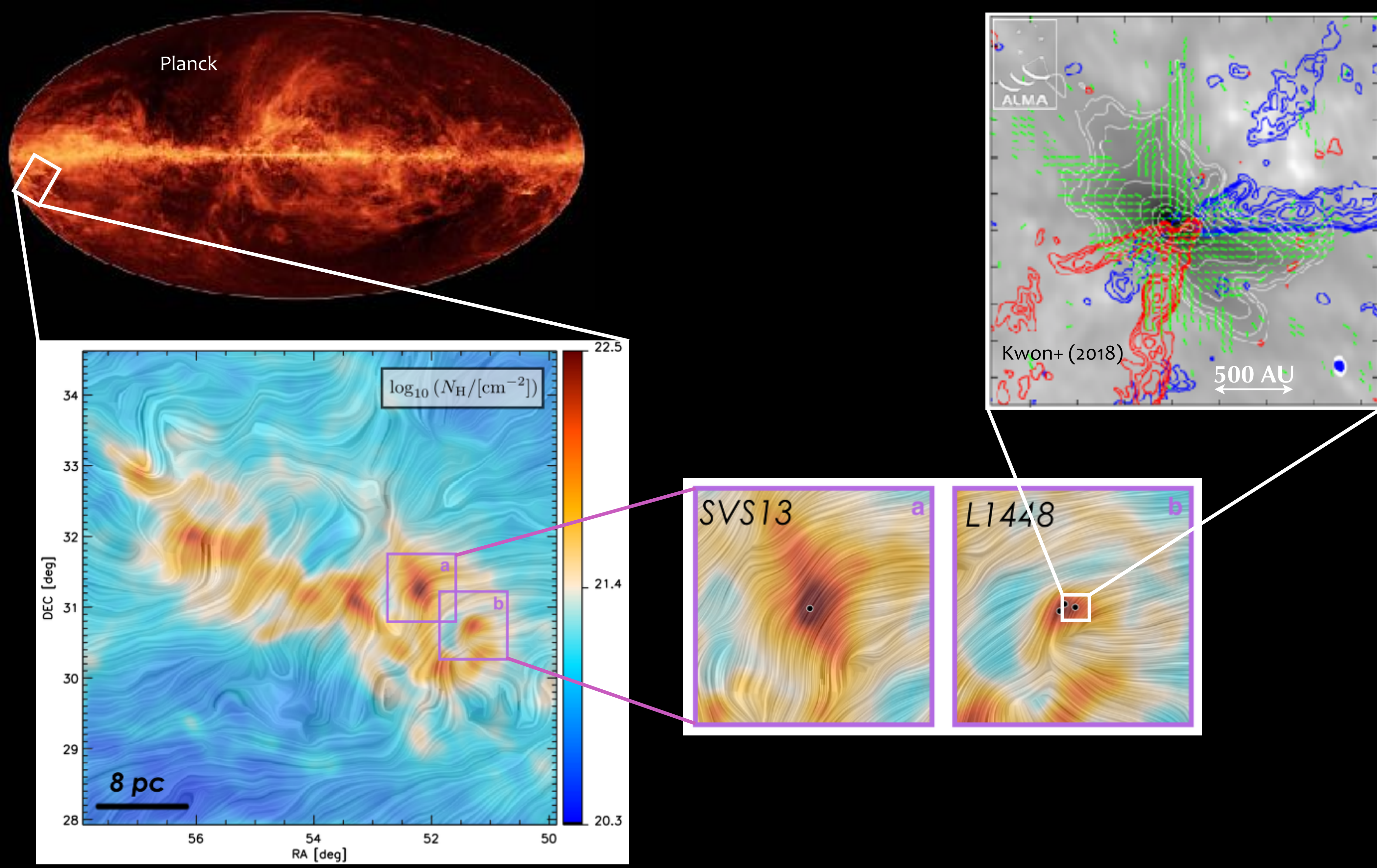
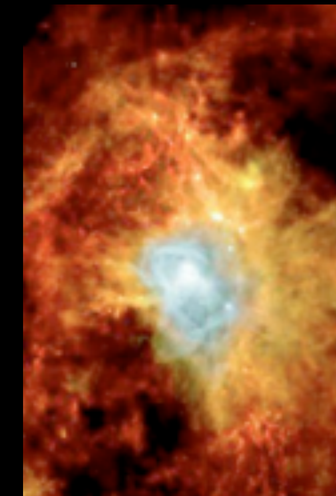


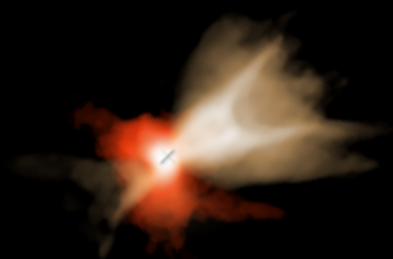
Roles and properties of magnetic fields from molecular clouds to protoplanetary disks

Anaëlle Maury

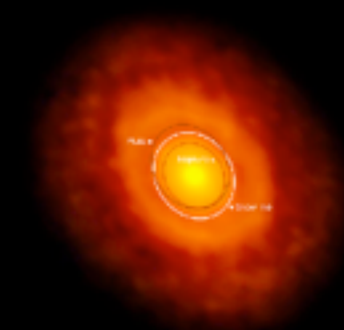
- Star Formation Rates ? - B in Molecular clouds

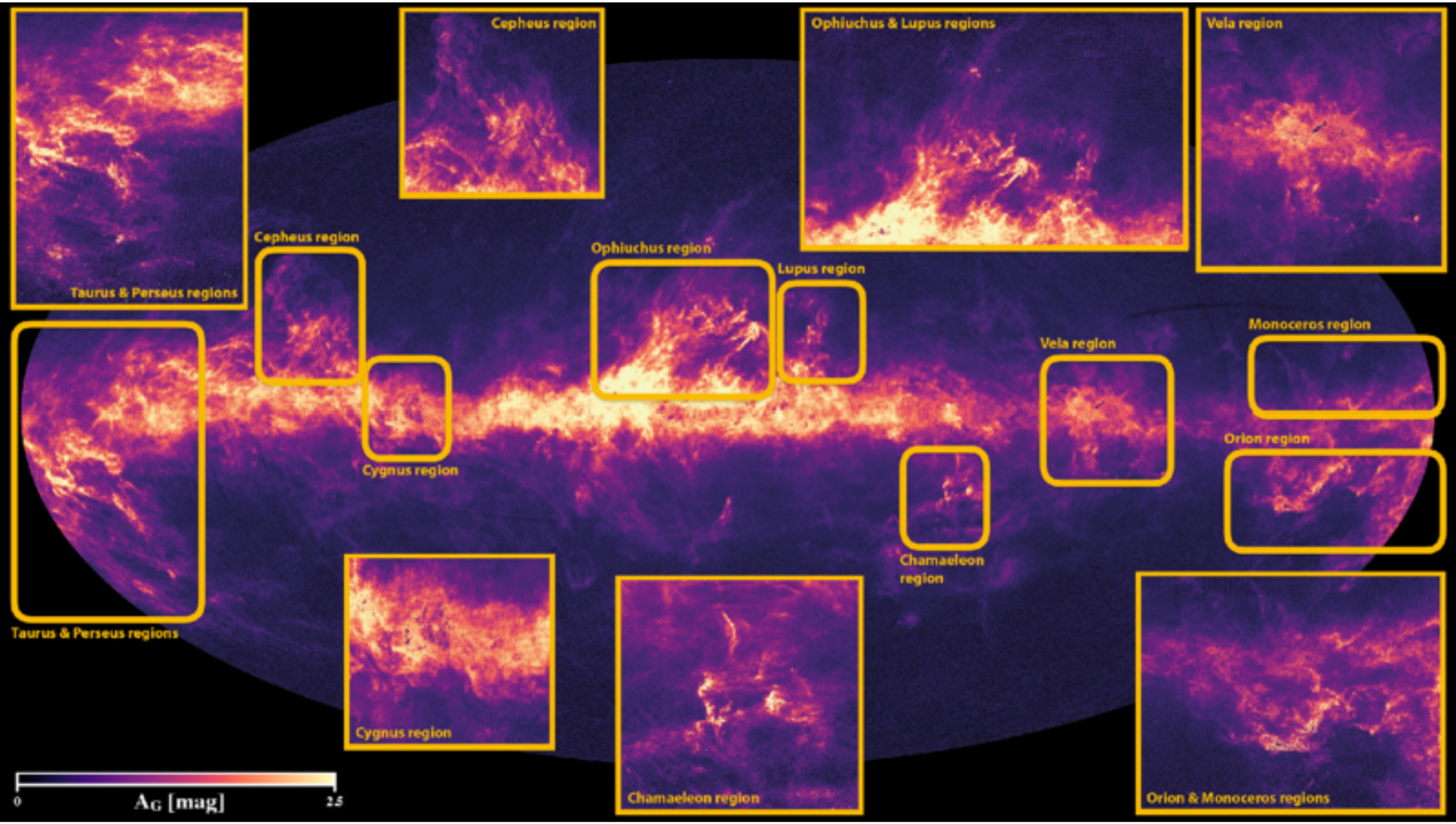


- Conservation of angular momentum ? - B in Protostars



- Transport by MRI ? - B in PP Disks





Gaia DR2 extinction map of the Milky Way

- **In our Galaxy: mass of gaz with ρ>10³ cm⁻³ is ~ 10⁹ Mₒ** (Battisti & Heyer 2014; Rice et al. 2016)
- **Without support against gravity: expected galactic SFR ~ 300-500 Mₒ / year**

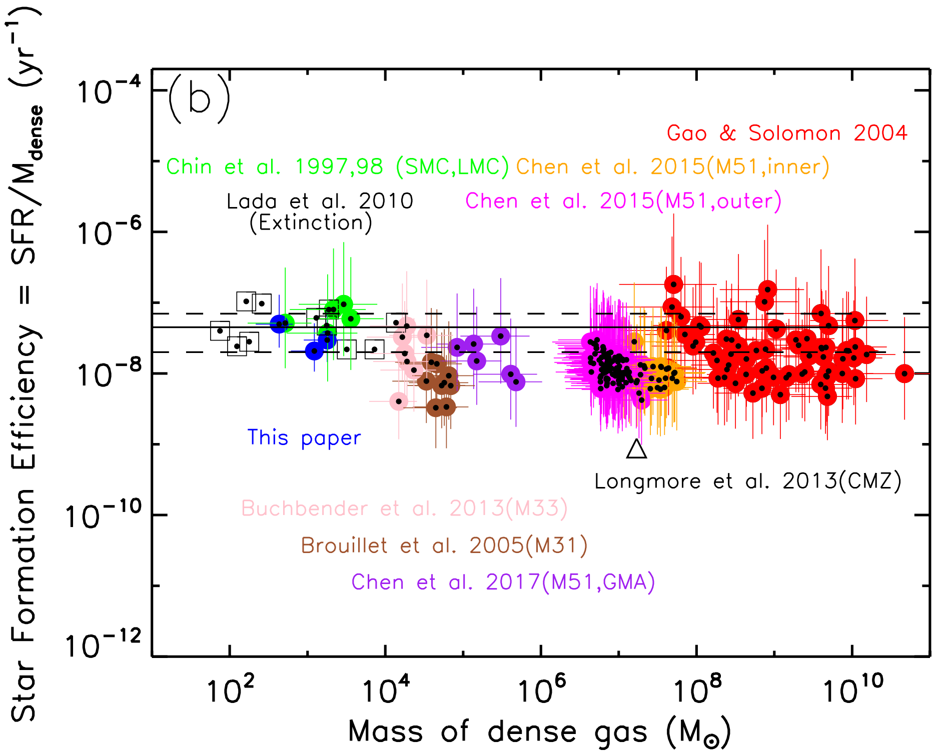
$t_{ff} = (3\pi/32G\rho)^{1/2}$ $\qquad M_J = \frac{\pi^{3/2}}{8}\frac{c_s^3}{\sqrt{G^3\rho}}$

- **But observations: SFR ~ 3 Mₒ / year**

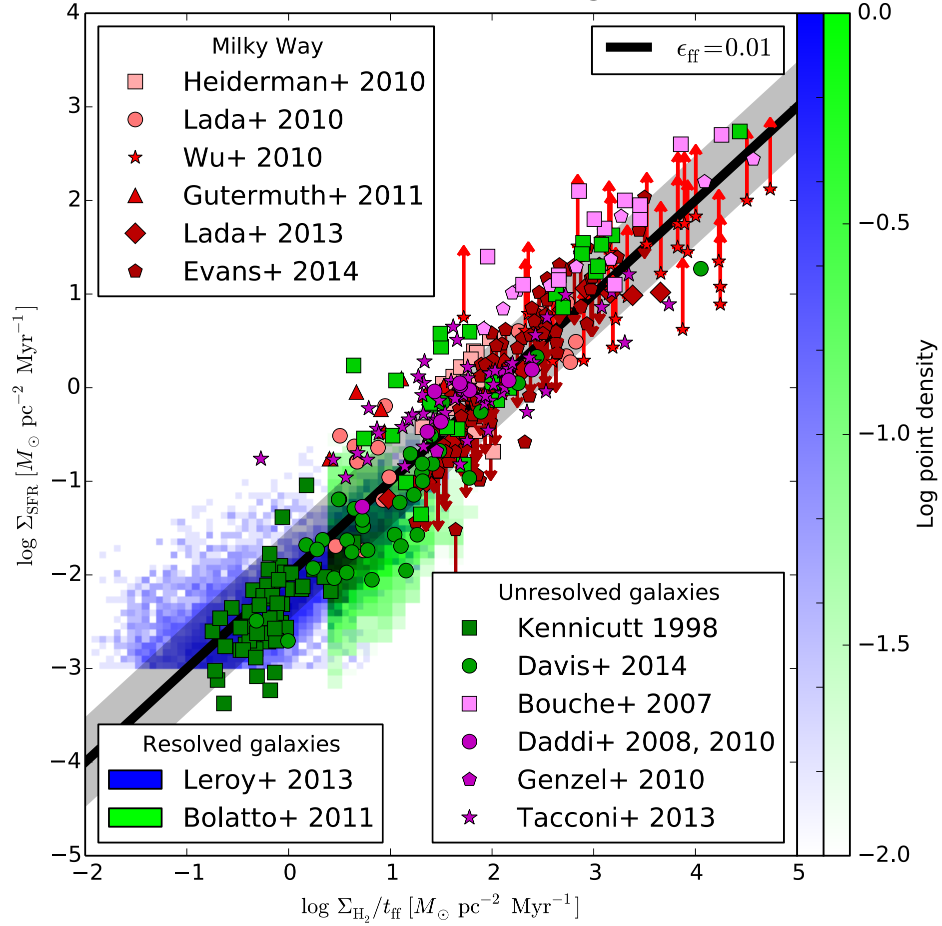
Evans+ (2014):

$\varepsilon_{ff} \sim 0.01 - 0.1$ for clouds with mean densities $n_{H_2} \sim 10^3$ cm^{-3}

Shimajiri+ (2017): Find similar SFE in HGBS filaments



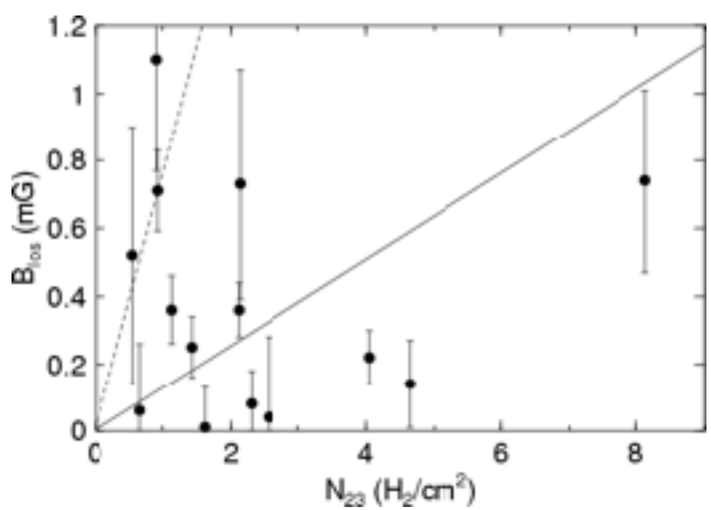
Krumholz (2014): on average εff ~0.01



All the dense gas does NOT undergo free-fall collapse

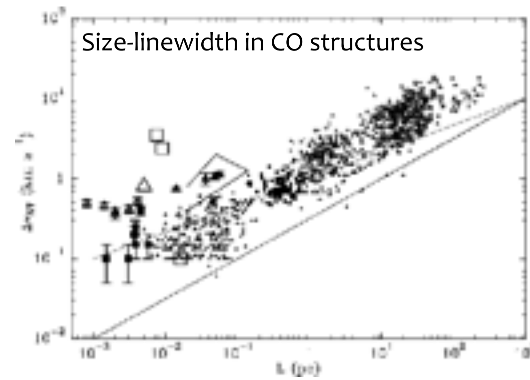
The ISM is magnetized

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)



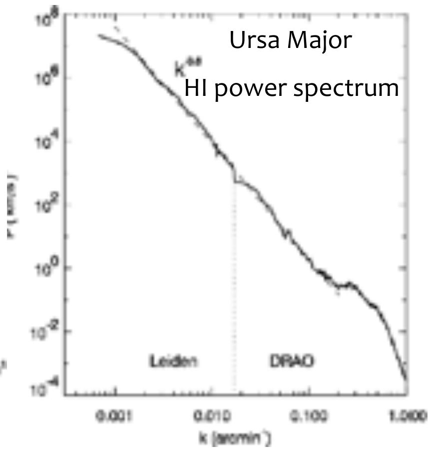
Zeeman in molecular cores:
Median B ~0.56 mG
Falgarone+ (2009)

The ISM is turbulent



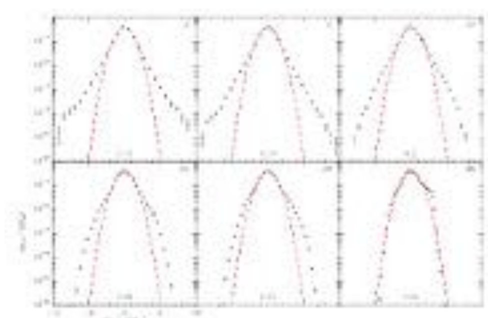
Falgarone+ (2009)

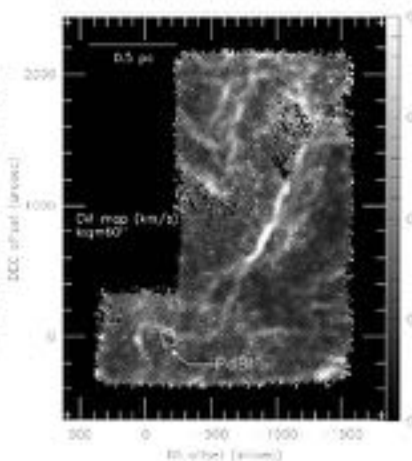
Larson (1981)



-3.6±0.1 ~ Kolmogorov

Miville-Deschênes+ (2003)





Pdfs of line centroid velocity increments in Polaris (Hily-Blant+ 2009)

Star Formation Rates ? - B in Molecular clouds

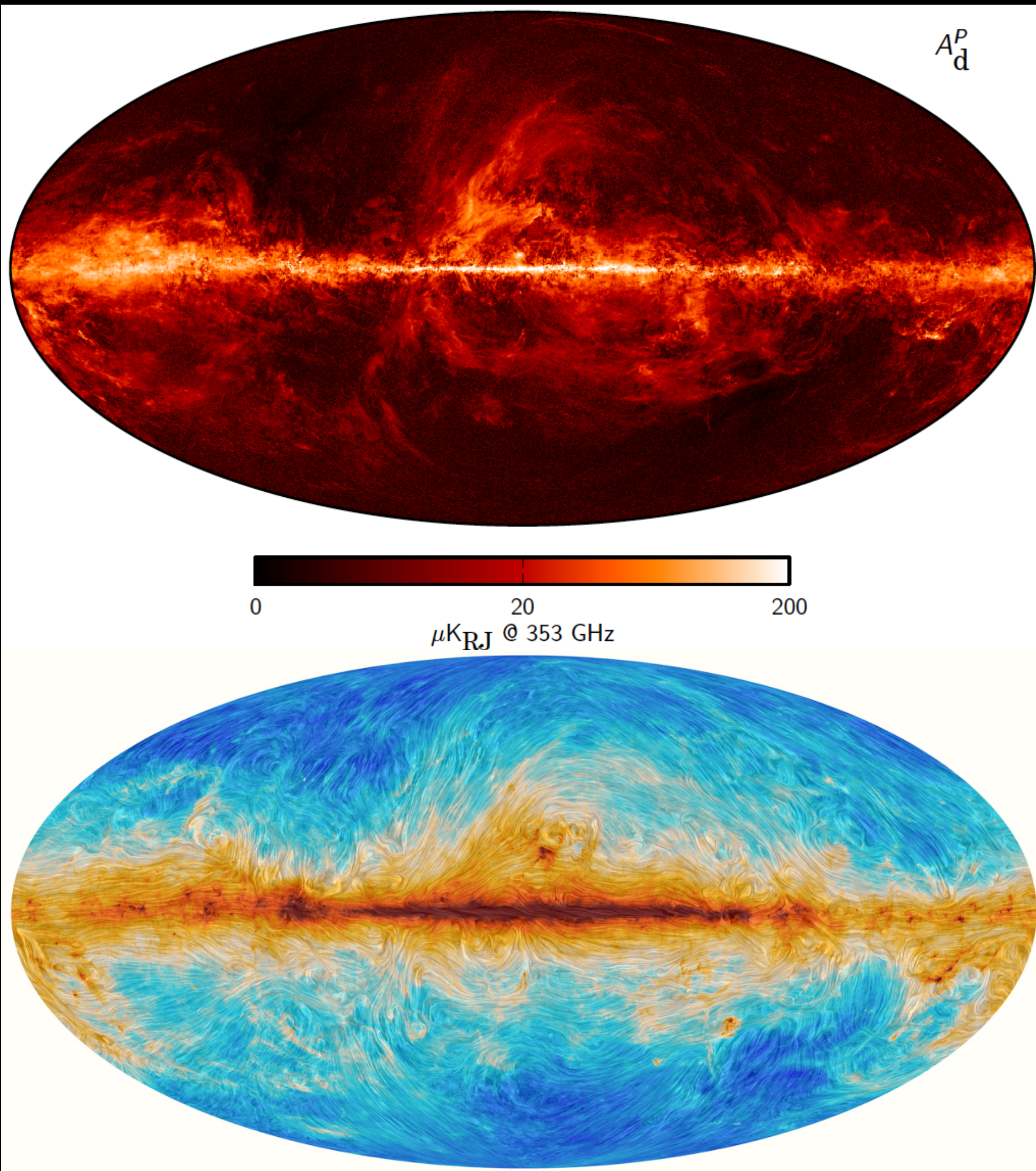
Planck

Planck intermediate results XIX. 2016: A&A 576, 104

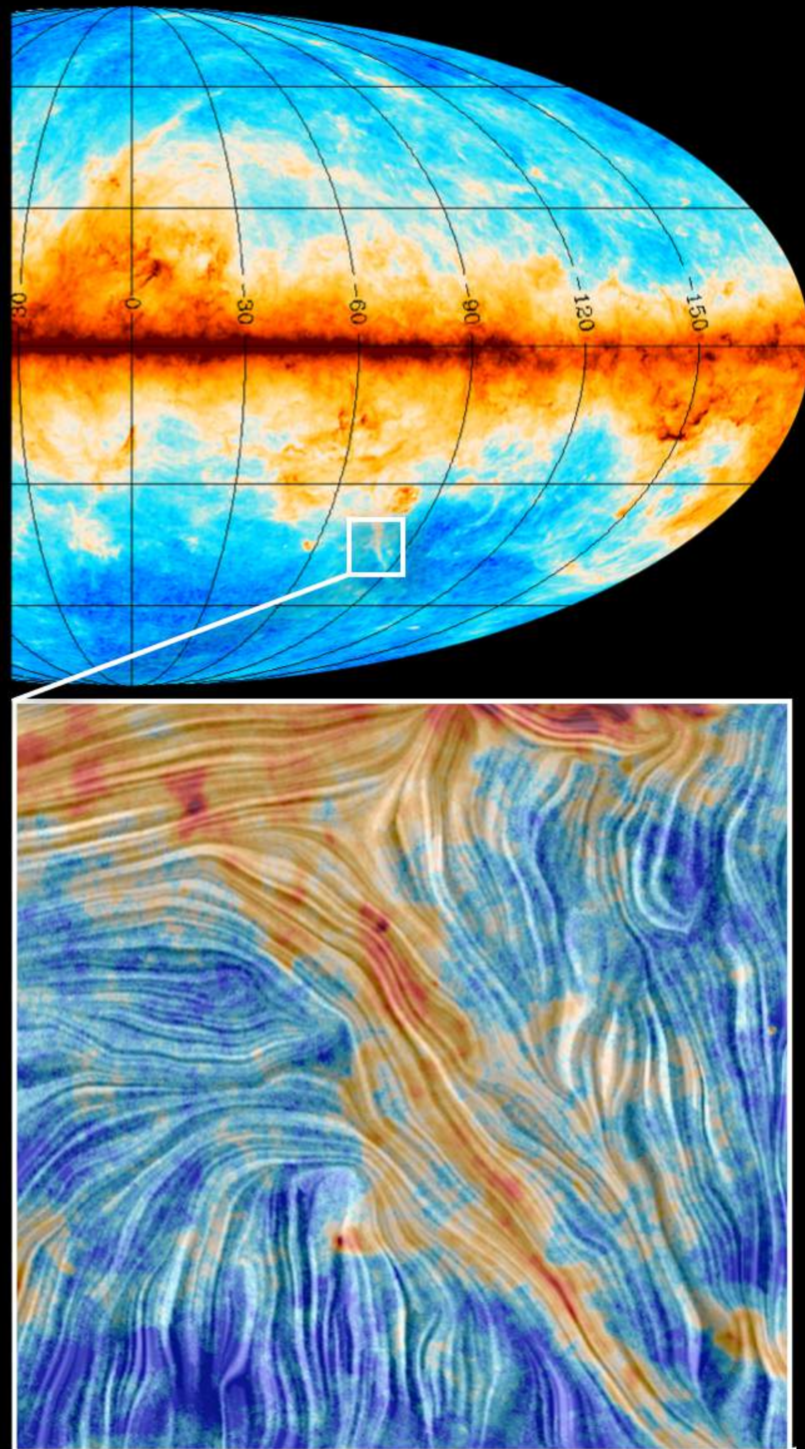
Planck results I. 2016: A&A 594, 1

Polarized Intensity

B-field Orientation



[Planck Intermediate XXXII 2014, arXiv:1409.6728]



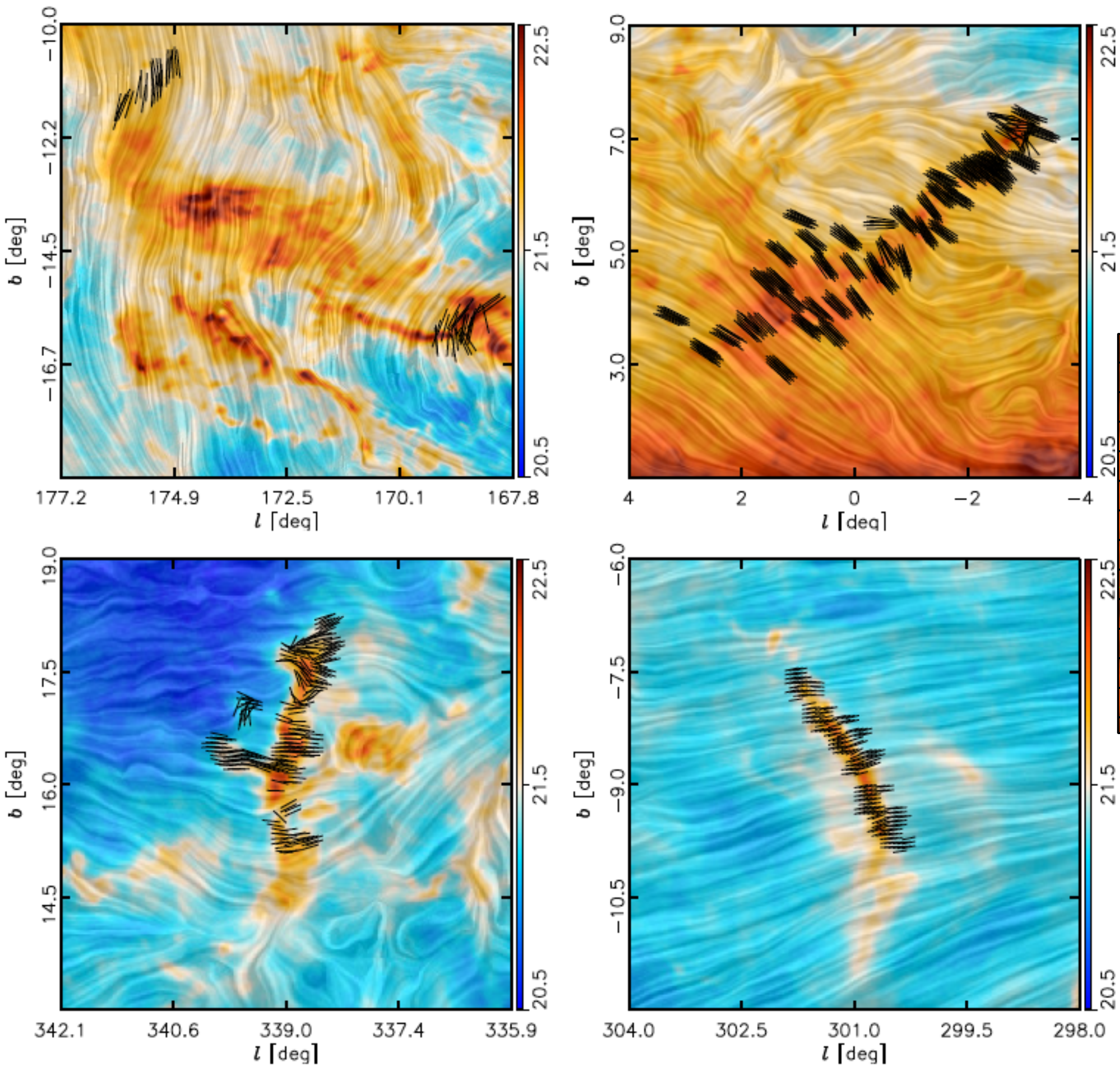
(*Planck* intensity 353GHz, B-field lines)

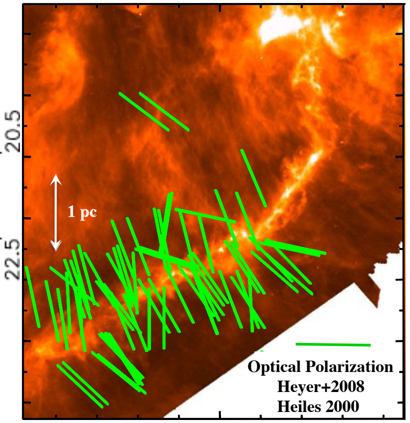
In the diffuse ISM :
The magnetic field is **parallel** to filamentary CNM structures

Star Formation Rates ? - B in Molecular clouds

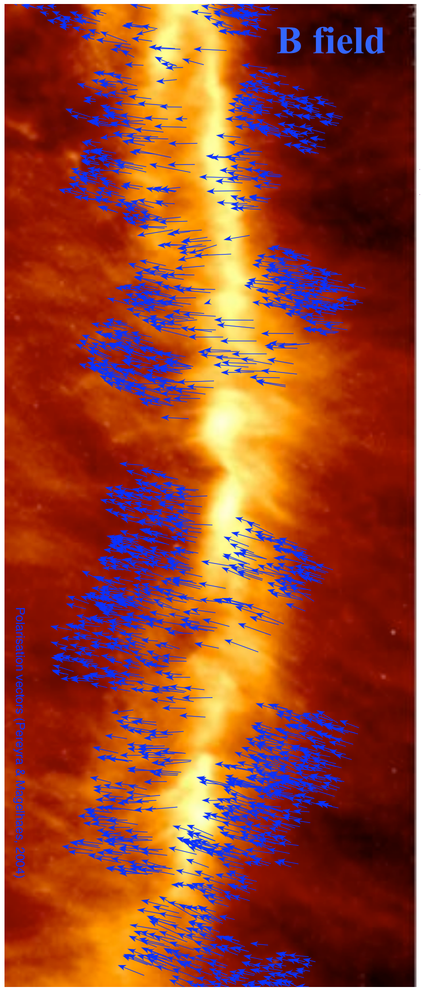
Planck

Planck Intermediate XXXV 2014, arXiv:1502.04123
Soler+2016 arXiv:1605.09371





Taurus



Musca

Magnetic field tends to be **perpendicular** to (dense) star forming filaments

Signature of the formation of gravitationally bound structures
for a dynamically important magnetic field.

Star Formation Rates ? - B in Molecular clouds

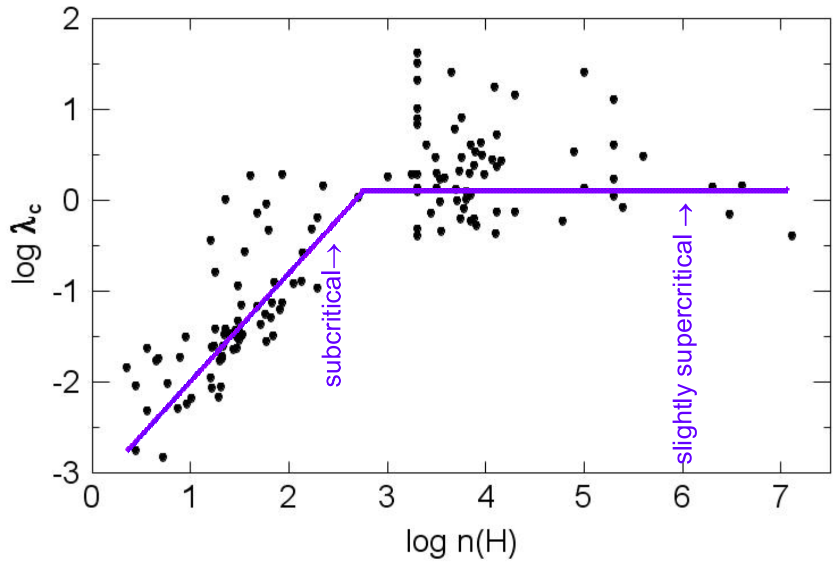
$$M_{cr} = 0.13G^{-1/2}\int B\, dA = 10^3\ M_{sun}\ (B/30\mu G)(R/2\,pc)^2$$

Set magnetic energy = gravitational energy

$$\left(\frac{M}{\Phi}\right)_{crit} \approx \left(\frac{1}{8\pi G}\right)^{1/2}$$

$$\lambda \equiv \frac{(M/\Phi)}{(M/\Phi)_{critical}} \approx 5.0\times10^{-21}\frac{N(H)}{B}$$

	H I Clouds	OH Clouds	CN Clouds
T(K)	50	10	50
N_H (cm^{-3})	1×10^{20}	8×10^{21}	9×10^{22}
n_H (cm^{-3})	54	3.6×10^{3}	3×10^{5}
thickness (pc)	0.6	0.7	0.1
σ_{NT} (km/s)	1.2	0.37	1.2
$B_{total,1/2}$ (μG)	6.0	14	280
M_{sonic}	5.0	3.4	5.0
$M_{Alfvenic}$	1.4	1.5	2.2
M/Φ (wrt critical)	0.06	2.2	1.2



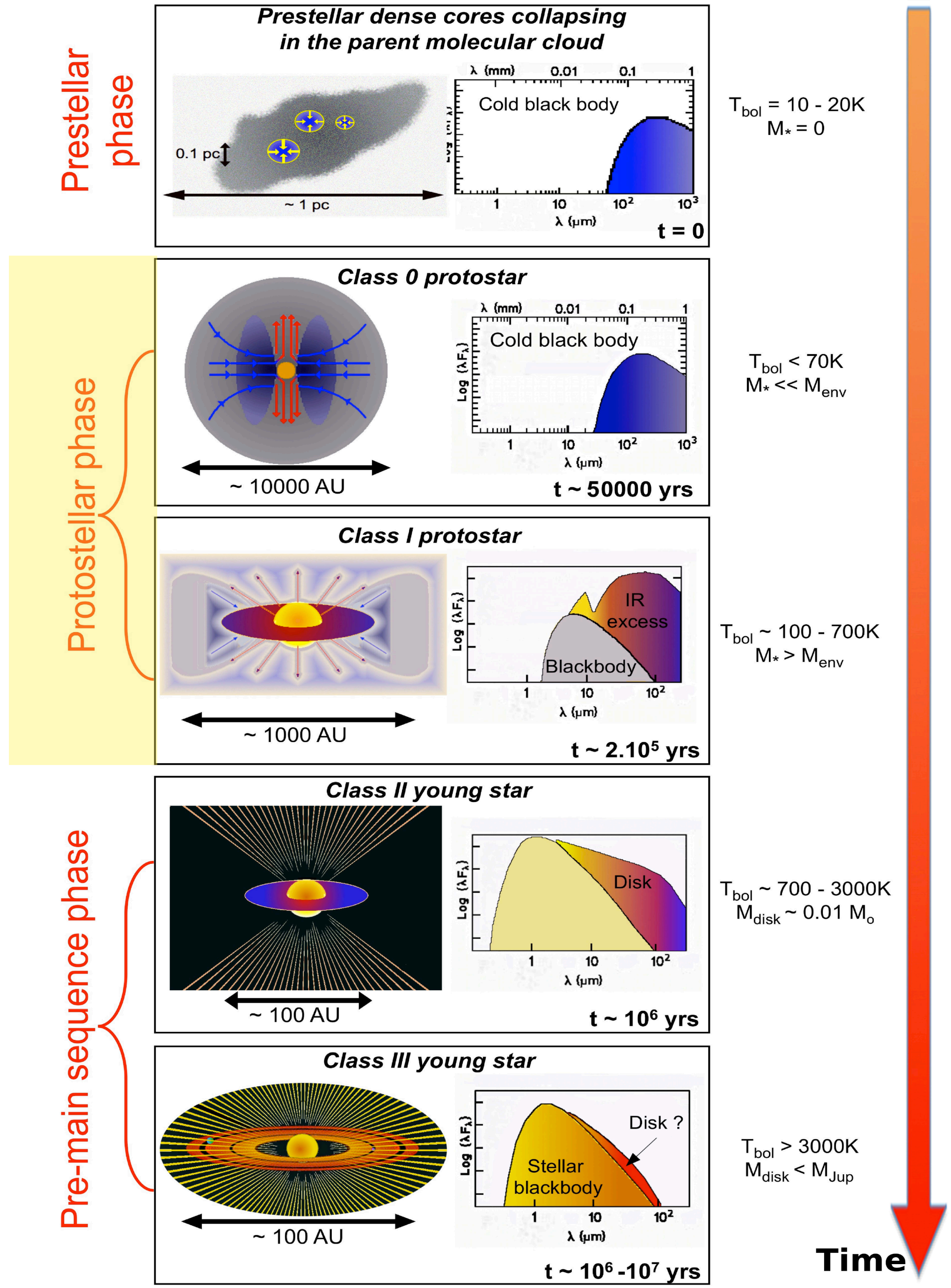
B-fields measured with Zeeman measurements.

Crutcher (2012)

What about filaments ?
Critical line mass can be greater when threaded by magnetic field perpendicular to filament
(Tomisaka 2014, Hanawa & Tomisaka 2015)

Li et al. (2016):
Suggest lower SFR for clouds almost perpendicular to the B-fields
To be confirmed !

Conservation of angular momentum ? - B in protostars

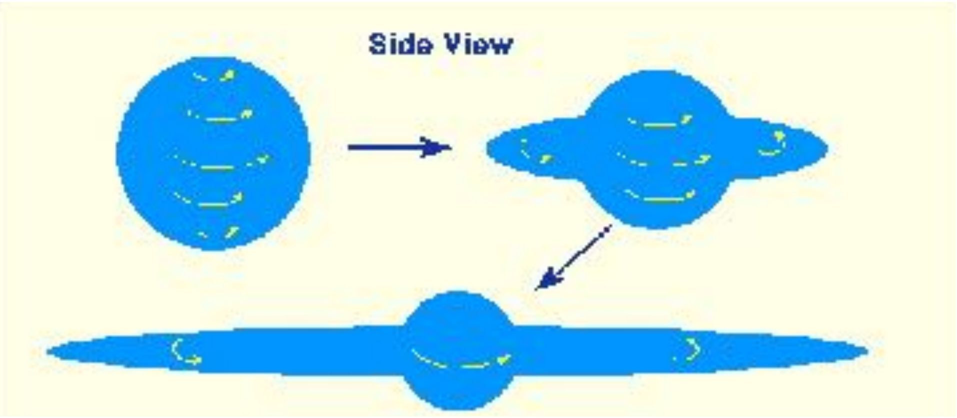


Shu et al. 1987

Lada 1987

André et al. 1993

André et al. 2001



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

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

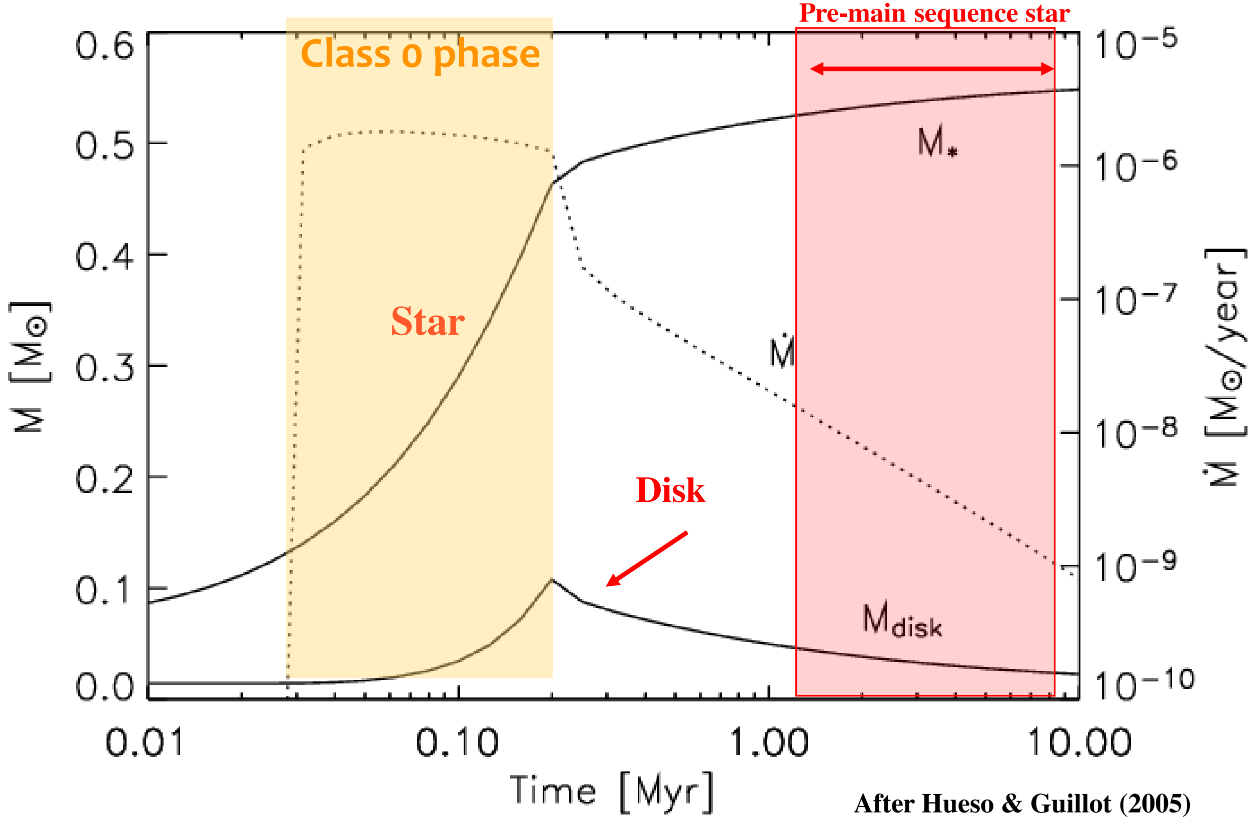
$$L = Mr^2\Omega$$ final size r, final spin Ω

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

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

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

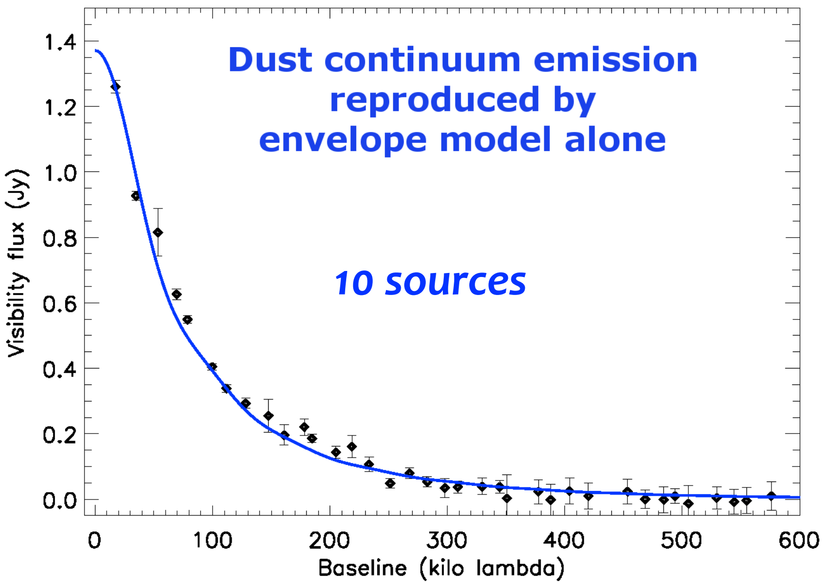
Where the gravitational acceleration is balanced by the centrifugal force.

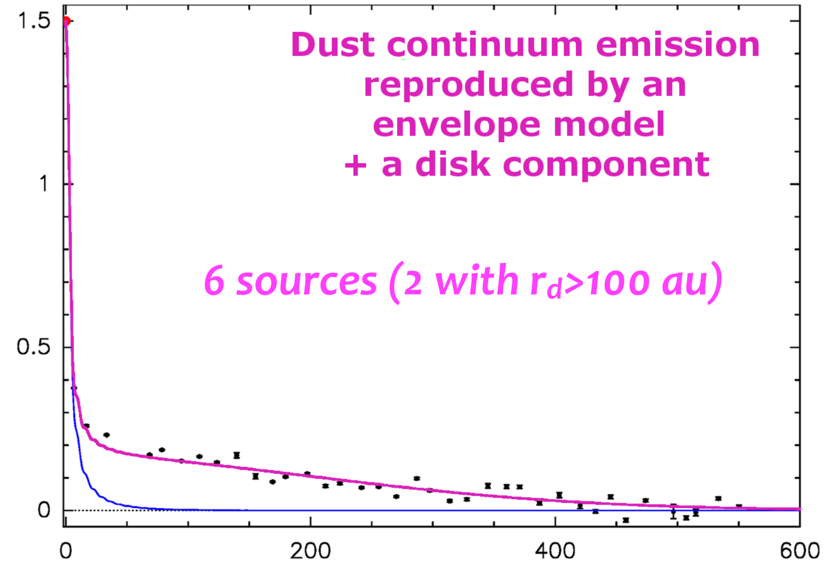


After Hueso & Guillot (2005)

Class 0 disks

PdBI visibilities of the dust continuum emission: DENSITY PROFILE





16 Class 0 sources:

Dust continuum @ 1.3mm + 3mm

Maury & CALYPSO collab. (2018b)

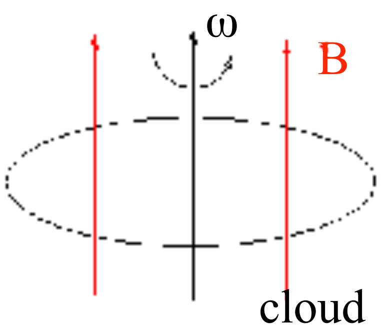
CALYPSO survey: at most 25% of Class 0 protostars with continuum disk-like structures at r>60 au

Combining the VANDAM and CALYPSO samples

+ the recent ALMA results probing radii ~ 60 au:

4-7 out of 28 Class 0 protostars, i.e ≤ 25%, have confirmed or candidate disks at radii $^{>}$ 60 au

Observations show mostly (>75%) small Class 0 disks
(Segura-Cox+ 2015, Yen+ 2015, Maury+ 2010, 2014, 2018b)

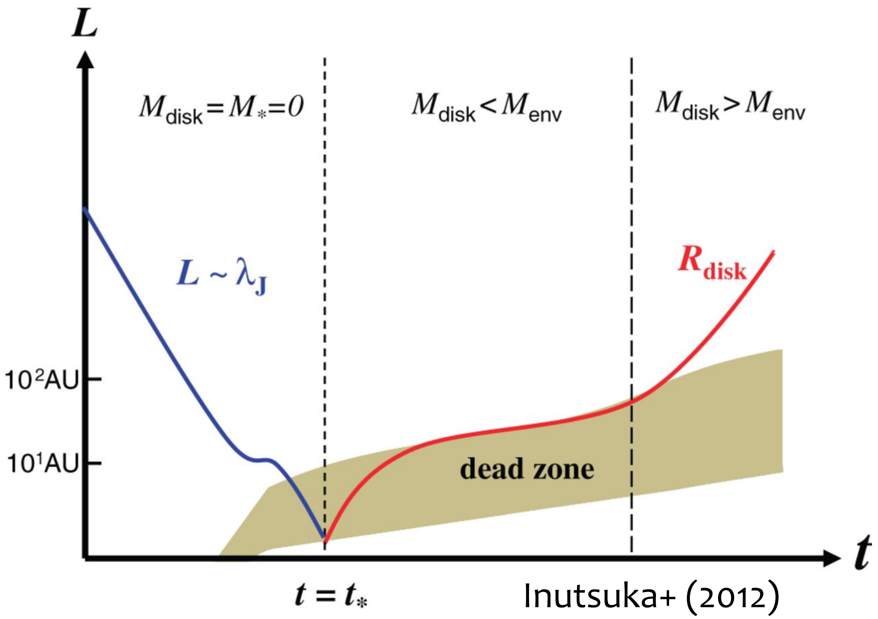


Rotation motions generate Alfven torsional waves
=> can transport angular momentum to the outer parts of the contracting cloud.

i.e, magnetic braking is more effective perpendicular to field lines

(Mouschovias & Paleologou 79,80, Basu & Mouschovias 95, Galli 06)

Magnetic braking allows to redistribute the angular momentum from the inner infalling envelope to the outer parts of the envelope, and therefore reduces the centrifugal radius: only small (r<50 au) rotationally-supported protostellar disks.



Inutsuka+ (2012)

Does magnetic braking totally suppress the disk ?

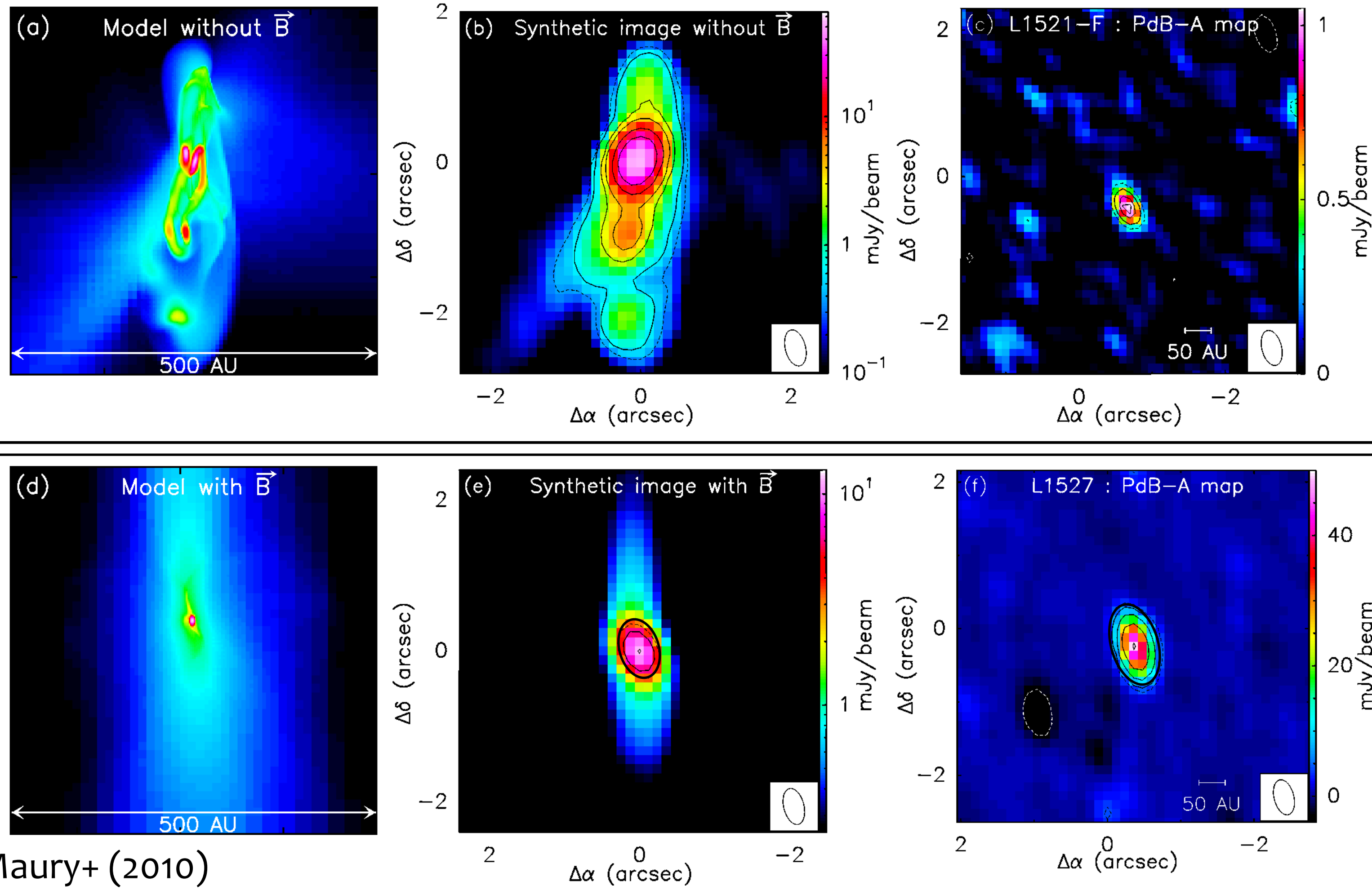
No

B decouples in high-density gas region
(Ohmic dissipation and Ambipolar diffusion mostly).
→ matter within ~10–50 au central region can conserve angular momentum and form a disk.

This disk can expand later, when envelope is not massive enough to maintain efficient magnetic braking.

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

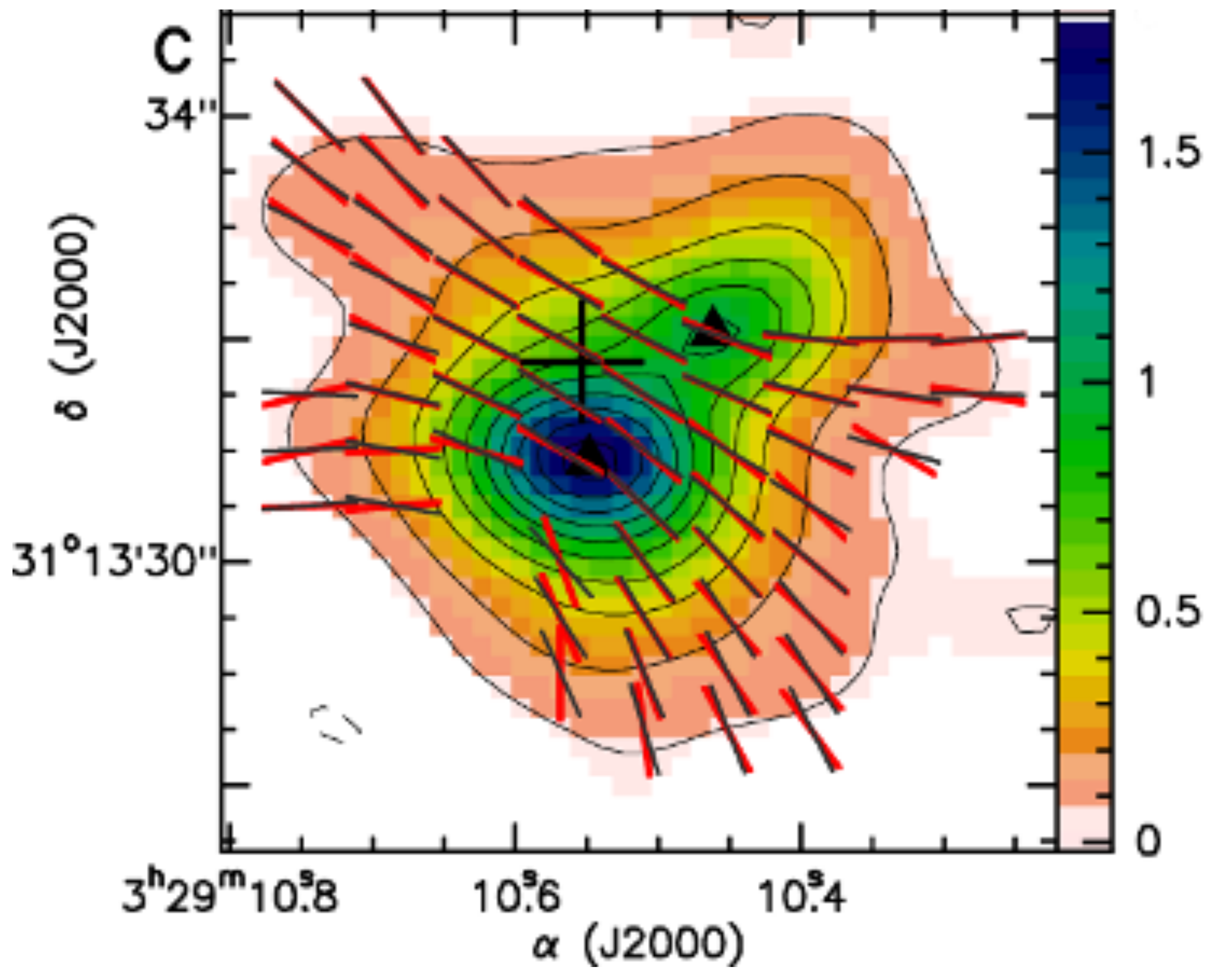


Maury+ (2010)

Observations more reminiscent of MHD protostellar disks (Maury+ 2010, 2018a)

All protostars are magnetized to some level

Girart, Rao, Marrone (2006):
first interferometric map of B-fields in a protostar



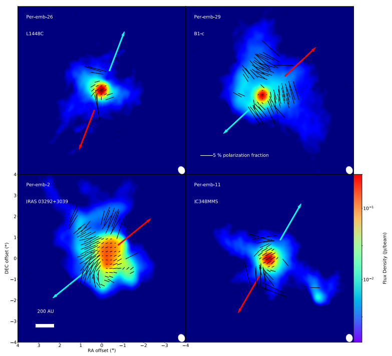
SMA 0.8 mm dust polarization map

All protostars are magnetized to some level

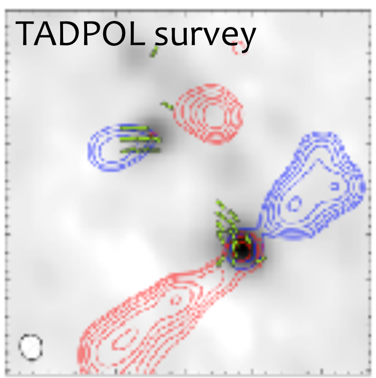
Cox+ (2018):

ALMA 0.8mm polarized emission

10 Class 0 protostars

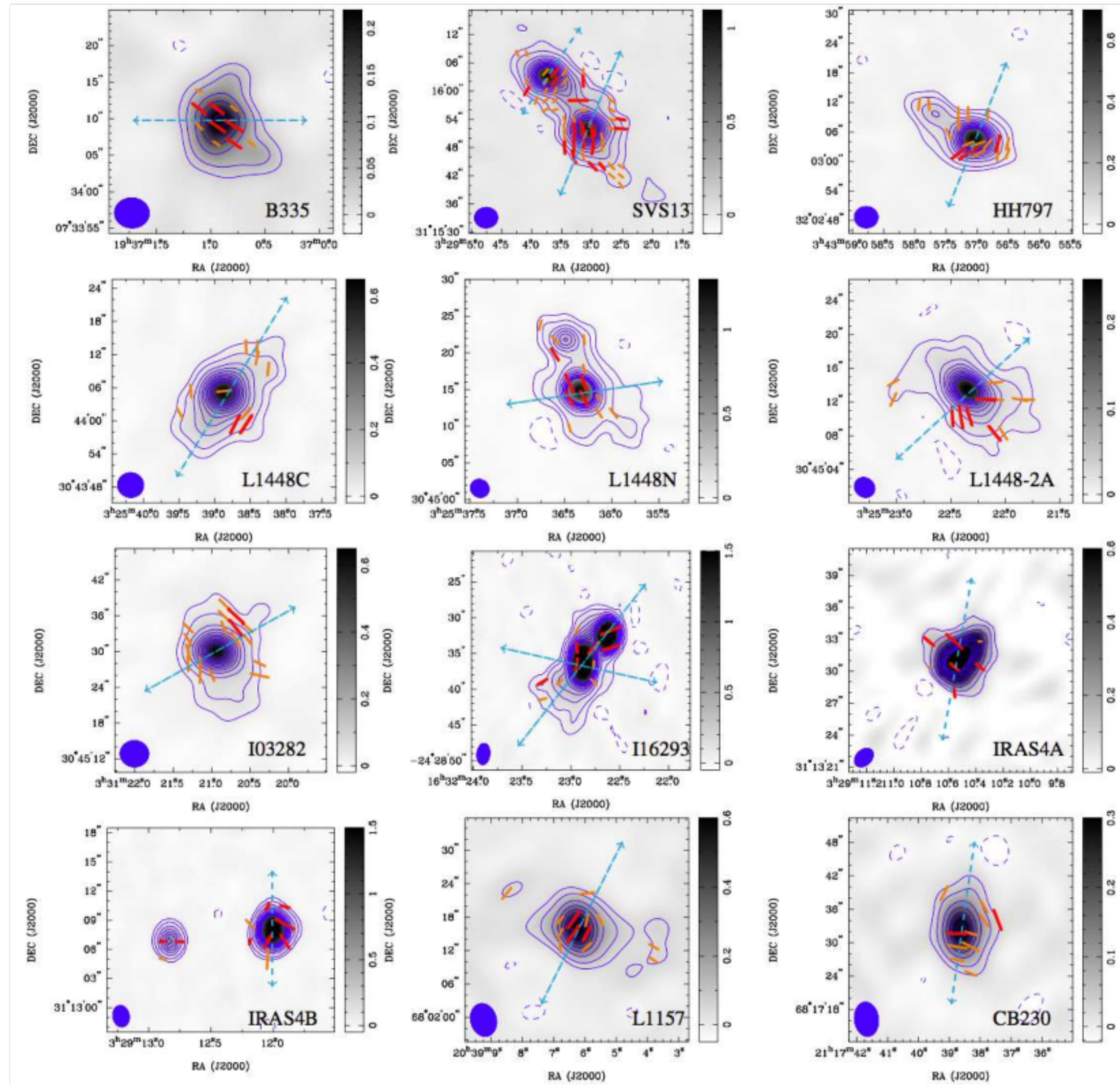


TADPOL survey



1 mm polarization, 13 Class 0 protostars
Dust polarization maps @ 2000 au
Hull et al. (2013, 2014)

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

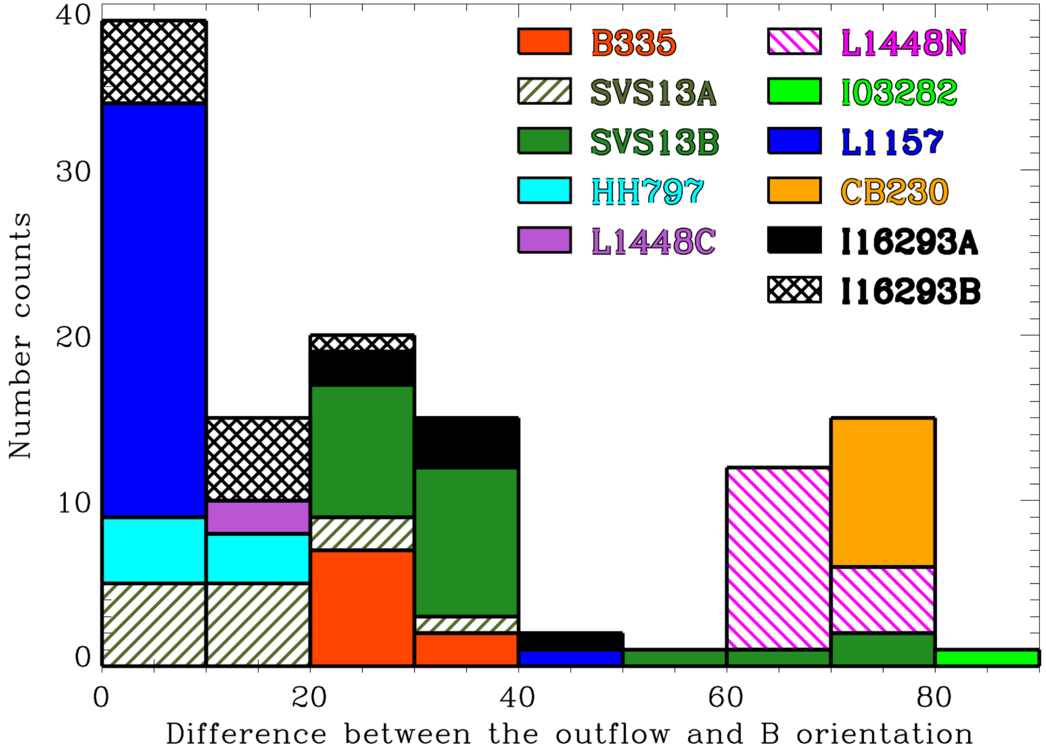


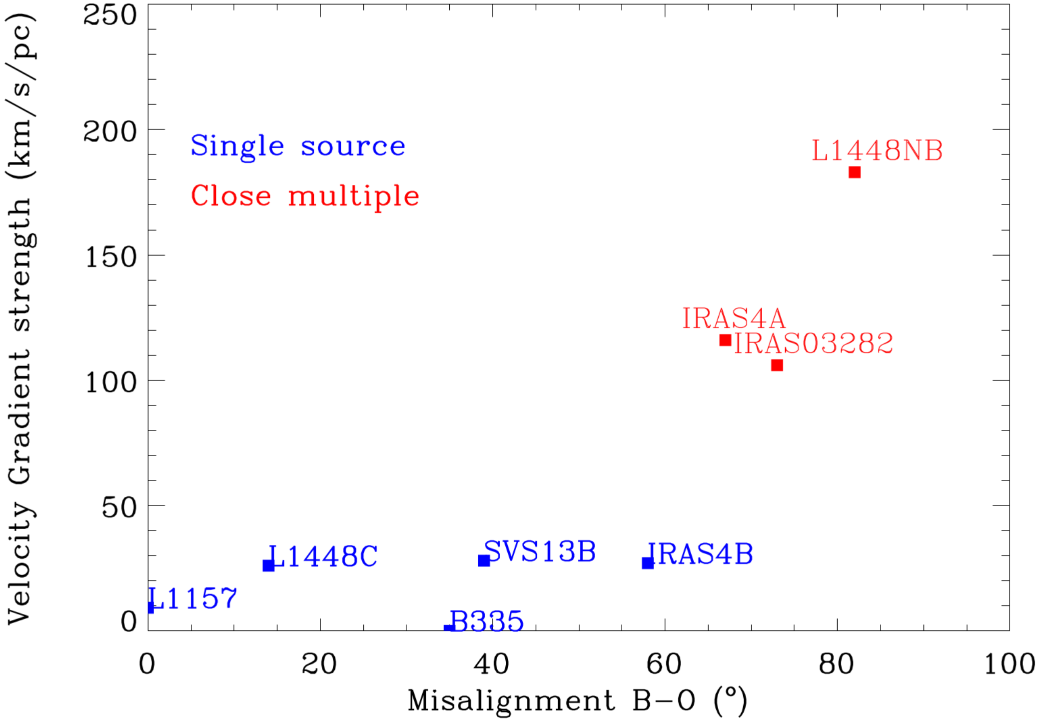
A link between B topology and the formation of large disks ?

In the Class 0 envelopes with large rotation: the main envelope B-field direction is observed aligned with the equatorial velocity gradient

For protostellar envelopes showing no/little rotation: B aligned quite well with the jet direction.

Galametz+ (2018)

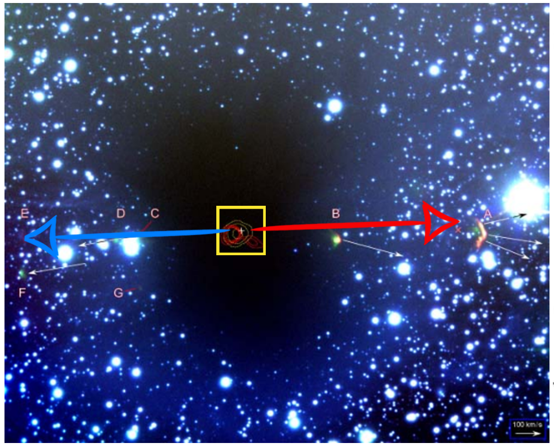


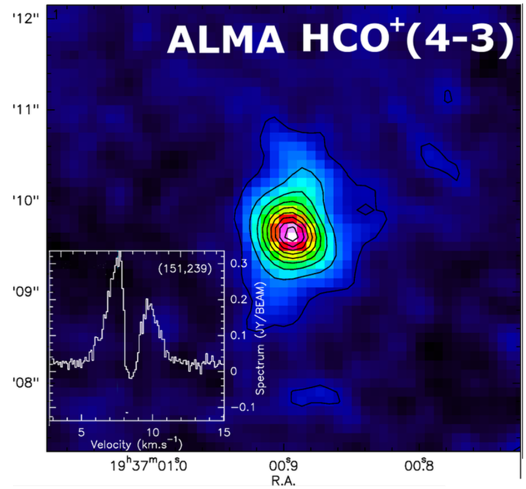


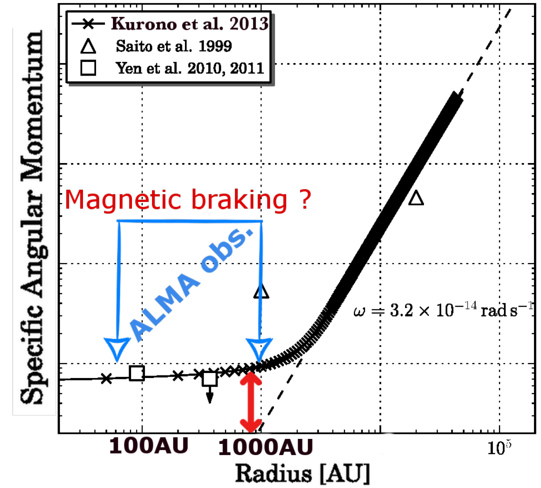
Envelope-scale B-field misalignment is found preferentially

in protostars that are close multiple and/or harbor a larger Keplerian disk ?

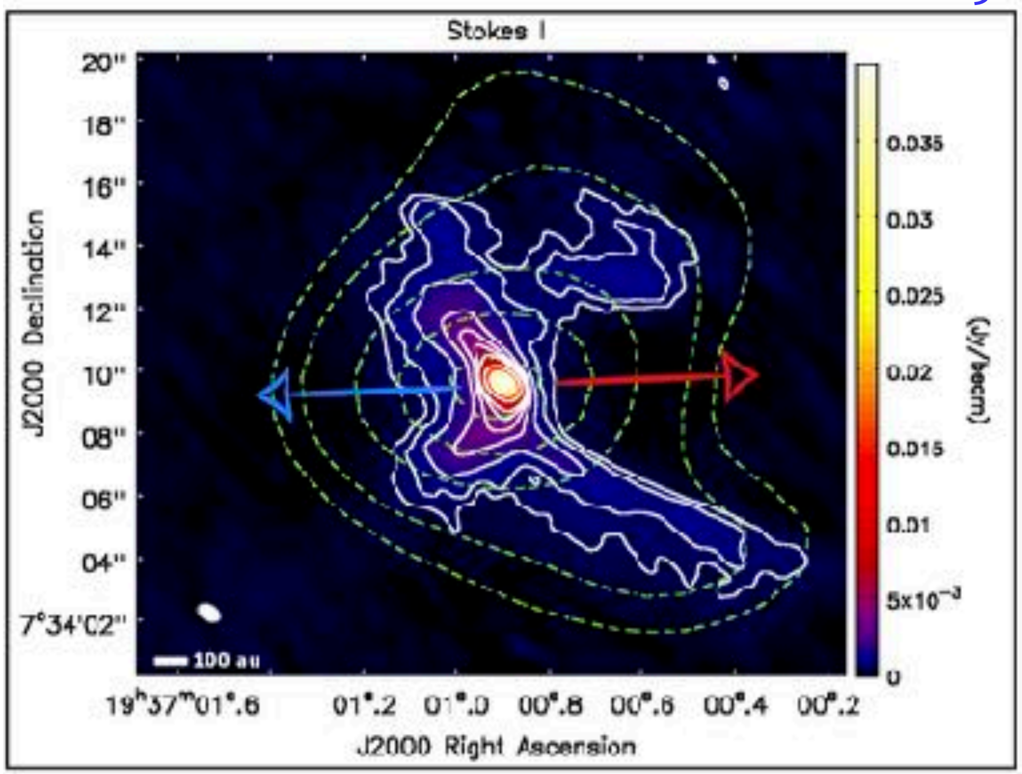
A magnetically-regulated collapse in B335 ?

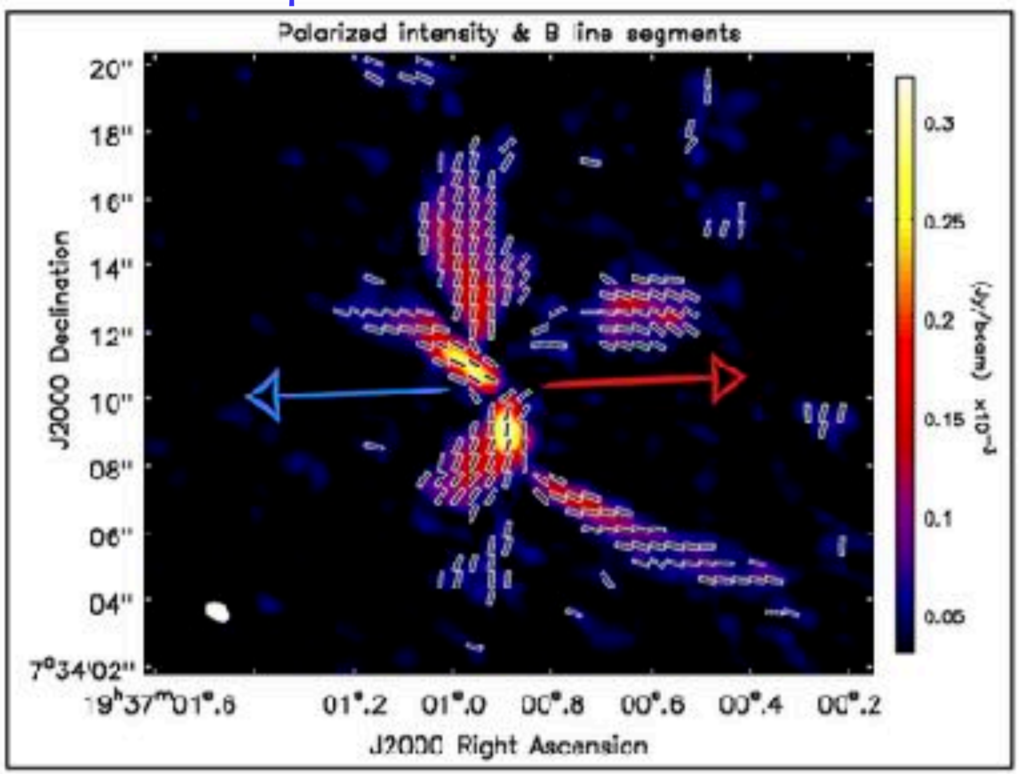




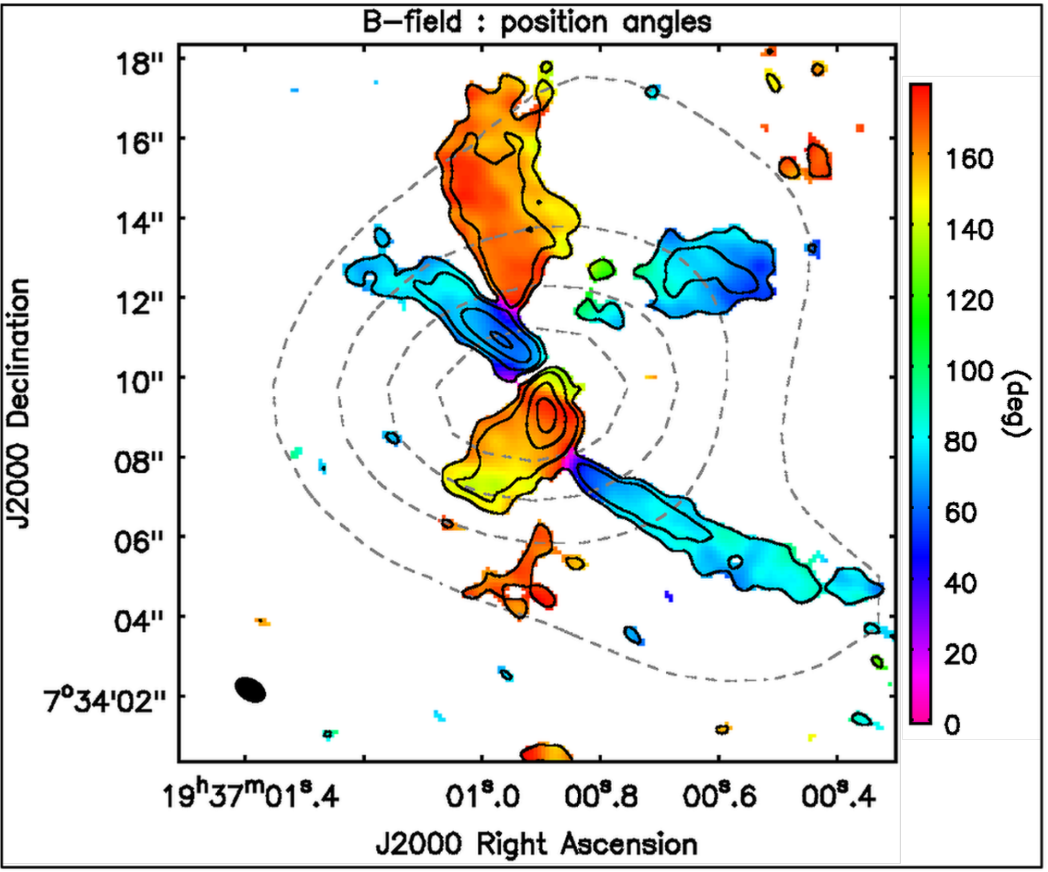


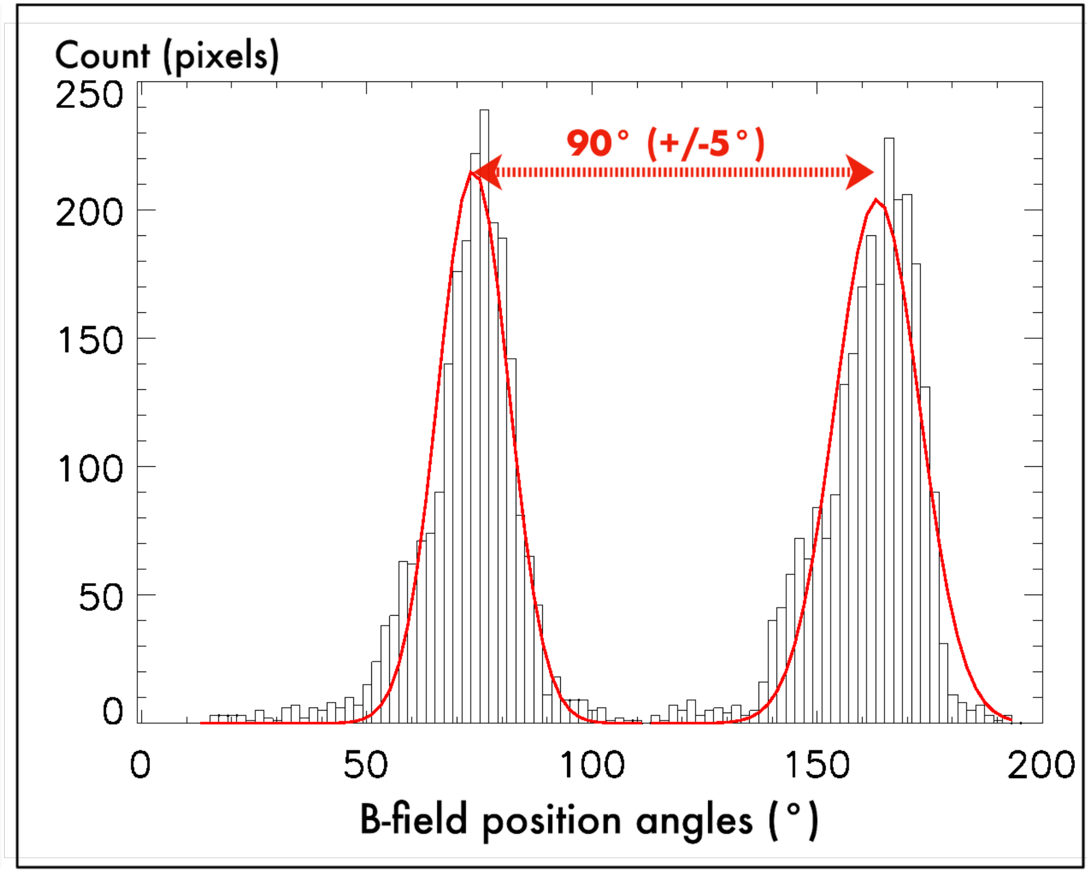
ALMA observations of the 1.3mm dust continuum polarization





A magnetically-regulated collapse in B335 ?

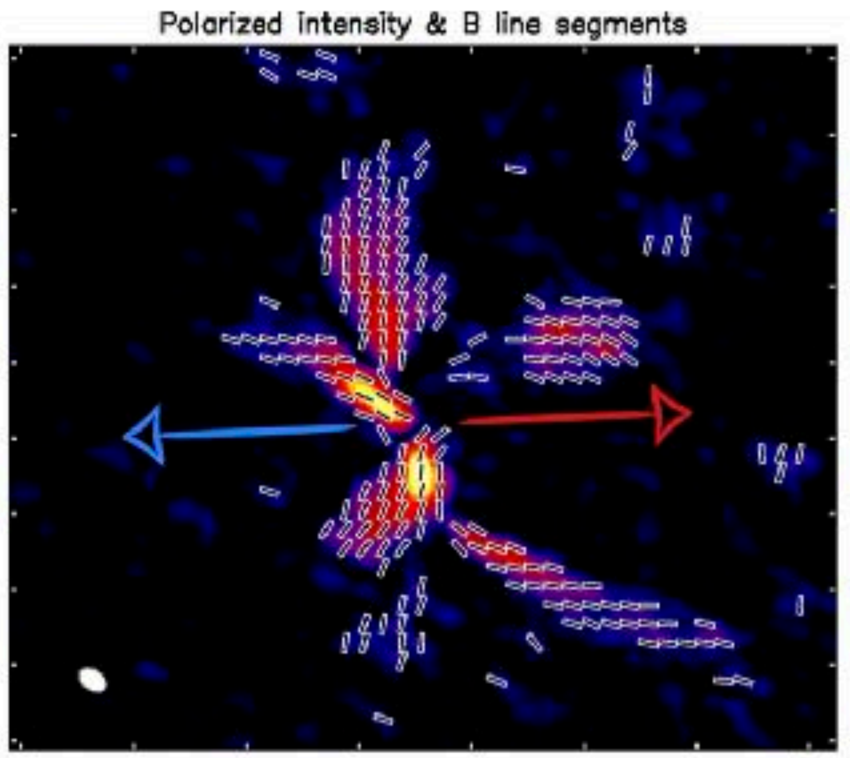


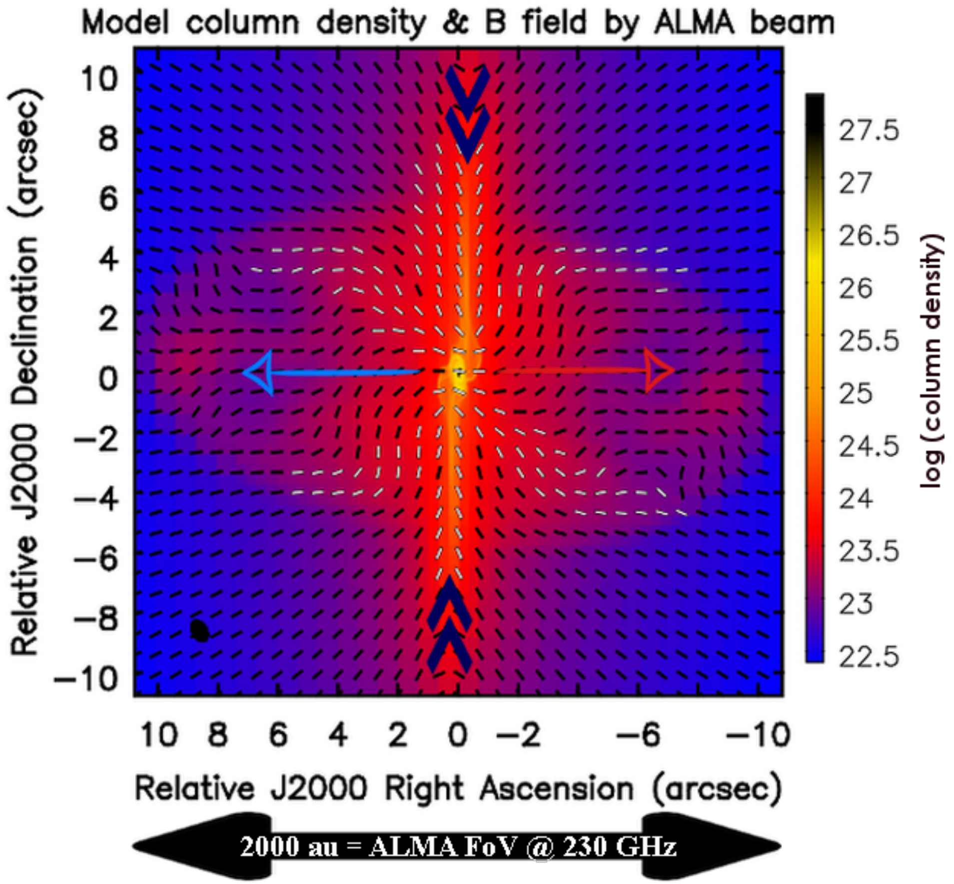


Observations reveal a strikingly ordered magnetic field in this young accreting protostar

A magnetically-regulated collapse in B335 ?

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





=> B might be regulating the distribution of angular momentum, and the formation of the protostellar disk

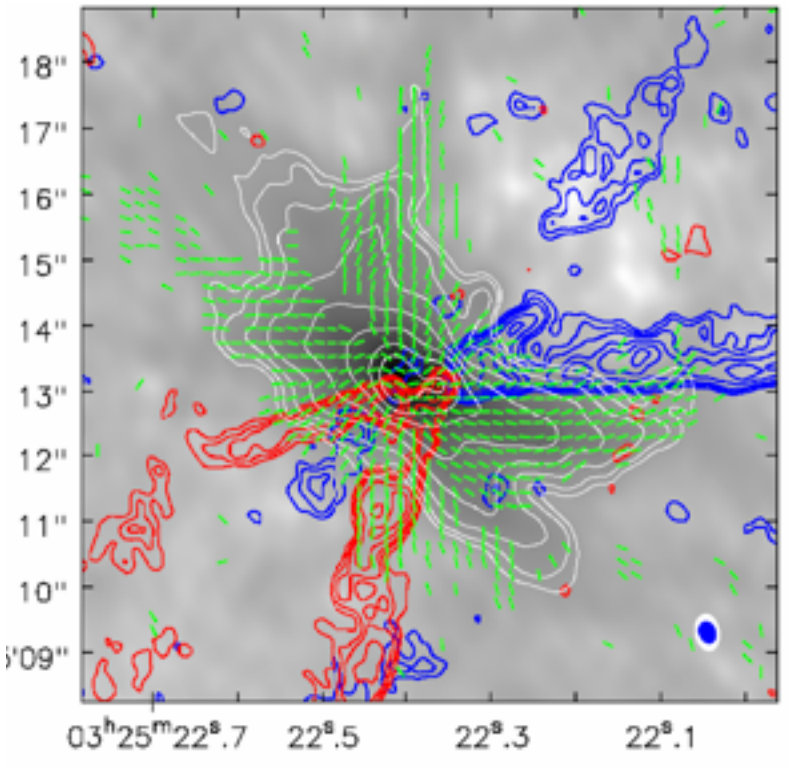
Maury+ (2018a)

Hour-glass and toroidal fields in protostars ?

L1448 IRS2A (Perseus)

B vectors: very organized pattern.

Debate wether the field is dynamically relevant or not

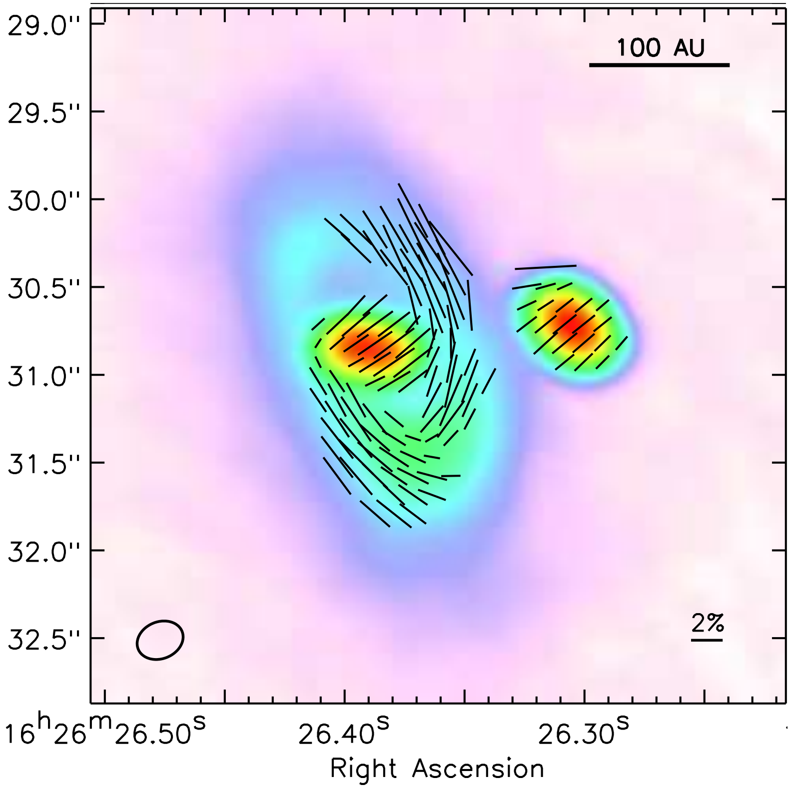


Kwon+ (2018)

VLA1623 (Ophiuchus)

E vectors: complex structure.

Debate wether tracing the field or other alignment

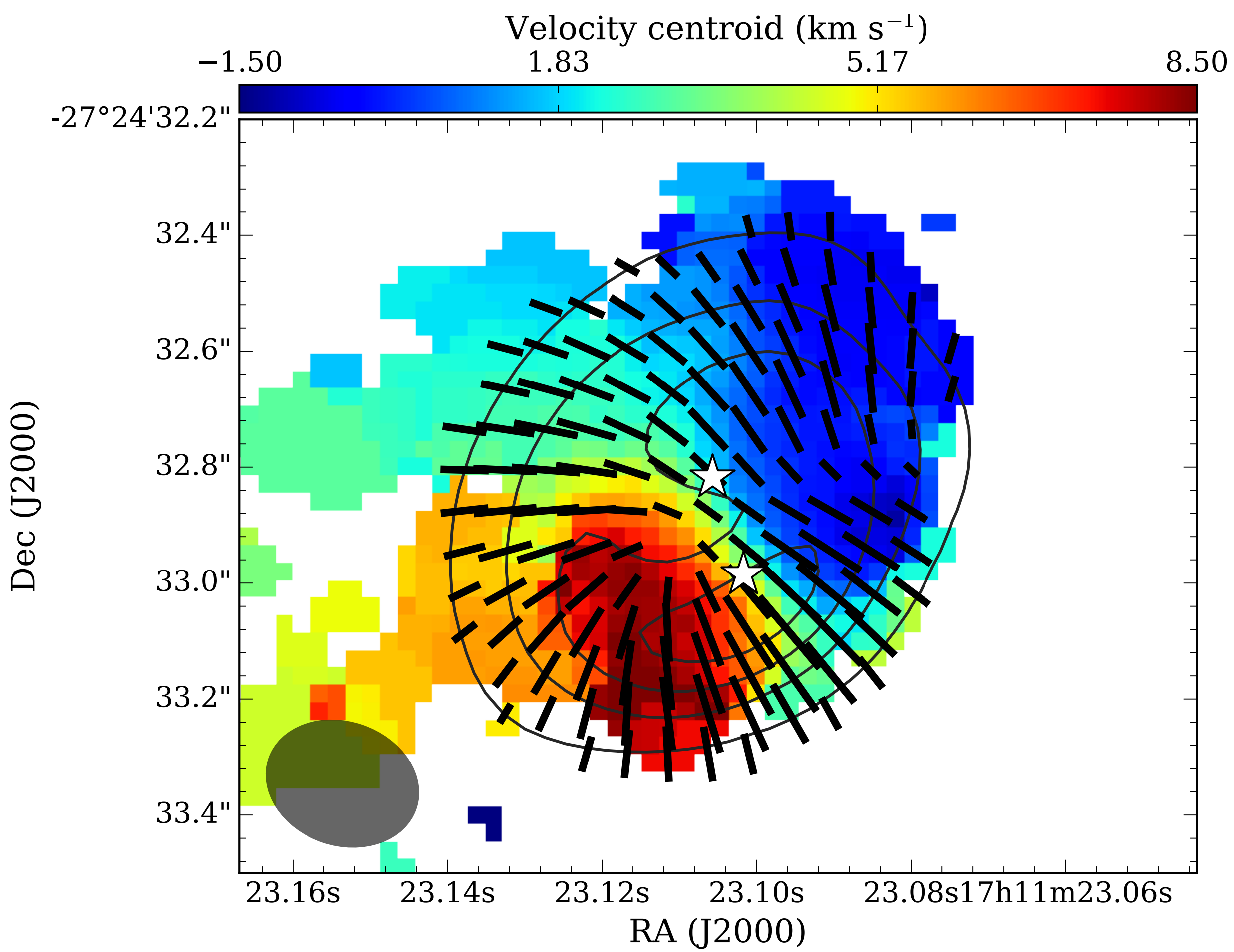


Sadavoy+ (2018)

Also cases of less dynamically dominant B

BHB07 Class I circumbinary disk:

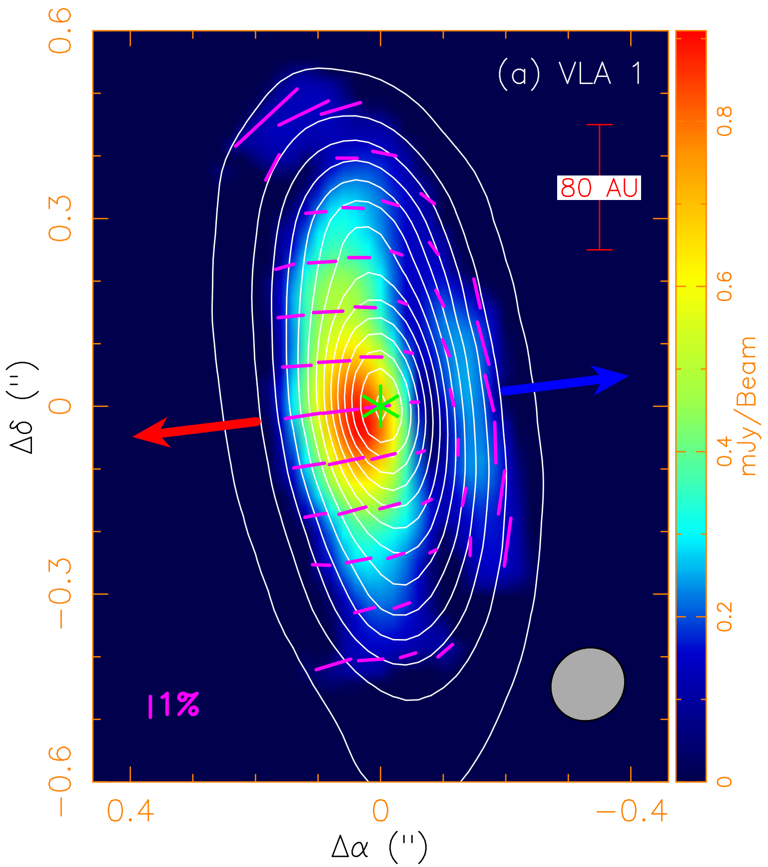
ALMA reveals a toroidal field component produced by disk rotation at scales 100 au

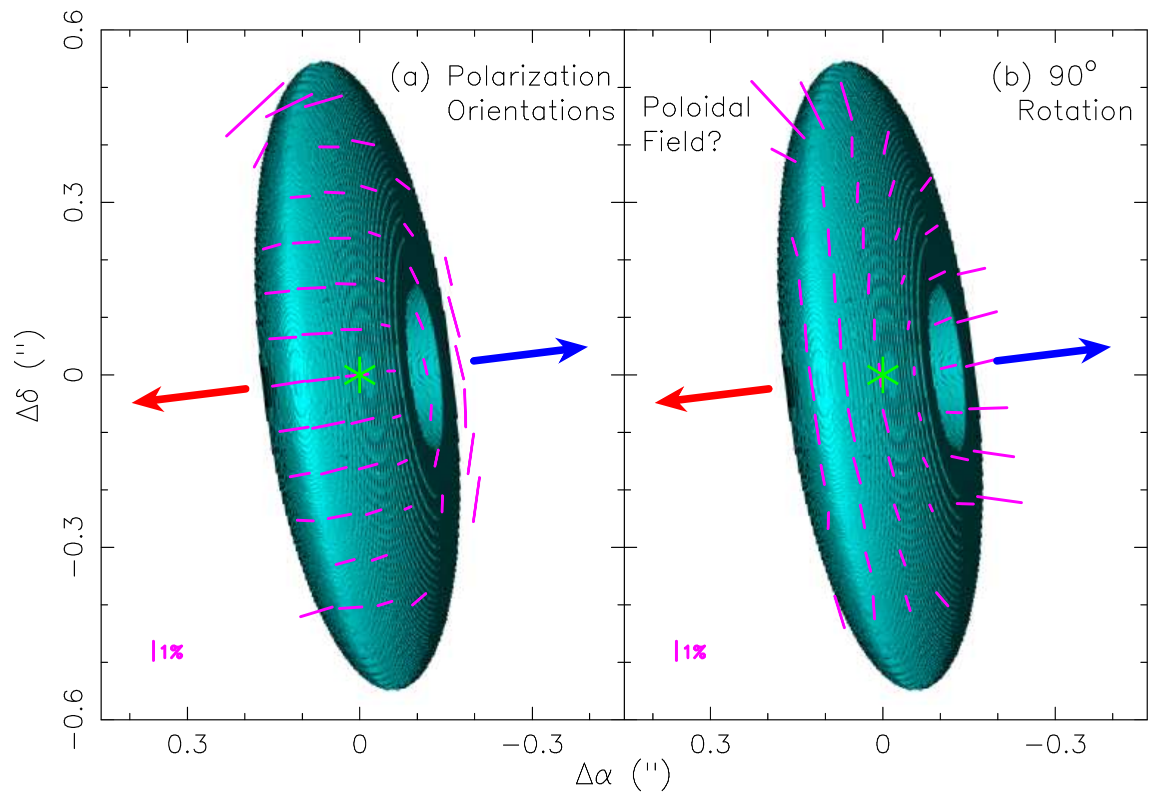


Alves+ (2018)

ALMA dust polarization = B-fields ?

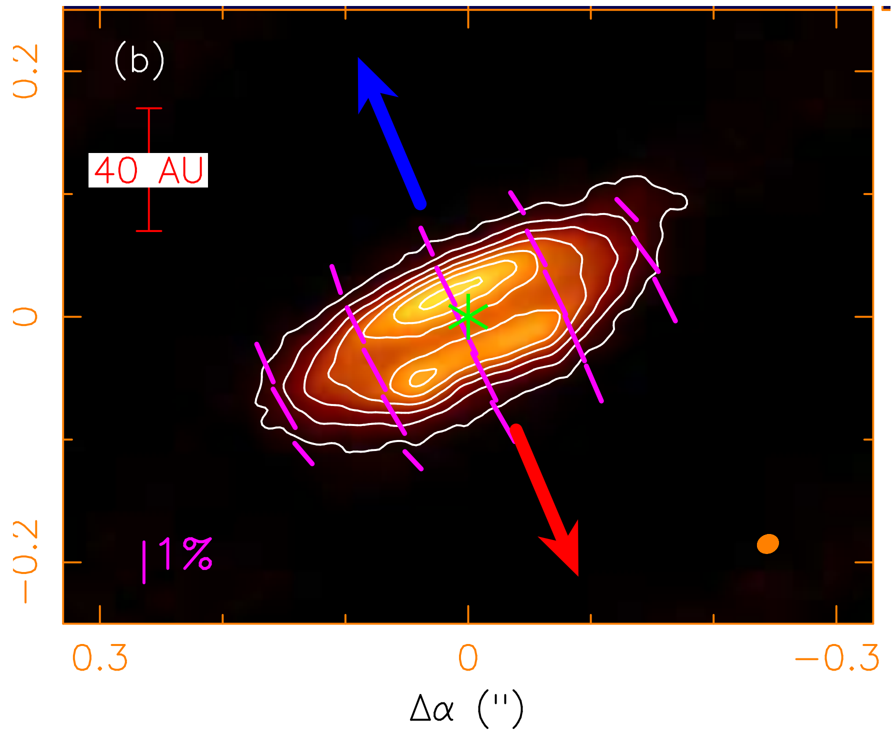
Subarcsec ALMA polarized dust emission in edge-on disk HH111 (Lee + 2018)





ALMA dust polarization = B-fields ?

Subarcsec ALMA polarized dust emission in edge-on disk HH212 (Lee + 2018)



tion mechanisms. In HH 212, the dust polarization is consistent with either scattering or emission by grains aligned with a *poloidal* field around the outer edge of the disk because of optical depth effect and temperature gradient. One may be able to tell these two apart with polarization observations at another wavelength in the future. For HH 111 VLA 1, it is possible that a combination of toroidal and poloidal magnetic field may explain the polarization on the near and far side of the disk, although we do not have good detailed models for scattering for disks that are as edge-on as HH 111; scattering may or may not work, and it needs more exploration. In addition, alignment of dust grains by radiation flux may play a role in the farside. Perhaps, different polarization mechanisms are operating in different parts of a disk and in different disks. Additional multi-wavelength polarization observations and detailed modeling are required to make further progress in this important field that is being revolutionized by ALMA.

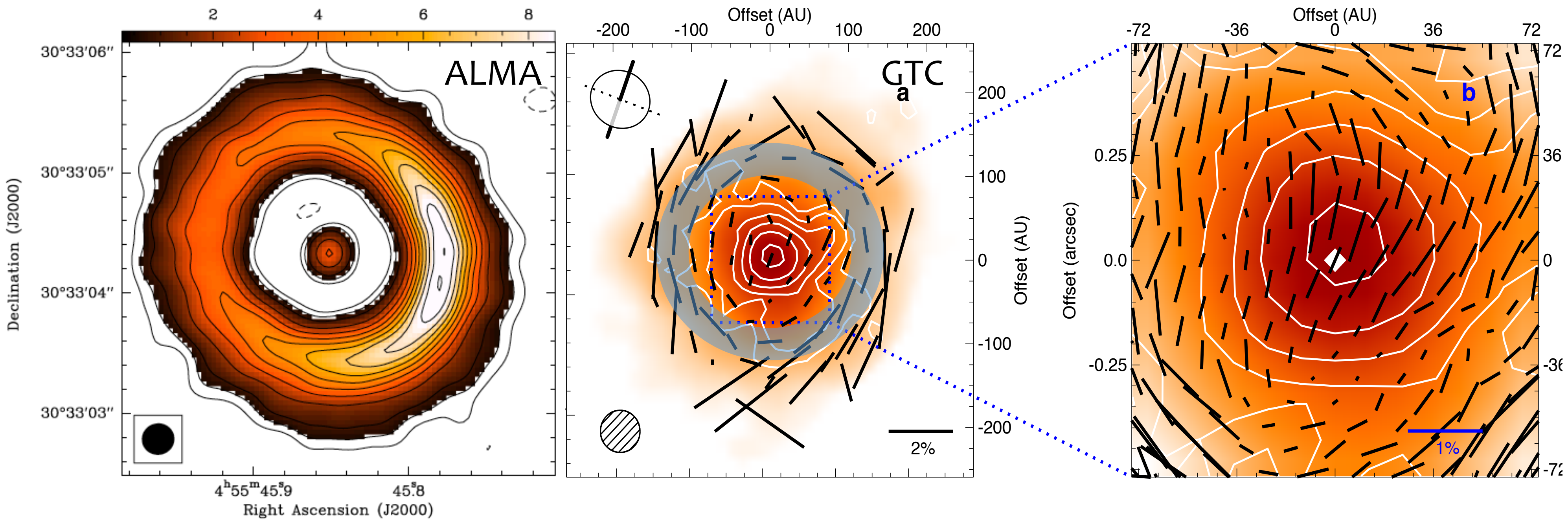
Polarization = B-fields ?

Subarcsec mid-IR polarimetry survey of protoplanetary disks with GTC CanariCam
Li, Telesco, Zhang + (2018)

AB Auriga (D=140 pc)

Mass 2.4$M_\odot$ Age 4±1 Myr   Inclination ~23°

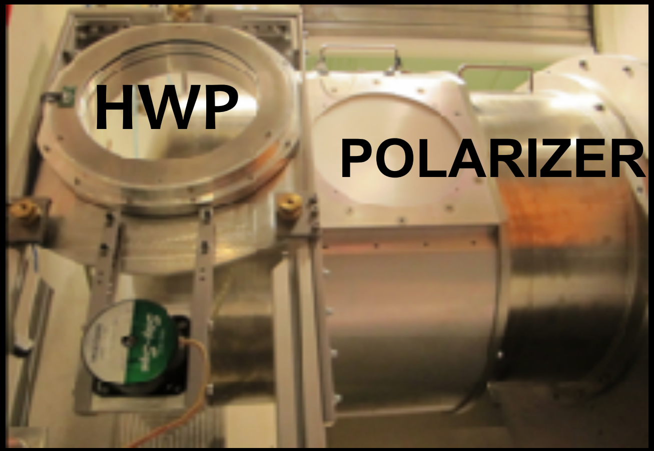
Accretion rate 10^{-7} $M_\odot$/yr (Tang+ 2012;Perrin+ 2009)



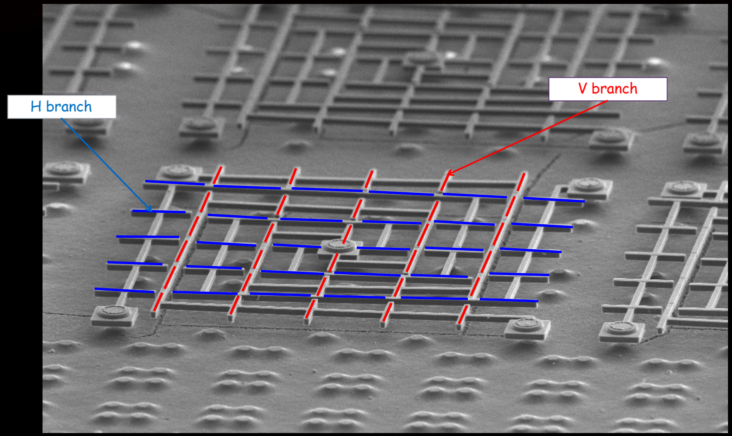
Great future for magnetic field studies

ALMA @ sub-arcsecond
SMA @ arcsecond
Sphere on VLT @ IR

2019: NIKA2-Pol 10'' @ 260 GHz



2030?: SPICA SAFARI-Pol 10'' @ 100microns



Also starting a collaboration with IRAM to enable NOEMA linear polarization capabilities

Dust polarization: a reliable tool to trace B ?

Multiple polarization mechanisms :

--If magnetically aligned => dust polarization to map the B field structure
=> Molecular lines polarization to constrain the B field strength.

--If dust scattering, it constrains dust properties.

Critical to obtain consistent constraints from several B tracers

Multi-wavelength polarimetry: mid-IR to (sub-)mm (tomography)

Multi-medium (dust, molecules)