Inefficient star formation: the role of magnetic fields and radiative feedback

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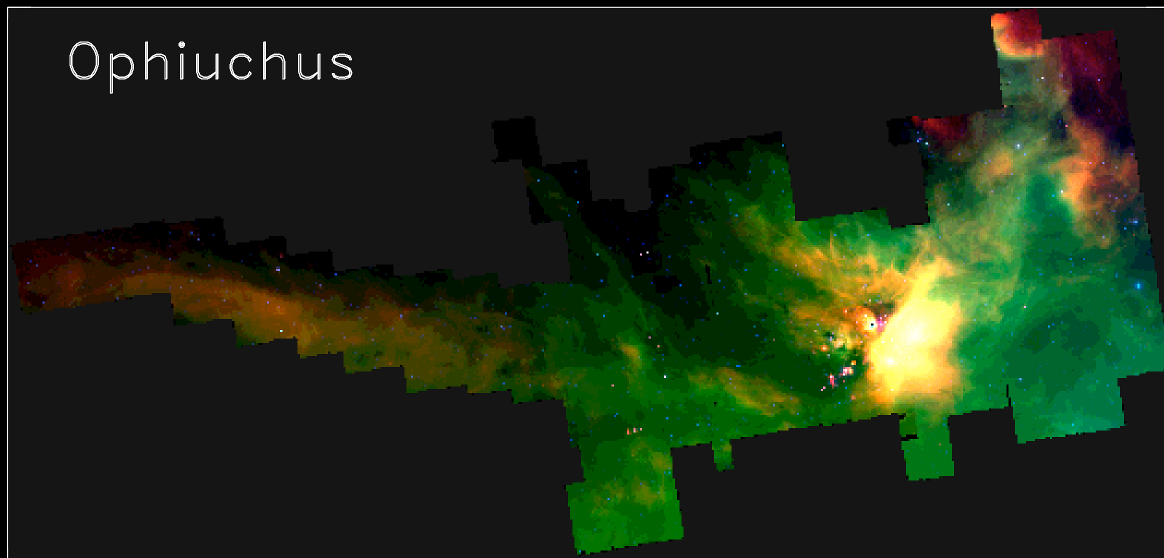
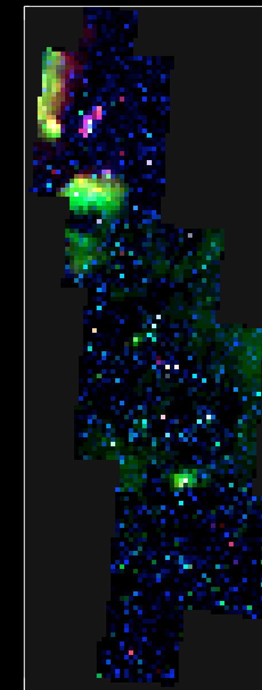
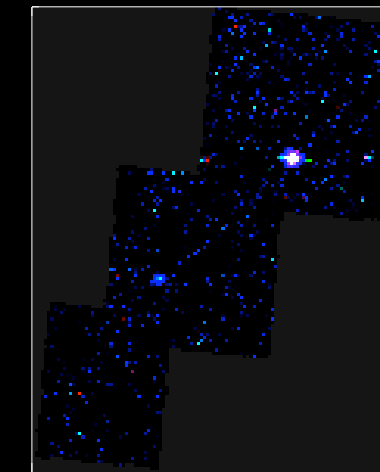
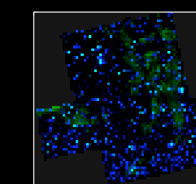
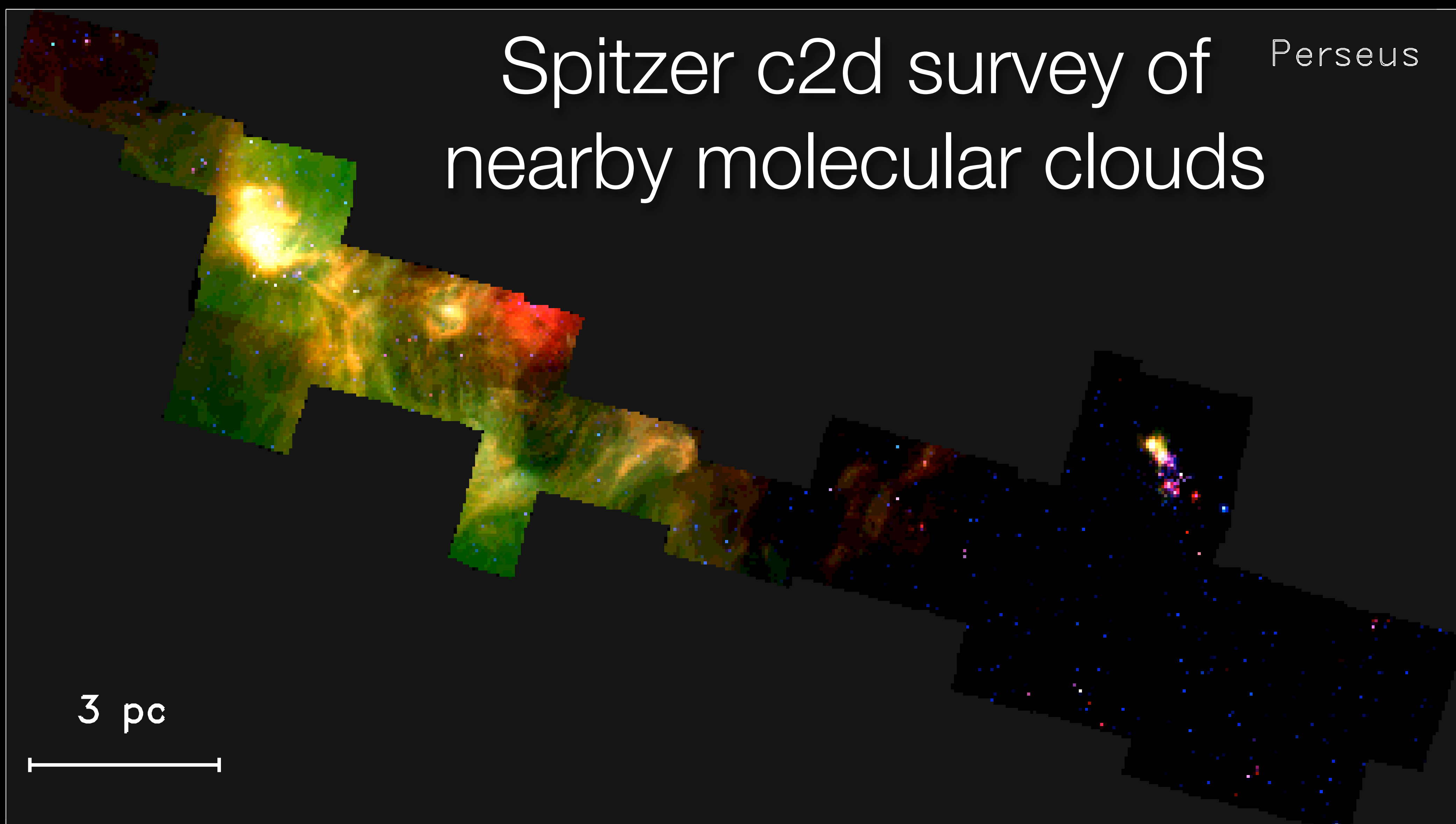
Spitzer c2d survey of nearby molecular clouds

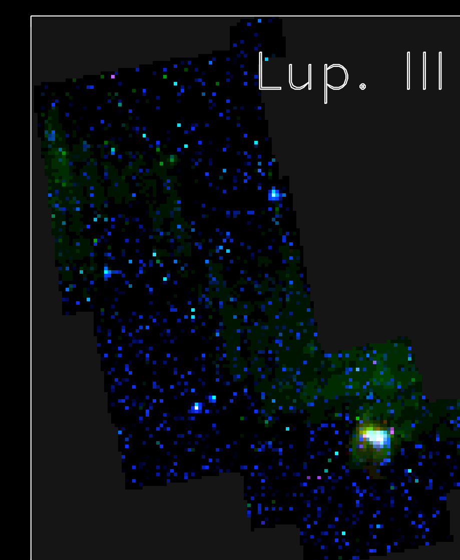


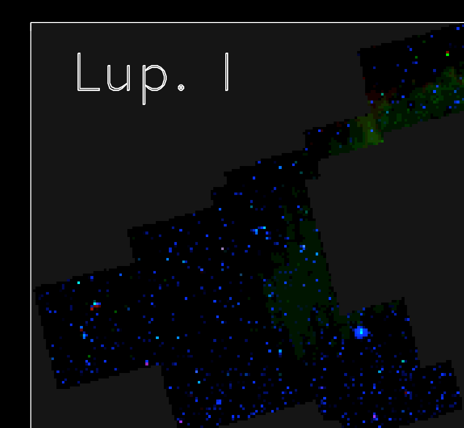




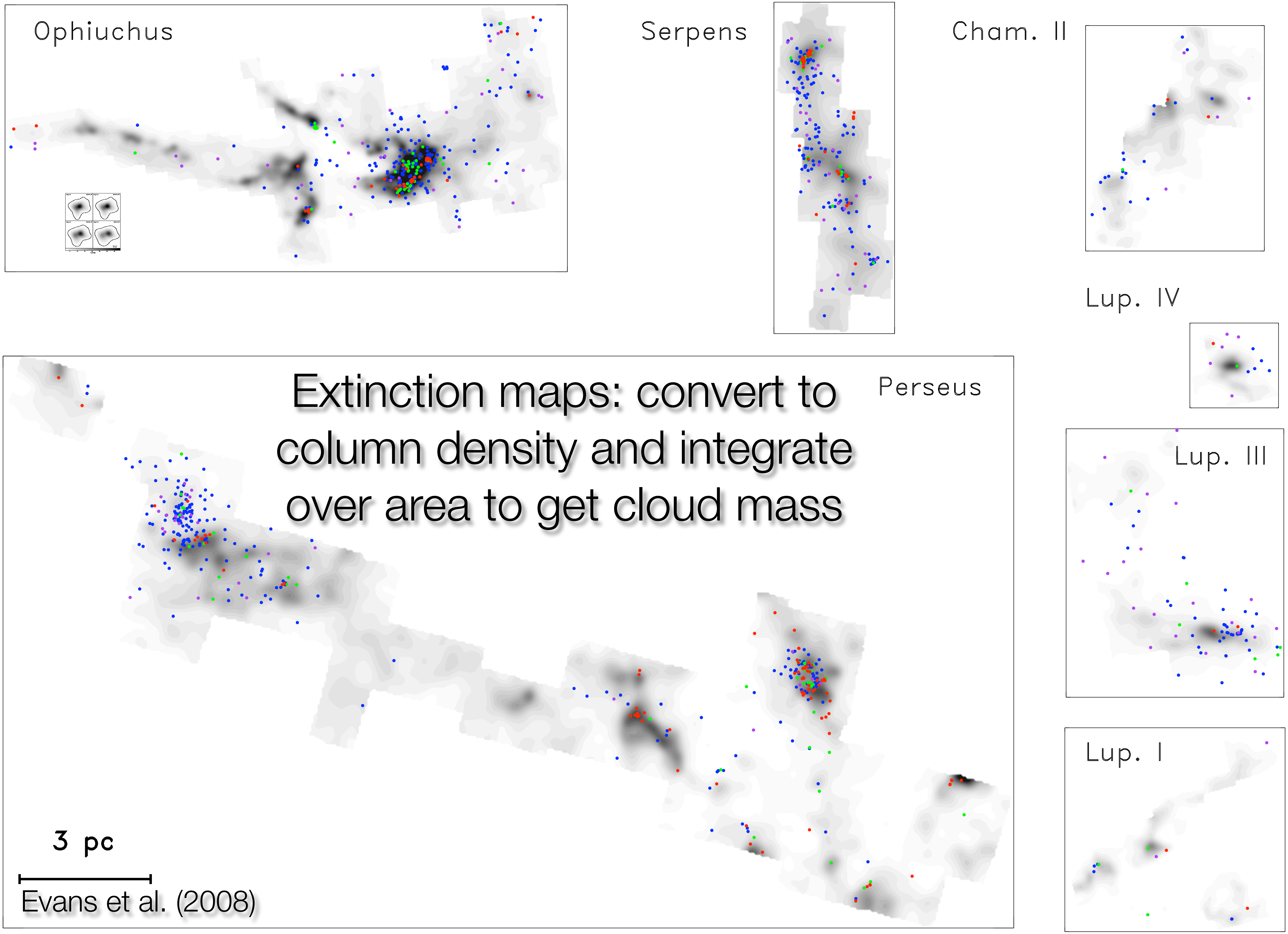








Evans et al. (2008)



Ophiuchus
Serpens
Cham. II
Lup. IV
Lup. III
Lup. I
Perseus
Extinction maps: convert to column density and integrate over area to get cloud mass
3 pc
Evans et al. (2008)

Evans et al. (2008):

TABLE 1

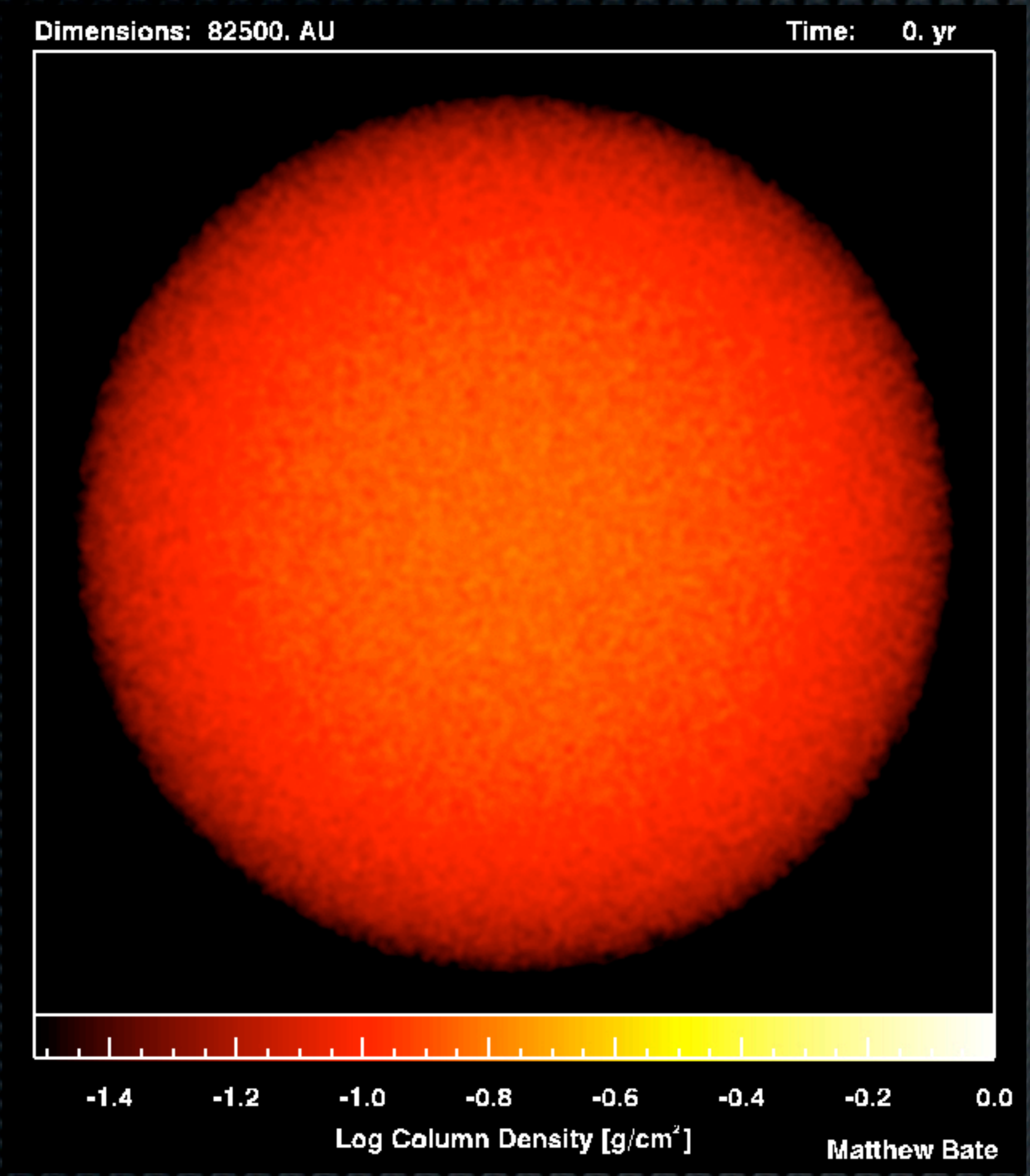
FACTS ABOUT CLOUDS

Cloud	Solid angle (deg^2)	Distance (pc)	Area (pc^2)	Δv (km s^{-1})	Mass[a] (M$_\odot$)	$\langle n \rangle$[b] (cm^{-3})	t(cross) (Myr)	Refs
Cha II	1.038	178 ± 18	10.0 ± 2.0	1.2	426 ± 86	345	3.7	1, 2
Lupus	3.101	150 ± 20[c]	28.4 ± 6.5	1.2	816 ± 188	381	4.7[d]	3, 4
Perseus	3.864	250 ± 50	73.6 ± 29.4	1.54 ± 0.11	4814 ± 1925	196	7.8	5, 6
Serpens	0.850	260 ± 10	17.5 ± 1.4	2.16 ± 0.01	2016 ± 155	707	2.7	7, 6
Ophiuchus	6.604	125 ± 25	31.4 ± 12.6	0.94 ± 0.11	2182 ± 873[e]	318	8.4	8, 6
Total	15.457	...	160.9 ± 51.9	...	10254 ± 3228	389	...	

- efficiency is mstar / (mstar + mcloud) where star = class II object (star+disc)
- ~3-6% efficiency (also 3-6% converted into stars per free-fall time)

Dynamical ("rapid") models of star formation

e.g. Bate, Bonnell & Bromm (2003), Bonnell, Bate & Vine (2003), Bate & Bonnell (2005), Bate (2008)



Bate, Bonnell & Bromm (2003)

- main ingredients are turbulence, gravity
- reproduce gross characteristics of the IMF, multiplicity as a function of mass, frequency of low mass binaries, ...
- BUT star formation efficiency too high (all gas would eventually form stars). Observations suggest 3-6%
- produce too many brown dwarfs (Bate 2009).
- missing observationally constrained physics in the form of magnetic fields and radiative feedback

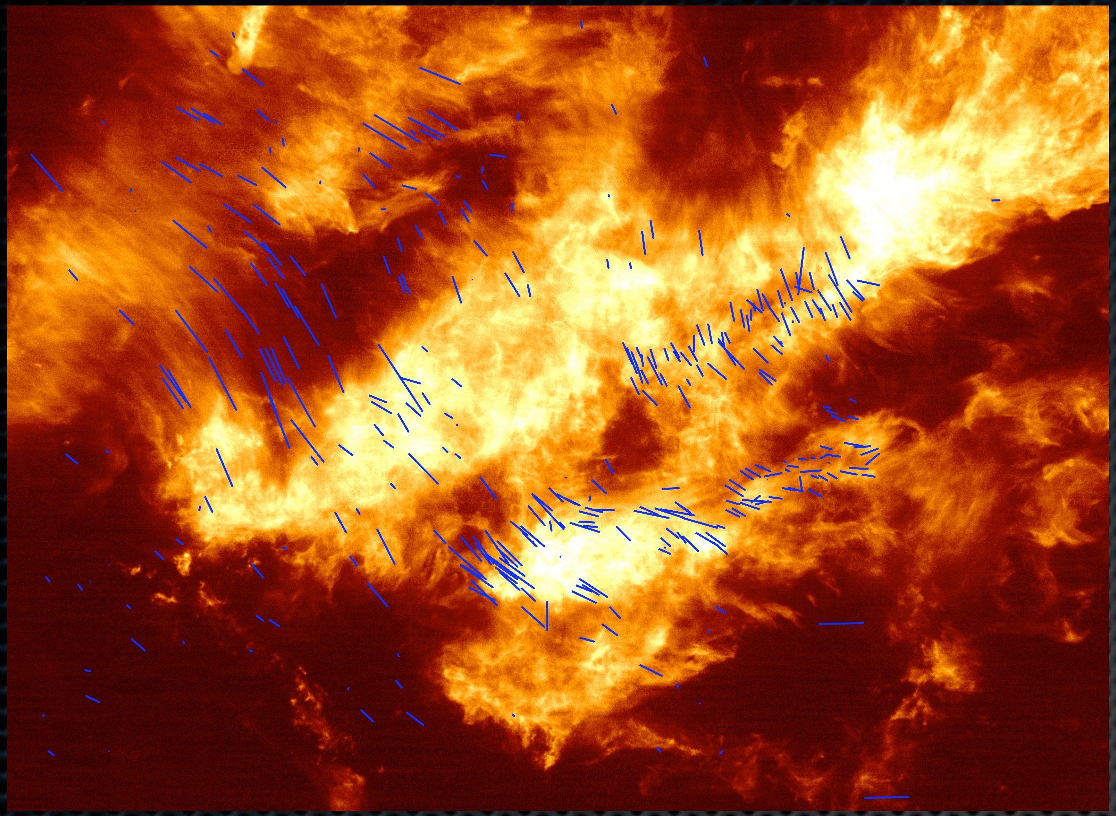
How to make star formation inefficient

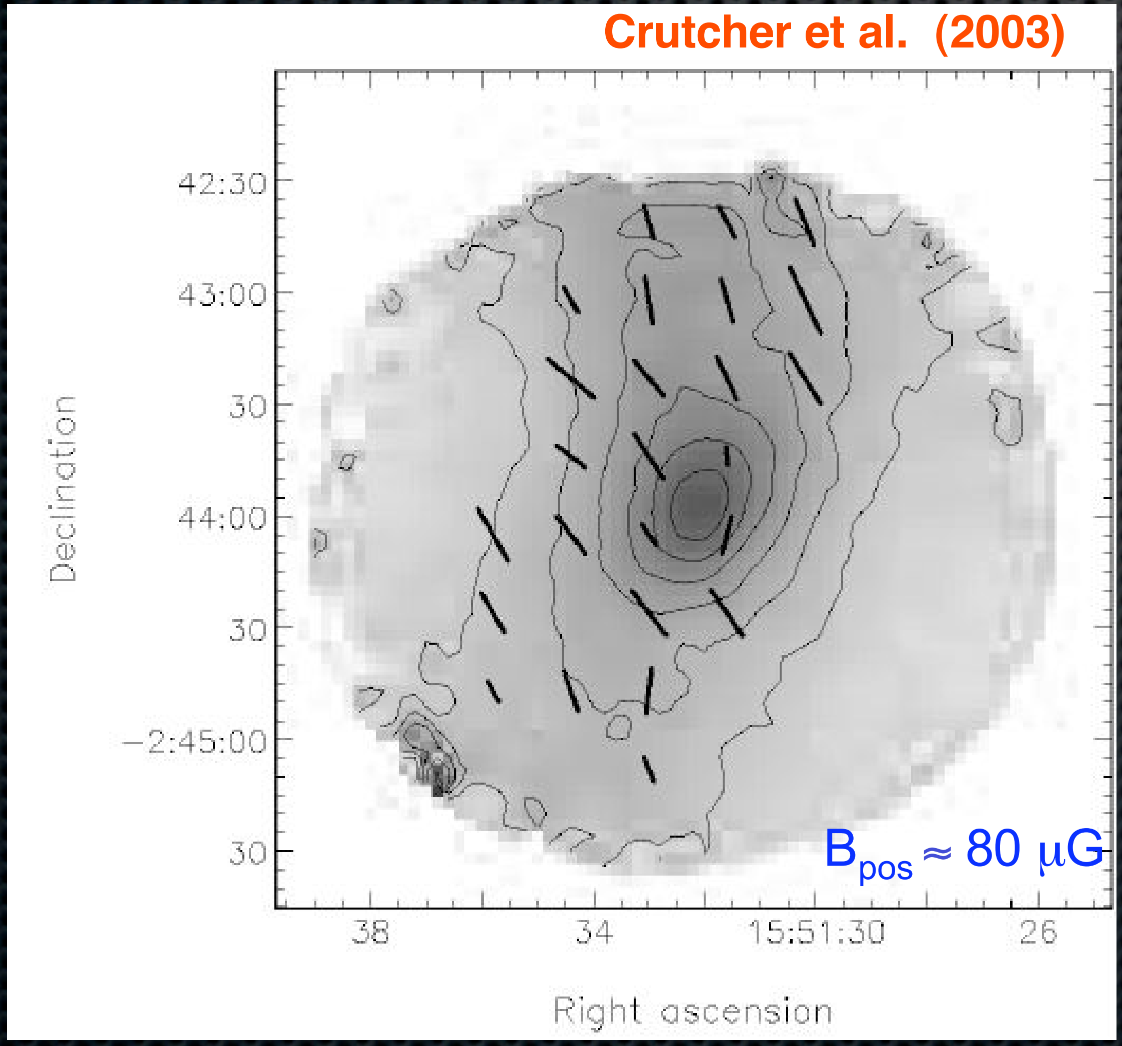
- increase the level of turbulence (Clark & Bonnell 2004) / continual driving (Klessen et al.)
- feedback from jets and outflows (Matzner & Mckee 2000, Nakamura & Li 2007)
- tidal forces in the Galaxy pulling cloud apart again (Ballesteros-Peredes et al. 2009)
- include more physics... like magnetic fields and radiative feedback

Radiation

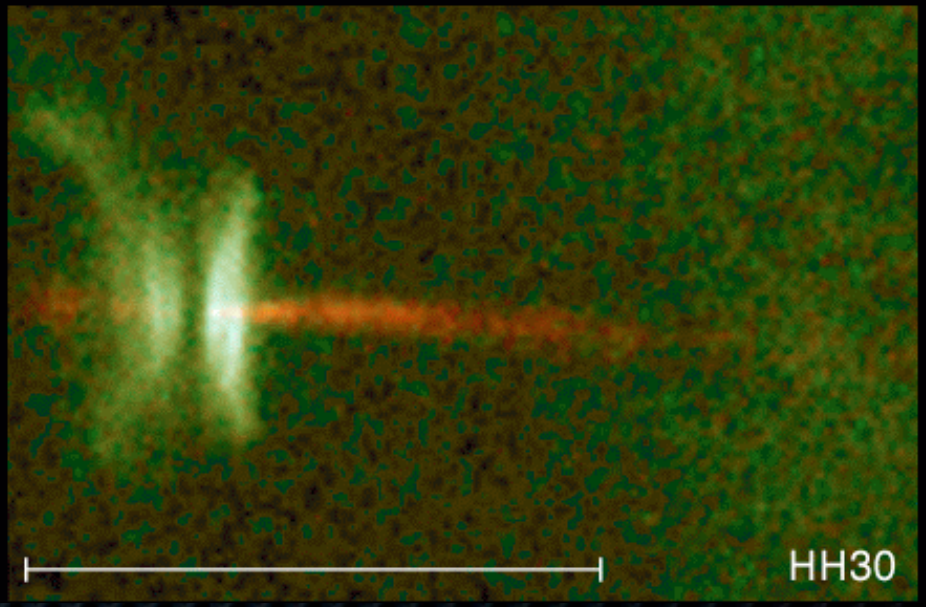
- heats surrounding material
- hot gas does not collapse to form stars

Magnetic fields





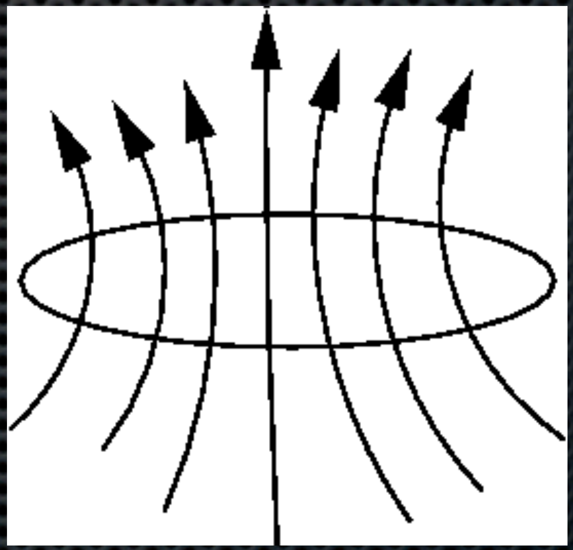
- star formation regions known to contain magnetic fields of significant strengths
- want to determine their role in the star formation process



Magnetic fields and star formation

e.g. Maclow & Klessen 2004, Mestel 1999

- magnetic flux conserved during collapse
- critical "mass to flux ratio"



$$\left(\frac{M}{\Phi}\right)_{cr} = 490 g G^{-1} \mathrm{cm}^{-2}$$

$$\left(\frac{M}{\Phi}\right) < \left(\frac{M}{\Phi}\right)_{cr}$$ "subcritical" (stable against collapse)

$$\left(\frac{M}{\Phi}\right) > \left(\frac{M}{\Phi}\right)_{cr}$$ "supercritical" (will collapse rapidly)

once unstable to collapse, will collapse on free-fall timescale:
changes nothing about the rate of star formation

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)

Star formation modelling

length scales: 7 orders of magnitude

$$R_{GMC} \sim 10^{12}\mathrm{km}(100\mathrm{pc}) \longrightarrow \quad R_{\odot} \sim 10^{5}\mathrm{km}$$

time scales: 11 orders of magnitude

$$10^{6}\mathrm{years} \longrightarrow \text{ 5 minutes!}$$

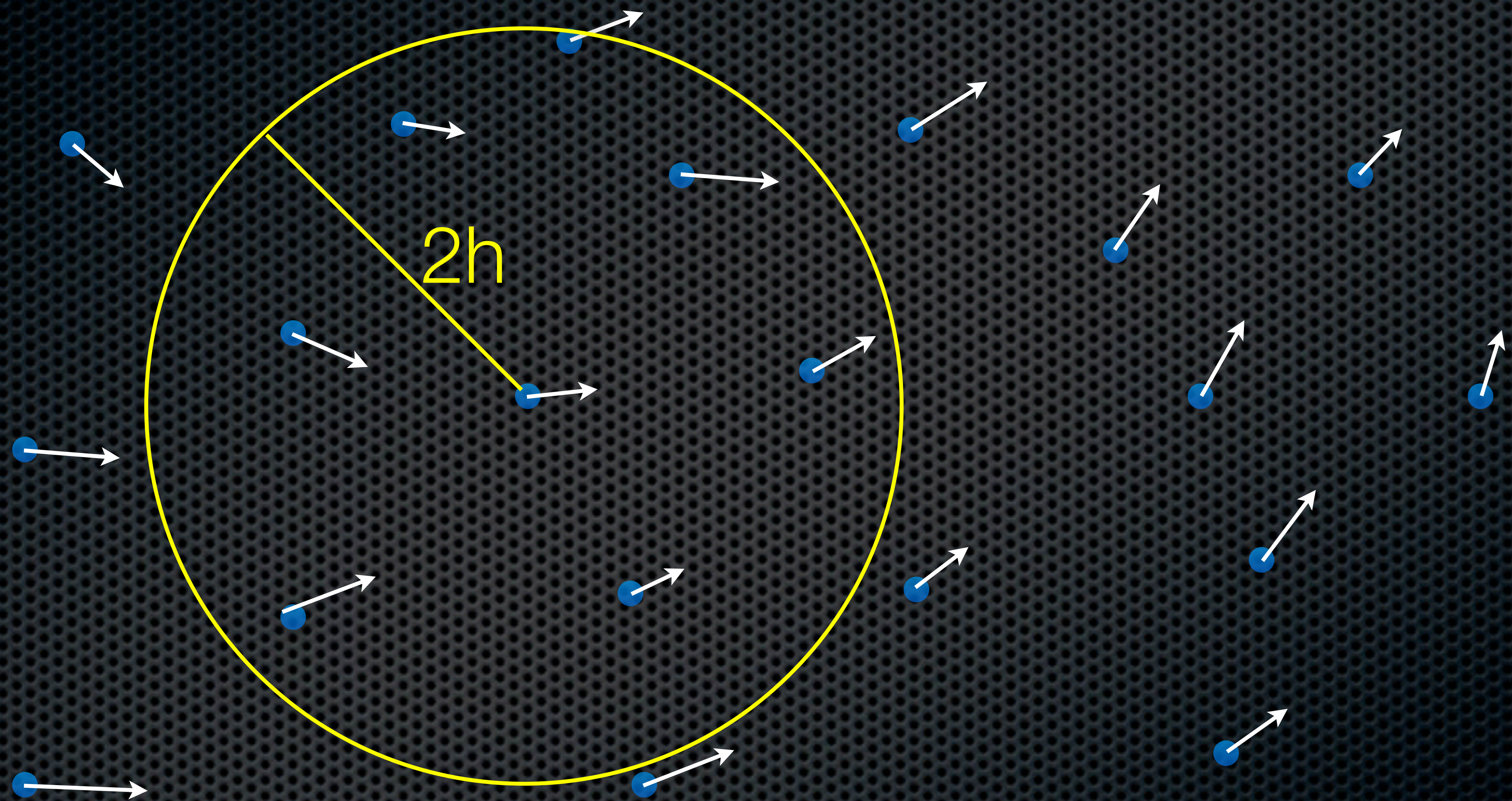
density change: 17 orders of magnitude

$$10^{4} M_{\odot}/(R_{GMC})^{3} \longrightarrow M_{\odot}/(R_{\odot})^{3}$$

Physics: self-gravity, gas dynamics, magnetic fields (non-ideal), radiation transport, dust chemistry...

Smoothed Particle Hydrodynamics

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



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

Magnetohydrodynamics (MHD)

- One-fluid approximati
  to plasma physics
- no charge separa
- we assume ide
  (no resistivity or
  ambipolar diffusio

$$\frac{d\rho}{} \quad \nabla \cdot \mathbf{v}$$

$$\left(P + \frac{1}{2}\frac{B^2}{\mu_0}\right)\mathbf{I} - \frac{\mathbf{B}\mathbf{B}}{\mu_0}\bigg]$$

GRATUITOUS
EQUATION WARNING!

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

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

Technical issues with MHD+SPH

1) Momentum conserving force is unstable

use force which vanishes for constant stress

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

(Morris 1996)

2) Shocks

formulate artificial dissipation terms (PM04a)

$$\left(\frac{d\mathbf{v}}{dt}\right)_{diss} = -\sum_b m_b \frac{\alpha v_{sig}(\mathbf{v}_a - \mathbf{v}_b)\cdot\hat{r}}{\bar{\rho}_{ab}} \nabla_a W_{ab},$$

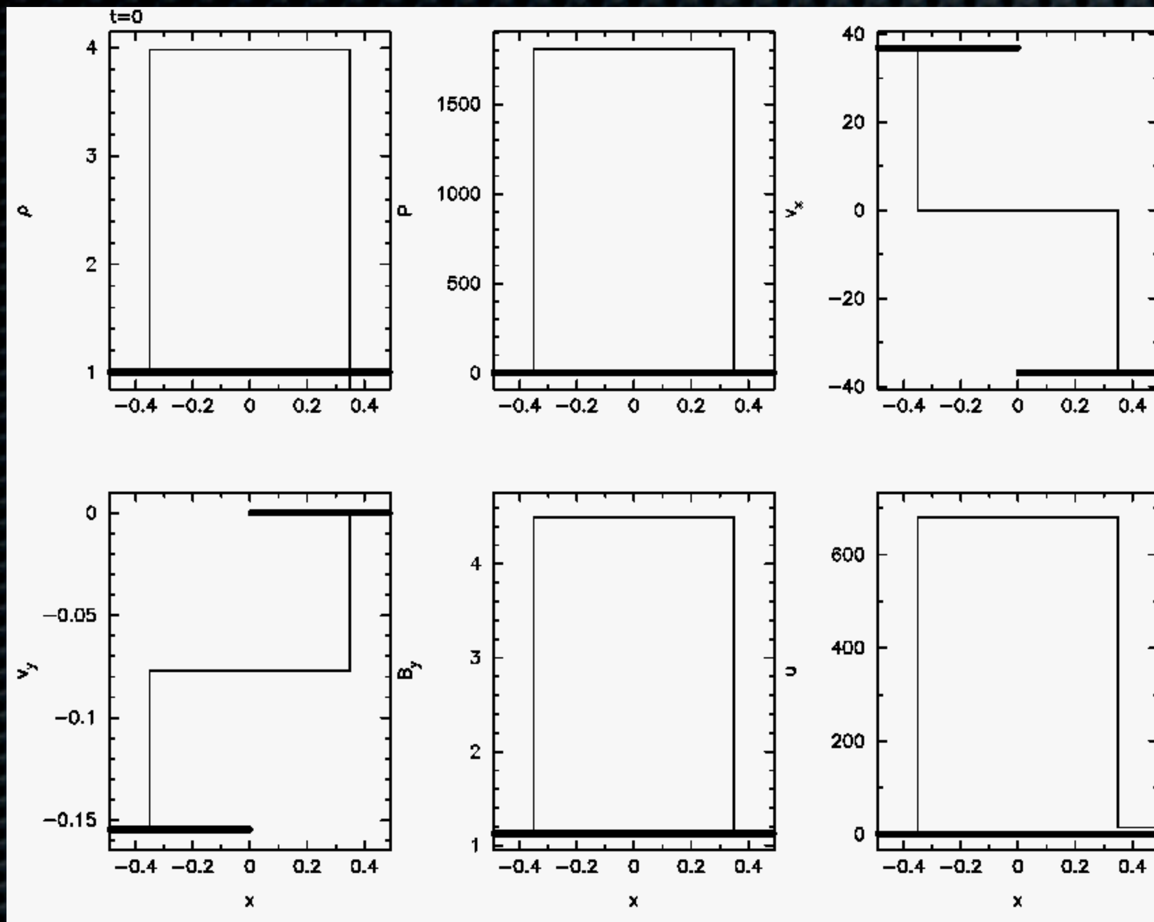
$$\left(\frac{d\mathbf{B}}{dt}\right)_{diss} = \rho_a \sum_b m_b \frac{\alpha_B v_{sig}}{\bar{\rho}_{ab}^2} (\mathbf{B}_a - \mathbf{B}_b)\, \hat{r}\cdot\nabla_a W_{ab}$$

$$\left(\frac{de_a}{dt}\right)_{diss} = -\sum_b m_b \frac{v_{sig}(e_a^* - e_b^*)}{\bar{\rho}_{ab}} \hat{r}\cdot\nabla_a W_{ab}$$

3) Variable h

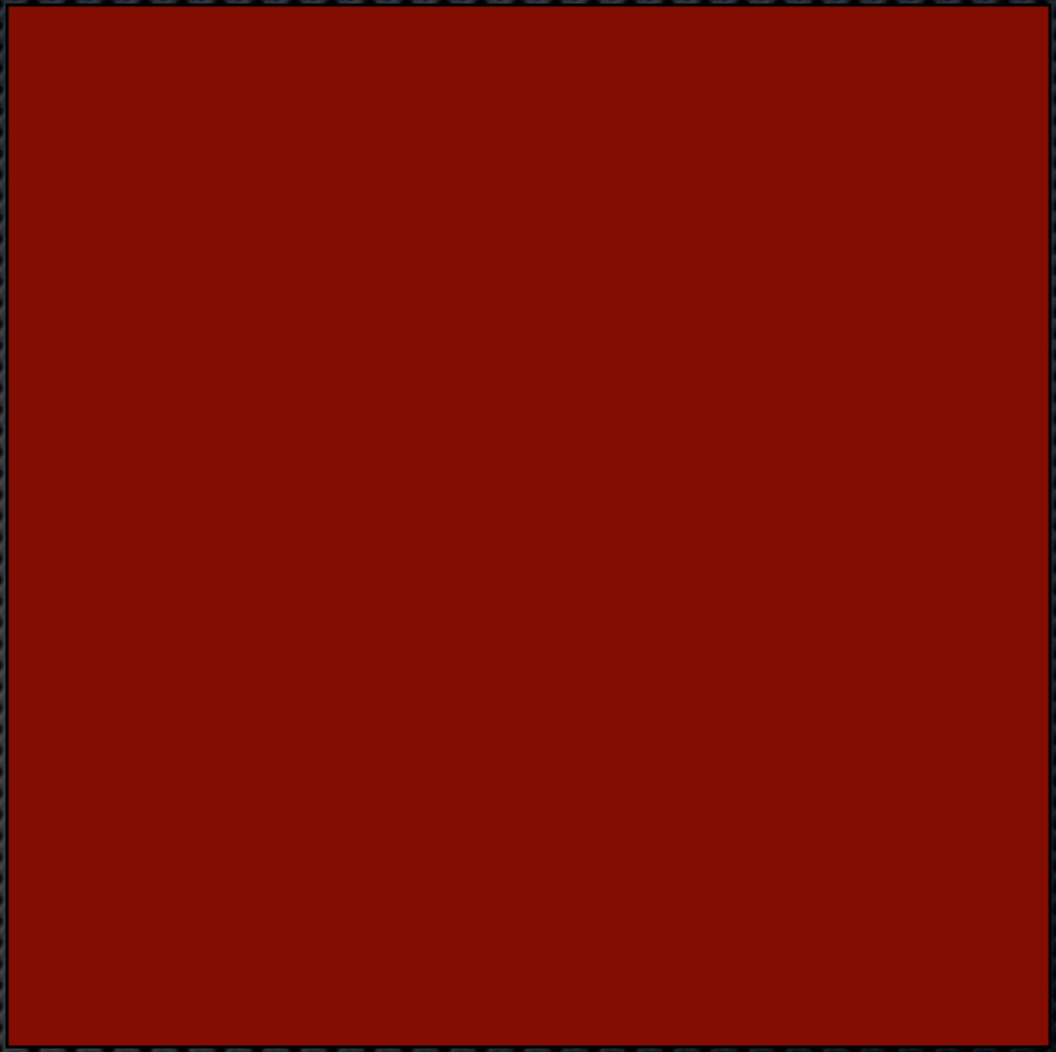
use Lagrangian (Price & Monaghan 2004b)

Test problems



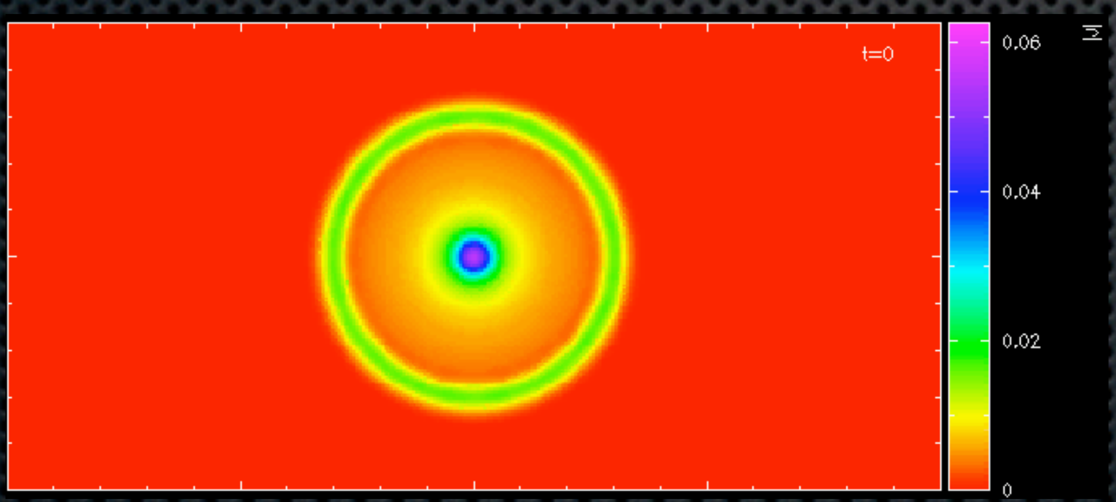
Mach 25 MHD shock (e.g. Balsara 1998)

(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 ∇•B = 0 constraint

- lots of things *don't* work very well (e.g. Dedner et al. cleaning)
- Euler potentials:

Euler (1770), Stern (1976),
Phillips & Monaghan (1985)

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

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'

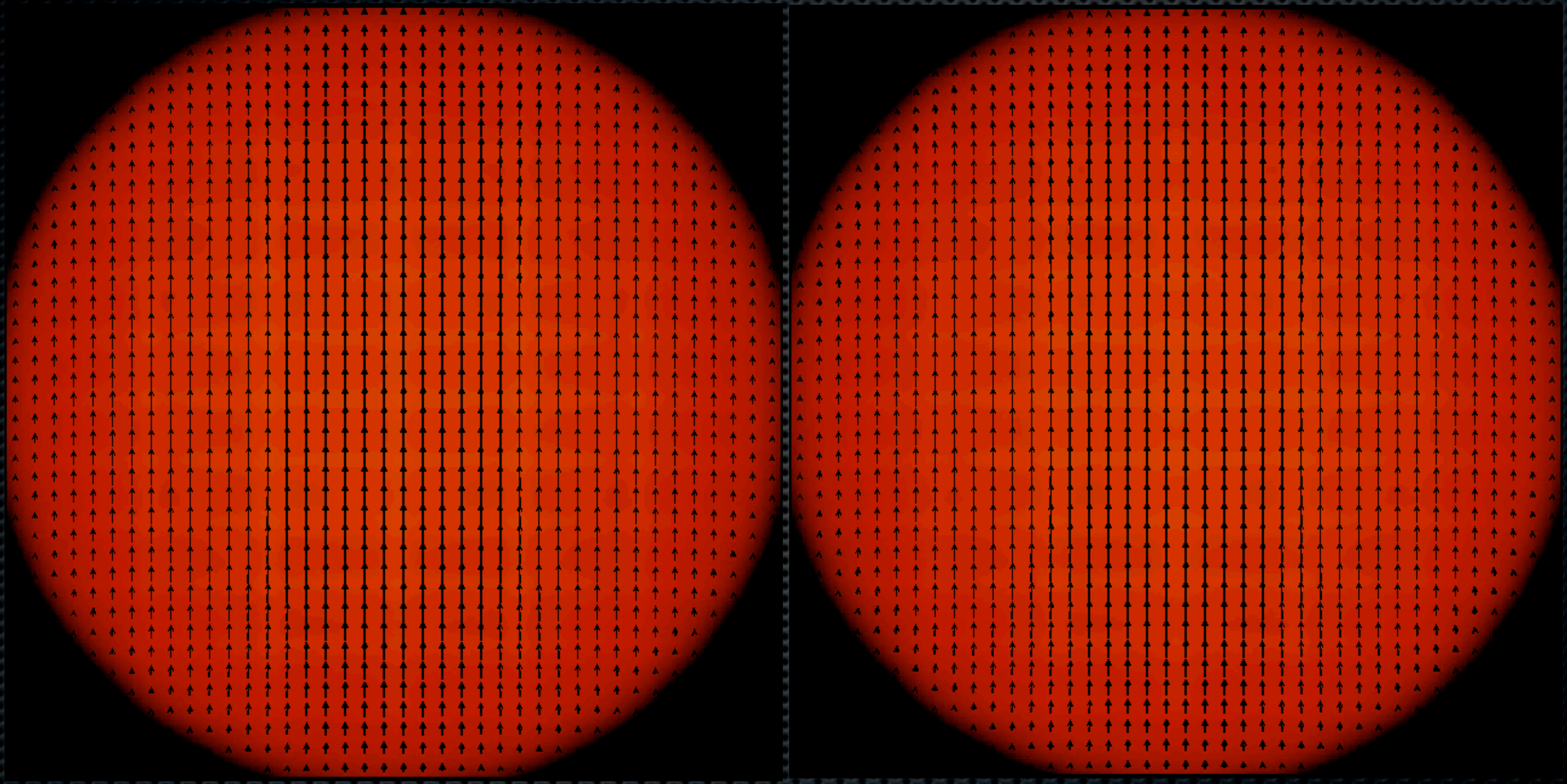
add shock dissipation

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

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

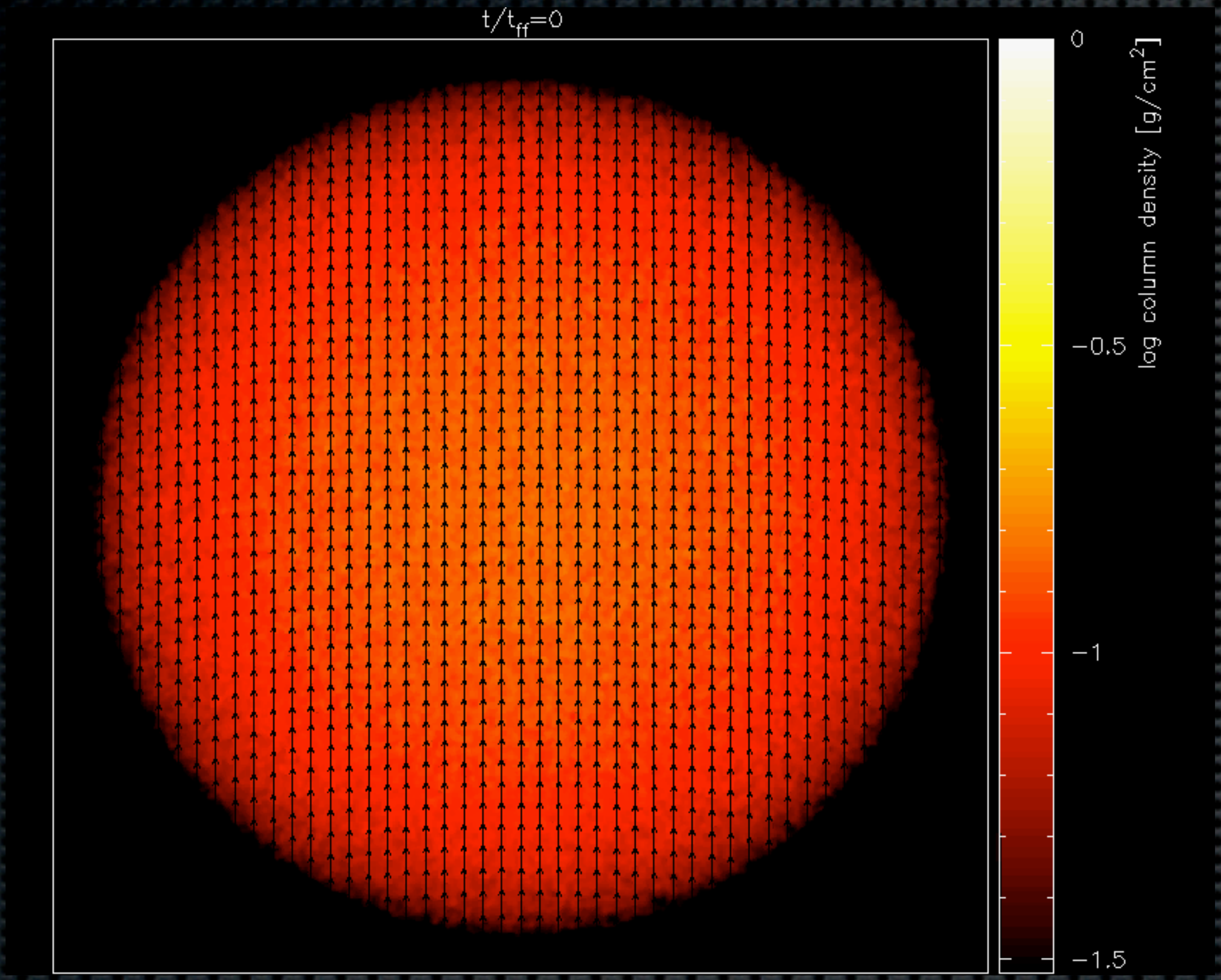
- disadvantages: helicity constraints (A.B = 0)
- field growth suppressed once clear mapping from initial to final particle distribution is lost - DON'T FOLLOW FIELD WINDING (for long)

Star formation



Magnetic fields in star cluster formation

Price & Bate (2008) MNRAS 385, 1820

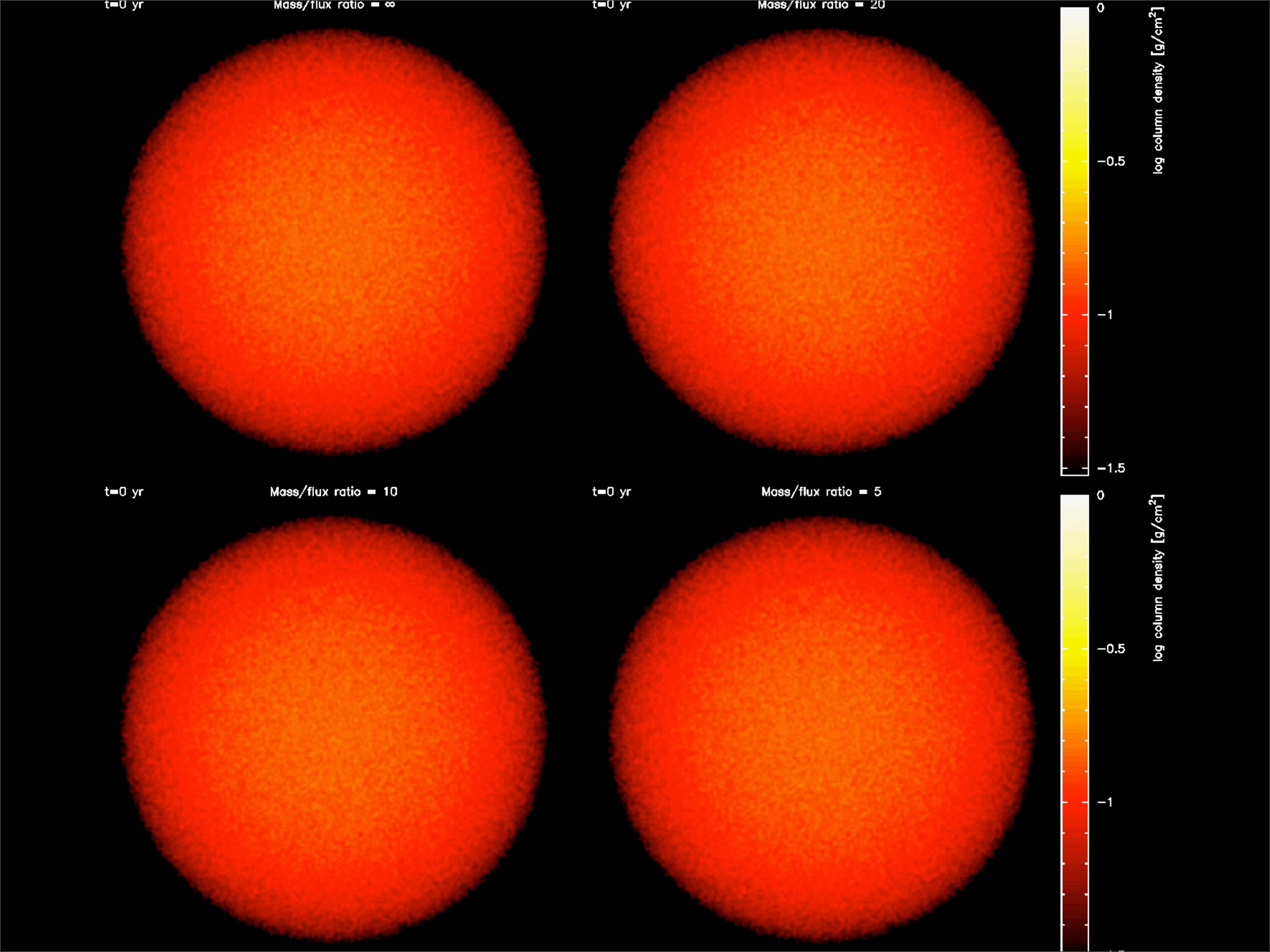


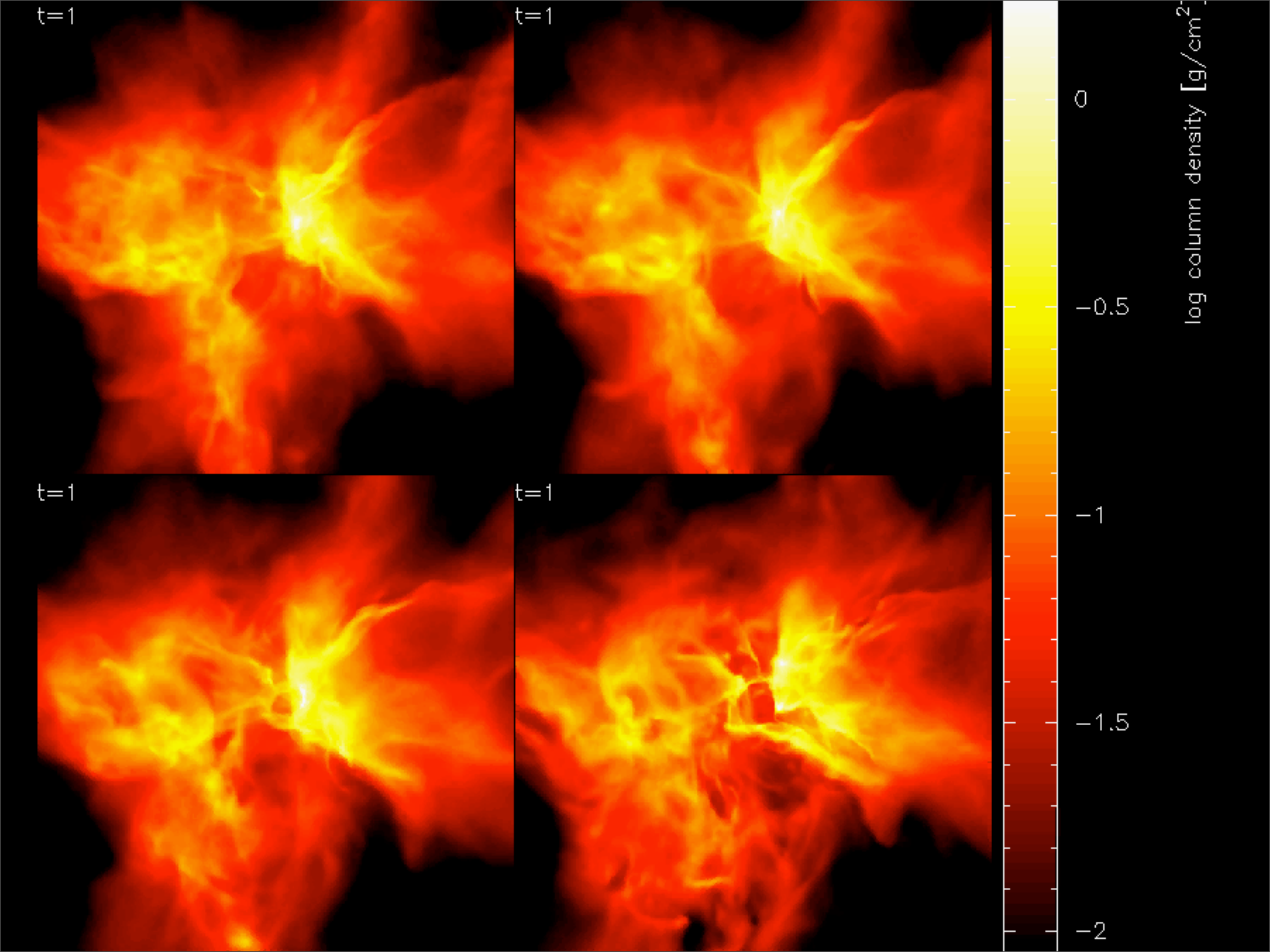
- 50 solar mass cloud
- diameter 0.375 pc, $n_{H2} = 3.7 \times 10^4$
- initial uniform B field
- T=10K
- turbulent velocity field $P(k) \propto k^{-4}$
- RMS Mach number 6.7
- barytropic equation of state

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

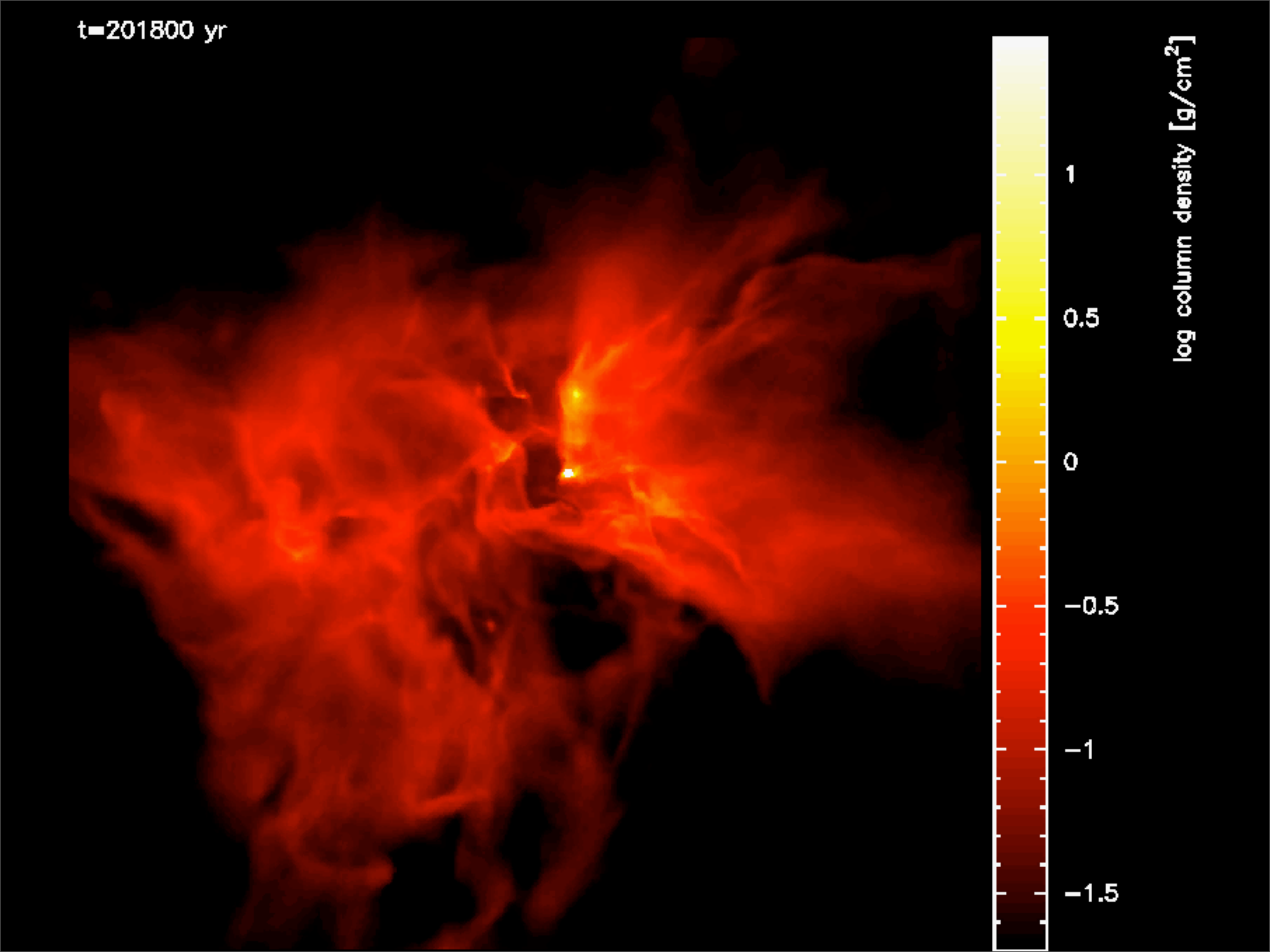
$$\gamma = 1, \qquad \rho \le 10^{-13}\text{g cm}^{-3},$$
$$\gamma = 7/5, \qquad \rho > 10^{-13}\text{g cm}^{-3}.$$

vary magnetic field strength...

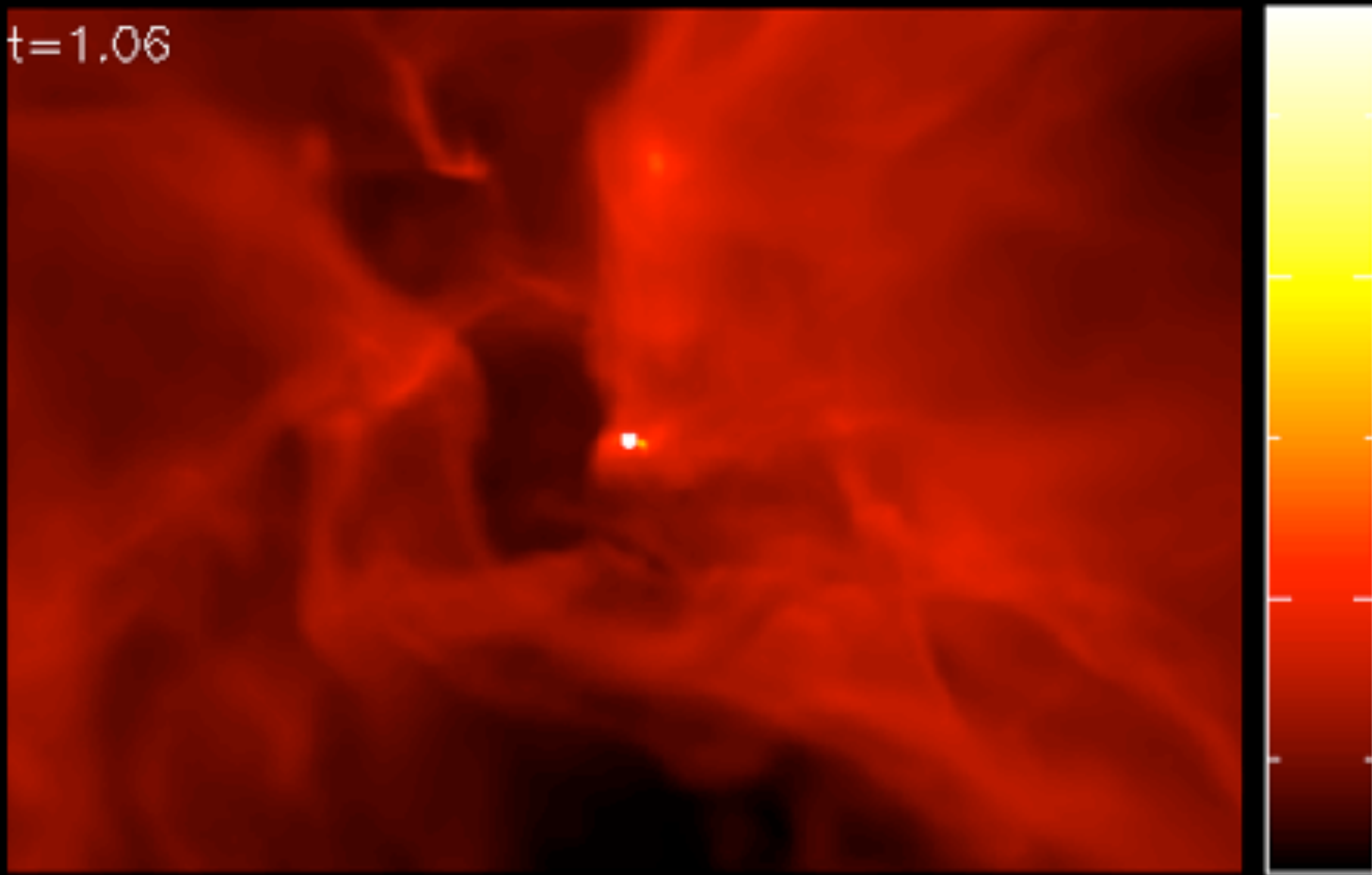

t=0 yr
Mass/flux ratio = ∞
t=0 yr
Mass/flux ratio = 20
0
−0.5
−1
−1.5
log column density [g/cm²]
t=0 yr
Mass/flux ratio = 10
t=0 yr
Mass/flux ratio = 5
0
−0.5
−1
log column density [g/cm²]

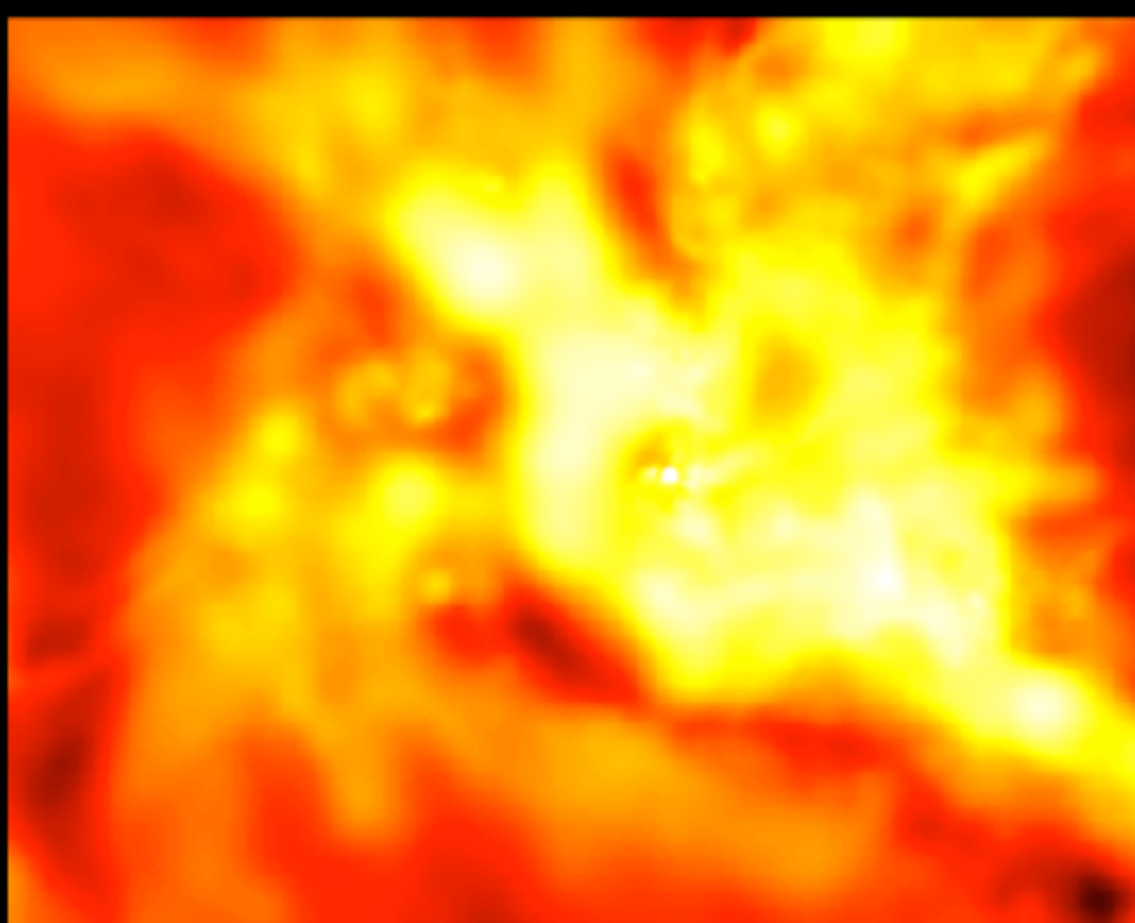


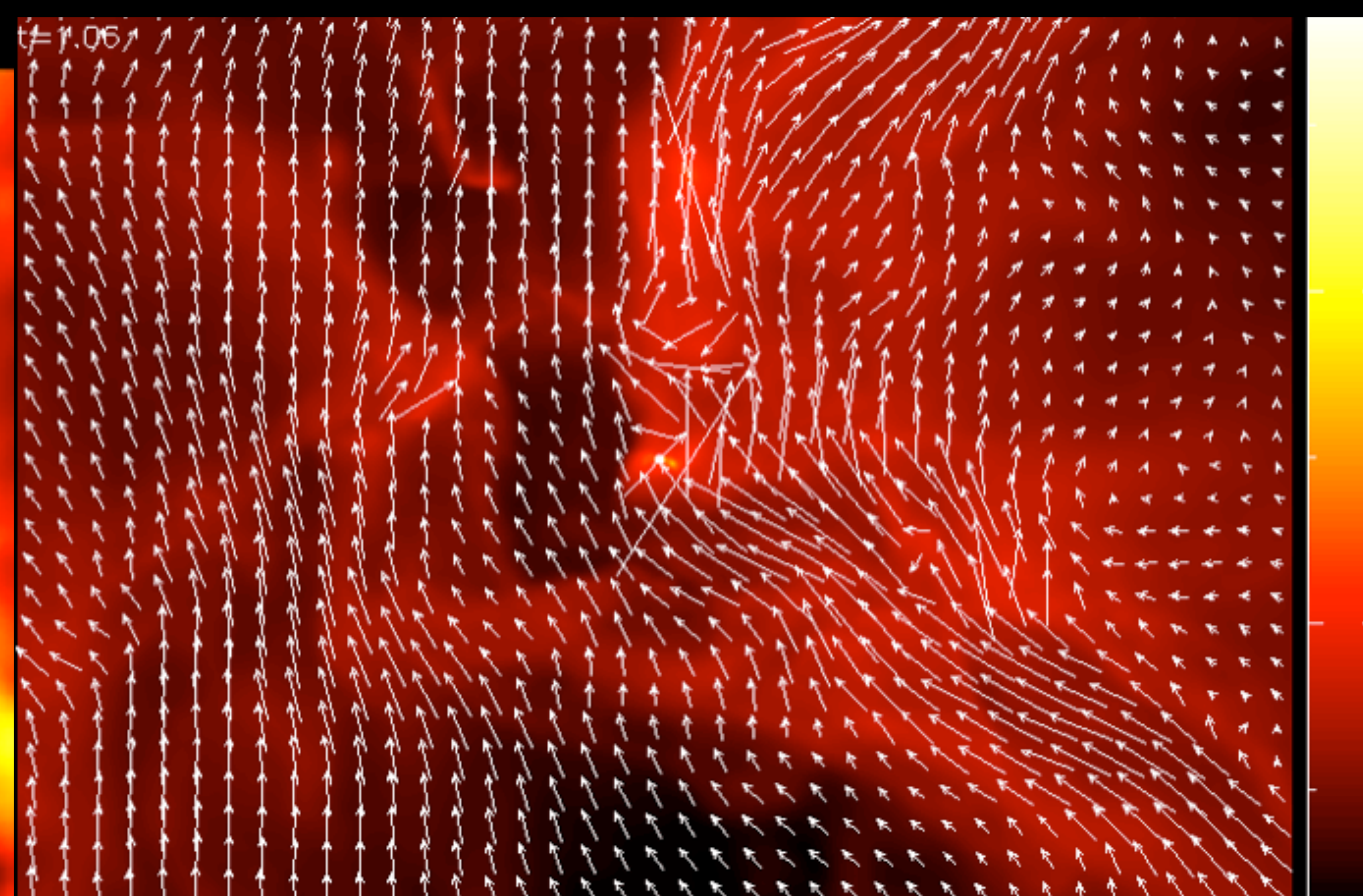
t=1
t=1
t=1
t=1
0
−0.5
−1
−1.5
−2
log column density [g/cm²]


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

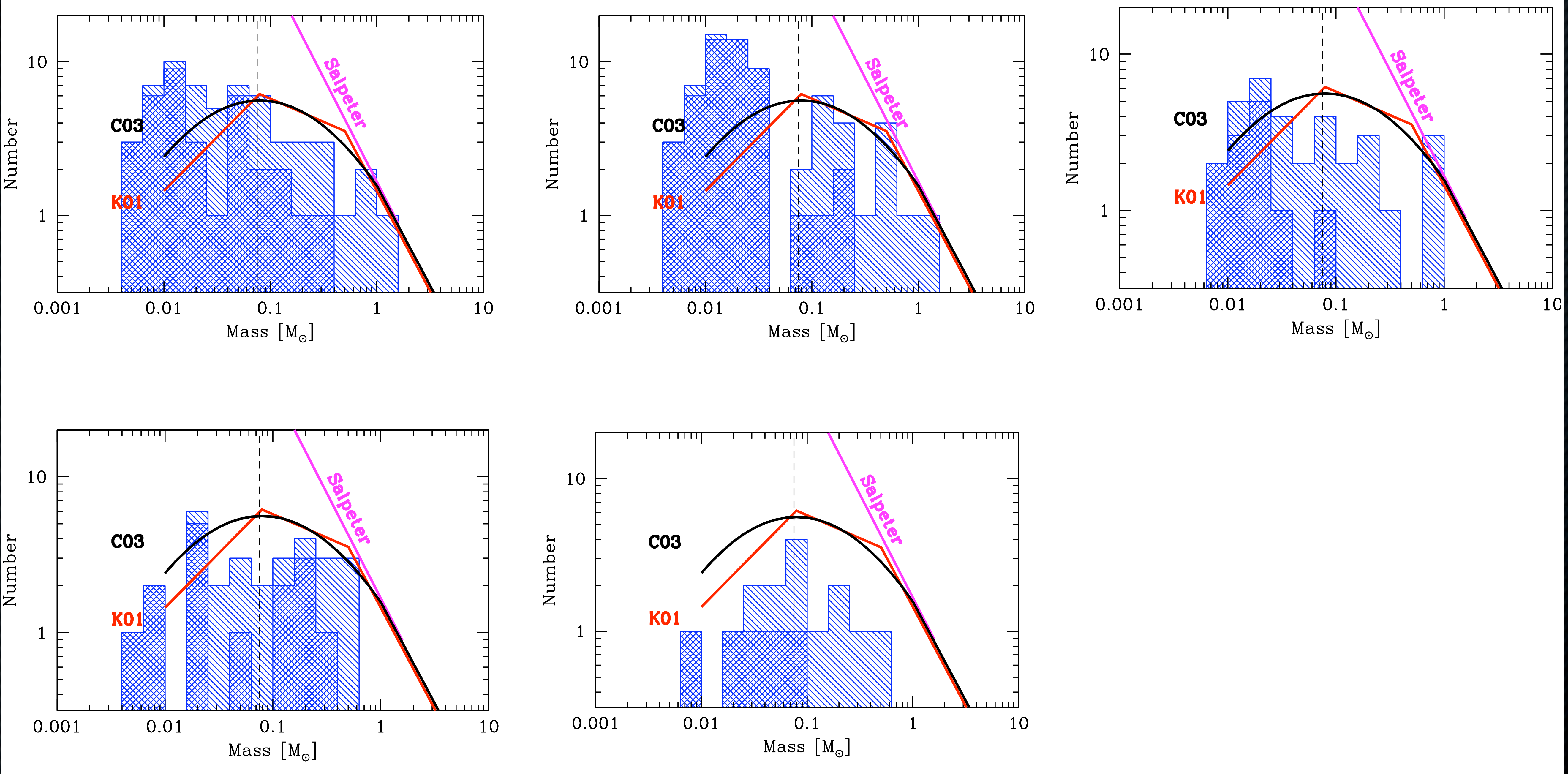
Magnetic cushioning in voids







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

Radiation

- collapsing gas becomes optically thick beyond a certain density - the "opacity limit for fragmentation"
- but radiation can be transported from hot to cold regions either diffusively in the optically thick regime or at the speed of light if optically thin
- flux-limited diffusion approximation is one that captures both optically thick and thin regimes

Self-gravitating radiation-MHD

$$\rho = \int \delta(\mathbf{r}-\mathbf{r}')\rho' dV',$$

$$\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho}\nabla\left(P + \frac{1}{2}\frac{B^2}{\mu_0} - \frac{\mathbf{BB}}{\mu_0}\right) + \frac{\chi}{c}\mathbf{F} - \nabla\Phi,$$

$$\frac{du}{dt} = -\frac{P}{\rho}\nabla\cdot\mathbf{v} + ac\kappa\left[\frac{\rho\xi}{a} - \left(\frac{u}{c_v}\right)^4\right],$$

$$\frac{d\xi}{dt} = -\frac{\nabla\cdot\mathbf{F}}{\rho} - \frac{\nabla\mathbf{v}:\mathbf{P}_{rad}}{\rho} - ac\kappa\left[\frac{\rho\xi}{a} - \left(\frac{u}{c_v}\right)^4\right],$$

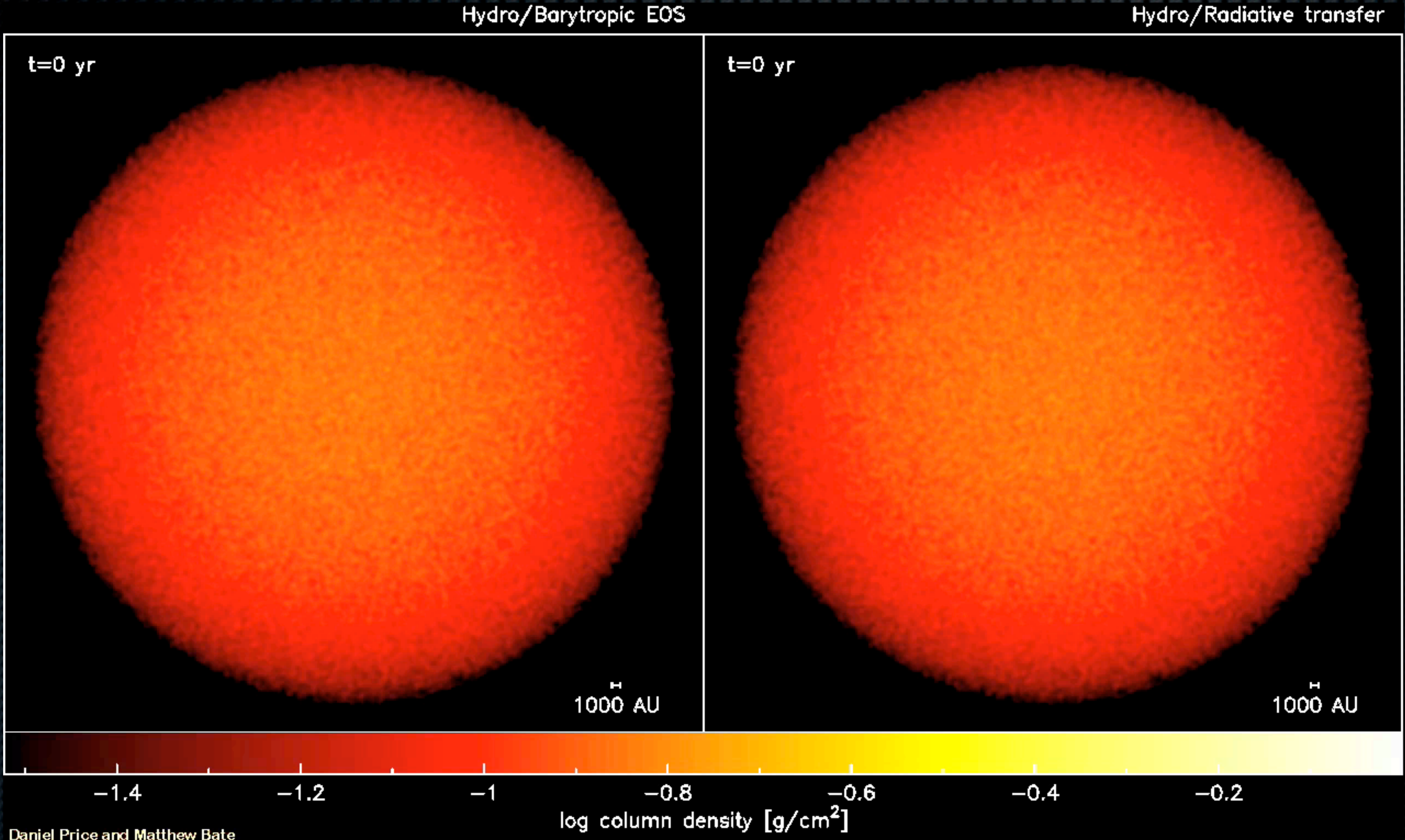
$$\mathbf{B} = \nabla\alpha_E \times \nabla\beta_E,$$

$$\frac{d\alpha_E}{dt} = 0; \qquad \frac{d\beta_E}{dt} = 0.$$

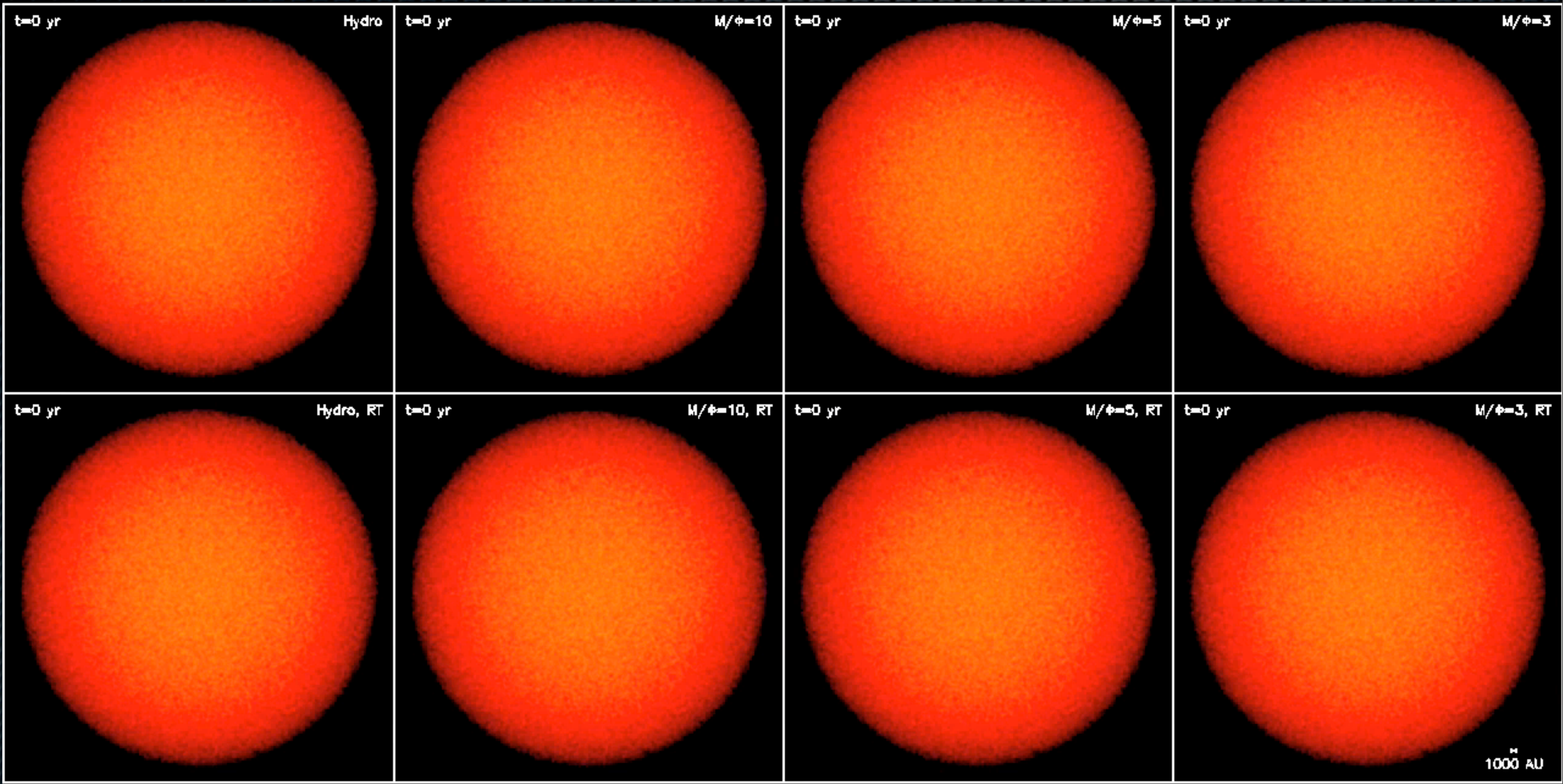
$$\nabla^2\Phi = 4\pi G\rho,$$

$$\mathbf{F} = \frac{c\lambda}{\kappa\rho}\nabla(\rho\xi)$$

Radiation hydro

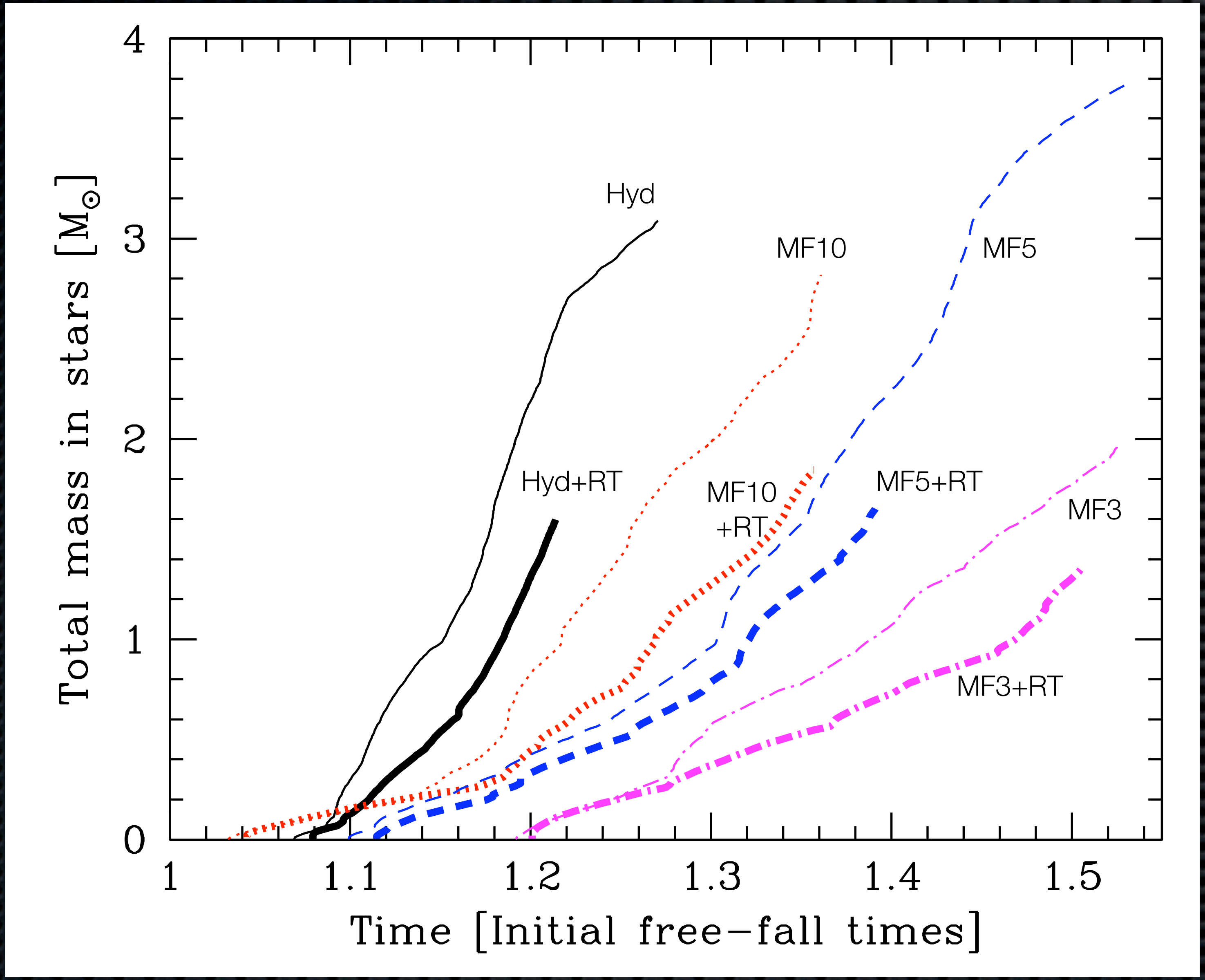


Radiation + MHD

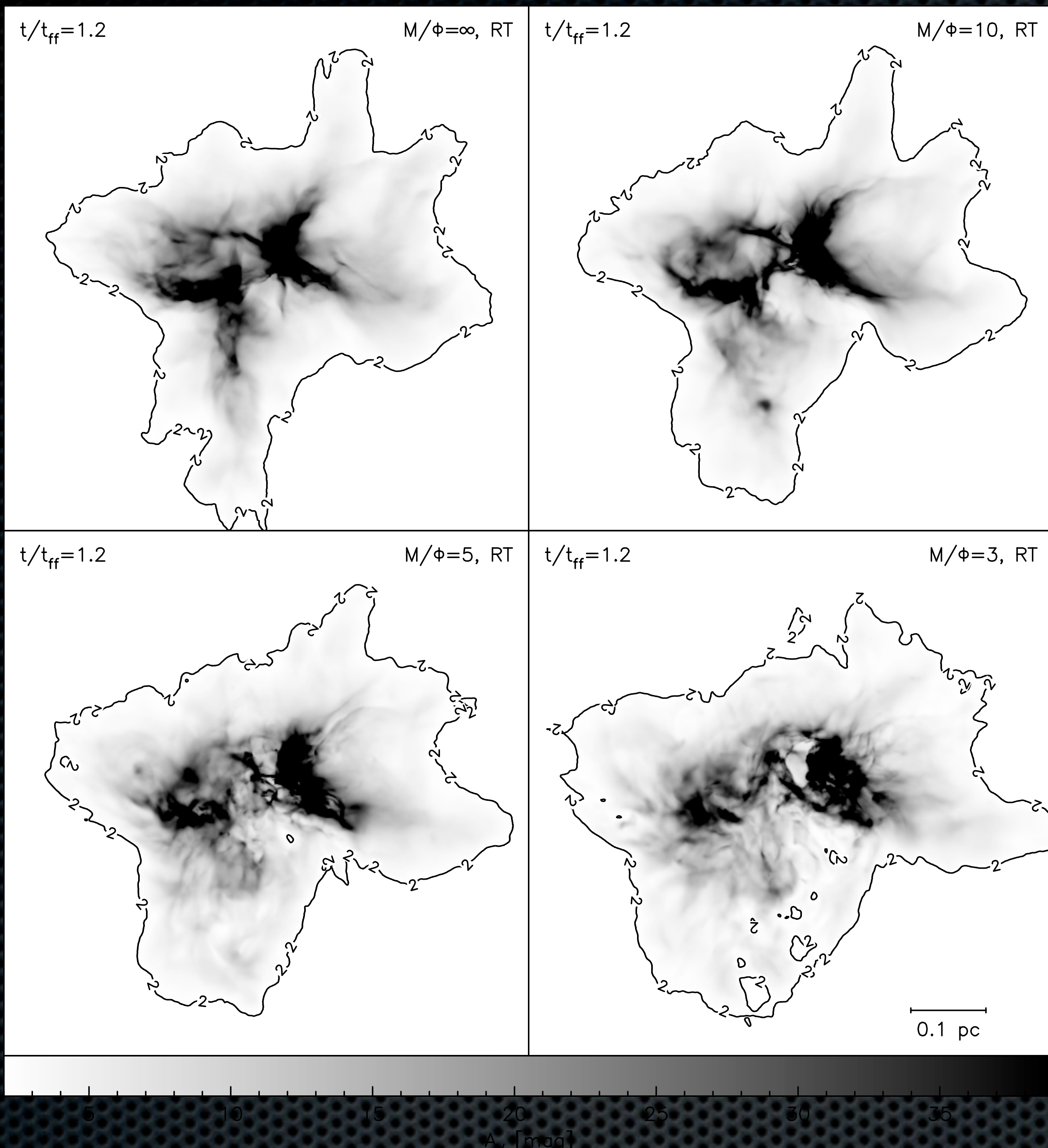


Daniel Price and Matthew Bate

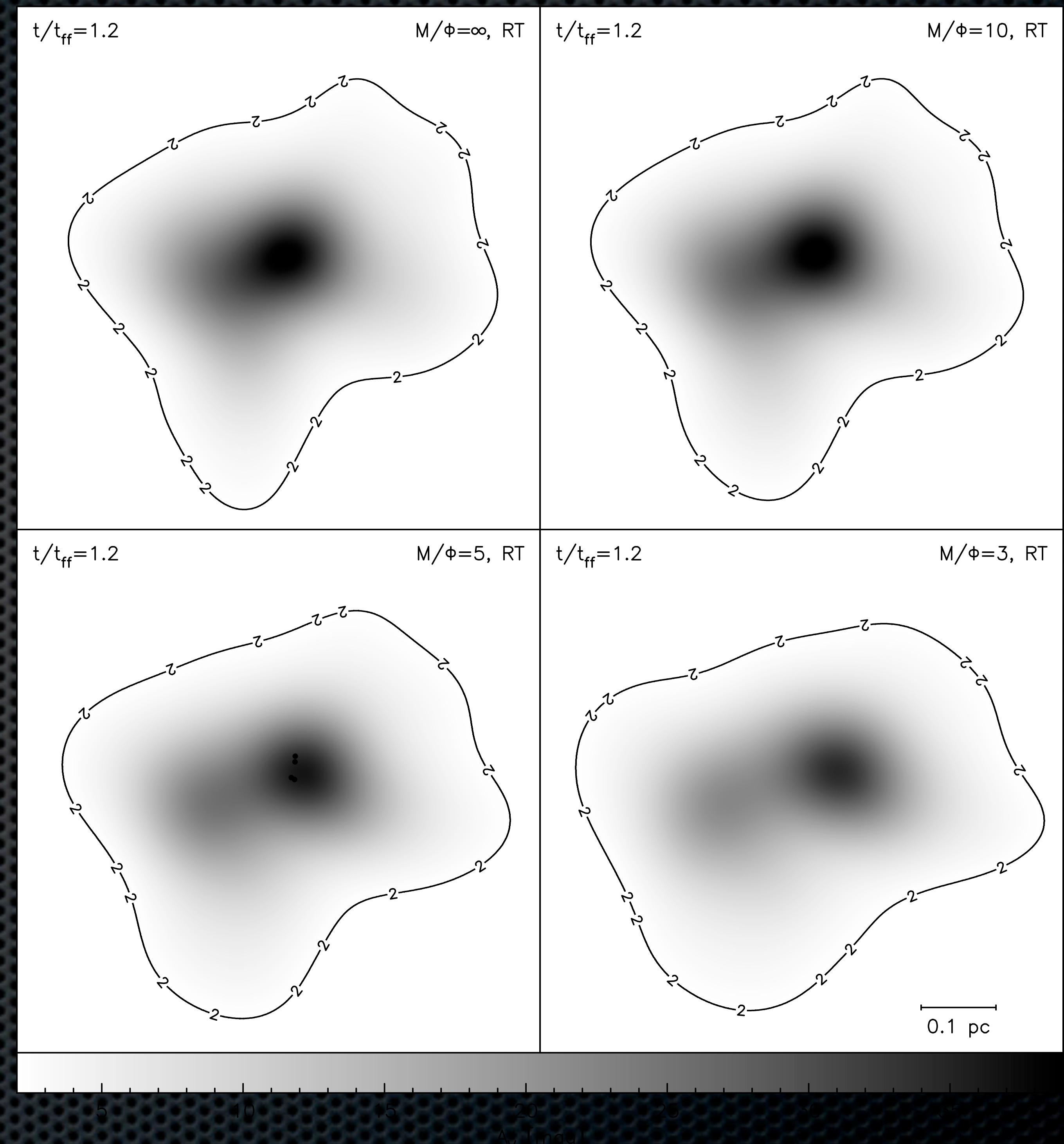
The punchline: Effect on star formation rate / efficiency



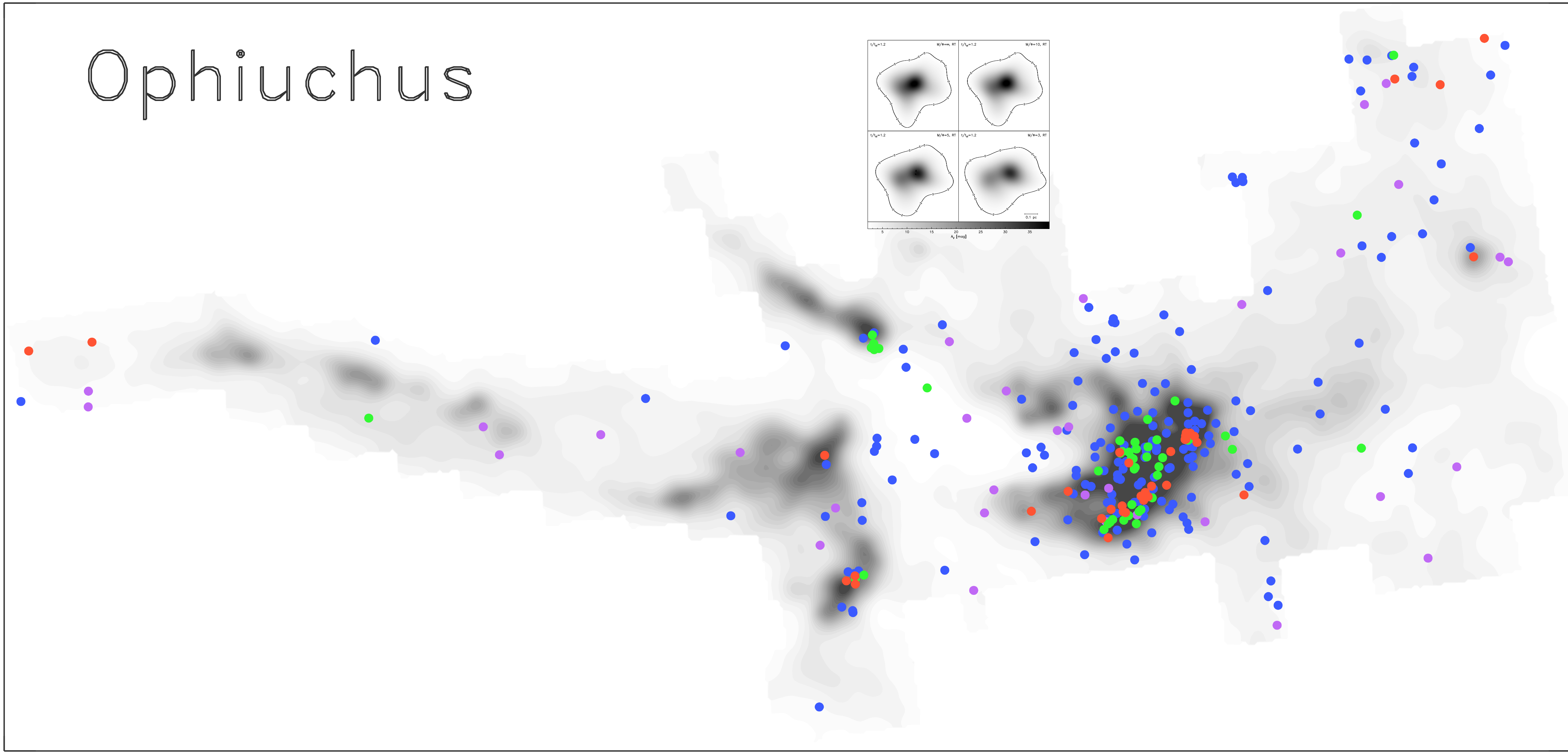
- for mass-to-flux=3 + radiative transfer, convert ~7% of gas into stars per free-fall time, in much better agreement with observations



our clouds



as observed by Spitzer


Ophiuchus

Summary

- with a proper treatment of radiative feedback and realistic magnetic field strengths, models show efficiencies of ~7% per free-fall time, in much better agreement with observations
- also form fewer brown dwarfs, solving another problem
- magnetic fields and radiative feedback may indeed regulate star formation