

Simulations of Rising Hydrodynamic and Magnetohydrodynamic Bubbles

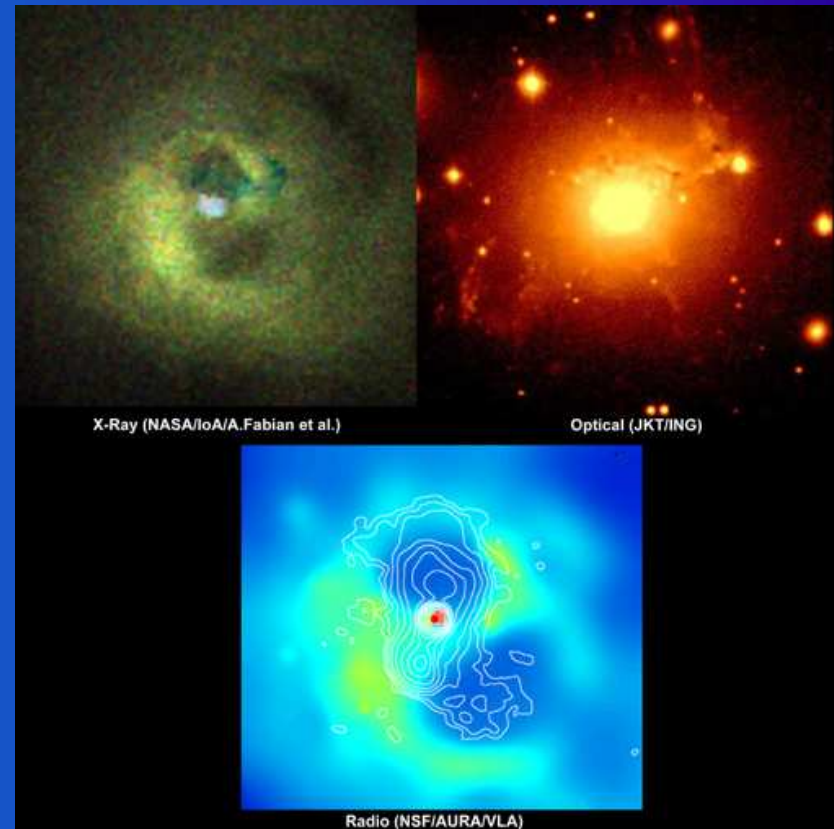
P. M. Ricker (U. Illinois); K. Robinson (Lawrence U.);
L. J. Dursi, R. Rosner, T. Linde (U. Chicago), M. Zingale (UCSC),
A. C. Calder, B. Fryxell, T. Plewa, J. W. Truran, A. Caceres (U. Chicago),
K. Olson (NASA/GSFC), K. Riley, A. Siegel, N. Vladimirova (U. Chicago)

Recent Chandra X-ray observations of galaxy clusters have revealed emission voids of order 30 kpc in size which have been identified with underdense, buoyant, magnetized bubbles fed by central active galaxies. We present adaptive-mesh fluid simulations, performed using the FLASH code, of rising bubbles in a stratified atmosphere, performed using two different hydrodynamics solvers, with and without the effects of magnetic fields and with varying bubble size and stratification. Purely hydrodynamic bubbles are found to be unstable; a dynamically important magnetic field is required to maintain a bubble's integrity. The required magnetic field strength is consistent with values required to explain Faraday rotation measurements.

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Introduction

- Observations of “relaxed” cluster cores by *Chandra* and XMM show evidence for interaction of central active galaxies with the intracluster medium
- These take the form of “bubbles” of magnetized plasma that displace and heat the intracluster gas
- Questions:
 - How efficiently do they mix?
 - Does AGN heating prevent the formation of cold multiphase gas?
 - What fraction of the total energy budget of a cluster is in bubbles?



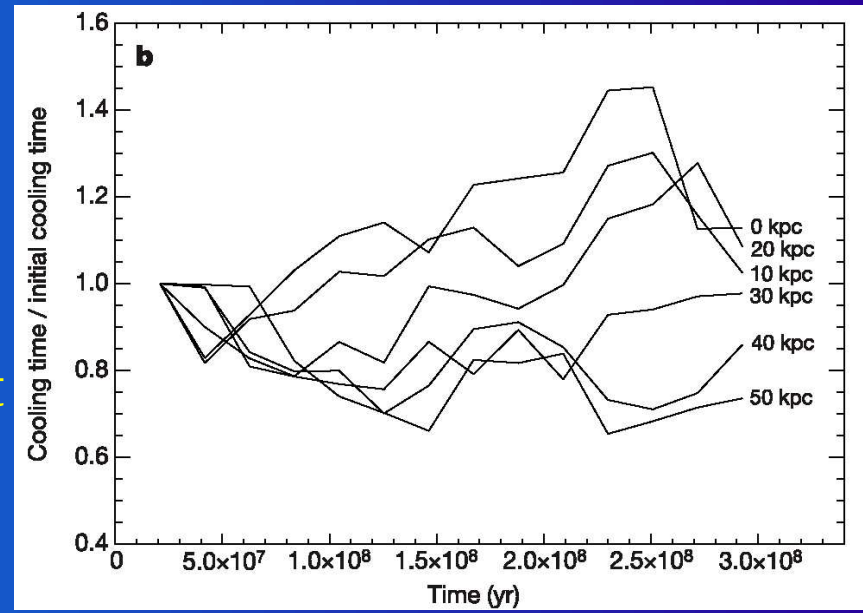
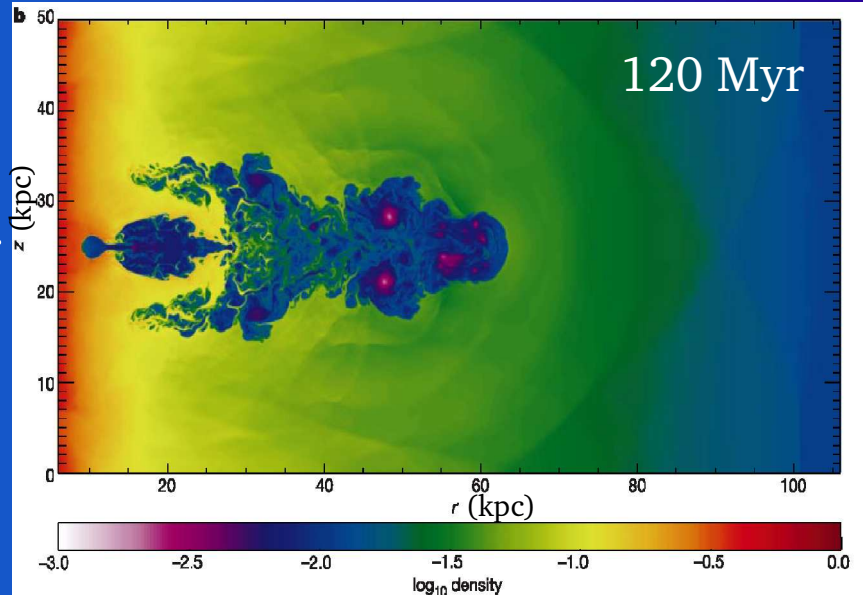
Perseus A ($z = 0.018$)

- Emerging picture: (Reynolds et al. 2002)

- Bubbles represent late stages of magnetized, relativistic AGN jets

- Jets slow once they reach approx. pressure equilibrium with ICM (several $\times 10$ Myr)

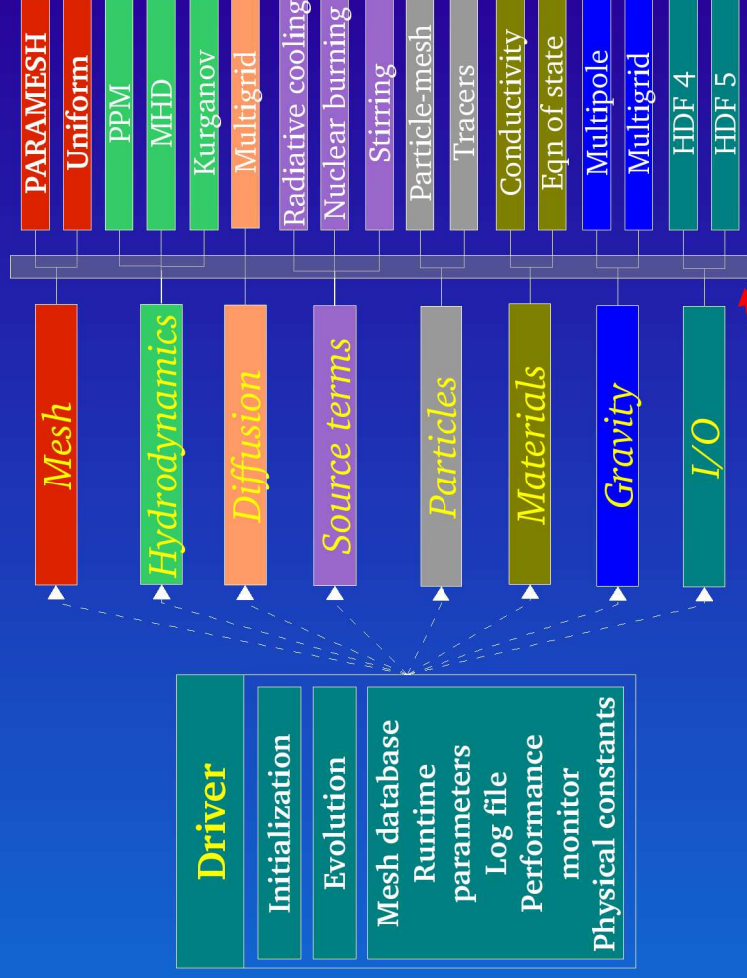
- FLASH simulations by Brüggén & Kaiser (2002) show bubbles with continuous energy input can shut off cooling in ICM



Brüggén & Kaiser (2002)

FLASH

- Parallel AMR hydro code originally developed for astrophysical thermonuclear flash simulations (Fryxell et al. 2000)
- Advanced framework designed to make creation and testing of physics modules “easy”
- New modules suitable for cosmological problems:
 - Dark matter, galaxies
 - Particle-mesh N-body solver
 - Hydrodynamics, MHD
 - Piecewise-parabolic method, TVD MHD
- Gravity
 - Multigrid, multipole, FFT
- Radiative cooling
 - ODE solvers
- Cosmic rays (with F. Miniati)
 - ODE solvers, implicit diffusion



FLASH code
framework

Ricker et al. (2001)
(astro-ph/0011502)

Bubble simulations

- Initial conditions:

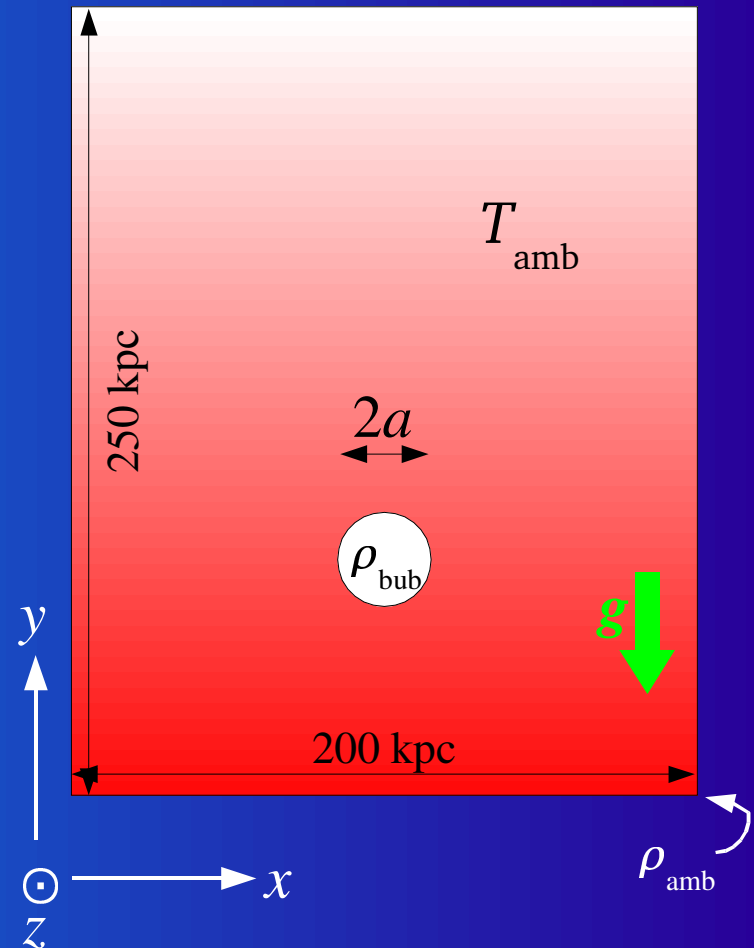
- Plane-parallel stratified atmosphere
- Buoyant bubble in horizontal pressure (thermal + magnetic) equilibrium

- Domain:

- 200×250 kpc (2D)
- About 3 pressure scale heights
- AMR with effective 512×640 mesh

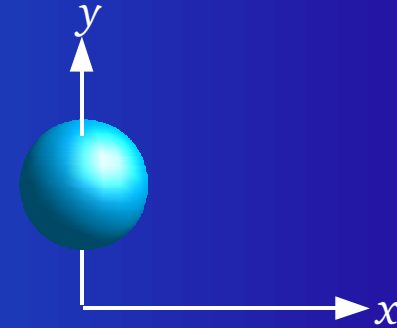
- Solvers:

- PPM with hydrostatic modifications for hydrodynamic cases (Zingale et al. 2002)
- TVD MHD solver using diffusive cleaning to enforce $\nabla \cdot \mathbf{B} = 0$ (Marder 1987)



Vary:

- Density contrast: 10:1 and 100:1
($n_{e,amb} = 5 \times 10^{-3} \text{ cm}^{-3}$, $T_{amb} = 8.9 \text{ keV}$)
- Geometry: planar and axisymmetric
- Bubble size: $a = 15 \text{ kpc}$ and 25 kpc
- Stratification: $g = (5, 1.25) \times 10^{-8} \text{ cm s}^{-2}$
(field of $10^{14} M_{\odot}$ point mass @ 170 kpc)
- Physics: hydrodynamic and MHD
(MHD in planar geometry only)
- Magnetic field with varying $\beta \equiv 8\pi P/B^2$
($\beta = 460, 0.19, 0.046, 0.012$)
 - Horizontal (z)
 - Horizontal (x)
 - Vertical (y)
 - Force-free field with background horizontal z field \longrightarrow
(Cargill & Chen 1996)



Axisymmetric geometry

“Flux rope” field configuration

$$B_{\theta} = \begin{cases} B_b \frac{r}{a} & r < a \\ 0 & r \geq a \end{cases}$$

$$B_z = \begin{cases} B_b \left[4 - 2(r/a)^2 \right]^{1/2} & r < a \\ B_{z0} & r \geq a \end{cases}$$

$$B_b \equiv \frac{1}{\sqrt{3}} \sqrt{8\pi (P_{amb} - P_{bub}) + B_{z0}^2}$$

Results:

- Purely hydrodynamic bubbles are disrupted by fluid instabilities

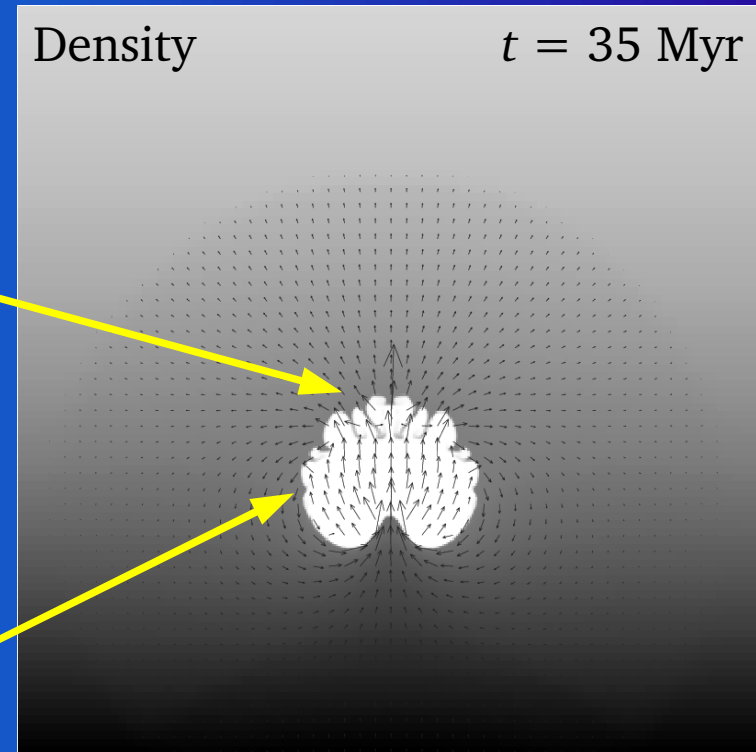
Rayleigh-Taylor at top

$$\text{Growth time } t_{\text{RT}} = \sqrt{\frac{a}{2\pi g}} \sim 10 \text{ Myr}$$

$$\text{Rise time } t_{\text{rise}} = \sqrt{\frac{4a}{g}} \sim 60 \text{ Myr}$$

Kelvin-Helmholtz along sides

Density $t = 35 \text{ Myr}$



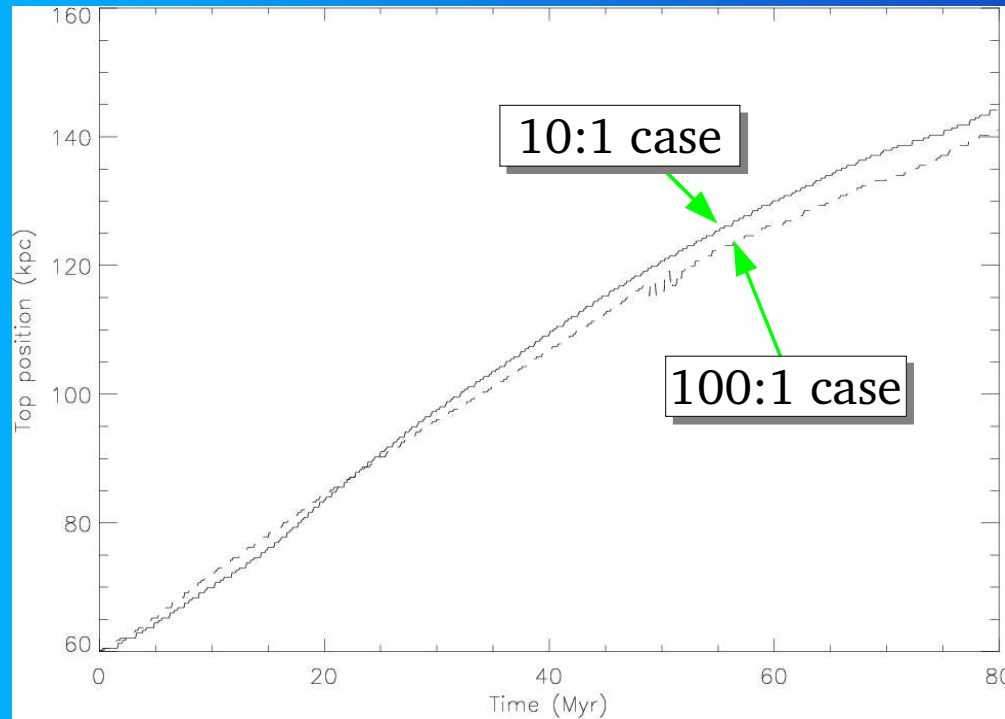
- Instability growth rate controlled by Atwood number

$$A \equiv \frac{\rho_{\text{amb}} - \rho_{\text{bub}}}{\rho_{\text{amb}} + \rho_{\text{bub}}}$$

⇒ changes only from 0.82 (10:1) to 0.98 (100:1)

Vertical position of top of bubble vs. time

- Relatively insensitive to density contrast (denser bubble entrains less ambient fluid)

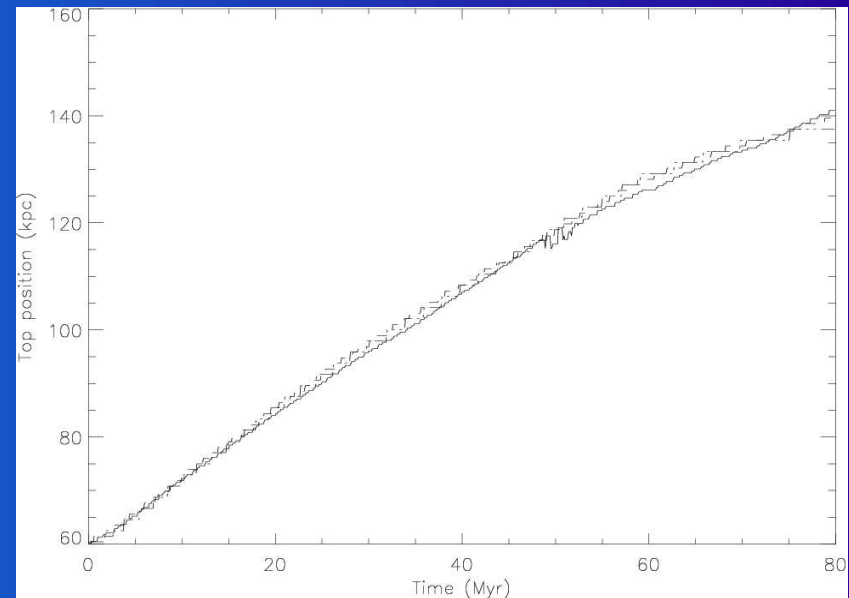


Resolution study

Solid line $\Delta_{\min} = 0.4$ kpc

Dotted line $\Delta_{\min} = 1.0$ kpc

Dashed line $\Delta_{\min} = 2.0$ kpc

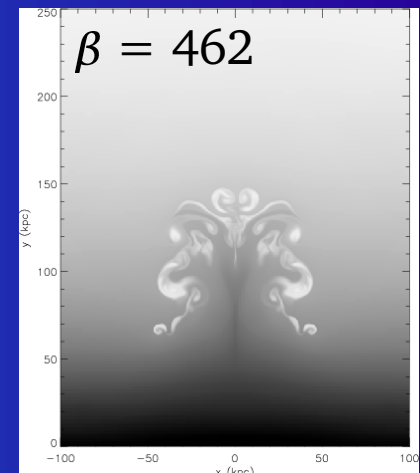
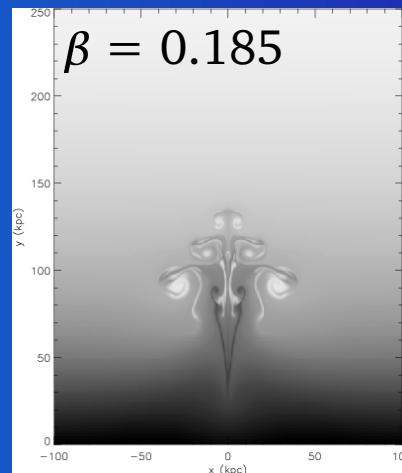
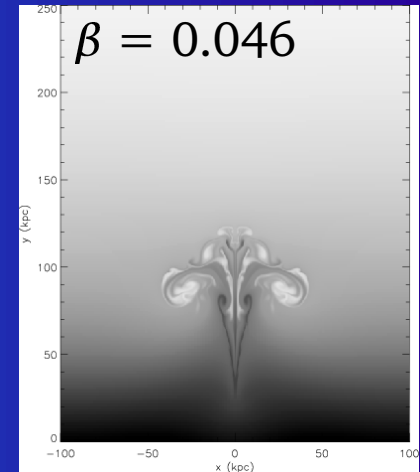
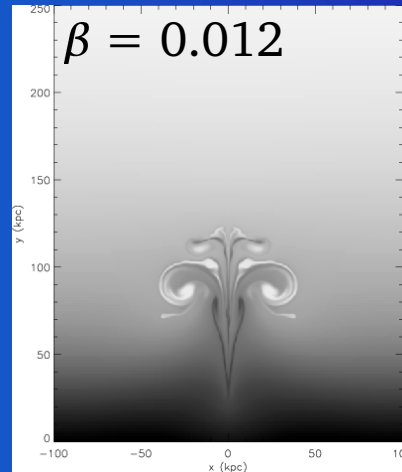


Pressure-supported bubbles with external magnetic fields

- **Horizontal (z) field** acts to reduce effective stratification

$$\frac{\nabla P}{P} \rightarrow \frac{\beta}{\beta + 1} \frac{\nabla P}{P}$$

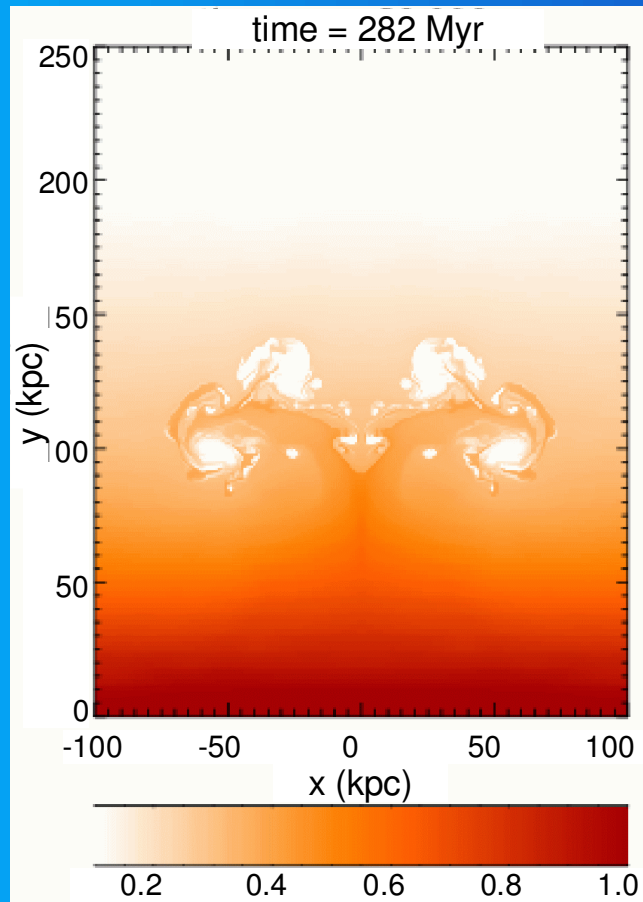
- Decreasing β acts to tighten vortical structures
- **Horizontal (x) field** completely contains bubble – acts as surface tension
- Artifact of geometry
- **Vertical (y) field** helps to suppress KH instability along sides
- Sufficiently strong field ($\beta=0.019$) can prevent disruption (probably unrealistic)



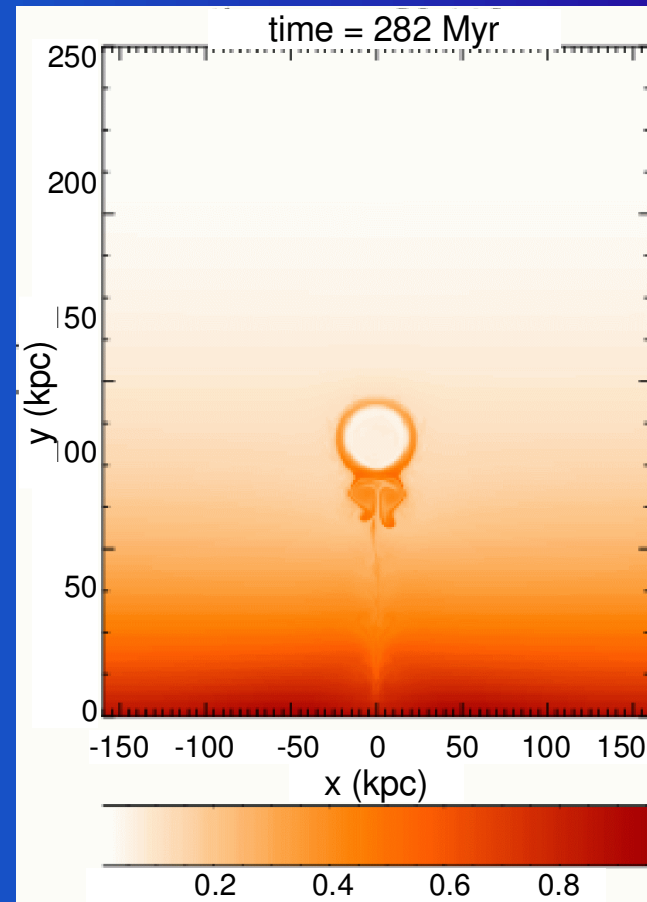
Gas density at $t = 250$ Myr for horizontal z field configurations

Magnetically supported bubbles with horizontal (z) external field

No magnetic field



Force-free field, $\beta \simeq 0.9$



Density ($10^{-26} \text{ g cm}^{-3}$)

Conclusions

- Bubbles without supporting magnetic fields are torn apart by buoyant and shear instabilities before they can move an entire bubble height (timescale ~ 10 Myr)
- Magnetically supported bubbles remain stable for as long as 250 Myr; they possess a ring of bright material and a wake that may be observable
- Next steps:
 - Realistic cluster potential
 - Radiative cooling
 - Continuous energy injection
 - Aim: create a physically motivated AGN subgrid model for cluster evolution simulations

References

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