The role of magnetic helicity in stabilizing magnetic cavities in the intergalactic medium

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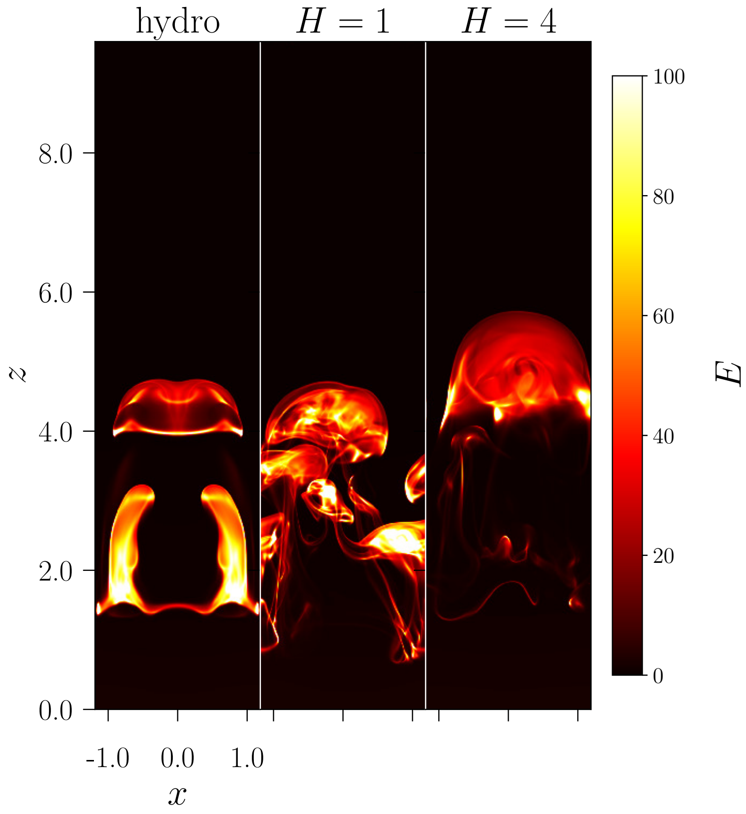
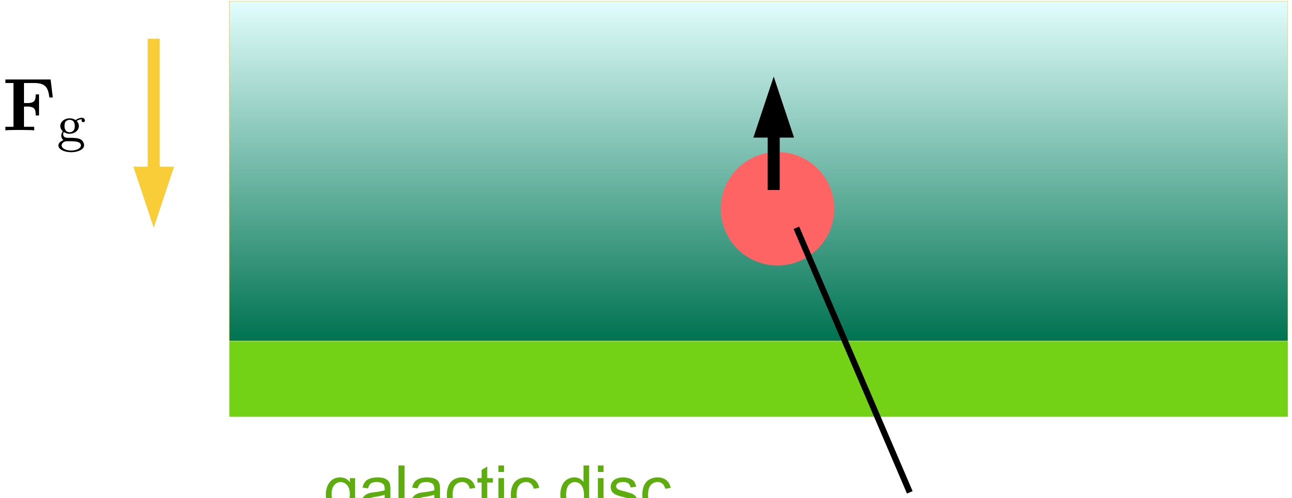


Intergalactic Bubbles



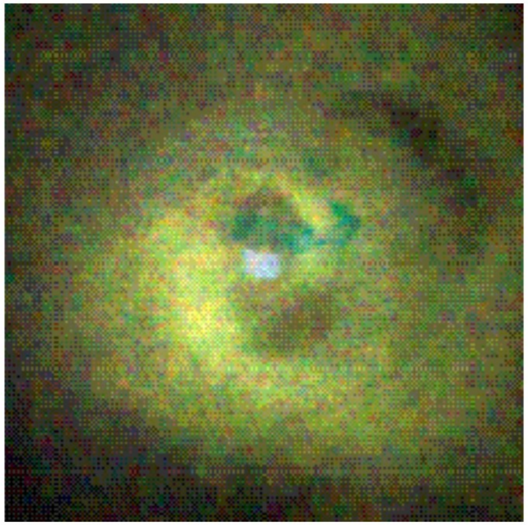
$\mathbf{F}_g$

stratified medium

galactic disc

hot, under-dense bubble

$\approx 30\mathrm{kpc}$

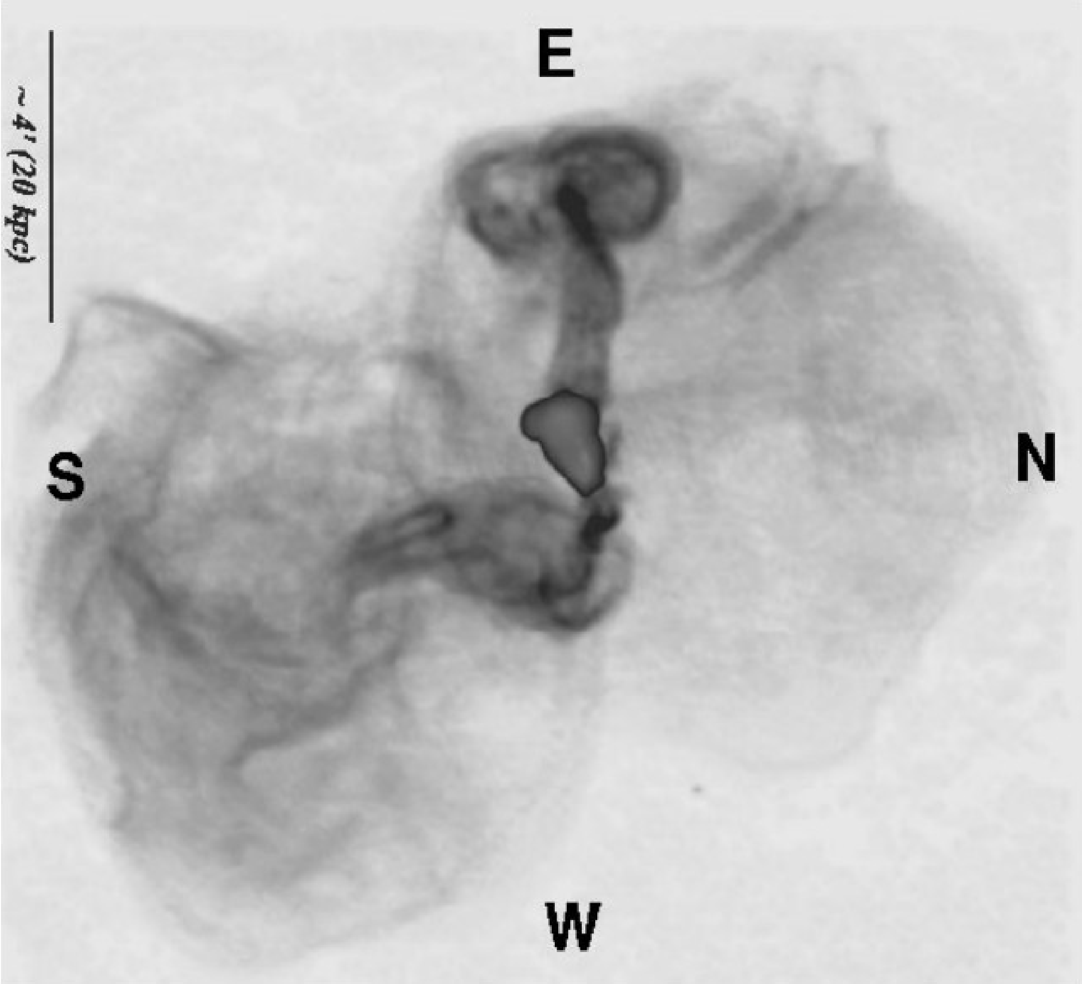


- Bubbles rise buoyantly through density difference.
- Bubbles' age is several tens of millions of years.

Chandra: X-ray, Perseus cluster

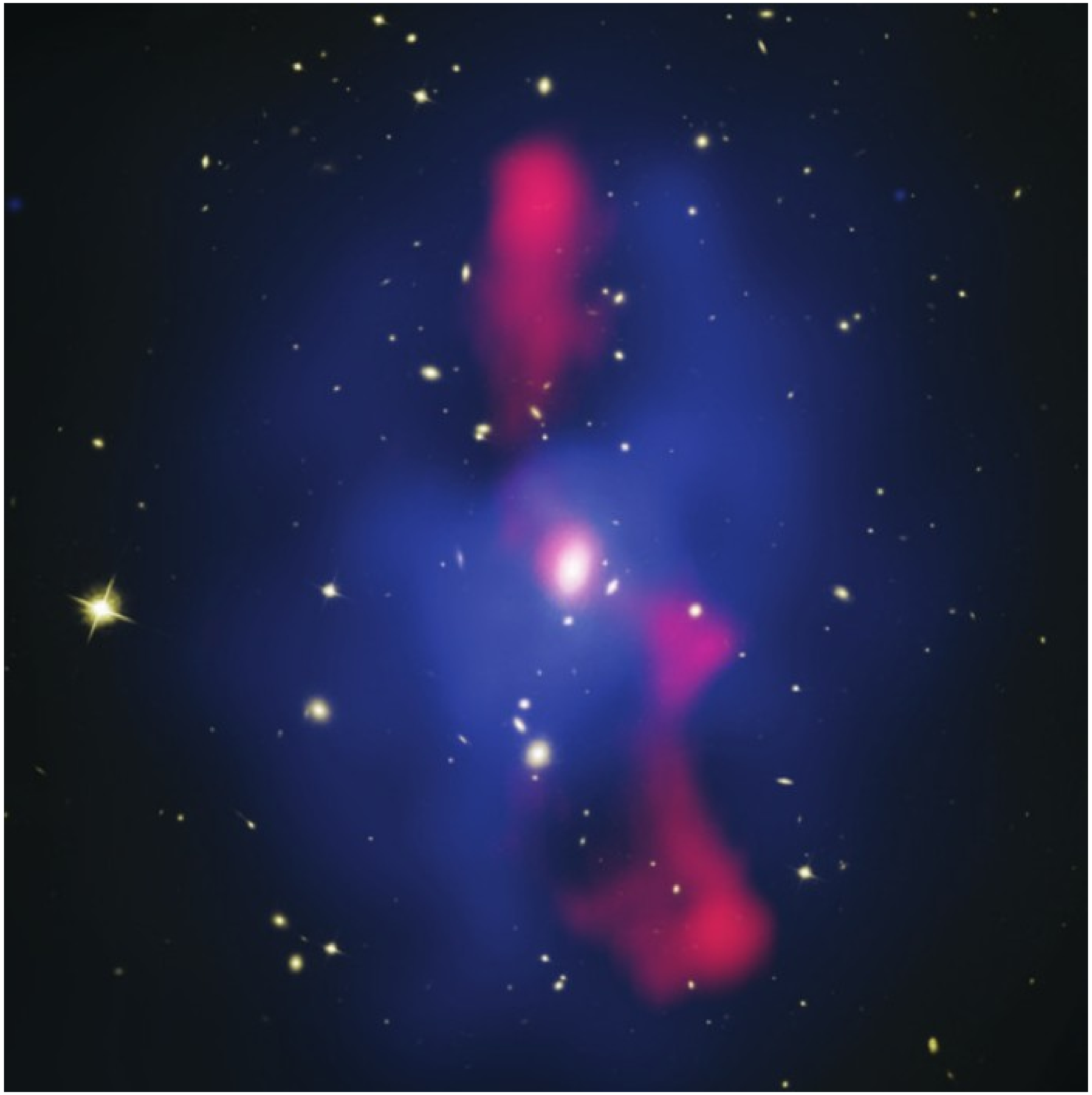
(Fabian et al. 2000)

M87 in radio



(Churazov et al. 2001)

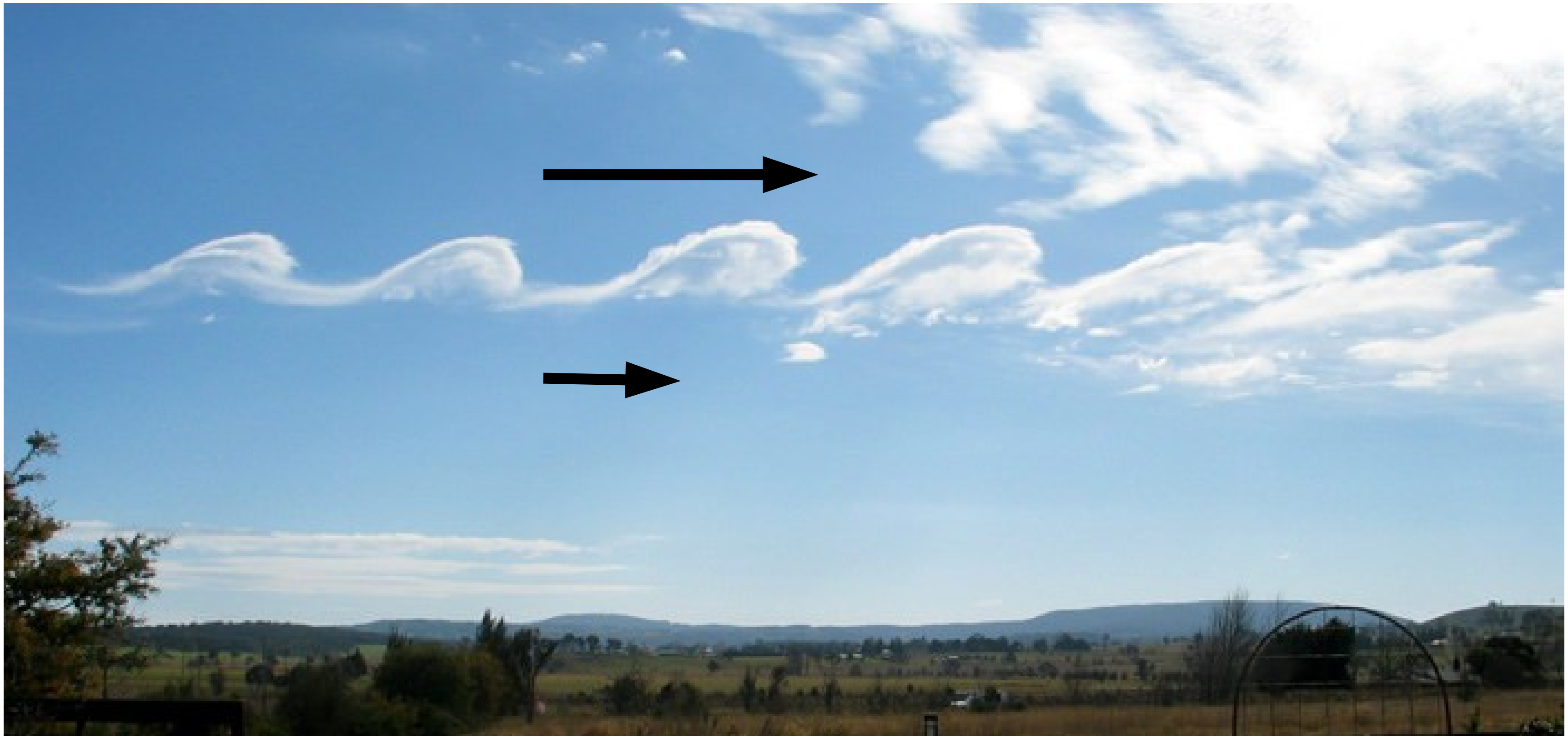
MS0735.6+7421 cluster



Hubble (visual) + Chandra (X-ray)

(McNamara and Nulsen 2007)

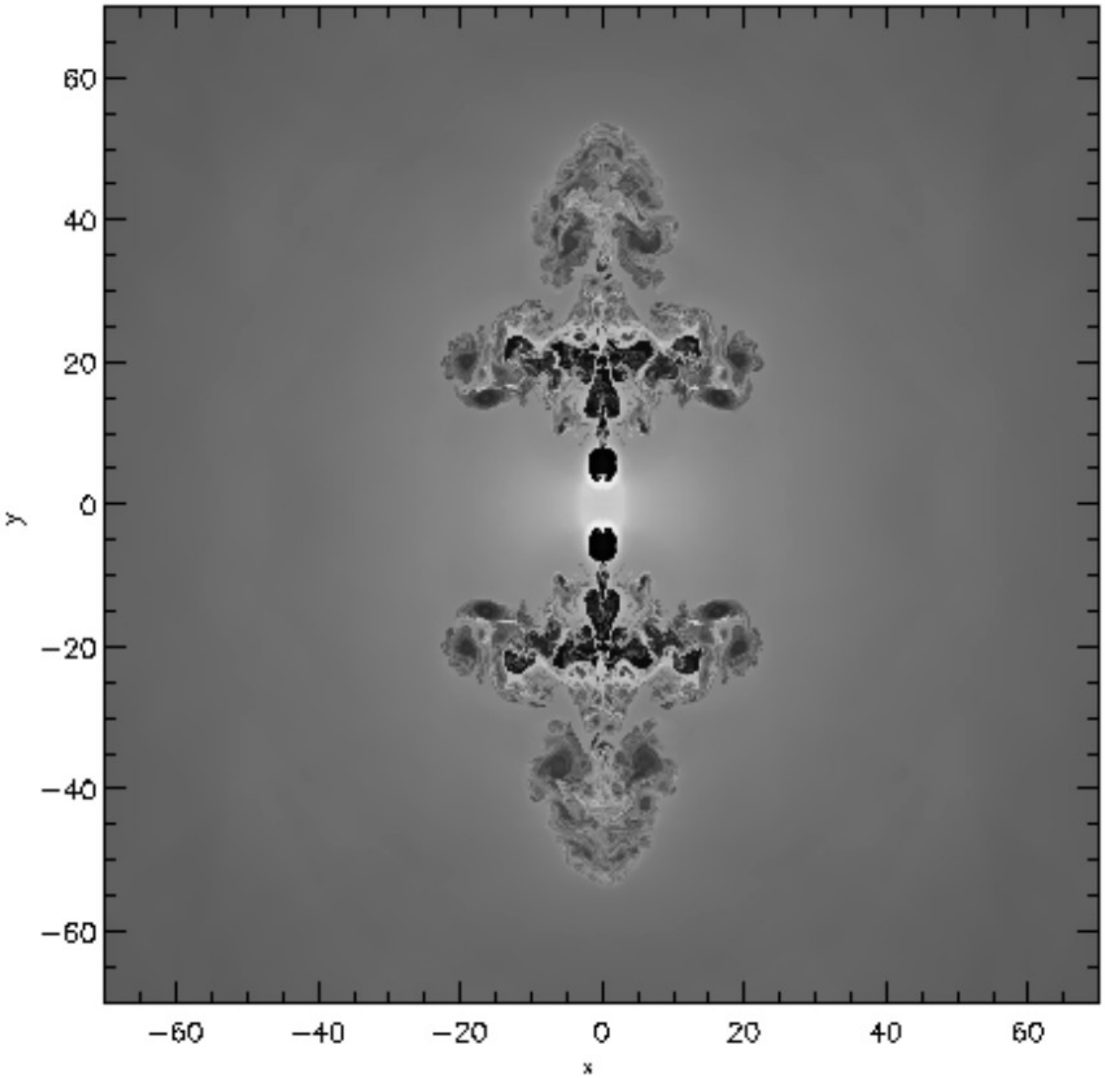
Kelvin-Helmholtz Instability



(GRAHAMUK/Wikimedia Commons)

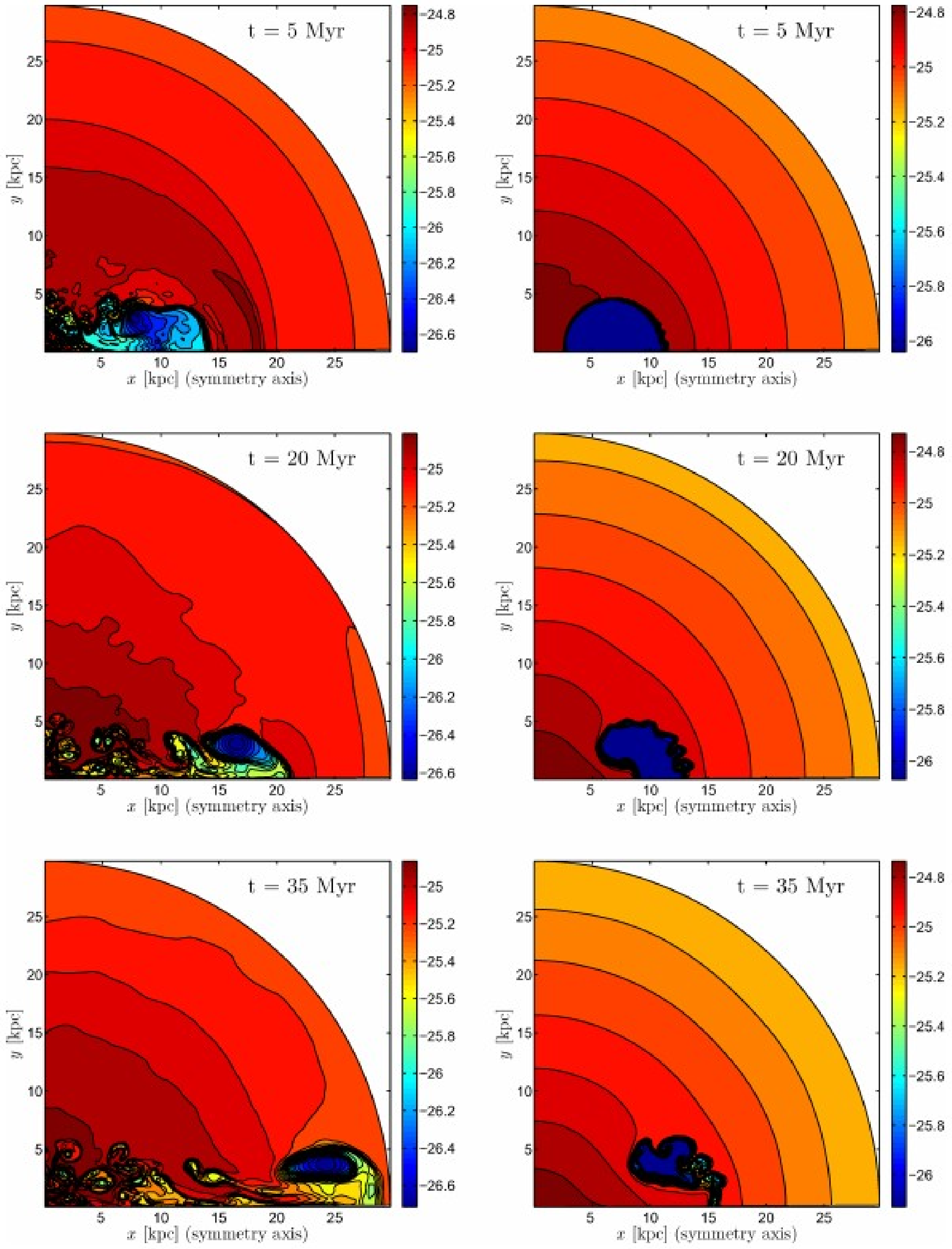
- Bubbles should get disrupted.
- What is the reason for their stability?

Simulations (hydro)



(Brüggen 2003)

Simulations (jet inflation)



(Sternberg, Soker 2008)

Magnetic Helicity

Conservation of magnetic helicity:

$$\lim_{\eta\to 0} \frac{\partial}{\partial t} \int \boldsymbol{A} \cdot \boldsymbol{B} \, \mathrm{d}V = 0 \qquad \eta = \text{ magnetic resistivity}$$

Realizability condition:

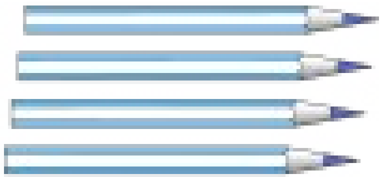
$$E_{\mathrm{m}}(k) \geq k|H(k)|/2\mu_0$$

⇒ Magnetic energy is bound from below by magnetic helicity.

Can magnetic helicity stabilize intergalactic cavities?

Numerical Experiments

Full resistive magnetohydrodynamics simulations with the PencilCode.

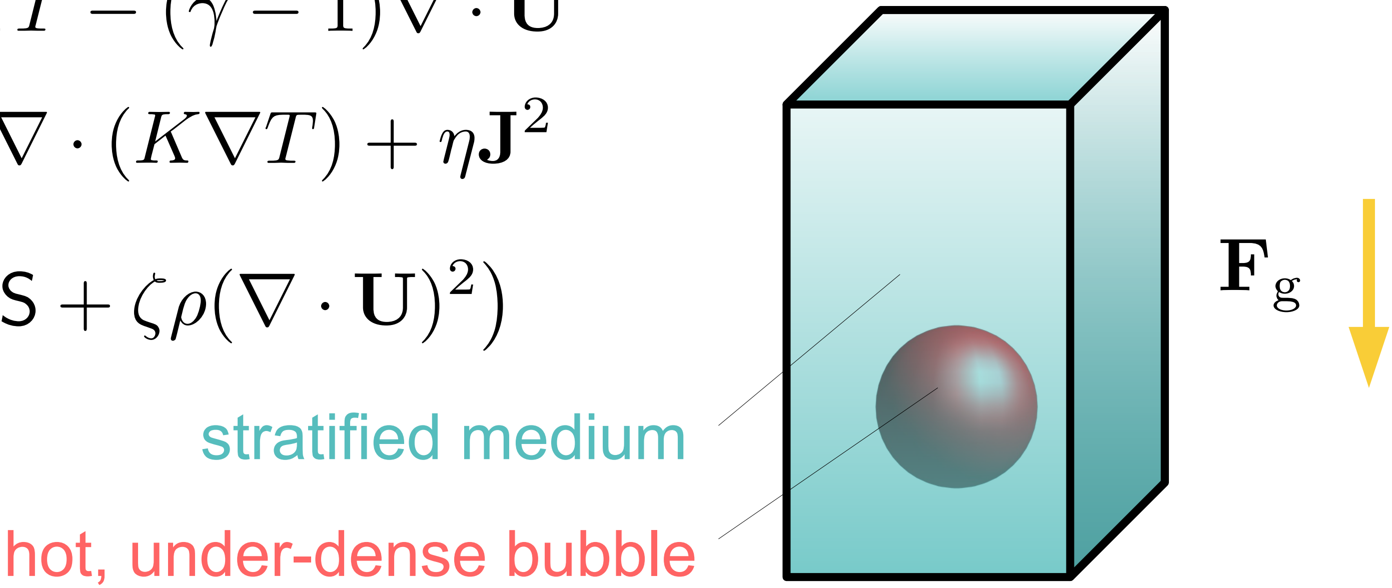


$$\frac{\partial \mathbf{A}}{\partial t} = \mathbf{U} \times \mathbf{B} + \eta \nabla^2 \mathbf{A}$$

$$\frac{\mathrm{D}\mathbf{U}}{\mathrm{D}t} = -c_\mathrm{S}^2 \nabla \left(\frac{\ln T}{\gamma} \ln \rho \right) + \mathbf{J} \times \mathbf{B}/\rho - \mathbf{g} + \mathbf{F}_\mathrm{visc}$$

$$\begin{aligned} \frac{\partial \ln T}{\partial t} = & -\mathbf{U} \cdot \nabla \ln T - (\gamma - 1) \nabla \cdot \mathbf{U} \\ & + \frac{1}{\rho c_V T} \left(\nabla \cdot (K \nabla T) + \eta \mathbf{J}^2 \right. \\ & \left. + 2\rho\nu \mathsf{S} \otimes \mathsf{S} + \zeta\rho(\nabla \cdot \mathbf{U})^2 \right) \end{aligned}$$

$$\frac{\mathrm{D} \ln \rho}{\mathrm{D}t} = -\nabla \cdot \mathbf{U}$$



stratified medium

hot, under-dense bubble

Numerical Experiments

box size	L_{xy}, L_z	$24, 96\mathrm{kpc}$
bubble radius	r_b	$8\mathrm{kpc}$
bubble density	ρ_b	$2.5 \times 10^{-26}\mathrm{gcm}^{-3}$
bubble temperature	T_b	$4 \times 10^6\mathrm{K}$
medium density	ρ_0	$10^{-25}\mathrm{gcm}^{-3}$
medium temperature	T_0	$10^6\mathrm{K}$
gravitational acceleration	g	$3 \times 10^{-7}\mathrm{cms}^{-2}$
magnetic field strength	B_0	$2.5 \times 10^{-6}\mathrm{G}$
viscosity	ν	$3 \times 10^{27}\mathrm{cm}^2 s^{-1}$
magnetic diffusivity	η	$9 \times 10^{26}\mathrm{cm}^2 s^{-1}$
total time	t_end	$200 - 250\mathrm{Myr}$

Initial Condition: Beltrami Field

$$\mathbf{A} = f(r) A_0 \begin{pmatrix} \cos(yk) + \sin(zk) \\ \cos(zk) + \sin(xk) \\ \cos(xk) + \sin(yk) \end{pmatrix}$$

smoothing function: $f(r) = 1 - (r/r_\mathrm{b})^{n_\mathrm{smooth}}$

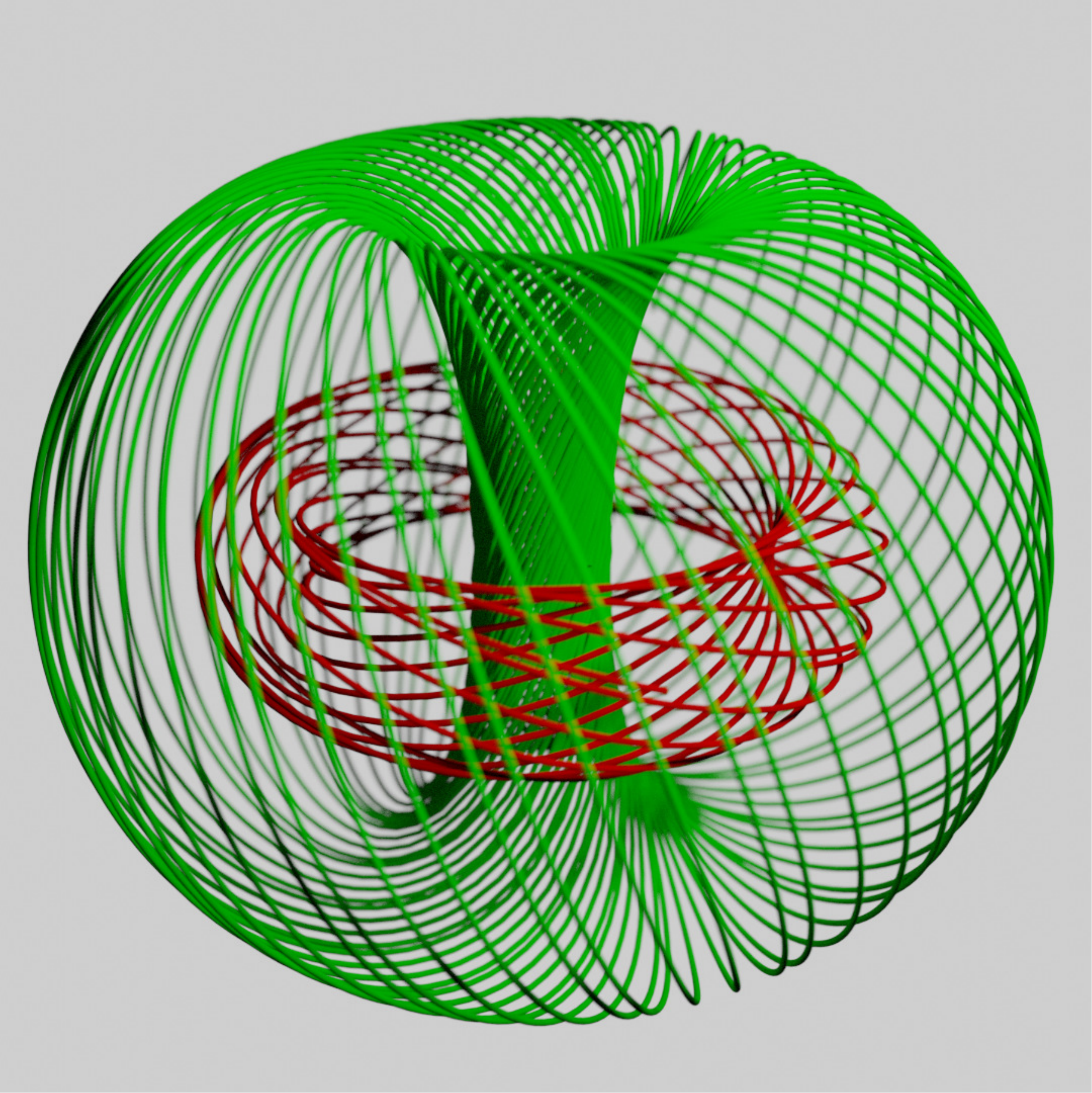
inside bubble: $\nabla \times \mathbf{A} \approx k\mathbf{A}$

➡ $E_\mathrm{m} \propto A_0^2 k^2$

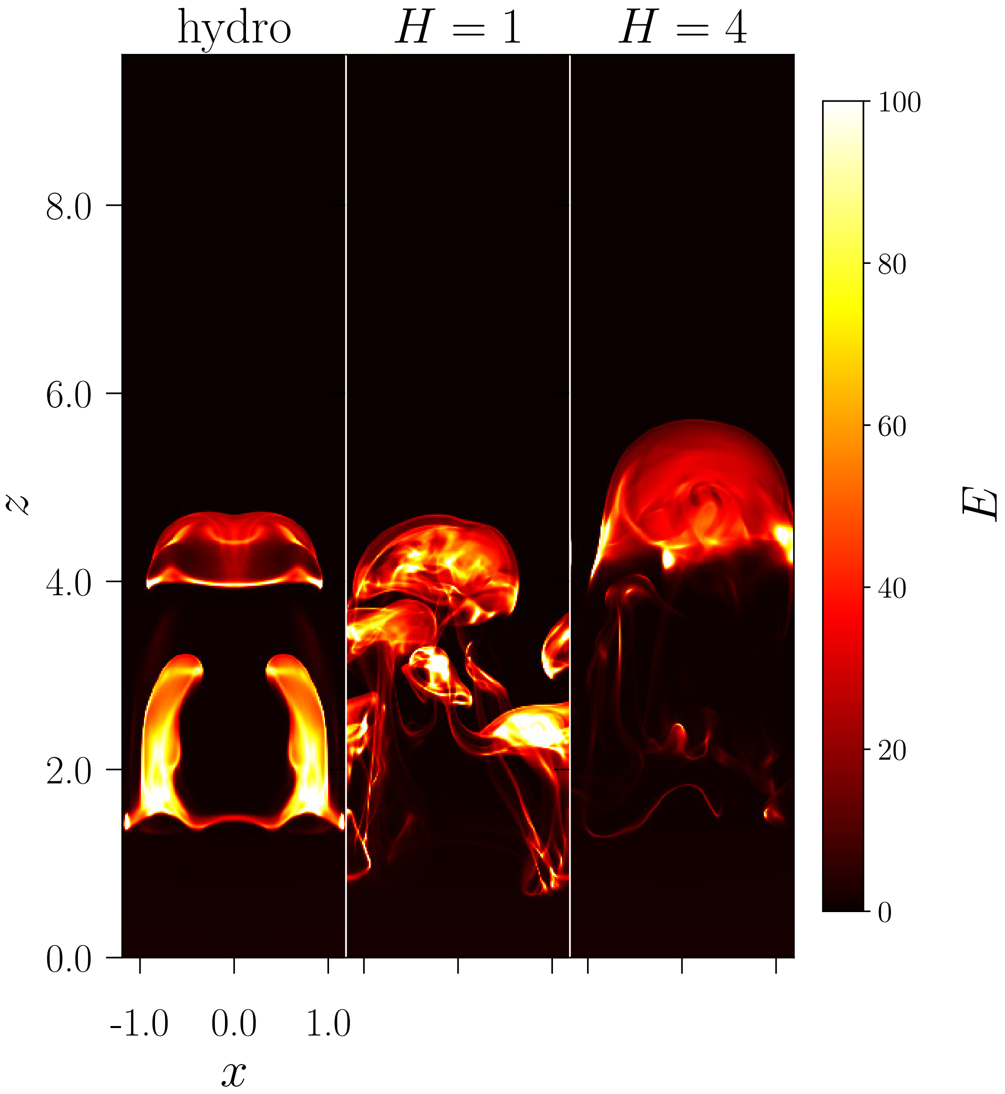
➡ $H_\mathrm{m} \propto A_0^2 k$

➡ Fix magnetic energy, vary magnetic helicity.

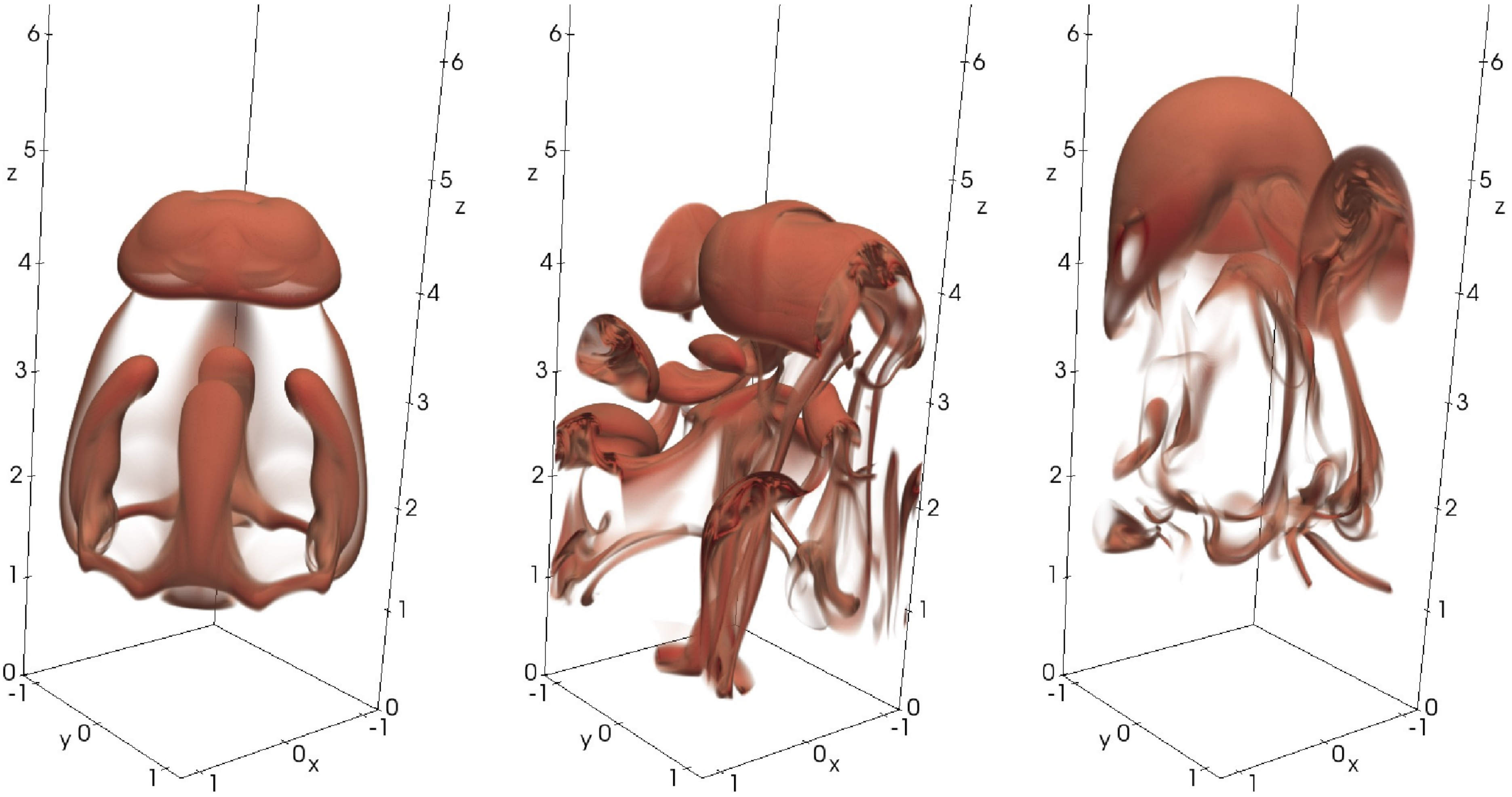
Initial Condition: Spheromak



Thermal Emission



Temperature Iso-Surfaces

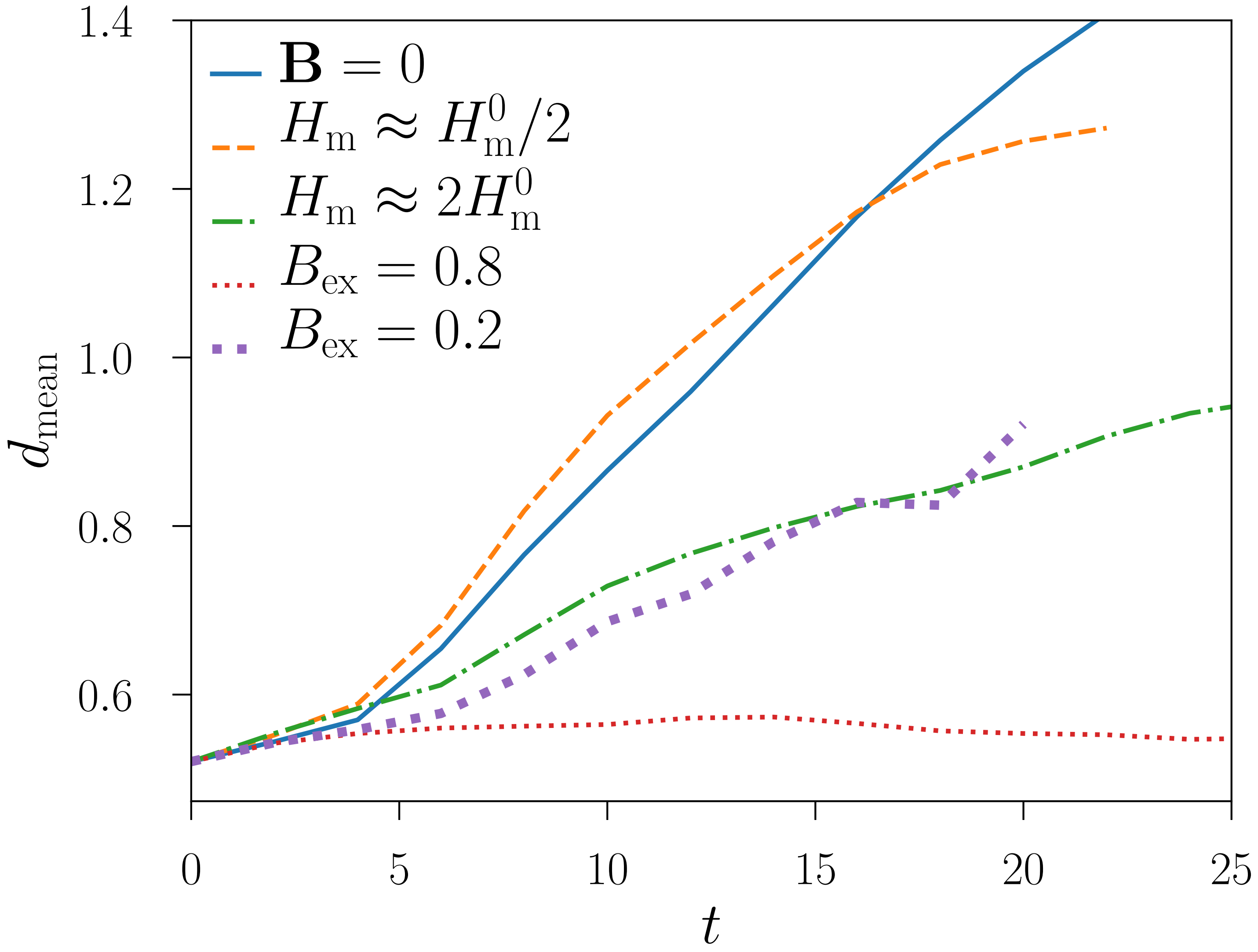


hydro

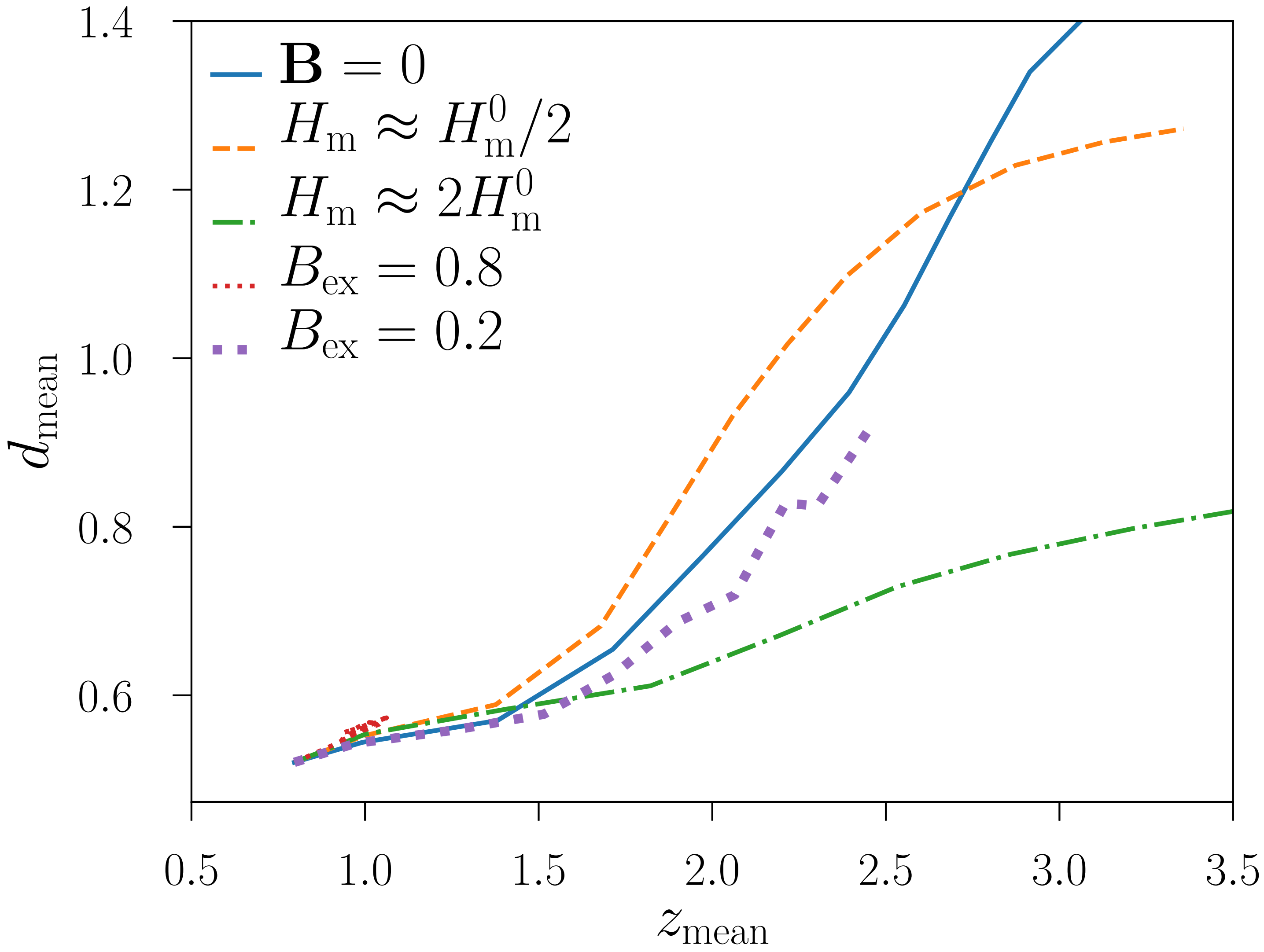
low helicity

high helicity

Bubble Coherence



Bubble Coherence



➡ Helical magnetic fields can stabilize the bubbles.

Conclusions

- Magnetic helicity as constraint on plasma dynamics.
- Magnetic helicity leads to stability at small magnetic energy.
- Mechanism to stabilize intergalactic bubbles.

(Candelaresi and Del Sordo 2020 ApJ **896** 86)

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