hamburger sternwarte

Star Formation out of the Magnetised Interstellar Medium

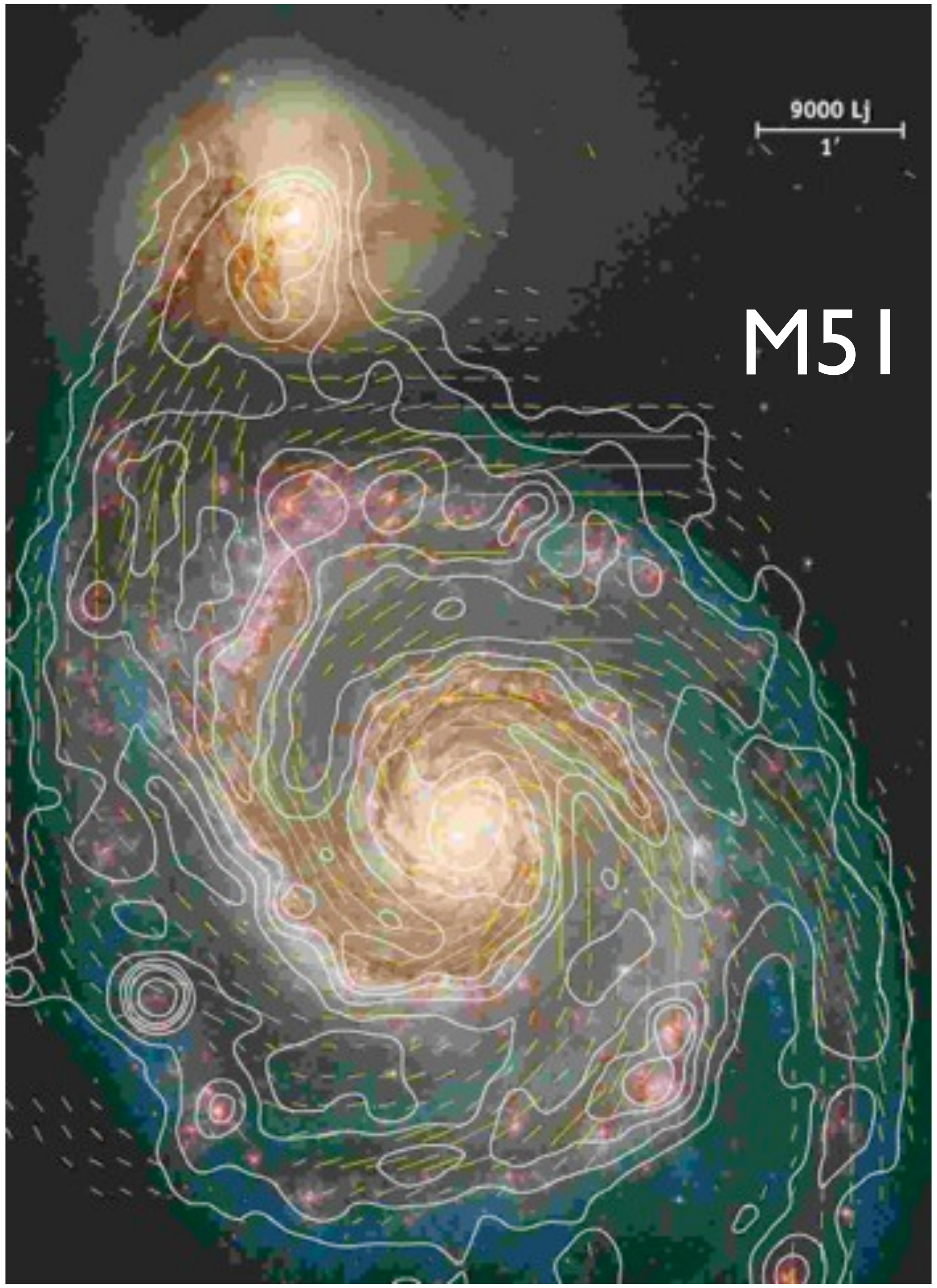
Robi Banerjee

University of Hamburg

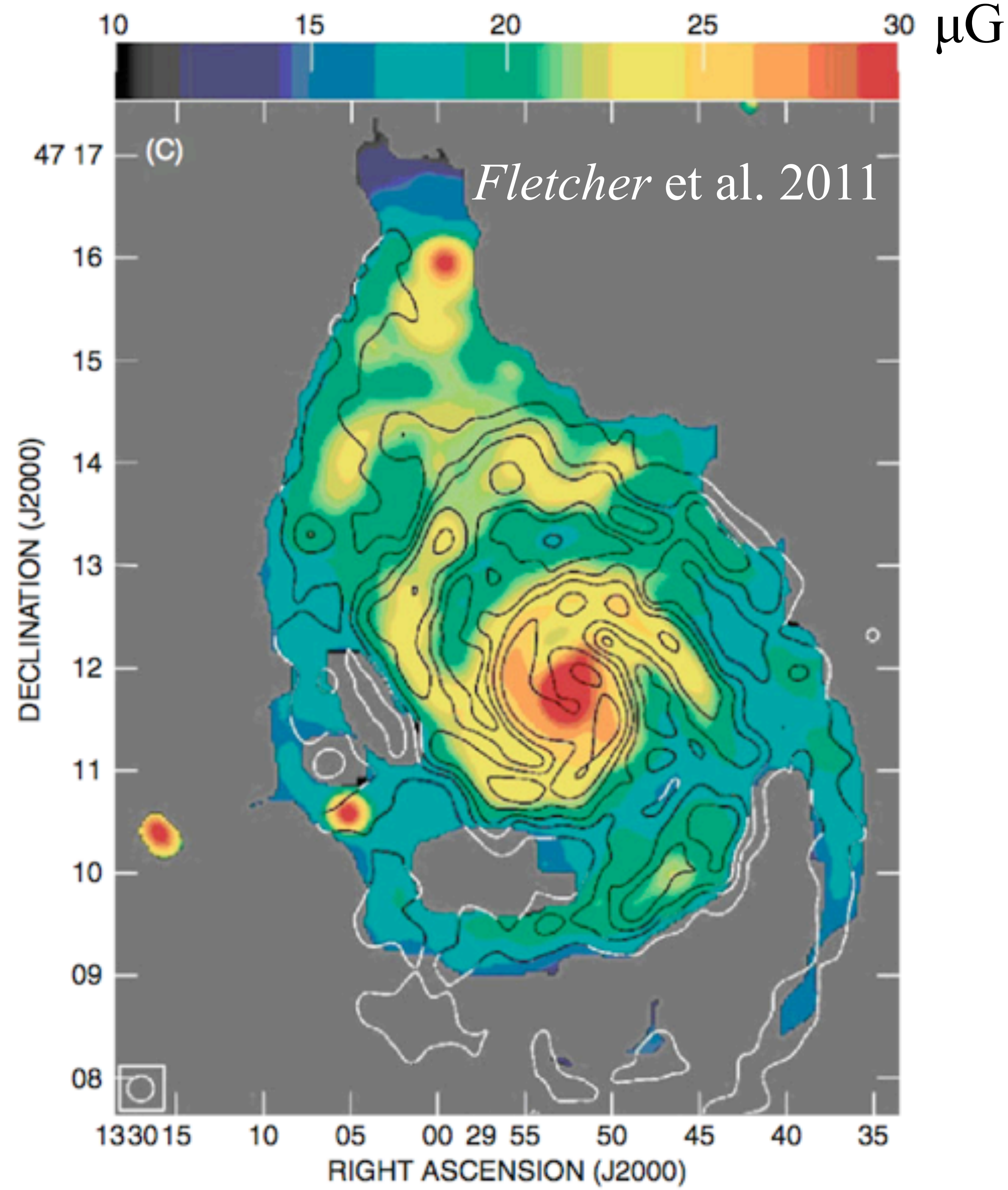
based on work by: **Daniel Seifried** (Cologne), **Bastian Körtgen** (HS)

co-workers: Ralph Pudritz (McMaster), Ralf Klessen (ITA),
Enrique Vazquez-Semadeni (UNAM, Mexico)

Magnetic Fields in the ISM

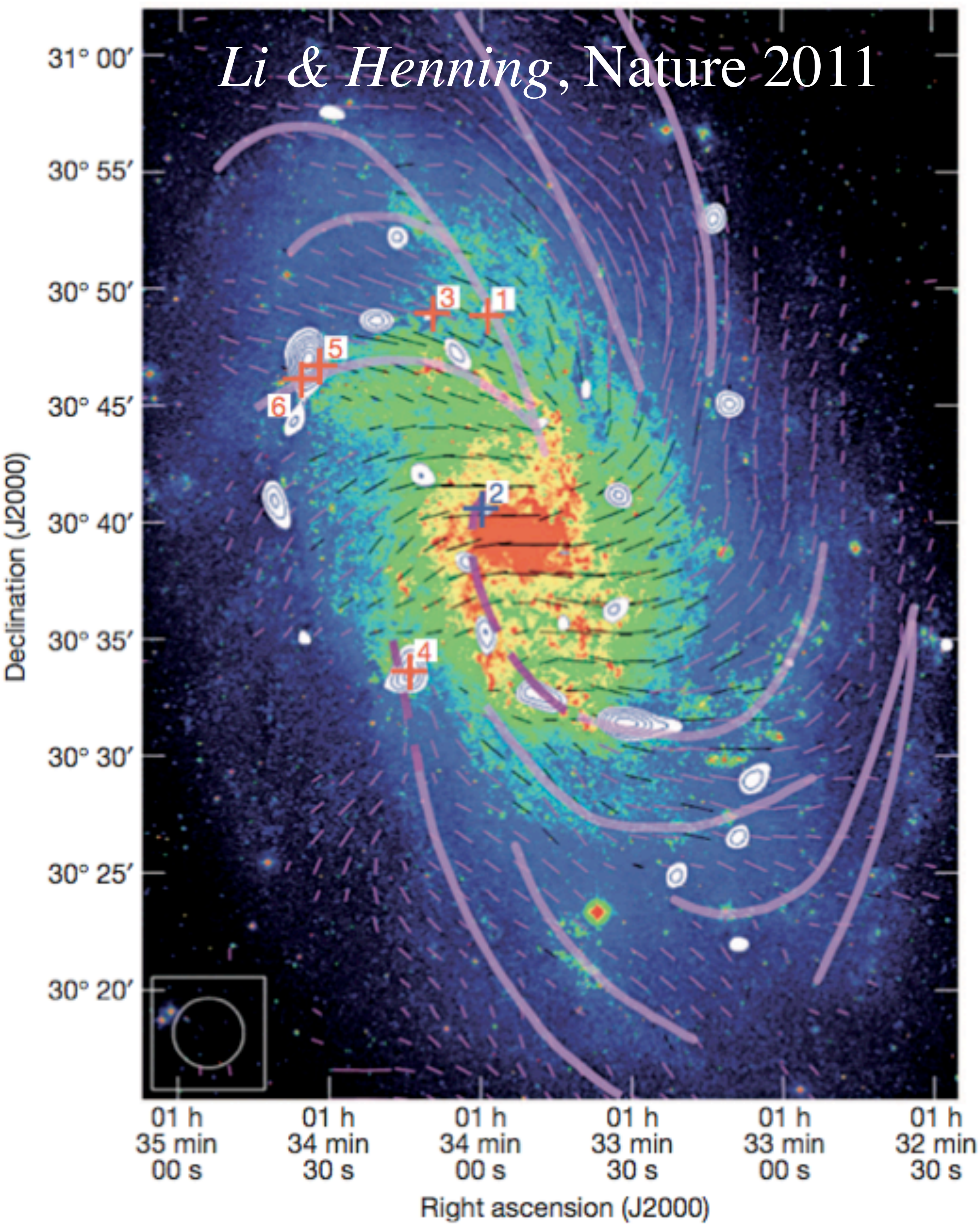


The ISM is *highly* magnetised: $E_{mag} \sim E_{therm}$



galactic B-fields (e.g. *R.Beck* 2001)
large scale component: $B \sim 6\mu G$
total field strength: $> 10\ \mu G$

Magnetic Fields in the ISM



- M33: $B_{pos} \sim 100 \ldots 500\ \mu G$ in GMCs from linearly polarised CO emission (Goldreich-Kylafis 1981)

$\Longrightarrow$ sub Alfvenic turbulence:

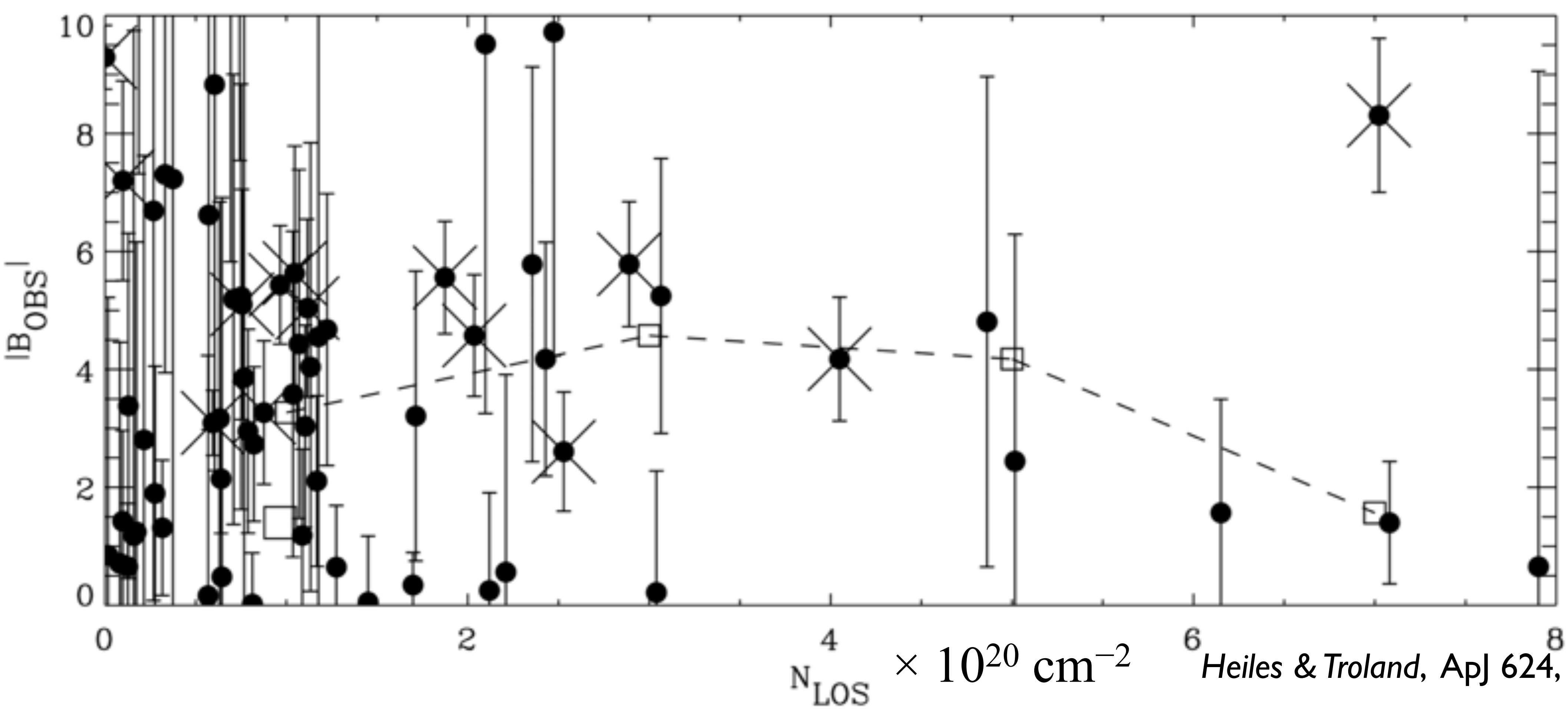
$$v_{turb} \lesssim v_A$$

(see also: *Hua-bai Li et al.* Nature 2015 for NGC 6334 $\Longrightarrow$ dynamically important fields)

Magnetic Fields in the ISM

- *Heiles & Troland* 2003:
  Millennium Arecibo 21 cm survey of the Milky Way

  B-field from polarised Zeeman effect



Heiles & Troland, ApJ 624, 2005

Magnetic Fields in the ISM

THE MILLENNIUM ARECIBO 21 CENTIMETER ABSORPTION-LINE SURVEY. IV. STATISTICS OF MAGNETIC FIELD, COLUMN DENSITY, AND TURBULENCE

Carl Heiles
Astronomy Department, University of California, 601 Campbell Hall 3411, Berkeley, CA 94720-3411;
cheiles@astron.berkeley.edu

and

T. H. Troland
Department of Physics and Astronomy, University of Kentucky, 177 Chemistry/Physics Building,
Lexington, KY 40506; troland@pa.uky.edu
Received 2004 October 26; accepted 2005 January 13

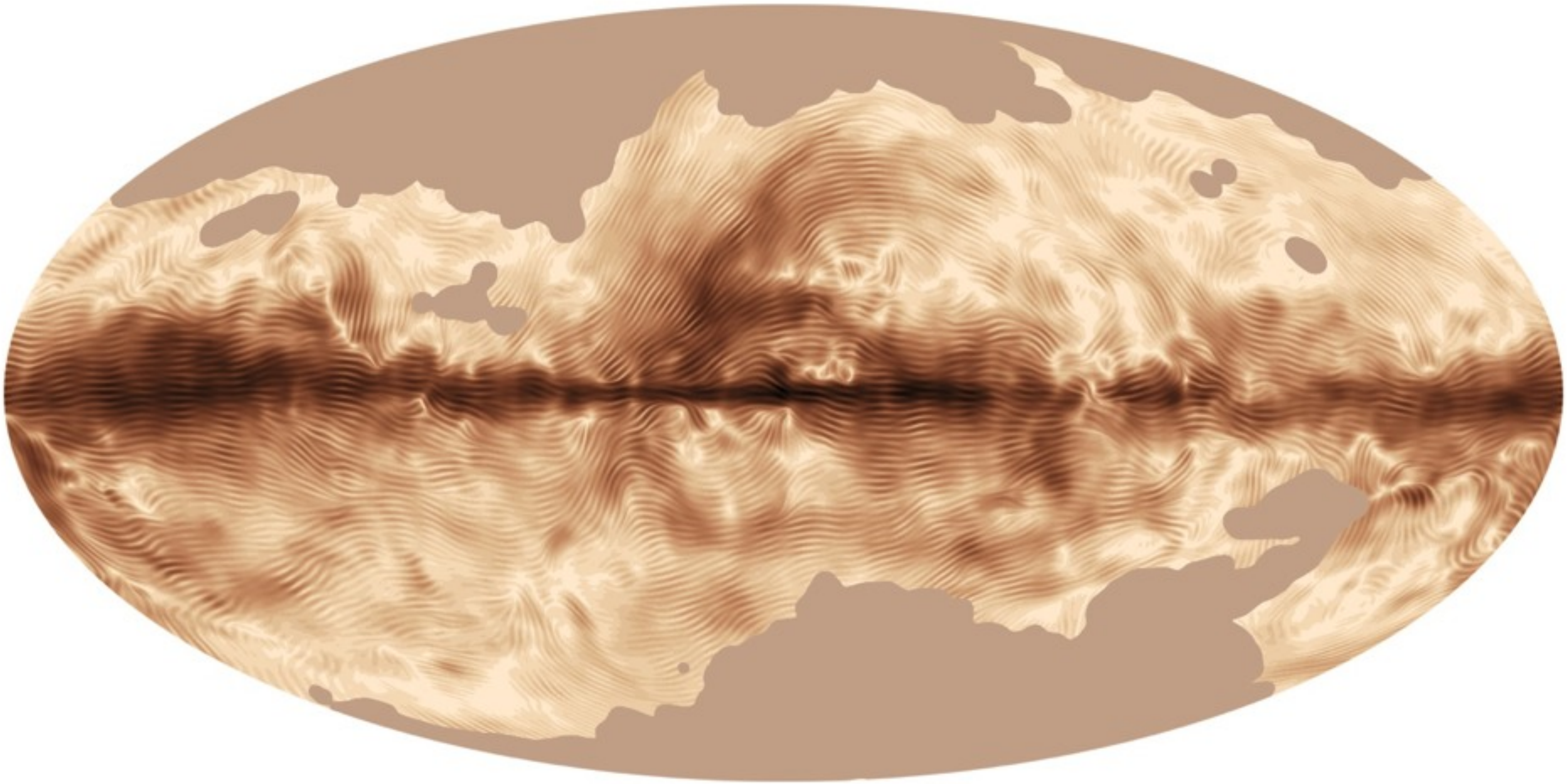
ABSTRACT

We discuss observations of the magnetic field, column density, and turbulence in the cold neutral medium (CNM). The observed quantities are only indirectly related to the intrinsic astronomical ones. We relate the observed and intrinsic quantities by relating their univariate and bivariate probability distribution functions (pdf's). We find that observations of the line-of-sight component of a magnetic field do not constrain the pdf of the total field B_{tot} very well but do constrain the median value of B_{tot}. In the CNM, we find a well-defined median magnetic field $6.0 \pm 1.8\ \mu$G. The CNM magnetic field dominates thermal motions. Turbulence and magnetism are in approximate equipartition. We find that the probability distribution of column density $N_\perp(\mathrm{H\,I})$ in the sheets closely follows $N_\perp(\mathrm{H\,I})^{-1}$ over a range of 2 orders of magnitude, $0.026 \lesssim N_\perp(\mathrm{H\,I}) \lesssim 2.6 \times 10^{20}$ cm^{-2}. The bivariate distributions are not well enough determined to constrain structural models of CNM sheets.

ApJ 624, 2005

Magnetic Fields in the ISM

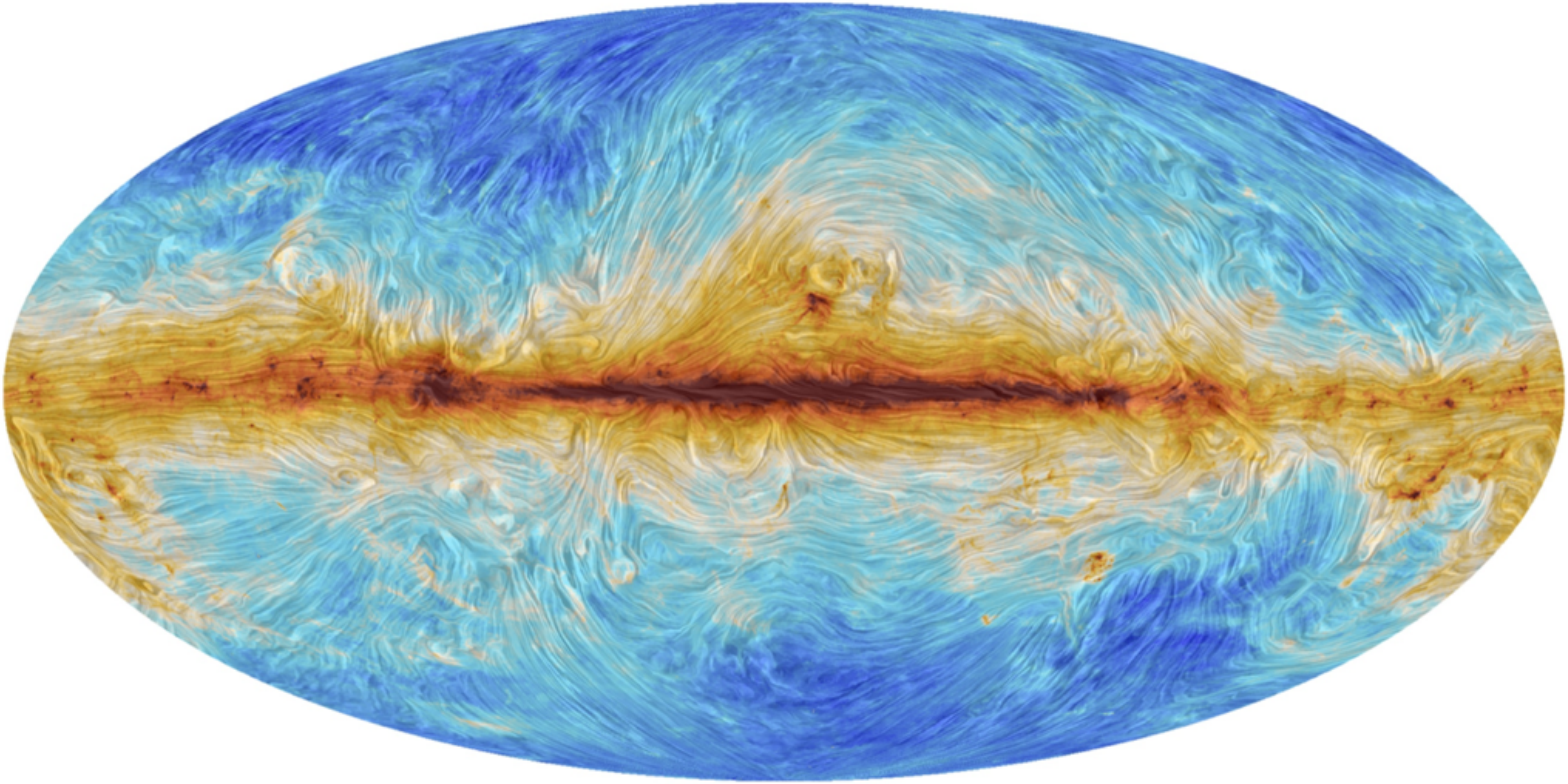
- PLANCK: magnetic field of the Milky Way
  from dust polarisation



ESA PLANCK: *Milky Way's magnetic fingerprint*, May 2014

Magnetic Fields in the ISM

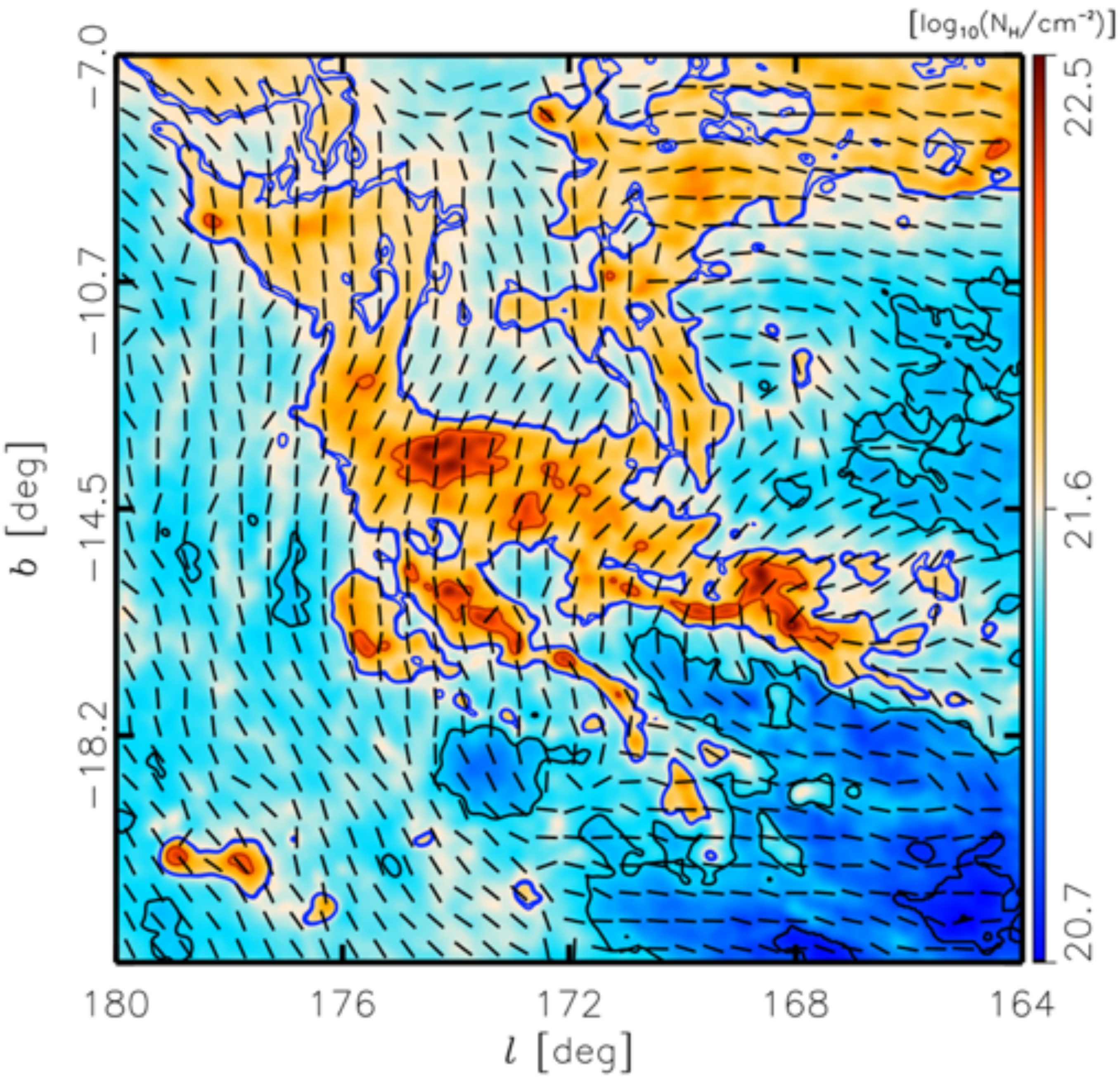
- PLANCK: magnetic field of the Milky Way from dust polarisation

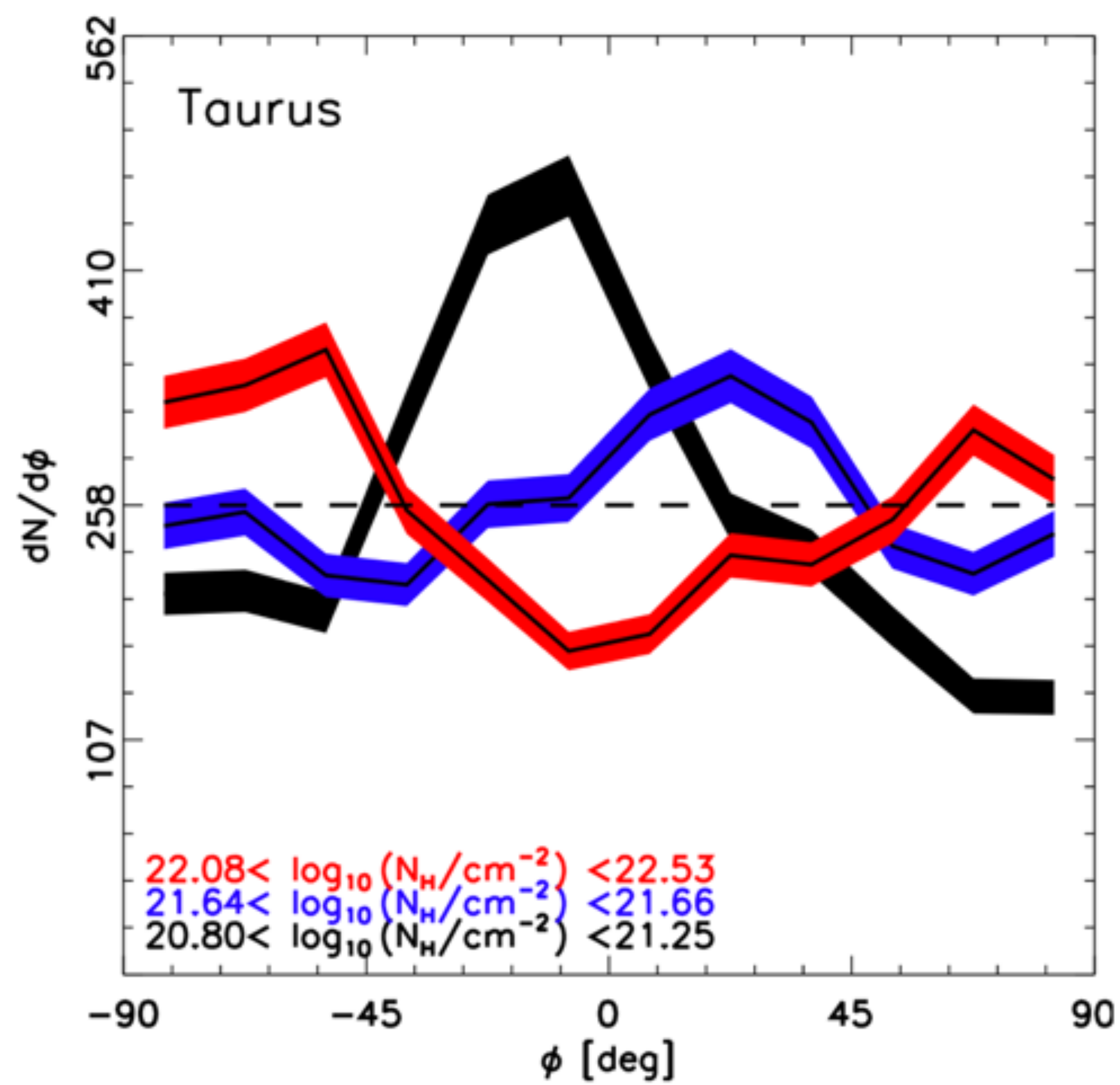


ESA PLANCK: *Milky Way's magnetic fingerprint*, May 2014

Magnetic Fields in Molecular Clouds

- PLANCK XXXV 2015: dust polarisation in molecular clouds

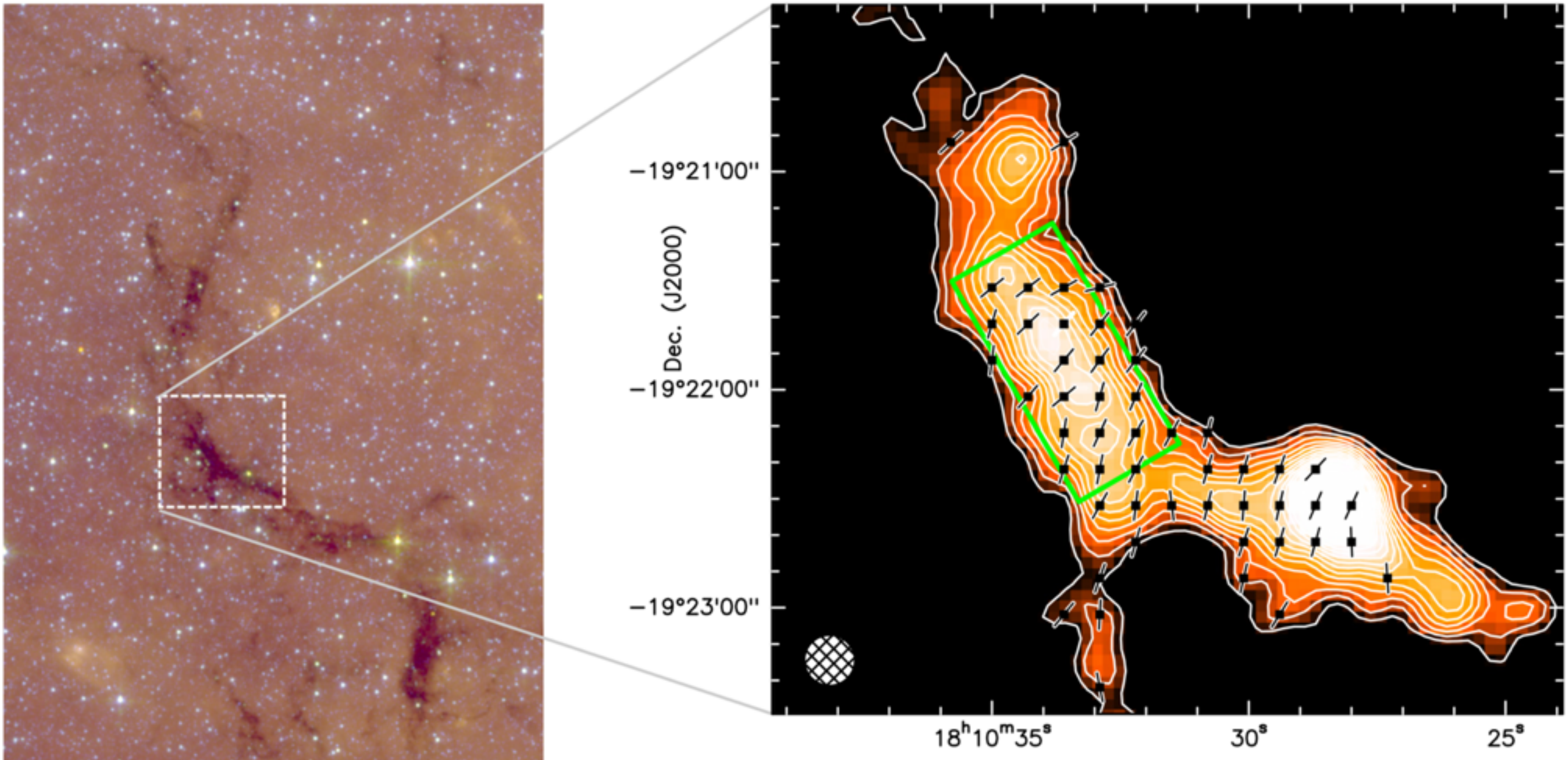




$\Longrightarrow$ magnetic fields are dynamically important

$\Longrightarrow$ by comparing with num. simulations: $B = 4 \ldots 12\ \mu\mathrm{G}$

Magnetic Fields in Molecular Clouds

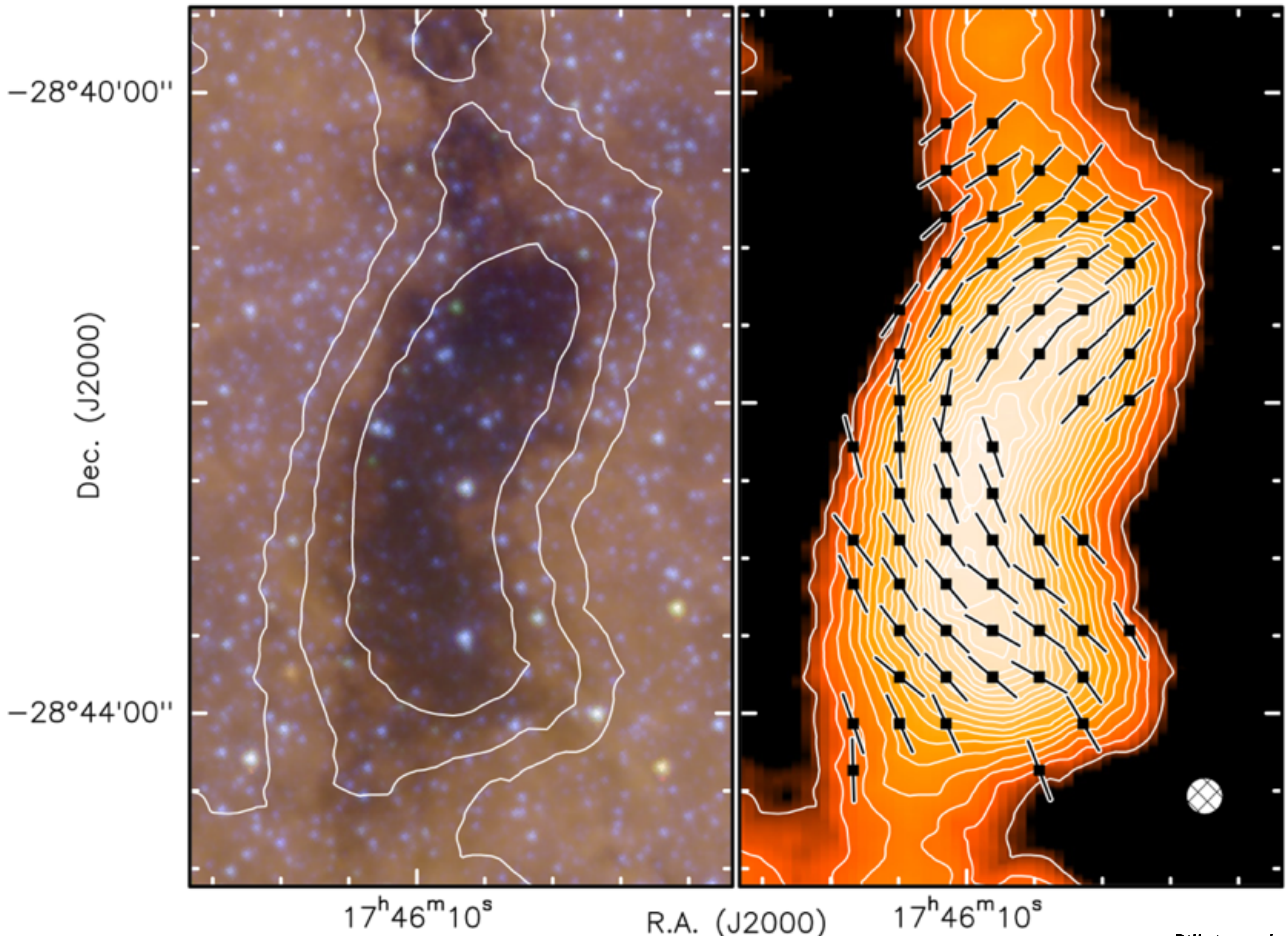


Pillai et al., ApJ 799, 2015

polarisation measurement of G11.11-0.12

$\Longrightarrow$ from CF-method strongly magnetised massive IRDCs: $> 260\ \mu G$

Magnetic Fields in Molecular Clouds

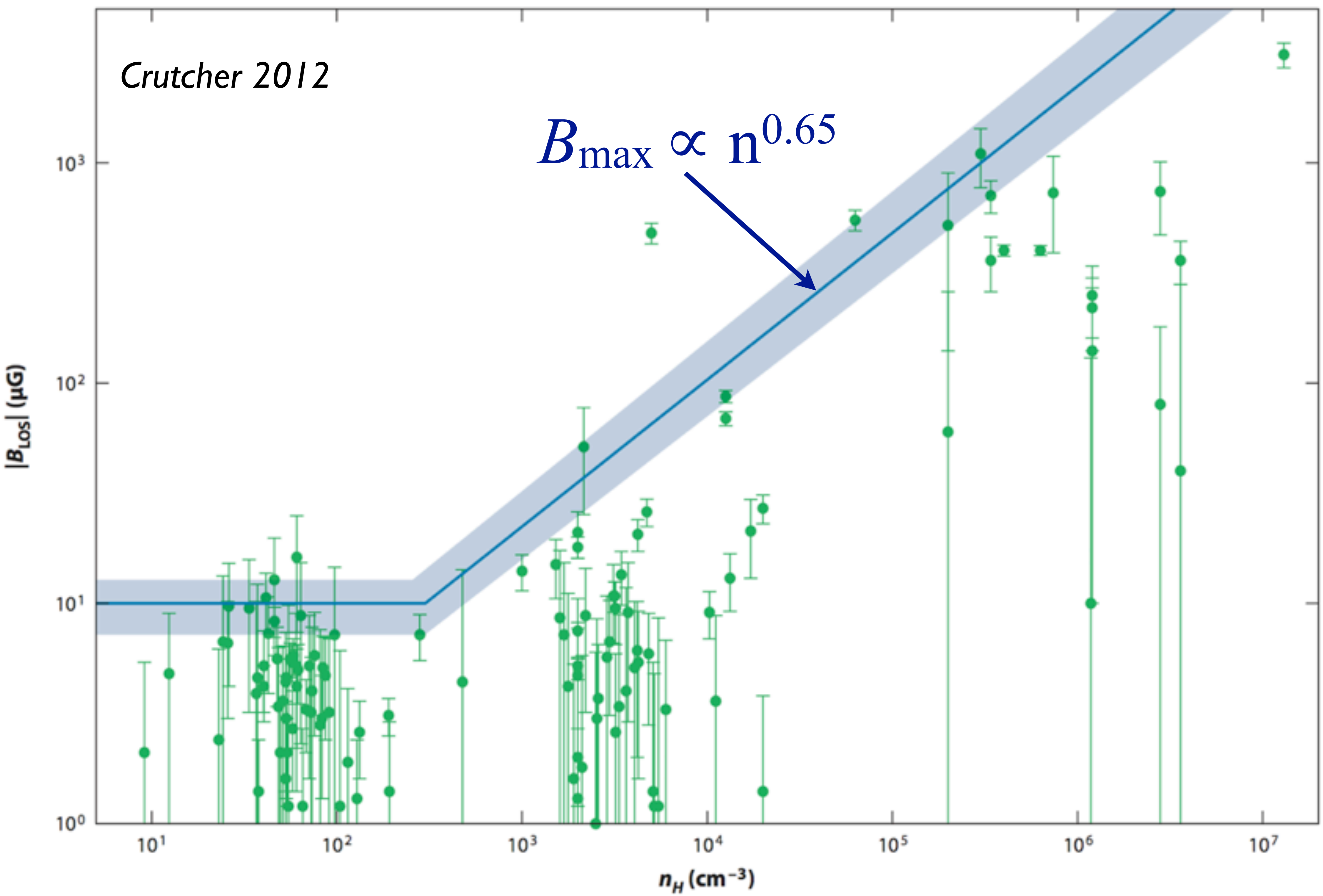


Pillai et al., ApJ 799, 2015

in G0.253-0.06 IRDC: $B > 5$ mG

Magnetic Fields in the ISM

- stronger magnetic fields in dense regions

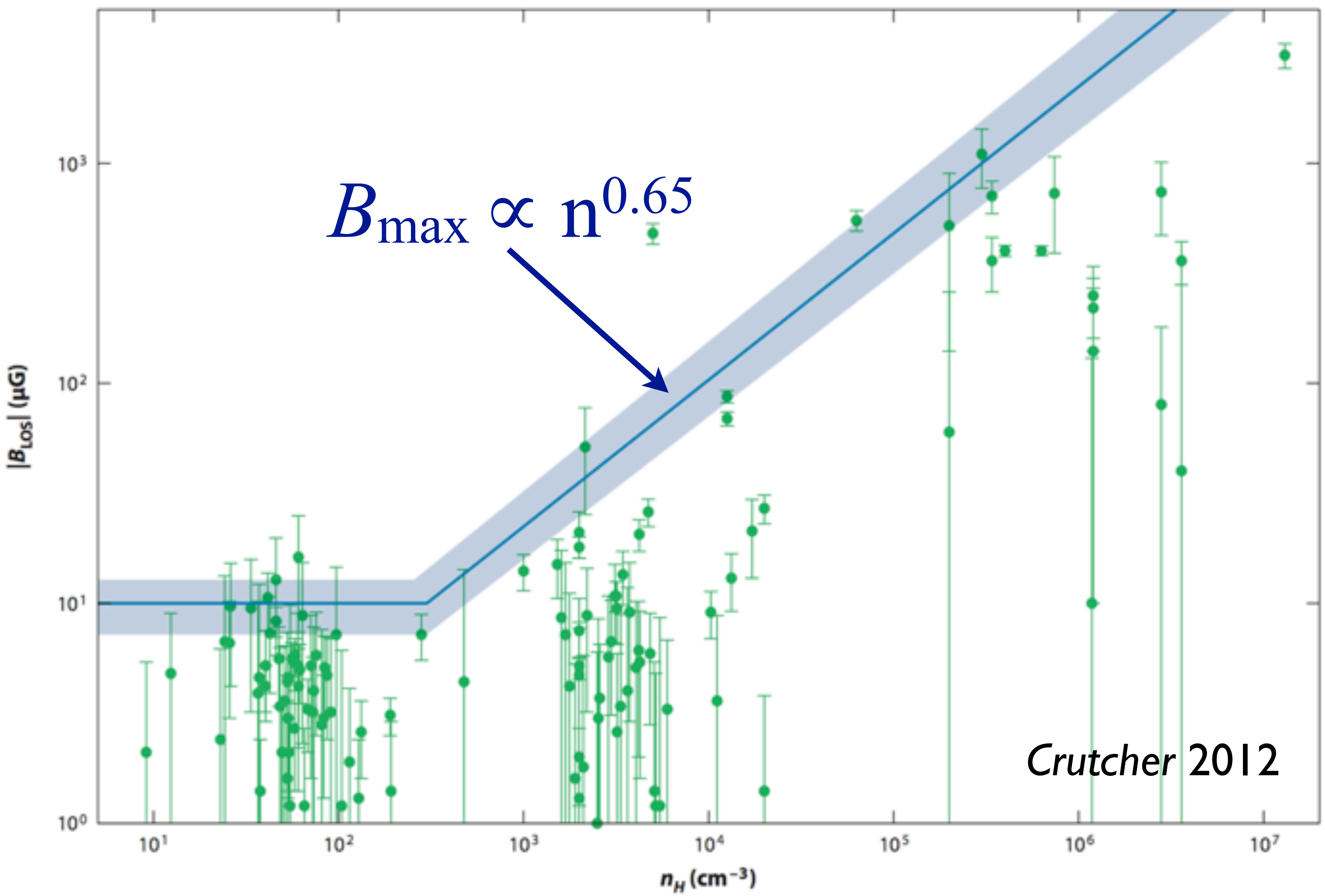


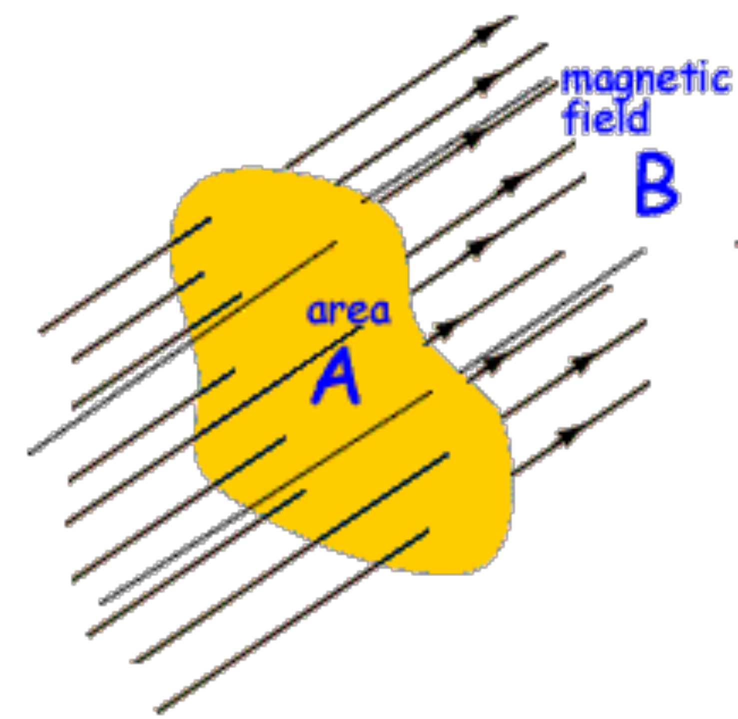
Magnetic Fields in the ISM

- stronger magnetic fields in dense regions

$\Longrightarrow$ B gets compressed due to flux-freezing:

$$\Phi = \mathbf{A} \cdot \mathbf{B} = \text{const.}$$





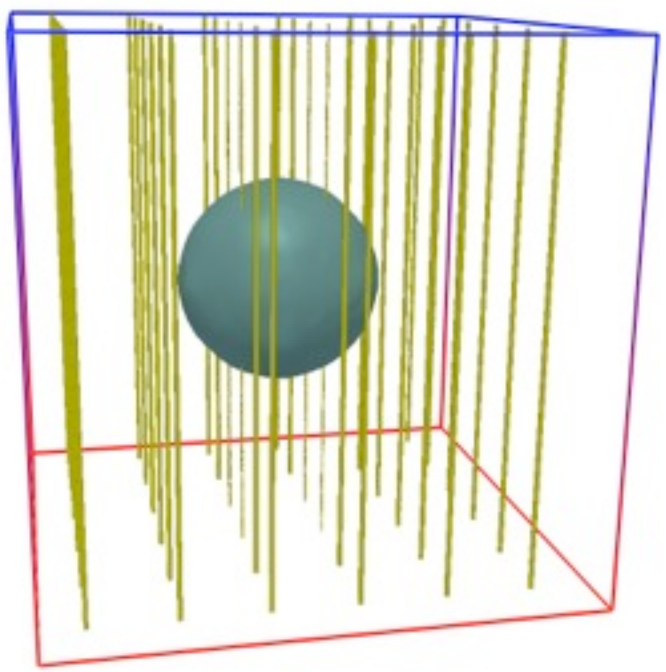
Impact of Magnetic Fields

magnetic flux is frozen into the plasma:

$\Longrightarrow$

mass-to-flux ratio:

$$\mu \equiv \left(\frac{M}{\Phi}\right)$$ = self-gravity / magnetic energy



$$\Longrightarrow \quad \mu = \frac{\Sigma}{B} \quad \Longrightarrow \quad B \propto N$$

critical value for collapse:

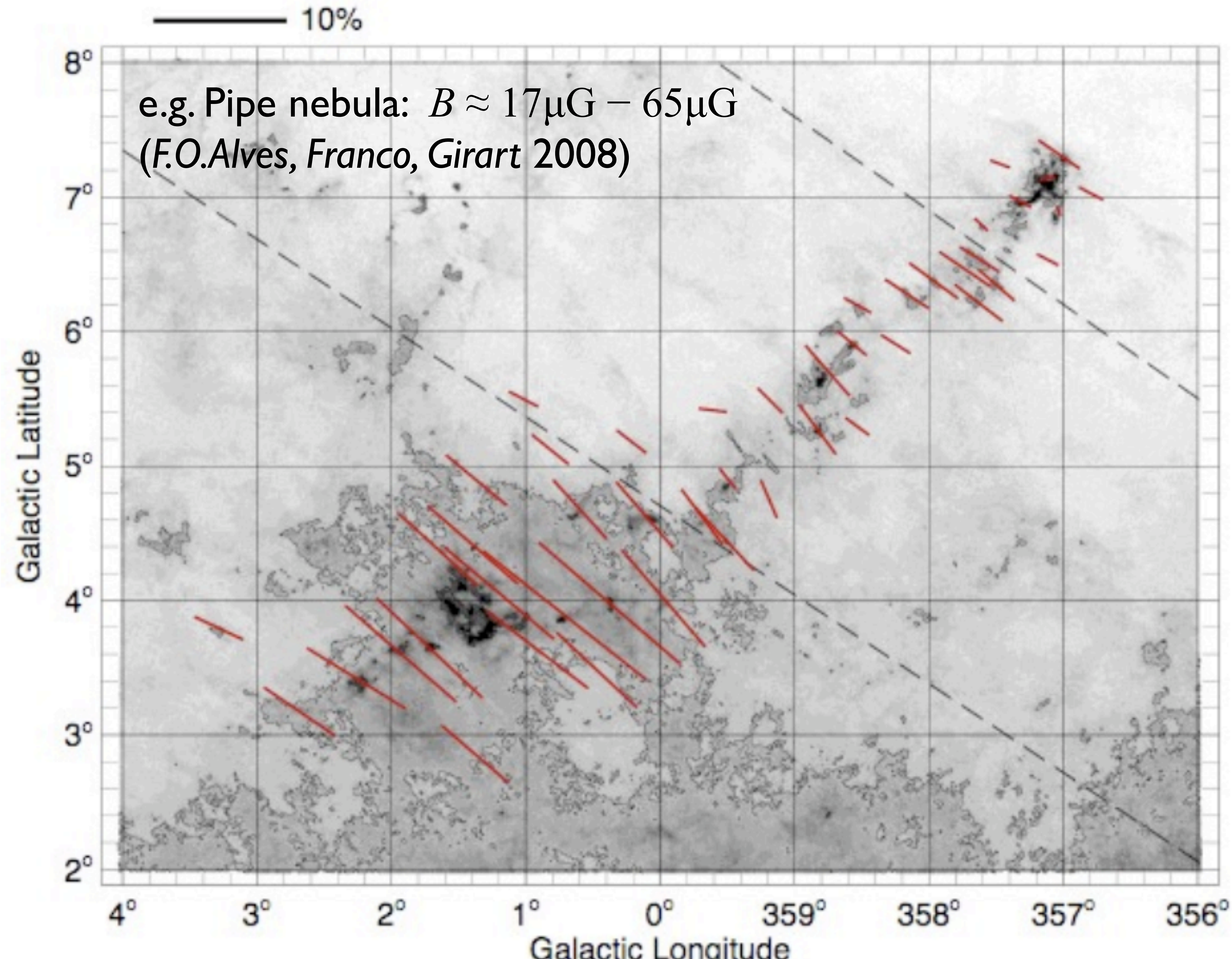
$$\mu_{\rm crit} = 0.13/\sqrt{G}$$

spherical structure
Mouschovias & Spitzer 1976

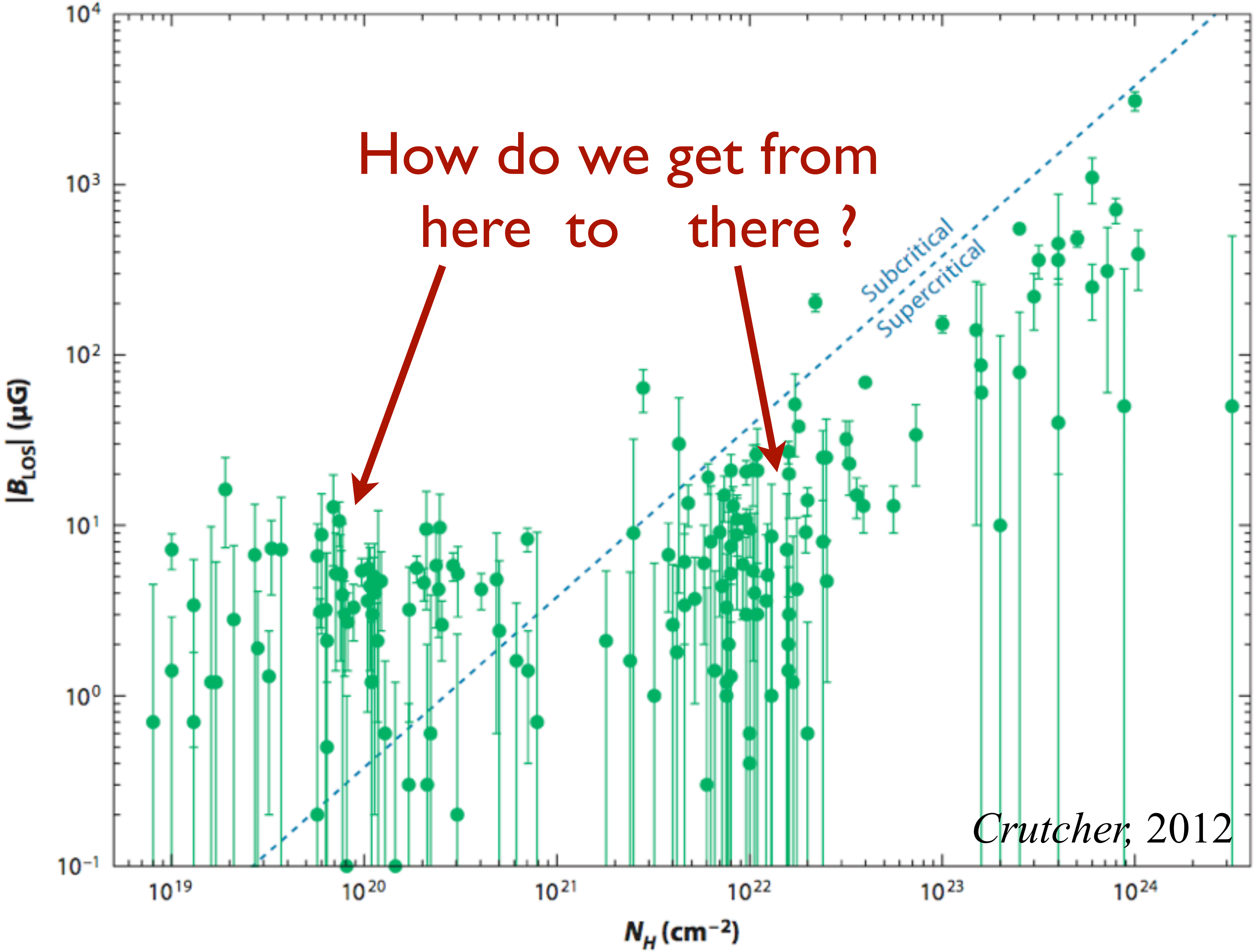
$$\mu_{\rm crit} = \frac{1}{2\pi\sqrt{G}} \approx 0.16/\sqrt{G}$$

uniform disc
Nakano & Nakamura 1978

Impact of MF on Molecular Clouds?

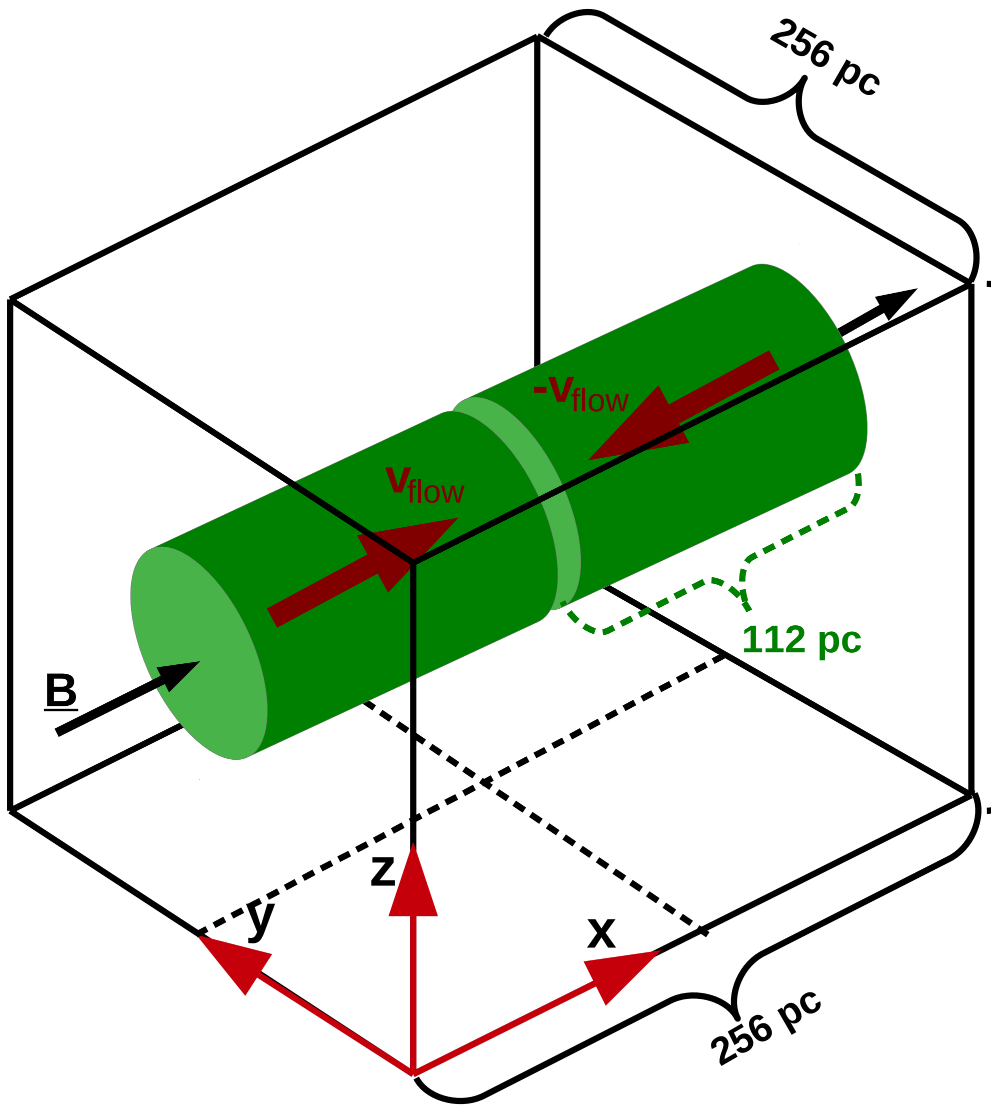


Magnetic Fields in the ISM



Impact of Magnetic Fields on MCs

critical mass-to-flux ratio: $\mu_{\rm crit} = 0.13/\sqrt{G}$



$\Longrightarrow$ minimal column density:

$$N_{\rm crit} \approx 2.4 \times 10^{21}\,{\rm cm}^{-2} \left(\frac{B}{10\,\mu{\rm G}}\right)$$

$\Longrightarrow$ minimal length scale:

$$L_{\rm crit} \approx 10^3\,{\rm pc} \left(\frac{B}{10\,\mu{\rm G}}\right) \left(\frac{n}{1\,{\rm cm}^{-3}}\right)^{-1}$$

$\Longrightarrow$ accumulation scale:

$$L_{\rm acc} \approx 1.2\ {\rm kpc}\ (B/3\ \mu{\rm G})$$: *L. Mestel* PPII (1985)

$\Longrightarrow$ time-scale for colliding flows:

$$t_{\rm crit} \approx 100\,{\rm Myr} \left(\frac{B}{10\,\mu{\rm G}}\right) \left(\frac{n}{1\,{\rm cm}^{-3}}\right)^{-1} \left(\frac{v_{\rm flow}}{10\,{\rm km\ sec}^{-1}}\right)^{-1}$$

SF from Magnetised Medium

Solutions?

- **flux loss** by:
  - Ambipolar Diffusion (*Mestel & Spitzer* 1956, *Shu* 1987, *Mouschovias* 1987)

    $\Longrightarrow$ old AD-mediated star formation picture
  - Turbulence + AD (e.g. *Heitsch et al.* 2004, *Kudoh & Basu* 2008, 2001)
  - Turbulent reconnection (Lazarian & Vishniac 1999)
  - Ohmic resistivity (e.g. *Dapp & Basu* 2010, *Krasnopolsky et al.* 2010)
  - ...
- **Super-Alfvenic turbulence**:

  (e.g. *Padoan et al.* 1999, *Mac Low & Klessen* 2004, *Ballesteros-Paredes* 2007)

  $\Longrightarrow$ no need for flux loss:

  clouds assumed to be supercritical

$\Longrightarrow$ correct assumption ?

Ambipolar Diffusion in the WNM

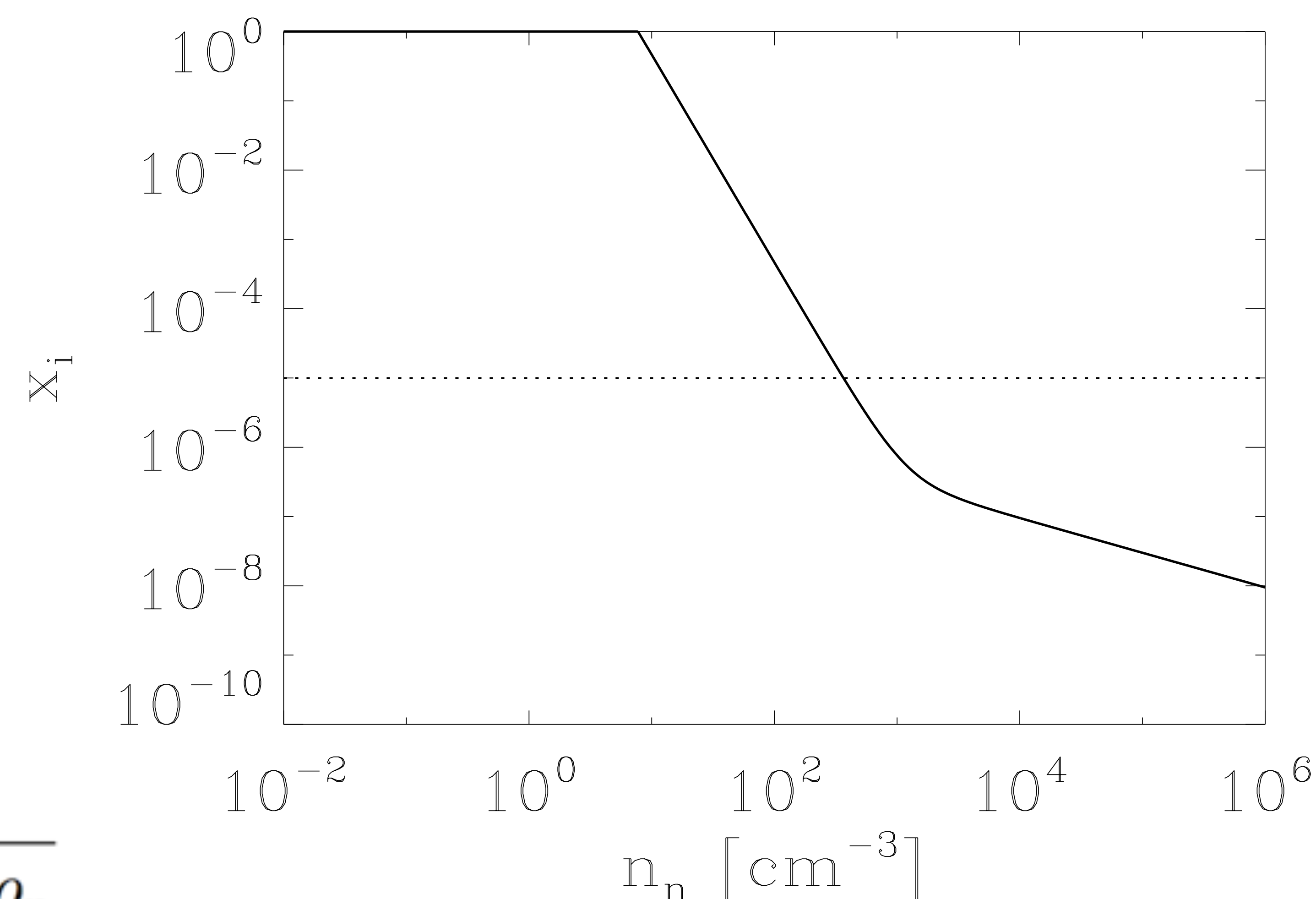
- Ionisation degree of the diffuse ISM:

$$n_i = K\left(\frac{n_n}{10^5\,\mathrm{cm}^{-3}}\right)^{1/2} + K'\left(\frac{n_n}{10^3\,\mathrm{cm}^{-3}}\right)^{-2}$$

$K=3\times10^{-3}\ \mathrm{cm}^{-3}$, $K'=4.6\times10^{-4}\ \mathrm{cm}^{-3}$

(e.g. Fiedler & Mouschovias 1993, Hosking & Whitworth 2004)

$\Longrightarrow \quad x_e \sim 10^{-5} \ldots 0.1$



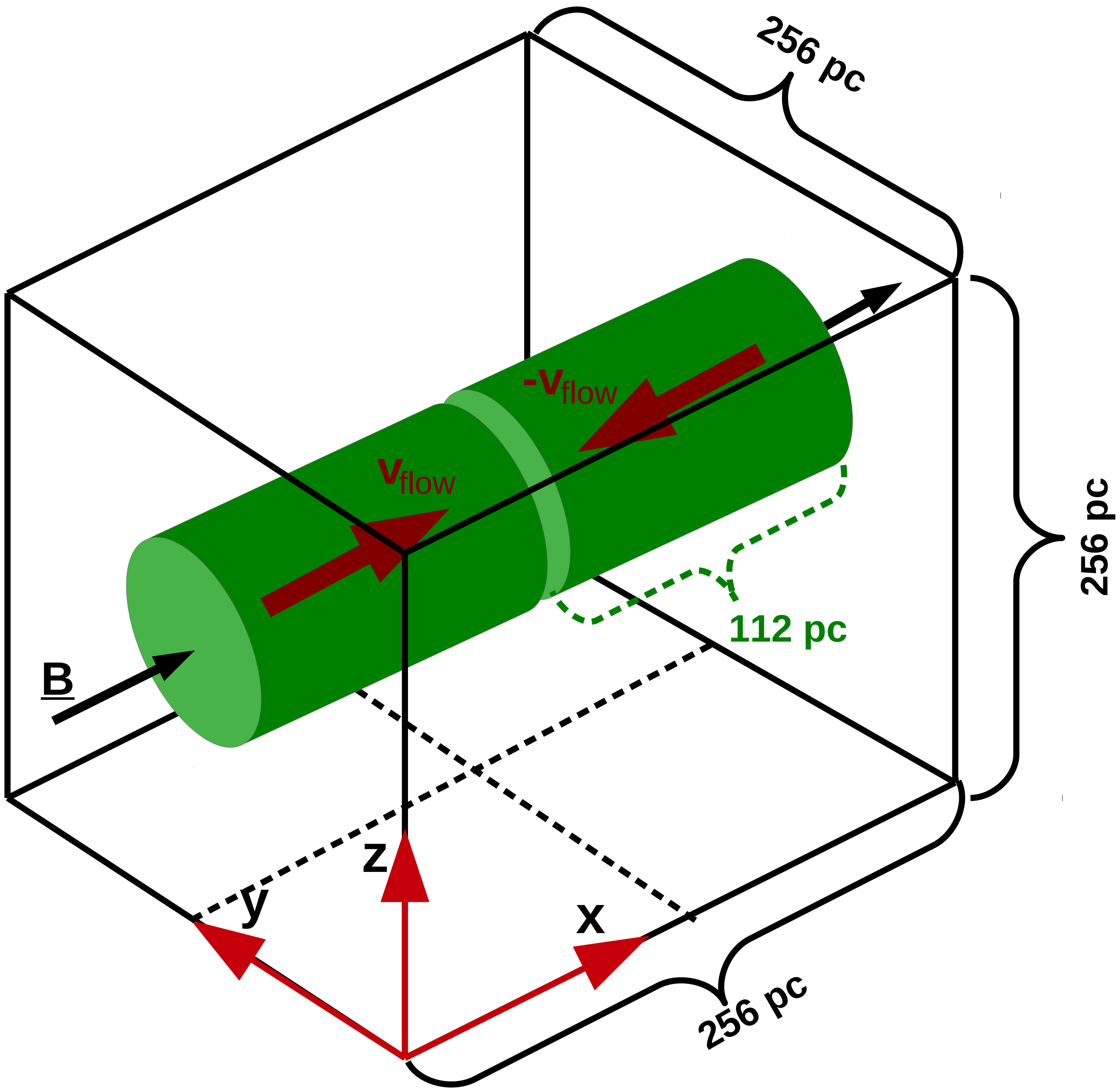
$\Longrightarrow$ AD timescale:

$$t_{AD} \approx \frac{L}{v_d} \quad ; \quad v_d \approx \frac{1}{L}\,\frac{B^2}{4\pi}\,\frac{1}{\gamma\,\rho_i\,\rho_n}$$

$$\sim 10^3\,\mathrm{Myr}\left(\frac{L}{10\,\mathrm{pc}}\right)^2\left(\frac{B}{10\,\mu\mathrm{G}}\right)^{-2}\left(\frac{n_H}{100\,\mathrm{cm}^{-3}}\right)^{-1}$$

Simulations of colliding flows

MC formation & star formation



see also *Vazquez-Semadeni et al.* 2007, 2010

Model parameter:

- $n = 1\ \mathrm{cm}^{-3}$
- $r = 32 \ldots 64$ pc

  $\Longrightarrow M_{\mathrm{inf}} = 2.3 \times 10^4\ \mathrm{M}_\odot$

  $\Longrightarrow N \approx 7 \times 10^{20}\ \mathrm{cm}^{-2}$
- $\mathrm{v}_{\mathrm{inf}} = 14$ km/sec

\+ turbulence:

$\mathrm{v}_{\mathrm{turb}} = 0.2 \ldots 12$ km/sec

\+ ambipolar diffusion

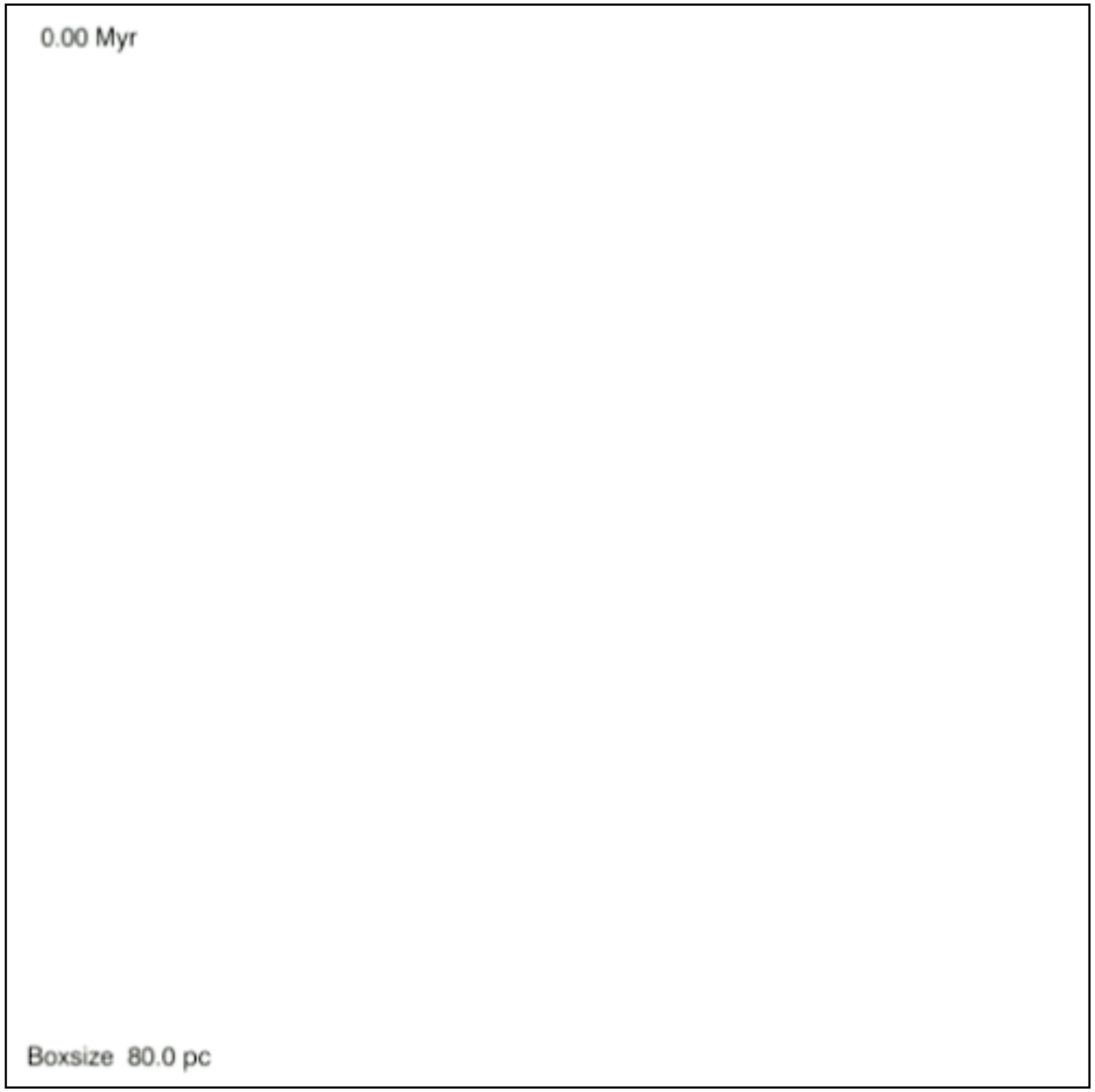
- $B_x = 1 \ldots 5\ \mu\mathrm{G}$

  $\Longrightarrow \mu/\mu_{\mathrm{crit}} = 1.1\ (B/3\mu\mathrm{G})^{-1}$

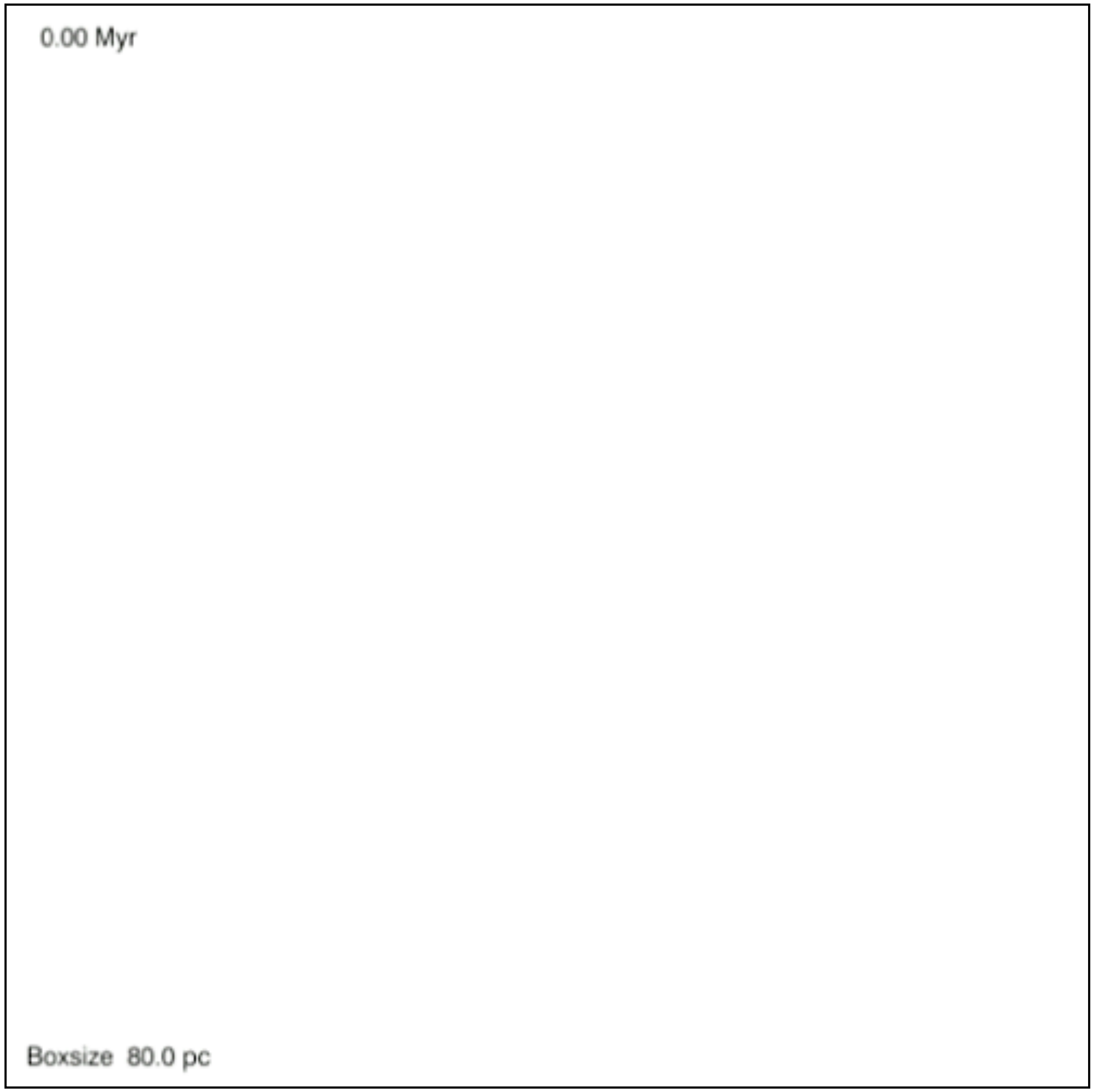
  $\Longrightarrow t_{\mathrm{crit}} \approx 15$ Myr $(\mathrm{B}/3\mu\mathrm{G})$

Simulations of colliding flows

influence of magnetic fields



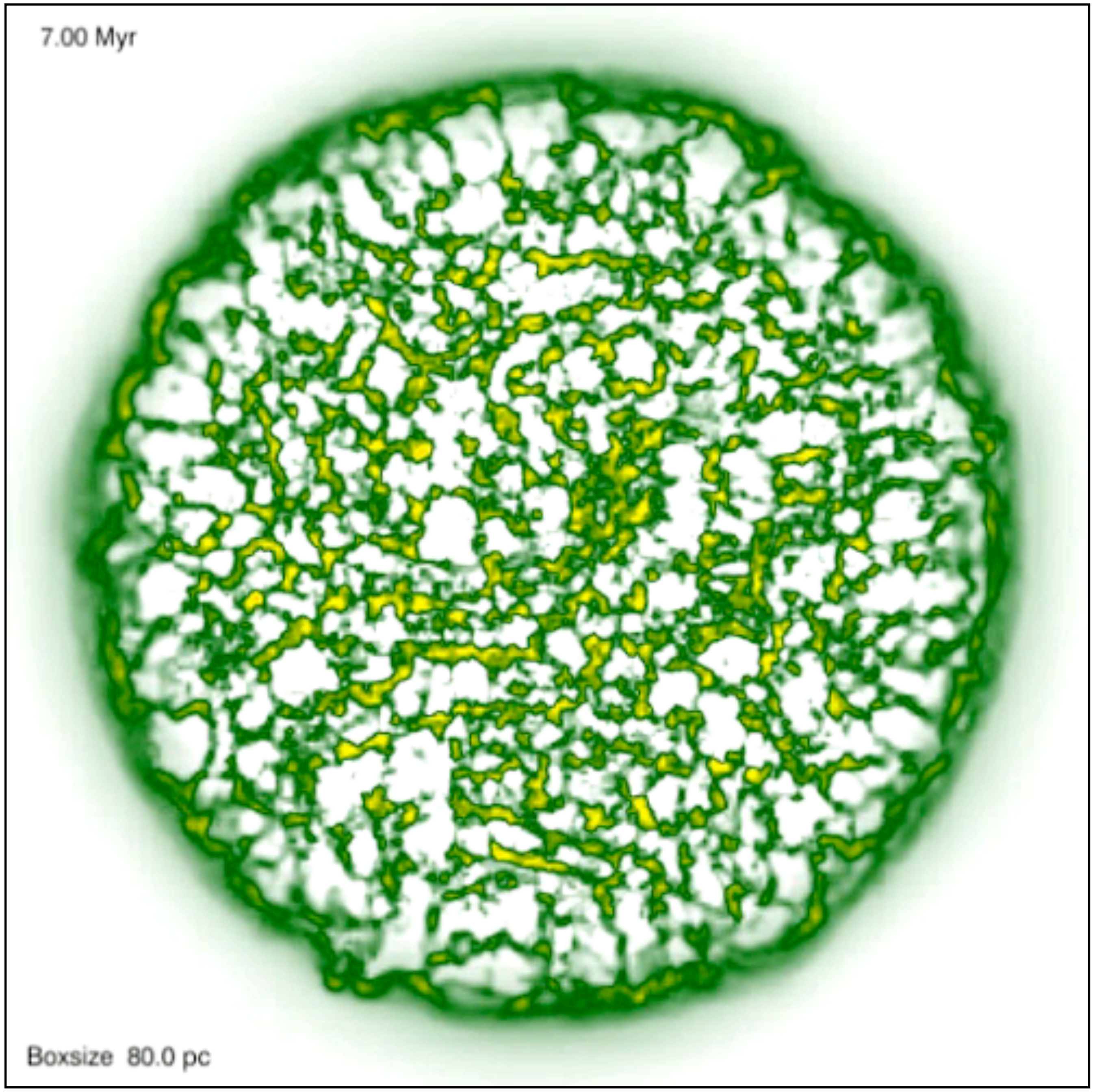
$B = 3\mu G$

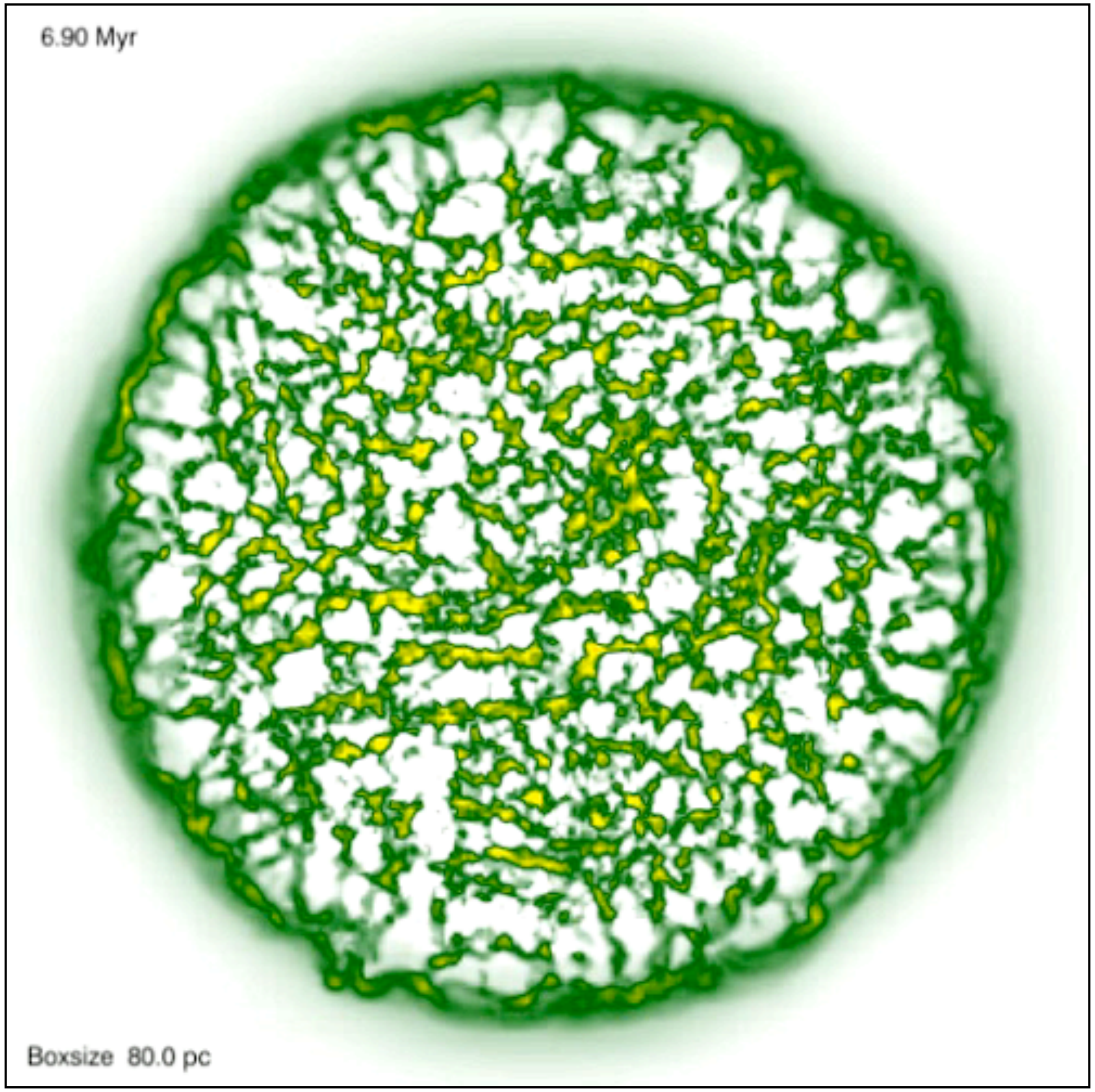


$B = 4\mu G$

Simulations of colliding flows

influence of ambipolar diffusion





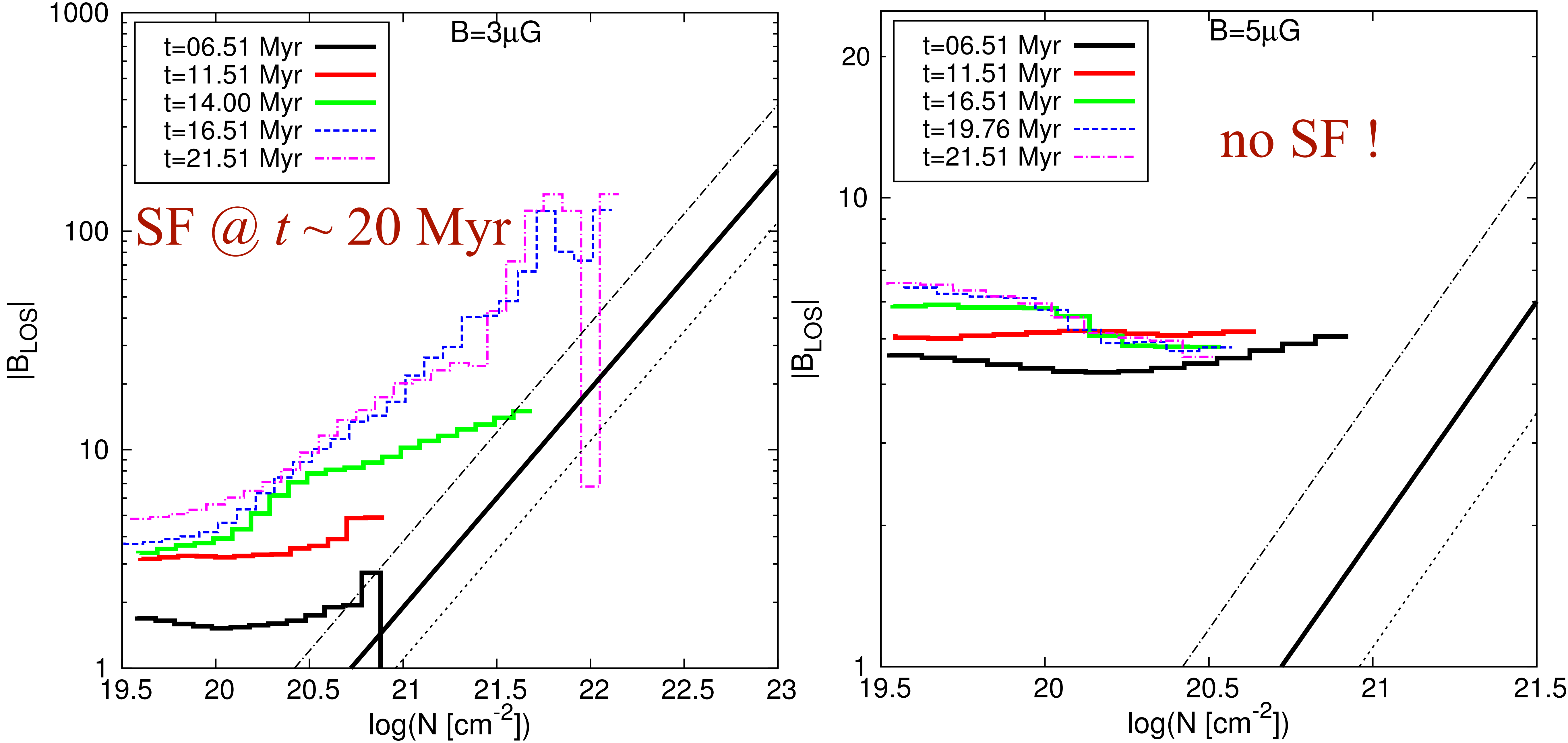
ideal case

$B = 4\mu G$

with ambipolar diffusion

Simulations of colliding flows

results from head-on colliding flows with different field strengths



B. Körtgen, RB, MNRAS (2015)

Simulations of oblique flows

Simulations setup of oblique flows

$\Longrightarrow$ resemble non-ideal MHD

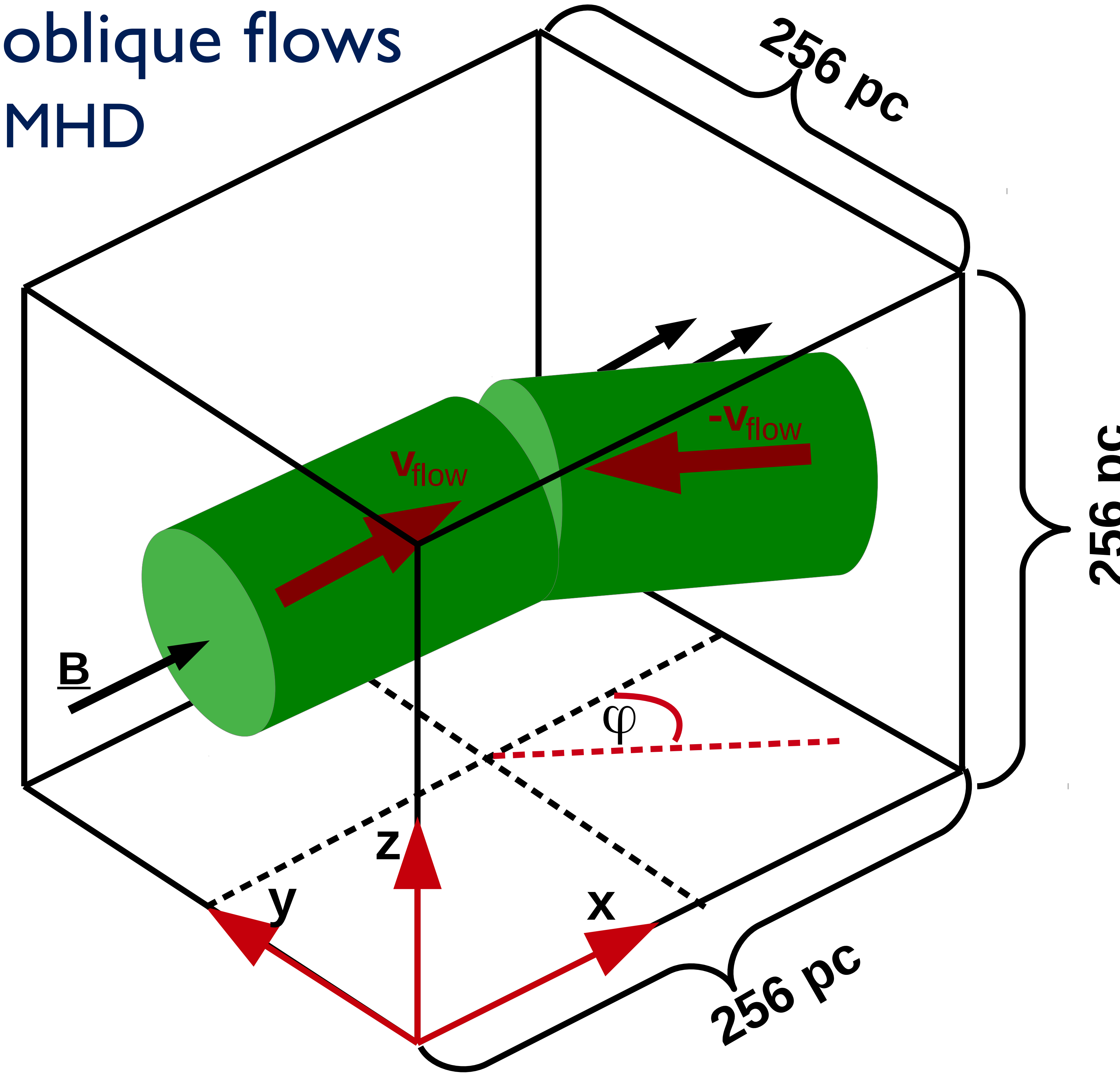
Model parameter:

- $\varphi = 0, 30, 60$

- $n = 1 \ldots 10\ \mathrm{cm}^{-3}$
- $r = 32 \ldots 64$ pc

- $v_{\mathrm{inf}} = 14$ km/sec
- $v_{\mathrm{turb}} = 2..10$ km/sec

- $B_x = 1 \ldots 5\ \mu\mathrm{G}$



B. Körtgen, RB, MNRAS (2015)

Simulations of oblique flows

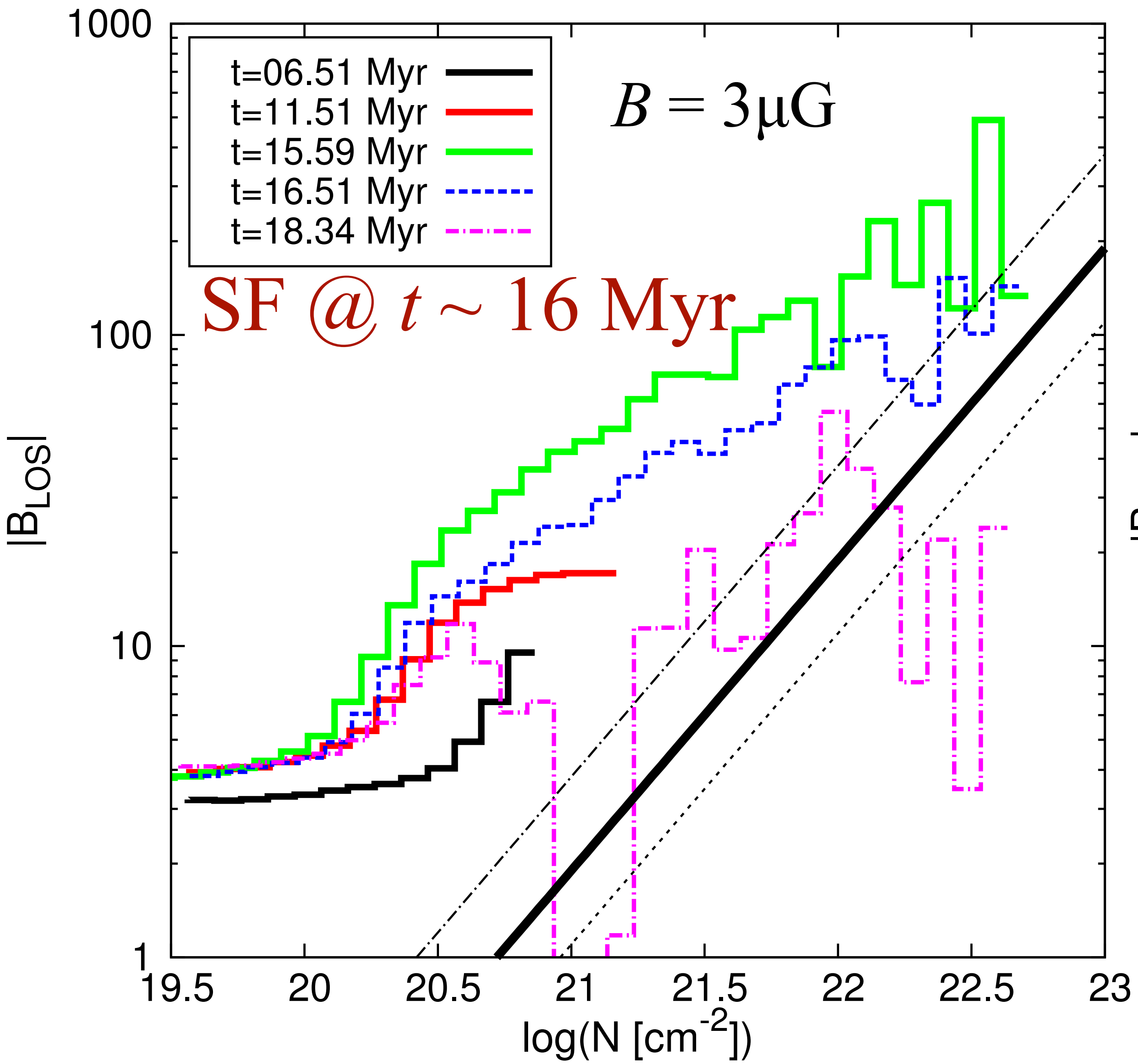
$\varphi = 30°$

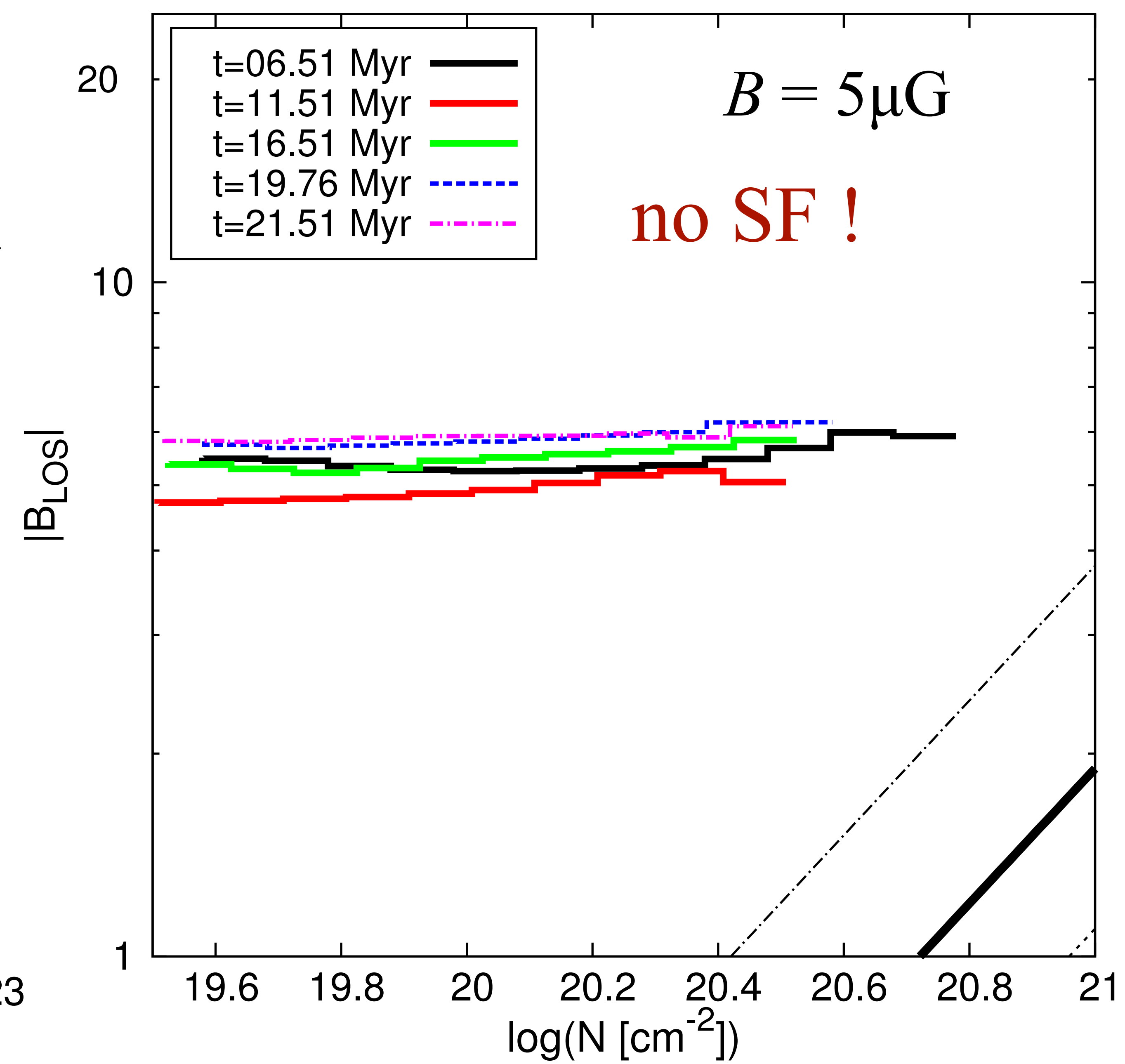
$B = 3\mu G$

$B = 5\mu G$

Simulations of oblique flows

results from *oblique* flows with different field strengths at $\varphi = 30°$



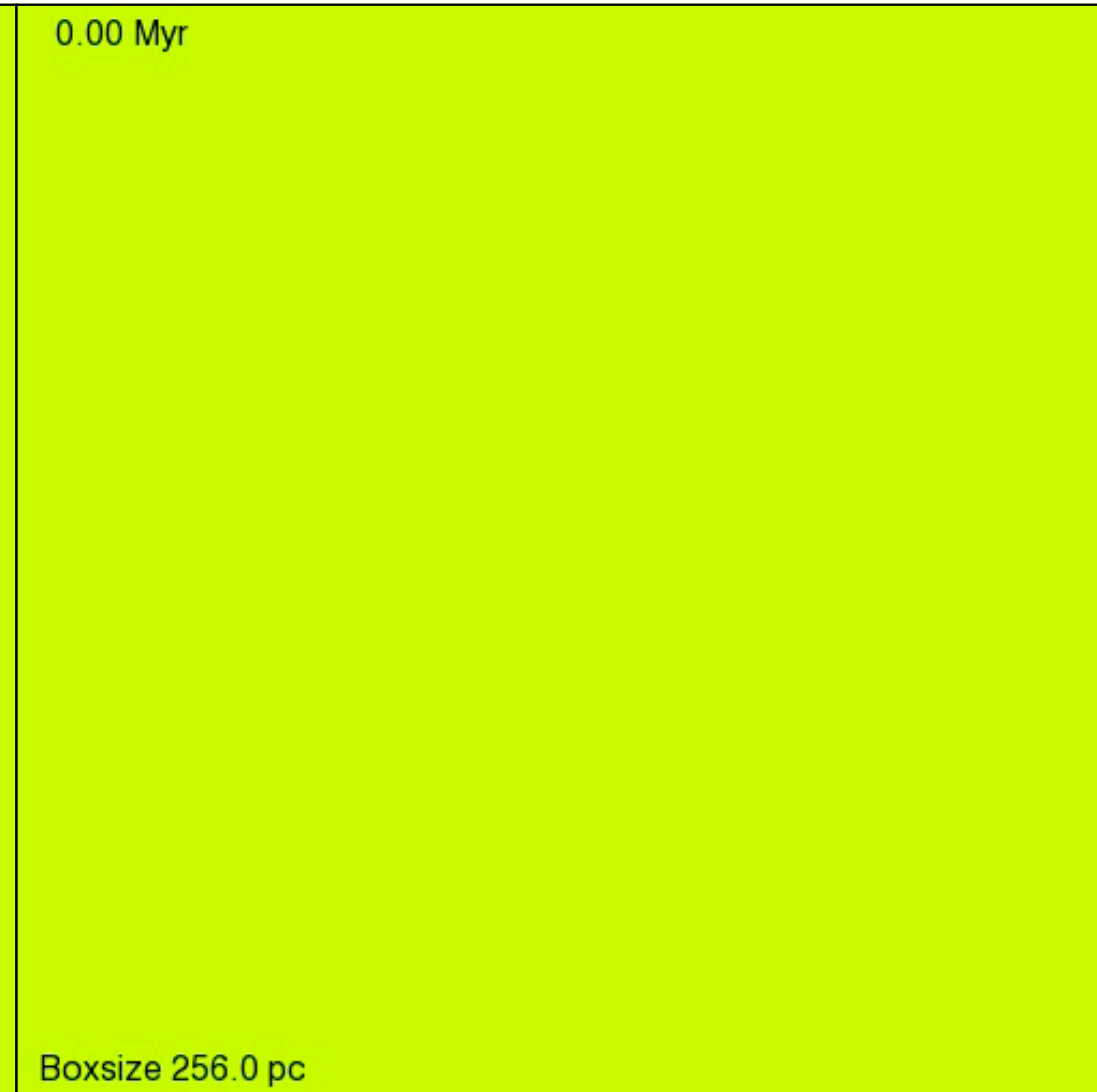


B. Körtgen, RB, MNRAS (2015)

Simulations of oblique flows

$\varphi = 60°$

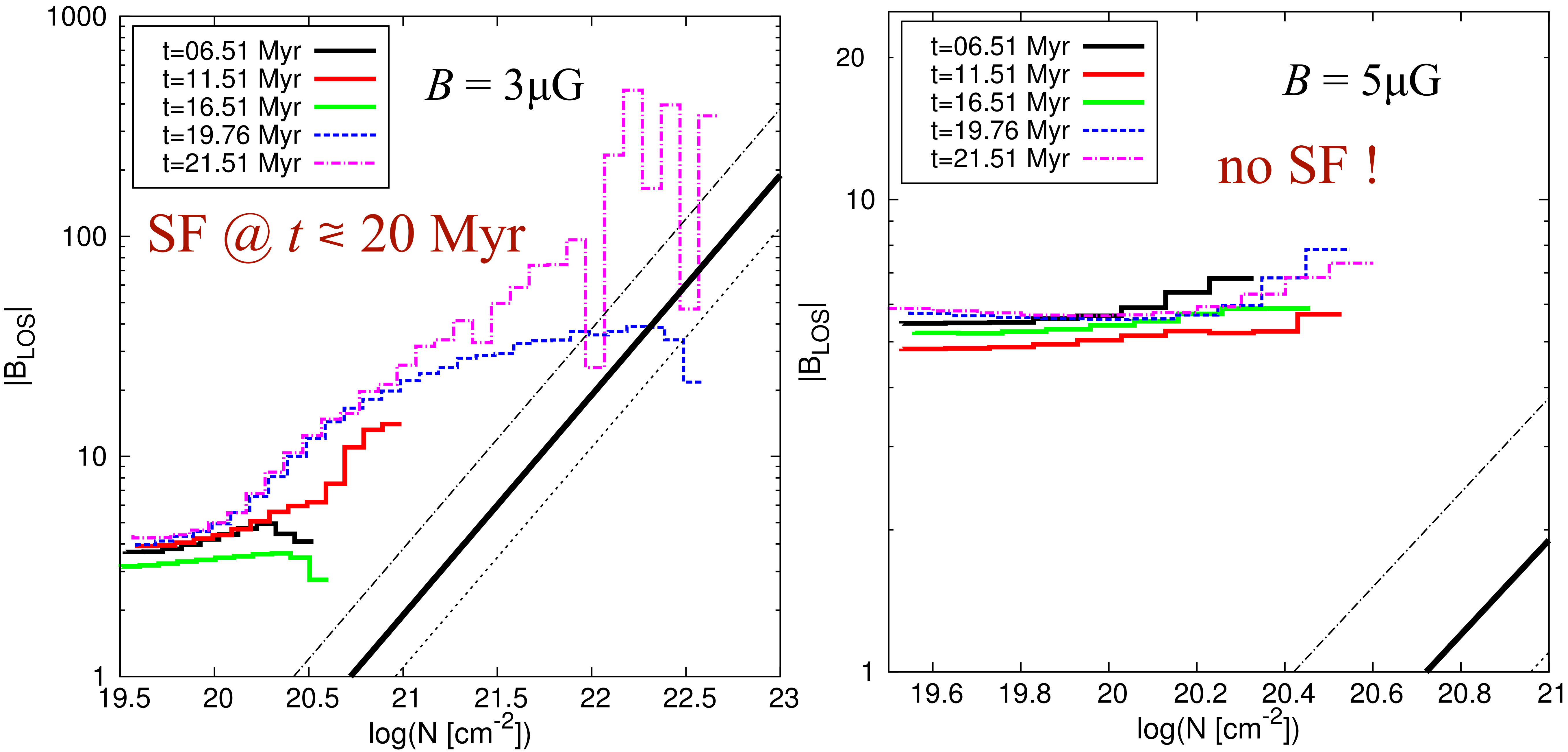
$B = 3\mu G$



$B = 5\mu G$

Simulations of oblique flows

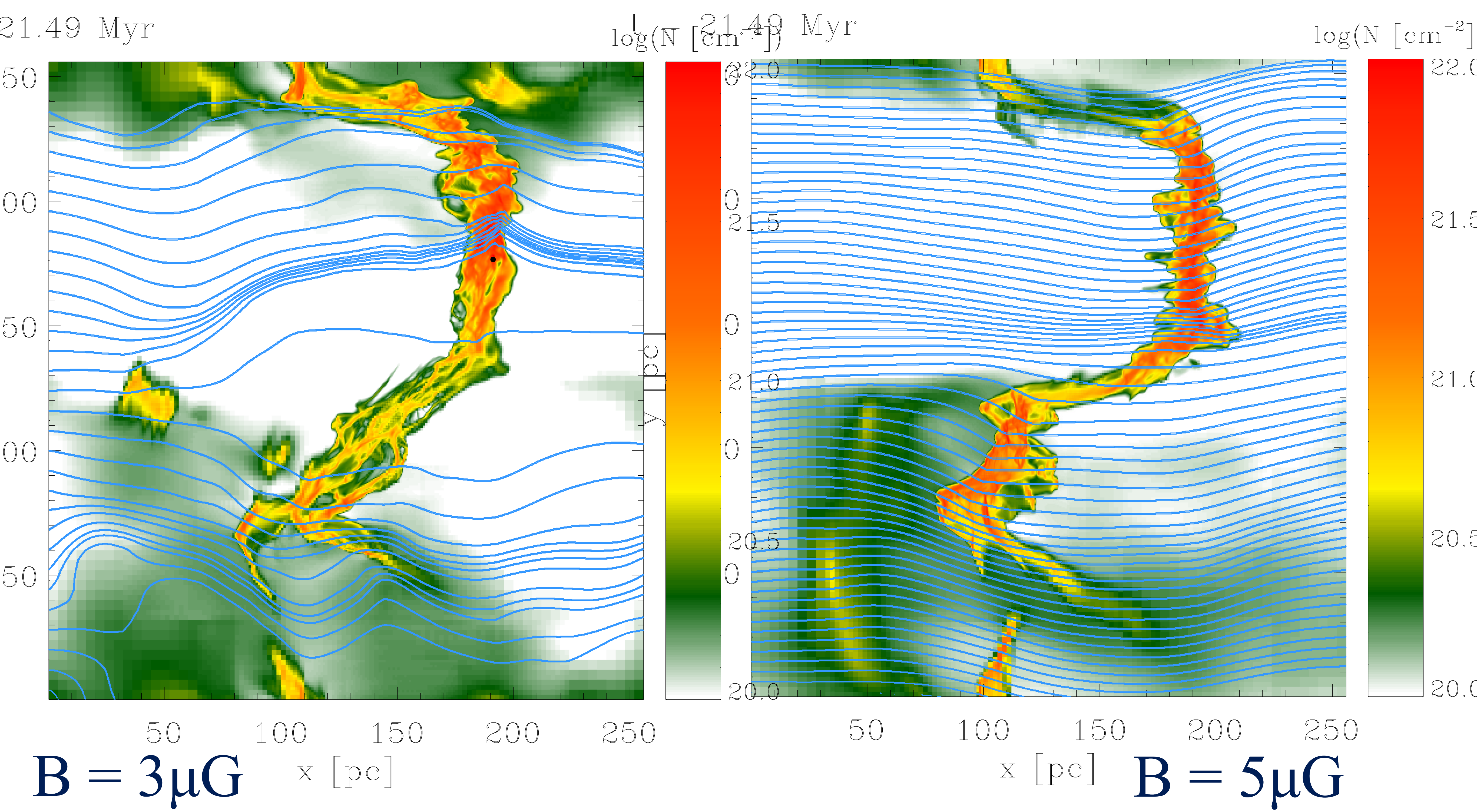
results from *oblique* flows with different field strengths at $\varphi = 60°$



B. Körtgen, RB, MNRAS (2015)

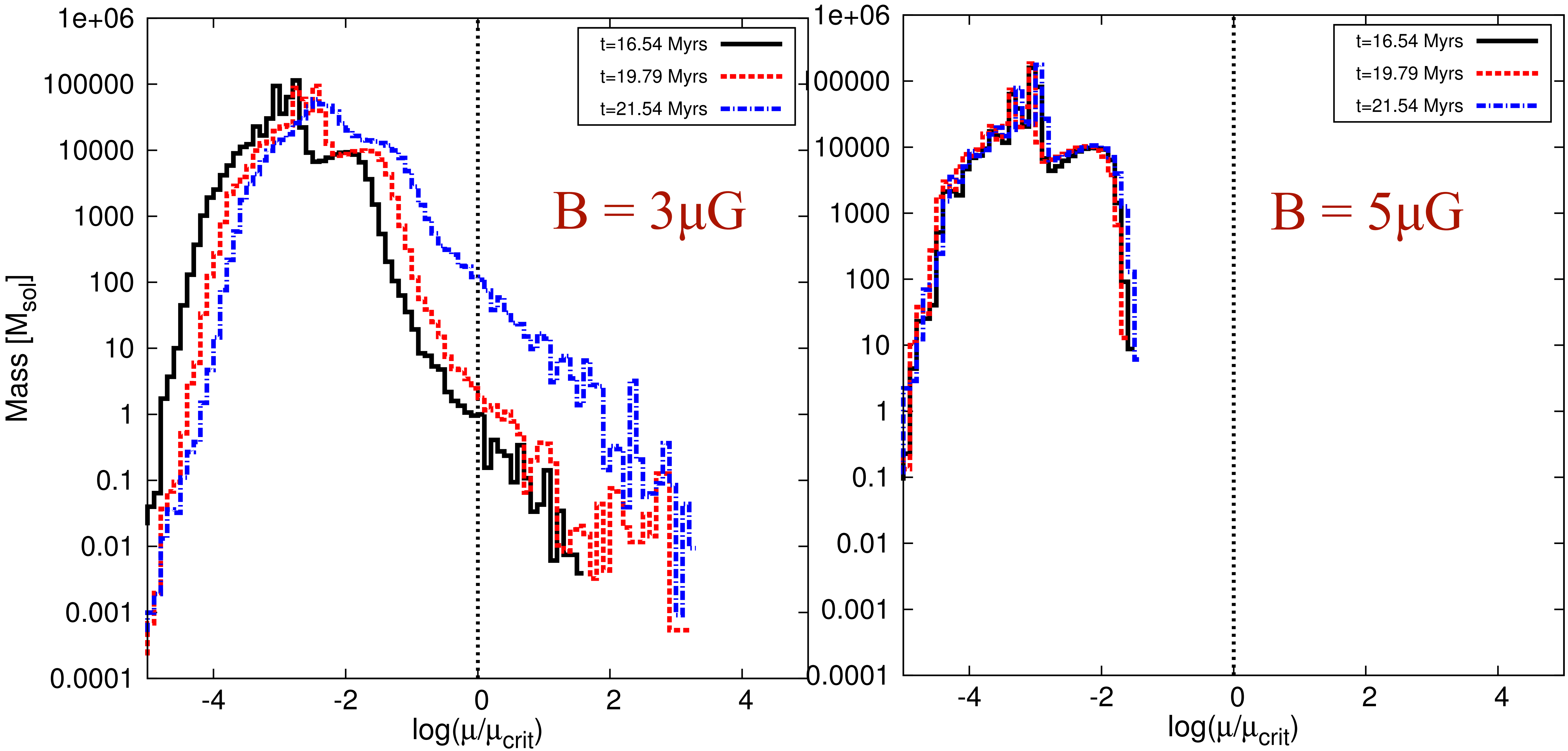
Simulations of oblique flows

results from *oblique* flows with different field strengths at $\varphi = 60°$



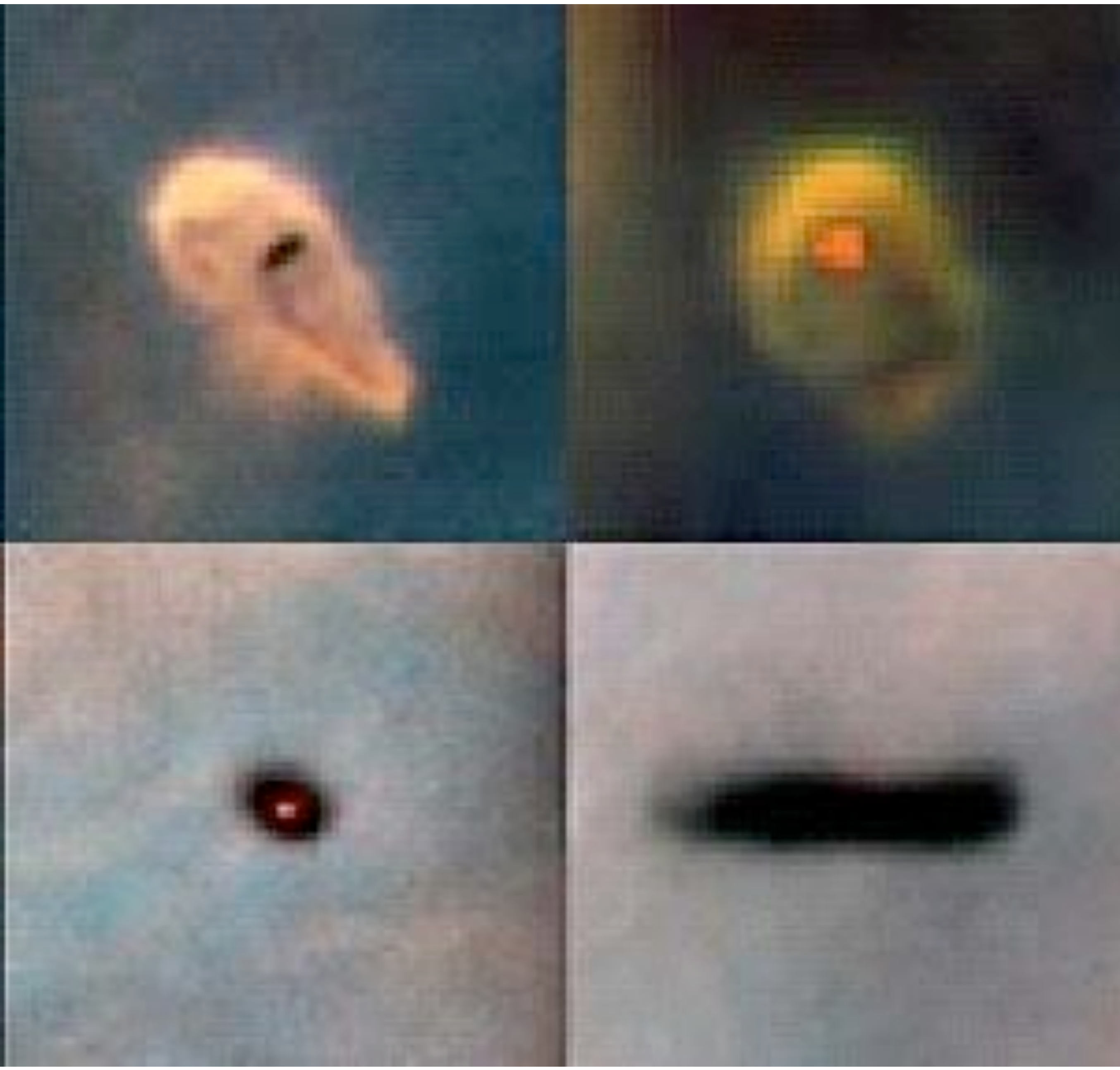
Simulations of oblique flows

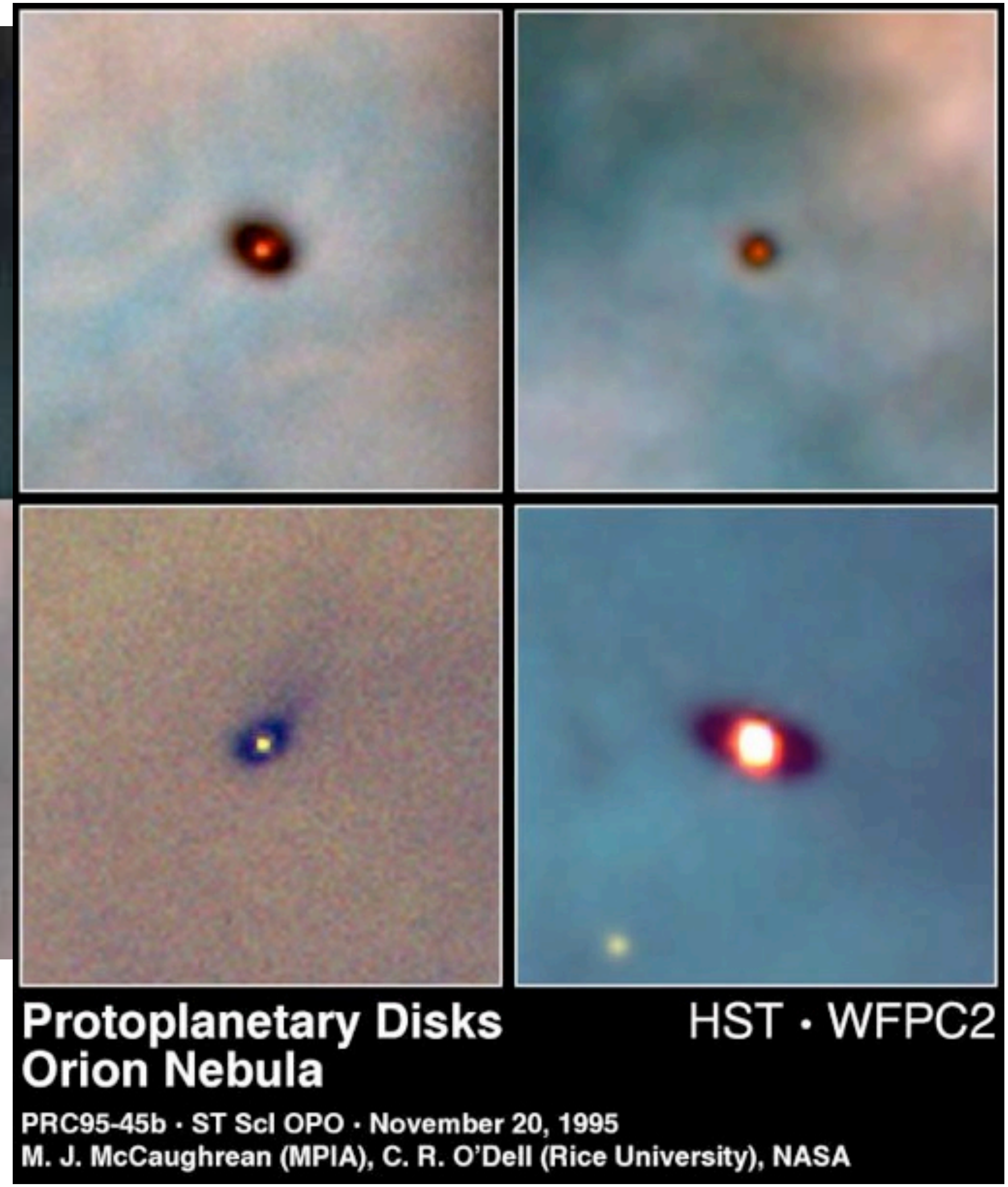
results from *oblique* flows with different field strengths at $\varphi = 60°$



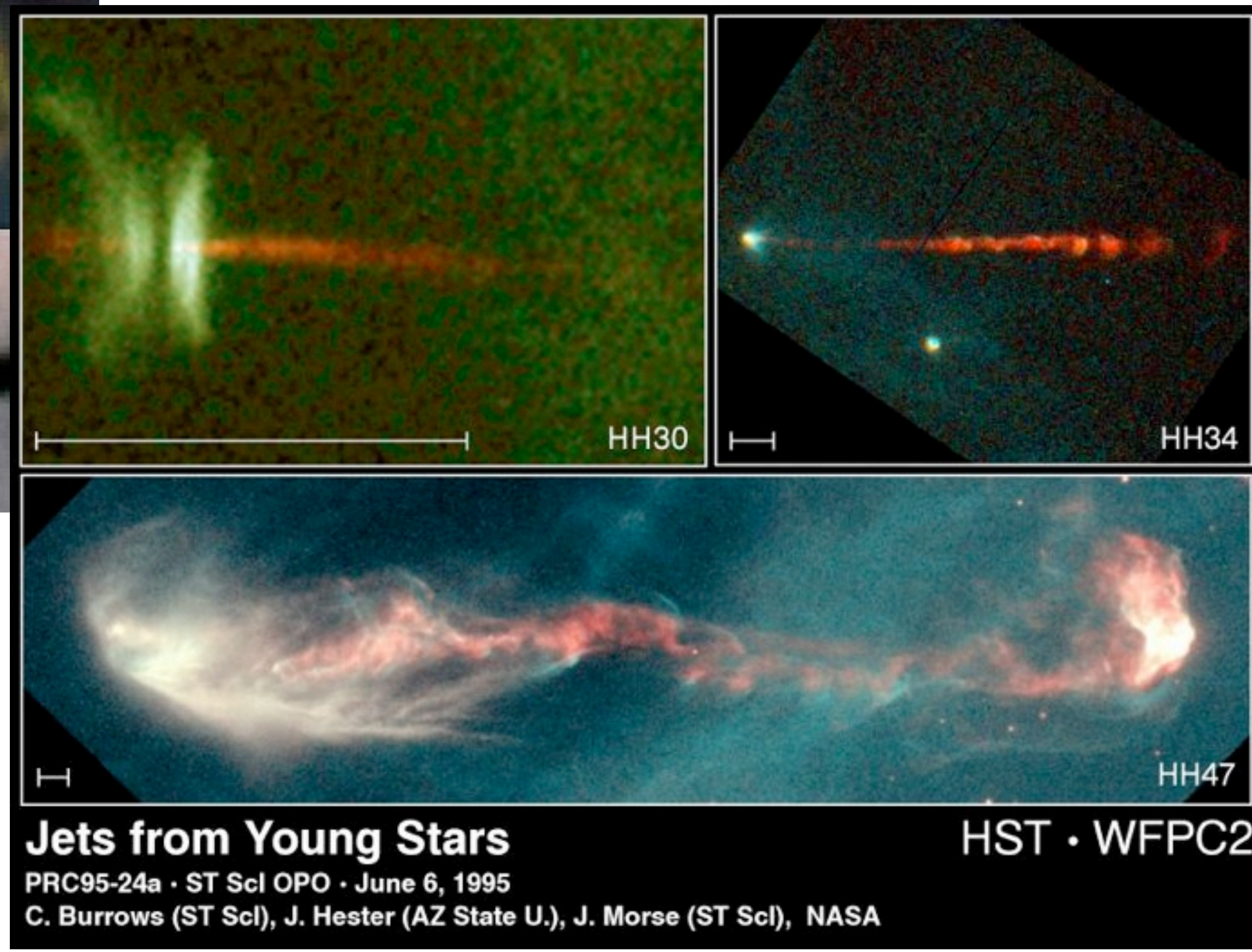
B. Körtgen, RB, MNRAS (2015)

Impact of Magnetic Fields: Protostellar Discs





Impact of Magnetic Fields: Protostellar Discs



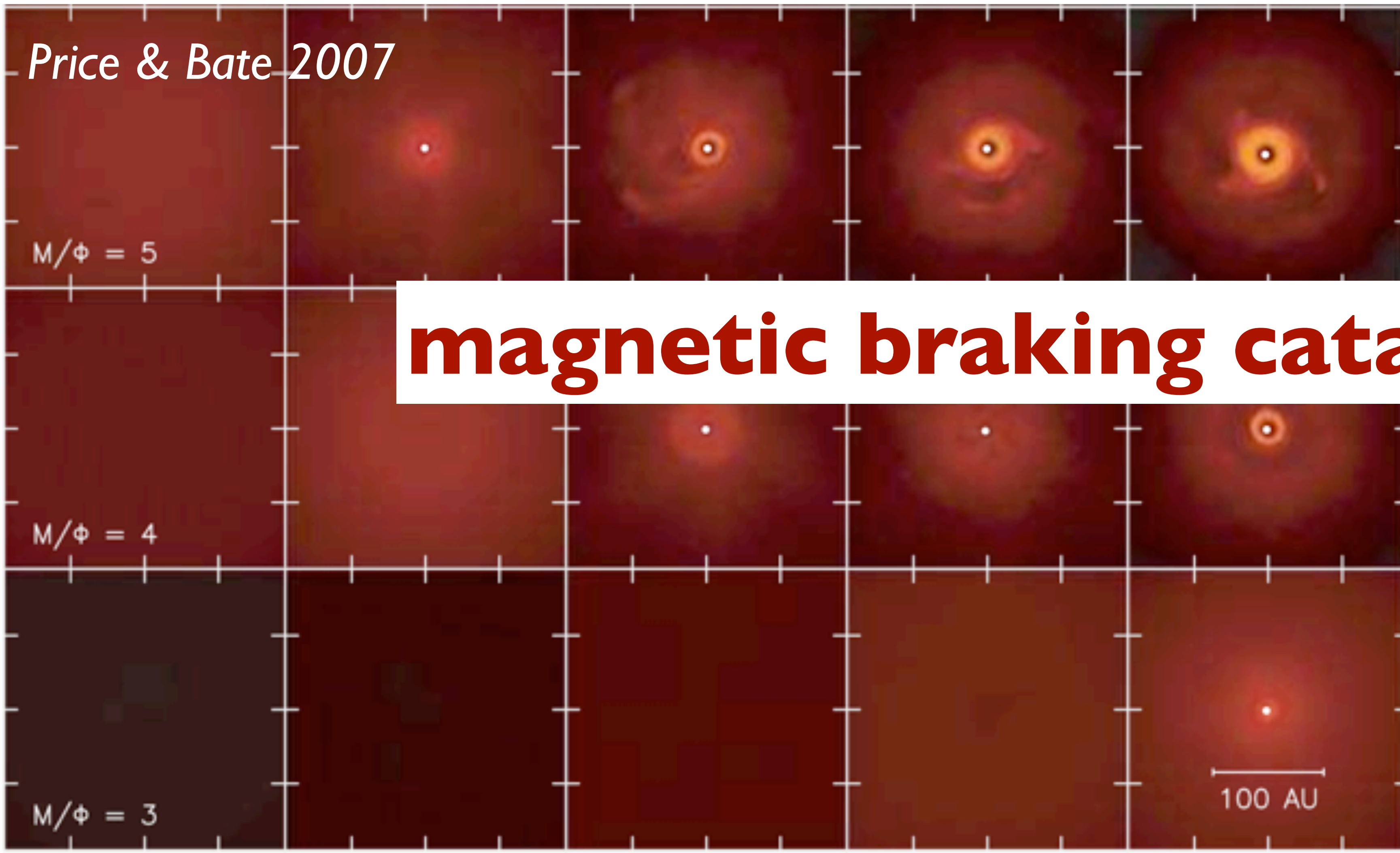
$\Longrightarrow$ jets & outflows are driven by magnetic fields + discs

(e.g. *Blandford & Payne* 1982, *Pudritz & Norman* 1983)

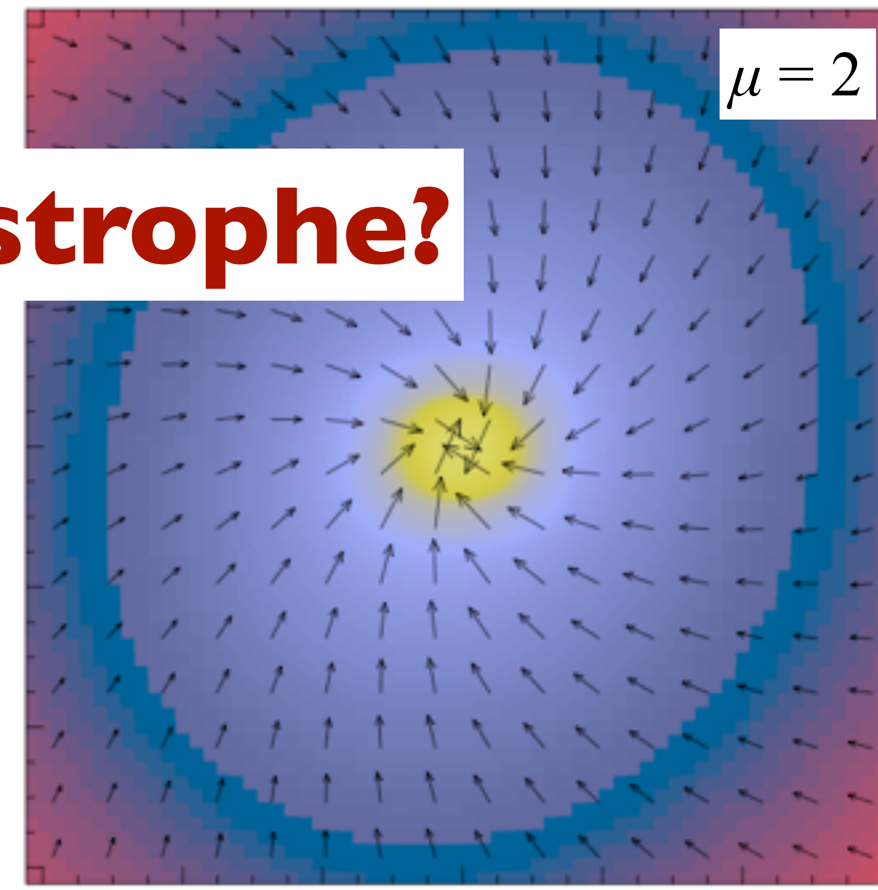
Impact of Magnetic Fields: Protostellar Discs

⟹ discs necessary for disc winds / outflows

- observed magnetic fields indicate $\mu < 5$ (e.g. *Crutcher et al.* 2010)



magnetic braking catastrophe?

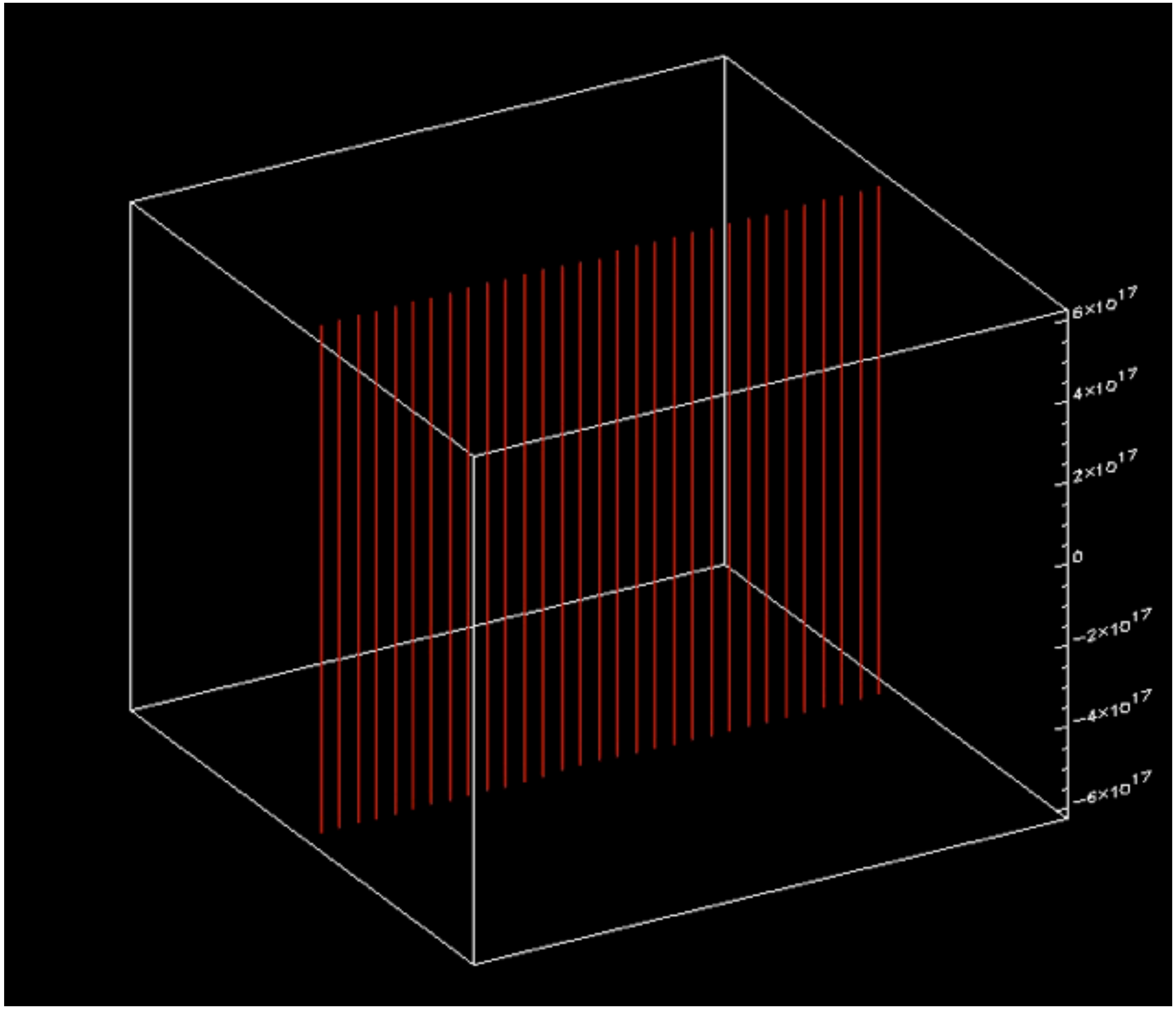


Hennebelle & Teyssier 2008, ...

⟹ ***too*** efficient magnetic braking

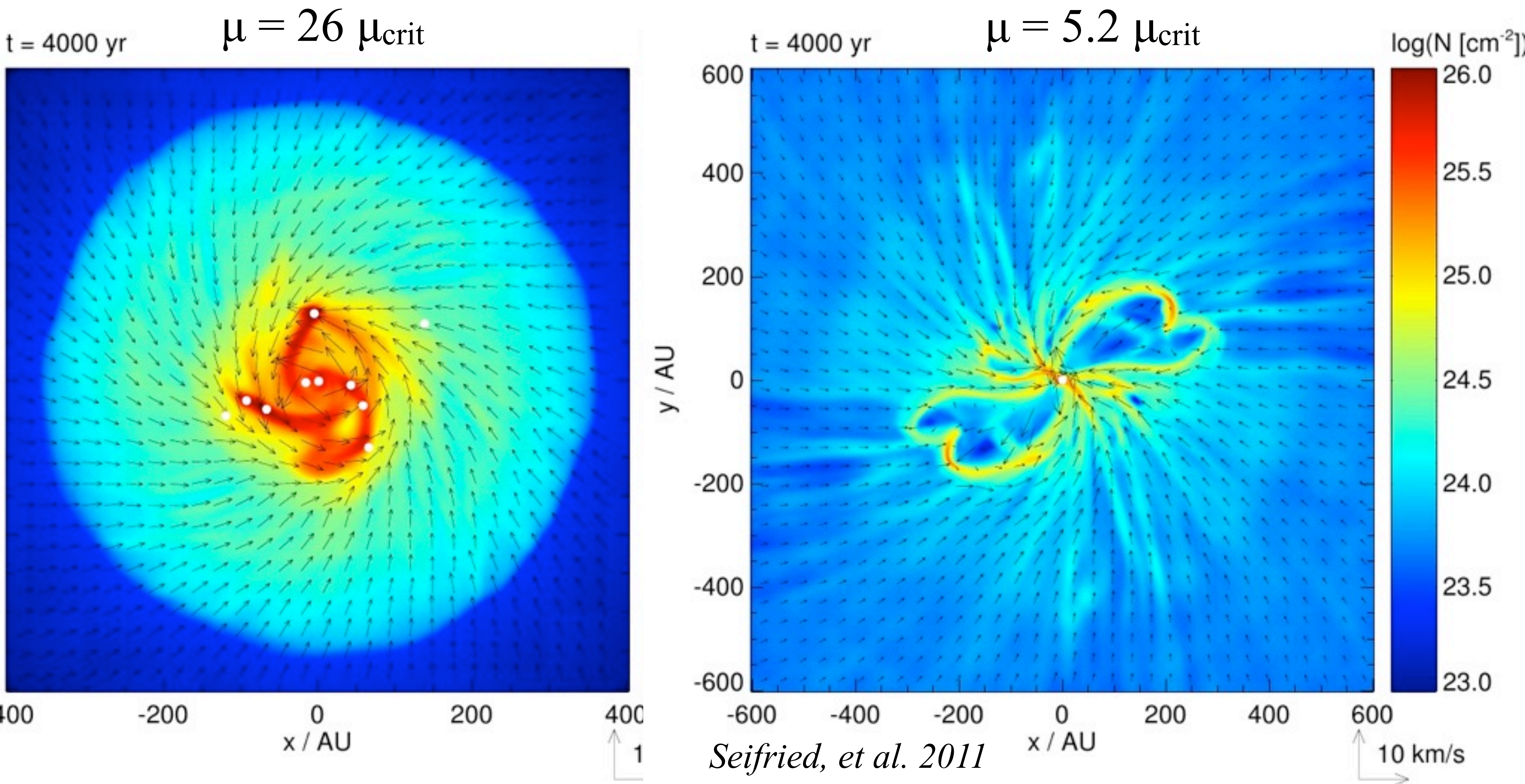
⟹ ***no*** disc formation with smooth initial conditions

Impact of Magnetic Fields: Protostellar Discs



- magnetic braking $\Longrightarrow$ transfer of angular momentum by torsional Alfven waves

Impact of Magnetic Fields: Protostellar Discs



Seifried, et al. 2011

stronger fields ⇒ efficient magnetic braking and suppression of disc formation

Impact of Magnetic Fields: Protostellar Discs

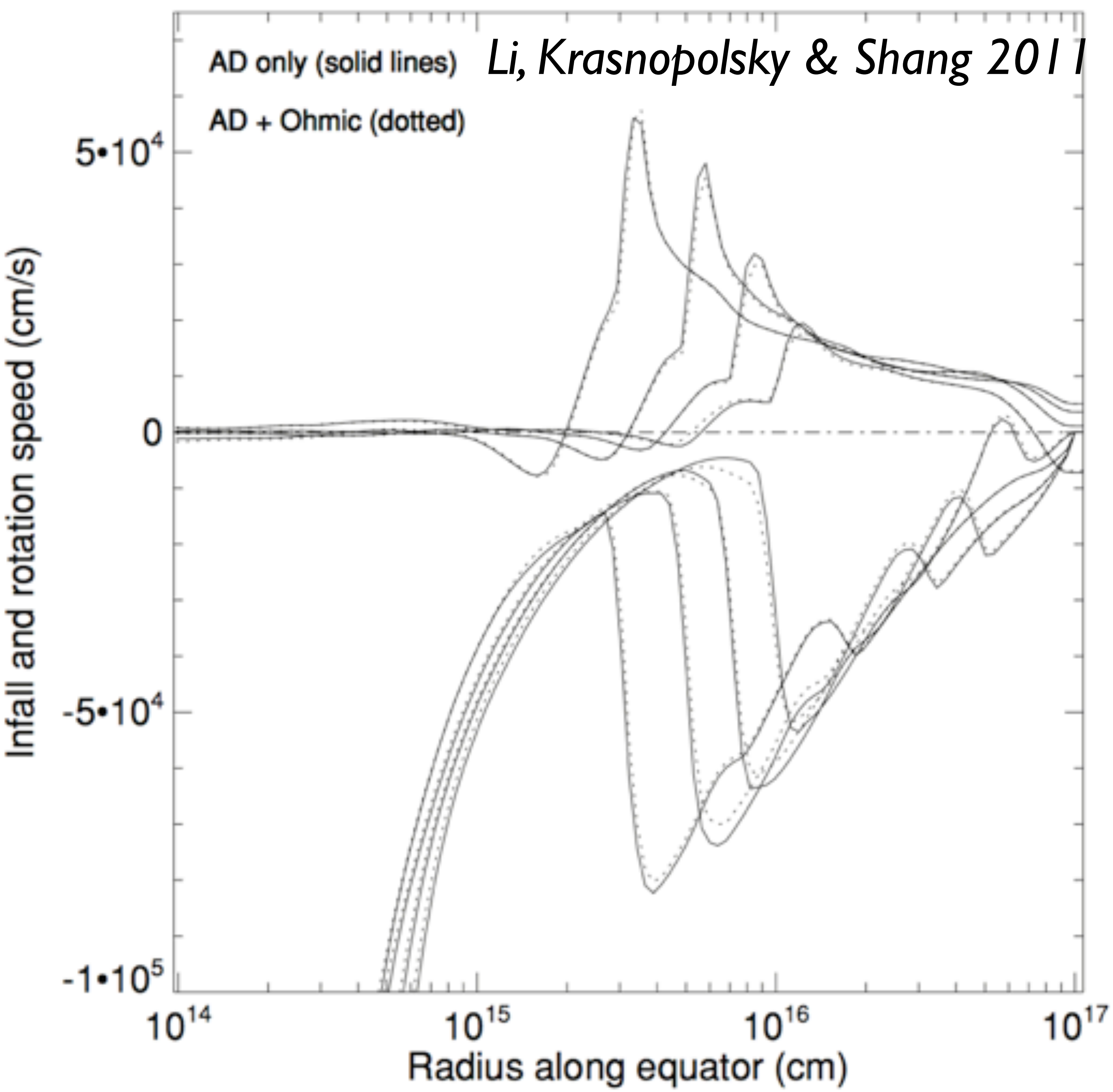
suggested **solutions** to the magnetic braking catastrophe:

- Ambipolar diffusion (*Mellon & Li* 2009, *Li et al.* 2011)
- Turbulent reconnection (*Santos-Lima et al.* 2012)
- Ohmic resistivity (e.g. *Dapp & Basu* 2010, *Krasnopolsky et al.* 2010)
- Misaligned configuration (*Hennebelle & Ciardi* 2009, *Joos et al.* 2012)

Dissipation processes

$\Longrightarrow$ Non-ideal MHD and reconnection active only at small scales/high density

$\Longrightarrow$ not effective enough to reduce magnetic braking



$\Longrightarrow$ *Li, Krasnopolsky & Shang* 2011*:*

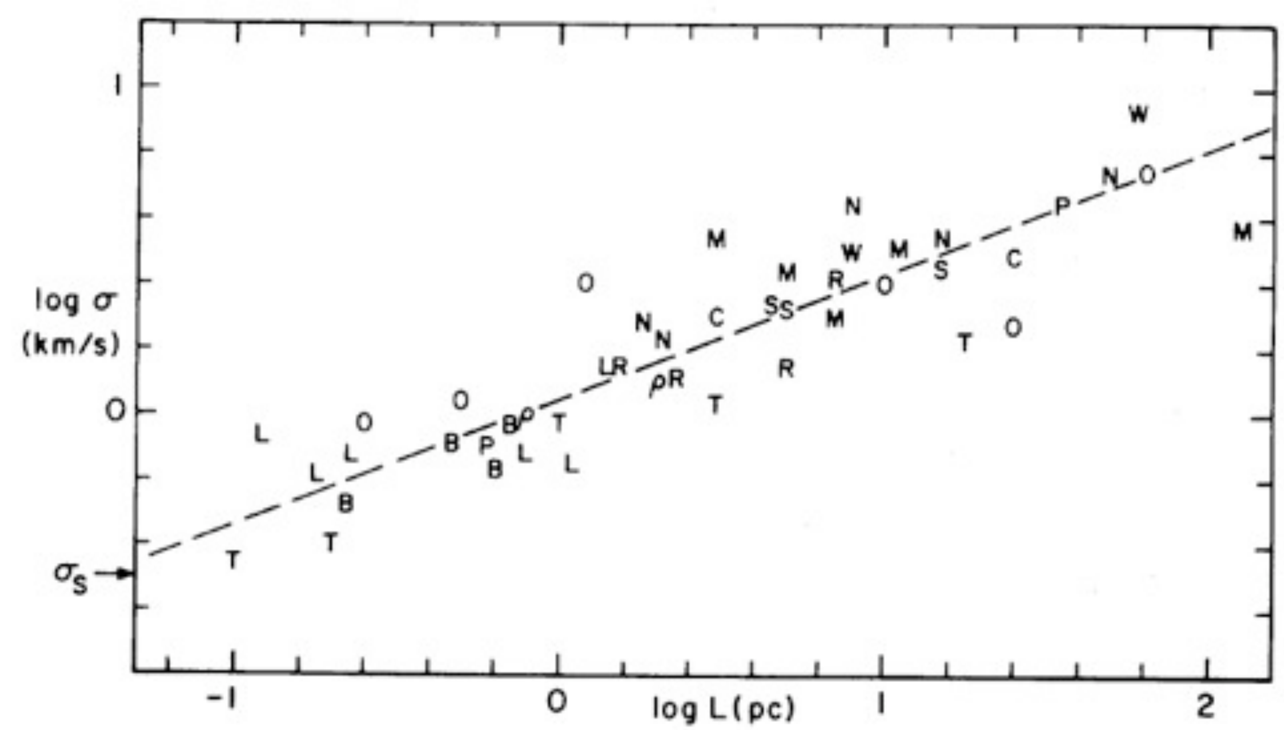
"The problem of catastrophic magnetic braking that prevents disk formation in dense cores magnetized to realistic levels remains unresolved"

Star Formation: Early-type discs

suggested solutions to the magnetic braking catastrophe:

- Ambipolar diffusion (*Mellon & Li* 2009, *Li et al.* 2011)
- Turbulent reconnection (*Santos-Lima et al.* 2012)
- Ohmic resistivity (e.g. *Dapp & Basu* 2010, *Krasnopolsky et al.* 2010)
- Misaligned configuration (*Hennebelle & Ciardi* 2009, *Joos et al.* 2012)

$\Longrightarrow$ what about **turbulence** ?
i.e. velocity and density *fluctuations*



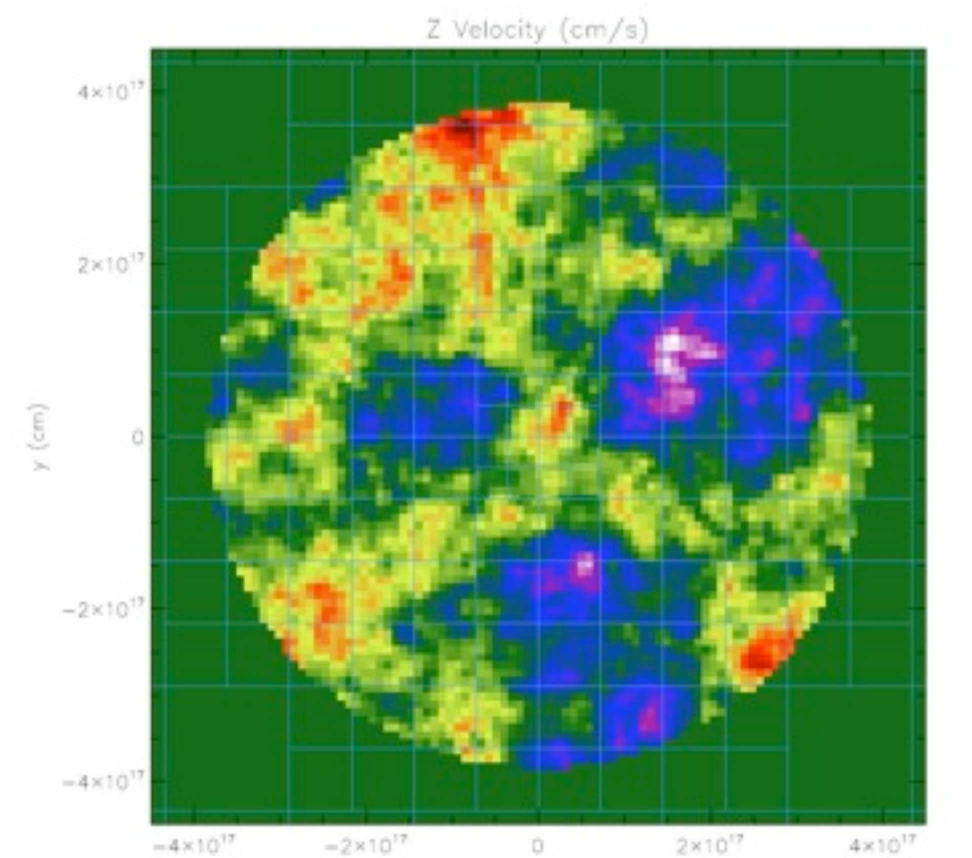
Collapse of Turbulent Cloud Cores

Seifried, et al. 2013

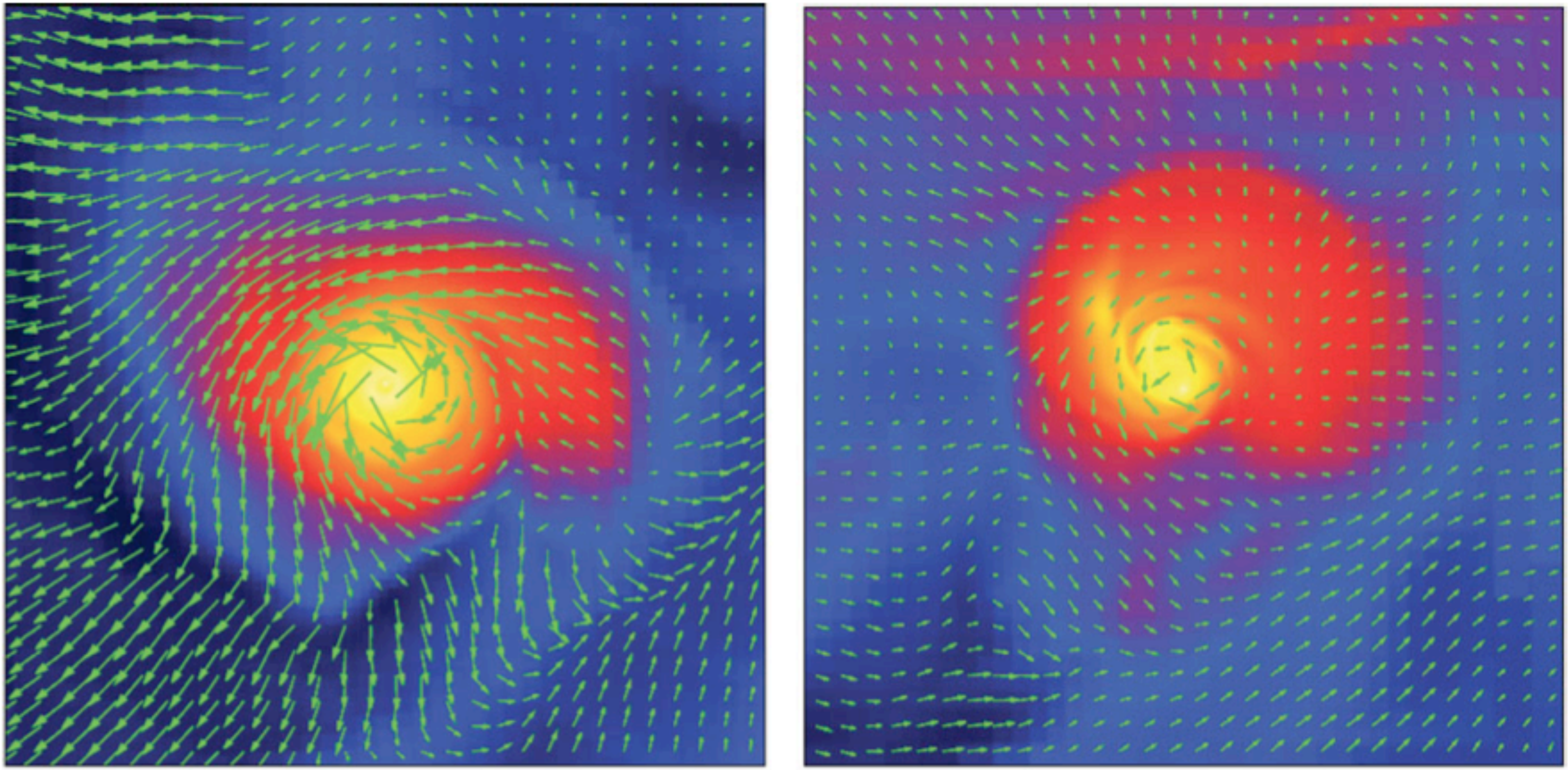
Run	m_{core} ($M_{\odot}$)	r_{core} (pc)	μ	Rotation	Ω (10^{-13} s^{-1})	β_{turb}	Turbulence seed	p	M_{rms}	t_{sim} (kyr)
2.6-NoRot-M2	2.6	0.0485	2.6	No	0	0.087	A	5/3	0.74	15
2.6-Rot-M2	2.6	0.0485	2.6	Yes	2.20	0.087	A	5/3	0.74	15
2.6-NoRot-M100	100	0.125	2.6	No	0	0.084	A	5/3	2.5	15
2.6-Rot-M100	100	0.125	2.6	Yes	3.16	0.084	A	5/3	2.5	15
2.6-Rot-M100-B	100	0.125	2.6	Yes	3.16	0.084	B	5/3	2.5	15
2.6-Rot-M100-C	100	0.125	2.6	Yes	3.16	0.084	C	5/3	2.5	15
2.6-Rot-M100-p2	100	0.125	2.6	Yes	3.16	0.084	A	2	2.5	15
2.6-NoRot-M300	300	0.125	2.6	No	0	0.12	A	5/3	5.0	10
2.6-Rot-M1000	1000	0.375	2.6	Yes	1.90	0.081	A	5/3	5.4	10

- low + high mass cores
- strong magnetic field
- with/without global rotation
- sub-/supersonic **turbulence**

- resolution: 1.2 AU



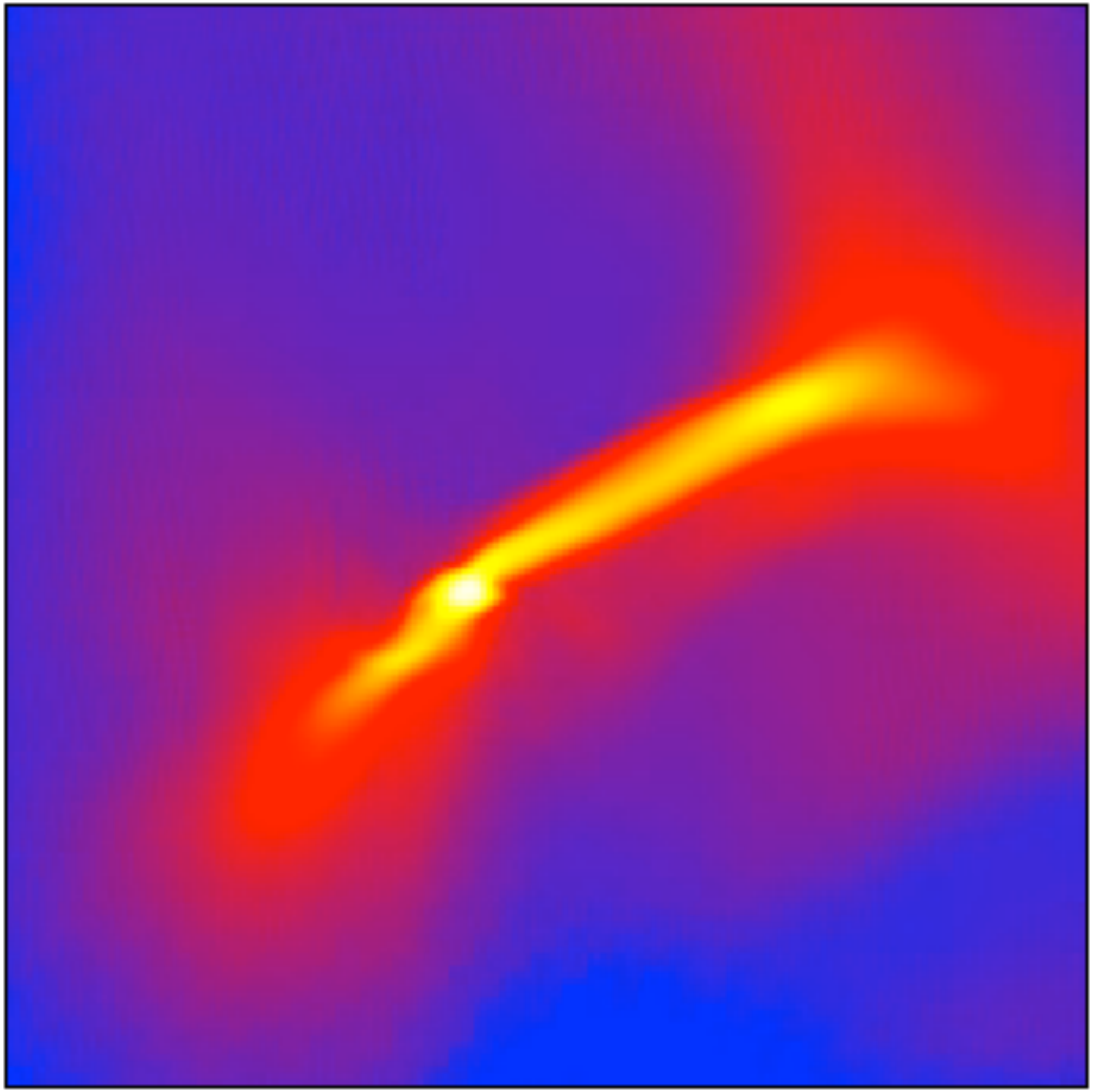
Collapse of Turbulent Cores



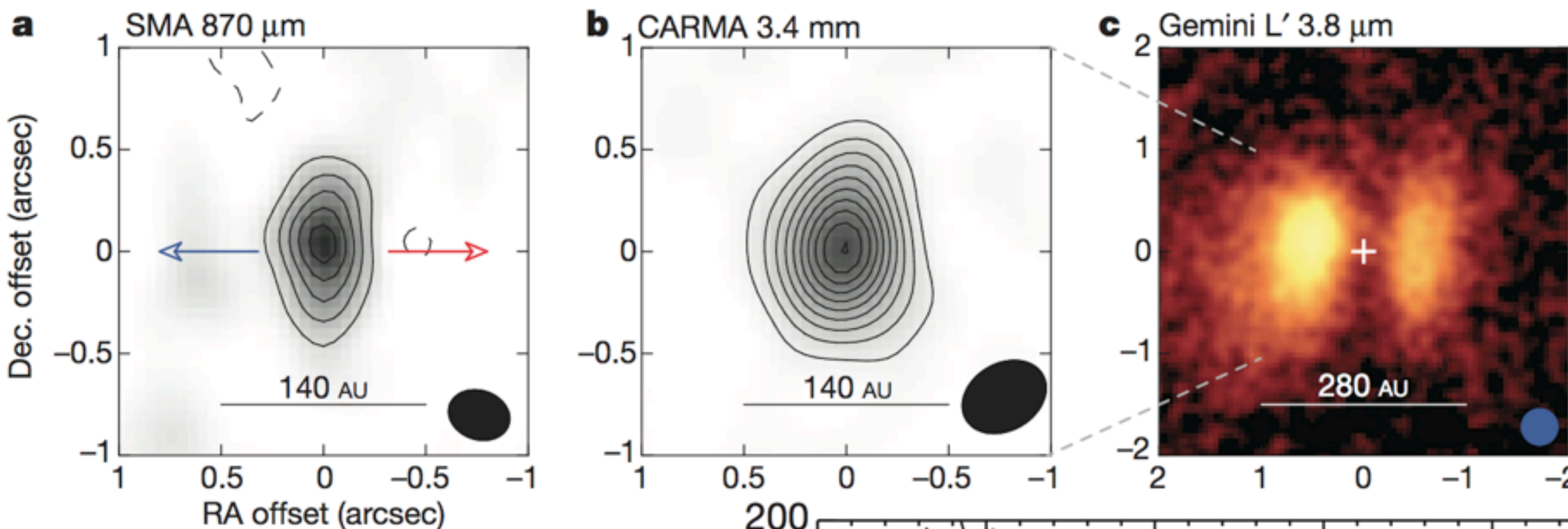
Seifried, RB, Pudritz, Klessen 2012

$\Longrightarrow$ discs “reappear”

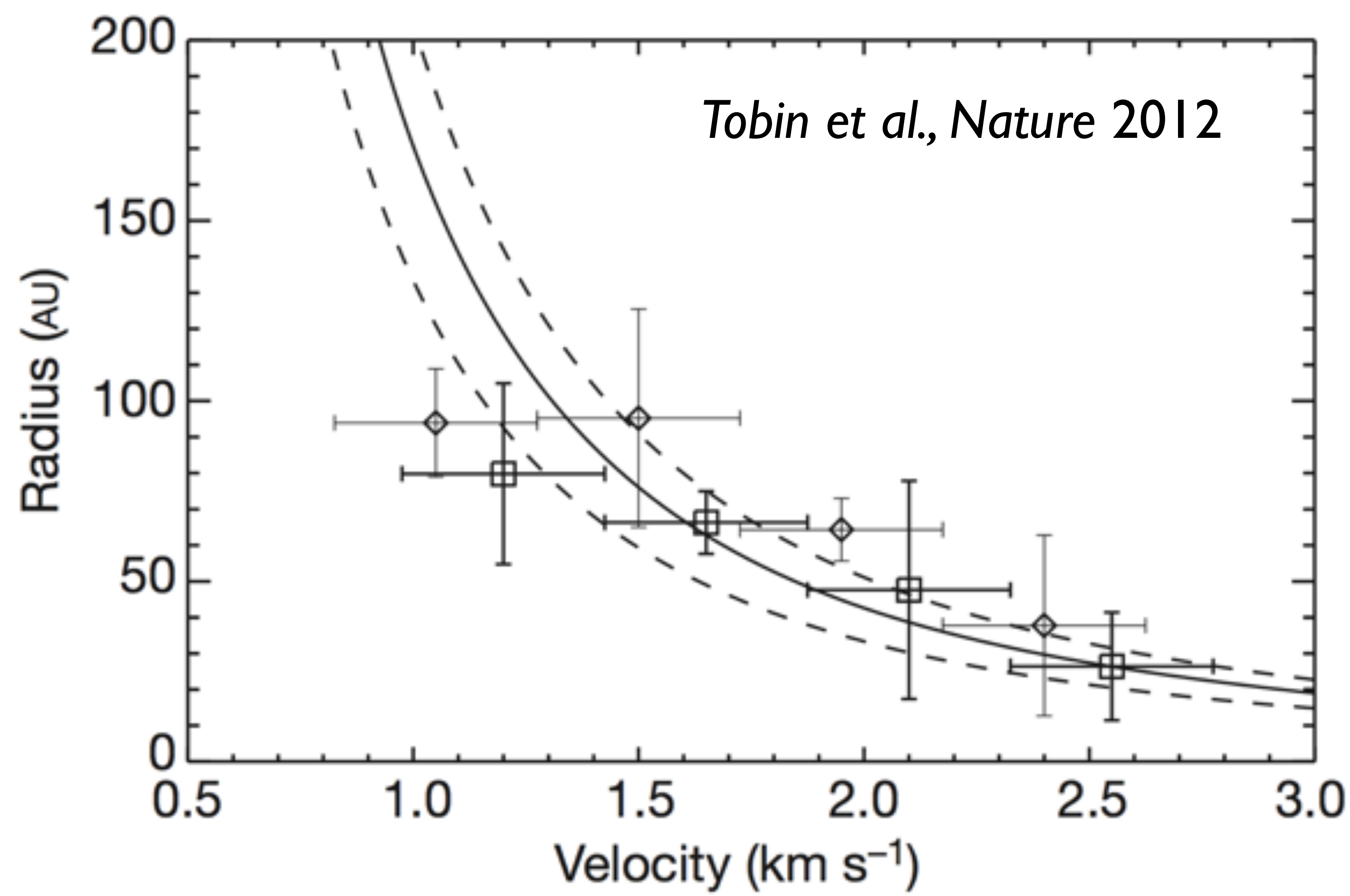
Collapse of Turbulent Cores



Discs around Class 0 protostars

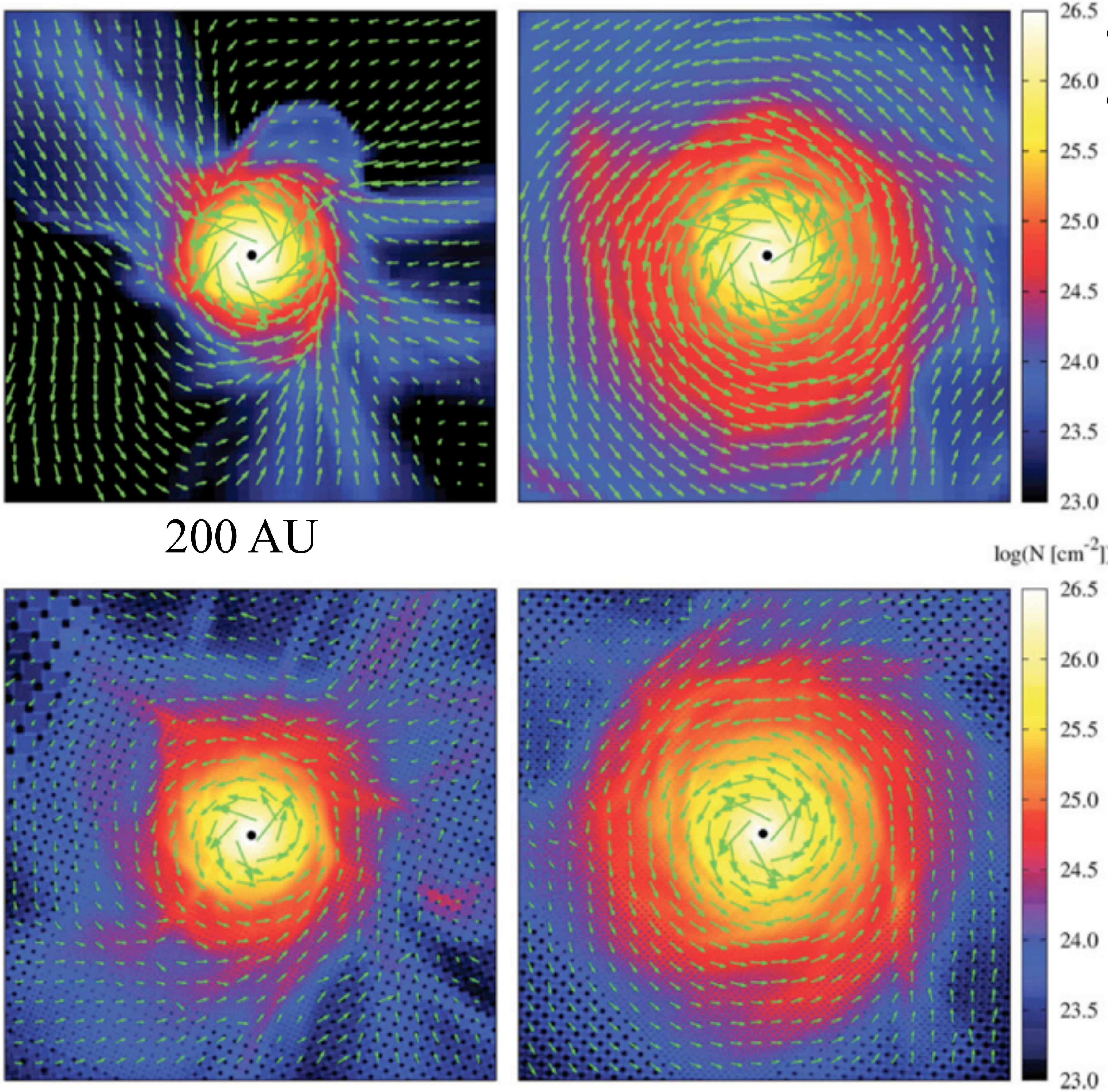


- L1527 IRS:
  very young protostar with disc:
  $t < 300.000$ yr
  $M \sim 0.2\ M_\odot$
  $dM/dt \sim 6.6 \times 10^{-7}\ M_\odot/yr$



see also *Tobin et al.* ApJ 805, 2015

Collapse of Turbulent Cores

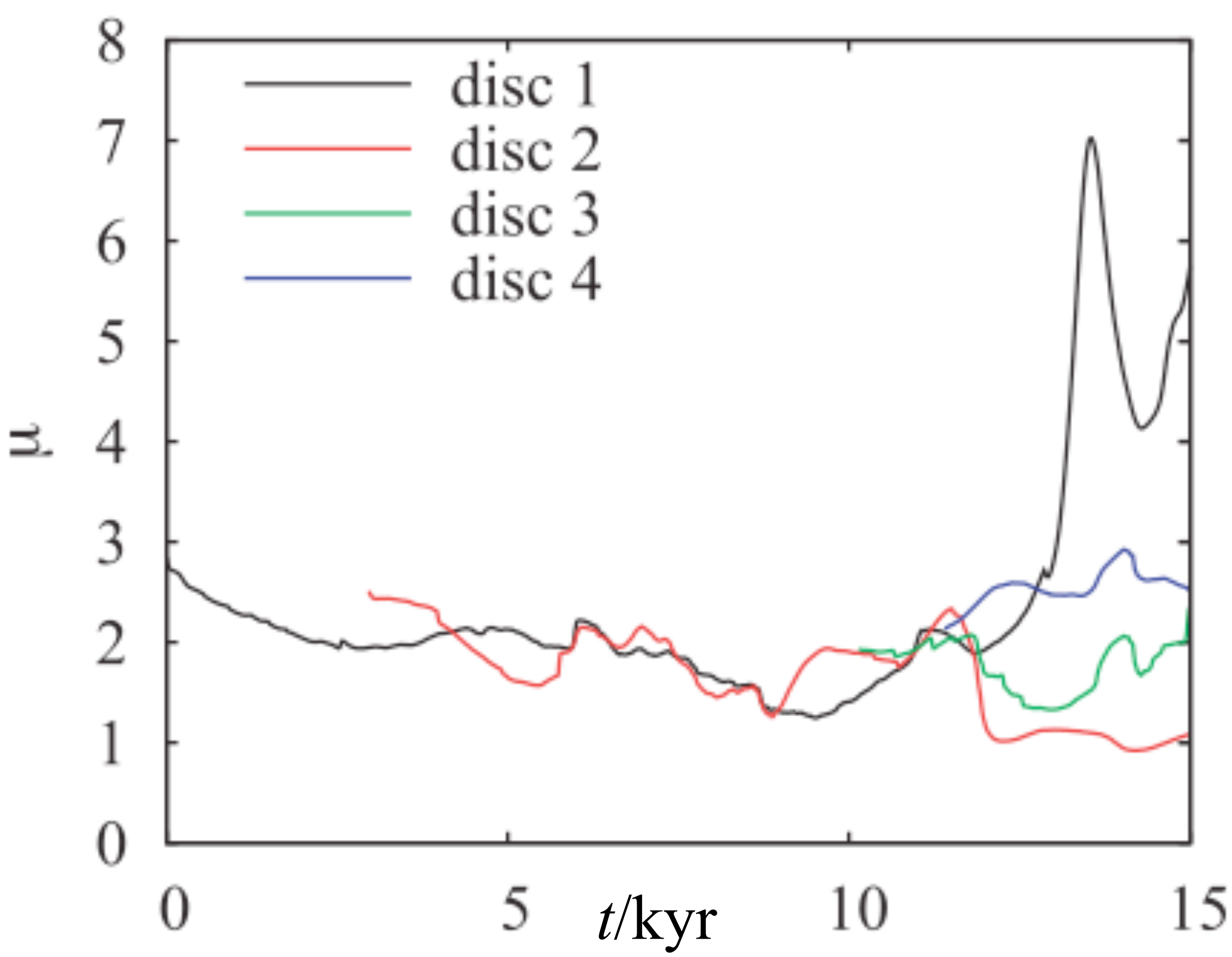


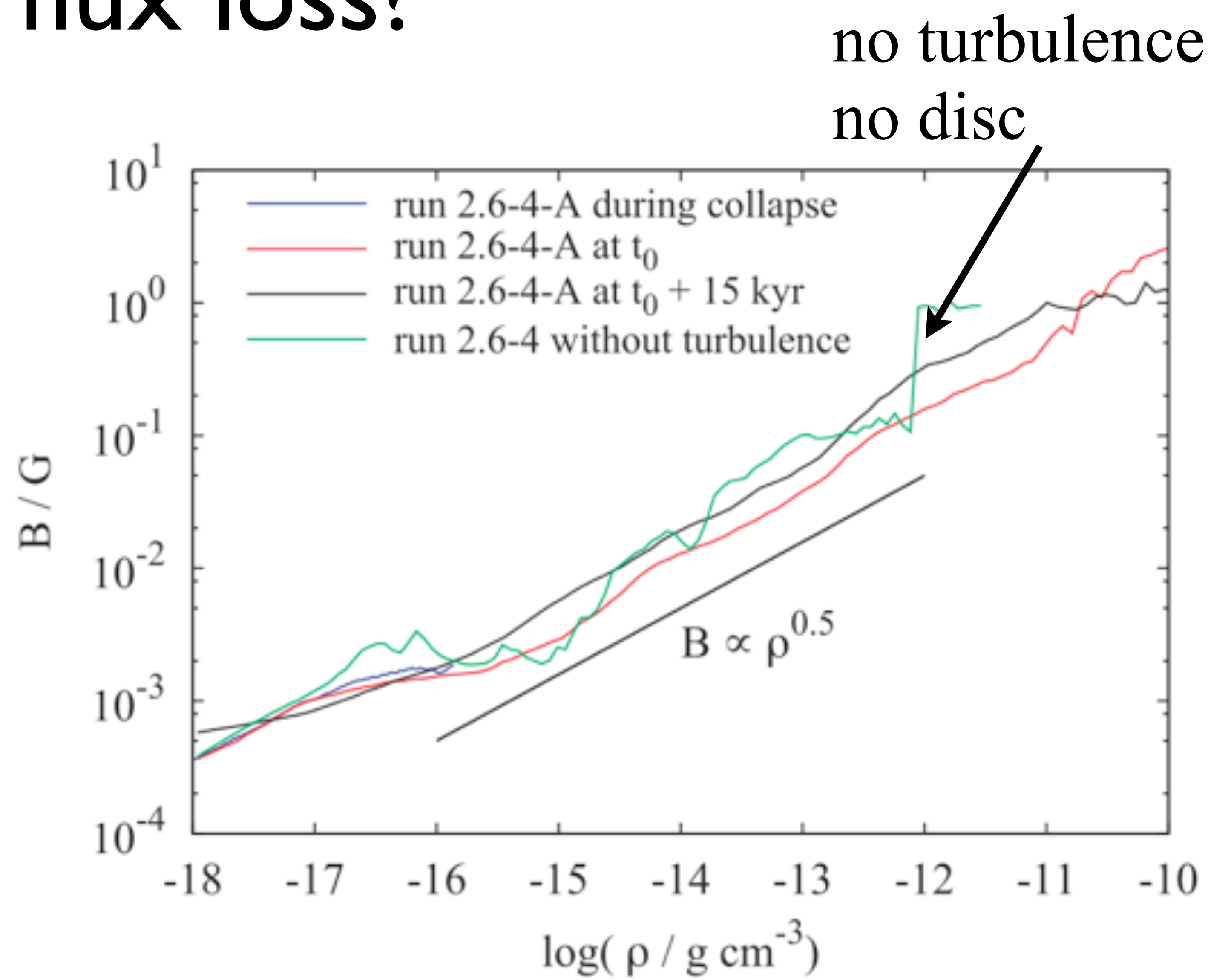
- low mass cores
- strong magnetic field: $\mu = 2.6\ \mu_{crit}$
- transonic turbulence $Ma = 0.74$
- **no** global rotation
- with global rotation

Seifried, et al. 2013

Collapse of Turbulent Cores

due to flux loss?

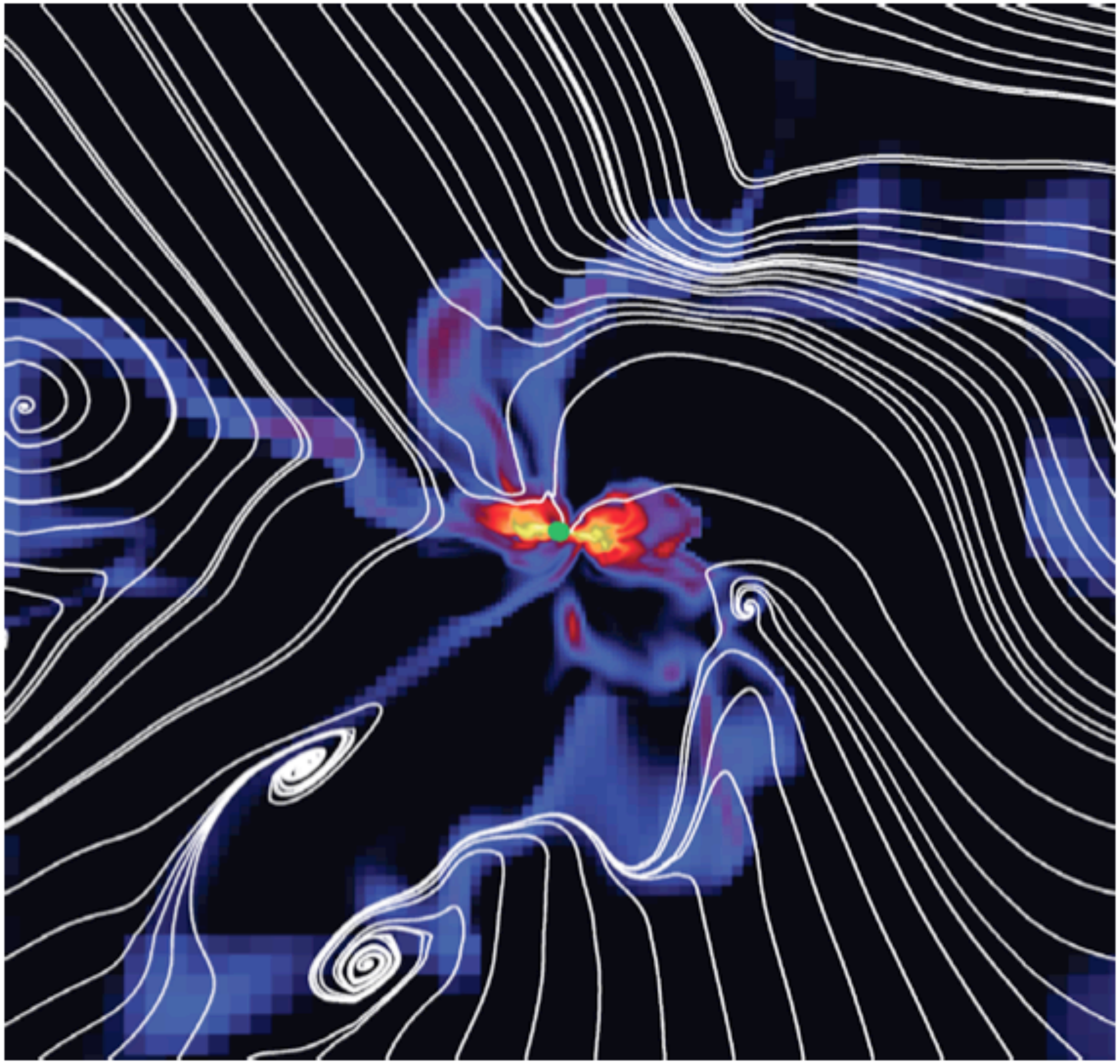




$\Longrightarrow$ no flux loss

Collapse of Turbulent Cores

Magnetic field structure

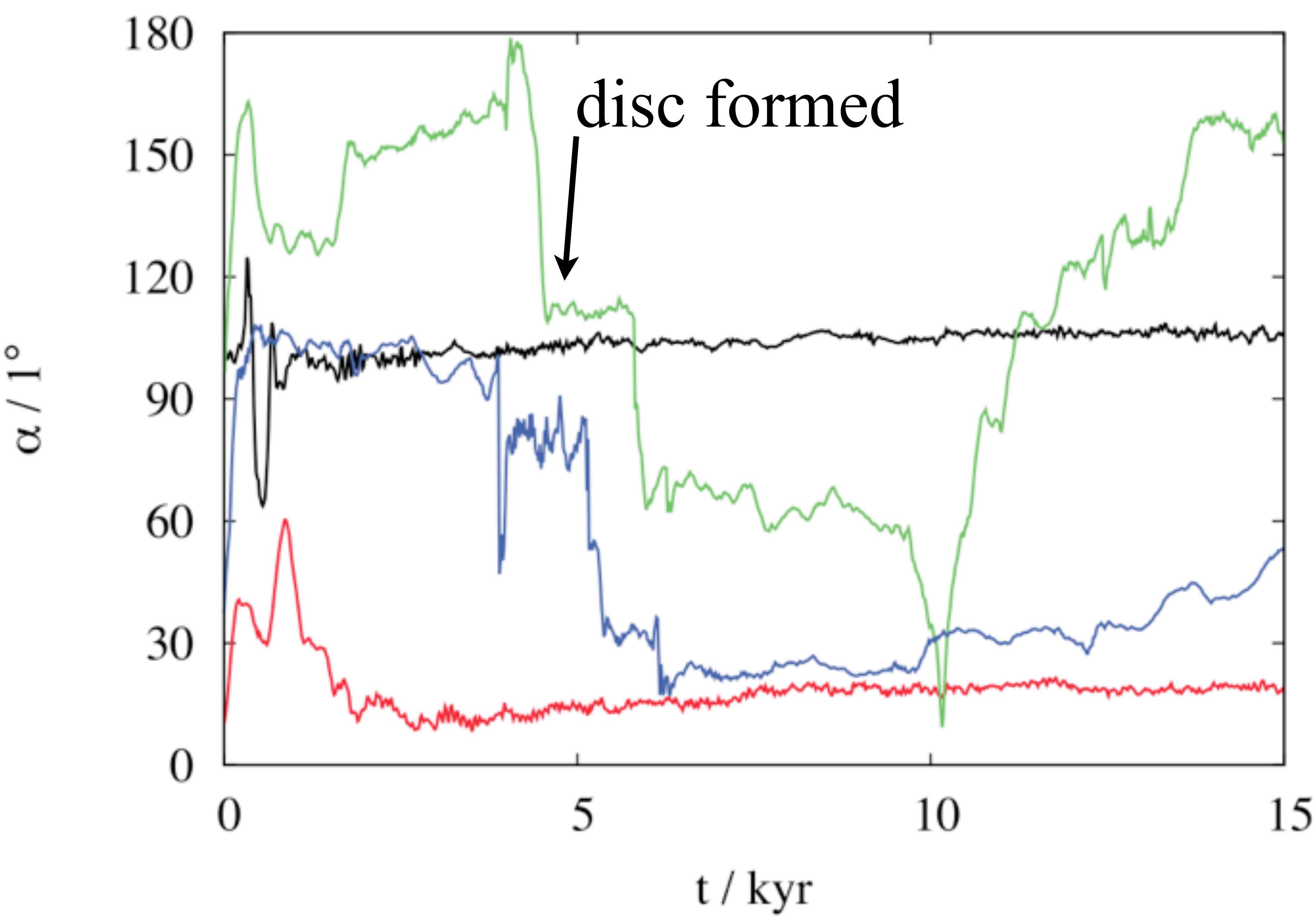


Collapse of Turbulent Cores

rotation vs. magnetic field orientation

$\Longrightarrow$ inclined rotation helps to form discs?

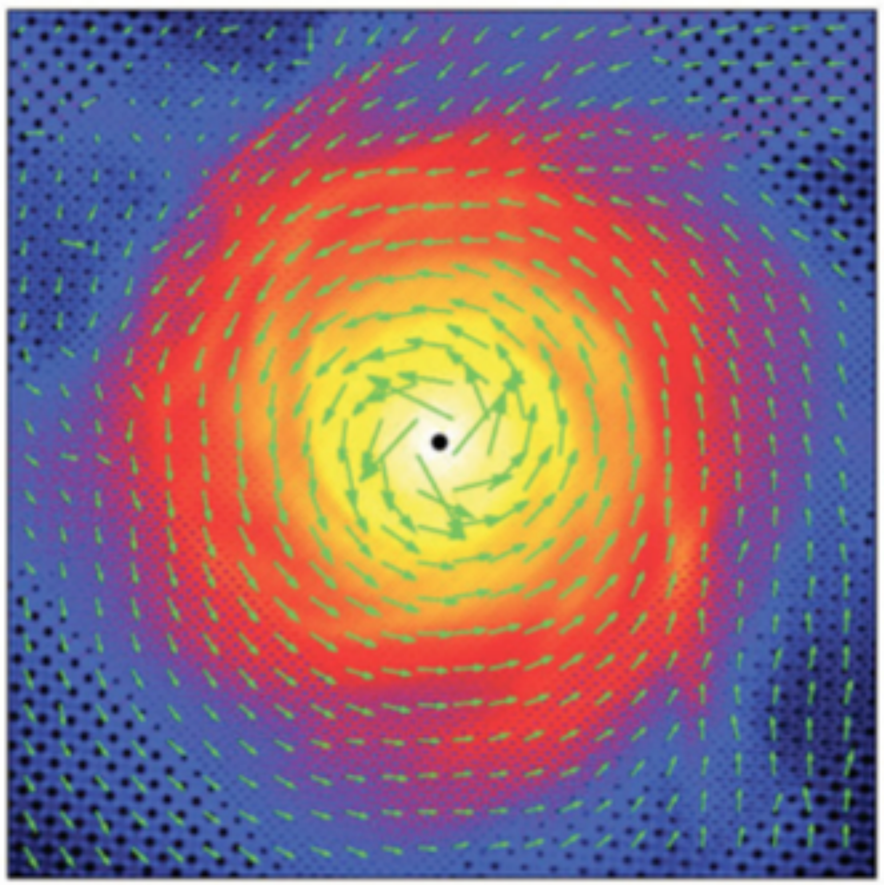
(*Hennbelle & Ciardi* 2009, *Joos et al.* 2012)



$\Longrightarrow$ but no large scale magnetic field component

Conclusion

Magnetic Fields are important!



- "turbulence" solves magnetic braking problem

  $\Longrightarrow$ discs form easily

  out of magnetised cores

- How to generate supercritical cloud cores is an open issue