hamburger sternwarte

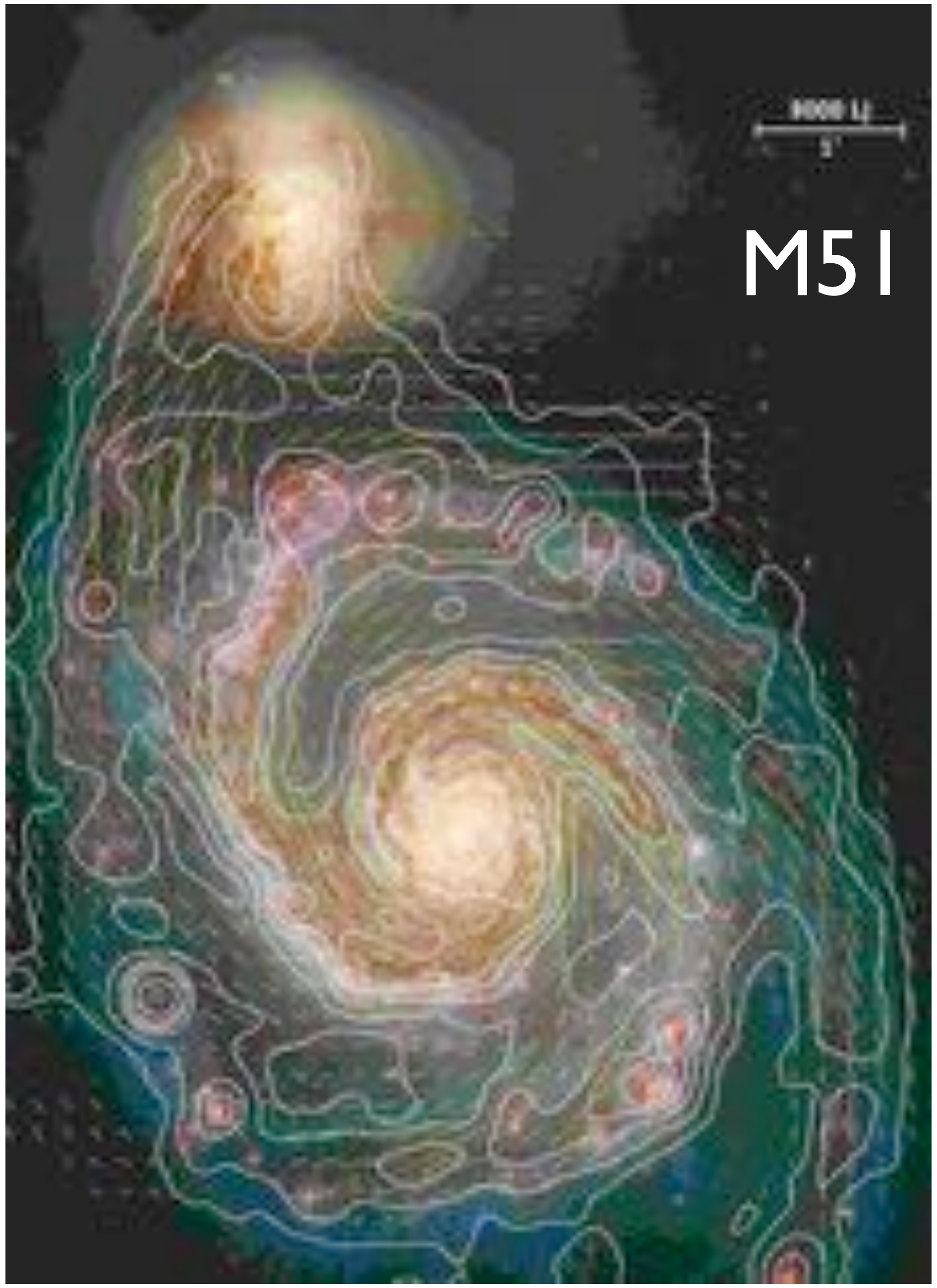
Magnetic Fields
&
High Mass Star Formation

Robi Banerjee
Hamburger Sternwarte

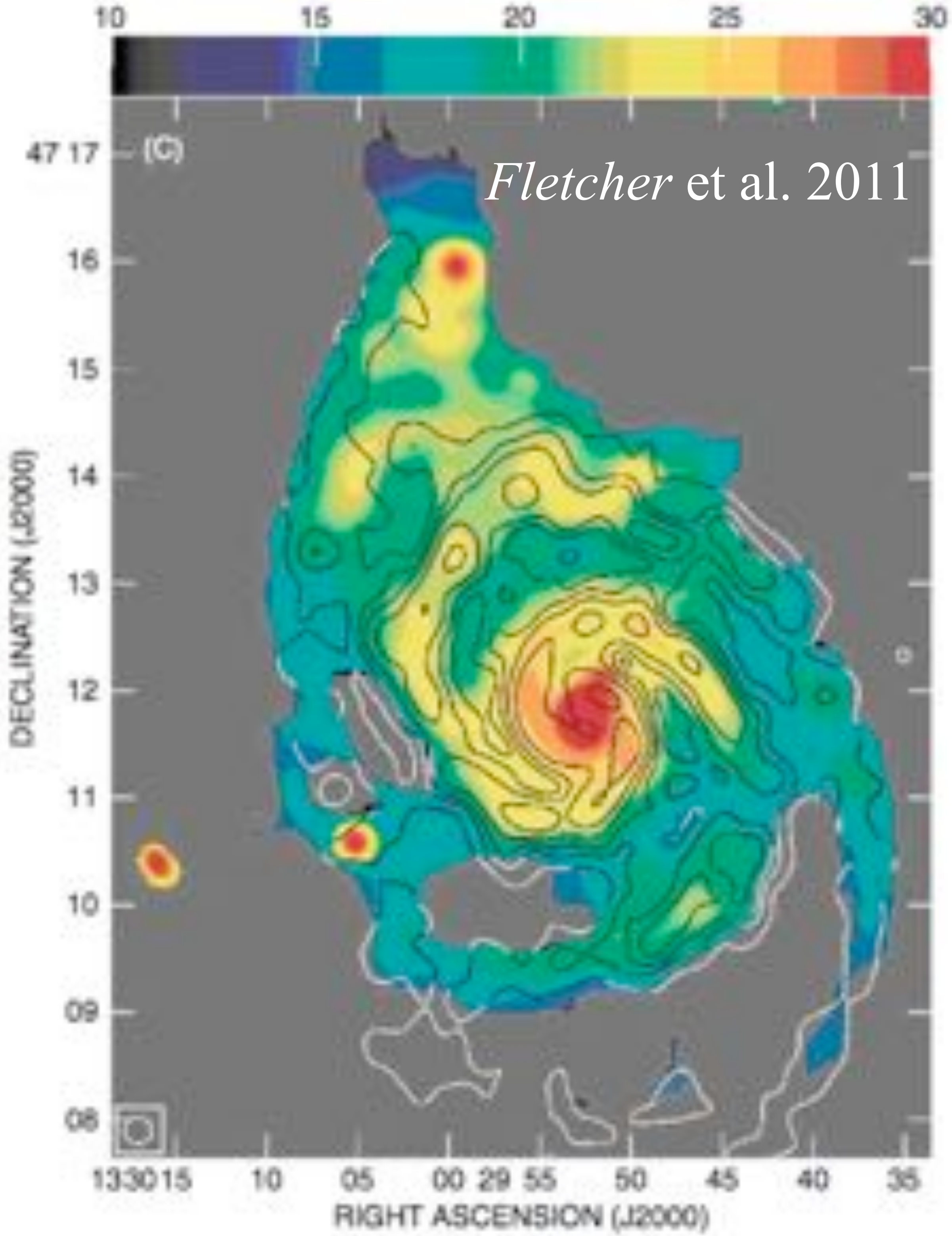
based on work by: **Bastian Körtgen** (HS), Daniel Seifried (Cologne), Thomas Peters (MPA)

co-workers: Ralph Pudritz (McMaster, Canada), Enrique Vazquez-Semadeni (UNAM), Wolfram Schmidt (HS)

Magnetic Fields in the ISM

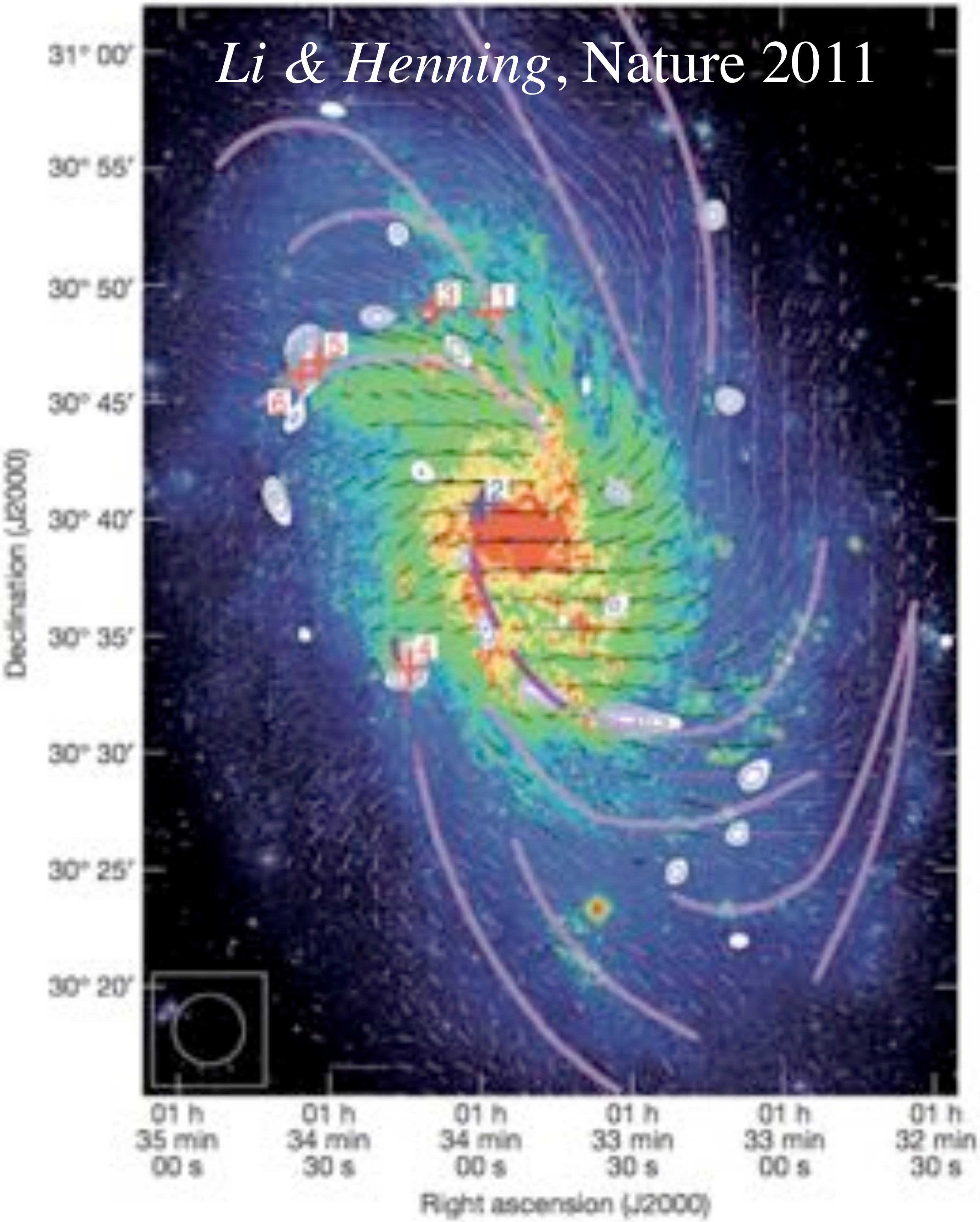


The ISM is *highly* magnetised: $E_{mag} \sim E_{therm}$



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

$\Longrightarrow$ sub Alfvenic turbulence:

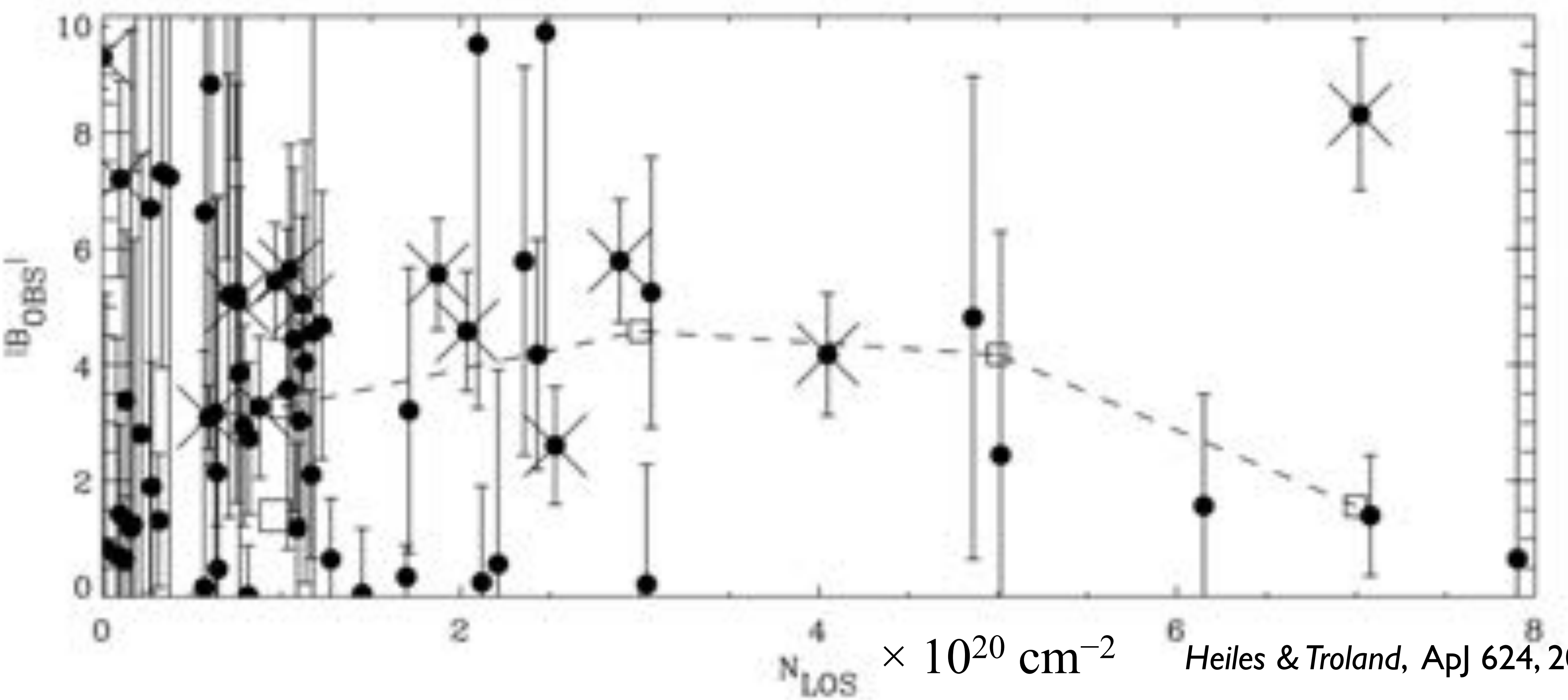
$v_{\mathrm{turb}} \lesssim v_A$

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

$\Longrightarrow$ Magnetic fields in HI clouds
(incl. warm neutral media, WNM)



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

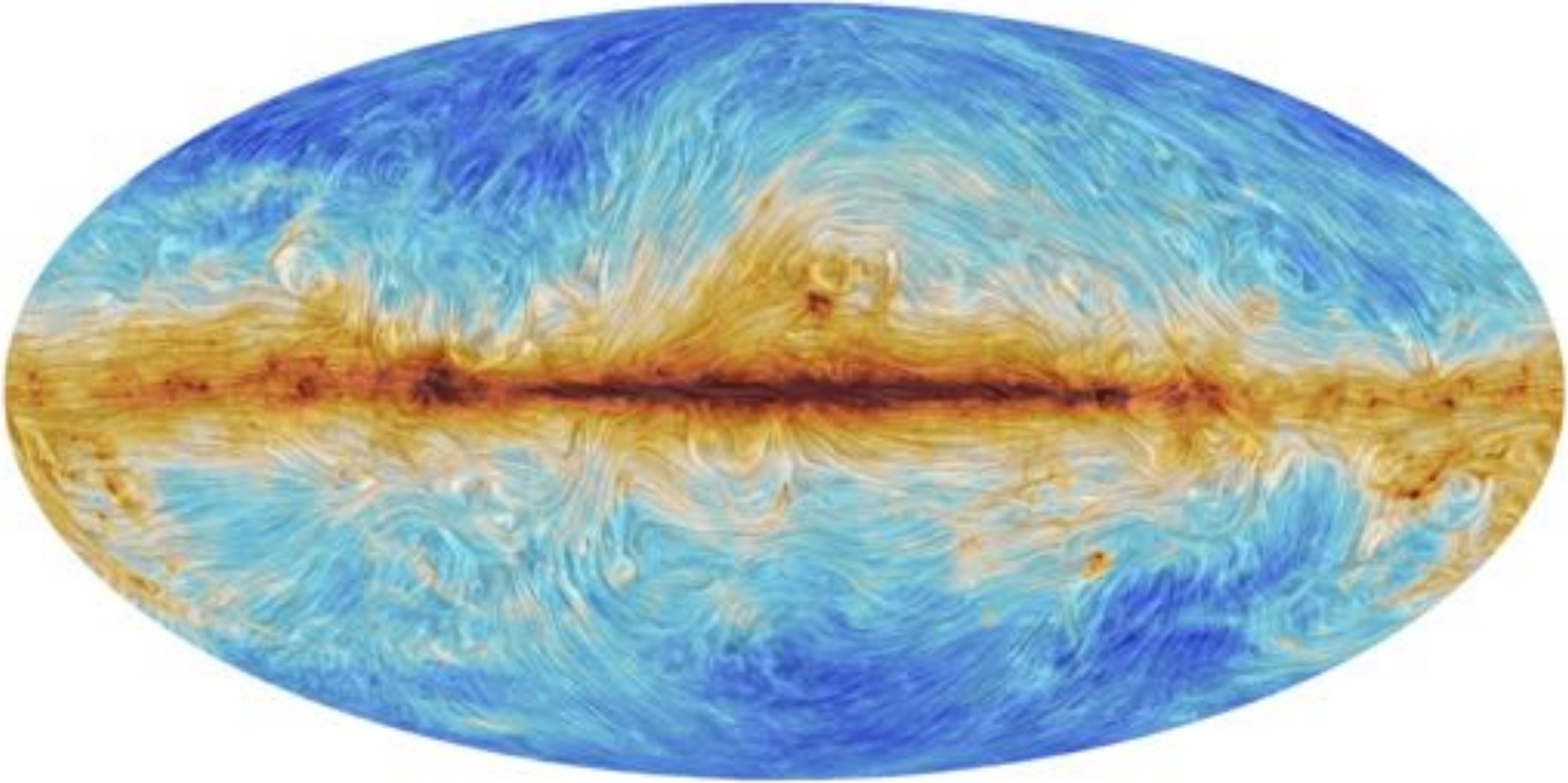
Heiles & Troland, ApJ 624, 2005

B-field from polarised Zeeman effect

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

Magnetic Fields in the ISM

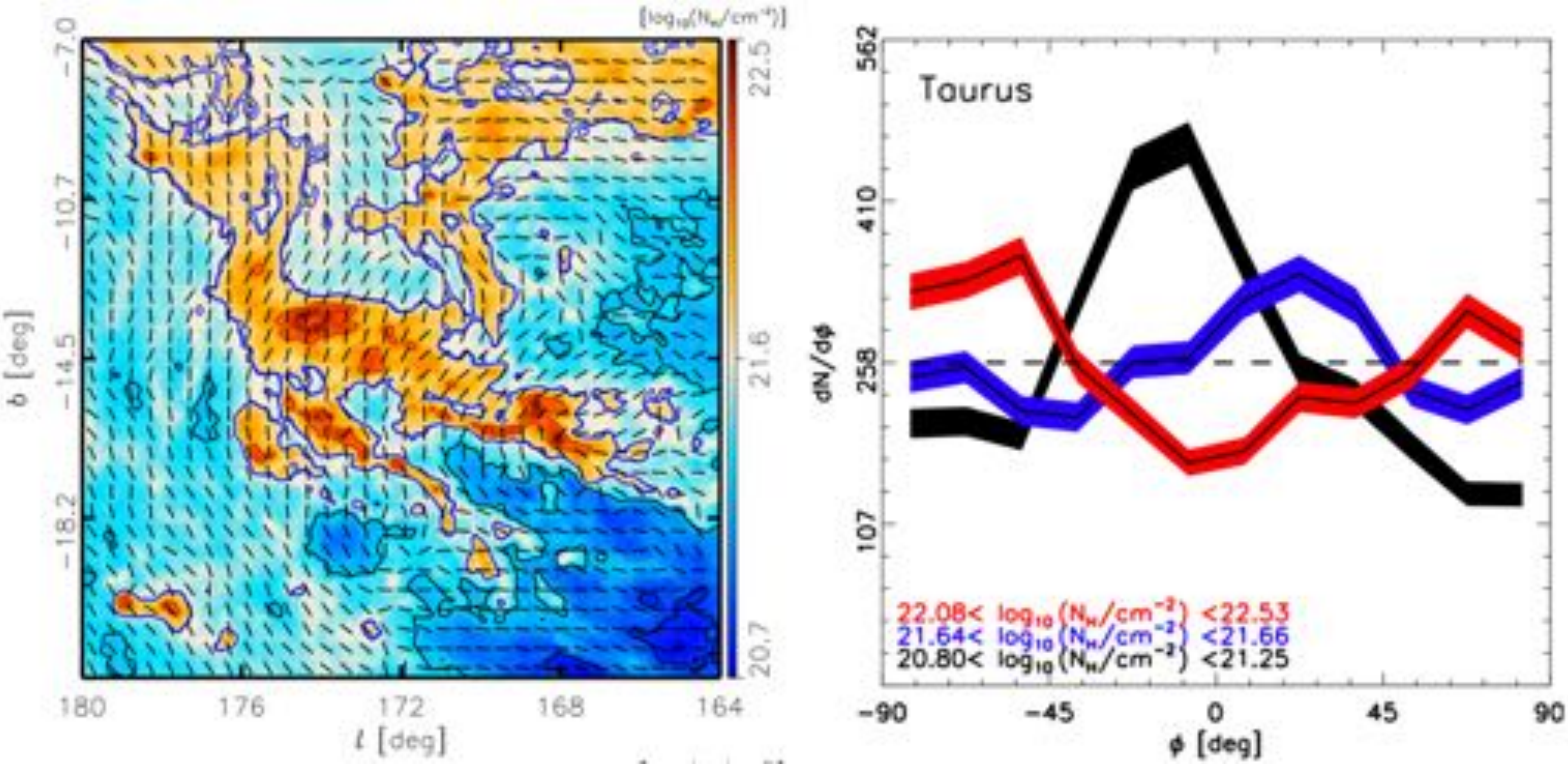
- PLANCK: magnetic field of the Milky Way from dust polarisation



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

Magnetic Fields in Molecular Clouds

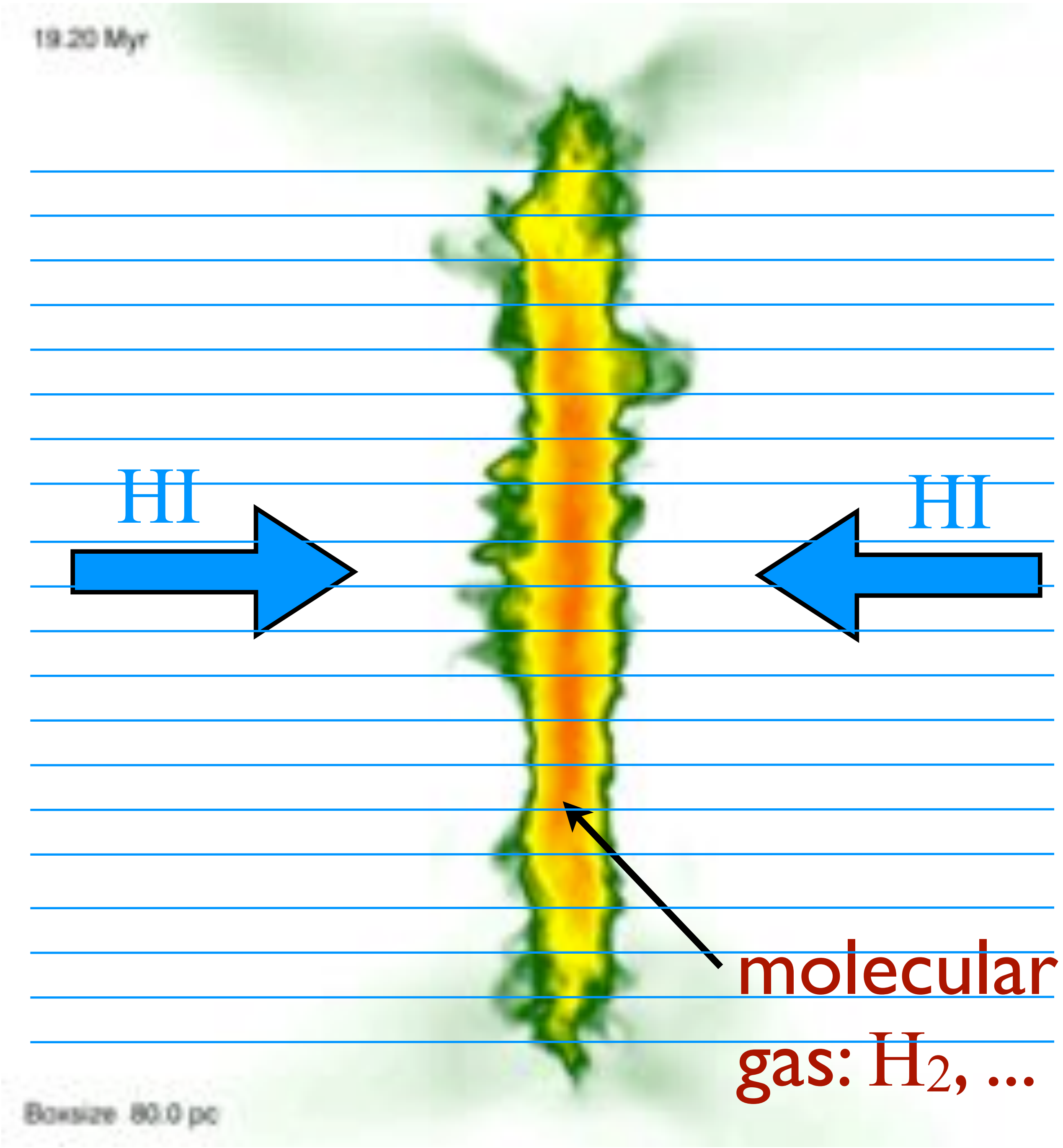
- PLANCK XXXV 2015: dust polarisation in molecular clouds



$\Longrightarrow$ magnetic fields are dynamically important

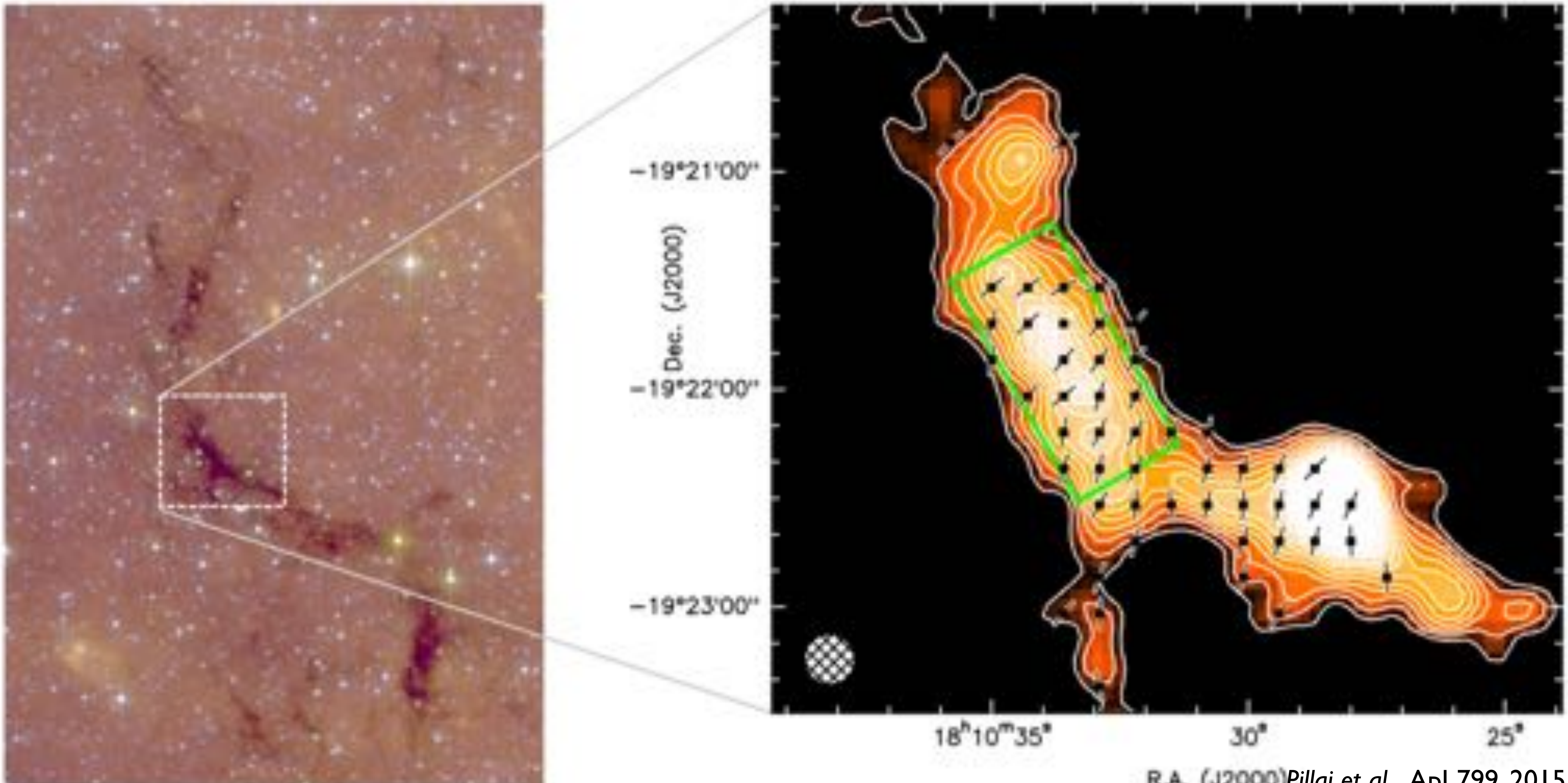
$\Longrightarrow$ by comparing with num. simulations: $B = 4 \ldots 12\ \mu G$

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

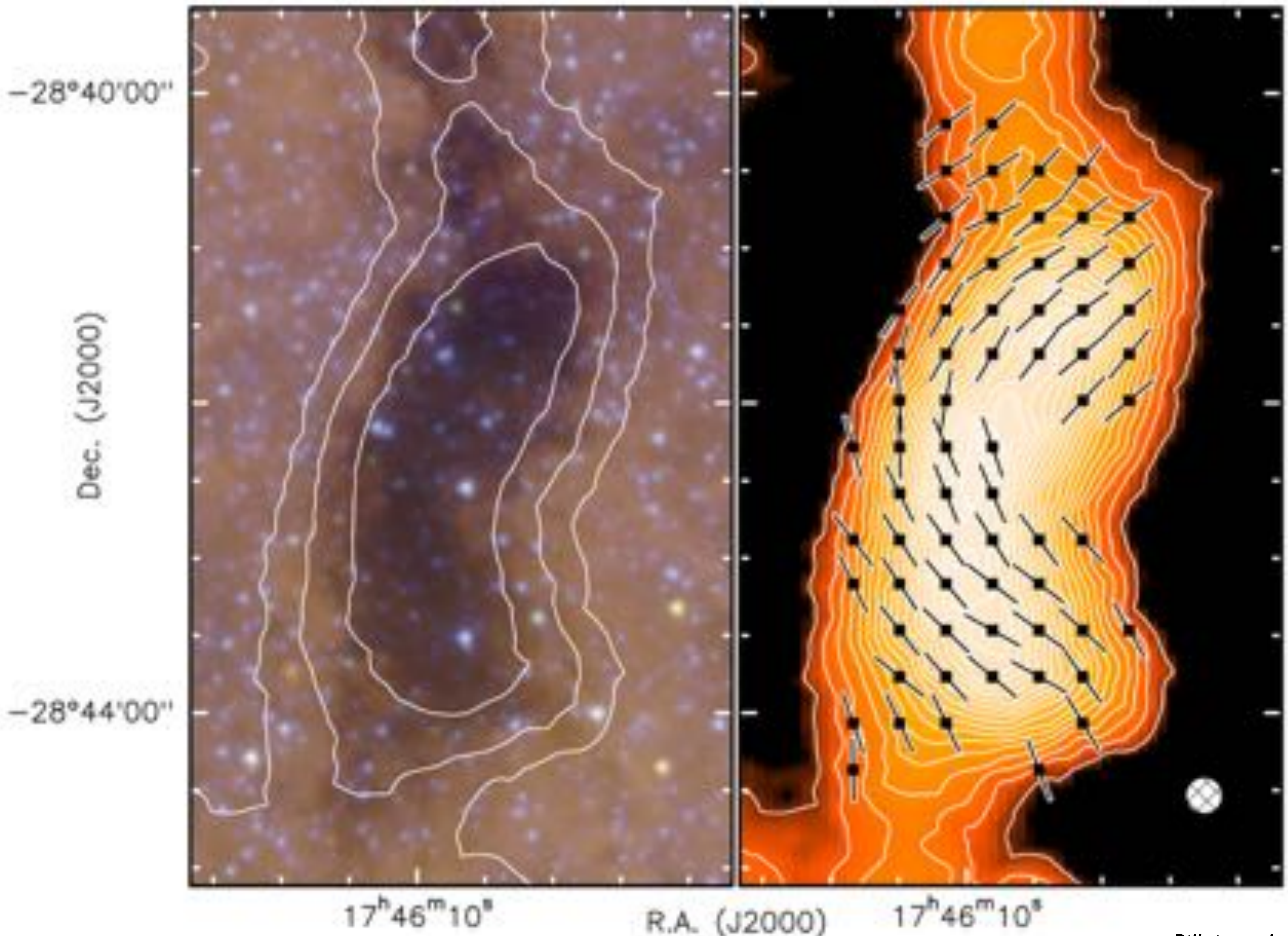


Pillai et al., ApJ 799, 2015

polarisation measurement of G11.11-0.12

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

Magnetic Fields in Molecular Clouds

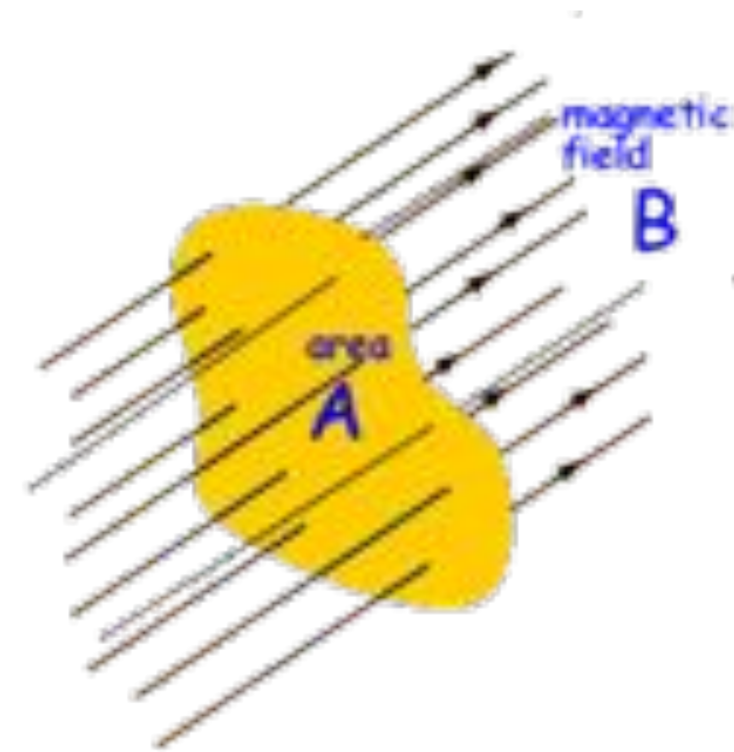


Pillai et al., ApJ 799, 2015

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

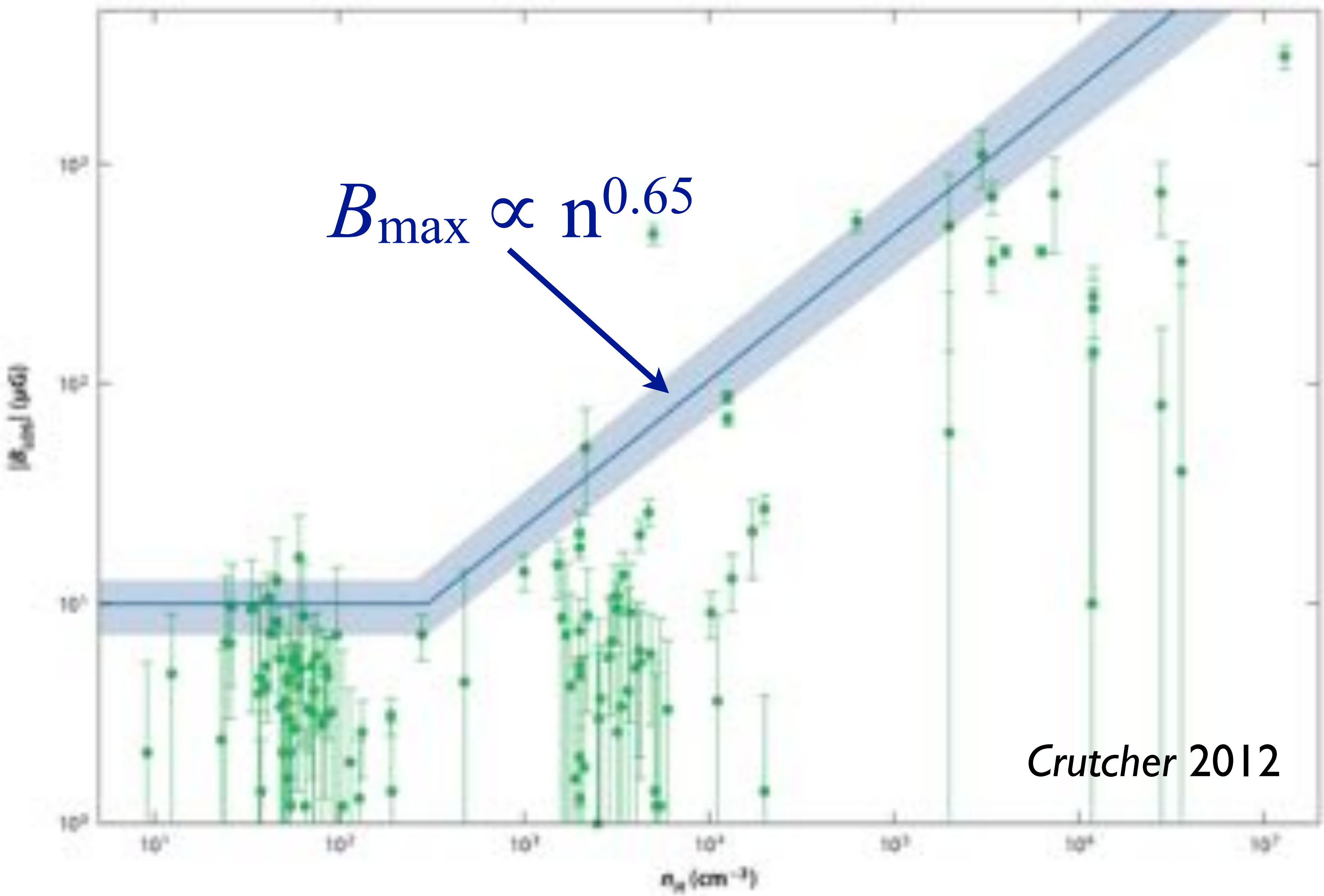
Magnetic Fields in the ISM

- stronger magnetic fields in dense regions



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

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



- spherical compression:

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

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

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

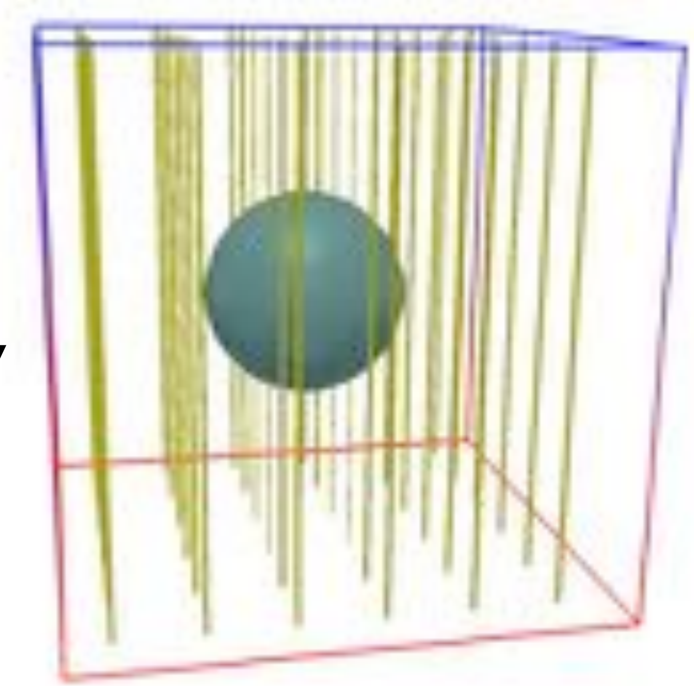
Impact of Magnetic Fields

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:

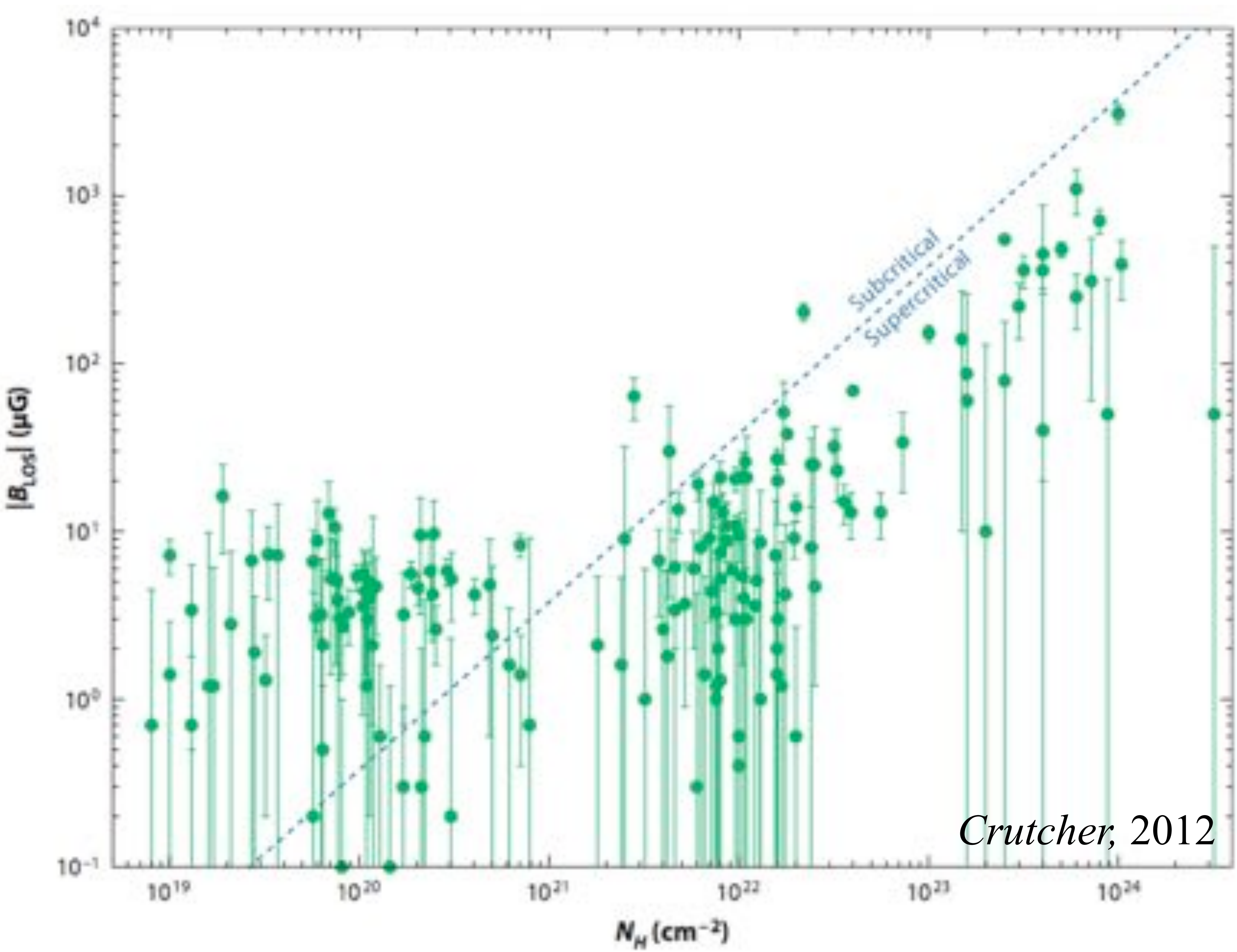
$$\mu_{\mathrm{crit}} = 0.13/\sqrt{G}$$

spherical structure
Mouschovias & Spitzer 1976

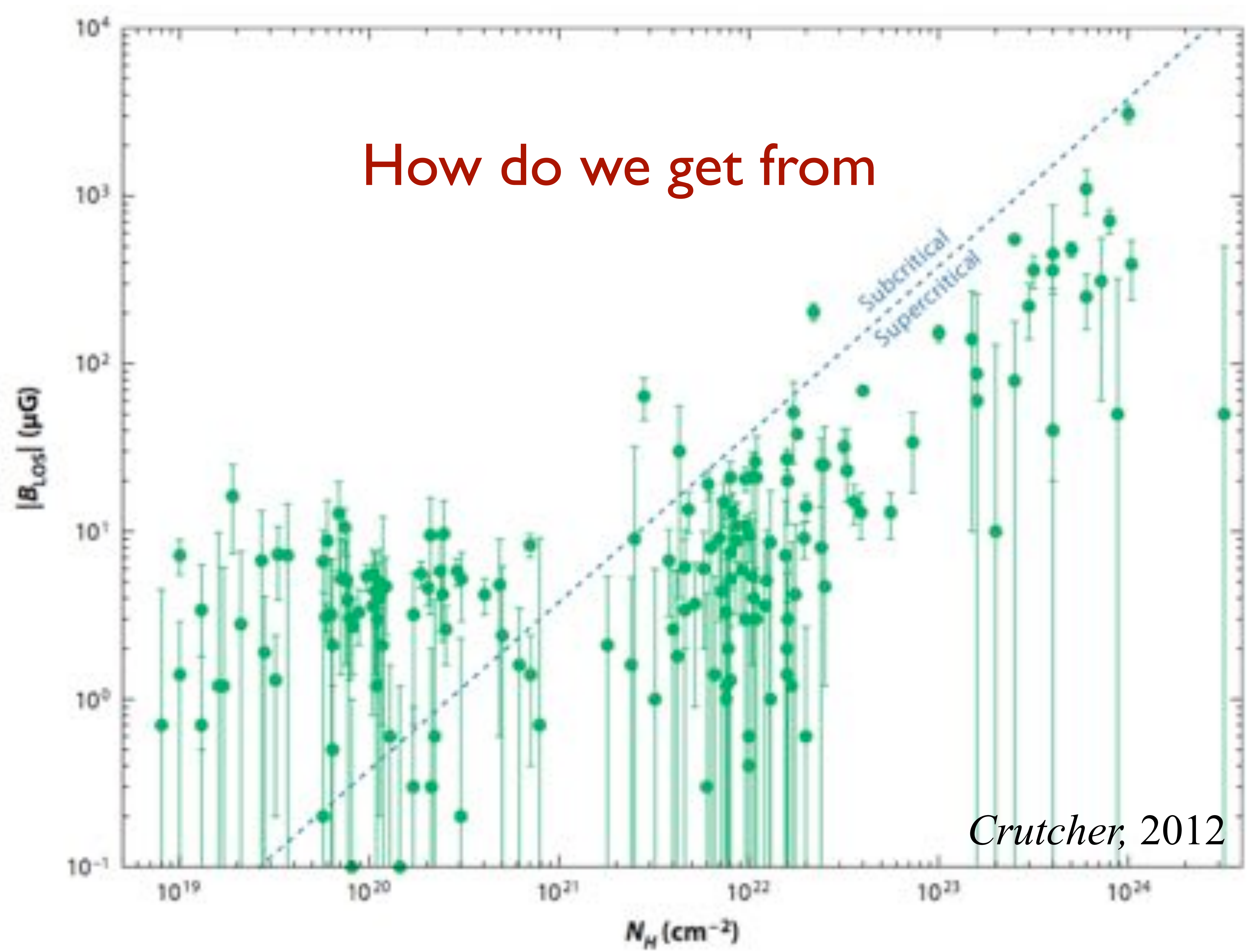
$$\mu_{\mathrm{crit}} = \frac{1}{2\pi\sqrt{G}} \approx 0.16/\sqrt{G}$$

uniform disc
Nakano & Nakamura 1978

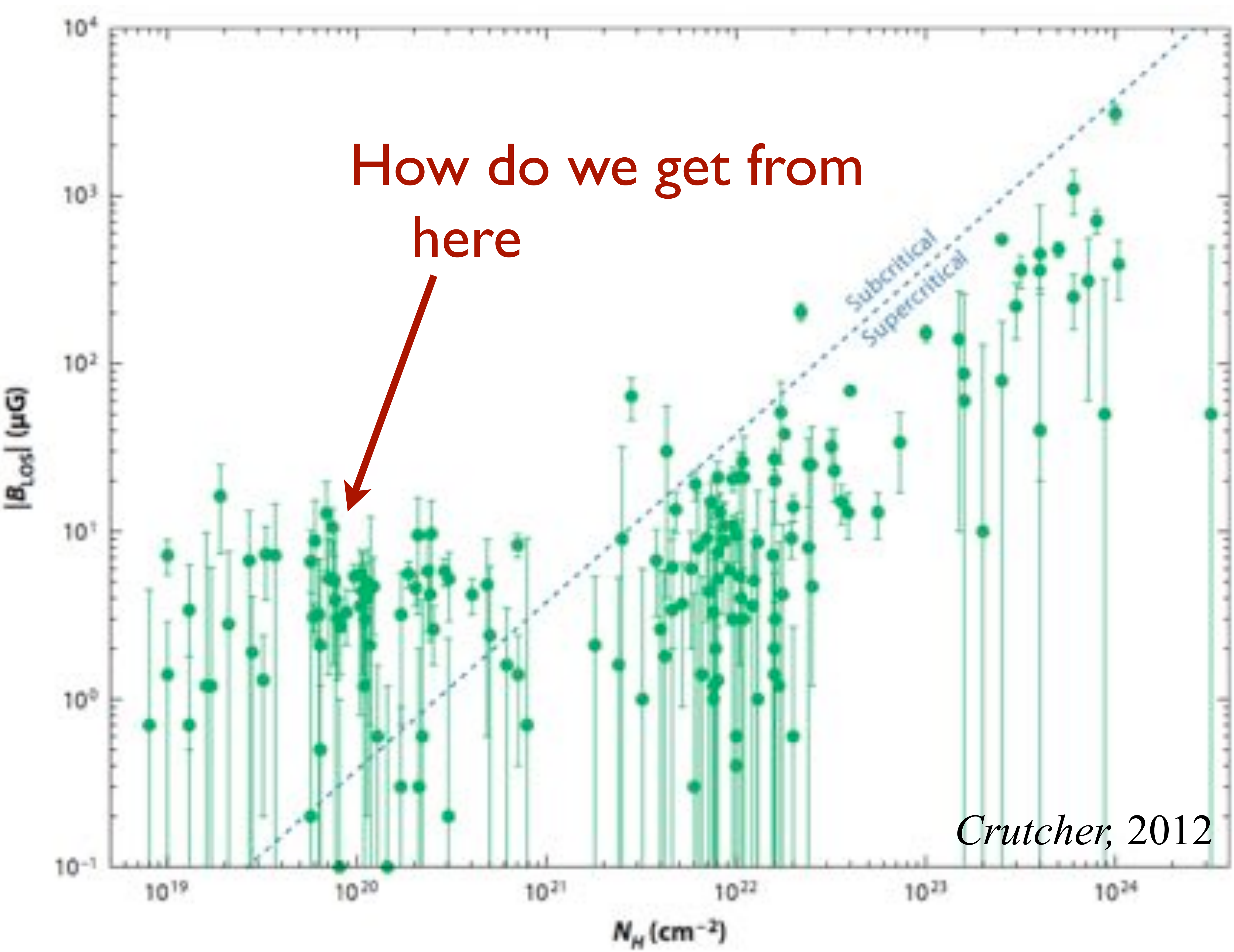
Magnetic Fields in the ISM



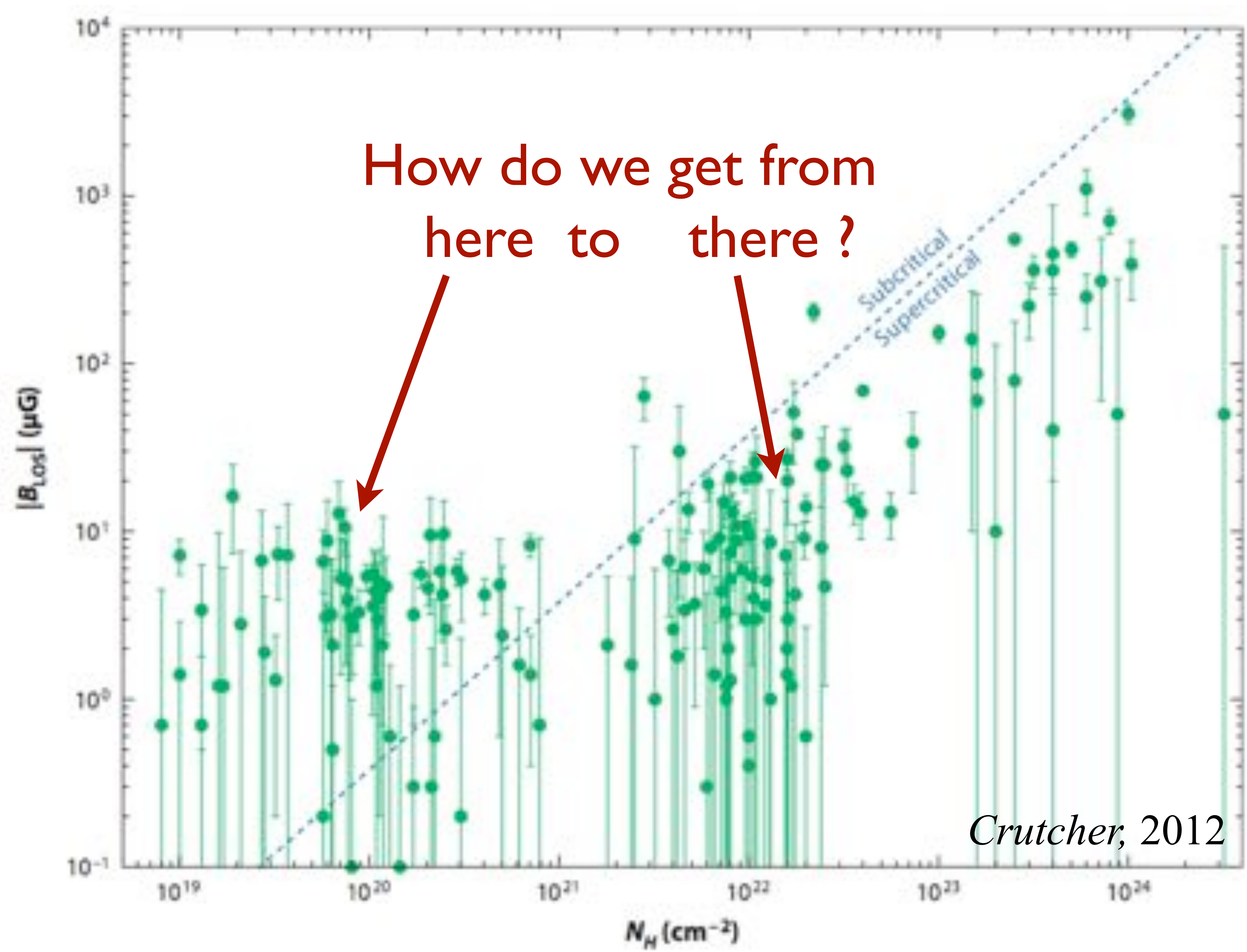
Magnetic Fields in the ISM



Magnetic Fields in the ISM

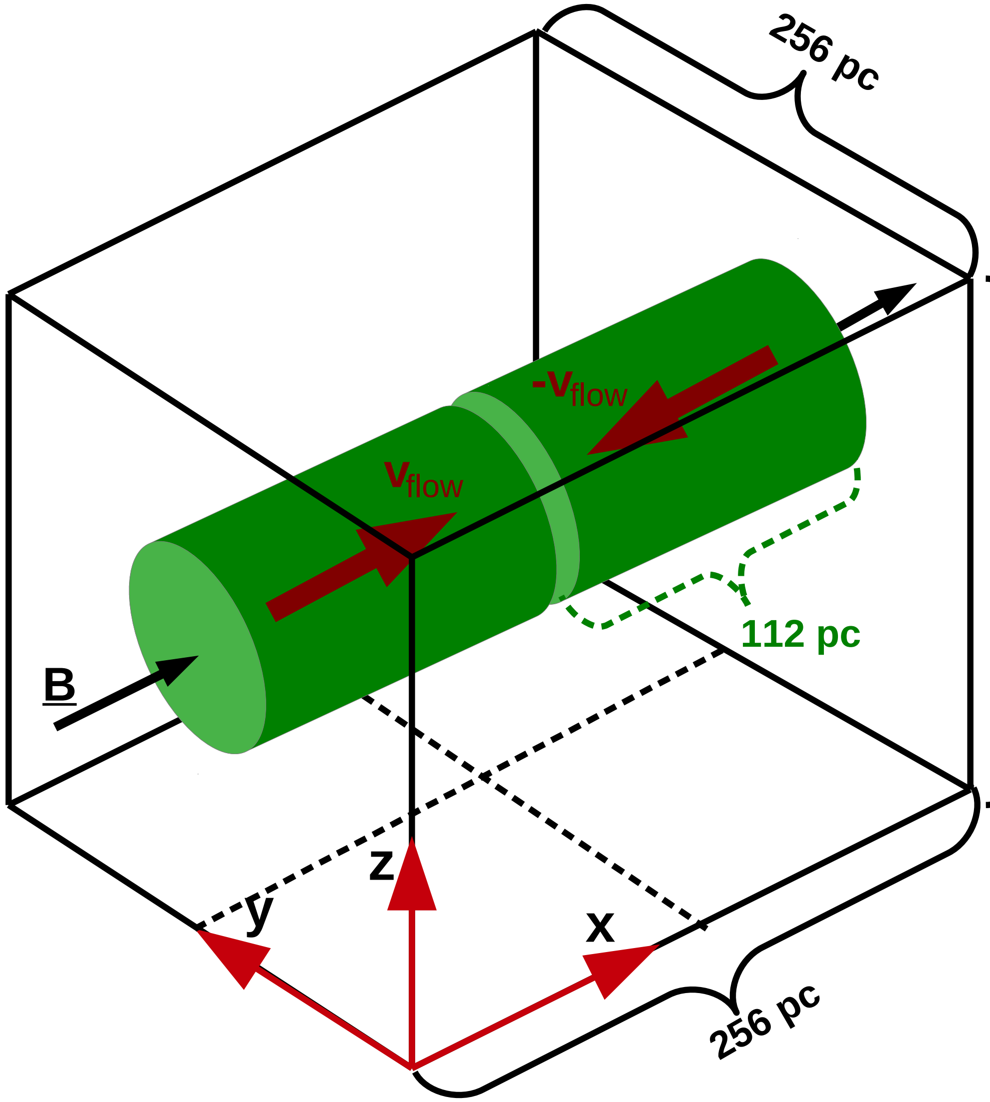


Magnetic Fields in the ISM



Impact of Magnetic Fields on MCs

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



$\Longrightarrow$ minimal column density:

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

$\Longrightarrow$ minimal length scale:

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

$\Longrightarrow$ accumulation scale:

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

$\Longrightarrow$ time-scale for colliding flows:

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

SF from Magnetised Medium

Solutions?

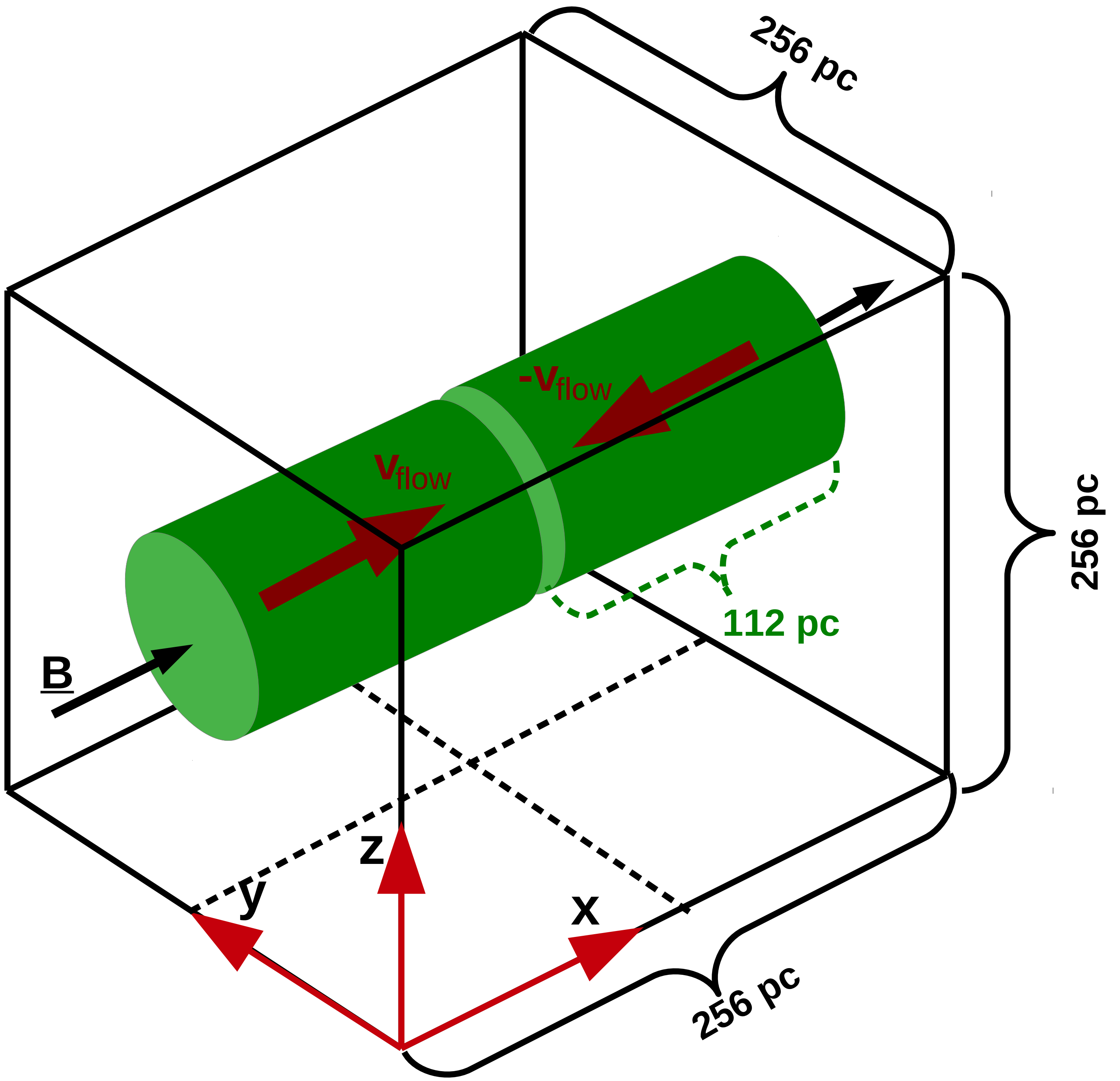
- **flux loss** by:
  - Ambipolar Diffusion (*Mestel & Spitzer* 1956, *Shu* 1987, *Mouschovias* 1987)

    $\Longrightarrow$ 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:

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

  $\Longrightarrow M_{\mathrm{inf}} = 2.3\times10^4\ \mathrm{M}_\odot$

  $\Longrightarrow N \approx 7\times10^{20}\ \mathrm{cm}^{-2}$
- $\mathrm{v}_{\mathrm{inf}} = 14\ \mathrm{km/sec}$

\+ turbulence:

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

\+ ambipolar diffusion

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

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

  $\Longrightarrow t_{\mathrm{crit}} \approx 5\ \mathrm{Myr}\ (\mathrm{B}/1\mu\mathrm{G})$

Simulations of colliding flows

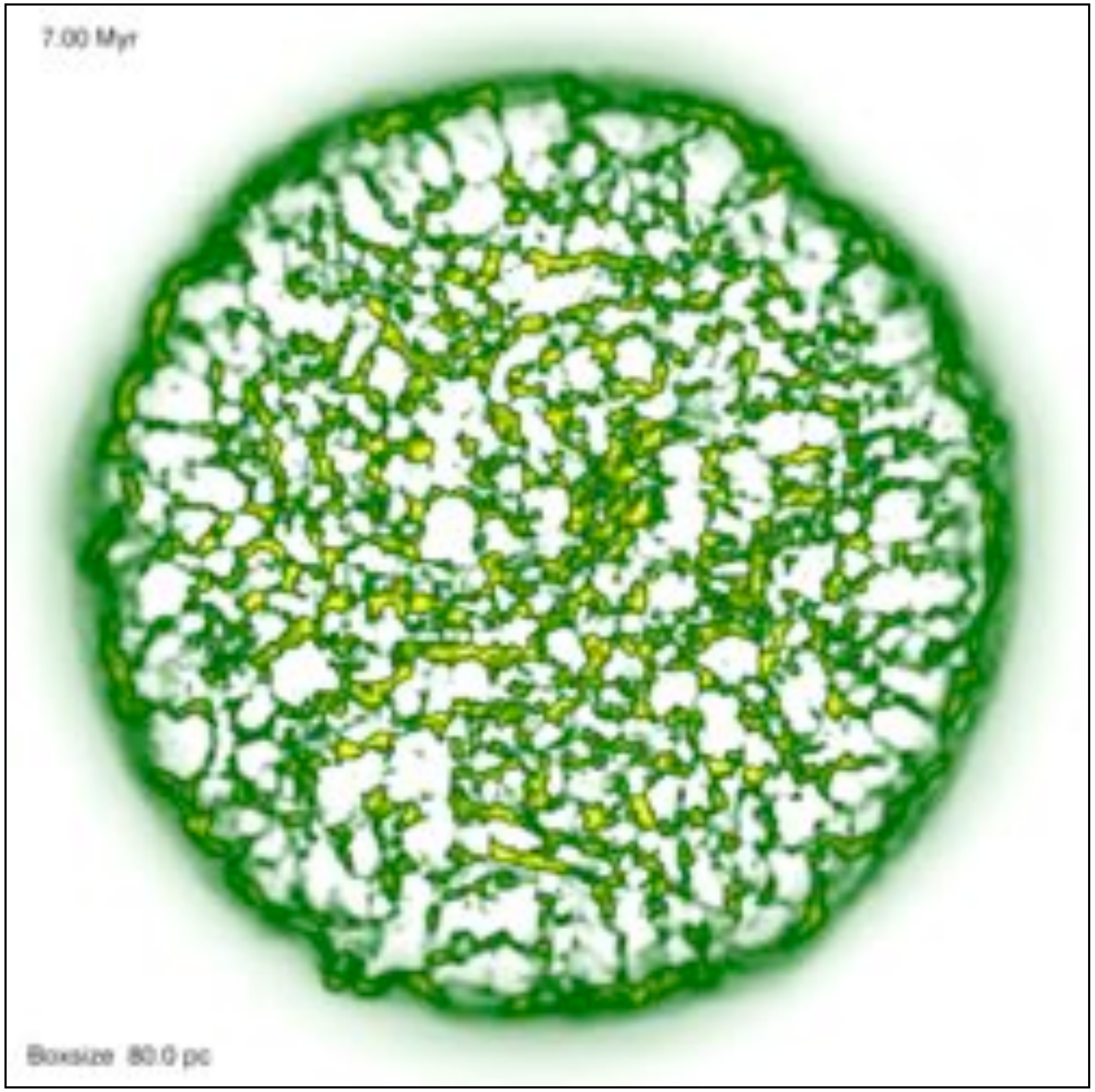
influence of magnetic fields

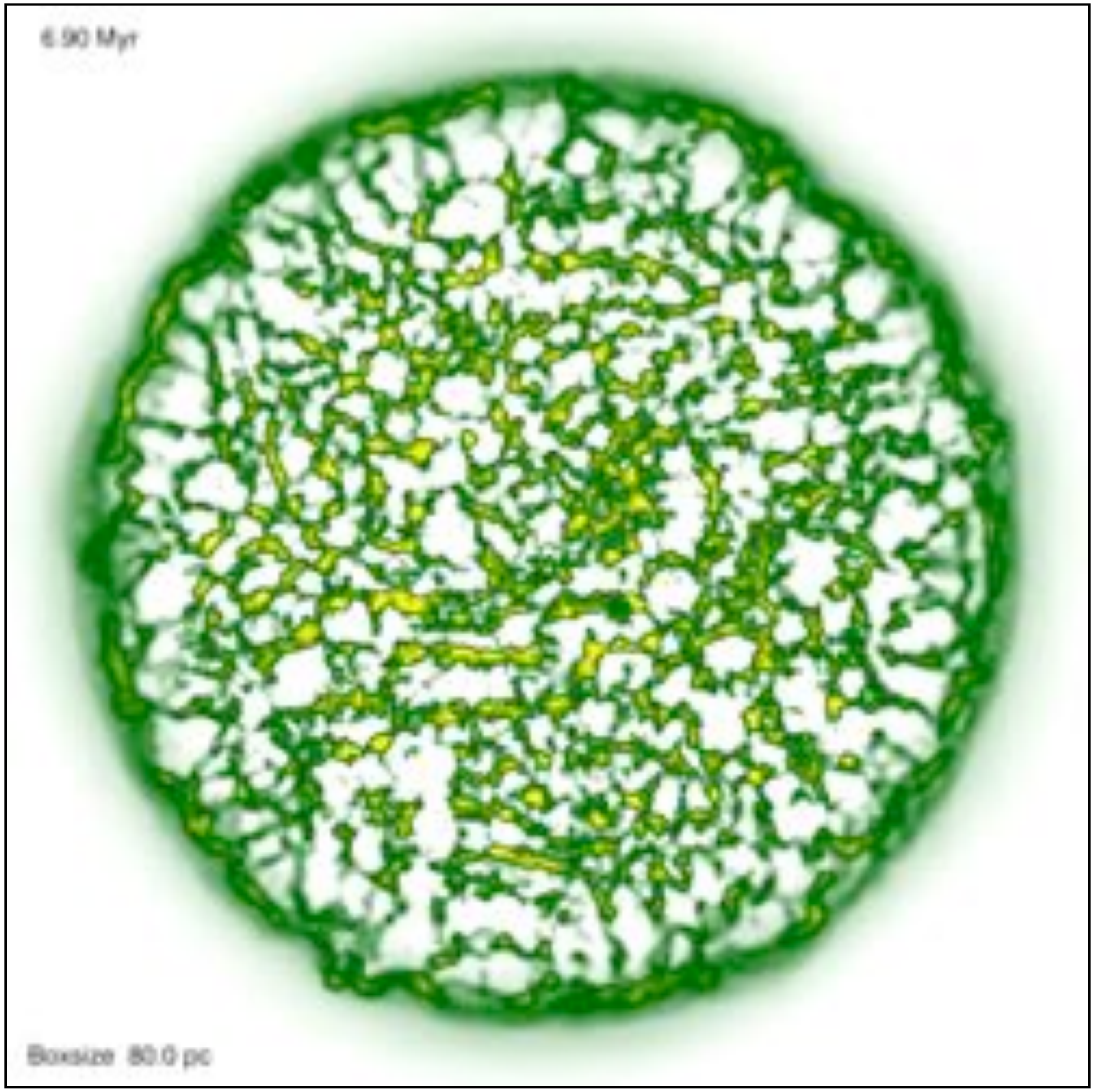
$B = 3\mu G$

$B = 4\mu G$

Simulations of colliding flows

influence of ambipolar diffusion

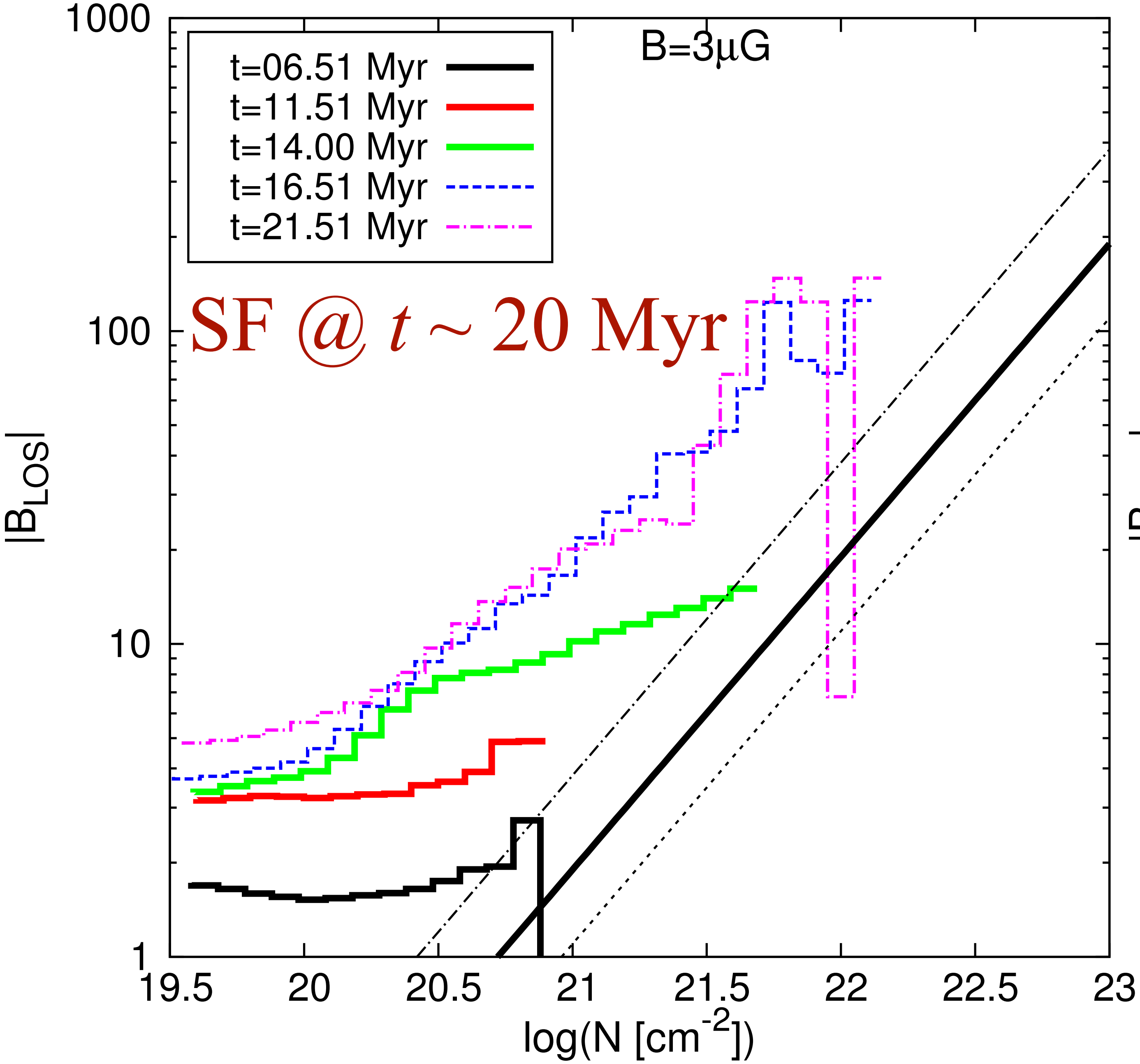


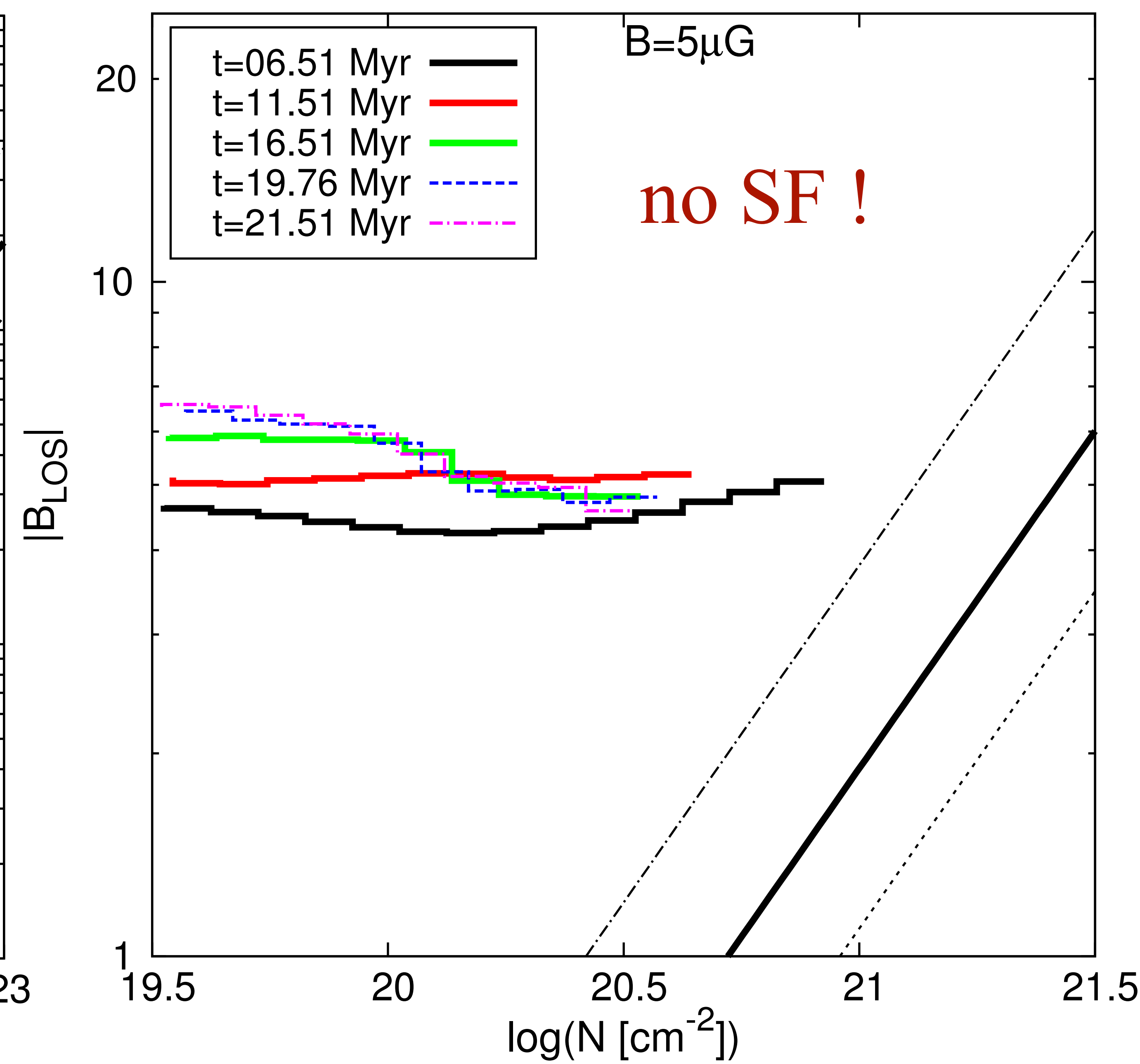


ideal case $B = 4 \mu G$ with ambipolar diffusion

Simulations of colliding flows

results from head-on colliding flows with different field strengths

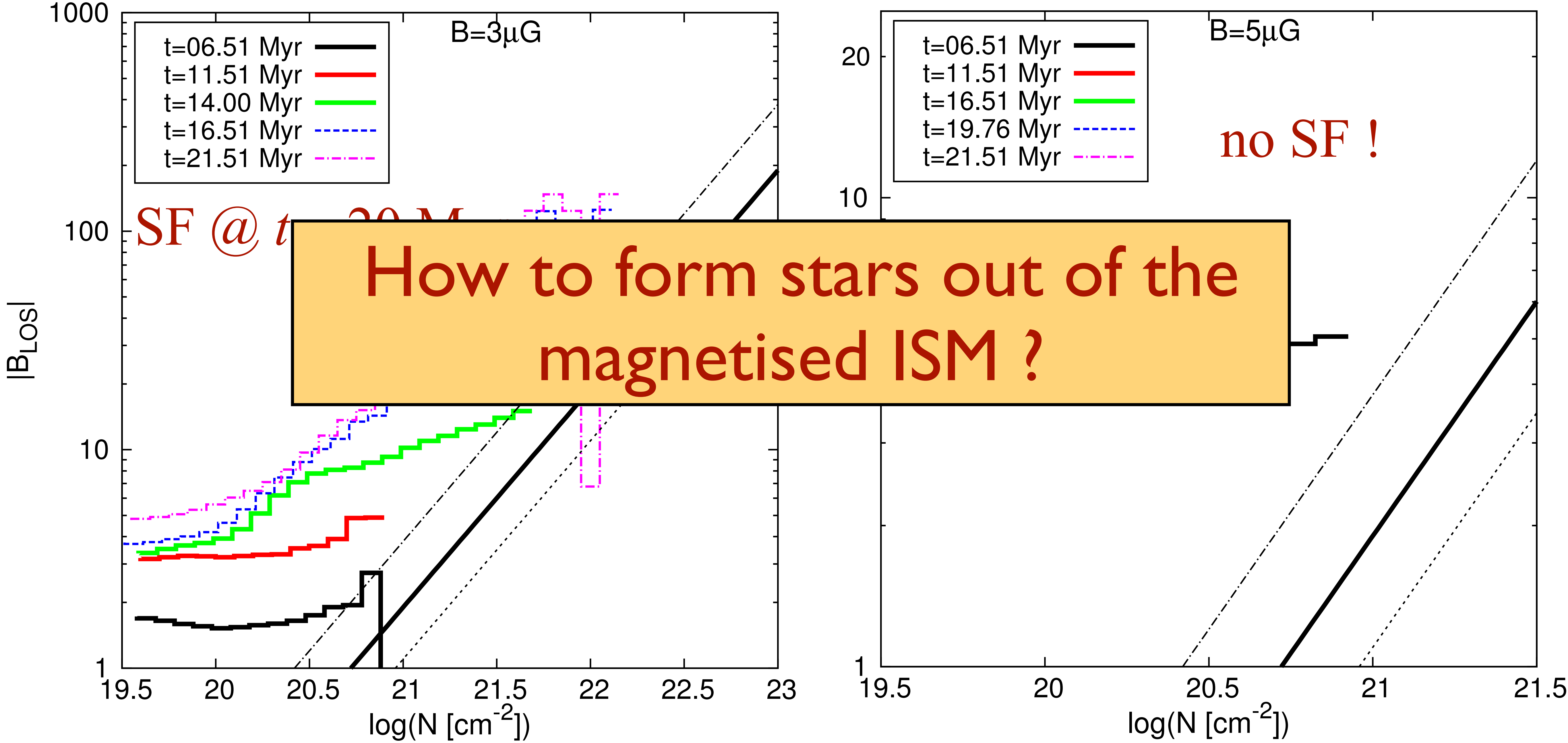




B. Körtgen & RB, MNRAS (2015)

Simulations of colliding flows

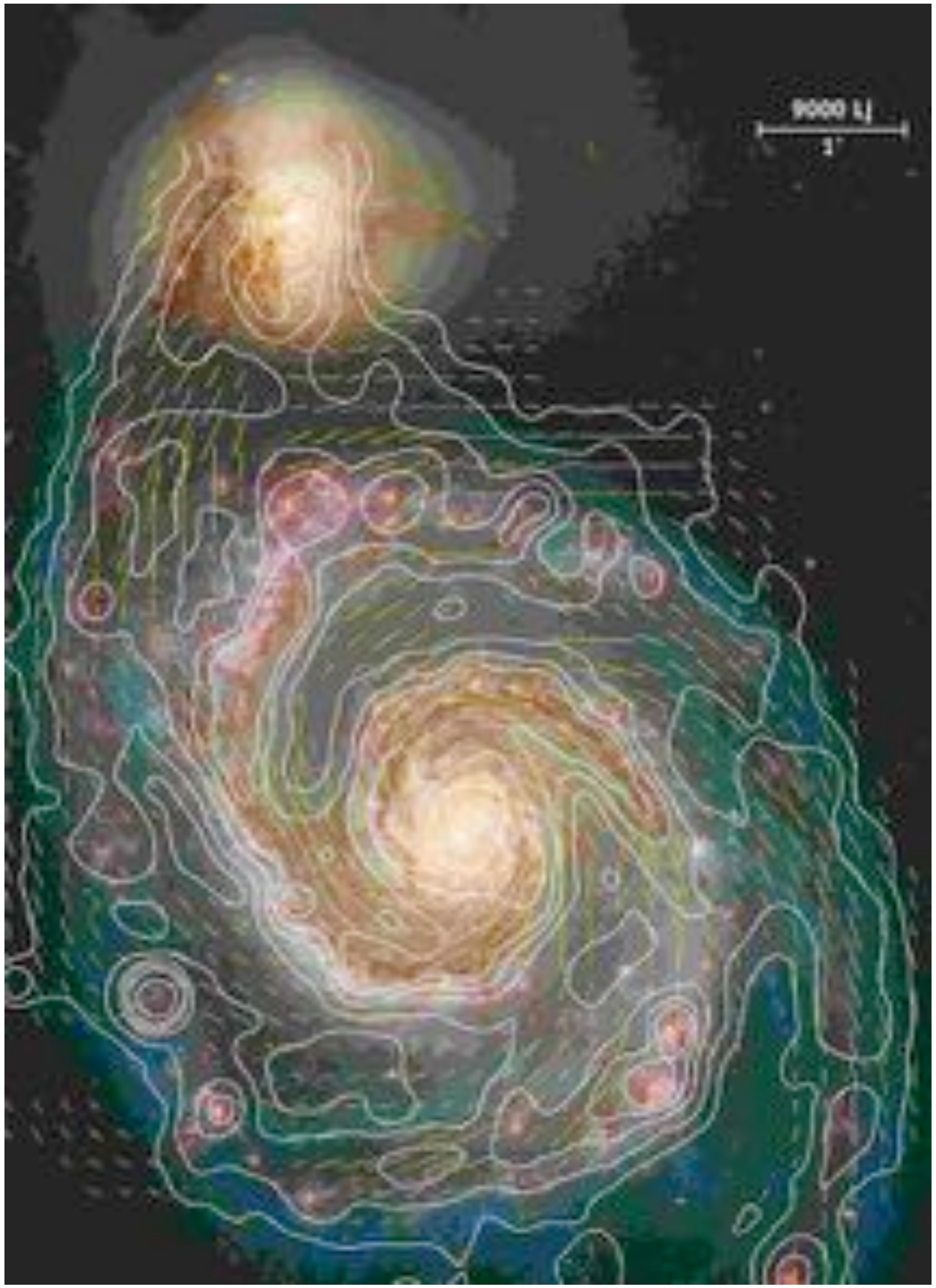
results from head-on colliding flows with different field strengths

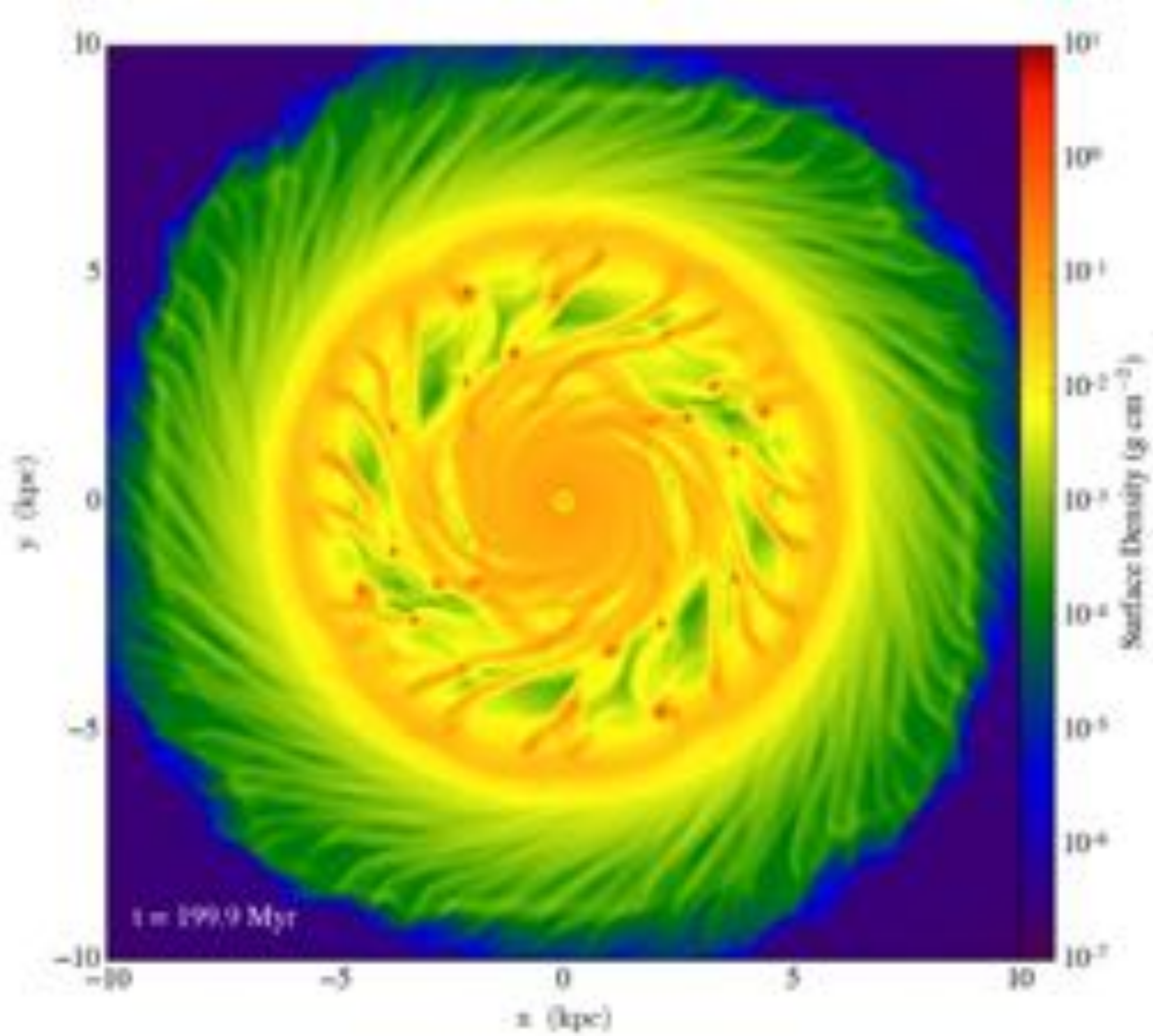


How to form stars out of the magnetised ISM ?

B. Körtgen & RB, MNRAS (2015)

Global Galactic Simulations

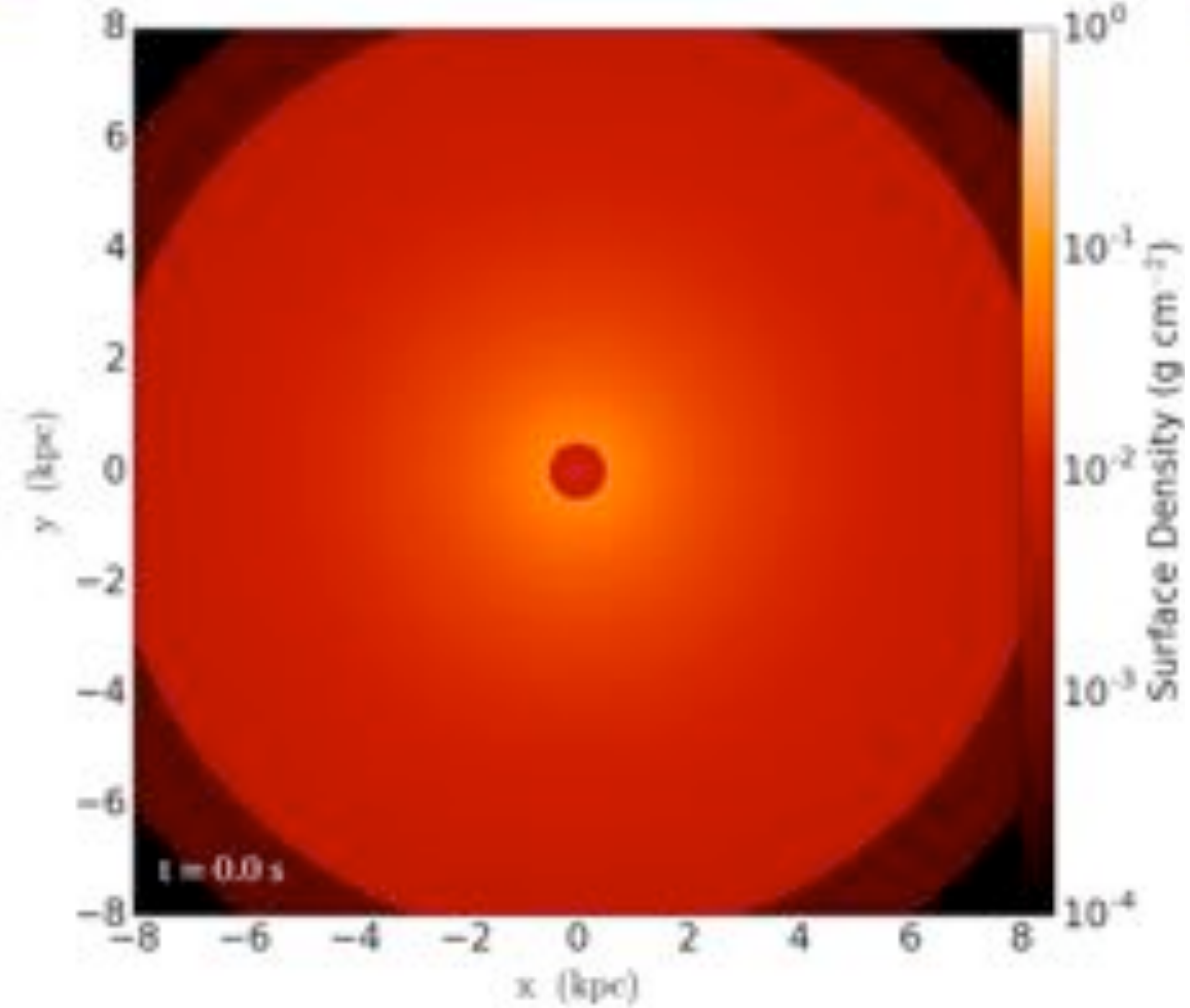




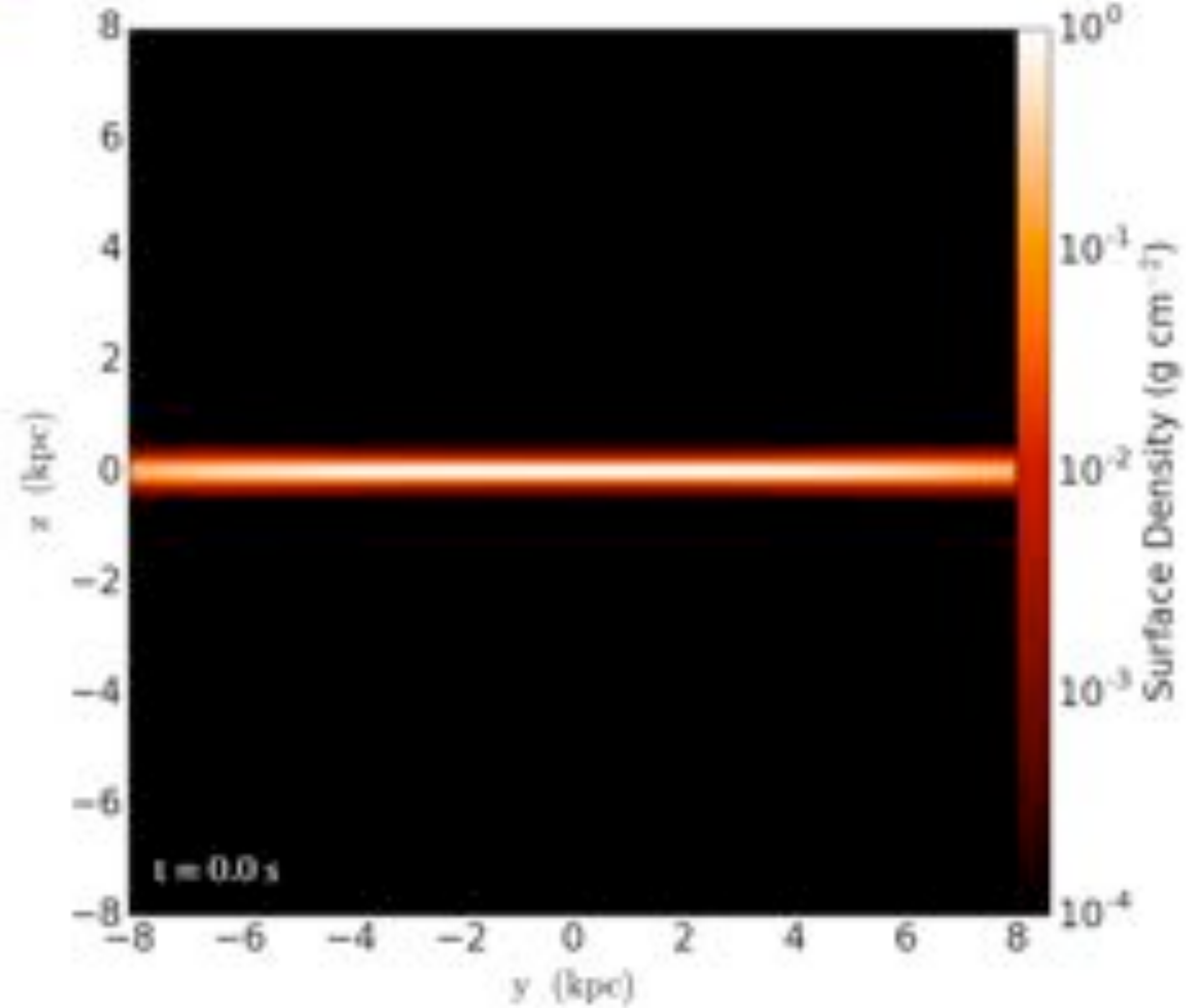
does Mestel's accumulation idea work?

Global Galactic Disc Simulations

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



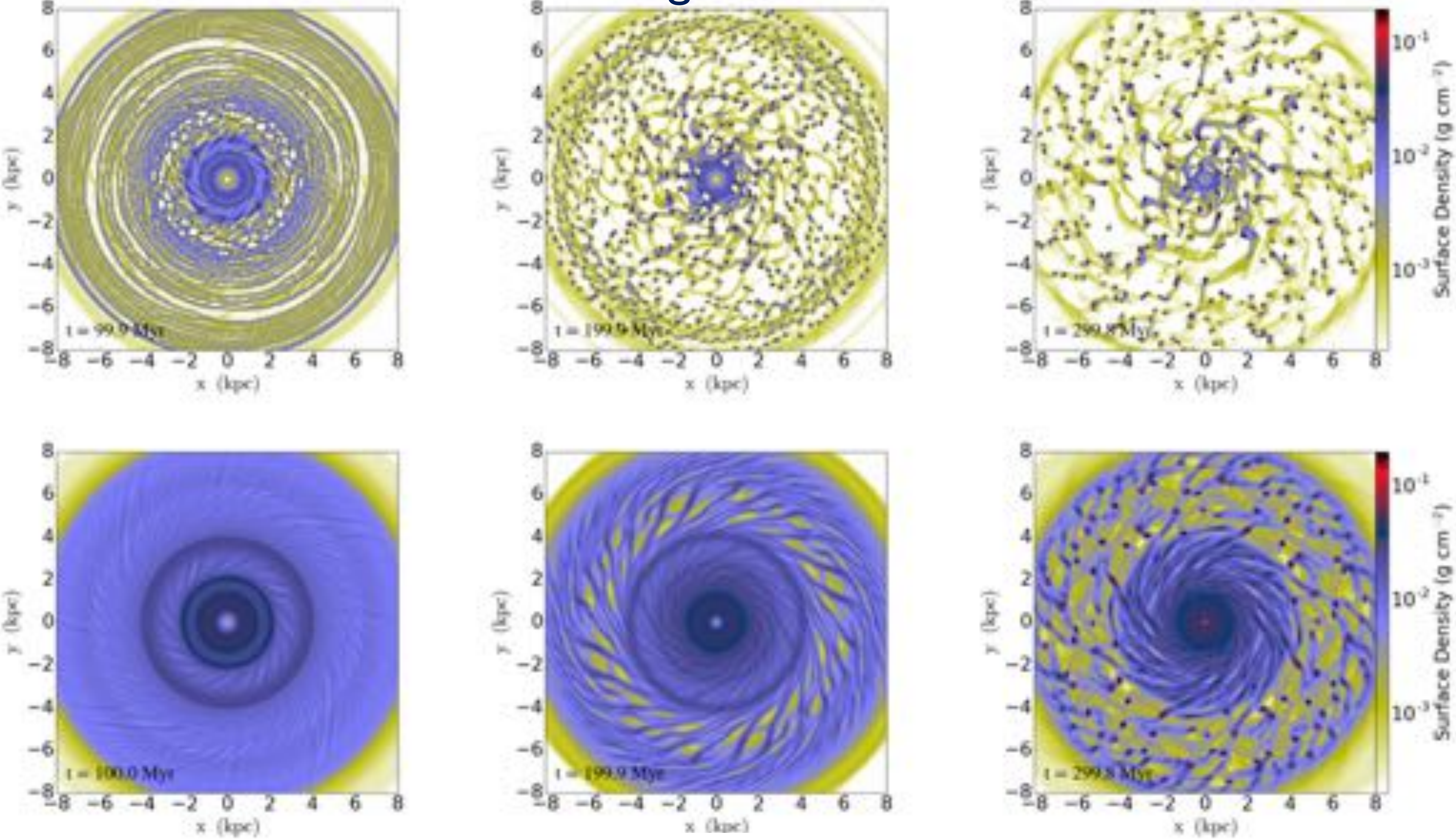
face-on



edge-on

Global Galactic Disc Simulations

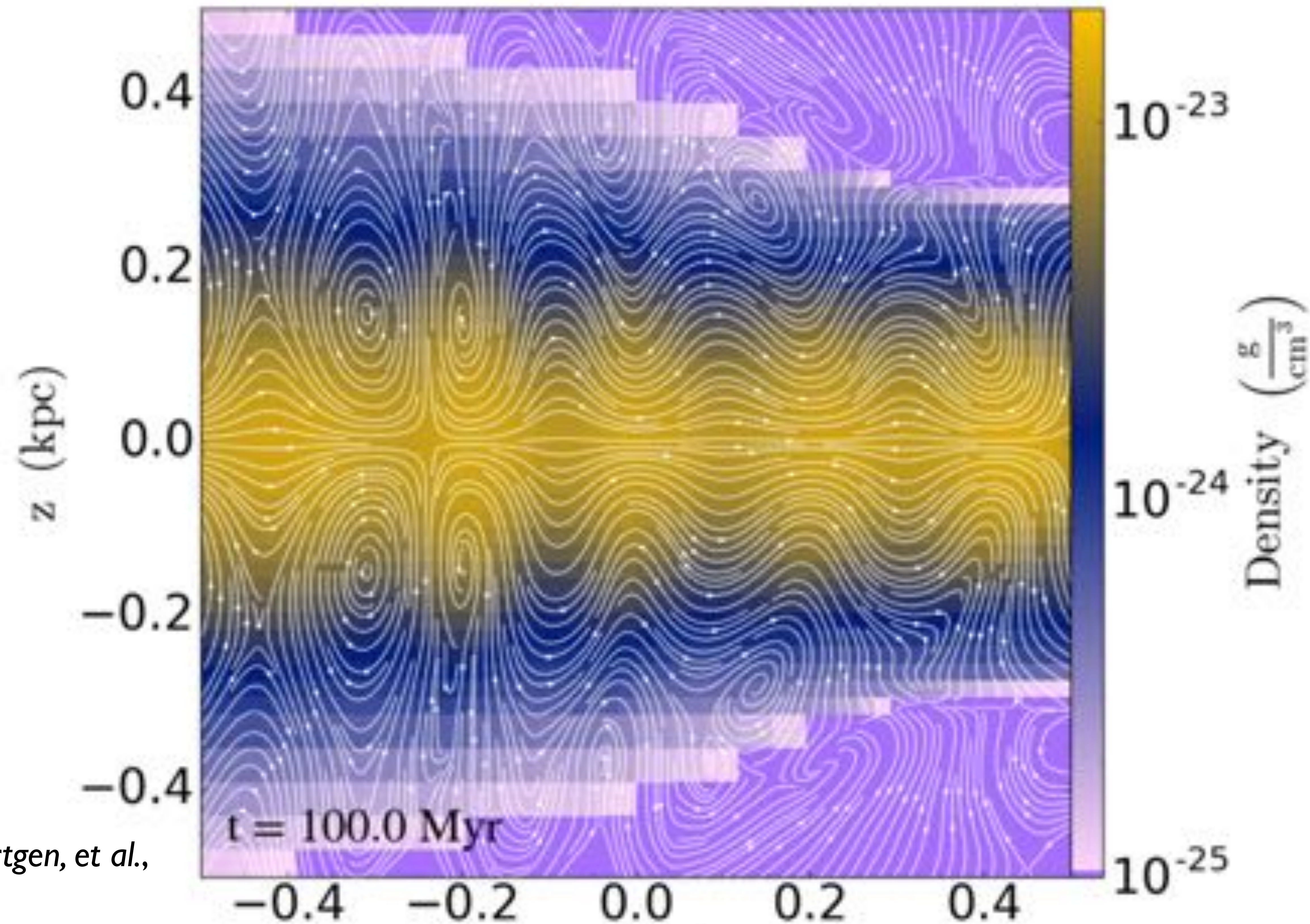
non magnetised case



strongly magnetised case: $\beta = 0.25$

Global Galactic Disc Simulations

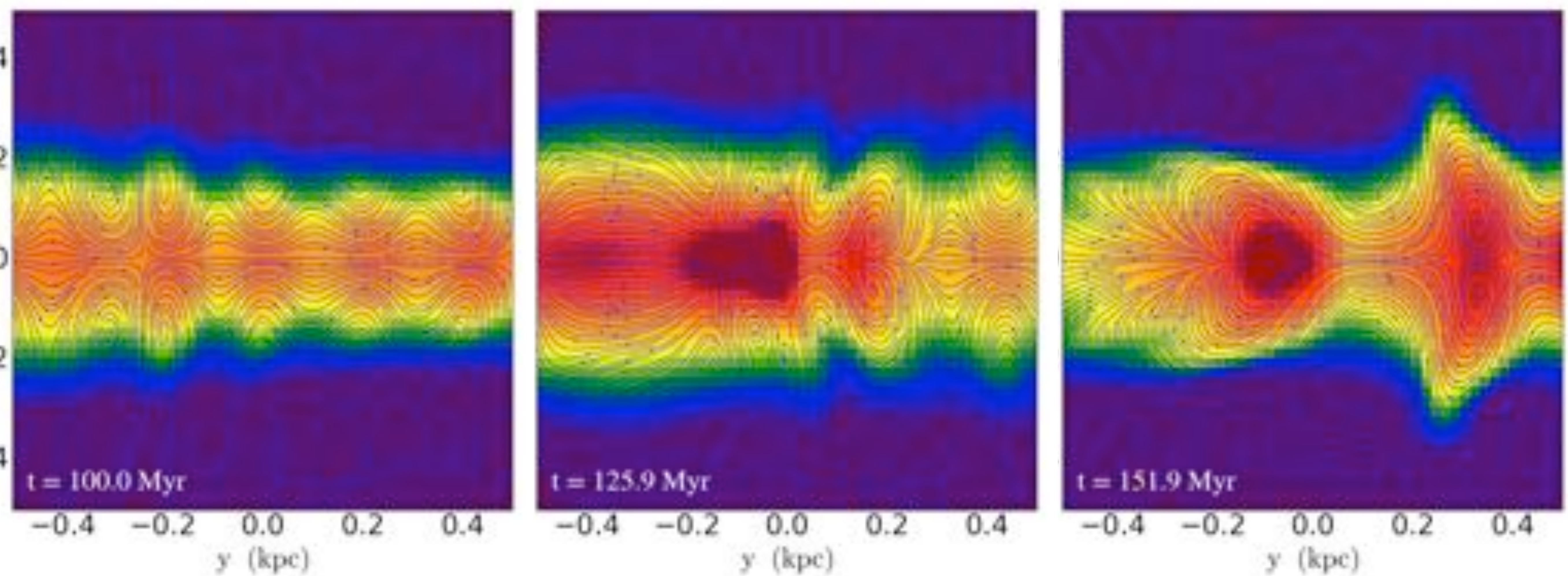
Parker Instability



B. Körtgen, et al., 2018

Global Galactic Disc Simulations

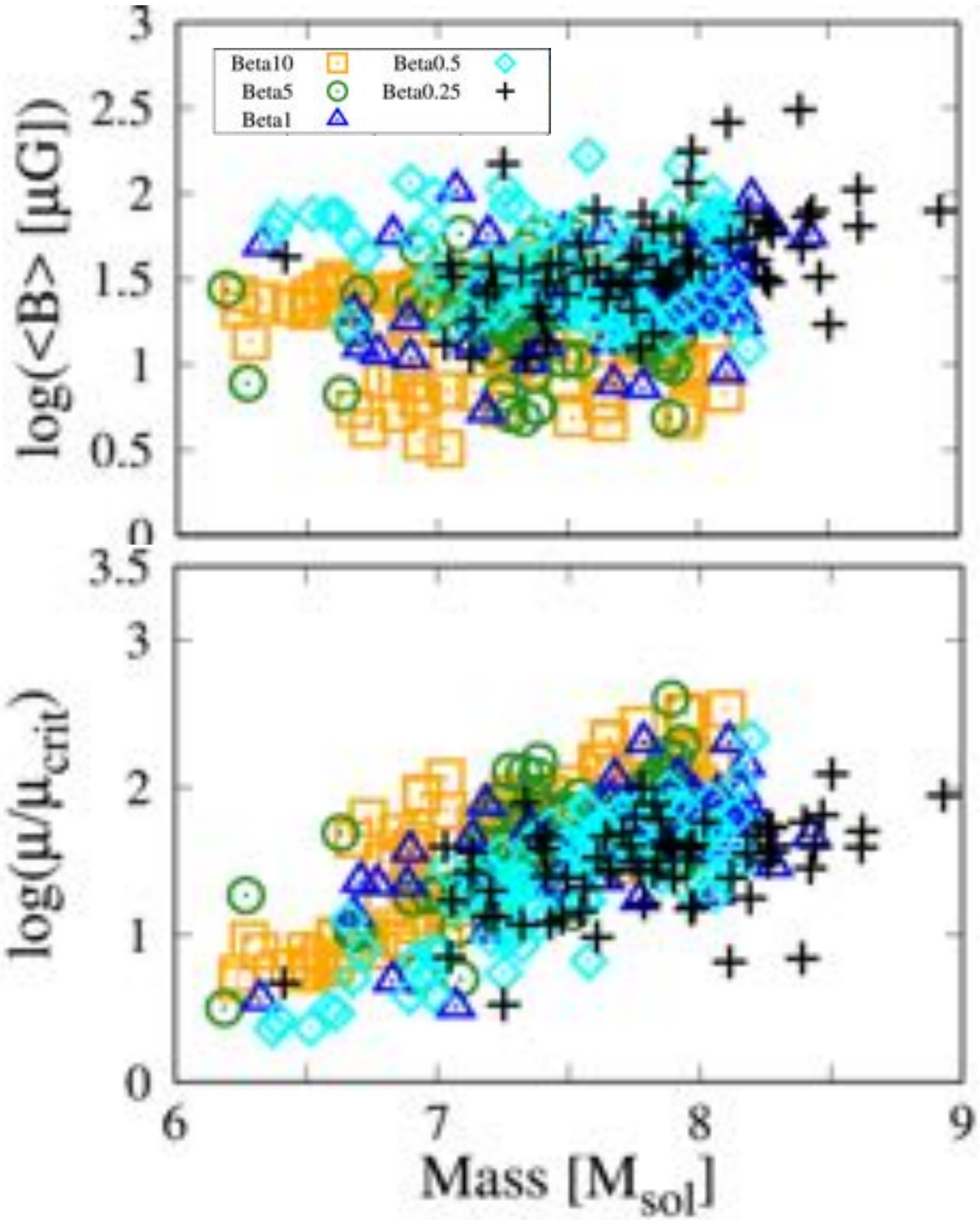
Parker Instability

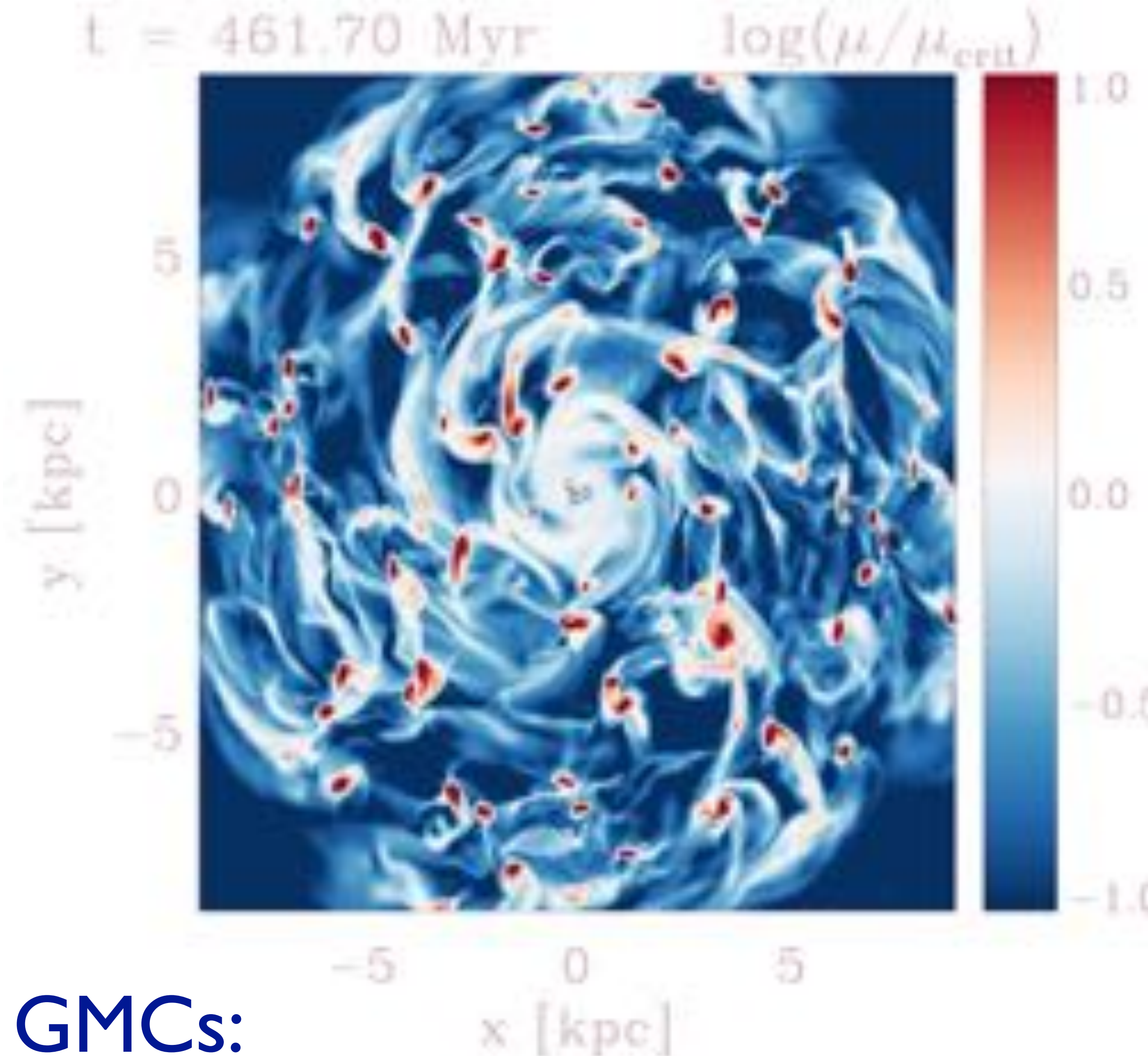


$\Longrightarrow$ supercritical GMCs from along magnetic field lines

B. Körtgen, et al., 2018

Parker Instability: GMC properies



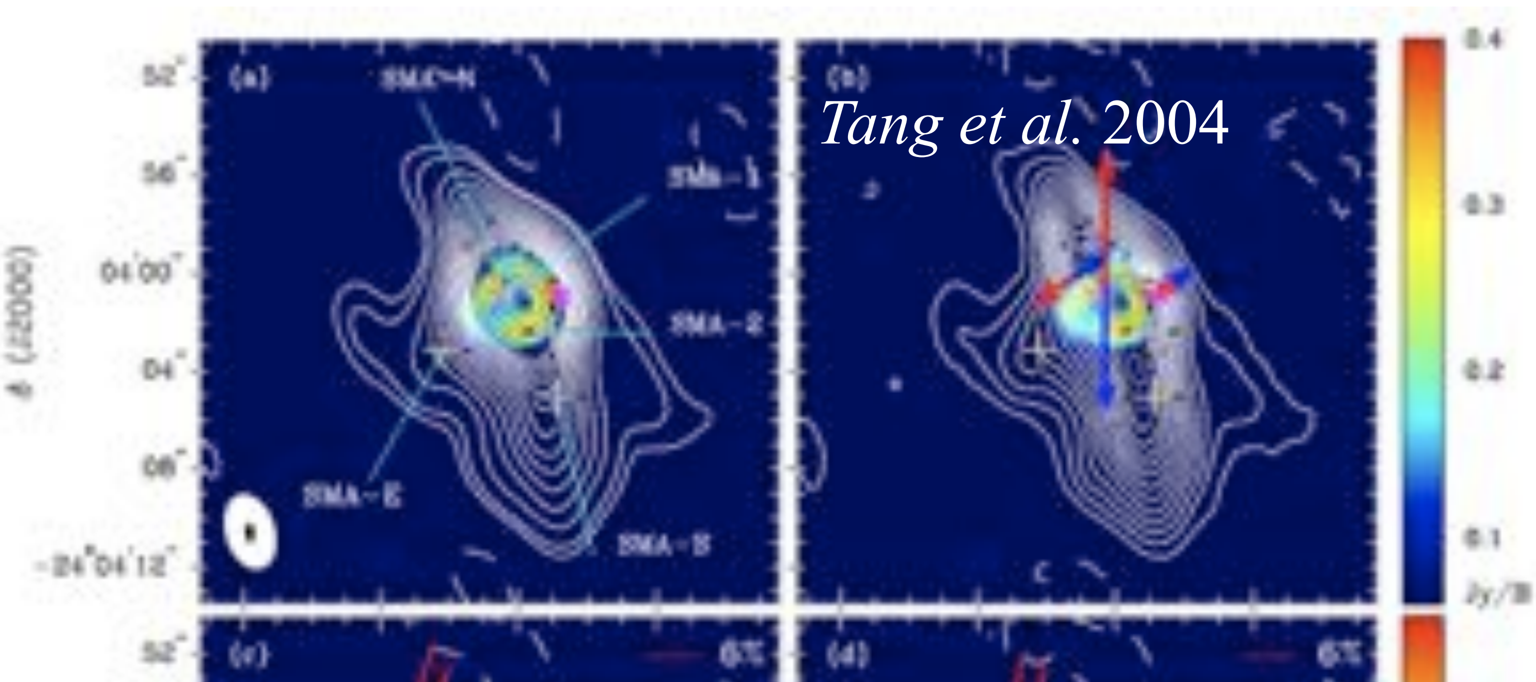


GMCs:

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

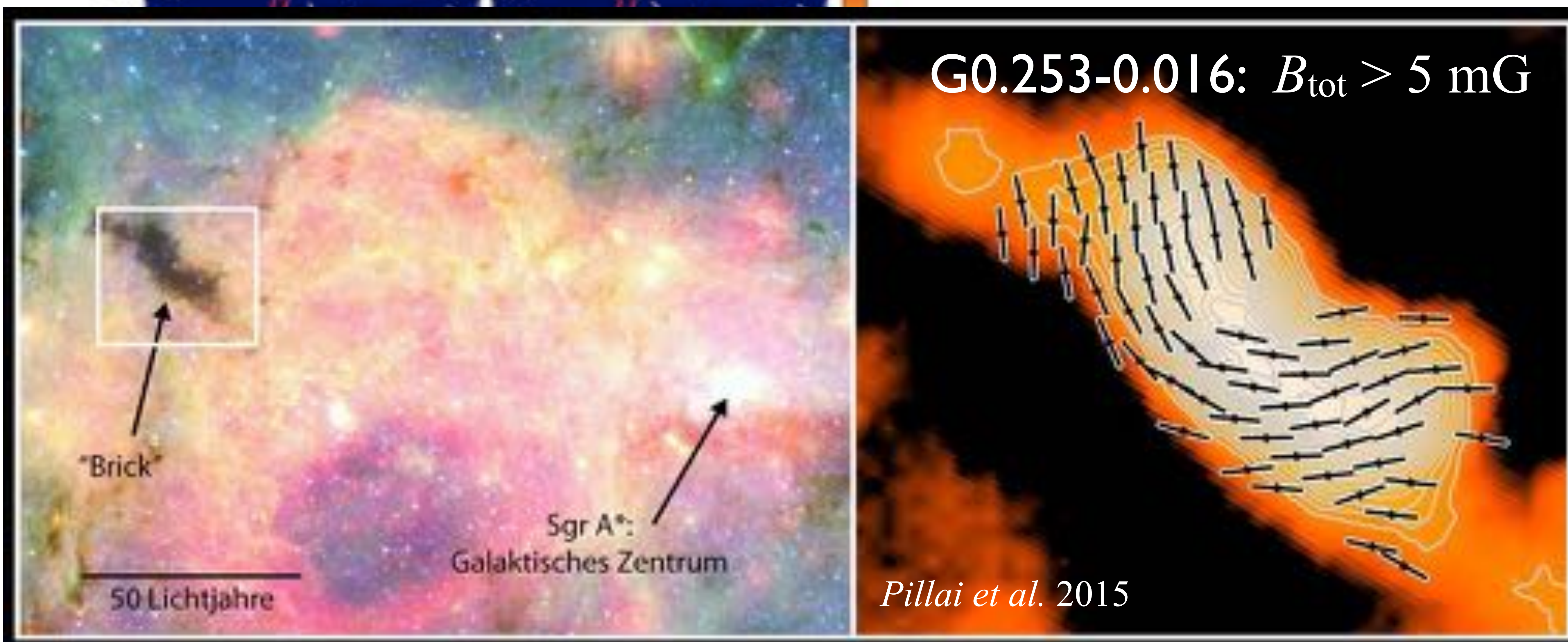
B. Körtgen, et al., 2018

Magnetic fields during Massive Star Formation



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

$B \sim$ 2-3 mG

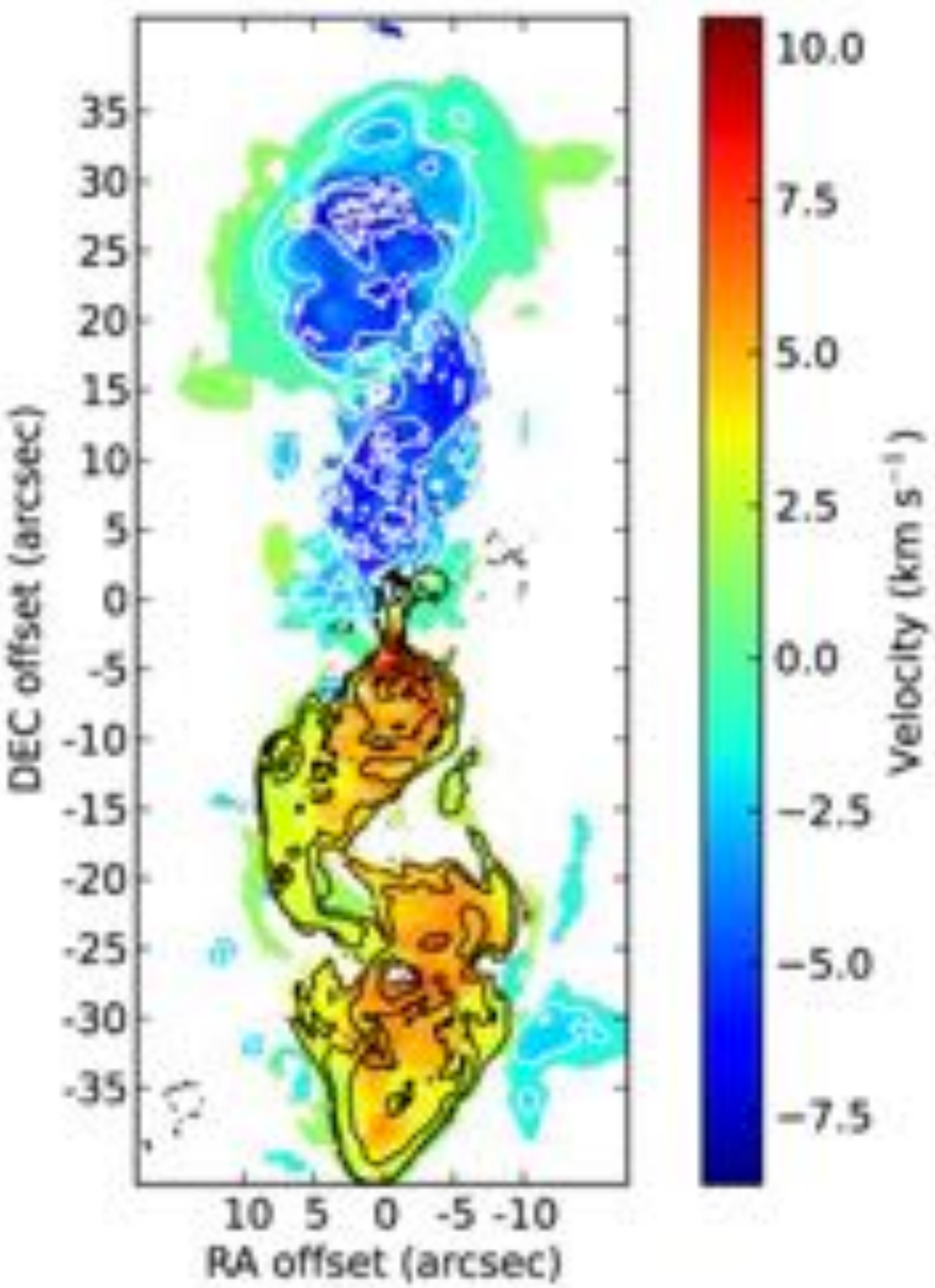


Magnetic fields during Massive Star Formation

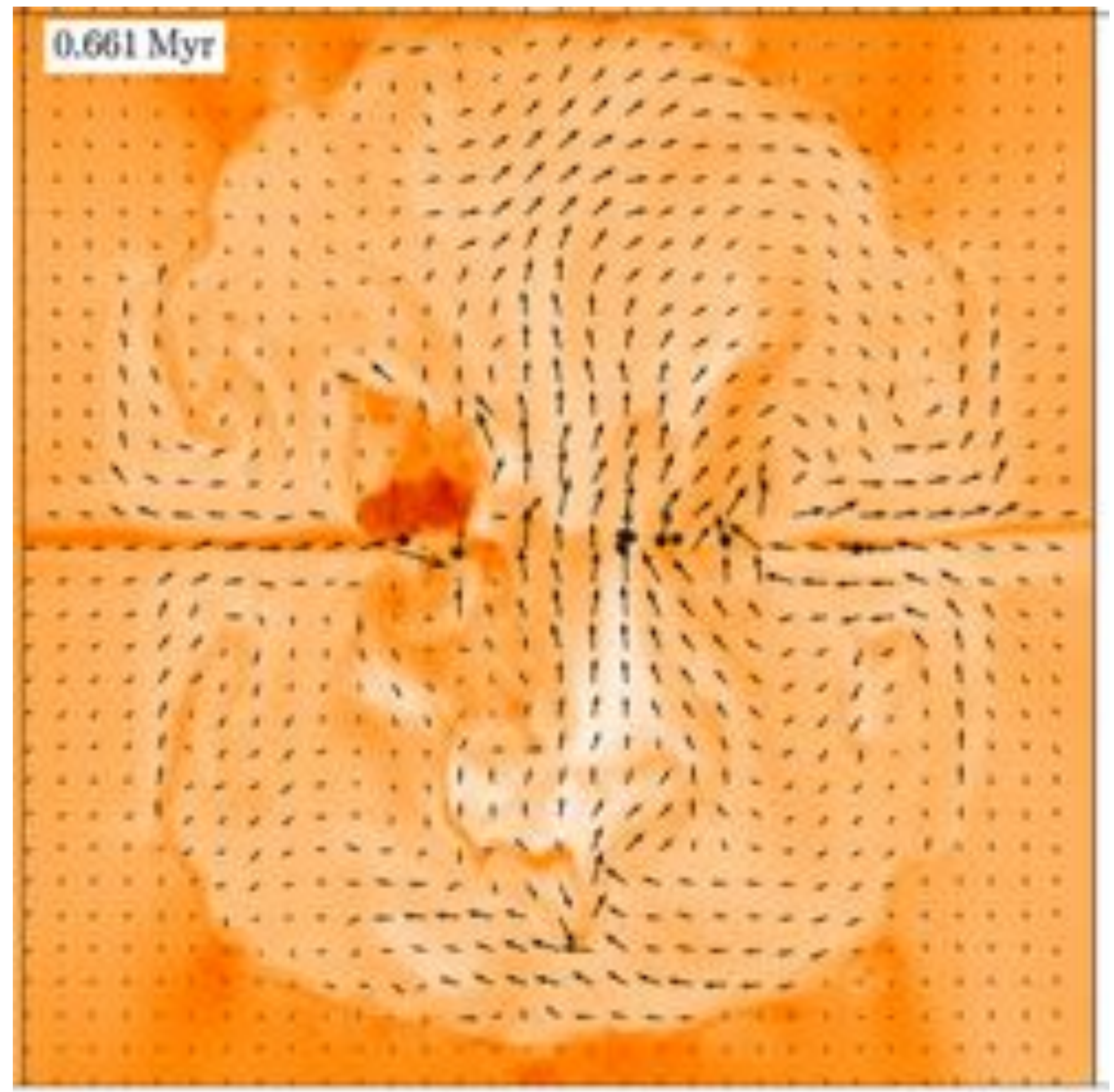
influence of magnetic fields:

magnetically launched outflows around high mass YSOs

Peters et al. 2011

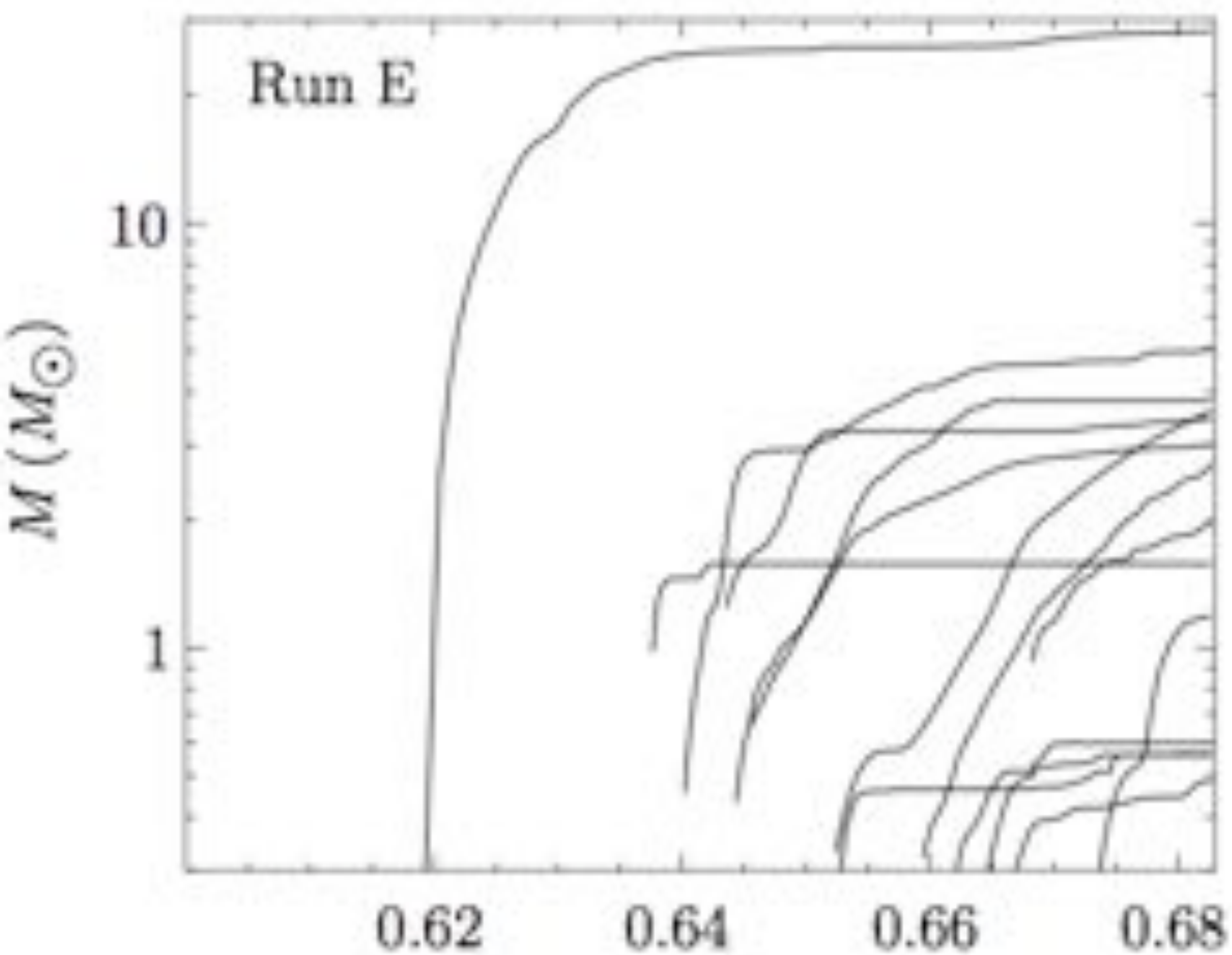


Peters, Klaassen, Seifried, RB, Klessen 2014

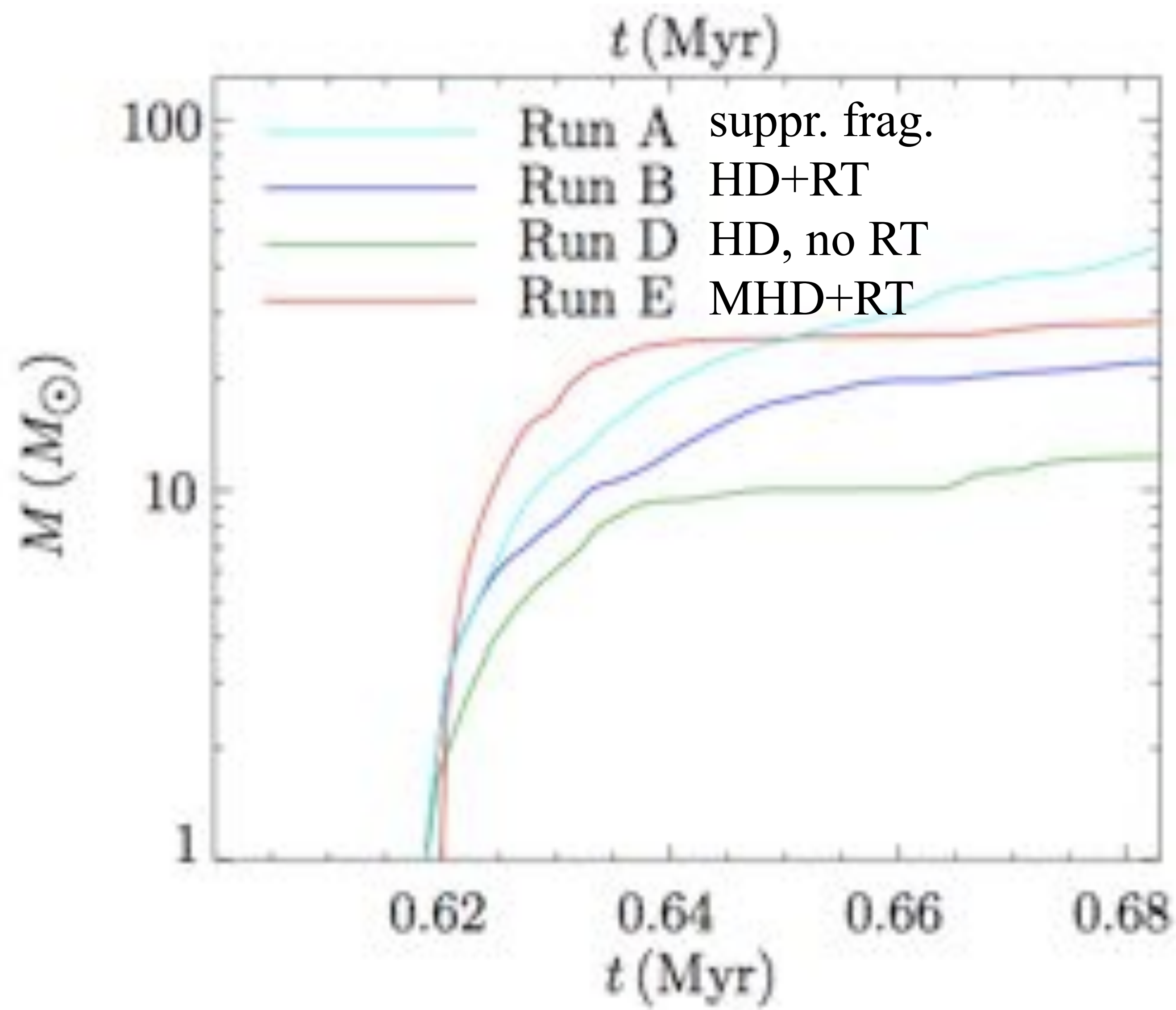


Massive Star Formation: Magnetic fields

The magnetised case: Run E



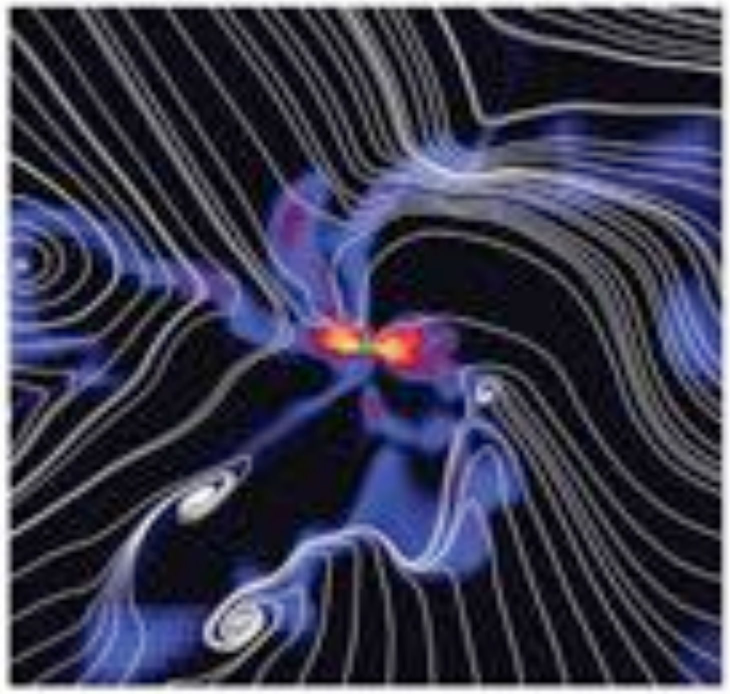
Peters et al. 2011



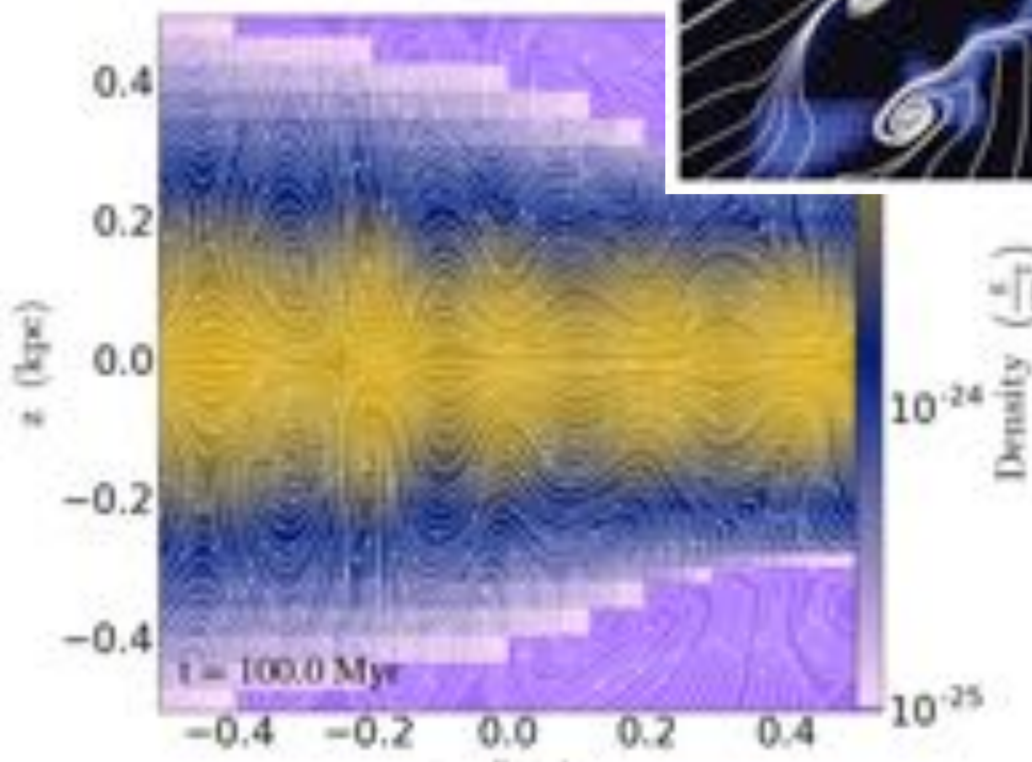
- weakening of fragmentation
- most massive star is *more* massive compared to hydro-case
- but: *Fragmentation Induced Starvation* is still 'active'

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

HansFest, Edinburgh, September 4, 2018, Robi Banerjee


Please release your foto-data!