Magnetic fields in protostellar clusters

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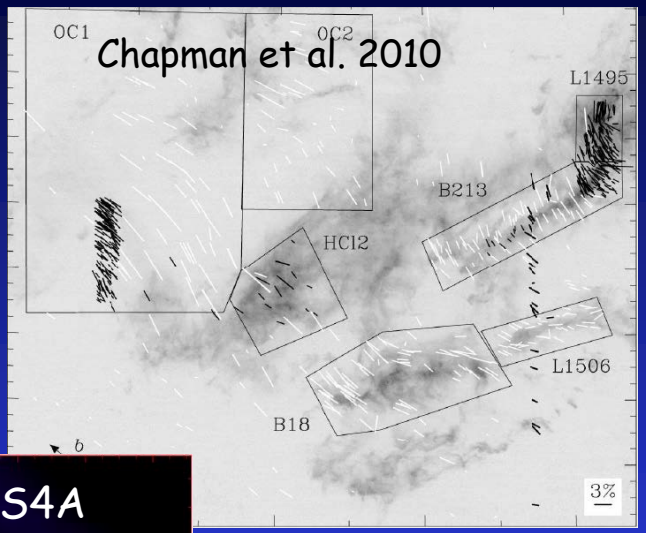
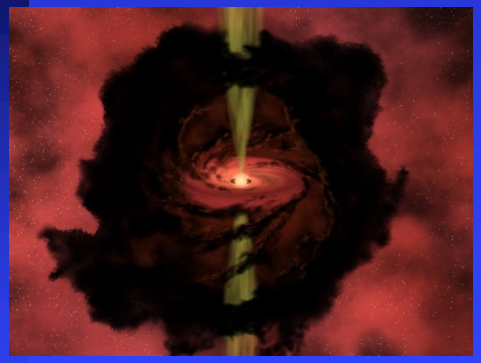
CENTER FOR ASTROPHYSICS

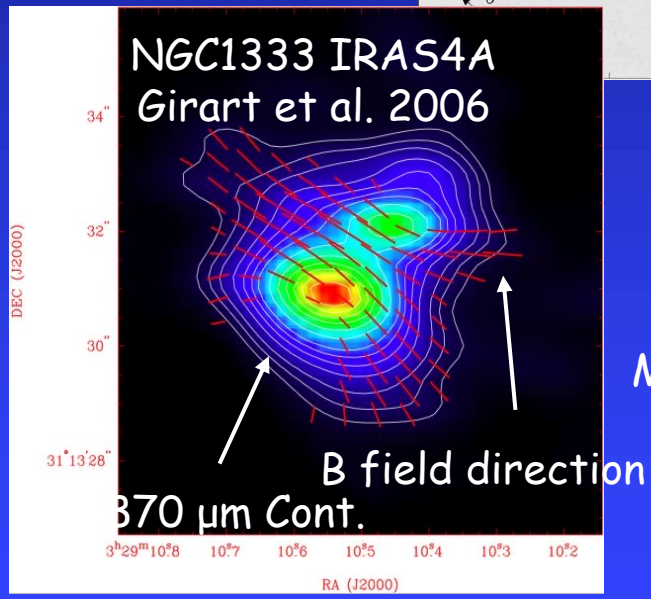
HARVARD & SMITHSONIAN

Role of Magnetic Fields in Star Formation

- Cloud scale (10pc): Cloud support/filament formation – magnetic or turbulent ?
- Clump/Core scales (1 – 0.1pc): Fragmentation and ambipolar diffusion ?
- Disk scale: Disk formation/Magnetic braking - remove angular momentum, launch/collimation of outflows



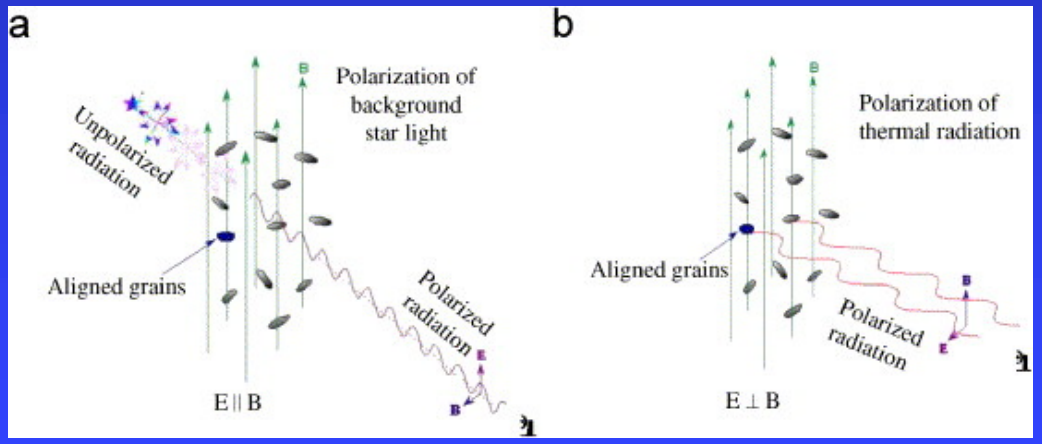




See review by
McKee & Ostriker 2007
Crutcher 2012
Li et al. 2014

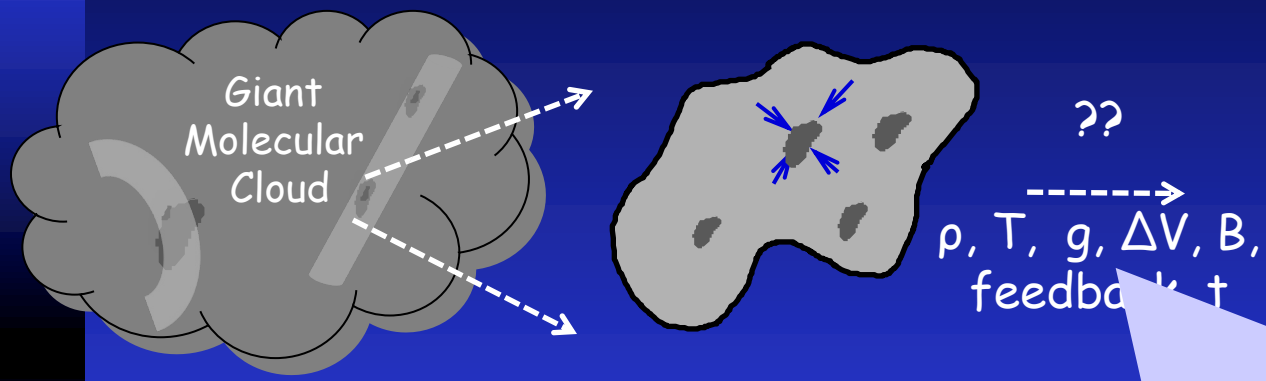
Techniques to Measure B-fields

- Zeeman splitting: B_{los}, limited by sensitivity unless for masers.
- Linear polarization caused by aligned aspherical dust grains in presence of Bpos fields (Emission: Pol ⊥ B; Absorption: Pol ∥ B): Measure morphology only, infer B_{pos}
- Goldreich & Kylafis effect (e.g. CO)
- Faraday rotation: rotation measure ~ ∫ ne∗Blos * ds



See Review by Crutcher 2012, Lazarian 2007

Massive Star (Cluster) Formation



10^2 pc
$n(H_2) \sim 10^2$ cm^{-3}
$M \sim 10^5$ Msun

- **How do massive clumps fragment into cores ?**
- **Which processes affect fragmentation (thermal, turbulent, magnetic fields)?**
- **How does the role of magnetic fields evolve?**

Magnetic fields in protocluster formation

SMA Legacy Survey: 21 massive molecular clumps, largest by (sub)mm interferometer, 1-3”

Goal: unprecedentedly large sample of massive molecular clumps to investigate the **role of magnetic fields in fragmentation of massive molecular clumps and the formation of stellar clusters**.

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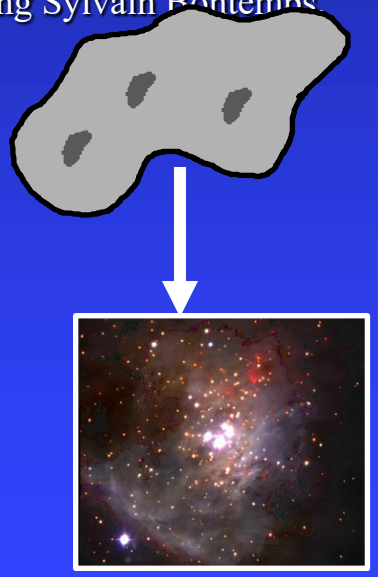
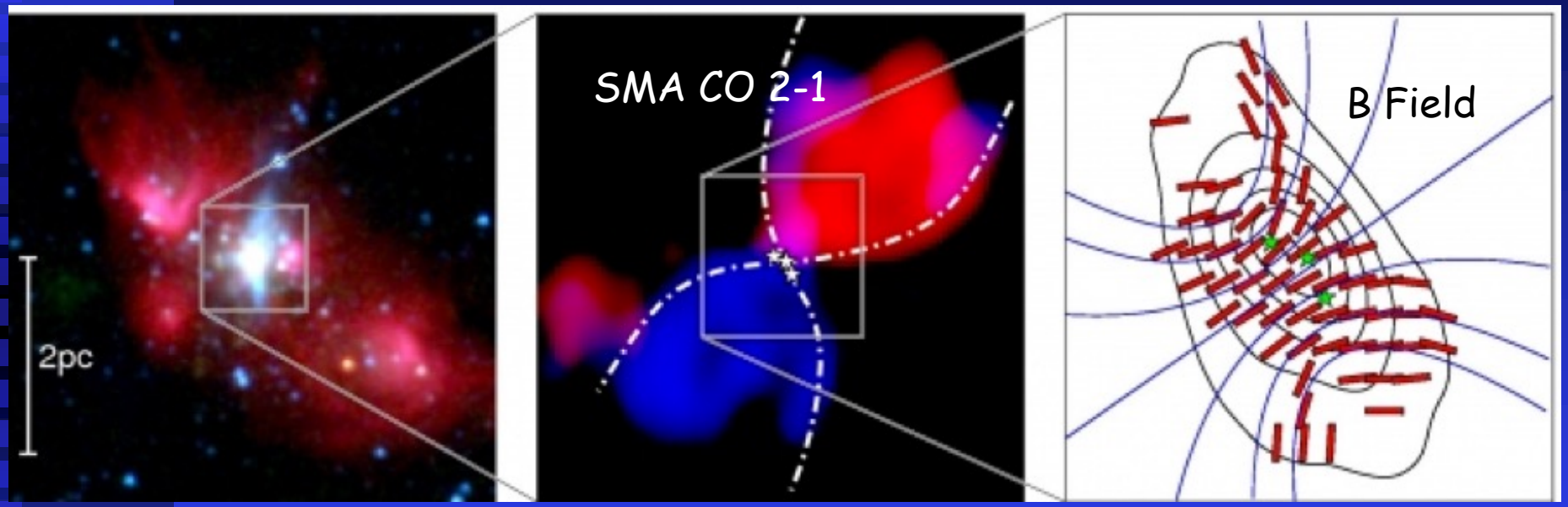
Co-Is: Keping Qiu, Ya-Wen Tang, Hau-Yu Liu, How-Huan Chen, Josep Girart, Ramprasad Rao, Paul Ho, Patrick Koch, Shih-Ping Lai, Hue-Ru Chen, Eric Keto, Zhi-Yun Li, Tao-Chung Ching Sylvain Bontemps, Timea Csengeri, Huabai Li, Pau Frau, Marco Padovani



Summary papers:

- Zhang, Q., Qiu, K., Girart, J. M., et al. 2014, ApJ, 792, 116
- Palau, A, Zhang, Q., et al. 2021, ApJ. 912, 159

G240: Dust Polarization and Outflow

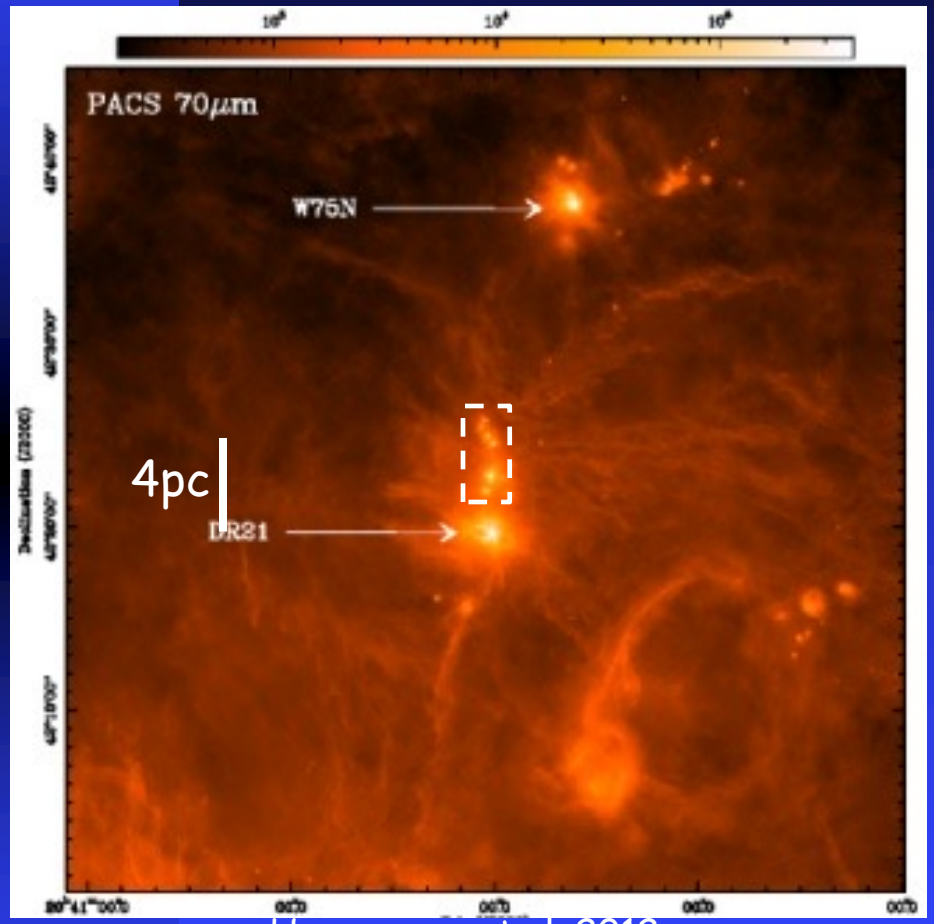


G240.31 ($10^{4.7}$ $L_\odot$)

Qiu, Zhang et al. 2009, 2014

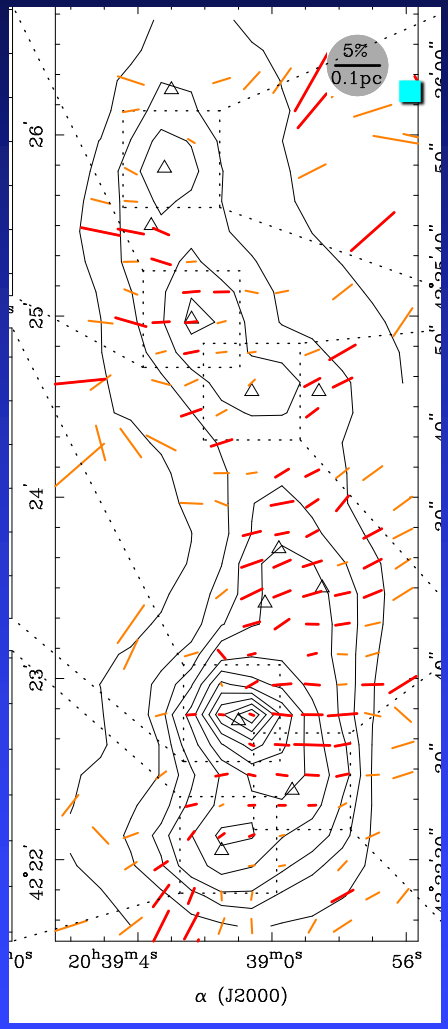
Zhang et al. 2014

Magnetic Fields in DR21 Filament in Cygnus X



Hennemann et al. 2012

JCMT



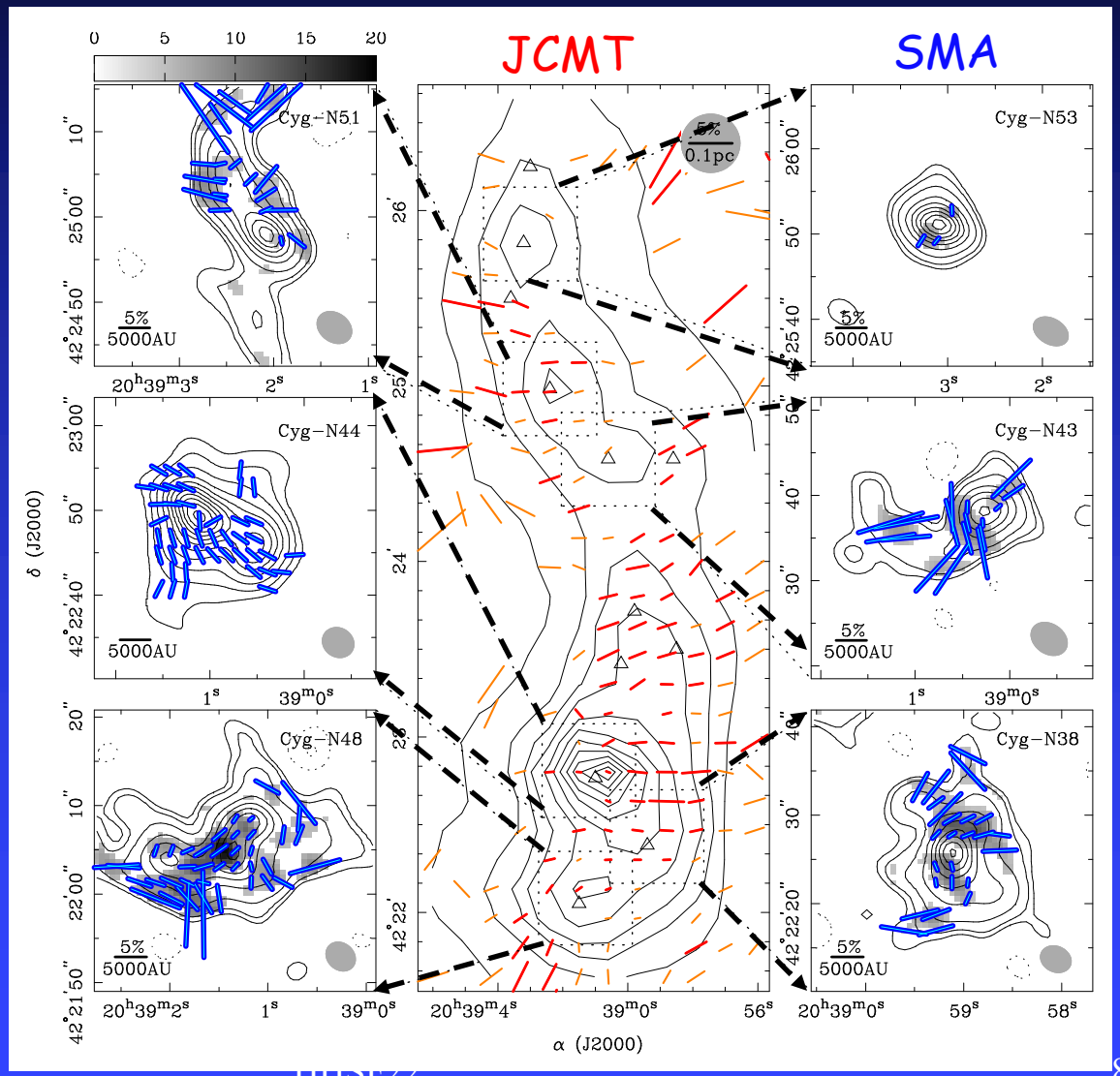
Ordered E-W oriented magnetic fields

Vallee & Fiege 2006
Matthews+ 2009
Ching+ 2017

Magnetic fields in DR 21 filament

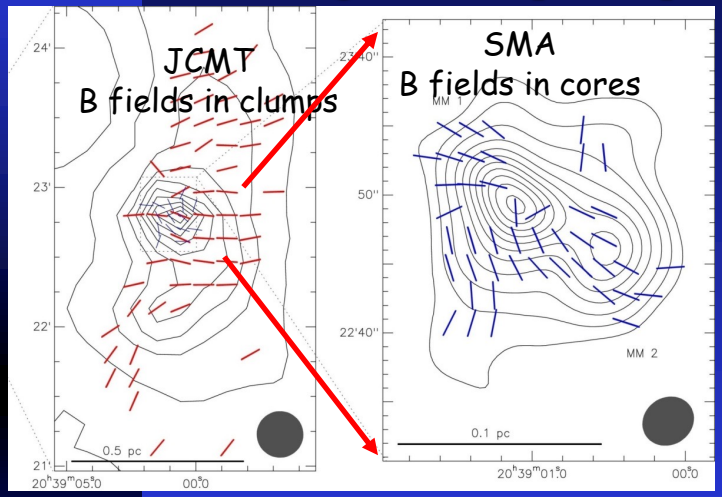
- All segments show magnetic field direction
- Blue: SMA
- Scattered magnetic fields in the cores

Ching+ 2017; Girart+ 2013



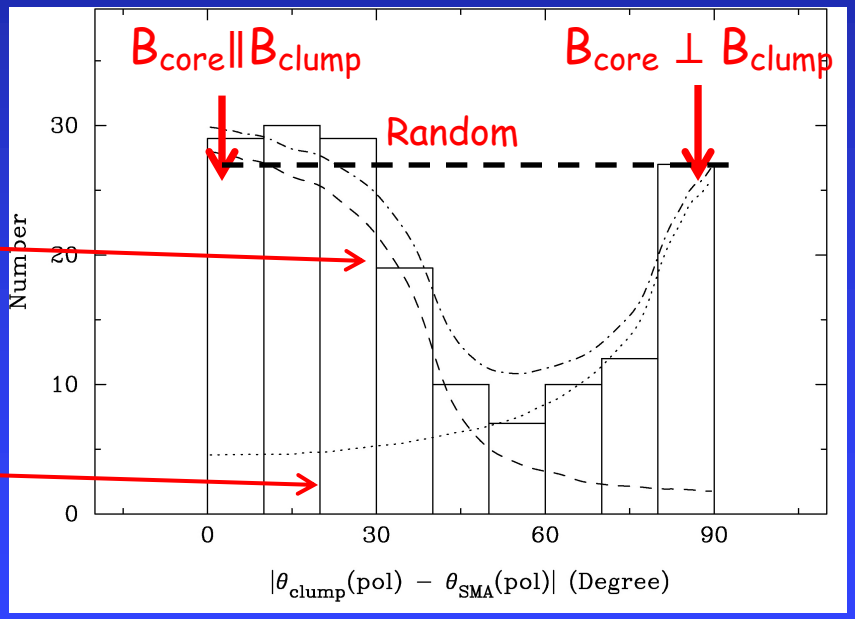
B field in core scales versus B field in clump

- The bi-modal distribution suggests that B fields are dynamically important during the collapse of pc-scale clumps and the formation of 0.1pc dense cores.



Girart+ 2013

Zhang+ 2014



Simulation: B-fields aligned within a 35° cone

Simulation: B-fields aligned within a 80-90°

See also Koch+ 2014

Magnetic fields & fragmentation

Palau, Zhang et al. 2020

1.3mm continuum and magnetic fields

Does the magnetic field suppress fragmentation in massive dense cores?

Aina Palau,[1] Qizhou Zhang,[2] Josep M. Girart,[3,4] Junhao Liu,[2,5,6] Ramprasad Rao,[2] Patrick M. Koch,[7] Robert Estalella,[8] Huei-Ru Vivien Chen,[9] Hauyu Baobab Liu,[7] Keping Qiu,[5,6] Zhi-Yun Li,[10] Luis A. Zapata,[1] Sylvain Bontemps,[11] Paul T. P. Ho,[7] Henrik Beuther,[12] Tao-Chung Ching,[7] Hiroko Shinnaga,[13] and Aida Ahmadi[14]

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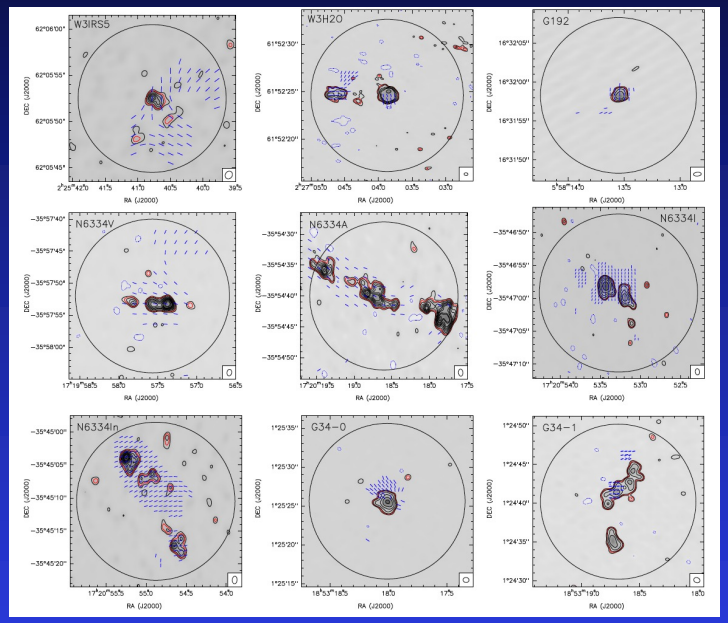
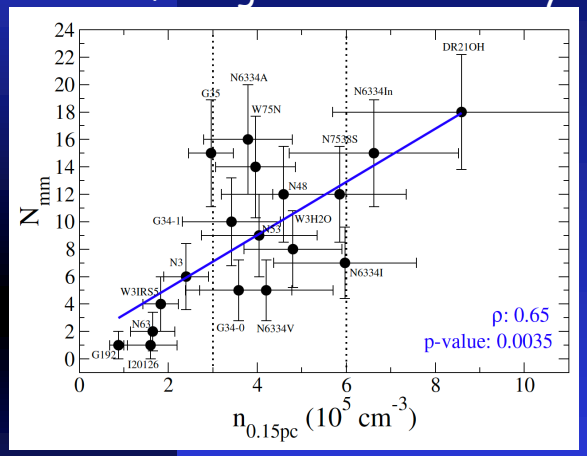


- Analyzed effect of gravity, turbulence and magnetic fields on fragmentation (18 objects at D<3kpc)

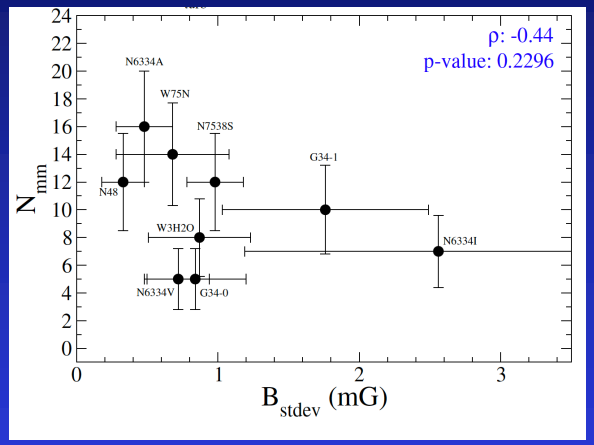
Magnetic fields & Fragmentation

Palau, Zhang et al. 2020

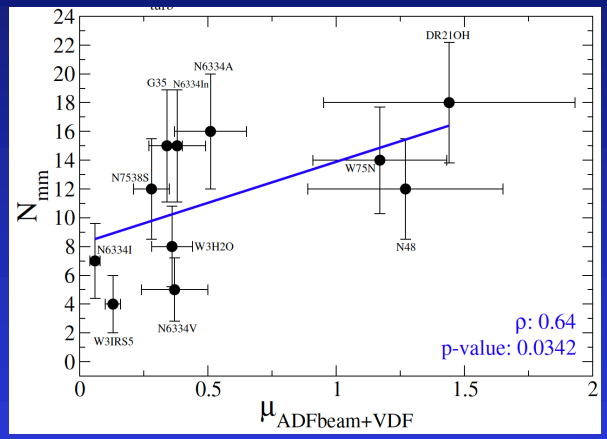
No. of Fragments vs. Density



No. of Fragments vs. B field



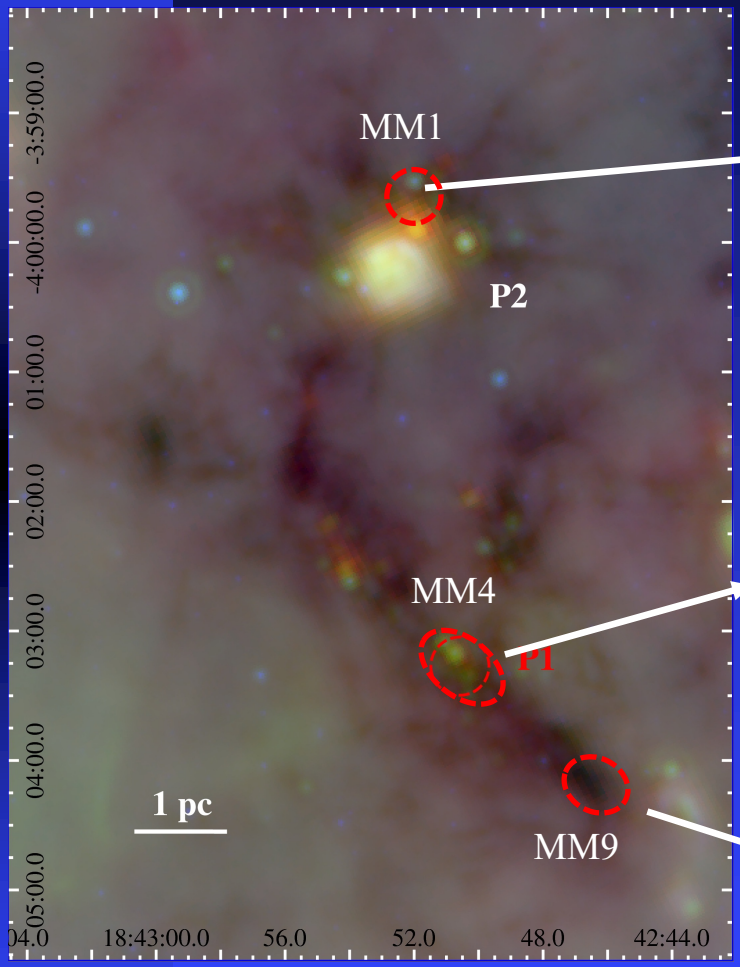
No. of Fragments vs. mass-flux ratio

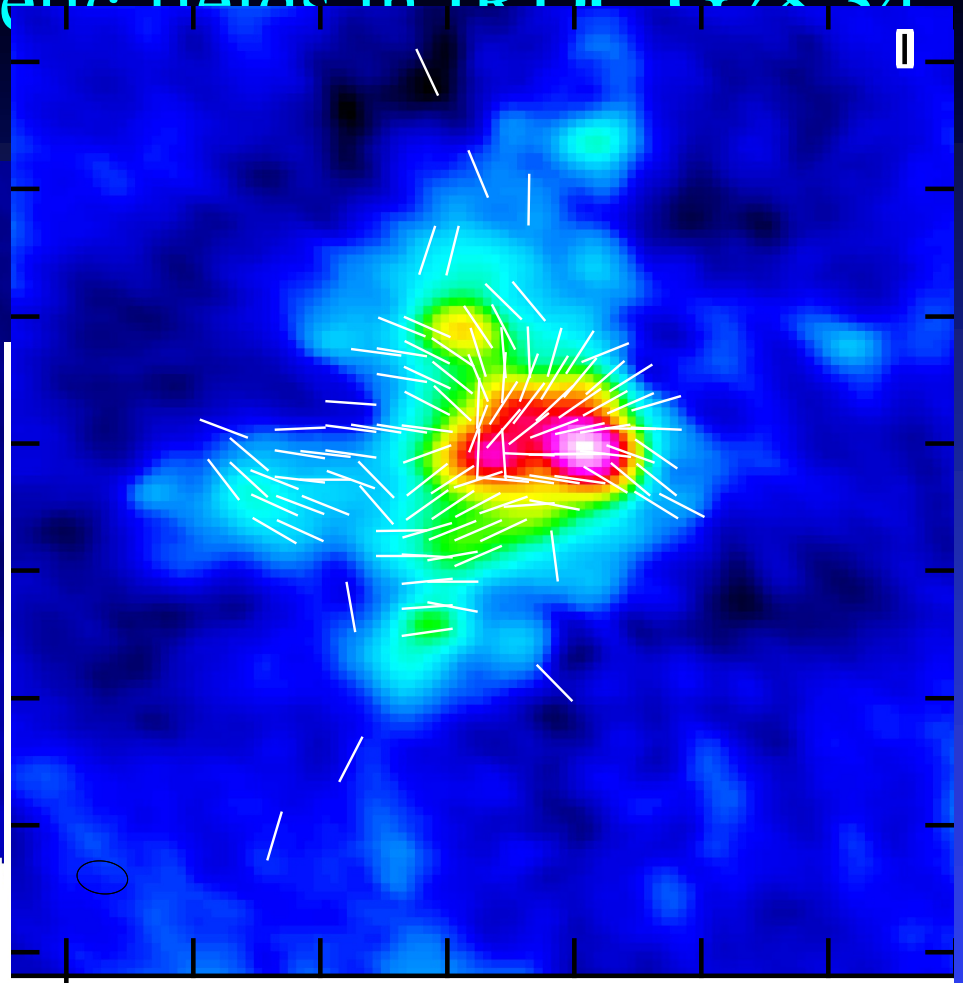


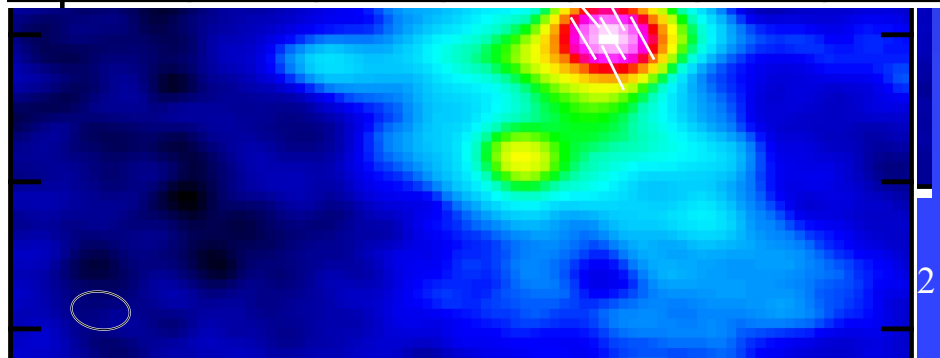
- A strong positive correlation between Nmm and average density
- A weak trend between Nmm and μ, the mass-flux ratios
- Derived magnetic field strengths via DCF or ADF methods, Bpos ~ 0.2 – 4.1 mG (see Liu, Zhang et al. 2020 on accuracy of DCF method, and review by Liu, Zhang, & Qiu 2022 on analysis techniques.)

Initial conditions: Magnetic fields in IRDC G28.34

Liu, Zhang et al. 2020







See Pillai+ 2015; Tang+ 2018; Beuther+ 2018

Evolution of B fields ?

Table 4
Physical Parameters Relevant to the ADF Analysis

Source	n_{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

Note.
[a] Equivalent correction factor $Q_c' = 1/\sqrt{N}$ for the signal-integration effect.

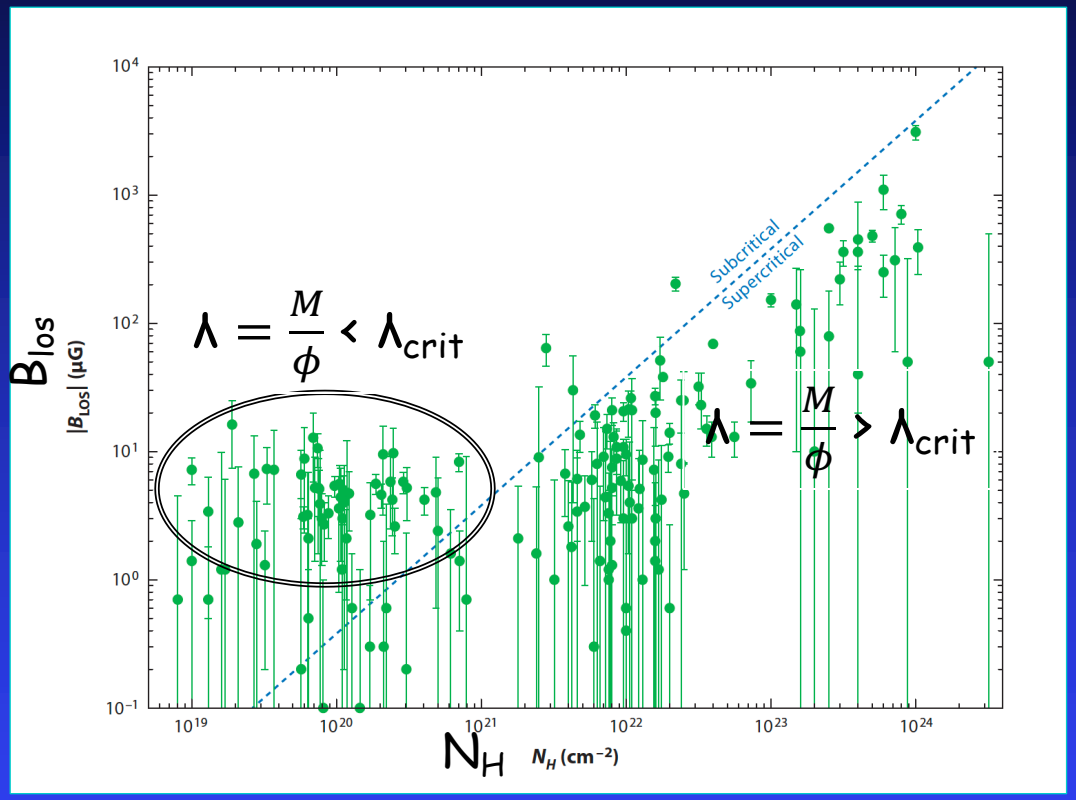
Table 5
Physical Parameters Relevant to the Virial Analysis

Source	$\sigma_{th,3D}$ (km s^{-1})	$\sigma_{turb,3D}$ (km s^{-1})	$V_{A,3D}$ (km s^{-1})	M $M_\odot$	M_{th} $M_\odot$	M_{turb} ($M_\odot$)	M_B ($M_\odot$)	M_B^{mod} ($M_\odot$)	M_{k+B} ($M_\odot$)	M_{k+B}^{mod} ($M_\odot$)	α_{k+B}	α_{k+B}^{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

- MM1 is more evolved than MM4.
- Virial parameters $\alpha_{MM1} > \alpha_{MM4}$, but still < 1 after considering the magnetic support.
- Mass-to-flux ratios $\lambda_{MM1} > \lambda_{MM4} > \lambda_{crit}$

Mass-to-flux ratios: Criticality of clouds

Crutcher el. al 2009, 2010
B fields from Zeeman



Mass-to-flux ratios

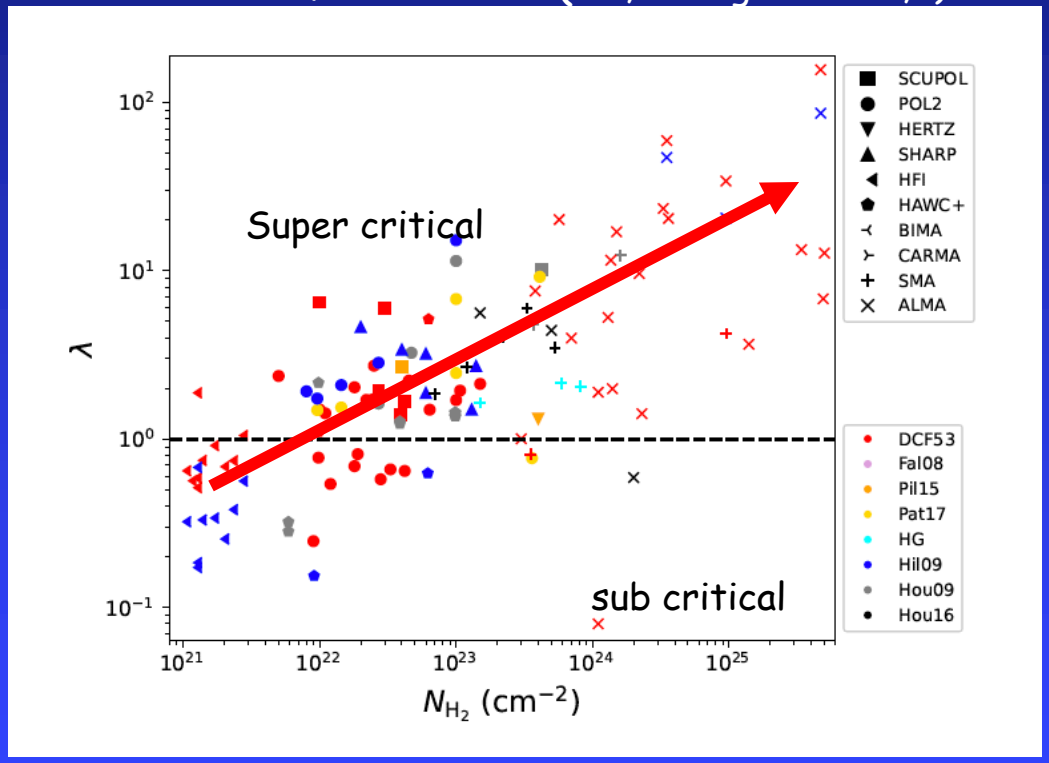
Bpos derived from Davis-Chandrasekhar-Fermi or DCF-like methods for 230 SF regions

Mass-to-flux ratios increase with N_{H2}

The transition from $\lambda<1$ to $\lambda > 1$ at 3×10^{21} cm^{-2} , cloud evolution?

Caveat: data from different SF regions

Mass-to-flux ratios (Liu, Zhang + 2022a,b)



See also Pattle & Fissel 2019; Myers & Sasu 2021

Conclusions

- Magnetic fields in the majority of dense cores are organized and are aligned in a bimodal distribution w.r.t. the parsec-scale magnetic fields.
- A tentative trend is revealed between no. of fragments and mass-to-flux ratios.
- Quantitative analysis → Bpos ~ mG (with caveates).
- The large sample shows on a statistical basis that magnetic fields play an important role during collapse of clumps and the formation of dense cores.
- There appears to be an evolution in mass-to-flux ratios with densities in clouds