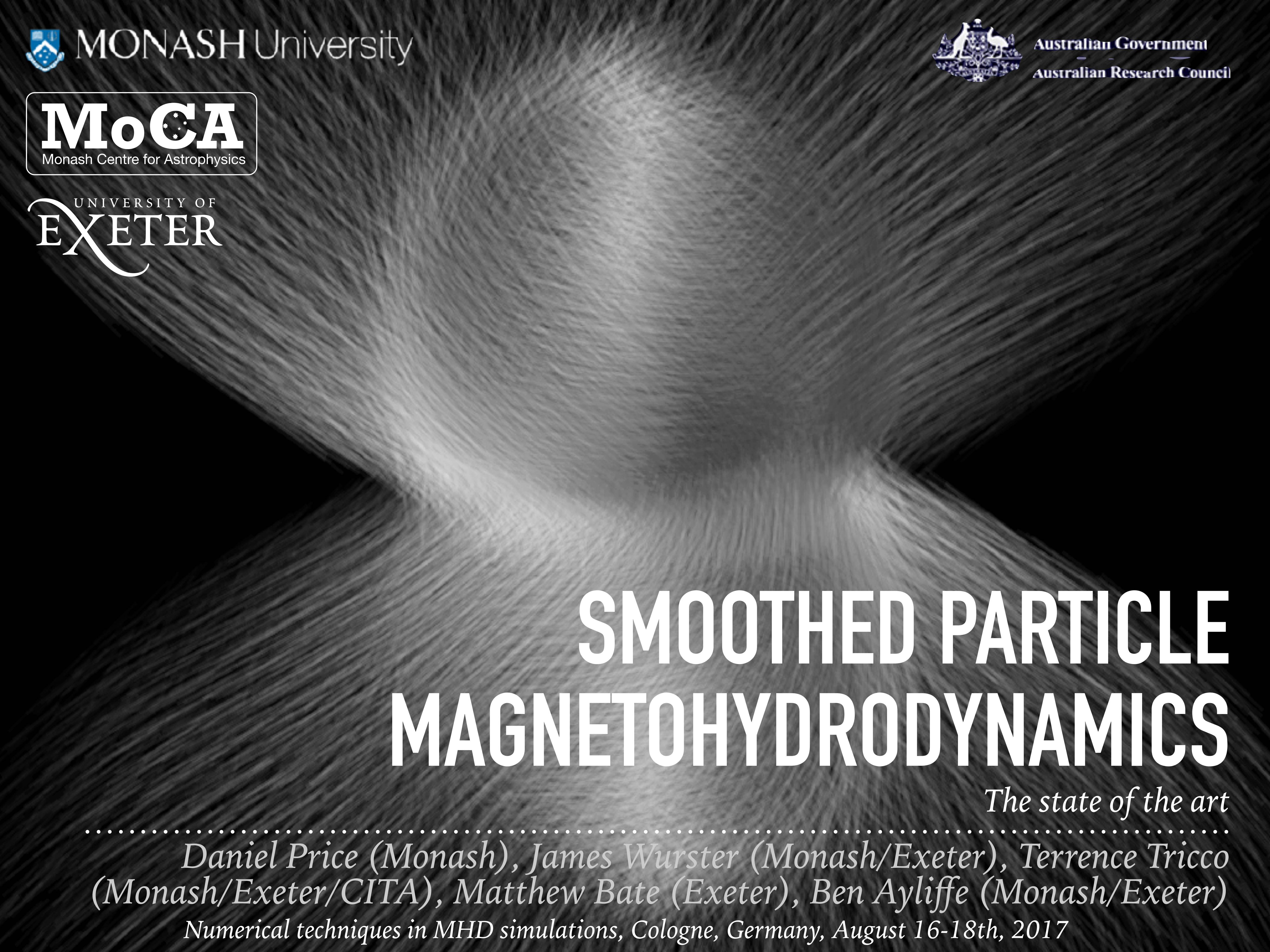


MONASH University

MoCA Monash Centre for Astrophysics

UNIVERSITY OF EXETER

Australian Government Australian Research Council

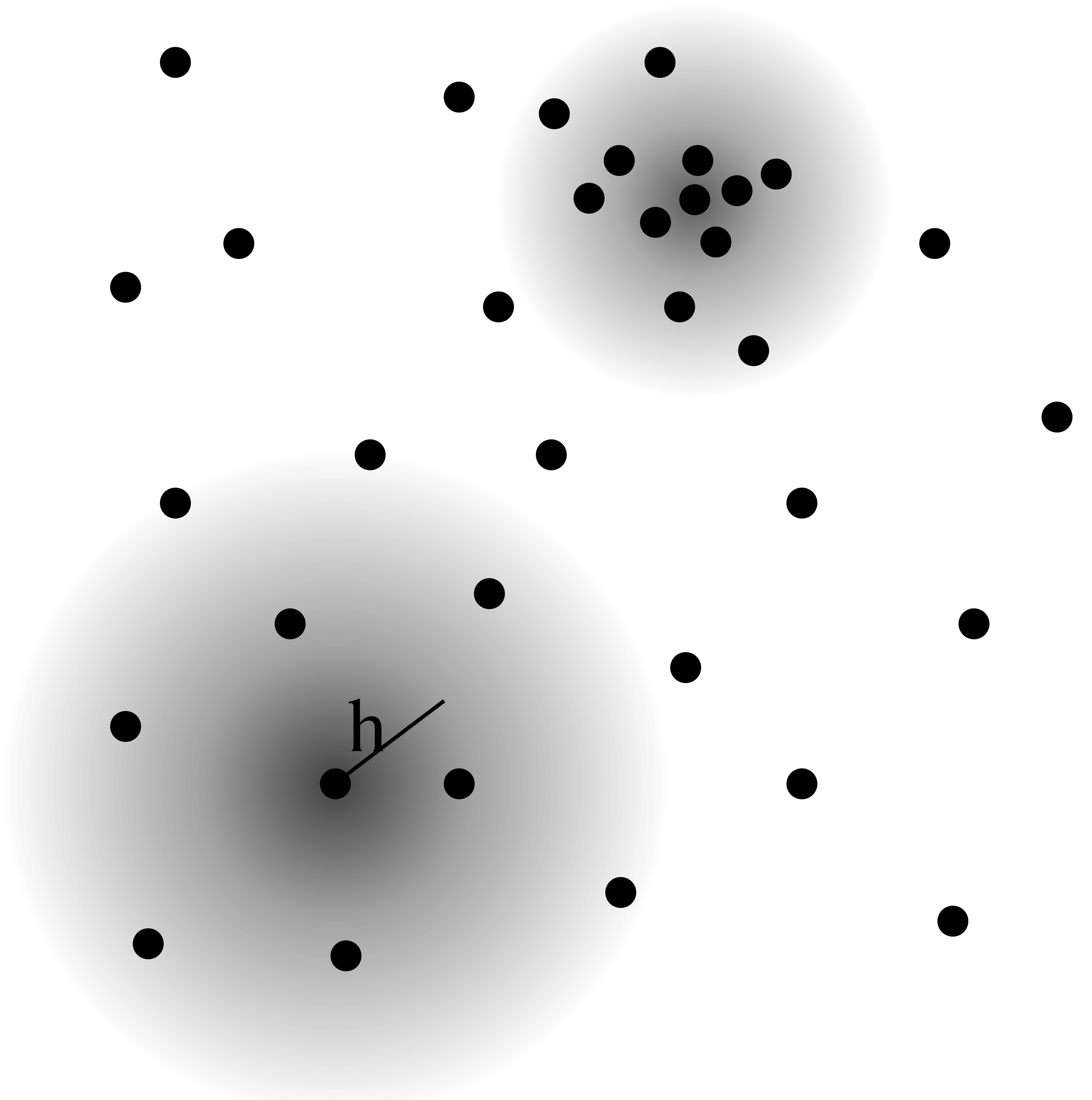
# SMOOTHED PARTICLE MAGNETOHYDRODYNAMICS

*The state of the art*

*Daniel Price (Monash), James Wurster (Monash/Exeter), Terrence Tricco (Monash/Exeter/CITA), Matthew Bate (Exeter), Ben Ayliffe (Monash/Exeter)*

*Numerical techniques in MHD simulations, Cologne, Germany, August 16-18th, 2017*

# SMOOTHED PARTICLE HYDRODYNAMICS




**What is the density?**

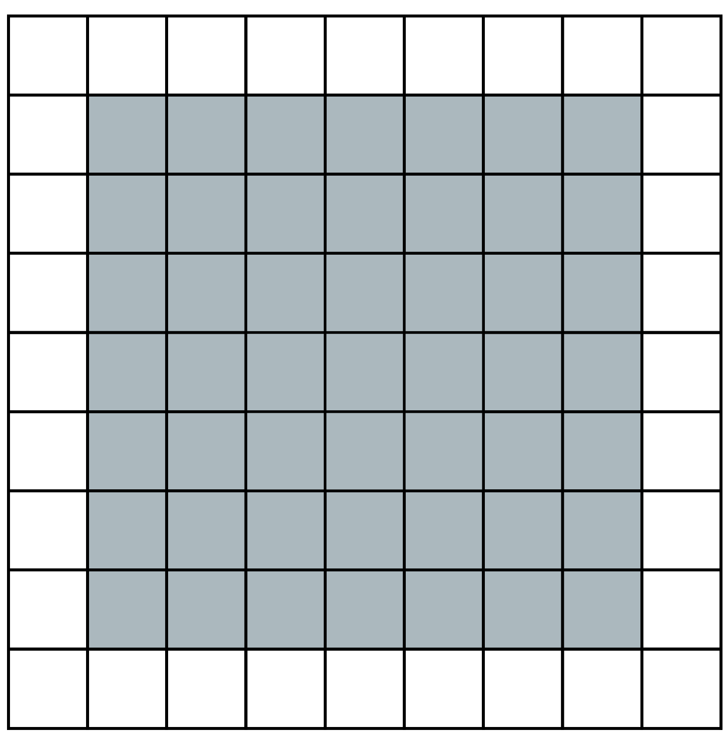
Weighted sum over neighbours

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

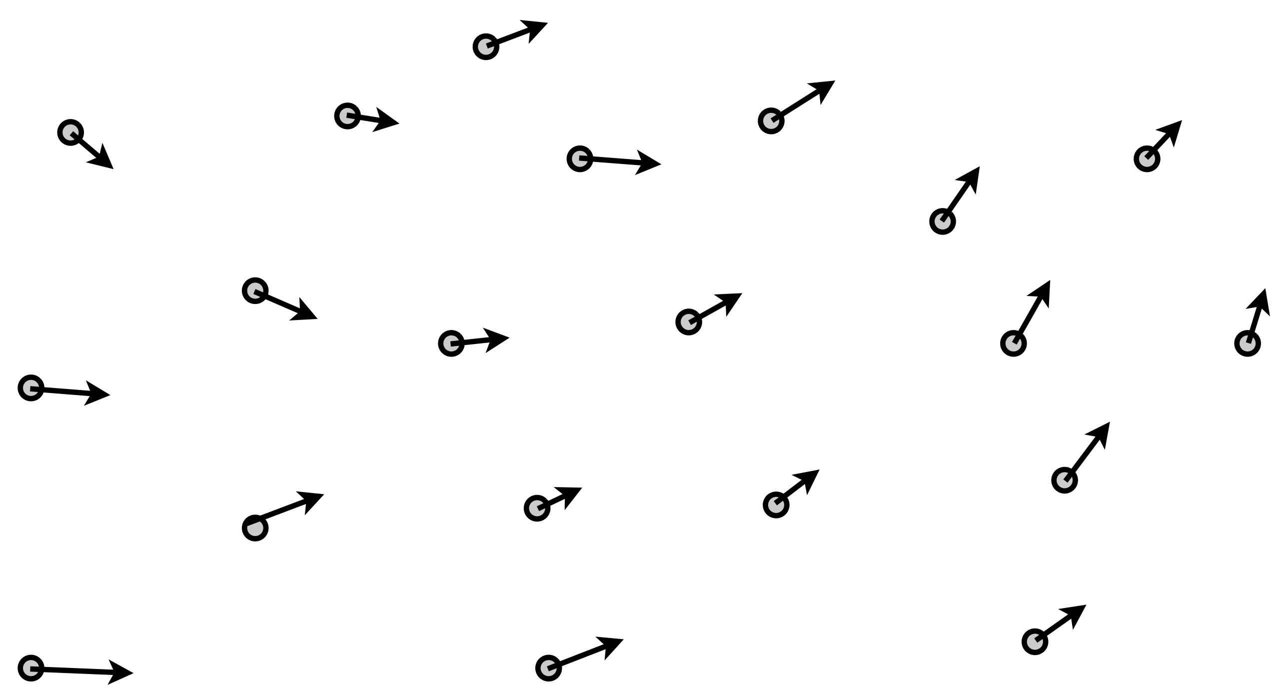
$$e.g.\ W = \frac{\sigma}{h^3} e^{-r^2/h^2}$$

# RESOLUTION FOLLOWS MASS

*Grid*



*SPH*



$$\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t} = \mathbf{v}$$

# FROM DENSITY TO HYDRODYNAMICS

$$L_{sph} = \sum_j m_j \left[\frac{1}{2}v_j^2 - u_j(\rho_j, s_j)\right]$$ ← Lagrangian

$+$

$$\mathrm{d}u = \frac{P}{\rho^2}\mathrm{d}\rho$$ ← 1st law of thermodynamics

$+$

$$\nabla\rho_i = \sum_j m_j \nabla W_{ij}(h)$$ ← density sum

$+$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \mathbf{v}}\right) - \frac{\partial L}{\partial \mathbf{r}} = 0$$ ← Euler-Lagrange equations

$=$

$$\frac{\mathrm{d}\mathbf{v}_i}{\mathrm{d}t} = -\sum_j m_j \left(\frac{P_i}{\rho_i^2} + \frac{P_j}{\rho_j^2}\right)\nabla_i W_{ij}(h)$$

← equations of motion!

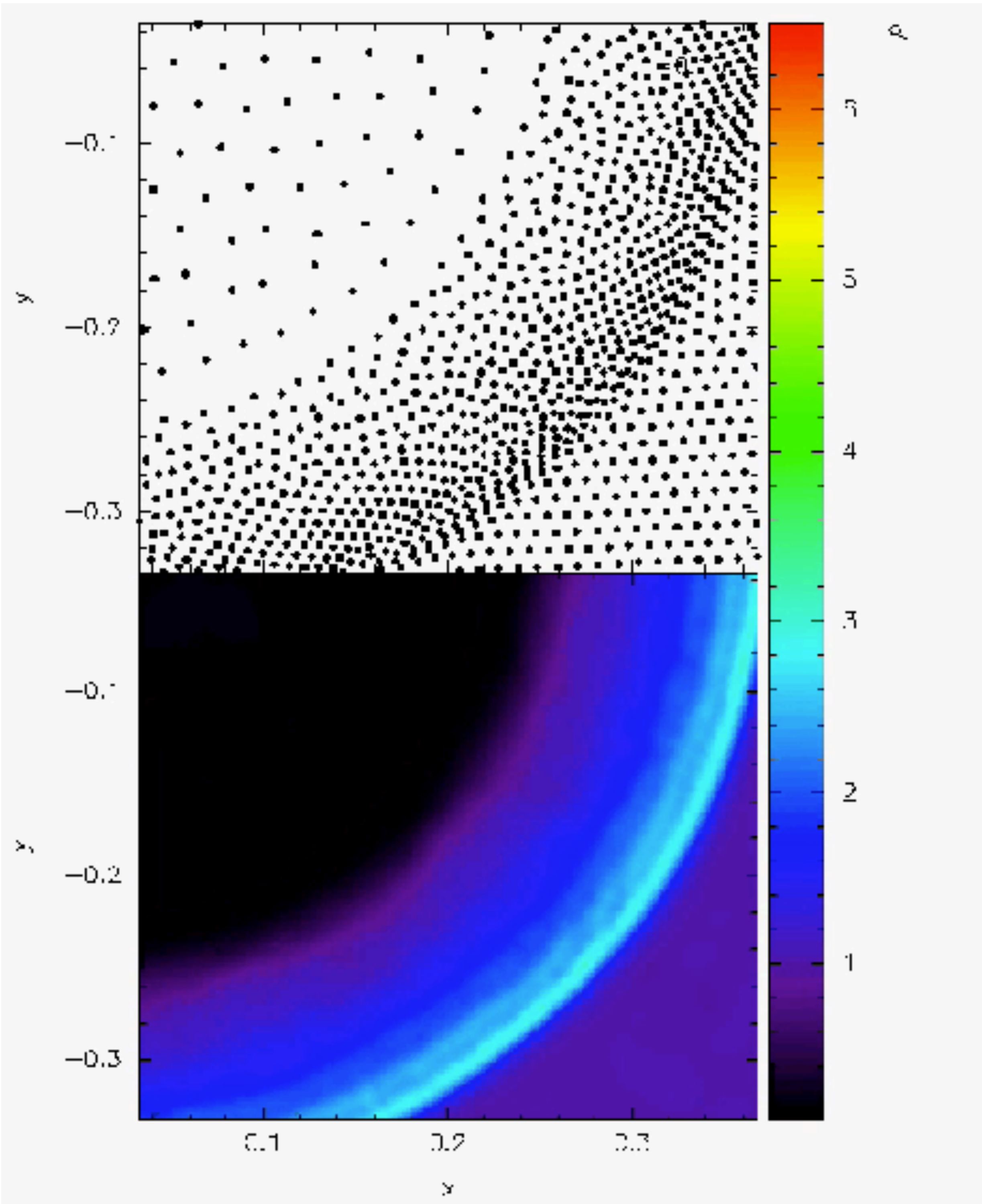
$$\left(\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho}\right)$$

# WHAT THIS GIVES US: ADVANTAGES OF SPH

- Exact solution to the mass continuity equation
- Resolution follows mass
- Zero numerical dissipation
- Advection done perfectly
- Exact and simultaneous conservation of mass, momentum, angular momentum, energy and entropy
- A guaranteed minimum energy state

# THE "GRID" IN SPH

*Monaghan (2005)*
*Price (2012) J. Comp. Phys. 231, 759*



- Existence of minimum energy state guarantees local ordering of particle distribution
- BUT: requires positive pressure

# SMOOTHED PARTICLE MAGNETOHYDRODYNAMICS

*see review by Price (2012)*
*J. Comp. Phys. 231, 759*

$$L = \int \left( \frac{1}{2}\rho v^2 - \rho u - \frac{1}{2\mu_0} B^2 \right) \mathrm{d}V$$

$$L = \sum_a m_a \left( \frac{1}{2} v_a^2 - u_a - \frac{B_a^2}{2\mu_0 \rho_a} \right)$$

*Price & Monaghan (2004a,b, 2005)*

*Euler-Lagrange equations give discrete form of:*

Include div B source term for stability

$$\frac{\mathrm{d}\boldsymbol{\rho}}{\mathrm{d}\boldsymbol{t}} = -\boldsymbol{\rho}(\nabla \cdot \mathbf{v})$$

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

$$\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}\boldsymbol{t}} = -\frac{P}{\boldsymbol{\rho}} (\nabla \cdot \mathbf{v})$$

Method is dissipationless

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

Need to separately handle div B = 0

These equations are equivalent to the 8-wave formulation of Powell et al. 1994

# SOURCE TERMS, OR NOT?

*Price & Monaghan (2005)*

$$\delta L = m_a \boldsymbol{v}_a \cdot \delta \boldsymbol{v}_a - \sum_b m_b \left[ \left. \frac{\partial u_b}{\partial \rho_b} \right|_s \delta \rho_b + \frac{1}{2\mu_0} \left( \frac{B_b}{\rho_b} \right)^2 \delta \rho_b - \frac{1}{\mu_0} \boldsymbol{B}_b \cdot \delta \left( \frac{\boldsymbol{B}_b}{\rho_b} \right) \right]$$

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

$$\left. \frac{\mathrm{d}u}{\mathrm{d}\rho} \right|_s = \frac{P}{\rho^2}.$$

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

**Div B source term present in induction equation**

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

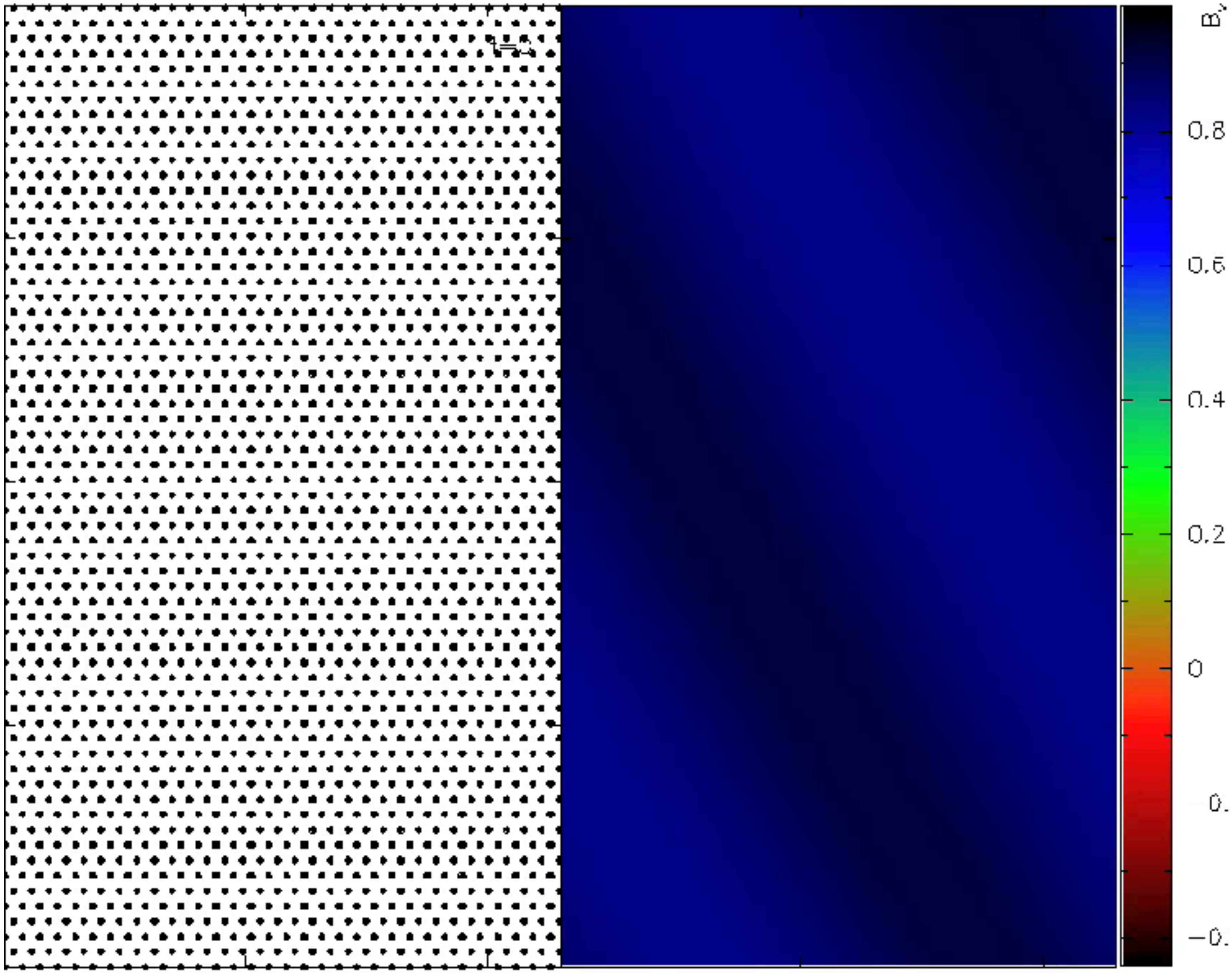
**Obtain CONSERVATIVE momentum equation**

*Consistent with Janhunen formulation of div B terms*

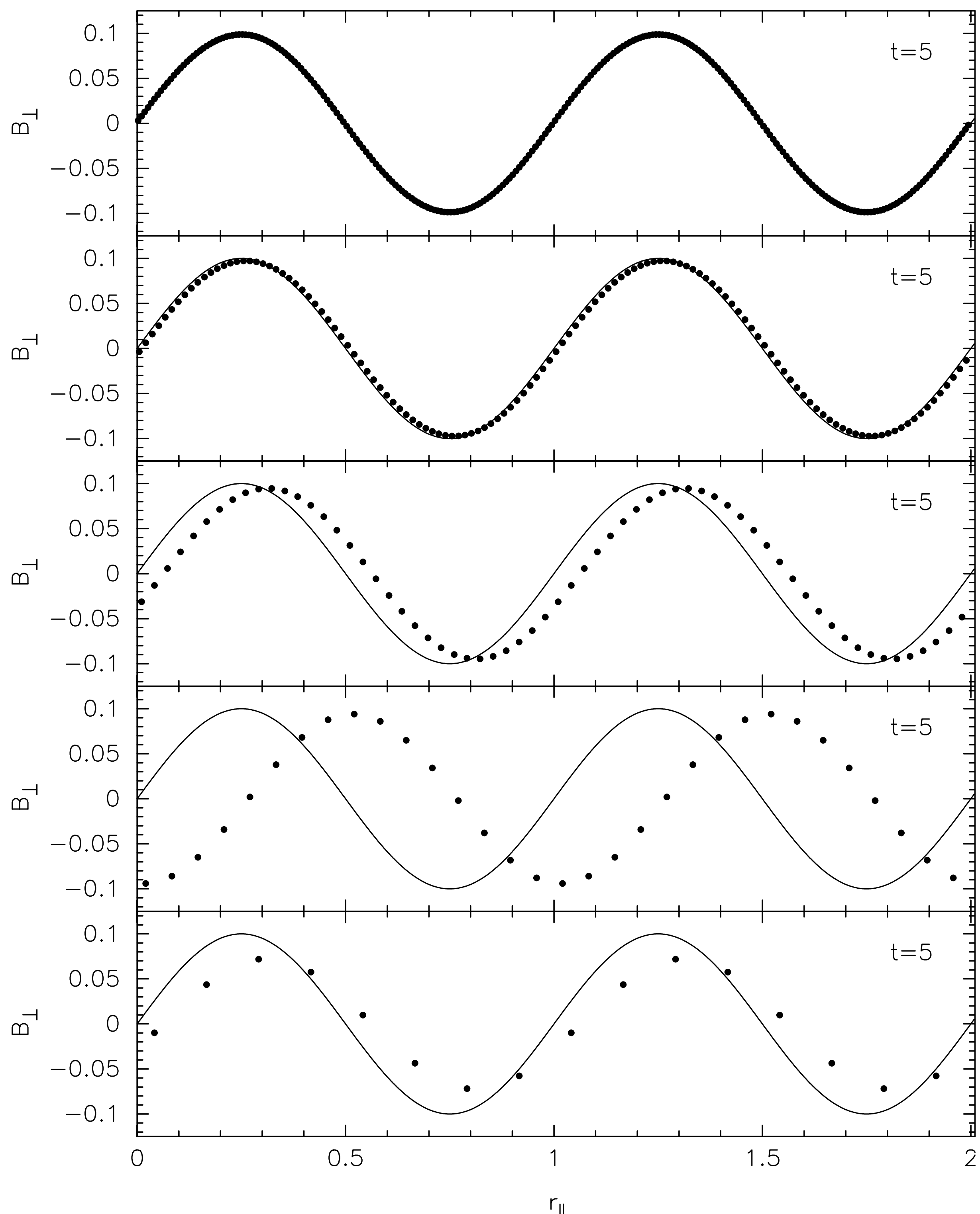
# PHILLIPS & MONAGHAN (1985): SPH WITH MHD IN CONSERVATIVE FORM IS UNSTABLE WHEN BETA < 1

# WITH SOURCE TERM IN MOMENTUM EQUATION

*Morris (1996), Børve, Omang & Trulsen (2001, 2004)*

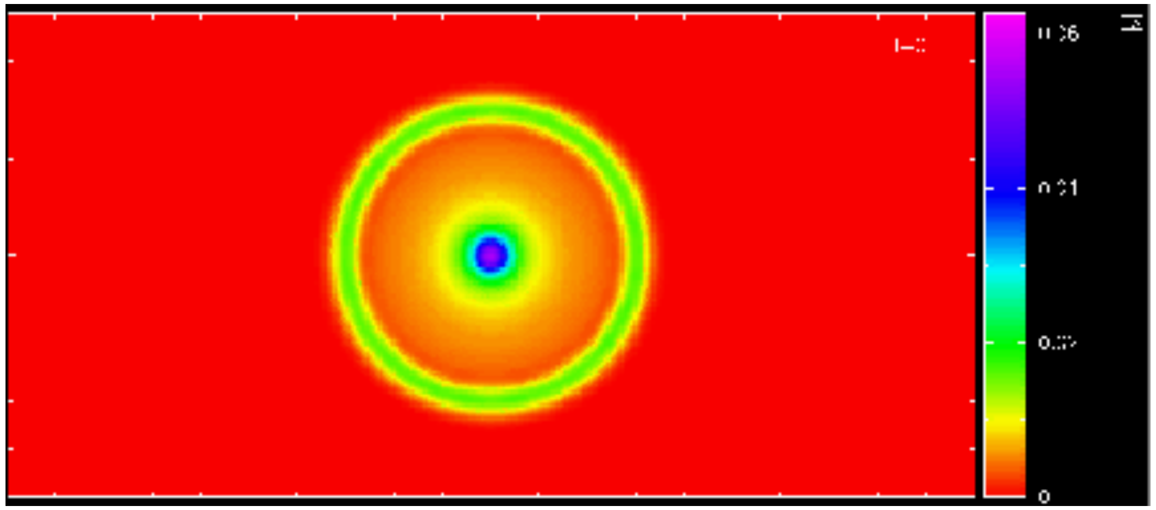


# ZERO DISSIPATION - EXAMPLE I

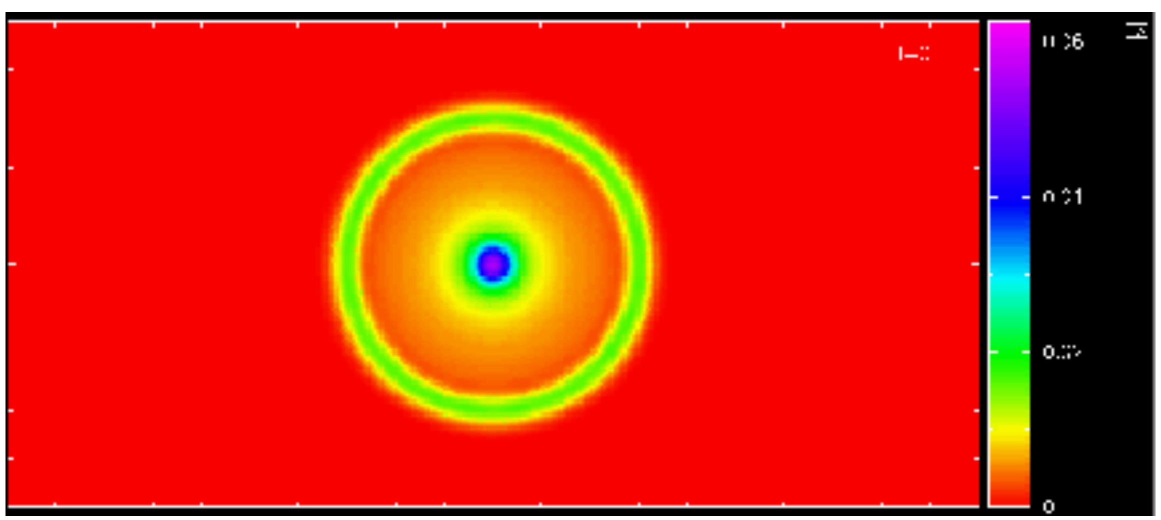



*Circularly polarised Alfvén wave*

# ZERO DISSIPATION – II. ADVECTION OF A CURRENT LOOP



*first 25 crossings*



*1000 crossings (Rosswog & Price 2007)*

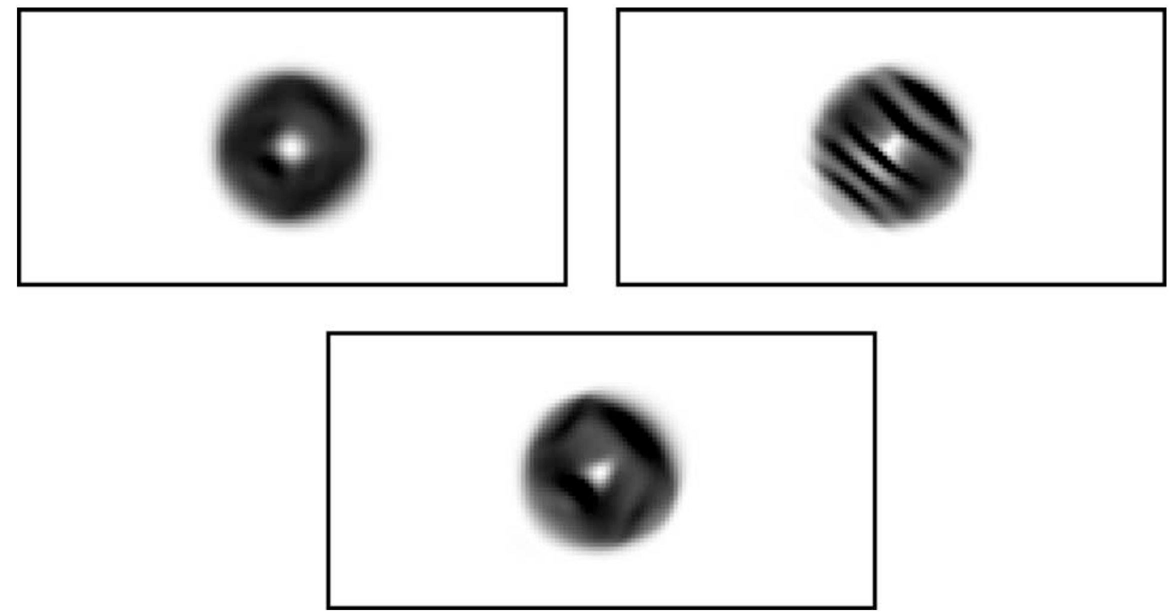


Fig. 3. Gray-scale images of the magnetic pressure $(B_x^2 + B_y^2)$ at $t = 2$ for an advected field loop ($v_0 = \sqrt{5}$) using the $\mathscr{E}_z^{\alpha}$ (top left), (top right) and $\mathscr{E}_z^{c}$ (bottom) CT algorithm.

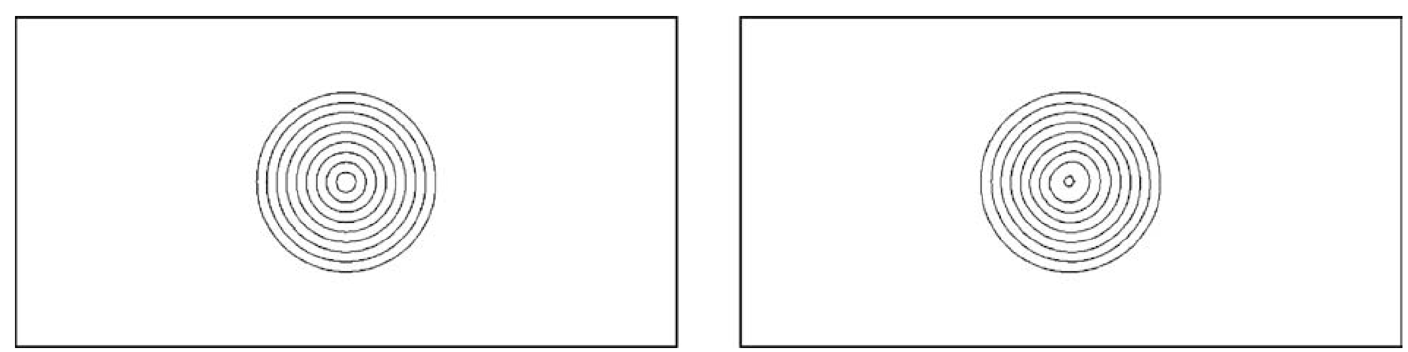


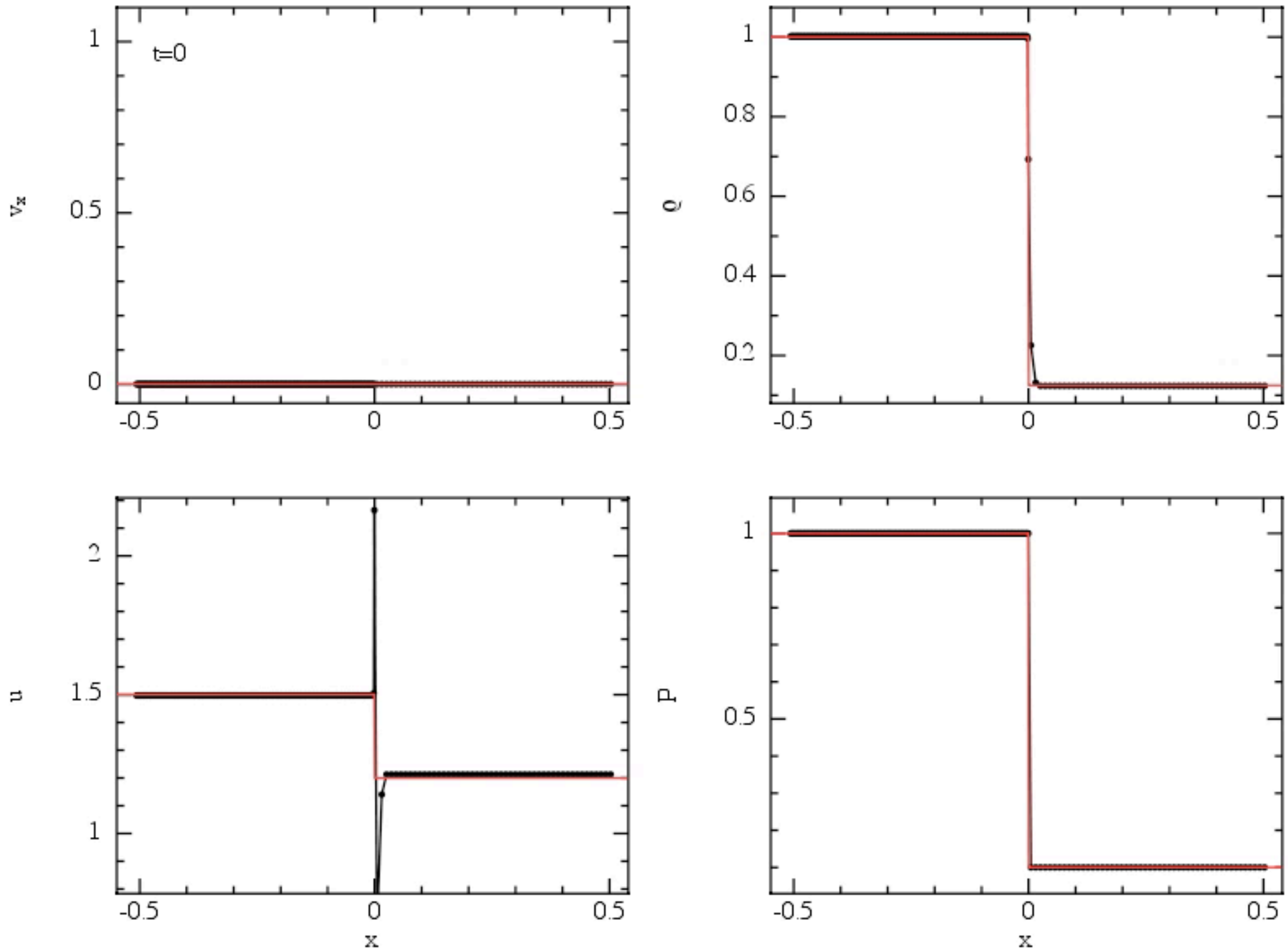
Fig. 8. Magnetic field lines at $t = 0$ (left) and $t = 2$ (right) using the CTU + CT integration algorithm.

*2 crossings (Gardiner & Stone 2005)*

SPH

Grid

# ZERO DISSIPATION III



# SHOCK CAPTURING IN SPH

*Monaghan (1997), Price (2008, 2012)*

$$\frac{\mathrm{d}\boldsymbol{U}_a}{\mathrm{d}t} = \sum_b \frac{m_b}{\bar{\rho}_{ab}} \alpha v_{\rm sig} (\boldsymbol{U}_a - \boldsymbol{U}_b) \hat{r}_{ab} \cdot \nabla W_{ab}$$

- Formulate dissipative terms similar to approximate Riemann solvers

$$\left(\frac{\mathrm{d}\mathbf{v}_i}{\mathrm{d}t}\right)_{\rm diss} = \sum_j m_j \frac{\alpha v_{\rm sig}(\mathbf{v}_i - \mathbf{v}_j)\cdot \hat{\mathbf{r}}_{ij}}{\bar{\rho}_{ij}} \overline{\nabla_i W_{ij}},$$

$$\left(\frac{\mathrm{d}e_i}{\mathrm{d}t}\right)_{\rm diss} = \sum_j m_j \frac{(e_i^* - e_j^*)}{\bar{\rho}_{ij}} \hat{\mathbf{r}}_{ij} \cdot \overline{\nabla_i W_{ij}},$$

$$e = \frac{1}{2}v^2 + u$$

- Enforce positive definite contribution to entropy

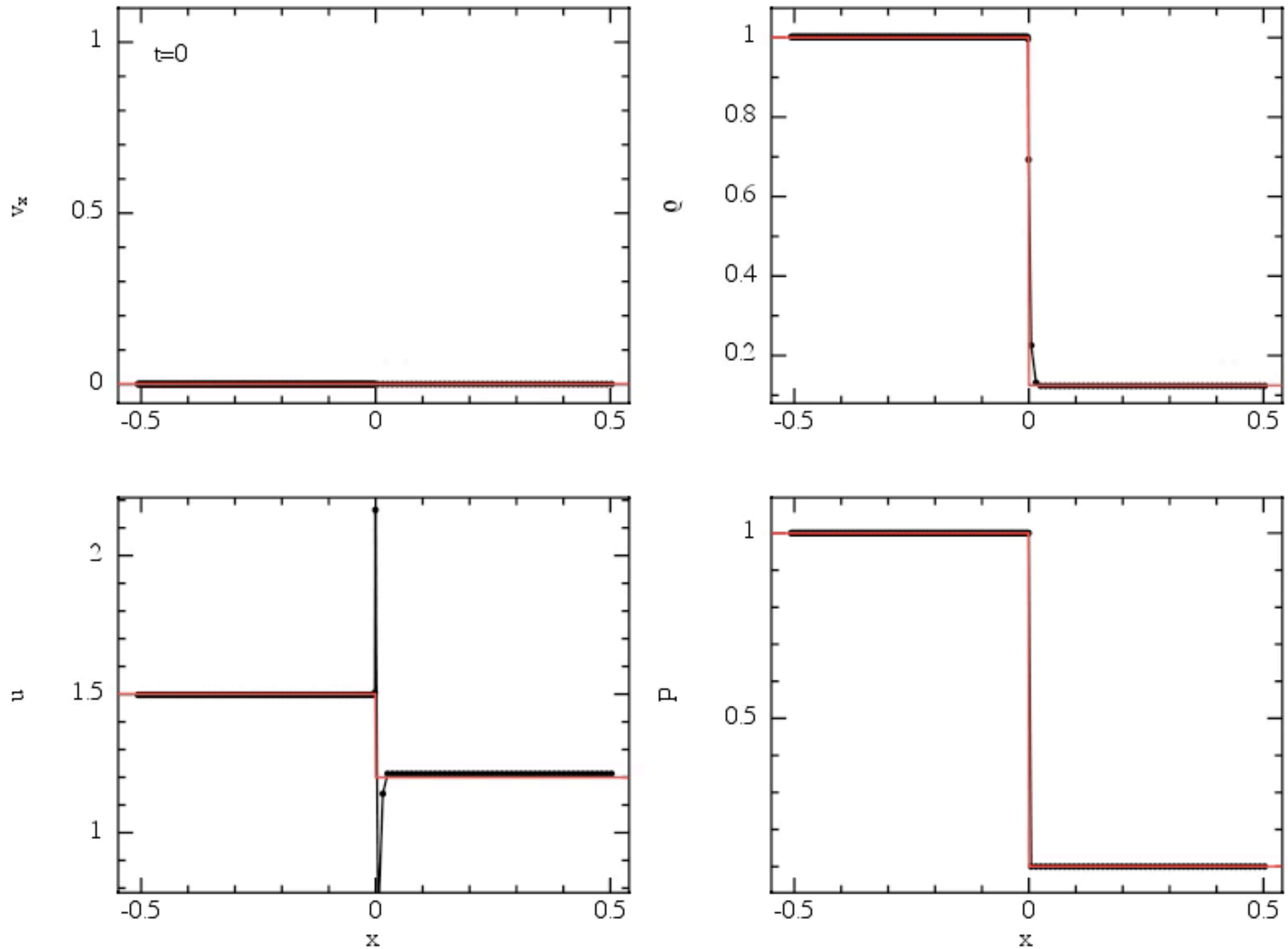
$$\left(\frac{\mathrm{d}u}{\mathrm{d}t}\right)_{\rm diss} = -\sum_j \frac{m_j}{\bar{\rho}_{ij}} \left\{ \frac{1}{2}\alpha v_{\rm sig}(\mathbf{v}_{ij}\cdot\hat{\mathbf{r}}_{ij})^2 + \alpha_u v^u_{\rm sig}(u_i - u_j)\right\} \hat{\mathbf{r}}_{ij} \cdot \nabla_i W_{ij}.$$

Viscous heating        Thermal conduction

- Gives artificial dissipation terms equivalent to artificial viscosity, conductivity and (in MHD) resistivity
- Viscosity terms = Navier Stokes equations with $\nu = \frac{\alpha}{10} v_{\rm sig} h$

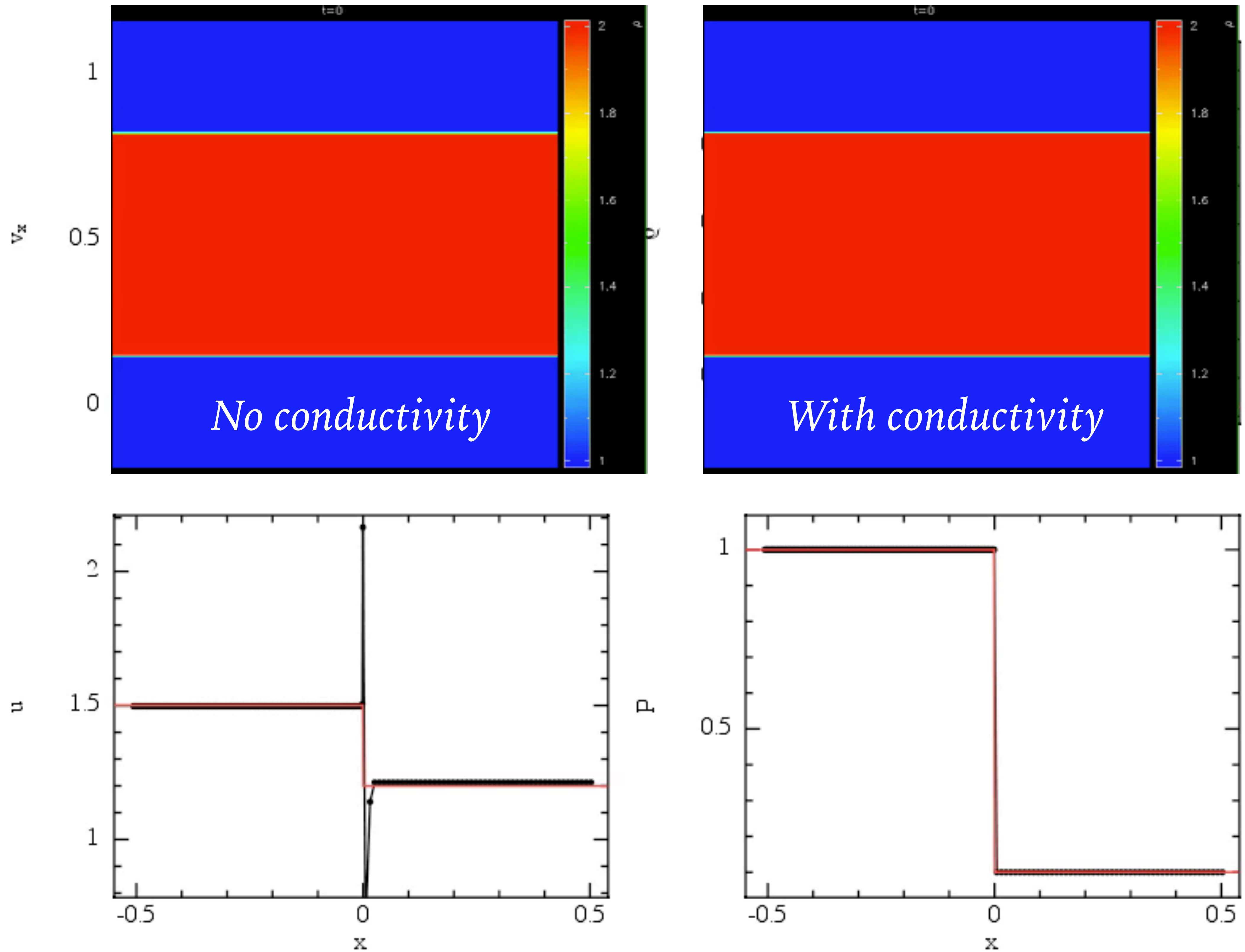
BUT dissipation terms are first order

# ARTIFICIAL VISCOSITY



# ARTIFICIAL CONDUCTIVITY

*Chow & Monaghan (1997)*
*Price (2008), JCP*



# APPROACHES TO DIV B = 0

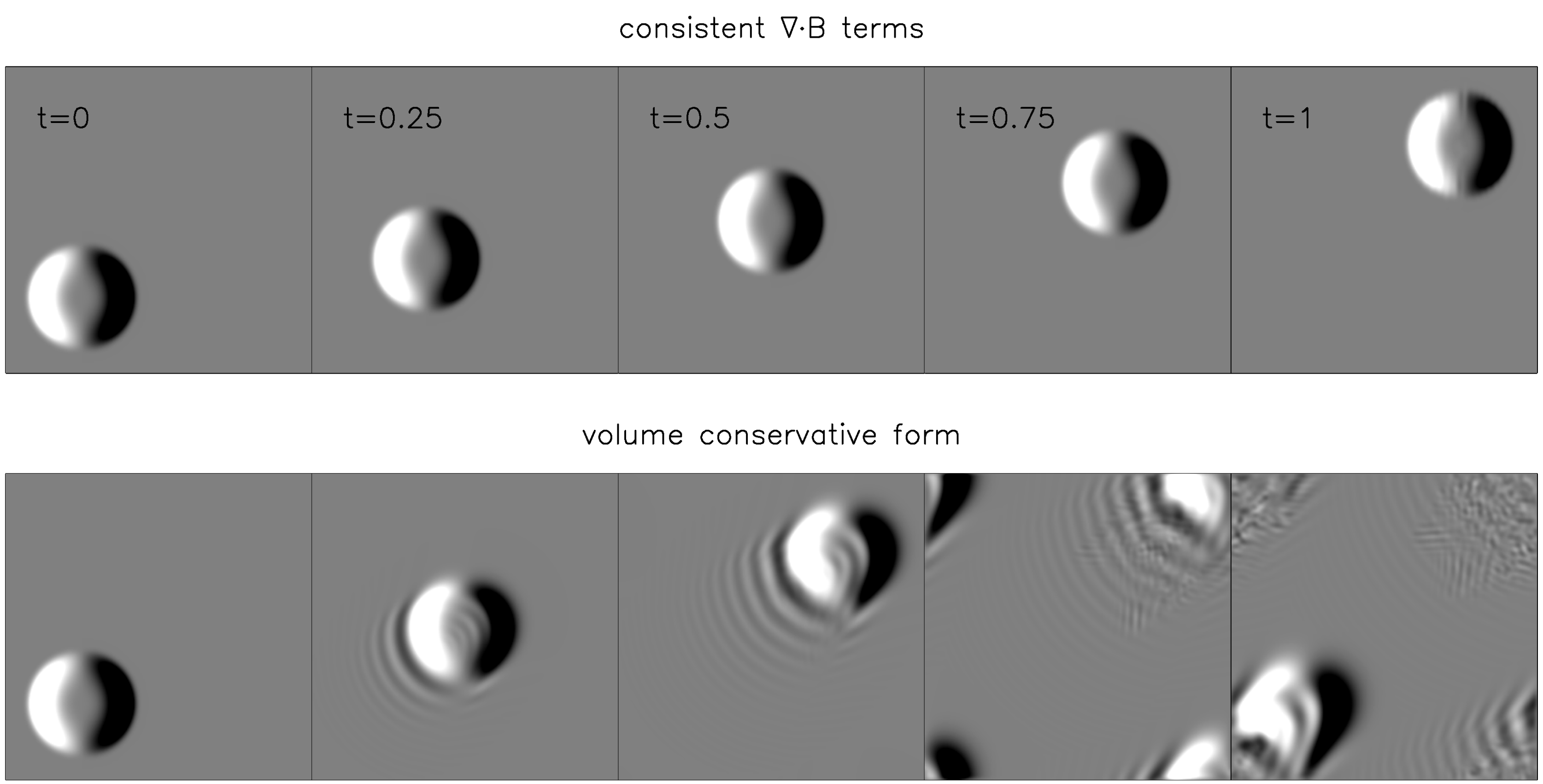
1. Ignore
2. Prevent
3. Clean

# POWELL'S 8 WAVE METHOD = IGNORE BUT PRESERVE

*Powell et al. (1999), Janhunen (2000), Dellar (2001), Tóth (2000)*

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) \quad \longrightarrow \quad \frac{\partial}{\partial t}(\nabla \cdot \boldsymbol{B}) = 0$$

$$\frac{d\boldsymbol{B}}{dt} = (\boldsymbol{B} \cdot \nabla)\boldsymbol{v} - \boldsymbol{B}(\nabla \cdot \boldsymbol{v}) \quad \longrightarrow \quad \frac{\partial}{\partial t}(\nabla \cdot \boldsymbol{B}) + \nabla \cdot (\boldsymbol{v}\nabla \cdot \boldsymbol{B}) = 0$$



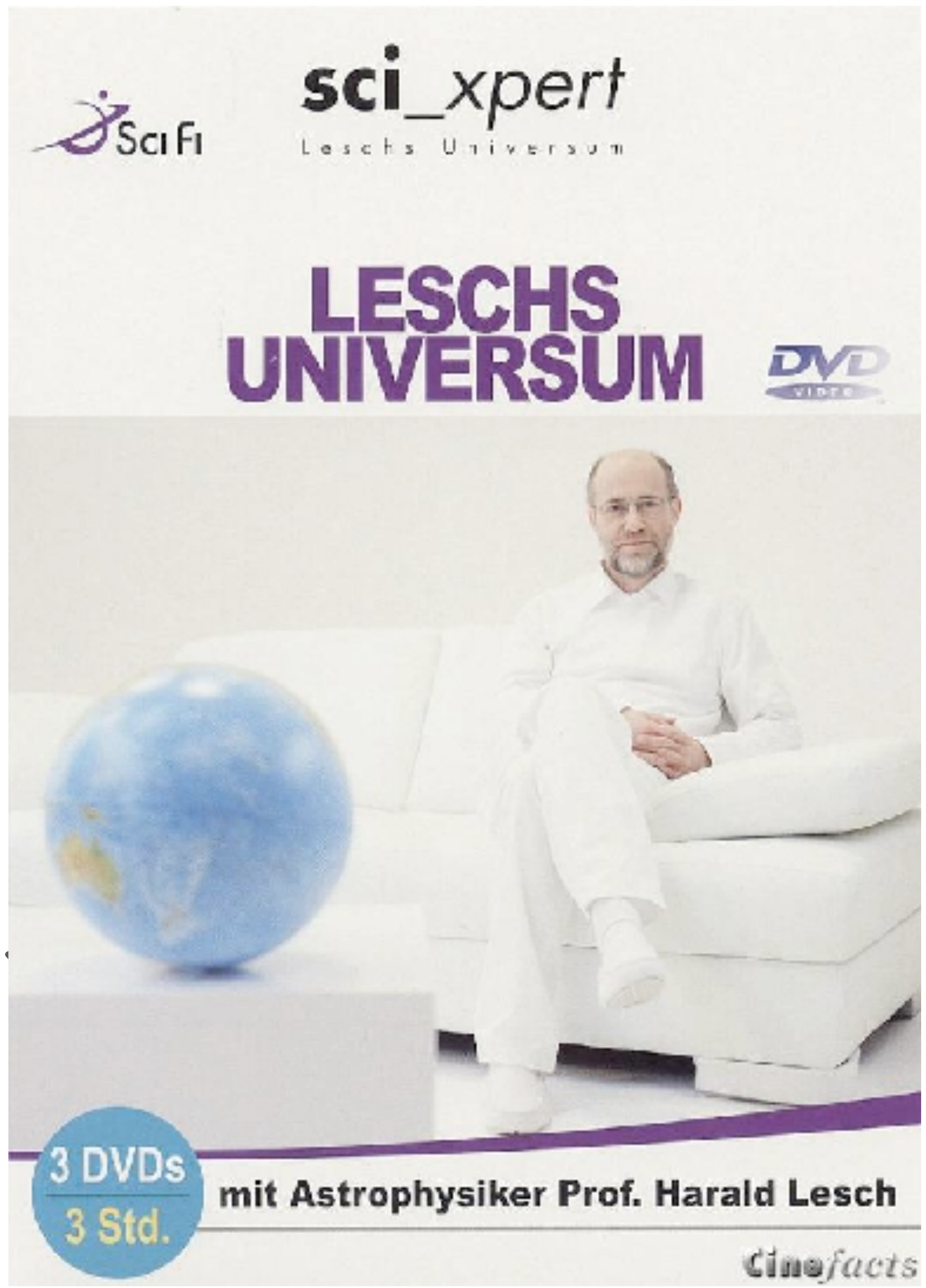

*Preserve*

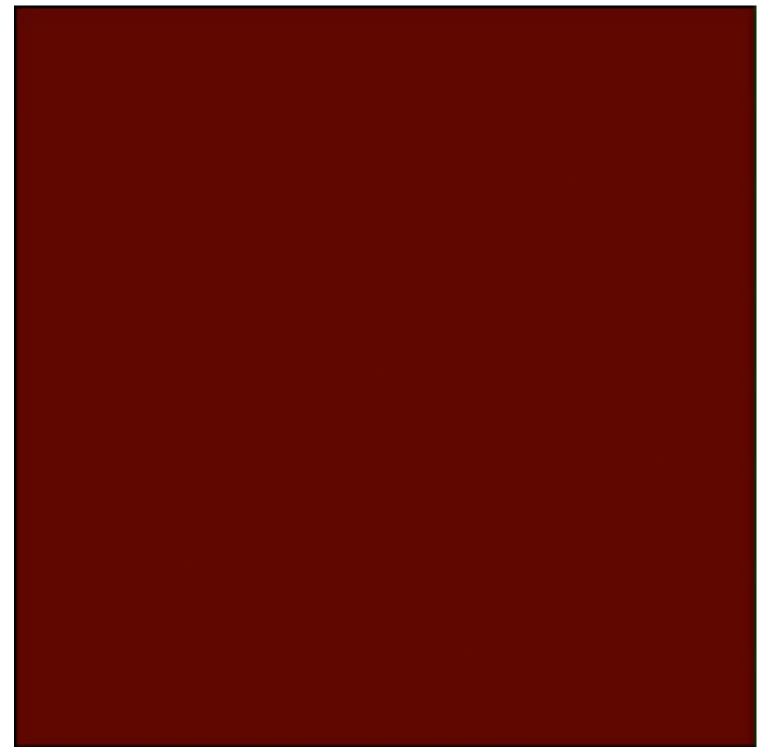
*Divergence advection test from Dedner et al. (2002)*

*Smear*

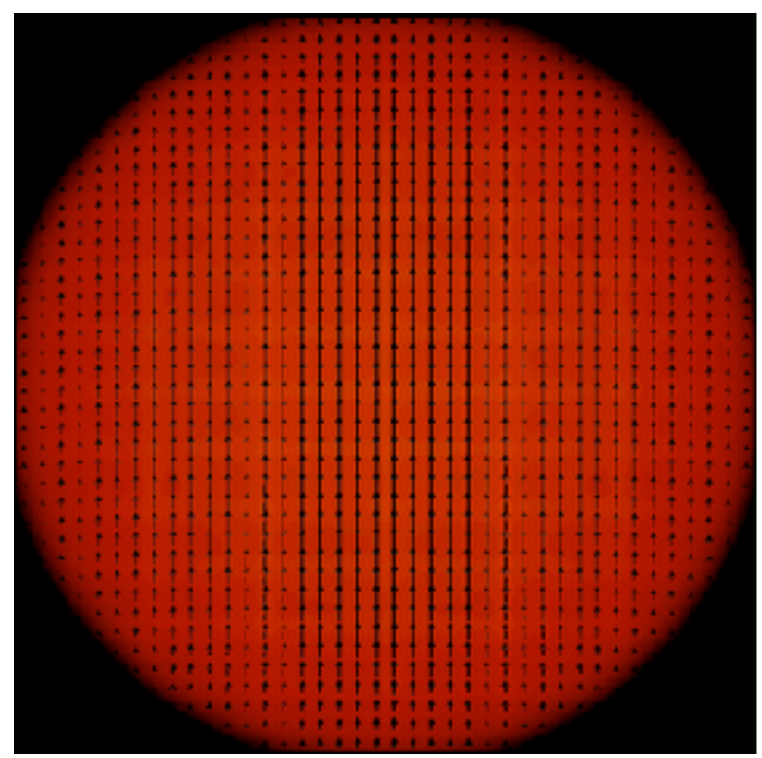
*Application to SPH: Price & Monaghan (2005)*

# USE OF POWELL-ONLY DIV B CONTROL IN SPMHD



*Orszag-Tang vortex problem in SPMHD (Price & Monaghan 2005, Rosswog & Price 2007)*



# PREVENT: DIV B = 0 BY CONSTRUCTION IN SPH

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

*Euler potentials (e.g. Stern, 1976)*

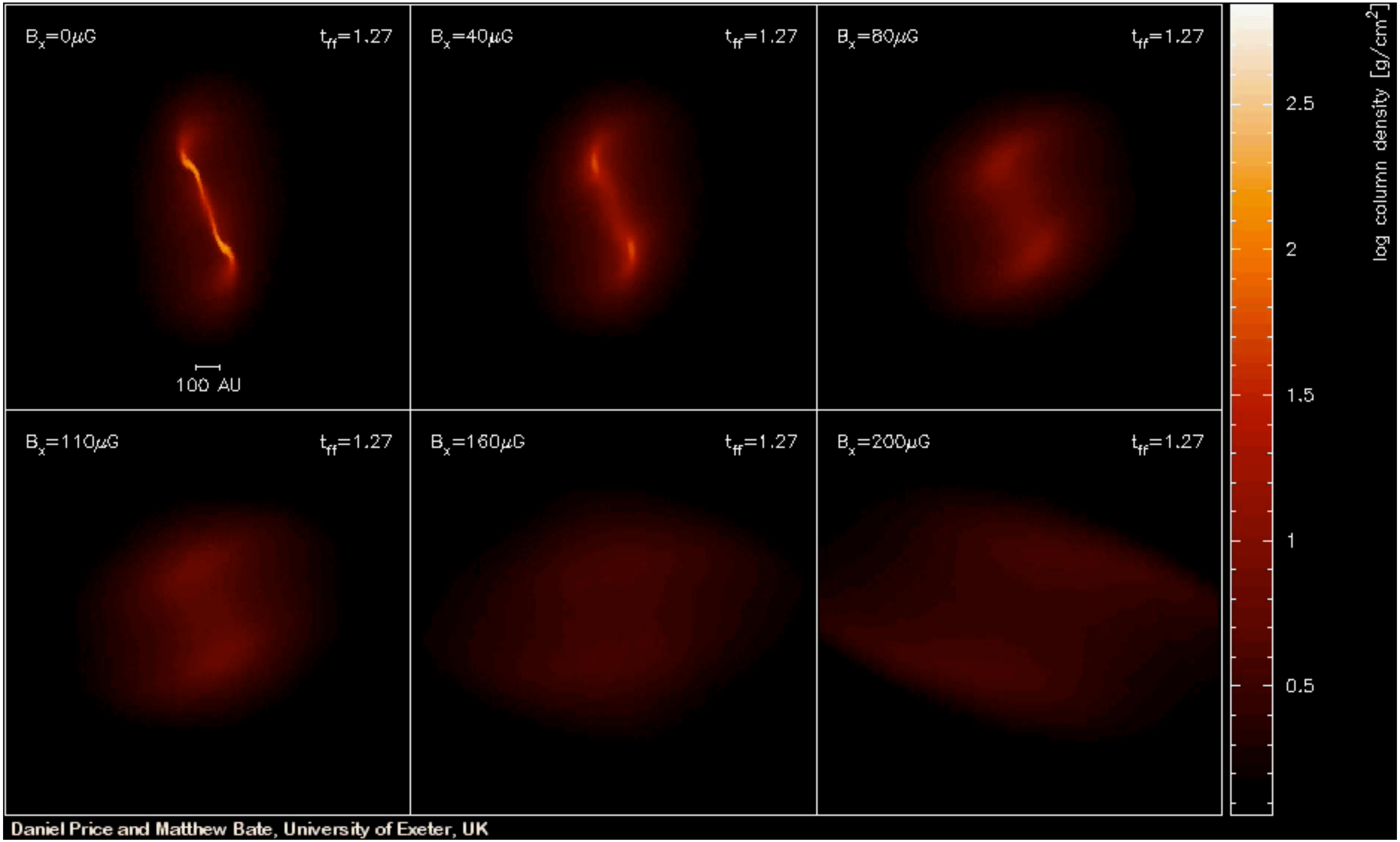
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

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

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

*(advection of magnetic field lines by Lagrangian particles)*

## PRICE & BATE (2007): EFFECT OF MAGNETIC FIELDS ON SINGLE AND BINARY STAR FORMATION




*…problem forming discs and binaries in the presence of magnetic fields?*

*see also Allen et al. (2003), Galli et al. (2006), Mellon & Li (2008), Hennebelle & Fromang (2008), Commerçon et al. (2010), Krasnopolsky et al. (2010), Seifried et al. (2012), Santos-Lima et al. (2012), Joos et al. (2013) and many others*

# LIMITATIONS OF THE EULER POTENTIALS APPROACH

*Rosswog & Price (2007), Price & Bate (2008), Brandenburg (2010)*

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

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

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

- advection of magnetic fields: no change in topology (A.B = 0)
- does not follow wind-up of magnetic fields
- difficult to model resistive effects — reconnection processes not treated correctly

# HYPERBOLIC/PARABOLIC DIVERGENCE CLEANING

*Dedner et al. (2002)*
*Price & Monaghan (2005)*
*Mignone & Tzeferacos (2010)*

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \psi$$

$$\frac{\partial \psi}{\partial t} = -c_h^2 (\nabla \cdot \mathbf{B}) - \frac{\sigma c_h}{h} \psi$$

Hyperbolic

Parabolic

Use dimensionless parameter

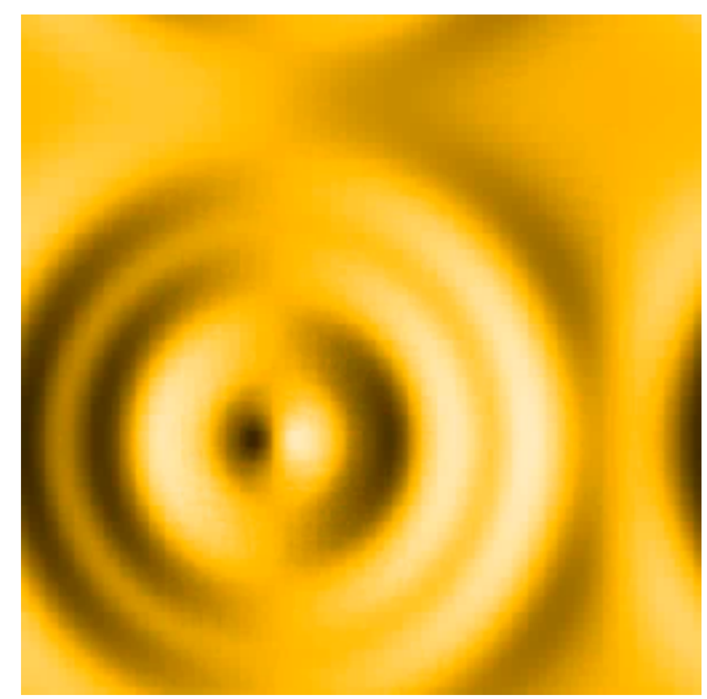
*Price & Monaghan (2005); Mignone & Tzeferacos (2010)*

Critical damping on resolution length

*Price & Monaghan (2005); Mignone & Tzeferacos (2010)*

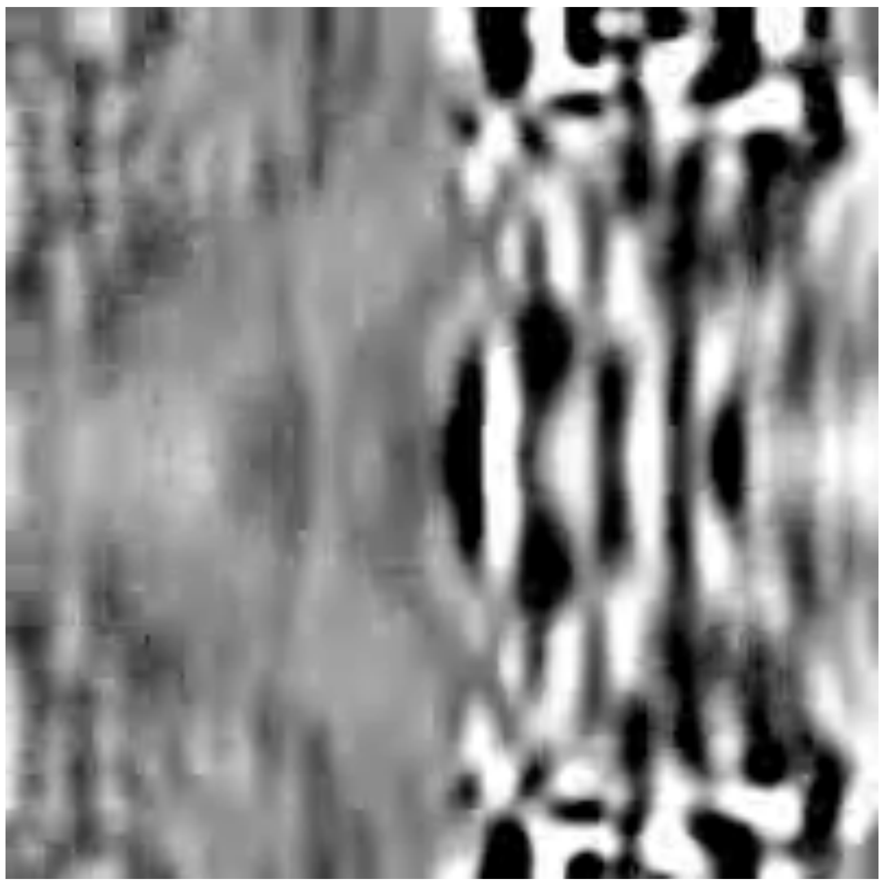
$$\frac{1}{c_h^2} \frac{\partial^2 (\nabla \cdot \mathbf{B})}{\partial t^2} + \nabla^2 (\nabla \cdot \mathbf{B}) + \frac{1}{\lambda c_h} \frac{\partial (\nabla \cdot \mathbf{B})}{\partial t} = 0$$

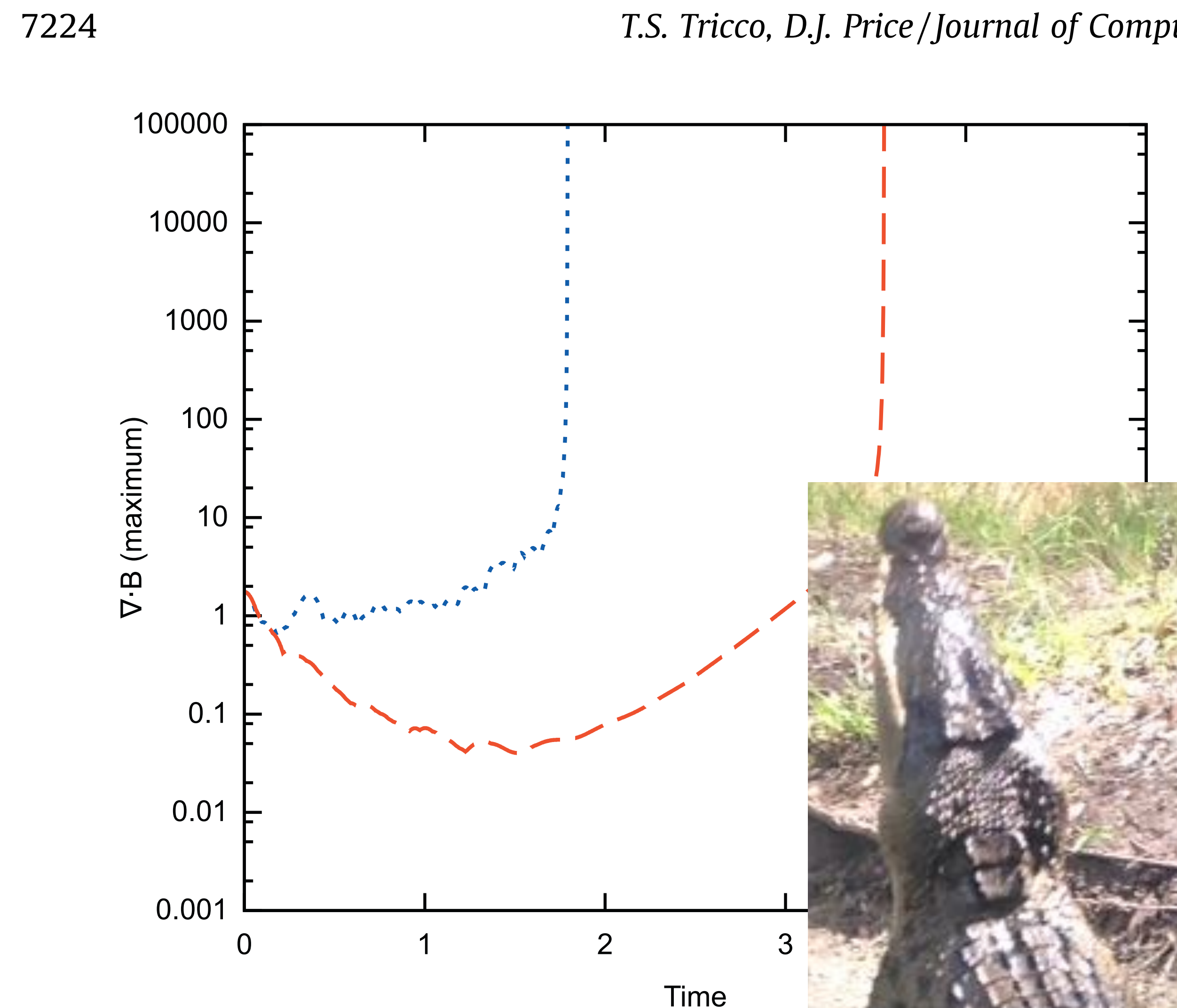
Wavelength of critical damping



*Hyperbolic term only*

# WHEN CLEANING ATTACKS






*Divergence advection test (Dedner et al. 2002)*
*with 10:1 jump in density*

# "CONSTRAINED" HYPERBOLIC/PARABOLIC DIVERGENCE CLEANING

*Tricco & Price (2012); Tricco, Price & Bate (2016)*

- Define energy associated with cleaning field

$$E = \int \left[ \frac{1}{2} \frac{B^2}{\mu_0} + \frac{1}{2} \frac{\psi^2}{\mu_0 c_h^2} \right] \mathrm{dV}$$

- Enforce energy conservation in hyperbolic terms

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \int \left[ \frac{\mathbf{B}}{\mu_0} \cdot \left( \frac{\mathrm{d}\mathbf{B}}{\mathrm{d}t} \right)_{\psi} + \frac{\psi}{\mu_0 c_\mathrm{h}^2} \frac{\mathrm{d}\psi}{\mathrm{d}t} - \frac{\psi^2}{2\mu_0 \rho c_\mathrm{h}^2} \frac{\mathrm{d}\rho}{\mathrm{d}t} - \frac{\psi^2}{\mu_0 c_\mathrm{h}^3} \frac{\mathrm{d}c_\mathrm{h}}{\mathrm{d}t} \right] \mathrm{d}V = 0$$

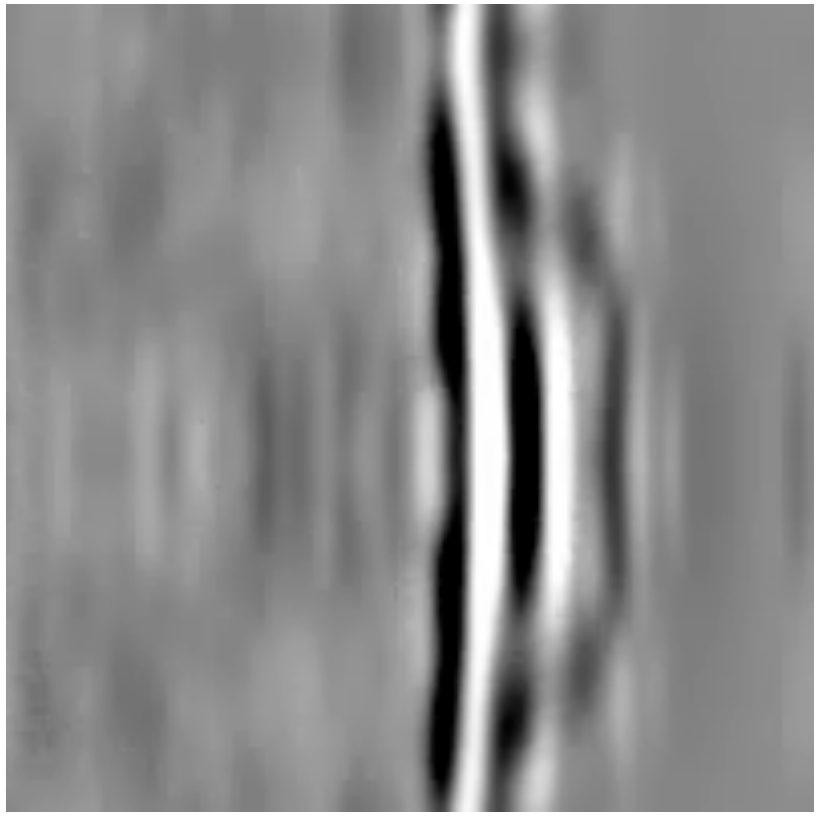
$$\frac{\mathrm{d}\mathbf{B}}{\mathrm{d}t} = -\nabla \psi$$

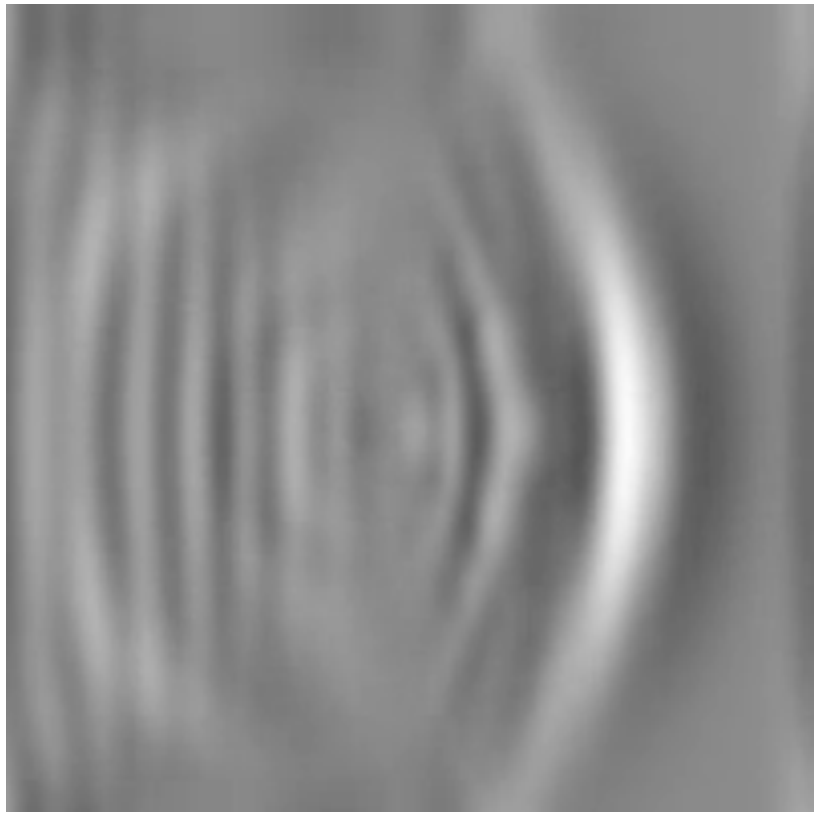
$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = -c_h^2 (\nabla \cdot \mathbf{B}) - \frac{\sigma c_h}{h} \psi - \frac{1}{2} \psi (\nabla \cdot \mathbf{v})$$

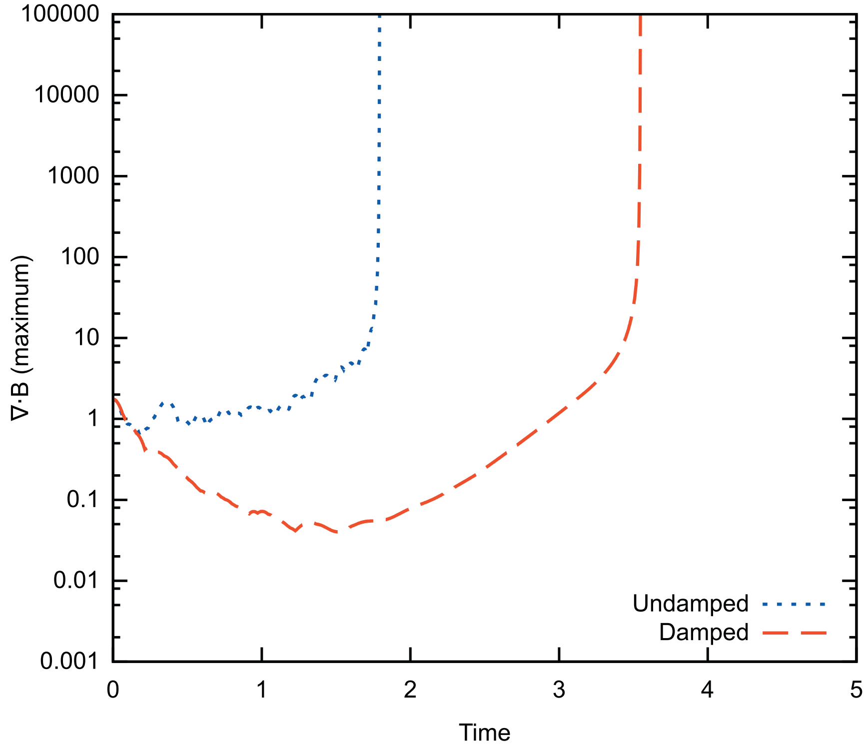
**Requires particular choice of operators here**

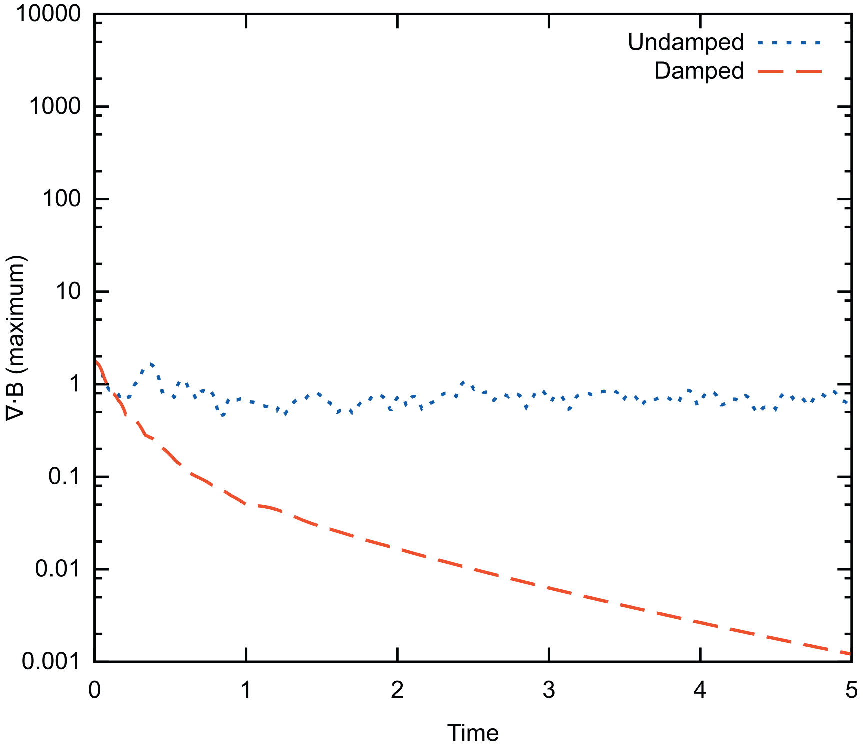
- Can enforce exact energy conservation in SPH discretisation

# CONSTRAINED HYPERBOLIC/PARABOLIC CLEANING








Parabolic term is negative definite!

# WHAT IF THE CLEANING SPEED VARIES?

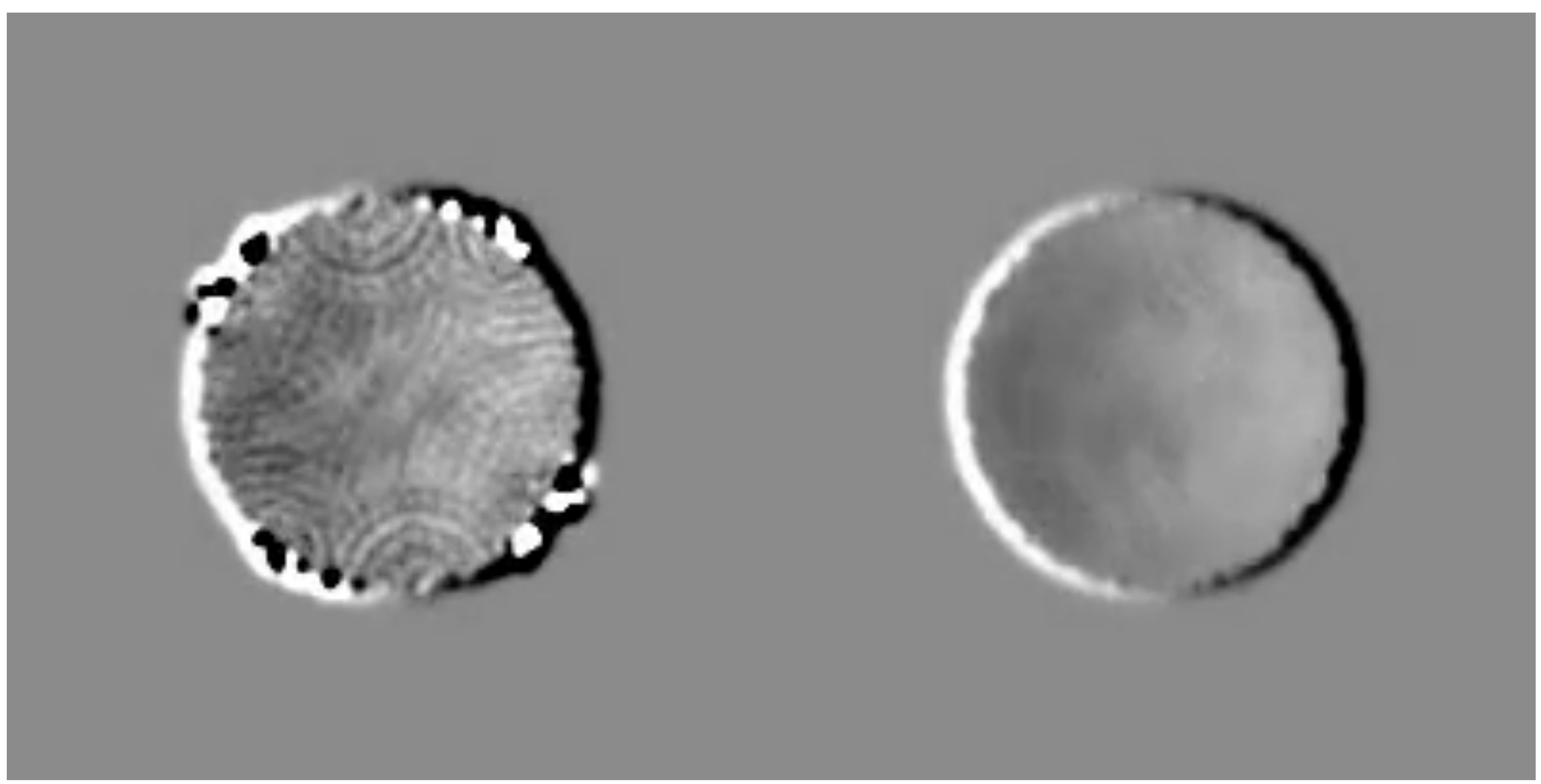
*Tricco, Price & Bate (2016)*
*J. Comp. Phys. 322, 326*

With thanks to Gabor Tóth for inspiration!

$$\frac{\mathrm{d}\mathbf{B}}{\mathrm{d}t} = -\nabla\psi$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\psi}{c_h}\right) = -c_h(\nabla\cdot\mathbf{B}) - \frac{\psi}{2c_h}(\nabla\cdot\mathbf{v}) - \frac{\sigma}{h}\frac{\psi}{c_h}$$

*Hyperbolic terms conserve energy even with variable wave speed!*



*Non-conservative method* *Conservative method*

# APPLICATION TO FINITE VOLUME SCHEMES

*Price, this week*
*See also: Derigs, Gassner, Walch & Winters (2017)*
*+ Florian Hindenlang talk*

**Original method (Dedner et al. 2003):**

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho\\ \rho\boldsymbol{v}\\ E\\ \boldsymbol{B}\\ \psi\end{bmatrix} + \nabla\cdot\begin{bmatrix}\rho\boldsymbol{v}\\ \rho\boldsymbol{v}\boldsymbol{v} + (P+\frac{1}{2}B^2)\mathcal{I} - \boldsymbol{B}\boldsymbol{B}\\ \boldsymbol{v}(E+P+\frac{1}{2}B^2) - \boldsymbol{B}(\boldsymbol{v}\cdot\boldsymbol{B})\\ \boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v}\\ c_h^2\boldsymbol{B}\end{bmatrix} = \begin{bmatrix}0\\ 0\\ 0\\ 0\\ -\frac{\psi}{\tau}\end{bmatrix}$$

**Constrained hyperbolic cleaning with variable wave speed:**

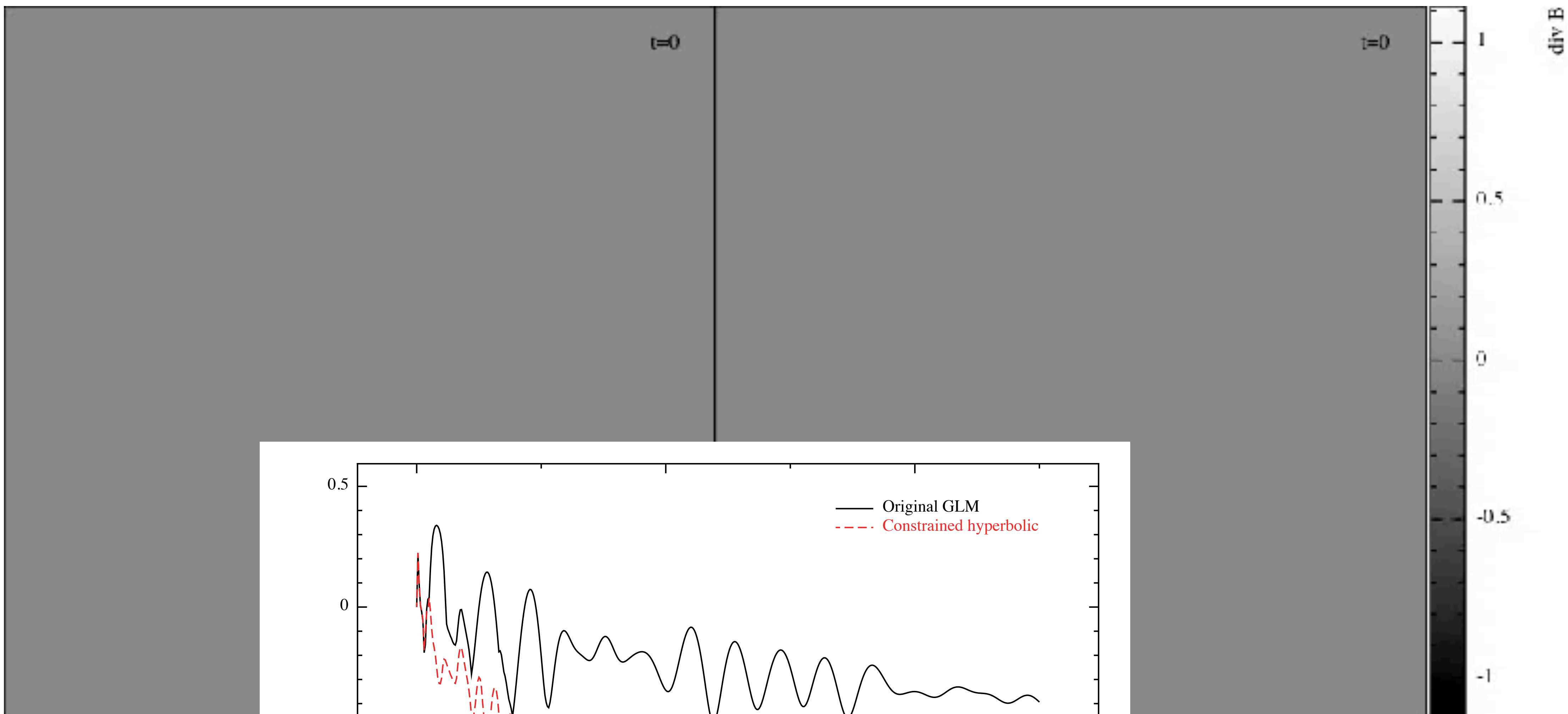
$$\frac{\partial}{\partial t}\begin{bmatrix}\rho\\ \rho\boldsymbol{v}\\ E'\\ \boldsymbol{B}\\ \phi\end{bmatrix} + \nabla\cdot\begin{bmatrix}\rho\boldsymbol{v}\\ \rho\boldsymbol{v}\boldsymbol{v} + (P+\frac{1}{2}B^2)\mathcal{I} - \boldsymbol{B}\boldsymbol{B}\\ \boldsymbol{v}(E'+P+\frac{1}{2}B^2) - \boldsymbol{B}(\boldsymbol{v}\cdot\boldsymbol{B}) + \psi\boldsymbol{B}\\ \boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v}\\ \phi\boldsymbol{v}\end{bmatrix} = \begin{bmatrix}0\\ 0\\ -\frac{\psi^2}{c_h^2\tau}\\ \boldsymbol{v}(\nabla\cdot\boldsymbol{B})\\ -\frac{c_h}{\sqrt{\rho}}(\nabla\cdot\boldsymbol{B}) - \frac{\phi}{\tau}\end{bmatrix}$$

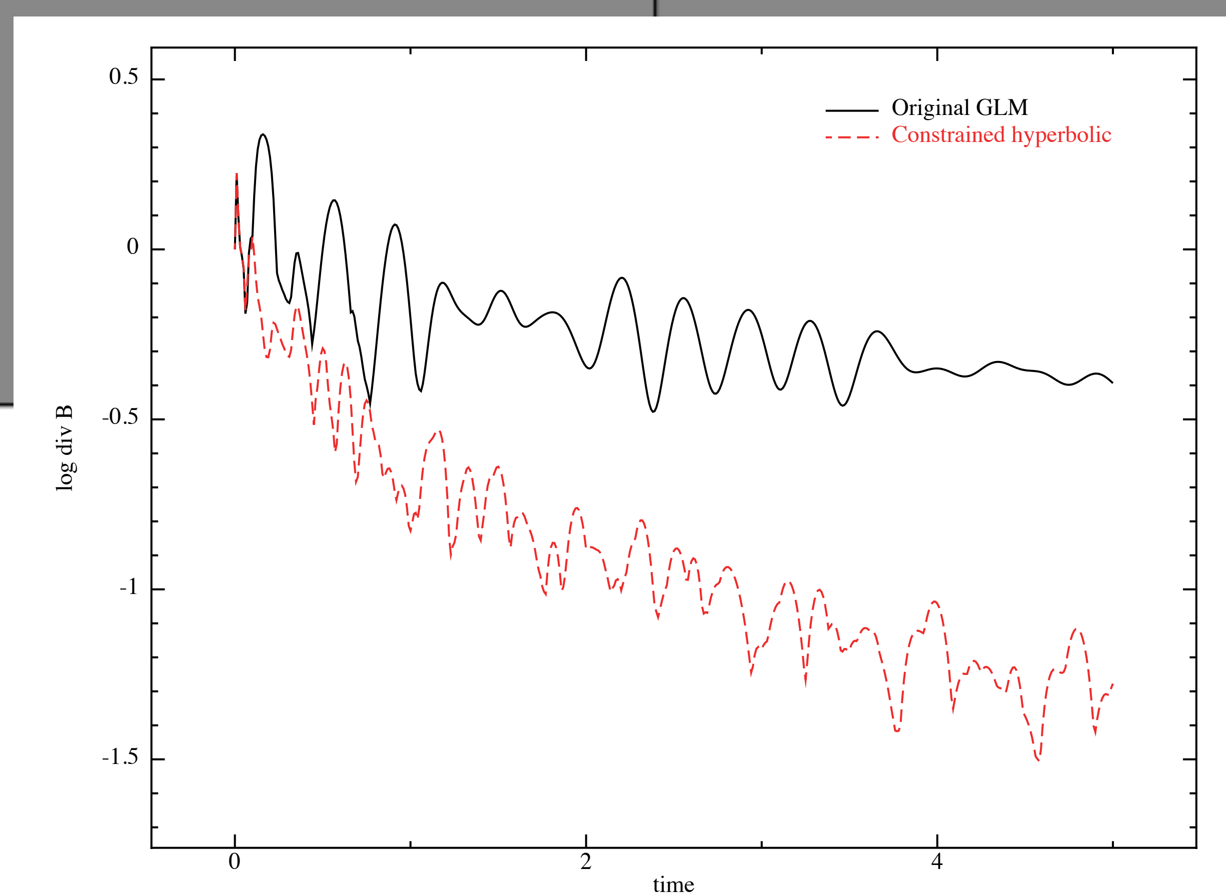
$$E' = E + \frac{1}{2}\frac{\psi^2}{c_h^2} \qquad\qquad \phi = \frac{\psi}{c_h\sqrt{\rho}}$$

# APPLICATION TO FINITE VOLUME CODES

*Price, this week*

*Original GLM* *Constrained hyperbolic cleaning*

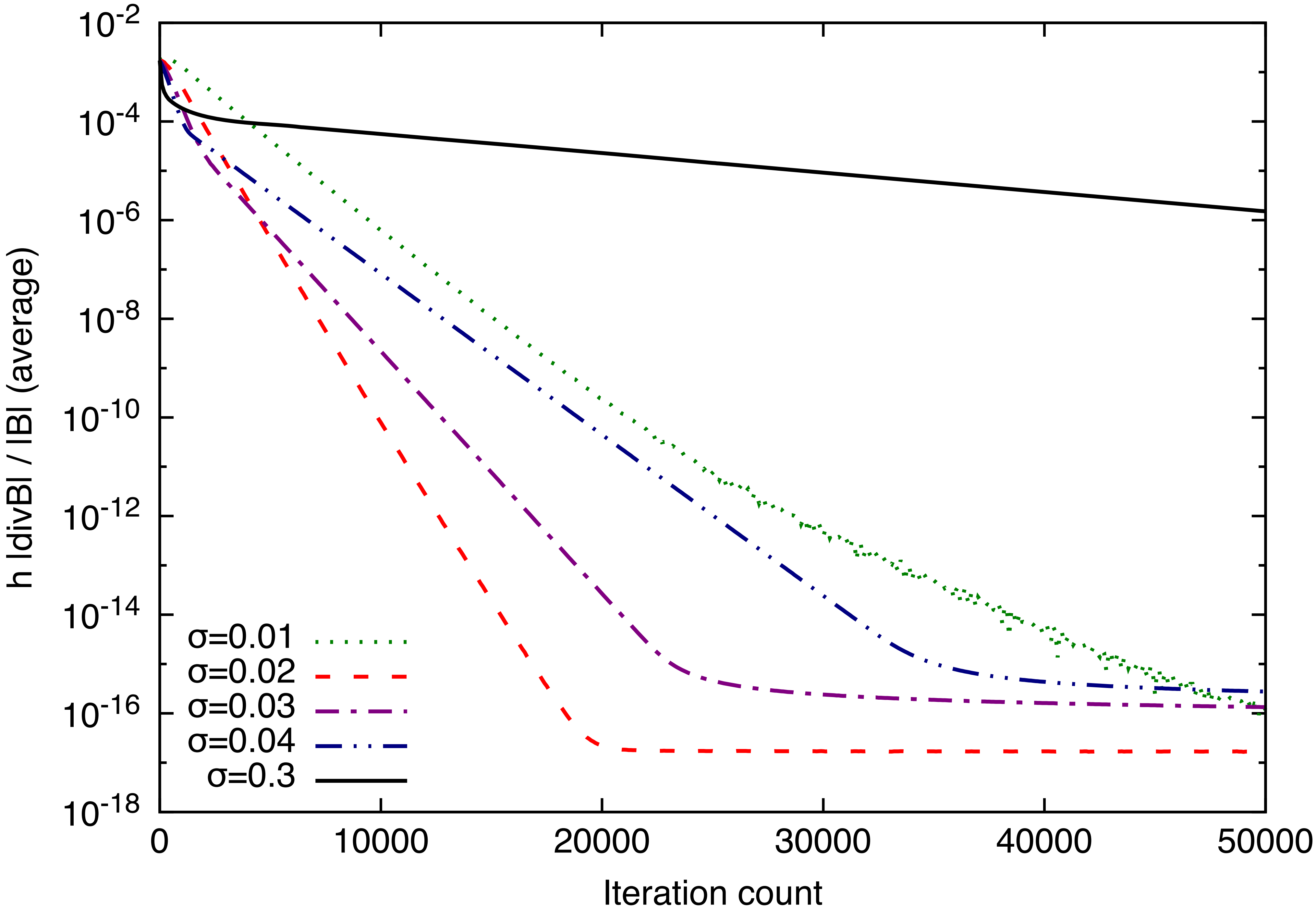



Pure hyperbolic case

# CAN WE ENFORCE DIVB = 0 EXACTLY?

*Tricco, Price & Bate (2016)*
*J. Comp. Phys. 322, 326*

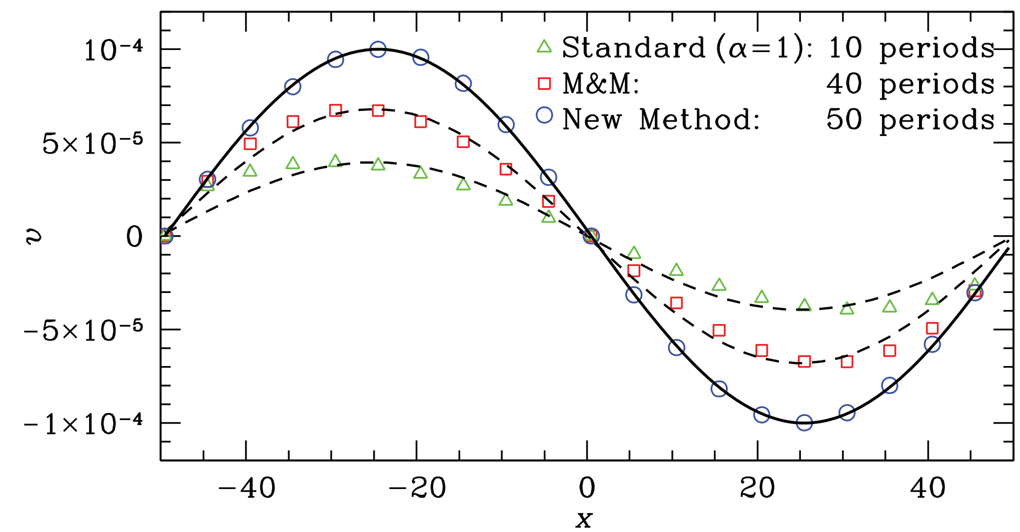



Achievable in principle, not currently practical

# SHOCK DISSIPATION SWITCHES

- Cullen & Dehnen (2010) switch for shock viscosity

$$A = \max\left[-\frac{\mathrm{d}}{\mathrm{d}t}(\nabla\cdot\mathbf{v}), 0\right] \quad \alpha_{loc} = \min\left(\frac{10h^2 A}{c_\mathrm{s}^2 + h^2 A}, 1\right)$$



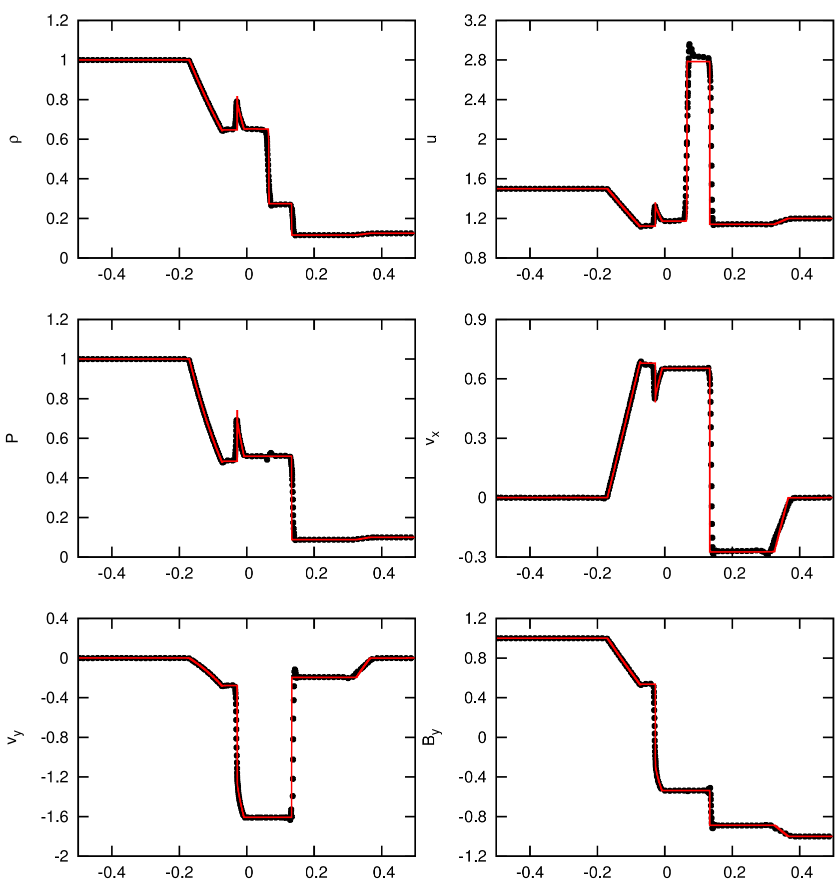
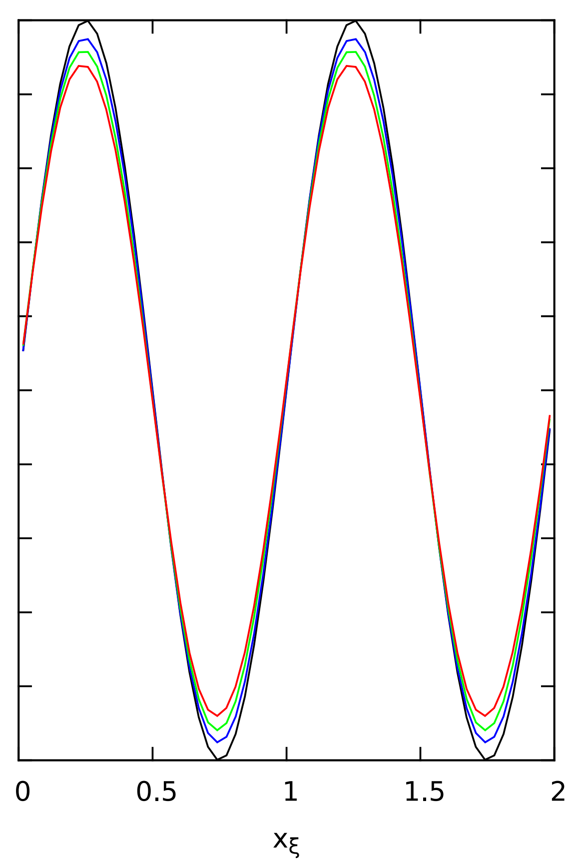




**Figure 3.** Shocktube test 5A from RJ95 performed in 2D with left state ($\rho$, $P$, $v_x$, $v_y$, $B_y$) = (1, 1, 0, 0, 1) and right state ($\rho$, $P$, $v_x$, $v_y$, $B_y$) = (0.125, 0.1, 0, 0, −1) with $B_x = 0.75$ at $t = 0.1$. Black circles represent the particles and the red line represents the solution obtained with the ATHENA code using $10^4$ grid cells.



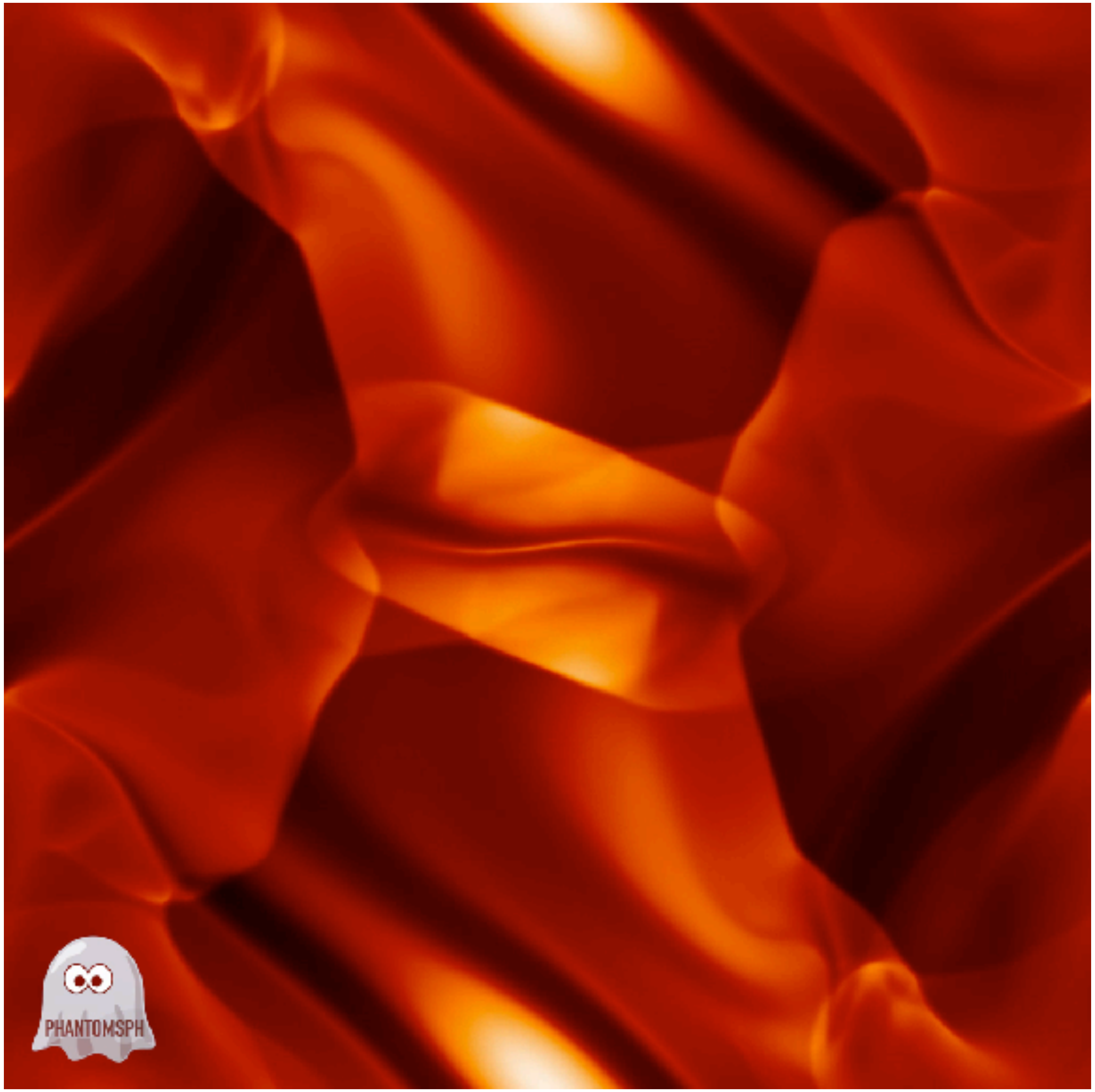

- Tricco & Price (2013) switch for resistivity

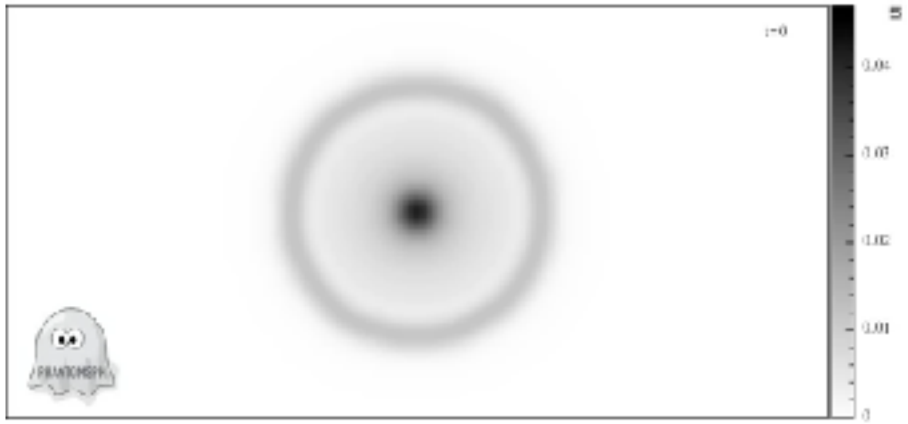
$$\alpha^B = \min\left(\frac{h|\nabla\mathbf{B}|}{|\mathbf{B}|}, 1\right)$$

- Revised further in Phantom - 2nd order artificial resistivity, vanishes when v=const

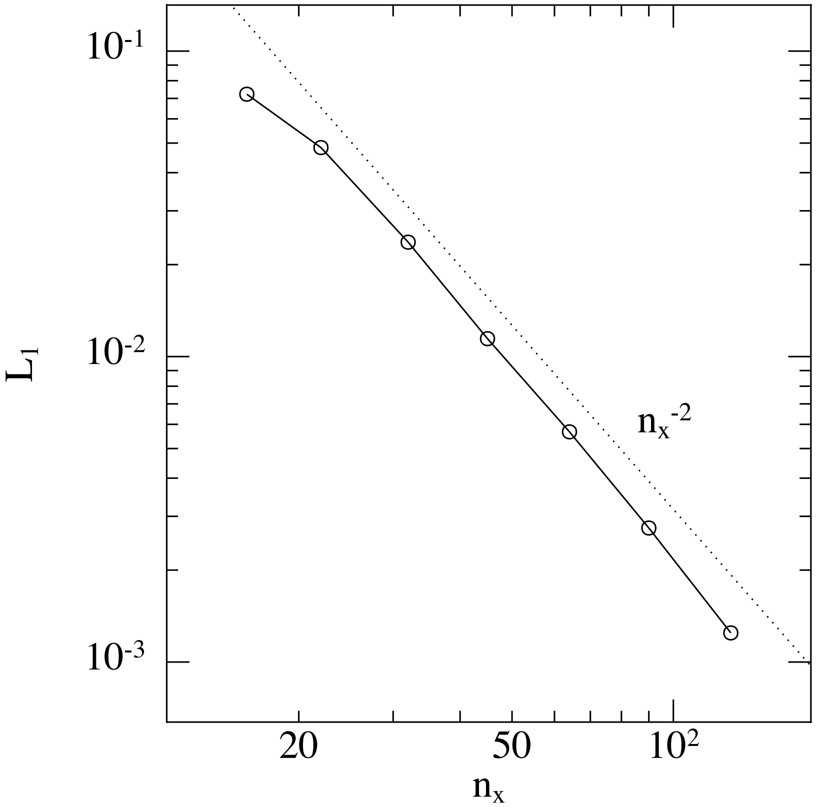
# PHANTOM SPMHD CODE

*Price et al. (2017), arXiv:1702.03930*



*Advection of current loop (Gardiner & Stone 2005, 2008)*

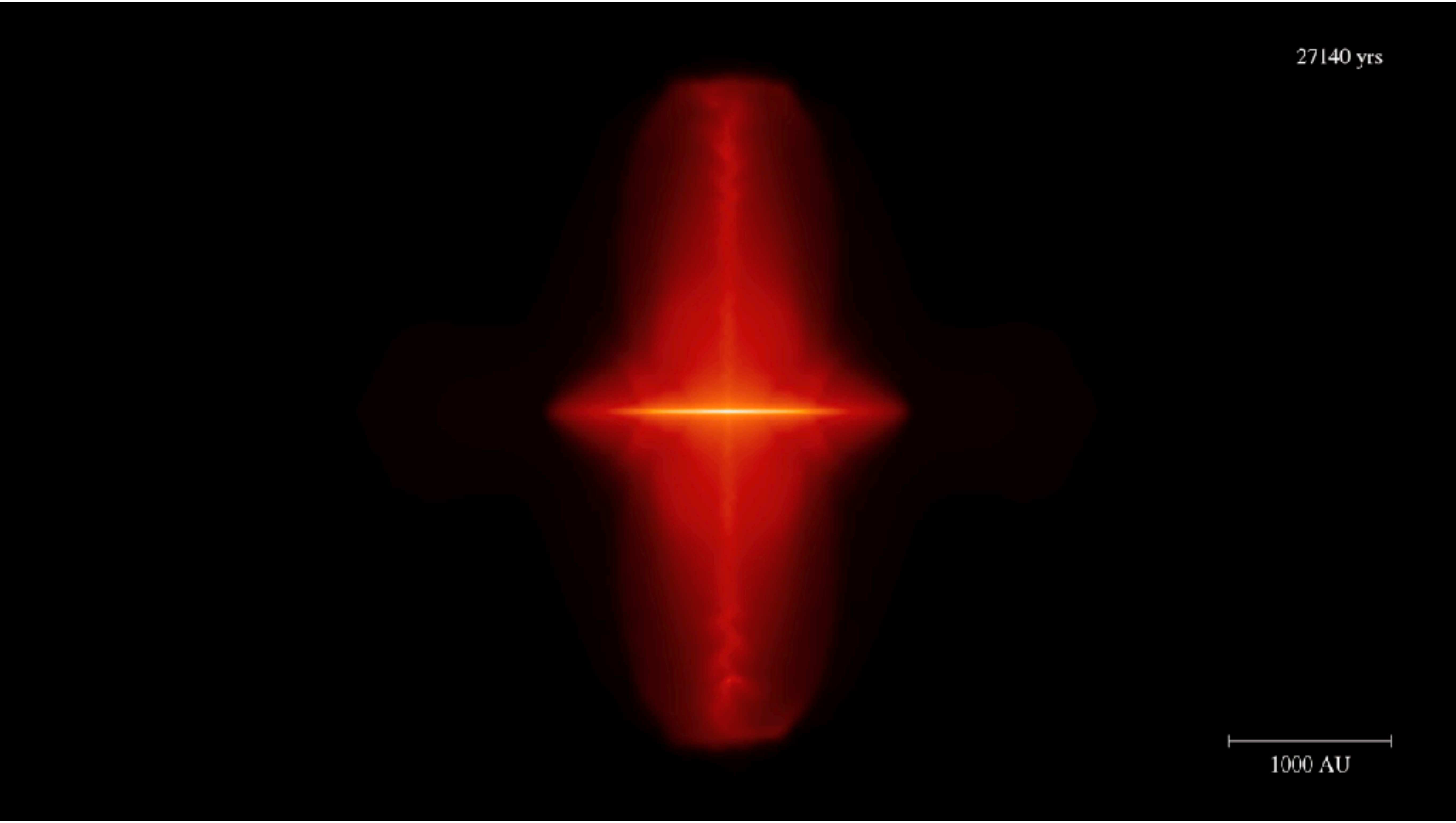



*Convergence on circularly polarised Alfvén wave with ALL dissipation turned on*

**Performed with all dissipation, shock capturing and divergence cleaning turned on**

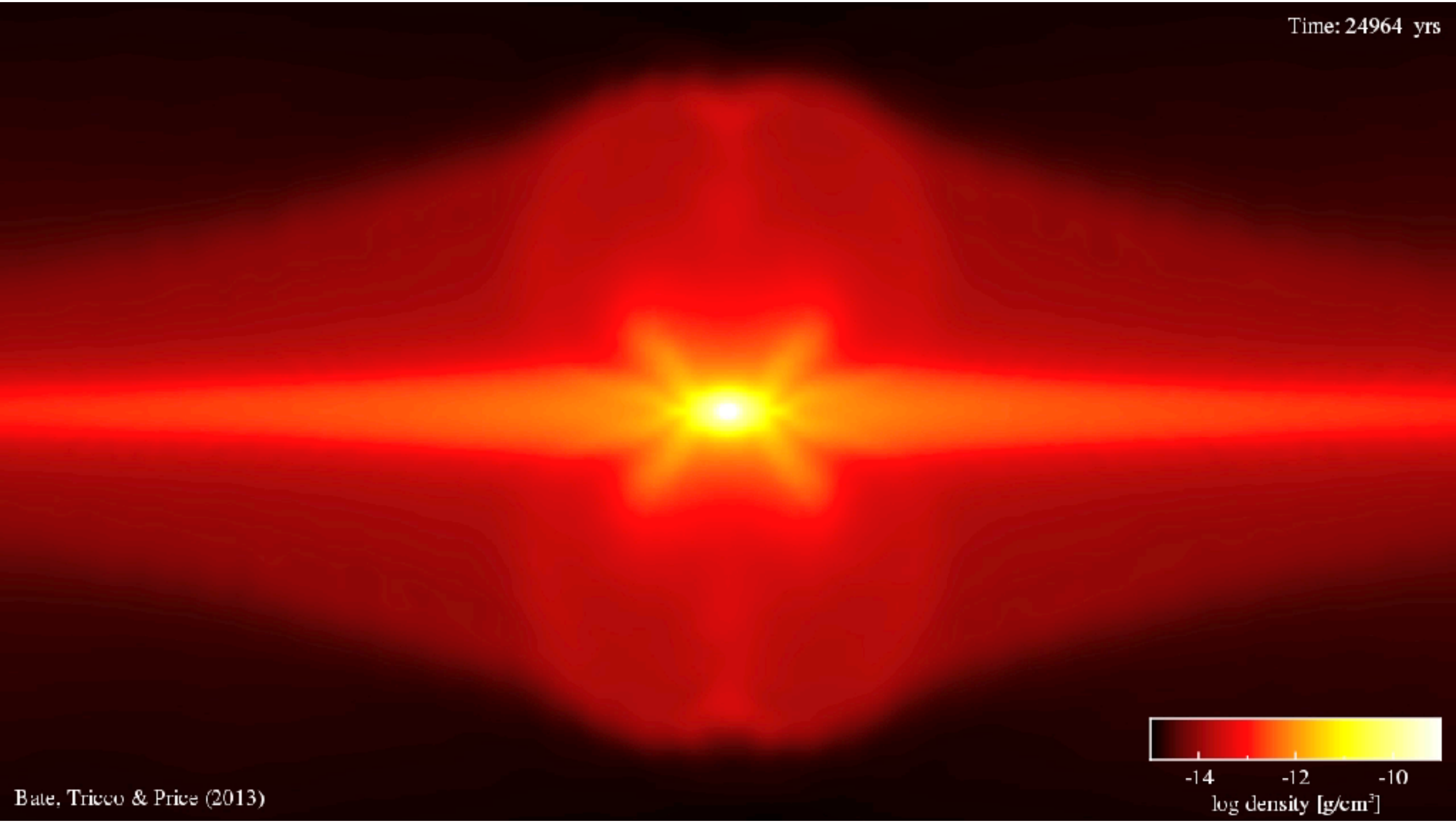
# JETS FROM THE FIRST CORE

*Price, Tricco & Bate (2012); see also Machida et al. (2008)*



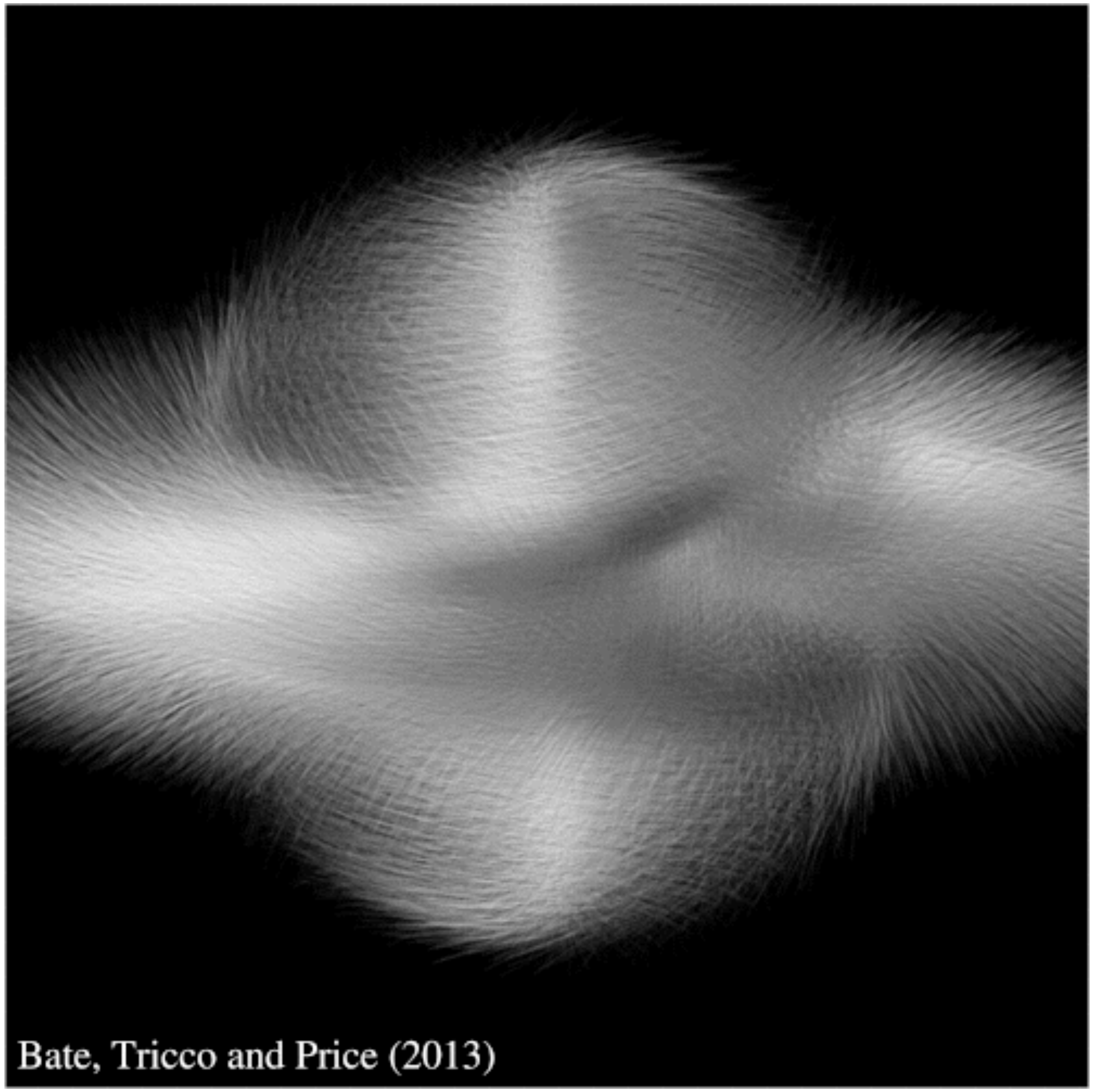
# PROTOSTELLAR JETS: SECOND COLLAPSE

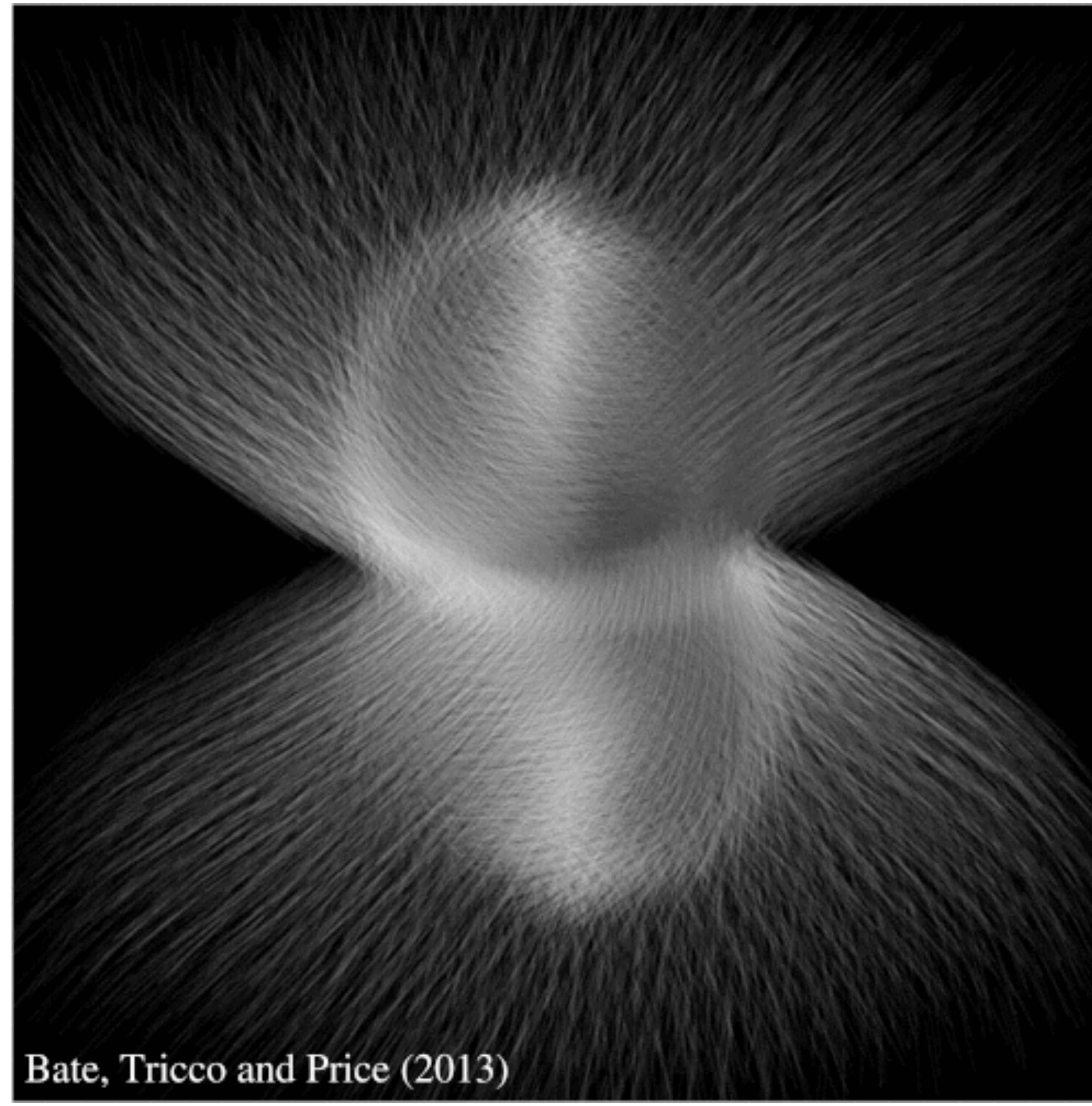
*Bate, Tricco & Price (2014)*




*Performed with radiation magnetohydrodynamics (gray FLD: Whitehouse & Bate 2004a,b; Whitehouse, Bate & Monaghan 2006)*

# MAGNETICALLY LAUNCHED OUTFLOWS

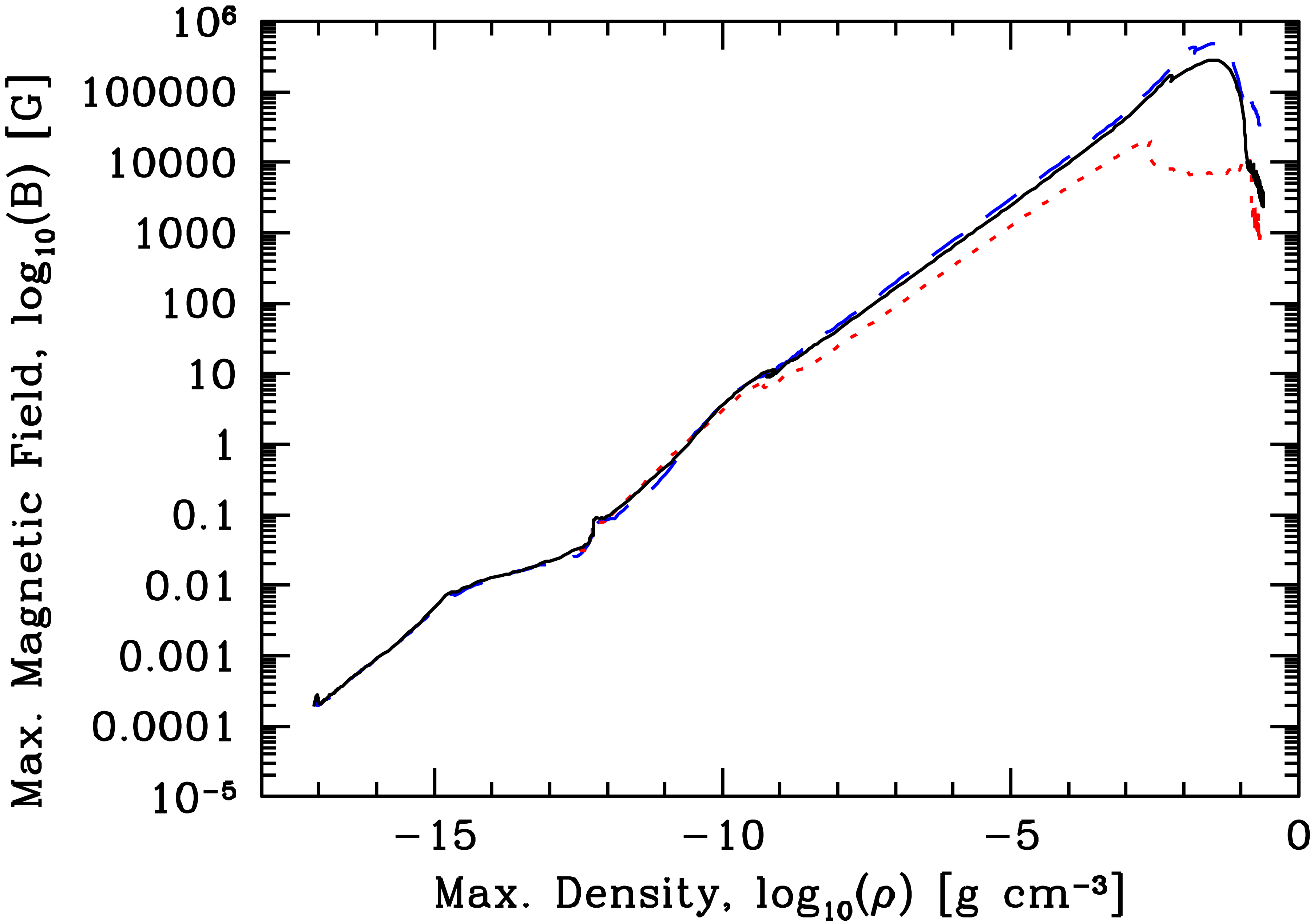



*First core (100 x 100 au)*

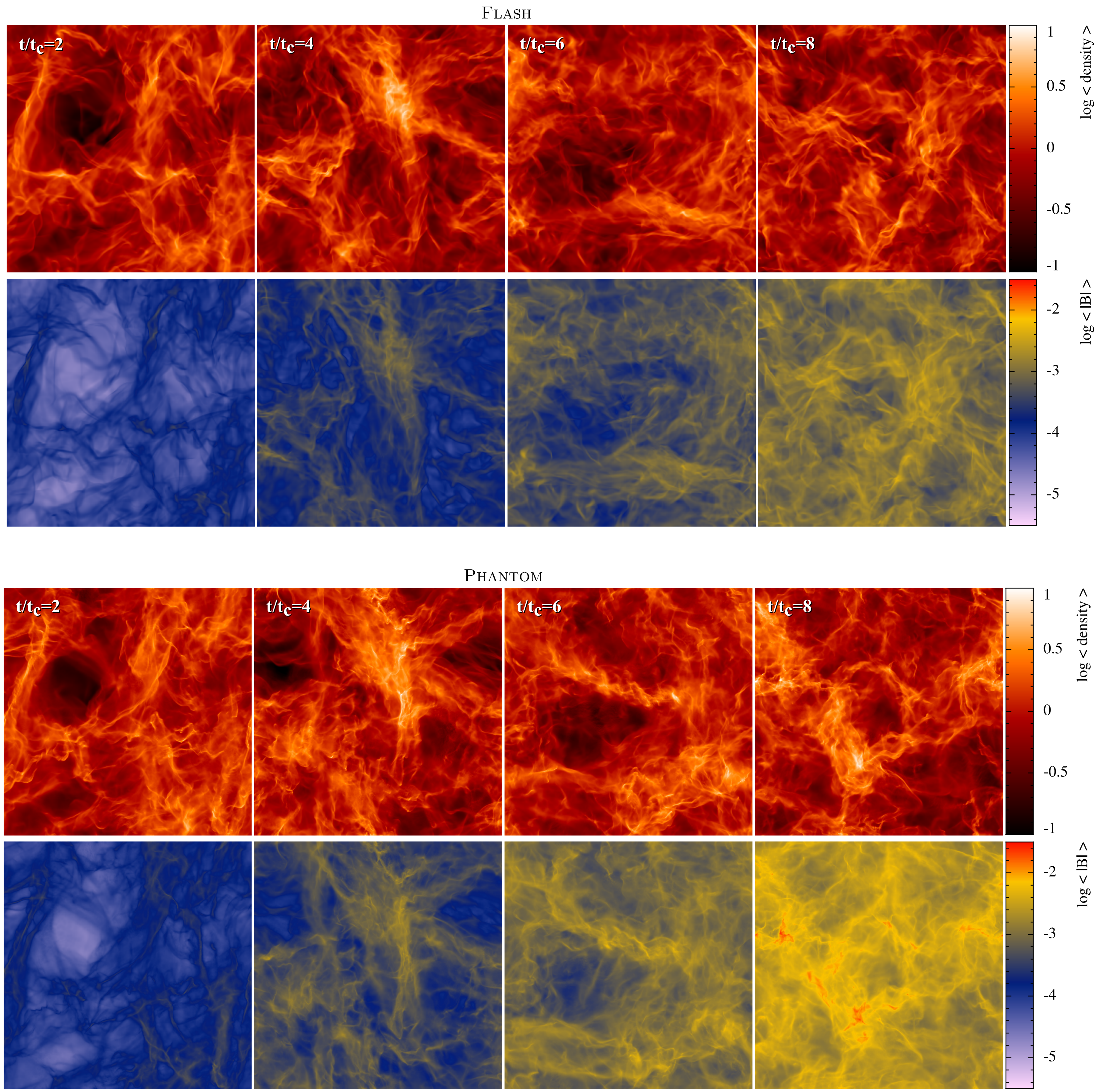
*Second (protostellar) core (10 x 10 au)*

# STRONG MAGNETIC FIELDS IMPLANTED IN STARS AT BIRTH



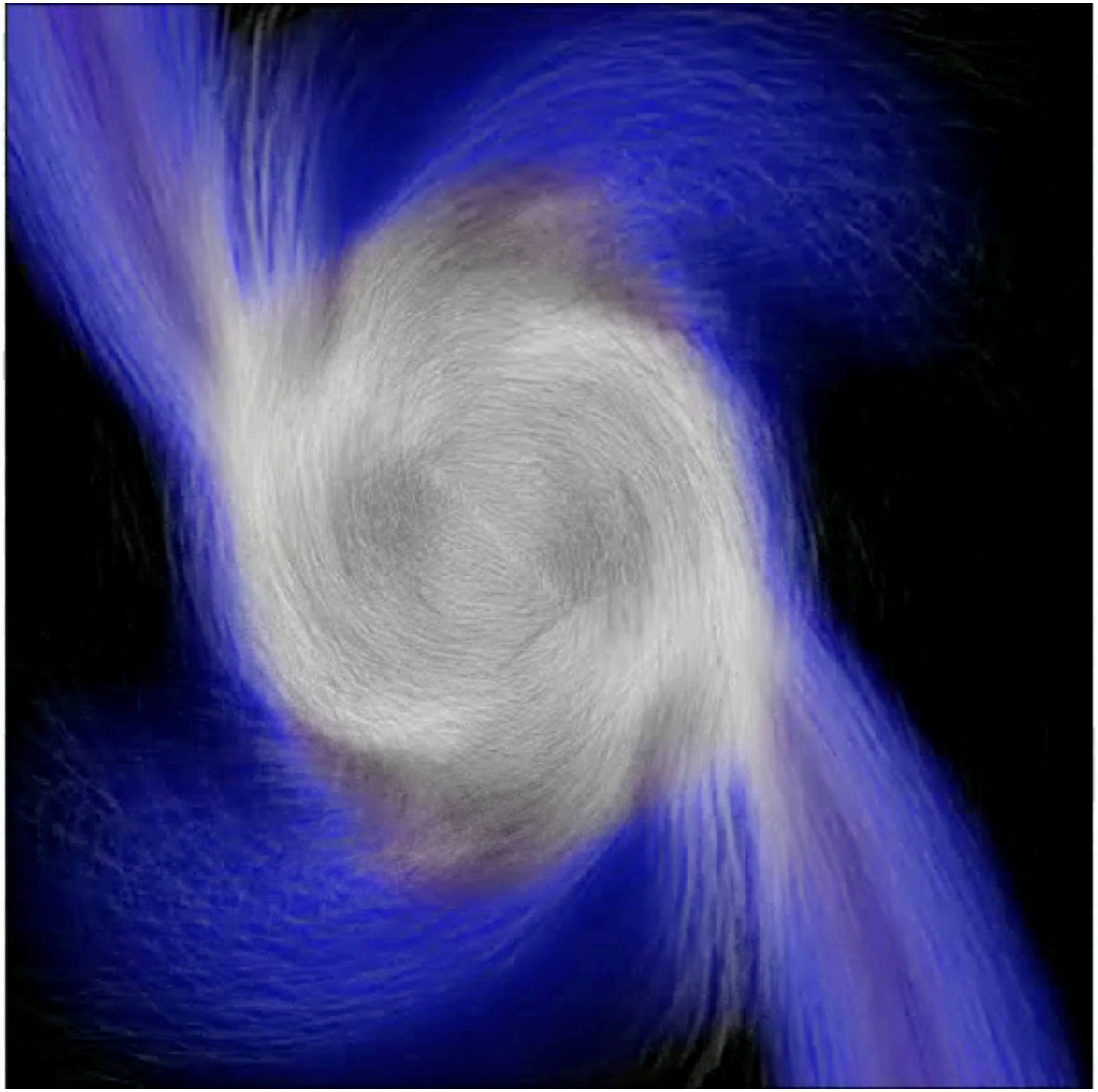
# SMALL SCALE DYNAMO: FLASH VS PHANTOM

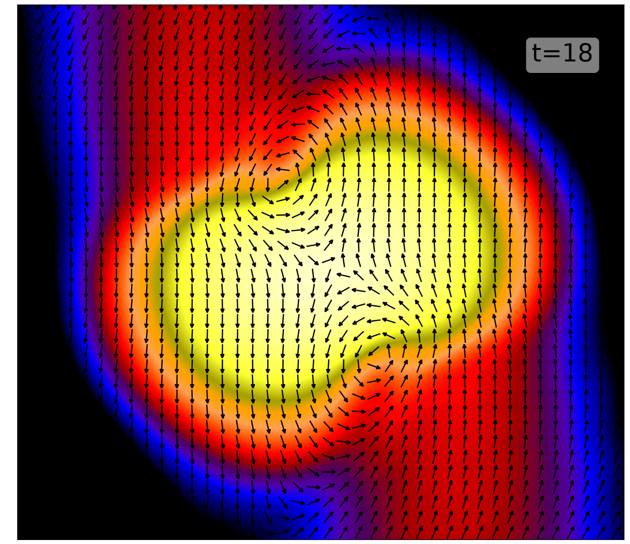
*Tricco, Price & Federrath (2016)*

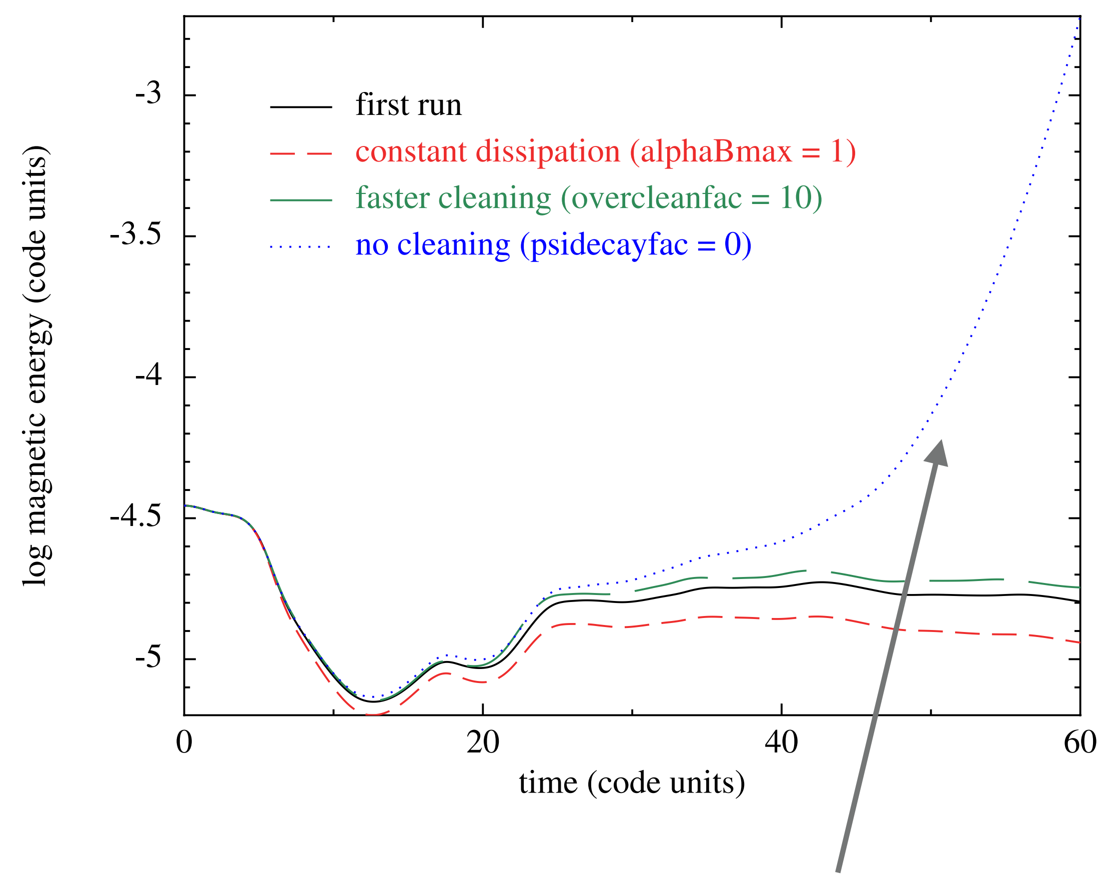


# MAGNETIC FIELDS IN TIDAL DISRUPTION EVENTS

*Bonnerot, Price, Rossi, Lodato (2017), MNRAS*






*Artificial dynamo with Powell-terms only*

# NON-IDEAL SPMHD

*Wurster, Price & Ayliffe (2014), Wurster, Price & Bate (2016), MNRAS*

*Strong coupling approximation:* $\rho \approx \rho_n; \;\; \rho_i \ll \rho$

$$\frac{\mathrm{d}\mathbf{B}}{\mathrm{d}t} = -\mathbf{B}(\nabla \cdot \mathbf{v}) + (\mathbf{B} \cdot \nabla)\mathbf{v} - \nabla \times \left[\eta_O \mathbf{J} + \eta_H \mathbf{J} \times \hat{\mathbf{B}} - \eta_A (\mathbf{J} \times \hat{\mathbf{B}}) \times \hat{\mathbf{B}}\right]$$

Ohmic Hall Ambipolar

- Spatial discretisation exactly conserves energy
- Guaranteed positive definite contribution to entropy
- RKC super-timestepping for ambipolar/Ohmic terms (Alexiades et al. 1996; O'Sullivan & Downes 2006)

Tests:
Mac-Low et al. (1995)
O'Sullivan & Downes (2006)
Choi et al. (2009)
Falle (2003)

*Whistler/Ion-cyclotron modes*

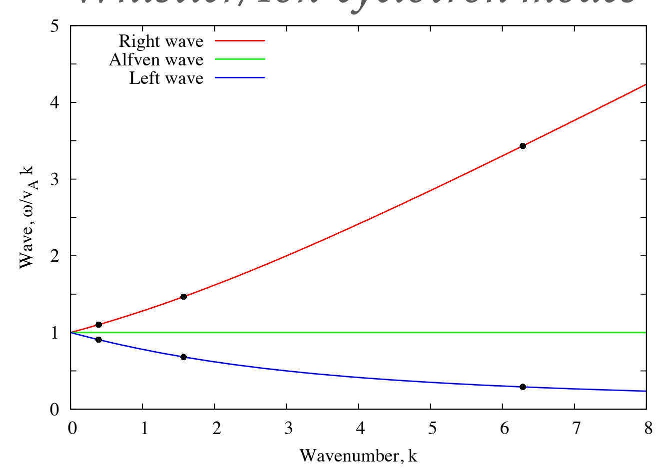
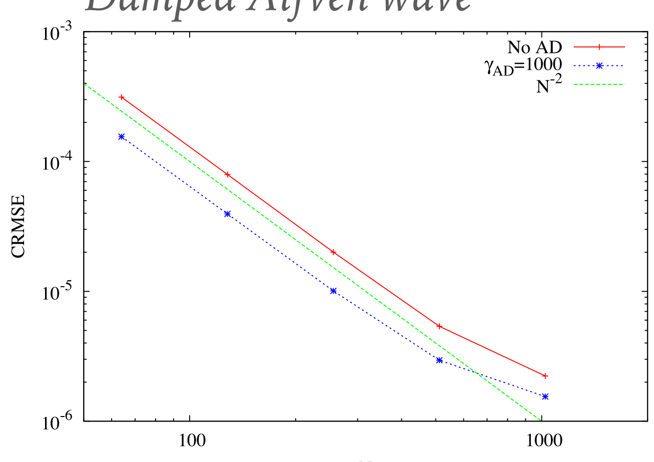
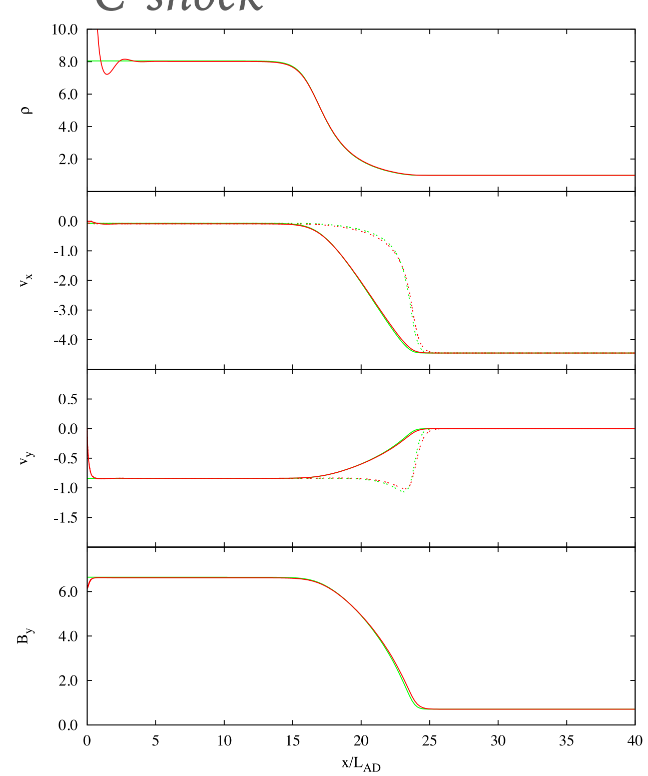



**Figure C1.** Dispersion relation for the left- and right-circularly polarised wave, corresponding to $\eta_{\rm HE} < 0$ and $> 0$, respectively. The solid circles are the numerically calculated phase velocities.

*Damped Alfvén wave*




*C-shock*




*Standing C-shock*

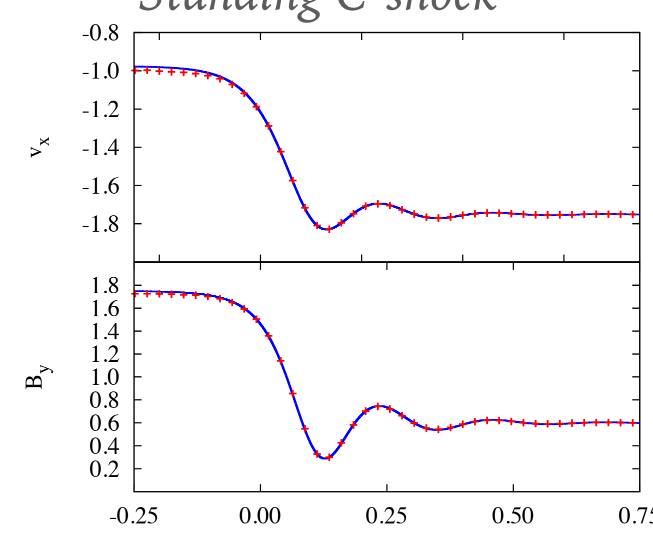
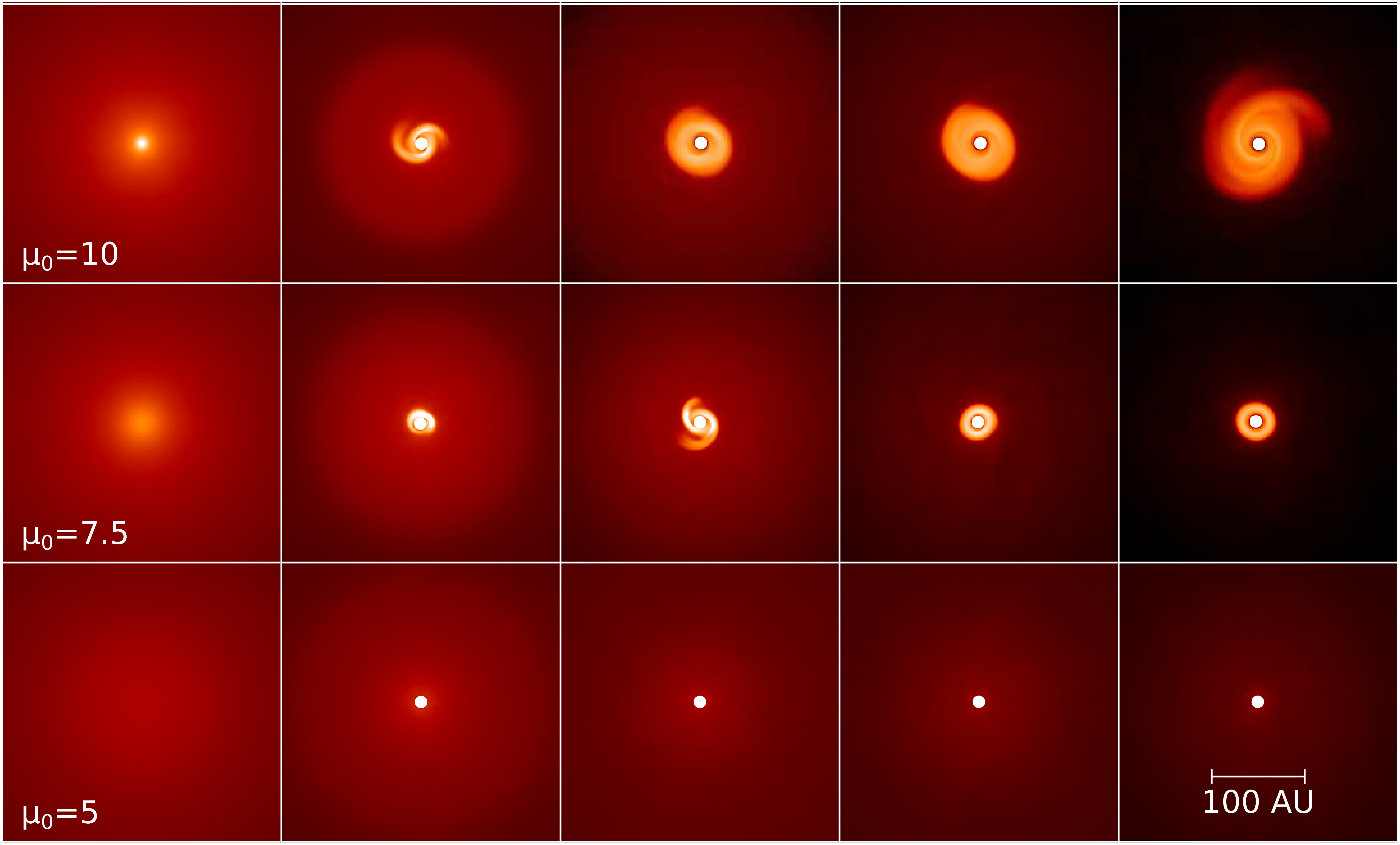



**Figure C2.** The analytical (solid line) and numerical (crosses) results for the isothermal standing shock. The initial conditions are given in the text. At any given position, the analytical and numerical solutions agree within 3 per cent.

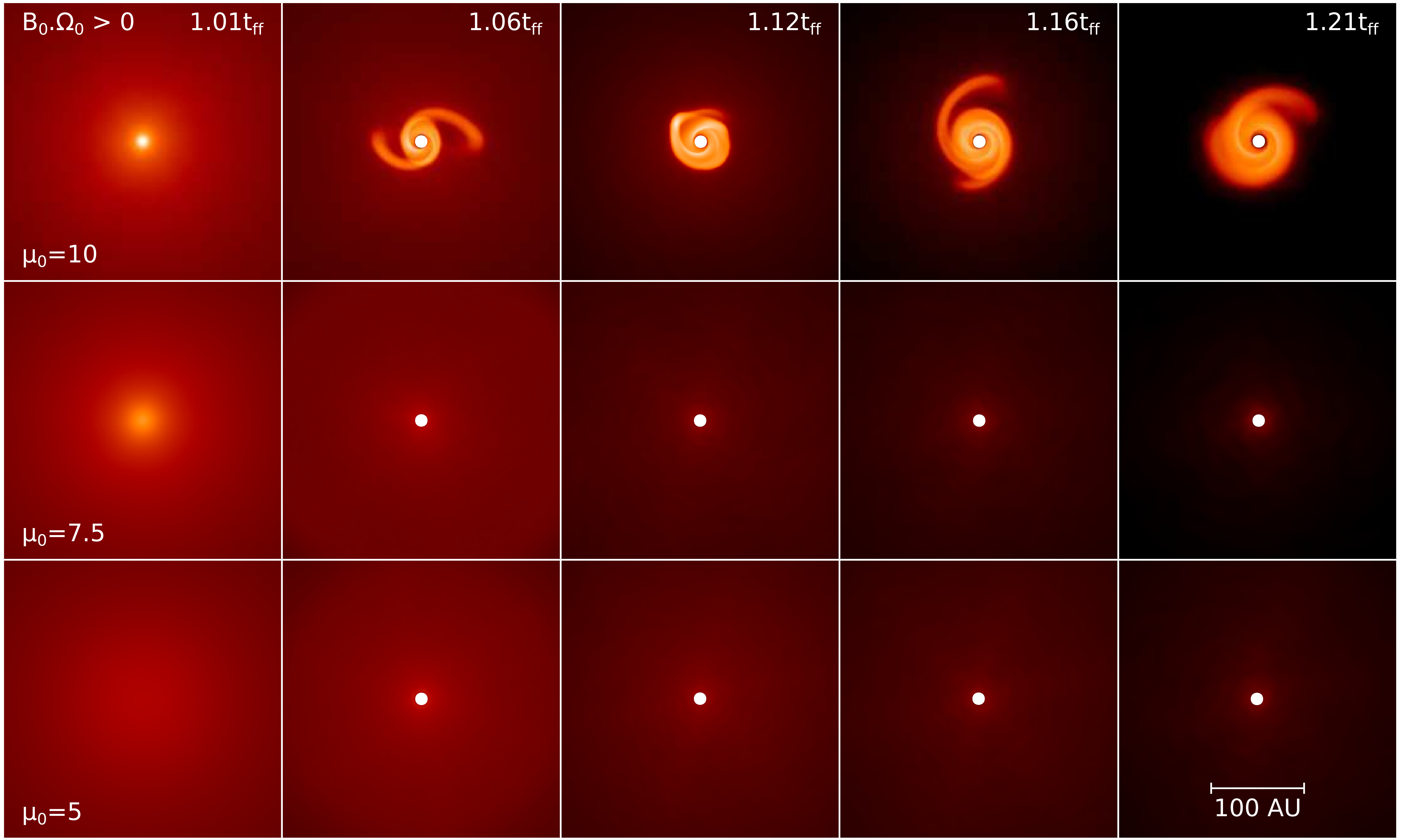
# IDEAL MHD: MAGNETIC BRAKING CATASTROPHE

*Wurster, Price & Bate (2016) MNRAS 457, 1037*



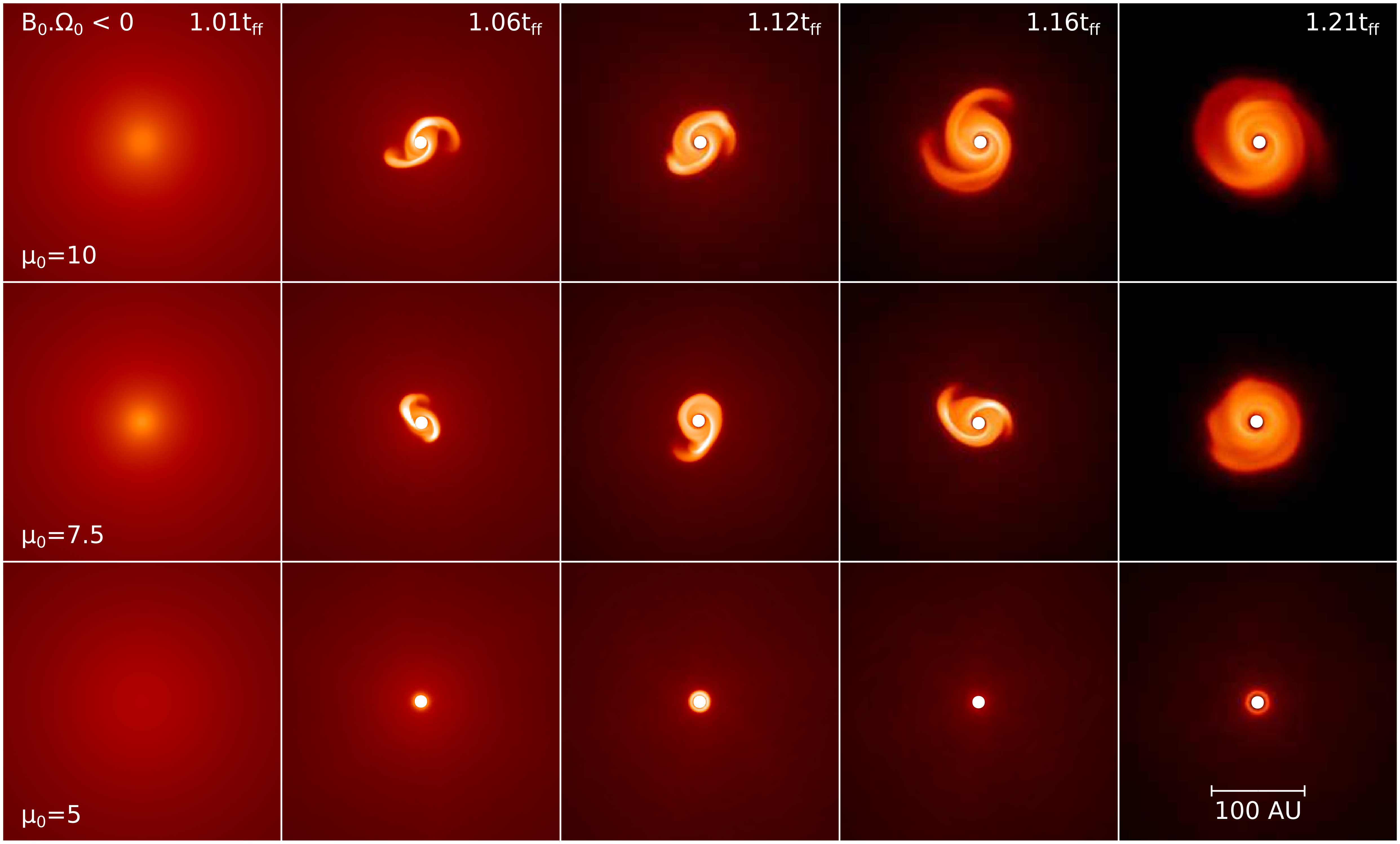
# NON-IDEAL MHD: ALIGNED INITIAL FIELD

*Wurster, Price & Bate (2016)*



# NON-IDEAL MHD: ANTI-ALIGNED INITIAL FIELD

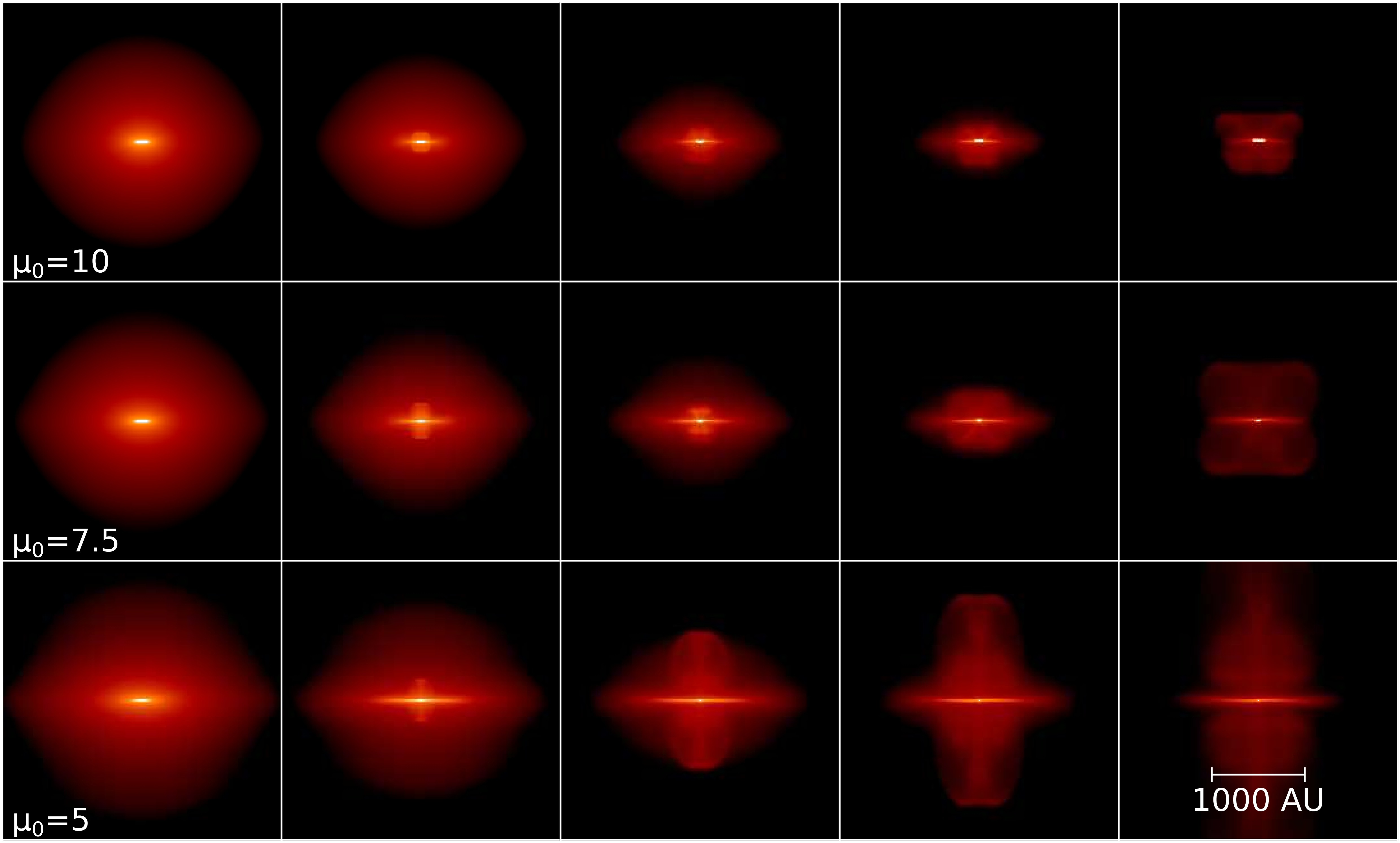
*Wurster, Price & Bate (2016)*



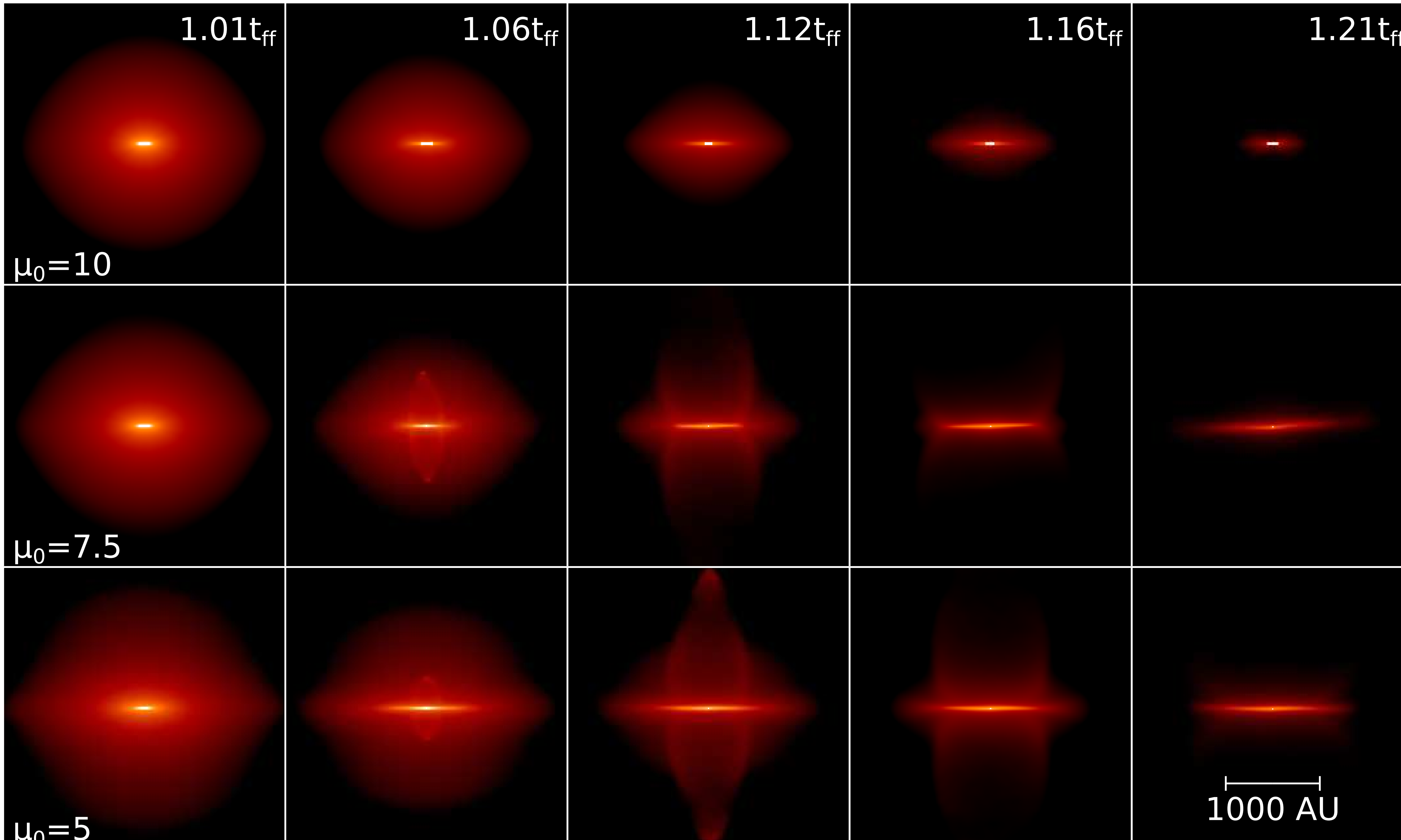

*see also Tsukamoto et al. (2015)*

# OUTFLOWS - IDEAL MHD

*Wurster, Price & Bate (2016)*

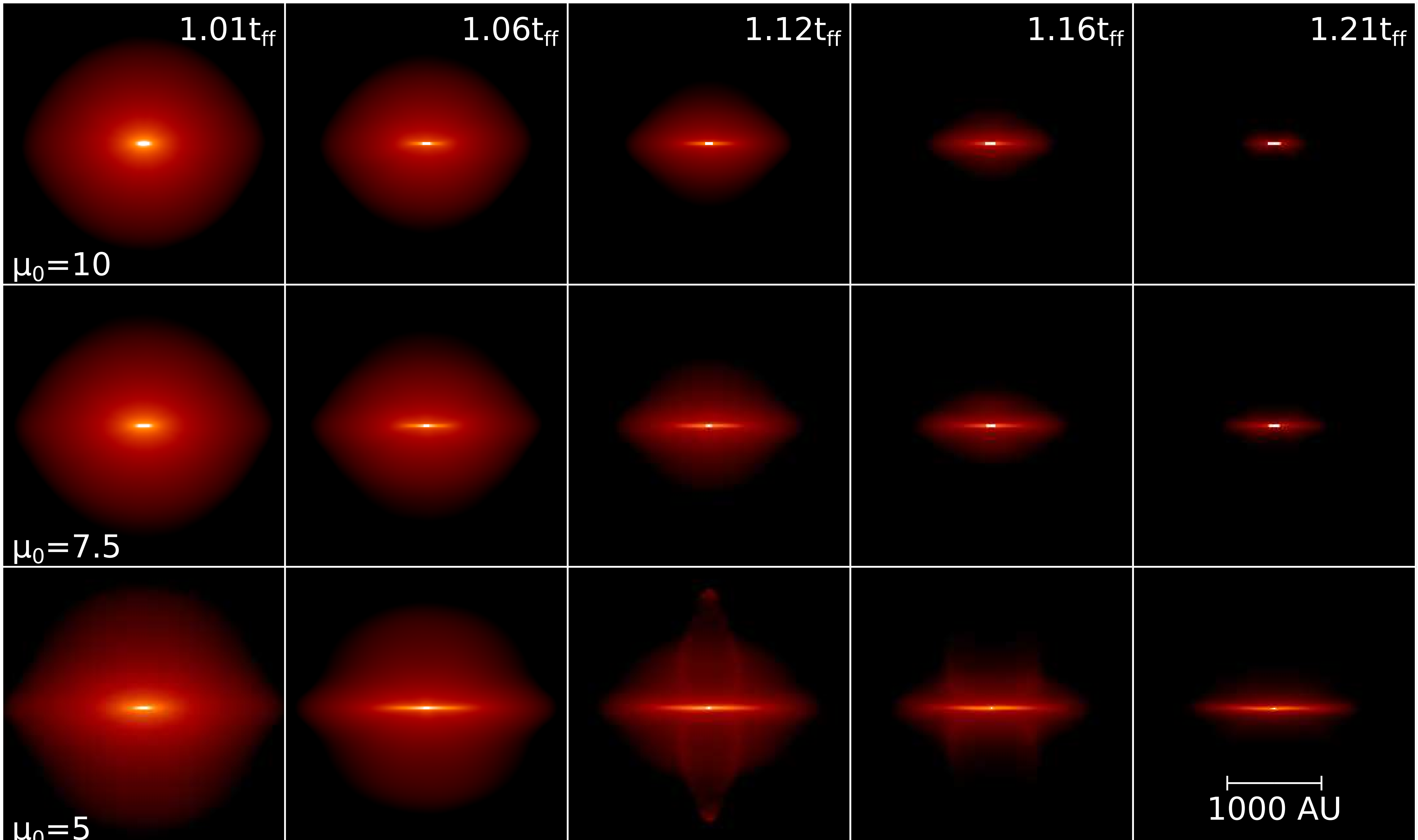


# OUTFLOWS: NON-IDEAL MHD / ALIGNED INITIAL FIELD



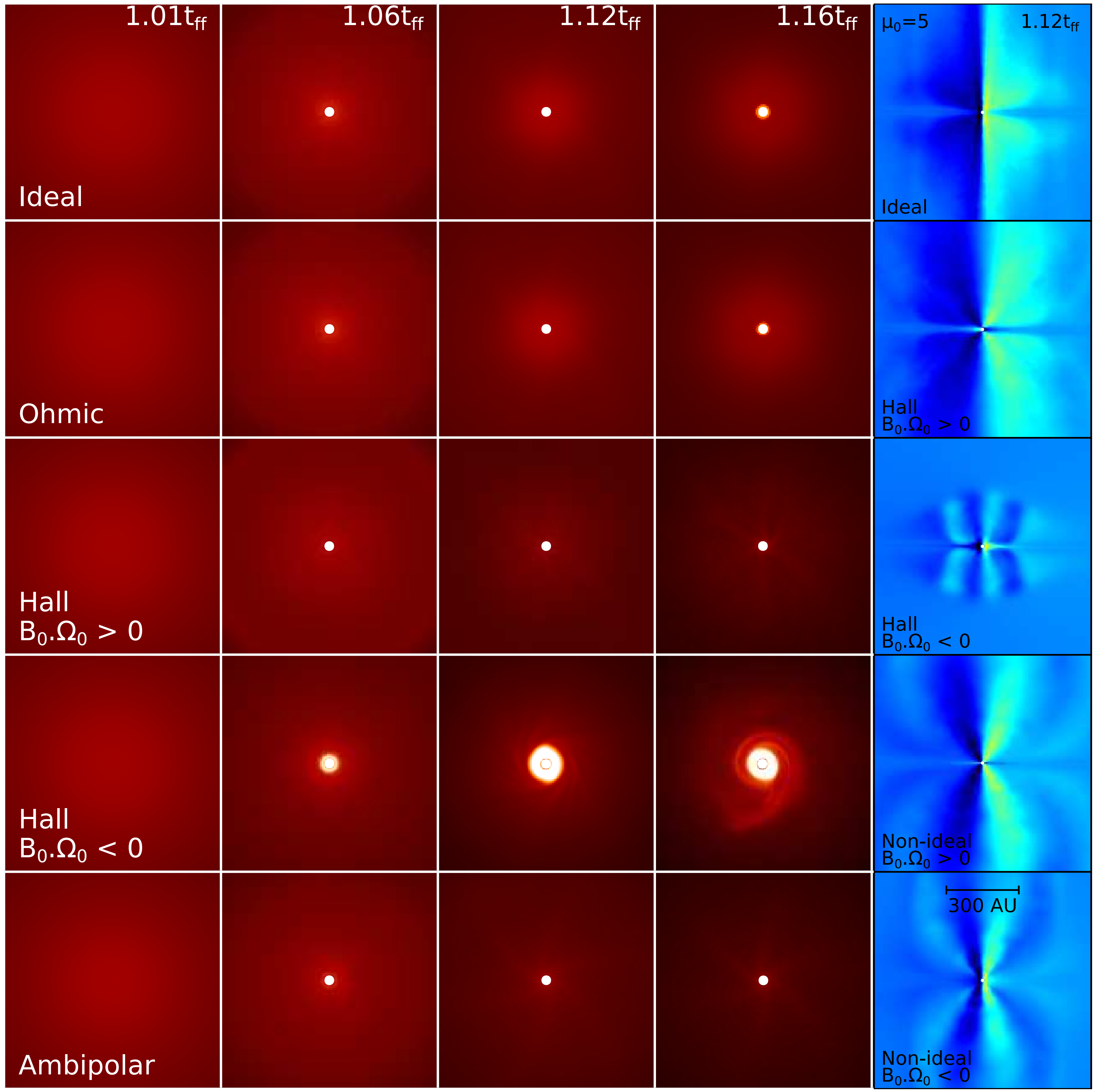

*Wurster, Price & Bate (2016)*

# OUTFLOWS: NON-IDEAL MHD / ANTI-ALIGNED




*Outflows are anti-correlated with disc formation!*

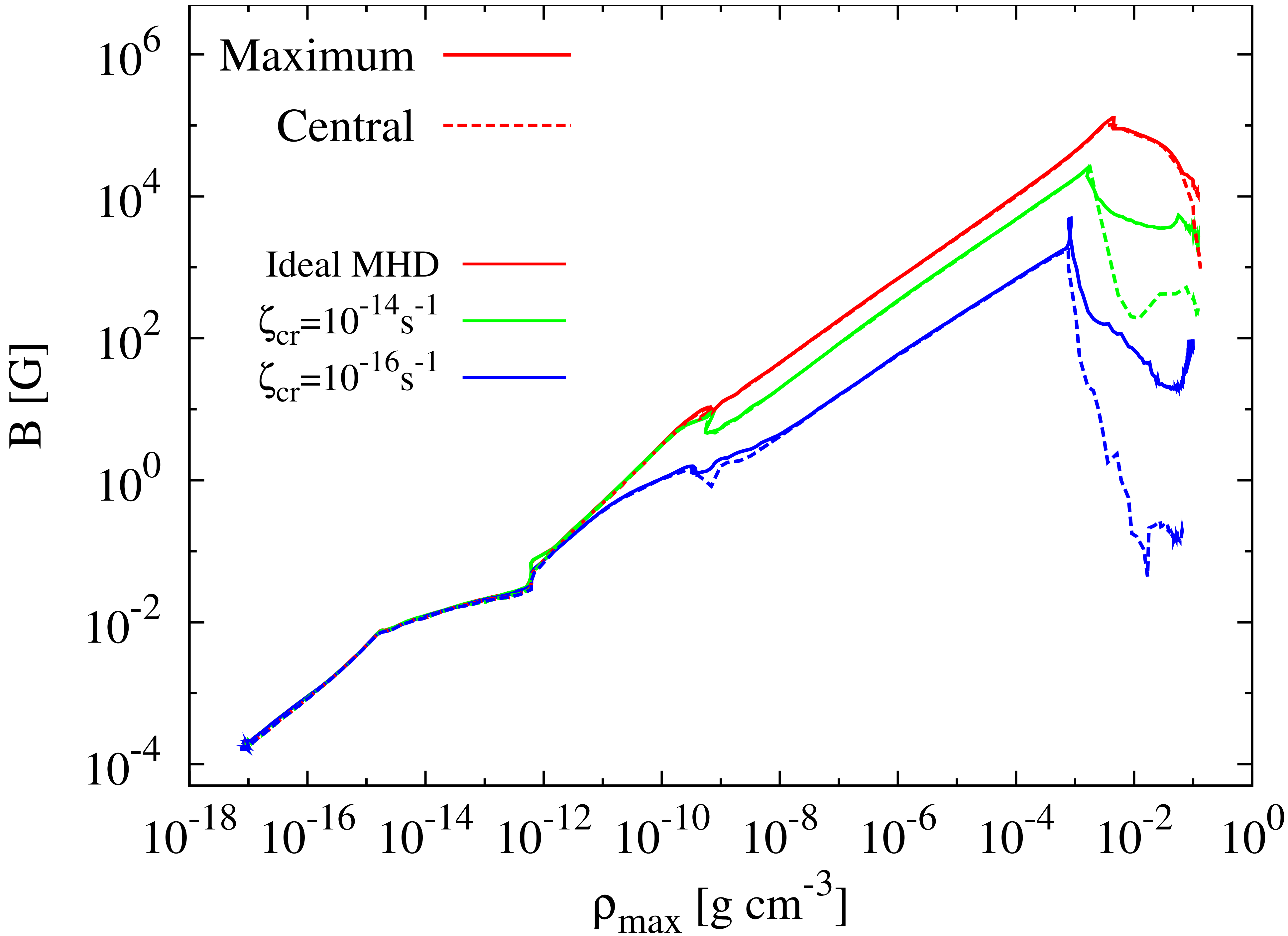
# WHICH NON-IDEAL EFFECTS ARE IMPORTANT?




- Hall effect is dominant during disc formation
- Produces counter-rotating envelope when B and rotation are misaligned
- Maybe why half of all stars have planets?

# ARE FOSSIL FIELDS POSSIBLE IN NON-IDEAL MHD?

*Wurster, Price & Bate (2018)*



# CONCLUSIONS

- Enforcing div B = 0 is main issue in accurate SPMHD simulations
- Current best approach to enforcing div B = 0 in SPMHD is to use “constrained” hyperbolic/parabolic cleaning
- Phantom SPMHD code now public
- Non-ideal MHD, in particular the Hall effect, plays a crucial role in the formation of protostellar discs
- Can seemingly rule out fossil field hypothesis for origin of magnetic fields in stars