Observing Magnetic Field In Molecular Clouds

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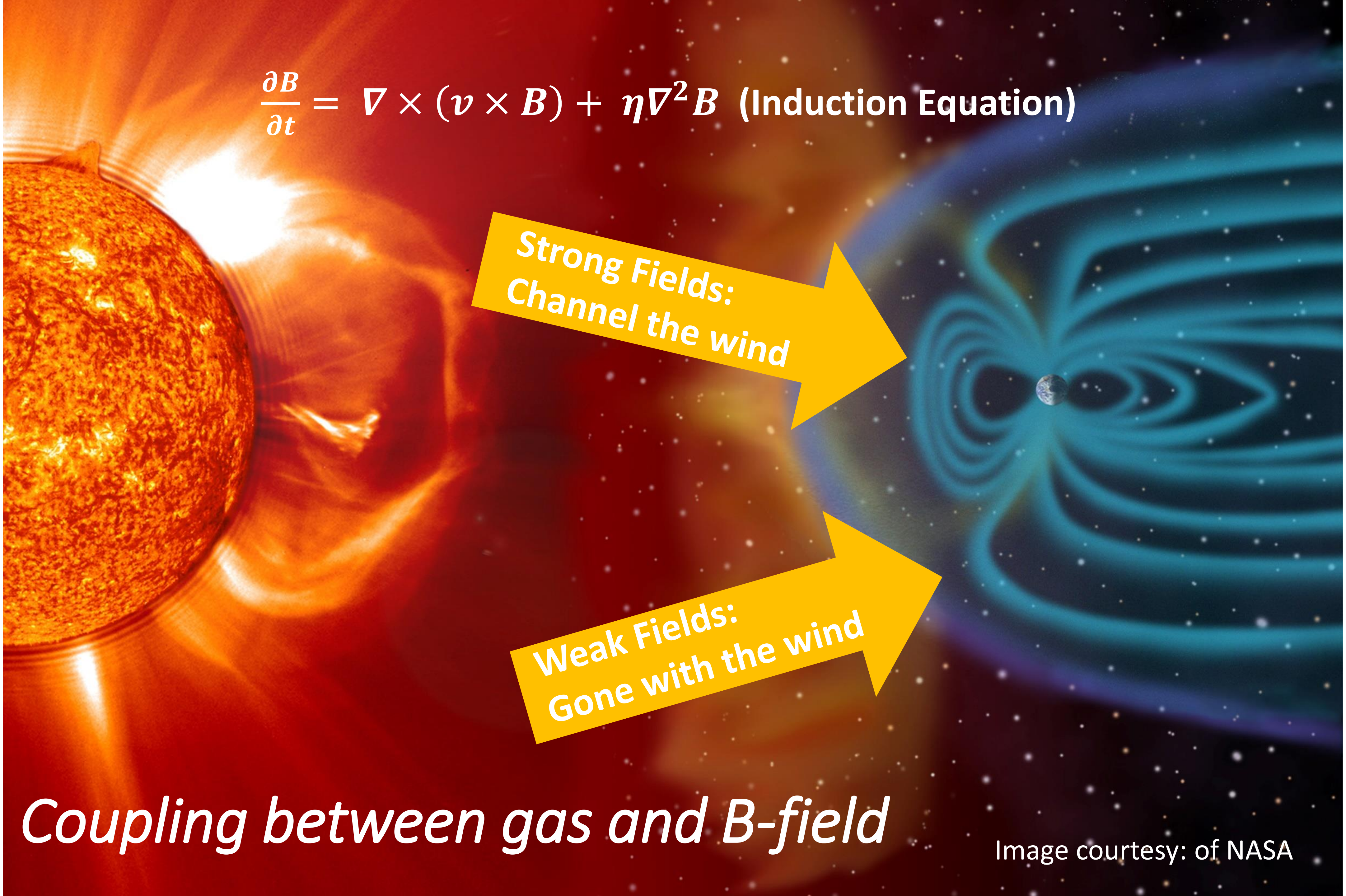
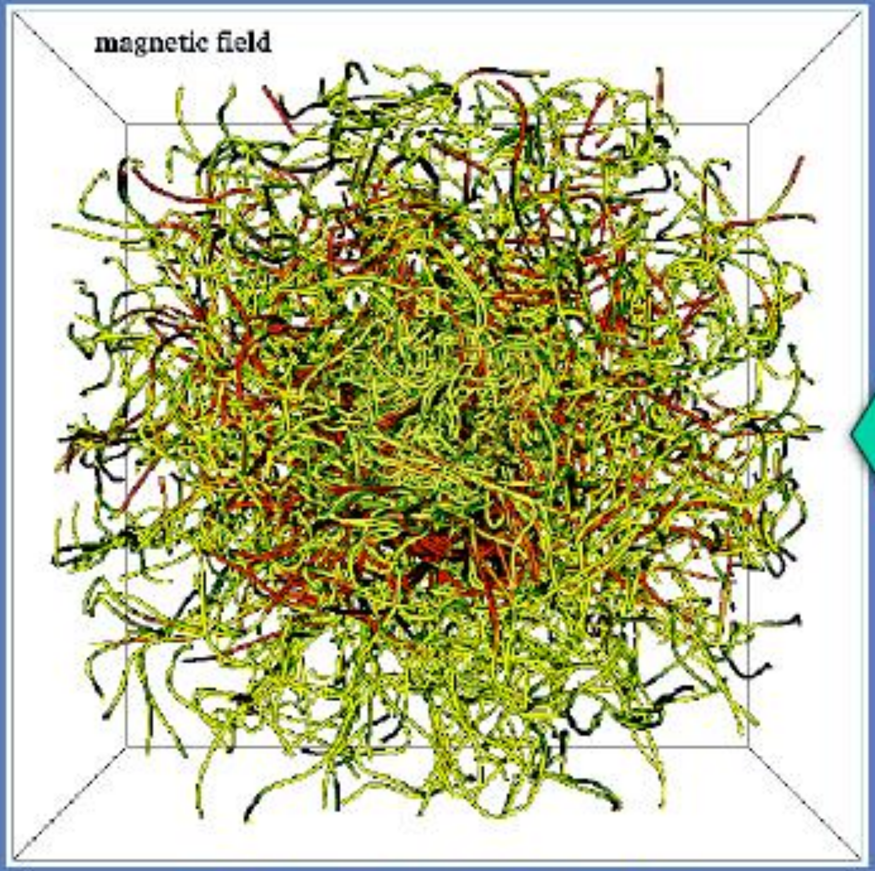
$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) + \eta \nabla^2 B \quad \text{(Induction Equation)}$$



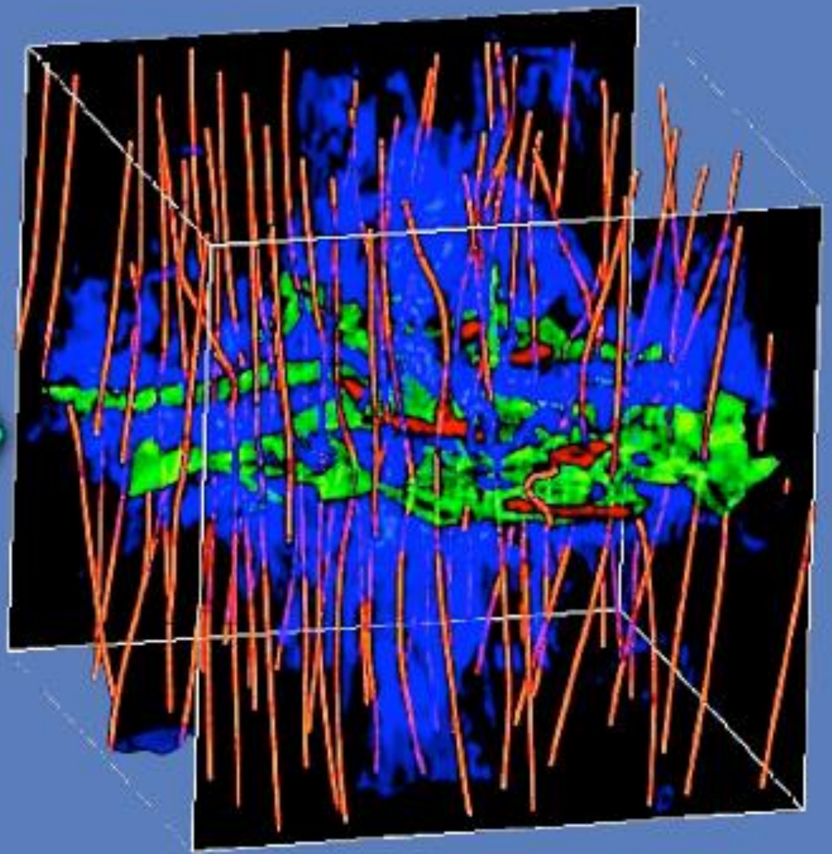
Coupling between gas and B-field

Image courtesy: of NASA

***turbulence* > the B-field** turbulence < *the B-field*



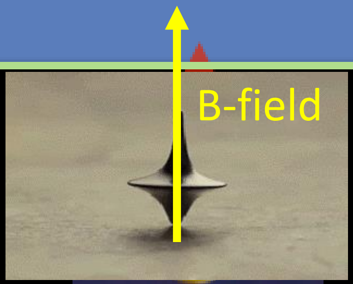
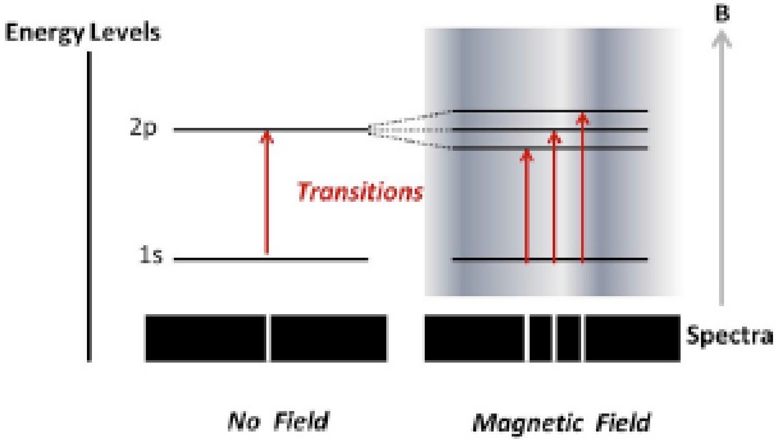
Federrath+, *ApJ* 2011



Nakamura & Li, *ApJ* 2008

Coupling between gas and B-field

$$M_A = \frac{\sigma}{V_A}$$

Observation tools	how to observe	results	note
 **Dust grain alignment**: a grain spins along the short axis, which precesses around B fields	*polarization* of dust thermal emission	⊥B	$A_v > 100$ mag
	polarization of background star light	// B	$A_v < 5$ mag
Zeeman effect 	freq. splitting of *circular* line polarization	B_{los}	difficult due to small B
	linear line polarization	⊥ or // B	Goldreich-Kylafis effect

FIRST MULTISCALE STUDY of CLOUD MAGNETIC FIELDS from 10^2 to 10^{-2} pc

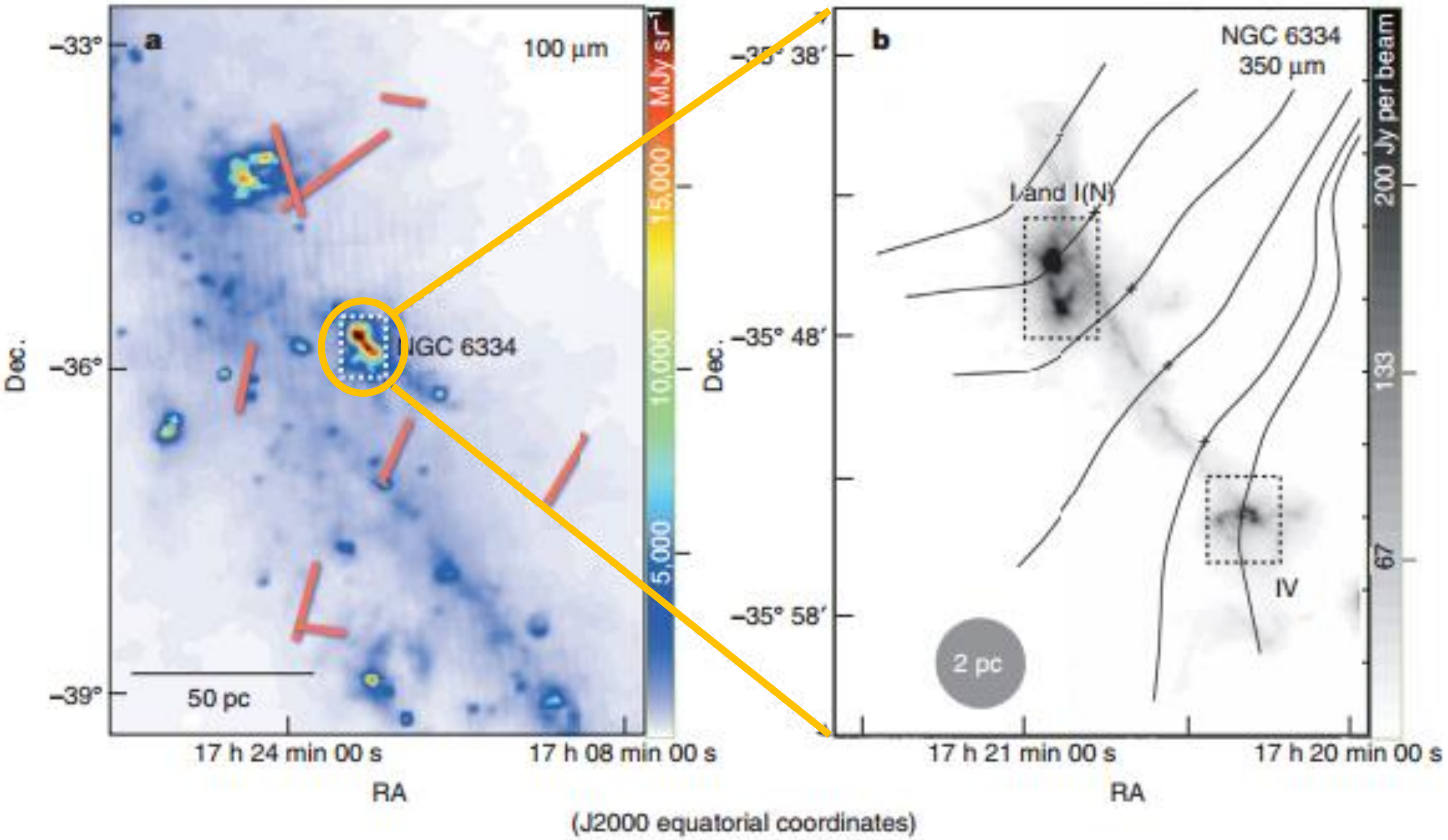
mage credit: S. Willis (CfA+ISU); ESA/Herschel; NASA/JPL-Caltech/ Spitzer; CTIO/NOAO/AURA/NSF

- One of the nearest massive star forming region (~1.7 kpc away)
- Other sites forming massive stars are usually too far away to use starlight polarization
- Combine optical/sub-mm polarization data and try to understand the role of B-field

Li, Yuen, Otto, Leung+, ***Nature, 2015***

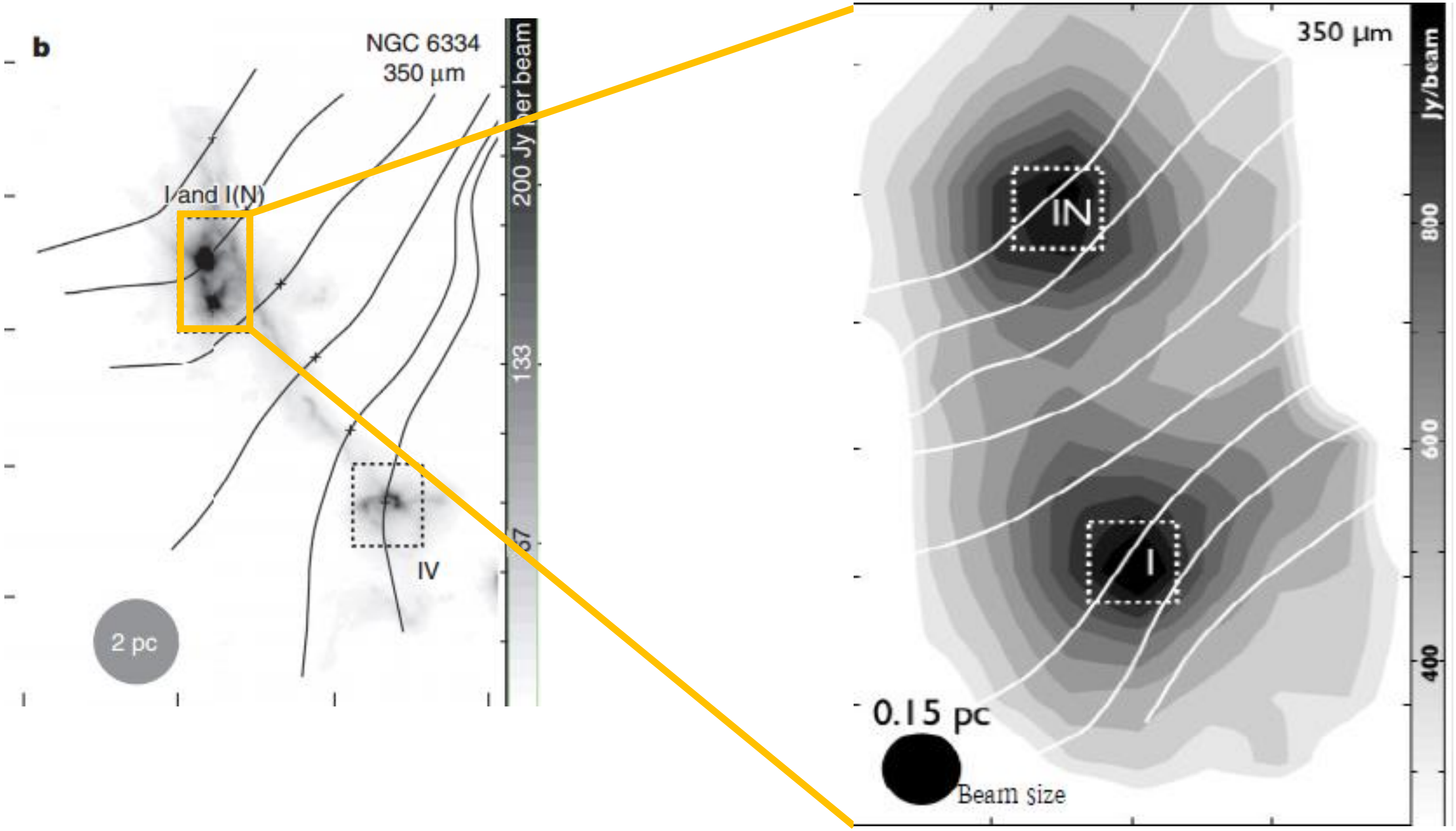
Multiscale Study of B-field in NGC6334: From 100pc to 10pc scale

- Intercloud medium (ICM)
  - Optical Polarimetry (Heiles 2000)
  - IRAS 100- μm map
- **Zooming in to the cloud**
  - **SPARO 450-μm polarimetry**
  - **CSO 350-μm map**
- **The cloud preserve the initial B-field direction**
- **Pinching of field lines at density peaks**



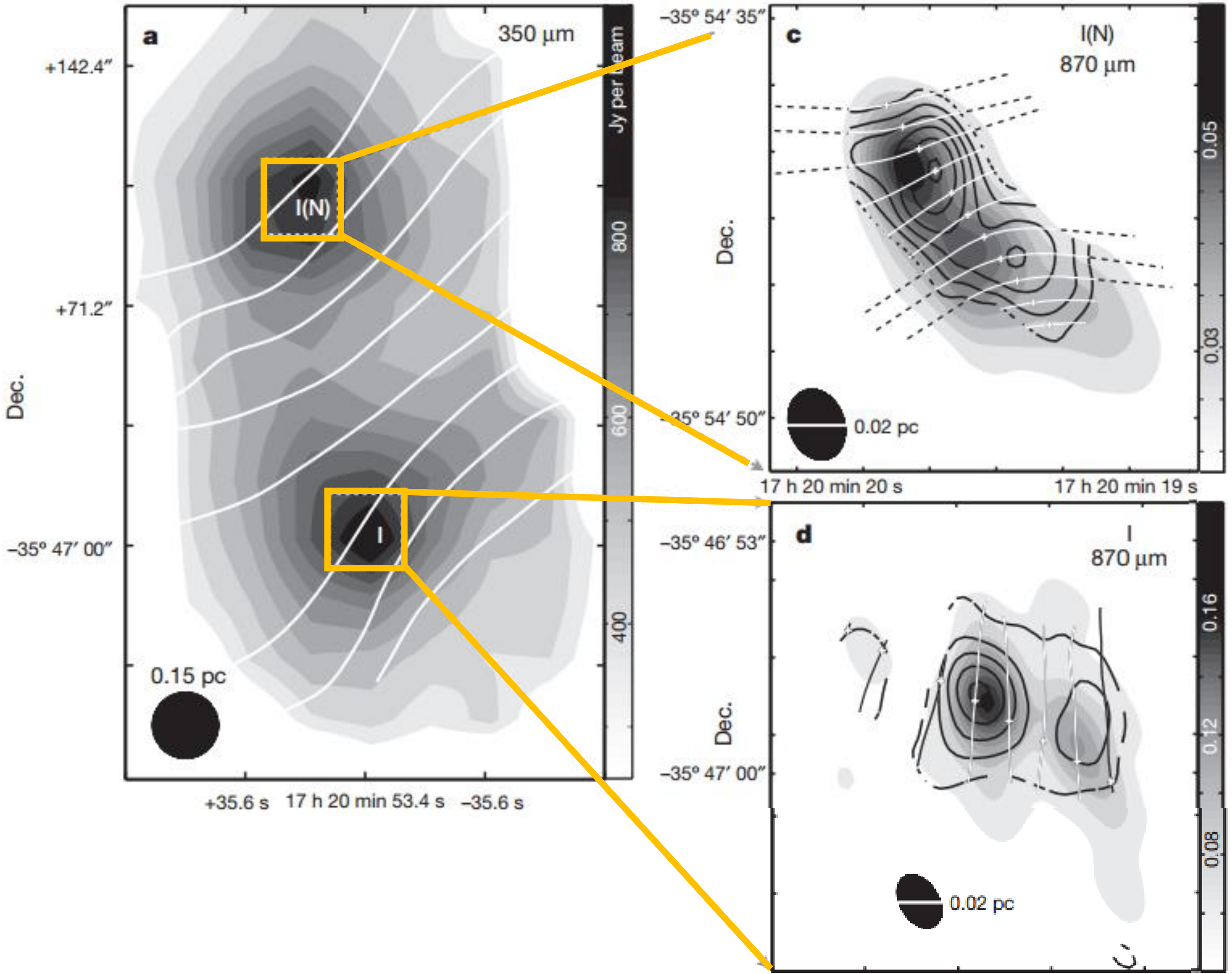
Multiscale Study of B-field in NGC6334: From 10pc to 1pc scale

- Cloud scale
  - SPARO 450-µm polarimetry
  - CSO 350-µm map
- **Zooming into the clump scale**
  - **CSO 350-µm polarimetry & map (Dotson et al. 20)**
- **The cloud preserve the initial B-field direction**
- **Pinching of field lines at density peaks**

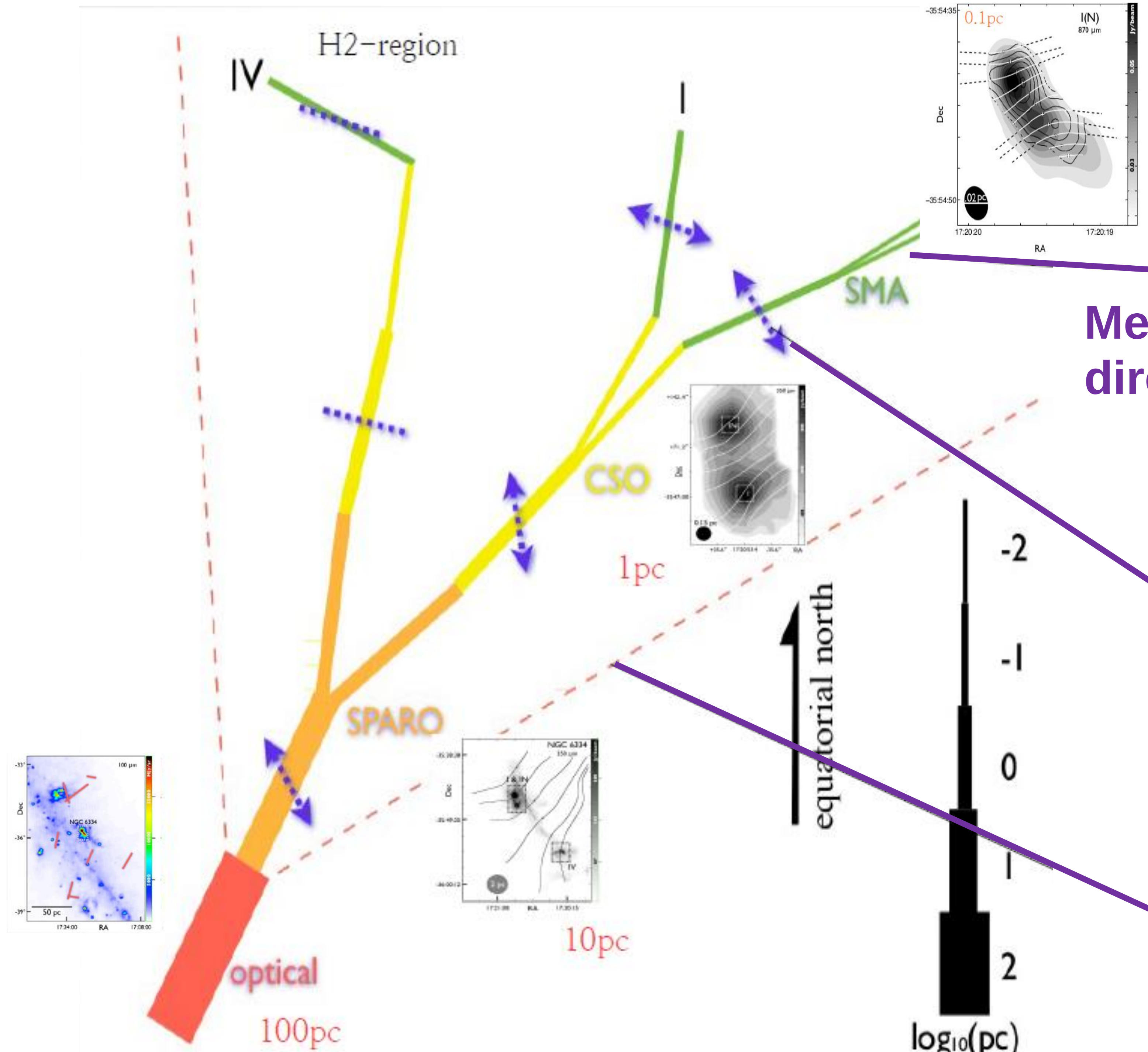


Multiscale Study of B-field in NGC6334: From 1pc to 0.1pc scale

- Clump scale
  - CSO 350-µm polarization & intensity map
- **Zooming into the core scale**
  - **SMA 870-µm polarization & intensity map**
- **The cloud preserve the initial B-field direction**
- **Pinching of field lines at density peaks**



Sub-Alfvenic Turbulence?



Mean magnetic field direction in respective cores

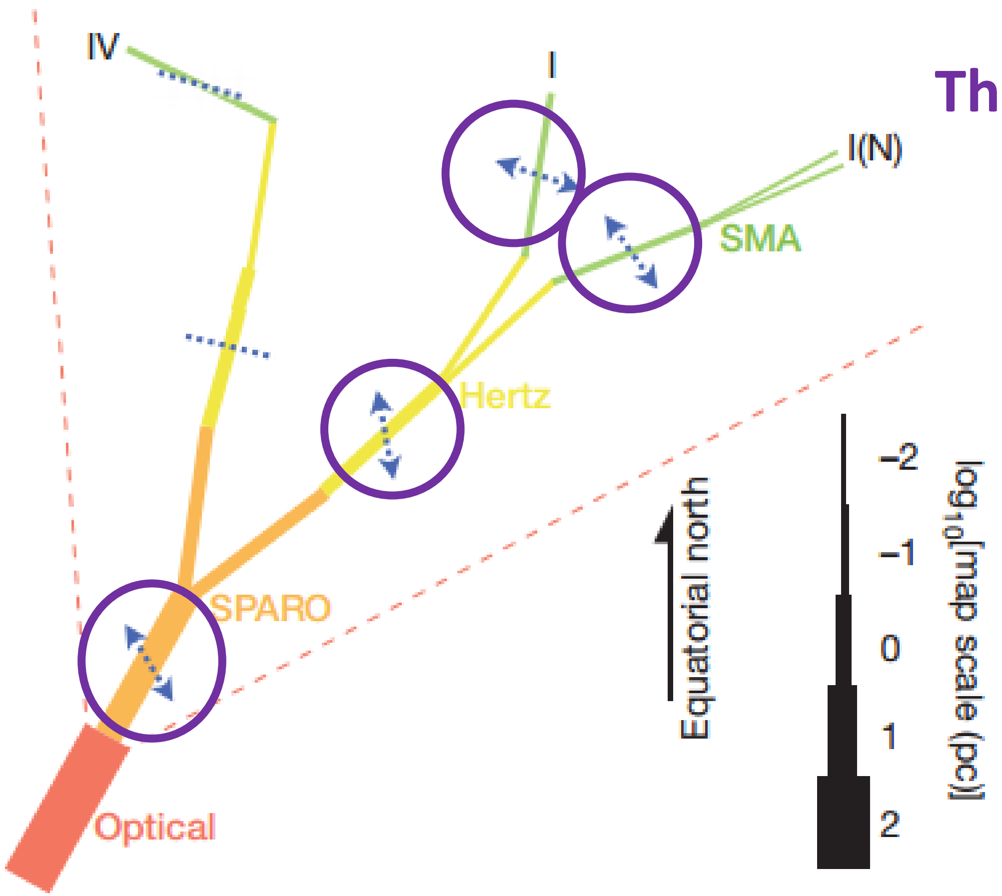
Orientation of the cloud

- **Its relation with B-field**

Opening Angle of 30°

- **Competition between B-field & turbulence**

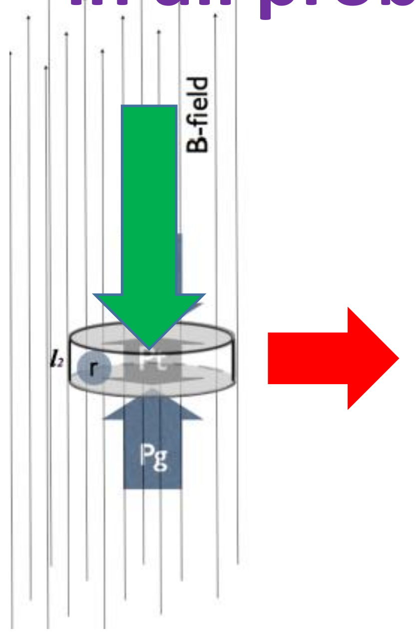
Sub-Alfvenic Turbulence!



Observation I:

The cloud orientation are preferentially aligned perpendicular to the mean B-field

in all probed scales



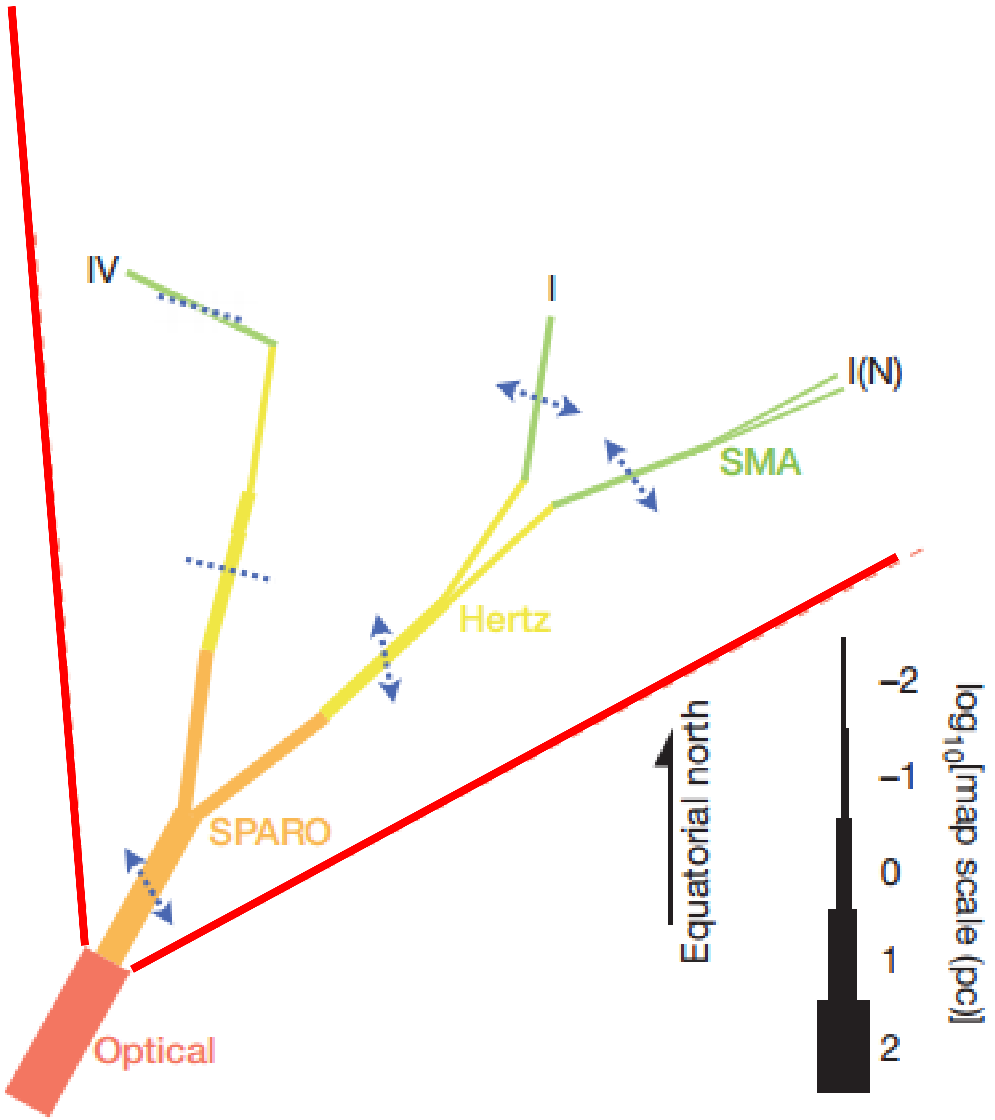
Li et al. 2013

Lorentz Force keeps the gas from collapsing ⊥ to B-field

Channel of matter along the field Lines

competition between gravity and turbulence in a medium dominated by B fields

Sub-Alfvenic Turbulence!



Observation II

All the field orientations in Fig. 3 are within this 30°

Assume turbulence is:

- The Only force that drives the B-field
- Carrying the same energy as the B-fields

$$\Delta\phi \sim 30^\circ$$

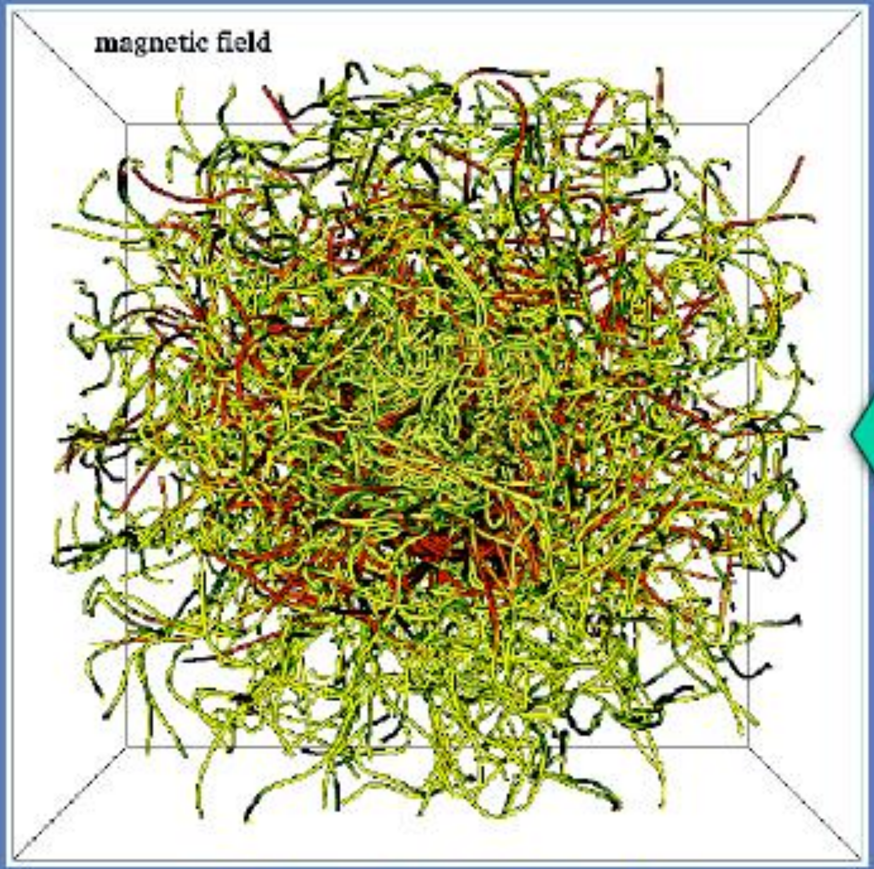
Chandrasekhar Fermi method (1953)

$$B_\perp = (4\pi\rho)^{1/2}\frac{\Delta V}{\Delta\phi}$$

$$\Delta\phi < 30^\circ$$

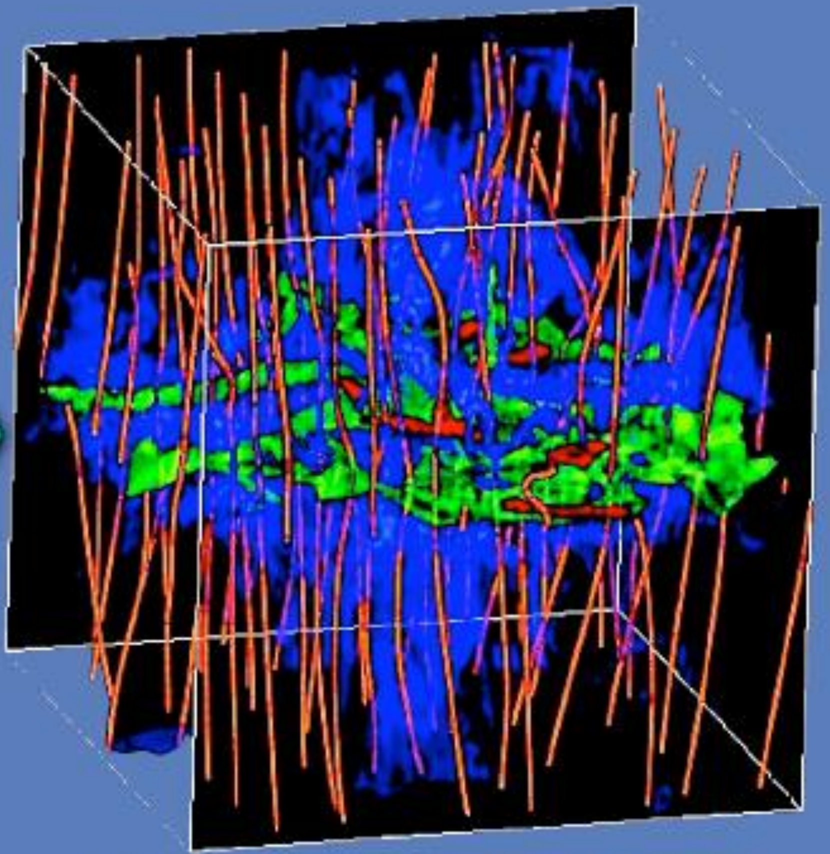
Turbulence is sub-alfvenic !!

turbulence > the B-field turbulence < ***the B-field***



Federrath+, *ApJ* 2011

or

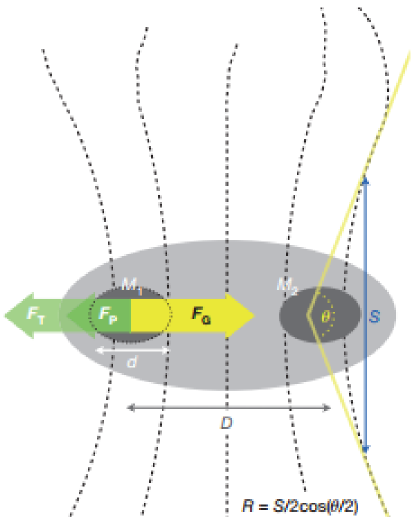


Nakamura & Li, *ApJ* 2008

Coupling between gas and B-field

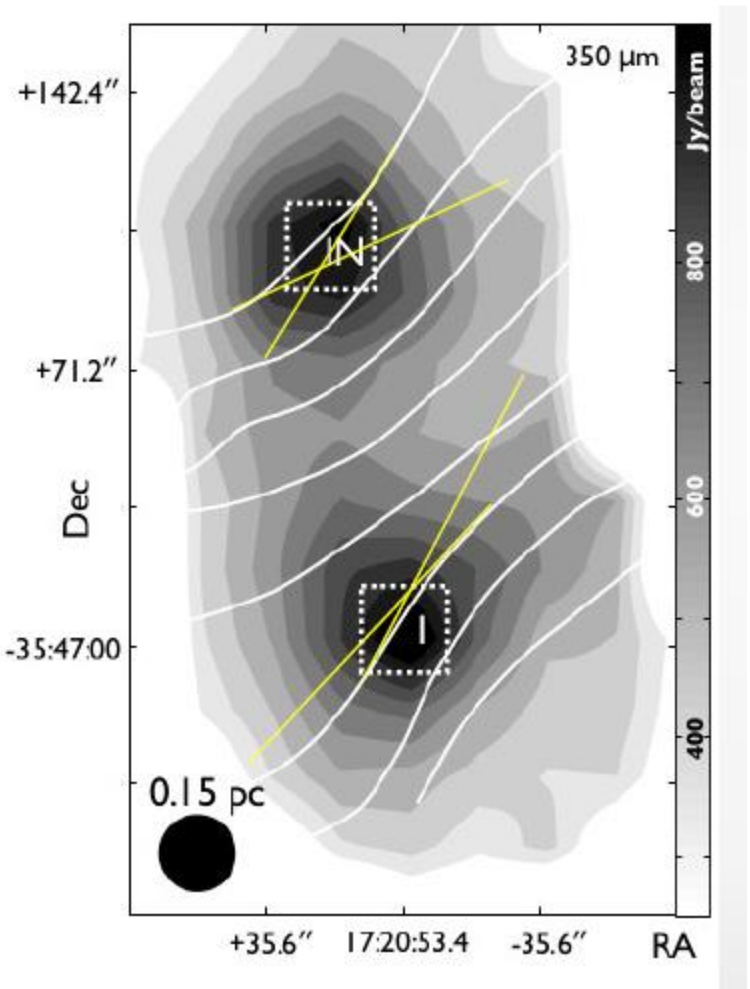
$$M_A = \frac{\sigma}{V_A}$$

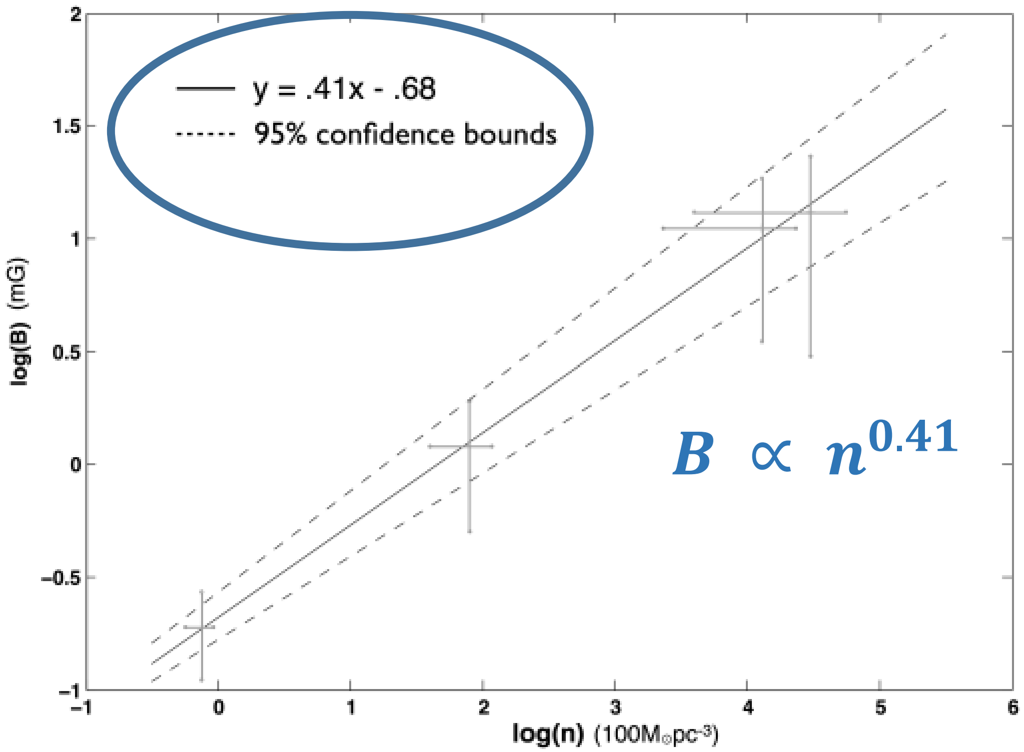
Estimating the B-n relation



Applying force balance

$$F_G = F_P + F_T$$





$$B \propto n^{0.41}$$

If B-field is dynamically **unimportant:**

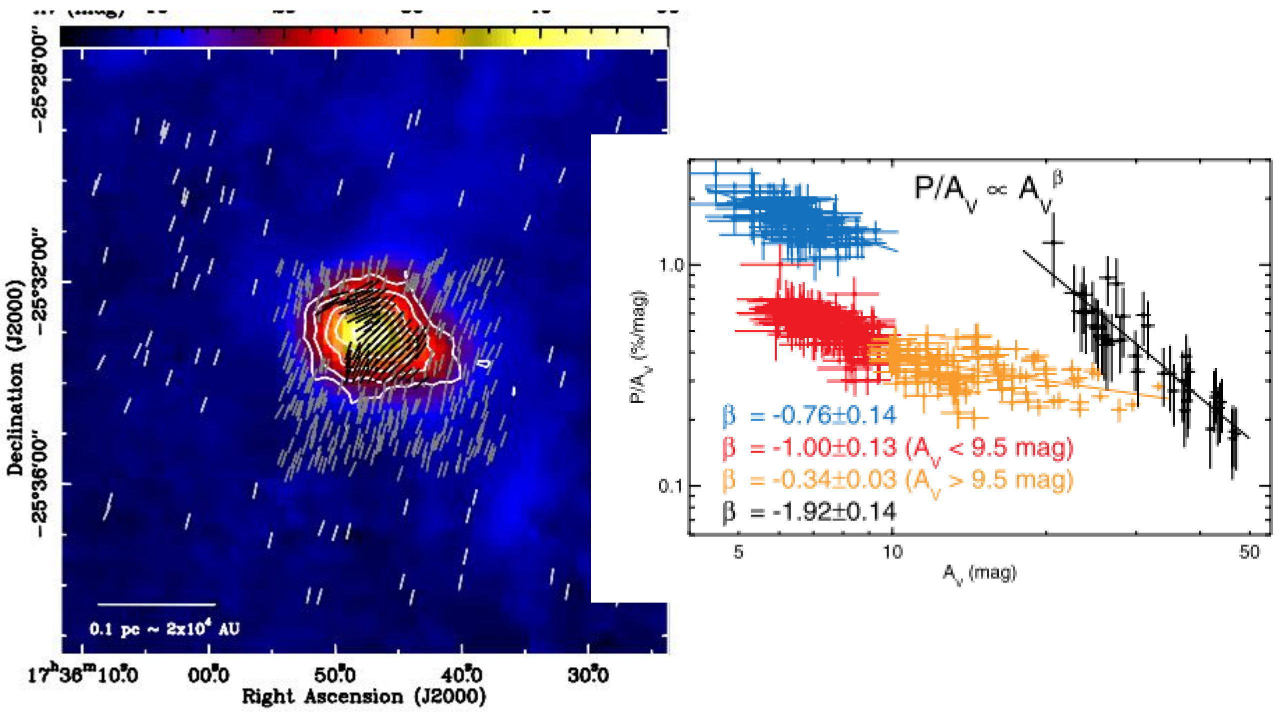
$$B \propto n^{\frac{2}{3}}$$

Some might say:
Are you really tracing the B-field?

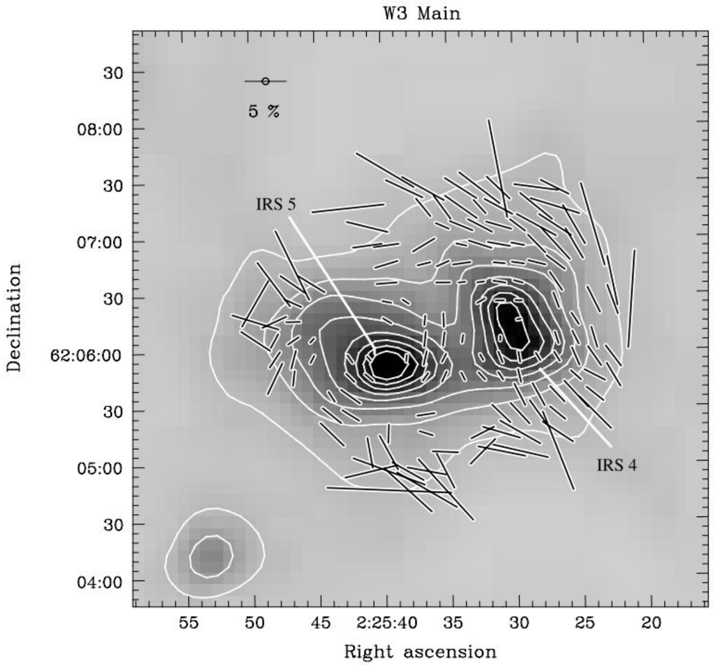
Polarization Hole?

Polarization Fraction decreases with increasing density

It is often seen from dark clouds to active star forming region

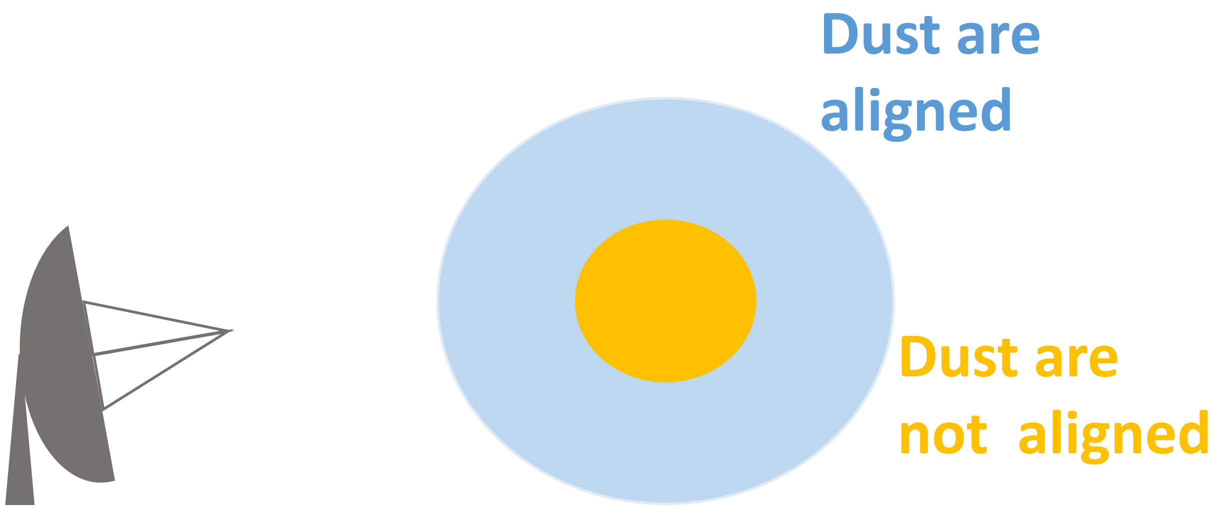


Alves et al. 2014
Starless core in pipe nebula

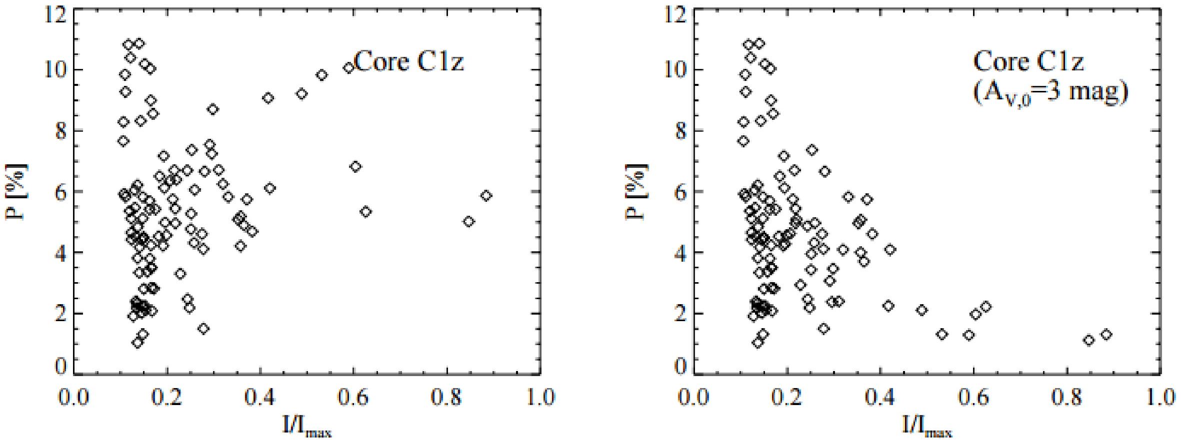


Matthews et al. 2009
W3 main
massive star-forming complex

Explanation given to understand P.Hole:
1. Low grain alignment efficiency in high density



MHD Simulation:
Super-Alfvenic and Supersonic



e.g. high density / temperatures toward the core:
→ higher collision rate
→ misalignment of dust grains
→ Growth of rounder grains ?!
→ Lack of radiation to align dust grains?

<u>Padoan et al. 2001:</u>

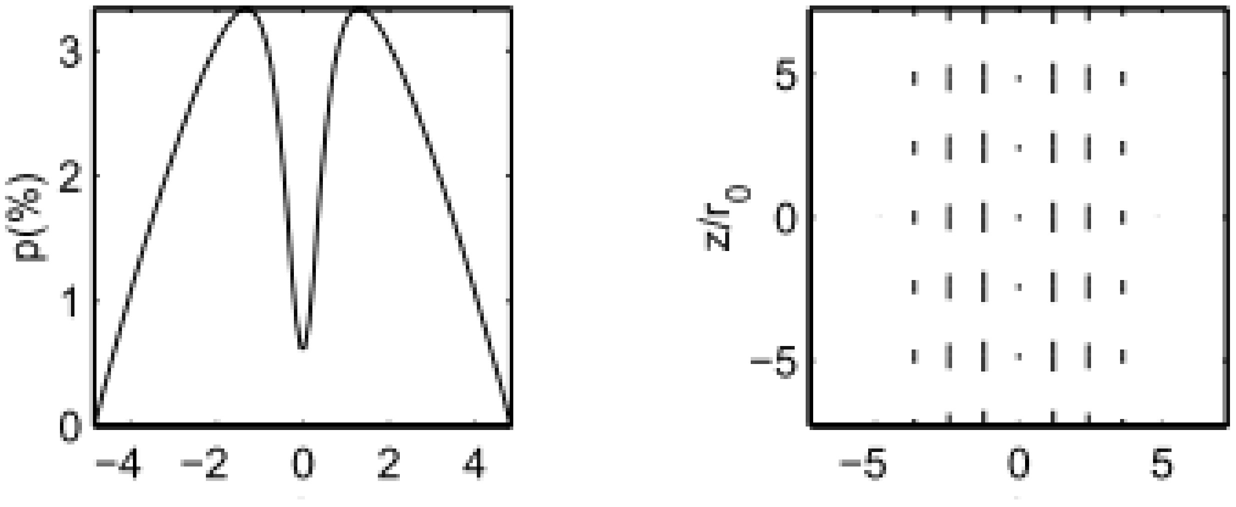
Dust grains are no longer aligned with magnetic field at some particular density: Av > 3 mag

Explanation given to understand P.Hole
2. Geometrical Effect of magnetic field

Cloud Scale

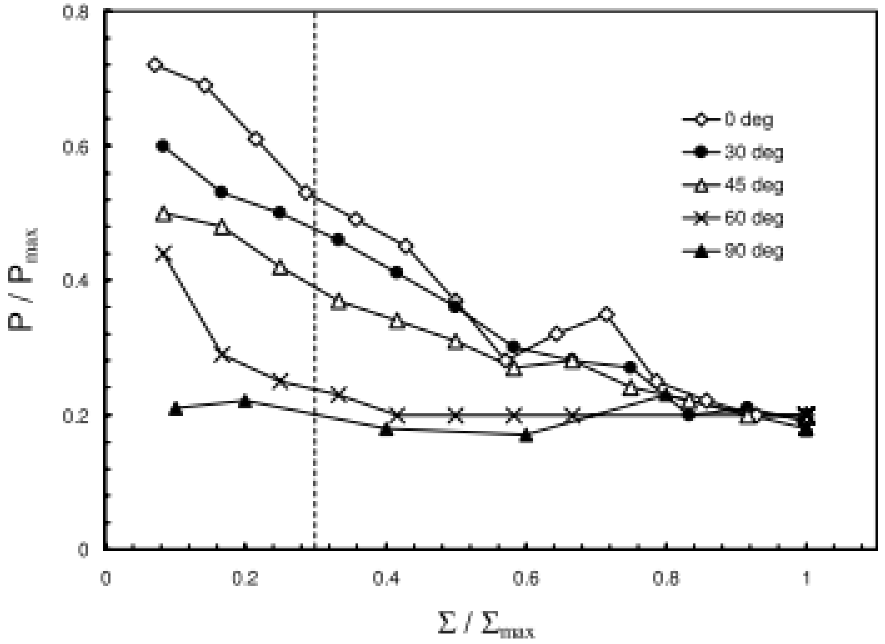
Fiege & Pudritz 2000

Model the polarization pattern
For filamentary cloud threaded by
Helical magnetic field



Goncalves et al. 2008

Simulate polarization map
from supersonic/sub-alfvenic simulation



Explanation given to understand P.Hole
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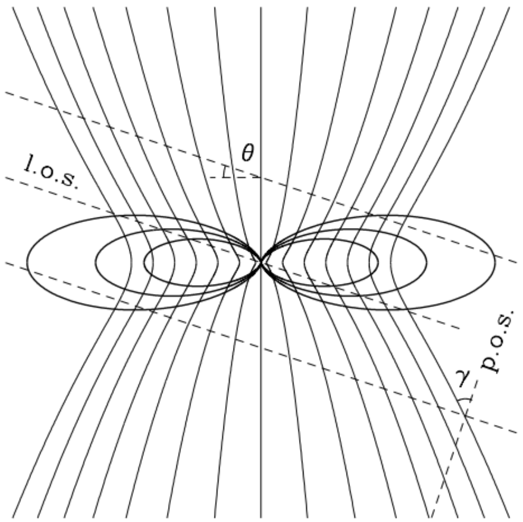
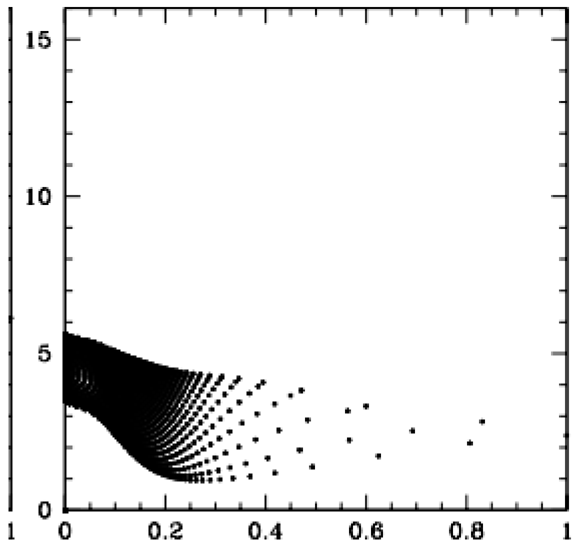
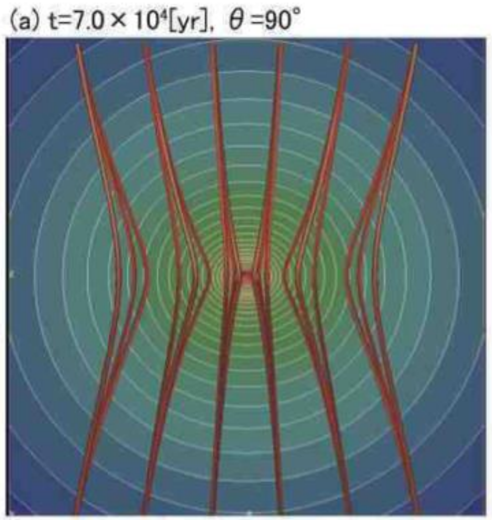
Core Scale

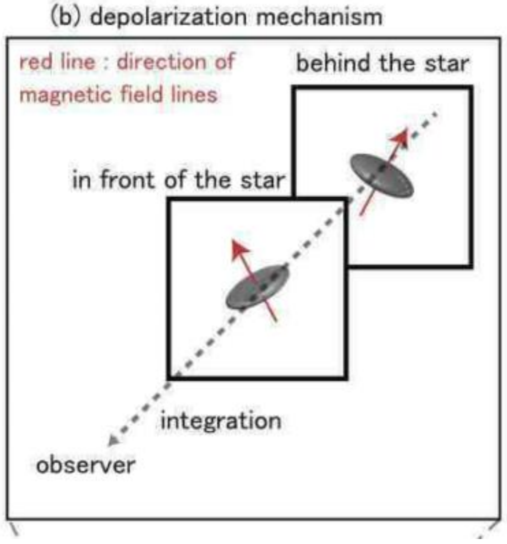
0.2 pc   Gonçalves et al. 2005





6000 AU   Kataoka et al. 2012





Bending of magnetic field lines
that counteract the inward pull of gravity

When B-field lies closer to the line of sight,
Lower degree of polarization should be observed

Insights from archival data?

1. Zoom into the polarization holes
2. Synthesize the beam of single dish telescope
3. Implication of this study

Sub-mm Polarization Data

Interferometer

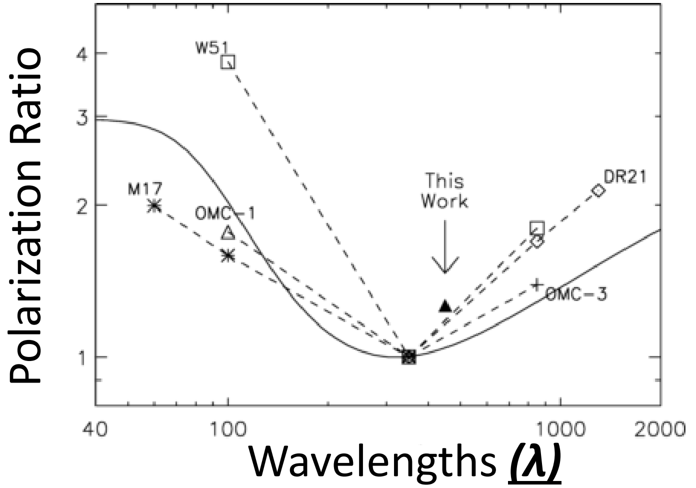
- CARMA
- ~ 2.5 " resolution
- Capable of resolving cores/discs
- TADPOL *1330um* survey (Hull et al. 2014)

Single Dish Telescope

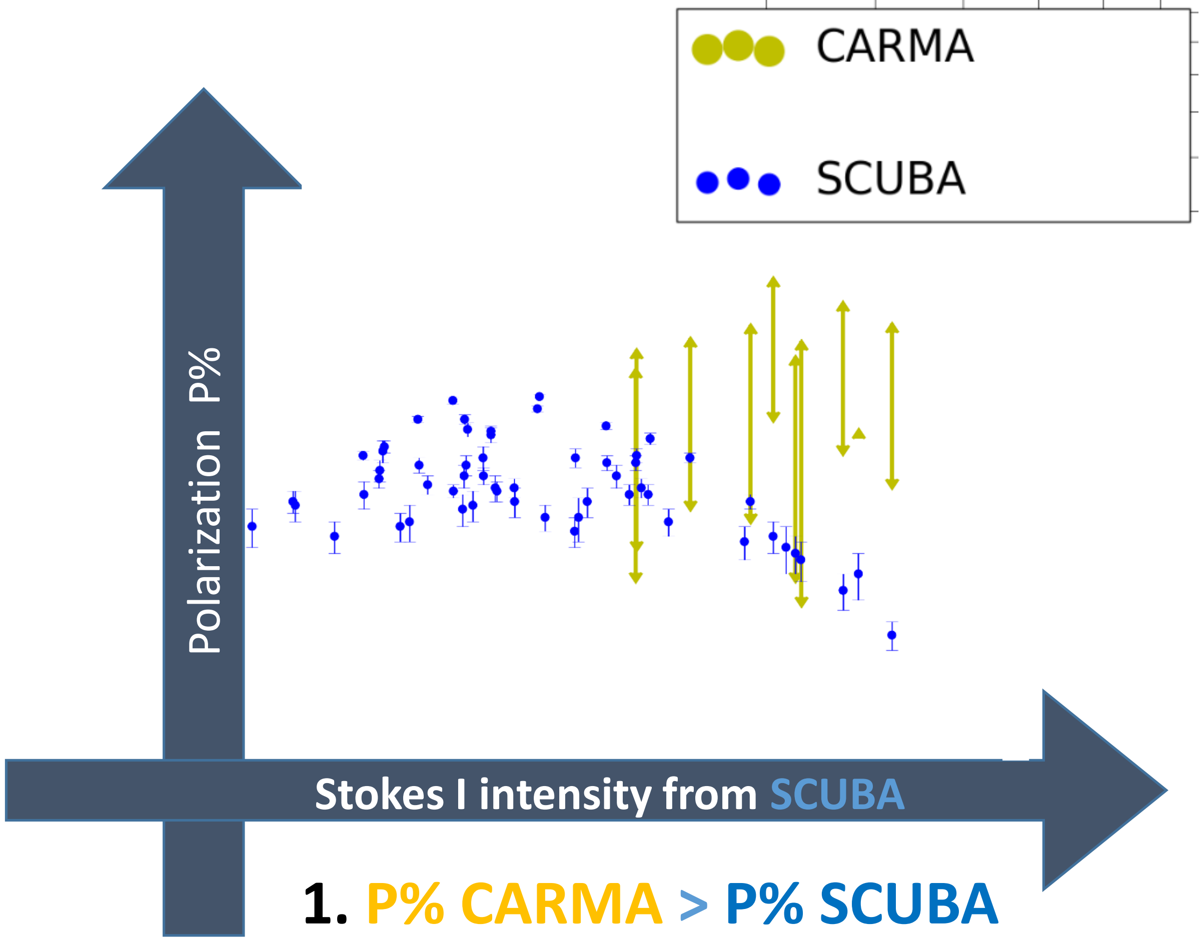
- JCMT
- ~ 20" resolution
- Field morphology of clumps
- SCUPOL *850um* legacy survey (Matthews et al. 2009)

Calibration on wavelengths for Polarization Fraction:

- ***Polarization Ratio (λ) compiled from 17 clouds***
- ***Vailliancourt et al. 2008***
- ***P(850um) / P(1330um) ~ 1.7/2.1***



Observation I:
Degree of Polarization is HIGHER in the core?!



1. P% CARMA > P% SCUBA in the same telescope pointing!
2. Detection at High density

Observation I:
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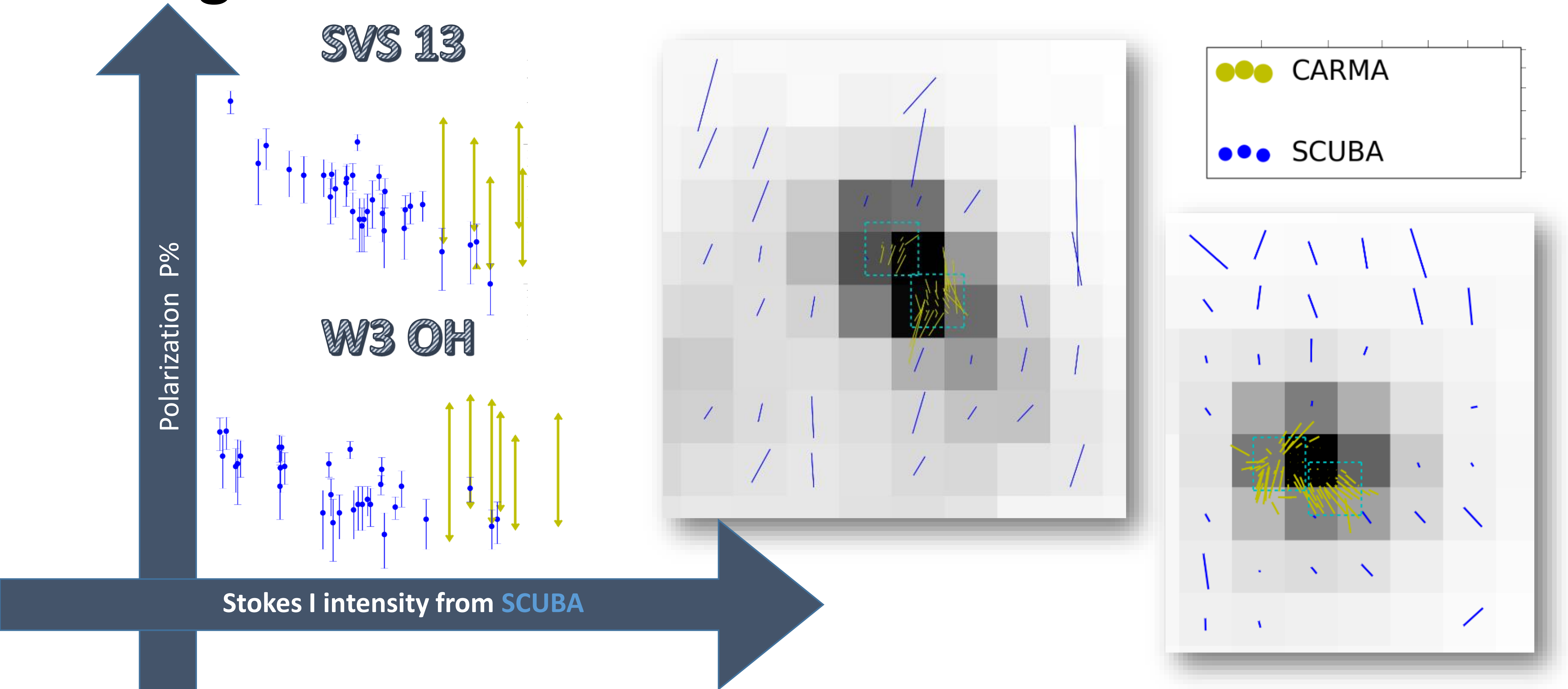

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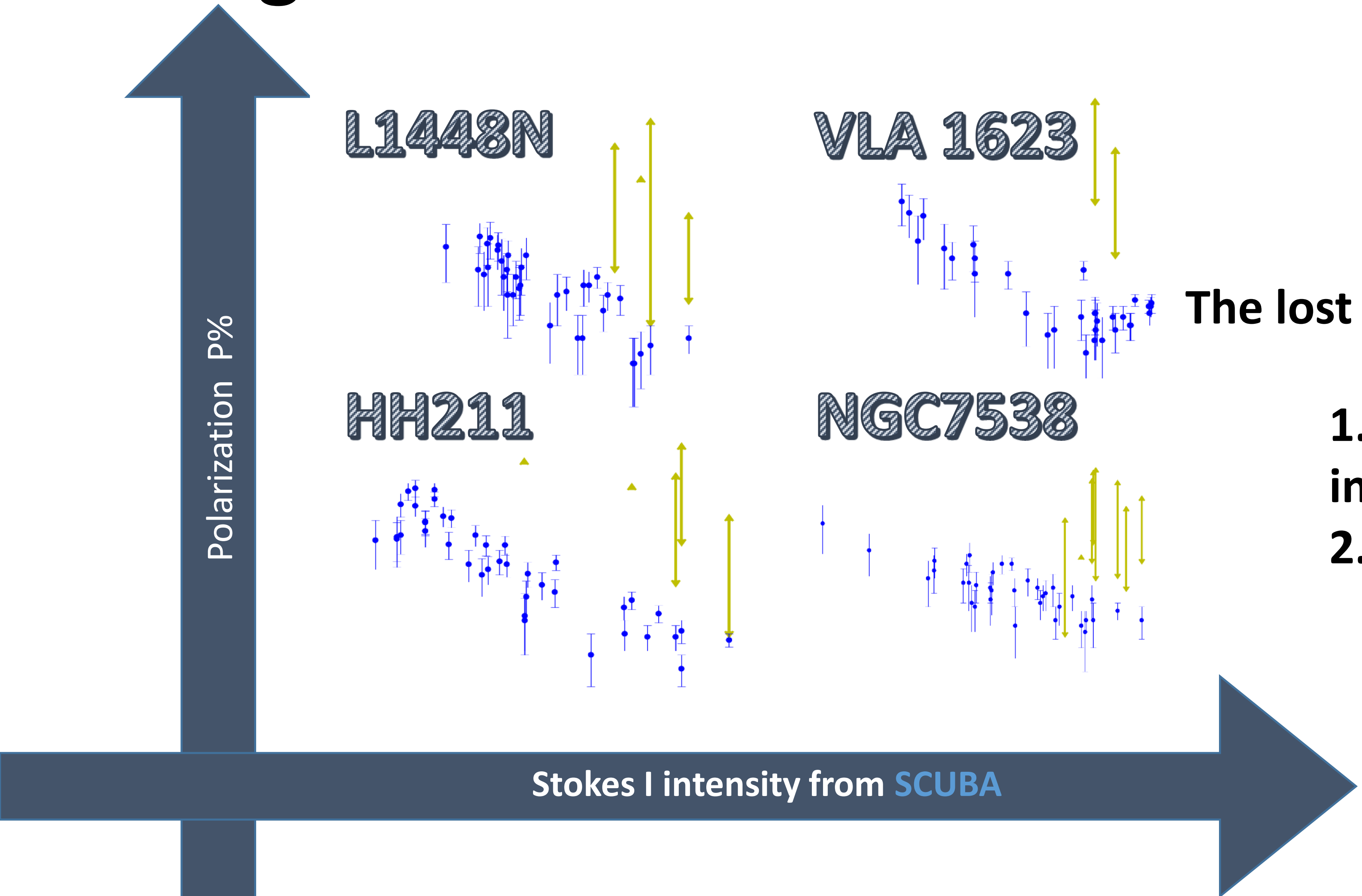
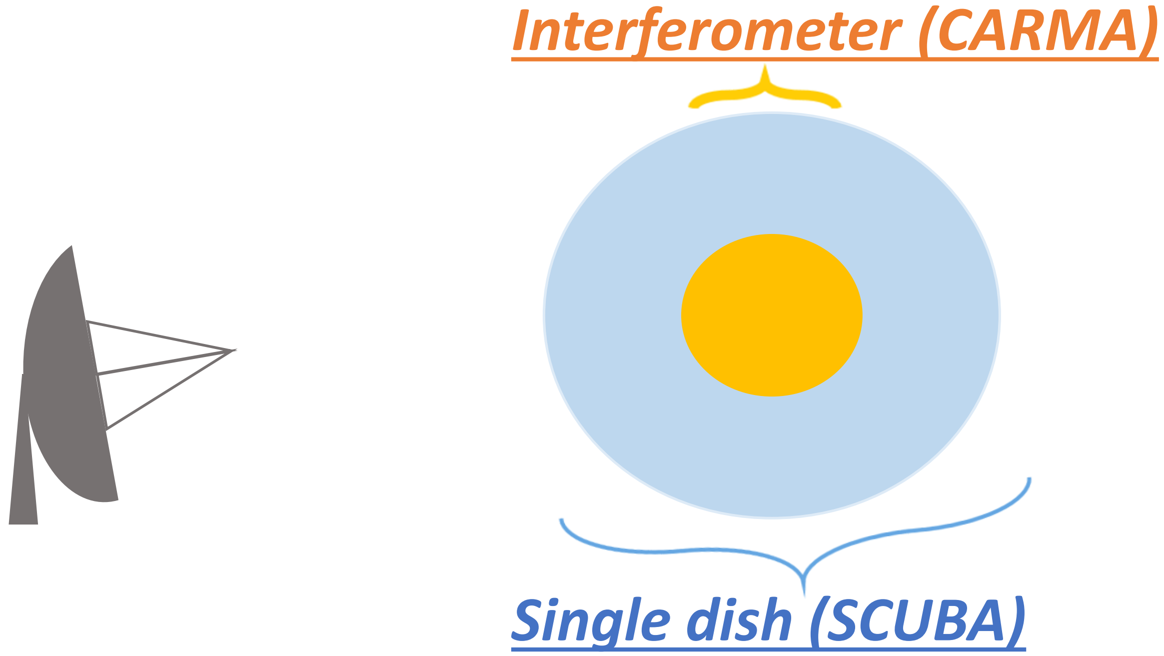


Polarization Hole
from single dish telescope
cannot be explained with:

The lost of alignment in the dense core!

1. P% CARMA > P% SCUBA
in the same telescope pointing!
2. Detection at High density

Observation I:
Degree of Polarization is HIGHER in the core?!



Polarization Hole
from **single dish telescope** ***cannot be explained with***:

Interferometer filters out the diffuse region, sampling *a shorter line of sight*, Focusing in ***high density region***.

The lost of alignment in the dense core!

1. P% CARMA > P% SCUBA
in the same telescope pointing!
2. Detection at High density

If grain alignment is ***turned off*** in high density region:
Low degree of polarization should be observed instead from high density region, **opposite to what is observed**

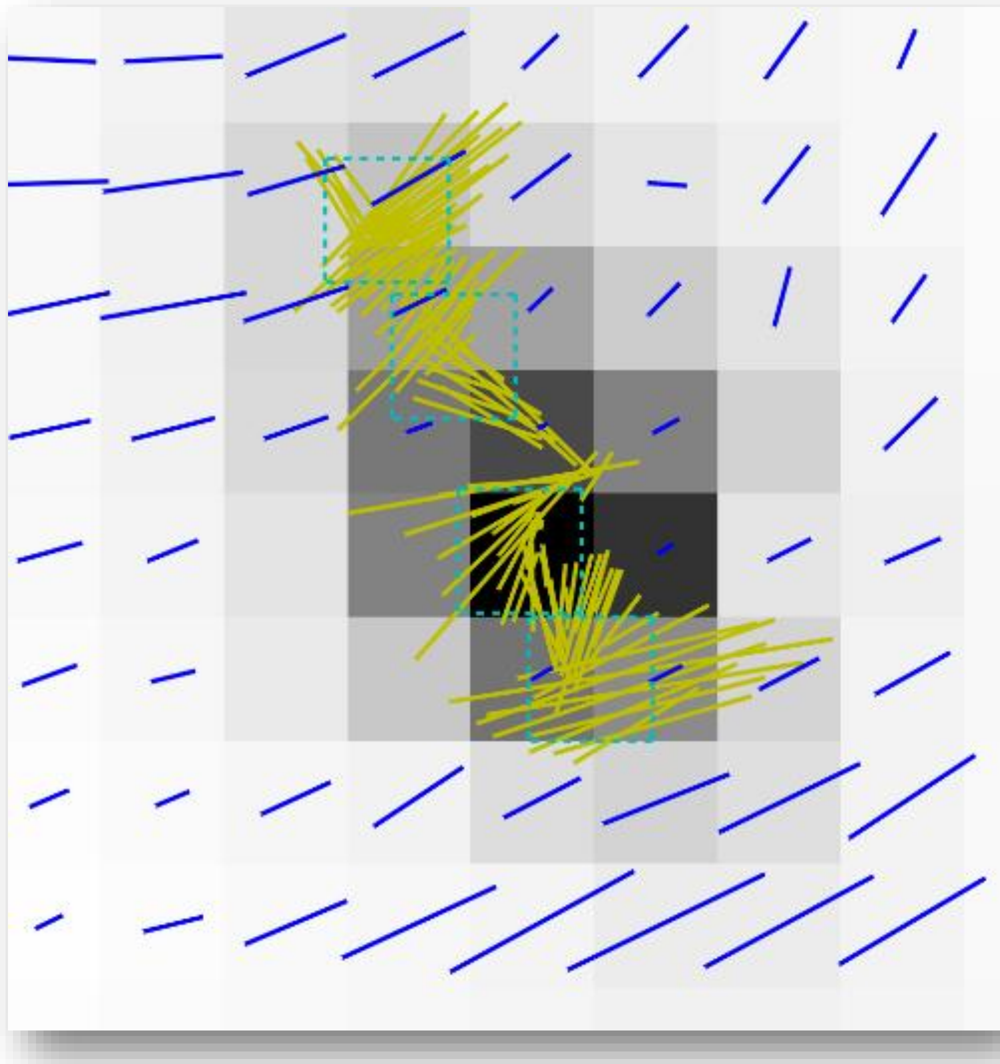
Then why would we see a lower polarization degree in ***dense region***?

- To what extent the unresolved structures on the plane of sky would lower the P%
- Recover the P% (Single dish trend) ?!
- Smoothing of ***CARMA detection to SCUBA resolution → Synthesized SCUBA***

$$Q_i = I_i P_i cos2\theta_i, U_i = I_i P_i sin2\theta_i$$

$$U_{tot} = \sum_{Beam} U_i \,, Q_{tot} = \sum_{Beam} Q_i \,, I_{tot} = \sum_{Beam} I_i$$

$$\langle P \rangle = \frac{\sqrt{{Q_{tot}}^2 + {U_{tot}}^2}}{I_{tot}}$$



Observation II:
Smearing effect within the beam

$$Q_i = I_i P_i cos2\theta_i, U_i = I_i P_i sin2\theta_i$$

$$U_{tot} = \sum_{Beam} U_i\,, Q_{tot} = \sum_{Beam} Q_i\,, I_{tot} = \sum_{Beam} I_i$$

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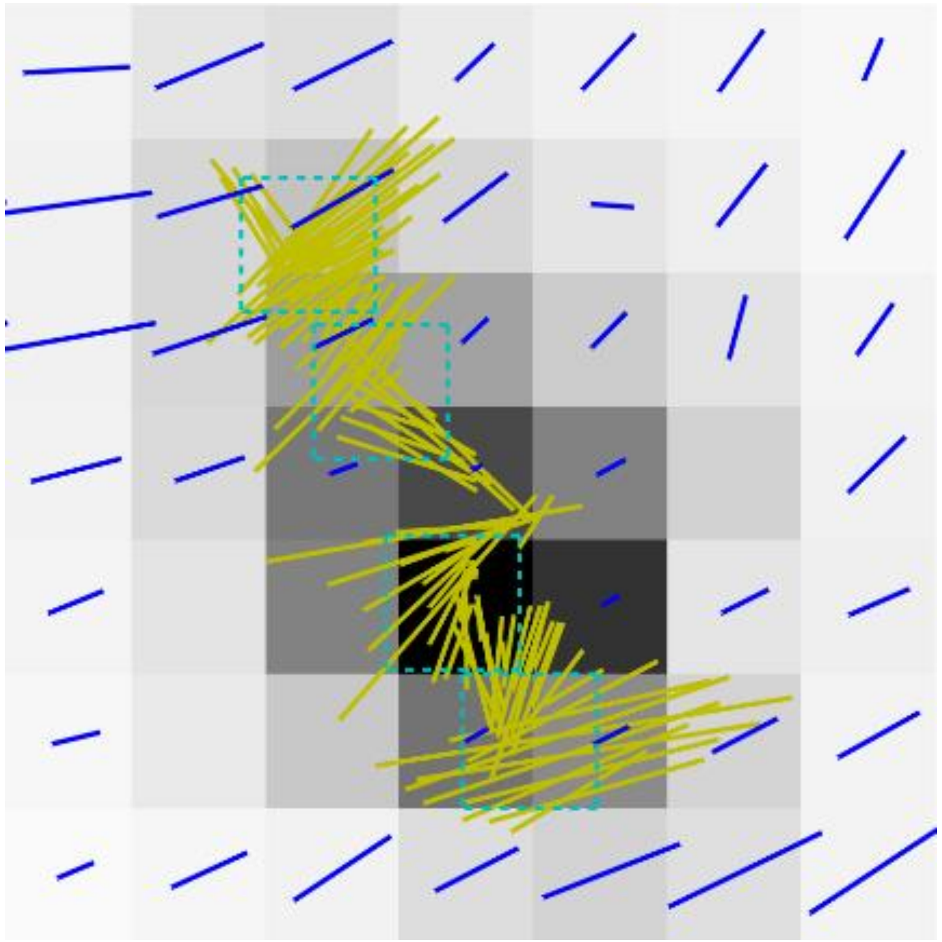
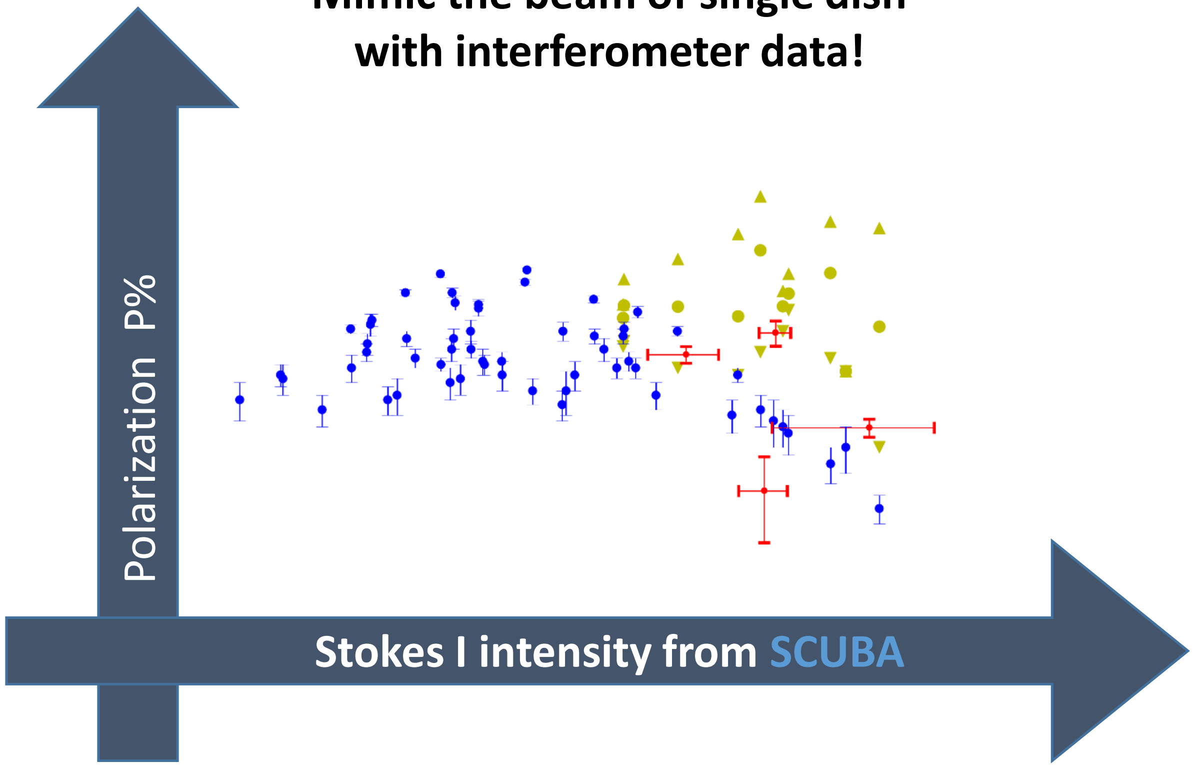
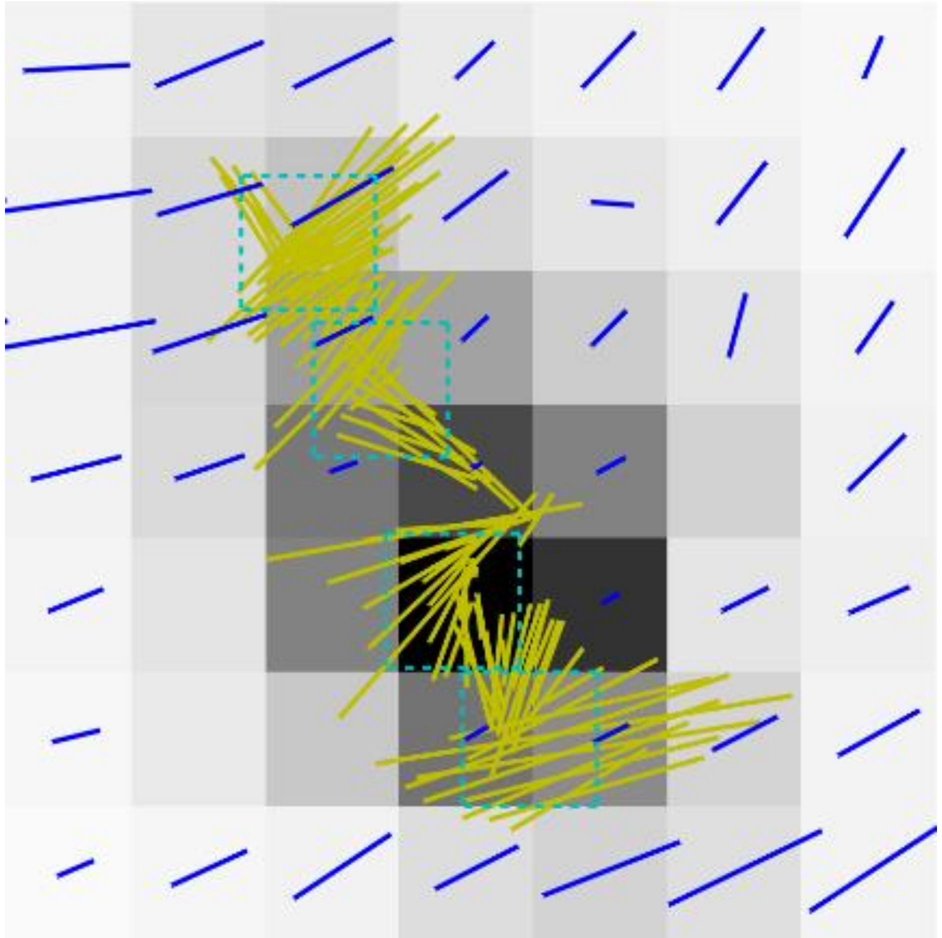


Recipe:
Mimic the beam of single dish with interferometer data!

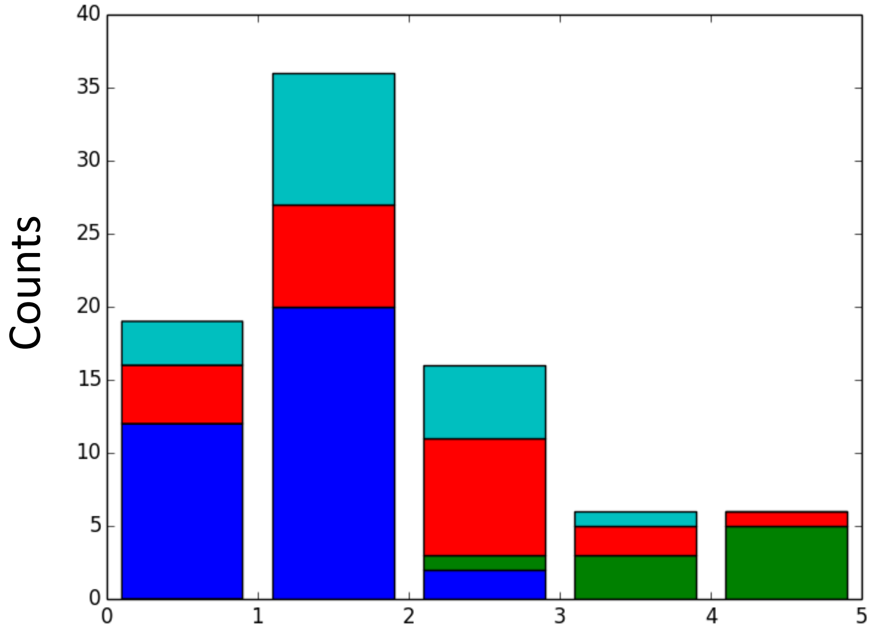


Smoothing the interferometer polarization:
Recover the trend traced by SINGLE DISH

Observation II:
Smearing effect within the beam



Histogram of polarization ratio

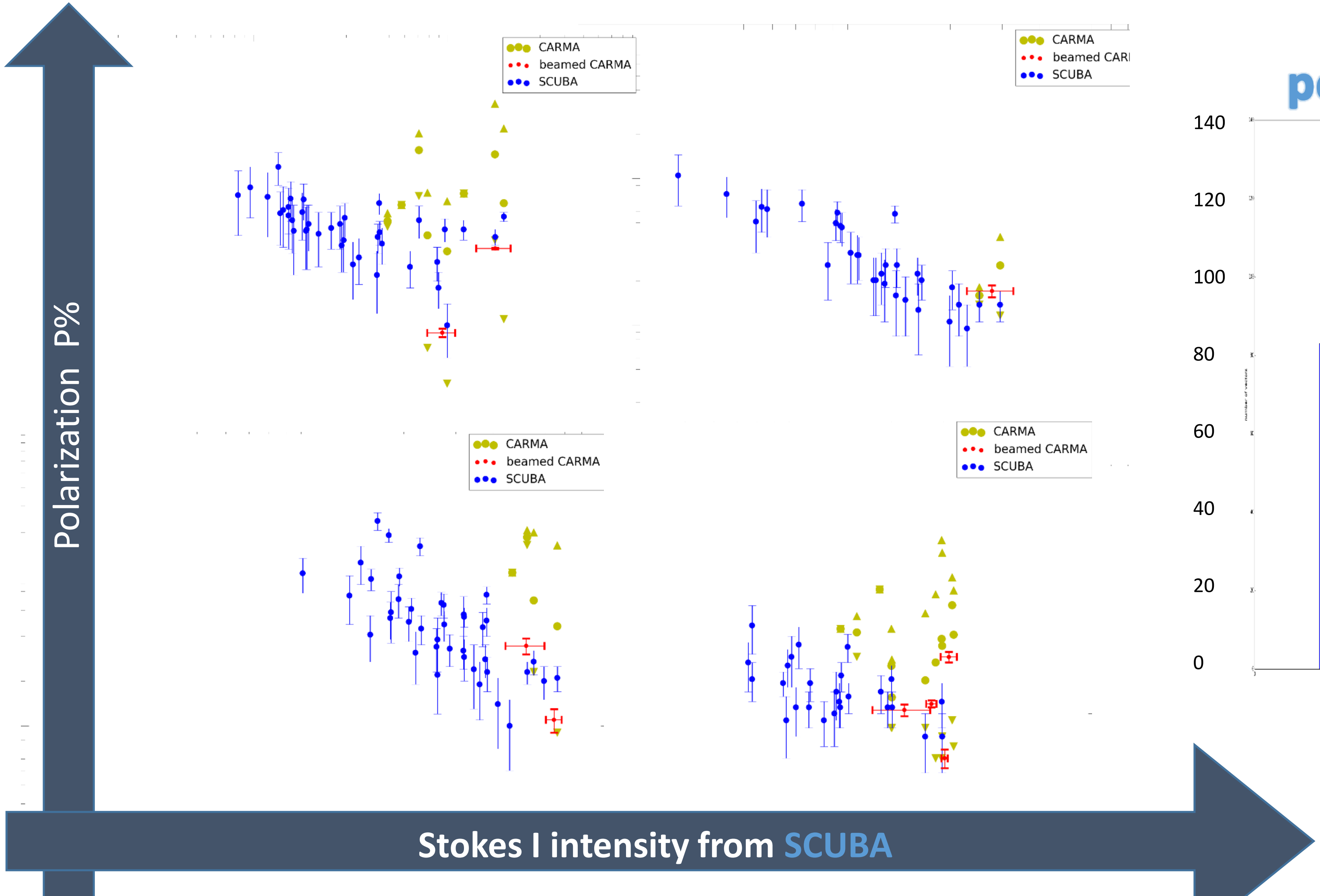


$$\text{Ratio} = \frac{P_{CARMA}\%}{P_{synthesizd}\%}$$

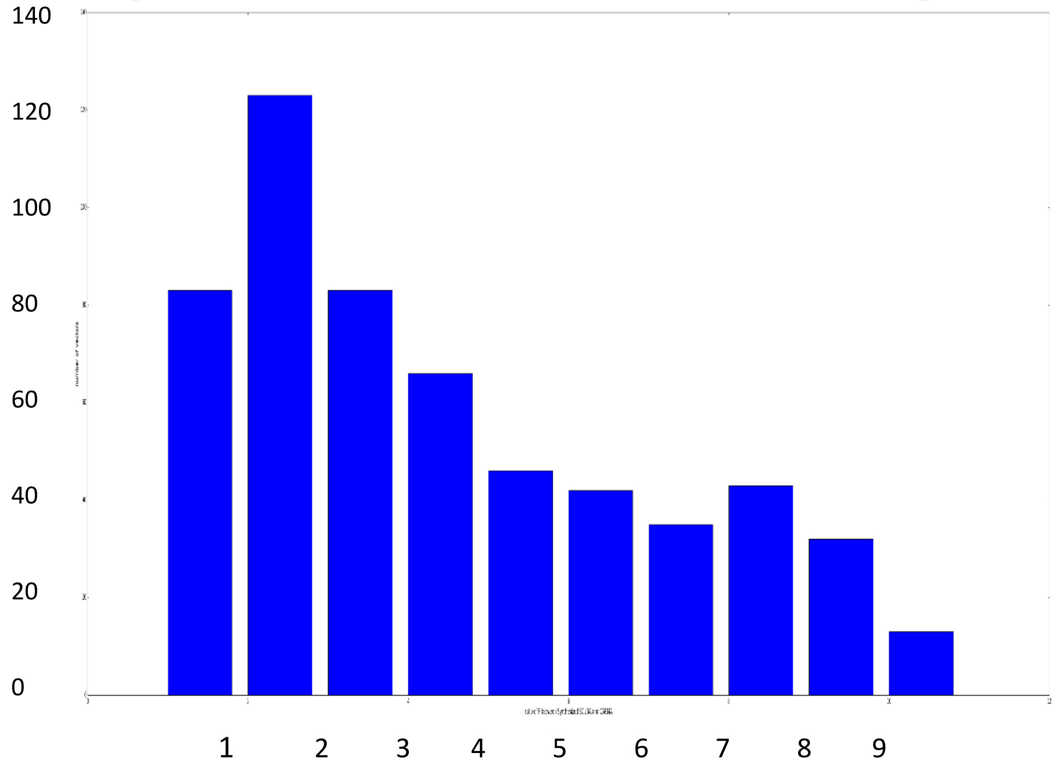
Majority of the CARMA data has higher P% than the synthesized beam !!!!

The fluctuation within the beam has significant effect in bringing down the P%

Observation II:
Smearing effect within the beam



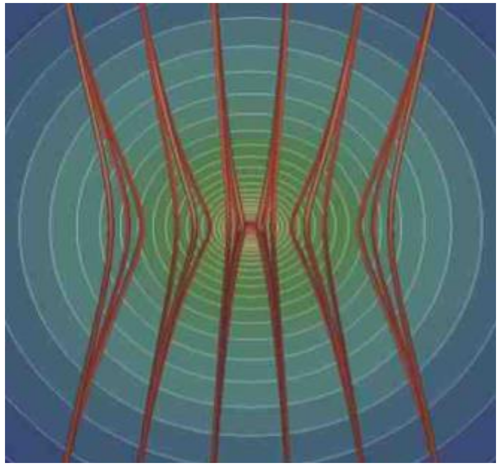
Histogram of polarization ratio for all samples

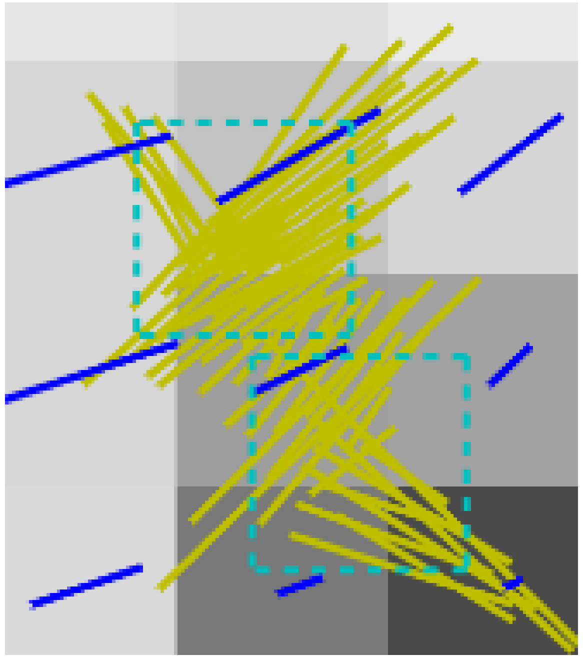


$$\text{Ratio} = \frac{P_{CARMA}\%}{P_{synthesizd}\%}$$

Discussion:
Efficiency of grain alignment ?!

- High Column density
  → *longer line of sight dimension l*
  → *Host more turbulent energy*
  → *B-field as Alfven waves* $\sigma_v \propto l^{\frac{1}{3}}$ *(Larson's Law)*
  → ***Fluctuations of B-field***
  $\propto$ to turbulent energy σ_v
  (Chandrasekhar and Fermi 1953)
- *Many unresolved B-field structures within the beam*
  - *Fluctuating B-field on the line of sight volume*
  - *Pinching of magnetic field by gravity*
- *Depolarization/Polarization Hole originates from the unresolved structures within the beam*





Conclusion and Further Work

- Even Higher P% is observed when zooming into Polarization Hole
- Unresolved B-field structure significantly bring down the P%
- Cannot be Explained by the lost of alignment at some particular density/ Av
- We believe line of sight structures would bring P% down greatly
- P% (850um) =/= P%(1100um): contribution from different grains?
  - Can be tested with polarization data with same wavelengths
- Filtering effect of interferometer on polarization?
- Need some better understanding in grain alignment theory!