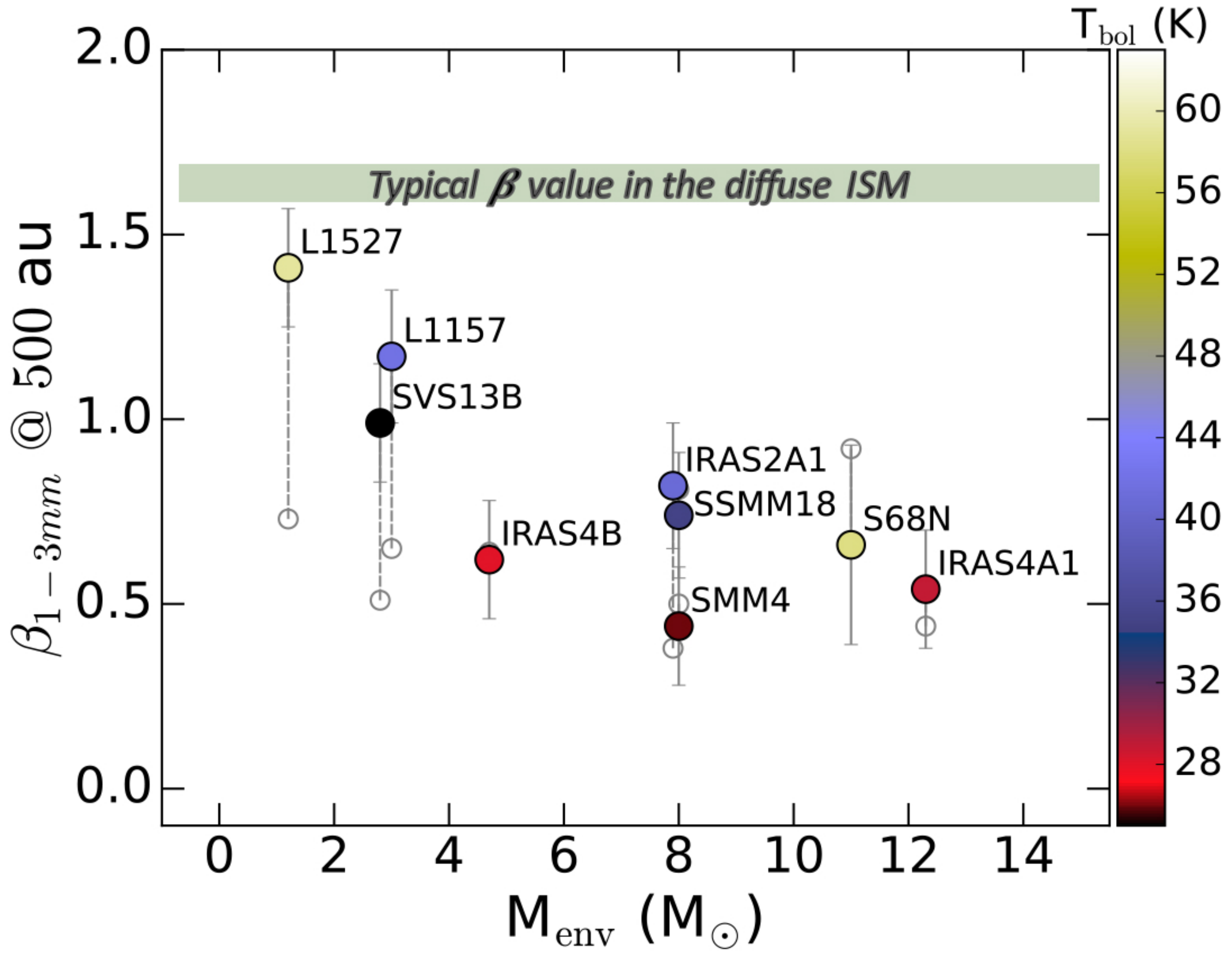
Analysis of mm dust emissivities in the CALYPSO protostars

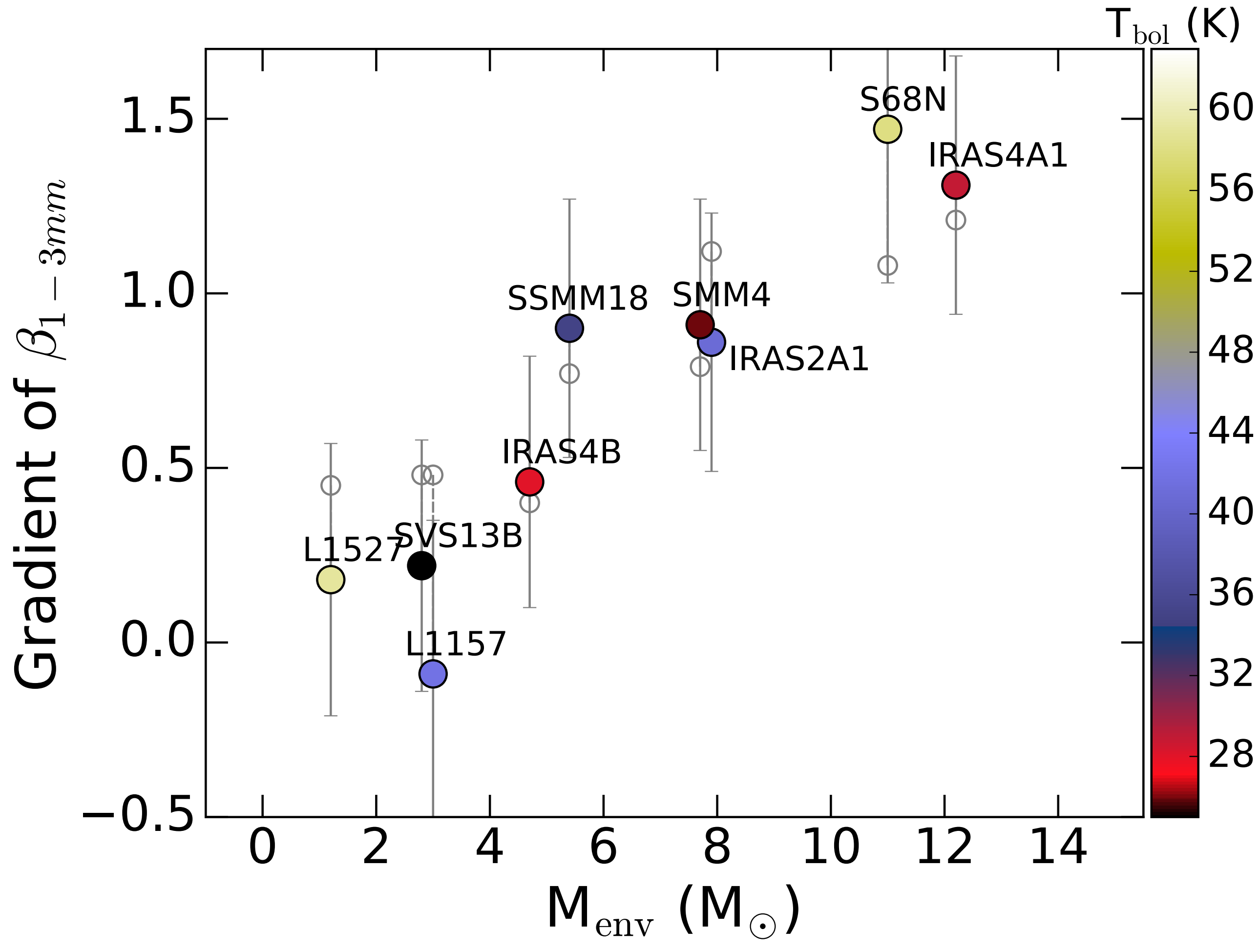


Observational signatures of early grain growth in the youngest protostars ?

VERY low dust opacity spectral indices in ALL of the CALYPSO Class 0 envelopes

+ radial gradients
+ dependent on envelope mass



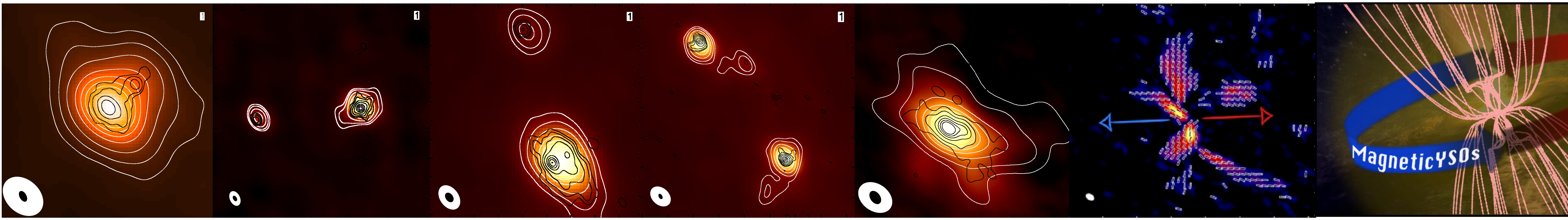


Galametz, Maury, Valdivia + (2019) : early grain growth < 0.1 million years after the onset of collapse

Pebbles up to mm size at scales 500 – 2000 au ?!!!

See also some low dust emissivities in Miotello+ 2014 (Class I), Sadavoy+ 2017 (Orion cores)

Disks, dust and magnetic fields in the youngest accreting protostars: summary



- ALMA and NOEMA reveal few large Class 0 disks : $<28\%$ have $r_{disk} > 60$ au + median Class 0 disk radius ~40 au
- Disk radii are smaller by at least 50 % than radii expected from hydrodynamical models with AM conservation
- Disk size distribution favors magnetized models of protostellar disk formation
- All protostellar envelopes are magnetized ?
- In B335, the collapse is magnetized and the disk size is dictated by magnetic braking
- The properties of dust emission(widely used to weight protostars and derive B-field) are at odds with ALL ISM dust models currently on the market
- If verified, our results suggest the first mm pebbles are already present in Class 0 envelopes: quid of the planet formation timeline ?

Thanks !

CALYPSO dust continuum emission analysis

Envelope description in the spatial domain

$$\rho(r) = \rho_{\rm flat}\left[\frac{R_{\rm flat}}{\left(R_{\rm flat}^2 + r^2\right)^{1/2}}\right]^p \equiv \frac{\rho_{\rm flat}}{\left(1+(r/R_{\rm flat})^2\right)^{p/2}} \qquad T(r) = 60\left(\frac{r}{2\times10^{15}\ {\rm m}}\right)^{-q}\left(\frac{L_{\rm bol}}{10^5\ {\rm L}_\odot}\right)^{q/2}\ {\rm K}$$

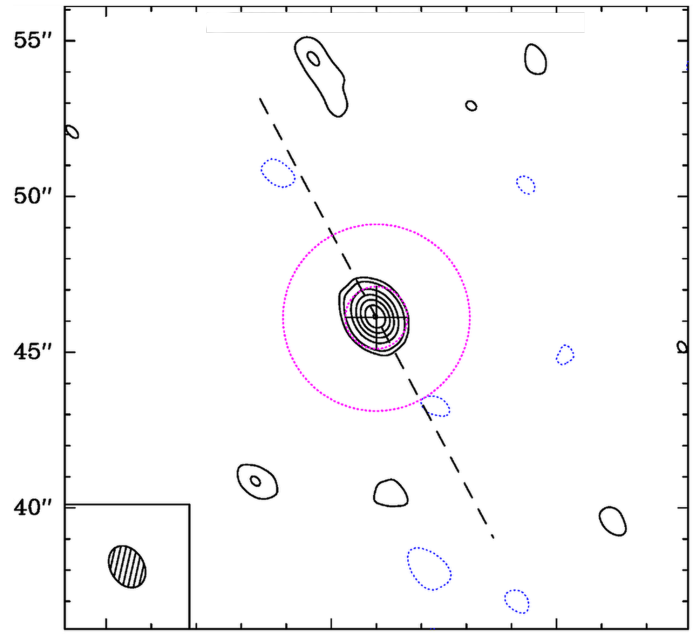
$$\Longrightarrow I(r) \propto r^{-(p+q-1)}$$

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

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

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

IRAM04191: continuum @ 231Ghz



IRAM04191 envelope visibility profile

Zoom on the PdBI data