Polarized dust emission in massive star forming regions

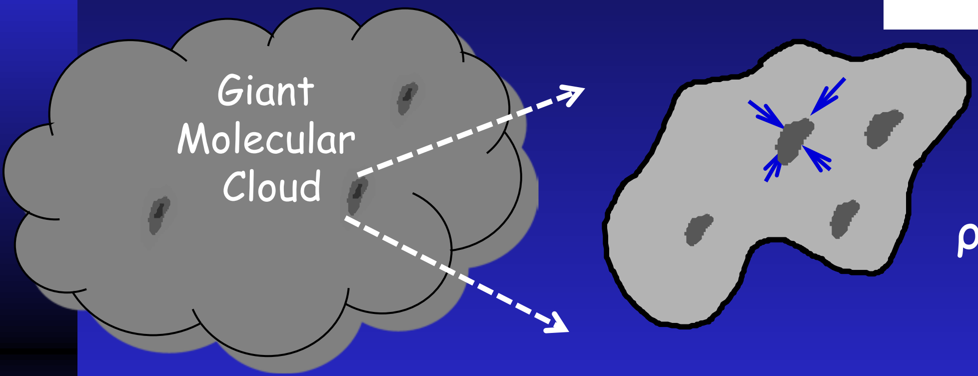
Qizhou Zhang

Harvard-Smithsonian Center for Astrophysics

Massive Star (Cluster) Formation

$$M_J = \frac{\pi}{6}\left(\frac{\pi C_s^2}{G}\right)^{3/2}\rho_o^{-1/2}$$

$M_J \sim 1$ Msun



??

ρ, T, ΔV, B,
feedb ck

r

ge

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

- **How do massive clumps fragment into cores :**
- **Which processes control fragmentation (thermal, turbulent, magnetic fields)?**
- **How to make massive cores?**
- **Does cluster star formation proceed in equilibrium?**

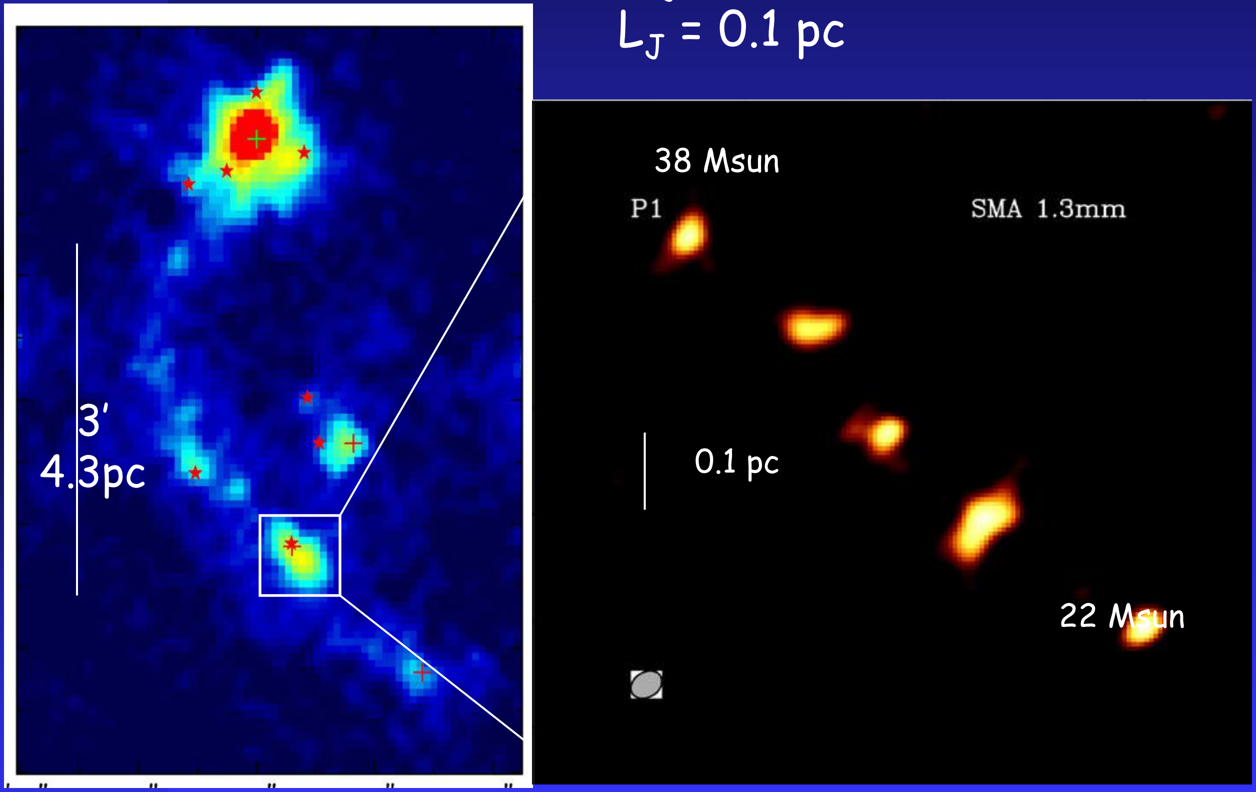
See review by
Zinnecker & Yorke 2007

Cores contain many Jeans mass (Case study G28.34)

$n(H_2)=7\times10^4\ cm^{-3}$, T=15K
M_J (thermal) = 2 Msun
L_J = 0.1 pc

➔ For spatially resolved cores (res < L_J) $M_{core}/M_J > 10$,

$$M_J = \frac{\pi}{6}\left(\frac{\pi C_s^2}{G}\right)^{3/2} \rho_o^{-1/2}$$



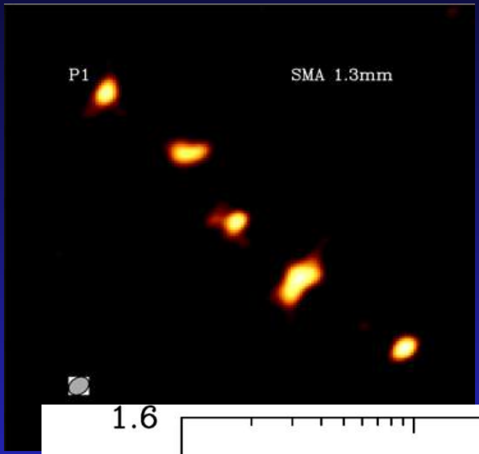
σv=0.7 km/s
M_{turb_J} ~ 30 Msun
L_{turb_J} ~ 0.3 pc

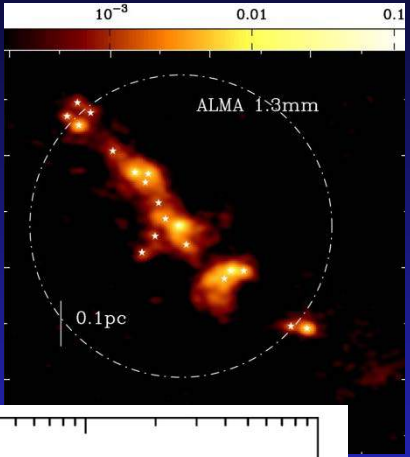
Turbulence (and B field) supported fragmentation?

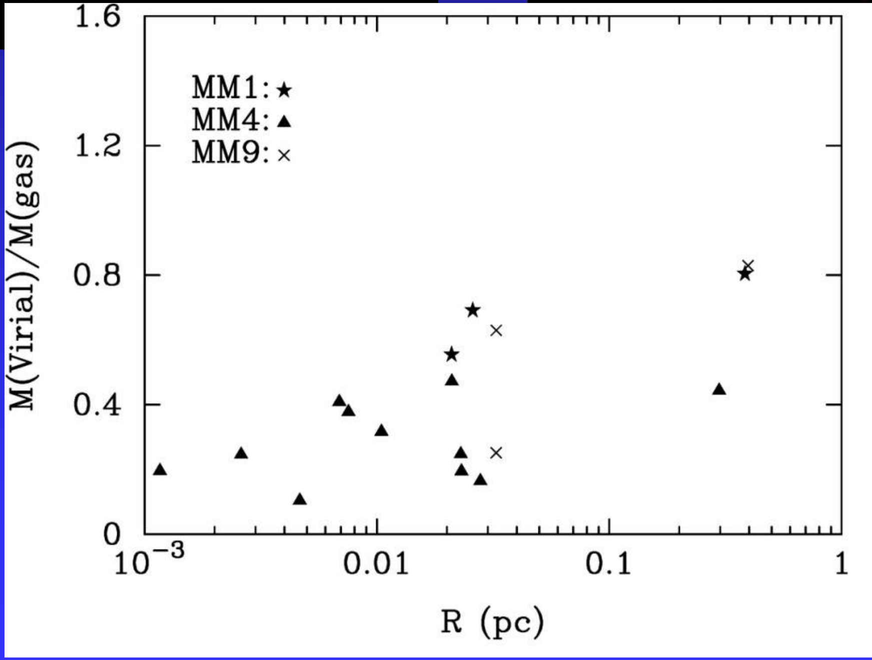
Zhang, Wang, Pillai, Rathborne 2009

See also Brogan et al. 2009; Longmore et al 2010; Csengeri et al. 2010, 11; Pillai et al. 2011; Tan et al. 2013

Is cluster forming region G28 in equilibrium



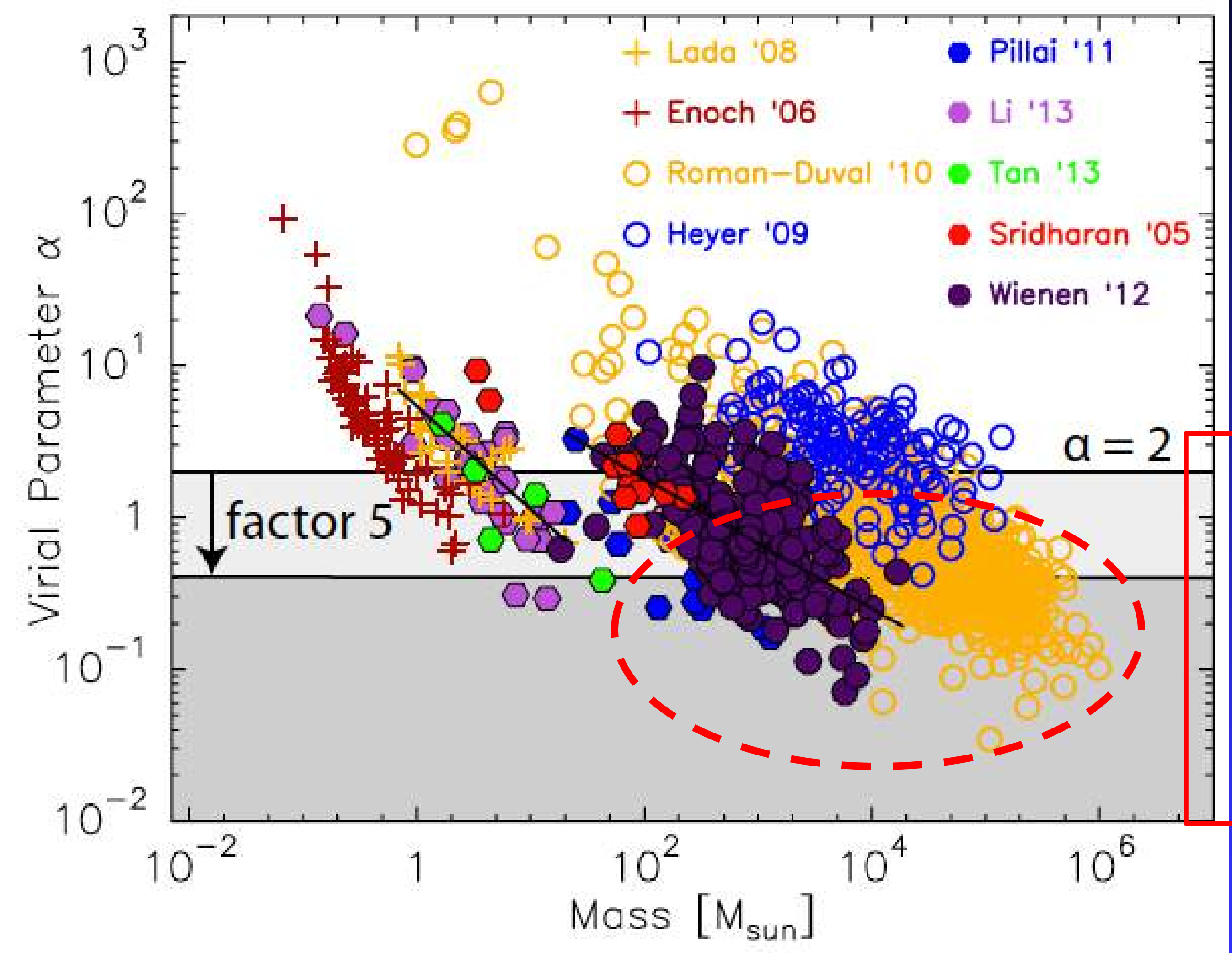




$$\alpha = \frac{M_{vir}}{M} = \frac{5\sigma^2 R}{GM}$$

Zhang et al. 2009; 2015; Zhang et al. in prep.

Virial parameter: A large sample



$$\alpha = \frac{M_{vir}}{M} = \frac{5\sigma^2 R}{GM}$$

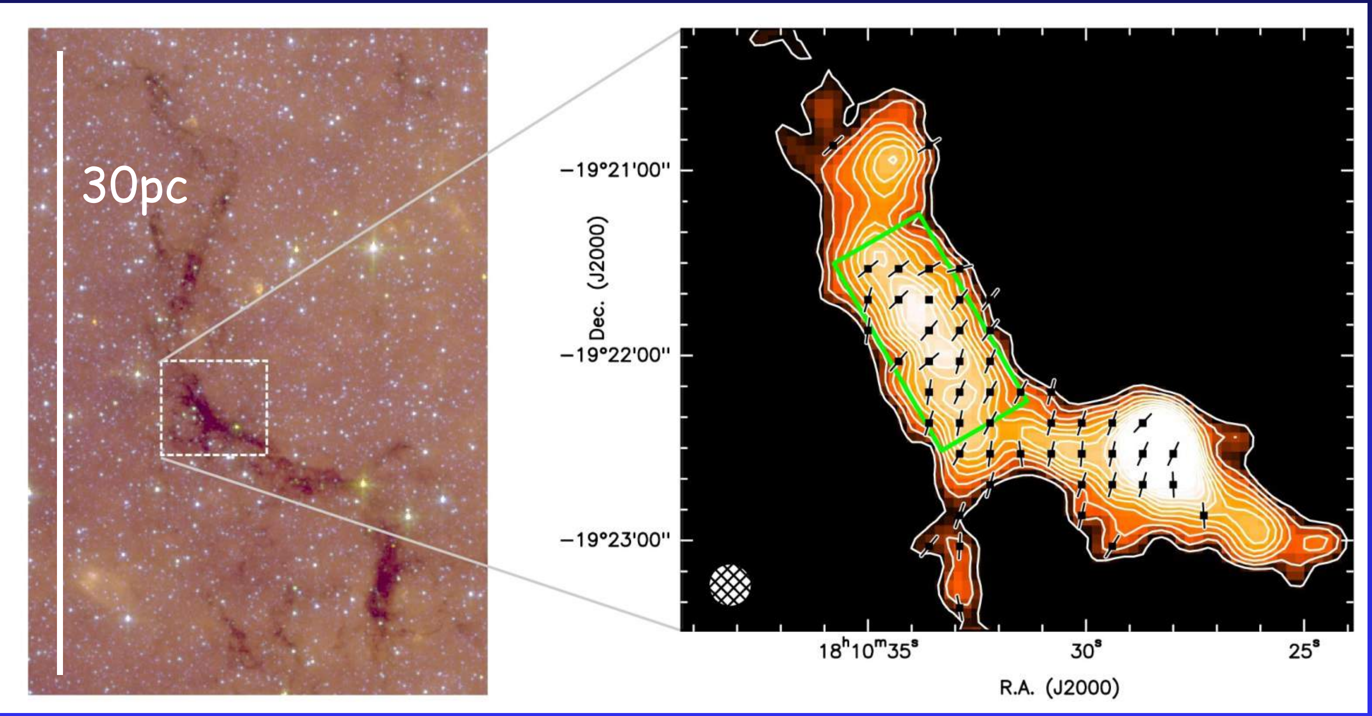
many massive clumps/cores observed in high-density tracers are sub-virial

Additional magnetic support?

~1300 objects from clouds to cores
~ low mass to high mass

Kauffmann, Pillai & Goldsmith 2013

IRDC G11.11-0.12



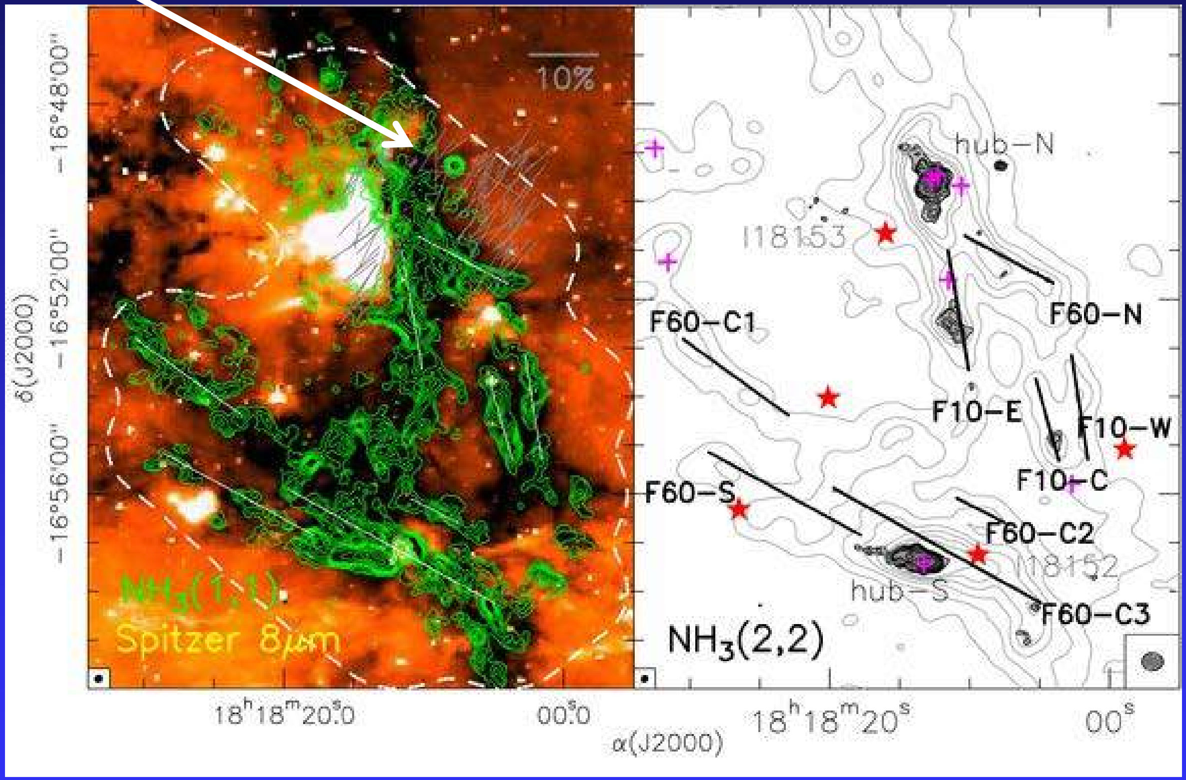
B = 0.27 mG, Pillai et al. 2015,
see also Carey et al. 1998, Henning et al. 2010, Wang et al. 2014

Massive Filaments in G14.2

B field from IR

Busquet, Zhang et al. 2012

- Cloud size ~ 8 pc
- 74 clumps
- Masses:11-1000 $M_{\odot}$
- Clump sizes: 0.2-1.2 pc



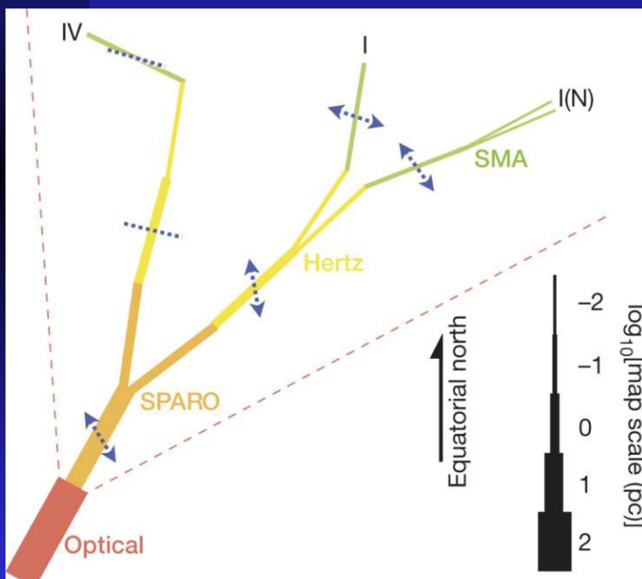
VLA NH_3 on Spitzer 8 μm

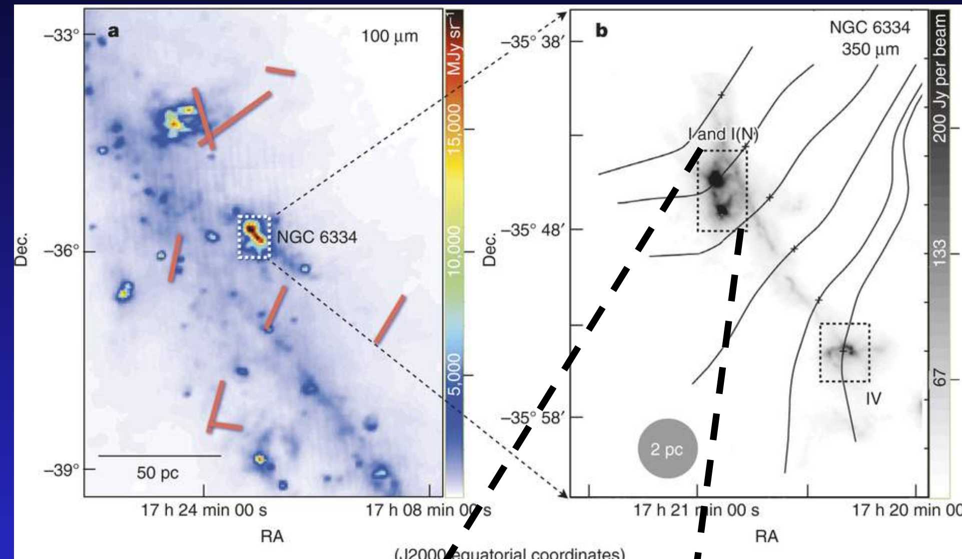
Array of filaments

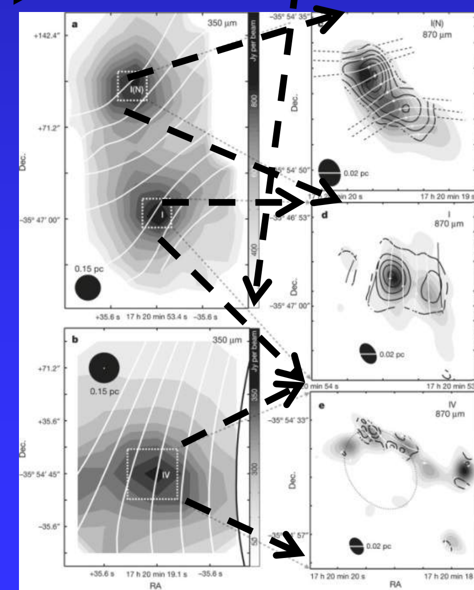
B field ⊥ filaments

NGC 6334: Magnetic fields from GMC to cores

- Magetic field orientation maintained from 100pc to 0.1 pc

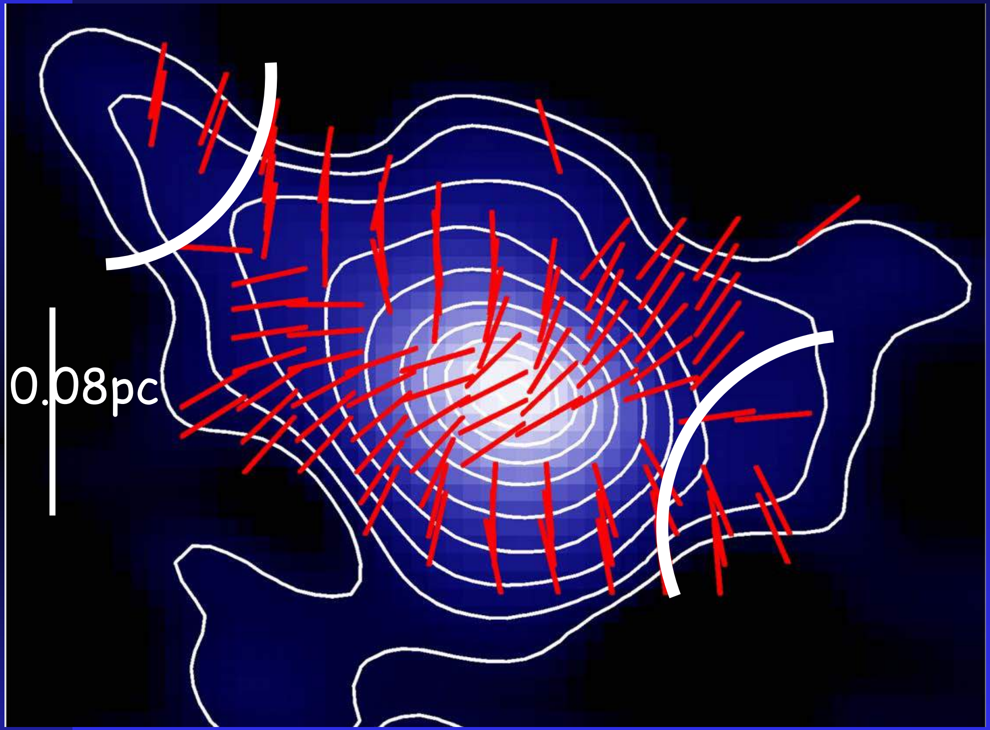






Li et al. 2015
See also Zhang et al. 2014

Polarization: G31.41+0.31



A hot molecular core with 3×10^5 Lsun and 500Msun.

Contour: 870 μm Stokes I
Vector: B Field direction
Field lines are pinched along the major axis

Magnetic field strength: **B ≈ 10 mG**

Girart, Beltran, Zhang, Rao, Estalella 2009
See also Lai et al. 2003; Rao et al. 1998; Cortes et al. 2000; Tang et al. 2008, 2009,2012; Kock 2012; Hull et al. 2013. Sridharan et al. 2013
Single Dish: Matthews et al. 2009; Dotson et al. 2010

SMA Polarization Legacy Survey

21 massive molecular clumps, largest by (sub)mm interferometer

Subcompact/compact/extended configurations → 1-3”

PI: Qizhou Zhang

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 paper:

- Zhang, Q., Qiu, K., Girart, J. M., et al. 2014, ApJ, 792, 116

Detailed analysis:

- Girart, J. M., Frau, P., Zhang, Q., et al. 2013, ApJ, 772, 69
- Koch, P. M., Tang, Y.-W., Ho, P. T. P., et al. 2014, ApJ, 797, 99
- Li, H. et al. 2015, Nature, 520, 518
- Liu, H. B., Qiu, K., Zhang, Q., Girart, J. M., & Ho, P. T. P. 2013, ApJ, 771, 71
- Qiu, K., Zhang, Q., Menten, K. M., Liu, H. B., & Tang, Y.-W. 2013, ApJ, 779, 182
- Qiu, K., Zhang, Q., Menten, K. M., et al. 2014, ApJ, 794, L18

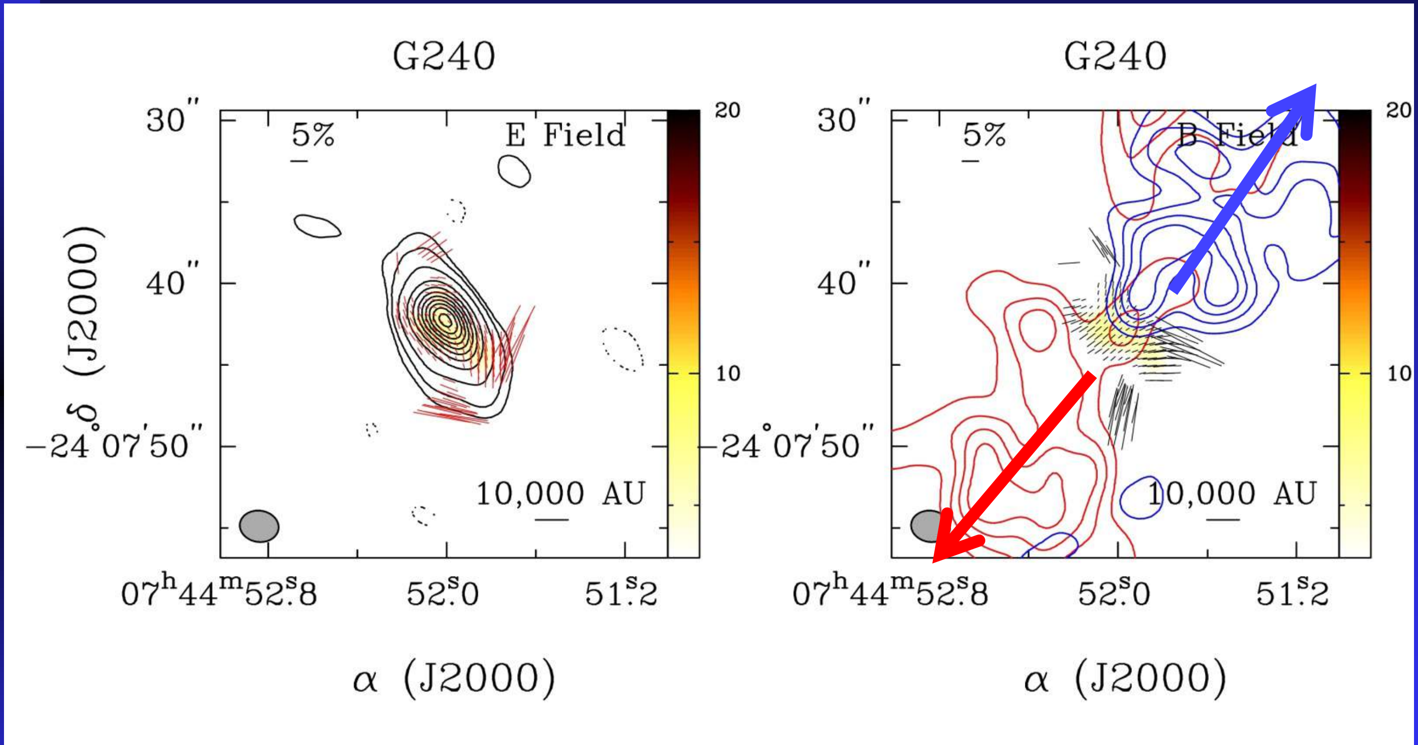
Sample:

29 massive clumps with embedded massive stars +W75N/W3-IRS5 250 hours

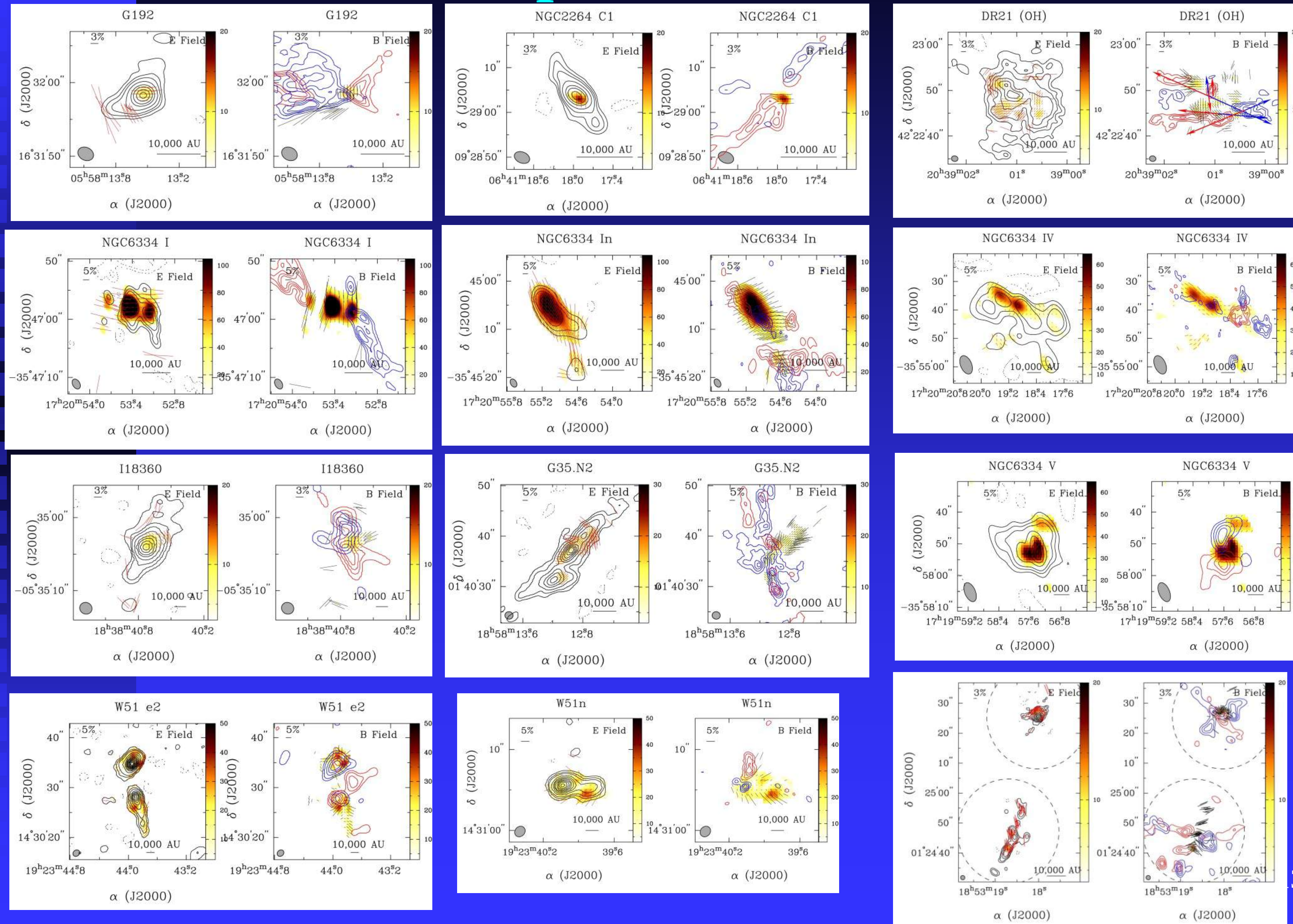
Source	α (J2000)	δ (J2000)	V_{lsr}(km/s)	Note
*NGC6334A	17:20:19.1	-35:54:45.0	-8	Pol at optical, FIR and SMA. Miss subcomp and EXT track.
*NGC6334I	17:20:53.44	-35:47:2.2	-8	Two Clump at end of filament
*NGC6334In	17:20:54.63	-35:45:08.5	-8	Miss subcomp and EXT track
NGC6334V	17:19:57.40	-35:57:46.0	-8	A Clump at end of filament
G14.2.0	18:18:13.0	-16:57:15	20	Filamentary IRDC.
G14.2.1	18:18:12.0	-16:57:20.8	20	Filamentary IRDC.
G14.2.2	18:18:13.8	-16:57:03	20	Filamentary IRDC.
G28.34P2	18:42:52.07	-3:59:54	78.4	IRDC. At the tip of a filament.
G34.4.0	18:53:18.01	01:25:25.6	57	IRDC. MM source. BIMA pol. No SCUPOL. In the middle of a filament.
G34.4.1	18:53:18.68	01:24:47.2	57	The south mm peak in G34.4. UCHII region.
*G35.2	18:58:12.96	01:40:36.9	34	Filamentary IRDC. Miss subcom and EXT track.
*W51e2/e8	19:23:43.95	14:30:34.00	58	BIMA pol. SMA pol. Miss CMP track.
*W51North	19:23:40.05	14:31:05.00	58	BIMA pol. SMA pol. Miss CMP track.
DR 17	20:35:34.63	42:20:08.8	15	IRDC. CygX-N 3. At the tip of a filament. Four cores are aligned and two brightest are comparably strong.
DR21-W	20:36:57.65	42:11:30.2	15	IRDC. CygX-N12. At the tip of a curved filament. Four cores are aligned.
*DR21OH	20:39:01.2	42:22:48.5	-3.5	IRDC. CygX-N44. MM1 is a hot core. SCUPOL obs. BIMA pol obs. In the middle of a filament.
DR21(OH)W	20:38:59.11	42:22:25.96	-3.5	IRDC. CygX-N38. Two cores.
DR21(OH)S	20:39:01.34	42:22:04.9	-3.5	IRDC. CygX-N48. Six cores are resolved in a curved filament.
DR21(OH)N	20:39:02.96	42:25:51.0	-3.5	IRDC. CygX-N53. Seven cores resolved in a filament. SCUPOL obs.
DR 22	20:40:05:39	41:32:13.1	-3.5	IRDC. CygX-N63. Not covered in SCUPOL obs. The brightest core at the tip of a filament.
*W3(OH)	02:27:03.87	61:52:24.5	-50.0	Two dust continuum peaks: W3(OH) and W3(H_2O). Miss subcom and EXT track.
NGC2264C.1	06:41:17.95	09:29:03	7	MM1. Seven cores (including MM 3 and 4) aligned in a 0.5 pc filament.
NGC2264C.3	06:41:12.3	09:29:12	7	MM3
NGC2264C.4	06:41:09.95	09:29:22	7	MM4
G240.31	07:44:52.0	-24:07:42	67.5	Filamentary.

List of Sample. Sources with * have portion of SMA polarization data taken, except DR21OH which shows strong polarization from BIMA observations. Sources in the RA 2 to 8h range will be proposed in the 2011B semester.

Polarization Map for G240

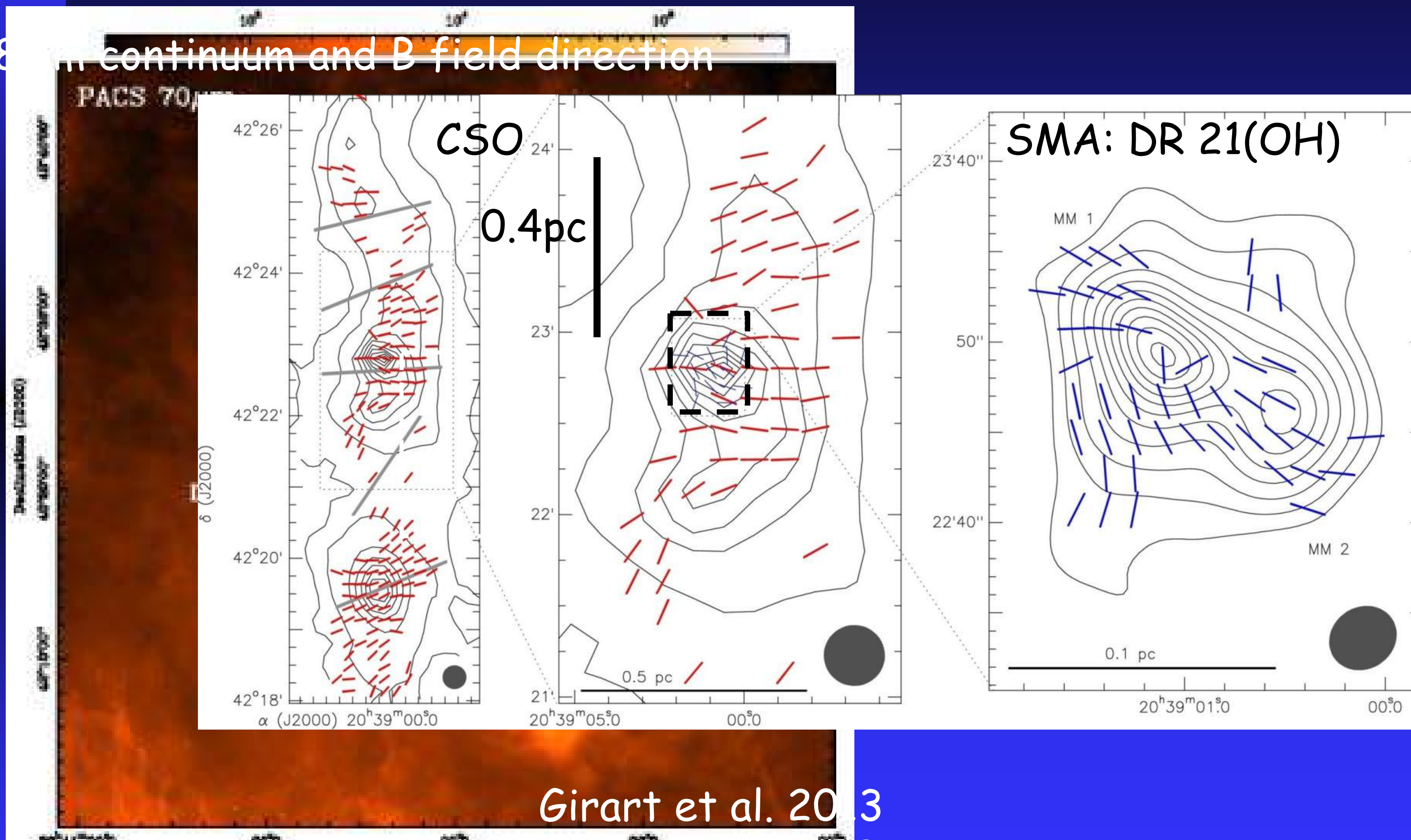


Polarization Maps



DR21 Filament in Cygnus X

0.8 m continuum and B field direction



Girart et al. 2013

Kirby et al. 2009

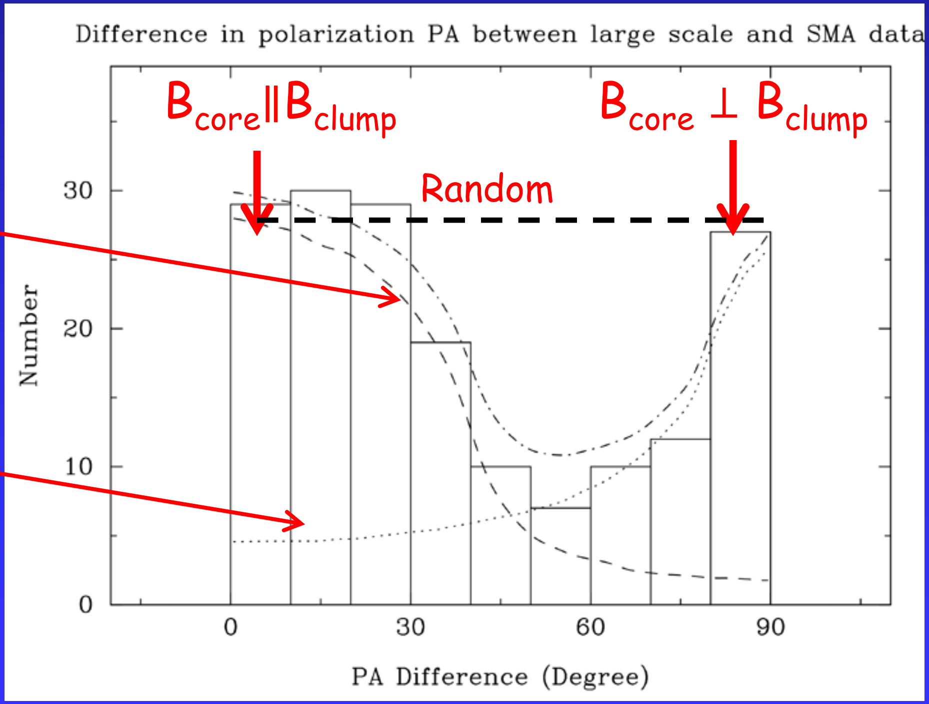
Hennemann et al. 2012

B field in core scales versus B field in clump

- Two groups of cores: One group with $B_{core} \| B_{clump}$, Other group $B_{core} \perp B_{clump}$.
- > 60% of small scale B follow direciton of B_{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.

Simulation: B-fields aligned within a 35° cone

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



Zhang et al. 2014

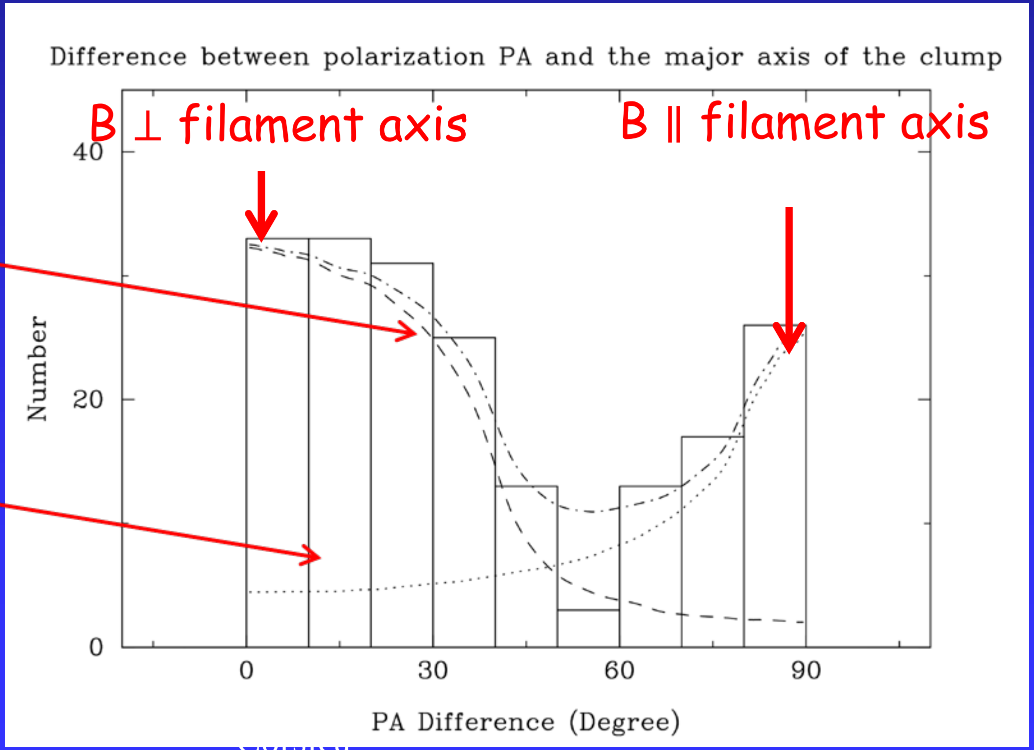
B field in core scale versus morphology of clumps

- Two groups of cores: One group with B_{core} ∥ Filament Axis, Other group B_{core} ⊥ Filament Axis.
- The bi-modal distribution confirms that B field is dynamically important during the collapse of pc-scale clumps and the formation of dense cores.

Simulation: B-fields aligned within a 35° cone

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

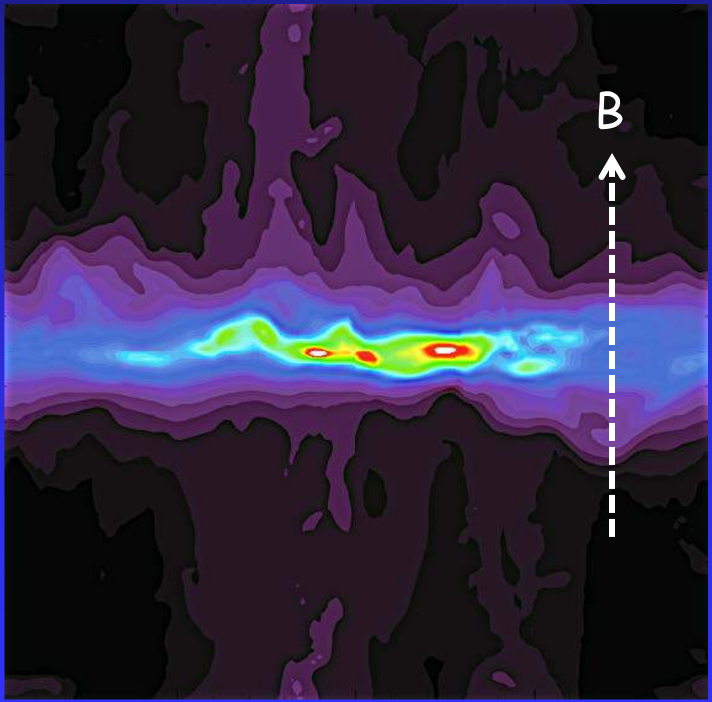
See also Tassis et al. (2009), Li et al. 2013

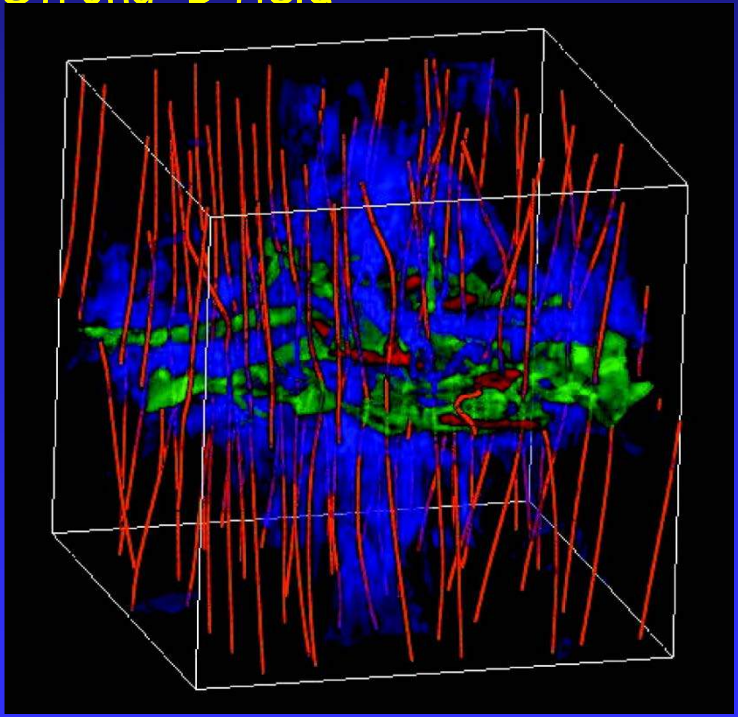


Magneto hydrodynamic simulation with turbulence: Sheets

- Gas collapse along field lines to form dense filaments ⊥ B
- Diffuse and lower density gas ∥ B

$\beta = P_{th}/P_B = 1/24$, Strong B field





Nakamura & Li (2008)

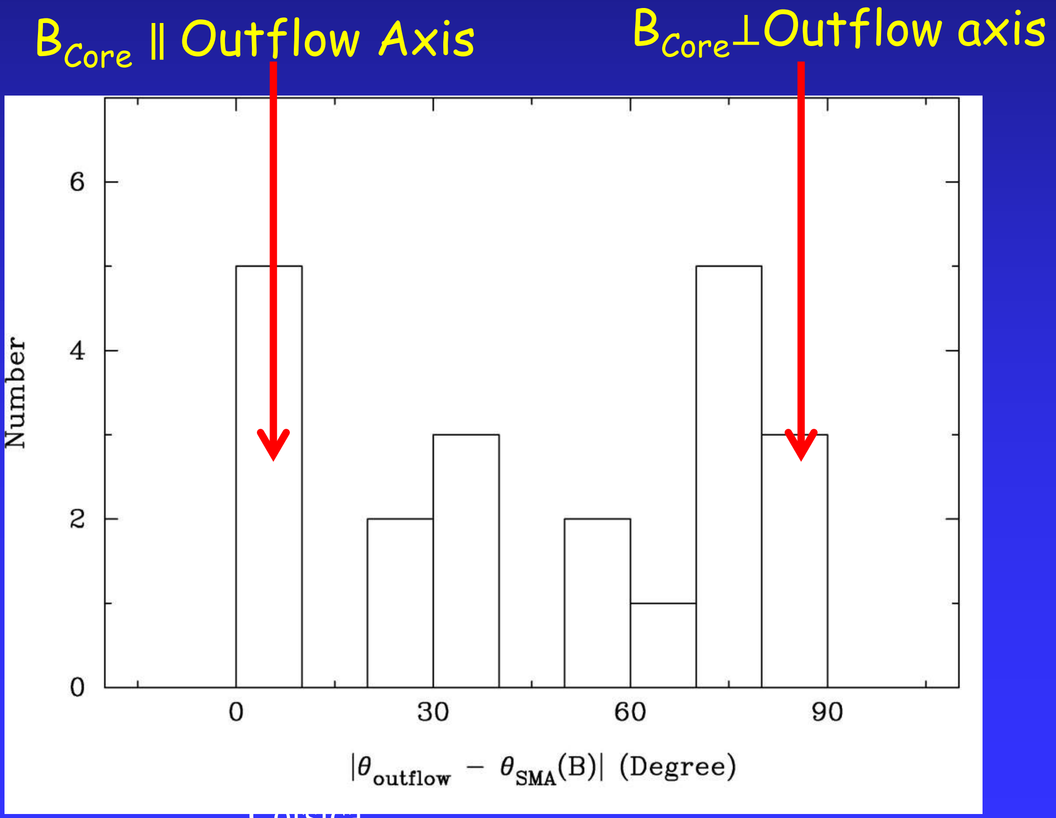
See also Nagai et al. 1998; Soler et al. 2013; van Loo et al. 2014

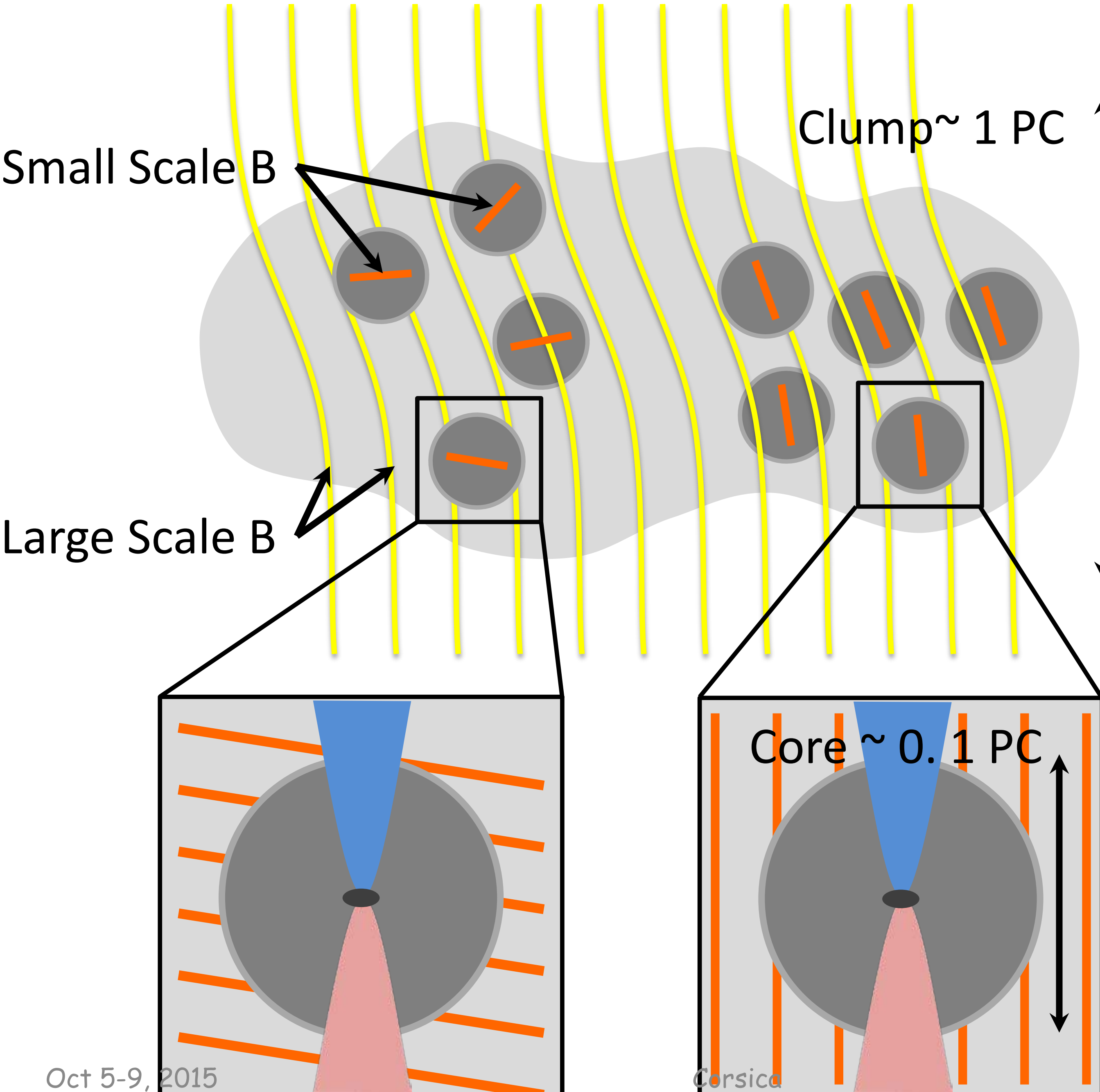
Why there is a peak at 90d?

- From the lower density gas draged along the large scale magnetic field lines ? (sample is too small to tell).
- Angular momentum (rotation) at core scales drags the field, rendering it perpendicular to the large scale field ? (There is a hint in the data, and should be investigated further)
- Sample studied is still small, the peak at 90d might be caused by few objects.

B field in cores versus outflows

- Small # of statistics, but there appears to be no preferred alignment → Angular momentum dominates B field at 10^3 AU scale ? Or gas and B decoupled in dense regions ?





B_{core} either parallel or perpendicular to B_{clump}

B_{core} does not correlate with outflow axis

Analysis Techniques → Field strength:

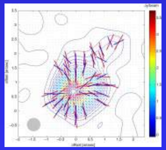
- Chandrasekhar-Fermi method (1953): MHD waves perturb the B field (assuming small perturbation, smooth large-scale field, but turbulence is supersonic and sometime super Alfvenic).

$$B_{pos} = \left(\frac{4}{3}\pi\rho\right)^{1/2} \frac{\sigma_{3D}}{\sigma(\phi)}$$

- The second–order structure function of the polarization angle (Falceta-Gonccalves et al. 2008; Hildebrand et al. 2009; Houde et al. 2009) (assuming smooth large scale field, turbulence not correlated at large scale).

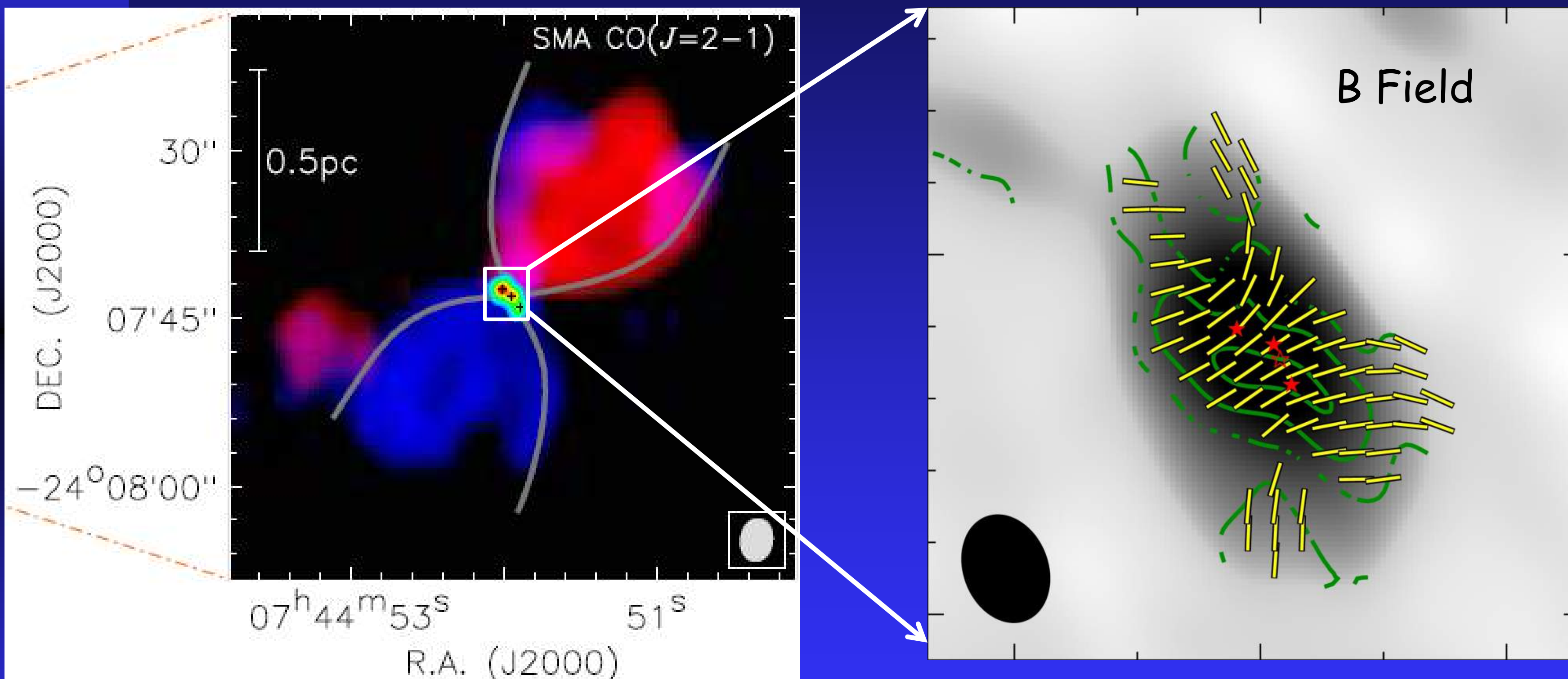
$$B_0 = (8\pi\rho)^{1/2} \frac{\sigma(v)}{b}$$

- Polarization – intensity gradient technique (Koch et al. 2012). (assuming force balance between gravity and magnetic field)



- Numerical MHD simulation including turbulence and B field → synthetic polarization maps to compare with observations (Ostriker 2001; Heitsch et al. 2001; Falceta-Gonçalves et al. 2008; Frau et al. 2011, Soler et al. 2013).

G240: Dust Polarization and Outflow



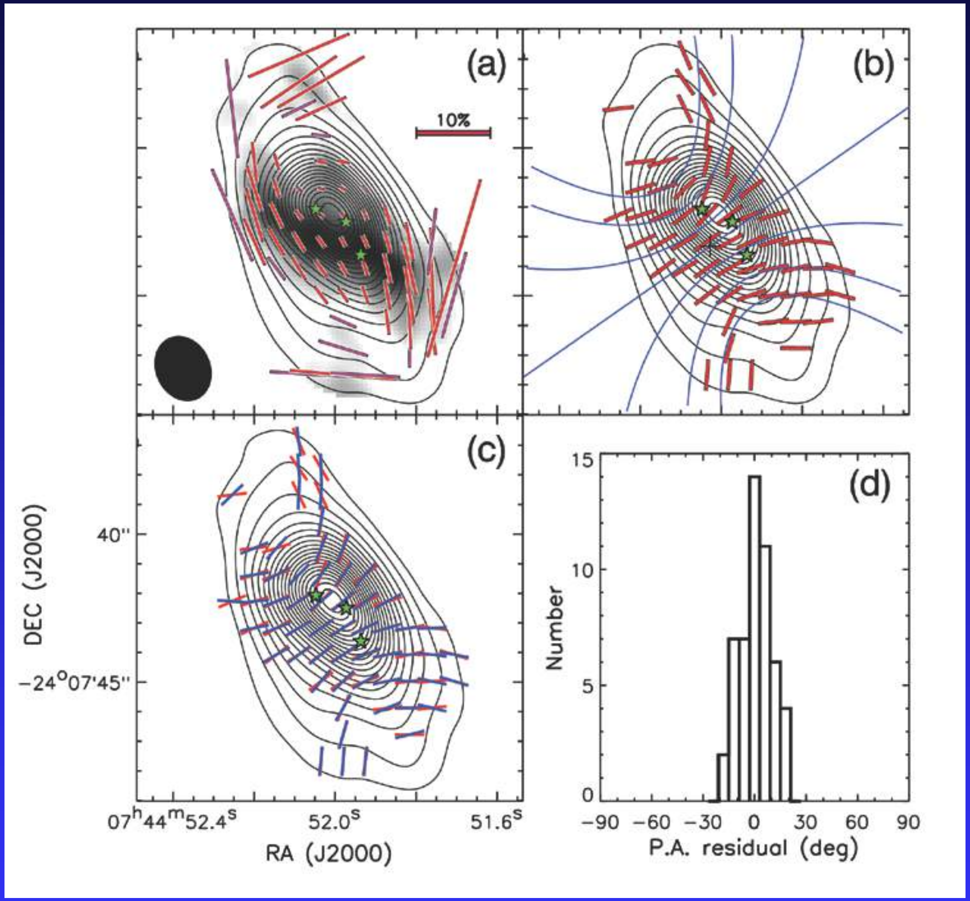
G240.31 ($10^{4.7}$ $L_\odot$)

Qiu et al. 2009, 2014

G240: Polarization Analysis

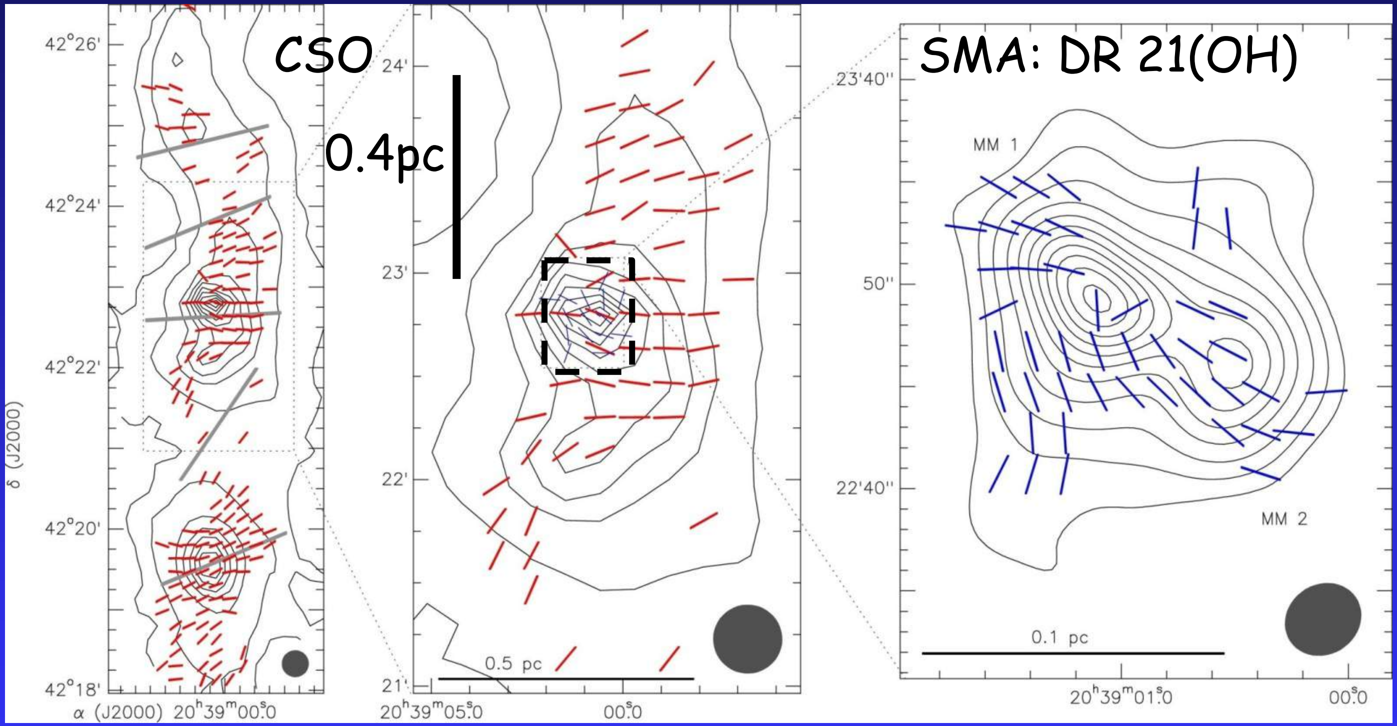
B = 1.2 mG
β = 0.4
M/Flux = 1.1

B= 1 – 10 mG for the SMA sample



Magnetic field strengths

0.8mm continuum B field direction



Bpos = 2.1 mG
Zeeman: Blos = 2-8 mG (based on Crutcher's talk)
Girart et al. 2013
Kirby et al. 2009

Clumps and Cores are Sub-Virial

Core	Offsets arcsec	v_{LSR} km s^{-1}	Δv[a] km s^{-1}	τ_{tot}[b]	R_{eff} parsec	M_{vir}[c] $M_\odot$	M_{dust}[c] $M_\odot$	α[d]	ρ[e] 10^5(cm^{-3})
				G29.96e					
P1	(6.0, 25.0)	103.67 (0.01)	0.94 (0.02)	2.40 (0.29)	0.24	44	25	0.2	1
P2	(0.0, 8.0)	103.17 (0.01)	1.41 (0.02)	3.81 (0.2)	0.219	91	116	0.1	4
P3	(23.0,-16.0)[1]	102.77 (0.02)	0.73 (0.03)	2.69 (0.59)	0.135	15	< 5	–	–
P4	(-2.0,-33.0)[1]	102.87 (0.03)	1.11 (0.04)	5.78 (0.78)	0.145	37	<	–	–
P5	(10.0,-18.0)[1]	101.57 (0.01)	0.72 (0.02)	3.26 (0.48)	0.127	12	< 7	–	–
P6	(16.0,-11.0)[1]	102.47 (0.01)	0.68 (0.03)	1.5 (0.52)	0.117	11	< 7	–	–
P7	(-1.0,-26.0)[1]	103.27 (0.02)	0.98 (0.04)	7.48 (0.9)	0.125	25	< 7	–	–
P8	(3.0,-13.0)	103.37 (0.03)	1.22 (0.04)	5.0 (0.56)	0.074	23	13	0.2	11
P9	(3.0, 6.0)	103.17 (0.01)	1.42 (0.02)	3.74 (0.2)	0.19	80	98	0.1	5
P10	(-6.0, -4.0)	102.37 (0.27)	0.8 (0.91)	0.95 (0.1)	0.154	21	28	0.1	3
P11	(-15.0, 28.0)[3]	101.87 (0.03)	0.69 (0.05)	7.29 (1.95)	–	–	<	–	–
				G35.20w					
		km s^{-1}	km s^{-1}		parsec	$M_\odot$	$M_\odot$		10^5(cm^{-3})
P1	(-13.0, -5.0)	41.70 (0.01)	0.71 (0.01)	3.58 (0.22)	0.118	13	12	0.1	0.3
P2	(-3.0, 4.0)[2]	41.40 (0.02)	0.98 (0.05)	2.76 (0.23)	0.067	–	16	–	2
		42.60 (0.02)	0.74 (0.03)	3.82 (0.32)	0.067	–	15	–	2
P3	(-5.0, 7.0)[2]	41.70 (0.04)	1.56 (0.08)	3.56 (0.29)	0.065	–	11	–	1
		42.70 (0.01)	0.68 (0.02)	3.59 (0.33)	0.065	–	10	–	1
P4	(-8.0, 5.0)	42.00 (0.01)	1.22 (0.02)	3.98 (0.26)	0.043	13	46	0.3	2
P5	(7.0, 4.0)	42.00 (0.02)	1.37 (0.03)	2.56 (0.33)	0.056	22	18	0.1	4
P6	(13.0, -1.0)	42.70 (0.03)	1.69 (0.06)	2.89 (0.41)	0.049	29	14	0.2	4
P7	(8.0, 0.0)	42.40 (0.02)	1.33 (0.04)	3.14 (0.35)	0.058	21	25	0.1	4
P8	(-21.0, 1.0)[3]	42.40 (0.01)	0.5 (0.03)	5.56 (1.01)	–	–	< 2	–	–
P9	(11.0, -6.0)	43.70 (0.02)	0.9 (0.04)	1.6 (0.53)	0.036	6	54	0.1	4
P10	(-15.0, 10.0)[4]	42.20 (0.27)	1.25 (0.91)	0.98 (0.1)	–	–	< 1	–	–
P11	(-15.0, 13.0)	42.00 (0.02)	0.6 (0.04)	2.97 (0.78)	0.023	2	19	0.1	5
P12	(6.0, -1.0)[4]	42.50 (0.02)	1.01 (0.03)	3.32 (0.43)	–	–	95	–	–
P13	(-20.0, 17.0)[5]	42.30 (0.02)	0.54 (0.05)	1.83 (1.18)	–	–	<	–	–

$$\alpha = \frac{M_{vir}}{M} = \frac{5\sigma^2 R}{GM}$$

Pillai et al. 2011

See also Csengeri et al. 2011, Tan et al. 2013

Does magnetic field play a role in supporting ? Need B < 1 mG

B is sufficient based on observations

Conclusions and Future Prospect

- Recent polarization data of statistically significant samples found magnetic fields are correlated in scales from clumps (1pc) → cores (0.01-0.1pc).
- Magnetic fields appear to be either parallel or perpendicular to filaments/striations.
- Statistical analysis to 1 - 10 mG in clumps and cores.
- These findings indicate magnetic fields are dynamically important at these scales and play a dynamically important role in massive star formation.
- Magnetic fields in dense cores do not correlate with outflow axis, suggesting that in (peudo)disk scales, angular momentum dominates over magnetic fields.

Remaining Issues

- Despite unprecedented effort (e.g. CARMA/SMA), the sample is still relatively small and biased (how to account for non detections)
- While submm interferometers promise more 1” resolution polarzation data, there is a lack of polarization instruments with <30” resolution (pc scale for clumps at a few kpc).
- How does feedback affect magnetic fields ?