Studying Magnetic Fields in with CCATp

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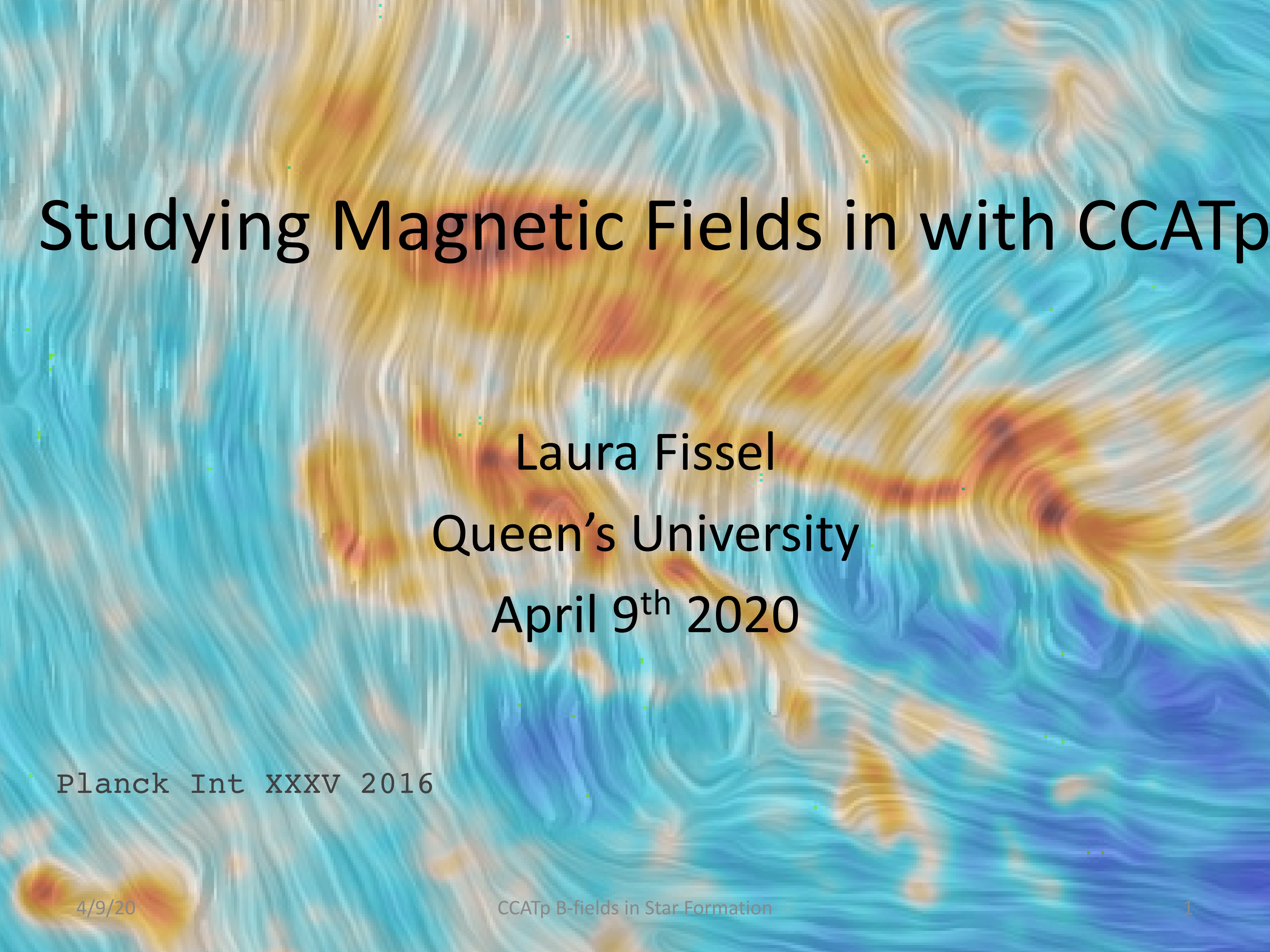
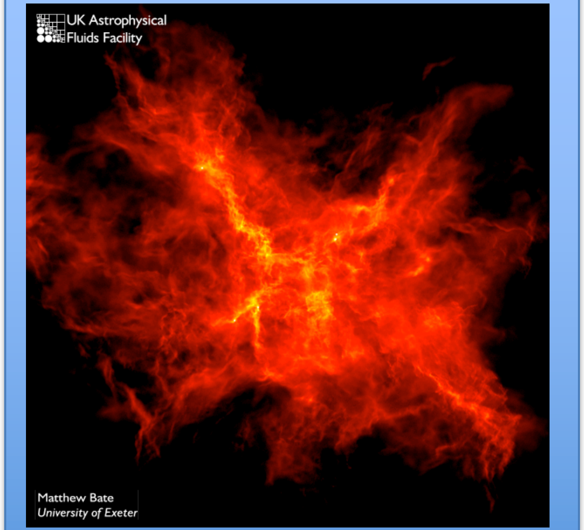


Planck Int XXXV 2016

What regulates Star Formation?

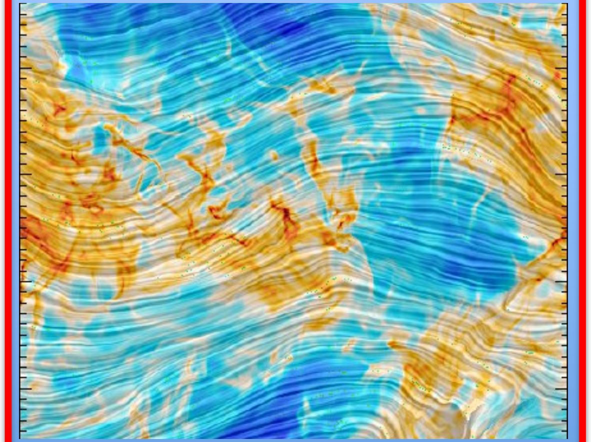
(in addition to gravity)

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.

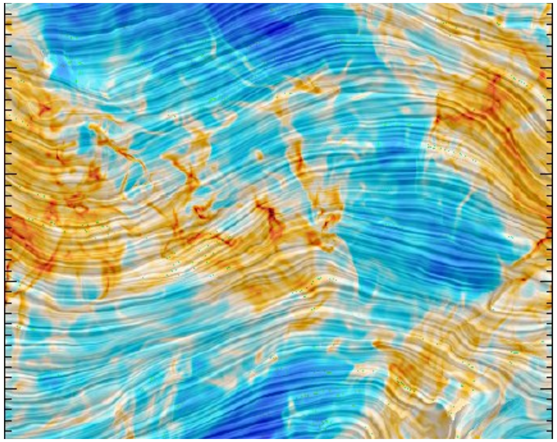
Key Science Questions for CCAT-prime

Cloud Scales

1 – 100 pc

1) Do B-fields affect molecular cloud structure and star formation efficiency?

Inutsuka et al. 2015
Walch et al. 2015



Soler 2013

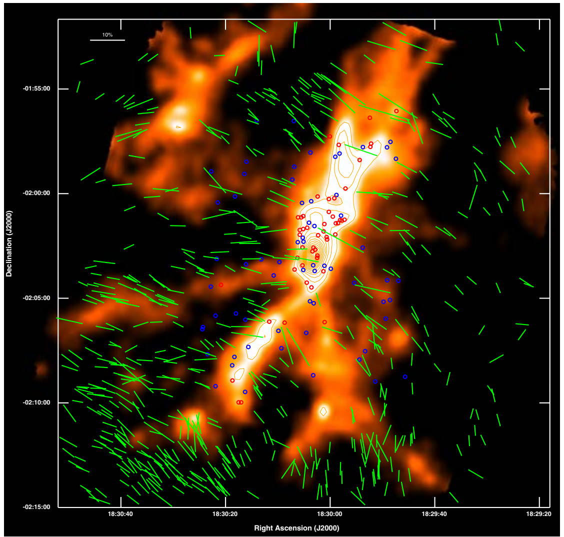
Make maps of unprecedented depth for large # of molecular clouds

Filaments and Cores

0.01 – 1 pc

2) Do B-fields provide significant support against gravitational collapse, and slow down their collapse, fragmentation?

Li et al. 2014 PPVI



Sugitani 2011

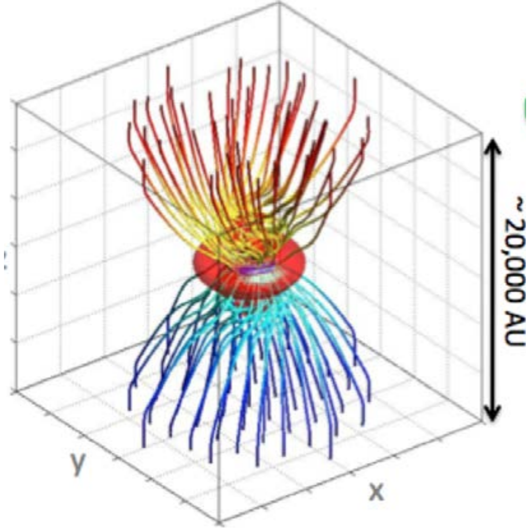
Map magnetic fields in hundreds of filaments.

Protostellar Disks

<0.01 pc

Do B-fields inhibit formation of large protostellar and disks

Galli & Shu 1993
Joos et al. 2012

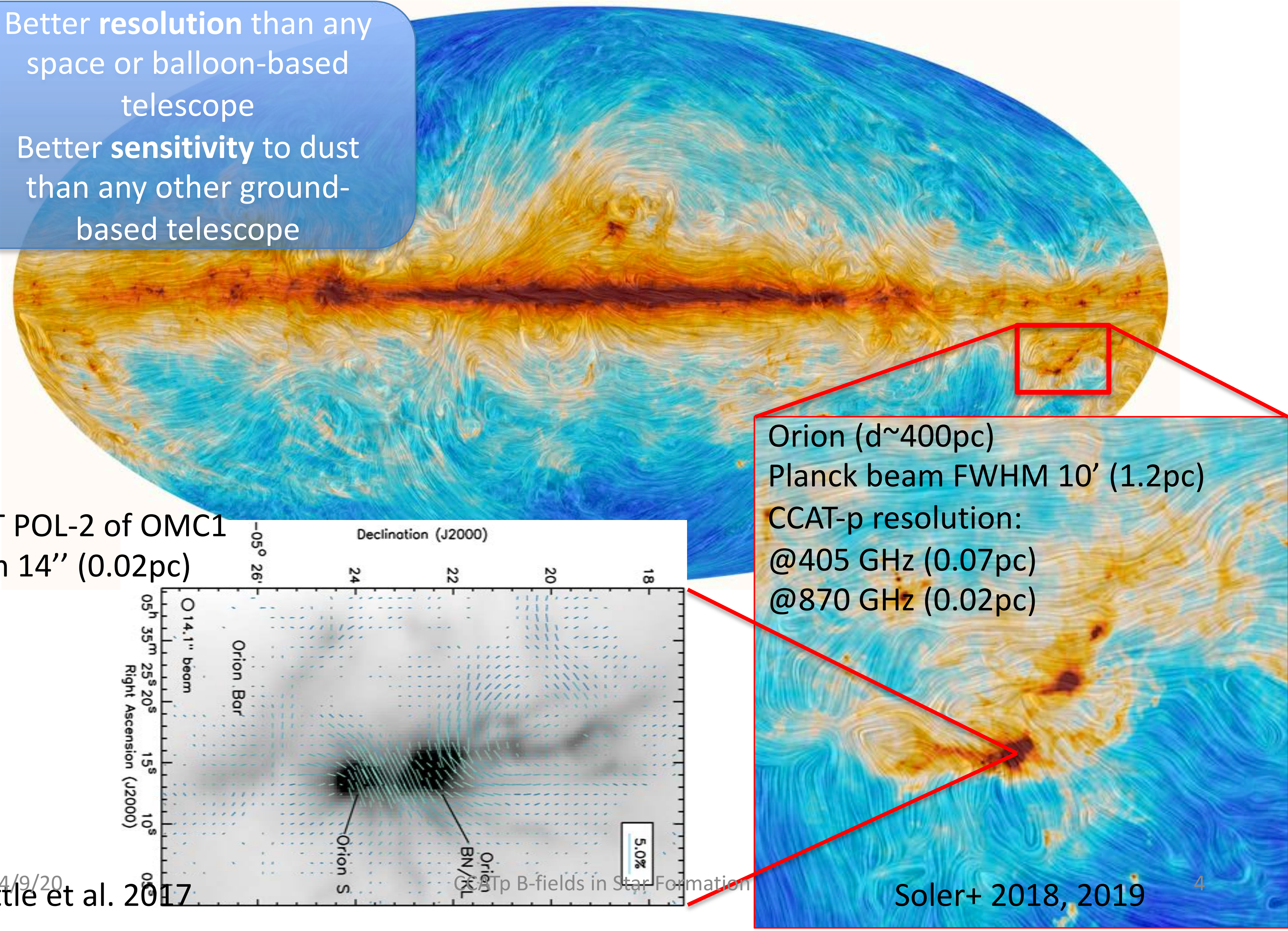


Davidson et al. 2014

Map B-fields in thousands of star forming cores which have embedded disks.

Why is CCAT ideal for this science?

- Better **resolution** than any space or balloon-based telescope
- Better **sensitivity** to dust than any other ground-based telescope



JCMT POL-2 of OMC1
Beam 14'' (0.02pc)

Pattle et al. 2017

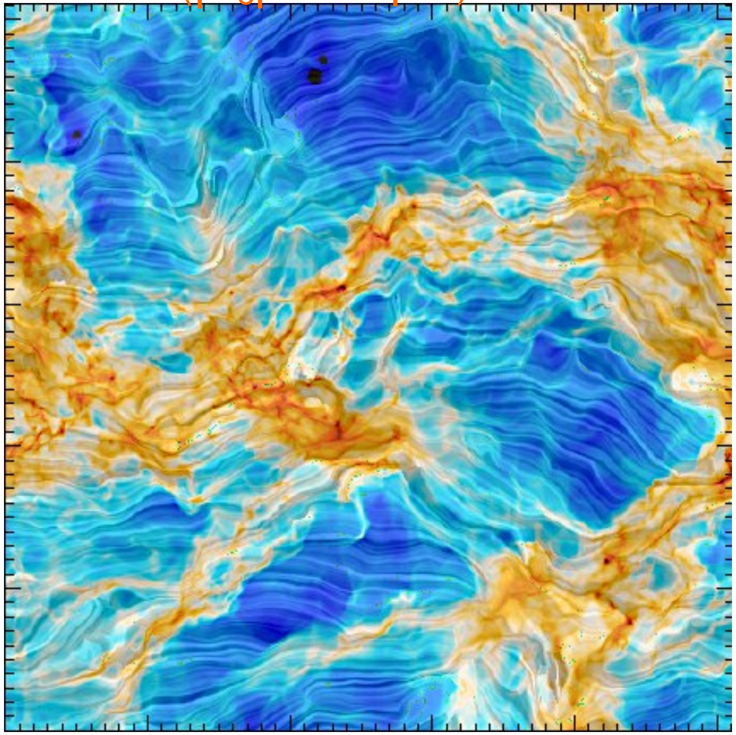
Orion (d~400pc)
Planck beam FWHM 10' (1.2pc)
CCAT-p resolution:
@405 GHz (0.07pc)
@870 GHz (0.02pc)

Soler+ 2018, 2019

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 $\beta = (c_s/v_A)^2$
- Ratio of *Magnetic Support vs Gravitational Potential Energy*
  - Mass to Flux ratio $\mu = M/M_{\Phi}$, $M_\Phi = \Phi/2\pi G^{1/2}$, $\Phi \sim \pi r^2 B$

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

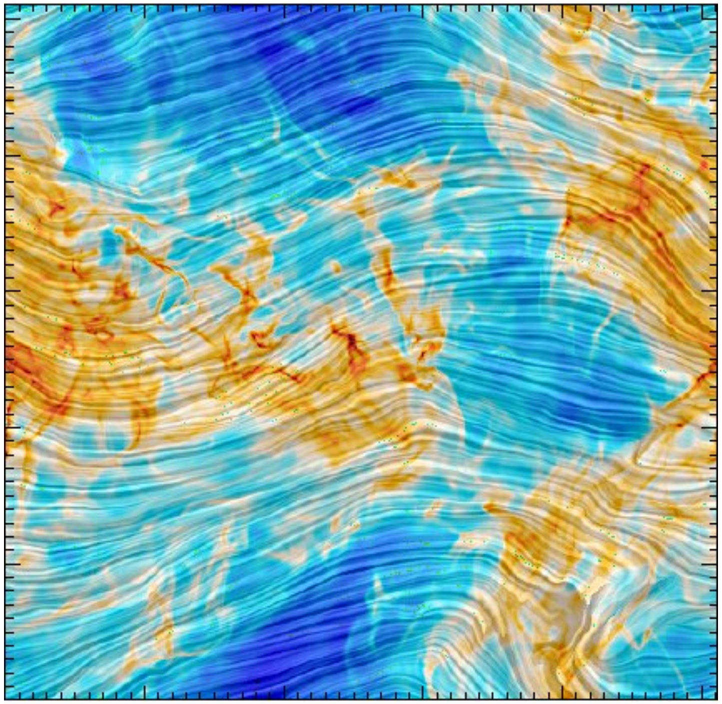


Weak magnetic field ($|B_0|=0.35\mu G$)

disordered B-field

low N_H ➔ B-field || to N contours

high N_H ➔B-field || to N contours



Strong magnetic field ($|B_0|=10.97\mu m$)

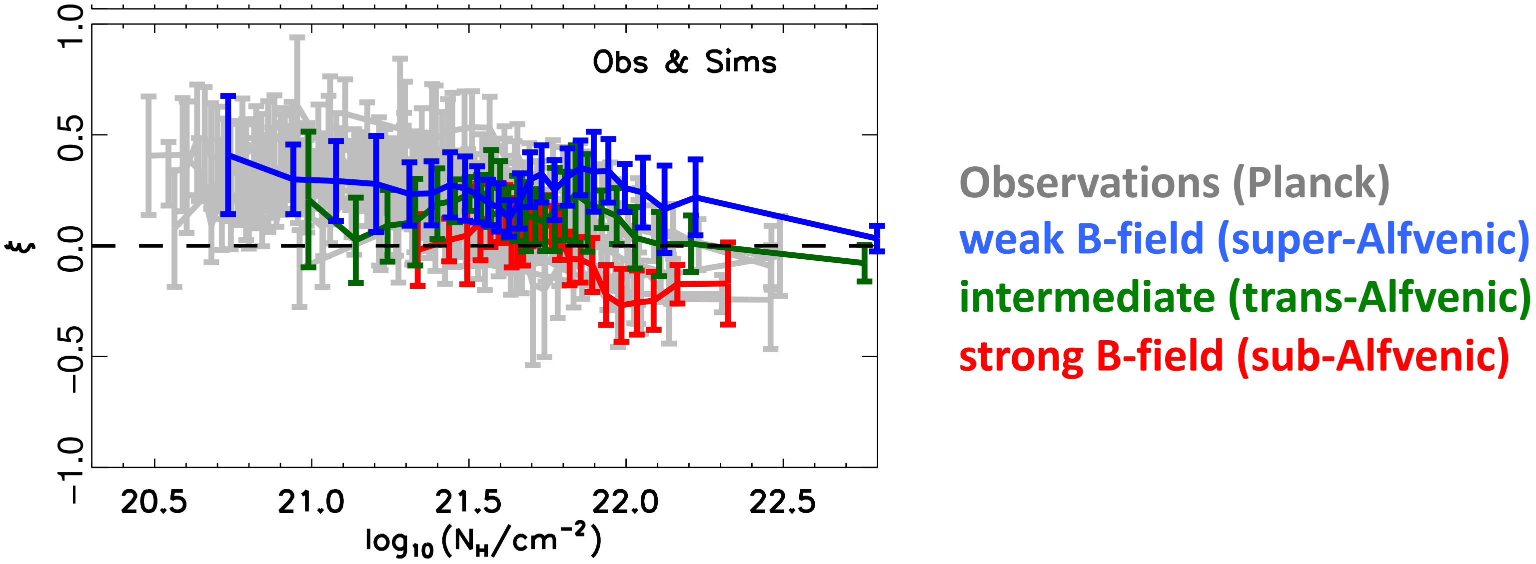
ordered B-field

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 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

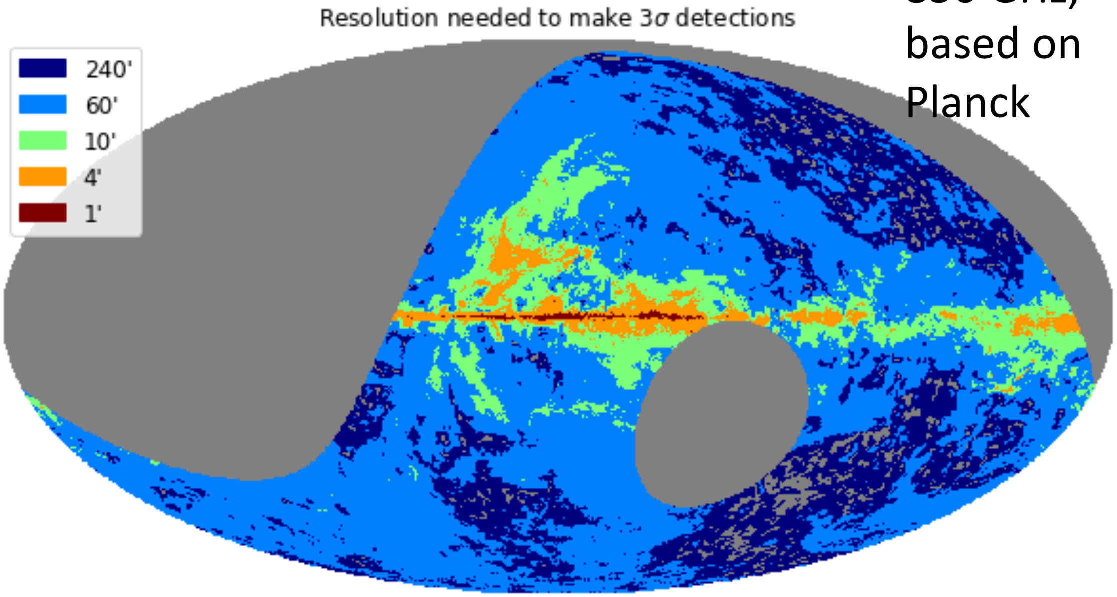
Polarization Statistical Analysis Methods

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+ 2019
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, Pattle+ 2017, Pillai+2019
PDFs of Polarization observables	3-D field orientation, B, M_A	polarization	Jones 1989, Falceta-Goncalves 2008, Fissel+ 2016, King+ 2017, Chen+ 2019, Sullivan+ submitted
Velocity Gradient vs Magnetic Field Direction	B, M_A, μ	polarization, molecular line observations	Lazarian+2017, Yuen+2017, Hue 2019a,b

All of these techniques require large, detailed polarization maps.

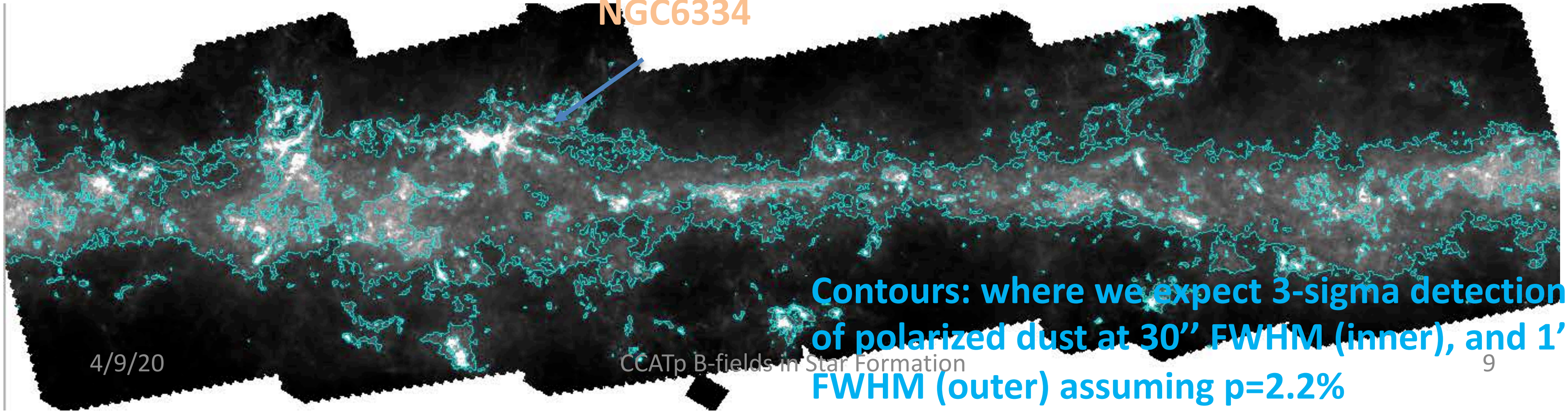
What can we do with the planned large area surveys?

- Large area CMB 25,000deg^2 mapped ove 4,000 hours.
  - dP = 9.6 Mjy/Sr. Too shallow to detect polarization at full resolution
  - But we could map many, probably hundreds of clouds if we degrade our resolution.Most fairly distant (2-10kpc)



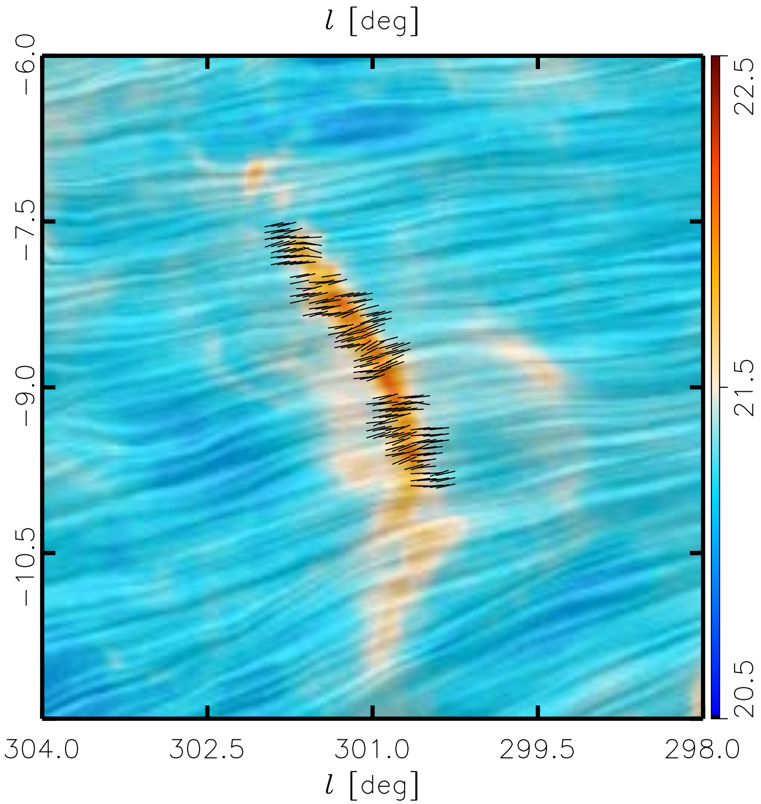
850 GHz, based on Planck

Herschel HiGal 850 GHz map of 14 degrees of the Galactic Plane:

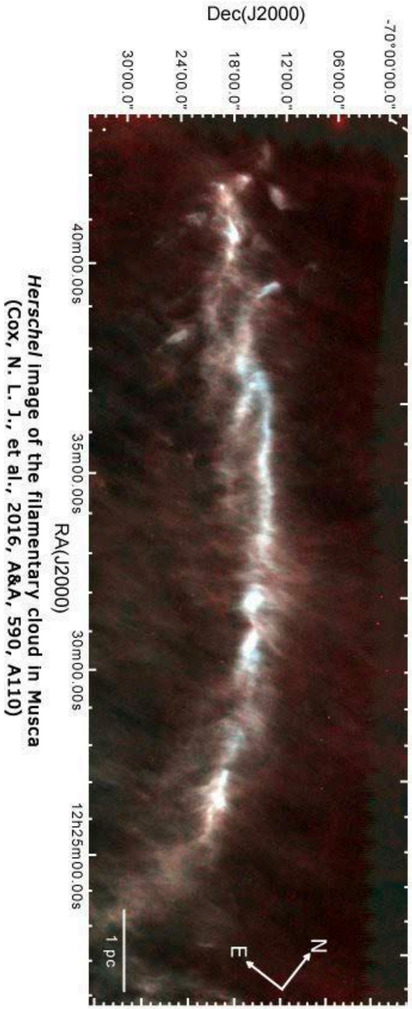


Contours: where we expect 3-sigma detections of polarized dust at 30'' FWHM (inner), and 1' FWHM (outer) assuming p=2.2%

We would like to request additional extremely deep small area ~4deg^2 surveys



Soler et al 2016: Planck + Optical/Near-IR inferred B-field



Cox et al. 2016 Herschel

Has a highly ordered (potentially unusually strong) magnetic field.

Has no protostars, so this is potentially an extremely young molecular cloud.

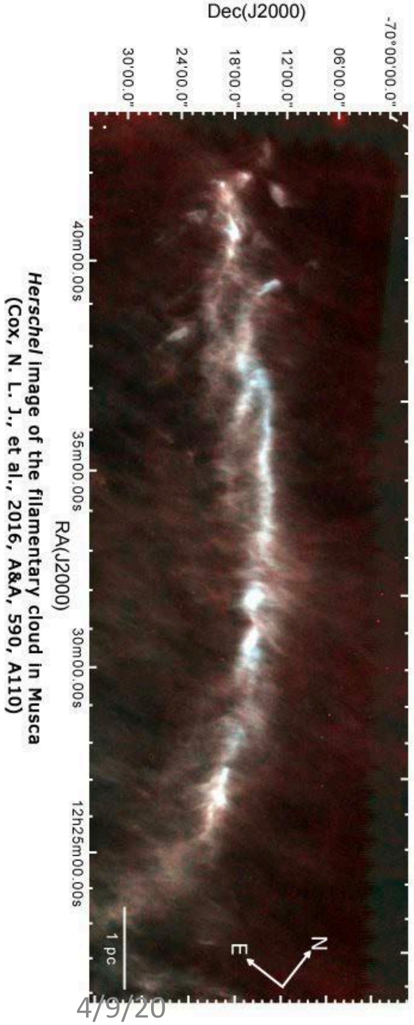
Not visible to BLAST, too faint for other ground based polarimeters.

CCATprime 850 GHz Map of Musca

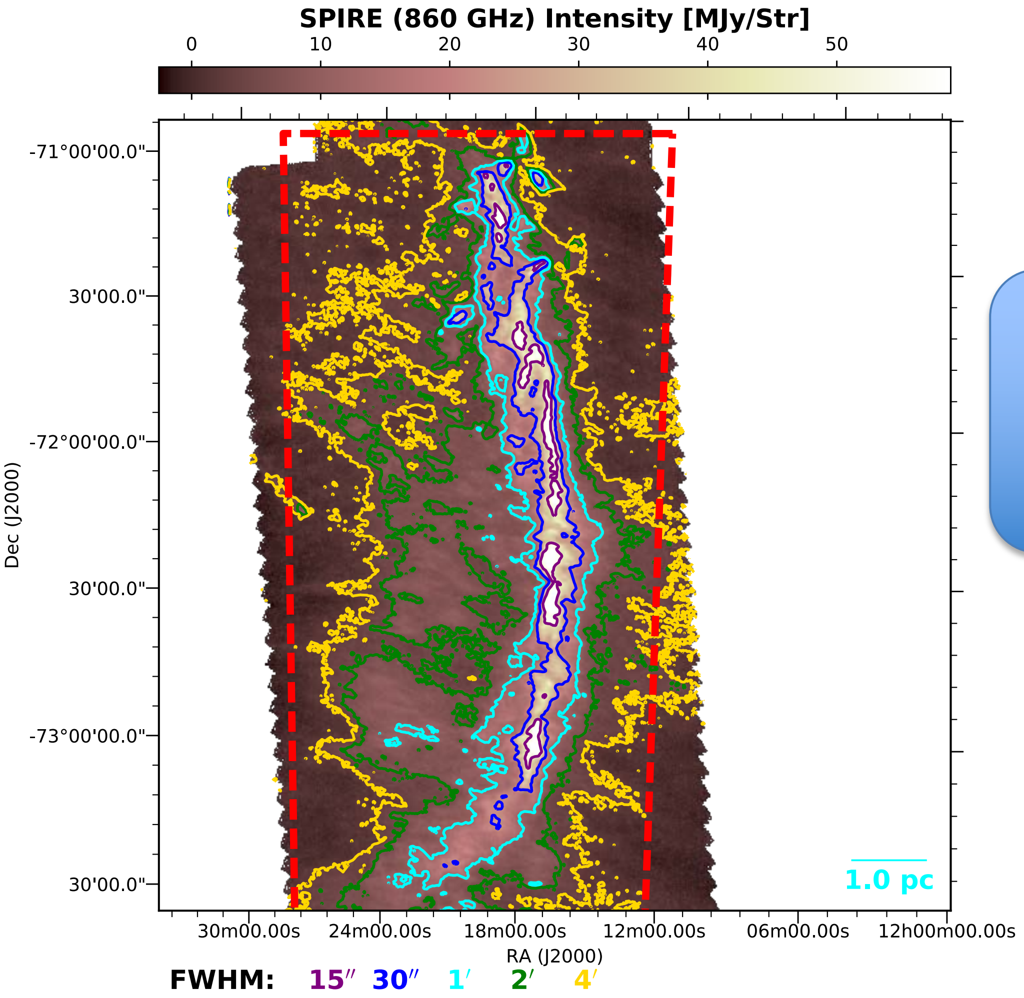
4deg^2 mapped to a depth of dP = 0.83 MSy/Sr 12x deeper than the CMB survey

(would require 80 hours at the sensitivities in Table 1 of Choi et al., 160 hours of early science time)

Resolution for which we could obtain 3 sigma detections (assuming p = 5%)



Herschel image of the filamentary cloud in Musca (Cox, N. L. J., et al., 2016, A&A, 590, A110)

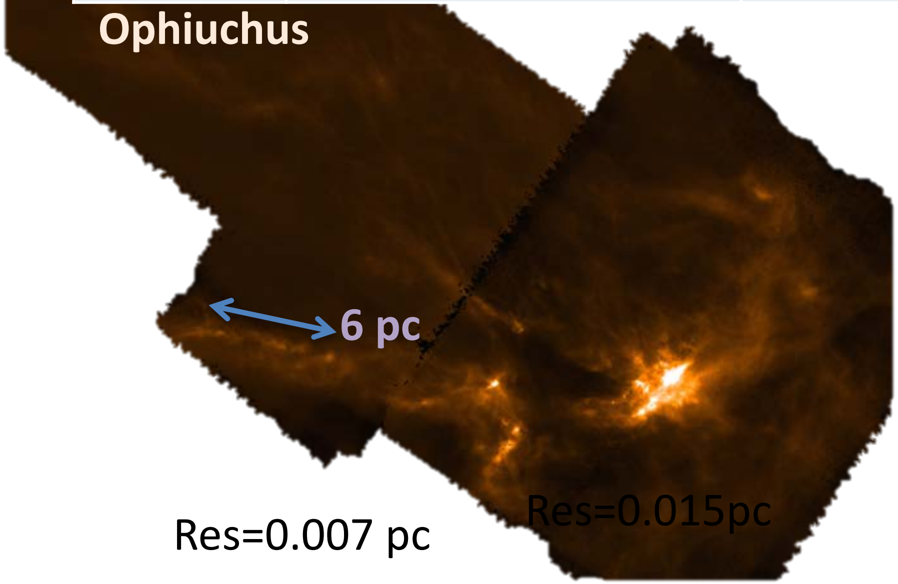


# of 3σ detections with FWHM 860 GHz = 15″ : 6293.0, 1′: 1395.0, 4′: 288.0

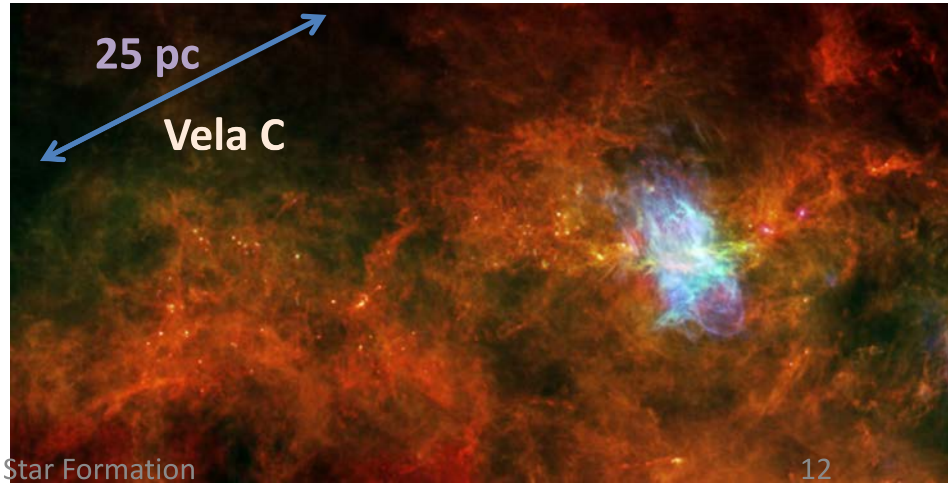
Suggested Early Science Project!

Longer Term Goal: CCATPrime Survey of Nearby Star forming regions

Molecular cloud	SF Activity	Cloud Mass	Distance	Poln expected	Area Covered	Hours Spent
			[pc]	(conservative)	(deg^2)	(full science)
Musca	quiescent	low mass	200	5%	4	80
Chamaeleon	low activity	low mass	200	4%	4	50
Aquila	lots of SF activity, lots of protostars sources	low mass	400	4%	4	50
Serpens South	active clustered SF	intermediate mass	400	3%	4	50
Orion	evolved high mass SF	high mass	450	3%	4	50
VelaC	many protostars	high mass	900	2.50%	4	50
Ophiuchus	moderate	intermediate mass	160	3%	4	50
Pipe Nebula	quiescent	low mass	150	3%	4	80



About 300 hours to map 6 clouds
450 hours to map 8 clouds.



Res=0.05pc