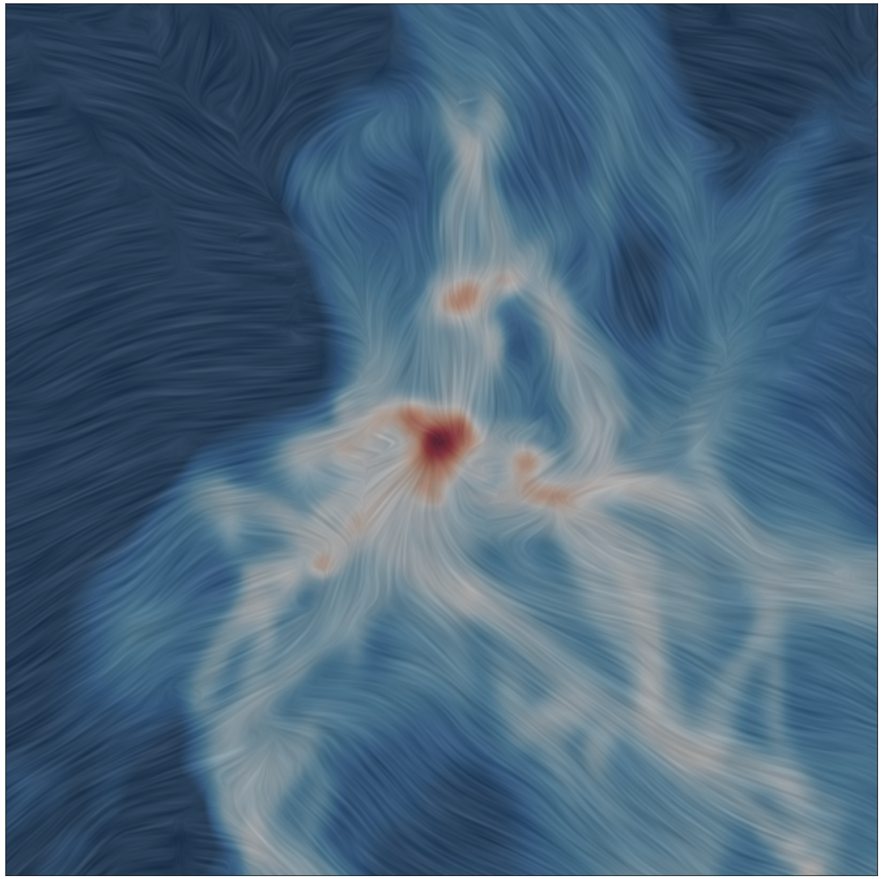
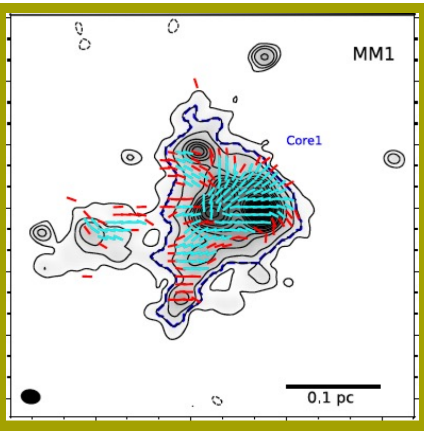
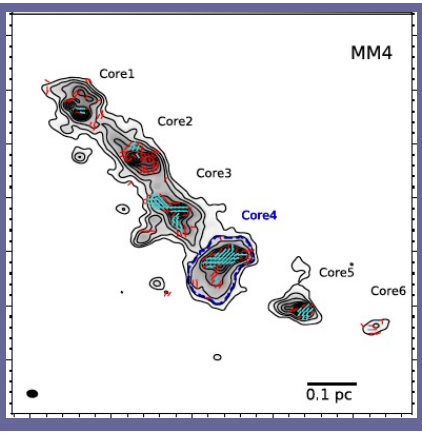
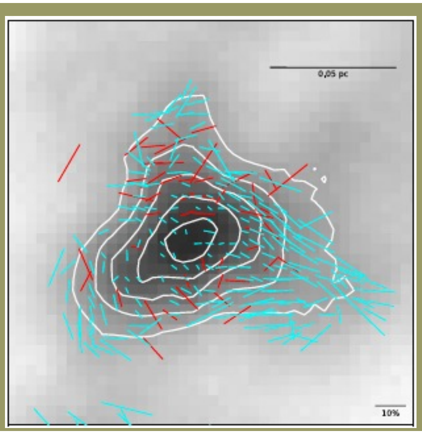








James Clerk Maxwell Telescope
East Asian Observatory

Magnetic fields in early stages of star formation revealed by dust polarization observations

Junhao Liu (刘峻豪)

2021.06-2023.07 Postdoctoral Fellow. EAO
2018.08-2021.05 Predoctoral Fellow. CfA
2015.08-2021.03 Ph.D. Nanjing University.

- Star formation (SF)
  - Extragalactic SF
  - Galactic SF
    - Macro: CMF, IMF, SF Rate (SFR), SF Efficiency (SFE)
    - Micro: cloud complexes to individual stars


Competing forces

Inward: gravity (G)

Outward: turbulence (K), **magnetic field (B)**, thermal pressure, rotation, stellar feedback…

Hierarchical fragmentation

- 100 pc cloud complexes
- 10 pc clouds
- **1 pc clumps**
- **0.1 pc dense cores**
- 0.01 pc condensations

Outline: Magnetic fields in star formation

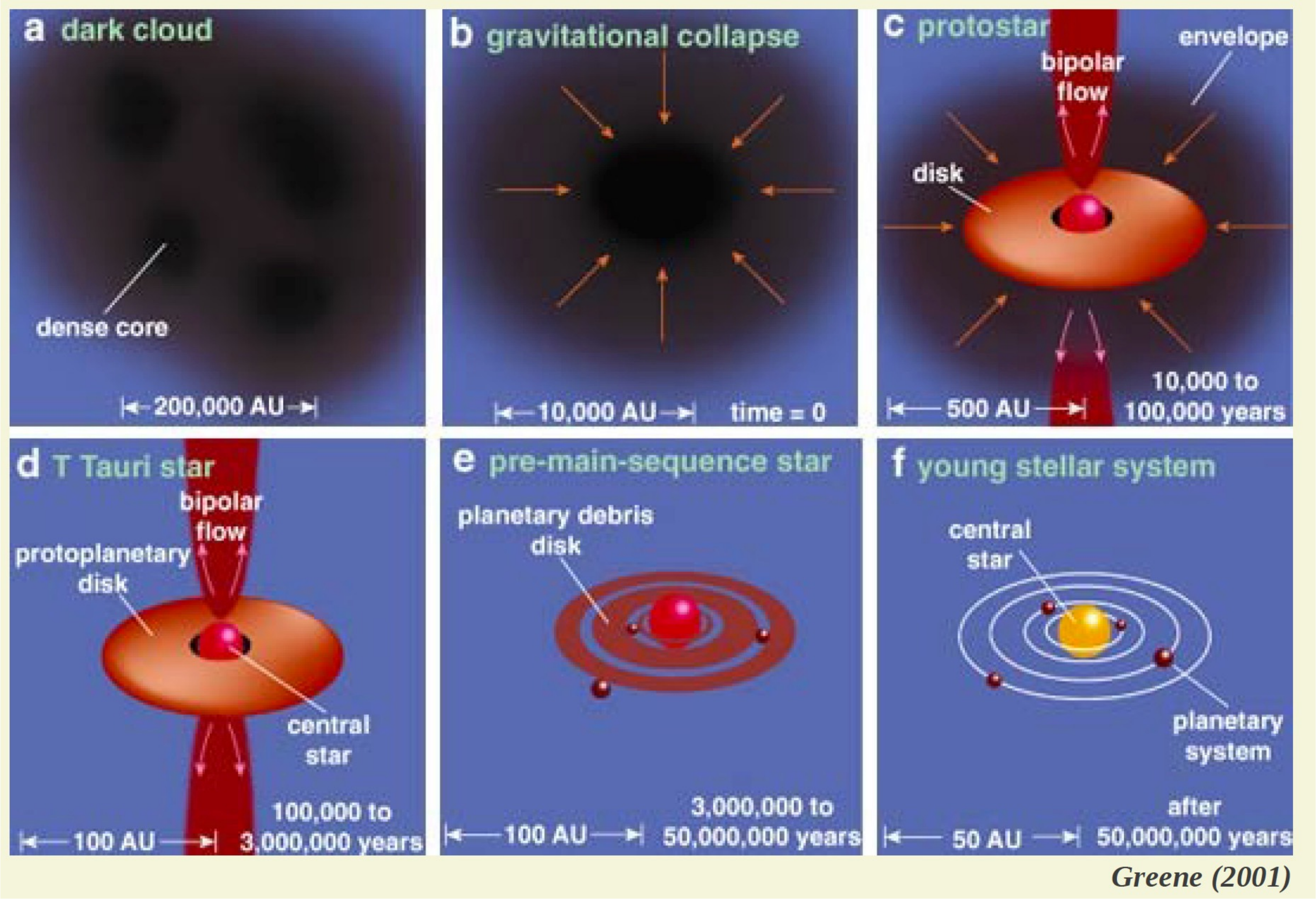
- Research history
  - B fields in early stages of low-mass star formation: JCMT POL-2 observations of low-mass starless Ophiuchus C
  - B fields in early stages of high-mass star formation: ALMA observations of 3 massive clumps in IRDC G28.34
  - Test the Davis-Chandrasekhar-Fermi (DCF) method with numerical simulations
- Current research and research plan
  - A compilation of all the previous DCF estimations (current research)
  - Multi-scale pol survey of B fields of massive dense cores in Cygnus-X with JCMT and SMA
  - ALMA polarization survey of B fields in NGC 6334 sources
  - Test the Koch 2012 method with simulations
  - Polarization survey of massive clumps/cores in IRDCs

Outline: Magnetic fields in star formation

- Research history
  - **B fields in early stages of low-mass star formation: JCMT POL-2 observations of low-mass starless Ophiuchus C**
  - B fields in early stages of high-mass star formation: ALMA observations of 3 massive clumps in IRDC G28.34
  - Test the Davis-Chandrasekhar-Fermi (DCF) method with numerical simulations
- Current research and research plan
  - A compilation of all the previous DCF estimations (current research)
  - Multi-scale pol survey of B fields of massive dense cores in Cygnus-X with JCMT and SMA
  - ALMA polarization survey of B fields in NGC 6334 sources
  - Test the Koch 2012 method with simulations
  - Polarization survey of massive clumps/cores in IRDCs

Low-mass star formation

Starless core Prestellar(starless)core Protostellar core



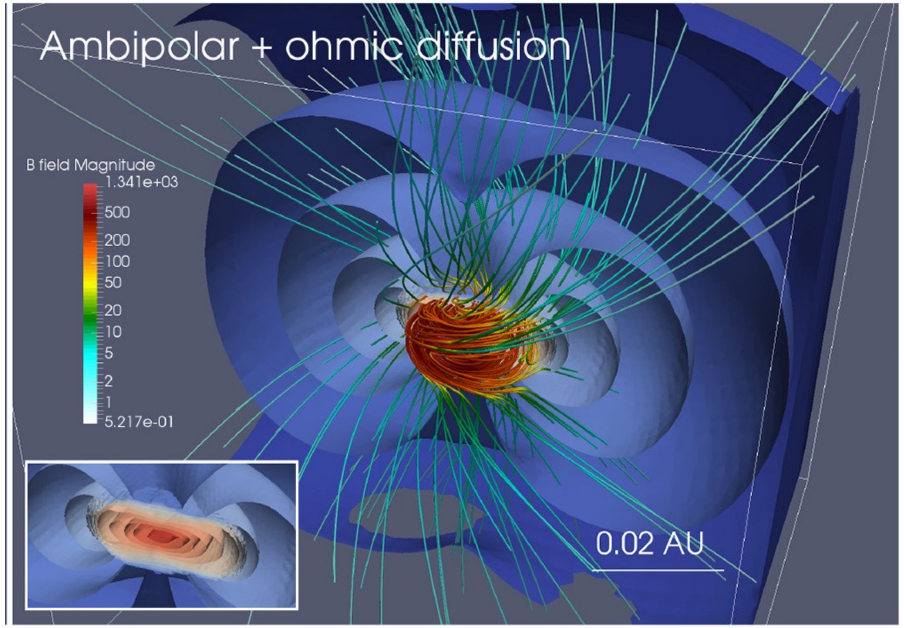
Greene (2001)

Magnetic field or turbulence?

Magnetic field-dominated model

(Mouschovias et al. 2006)

G $\lesssim$ B to G$\gtrsim$B: ambipolar diffusion

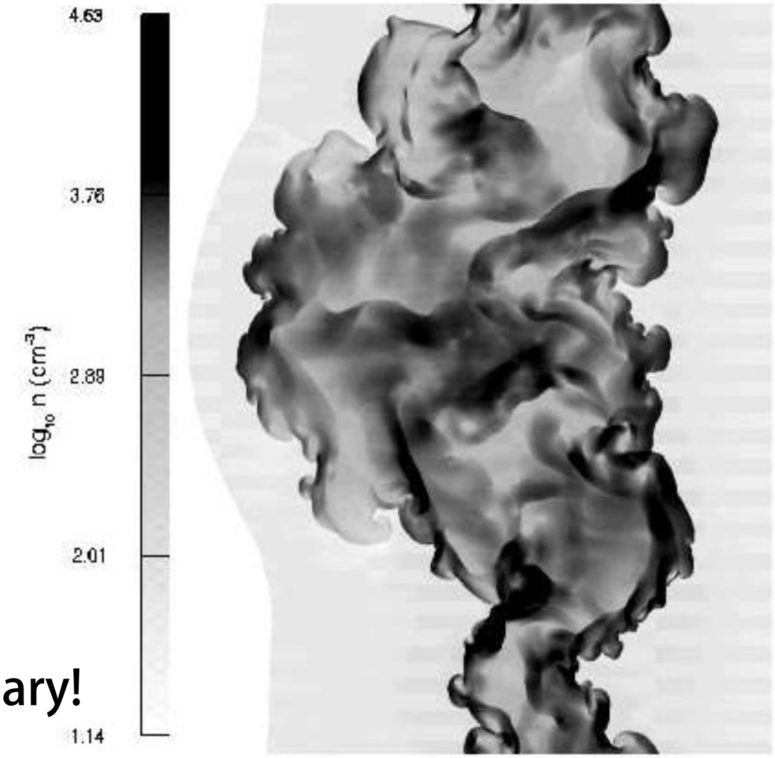


Vaytet 2018

Turbulence-dominated model

(Mac Low & Klessen, 2004)

G>B: intersecting turbulent flow create over-densed region



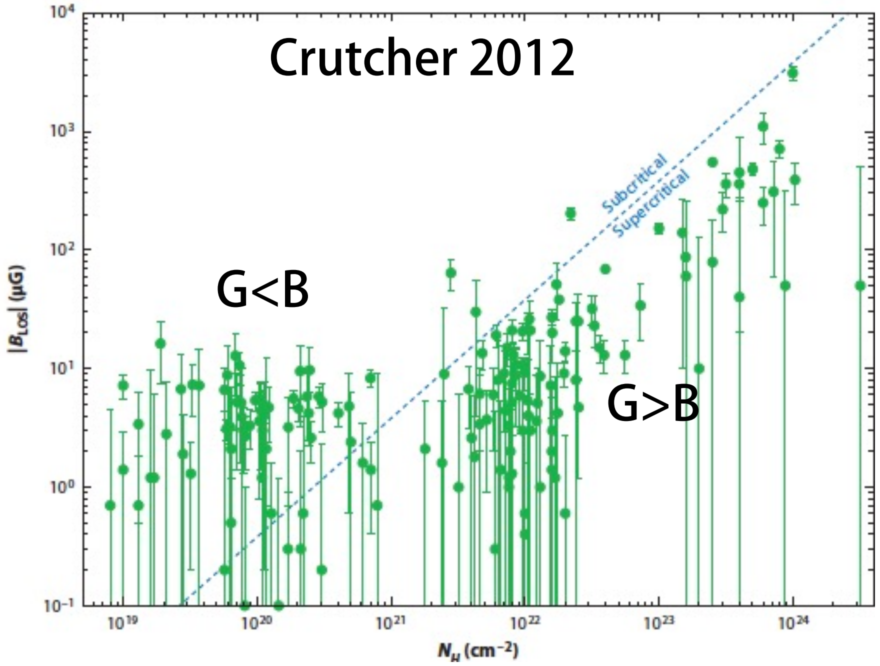
Mac Low & Klessen, 2004

Observing B is necessary!

Zeeman observations

Line of sight (LOS) B strength (lower limit)

Compilation (Crutcher 2012):
G>B in protostellar cores
K $\gtrsim$B in protostellar cores



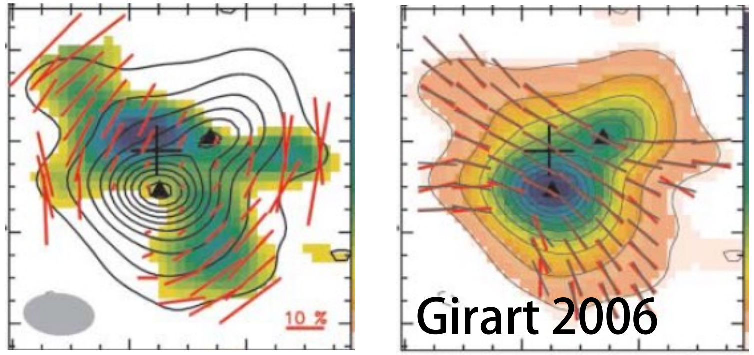
Crutcher 2012

G<B

G>B

Dust polarization observations

Plane of sky (POS) B orientation



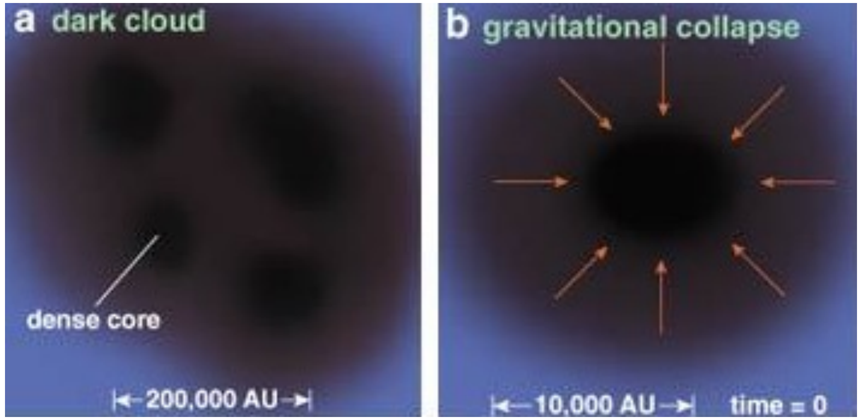
Girart 2006

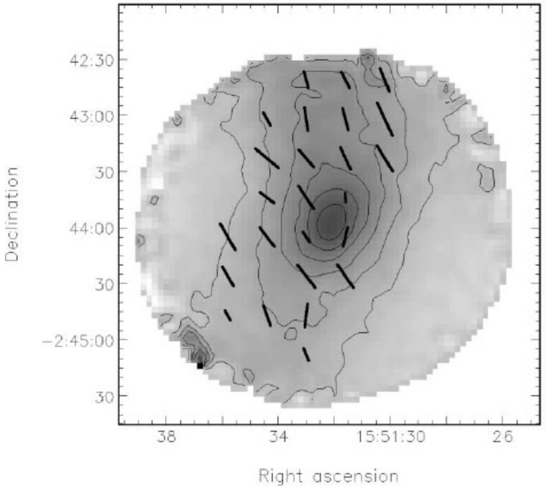
POS B Strength: DCF method

$$B_{\rm pos} = Q\sqrt{4\pi\rho}\,\frac{\delta V}{\delta\phi}$$

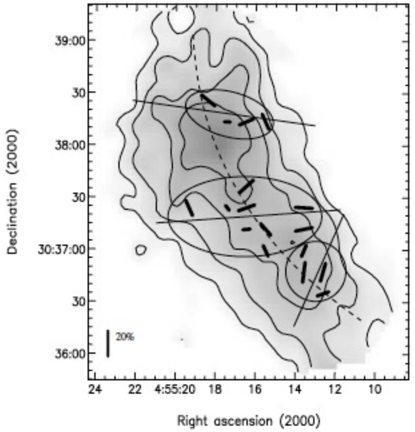
Compilation:
G>B in protostellar cores
K $\lesssim$B in protostellar cores

Initial conditions of low-mass star formation

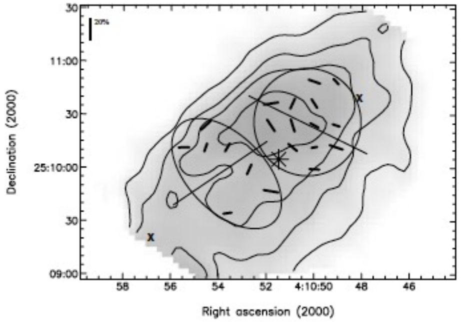




Crutcher 2004: L183.
JCMT SCUPOL

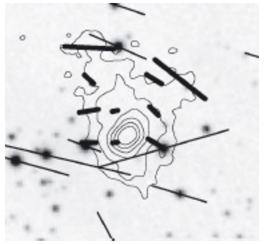


Kirk 2006: L1517B.
JCMT SCUPOL

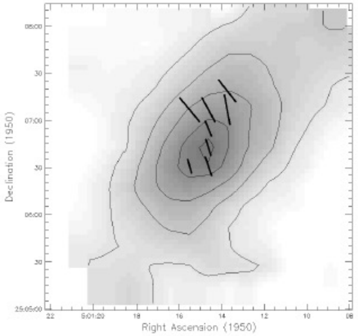


Kirk 2006: L1498.
JCMT SCUPOL

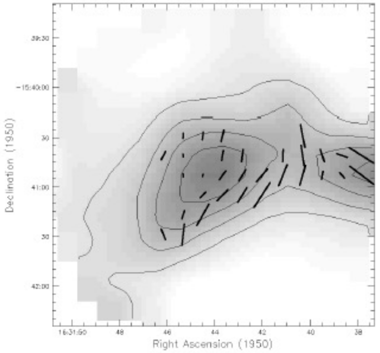
Dynamical states of low-mass starless cores?
Gravity VS B?
Turbulence VS B?



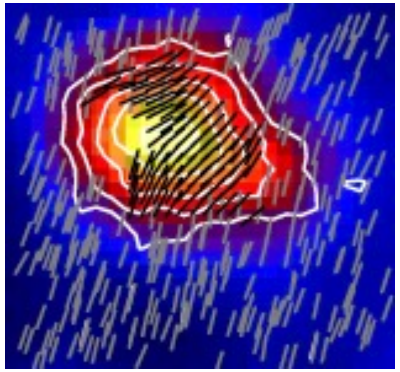
Ward-Thompson 2009:
CB3. JCMT SCUPOL



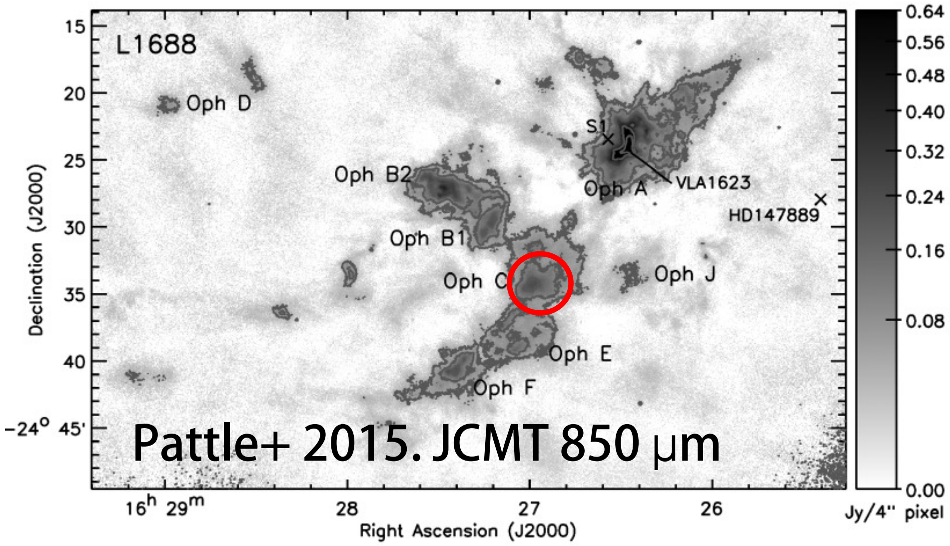
Ward-Thompson 2000:
L1544. JCMT SCUPOL



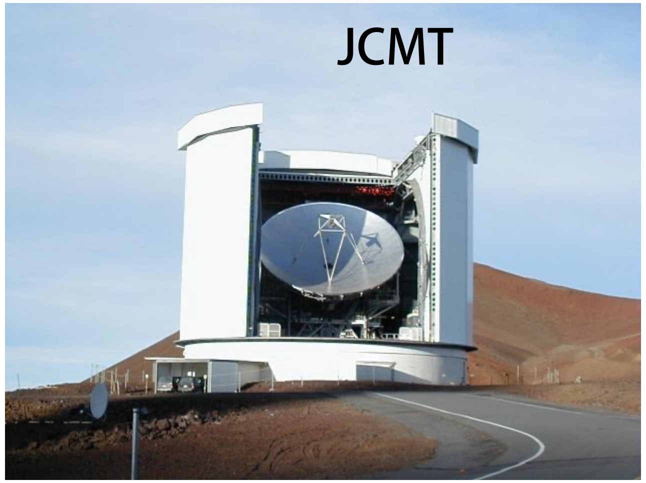
Ward-Thompson 2000:
L43. JCMT SCUPOL



Alves 2014: Pipe-109. APEX



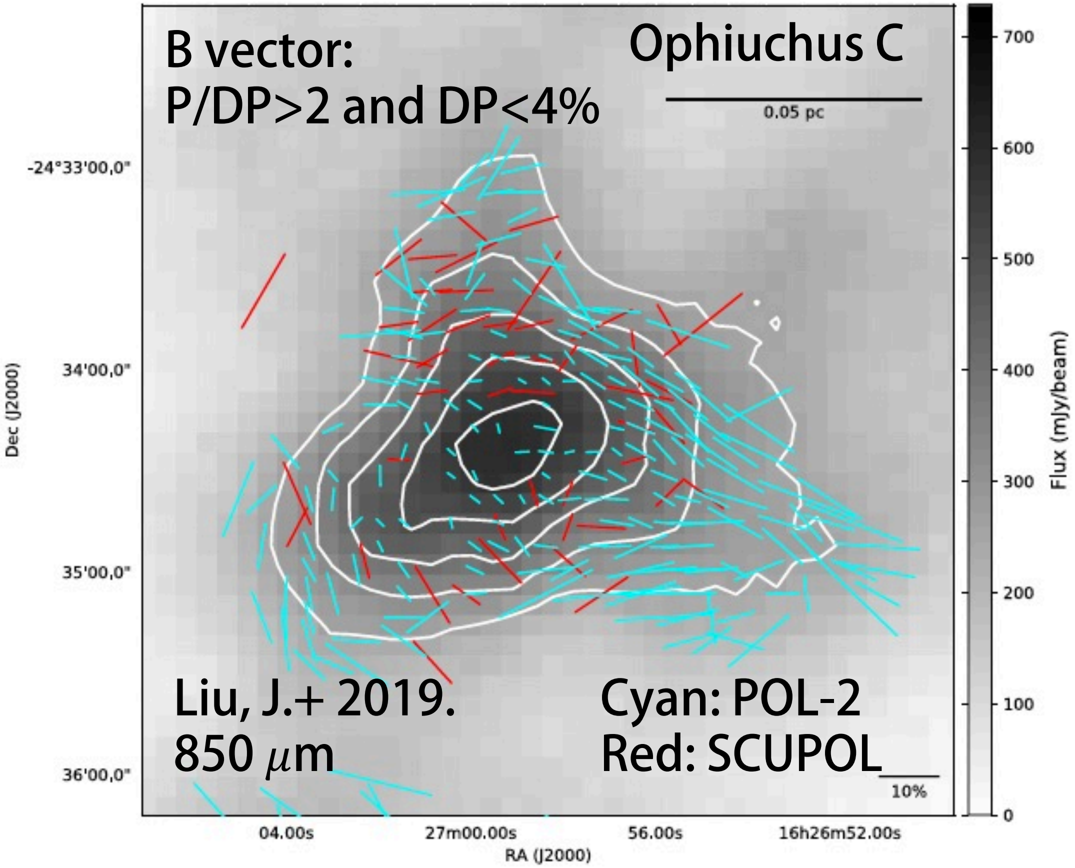
Pattle+ 2015. JCMT 850 μm


JCMT

- Low-mass Starless core: 12 $M_\odot$
- 10 K (Stamatellos 2007).
- Least evolved core in Ophiuchus.

- B-Fields in STar-Forming Region Observations (BISTRO)
- 14″ (~0.008pc) at 125 pc.
- 14 hrs observation. 2 mJy/beam

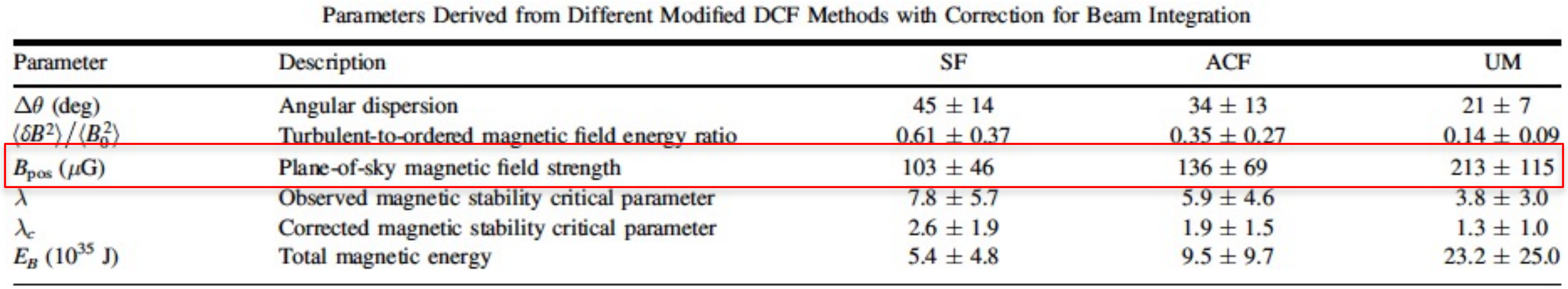
Collaborators: Keping Qiu (NJU), David Berry (EAO), and other members of the BISTRO team.


B vector:
P/DP>2 and DP<4%

Ophiuchus C

Liu, J.+ 2019.
850 μm

Cyan: POL-2
Red: SCUPOL



Parameters Derived from Different Modified DCF Methods with Correction for Beam Integration

Parameter	Description	SF	ACF	UM
$\Delta\theta$ (deg)	Angular dispersion	45 ± 14	34 ± 13	21 ± 7
$\langle\delta B^2\rangle/\langle B_0^2\rangle$	Turbulent-to-ordered magnetic field energy ratio	0.61 ± 0.37	0.35 ± 0.27	0.14 ± 0.09
$B_{\rm pos}$ (μG)	Plane-of-sky magnetic field strength	103 ± 46	136 ± 69	213 ± 115
λ	Observed magnetic stability critical parameter	7.8 ± 5.7	5.9 ± 4.6	3.8 ± 3.0
λ_c	Corrected magnetic stability critical parameter	2.6 ± 1.9	1.9 ± 1.5	1.3 ± 1.0
E_B (10^{35} J)	Total magnetic energy	5.4 ± 4.8	9.5 ± 9.7	23.2 ± 25.0

- Different modified DCF methods:
  - Structure function (SF; Hildebrand 2009)
  - Auto-correlation function (ACF; Houde 2009)
  - Unsharp masking method (UM; Pattle 2017)

- B strength: UM>ACF>SF. Similar to the behavior in OMC-1 (Hildebrand 2009, Houde 2009, Pattle 2017)

- G>B and K $\lesssim$B. Consistent with protostellar cores.

- A pilot polarization observation toward a low-mass starless core in BISTRO-1.

- BISTRO-3 covers more low-mass starless cores (L1544, L1498, L1517B, L43, and FeSt 1-453) as a larger sample.

Outline: Magnetic fields in star formation

- Research history
  - B fields in early stages of low-mass star formation: JCMT POL-2 observations of low-mass starless Ophiuchus C
  - **B fields in early stages of high-mass star formation: ALMA observations of 3 massive clumps in IRDC G28.34**
  - Test the Davis-Chandrasekhar-Fermi (DCF) method with numerical simulations

- Current research and research plan
  - A compilation of all the previous DCF estimations (current research)
  - Multi-scale pol survey of B fields of massive dense cores in Cygnus-X with JCMT and SMA
  - ALMA polarization survey of B fields in NGC 6334 sources
  - Test the Koch 2012 method with simulations
  - Polarization survey of massive clumps/cores in IRDCs

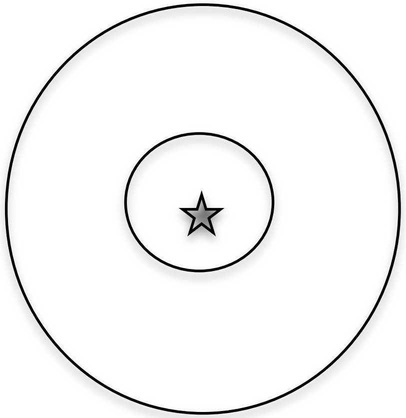
High-mass star formation

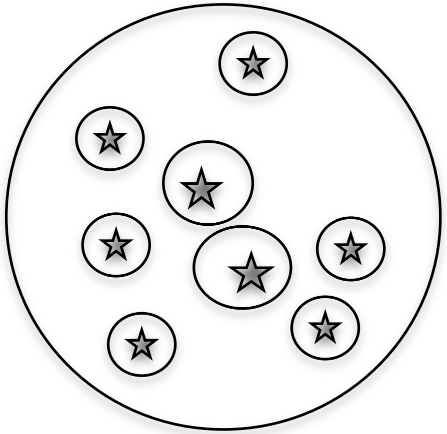
Turbulent core model (McKee & Tan 2002)

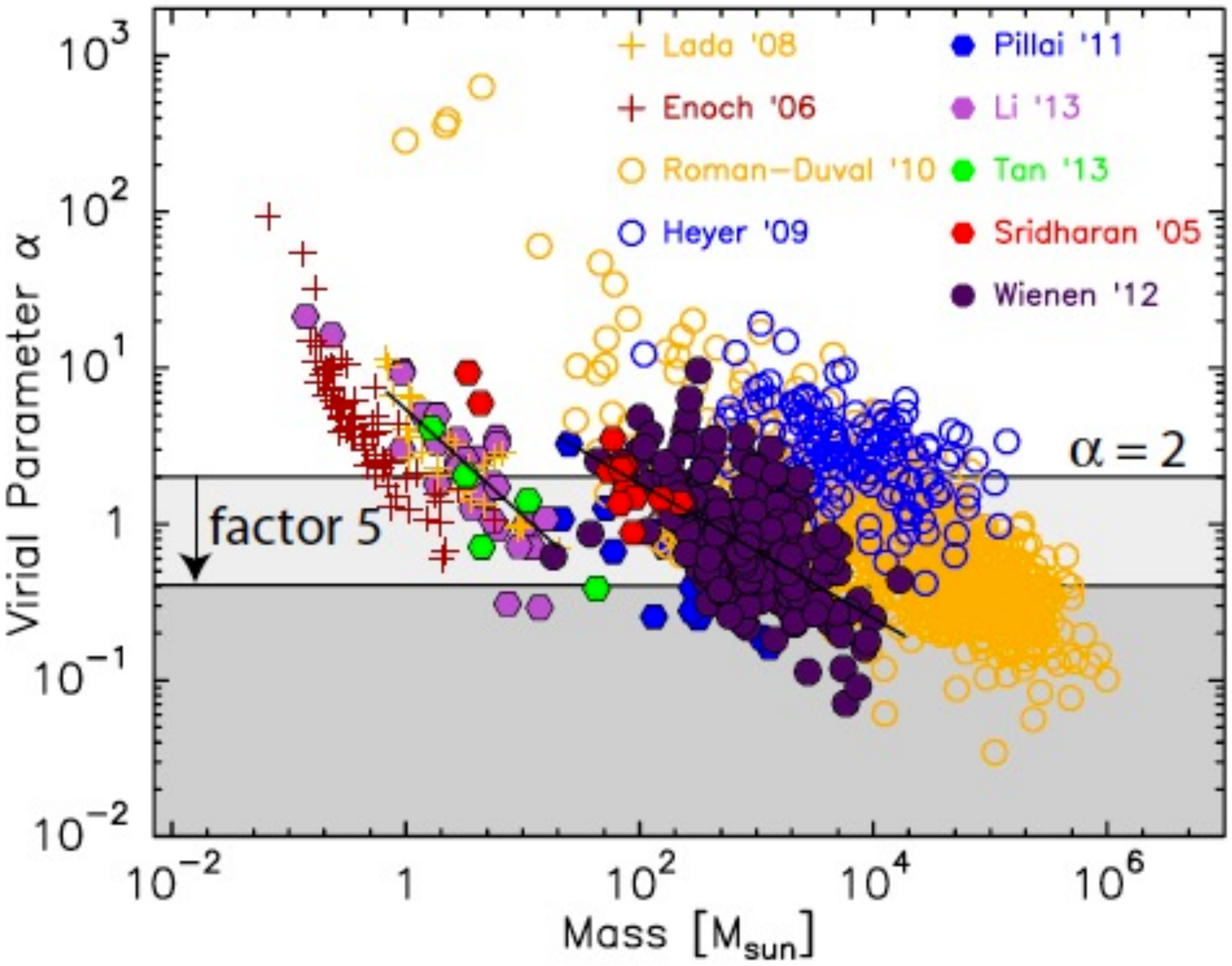
- Scaled-up version of low-mass star formation
- Core in equilibrium.
- K and B support G

Competitive accretion model (Bonnell et al. 1997)

- Competitive accretion of stellar embryos
- Core in non-equilibrium
- K and B cannot support G





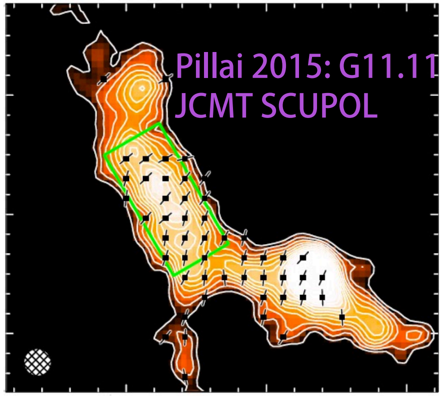


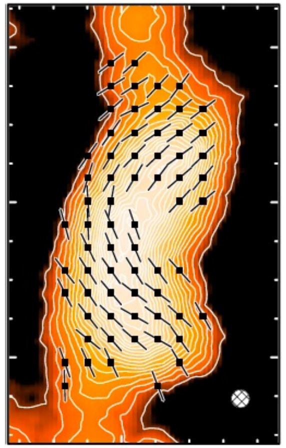
Kauffmann 2013: K cannot solely support G in massive clumps/cores.

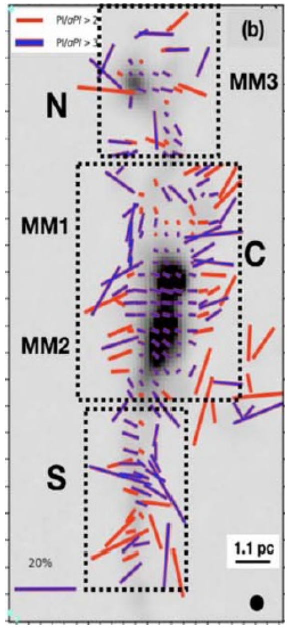
How about K+B VS G?

Observing B is necessary!

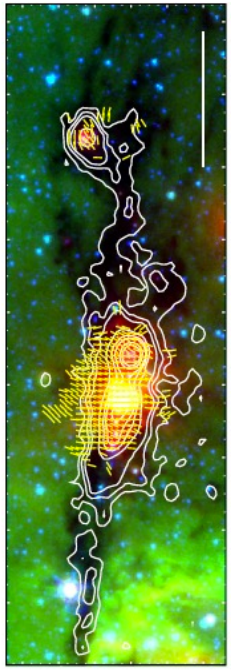
Infrared dark clouds (IRDCs)

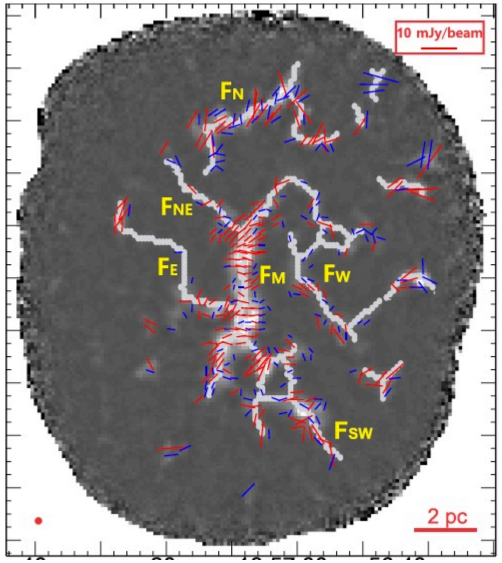

Pillai 2015: G11.11
JCMT SCUPOL


Pillai 2015: G0.353
CSO

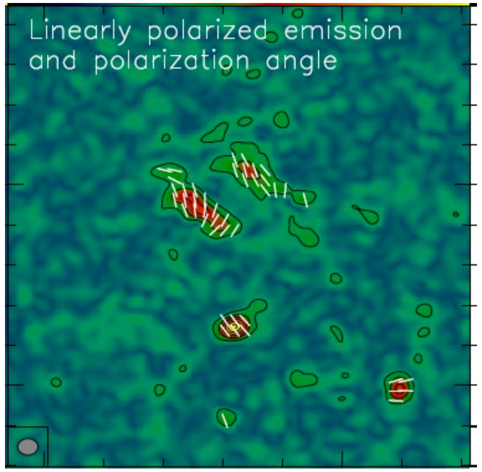


Soam 2018: G34.43
JCMT POL-2


Tang 2019: G34.43
CSO



Liu 2018: G035.39
JCMT POL-2

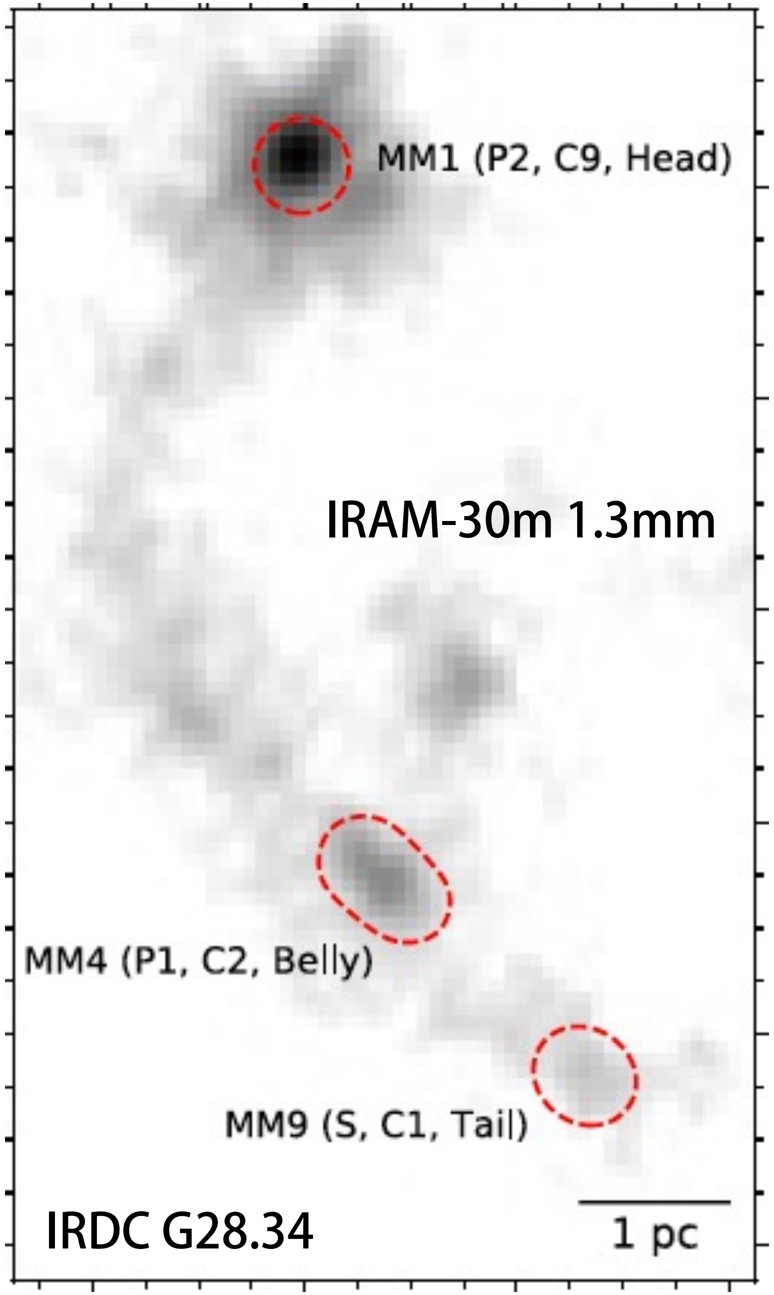


Beuther 2018: 18310-4
ALMA

Few single-dish polarization observations revealing the clump-scale B field. G≳B. K≲B.

Only one interferometer polarization observation of the core-scale B field. Marginal detection.

B in massive cores in IRDCs?



ALMA C1+C3 observations

Resolution 0.6 “ – 0.8” (0.015-0.02 pc)

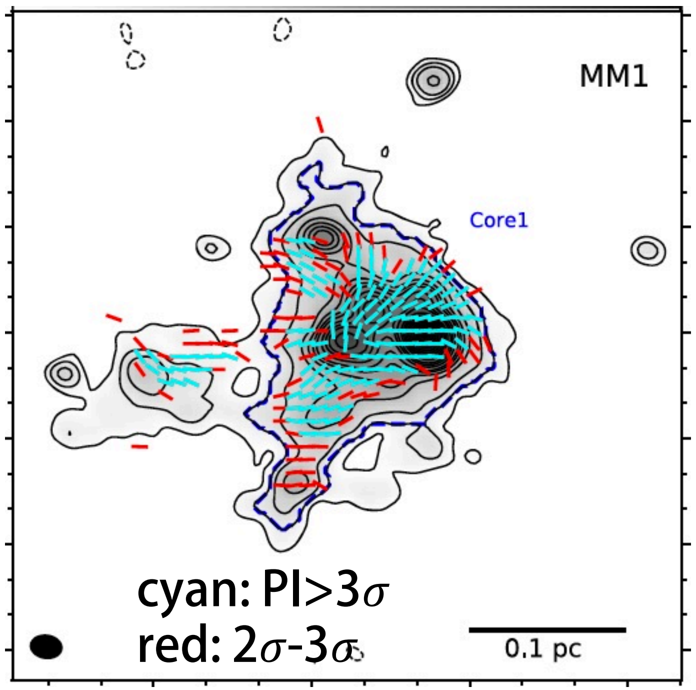
Three massive clumps: MM1, MM4, and MM9

Mass: each >100 $M_\odot$

Evolution: MM1> MM4> MM9

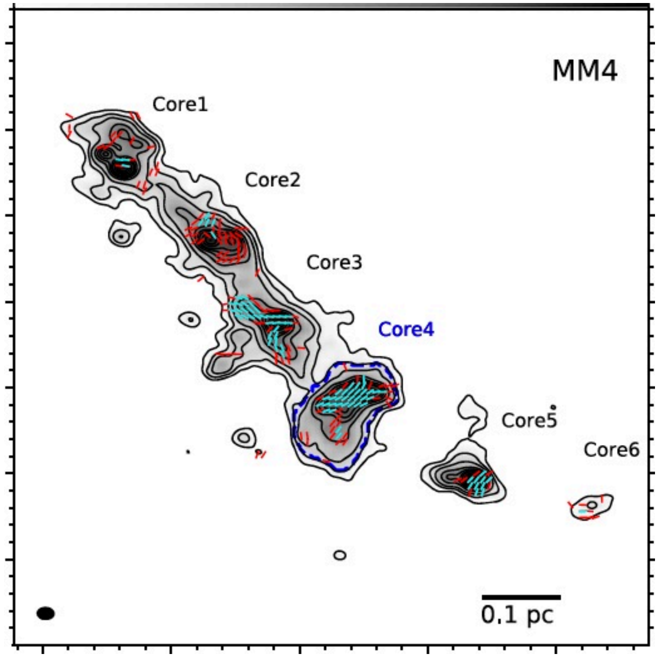
Zhang+ 2015: MM4 K<G

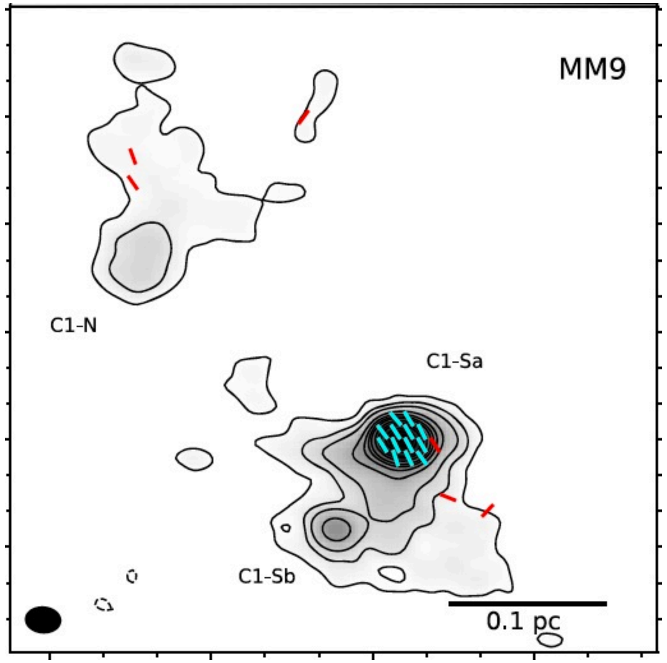
Collaborators: Qizhou Zhang (CfA), Keping Qiu (NJU), Hauyu Baobab Liu (ASIAA), Thushara Pillai (BU & MPIfR), Josep Girart (ICE & IEEC), Zhi-Yun Li (UVA), and Ke Wang (PKU)



cyan: PI>3σ
red: 2σ-3σ

ALMA C1+C3. 1.3mm. Liu, J.+ 2020.





Non-equilibrium massive star formation?

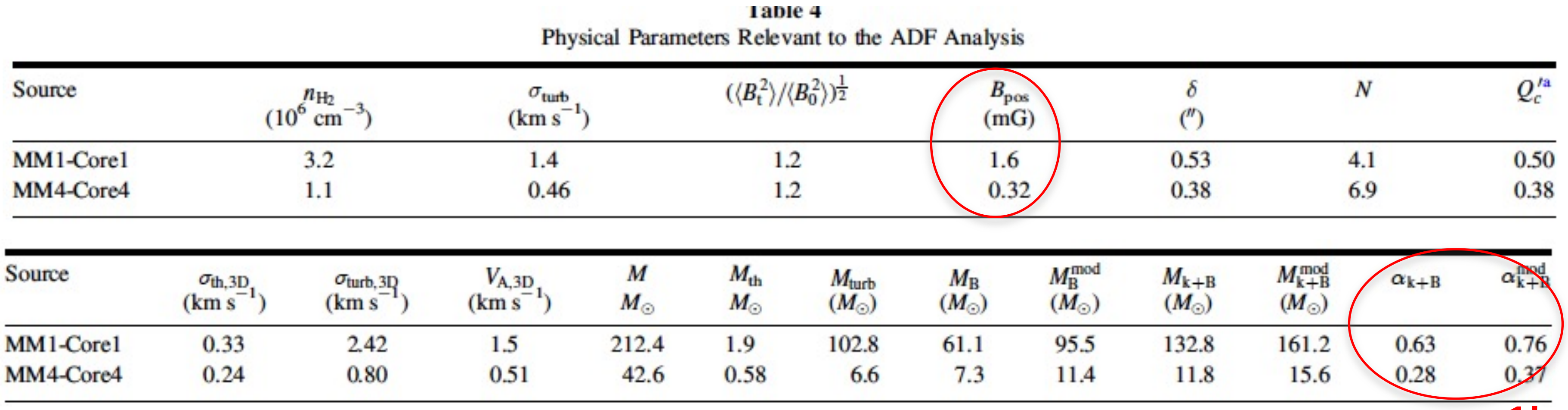


Table 4
Physical Parameters Relevant to the ADF Analysis

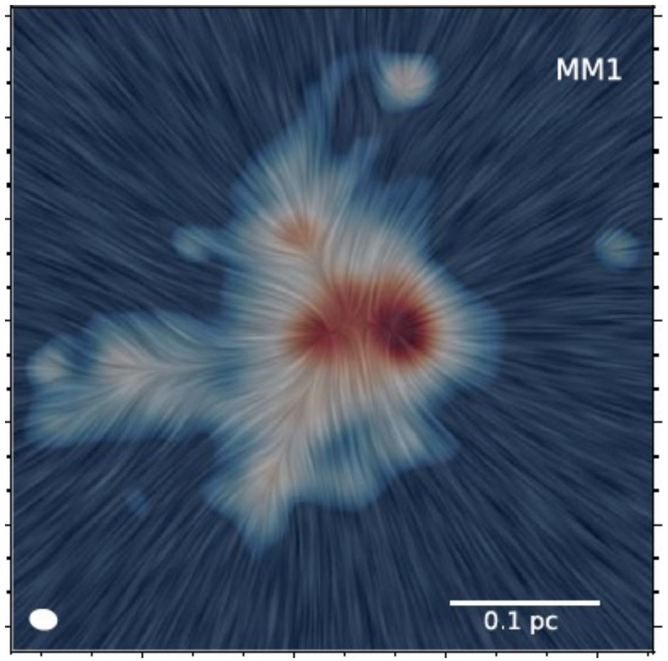
Source	$n_{\mathrm{H_2}}$ (10^6 cm^{-3})	σ_{turb} (km s^{-1})	$(\langle B_t^2\rangle/\langle B_0^2\rangle)^{\frac{1}{2}}$	B_{pos} (mG)	δ (″)	N	$Q_c'^{a}$
MM1-Core1	3.2	1.4	1.2	1.6	0.53	4.1	0.50
MM4-Core4	1.1	0.46	1.2	0.32	0.38	6.9	0.38

Source	$\sigma_{\mathrm{th,3D}}$ (km s^{-1})	$\sigma_{\mathrm{turb,3D}}$ (km s^{-1})	$V_{\mathrm{A,3D}}$ (km s^{-1})	M $M_\odot$	M_{th} $M_\odot$	M_{turb} ($M_\odot$)	M_{B} ($M_\odot$)	$M_{\mathrm{B}}^{\mathrm{mod}}$ ($M_\odot$)	$M_{\mathrm{k+B}}$ ($M_\odot$)	$M_{\mathrm{k+B}}^{\mathrm{mod}}$ ($M_\odot$)	$\alpha_{\mathrm{k+B}}$	$\alpha_{\mathrm{k+B}}^{\mathrm{mod}}$
MM1-Core1	0.33	2.42	1.5	212.4	1.9	102.8	61.1	95.5	132.8	161.2	0.63	0.76
MM4-Core4	0.24	0.80	0.51	42.6	0.58	6.6	7.3	11.4	11.8	15.6	0.28	0.37

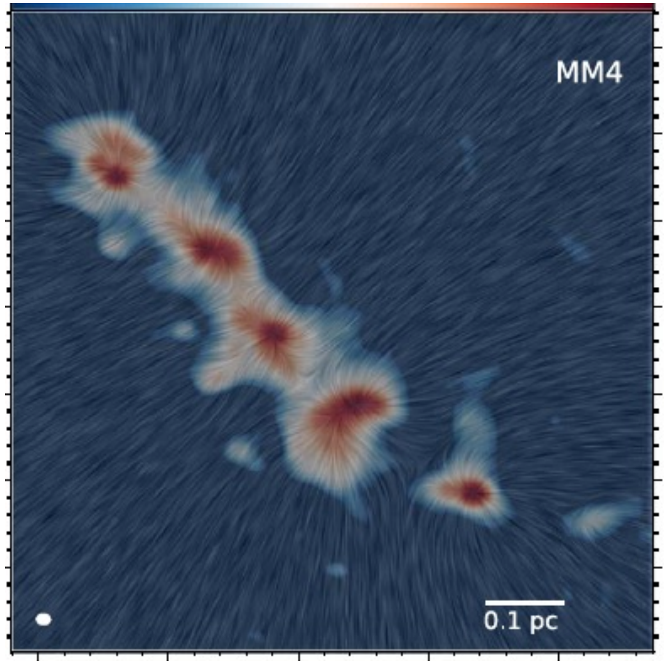
α<1!

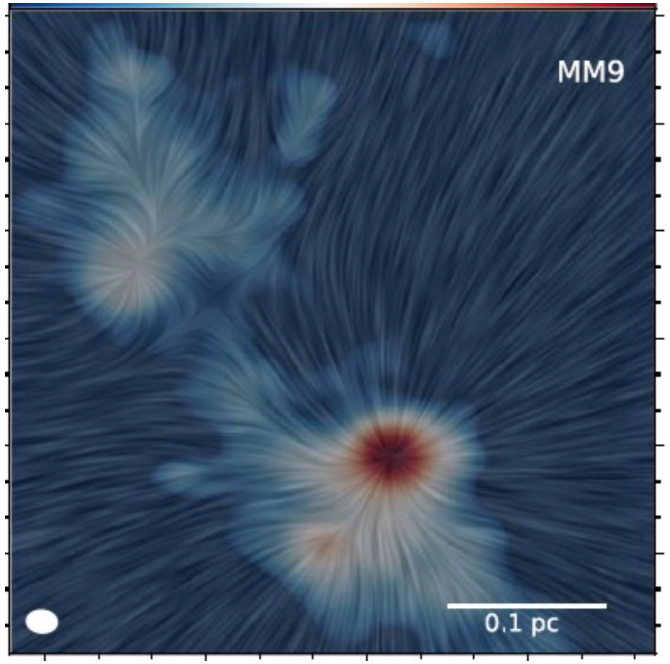
- B strength estimated with the angular dispersion function method (Houde 2016)
- Massive cores in non-equilibrium. α<1.
- Virial parameter in MM1-Core1 larger than that in MM4-Core4. α increases as core evolves?
- The only B virial analysis of massive dense cores at ~0.1 pc in IRDCs

Competitive accretion model: non-equilibrium
~~Turbulent core model: equilibrium~~



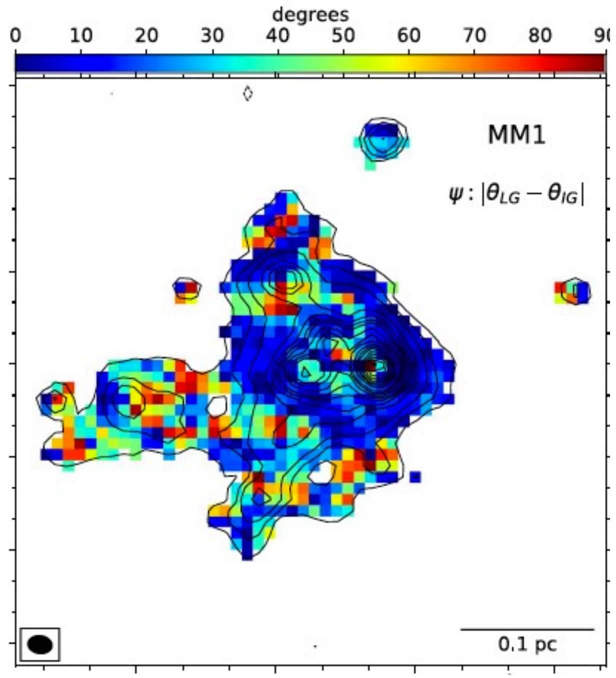
Gravity directions

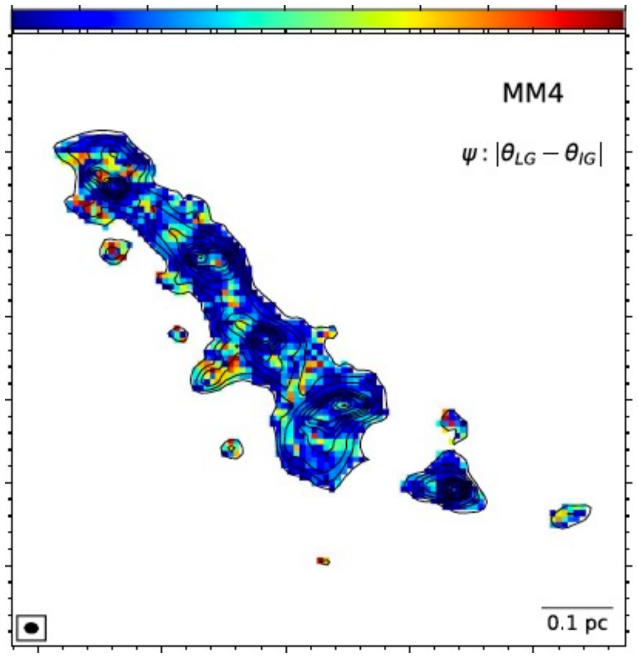


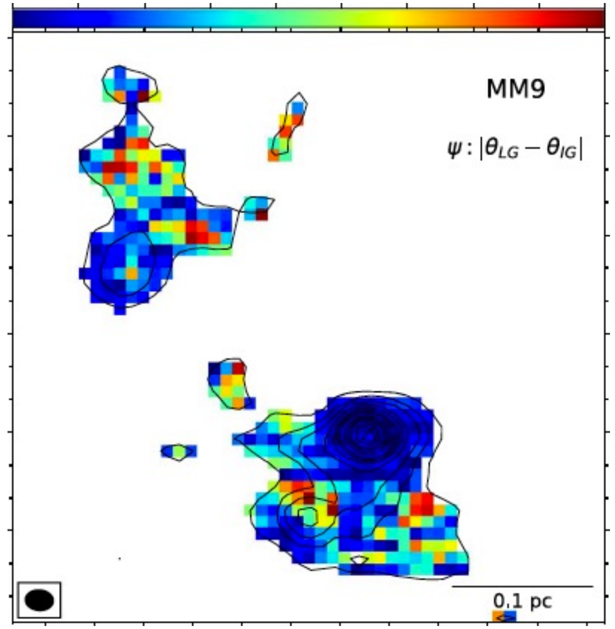


Average orientation between local gravity (LG) and intensity gradient (IG): 30° , 22° , and 28° for MM1, MM4, and MM9, respectively

Intensity gradient tend to be aligned with local gravity

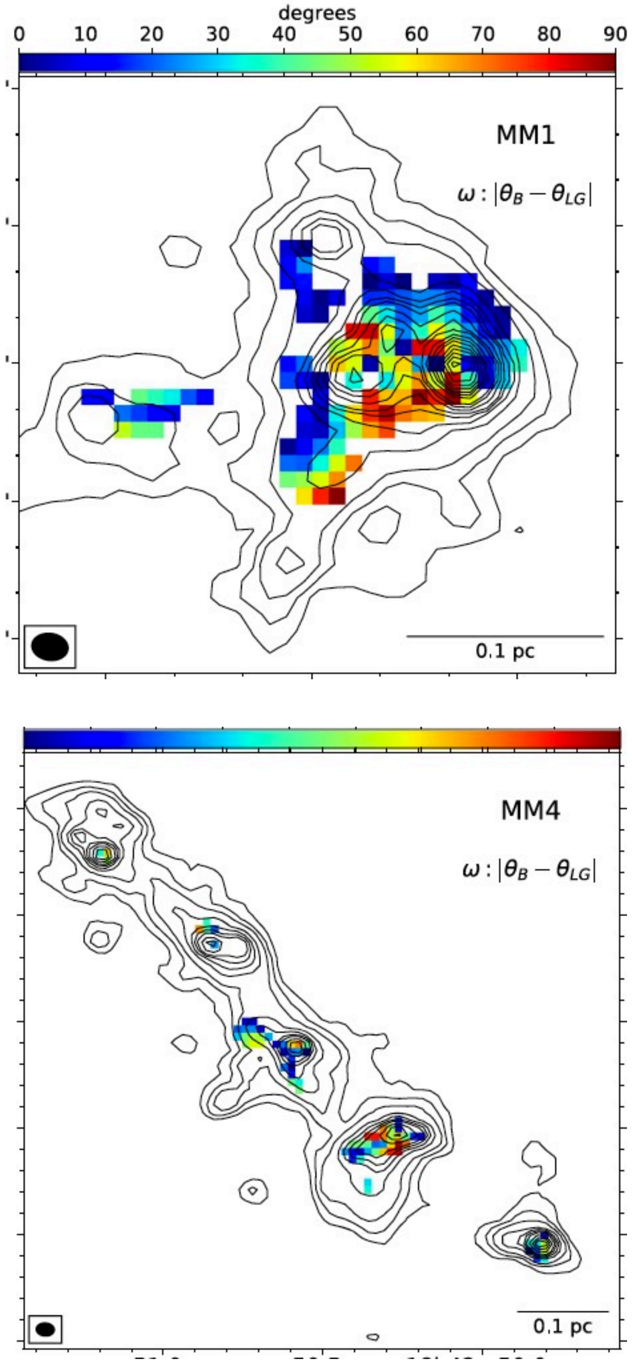




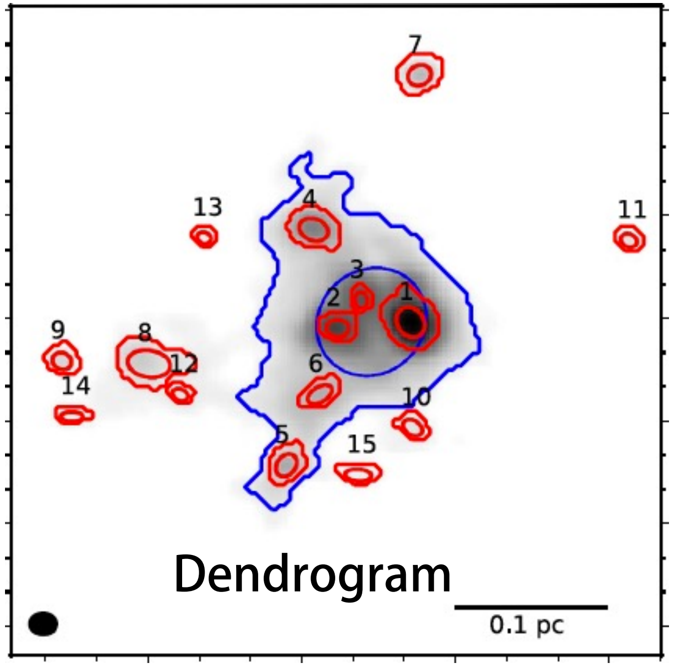


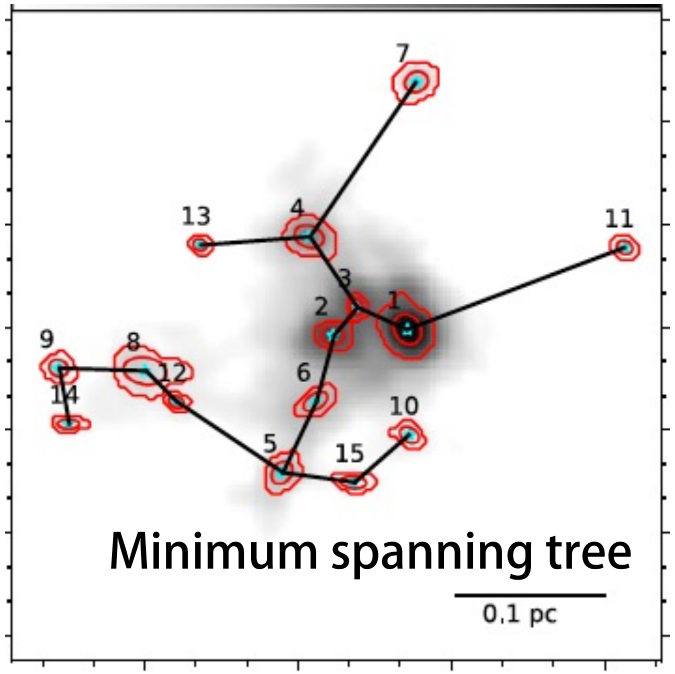
Average orientation difference between B and LG:
34° and 36° for MM1 and MM4, respectively

B and gravity poorly aligned toward the peak, well aligned toward the edge



Fragmentation in MM1


Dendrogram


Minimum spanning tree

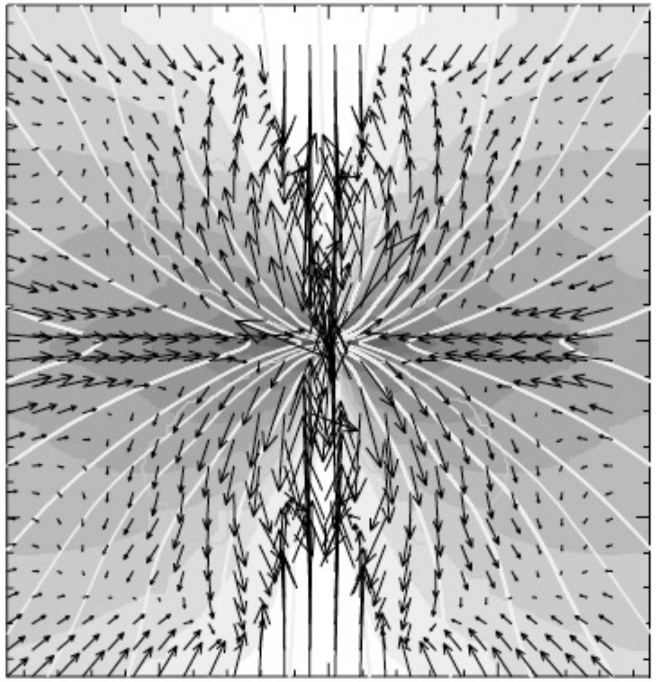
Turbulent Jeans mass 309 $M_\odot$	Turbulent Jeans length 0.14 pc
Average mass 14.3 $M_\odot$	Corrected average separation 0.069 pc
Thermal Jeans mass 0.76 $M_\odot$	Turbulent Jeans length 0.019 pc

Deviation from initial environment

B VS outflow

Theories and simulations

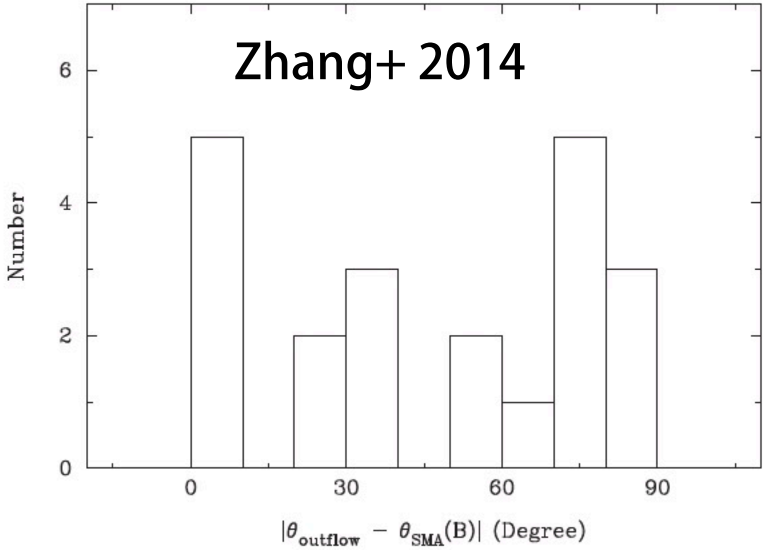
Outflows related to disk-scale B
Strong B can align outflows

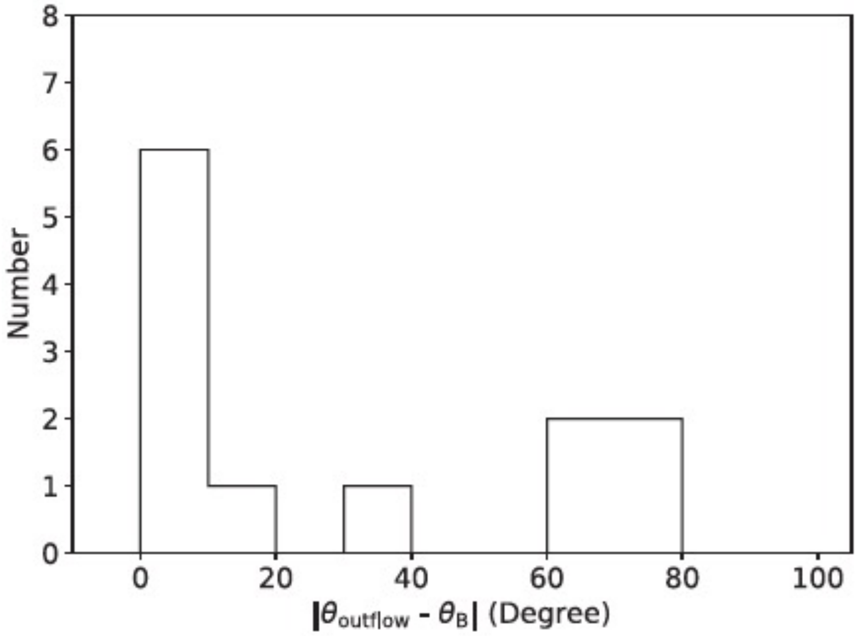


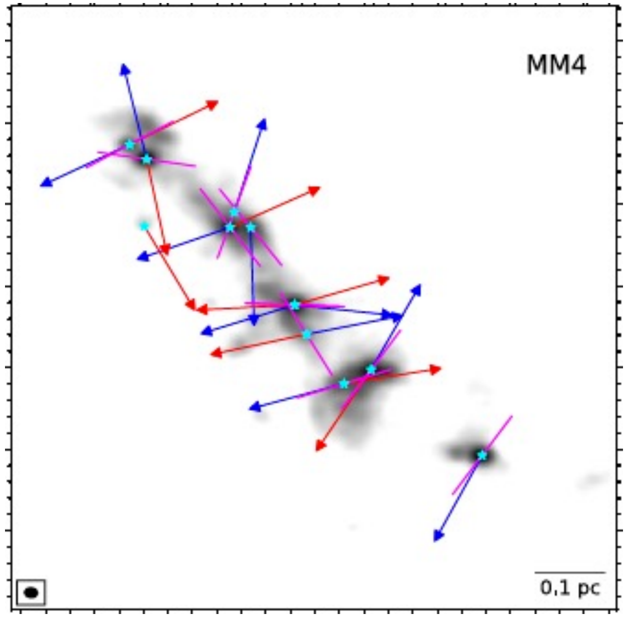
Banerjee 2006

Observations

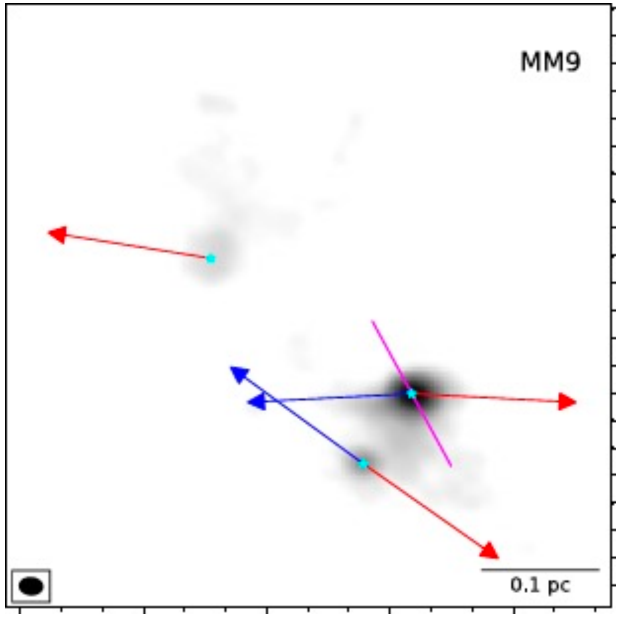
No strong relation between core-scale B and outflows in evolved massive clumps







Red and blue: outflow
Magenta: average B



B VS outflows in MM4 and MM9

- Half aligned
- B plays an important role from condensation to disk scale in early stage?

Outline: Magnetic fields in star formation

- Research history
  - B fields in early stages of low-mass star formation: JCMT POL-2 observations of low-mass starless Ophiuchus C
  - B fields in early stages of high-mass star formation: ALMA observations of 3 massive clumps in IRDC G28.34
  - **Test the Davis-Chandrasekhar-Fermi (DCF) method with numerical simulations**

- Current research and research plan
  - A compilation of all the previous DCF estimations (current research)
  - Multi-scale pol survey of B fields of massive dense cores in Cygnus-X with JCMT and SMA
  - ALMA polarization survey of B fields in NGC 6334 sources
  - Test the Koch 2012 method with simulations
  - Polarization survey of massive clumps/cores in IRDCs

The Davis-Chandrasekhar-Fermi (DCF) method

Popularity

The most widely used method to estimate the Plane-of-sky B strength (B_{pos}) from dust polarization observations

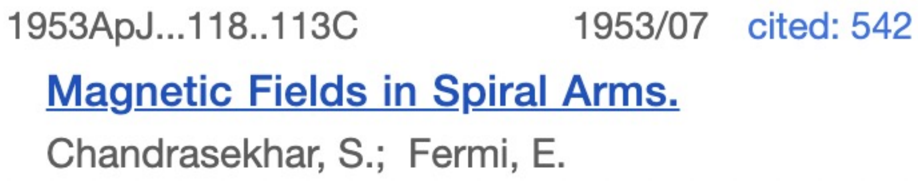
Components of magnetic fields

Total (rms) B: $B^{tot} = <B^2>^{1/2}$
Mean (uniform) B: $B^{u} = <B>$
Turbulent B: $B^{t} = (<B^2> - <B>^2)^{1/2}$

1951PhRv...81..890D 1951/03 cited: 116

The Strength of Interstellar Magnetic Fields

Davis, Leverett



1953ApJ...118..113C 1953/07 cited: 542

Magnetic Fields in Spiral Arms.

Chandrasekhar, S.; Fermi, E.

Four assumptions of the DCF method

- 1. The mean (uniform or ordered) B component B^u is prominent (i.e., small angle approximation, $B^t << B^u \sim B^{tot}$)

- 2. Alfvenic B perturbation. i.e., turbulent kinetic energy E_K^t = turbulent magnetic energy E_B^t

$$E_{\mathrm{K}}^{\mathrm{t}} = \rho V \delta v^2/2 = E_B^{\mathrm{t}} = (B^{\mathrm{t}})^2 V/(2\mu_0)$$

$$\downarrow$$

$$B_{\mathrm{pos}\perp}^{\mathrm{t}} = \sqrt{\mu_0 \rho}\,\delta v_{\mathrm{pos}\perp}$$

- 3. Isotropic turbulence $B_{\mathrm{pos}\perp}^{\mathrm{t}} = \sqrt{\mu_0 \rho}\,\delta v_{\mathrm{pos}\perp}$

$$\delta v_{\mathrm{pos}\perp}^2 = \delta v_{\mathrm{pos}\|}^2 = \delta v_{\mathrm{los}}^2 = \delta v_{\mathrm{3d}}^2/3 \downarrow$$

$$B_{\mathrm{pos}\perp}^{\mathrm{t}} = \sqrt{\mu_0 \rho}\,\delta v_{\mathrm{los}}$$

$$\swarrow \qquad \searrow$$

$$B_{\mathrm{pos}}^{\mathrm{u}} = \sqrt{\mu_0 \rho}\frac{\delta v_{\mathrm{los}}}{B_{\mathrm{pos}\perp}^{\mathrm{t}}/B_{\mathrm{pos}}^{\mathrm{u}}} \qquad B_{\mathrm{pos}}^{\mathrm{tot}} = \sqrt{\mu_0 \rho}\frac{\delta v_{\mathrm{los}}}{B_{\mathrm{pos}\perp}^{\mathrm{t}}/B_{\mathrm{pos}}^{\mathrm{tot}}}$$

- 4. Ratios of B components (B^t/B^{tot} or B^t/B^u) traced by angular dispersions

$$B_{\mathrm{pos}\perp}^{\mathrm{t}}/B_{\mathrm{pos}}^{\mathrm{u}} \sim \delta(\tan\phi) \qquad B_{\mathrm{pos}\perp}^{\mathrm{t}}/B_{\mathrm{pos}}^{\mathrm{tot}} \sim \delta(\sin\phi)$$

DCF Equation

B_{pos}^{tot} or B_{pos}^{u} can be estimated with the density, the line-of-sight turbulent velocity dispersion, and the angular dispersion

$$B_{\mathrm{pos}}^{\mathrm{tot,dcf}} \sim \sqrt{\mu_0 \rho}\frac{\delta v_{\mathrm{los}}}{\delta(\sin\phi)}$$

$$B_{\mathrm{pos}}^{\mathrm{u,dcf}} \sim \sqrt{\mu_0 \rho}\frac{\delta v_{\mathrm{los}}}{\delta(\tan\phi)}$$

Small angle approximation $\sim \sqrt{\mu_0 \rho}\dfrac{\delta v_{\mathrm{los}}}{\delta\phi}$

Test the DCF method with simulations

The estimated B strength may deviate from the true B strength due to non-satisfaction of the DCF assumptions.

Correction factors (Q_c) from simulations are required (e.g., ~0.5 for B^{u}_{pos}, Ostriker 2001): $B_{true} = Q_c \, B_{estimated}$

None of the previous simulations have conditions comparable to small-scale regions with high-density and significant self-gravity.

Previous simulations on DCF	Box length (pc)	Resolution	Gravity	Application
Ostriker 2001	8	256^3	Yes	ISM, clouds and clumps
Padoan 2001	6.25	128^3	Yes	ISM, clouds and clumps
Heitsch 2001	Scale-free	128^3-512^3	No	Inside clouds. No significant gravity
Falceta-Gonalves 2008	Scale-free	512^3	No	Inside clouds. No significant gravity

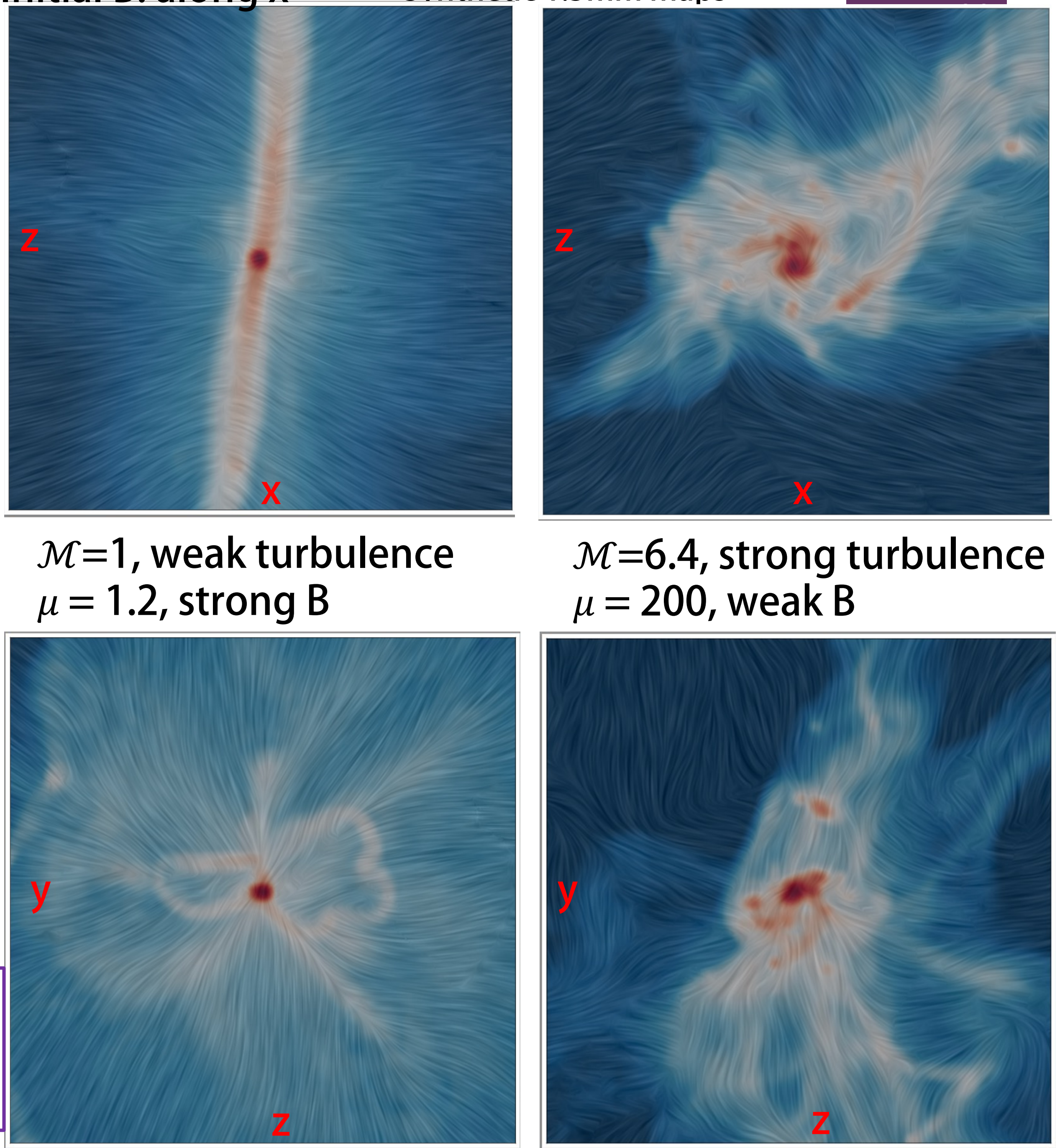
Our simulations

- Simulations of clustered massive star-forming regions (Box size ~ 1-2 pc)
- Ideal MHD simulation (RAMSES) + dust heating and radiative transfer simulation (POLARIS). Some MHD simulations adopted from Fontani 2018
- Different initial turbulent levels ($\mathcal{M}$: 1-6.4) and magnetic levels (μ: 1.2-200): 11 models
- Adaptive Mesh Refinement (AMR). Resolution down to 13 AU.
- Consider 2 time snapshots for each model
  - First sink (protostar) forms
  - SFE=15%

Collaborators: Qizhou Zhang (CfA), Benoit Commercon (U. Lyon), Valeska Valdivia (CEA), Anaelle Maury (CEA & CfA), Keping Qiu (NJU)

Initial B: along x

Synthetic 1.3mm maps



$\mathcal{M}$=1, weak turbulence
μ = 1.2, strong B

$\mathcal{M}$=6.4, strong turbulence
μ = 200, weak B

Test assumptions of the DCF method

1. The mean B component is prominent (small angle approximation)?
   Only required for deriving B^u, not required for deriving B^{tot}

2. Energy equipartition?
   Only satisfied in strong field cases. The B strength can be significantly overestimated in weak field cases

3. Isotropic turbulence?
   Yes. Within a factor of ~2

4. B components ratio traced by angular dispersions?
   Yes. With some criteria: R>0.1 pc. $\delta\phi<25^o$ for B^t/B^u . Avoid using $\delta(\tan\phi)$ or $\tan\delta\phi$ for B^t/B^u .

Factors affecting the measured angular dispersion

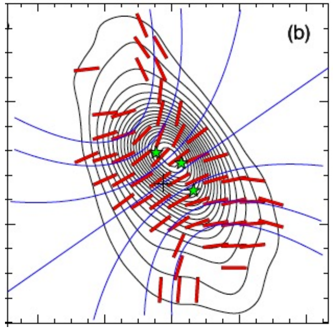
- Contribution from large-scale ordered field structure
  - Fit with specific field model (e.g., Girart 2006, Myers 2018)
  - The angular dispersion function (ADF) method: structure function (SF, Hildebrand 2009); auto-correlation function (ACF, Houde 2009, 2016)
  - The unsharp masking method (Pattle 2017)
  - The spatial filtering method (Pillai 2015)

- Signal integration and averaging along the line of sight
  - The ADF method (Houde 2009 , 2016)
  - The CY16 method (Cho & Yoo 2016)

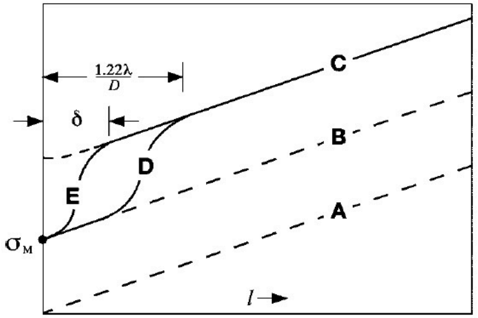
- Contribution at scales smaller than turbulent correlation scale
  - The ADF method (Houde 2009 , 2016)

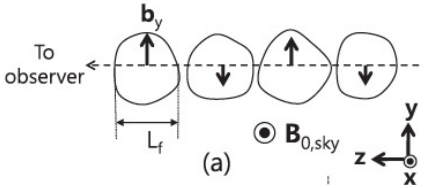
- Observation: Beam smoothing and interferometer filtering
  - The ADF method (Houde 2016)

Qiu 2014

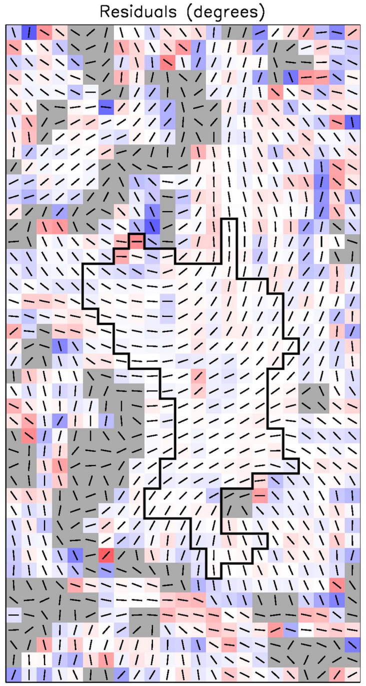


Hildebrand 2009





Cho & Yoo 2016



Pattle 2017

Test the ADF method on factors affecting the measured angular dispersion

1. Ordered field structure
   Works well

2. Signal integration along the line of sight
   May not be applicable in most cases

3. Effect of turbulence correlation
   Did not test

4. Observation: Beam-smoothing and interferometric filtering
   Works well

The Cho & Yoo 2016 method works well for line-of-sight signal integration at R>0.1 pc.

Discussion: compare B with turbulence (my recent thoughts)

- Compare B^u with turbulence: B^t/B^u
  - DCF is not applicable when $B^t/B^u > 1$, so the derived uniform B energy > turbulent kinetic energy
- Limitation of random fields: Angular dispersion cannot trace $B^t/B^u > 1$
  - Dispersion of random ϕ: 52° <1
  - Average of cosϕ for random ϕ: 0.64
  - Maximum value of B^t/B^u and B^t/B^{tot} derivable from the ADF method are 0.76 and 0.6, respectively. (a2 should>0)

$$1 - \langle \cos[\Delta\Phi(l)] \rangle \simeq a_2' l^2 + \left(\frac{\langle B_t^2 \rangle}{\langle B^2 \rangle}\right)_{\rm or}^{\rm adf}$$

- Compare B^{tot} with turbulence
  - The energy equipartition assumption ($E_K^t = E_B^t$) of DCF implicitly assumes the total B energy ($E_B^{tot} = E_B^u + E_B^t$) > turbulent kinetic energy (E_K^t).

Conclusion: B derived from the DCF method may not be properly compared with turbulence? (arguable)

Discussion: compare B with gravity

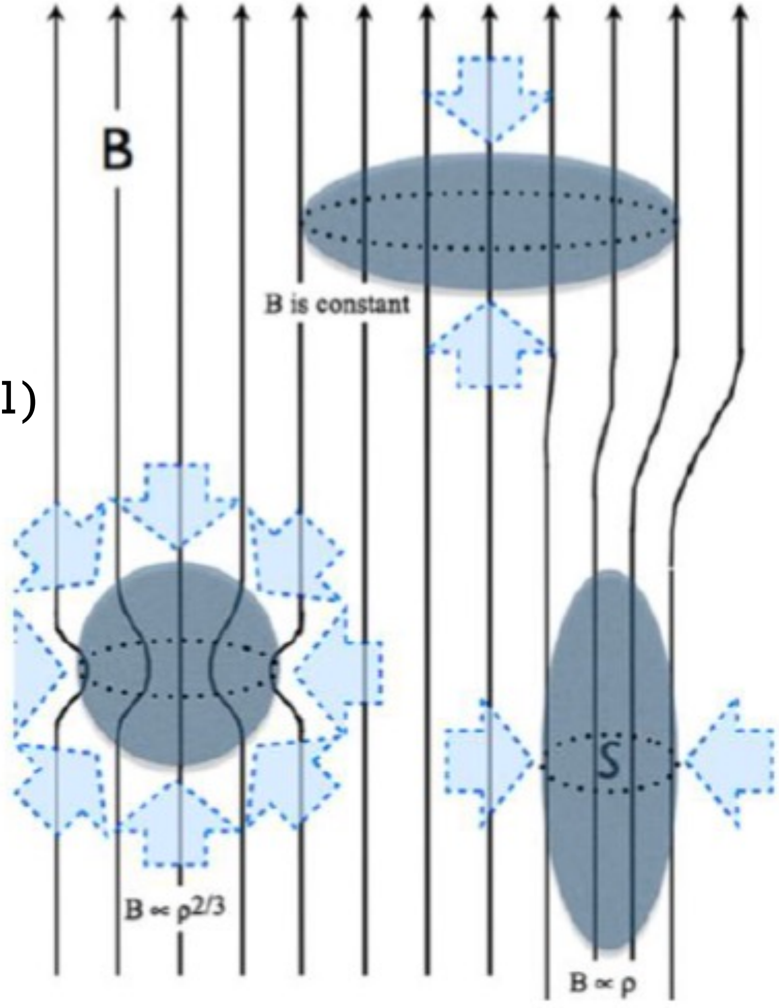
- Most previous DCF studies only derived the uniform B strength B^u
- If there is significant turbulent B energy, only comparing uniform B with gravity (i.e., use B^u in the derivation of mass-to-flux ratio to critical value) might underestimate the B support
- Suggestion: consider to use B^{tot} instead of B^u in the comparison

+ Outline: Magnetic fields in star formation

- Research history
  - B fields in early stages of low-mass star formation: JCMT POL-2 observations of low-mass starless Ophiuchus C
  - B fields in early stages of high-mass star formation: ALMA observations of 3 massive clumps in IRDC G28.34
  - Test the Davis-Chandrasekhar-Fermi (DCF) method with numerical simulations
- Current research and research plan
  - **A compilation of all the previous DCF estimations (current research)**
  - Multi-scale pol survey of B fields of massive dense cores in Cygnus-X with JCMT and SMA
  - ALMA polarization survey of B fields in NGC 6334 sources
  - Test the Koch 2012 method with simulations
  - Polarization survey of massive clumps/cores in IRDCs

B-n relation: $B \propto n^i$

- Textbook model

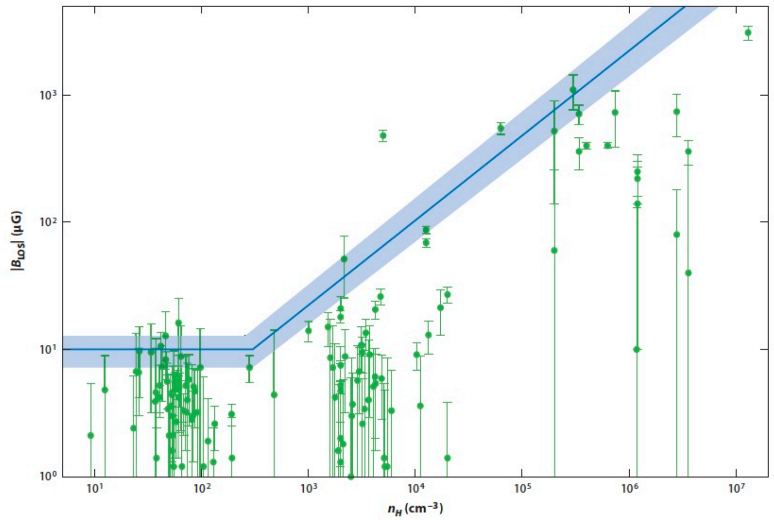


Contraction along B.
Extremely strong field
$B \propto n^0$

Li, H. (2021)

Isotropical contraction.
Extremely weak field.
$B \propto n^{2/3}$

Contraction
perpendicular to B
Not happen in
gravitational
contraction

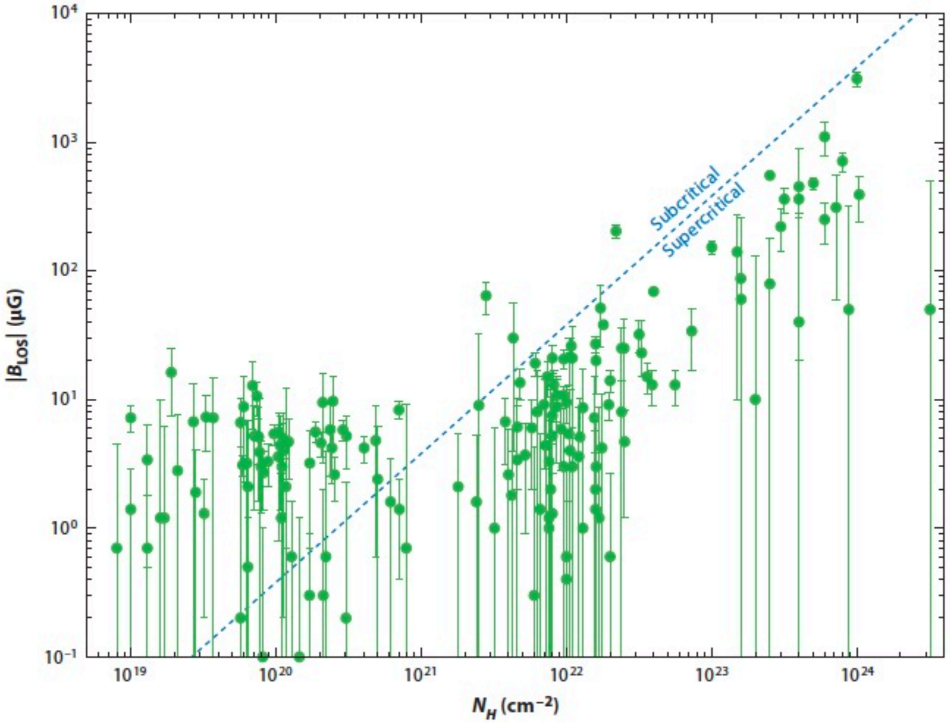


Crutcher 2012. $B \propto n^{0.65}$.
Compilation of Zeeman observations.

B-N relation: supercritical or subcritical

- Mass-to-flux-ratio-to-critical-value

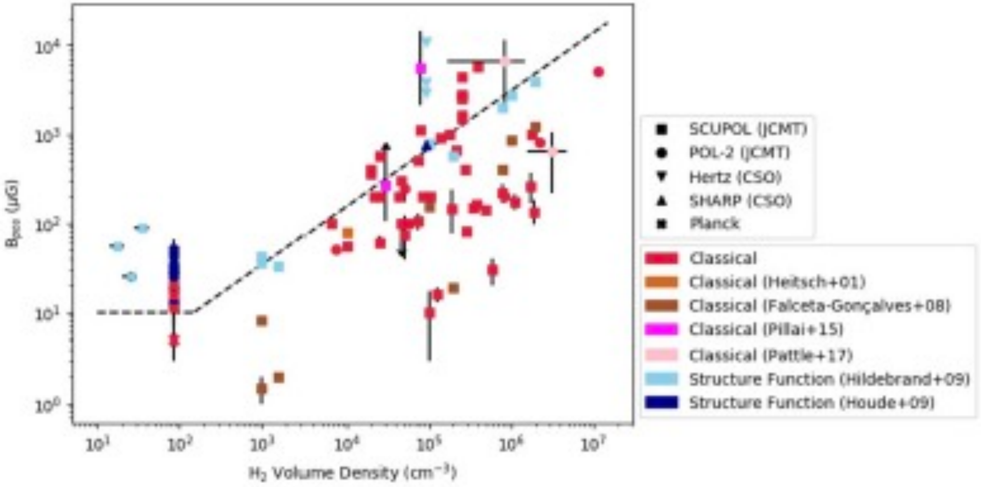
$$\lambda = \frac{(M/\Phi)_{\text{observed}}}{(M/\Phi)_{\text{crit}}} = \frac{mNA/BA}{1/2\pi\sqrt{G}} = 7.6 \times 10^{-21} \frac{N(\mathrm{H}_2)}{B}$$



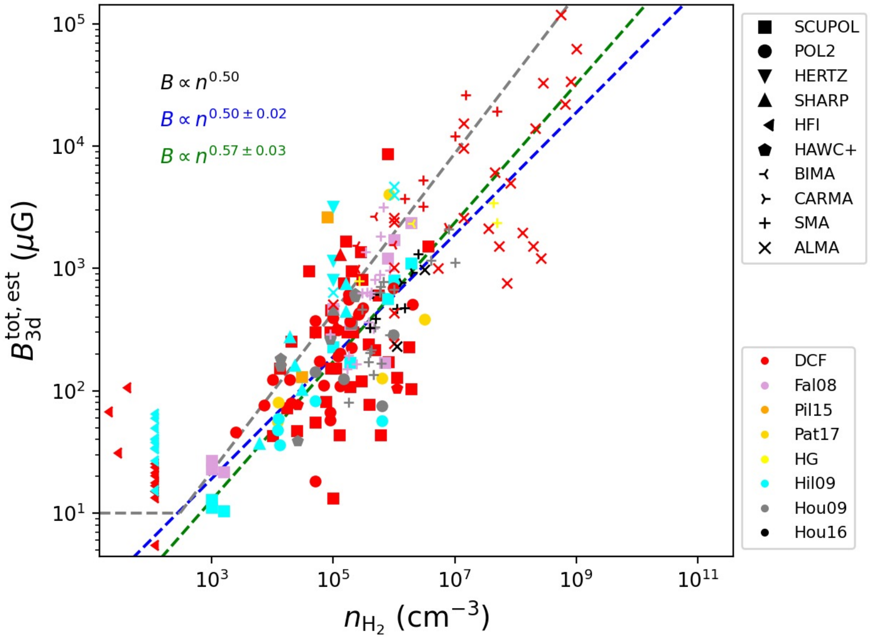
Crutcher 2012. Compilation of Zeeman observations

A compilation of previous DCF estimations

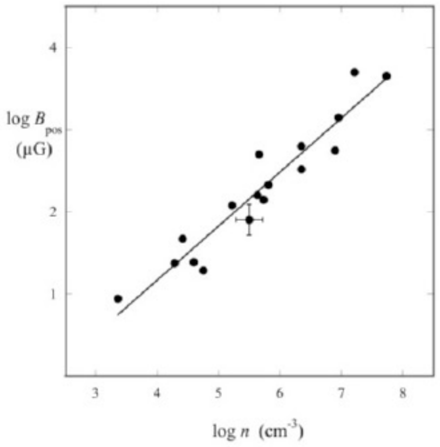
- A compilation of all previous DCF estimations
- Re-calculate the B strength with simulation results
- Investigate the B-n and B-N relation.



Pattle+ (2019). A compilation of B-n relation from previous single-dish DCF estimations



Our preliminary results on the B-n relation



Myers+ (2021). B-n relation from DCF estimations of 17 low-mass dense cores.

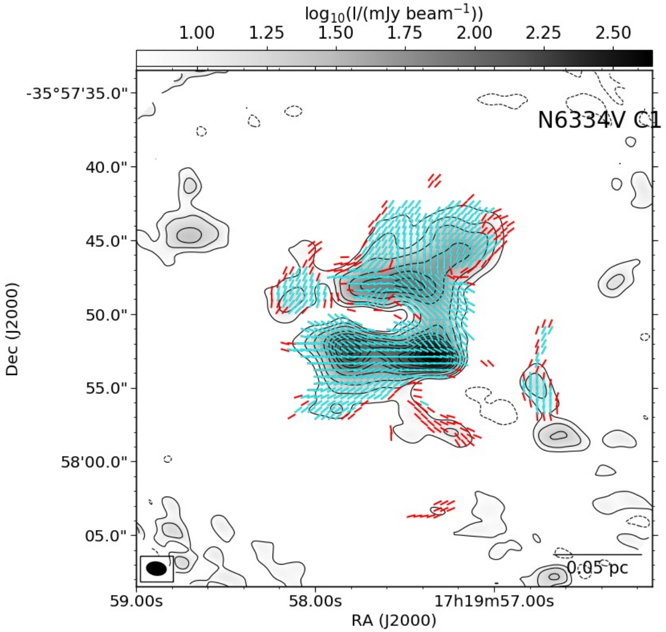
Outline: Magnetic fields in star formation

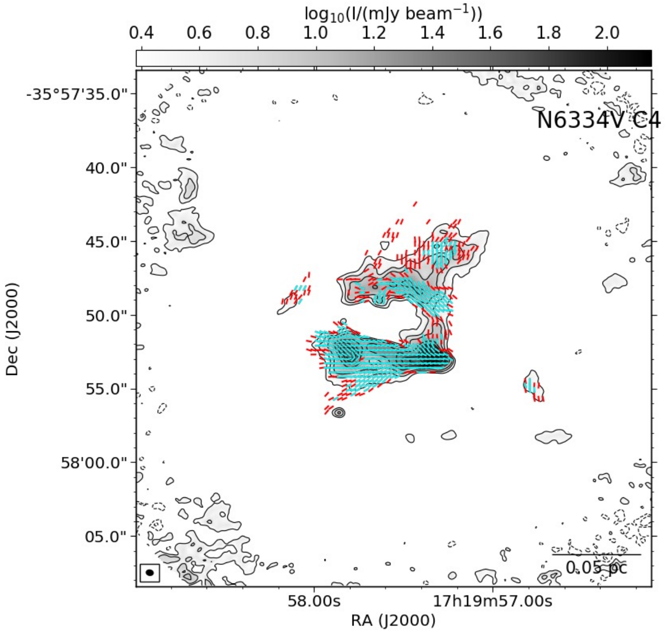
- Research history
  - B fields in early stages of low-mass star formation: JCMT POL-2 observations of low-mass starless Ophiuchus C
  - B fields in early stages of high-mass star formation: ALMA observations of 3 massive clumps in IRDC G28.34
  - Test the Davis-Chandrasekhar-Fermi (DCF) method with numerical simulations

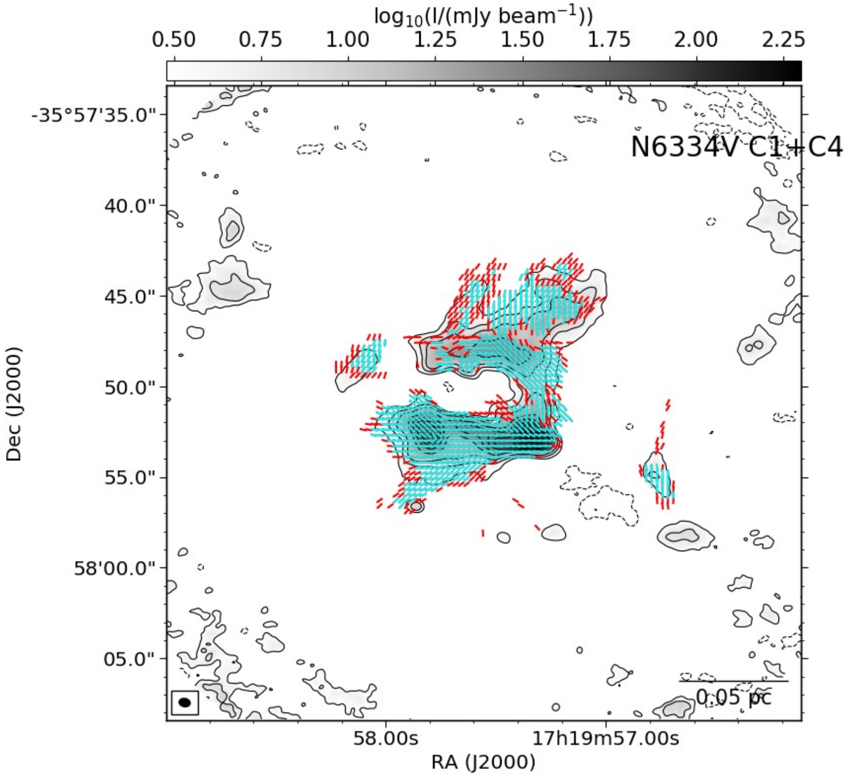
- Current research and research plan
  - A compilation of all the previous DCF estimations (current research)
  - **ALMA polarization survey of B fields in NGC 6334 sources**
  - **Multi-scale pol survey of B fields of massive dense cores in Cygnus-X with JCMT and SMA**
  - **Test the Koch 2012 method with simulations**
  - **Polarization survey of massive clumps/cores in IRDCs**

ALMA pol survey of B fields in NGC 6334 sources

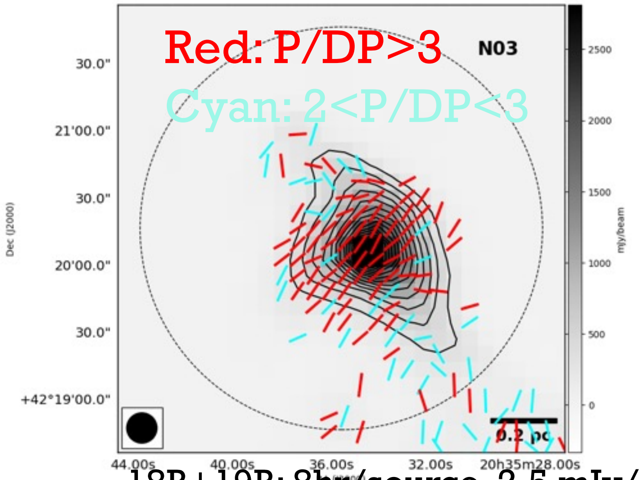
- Continuation of a SMA pol survey (Zhang et al. 2014).
- Source: NGC 6334 I, In, IR, V, VI
- ALMA C1 + C4 configurations





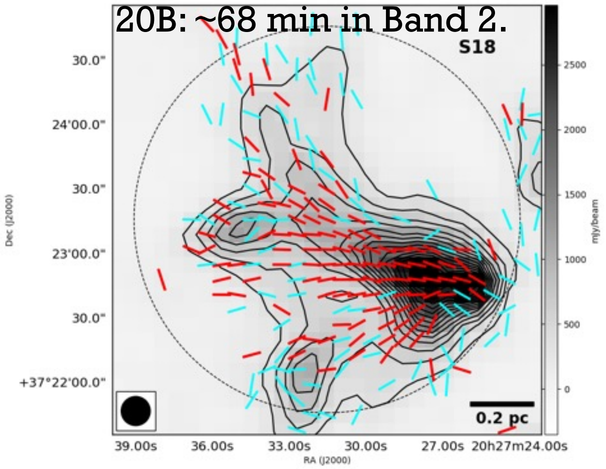


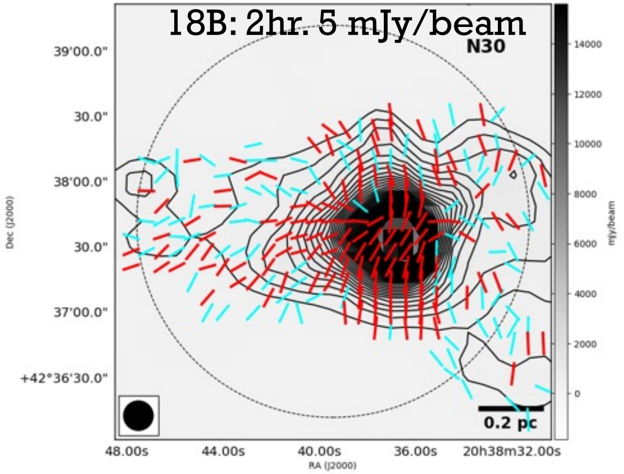
Multi-scale pol survey of B fields of massive dense cores in Cygnus-X

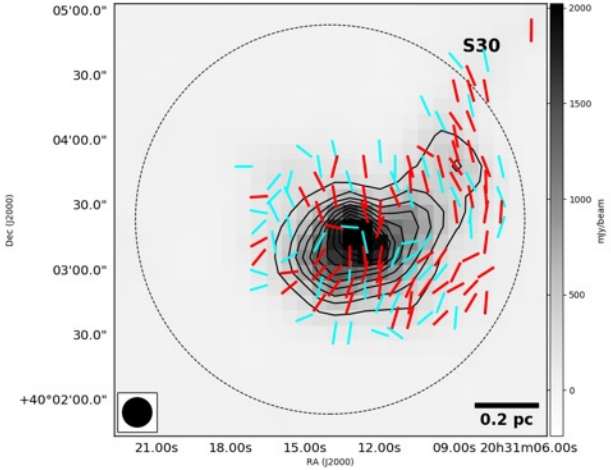

Red: P/DP>3

Cyan: 2<P/DP<3

18B+19B: 8hr/source. 2.5 mJy/beam


20B: ~68 min in Band 2.

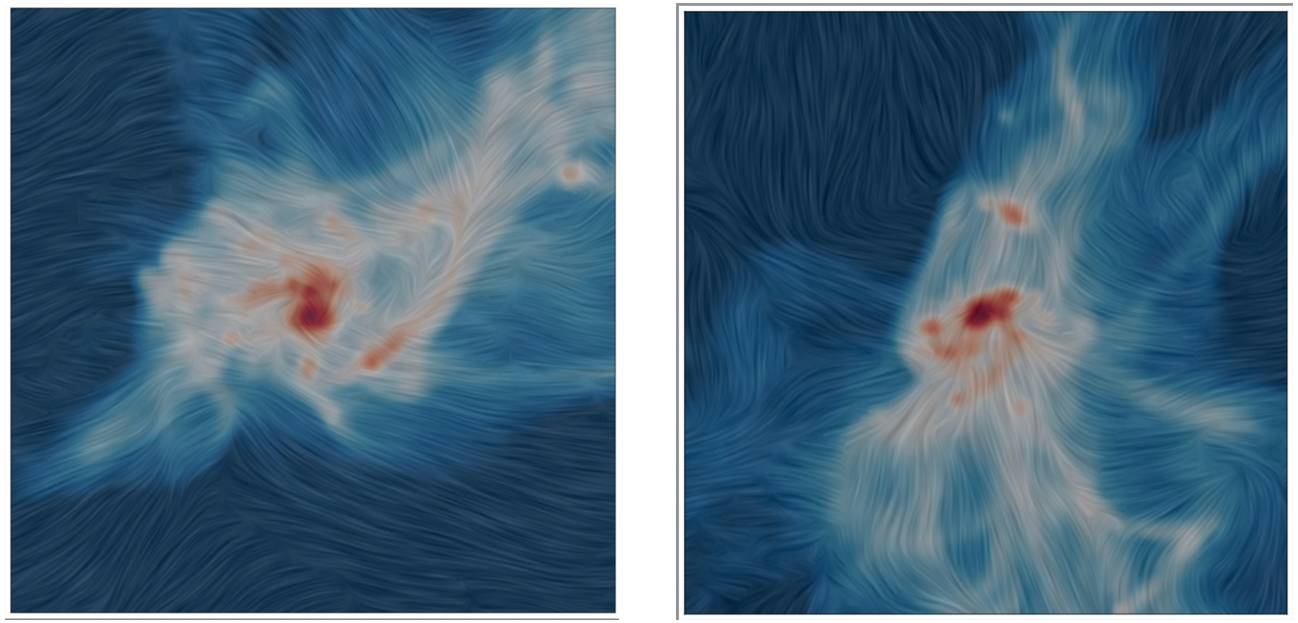

18B: 2hr. 5 mJy/beam

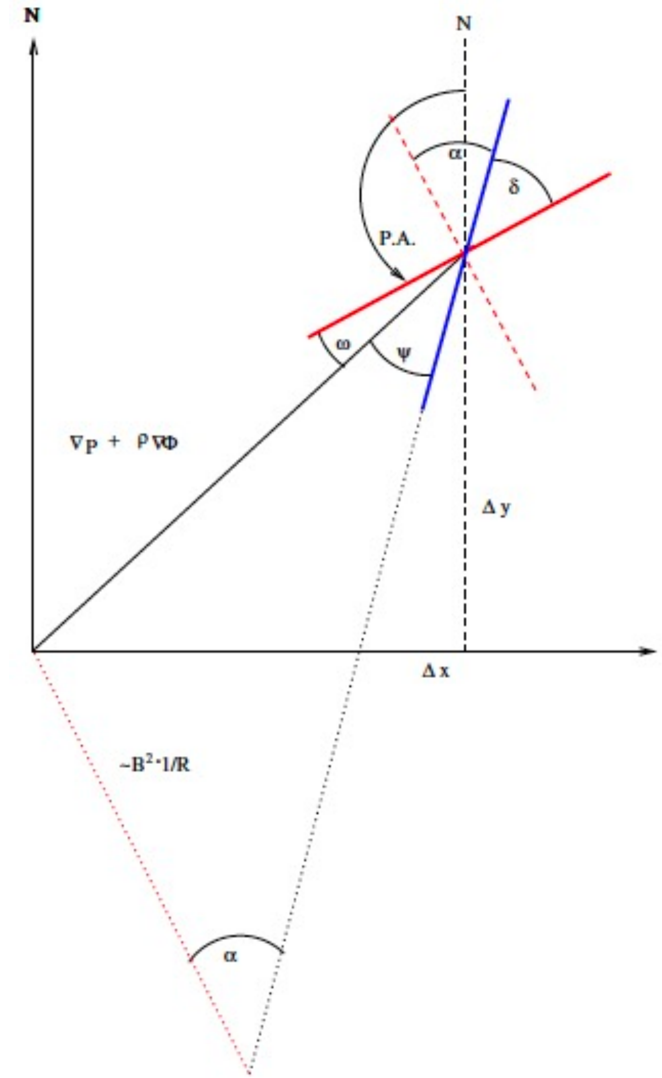


- Goal: map most of the massive dense cores in Cygnus-X with JCMT and SMA.
- Pilot polarization survey with JCMT POL-2: obtained usable data of 4 cores.
- Parallel SMA proposal accepted every year but with no usable data……

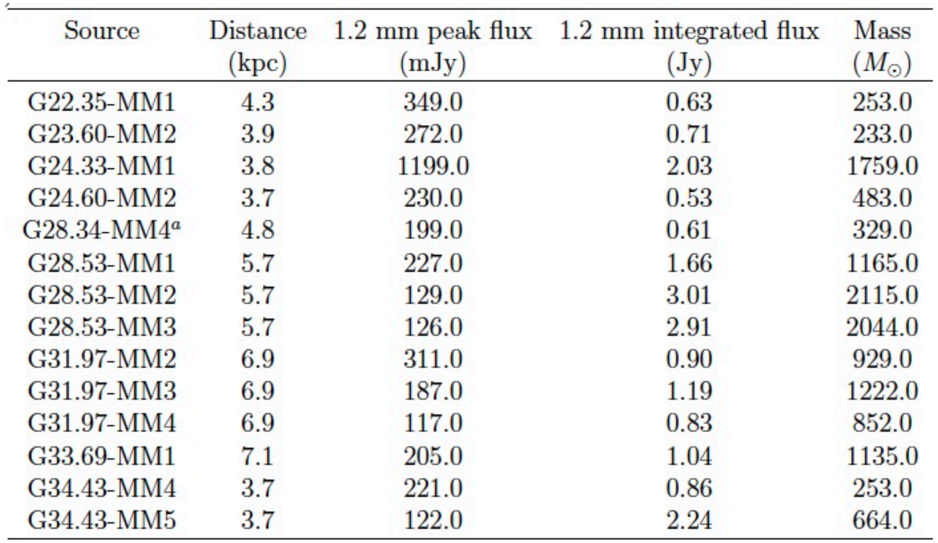
Test the Koch 2012 method with simulations

- Compare orientations of B, gravity, intensity orientation
- An alternative method to estimate B other than DCF.



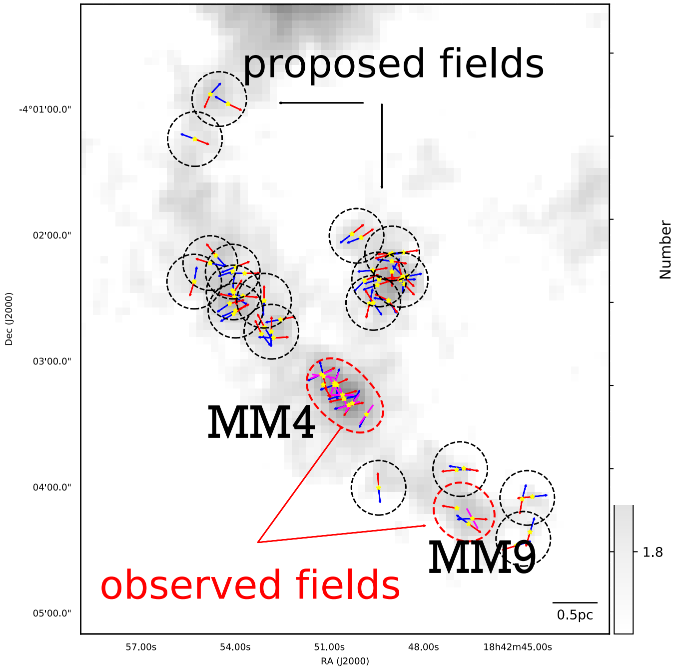


B fields in the early stage of high-mass star formation: Polarization survey of massive clumps/cores in IRDCs

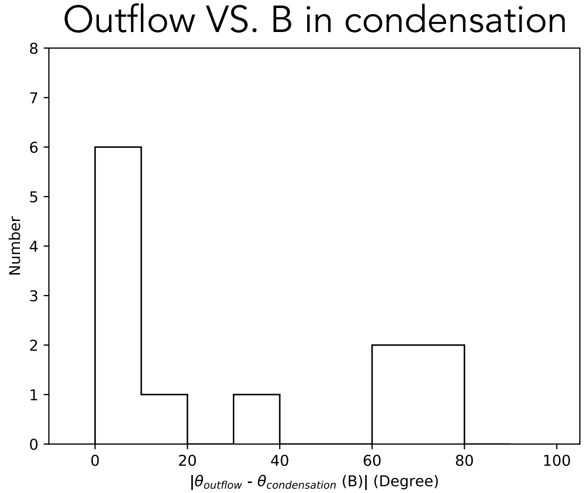


Source	Distance (kpc)	1.2 mm peak flux (mJy)	1.2 mm integrated flux (Jy)	Mass ($M_\odot$)
G22.35-MM1	4.3	349.0	0.63	253.0
G23.60-MM2	3.9	272.0	0.71	233.0
G24.33-MM1	3.8	1199.0	2.03	1759.0
G24.60-MM2	3.7	230.0	0.53	483.0
G28.34-MM4[a]	4.8	199.0	0.61	329.0
G28.53-MM1	5.7	227.0	1.66	1165.0
G28.53-MM2	5.7	129.0	3.01	2115.0
G28.53-MM3	5.7	126.0	2.91	2044.0
G31.97-MM2	6.9	311.0	0.90	929.0
G31.97-MM3	6.9	187.0	1.19	1222.0
G31.97-MM4	6.9	117.0	0.83	852.0
G33.69-MM1	7.1	205.0	1.04	1135.0
G34.43-MM4	3.7	221.0	0.86	253.0
G34.43-MM5	3.7	122.0	2.24	664.0

- ALMA pol survey of massive clumps in IRDCs catalogued by Rathborne+ (2006).
- ALMA proposal submitted



- Goal:
  - 1. Study the dynamical state of cores in IRDCs.
  - 2. Study the B-outflow relation in IRDCs.


Outflow VS. B in condensation

- ALMA pol survey of other clumps in IRDC G28.34
- ALMA proposal submitted

Outline: Magnetic fields in star formation

- Research history
  - B fields in early stages of low-mass star formation: JCMT POL-2 observations of low-mass starless Ophiuchus C
  - B fields in early stages of high-mass star formation: ALMA observations of 3 massive clumps in IRDC G28.34
  - Test the Davis-Chandrasekhar-Fermi (DCF) method with numerical simulations
- Current research and research plan
  - A compilation of all the previous DCF estimations (current research)
  - ALMA polarization survey of B fields in NGC 6334 sources
  - Multi-scale pol survey of B fields of massive dense cores in Cygnus-X with JCMT and SMA
  - Test the Koch 2012 method with simulations
  - ALMA polarization survey of massive clumps/cores in IRDCs