B-BOP: The SPICA far-IR imaging polarimeter

Ph. André   CEA - Lab. AIM Paris-Saclay

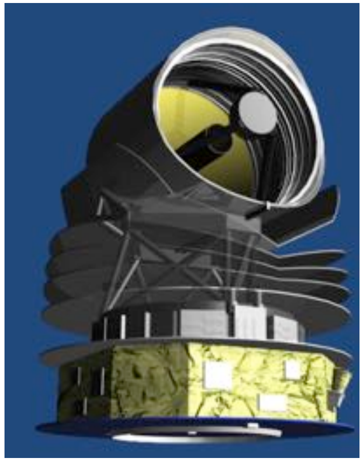
On behalf of the B-BOP Consortium
and the co-authors of the SPICA-B-BOP White Paper

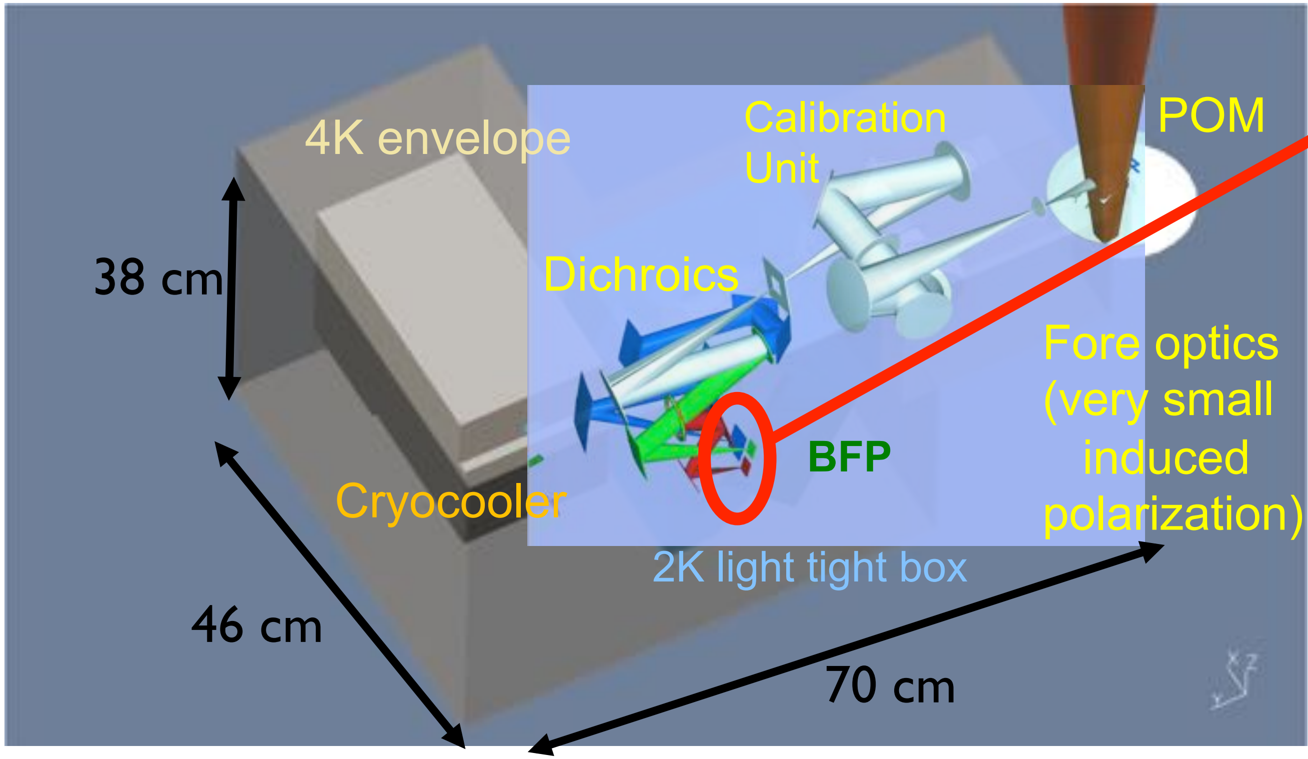
B-BOP Instrument Team: M. Sauvage (PI), M. Berthé (PM),
L. Rodriguez, J. Martignac, V. Revéret, A. Poglitsch….

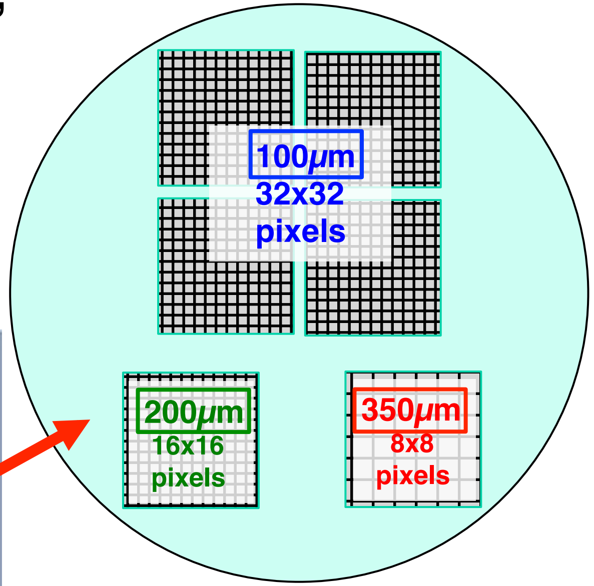
White Paper: A. Hughes, V. Guillet, F. Boulanger, A. Bracco,
E. Ntormousi, D. Arzoumanian, A. Maury, J.-Ph. Bernard, S. Bontemps,
J.M. Girart, F. Motte, K. Tassis, E. Pantin, T. Montmerle, A. Tritsis,
D. Johnstone, A. Fletcher, S. Gabici, A. Efstathiou, N. Peretto, L. Spinoglio,
F. van der Tak, D. Ward-Thompson …

B-BOP: An imaging polarimeter for SPICA

B-BOP = "B-fields with BOlometers and Polarizers"





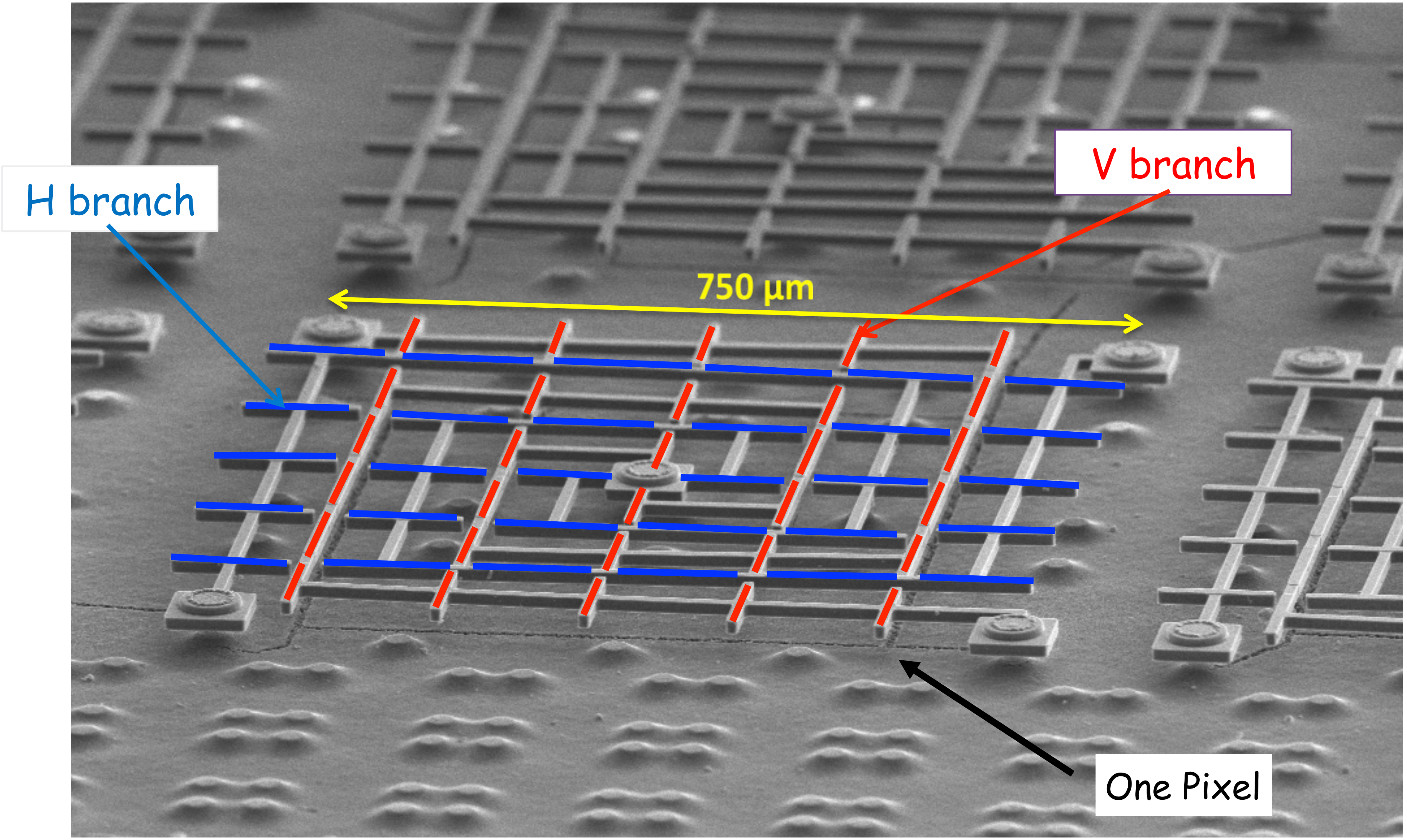


B-BOP Focal Plane

Three bands observing the same FOV (2.6' × 2.6') on the sky <u>simultaneously</u>

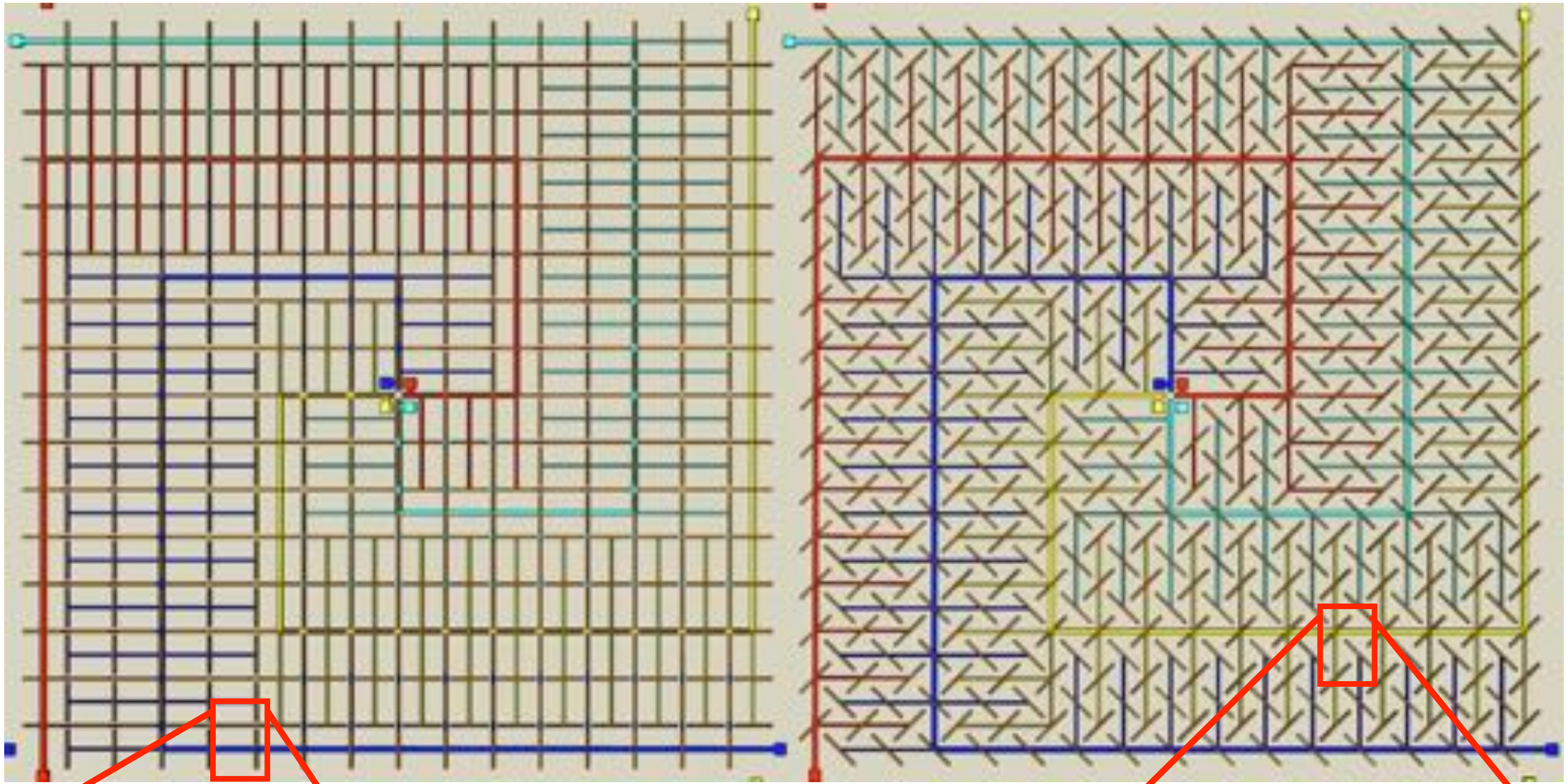
18" resolution @ 200 μm

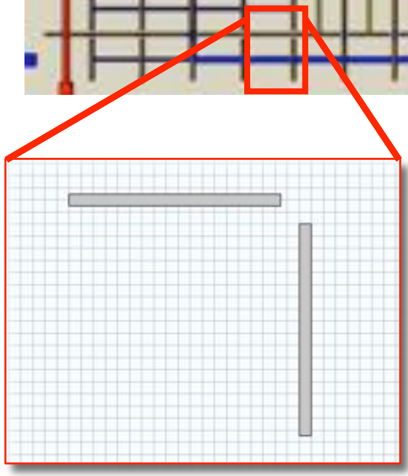
Polarization-sensitive bolometers at the heart of the B-BOP instrument



- Two orthogonal (V & H) branches of dipoles
- Double spiral architecture to retrieve V & H (Tot. flux + diff. V/H)

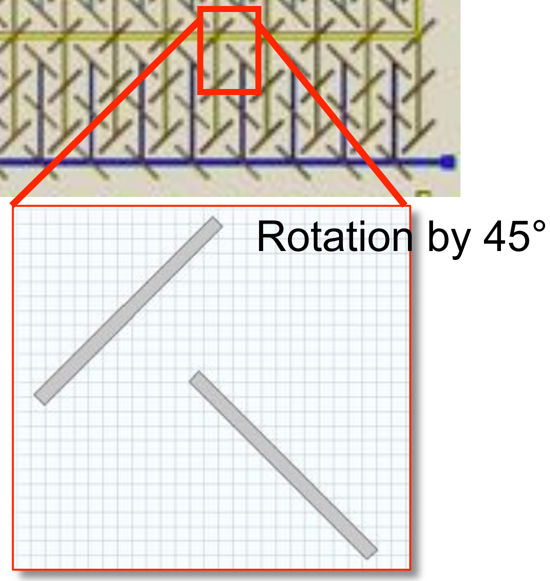
The “Stokes” pixels of B-BOP





- Pixels are alternatively « 0° » and « 45° »
- **Stokes parameters can be obtained “in a single shot”**
- No need for a HWP?

(L. Rodriguez, S. Bounissou, O. Adami, A. Poglitsch)

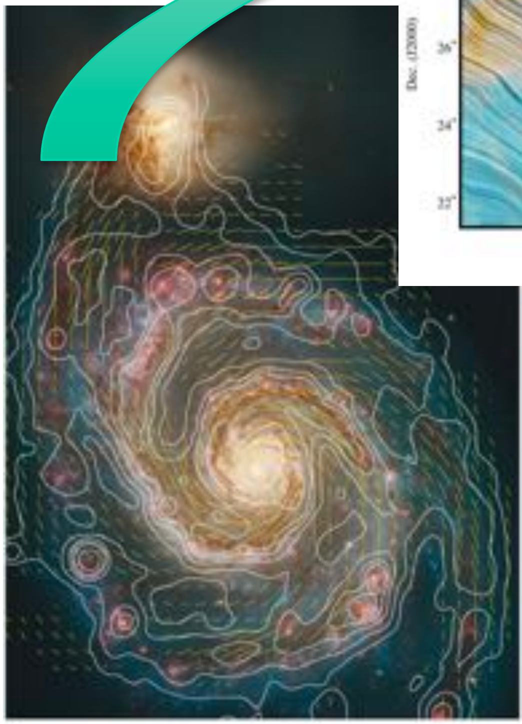


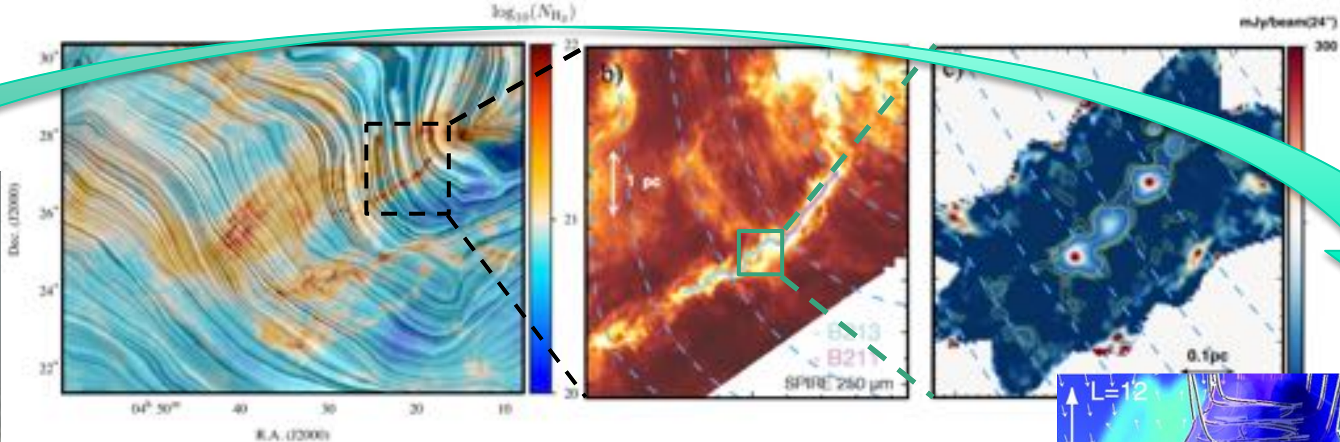
Status of SPICA-POL (B-BOP) White Paper

- **White Paper just submitted to PASA**
- **Main science topics:**
  - **Magnetic fields and star formation in (Galactic) filamentary clouds** (including protostars & high-mass star/cluster formation)
  - **Magnetic fields in nearby galaxies** (**A. Hughes, J.Ph. Bernard**)
  - **Dust physics** (**V. Guillet, I. Ristorcelli**)
- **Additional science topics:**
  - Magnetized interstellar turbulence (F. Boulanger, E. Falgarone)
  - Interaction of cosmic rays with molecular clouds (T. Montmerle)
  - Polarized emission from protoplanetary disks (E. Pantin)
  - Variability of protostars in the far-IR (D. Johnstone)

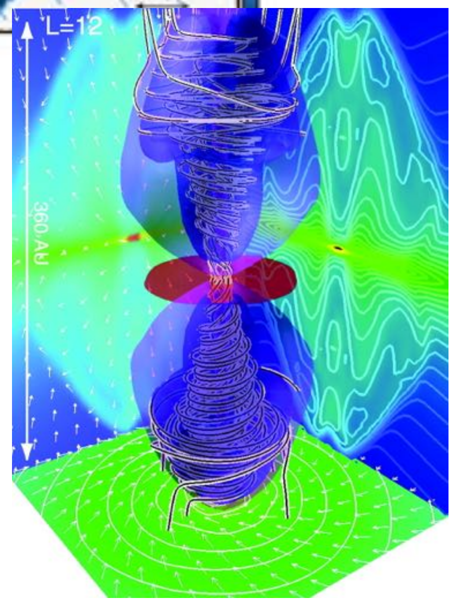
Magnetic fields: A largely unexplored "dimension" of the cold Universe

A key 'dark' ingredient of the star formation process from galactic scales to protoplanetary disks





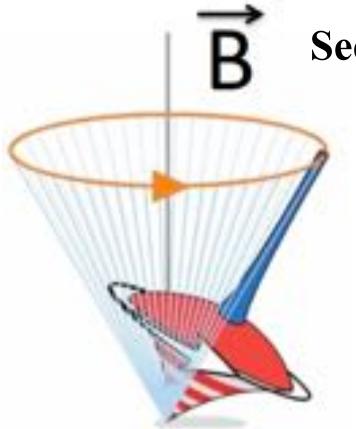
- On large scales (GMCs > 10-100 pc), regulate the formation of molecular clouds and filaments (Mouschovias & Ciolek 1991, McKee & Ostriker 2007…)
- On small scales (proto* cores < 0.1 pc), key role to generate protostellar outflows and control disk formation
- Very poorly constrained observationally (eg. Crutcher 2012 ARA&A)



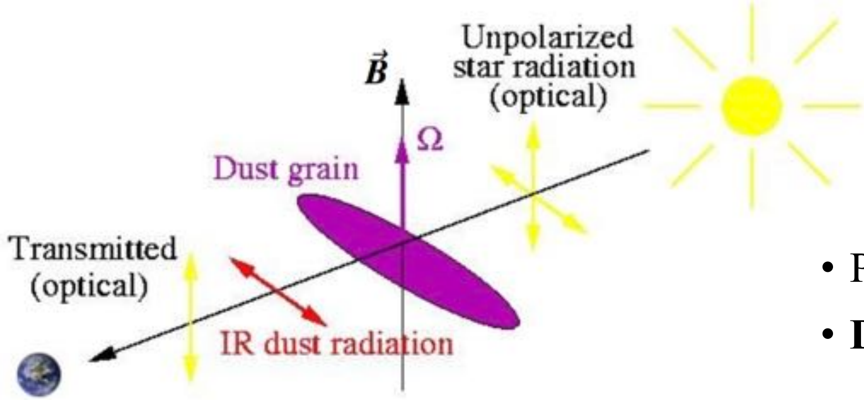
Machida+2008

Polarized dust emission: A unique tool to trace B fields

- **Non-spherical dust grains spin like tops about their axis of maximal inertia (= minor axis)**
- **Grains precess around B-field lines and tend to align their minor axis with $\vec{B}$**



See V. Guillet for the physics of grain alignment



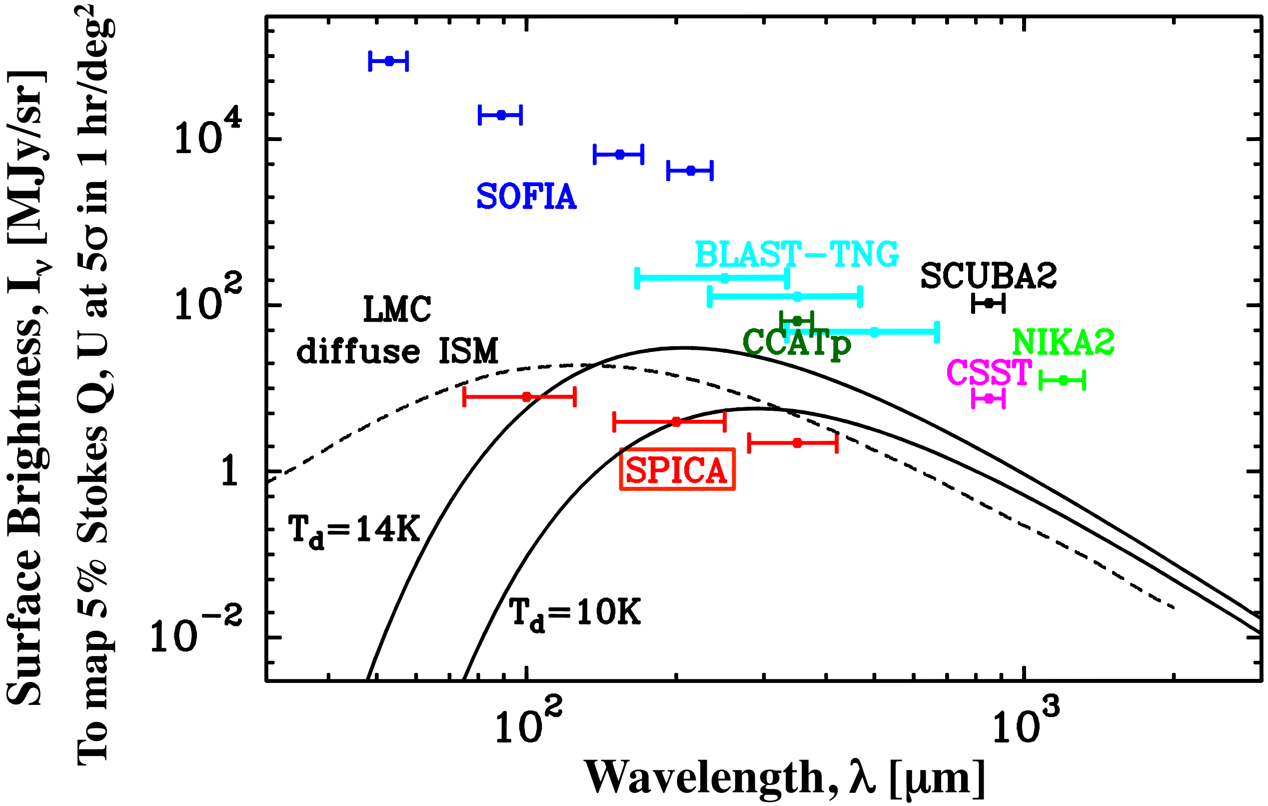
- Polarized starlight (extinction) // B_{POS}
- **Dust emission polarized ⊥ B_{POS}**

Figure Credit: *Ponthieu & Lagache (2004)*

➢ **Interstellar dust grains behave like a compass and can be used to trace the plane-of-sky component of the B field (B_{POS})**

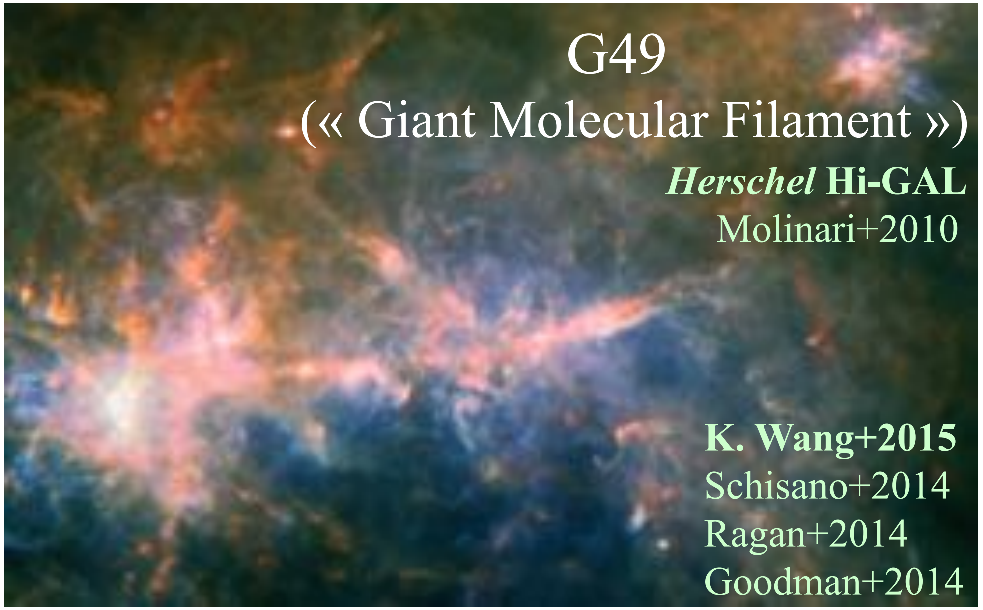
SPICA: A future revolution in FIR polarimetric imaging

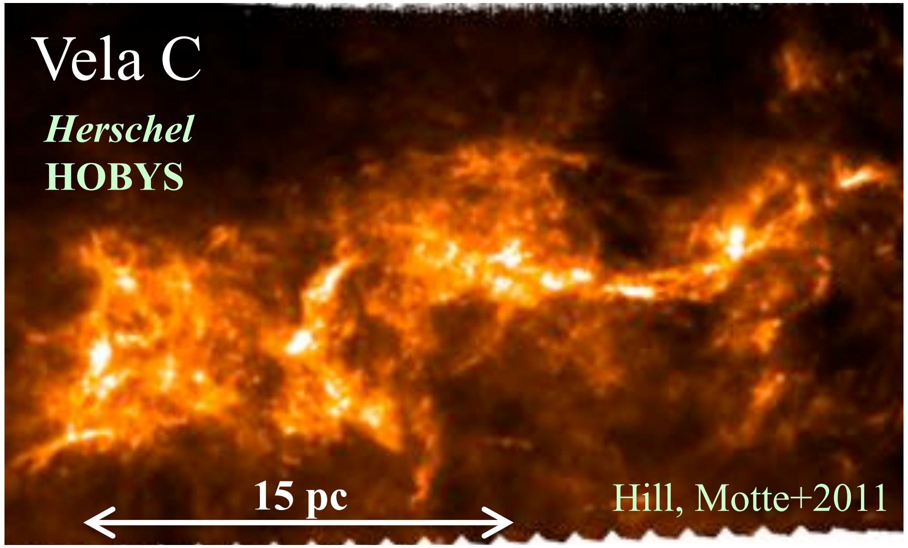
- Thanks to a cooled telescope, SPICA-POL = B-BOP will be 2-3 orders of magnitude more sensitive (4-6 orders of magnitude faster) than other far-IR/submm imaging polarimeters

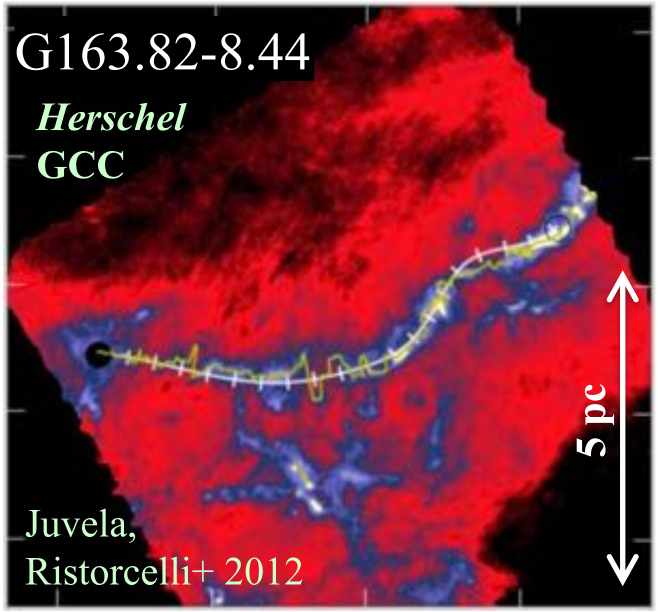


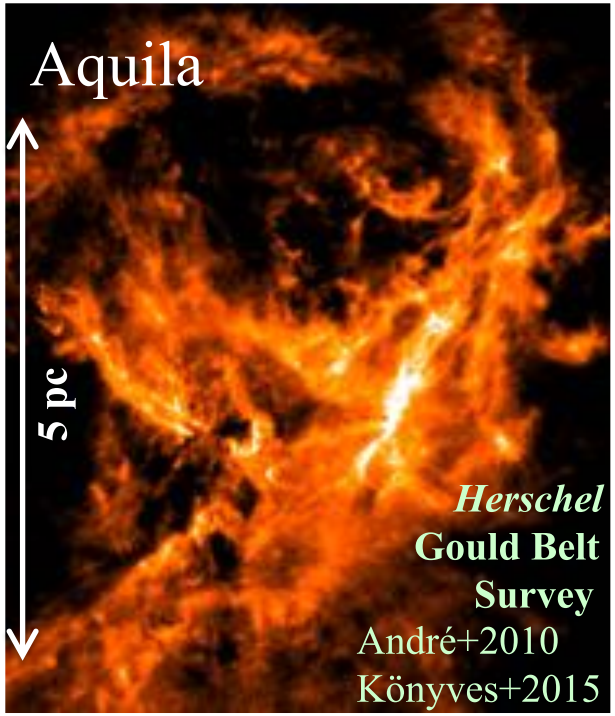
- B-BOP will deliver wide-field 100-350 μm images of polarized emission (Stokes Q, U) with a resolution, S/N ratio, and intensity/spatial dynamic ranges comparable to *Herschel* images in total intensity (I).

Herschel has revealed the presence of a ‘universal’ filamentary structure in the cold ISM



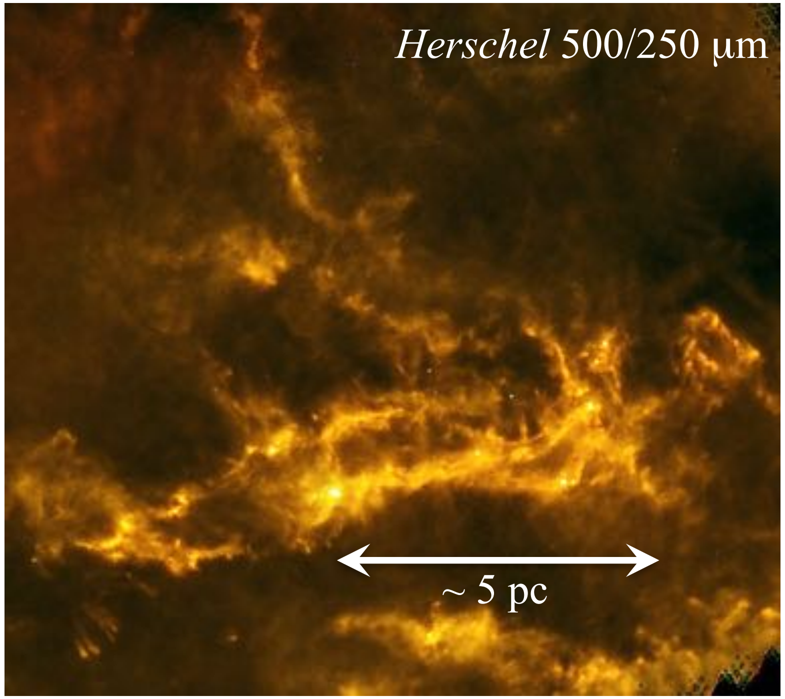




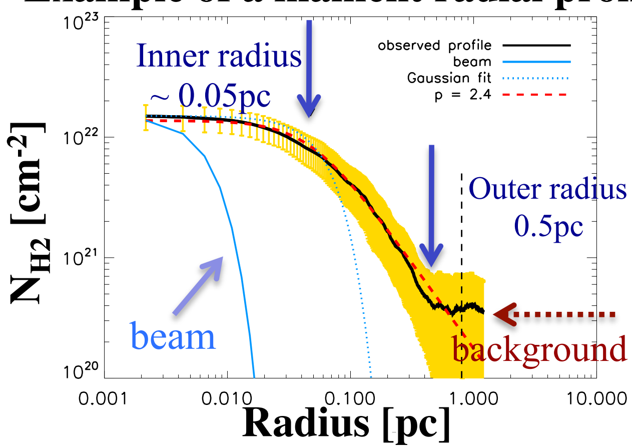


Nearby filaments have a common inner width ~ 0.1 pc

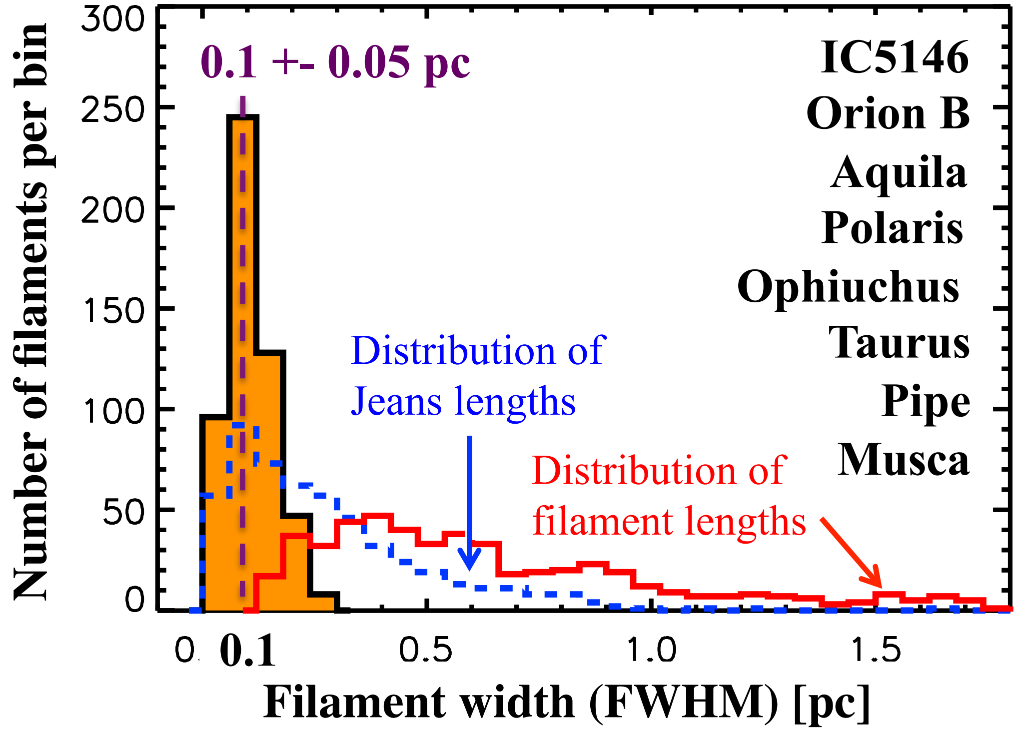
Network of filaments in IC5146



Example of a filament radial profile



Distribution of mean inner widths for ~ 600 nearby (d < 450pc) filaments



D. Arzoumanian+2011 & 2018 (astro-ph/1810.00721)

[see also Koch & Rosolowsky 2015]

Possibly linked to magneto-sonic scale of turbulence?

(cf. Padoan+2001; Federrath 2016)

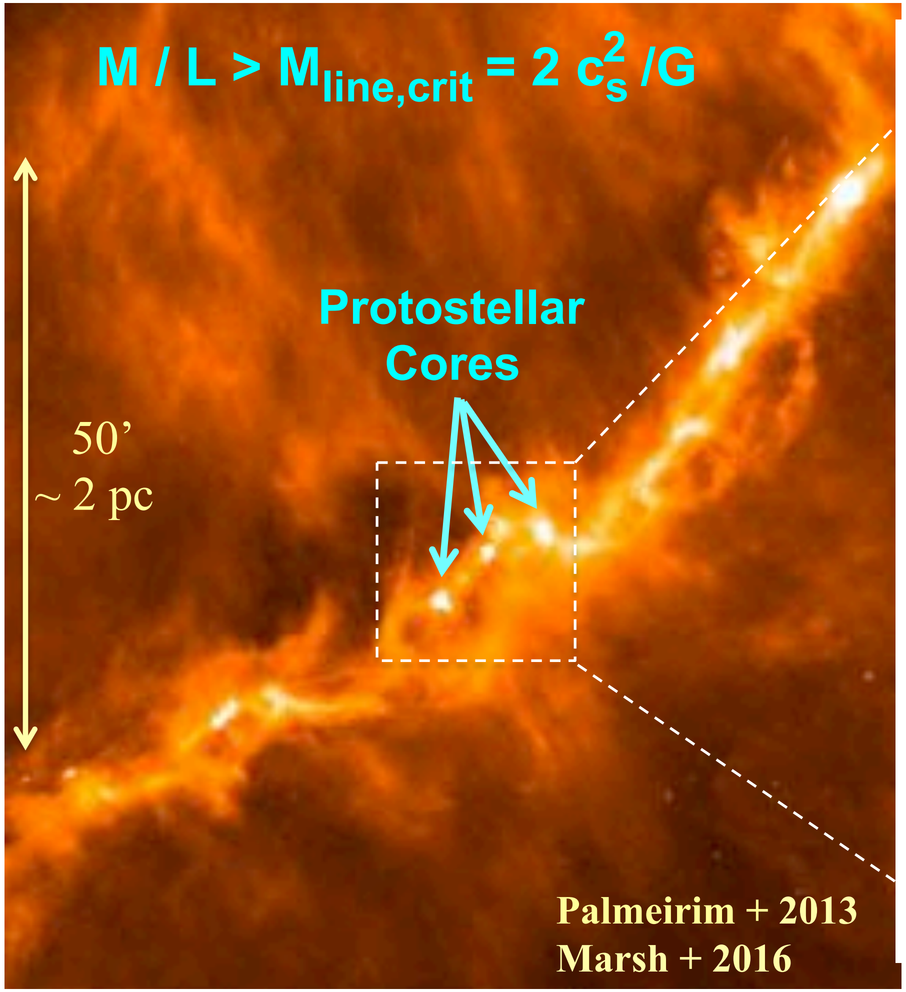
Challenging for numerical simulations

(cf. R. Smith+2014; Ntormousi+2016)

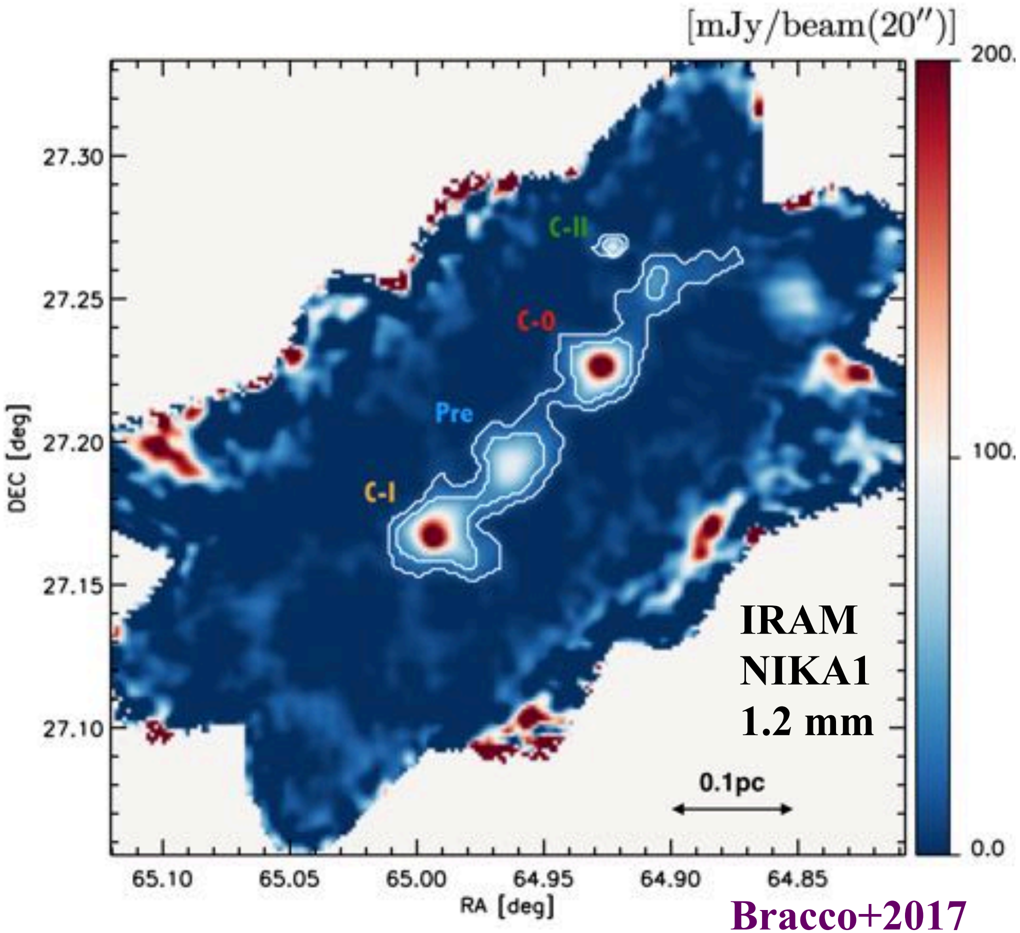
~ 75^{+15}_{-5} % of prestellar cores form in filaments, above a column density threshold $N_{H_2} \gtrsim 7\times10^{21}$ cm^{-2}

<=> $\Sigma > 150\ M_\odot/pc^2$ or $M / L \gtrsim 15\ M_\odot/pc \sim M_{line,\,crit}$

cf. Protostars & Planets VI chapter Könyves+2015, Marsh+2016…



Taurus B211/3 – *Herschel* 250 µm



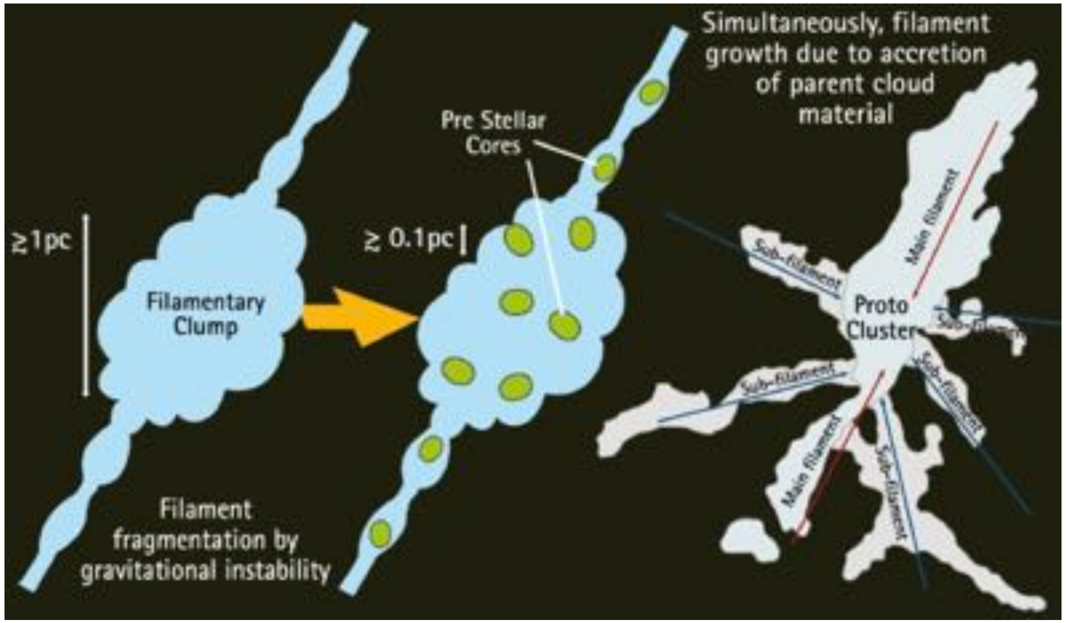
Bracco+2017

A filamentary paradigm for ~ $M_\odot$ star formation

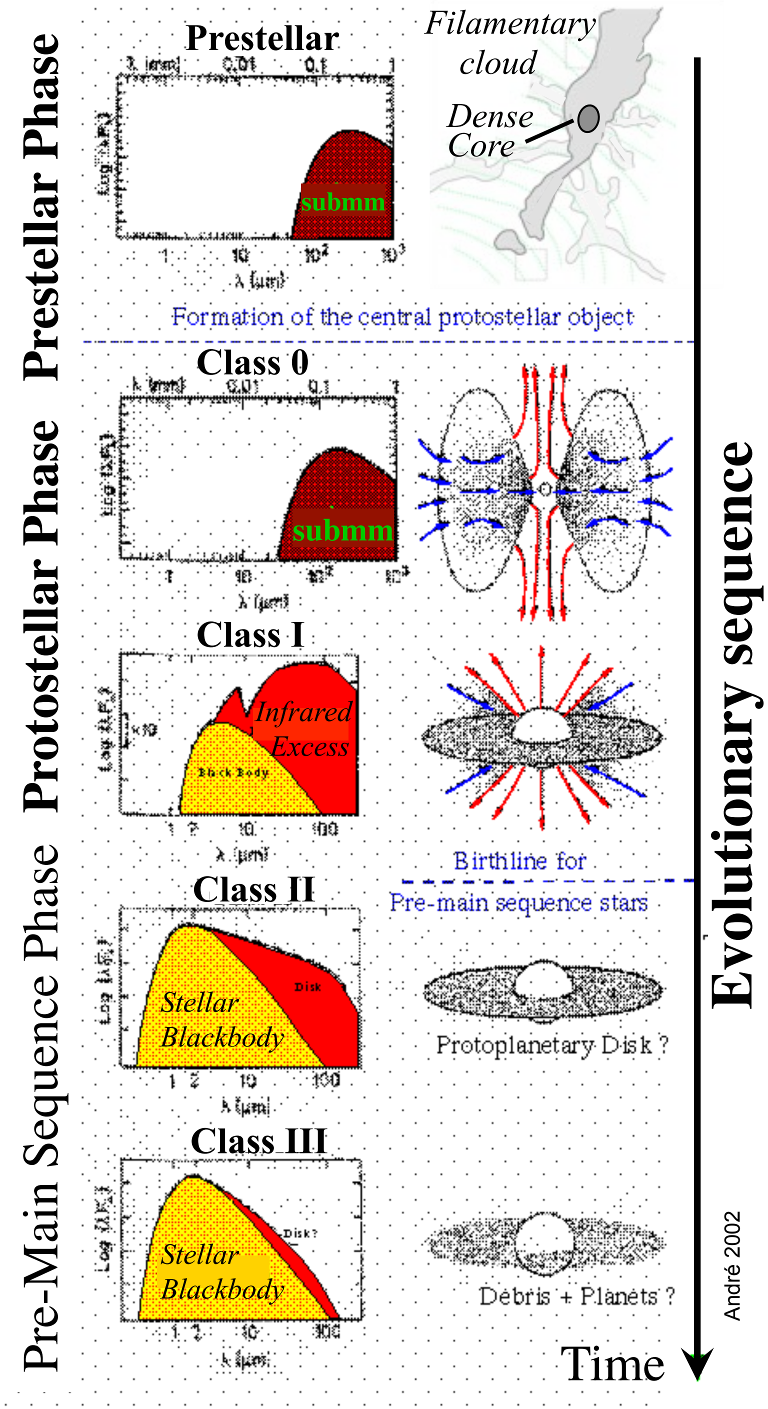
Schneider & Elmegreen 1979; Larson 1985; Inutsuka & Miyama 1997…

cf. Protostars & Planets VI chapter

(André, DiFrancesco, Ward-Thompson, Inutsuka, Pudritz, Pineda 2014)

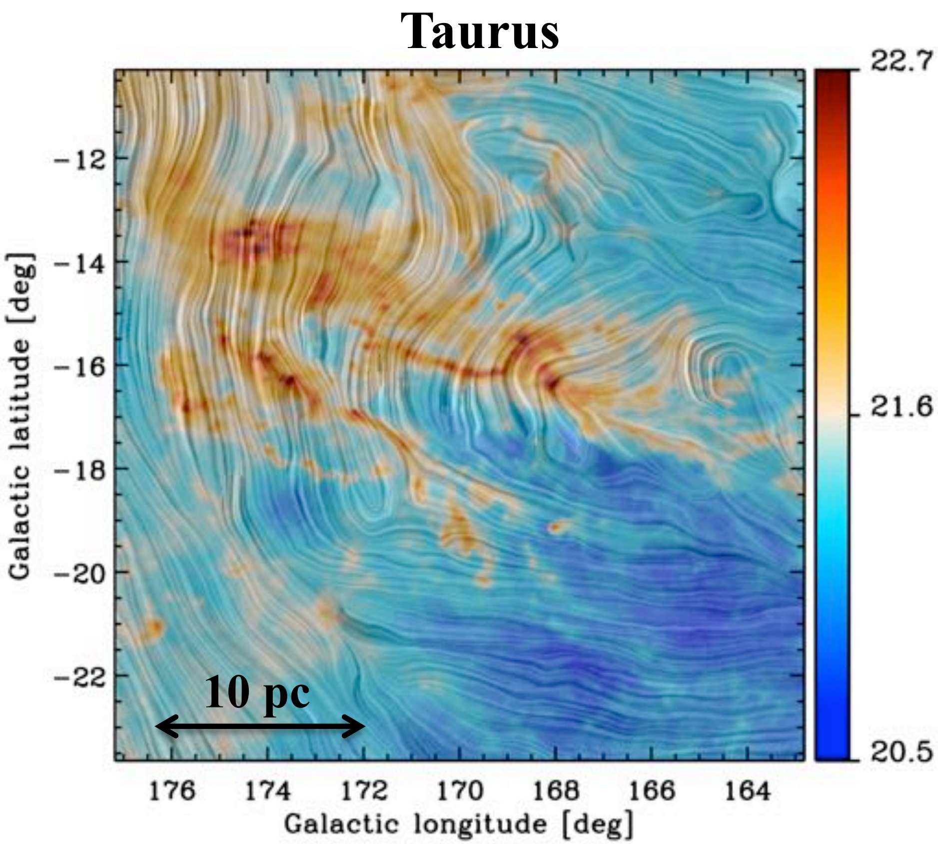


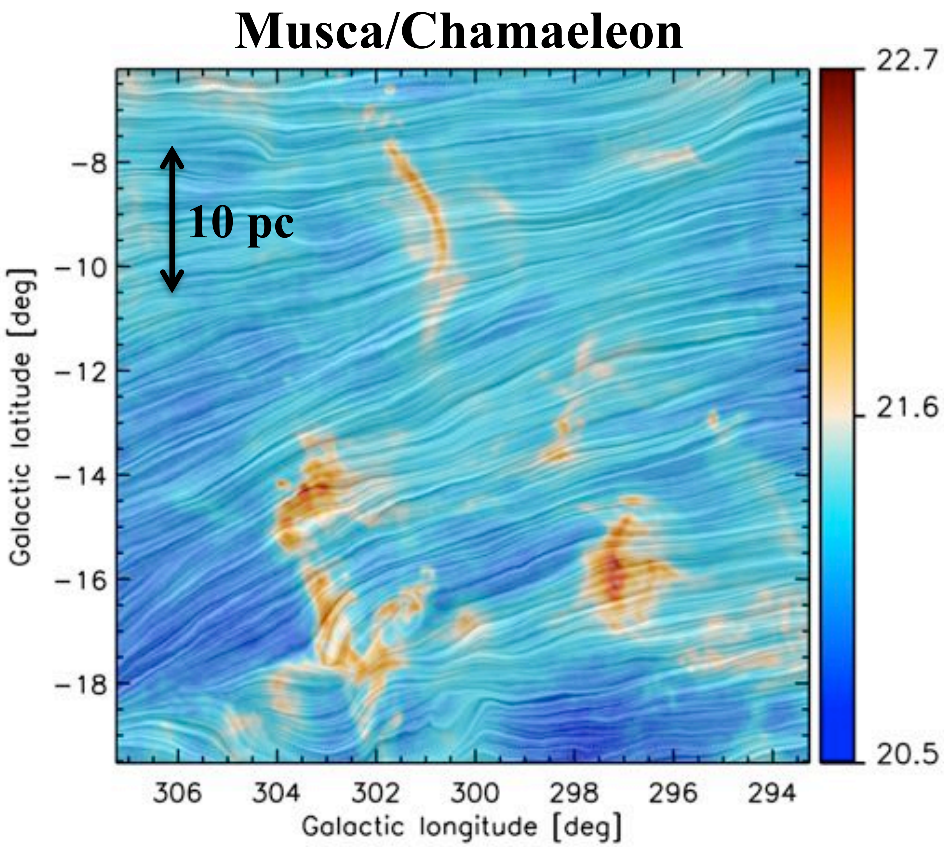
1) **Large-scale MHD compressive flows create ~ 0.1 pc-wide filaments**
2) **Gravity fragments the densest filaments into prestellar cores above $M_{line,crit}$ ~ 16 $M_\odot$ pc^{-1}**
3) **Prestellar cores collapse to protostars/YSOs**



A major open issue: Role of magnetic fields?

- ***Planck*** **polarization data reveal a very organized B field on large ISM scales,**
  ~ perpendicular to dense star-forming filaments, ~ parallel to low-density filaments
- **Suggests that the B field plays a key role in the physics of ISM filaments**





Planck intermediate results. XXXV. (2016 J. Soler)

Suggests sub-Alfvénic turbulence on cloud scales

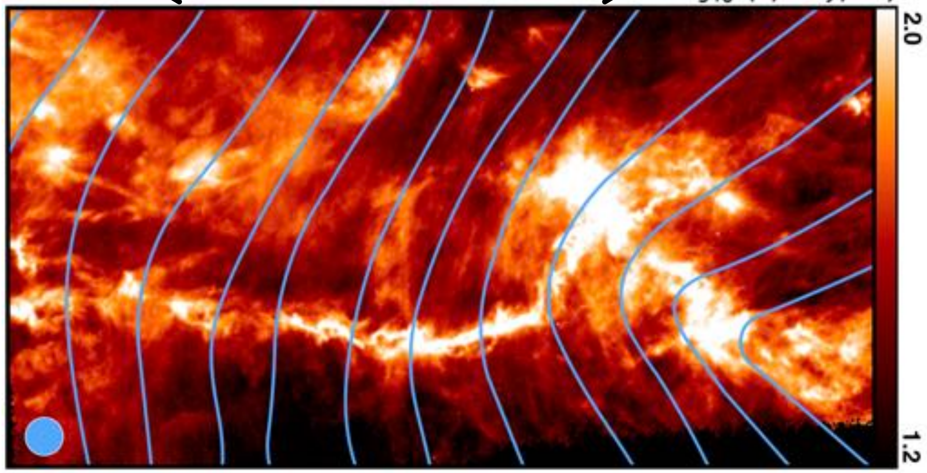
Color: N(H) from Planck data @ 5' resol. (~ 0.2-0.3 pc)

Drapery: B field lines from Q,U *Planck* 850 µm @ 10'

F. Boulanger's group

SPICA-B-BOP can unveil the role of magnetic fields in filament evolution and core/star formation

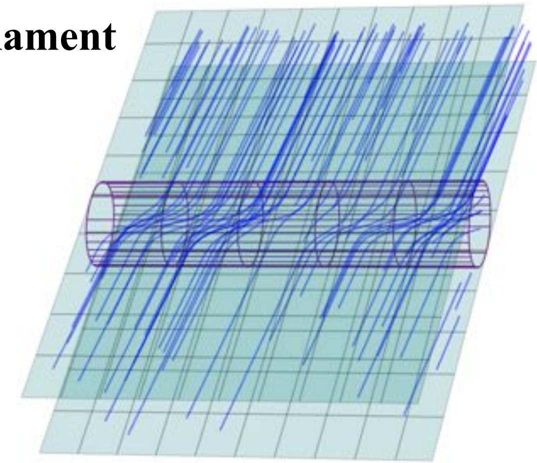
Taurus B211 filament
Herschel 250 µm
+ *Planck*
B lines



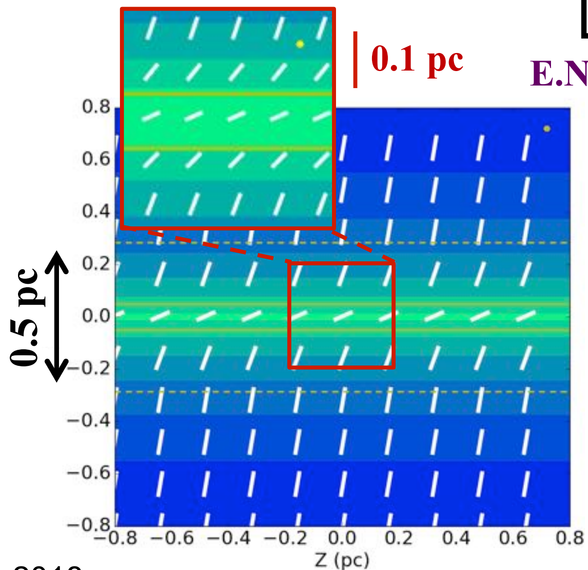
Palmeirim +2013
A. Bracco

- *Planck* pol. resolution (> 10’ or > 0.4 pc) insufficient to resolve the typical ~0.1 pc inner width of filaments. Can be done with SPICA
- SPICA will provide FIR polarized (Q, U) images with a S/N and dynamic range similar to *Herschel* images in I.

Plausible model of the B field in the central filament



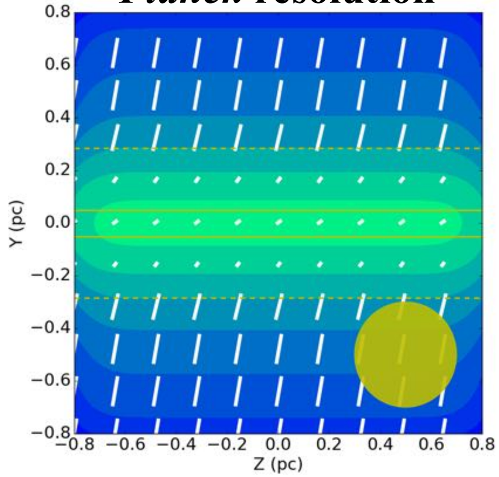
SPICA resolution



Synthetic polarization maps

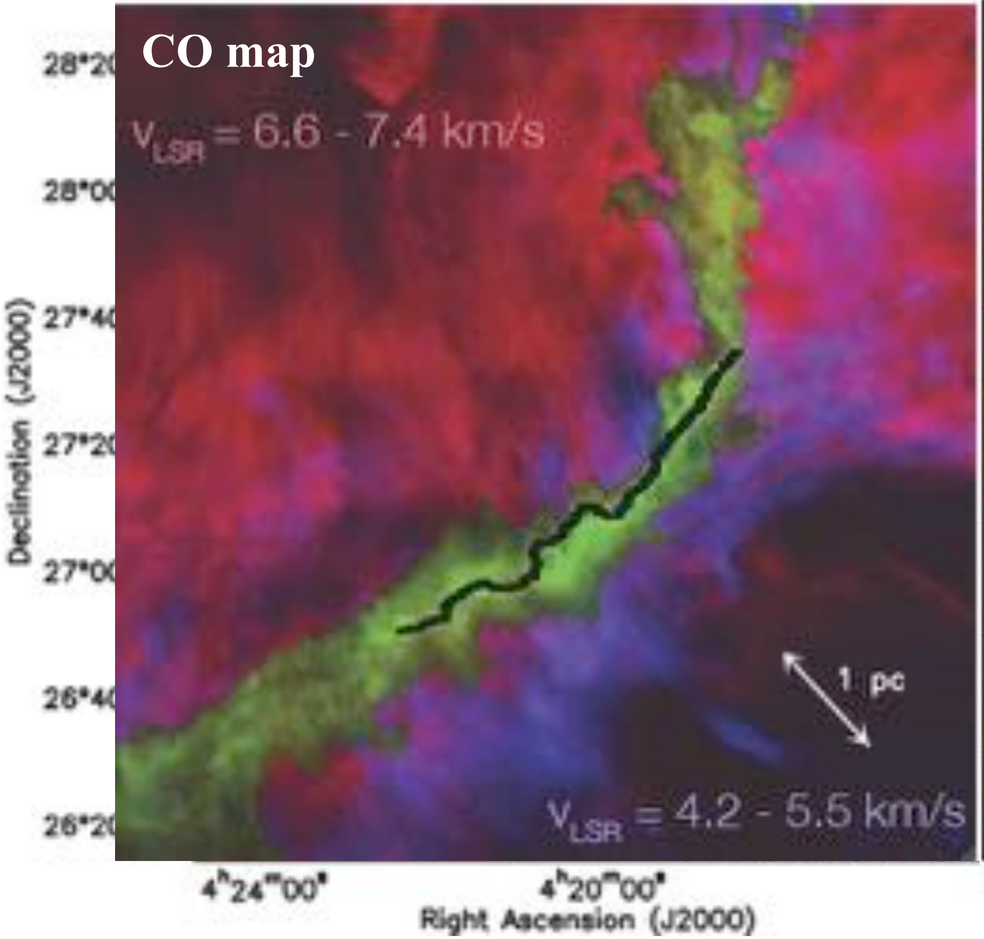
E.Ntormousi

Planck resolution



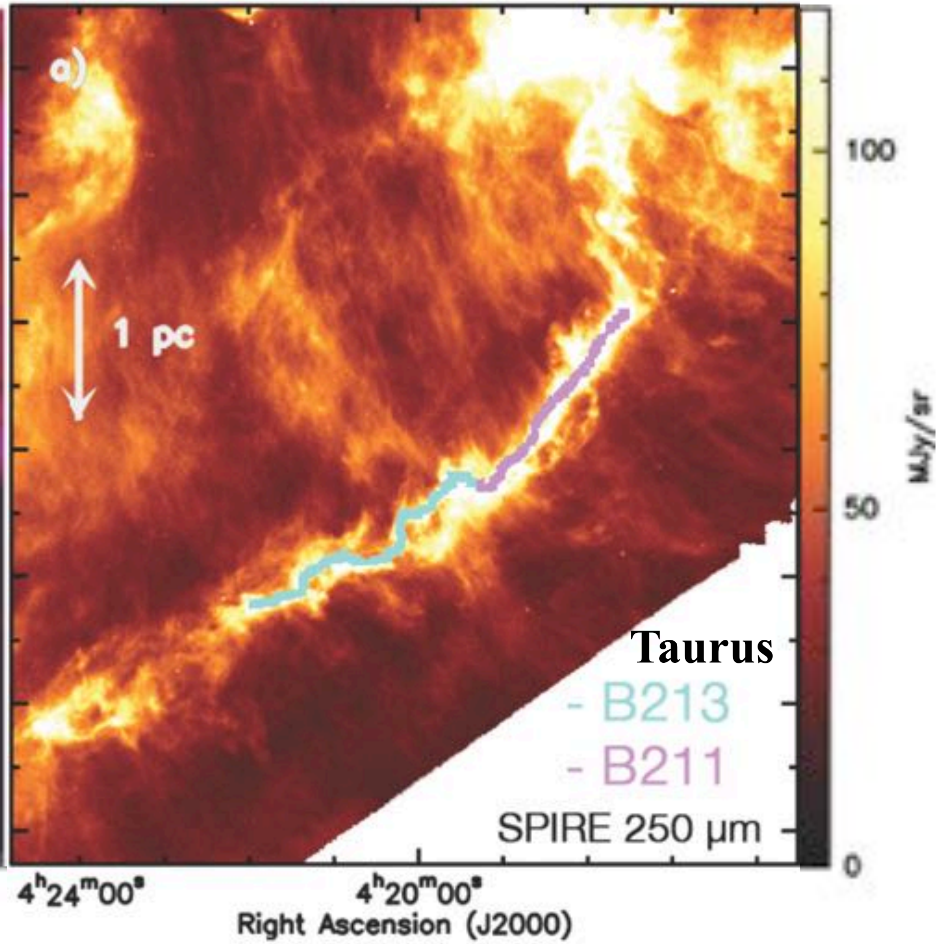
Evidence of accretion of background material (striations) onto self-gravitating filaments?

➢ Striations and sub-filaments are suggestive of accretion flows into the star-forming filaments - Tend to be // to the large-scale B field



CO observations from Goldsmith+2008

Taurus B211/3: M_{line} ~ 50 $M_\odot$/pc



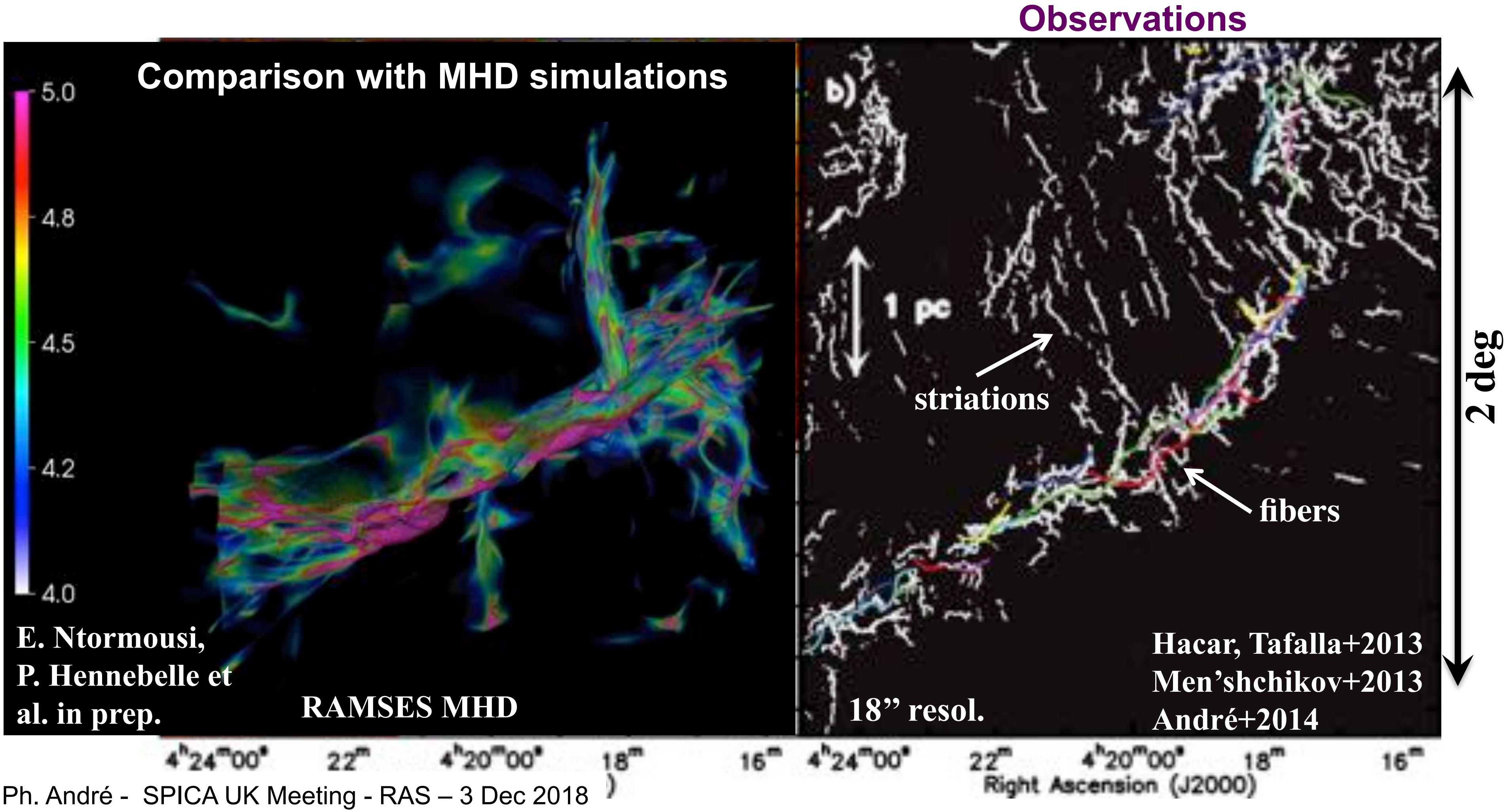
Estimated mass accretion rate:

$\dot{M}_{line}$ ~ 50 $M_\odot$/pc/Myr Palmeirim+2013

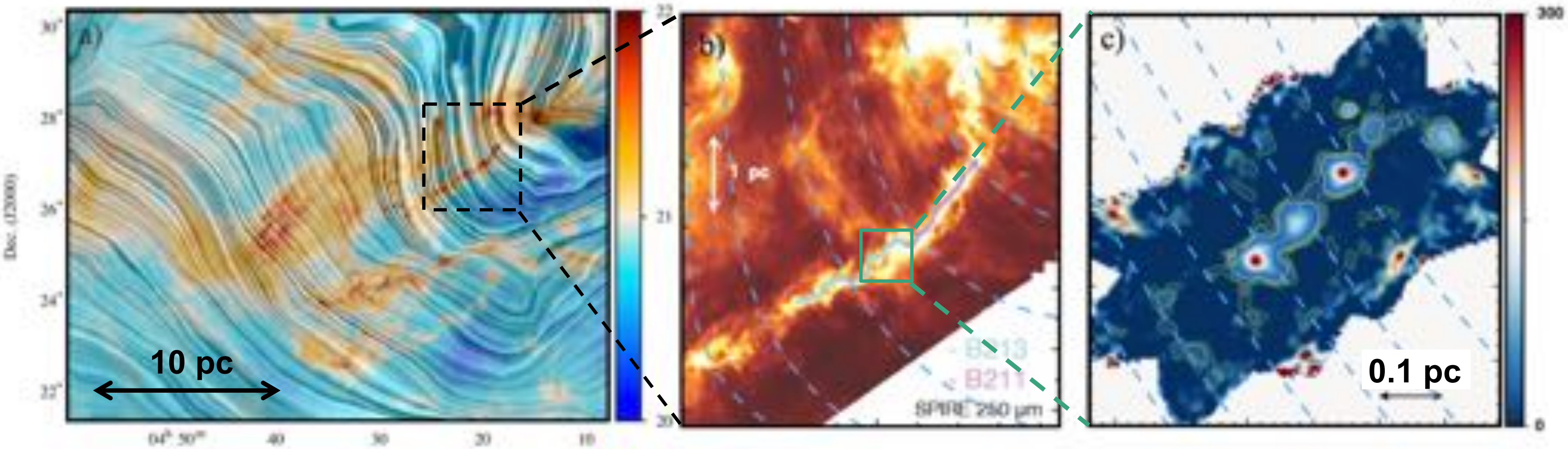
Probing the magnetic link between striations and fibers

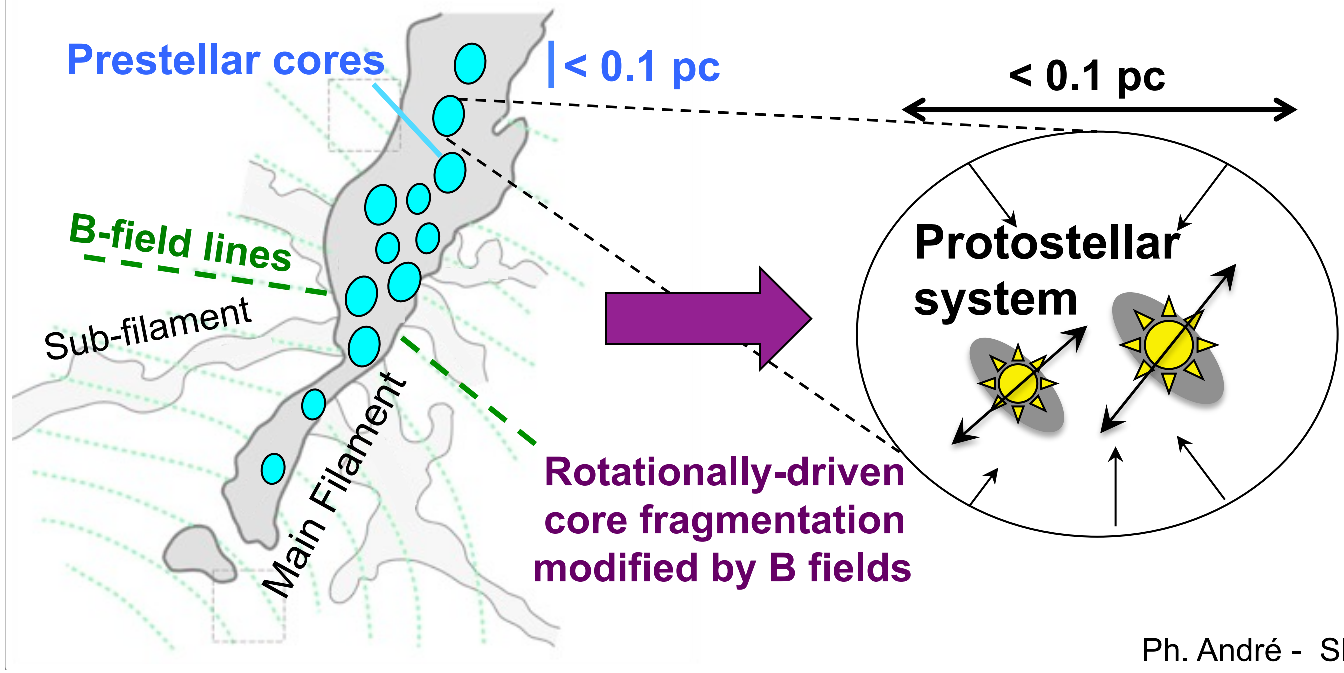
High resolution/dynamic range polarimetric imaging with B-BOP

- **Geometry of the B-field *within* the (~ 0.1 pc) system of intertwined « fibers » developing inside star-forming filaments and the connection with the striations seen on larger scales**



Role of B fields in regulating filament fragmentation and protostellar collapse to stellar/solar systems?



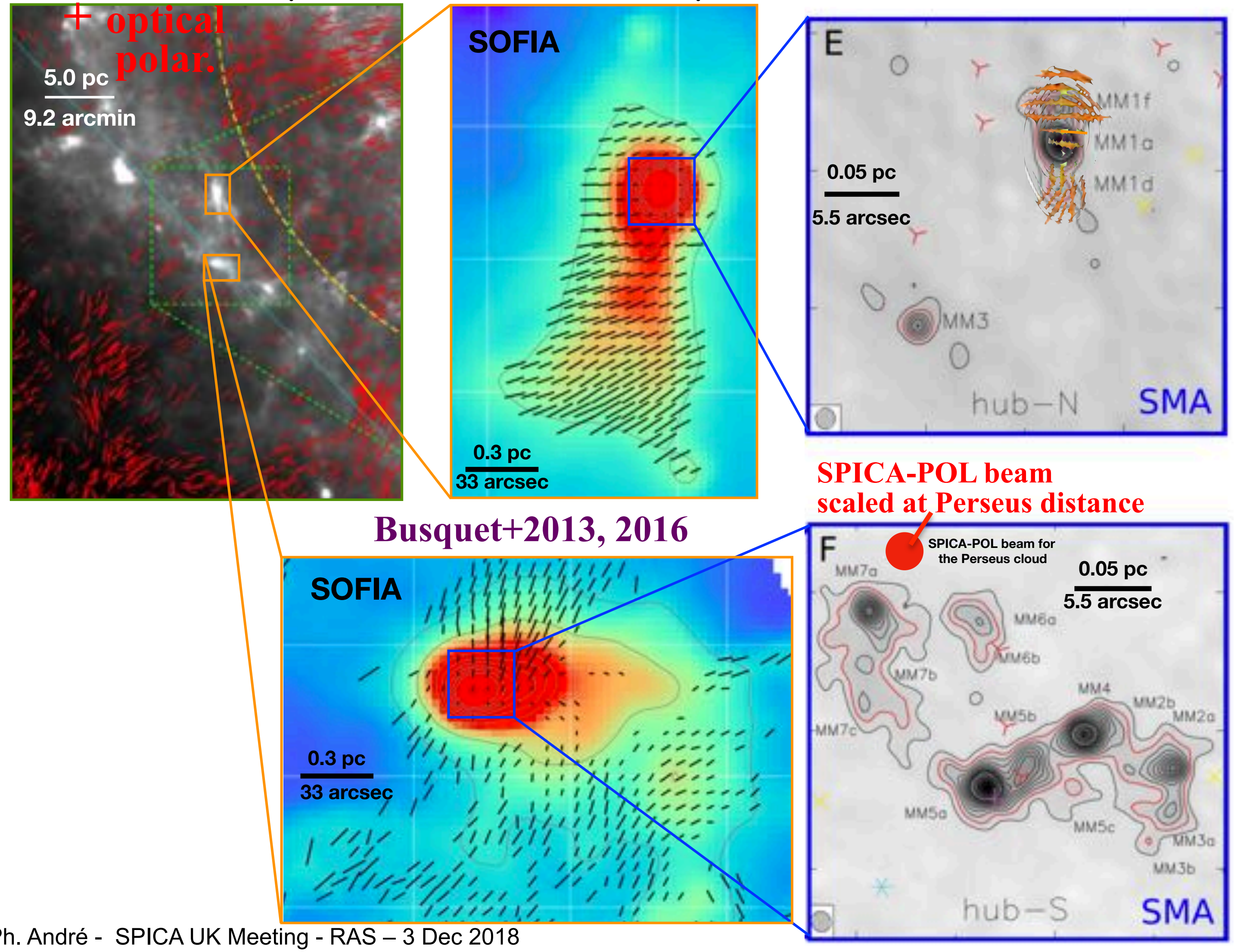


- **Magnetic field and angular momentum of protostars is likely inherited from filament formation/ fragmentation process**

Role of B fields in controling the sub-fragmentation of dense cores and the typical outcome of protostellar collapse?

G14.225-0.506 massive IRDC

Herschel 250 µm | HAWC+ 200 µm | SMA interferometer 1.2mm



Northern « Hub »:

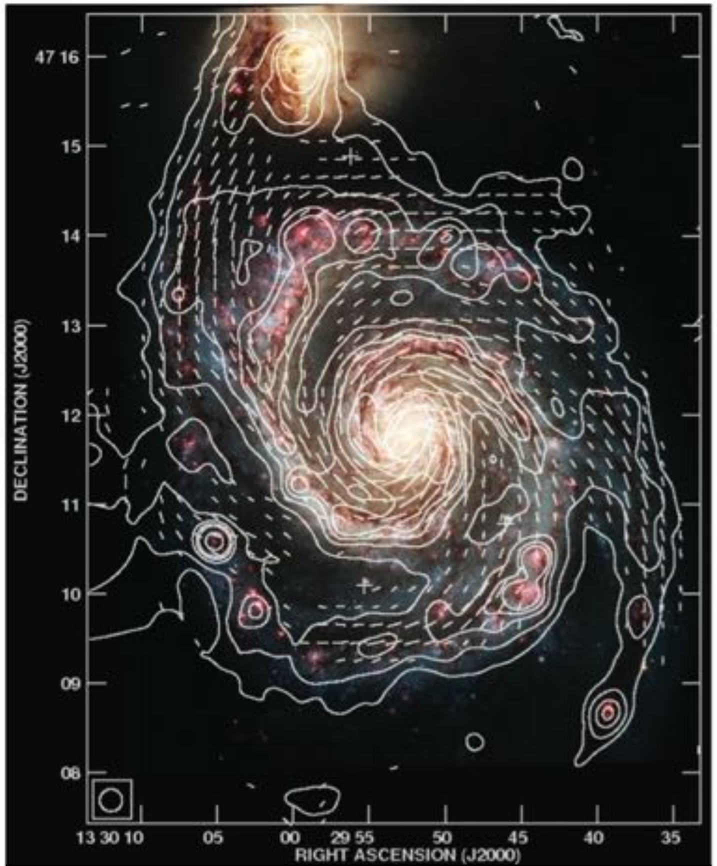
More regular B field at ~ 0.1-0.3 pc scales

→ Lower level of fragmentation

- **Present studies limited to the few brightest regions only**
- **Interferometers (ALMA) cannot probe the magnetic connection between cores and filaments**

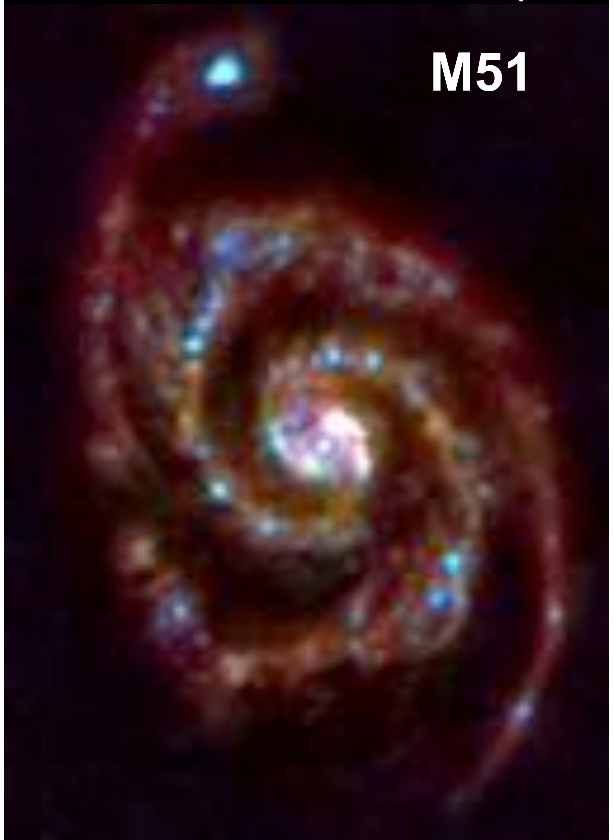
Polarimetric imaging of nearby galaxies to understand the origin of magnetic fields in GMCs

3cm radio synchrotron polar. overlaid on Hubble image



Fletcher et al. 2011

***Herschel*/PACS 70-160 μm**



ESA & PACS consortium

- **SPICA-Pol (B-BOP) can uniquely probe the B field within the GMCs (cold ISM) of nearby disk galaxies where star formation occurs.**
- Synchrotron polarization observations (e.g. SKA) can only probe the warm ionized ISM over the full volume of galaxies (including their halo).

The power of sensitive polarimetric imaging with B-BOP

Potential major advances/ discoveries on:

⇒ **Magnetic structure of galaxies,**

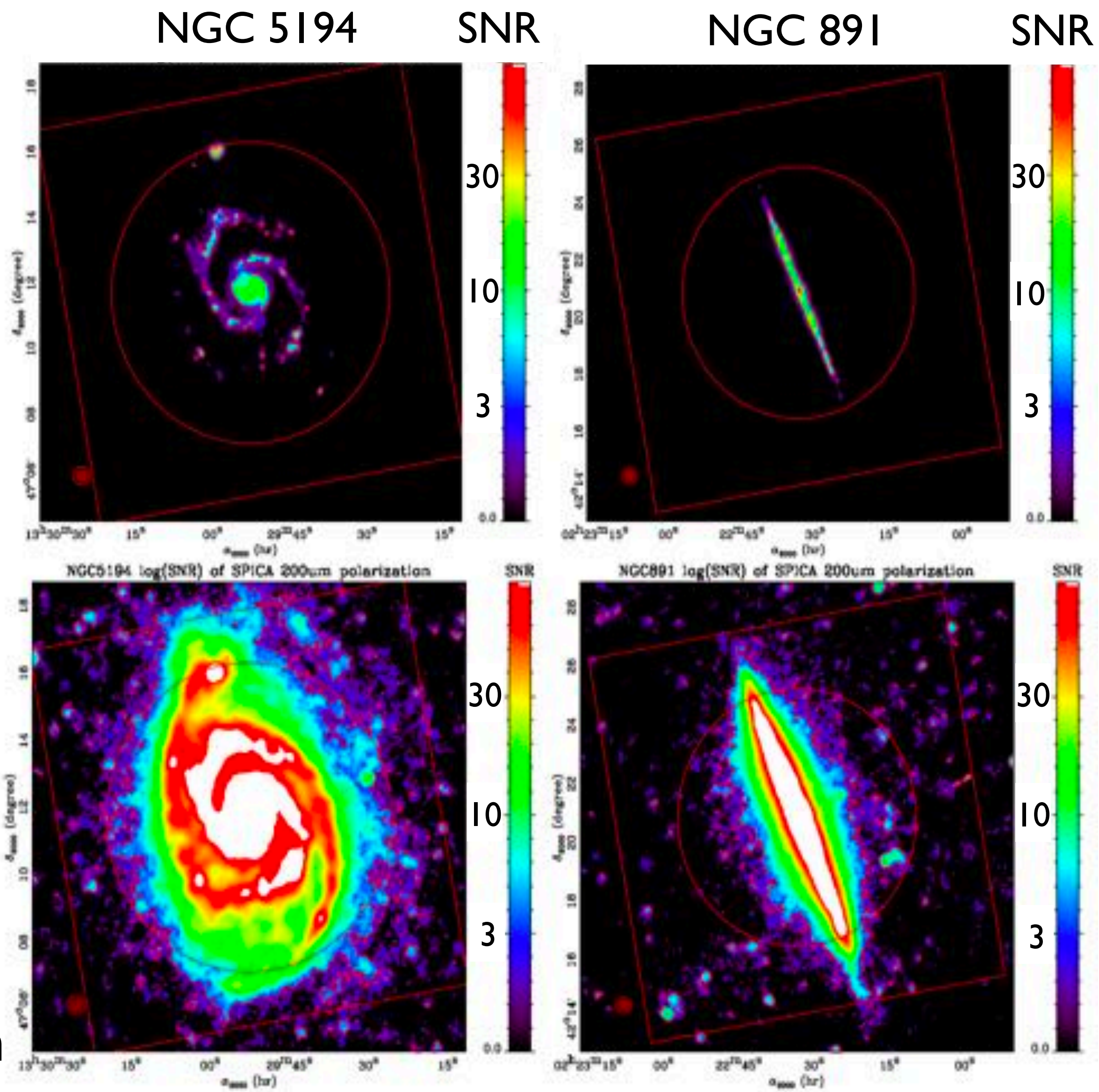
⇒ **Galactic dynamo models for the origin of B,**

⇒ **Polarization of the CIB.**

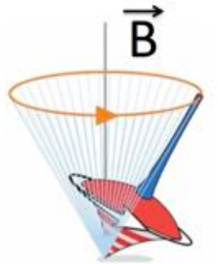
100 µm

- **B-BOP will map the whole LMC in ~50 hr and the galaxies of the VNGS & KINGFISH *Herschel* surveys in ~200 hr**

200 µm



Testing dust grain alignment models with SPICA/B-BOP

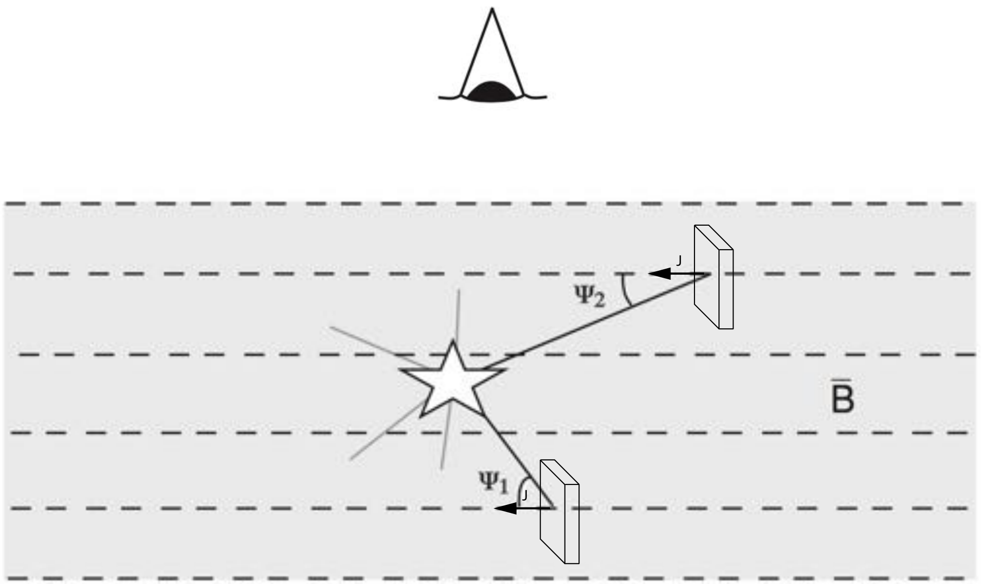


Leading grain alignment theory:
Radiative Alignment Torques (RATs)

(Hoang & Lazarian 2014, Andersson+2015)

Prediction of RATs model

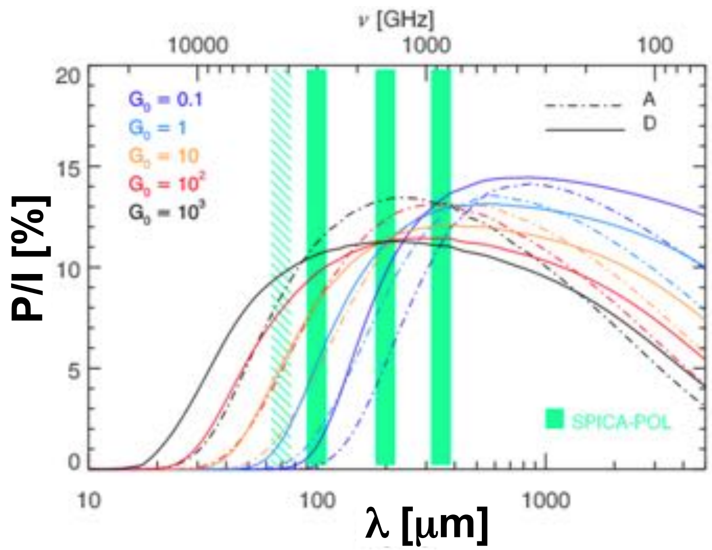
Stronger grain alignment/polarization fraction when incident radiation field is // to the B field ($\Psi = 0$)



With B-BOP:

Observations of polarized dust emission around **thousands of individual stars dominating the radiation field locally**

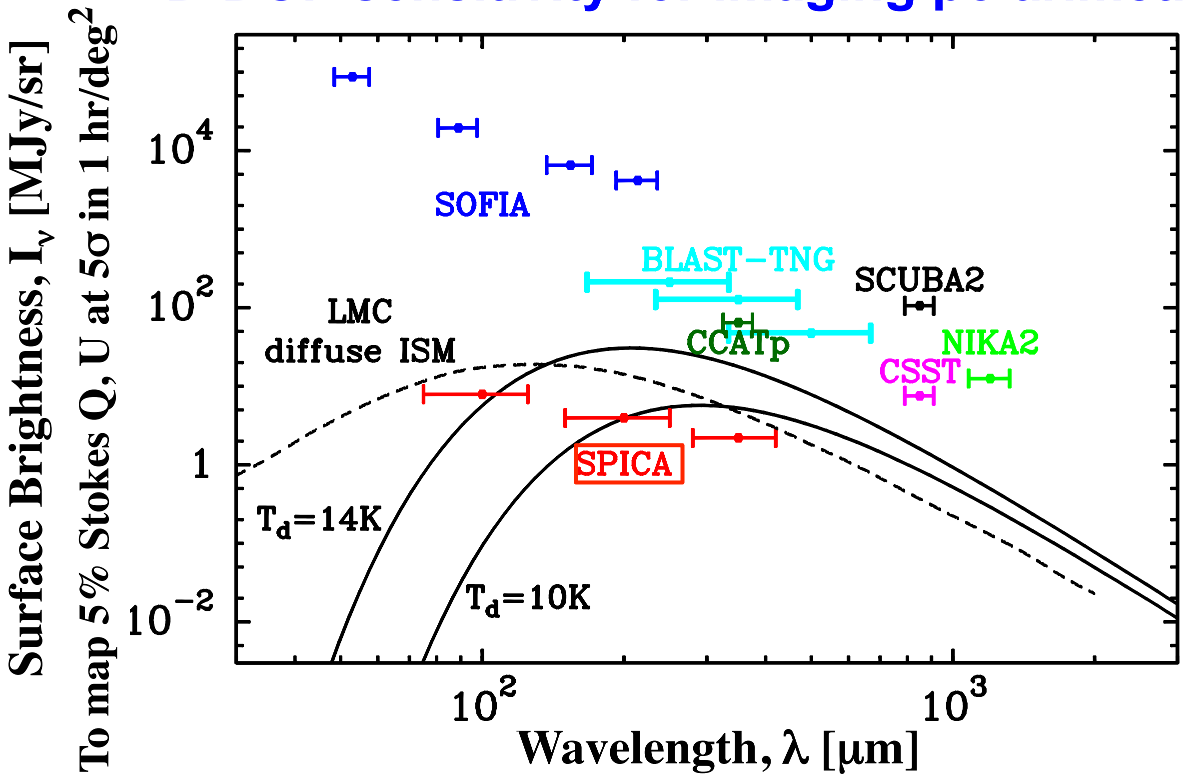
Spectral dependence of polarization fraction



(cf. Guillet+2018)

Conclusions

B-BOP sensitivity for imaging polarimetry



Key advantages of SPICA:

- **High spatial dynamic range ($\sim 10^3$)**
- **High angular resolution**

(can resolve < 0.1 pc scale out to d ~ 300 pc)

- **High surface brightness sensitivity**

1000× more sensitive than SOFIA

> 1000× faster than BLAST-TNG

- Polarimetric imaging survey of ~ 500 deg^2 (Gould Belt clouds) in $\lesssim$ 2 months
- Survey of nearby galaxies in ~ 200 hr

➢ **A systematic polarimetric imaging survey of Galactic molecular clouds and nearby galaxies with SPICA-B-BOP will revolutionize our understanding of the origin and role of B-fields in the cold ISM of galaxies on scales from ~0.01 pc to a few kpc**

(inaccessible to ALMA)