The Relationship Between Magnetic Fields and Molecular Cloud Structure: A BLASTPol Study of Vela C

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BLASTPol and BLAST-TNG collaborations
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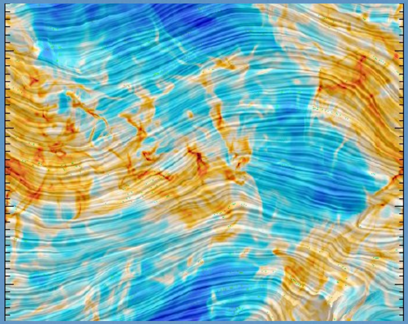
Tracing the Flow, Lake Windemere

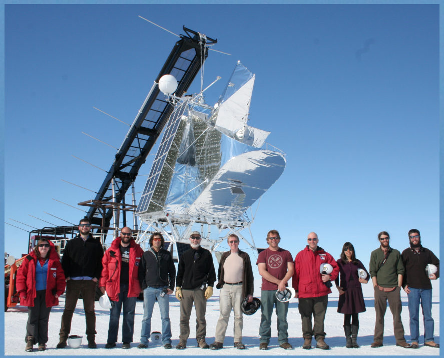
July 4th, 2018

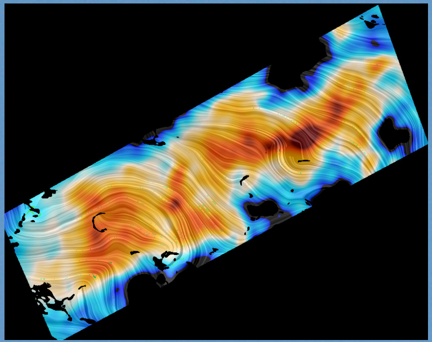
Outline:

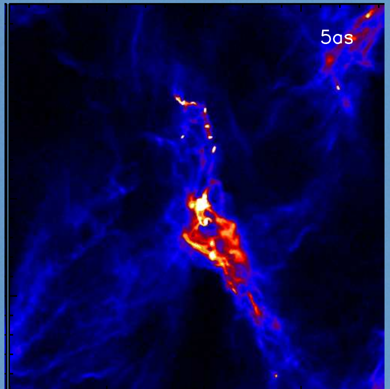
- **Background: What role do magnetic fields play in star formation and how can we study them?**

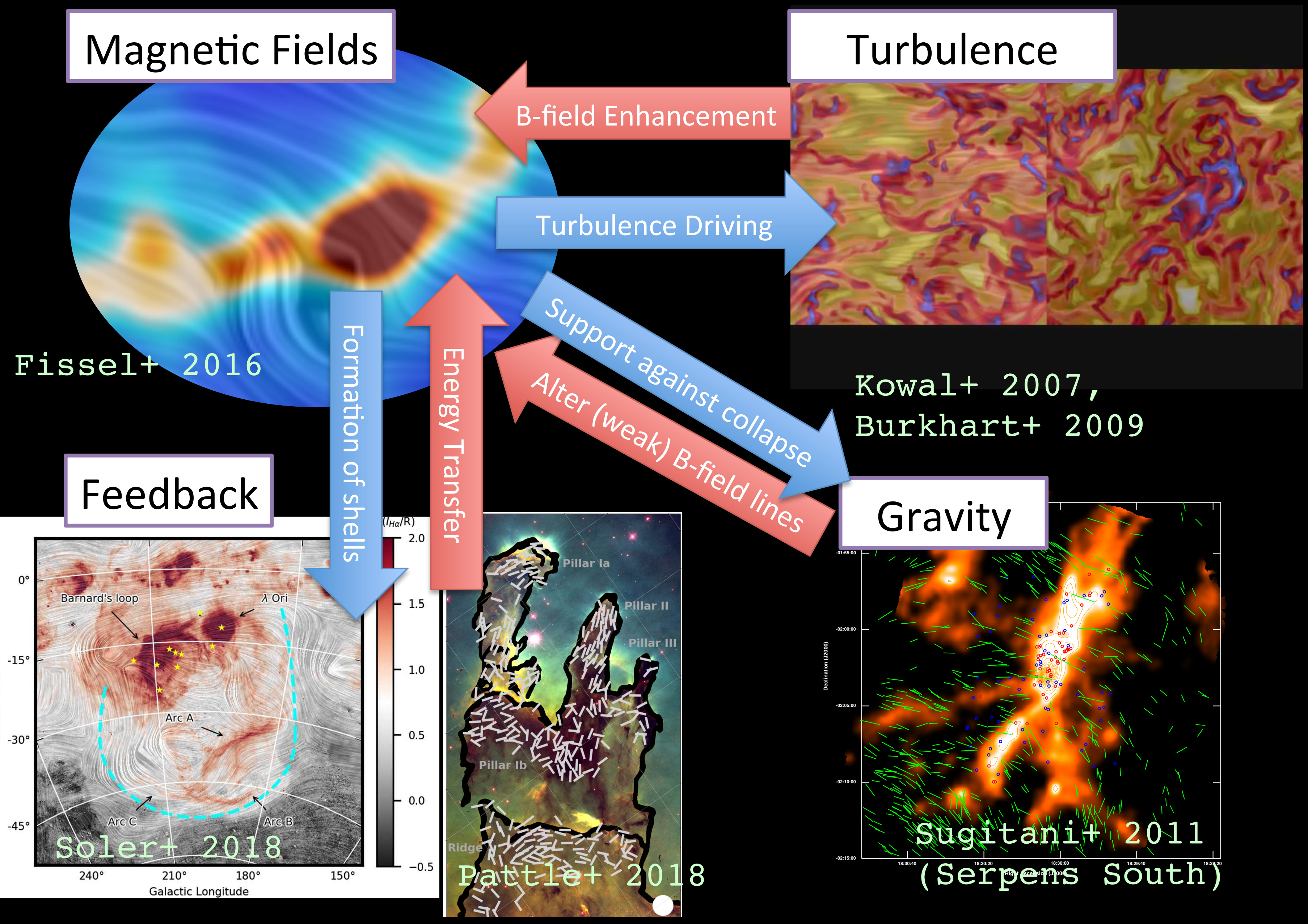
- **The relationship between *dense gas structure* in molecular clouds and the *magnetic field*.**
  - **Case Study: BLASTPol observations of Vela C**
  - **Comparisons of with simulations.**
- **Extending our understanding of B-fields and cloud structure to sub-filament scales.**
  - **Small scale structure and the magnetic field**
  - **Fields in Filaments**










Magnetic Fields
Turbulence
Feedback
Gravity
B-field Enhancement
Turbulence Driving
Support against collapse
Alter (weak) B-field lines
Formation of shells
Energy Transfer
Fissel+ 2016
Kowal+ 2007,
Burkhart+ 2009
Soler+ 2018
Pattle+ 2018
Sugitani+ 2011
(Serpens South)
Barnard's loop
λ Ori
Arc A
Arc B
Arc C
Galactic Longitude
Pillar Ia
Pillar II
Pillar III
Pillar Ib
Ridge

Magnetic Field Strength vs Column Density

B_{LOS} Zeeman Observations
(Crutcher+ 2010, 2012)

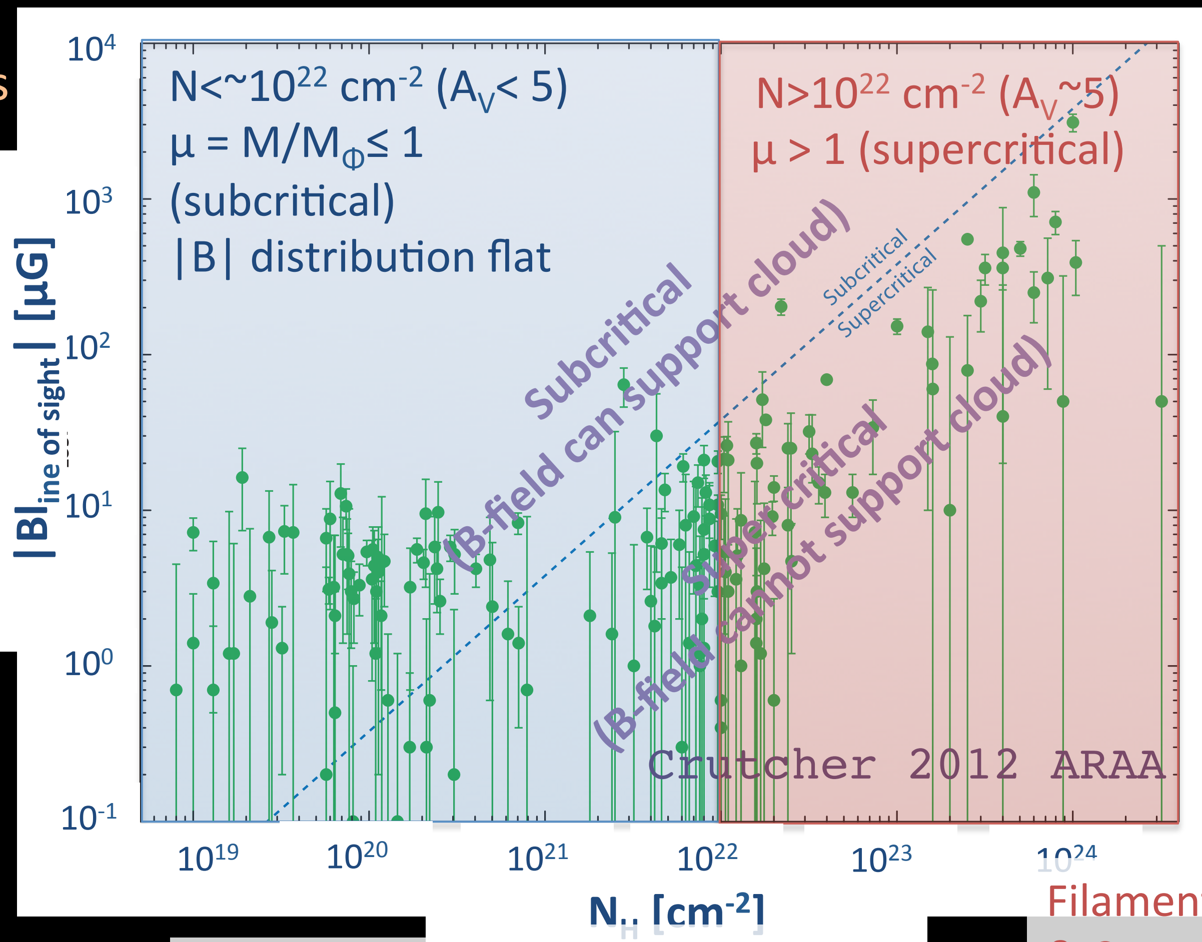
Mass to Flux Ratio:

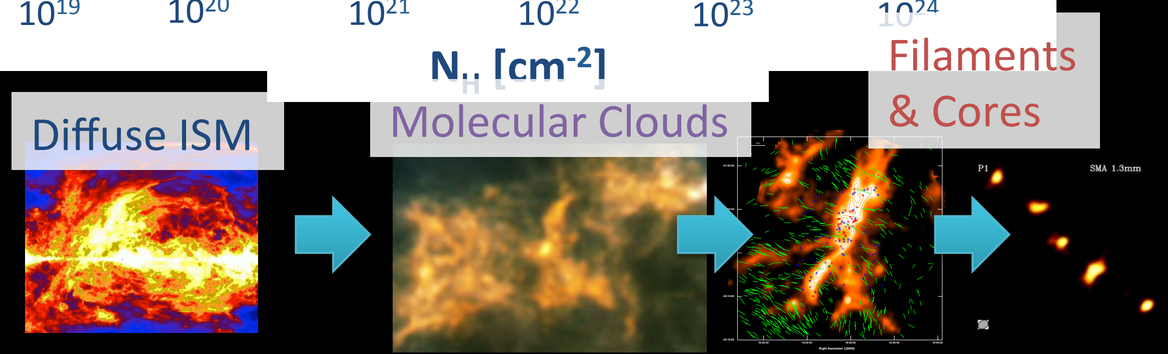
(importance B-field vs gravity)

$\mu = M/M_\Phi$

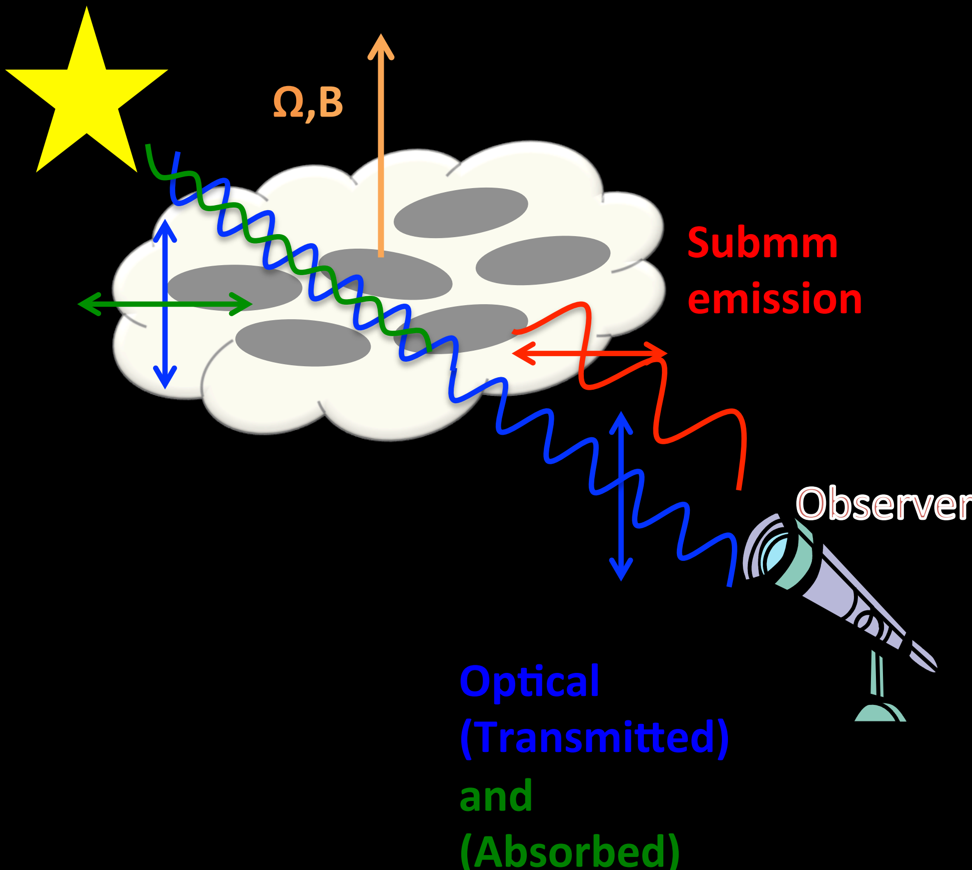
$= M/(\Phi/2\pi G^{1/2})$

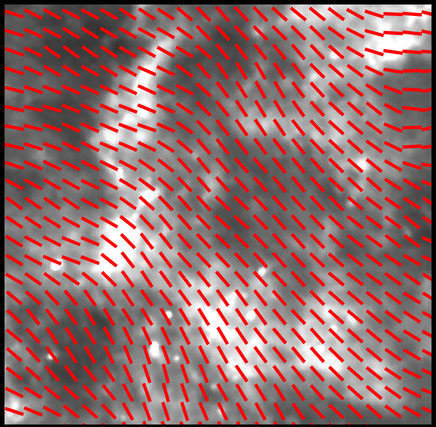
where Φ is the magnetic flux (~ $\pi r^2 B$)





Mapping B-fields with Dust Polarization





Grains alignment, likely due to torques from the local radiation field (λ<a)

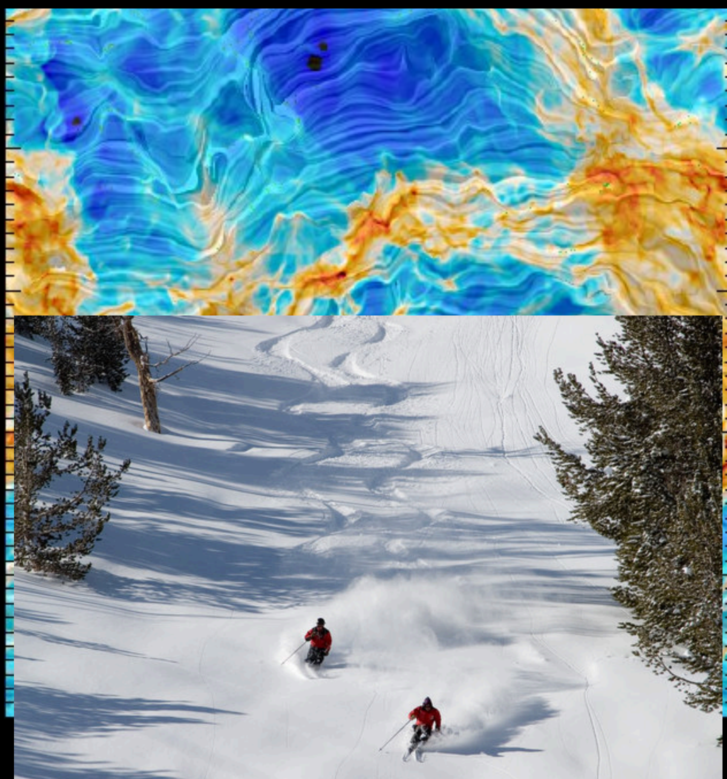
Lazarian 2007, Andersson+ 2015

Caveats:

- No direct measurement of the magnetic field strength.
- Inferred magnetic field weighted by dust properties:
  - dust temperature
  - emissivity
  - alignment efficiency
- Weak signal (few %)

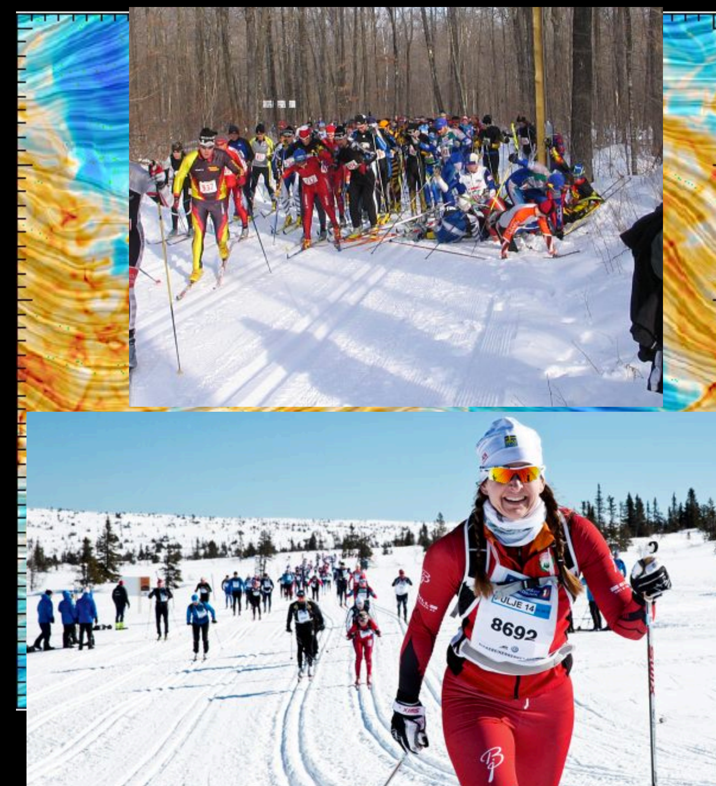
Relationship Between Magnetic Fields and Cloud Structure

Weak magnetic field
($|B_0|$=0.35μG)



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

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



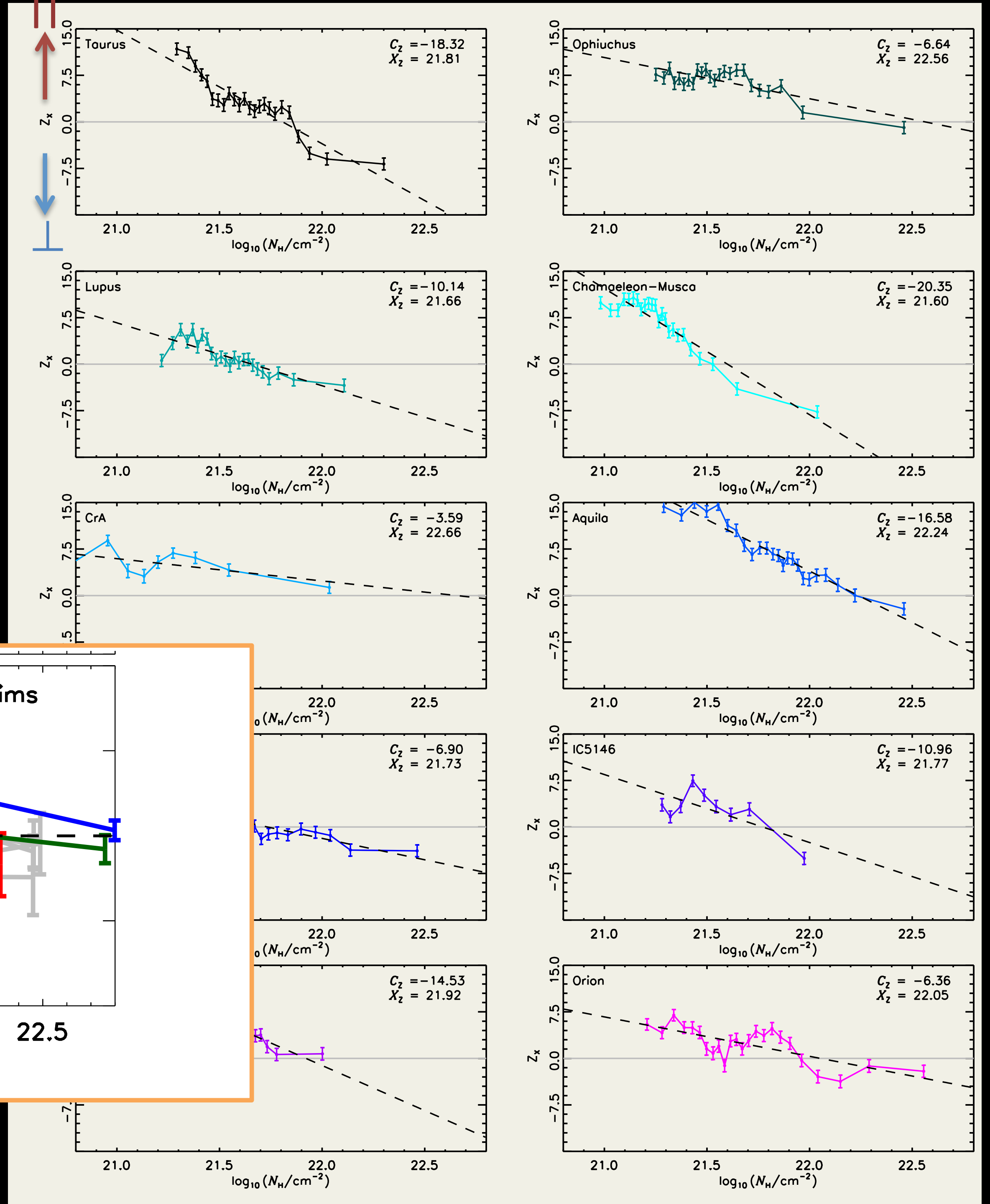
low N_H ➔ B-field | | to N contours
high N_H ➔B-field perp to N contours

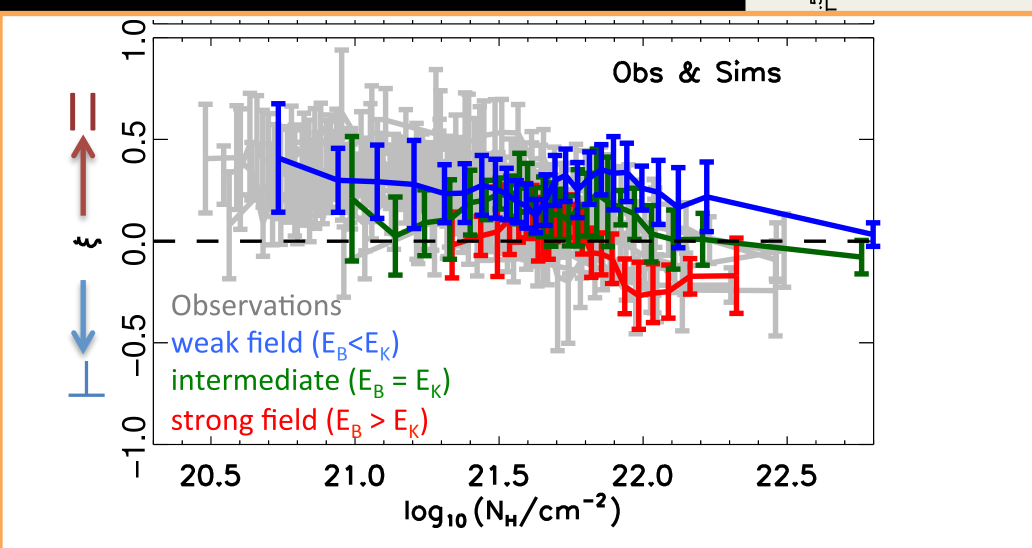
RAMSES MHD Simulations from Soler et al. 2013

Planck: Relative Orientation for 10 nearby low mass clouds

We use the gradient field to measure the direction of cloud structure, and compare with B-field to measure the relative orientation angle θ.

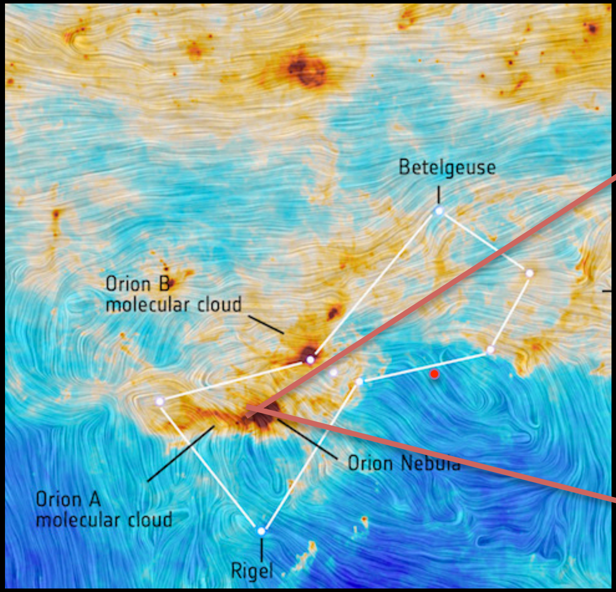
Planck XXXV, 2016
Jow et al. 2018

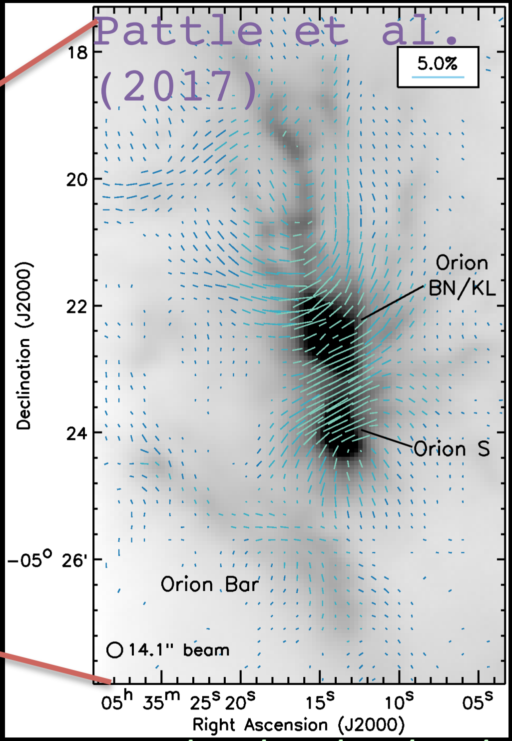




Planck Satellite
870 µm

JCMT POL-2: 850 µm





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)

Price: <<10 million USD

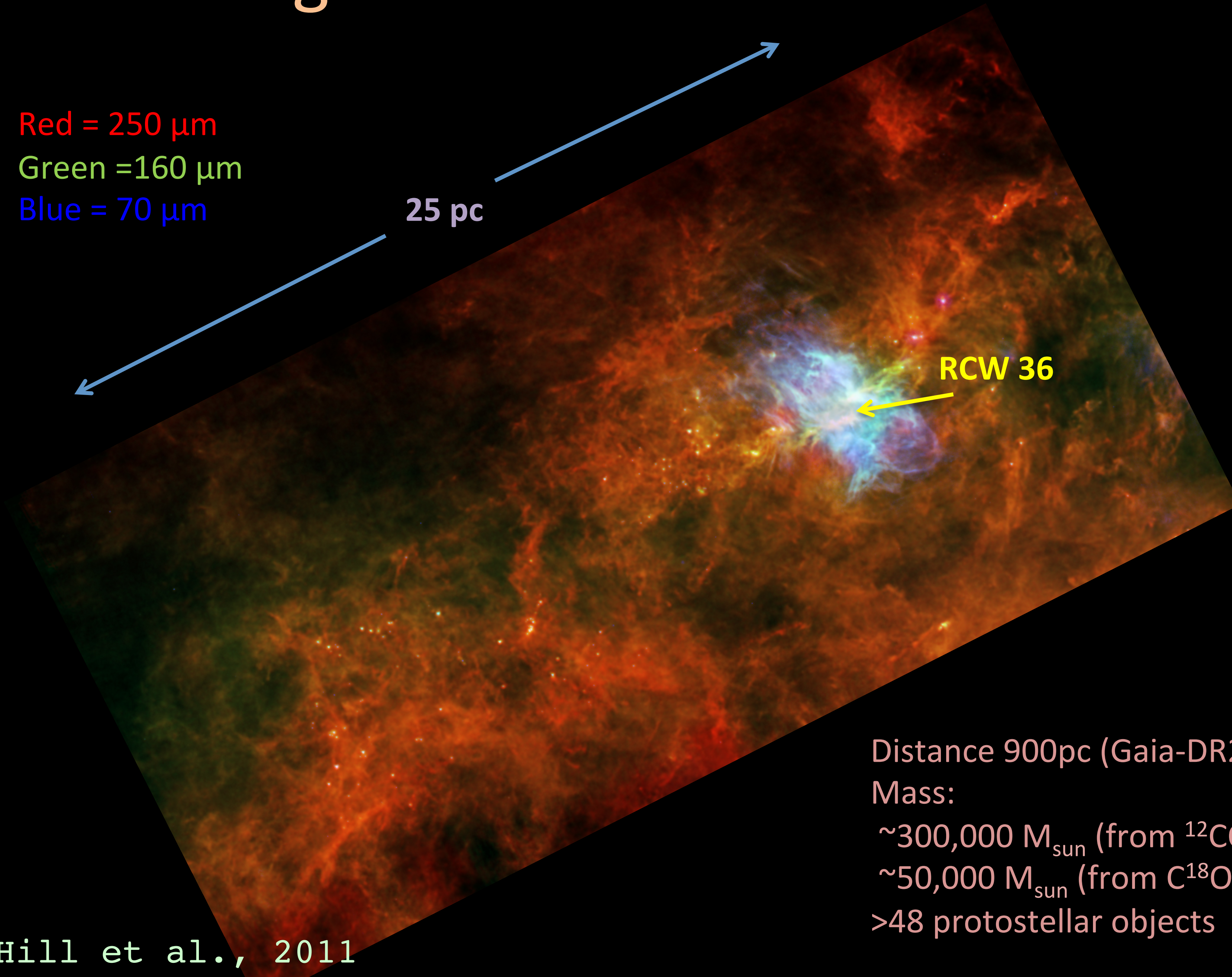
Picture from the Spider Telescope 2014

BLASTPol: The Balloon-borne Large Aperture Sub-mm Telescope for Polarimetry

- 1.8m primary mirror
- ~2" pointing reconstruction
- 266 detectors at 250, 350, 500 μm
  - Cooled to 300 mK by a Liquid He/N cryostat
- Beam FWHM 1' at 500 μm
- Polarimeter: Polarizing grid + achromatic half-wave plate
- Flights in 2010 and 2012

Target Cloud: The Vela C GMC

Red = 250 μm
Green =160 μm
Blue = 70 μm



Distance 900pc (Gaia-DR2)
Mass:
~300,000 M_{sun} (from ^{12}CO)
~50,000 M_{sun} (from $C^{18}O$)
>48 protostellar objects

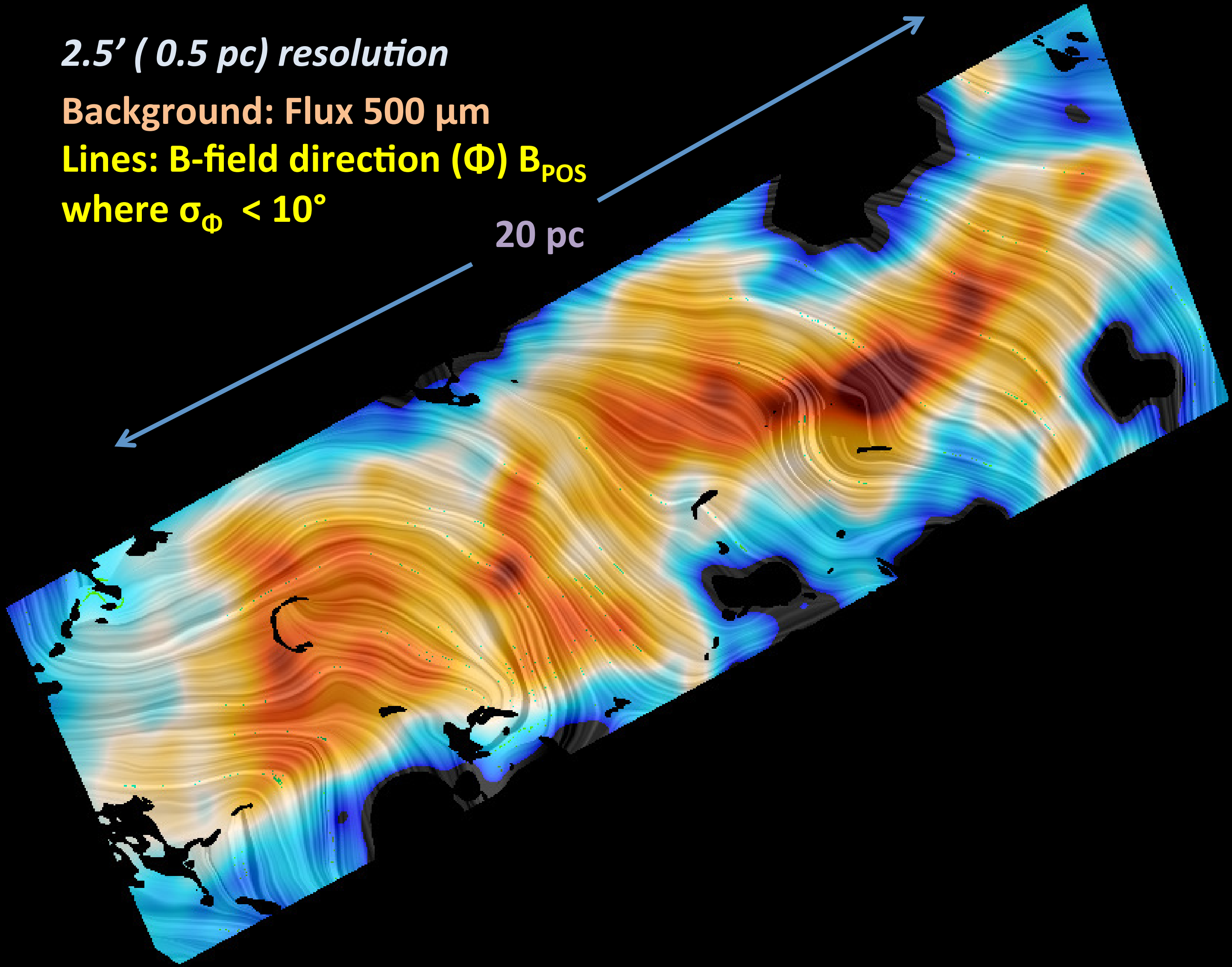
Hill et al., 2011

BLASTPol Inferred B-field Map of Vela C

2.5’ (0.5 pc) resolution

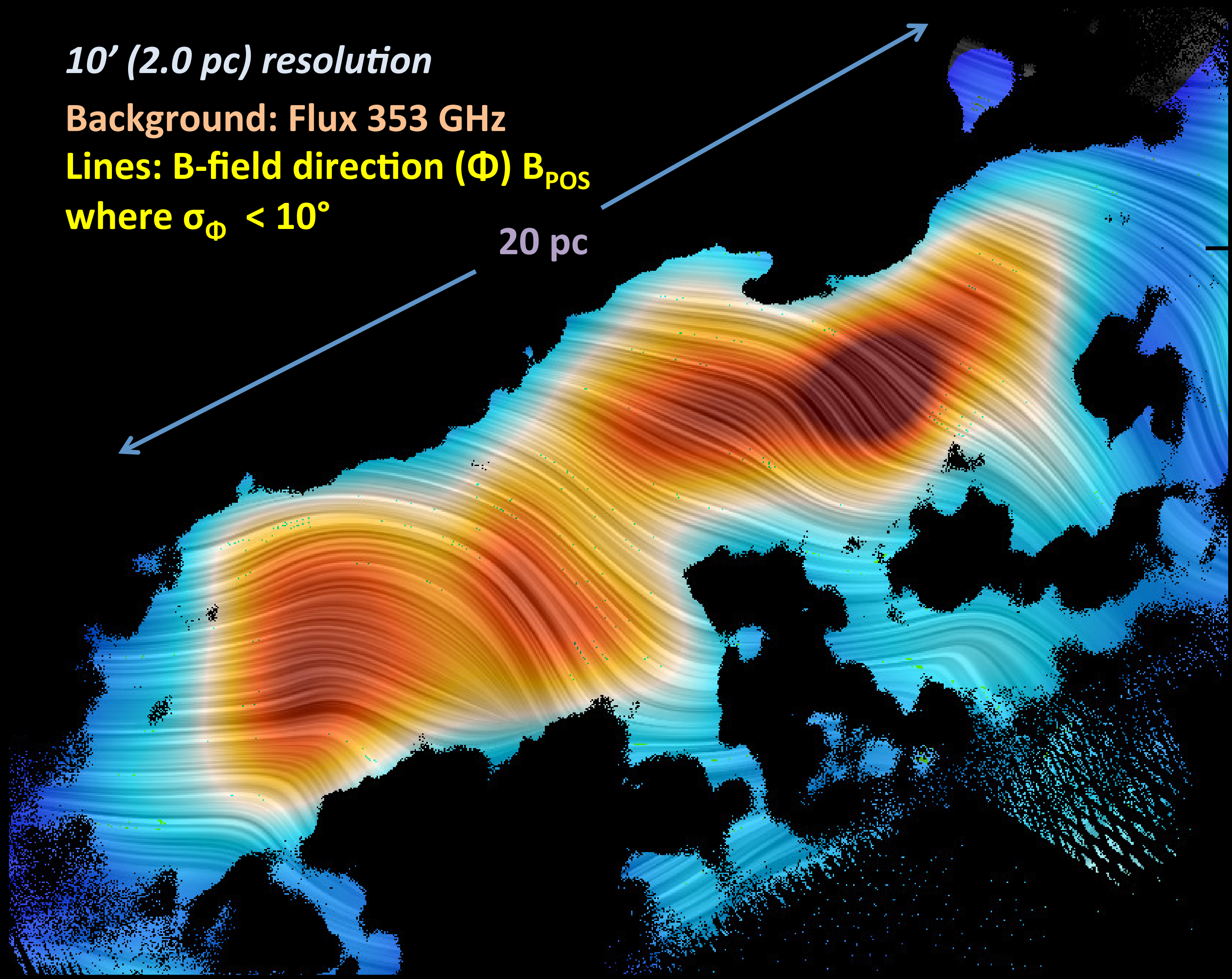
Background: Flux 500 µm

Lines: B-field direction (Φ) B_{POS} where σ_{Φ} < 10°



Fissel+ 2016

Planck B-field Map of Vela C



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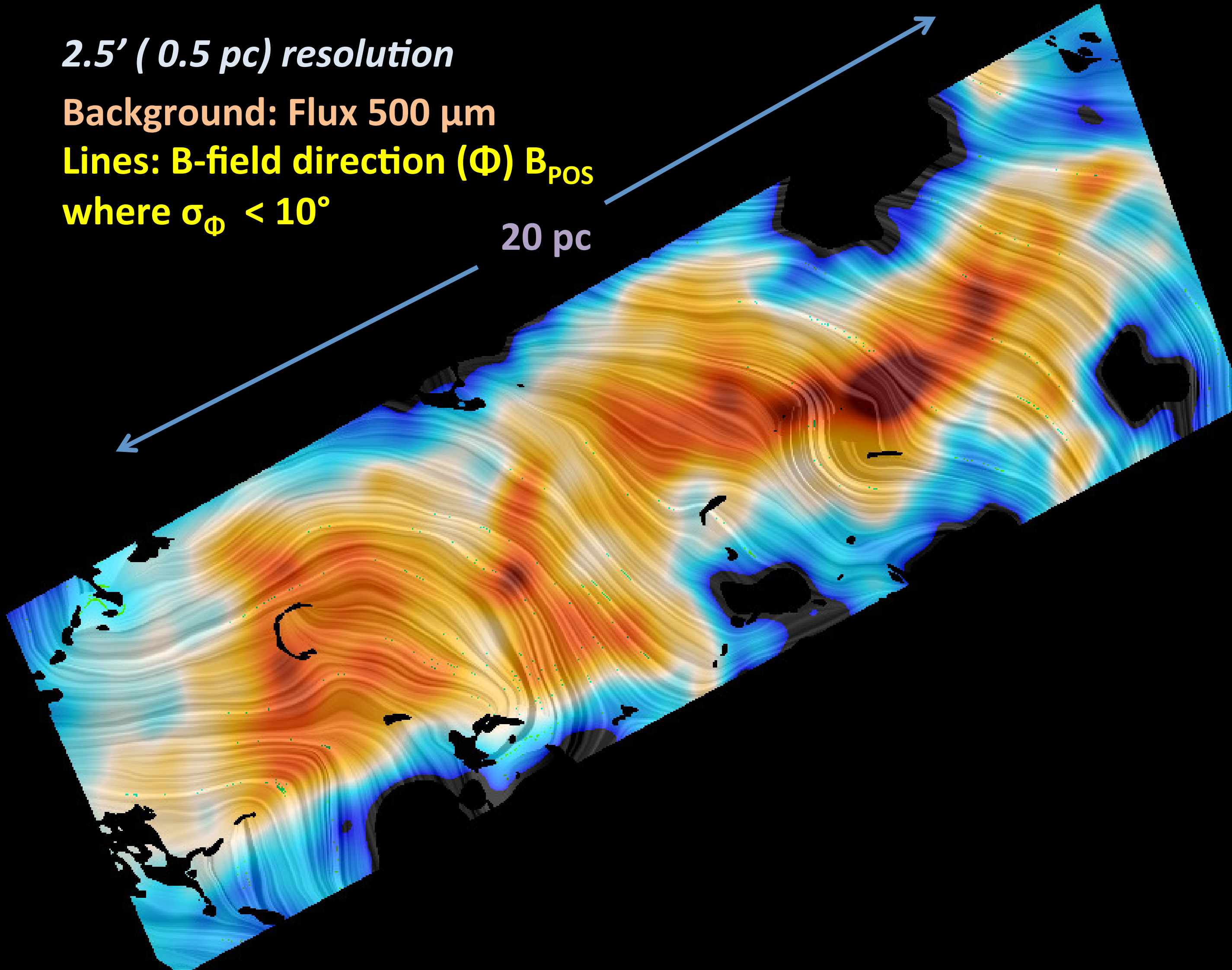
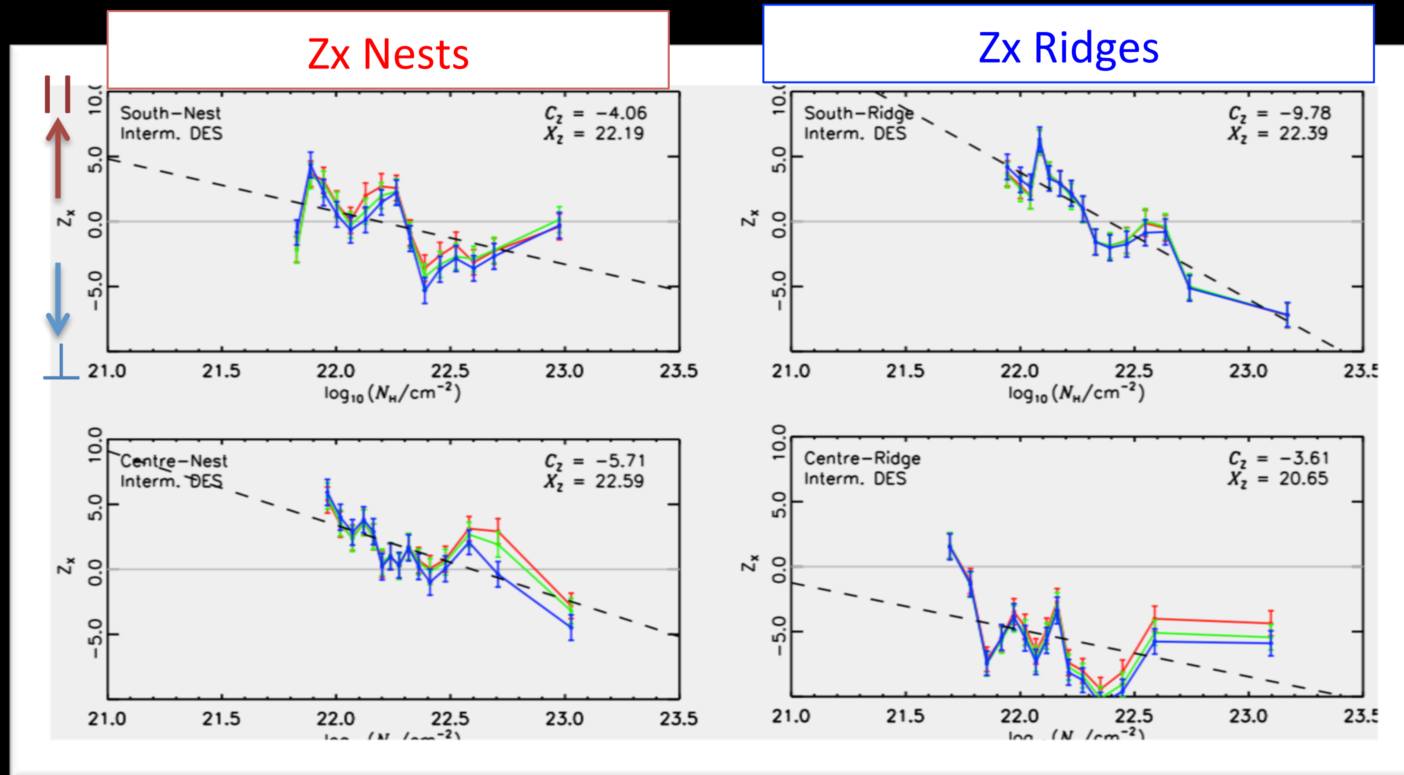
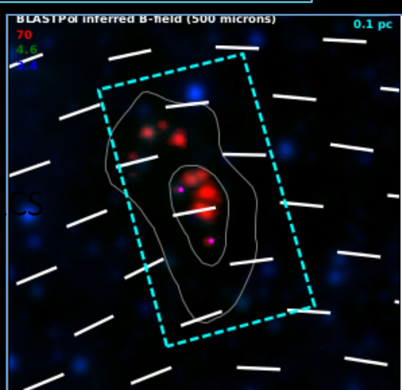
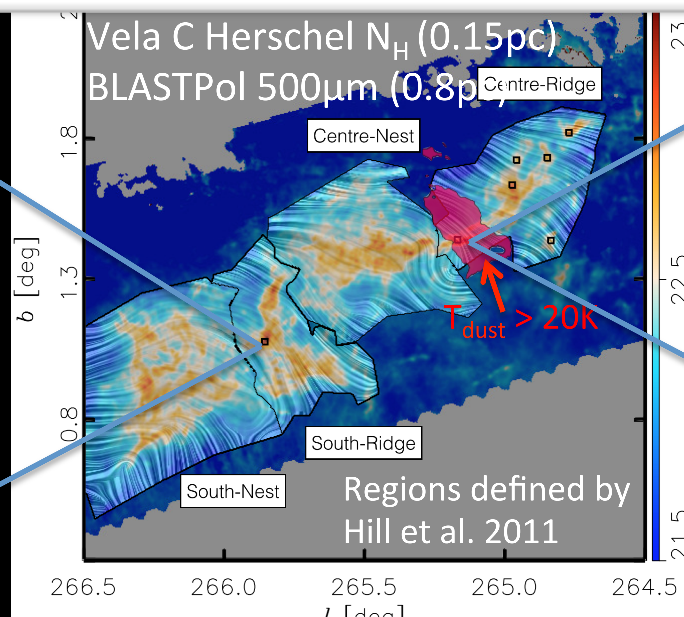


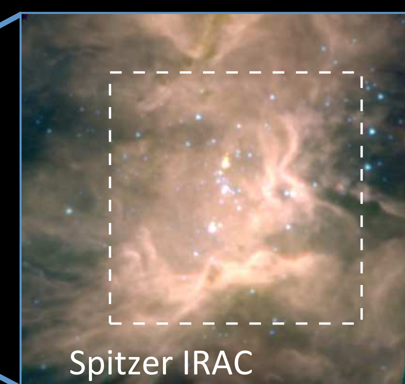
The filamentary structure traced changes relative orientation from parallel to perpendicular compared to the cloud B-field with N_H.

This change is much stronger for “ridge” (dominated by a single dense filament), than “nest” regions.





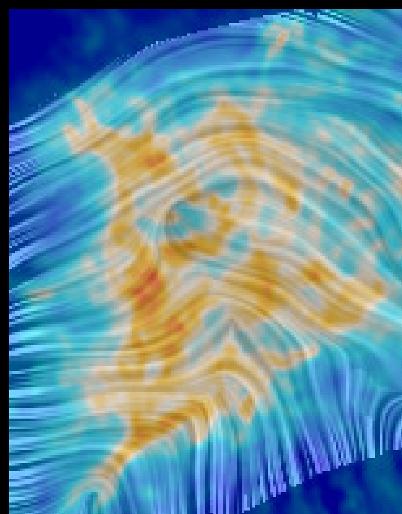




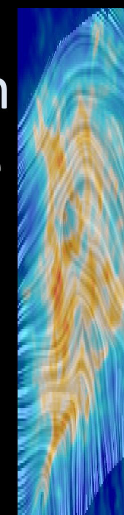
Ellerbroek+ 2013

Soler+ 2017

Or could this perhaps be a projection effect?



rotate
to an edge-on
viewing angle



BLASTPol + Mopra Survey of Vela C

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

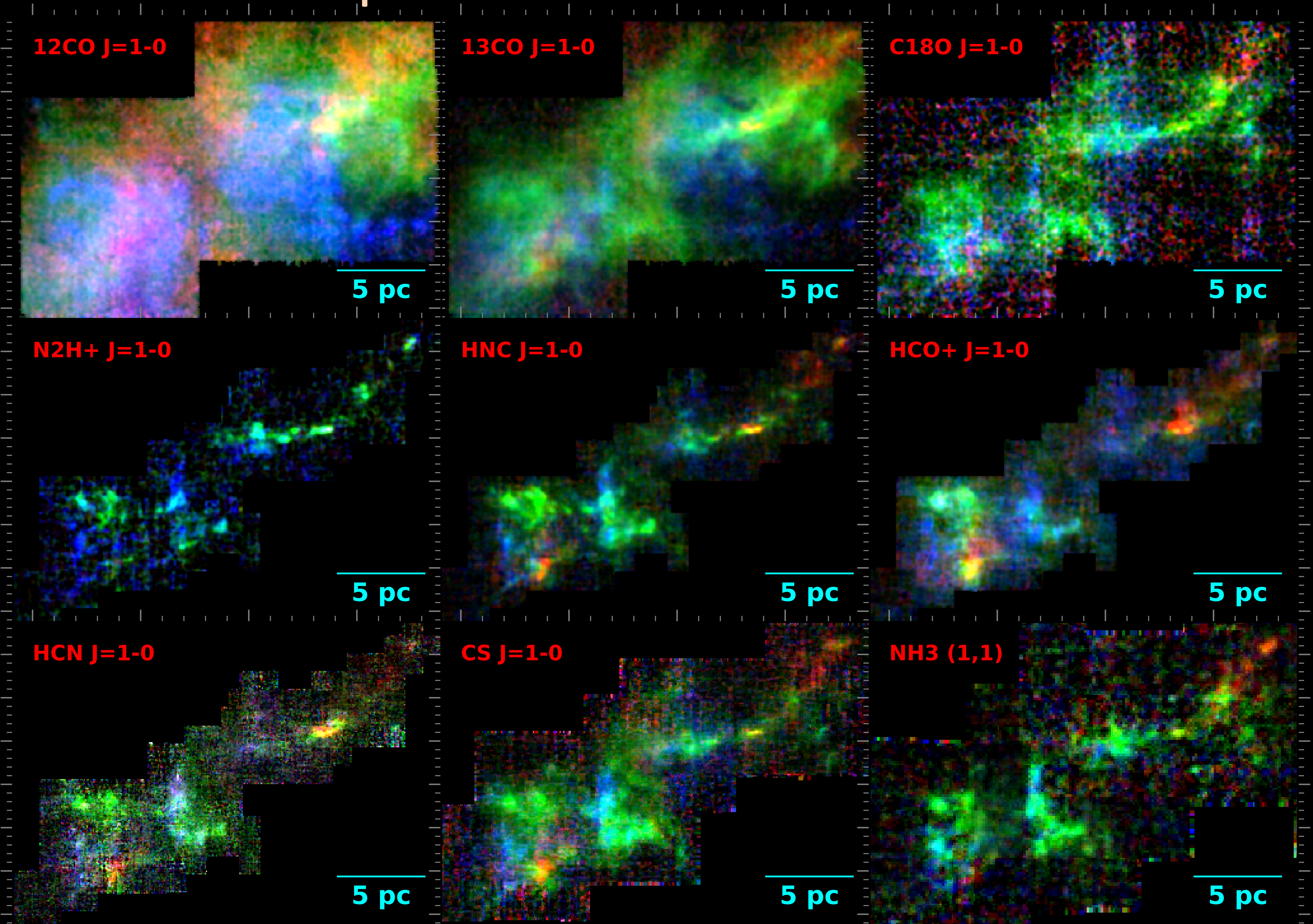
Molecule	Line	Freq (GHz)	Beam FWHM (")	Density
12CO	1-0	115.2712	28	Low
13CO	1-0	110.20132	28	Low
C18O	1-0	109.78217	28	Intermediate
CS	1-0	48.99095	64	Intermediate
HCO+	1-0	89.18852	35	Intermediate. Sensitive to outflows.
HCN	1-0	88.63185	35	Intermediate Warmer T>20K gas
HNC	1-0	90.66357	35	Intermediate Forms Colder T<20K
N2H+	1-0	90.66357	35	High density tracer
NH3	(1,1)	23.6945	132	High density tracer

Fissel+ 2018, submitted

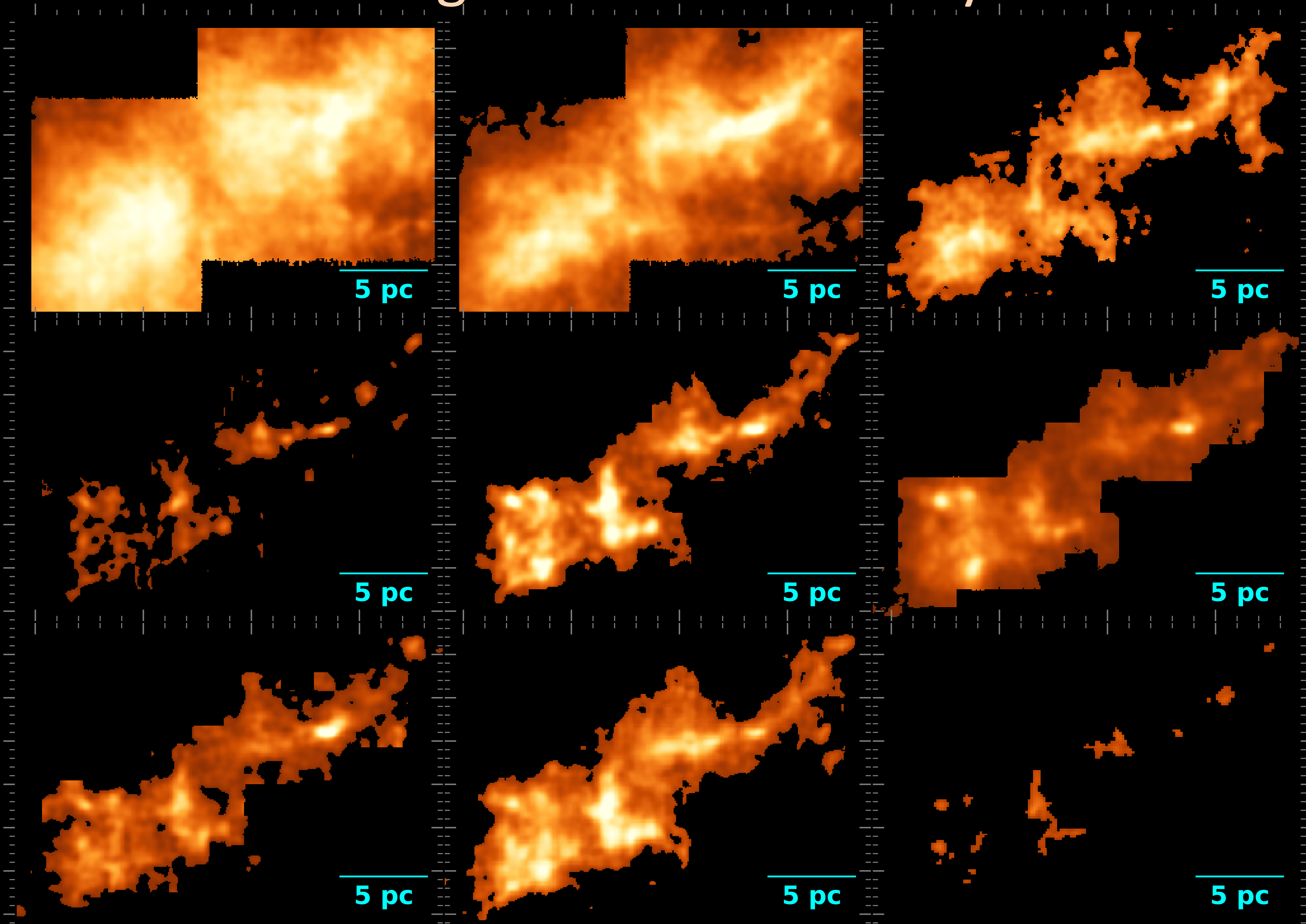
Mopra 22m telescope

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

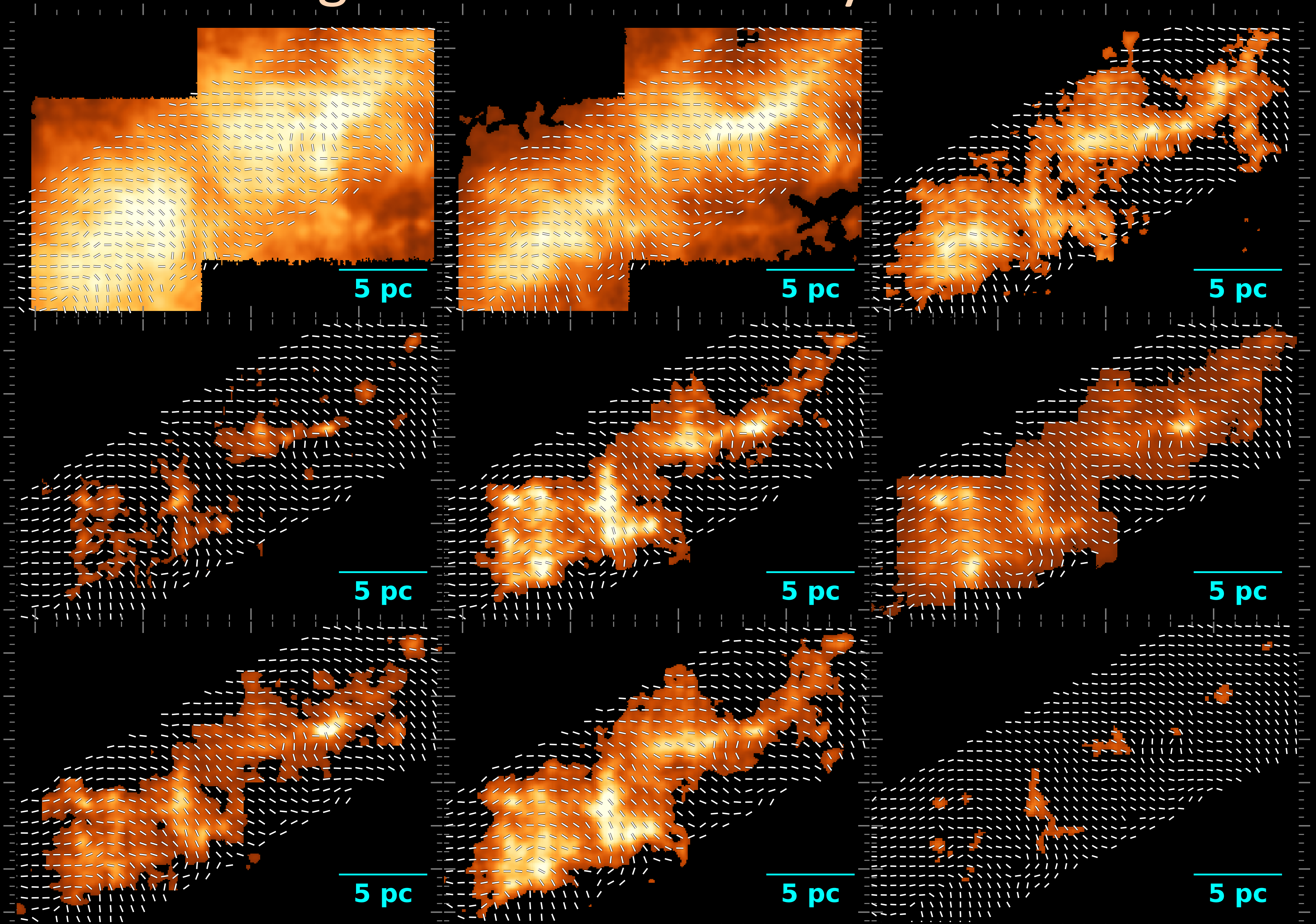
Vela C Mopra Molecular Line Observations



Integrated Line Intensity

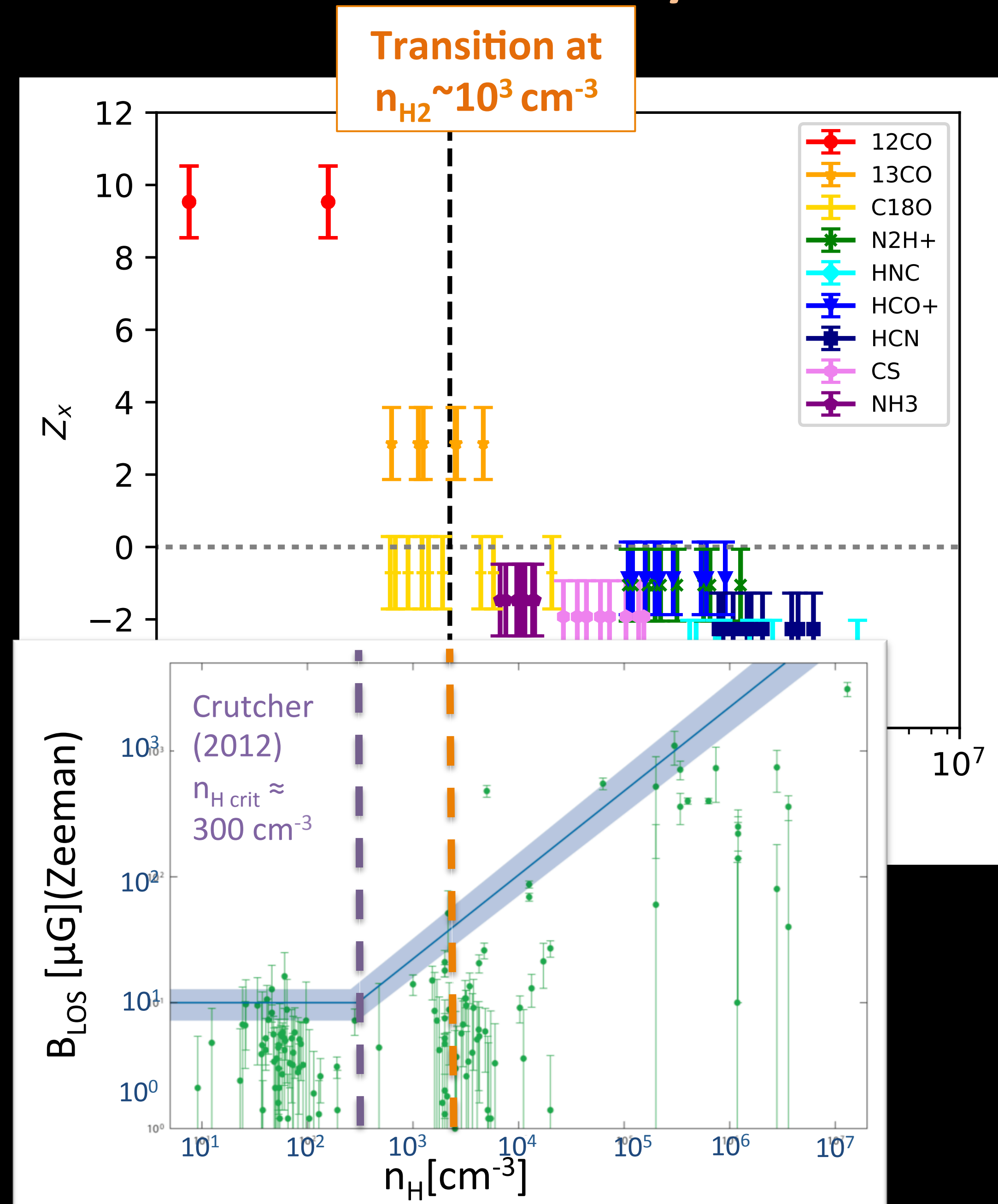


Integrated Line Intensity + B-field



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 field.
- Indicates formation of dense gas is affected by the cloud-scale magnetic field.



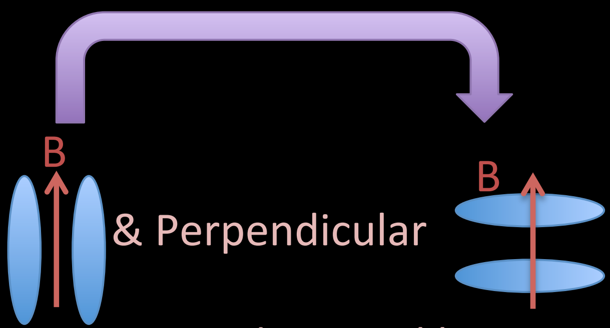
Fissel+, submitted

Towards a model for cloud formation

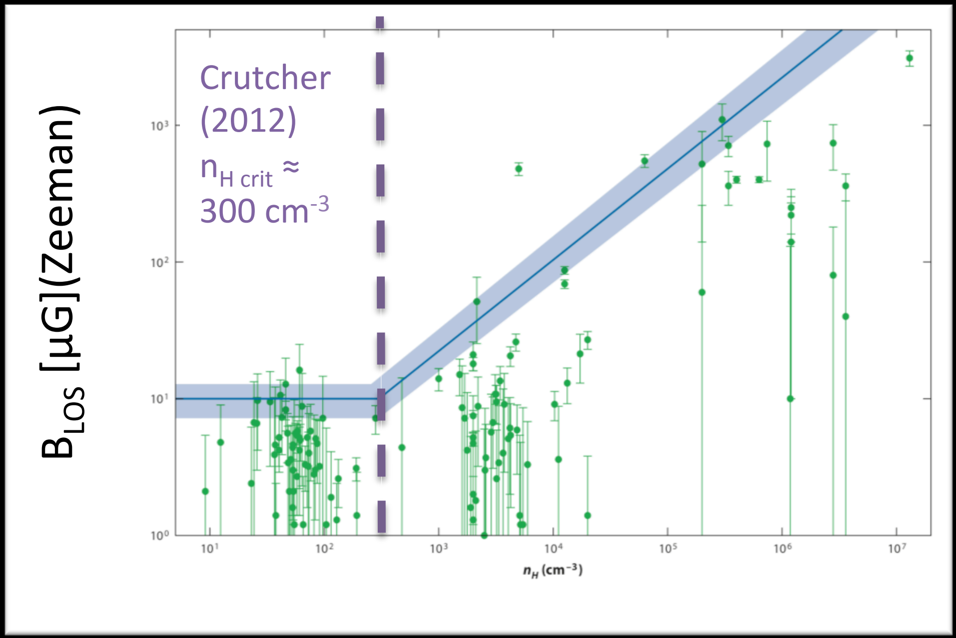
Soler & Hennebelle 2017: (Analyzed MHD Equations)

transition occurs where $\nabla \cdot \mathbf{v} < 0$

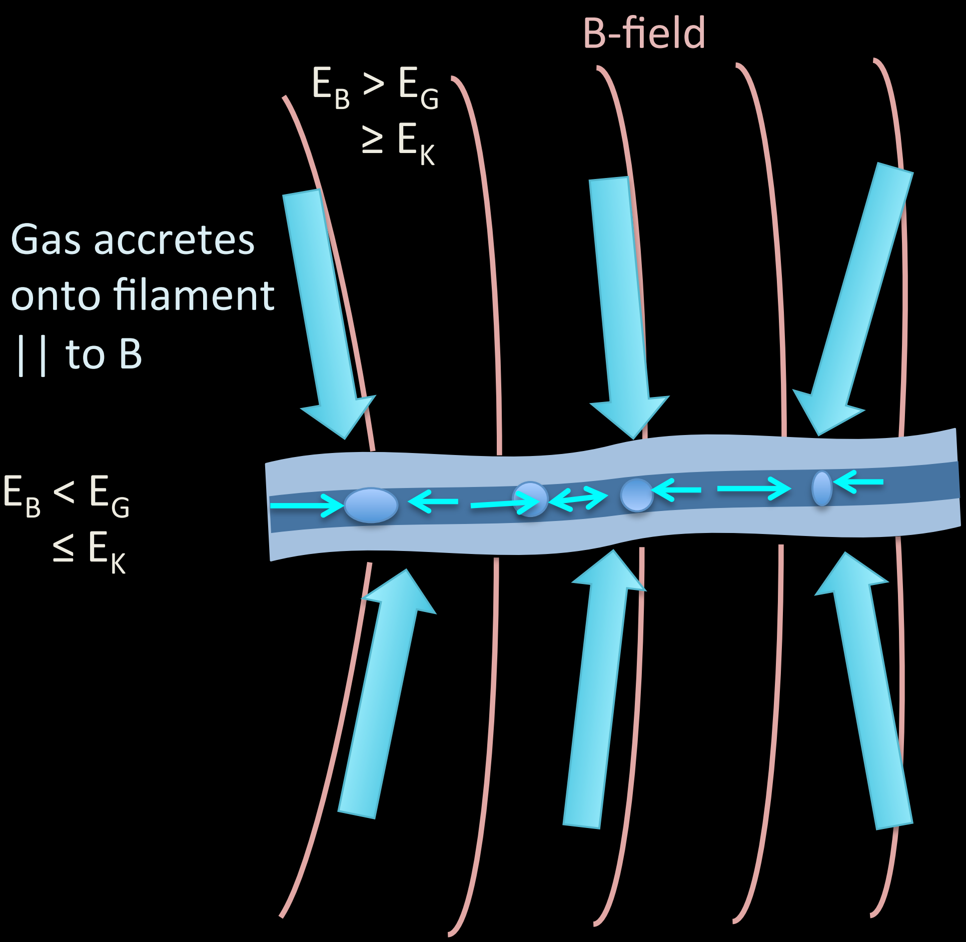
Parallel & Perpendicular



alignment correspond to equilibrium points.



A Cartoon Model for Discussion



Relative Orientation:

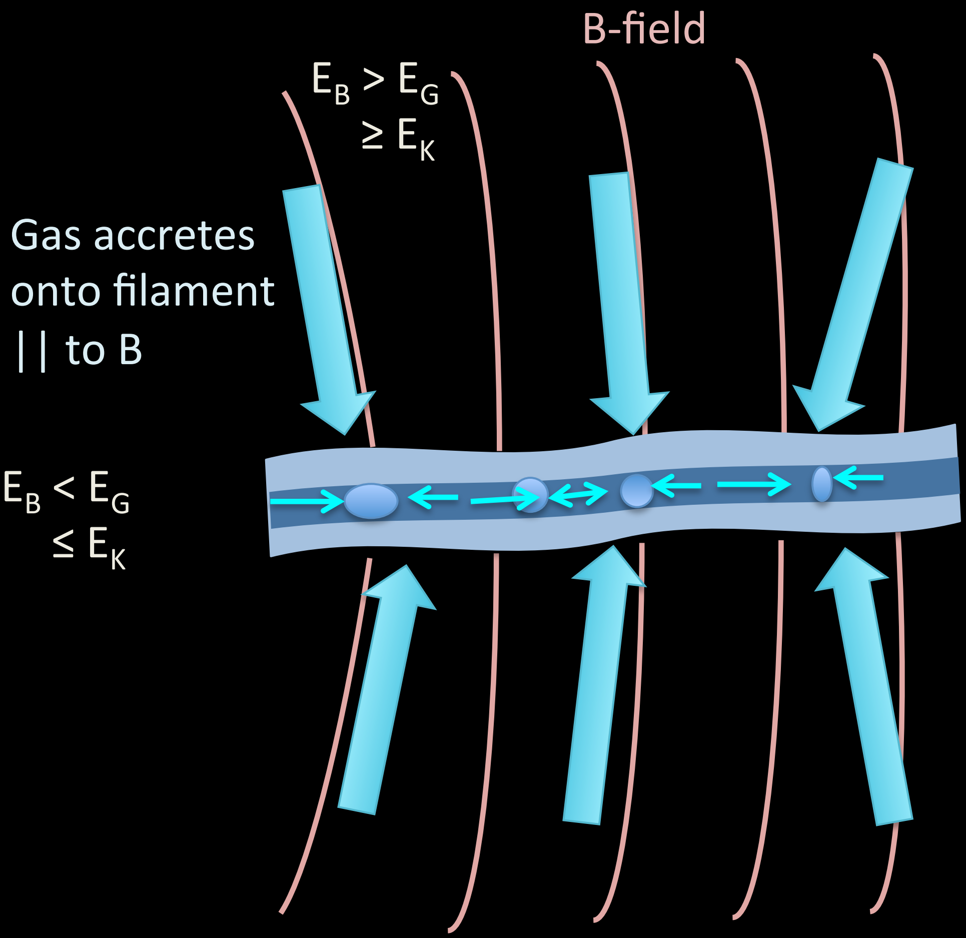
✔magnetic field at least as strong as turbulence on large scales

Zeeman:

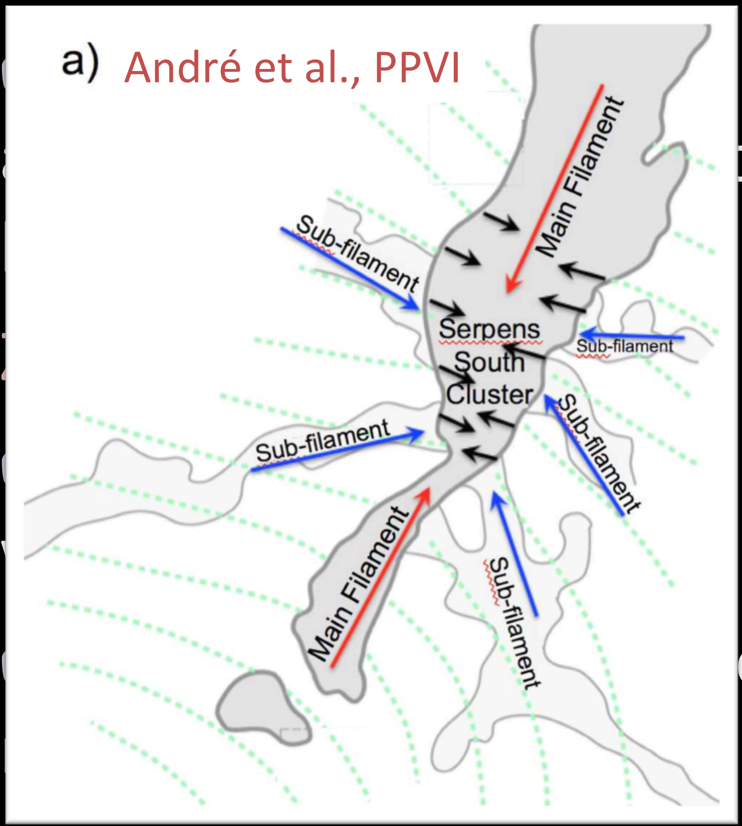
✔lack of increase in |B| with N_H at low N_H

✔cores and filaments are marginally supercritical

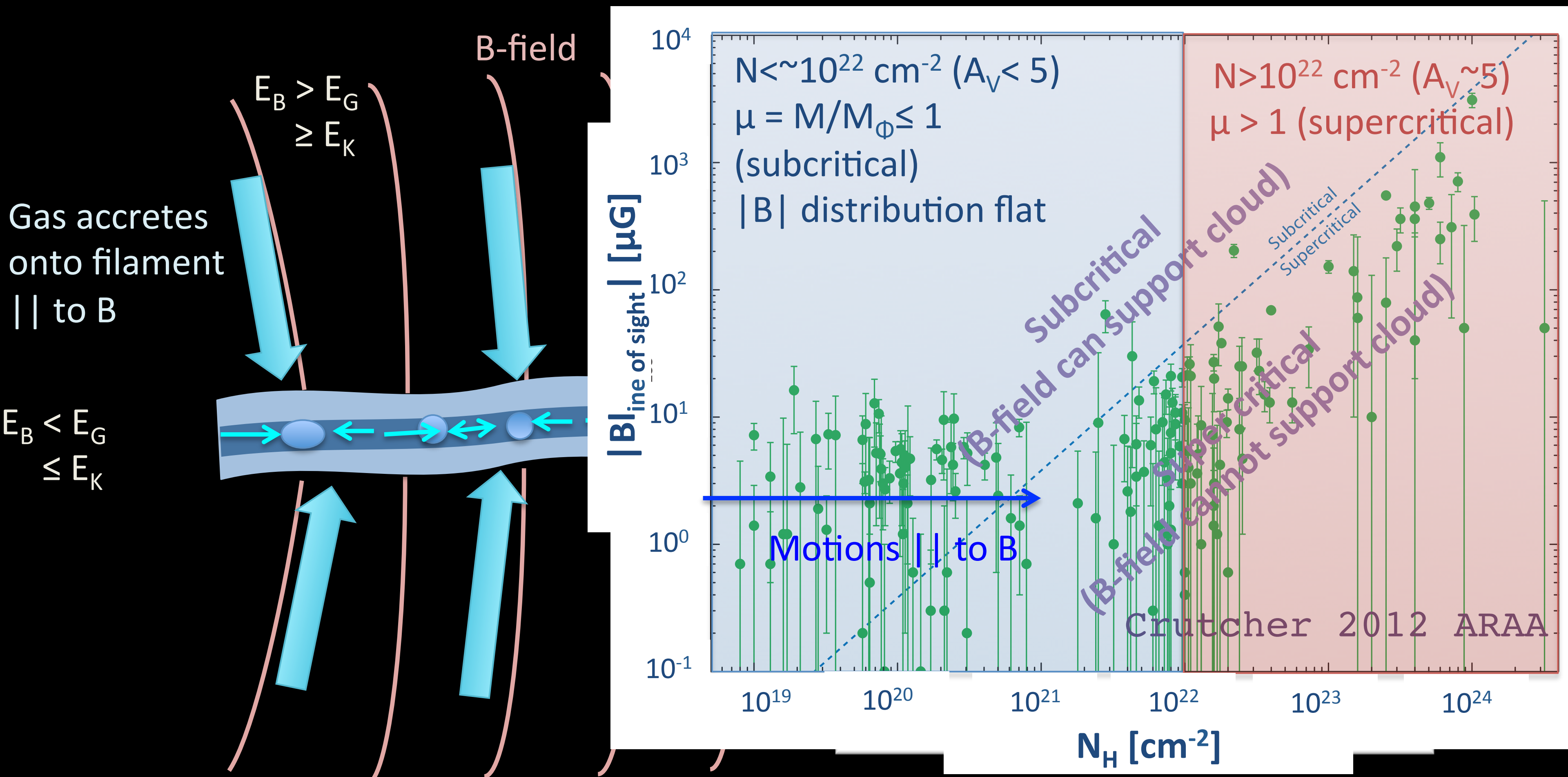
A Cartoon Model for Discussion



Relative Orientation:



A Cartoon Model for Discussion

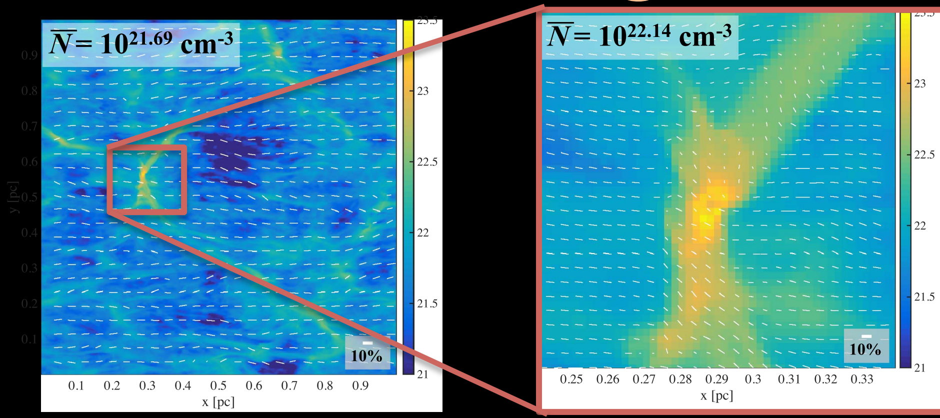


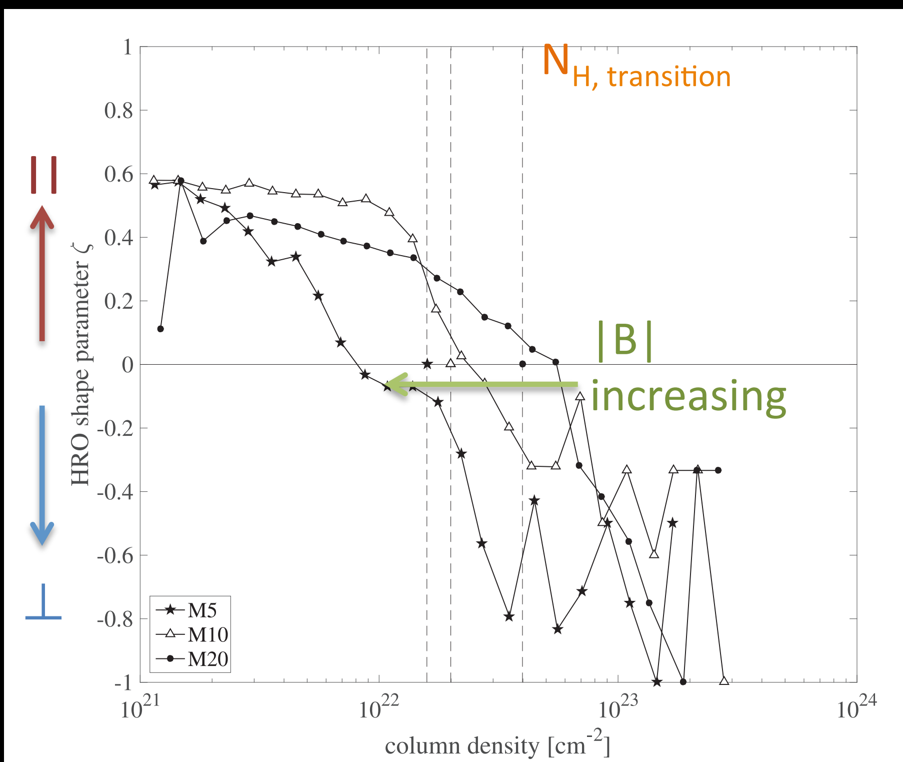
Magnetized filaments in a colliding flow

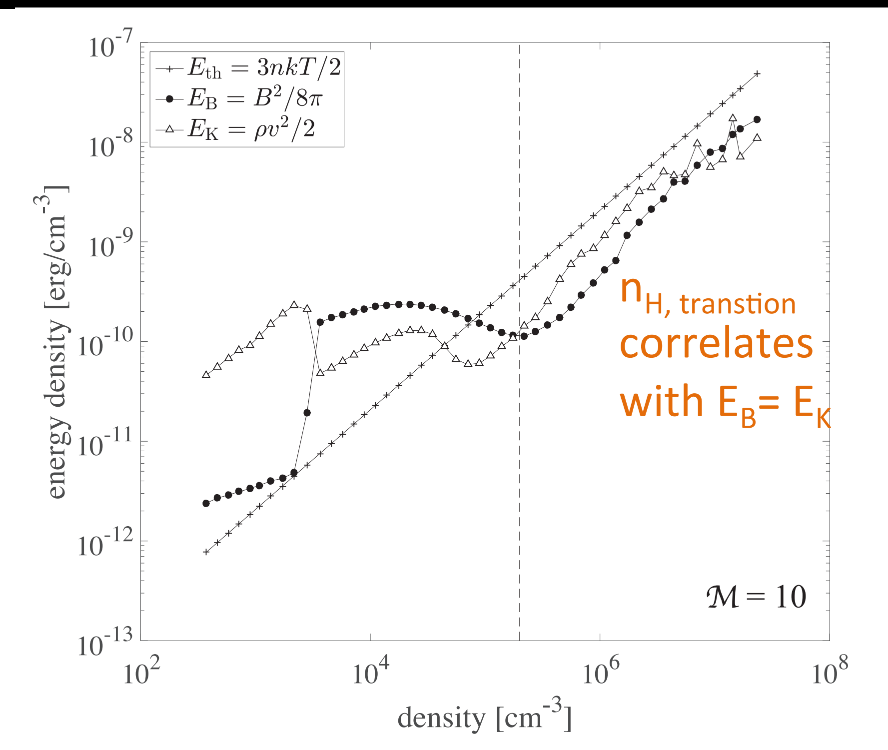
Chen & Ostriker 2014, Chen+ 2016

Synthetic polarization observations of ATHENA colliding flow cloud simulation.

Dense filaments form within a highly magnetized sheet.







AREPO Simulations of MHD Turbulence + Gravity

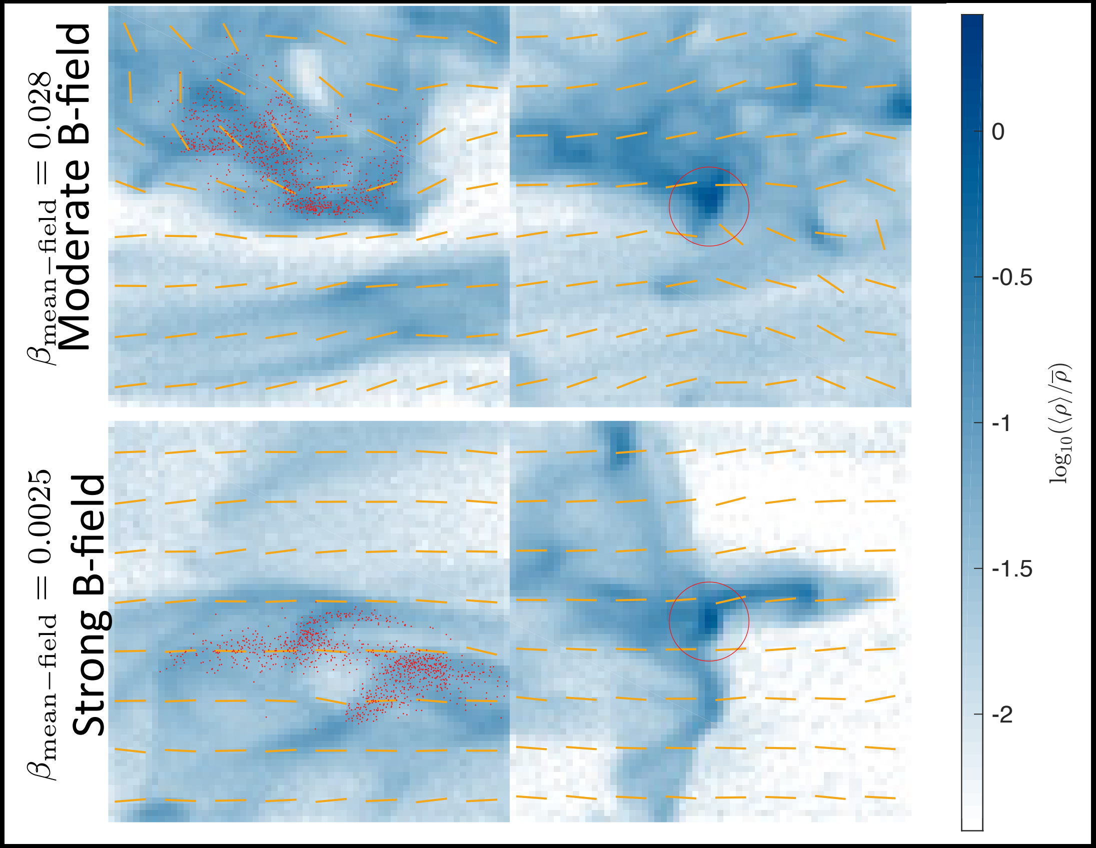
Mocz & Burkhart 2018

Strong B-Field Simulations:

Long-lived shocks form || to B-field (sweep up material)

Cores/dense filaments form from gravitational accretion parallel to B-field.

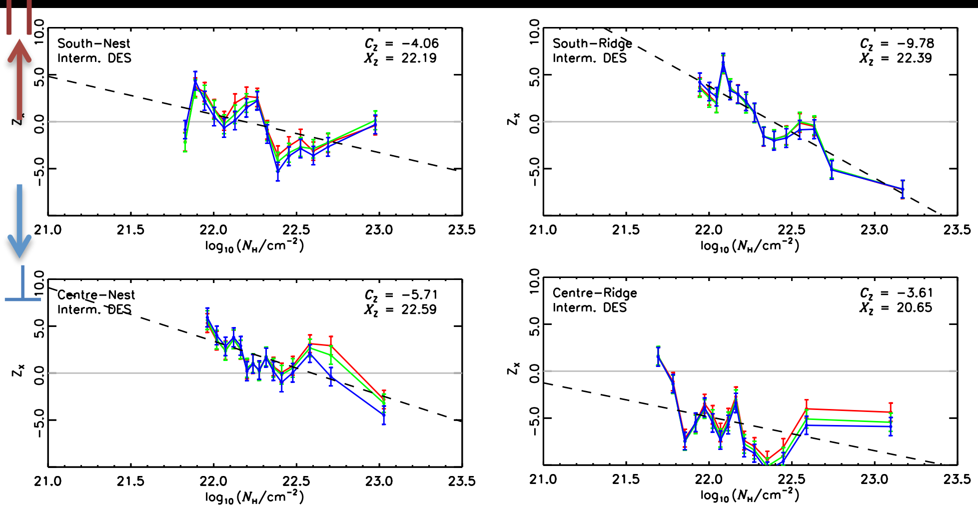
Pre-collapse: Collapse:



Regional Differences in Relative Orientation

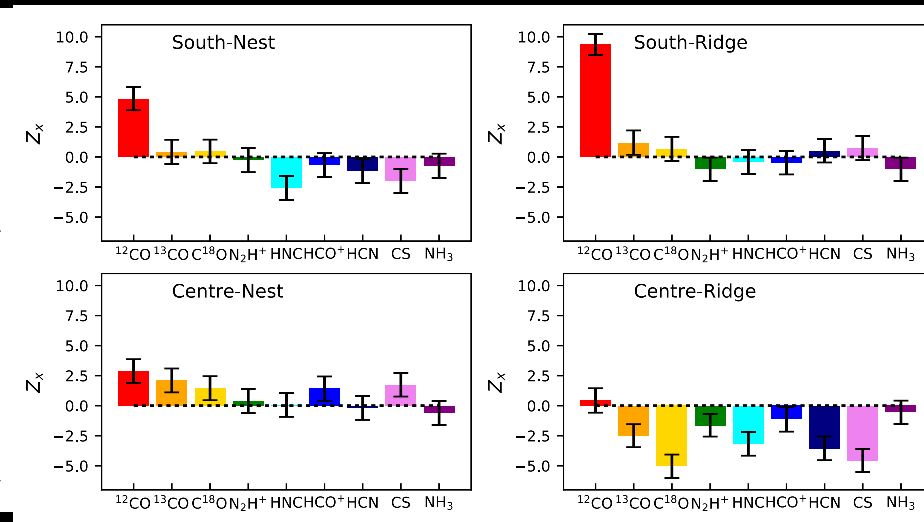
Column Density Alignment

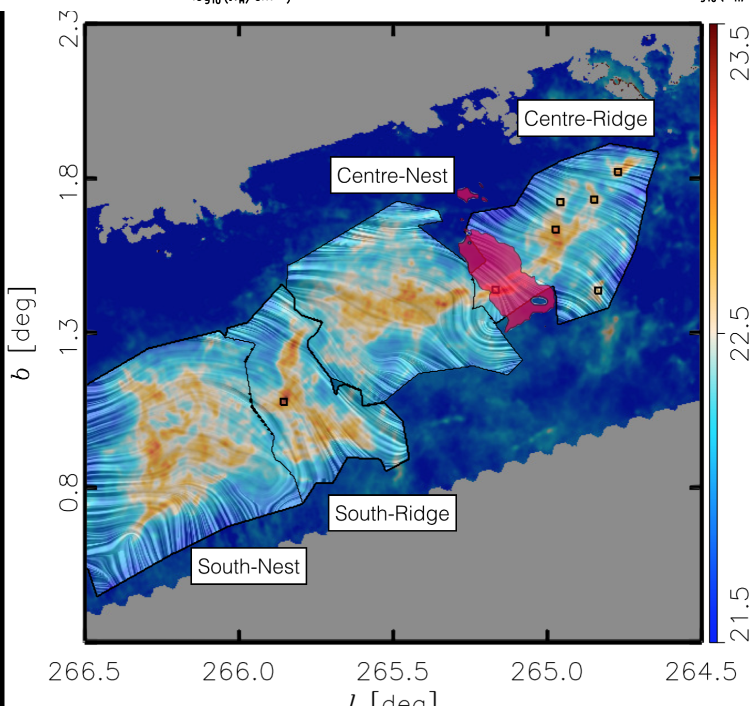
Soler+ 2017



Volume Density Alignment

Fissel+ submitted





The Centre-Ridge has a *stronger transition* in relative orientation with density, is *more polarized* and has a *less disordered* B-field.

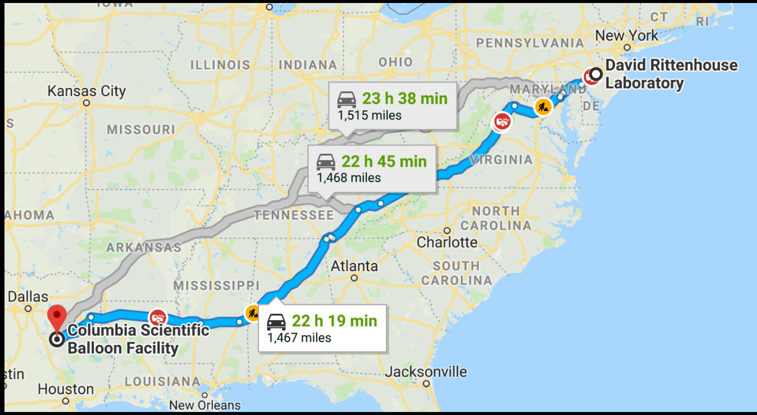
It also is the *most active star forming* region in Vela C.

- Is the magnetic field stronger compared to turbulence in the Centre-Ridge?
- Were the convergent flows that created the Centre-Ridge, more efficient at creating dense gas?
- Is the magnetic field geometry (coincidentally) more parallel to the plane-of-sky in the Centre-Ridge?

A Next Generation BLAST Polarimeter (BLAST-TNG)

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

First flight from Antarctica in late 2018

http://sites.northwestern.edu/blast

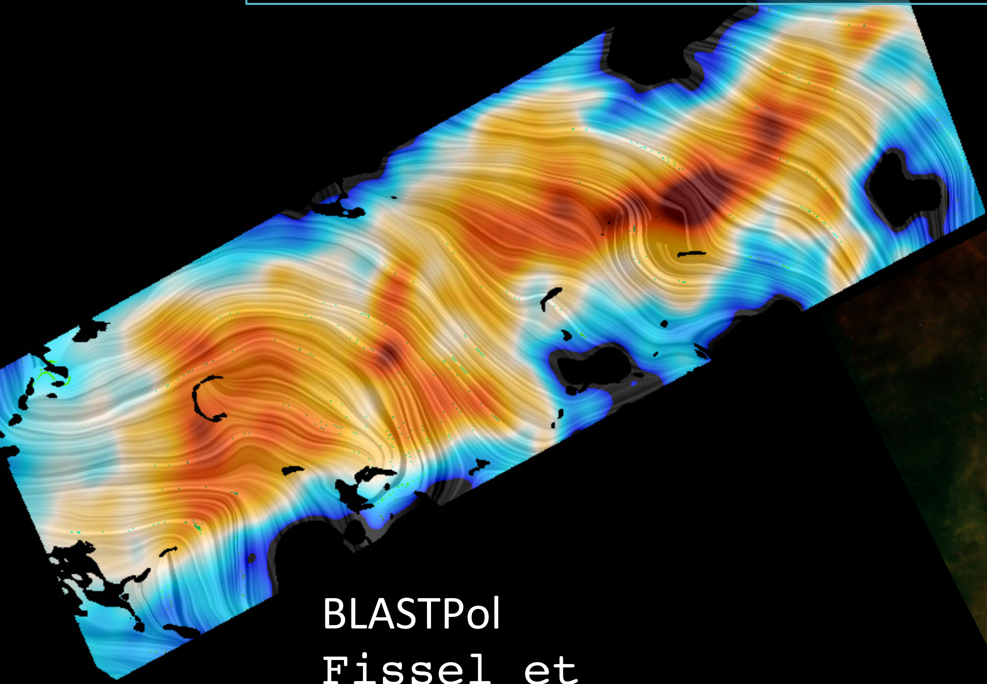
Poster #52

BLAST-TNG high resolution observations of dozens of GMCs/IRDCs

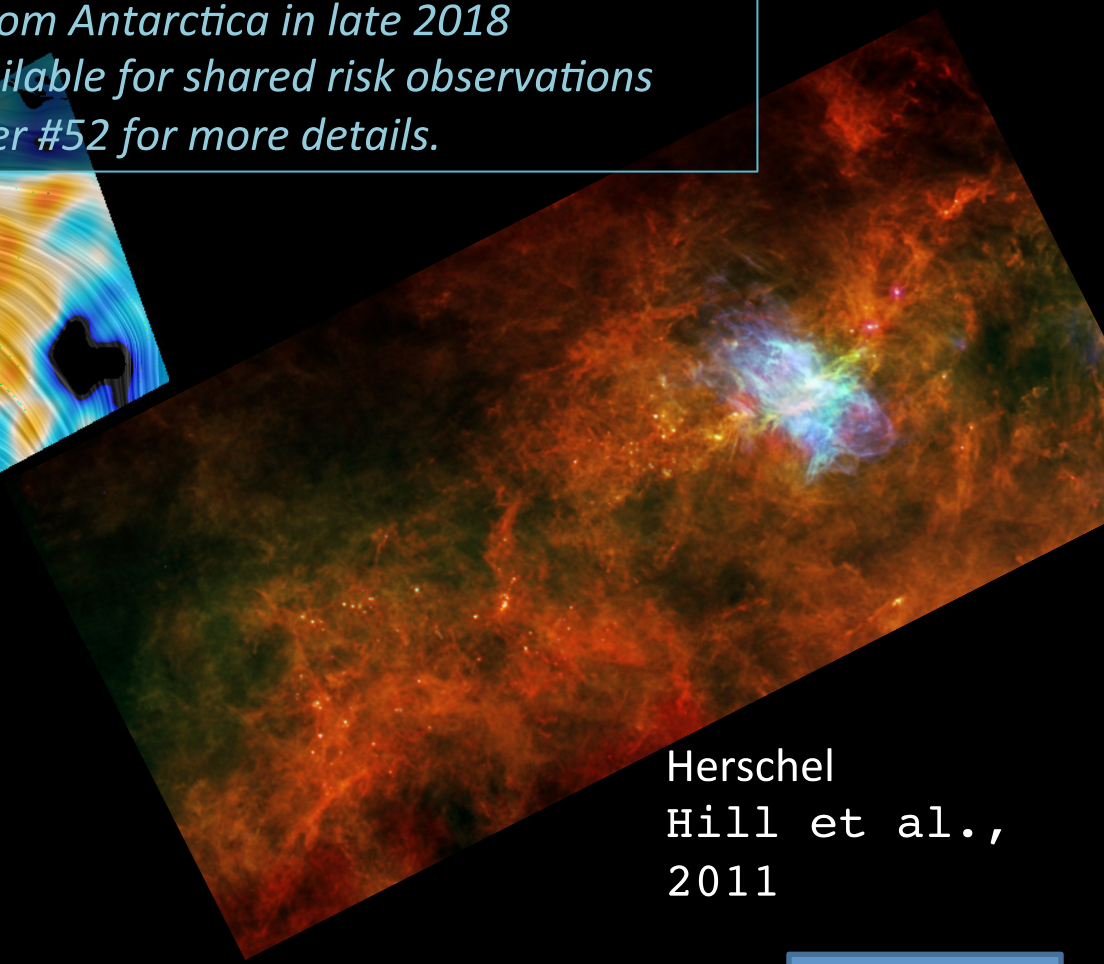
BLASTPol 2012
Resolution: 0.65pc

BLAST-TNG
Resolution: 0.13pc

First flight from Antarctica in late 2018
25% of the time available for shared risk observations
See Poster #52 for more details.



BLASTPol
Fissel et al., 2016



Herschel
Hill et al., 2011

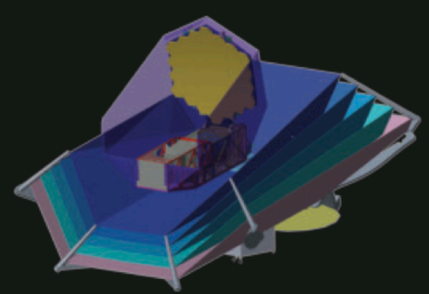
Poster #52

What about from space?

ORIGINS Space Telescope | From first stars to life

OST Mission Concept 1*

Observatory



- 9.1 m off-axis primary mirror
- Cold (4K) telescope
- Wavelengths 5 – 660 µm
- 5 science instruments
- Launch 2030s
- Mission operations at Sun-Earth L2
- Data rate: 348 Mb/s
- 5 year lifetime, 10 year goal

* OST is an evolving concept for the Far-IR Surveyor mission in NASA's visionary astrophysics roadmap. Stay tuned for Concept 2, coming in the fall of 2018.

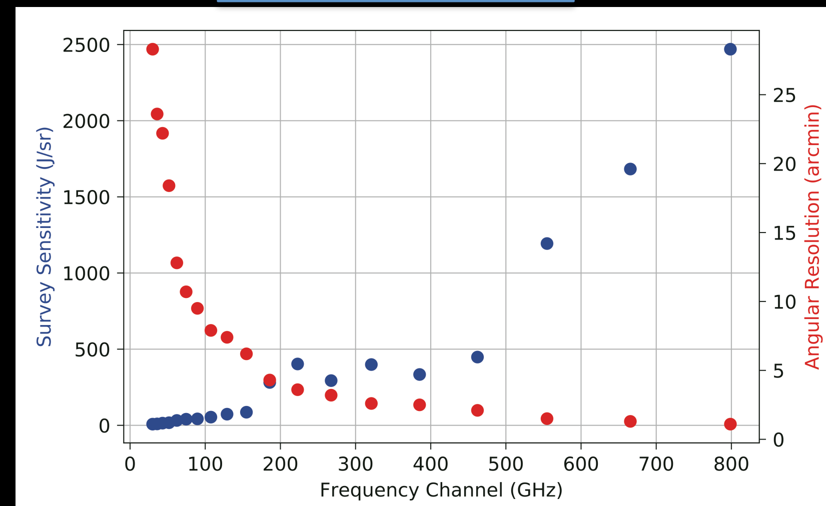
Instruments

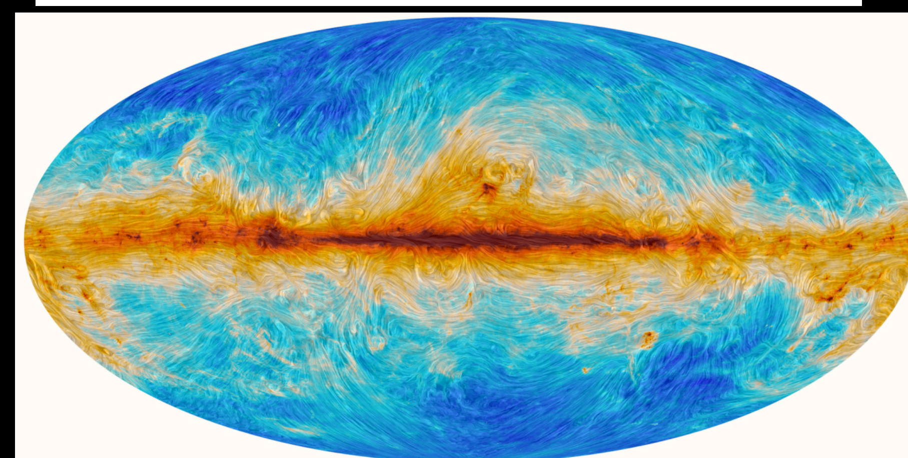
Instrument		Wavelength (µm)	Observing Modes
MISC	Mid-Infrared Imager, Spectrometer, Coronagraph	5-38	• Imaging, spectroscopy • Coronagraphy (10^{-6} contrast) • Transit Spectrometer < 10 ppm stability)
MRSS	Medium Resolution Survey Spectrometer - IFU	30-660	• Multi-band Spectroscopy
FIP	Far-Infrared Imager and Polarimeter	40, 80, 120, 240	• Broadband imaging • Field of view: 2.5'x5', 7.5'x15' • Differential polarimeteric imaging
HERO	Heterodyne Receiver for OST	63-66 , 111-610	• Multi-beam spectroscopy
HRS	High Resolution Spectrometer	25-200	• Spectroscopy

1" to 6" resolution polarimetry for hundreds of clouds

Probe of Cosmic Inflation (PICO)

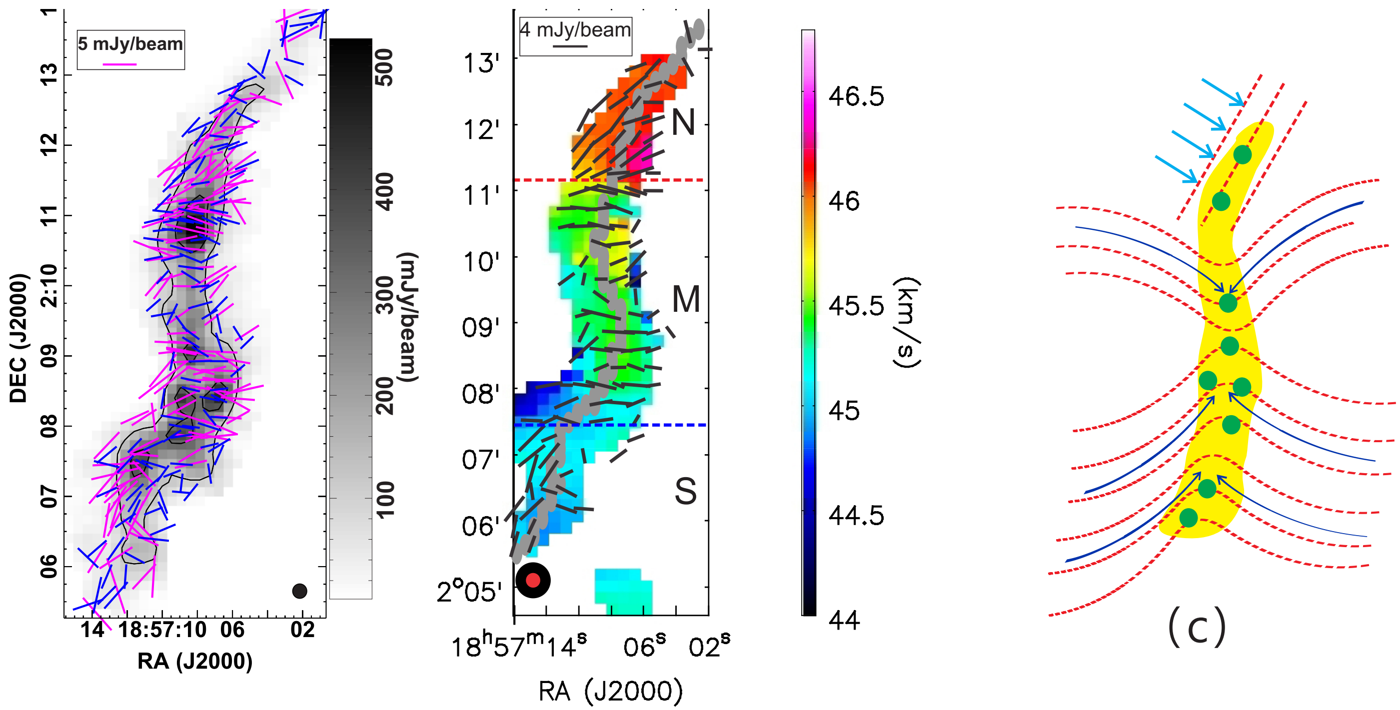
See Poster #51





1' resolution over the entire sky (thousands of molecular clouds)

Observations needed: Mapping fields within filaments



Liu+ 2018, submitted

- Possible detection in high mass 2.9 kpc distant IRDC G035.39 with POL-2 (14'' FWHM resolution)

Resolving Magnetic Fields in Filaments with TolTEC

Poster #52

TolTEC

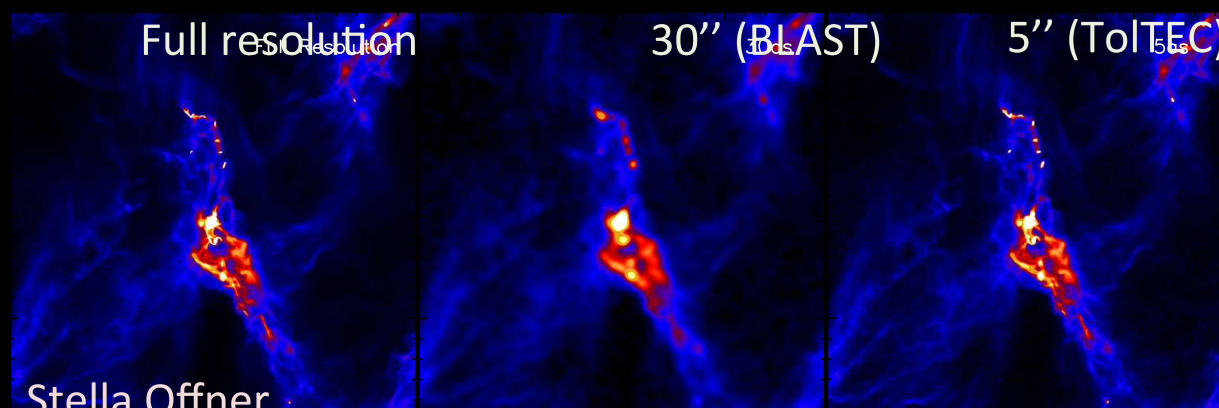
(PI Grant Wilson, UMass)

- 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 (2018-2021)

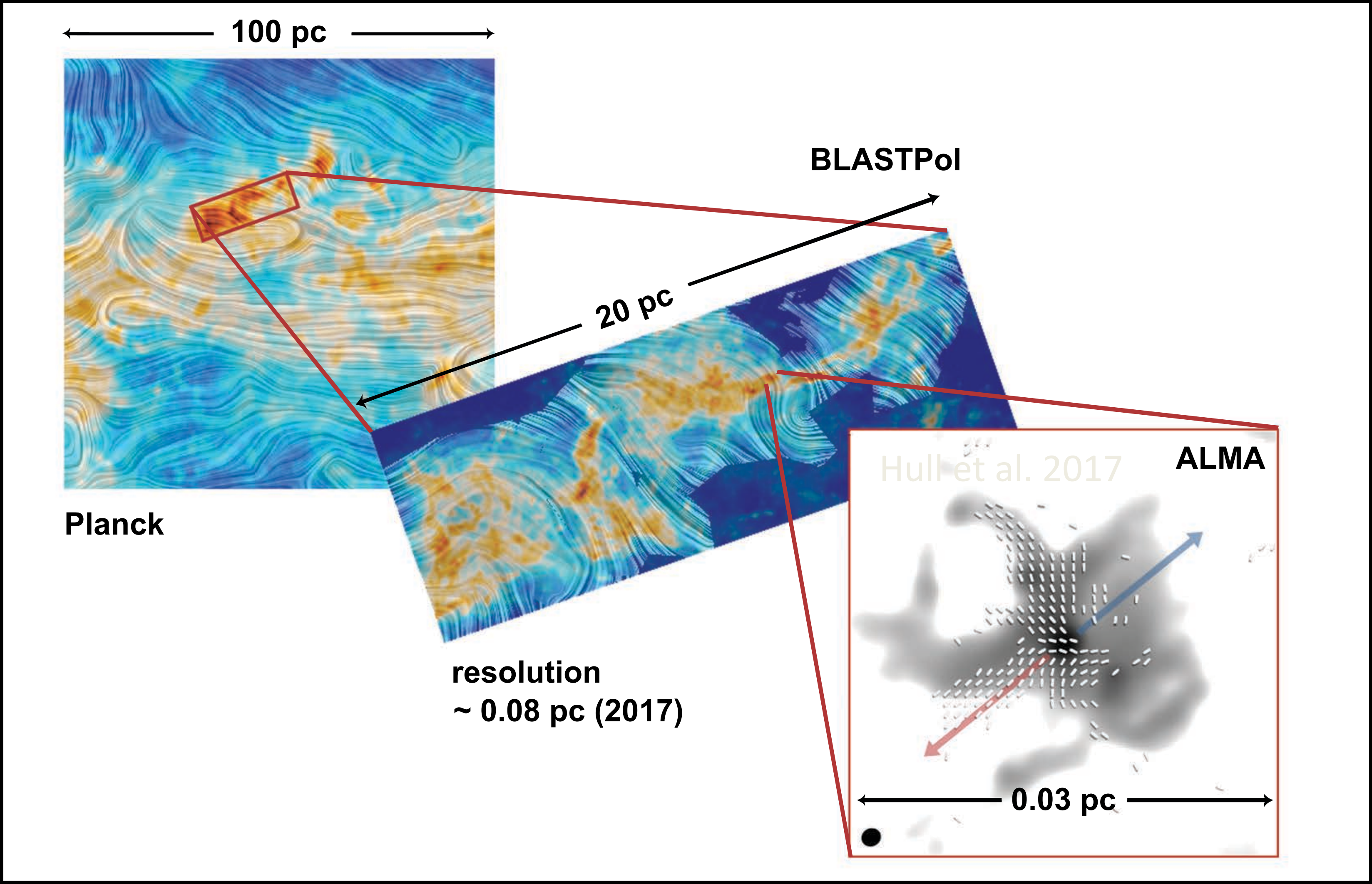
(Coordinators Giles Novak and Laura Fissel)

- 100 hours reserved for mapping filaments and cores over A_V>8



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

The Goal: measure the strength and energetic importance of magnetic fields across all scales in star formation.



Summary

Magnetic Field Discussion
Lunch today!
(meet in the lobby)

- In Vela C we see a change in orientation of cloud structure *from parallel* to the magnetic field *at low densities to perpendicular* to the magnetic field *at high densities*.
  - Implies that the cloud scale magnetic field is at least as strong as turbulence, and plays an important role in forming dense filaments within clouds.
  - Consistent with a model where dense filaments form from convergent flows perpendicular to the magnetic field, and accrete matter primarily parallel to the field.
- We see indication that the highest N_H region and most active star forming region in Vela C has a lower transition density:
  - Stronger magnetic field?
  - More favorable geometry of the flows that created the region?
  - Projection effect?