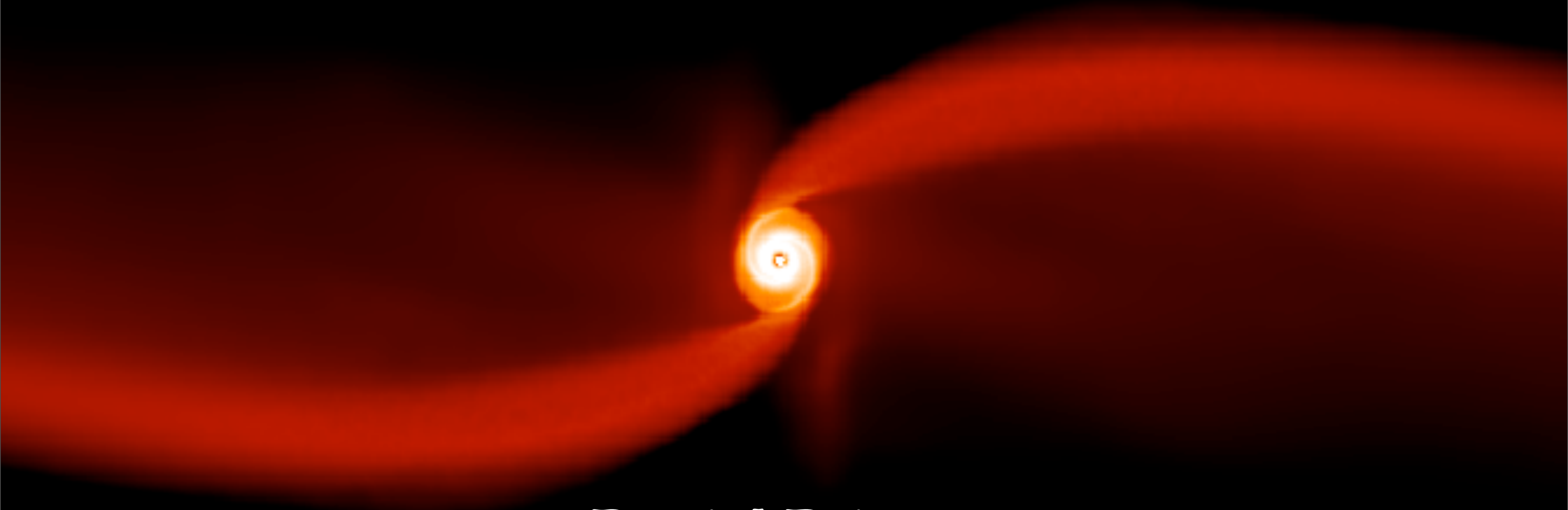
# Magnetic fields in star formation: from stars to galaxies



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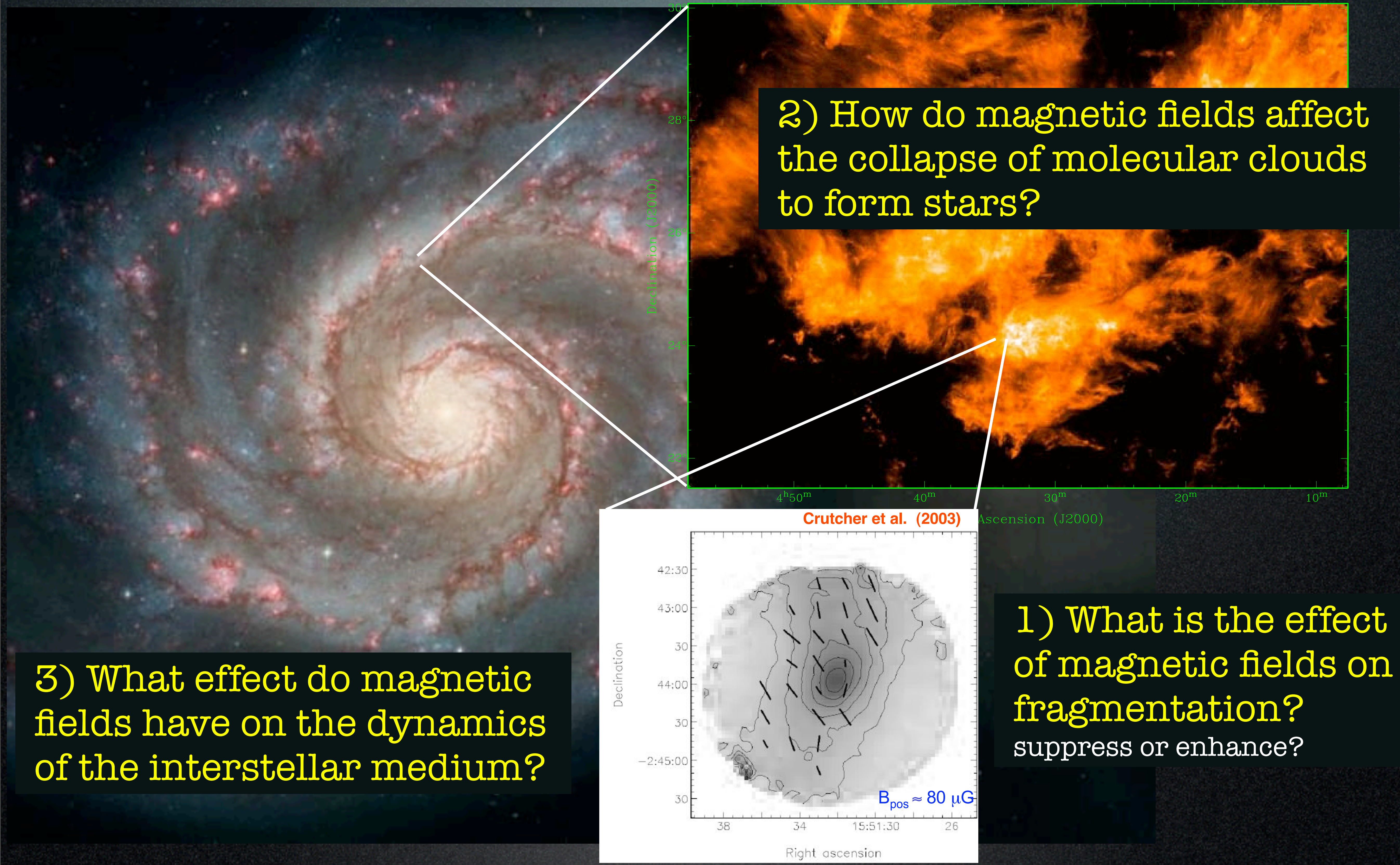
(Exeter)

www.astro.ex.ac.uk/people/dprice

"Magnetic fields in the universe II", Cozumel, Mexico




# Magnetic fields in star formation

M51: S. Beckwith, Hubble Heritage Team, ESA, NASA

# Smoothed Particle Magnetohydrodynamics

Price & Monaghan (2004a,b, 2005)

$$L_{sph} = \sum_b m_b \left[ \frac{1}{2} v_b^2 - u_b(\rho_b, s_b) - \frac{1}{2\mu_0} \frac{B_b^2}{\rho_b} \right]$$

$$\int \delta L \mathrm{dt} = 0$$

continuity equation

$$\delta \rho_b = \sum_c m_c \left( \delta \mathbf{r}_b - \delta \mathbf{r}_c \right) \cdot \nabla_b W_{bc},$$

mag field evolution

$$\delta \left( \frac{\mathbf{B}_b}{\rho_b} \right) = - \sum_c m_c (\delta \mathbf{r}_b - \delta \mathbf{r}_c) \frac{\mathbf{B}_b}{\rho_b^2} \cdot \nabla_b W_{bc}$$

equations of motion

$$\frac{dv_a^i}{dt} = \sum_b m_b \left[ \left( \frac{S^{ij}}{\rho^2} \right)_a + \left( \frac{S^{ij}}{\rho^2} \right)_b \right] \nabla_a^j W_{ab},$$

$$S_a^{ij} = - \left( P_a + \frac{1}{2\mu_0} B_a^2 \right) \delta^{ij} + \frac{1}{\mu_0} \left( B_a^i B_a^j \right),$$

# Technical issues

1) Momentum conserving force is unstable → use force which vanishes for constant stress

$$
\begin{aligned}
\frac{dv^i}{dt} &= -\sum_b m_b \left( \frac{P_a + \frac{1}{2}B_a^2/\mu_0}{\rho_a^2} + \frac{P_b + \frac{1}{2}B_b^2/\mu_0}{\rho_b^2} \right) \frac{\partial W_{ab}}{\partial x^i} \\
&+ \frac{1}{\mu_0} \sum_b m_b \frac{(B_i B_j)_b - (B_i B_j)_a}{\rho_a \rho_b} \frac{\partial W_{ab}}{\partial x_j}.
\end{aligned}
$$

(Morris 1996)

2) Shocks → formulate artificial dissipation terms (PM04a)

$$
\begin{aligned}
\left(\frac{d\mathbf{v}}{dt}\right)_{diss} &= -\sum_b m_b \frac{\alpha v_{sig} (\mathbf{v}_a - \mathbf{v}_b) \cdot \hat{r}}{\bar{\rho}_{ab}} \nabla_a W_{ab}, \\
\left(\frac{d\mathbf{B}}{dt}\right)_{diss} &= \rho_a \sum_b m_b \frac{\alpha_B v_{sig}}{\bar{\rho}_{ab}^2} (\mathbf{B}_a - \mathbf{B}_b)\, \hat{r} \cdot \nabla_a W_{ab} \\
\left(\frac{de_a}{dt}\right)_{diss} &= -\sum_b m_b \frac{v_{sig} (e_a^* - e_b^*)}{\bar{\rho}_{ab}} \hat{r} \cdot \nabla_a W_{ab}
\end{aligned}
$$

3) Variable h → use Lagrangian (Price & Monaghan 2004b)

# 4) The $\nabla \bullet \mathbf{B} = 0$ constraint

- prevention vs cleanup (Price & Monaghan 2005)
- Euler potentials:

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

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

use accurate SPH derivatives (Price 2004)

$$\chi_{\mu\nu}\nabla^{\mu}\alpha_i = -\sum_j m_j(\alpha_i - \alpha_j)\nabla_i^{\nu} W_{ij}(h_i)$$

$$\chi_{\mu\nu} = \sum_j m_j (r_i^{\mu} - r_j^{\mu})\nabla^{\nu} W_{ij}(h_i).$$

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

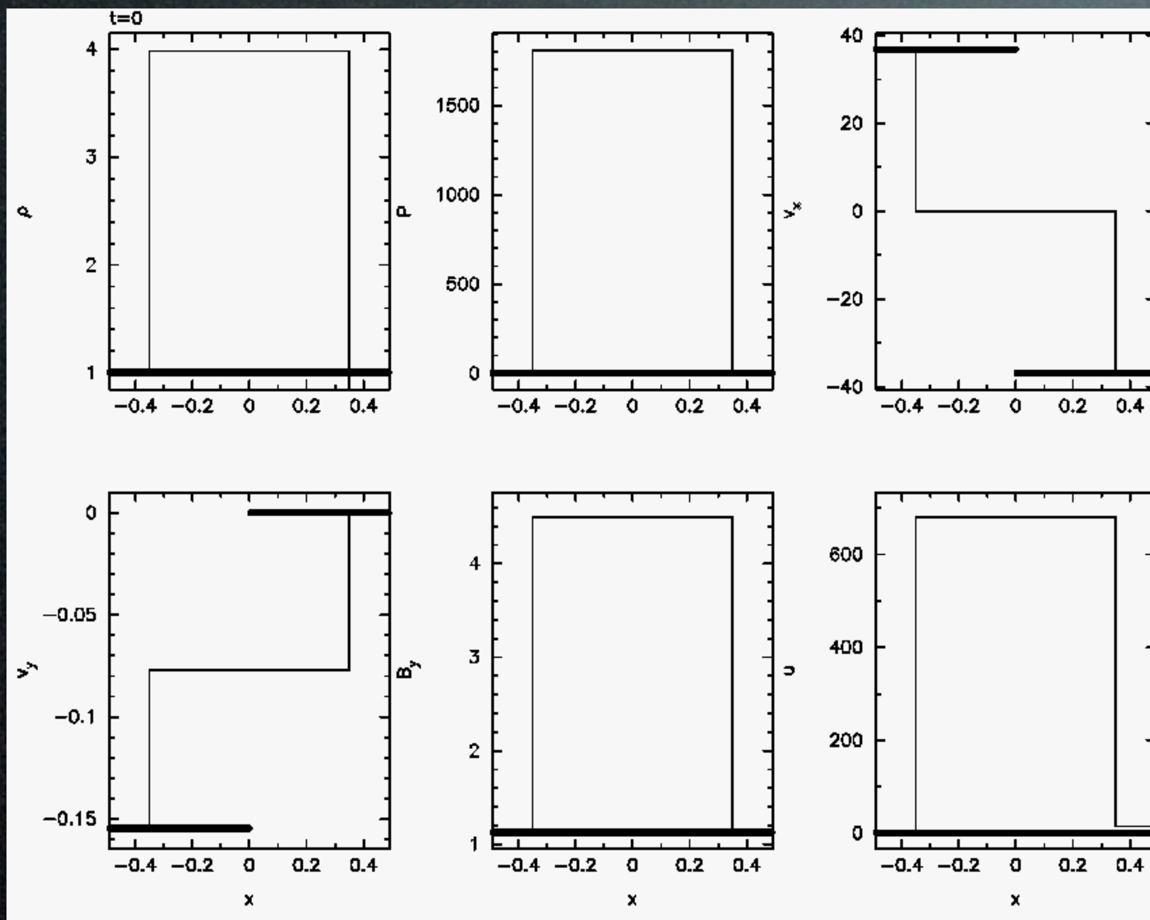
'advection of magnetic field lines'

add shock dissipation

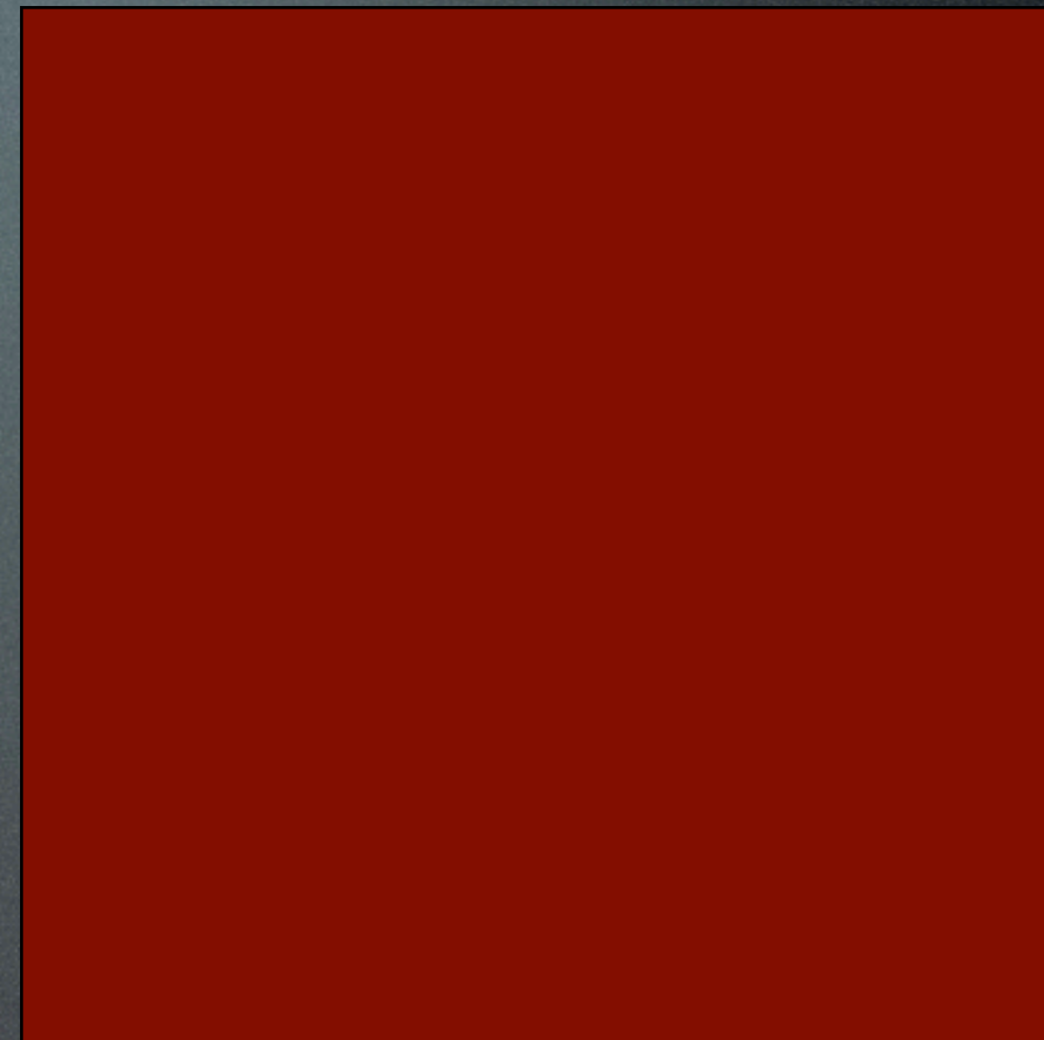
$$\frac{d\alpha}{dt} = \sum_b m_b \frac{\alpha_B v_{sig}}{\bar{\rho}_{ab}} (\alpha_a - \alpha_b)\,\hat{r}\cdot\nabla_a W_{ab}$$

$$\frac{d\beta}{dt} = \sum_b m_b \frac{\alpha_B v_{sig}}{\bar{\rho}_{ab}} (\beta_a - \beta_b)\,\hat{r}\cdot\nabla_a W_{ab}$$

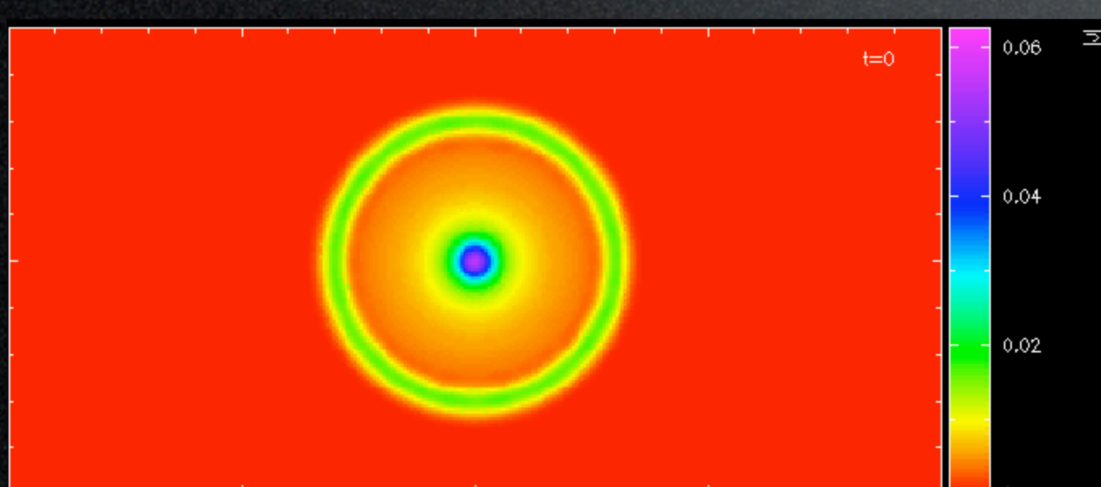
# Test problems




Mach 25 MHD shock (e.g. Balsara 1998)
(Price & Monaghan 2004a,b, Price 2004)



Orszag-Tang vortex (everyone)
(Price & Monaghan 2005, Rosswog & Price 2007)



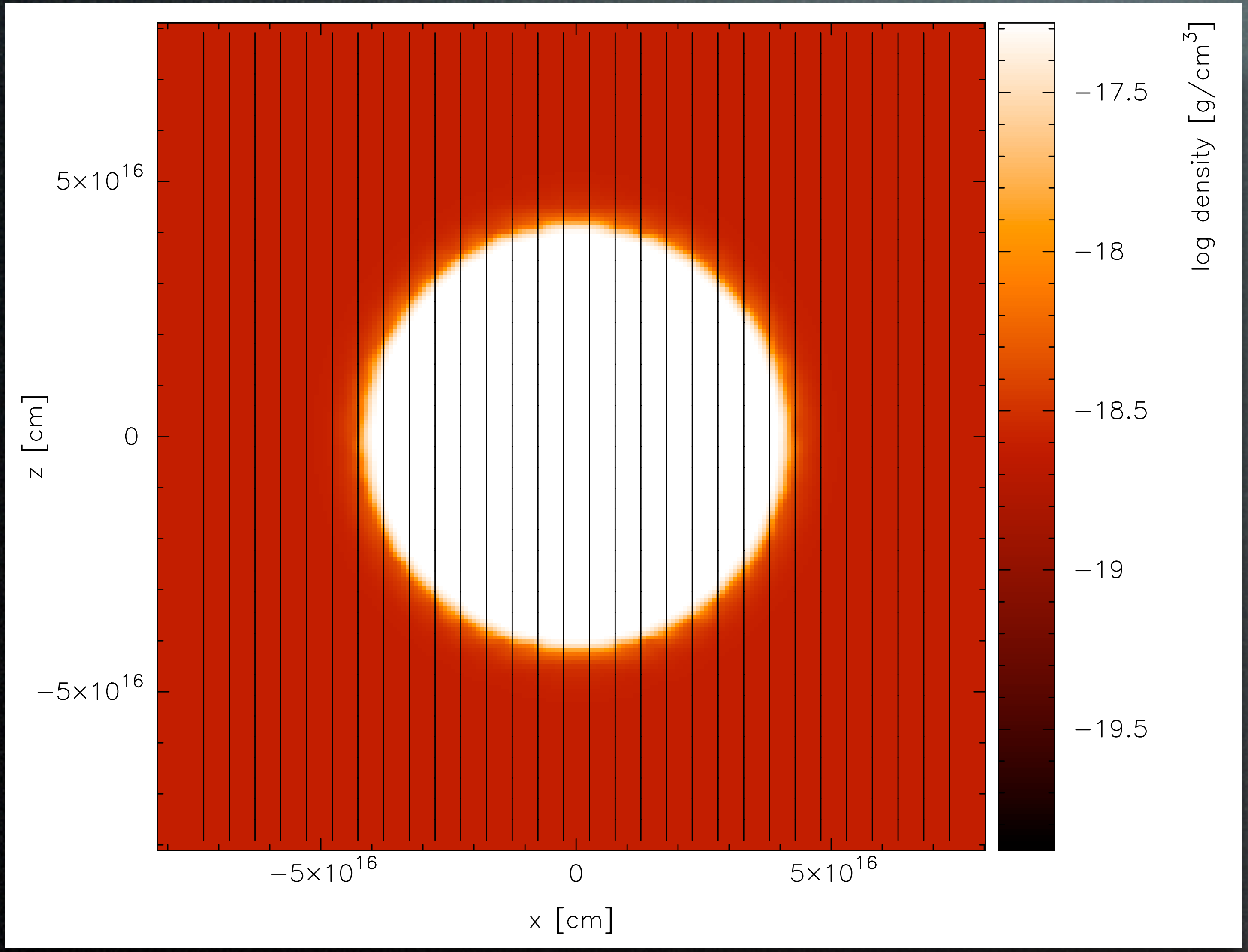

Current loop advection (e.g. Gardiner & Stone 2007)
(Rosswog & Price 2007)

# What is the effect of magnetic fields on fragmentation?

suppress (e.g. Hosking and Whitworth 2004)
or enhance (e.g. Boss 2002)?

# Single & binary star formation

(Price & Bate 2007)




- dense core R=4x$10^{16}$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:

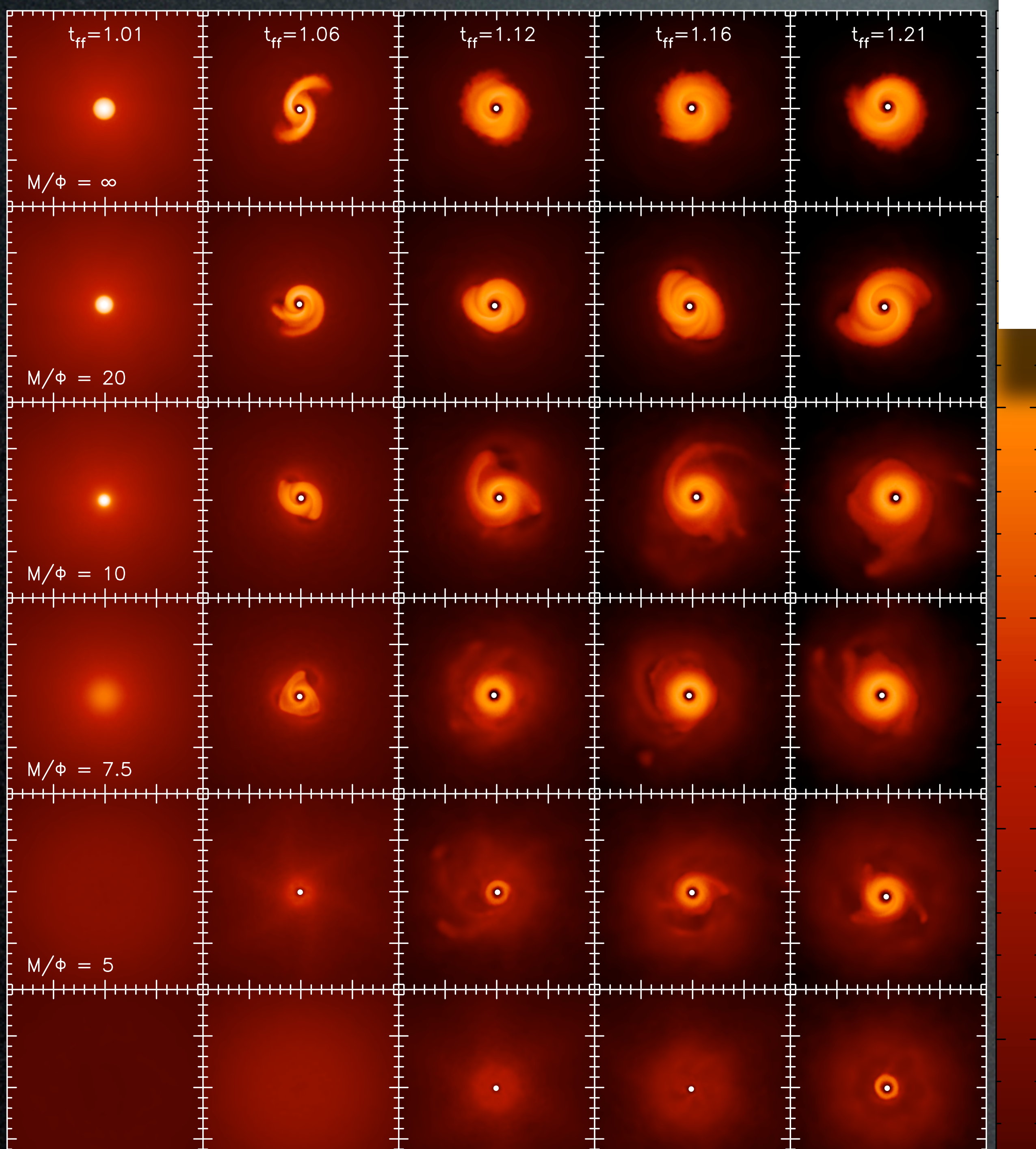
$$P = K\rho^{\gamma}$$

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

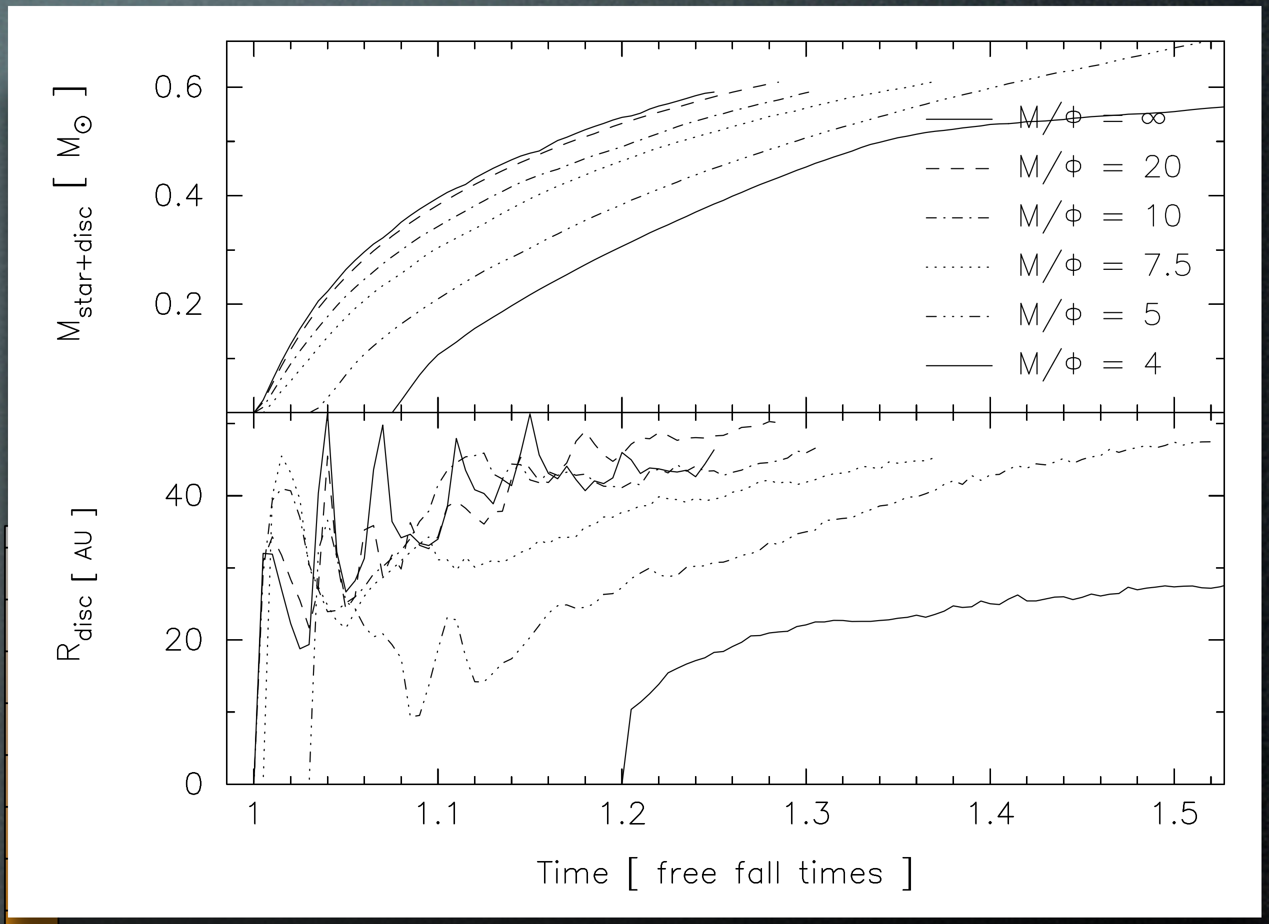
$$\gamma = 7/5, \qquad \rho > 10^{-14} \mathrm{g\ cm}^{-3},$$

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

# Effect of magnetic fields on circumstellar disc formation:

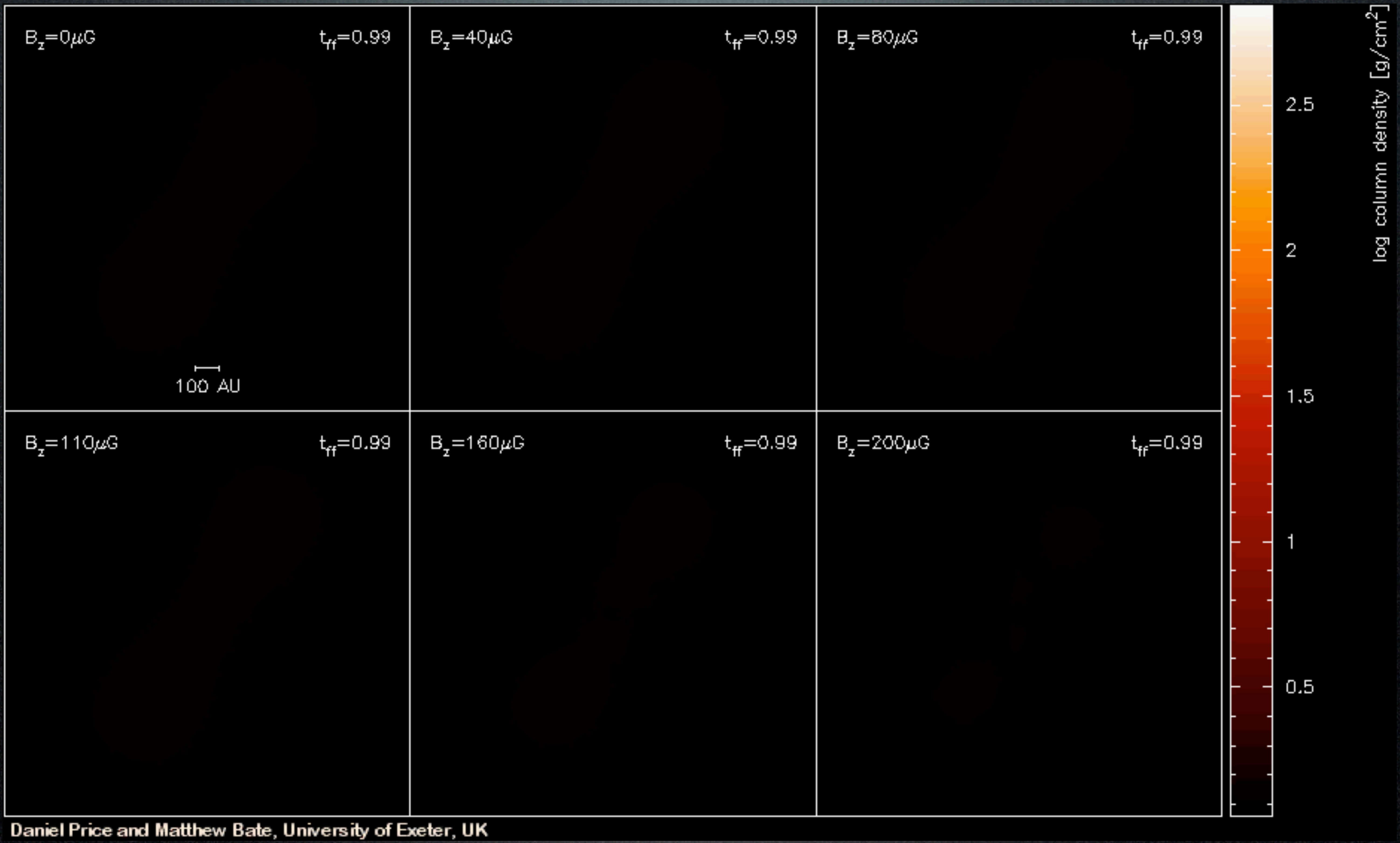



Price & Bate (2007)

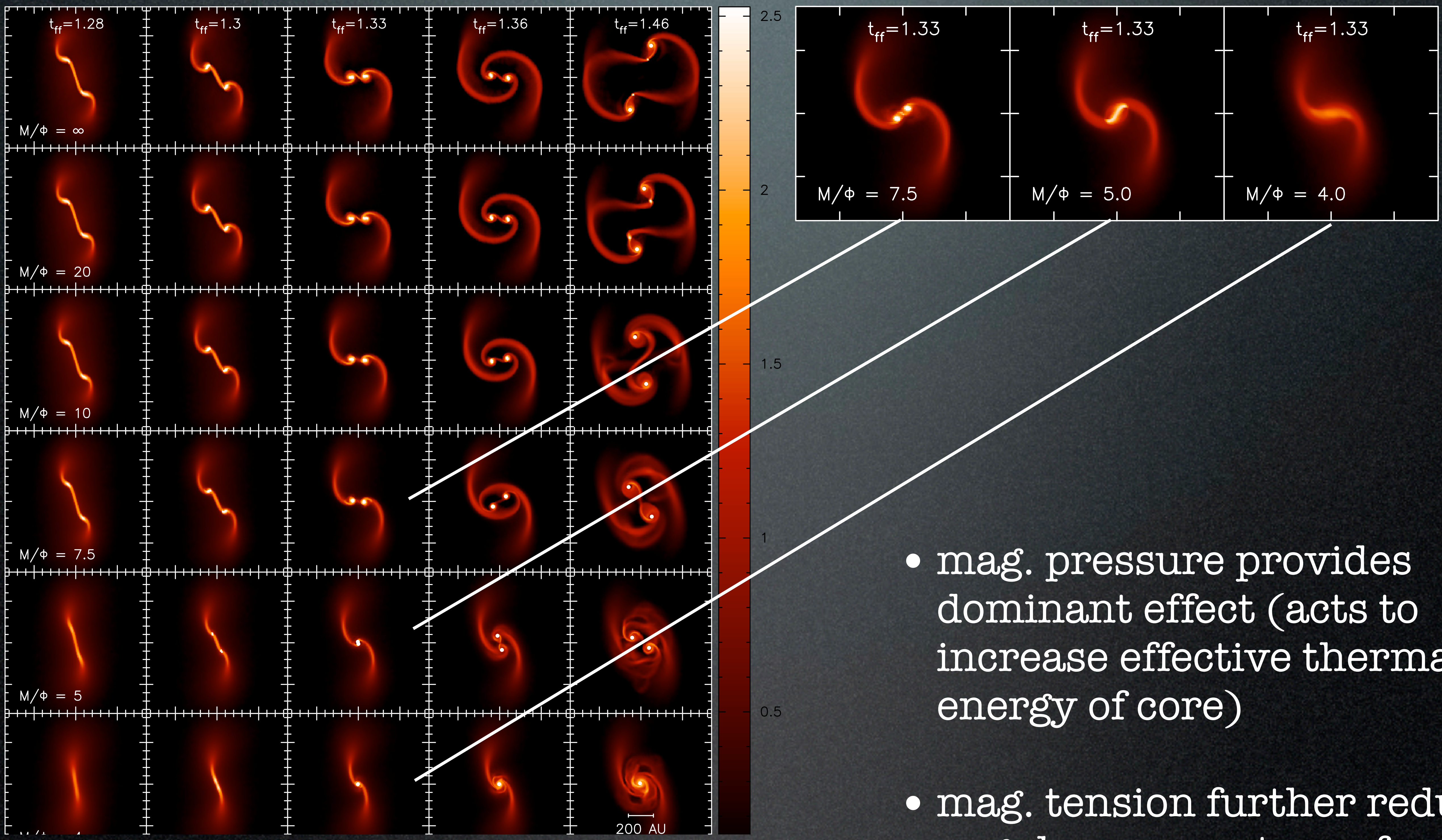



- discs form later
- less massive
- smaller
- slower accretion rates
- less prone to gravitational instability

# Effect on binary formation ($B_z$ field):



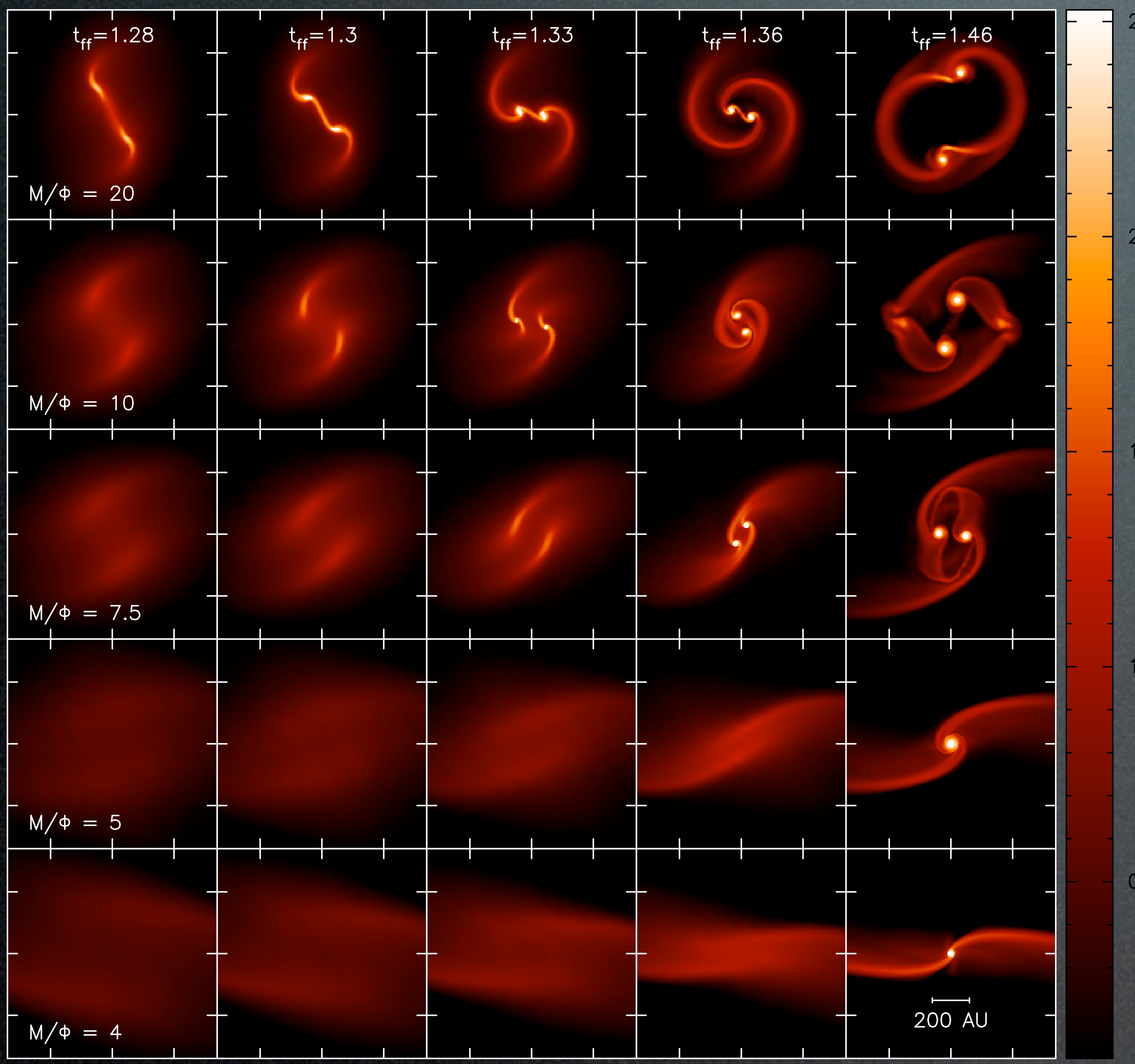
# z field: Pressure or tension?



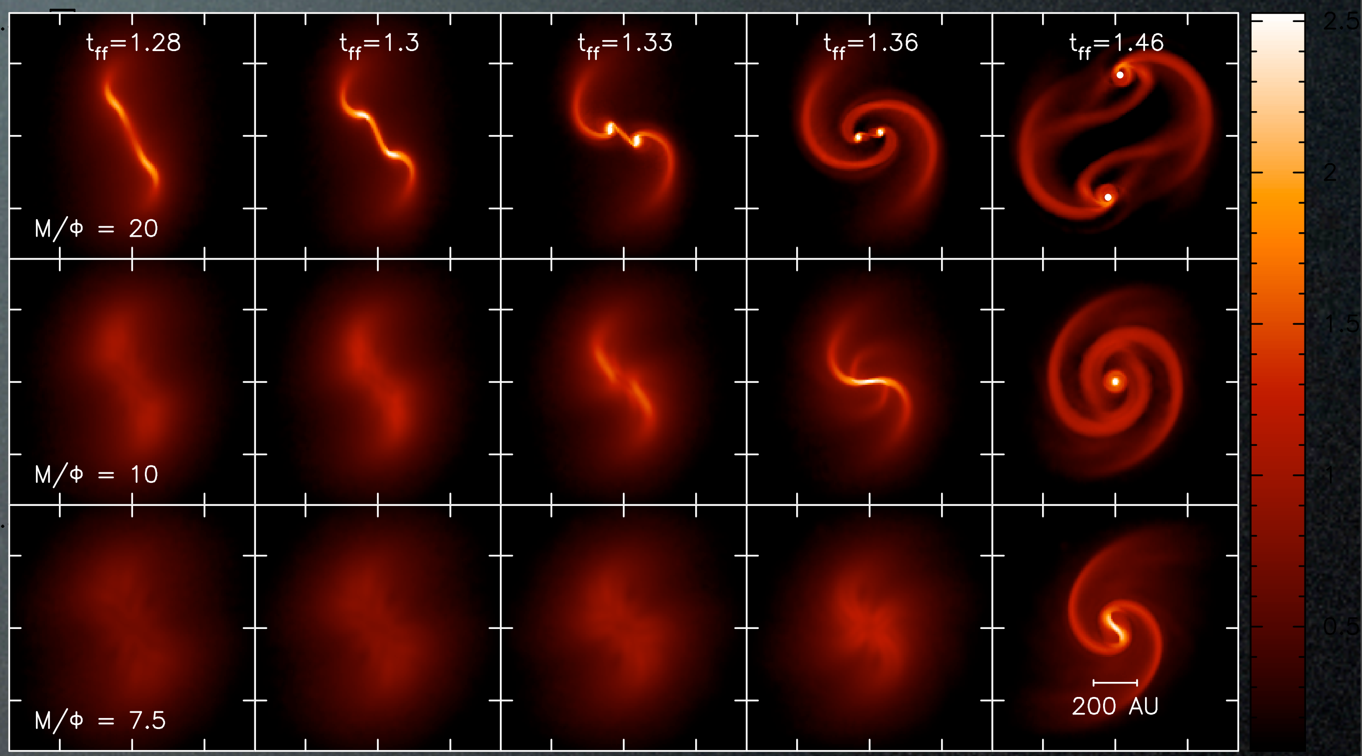

- mag. pressure provides dominant effect (acts to increase effective thermal energy of core)
- mag. tension further reduces angular momentum of collapsing core

# field in rotation plane: pressure vs tension

full MHD ($B_x$ field)

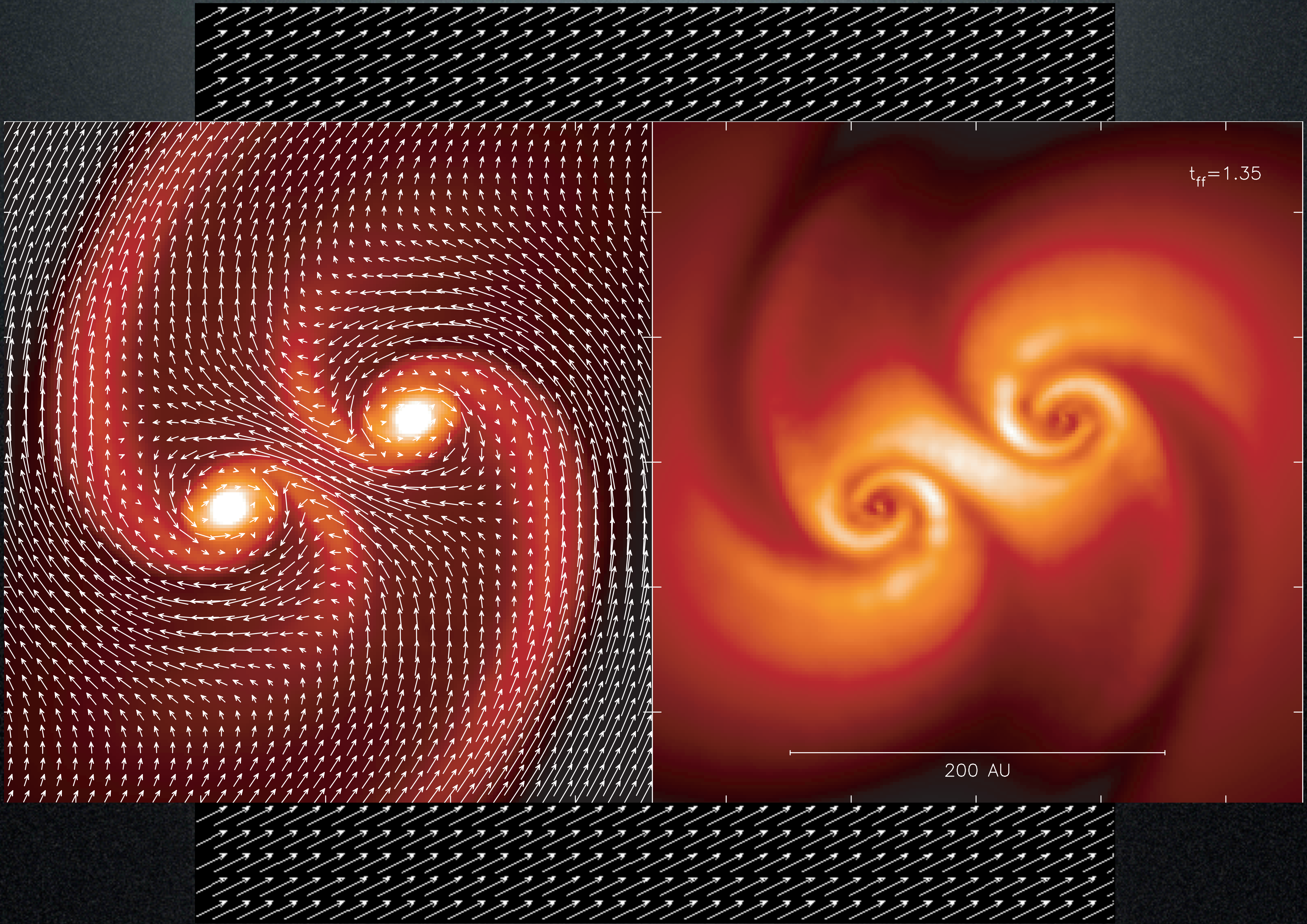



mag pressure only




- tension effect strongly dependent on field orientation
- tension acts to increase fragmentation (c.f. Boss 2000,2002)

# “Magnetic cushioning”



# What is the effect of magnetic fields on fragmentation?

net effect is always to SUPPRESS fragmentation, driven by magnetic pressure effects, although magnetic tension can dilute this to some extent depending on the field geometry.

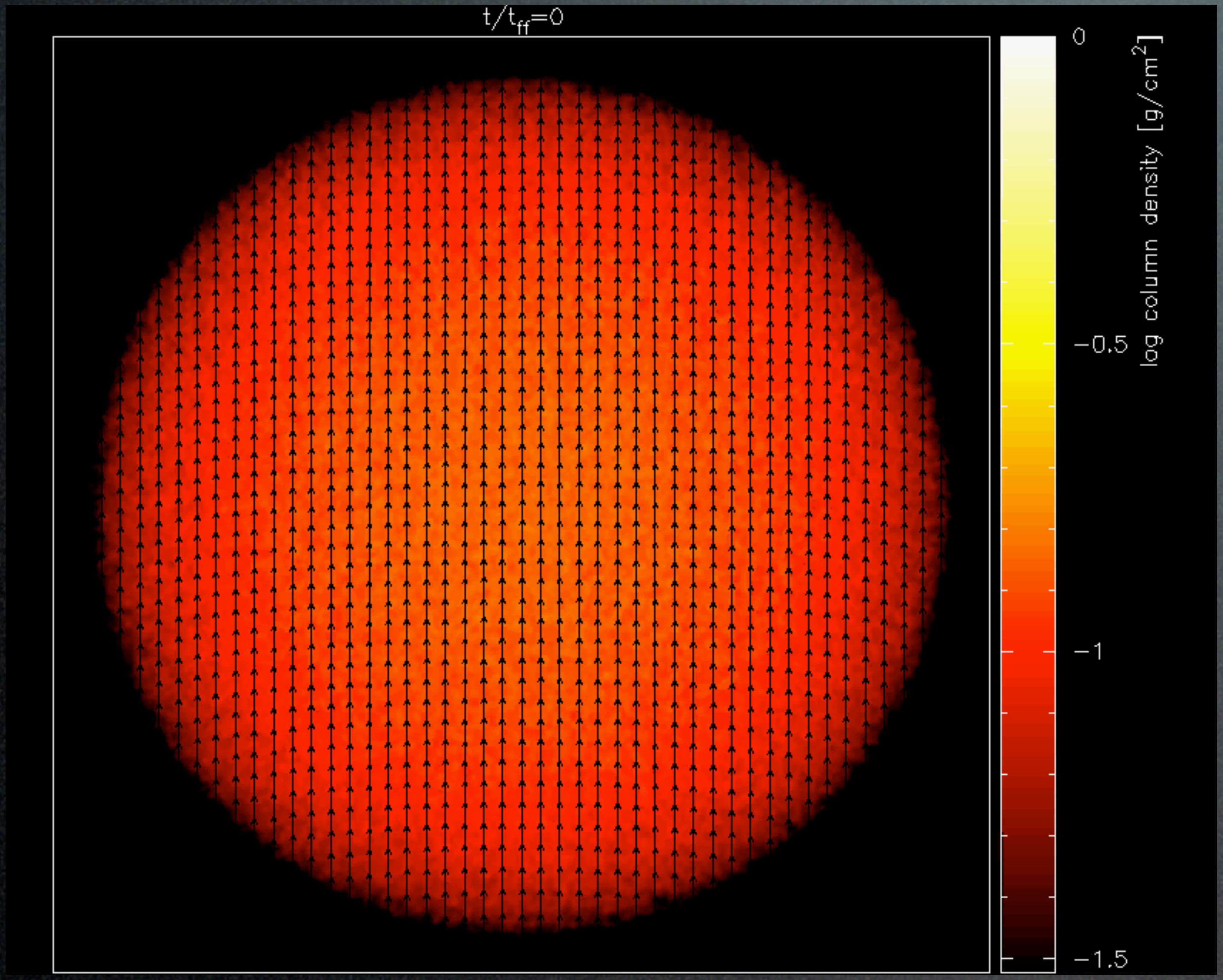
# How do magnetic fields affect the collapse of molecular clouds to form stars?

how do magnetic fields change the hydrodynamic picture?
(e.g. of Bate, Bonnell & Bromm 2003)

effect on initial turbulent decay?
star formation efficiency/molecular cloud lifetimes?
fragmentation of cores?
IMF/ ratio of stars to brown dwarfs?

# Magnetic fields in star cluster formation

Price & Bate (2008) arXiv:0801.3293




- 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
- barytropic equation of state

Bate, Bonnell & Bromm (2003) with magnetic fields...

# Important parameters

$$\left(\frac{M}{\Phi}\right) / \left(\frac{M}{\Phi}\right)_{crit}$$

magnetic field vs gravity

$$\beta = \frac{c_s^2 \rho}{\frac{1}{2} B^2 / \mu_0}$$

magnetic fields vs pressure

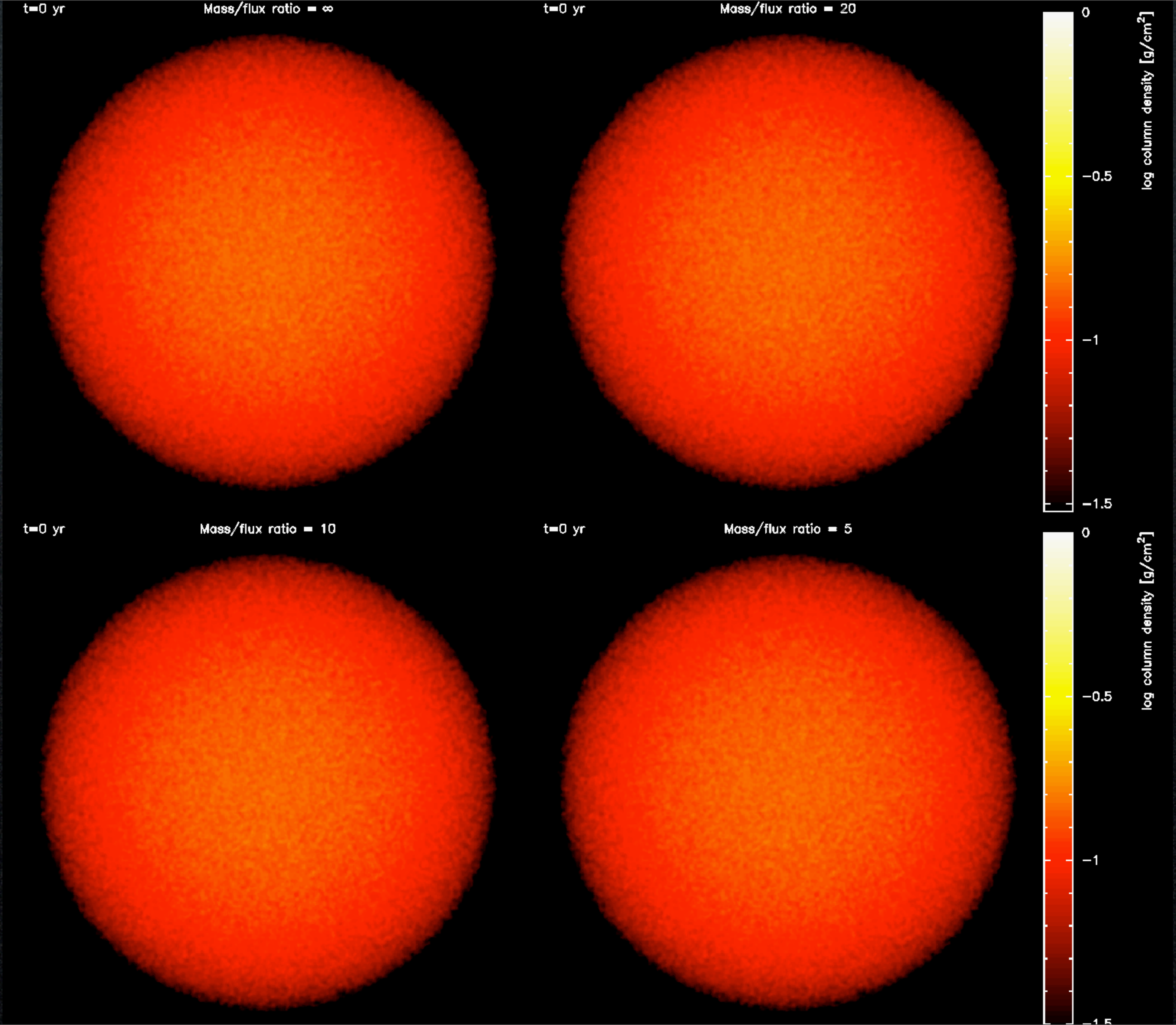
$$\frac{v_{turb}}{v_{Alfven}}$$

magnetic fields vs turbulence

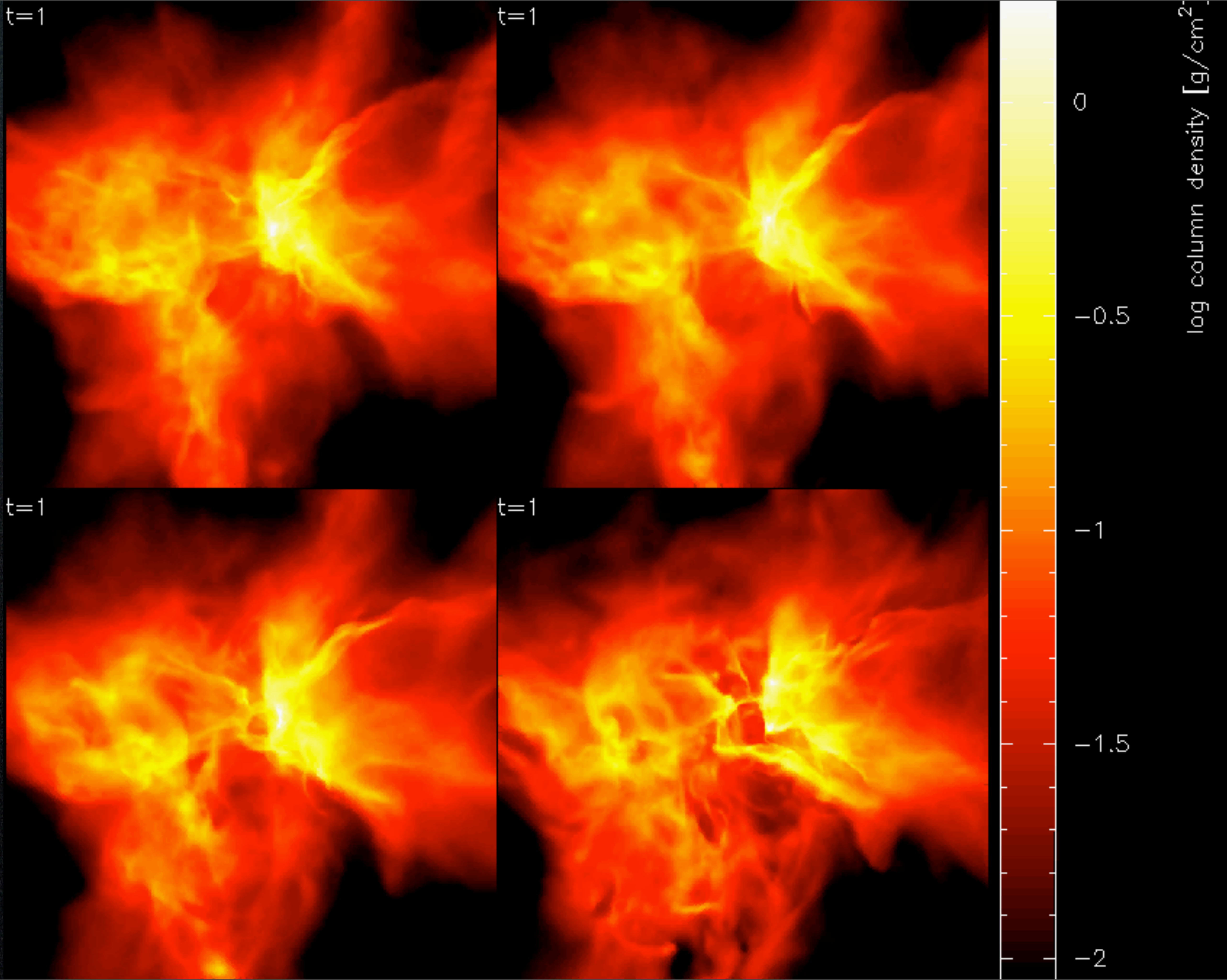
Observations suggest molecular clouds are:

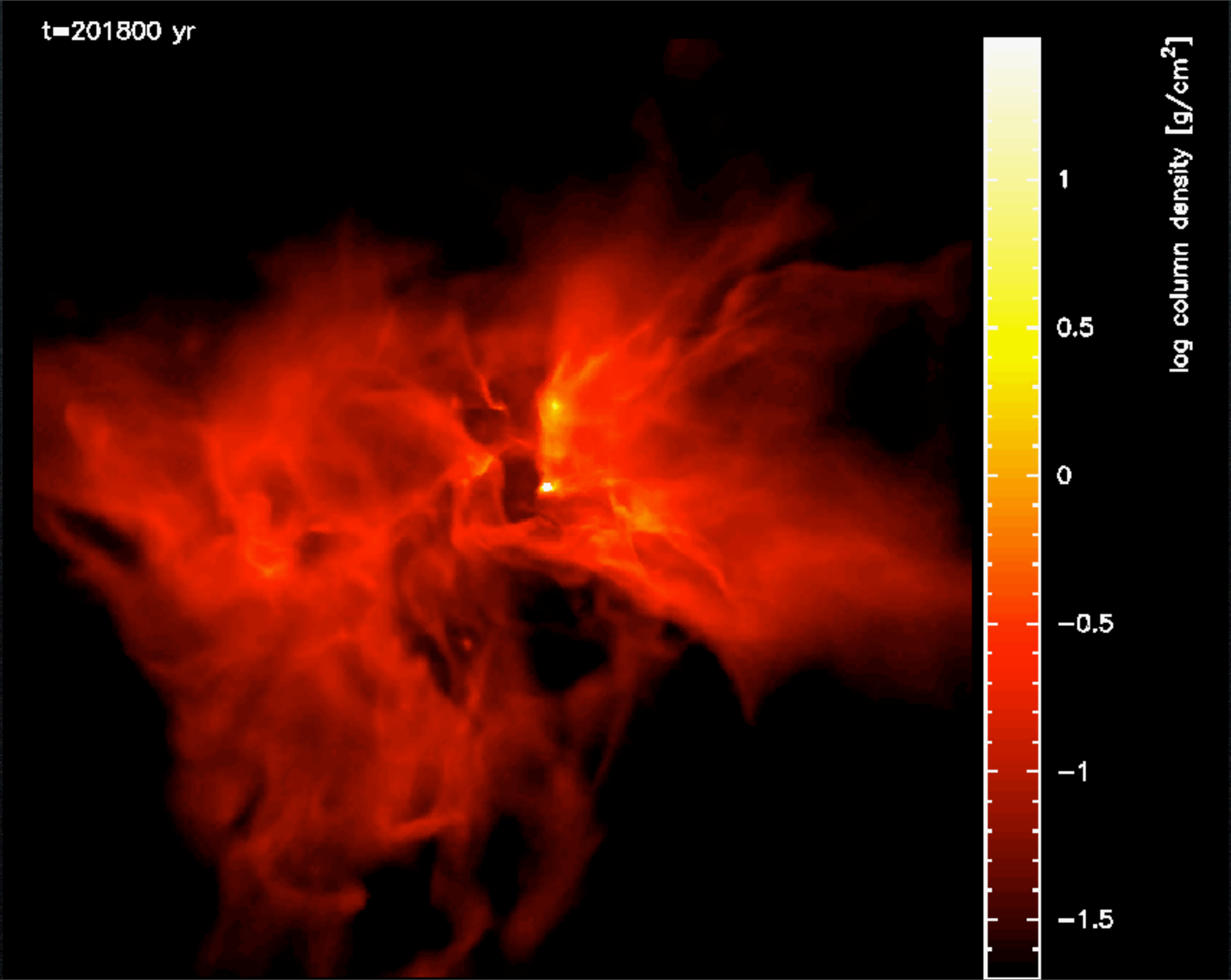
mildly supercritical
have beta < 1
marginally super-Alfvenic

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

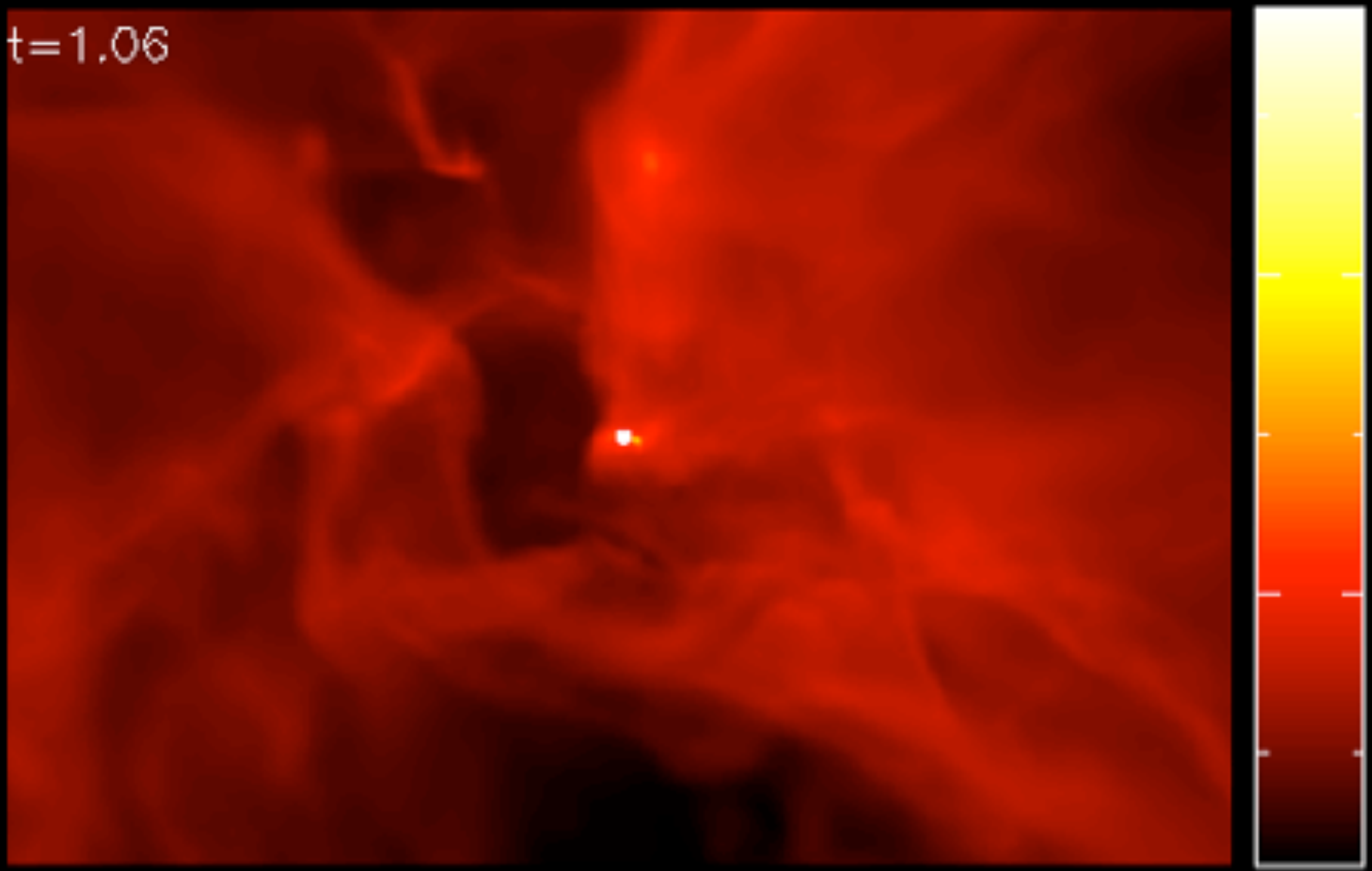


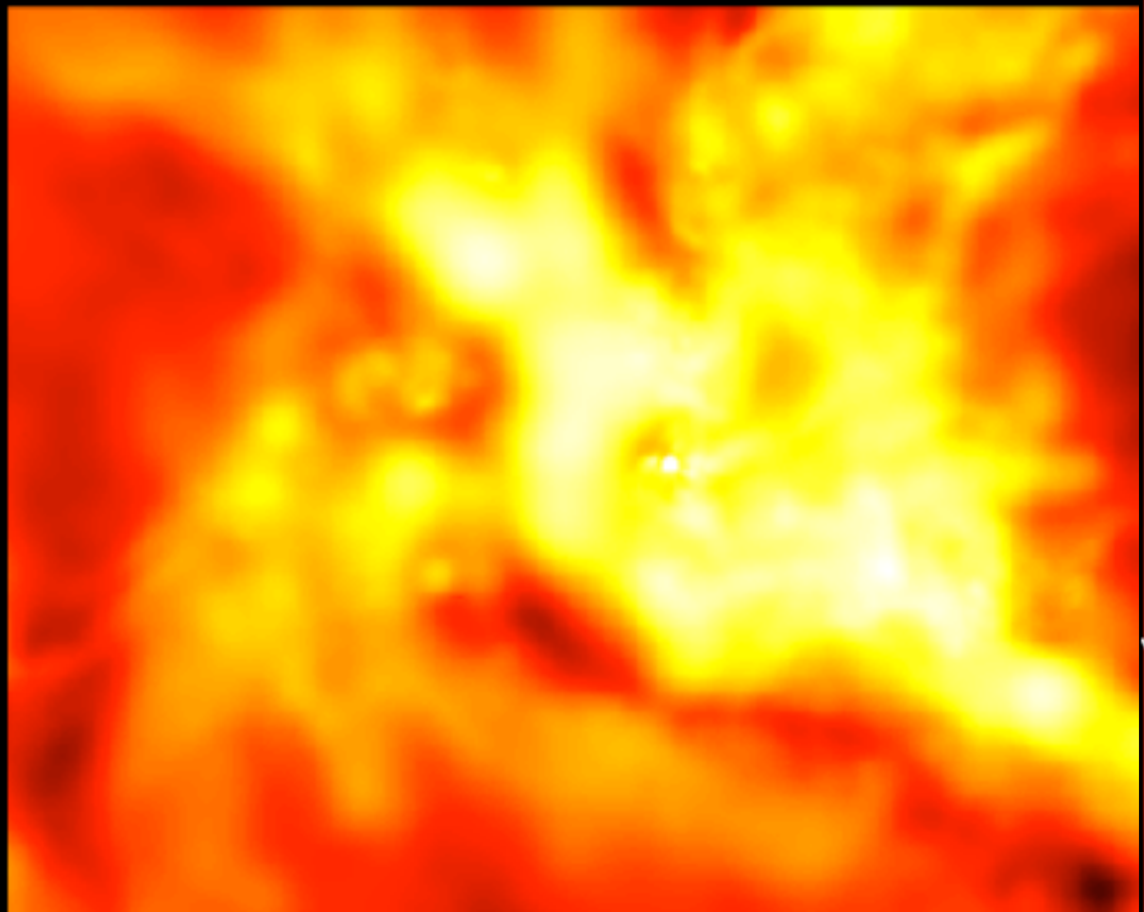
t=0 yr
Mass/flux ratio = ∞
t=0 yr
Mass/flux ratio = 20
t=0 yr
Mass/flux ratio = 10
t=0 yr
Mass/flux ratio = 5
0
−0.5
−1
−1.5
log column density [g/cm²]
0
−0.5
−1
log column density [g/cm²]

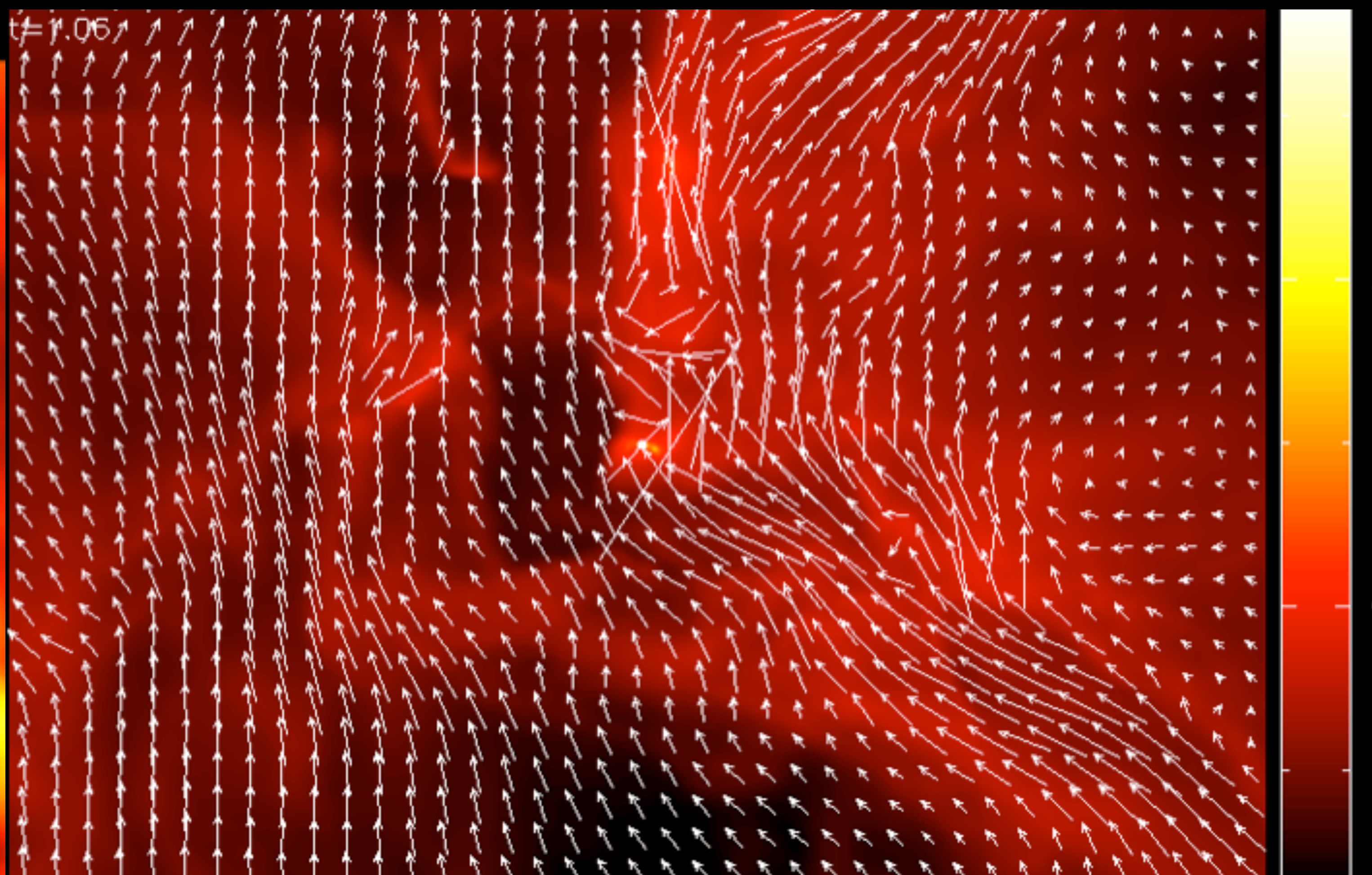

t=1
t=1
t=1
t=1
0
−0.5
−1
−1.5
−2
log column density [g/cm$^2$]


t=201800 yr
1
0.5
0
−0.5
−1
−1.5
log column density [g/cm$^2$]

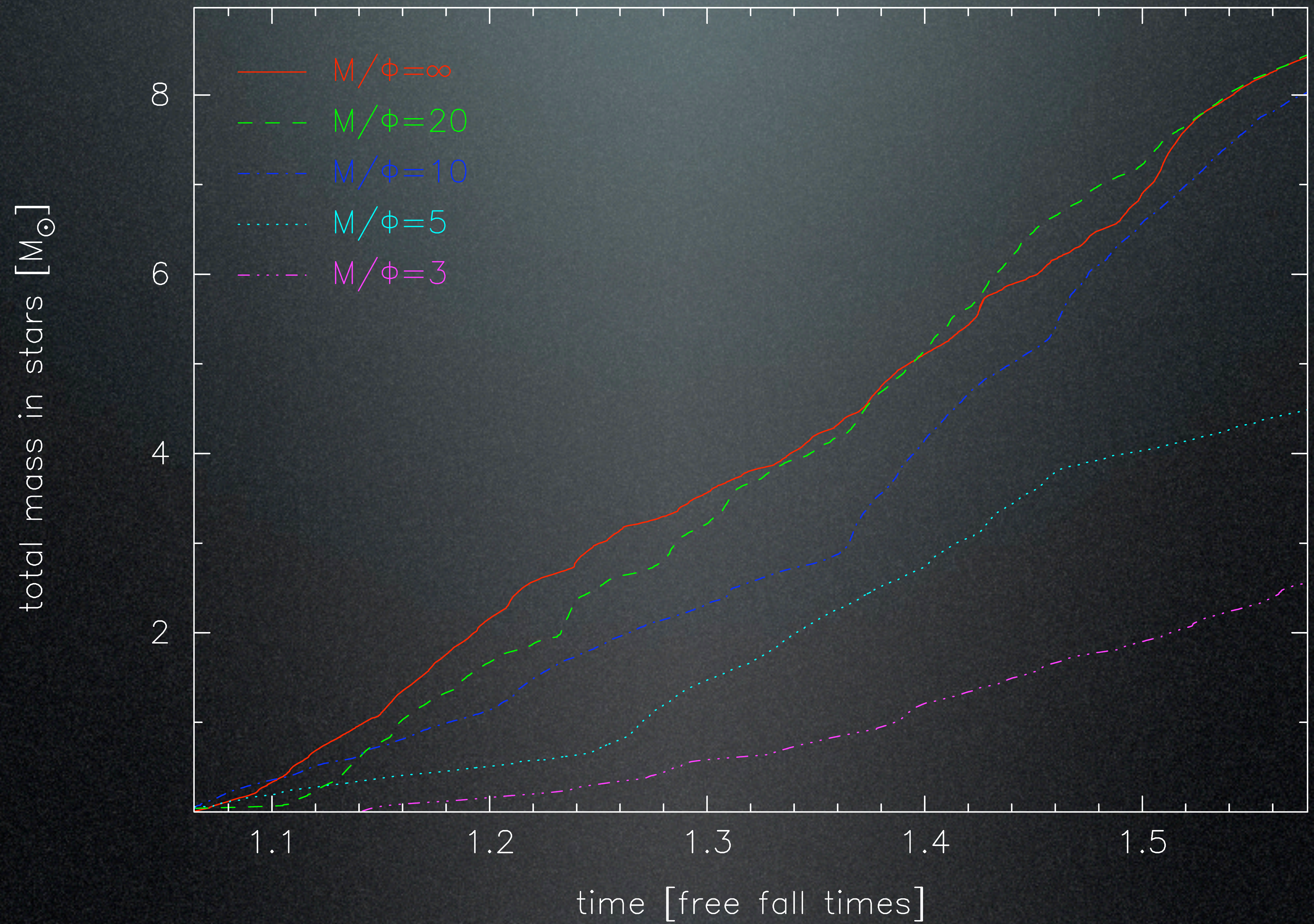
# Magnetic pressure-supported voids



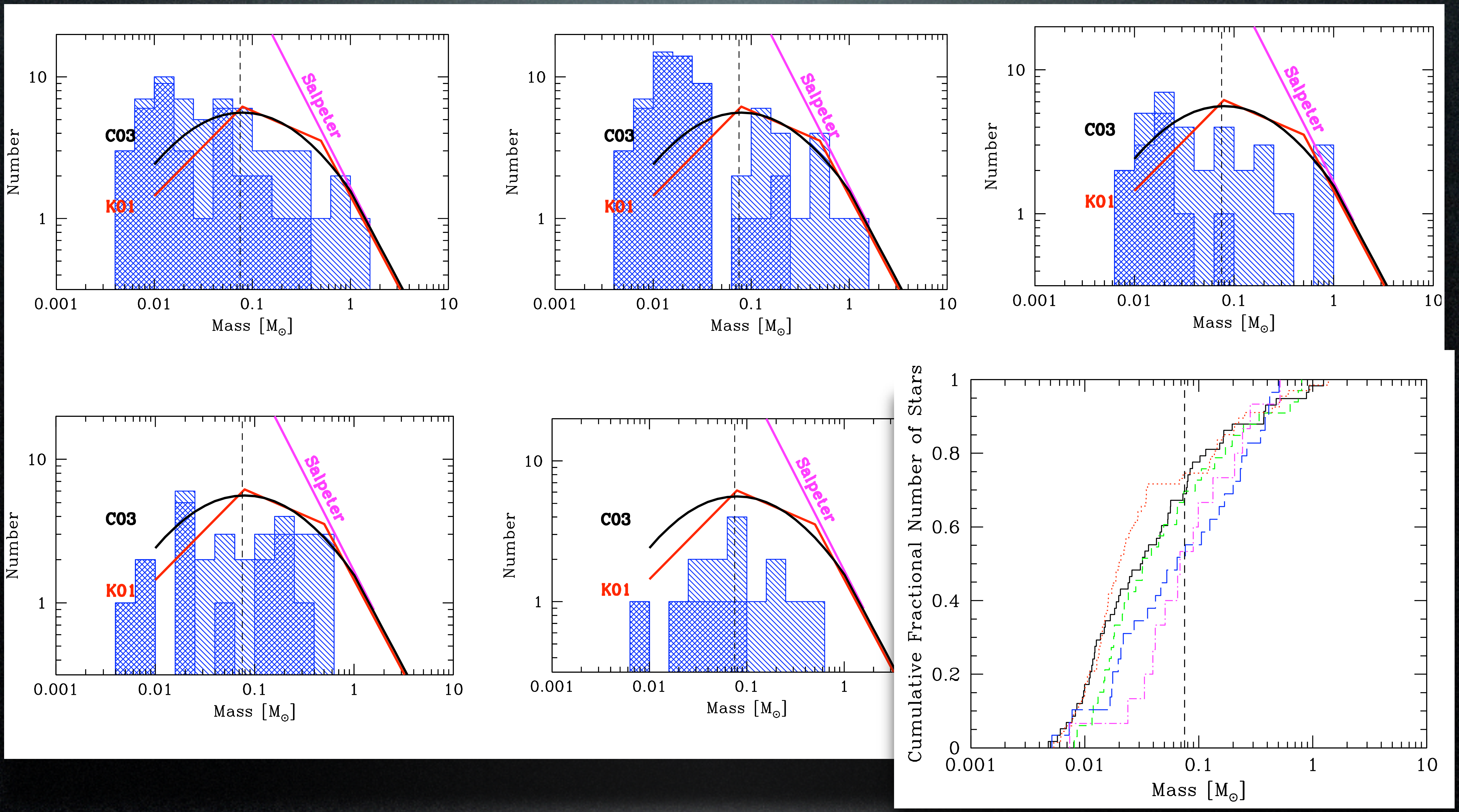





# Star formation rate



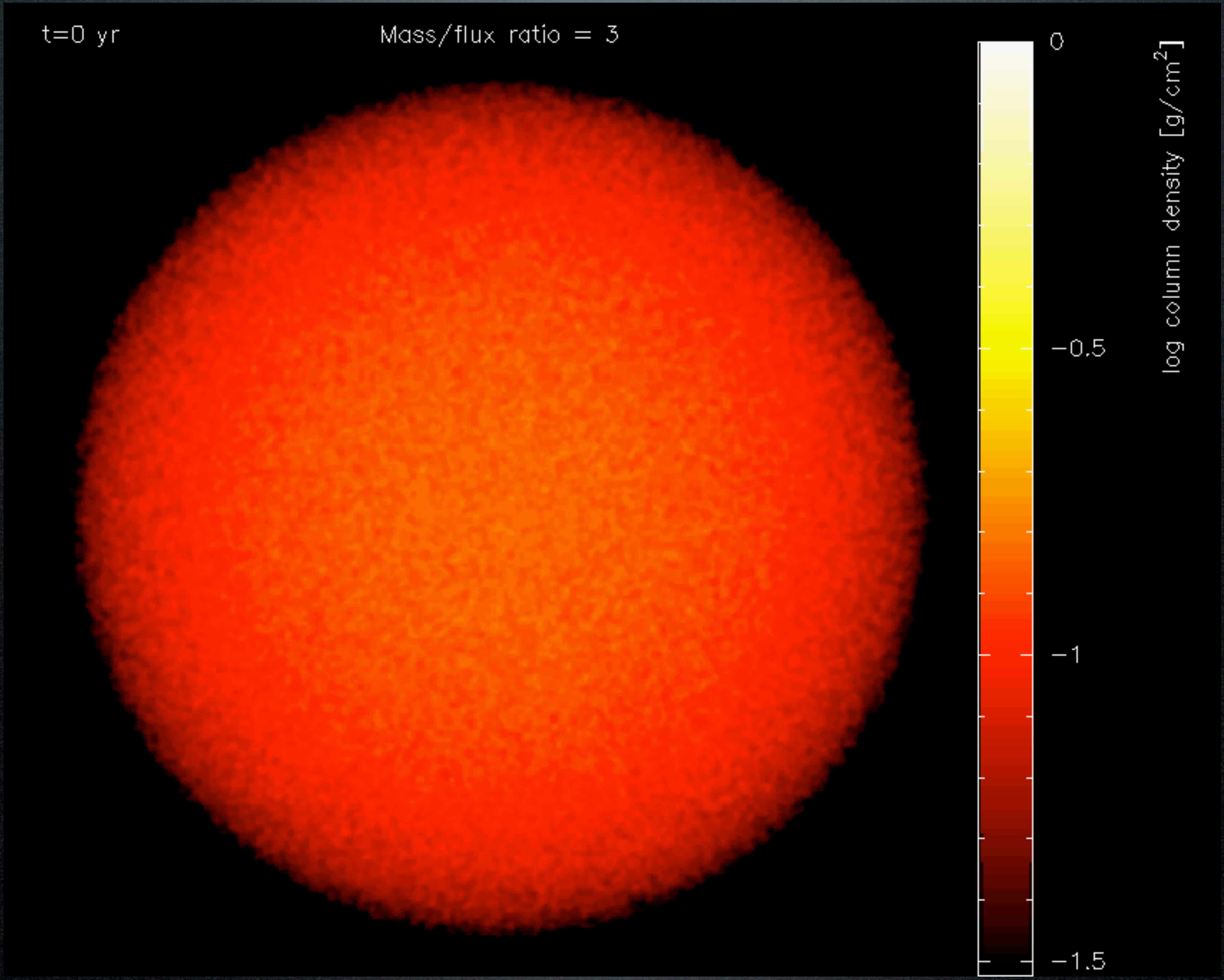
# Effect on IMF

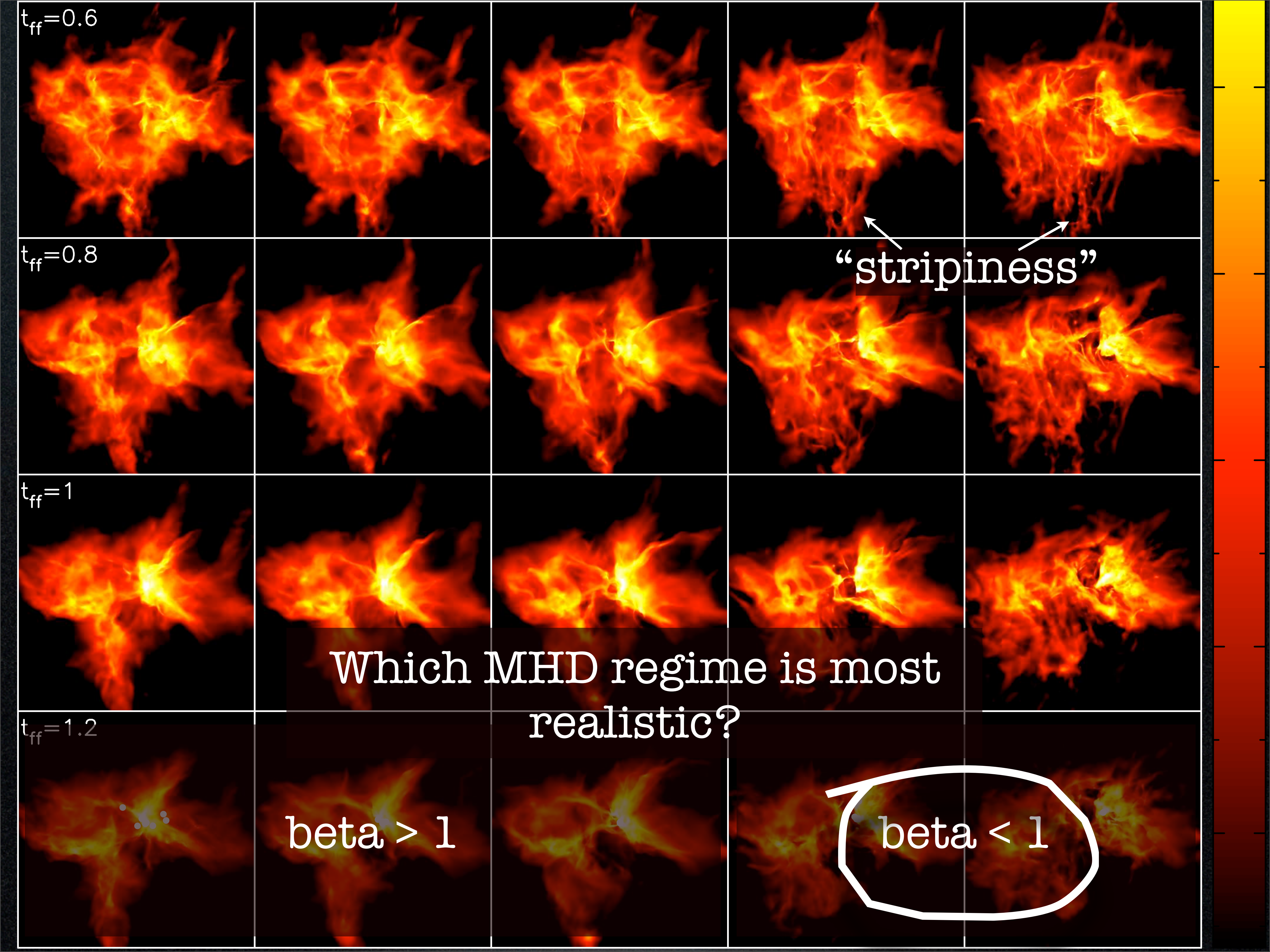


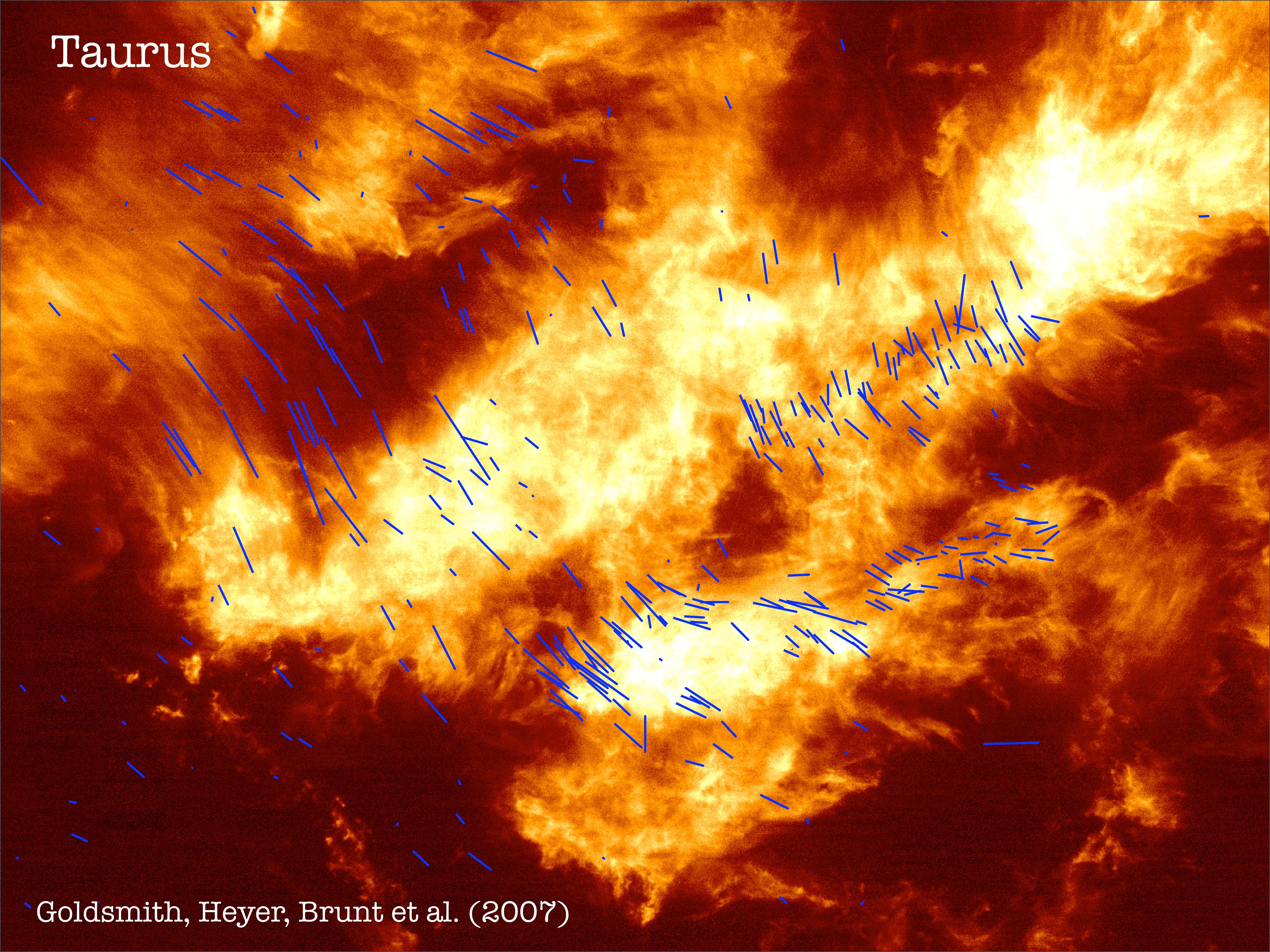
# Effect on IMF

| | $N_{BDs}$ | $N_{stars}$ | ratio |
|---|---|---|---|
| Hydro | 44 | 14 | 3.14 |
| $M/\Phi = 20$ | 51 | 18 | 2.83 |
| $M/\Phi = 10$ | 22 | 11 | 2.0 |
| $M/\Phi = 5$ | 15 | 14 | 1.07 |
| $M/\Phi = 3$ | 8 | 7 | 1.14 |

# even stronger field...

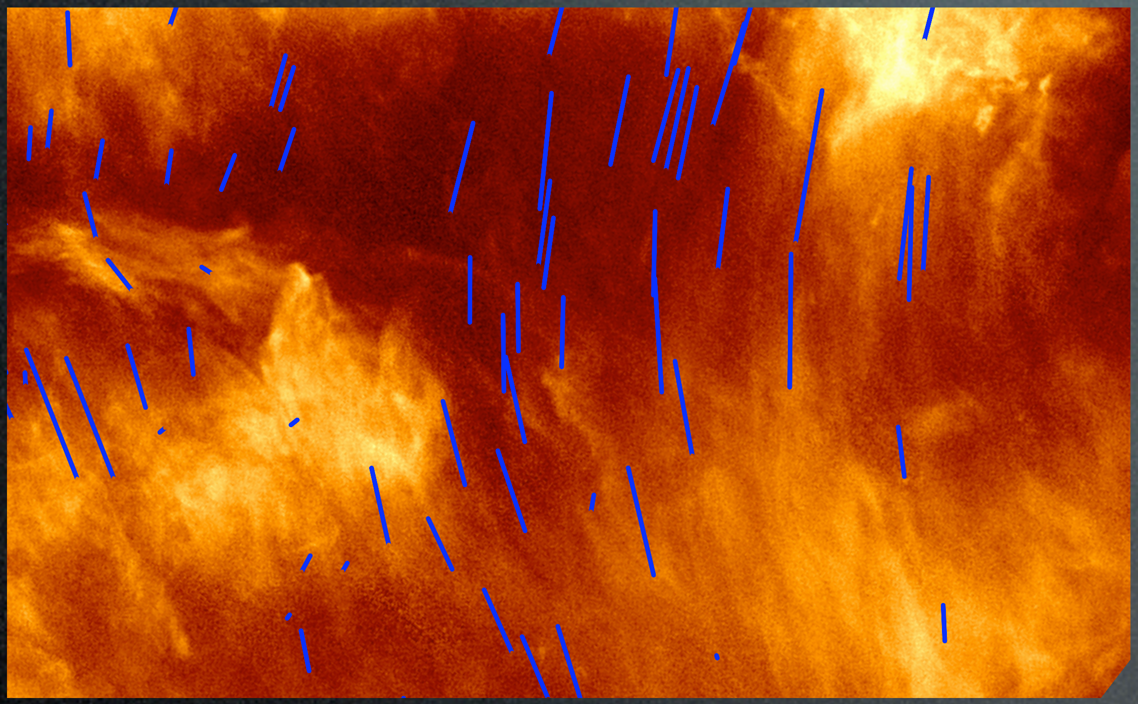


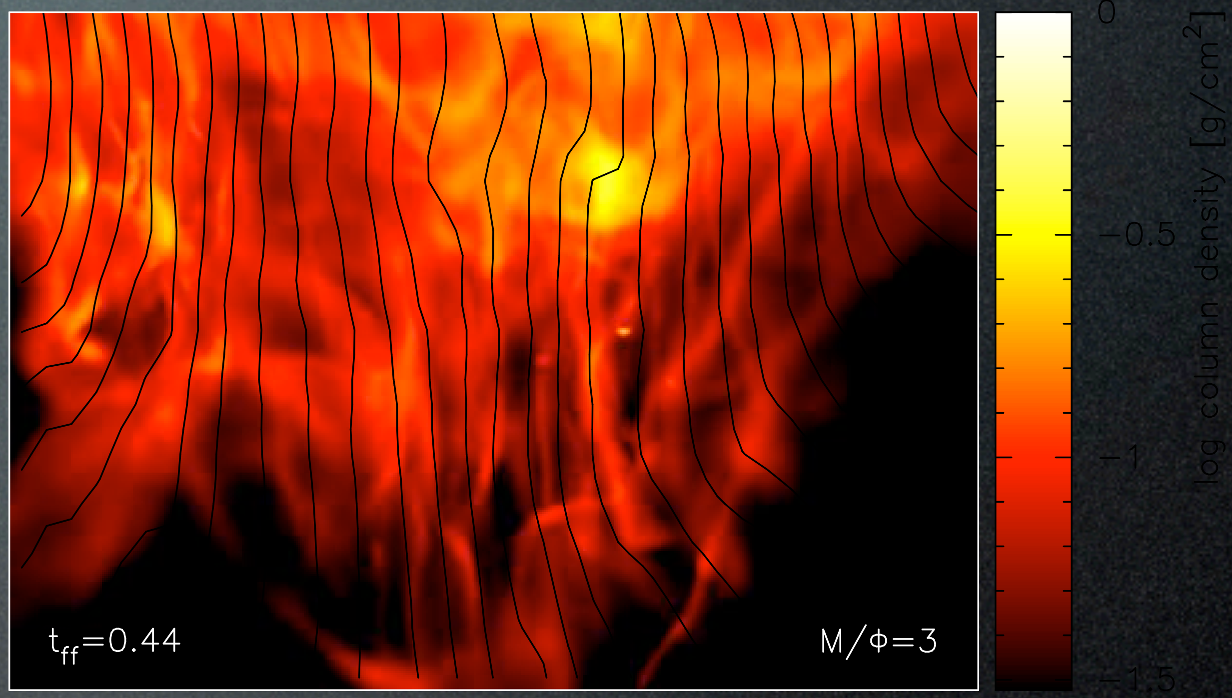

$t_{ff}$=0.6
$t_{ff}$=0.8
$t_{ff}$=1
$t_{ff}$=1.2
"stripiness"
Which MHD regime is most realistic?
beta > 1
beta < 1




Goldsmith, Heyer, Brunt et al. (2007)

# Column density striations along field lines






Taurus

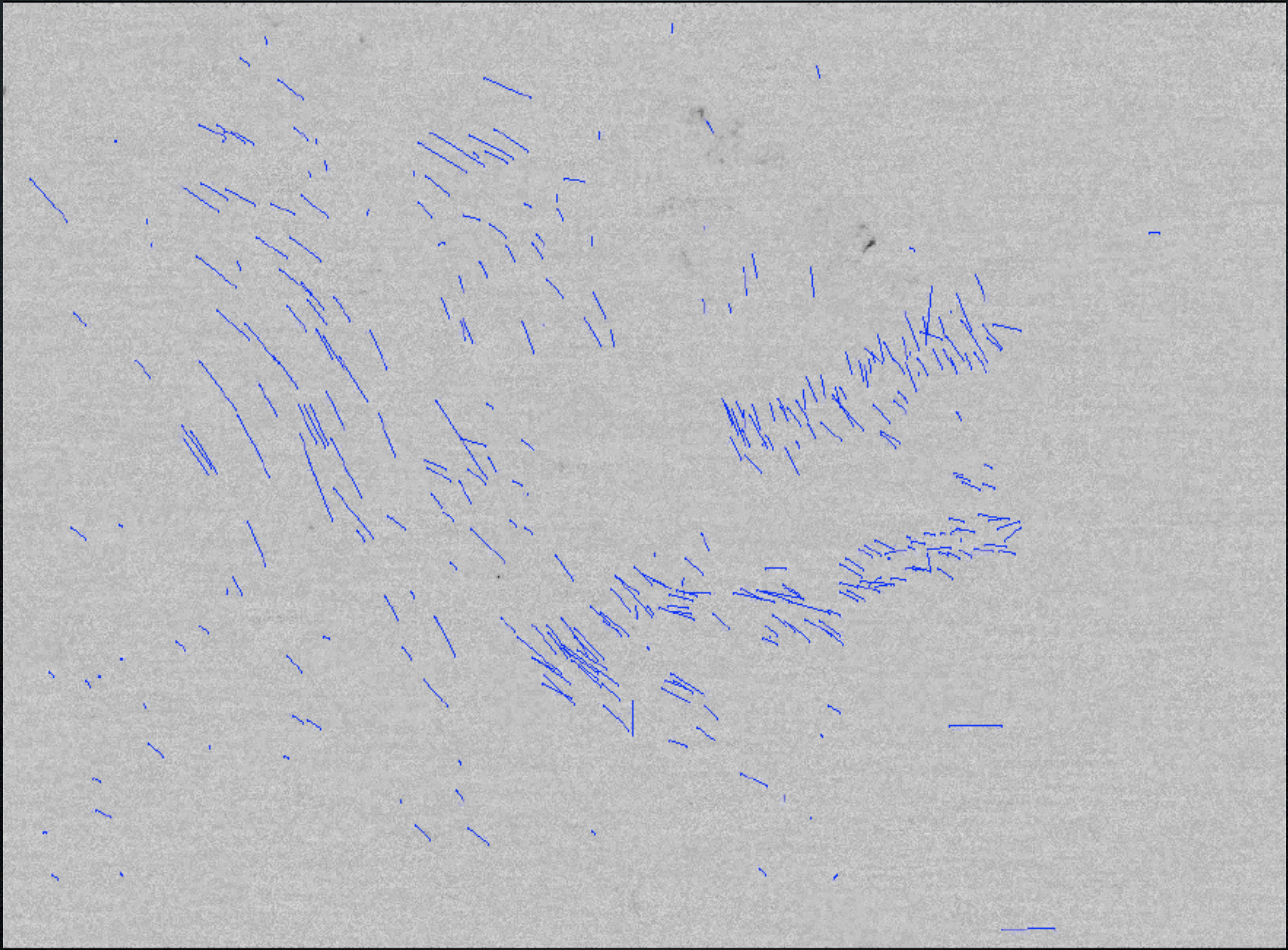
M/Φ = 3

?

Goldsmith, Heyer, Brunt et al. (2007)


"A hole…[where] it appears that some agent has been responsible for dispersing the molecular gas"
Goldsmith, Heyer, Brunt et al. (2007)
$^{13}$CO

# Taurus Molecular Cloud (Brunt/Heyer)



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

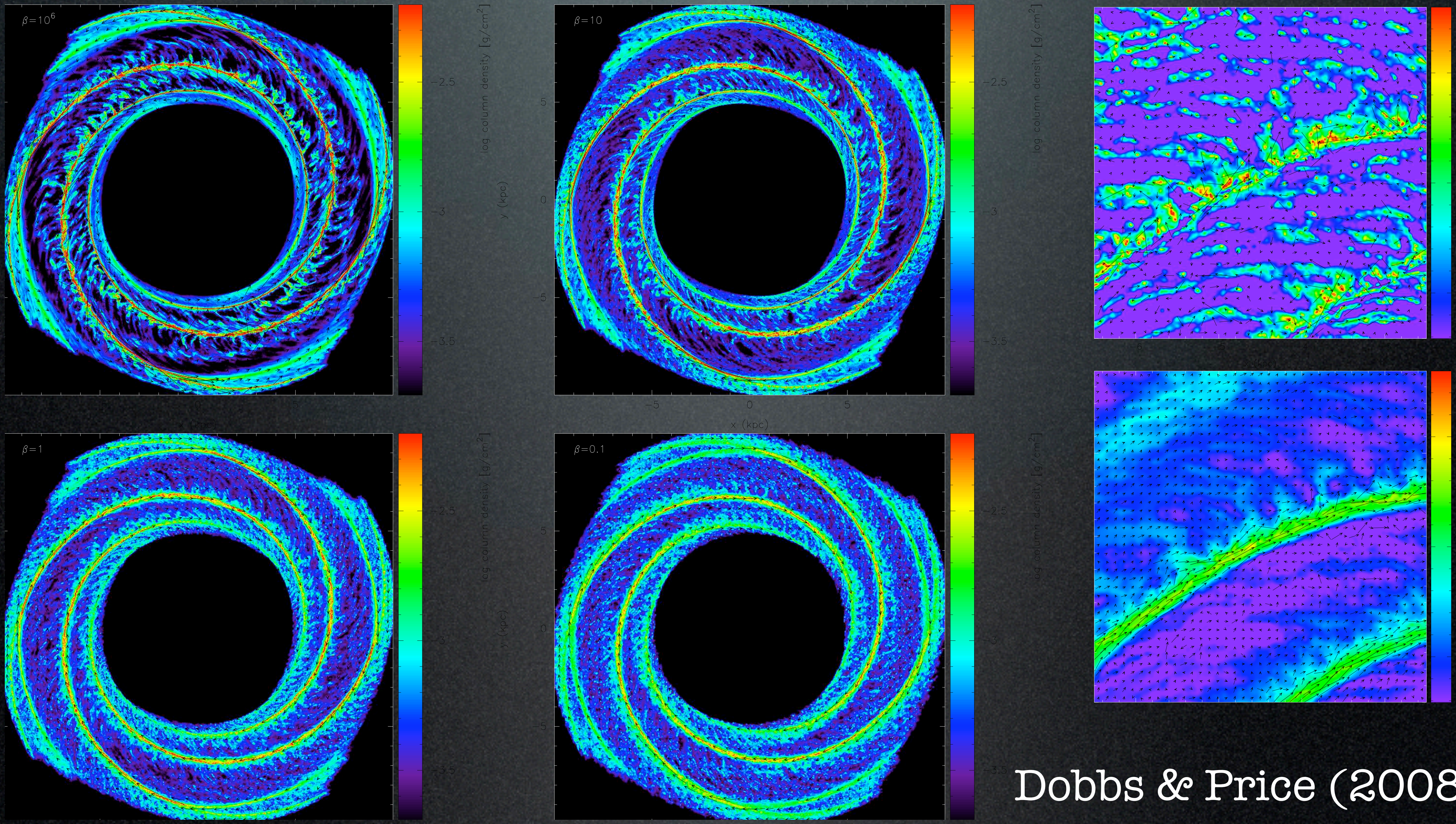
magnetic fields delay and suppress star formation

strongly inhibited accretion, resulting in a lower star formation rate (and efficiency?)

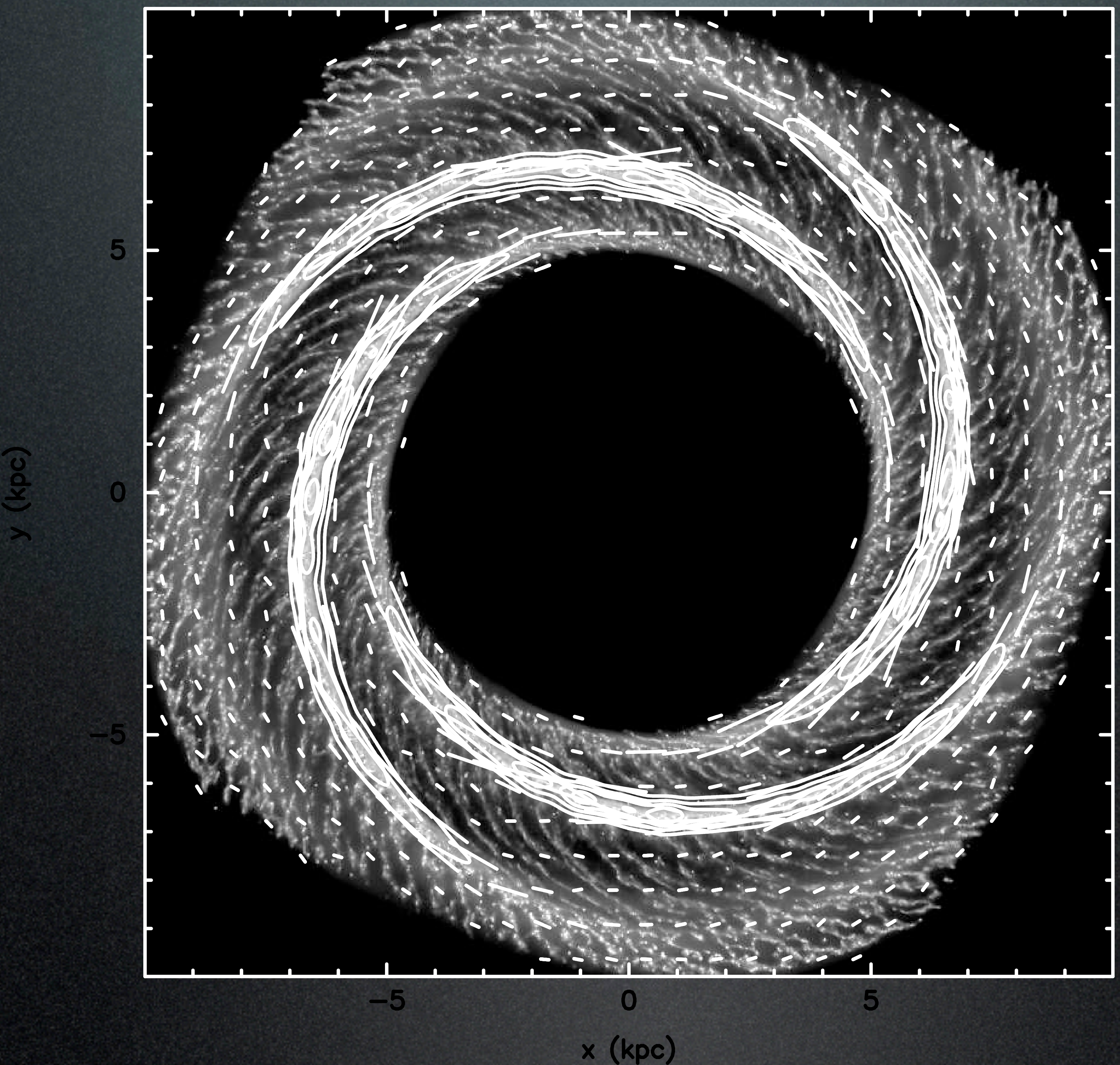
trend towards fewer brown dwarfs with increasing field strength

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

# How do magnetic fields influence the dynamics of the ISM?




Dobbs & Price (2008)


y (kpc)
x (kpc)
5
0
−5