hamburger sternwarte

The Dynamics of the Magnetised Interstellar Medium

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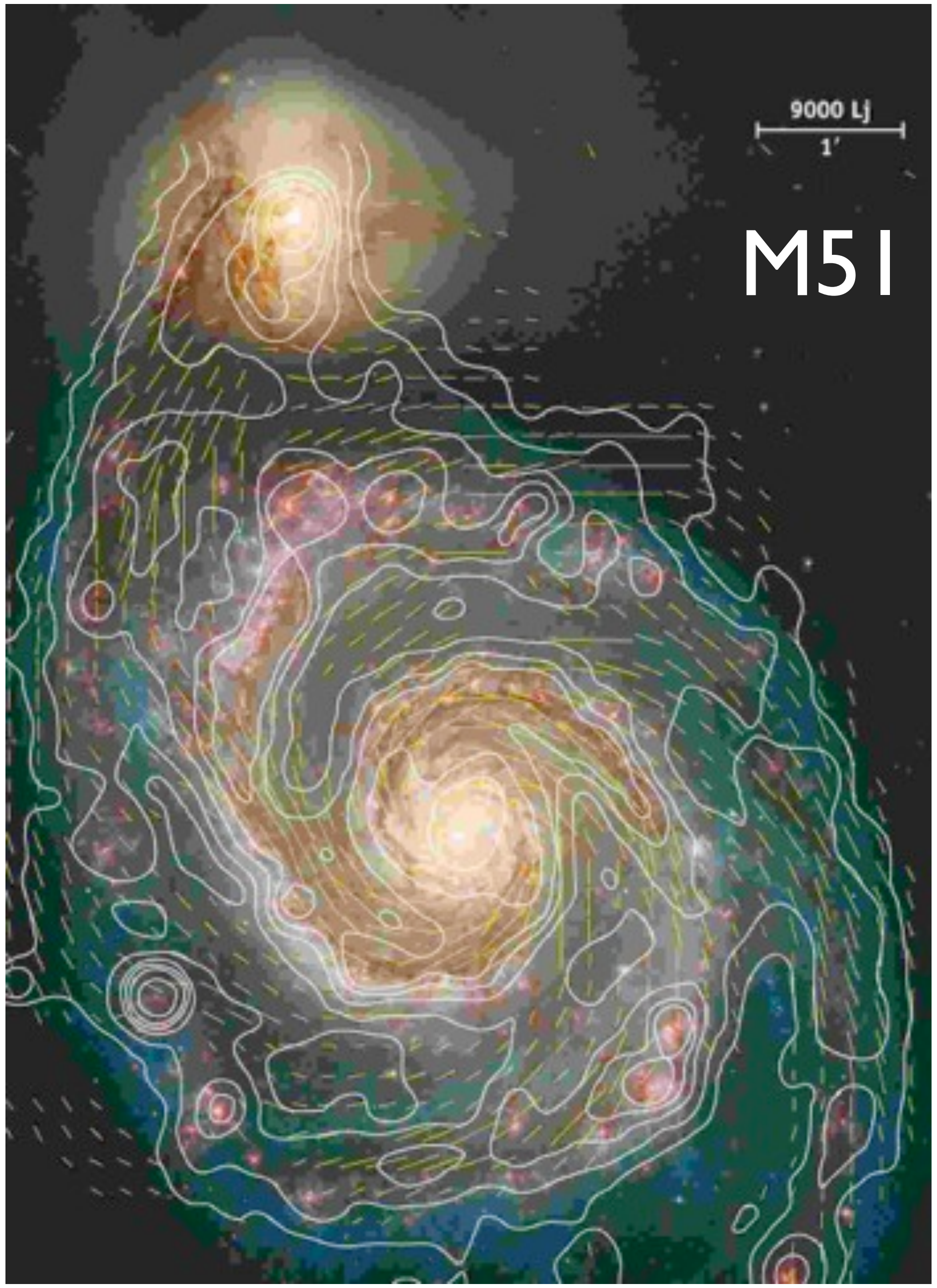
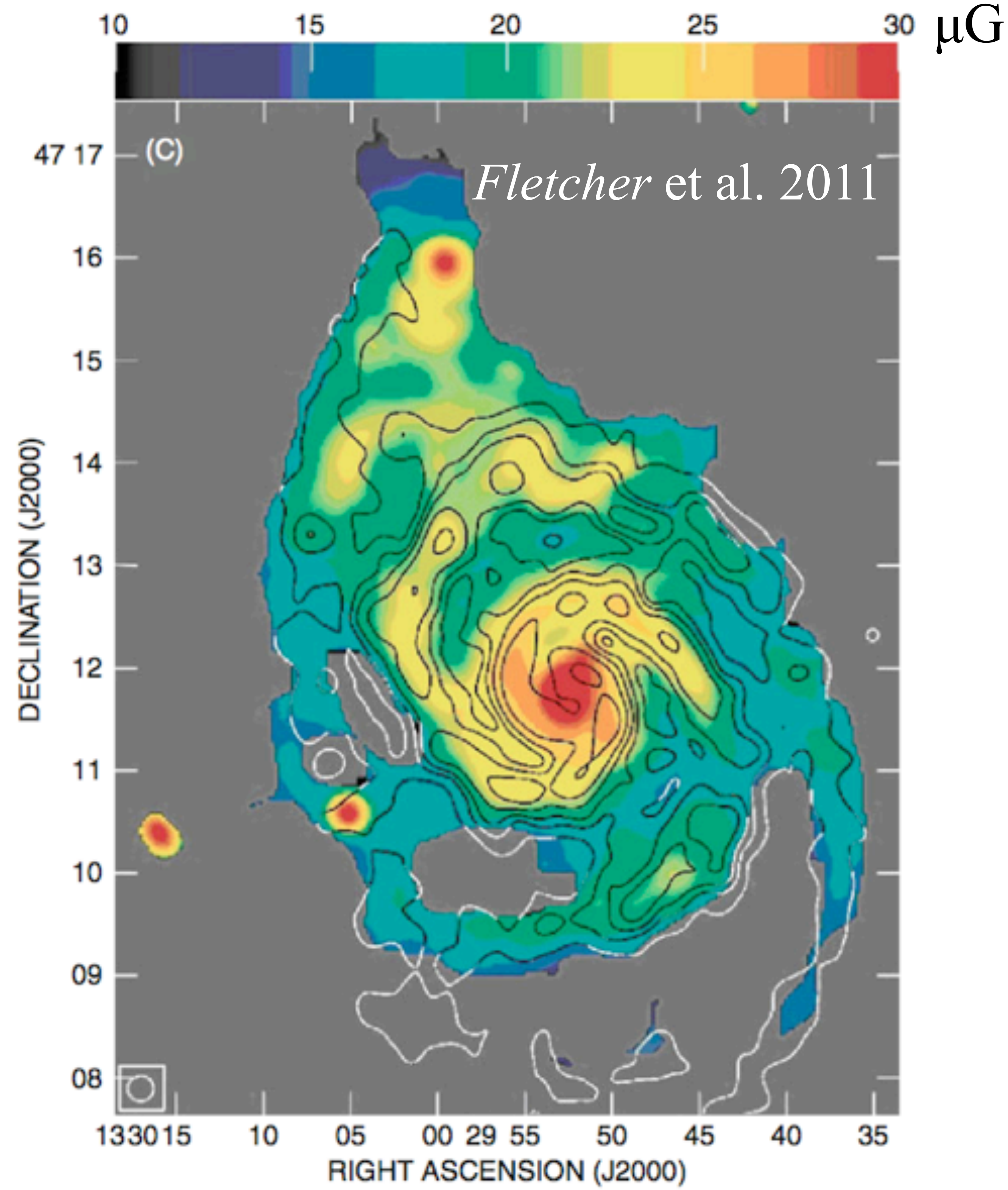
based on work by: **Bastian Körtgen** (HS)
co-workers: Ralph Pudritz (McMaster, Canada), Wolfram Schmidt (HS),
Enrique Vazquez-Semadeni (UNAM, Mexico)

Magnetic Fields in the ISM

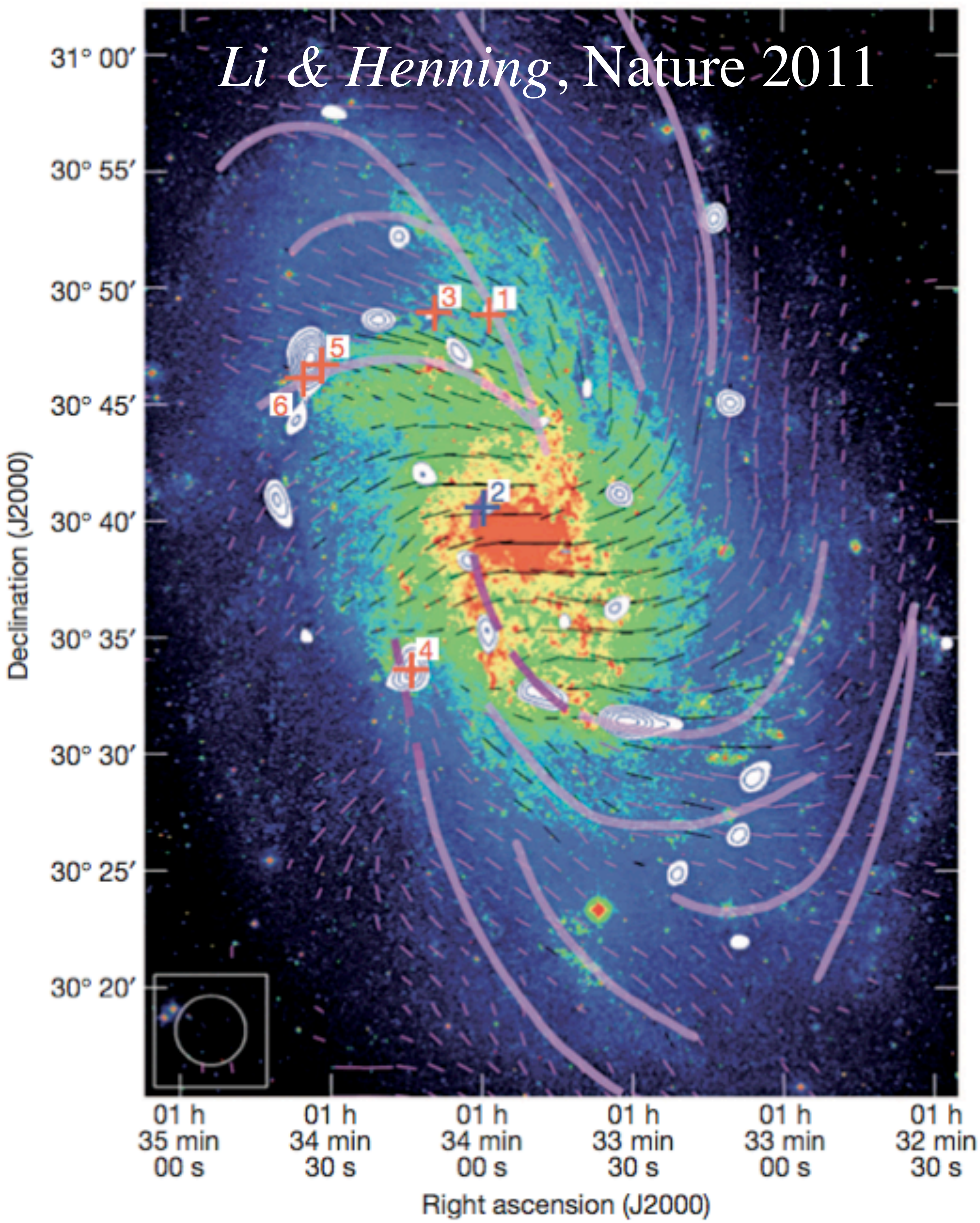


The ISM is *highly* magnetised: $E_{mag} \sim E_{therm}$



galactic B-fields (e.g. *R.Beck* 2001)
large scale component: ***B* ~ 6μG**
total field strength: **> 10 μG**

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:

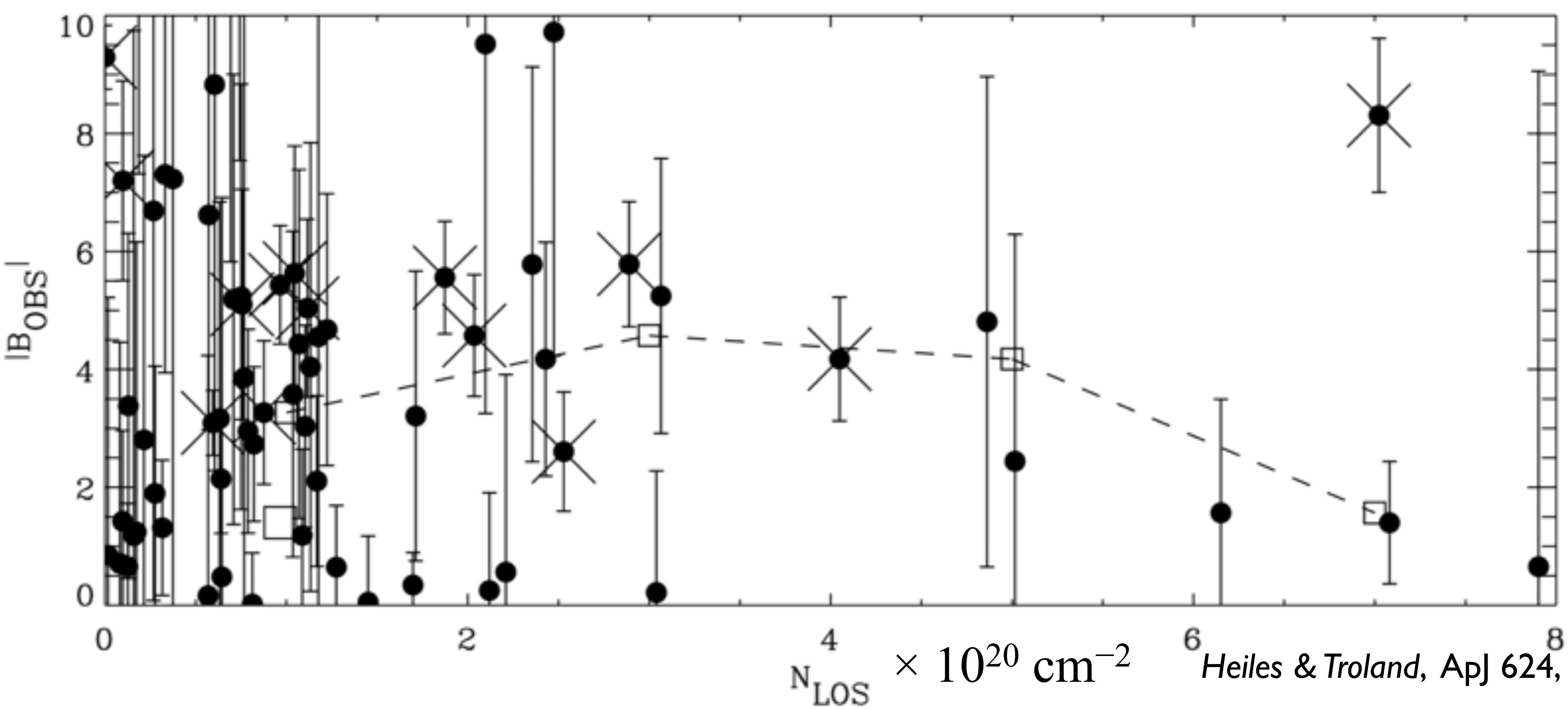
$v_{turb} \lesssim v_A$

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)



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

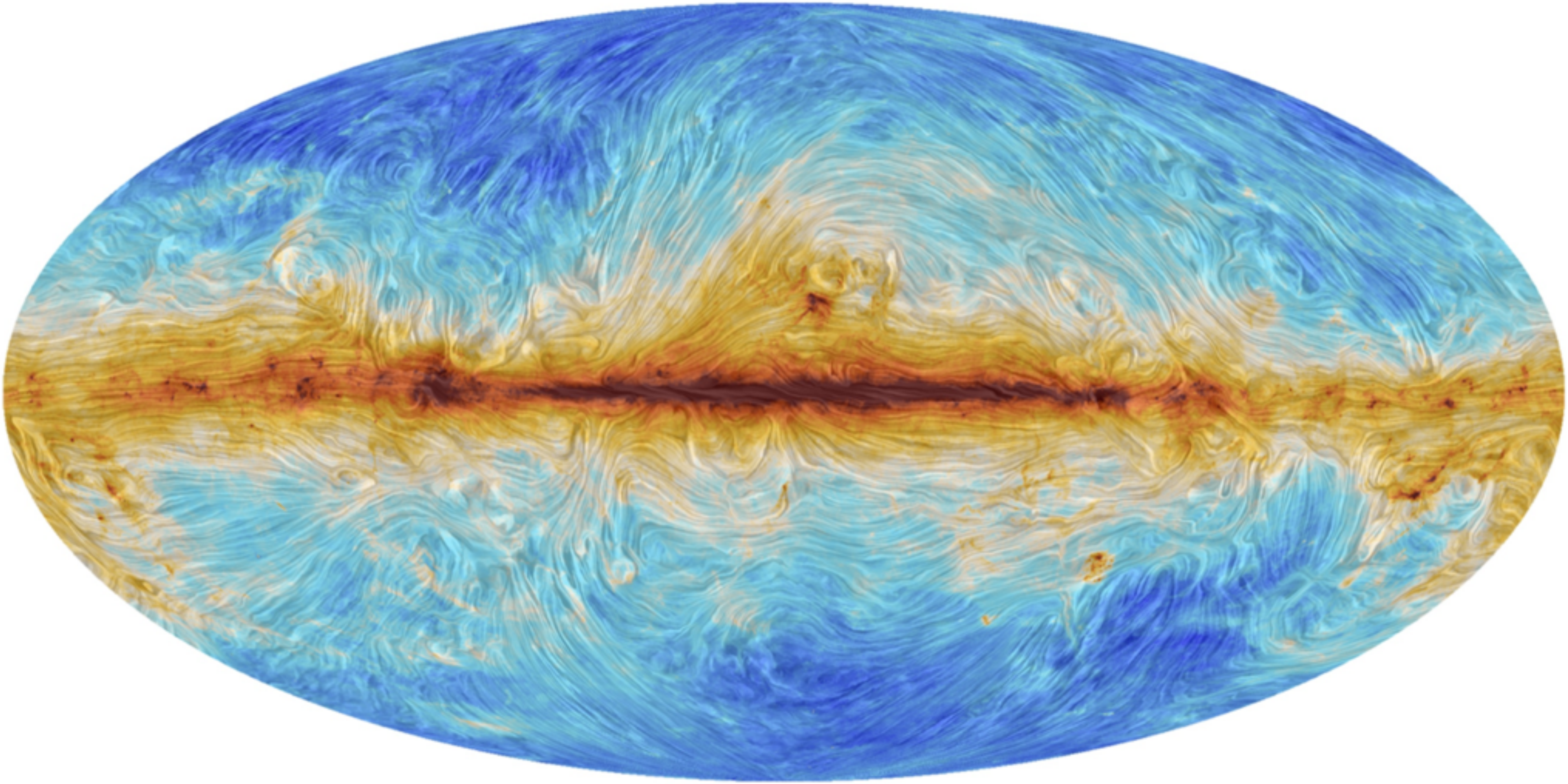
B-field from polarised Zeeman effect

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

Heiles & Troland, ApJ 624, 2005

Magnetic Fields in the ISM

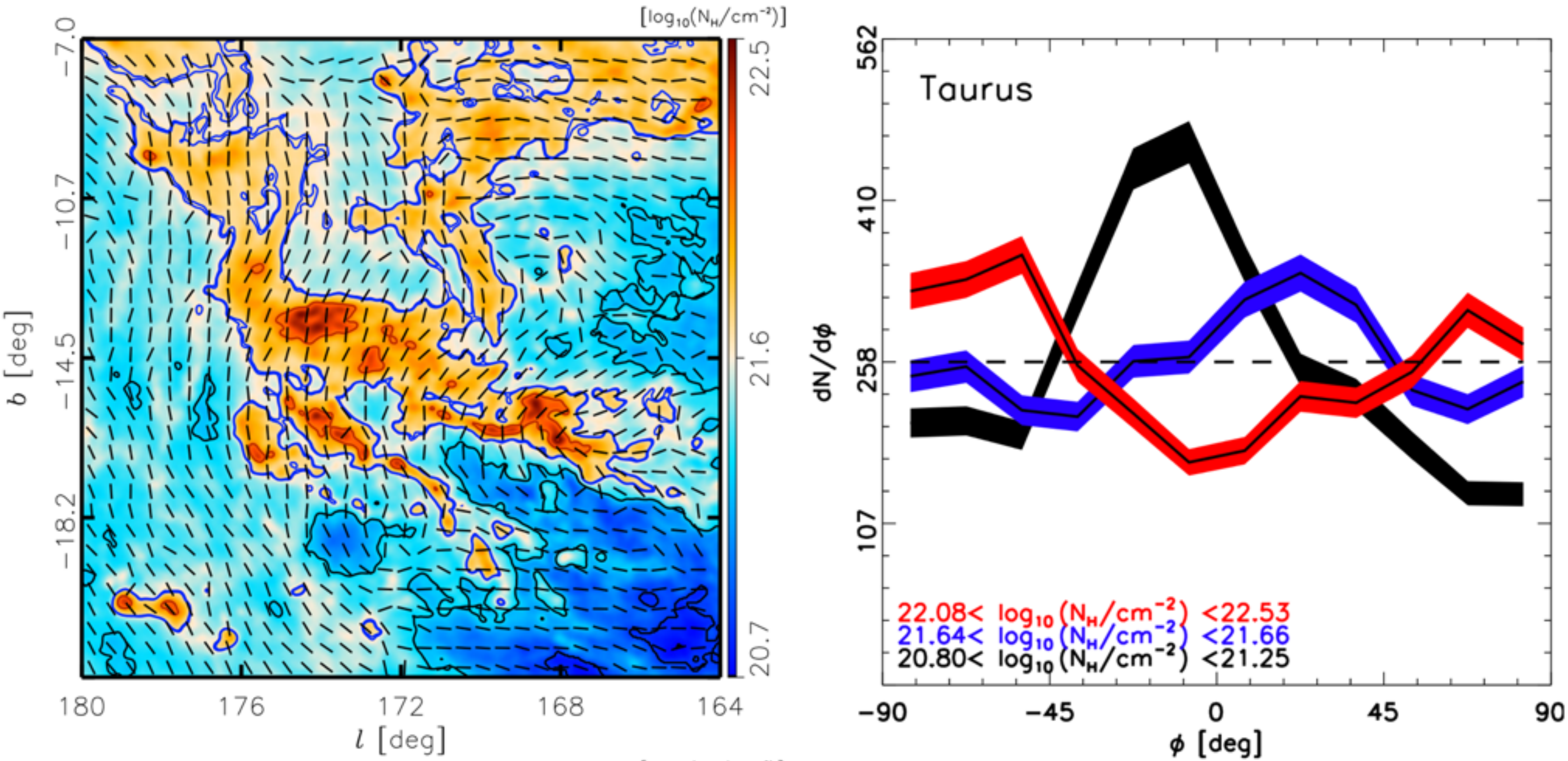
- PLANCK: magnetic field of the Milky Way from dust polarisation



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

Magnetic Fields in Molecular Clouds

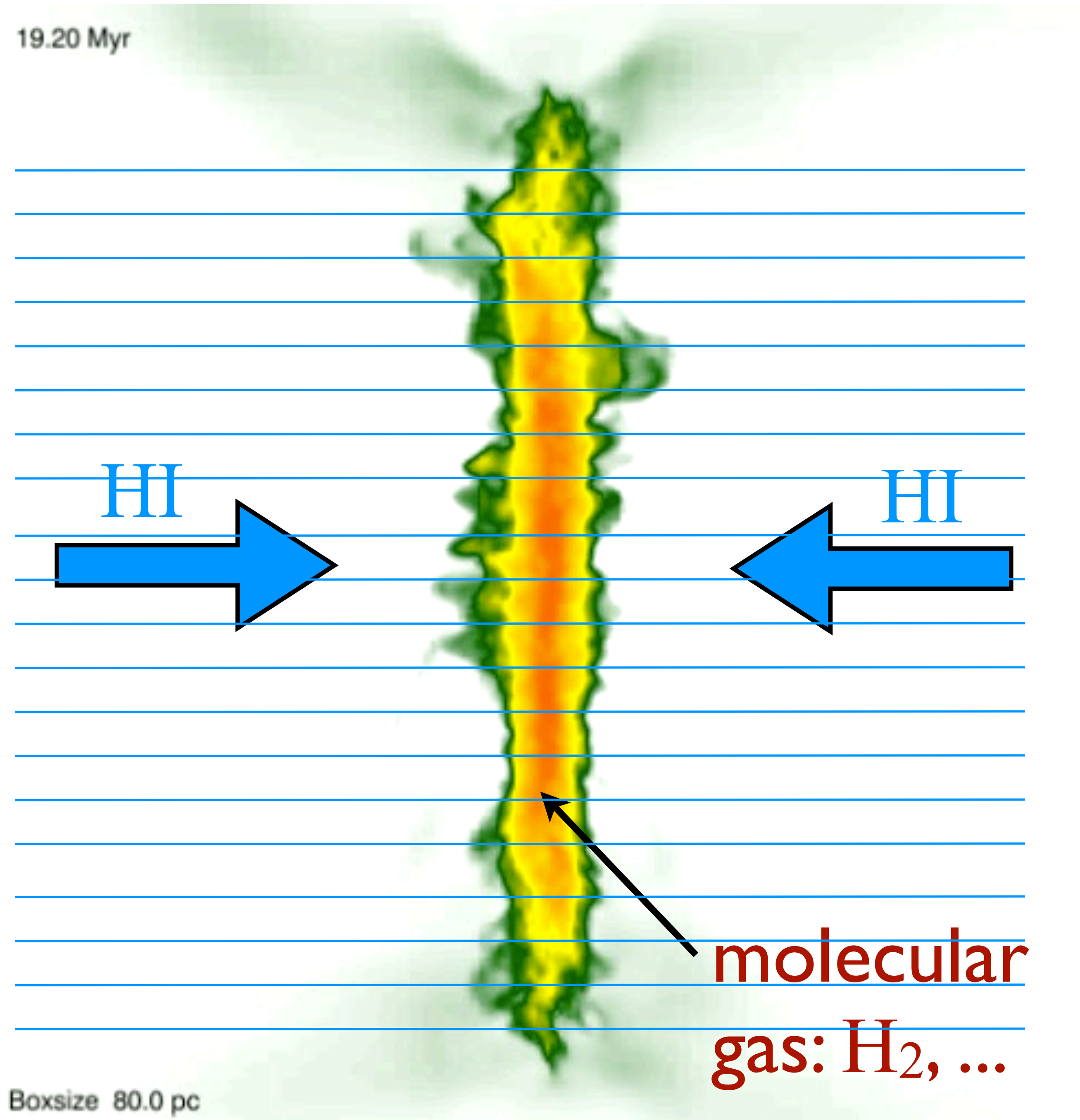
- PLANCK XXXV 2015: dust polarisation in molecular clouds

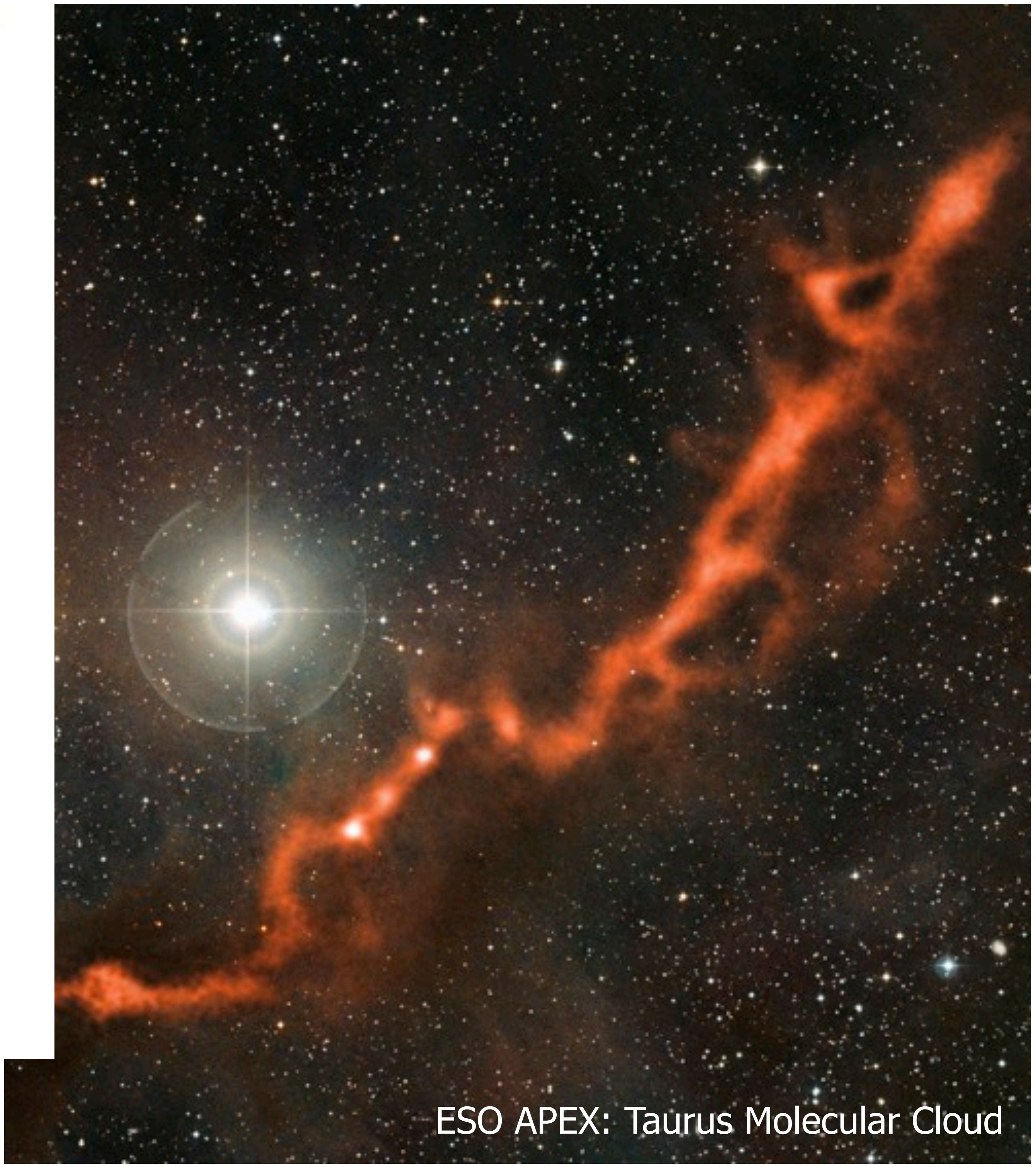


$\Longrightarrow$ magnetic fields are dynamically important

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

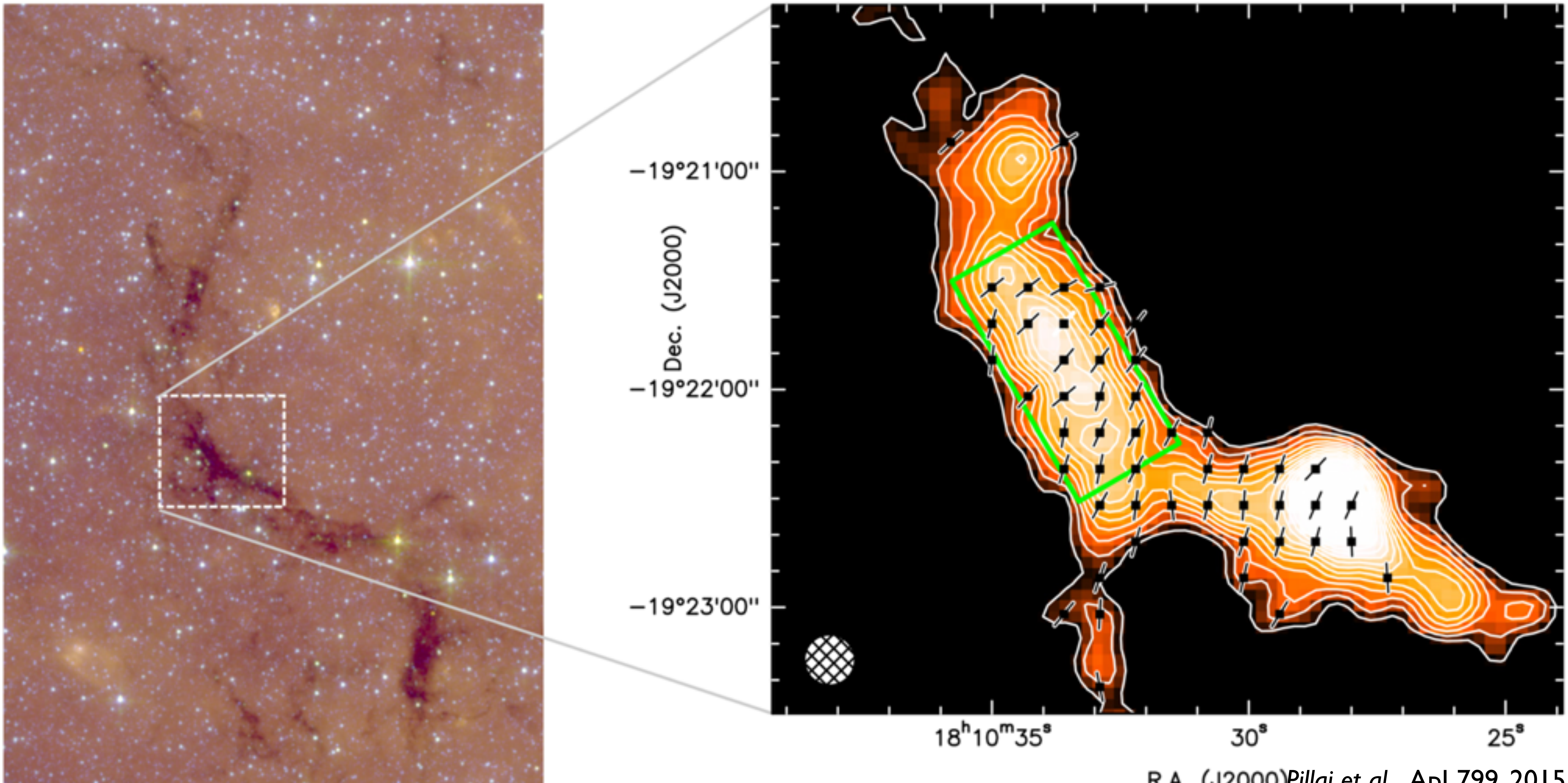
Formation of Molecular Clouds





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

Magnetic Fields in Molecular Clouds

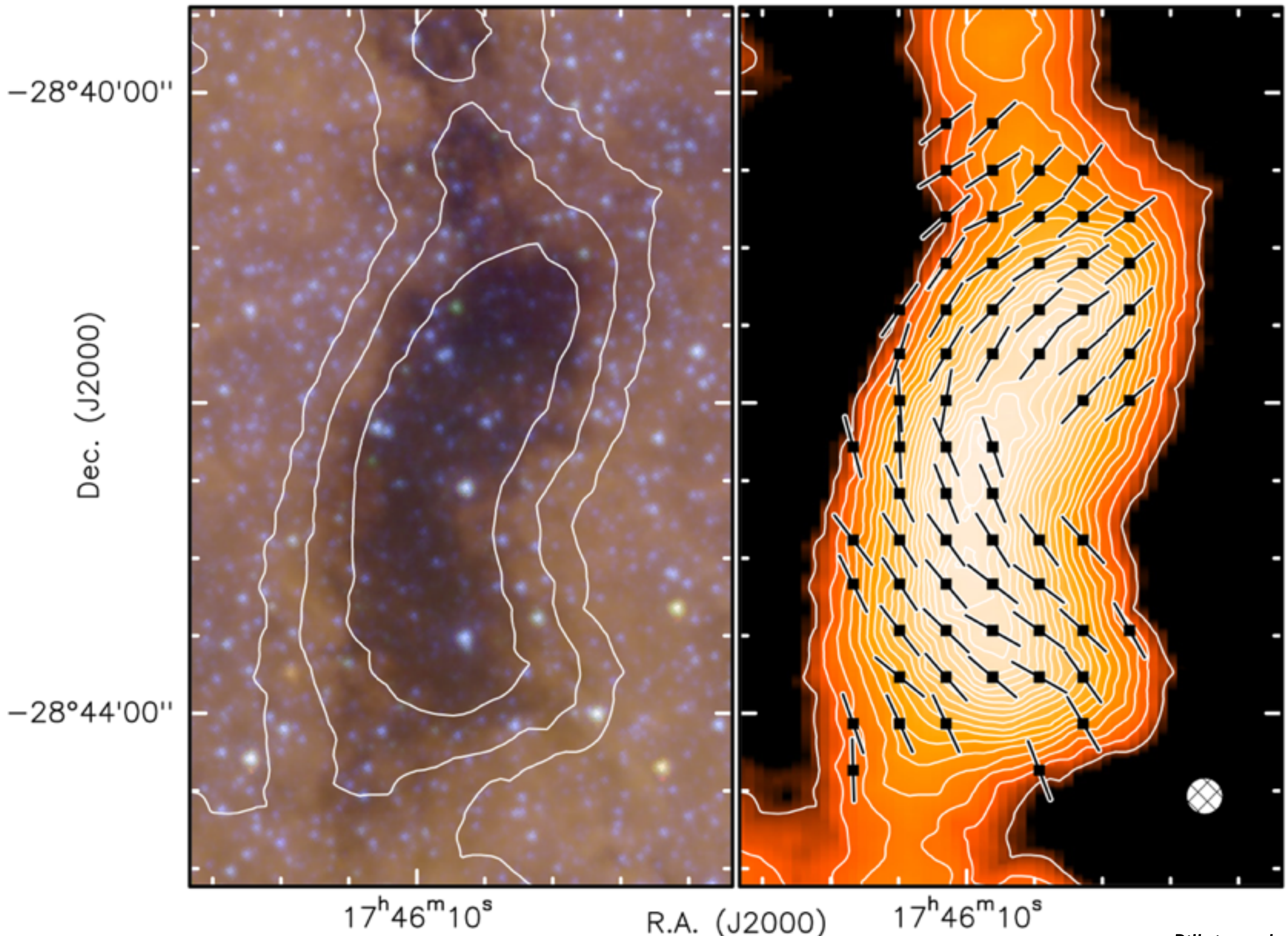


Pillai et al., ApJ 799, 2015

polarisation measurement of G11.11-0.12

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

Magnetic Fields in Molecular Clouds

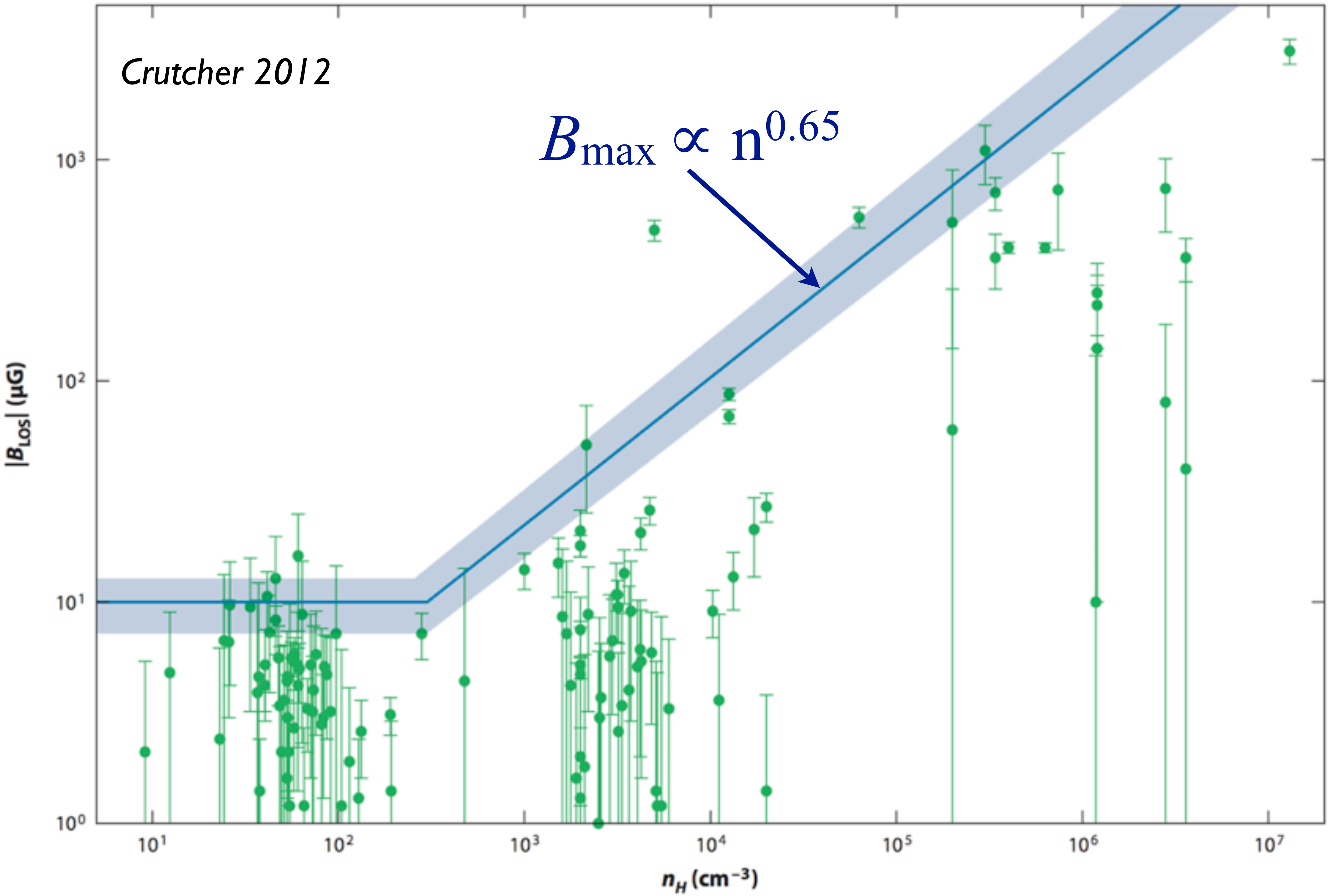


Pillai et al., ApJ 799, 2015

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

Magnetic Fields in the ISM

- stronger magnetic fields in dense regions

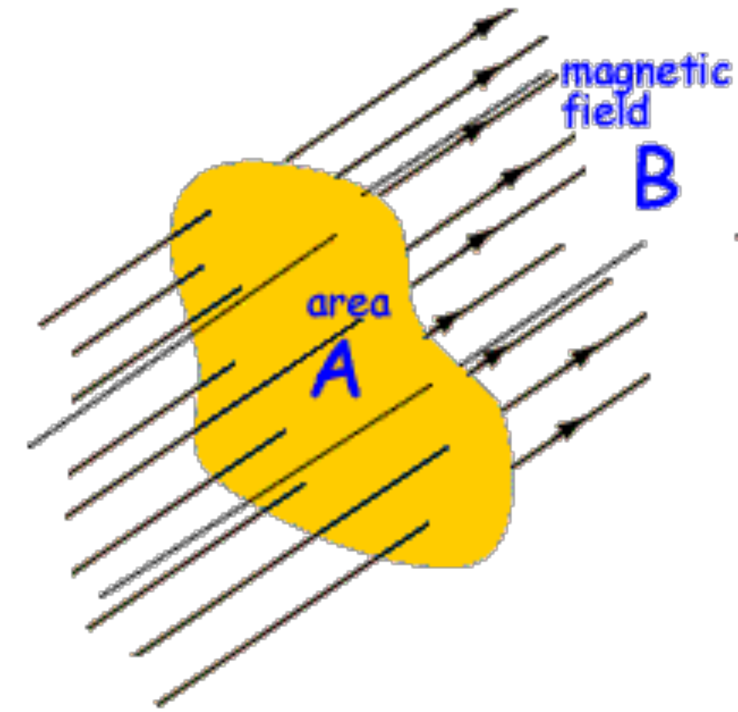


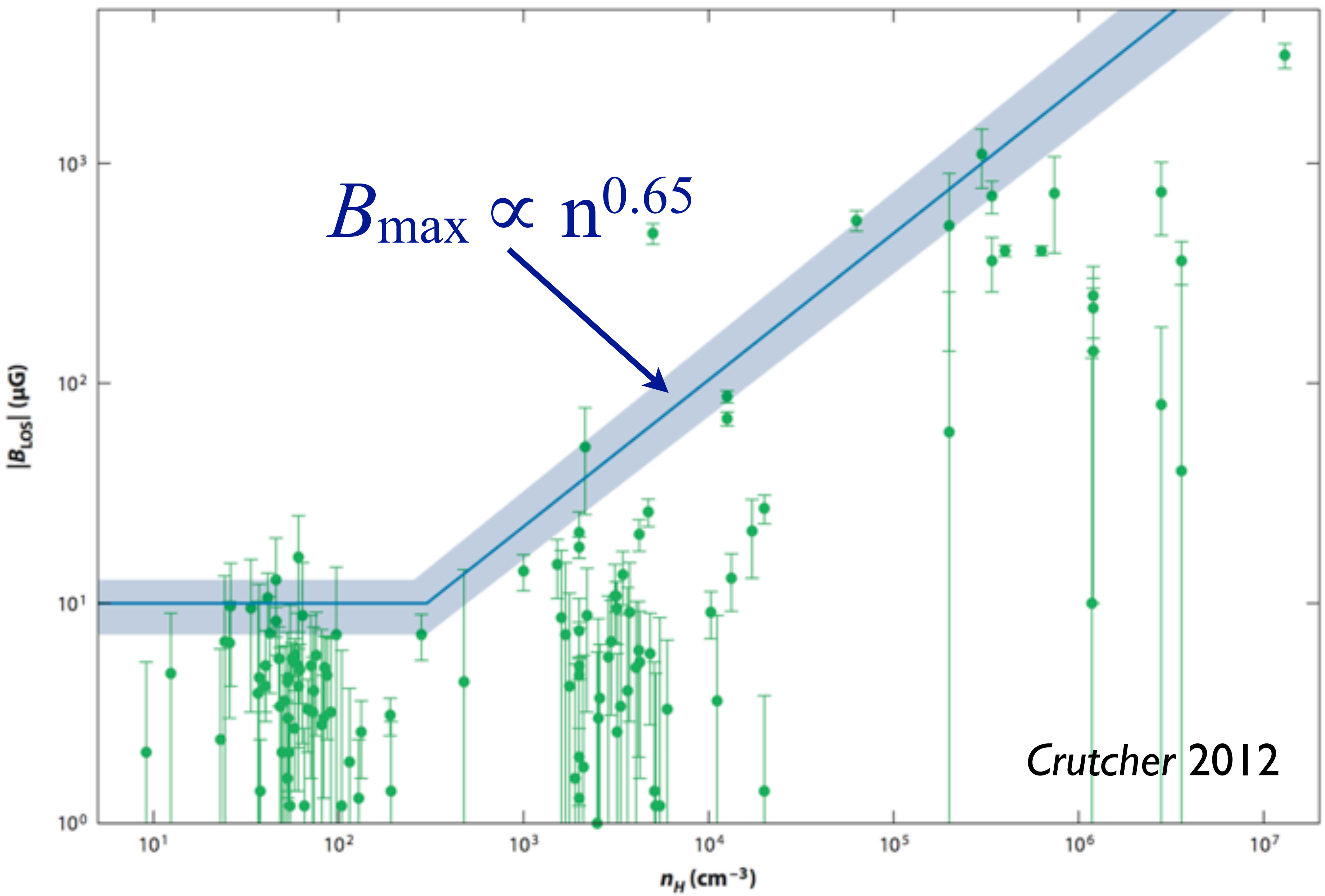
Magnetic Fields in the ISM

- stronger magnetic fields in dense regions

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

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





- spherical compression:

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

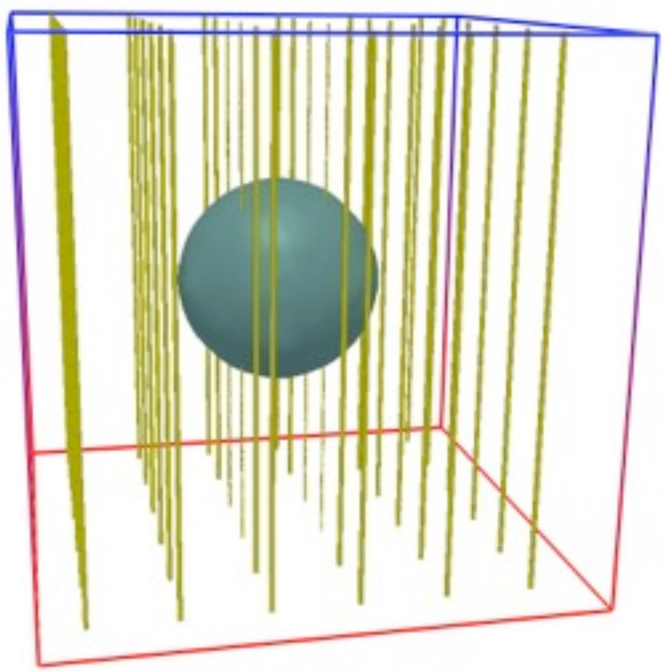
$\rightarrow$ $\Phi \propto l^2 B = \text{const}$

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

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:

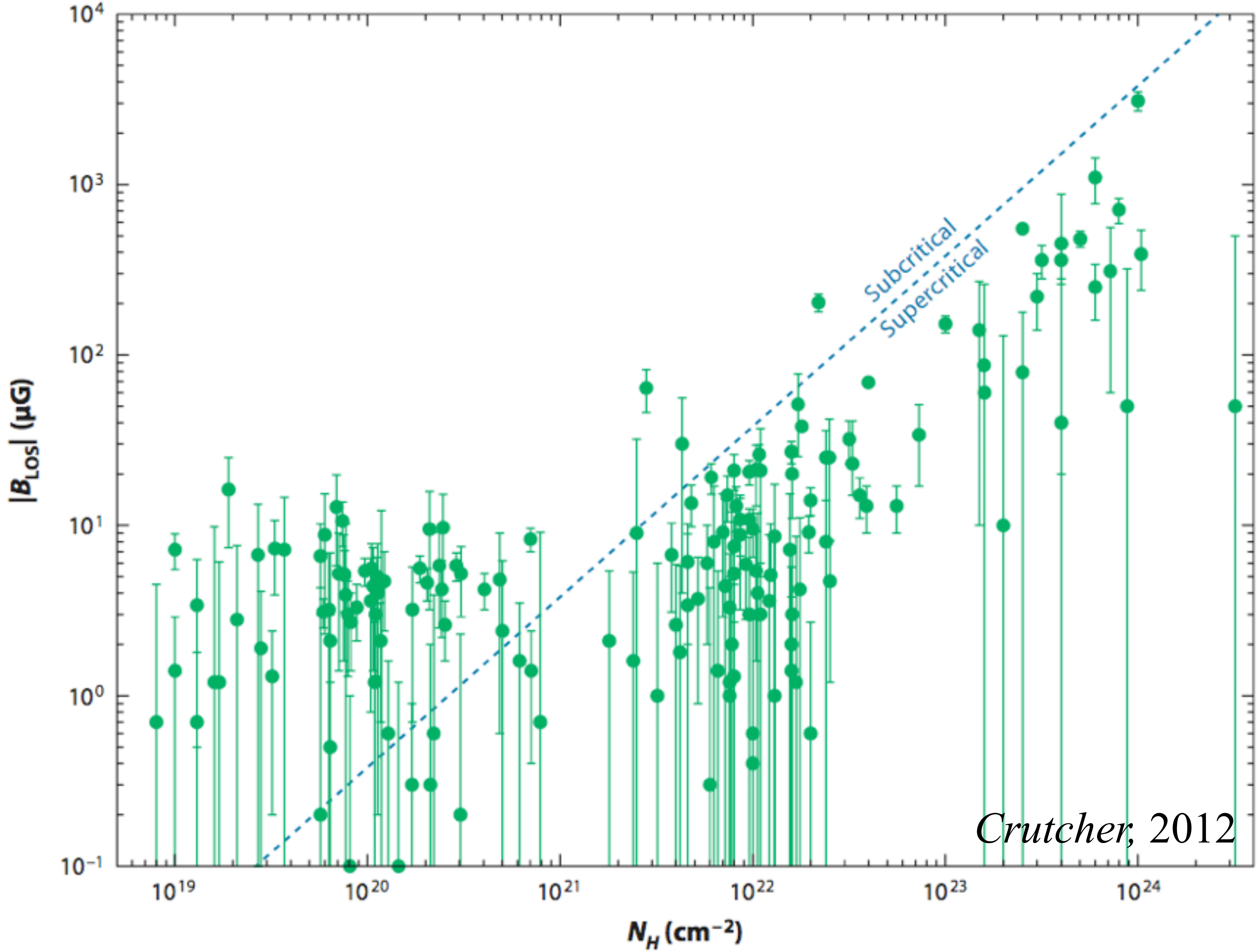
$$\mu_{\rm crit} = 0.13/\sqrt{G}$$

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



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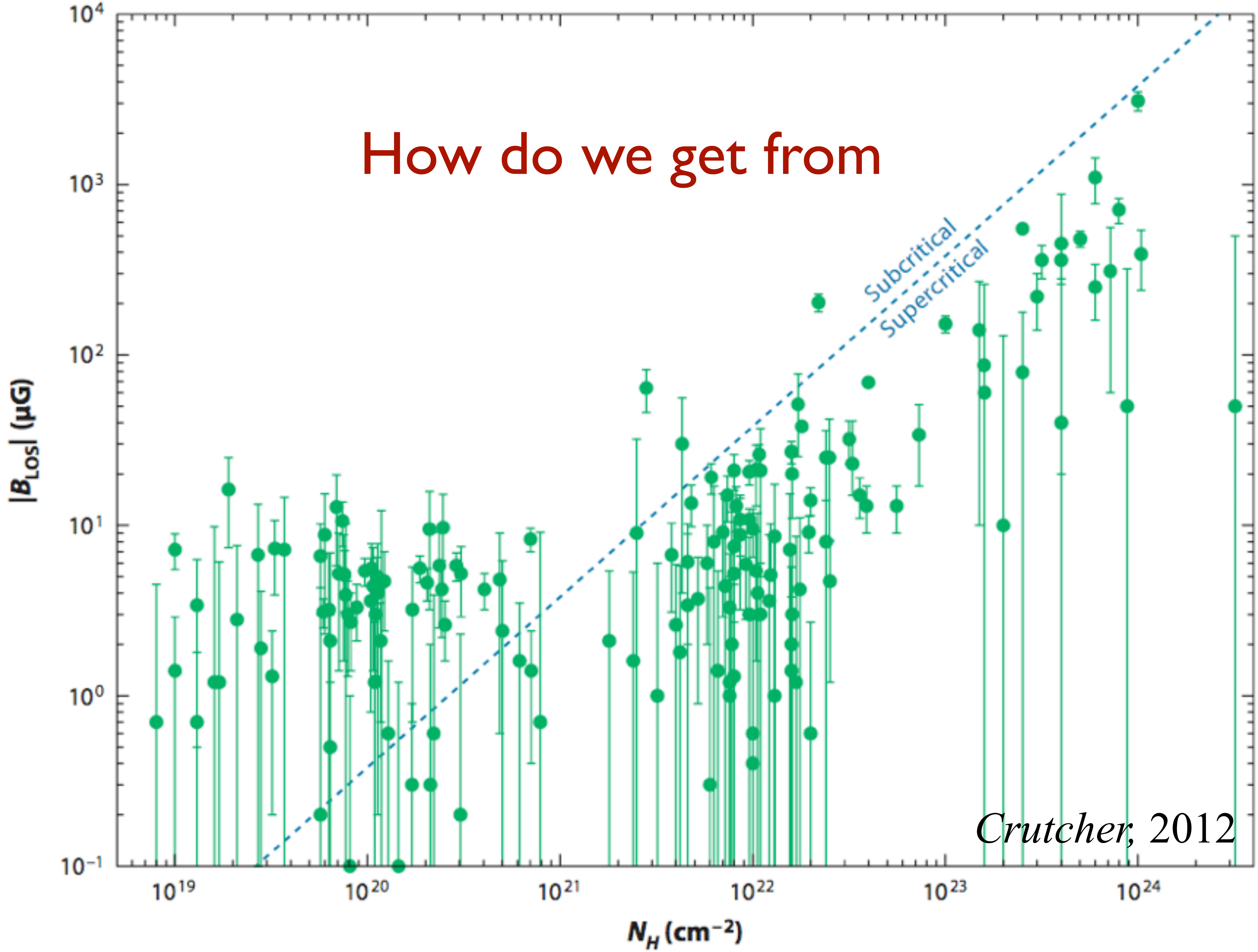
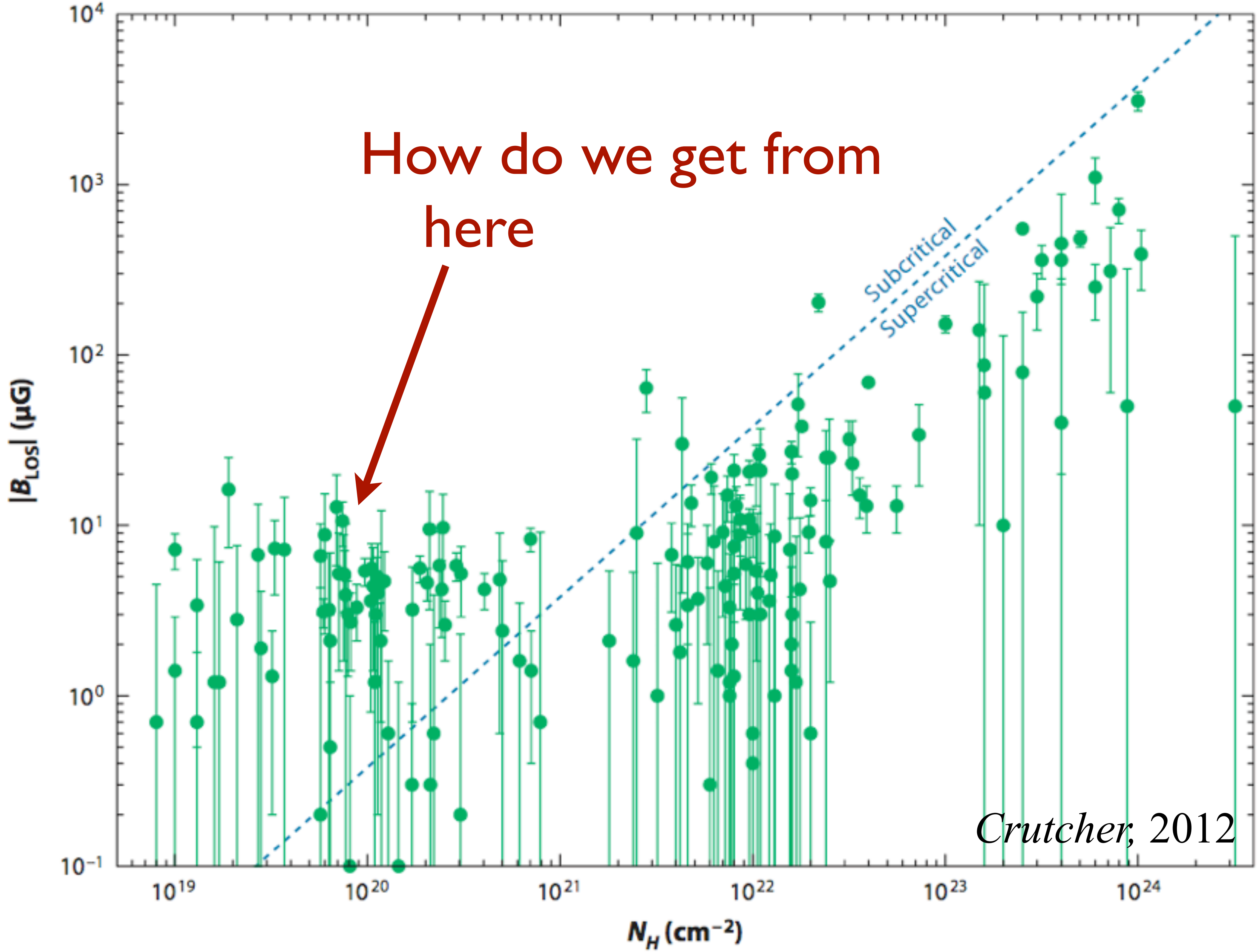


, Robi Banerjee

Magnetic Fields in the ISM



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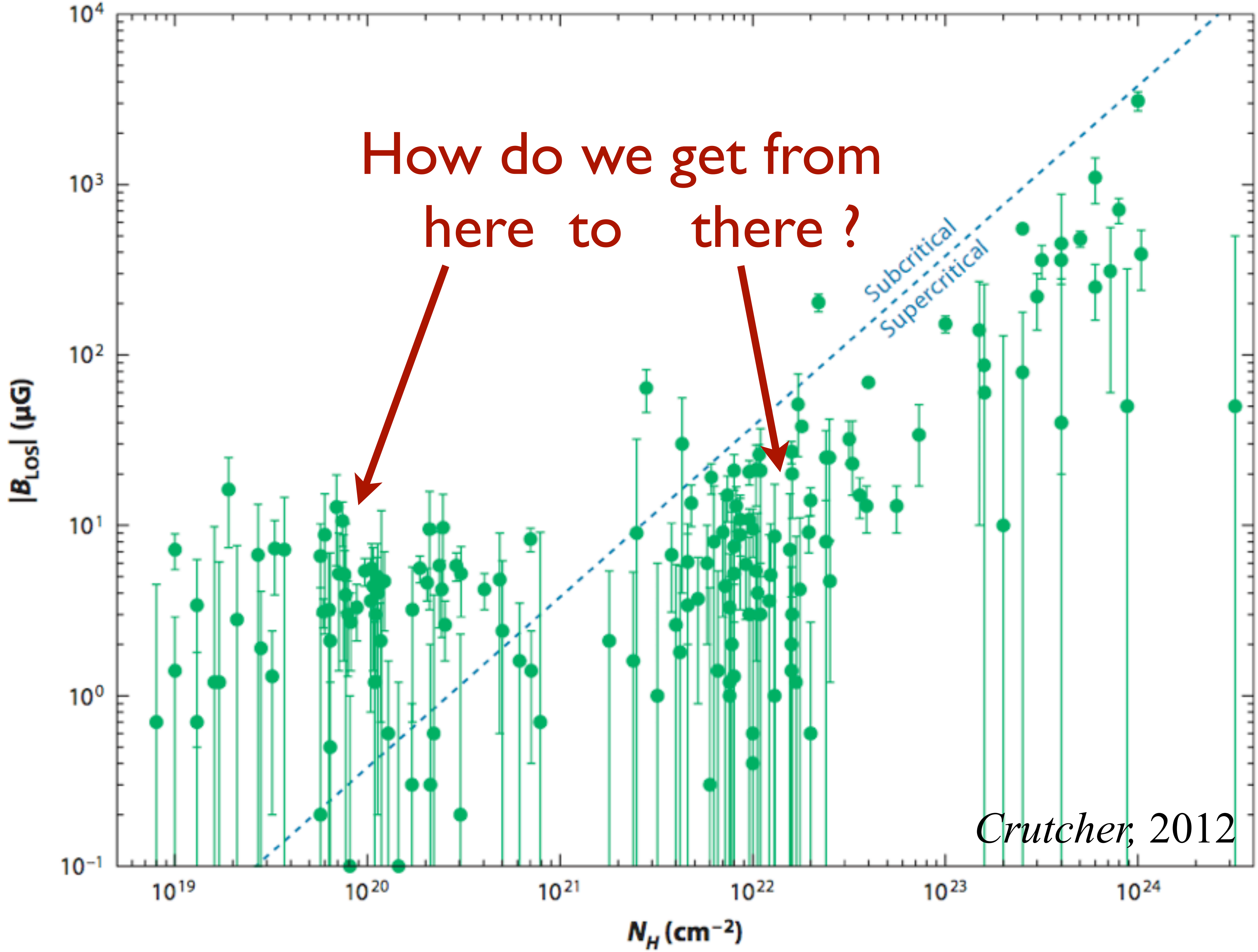
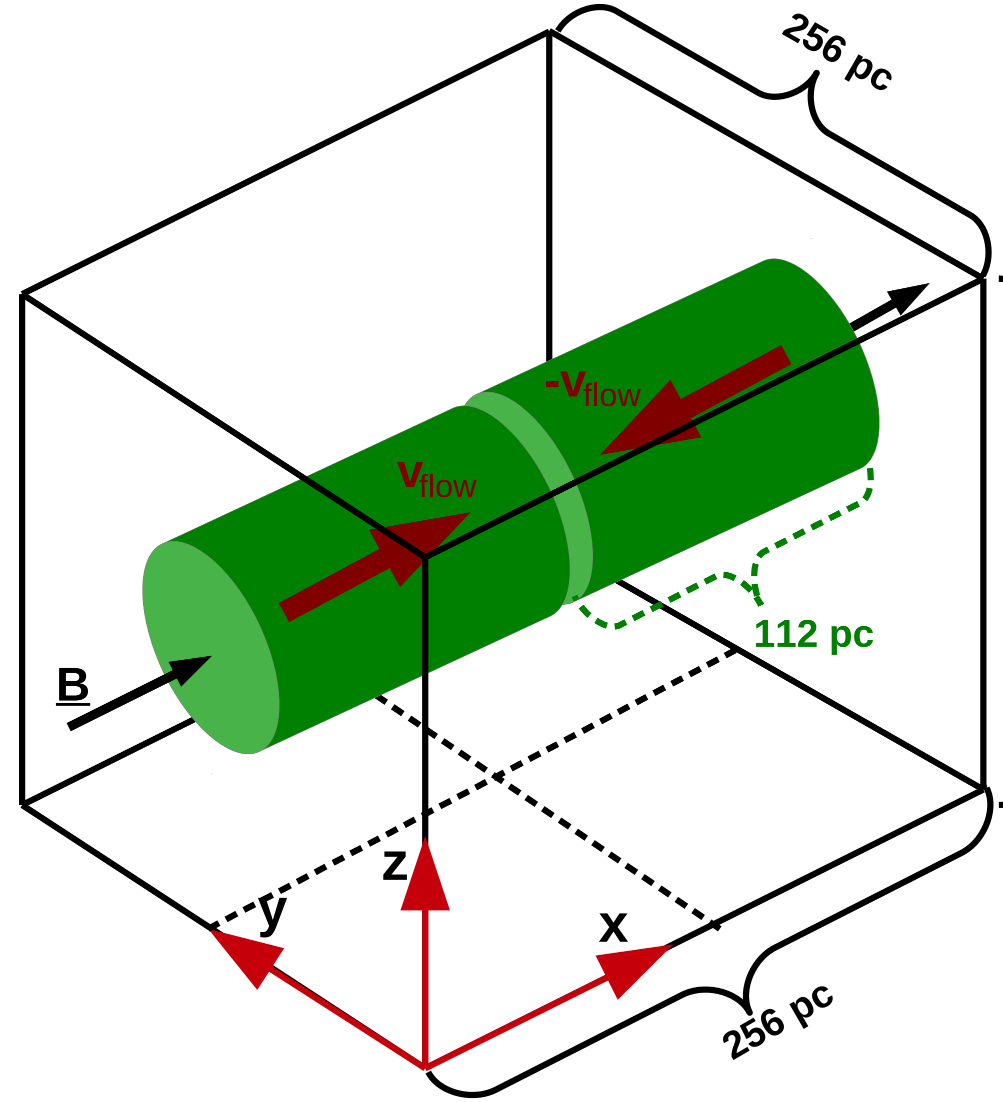


Impact of Magnetic Fields on MCs

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:

$L_{\rm acc} \approx 1.2$ 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)
  - ...

- **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

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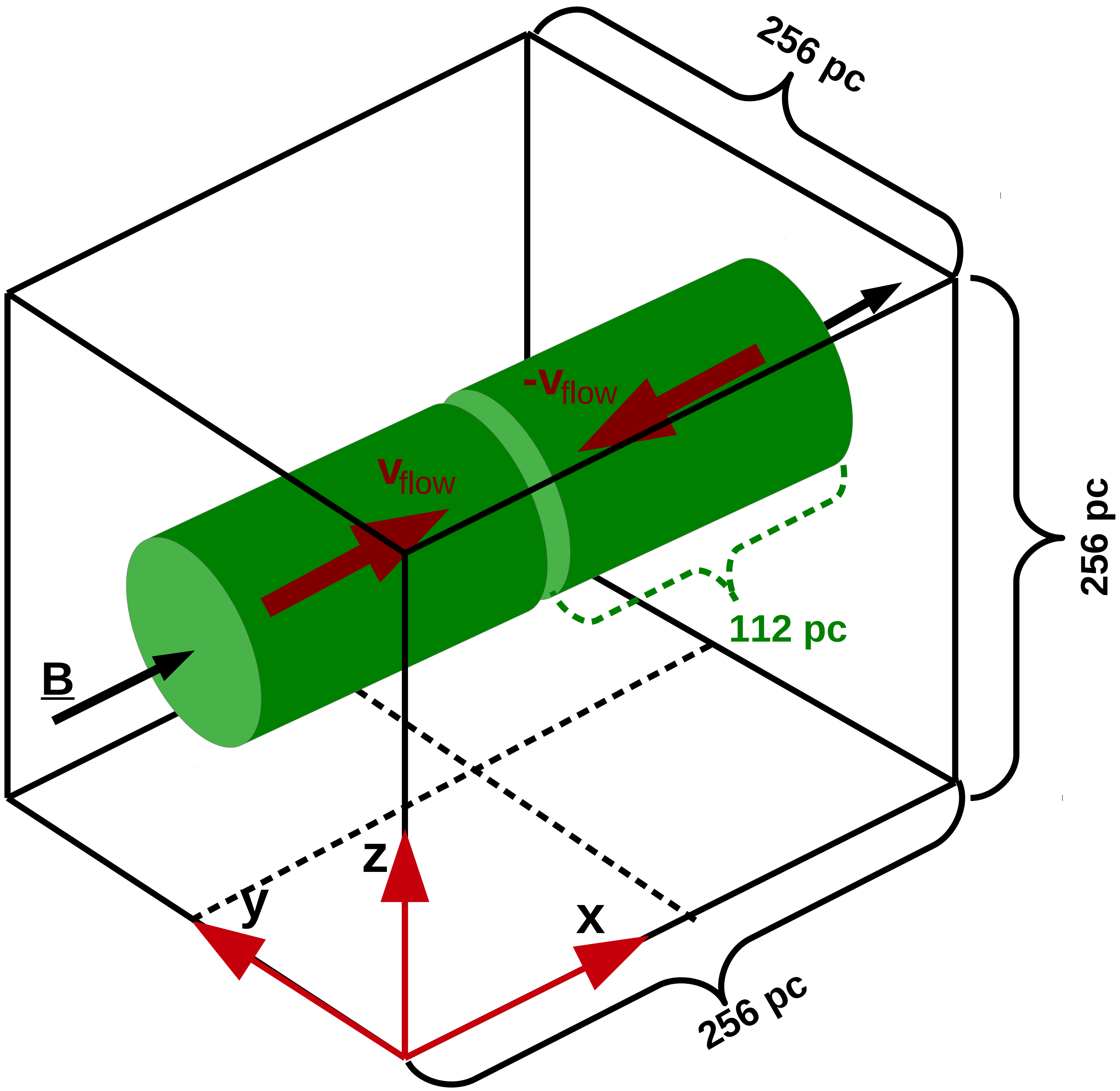
  $\Longrightarrow$ **correct assumption ?**

Simulations of colliding flows

MC formation & star formation



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

Model parameter:

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

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

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

+ turbulence:

  $v_{\text{turb}} = 0.2 \ldots 12$ km/sec

+ ambipolar diffusion

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

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

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

Simulations of colliding flows

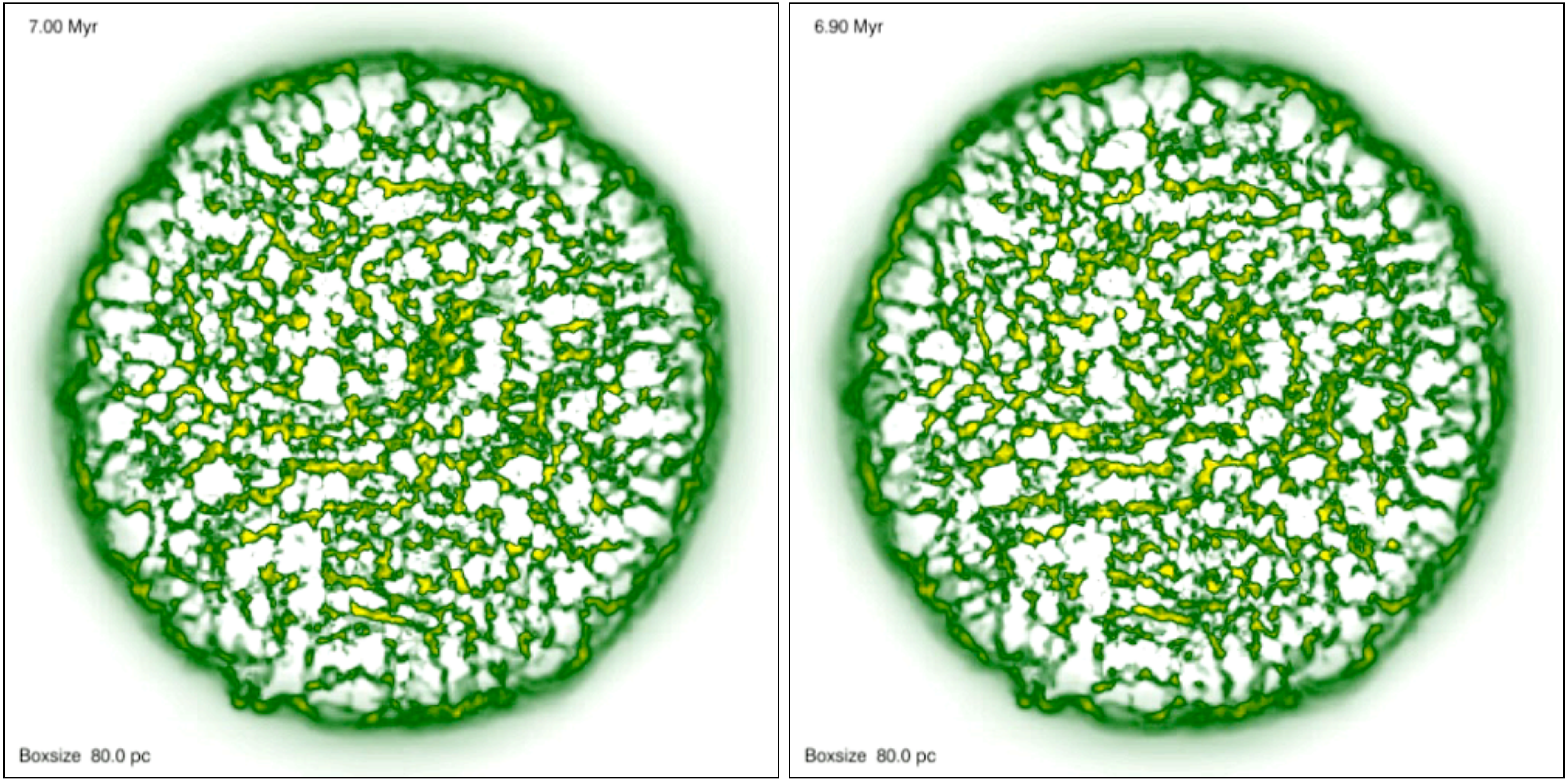
influence of magnetic fields

B = 3μG

B = 4μG

Simulations of colliding flows

influence of ambipolar diffusion



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

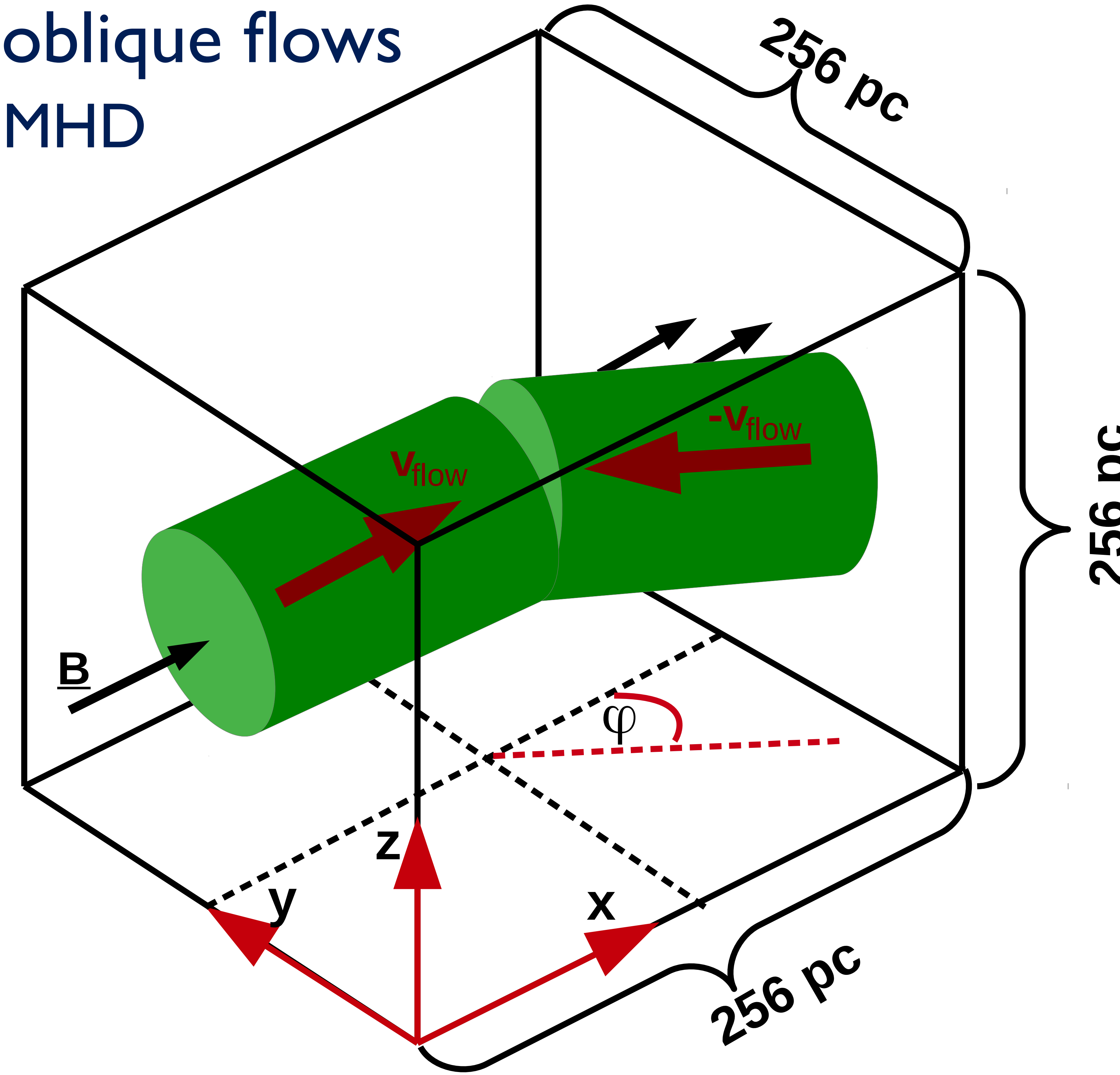
Simulations of oblique flows

Simulations setup of oblique flows

$\Longrightarrow$ resemble non-ideal MHD

Model parameter:

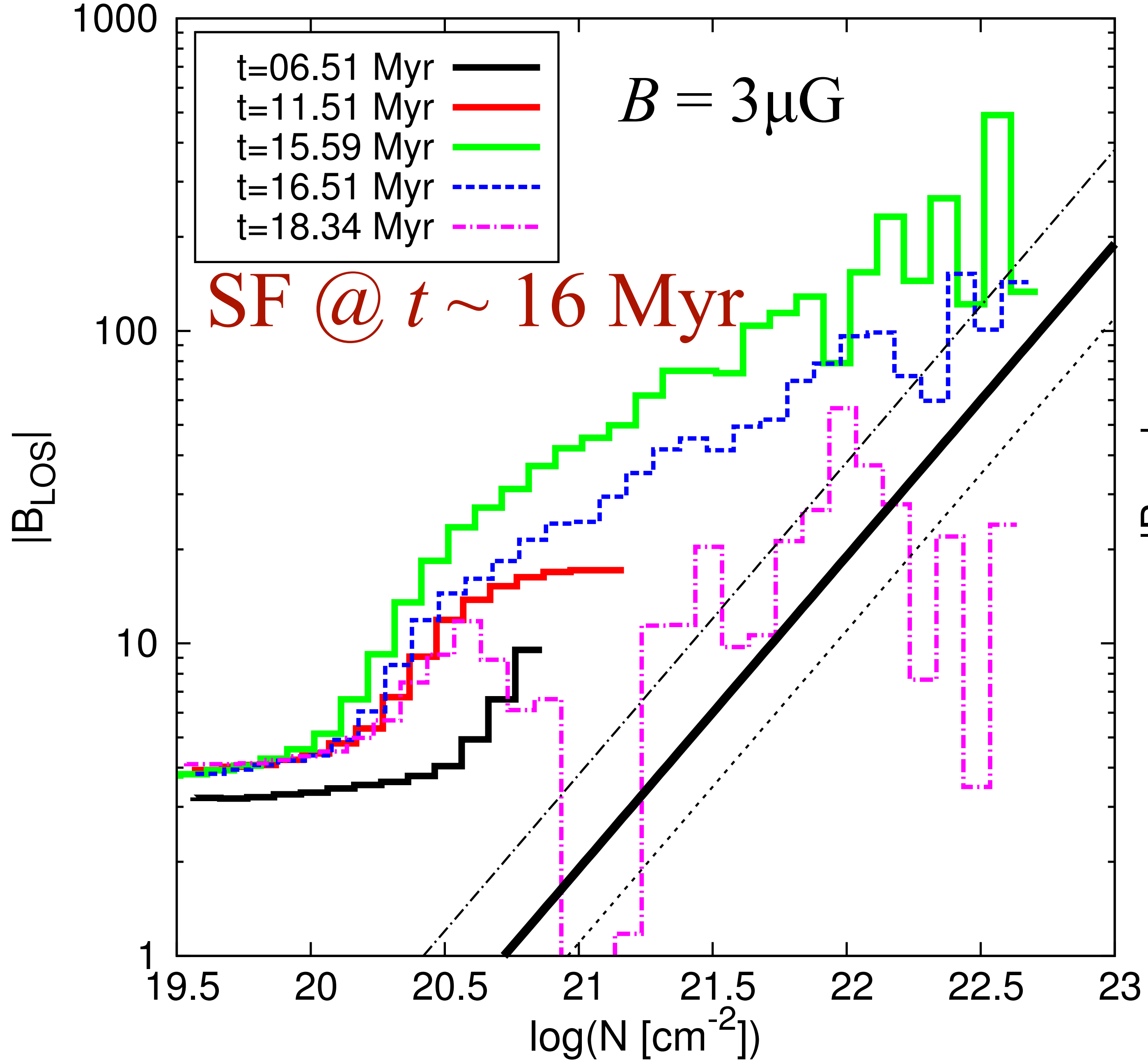
- $\varphi = 0, 30, 60$
- $n = 1 \ldots 10\ \mathrm{cm}^{-3}$
- $r = 32 \ldots 64$ pc
- $v_{\mathrm{inf}} = 14$ km/sec
- $v_{\mathrm{turb}} = 2..10$ km/sec
- $B_{\mathrm{x}} = 1 \ldots 5\ \mu\mathrm{G}$

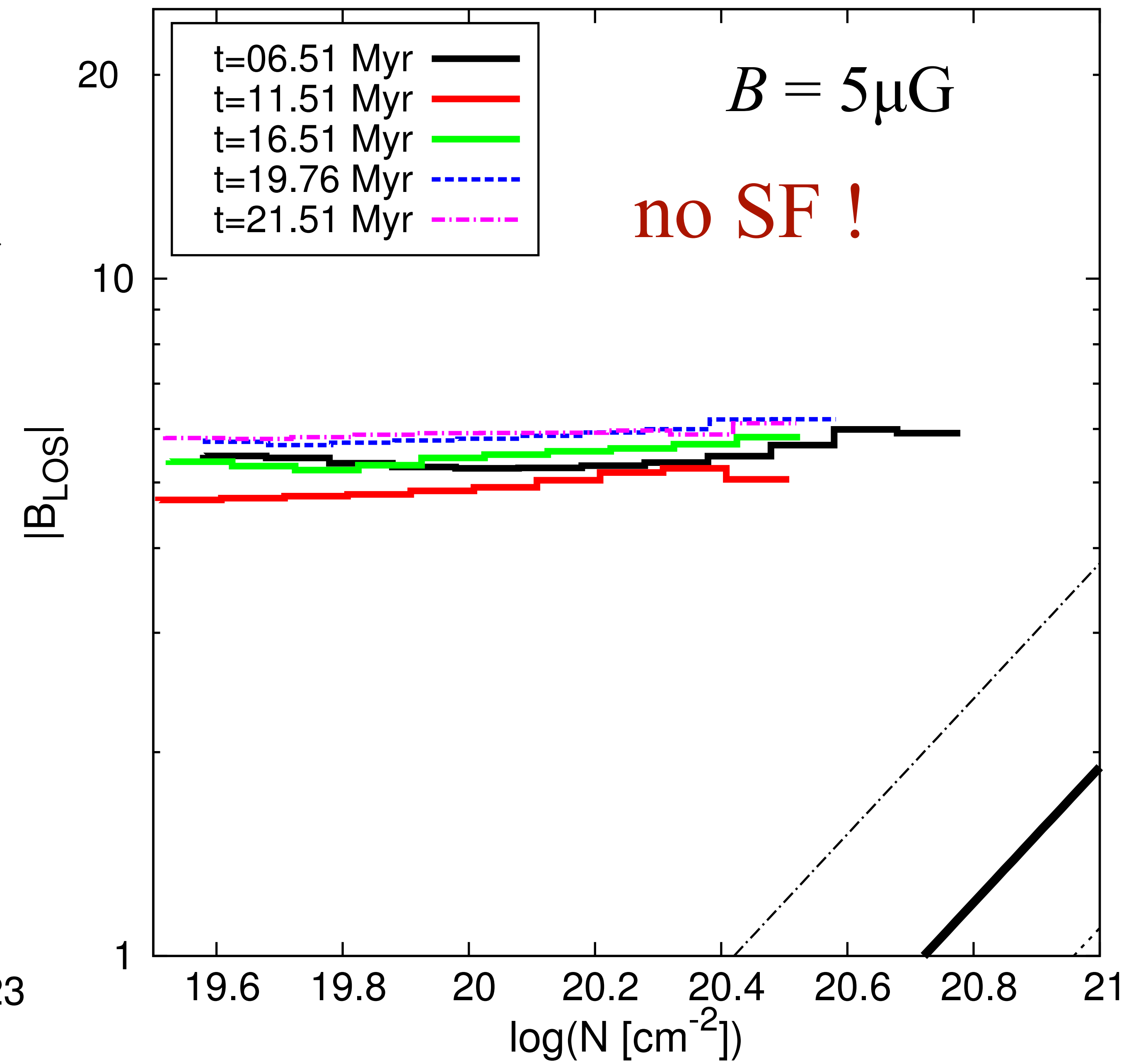


B. Körtgen & RB, MNRAS (2015)

Simulations of oblique flows

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

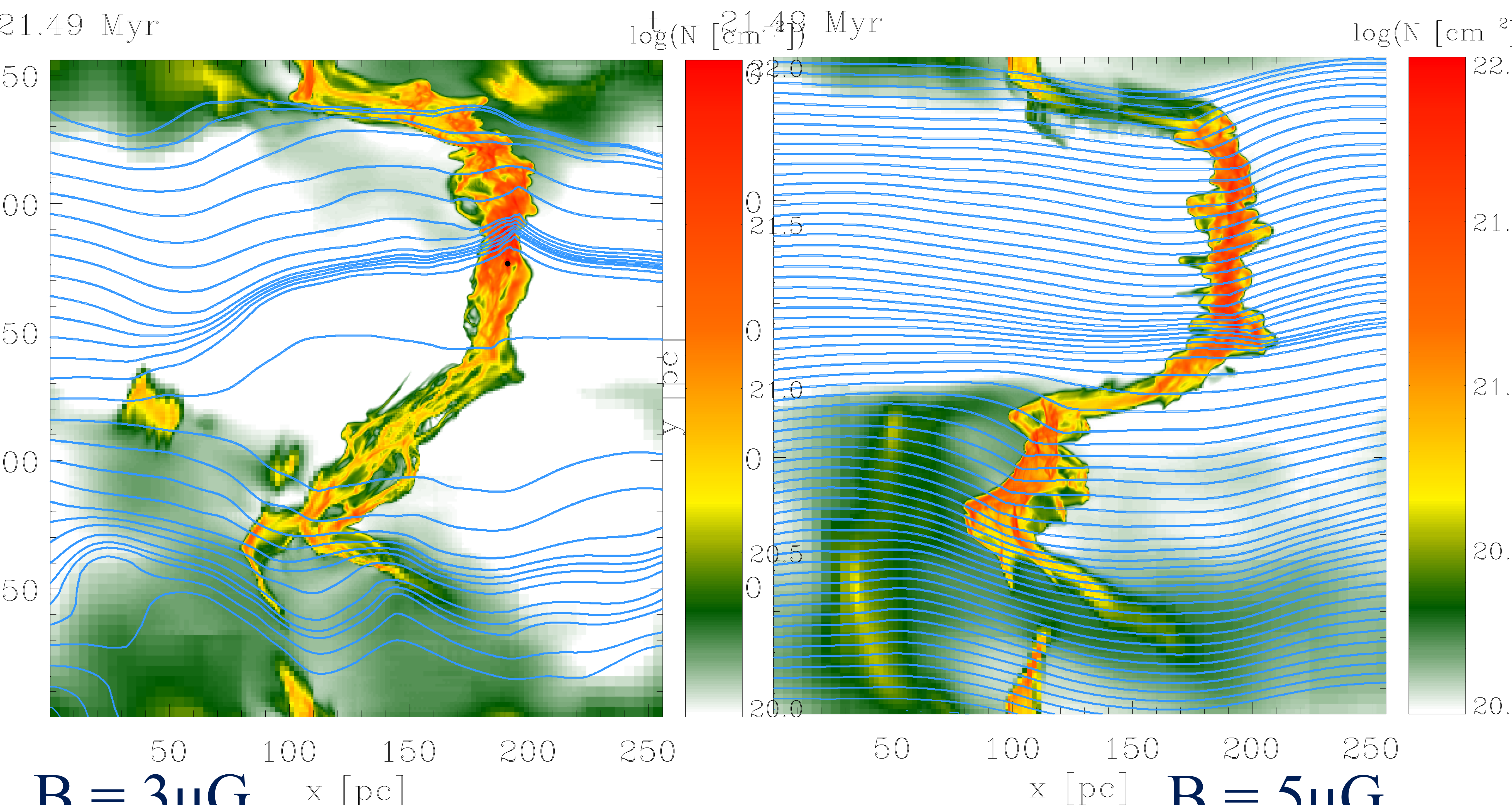




B. Körtgen & RB, MNRAS (2015)

Simulations of oblique flows

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

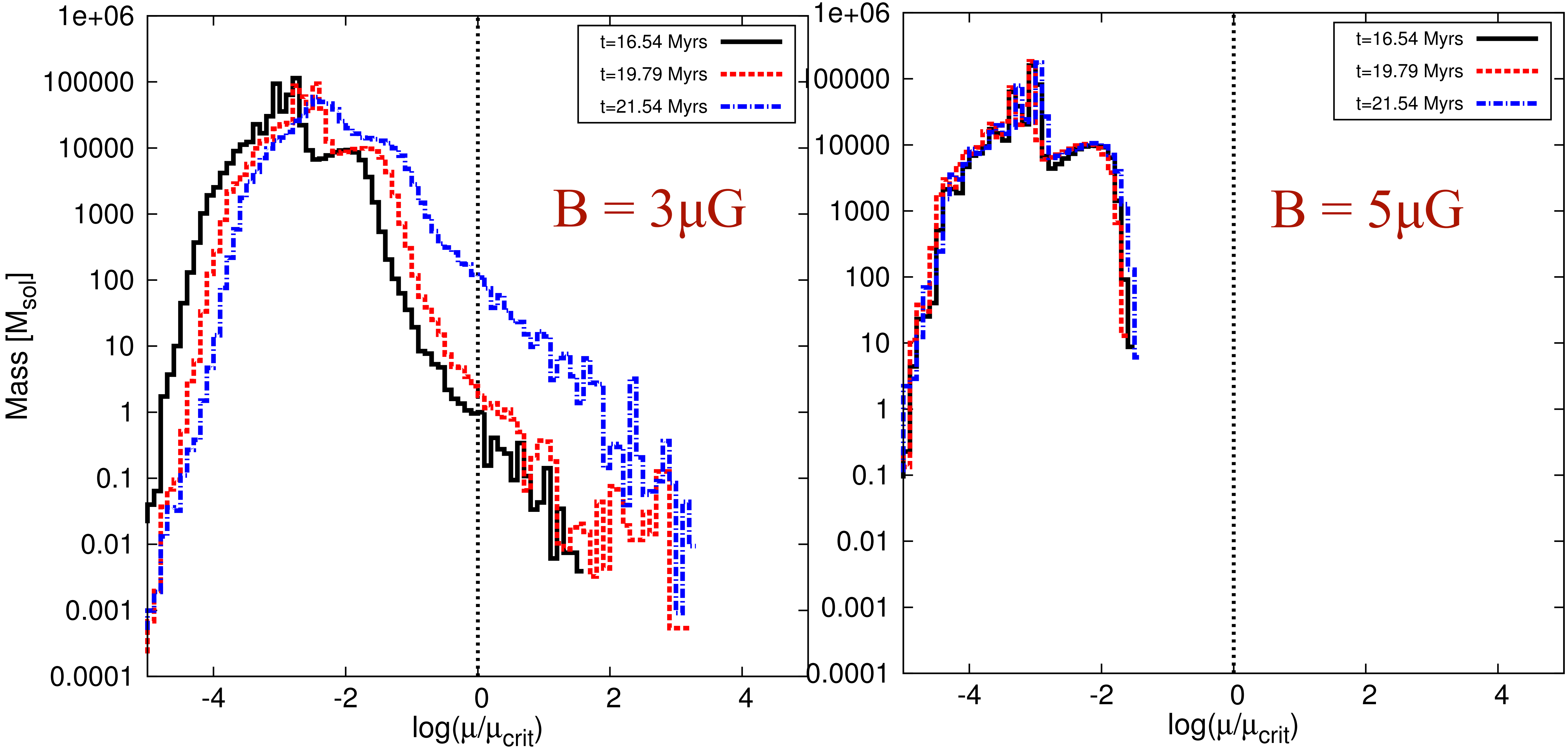


B = 3μG

B = 5μG

Simulations of oblique flows

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



B. Körtgen, RB, MNRAS (2015)

Simulations of oblique flows

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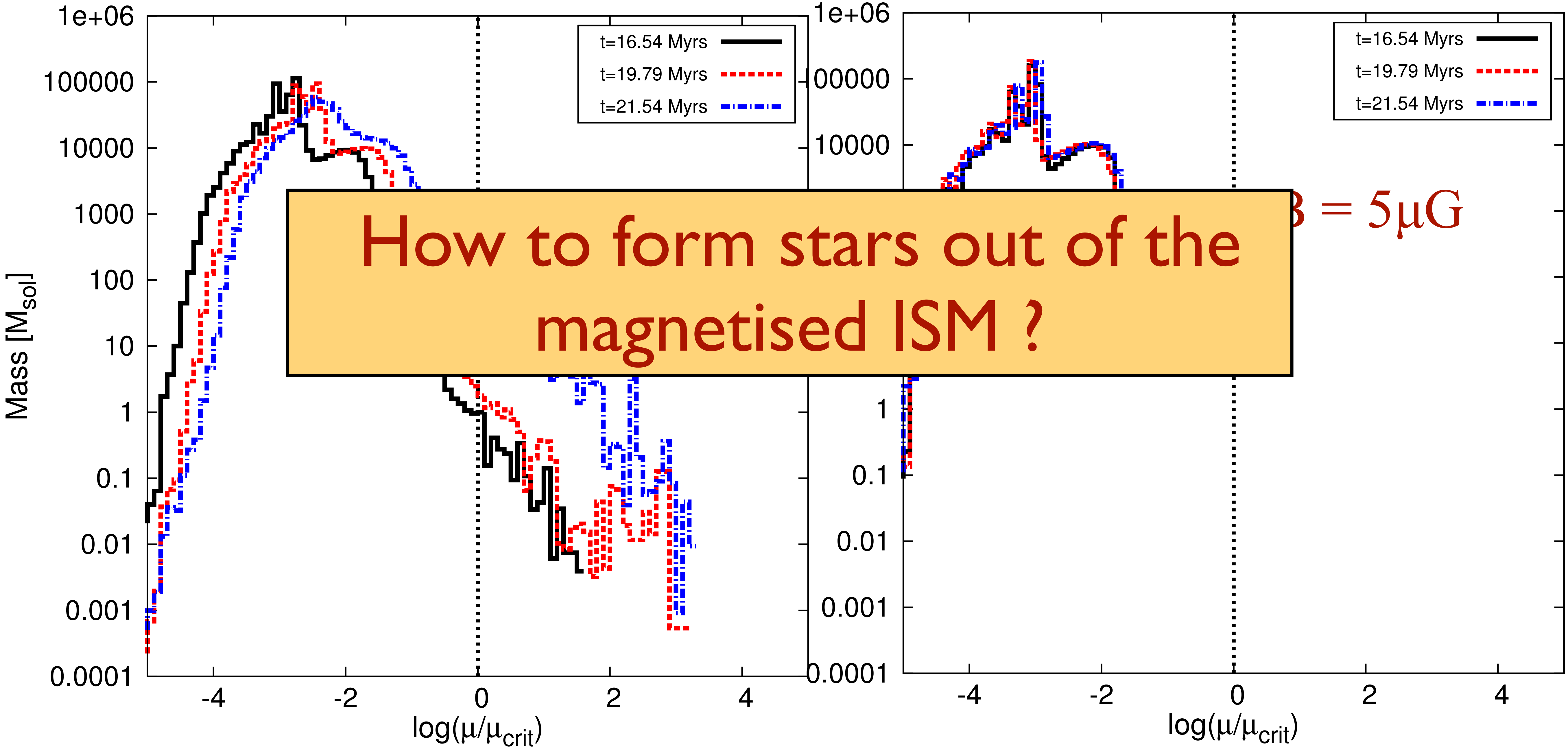
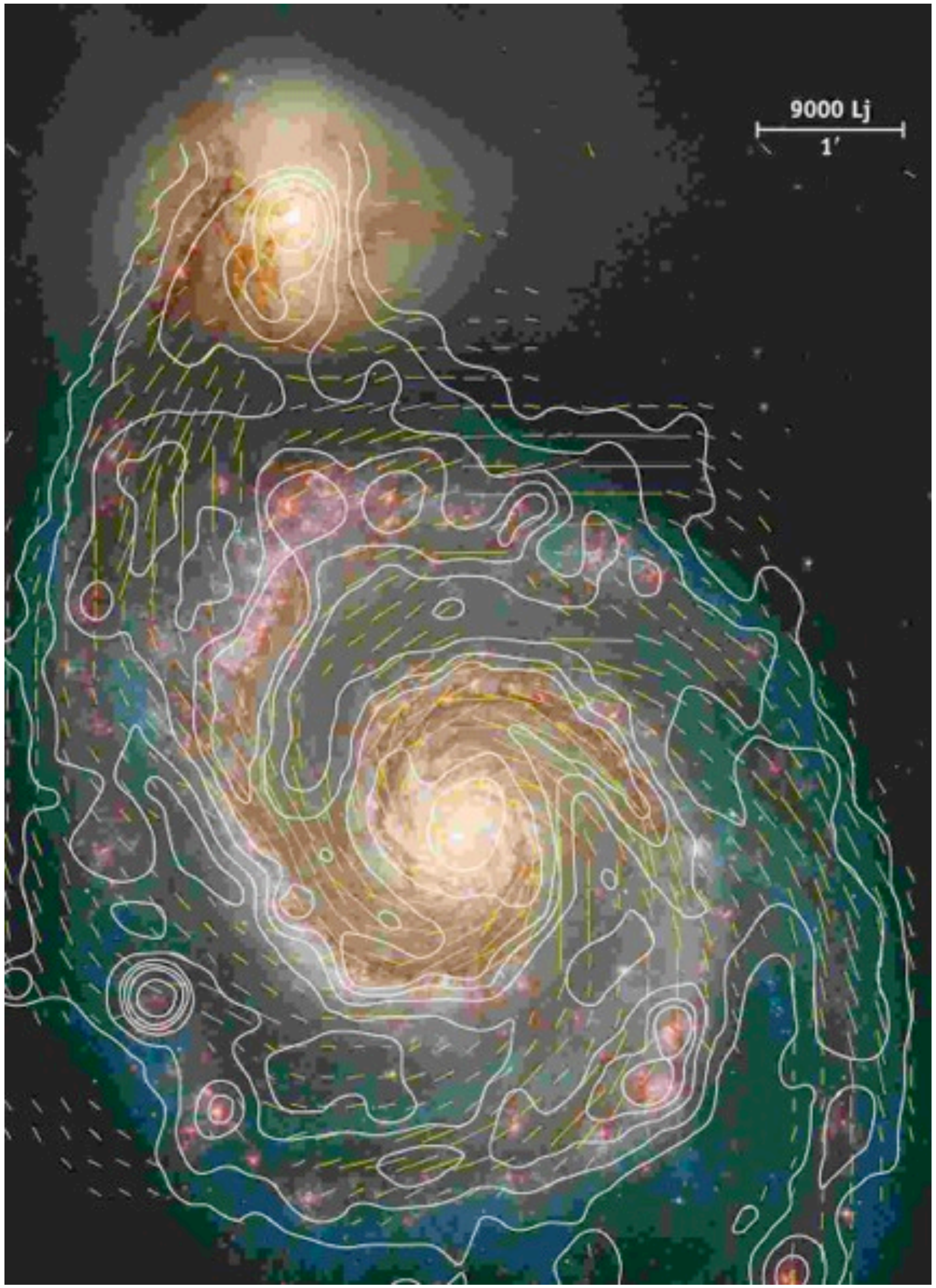
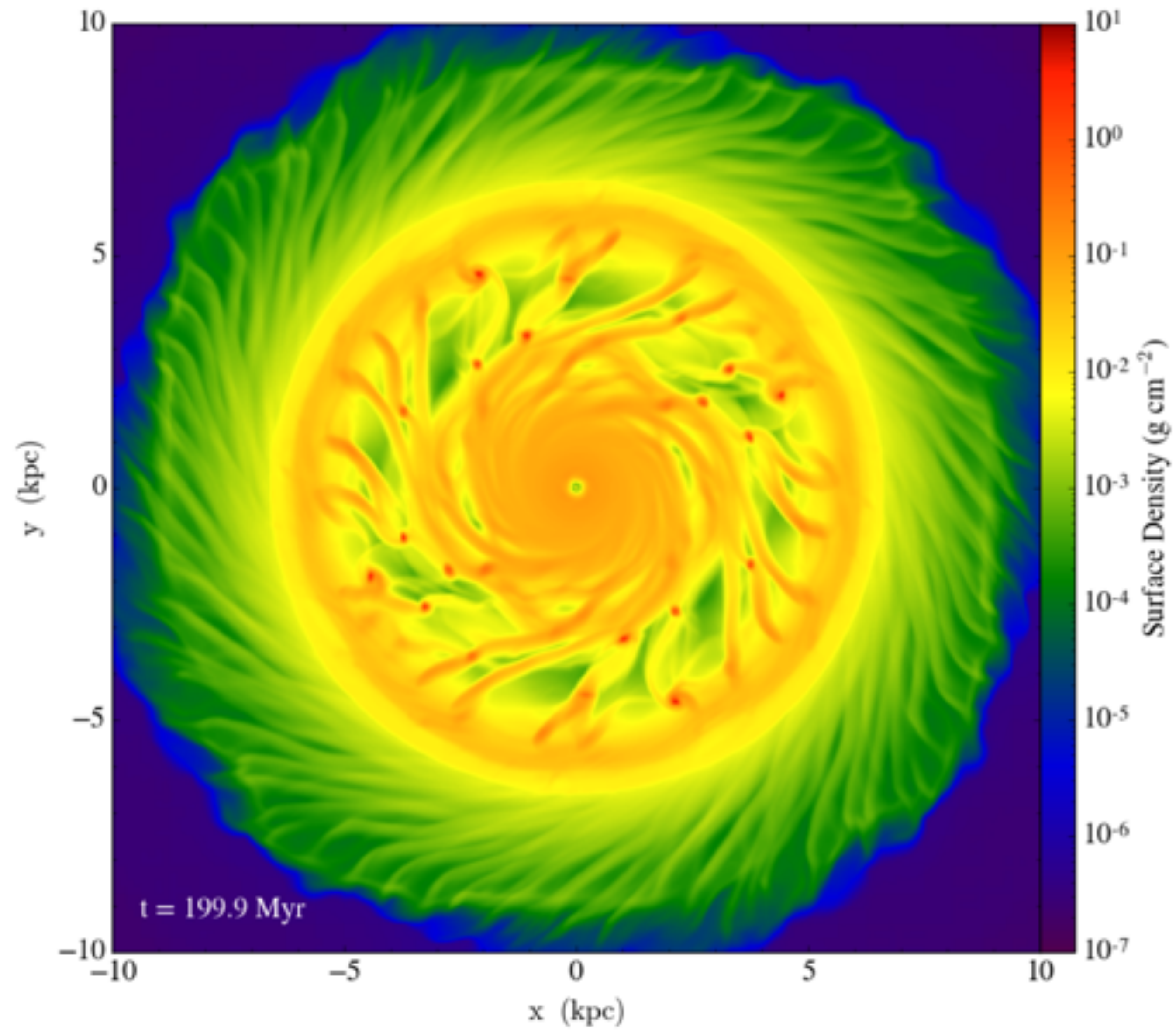


How to form stars out of the magnetised ISM ?

B. Körtgen, RB, MNRAS (2015)

Global Galactic Simulations

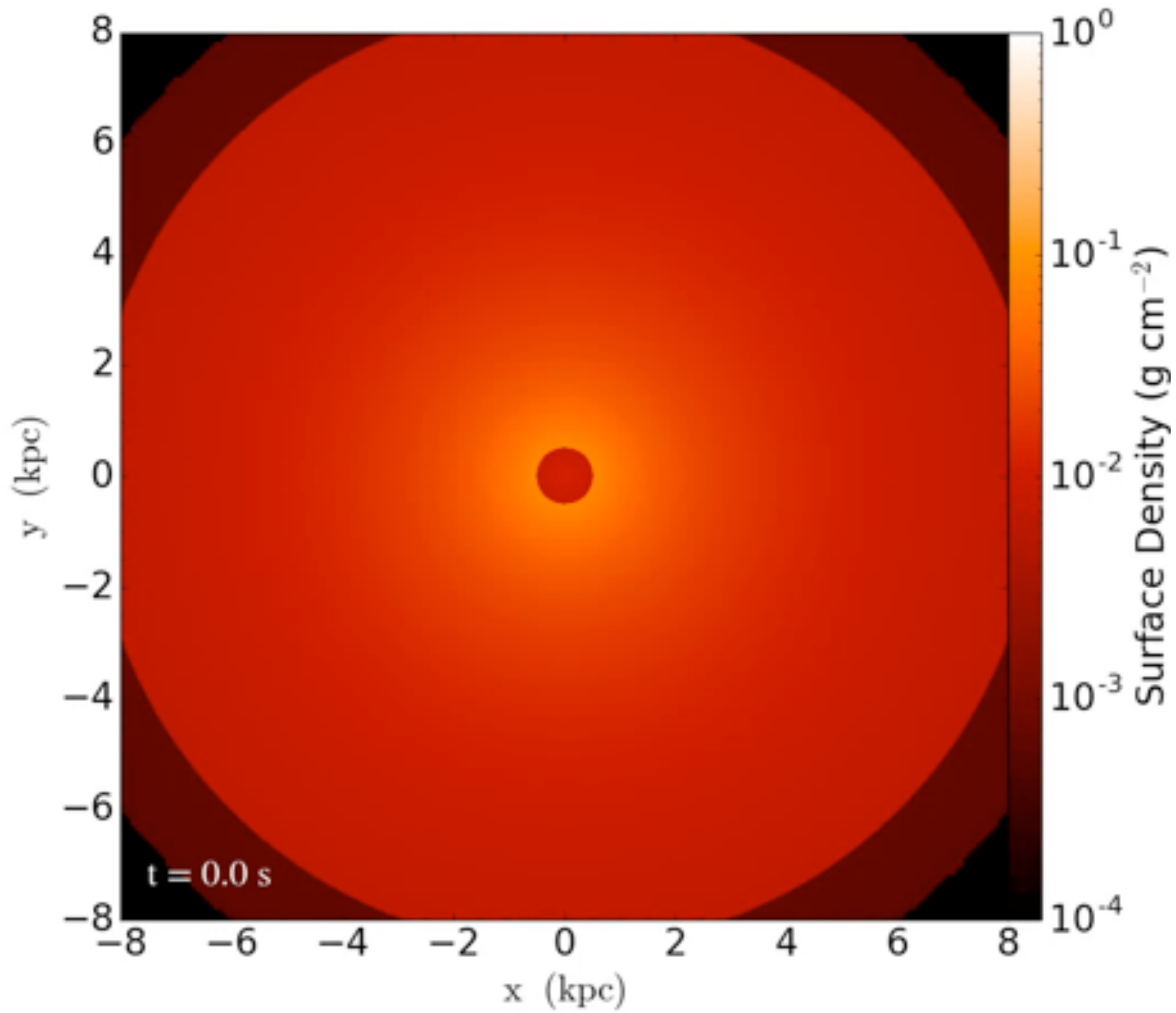




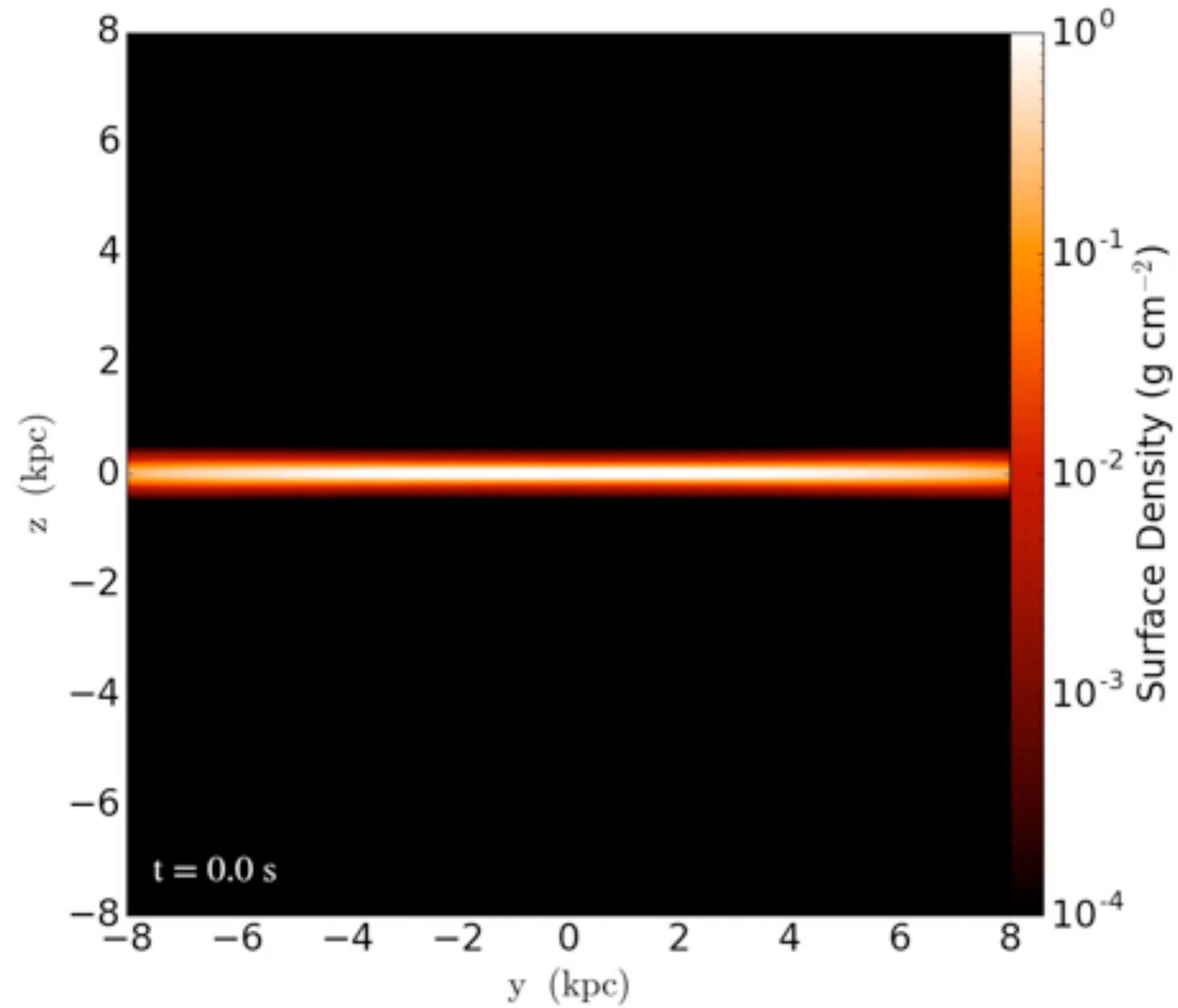
does Mestel's accumulation idea work?

Global Galactic Disc Simulations

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



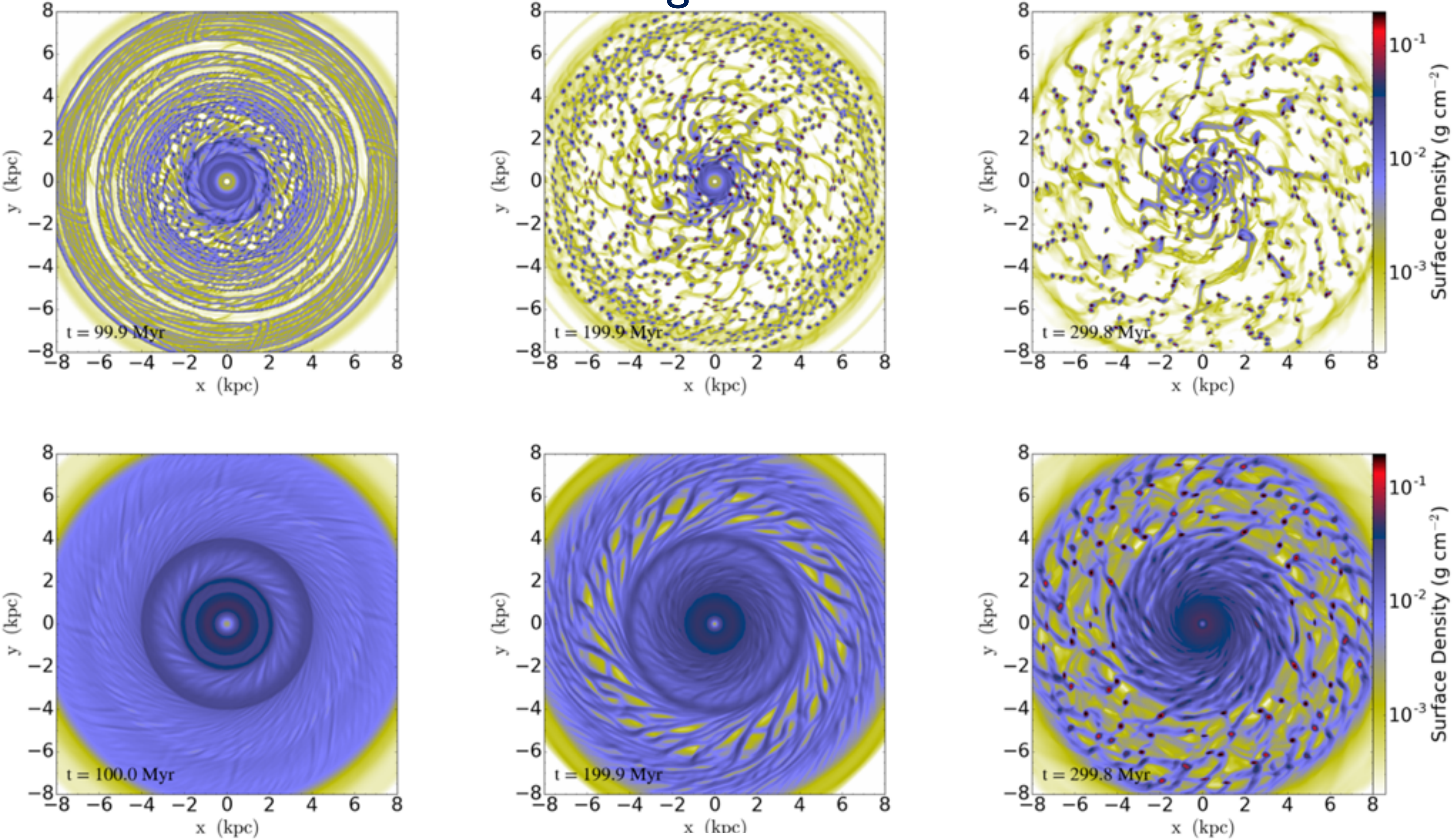
face-on



edge-on

Global Galactic Disc Simulations

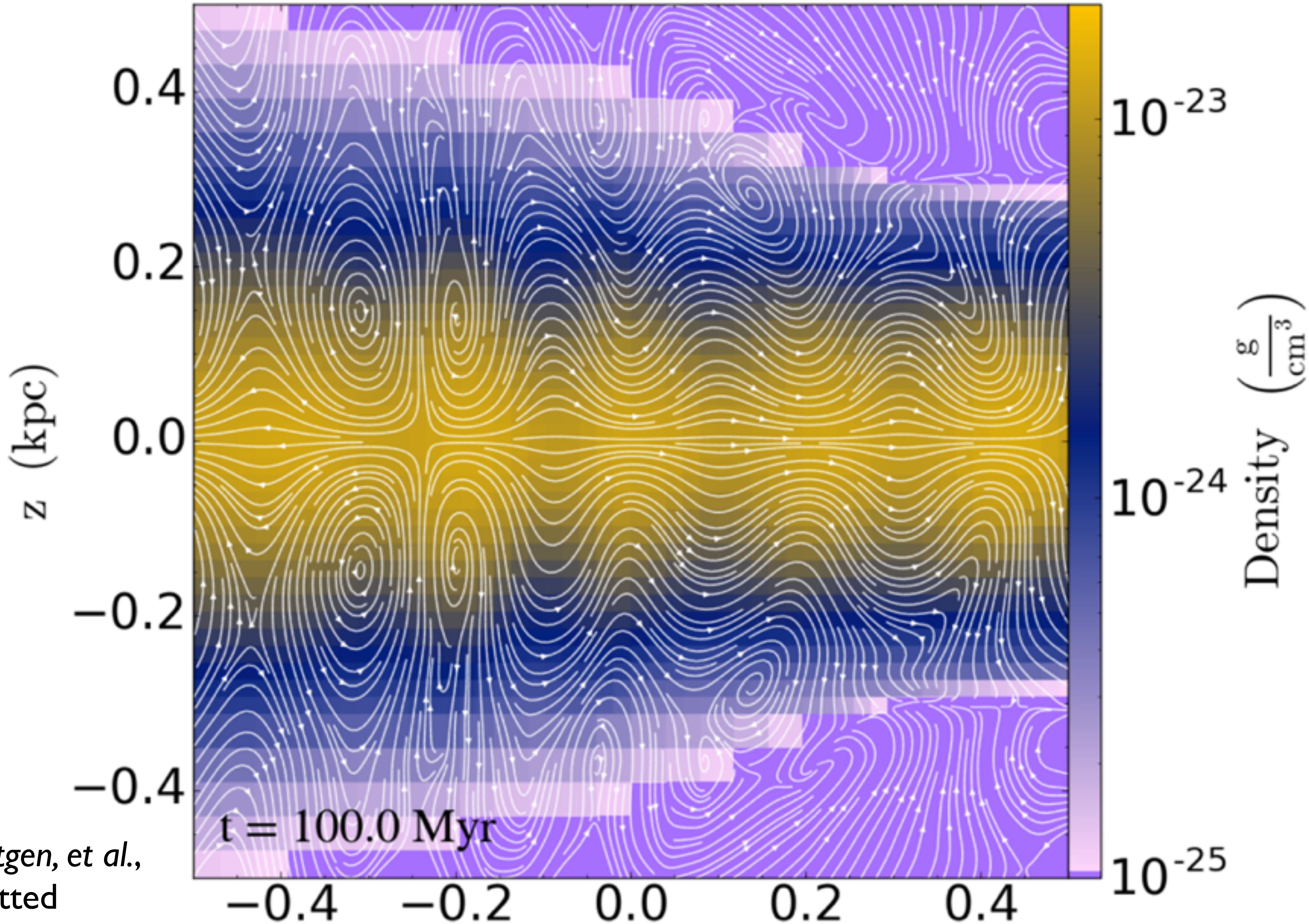
non magnetised case



strongly magnetised case: $\beta = 0.25$

Global Galactic Disc Simulations

Parker Instability



B. Körtgen, et al., submitted

Global Galactic Disc Simulations

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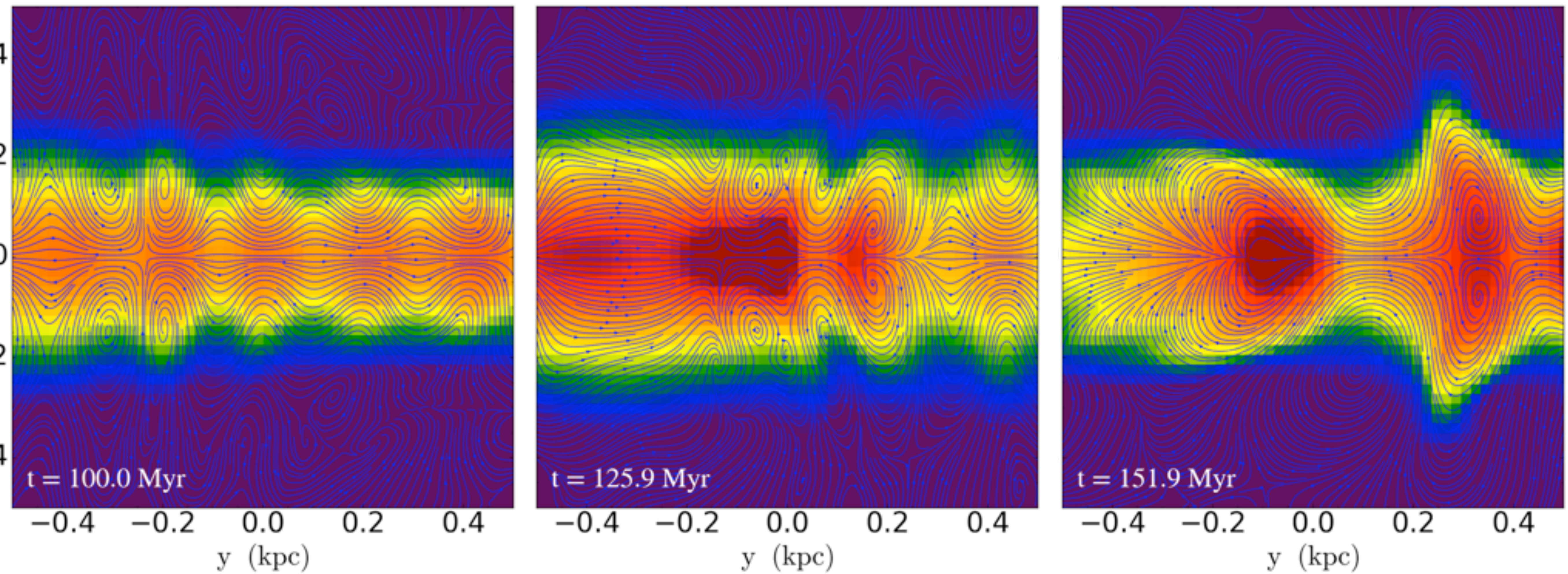

⟹ supercritical GMCs from along magnetic field lines

B. Körtgen, et al., submitted