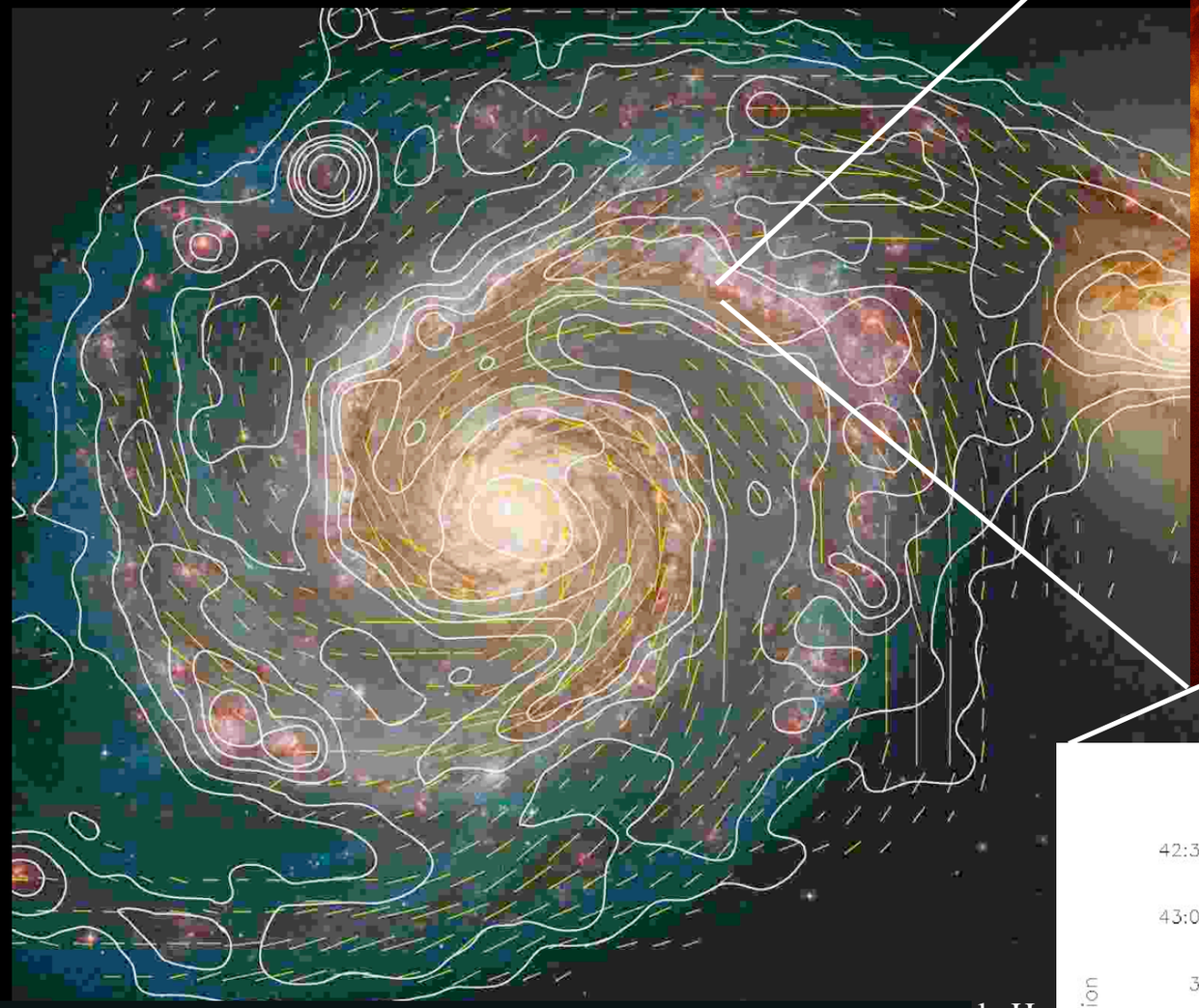
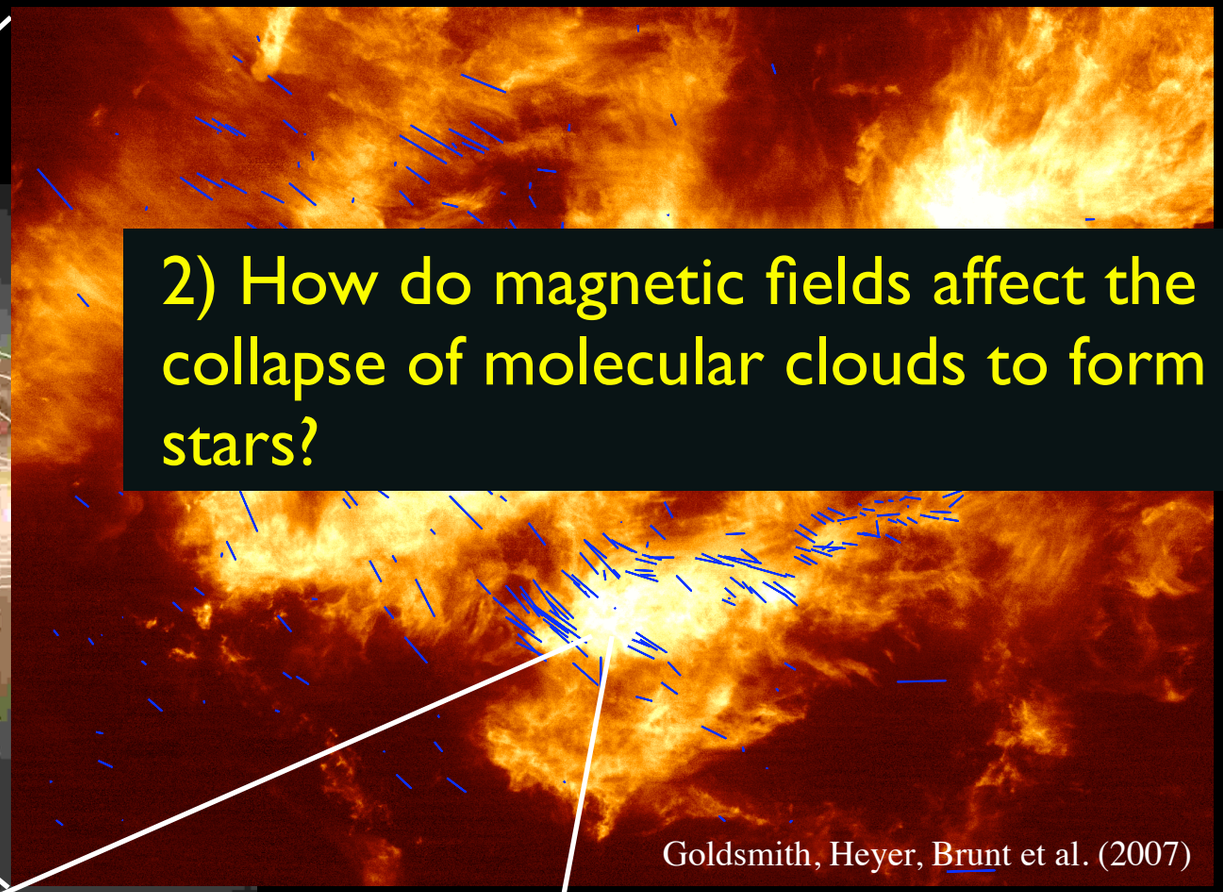
Cosmic Magnetism: From Stellar to Galactic Scales

Daniel Price (Monash University, Melbourne, AU)

with
Clare Dobbs (MPE)
Matthew Bate (Exeter, UK)

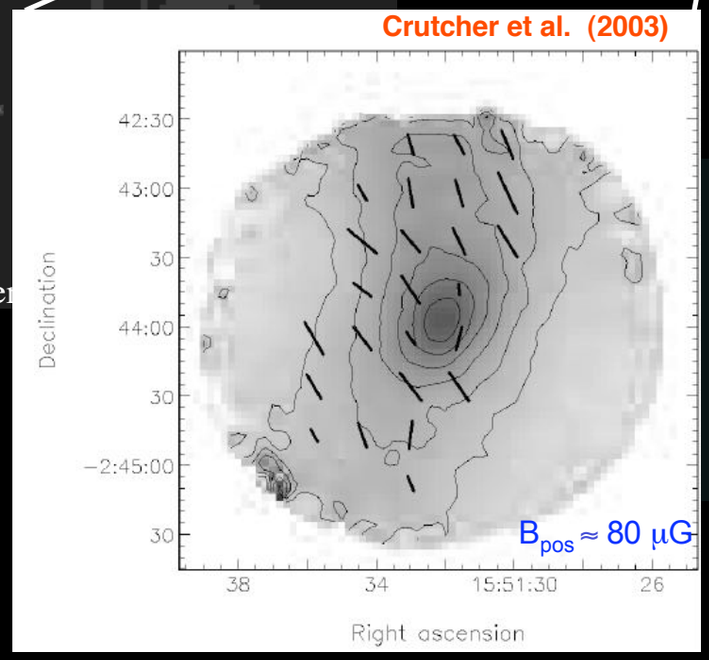
Cosmic Magnetism, Kiama, June 7th-11th 2010





Goldsmith, Heyer, Brunt et al. (2007)

2) How do magnetic fields affect the collapse of molecular clouds to form stars?



1) What is the effect of magnetic fields on fragmentation of molecular cloud cores?

3) What effect do magnetic fields have on the dynamics of the interstellar medium?

Magnetic fields in the star formation process

Are magnetic fields important?

$$\left(\frac{M}{\Phi}\right) / \left(\frac{M}{\Phi}\right)_{crit}$$ magnetic field vs gravity

$$\beta = \frac{c_s^2 \rho}{\frac{1}{2} B^2 / \mu_0}$$ magnetic fields vs pressure

$$\frac{v_{turb}}{v_{Alfven}}$$ magnetic fields vs turbulence

Observations suggest molecular clouds are:

mildly supercritical
have beta < 1
marginally super-Alfvenic

(Crutcher 1999, Bourke et al. 2001, Padoan et al. 2004, Heiles & Troland 2005)

MHD

$$\frac{d\rho}{dt} = -\rho \nabla \cdot \mathbf{v}$$

$$\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho} \nabla \cdot \left[\left(P + \frac{1}{2} \frac{B^2}{\mu_0} \right) \mathbf{I} - \frac{\mathbf{BB}}{\mu_0} \right]$$

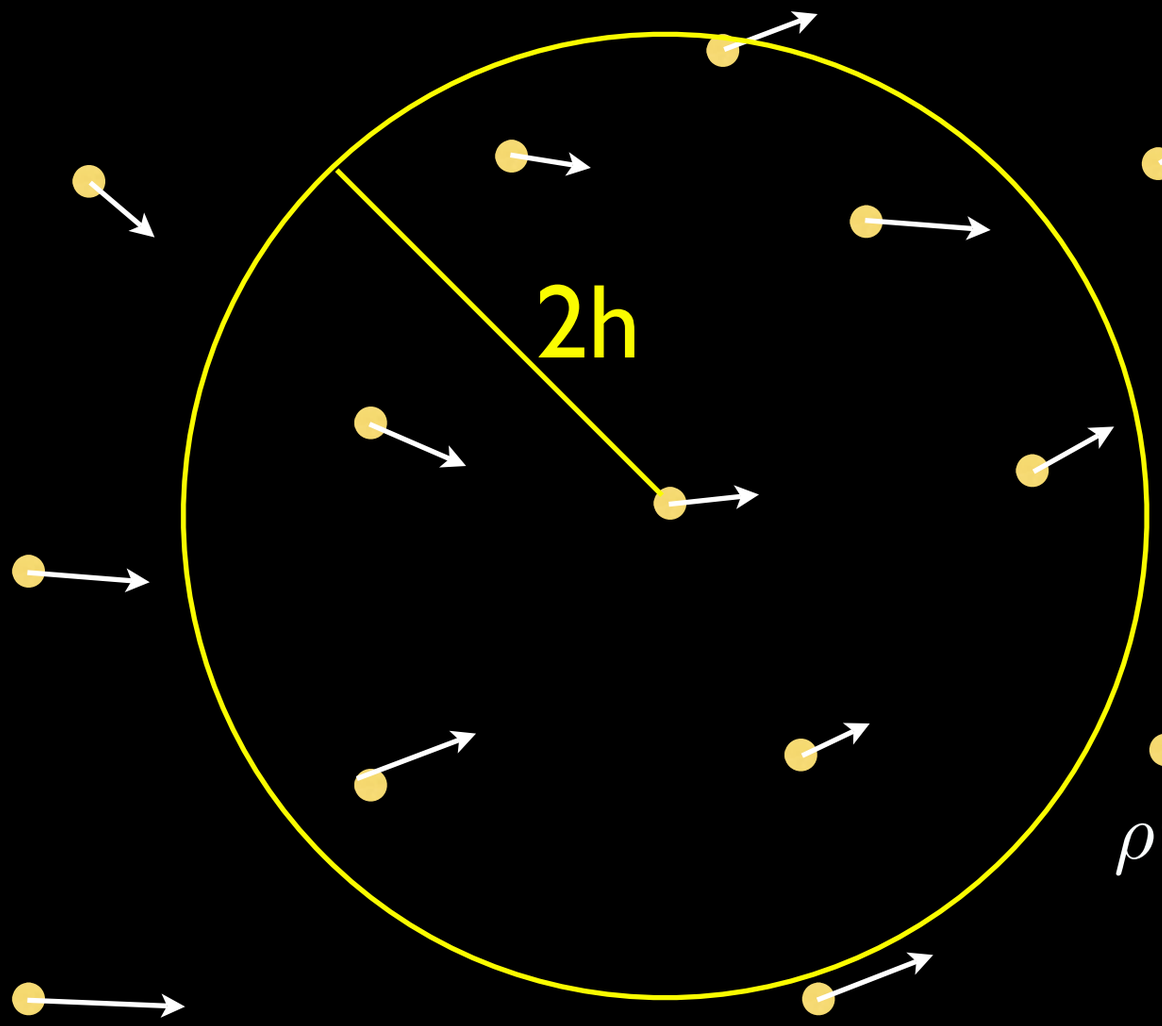
$$\frac{du}{dt} = -\frac{P}{\rho} \nabla \cdot \mathbf{v}$$

$$\frac{d}{dt} \left(\frac{\mathbf{B}}{\rho} \right) = \left(\frac{\mathbf{B}}{\rho} \cdot \nabla \right) \mathbf{v}$$

$$\nabla \cdot \mathbf{B} = 0$$

Smoothed Particle Hydrodynamics

Lucy (1977), Gingold & Monaghan (1977), Monaghan (1992), Price (2004), Monaghan (2005)



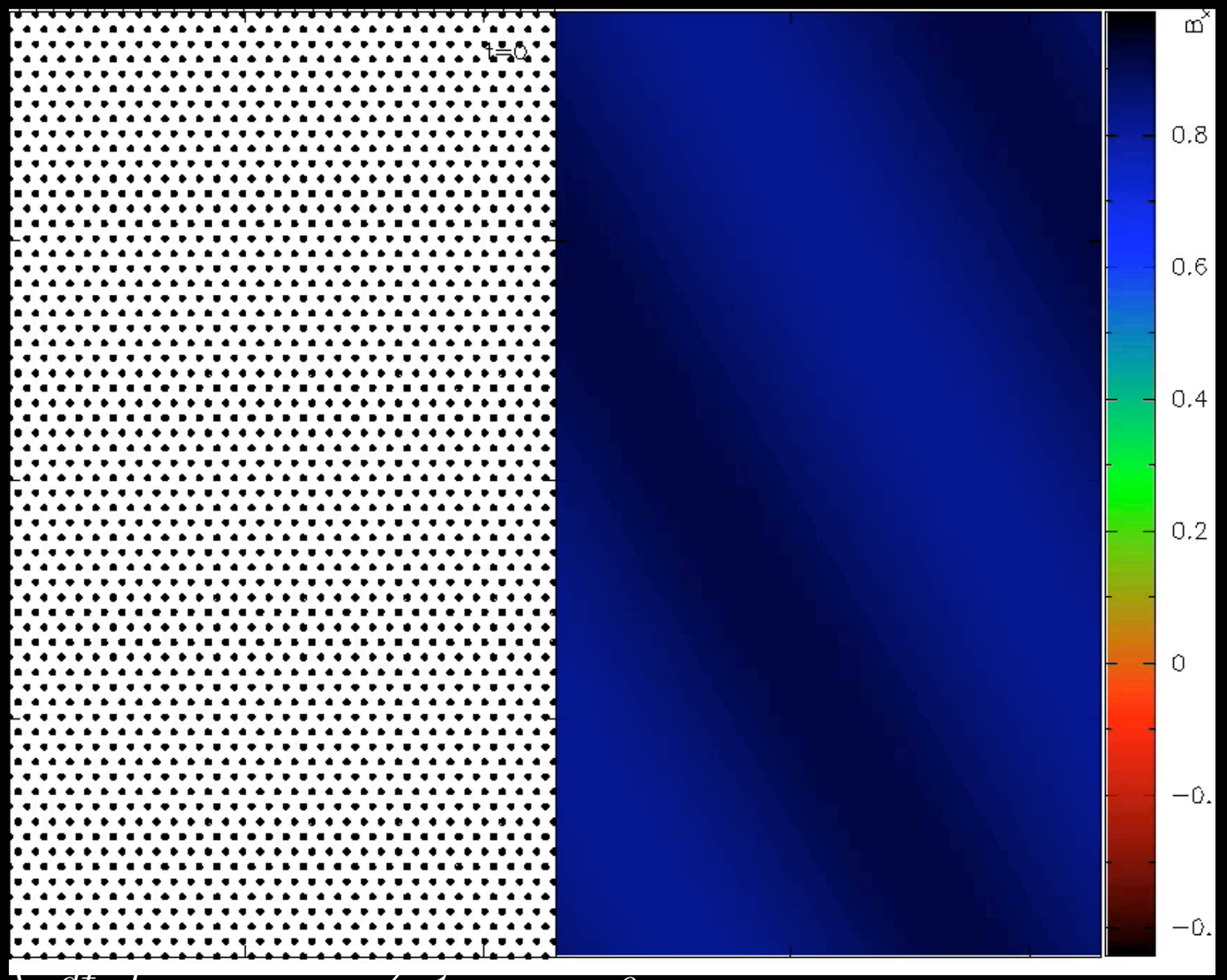
$$\rho(\mathbf{r}) = \sum_{j=1}^{N} m_j W(|\mathbf{r} - \mathbf{r}_j|, h)$$

solve equations of gas dynamics
on moving Lagrangian particles:

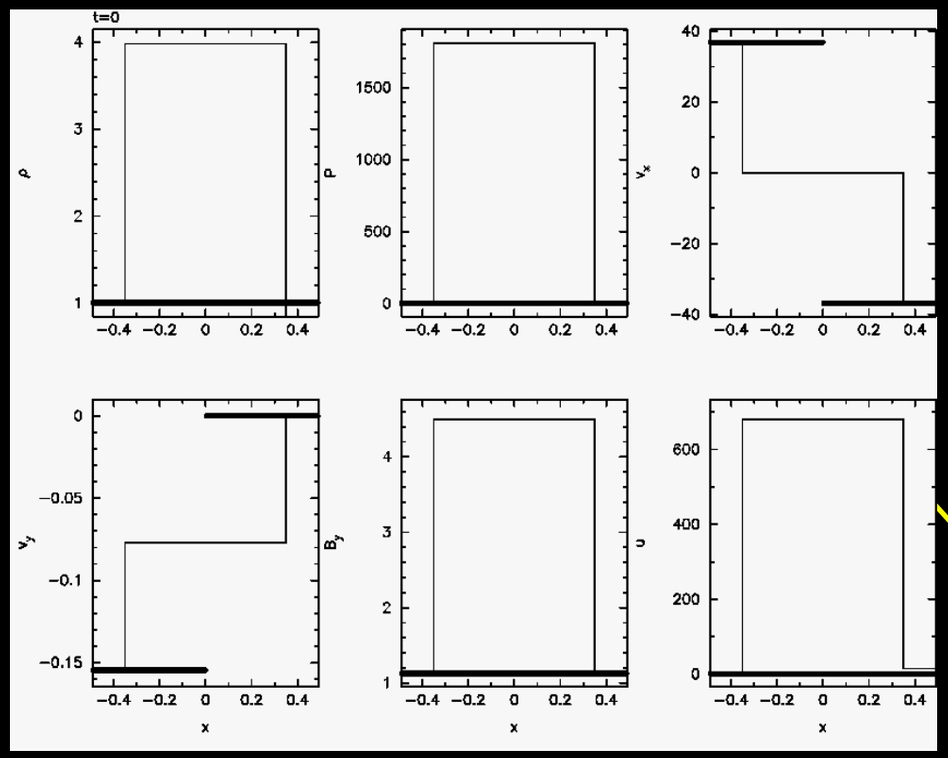
resolution follows mass

MHD+SPH: some issues

1) Conservative formulation of Lorentz force is unstable



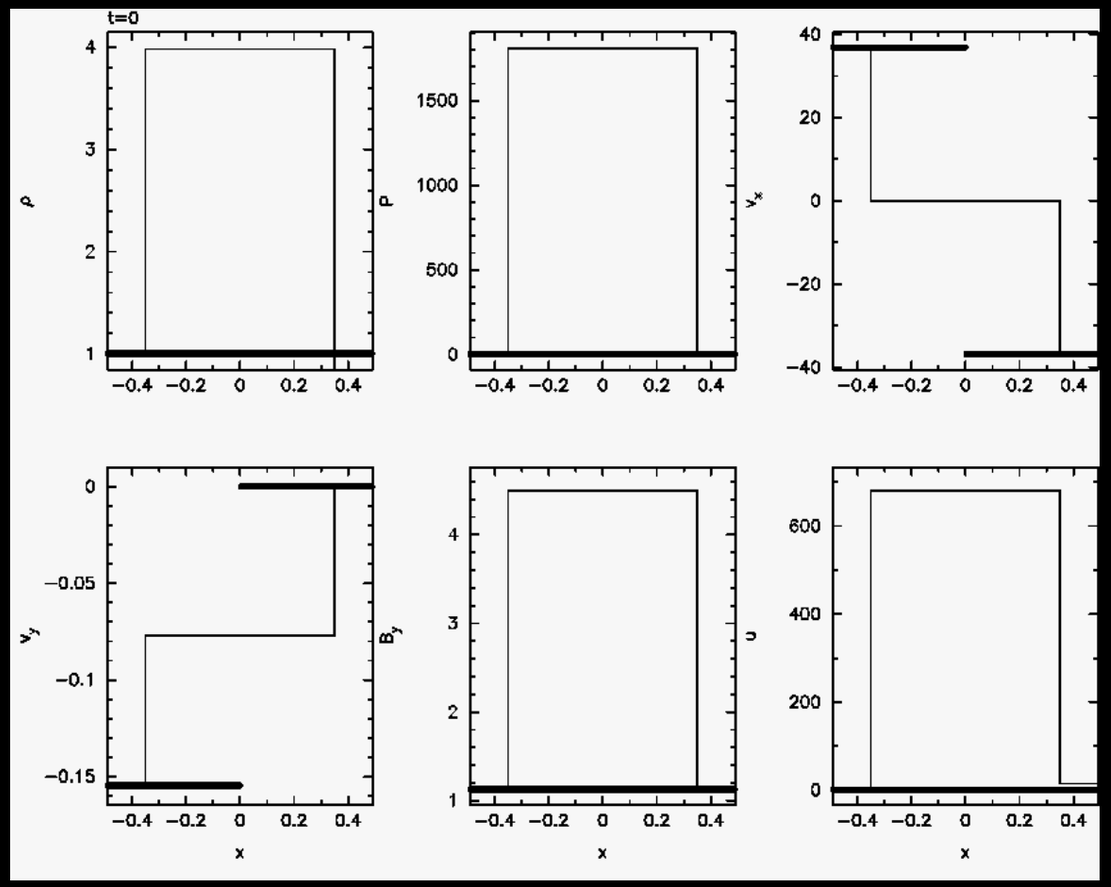
2) Shocks



$$\left(\frac{dv_a}{dt}\right)_{diss} = \sum_b \rho_{ab}$$

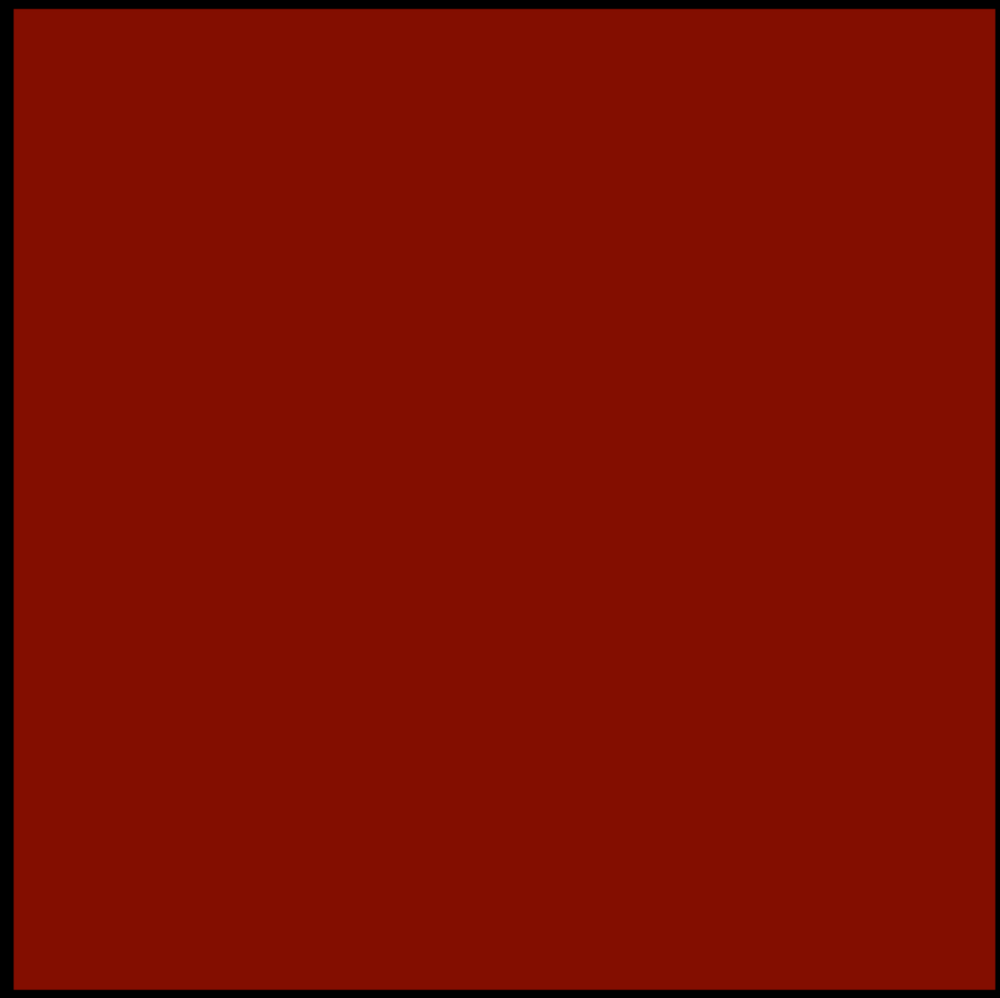
derive consistent formulation using Lagrangian (Price & Monaghan 2004b)

Test problems



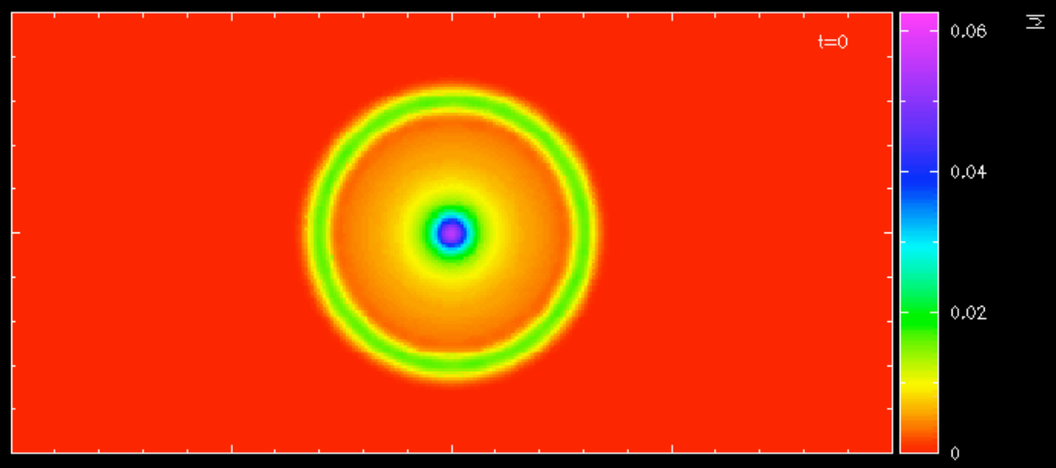
Mach 25 MHD shock (e.g. Balsara 1998)

(Price & Monaghan 2004a,b, Price 2004)



Orszag-Tang vortex (everyone)

(Price & Monaghan 2005, Rosswog & Price 2007)



Current loop advection (e.g. Gardiner & Stone 2007)

(Rosswog & Price 2007)

4) The $\nabla \bullet B = 0$ constraint

- IGNORE, CLEAN or PREVENT

IGNORE: $$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

CLEAN: $$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) \quad + \quad \nabla \cdot \mathbf{B} = 0$$

Price & Monaghan 2005,
Dolag & Stasyszyn 2008

PREVENT: The "Euler potentials"

(Euler 1770, Stern 1976, Phillips & Monaghan 1985,
Price & Bate 2007, Rosswog & Price 2007, PB08)

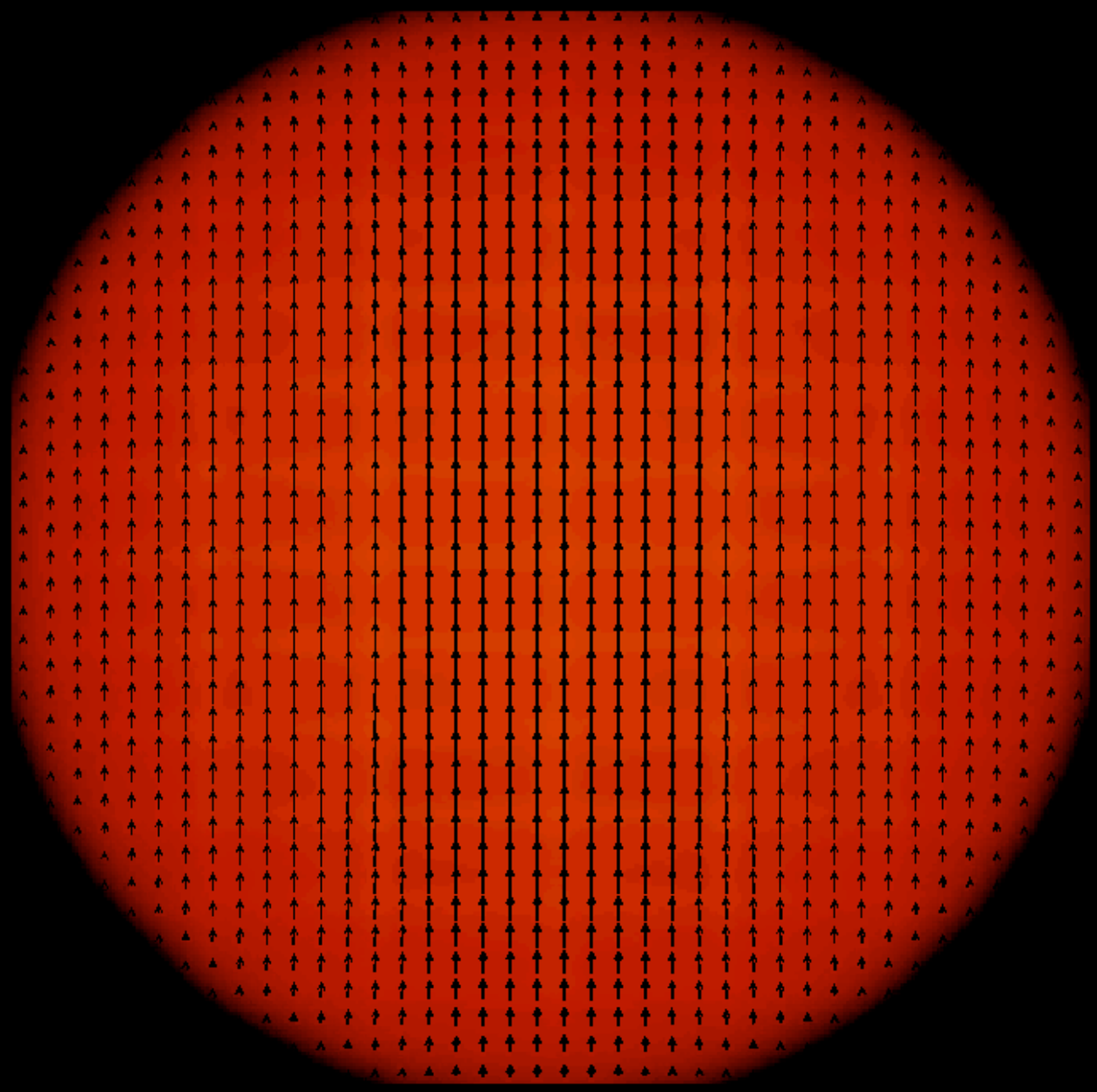
$$\mathbf{B} \equiv \nabla\alpha \times \nabla\beta$$

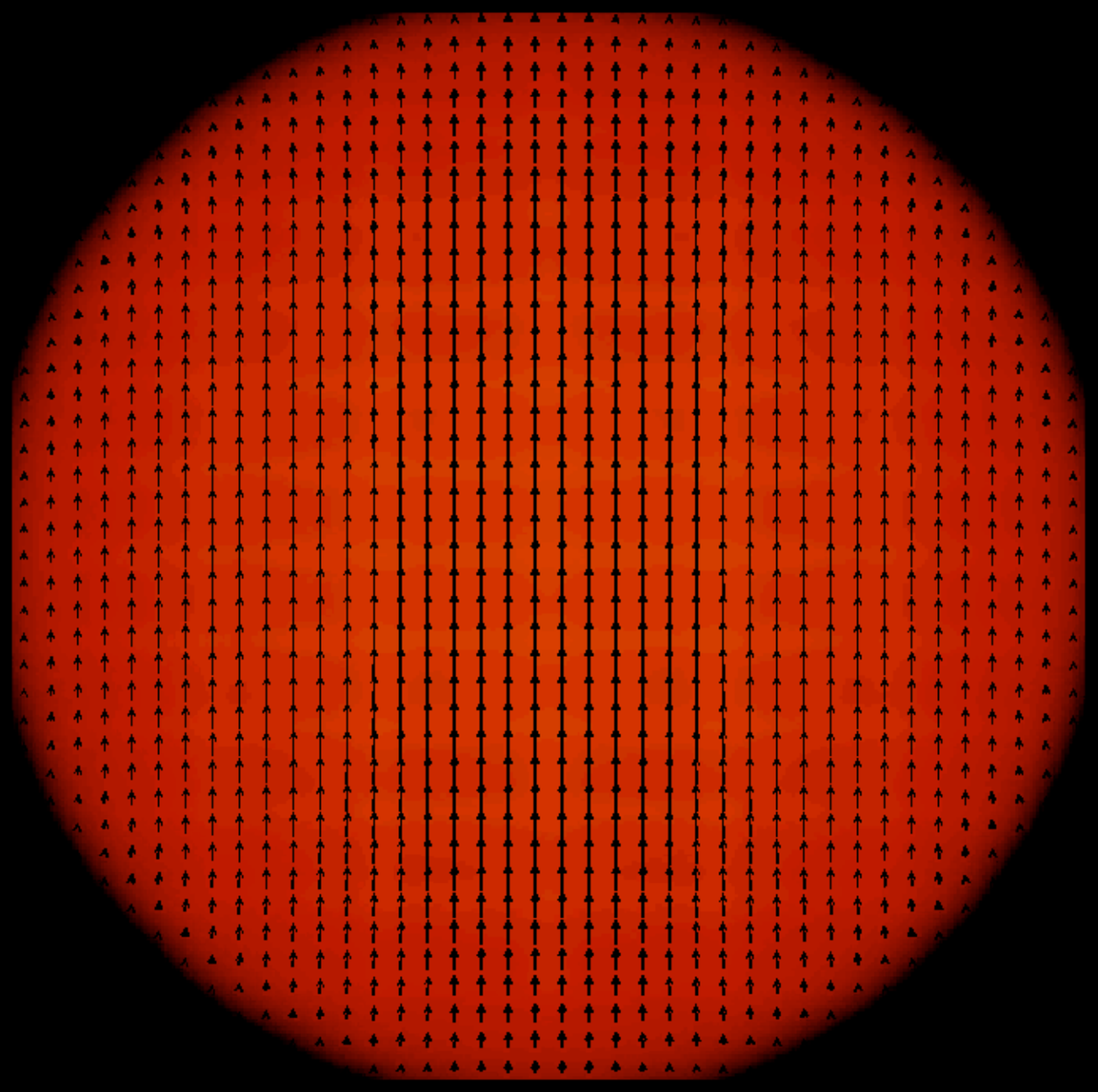
$$\frac{d\alpha}{dt} = 0, \frac{d\beta}{dt} = 0$$

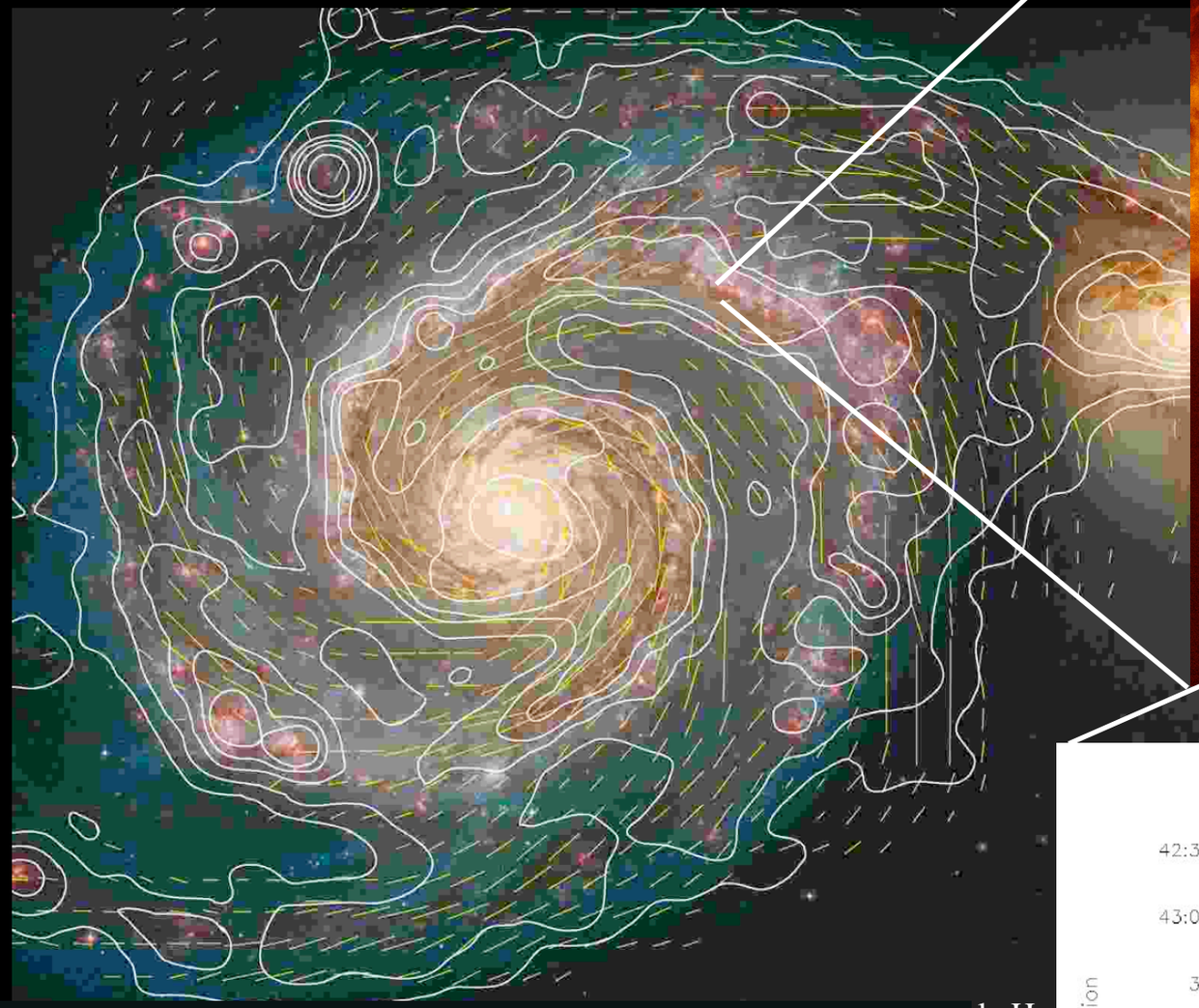
'advection of magnetic field lines'

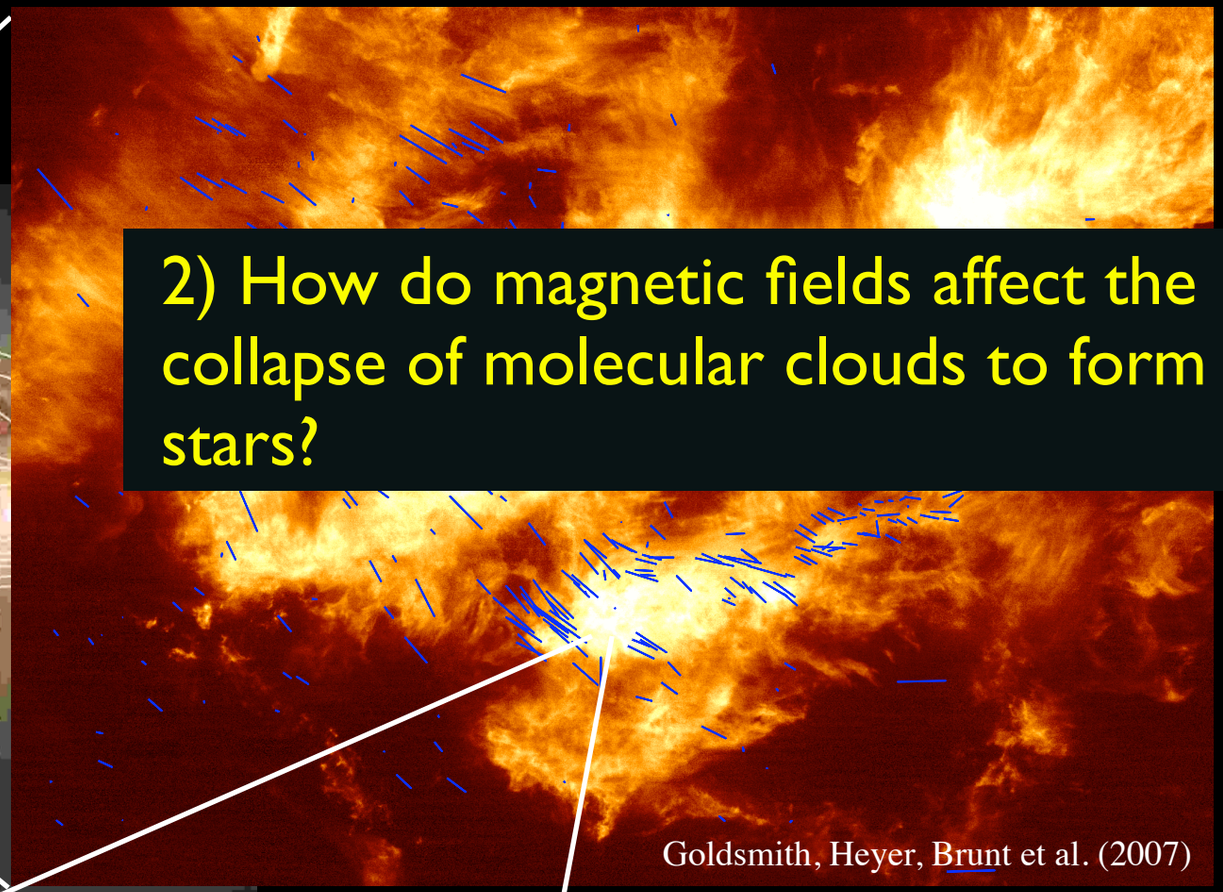
- divergence-free by construction
- disadvantages: helicity constraints (A.B = 0)
- field growth suppressed once clear mapping from initial to final particle distribution is lost - DON'T FOLLOW FIELD WINDING (for long)

Star formation



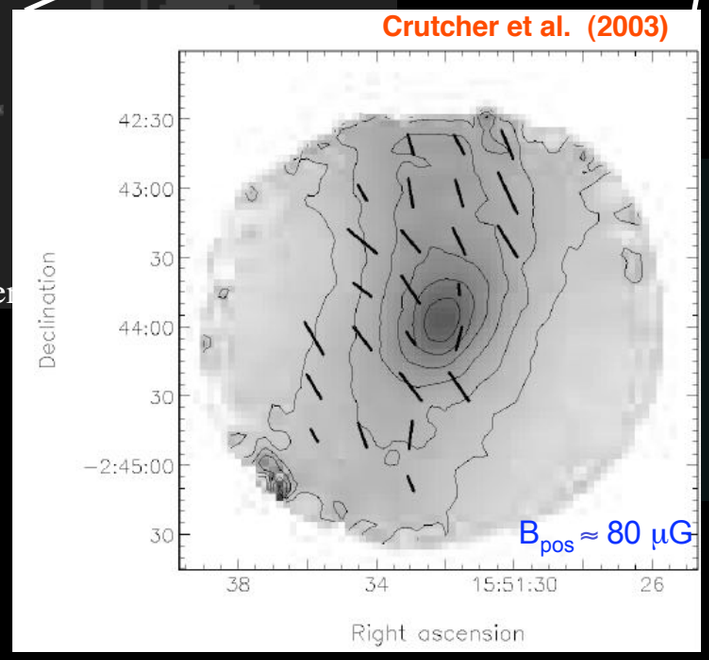






Goldsmith, Heyer, Brunt et al. (2007)

2) How do magnetic fields affect the collapse of molecular clouds to form stars?



1) What is the effect of magnetic fields on fragmentation of molecular cloud cores?

3) What effect do magnetic fields have on the dynamics of the interstellar medium?

Magnetic fields in the star formation process

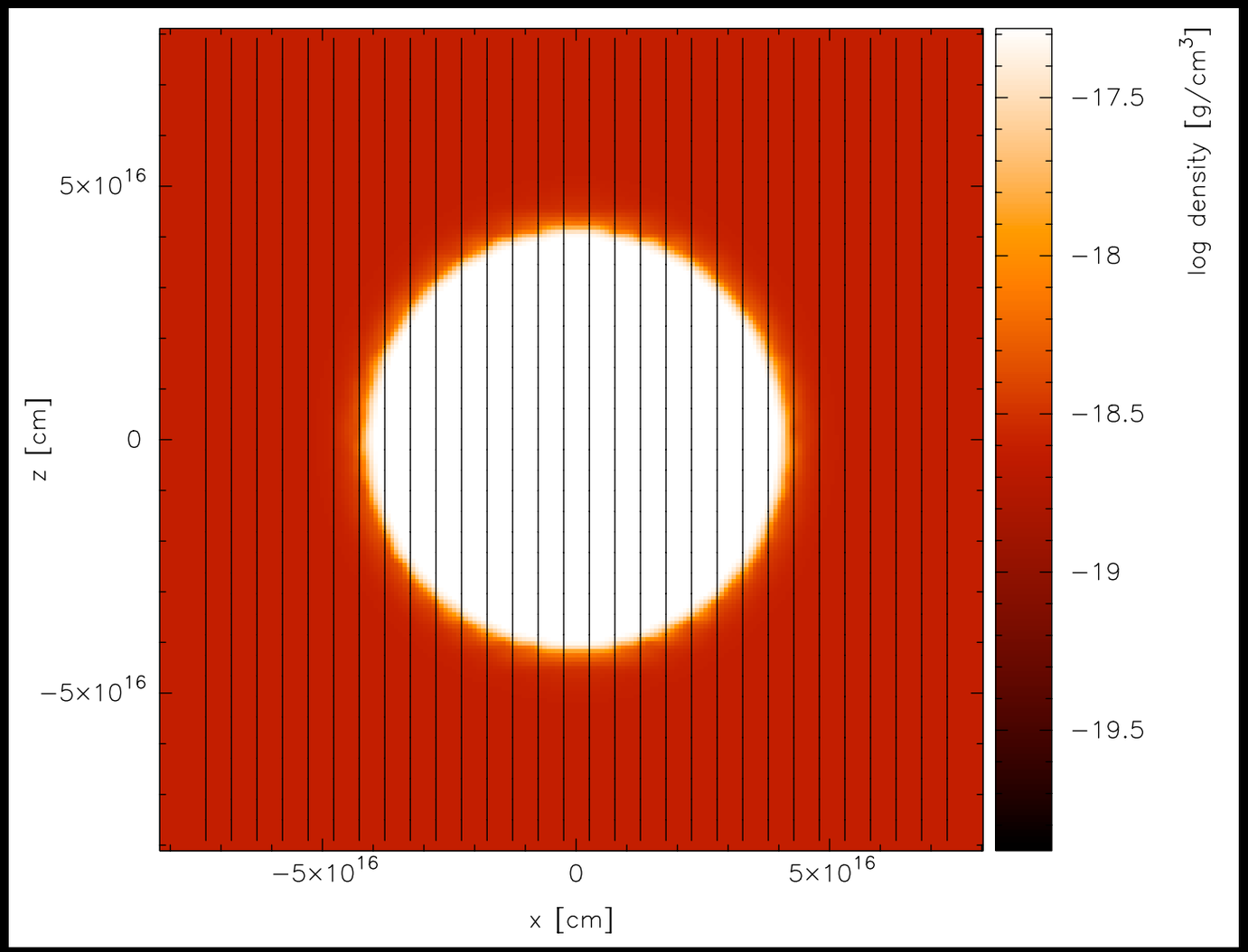
1) What is the effect of magnetic fields on fragmentation of molecular cloud cores?

do magnetic fields suppress (e.g. Hosking and Whitworth 2004)
or enhance (e.g. Boss 2002) small-scale fragmentation?

how do magnetic fields affect the formation of accretion discs
and or binary systems?

Single & binary star formation

(Price & Bate 2007)



resolution ~ 300,000 particles in core
(30,000 required to resolve Jeans mass, ie. fragmentation)

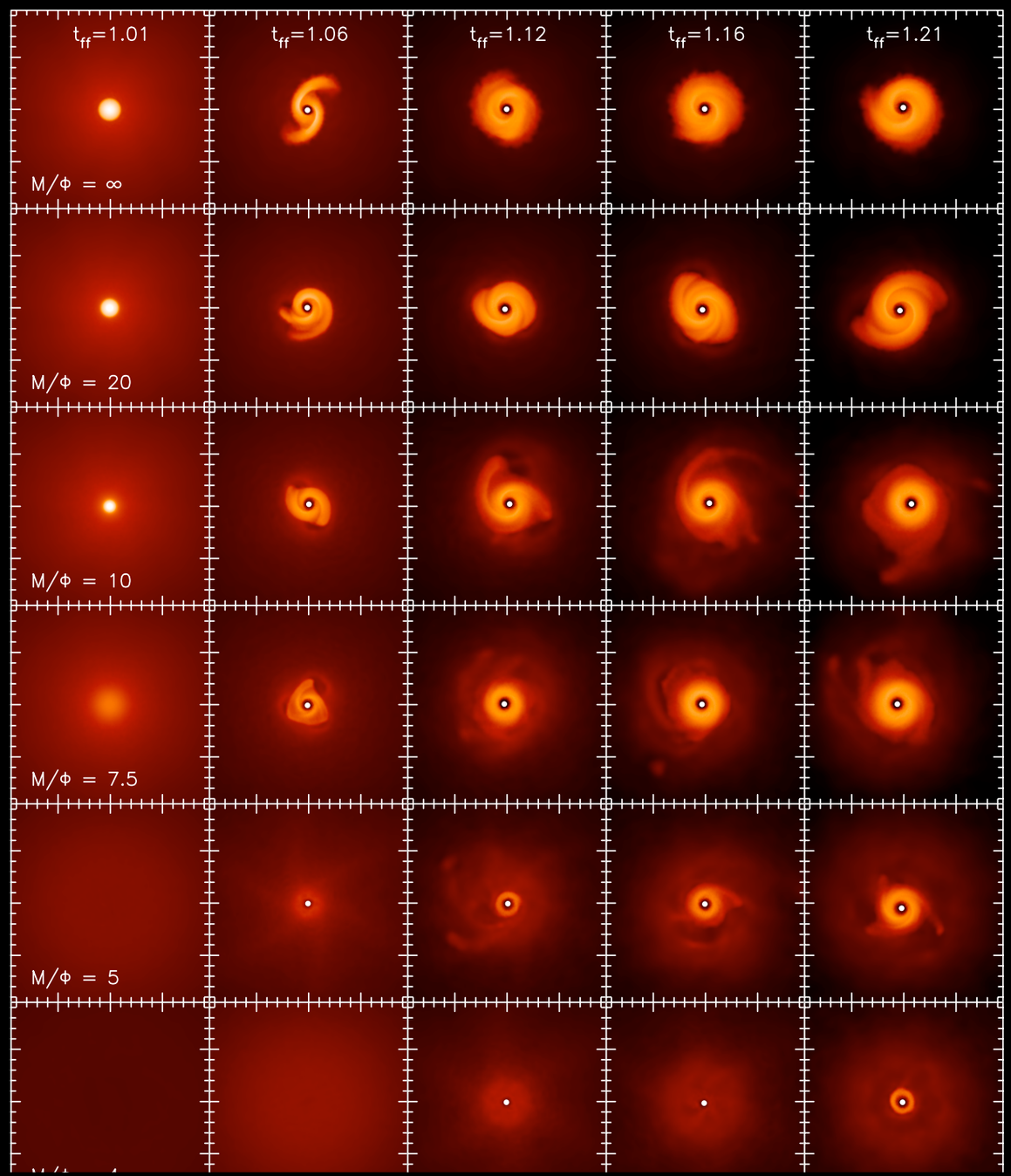
- dense core R = 4×10^{16}cm (0.013pc, 2674 AU)
- embedded in warm, low density medium
- M=1 M_{sun} in core
- initial uniform B_z field
- T ~10K
- solid body rotation
- equation of state:

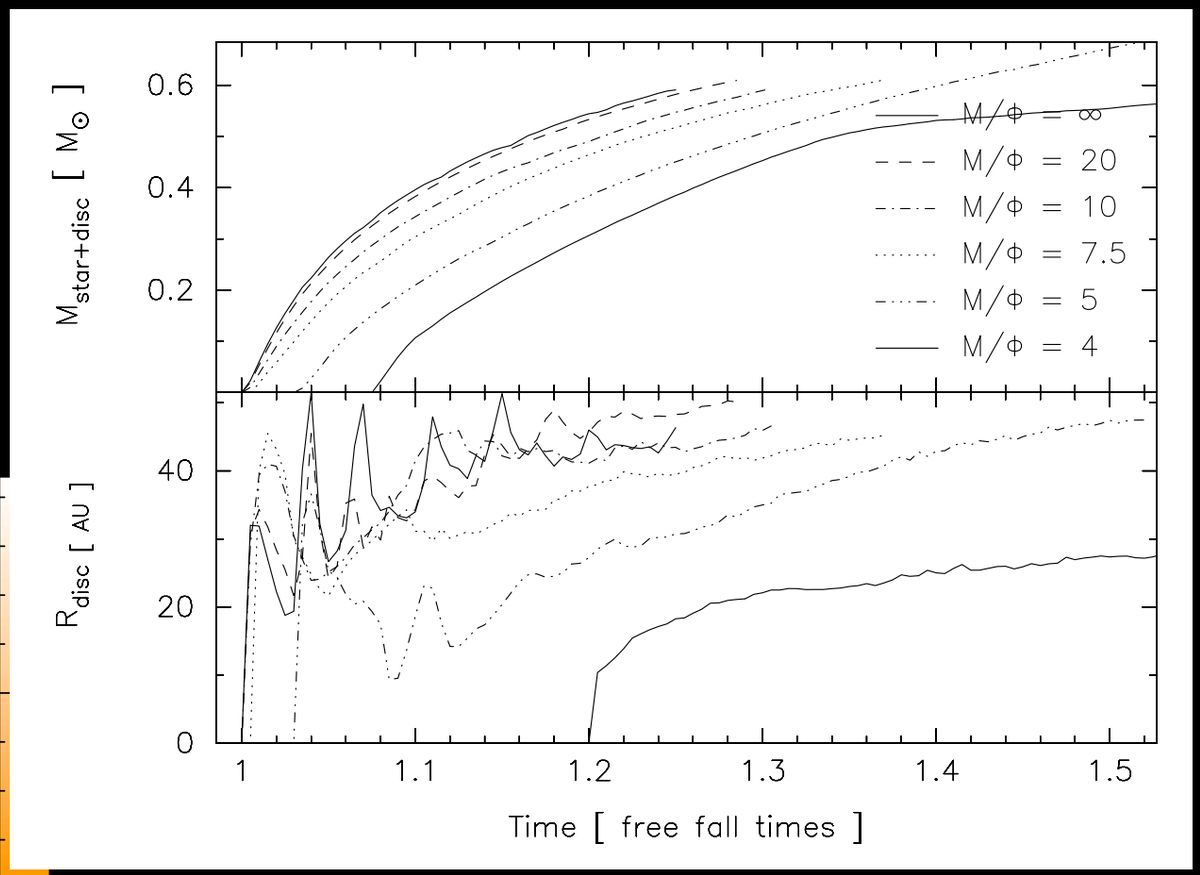
$$P = K\rho^\gamma$$

$$\gamma = 1, \qquad \rho \leq 10^{-14}\mathrm{g\ cm^{-3}},$$
$$\gamma = 7/5, \qquad \rho > 10^{-14}\mathrm{g\ cm^{-3}},$$

Effect of magnetic fields on circumstellar disc formation:

(Price & Bate 2007)





- discs form later
- less massive
- smaller
- slower accretion rates
- less prone to gravitational instability

see also Hennebelle & Fromang (2008), Hennebelle & Ciardi (2009), Mellon & Li (2009), Duffin & Pudritz (2009)

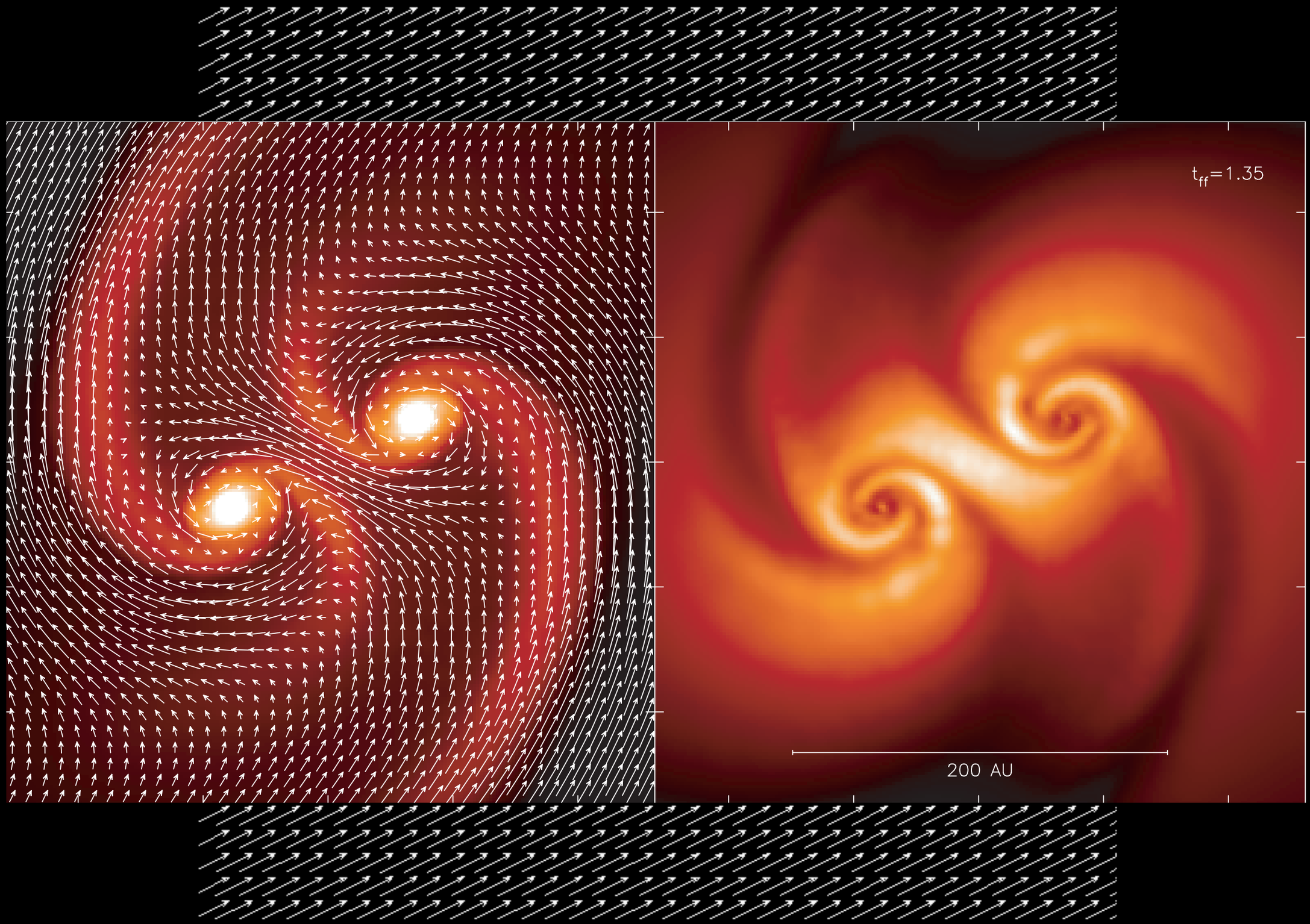
Effect on binary formation

Daniel Price and Matthew Bate, University of Exeter, UK

a fragmentation crisis? or just should be non-ideal MHD?

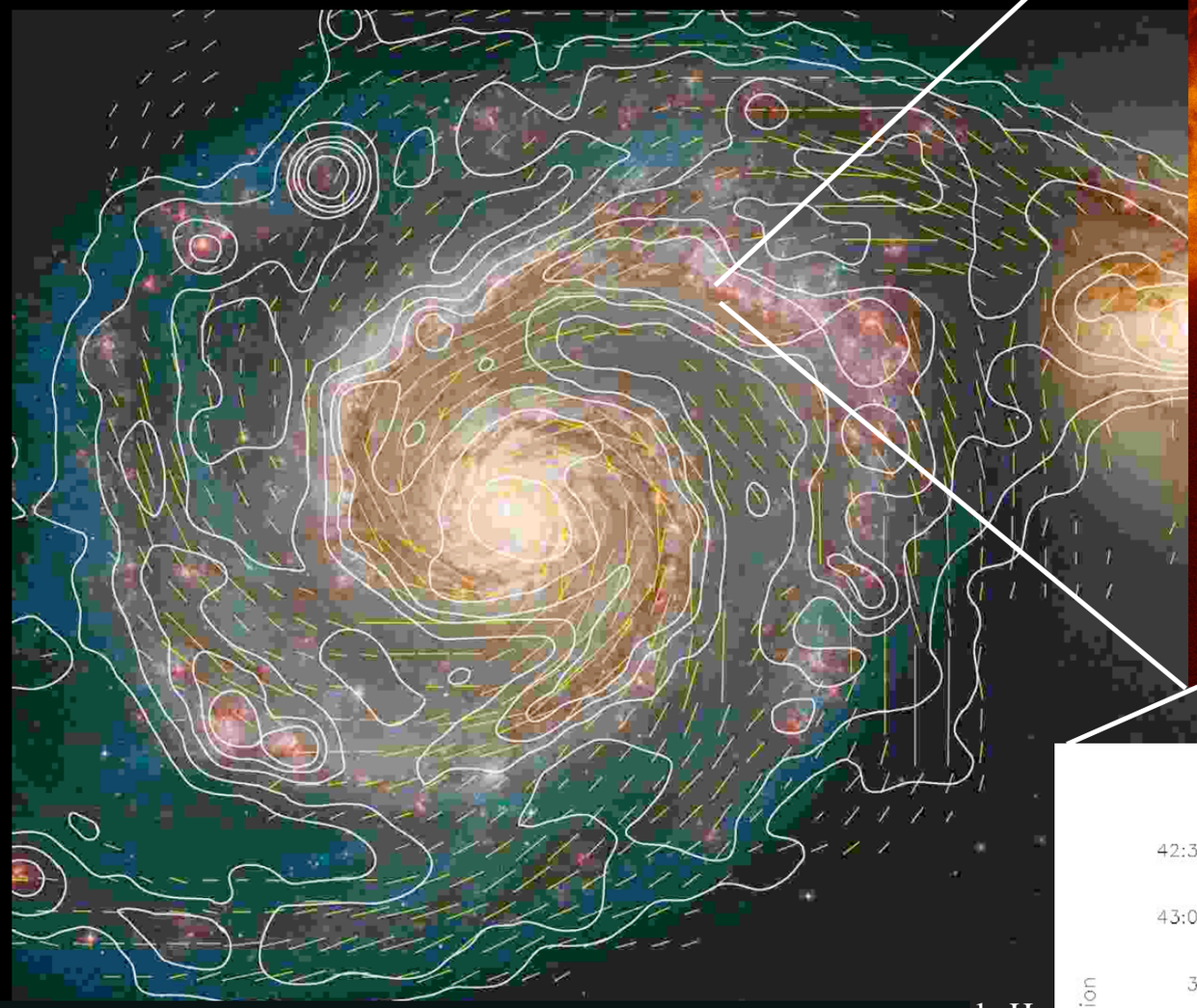
cf. Hennebelle & Teyssier (2009), Mellon & Li (2008), Machida et al. (2008)

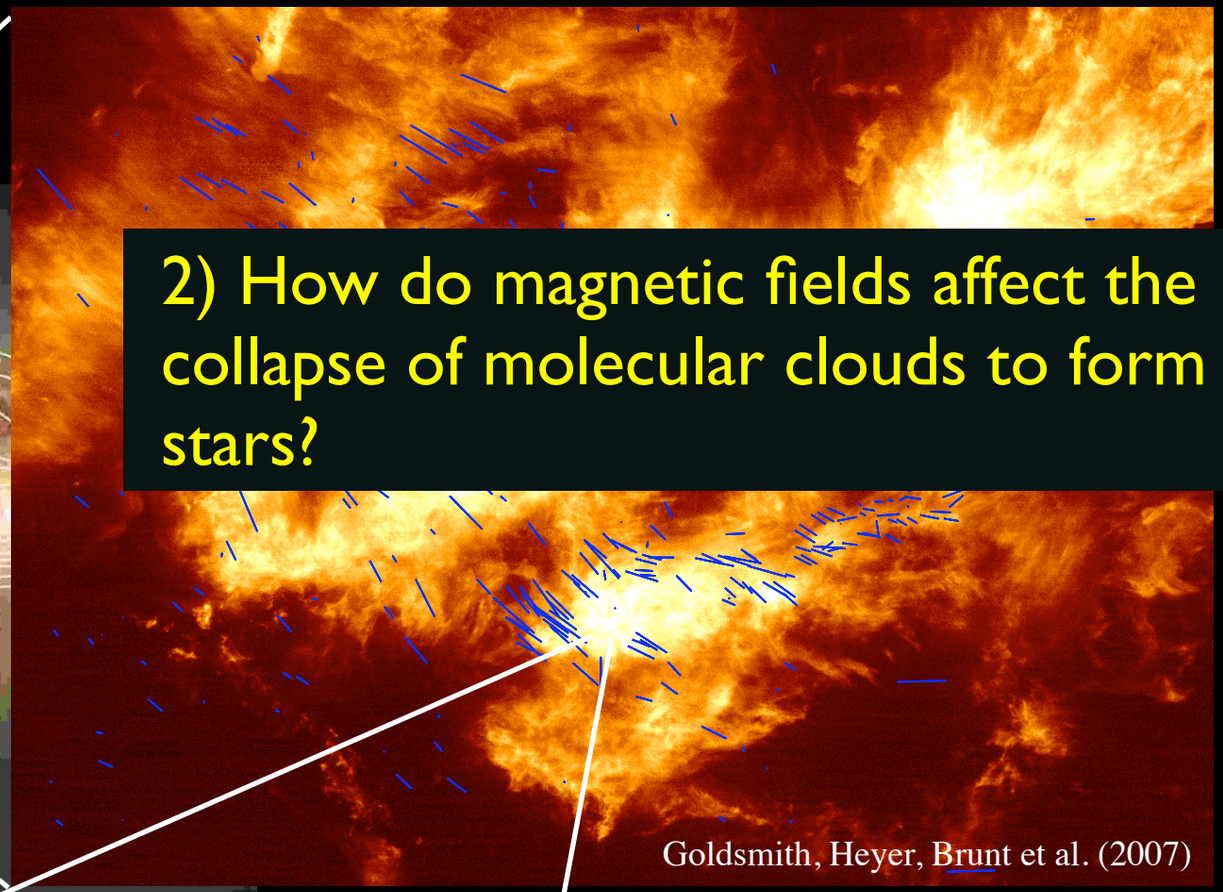
“Magnetic cushioning”



1) What is the effect of magnetic fields on fragmentation of molecular cloud cores?

- Magnetic fields (even at supercritical strengths) can severely inhibit disc formation.
- Magnetic fields can prevent binary formation.
- Net effect of magnetic fields is always to suppress fragmentation

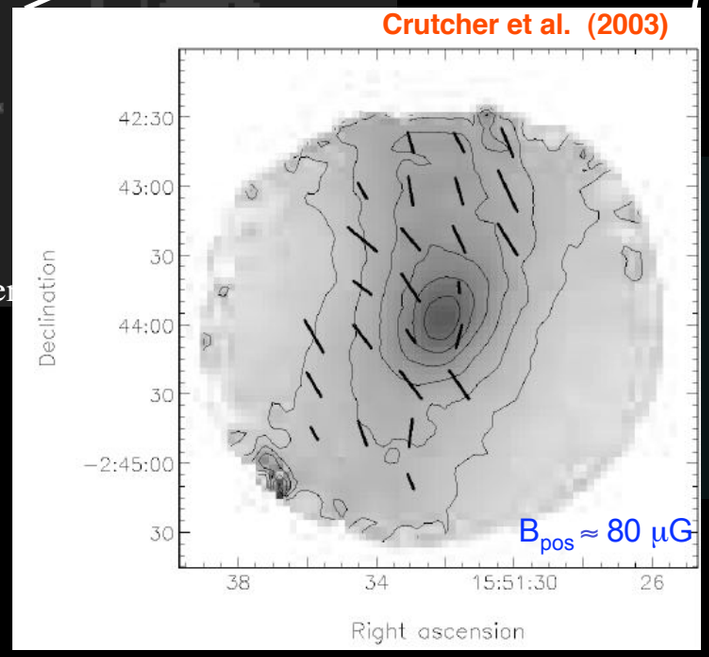




Goldsmith, Heyer, Brunt et al. (2007)

2) How do magnetic fields affect the collapse of molecular clouds to form stars?

Crutcher et al. (2003)



1) What is the effect of magnetic fields on fragmentation of molecular cloud cores?

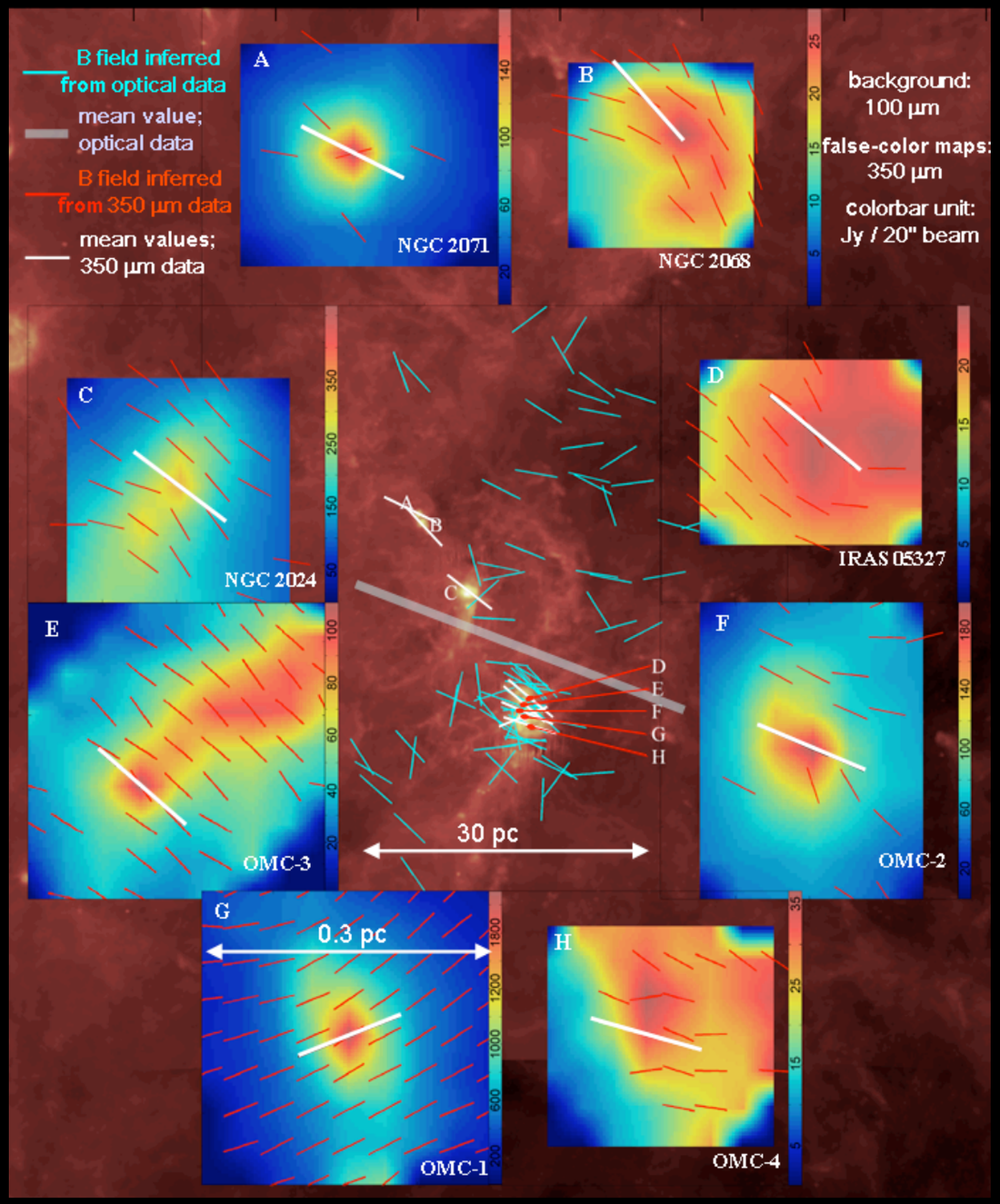
3) What effect do magnetic fields have on the dynamics of the interstellar medium?

2) How do magnetic fields affect the collapse of molecular clouds to form stars?

What is the role of magnetic fields in the turbulent star formation picture?

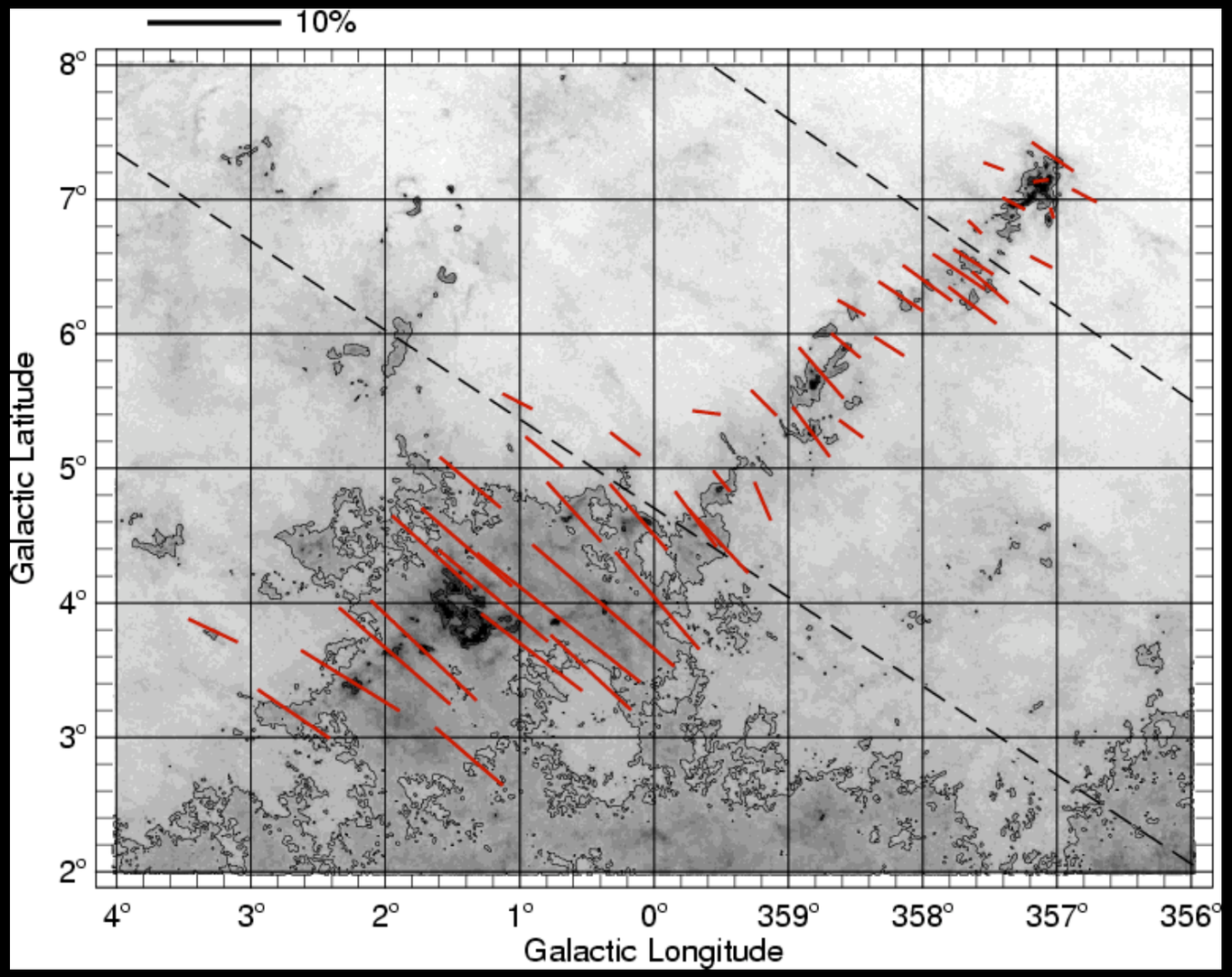
How does the presence of magnetic fields at observed strengths affect the statistics and timescales of star formation?

Orion



Li, Dowell, Goodman, Hildebrand and Novak (2009)

Pipe Nebula

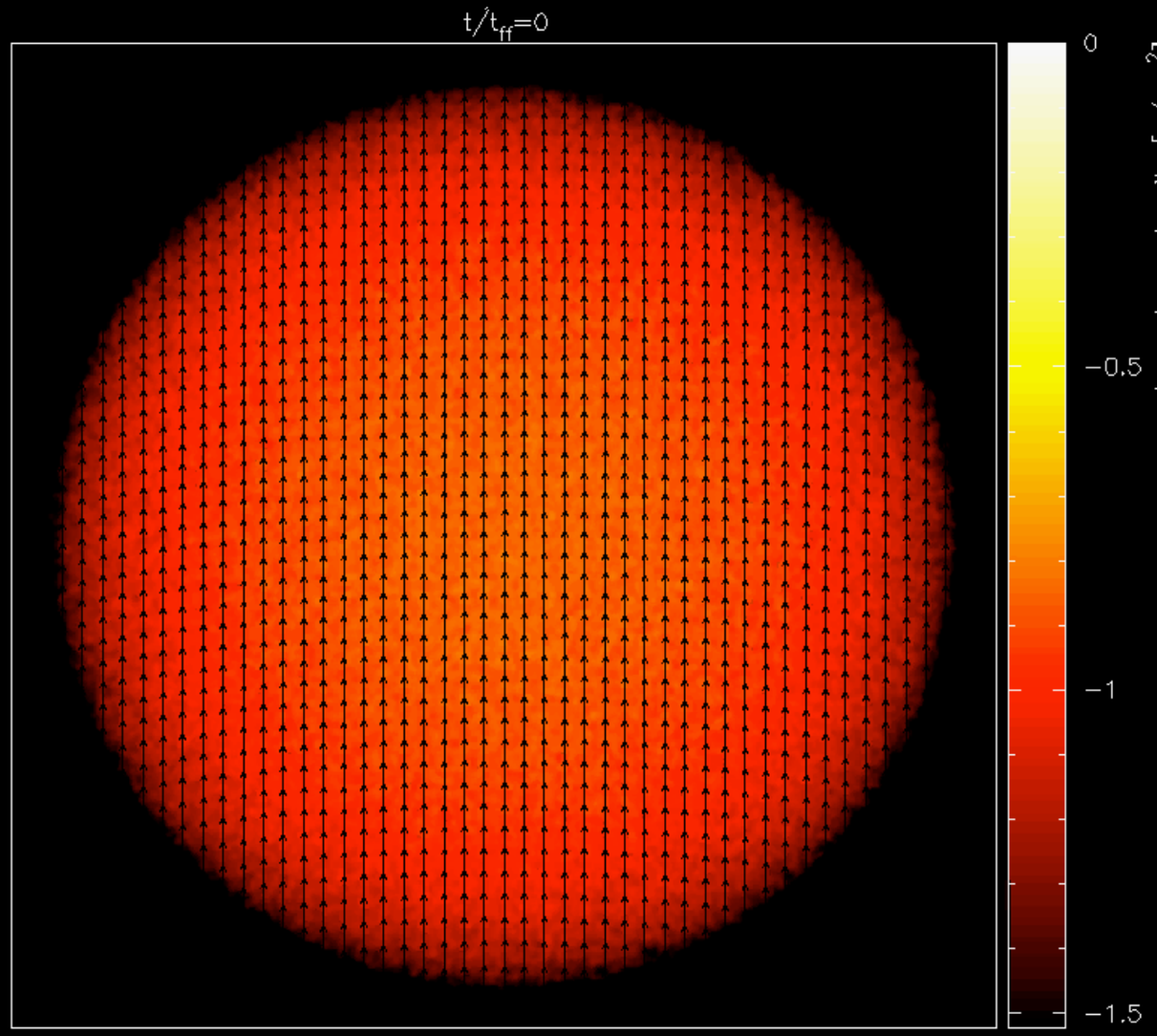


Alves et al. (2008)

can magnetic fields explain differences in star formation rate/efficiency between clouds?

Magnetic fields in star cluster formation

Price & Bate (2008)



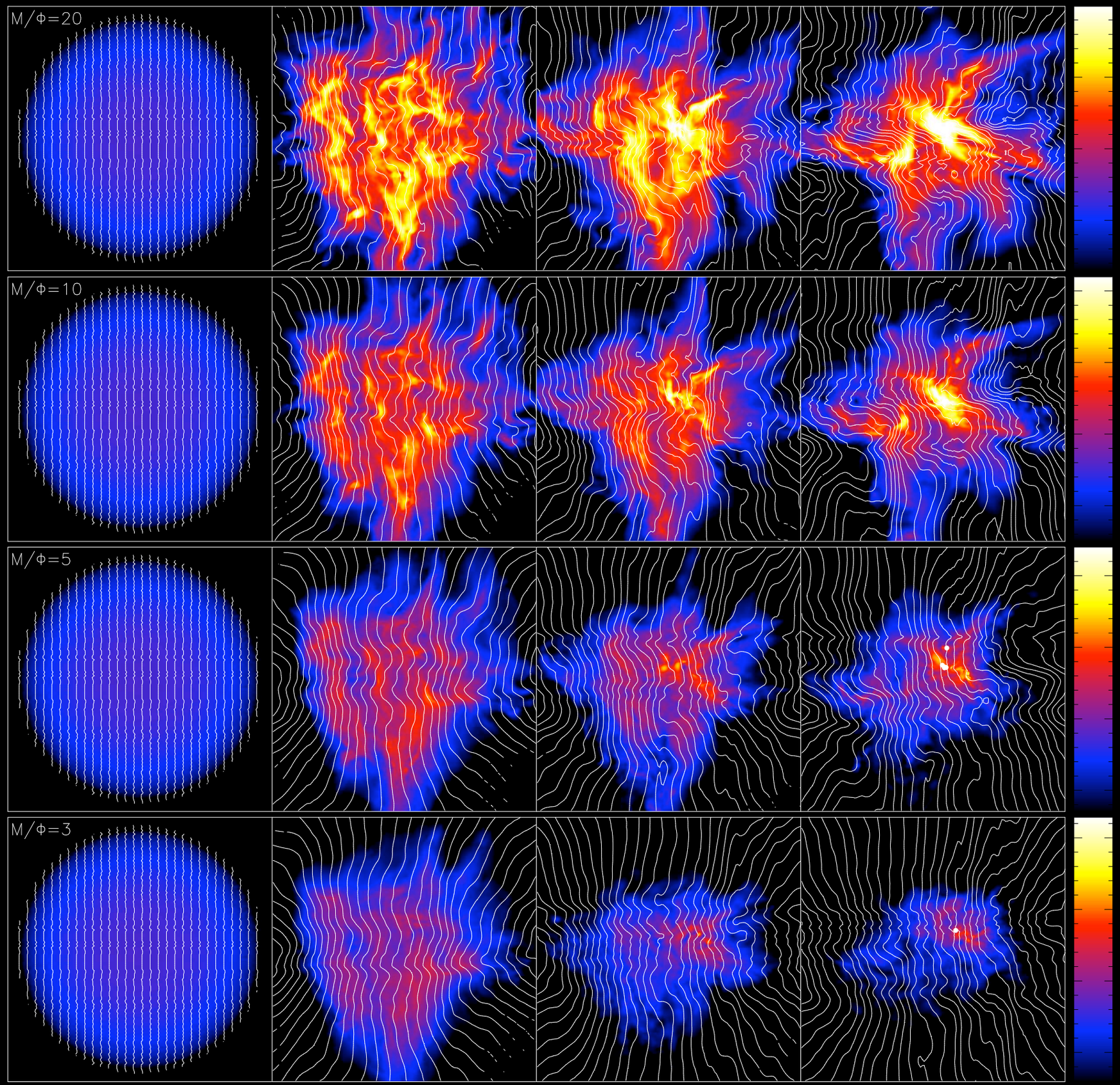
Magnetised version of Bate, Bonnell & Bromm (2003)

- 50 solar mass cloud
- diameter 0.375 pc, n_{H2} = 3.7 x 10^4
- initial uniform B field
- T=10K
- turbulent velocity field P(k)$\propto k^{-4}$
- RMS Mach number 6.7
- barotropic equation of state

$$P = K\rho^\gamma$$

$$\gamma = 1, \qquad \rho \leq 10^{-13}\mathrm{g\ cm^{-3}},$$
$$\gamma = 7/5, \qquad \rho > 10^{-13}\mathrm{g\ cm^{-3}}.$$

vary magnetic field strength...


M/Φ=20
M/Φ=10
M/Φ=5
M/Φ=3

t=0 yr
Mass/flux ratio = ∞
t=0 yr
Mass/flux ratio = 20
t=0 yr
Mass/flux ratio = 10
t=0 yr
Mass/flux ratio = 5
0
−0.5
−1
−1.5
log column density [g/cm^2]

t=1

t=1

t=1

t=1

0

−0.5

−1

−1.5

−2

log column density [g/cm^2]

t=201800 yr

log column density [g/cm^2]

1

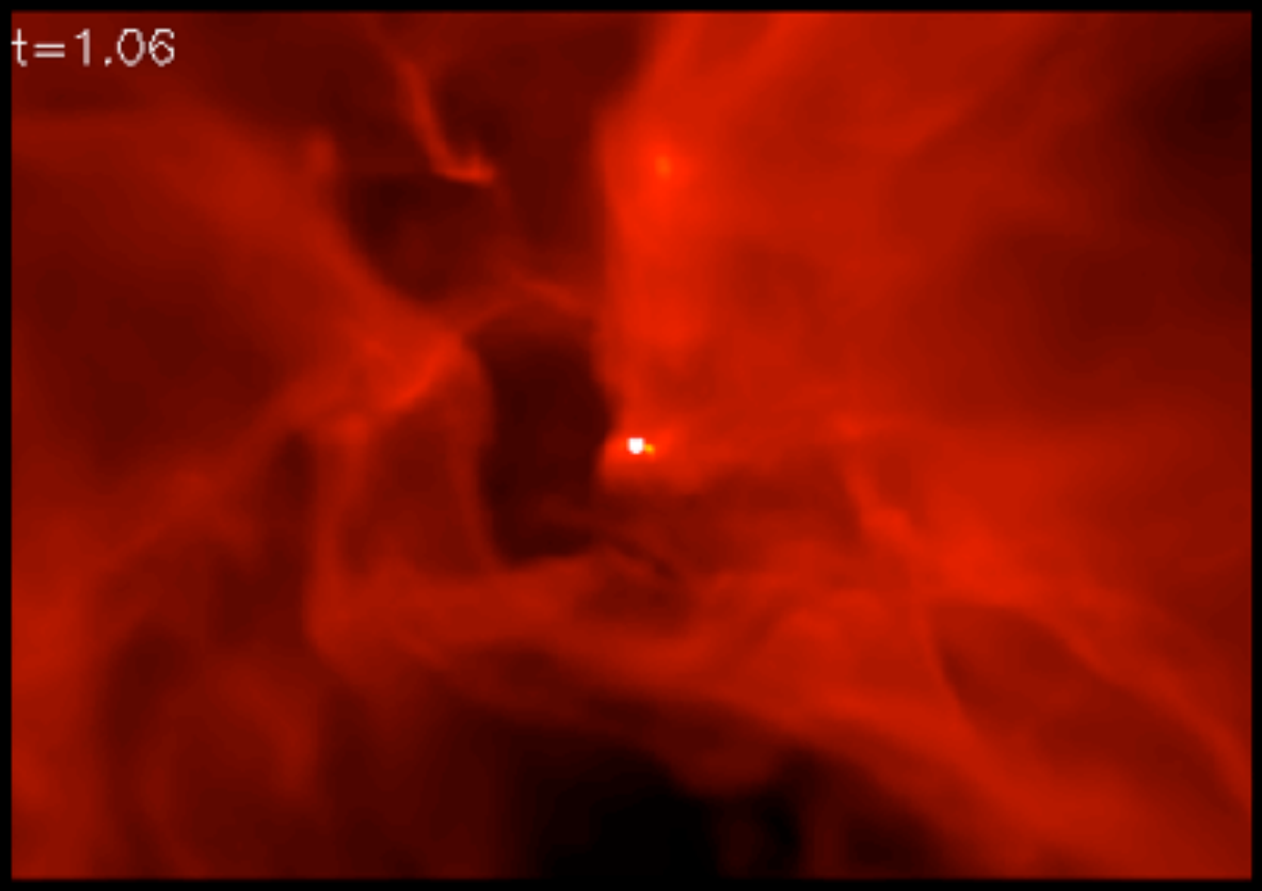
0.5

0

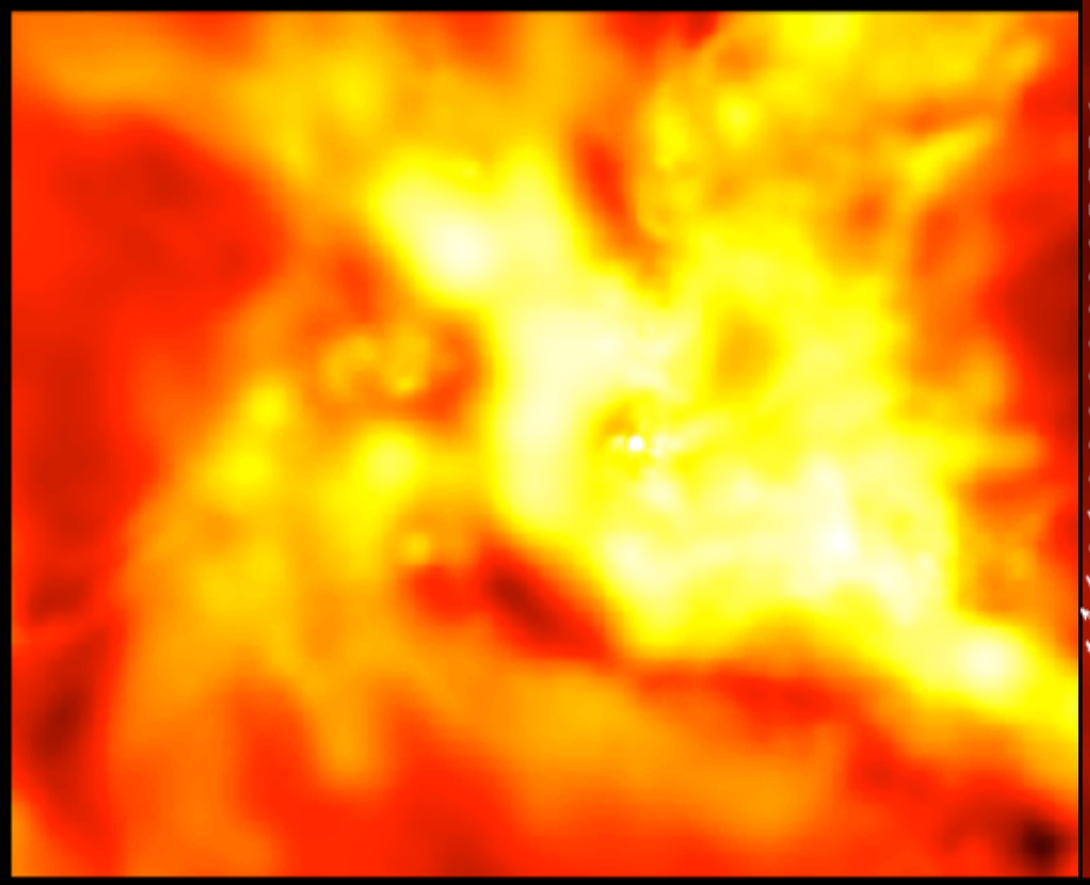
−0.5

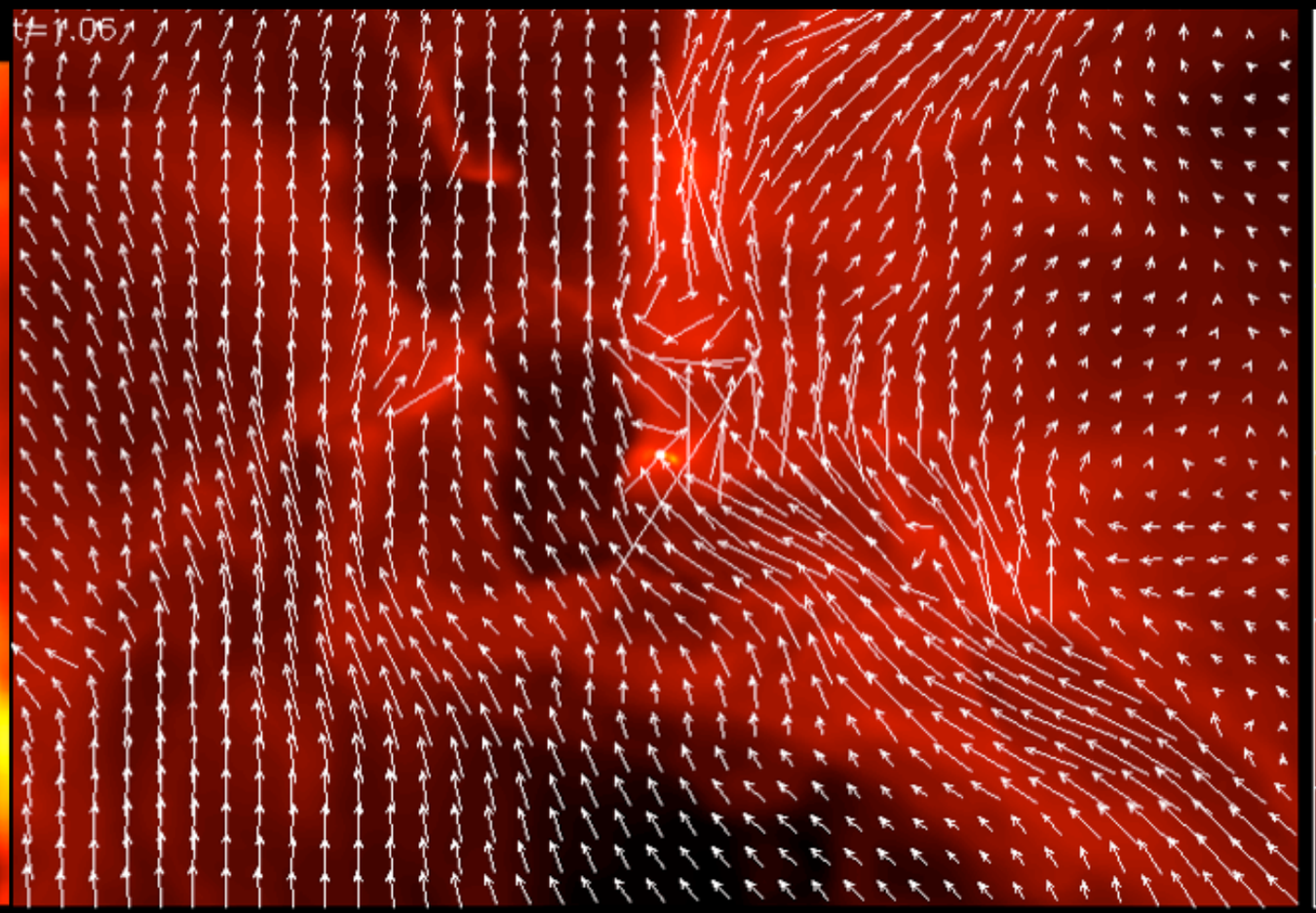
−1

−1.5

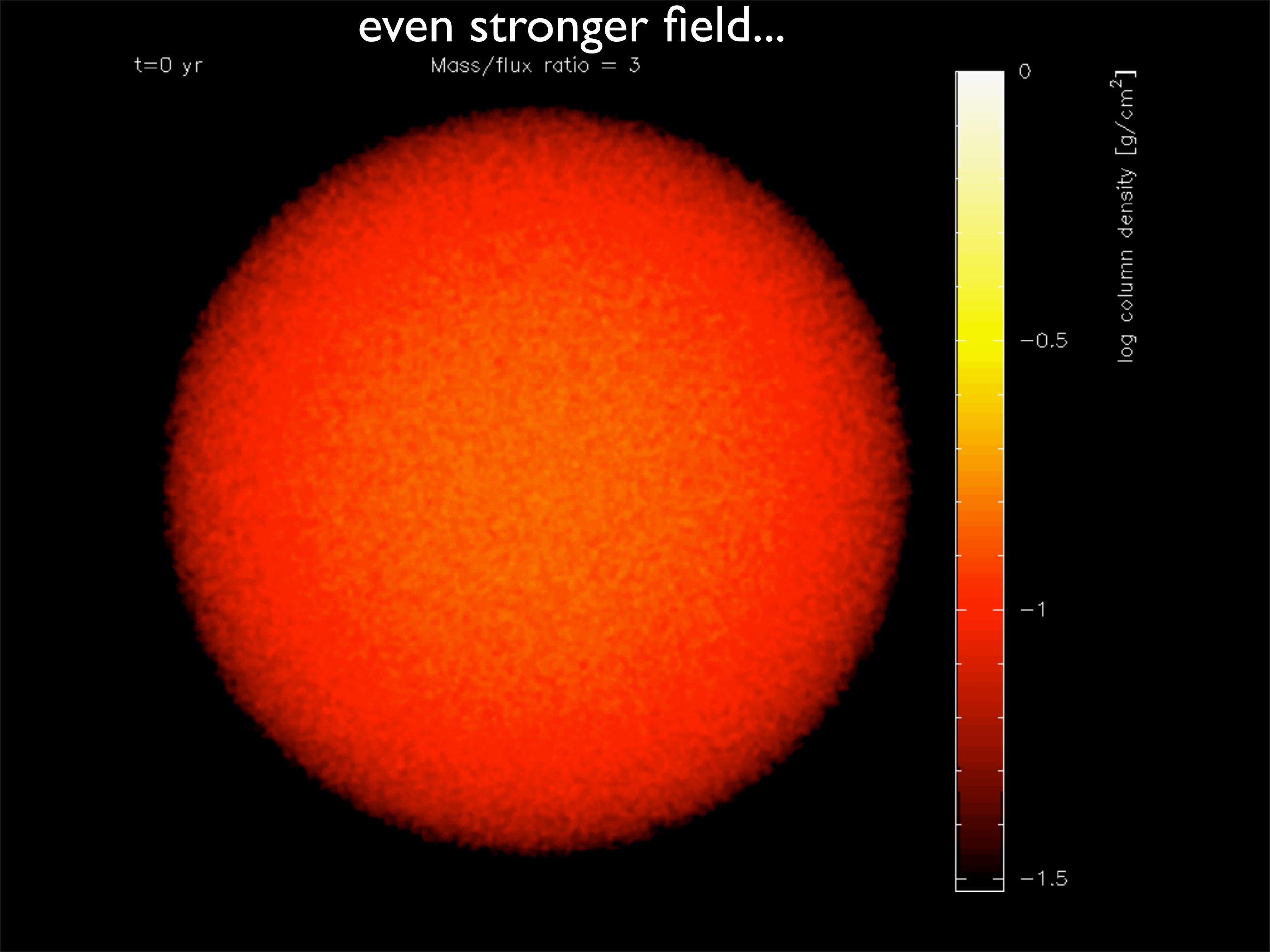


Magnetic cushioning in voids





even stronger field...



t_{ff}=0.6

t_{ff}=0.8

"stripiness"

t_{ff}=1

t_{ff}=1.2

beta > 1

beta < 1

Taurus

"Magnetically aligned velocity anisotropy" (Heyer et al. 2008)

Goldsmith, Heyer, Brunt et al. (2007)

Riegel-Crutcher Cloud (McClure-Griffiths et al. 2006)

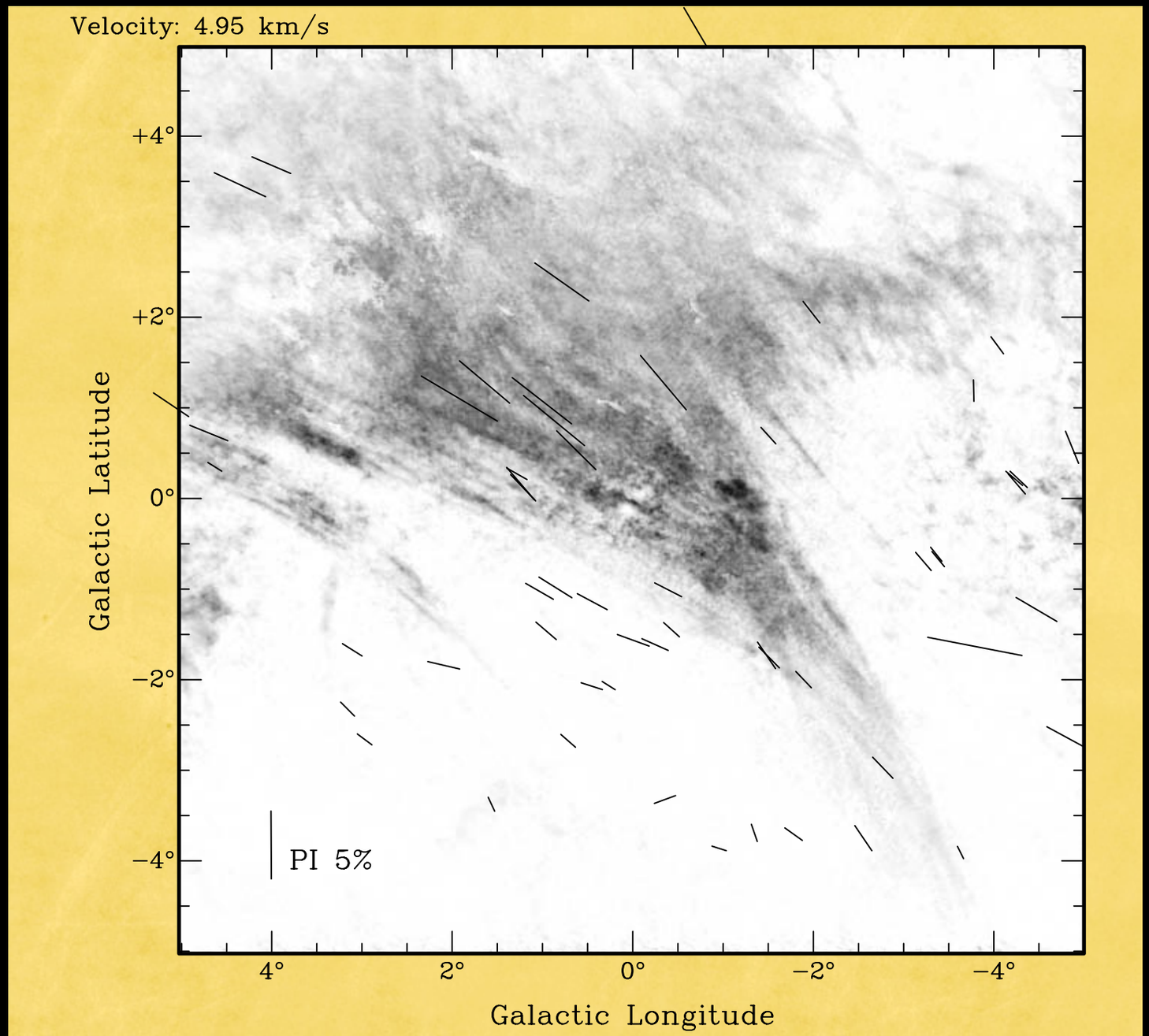


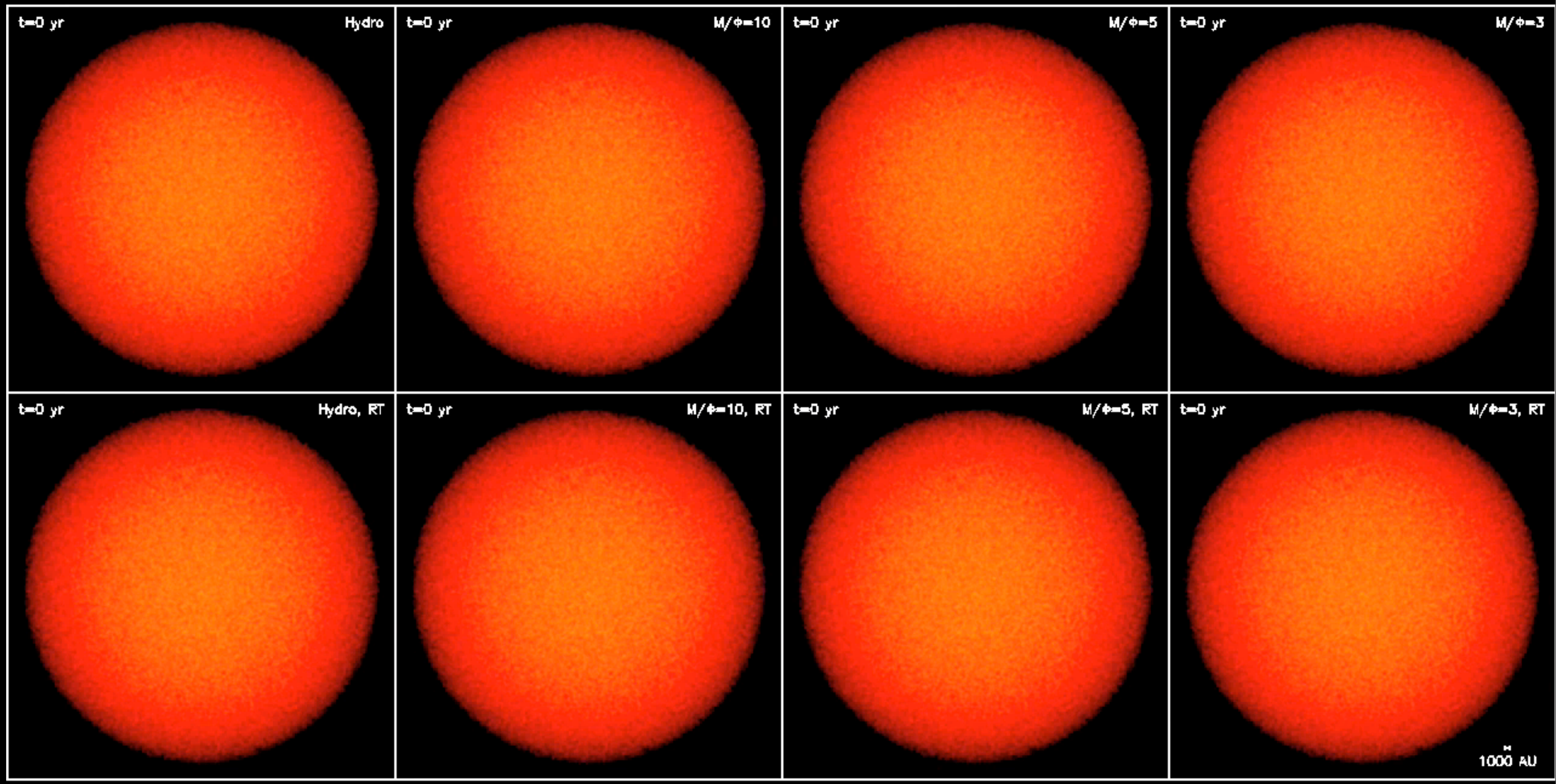
FIG. 6.—H I image of the R-C cloud at $v = 4.95$ km s^{-1} overlaid with vectors of stellar polarization from Heiles (2000). The measured polarization vectors are aligned with the magnetic field direction. The length of the vectors is proportional to the measured fractional polarized intensity, with the scale given by the 5% fractional polarized intensity vector shown by the scale of the vector in the bottom left corner.

"A hole...[where] it appears that some agent has been responsible for dispersing the molecular gas"

^{13}CO

Goldsmith, Heyer, Brunt et al. (2007)

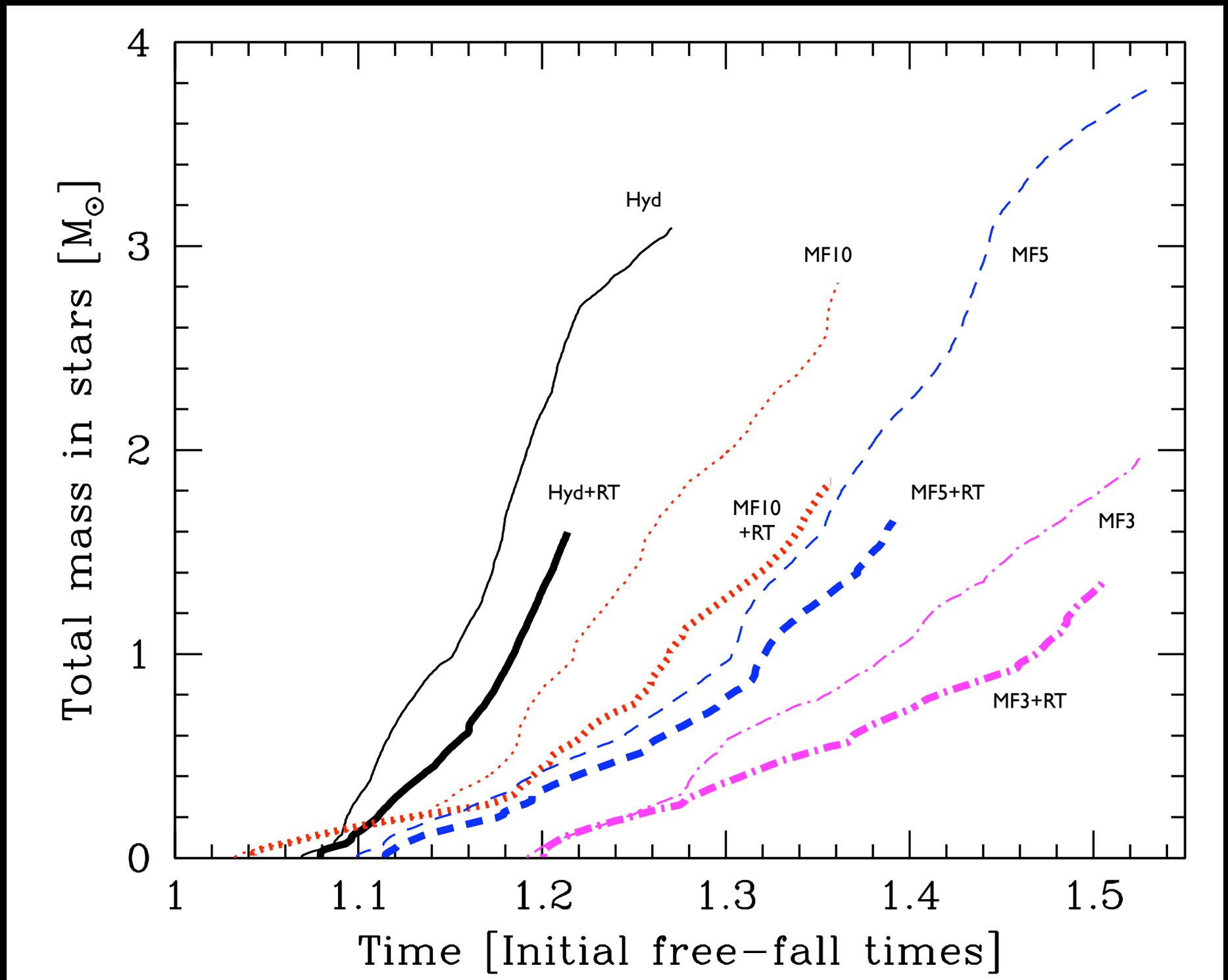
Combined radiation and MHD



Daniel Price and Matthew Bate

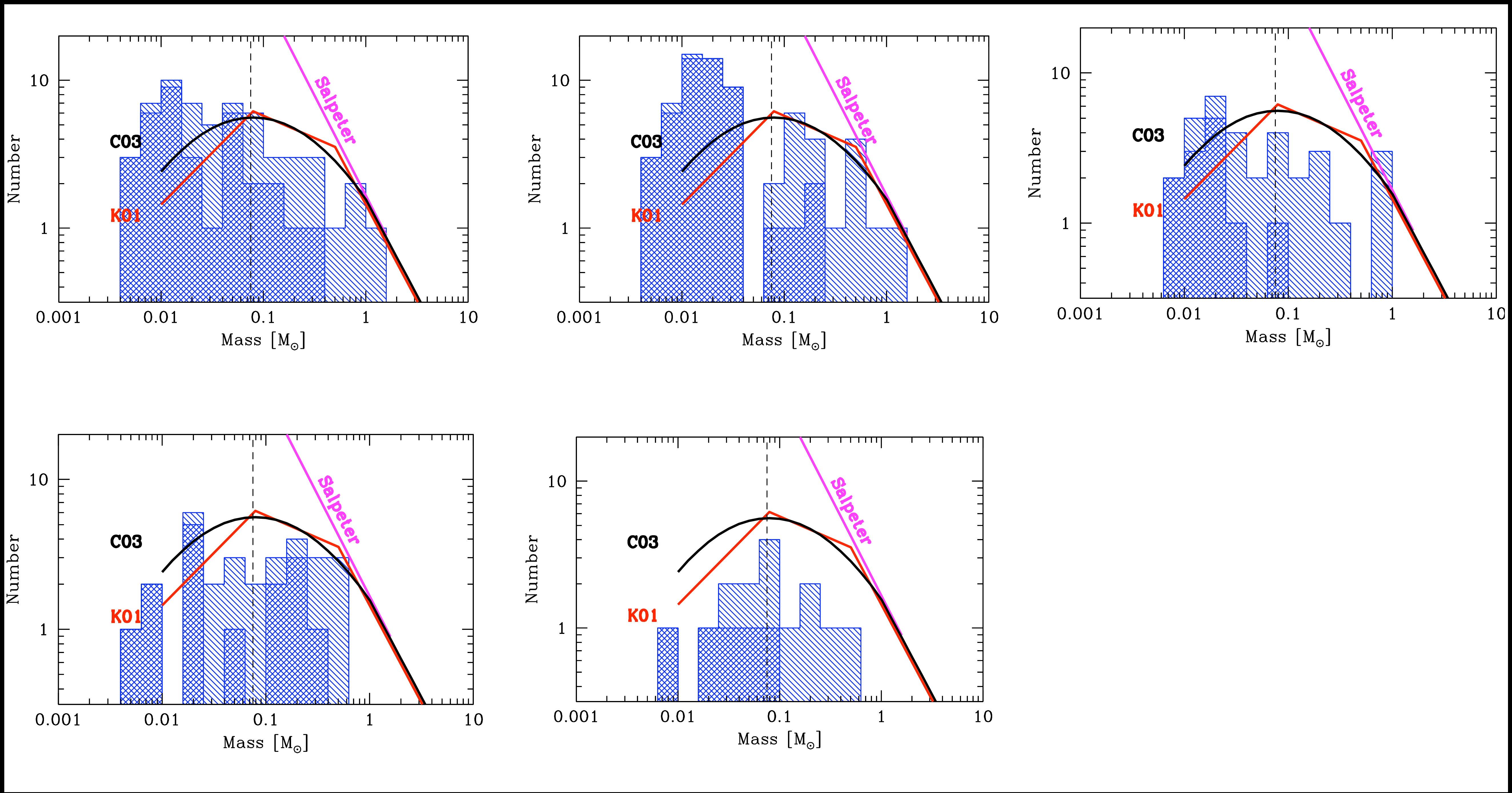
(using Smoothed Particle Radiation-Magnetohydrodynamics:
Whitehouse & Bate 2005, Whitehouse et al. 2006, Price & Bate 2009)

Effect on star formation rate / efficiency



...strong field calculations in best agreement with observed ~few % per free-fall time

Effect on Stellar Masses



reduction in relative fraction of low mass objects
due to decreased importance of dynamical ejections

2) How do magnetic fields affect the collapse of molecular clouds to form stars?

- magnetic fields strongly affect the star formation rate resulting in a lower efficiency per free-fall time

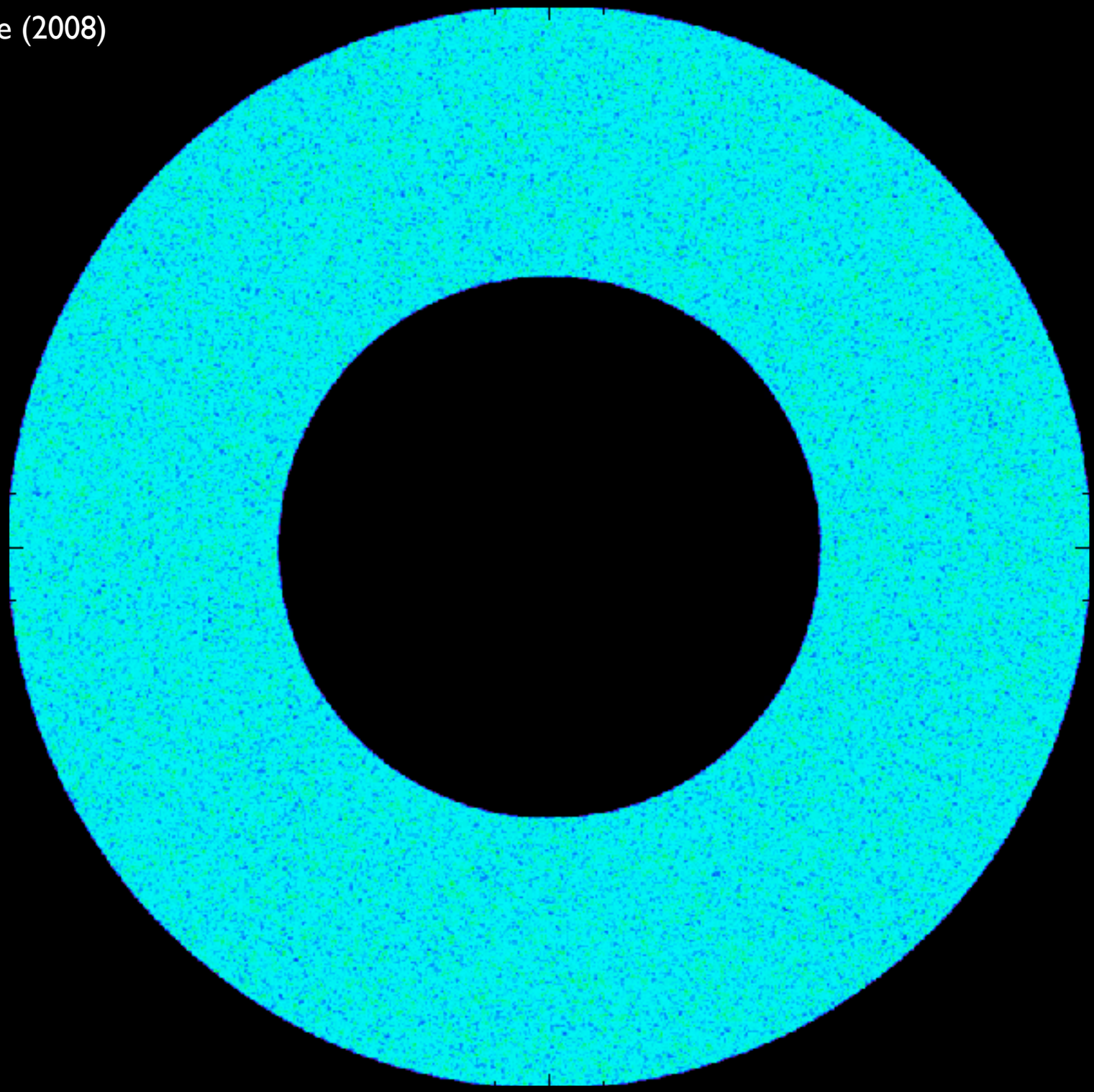
- magnetic fields affect the Initial Mass Function by reducing the importance of dynamical interactions, resulting in fewer very low mass objects

- strong magnetic fields (beta < 1) lead to large scale magnetic-pressure supported voids in the cloud, anisotropic turbulent motions and column density striations in the low density envelope (and these are observed!)

3) What effect do magnetic fields have on the dynamics of the interstellar medium?

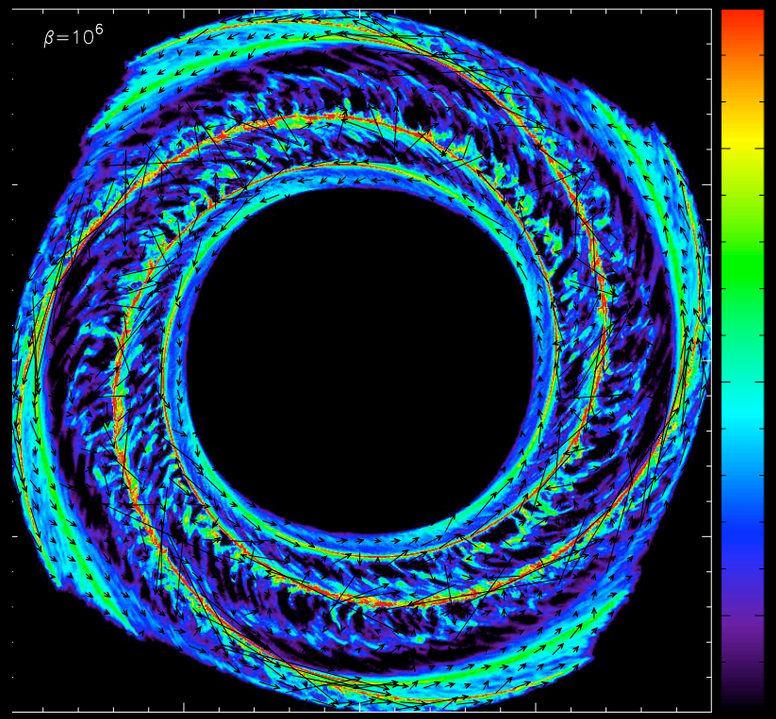
The dynamics of magnetic fields in galaxies

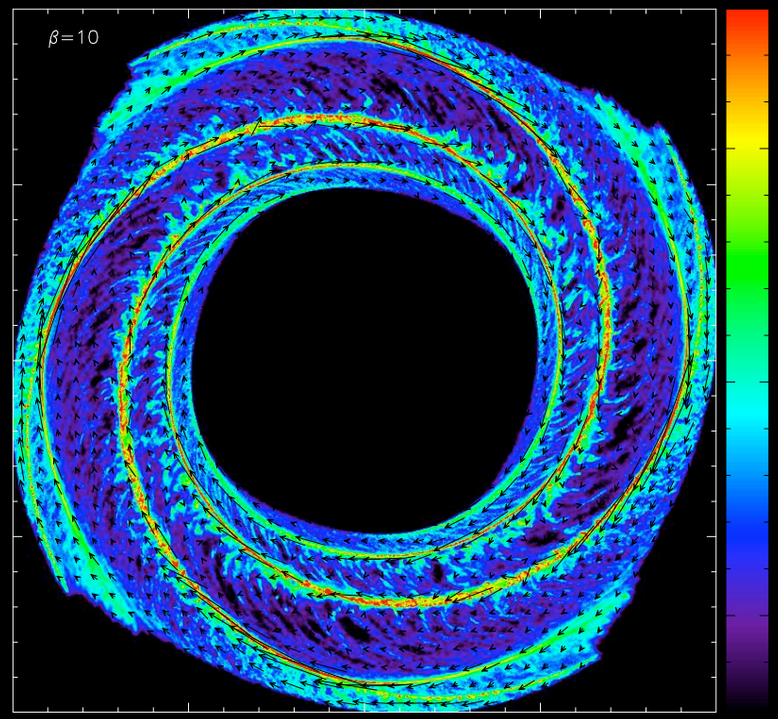
Dobbs & Price (2008)

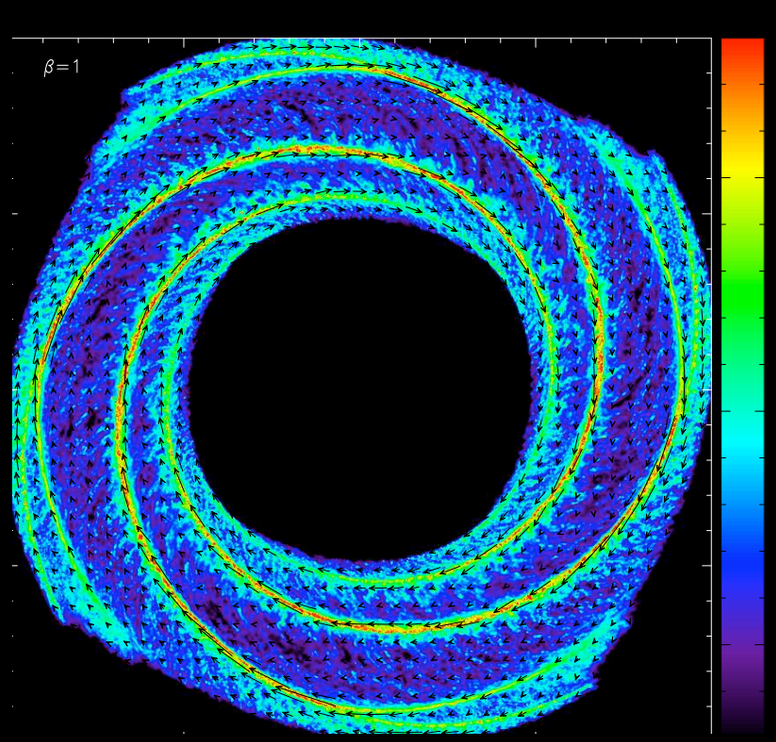


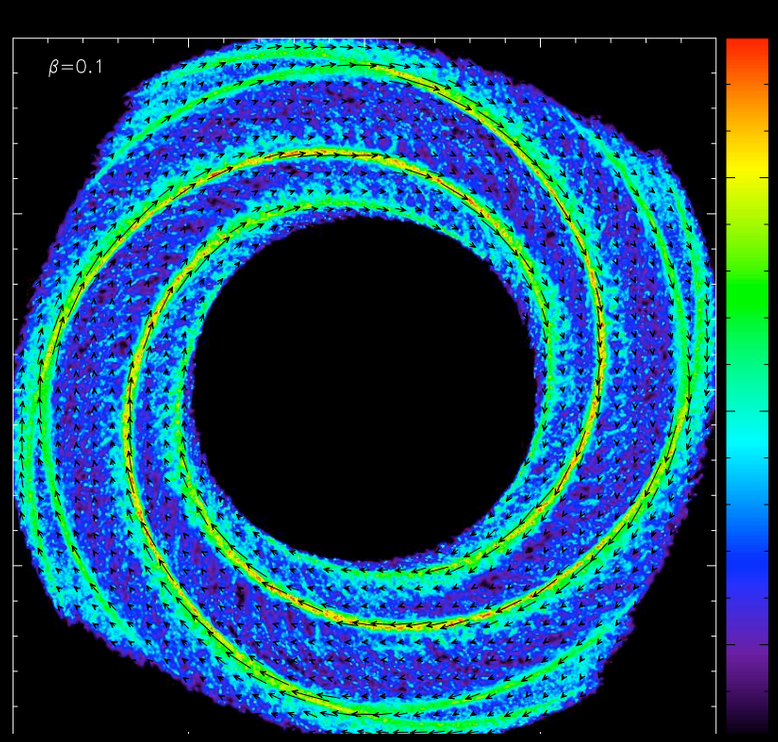
two-phase mixture of cold (100K) and warm (10^4 K) gas (+ magnetic field)

Dobbs & Price (2008)

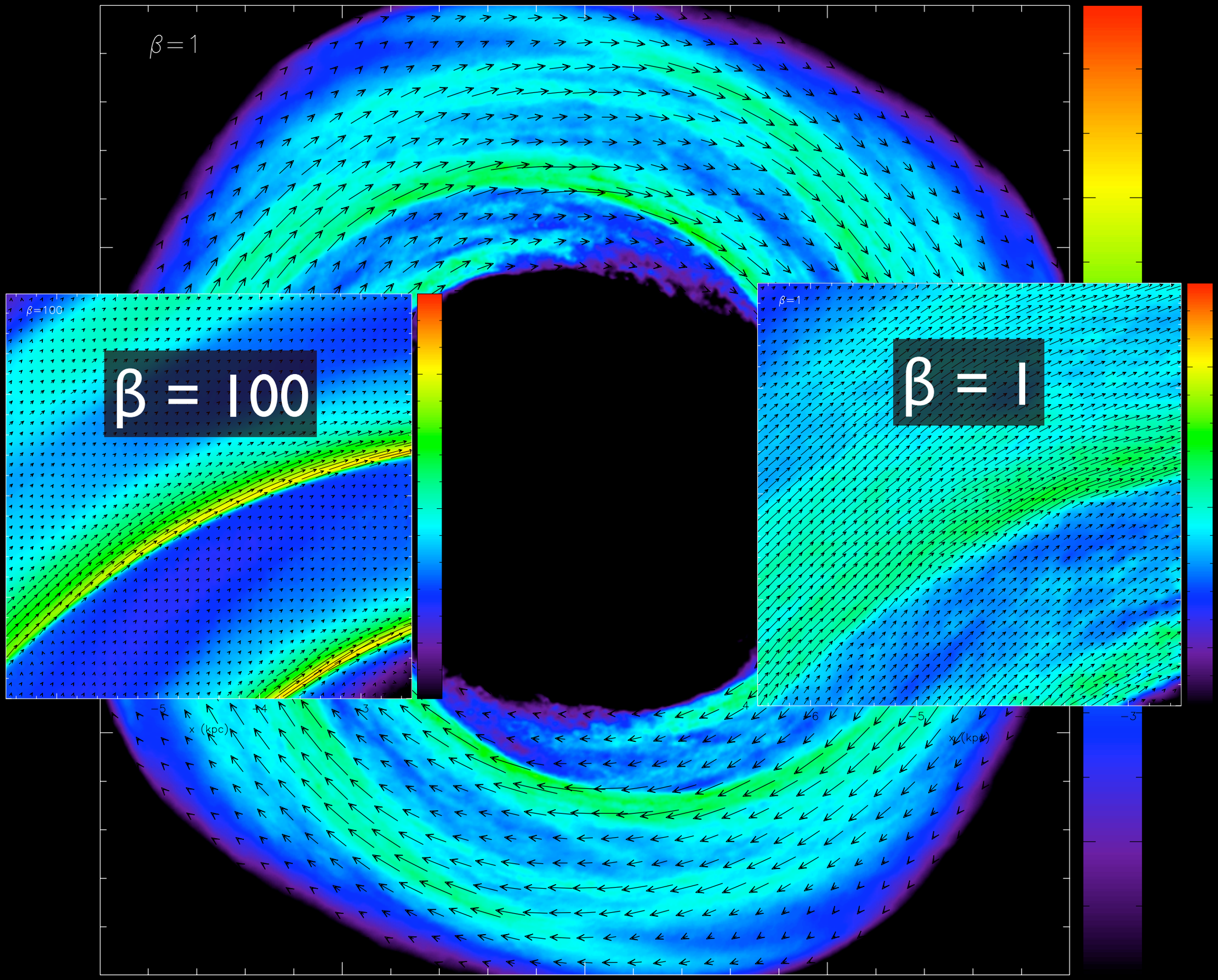








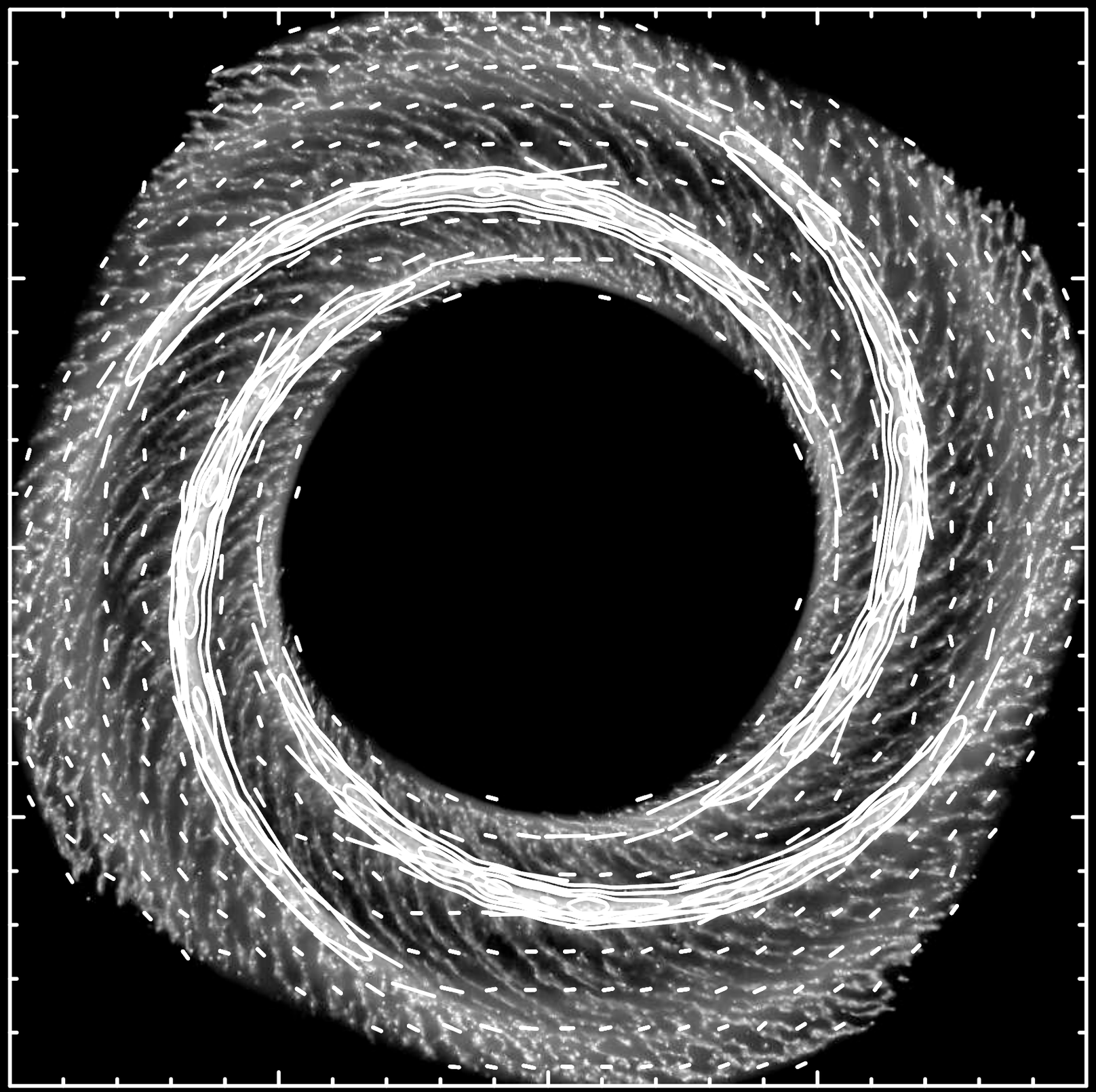
magnetic fields suppress but do not eliminate small scale structure



warm gas only: no structure, ordered fields

Presence of both cold and warm gas key to producing relative amounts of ordered/disordered field

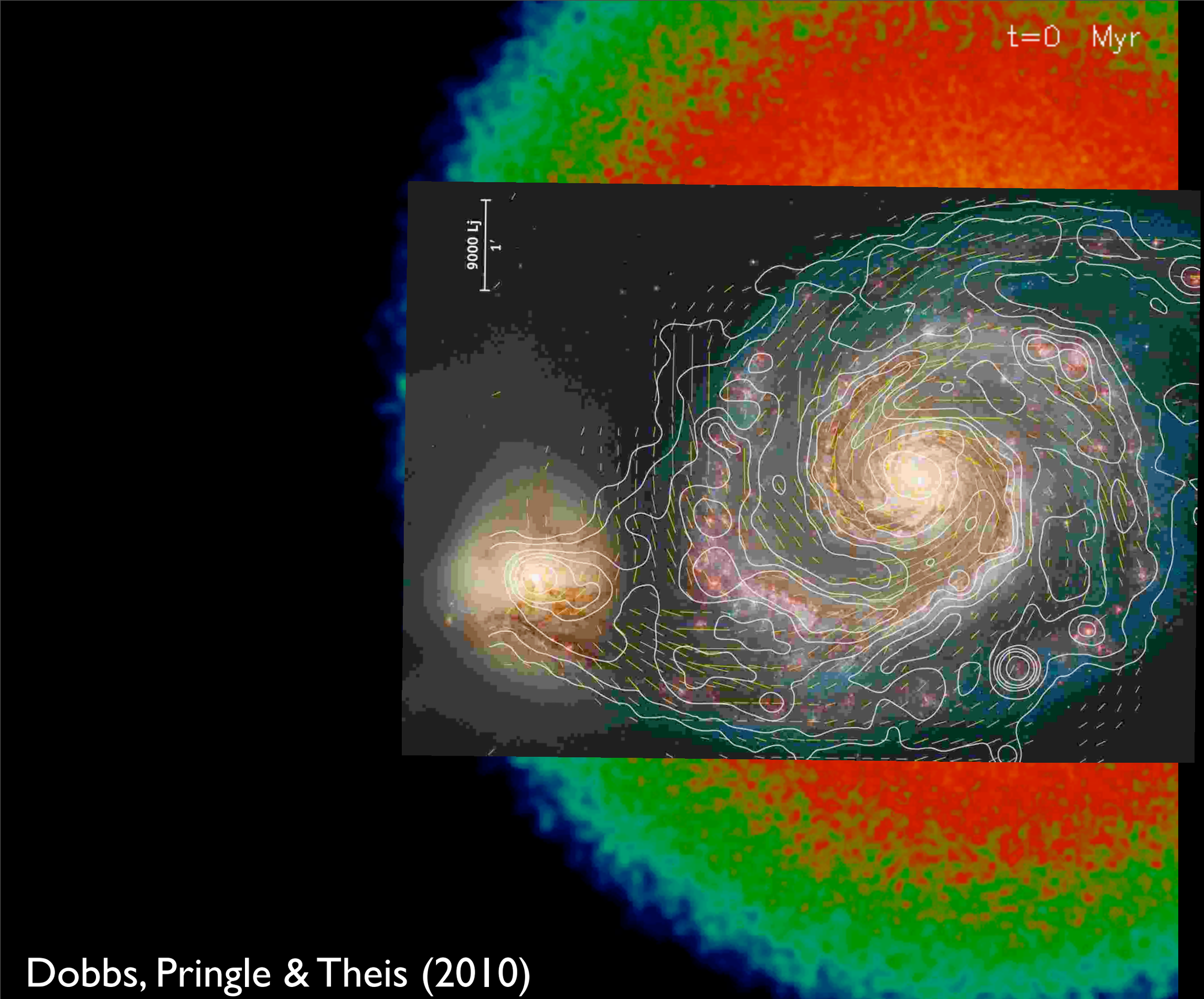
Synthetic synchrotron map



3) What effect do magnetic fields have on the dynamics of the interstellar medium (and vice versa)?

- presence of magnetic fields tend to suppress (but not eliminate) small scale ISM structure in galaxies produced by cold gas in clumpy shocks

- presence of cold gas induces significant disorder in the magnetic field



Dobbs, Pringle & Theis (2010)

Summary

- many of the issues plaguing Smoothed Particle Magnetohydrodynamics for decades have now been resolved and the method is being applied successfully to real astrophysical problems

- magnetic fields significantly alter fragmentation in star forming cores, leading potentially to problems with formation of discs and binary stars.

- strong magnetic fields lead to large scale voids, anisotropic turbulent motions and column density `stripes' aligned with the field lines in collapsing molecular clouds

- magnetic fields strongly affect the star formation rate and possibly also the initial mass function.

- magnetic fields can be important in more ways than one! Most important for molecular clouds is as a source of pressure.