Estimating the lifetime of extragalactic magnetized hot cavities

Fabio Del Sordo
INAF - Catania
Institute of Astrophysics, FORTH Crete
fabio.delsordo@inaf.it

with Simon Candelaresi
University of Glasgow

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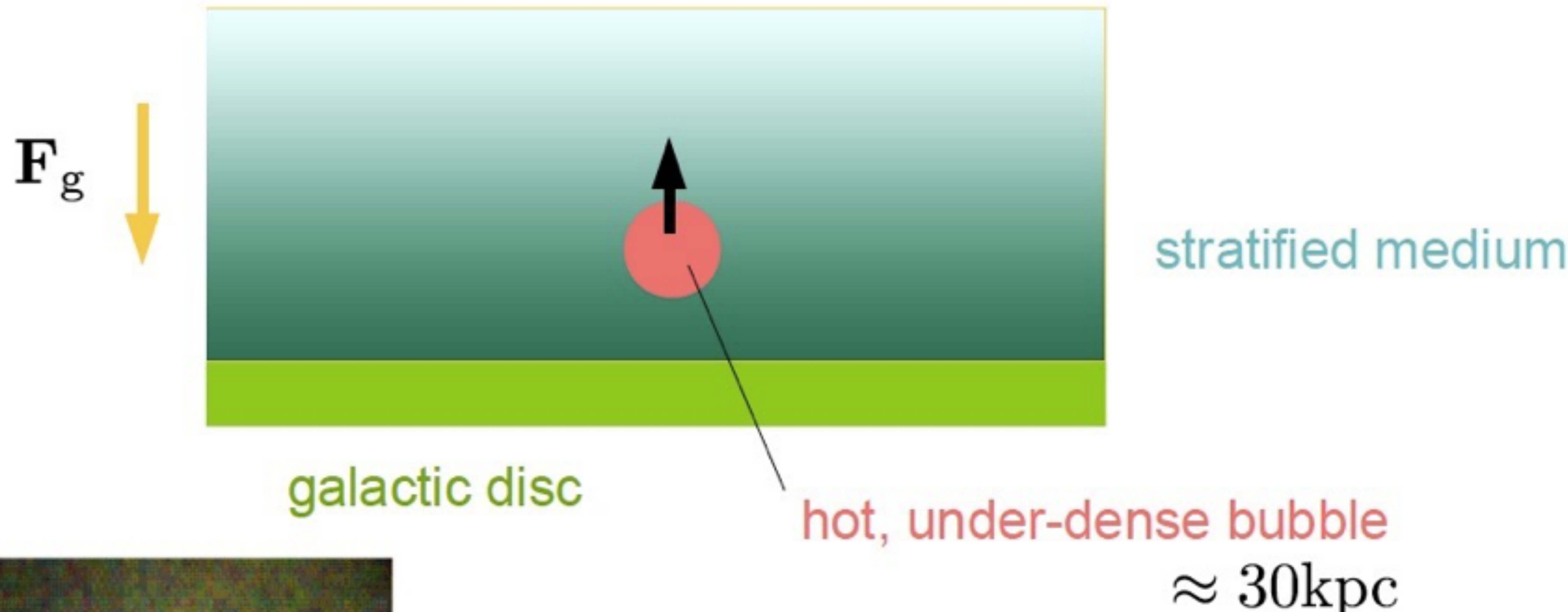
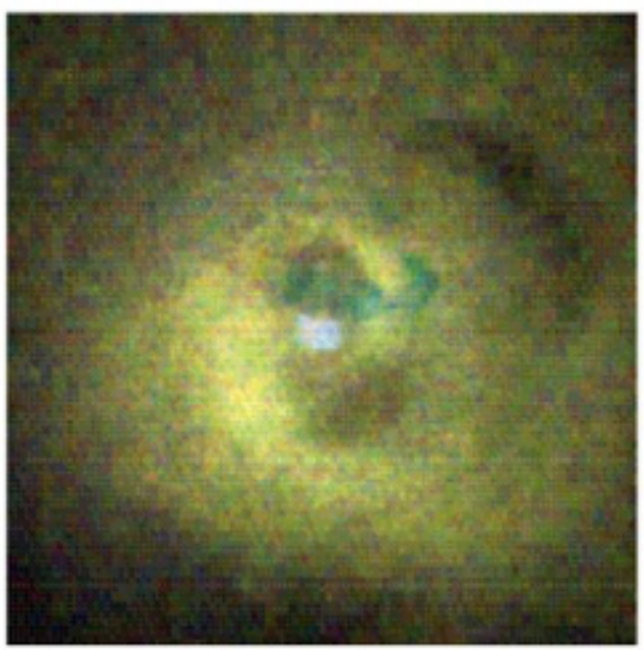
Candelaresi S. & Del Sordo F. , ApJ, 896 86C, 2020

Extragalactic bubbles



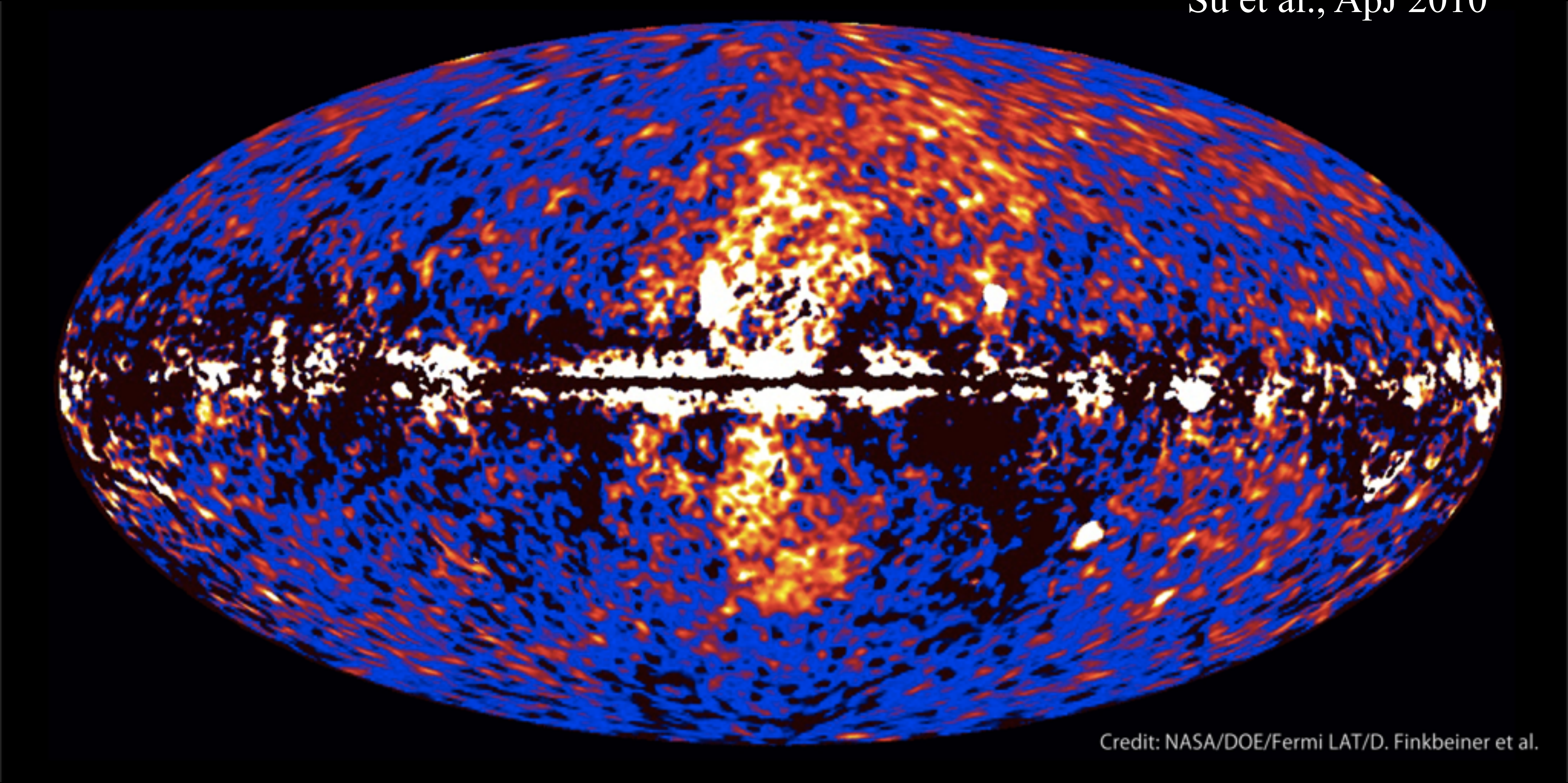


(Fabian et al. 2000)

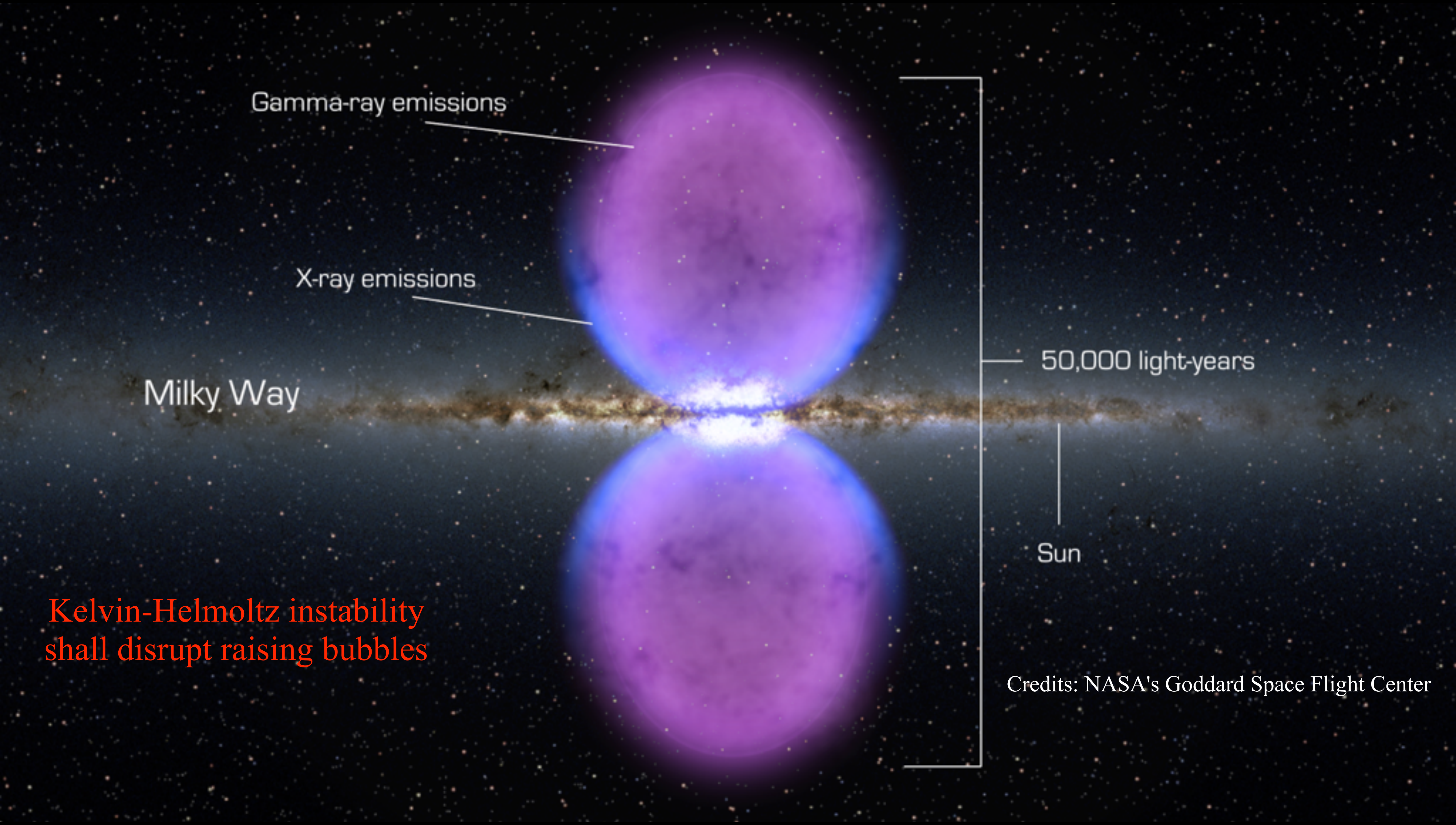
- Bubbles rise buoyantly through density difference.
- Bubbles' age is several tens of millions of years.

Fermi bubbles

Su et al., ApJ 2010



Fermi bubbles



Kelvin-Helmoltz instability shall disrupt raising bubbles

Credits: NASA's Goddard Space Flight Center

The possible role of helical magnetic fields

Can helical magnetic fields
act against the disruption of extragalactic bubbles?

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Can magnetic helicity make
extragalactic structures more stable?

The possible role of Magnetic Helicity

Conservation of magnetic helicity:

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

$\eta =$ magnetic resistivity

Realizability condition:

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

Magnetic energy is bound from below by magnetic helicity.

Numerical setup

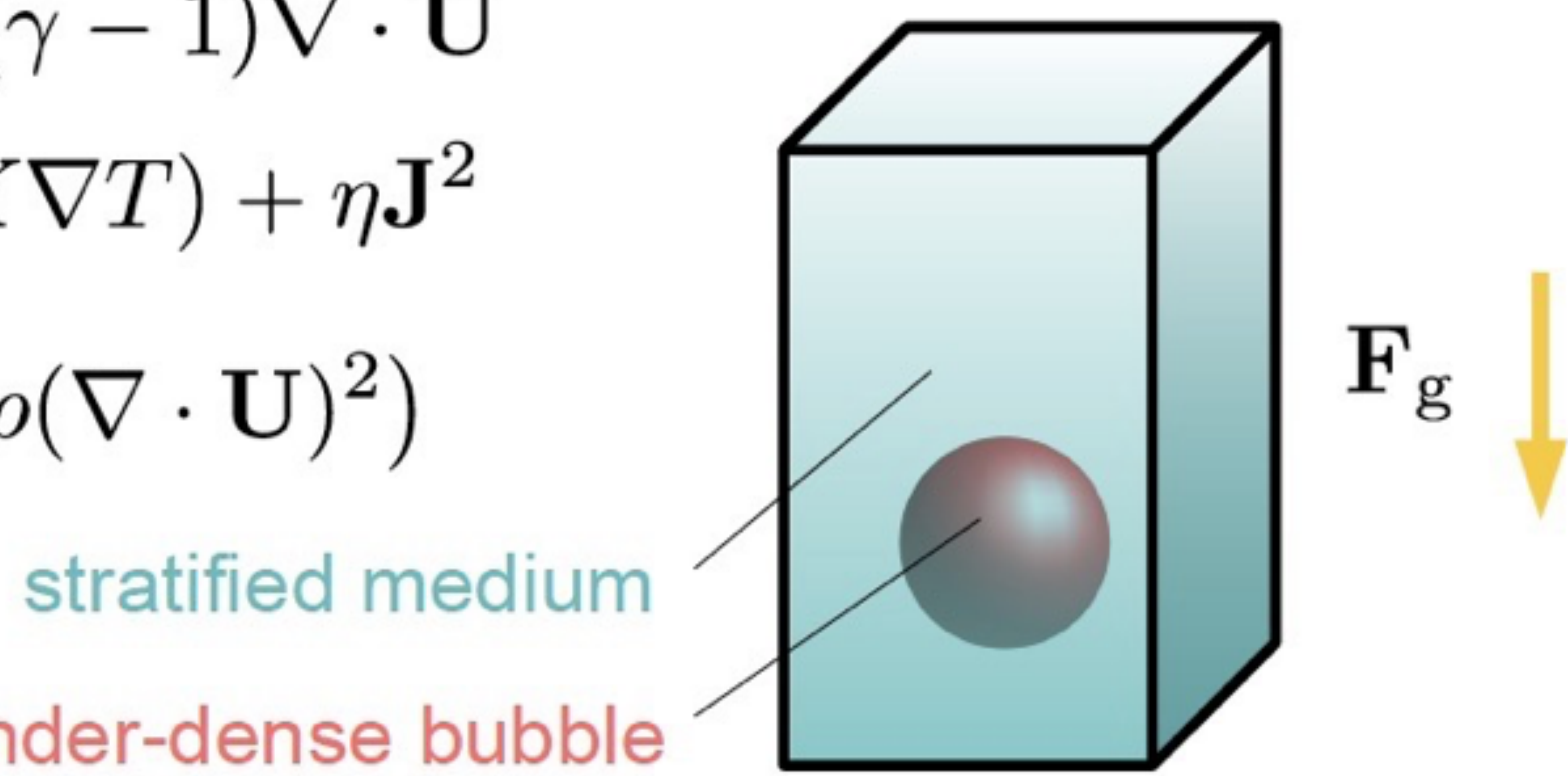
Full resistive magnetohydrodynamics simulations with the PencilCode.

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

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

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

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

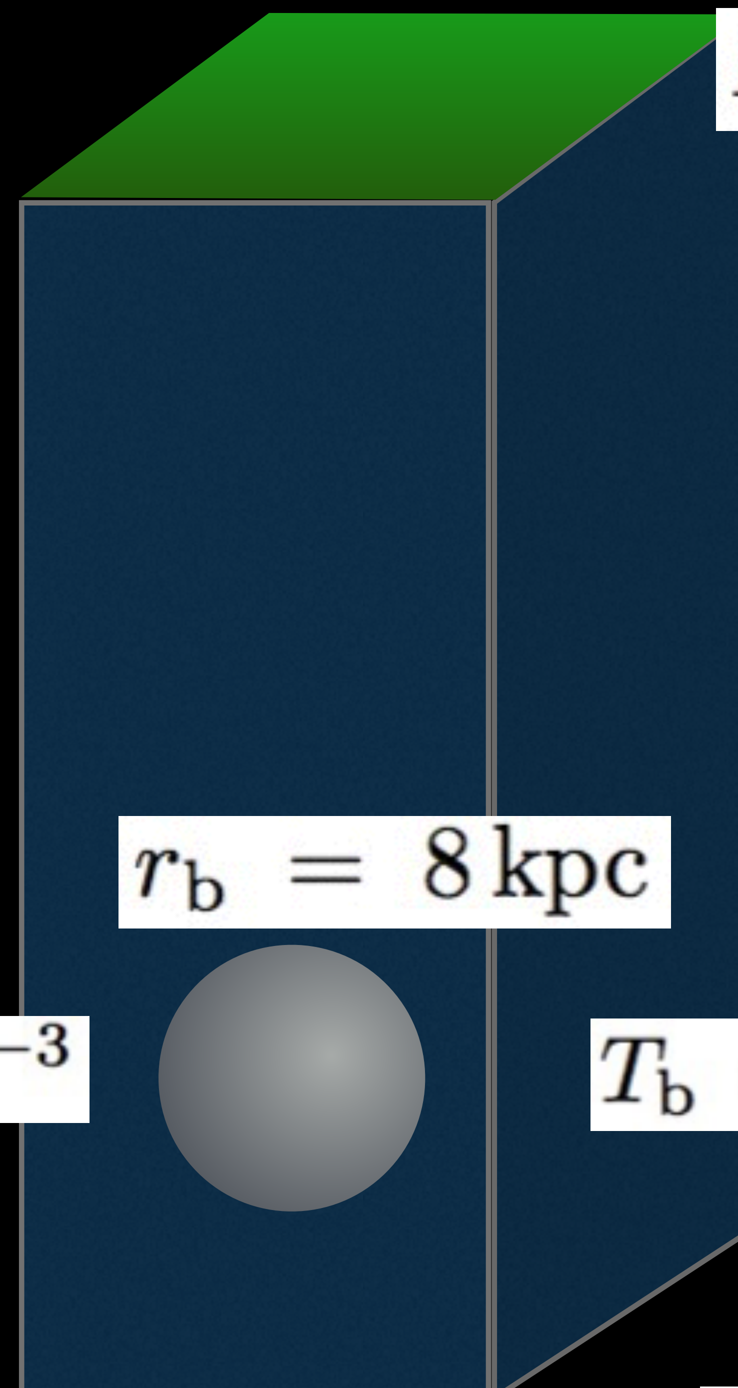


Physical units

$L_z = 96\,\mathrm{kpc}$

$L_{xy} = 24\,\mathrm{kpc}$

$g = 3.0985 \times 10^{-7}\,\mathrm{cm\,s^{-2}}$



$r_\mathrm{b} = 8\,\mathrm{kpc}$

$\rho_\mathrm{b} = 2.5 \times 10^{-26}\,\mathrm{g\,cm^{-3}}$

$T_\mathrm{b} = 4 \times 10^{6}\,\mathrm{K}$

$\rho_0 = 1 \times 10^{-25}\,\mathrm{g\,cm^{-3}}$

At z=0

$T_0 = 1 \times 10^{6}\,\mathrm{K}$

Numerical experiments

- 0: Hydrodynamic test case
- 1: Hydromagnetic Helical case #1: ABC field
- 2: Hydromagnetic Helical case #2: Spheromak field
- 3: Hydromagnetic Non-Helical case: Vertical field

Magnetic Initial conditions 1: Arnold-Beltrami-Childress field

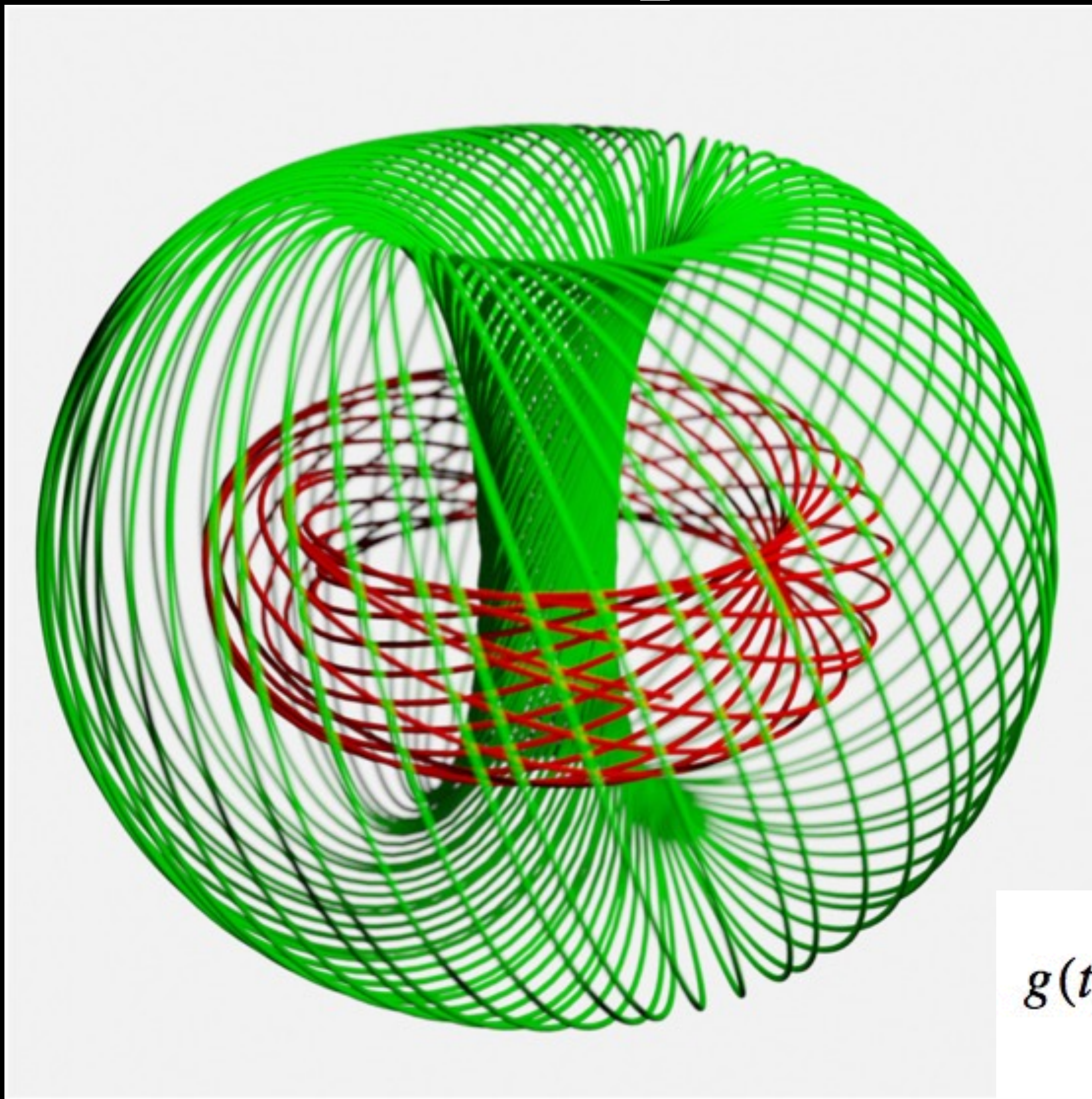
$$\mathbf{A} = f(r) A_0 \begin{pmatrix} \cos(yk) + \sin(zk) \\ \cos(zk) + \sin(xk) \\ \cos(xk) + \sin(yk) \end{pmatrix}$$

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.

Magnetic Initial conditions 2: Spheromak field



Two magnetic field lines at t=0

$$\boldsymbol{B} = 2A_0 \frac{g(\alpha r)}{(\alpha r)^2} \cos(\theta) \hat{e}_r - A_0 \frac{g'(\alpha r)}{\alpha r} \sin(\theta) \hat{e}_\theta + A_0 \frac{g(\alpha r)}{\alpha r} \sin(\theta) \hat{e}_\phi,$$

$$\alpha = \tau / r_{\mathrm{b}}$$

$$g(t) = \frac{t^2}{\tau^2} - \frac{3}{\tau \sin(t)} \left(\frac{\sin(t)}{t} - \cos(t) \right)$$

Magnetic Initial conditions 3: Vertical field

$$\boldsymbol{B} = B_0 \boldsymbol{e}_z$$

<u>Initial thermodynamical conditions for all models:</u>

Stably stratified atmosphere with an
under-dense hot cavity of spherical shape
Adiabatic gas

Models

Model		$B(A_0)$	H_m	Re	Re_M
hydro		⋯	⋯	960	⋯
hydro2		⋯	⋯	4800	⋯
hel_l	$\beta \approx 0.6$	0.025	1	1280	4200
hel_h	$\beta \approx 0.6$	0.1	4	1280	4200
hel_l2	$\beta \approx 0.6$	0.025	1	5600	3700
hel_h2	$\beta \approx 0.6$	0.1	4	6400	4200
sph_l	$\beta = 0.038$	6.39	1	7200	4800
sph_h	$\beta = 0.44$	1.7	4	11000	7500
ex_low	$\beta = 20$	0.2	0	320	1000
ex_high	$\beta = 1.25$	0.8	0	320	1000

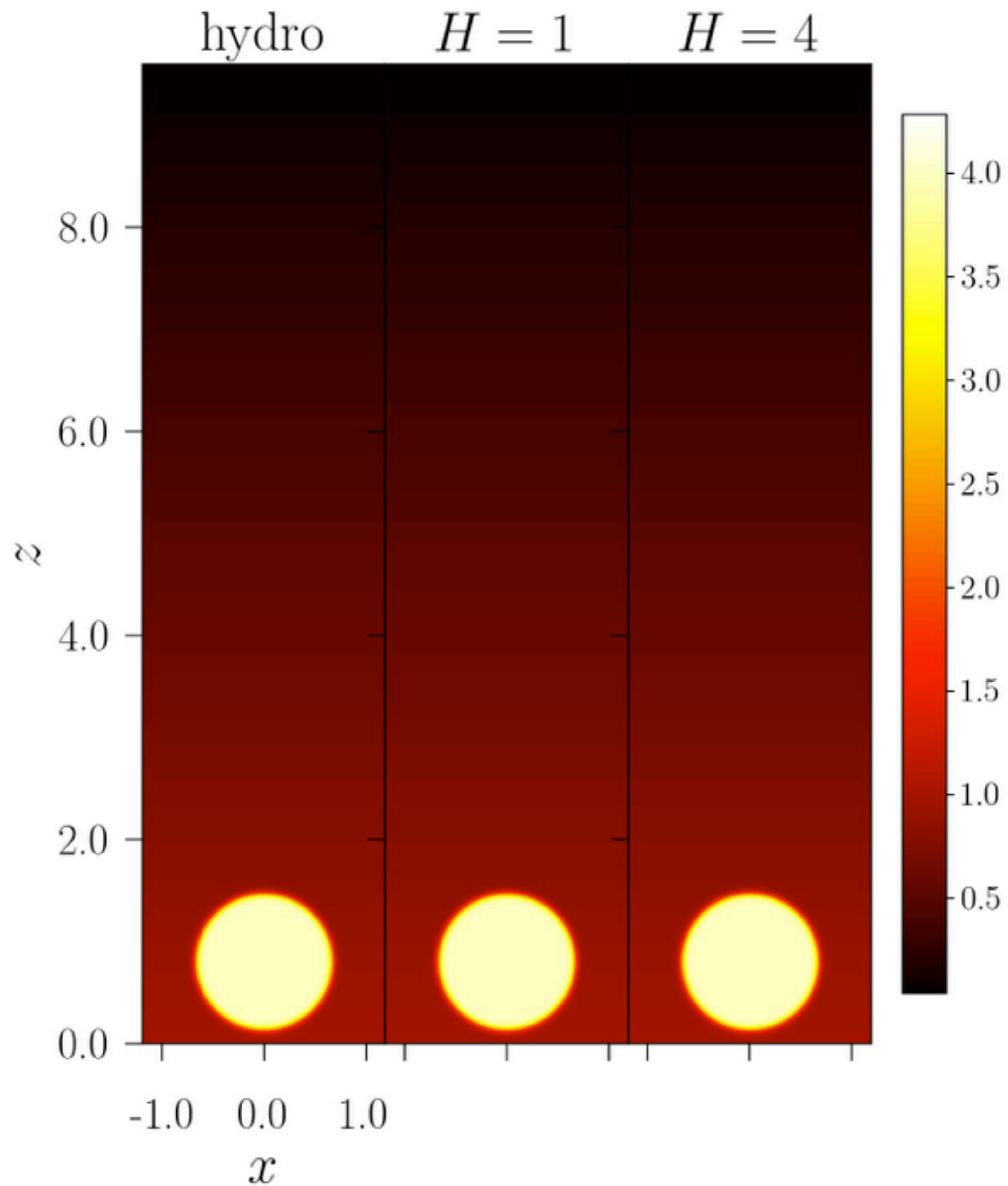
$$\mathrm{Re} = \frac{u_{\max} d}{\nu}, \qquad \mathrm{Re_M} = \frac{u_{\max} d}{\eta},$$

All magnetic cases have about the same magnetic energy

B min $B_0 = 2.5 \times 10^{-6}$ G

B max $B_0 = 6.39 \times 10^{-4}$ G

$$\beta = \min\left(\frac{2(R\rho T/\mu)}{B^2}\right)$$

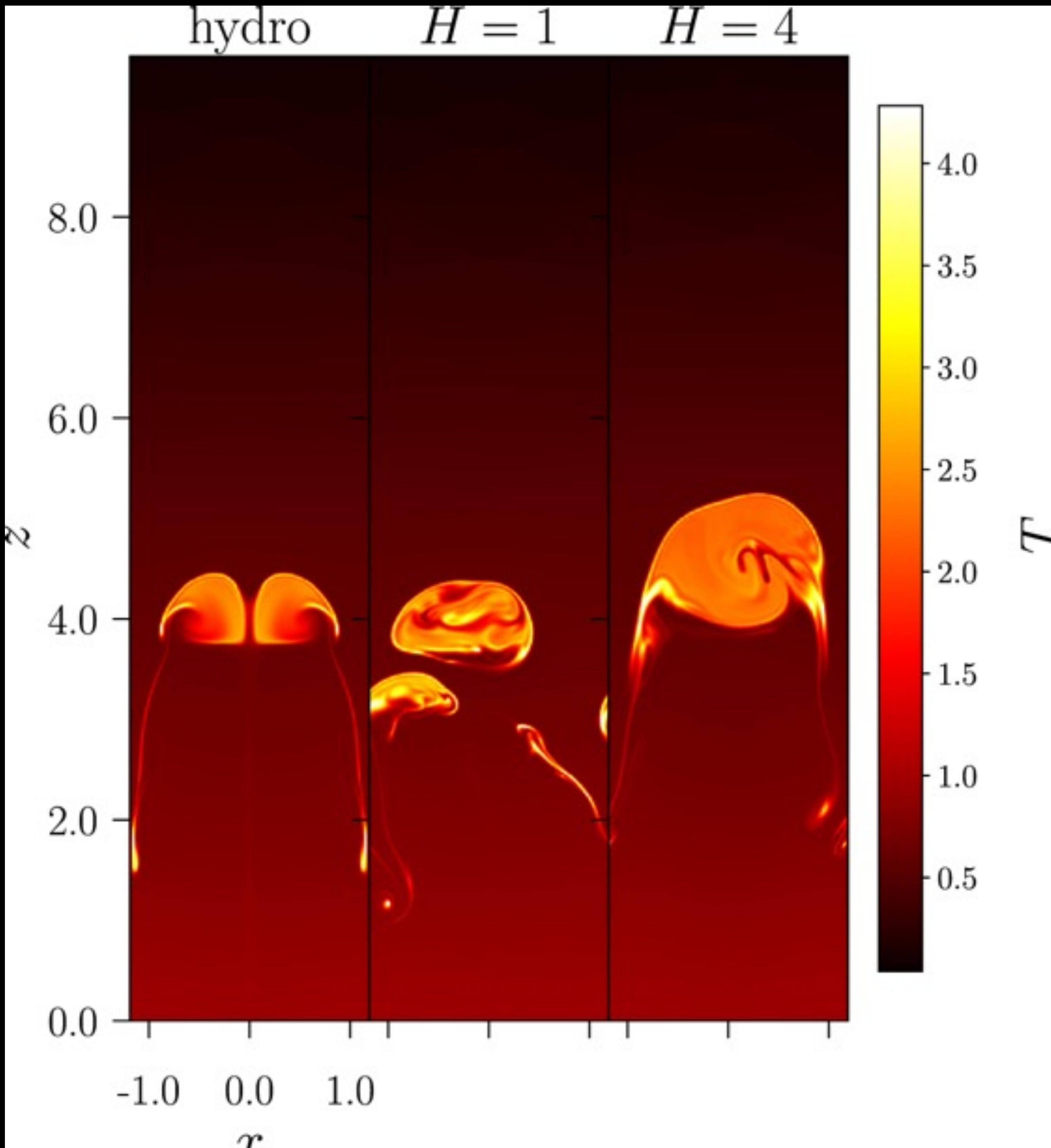


Evolution of Temperature distribution

Models:
Hydro
hel_l
hel_h

ABC field

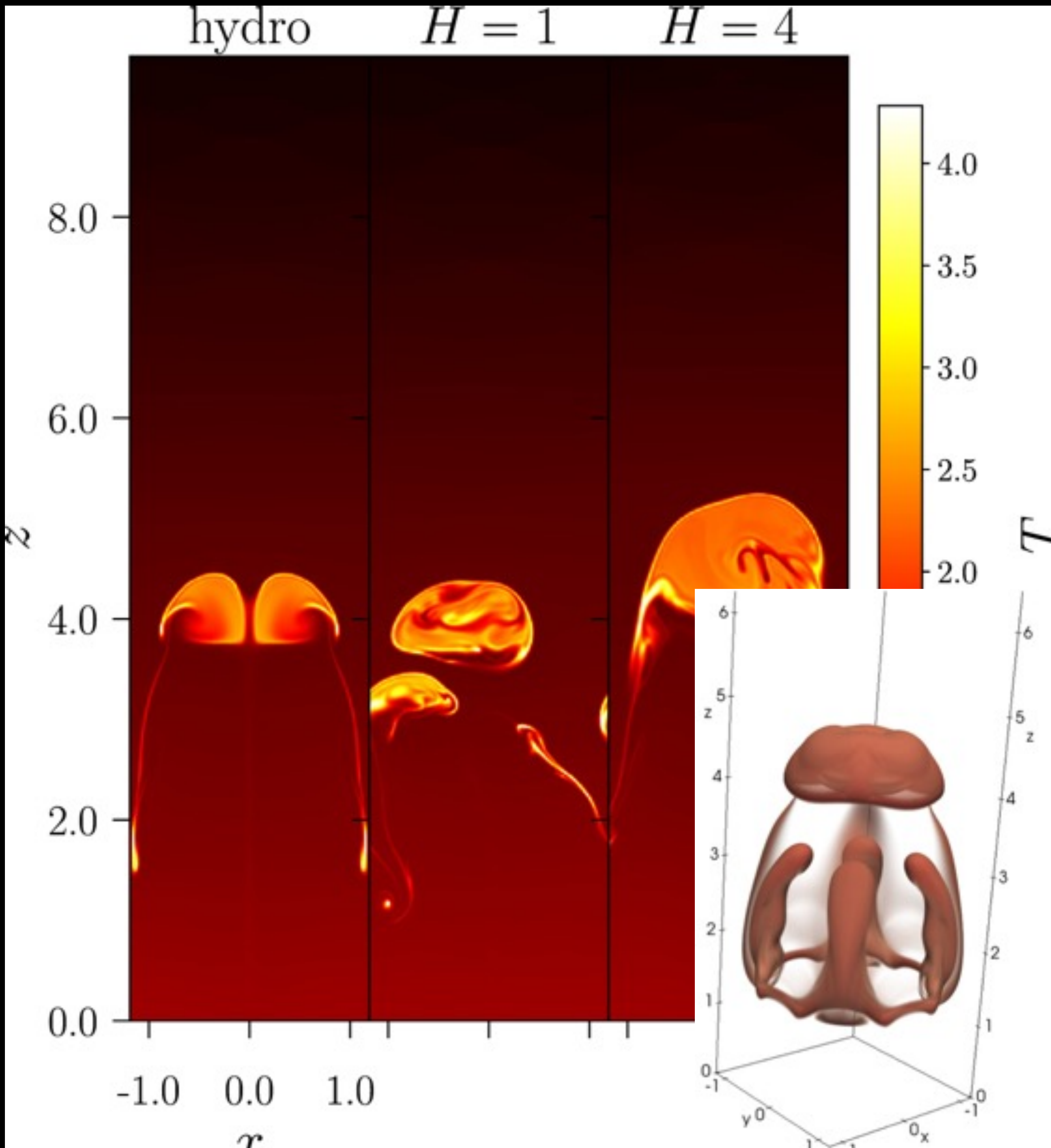
Results: ABC field



Temperature distribution at final time

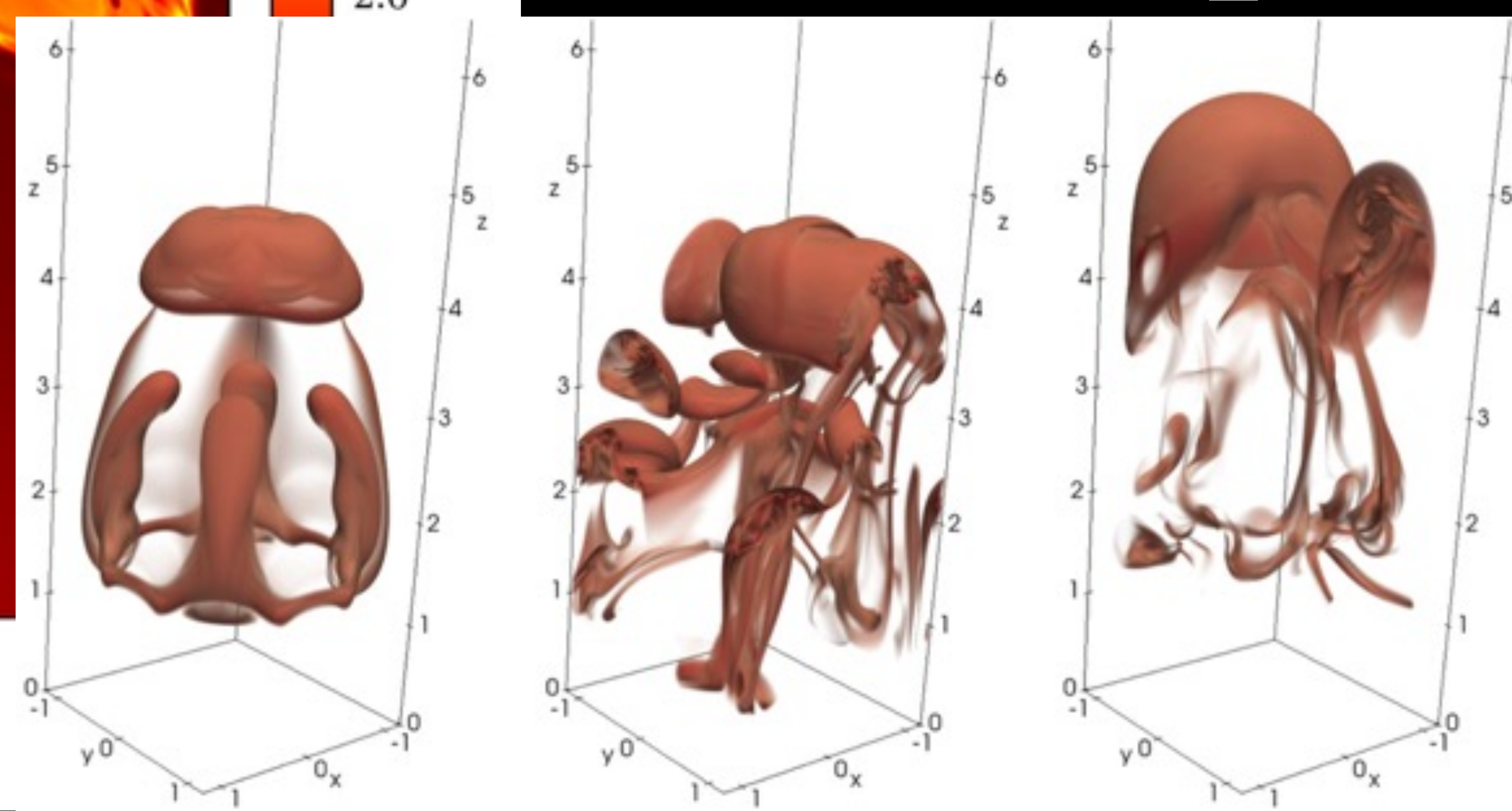
Models: Hydro
hel_l
hel_h

Results: ABC field

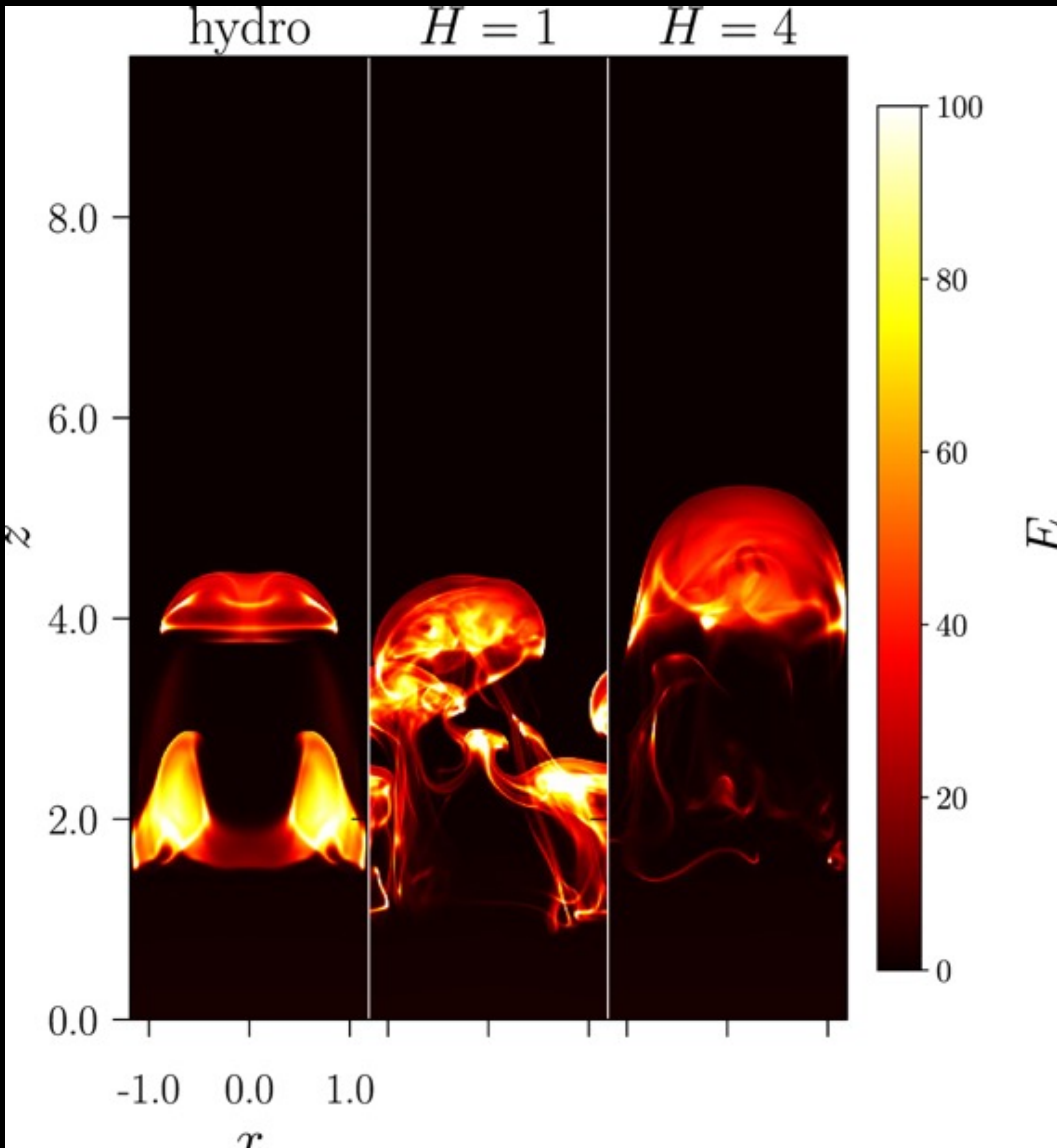


Temperature volume rendering at final time

Models: Hydro
hel_l
hel_h



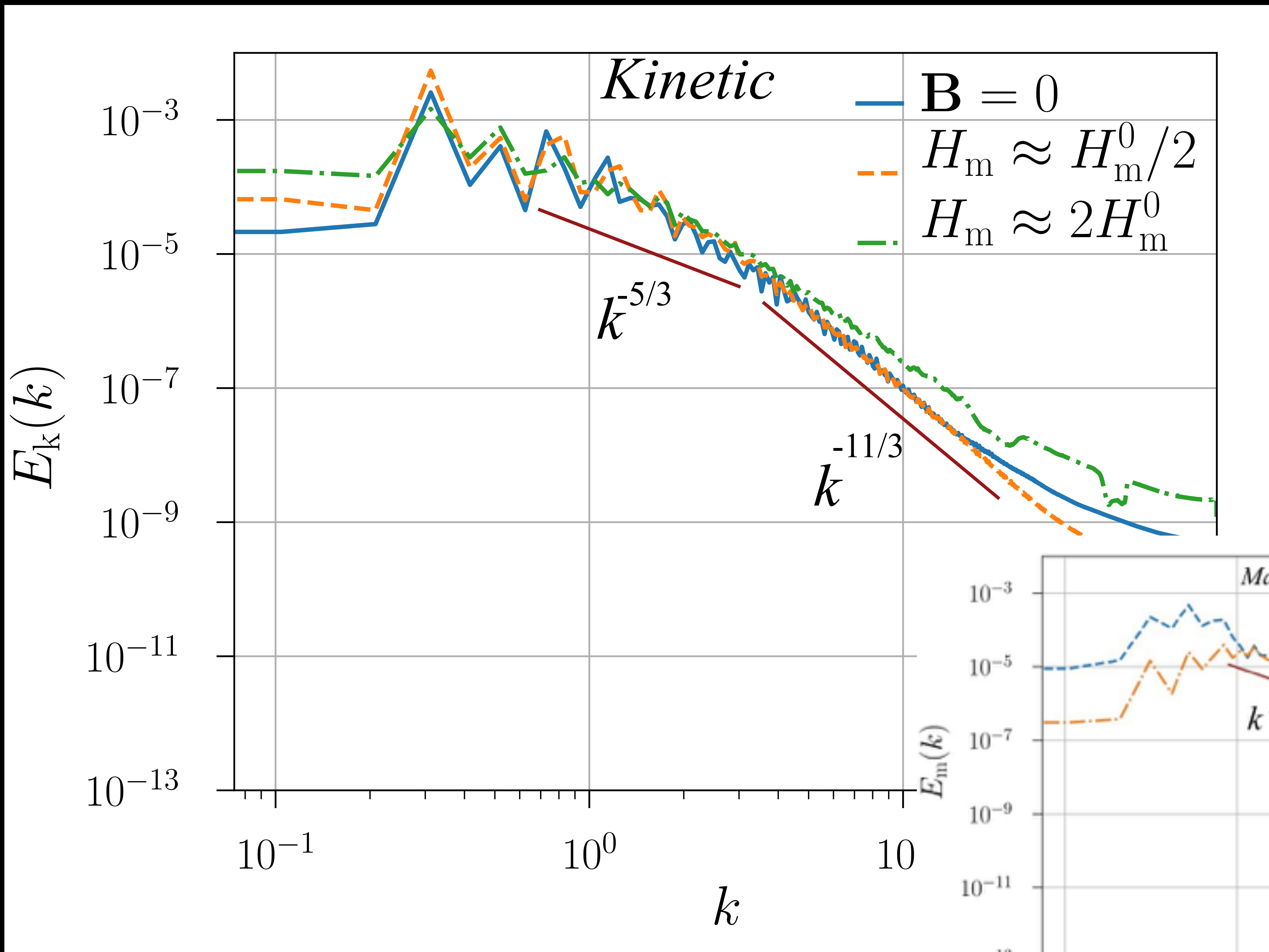
Results: ABC field

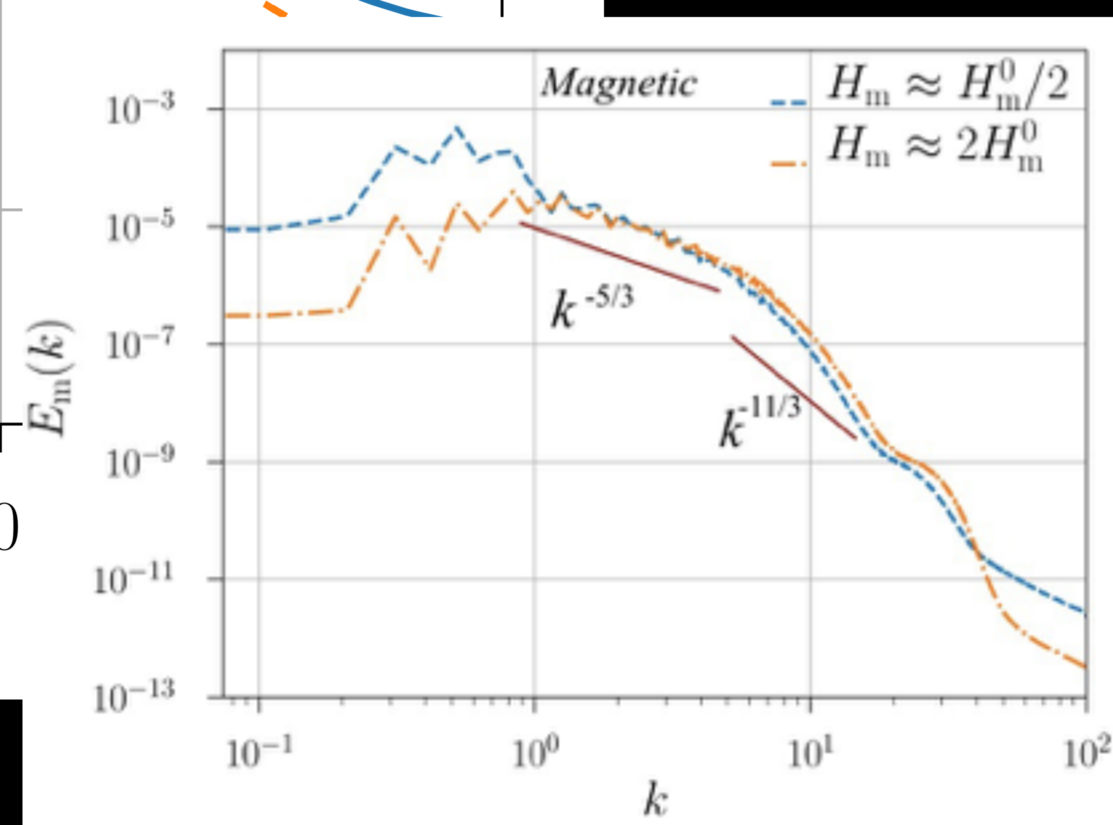


Emission
measure
at final time

$$E(x, z) = \int T^4 \, dy$$

Energy spectra





Models:

Hydro
hel_l
hel_h

Cavities' Coherence

Position vector in the cavity

Position of center of mass

Mean distance of all the points in the cavity

$$d_{\mathrm{mean}} = \langle |\boldsymbol{r}_{\mathrm{cavity}} - \boldsymbol{r}_{\mathrm{CM}}| \rangle$$

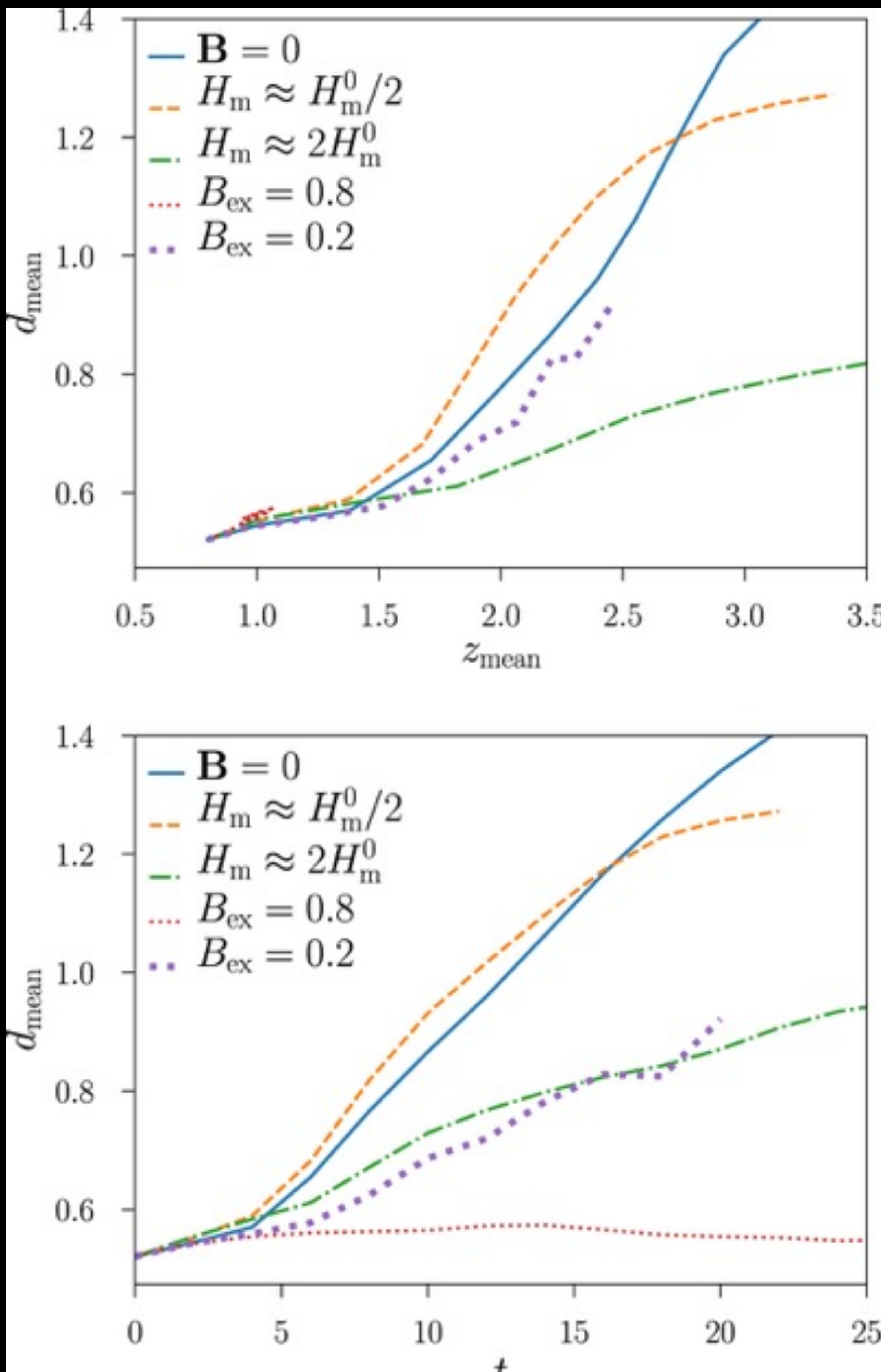
z vector in the cavity

z of center of mass

Mean height of the cavity

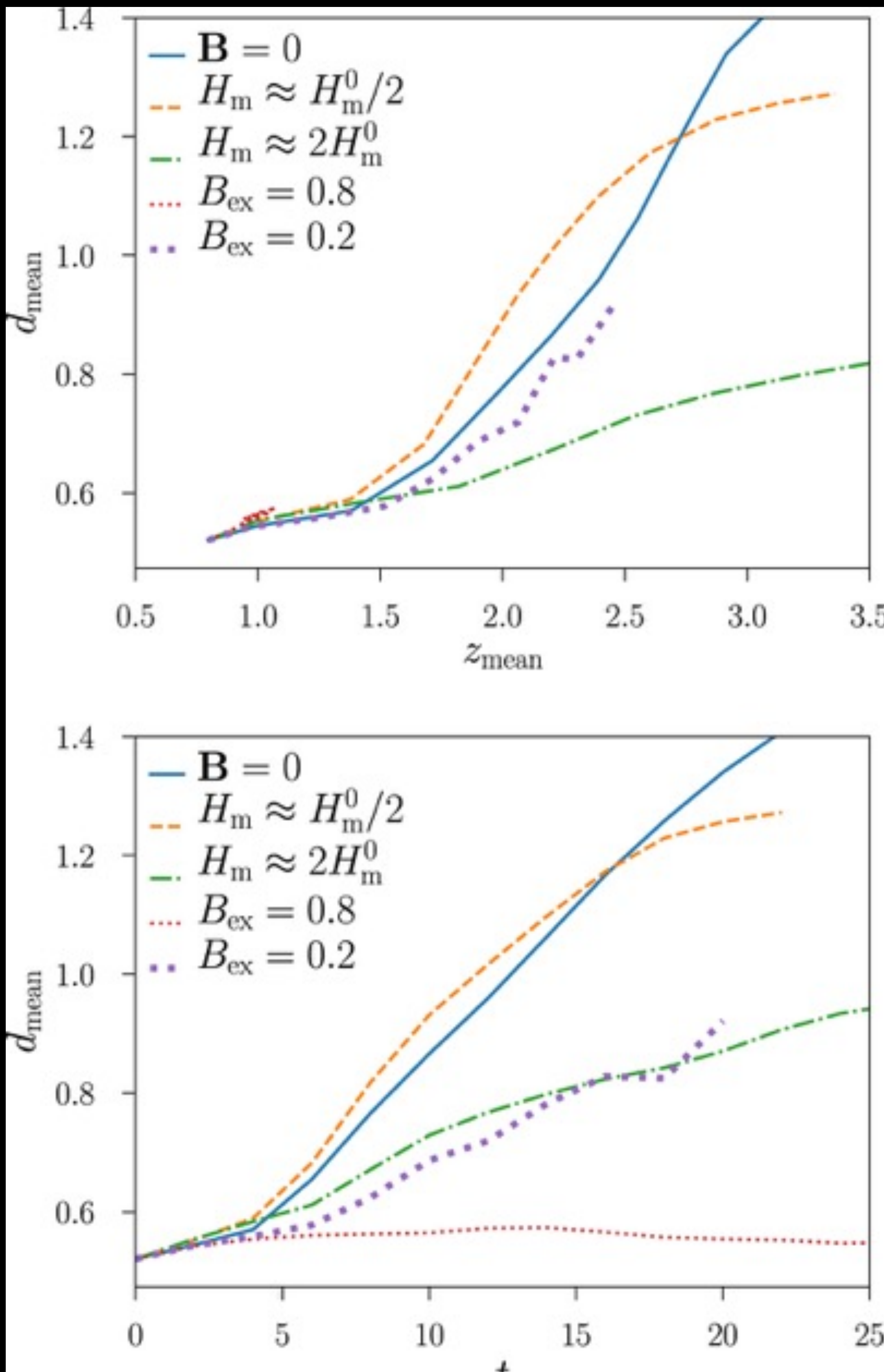
$$z_{\mathrm{mean}} = \langle |z_{\mathrm{cavity}} - z_{\mathrm{CM}}| \rangle$$

Results



Models	Disruption time (Myrs)
Hydro	t ~ 80
hel_l	t ~ 80
hel_h	t ~ 220
ex_low (B=0.2)	t ~ 150
ex_high (B=0.8)	t > 250

Results



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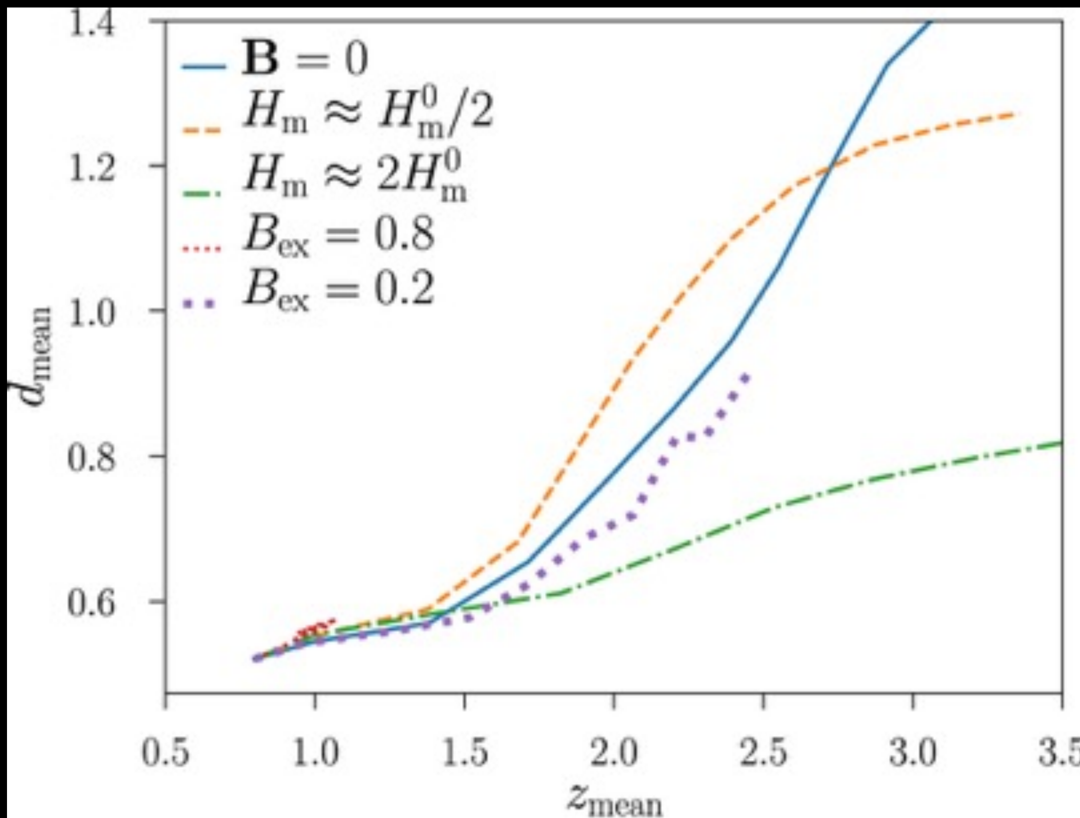
Unstable to Kelvin-Helmoltz

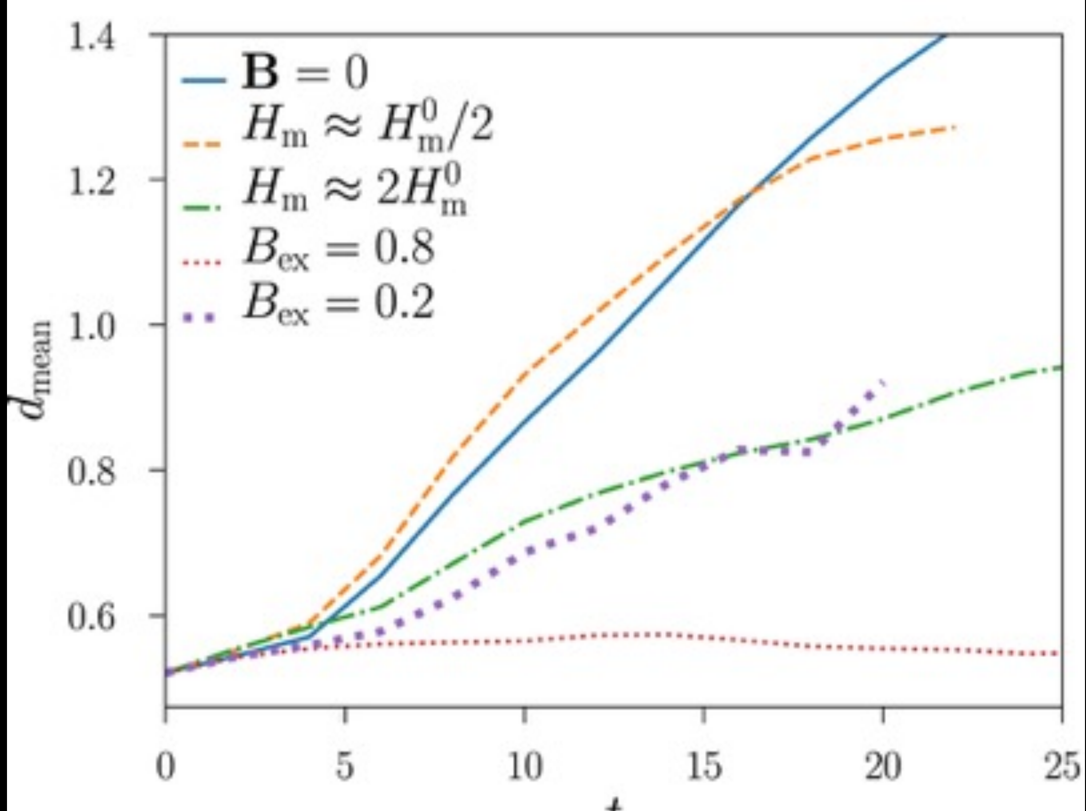
$$B^2 \geq 2\pi(u_1 - u_2)^2(\rho_1\rho_2)/(\rho_1 + \rho_2)$$

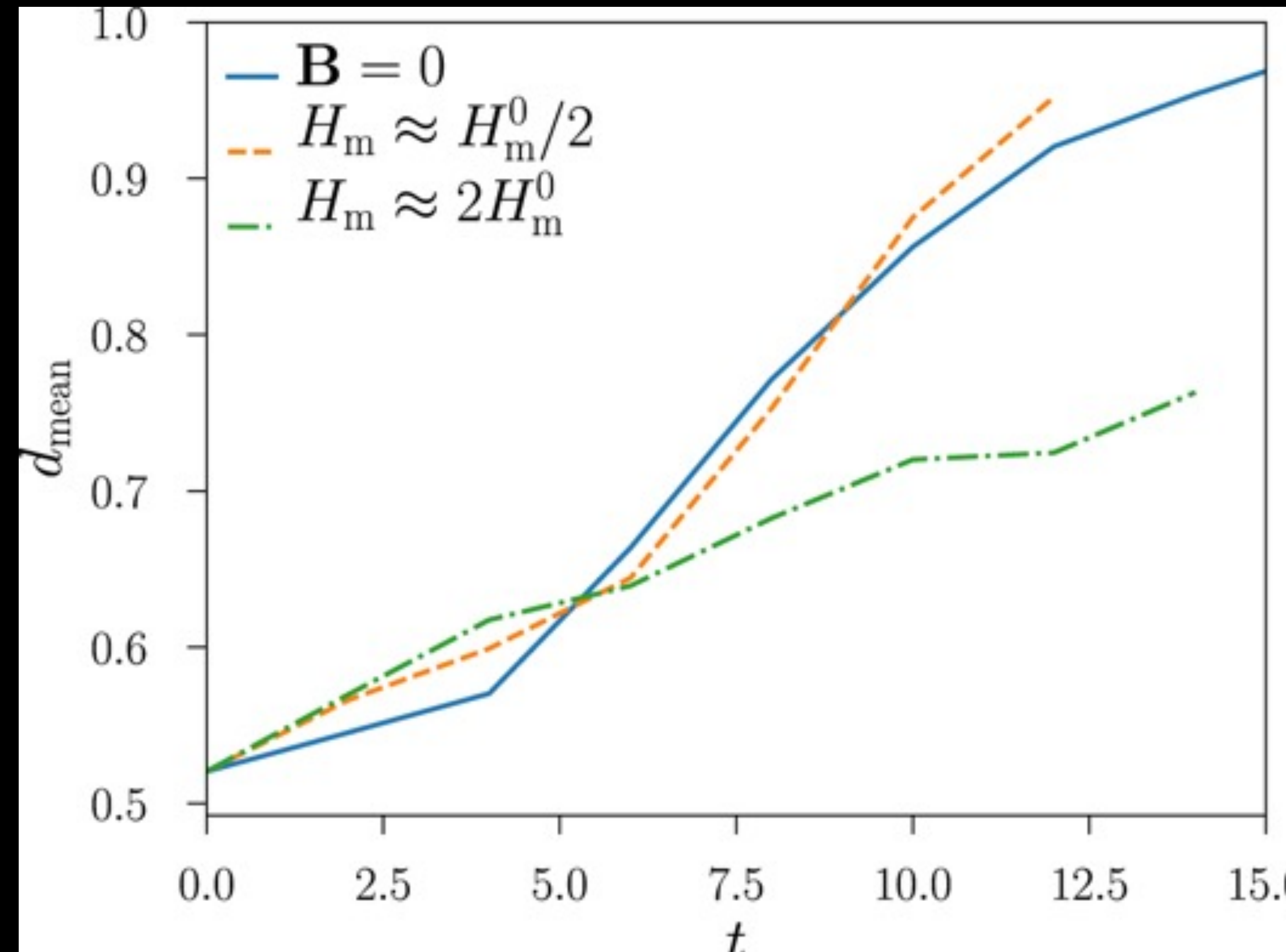
(Chandrasekhar 1961)

Threshold B ~ 0.56 for our models

Results







High Re Models:

Hydro2
hel_l2
hel_h2

The high Re regime shows similar trend

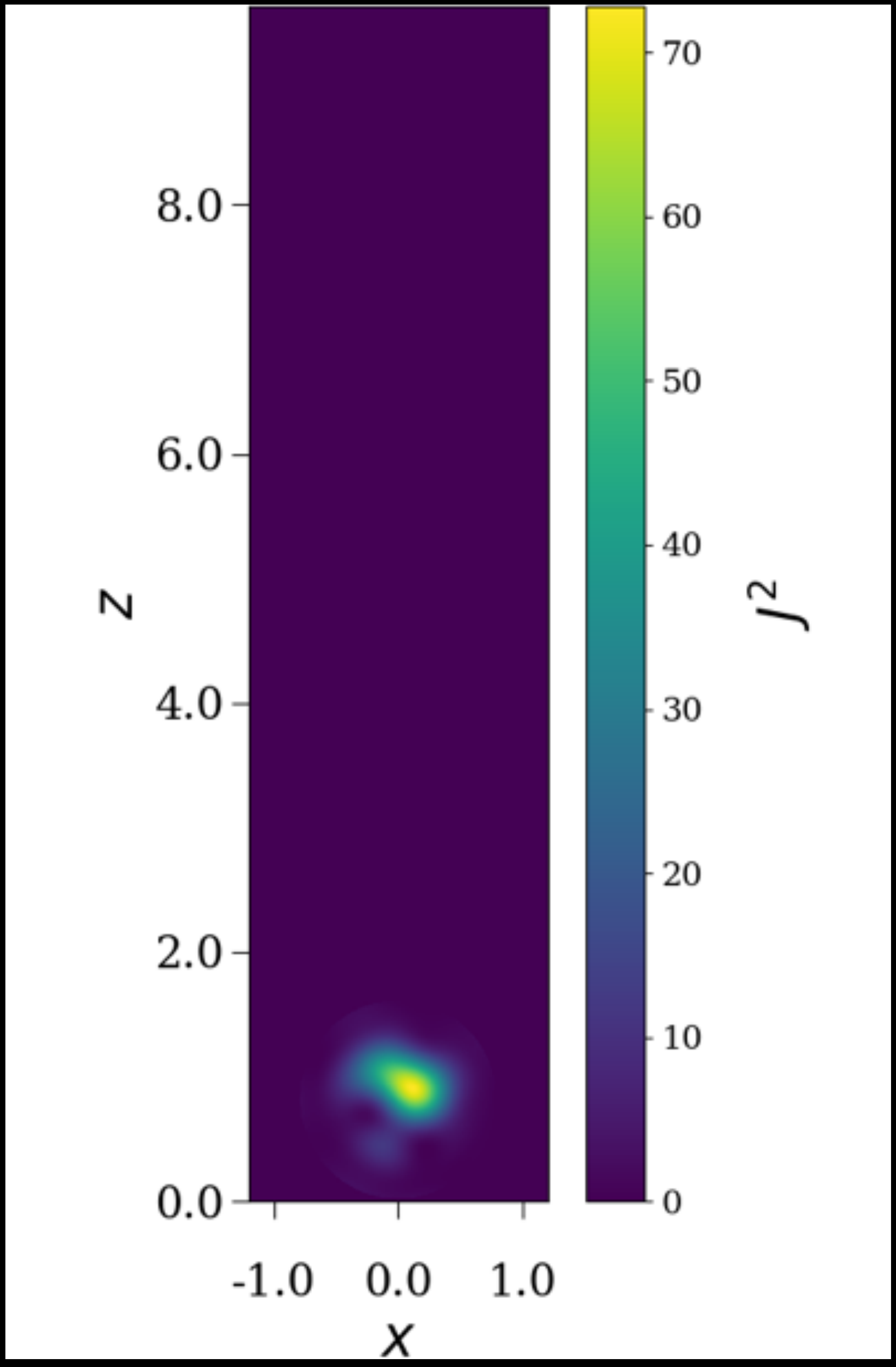
Questions:

Do surface currents play a role?

Does the initial geometry play a role?

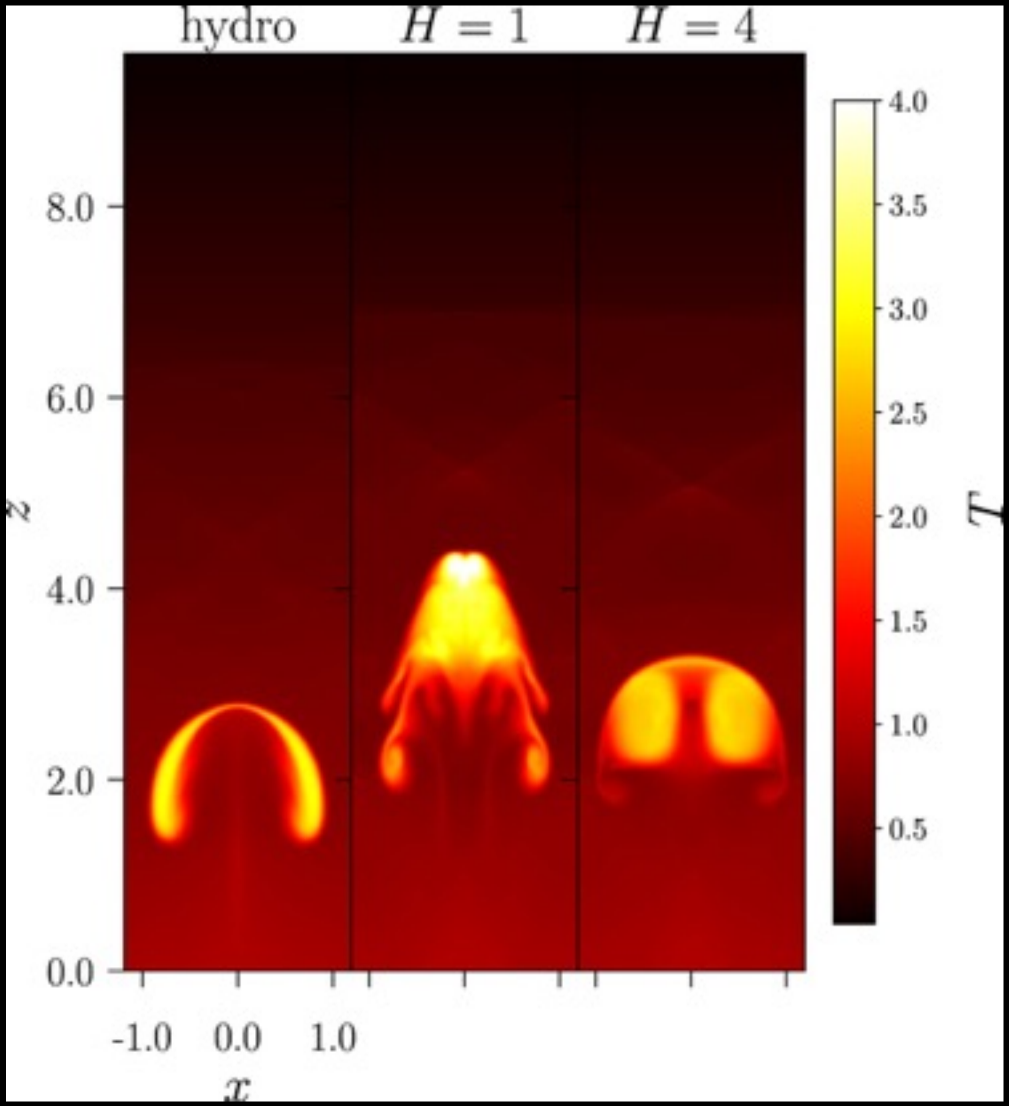
No current effects

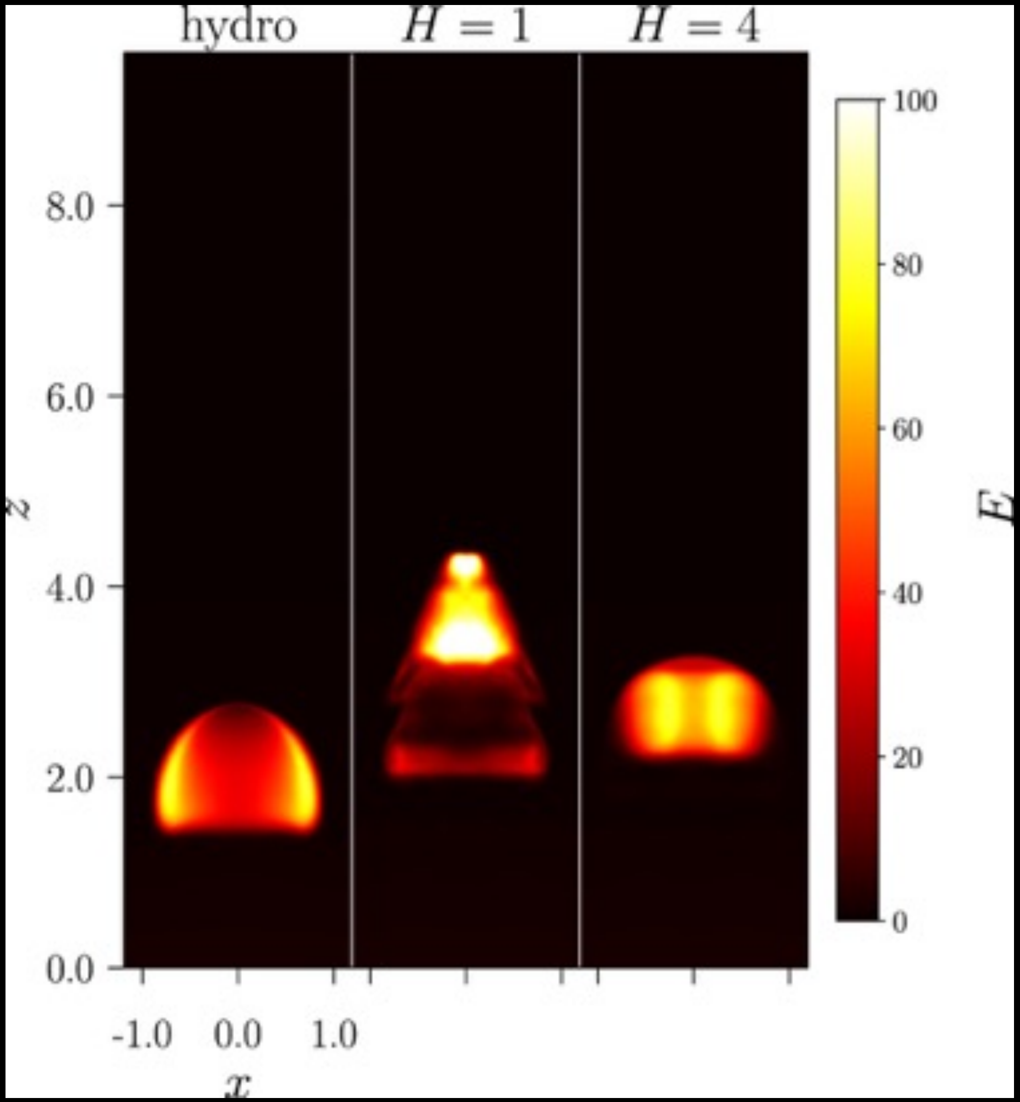
Currents at
t = 0
y=0
for the ABC field
case



Different initial B: Spheromak

Temperature distribution and Emission measure
at final time
Models: Hydro, sph_l, sph_h





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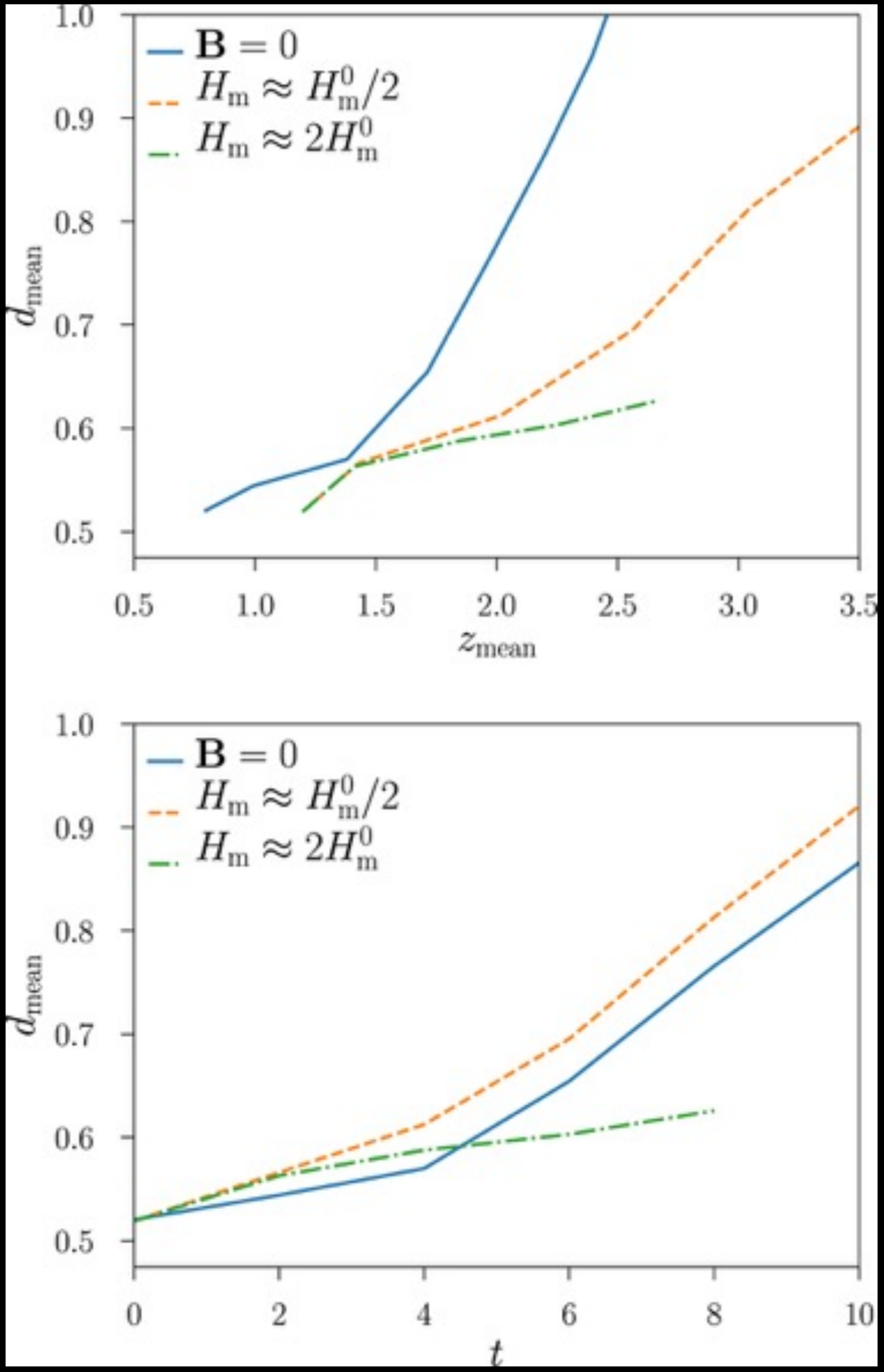
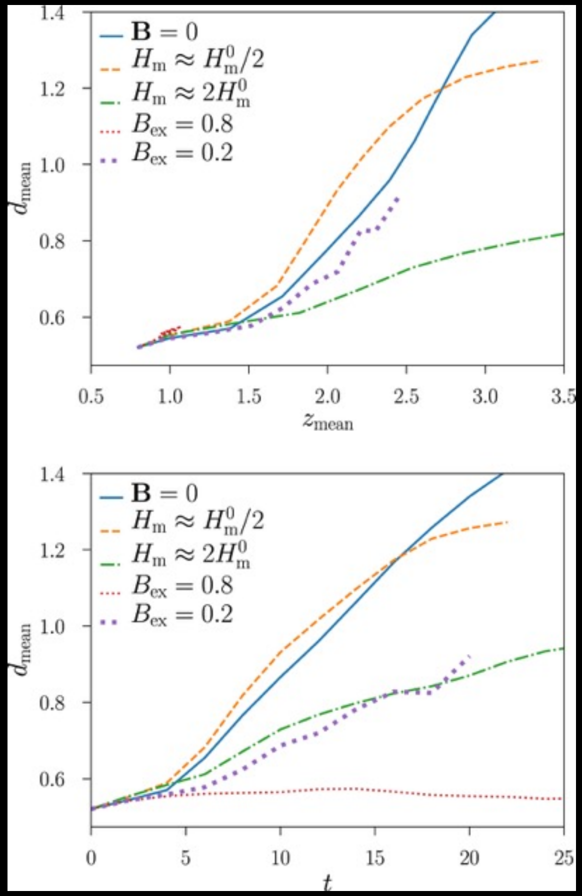


Models:

Hydro2
sph_l
sph_h



Models:

Hydro2
hel_h
hel_l
ex_low
ex_high

Results do not depend on initial field topology

Conclusions

- Hydro cases show stability for about 80 Myrs, with increase of 50% of coherence measure
- Helical fields of the order of 10^{-5}G can stabilize extragalactic buoyant bubbles for about 250 Myrs
- Results do not depend on B field initial geometry
- Vertical magnetic fields required for bubble stabilization are much higher (about 10^{-4}G)

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Grazie!