The Formation of Dense Gas Structures within a Magnetized Giant Molecular Cloud: A BLASTPol Study of Vela C

Collaborators:
BLASTPol and BLAST-TNG collaborations
PI Mark Devlin, U.Penn

Juan Soler (MPIA)

Mopra/ATCA Collaborators:
Maria Cunningham,
Paul Jones, Vicki Lowe,
Claire-Elise Green (UNSW)

Laura Fissel
Jansky Postdoctoral Fellow, NRAO-CV
NRAO Postdocs Symposium, Socorro
March 20th, 2018

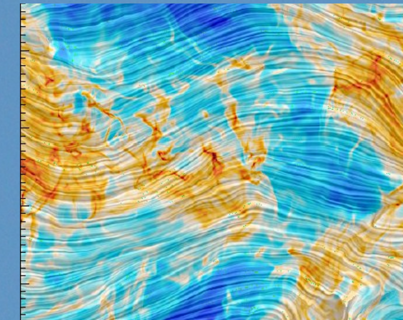
Outline:

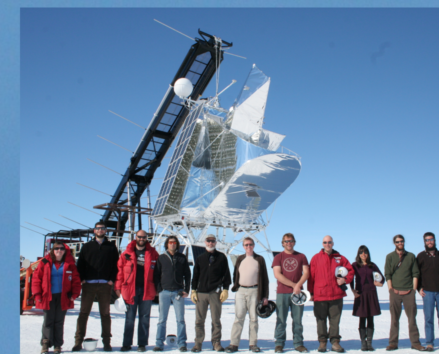
- **Background: How can we use polarization maps to study magnetic fields in star formation?**

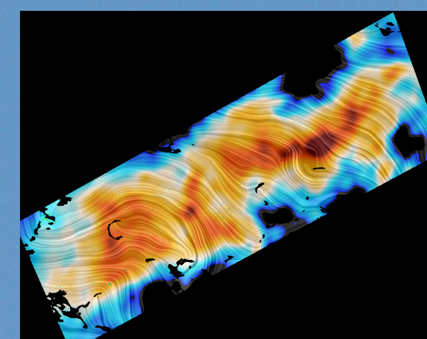
- **The Balloon-born Large Aperture Sub-mm Telescope for Polarimetry (BLASTPol)**

- **Case Study: BLASTPol observations of Vela C:**
  - **Alignment of Cloud structure vs. B-field**

- **Next Generation Polarimeters**

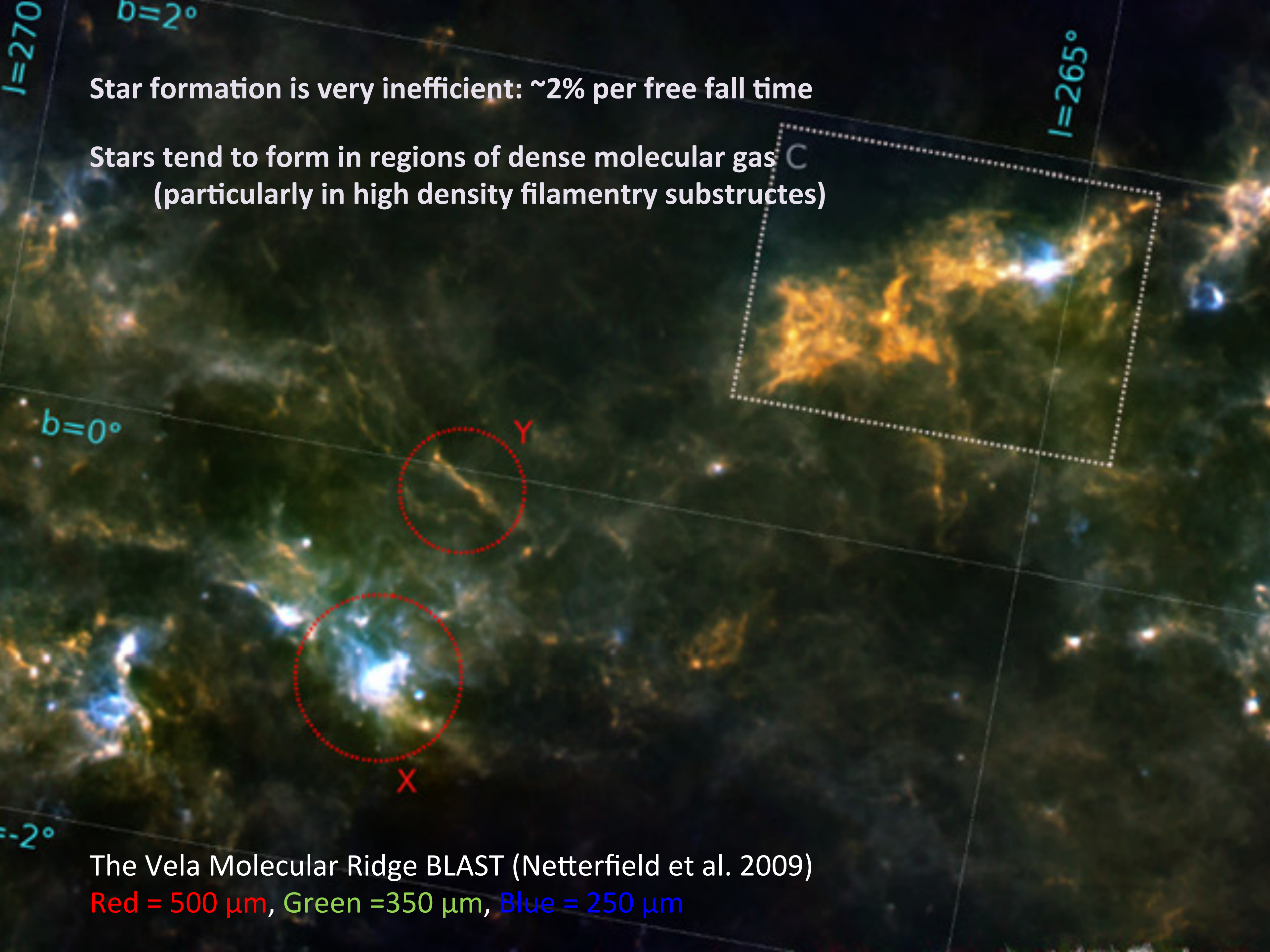






Star formation is very inefficient: ~2% per free fall time

Stars tend to form in regions of dense molecular gas
(particularly in high density filamentry substructes)



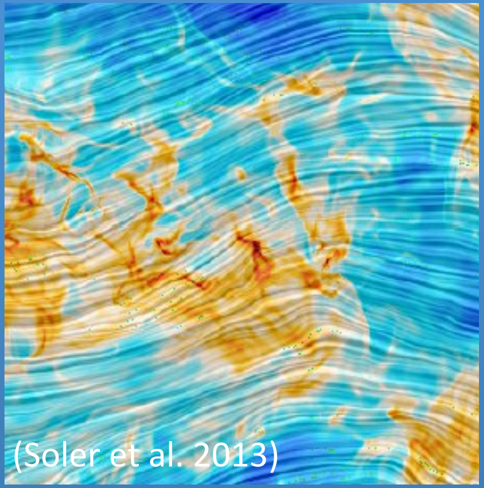
The Vela Molecular Ridge BLAST (Netterfield et al. 2009)
Red = 500 µm, Green =350 µm, Blue = 250 µm

What regulates Star Formation?

Supersonic Turbulence

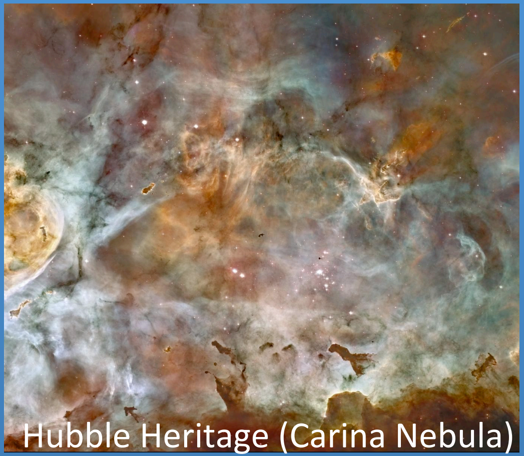
E.g. MacLow and Klessen, 2004

Magnetic Fields



Shu et al., 1984
Nakamura and Li, 2008

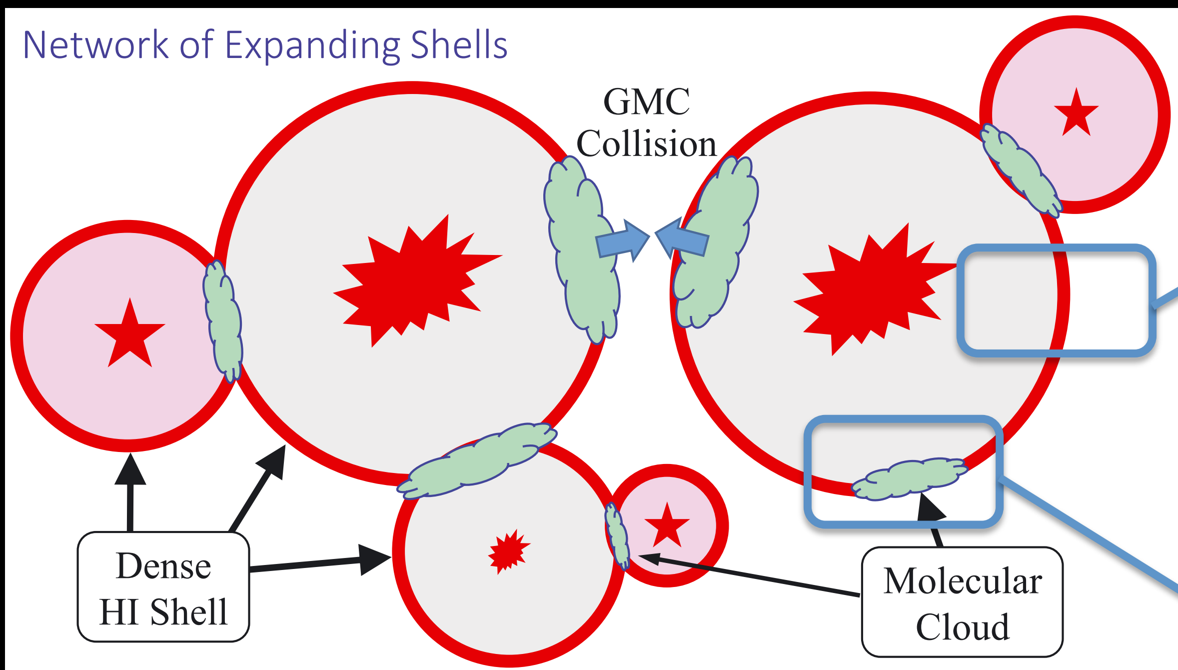
Feedback



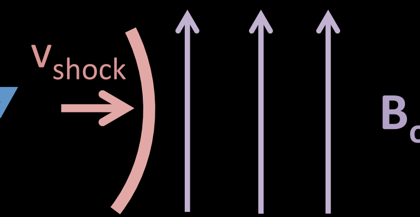
E.g. Krumholtz, Matzner and McKee, 2006

A Cartoon of Magnetized Cloud Formation

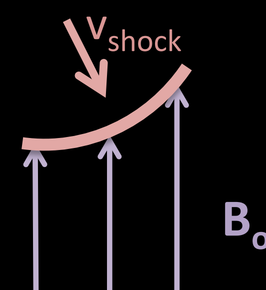
Inutsuka et al. 2015



Expansion nearly $\perp$ to Bo will not compress enough to form dense gas



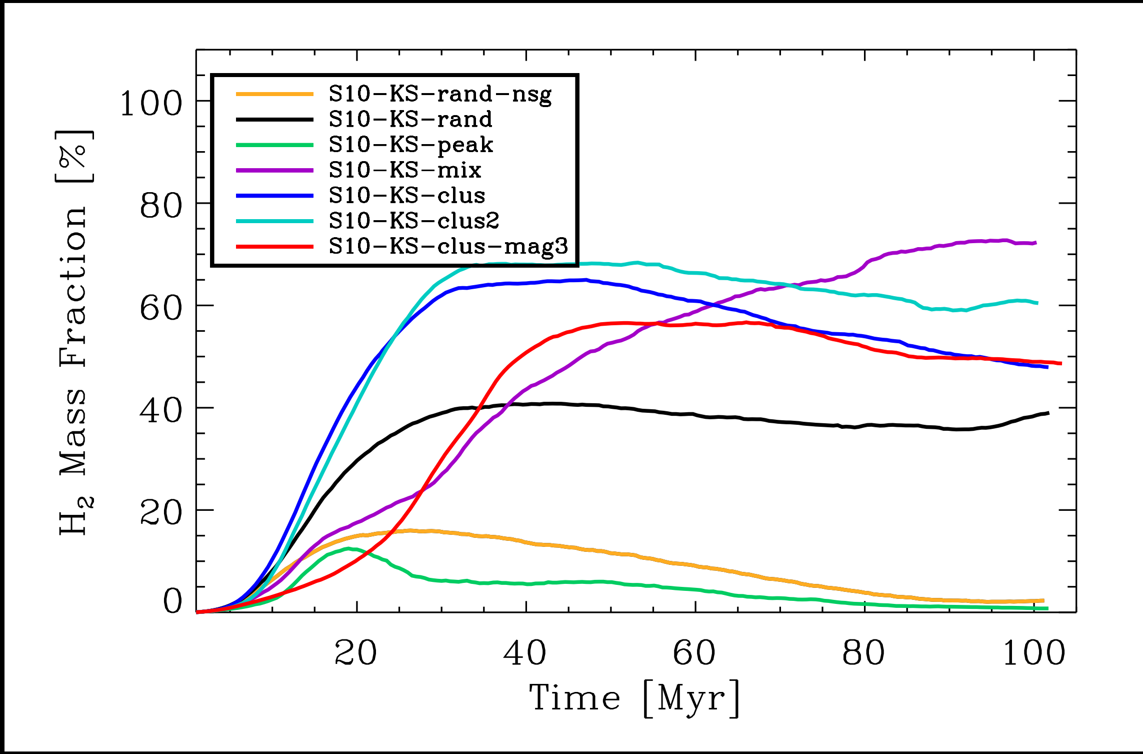
Expansion nearly || to Bo forms low density H_2



Magnetic fields set where clouds initially form, influence the direction of gas into clouds, and overall lower the rate of cloud formation.

Simulations from the SILCC Project

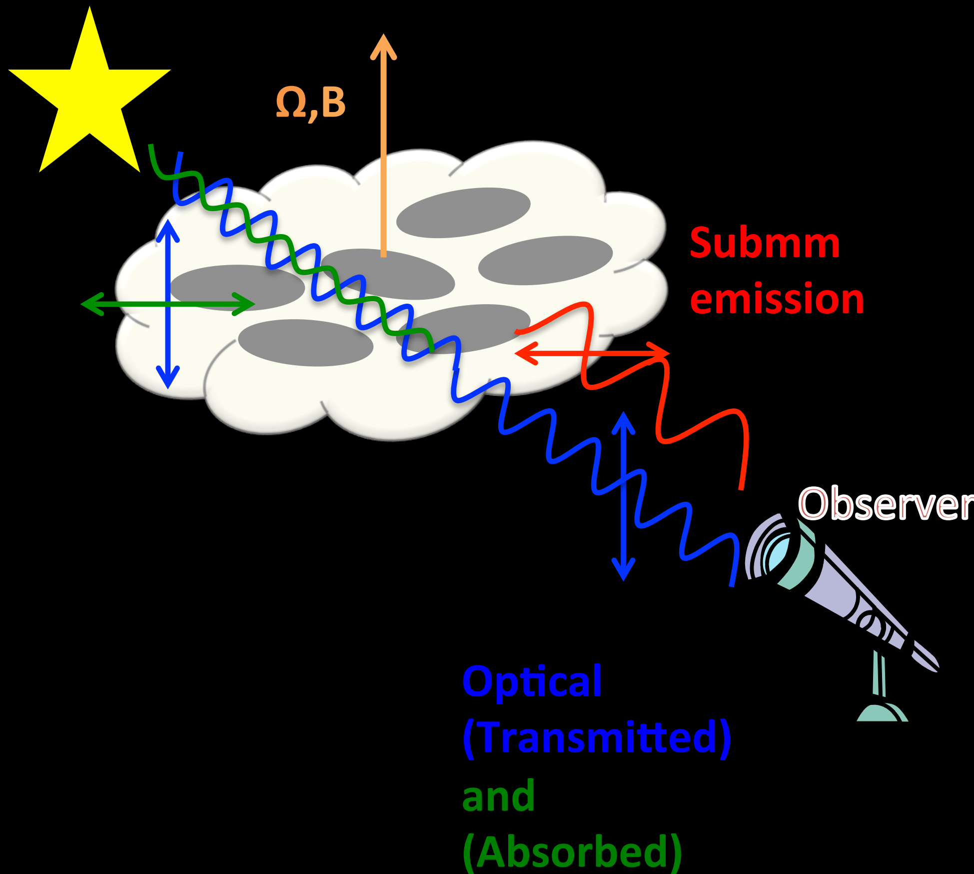
Walch et al.2015 (SN driving, with gas and dust cooling)

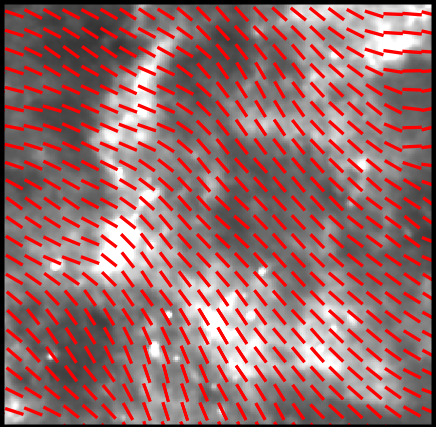


No magnetic field
H_2 fraction
plateaus ~20Myr

2μG magnetic field
H_2 fraction
plateaus ~40Myr

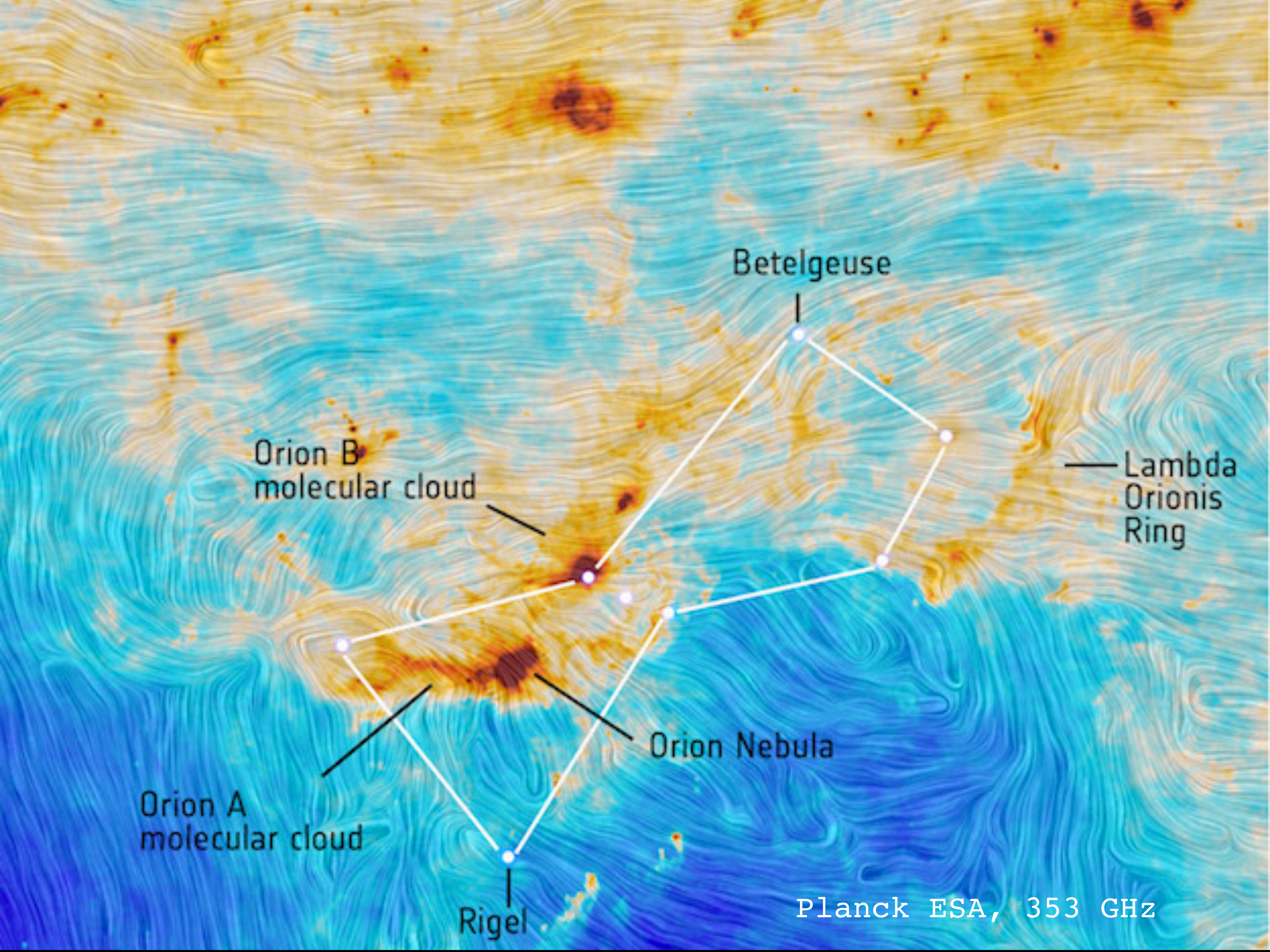
Dust Polarization



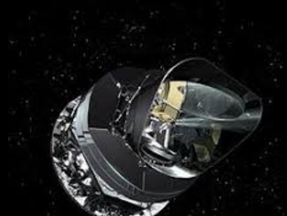


Grains alignment, likely due to torques from the local radiation field (λ<a)
See Lazarian 2007, Andersson et al. 2015

Caveats:
- No direct measurement of the magnetic field strength.
- Inferred magnetic field weighted by dust properties:
  - dust temperature
  - emissivity
  - alignment efficiency
- Weak signal (few %) ➔ *very difficult to observe from the ground!*


Betelgeuse
Orion B
molecular cloud
Lambda
Orionis
Ring
Orion Nebula
Orion A
molecular cloud
Rigel
Planck ESA, 353 GHz

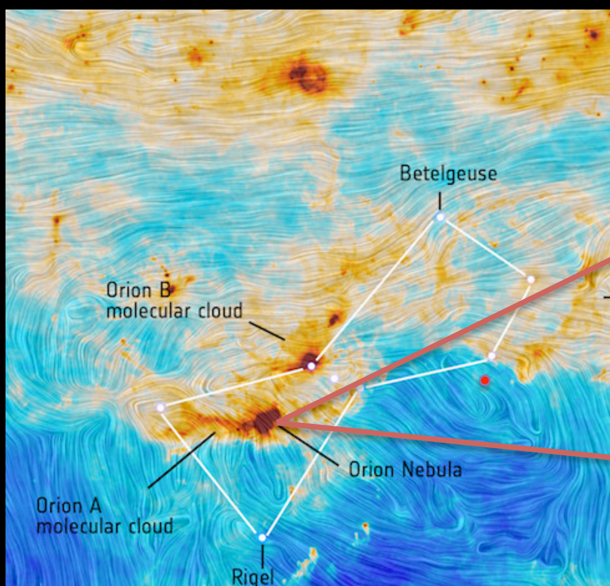
A New Era in Dust Polarization Studies

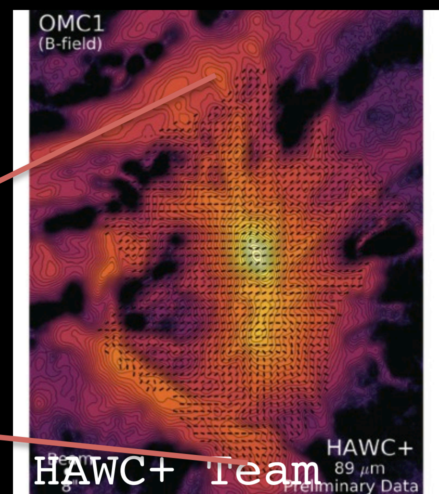


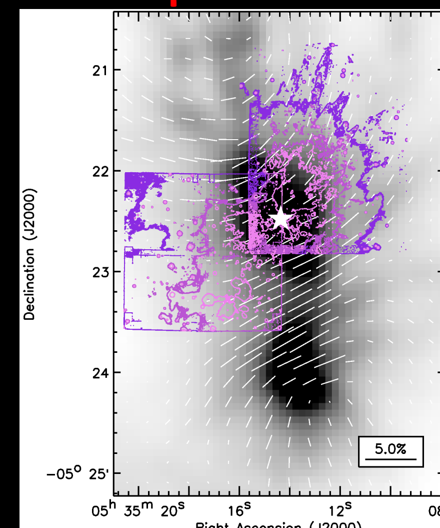
Planck Satellite
870 µm

SOFIA HAWC+:
89, 154, 214 µm

JCMT POL-2:
850 µm







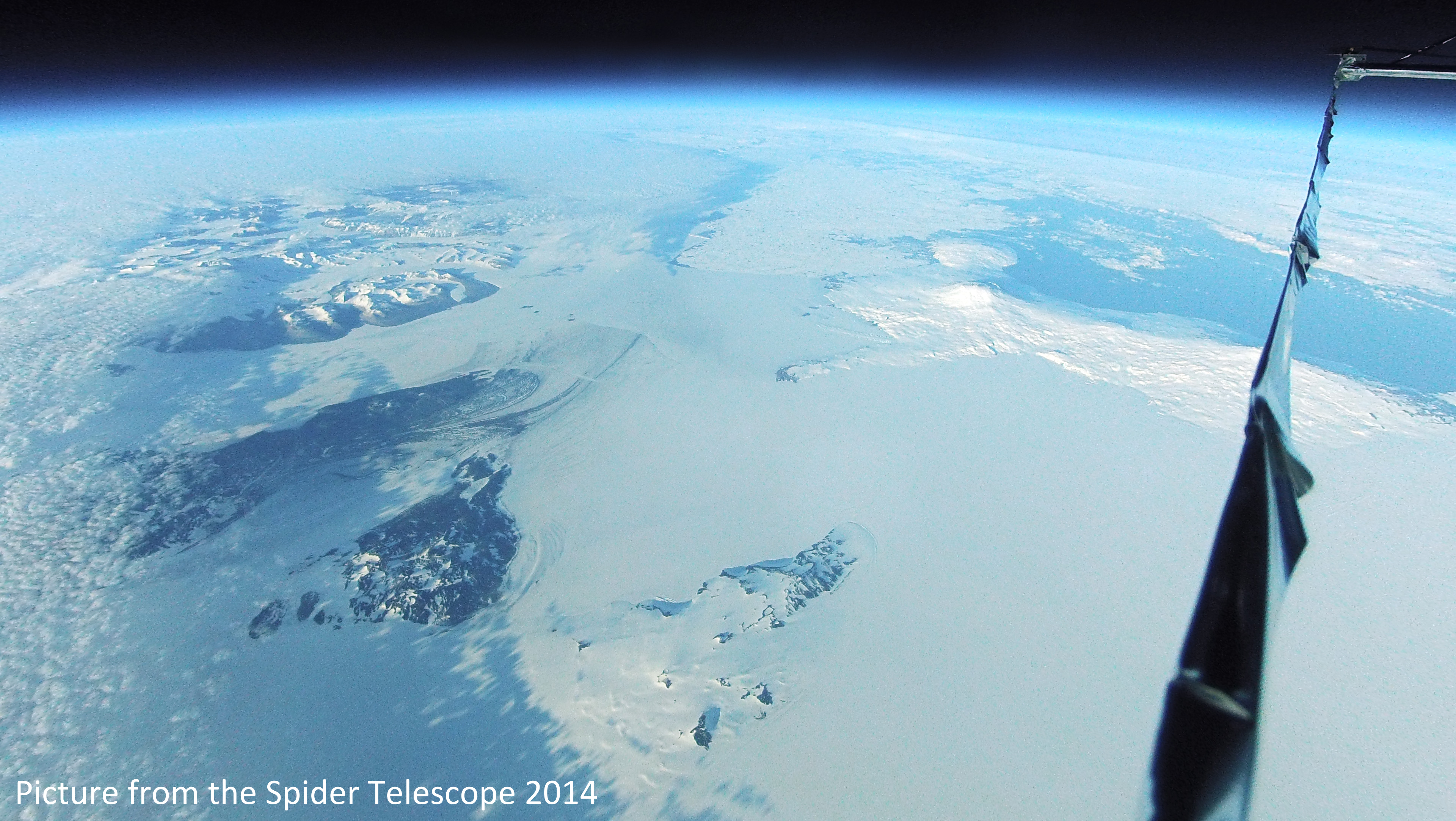
Pattle et al. 2017

Low resolution (10')

Restricted to bright clouds and small maps

The view from a stratospheric balloon

at 38 km above sea level (above 99.5% of the atmosphere)



Picture from the Spider Telescope 2014

BLASTPol: The Balloon-borne Large Aperture Submm Telescope for Polarimetry

- 1.8m aluminum primary mirror
- Bands: 266 detectors at 250, 350 and 500 μm
  - Uses detectors similar to Herschel SPIRE cooled to 300 mK by a Liquid He/N cryostat
- Beam FWHM 2.5' at 500 μm
- ~2" pointing precision/reconstruction

BLASTPol Team in Antarctica December 2012

BLASTPol Flights 2010 & 2012

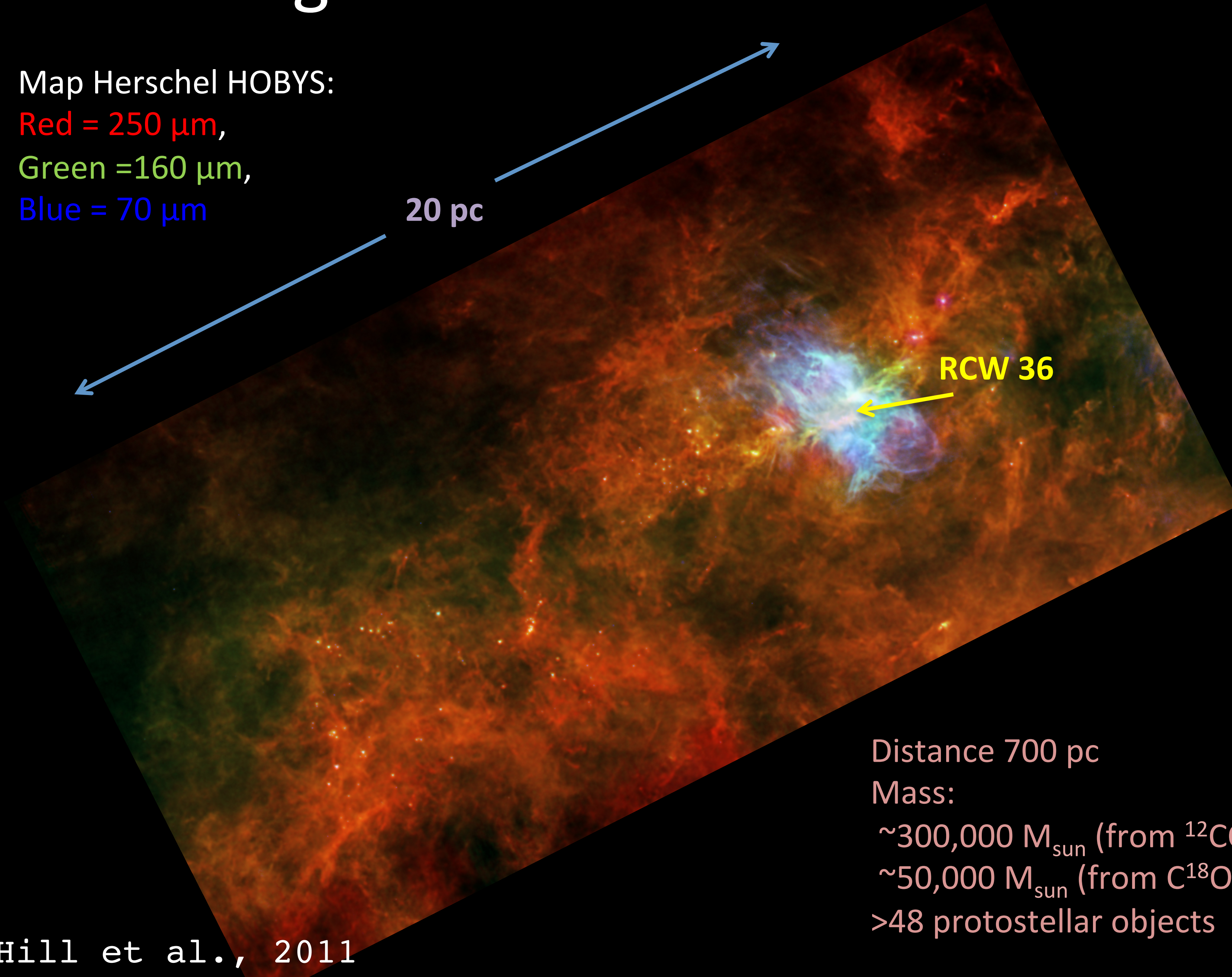
Flight Altitude ~38km

Terminated over the Ross Iceshelf.

Balloon Termination (SUNRISE)

Target Cloud: The Vela C GMC

Map Herschel HOBYS:
Red = 250 µm,
Green =160 µm,
Blue = 70 µm



Distance 700 pc
Mass:
~300,000 M_{sun} (from ^{12}CO)
~50,000 M_{sun} (from $C^{18}O$)
>48 protostellar objects

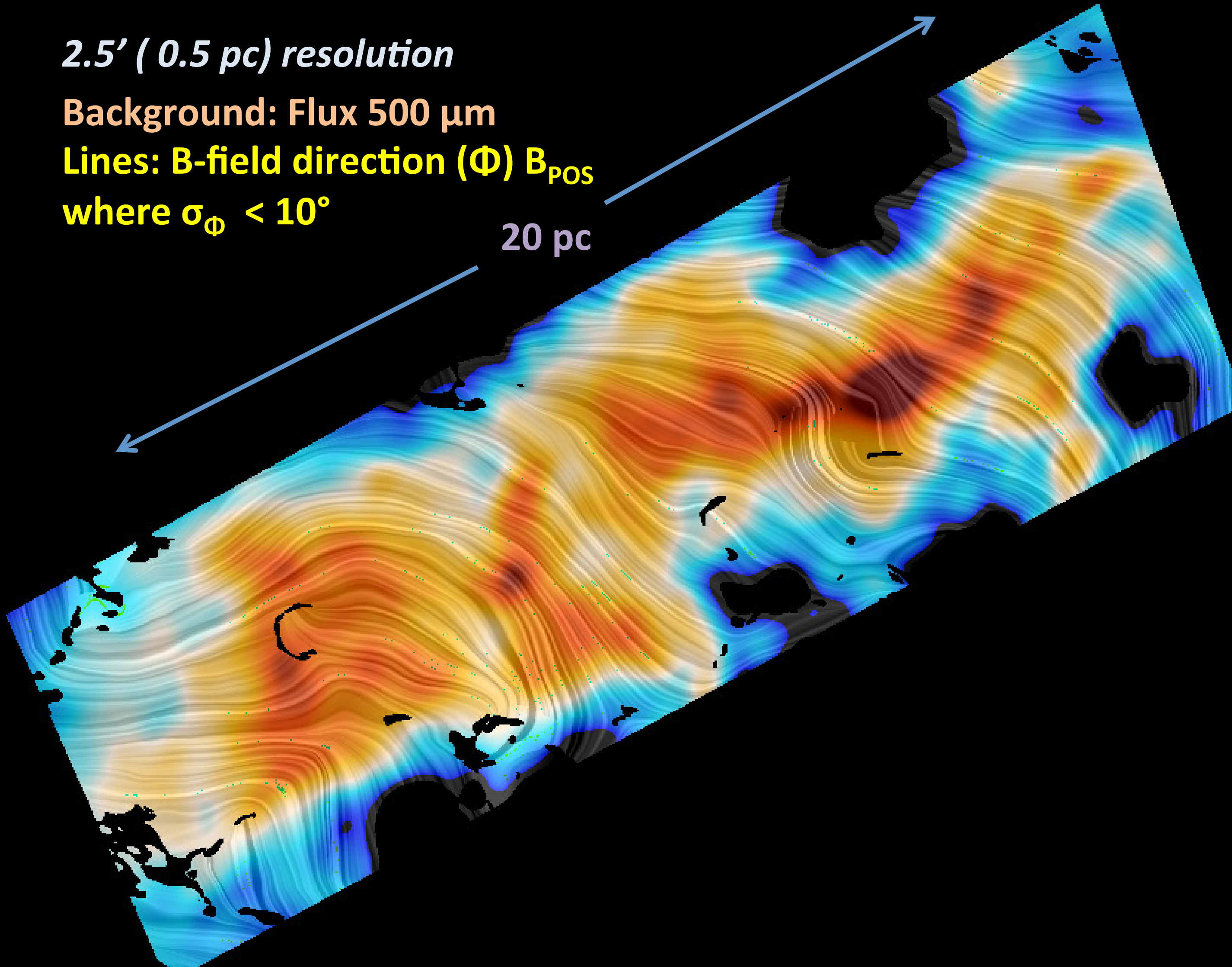
Hill et al., 2011

BLASTPol Inferred B-field Map of Vela C

2.5' (0.5 pc) resolution

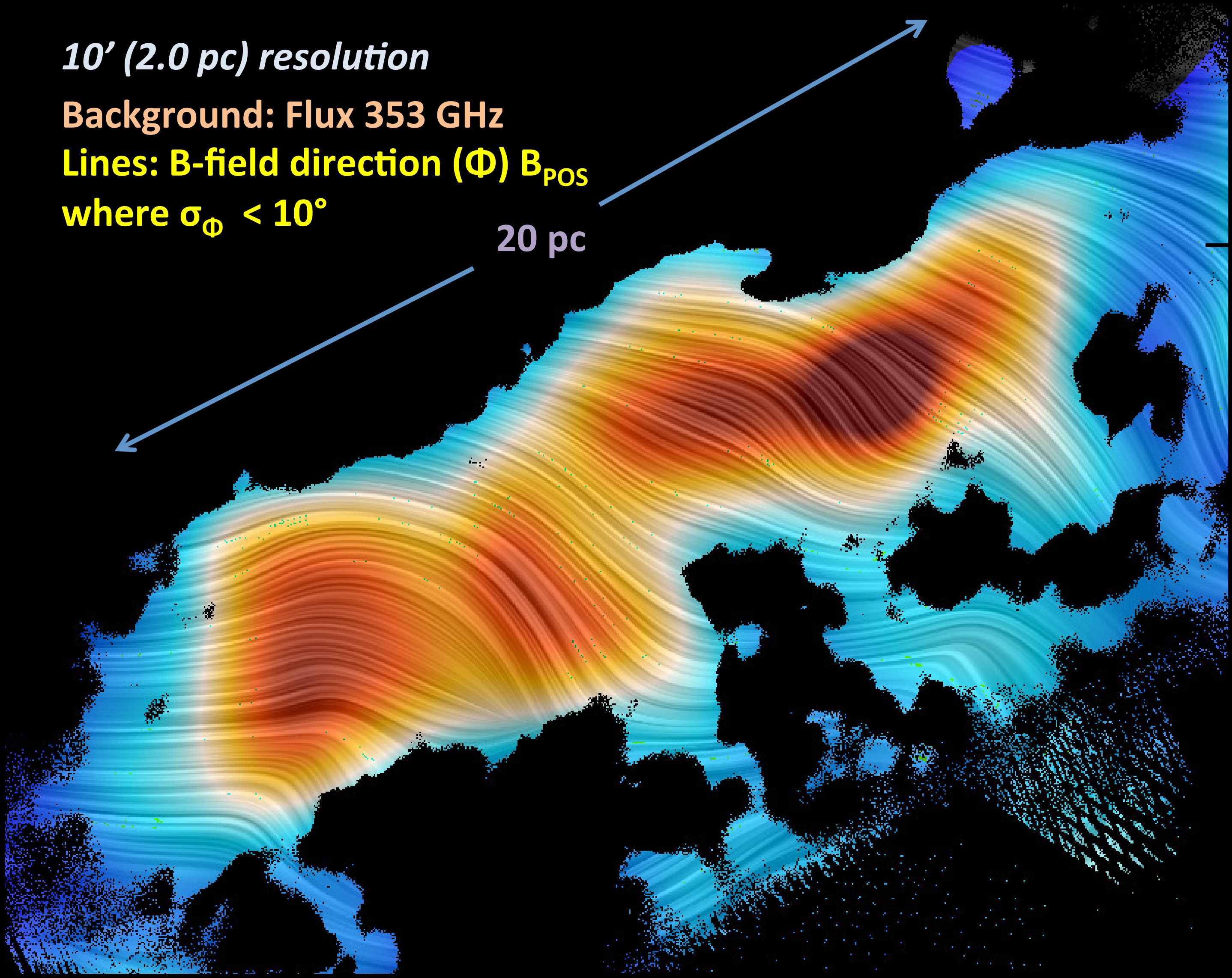
Background: Flux 500 µm

Lines: B-field direction (Φ) B_{POS} where $\sigma_{\Phi} < 10°$



Fissel et al. 2016

Planck B-field Map of Vela C



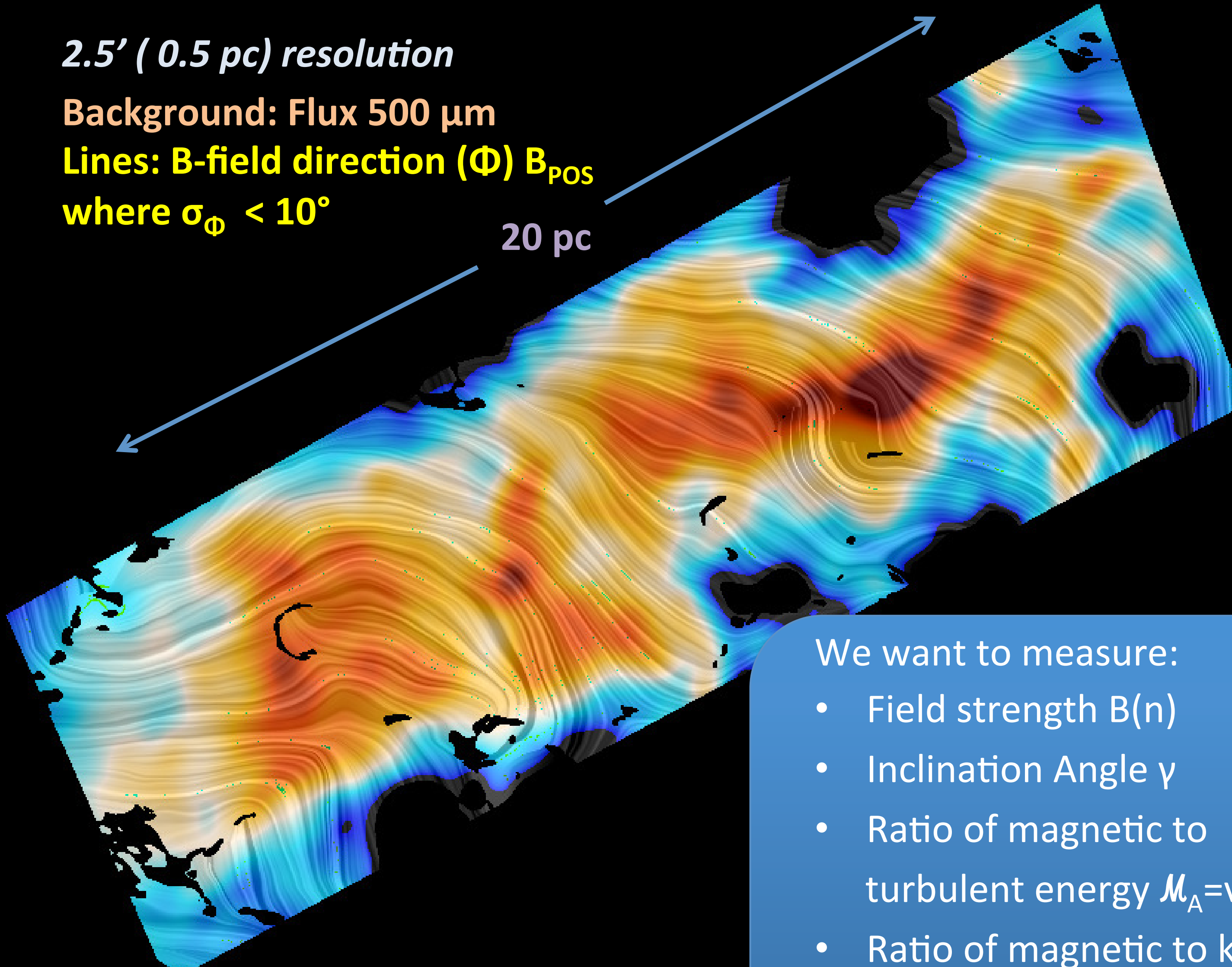
BLASTPol Inferred B-field Map of Vela C

2.5' (0.5 pc) resolution

Background: Flux 500 μm

Lines: B-field direction (Φ) B_{POS}

where $\sigma_{\Phi} < 10°$



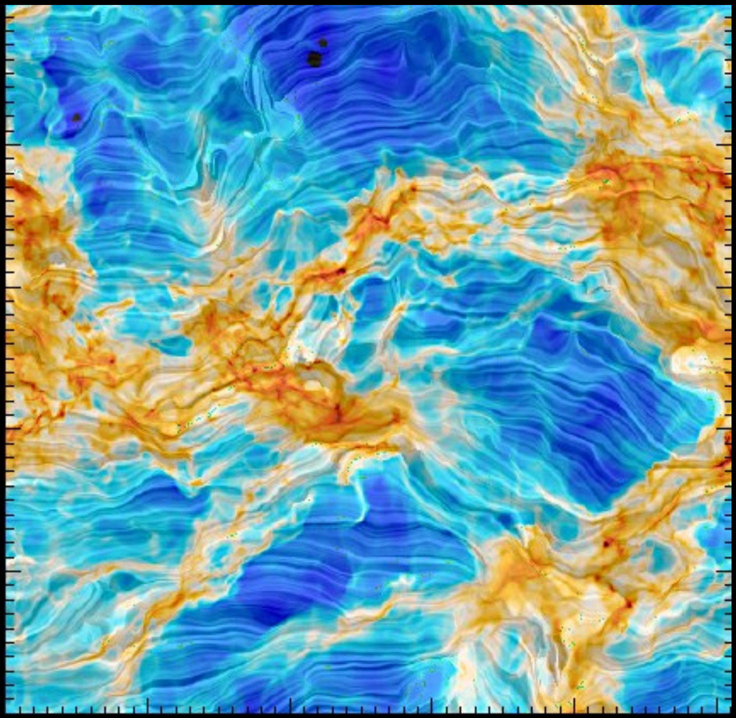
Fissel et al. 2016

We want to measure:

- Field strength B(n)
- Inclination Angle γ
- Ratio of magnetic to turbulent energy $\mathcal{M}_A = v/v_A$
- Ratio of magnetic to kinetic energy $\beta = (c_s/v_A)^2$

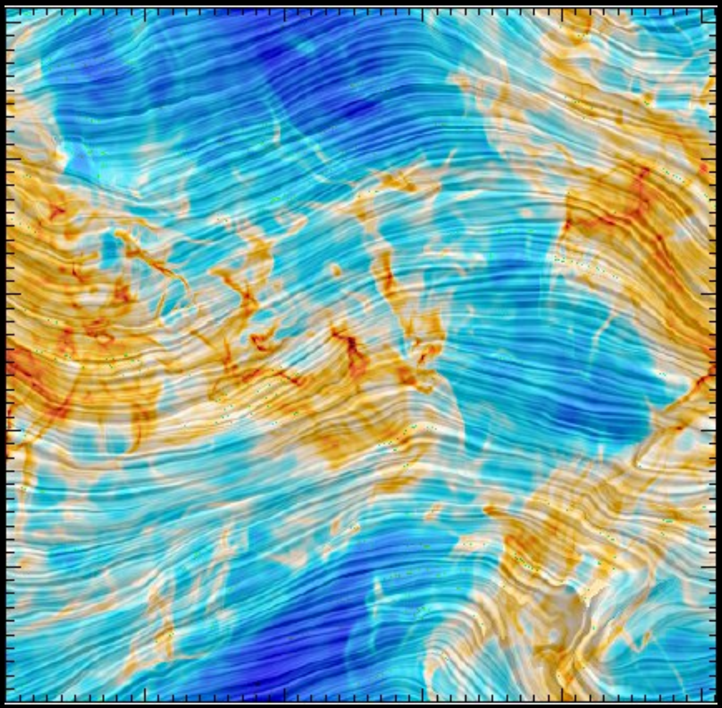
Statistical Comparisons with Synthetic Observations of Magnetized Cloud Models

Weak magnetic field
($|B_0|$=0.35μG)



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

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



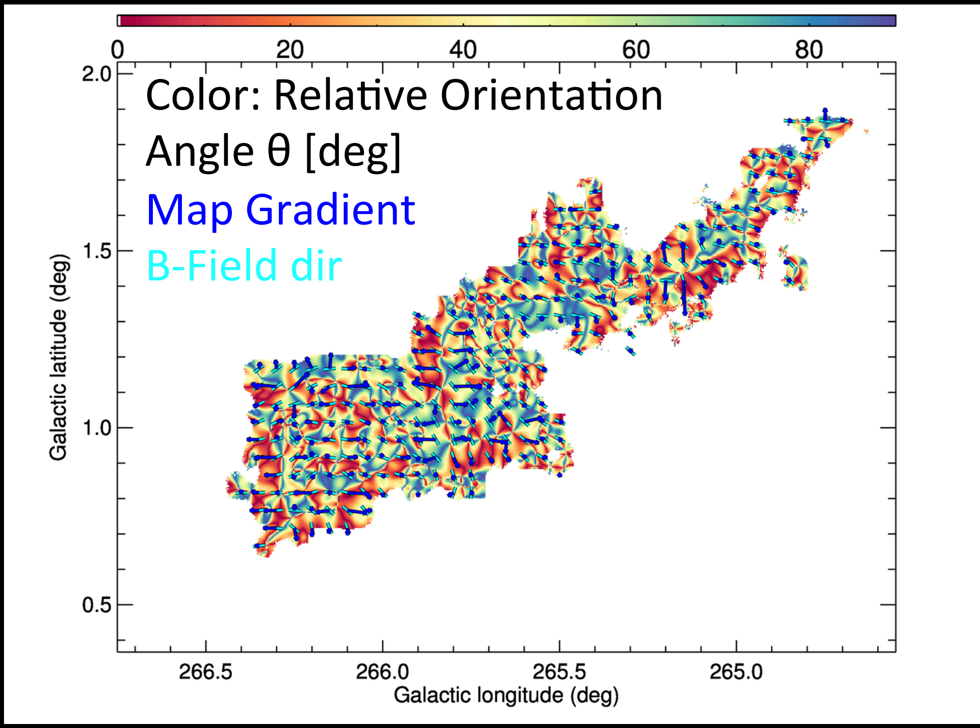
ordered B-field
low N_H ➔ B-field || to N contours
high N_H ➔ B-field perp to N contours

RAMSES MHD Simulations from Soler et al. 2013

Quantifying the Relative Orientation of cloud and magnetic field structure

- Orientation of the cloud structure from the gradient of the map
- Calculate the relative orientation angle θ between B-field and map iso-contours
- Quantify using the Projected Rayleigh Statistic:

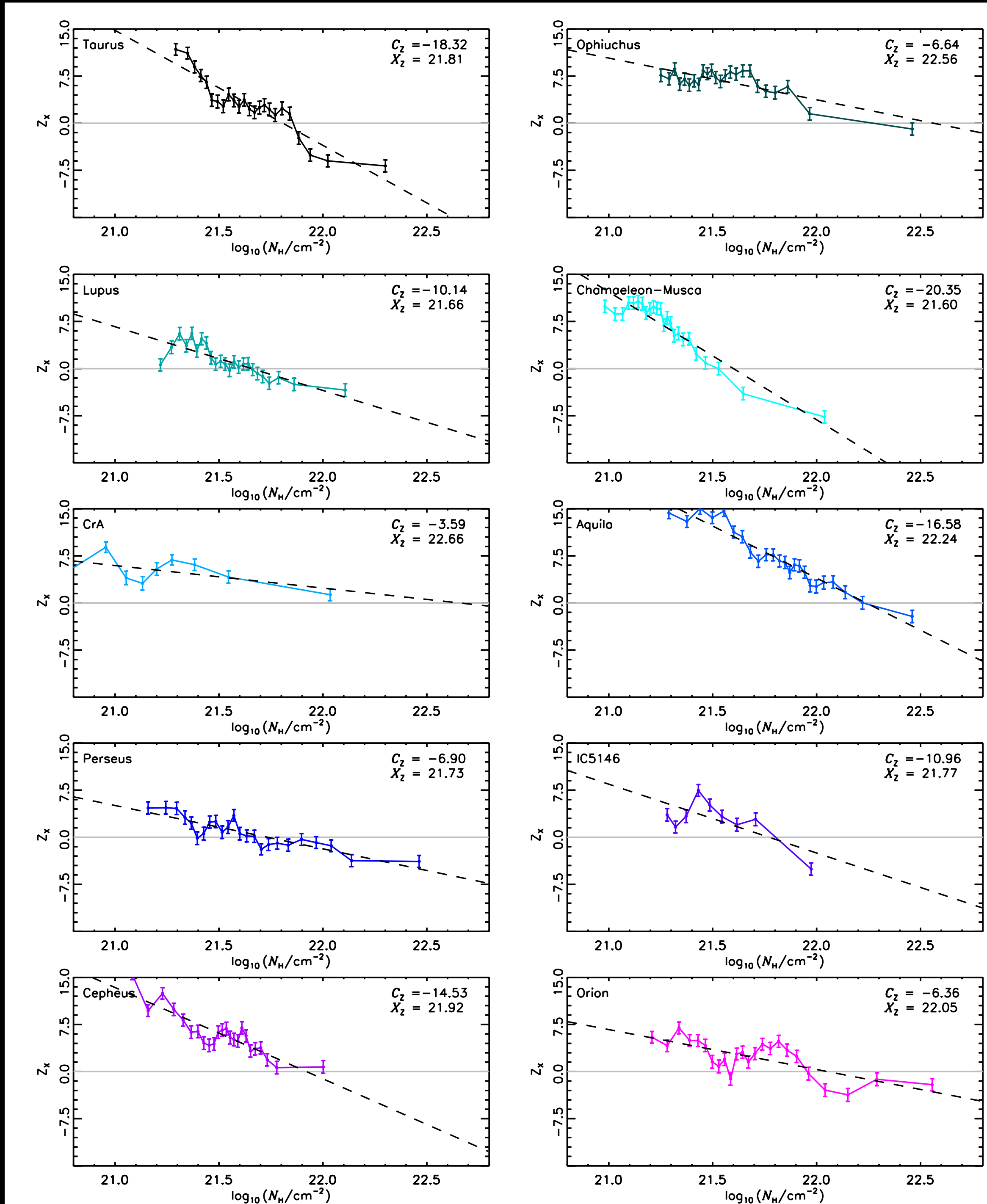
$$Z_x = \frac{\sum_i^n \cos(2\theta_i)}{\sqrt{\frac{n}{2}}}$$

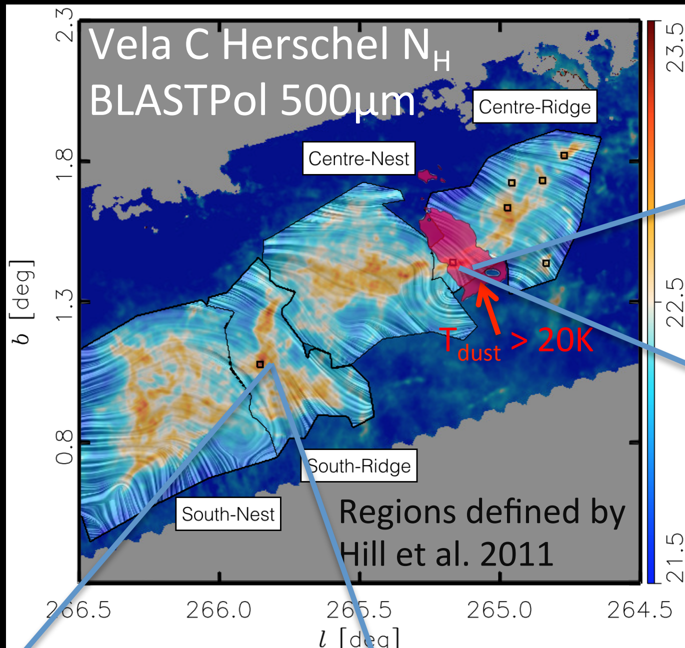


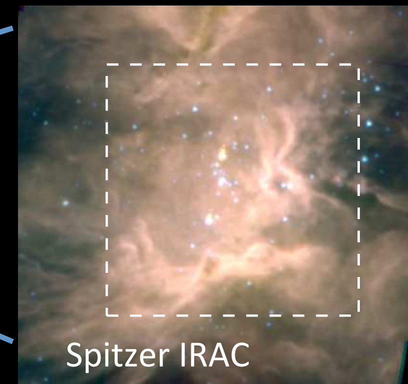
Projected Rayleigh Statistic for 10 nearby low mass clouds

Planck XXXV, 2016
Jow et al. 2017

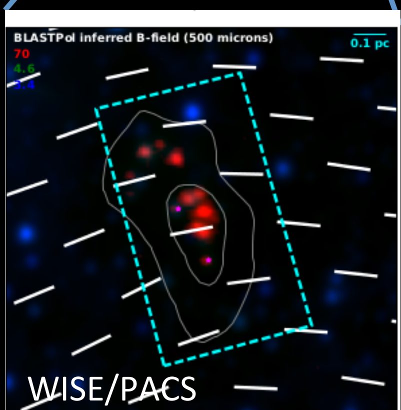
$$Z_x = \frac{\sum_i^n \cos(2\theta_i)}{\sqrt{\frac{n}{2}}}$$

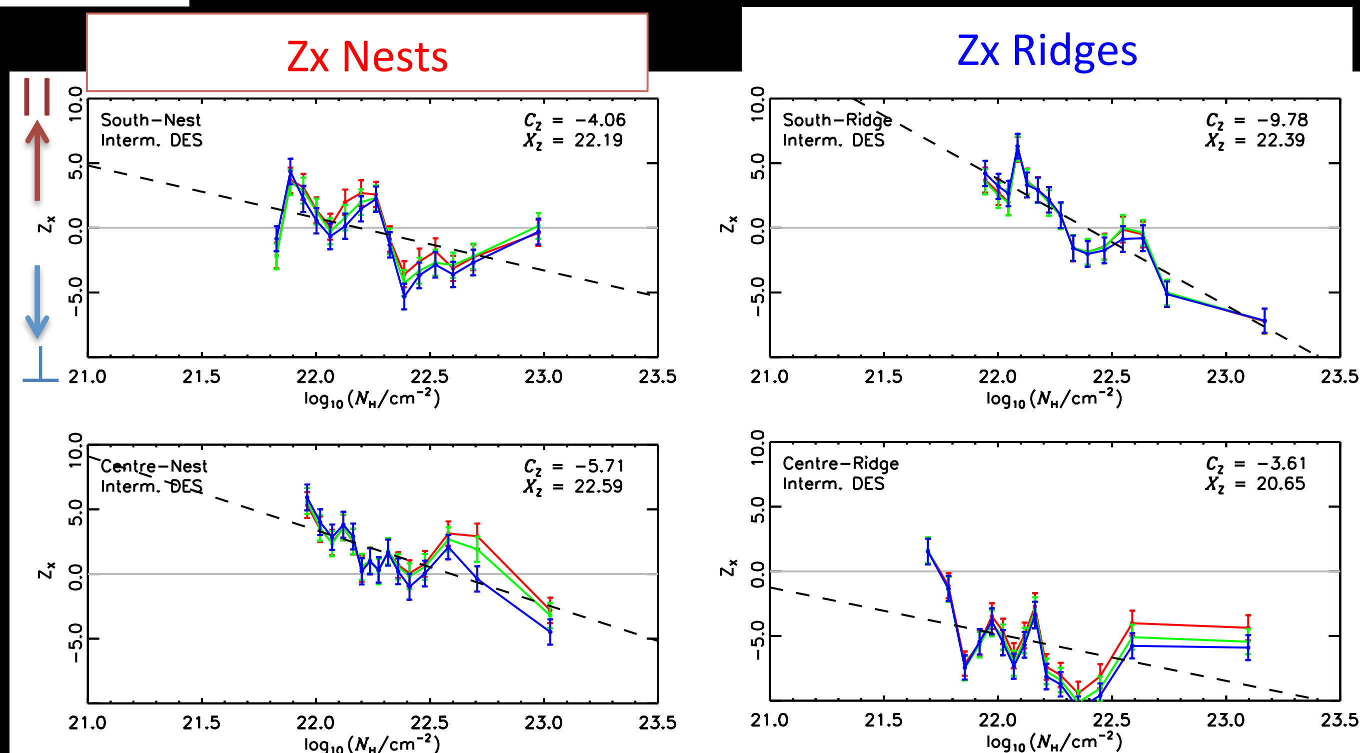






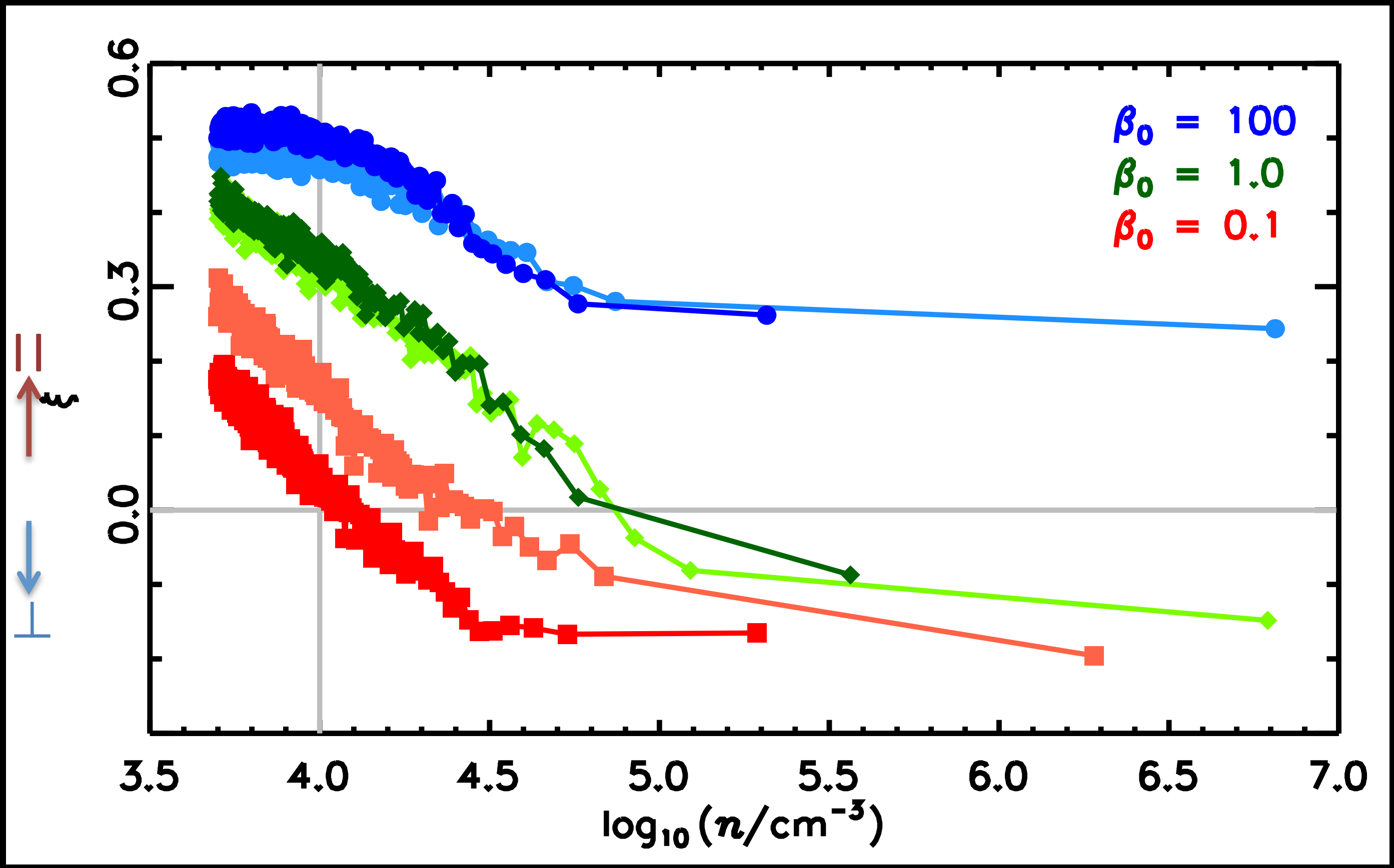
Ellerbroek et al., 2013





Soler et al, 2017

A Signature of Dynamically Important Magnetic Fields



Strong B-field strength, moderate B-field strength, weak B-field

Soler et al, 2013, 2017

BLASTPol + Mopra Survey of Vela C

Goal: Compare the Orientation of the Line Strength Map to the BLASTPol B-field map

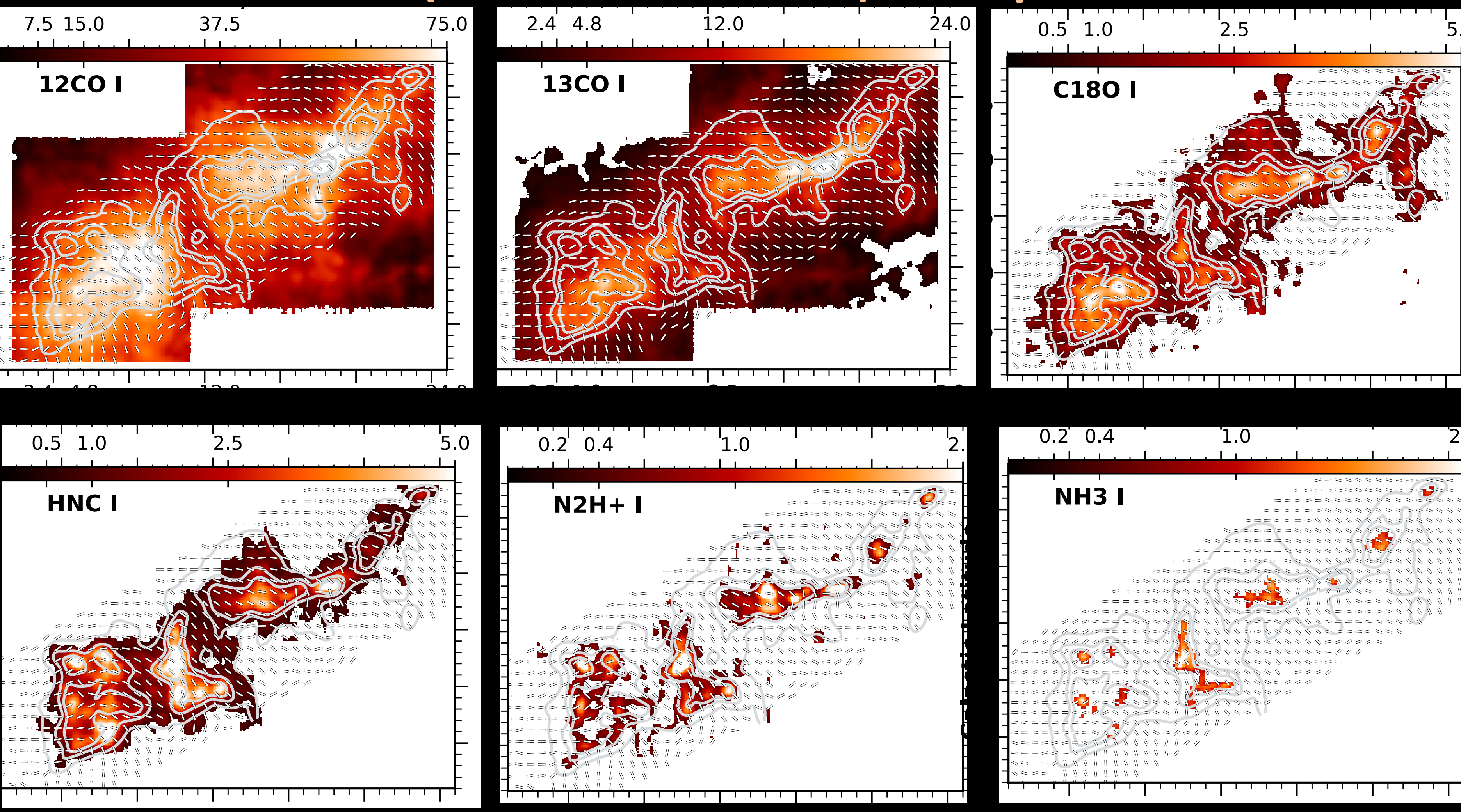
Molecule	Line	Freq (GHz)	Beam FWHM ('')	Density
12CO	1-0	115.2712	28	Low
13CO	1-0	110.20132	28	Low
C18O	1-0	109.78217	28	Intermediate
CS	1-0	48.99095	64	Intermediate
HCO+	1-0	89.18852	35	Intermediate. Sensitive to outflows.
HCN	1-0	88.63185	35	Intermediate Warmer T>20K gas
HNC	1-0	90.66357	35	Intermediate Forms Colder T<20K
N2H+	1-0	90.66357	35	High density tracer
NH3	(1,1)	23.6945	132	High density tracer

Fissel et al. in prep

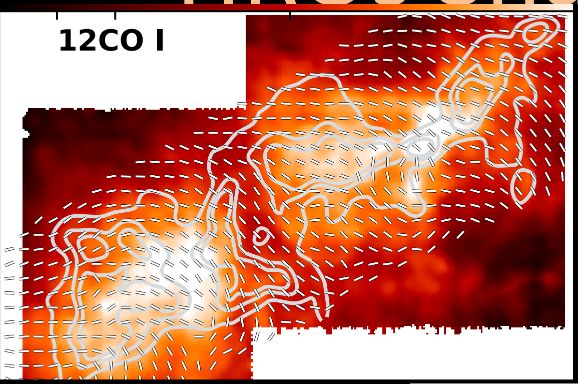
Mopra 22m telescope

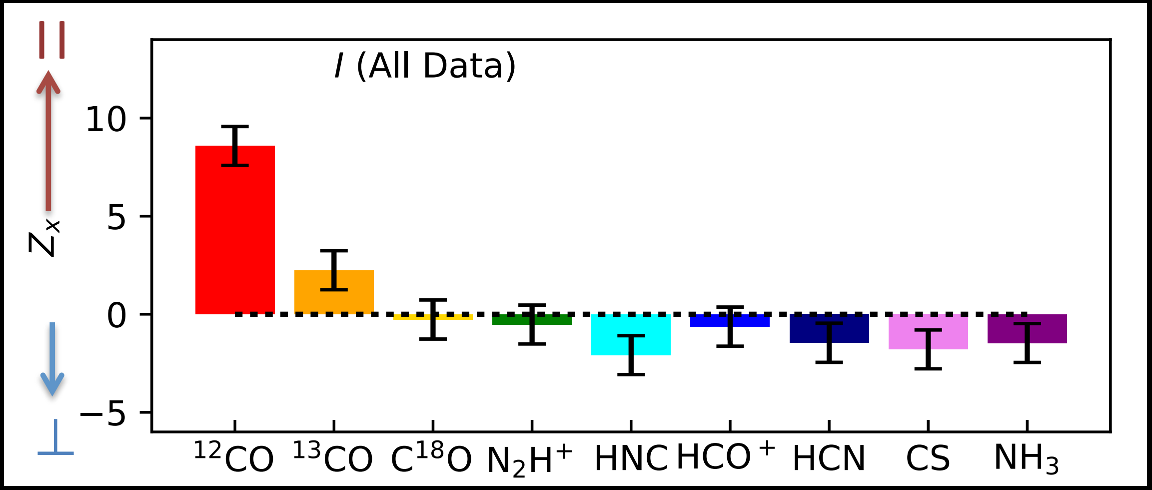
Collaborators:
Vicki Lowe, Maria Cunningham, Paul Jones, Claire-Elise Green (UNSW)

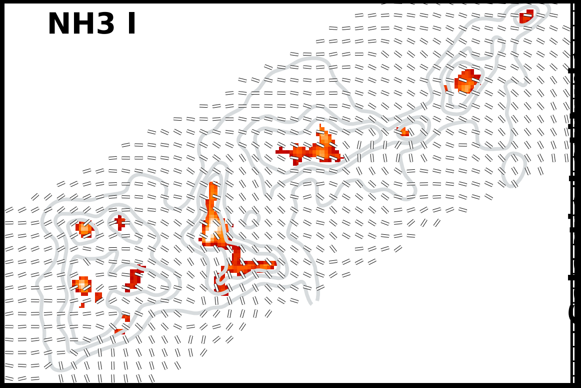
Mopra Integrated Line Intensity (Moment = 0) Maps



HROs Shape Parameter for Different Lines:





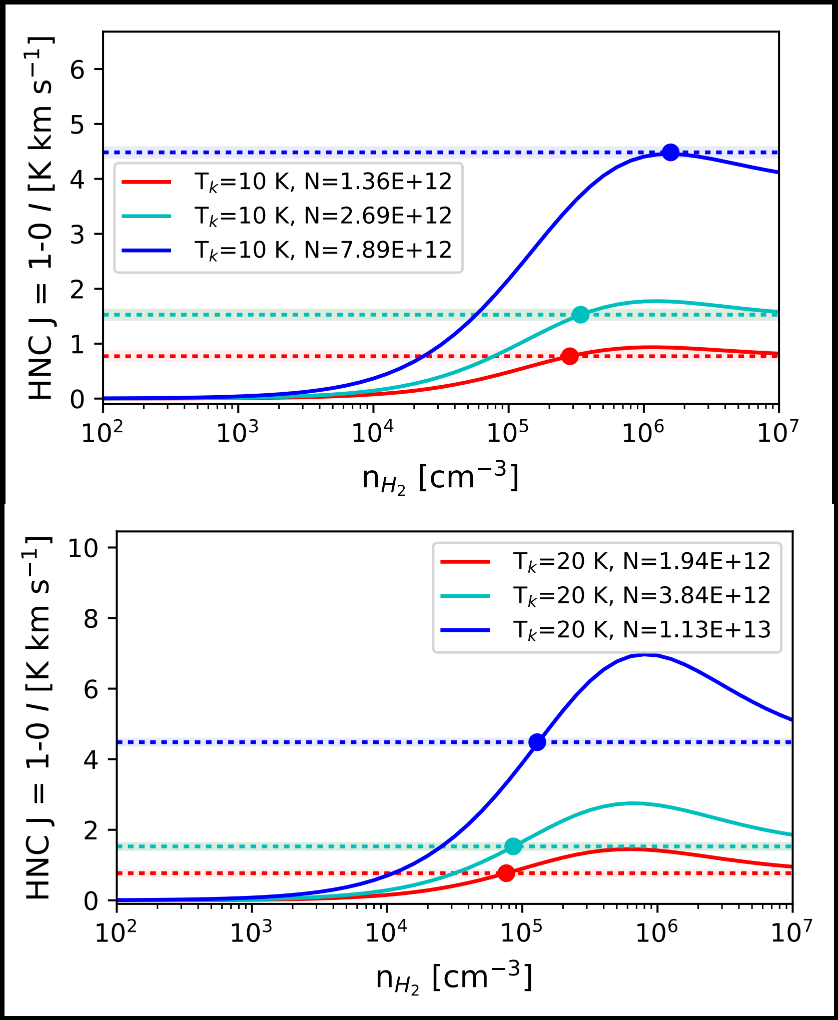


Fissel et al. in prep

Estimating Characteristic Density

(Based on Shirley 2015,
except 12CO J=1-0, where we use $n_{crit,\,thick}$)

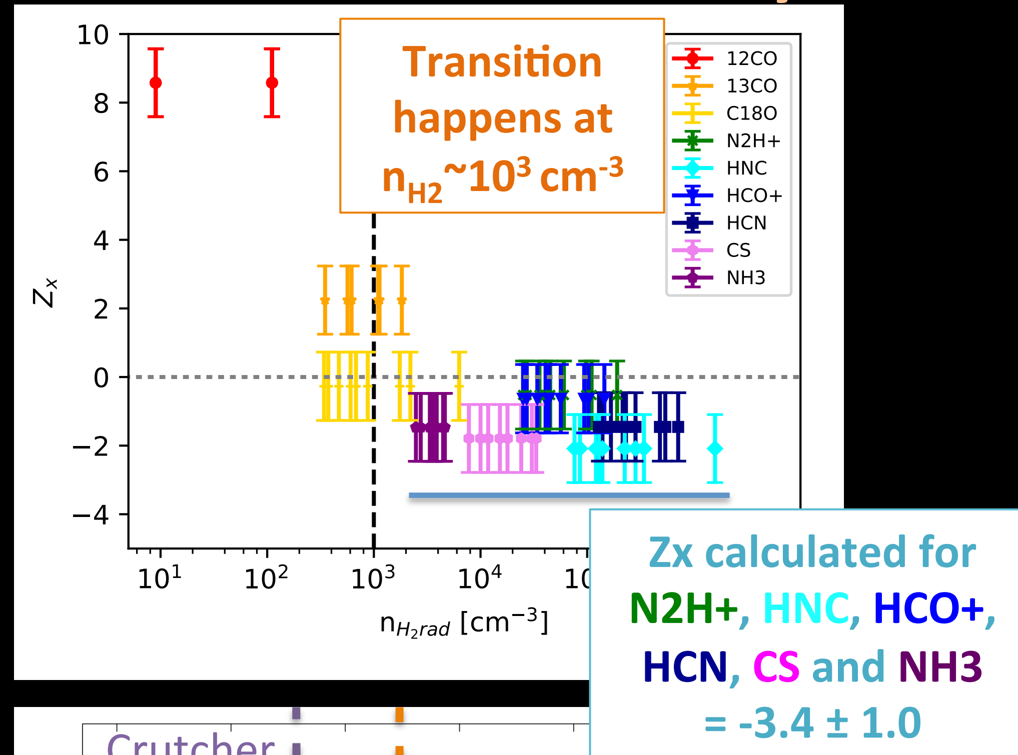
1. Estimate column density (assume τ << 1 Tx, Trot 10-20 K)
2. Use RADEX radiative transfer models to predict line intensity for different values of n_{H2}.
3. Compare models to observed line intensities.

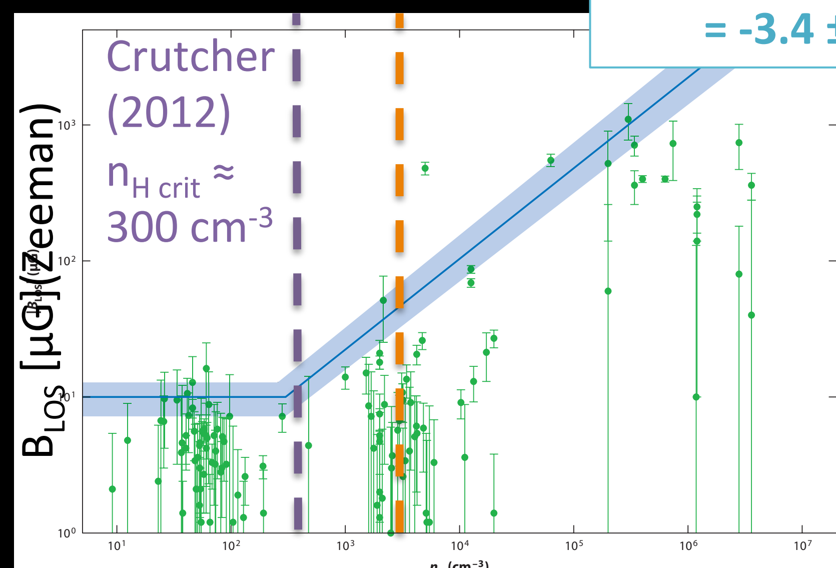


Fissel et al. in prep

Relative Orientation vs Density

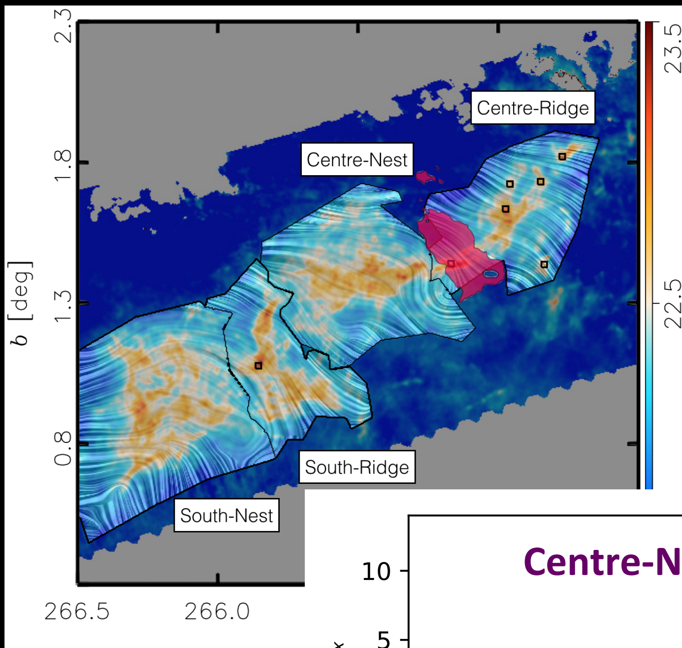
- Low density gas tends to align parallel to the magnetic field.
- Hints that higher density gas is more likely to align perpendicular to the cloud-scale field.





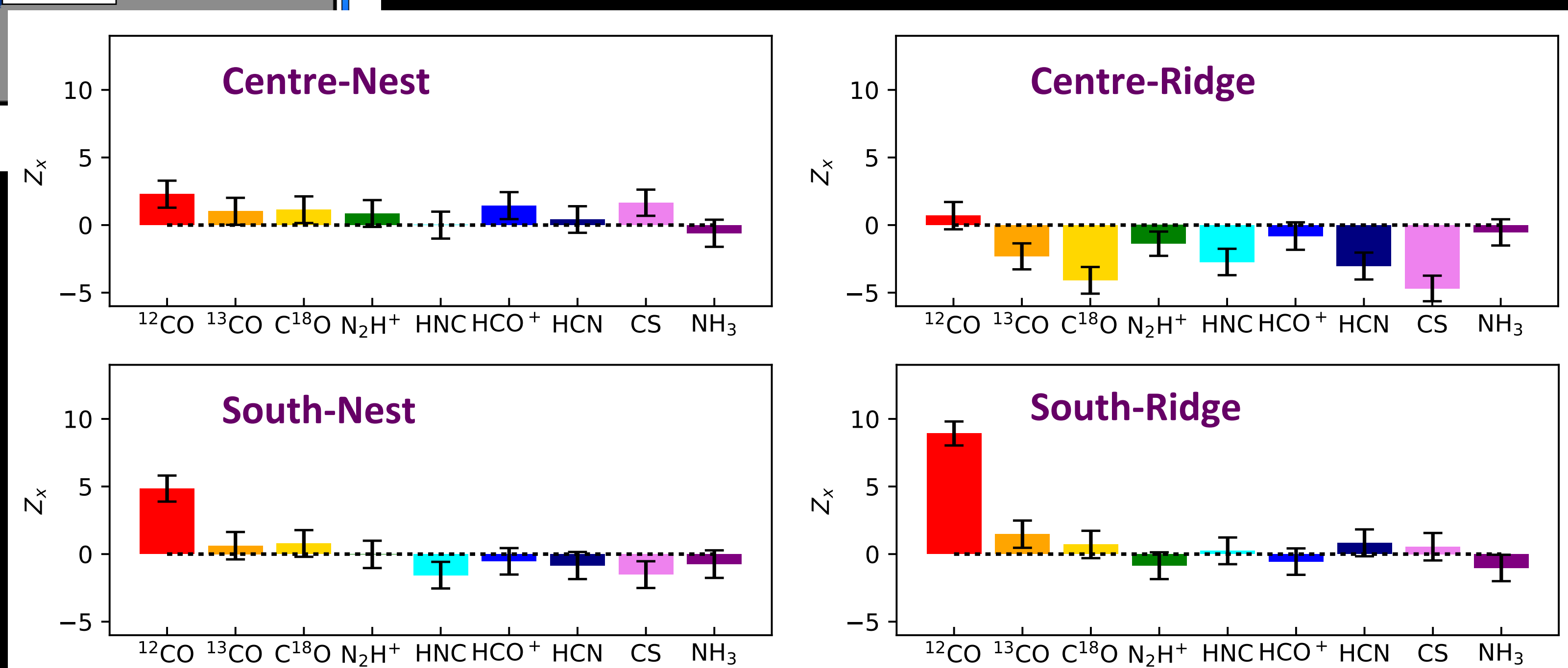
Fissel et al. in prep

Are there regional differences in Z_x vs n_{H2}?



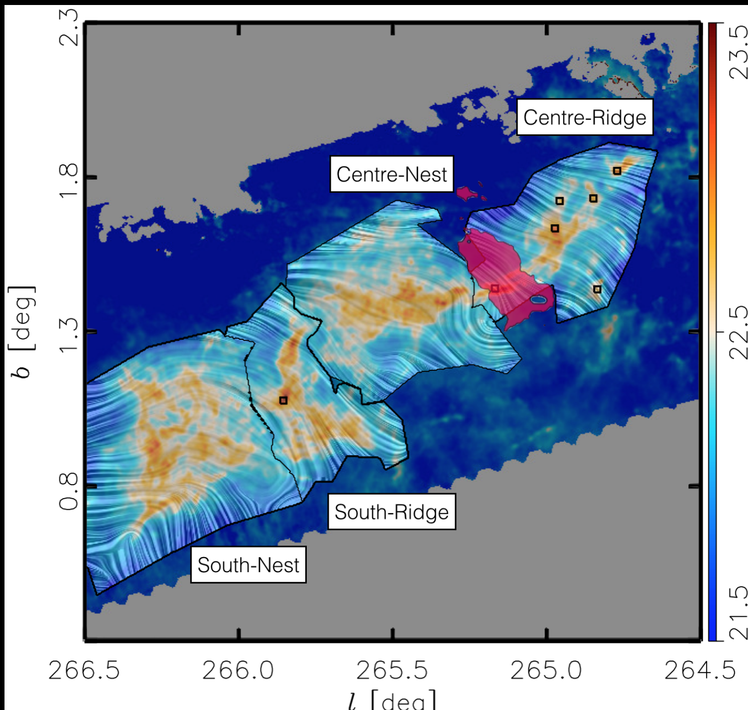
The most active star forming region (the Centre-Ridge) shows a strong alignment preference perpendicular the to magnetic field.

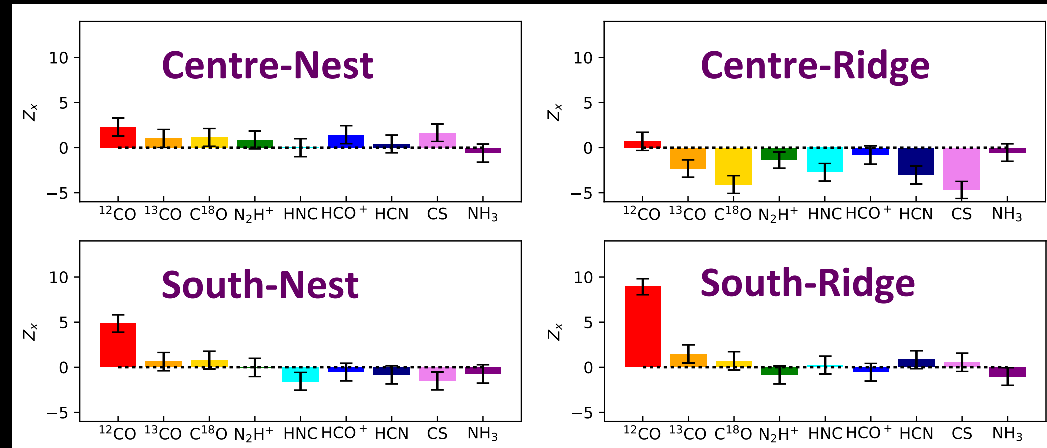
The transition density from parallel to perpendicular seems to be lower for the Centre-Ridge (n_{H2} ~ 10^2 cm^{-3} instead of ~10^3 cm^{-3}).

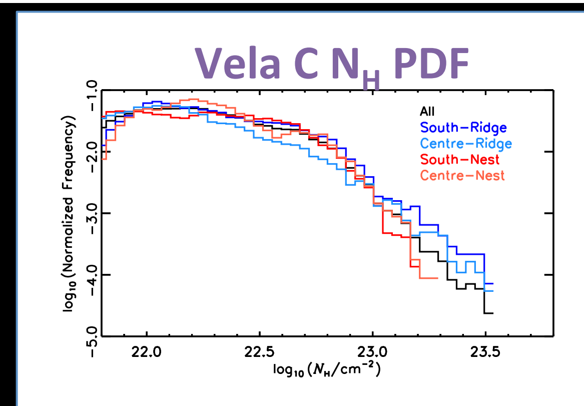


Fissel et al. in prep

Interpreting Regional Variations







Soler & Hennebelle 2017:

- $\cos(\phi) = 1$ (parallel) and $\cos(\phi) = -1$ (perp) are equilibrium points in the MHD fluid equations.
- Transition corresponds to convergent flows of material in the presence of strong magnetic fields.

Vela C:

- We see strong regional differences in the orientation of cloud vs. magnetic structure.
- Stronger transitions with density correspond to more regions with higher column density filaments (more dense gas for star formation)

Relative Orientation Conclusions

- Average orientation of the B-field changes from parallel to perpendicular to clouds structure
  - Implies that the magnetic field is at least trans-Alfvenic
    - Strong enough to play a role in forming the initial cloud structure.
- The density of the cross over from parallel to perpendicular is n_{H2}~10^3 cm^{-3}.
- Both the column density and density at which this transition occurs seems to depend on the cloud state.
  - Different field strengths?
  - Geometry of the initial flows with respect to the magnetic field?

Needed: Synthetic observations of simulations with different formation scenarios, viewing angles, physics included.

Observations of more clouds!

BLAST-TNG: Map more clouds at higher resolution!

Technological Improvements:

- New Focal Plane
  - Polarization sensitive detectors (MKIDS)
  - Larger focal plane (1000 detectors compared to 266 detectors for BLASTPol)
  - ***~10x increase in mapping speed***
- Larger Primary Mirror
  - 2.5 m gives 25'' resolution @ 250 microns
  - ***~6x increase in resolution***
- 30 day hold time cryostat
  - ***~3x longer flight time than BLASTPol***

Science Drivers:

- Detailed maps of magnetic morphology for dozens of clouds
  - Account for magnetic field projection effects
  - Better statistical comparison with numerical simulations

Integration of BLAST-TNG in March 2018

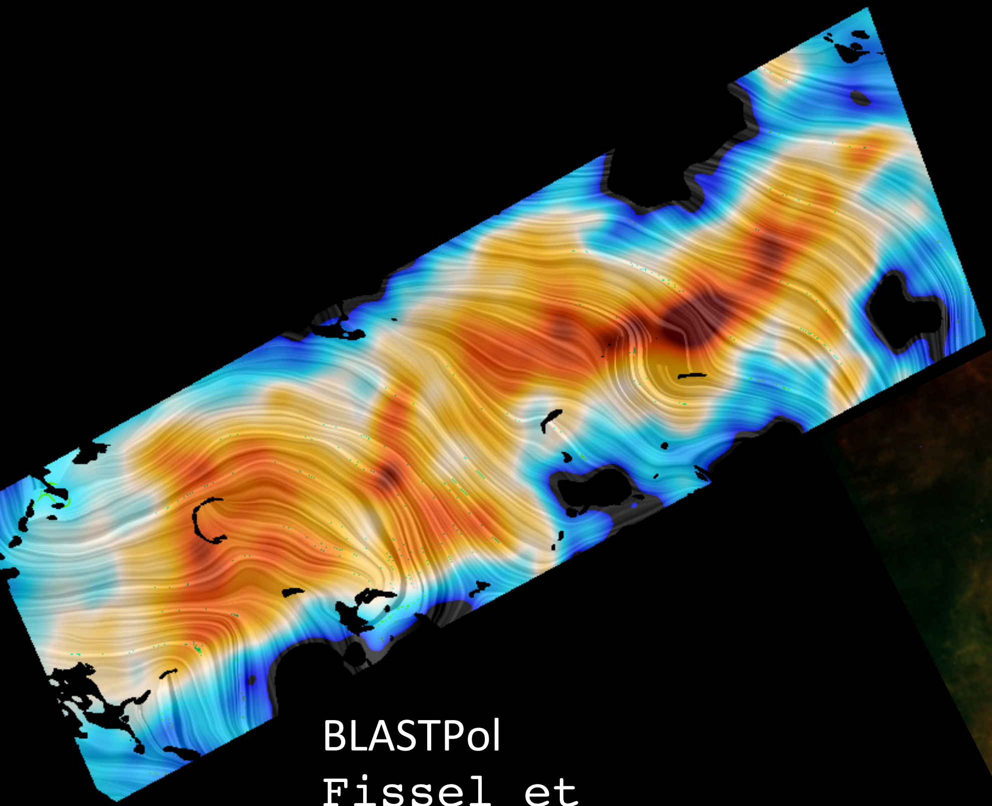
First flight from Antarctica hopefully in late 2018
25% of the time available for shared risk observations

http://sites.northwestern.edu/blast

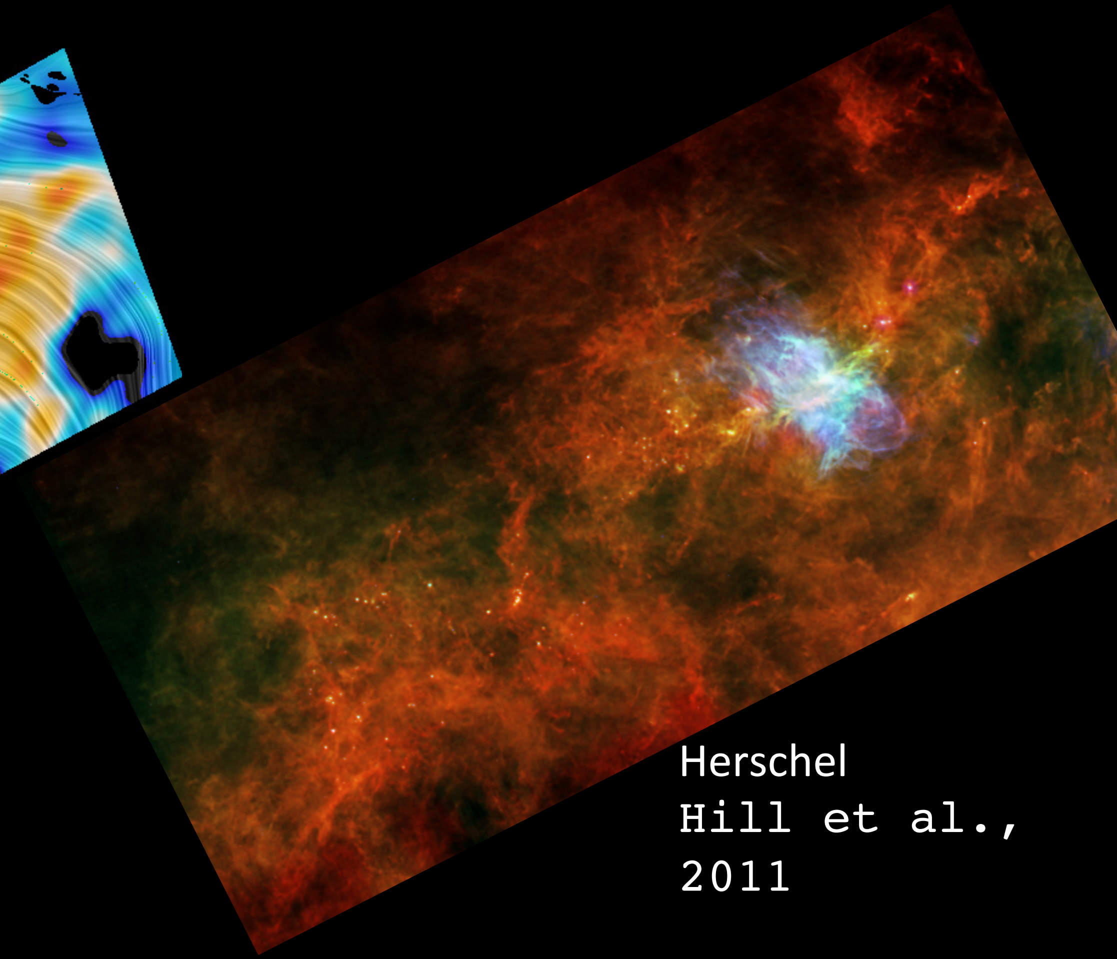
Example: Vela C

BLASTPol 2012
Resolution: 0.5pc

BLAST-TNG
Resolution: 0.08pc



BLASTPol
Fissel et al., 2016



Herschel
Hill et al., 2011

Resolving Magnetic Fields in Filaments with TolTEC

TolTEC

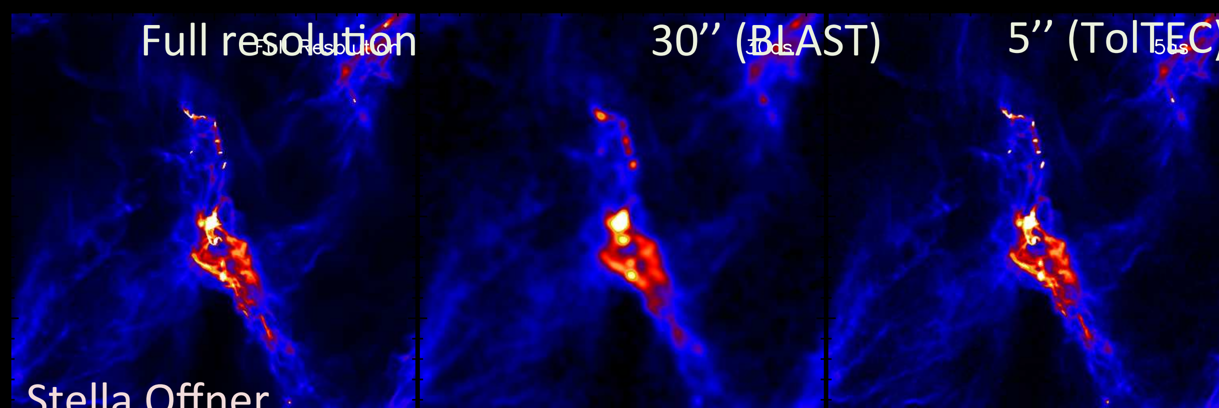
(PI Grant Wilson, UMass)

- mm camera/polarimeter on the upgraded 50 meter LMT
- Observes at 2.1, 1.4, 1.1mm, best res: 5’’
- Commissioning begins late 2018

Fields in Filaments Legacy Survey

(Coordinators Giles Novak and Laura Fissel)

- 100 hours reserved for mapping filaments and cores over A_V>8
- Survey duration 2018-2021 with scheduled data releases



http://toltec.astro.umass.edu/

The Goal: measure the strength and energetic importance of magnetic