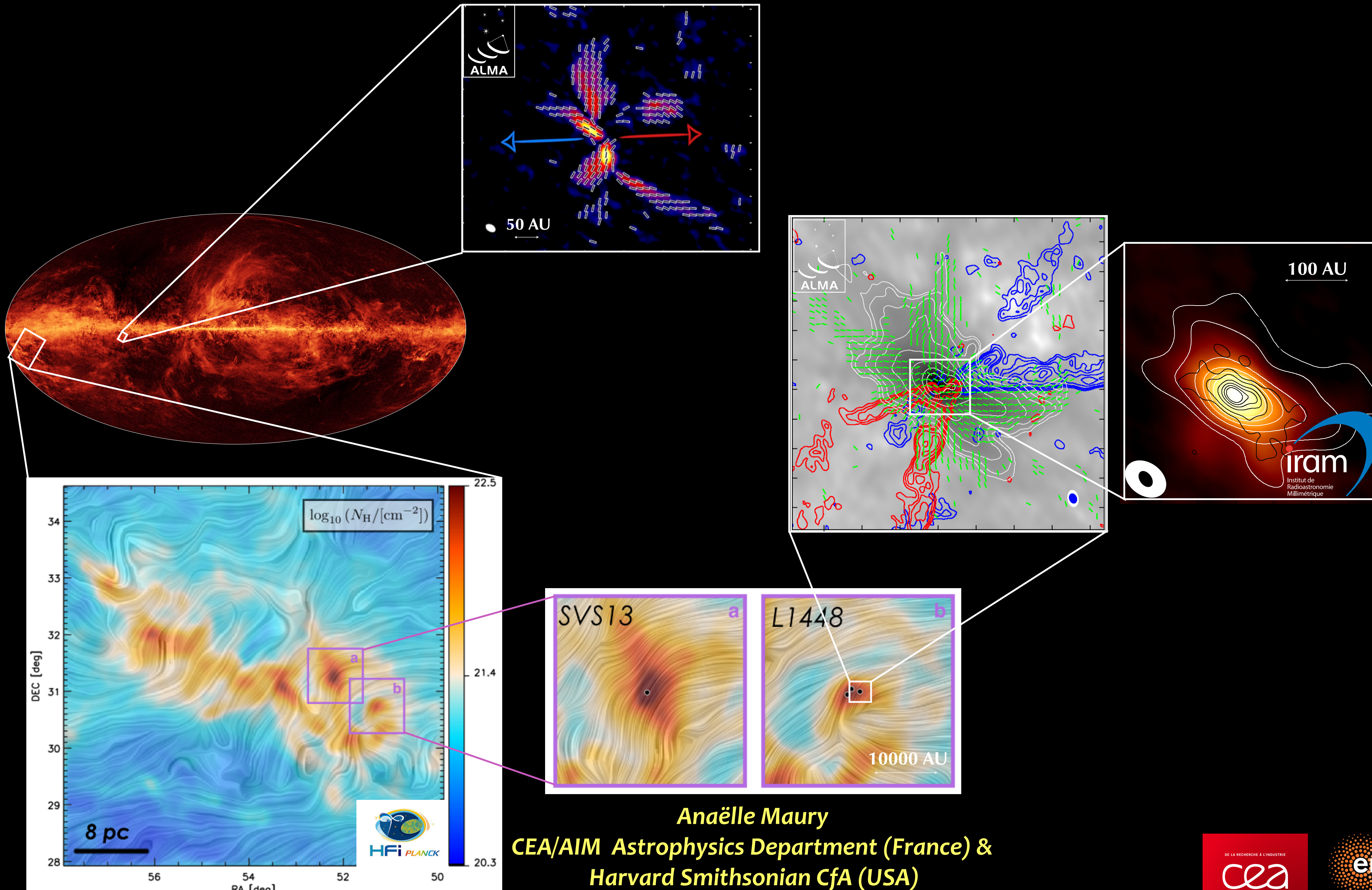
Dust properties and magnetic fields in protostars: state-of-the-art and remaining challenges



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

DE LA RECHERCHE À L'INDUSTRIE
cea
erc
European Research Council
Established by the European Commission

* PROTOSTELLAR CORES: PROPERTIES & QUESTIONS

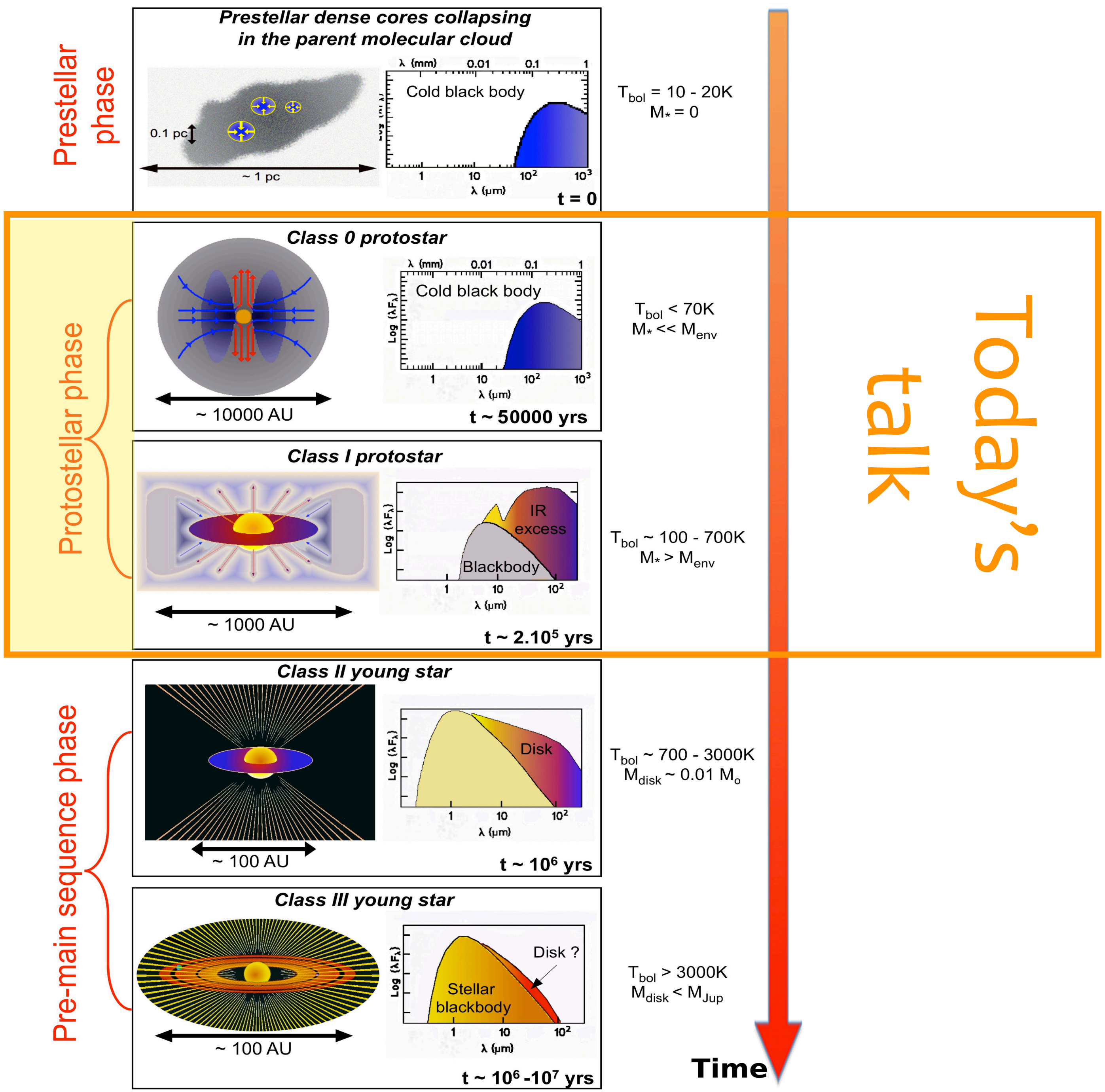
* DUST & POLARIZATION IN PROTOSTARS: A COMPLEX RELATIONSHIP
* DUST POLARIZATION TO INVESTIGATE B FIELD
* DUST POLARIZATION TO INVESTIGATE GRAIN PROPERTIES

Shu et al. 1987

Lada 1987

André et al. 1993

André et al. 2001



The main accretion phase: overview

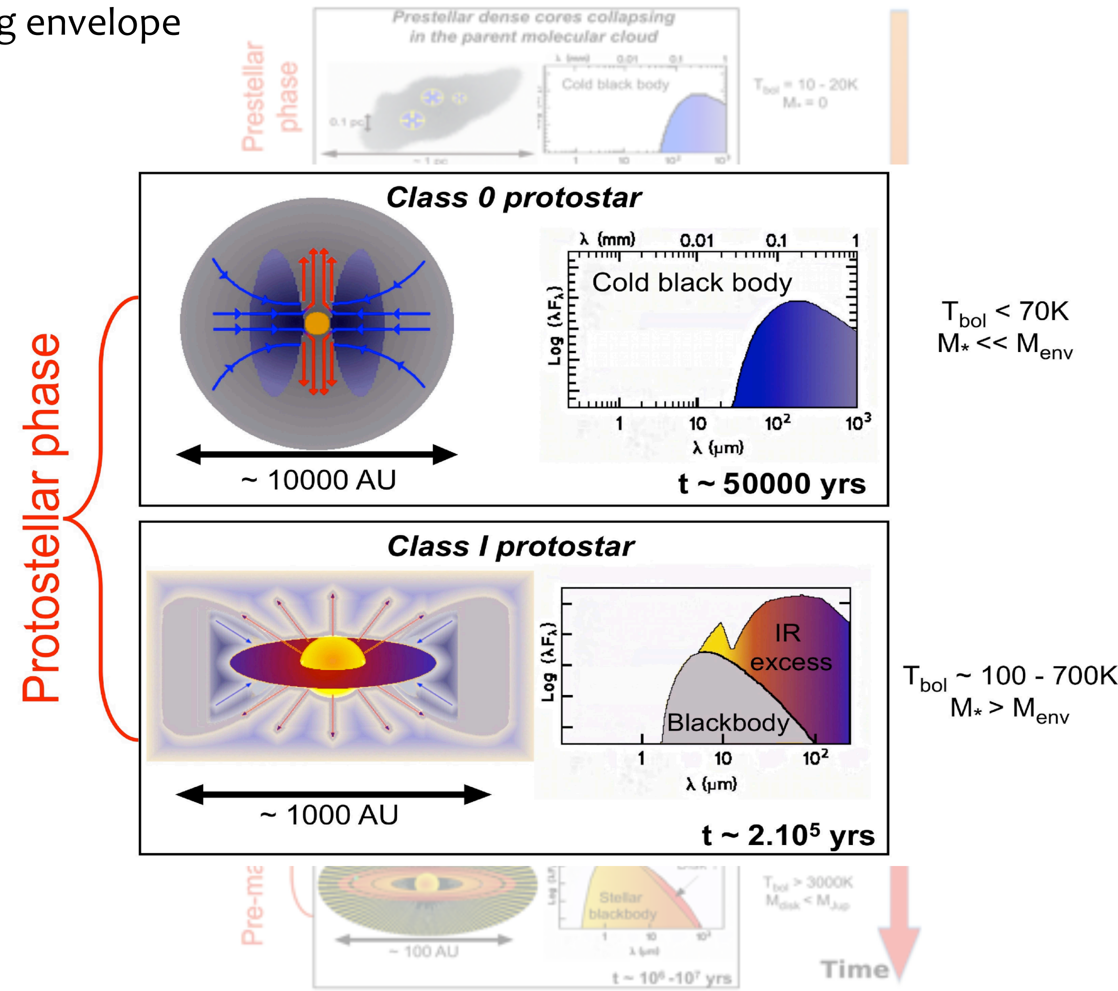
- The stellar embryo grows by accreting the surrounding envelope

- Accretion shock at the surface of the protostar:
  the kinetic energy is converted to heat, then radiated:
  $L_{acc} = \frac{1}{2} (dM/dt) V_{ff}^2 = GM/R(dM/dt)$
  L_{acc} dominates $L_{\star}$: it is a protostar
  (Shu et al. 1987)

- Conservation of angular momentum: disk formation

- Accretion/ ejection: protostellar outflows

- Cold, dense envelope: emission peaks in the submm

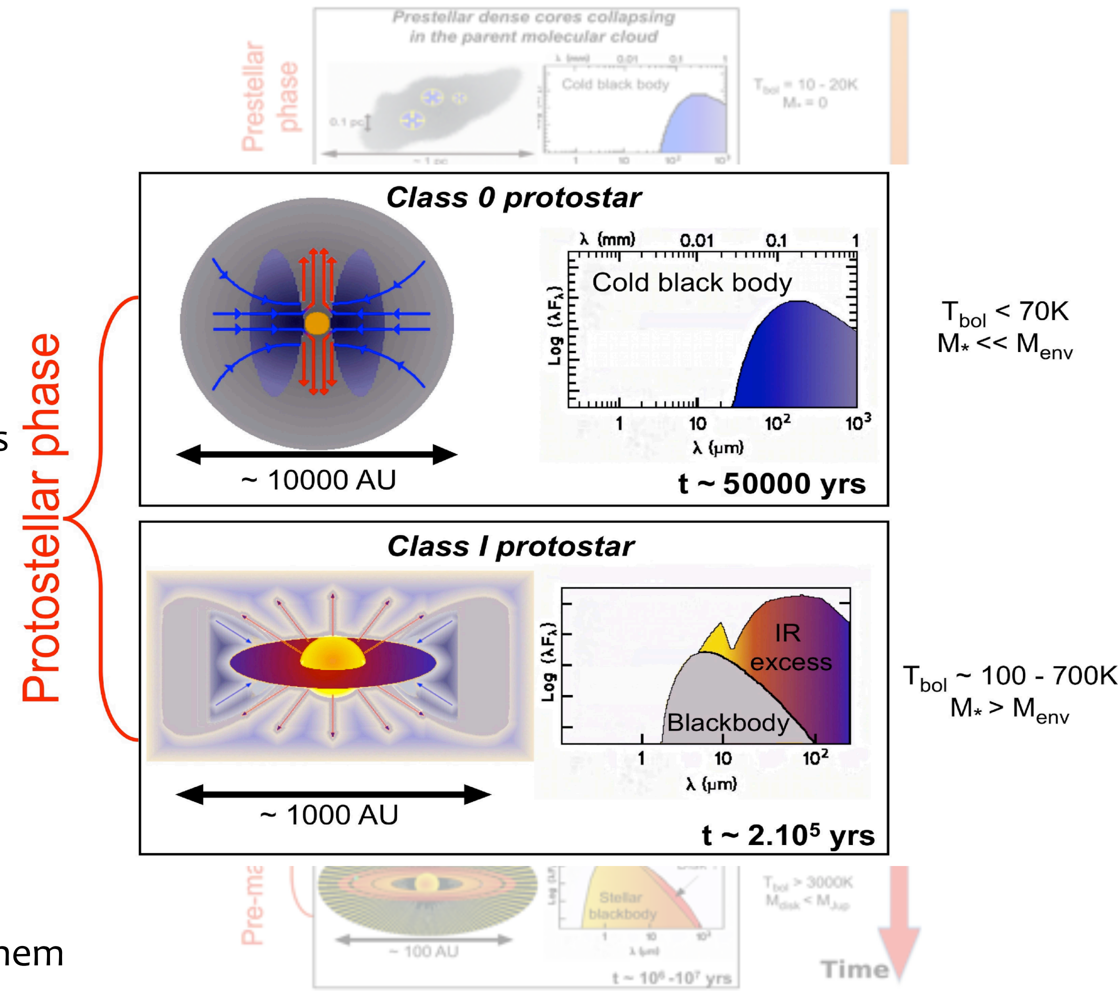


- The $M_{env} >> M_{star}$: envelope totally masks the stellar embryo in the making
  ➙ impossible to see its surface until the envelope becomes transparent (beginning of the T-Tauri phase)
  ➙ use the dust continuum emission to probe the density and temperature structure in the envelope (+disk)

The main accretion phase: questions

- **Accretion processes : Fast ? Slow ?**
  - Class 0 phase lifetime ~10^4 - 10^5 yrs
  - (Evans+ 2009, Maury+ 2011, Dunham+ 2014)
  - => rather short, vigorous accretion phase

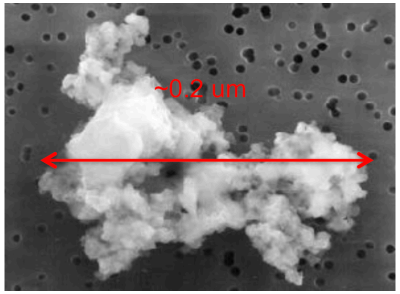
- Rotating infalling envelopes : angular momentum
  - **=> Role of outflows to carry away j ?**
  - Only few rotation signatures in disk jets & winds
  - j_{out} ~ 100-200 au.km s^{-1}
  - (Chrysostomou+ 2008, Lee+ 2017, Zhang+ 2018)
  - **=> Formation of disks ?**
  - >75% of Class 0 disks are small , radii <60 au
  - (Segura-Cox+ 2018, Maury+ 2010, 2014, 2019)



- **Are magnetic fields dynamically relevant ?**
  - => difficult to produce collimated jets without them
  - => observed in most cores
  - (Hull+ 2014, Lee+ 2017, Galametz+ 2018, Alina+ 2019)
  - => do they regulate mass accretion and disk formation ?
  - (Li+ 2014, Hennebelle+ 2016, Maury+ 2018)

* protostellar cores: Properties & Questions
* Dust & Polarization in Protostars: A complex relationship

* Dust Polarization To Investigate B Field
* Dust Polarization To Investigate Grain Properties



Recipes to make dust polarization:

Alignment with magnetic fields => B

(Hoang & Lazarian 2014)

Self-scattering of thermal dust emission => a_{max}

(Kataoka+ 2015)

Alignment with radiation fields => <grain size>

(Tazaki+ 2017)

Recipe to make dust polarization from B-fields:

1 / Spin the dust:

Use gaz/dust interaction: If equipartition grain rotational energy = gas thermal energy, one expects a spherical grain with radius a = 0.1 μm to rotate at a frequency ~100 MHz (using T ~100 K for diffuse medium)

=> Dust grains spinning

Since its average moment of inertia is $\bar{I} \approx \left(\frac{5}{3}\right) a^5 \rho_g$, the grain would have a root-mean-square angular velocity, the equipartition angular velocity, of

$$\omega_e = \left(\frac{2R_e}{\bar{I}}\right)^{1/2} = 1.57 \times 10^{-8} \left(\frac{T}{a^5 \rho_g}\right)^{1/2} \text{ rad/sec}$$

Davis & Greenstein 1951

2/ Induce precession around B lines

Use paramagnetic (or even better ferromagnetic, superparamagnetic with iron inclusions) material - or a Barnett effect

=> Dust grains spinning and precessing around B

3/ Align of the grain rotational velocity Ω with its axis of maximal inertia

Use internal or nuclear relaxation

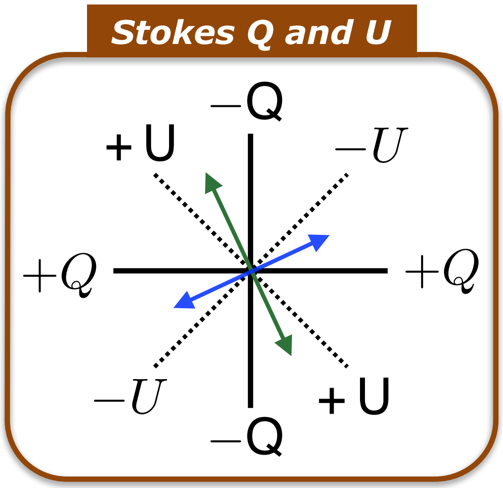
=> Grains are precessing around B, and spinning around their axis of maximal inertia with a momentum J

4/ Bring an extra torque aligning the spin axis of dust grains along the magnetic field

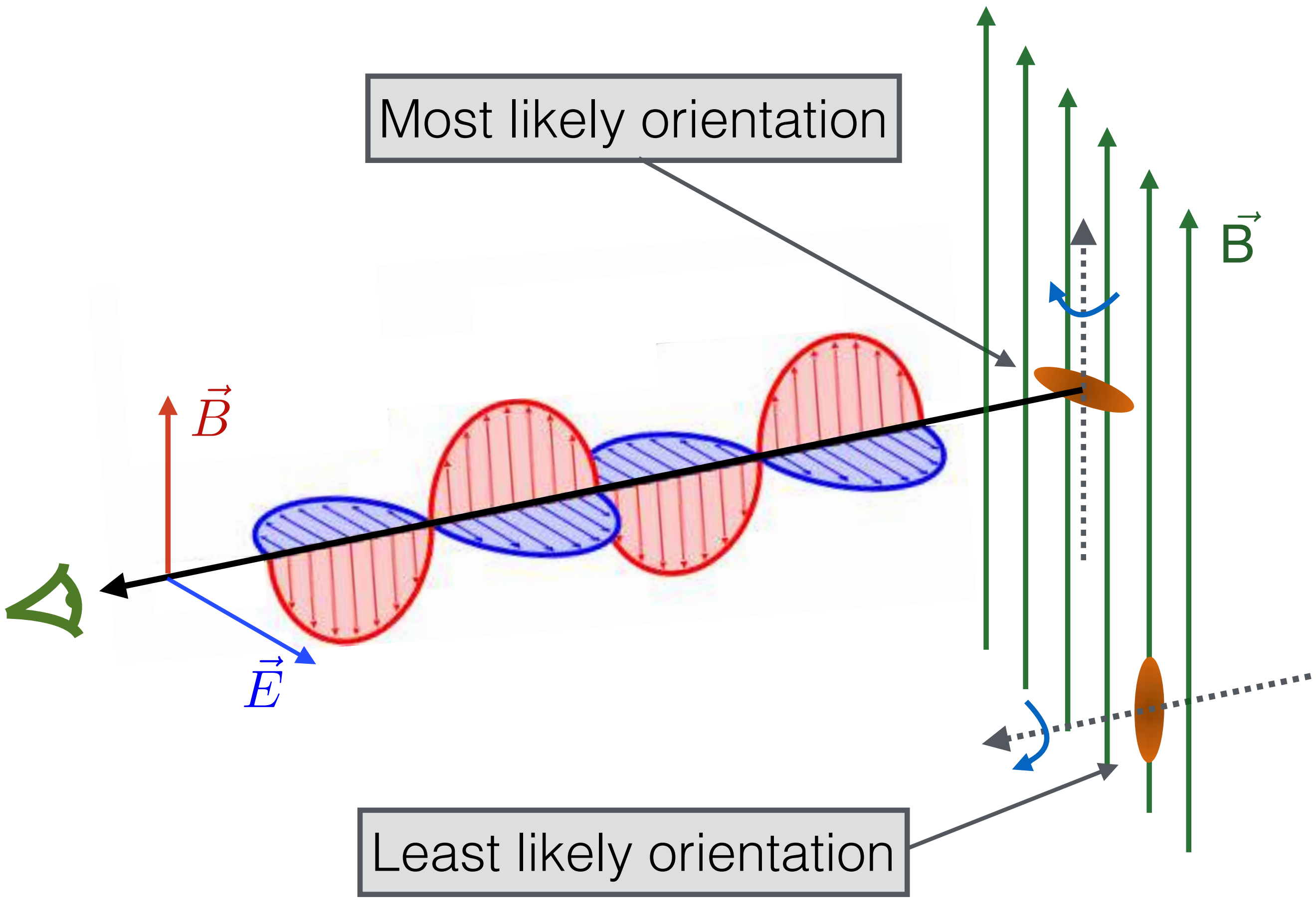
Use, eg, radiative or mechanical torques (paramagnetic alignment not efficient enough due to slow rotation, Hoang & Lazarian 2016)

=> The grain is now precessing around B, and spinning around its axis of maximal inertia with a momentum J, and is very well aligned with the local B line

Dust polarized emission due to B-fields:



Polarization orientation
Magnetic field orientation



- Alignment may be associated with paramagnetic relaxation or radiative torques: preferentially perpendicularly to the local magnetic field
- Cross sections are proportional to the size, so grains emit more radiation parallel to their long axes
- Polarized thermal emission arises, with an orientation perpendicular to the local magnetic field

Starlight polarized by dust **extinction** : different levels of extinction along the major and the minor axis, with the E-vectors pointing parallel to the field

=> B with optical and near-infrared polarization (most efficient for grains of sizes similar to lambda).

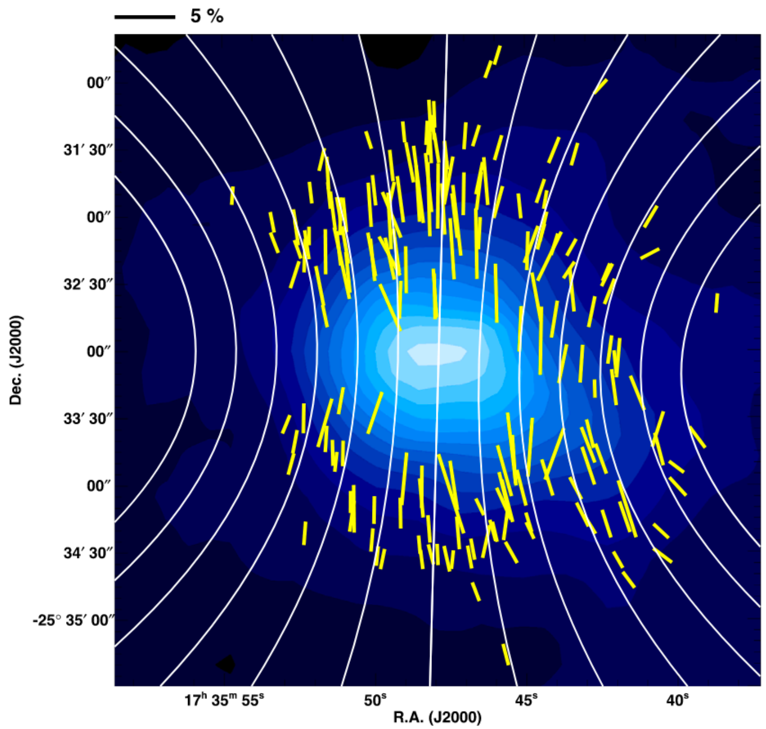
Polarized dust **emission:** emission of elongated dust grains is polarized if the grains are aligned, with the E-vectors point perpendicular to the field.

=> B with FIR and submillimeter polarization from grains with large sizes (the densest regions).

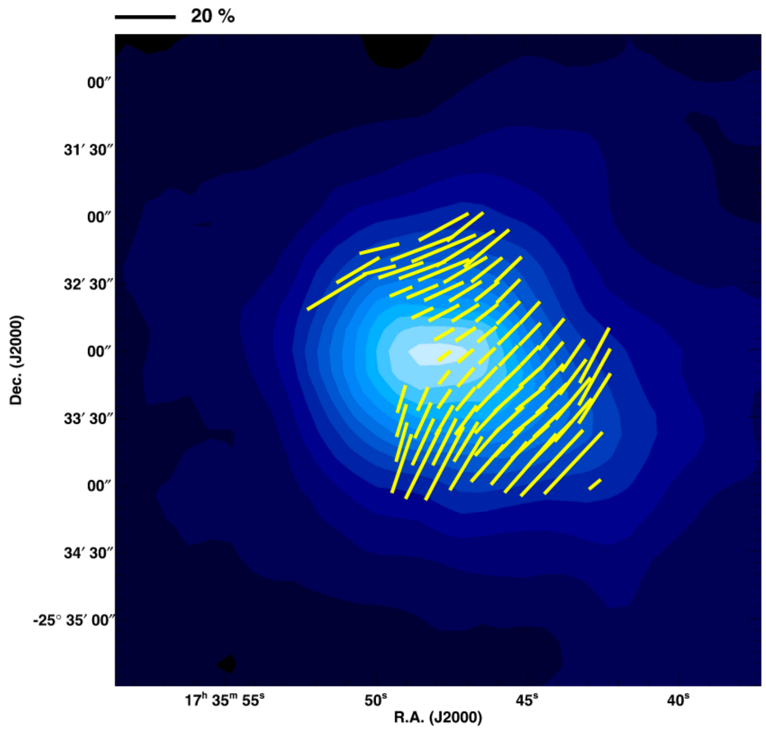
Starless core Pipe-109

The mean polarization angles at submillimeter and NIR wavelengths are 132° and 2°.7, respectively

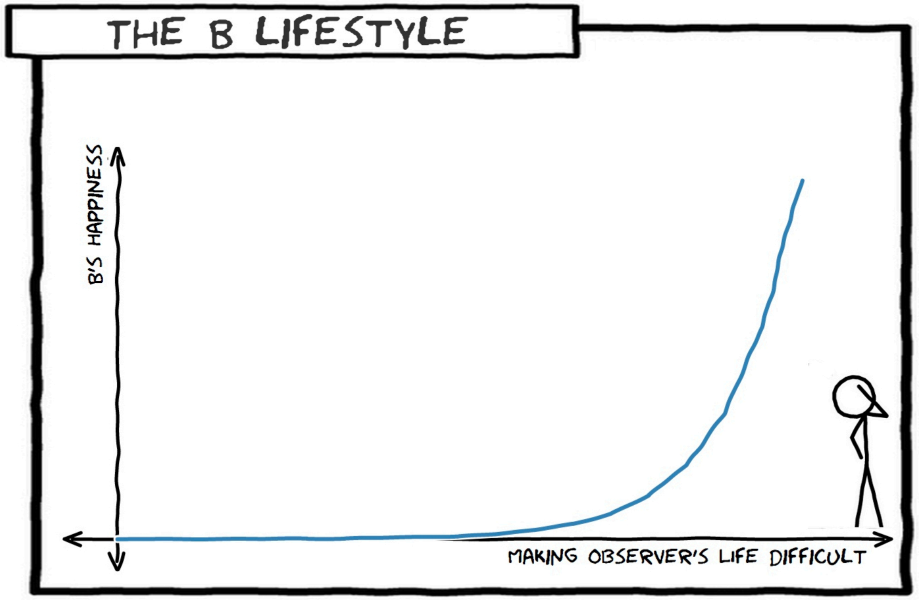
Kandori+ (2018): extinction



Alves+ (2014): emission

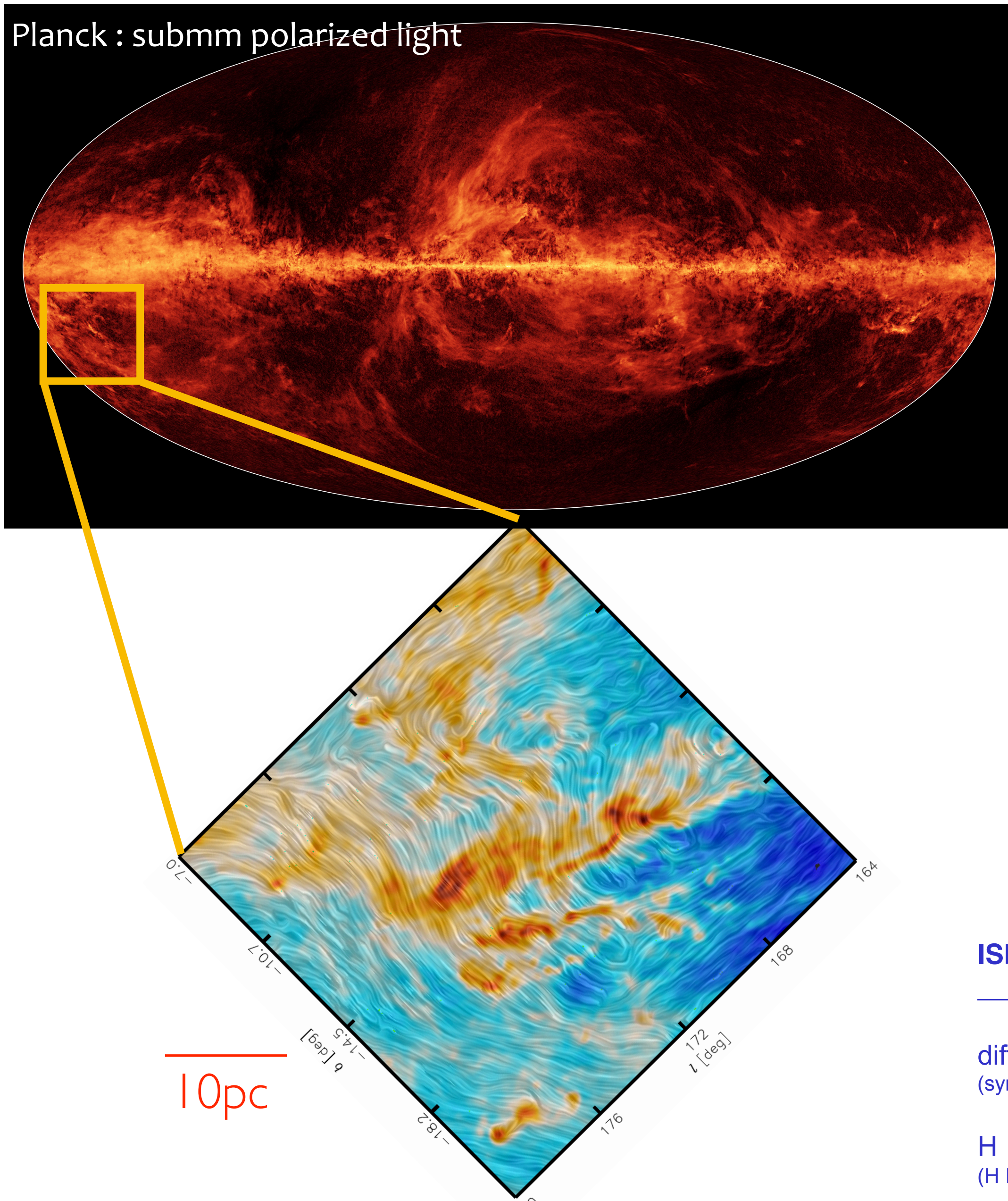


- protostellar cores: Properties & Questions
- Dust & Polarization in Protostars: A complex relationship
- **Dust Polarization To Investigate B Field**



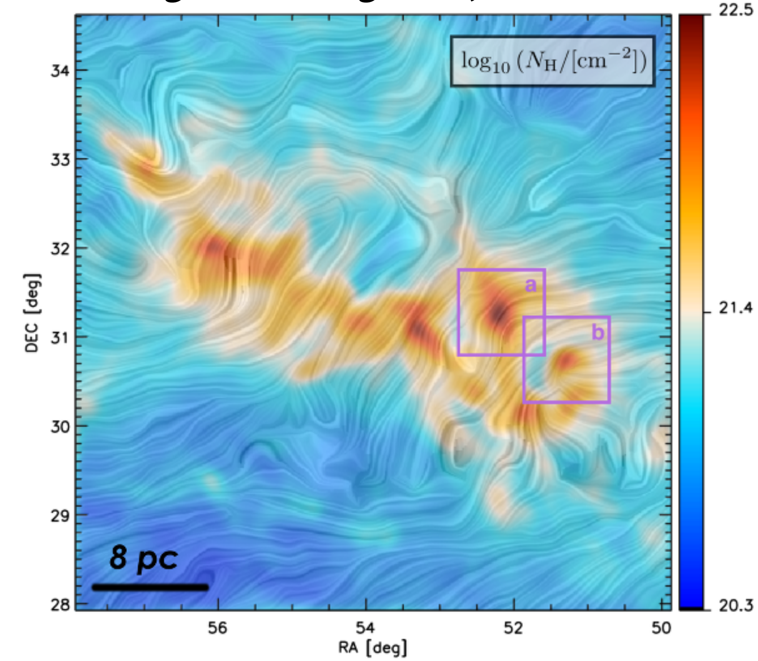
- Dust Polarization To Investigate Grain Properties

Dust Polarization => B

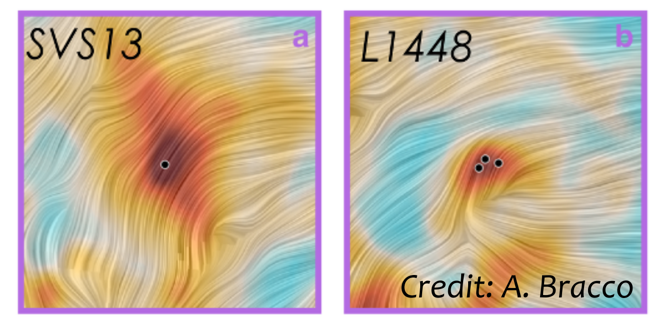


Planck: large-scale magnetic fields in Taurus

Planck: large-scale magnetic fields in Perseus

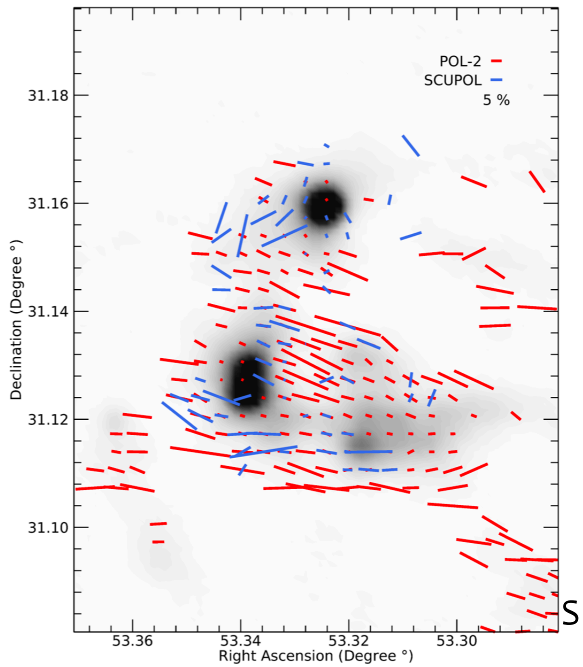


Also in protostars: see Maud Galametz's talk today



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)

All protostellar envelopes are magnetized to some level



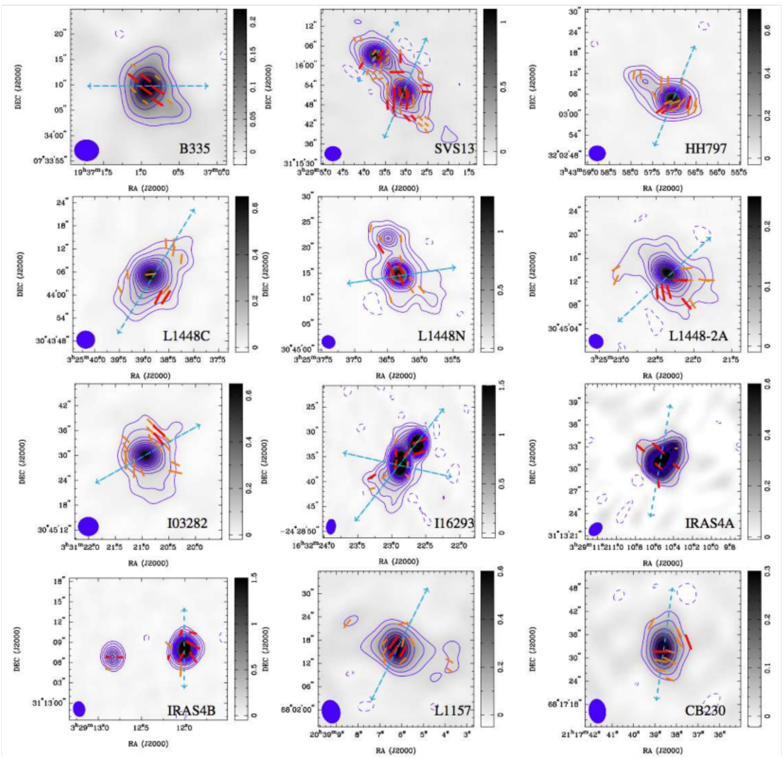
Coudé+ (2019):
0.8mm dust polarization
from JCMT/BISTRO
in Perseus B1

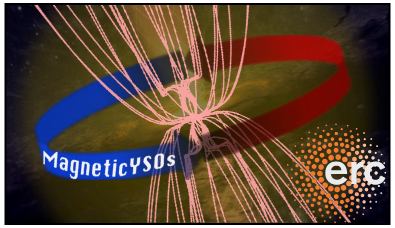
A turbulent field ?

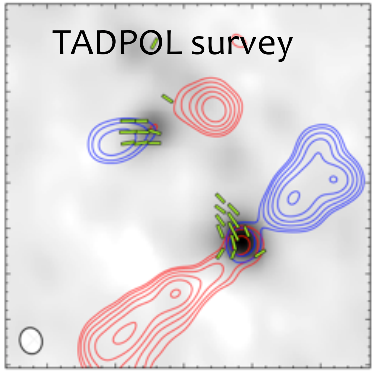
See also BISTRO+ in
Kwon et al. 2018;
Soam et al. 2018
Pattle et al. 2018 ...

SD depolarization recovered
with interferometers

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



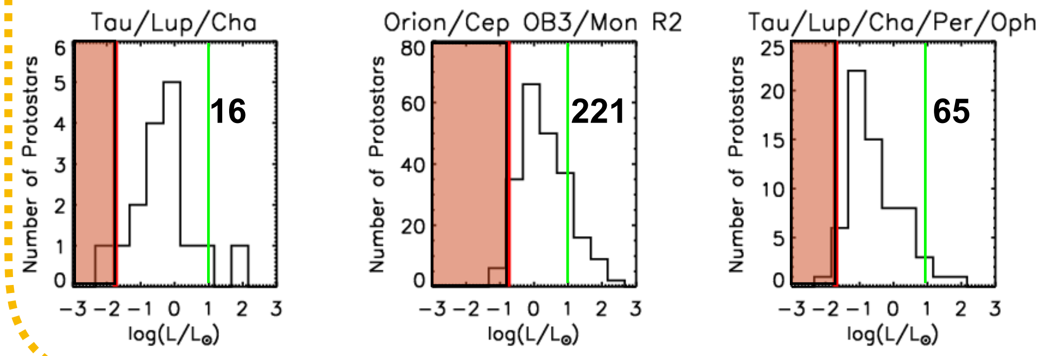




1 mm polarization, 13 Class 0 protostars
Dust polarization maps @ 2000 au
Hull et al. (2013, 2014)

Episodic accretion ?

Protostars have luminosities
<<
than would be expected
(see eg Kryukova+ 2012, Dunham+ 2014)



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

- L_p: Total protostellar luminosity
- $L_{\rm phot}$: Photospheric luminosity
- m: 0.25 M_{SUN}
- $\dot{m}$: 10^{-5} M_{SUN} yr^{-1}
- r: 3 R_{SUN}
- $f_{\rm acc}$: $\lesssim 1$

$L_{ACC} \sim 25$ L_{SUN} ↔ Median observed luminosity = 1.2 - 1.3 L_{SUN}

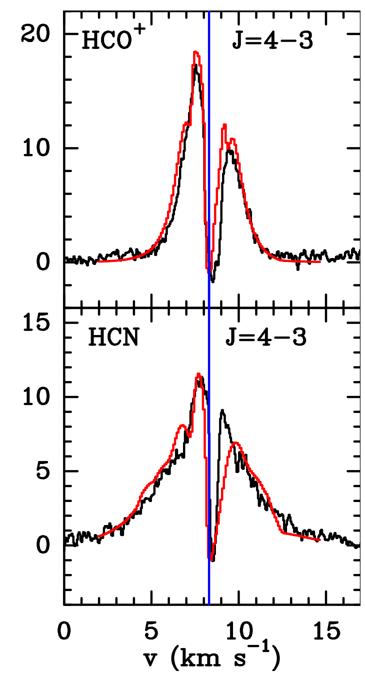
Impacting the collapse ?

Density profile $\rho(r) = c_s^2 / 2\pi G r^2$ ==> $GM(r)/r = 2c_s^2$

$dM/dt = M(r)/t_{ff}(r) = (2c_s^2 r/G) / (3\pi/32G\rho)^{1/2}$

$\sim c_s^3/G$

= 2 x 10^{-6} M_{sun}/yr assuming free-fall (for T = 10 K)



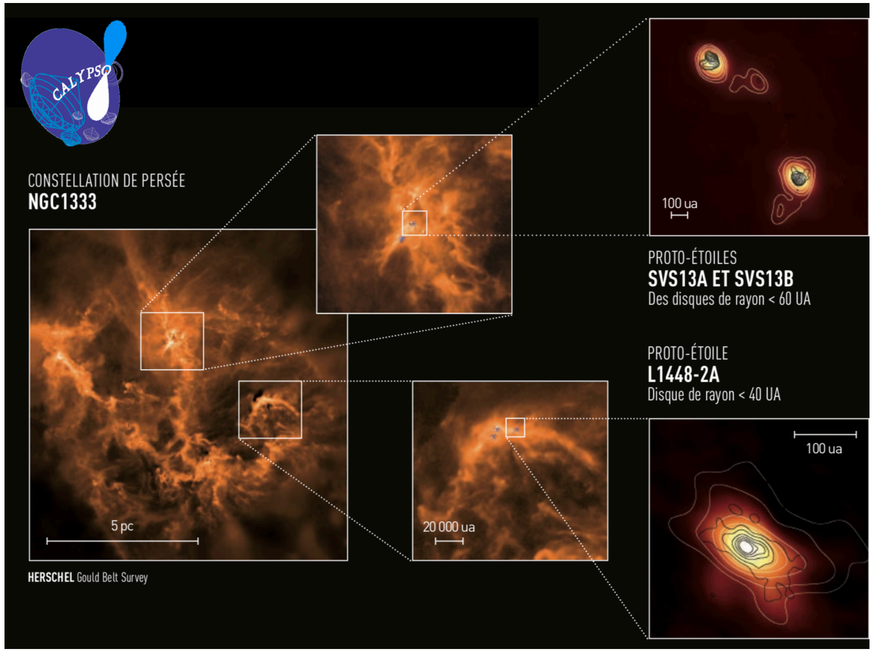
B335 (Evans+ 2015):
ALMA

infall radius 2000 AU
mass infall rate 3x10^{-6} $M_\odot$/yr
accretion rate 10^{-6} $M_\odot$/yr
age 5x10^4 yrs

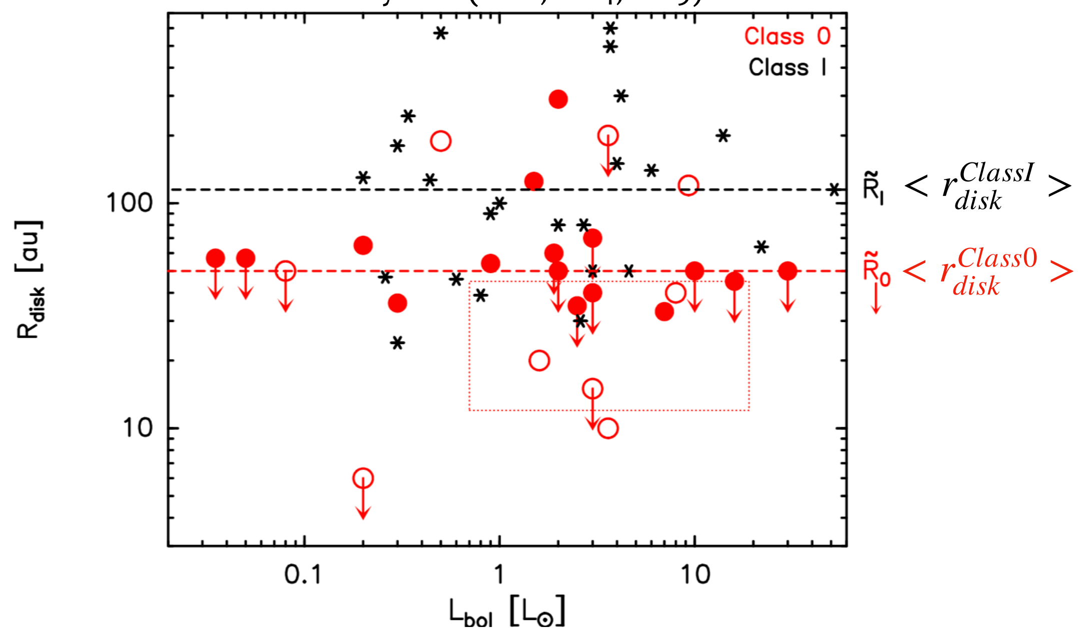
CALYPSO survey of 1.3+2.7 mm dust continuum emission

>72% Class 0 disks have r_{disk} < 60 au (26 Class 0 protostars)

Class 0 median disk radius < 40 au



Maury et al (2010, 2014, 2019)



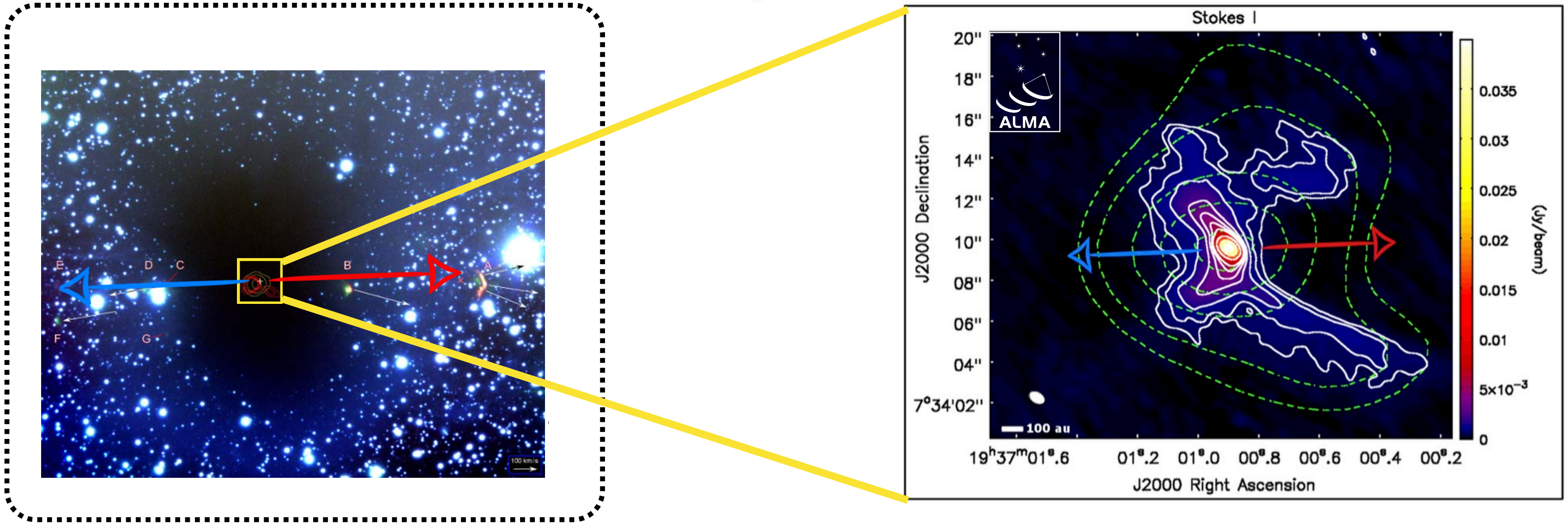
Ohashi et al. 2014, Murillo et al. 2013, Lee et al. 2018a, 2018b, Tobin et al. 2018, Gerin et al. 2017, Tokuda et al. 2017, Yen et al. 2015b, 2017, Chou et al. 2016

+ Also **Segura-Cox+ 2018** in 10 Class 0 + 4 Class I: < 33% Class 0 / I have candidate disks with r>12 au at 8mm
+ **Busquet et al. 2019** in GGD 27: paucity of disks with R_{disk} > 100 au
+ Recent **ALMA surveys** suggesting Class I/II disks are smaller than expected (Pascucci+ 2016, Barenfeld+ 2017, Tripathi+ 2017, Cazoletti+ 2019)

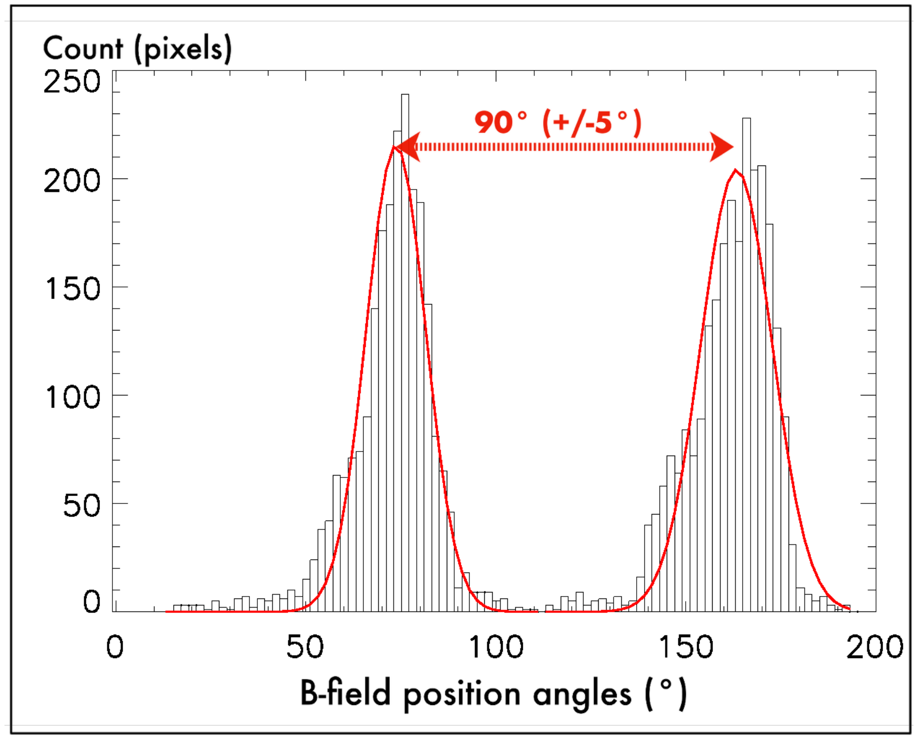
Magnetic braking delays the formation of large rotationally-supported disks

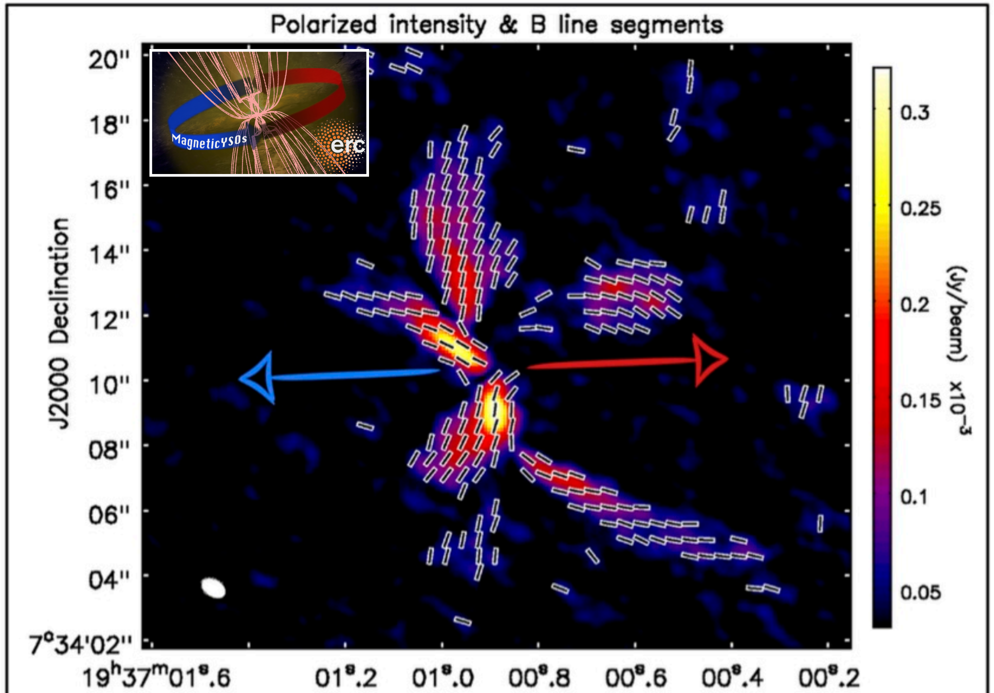
=> favors magnetized scenarii of protostellar collapse

A magnetically-regulated collapse in B335 ?



ALMA observations of the 1.3mm dust continuum polarization





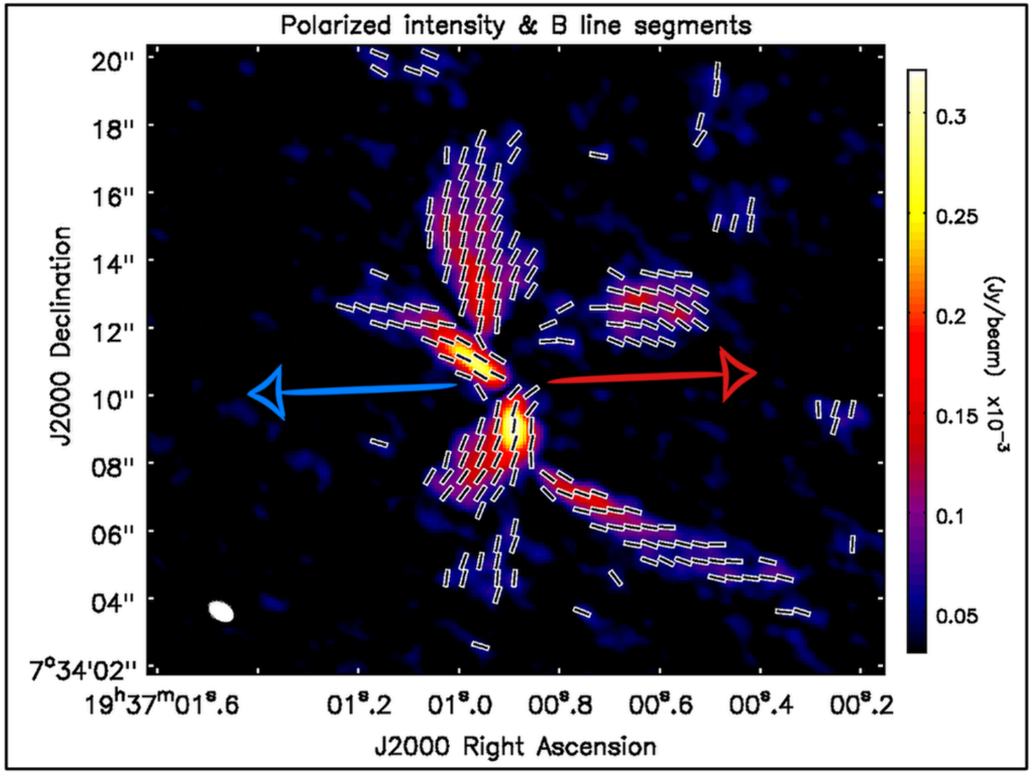
Maury+ (2018)

A magnetically-regulated collapse in B335 ?

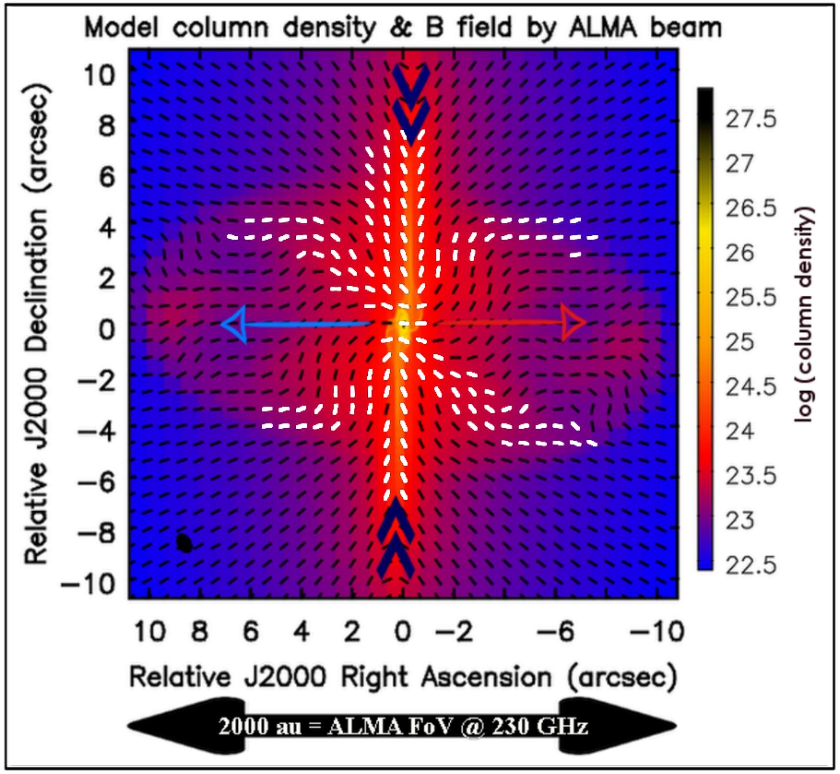
Comparison of our ALMA data to synthetic observations of non-ideal MHD models of protostellar collapse

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

OBSERVATIONS: B LINES



MODEL: SYNTHETIC B LINES



Best model: μ~6

=> B regulates the formation of the protostellar disk

Maury+ (2018)

Also cases of organized, but less dynamically dominant B

BHB07 Class I circumbinary disk:

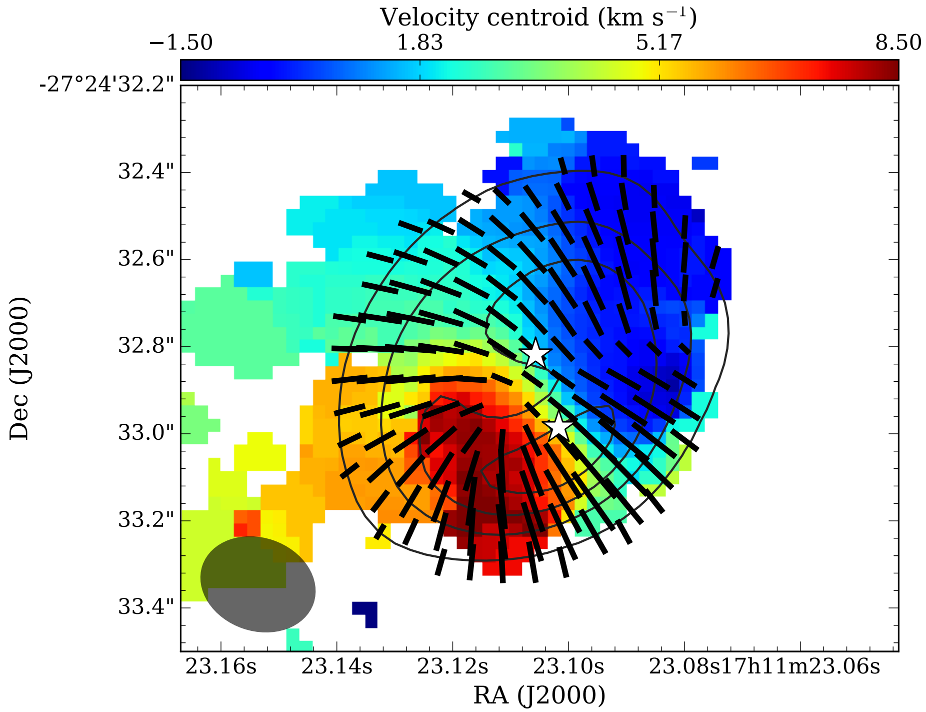
ALMA E-vectors reveal a toroidal field component

produced by disk rotation at scales 100 au ?

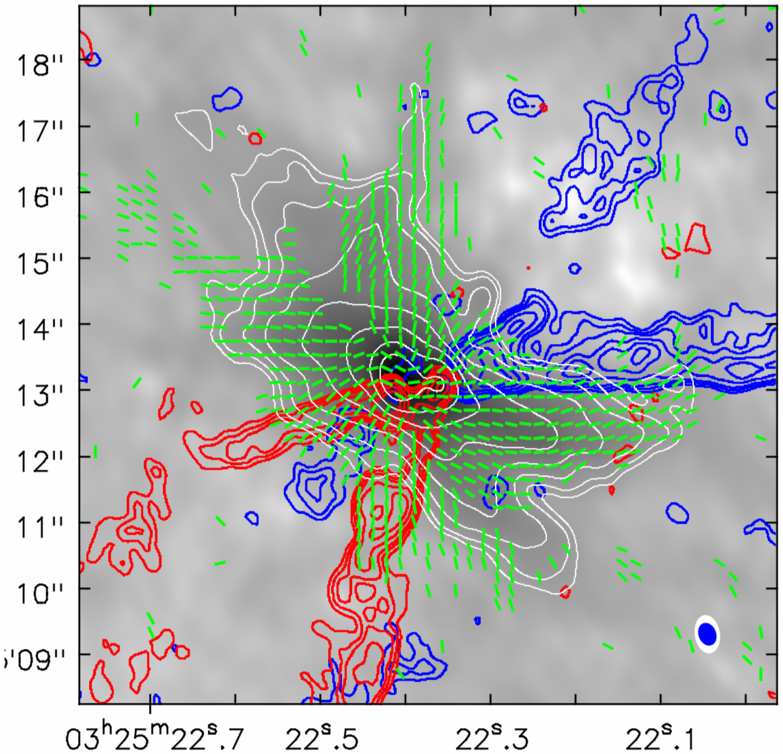
L1448 IRS2A (Perseus)

B vectors: very organized pattern.

Unclear wether the field is dynamically relevant or not

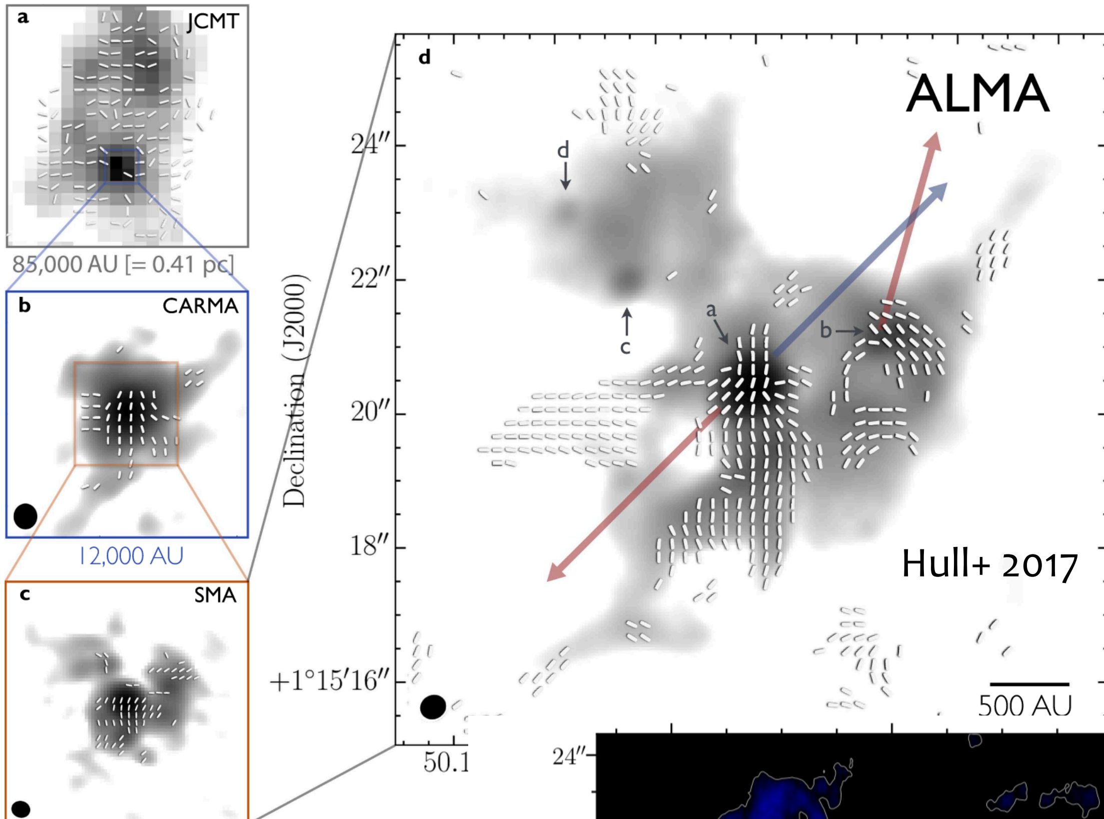


Alves+ (2018)



Kwon+ (2019)

The dust polarization also reveals more complex topologies …

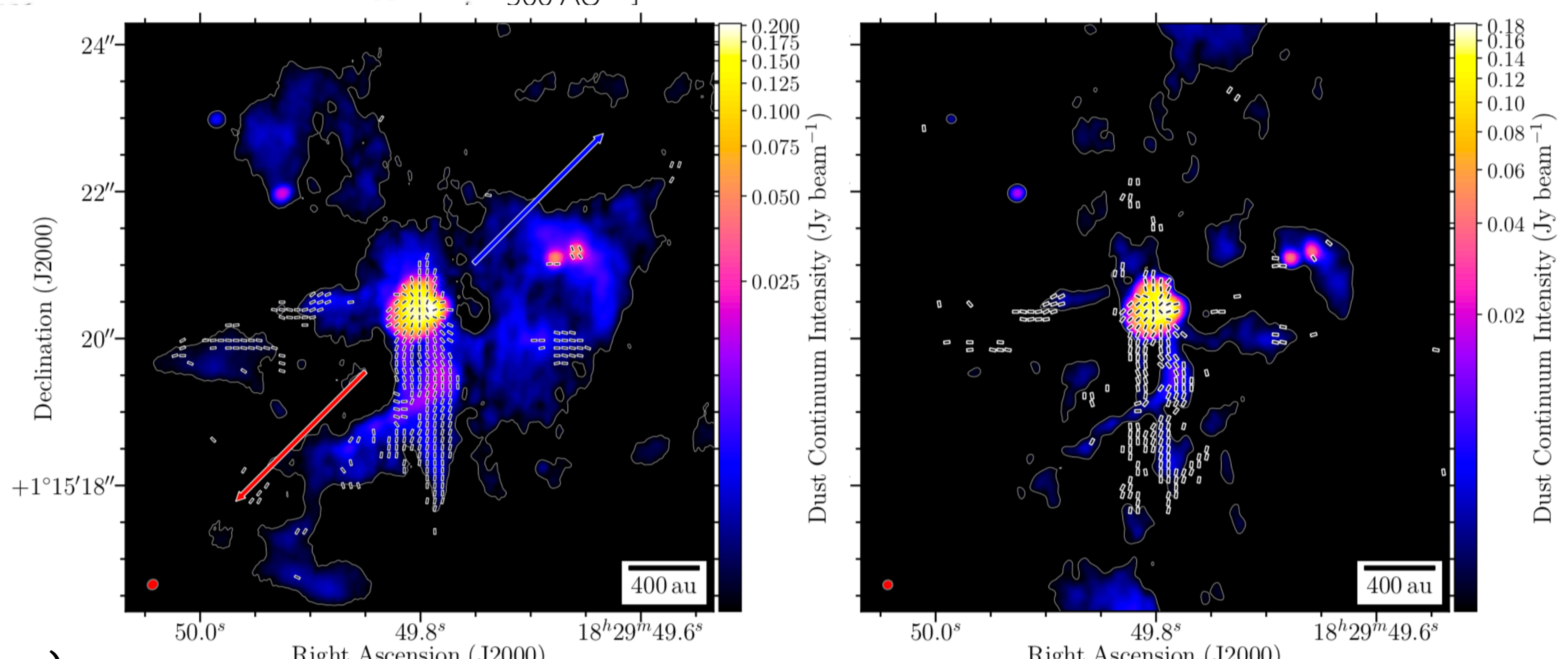


The polarized dust view of Serpens SMM1:

Multiple sources, cavities and patchy topology

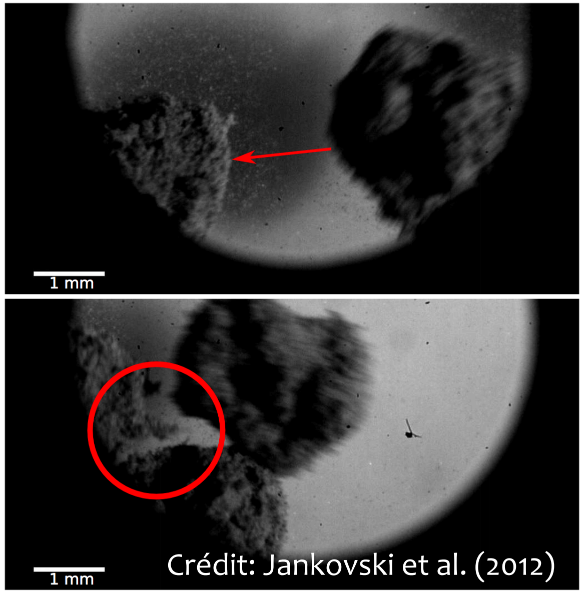
Polarization fraction up to 20%
(away from the dust continuum peak)

Different roles of B in low-mass and more massive star formation ?



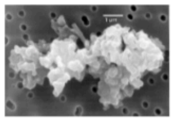
Le Gouellec, Hull, Maury+ (2019)

* protostellar cores: Properties & Questions
* Dust & Polarization in Protostars: A complex relationship
* Dust Polarization To Investigate B Field
* **Dust Polarization To Investigate Grain Properties**



*

Don't count your chickens before they're hatched ...



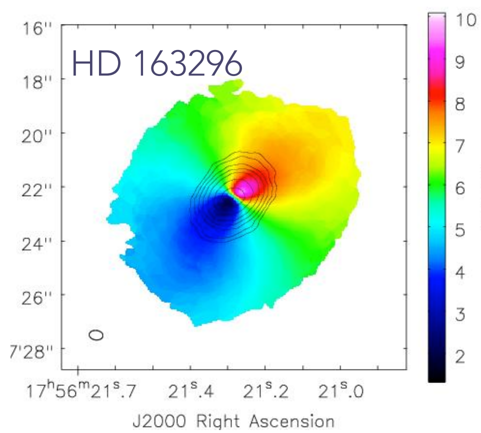
Dust coagulation

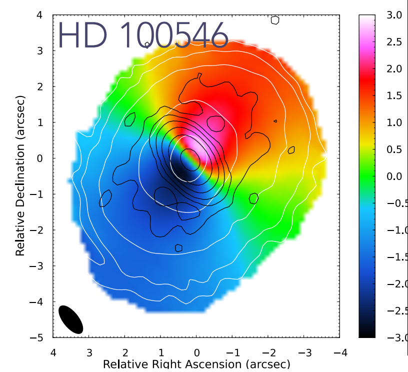
0.1μm — 1mm — 1m — 1km — $10^{2\text{-}4}$km

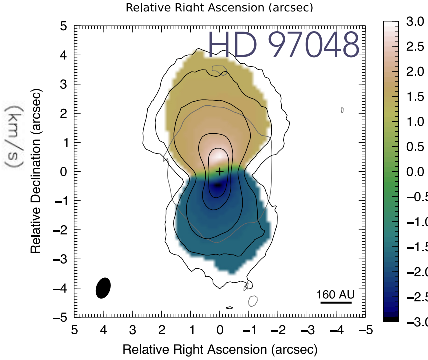
Mm size grains ~ in T-Tauri disks

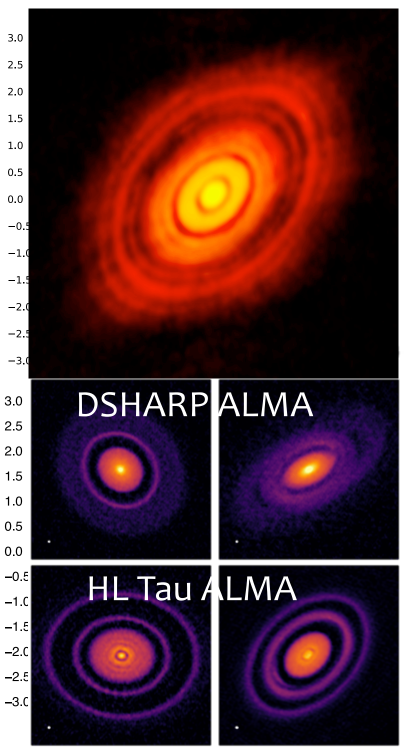
ALMA: dust evolution in disks is more advanced than previously thought

Growth plus radial drift?
Locked up in planetesimals?



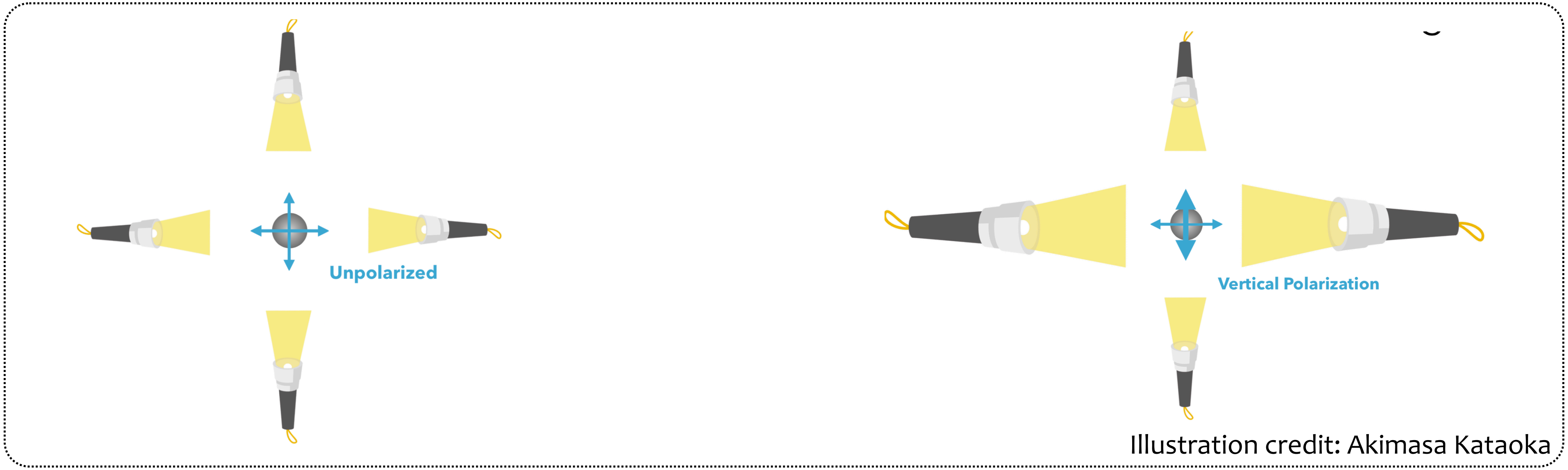




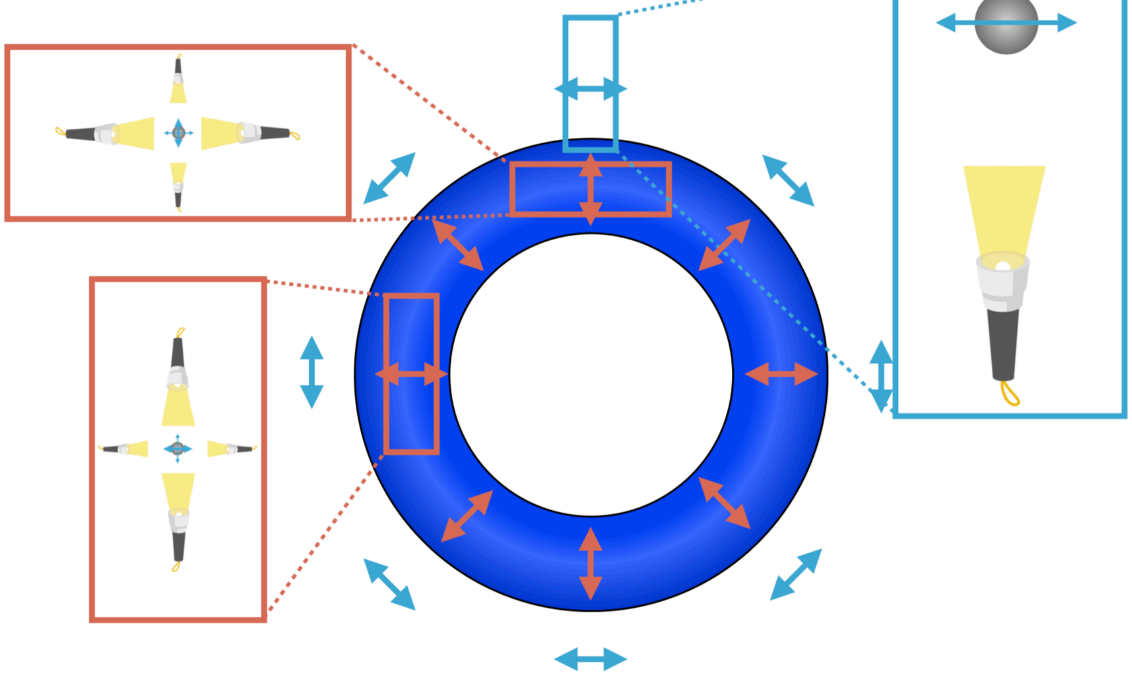


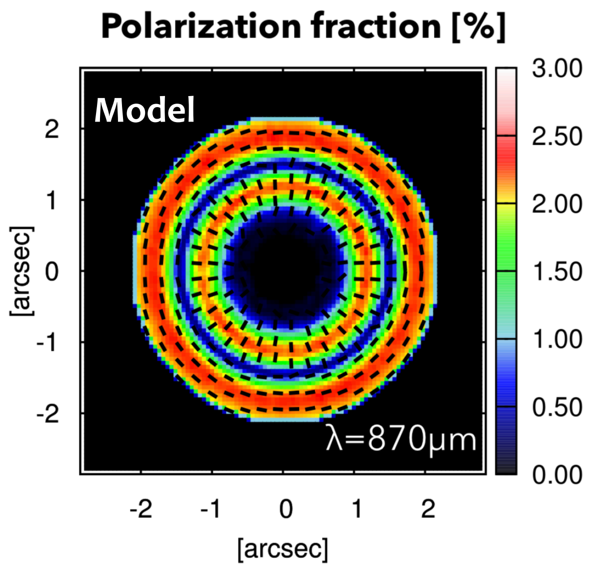
See also : Miotello+ 2014, Testi+ 2014

Dust polarization due to self-scattering



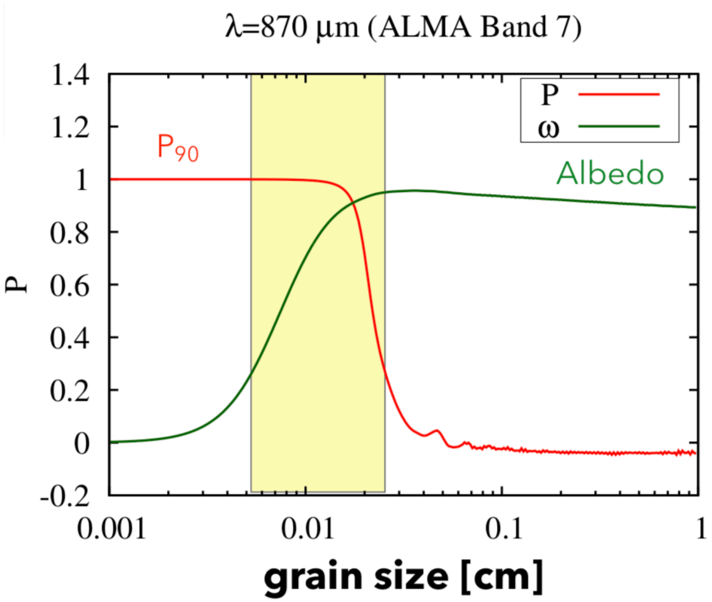
Disk = photons from the disk self-scatter on disk grains
+ ring geometry = strong anisotropy

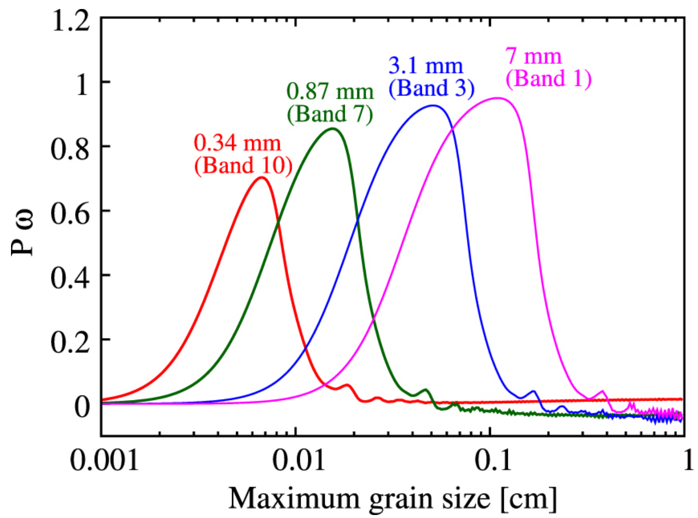




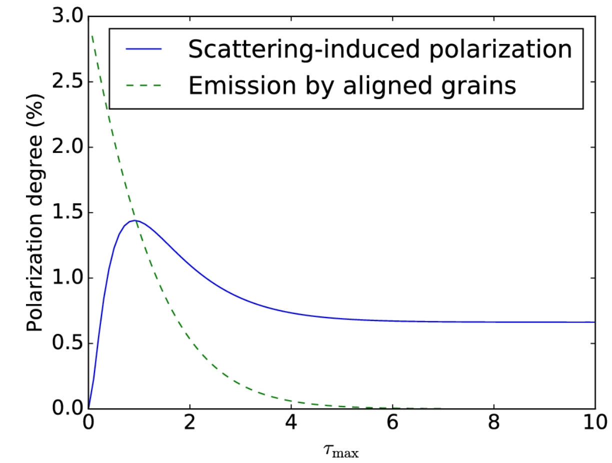
Discriminating feature:
change of polarization pattern
radial => toroidal

Dust polarization due to self-scattering





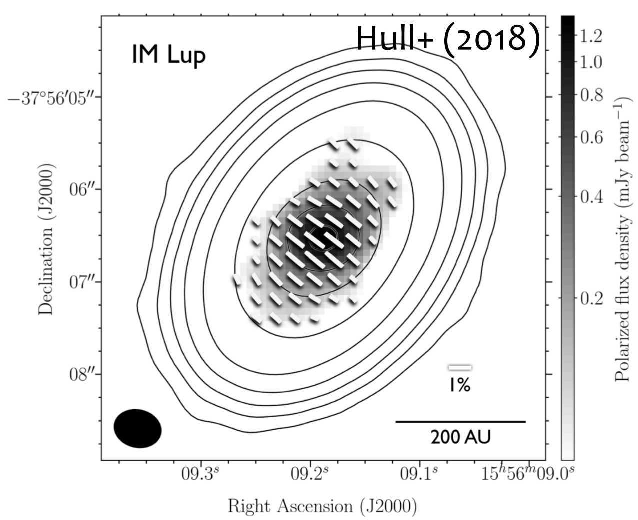
Variation of the degree of polarization & albedo against the maximum grain size (~ λ/(2π, Kataoka+ 2015)



Pol degree < 2% (Yang+ 2017)

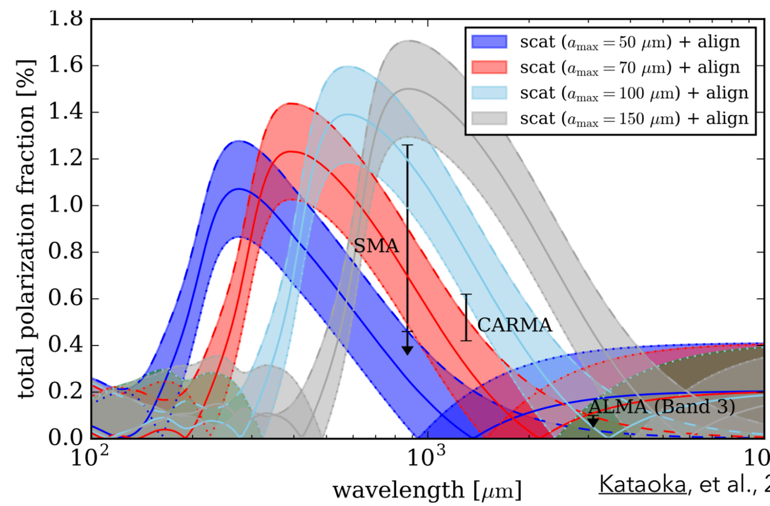
IM Lup: 0.8mm dust self-scattering

a_{max} ~ 60 microns



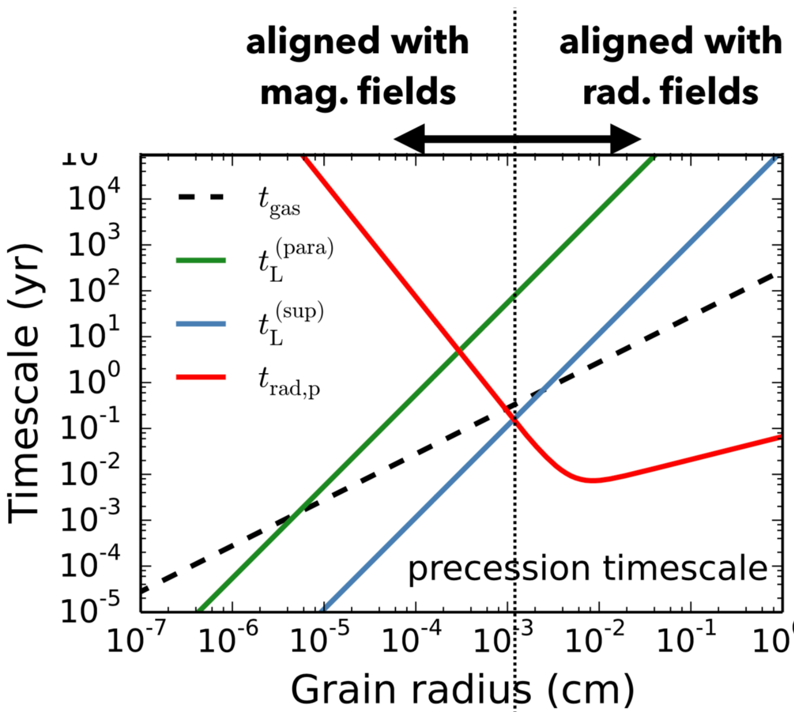
HL Tau: 3mm dust self-scattering

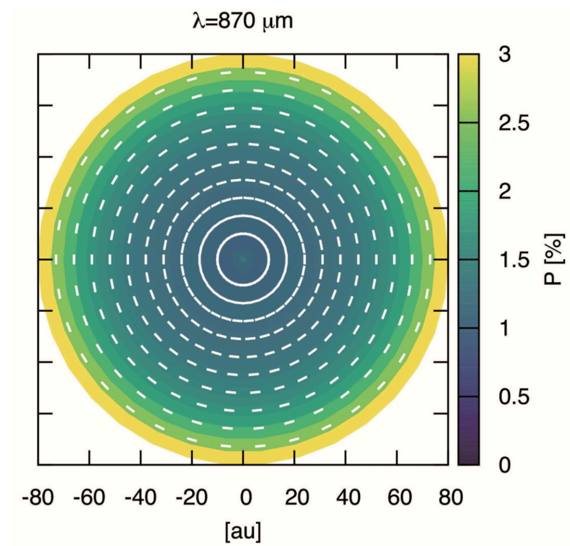
a_{max} ~70 microns



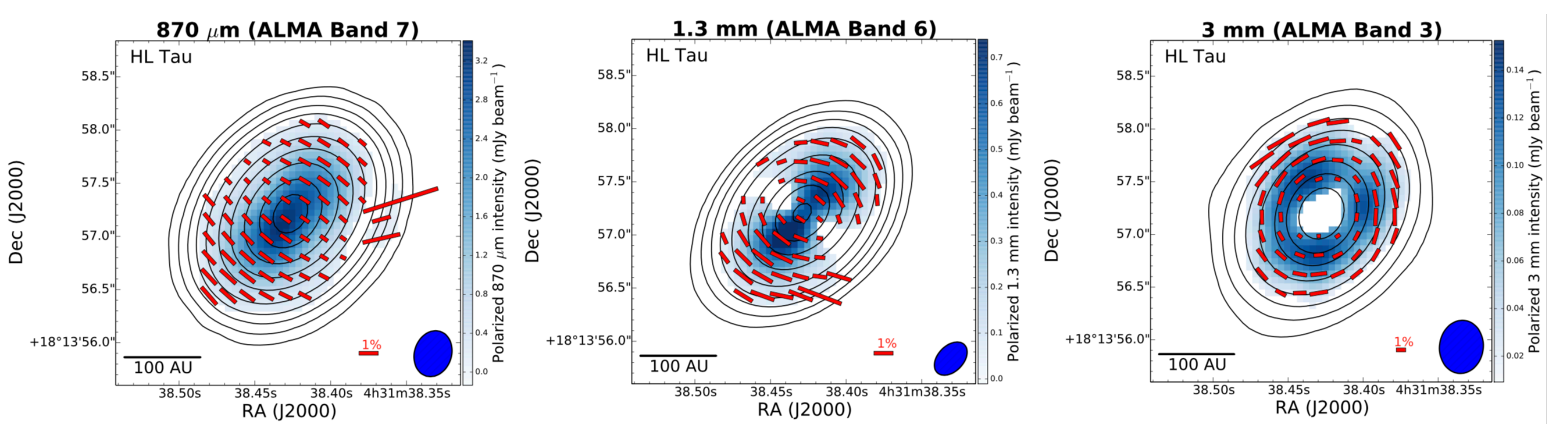
Kataoka, et al., 2017

Dust polarization due to radiative alignment





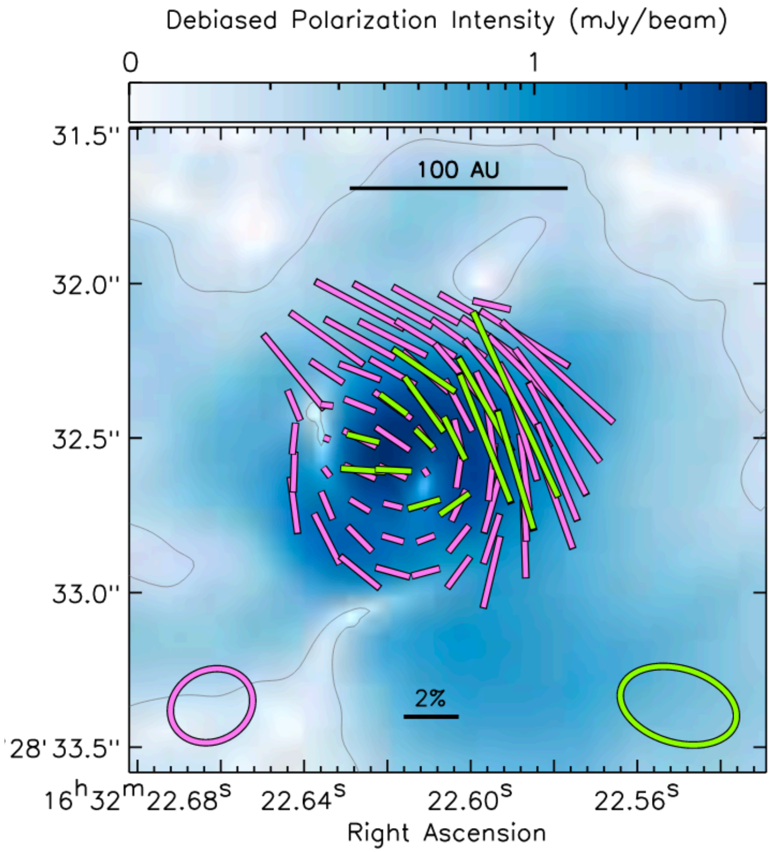
Needs big helical grains and highly anisotropic radiation field



HL Tau: 0.8 mm pol = dust self-scattering → 3mm pol = radiative alignment ?

Stephens+ 2017, Kataoka+ 2017

The dust polarization at <100 au can be a delicate mixture …



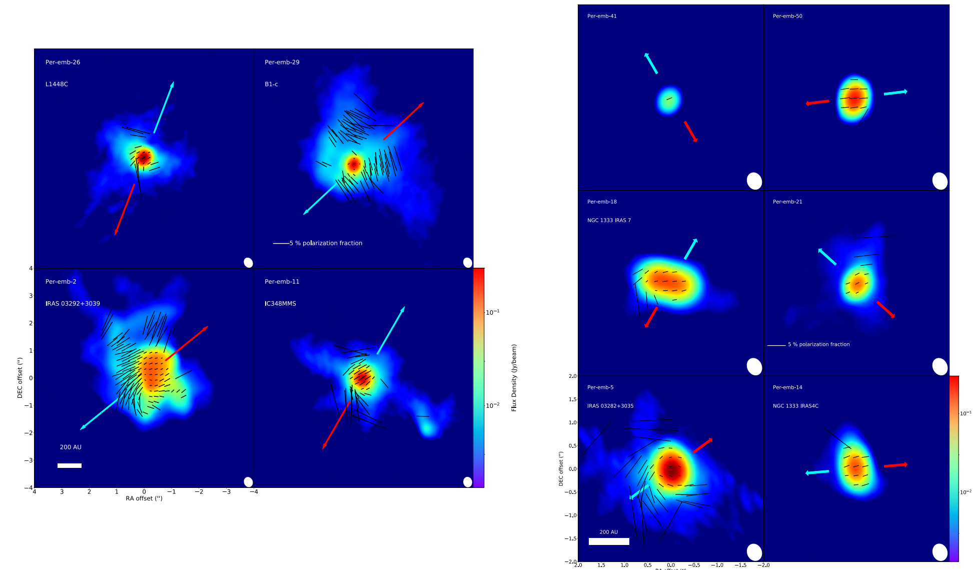
IRAS16293-B: optically thick dust emission

Polarization @ 1.3mm vs 6.9mm (Liu+ 2018)

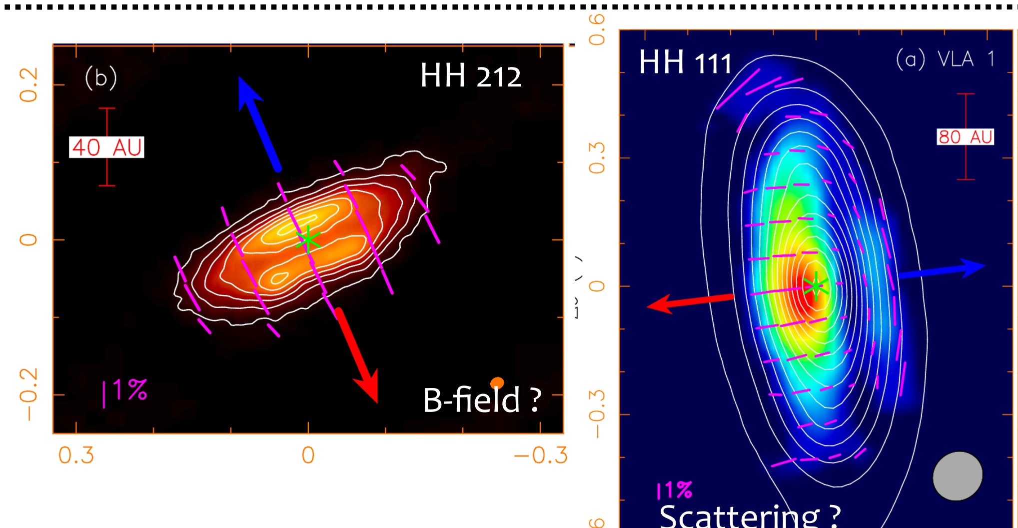
Reminiscent of dust self-scattering in a face-on disk

(Rao+ 2014, Sadavoy+ 2018)

Cox+ (2018): ALMA 0.8mm polarized emission in 10 Class 0 protostars



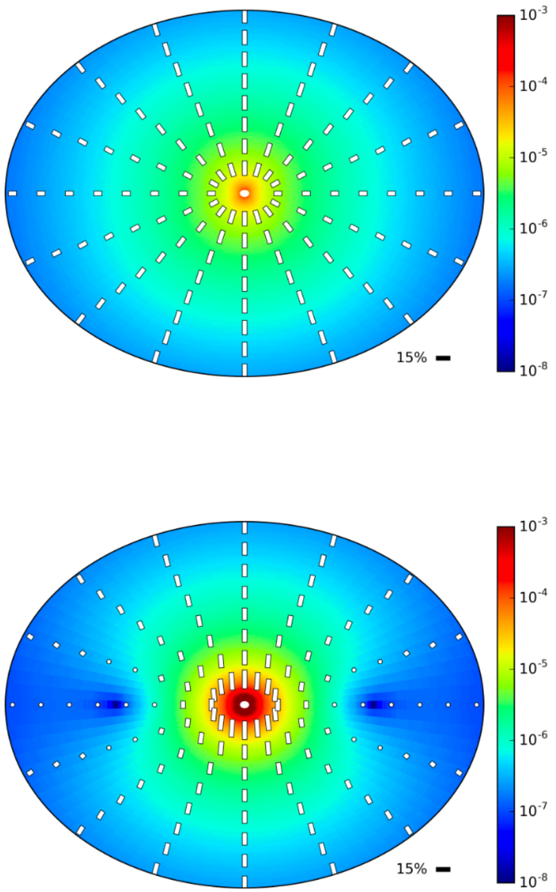
Some evidence of polarization due to dust scattering at small scales ?
See also Harris+ (2018) in VLA1623 and L1527

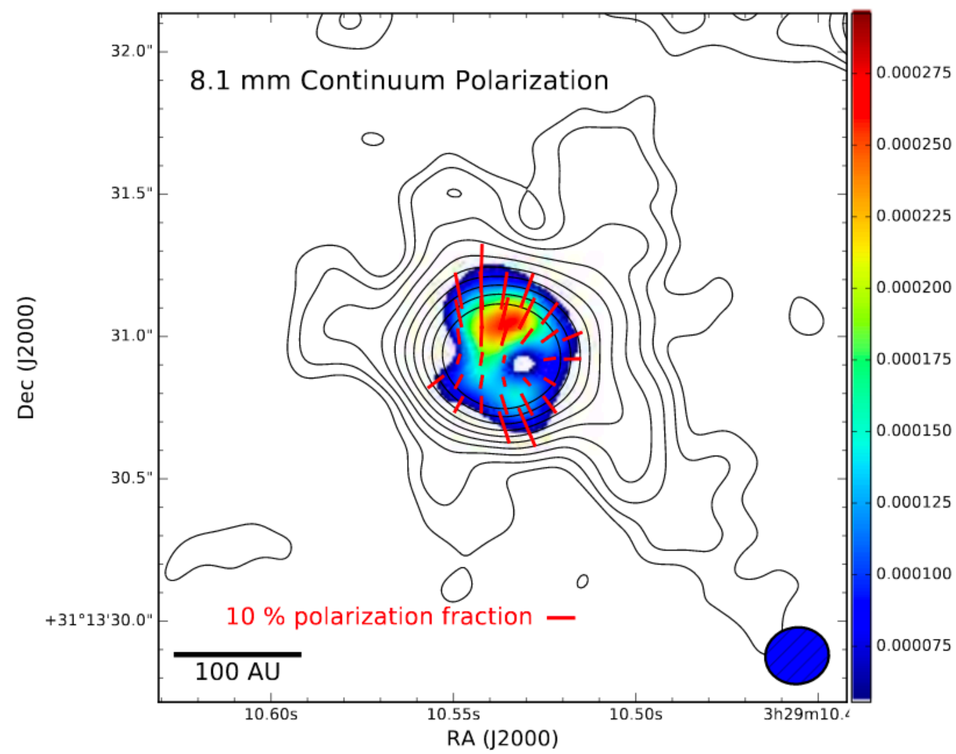


Lee+ 2018

The dust polarization at <100 au can be a delicate mixture …

IRAS 4A seen with VLA





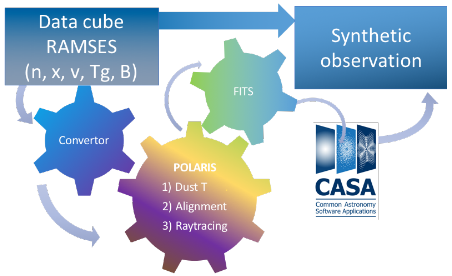
Polarizations from the two competing mechanisms tend to cancel each other on the major axis, producing two low polarization "holes" (under certain conditions).

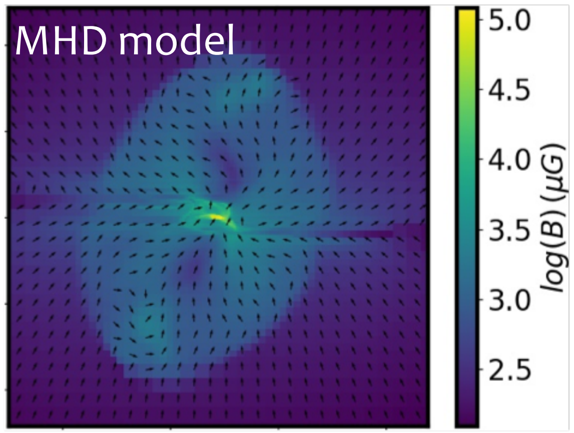
(Yang+ 2016)

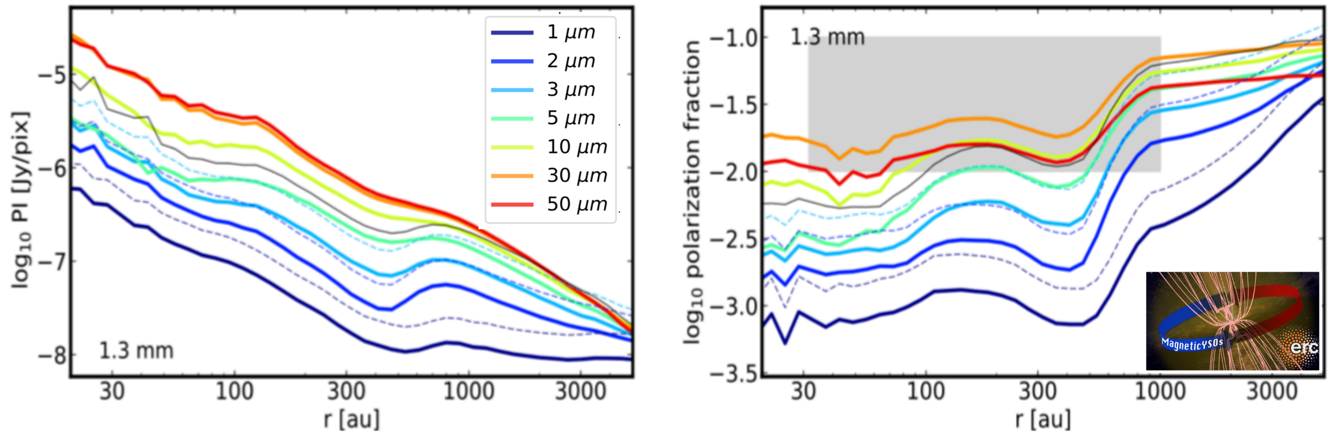
A real need for proper (i) laboratory experiments on (big+non-spherical) dust emissivity and polarization (ii) realistic radiative transfer models and (iii) multi-wavelength observations

Polarized dust

Need for big grains in Class 0 envelopes ?

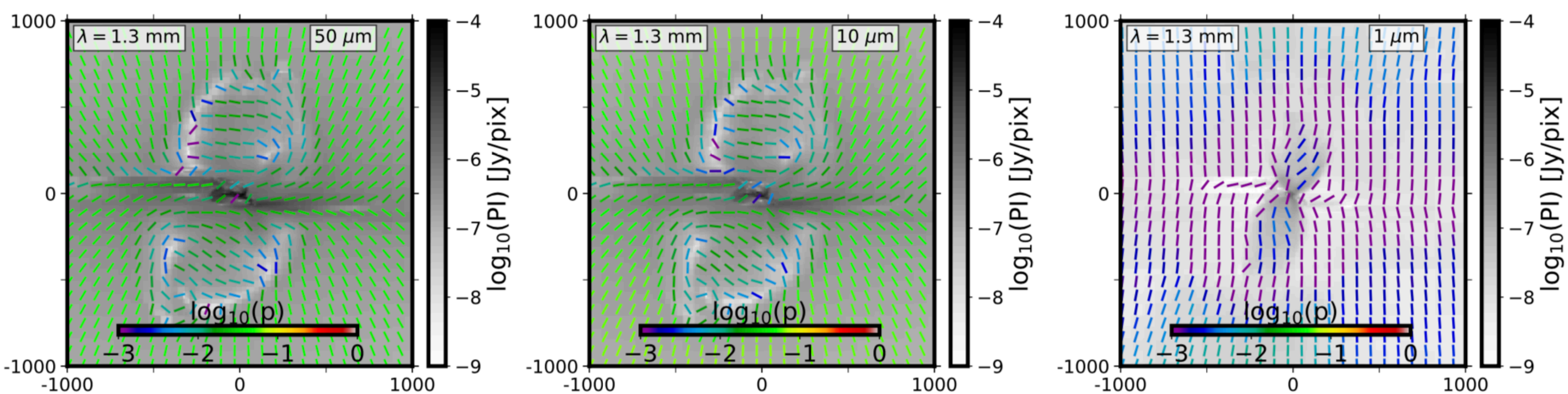






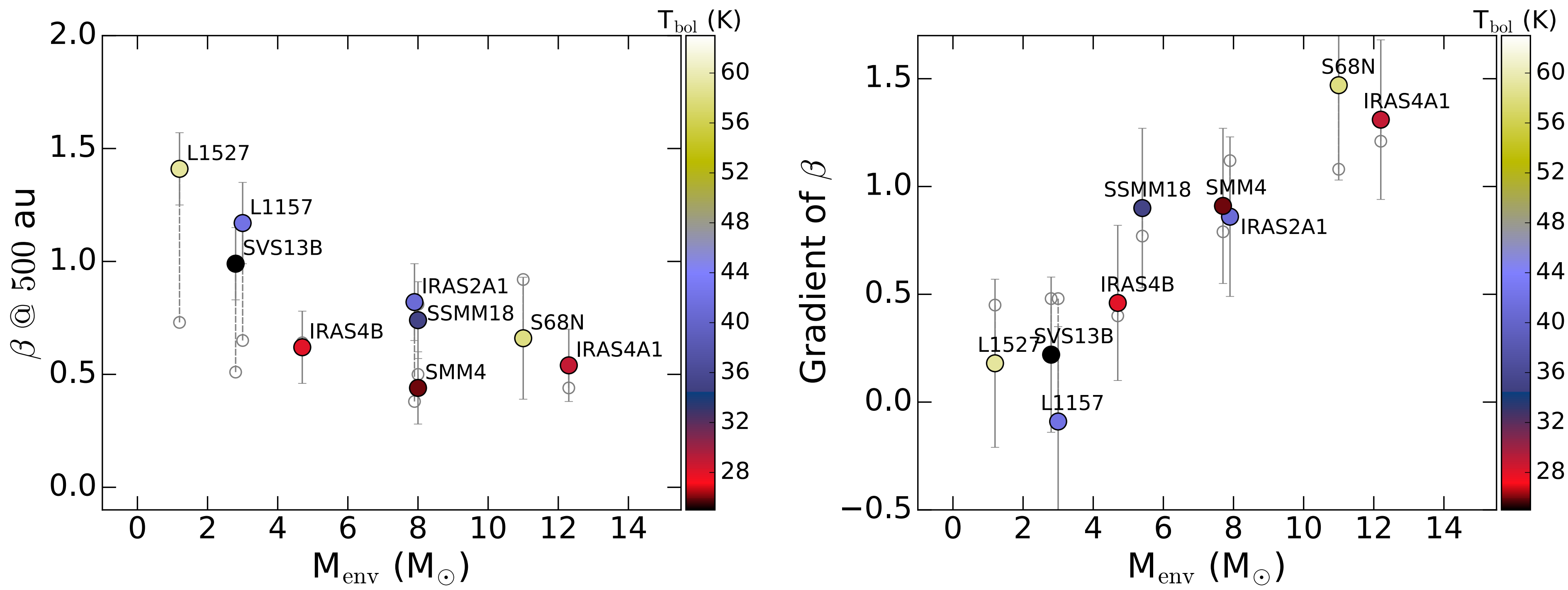
Valdivia, Maury, Brauer + (2019):

Current alignment theories **cannot reproduce the polarization fractions observed** in dense envelopes **without large grains (> 20 microns)**



Need for big grains in Class 0 envelopes ?

Also spectral indices suggesting **grain growth** in Class 0 envelopes



Galametz, Maury+ (sub.) at 500 au scales

Perspectives

MAGNETIZED COLLAPSE scenario seems necessary to reproduce the observed disk properties
(eg CALYPSO results, B335 as prototype)

Pristine disk properties are probably key to later evolution in star/planet system:
Class 0 disks should be better characterized

But grain properties largely unexplored in embedded protostars & disks

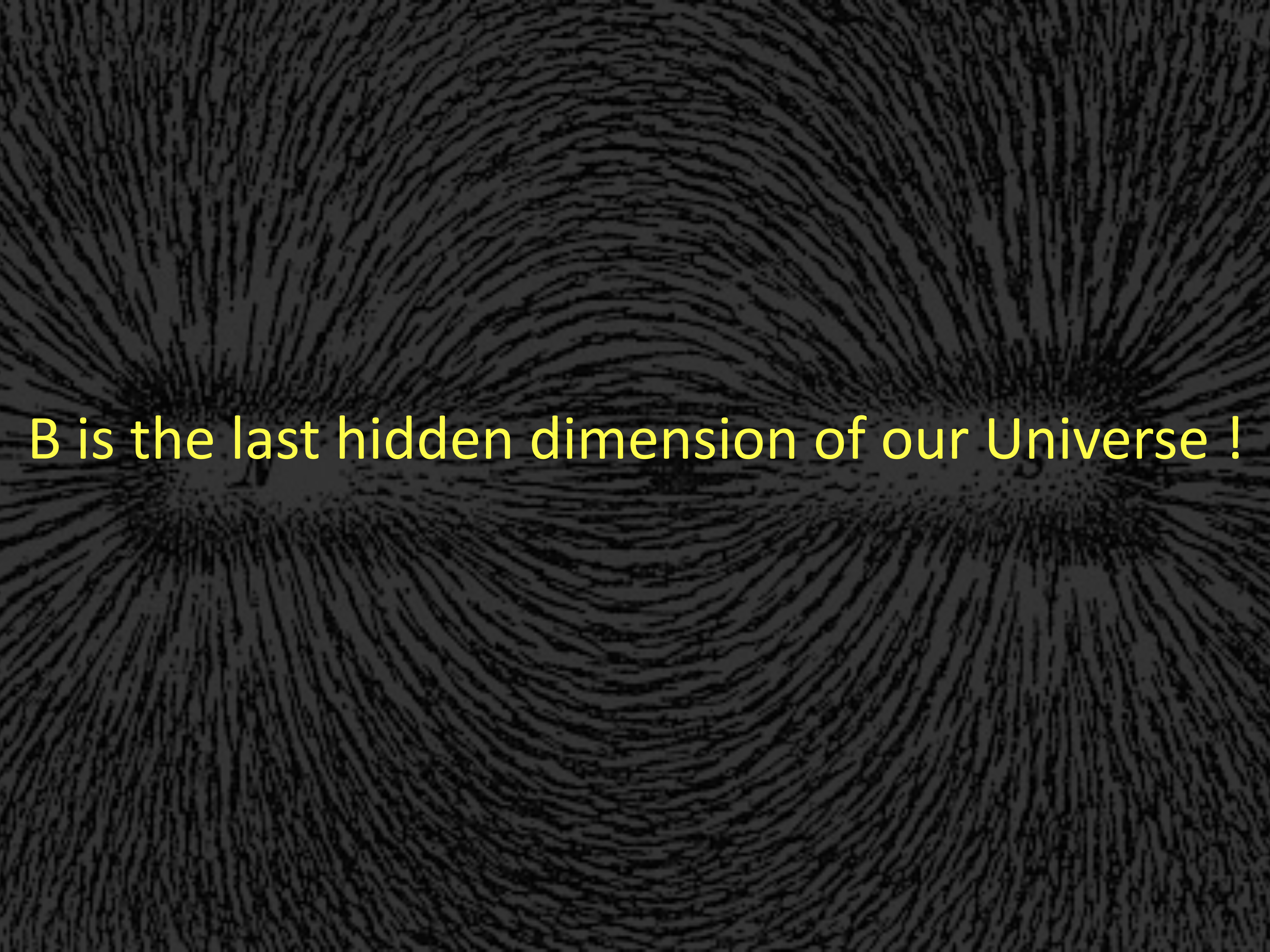
CRUCIAL to understand
the formation of planetesimals
the back-reaction of dust on gas (kinematics, heating, chemistry)
the properties of dust polarization used to trace B

Comparison observations/simulations will become crucial as we reach more details (and complexity) in observations

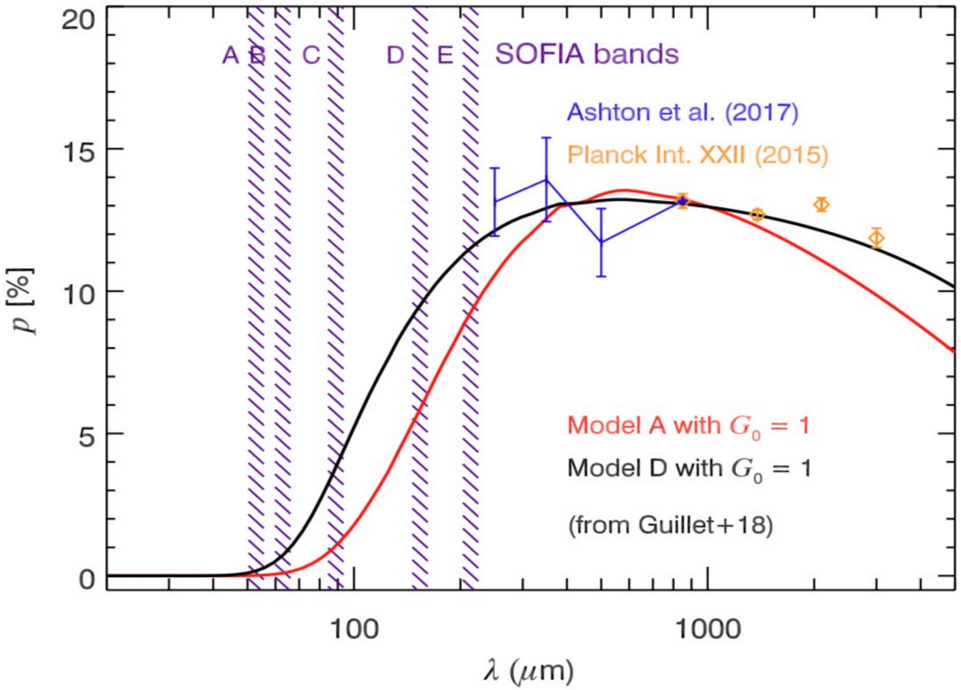
Observations:
Do dust continuum polarization, and polarization from molecular lines trace similar magnetic topologies ? (tomography ?)
Do submm observations go deep enough in dense environments (opacity) ?

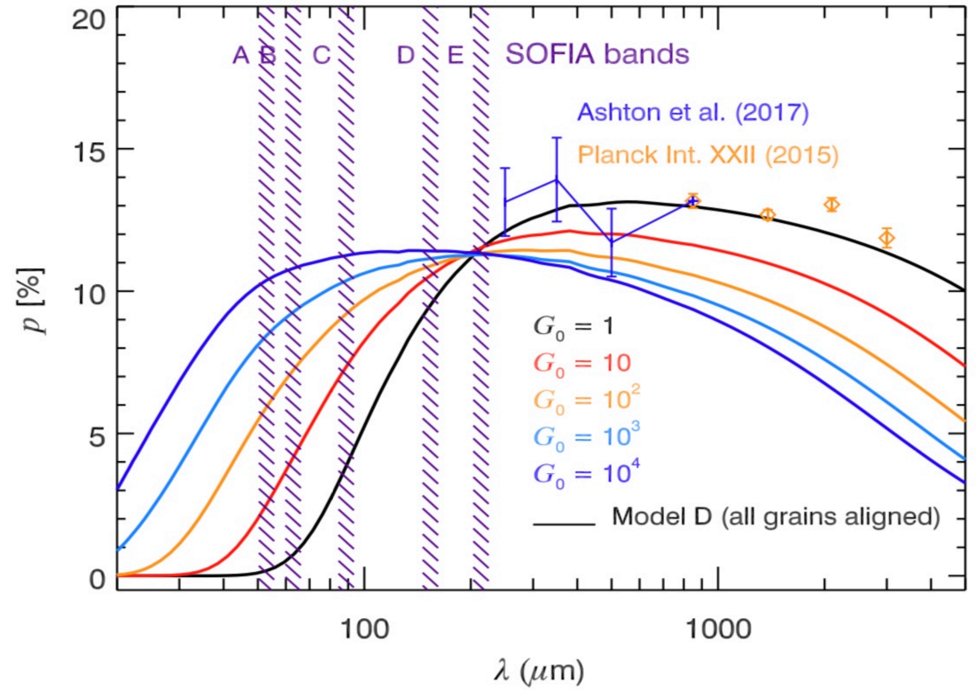
Laboratory works:
Large/elongated dust grains: emissivity, size, evolution ?
Size segregation / growth: how to maintain elongation with grains >1mu, does that affect polarization ?

Models:
How to realistically compute conditions for alignment in MHD simulations ?
How to treat dust correctly ?


B is the last hidden dimension of our Universe !

The Wien regime, an invaluable constraint on dust models





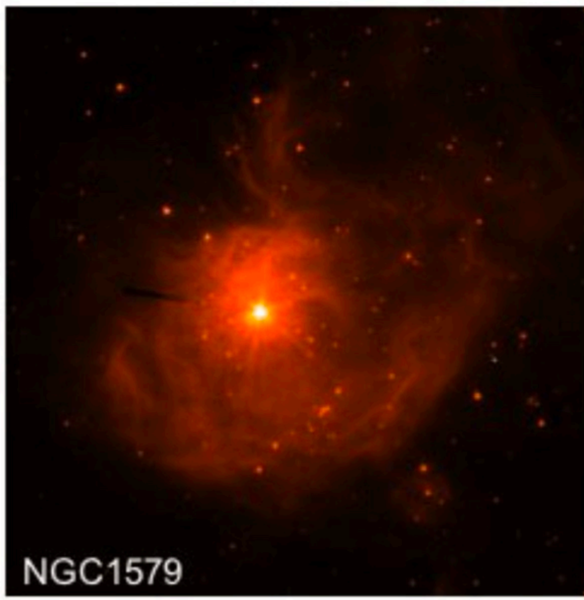
Model A includes silicates grains that are aligned and carbon grains that are not.

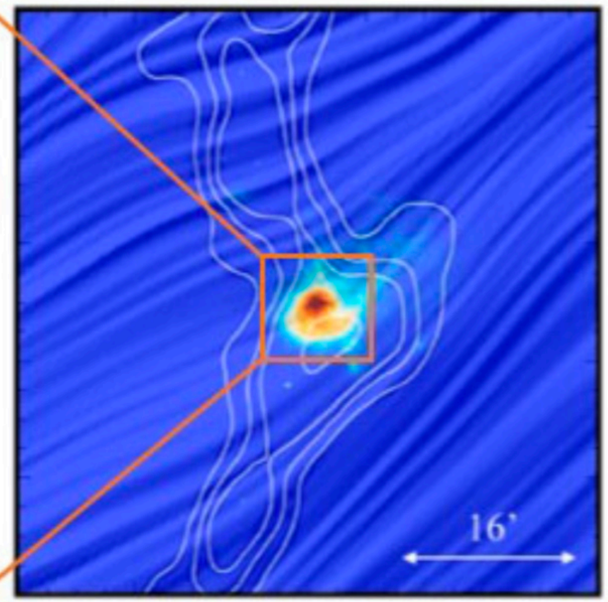
Both are aligned in model D, with carbon inclusions (6% in volume) in the silicate matrix.

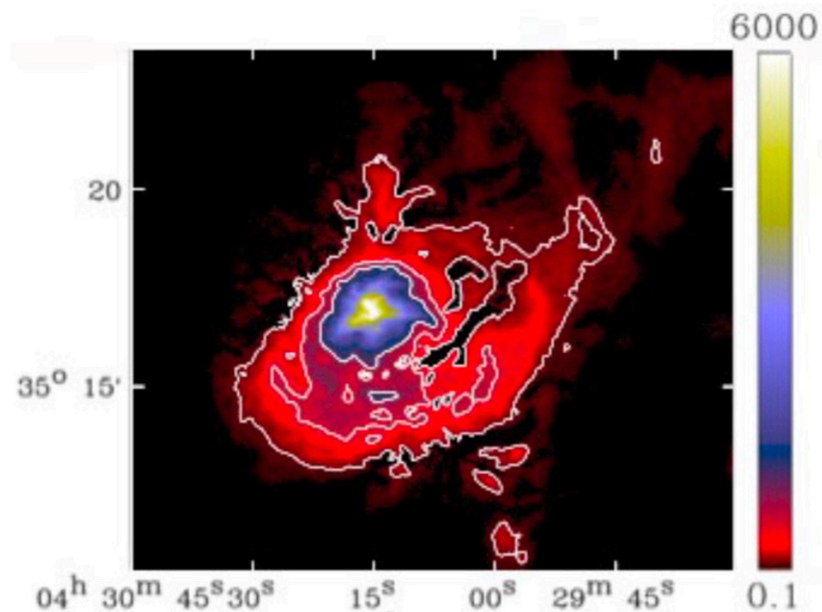
Right: Model D exposed to a range of radiation field, G_0, from diffuse ISM to highly-irradiated regions

The Wien regime, an invaluable constraint on dust models

Pilot project with HAWC+ by M. Galametz, V. Guillet, A. Maury







NGC1579 :

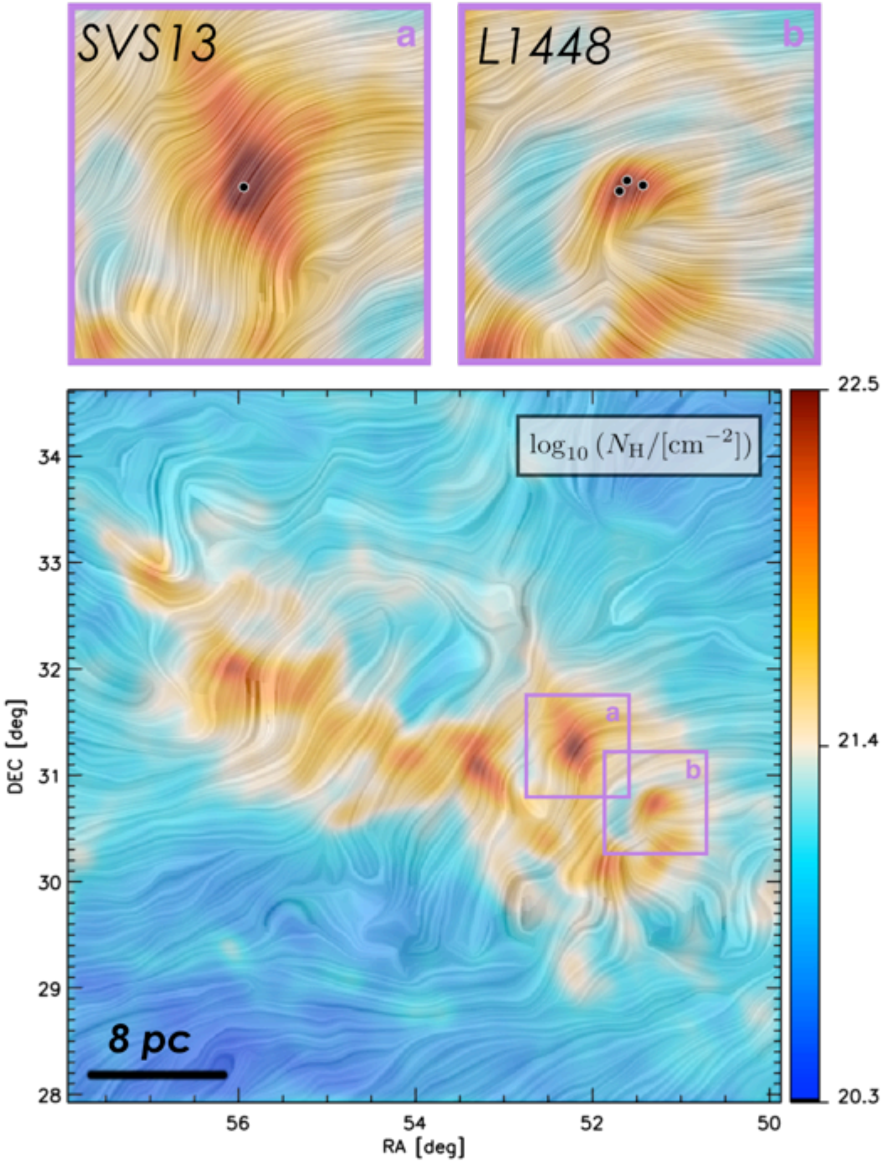
Spitzer map at 3.6 μm

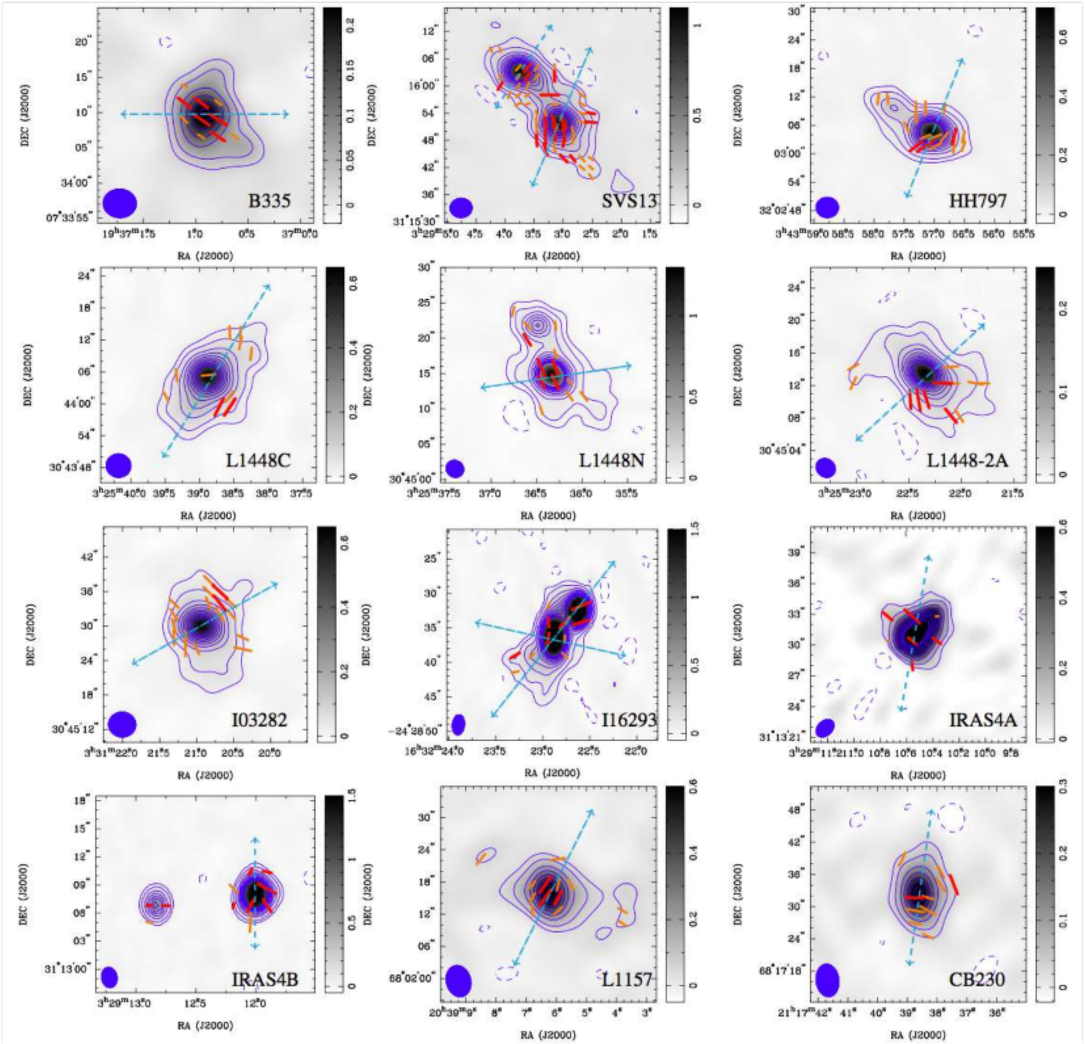
Column density contours (4, 5, 6, 10 × 10^{21} cm^{-2}) on Herschel 70 μm map, B-field lines derived from Planck.

Local irradiation field (G0) maps derived from the 70 and 100 μm Herschel maps (Shimajiri et al. 2017). Contours are G0=100, 500, 1000 Habings.

Millimetron can probe dust properties and dust alignment mechanisms in widely varying conditions !

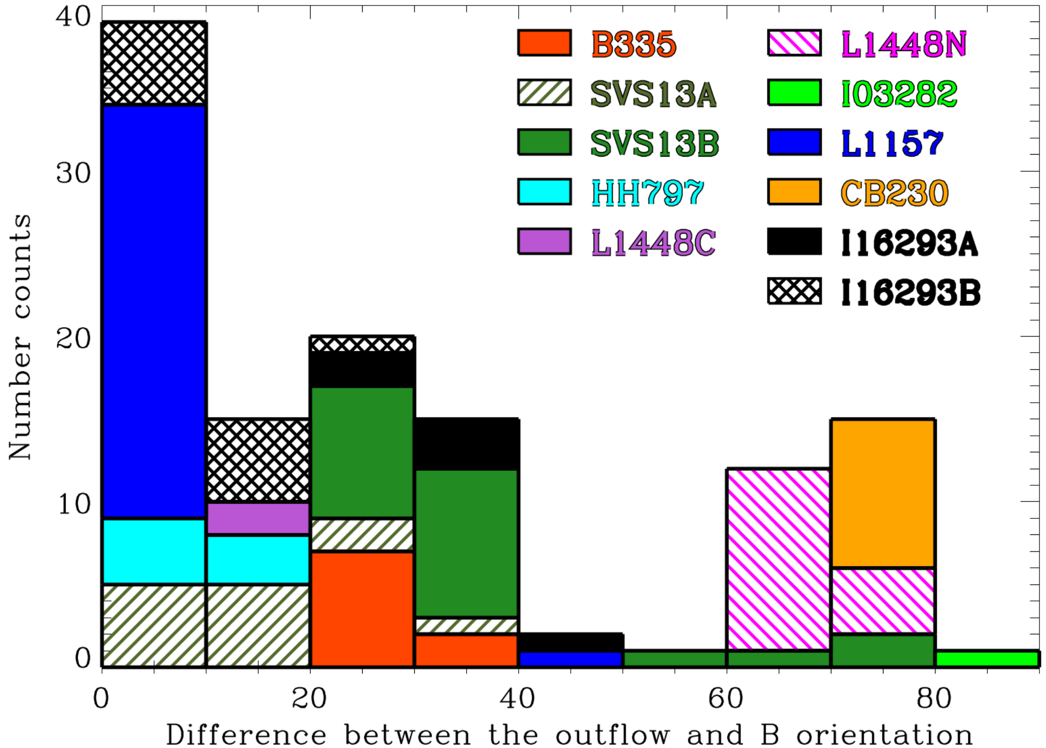
Is the magnetic field shaping the pristine protoplanetary disk properties ?

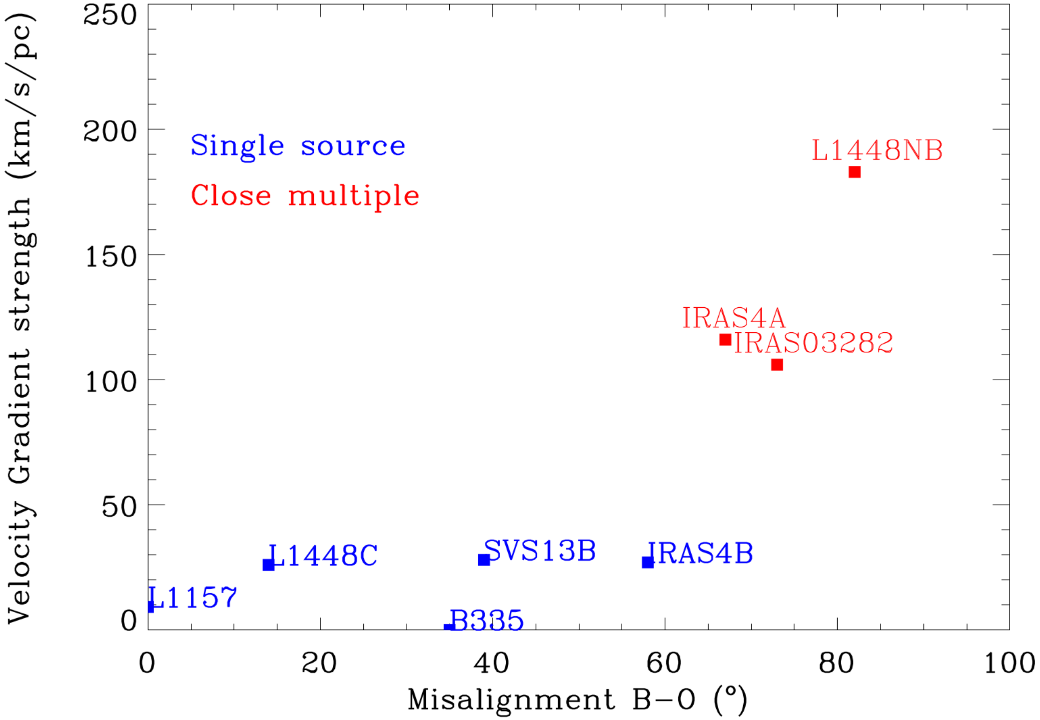




Is the magnetic field shaping the pristine protoplanetary disk properties ?

Galametz, Maury, Girart+ (2018)



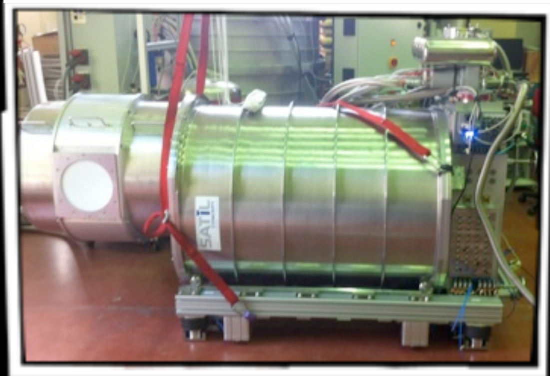


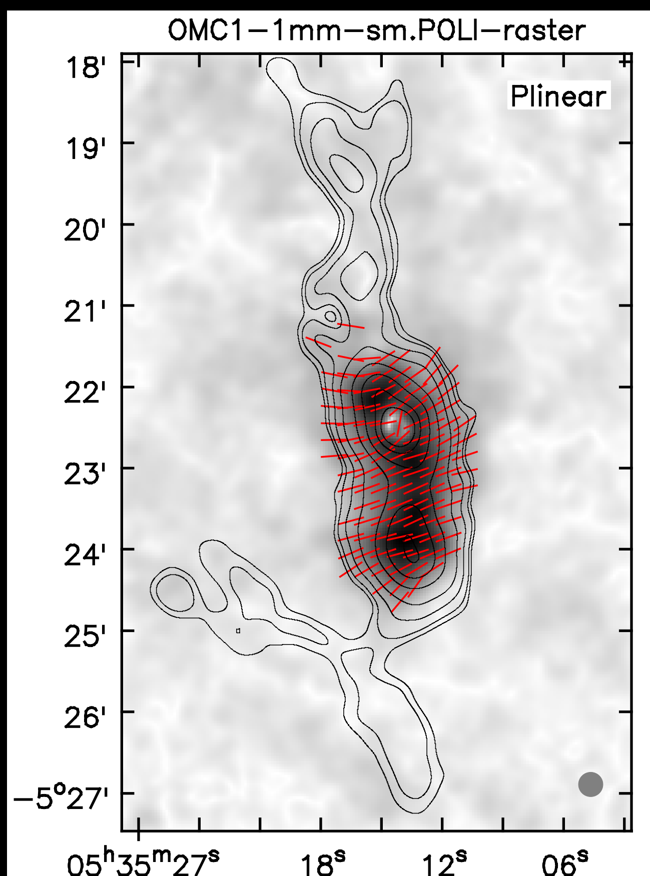
Envelope-scale B-field misalignment is found preferentially

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

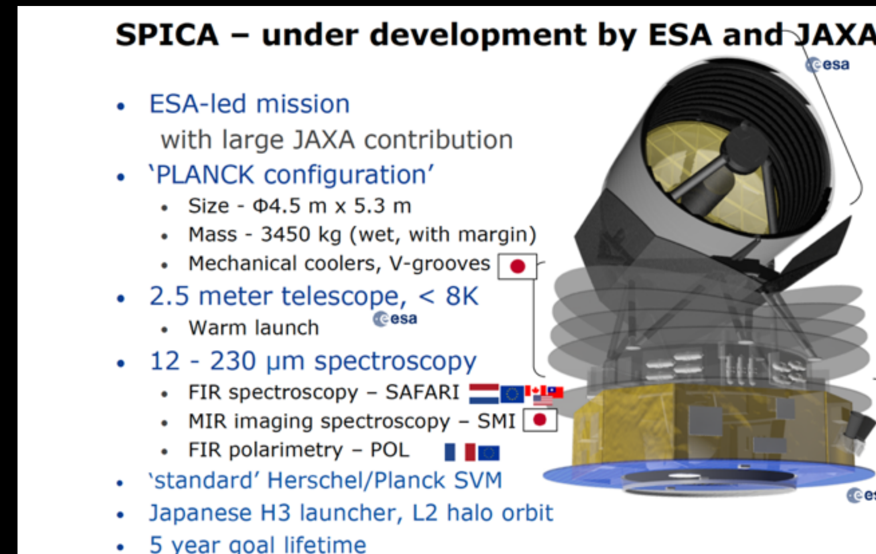
Millimetron can test magnetized star formation scenarii in large samples of protostars at the relevant scales !

NIKA2 POL

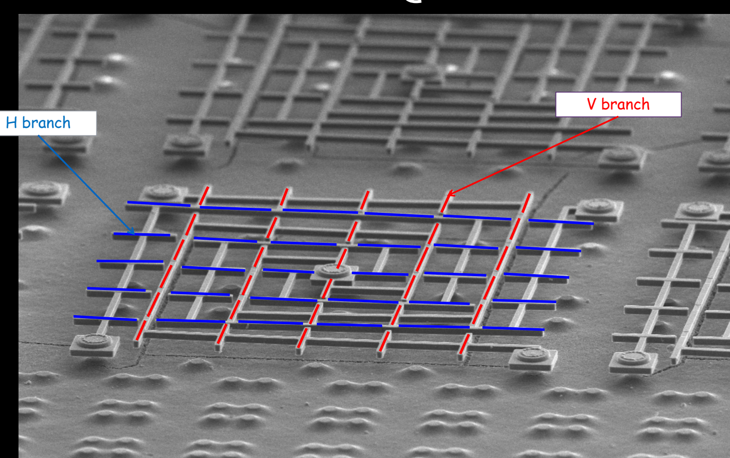




Orion with the NIKA prototype:
Ritacco+NIKA collaboration (2016)



SPICA B-BOP: 10'' @ 100microns



wide-field 100–350 μm images of linearly polarized dust emission

Resolution, signal-to-noise ratio, spatial dynamic ranges

comparable to *Herschel* images of the cold ISM in unpolarized emission