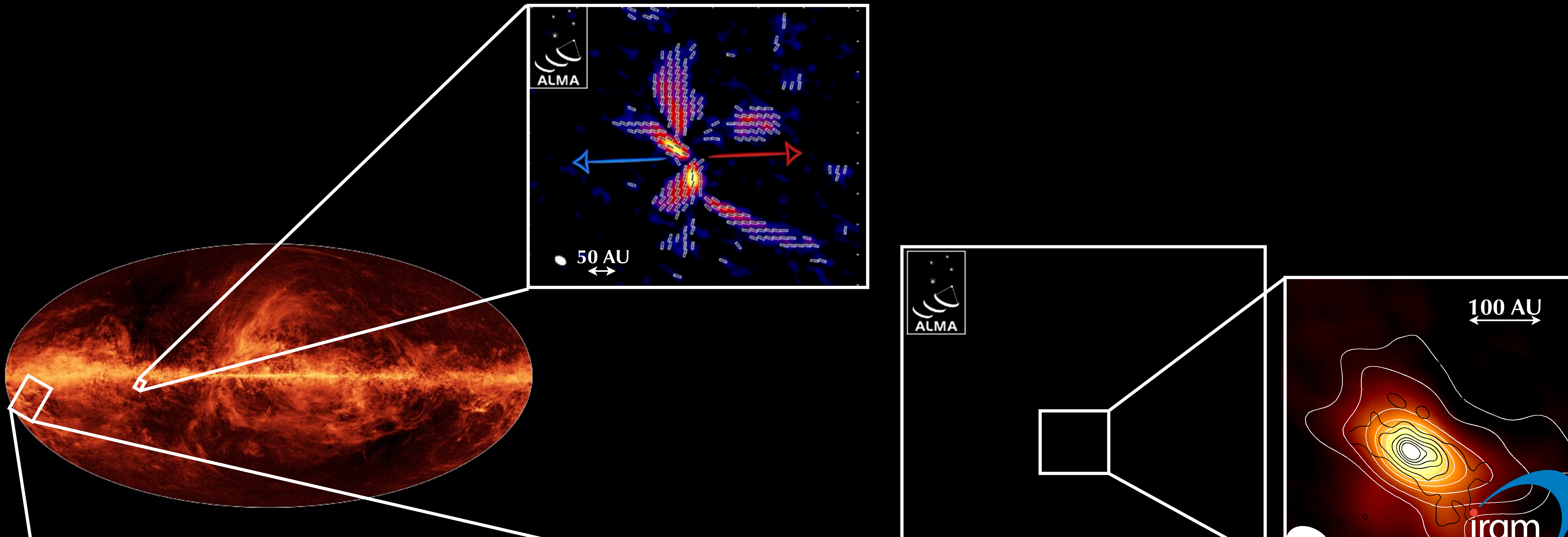
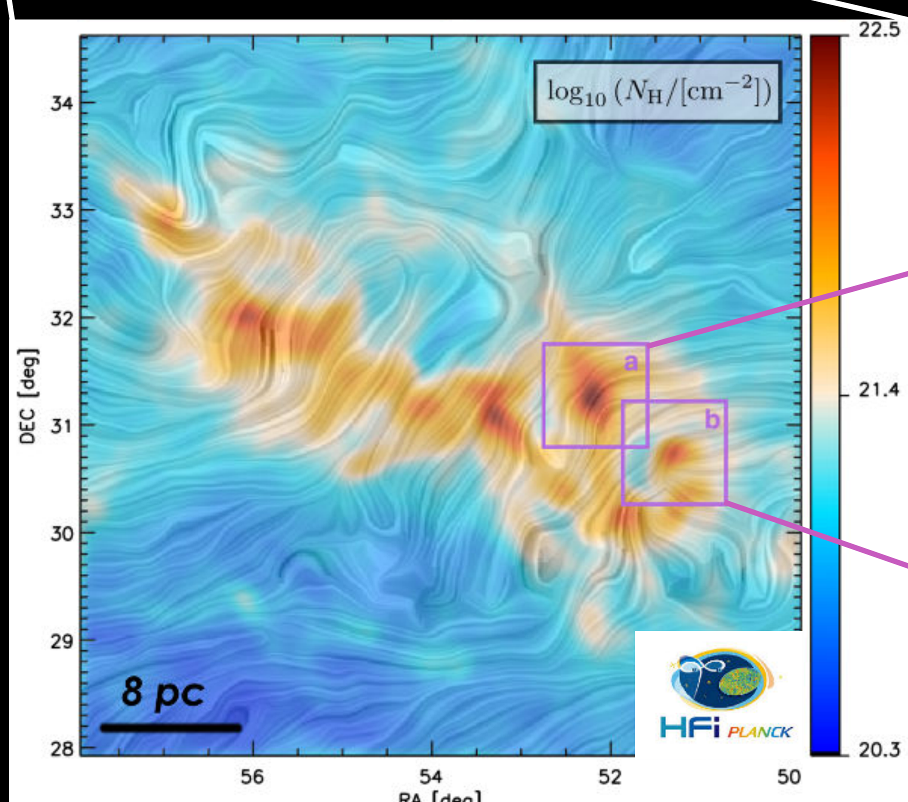
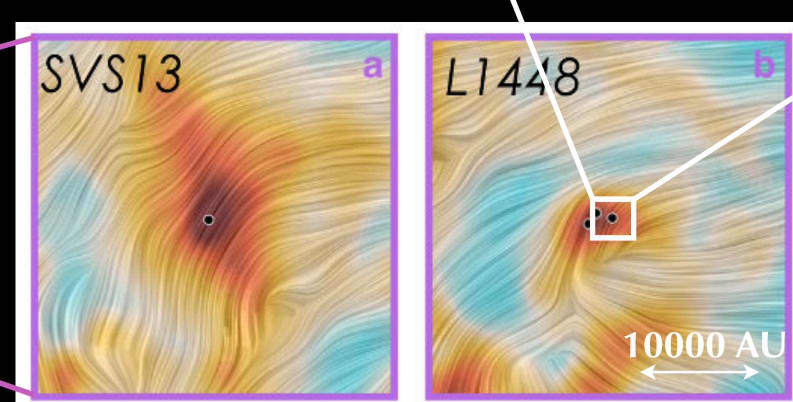
Birth and early life of protoplanetary disks: a tale from observations of Class 0 protostars and numerical models of star formation

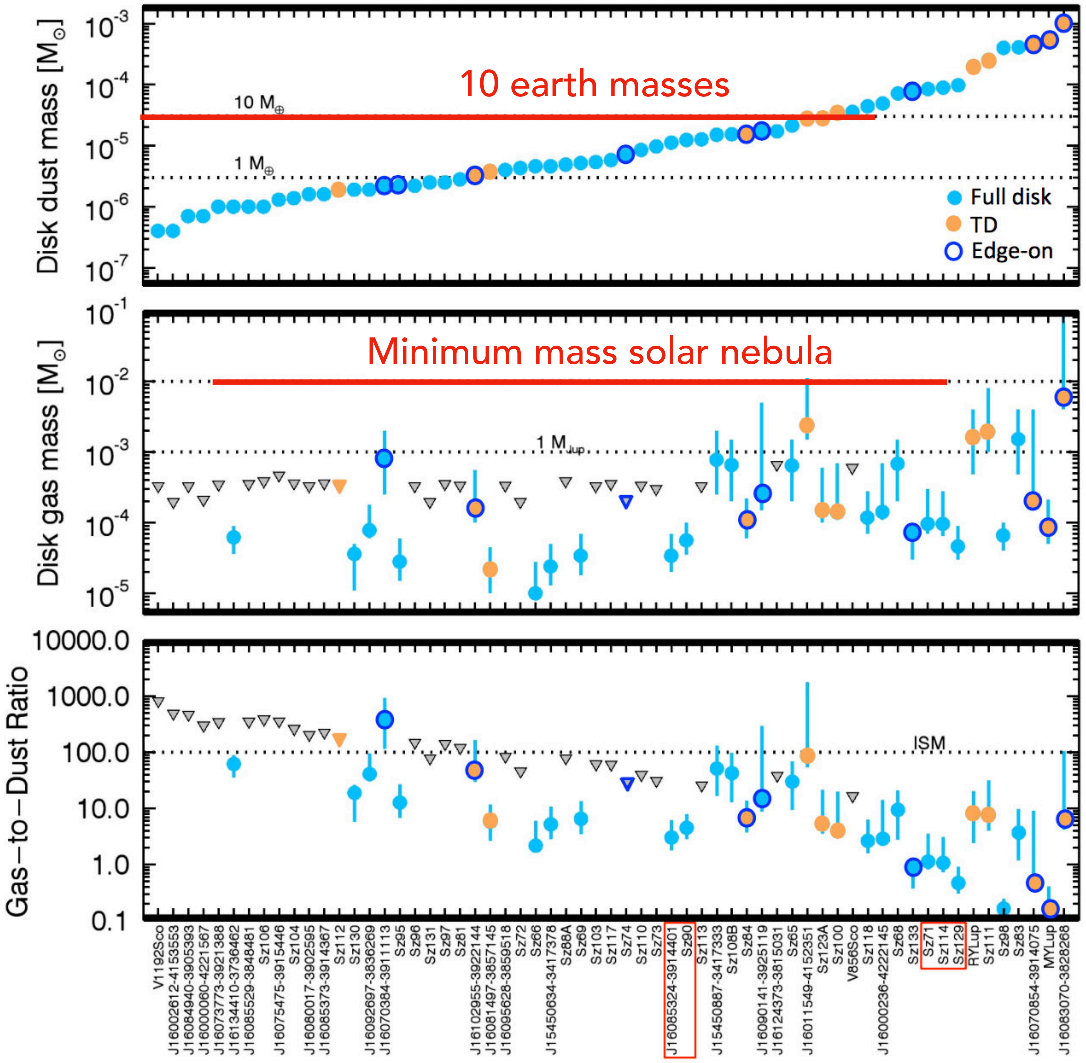




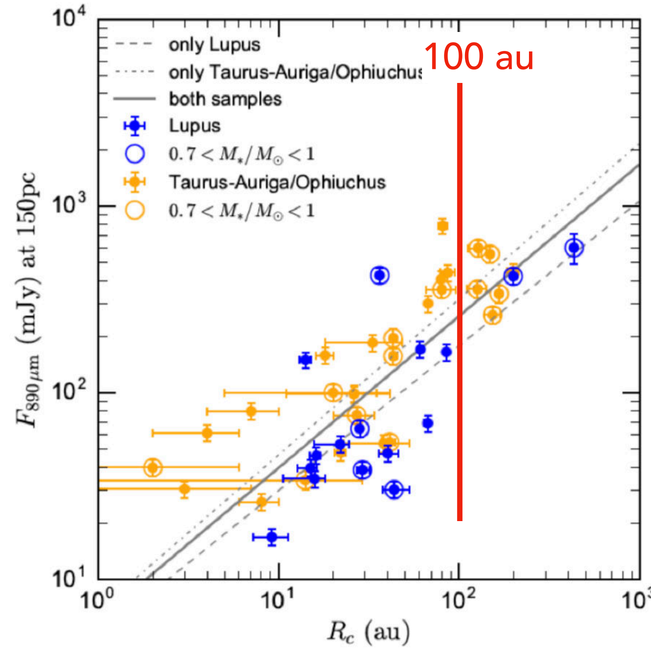


Anaëlle Maury
CEA/AIM (France) & Harvard/Smithsonian CfA (USA)

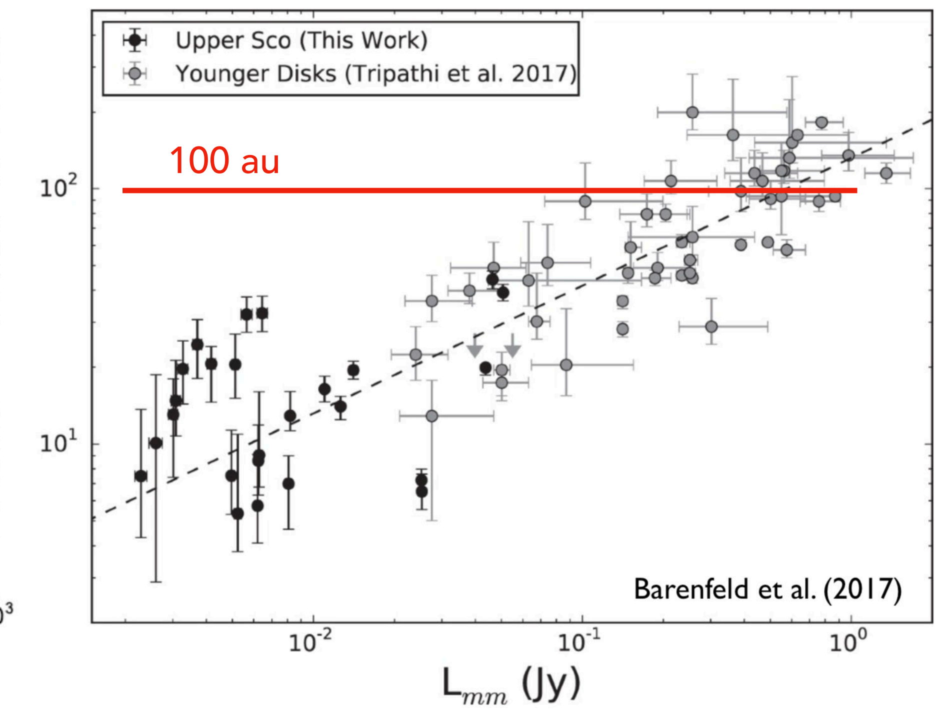
Miotello+ 2016 in Lupus



Tazzari+ 2017 in Lupus (1-3 Myr old)



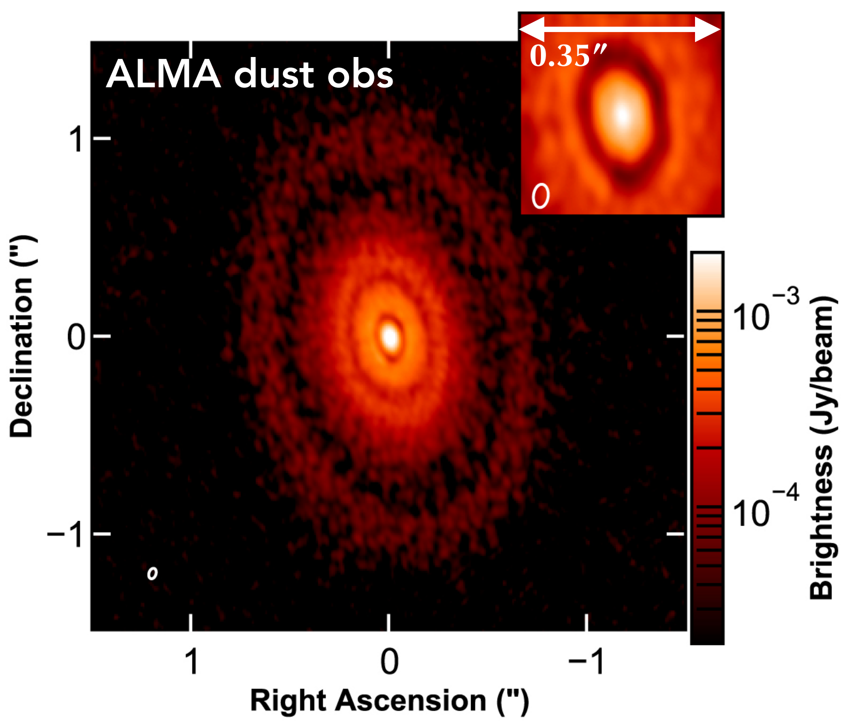
Barenfeld+ 2017 in USco (5-10 Myr old)



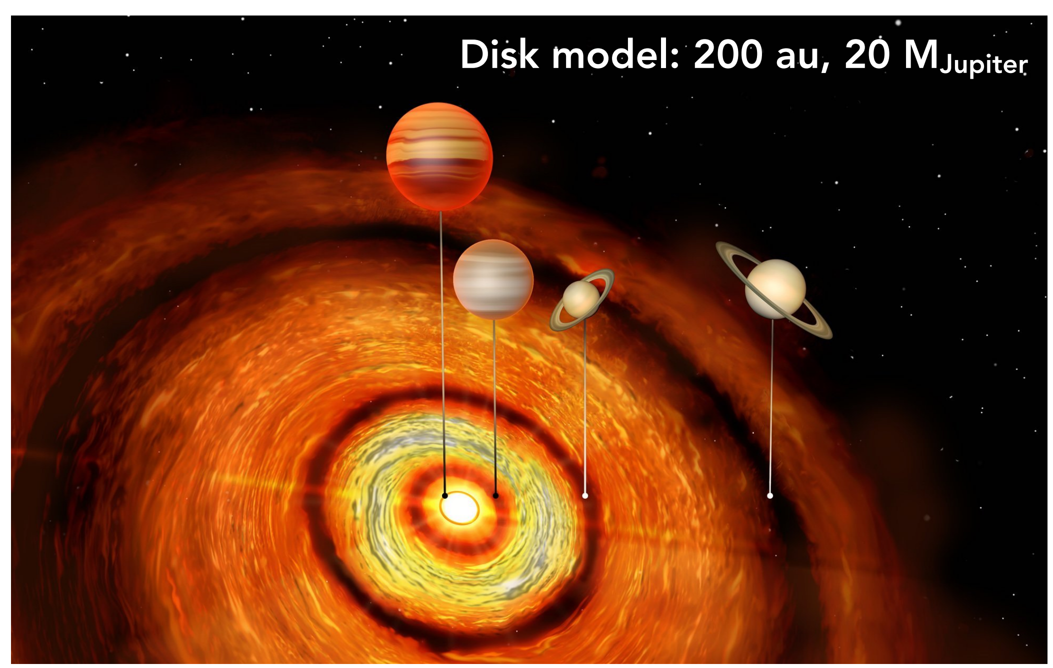
T-Tauri disks are found to be more compact, less massive (dust) and much more structured than expected

CI Tau (roughly 1Msun, 1Lsun, but only 2 million years old)

Johns-Krull et al. 2016 - Biddle et al. 2018 - Clarke et al. 2020



(a)



4 gas-giant planets of 0.1 to 11 Jupiter masses, orbiting at <1-100 AU

$J = m\, v\, r$

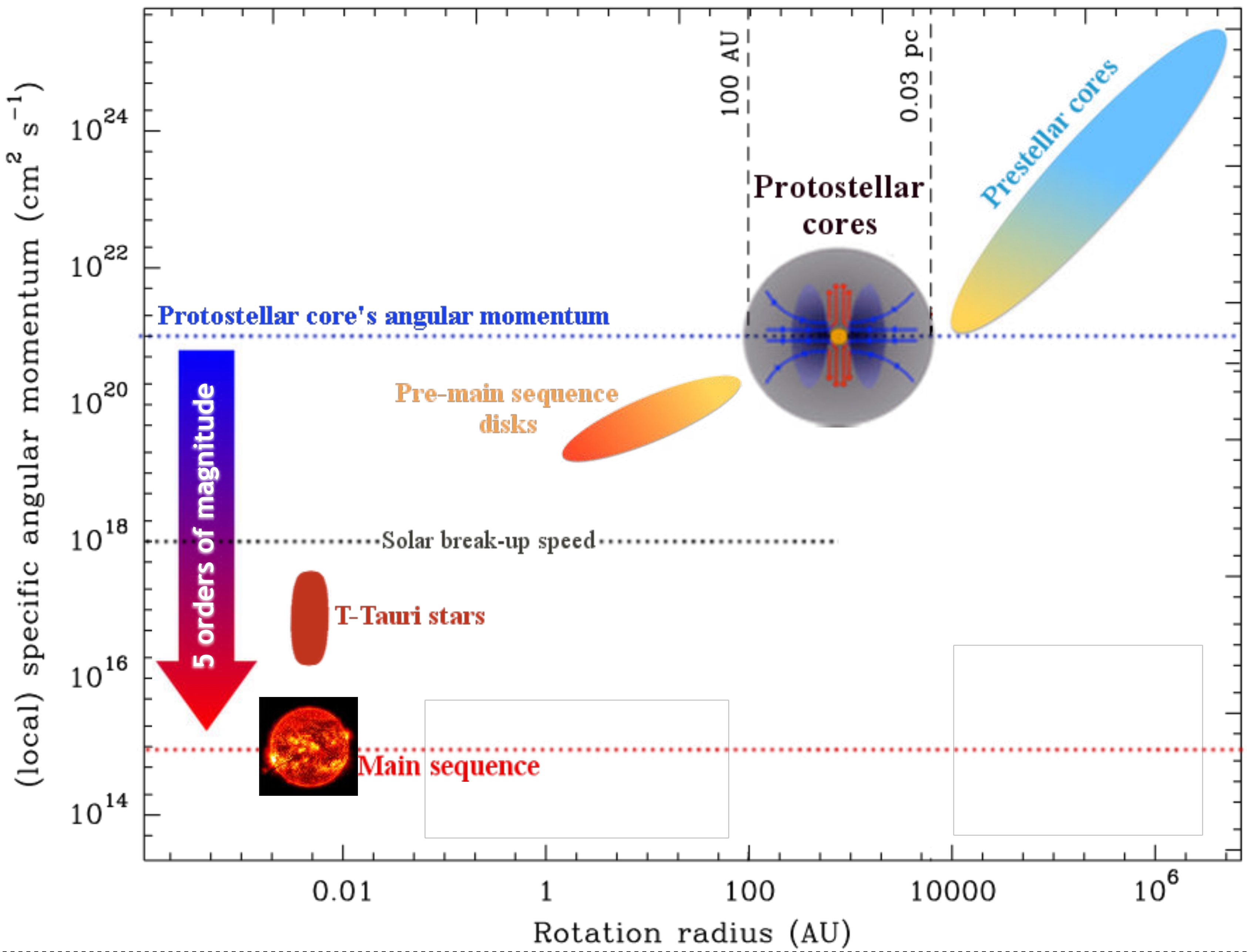
+ core collapses
=> rotation amplified by $(r_2/r_1)^2$

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

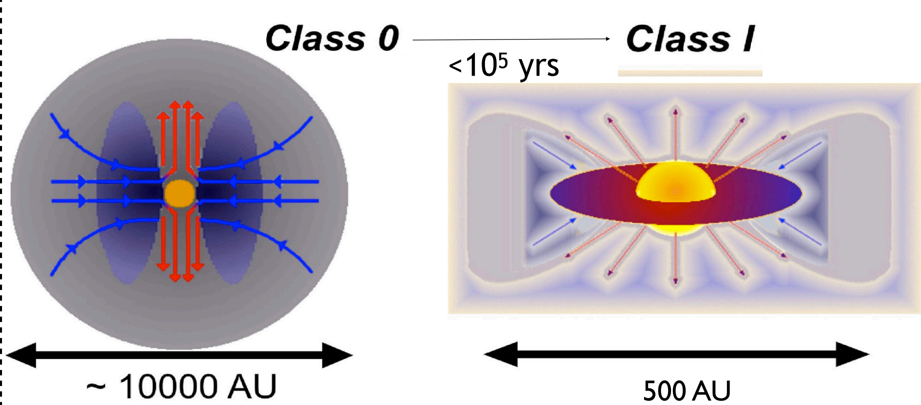
Protostars must lose >90% of the core's angular momentum prior to entering the T Tauri stage

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

Observations of angular momentum content in star-star-forming structures



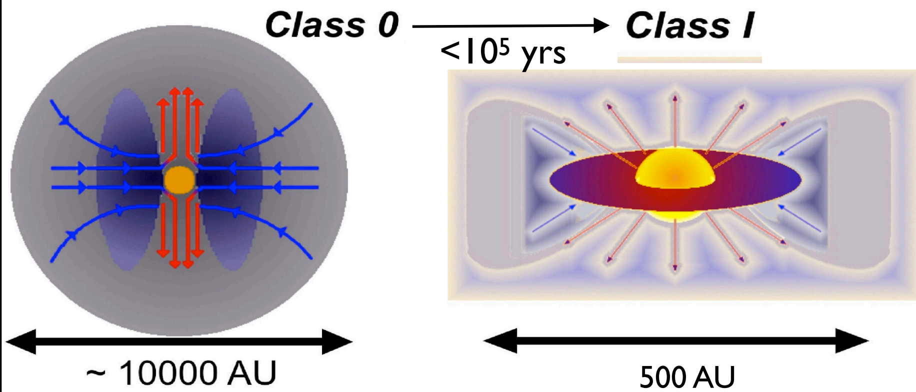
Class 0 protostars: a key stage for solving the AM problem



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 angular momentum during its accretion on 0.1 AU protostellar embryo

Need to characterize the youngest disks

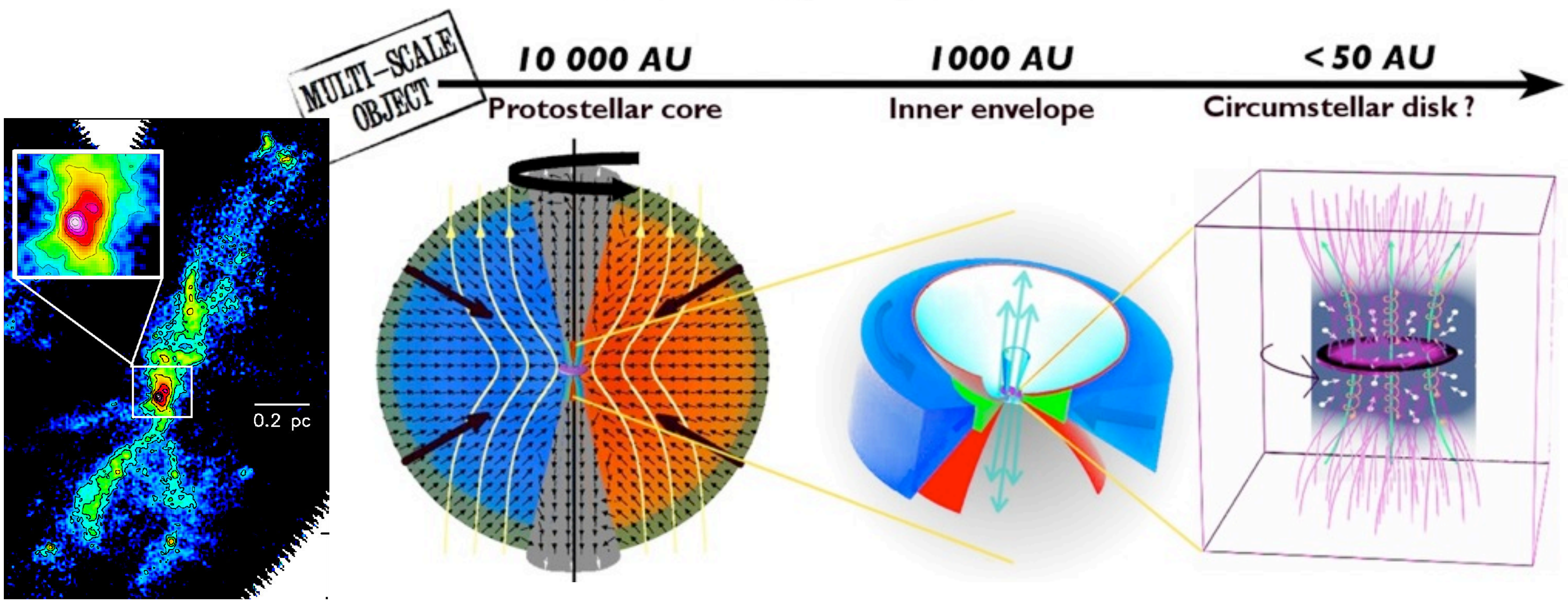


Class 0 phase = main accretion phase

>50% of the final stellar mass is assembled:
need to get rid of the 10.000 AU envelope's angular momentum during its accretion on 0.1 AU protostellar embryo

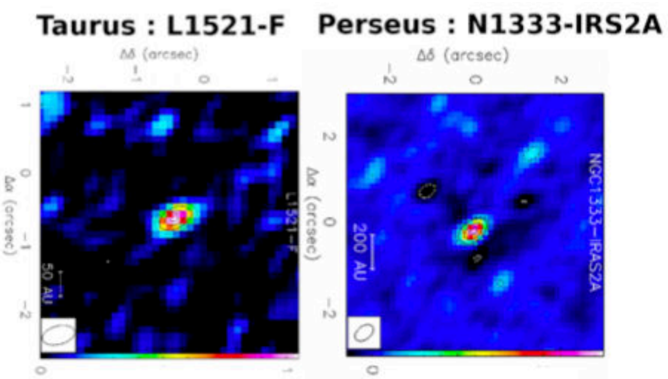
... by the formation of a protostellar disk ?

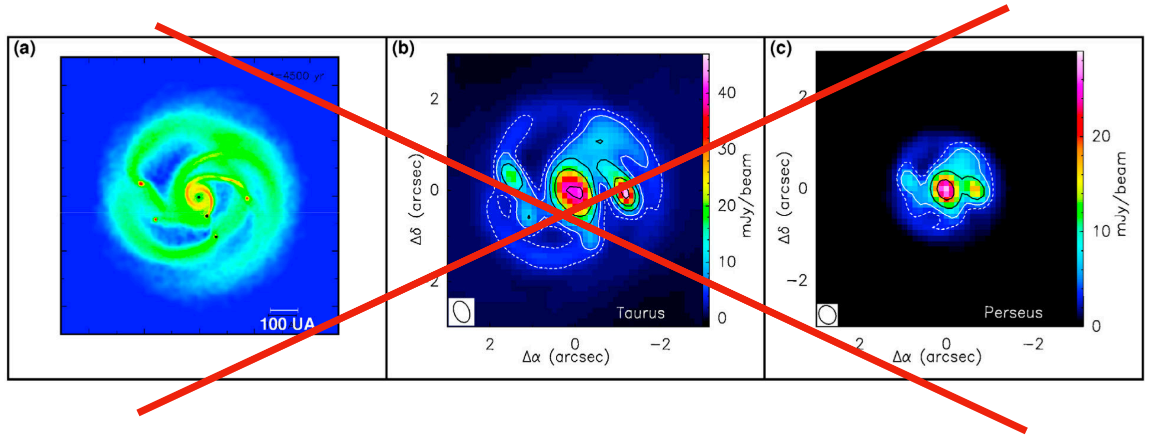
Anatomy of a typical protostar



Column density:	10^{21} N_{H2}/cm^2	---	10^{23} N_{H2}/cm^2
Temperature:	5K	---	500 K
Gas mass:	1-5 M_0	---	< 0.01 M_0

Our 2010 pilot IRAM-PdBI survey suggested small Class 0 disks





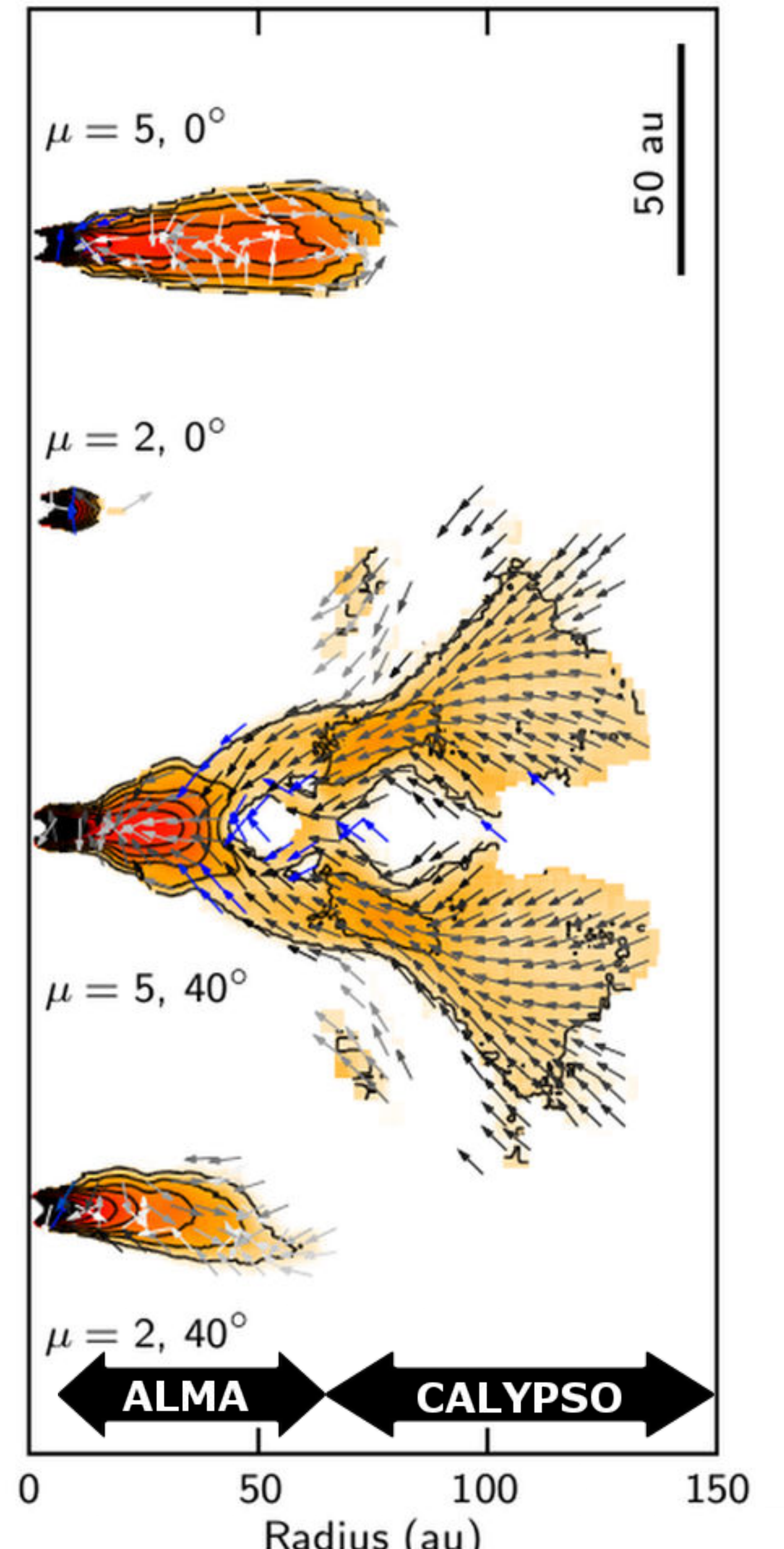
Taken at face value, therefore, our PdBI results are not consistent with the model of Stamatellos & Whitworth (2009). Note, however, that somewhat less massive (~0.1 $M_\odot$) disks, or initially massive disks observed at a later evolutionary stage, could be seen as compact structures, at the sensitivity achieved in our PdBI observations. One possible explanation for the absence of massive extended disks in our observations may be that the massive disks of the model are short-lived (~10^4 yr), as pointed out by Stamatellos & Whitworth (2009). On the other hand, the presence of massive, infalling envelopes around the Class 0 objects we observed (which are not modeled in the simulations by

Maury+ 2010 ==>
suggest magnetized scenario
to reduce young disk sizes

(but only 5 objects and ideal MHD)

8. Comparison of synthetic model images with our PdBI results shows that purely hydrodynamic models of protostellar collapse and disk formation have difficulties matching our observations, since these models typically produce multiple components, embedded in large-scale rotating structures, which are not observed toward our sample of five Class 0 sources. These large-scale rotating structures may be short-lived, however, and more observations would be needed to draw robust conclusions, given the currently large uncertainties on the Class 0 lifetime.
9. Comparison of synthetic model images from magnetohydrodynamic models with our PdBI results shows that magnetized models of protostar formation agree better with our observations, as magnetic fields tend to prevent the formation of extended disk-like structures and to suppress fragmentation into multiple components on small scales (100–1000 AU).

Non-ideal MHD Class 0 disks: sizes and shapes under various local conditions



Masson+ 2015

Note:
Previous studies with mm interferometers had also attempted to characterize young disks, but suffered from a lack of angular resolution (Looney+ 2001, Jorgensen+ 2009 for example)

CALYPSO:
the IRAM Plateau de Bure 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.

Core team: 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) - B. Commercon (MPIA) - L. Podio (Arcetri) - S. Anderl (IPAG) - M. Gaudel (AIM)

> 300 hours observing time

16 Class 0 protostars (<300pc)

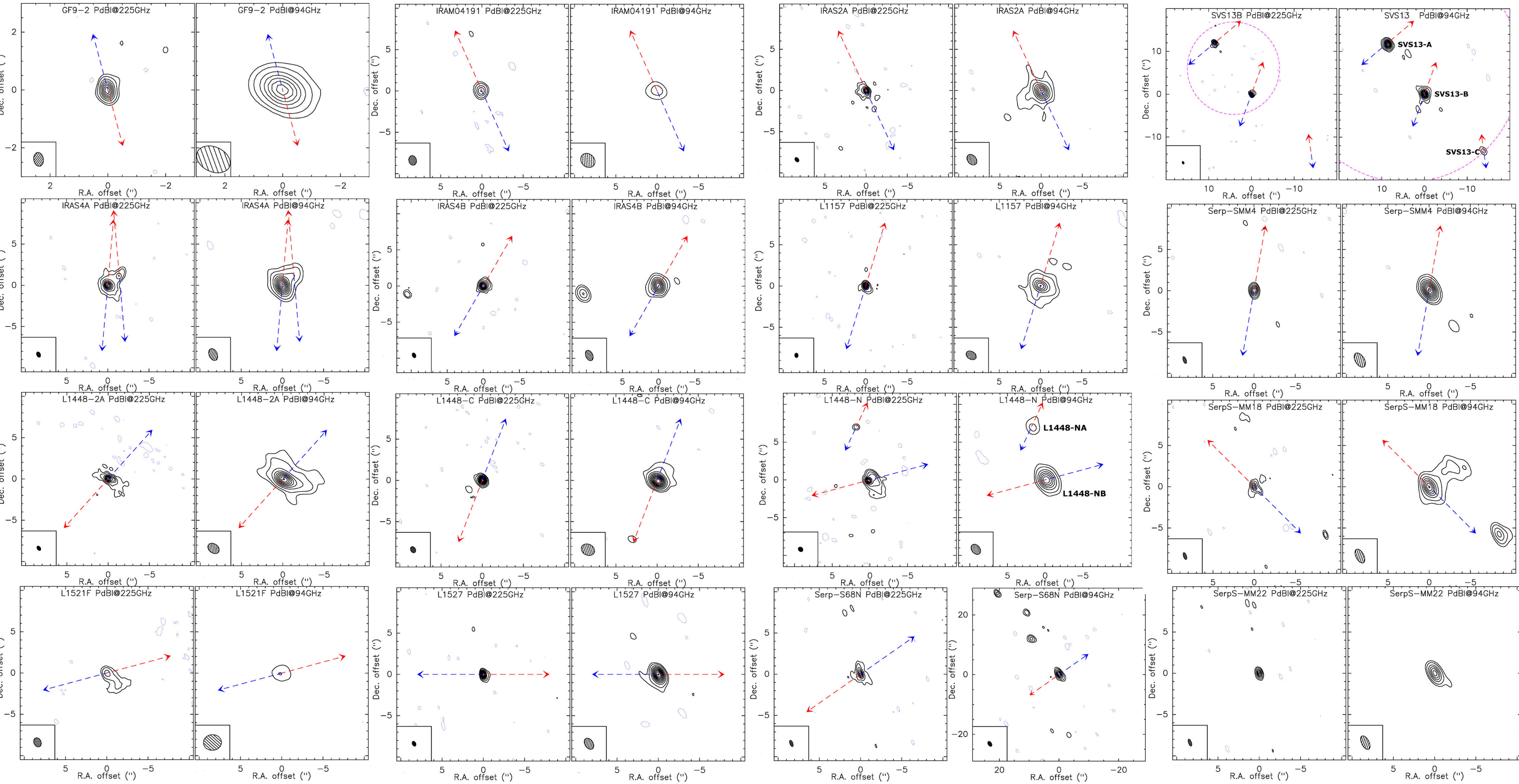
3 spectral setups
continuum and >20 lines

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. (2020) Gaudel et al. (2020) Belloche et al. (2020) Podio et al. (in prep)

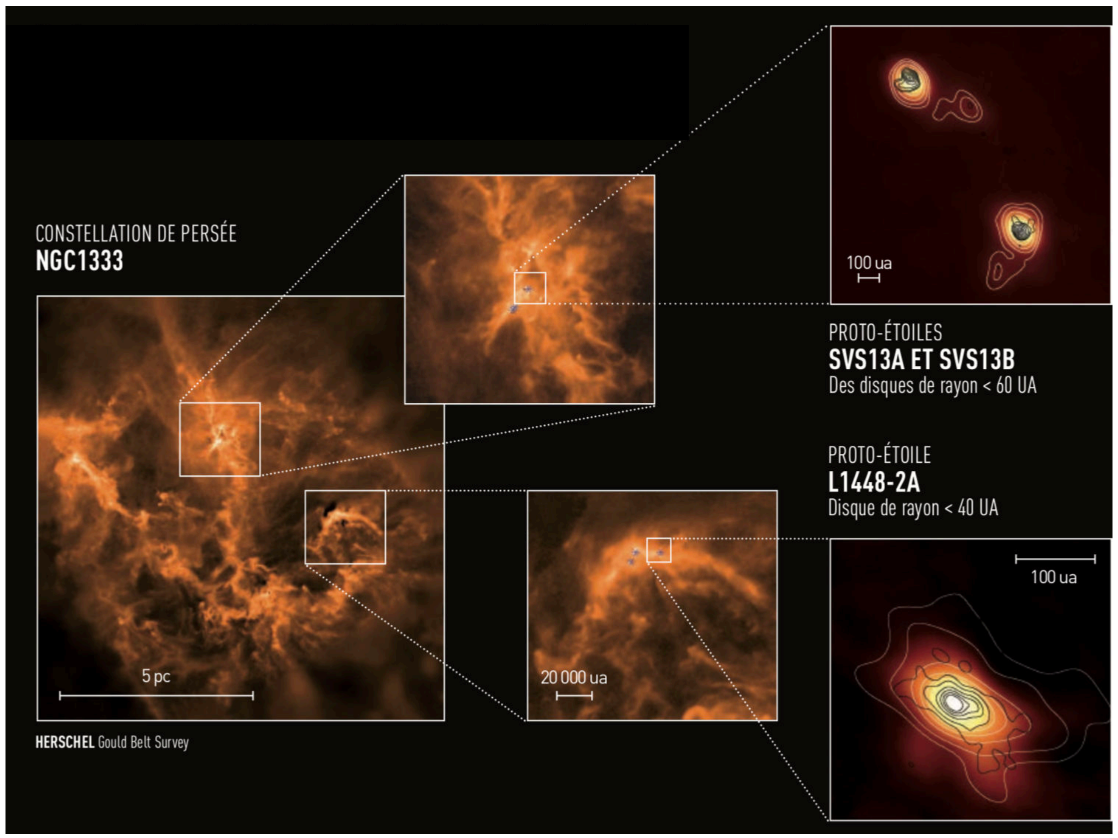
The survey



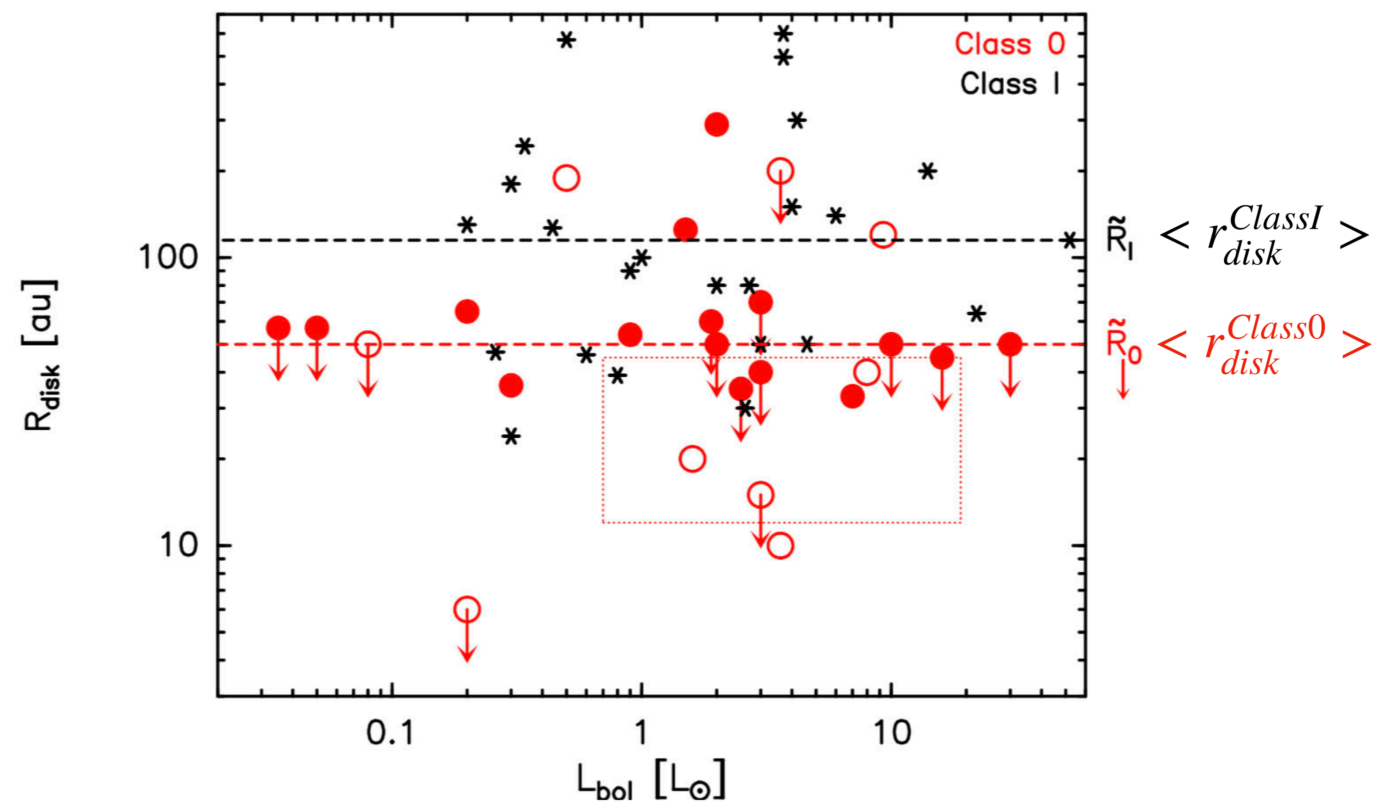
Maury et al (2010, 2014, 2019) Maret et al. (2014, 2020) Codella et al. (2014)
Santangelo et al. (2015) Anderl et al. (2016) Podio et al. (2016) De Simone et al. (2017), Gaudel et al. (2020) Belloche et al. (2020)

CALYPSO survey of 1.3+2.7 mm dust continuum emission

>70% Class 0 show disk components but >72% have r_{disk} < 60 au



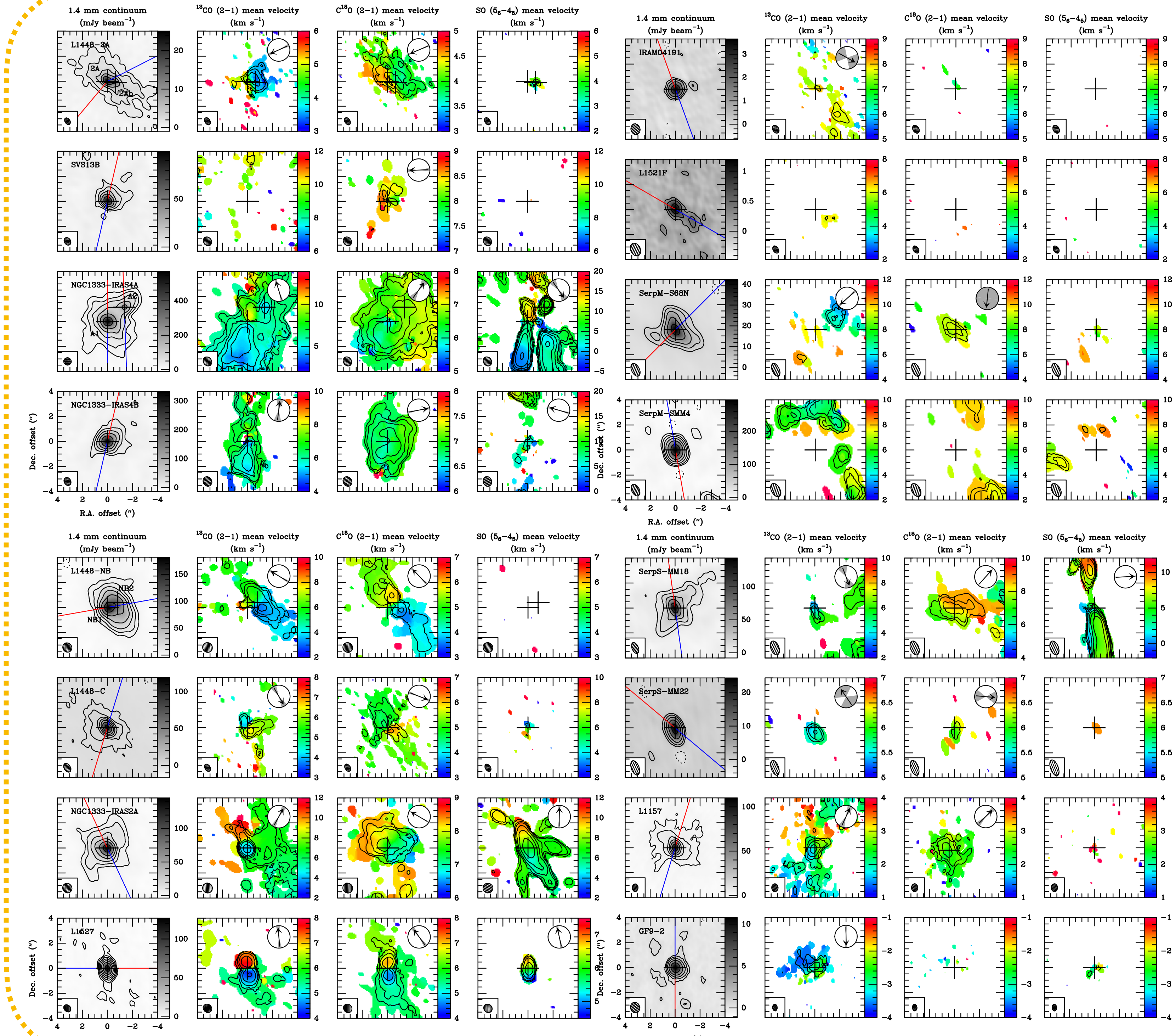
Class 0 median disk radius < 50 au



Including the literature (CARMA/Vandam, ALMA & SMA results, 26 Class 0 protostars):
>75% Class 0 disks have r_{disk} < 60 au

Protostars: disks are present but SMALL

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



Maret & CALYPSO (2020) :

analysis of the velocity field at sub-arcsec scales in 16 protostars

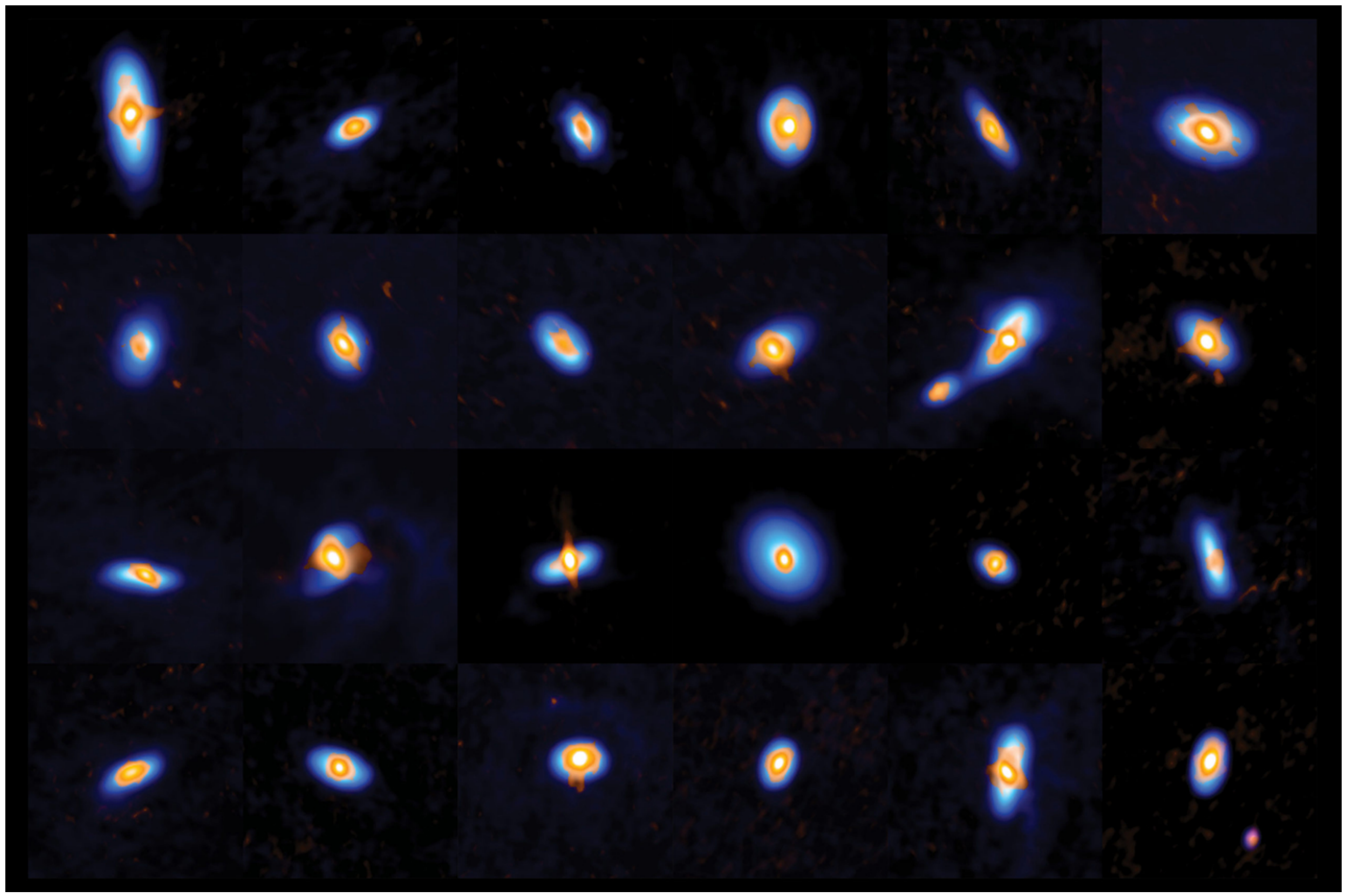
Keplerian disks at r>50 au **in only 2 out of 16 sources**

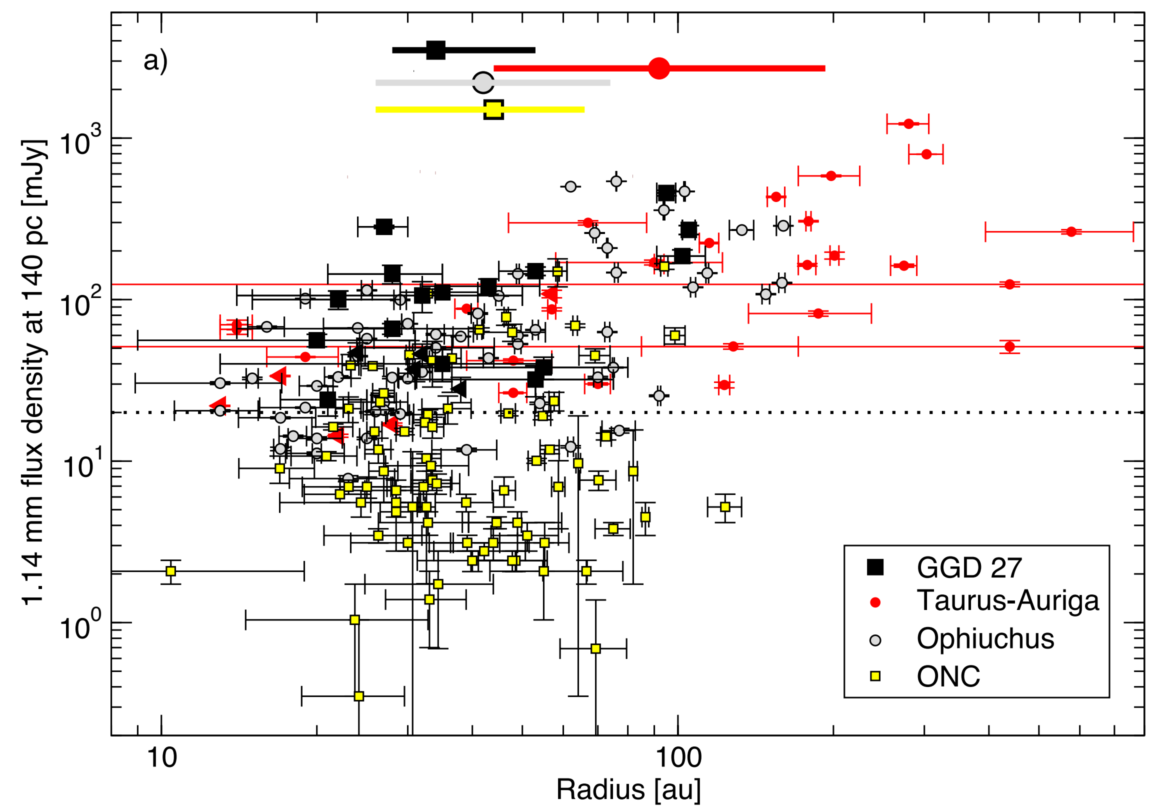
Even gas radii may be small (different from T-Tauri) ?

Note on protostellar disk masses: no robust study so far, all observational analysis suffer from inadequate hypothesis (dust opacity, flux due to disk vs envelope etc ….)

=> yet an open question for which we need resolved disk + kinematical studies to kick in

More recent ALMA surveys have confirmed the CALYPSO results, finding Rdisks <50 au





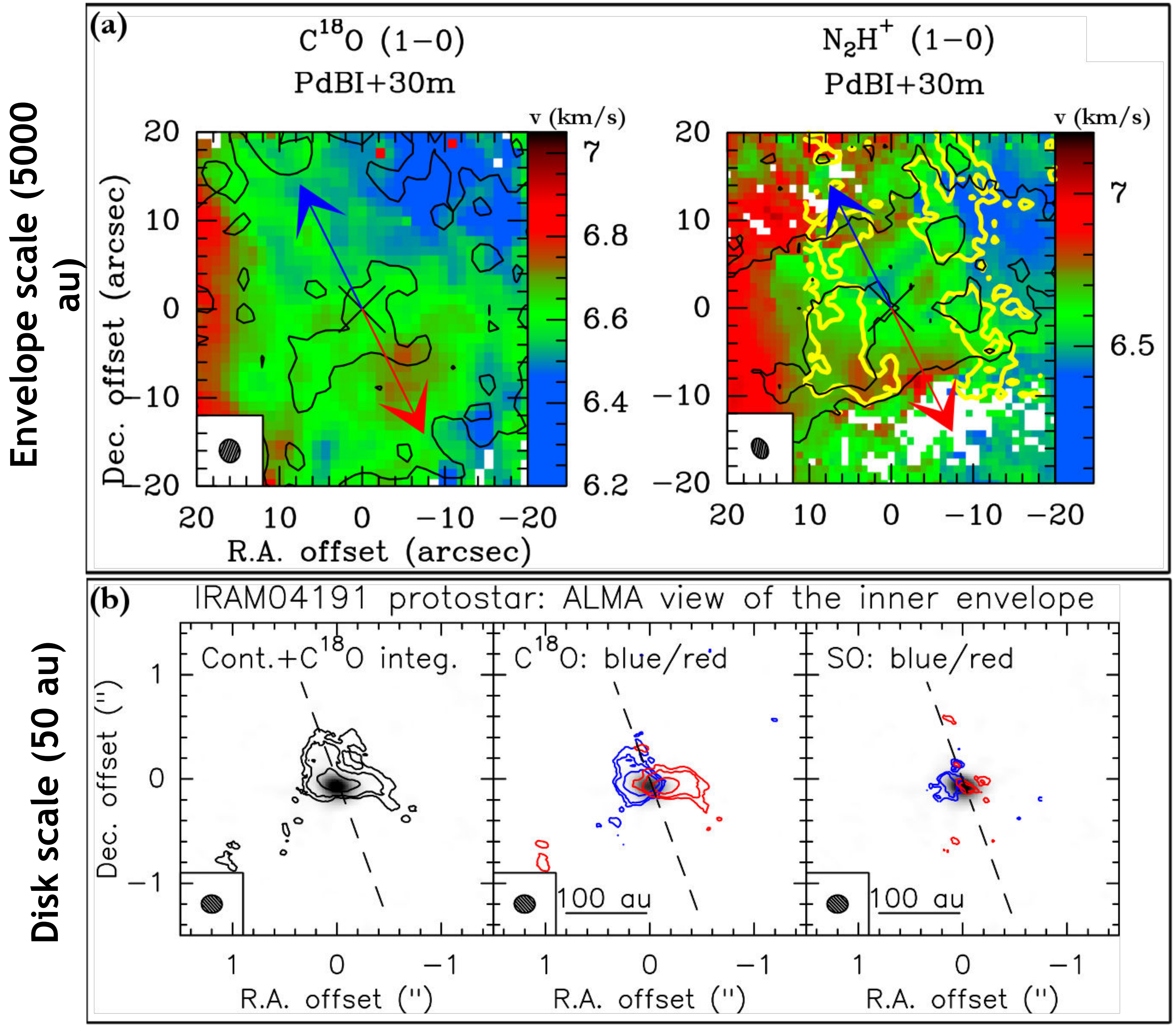
Tobin et al. 2020 in Orion:
Mean Class 0 R_{disk} ~ 45 au

Busquet et al. 2019 in GGD 27:
paucity of disks with R_{disk} > 100 au

Could be consistent with recent **ALMA surveys** suggesting Class I/II disks are small (Pascucci+ 2016, Barenfeld+ 2017, Tripathi+ 2017, Cazoletti+ 2019 etc)

Disks result from local angular momentum inhomogeneities ?

IRAM04191: envelope rotation - Gaudel & CALYPSO (2020), see also Belloche+ 2004

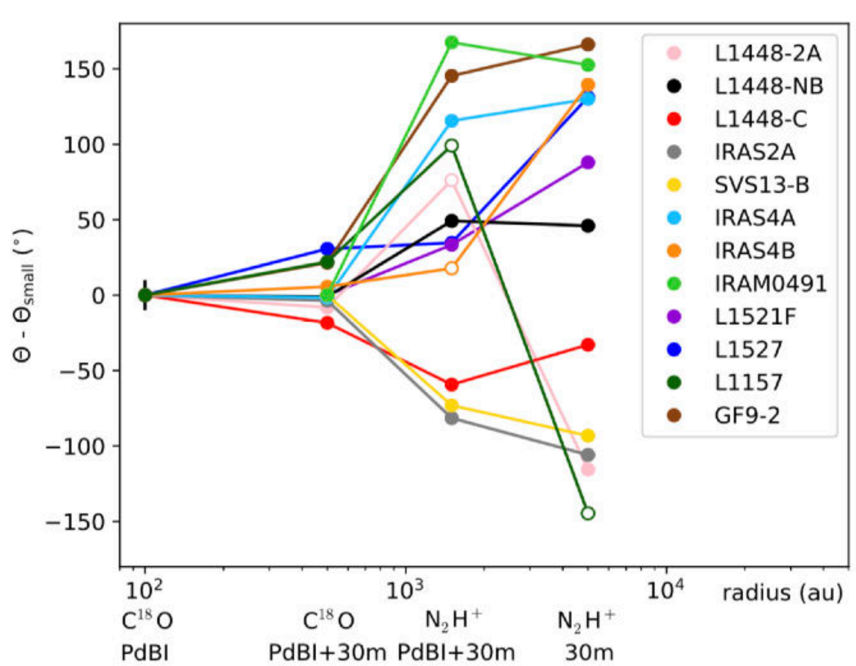


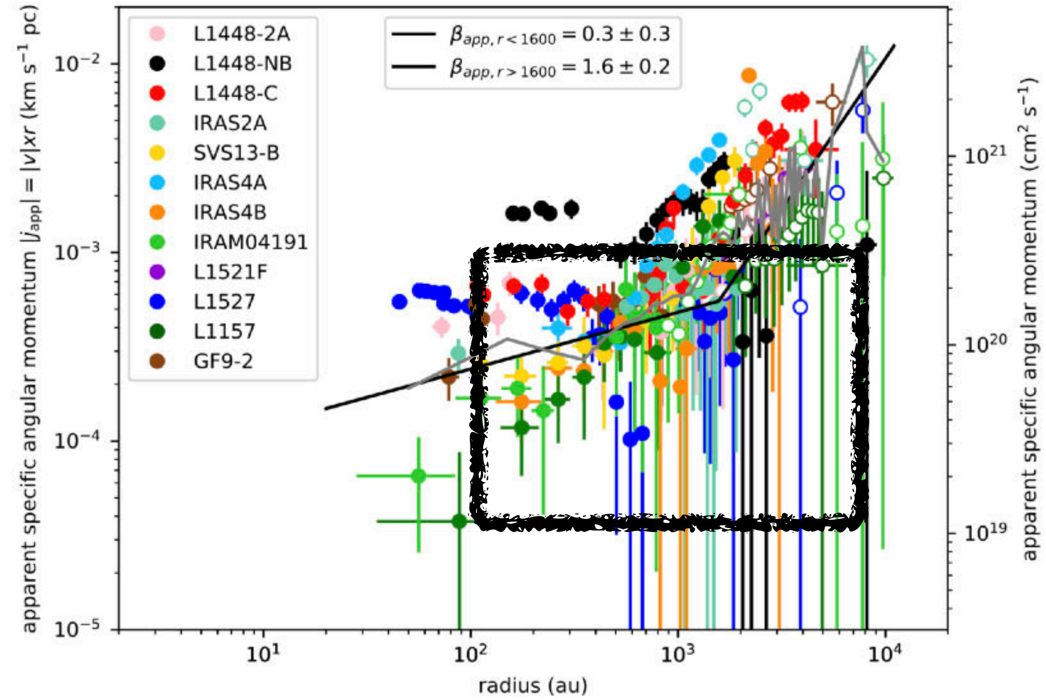
Are disks really formed by conservation of rotational motions in protostellar envelopes ?

See Maury+ 2020 (IAUS345)

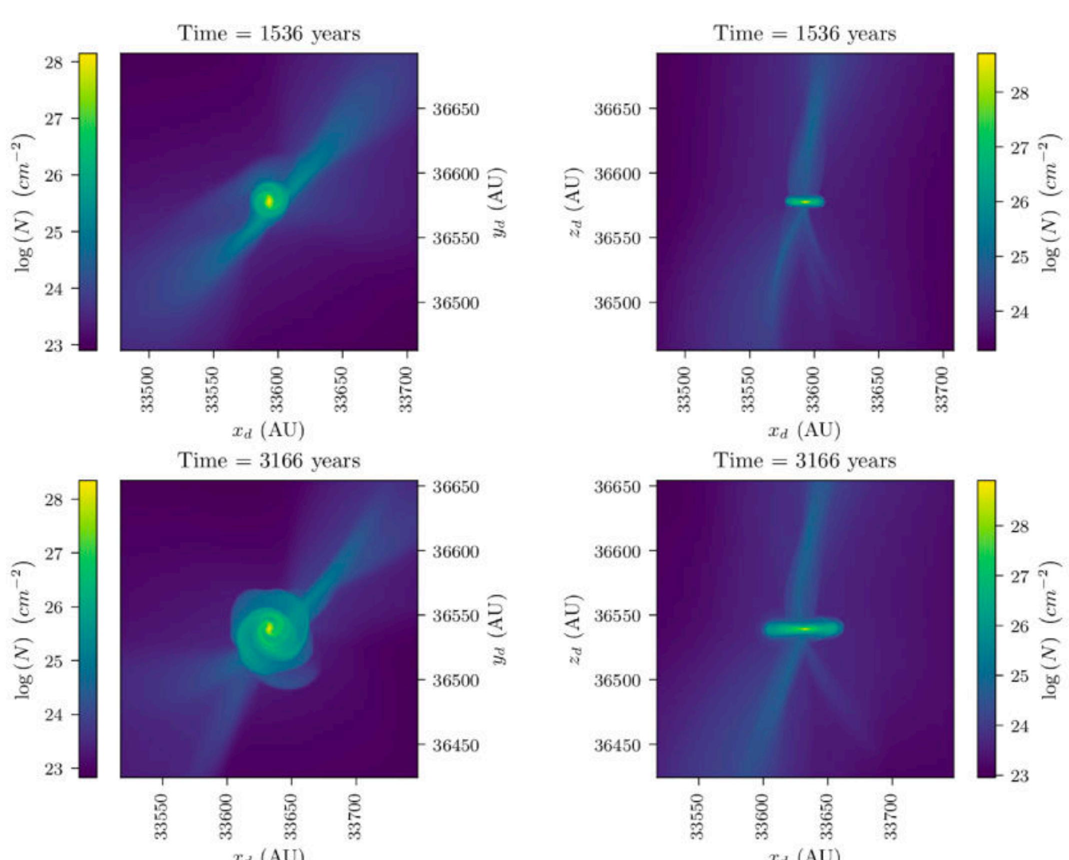
Disks result from local angular momentum inhomogeneities ?

Observations of specific angular momentum in protostars:
angular momentum at small scales is not inherited from envelope rotation ?

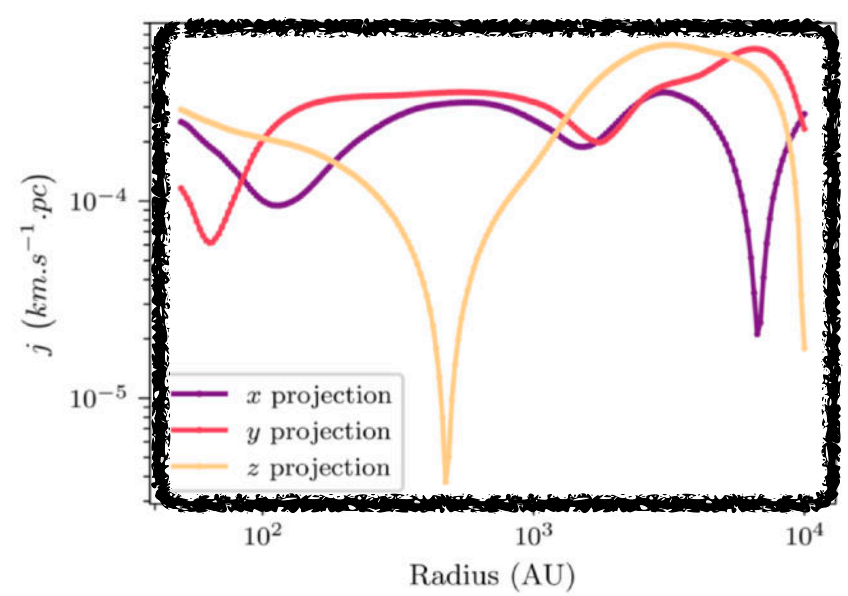




Gaudel+ 2020



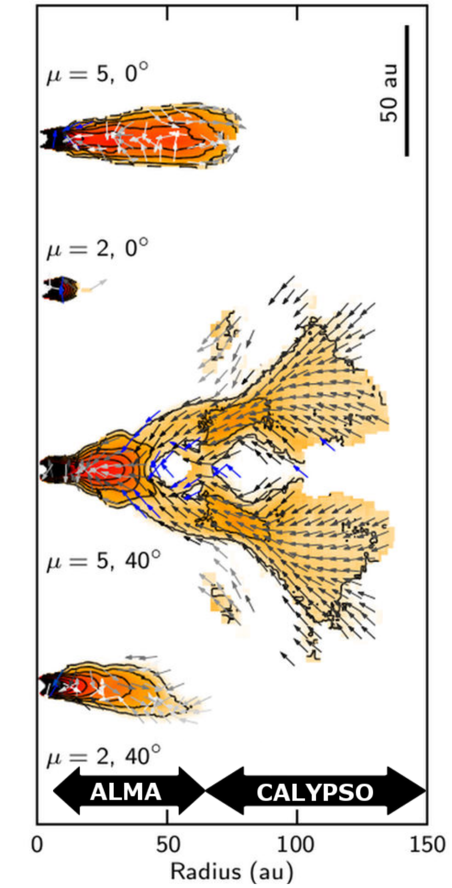
Verliat+ 2020



MHD models without core rotation:
observed values of j during collapse reproduced
+
disks form from j(grav.) !

Hennebelle+ 2016 : Analytical non-ideal MHD collapse leads to self-regulation of disks to small (20-50 au radii)

Non-ideal MHD Class 0 disks: sizes and shapes under various local conditions



Typical radius is:

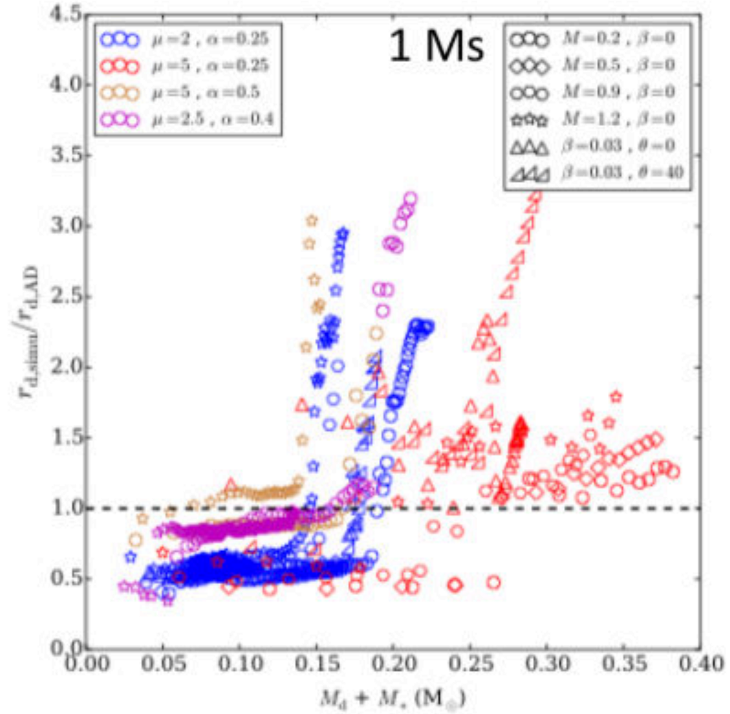
$$r_{d,AD} \simeq 18\,\mathrm{AU} \times \delta^{2/9} \left(\frac{\eta_{AD}}{0.1\,\mathrm{s}}\right)^{2/9} \left(\frac{B_z}{0.1\,\mathrm{G}}\right)^{-4/9} \left(\frac{M_d + M_*}{0.1\,M_\odot}\right)^{1/3}.$$

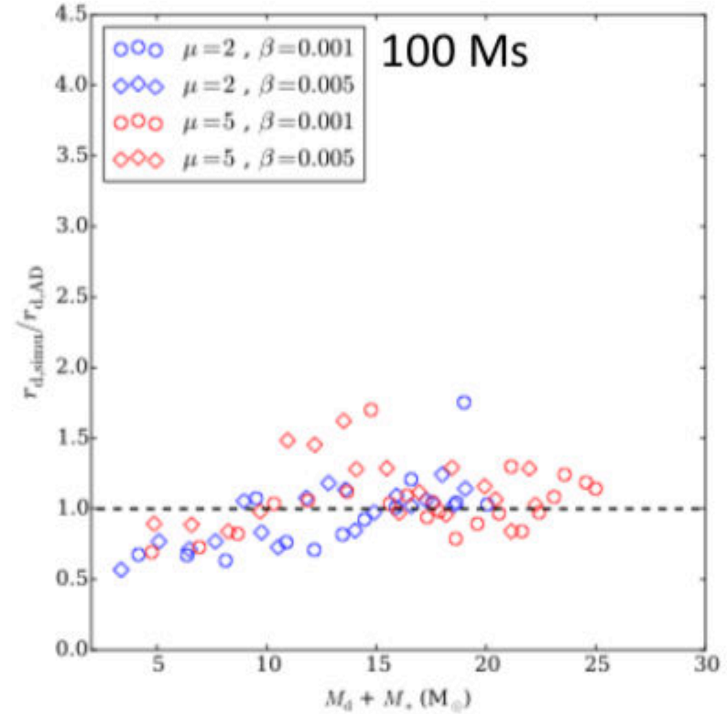
By contrast hydro would lead to:

$$r_{d,hydro} \simeq 106\,\mathrm{AU} \frac{\beta}{0.02} \left(\frac{M}{0.1\,M_\odot}\right)^{1/3} \left(\frac{\rho_0}{10^{-18}\,\mathrm{g\,cm^{-3}}}\right)^{-1/3}$$

=> **Early disk formation is magnetically *self-regulated* !**

Also checked to be consistent with numerical simulations





See also Hennebelle 2020

European Research Council

Established by the European Commission

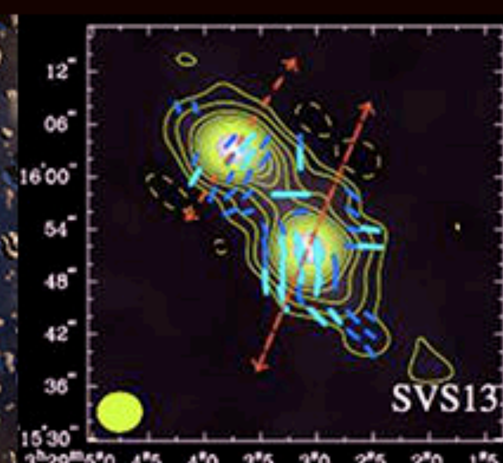
MAGNETIC YSOS

INTERPRETING DUST POLARIZATION MAPS TO CHARACTERIZE THE ROLE OF THE MAGNETIC FIELD IN STAR FORMATION PROCESSES

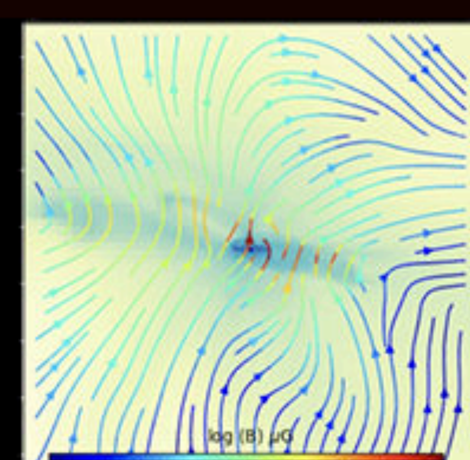
http://irfu.cea.fr/Pisp/anaelle.maury/MagneticYSOs/

OUR PROJECTS

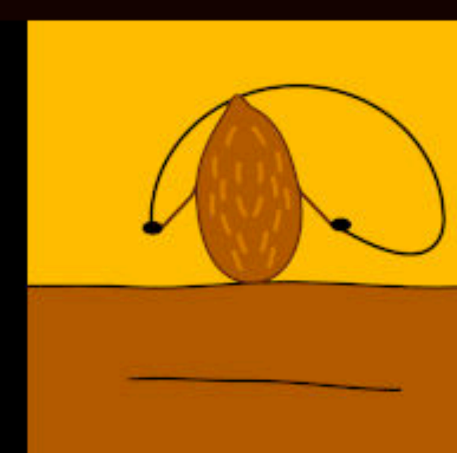
Protostellar structure



B-field properties

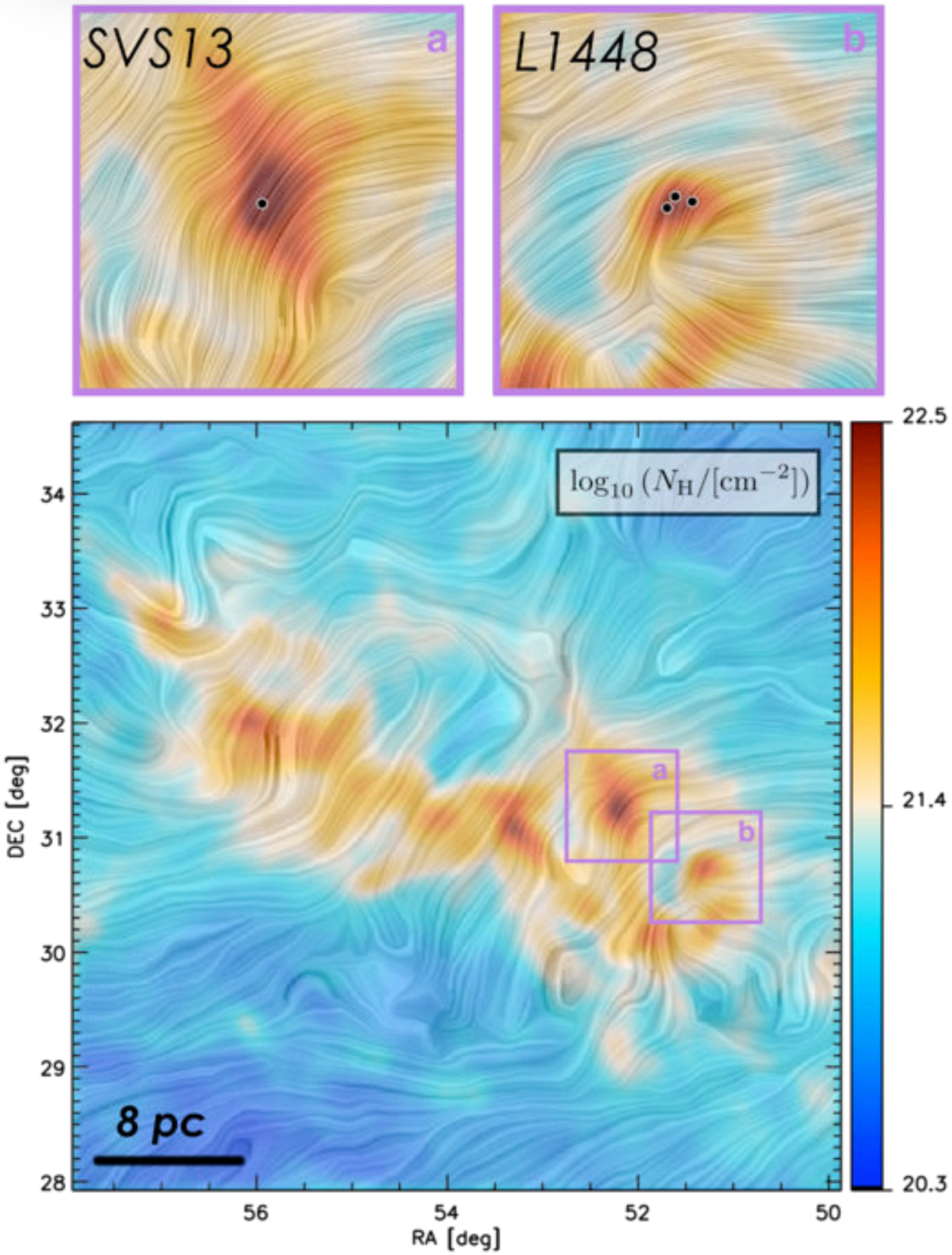


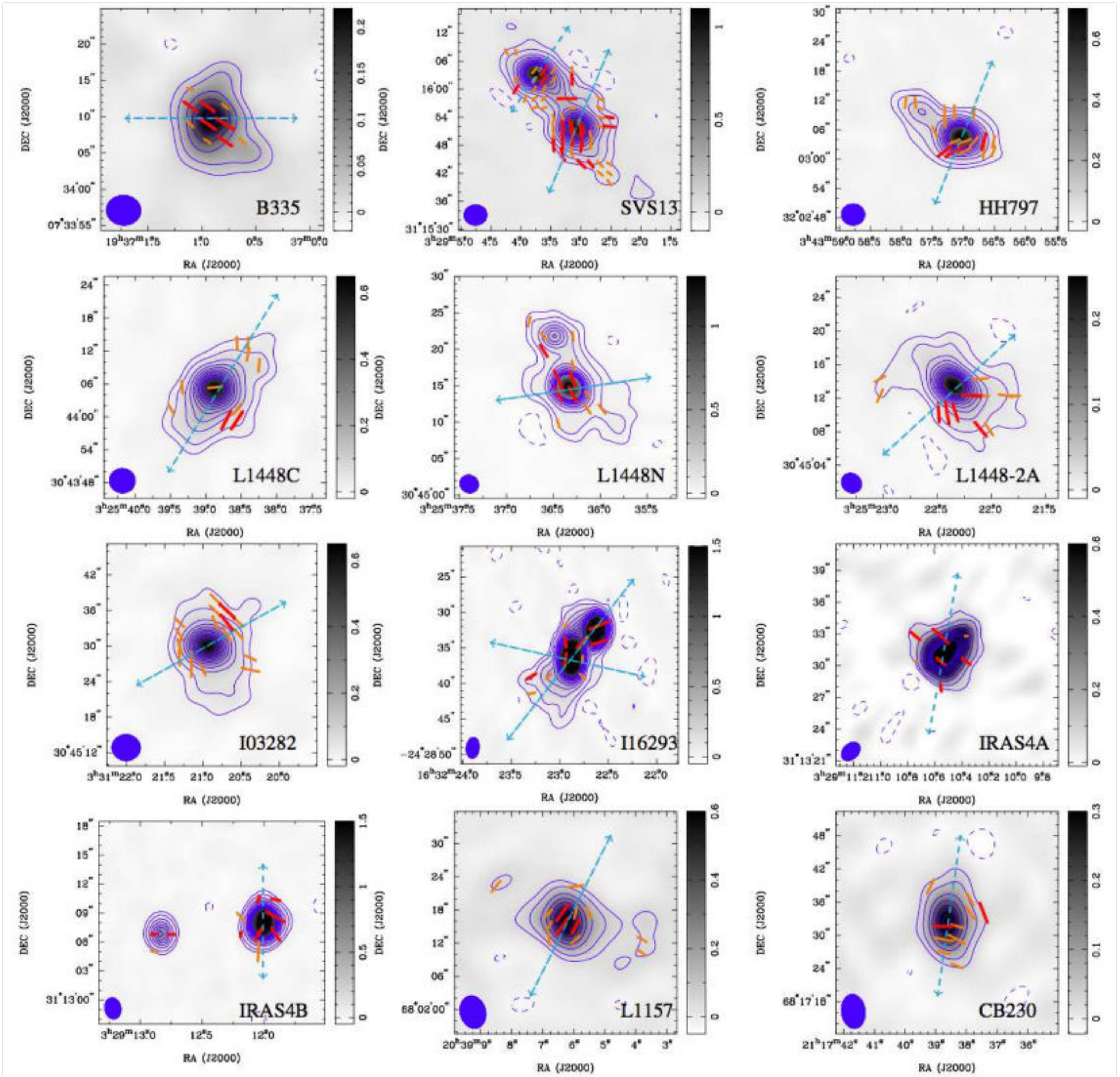
MHD models



Dust grains alignment

Our SMA survey: All protostellar envelopes are magnetized

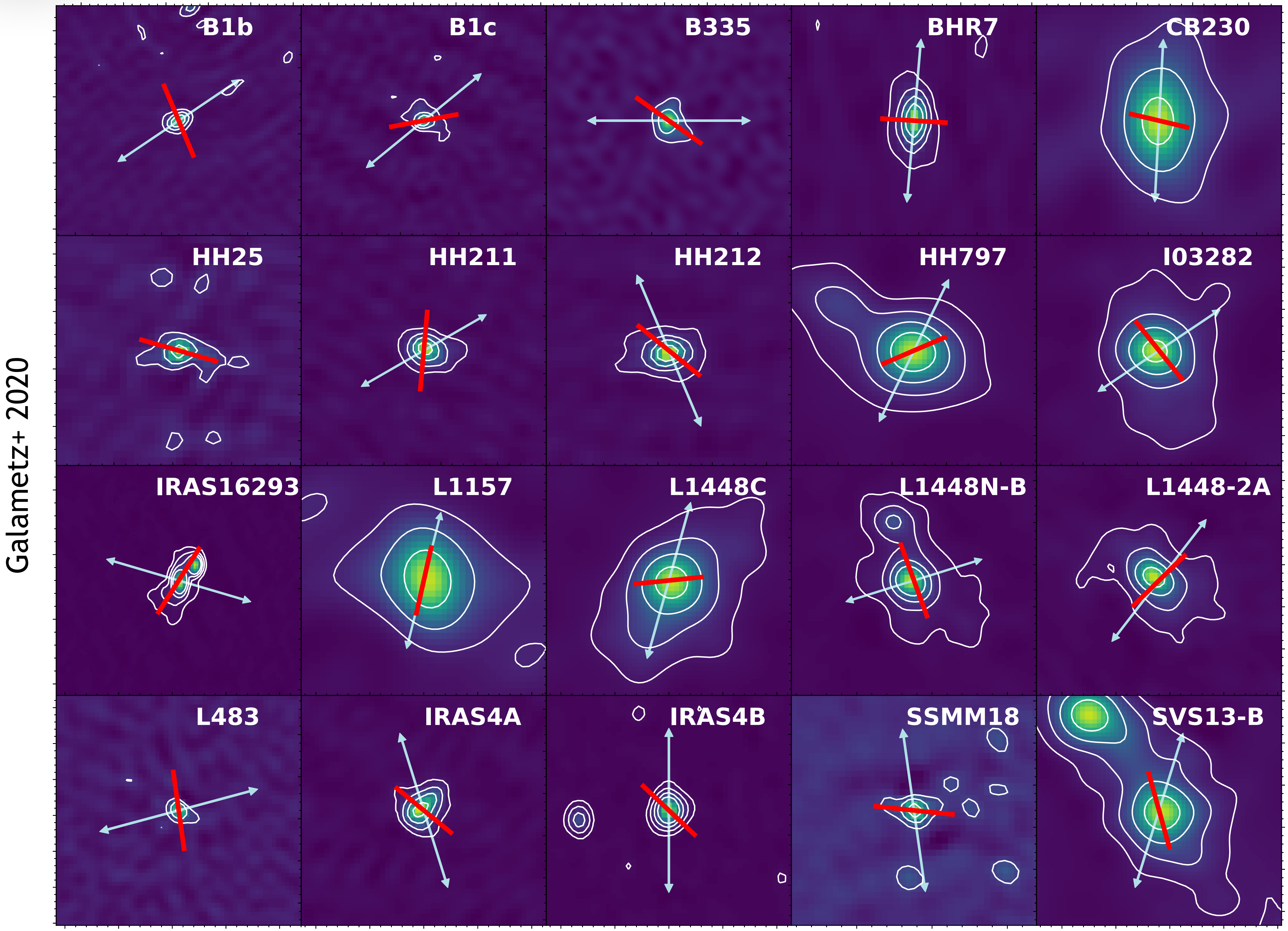




Galametz+ (2018): 0.8mm dust polarization
in 12 Class 0 low-mass protostars
B detected in all of them

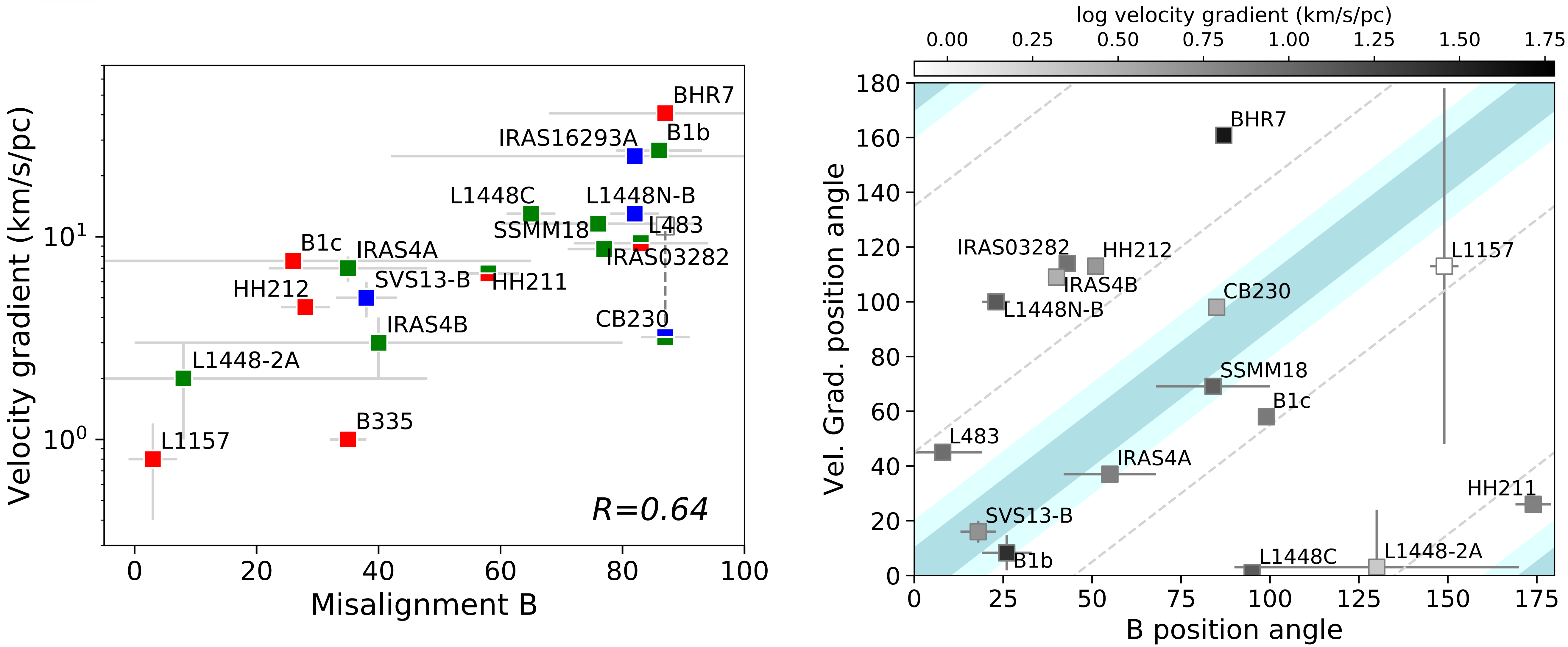
Is magnetic field randomly oriented at core scales ?

SMA observations of **20** solar-type protostellar envelopes



Is magnetic field randomly oriented at core scales ?

Galametz+ 2020



It seems NOT !

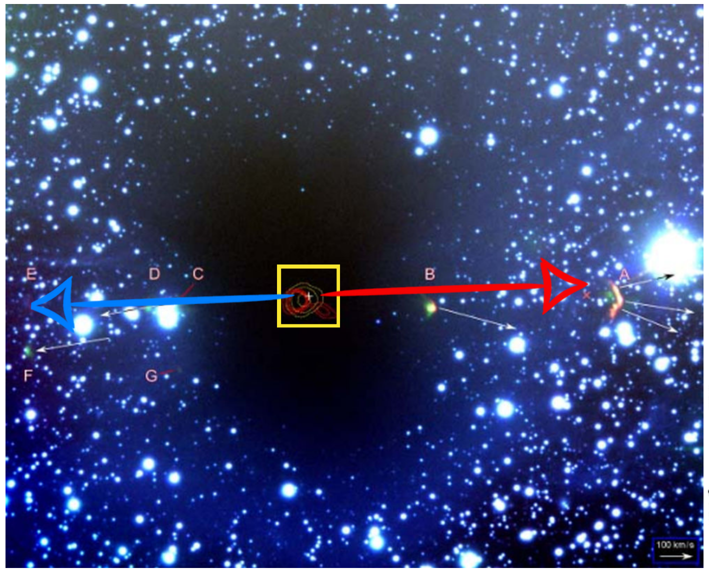
Protostars with aligned B configurations show :

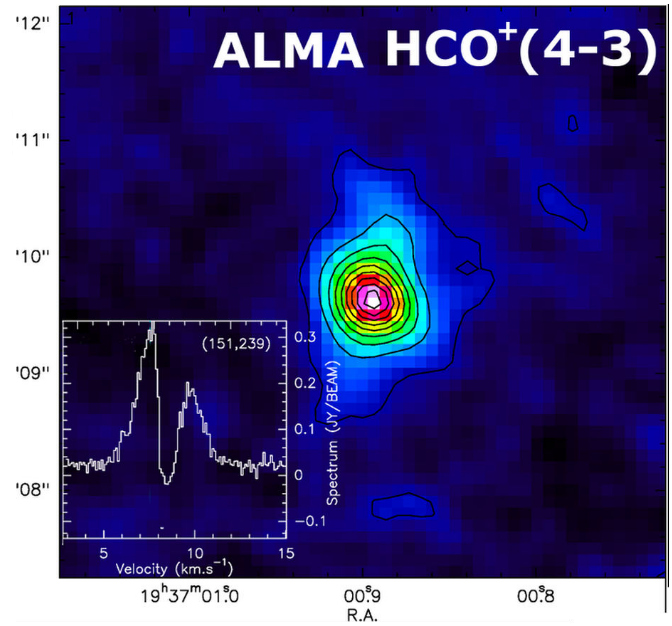
less kinetic energy in their inner envelopes + less multiple systems

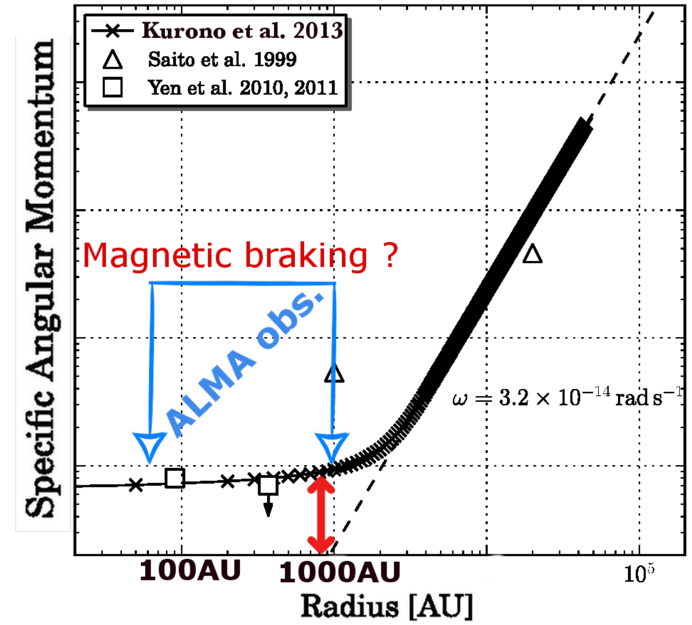
=> an expected outcome of more efficient magnetic braking ?

Exploration of MHD models to investigate underlying physics (ongoing w/ Hennebelle's group) ....

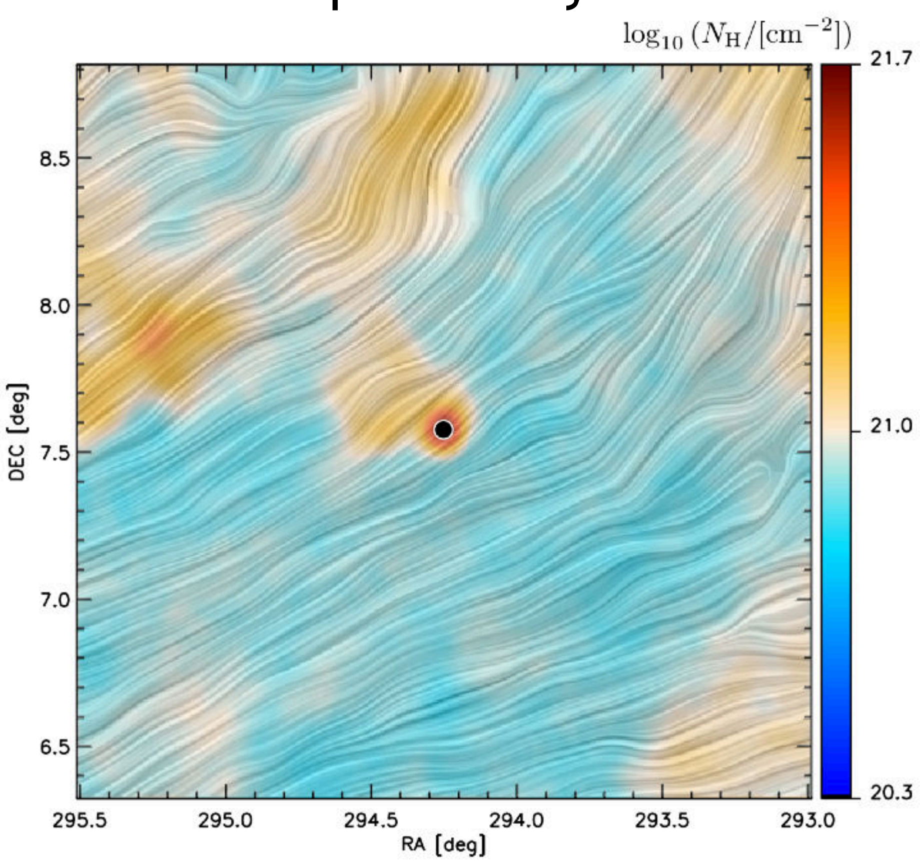
A magnetically-regulated collapse in B335 ?



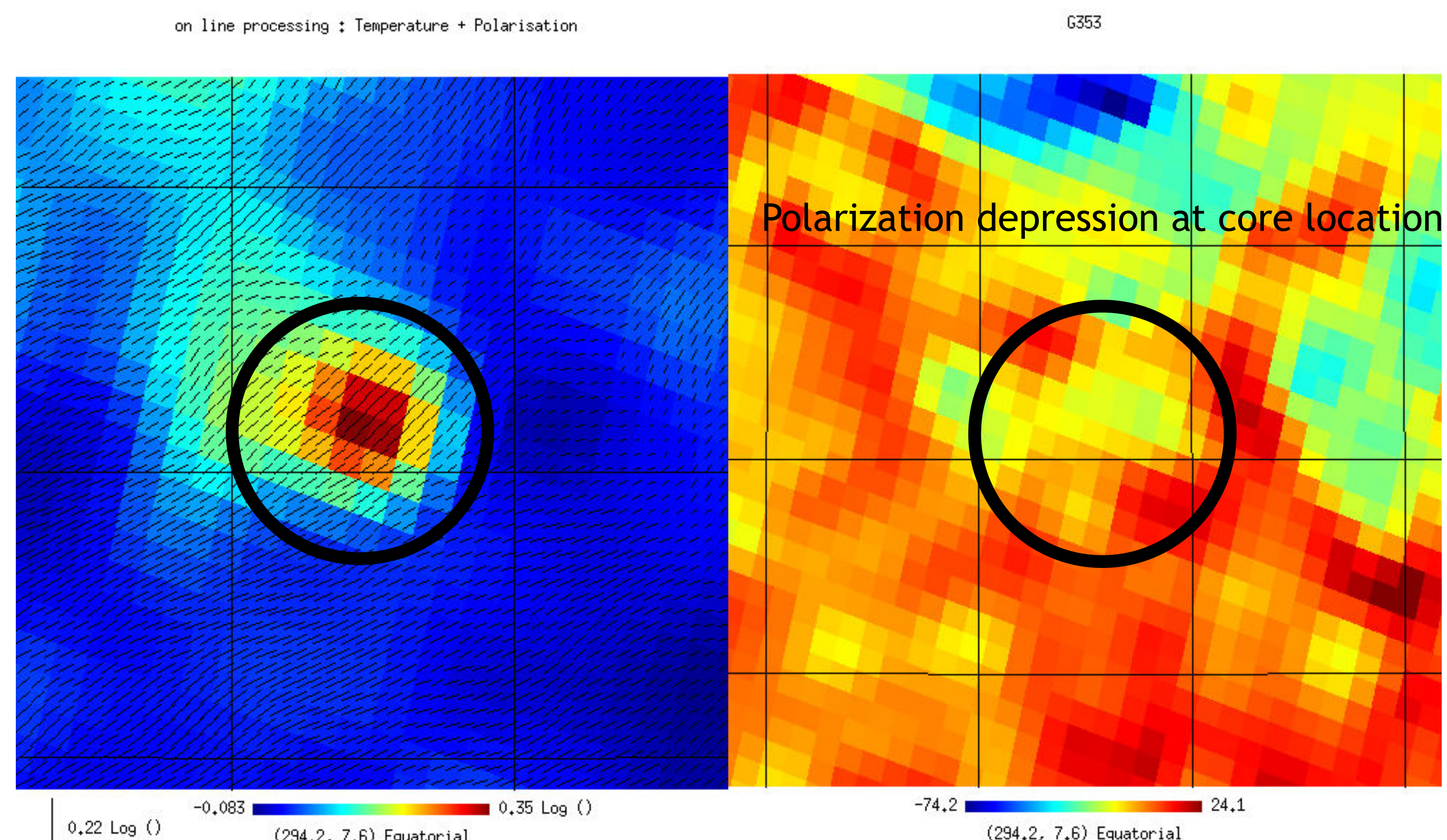




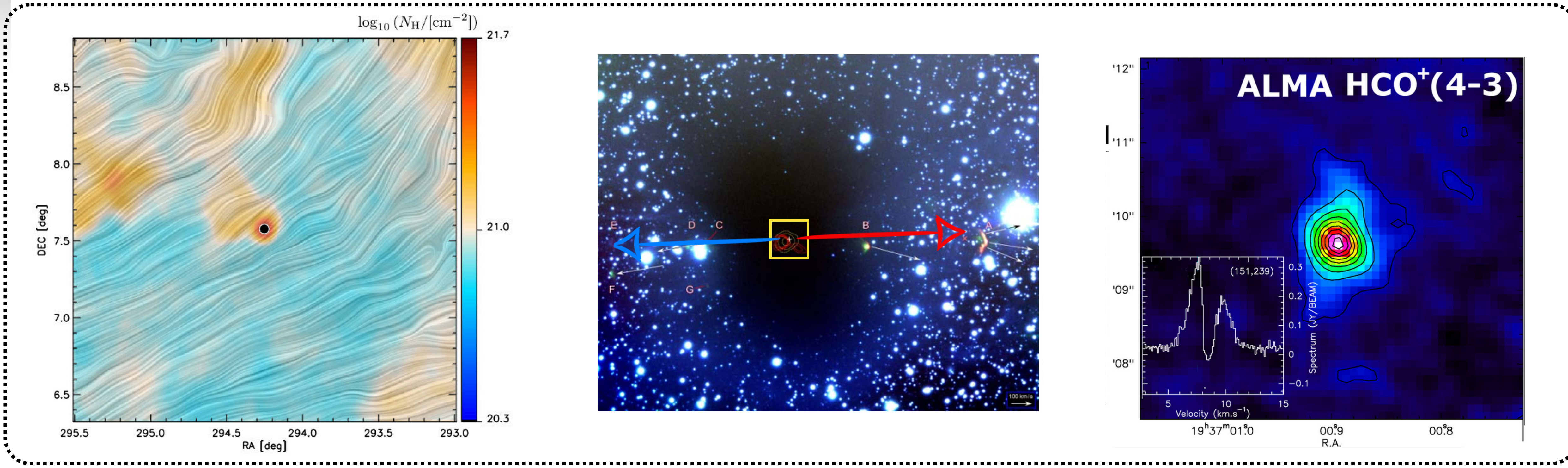
And it is embedded
in a large scale magnetic field …..
Planck map made by A. Bracco



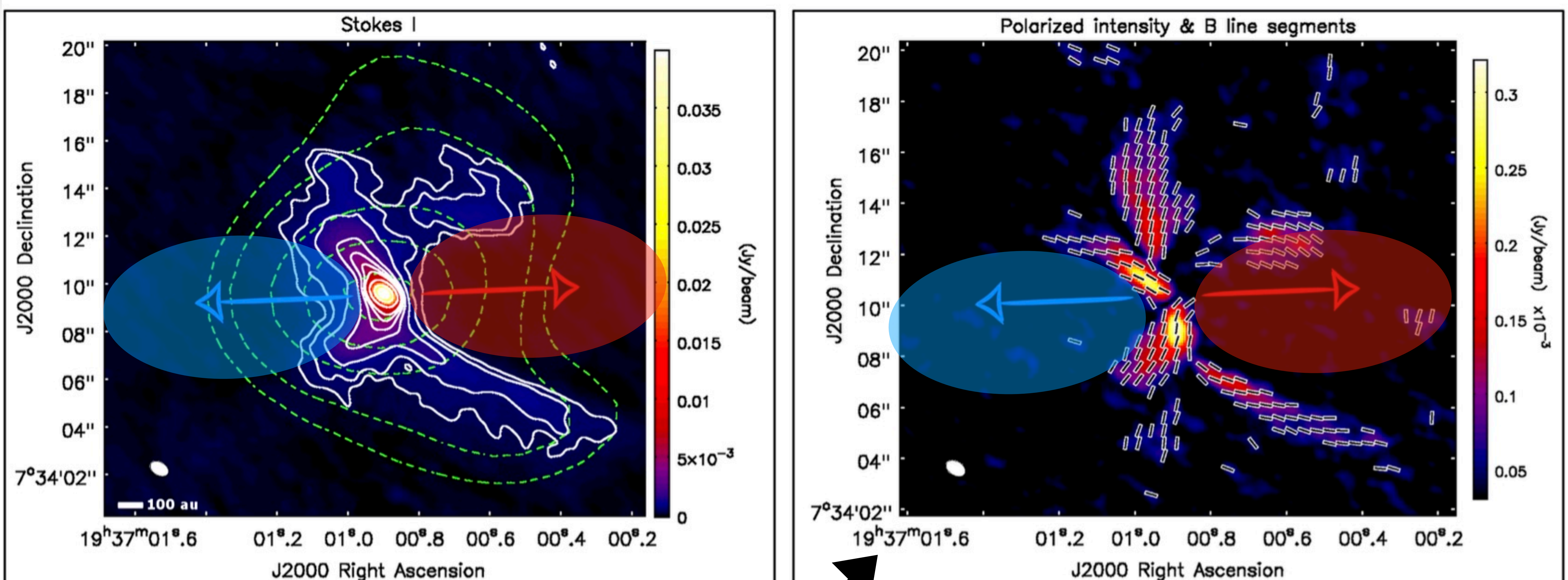
However not clear wether B mapped at Planck scales
is associated to core ….



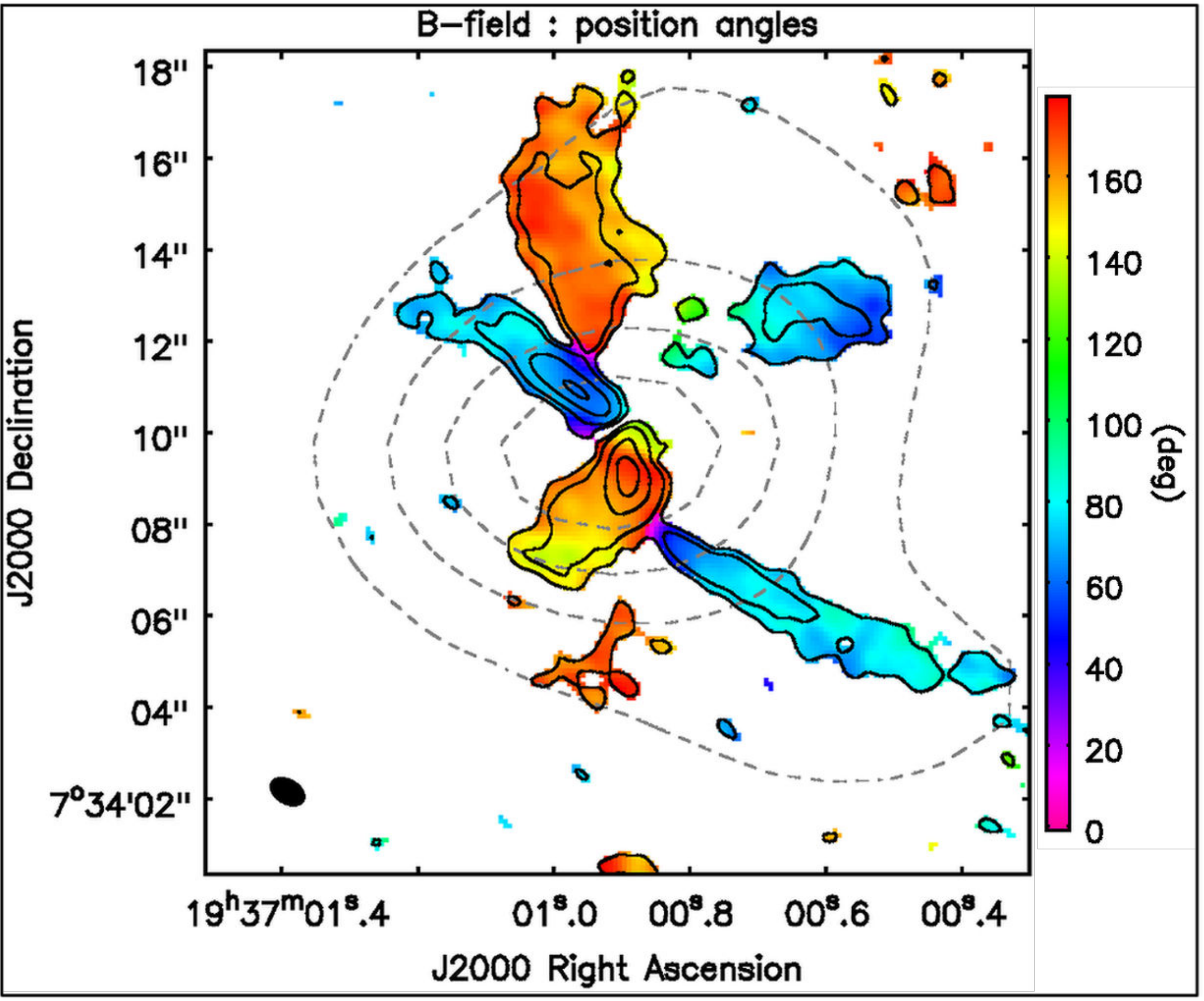
A magnetically-regulated disk size in B335 ?

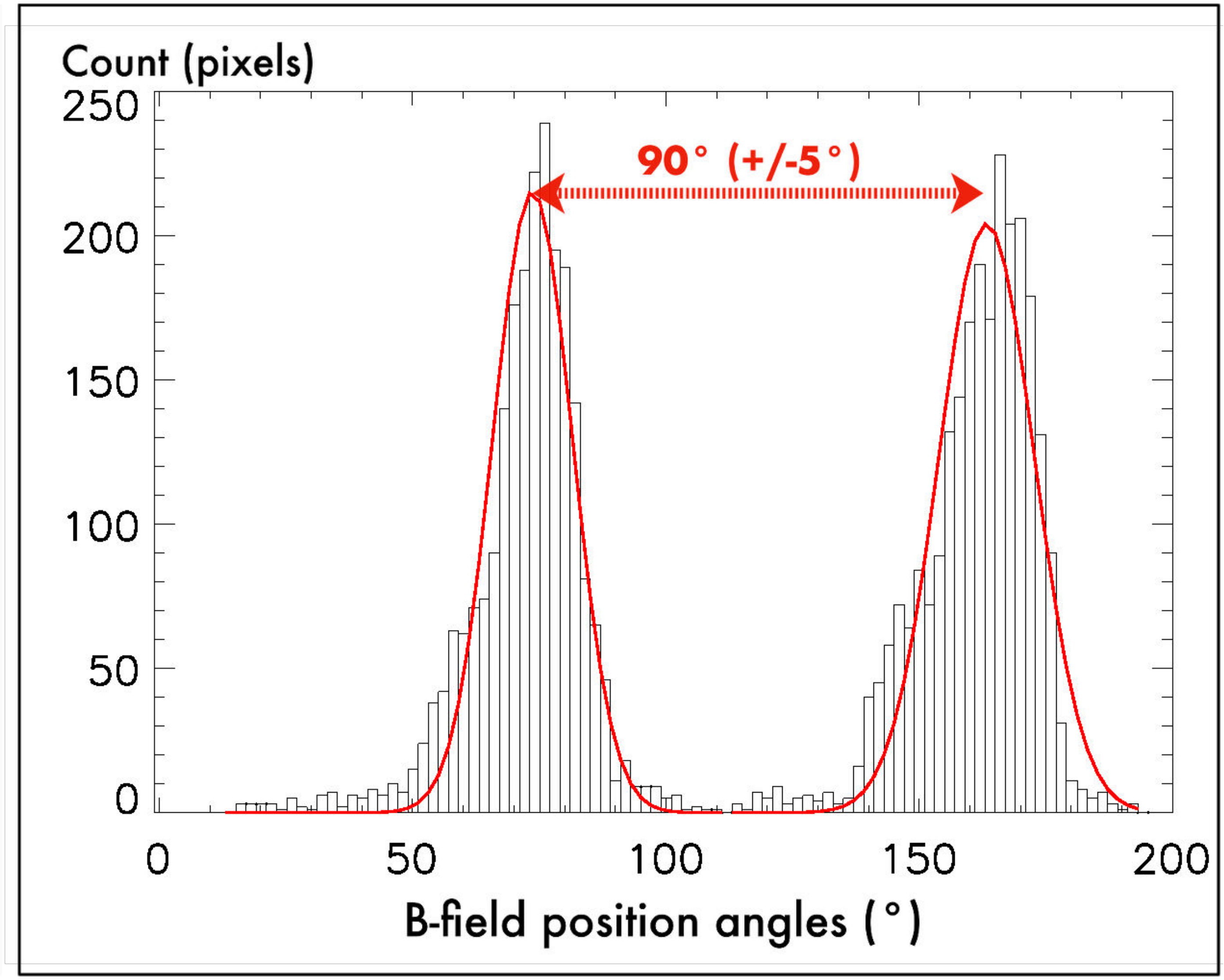


Our ALMA map of the magnetic field in B335 Maury+ (2018)



A very organized B topology at 500 au scales



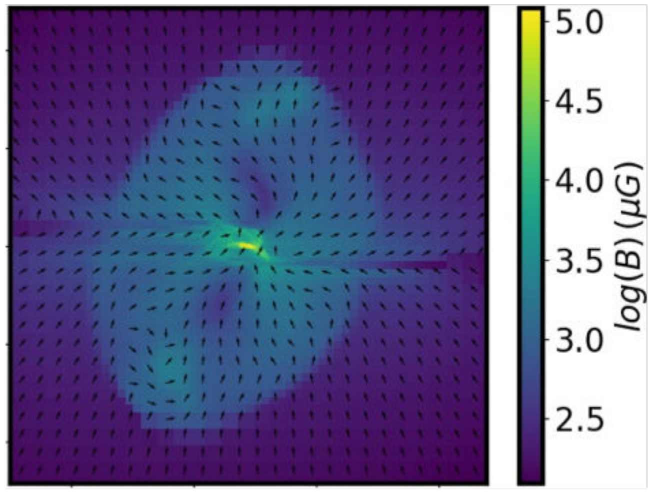


Observations reveal a **strikingly ordered magnetic field** in this young accreting protostar

Comparison to models: synthetic observations

❖ **Numerical simulation** with the RAMSES code (Teyssier 2002, Fromang+2006) performed by Patrick Hennebelle

Non ideal MHD, rotation, turbulence, gravitational collapse



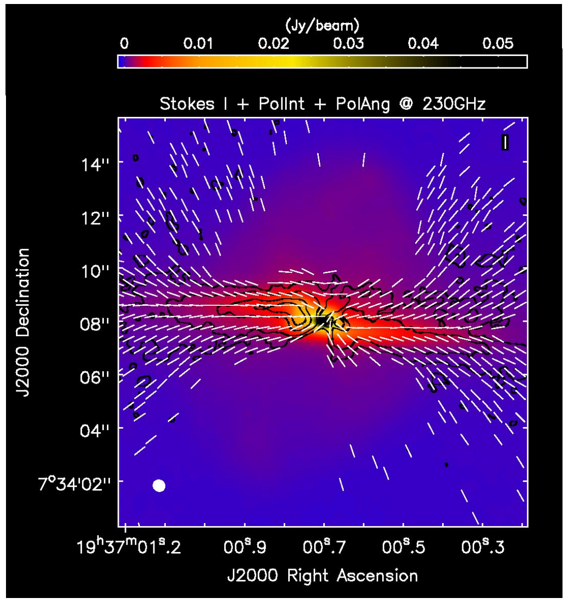
❖ **Radiative transfer** with the POLARIS code (Reissl+2017, Brauer+ 2019) performed by Valeska Valdivia

Dust heating, grain alignment and dust thermal emission

❖ **Observations of the wave plane with a synthetic interferometer** performed by Anaëlle

Fourier transform including filtering and atmospheric noise

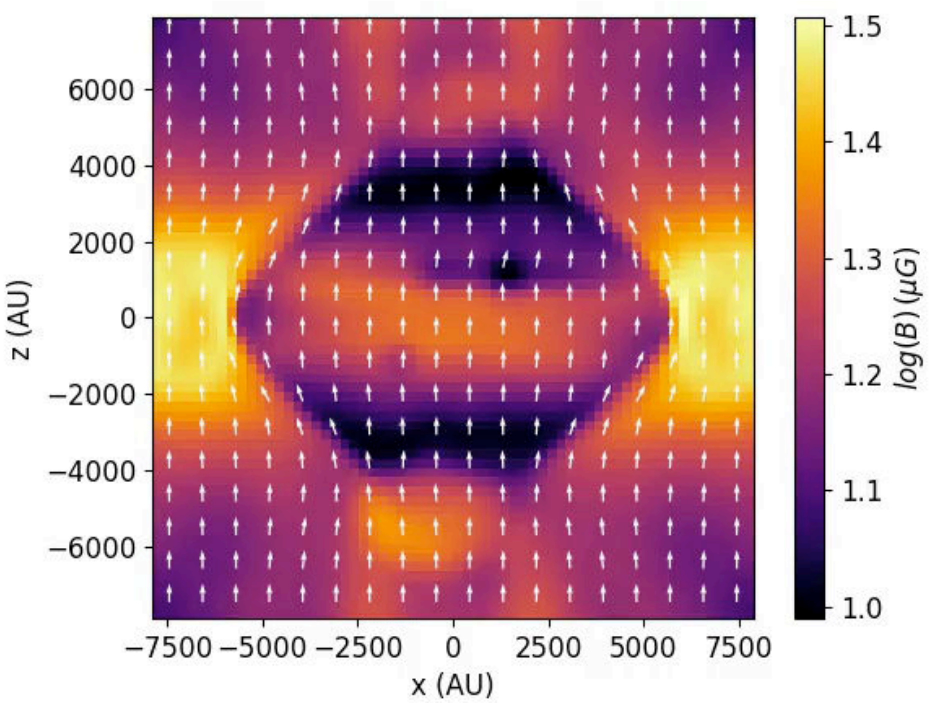
Inversion of the visibilities and cleaning of the map



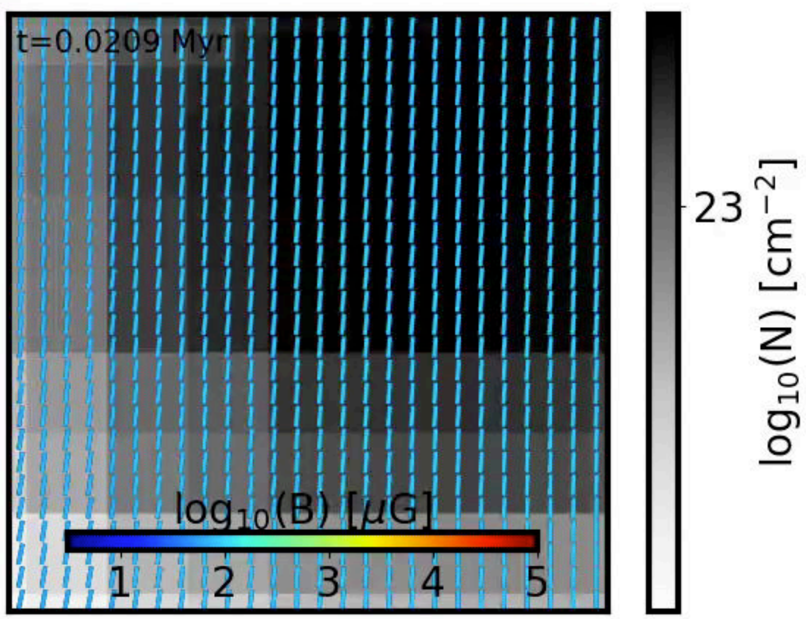
Comparing data to models

- **Numerical simulation** performed by P. Hennebelle with the RAMSES code (Teyssier 2002, Fromang+2006)
  - Adaptive Mesh refinement (AMR)
  - Non-ideal MHD

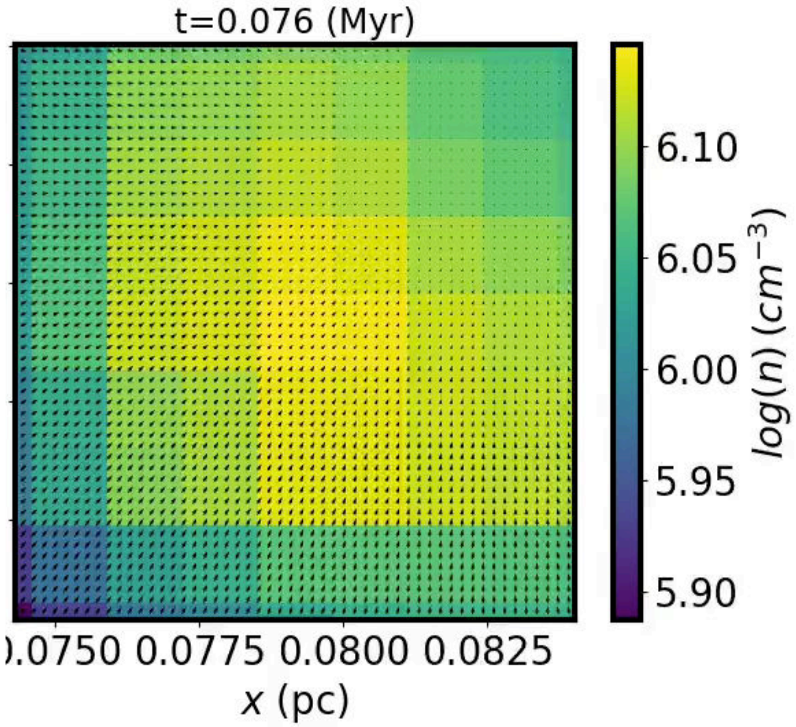
Integrated B field strength



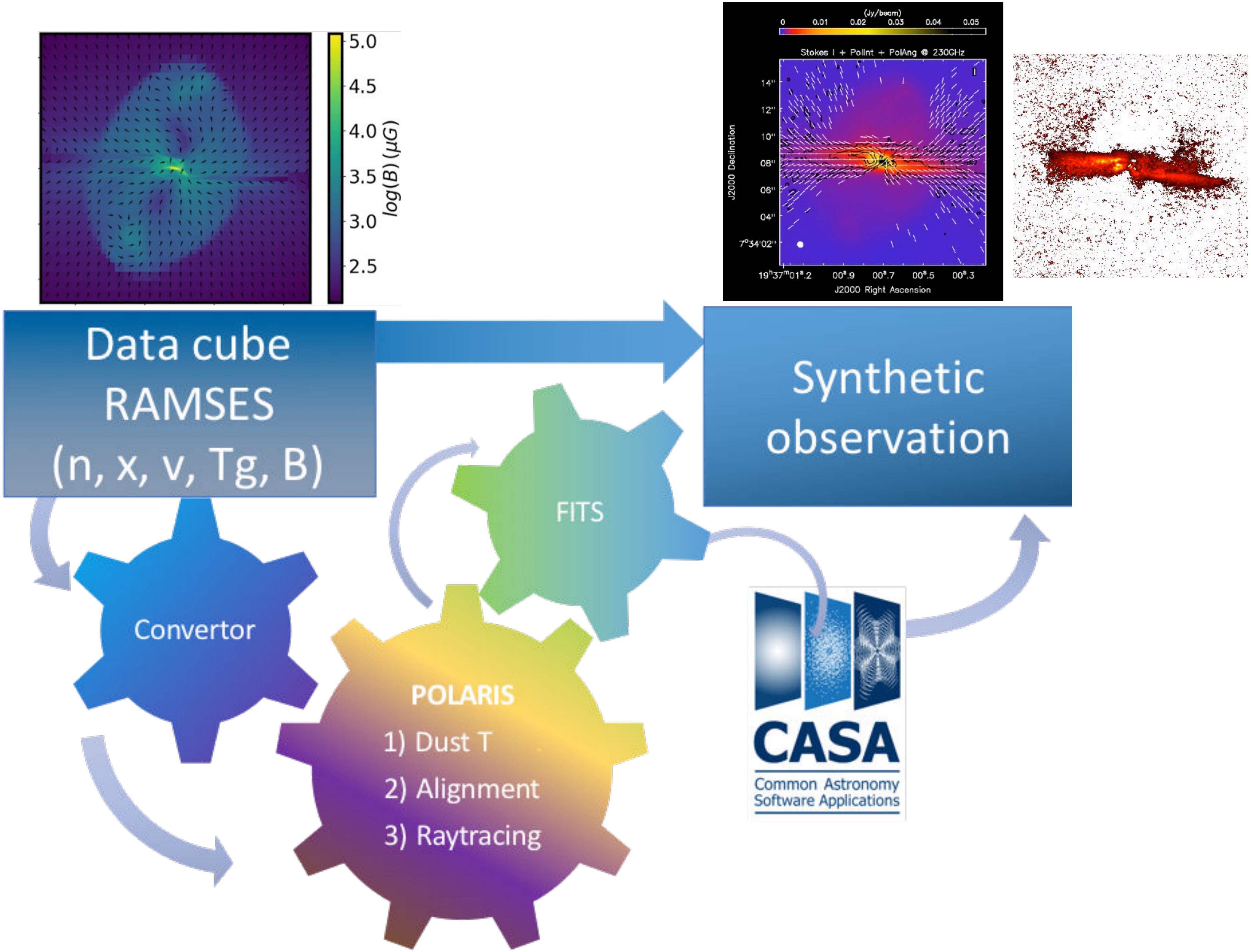
Column density time evolution



Density and velocity field evolution



Method

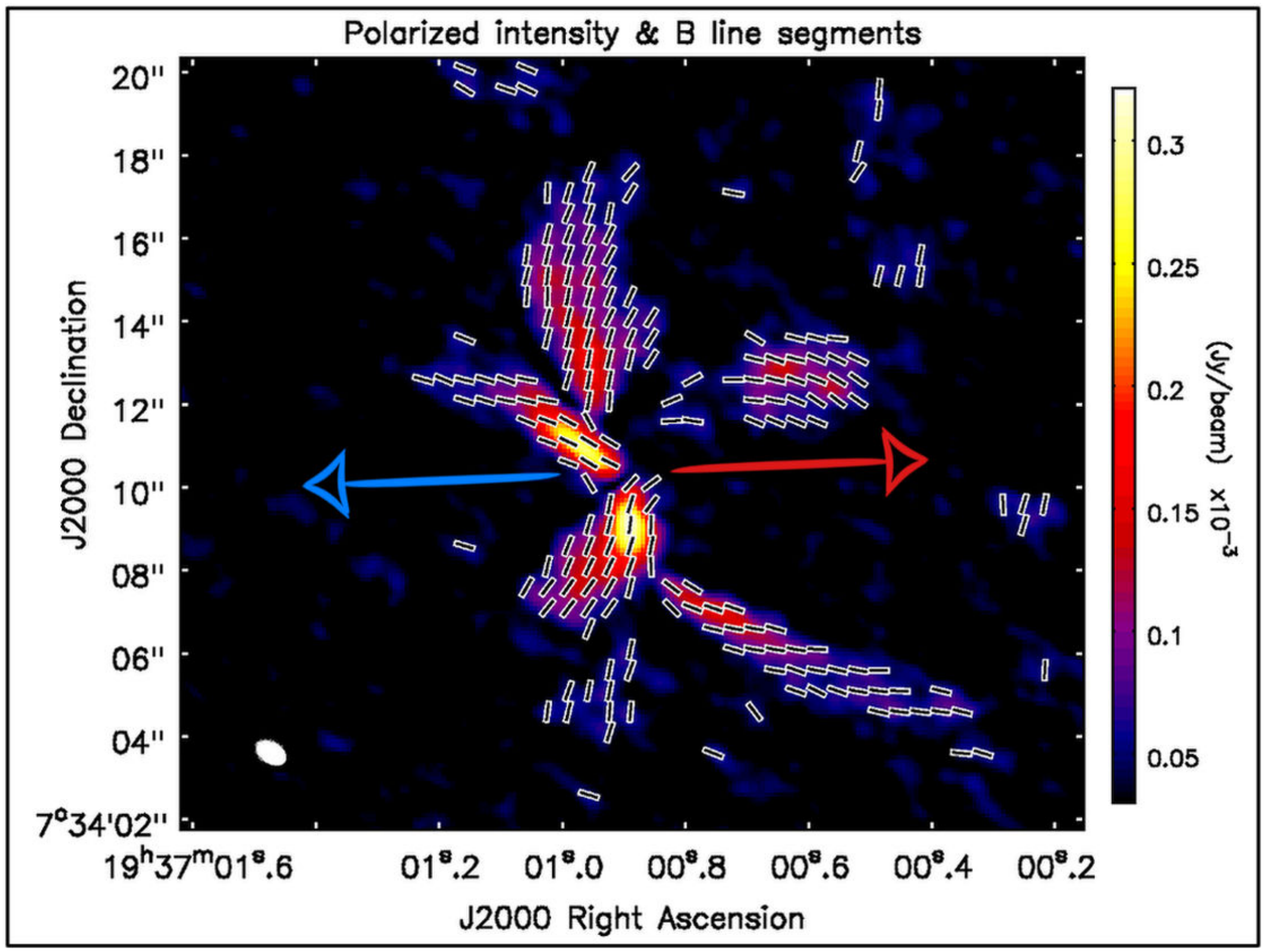


- ❖ **Radiative transfer** with the POLARIS code (Reissl+2017)
- ❖ **Observations of the wave plane with a synthetic interferometer (CASA)**

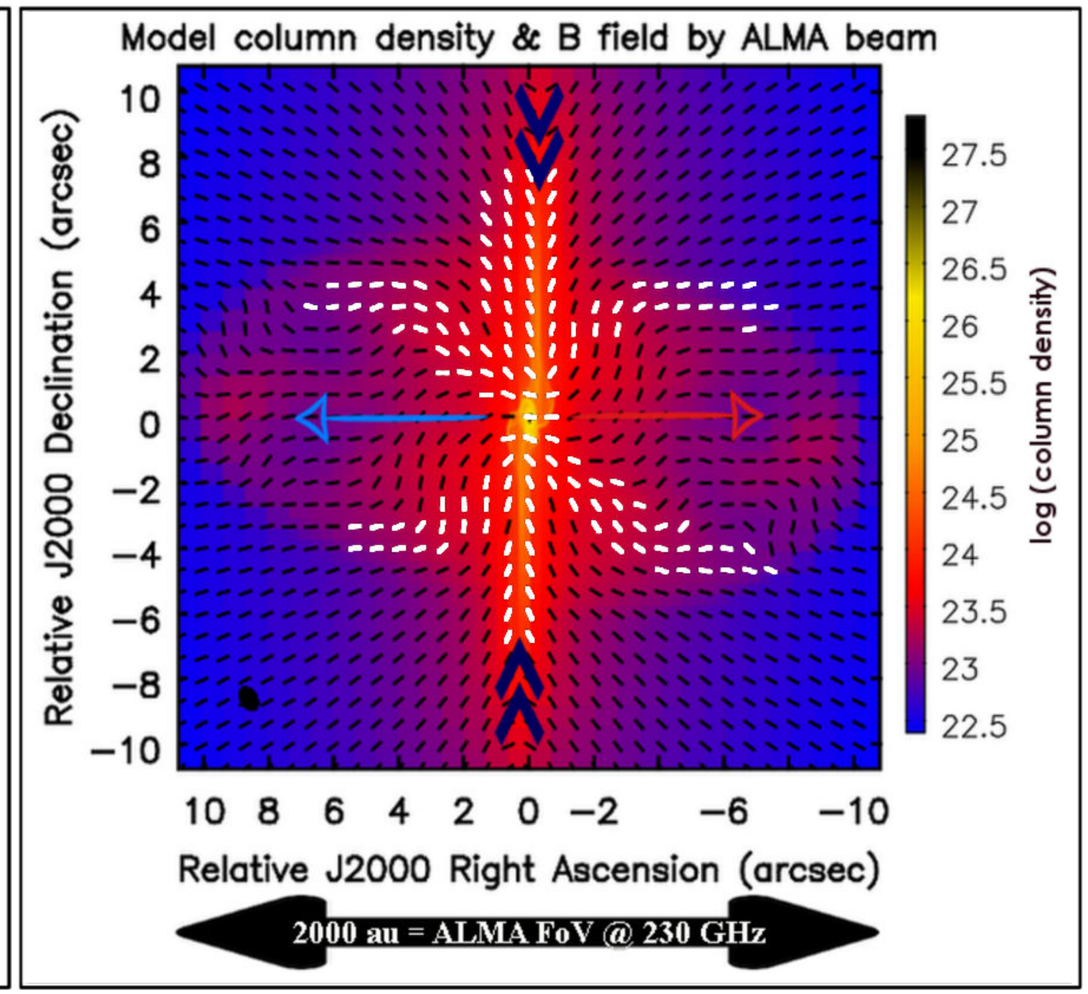
Comparison to models: B is dynamically relevant

RAMSES models (P. Hennebelle)
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

OBSERVATIONS: B LINES



MODEL: SYNTHETIC B LINES



Only models with dynamically relevant B-field match the data (best model μ~6)

=> B regulates the early properties of the protostellar disk in B335 Maury+ (2018)

Does B-field also changes the gas accretion ?

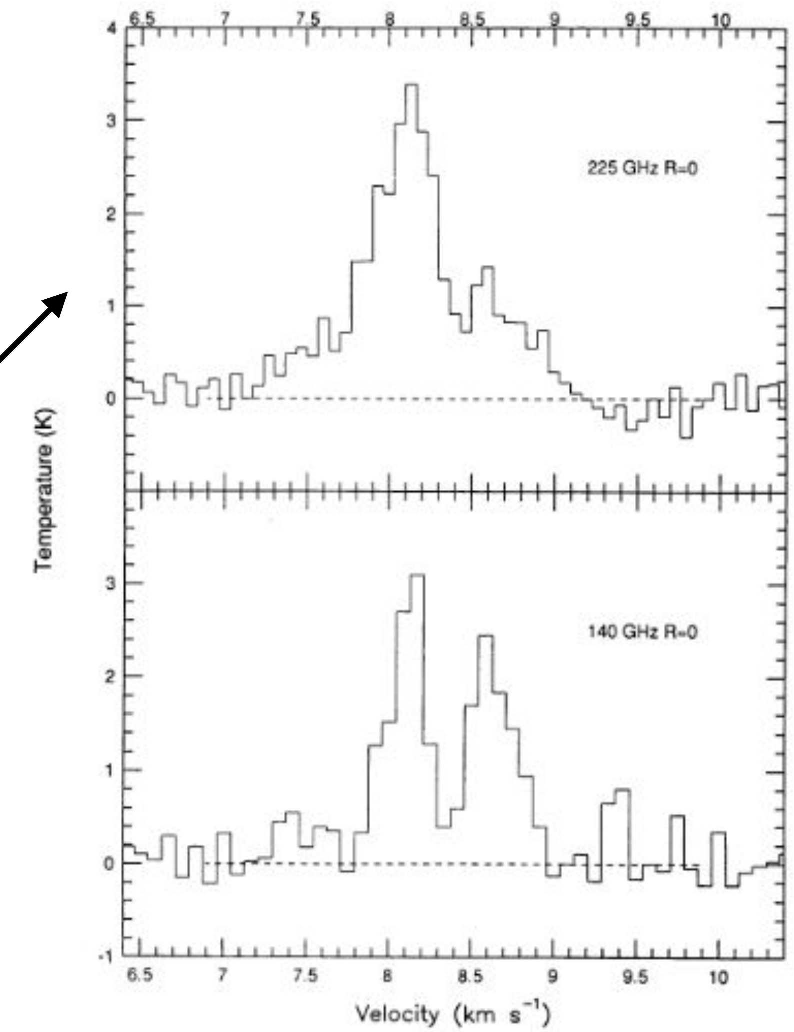
EVIDENCE FOR PROTOSTELLAR COLLAPSE IN B335

SHUDONG ZHOU,[1,2] NEAL J. EVANS II,[1] CARSTEN KÖMPE,[3,4] AND C. M. WALMSLEY[4]

Received 1992 March 17; accepted 1992 August 12

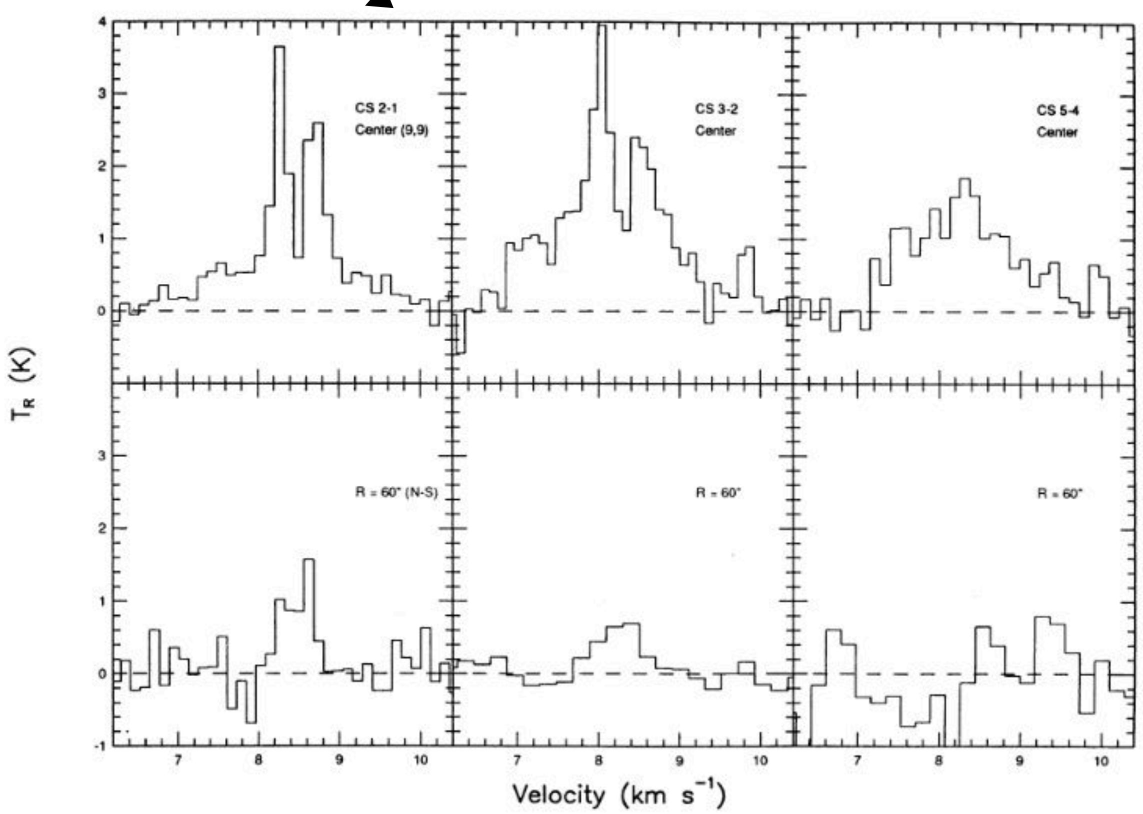
ABSTRACT

We have observed five rotational transitions of H_2CO and CS toward the Bok globule, B335, with high spatial and spectral resolution. The characteristic shape of the observed profiles provides direct, kinematic evidence of collapse. In addition, we have modeled line profiles of collapsing dense cores with density and velocity structures taken from the theory of Shu and coworkers. Using the age of collapse as the only free parameter, we found that the strengths and profiles of the observed lines can be well fitted by the theoretical model. Our best-fit model gives an age of 1.5×10^5 yr, corresponding to an infall radius of 0.04 pc (30″) and a total mass of 0.4 $M_\odot$ for the central star and disk. Outside the infall radius, there is a static envelope with a r^{-2} density distribution, an average temperature of 13 K, and a turbulent velocity (1/e width) of 0.12 km s^{-1}. The CS abundance is 3.6×10^{-9} with about 30% uncertainty.

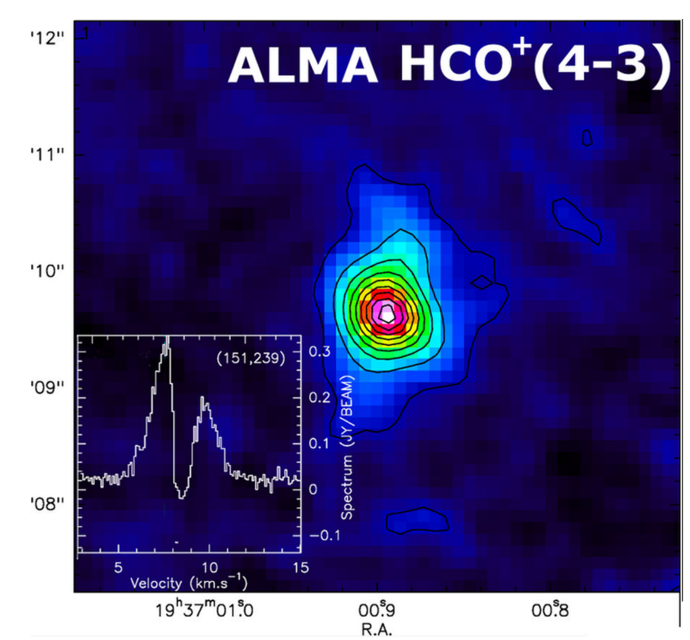


Zhou et al. 1992:

H_2CO single dish observations
CS single dish observations



Evans et al. 2015
@200 au scales



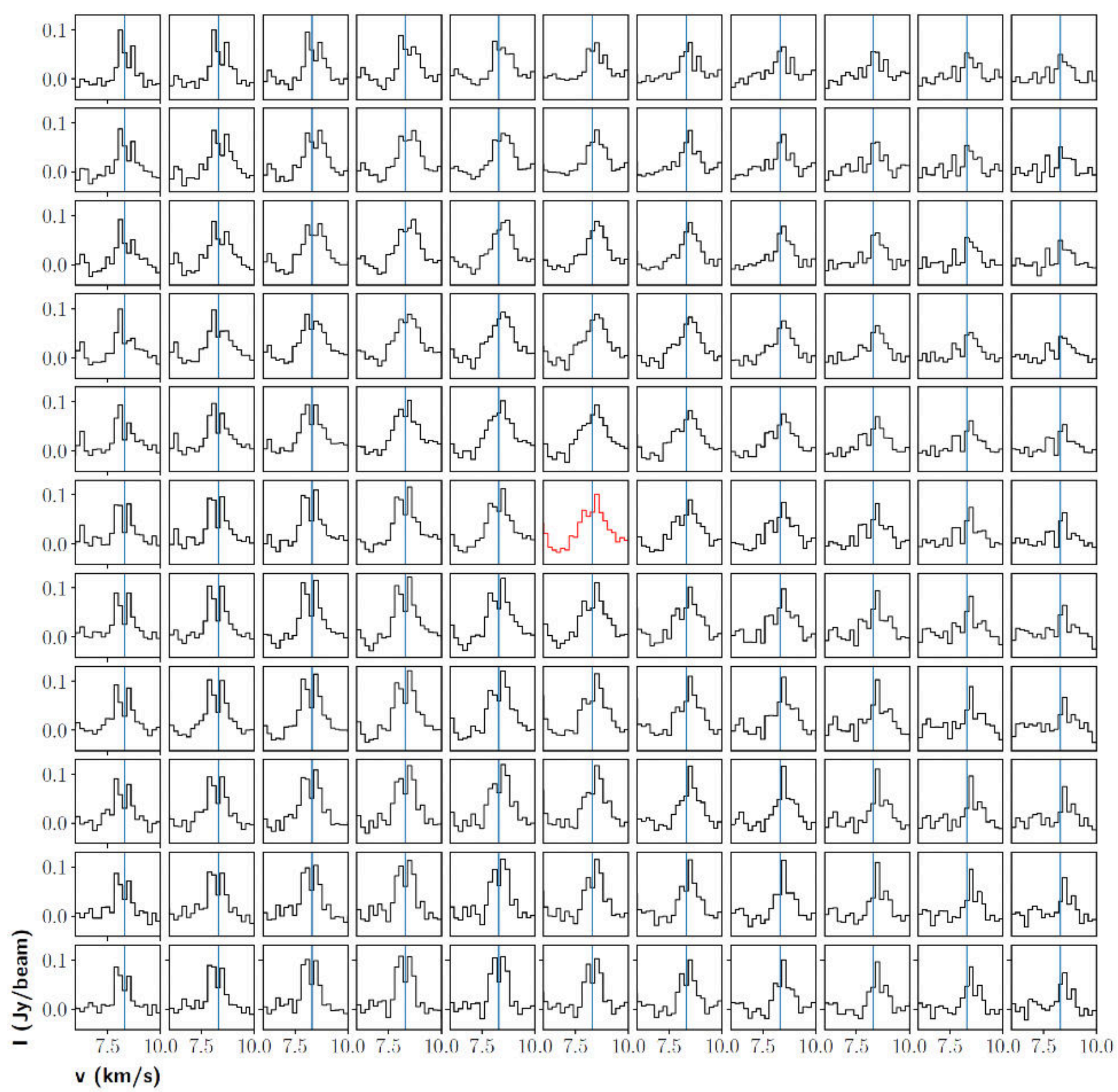
Does B-field also changes the gas accretion ?

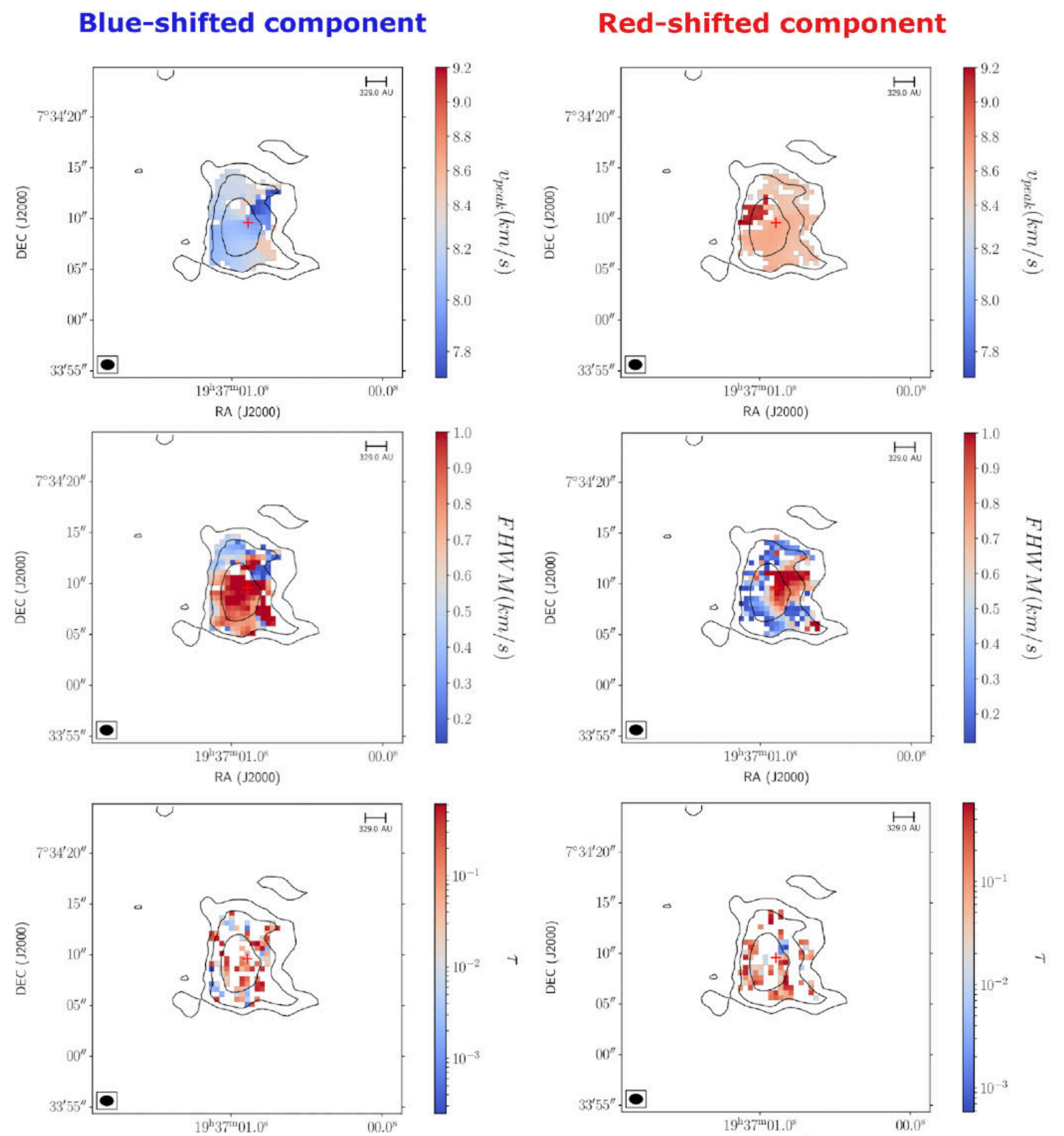
Observations of the kinematical structure from the infalling gas

Cabedo-Soto et al. (2021)

C[17]O ALMA observations in B335

Shows double peaked profiles in the inner envelope
Not an optically-thick infall signature (optically thin gas tracer)
Not associated to outflow motions
High velocity patterns: supersonic infall along cavity walls





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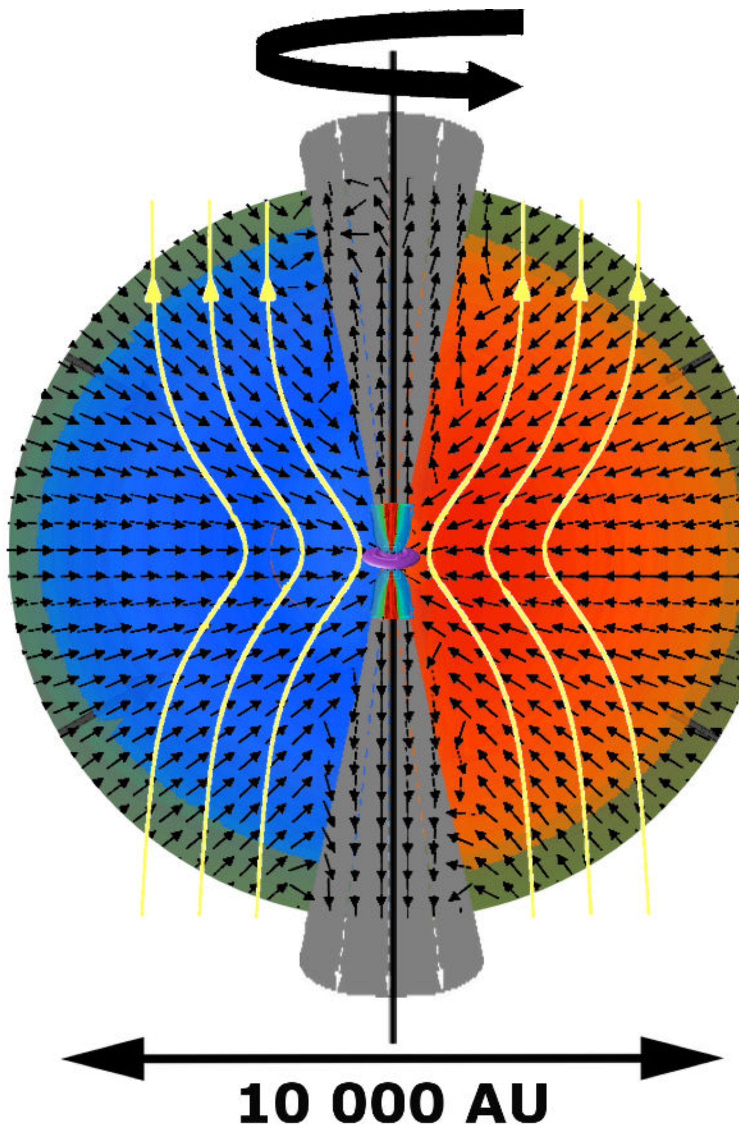

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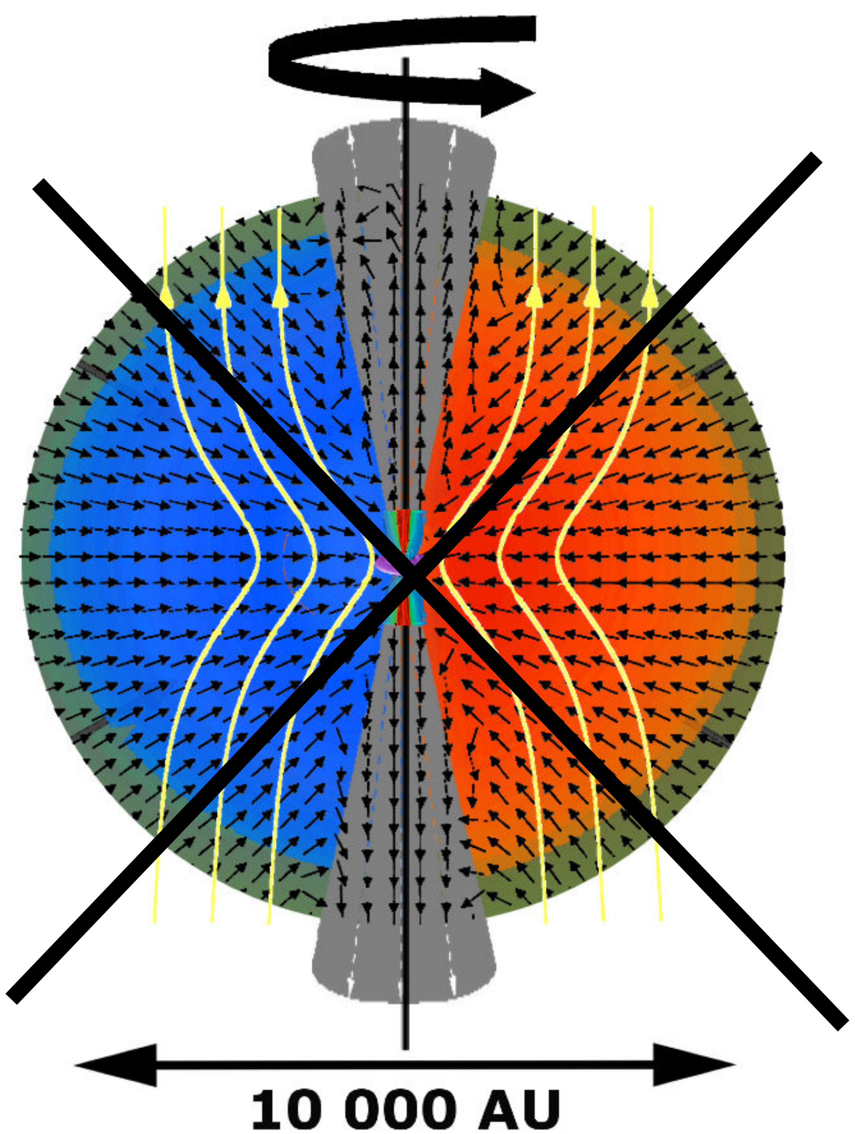
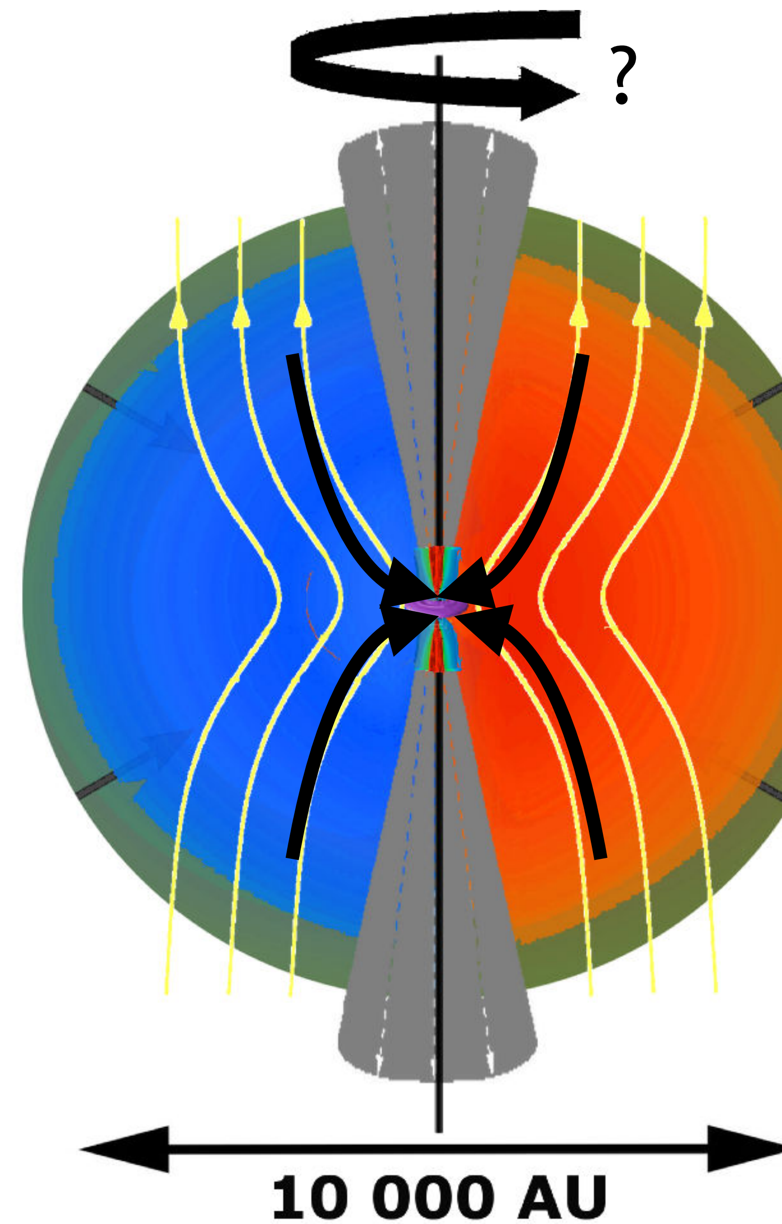




Why does it matter ?
Protostellar mass accretion rates derived
from simple spherical infall models of double-peaked line profiles may be revised

Does B-field also changes the gas accretion ?

Observations of the kinematical structure from the infalling gas

Cabedo-Soto et al. (2021)

- Timescales:

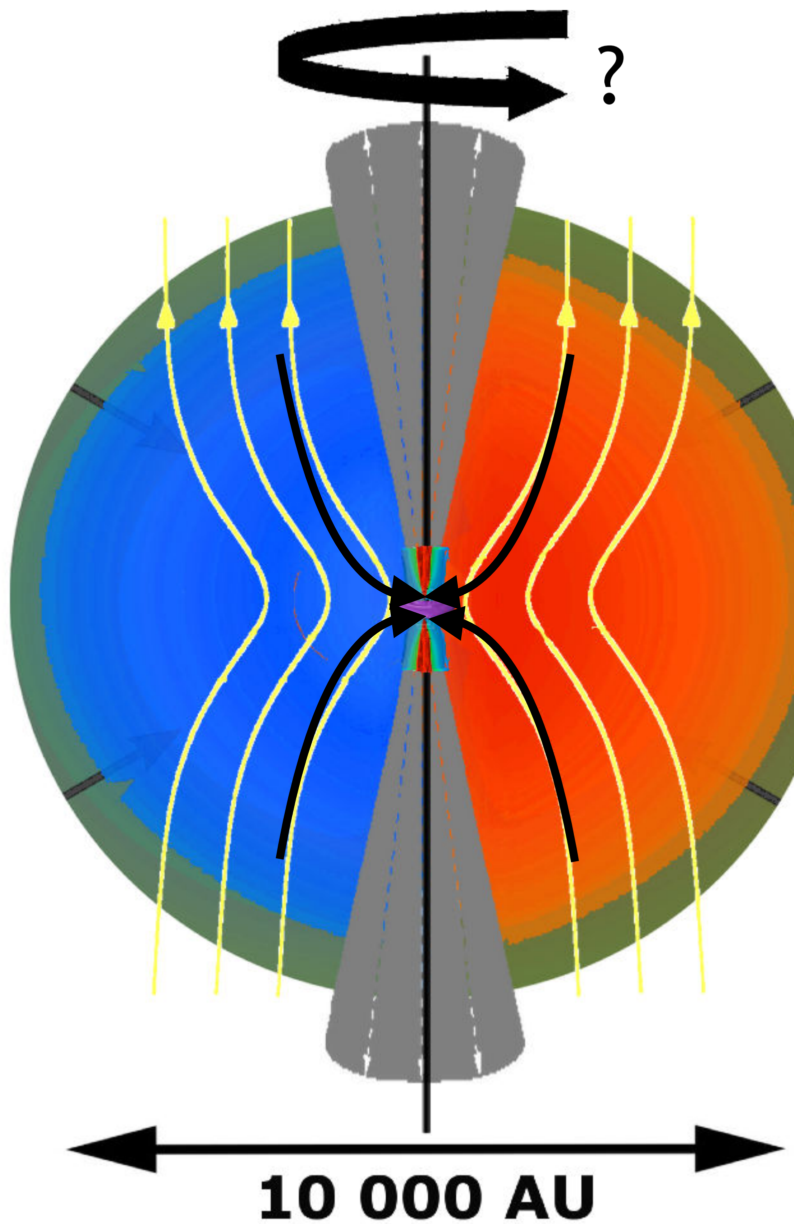
  ~10^4 to 10^5 years to form a 0.6 $M_\odot$ embryo

  (Evans+ 2009, Maury+ 2011) ?

- Accretion shock at the surface of the protostar: the kinetic energy is converted into heat, then radiated:

  $L_{acc} = \frac{1}{2} (dM/dt) V_{ff}^2 = GM/R(dM/dt)$

  L_{acc} dominates $L_\odot$: luminosity problem



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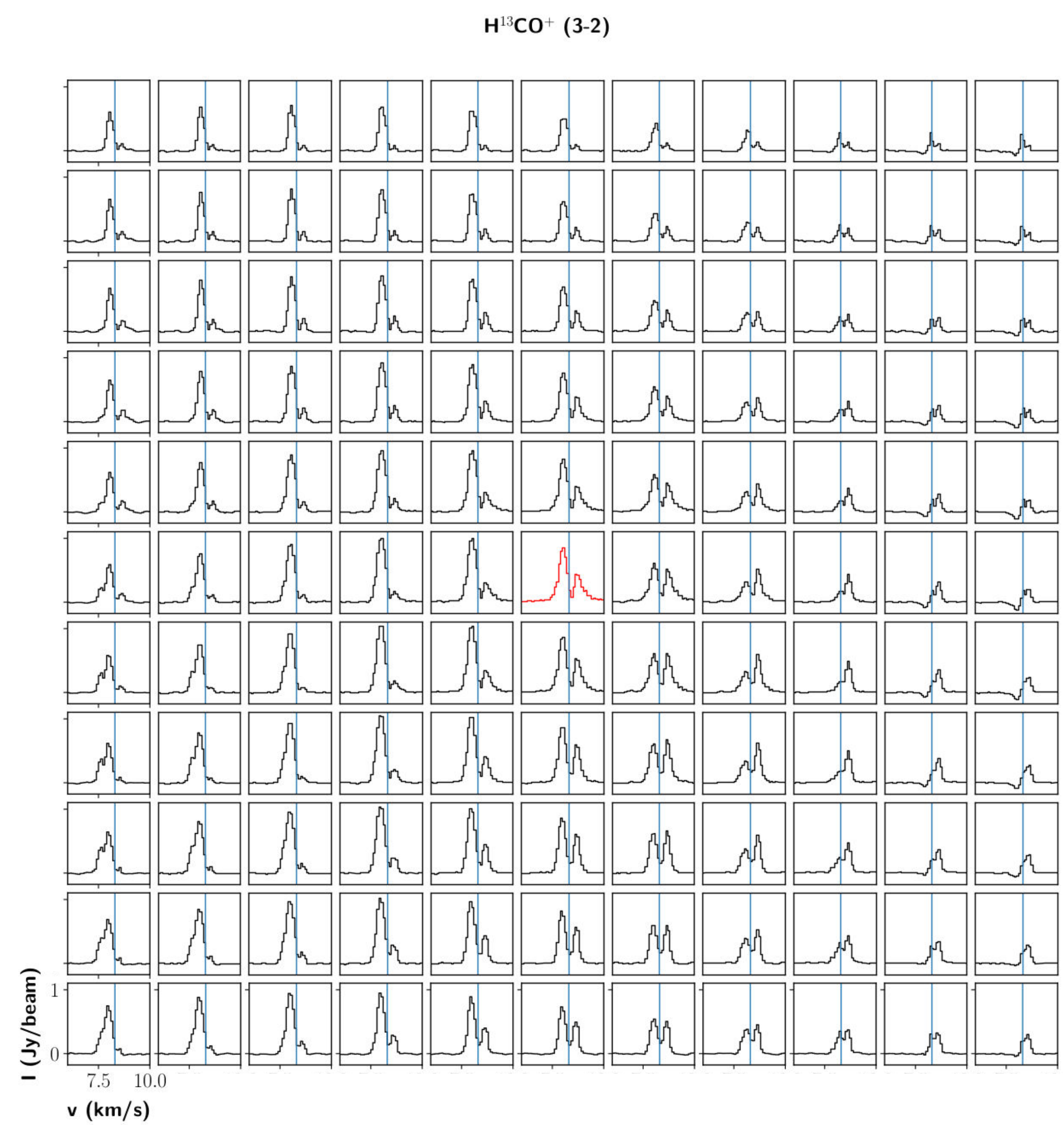
A magnetically-regulated collapse in B335 ?

Observational clues of a good coupling of the B-field with infalling gas



Cabedo-Soto et al. (2021, & in prep.)

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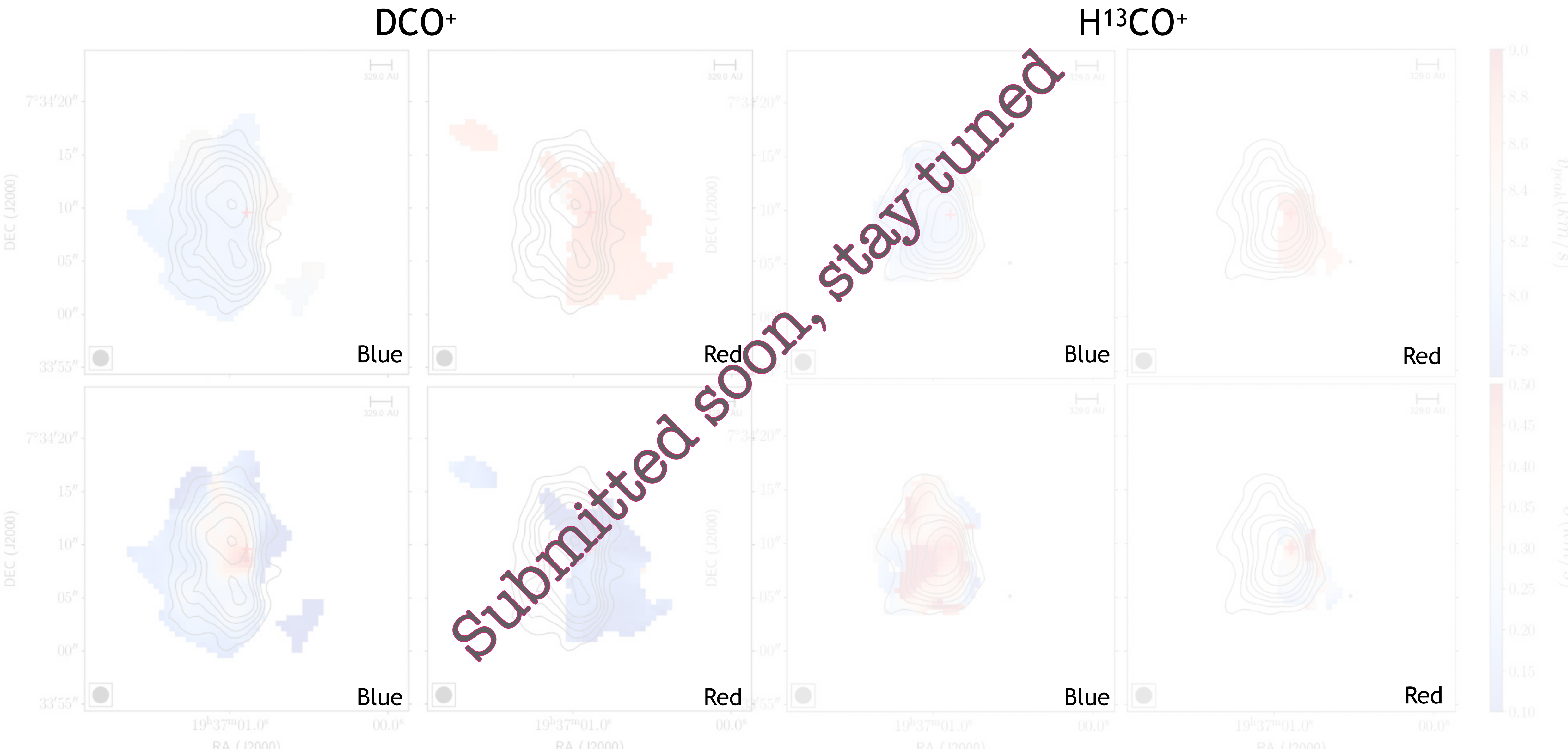


Cabedo-Soto et al. (2021, & in prep.)

A magnetically-regulated collapse in B335 ?

Observational clues of a good coupling of the B-field with infalling gas

ALMA & ACA: $DCO^+/H^{13}CO^+$

We find gas ionization several 10^{-6}

F_{ion} in cores normally lie around 10^{-7}

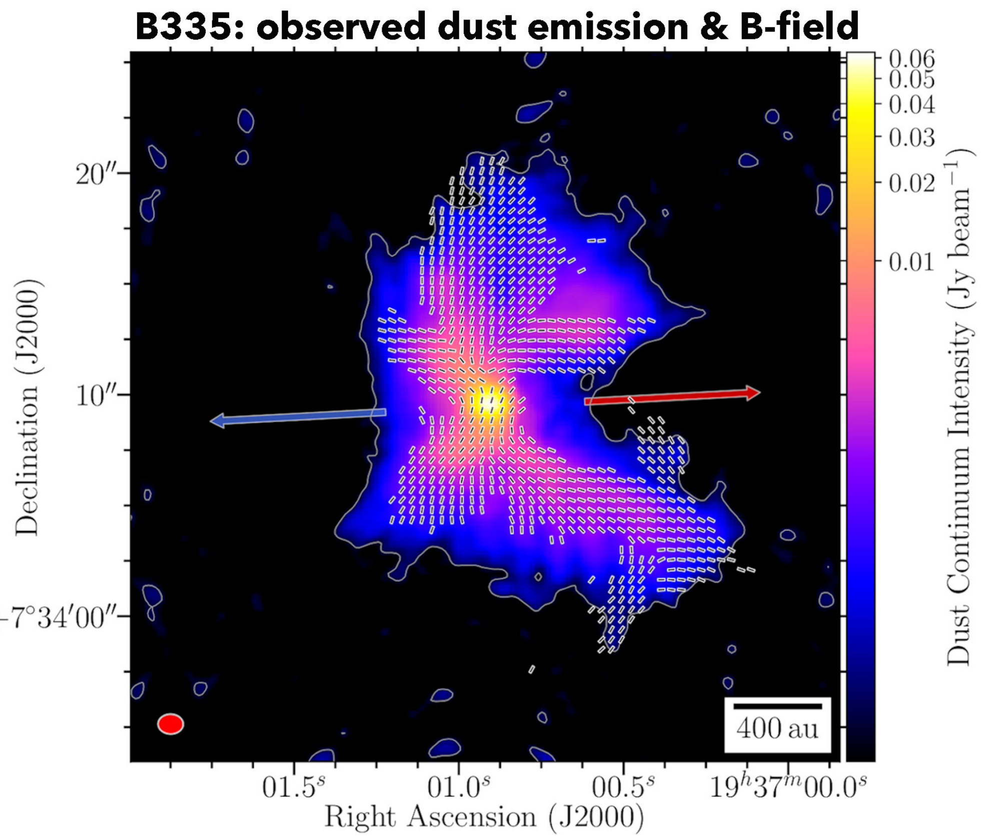
↓

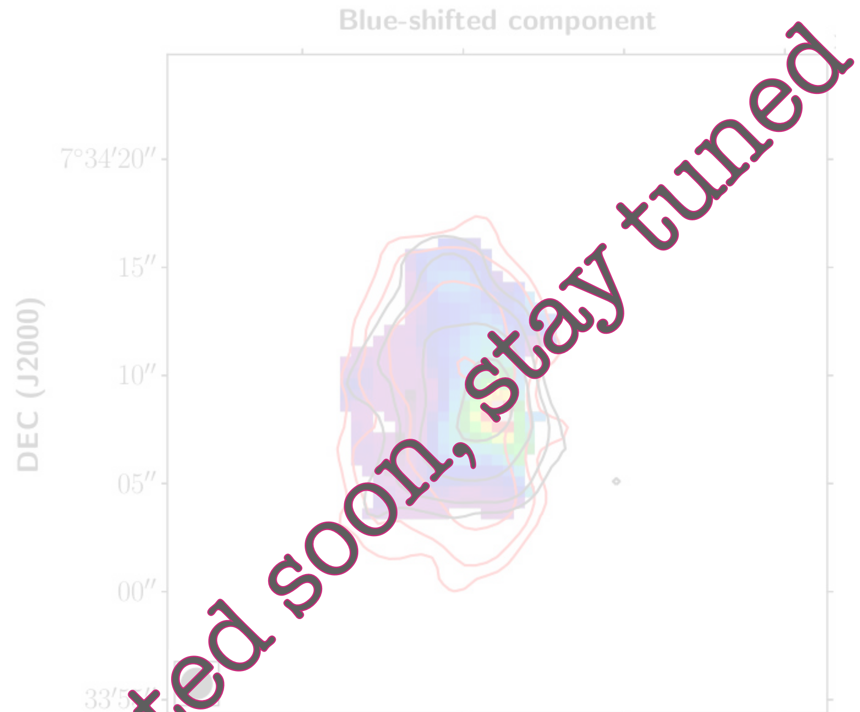
Enhanced ionization around the protostar
Also along the supersonic infall structure

Cabedo-Soto et al. (2021, & in prep.)

A magnetically-regulated collapse in B335 !

Observational clues of a good coupling of the B-field with infalling gas





Submitted soon, stay tuned

Small disk
+
Highly organized polarization vectors
+
High polarization fraction
+
Supersonic infall along cavity walls

Magnetic field organized
-> setting disk size
-> funneling gas accretion ?

ALMA & ACA: DCO^+/$H^{13}CO^+$

We find gas ionization several 10^{-6}

F_{ion} in cores normally lie around 10^{-7}

Enhanced ionization around the protostar
Good coupling of B with gas

Indication of lower velocity dispersion for the ions

where the ionization is seen high ?

A clue of efficient ambipolar diffusion ?

Cabedo-Soto et al. (2021, & in prep.)

New results in a Class I protostar

Which Part of Dense Cores Feeds Material to Protostars?: The Case of L1489 IRS

Jinshi Sai (Insa Choi),[1,2] Nagayoshi Ohashi,[2] Anaëlle J. Maury,[3,4] Sébastien Maret,[5] Hsi-Wei Yen,[2]
Yusuke Aso,[6] and Mathilde Gaudel[7]

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[5]Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France
[6]Korea Astronomy and Space Science Institute (KASI), 776 Daedeokdae-ro, Yuseong-gu, Daejeon 34055, Republic of Korea
[7]LERMA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Université, 75014 Paris, France

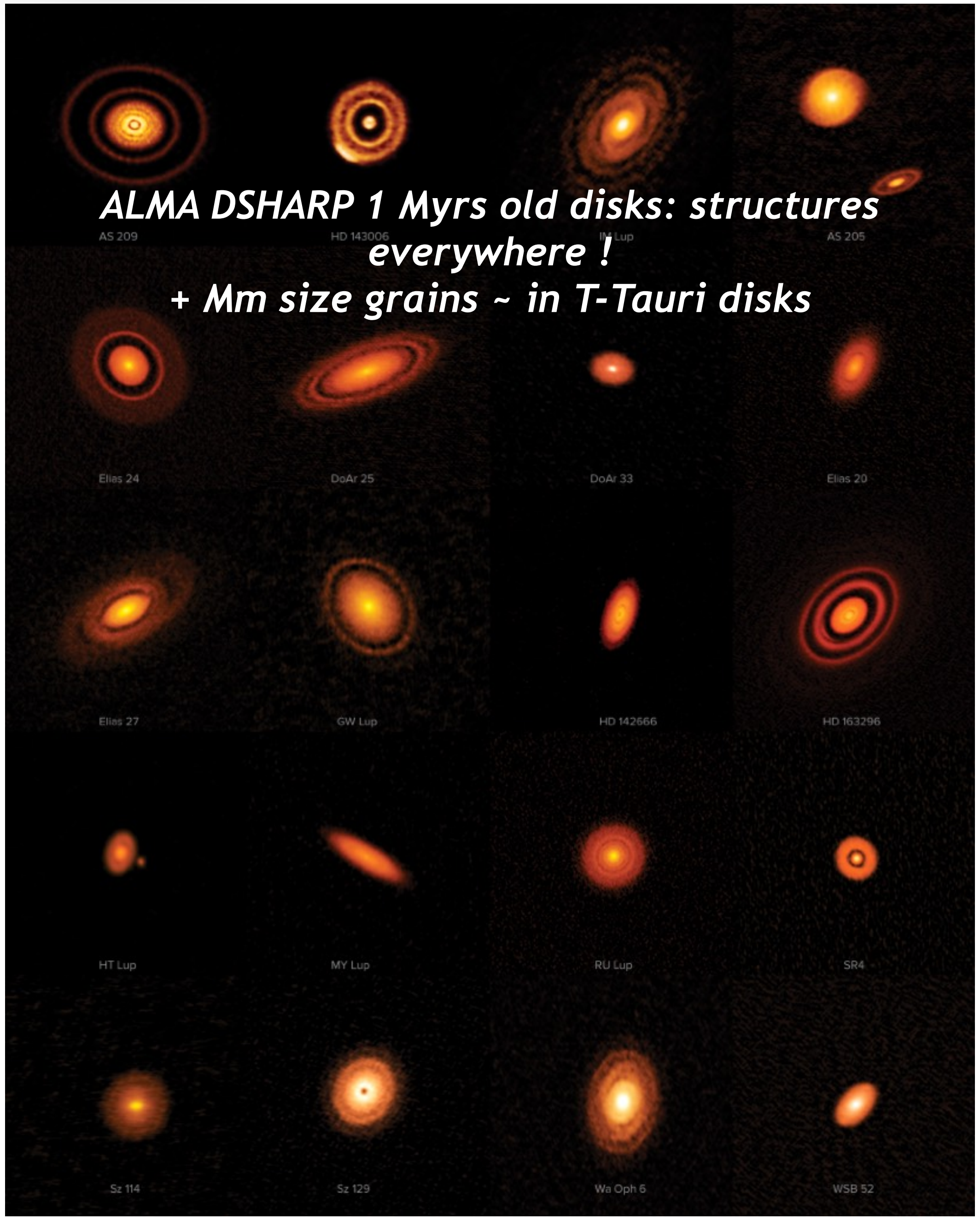
(Received October 25, 2021; Revised; Accepted)

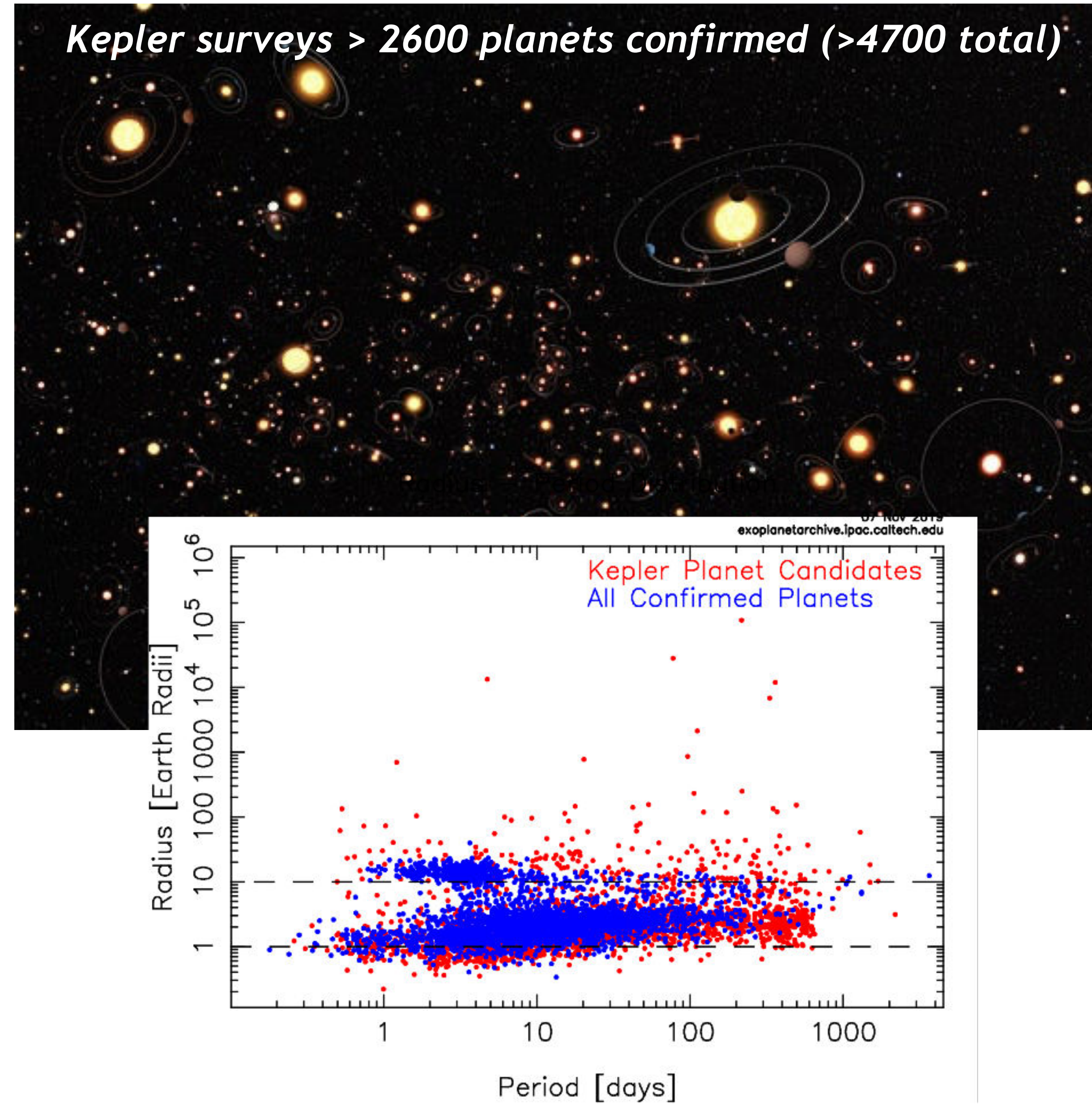
Submitted to ApJ

ABSTRACT

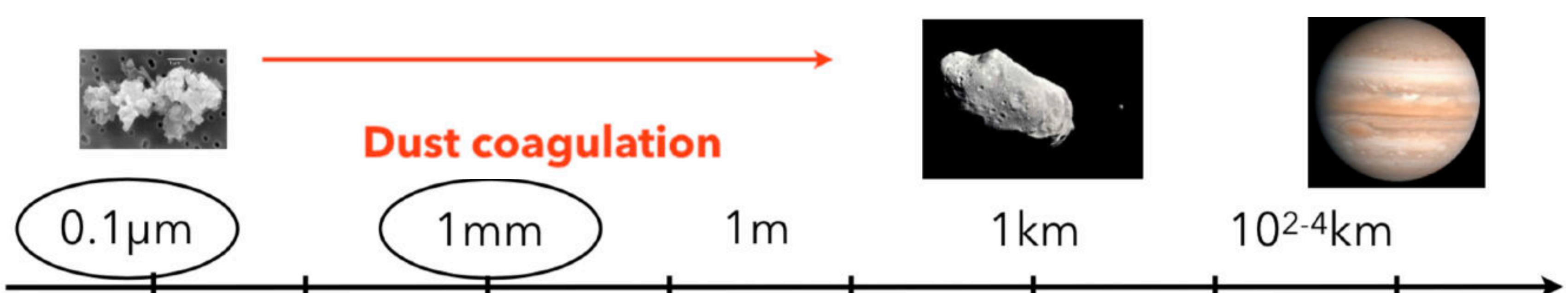
We have conducted mapping observations ($\sim 2' \times 2'$) of the Class I protostar L1489 IRS using the 7-m array of the Atacama Compact Array (ACA) and the IRAM-30m telescope in the $C^{18}O$ 2–1 emission to investigate the gas kinematics on 1000–10,000 au scales. The $C^{18}O$ emission shows a velocity gradient across the protostar in a direction almost perpendicular to the outflow. The radial profile of the peak velocity was measured from a $C^{18}O$ position-velocity diagram cut along the disk major axis. The measured peak velocity decreases with radius at a radii of ∼1400–2900 au, but increases slightly or is almost constant at radii of $r \gtrsim$2900 au. Disk-and-envelope models were compared with the observations to understand the nature of the radial profile of the peak velocity. The measured peak velocities are best explained by a model where the specific angular momentum is constant within a radius of 2900 au but increases with radius outside 2900 au. We calculated the radial profile of the specific angular momentum from the measured peak velocities, and compared it to analytic models of core collapse. The analytic models reproduce well the observed radial profile of the specific angular momentum and suggest that material within a radius of ∼4000–6000 au in the initial dense core has accreted to the central protostar. Because dense cores are typically ∼10,000–20,000 au in radius, and as L1489 IRS is close to the end of mass accretion phase, our result suggests that only a fraction of a dense core eventually forms a star.

All star(s) also have planets: dust grows !

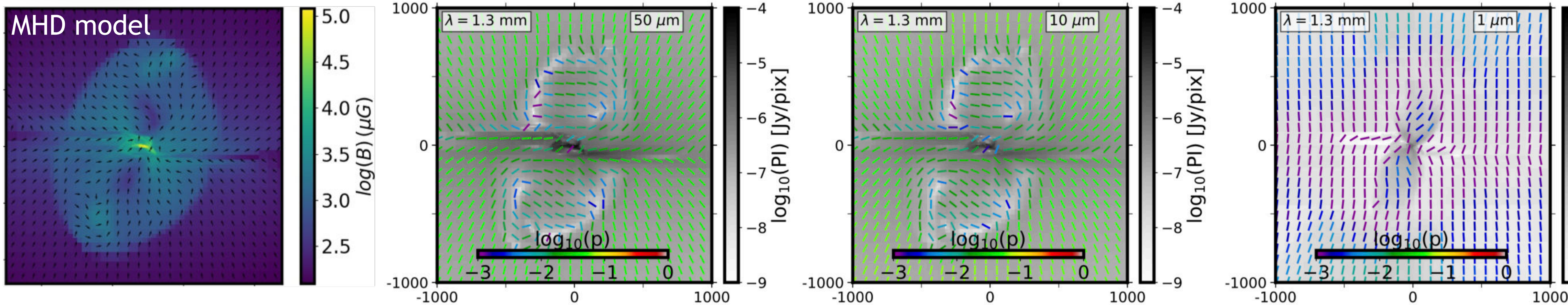




>25 % of FGK stars with Earth-like planets (Danley+ 2019)

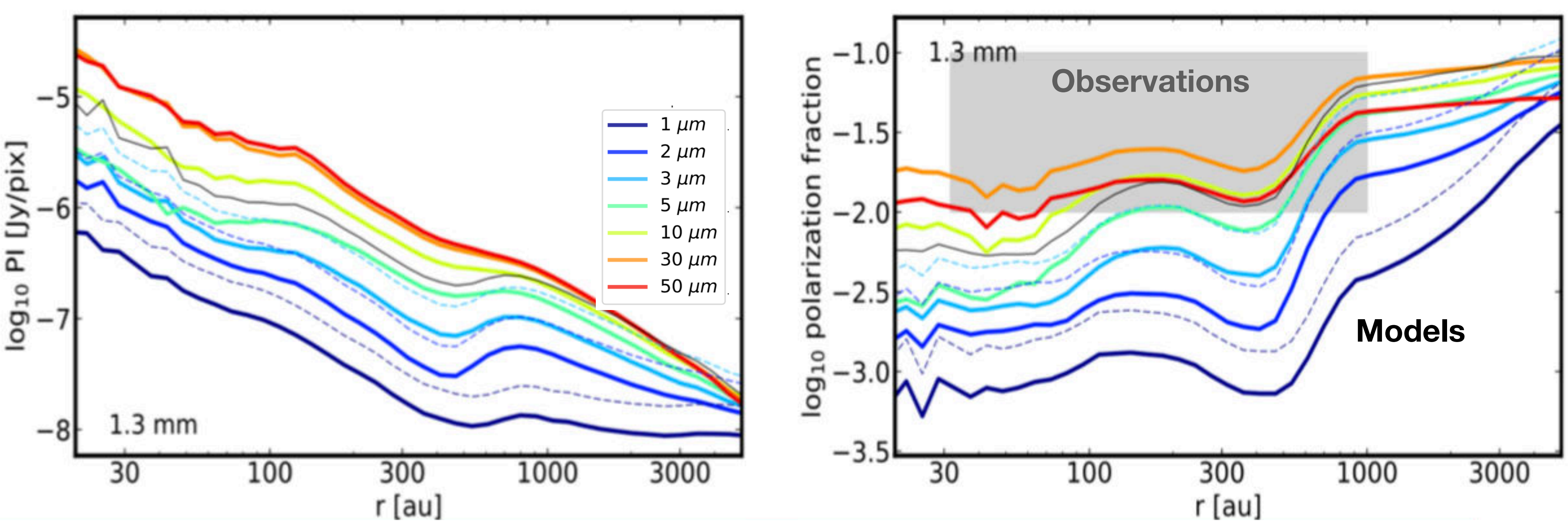


Polarized emission as a grain size indicator



Valdivia + (2019):

Current alignment theories **can only reproduce the polarization fractions observed** in dense envelopes with **large grains (> 20 microns)** present at scales 100-1000 au

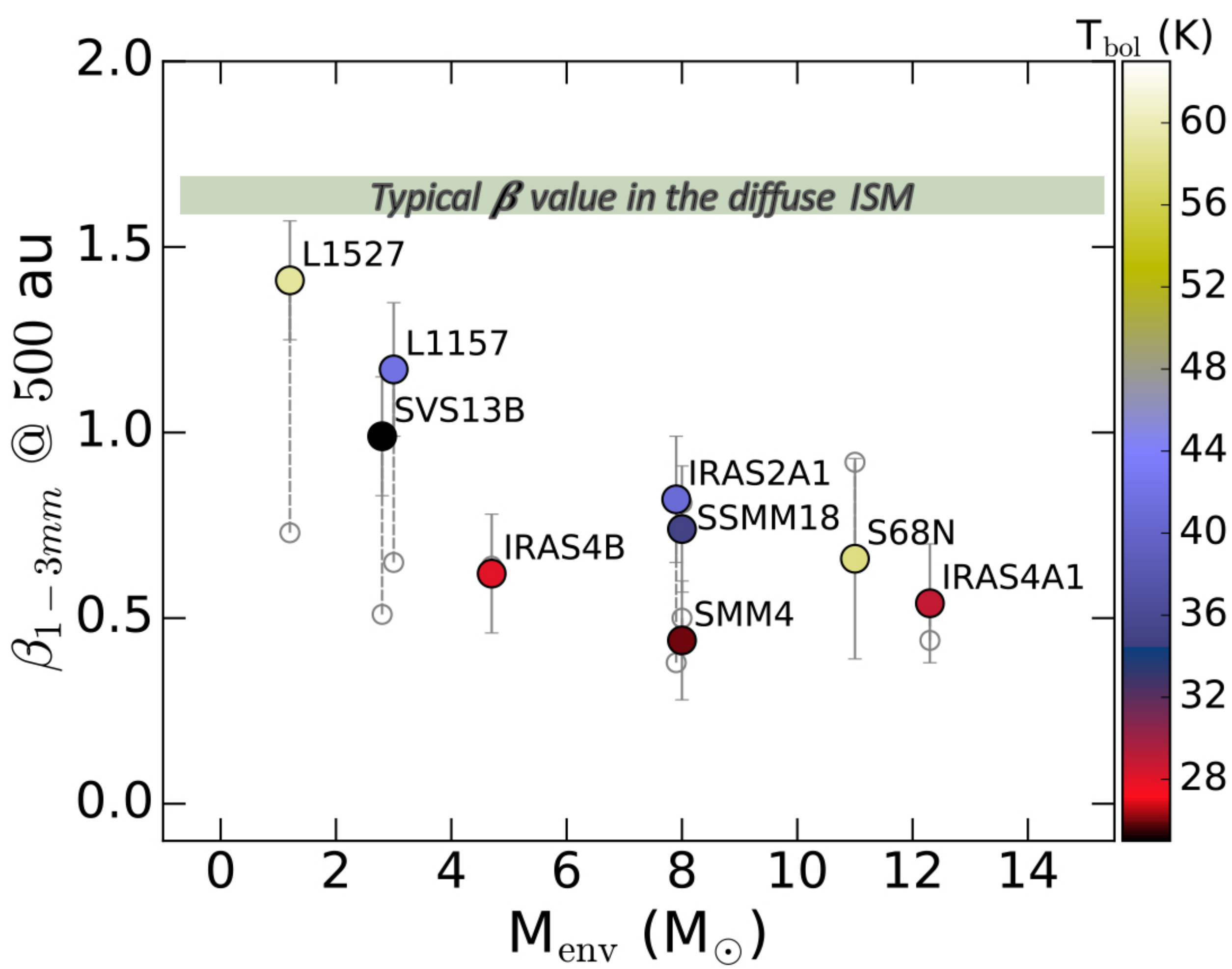


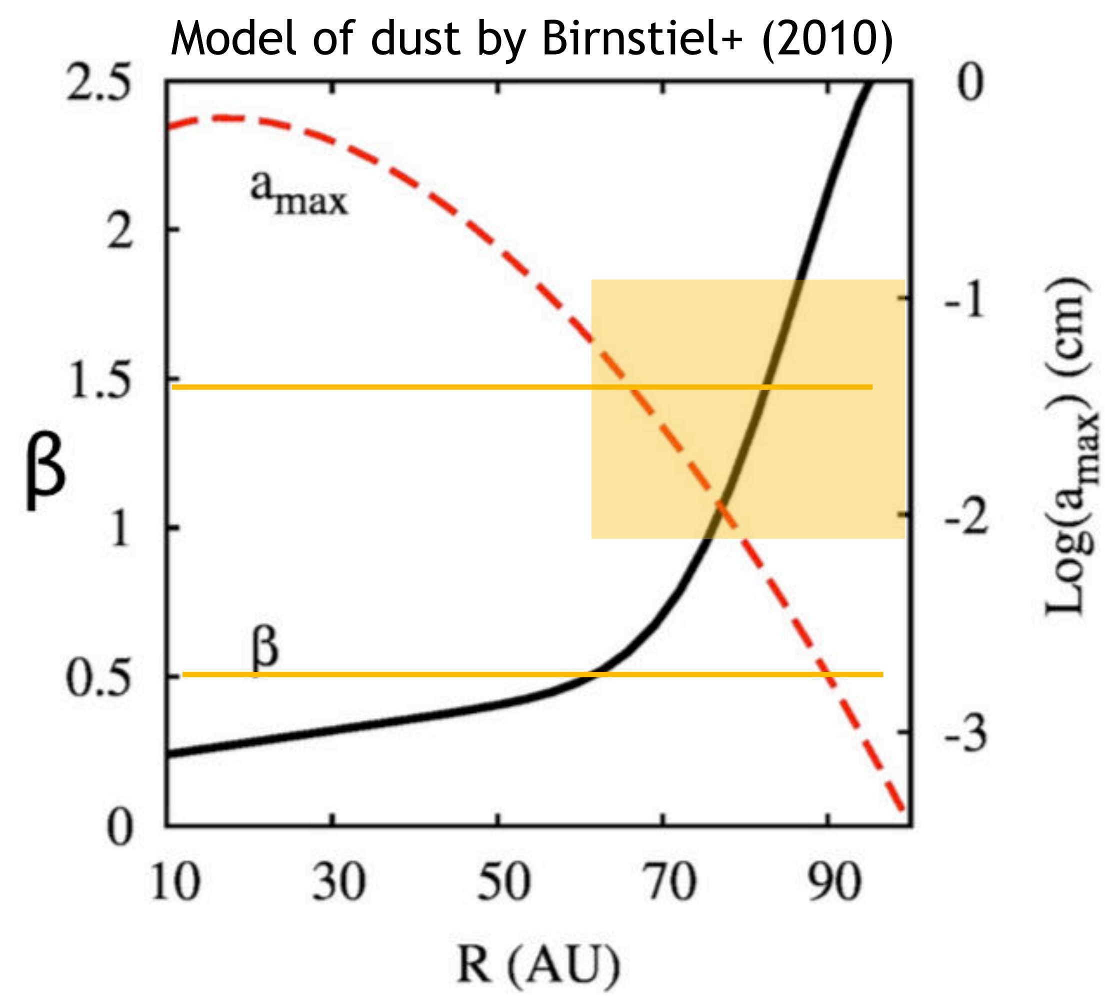
Also found in Le Gouellec+ 2019: polarization in irradiated cavity walls consistent with RAT aligned grains if they have grown larger than the 0.1μm typical ISM grains

Also observational hint from dust emissivity

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

+ radial gradients
+ dependent on envelope mass





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

(1) Do we need a revised planet formation scenario ?
(2) Do we trust the masses computed using typical ISM but non-adequate dust emissivities ?
(3) Dust composition could also be a culprit, but correlation with envelope mass makes it unlikely

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

Birth and early life of protoplanetary disks: a tale from observations of Class 0 protostars and numerical models of star formation

ALMA reveals T-Tauri disks seem more evolved than expected?
=> Pristine disk properties are probably key to evolution in star/planet system

=> Class 0 disks should be better characterized

ALMA and NOEMA reveal few large Class 0 disks : <25% have r_{disk} > 60 au

Median Class 0 disk radius ~40 au, smaller by at least 50 % than radii expected from hydrodynamical models with AM conservation

Disk size distribution favors magnetized models of protostellar disk formation
Origin of angular momentum responsible for disk formation still unclear

Magnetized collapse scenario may help reproduce the observed properties.

Also important to understand transformation of gas into stars, B335 as prototype

All protostellar envelopes are magnetized

Non-random magnetic field at envelope scales:
a link with envelope kinetic energy and fragmentation
=> a possible smoking gun for the role of magnetic braking ?

To be properly adressed: link with disk properties & larger samples

Observations of dust emissivities and models/obs dust polarization fraction:
Large grains already present in < 0.1 Myrs protostellar envelopes at ~100-1000 au ?