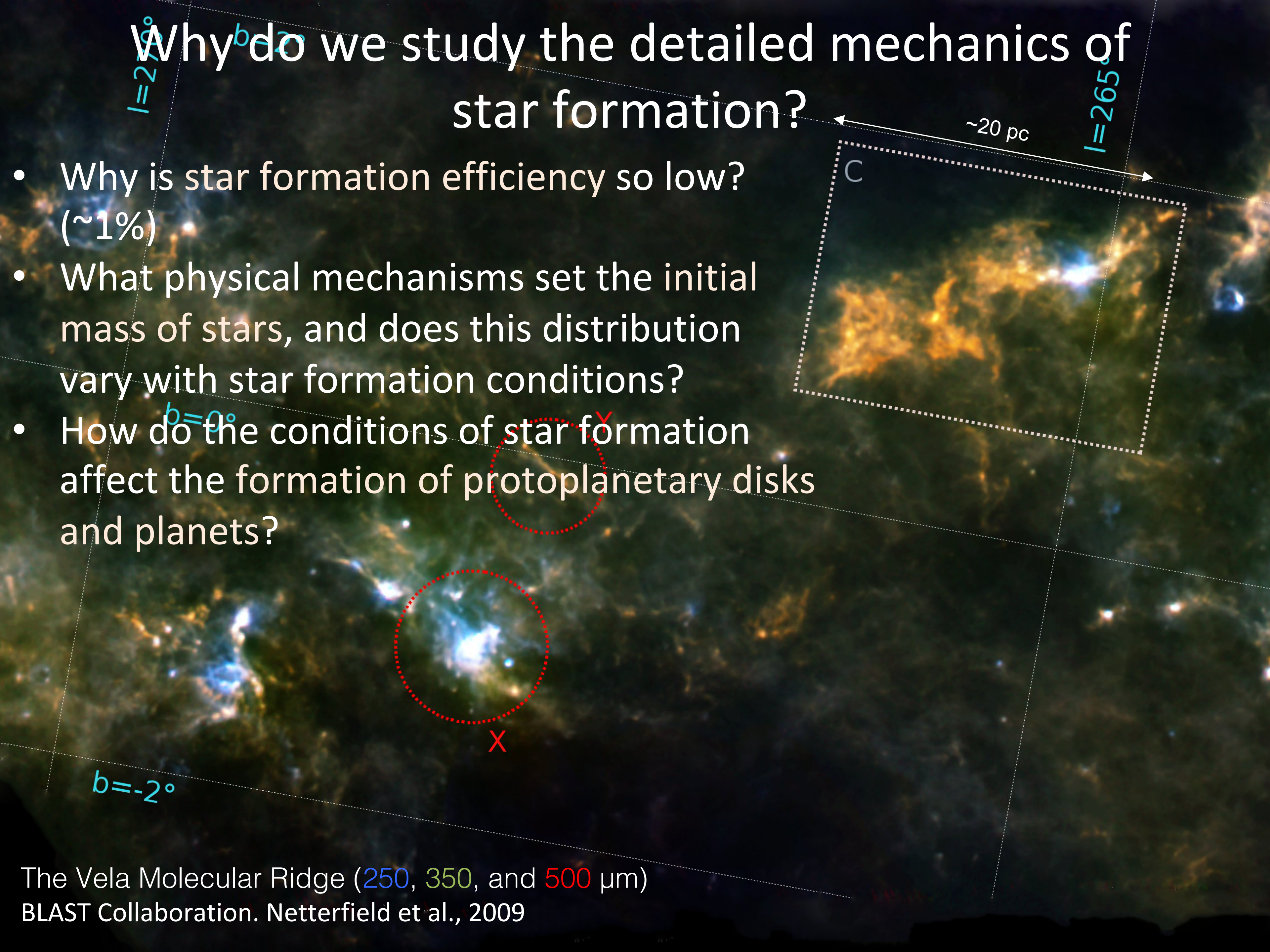
Studying Star Formation with PICO

Laura Fissel
For the PICO Galactic Science Working Group
National Radio Astronomy Observatory
May 2nd, 2018
PICO Science Team Meeting, U. Minnesota

Planck Int XXXV 2016

Why do we study the detailed mechanics of star formation?

- Why is star formation efficiency so low? (~1%)
- What physical mechanisms set the initial mass of stars, and does this distribution vary with star formation conditions?
- How do the conditions of star formation affect the formation of protoplanetary disks and planets?



The Vela Molecular Ridge (250, 350, and 500 μm)
BLAST Collaboration. Netterfield et al., 2009

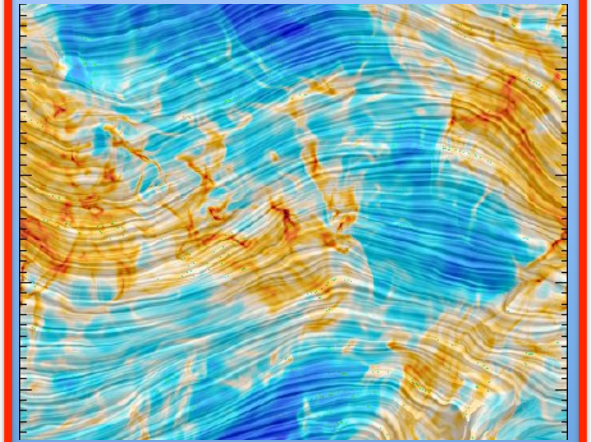
What regulates Star Formation?

(in addition to gravity)

Supersonic Turbulence

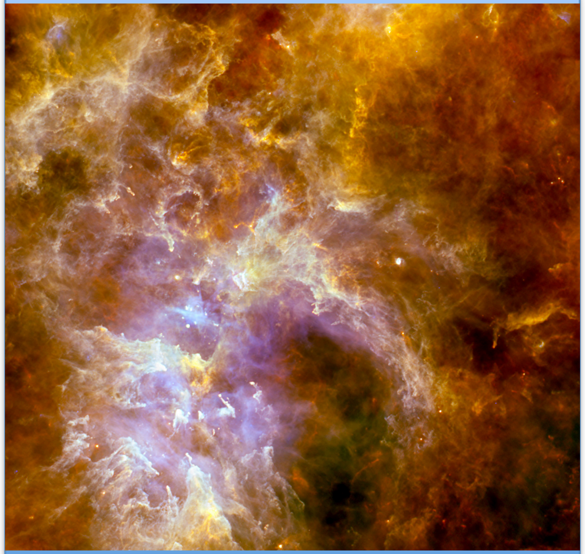
E.g. MacLow and Klessen, 2004

Magnetic Fields



Shu et al., 1984
Nakamura and Li, 2008

Feedback



E.g. Krumholtz, Matzner and McKee, 2006

Answer: All contribute and are important on different size and density scales.

But the (by far) least understood/hardest to observe is the magnetic field.

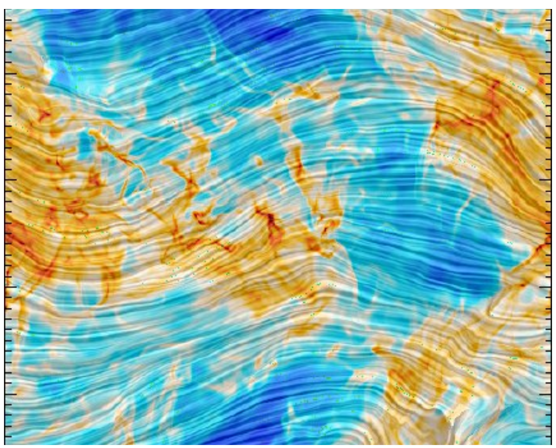
How can magnetic fields affect star formation?

Cloud Scales

1 – 100 pc

Influence where dense molecular gas clouds form

Inutsuka et al. 2015
Walch et al. 2015



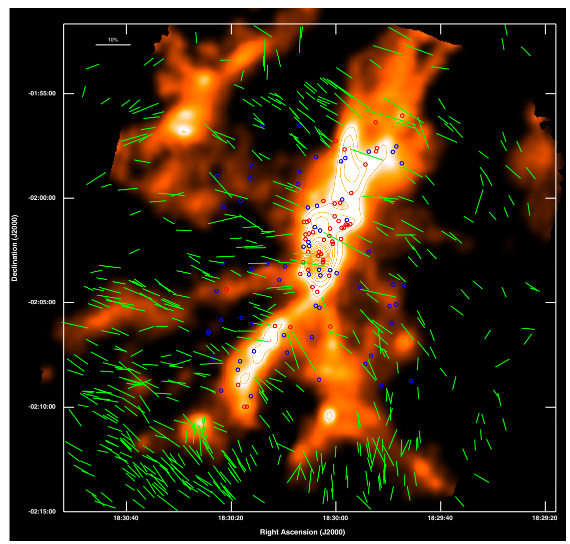
Soler 2013

Filaments and Cores

0.01 – 1 pc

Direct accretion of gas, possibly slow down of collapse, fragmentation?

Li et al. 2014 PPVI



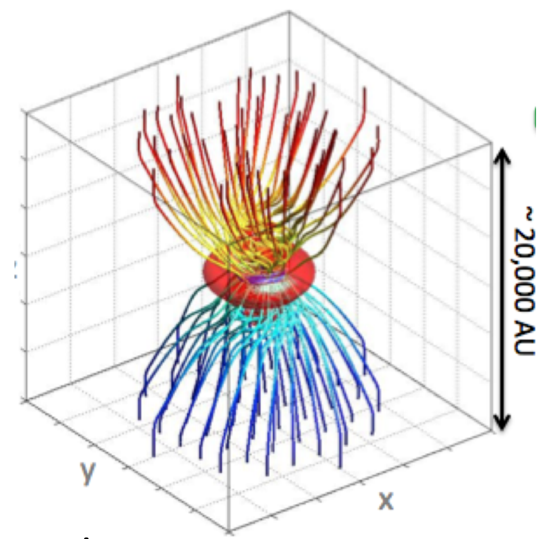
Sugitani 2011

Protostellar Disks

<0.01 pc

Inhibit formation of large disks

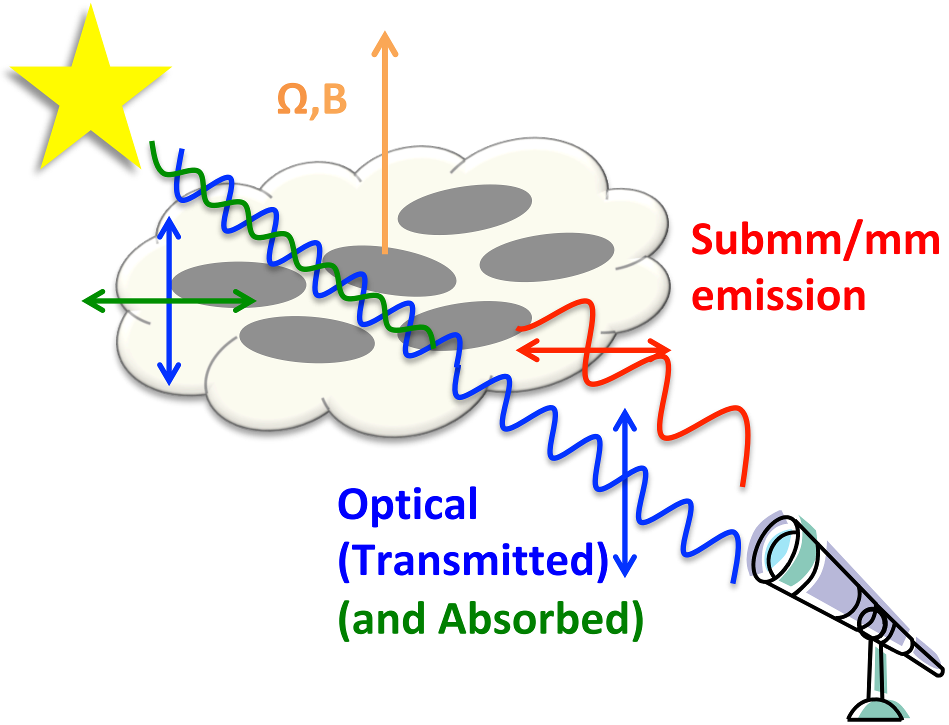
Galli & Shu 1993
Joos et al. 2012



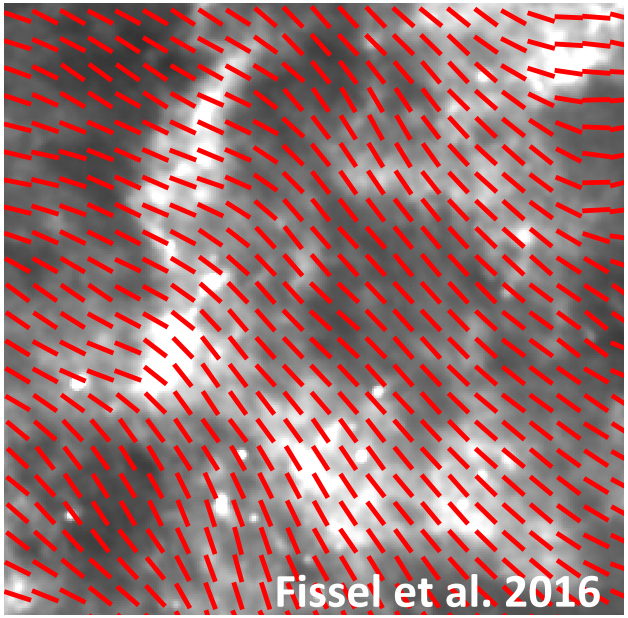
Davidson et al. 2014

Are magnetic fields strong enough to influence the gas motions on these different scales?

Using polarized dust emission to trace magnetic fields

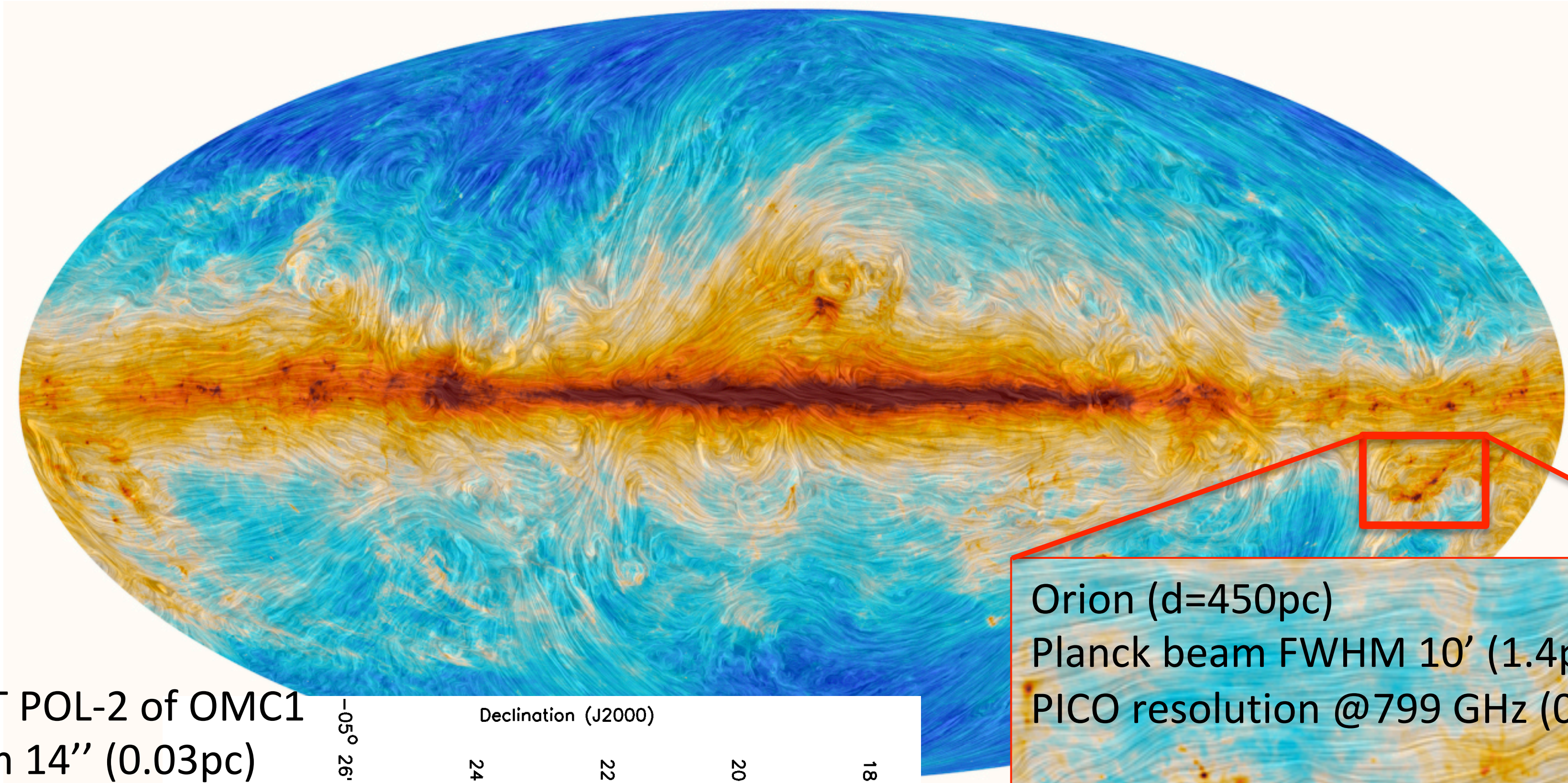


Inferred B-field orientation
(500 μm Polarization rotated by 90°)

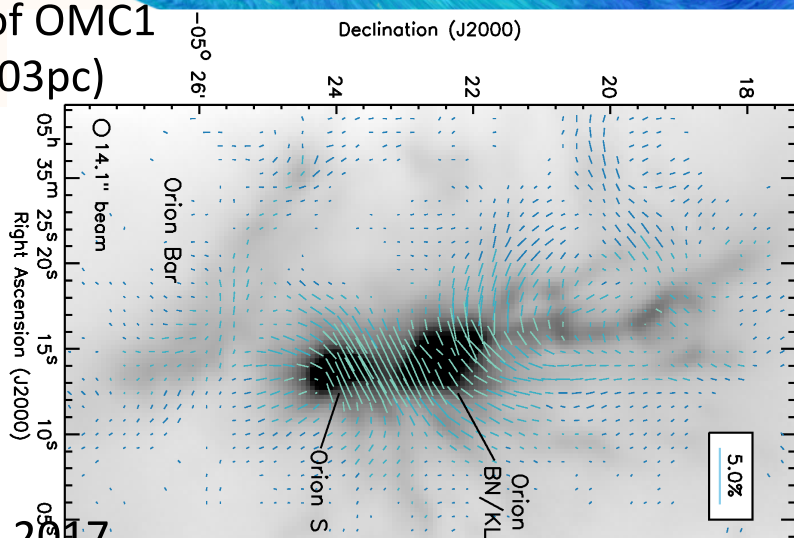


- Dust grains tend to align perpendicular to the B-field through radiative torques (see See Lazarian 2007, Andersson et al. 2015)
- Leads to polarization parallel to B (optical, near-IR), or perpendicular to B (thermal emission, sub-mm/mm)
- Caveats:
  - Only measures the magnetic field direction (projected on the sky) not the magnetic fields strength.
  - Where the polarization best traces the magnetic field depends on dust properties (shape, alignment to B, temperature).

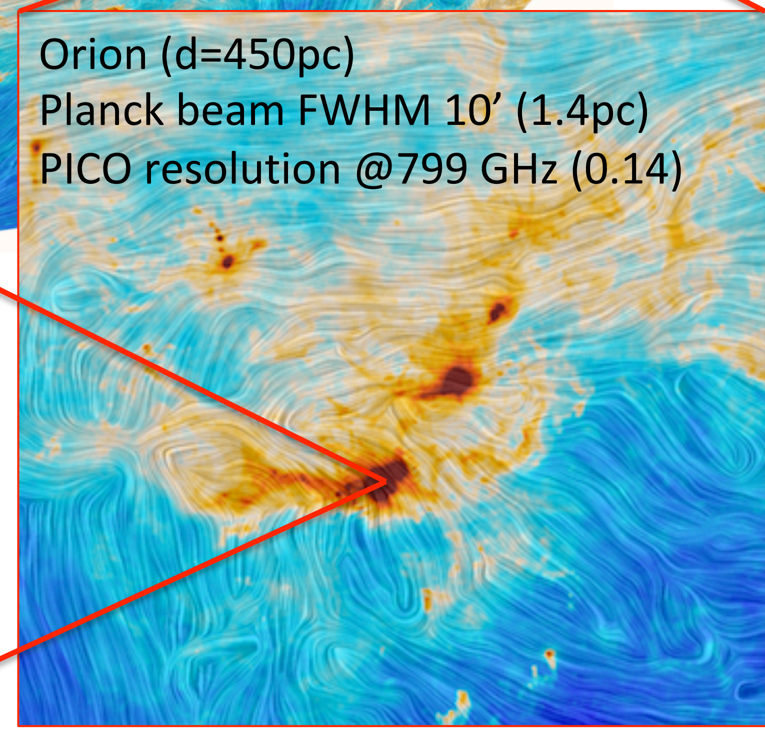
Dust Polarization with Planck



JCMT POL-2 of OMC1
Beam 14'' (0.03pc)

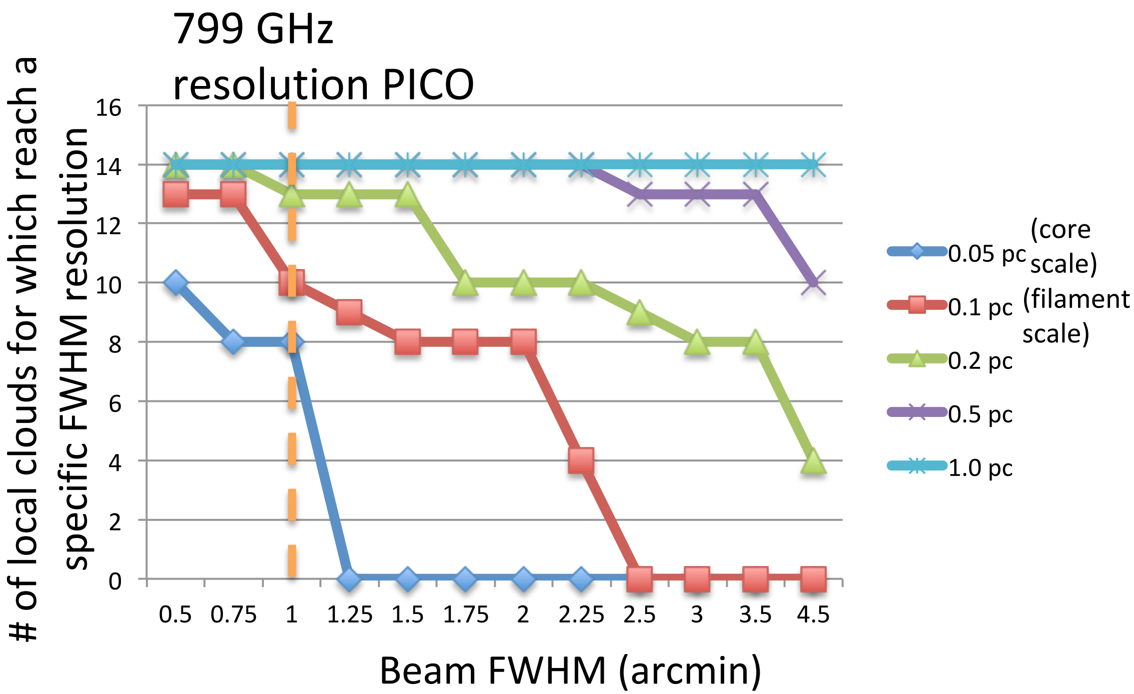


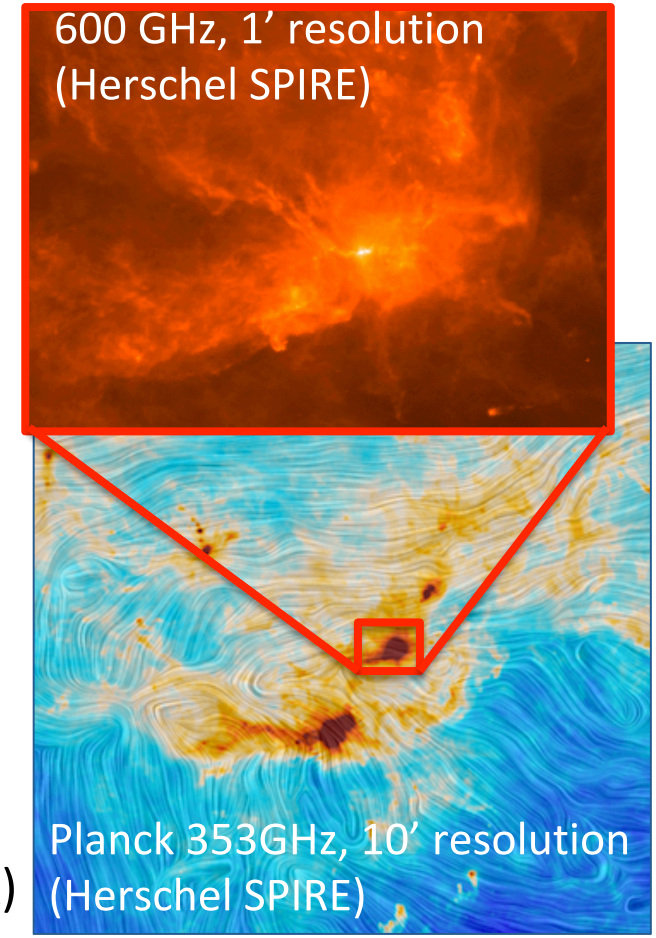
Pattle et al. 2017



Orion (d=450pc)
Planck beam FWHM 10' (1.4pc)
PICO resolution @799 GHz (0.14)

PICO vs Planck





- 1.1 arcmin resolution (>10x better than Planck)
  - more clouds
  - can resolve dense filaments (width ~0.1pc) and cores (~0.05-0.1pc) where stars are forming
- Huge increase in sensitivity compared to ground based telescopes.
  - can access high frequency bands where the dust emission is brightest.

Key Science Goal for PICO

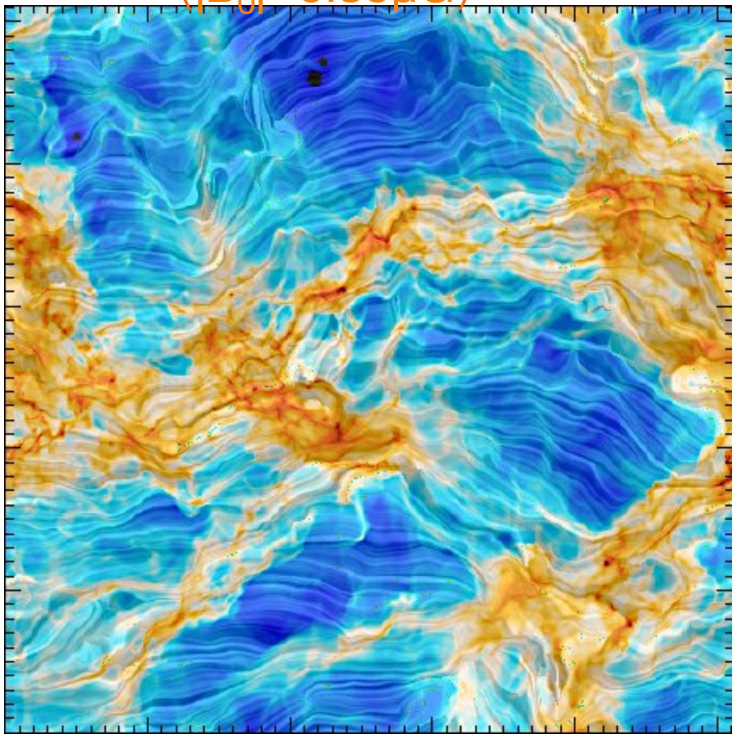
Determine whether magnetic fields are a dominant cause of low star formation efficiency.

Parameters to Constrain:

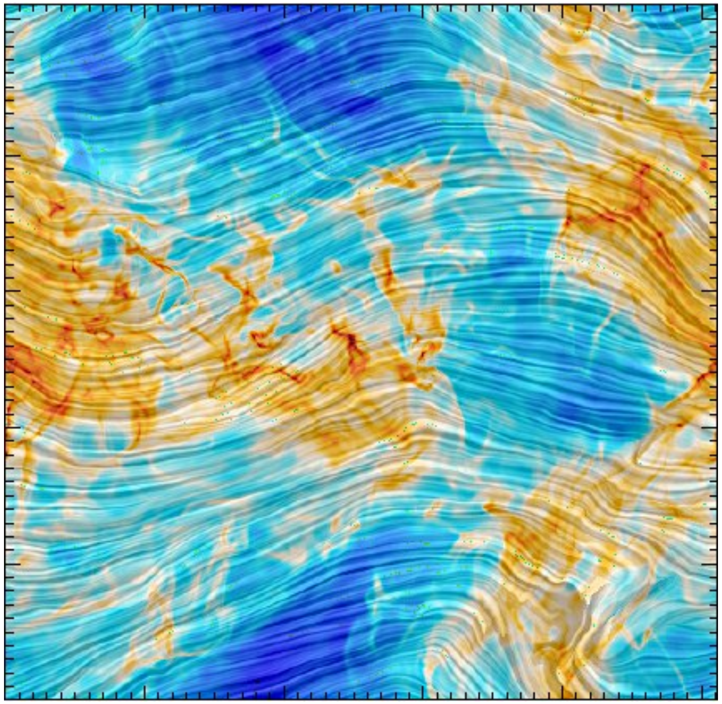
- Magnetic field strength (B)
- Ratio of *turbulent to magnetic energy*
  - Alfven Mach number $M_A = (v/v_A)^2$, $v_A = B/(\mu_o \rho)^{1/2}$
- Ratio of *thermal to magnetic energy*
  - Plasma $\beta = (c_s/v_A)^2$
- Magnetic Support vs Gravitational Energy
  - Mass to Flux ratio $\mu = M/M$, $M = \Phi/2\pi G^{1/2}$, $\Phi \sim \pi r^2 B$

Our Strategy: Statistical Measurements of Polarization Maps compared to Synthetic Observations of Numerical Models

Weak magnetic field
($|B_0|$=0.35μG)



Strong magnetic field
($|B_0|$=10.97μm)

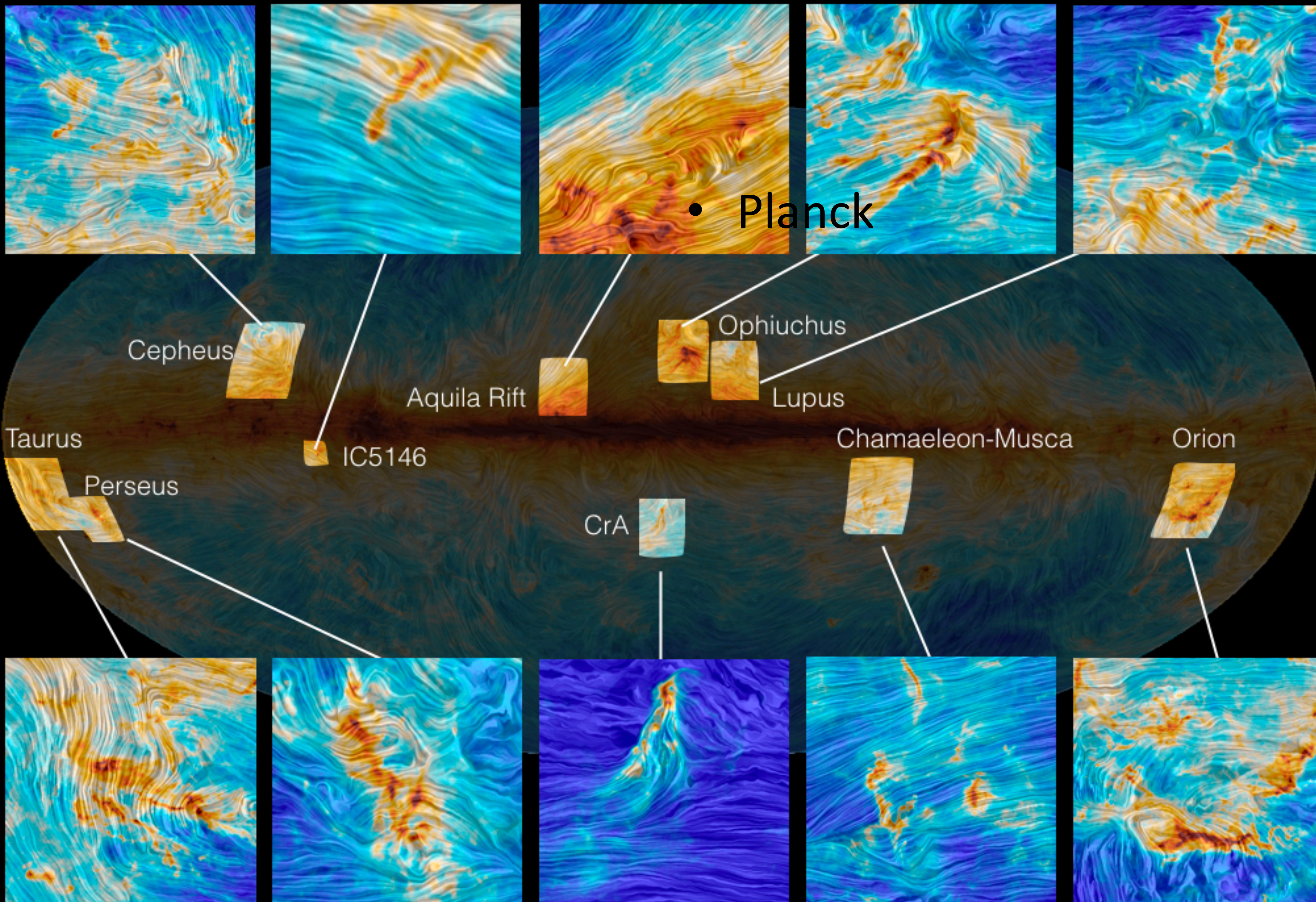


disordered B-field
low N_H ➔ B-field || to N contours
high N_H ➔B-field || to N contours

ordered B-field
low N_H ➔ B-field || to N contours
high N_H ➔B-field perp to N contours

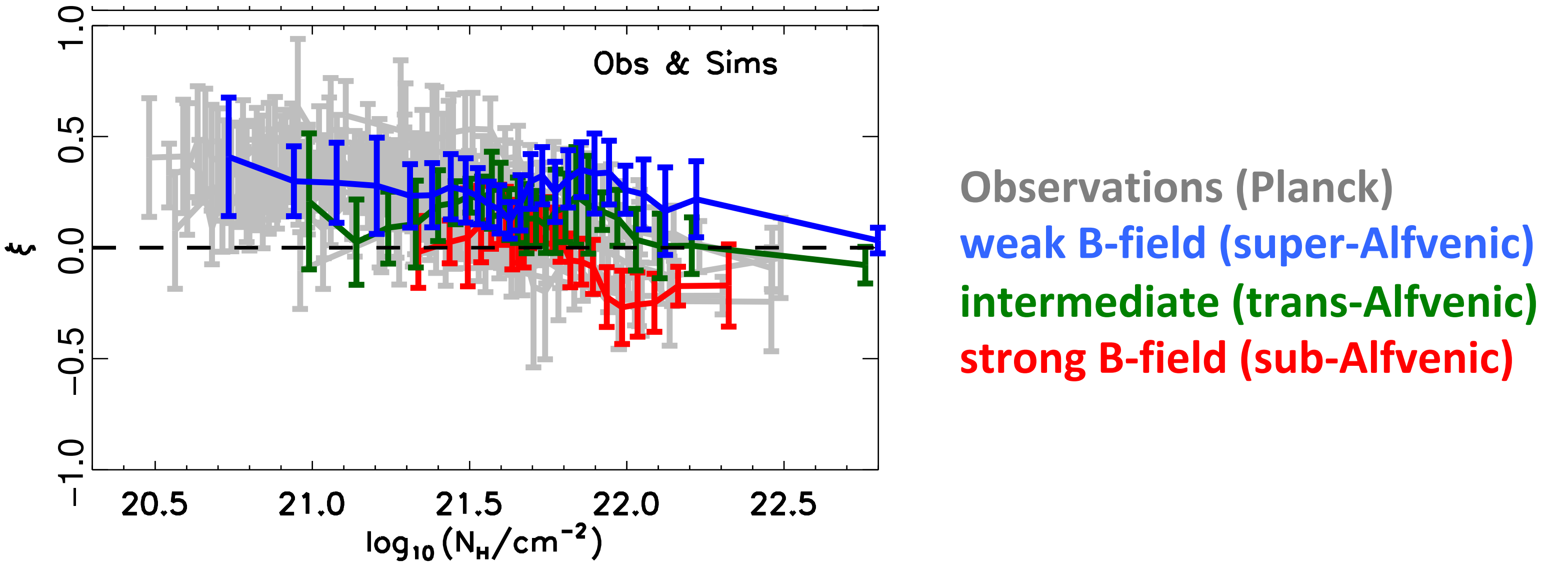
RAMSES MHD Simulations from Soler et al. 2013

Planck intermediate results. XXXV. A&A, 586 (2016) A138
Corresponding author: Juan D. Soler



Juan D. Soler (Max Planck Institute for Astronomy). 2018.

Planck measurements of the relative orientation of B-field vs. cloud elongation for 10 nearby molecular clouds



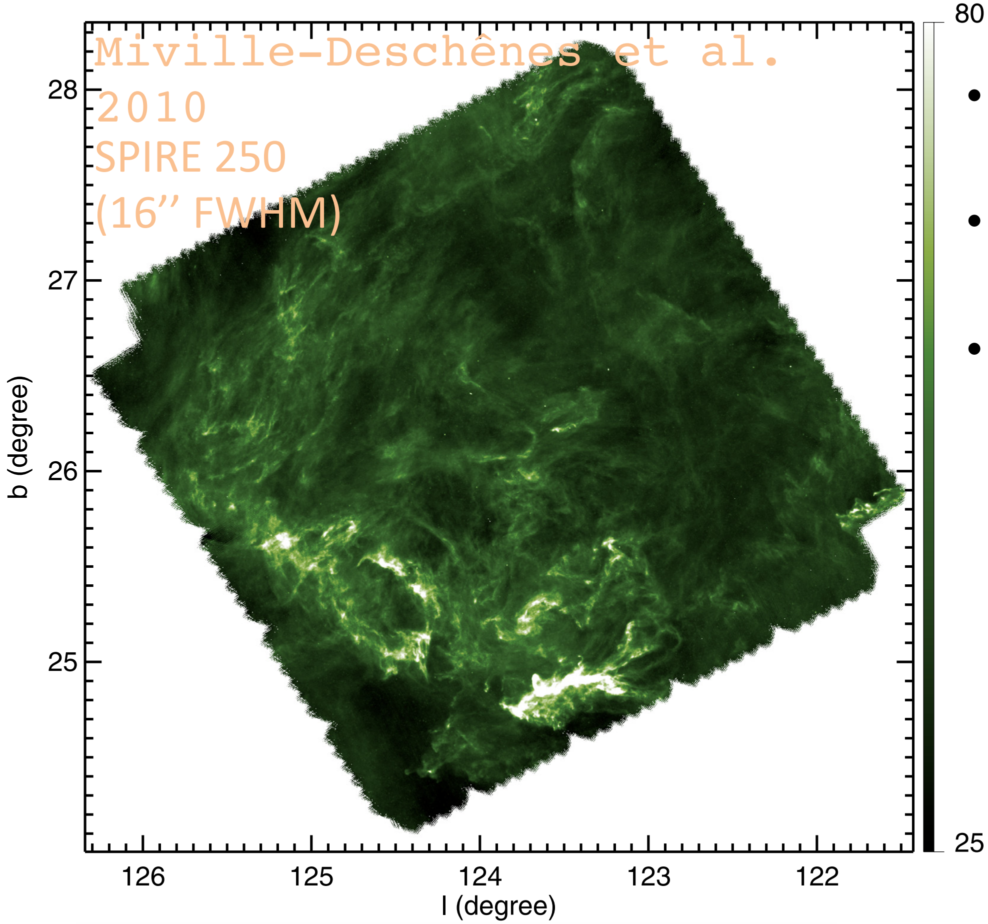
- Planck XXXV found a change in relative orientation from B-field parallel to cloud structures (low N_H) to perpendicular (high N_H).
- Implies a strong magnetic field (sub- or trans-Alfvenic)
- Large error bars are due to low number of detections

Statistical Analysis Methods

Technique	Sensitive to	Data Required	Examples
Relative Orientation Analysis	B, M_A	polarization, column density/gas maps	Soler+ 2013, Planck XXXII, XXXV, Soler+ 2017, Fissel+ submitted.
Polarization Angle Dispersion	3-D field orientation, B, $M_{A,}$	polarization, molecular line observations	Davis 1951, Chandrasekhar & Fermi 1953, Ostriker, Stone & Gammie '01, Falceta-Goncalves+ 2008, Hilldebrand 2009, Houde 2009, 2011
PDFs of Polarization observables	3-D field orientation, B, M_A	polarization	Jones 1989, Falceta-Goncalves 2008, Fissel+ 2016, King+ 2016
Velocity Gradient vs Magnetic Field Direction	B, M_A, μ	polarization, molecular line observations	Lazarian+2017, Yuen+2017

Example PICO Science: High Resolution Studies of the Diffuse Cloud Polaris

High Latitude Cirrus Cloud, distance ~150 pc

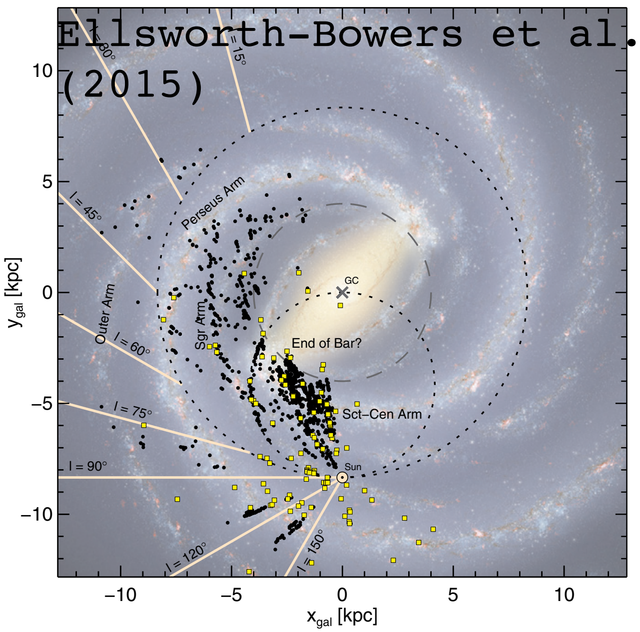


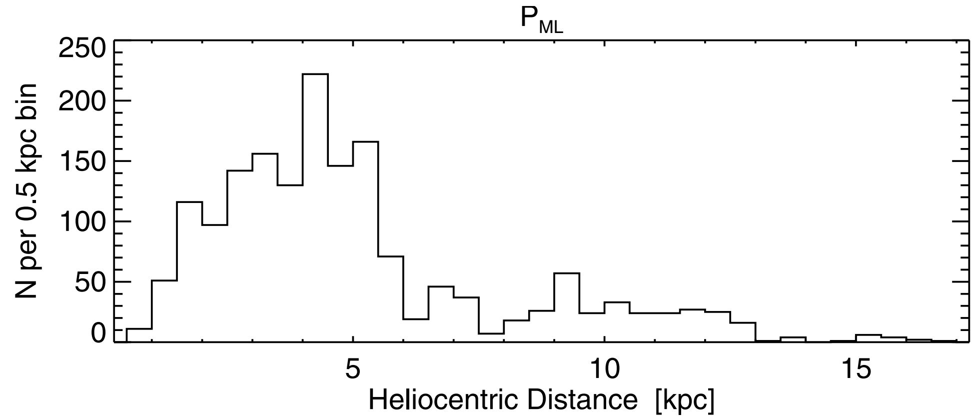
Planck (10') resolution: 0.43pc
PICO 799 GHz resolution:: 0.048pc

- Intensity of diffuse emission ($A_V << 1$) at 500 microns: ~5 MJy/Sr.
- To resolve the HI to H2 transition we want a 3-sigma detection of 2% polarized dust.
- Assume T_d = 14.3, β = 2 and scale 5 MJy/Sr to PICO bands (I_{ref})
- We expect 60,000 independent measurements of field direction in this region.

Freq [GHz]	lamda [microns]	Beam FWHM (arcmin)	σ_I v32 [Jy/Sr]	p_min (v32) (3-sigma)
107	2803.7	7.9	53.8	3.90%
129	2325.6	7.4	73.2	2.47%
155	1935.5	6.2	86.0	1.38%
186	1612.9	4.3	281.5	2.19%
223	1345.3	3.6	402.8	1.54%
267	1123.6	3.2	293.6	0.57%
321	934.6	2.6	398.9	0.39%
385	779.2	2.5	333.7	0.17%
462	649.4	2.1	448.1	0.12%
555	540.5	1.5	1193.5	0.18%
666	450.5	1.3	1682.7	0.15%
799	375.5	1.1	2469.4	0.14%

Example PICO Science: Detailed Studies of Magnetic Fields





BOLOCAM Galactic Plane Survey (BGPS) observed 1/3 of the Galactic plane, ~50% of their clouds have well characterized kinematic distances

- Planck mapped magnetic fields made detailed maps with <1pc resolution for about a dozen molecular clouds.
- PICO at 799 GHz will have <1pc resolution to 3.2 kpc, will produce detailed maps of 700 BGPS clouds➔ thousands over the entire Galactic Plane (compared to 14 with Planck).

Summary

- PICO will be an incredibly powerful tool for the study of importance of magnetic fields (and turbulence) in regulating star formation.
  - 10x better resolution for most clouds than Planck
    - We will resolve 0.1pc scales for 10 nearby clouds and study resolve magnetic fields in the dense regions where stars are forming (cores and filaments).
    - Study in detail the magnetic fields of thousands of clouds (compared to 10 for Planck).
- Our science will require a complementary effort to produce numerical simulations for different field strengths, turbulence levels, and will require complementary molecular line data.