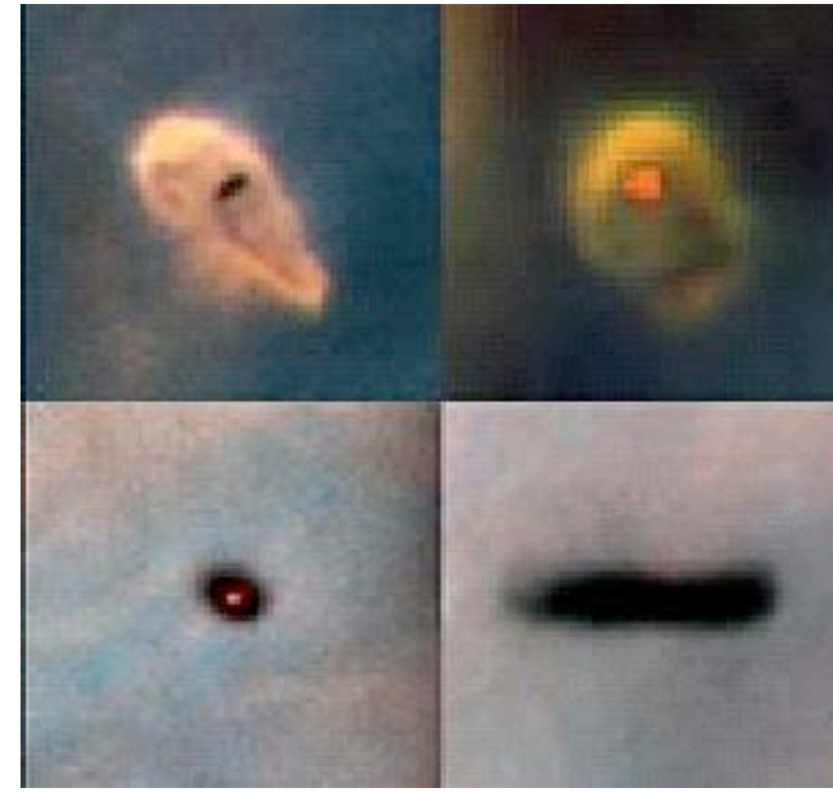
Numerical Simulations on ISM Dynamics and Star Formation

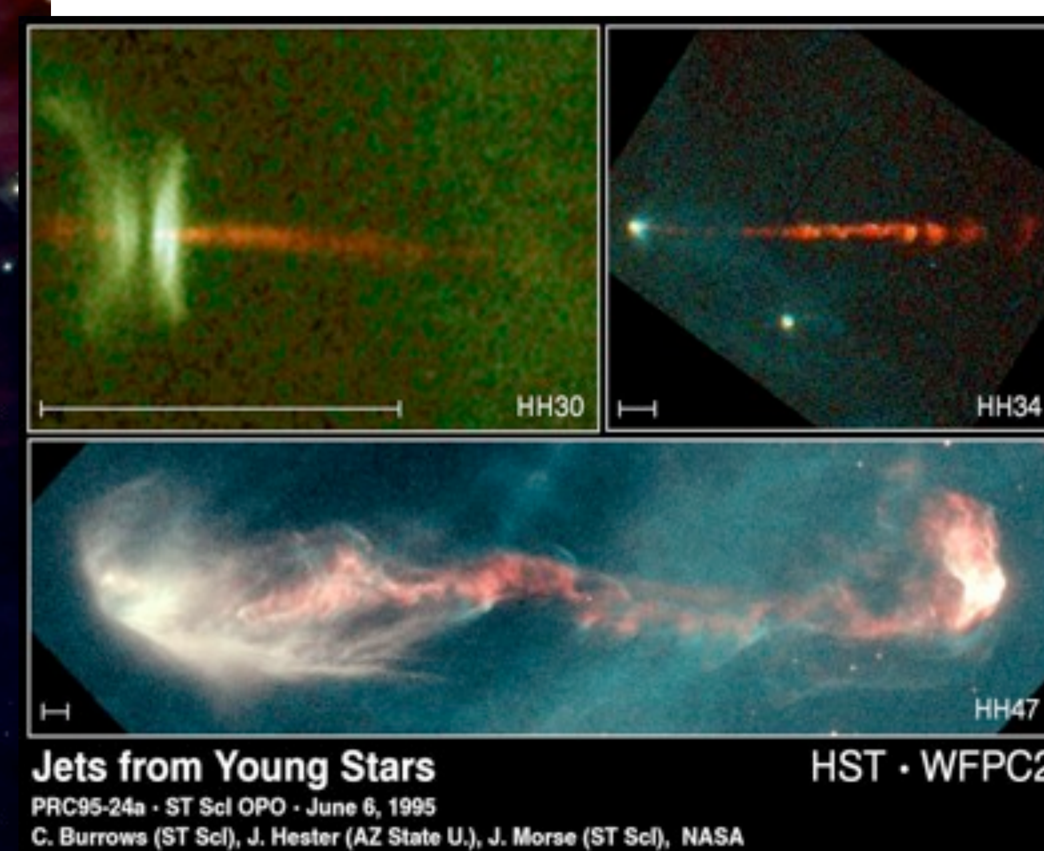
Robi Banerjee
Hamburger Sternwarte

based on work by: Bastian Körtgen (HS), Dandiel Seifried (Cologne)
co-workers: Ralph Pudritz (McMaster), Enrique Vazquez-Semadeni (UNAM, Mexico)

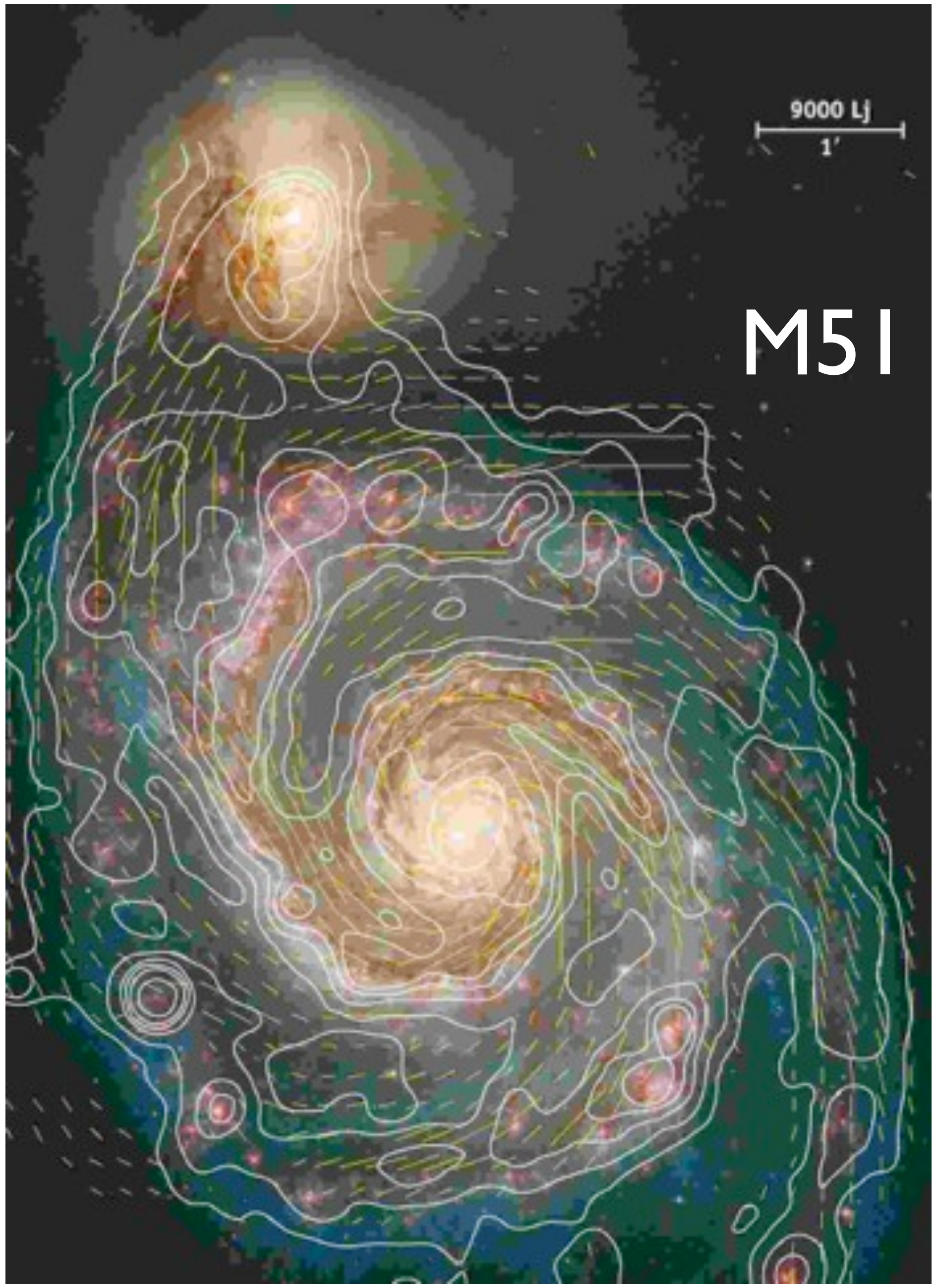
ISM Dynamics & Star Formation

multi scale and multi physics process (gravity, thermodynamics, turbulence, radiation, feedback, ...)



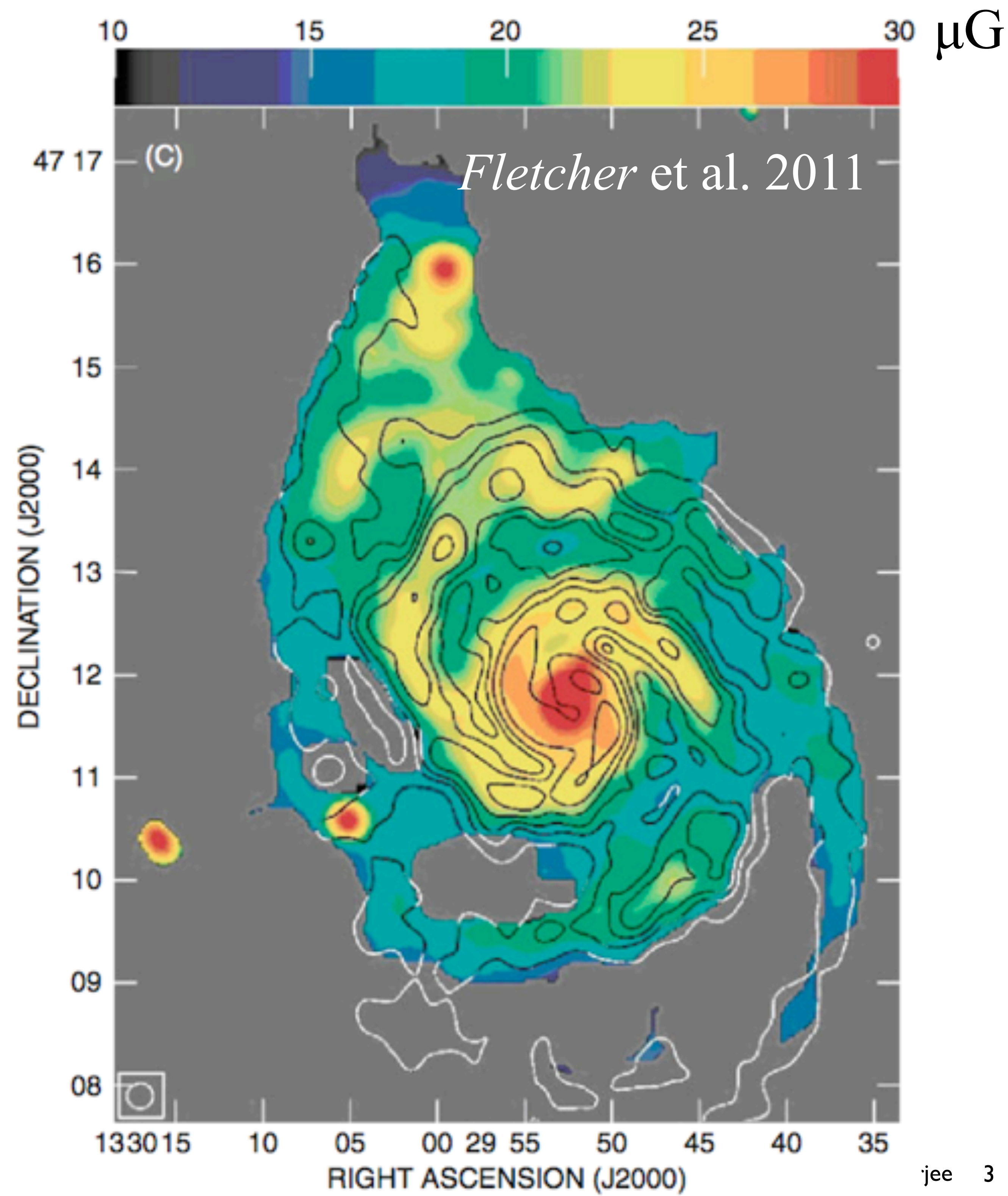


Magnetic Fields in the ISM



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: $> 10\ \mu G$

FLASH: Numerical Modelling

- ✓ AMR (various geometries)
- ✓ MHD / nonideal MHD

  D.Lee (2013), *D.Duffin et al.* (2008)
- ✓ Selfgravity (Multi-Grid, BH-Tree)

  P.Ricker (2008), *R. Wunsch* (2009), *G.Lukat & R.B* (2015)
- ✓ Radiation transfer

  E.-J.Rijkhorst (2006), *T.Peters et al.* (2010), *L.Buntemeyer et al.* (2016), *M.Klassen* et al. (2016)
- ✓ Chemistry / Dust physics / KROME (*T. Grassi, S.Bovino, et al.*)

  M.Micic, S.Glover et al. (2010), *T.Grassi et al.* (2014)
- ✓ Sink particles

  Ch. Federrath et al. (2010)
- ✓ Sub-grid feedback (SNe, Winds, Outflows)

  B.Körtgen et al. (2015), *Ch.Federrath et al.* (2014), *A.Gatto et al.* (2017)
- ✓ Support of hardware acceleration (GPU, KNL)

  G.Lukat & R.B. (2015)

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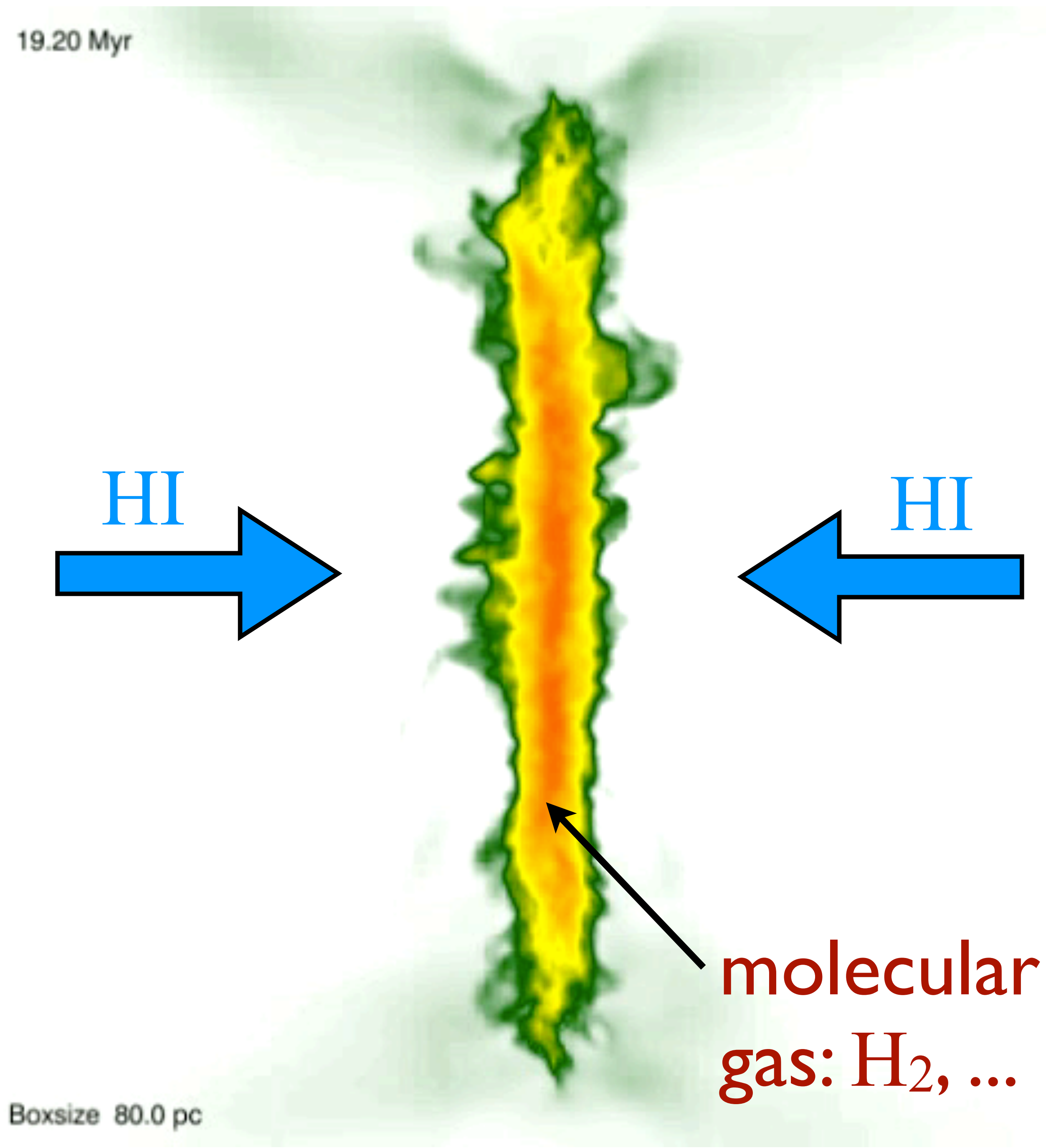
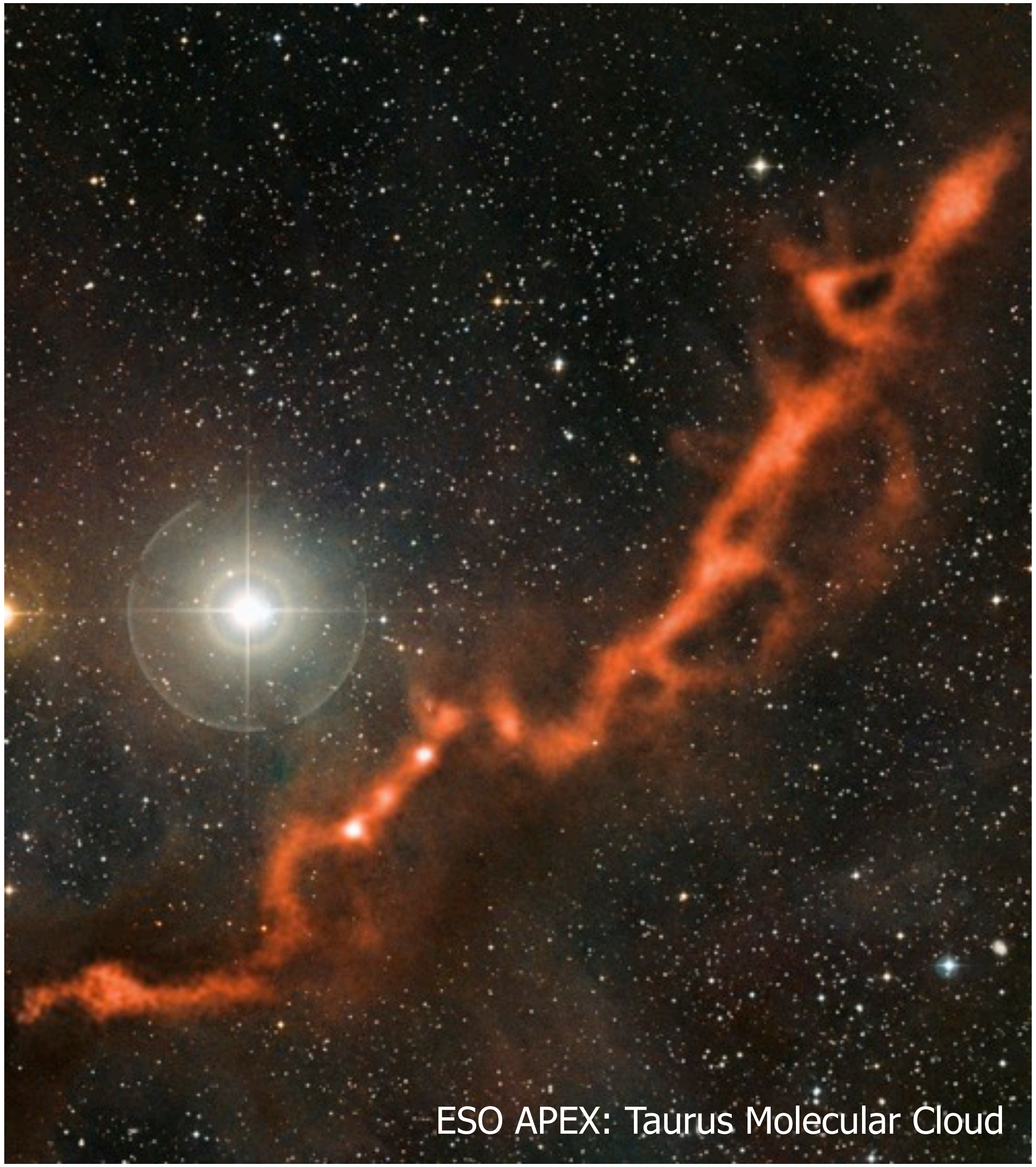
see also **RAMSES**, **ENZO**, **Gadget**, **Arepo**, **ATHENA**, **PHANTOM**, ...

Formation of Molecular Clouds

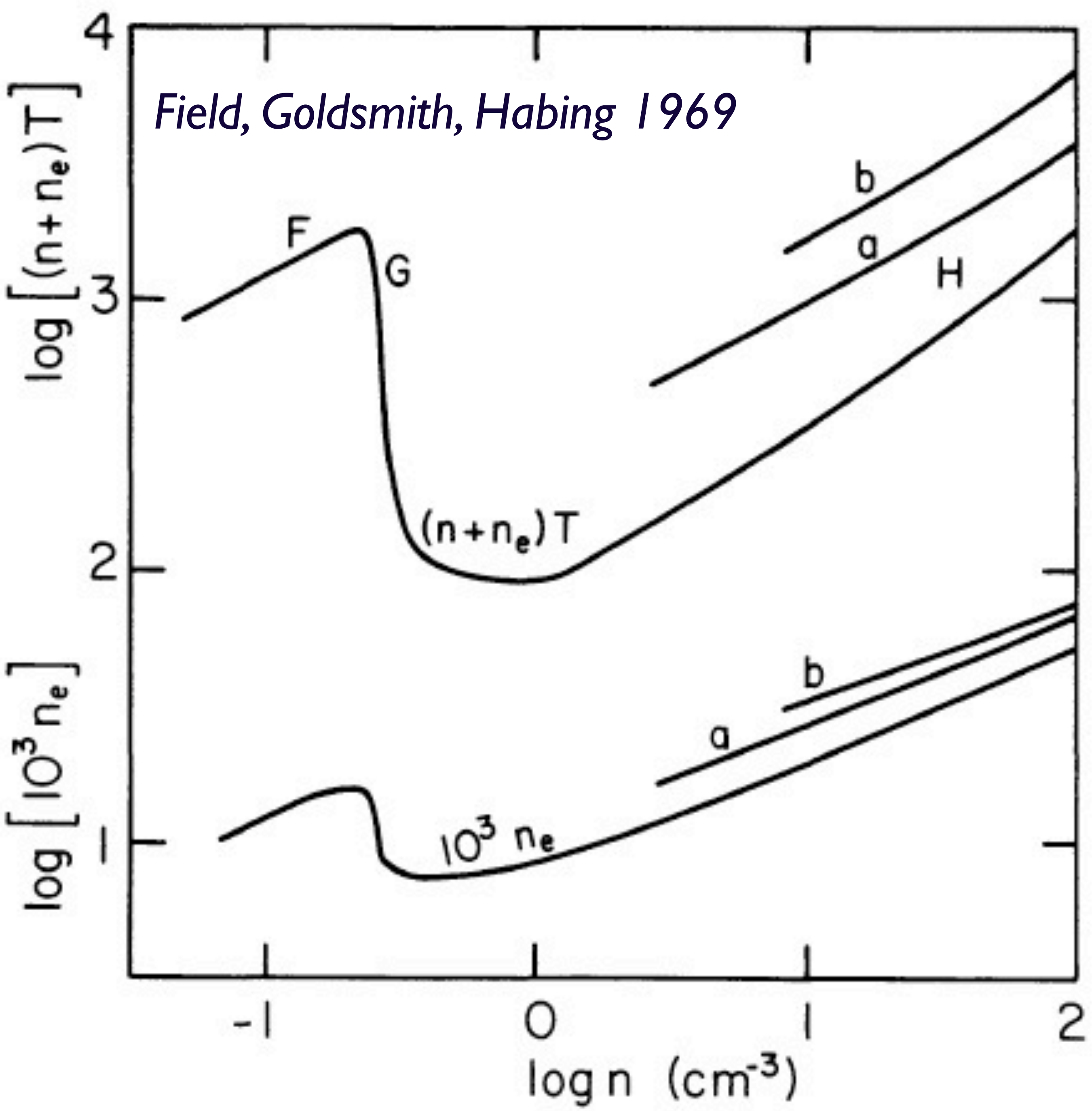




dynamical MC / GMC formation
out of the WNM atomic media (e.g. *Blitz et al.* ,2007, PPV)

Formation of Molecular Clouds

Formation of dense, cold clouds out of the warm medium through thermal instability (*Field 1965*)



$$\frac{\partial \ln p}{\partial \ln \rho} < 0$$ necessary condition for TI

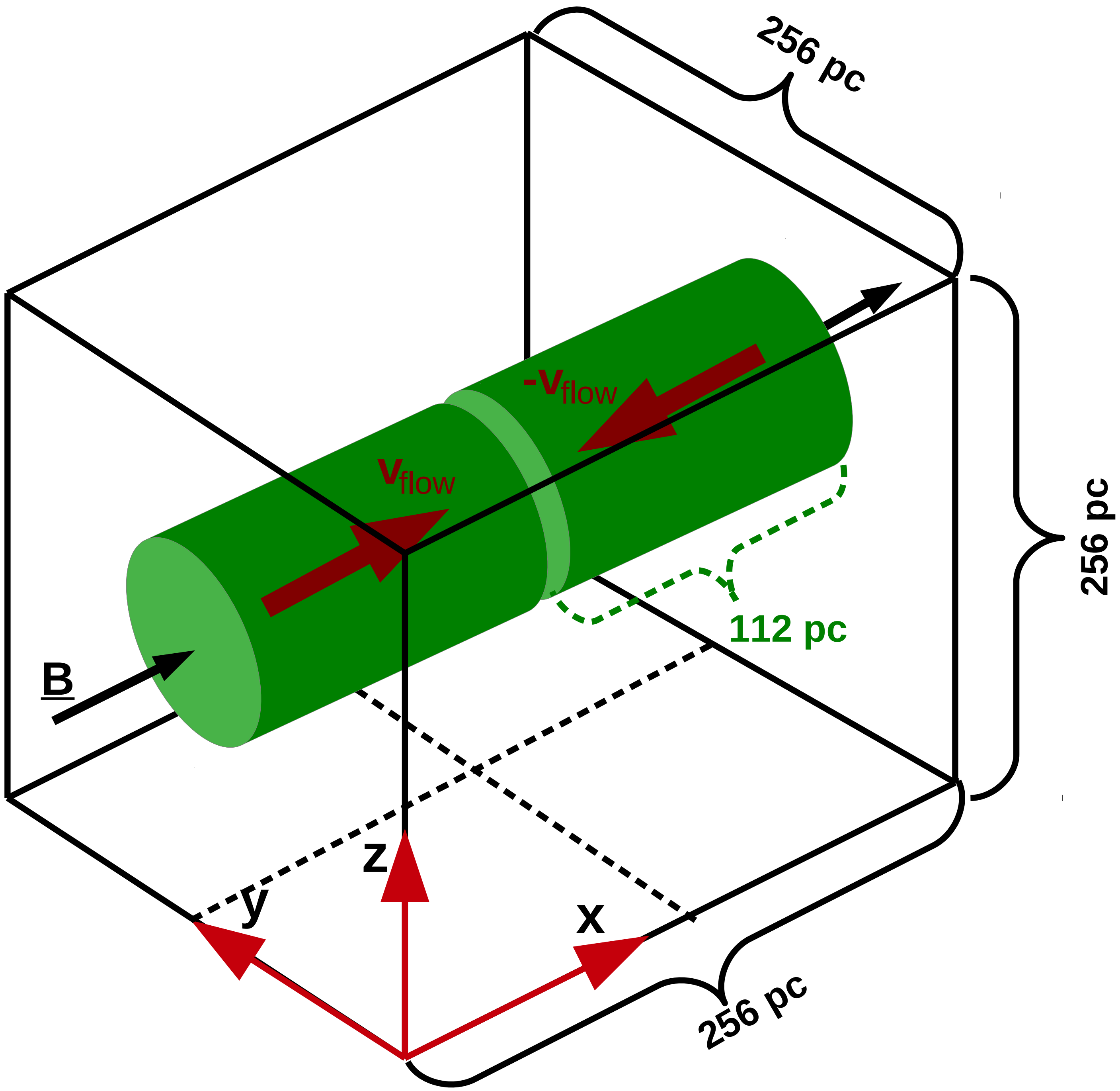
heating (UV, cosmic ray) and cooling (atomic and molecular line emission, gas-dust coupling) regulate thermodynamics

Note:

M_{Jeans}(warm gas) >> M_{cloud}

Simulations of colliding flows

MC formation & star formation



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

Model parameter:

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

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

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

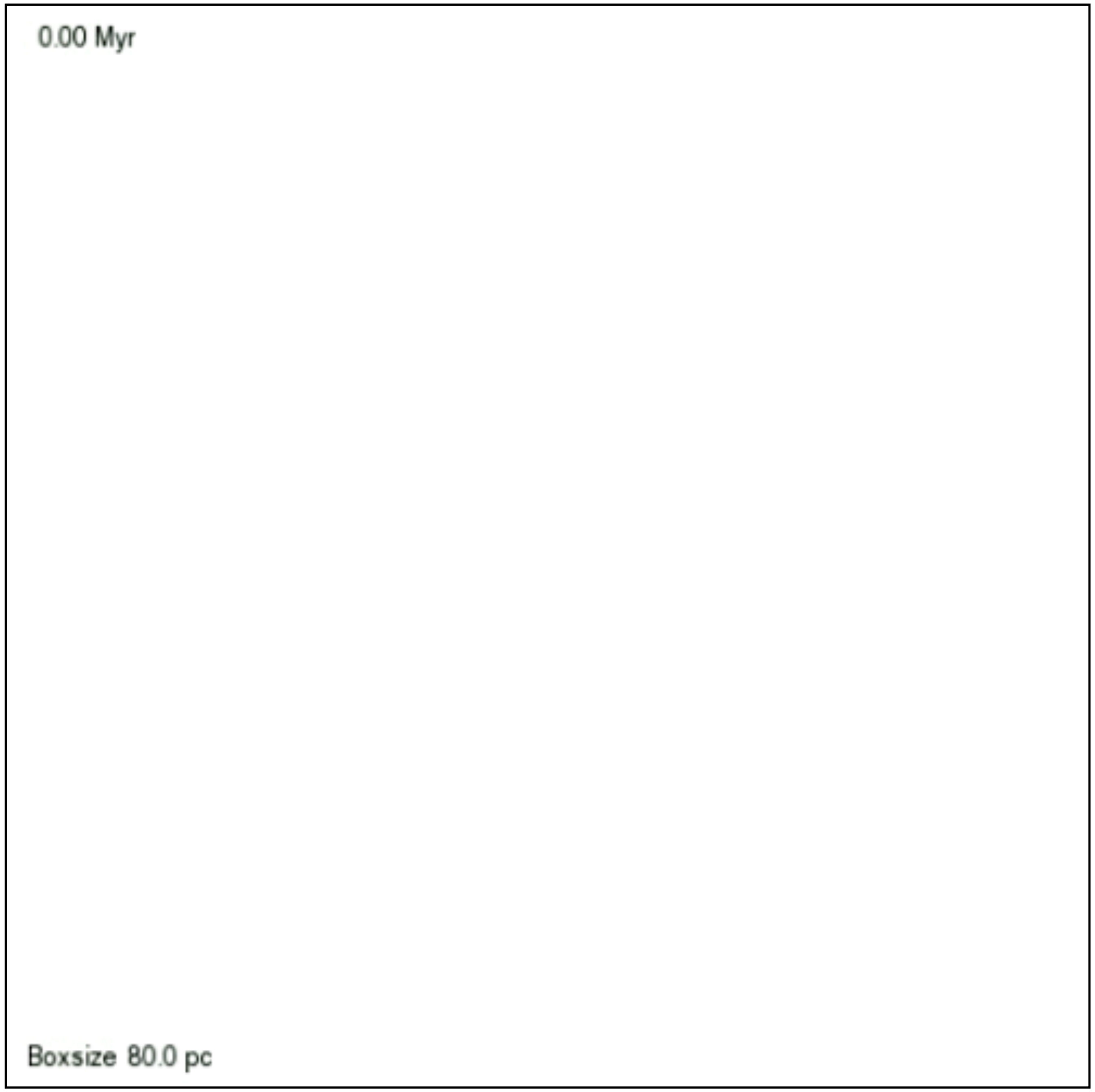
+ turbulence:

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

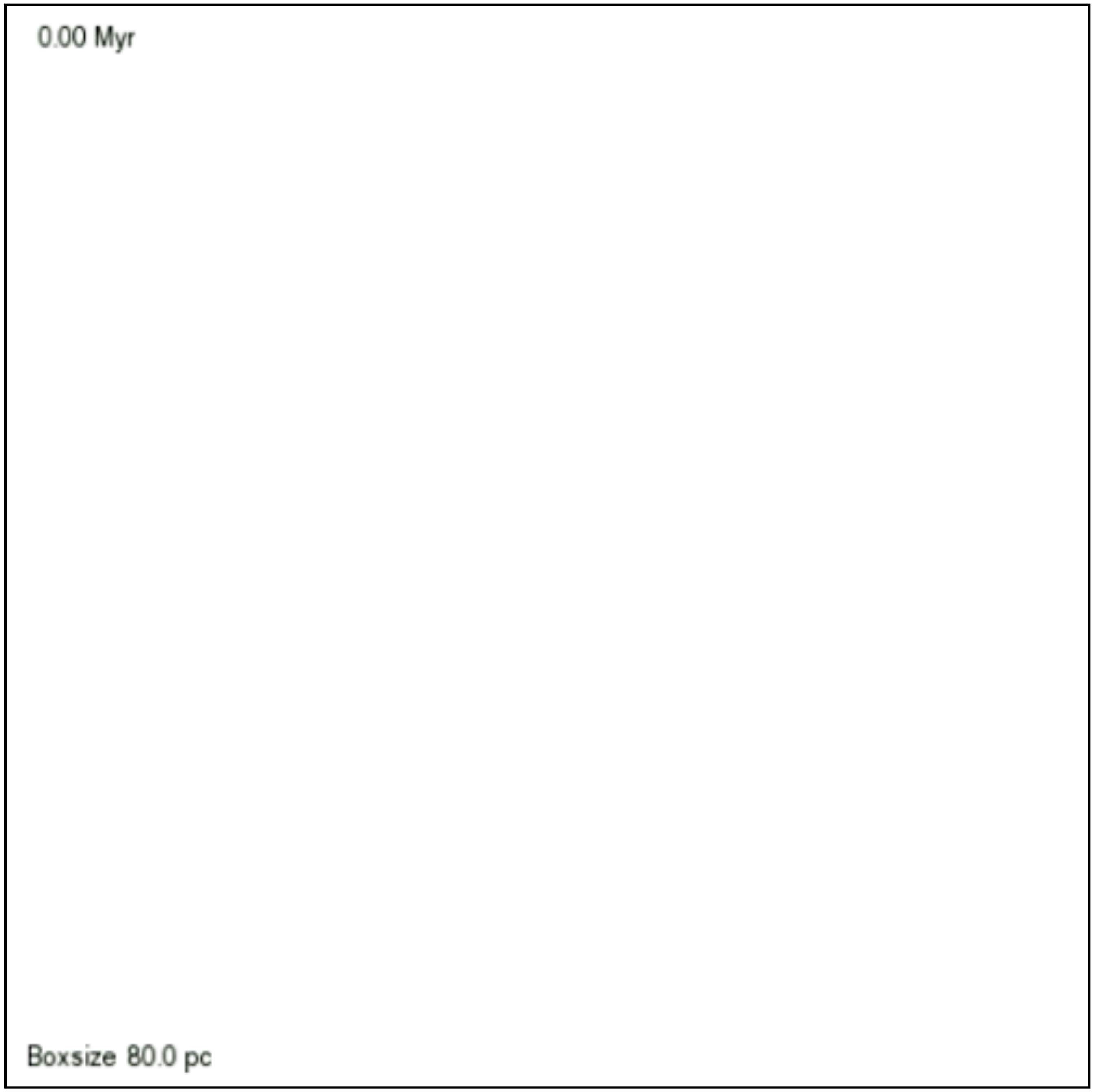
- $B_x = 1 \ldots 5\ \mu\mathrm{G}$

Formation of Molecular Clouds

the weakly magnetized ($B_x = 1 \mu G$) case



edge-on view

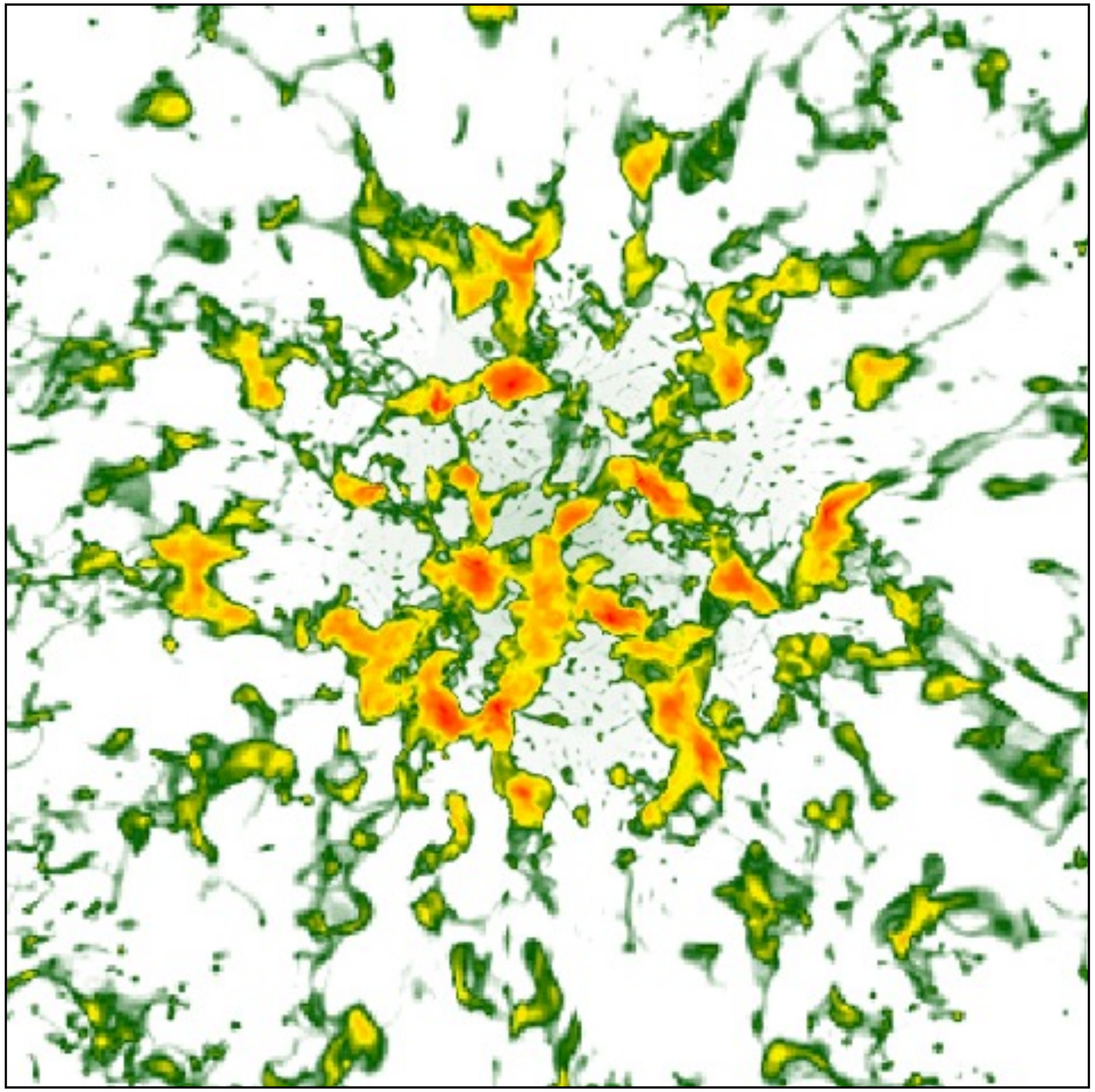


face-on view

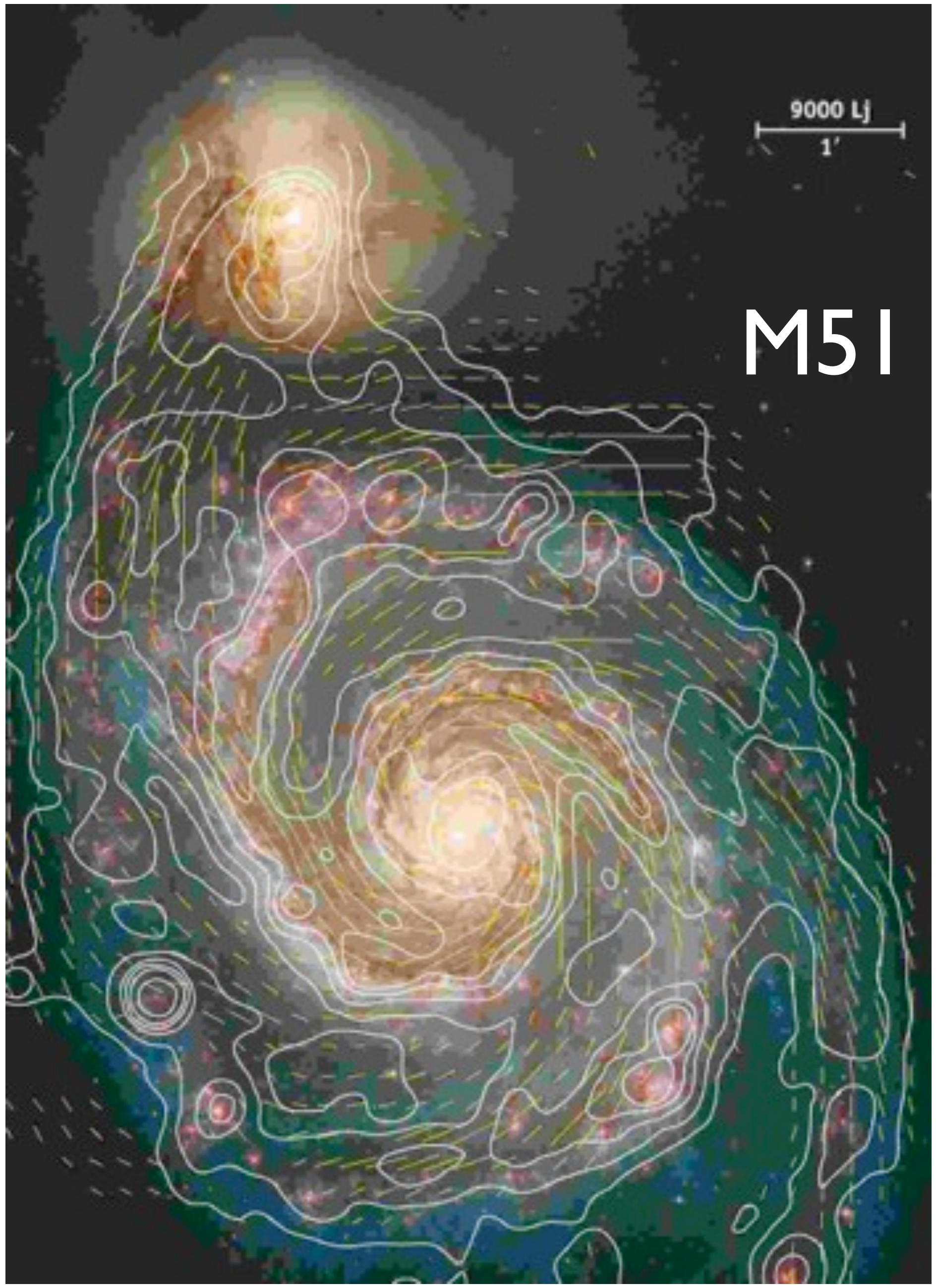
Formation of Molecular Clouds

main properties of MCs:

- highly patchy and clumpy
- high fraction of substructure
- cold dense molecular clumps coexist with warm atomic gas
- not a well bounded entity
- dynamical evolution (different star formation modes: from low mass to high mass SF?)



Magnetic Fields in the ISM



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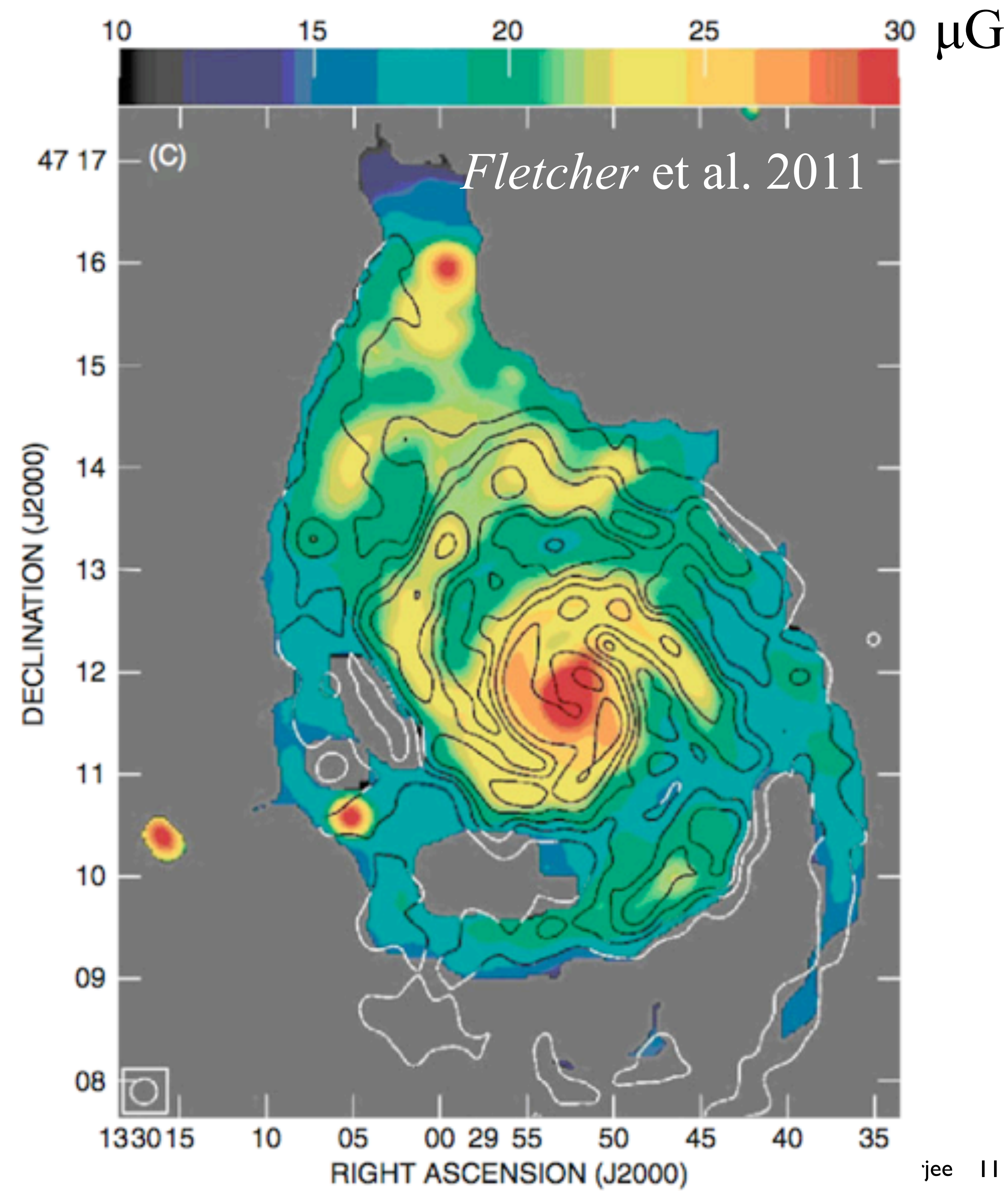


galactic B-fields (e.g. *R.Beck* 2001)

large scale component: $B \sim 6\mu G$

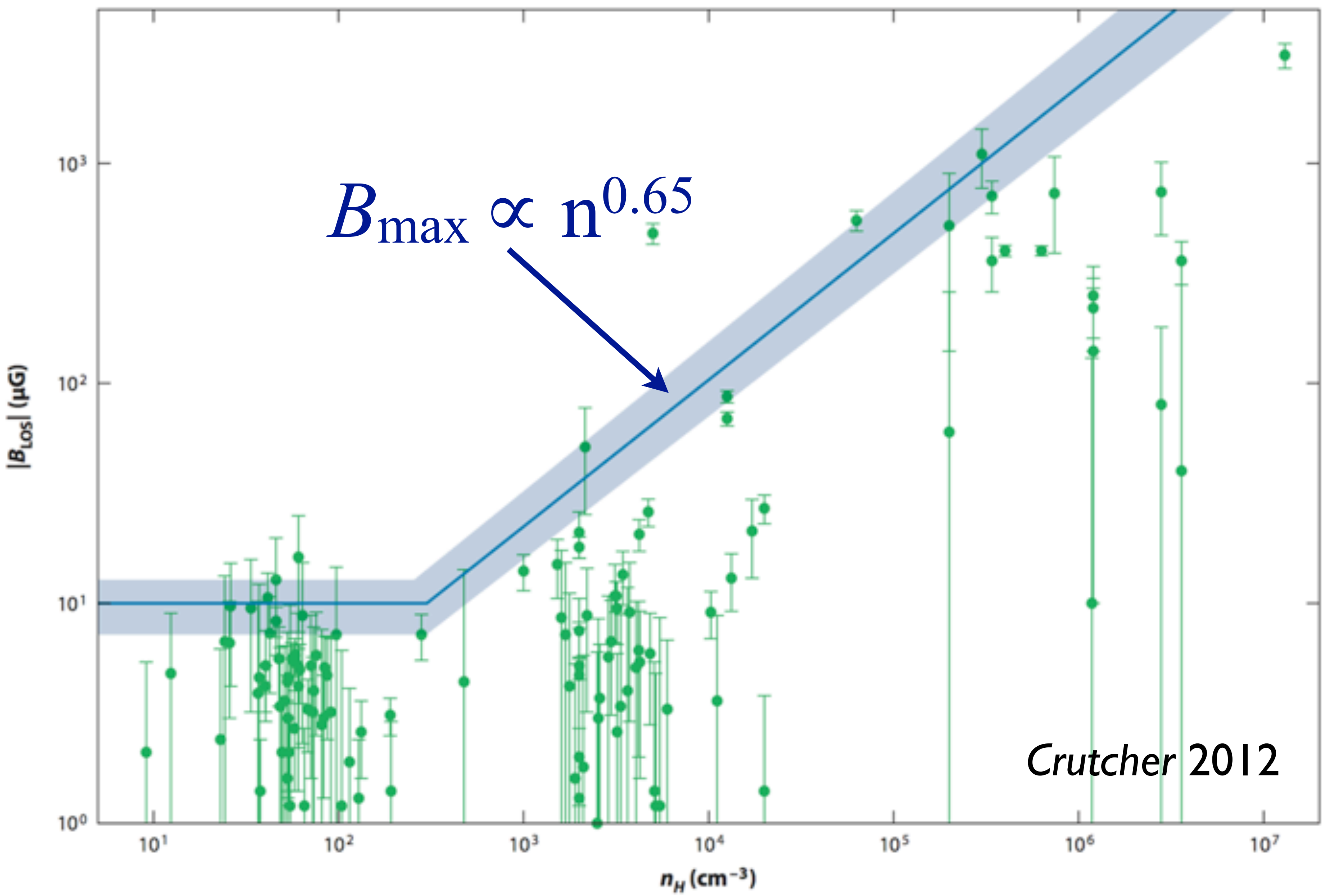
total field strength: $> 10\ \mu G$

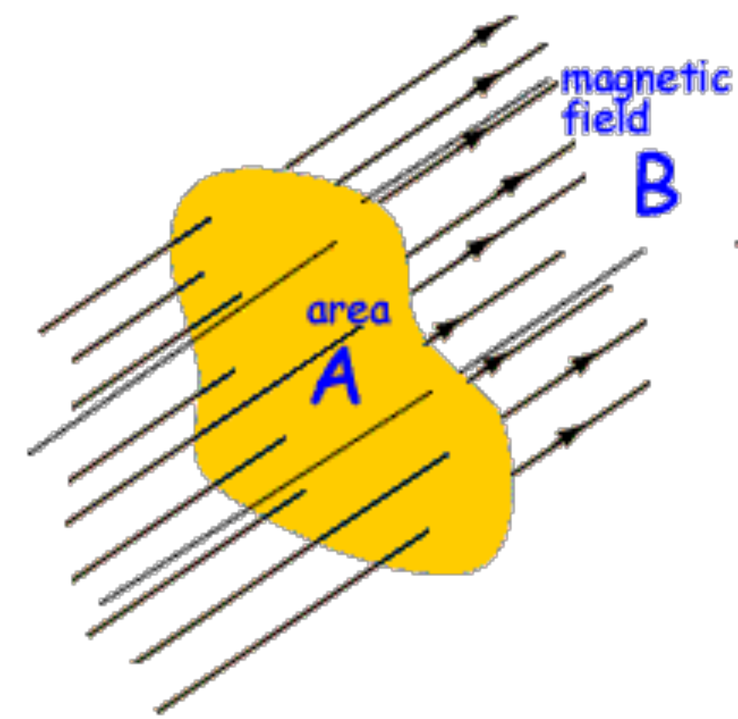
Magnetic Fields in the ISM

- stronger magnetic fields in dense regions

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

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

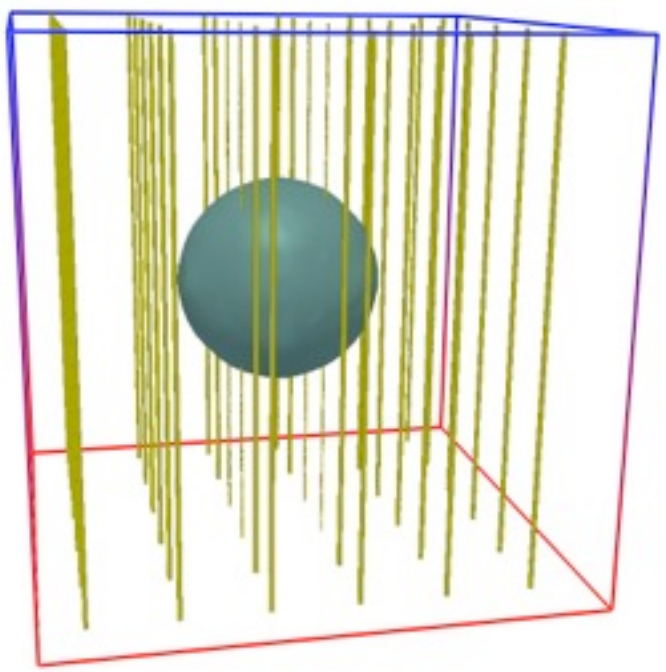




Impact of Magnetic Fields

magnetic flux is frozen into the plasma:

mass-to-flux ratio:



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

(cf. thermal Jeans mass)

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

critical value for collapse:

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

spherical structure

Mouschovias & Spitzer 1976

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

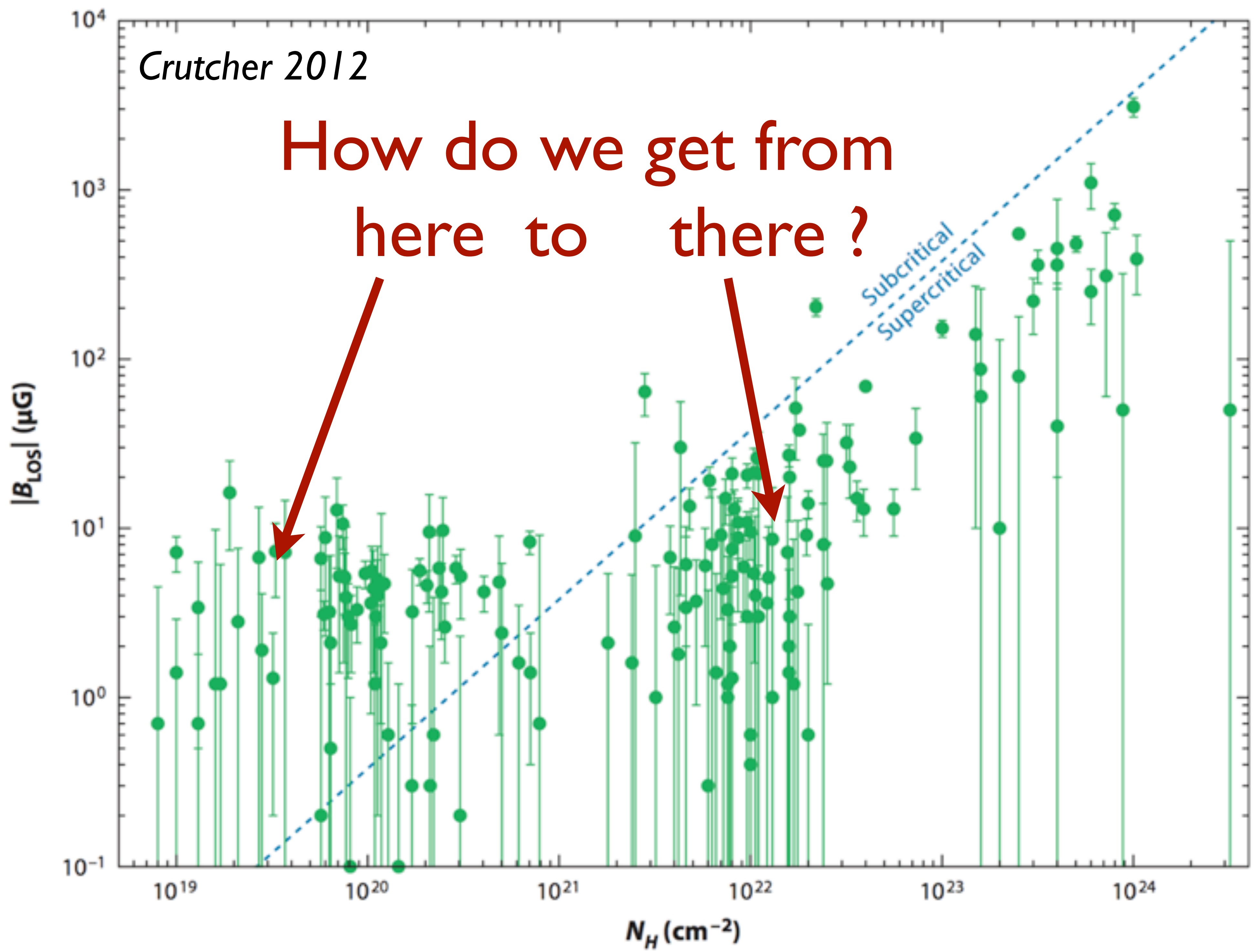
uniform disc

Nakano & Nakamura 1978

Magnetic Fields in the ISM

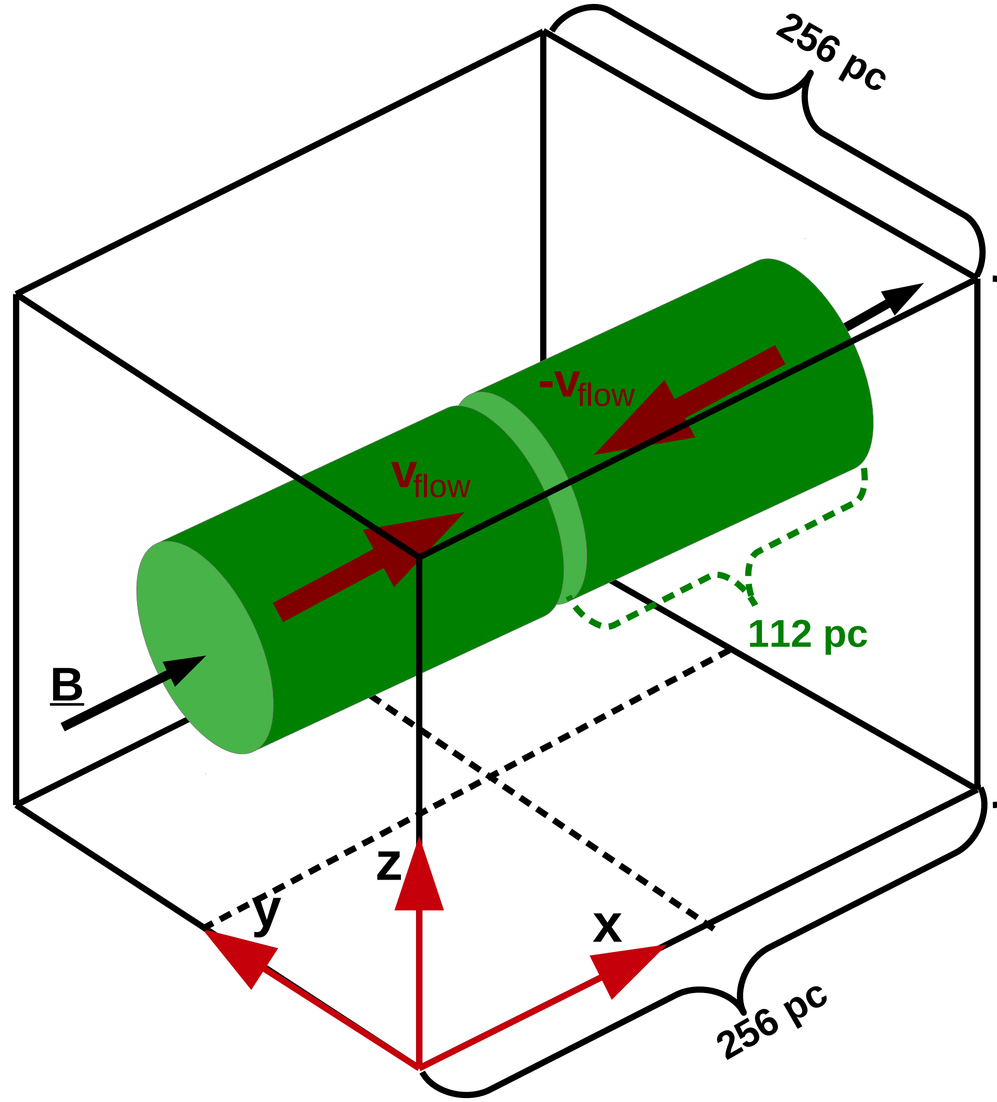
- field strength B : important for star formation

$\Longrightarrow$ mass-to-flux ratio: $\mu \propto \Sigma/B$ (Σ : column density)



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 AD-mediated star formation picture
  - Turbulence + AD (e.g. *Heitsch et al.* 2004)
  - 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)

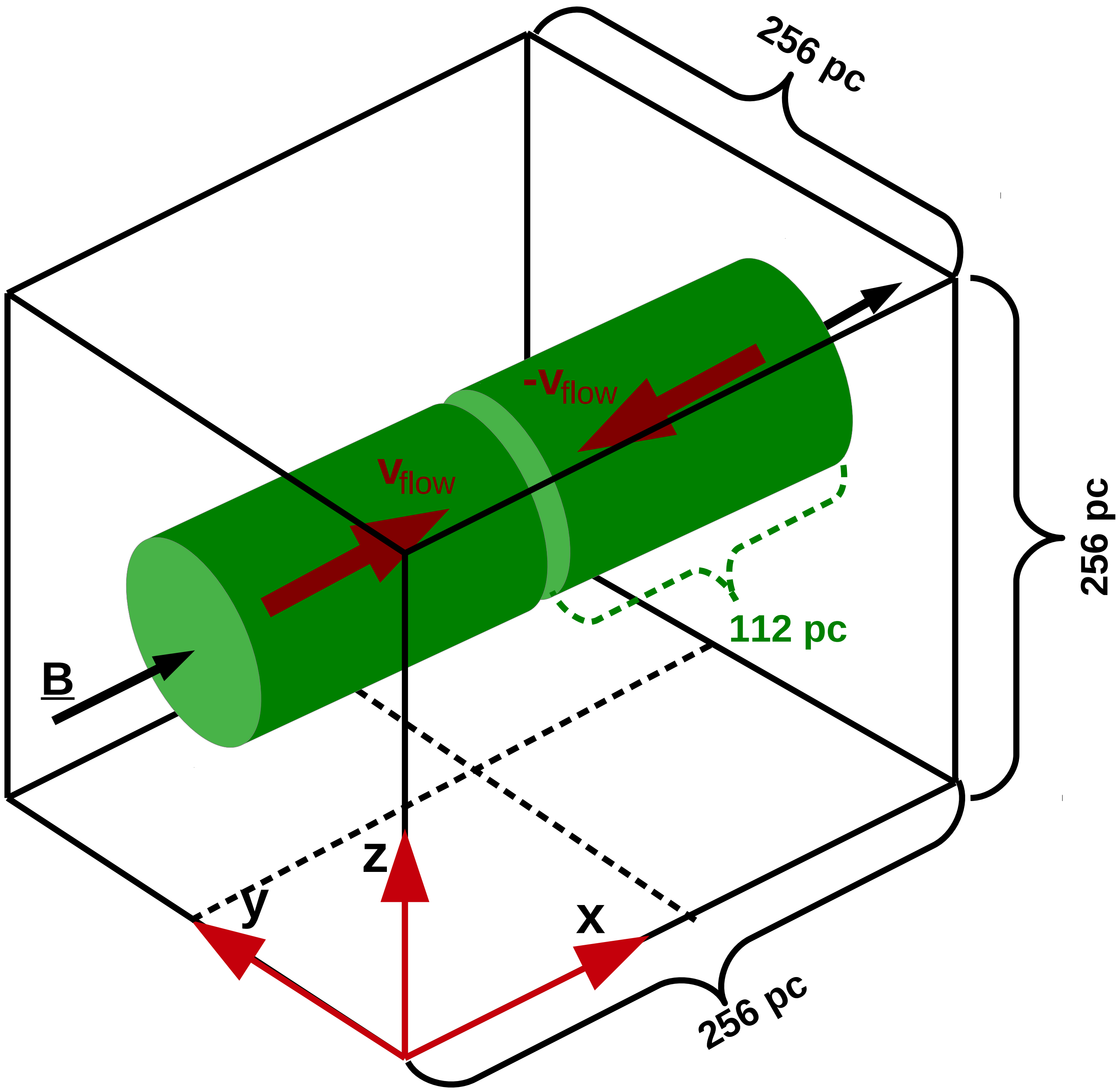
  $\Longrightarrow$ no need for flux loss:

  clouds assumed to be supercritical

$\Longrightarrow$ correct assumption ?

Simulations of colliding flows

MC formation & star formation



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

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

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

\+ turbulence:

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

\+ ambipolar diffusion

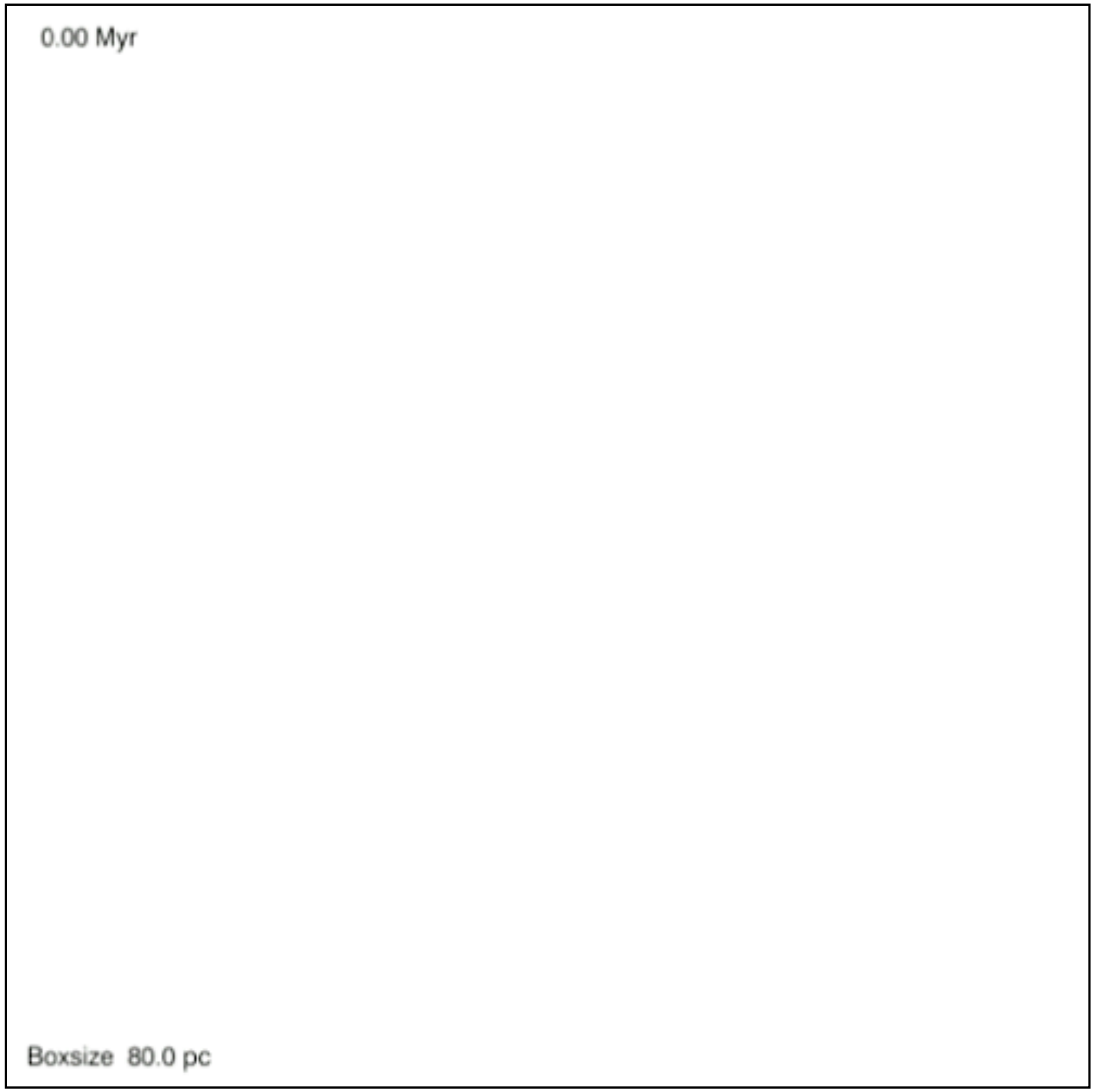
- $B_x = 1 \ldots 5\ \mu\mathrm{G}$

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

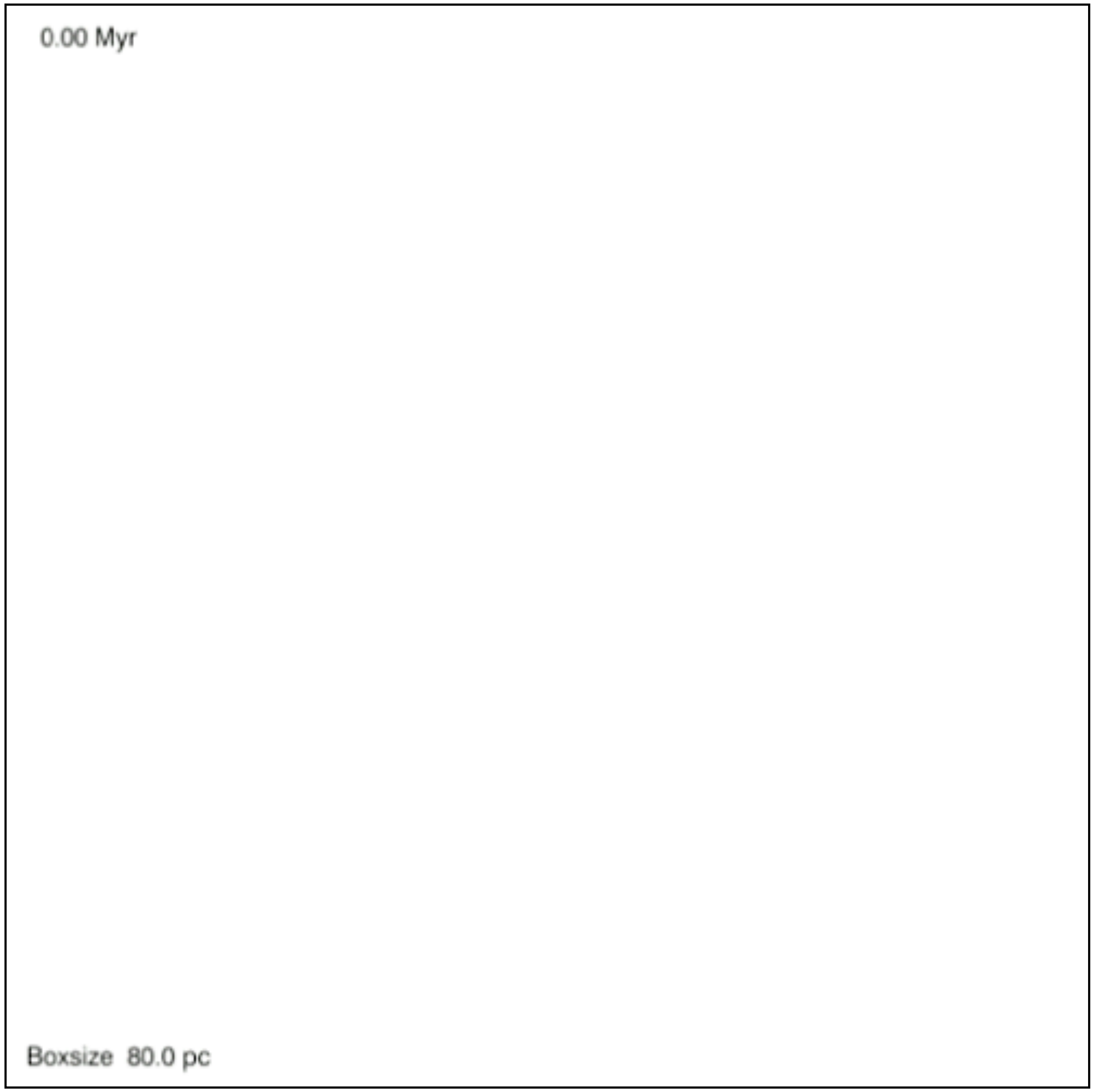
  $\Longrightarrow t_{\mathrm{crit}} \approx 15\ \mathrm{Myr}\ (B/3\mu\mathrm{G})$

Simulations of colliding flows

influence of magnetic fields



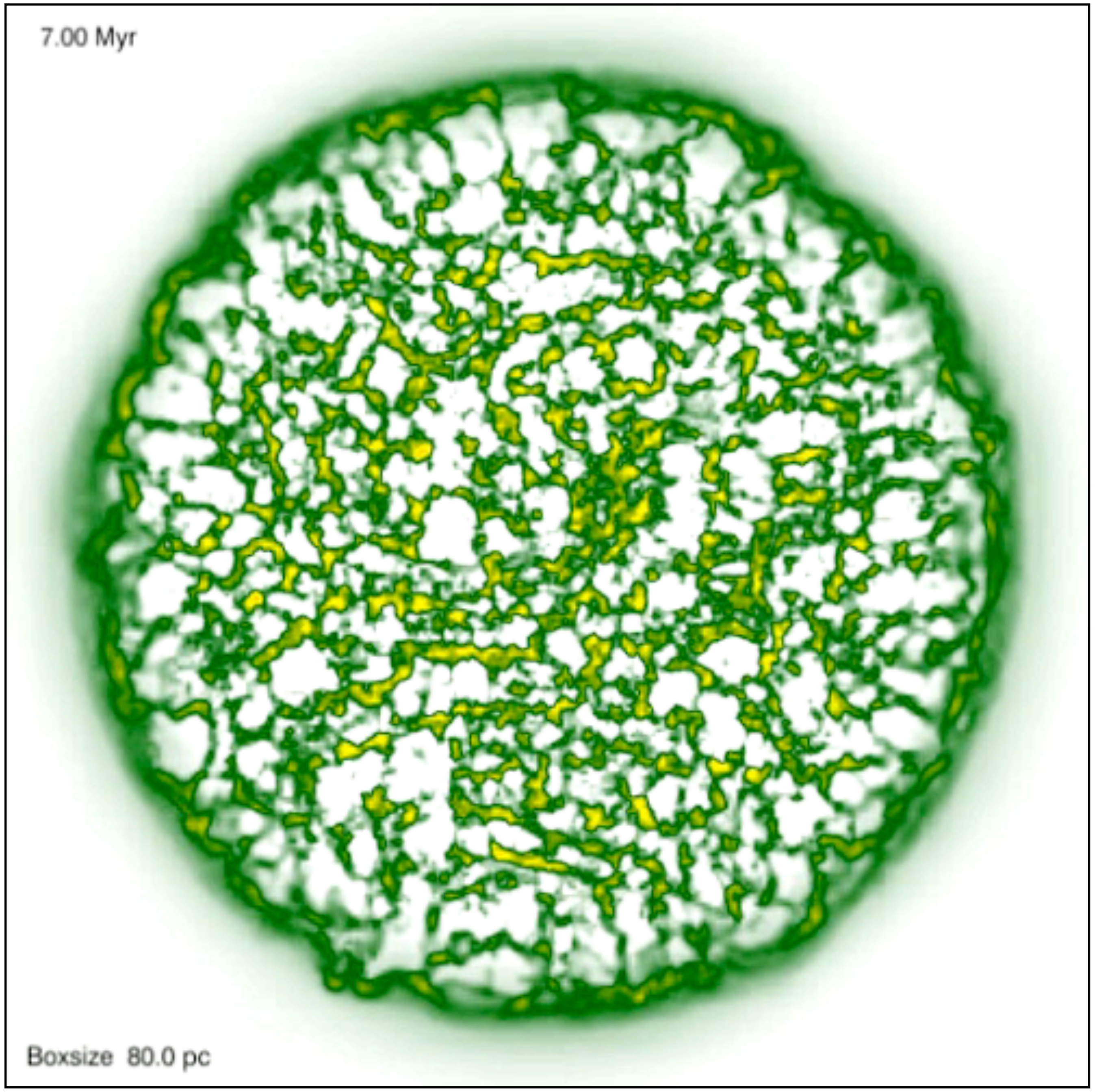
$B = 3\mu G$

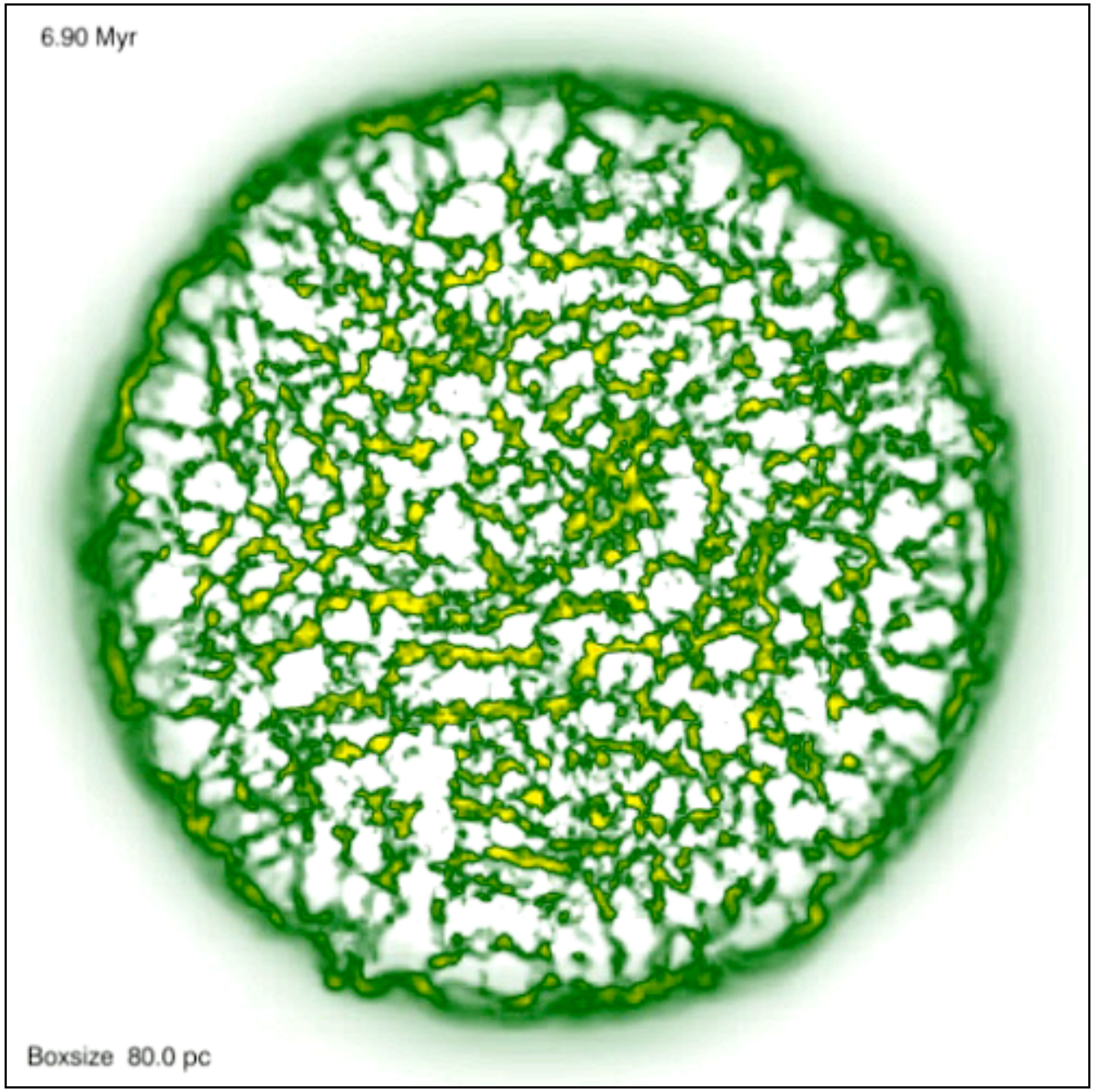


$B = 4\mu G$

Simulations of colliding flows

influence of ambipolar diffusion

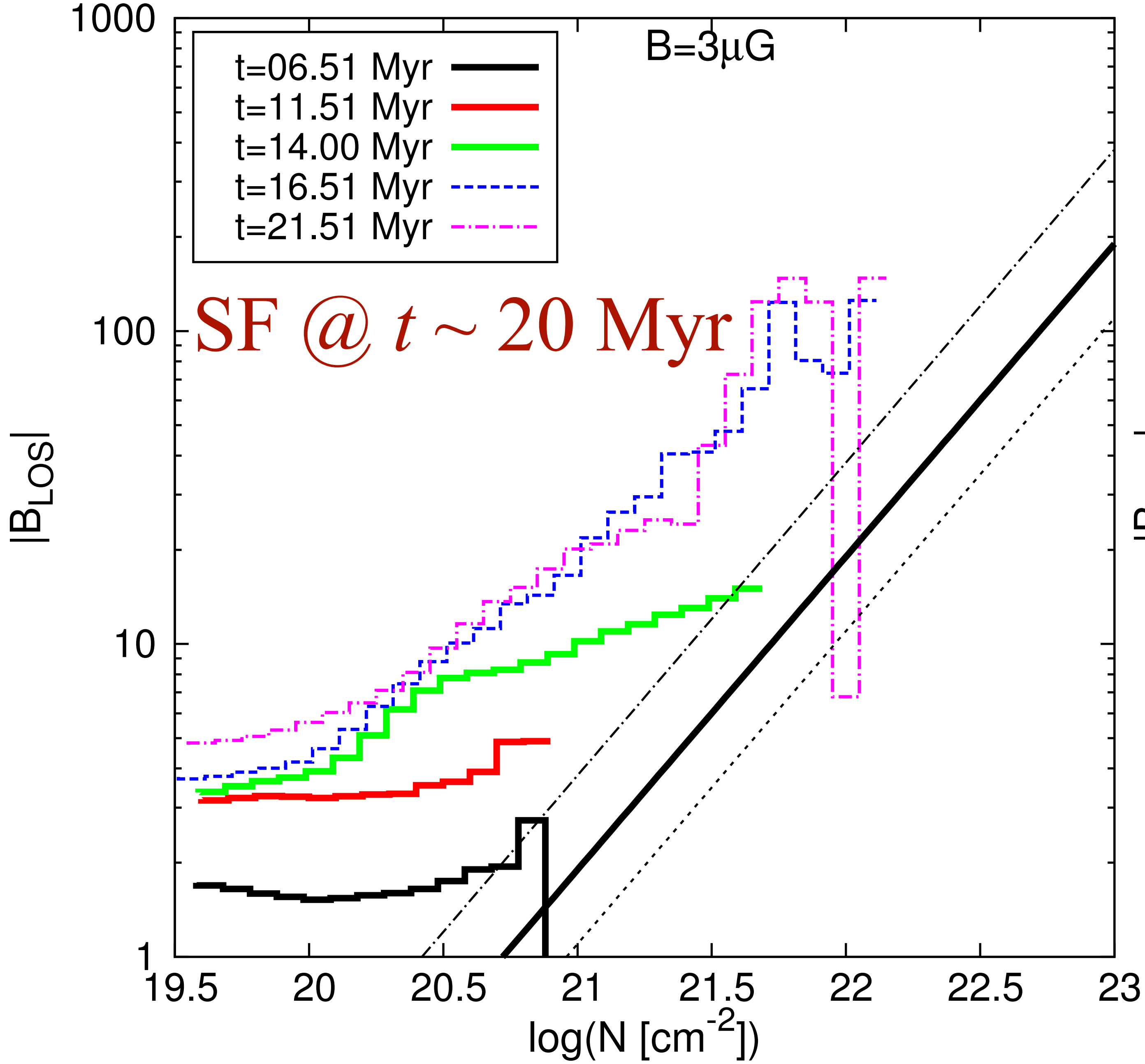


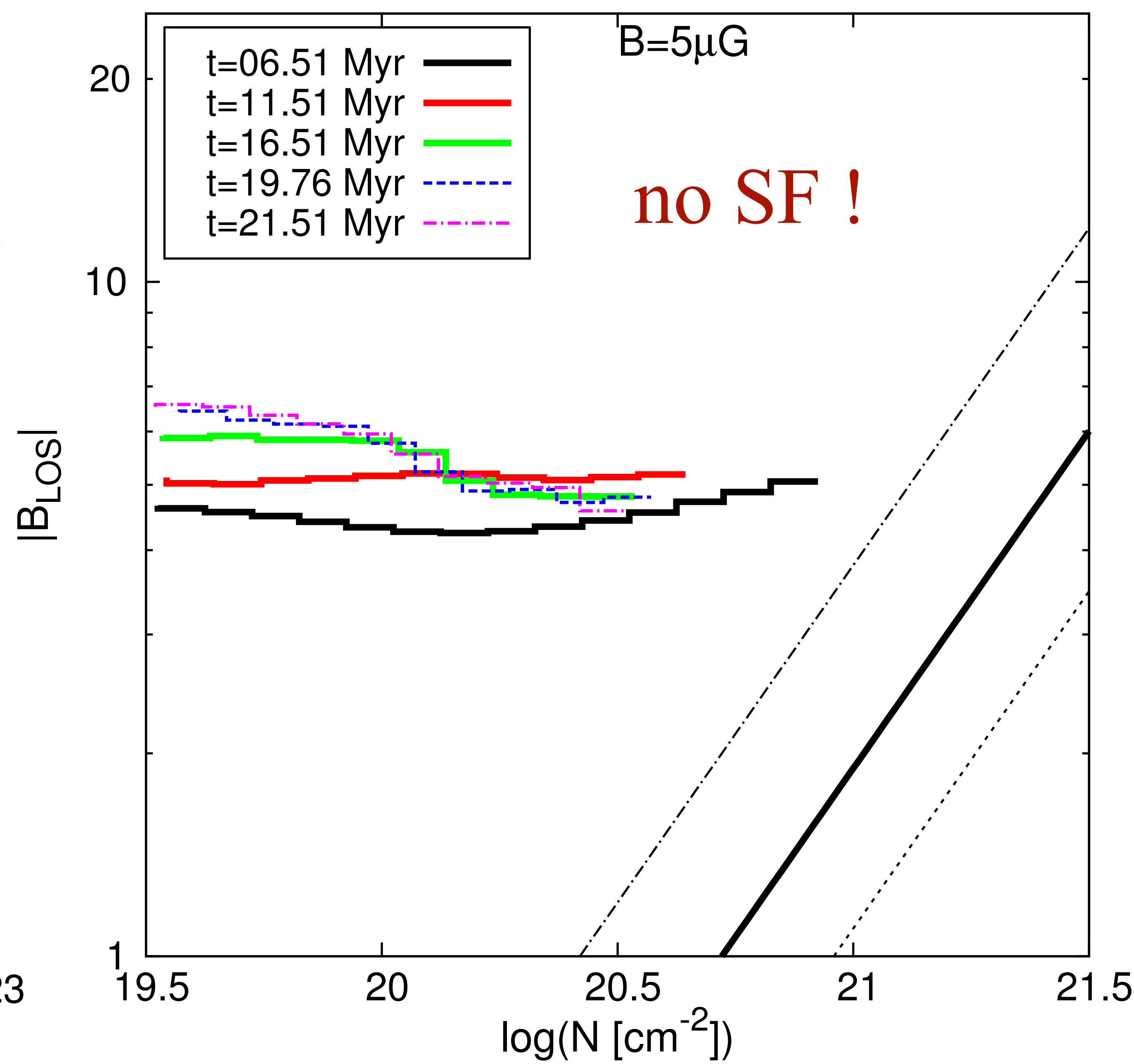


ideal case $B = 4\mu G$ with ambipolar diffusion

Simulations of colliding flows

results from head-on colliding flows with different field strengths





B. Körtgen, RB, MNRAS (2015)

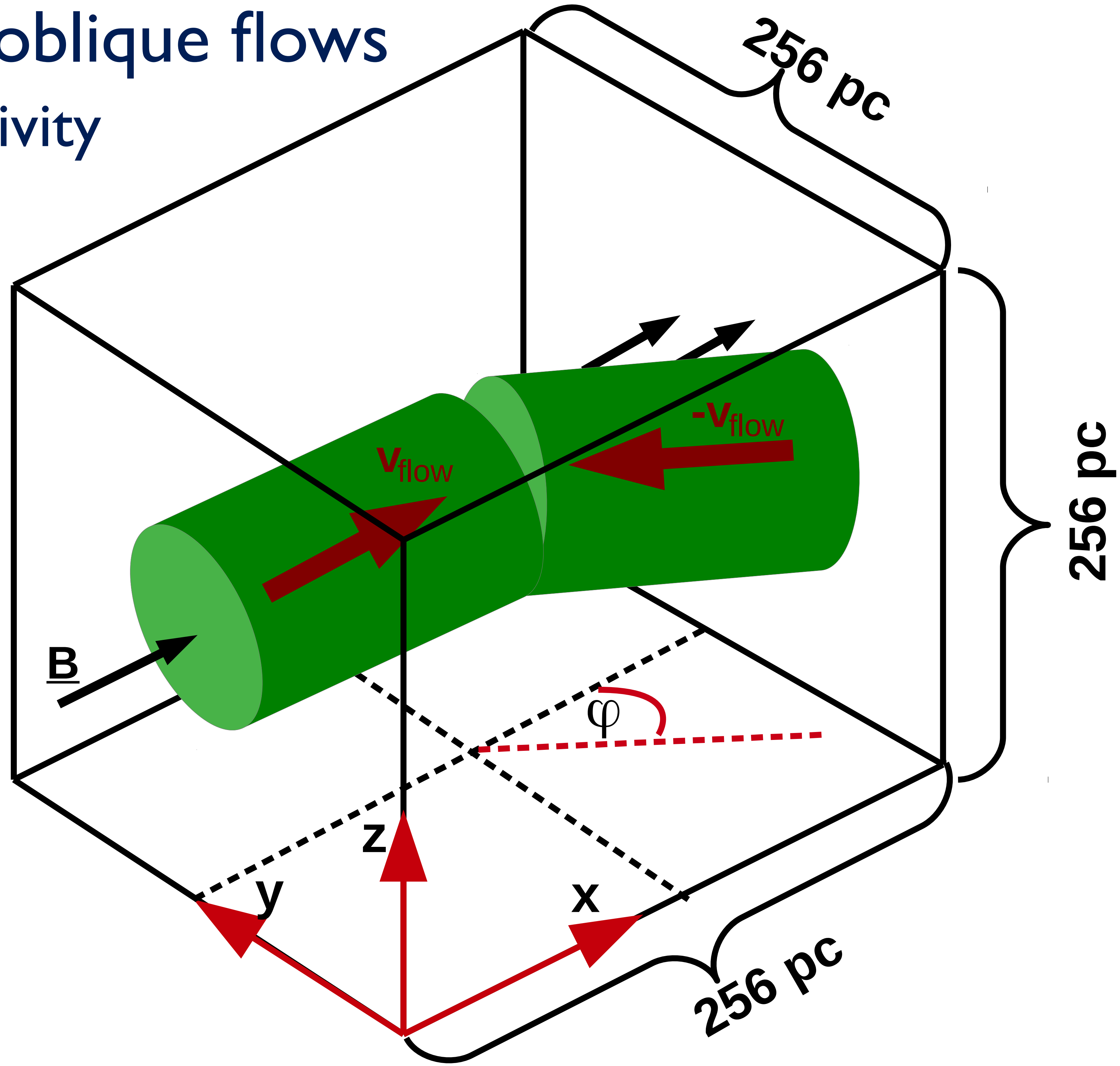
Simulations of oblique flows

Simulations setup of oblique flows

$\Longrightarrow$ enhanced flux-diffusivity

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



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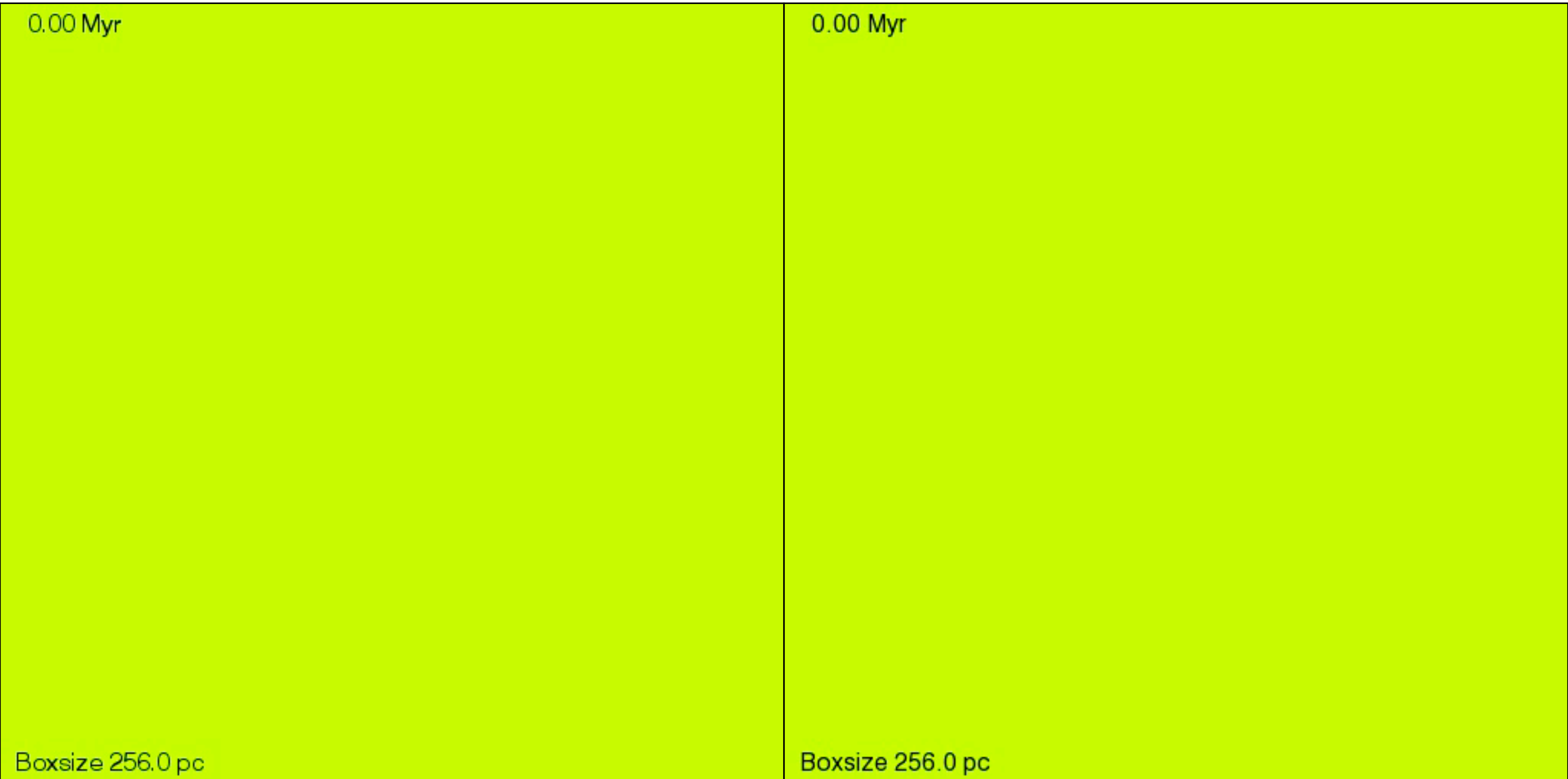
Simulations of oblique flows

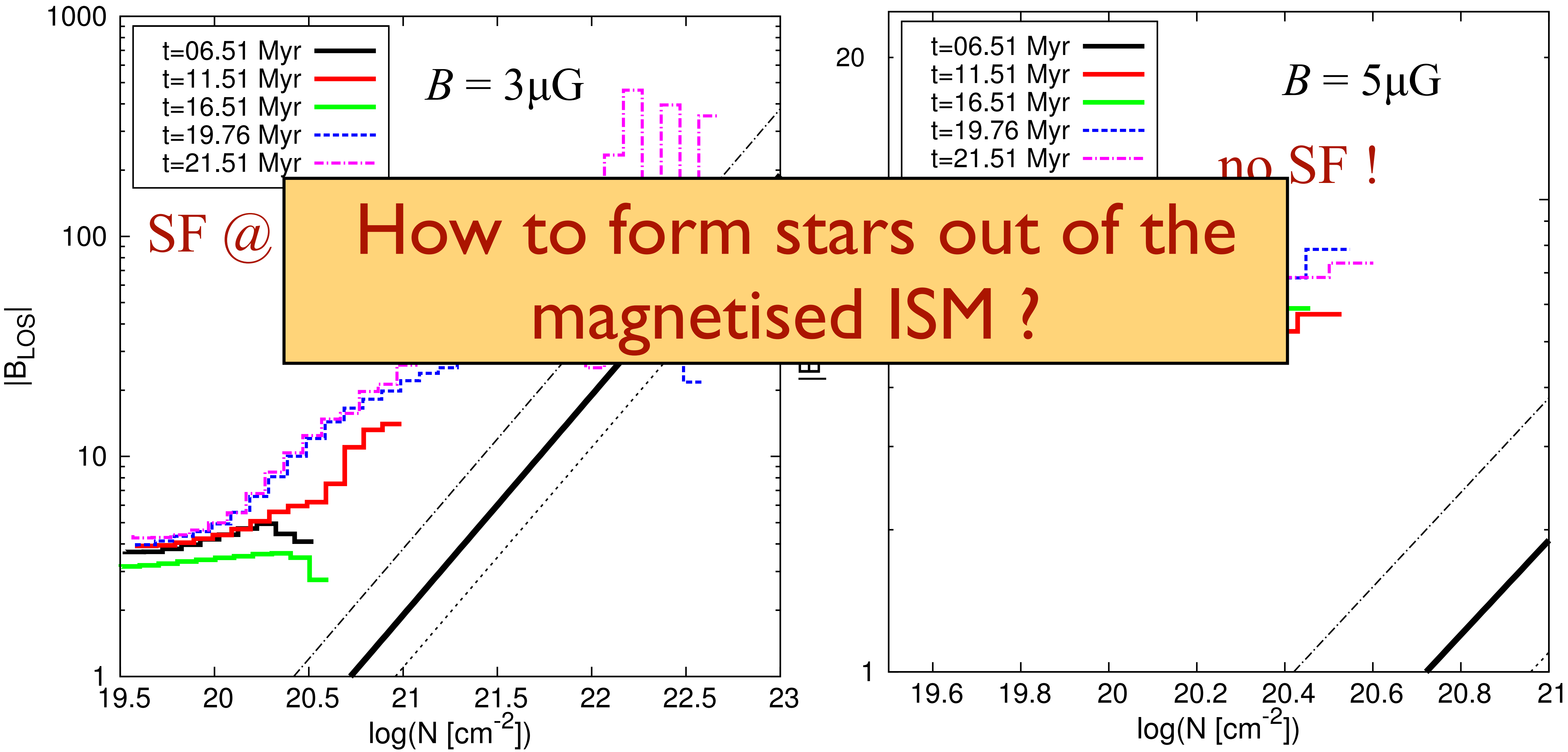
$\varphi = 60°$



$B = 3\mu G$ $B = 5\mu G$

Simulations of oblique flows

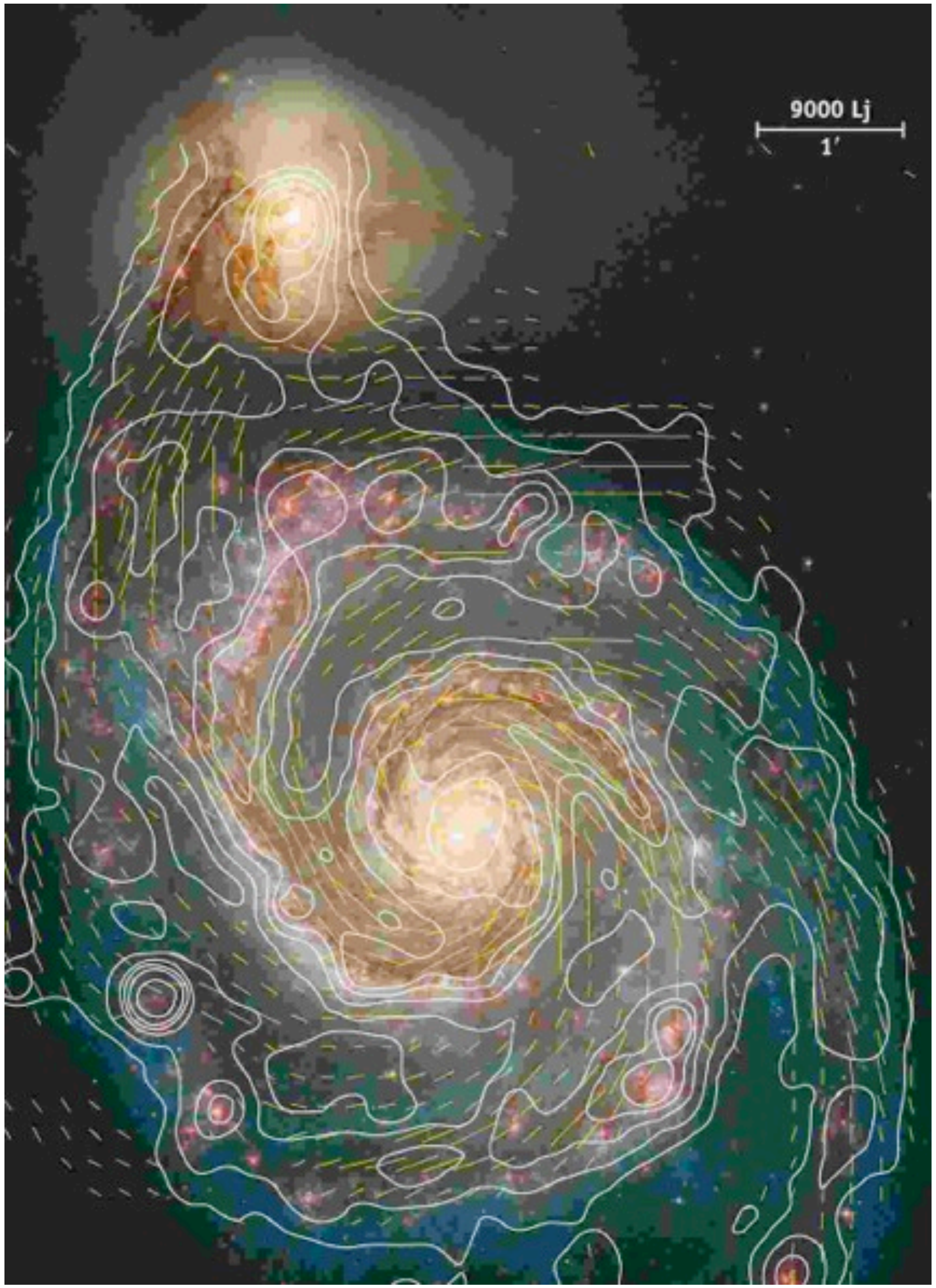
results from *oblique* flows with different field strengths at $\varphi = 60°$

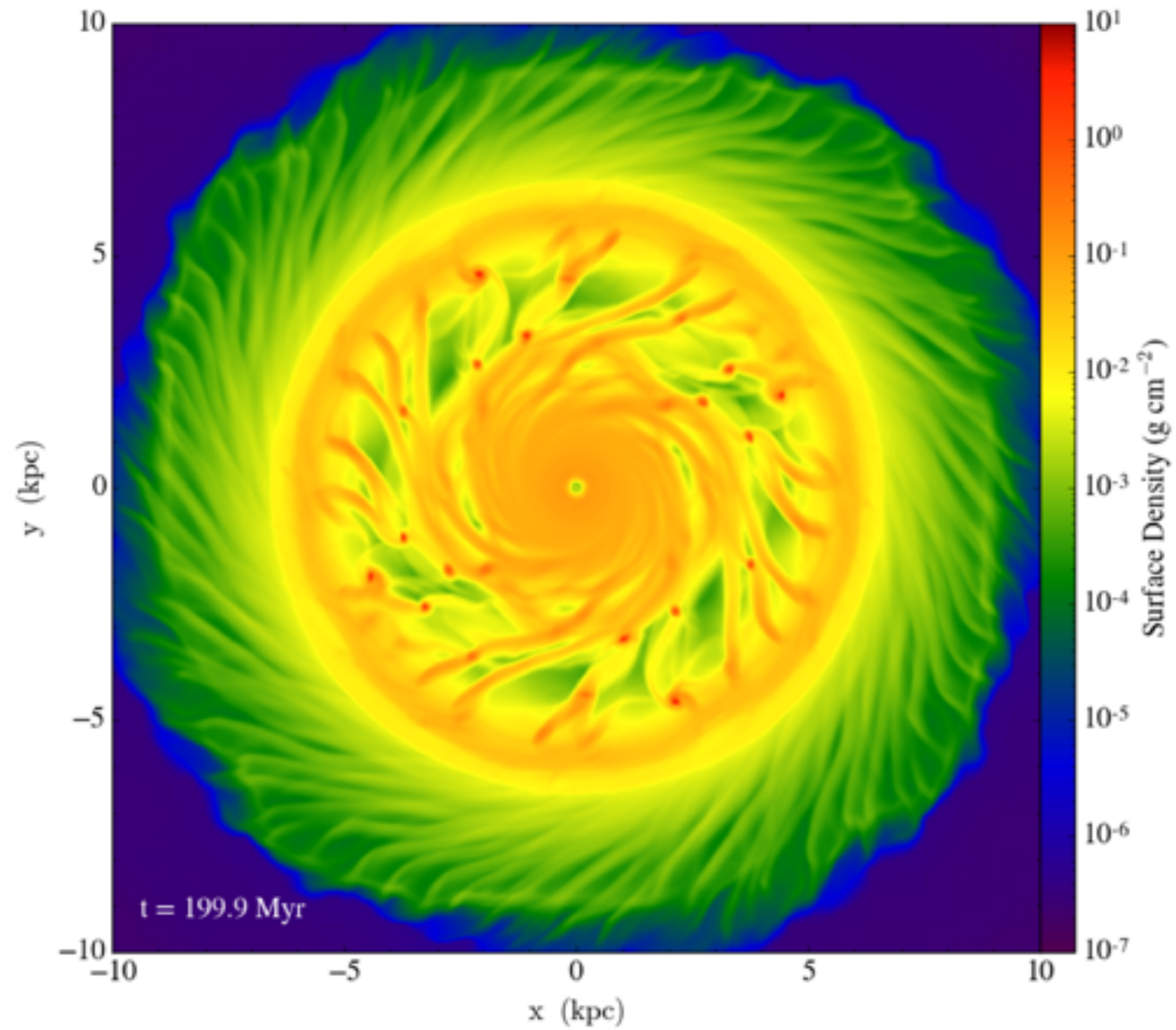


How to form stars out of the magnetised ISM ?

B. Körtgen, RB, MNRAS (2015)

Global Galactic Simulations



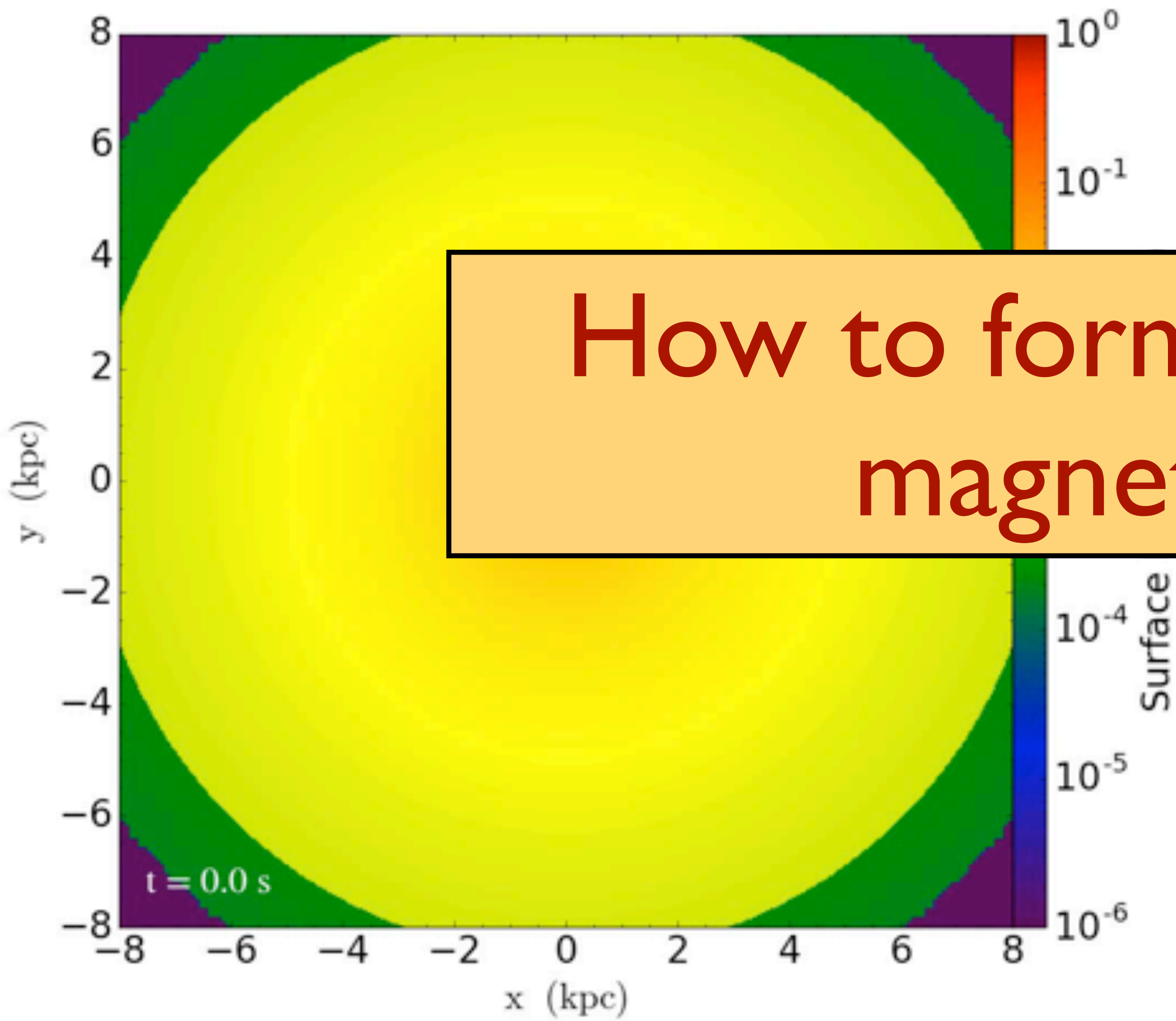


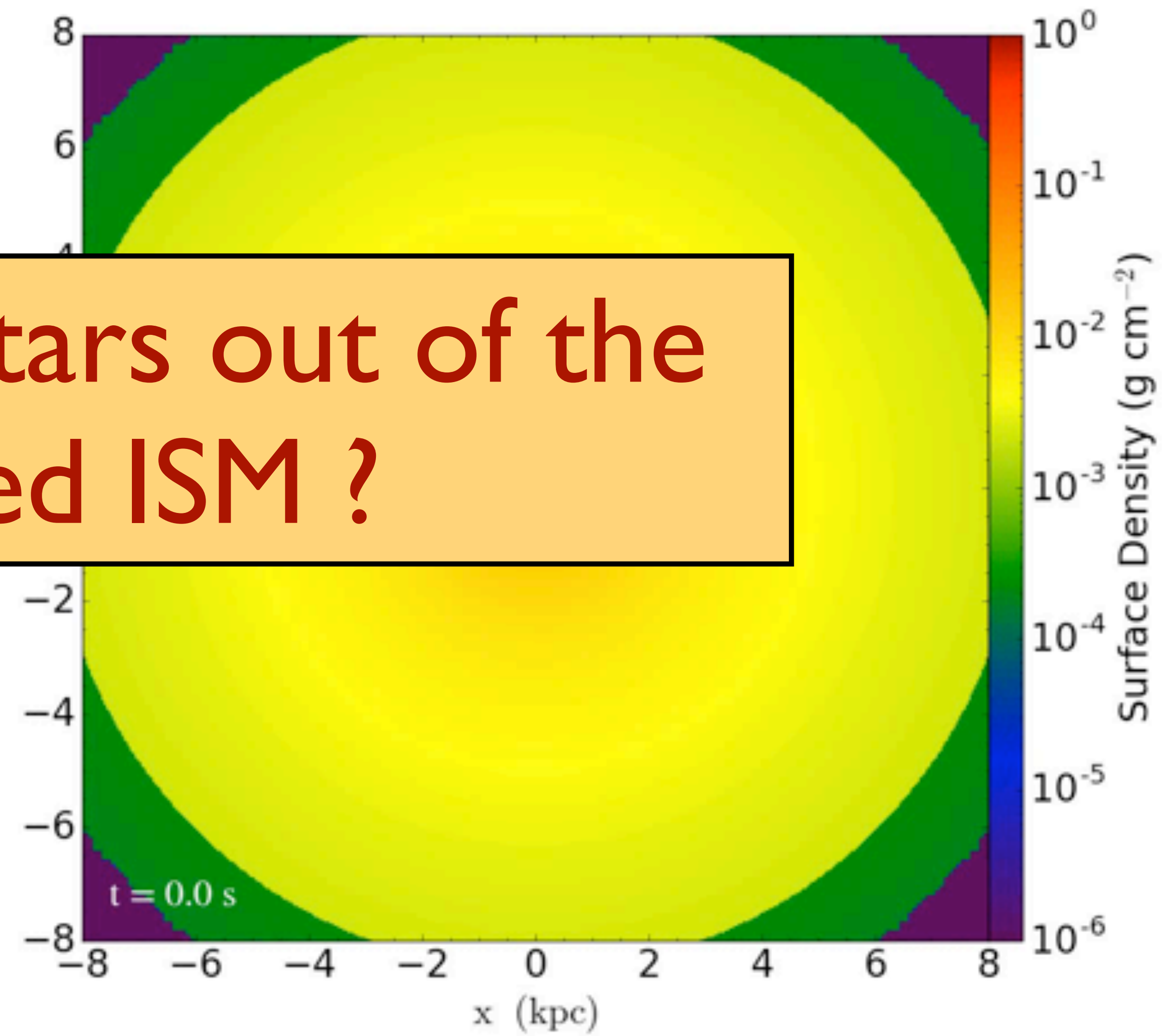
B. Körtgen, et al., preliminary work

does Mestel's accumulation idea work?

Global Galactic Disc Simulations

with toroidal magnetic field B_φ





How to form stars out of the magnetised ISM ?

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$B = 5\ \mu G$

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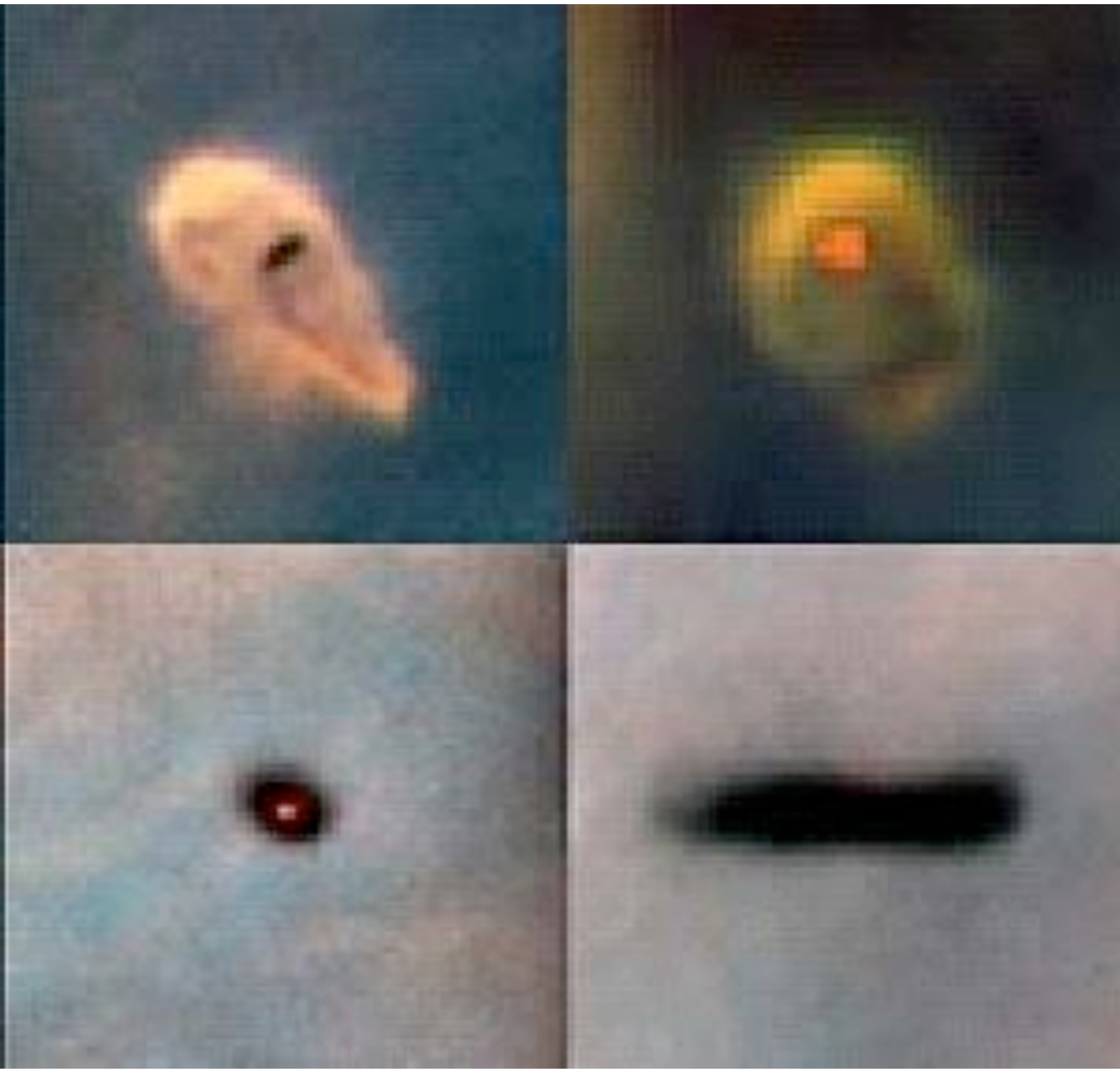
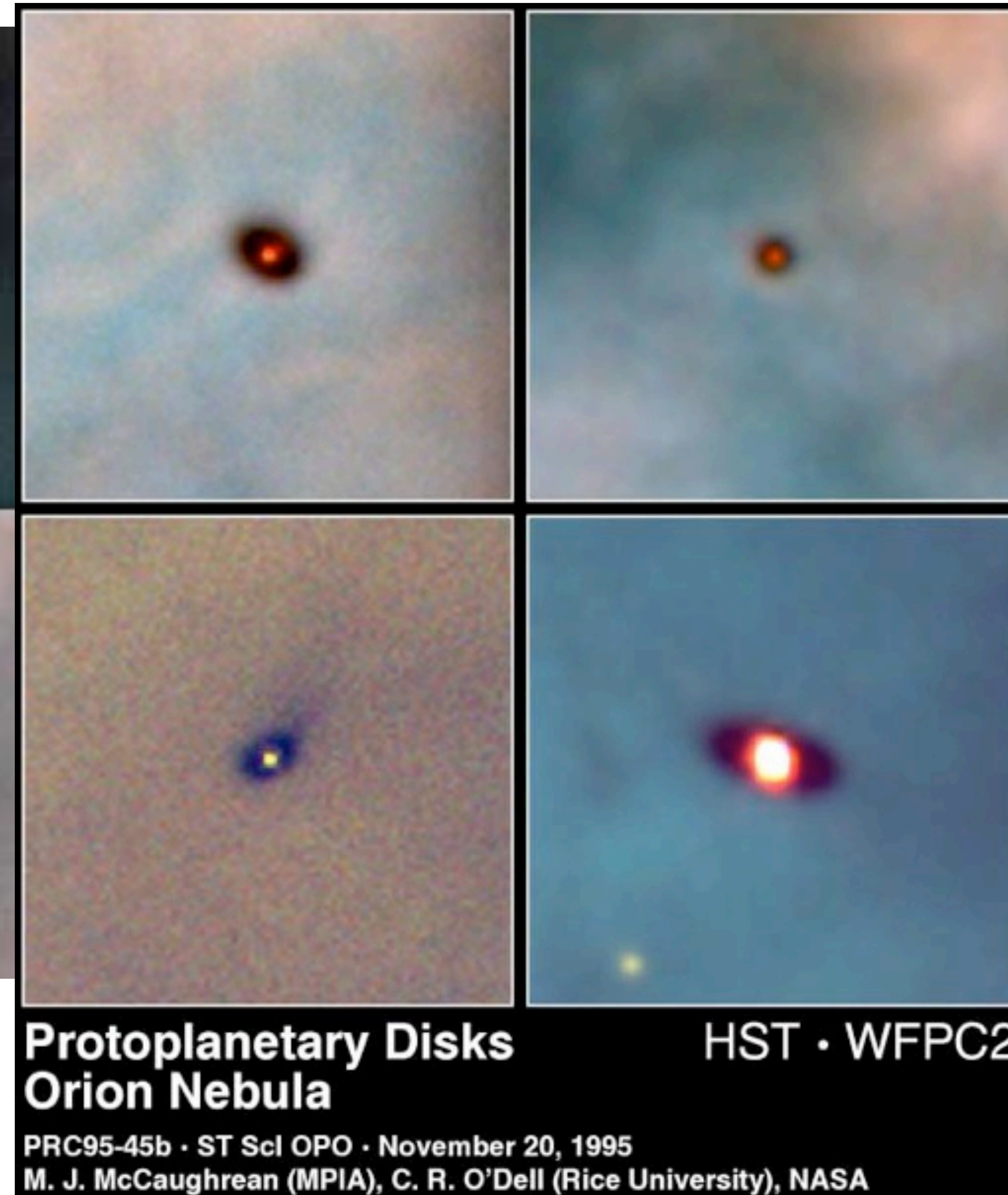
Protostellar Discs

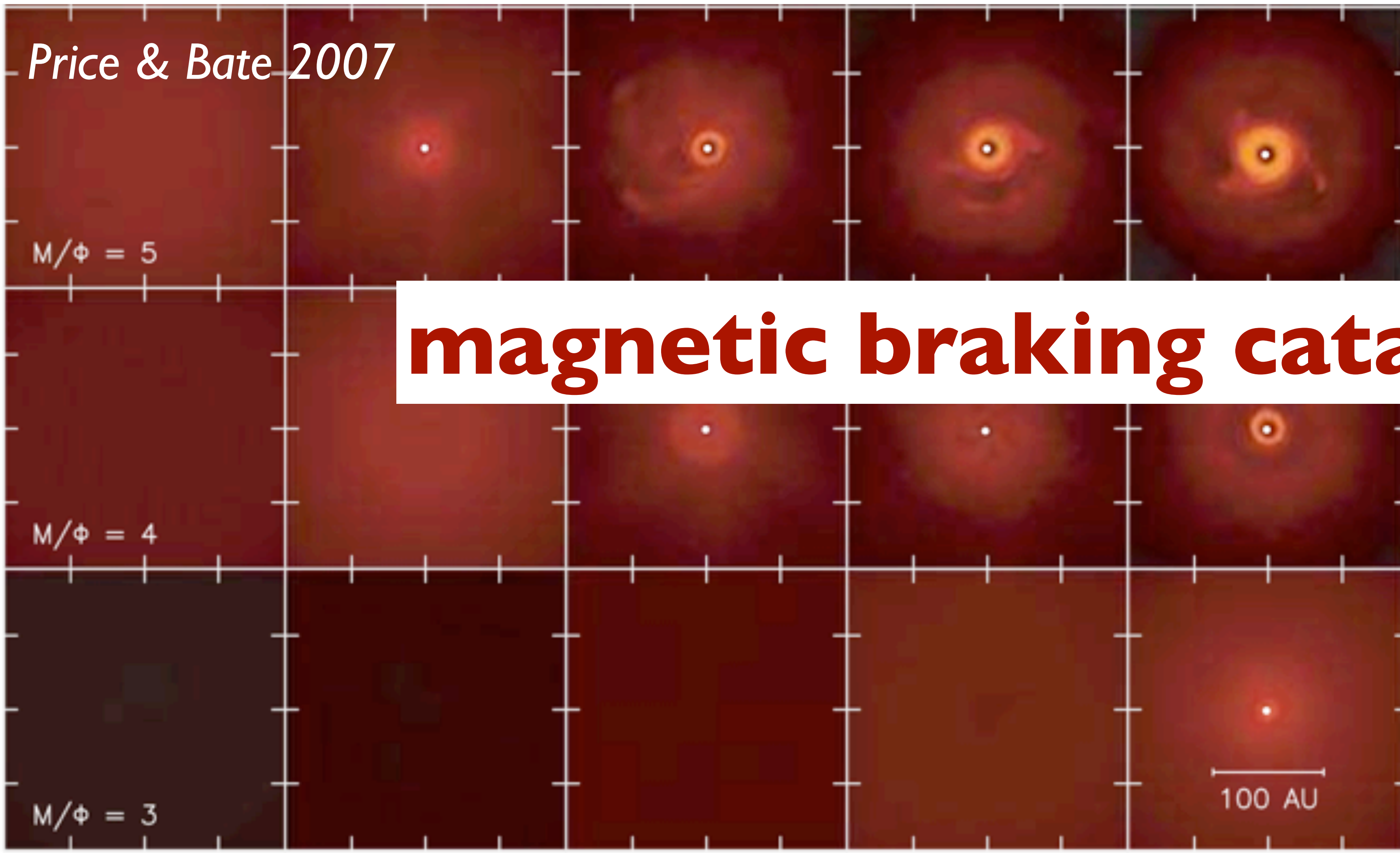


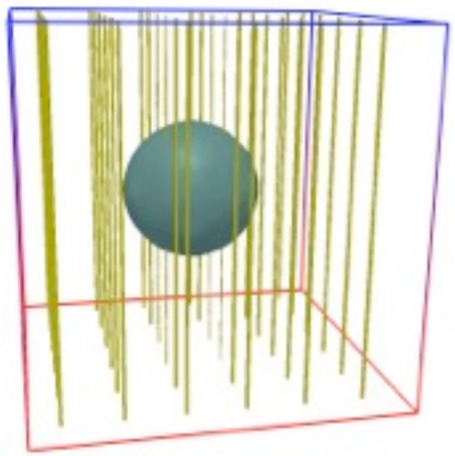


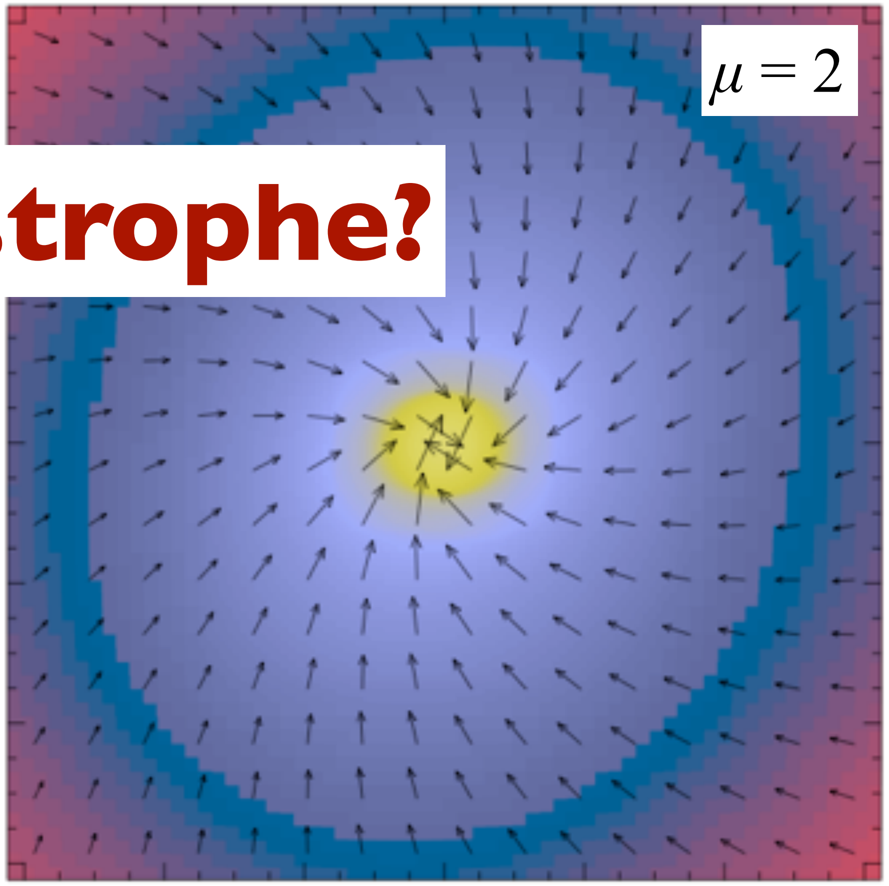
Star Formation: Early-type discs

$\Longrightarrow$ discs necessary for disc winds / outflows

- observed magnetic fields indicate $\mu < 5$







magnetic braking catastrophe?

Hennebelle & Teyssier 2008, ...

$\Longrightarrow$ very efficient magnetic braking

$\Longrightarrow$ ***no*** disc formation with smooth initial conditions

Star Formation: Early-type discs

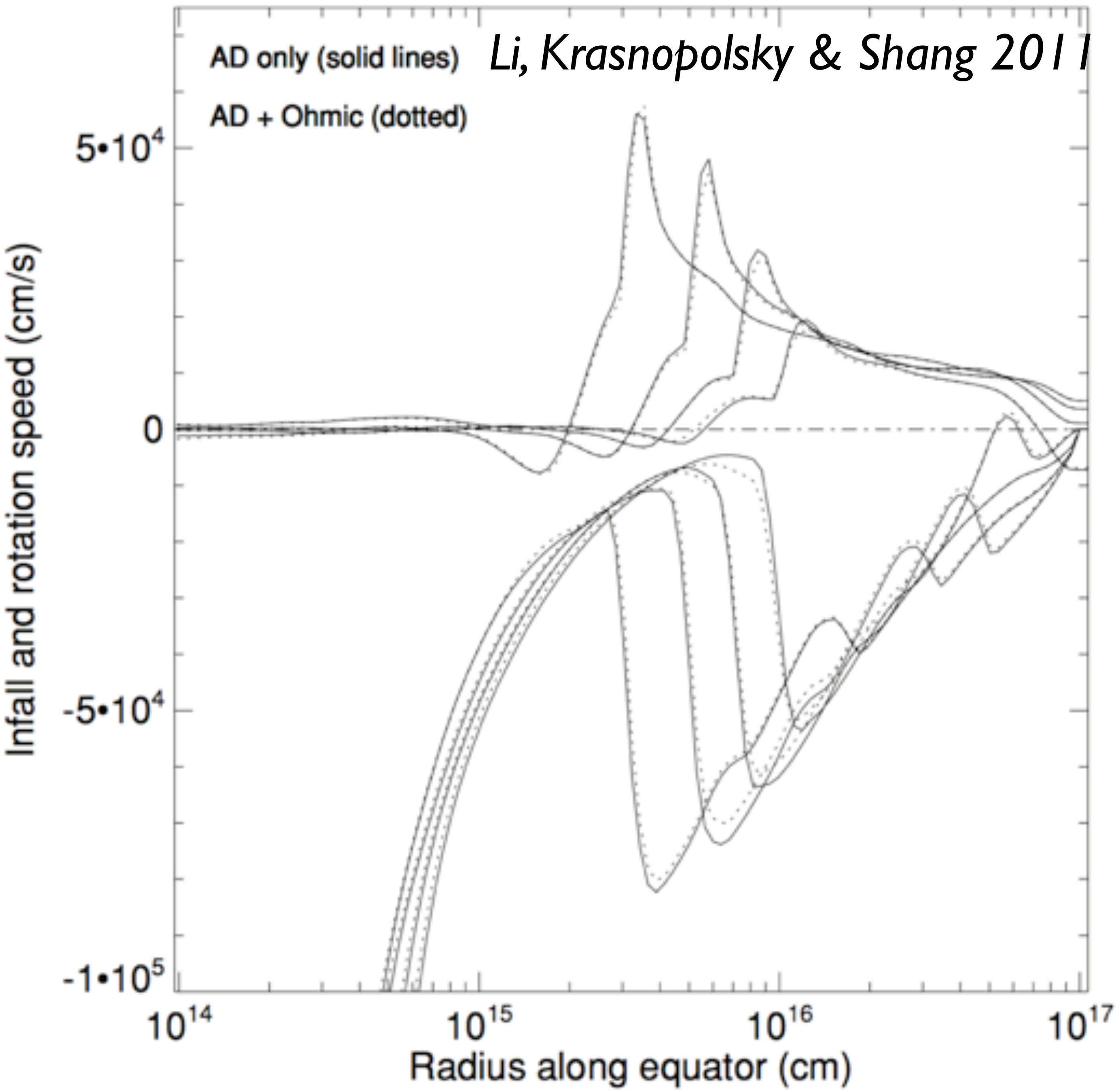
suggested solutions to the magnetic braking catastrophe:

- 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)

Star Formation: Early-type discs

⟹ Non-ideal MHD and reconnection 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

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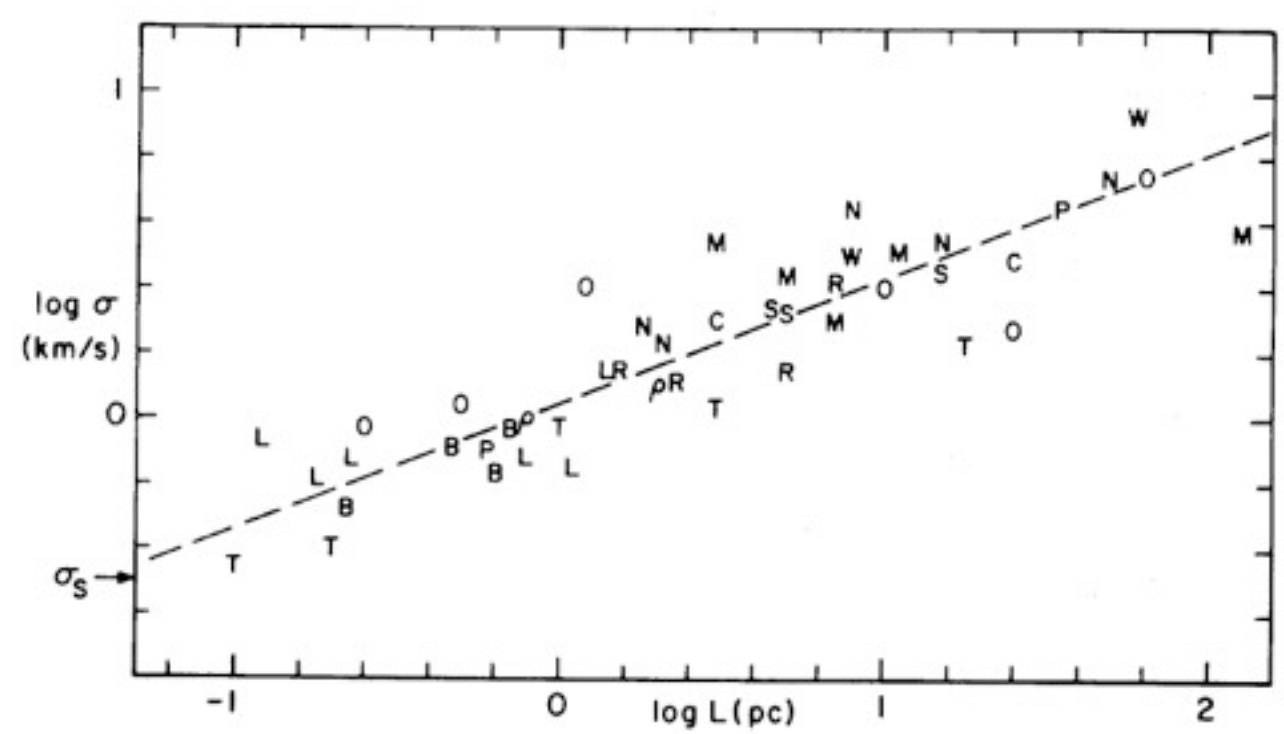
$\Longrightarrow$ what about **turbulence** ?



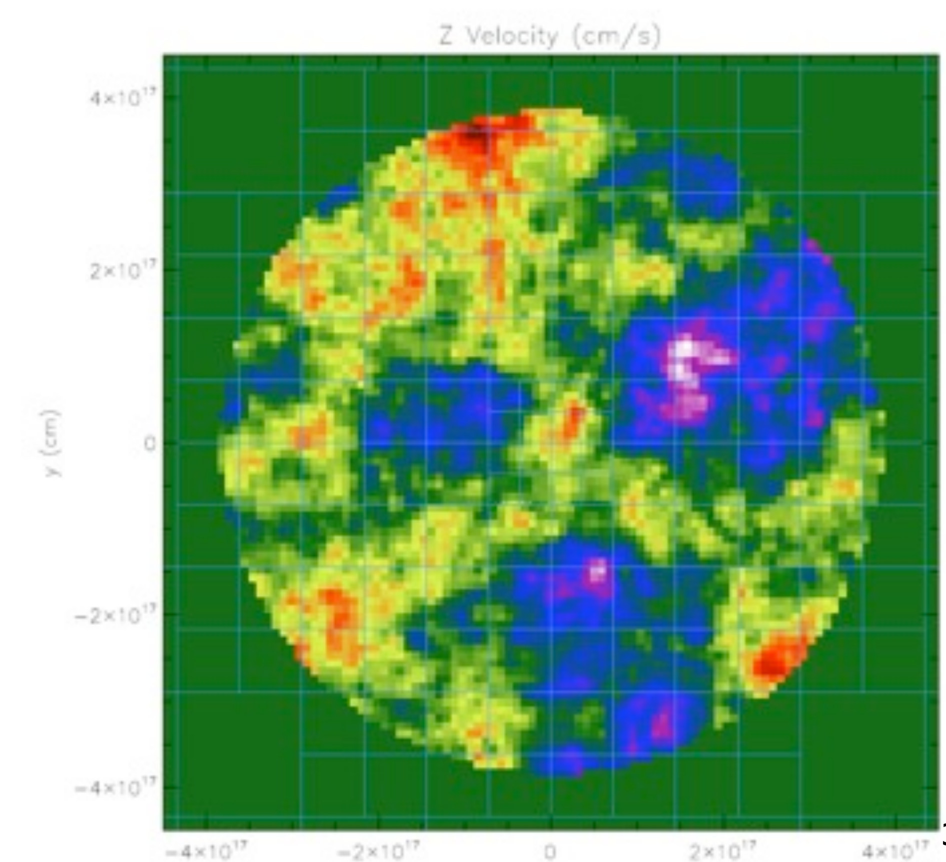
Collapse of Turbulent Cloud Cores

Seifried, et al. 2013

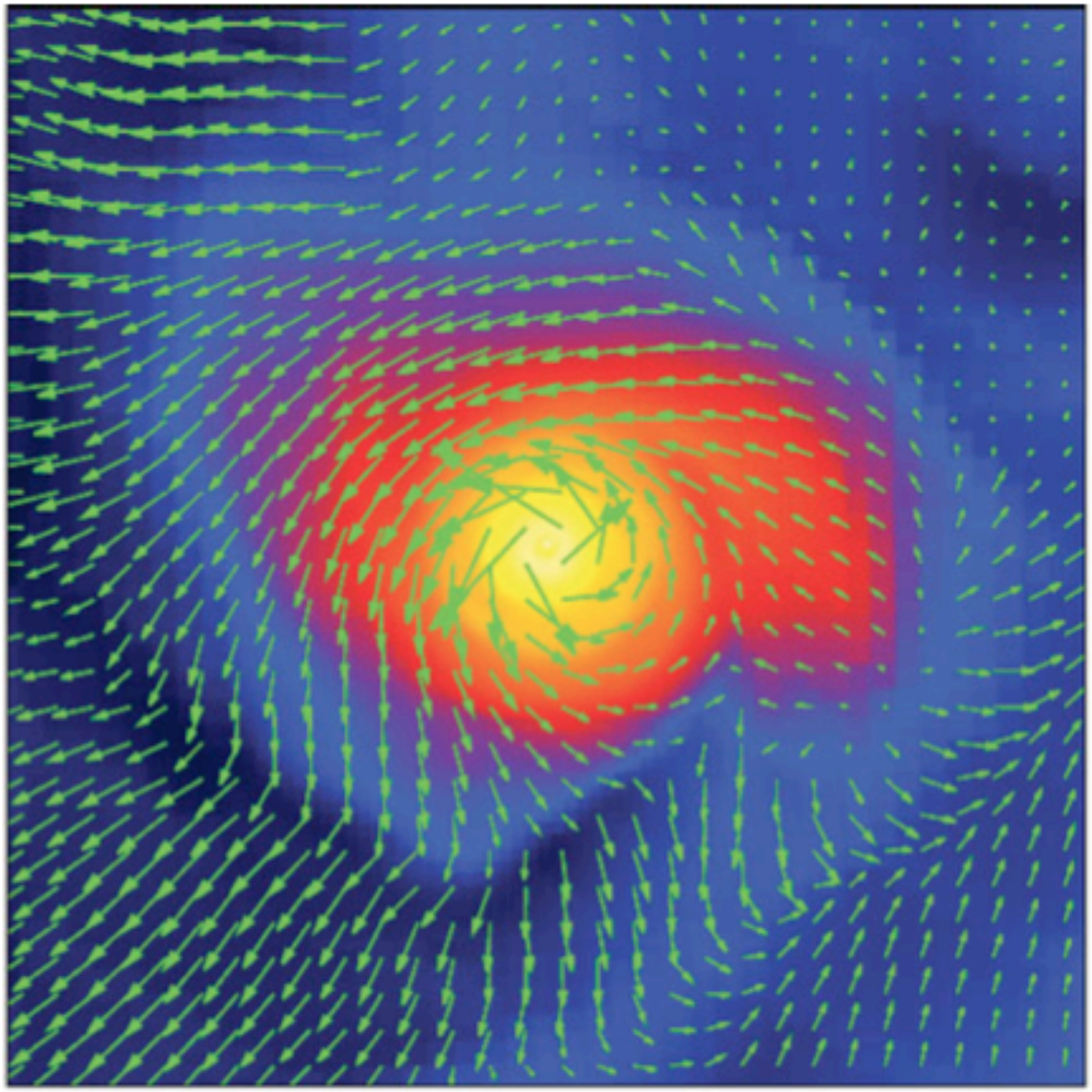
Run	m_{core} ($M_\odot$)	r_{core} (pc)	μ	Rotation	Ω (10^{-13} s^{-1})	β_{turb}	Turbulence seed	p	$\mathcal{M}_{rms}$	t_{sim} (kyr)
2.6-NoRot-M2	2.6	0.0485	2.6	No	0	0.087	A	5/3	0.74	15
2.6-Rot-M2	2.6	0.0485	2.6	Yes	2.20	0.087	A	5/3	0.74	15
2.6-NoRot-M100	100	0.125	2.6	No	0	0.084	A	5/3	2.5	15
2.6-Rot-M100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

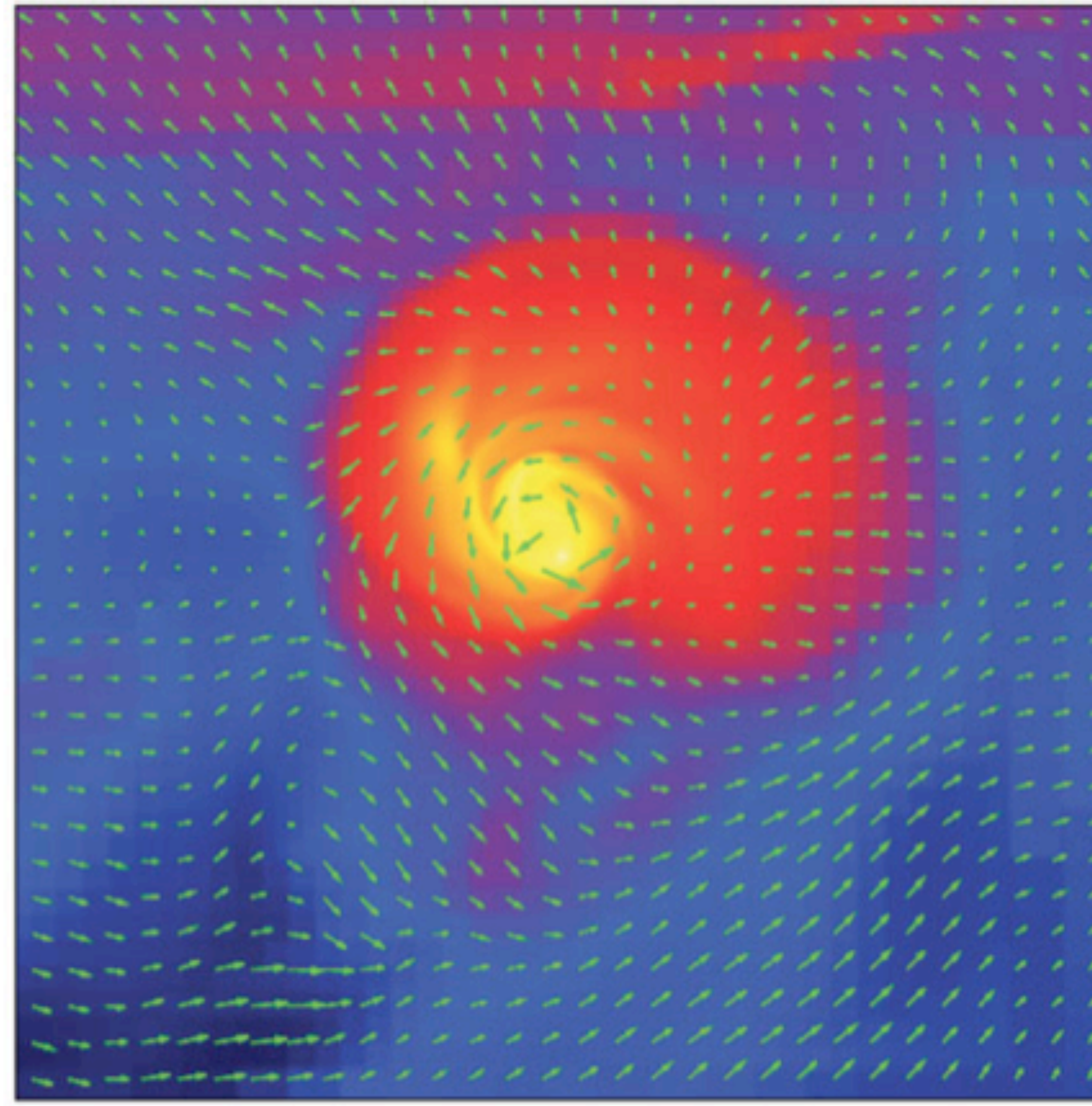
- low + high mass cores
- strong magnetic field
- with/without global rotation
- sub-/supersonic **turbulence** = velocity/density fluctuations

- resolution: 1.2 AU



Collapse of Turbulent Cores



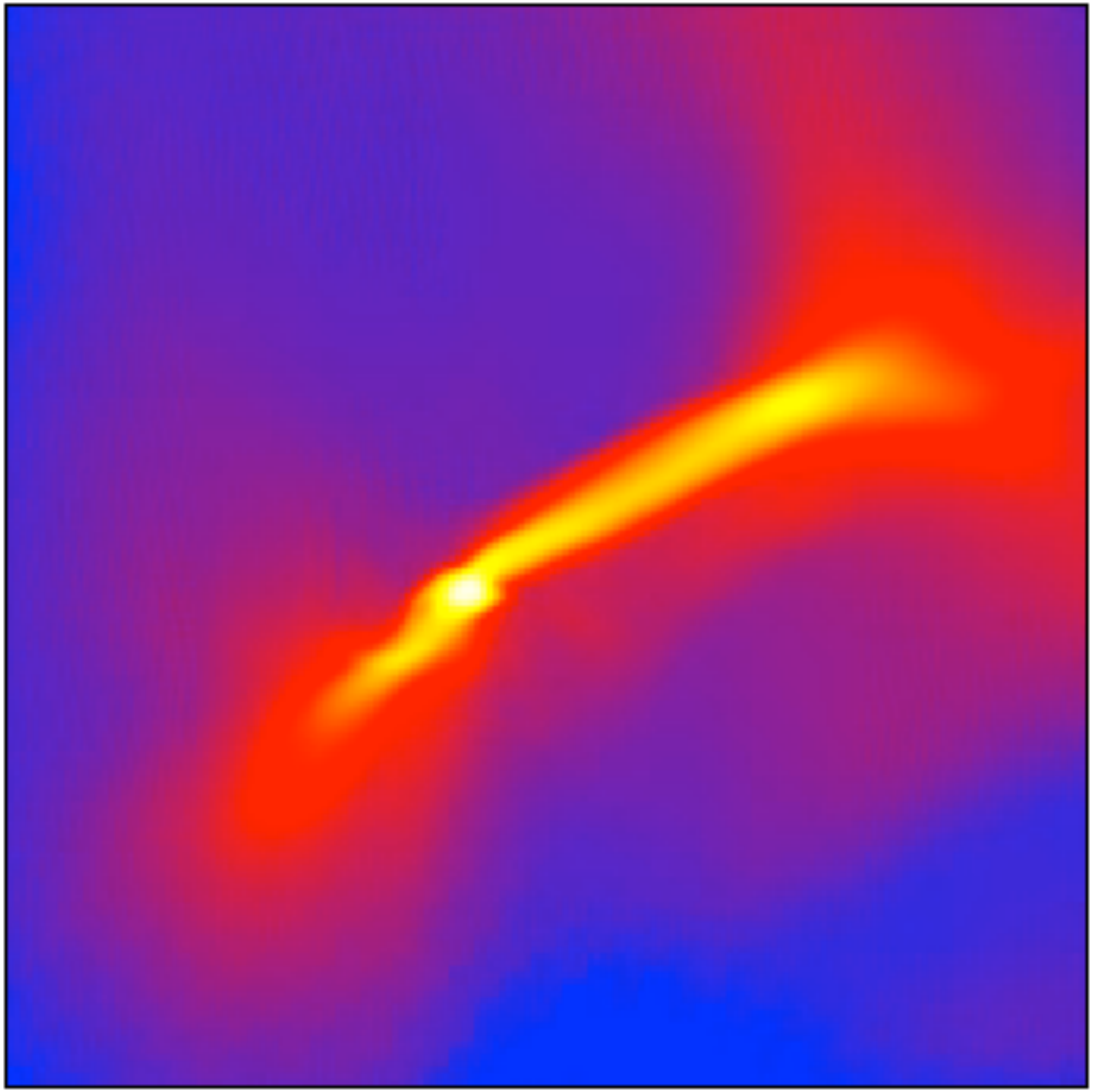


← 200 AU →

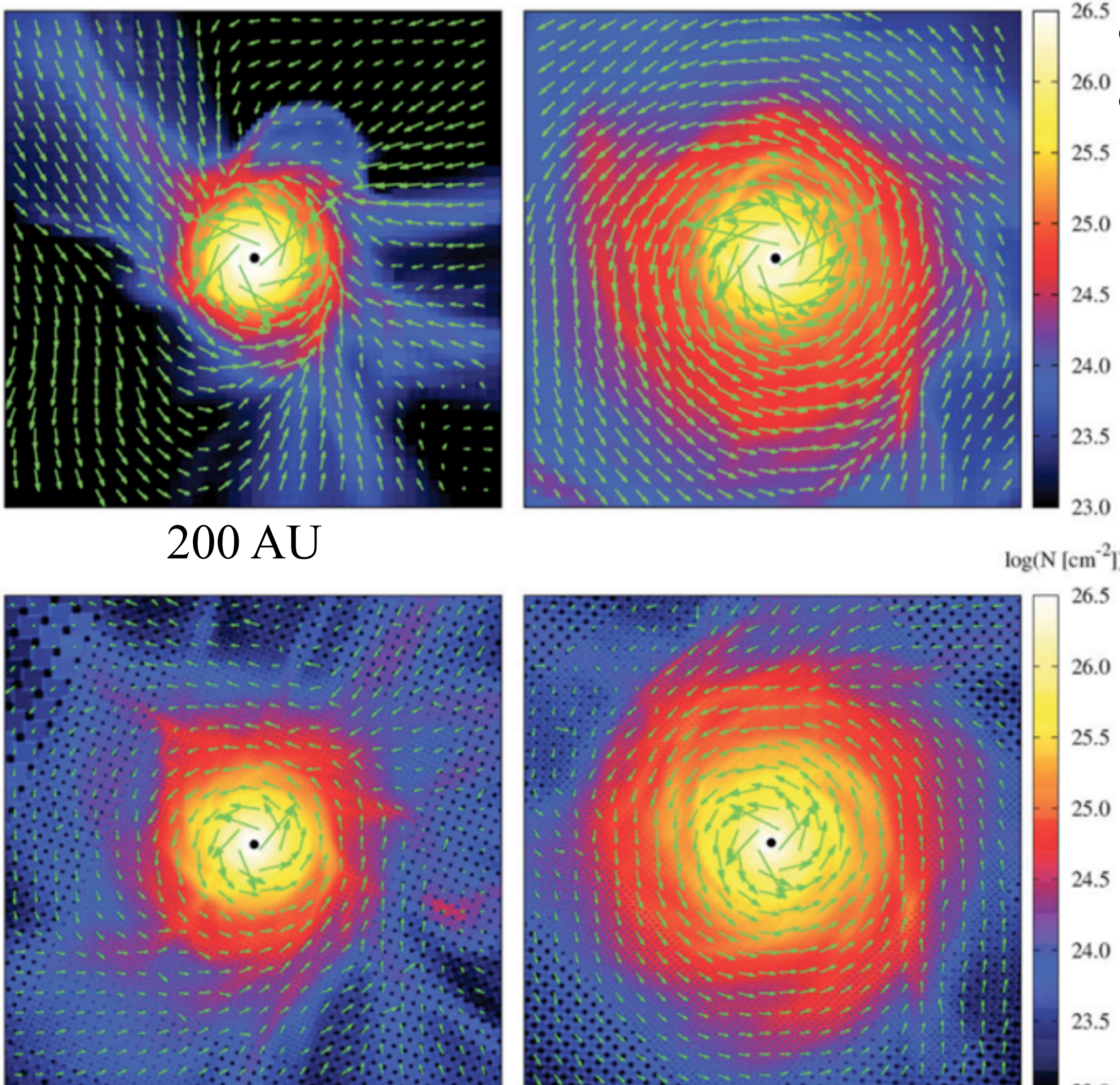
Seifried, RB, Pudritz, Klessen 2012

$\Longrightarrow$ discs "reappear"

Collapse of Turbulent Cores



Collapse of Turbulent Cores

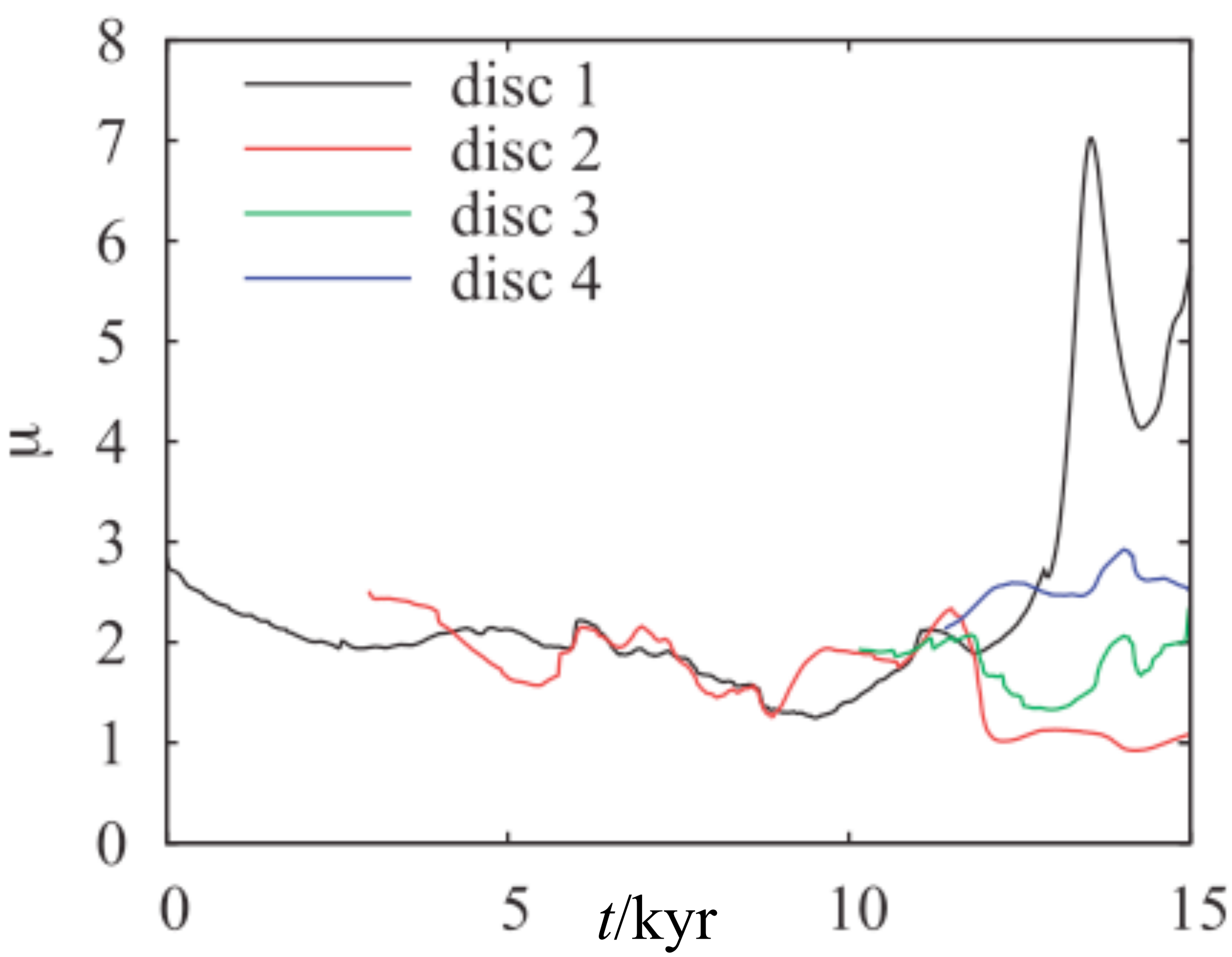


- low mass cores
- strong magnetic field: $\mu = 2.6\ \mu_{crit}$
- transonic turbulence $\mathcal{M}a = 0.74$
- **no** global rotation
- with global rotation

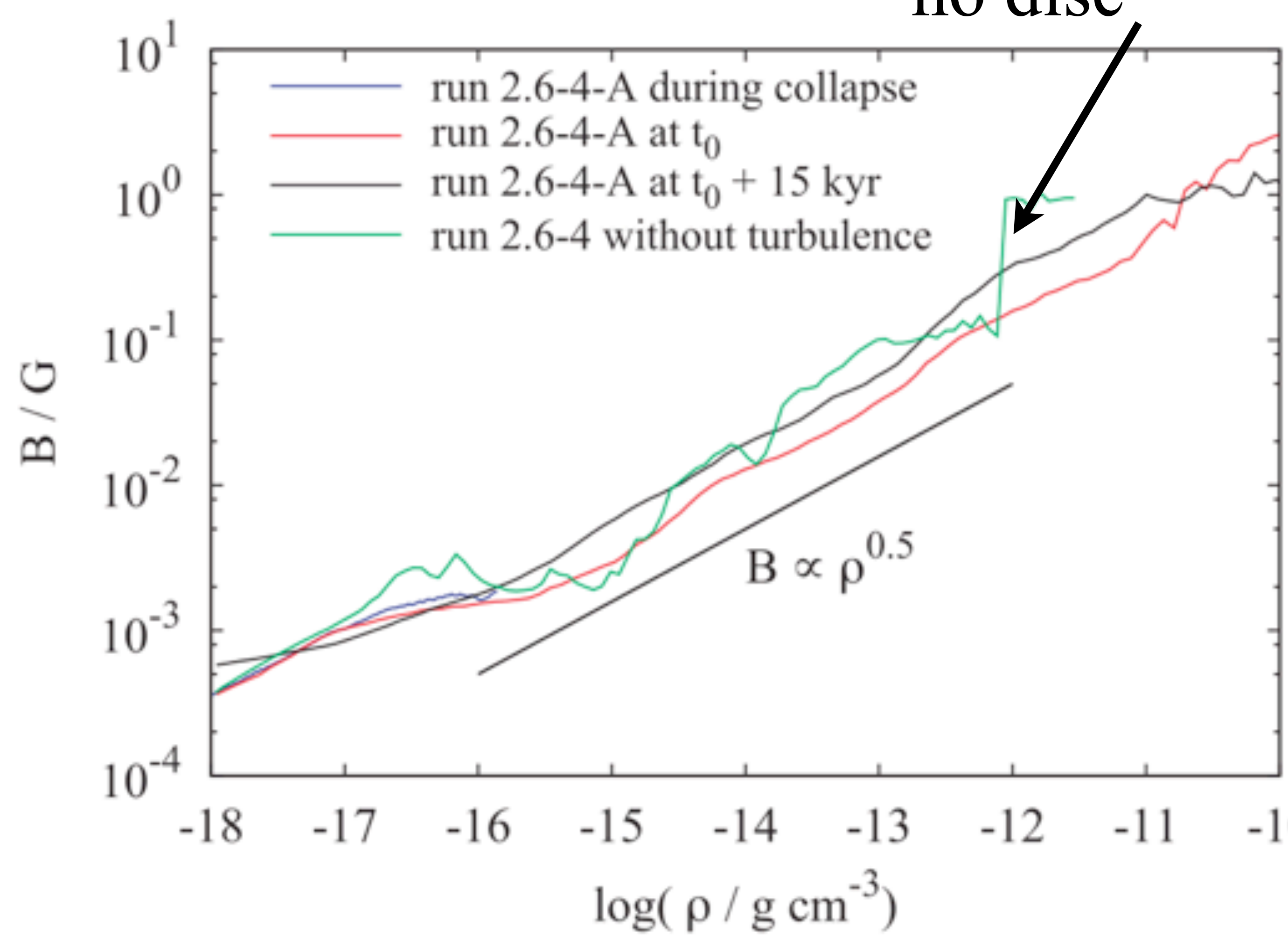
Seifried, et al. 2013

Collapse of Turbulent Cores

due to flux loss?



no turbulence
no disc



$\Longrightarrow$ no flux loss

Conclusion

ISM dynamics & Star Formation

- multi-scale + multi-physics challenge

- single ingredient/idealised studies can be misleading

- but: numerical experiments are necessary to probe the underlying physics (predictive power?)