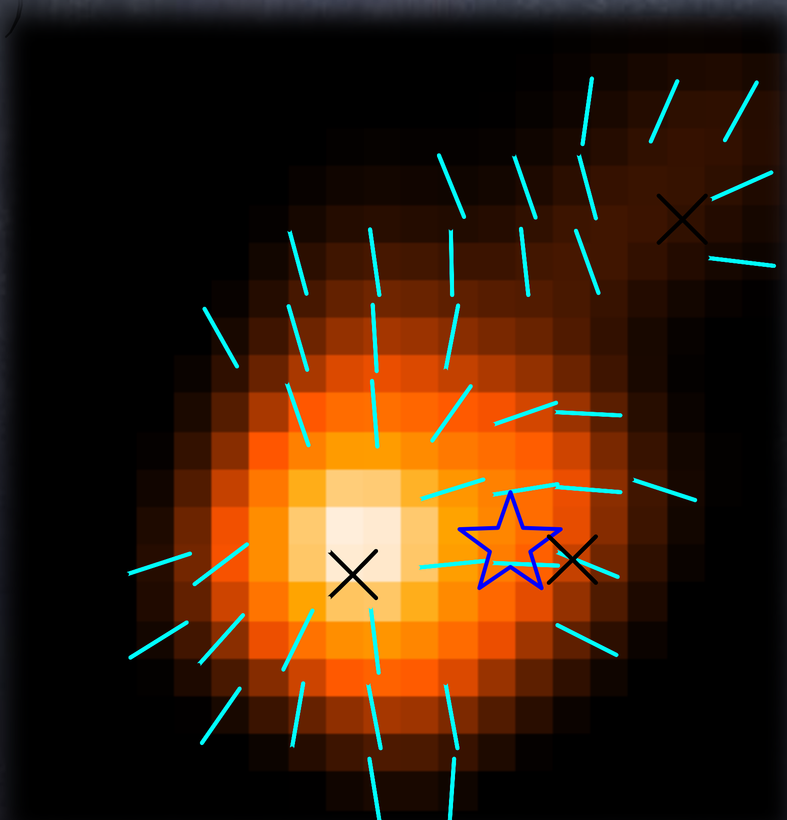
Magnetic Fields in Molecular Clouds

Patrick Koch (ASIAA, Taiwan)

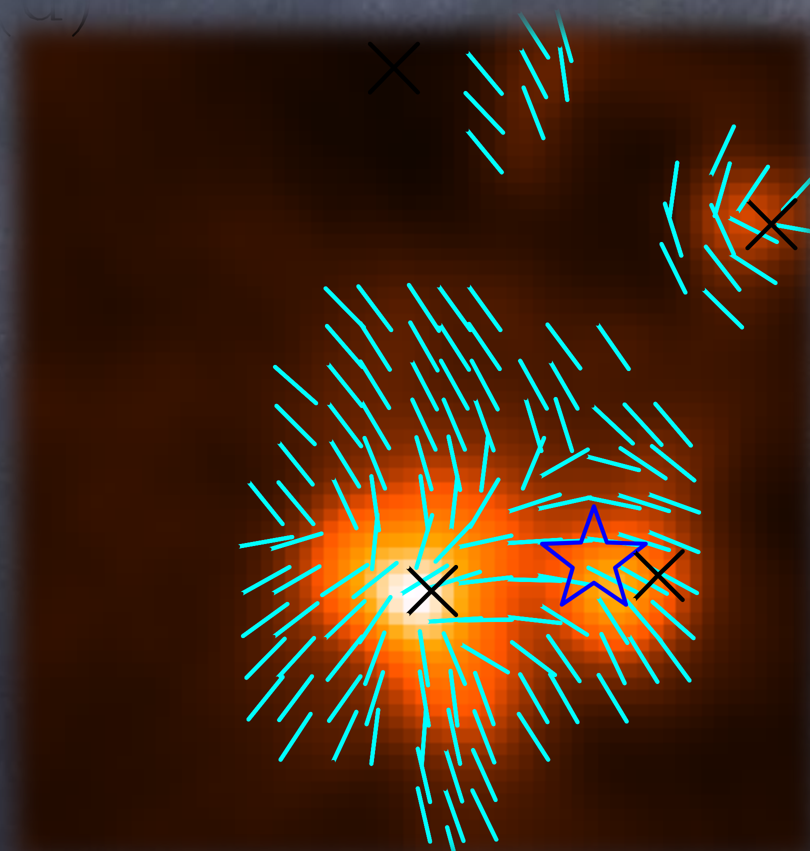
with

Ya-Wen Tang, Hsi-Wei Yen, Paul Ho, Shigehisa Takakuwa,
Yu-Nung Su, Nicolas Peretto, Ana Duarte Cabral,
Giles Novak, Nicholas Chapman

SMA



ALMA



Quy Nhon, Vietnam; July 12, 2018

outline

- motivation: B-field, why and how?
- filamentary infrared dark cloud G34.43
- high-mass star-forming region: W51 e2, e8, North
- beyond imaging: novel analysis techniques and statistics
- indirect constraint on B-field: specific angular momentum profile in young stellar objects

why should you care about magnetic fields in star-forming regions ?

* field strength is measured (e.g. Zeeman splitting), 0.1 mG to a few mG, can be dominating, comparable or at least non-negligible as compared to thermal pressure, gravity, centrifugal force

* magnetic field is fundamental physical constituent, i.e., Lorentz force, addressing basic concepts of flux-freezing, ambipolar diffusion

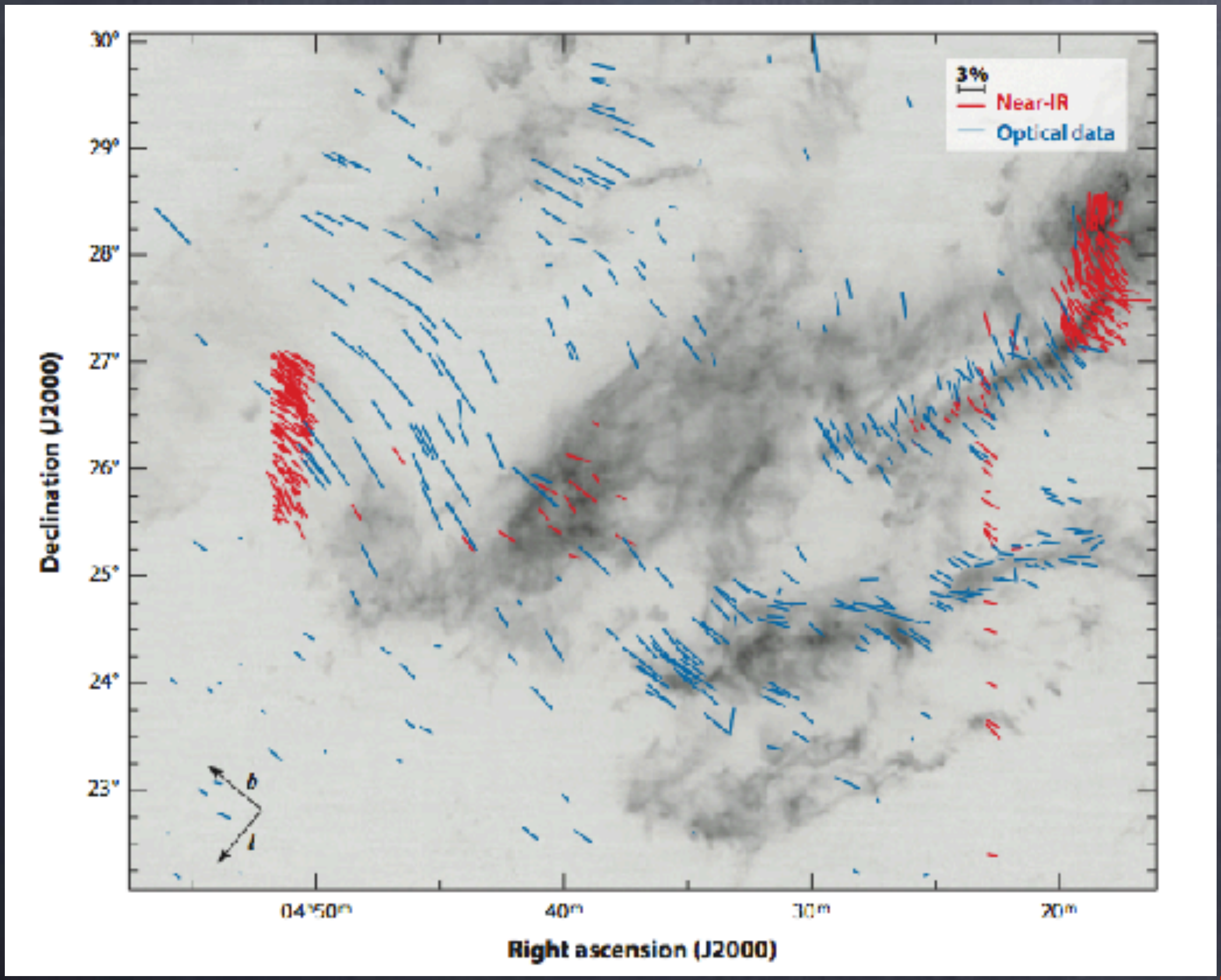
* with ALMA' s sensitivity, fidelity and absolute calibration: need to expect to see magnetic field influence ("indirect" measurements) e.g. different dynamics, different velocities and time scales

context and key questions around B-field

- how does the B-field affect dynamics of star formation ?
- B-field versus gravity, B-field versus turbulence ?
- can the B-field influence star-formation efficiency ?
- how are B-field and gas coupled ?
- is magnetic braking in protostellar disks happening ?
- how far can we constrain dust properties with polarization ?

Magnetic Field Observational Techniques

main difficulty: weak signal,
~ few % of Stokes I



(Chapman et al. 2011)

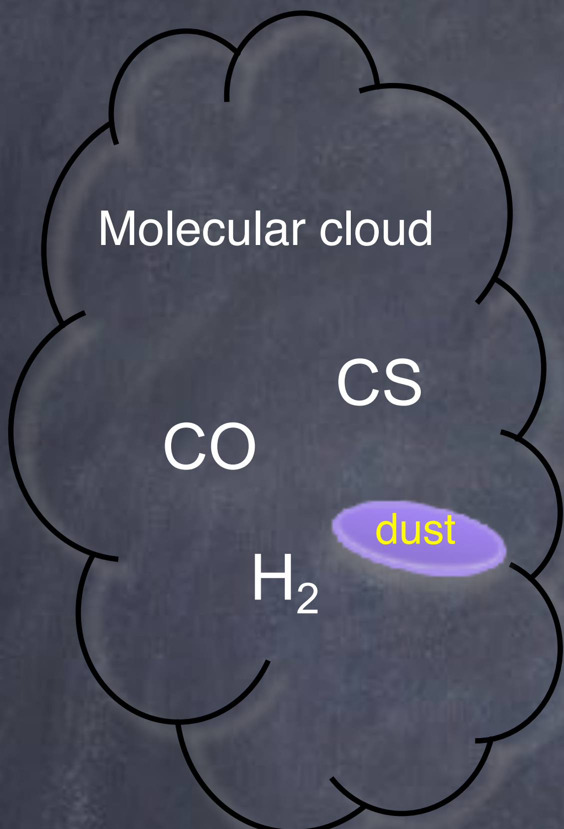
* Zeeman splitting:
  needs strong enough line emission,
  can get field strength, typically
  isolated and local

* synchrotron radiation:
  needs relativistic electrons,
  typically not observed

* absorption of background
  star light by dust
  (polarization in optical / NIR)
  only morphology, no field strength

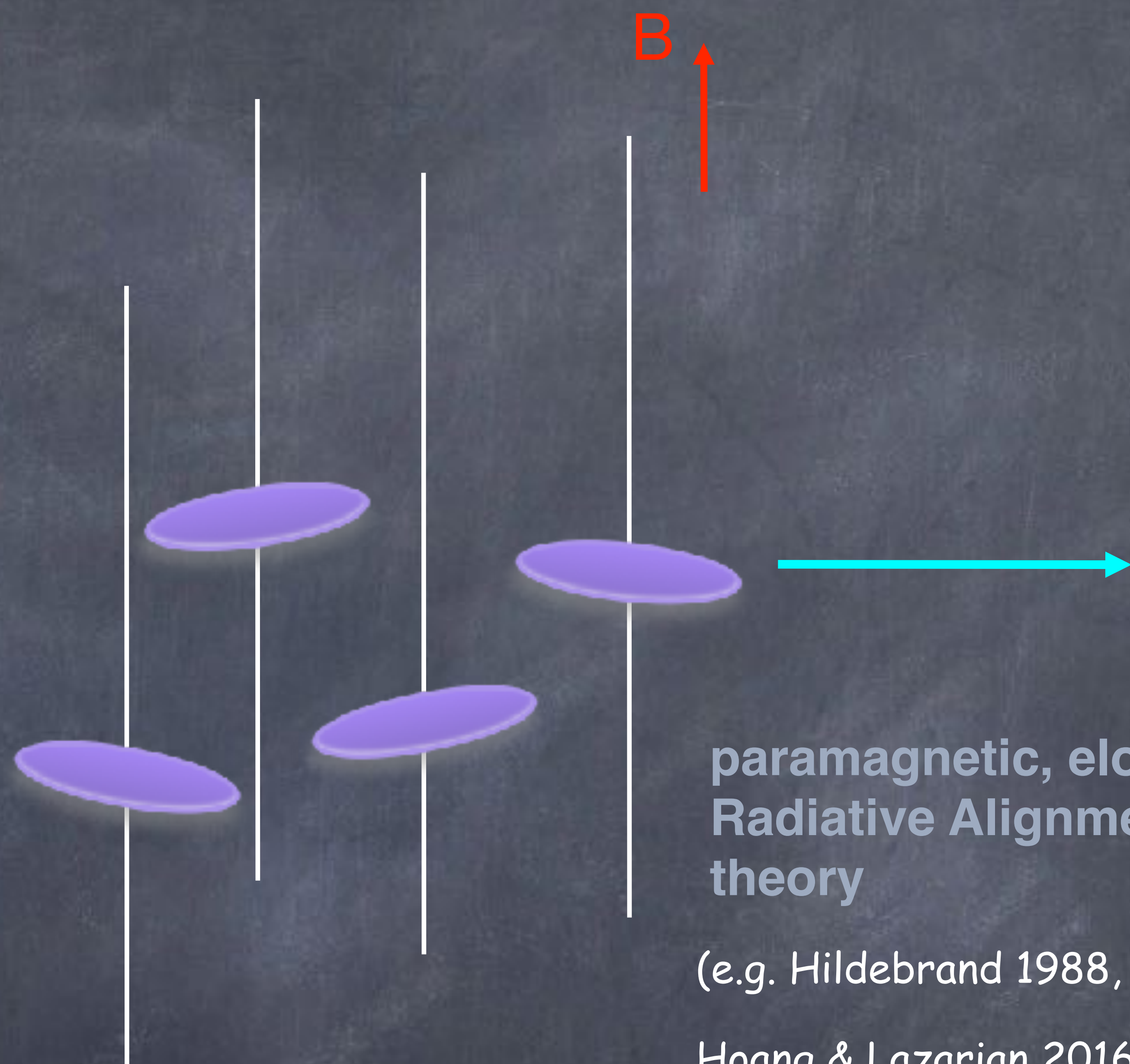
* thermal dust emission
  (polarization in mm / submm bands)
  only morphology, no field strength

Dust Polarization Mechanism



$n_{H_2} \sim 10^{4-7}$ (cm^{-3})

T ~ 10 (K)



paramagnetic, elongated, rotating
Radiative Alignment Torque (RAT) theory

(e.g. Hildebrand 1988, Lazarian 2000,

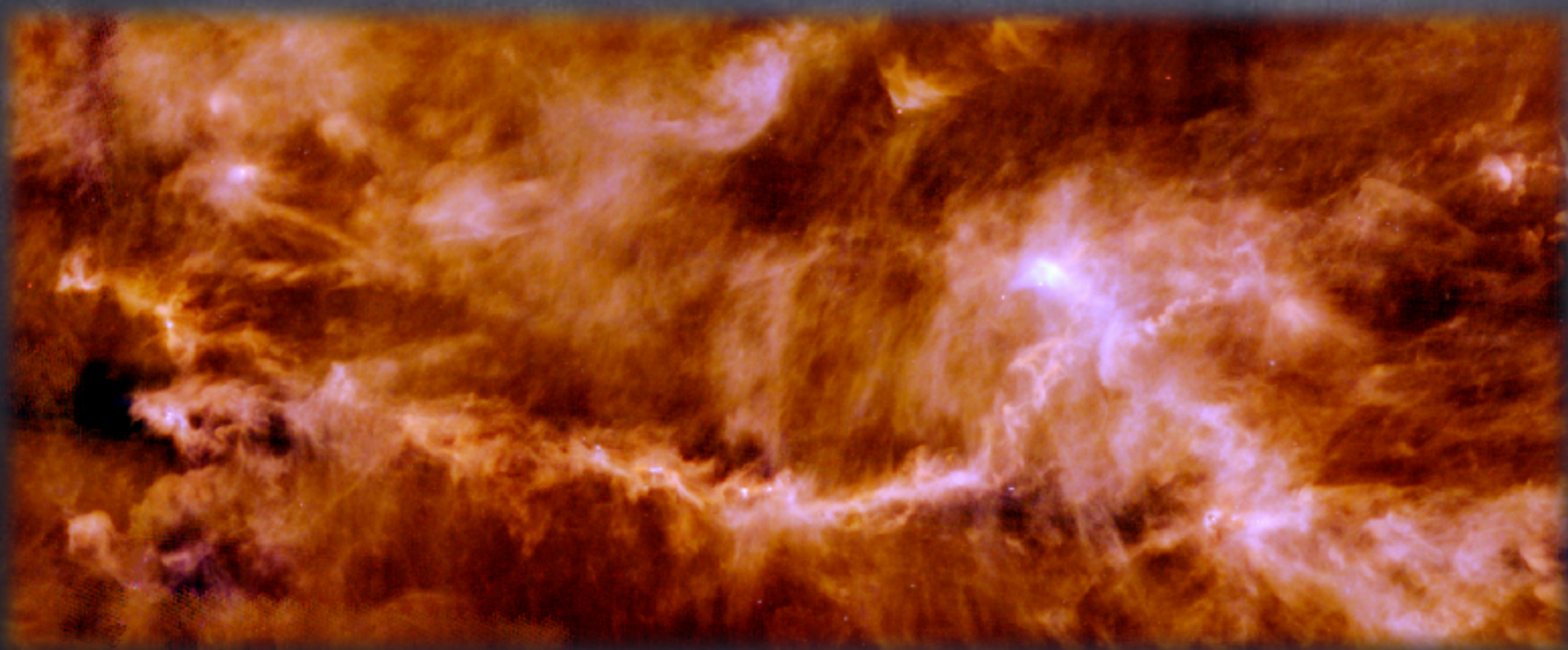
Hoang & Lazarian 2016, Andersson+2015)

- individual dust particle: dipole
- in submm: linear polarization from thermal dust emission
- coherent alignment mechanism: B field is one possibility
- mechanism provides only projected field orientation/morphology
- need something more to derive field strength

Magnetic Field in Filamentary IRDC

- filaments are ubiquitous (Herschel)
- being established as an essential building block in SF process
- how are they formed in a first place? how are the denser structures within filaments formed?
  what is the role of the B-field in this process?

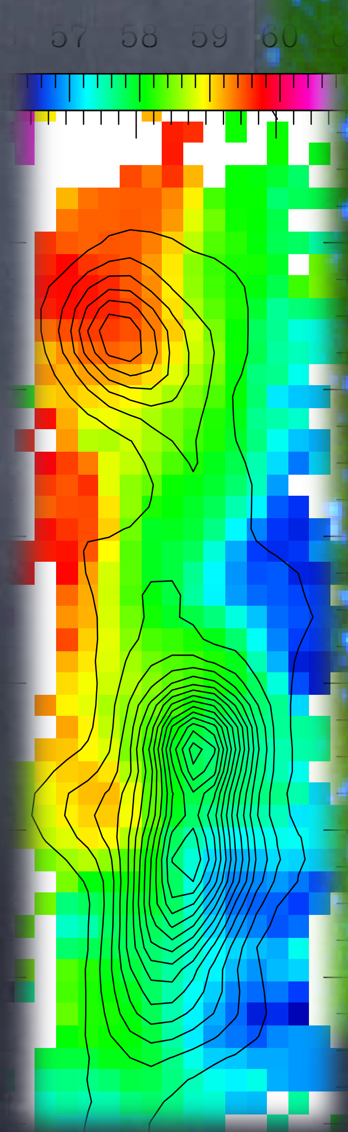
- example observation/analysis: G34.43



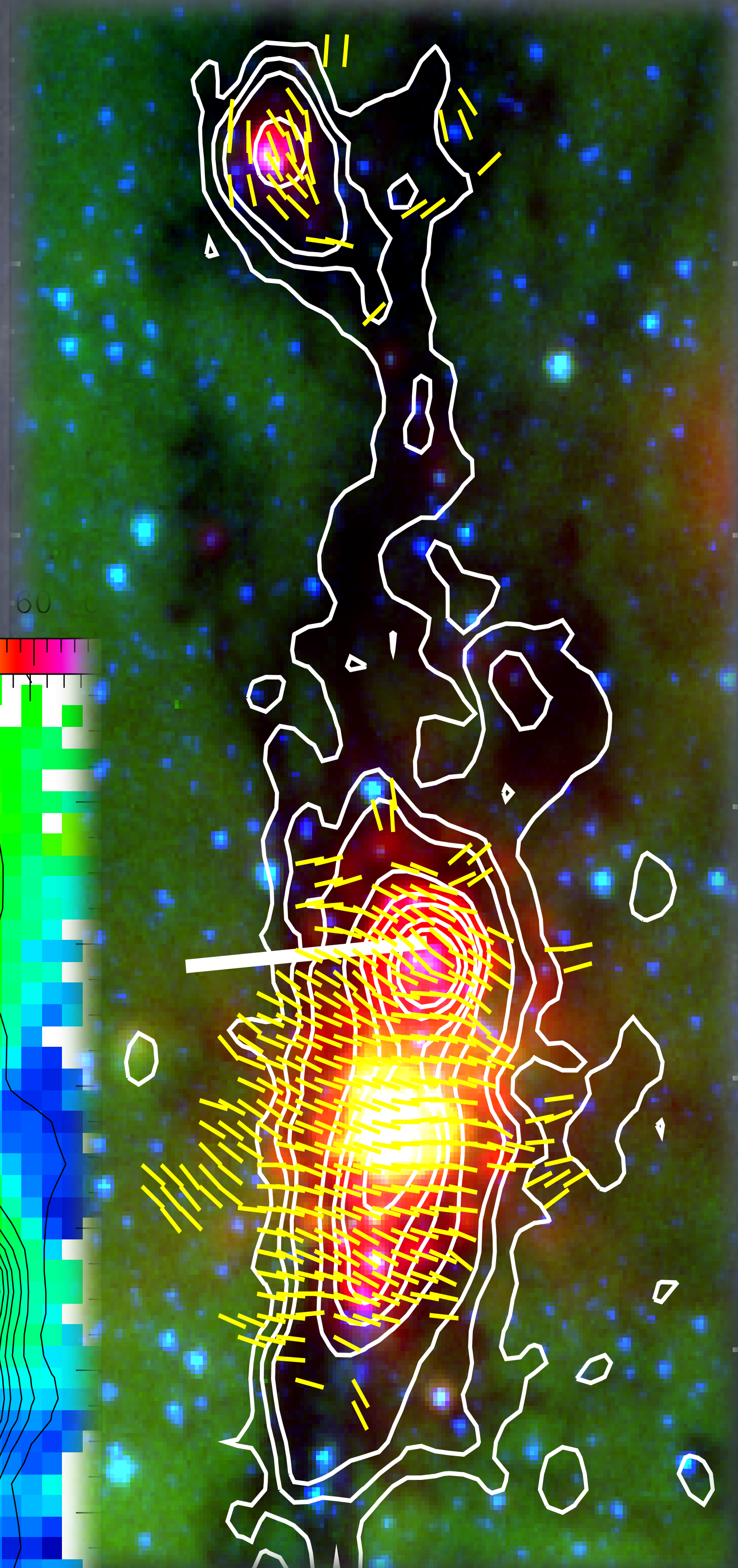
B211/213 filament in Taurus; (ESA/Herschel)

IRDC G34.43

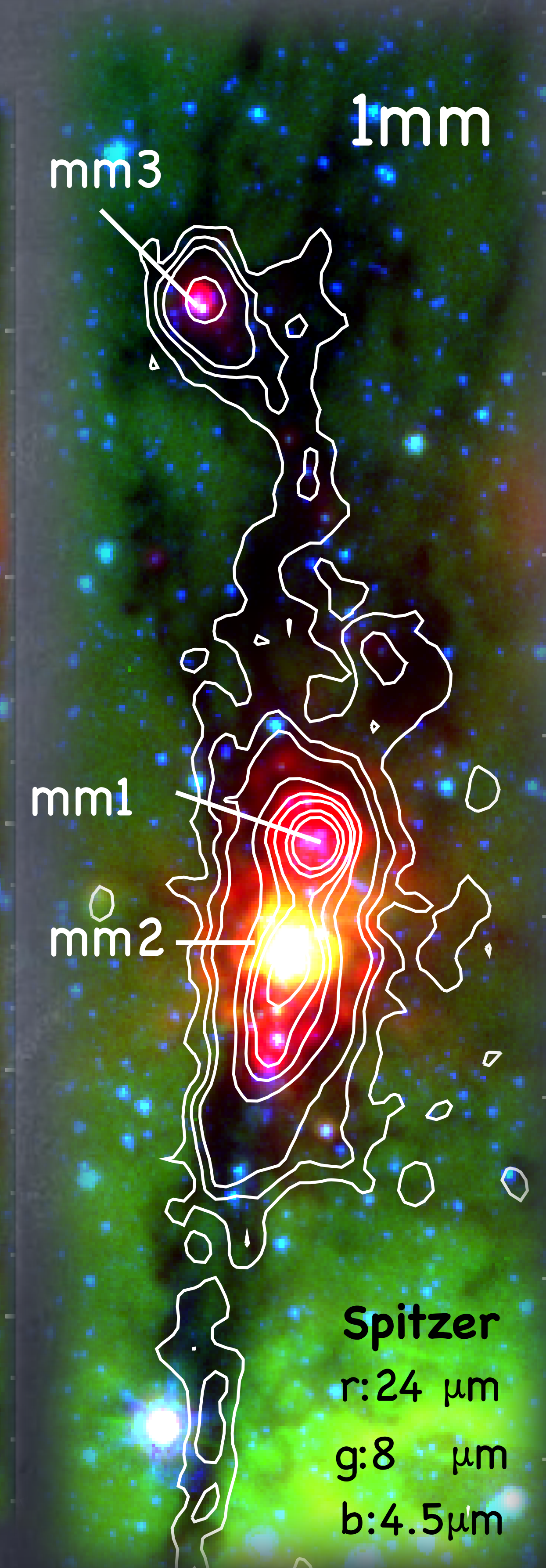
- distance: 3.7 kpc, elongated length ~ 8 pc
- mass: 1200 M_sol (mm1), 1300 M_sol (mm2)
  300 M_sol (mm3)
- overall, very small viral parameter
  (α ~ 0.2), system gravitationally bound, but
  SF efficiency only ~ 7%.
  additional support from B-field ?
- observed with the CSO/SHARP
  (350μm, resolution 10")
- polarization percentage 0.4 - 10%
- B-field clearly organized
  perpendicular to longer axis around
  mm1/mm2; more aligned with longer
  axis on mm3, small dispersion
- add line kinematics:
  N_2H^+ (1-0) from IRAM-30m (θ~28"),
  clear large-scale gradient



Peretto+2017



Tang+2018

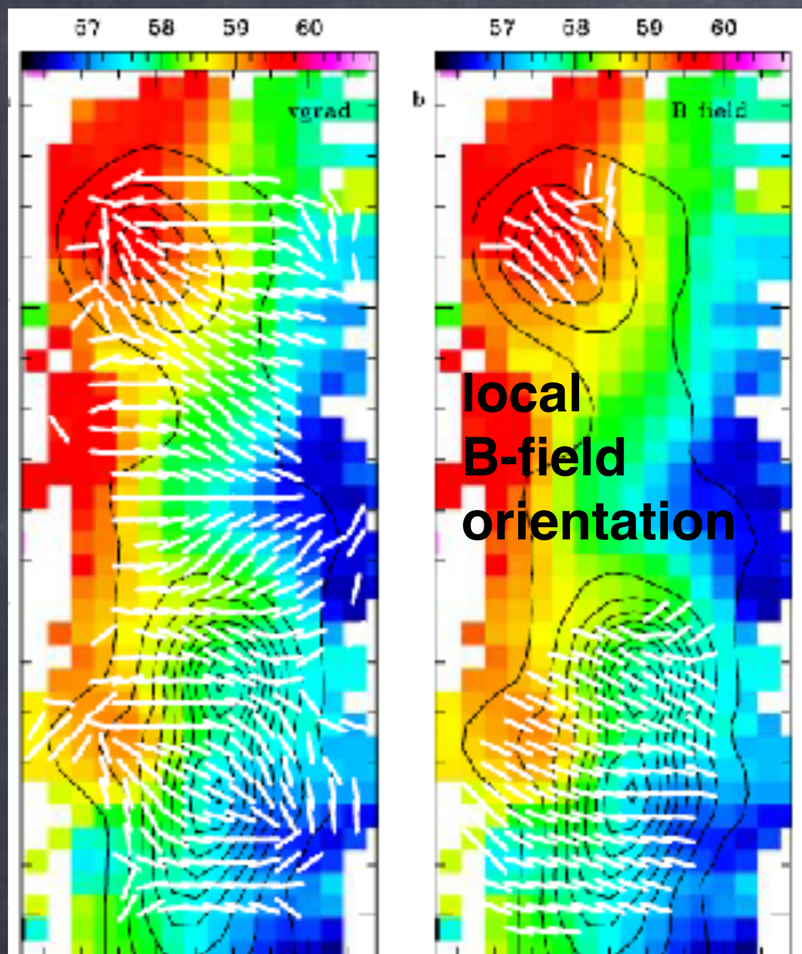


Rathborne+2006

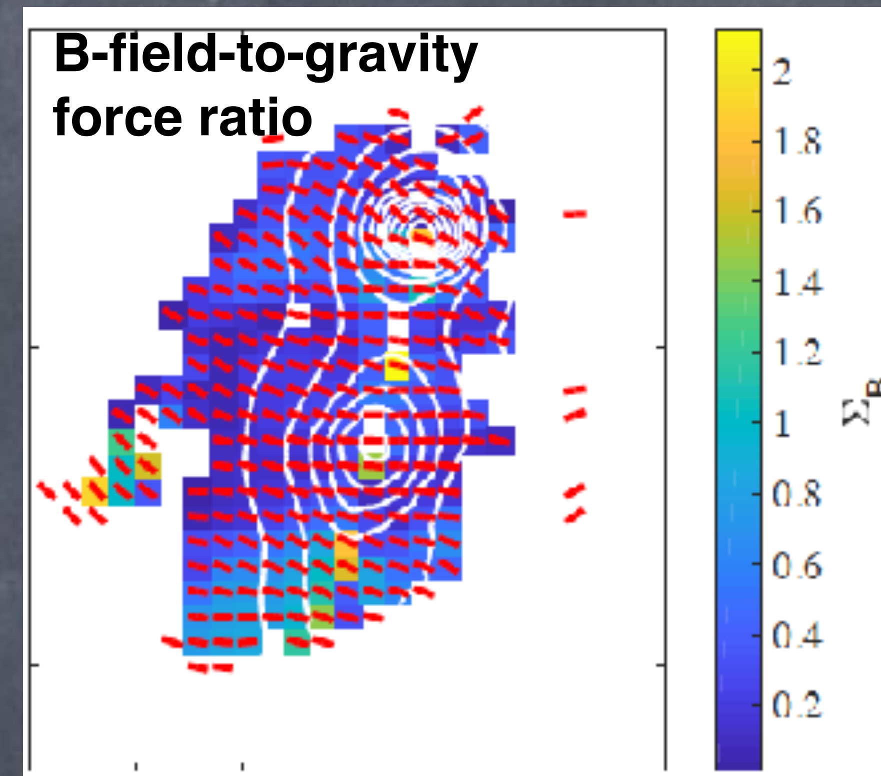
B-field, velocity gradient, turbulence & gravity

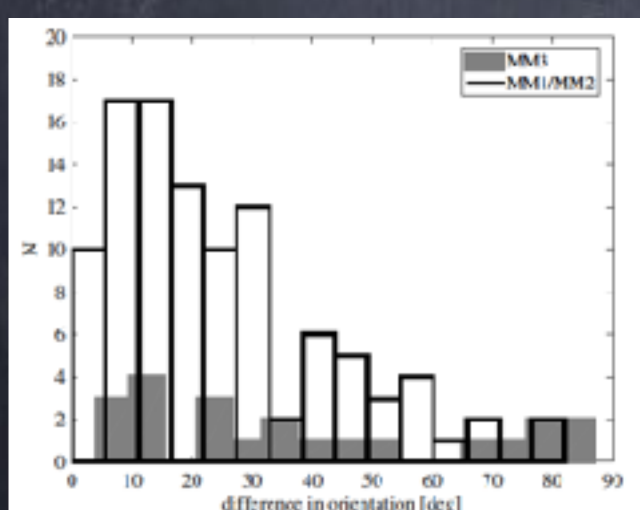
which component is dominant? negligible?   - benchmark analysis

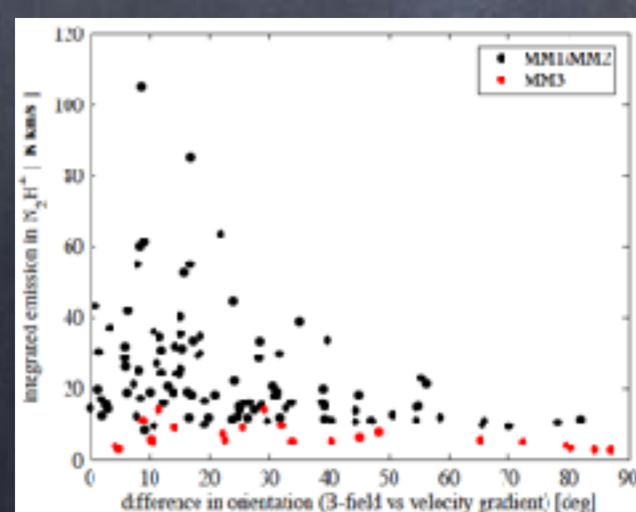
local velocity gradient

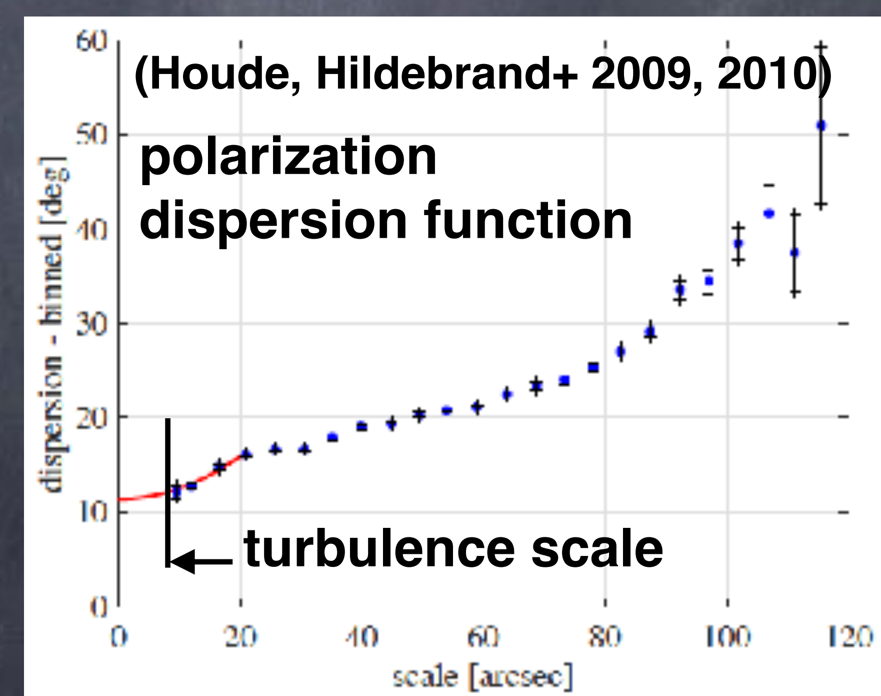


difference local velocity gradient - local B-field









B vs v: small differences and spatially not random, but organized

B vs G: spatially not random, but organized   (Tang+2018)

How Important is the B-field in G34.43 ?

which component is dominant? negligible? - benchmark analysis

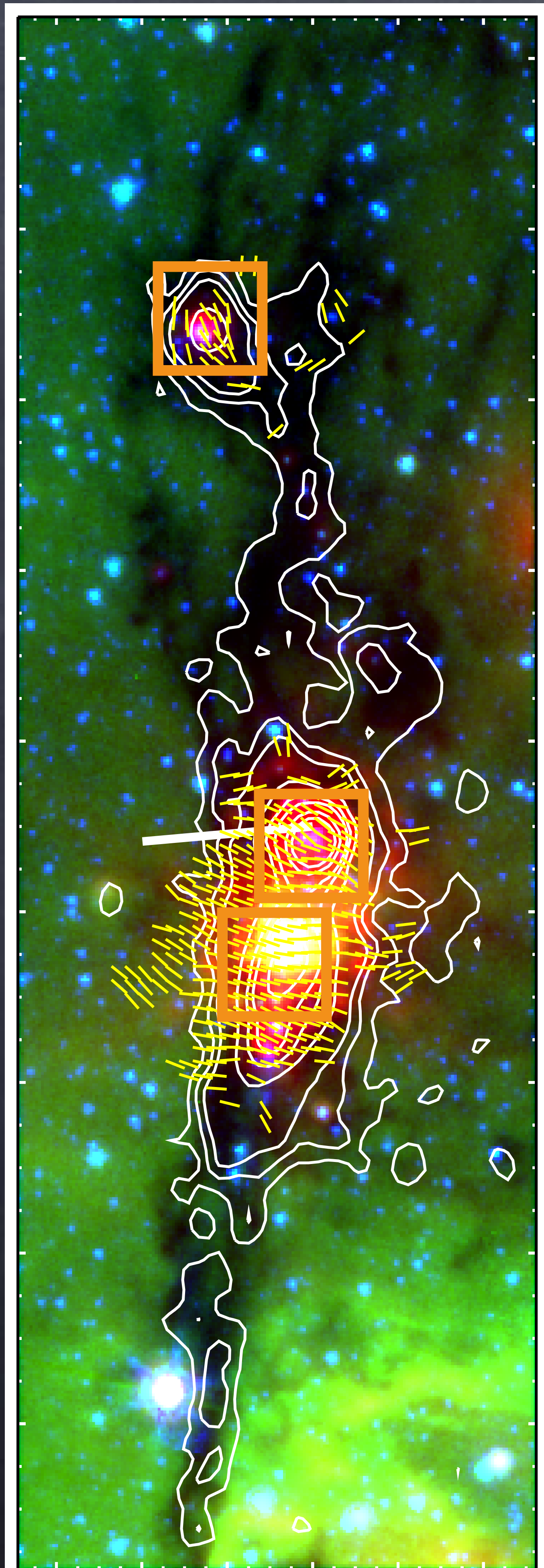
Object	M ($M_\odot$)	R (pc)	n_{H_2} (cm^{-3})	Δv (km/s)	$\frac{\sqrt{\langle B_t^2 \rangle}}{B_0}$	$\frac{\sqrt{\langle B_t^2 \rangle}}{B_0}_N$	N	ϕ_B (°)	$B_\perp$ (mG)	Σ_B	λ	α_{vir}	P_T (10^{-9} dyn/cm^2)	P_B	u_G	Relative importance
MM1	422	0.23	$1.2 \cdot 10^5$	1.2	0.21	0.92	21	17	0.5	0.35	1.3	0.9	12.1	14.2	26.5	G>B>T
MM2	422	0.23	$1.2 \cdot 10^5$	1.5	0.11	0.49	22	9	1.1	0.44	0.6	1.4	18.9	78.9	26.5	B>G>T
MM3	275	0.32	$2.9 \cdot 10^4$	0.9	0.35	1.07	11	20	0.2	0.63	1.4	1.1	1.6	1.4	3.0	G>T≥B

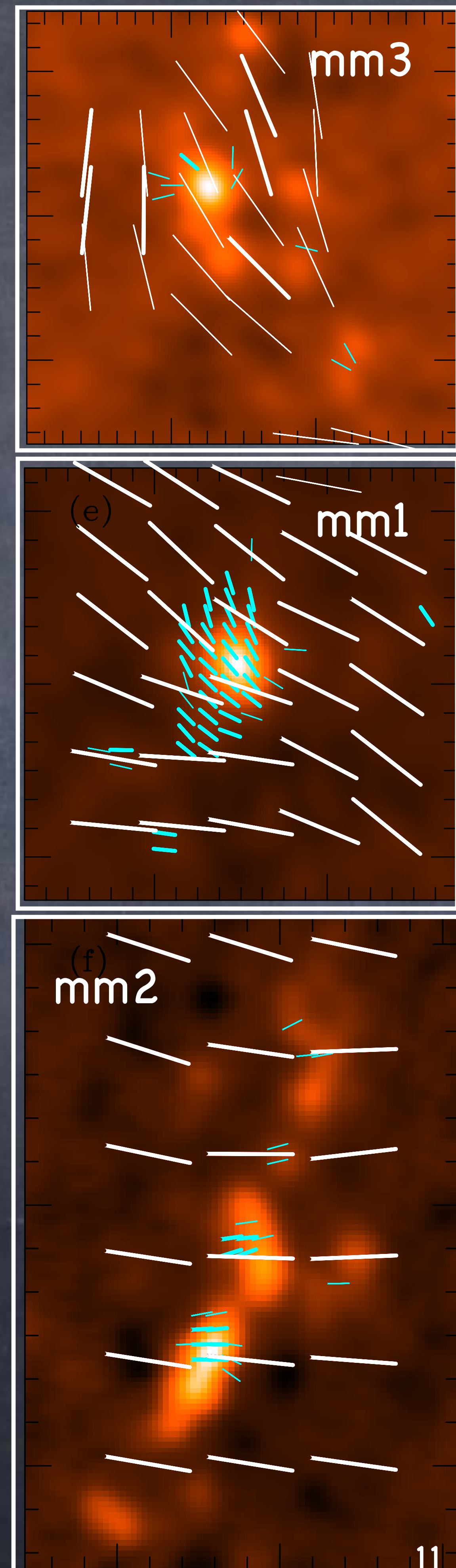
NOTE. Columns are mass (M), radius (R), number density (n), velocity dispersion along the line of sight (Δv), turbulent-to-mean magnetic field ratio ($\frac{\sqrt{\langle B_t^2 \rangle}}{B_0}$), turbulent-to-mean magnetic field ratio corrected for the number of turbulent cells ($\frac{\sqrt{\langle B_t^2 \rangle}}{B_0}_N$), number of turbulent cells within the beam (N), dispersion of the polarization position angles at the resolution scale of 9.″5 (ϕ_B), B field strength in the plane of sky derived from the CF method ($B_\perp$), magnetic field-to-gravity force ratio Σ_B based on the intensity gradient method, ratio of the observed mass-to-flux ratio and the critical mass-to-flux ratio (λ), virial parameter (α_{vir}), turbulent pressure (P_T), B field pressure (P_B), gravitational energy density (u_G), and the relative importance between gravity (G), B field (B), and turbulence (T).

different local interplay between B-field, turbulence, and gravity on core scale

⇒ consequence for fragmentation towards next smaller scale?

Fragmentation in G34.43





G > T ≧ B

clustered fragmentation

largest dispersion in B

weakest B

smallest mass

G > B ≧ T

no fragmentation

systematic dispersion in B (drag)

medium B

larger mass

B > G > T

aligned fragmentation

smallest dispersion in B

strongest B

larger mass

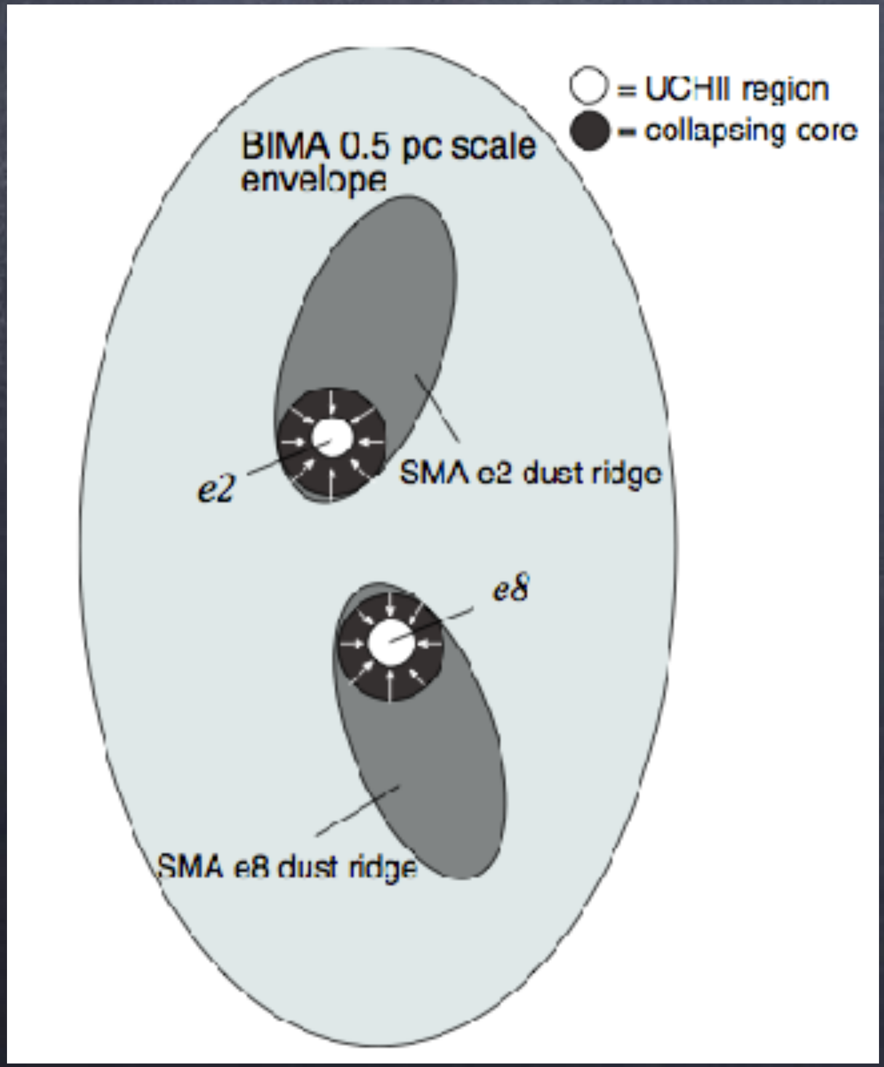
Tang+2018

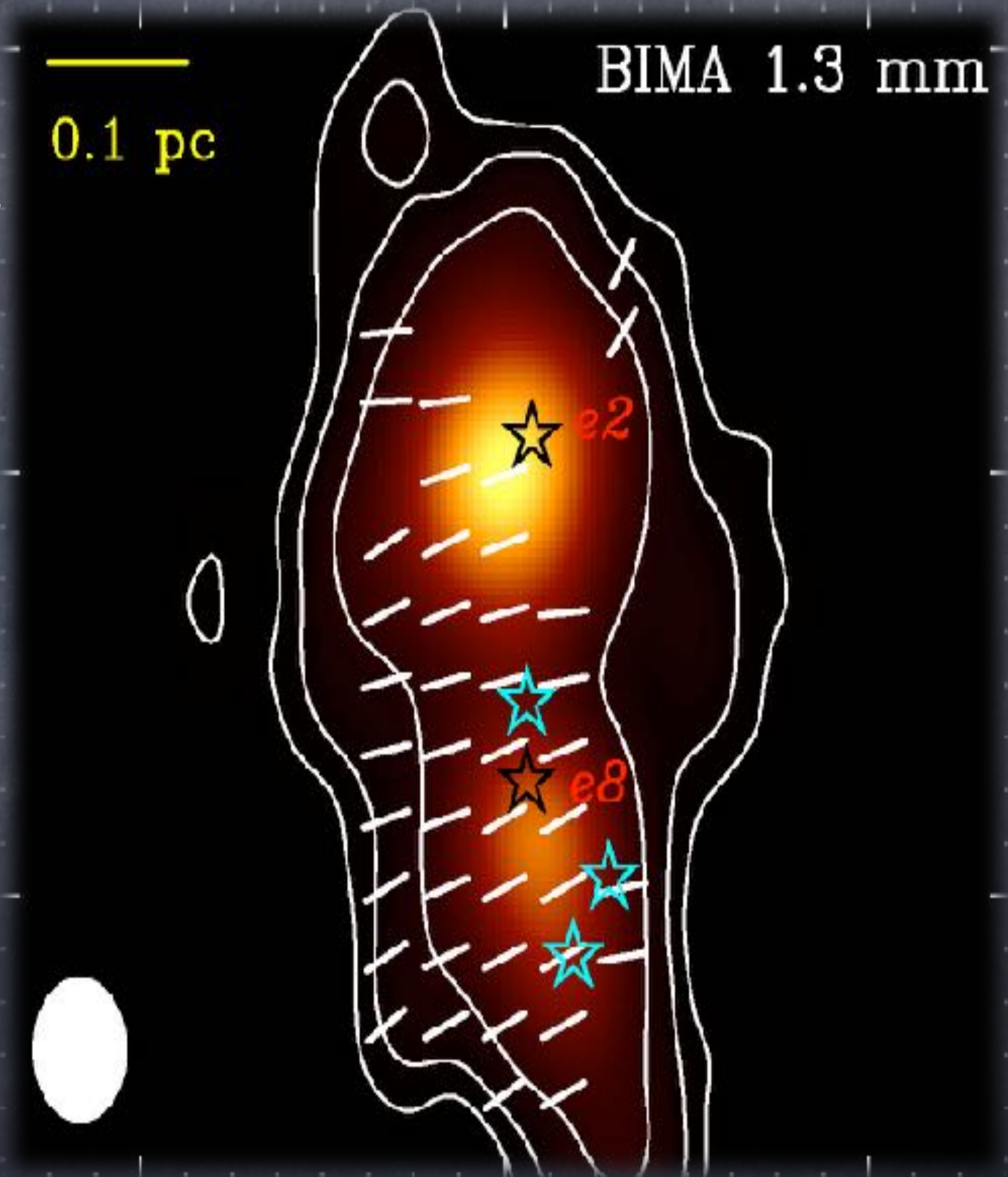
SMA: Zhang+14; Chen+in prep.

CARMA: Hull+14

Higher-Resolution B-field Measurements

- W51 high-mass SF site at d~5.4 kpc
- several UCHII regions and infalling signatures detected
- elongated structure, with B-field mostly perpendicular (BIMA, θ~ 3", Lai+2001)
- SMA observations: resolved B-field in cores with θ~ 0.7" (Tang+2009)





Lai+2001

W51 e2/e8 with BIMA and SMA

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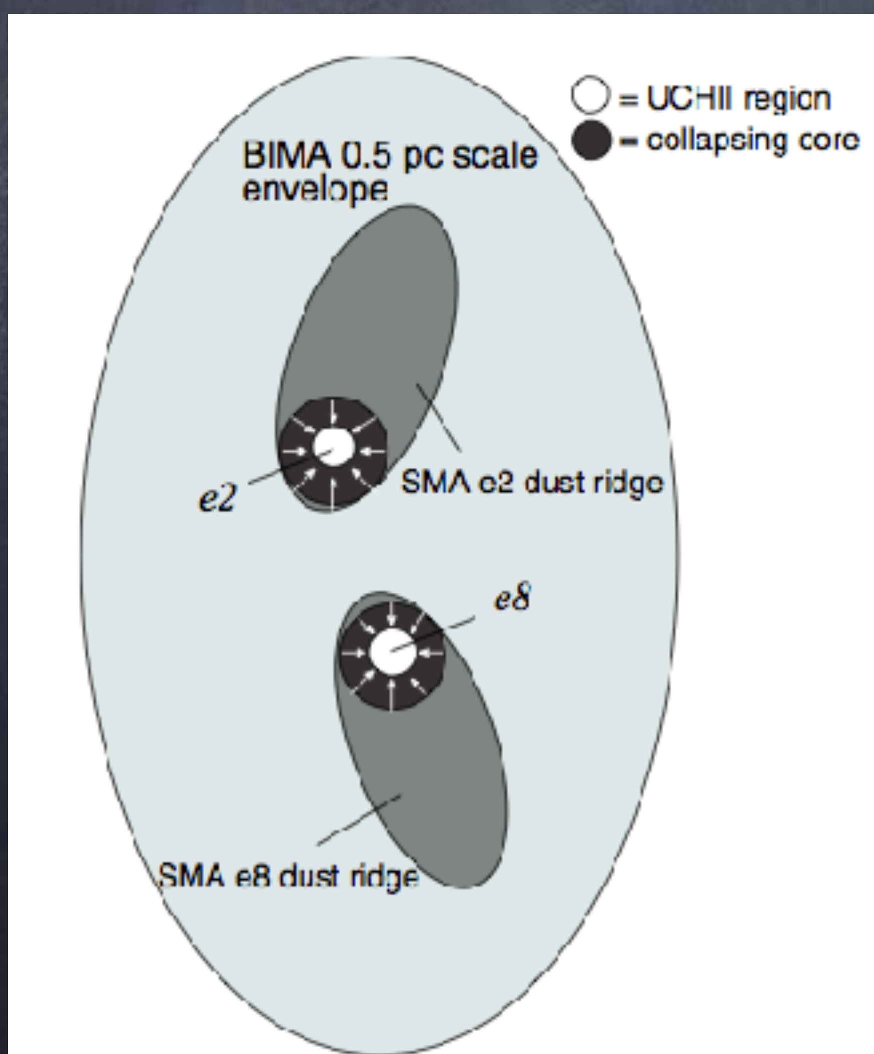
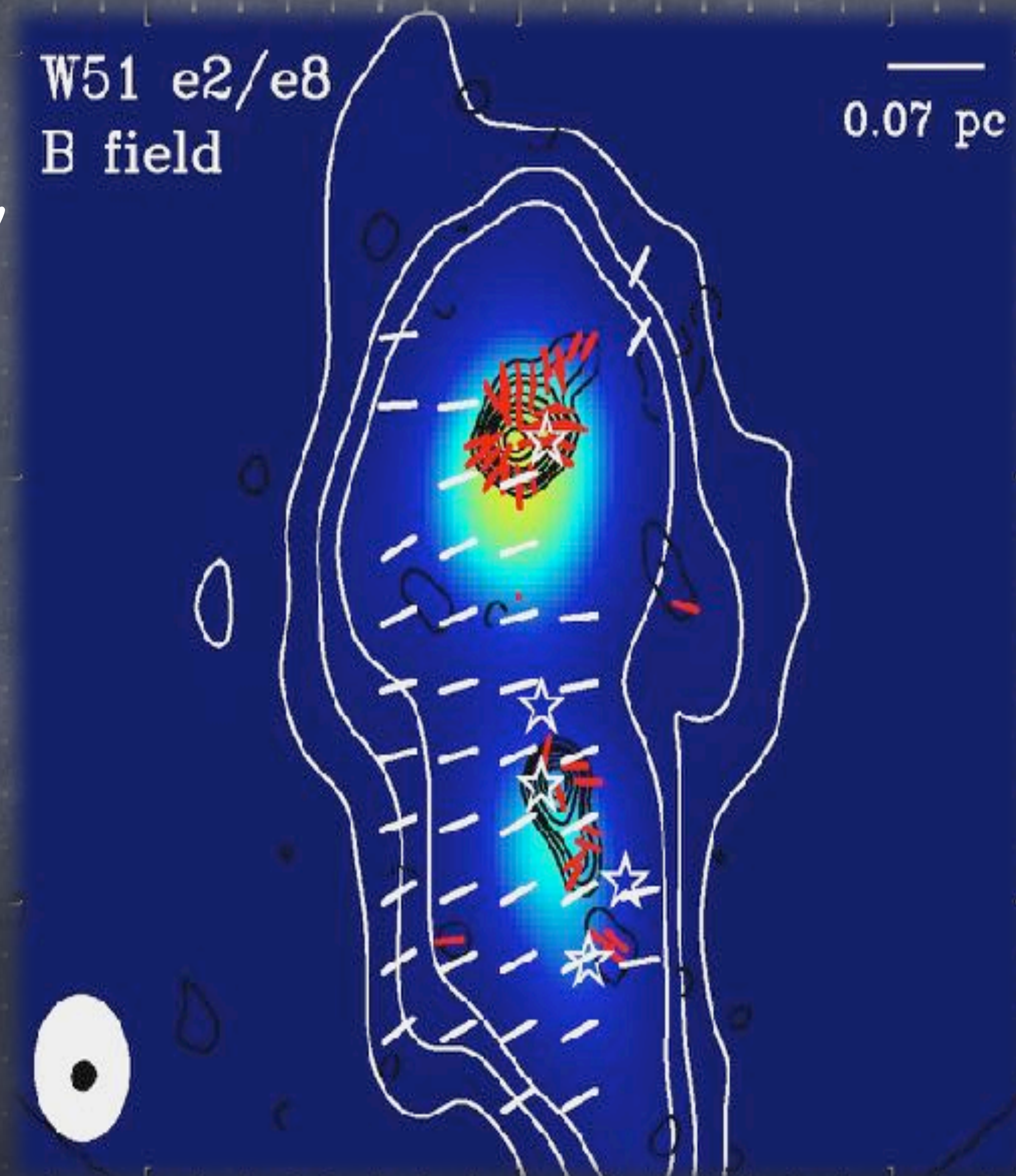
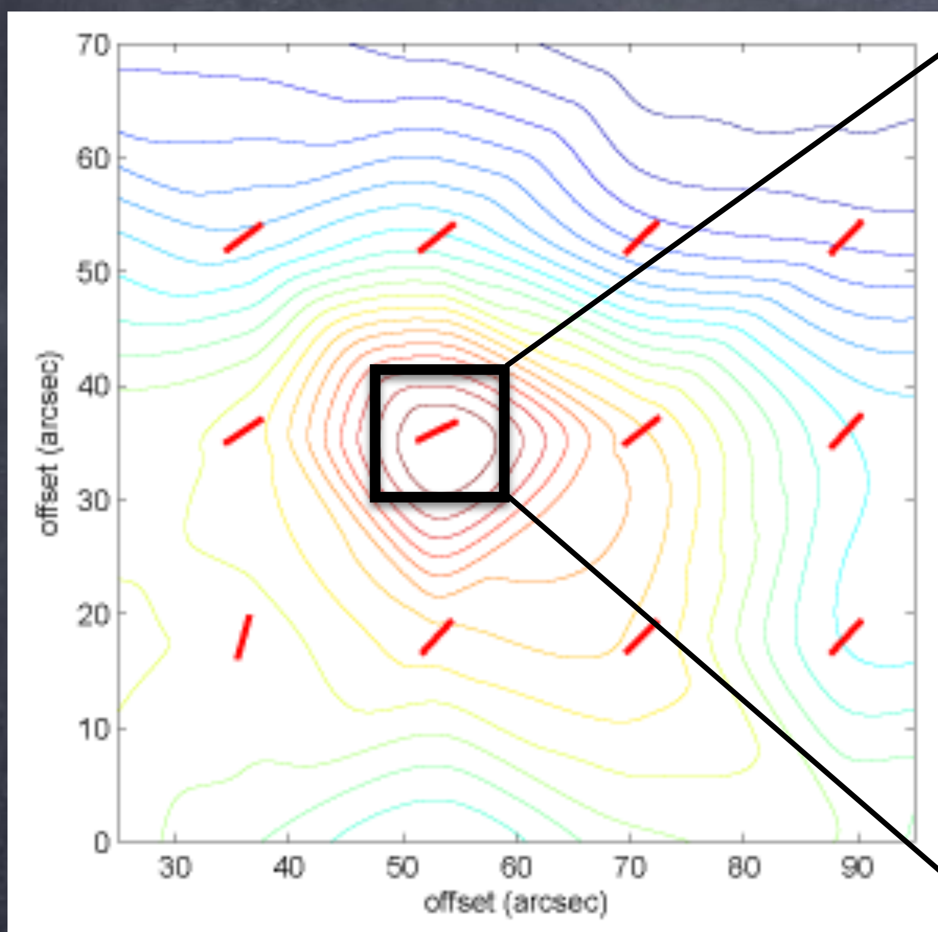




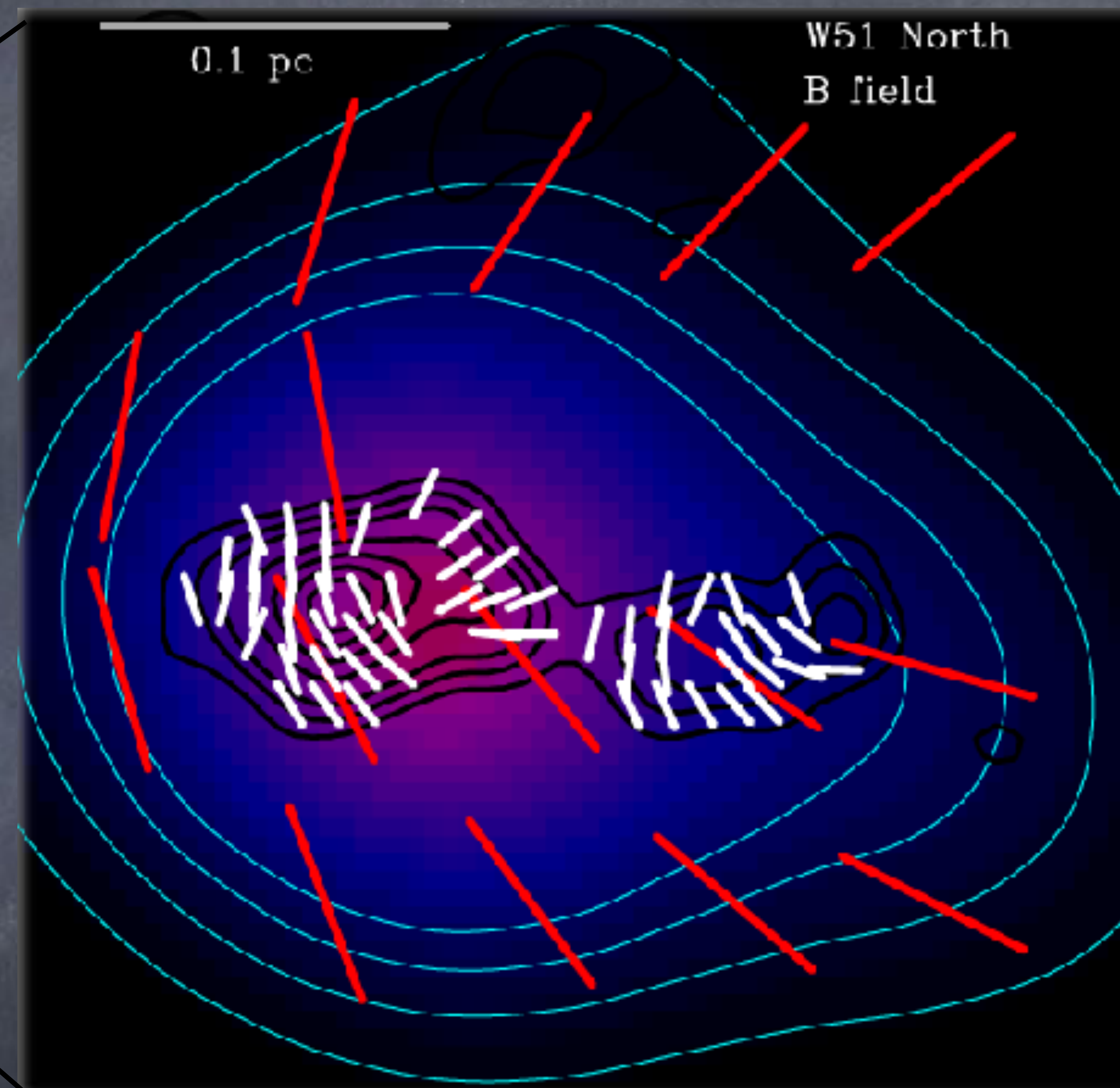
Tang+2009

W51 North with CSO and SMA

CSO/Hertz, 350μm, θ~20”



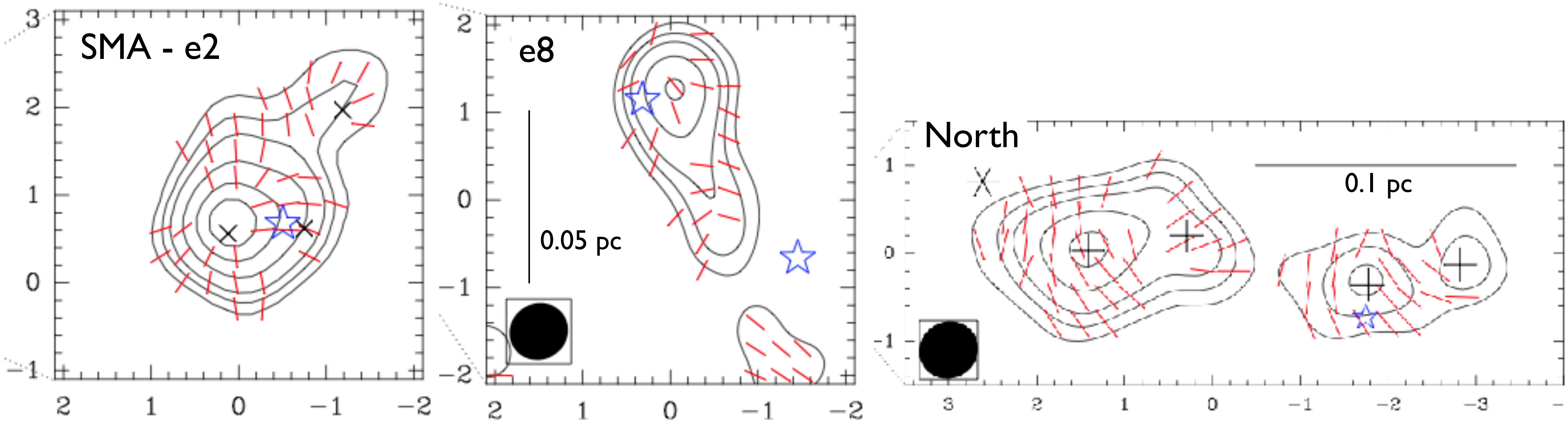
SMA, 870μm, θ~2” and 0.7”



(Tang+2013)

- clearly varying B-field structure as a function of scale
- channeling from North and South towards mid-plane
- denser cores in mid-plane along east-west direction

First ALMA Polarization Observations towards W51



(Tang+2009; 2013)

- ALMA cycle 2/3 (230 GHz (B6), θ ~ 0.26"~ 5 mpc; Koch+2018)
- pol. percentages ~ 0.1 - 10%; sensitivities 1mJy/b in Stokes I, 0.1 mJy/b in Q,U

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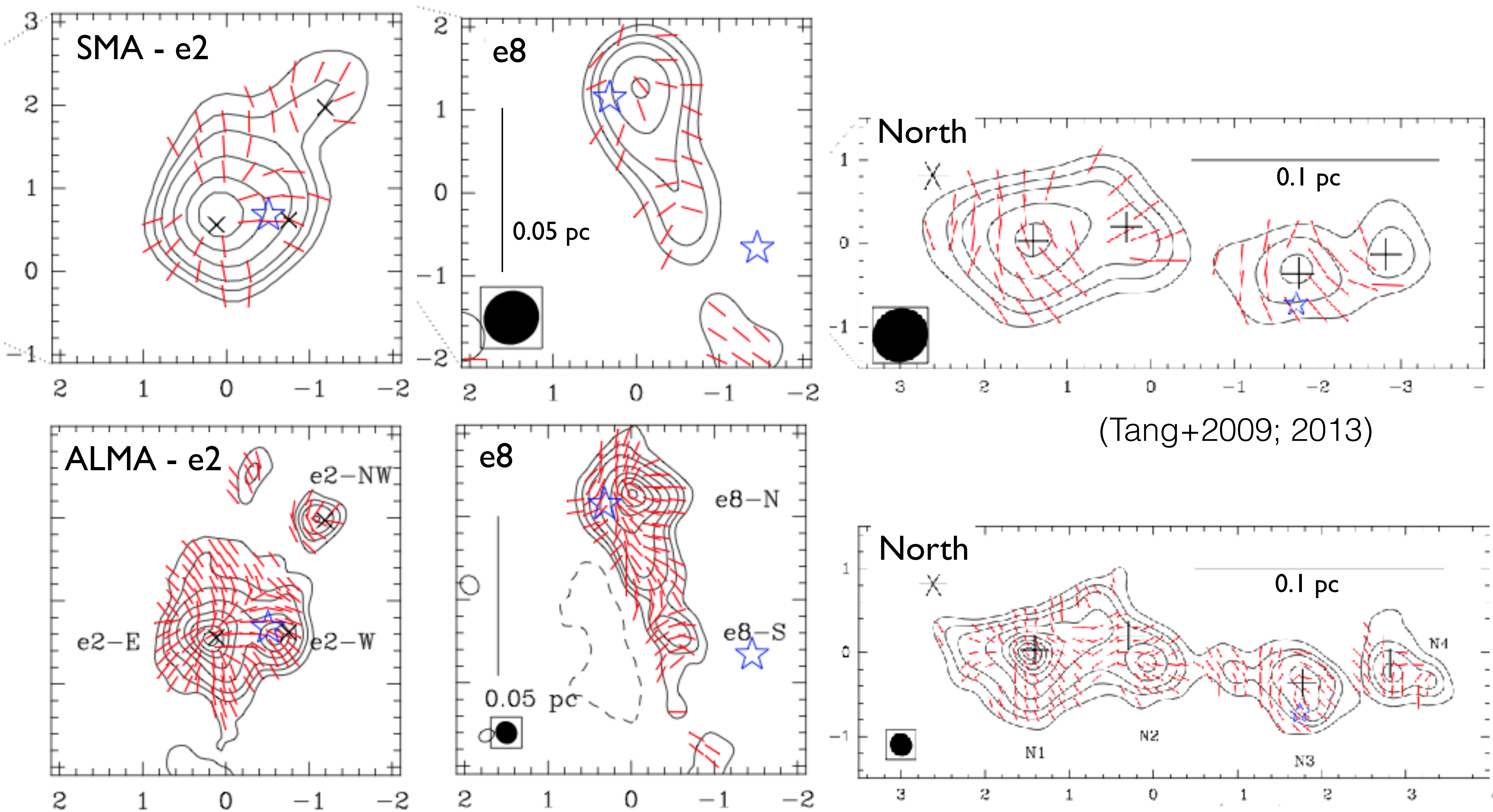

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- new sub-structures:
  cometary-shaped B-field in e2-NW, e8-S, **symmetric convergence zones** (yellow)

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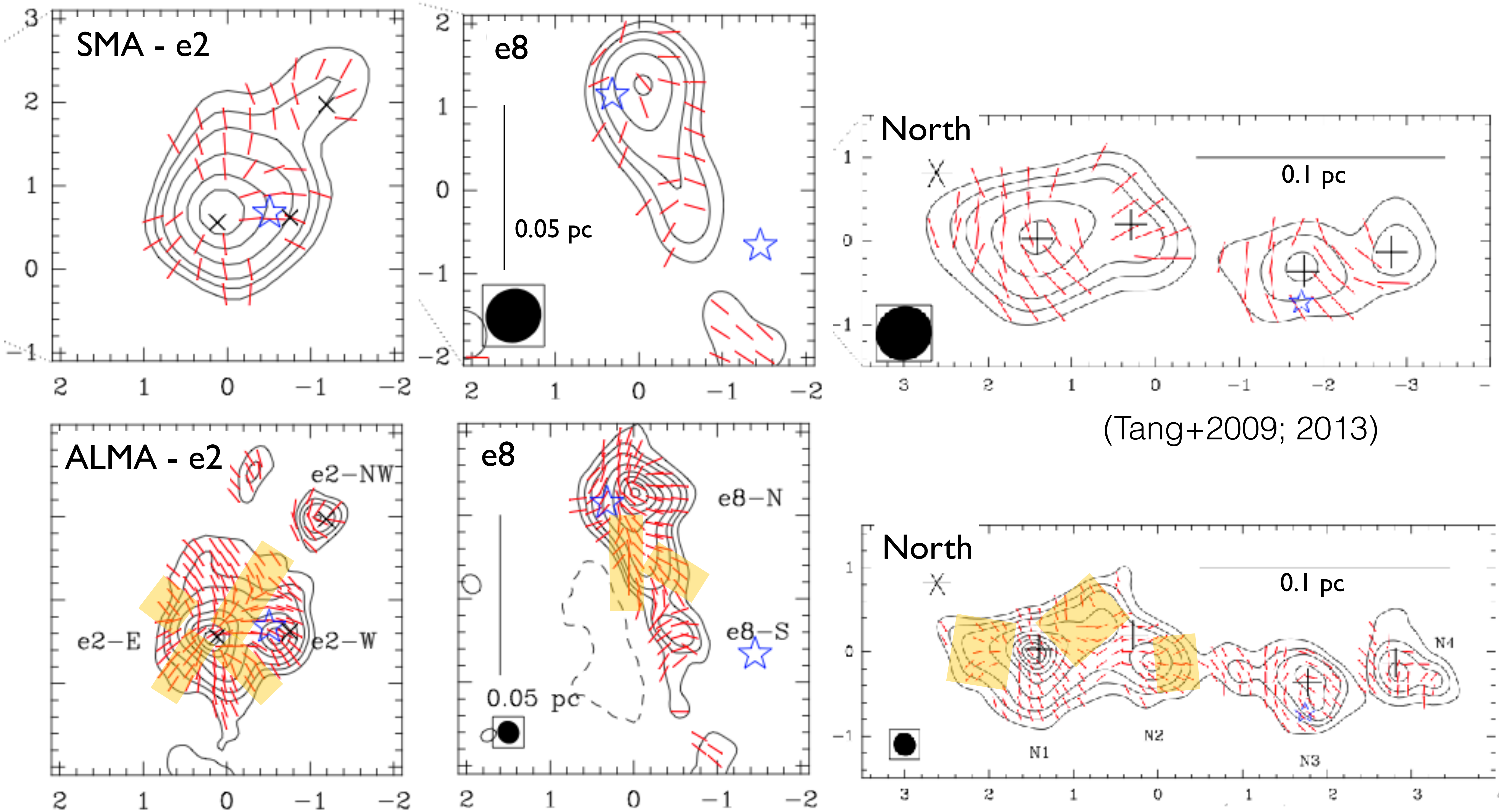

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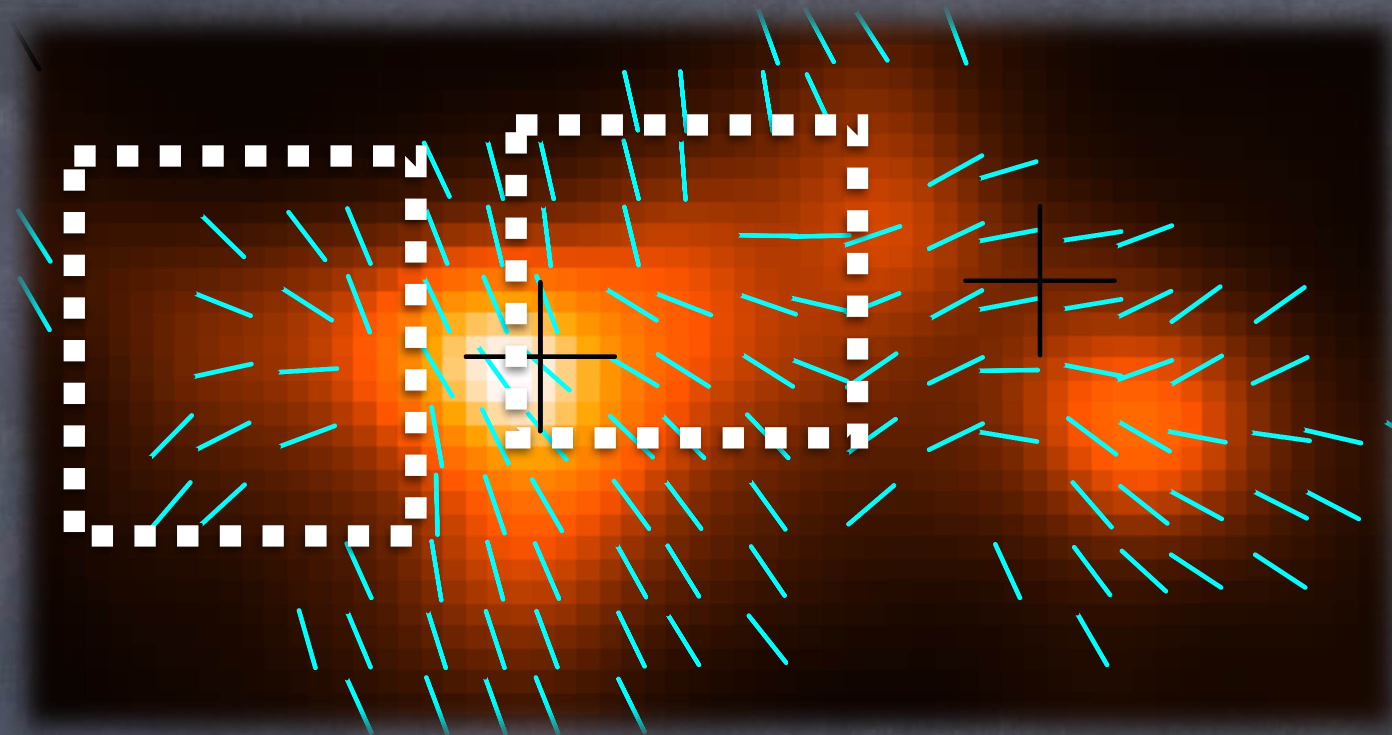
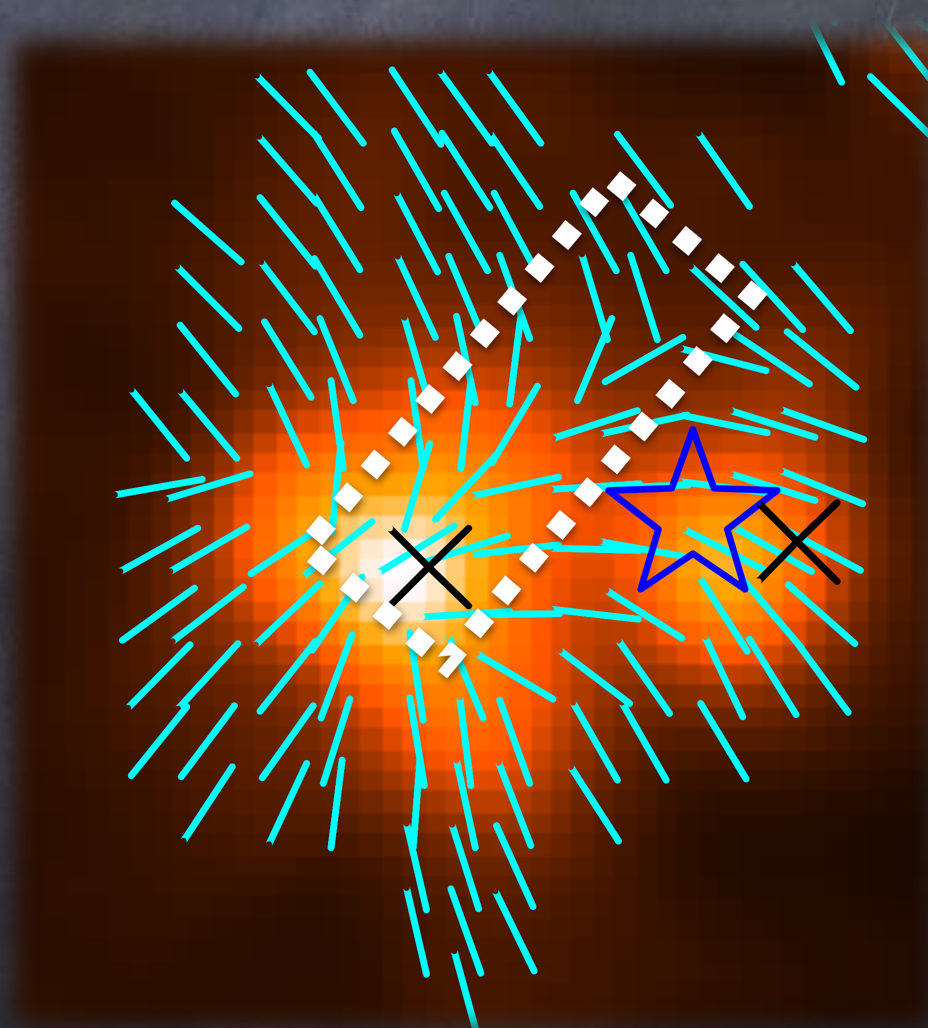
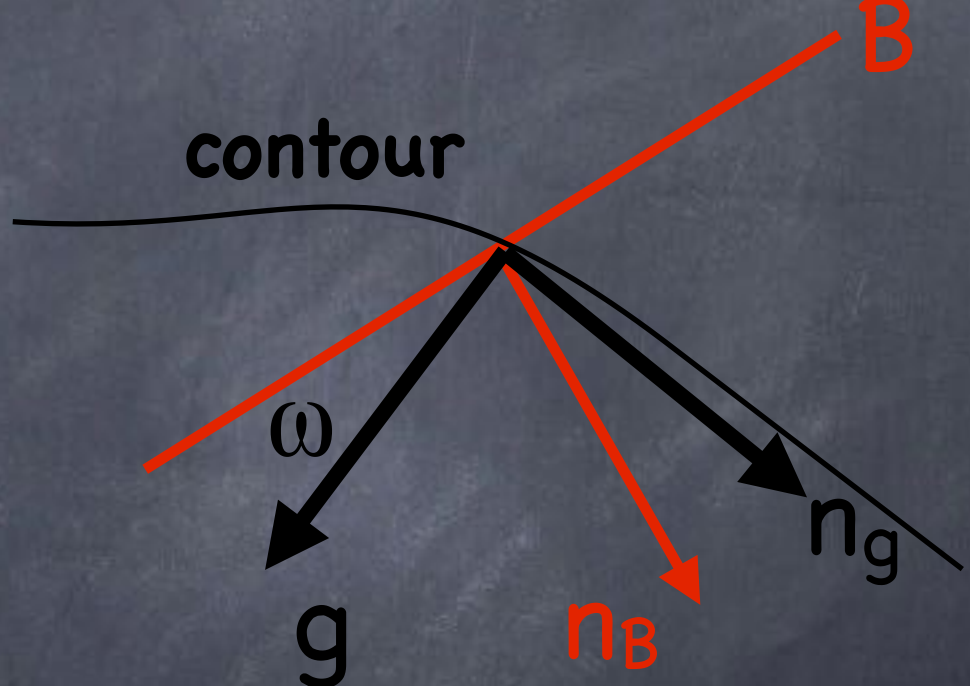
Magnetic Field Convergence Zones

Gravity vs Magnetic Field

- *How important is the magnetic field in e2-E, e2-W and e2-NW ?*
- *In which cores can it still slow down gravitational infall ?*
- *Where is the field already overwhelmed by gravity, and might there be even local differences within the same core?*



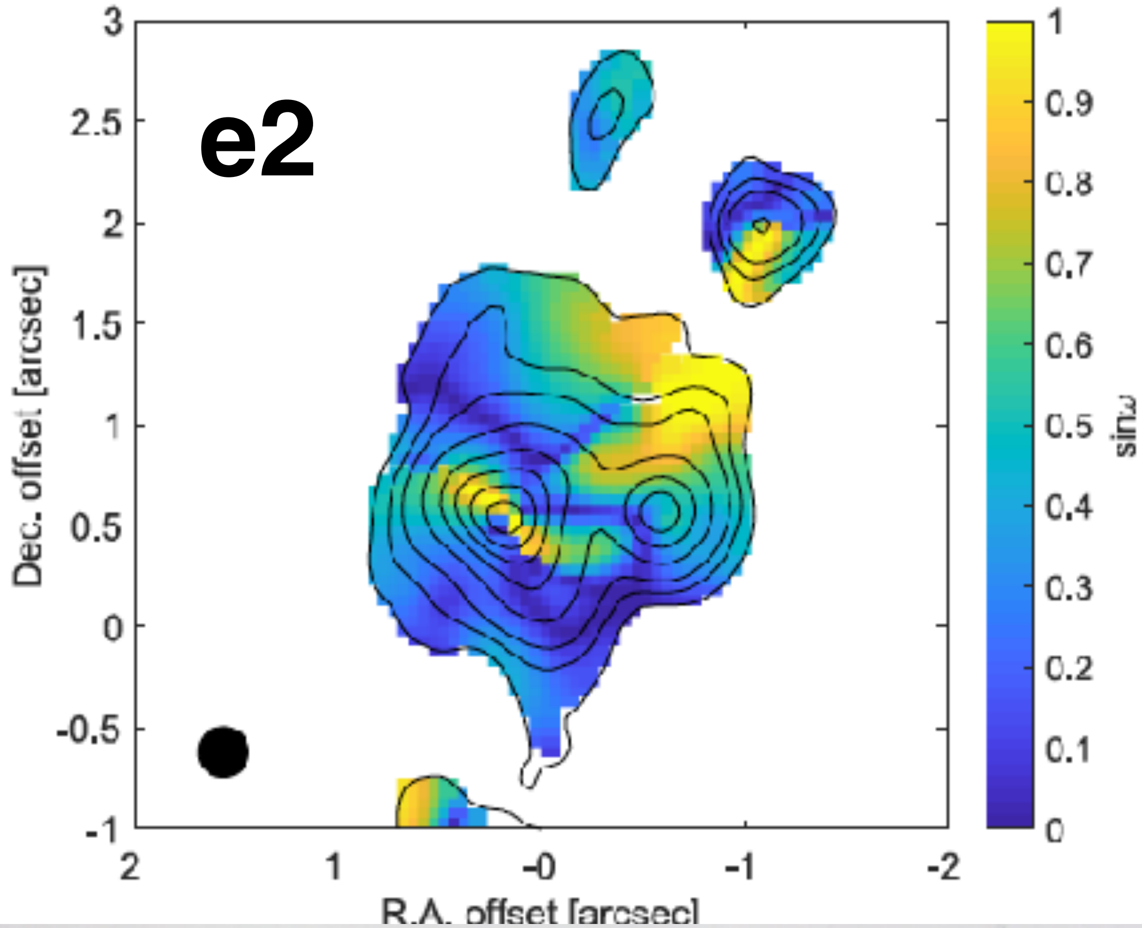
- compare local direction of B-field (n_B) with direction of local gravity (g)
- adopt ideal MHD force equation

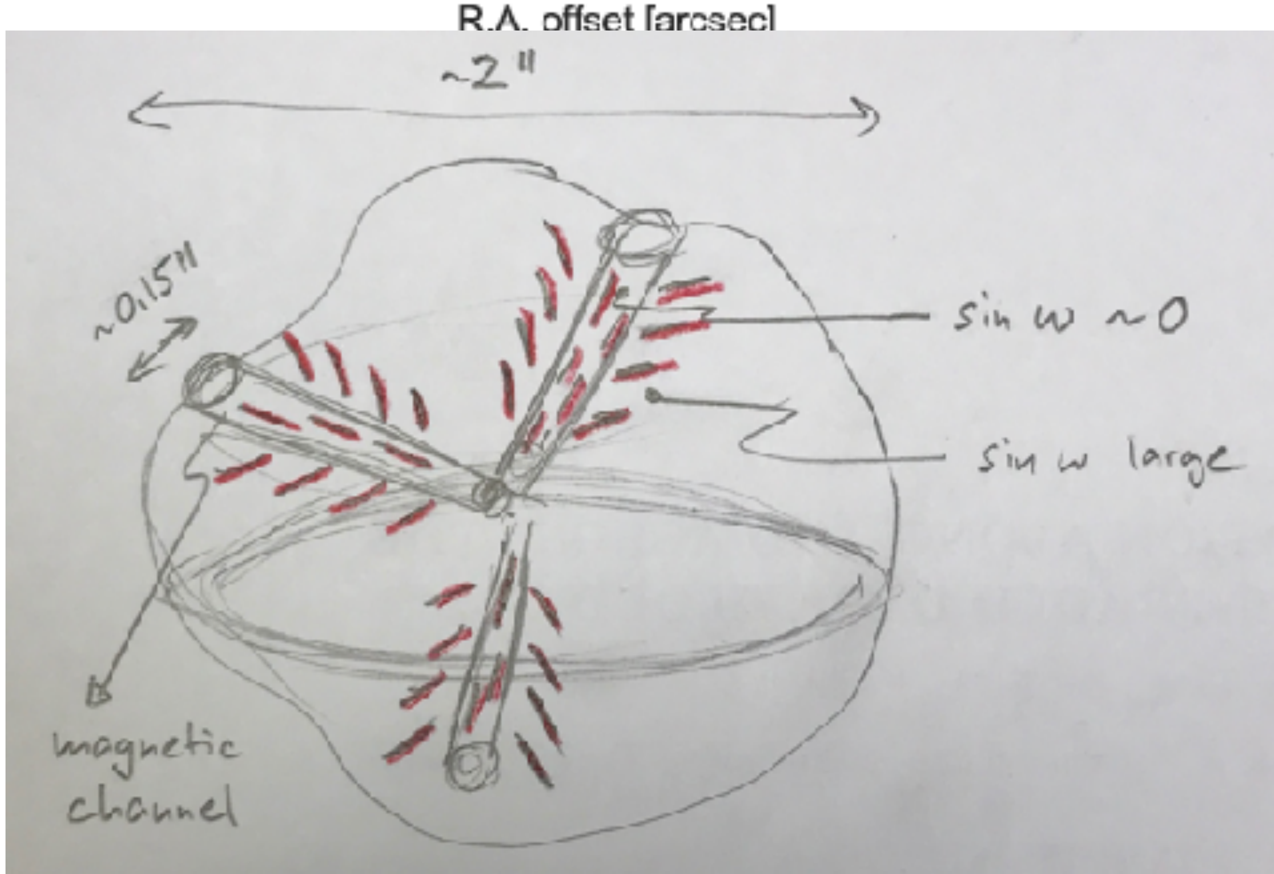
$$\rho\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)\mathbf{v}=-\nabla P-\rho\nabla\phi+\frac{1}{4\pi}\frac{1}{R}B^2\,\mathbf{n}_B$$

$$\rho\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)\mathbf{v}=-\nabla P-\rho|\nabla\phi|\mathbf{g}+\boxed{\frac{1}{4\pi}\frac{1}{R}B^2\,\sin\omega\,\mathbf{g}}+\frac{1}{4\pi}\frac{1}{R}B^2\,\cos\omega\,\mathbf{n}_g$$

sin ω quantifies B-field effectiveness to oppose gravity (Koch+2018)

Convergence Zones, Magnetic Channelling and Star Formation Efficiency





- sinω, in the range between 0 and 1, measures how effectively the B-field can oppose gravity.
  sinω~0: gravity/collapse proceeds freely
  sinω~1: B-field works maximally against gravity, holding back material

- W51 e2: network of narrow magnetic channels (black) with sinω~0

- note: many channels coincide with convergence zones

- *consequence for star formation efficiency?*
  - assume ~ 2″ diameter sphere, ~0.15″ channel width, ~10 channels
  - 1 channel ~ 0.4% of entire mass (volume); if only mass within channels takes part in star-formation process: star-formation efficiency reduced to ~ 4% for W51 e2

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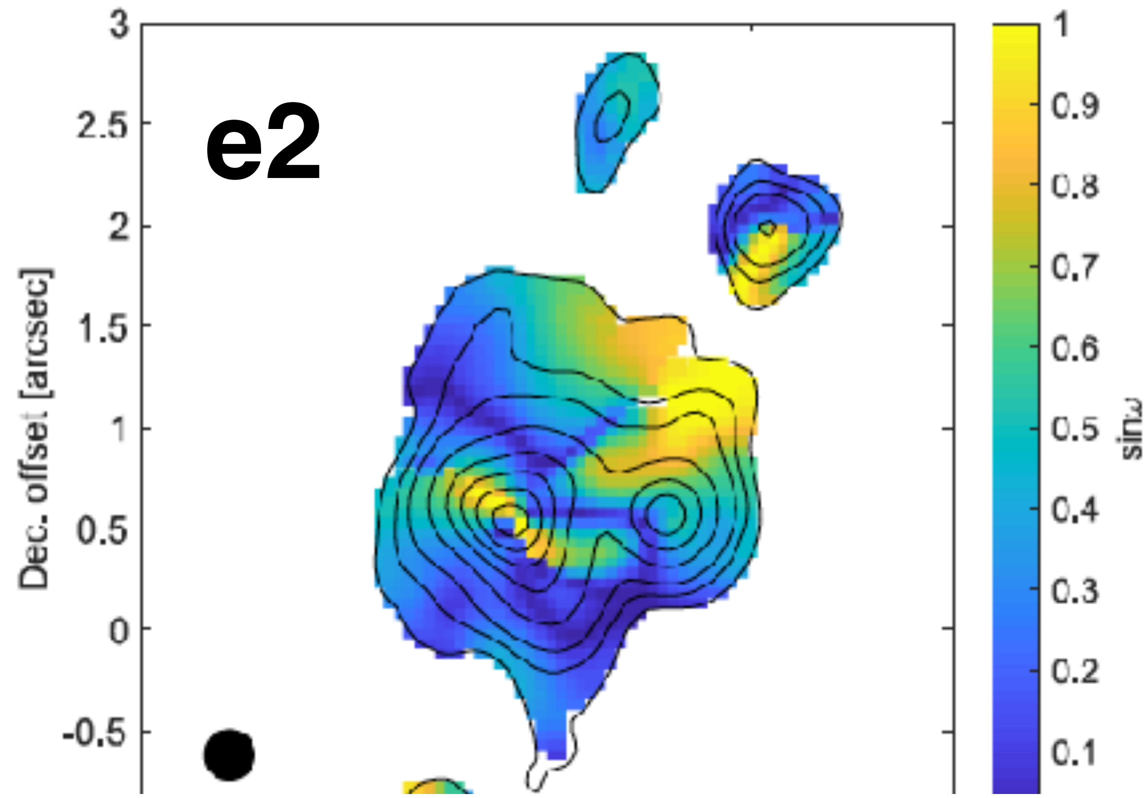

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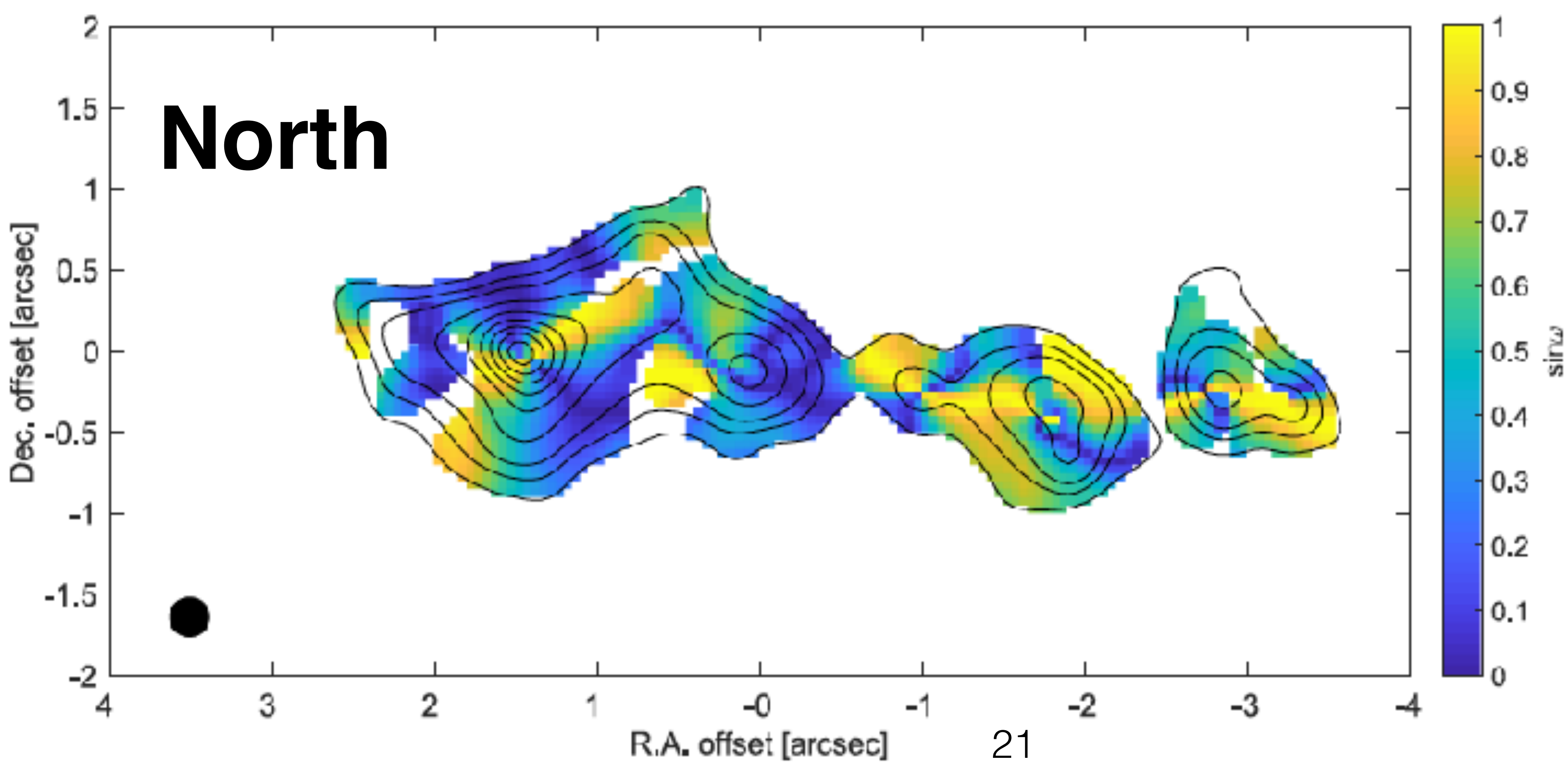
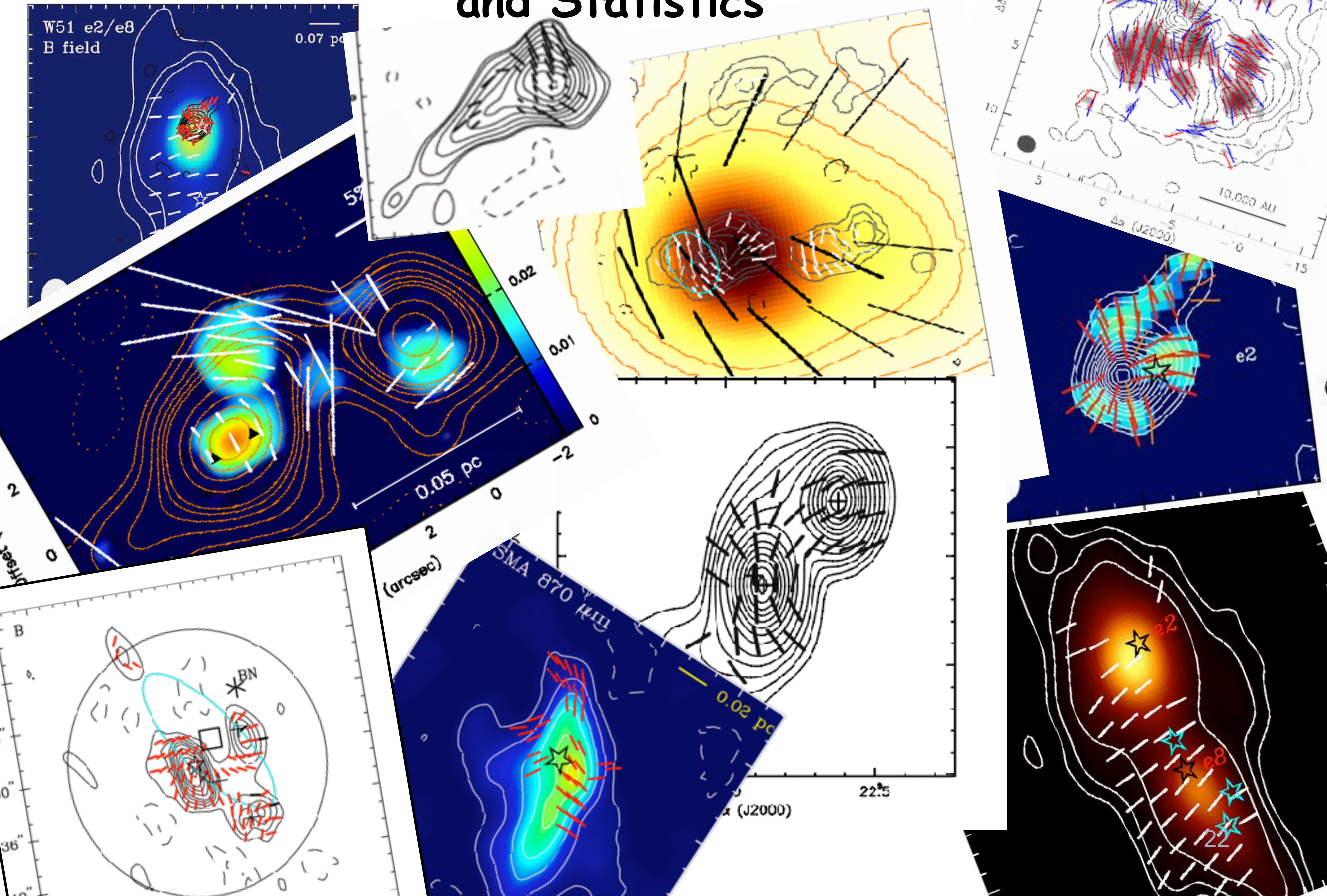


oincide with

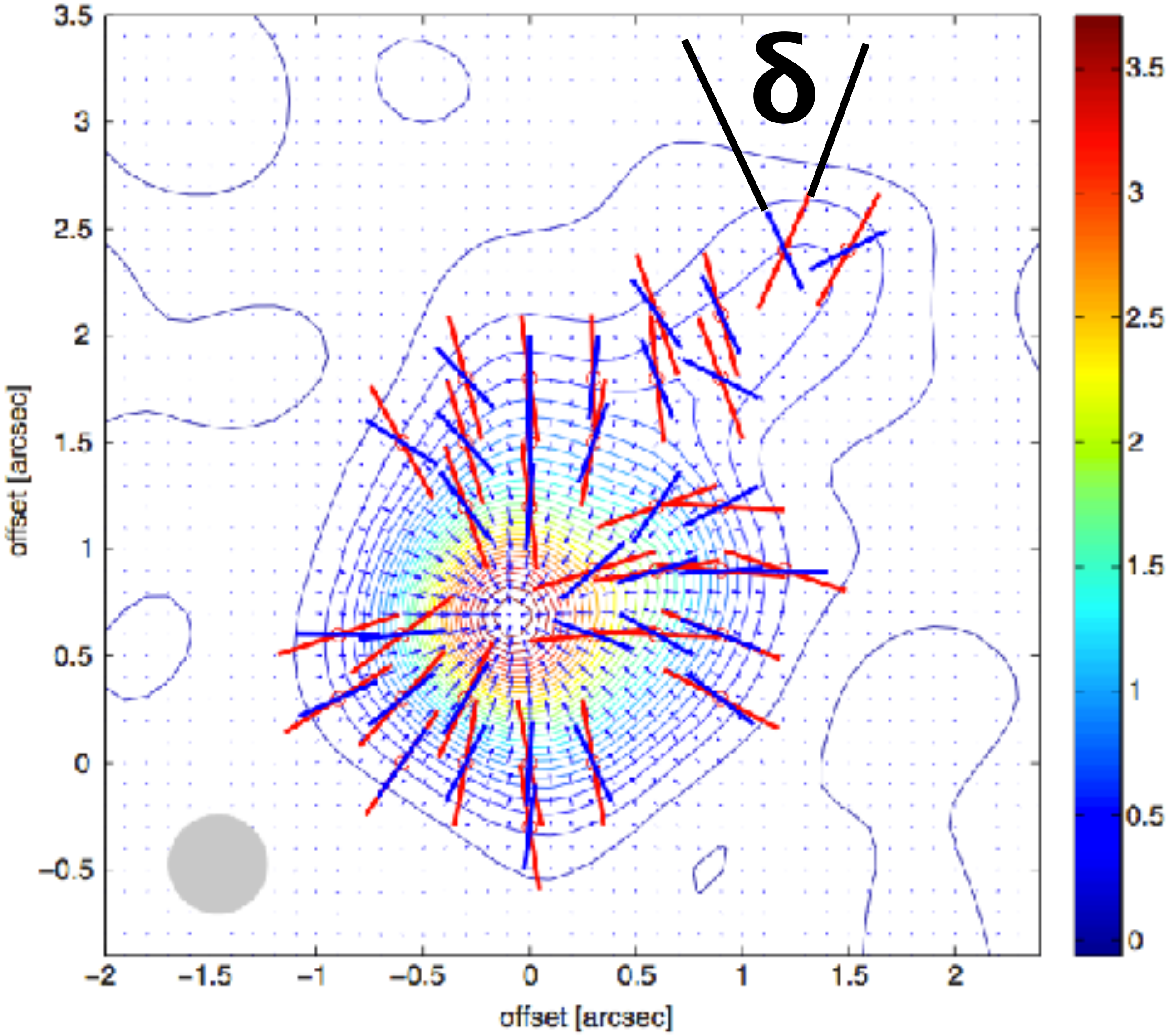
ormation efficiency?

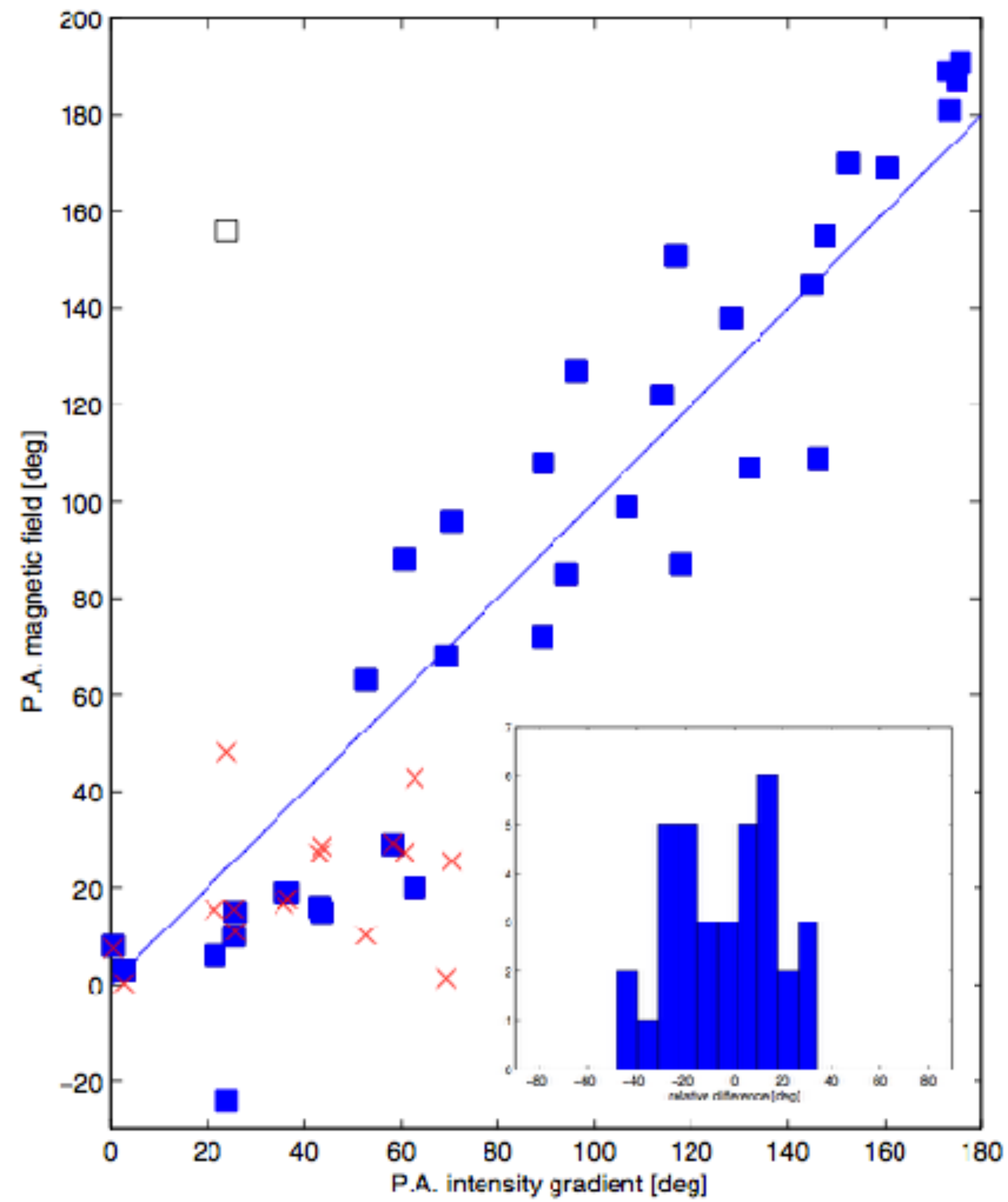
Beyond Imaging - Novel Analysis Techniques and Statistics



Key Observable: angle δ

W51 e2 (SMA, Θ ~ 0.7 ")





Koch, Tang & Ho, 2012

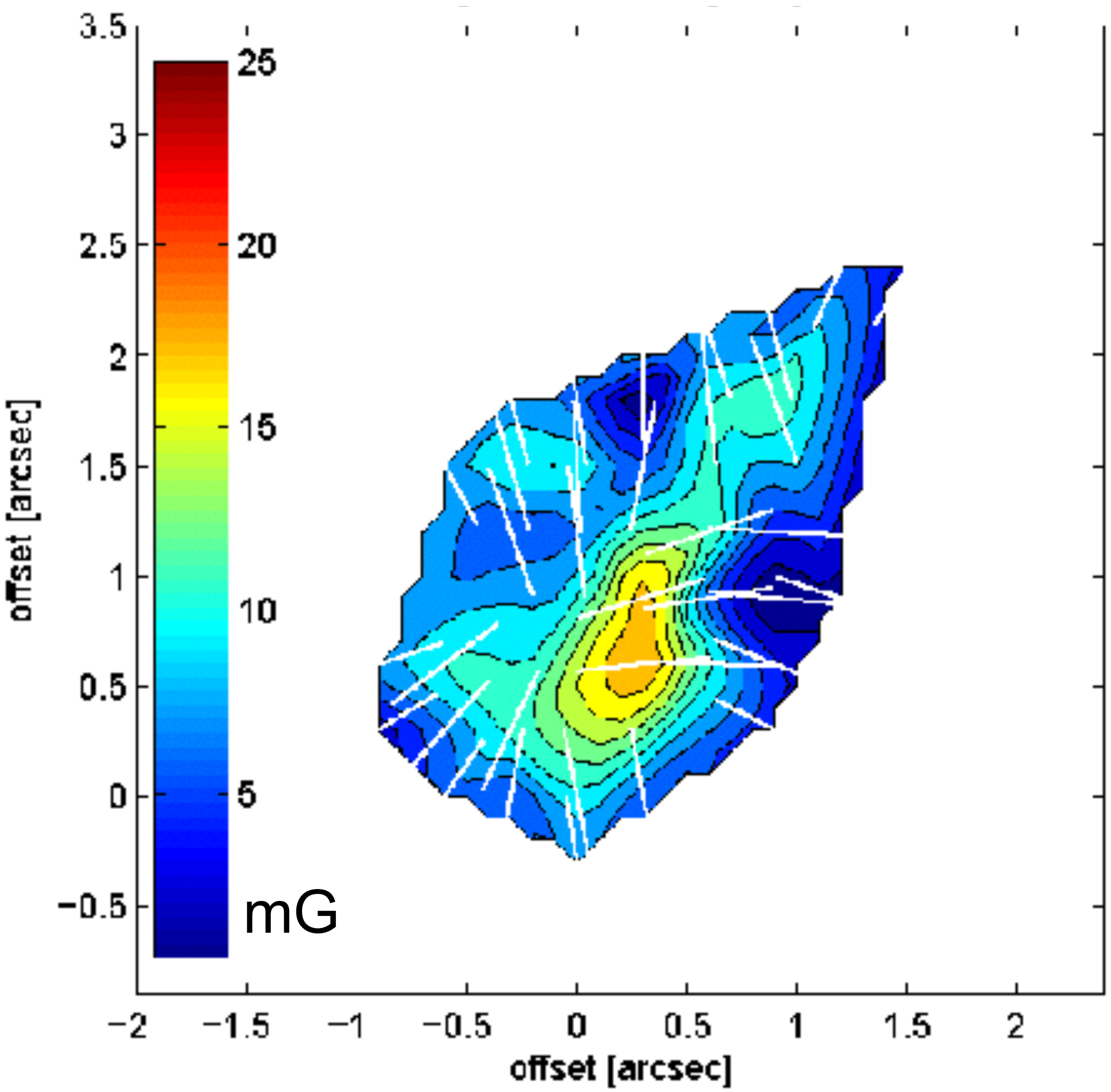
motivation:

clear correlation in orientations between intensity gradient and field orientations !

What can we learn from δ ?

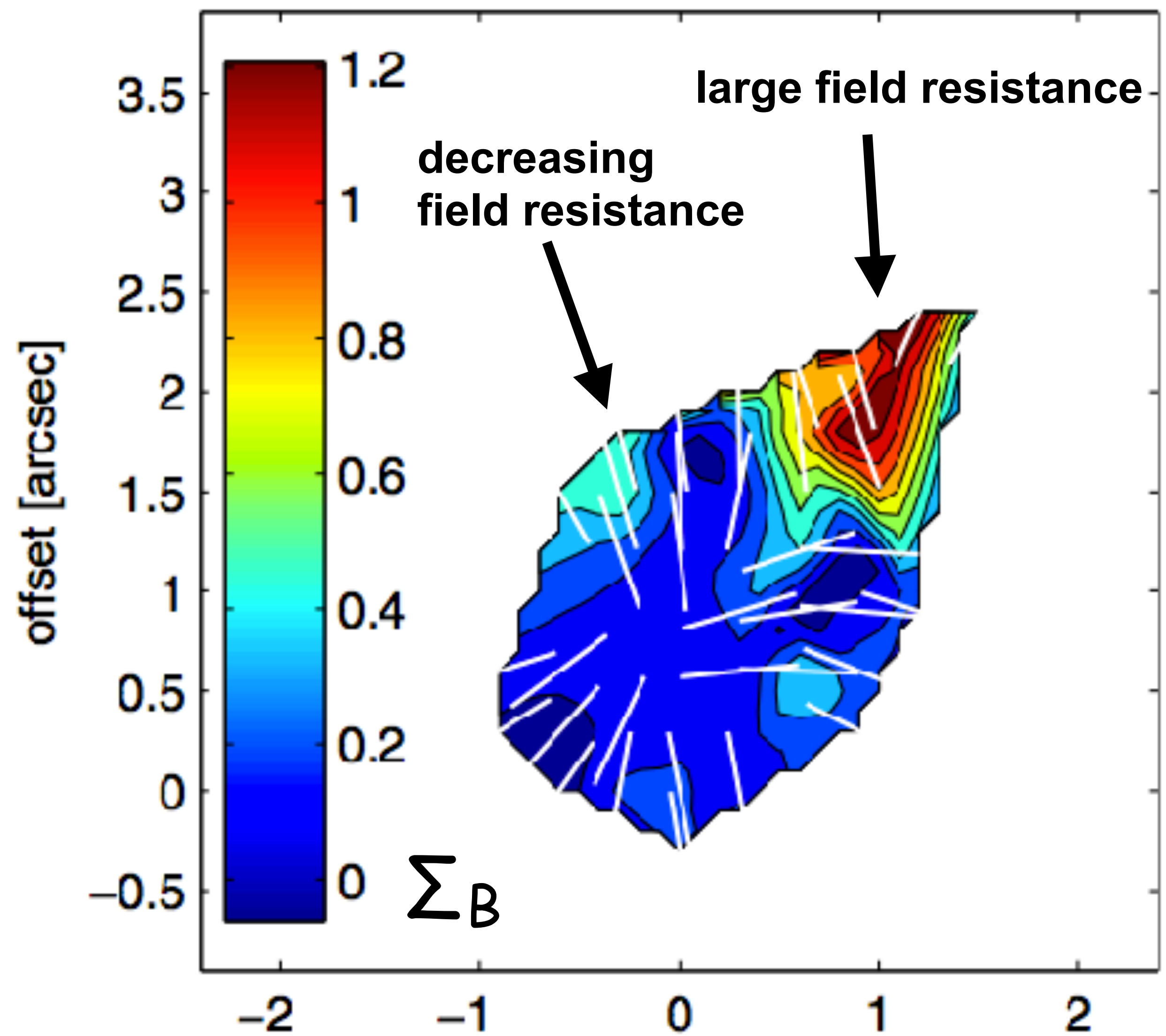
Magnetic Field Strength Map

$$B = \sqrt{\frac{\sin \psi}{\sin\left(\frac{\pi}{2} - |\delta|\right)} (\nabla P + \rho \nabla \phi) 4\pi\, R}$$



Field-to-Gravity Force Ratio Σ_B

$$\Sigma_B \equiv \frac{\sin \psi}{\sin\left(\frac{\pi}{2} - |\delta|\right)} = \frac{F_B}{|F_G + F_P|}$$



(Koch, Tang & Ho, 2012a,b;2013)

Increasing Sample Size: SMA Polarization Legacy Program and CSO archival data

* about 20 additional sources (new or deeper integration, dedicated SMA legacy program, Zhang + SMA pol legacy team, 2014)

  total: about 30 sources in polarization with the SMA

* high-mass sites with density > 10^5 cm^{-3} on scales 0.1 to 0.01 pc, resolutions around 1" - 3"

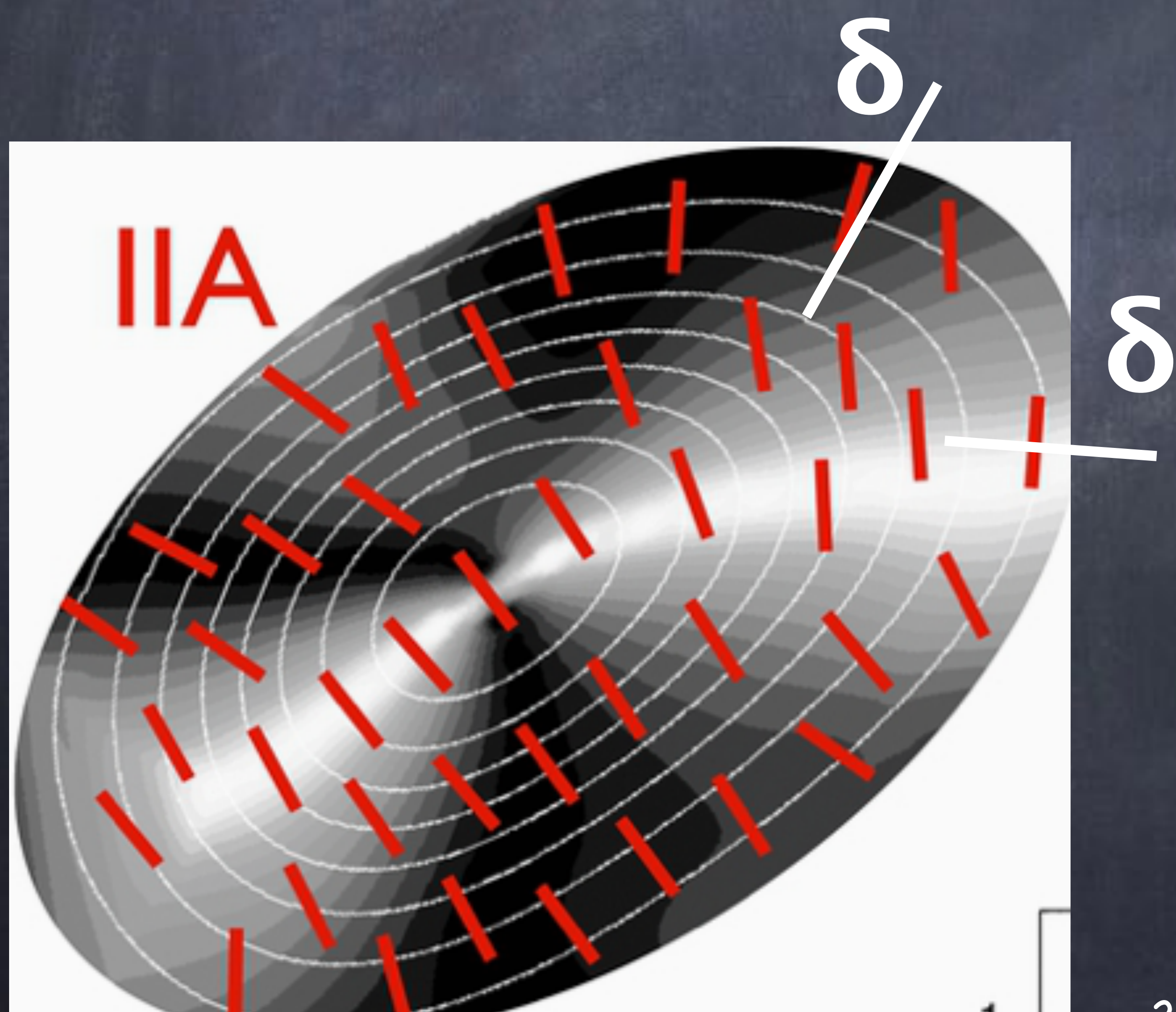
* additionally: CSO archival data (about 20 sources), covering scales around 1 pc

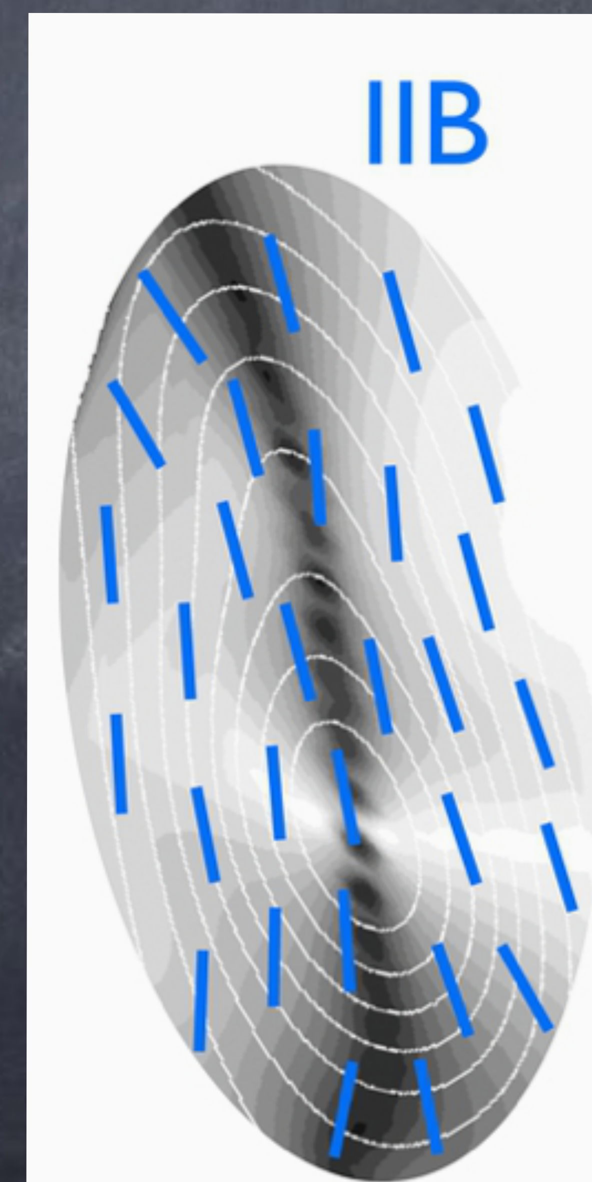
* total sample: 50 sources (low- and high-mass star forming regions)

Beyond Imaging: Statistics
50-source sample SMA / CSO observations

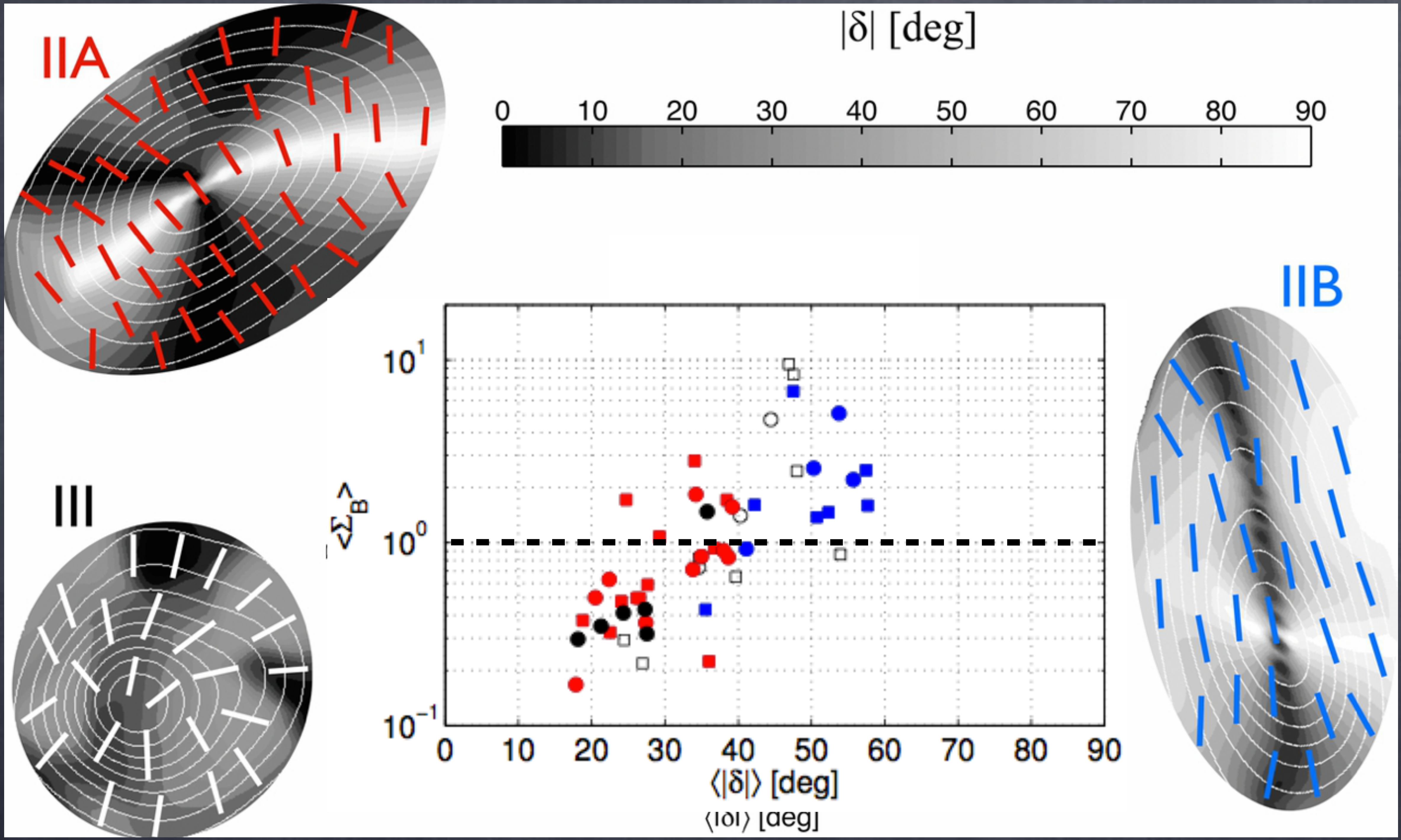
- field morphology is organized
  (not necessarily uniform, but clearly not random)

- field morphologies are systematic
  key observable: angle δ between emission gradient and magnetic field





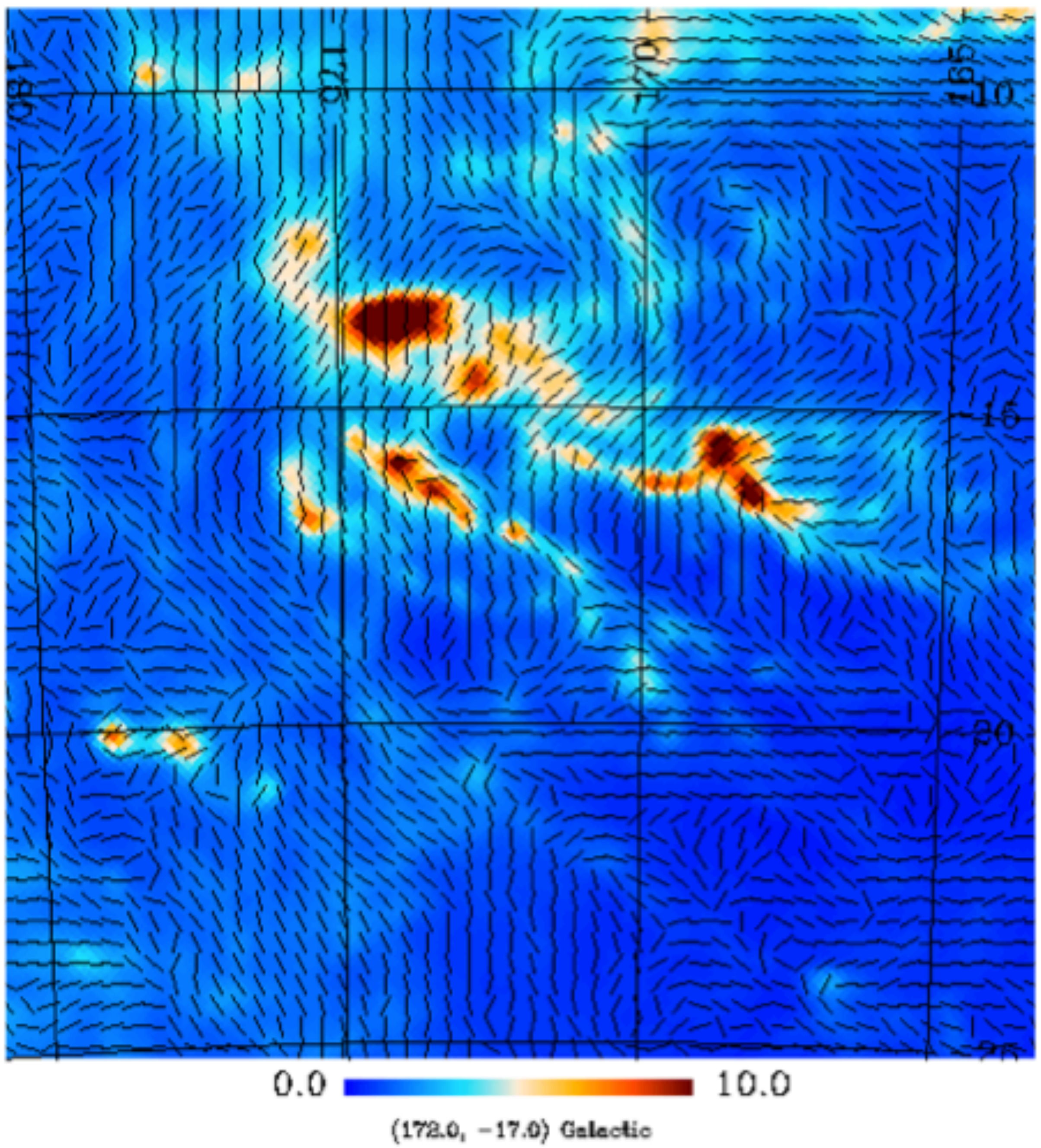
δ across a Sample of 50 sources (SMA+CSO)

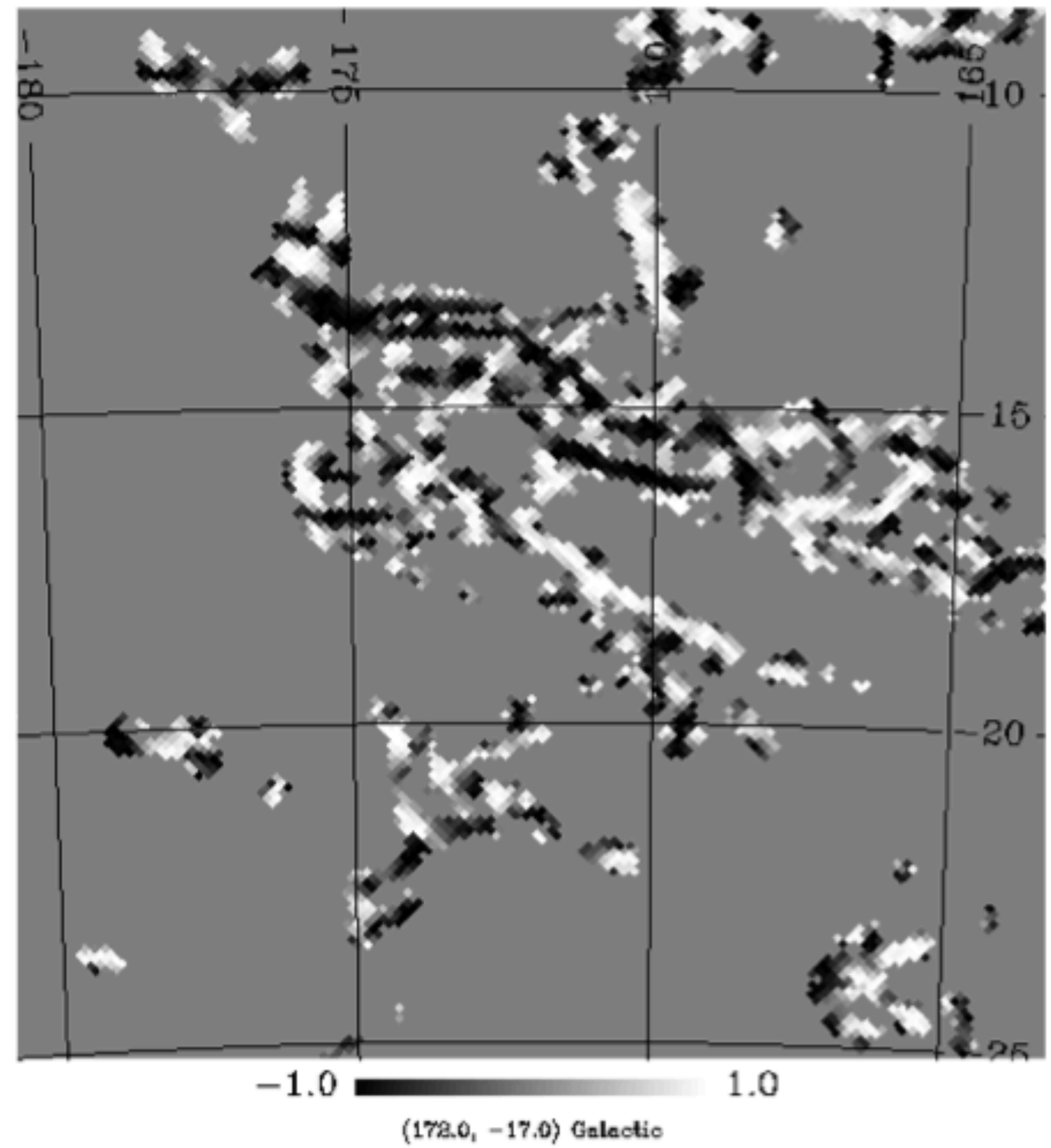


(Koch+ SMA pol legacy, 2014)

- average <|δ|> is systematically different across sample
- <|δ|> is typically small for sources with magnetic field parallel to source minor axis, <|δ|> grows for sources with field parallel to major axis
- $<\Sigma_B>$ grows systematically with <|δ|> with a transition across 1

where are we standing? one step back:
Larger Scale Interstellar Medium by Planck

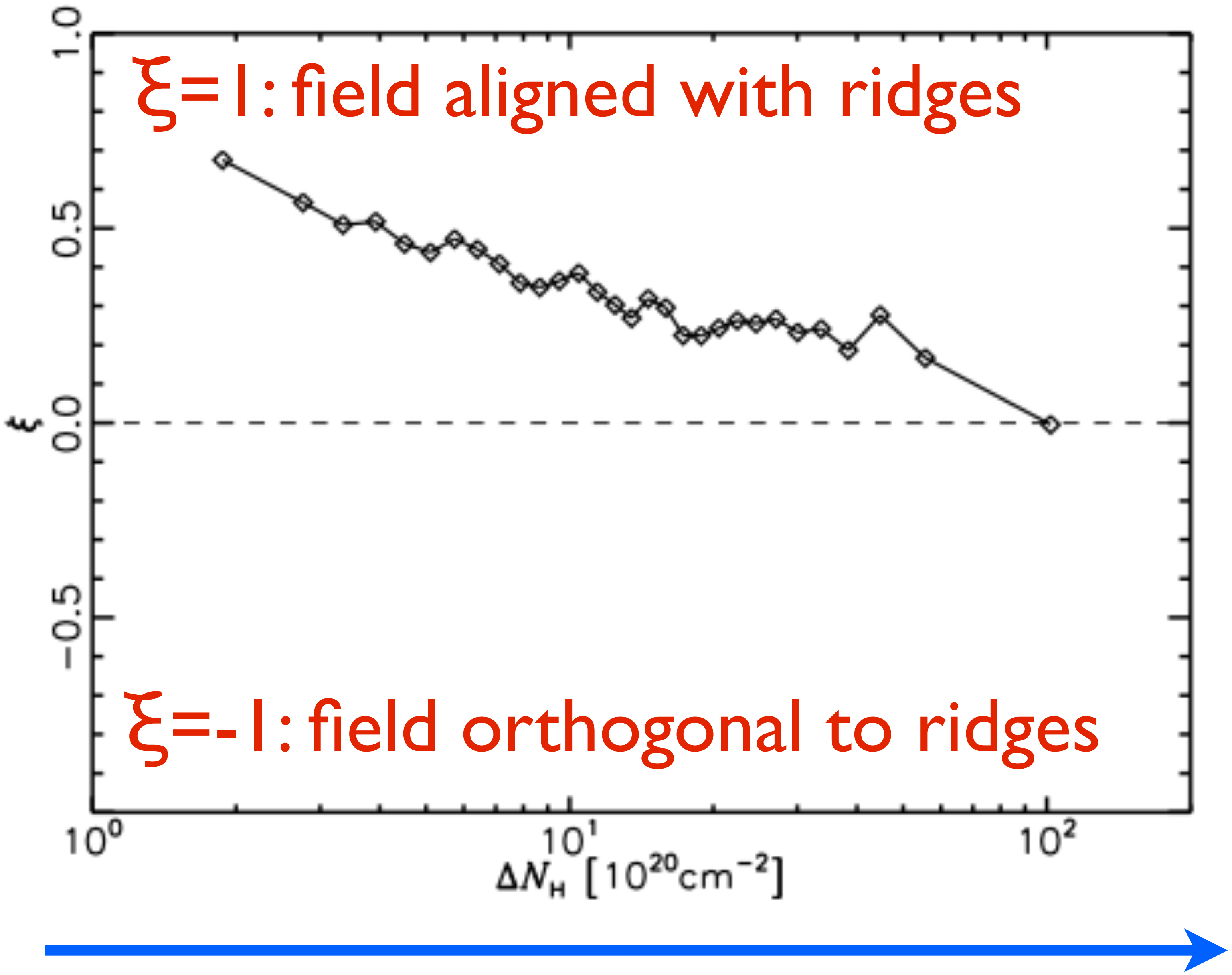




Taurus molecular cloud complex;
dust continuum at 350 GHz
15′ resolution

(Planck XXXII, 2014)

Planck: Interstellar Medium



filamentary ***molecular cloud***

(Planck XXXII, 2014)

magnetic field vs structure:

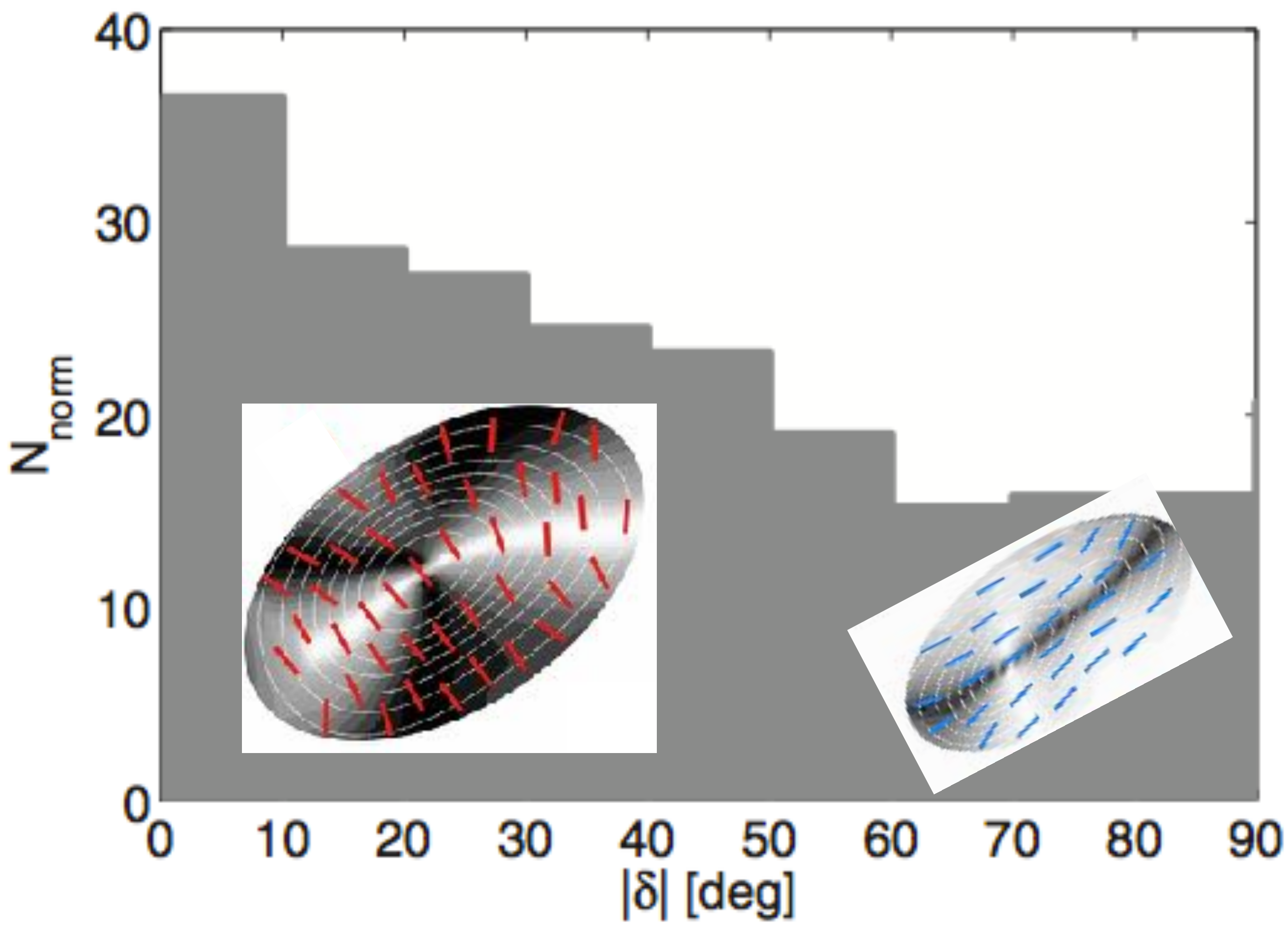
- field tends to be aligned with ridges in diffuse ISM
- alignment progressively changes as column density increases

- ***interpretation:***
  magnetic field is guiding material, possibly significant level of turbulence organizing material parallel to magnetic field

- ***question:***
  how does the role of the magnetic field evolve towards smaller scales?

- utilize dust polarization observations on smaller scales with the SMA, CSO, JCMT, (ALMA)

SMA Polarization Legacy Program + CSO Archival data: Magnetic Field vs Dust Continuum Structure



50 sources,
~ 4000 independent measurements

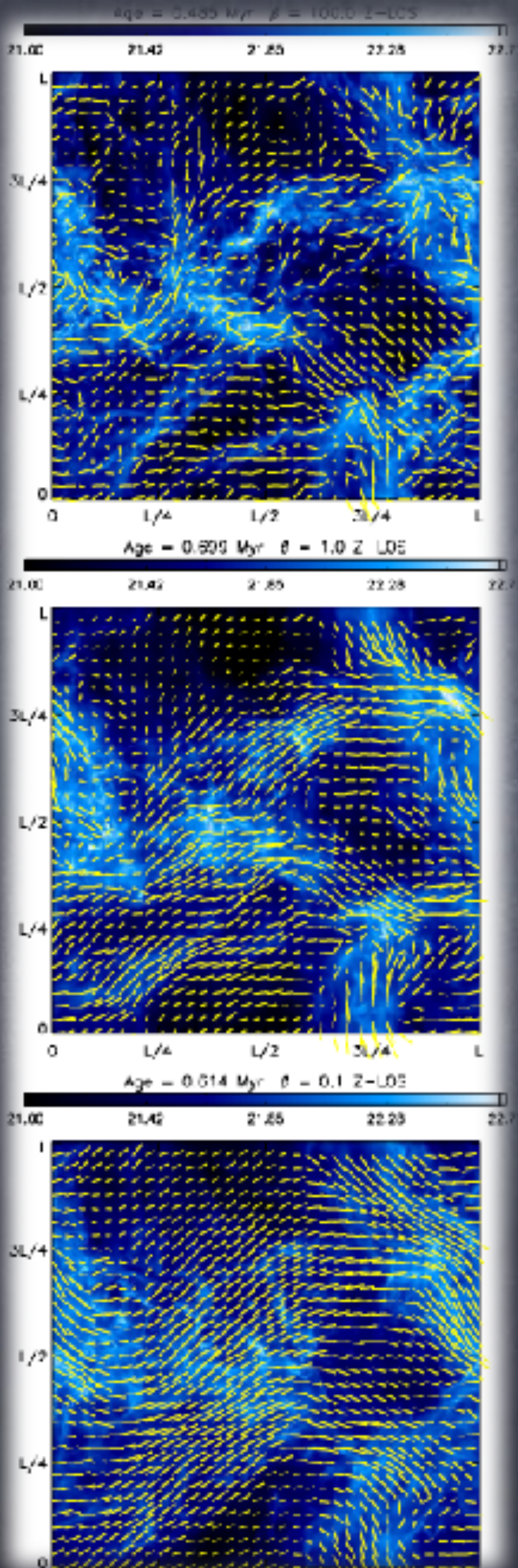
density regime: 10^5 cm^{-3} or higher

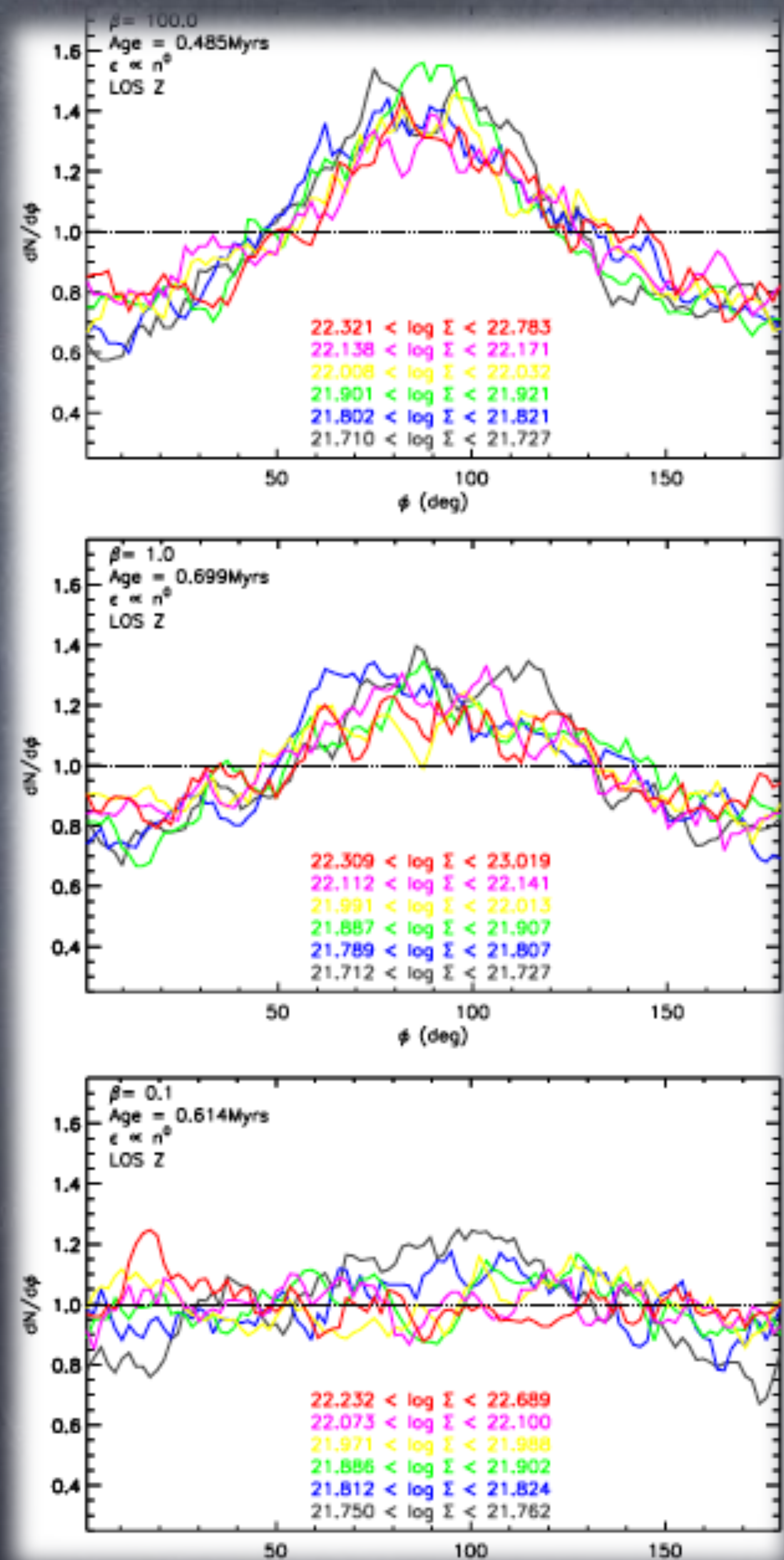
(Koch + SMA pol legacy, 2014)

- ***prevailing field orientation: roughly parallel to source minor axis***

- ***connecting to Planck result:*** (Planck XXXII, 2014/2016)
  field tends to be aligned with diffuse ridges in diffuse ISM, but progressively changes as column density increases
- magnetic field very likely plays different roles as a function of scales and location

Numerical Work





- simulating large-scale filamentary structures (Planck, BLASTPol)

- “Histogram of Relative Orientations” between magnetic field and density structures (equivalent to angle δ)

- histograms carry information on magnetization, age, and column density

(Soler, Hennebelle+2013)

Conclusions

- ***filament:*** * organized B-field, mostly perpendicular to filament, B-field channelling material, “G vs B vs T” locally different

  * relative significance of G,B, and T hints different fragmentation scenarios

- ***ALMA:*** * detailed magnetic field morphologies reveal dynamical picture: convergence zones, magnetic channelling, cometary-shaped satellites

  * sin ω quantifies B-field effectiveness to oppose gravity

- ***protostellar source:*** * tracing spec. ang. mom. profile can constrain magnetic braking

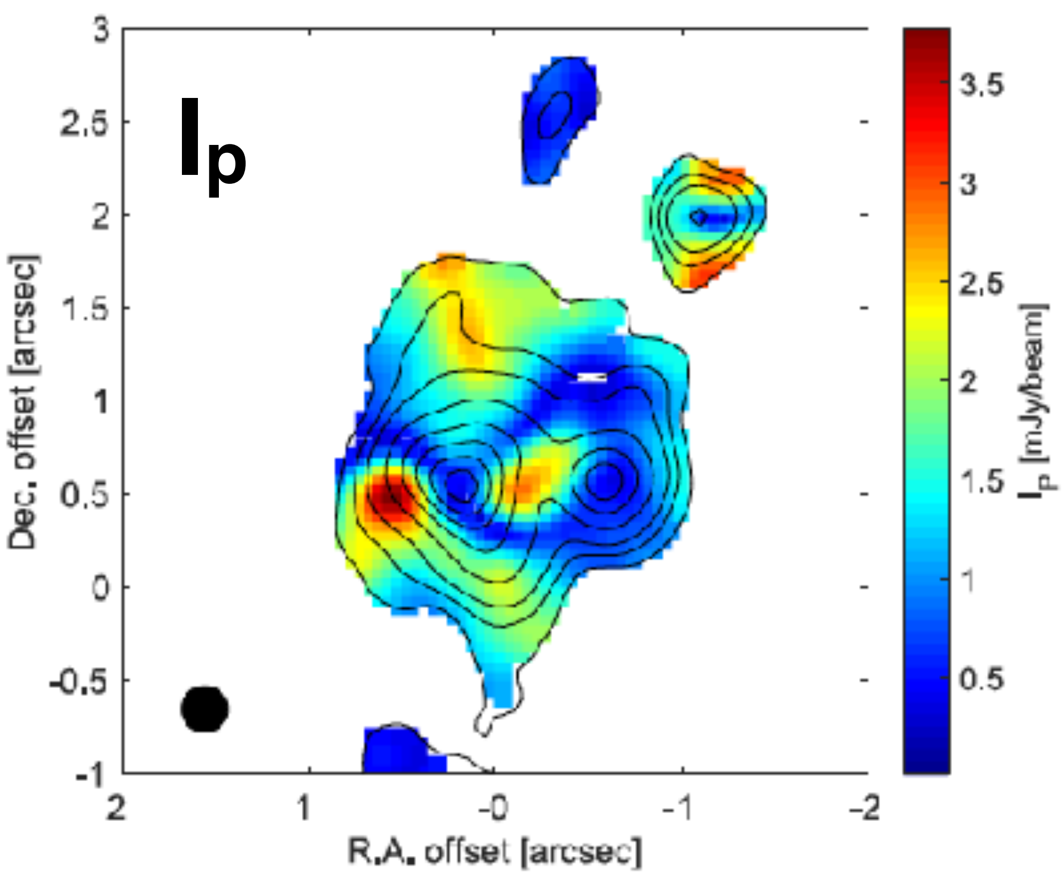
- ***analysis techniques:*** δ is a key observable, leading to local field strength measurement and local force ratio Σ_B

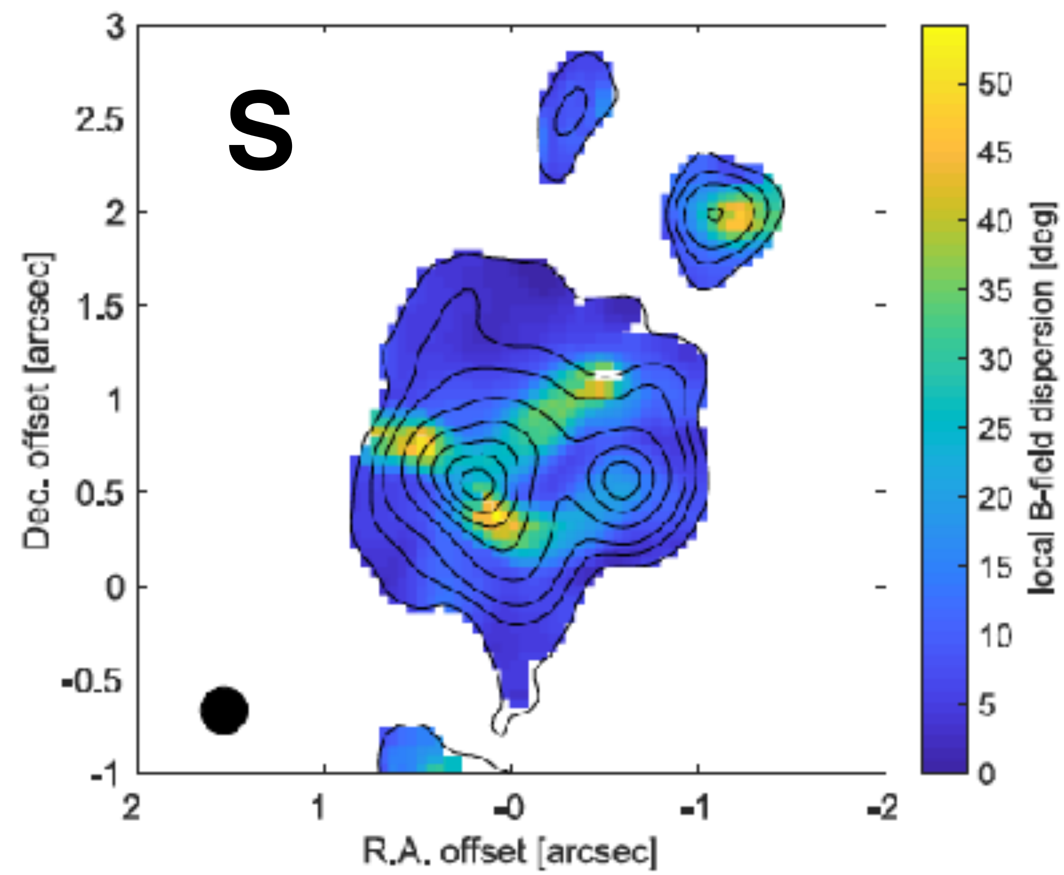
- ***sample:*** * δ and Σ_B discriminate between different types of magnetic-field configurations (possibly different evolutionary stages)

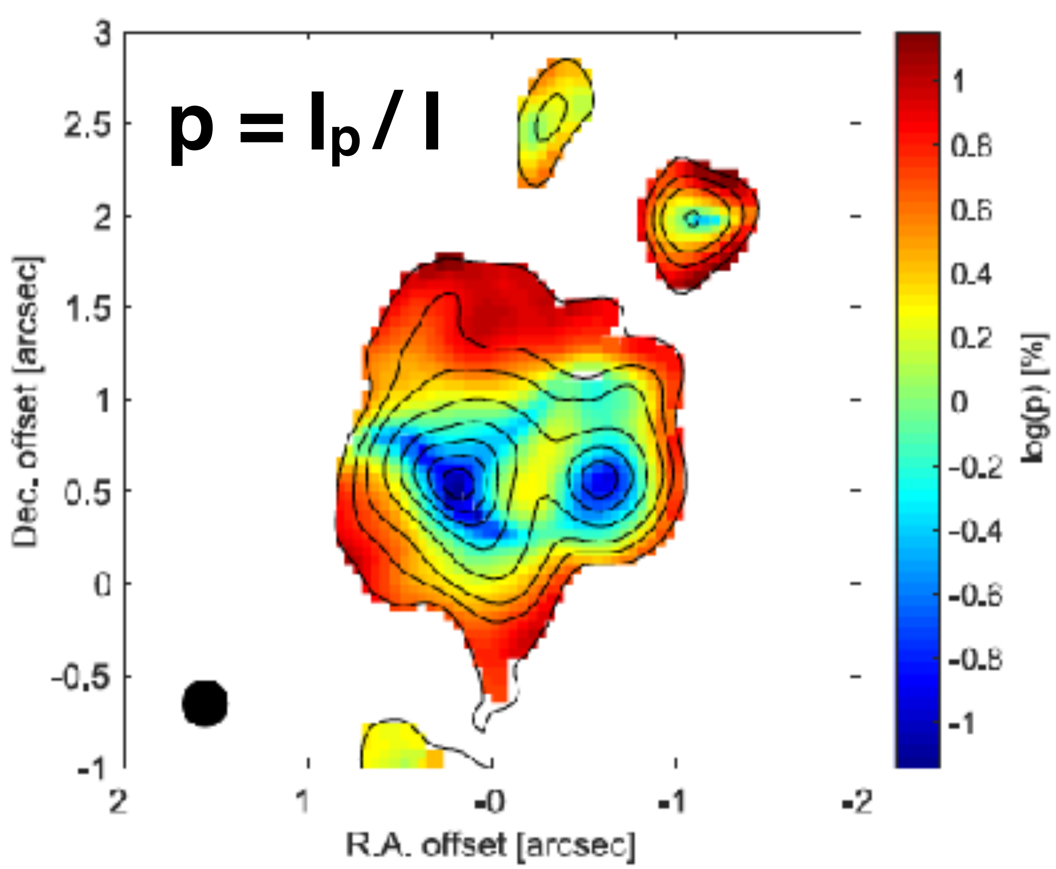
  * sample of 50 sources: δ and Σ_B show clear correlation; i.e., the larger δ, the more the field dominates gravity

additional slides

A Note on Polarized Emission and Polarization Percentages

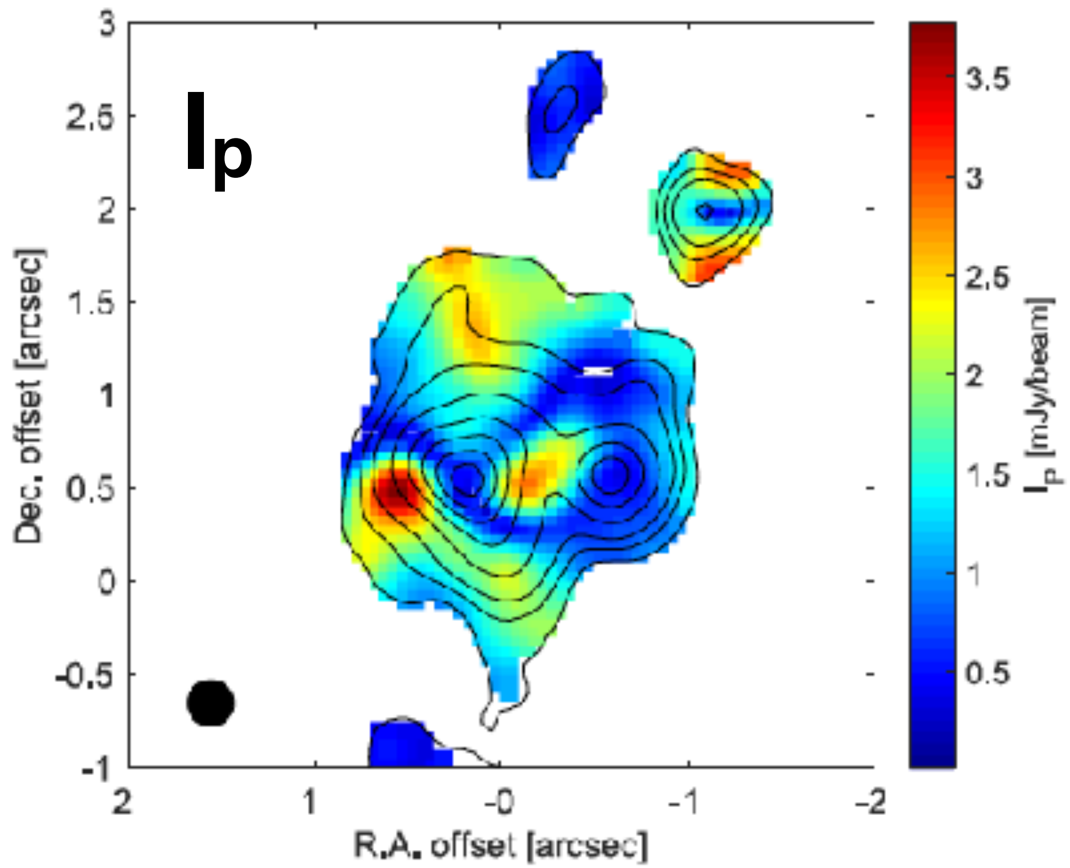


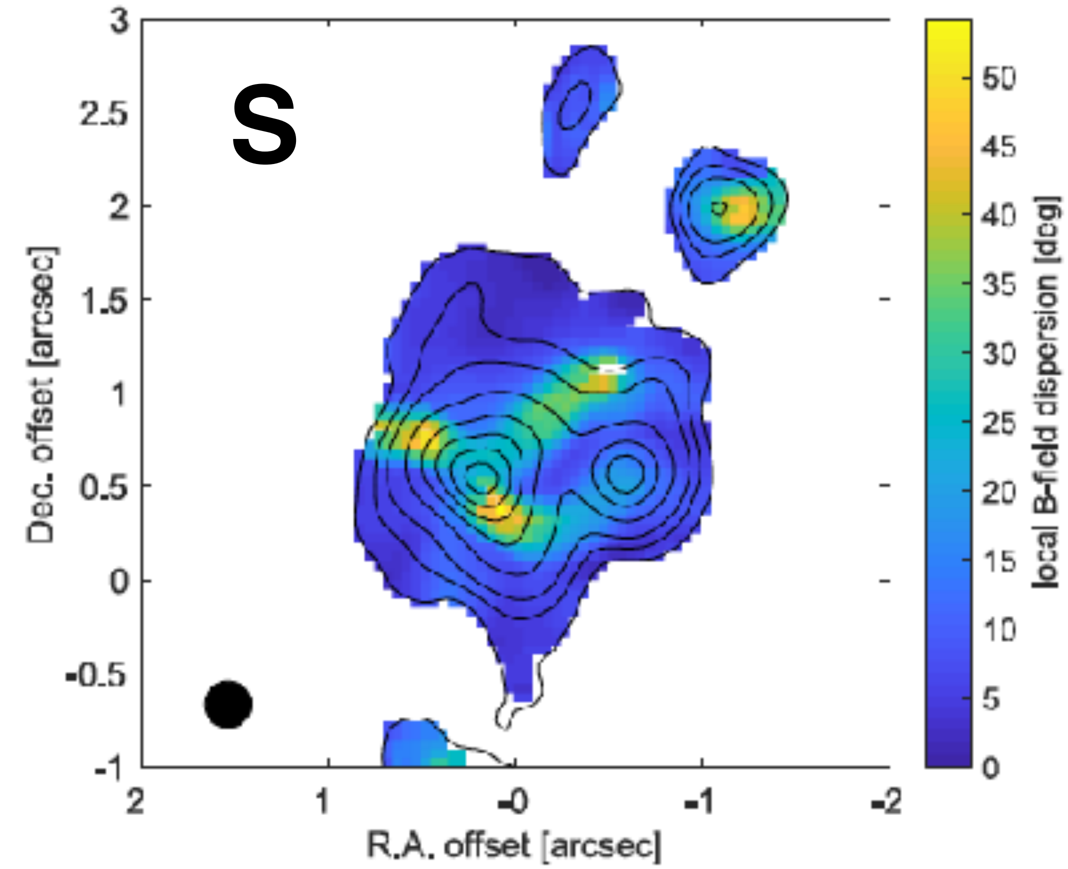


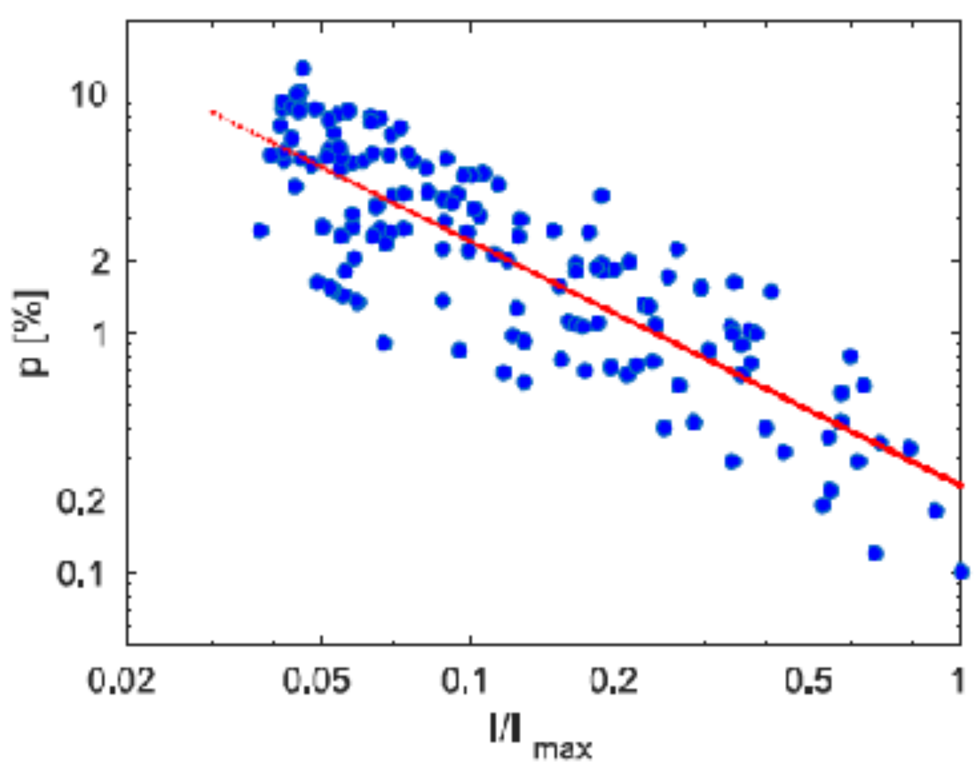


- complicated but organized structure in polarized emission I_p
- some correlation with local B-field dispersion S (also seen on larger scales in Fissel+2016; Planck XIX, XX, 2015)
- typical anti-correlation between polarization percentage p and total intensity Stokes I, slope ~ -1, but with very large scatter

A Note on Polarized Emission and Polarization Percentages







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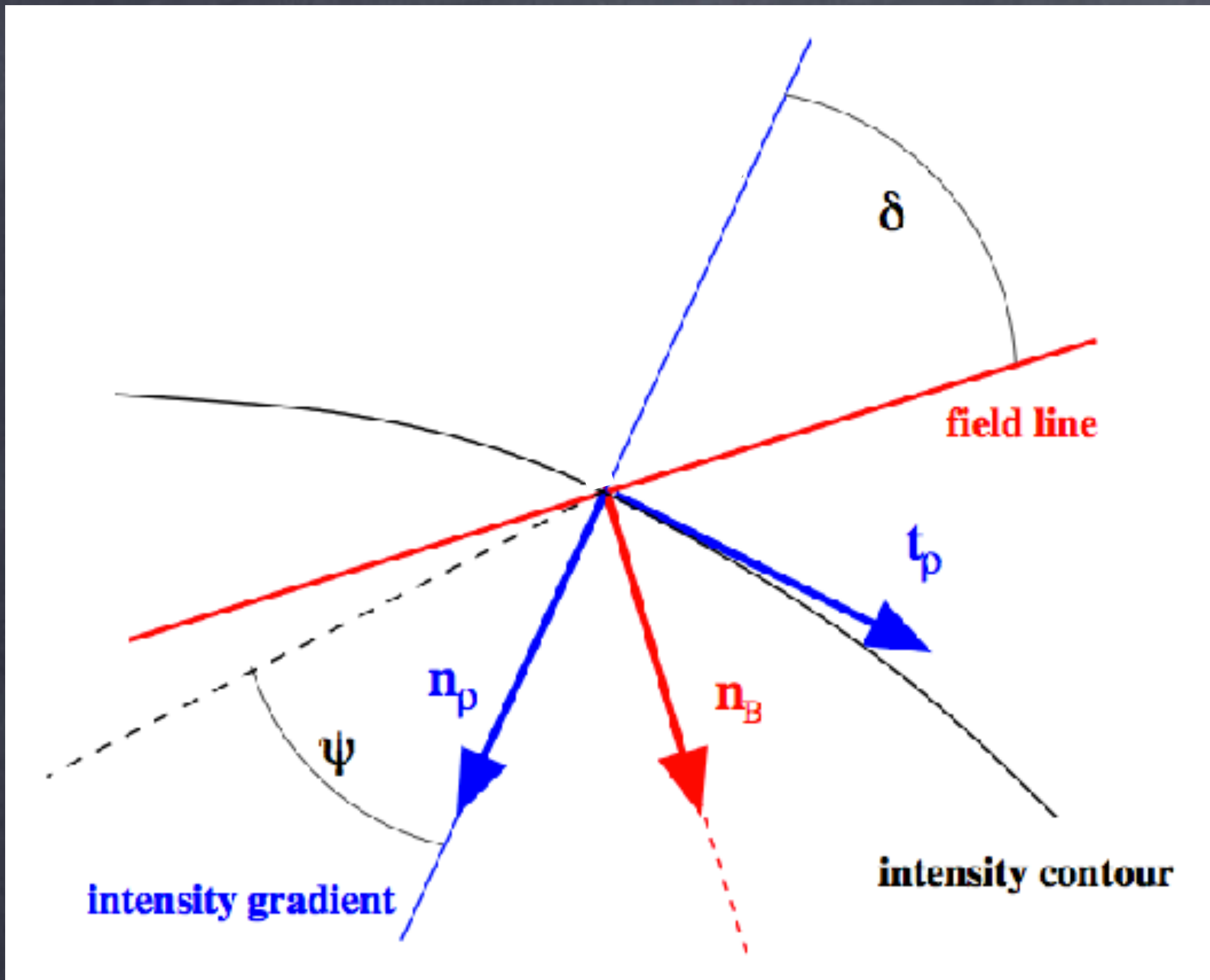
What is δ ?

(Koch, Tang & Ho, 2012a,b;2013)



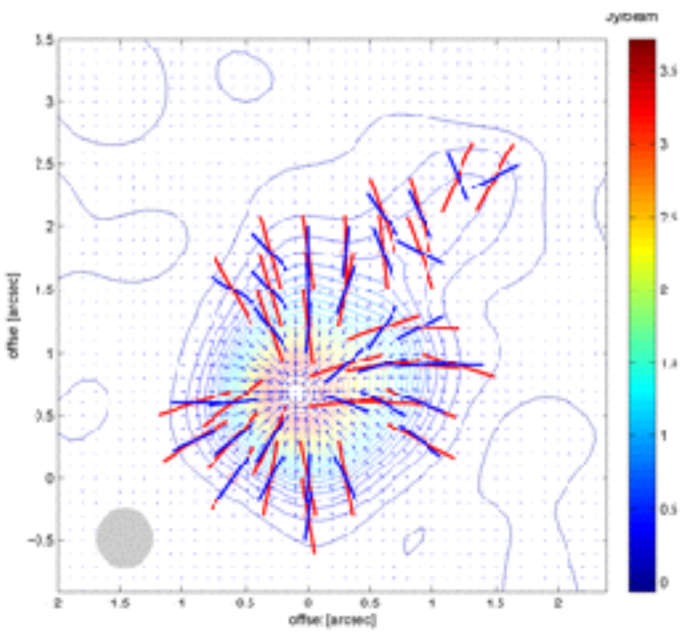
project n_B into orthonormal system (normal, tangential to contour)

$$\rho\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)\mathbf{v}=-\nabla P-\rho\nabla\phi+\frac{1}{4\pi}\frac{1}{R}B^2\,\mathbf{n}_B$$

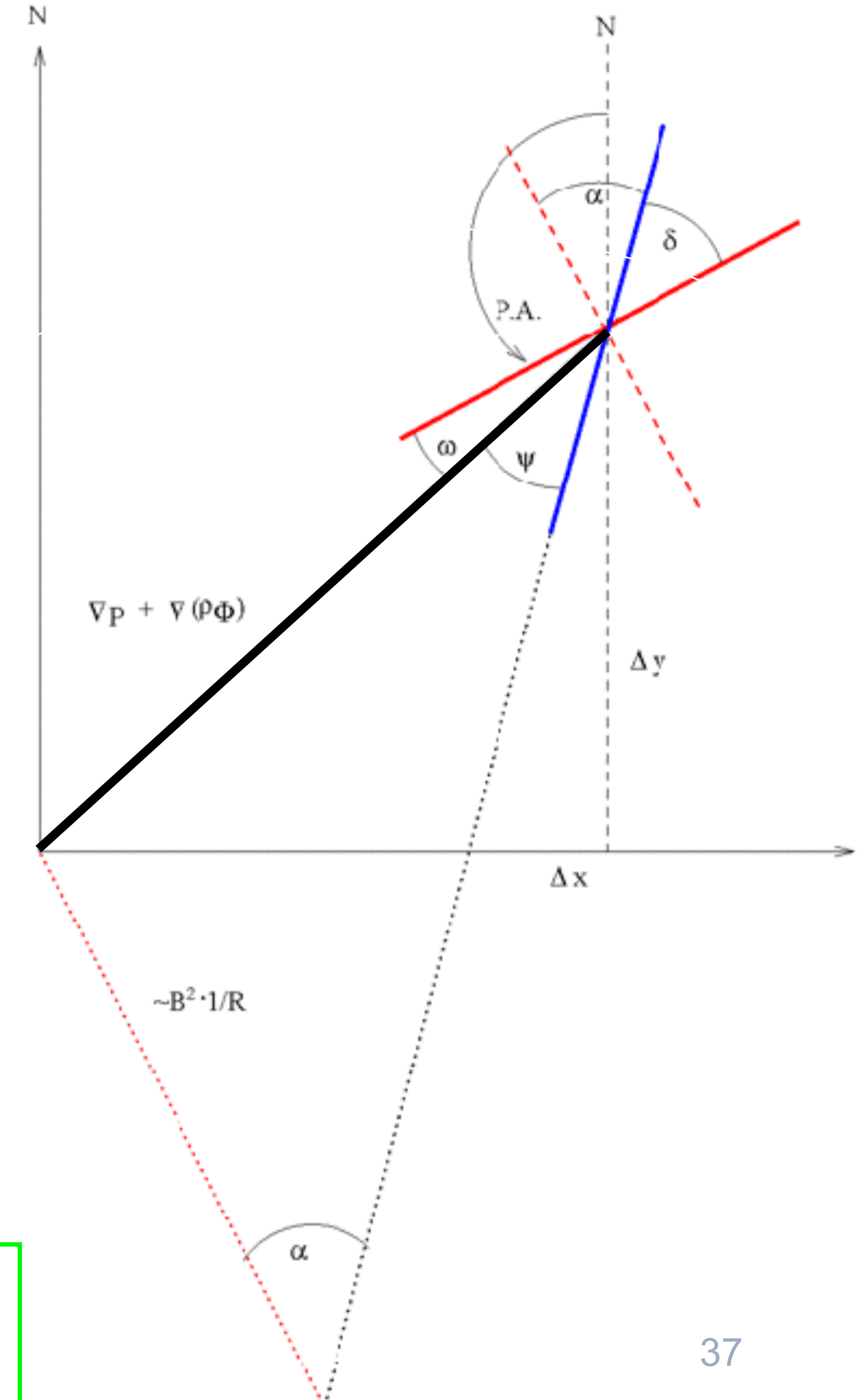
$$\rho\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)\mathbf{v}=-\nabla P-\rho\nabla\phi+\boxed{\sin|\delta|\,\frac{1}{4\pi}\frac{1}{R}B^2\,\mathbf{n}_\rho}+\sin|\alpha|\,\frac{1}{4\pi}\frac{1}{R}B^2\,\mathbf{t}_\rho$$

- δ measures alignment
- fraction of field tension force oriented along gradient
- δ quantifies local magnetic field-to-gravity force ratio Σ_B

New Method for Local Magnetic Field Strength



red: magnetic field orientations
blue: intensity gradient orientations



MHD force equation:

$$\rho v \frac{\partial v}{\partial s_v}\mathbf{e}_{s_v} + \rho v^2 \frac{\partial \mathbf{e}_{s_v}}{\partial s_v} = -\frac{\partial P}{\partial s_P}\mathbf{e}_{s_P} - \frac{\partial}{\partial s_\phi}(\rho\phi)\mathbf{e}_{s_\phi} + \frac{1}{4\pi}B^2\frac{1}{R}\mathbf{n}$$

associated with intensity gradient; result of all the acting forces leading to observed gas distribution

local gravity direction; derived from summing all the mass (emission) distribution

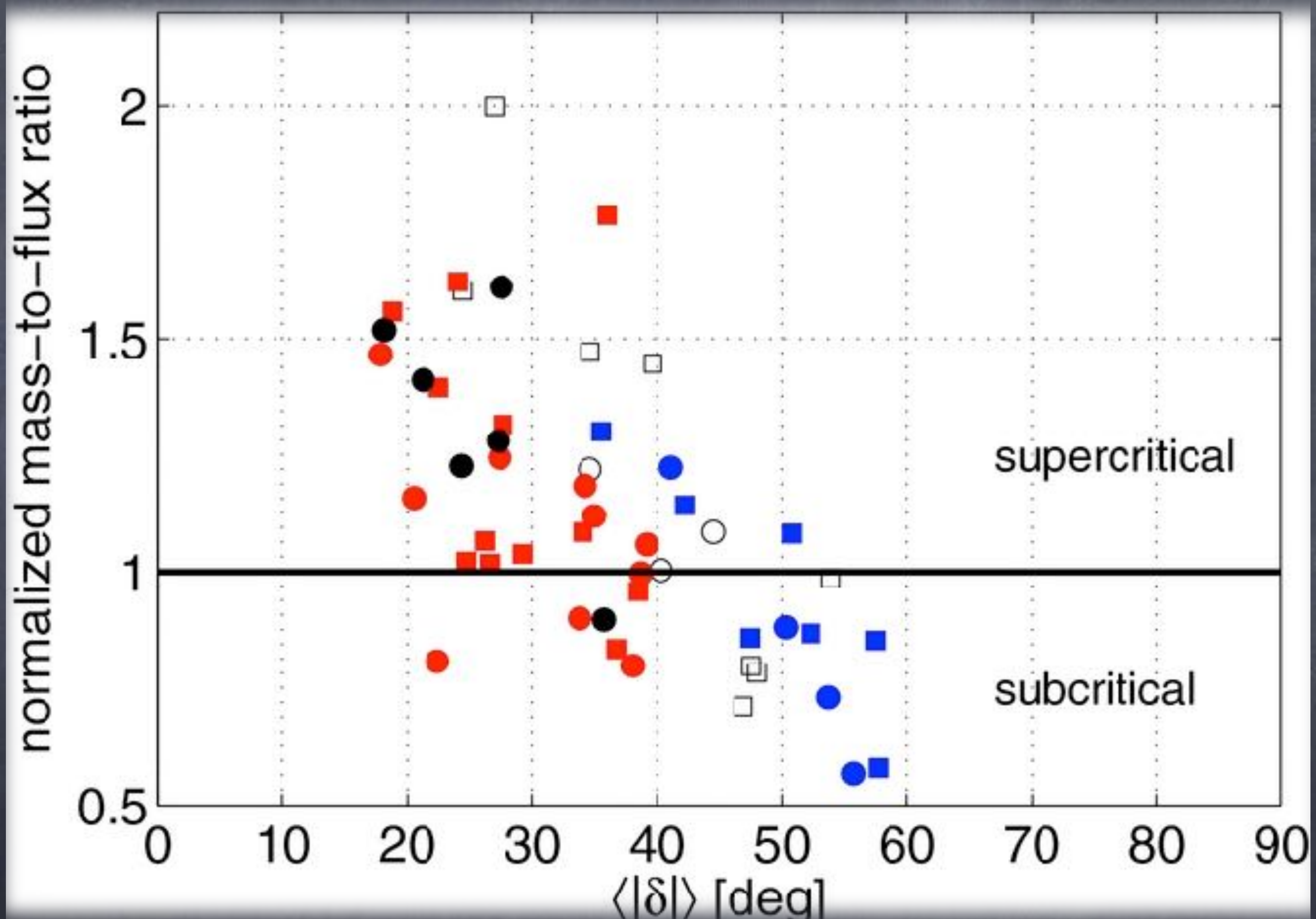
field tension force; orthogonal to detected field orientation

(1) assumption:
intensity gradient is a measure for resulting direction of motion

(2) close ‚force triangle':

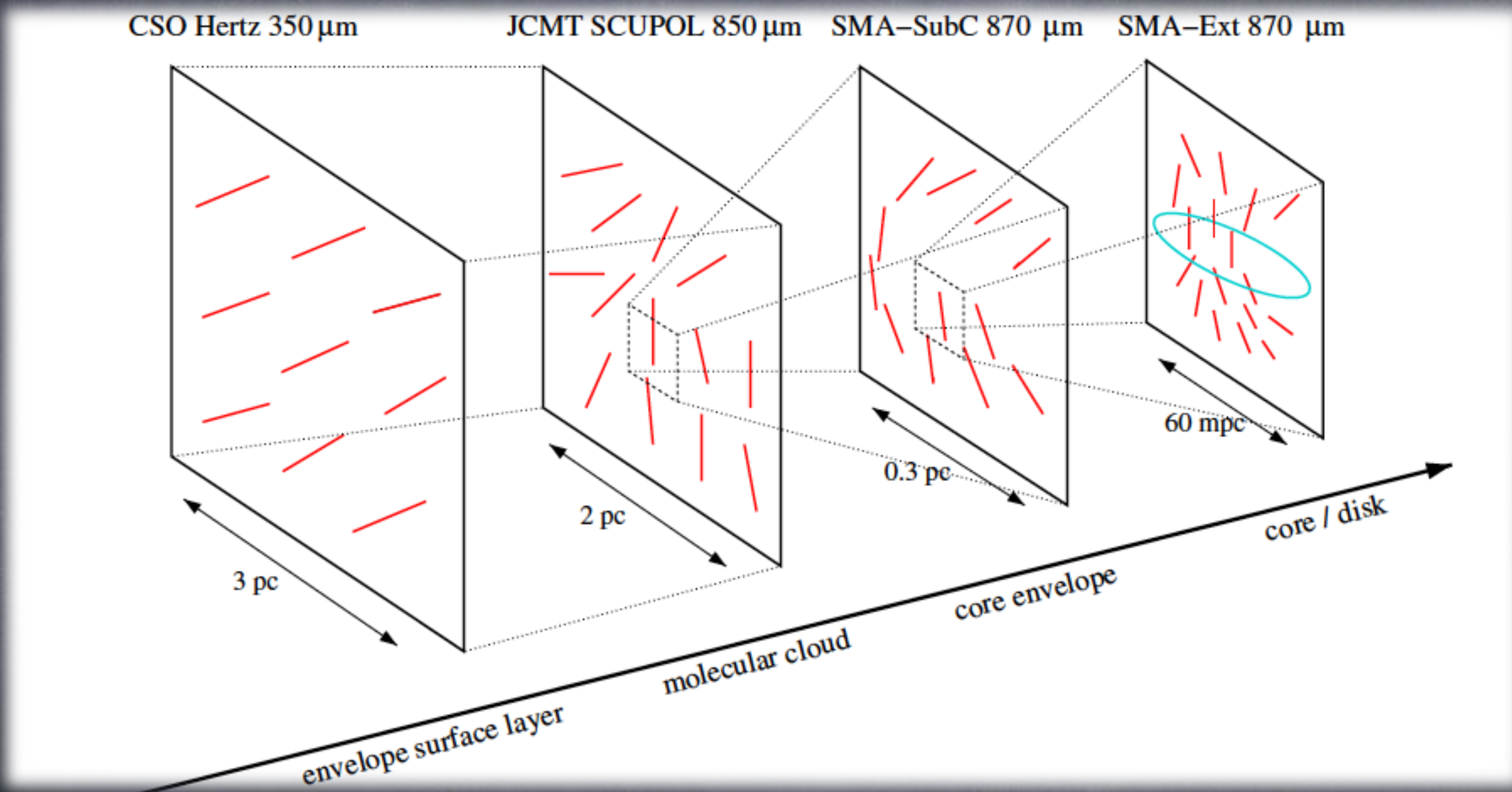
$$B = \sqrt{\frac{\sin\psi}{\sin\alpha}(\nabla P + \nabla(\rho\phi))4\pi R},$$

δ across a Sample of 50 sources (SMA+CSO): mass-to-flux ratio



(Koch+ SMA pol legacy, 2014)

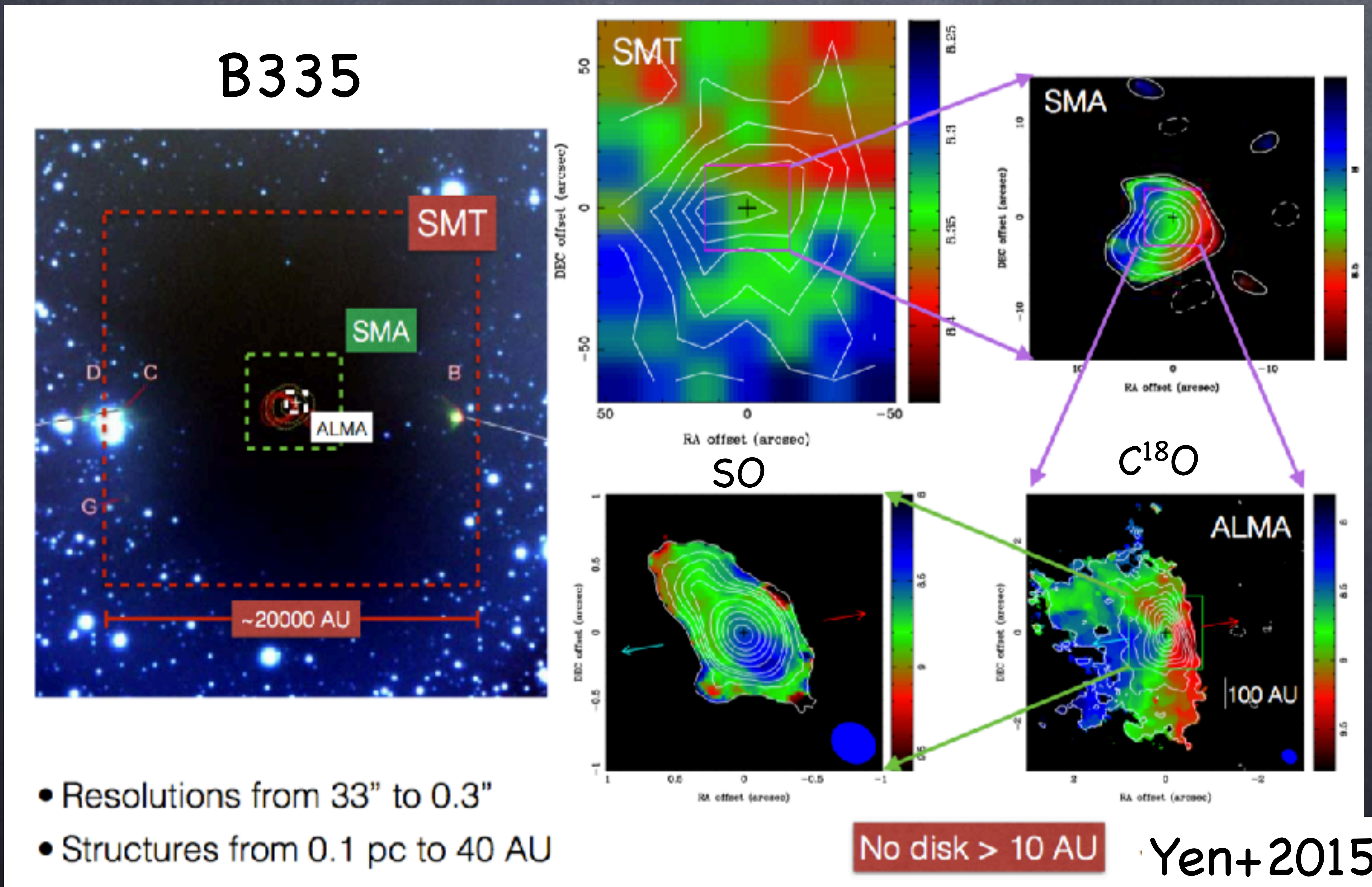
W51 North form large to small scales



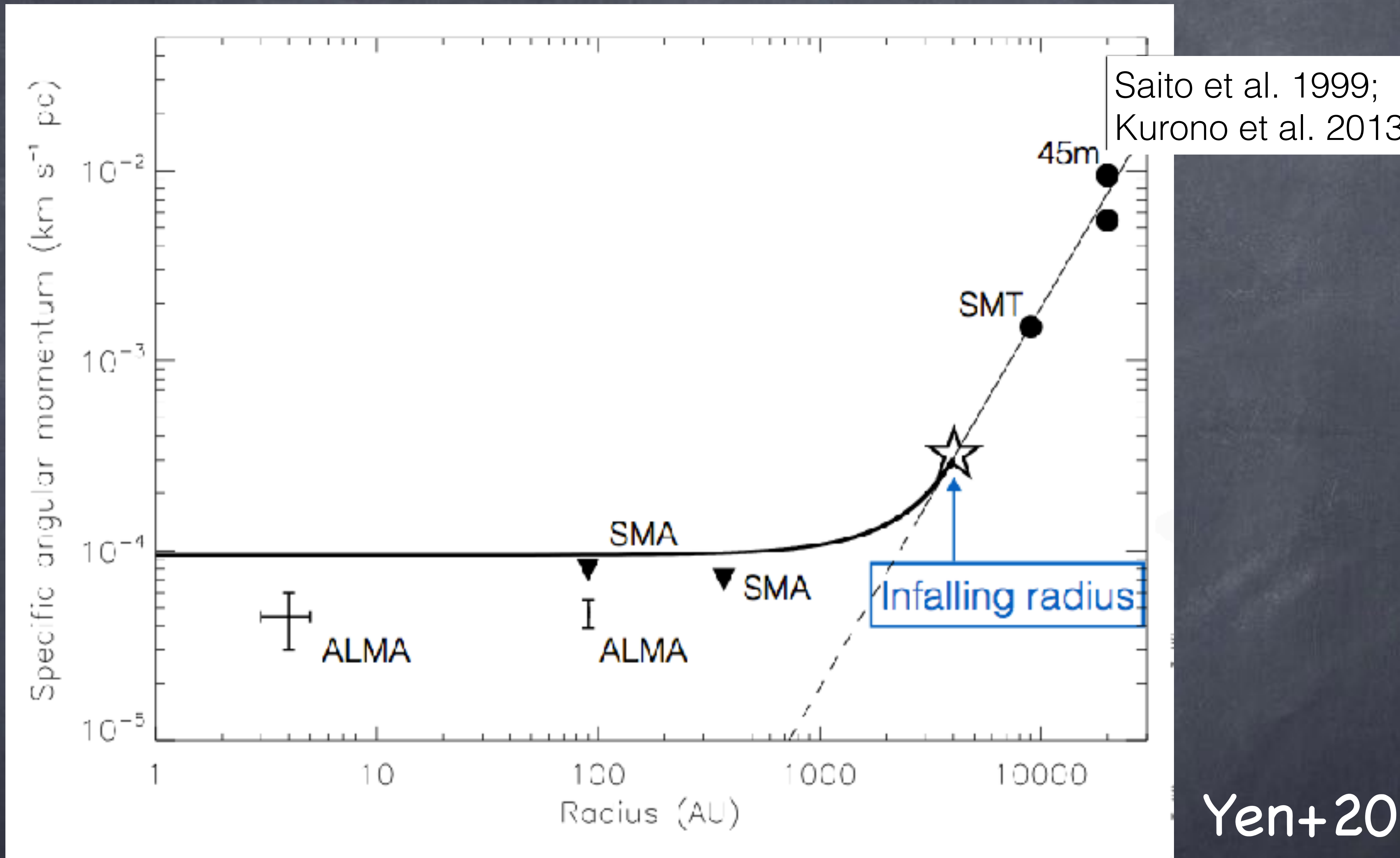
(Tang+2013)

Specific Angular Momentum Profile

indirect way: - can precisely measure / model profile with ALMA
- if angular momentum removed from envelope to inner disk, observable in profile
- associate removal with magnetic braking, get B strength

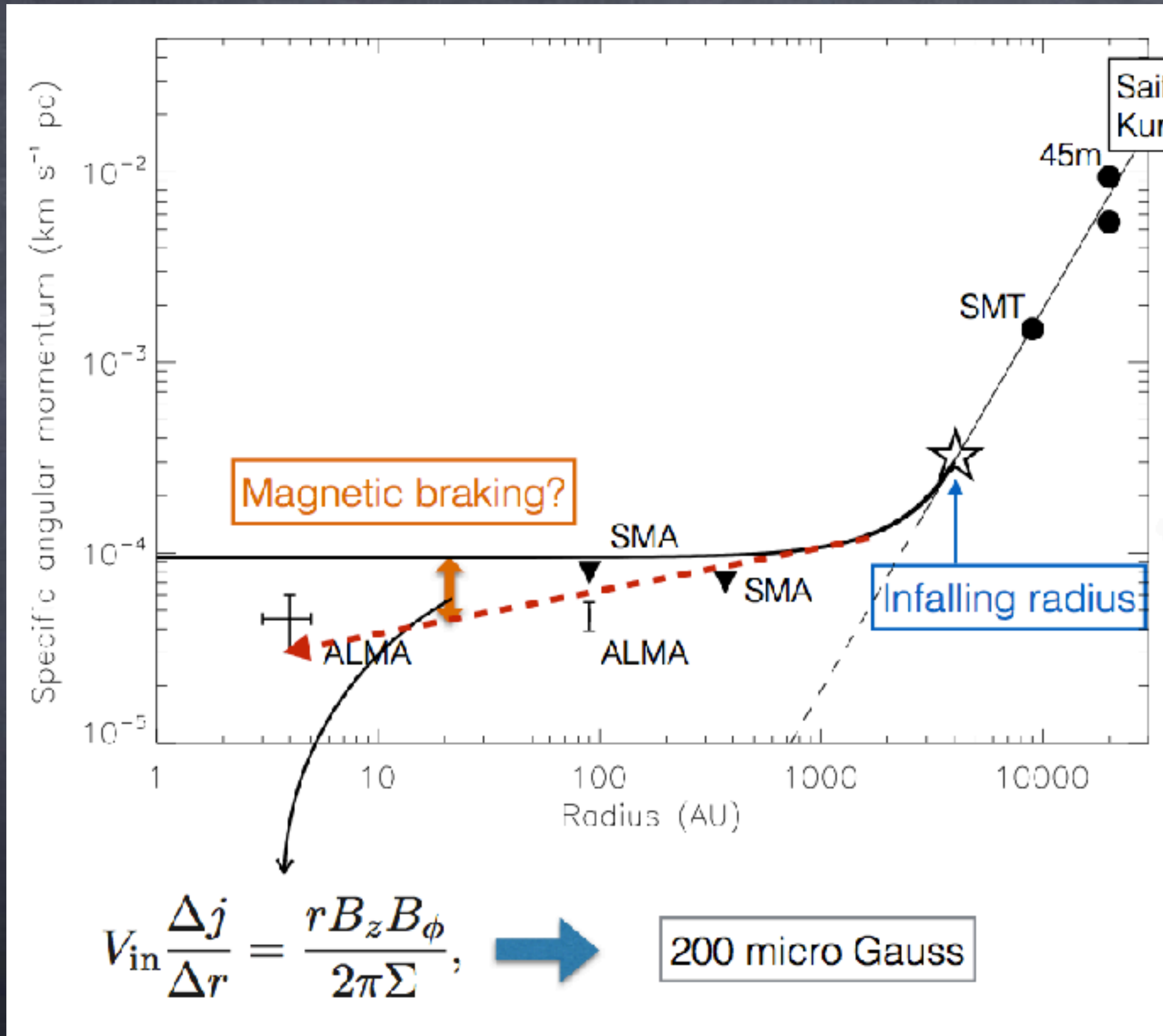


Specific Angular Momentum Profile



Yen+2015

Specific Angular Momentum Profile



Yen+2015

alternative: different infalling radius, younger age