Star Formation with Smoothed Particle Magnetohydrodynamics

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MHD Codes in Astrophysics

- 3 broad classes of hydrodynamics methods used in astrophysics:
  - Grid: (*e.g., Pluto, Athena, Ramses, Flash*)
  - SPH: (*e.g., Gadget, Gasoline, Hydra, Phantom*)
  - Moving Mesh: (*e.g., Arepo, Gizmo*)

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"*.. magnetic fields may be included without difficulty..*"
Gingold & Monaghan (1977)

Constrained Divergence Cleaning

Tricco & Price (2012)

- Control $\nabla \cdot \mathbf{B} = 0$
- Hyperbolic / parabolic cleaning (Dedner et al 2002):

$$\left(\frac{\mathrm{d}\mathbf{B}}{\mathrm{d}t}\right)_{\psi} = -\nabla\psi \qquad\qquad \frac{\mathrm{d}\psi}{\mathrm{d}t} = -c_h^2 \nabla \cdot \mathbf{B} - \frac{\psi}{\tau} - \frac{1}{2}\psi\nabla \cdot \mathbf{v}$$

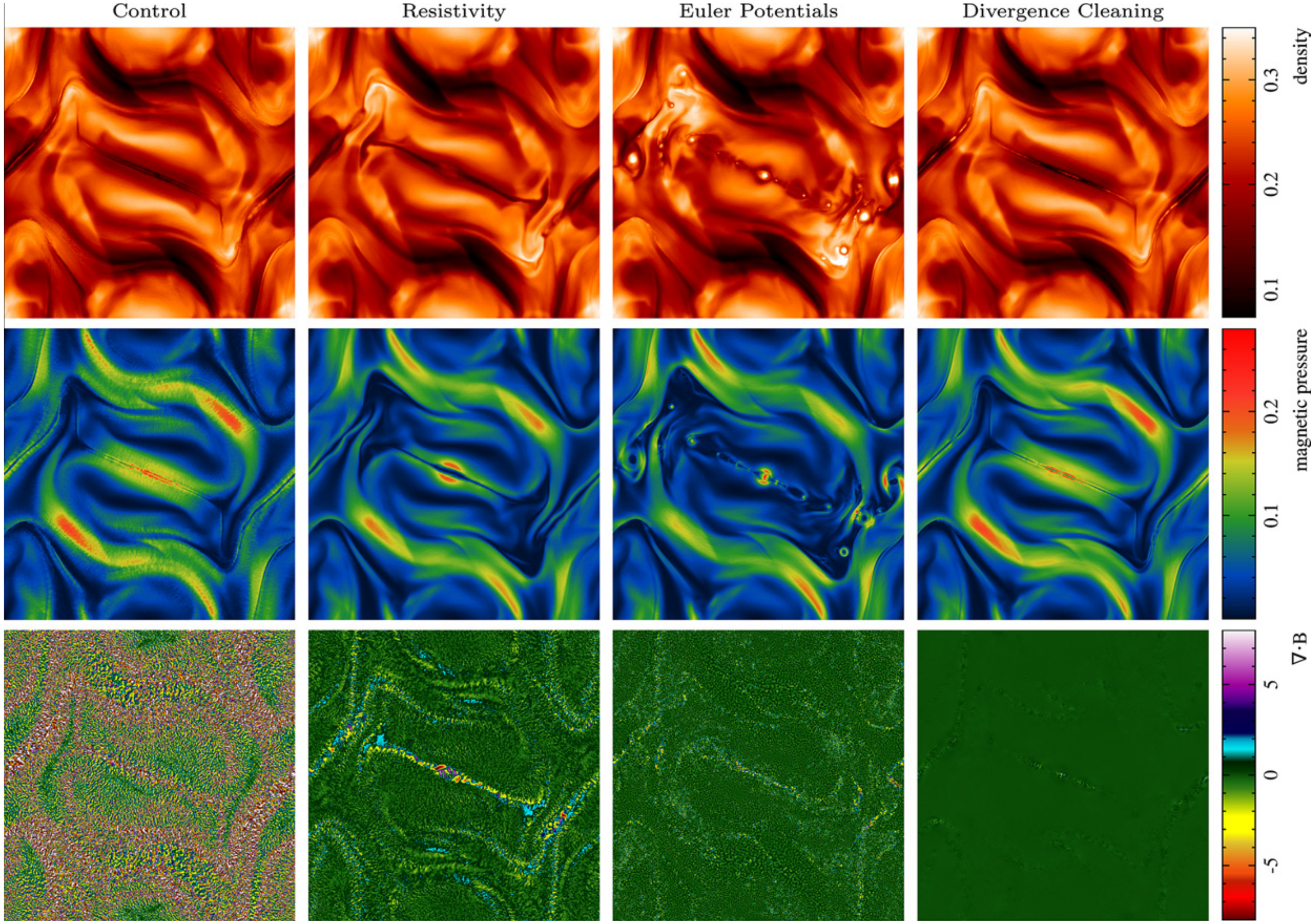
- Produces damped “divergence” waves:

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

- Implemented in a Lagrangian way, using the conservation properties of SPH
- Tricco, Price & Bate (2016; in review) formally accounts for variable wave speeds

Constrained Divergence Cleaning

Tricco & Price (2012)



Constrained Divergence Cleaning

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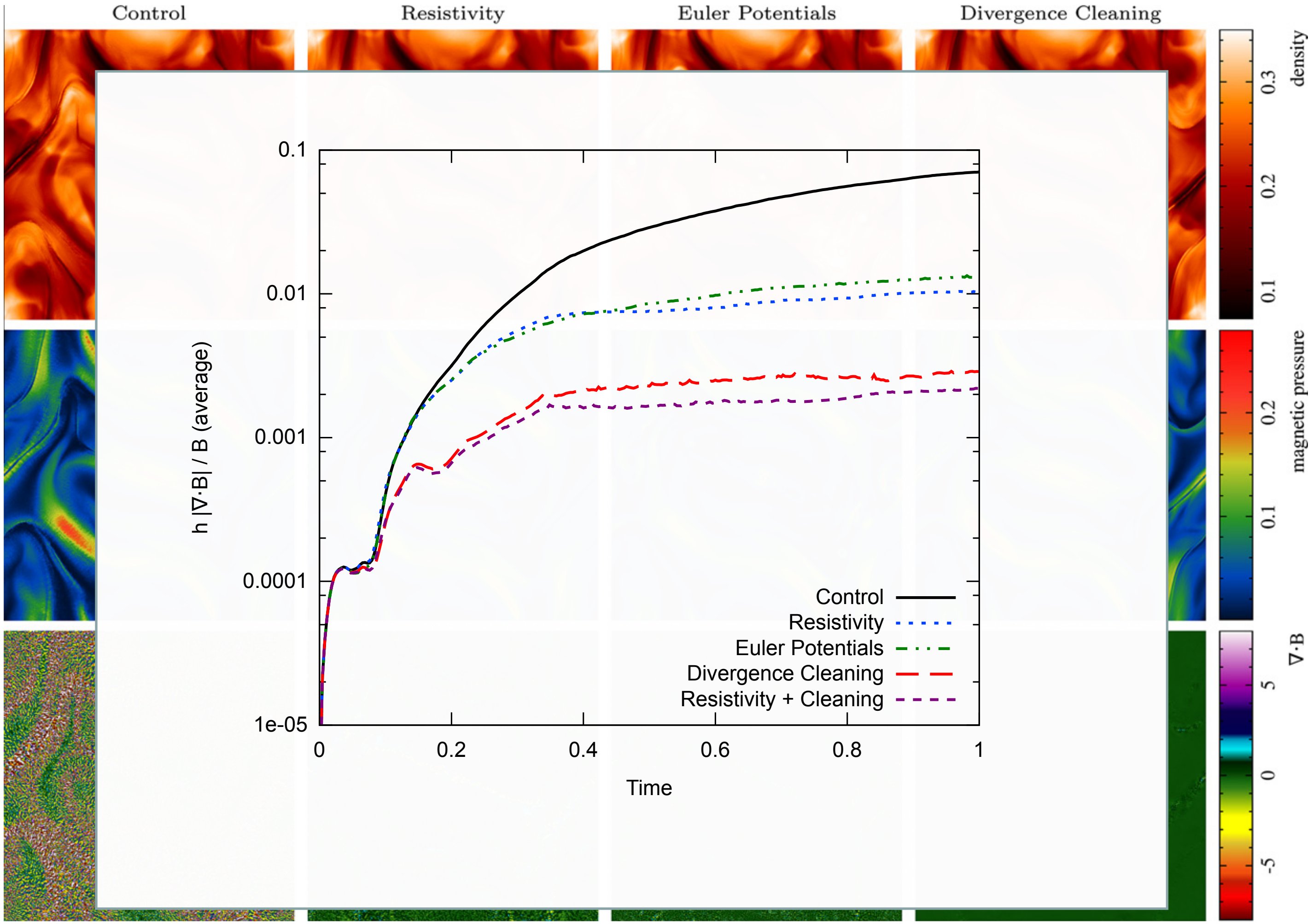


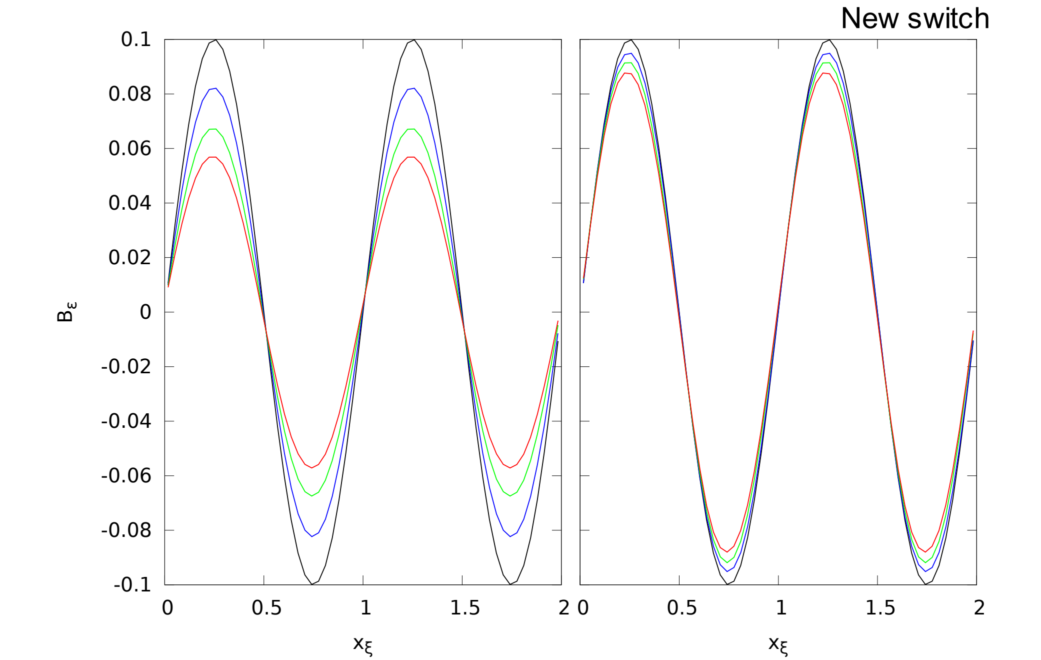
Reduced Numerical Dissipation

Tricco & Price (2013)

- Capture magnetic discontinuities with artificial resistivity:

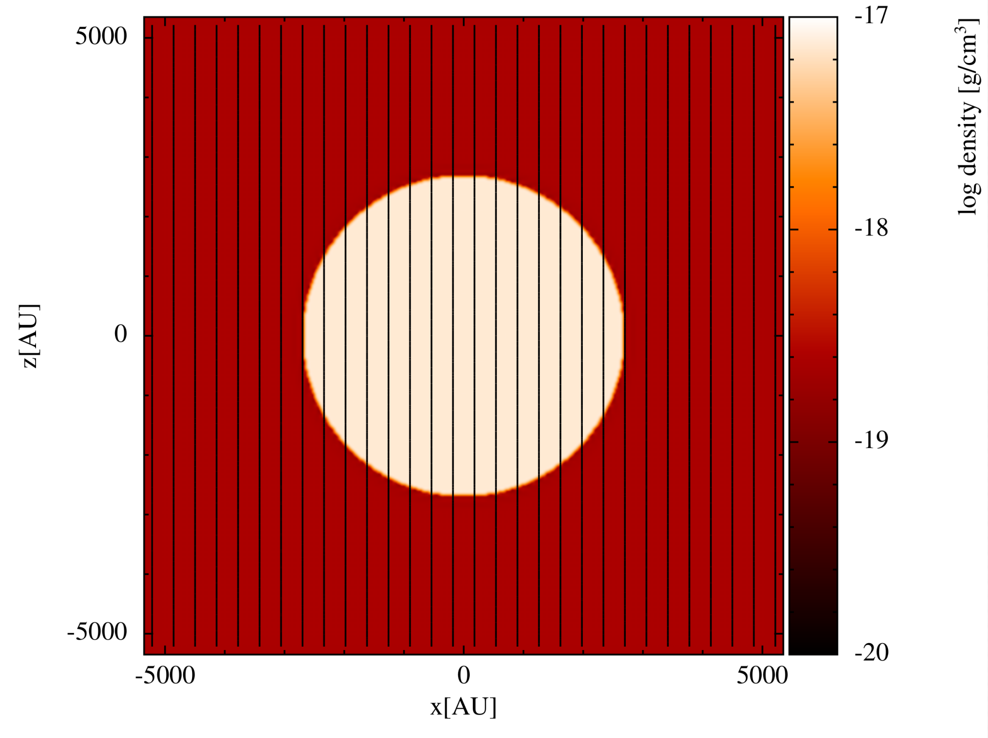
AR ~ $\eta_{\rm AR}\nabla^2\mathbf{B}$ where $\eta_{\rm AR} \sim \alpha_{\rm B} v_{\rm sig} h$

- Tricco & Price (2013) switch: $\alpha_{\rm B} = h|\nabla\mathbf{B}|/|\mathbf{B}|$



Propagation of Alfven wave

Protostellar Core Formation



Initial Conditions:

- 1 solar mass core
- 2700 AU radius
- Initial $\rho_0 = 7.4 \times 10^{-18}$ g/cm^3

- Solid body rotation
- Embedded in pressure equilibrium with ambient low density medium

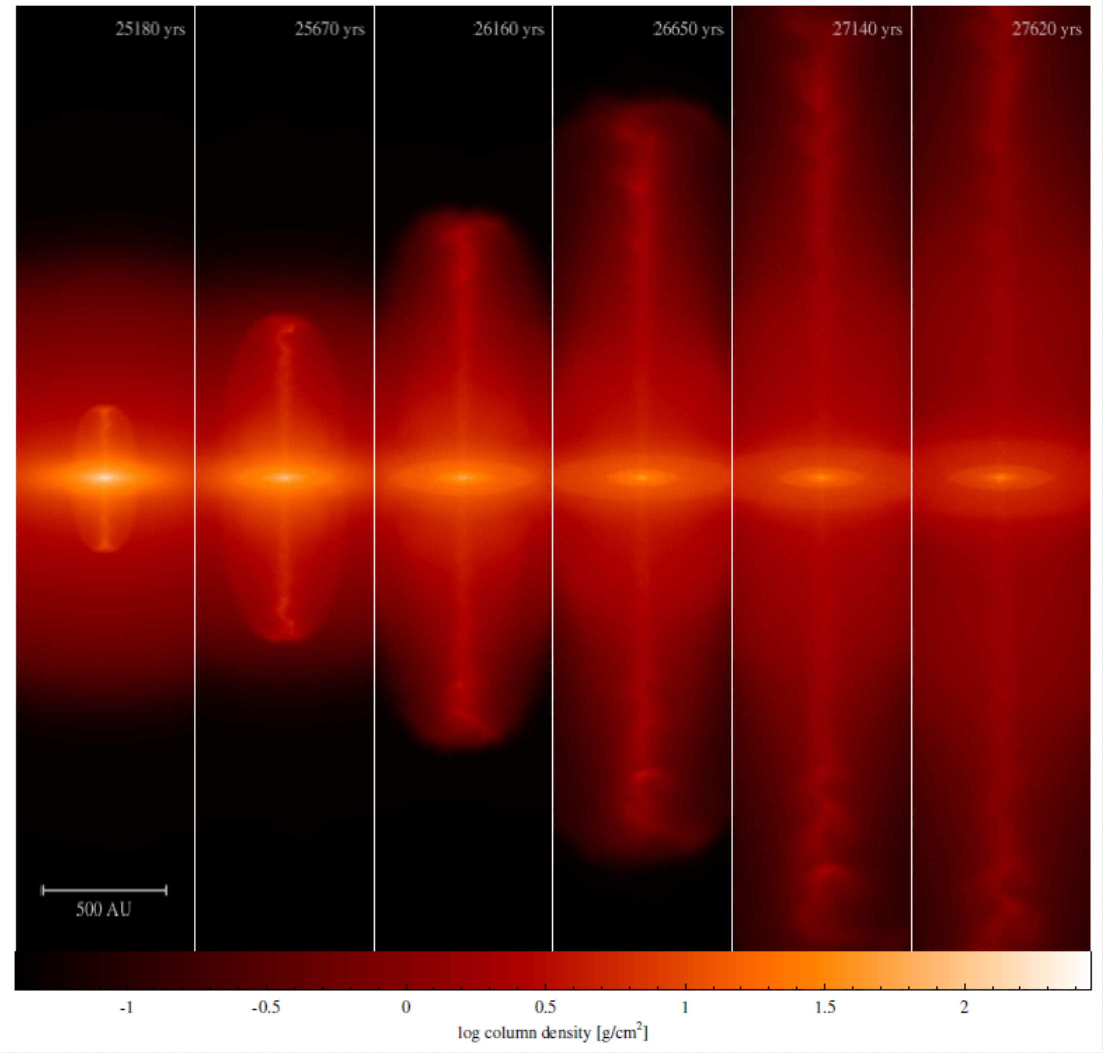
- Uniform *z*-magnetic field, ~160 μG (mass-to-flux ratio 5)

- Equation of state:
  - Isothermal: $\rho < \rho_c = 10^{-14}$ g/cm^3
  - Adiabatic: $\rho > \rho_c$

- Sink particle at $\rho_{sink} = 10^{-10}$ g/cm^3

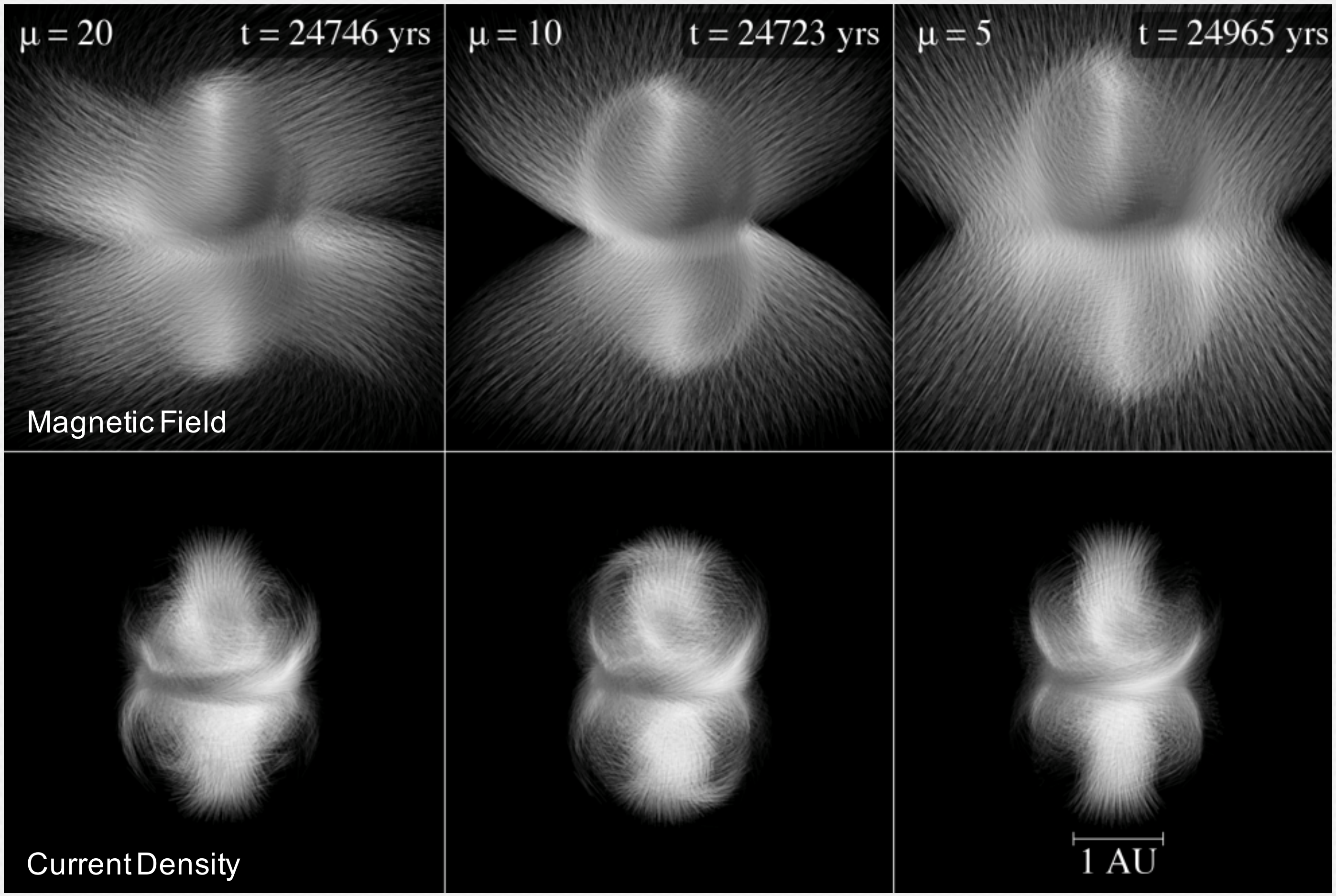
Collimated Jets from the First Core

Price, Tricco & Bate (2012)



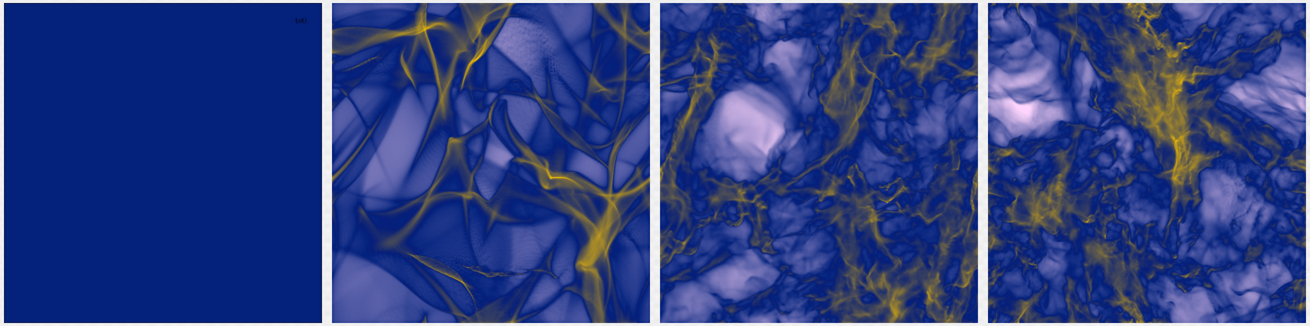
Collapse to Stellar Densities

Bate, Tricco & Price (2014)



Supersonic Magnetised Turbulence

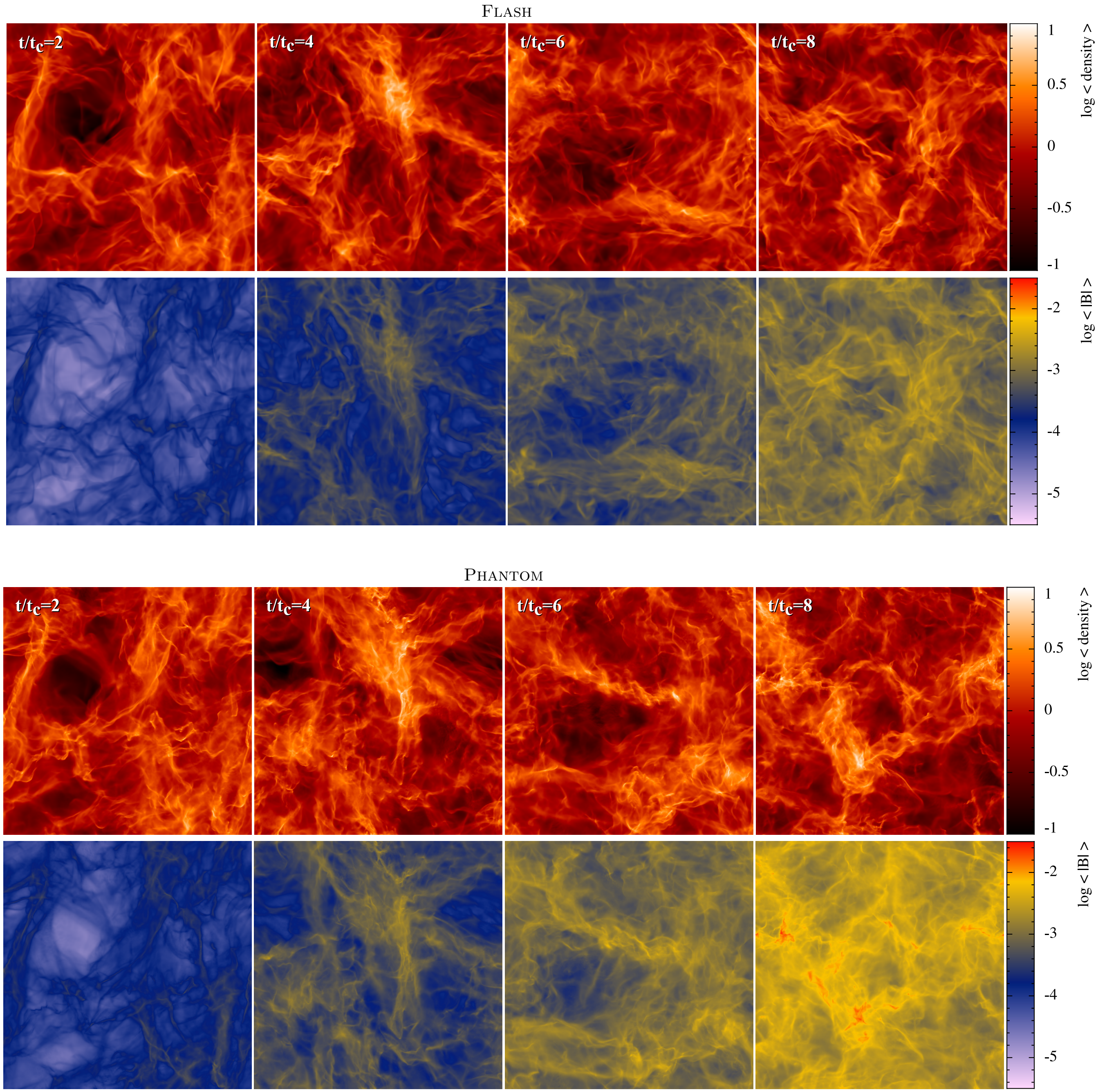
Tricco, Price & Federrath (2016)



Molecular Cloud conditions:
- Isothermal equation of state
- Mach 10 turbulence

Simulation details:
- Ornstein-Uhlenbeck stochastic solenoidal driving force at large scales (k=1-3)
- Periodic boundary conditions
- Initial magnetic energy 10^{11} weaker than turbulent kinetic energy; plasma $\beta = 10^{10}$
- Simulations performed with SPMHD and grid (Flash code)

Study the **small-scale dynamo** amplification of magnetic energy



Tricco, Price & Federrath (2016)

Turbulent Dynamo Amplification

Tricco, Price & Federrath (2016)

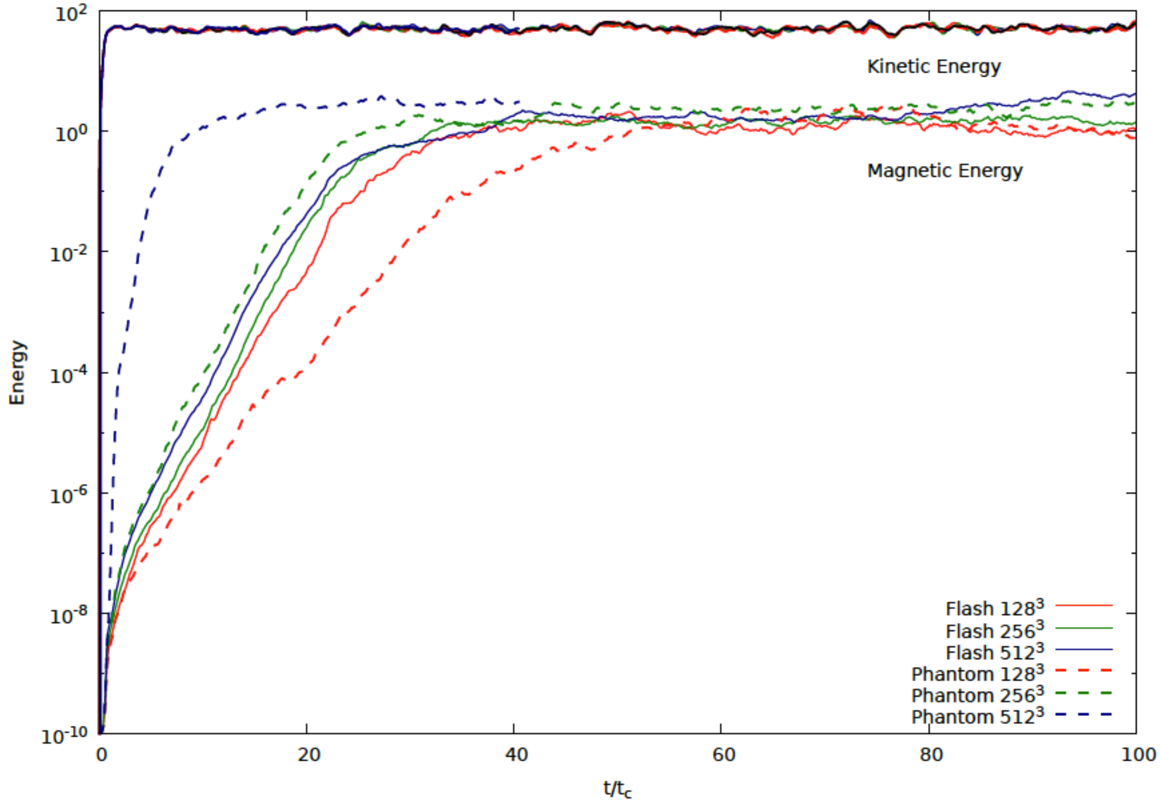
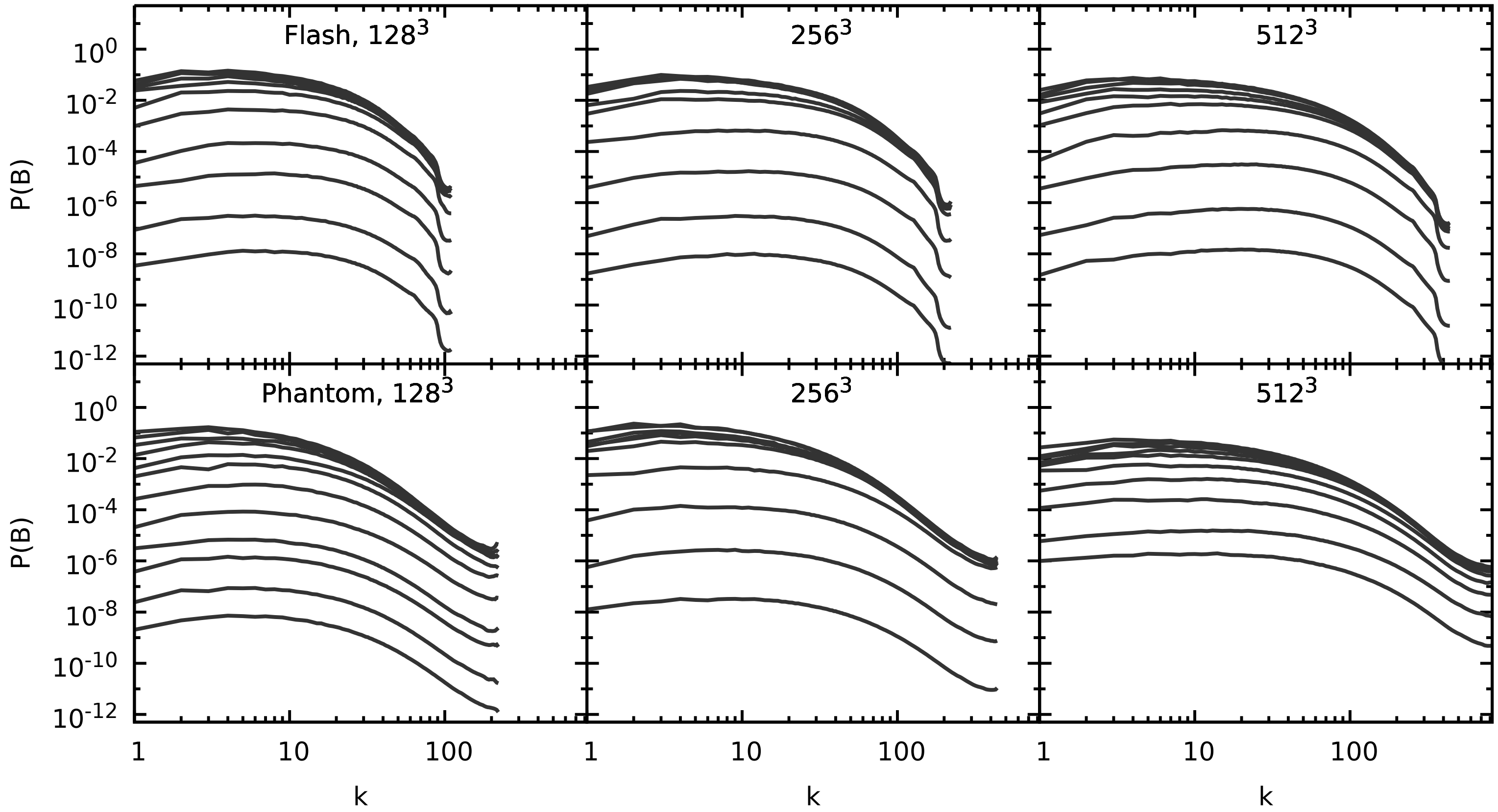


Figure 1. Growth and saturation of the magnetic energy for FLASH and PHANTOM at resolutions of 128^3, 256^3, and 512^3. The top lines are the kinetic energy for the six calculations. FLASH has similar growth rates across the resolutions simulated, while PHANTOM exhibits faster growth rates with increasing resolution. This resolution dependence is a consequence of the artificial dissipation terms. Both codes saturate the magnetic energy at similar levels.

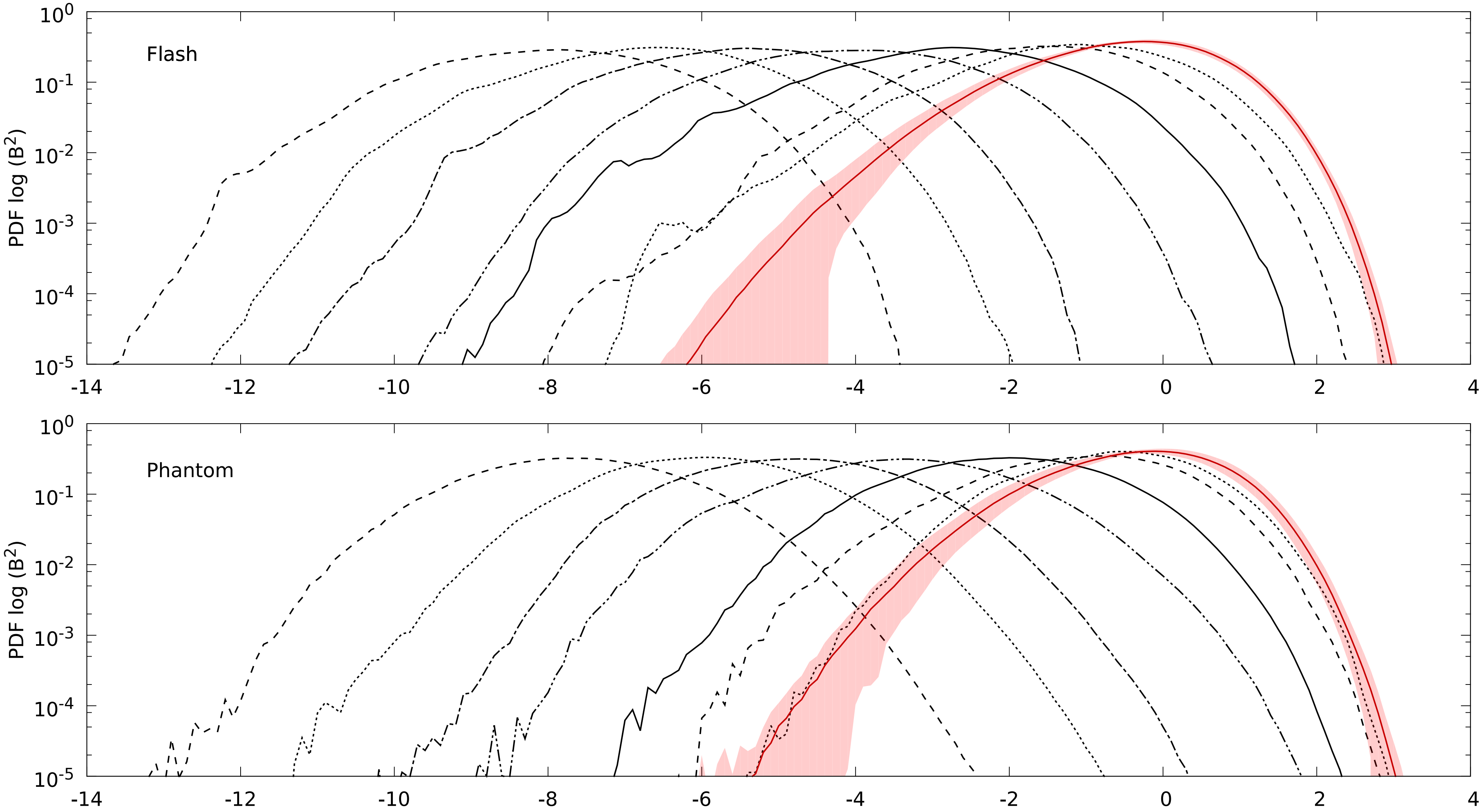
Magnetic Energy Power Spectra

Tricco, Price & Federrath (2016)



Distribution of Magnetic Field Strengths

Tricco, Price & Federrath (2016)



Summary

- SPH can simulate Magnetic fields:
  - $\nabla \cdot \mathbf{B} = 0$ via "constrained" hyperbolic divergence cleaning
  - Improved shock detection to reduce numerical dissipation

- Can produce jets/outflows from simulations of protostar formation (Price, Tricco & Bate 2012; Bate, Tricco & Price 2014; Wurster, Price & Bate 2015; Lewis, Bate & Price 2015)

- Magnetised, supersonic turbulence:
  - Can produce amplification of magnetic fields via small-scale dynamo
  - Results consistent with grid methods