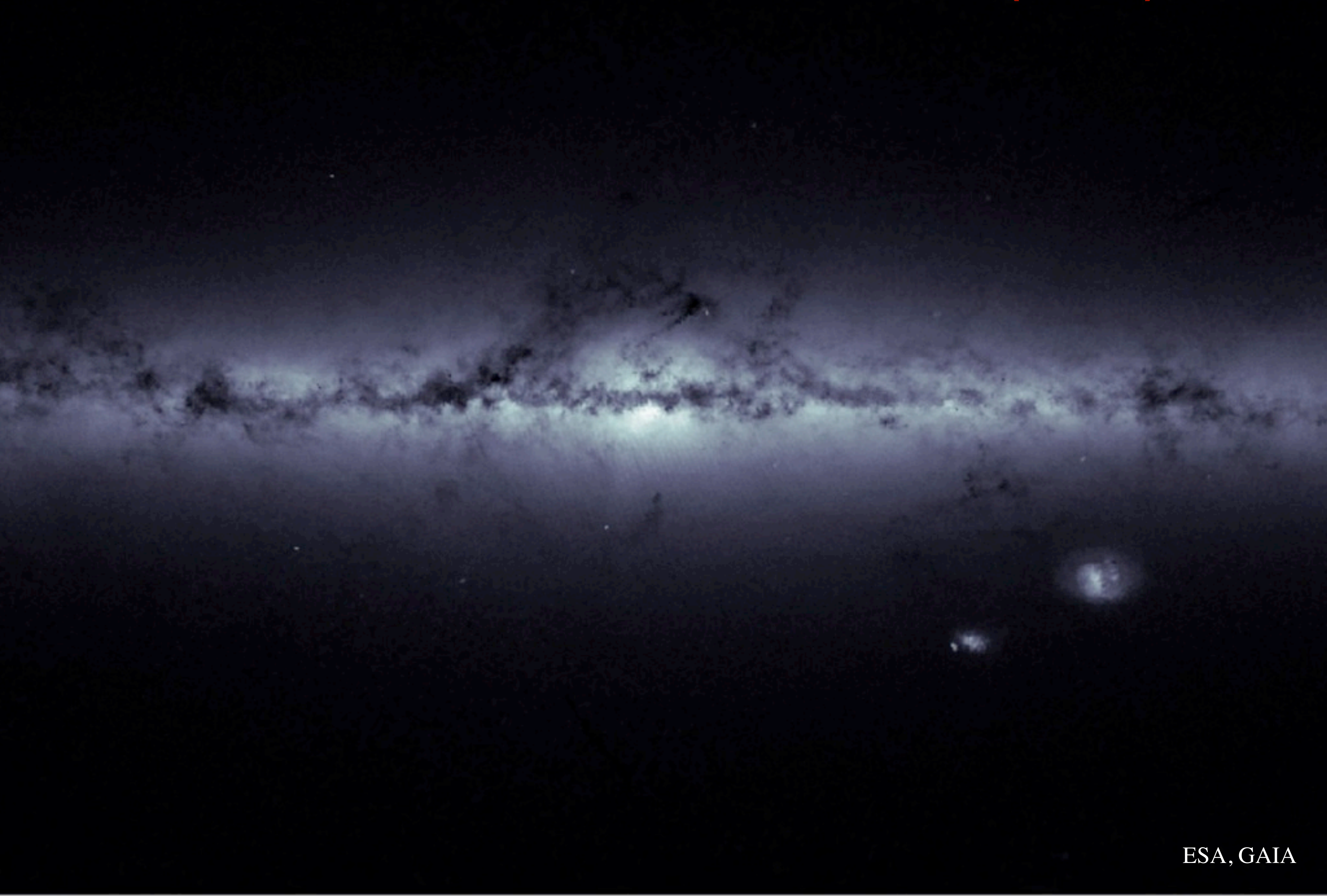
hamburger sternwarte

Star Formation
and
Magnetic Fields in the ISM

Robi Banerjee
Hamburger Sternwarte

based on work by: **Bastian Körtgen** (HS), **Daniel Seifried** (Cologne)
co-workers: Ralph Pudritz (McMaster, Canada), Enrique Vazquez-Semadeni (UNAM), Wolfram Schmidt (HS)

The Interstellar Medium (ISM)



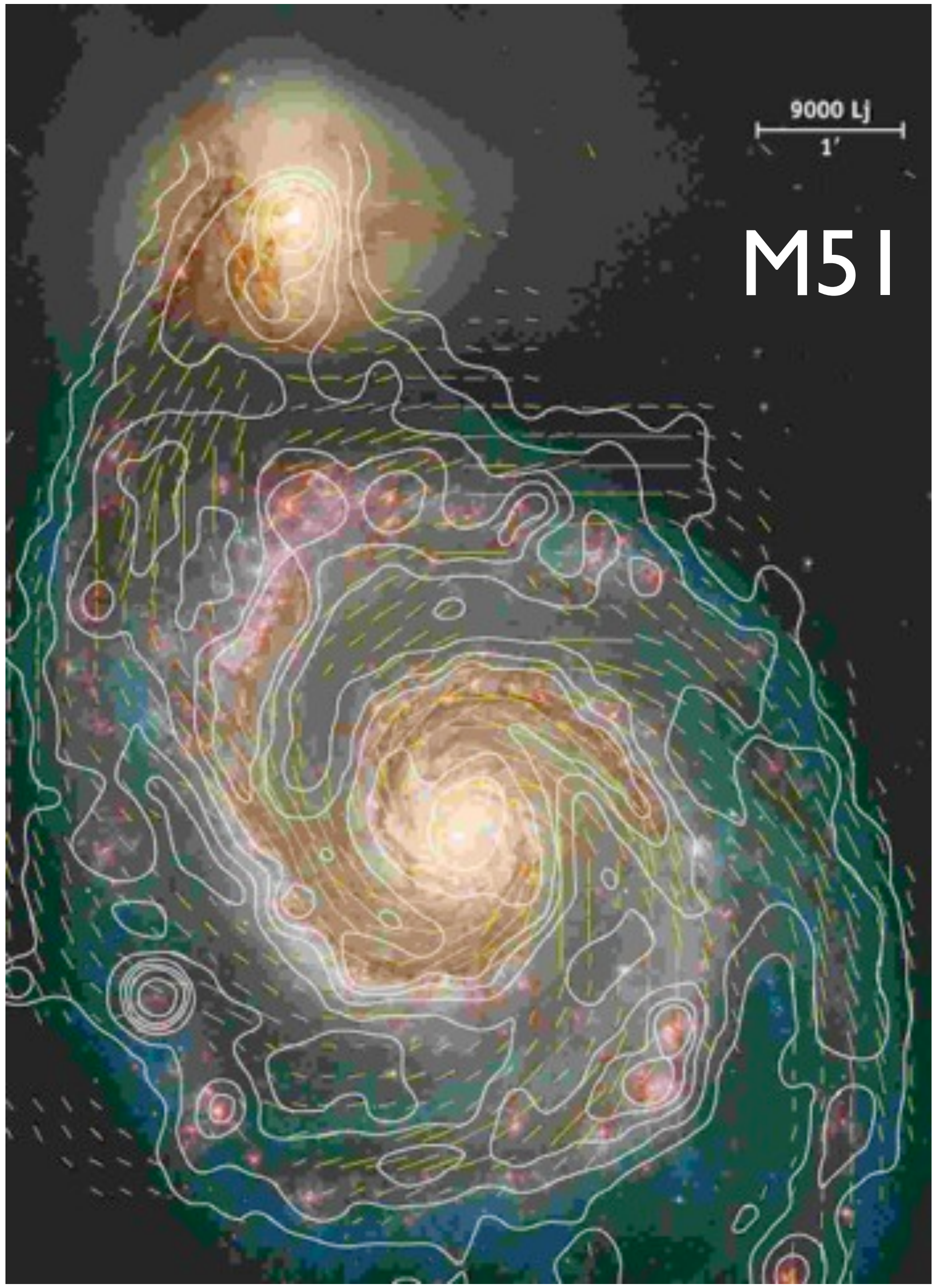
ESA, GAIA

The Interstellar Medium (ISM)

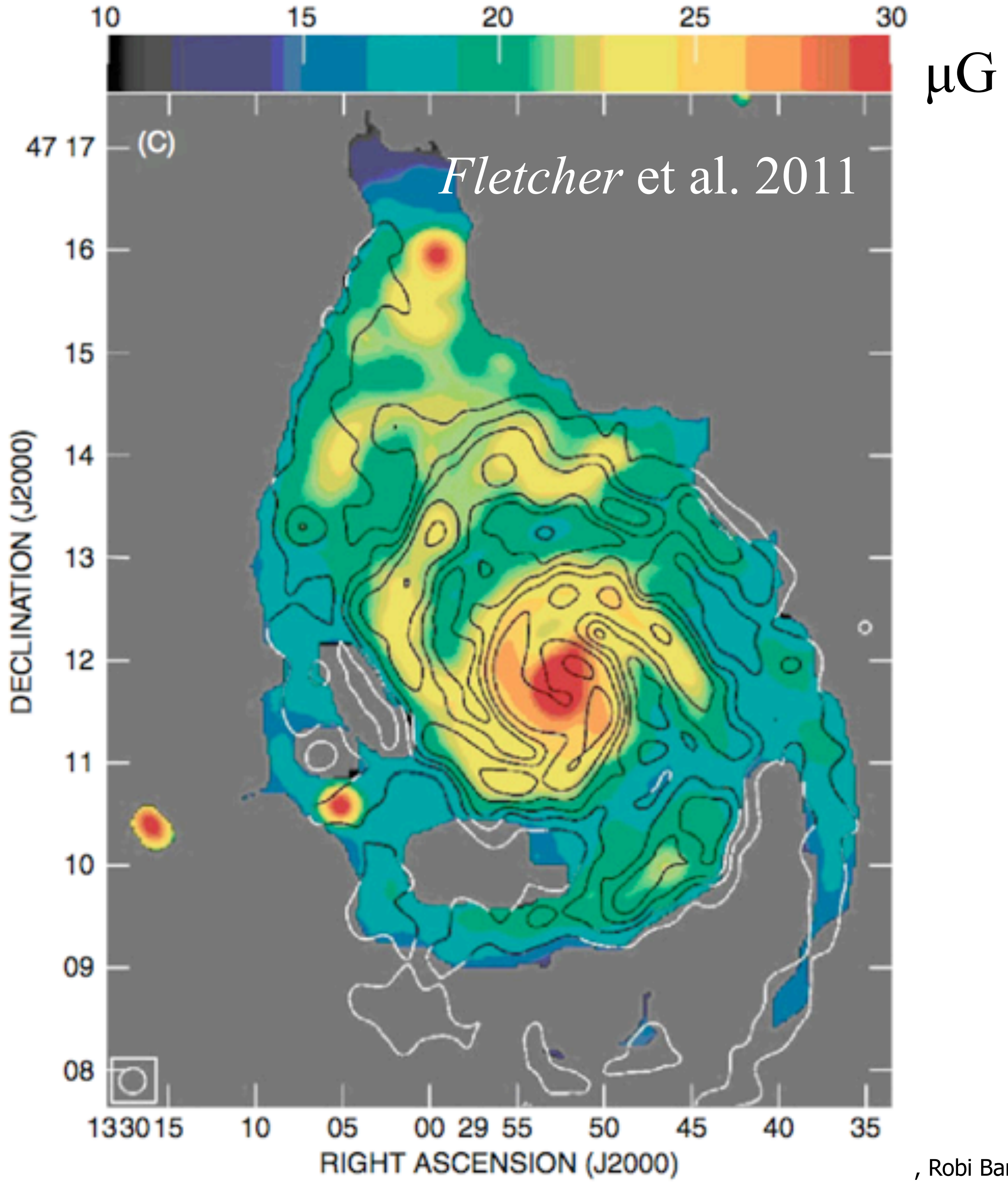
- Milky Way consists of ~ 200 billion stars and gas + dust + radiation, cosmic rays, ...
  = **Interstellar Medium (ISM)**

- Stars form in cold molecular/dark clouds (few % of the galactic volume)

Magnetic Fields in the ISM

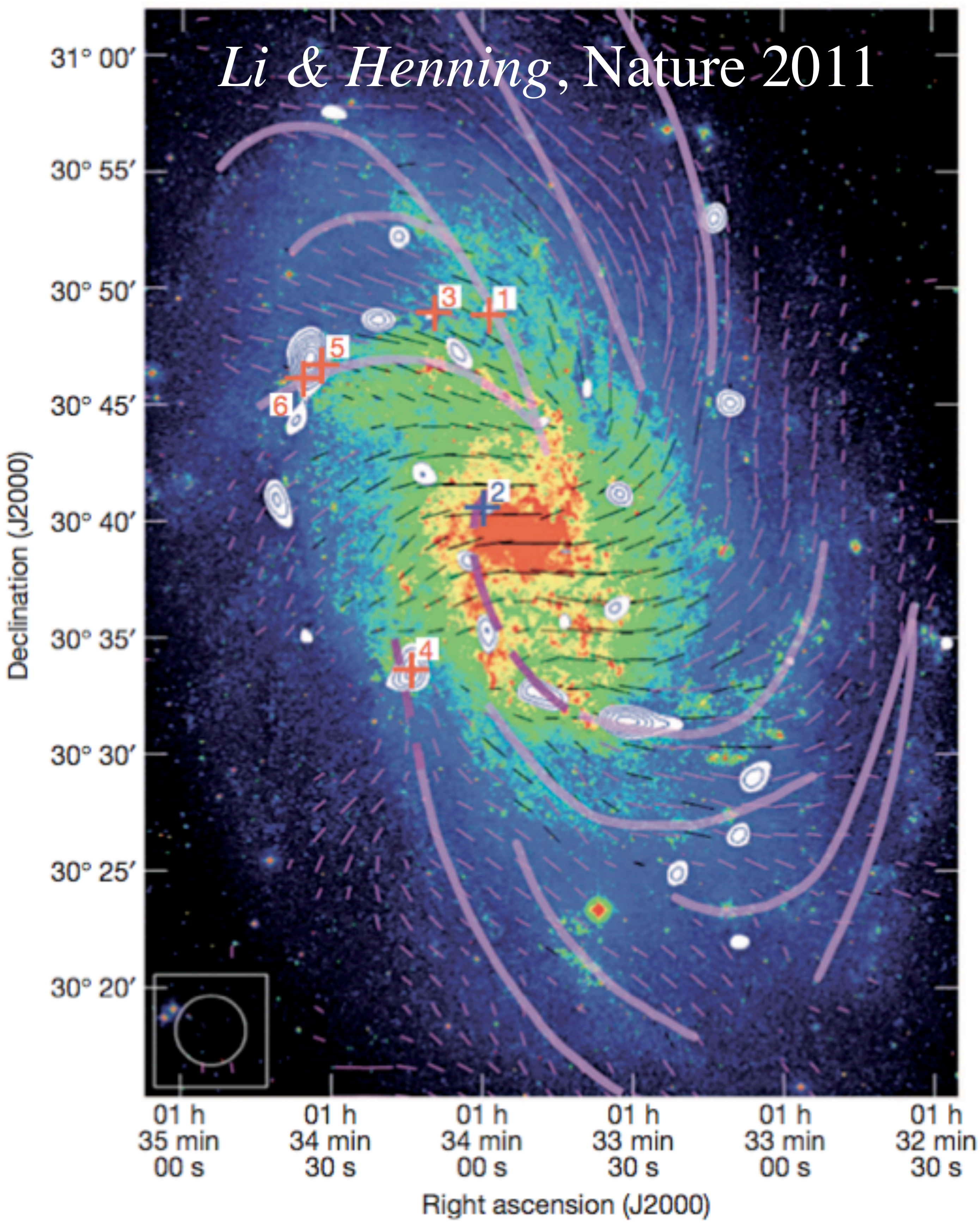


The ISM is *highly* magnetised: $E_{mag} \sim E_{therm}$
(i.e. $\beta \sim 1$)



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

$\Longrightarrow$ sub Alfvenic turbulence:

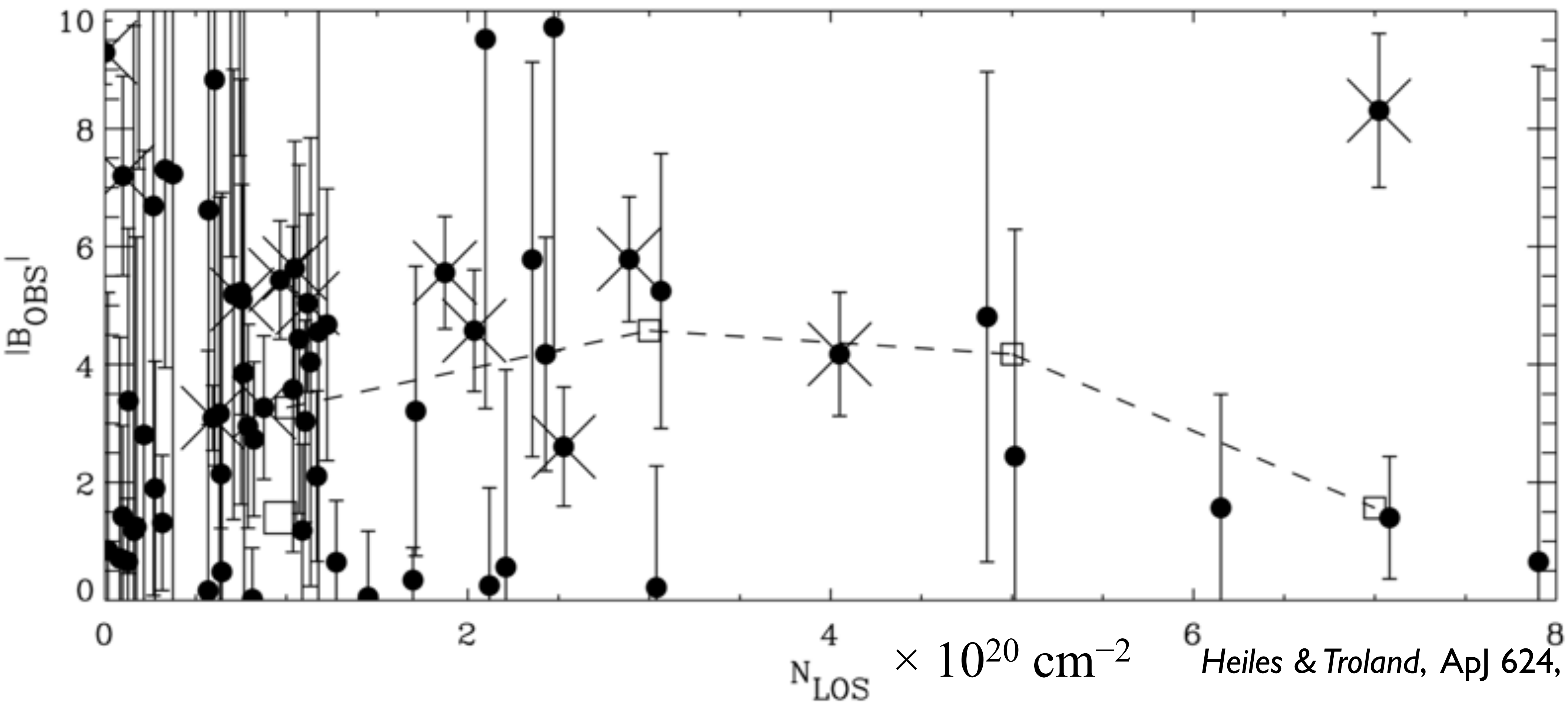
$v_{turb} \lesssim v_A$

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

⟹ Magnetic fields in HI clouds
(incl. warm neutral media, WNM)



$\times\, 10^{20}\ \mathrm{cm}^{-2}$

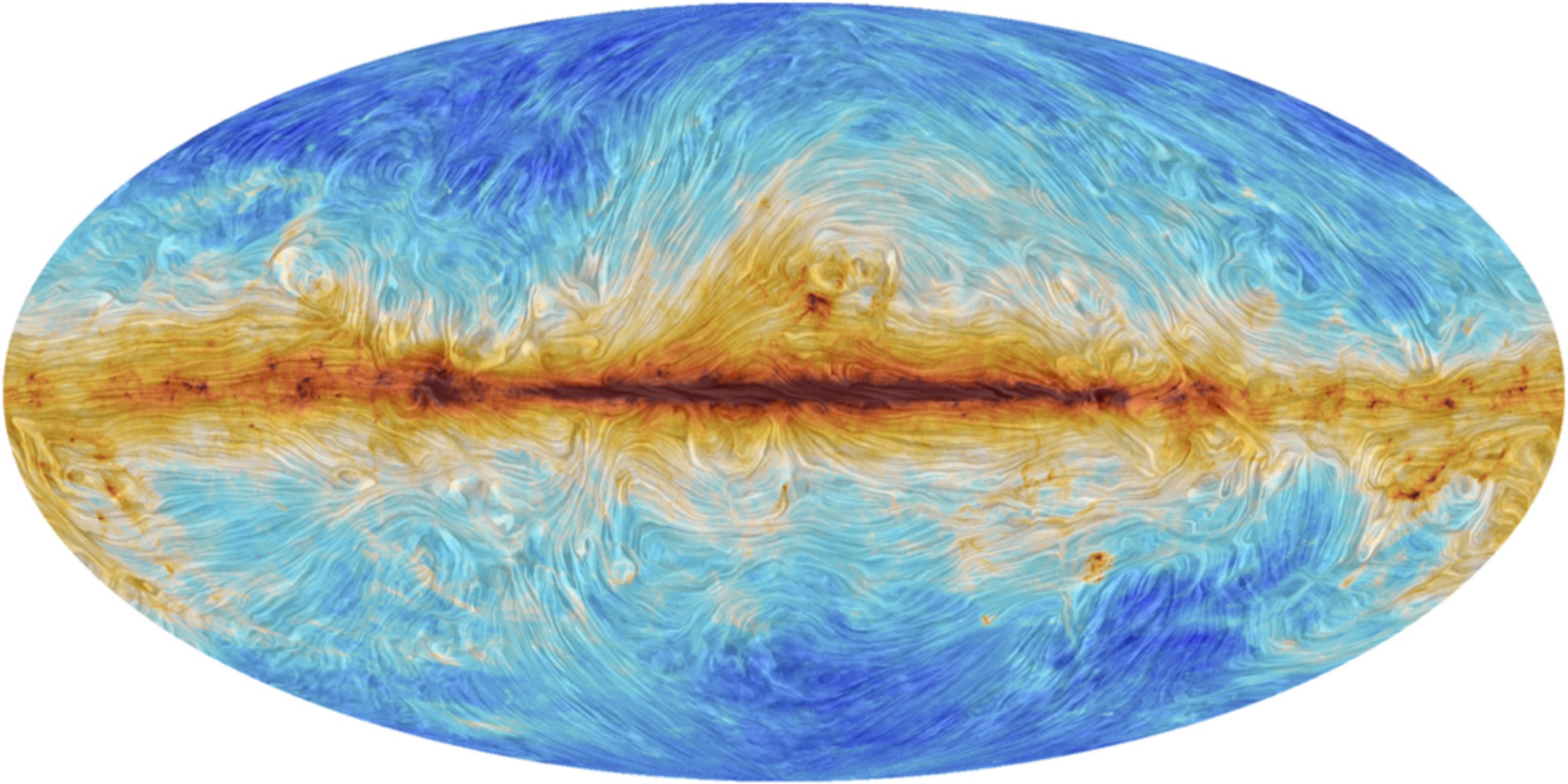
B-field from polarised Zeeman effect

$B_{\mathrm{median}} = 6\ \mu\mathrm{G}$

Heiles & Troland, ApJ 624, 2005

Magnetic Fields in the ISM

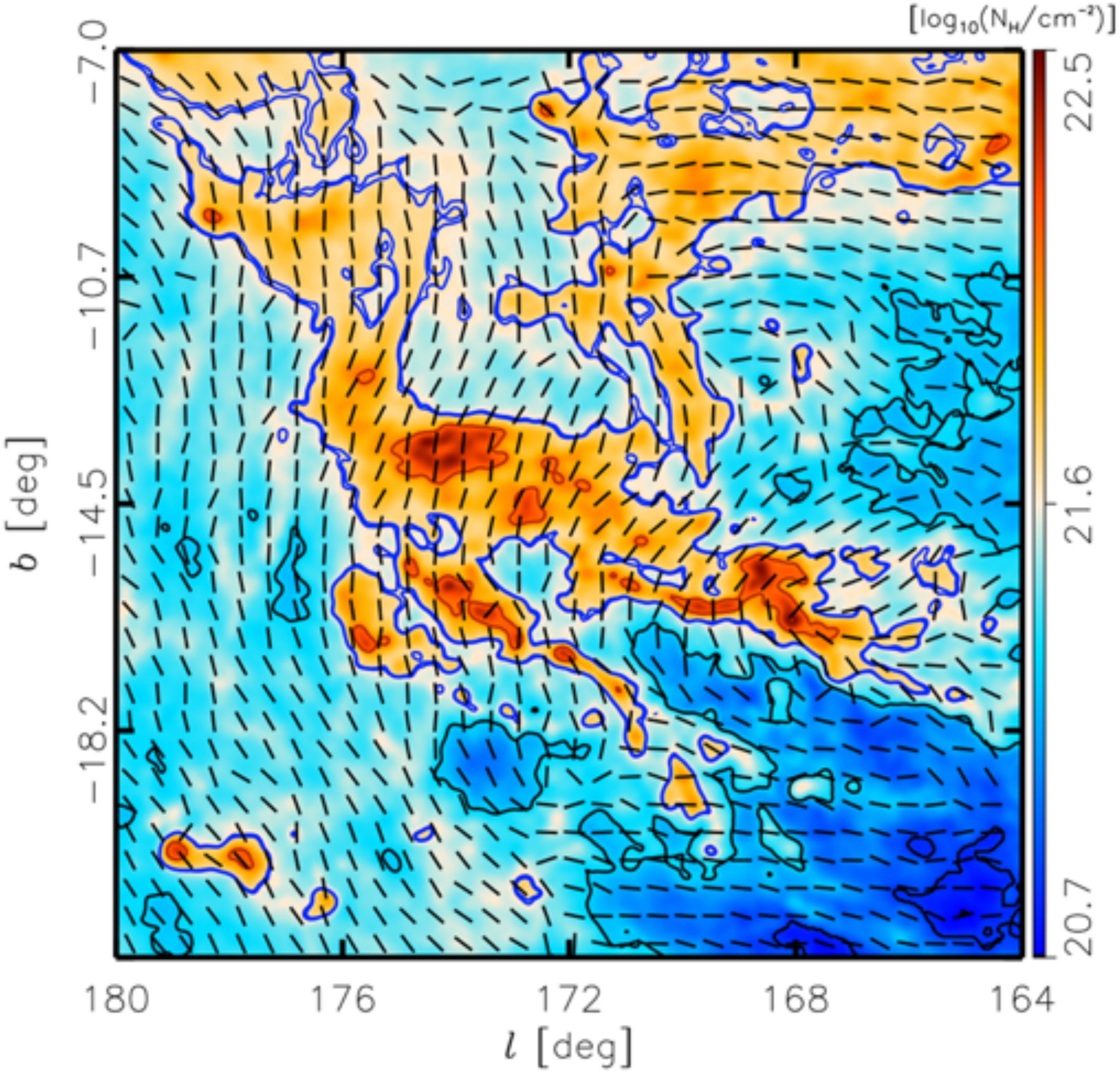
- PLANCK: magnetic field of the Milky Way from dust polarisation

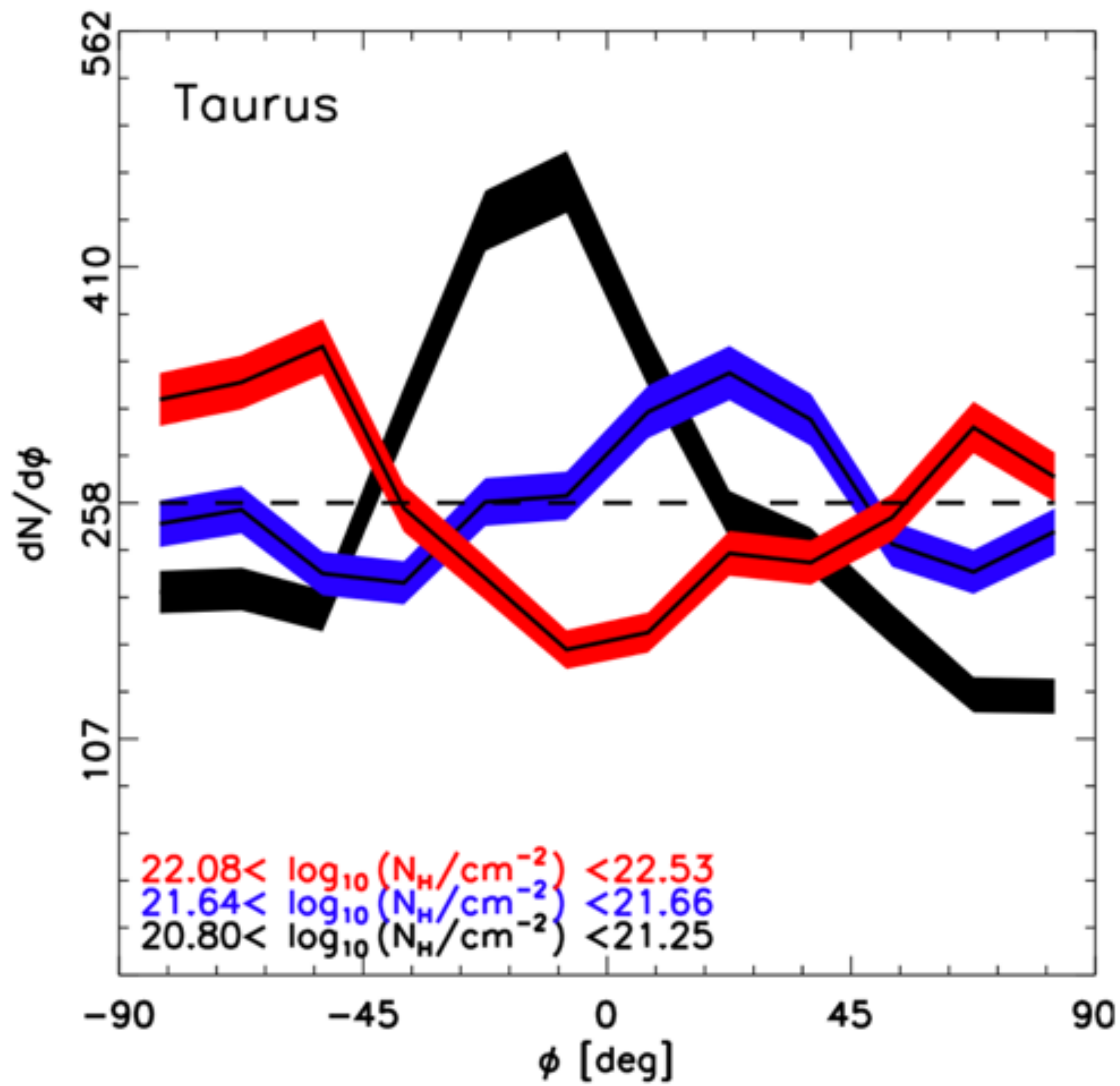


ESA PLANCK: *Milky Way's magnetic fingerprint (2015)*

Magnetic Fields in Molecular Clouds

- PLANCK XXXV 2015: dust polarisation in molecular clouds

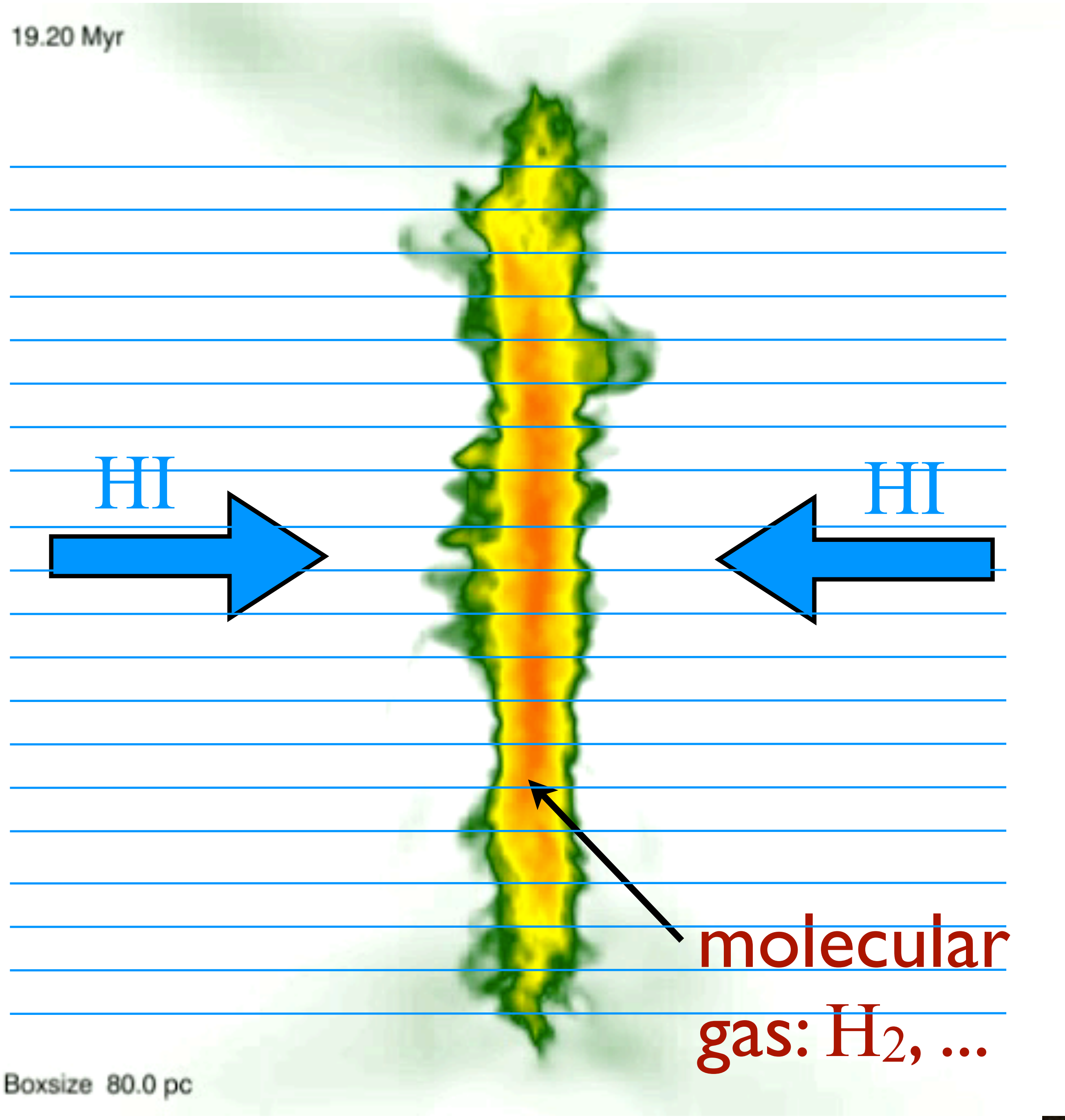


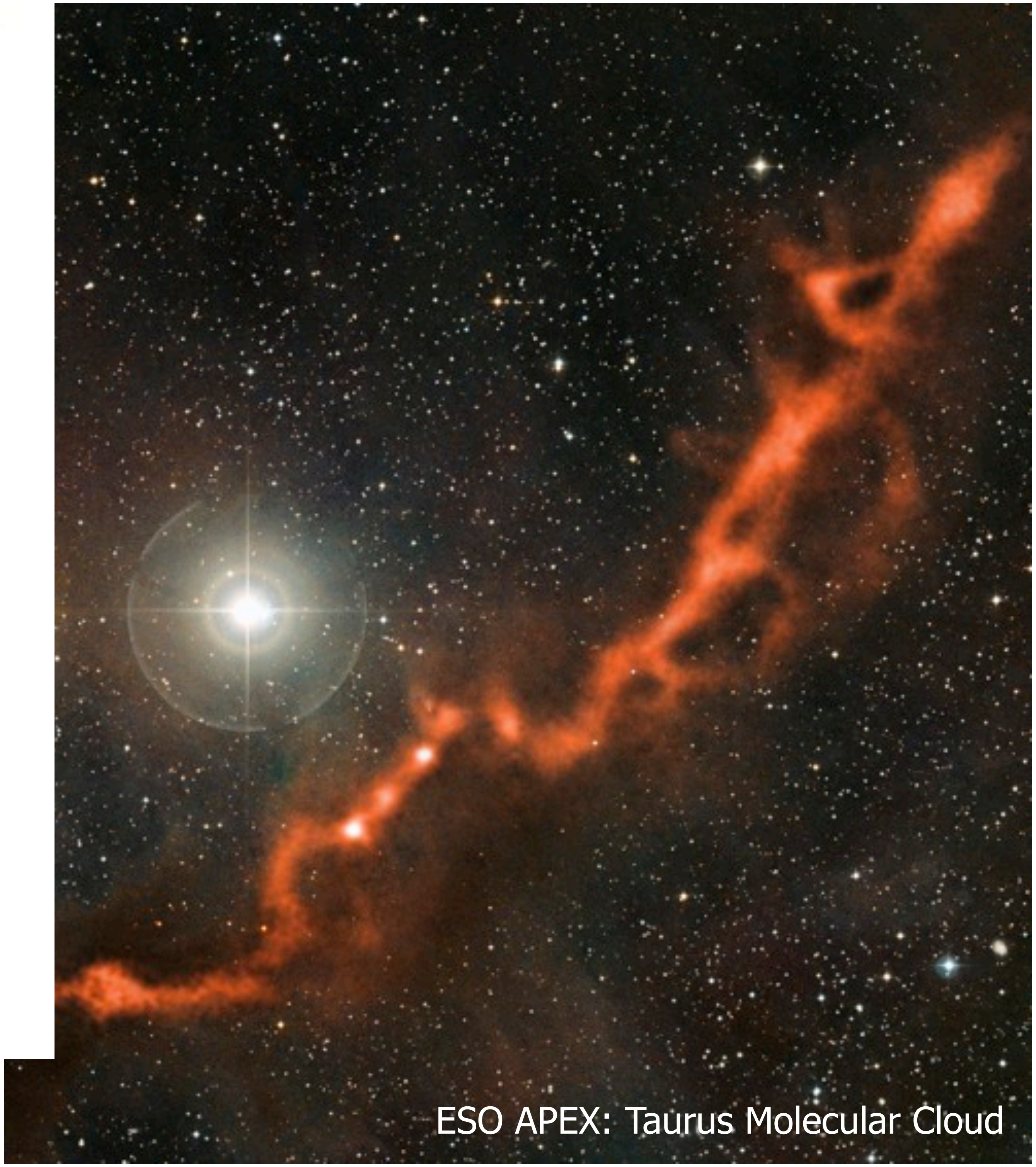


⟹ magnetic fields are dynamically important

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

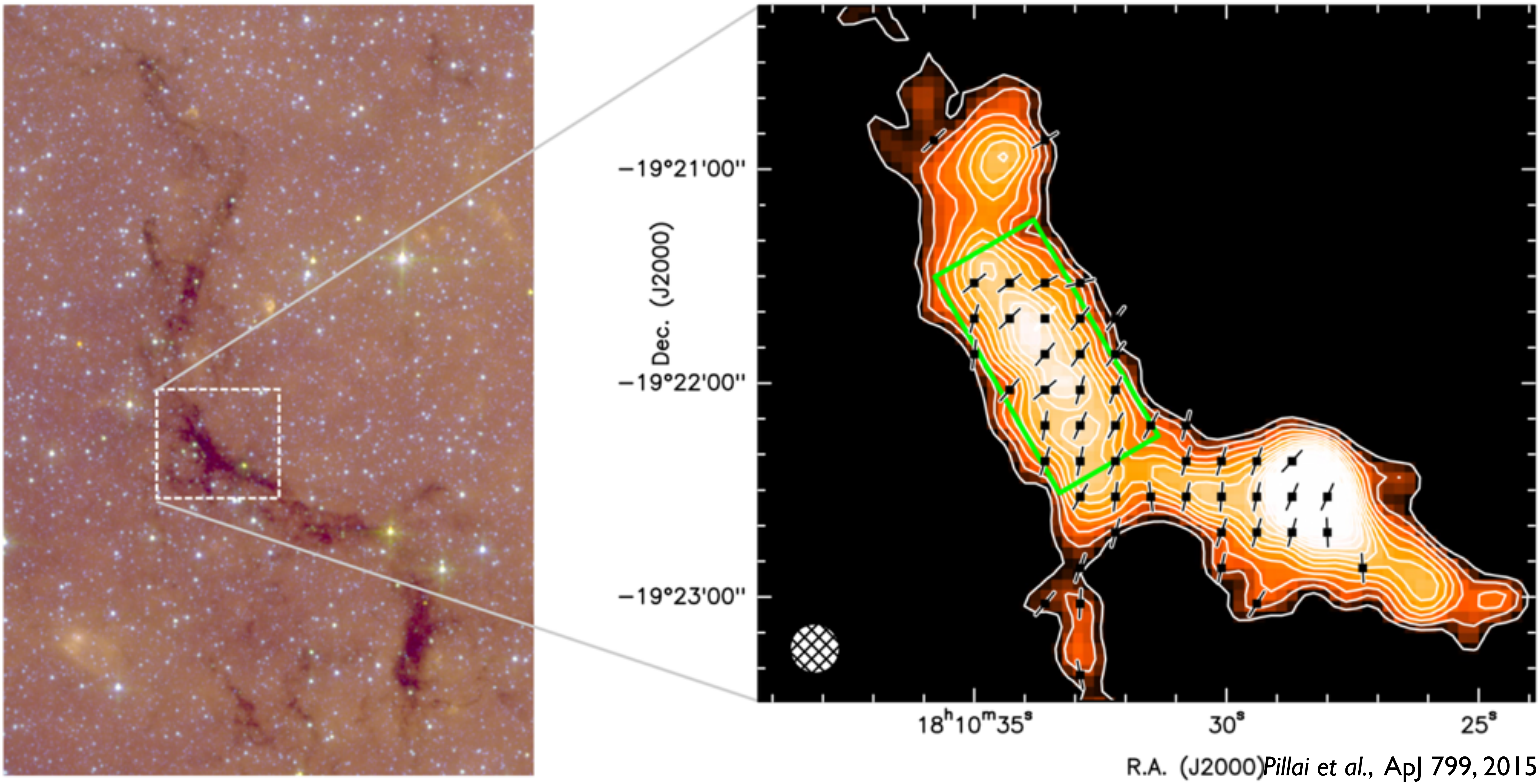
Formation of Molecular Clouds





dynamical MC / GMC formation
out of the WNM atomic media (e.g. *Blitz et al.* ,2007, PPV, also Inutsuka's talks)

Magnetic Fields in Molecular Clouds

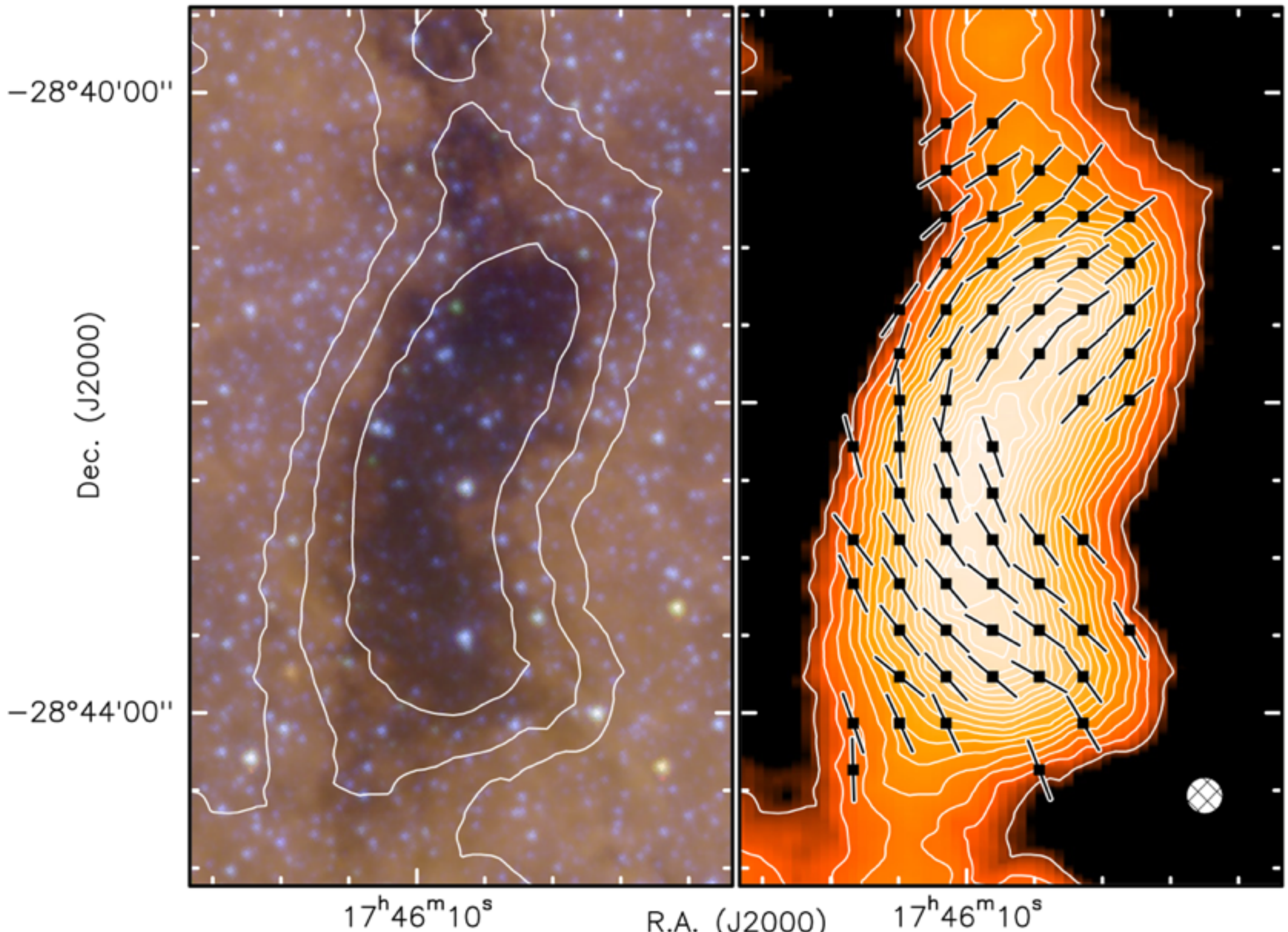


Pillai et al., ApJ 799, 2015

polarisation measurement of G11.11-0.12

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

Magnetic Fields in Molecular Clouds

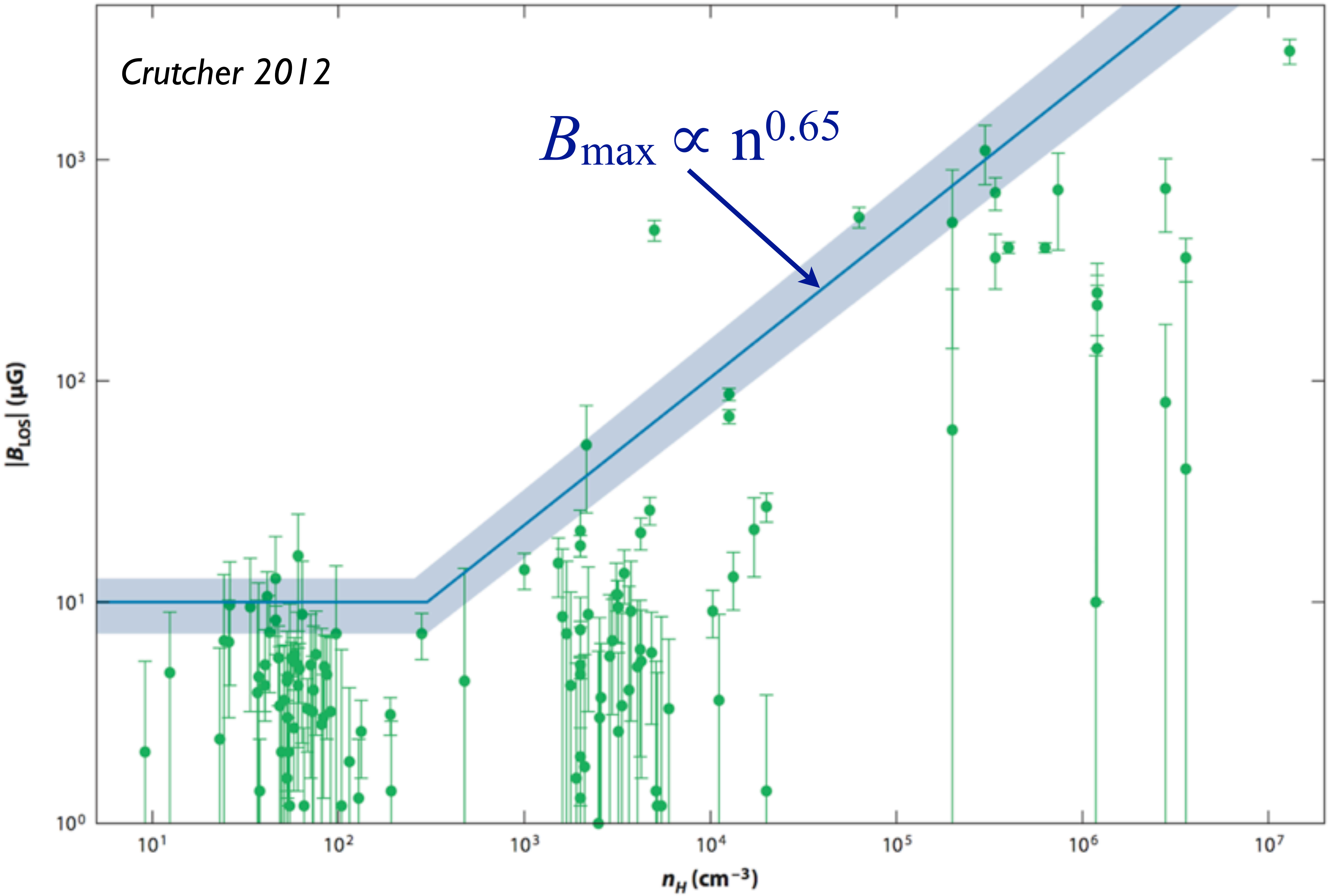


Pillai et al., ApJ 799, 2015

in G0.253-0.016 IRDC: $B_{\rm tot} > 5$ mG

Magnetic Fields in the ISM

- stronger magnetic fields in dense regions

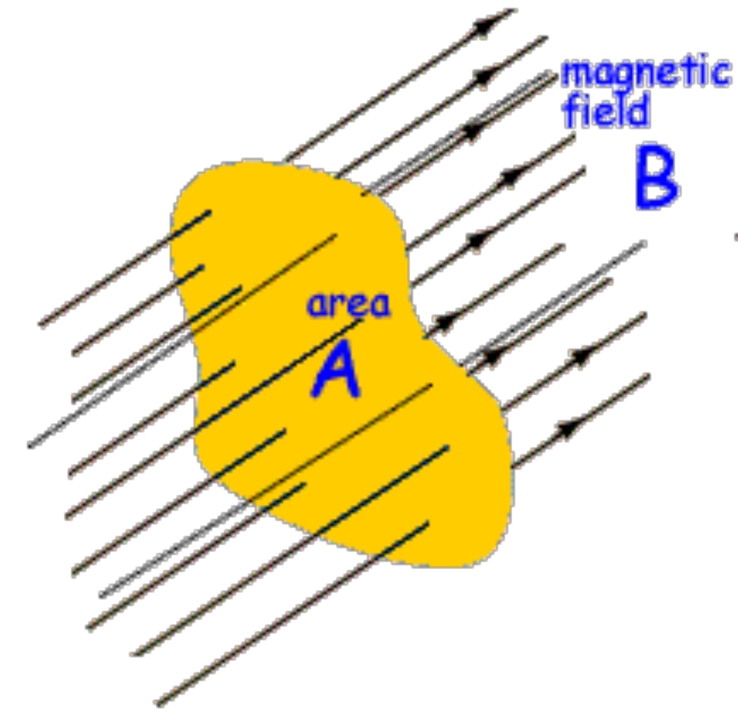


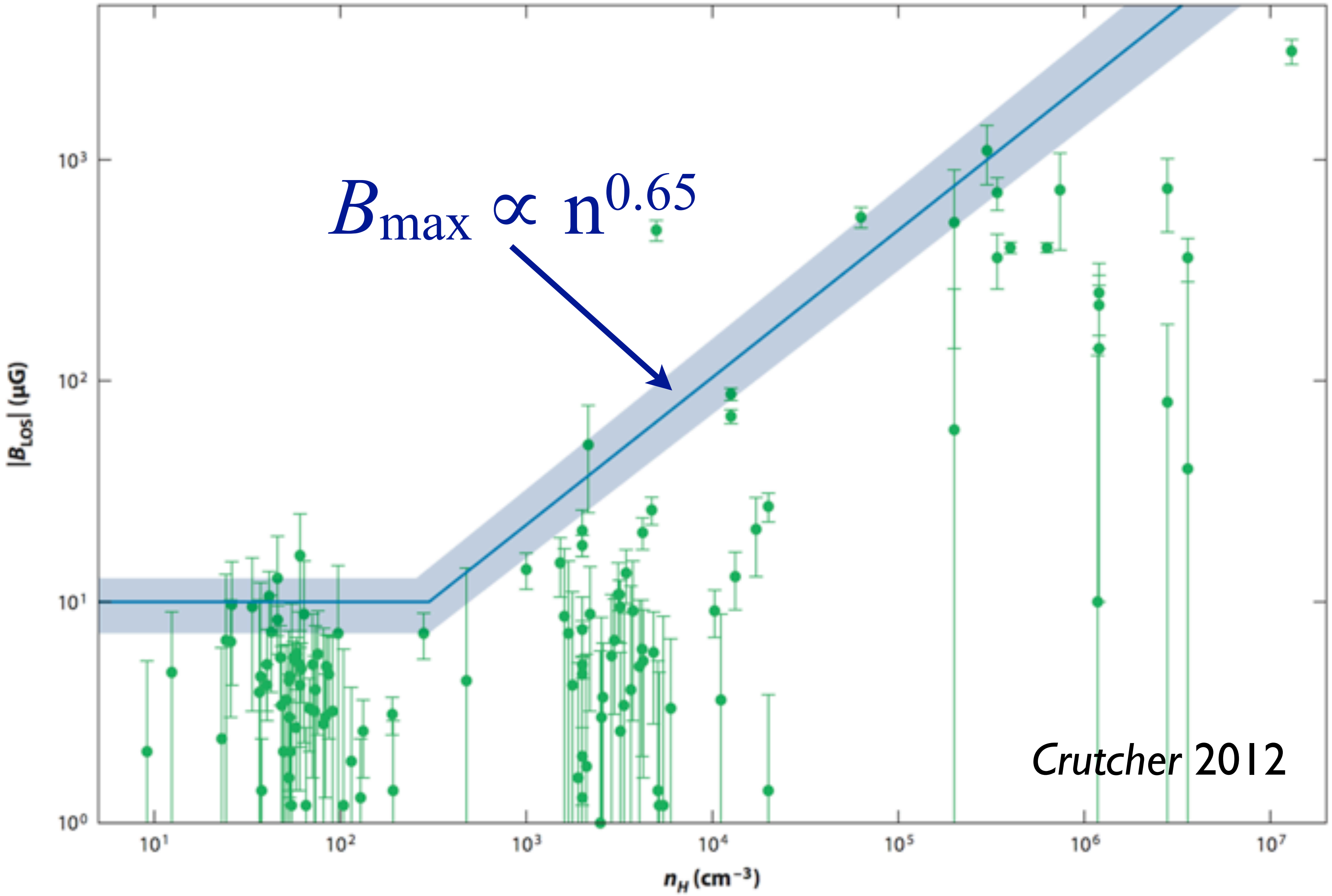
Magnetic Fields in the ISM

- stronger magnetic fields in dense regions

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

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





- spherical compression:

$\rightarrow \quad n \propto l^{-3}$

$\rightarrow \quad \Phi \propto l^2 \, B = \text{const}$

$\Longrightarrow B \propto n^{2/3}$

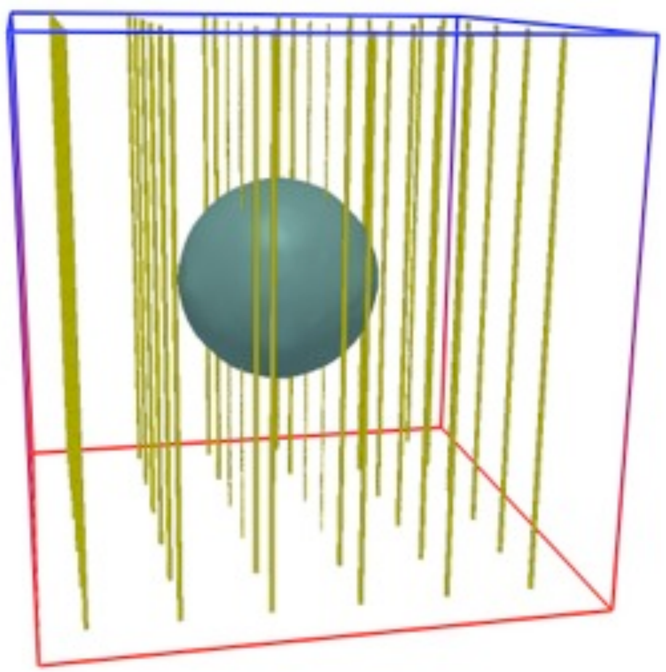
Impact of Magnetic Fields

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:

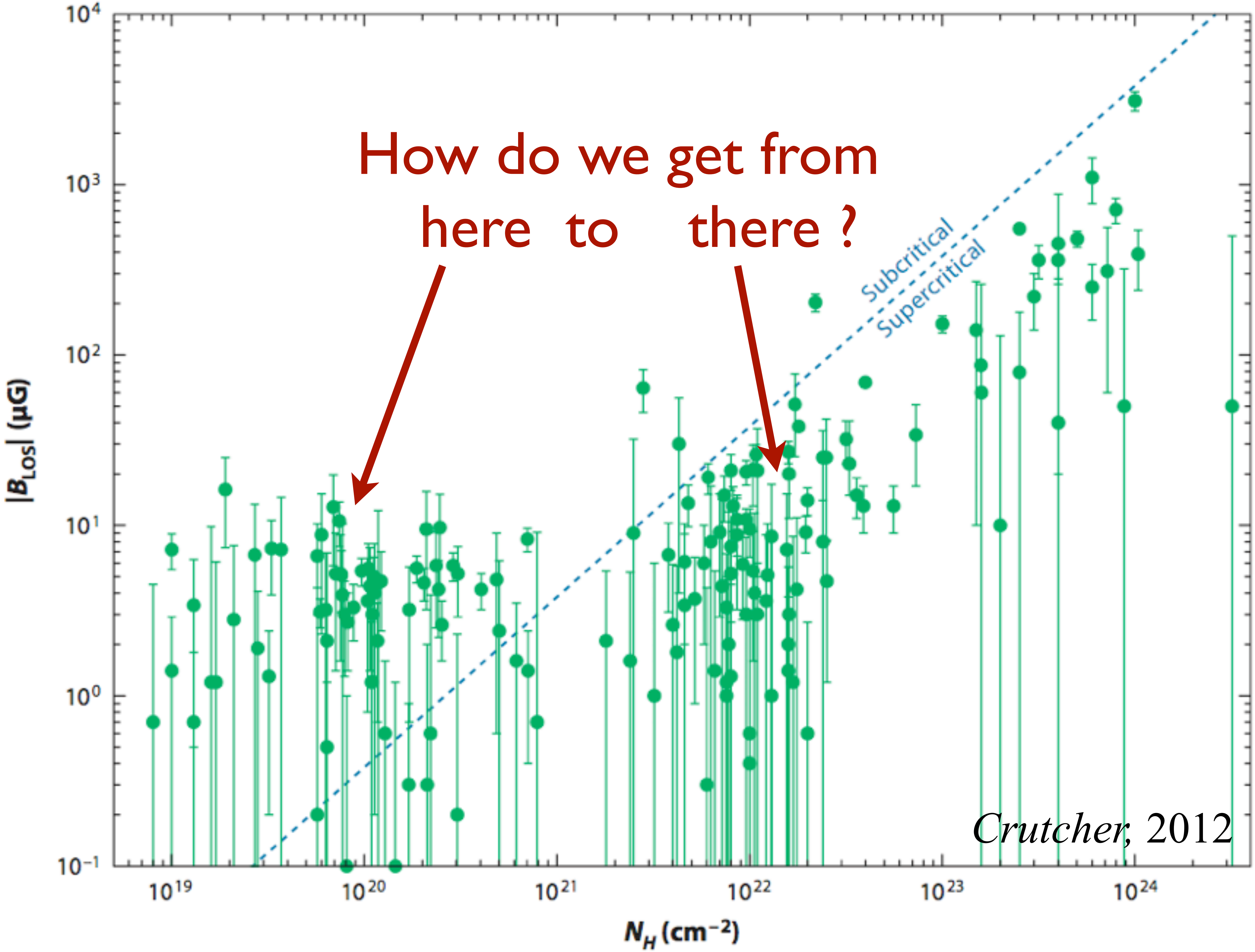
$$\mu_{\rm crit} = 0.13/\sqrt{G}$$

spherical structure
Mouschovias & Spitzer 1976

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

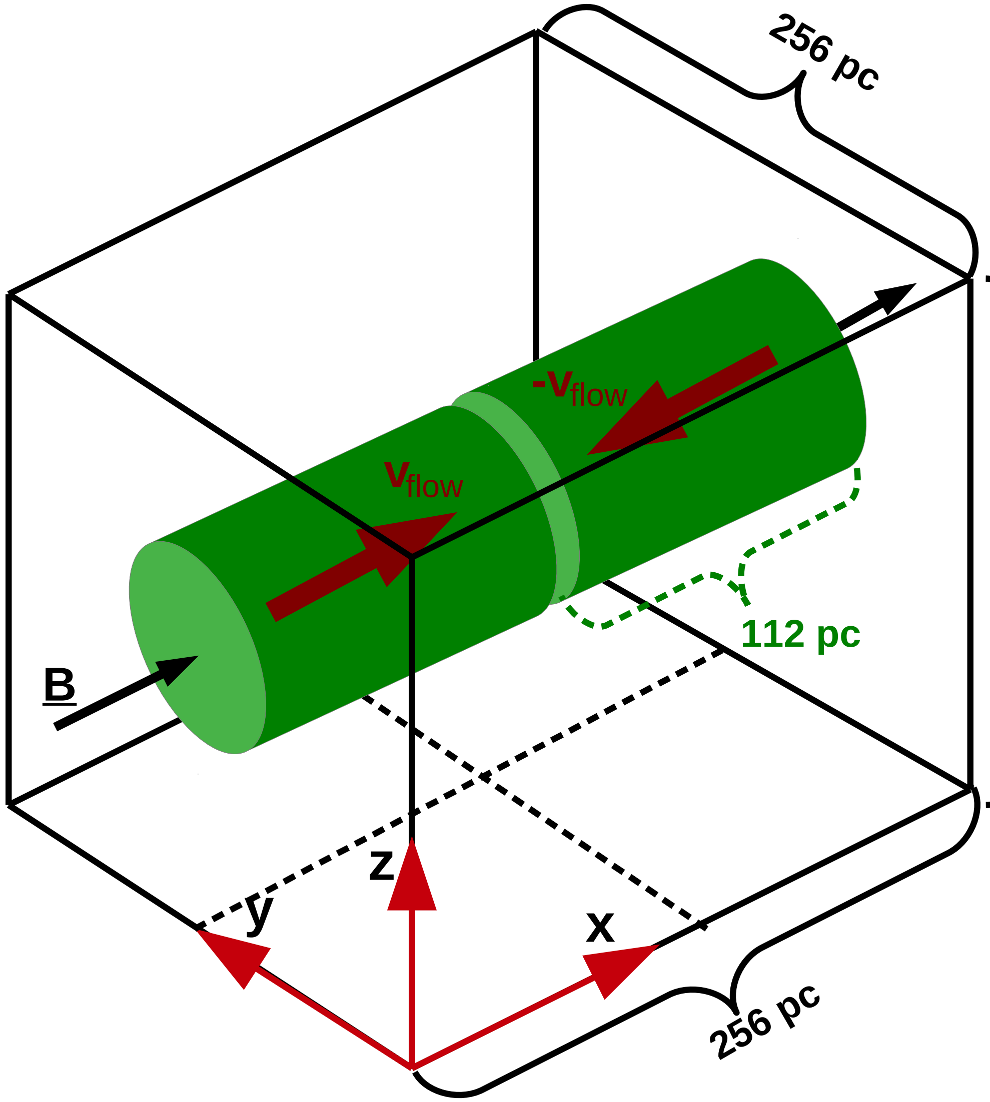
uniform disc
Nakano & Nakamura 1978

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?

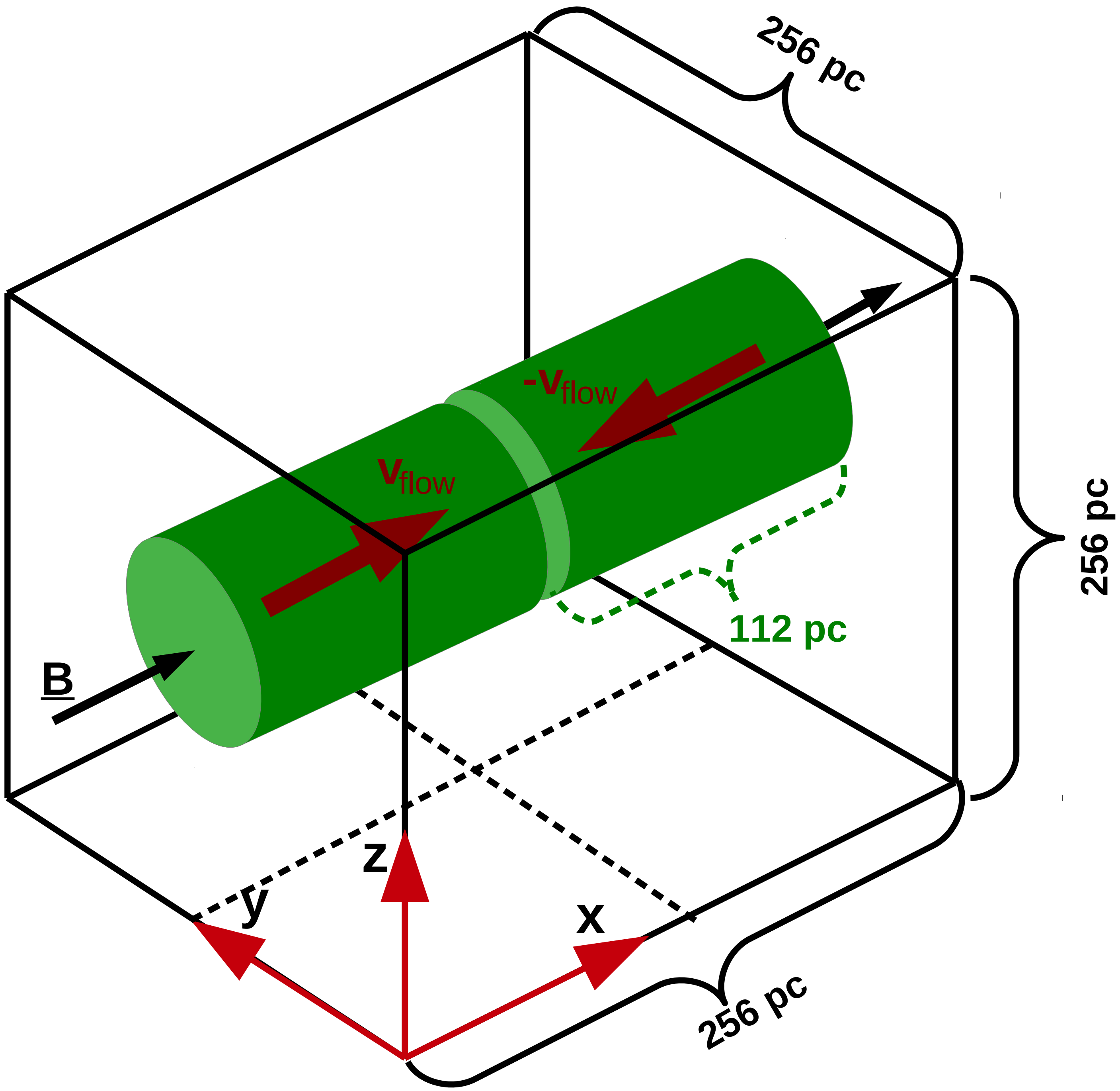
- **flux loss** by:
  - Ambipolar Diffusion (*Mestel & Spitzer* 1956, *Shu* 1987, *Mouschovias* 1987)

    $\Longrightarrow$ old picture: AD-mediated star formation

    (but, Osterbrock 1961: AD not efficient)
  - 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)
  - ...

Simulations of colliding flows

MC formation & star formation



RB *et al.* 2009, B. Körtgen & RB. 2015

Model parameter:

- $n = 1\ \mathrm{cm}^{-3}$
- $r = 32\ ...\ 64$ 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:

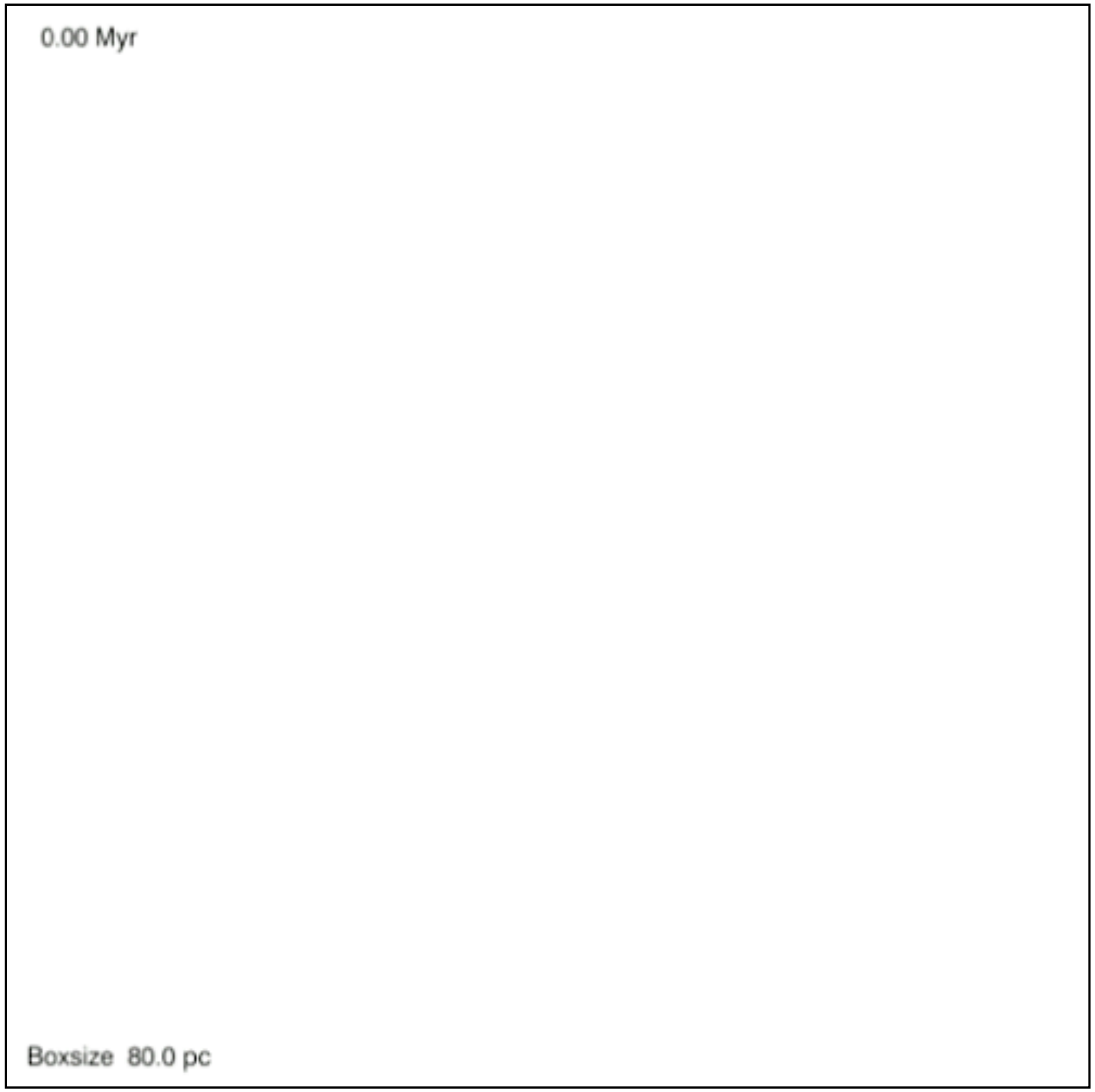
$\mathrm{v}_{\mathrm{turb}} = 0.2\ ...\ 12$ km/sec

\+ ambipolar diffusion

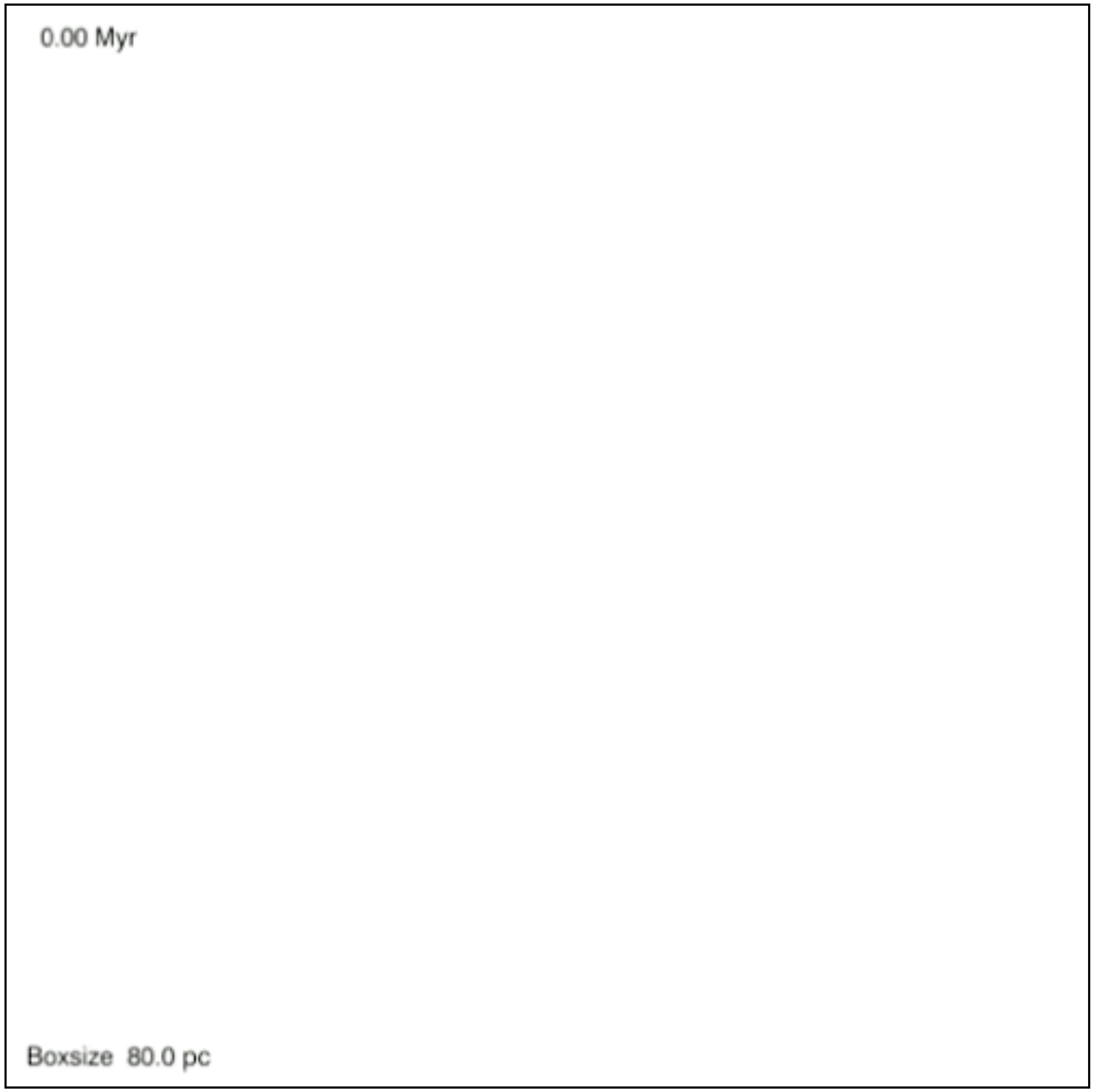
- $B_{\mathrm{x}} = 1\ ...\ 5\ \mu\mathrm{G}$
  - $\Longrightarrow \mu/\mu_{\mathrm{crit}} \sim 3\ (B/1\mu\mathrm{G})^{-1}$
  - $\Longrightarrow t_{\mathrm{crit}} \approx 5\ \mathrm{Myr}\ (\mathrm{B}/1\mu\mathrm{G})$

Simulations of colliding flows

influence of magnetic fields



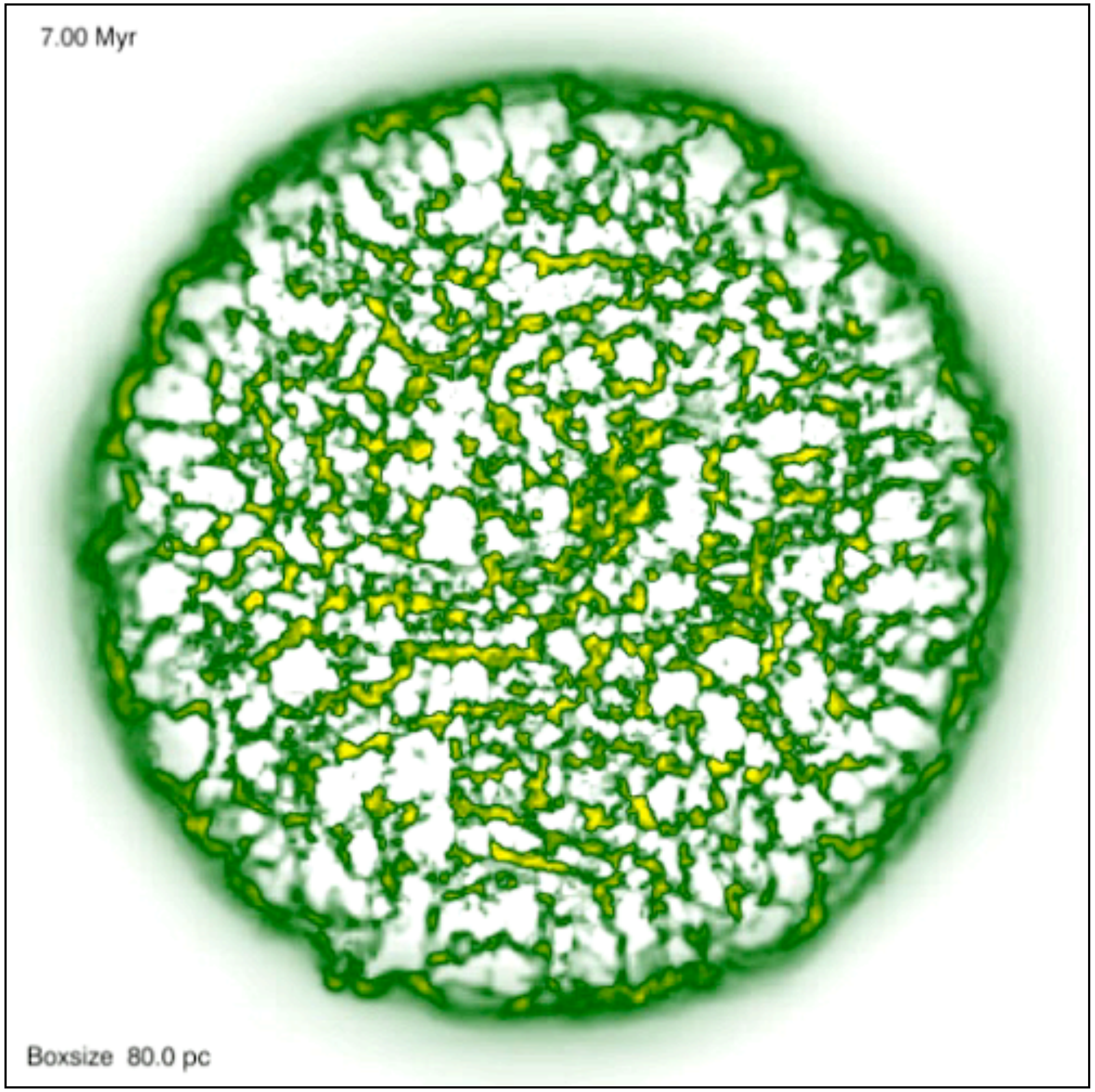
$B = 3\mu G$

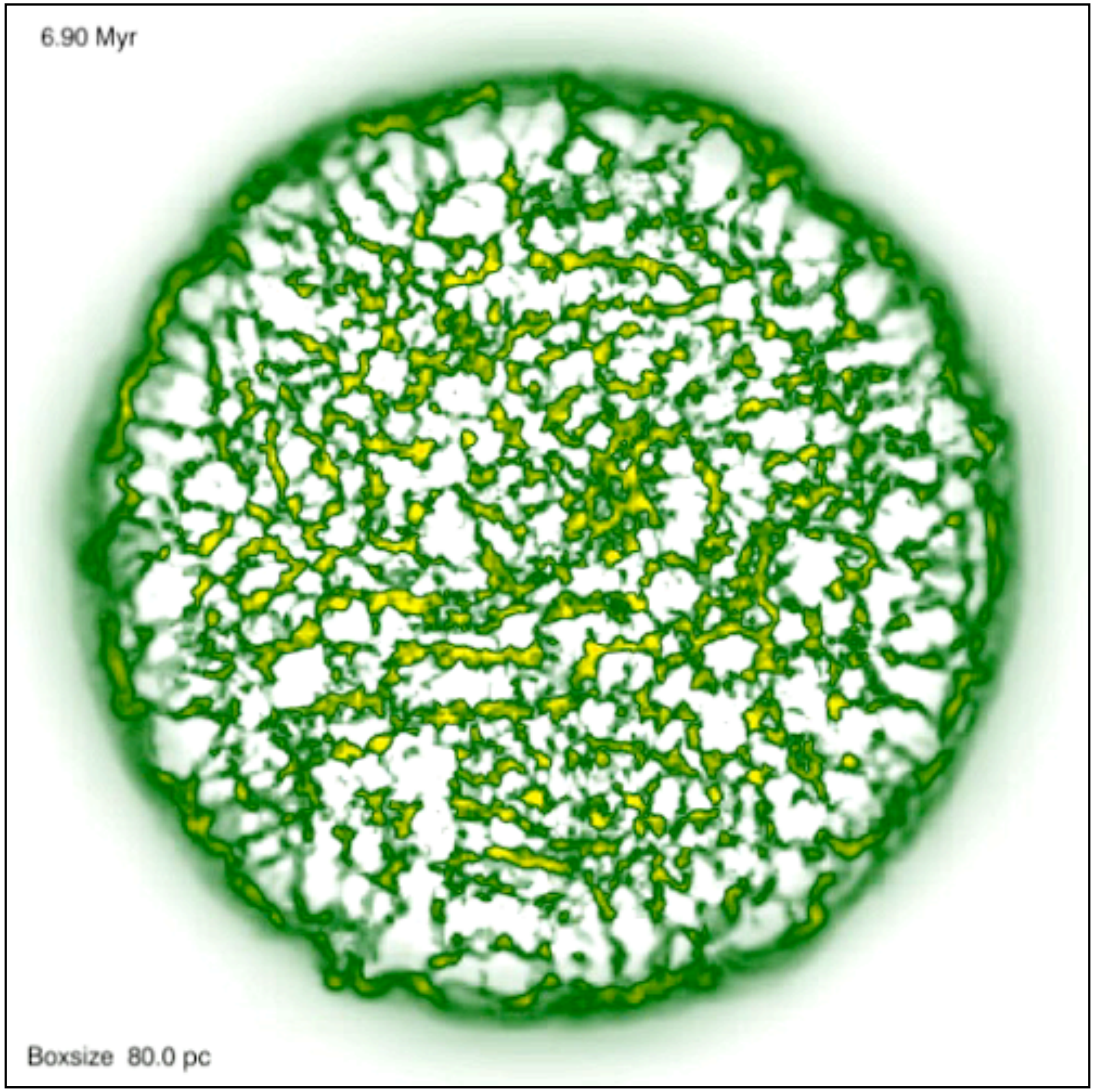


$B = 4\mu G$

Simulations of colliding flows

influence of ambipolar diffusion





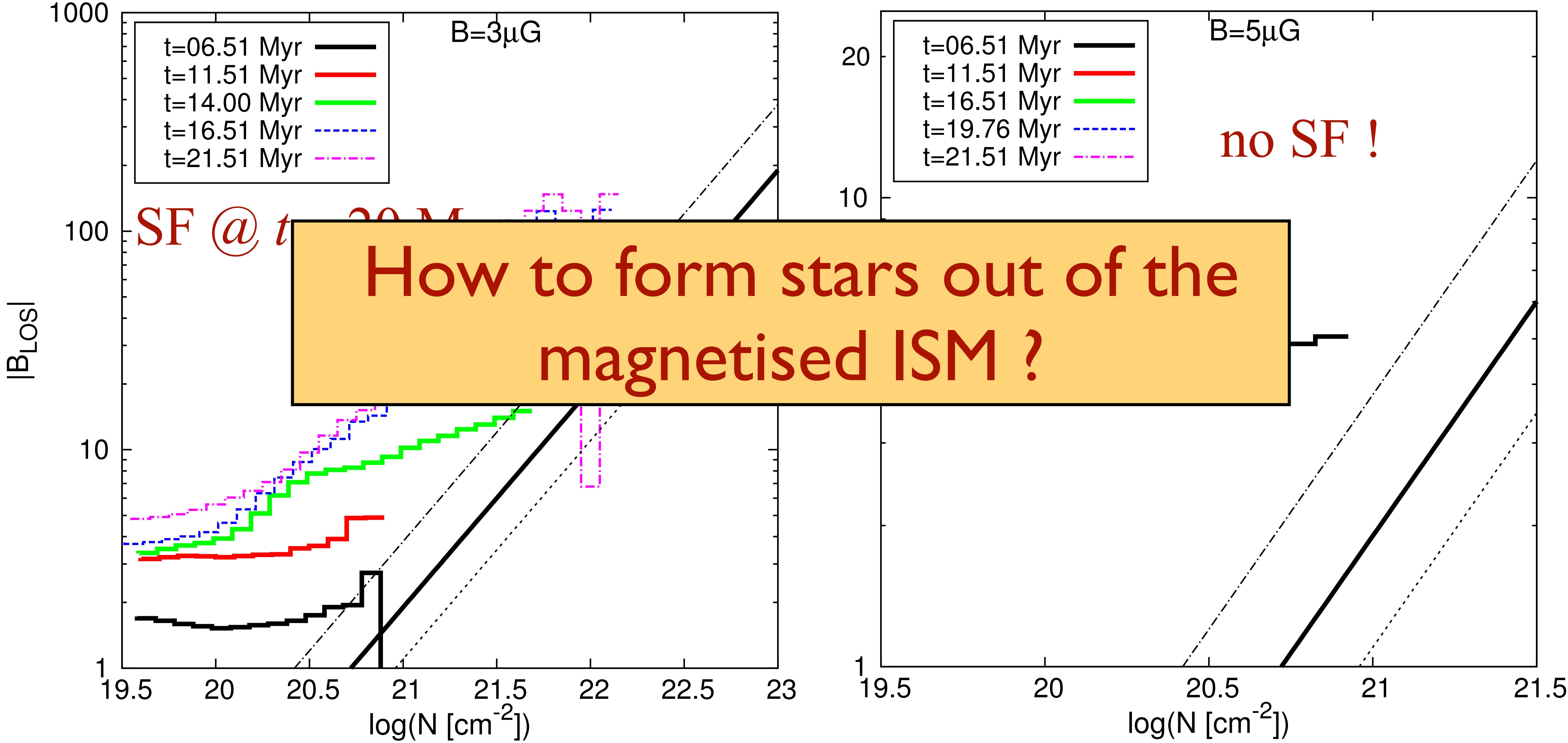
ideal case

$B = 4\mu G$

with ambipolar diffusion

Simulations of colliding flows

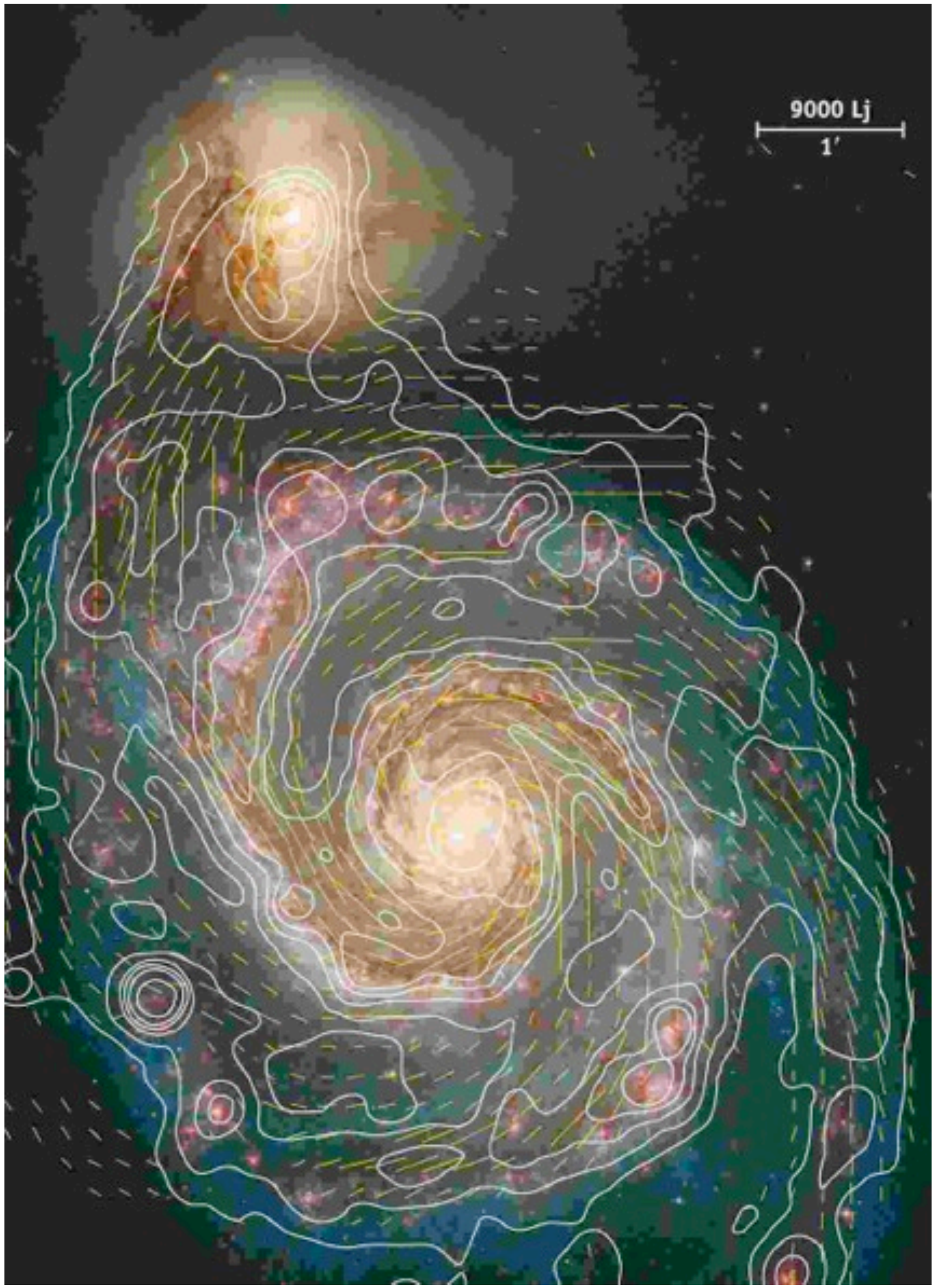
results from head-on colliding flows with different field strengths

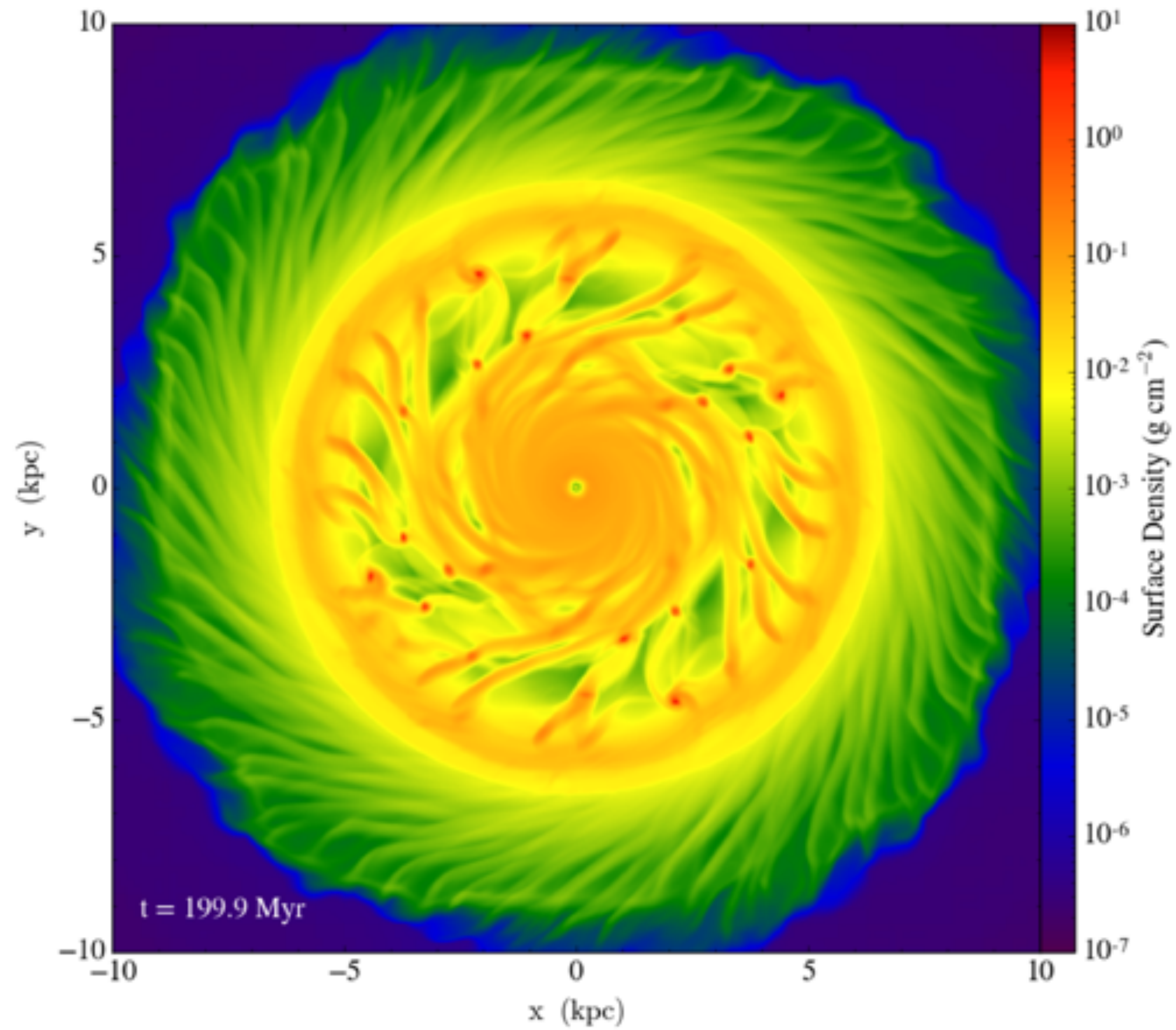


How to form stars out of the magnetised ISM ?

B. Körtgen & RB, MNRAS (2015)

Global Galactic Simulations

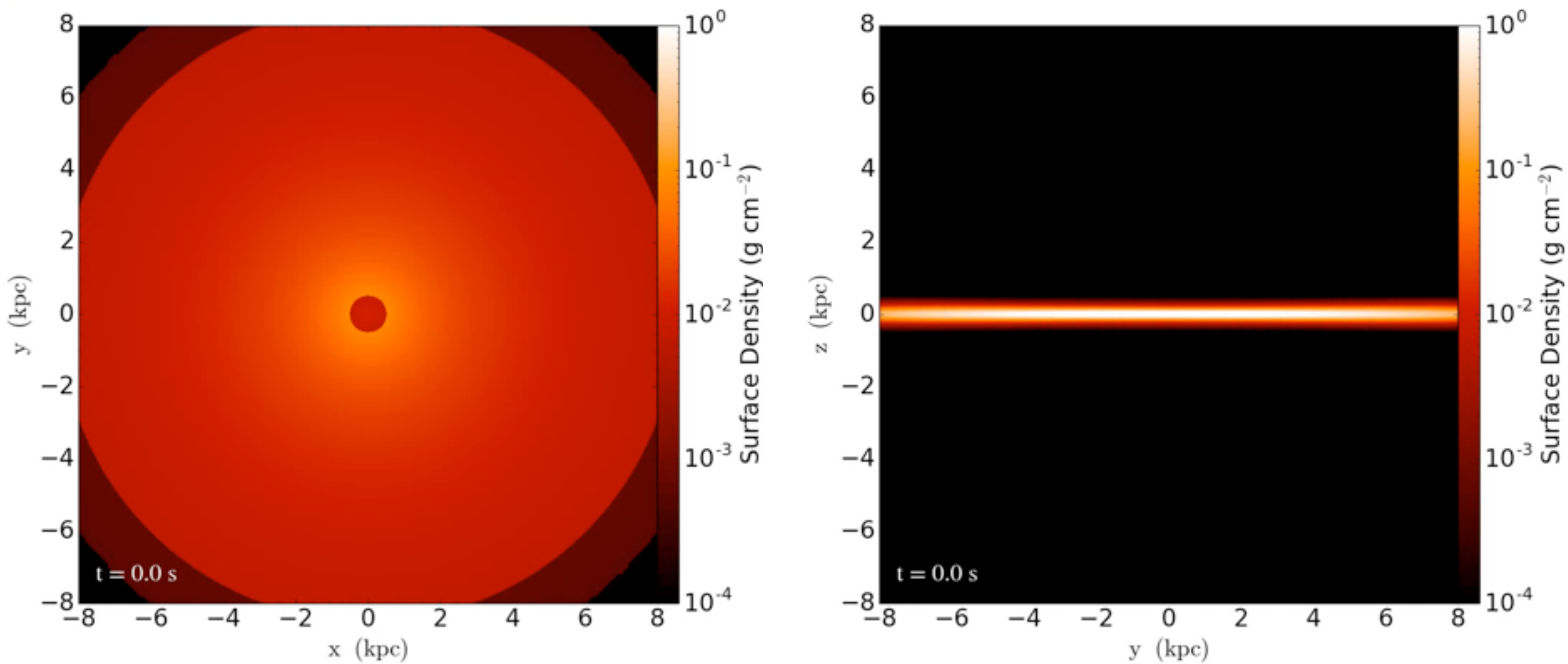




does Mestel's accumulation idea work?

Global Galactic Disc Simulations

with constant $\beta = P_{\rm therm}/P_{\rm mag} = 0.25$

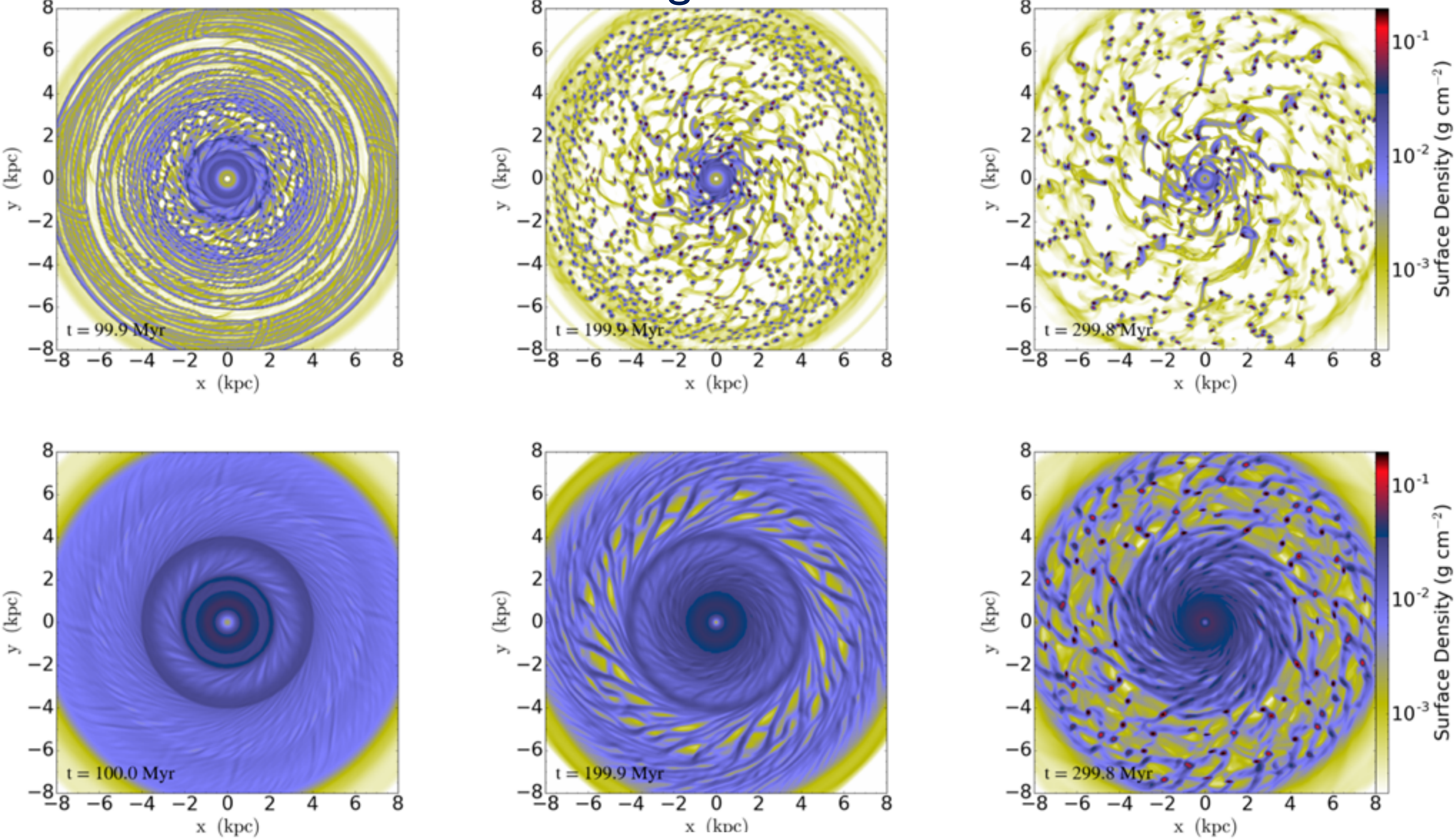


face-on

edge-on

Global Galactic Disc Simulations

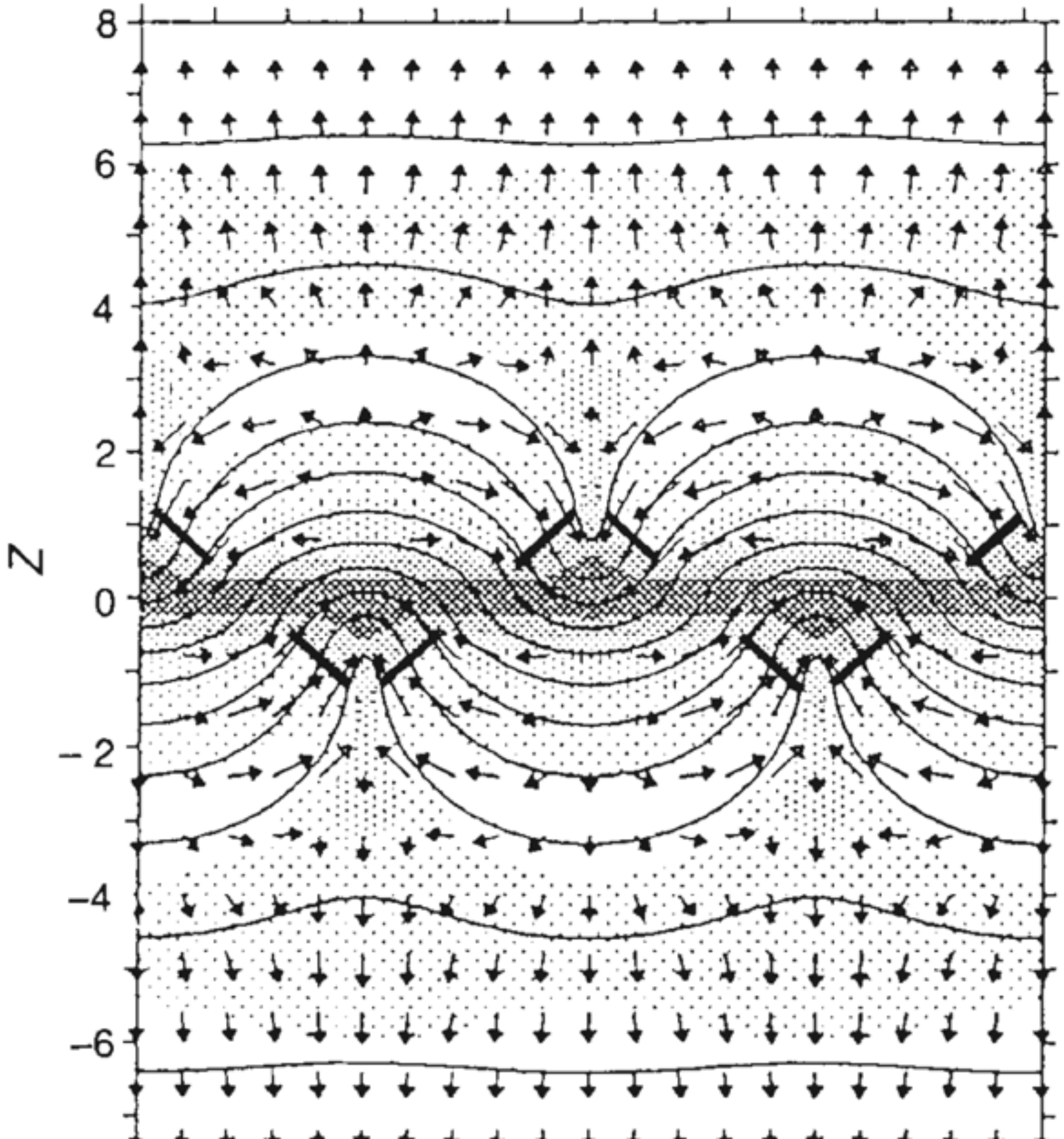
non magnetised case



strongly magnetised case: $\beta = 0.25$

Parker Instability

PI: *Parker* 1966



- buoyancy + magnetic field

⟹ gas streams along field lines

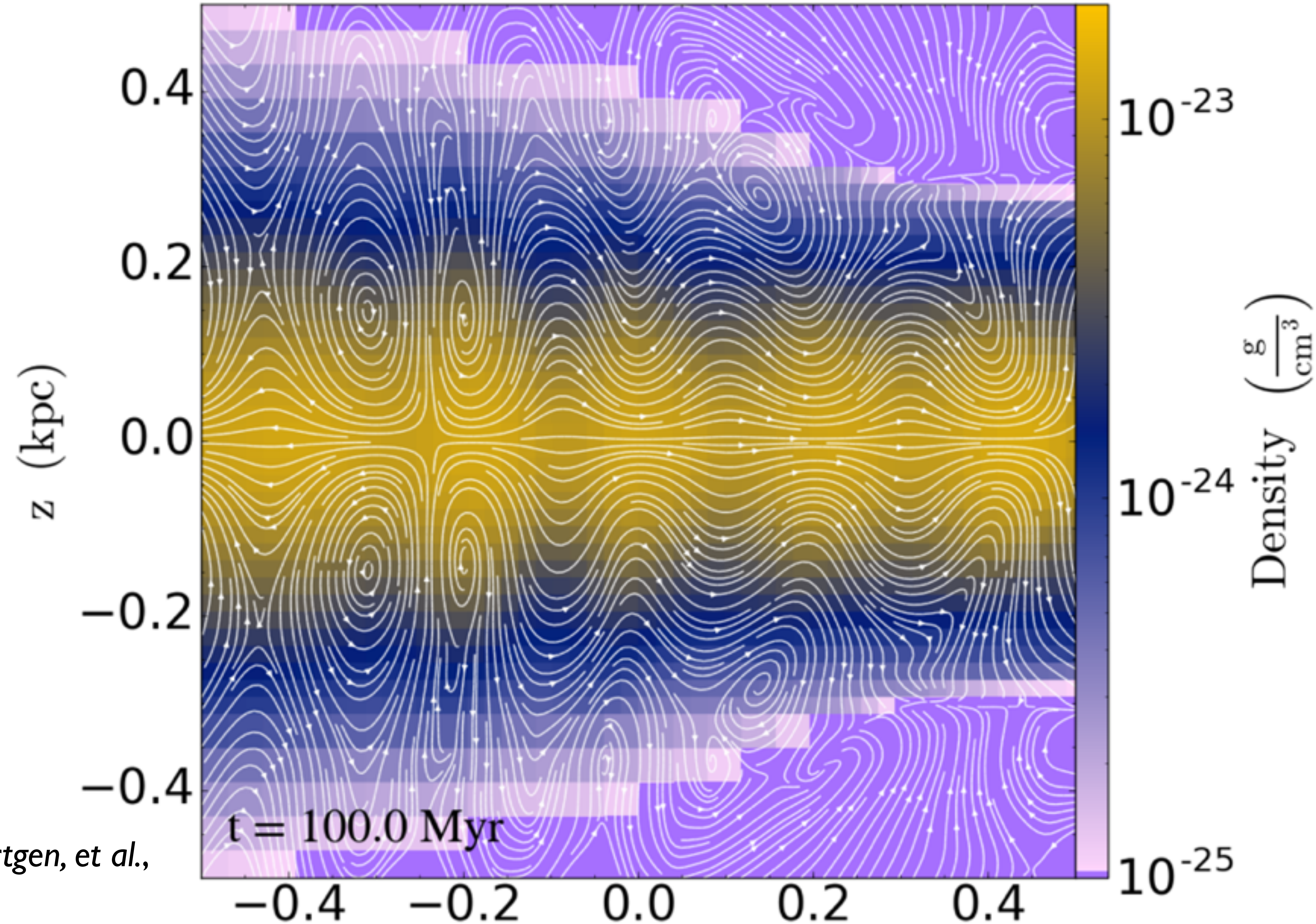
⟹ compression

⟹ GMC formation

Shibata & Matsumoto 1991

Global Galactic Disc Simulations

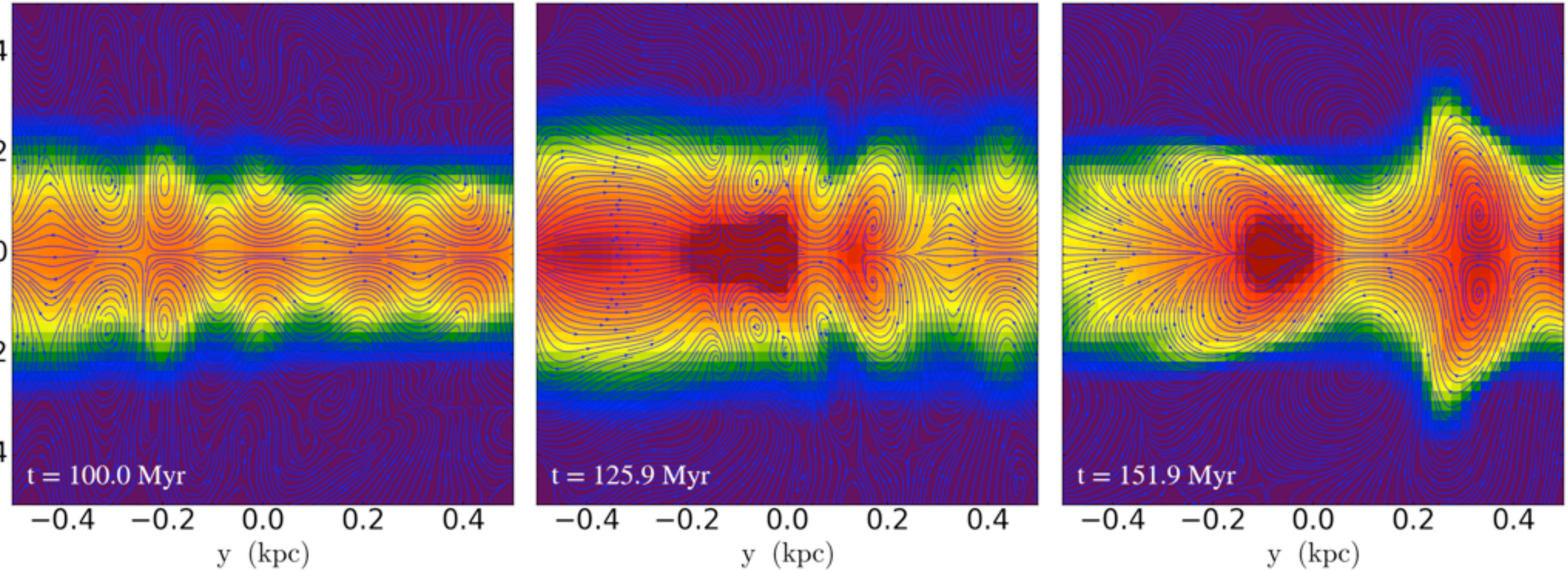
Parker Instability *(Parker 1966)*



B. Körtgen, et al., 2018

Global Galactic Disc Simulations

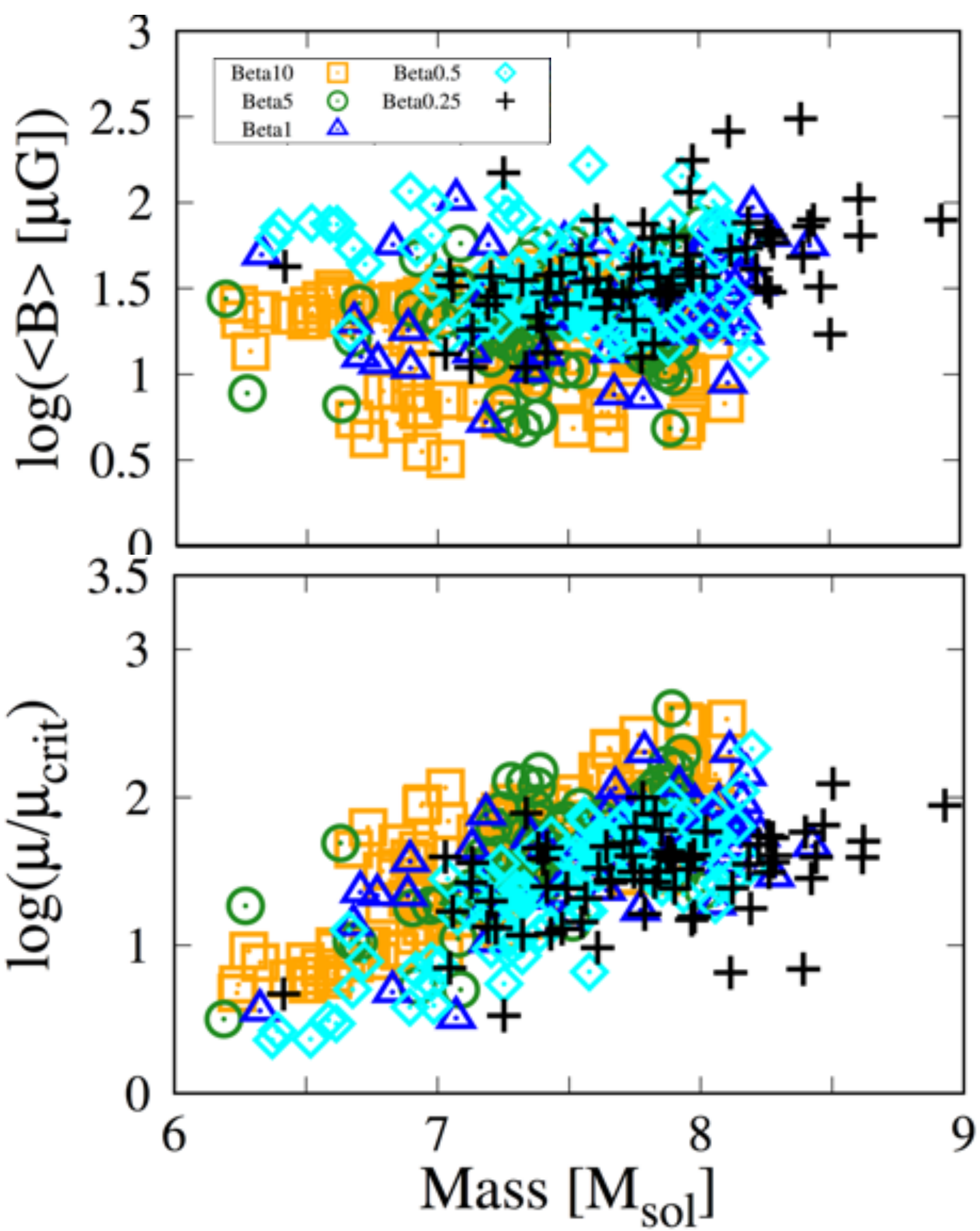
Parker Instability

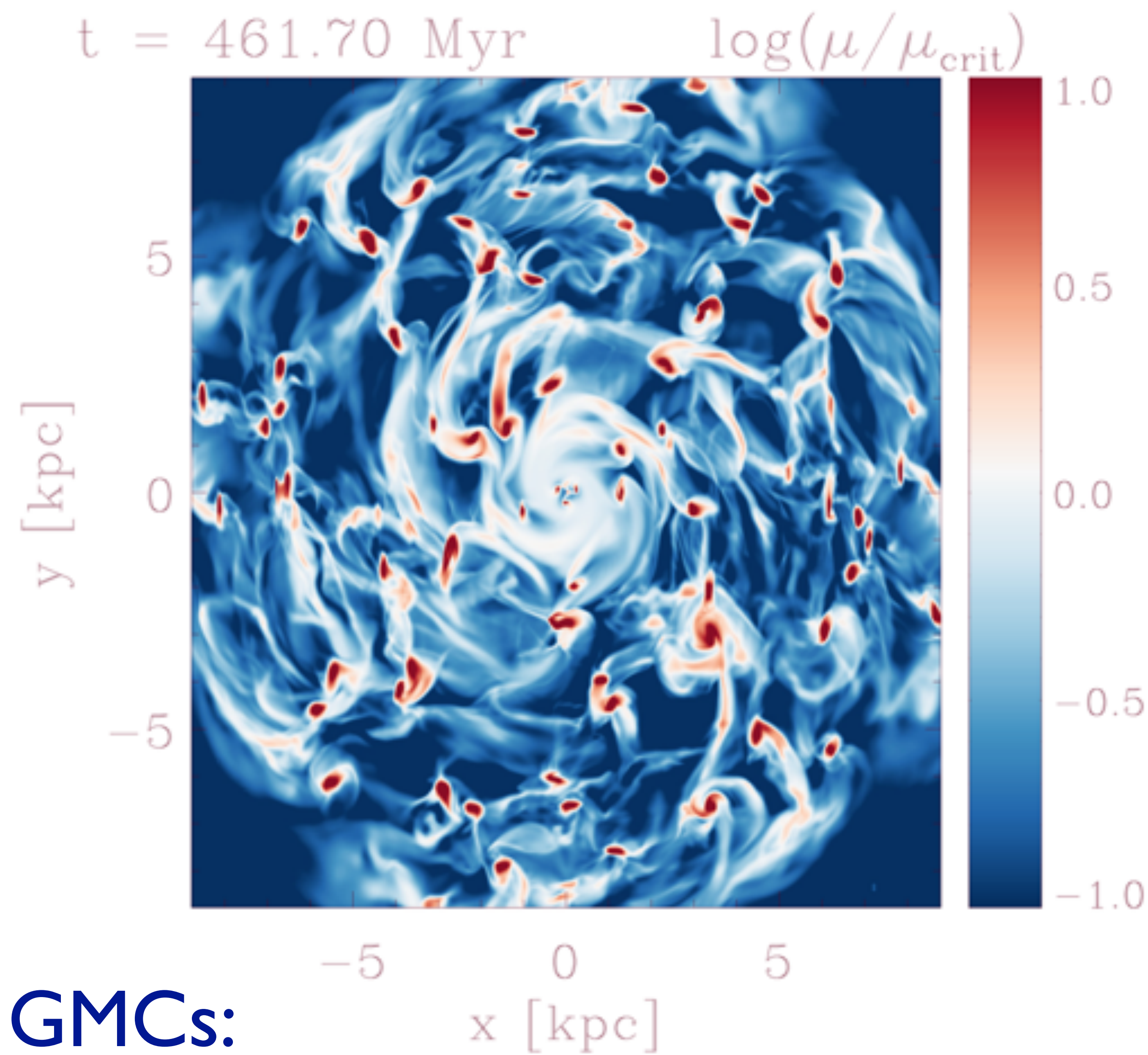


$\Longrightarrow$ supercritical GMCs from along magnetic field lines

B. Körtgen, et al., 2018

Parker Instability: GMC properies



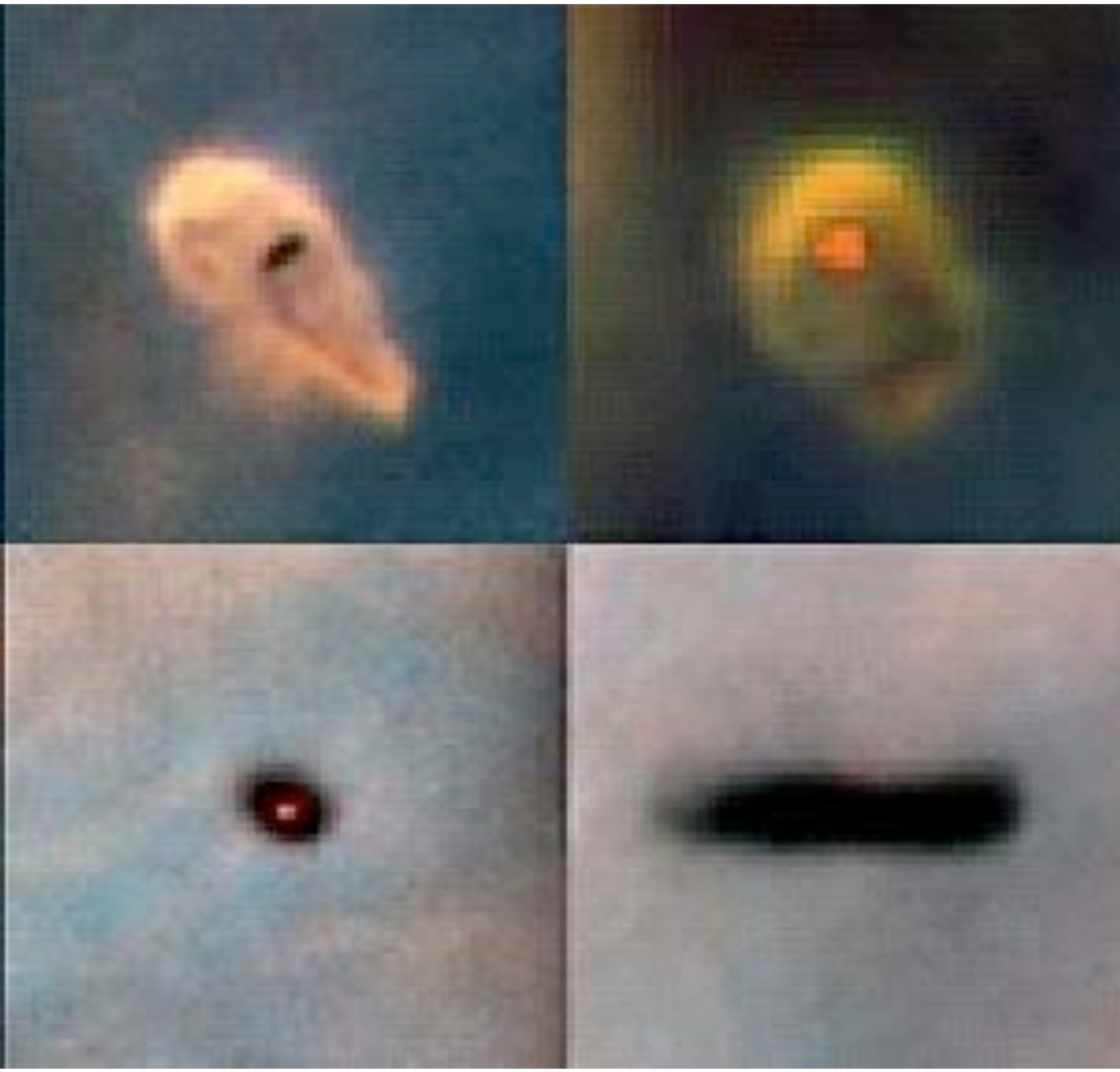


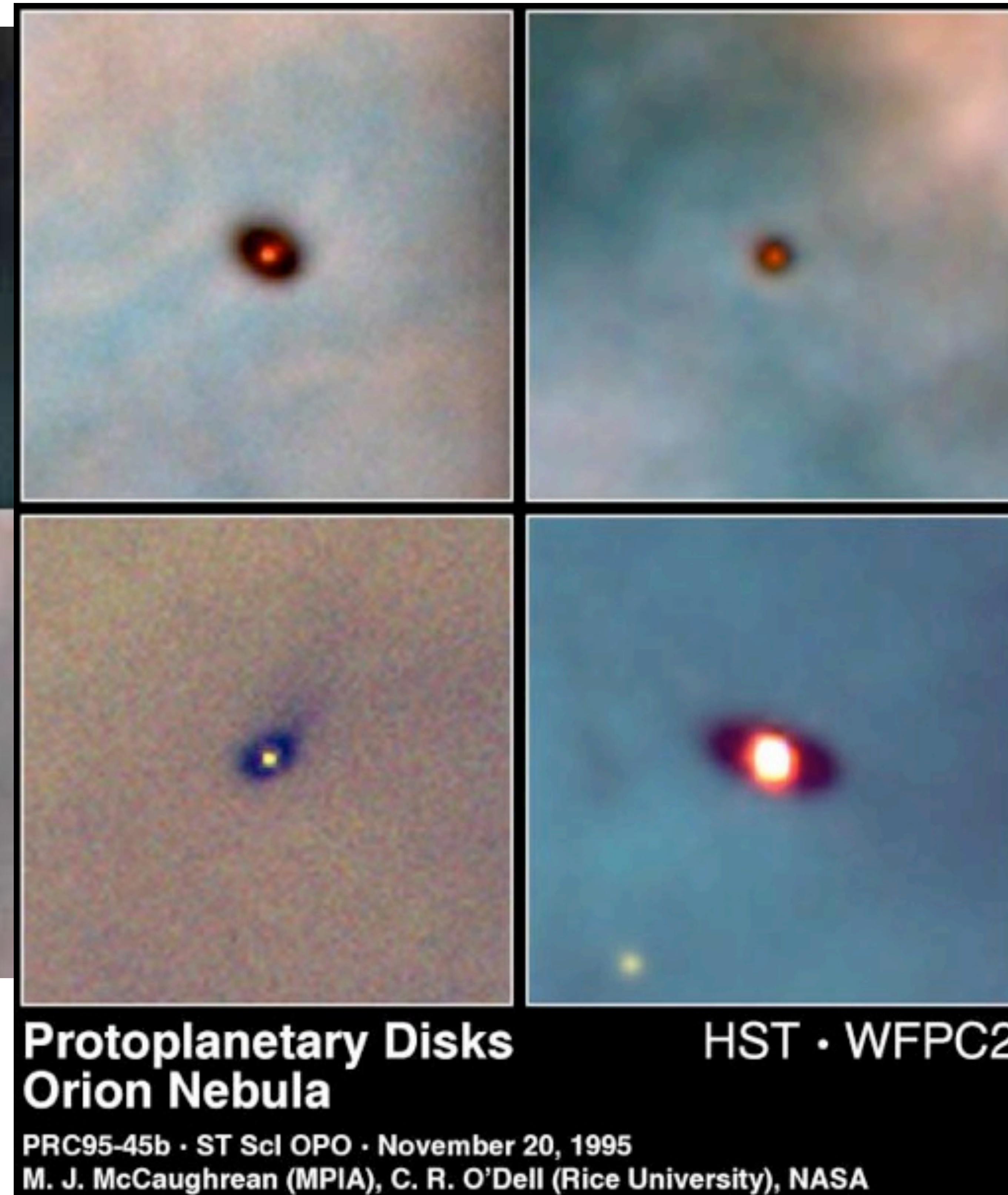
GMCs:

- are super-critical
- Magnetic field-determined MF?
- Initial conditions for high mass star formation

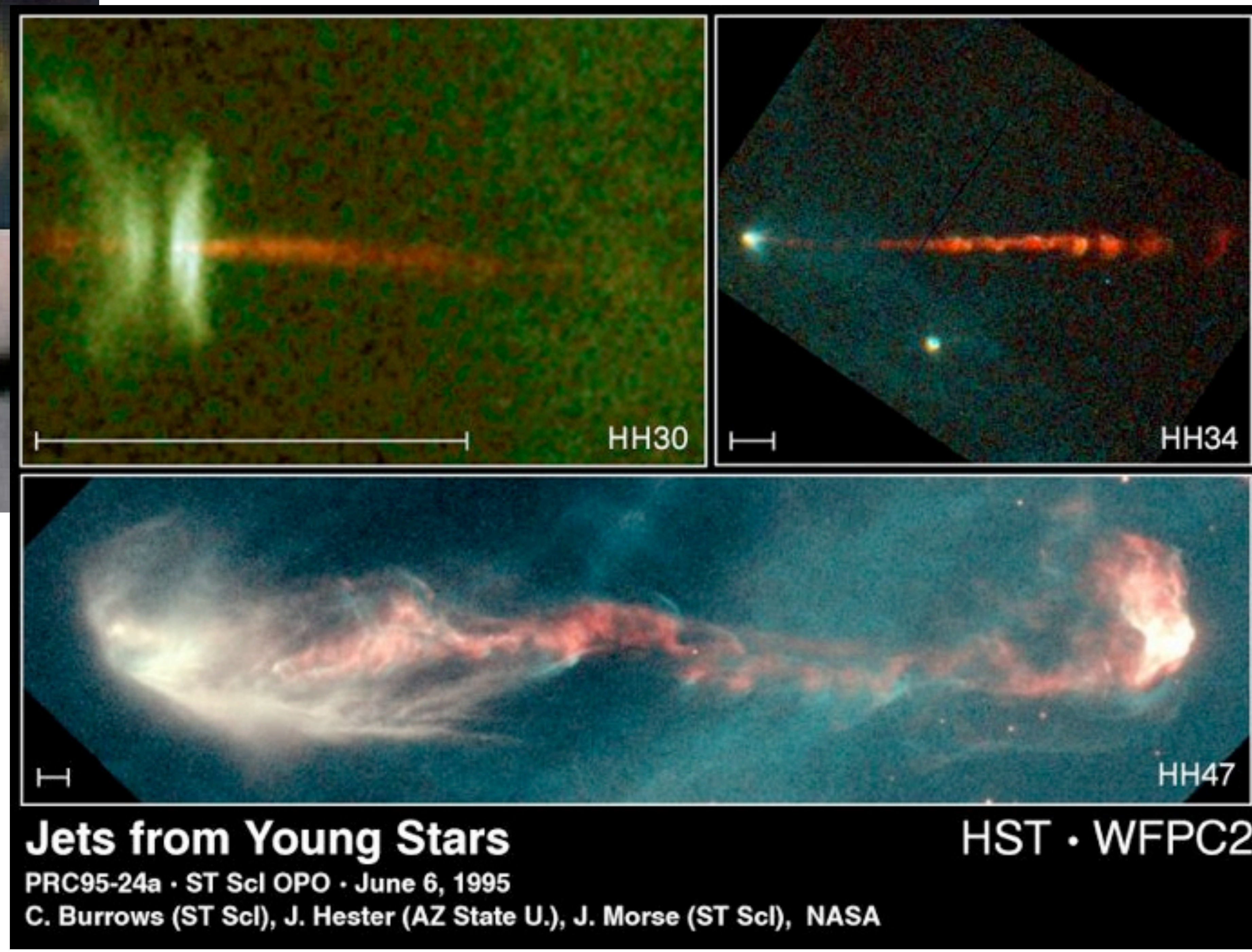
B. Körtgen, et al., 2018

Impact of Magnetic Fields: Protostellar Discs





Impact of Magnetic Fields: Protostellar Discs



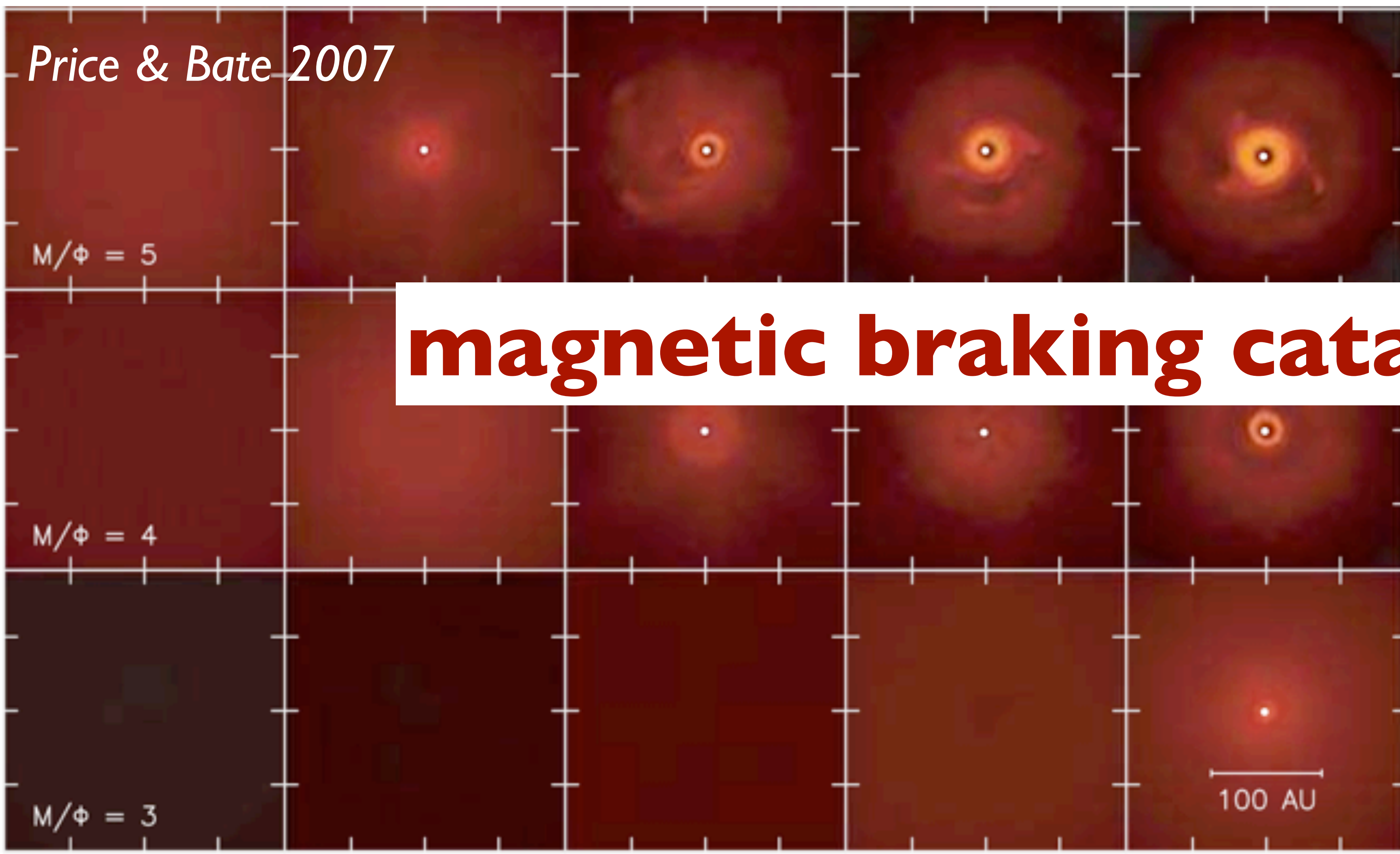
$\Longrightarrow$ jets & outflows are driven by magnetic fields + discs

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

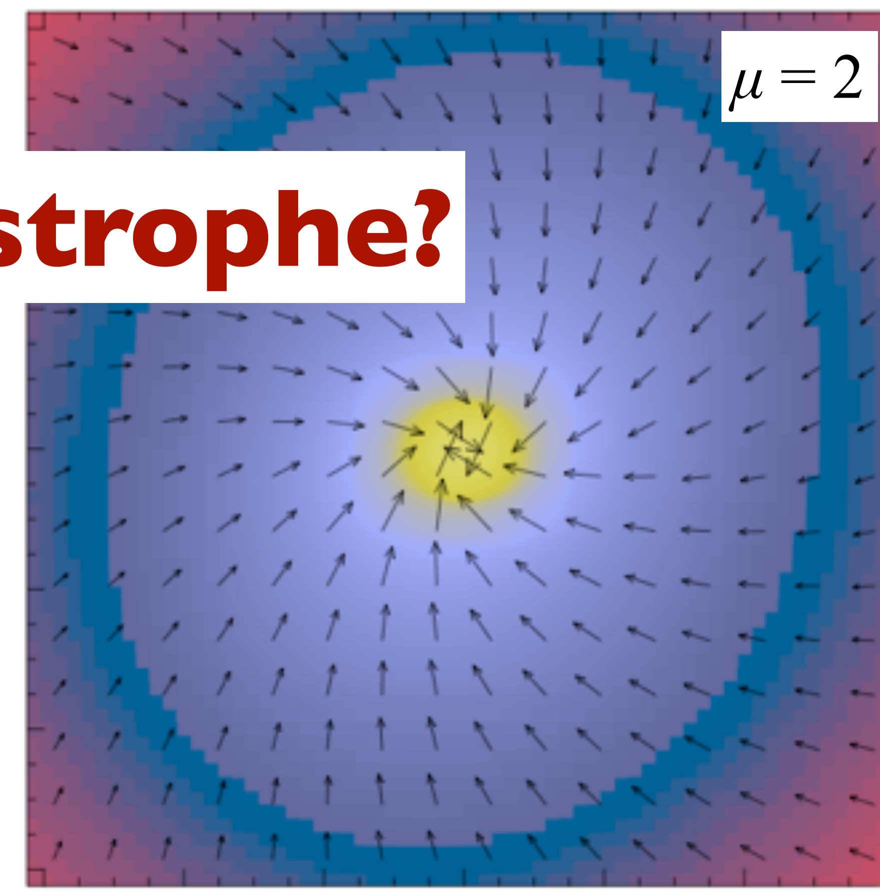
Impact of Magnetic Fields: Protostellar Discs

⟹ discs necessary for disc winds / outflows

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



magnetic braking catastrophe?

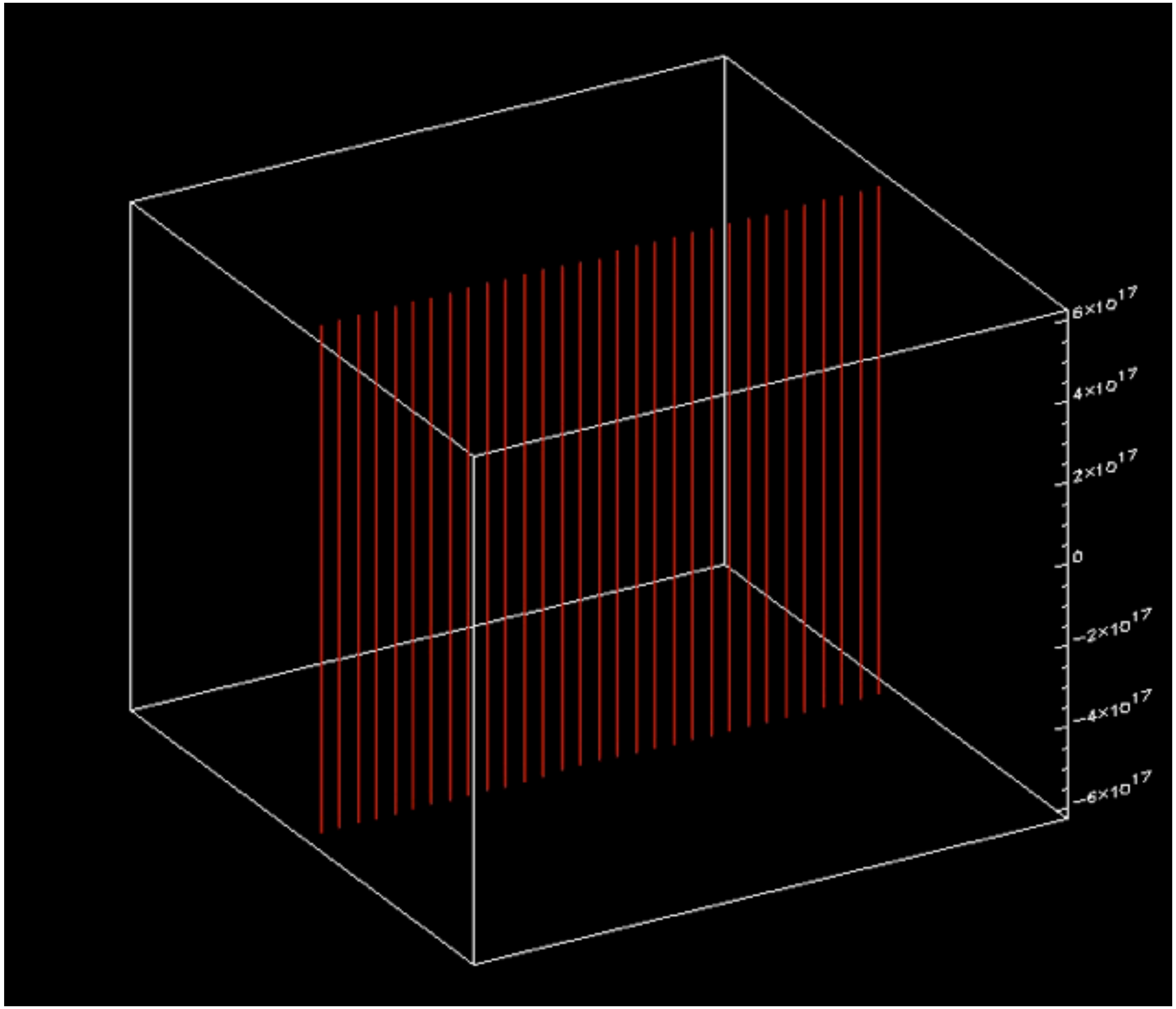


Hennebelle & Teyssier 2008, ...

⟹ ***too*** efficient magnetic braking

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

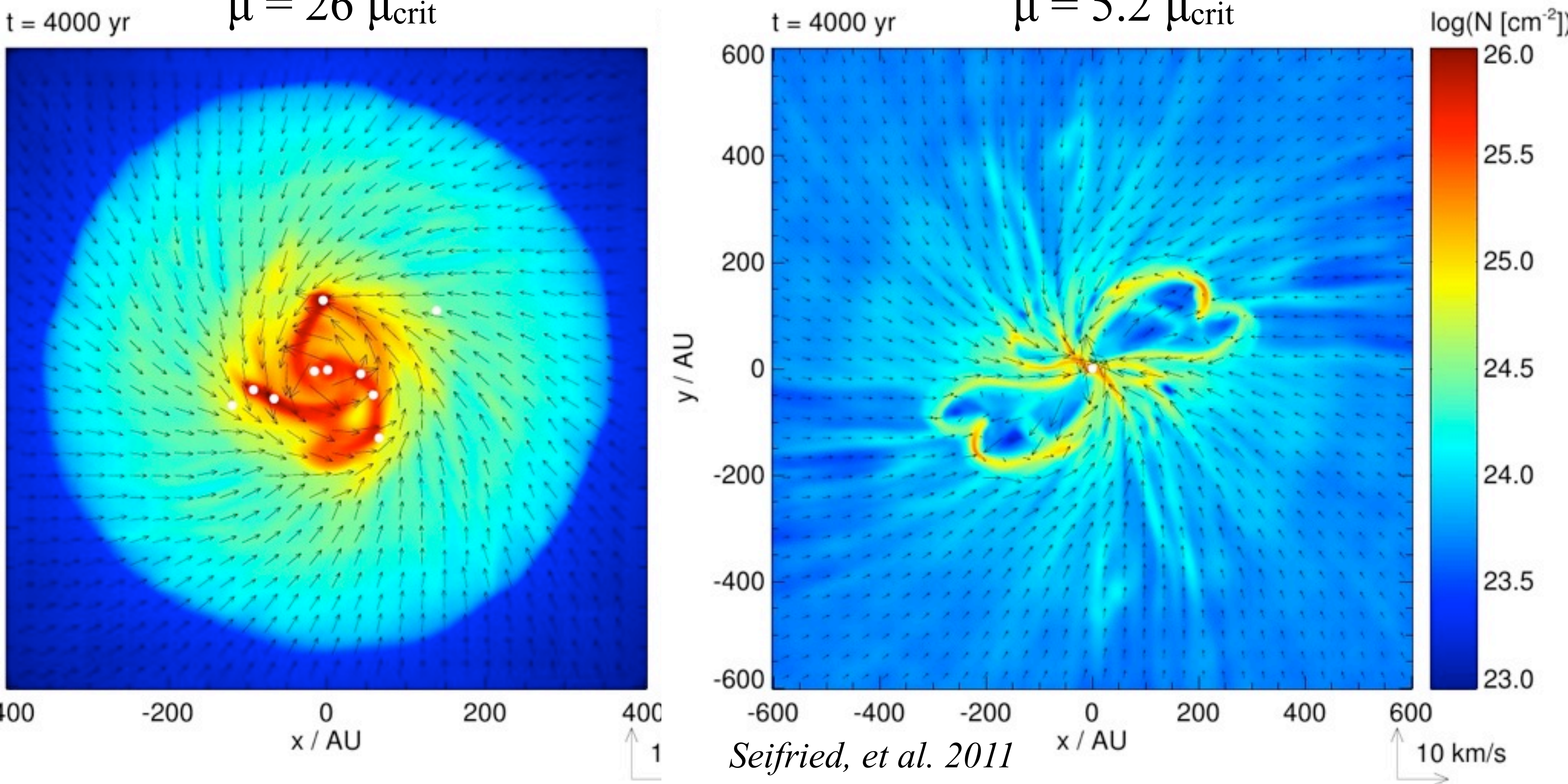
Impact of Magnetic Fields: Protostellar Discs



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

Impact of Magnetic Fields: Protostellar Discs

$\mu = 26\ \mu_{crit}$ $\mu = 5.2\ \mu_{crit}$



Seifried, et al. 2011

stronger fields ⇒ efficient magnetic braking and suppression of disc formation

Impact of Magnetic Fields: Protostellar Discs

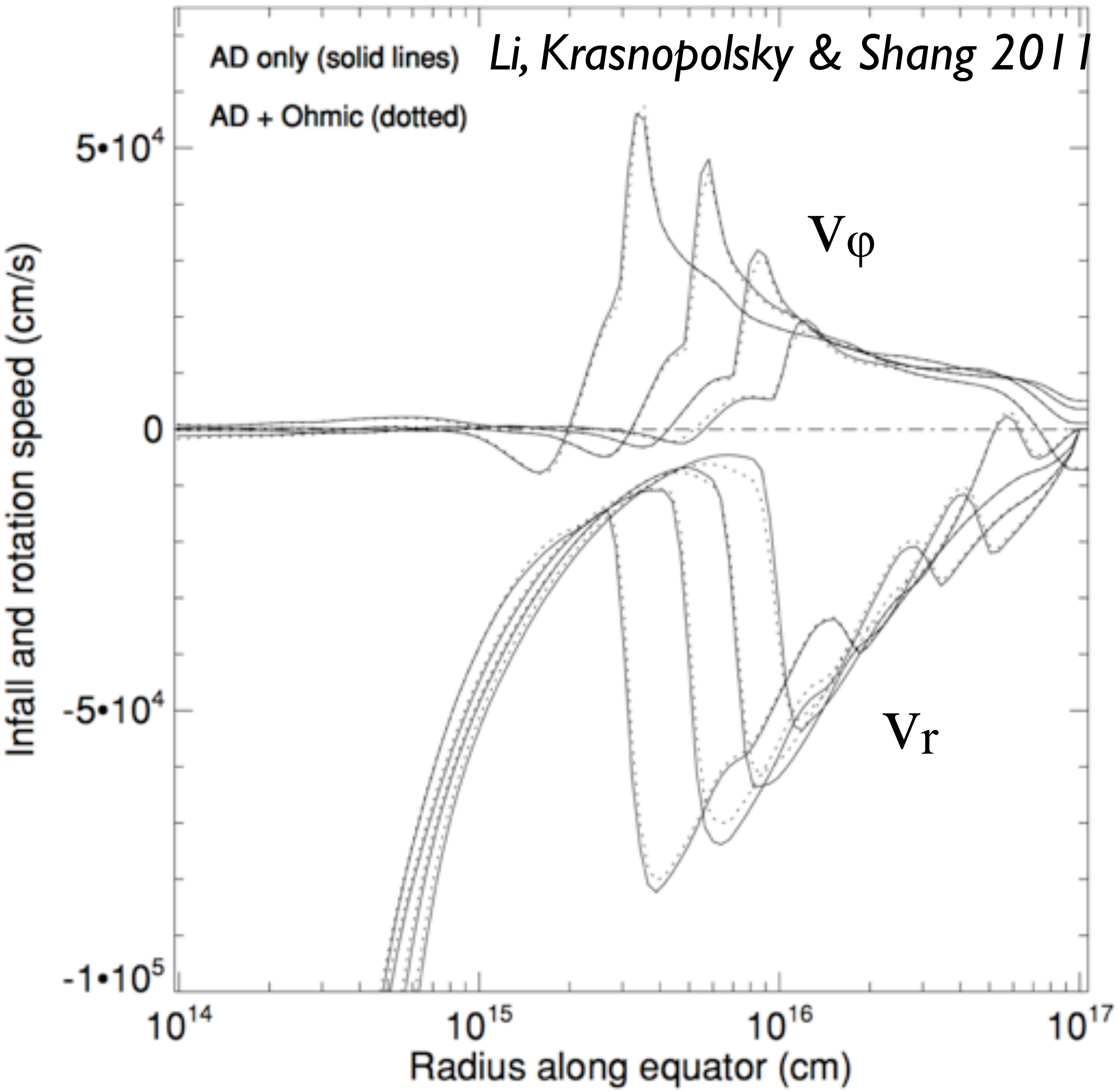
suggested **solutions** to the magnetic braking catastrophe:

- 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

⟹ Non-ideal MHD (AD, Ohmic dissipation) active only at small scales/high density

⟹ not effective enough to reduce magnetic braking



⟹ *Li, Krasnopolsky & Shang* 2011*:*

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

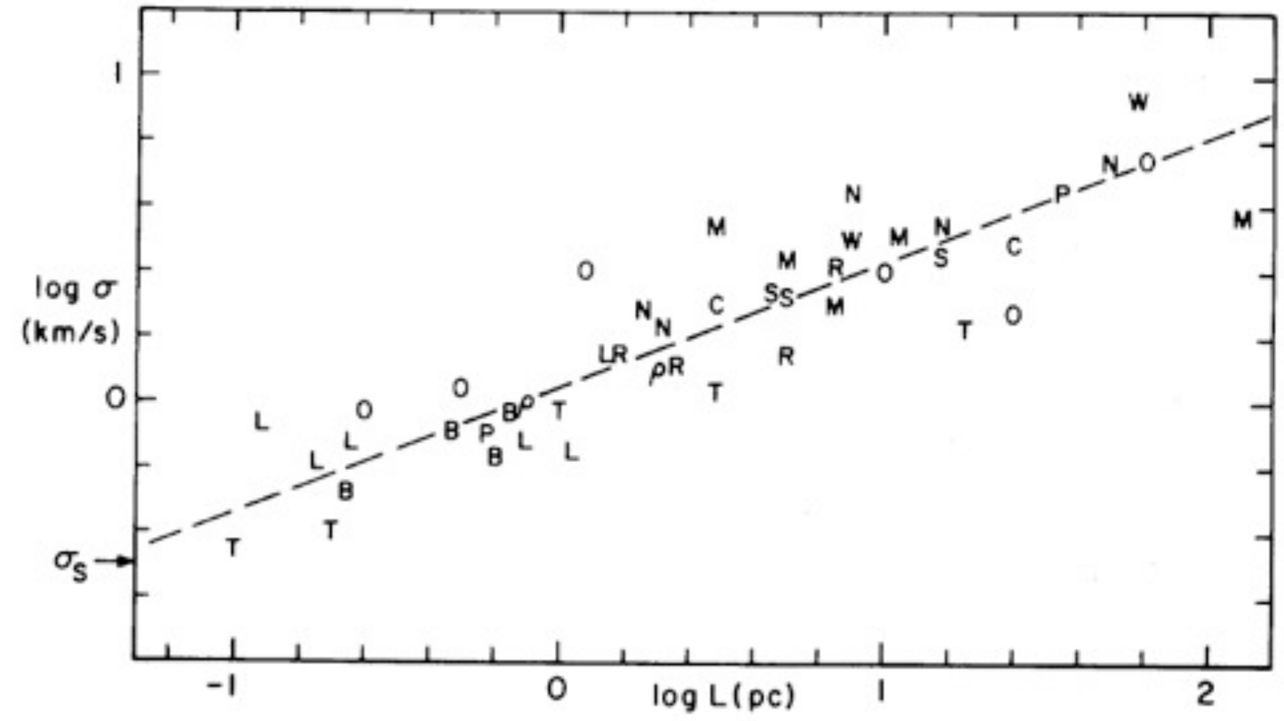
Star Formation: Early-type discs

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***



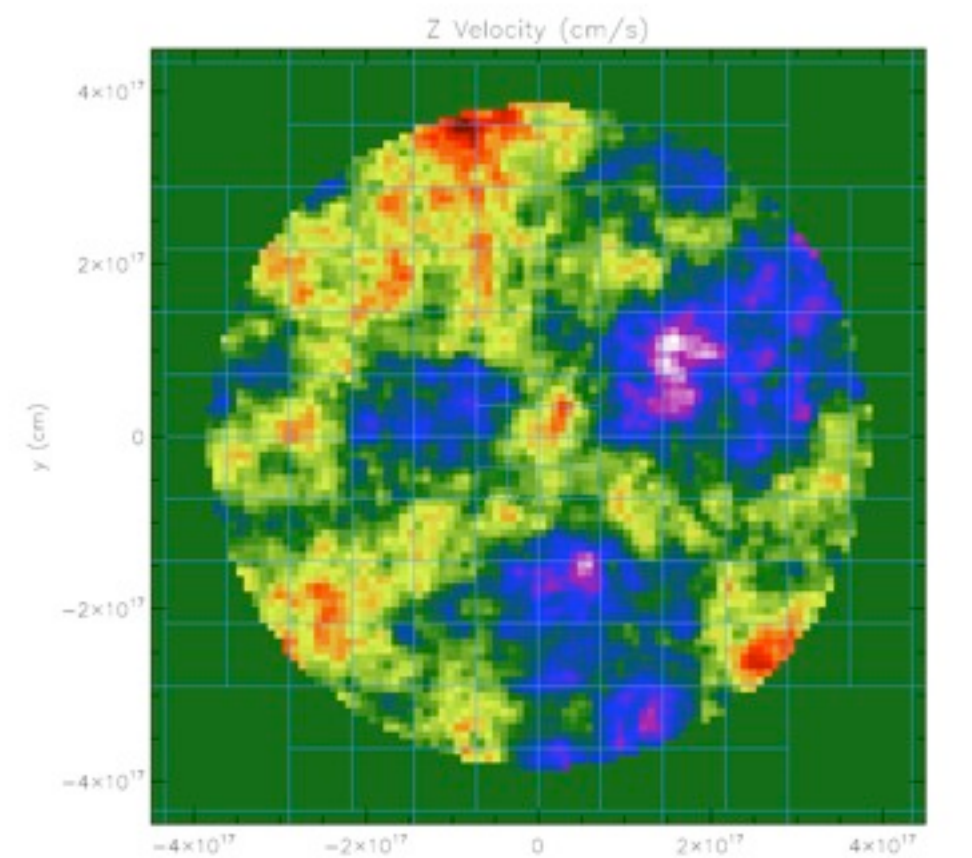
Collapse of Turbulent Cloud Cores

Seifried, et al. 2013

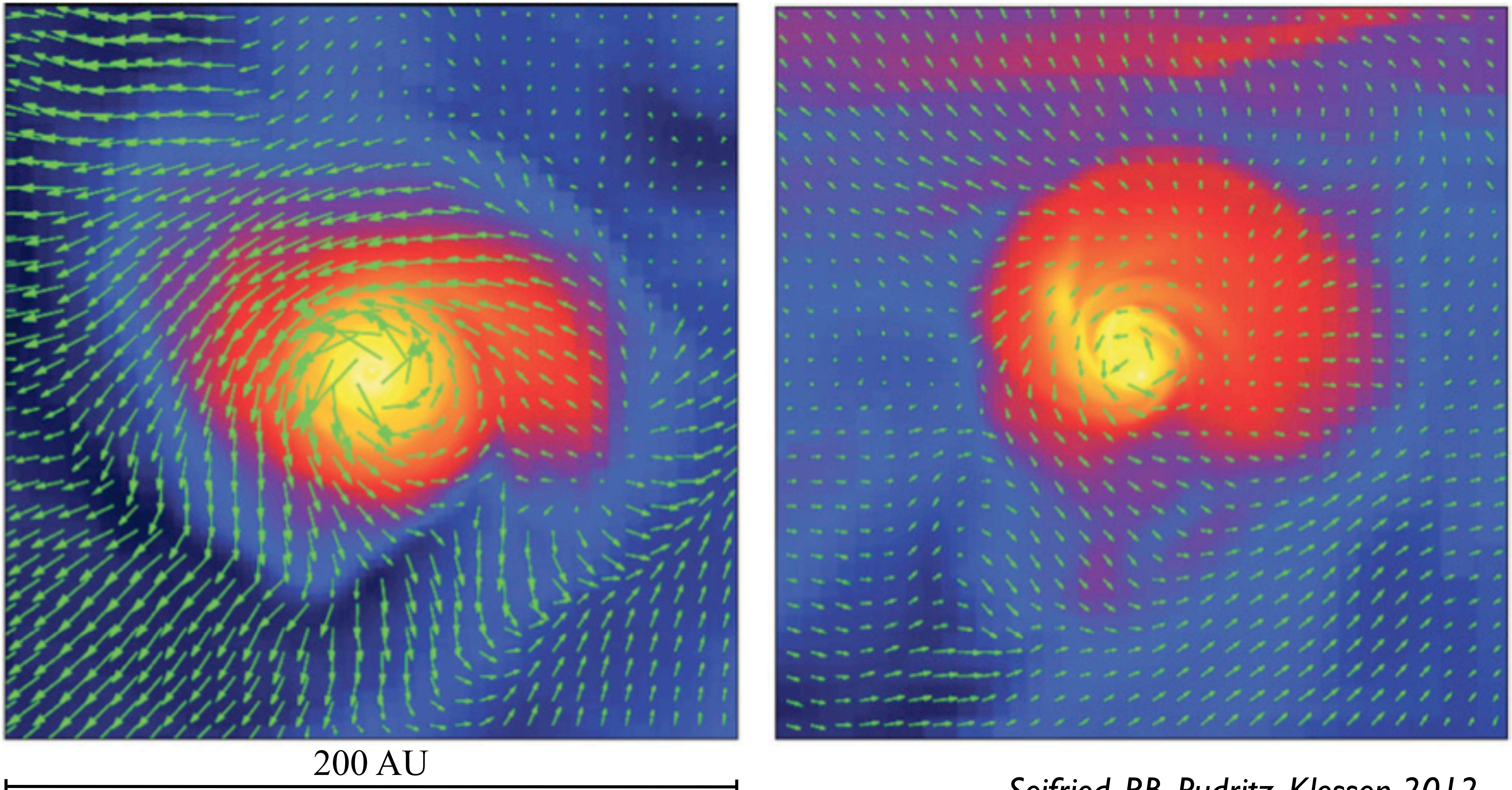
Run	m_{core} ($M_\odot$)	r_{core} (pc)	μ	Rotation	Ω (10^{-13} s^{-1})	β_{turb}	Turbulence seed	p	M_{rms}	t_{sim} (kyr)
2.6-NoRot-M2	2.6	0.0485	2.6	No	0	0.087	A	5/3	0.74	15
2.6-Rot-M2	2.6	0.0485	2.6	Yes	2.20	0.087	A	5/3	0.74	15
2.6-NoRot-M100	100	0.125	2.6	No	0	0.084	A	5/3	2.5	15
2.6-Rot-M100	100	0.125	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

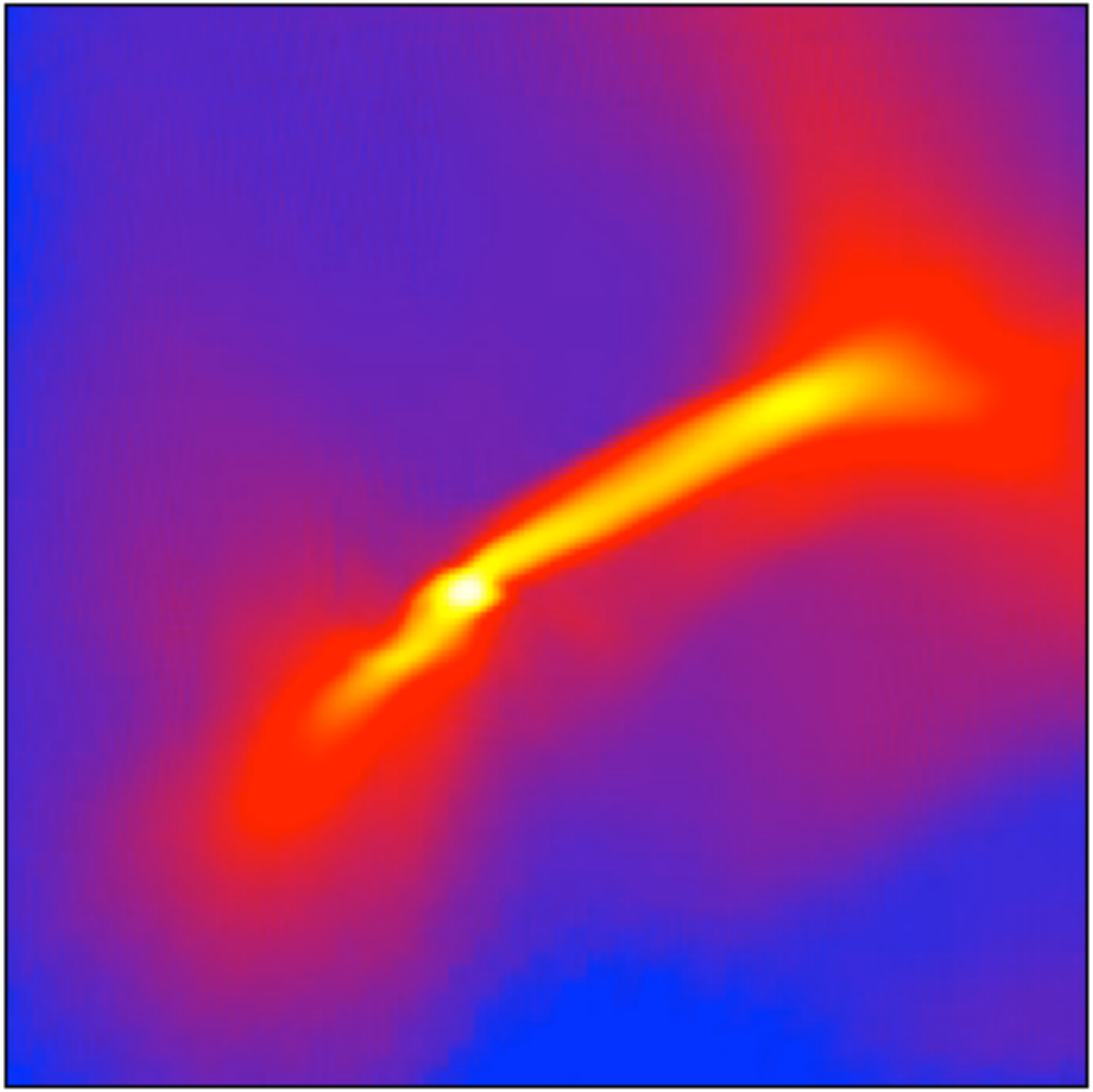


200 AU

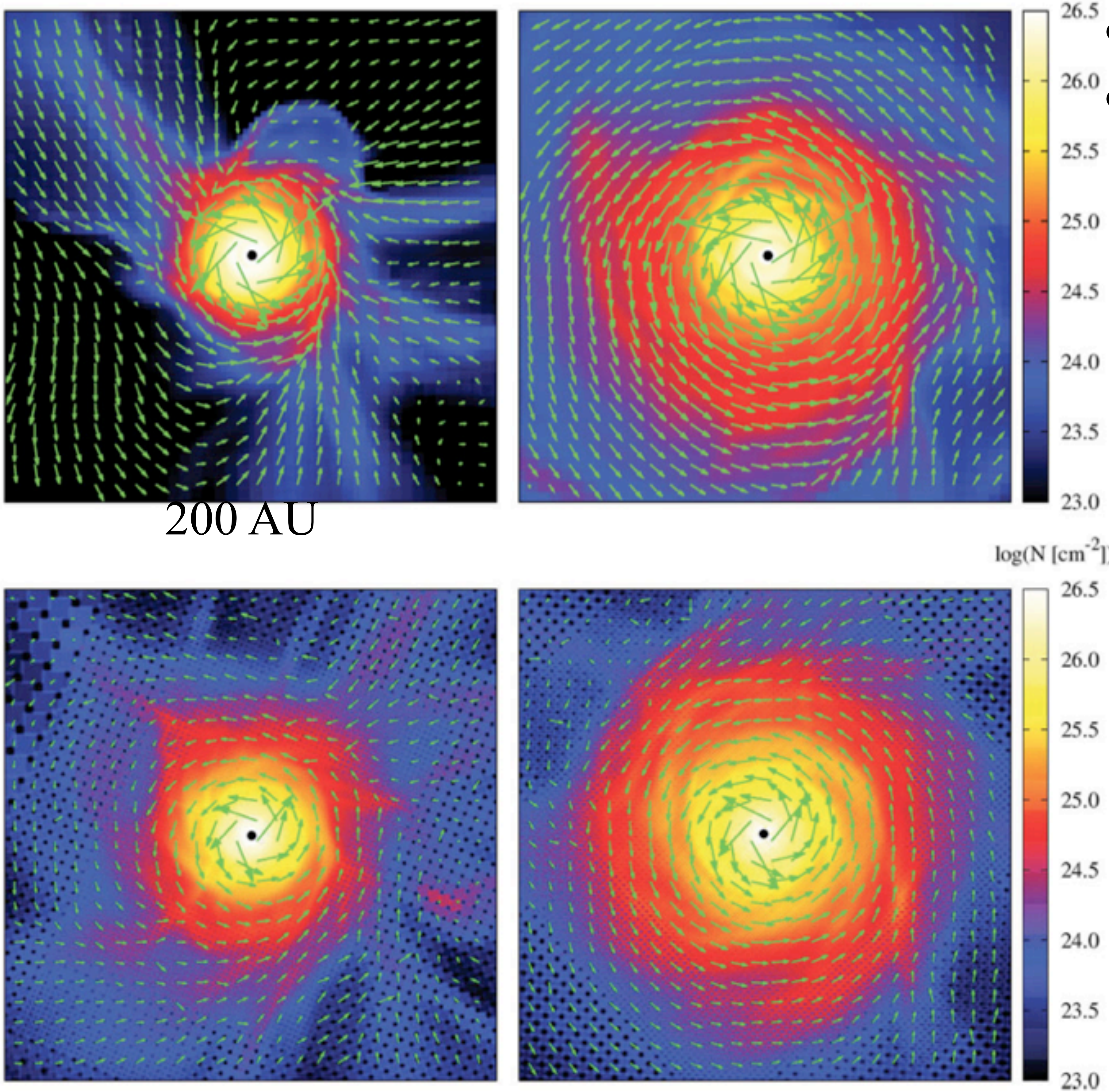
Seifried, RB, Pudritz, Klessen 2012

$\Longrightarrow$ discs “reappear”

Collapse of Turbulent Cores



Collapse of Turbulent Cores



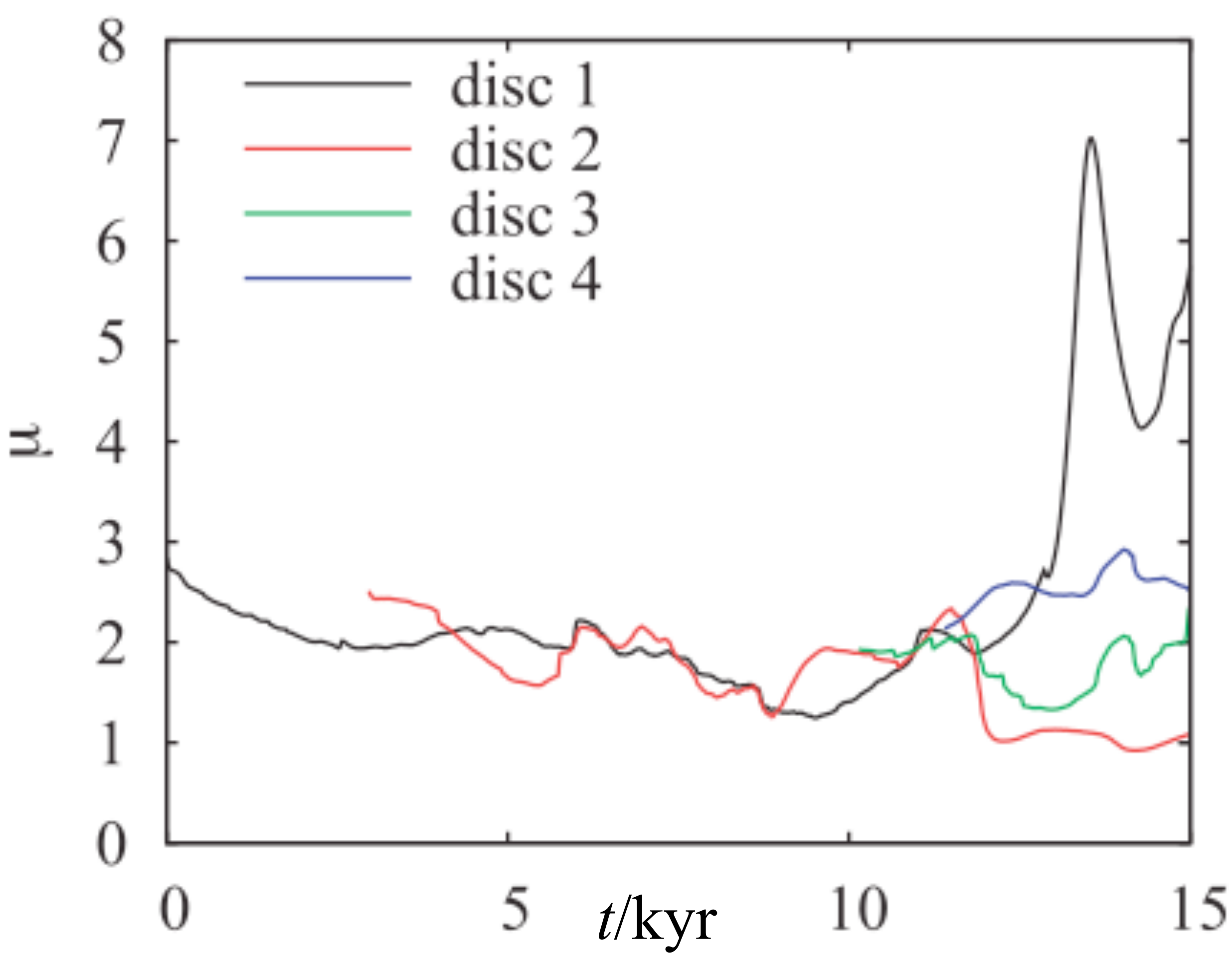
- low mass cores
- strong magnetic field: $\mu = 2.6\ \mu_{crit}$
- transonic turbulence $\mathcal{M}a = 0.74$
- **no** global rotation

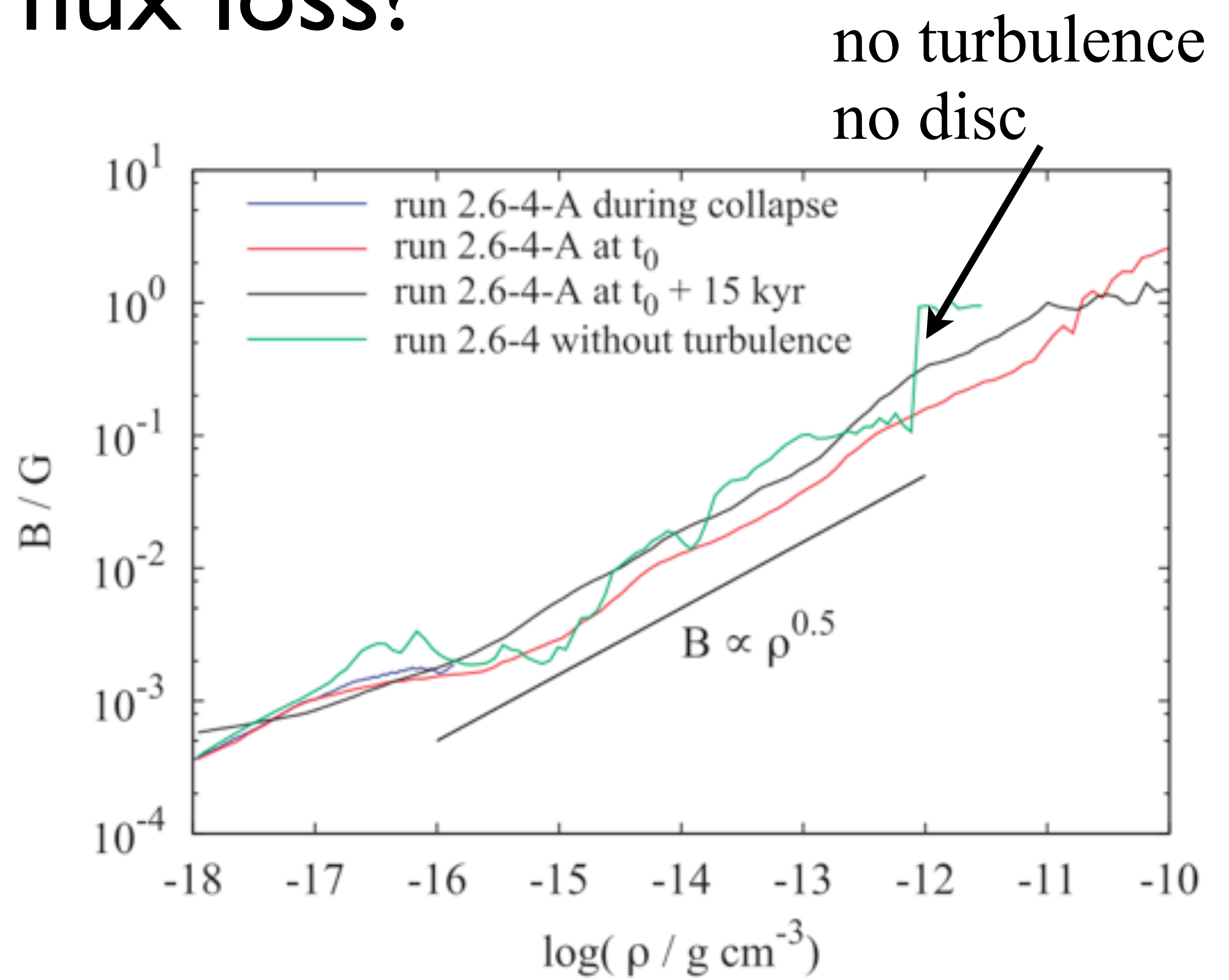
- with global rotation

Seifried, et al. 2013

Collapse of Turbulent Cores

due to flux loss?

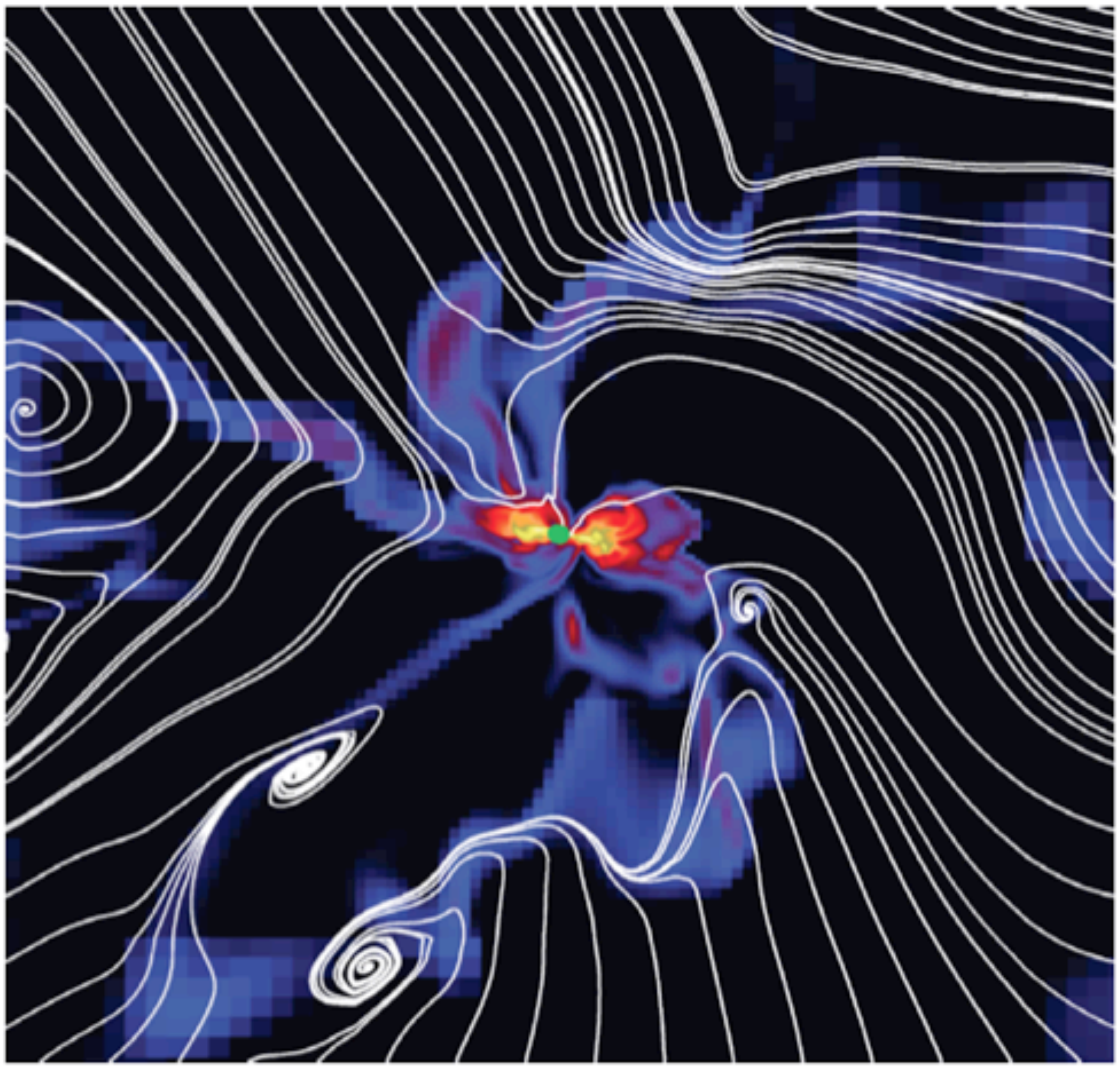


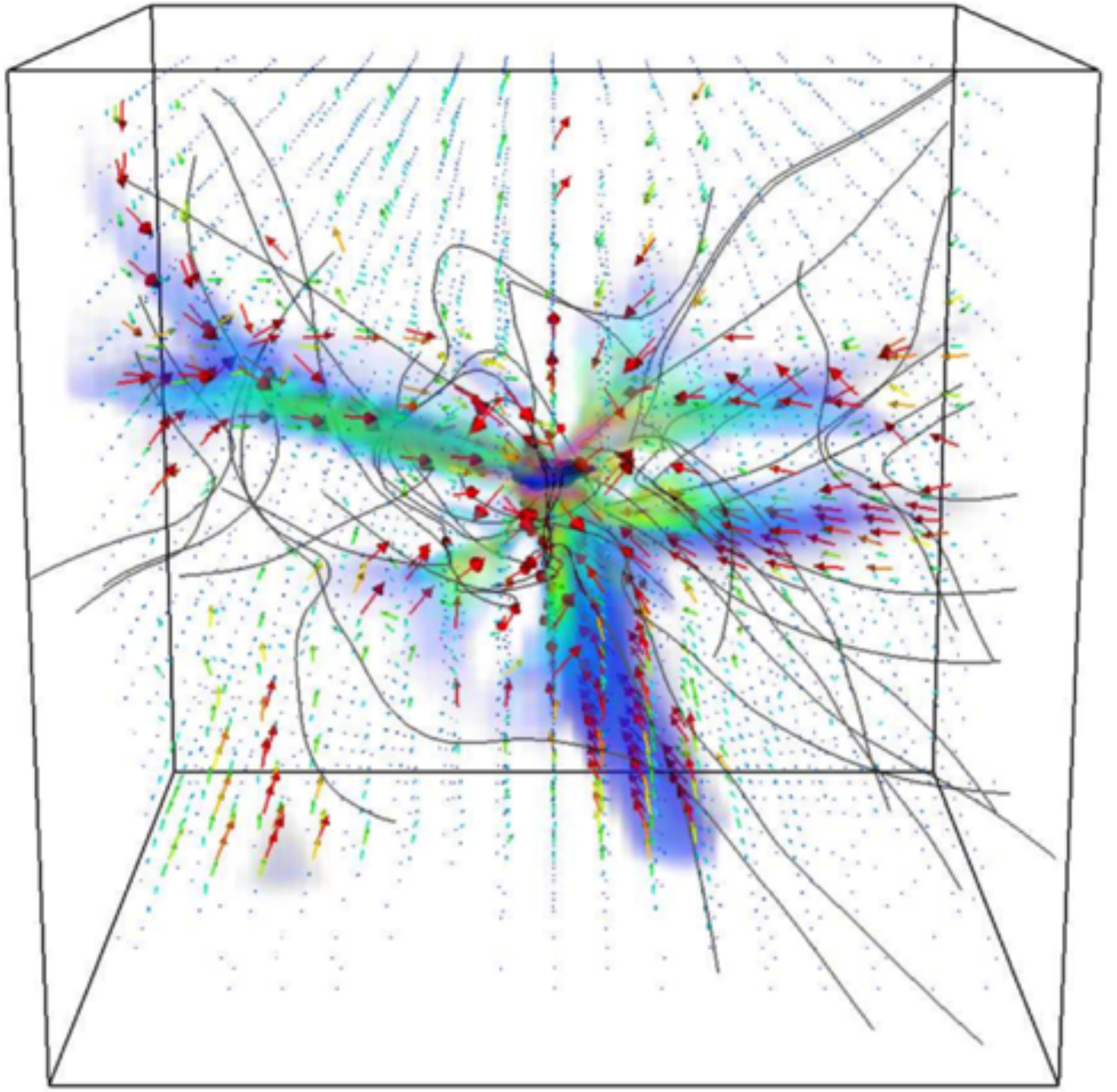


$\Longrightarrow$ no flux loss

Collapse of Turbulent Cores

Magnetic field structure



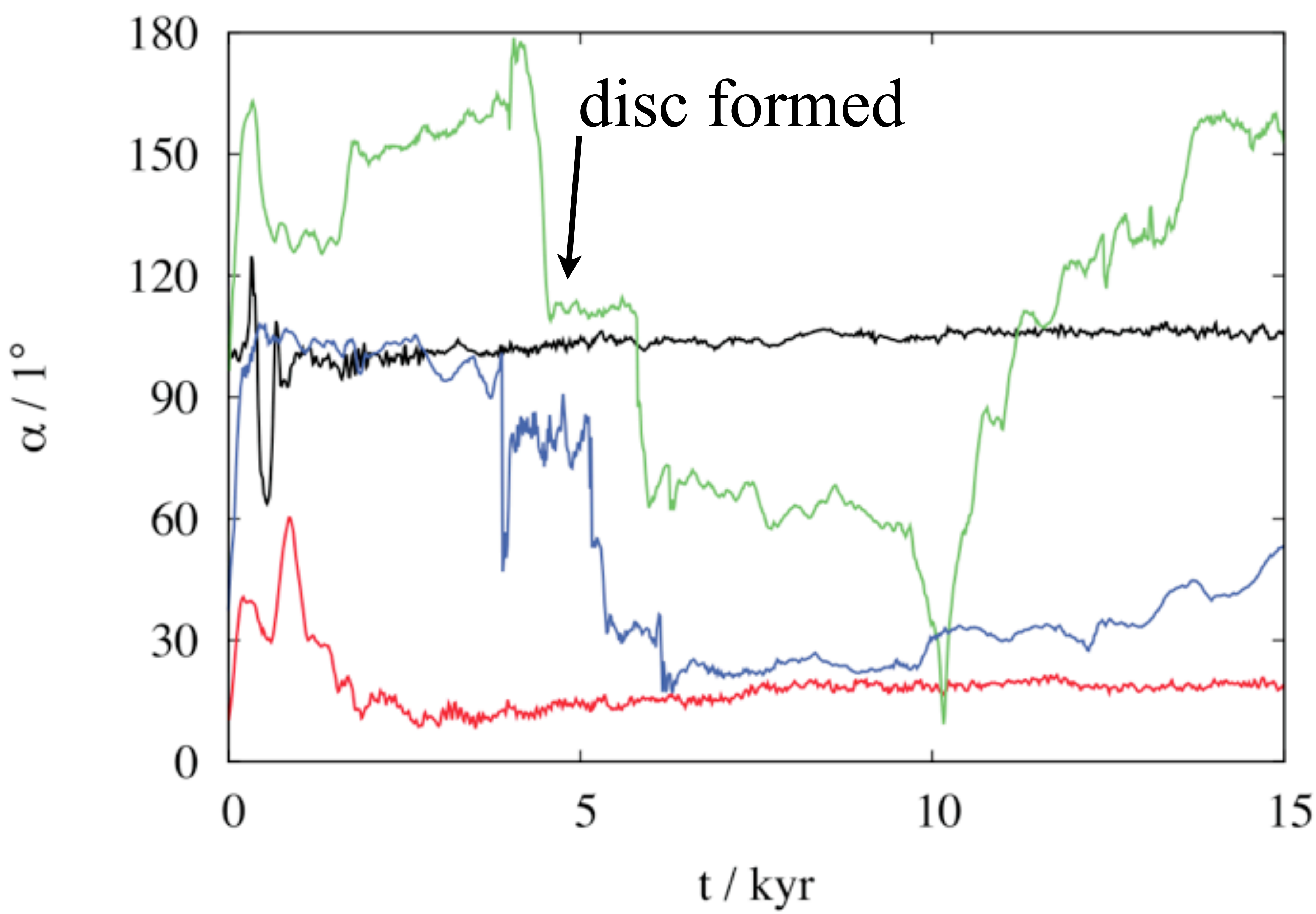


Collapse of Turbulent Cores

rotation vs. magnetic field orientation

$\Longrightarrow$ inclined rotation helps to form discs?

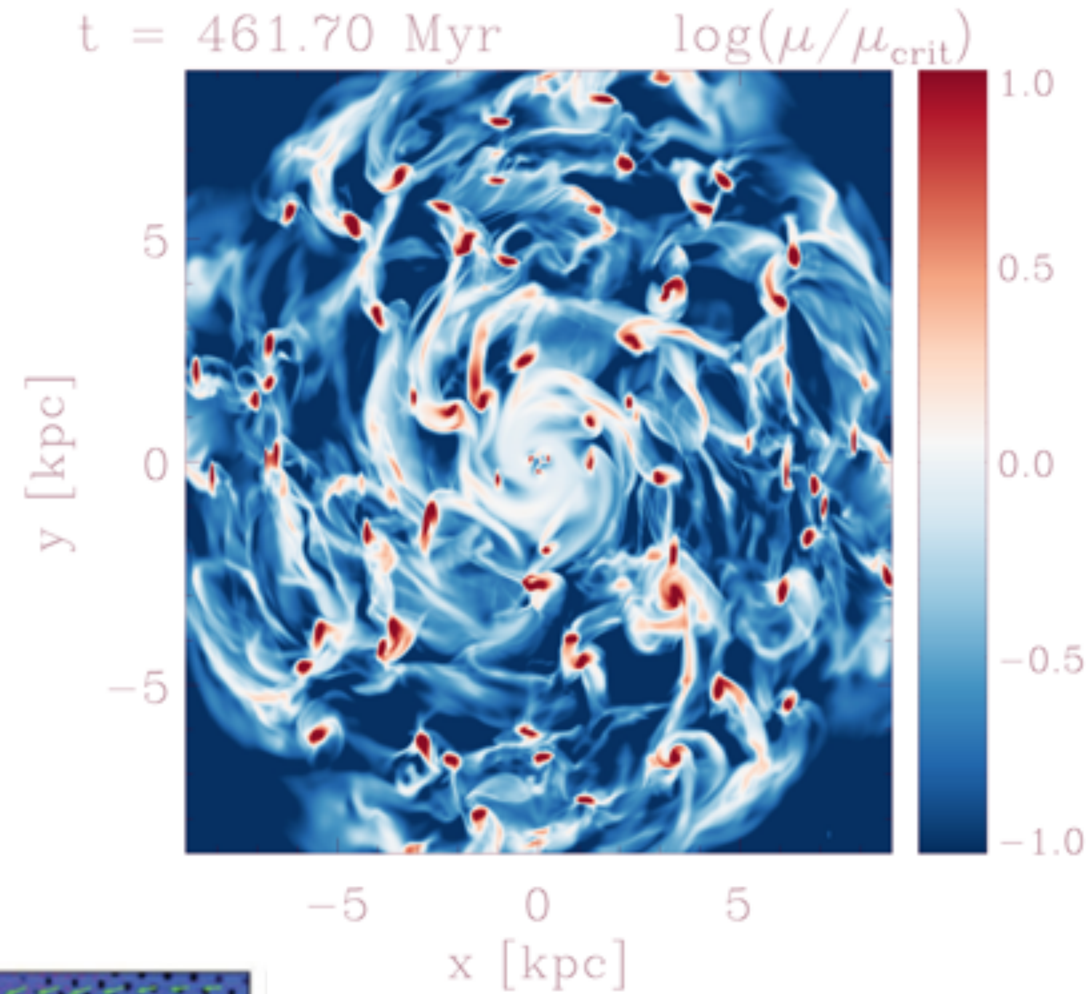
(*Hennbelle & Ciardi* 2009, *Joos et al.* 2012)

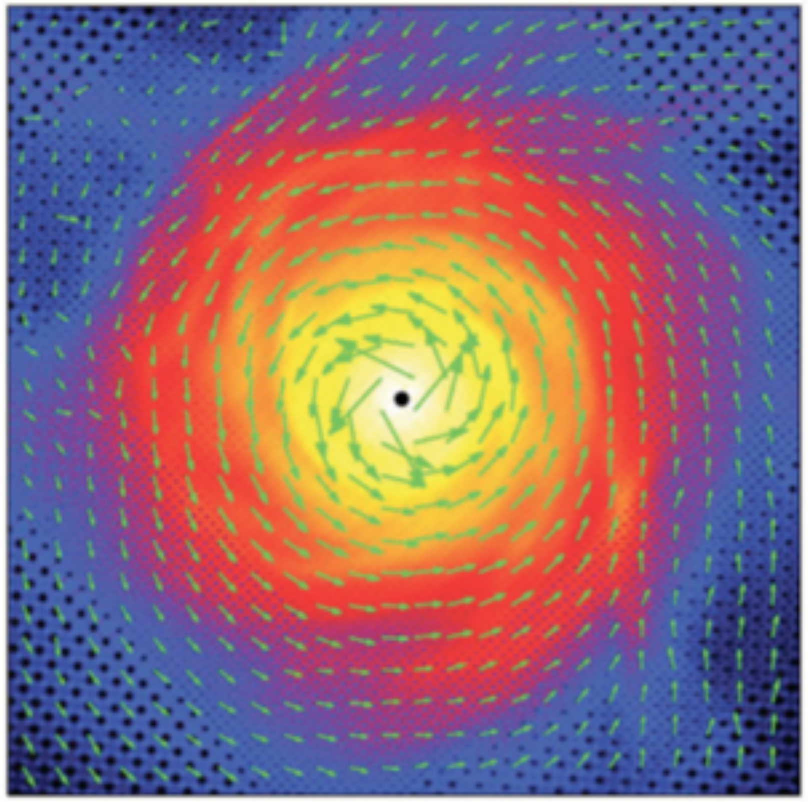


$\Longrightarrow$ but no large scale magnetic field component

Summary

- Magnetic fields have a large impact on the ISM dynamics
- MFs drive GMC formation
- “turbulence” relaxes “symmetry-issues”
  $\Longrightarrow$ e.g. no magnetic braking catastrophe,
  $\Longrightarrow$ no binary/ fragmentation crisis





Simulations of colliding flows

with random component: $B_x = 3\mu G + \delta b = 3\mu G$

face-on view

Numerical Method

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\mathbf{v}\,\rho) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B}) + \nabla p_* = -\rho \mathbf{g}$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\mathbf{v}\,(\rho E + p_*) - \mathbf{B}\,(\mathbf{v}\cdot\mathbf{B})) = \rho \mathbf{g}\cdot\mathbf{v} + \Gamma - \Lambda$$

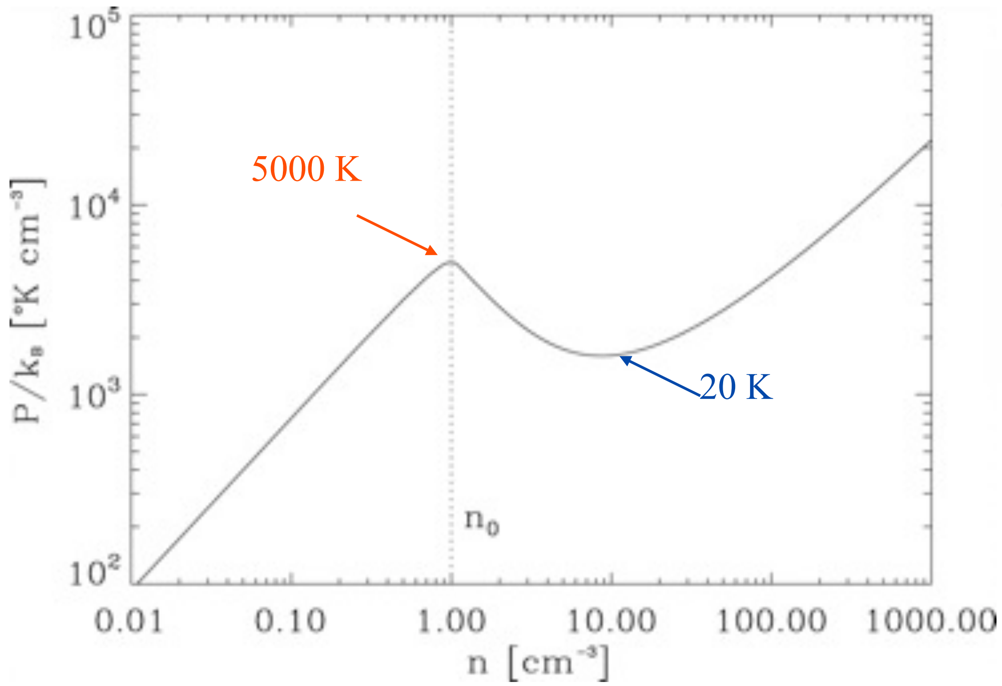
$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}) = 0$$

$$E = \frac{1}{2}v^2 + \varepsilon + \frac{1}{2}\frac{B^2}{\rho},$$

$$p_* = p + \frac{B^2}{2},$$

$$p = (\gamma - 1)\,\rho\epsilon$$

$$\mathbf{g} = -\nabla\Phi \qquad \Delta\Phi = 4\pi G\rho$$



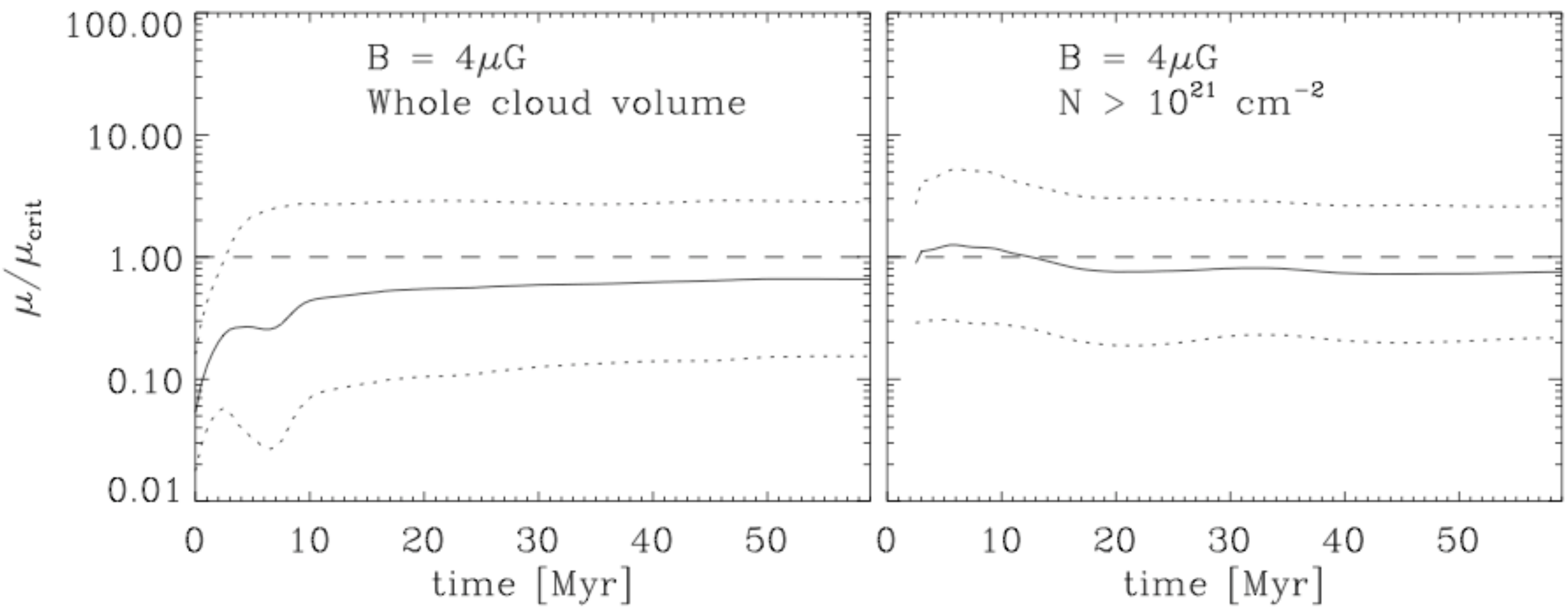
$$\Gamma = 2.0\times10^{-26}\ \mathrm{erg\,s^{-1}},$$

$$\frac{\Lambda(T)}{\Gamma} = 10^7 \exp\left(\frac{-1.184\times10^5}{T+1000}\right) + 1.4\times10^{-2}\sqrt{T}\exp\left(\frac{-92}{T}\right)\ \mathrm{cm}^3$$

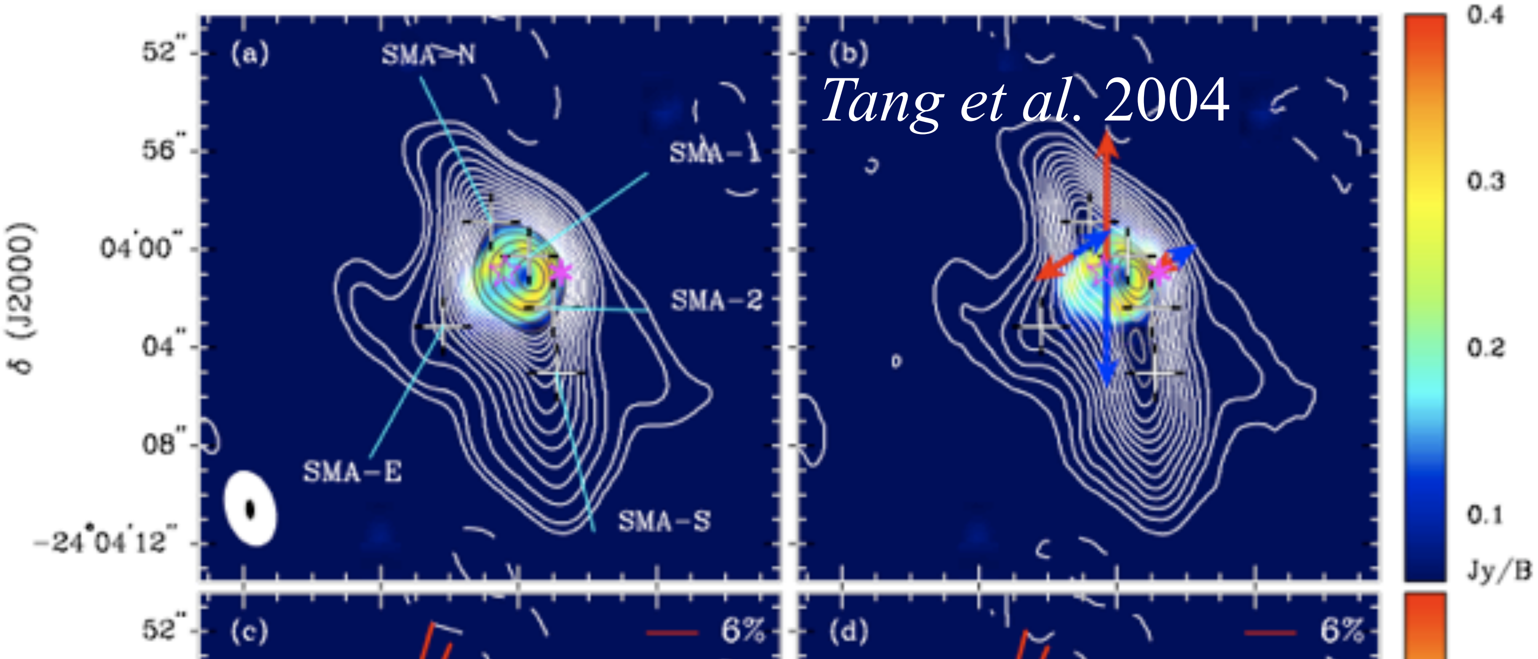
Koyama & Inutsuka '02

Ideal MHD + self-gravity + ideal gas + heating & cooling

Molecular Cloud Evolution

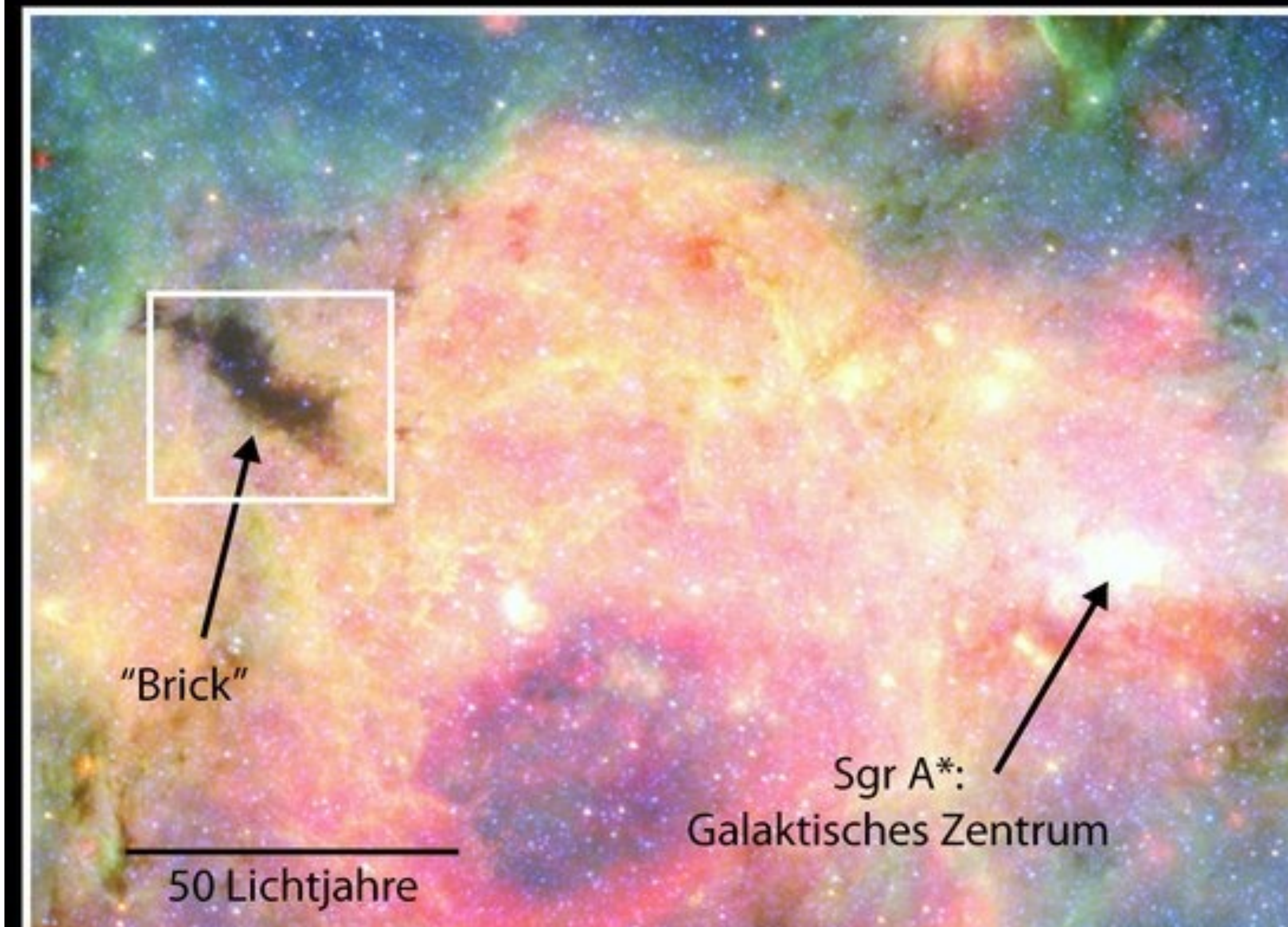


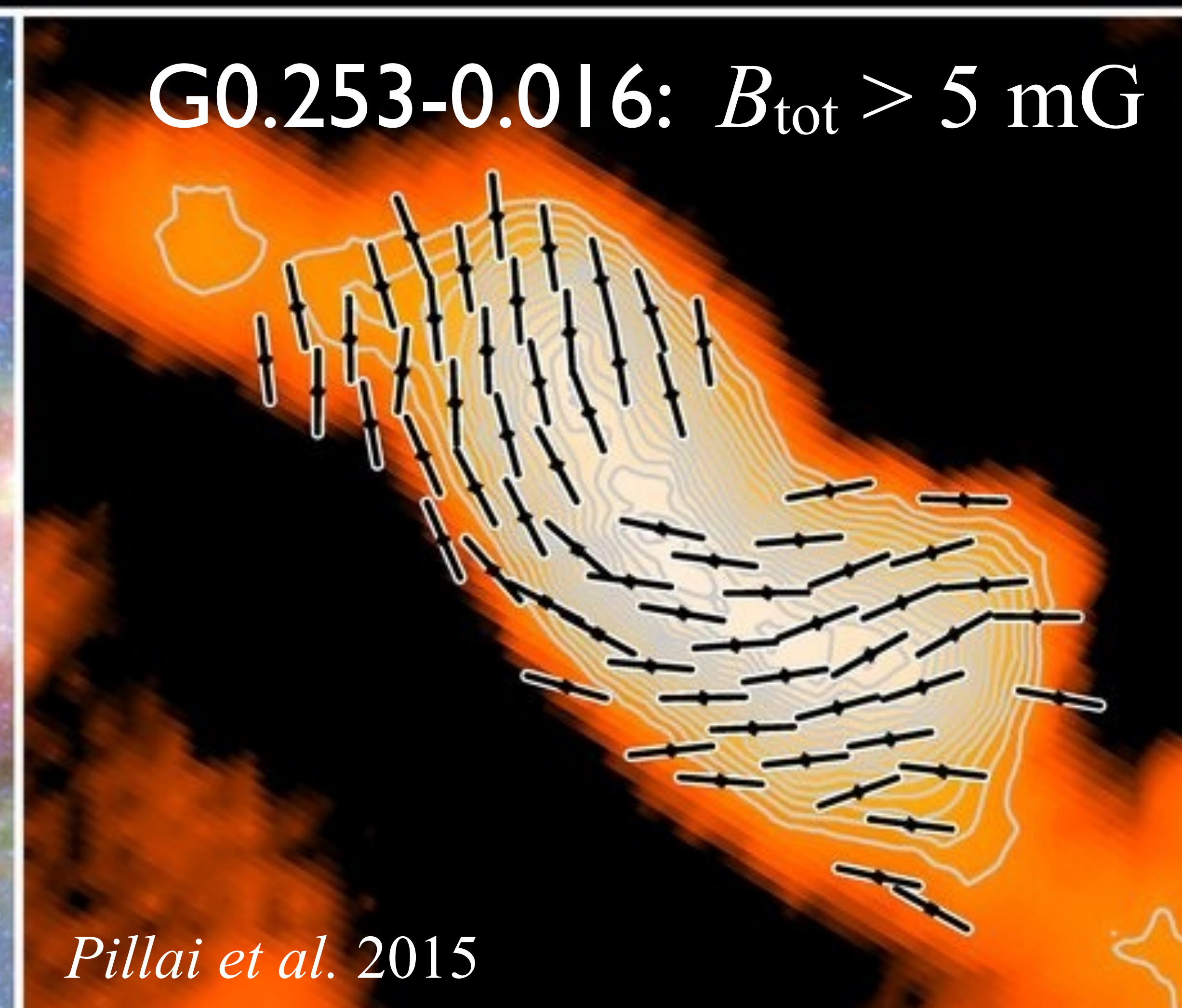
Magnetic fields during Massive Star Formation



e.g. Massive star forming region G5.89-0.39 UHII

$B \sim$ 2-3 mG



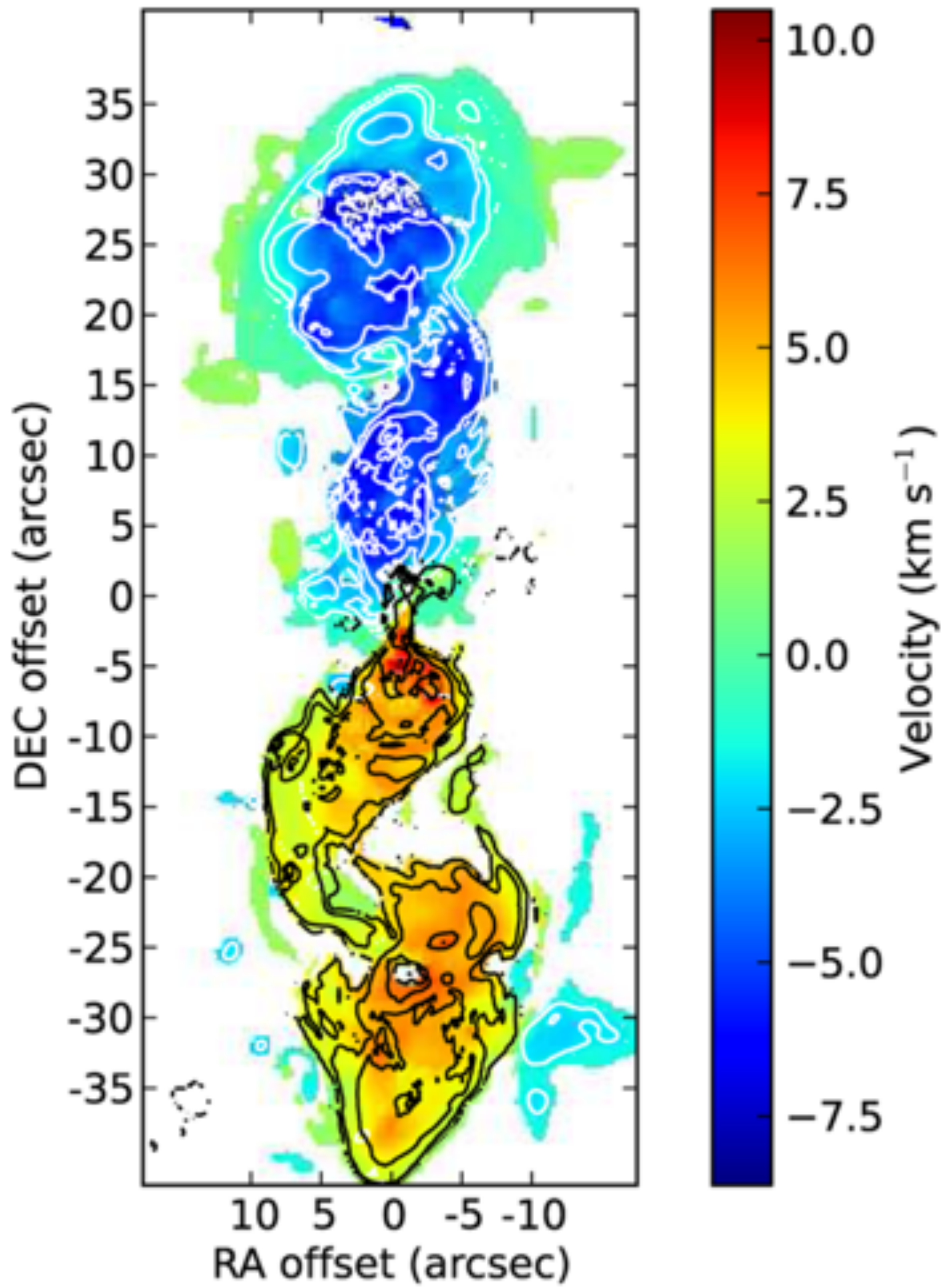


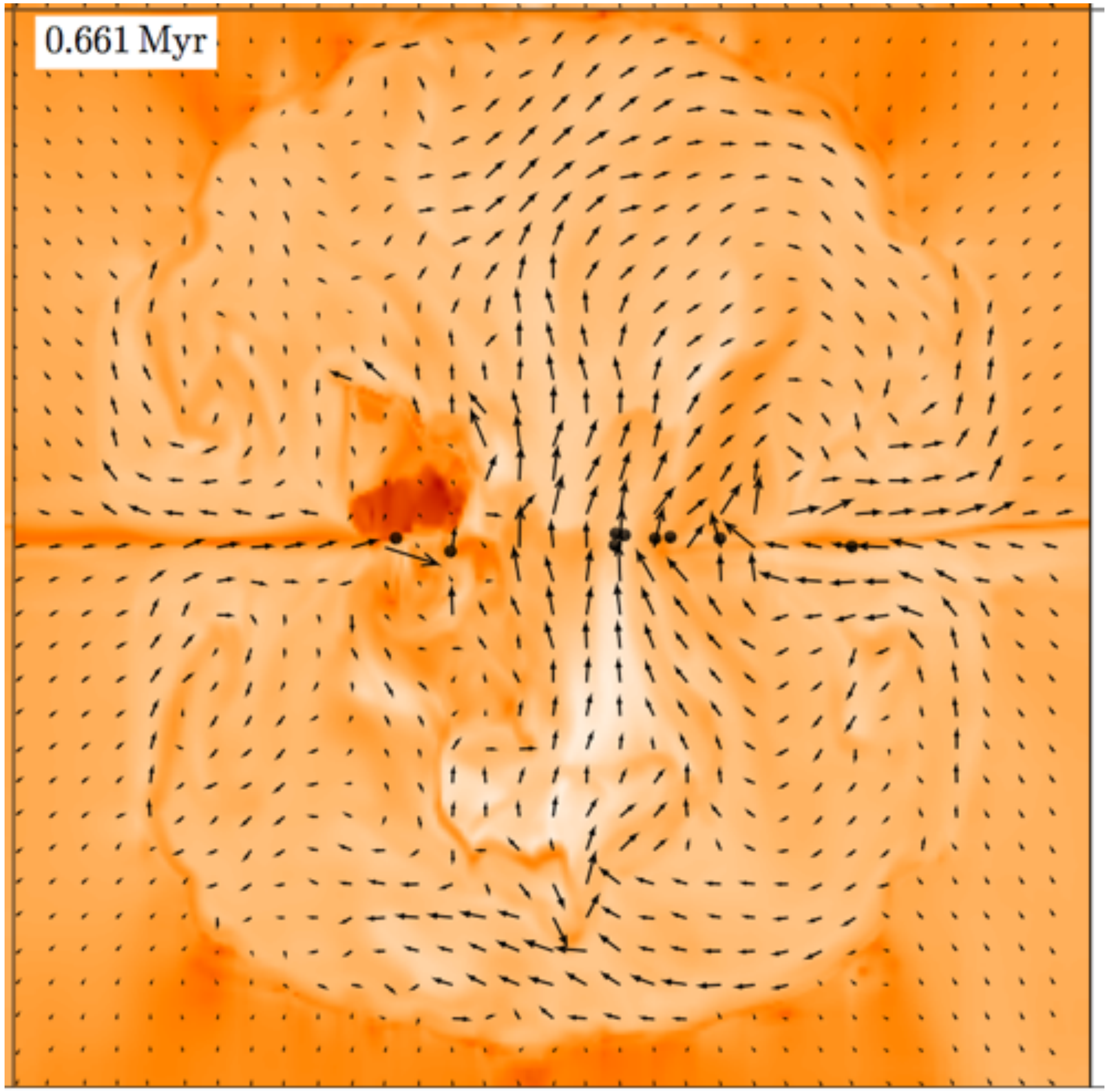
Magnetic fields during Massive Star Formation

influence of magnetic fields:

magnetically launched outflows around high mass YSOs

Peters et al. 2011

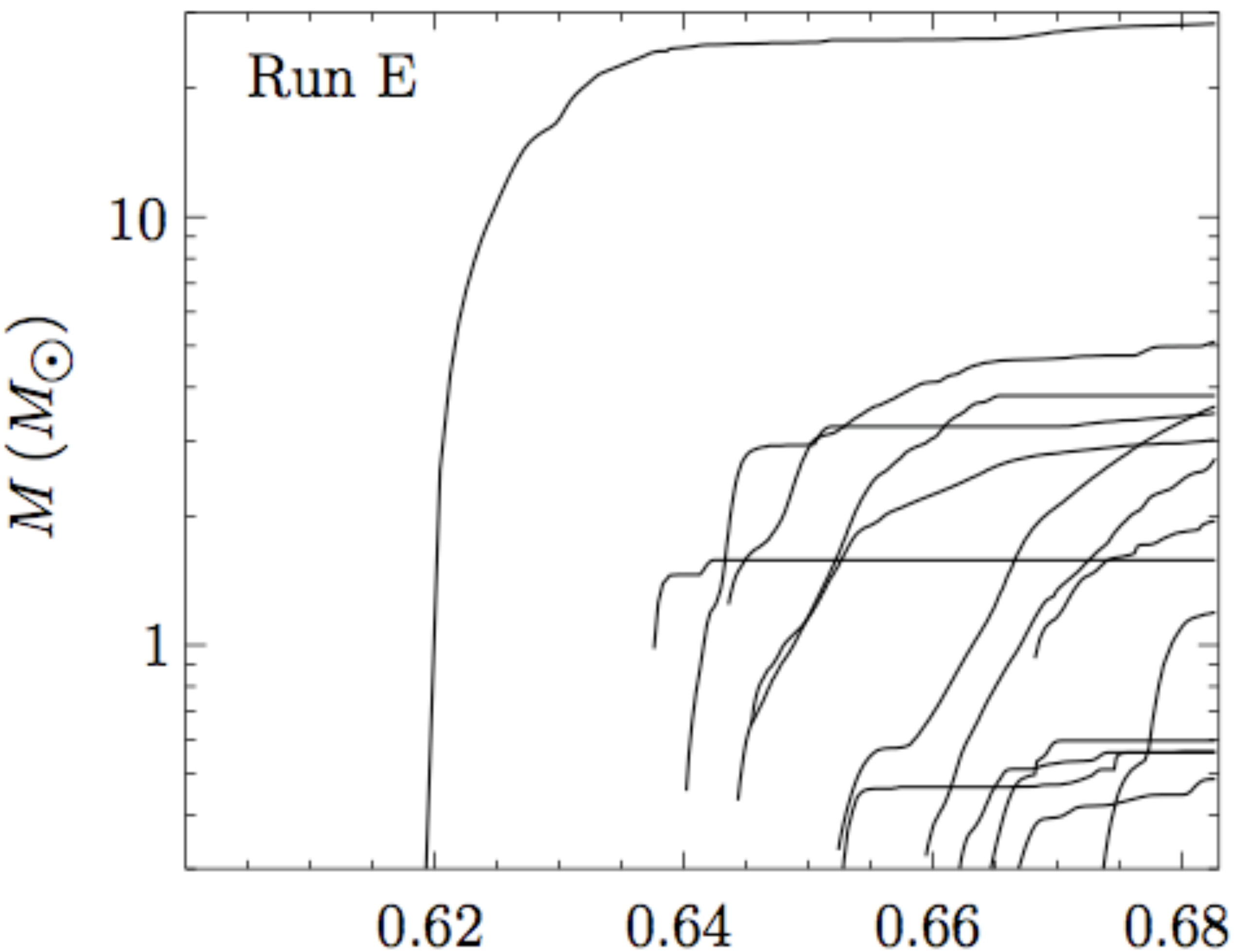




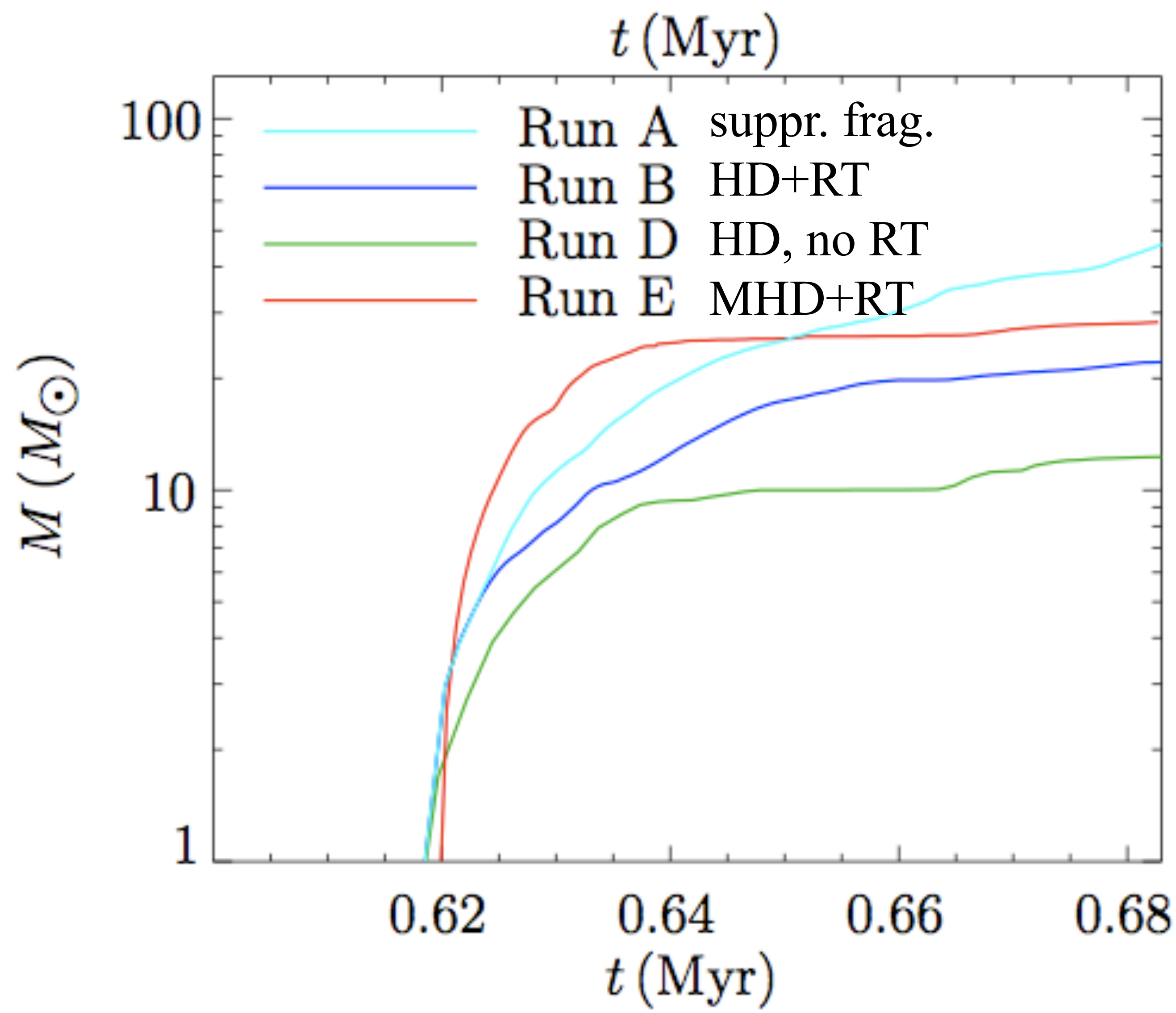
Peters, Klaassen, Seifried, RB, Klessen 2014

Massive Star Formation: Magnetic fields

The magnetised case: Run E



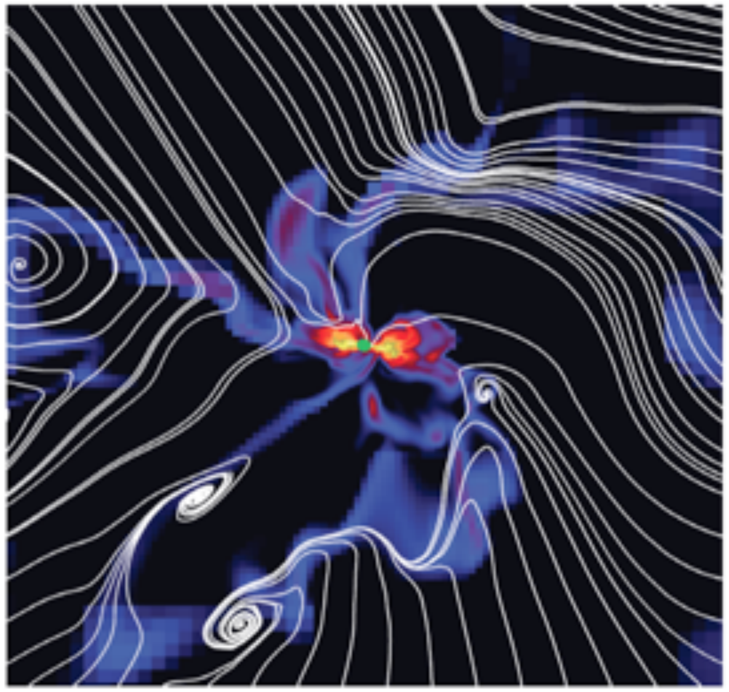
Peters et al. 2011



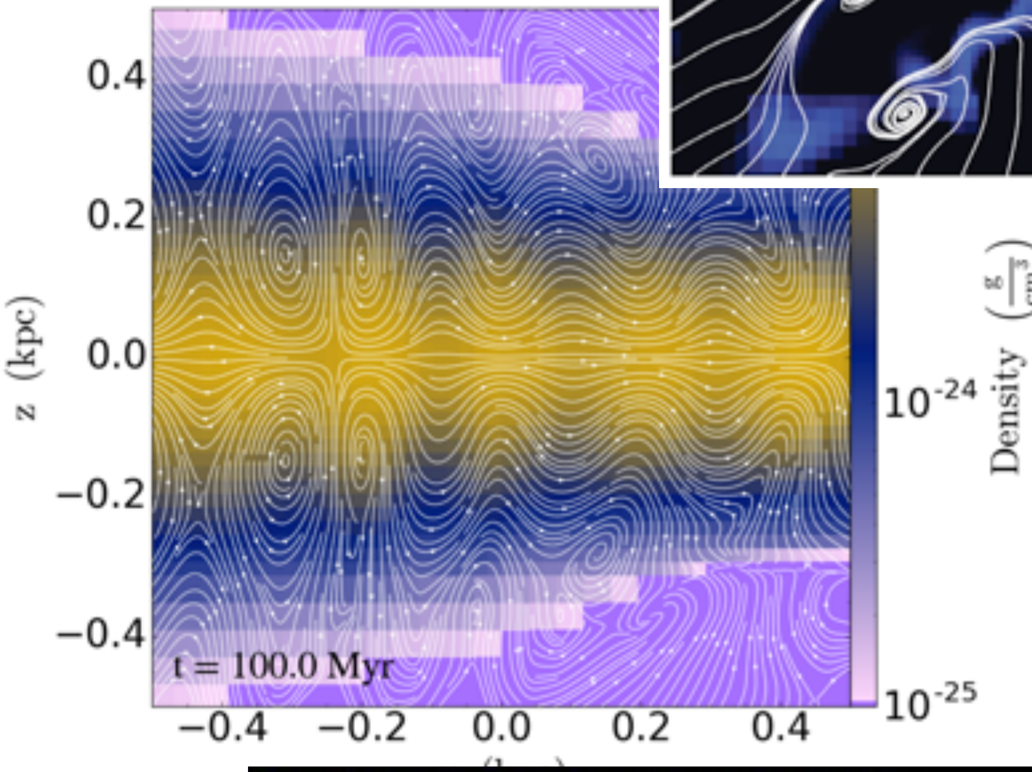
- weakening of fragmentation
- most massive star is *more* massive compared to hydro-case
- but: *Fragmentation Induced Starvation* is still 'active'

Conclusions

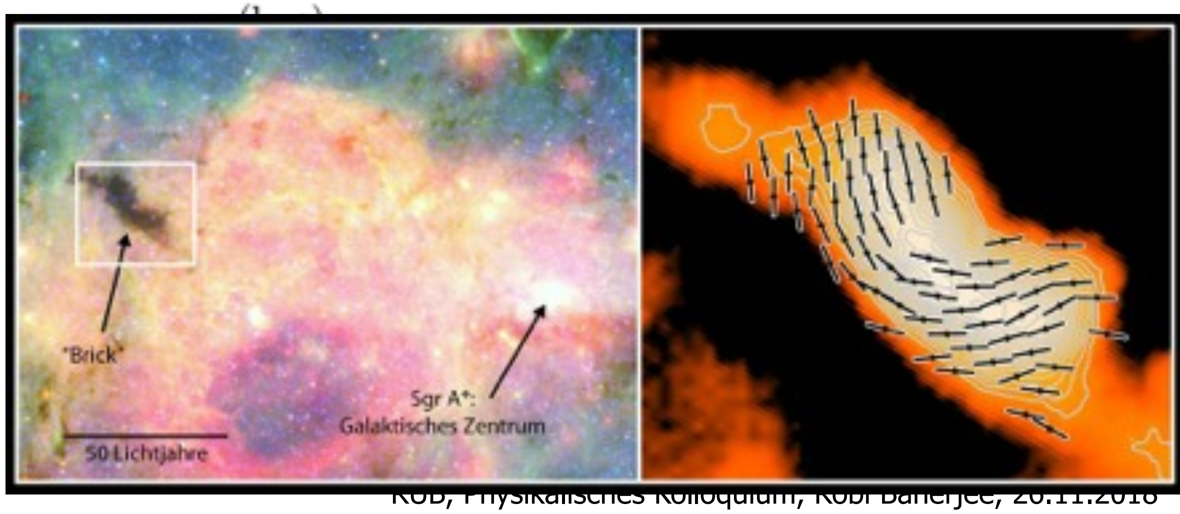
- Don't ignore **magnetic fields** !



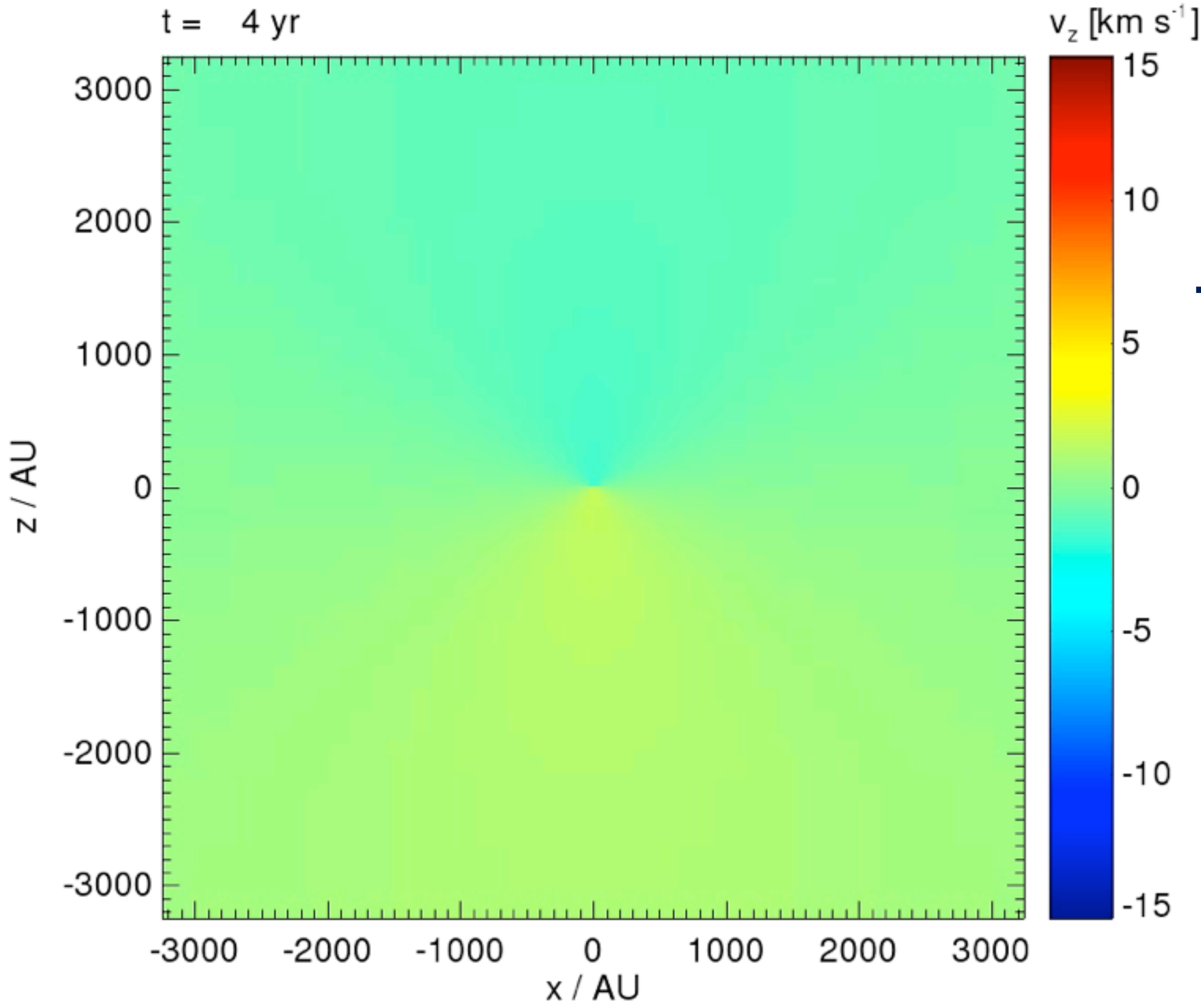
- Parker Instability: viable mechanism to generate super-critical clouds



- High mass stars:
    - MFs help to generate high mass clouds & clumps
    - MFs reduce fragmentation

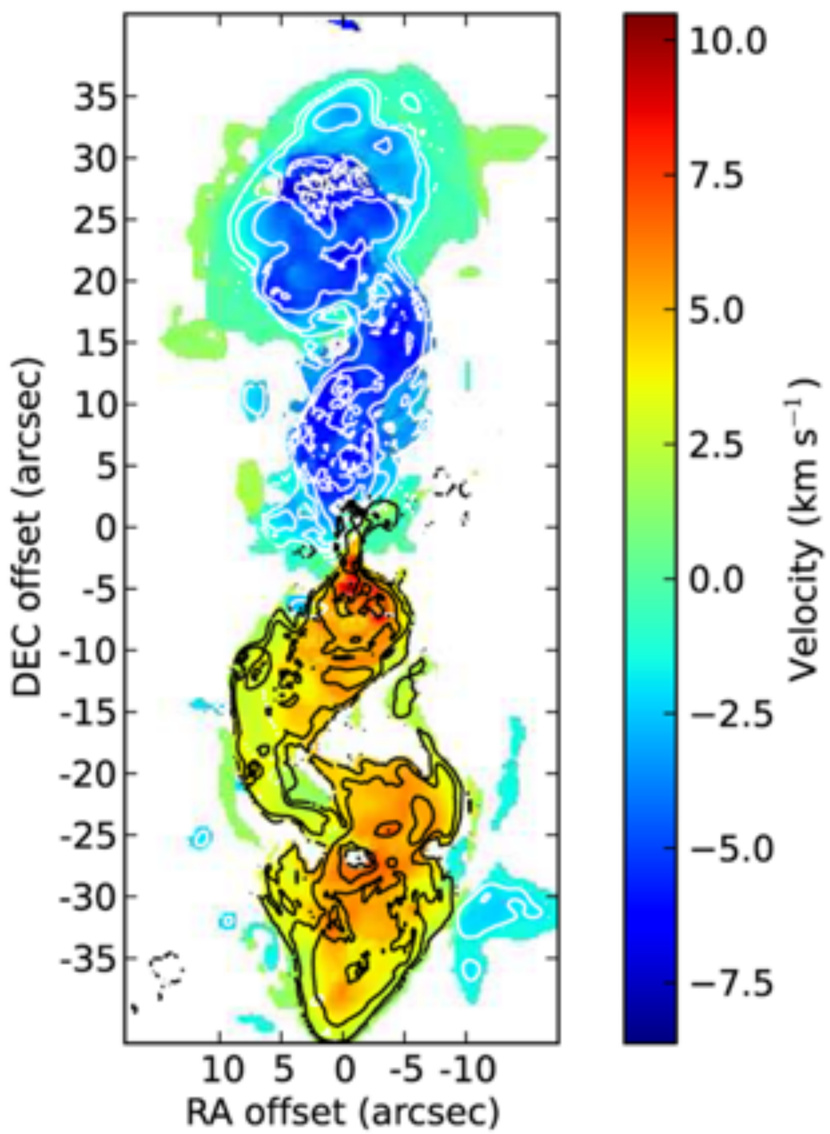


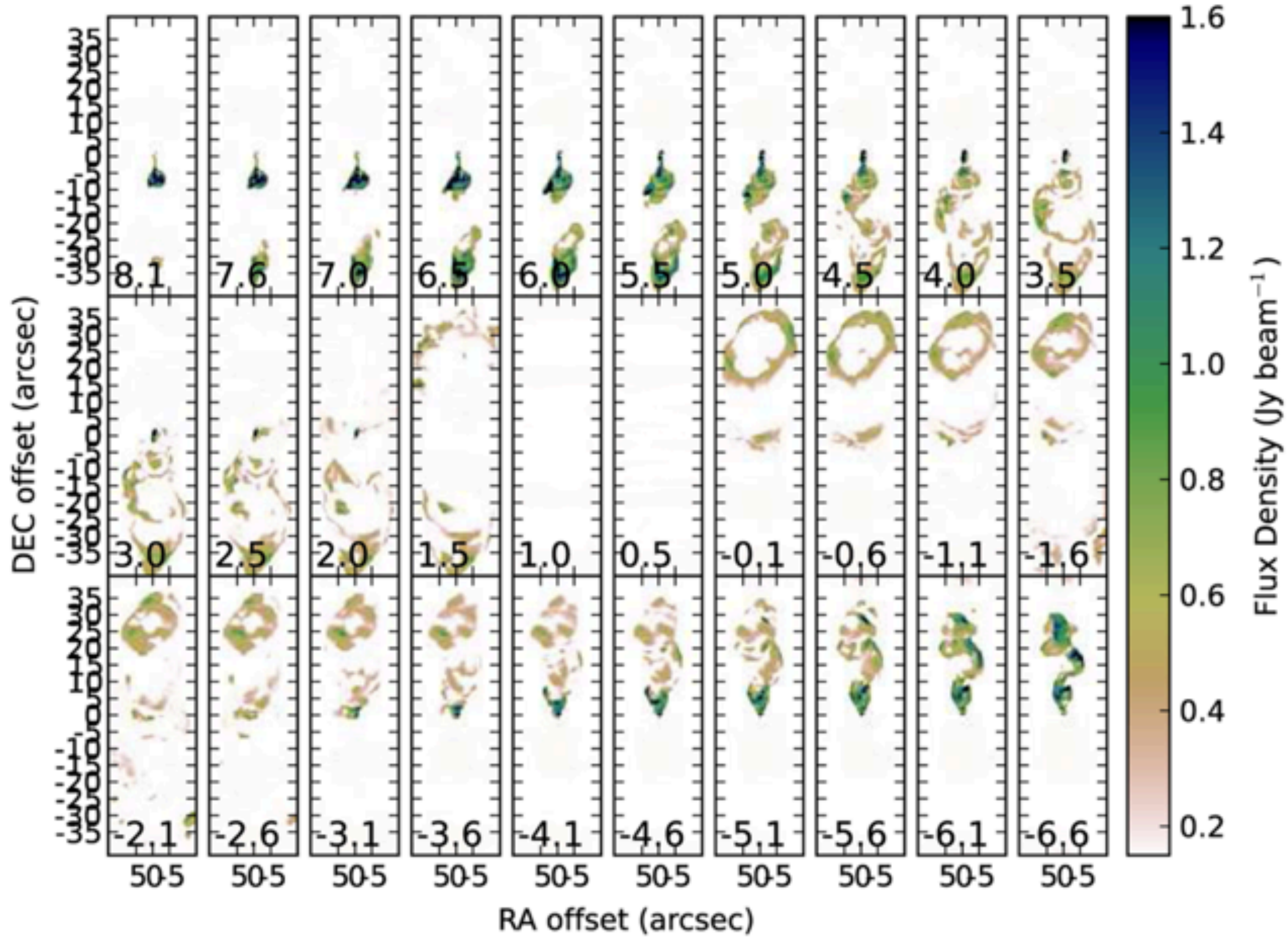
Magnetically driven outflows



→ disc winds expected also around massive protostars before ionization sets in

Magnetically driven outflows



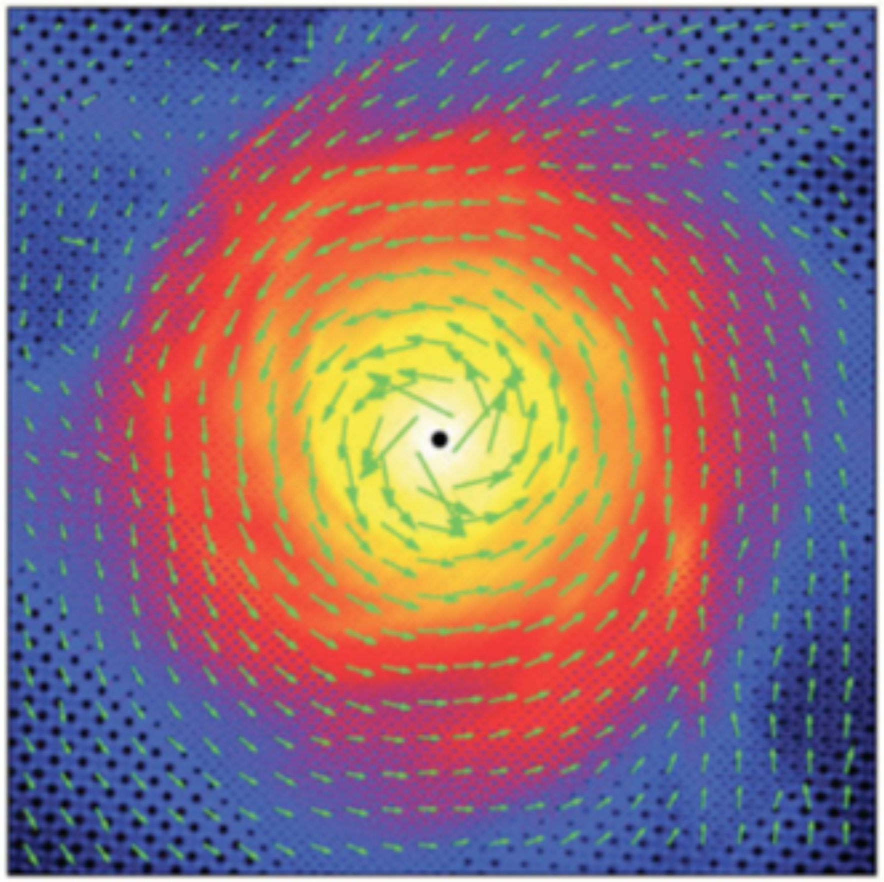


Peters, Klaassen, Seifried, RB, Klessen 2014

⟹ Helical structure similar to outflow around the A-type star HD 163296 (D = 122 pc)

Conclusions

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