Daniel Price

Royal Society Fellow
University of Exeter, UK

Matthew Bate (Exeter)

“The Cosmic Agitator”, Lexington, KY, March 25-29, 2008

THE ROYAL SOCIETY

PPARC

UNIVERSITY OF EXETER

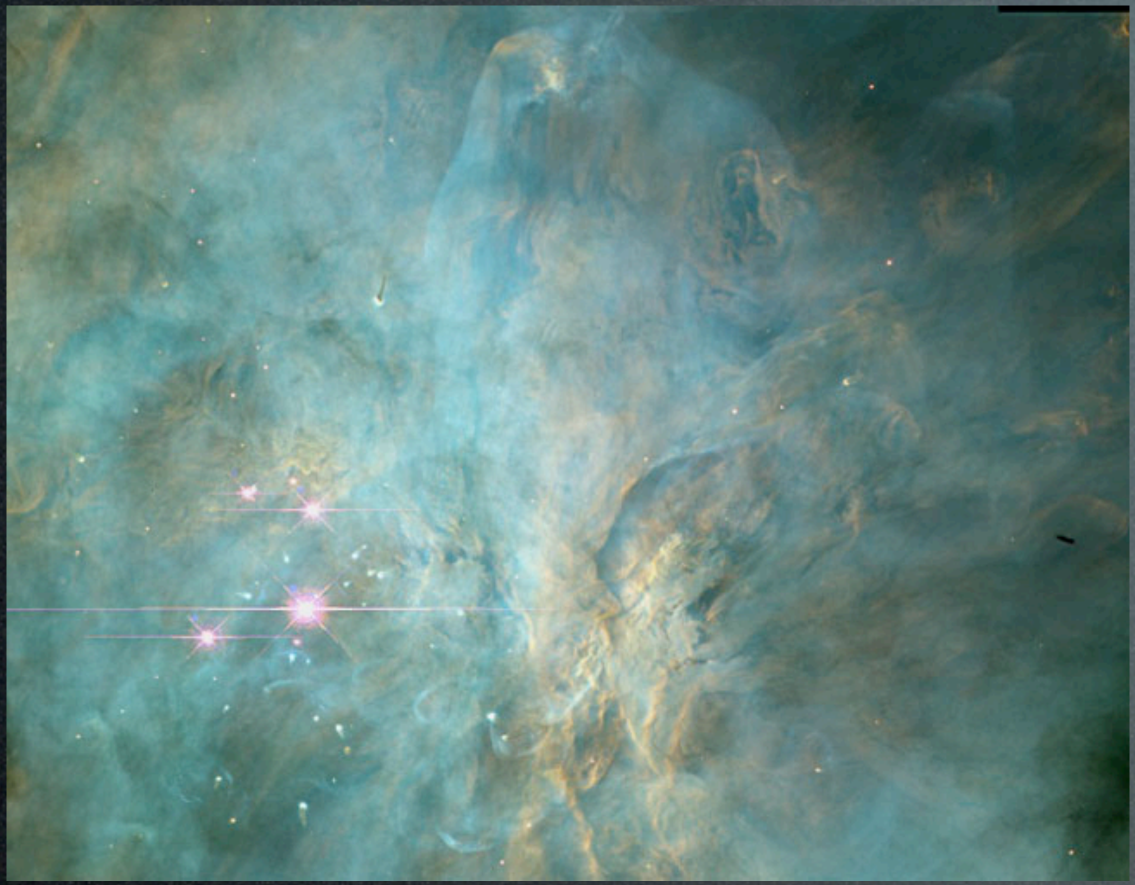
Magnetic fields in star cluster formation

Daniel Price
Royal Society Fellow
University of Exeter, UK

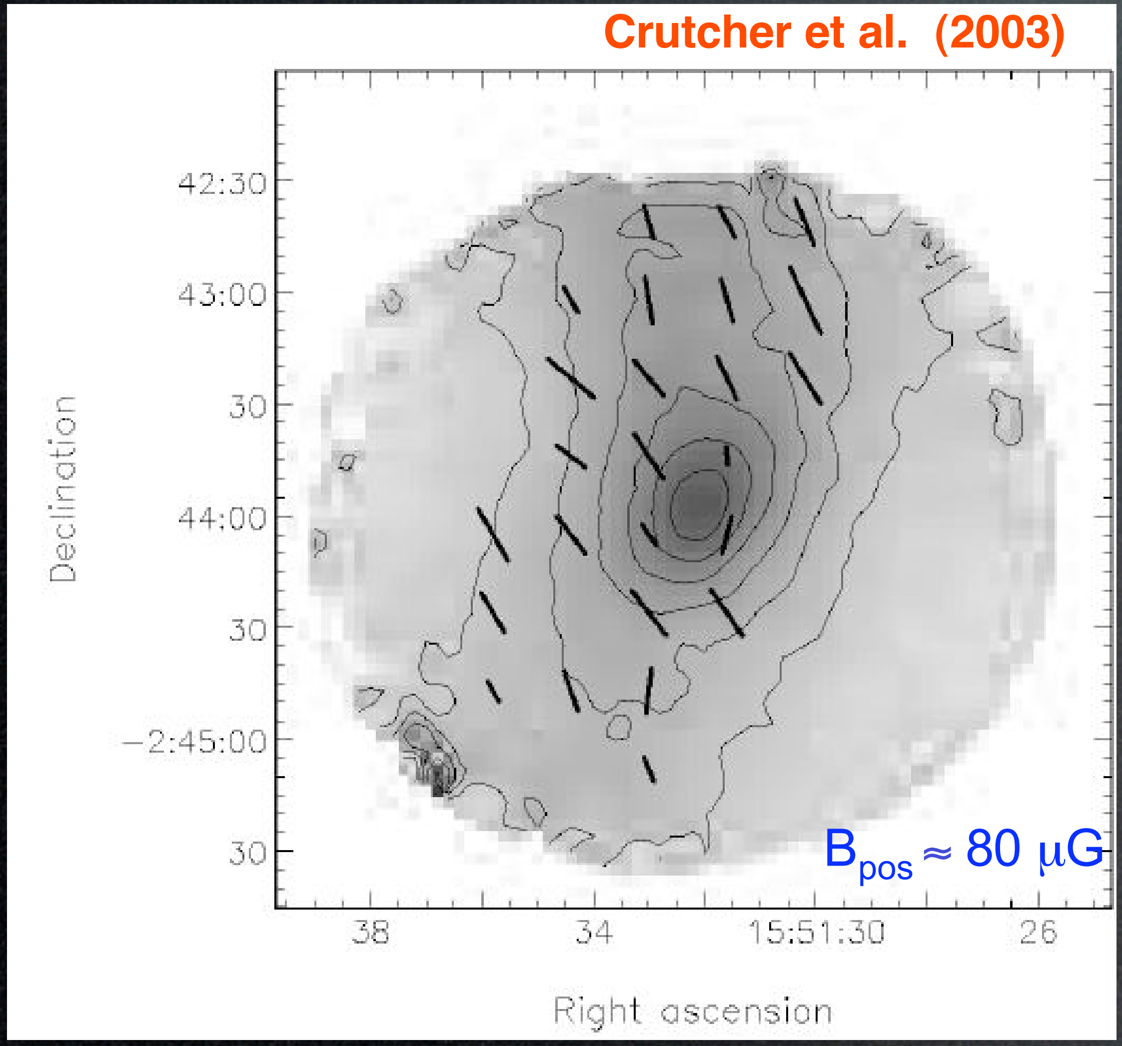
Matthew Bate (Exeter)

“The Cosmic Agitator”, Lexington, KY, March 25-29, 2008

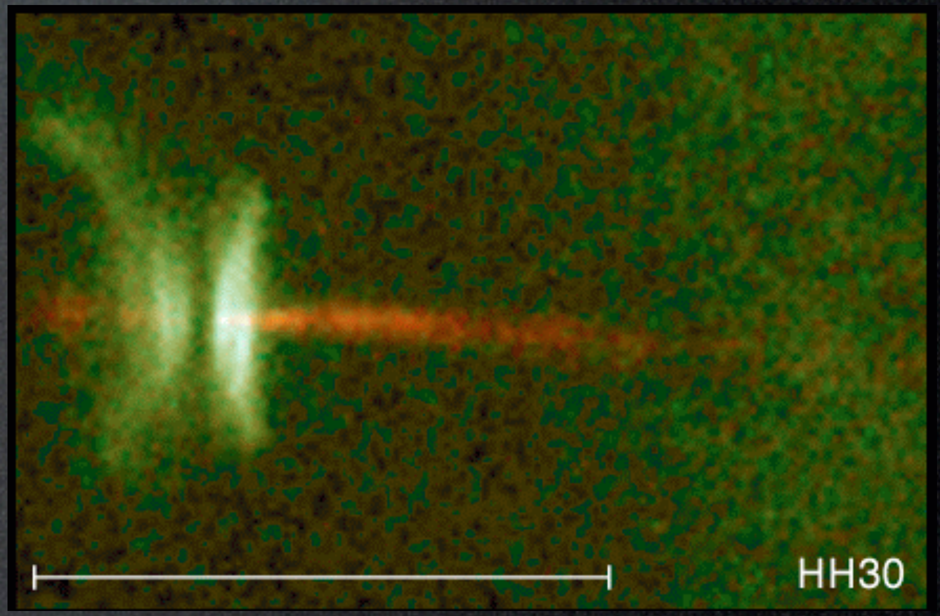
Motivation



Credit: NASA/C.R. O'Dell & S.K.Wong/HST

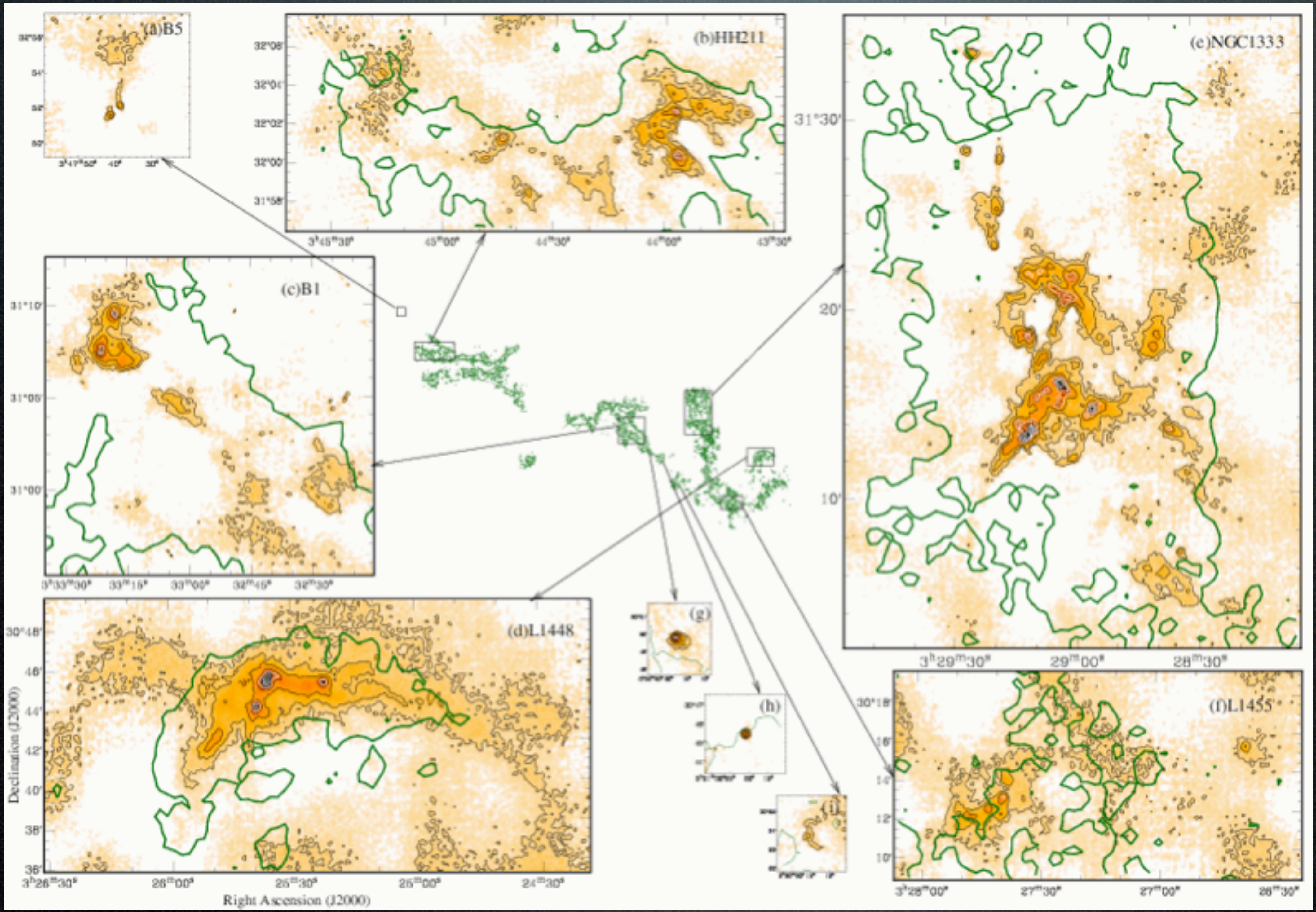


- star formation regions observed to contain magnetic fields of significant strengths
- want to determine their role in the star formation process



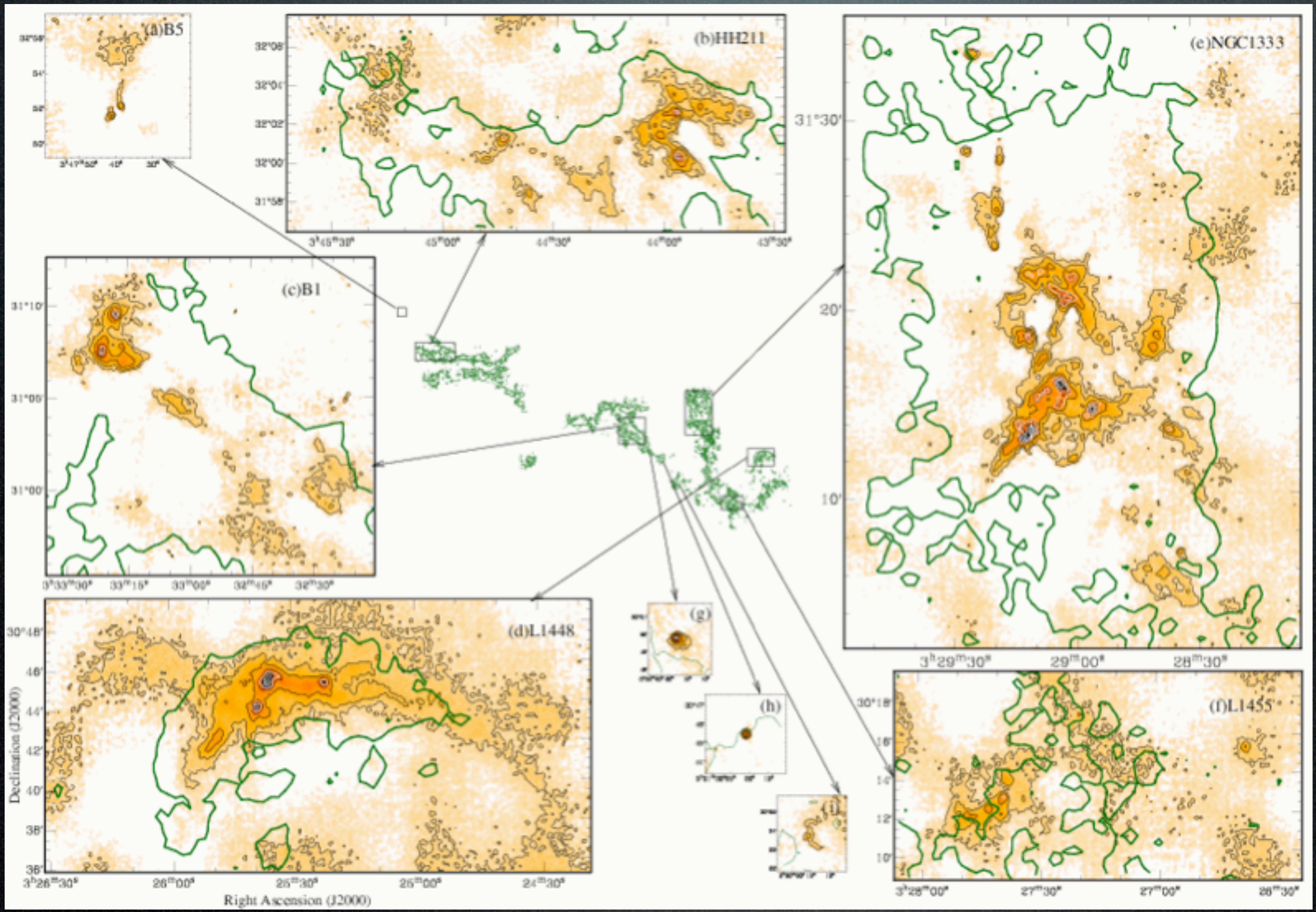
Credit: Burrows/STScI/HST

Star formation is clustered!



Credit: J. Hatchell (Exeter)

Star formation is clustered!

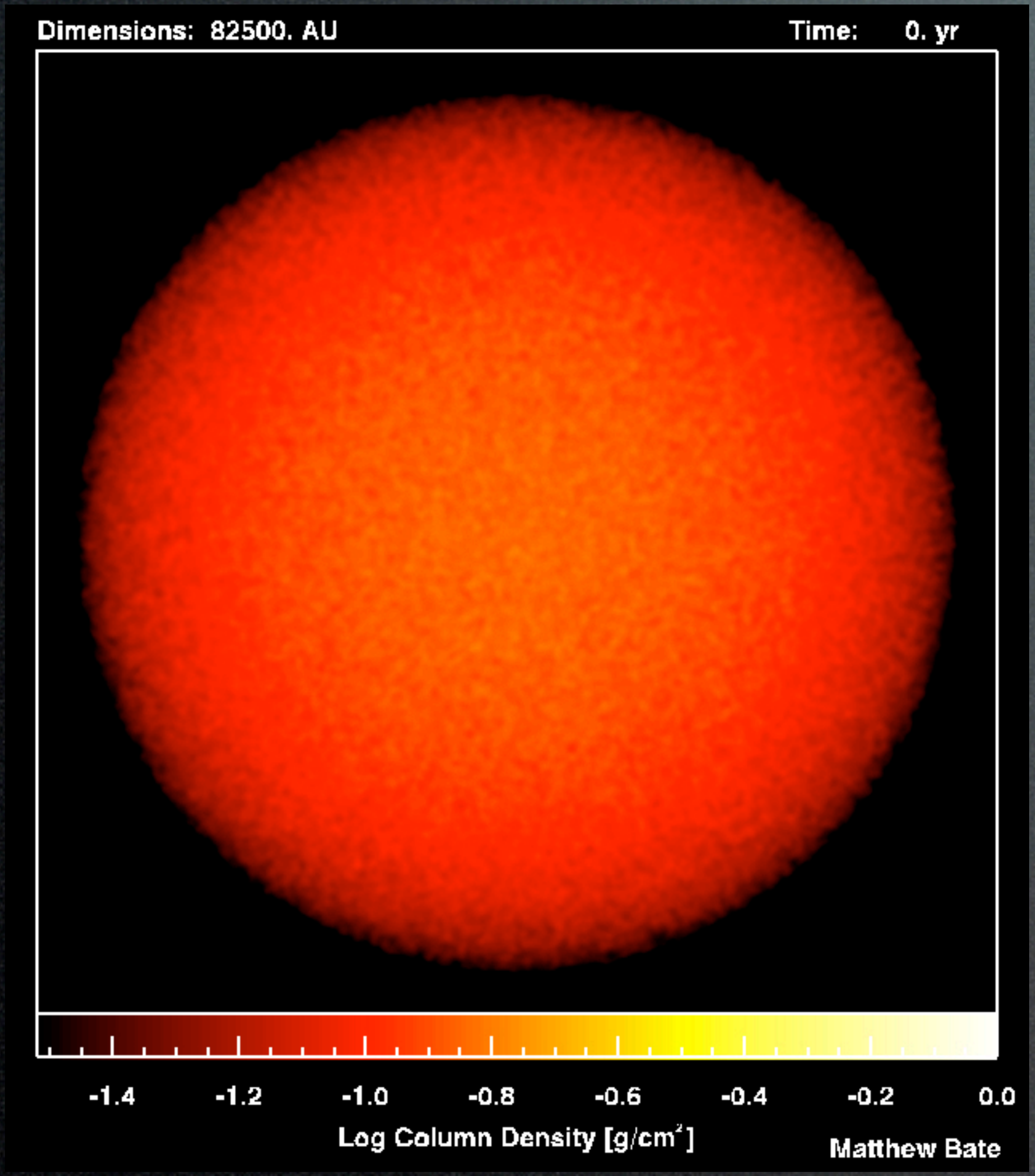


Perseus molecular cloud

Credit: J. Hatchell (Exeter)

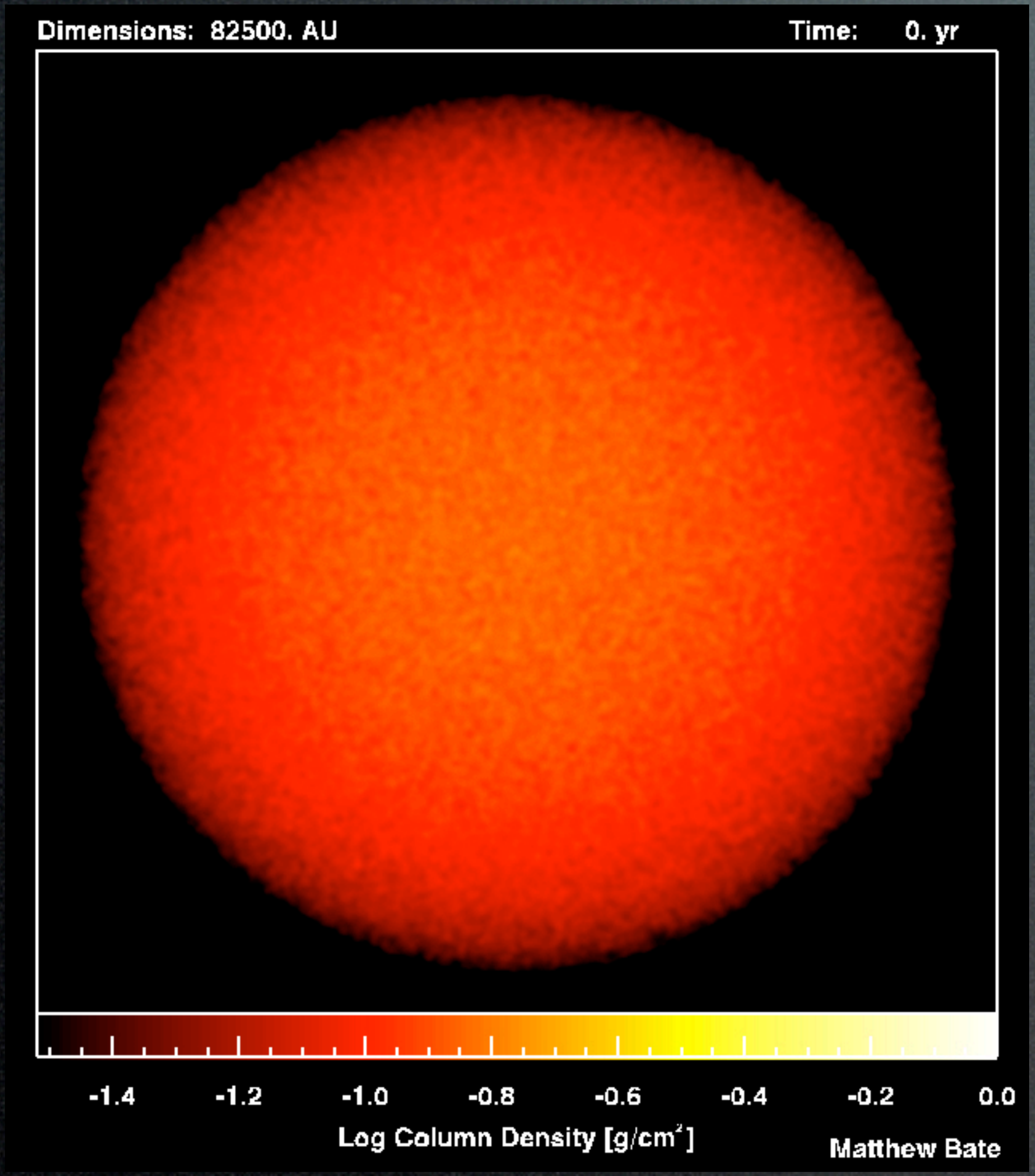
Dynamical models of star formation

e.g. Bate, Bonnell & Bromm (2003), Bonnell, Bate & Vine (2003), Bate & Bonnell (2005)



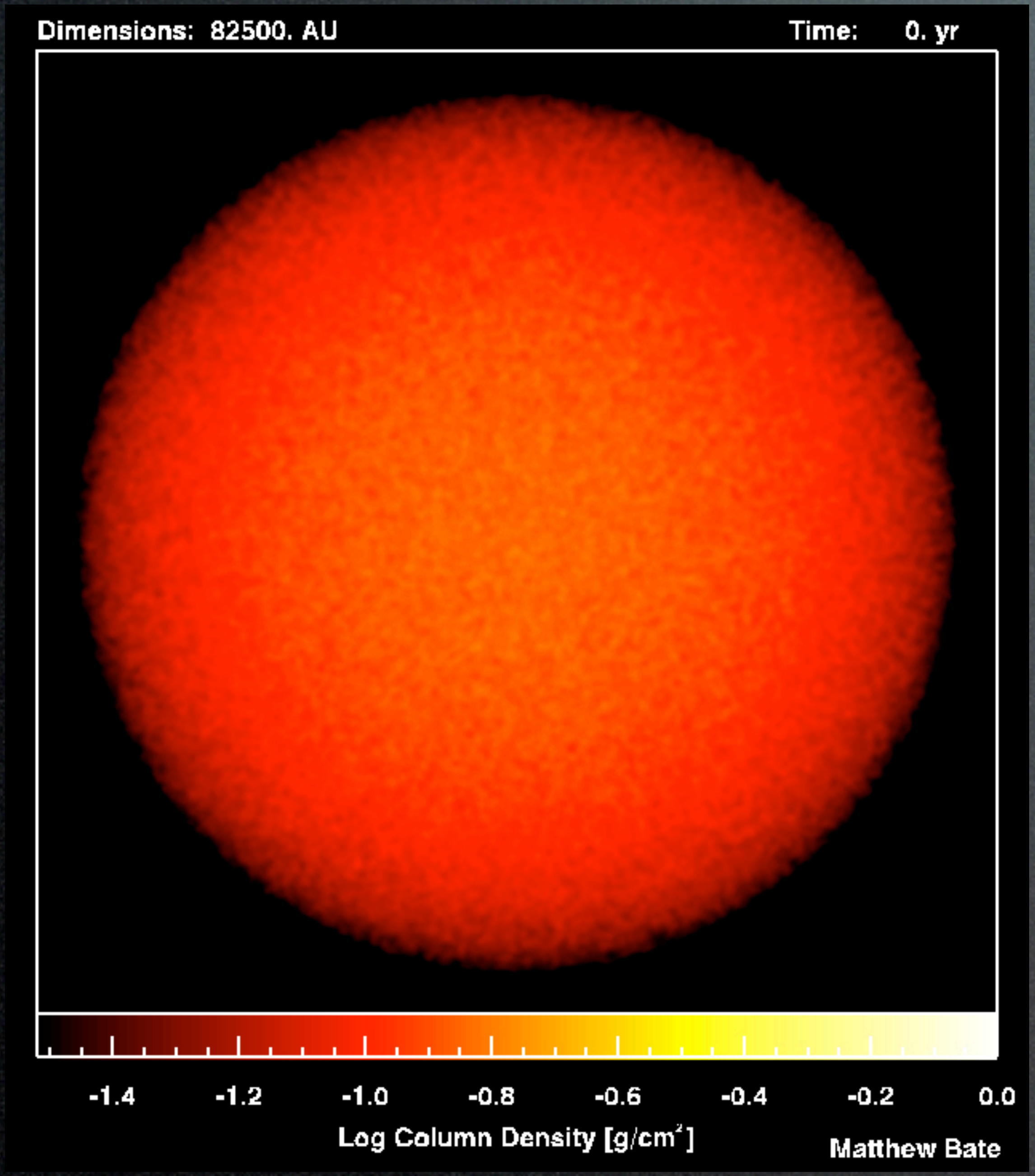
Dynamical models of star formation

e.g. Bate, Bonnell & Bromm (2003), Bonnell, Bate & Vine (2003), Bate & Bonnell (2005)



Dynamical models of star formation

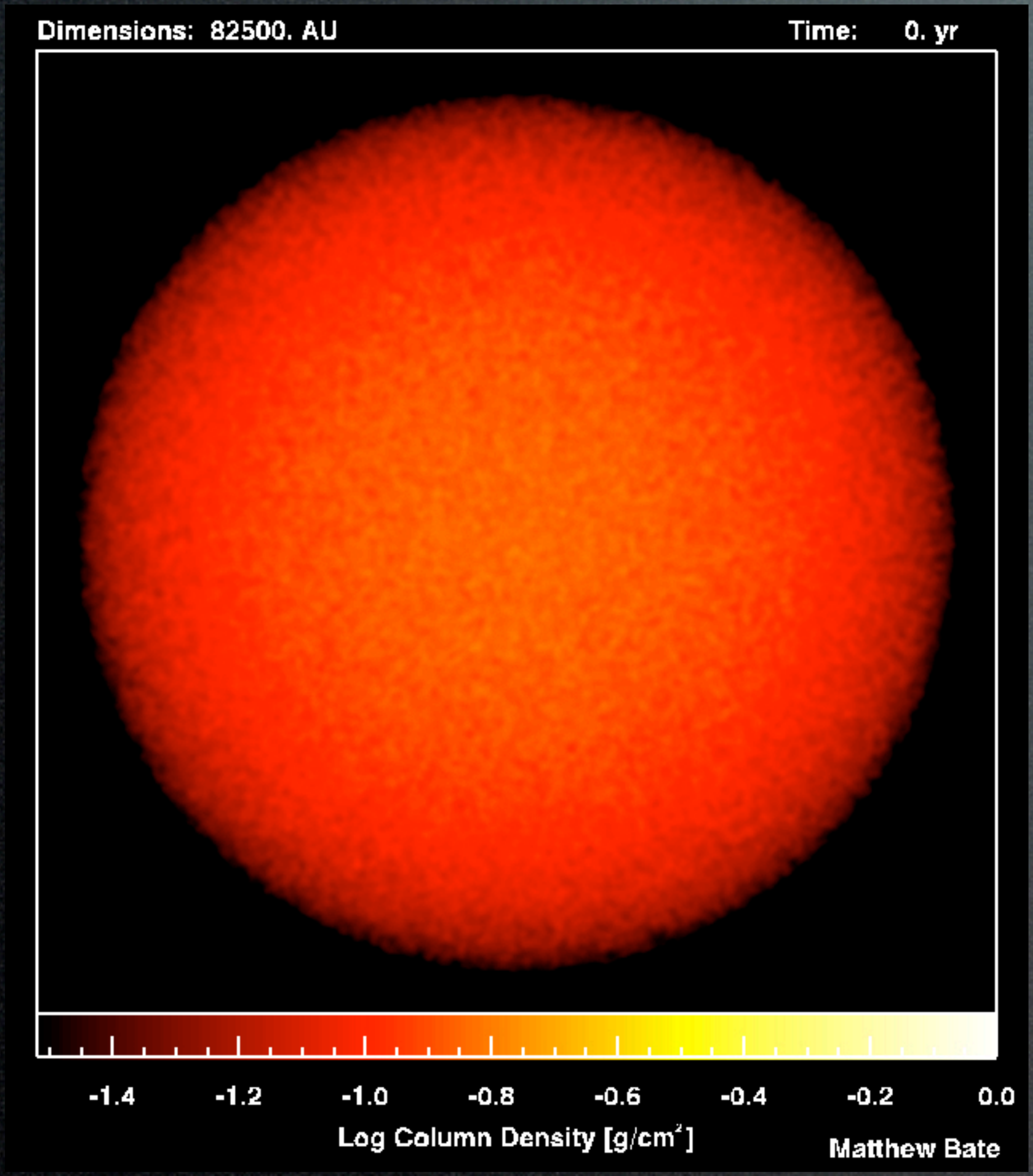
e.g. Bate, Bonnell & Bromm (2003), Bonnell, Bate & Vine (2003), Bate & Bonnell (2005)



- naturally explain multiplicity / binary fraction and clustering of star formation

Dynamical models of star formation

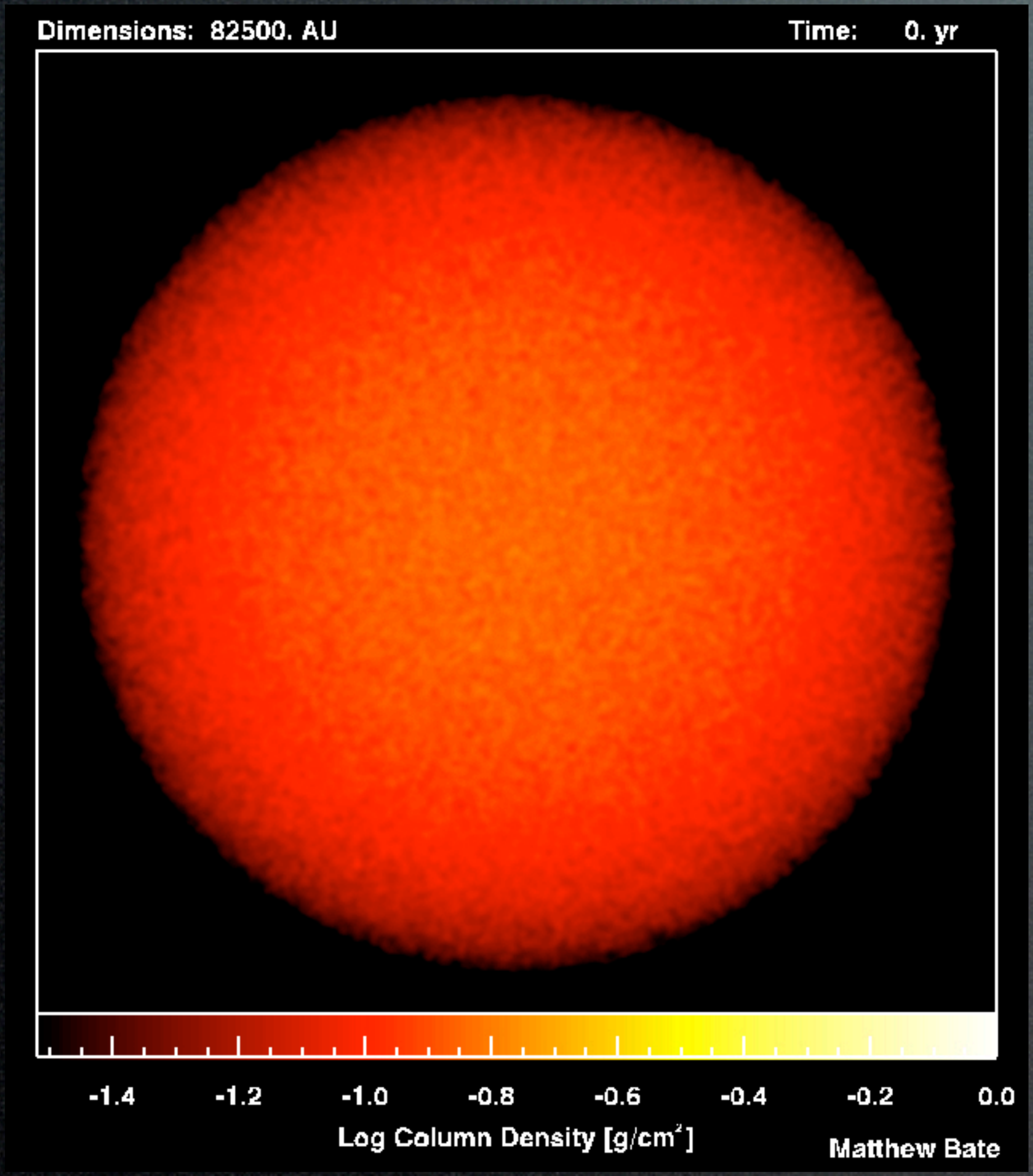
e.g. Bate, Bonnell & Bromm (2003), Bonnell, Bate & Vine (2003), Bate & Bonnell (2005)



- naturally explain multiplicity / binary fraction and clustering of star formation
- reproduce gross characteristics (slope, low mass turnover) of the IMF. Masses determined by "competitive accretion".

Dynamical models of star formation

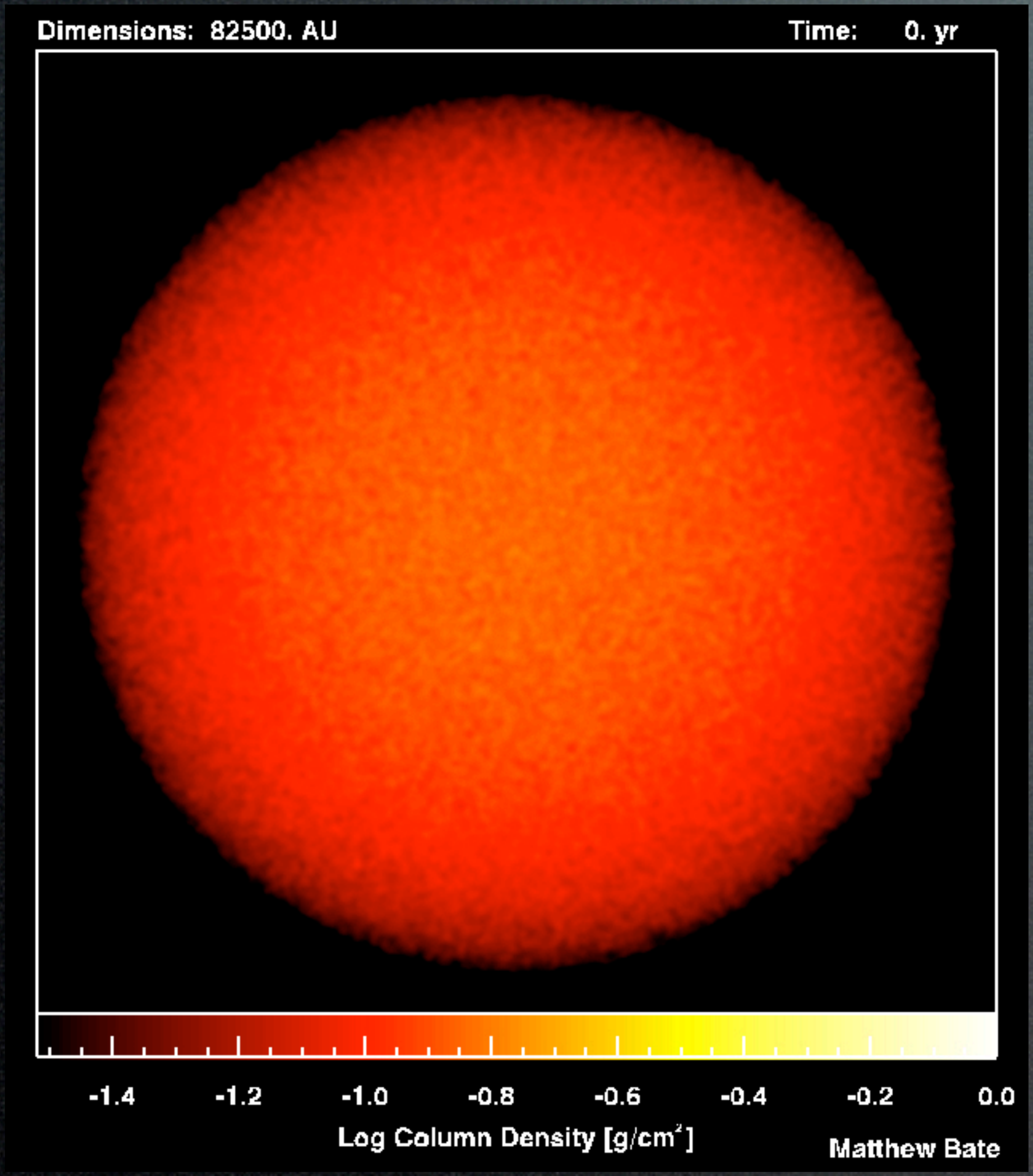
e.g. Bate, Bonnell & Bromm (2003), Bonnell, Bate & Vine (2003), Bate & Bonnell (2005)



- naturally explain multiplicity / binary fraction and clustering of star formation
- reproduce gross characteristics (slope, low mass turnover) of the IMF. Masses determined by "competitive accretion".
- BUT star formation efficiency too high (all gas would eventually form stars).

Dynamical models of star formation

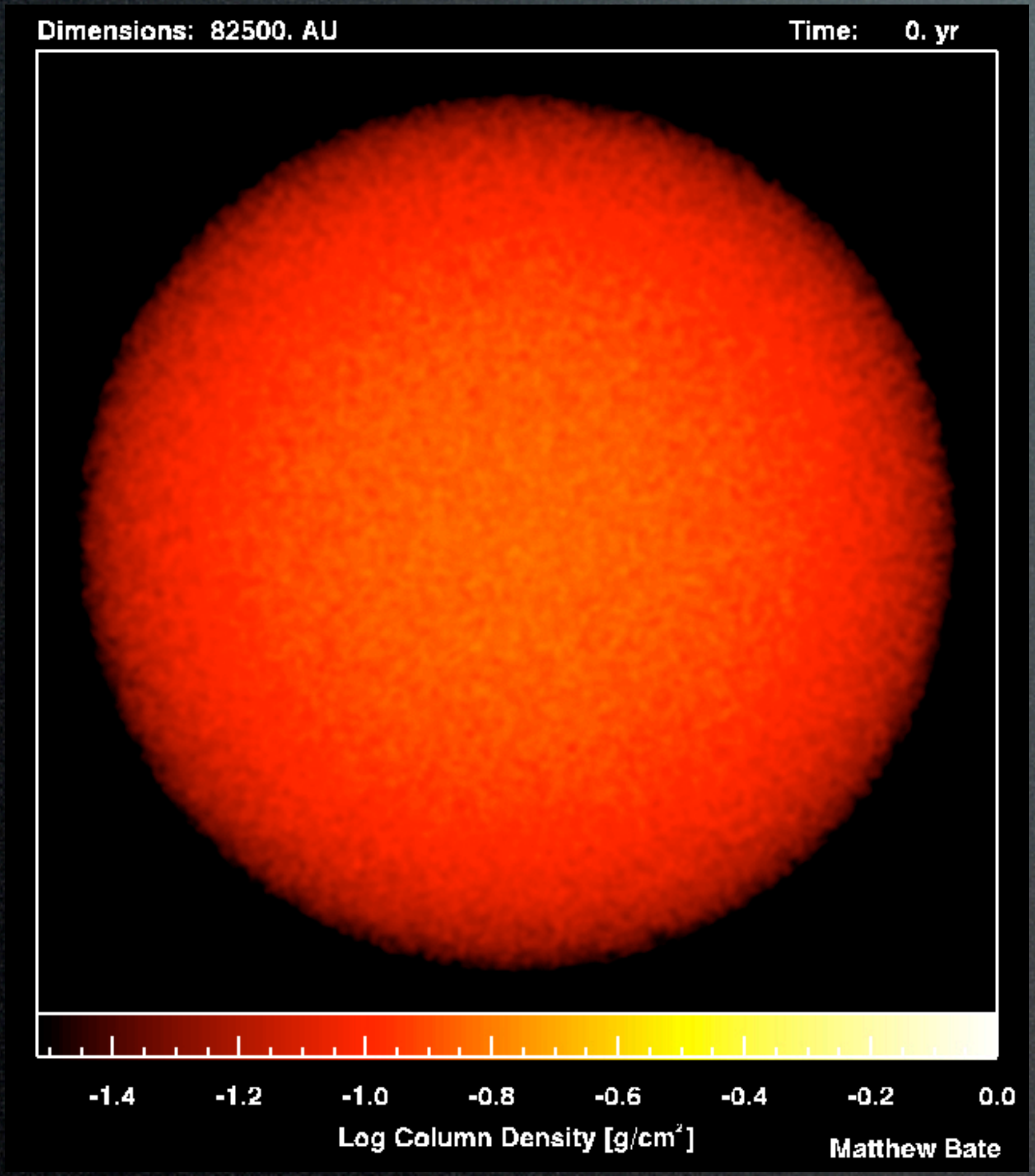
e.g. Bate, Bonnell & Bromm (2003), Bonnell, Bate & Vine (2003), Bate & Bonnell (2005)



- naturally explain multiplicity / binary fraction and clustering of star formation
- reproduce gross characteristics (slope, low mass turnover) of the IMF. Masses determined by "competitive accretion".
- BUT star formation efficiency too high (all gas would eventually form stars).
- produce too many brown dwarfs.

Dynamical models of star formation

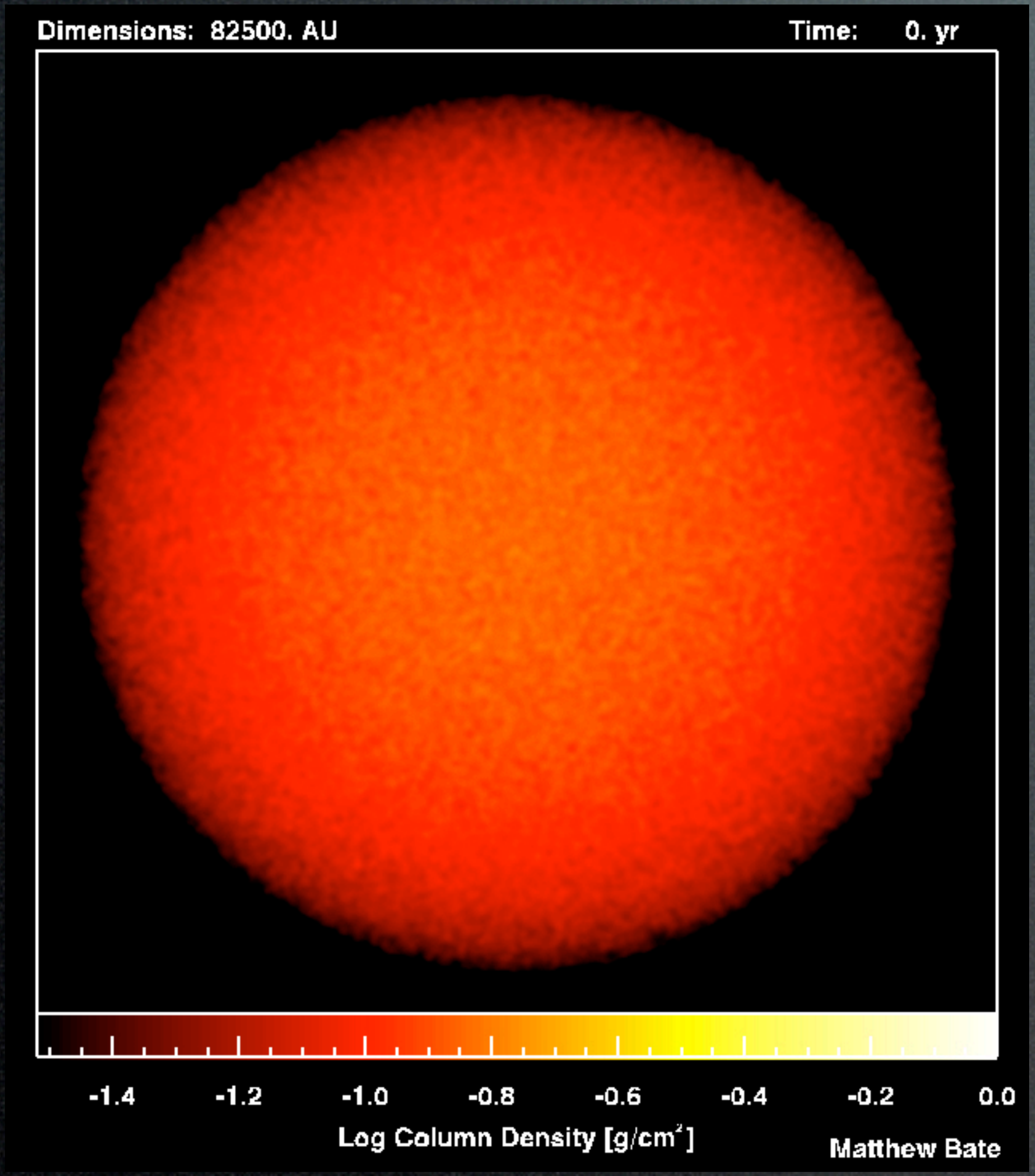
e.g. Bate, Bonnell & Bromm (2003), Bonnell, Bate & Vine (2003),
Bate & Bonnell (2005)



- naturally explain multiplicity / binary fraction and clustering of star formation
- reproduce gross characteristics (slope, low mass turnover) of the IMF. Masses determined by "competitive accretion".
- BUT star formation efficiency too high (all gas would eventually form stars).
- produce too many brown dwarfs.
- discrepancy with molecular cloud lifetimes?

Dynamical models of star formation

e.g. Bate, Bonnell & Bromm (2003), Bonnell, Bate & Vine (2003),
Bate & Bonnell (2005)



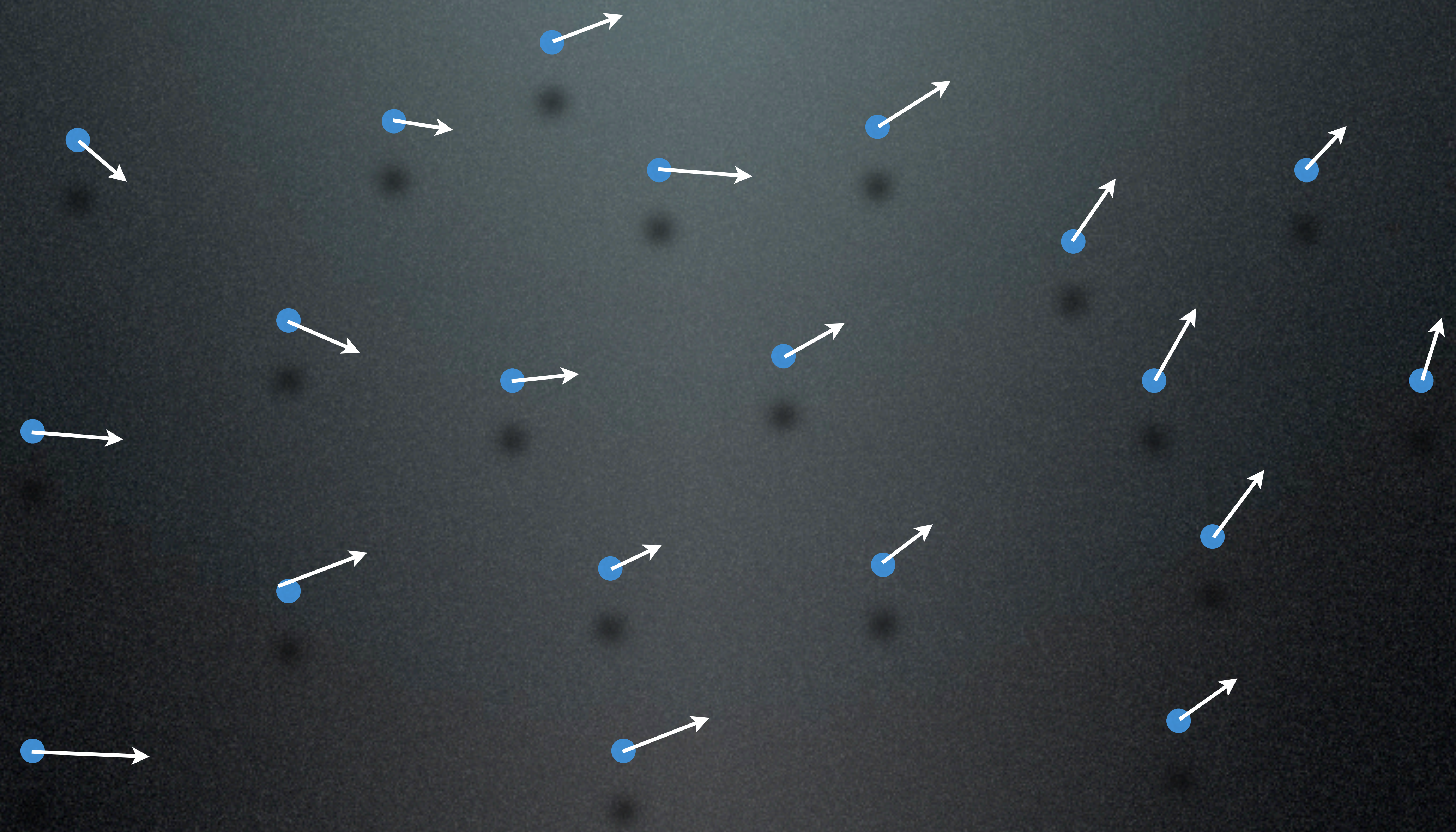
- naturally explain multiplicity / binary fraction and clustering of star formation
- reproduce gross characteristics (slope, low mass turnover) of the IMF. Masses determined by "competitive accretion".
- BUT star formation efficiency too high (all gas would eventually form stars).
- produce too many brown dwarfs.
- discrepancy with molecular cloud lifetimes?
- observations indicate magnetic fields cannot be ignored!

Smoothed Particle (Magneto)hydrodynamics

Gingold & Monaghan (1977), Phillips & Monaghan (1985), Price (2004), Price & Monaghan (2004a,b,2005)

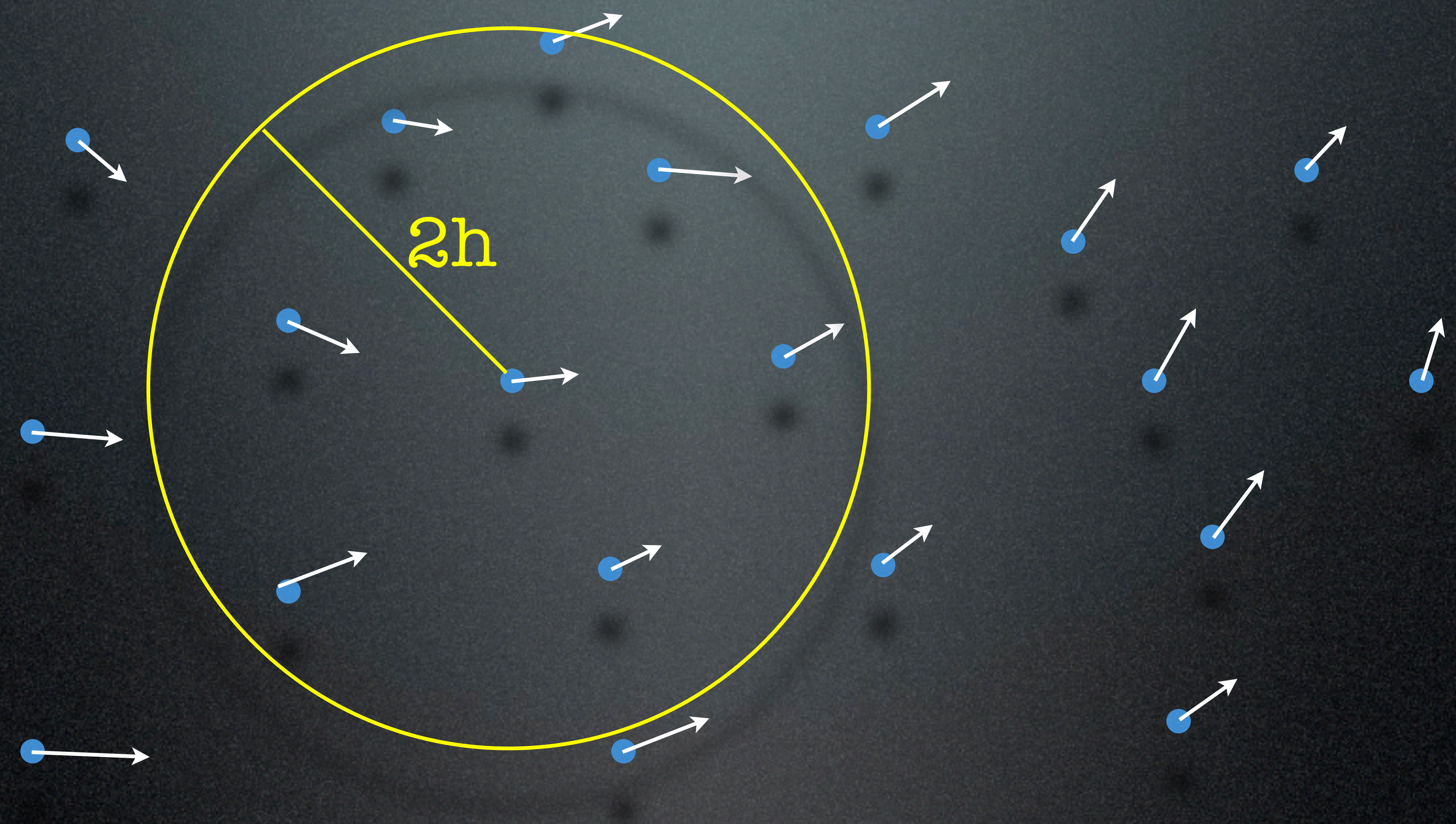
Smoothed Particle (Magneto)hydrodynamics

Gingold & Monaghan (1977), Phillips & Monaghan (1985), Price (2004), Price & Monaghan (2004a,b,2005)



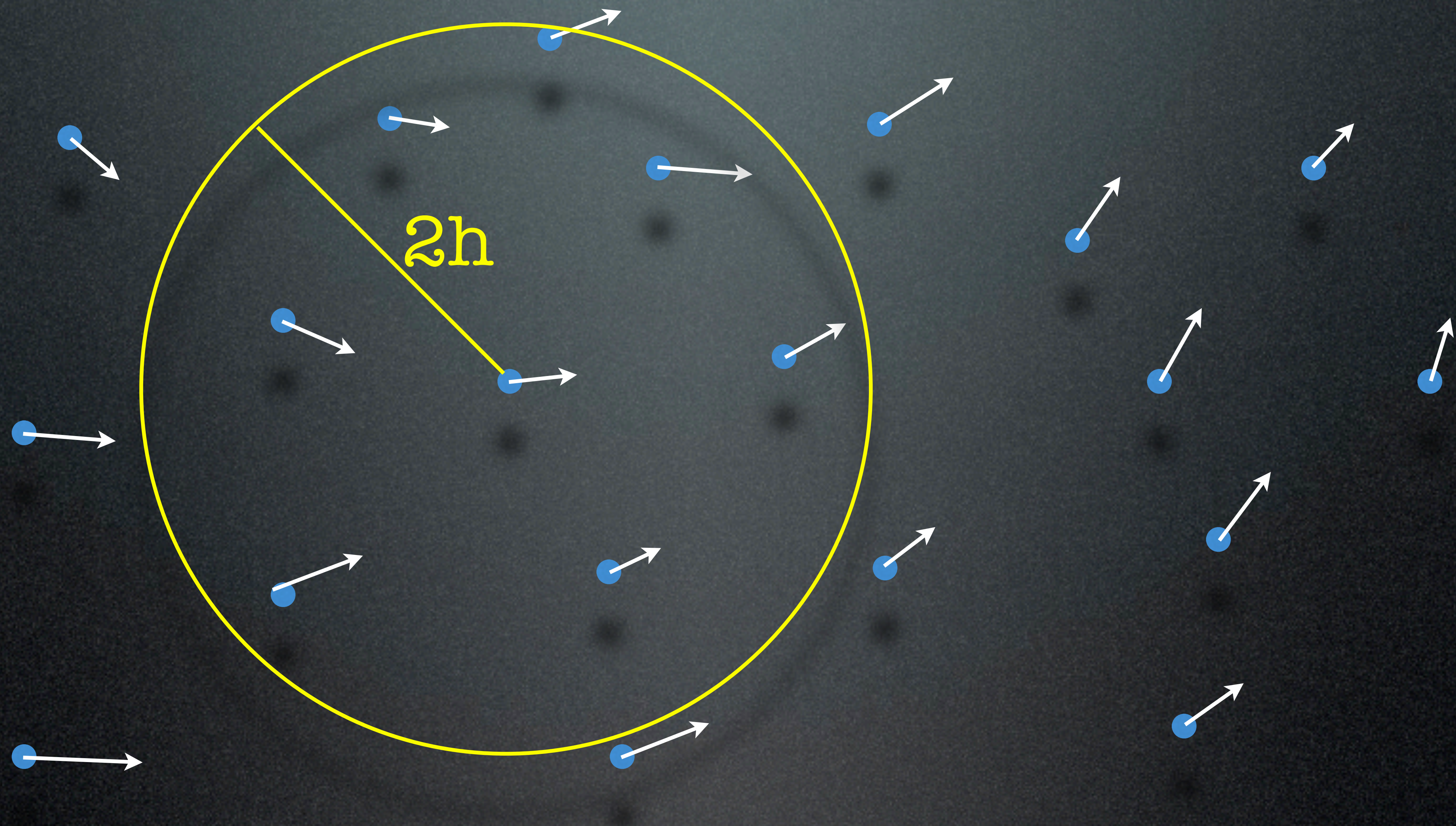
Smoothed Particle (Magneto)hydrodynamics

Gingold & Monaghan (1977), Phillips & Monaghan (1985), Price (2004), Price & Monaghan (2004a,b,2005)



Smoothed Particle (Magneto)hydrodynamics

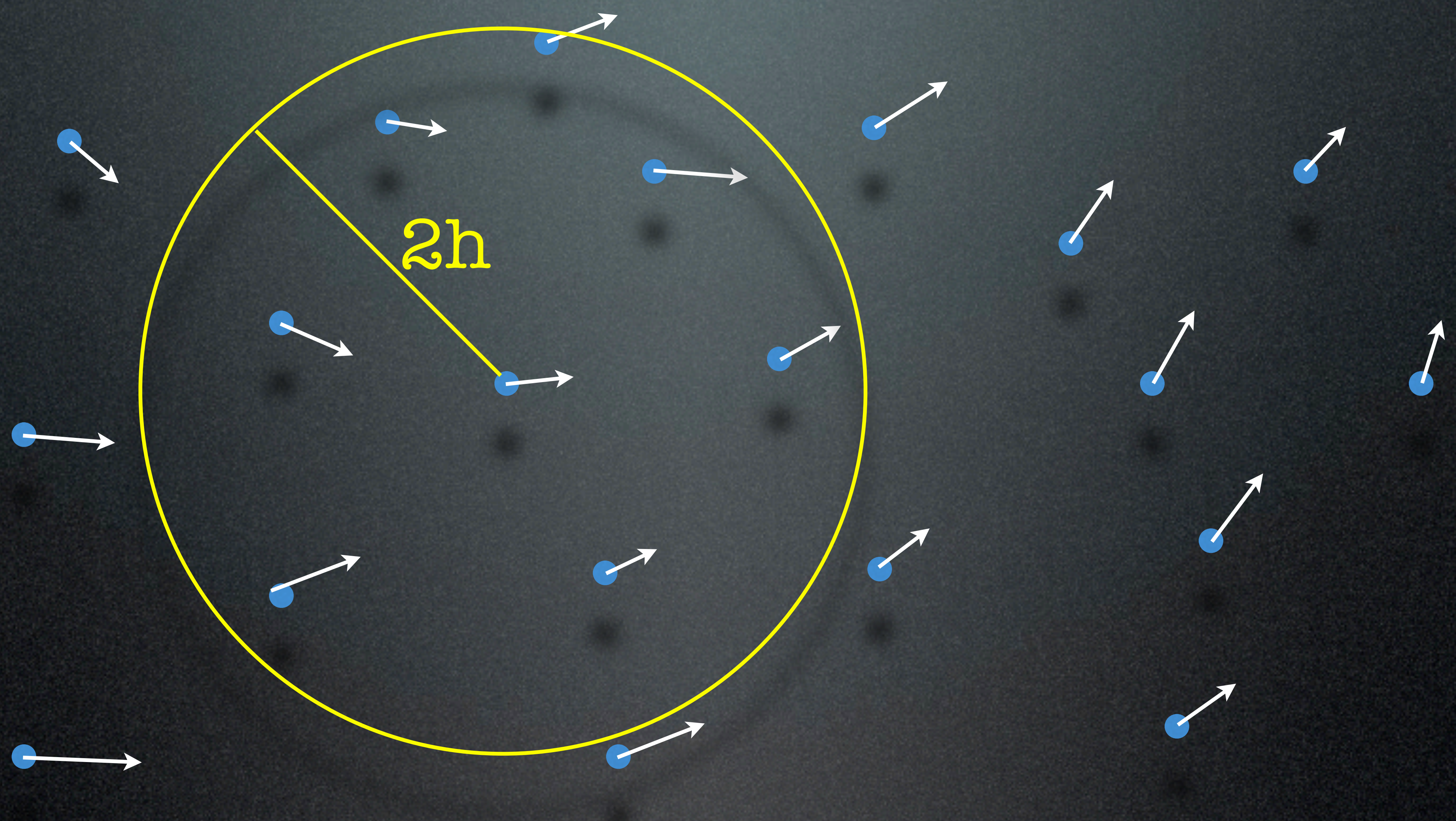
Gingold & Monaghan (1977), Phillips & Monaghan (1985), Price (2004), Price & Monaghan (2004a,b,2005)



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

Smoothed Particle (Magneto)hydrodynamics

Gingold & Monaghan (1977), Phillips & Monaghan (1985), Price (2004), Price & Monaghan (2004a,b,2005)



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

solve the equations of MHD on moving, Lagrangian particles

The $\nabla \bullet B = 0$ constraint

The $\nabla \cdot B = 0$ constraint

- use Euler potentials formulation for the magnetic field

The $\nabla \cdot B = 0$ constraint

- use Euler potentials formulation for the magnetic field

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

The ∇•B = 0 constraint

- use Euler potentials formulation for the magnetic field

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

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

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

- use Euler potentials formulation for the magnetic field

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

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

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

'advection of magnetic field lines by Lagrangian particles'

The $\nabla \cdot B = 0$ constraint

- use Euler potentials formulation for the magnetic field

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

need accurate SPH derivatives (Price 2004)

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

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

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

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

'advection of magnetic field lines by Lagrangian particles'

The ∇•B = 0 constraint

- use Euler potentials formulation for the magnetic field

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

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

need 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 by Lagrangian particles'

add shock dissipation

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

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

The ∇•B = 0 constraint

- use Euler potentials formulation for the magnetic field

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

need accurate SPH derivatives (Price 2004)

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

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

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

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

'advection of magnetic field lines by Lagrangian particles'

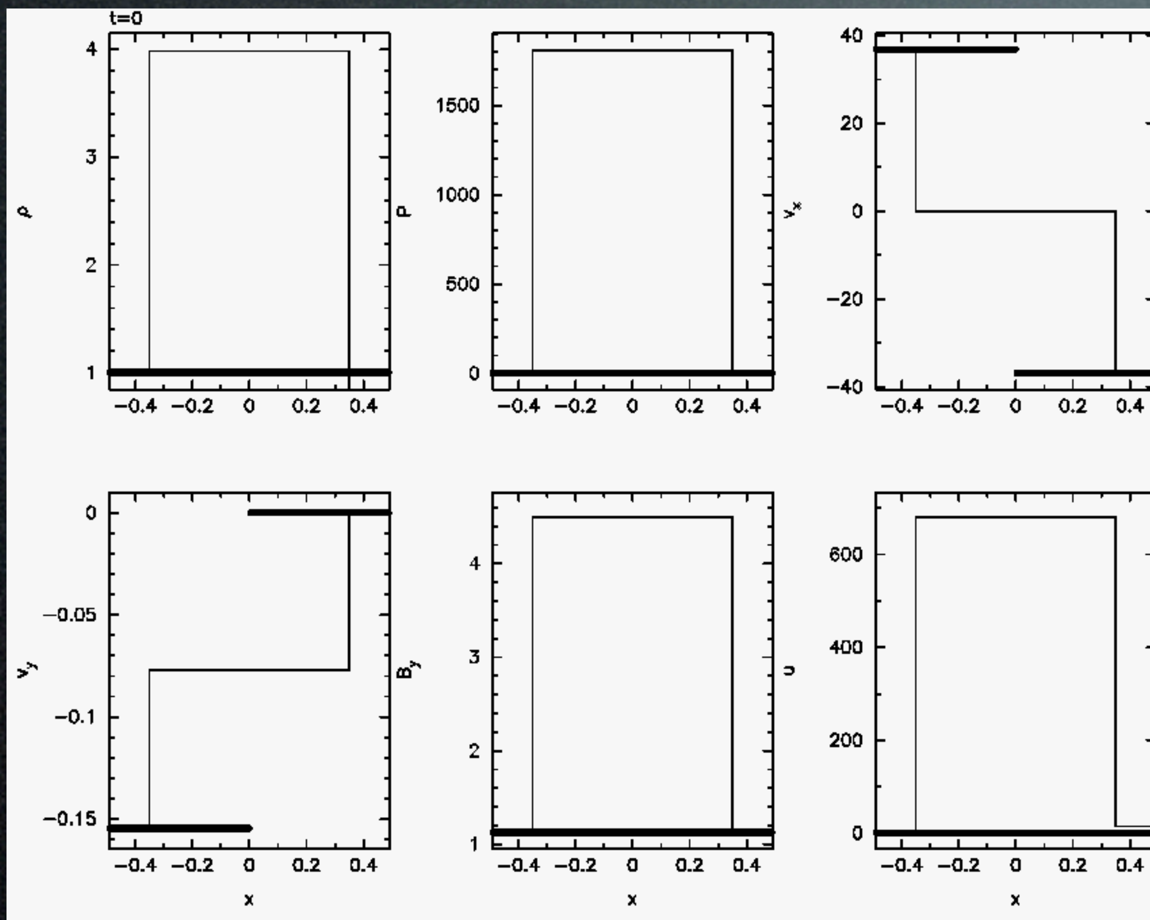
add shock dissipation

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

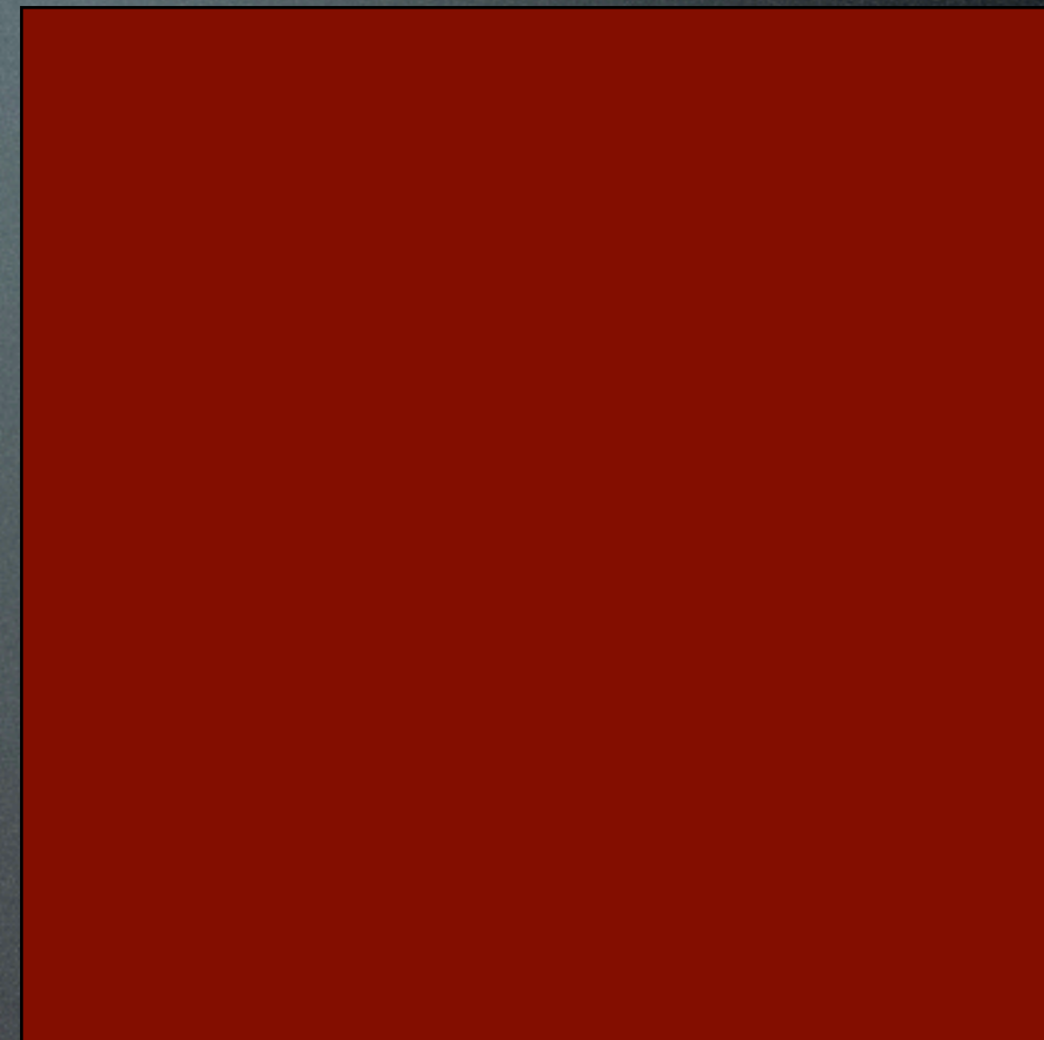
$$\frac{d\beta}{dt} = \sum_b m_b \frac{\alpha_B v_{sig}}{\bar{\rho}_{ab}} (\beta_a - \beta_b)\, \hat{r} \cdot \nabla_a W_{ab}$$

BUT: helicity constraints (A.B = const): cannot represent certain fields. Field growth suppressed once clear mapping from initial to final particle distribution is lost

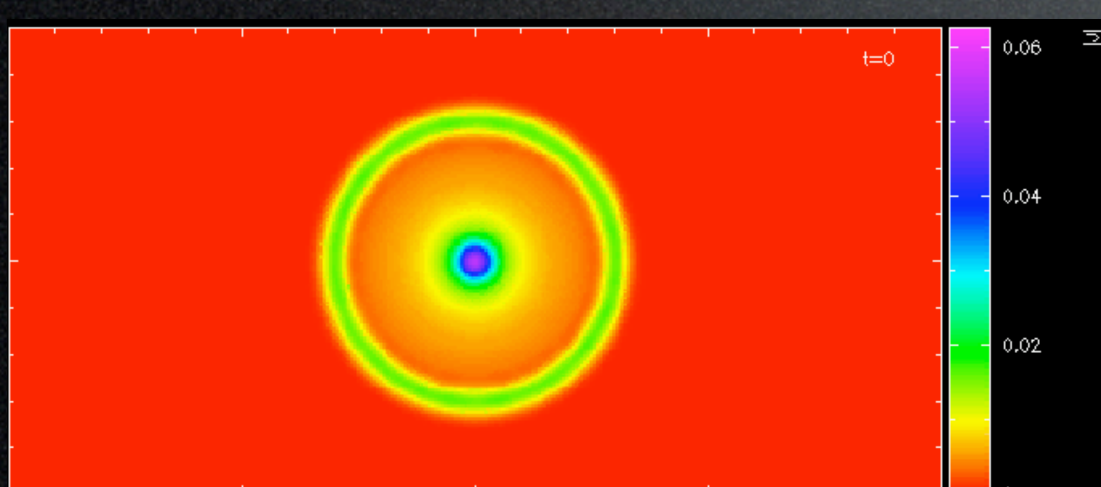
Test problems



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



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



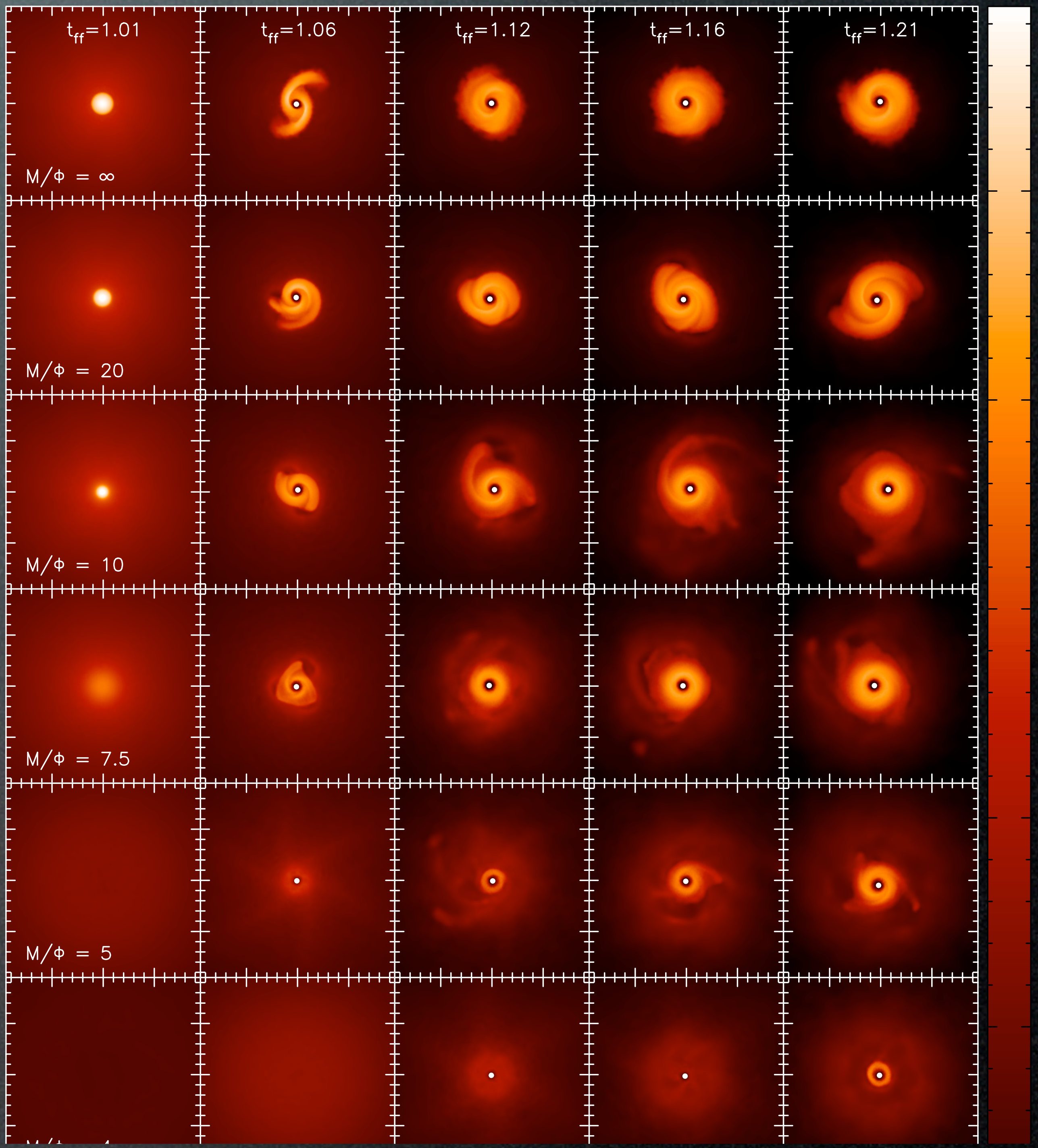
Current loop advection (e.g. Gardiner & Stone 2007)
(Rosswog & Price 2007)

Effect of magnetic fields on single and binary star formation:

Price & Bate (2007), MNRAS 377, 77

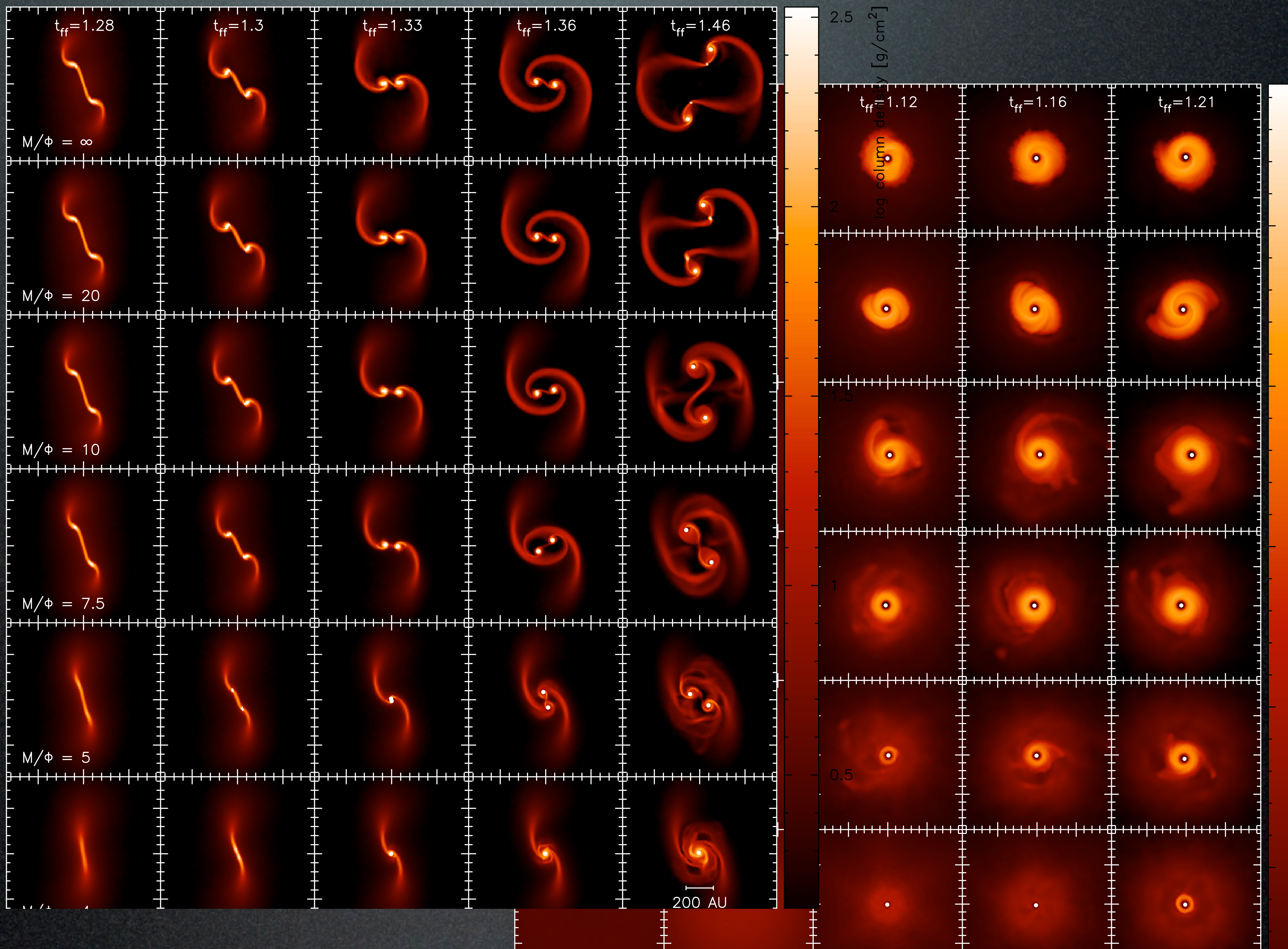
Effect of magnetic fields on single and binary star formation:

Price & Bate (2007), MNRAS 377, 77



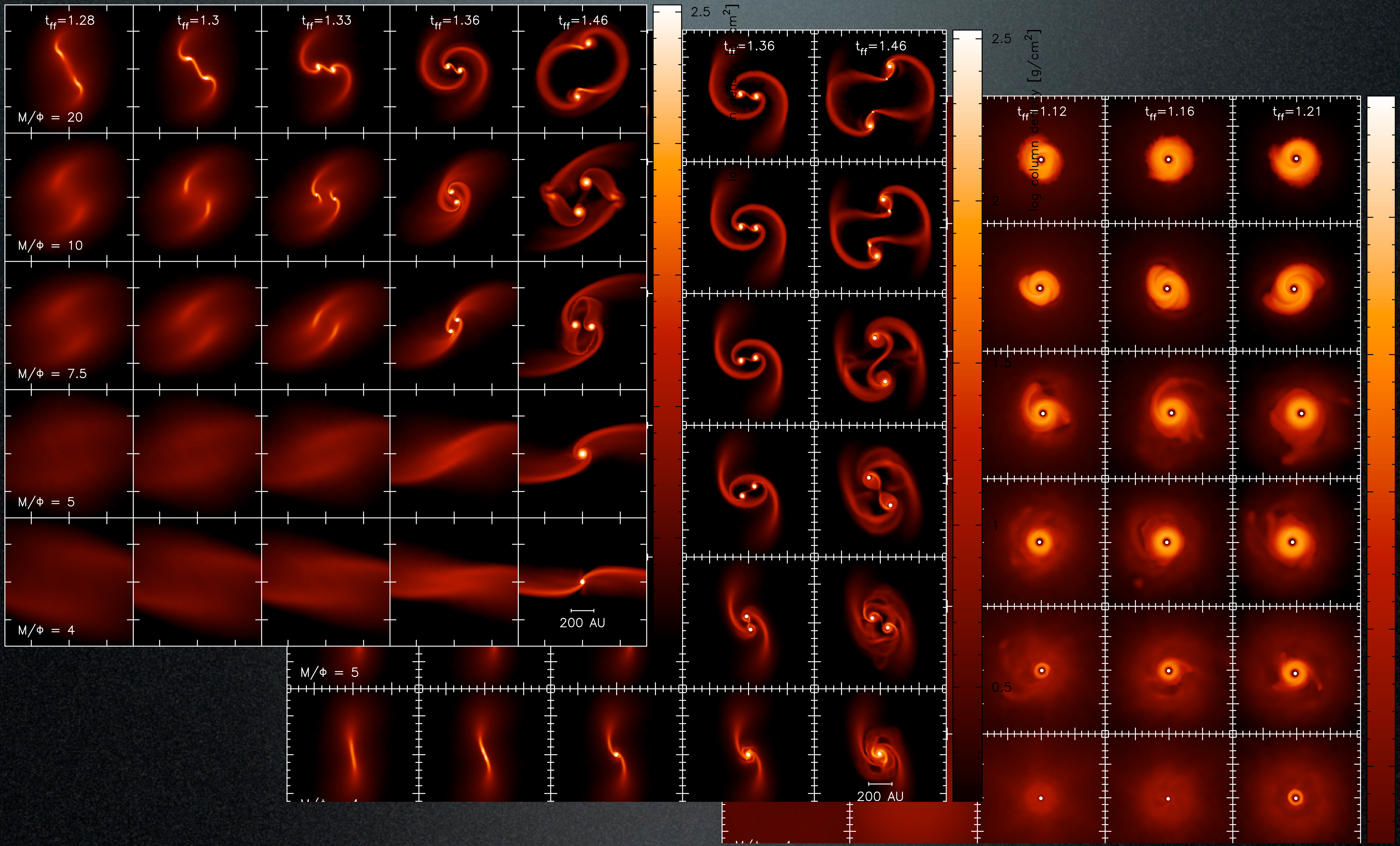
Effect of magnetic fields on single and binary star formation:

Price & Bate (2007), MNRAS 377, 77



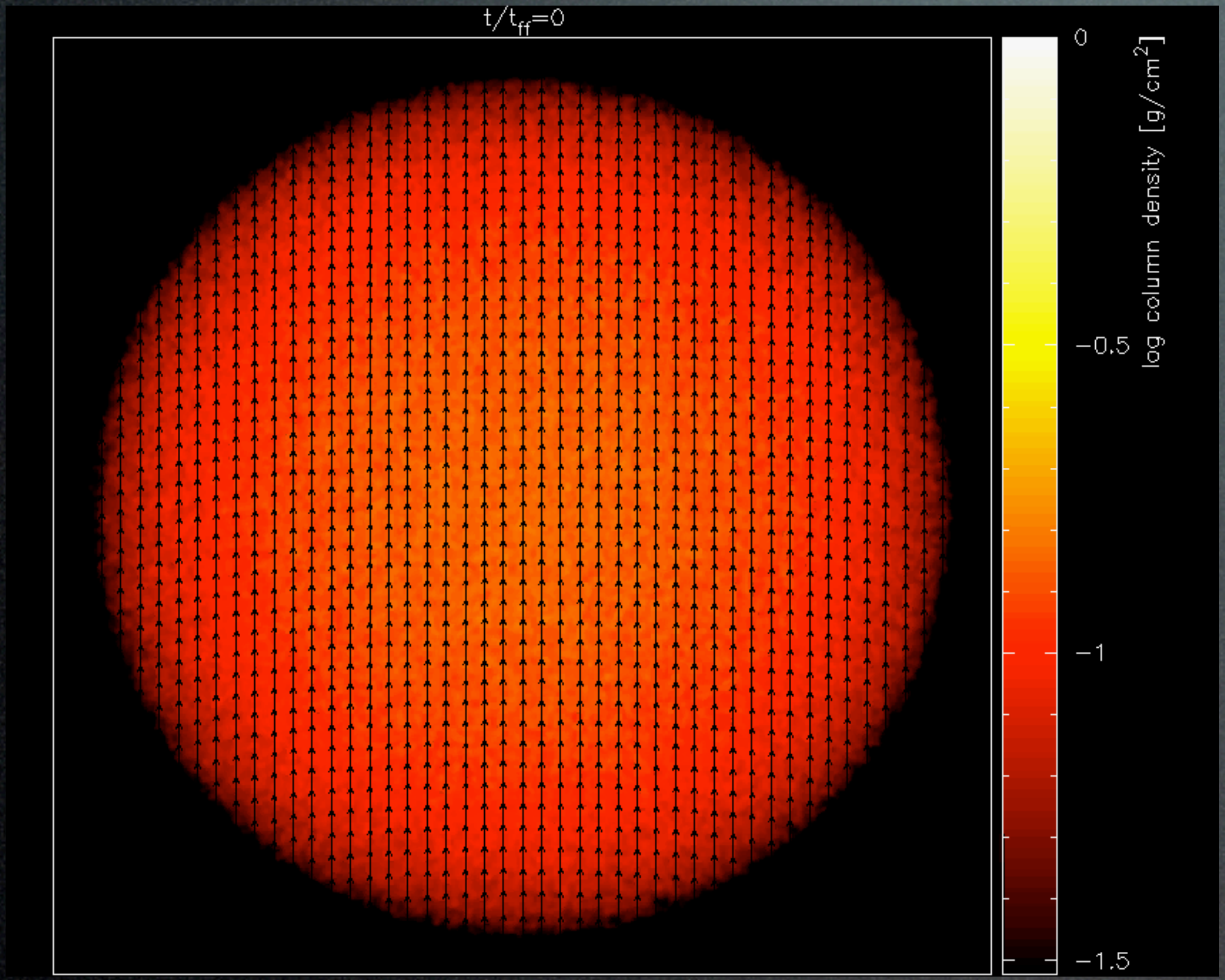
Effect of magnetic fields on single and binary star formation:

Price & Bate (2007), MNRAS 377, 77



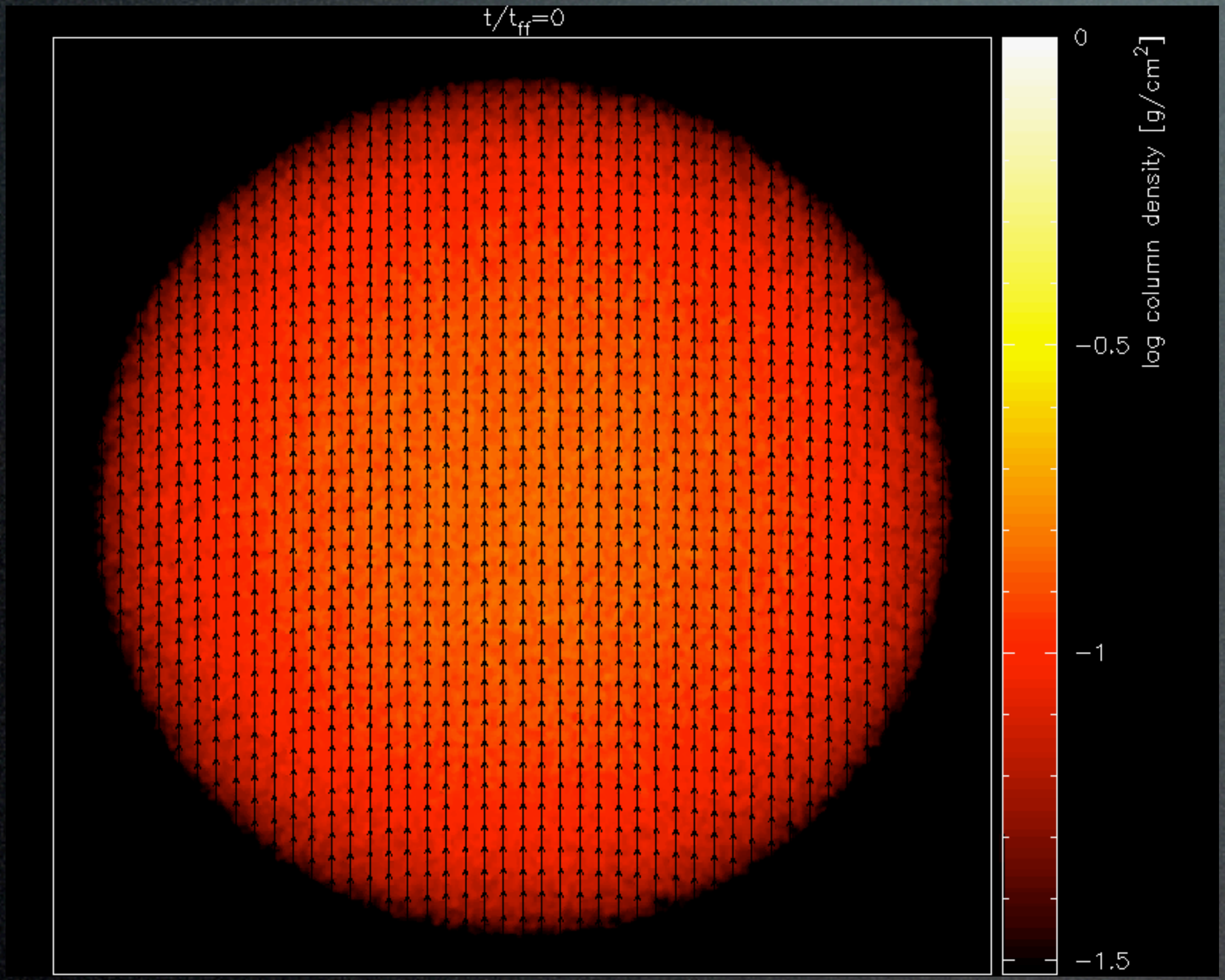
Magnetic fields in star cluster formation

Price & Bate (2008), MNRAS, in press (arXiv:0801.3293)



Magnetic fields in star cluster formation

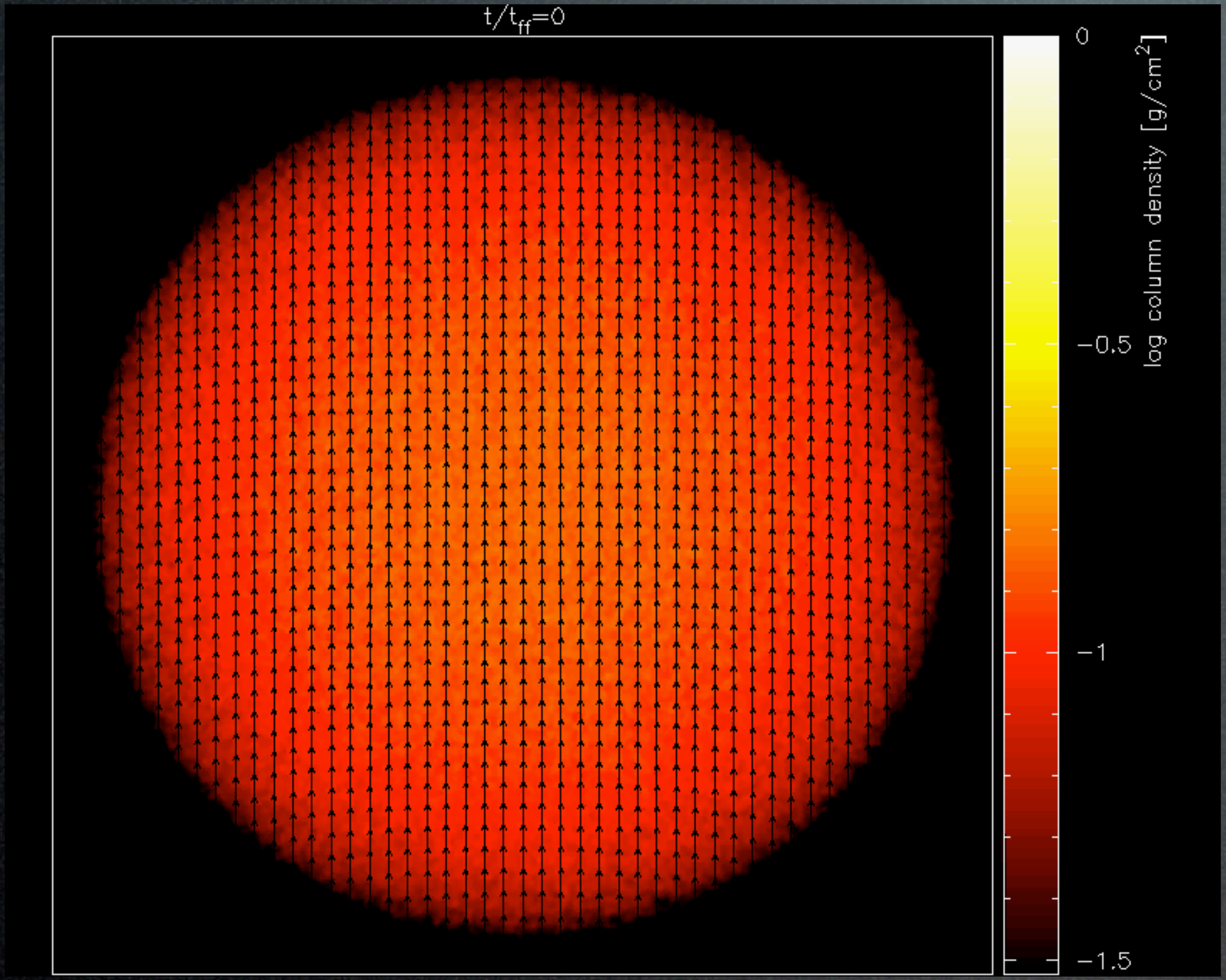
Price & Bate (2008), MNRAS, in press (arXiv:0801.3293)



- 50 solar mass cloud
- diameter 0.375 pc, n_{H2} = 3.7 x 10^4 cm^{-3}
- initial uniform B field
- T ~10K
- turbulent velocity field $P(k) \propto k^{-4}$
- RMS Mach number 6.7
- barytropic equation of state
- form sink particles at 10^{-11} g cm^{-3}

Magnetic fields in star cluster formation

Price & Bate (2008), MNRAS, in press (arXiv:0801.3293)



- 50 solar mass cloud
- diameter 0.375 pc, n_{H2} = 3.7 x 10^4 cm^{-3}
- initial uniform B field
- T ~10K
- turbulent velocity field $P(k) \propto k^{-4}$
- RMS Mach number 6.7
- barytropic equation of state
- form sink particles at 10^{-11} g cm^{-3}

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

Important parameters

Important parameters

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

magnetic field vs gravity

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

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

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

these parameters are independent!

Important parameters

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

magnetic field vs gravity

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

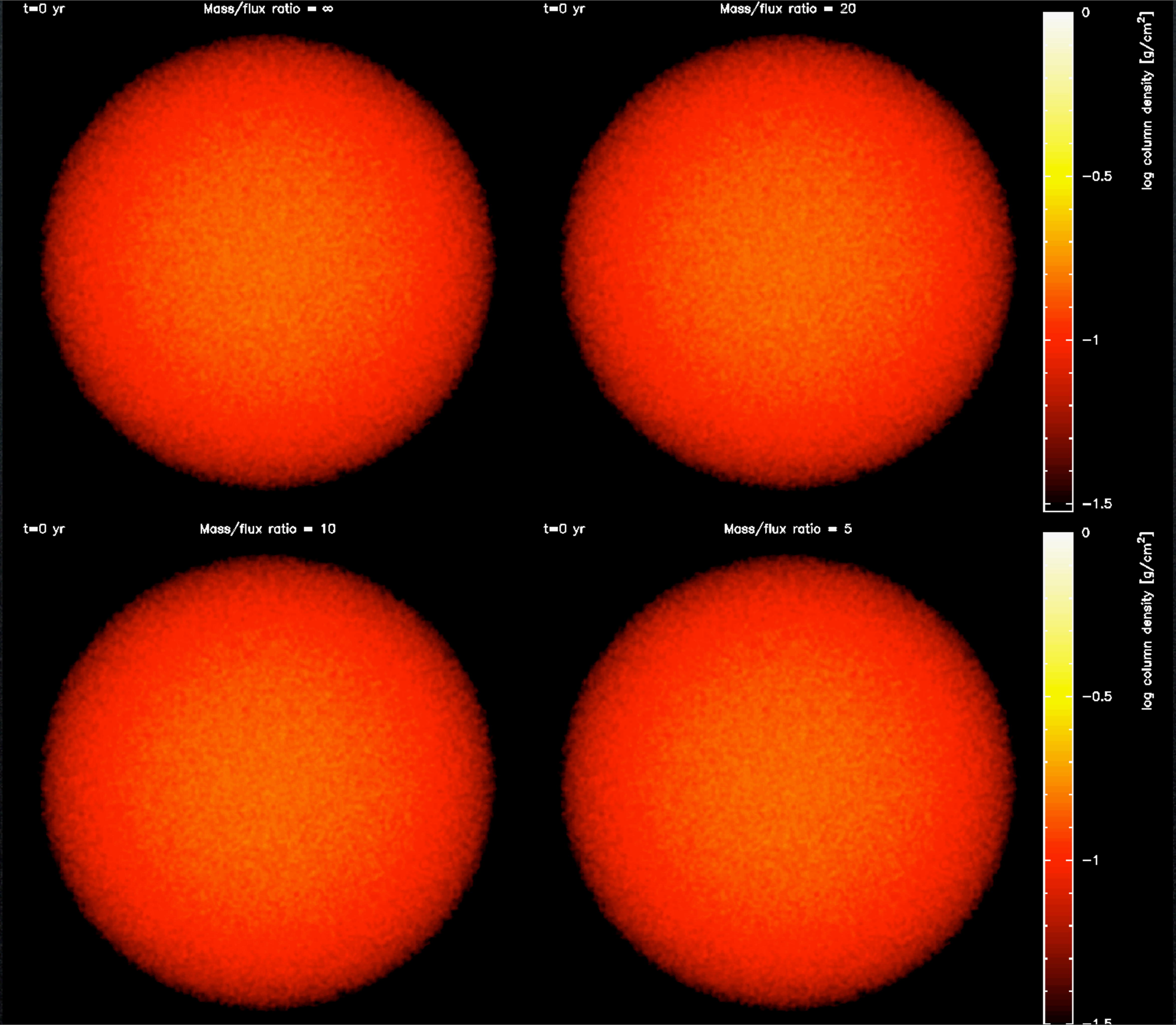
magnetic fields vs pressure

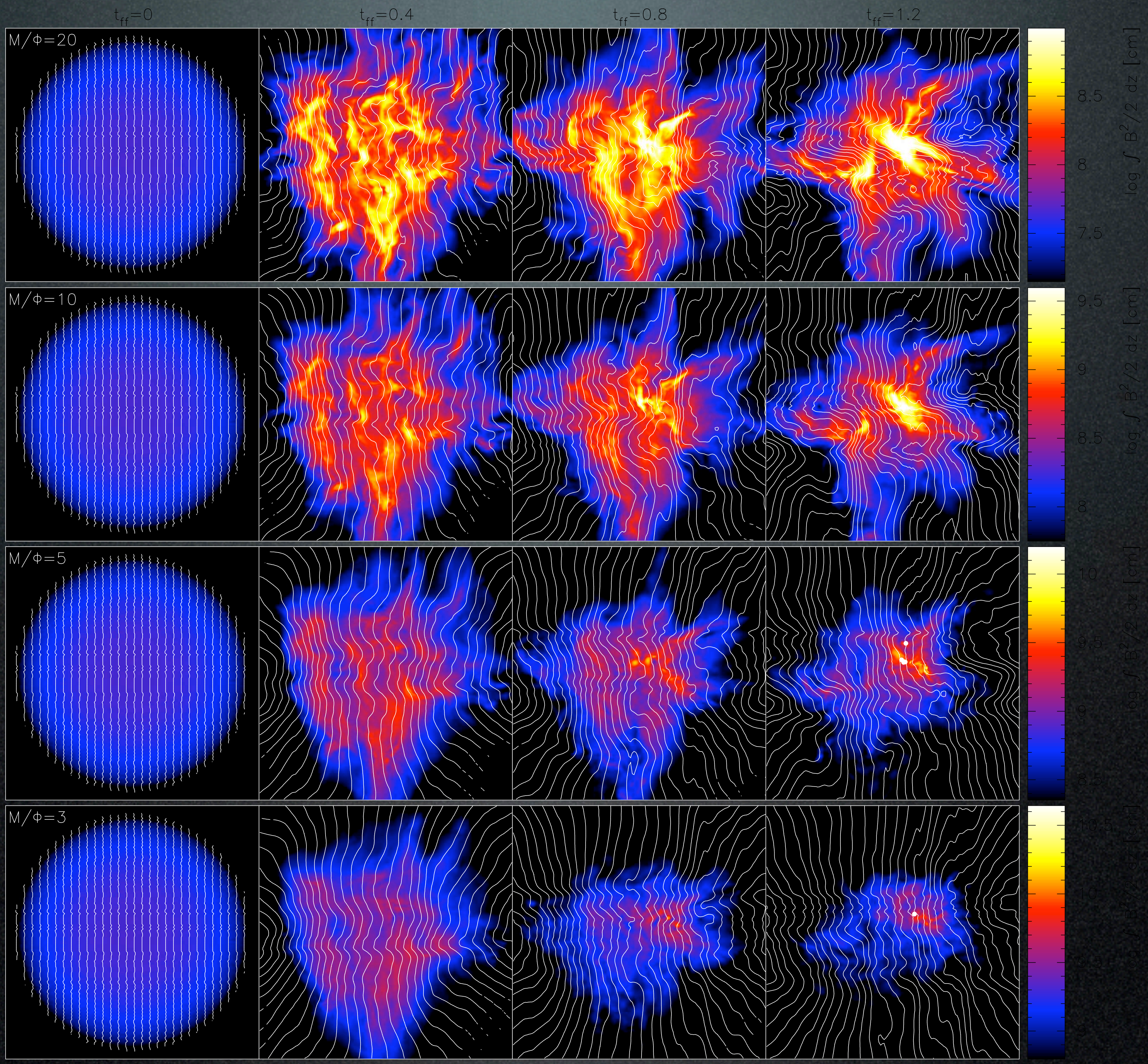
$$\frac{v_{turb}}{v_{Alfven}}$$

magnetic fields vs turbulence

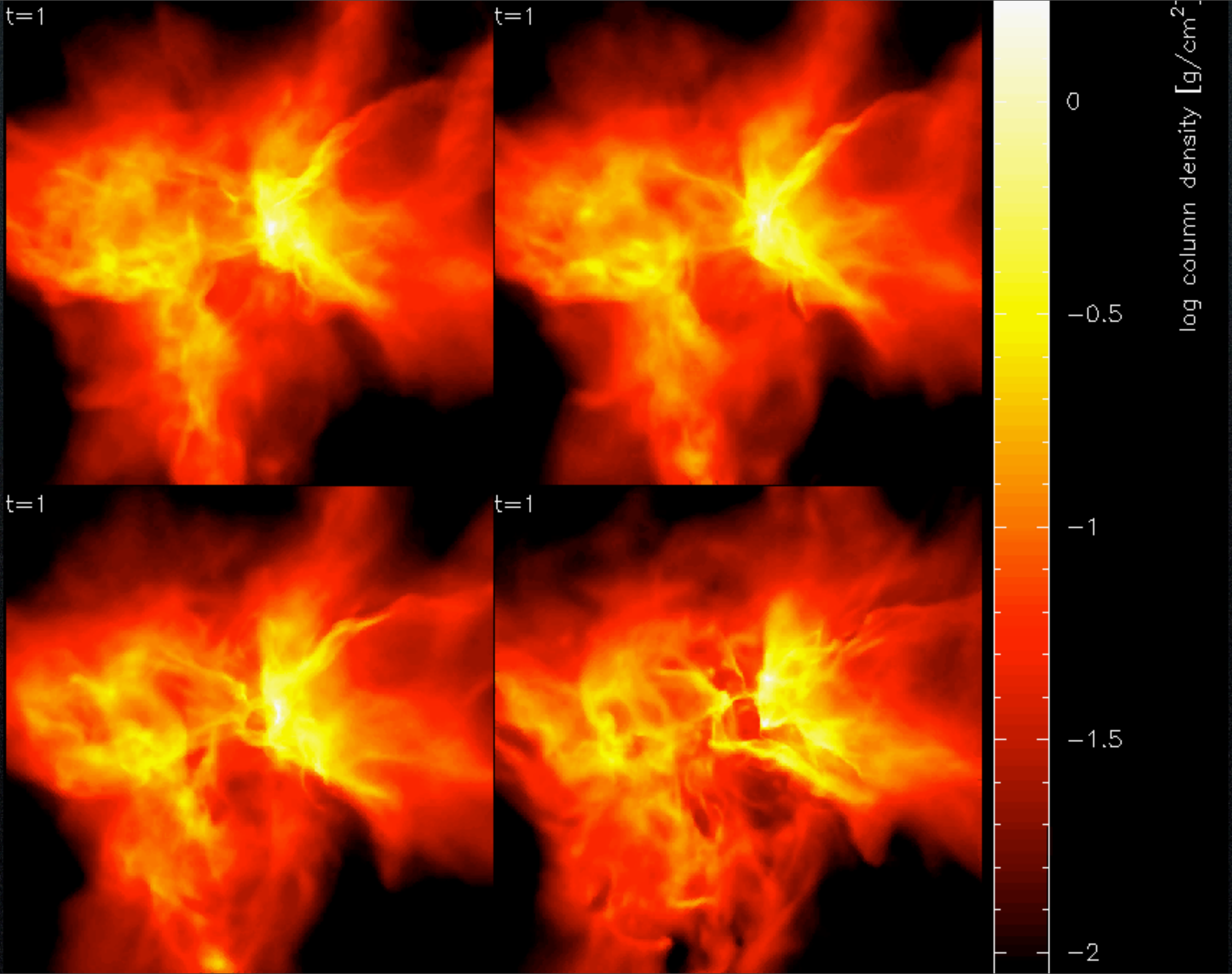
these parameters are independent!

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)

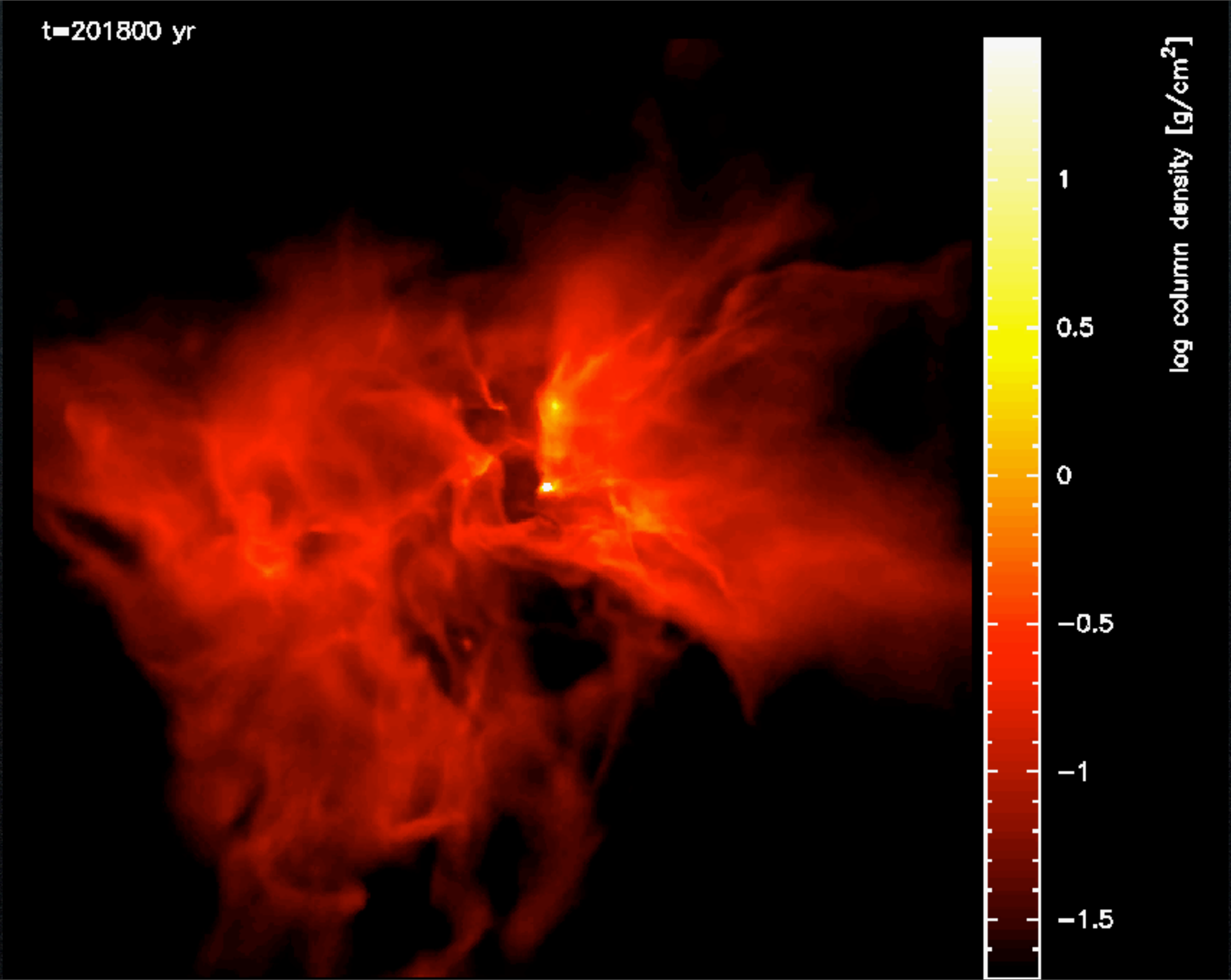

t=0 yr
Mass/flux ratio = ∞
t=0 yr
Mass/flux ratio = 20
t=0 yr
Mass/flux ratio = 10
t=0 yr
Mass/flux ratio = 5
0
−0.5
−1
−1.5
log column density [g/cm²]
0
−0.5
−1
log column density [g/cm²]



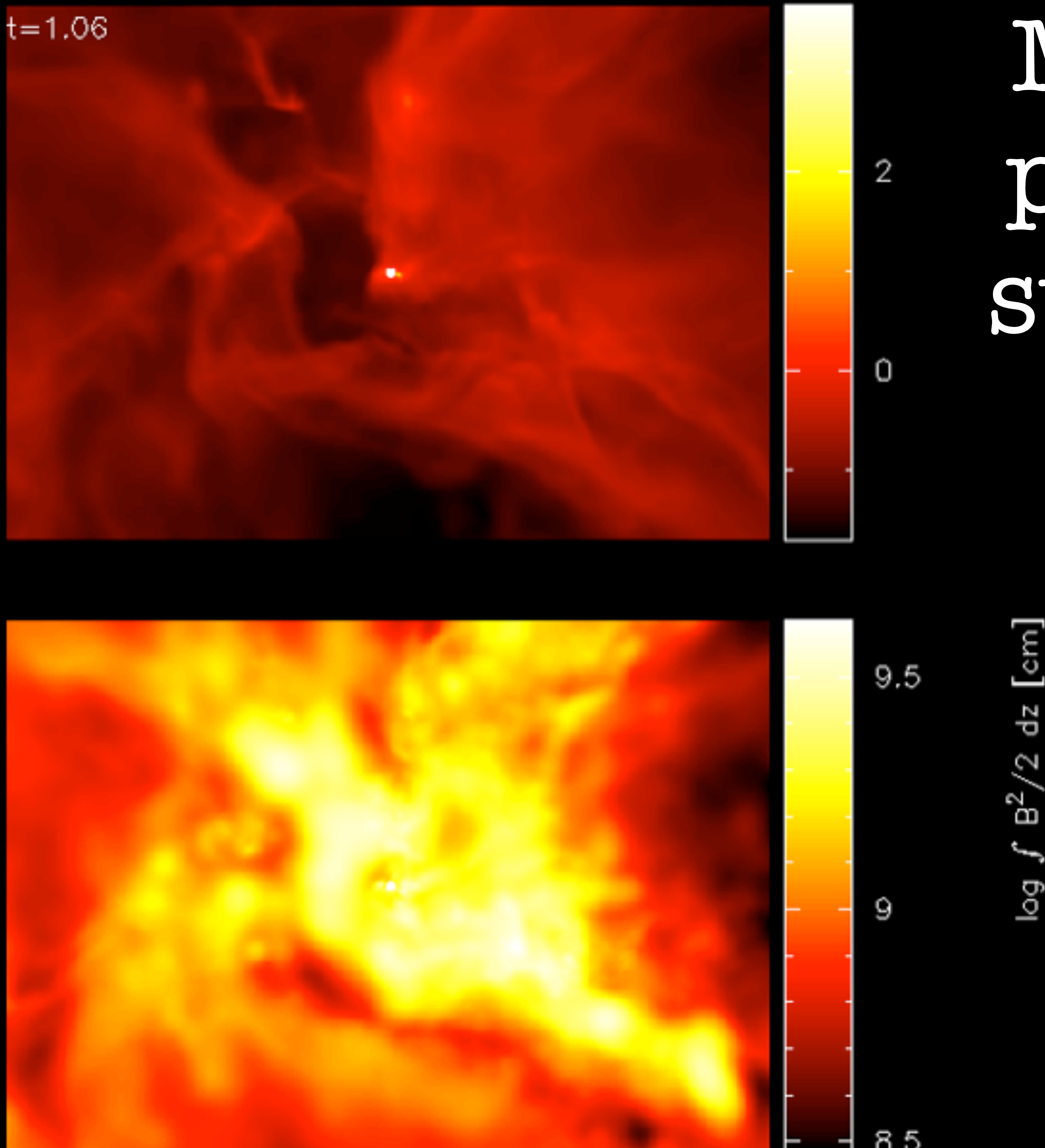
t_ff=0
t_ff=0.4
t_ff=0.8
t_ff=1.2
M/Φ=20
M/Φ=10
M/Φ=5
M/Φ=3
log ∫ B²/2 dz [cm]
8.5
8
7.5
9.5
9
8.5
8



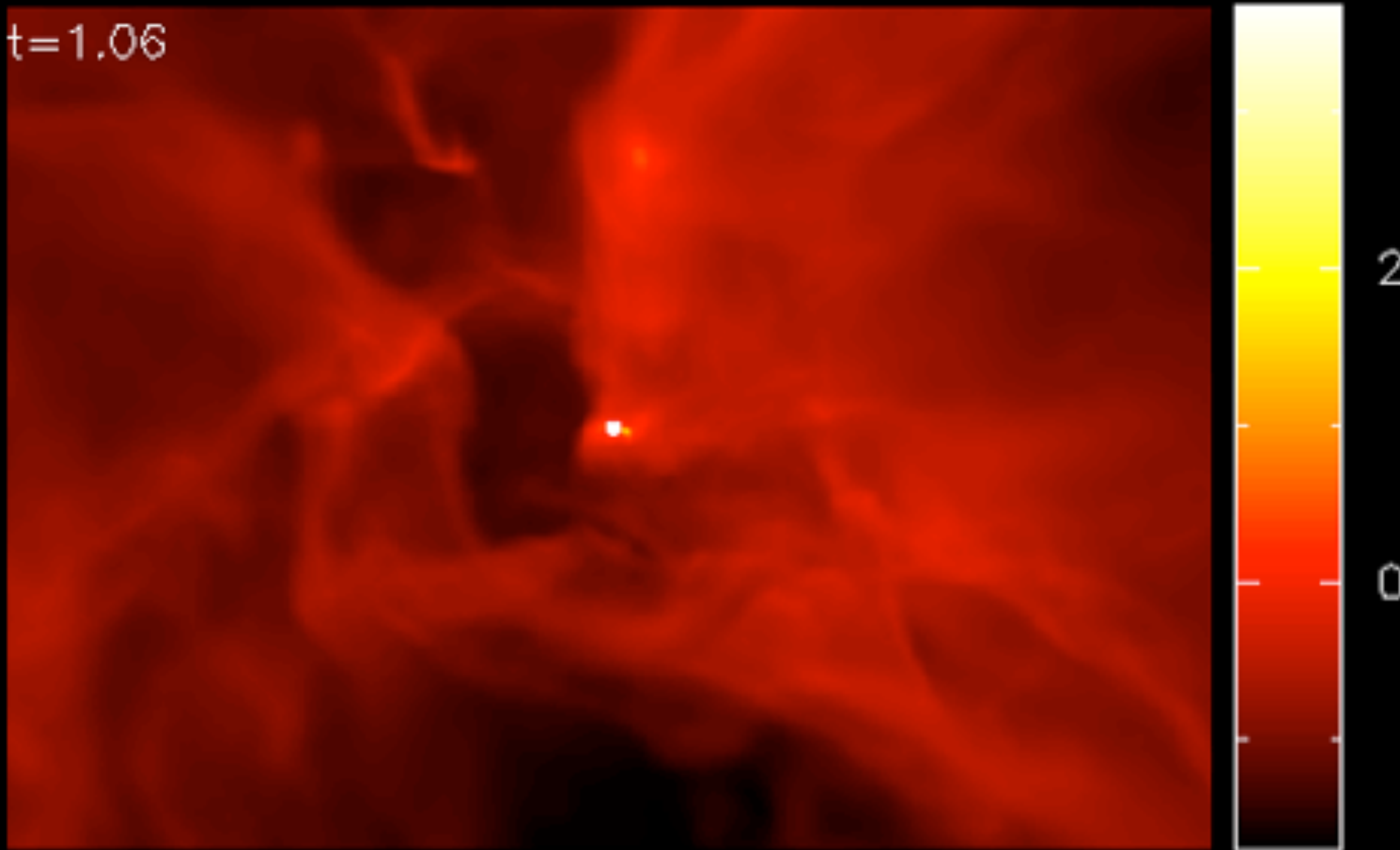
t=1
t=1
t=1
t=1
0
−0.5
−1
−1.5
−2
log column density [g/cm^2]

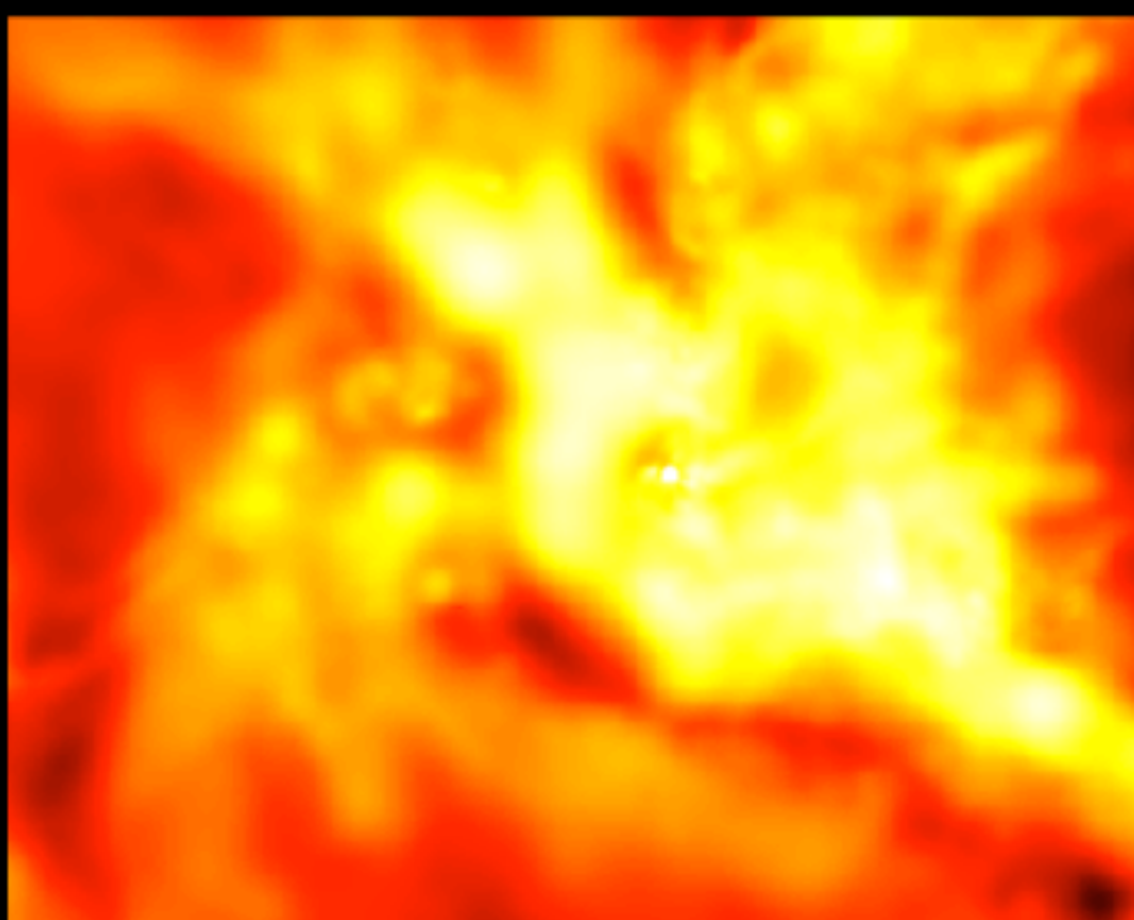

t=201800 yr
1
0.5
0
−0.5
−1
−1.5
log column density [g/cm^2]

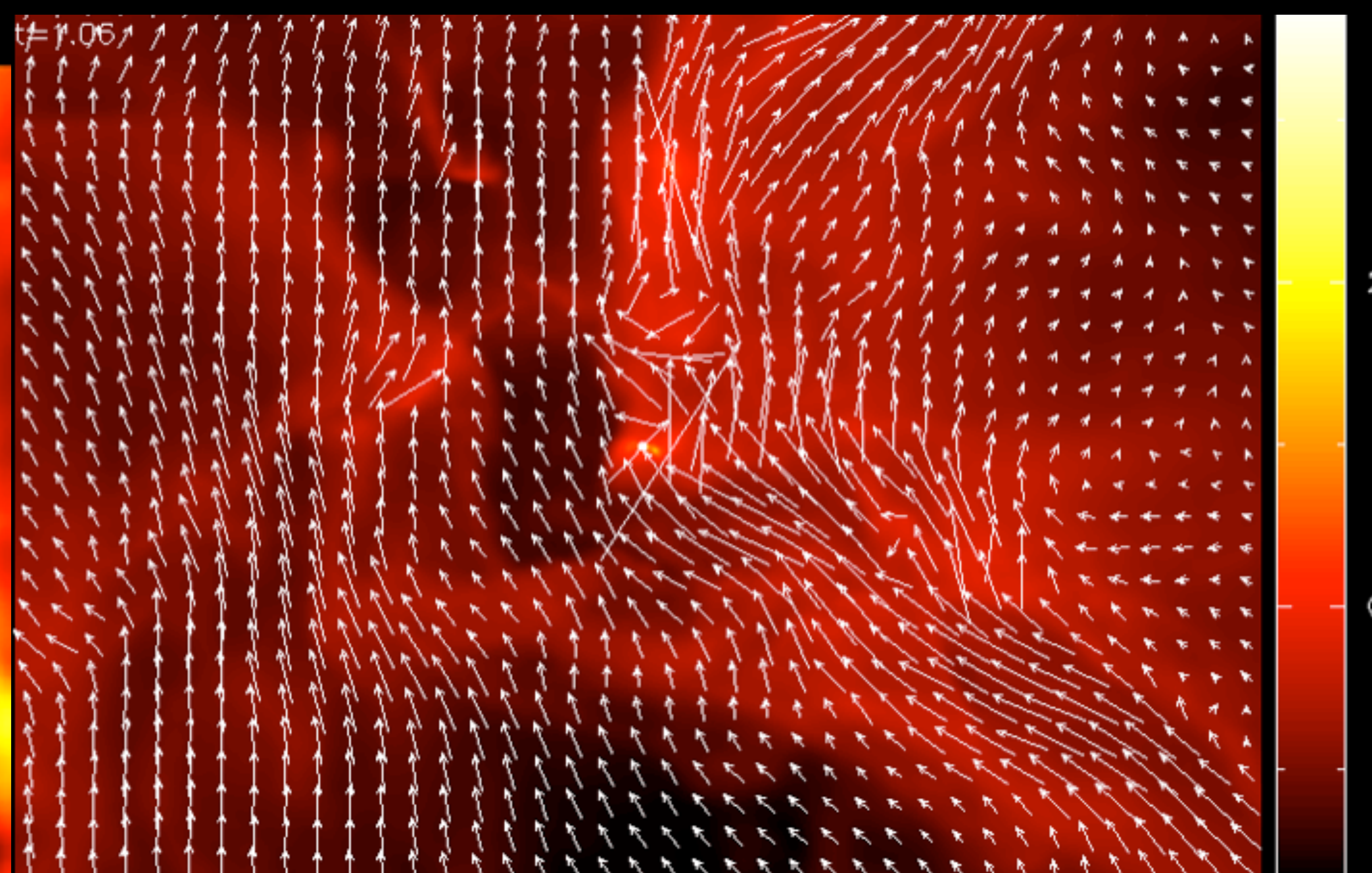
Magnetic pressure-supported voids

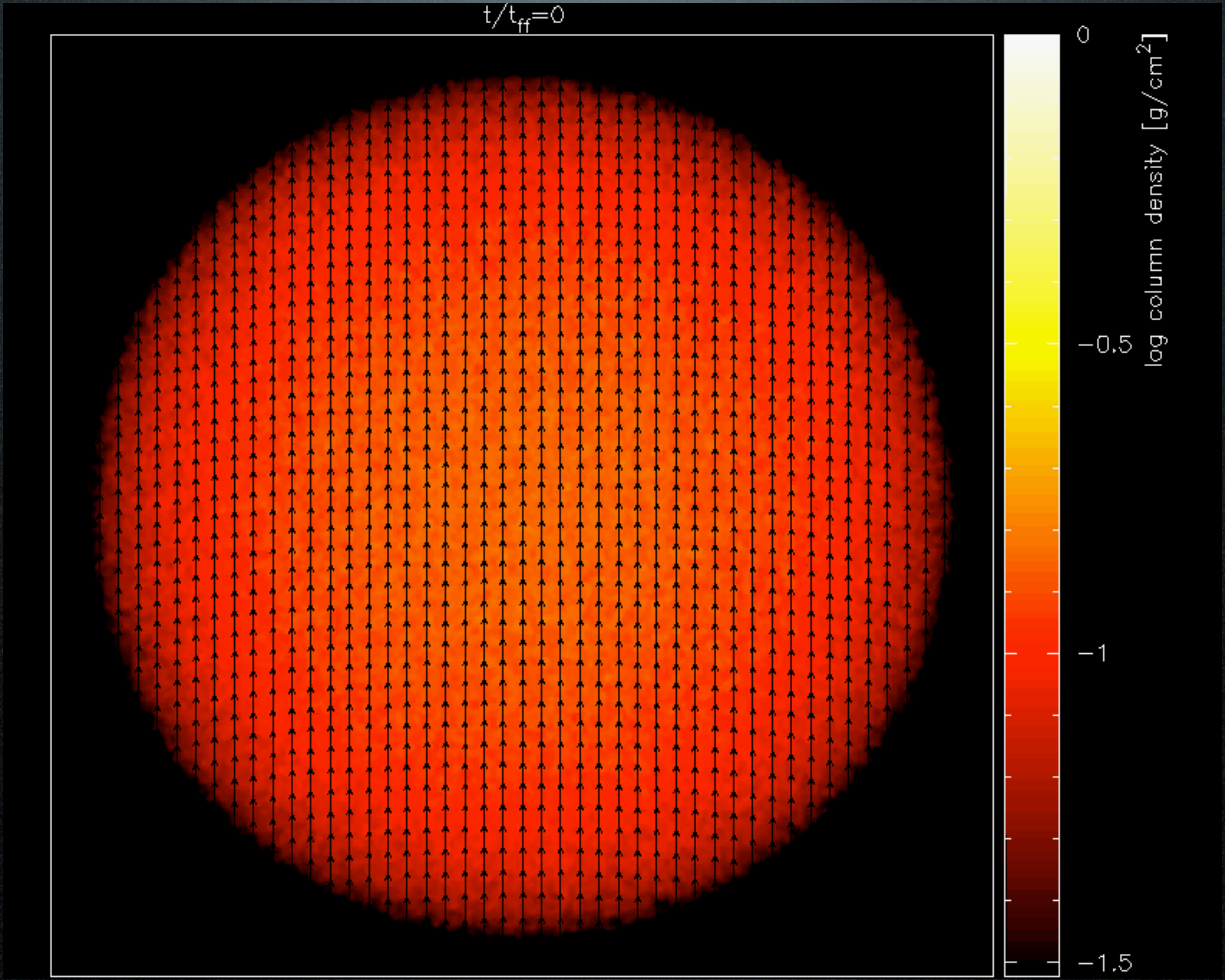


Magnetic pressure-supported voids



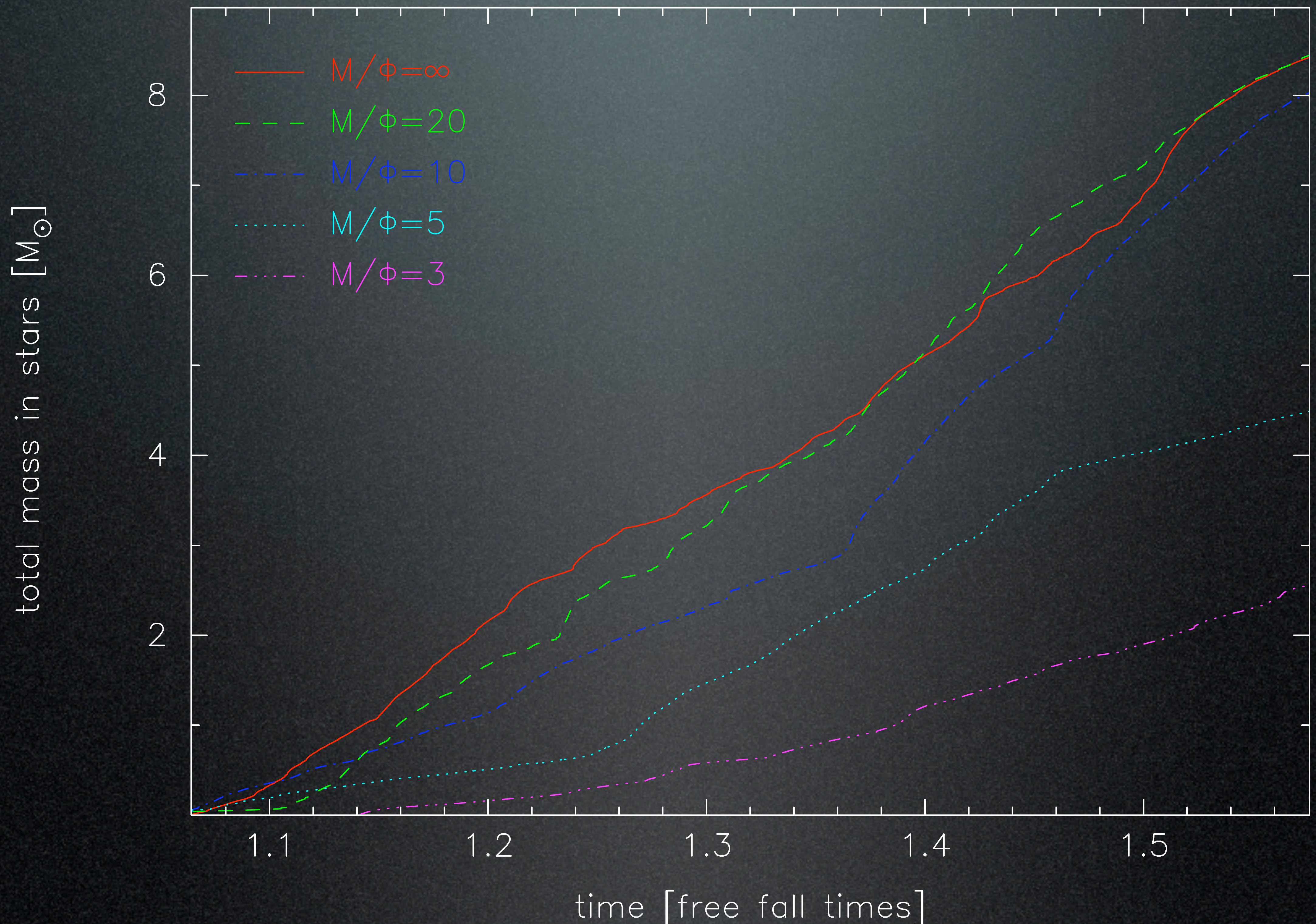




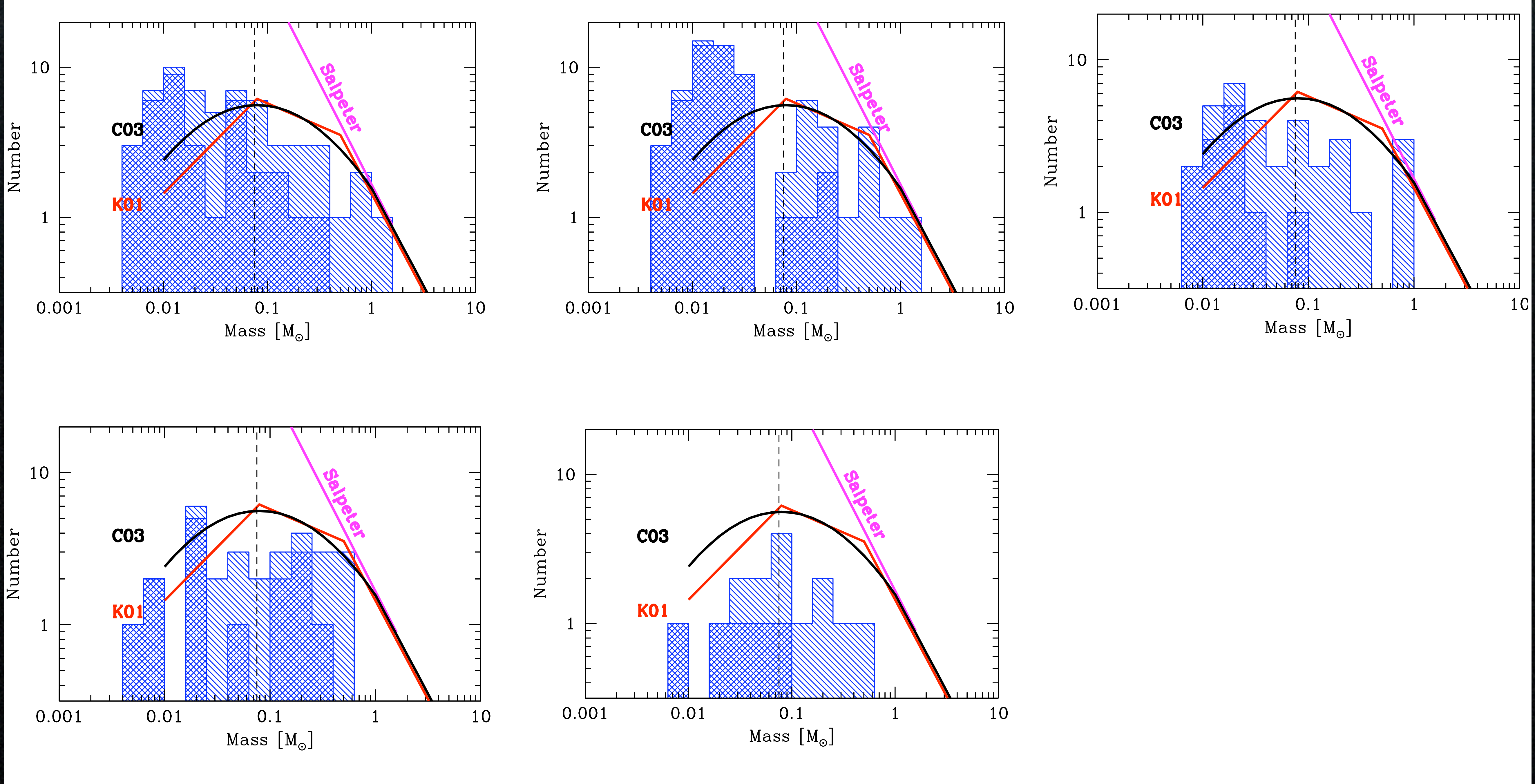


t/t_ff=0
0
−0.5
−1
−1.5
log column density [g/cm²]

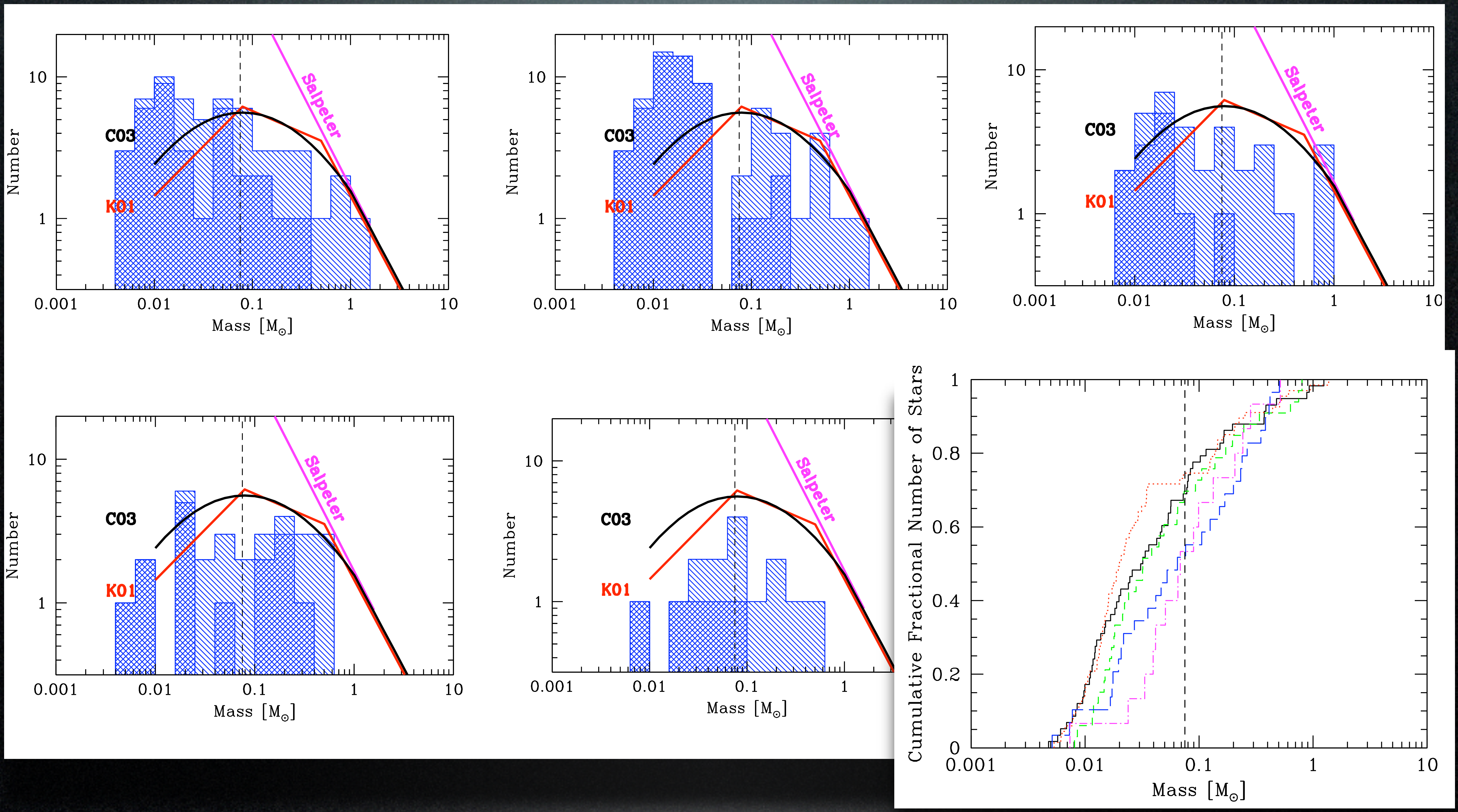
Star formation rate



Effect on IMF



Effect on IMF

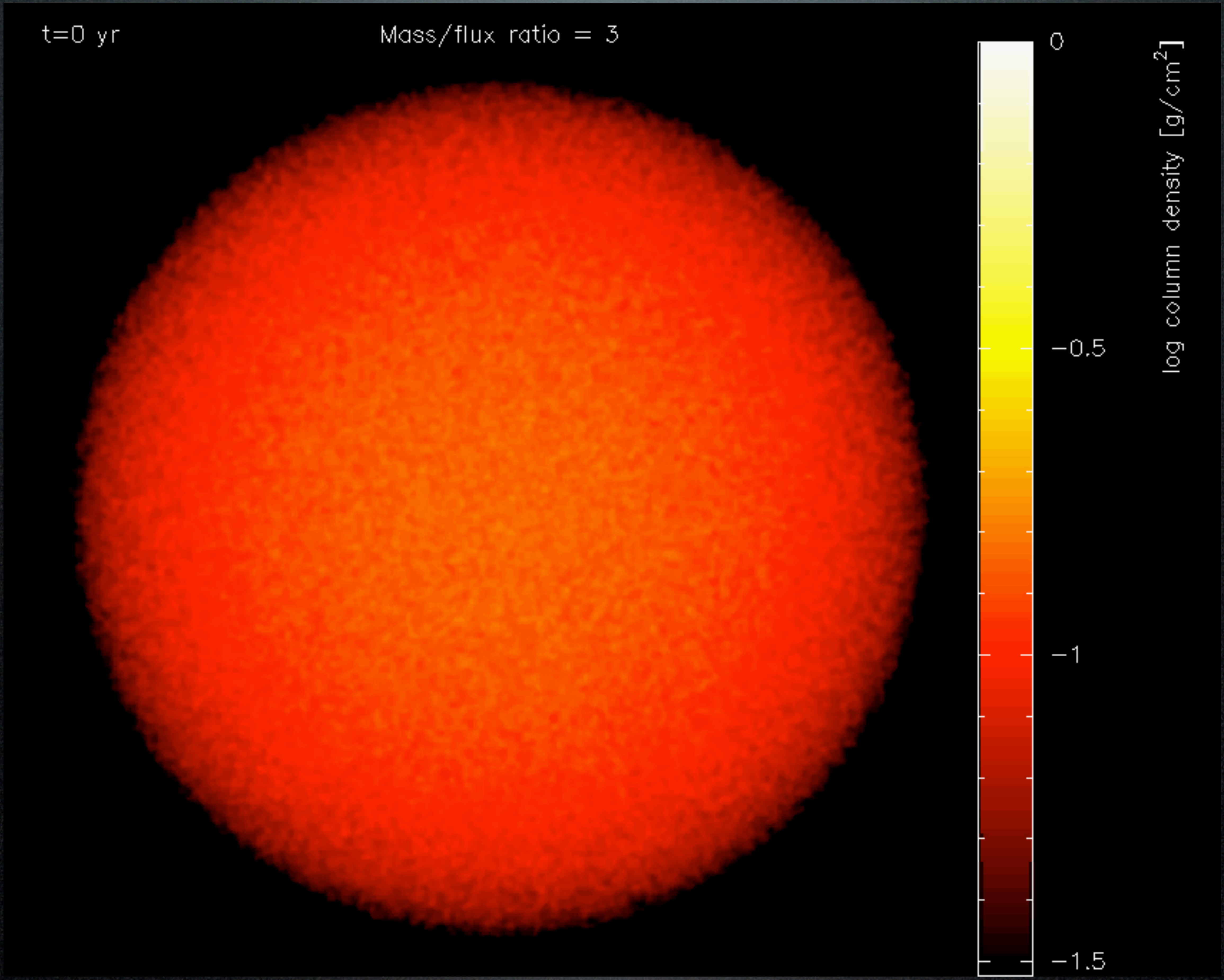


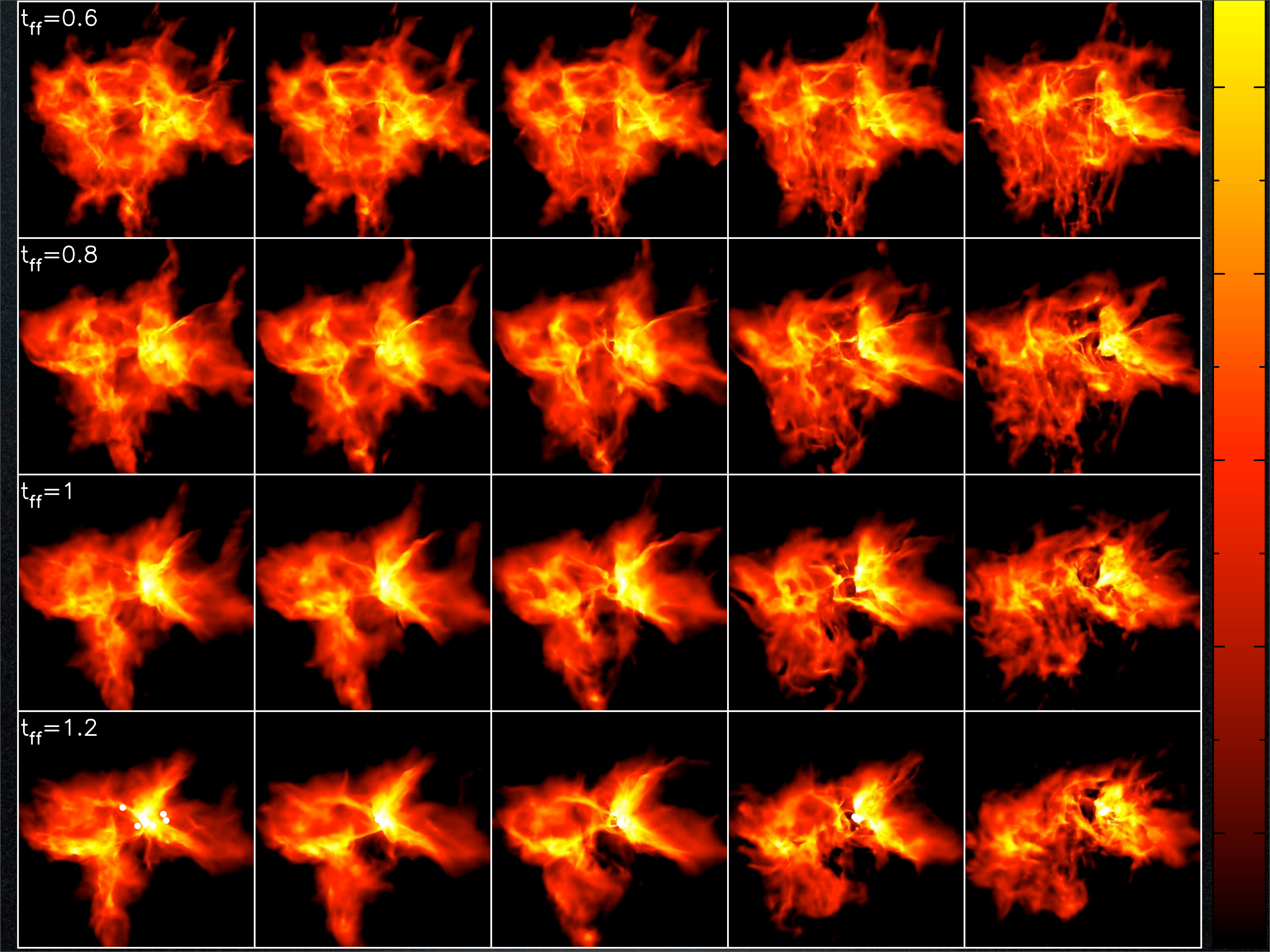
Effect on IMF

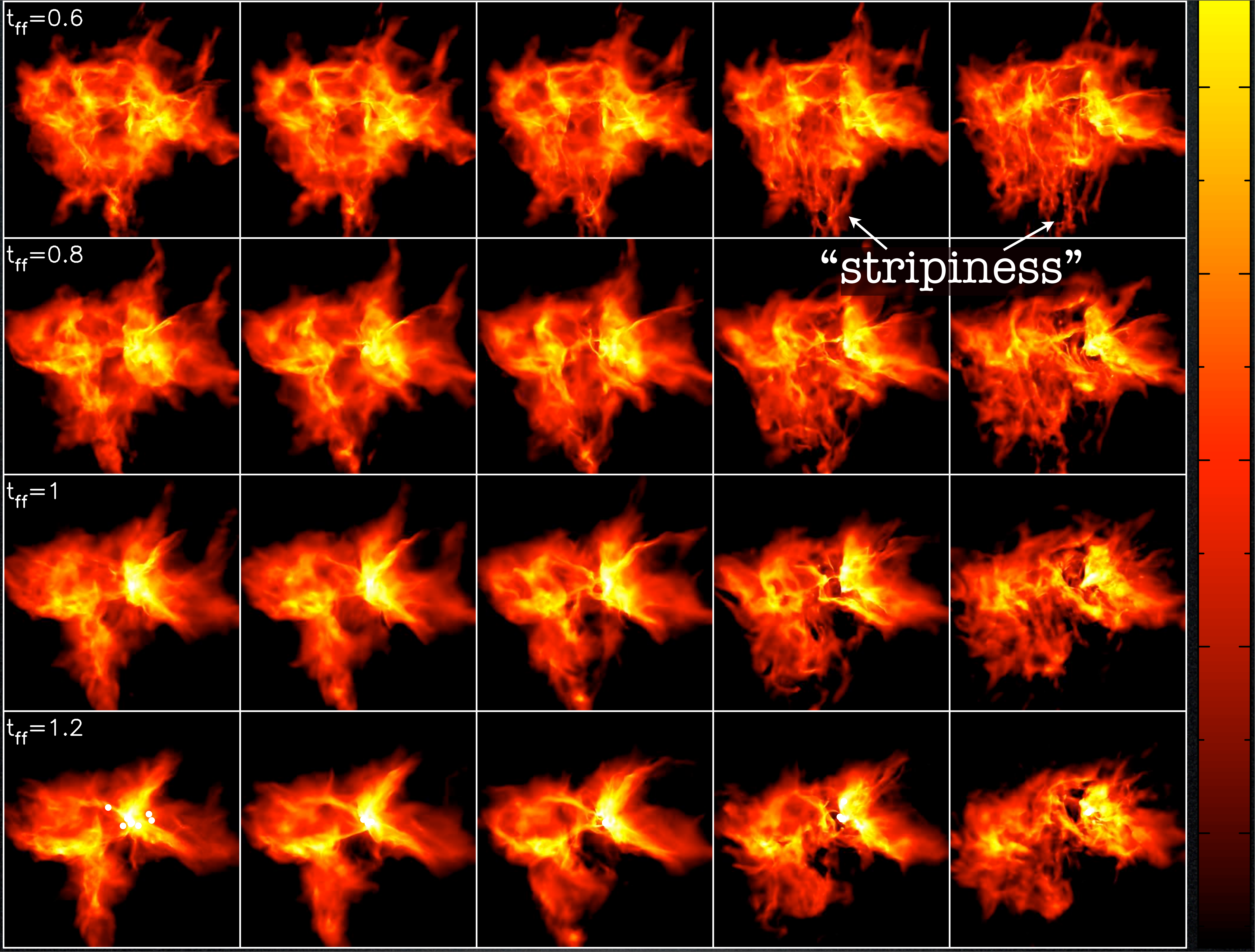
	N_{BDs}	N_{stars}	ratio
Hydro	44	14	3.14
$M/\Phi = 20$	51	18	2.83
$M/\Phi = 10$	22	11	2.0
$M/\Phi = 5$	15	14	1.07
$M/\Phi = 3$	8	7	1.14

even stronger field...

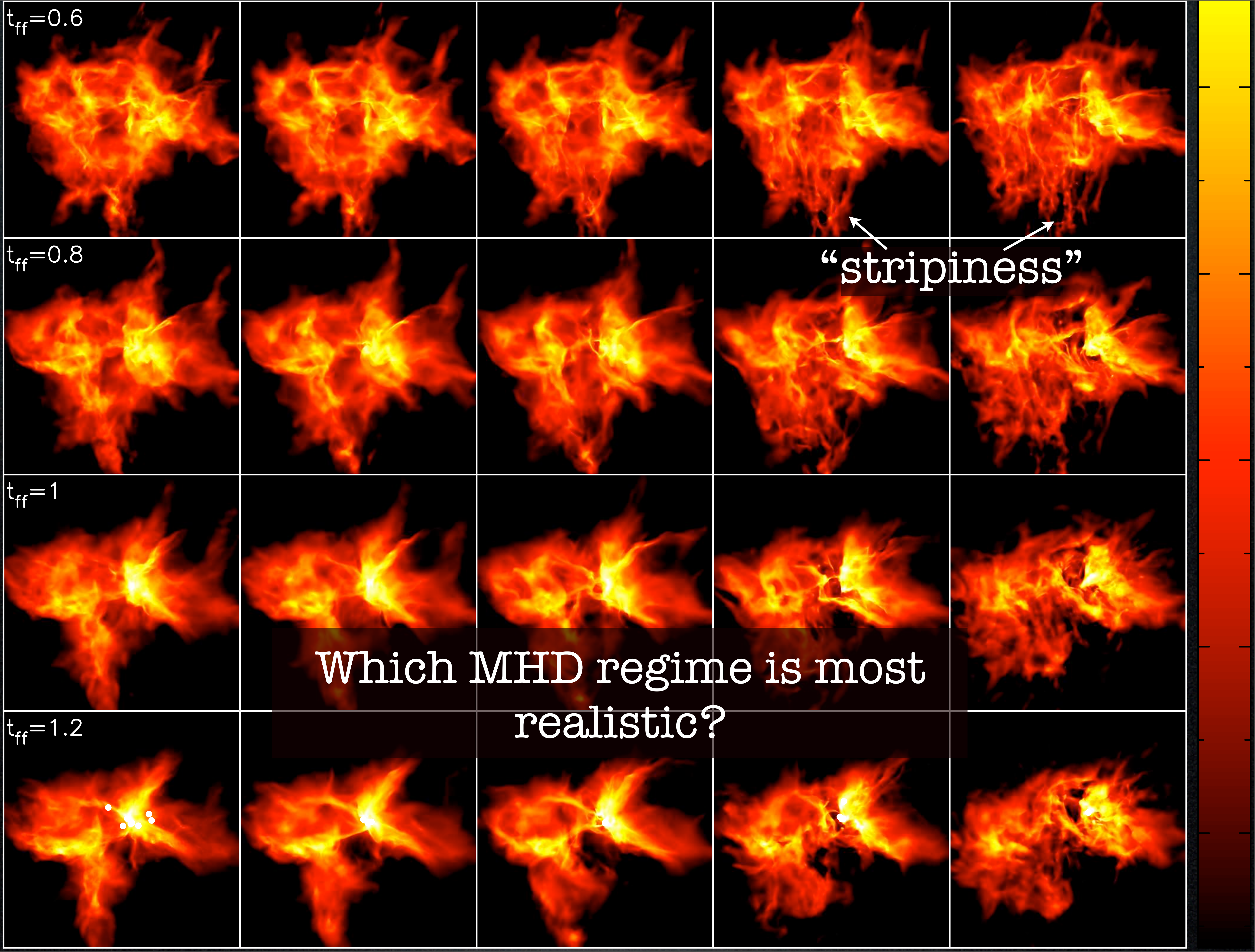
even stronger field...



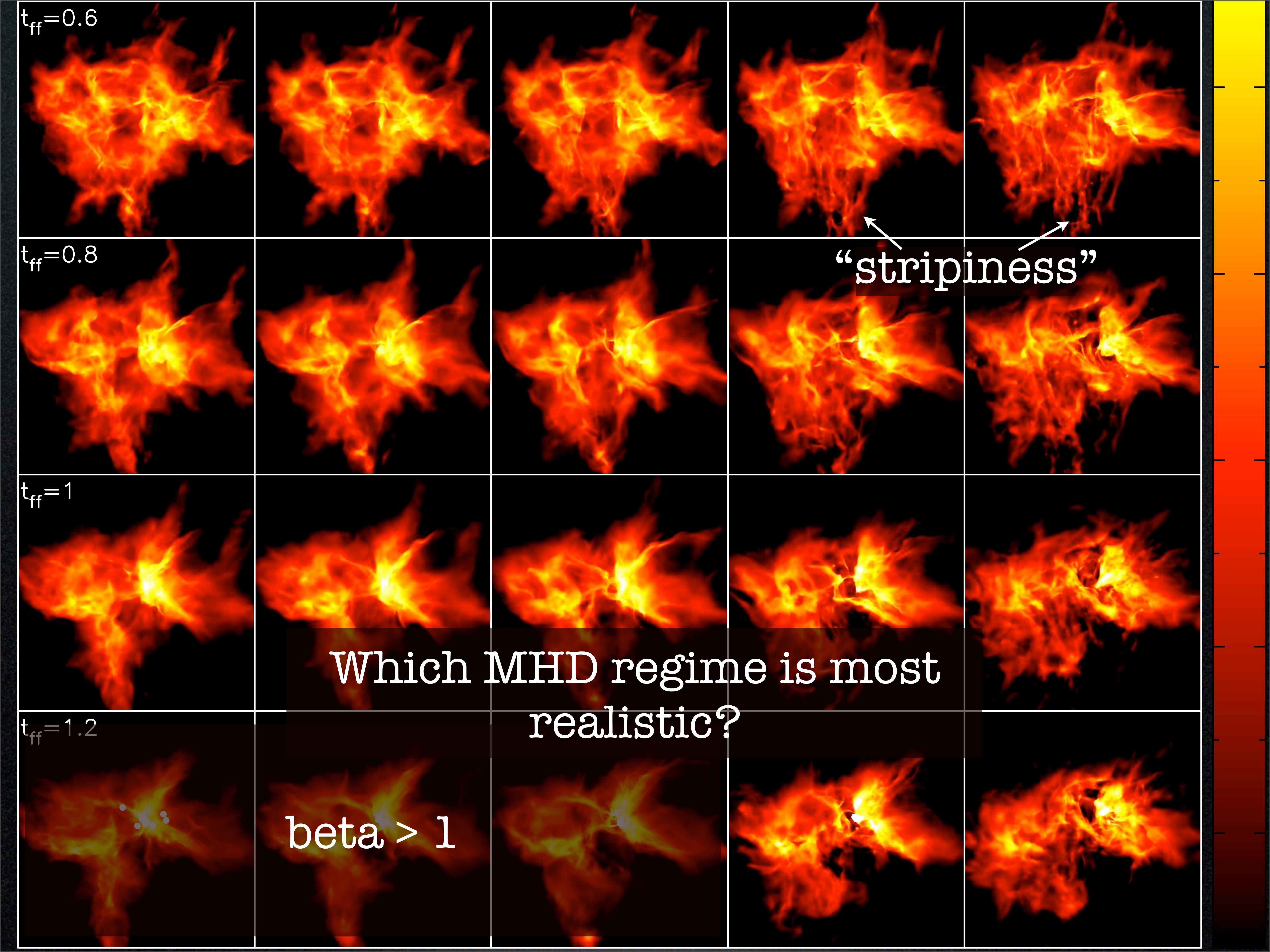

t_{ff}=0.6
t_{ff}=0.8
t_{ff}=1
t_{ff}=1.2

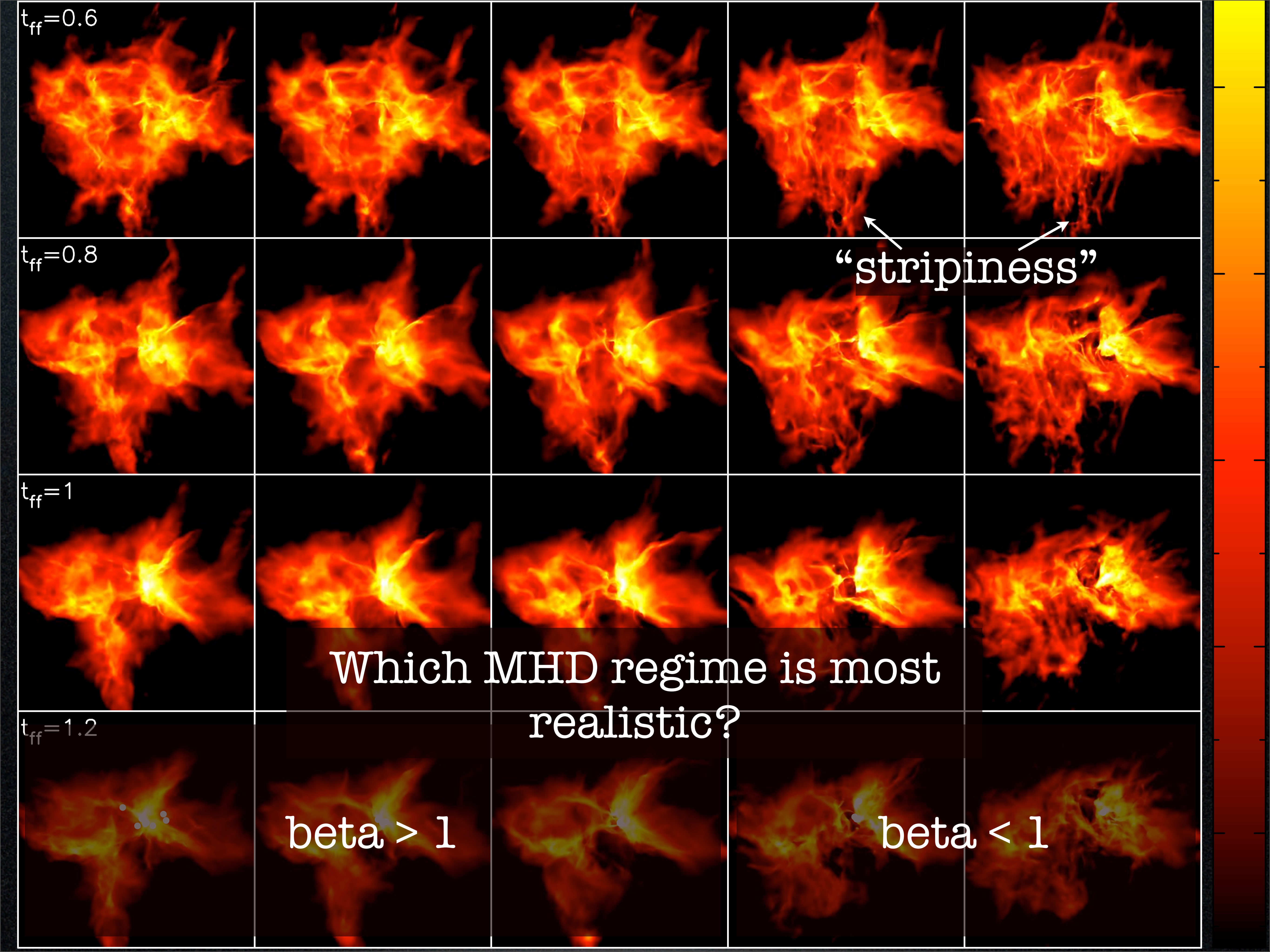


tff=0.6
tff=0.8
tff=1
tff=1.2
"stripiness"

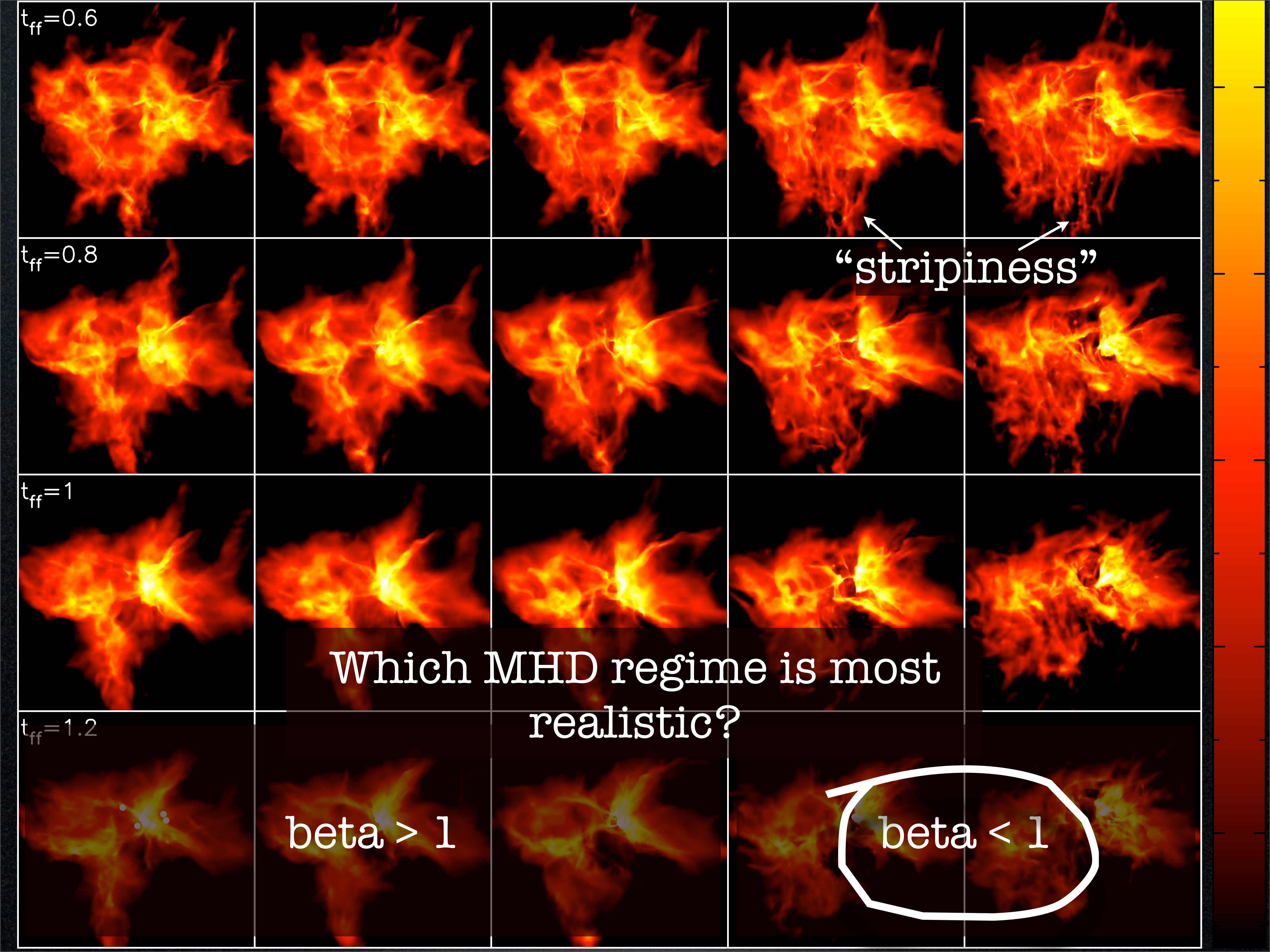


t_{ff}=0.6
t_{ff}=0.8
t_{ff}=1
t_{ff}=1.2
"stripiness"
Which MHD regime is most realistic?

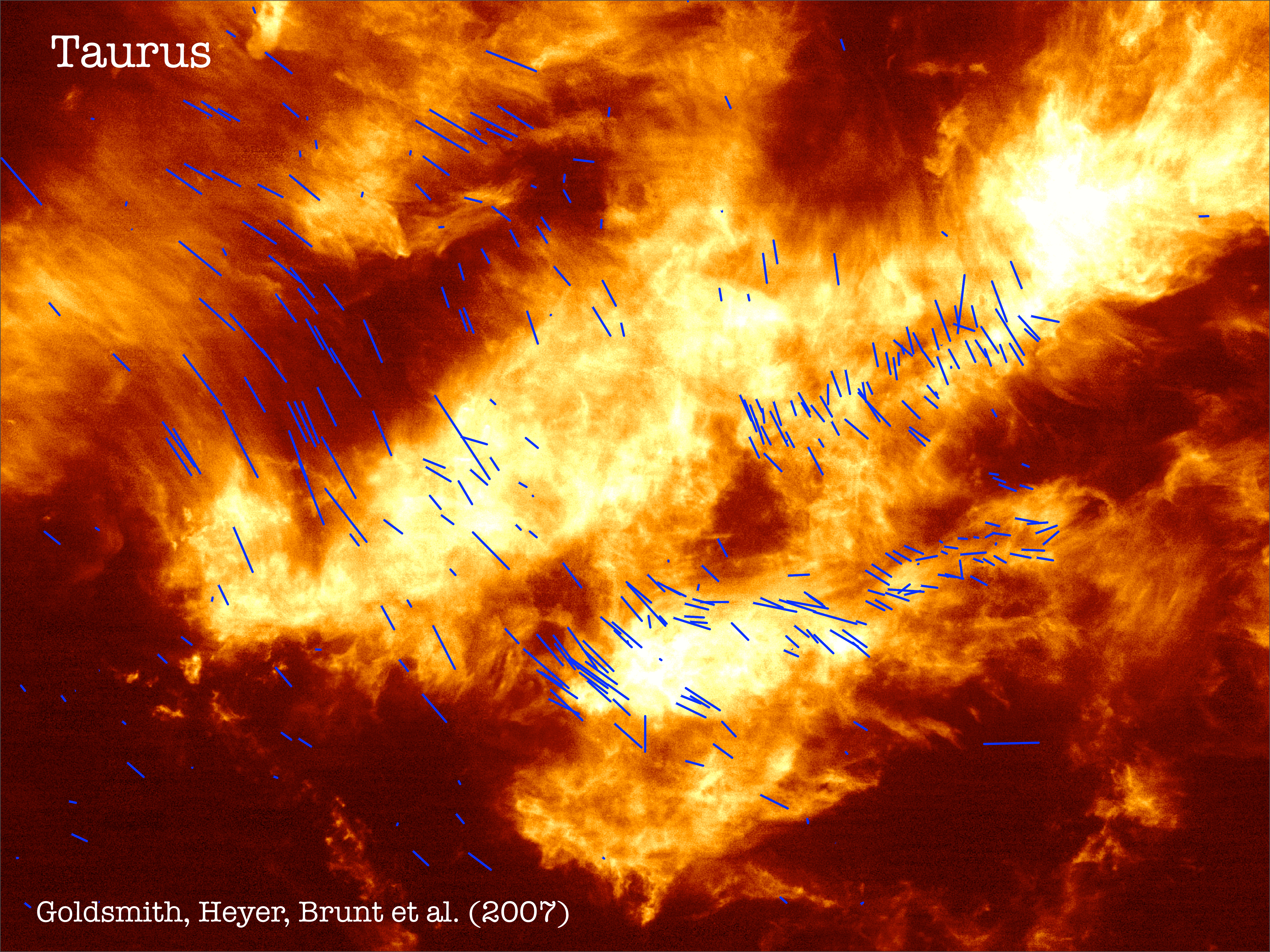

t_{ff}=0.6
t_{ff}=0.8
t_{ff}=1
t_{ff}=1.2
"stripiness"
Which MHD regime is most realistic?
beta > 1



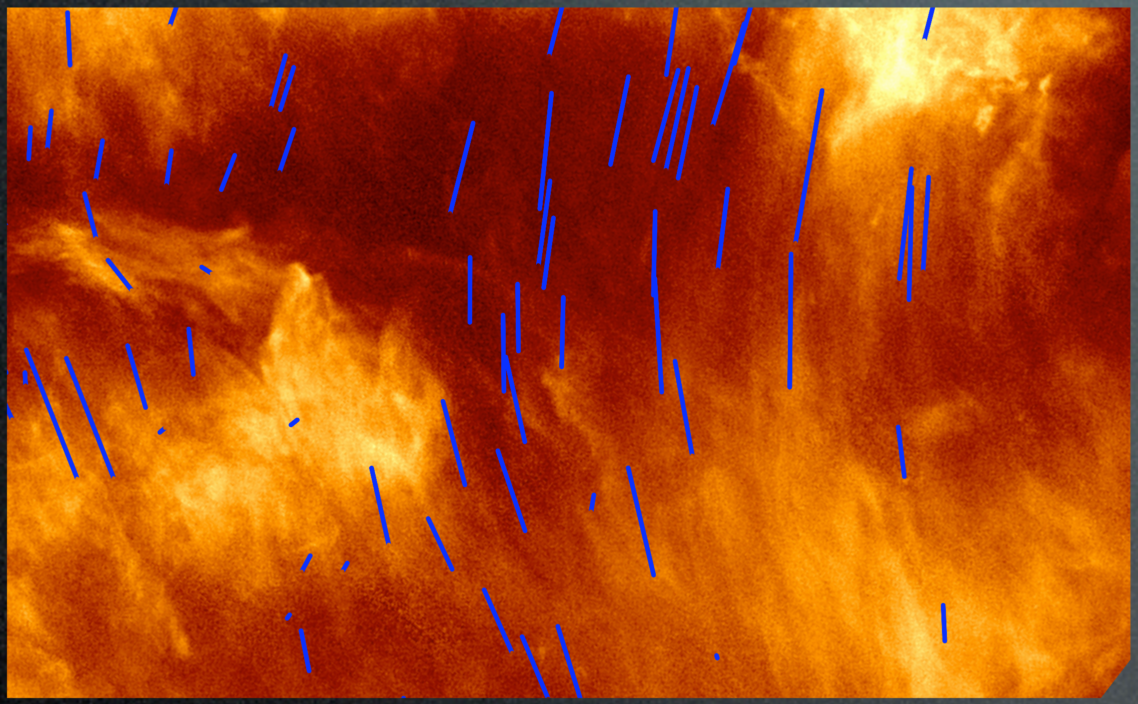
t_ff=0.6
t_ff=0.8
t_ff=1
t_ff=1.2
"stripiness"
Which MHD regime is most realistic?
beta > 1
beta < 1

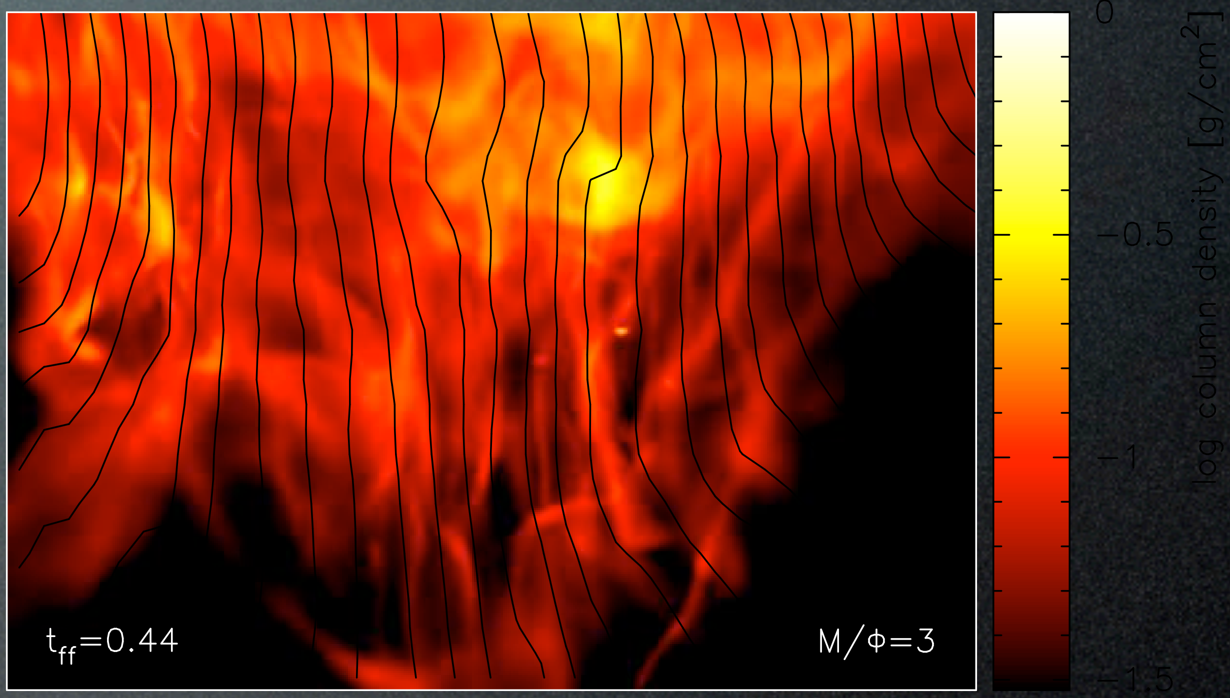


t_{ff}=0.6
t_{ff}=0.8
t_{ff}=1
t_{ff}=1.2
"stripiness"
Which MHD regime is most realistic?
beta > 1
beta < 1

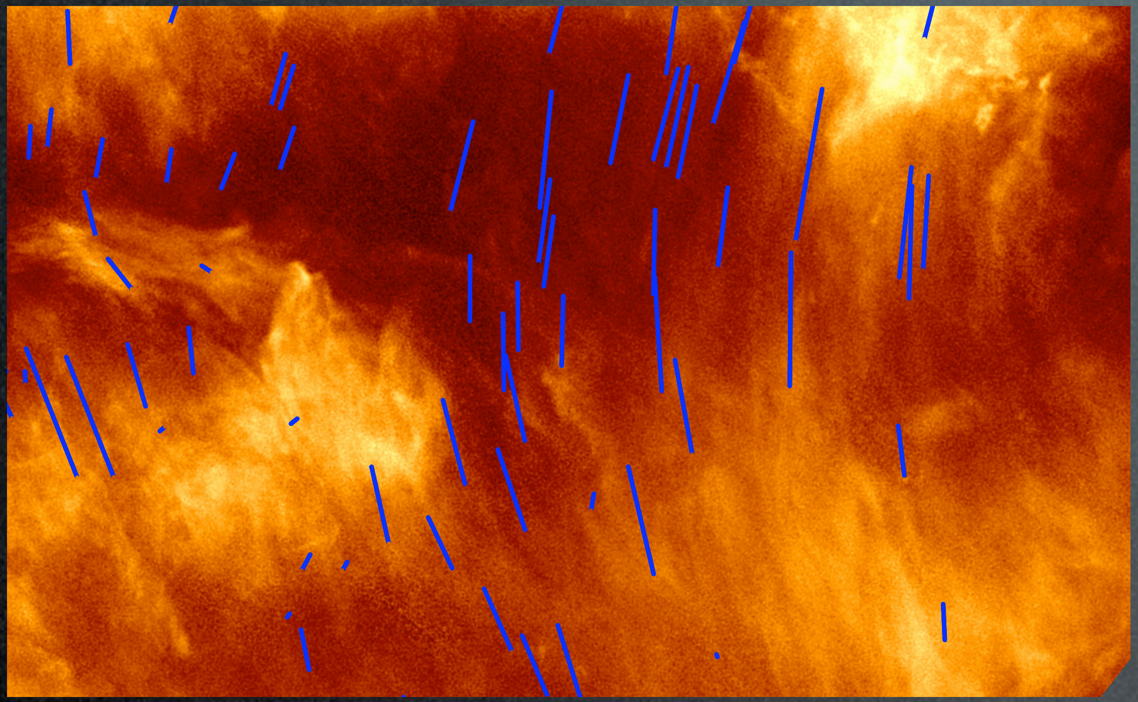

Taurus
Goldsmith, Heyer, Brunt et al. (2007)

Column density striations along field lines due to streaming motions in the gas

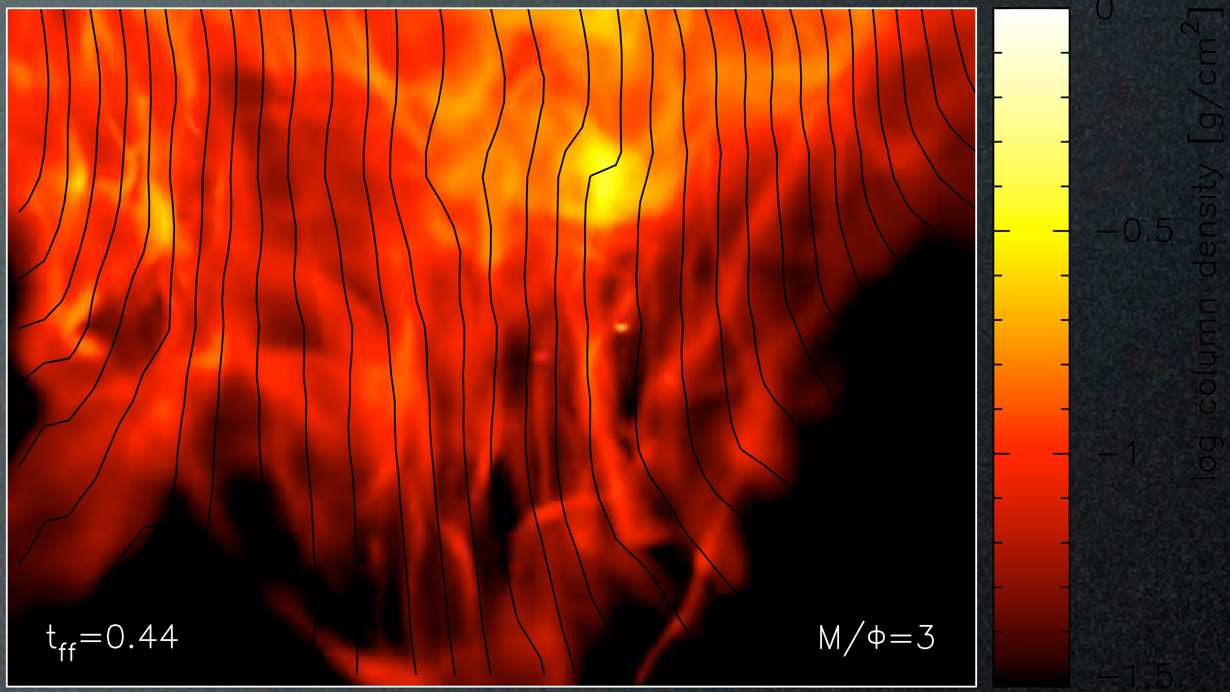




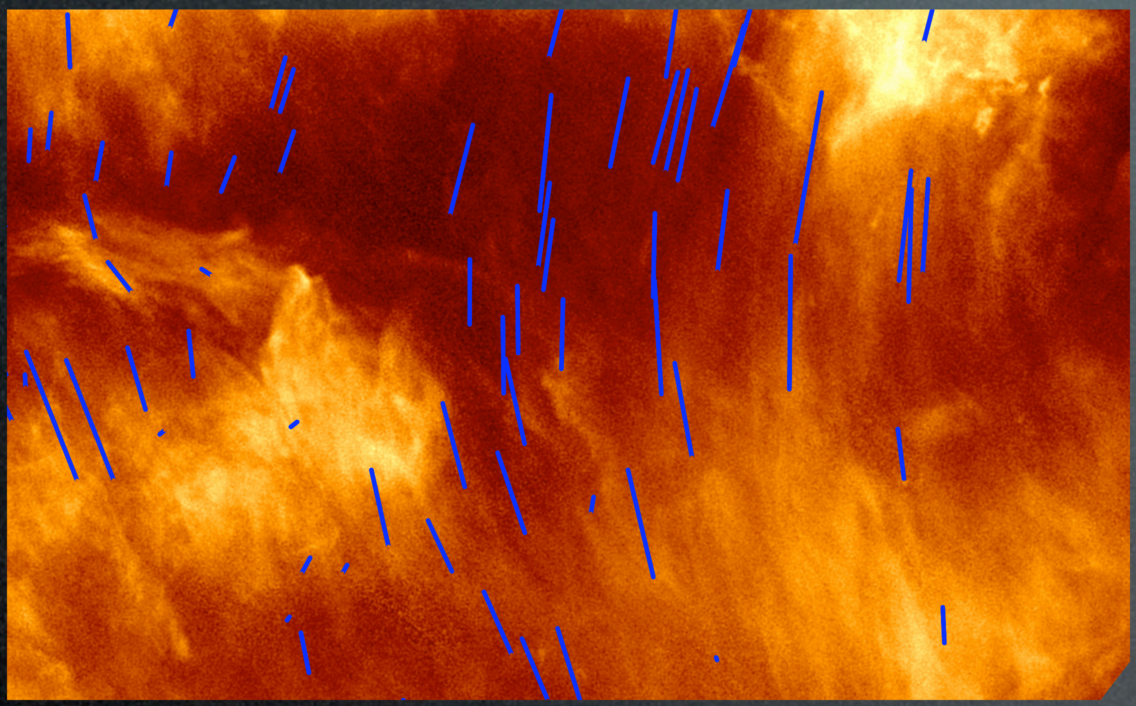
Column density striations along field lines due to streaming motions in the gas

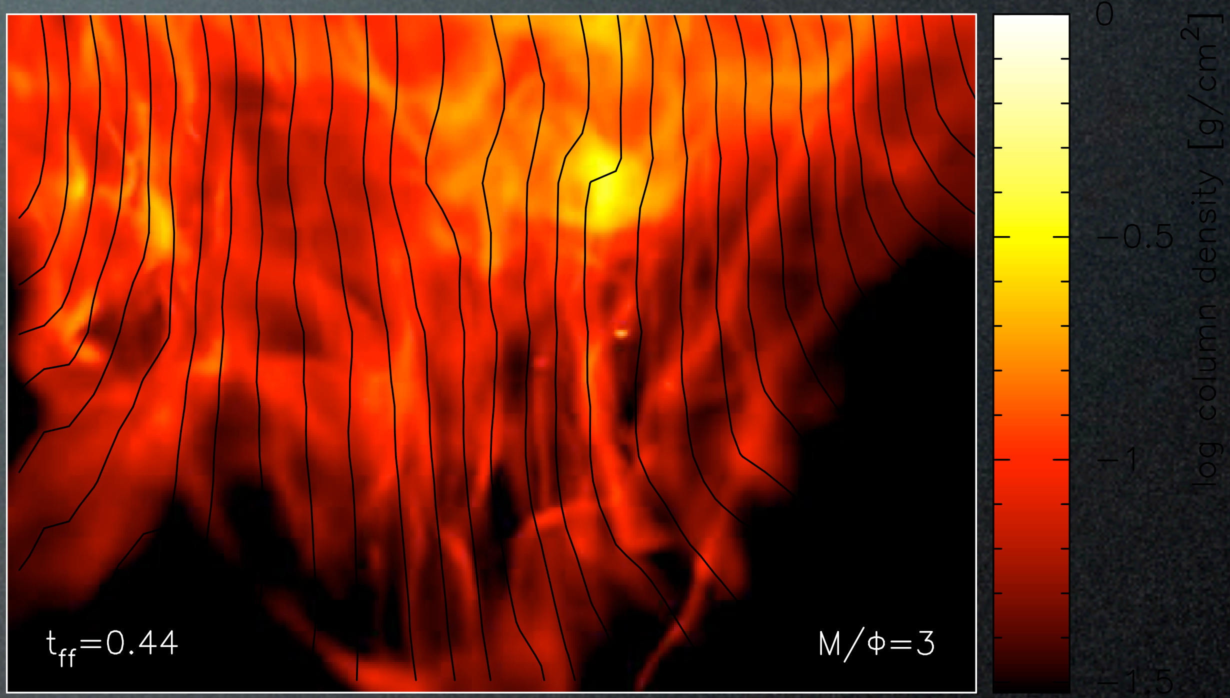


Taurus



Column density striations along field lines due to streaming motions in the gas

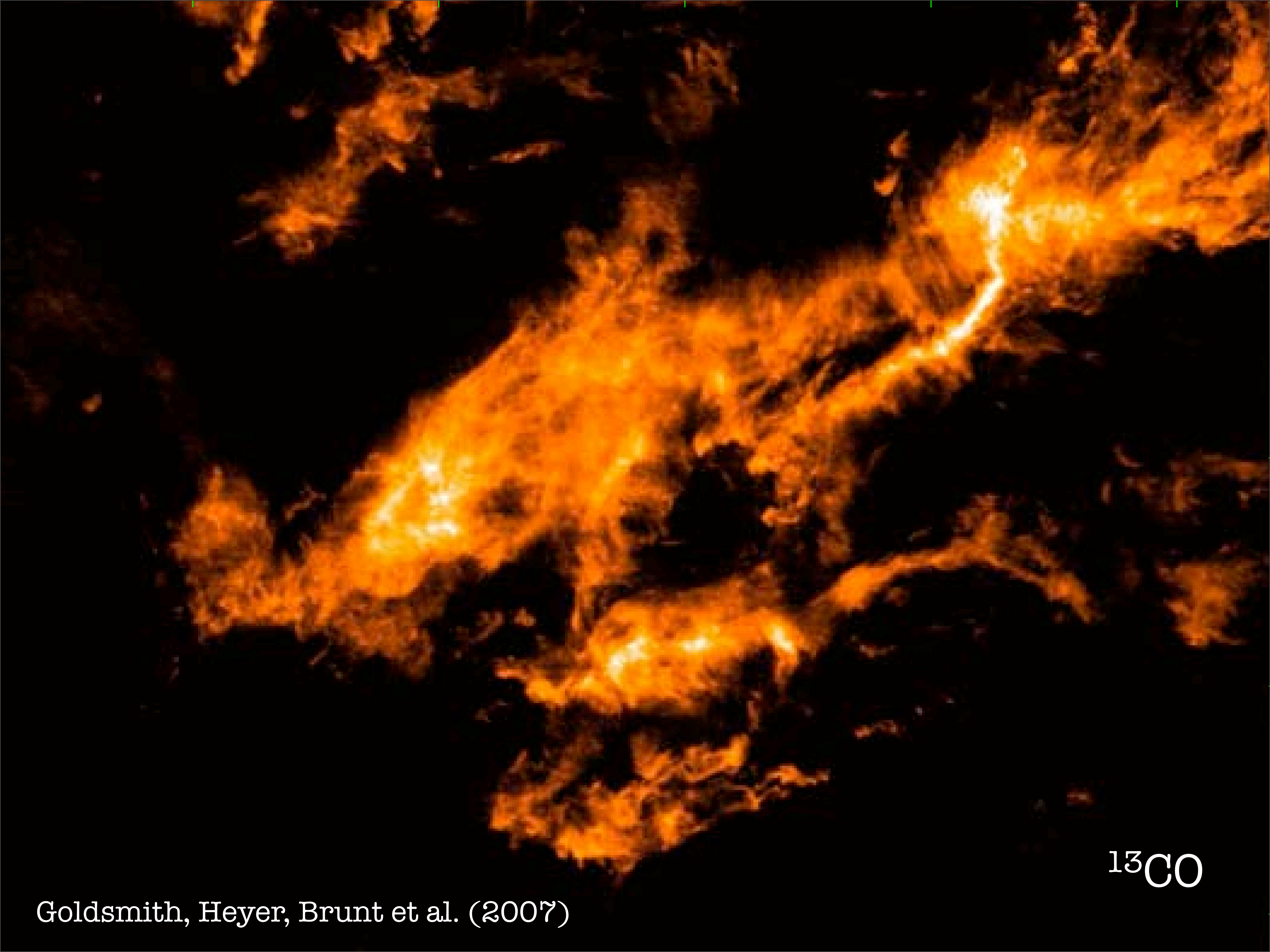




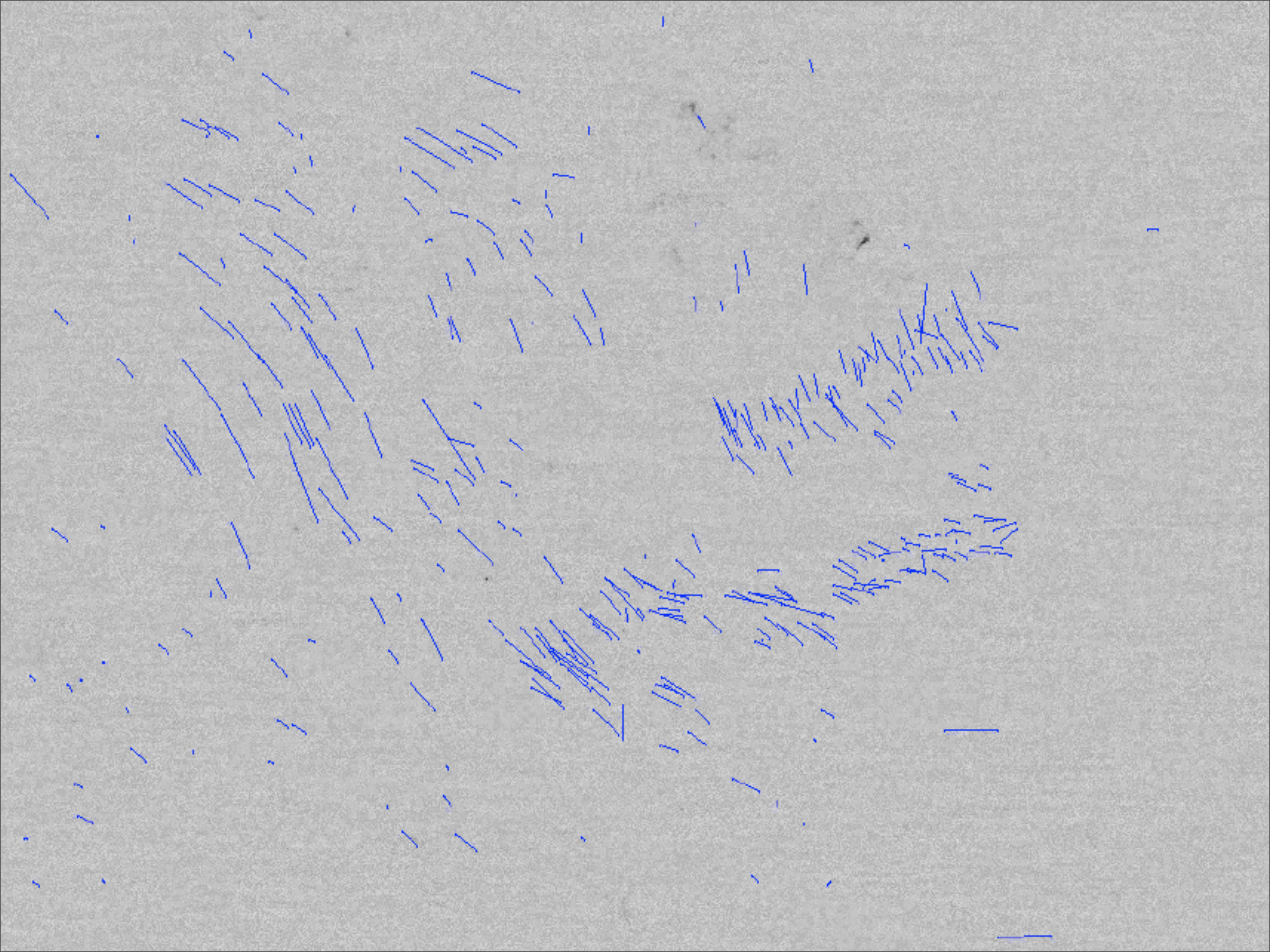
Taurus

$M/\Phi = 3$

Goldsmith, Heyer, Brunt et al. (2007)


^{13}CO
Goldsmith, Heyer, Brunt et al. (2007)


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



Summary

Summary

- (even supercritical) magnetic fields delay and suppress star formation.

Summary

- (even supercritical) magnetic fields delay and suppress star formation.
- strong magnetic fields (beta < 1) lead to large scale voids, anisotropic turbulent motions and column density striations in collapsing molecular clouds which we should expect to observe.

Summary

- (even supercritical) magnetic fields delay and suppress star formation.
- strong magnetic fields (beta < 1) lead to large scale voids, anisotropic turbulent motions and column density striations in collapsing molecular clouds which we should expect to observe.
- strongly inhibited accretion, resulting in a lower star formation rate and longer molecular cloud lifetimes.

Summary

- (even supercritical) magnetic fields delay and suppress star formation.

- strong magnetic fields (beta < 1) lead to large scale voids, anisotropic turbulent motions and column density striations in collapsing molecular clouds which we should expect to observe.

- strongly inhibited accretion, resulting in a lower star formation rate and longer molecular cloud lifetimes.

- trend towards fewer brown dwarfs with increasing field strength.

Where we're headed:

Where we're headed:

- new vector potential formulation for the magnetic field evolution without restrictions associated with Euler potentials

Where we're headed:

- new vector potential formulation for the magnetic field evolution without restrictions associated with Euler potentials
- using physical resistivity to solve the magnetic flux problem

Where we're headed:

- new vector potential formulation for the magnetic field evolution without restrictions associated with Euler potentials
- using physical resistivity to solve the magnetic flux problem
- MHD + radiation transport (flux-limited diffusion)