Magnetizing the ICM with AGN Feedback

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Some questions to consider regarding cluster simulations

1. How do we decide which models of AGN accretion and feedback yield the best representation of the behavior of these systems in real life?

2. How do we assess the relative importance of the various effects that we study in isolation or in combination? (cooling, anisotropic conduction/viscosity, magnetic fields, cosmic rays, star formation, AGN/supernova feedback, subgrid turbulence, two-fluid effects, ...)

3. Where are we headed with all of this simulation effort? Do we make genuine predictions? If so, of what?

Observations of magnetic fields in clusters

1. Faraday rotation of polarized background or embedded radio sources

$$\Delta \chi = \frac{\mathrm{RM} \cdot \lambda^2}{(1+z)^2}$$

$$\mathrm{RM} = (812 \text{ rad m}^{-2}) \int \left(\frac{n_e}{\mathrm{cm}^{-3}} \right) \left(\frac{B_{\|}}{\mu \mathrm{G}} \right) \left(\frac{ds}{\mathrm{kpc}} \right)$$

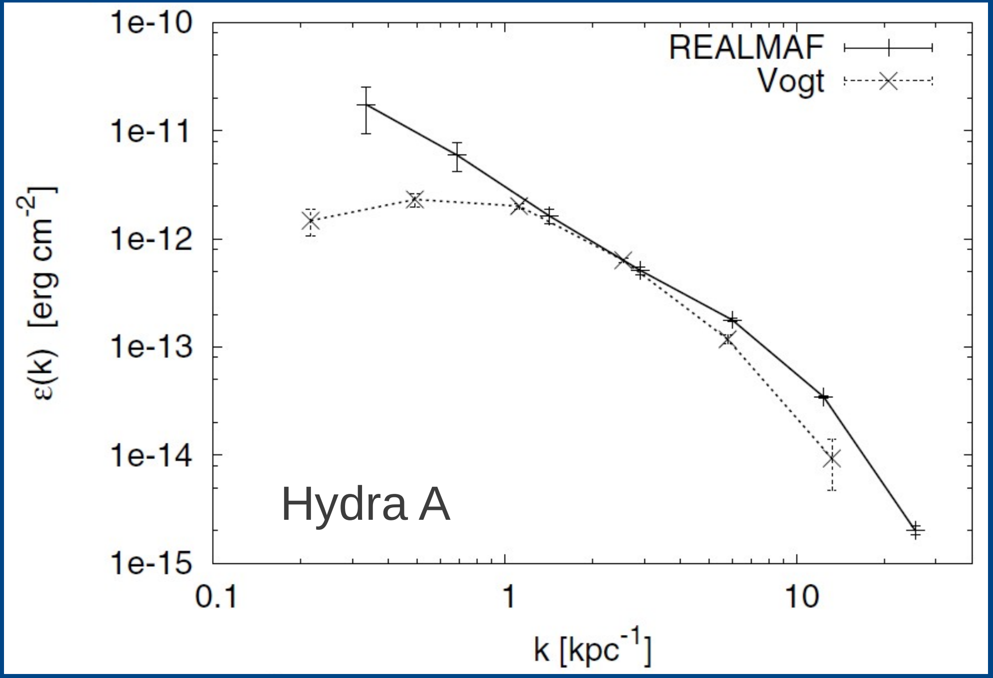
2. Synchrotron emission from radio halos and relics

$$I_\nu = \int j_\nu^{\mathrm{syn}} ds \propto \int \nu^{-(p-1)/2} n_e B^{(p+1)/2} ds$$

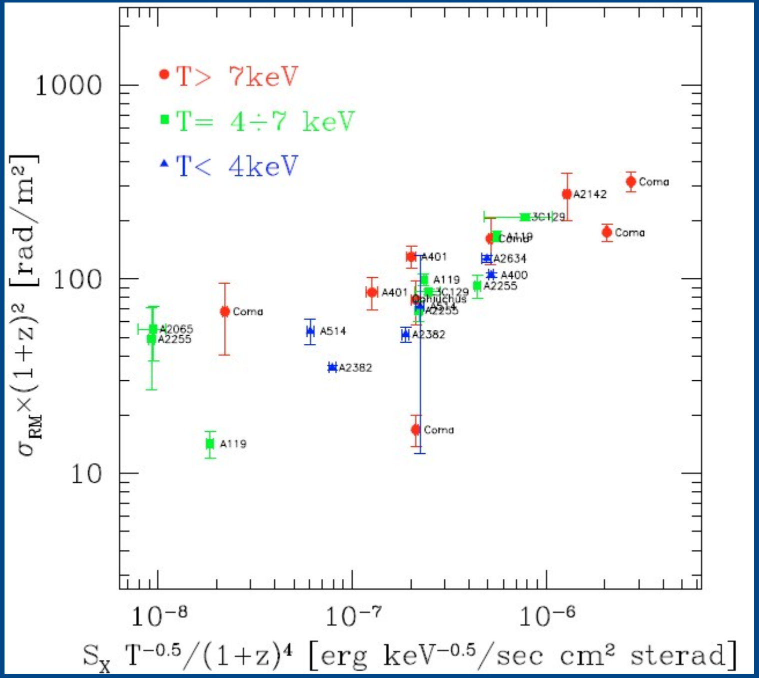
$$n_e(\gamma) \propto \gamma^{-p}, \quad p \sim 1-2$$

Observations of magnetic fields in clusters

- |**B**| ~ 1 – 10 μG, up to 40 μG in cool cores
- Power-law, Kolmogorov-like scale dependence
- Autocorrelation length ~ 1 – 10 kpc
- Correlation with gas density
- Weak/no correlation with gas temperature



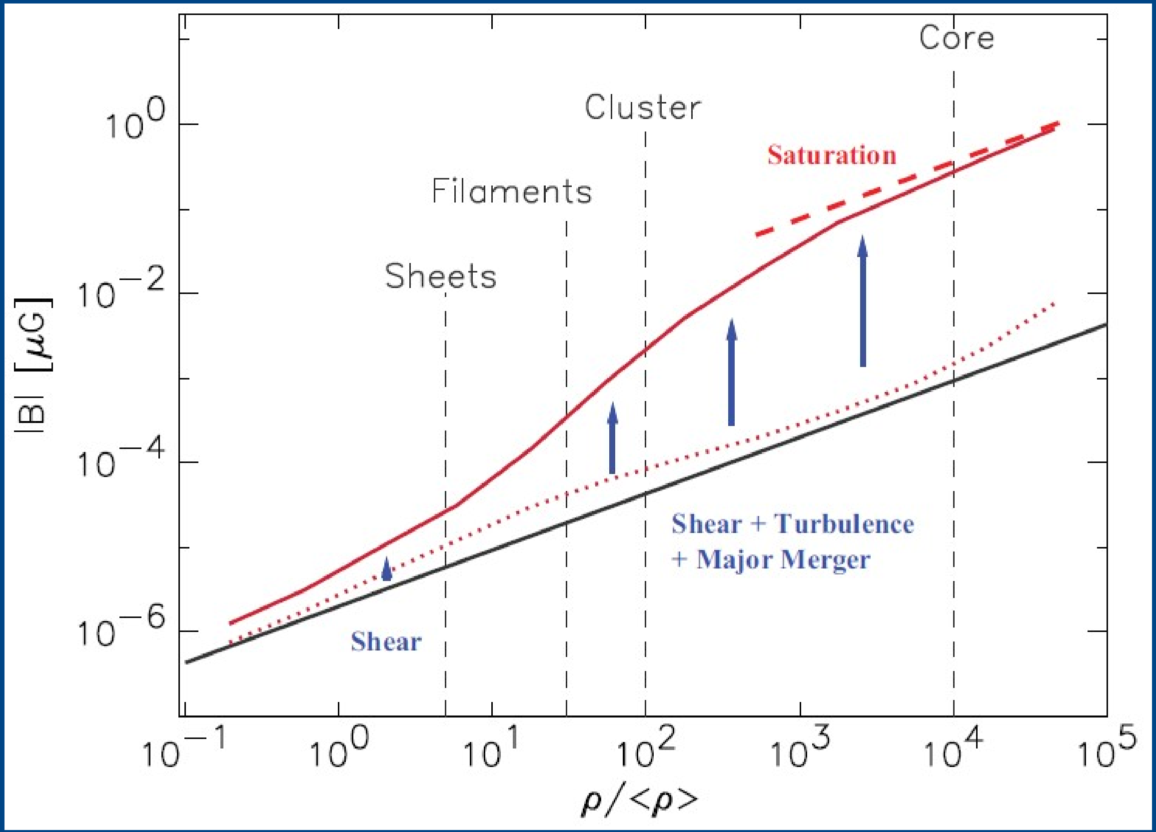
Kuchar & Ensslin (2011)

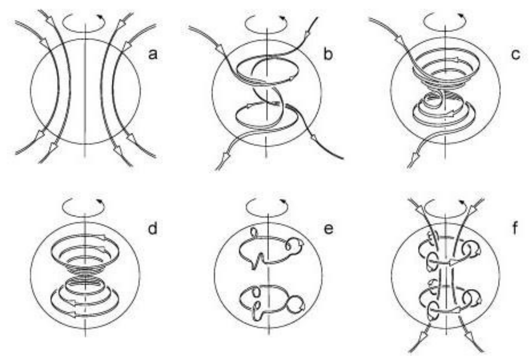


Govoni+ (2010)

Need for some sort of magnetic field amplification

- “Guaranteed” to have seed fields ~ 10^{-18} G (Widrow 02)
- Adiabatic compression insufficient to reach observed strengths
- Dynamo? Need > 10 e-folding times (Kulsrud & Zweibel 08)



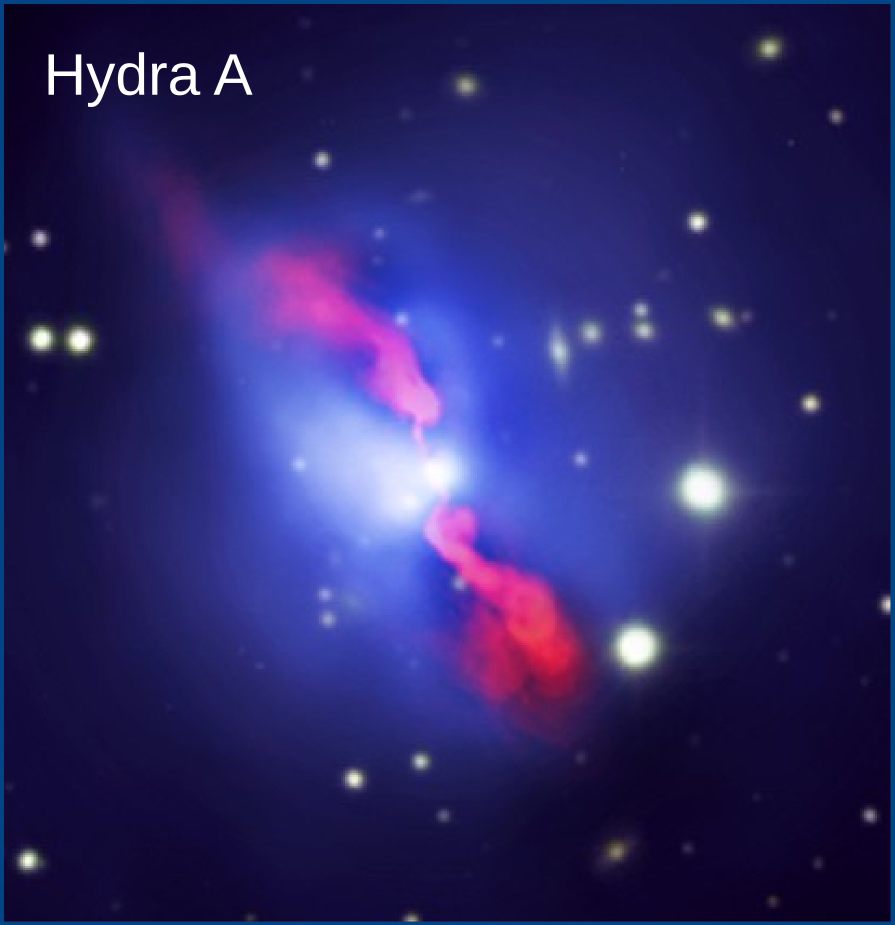


Love, J. J., 1999. Astronomy & Geophysics, 40, 6.14-6.19.

Dolag+ 06

AGN bubbles are magnetized

Might they supply the needed amplification?
(Hoyle 1969; Rees 1987; Daly & Loeb 1990)

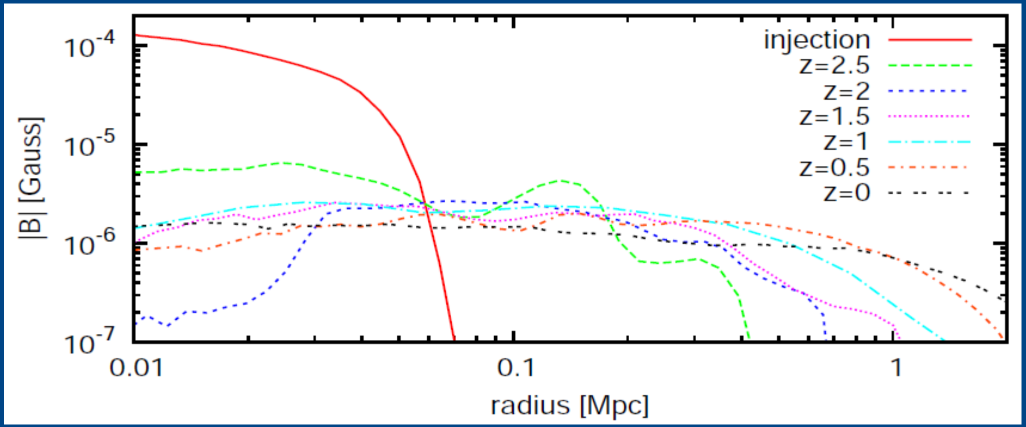


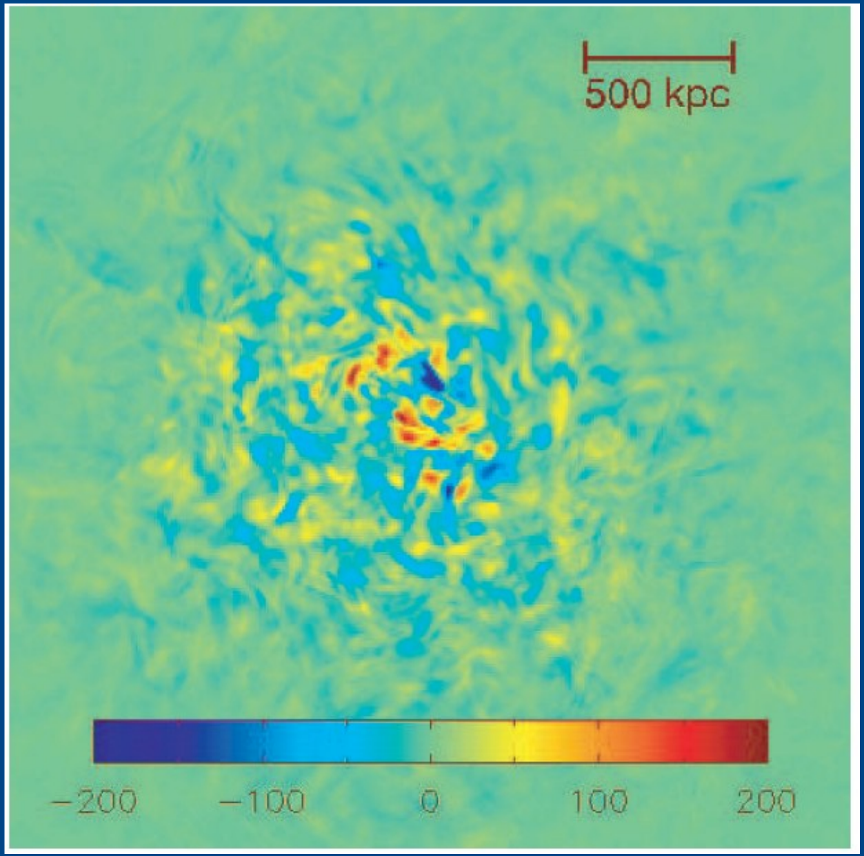
X-ray
Radio
Optical

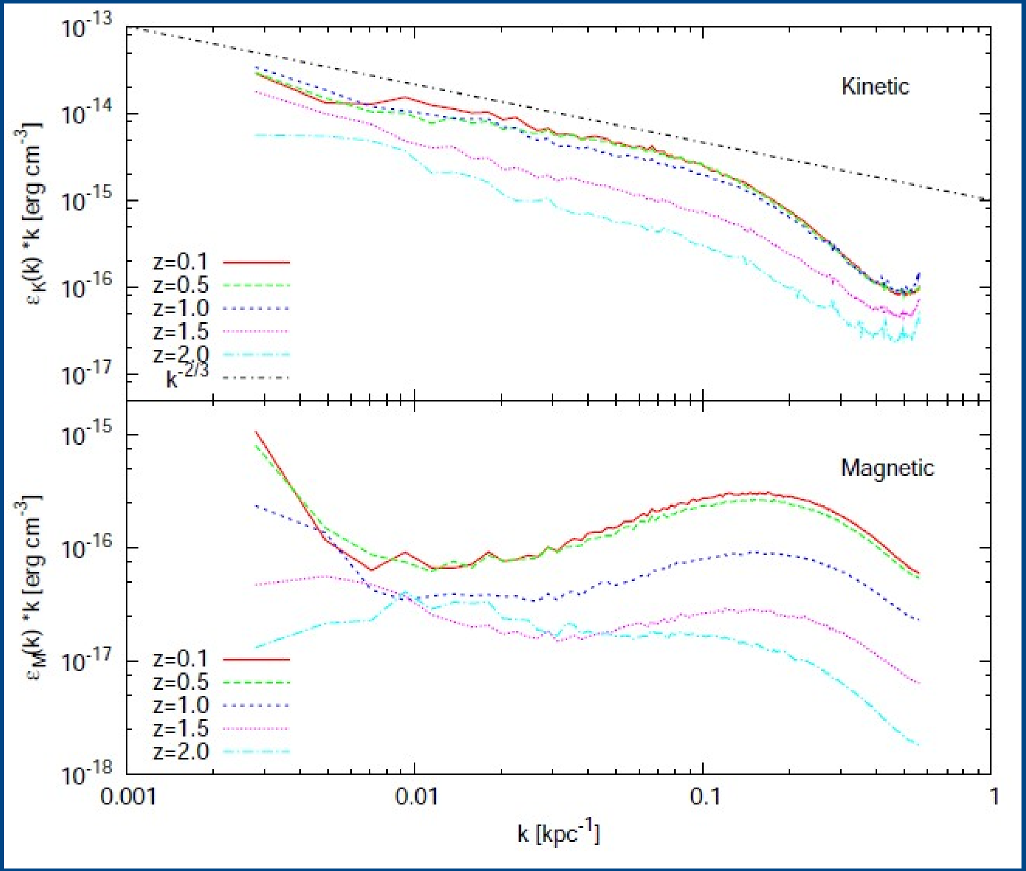
CXC/NRAO/CFHT

Xu+ 08, 09

- Single injection event
- Significant contribution from cluster-wide turbulent dynamo







Background cluster model and directly simulated physics

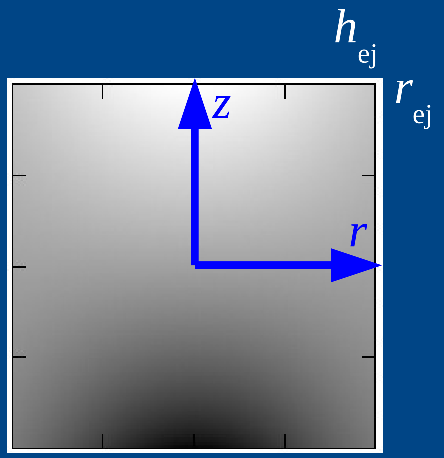
- FLASH 3.3 (Fryxell+ 00; Dubey+ 08)
  - MHD – unsplit CT Godunov (Lee+ 09)
  - Ideal gas EOS, $\gamma = 5/3$
  - Fixed NFW potential (Navarro+ 95)
  - Cooling with 1/3 solar metallicity (Sutherland & Dopita 93)
- Cluster
  - Total mass 1.5 x 10^{14} $M_\odot$
  - Concentration 5.53
  - Gas fraction 0.1, hydrostatic
  - Black hole mass 3 x 10^9 $M_\odot$
- Box
  - Size 2048 kpc
  - Poorest resolution 32 kpc
  - Best resolution 0.5 – 16 kpc within 80 kpc (jets)/160 kpc (bubbles) box

AGN subgrid models

- Accretion model

$$\dot{M}_{\rm bh} = \min\left[\alpha \dot{M}_{\rm Bondi}(M_{\rm bh}, \rho_{\rm grid}, c_{\rm s,grid}), \dot{M}_{\rm Edd}(M_{\rm bh})\right]$$

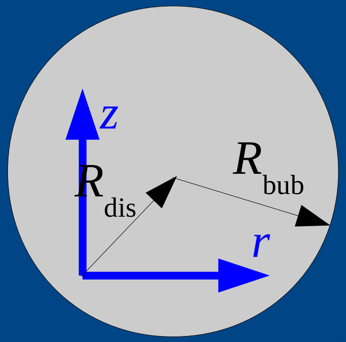
- Feedback model
  - Jets (Cattaneo & Teyssier 07)



$$\dot{M}_{\rm gas} = \eta \dot{M}_{\rm bh} |\Psi(\boldsymbol{x})|$$
$$\dot{\boldsymbol{P}}_{\rm gas} = \sqrt{2\epsilon_{\rm F}} \dot{M}_{\rm bh} c \Psi(\boldsymbol{x})$$
$$\dot{E}_{\rm gas} = \epsilon_{\rm F} \dot{M}_{\rm bh} c^2 (1-\eta) |\Psi(\boldsymbol{x})|$$

  - Bubbles (Sijacki+ 07)

$$\dot{E}_{\rm gas} = \epsilon_{\rm m} \epsilon_{\rm F} \Delta M_{\rm bh} c^2$$
$$R_{\rm bub} = R_0 \left(\frac{\dot{E} \Delta t}{E_0} \frac{\rho_0}{\rho} \right)^{1/5}$$

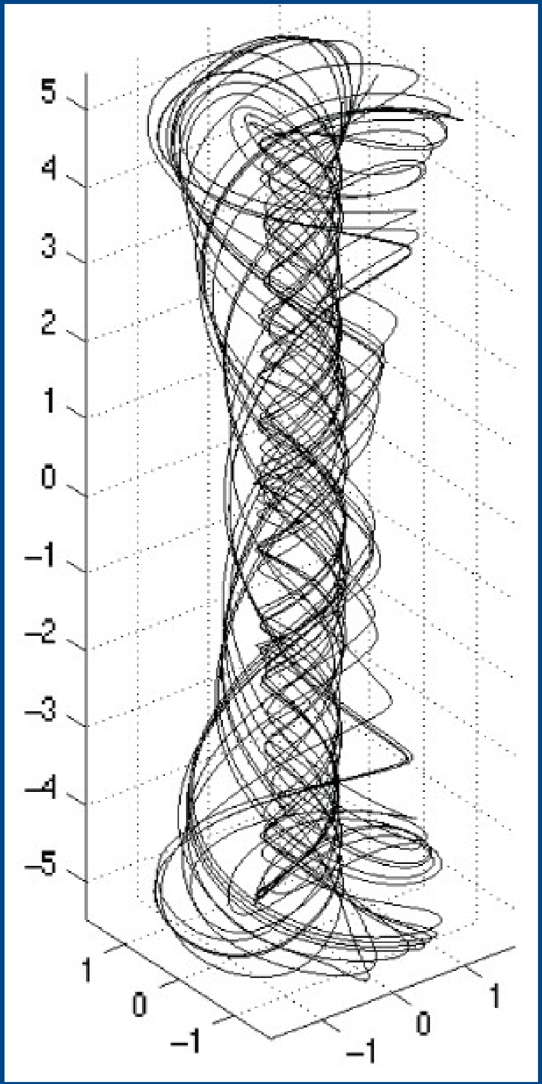


AGN subgrid models – injected magnetic field (Li+ 06)

$$B_r = 2B_0 z' r' \exp(-r'^2 - z'^2)$$
$$B_\phi = B_0 \alpha_B r' \exp(-r'^2 - z'^2)$$
$$B_z = 2B_0 (1 - r'^2) \exp(-r'^2 - z'^2)$$

$$r' \equiv \frac{\sqrt{x^2 + y^2}}{r_0}$$
$$z' \equiv \frac{z}{r_0}$$

$$r' = 0.5 \begin{cases} R_{\mathrm{ej}} & \text{jet} \\ R_{\mathrm{bub}} & \text{bubble} \end{cases}$$



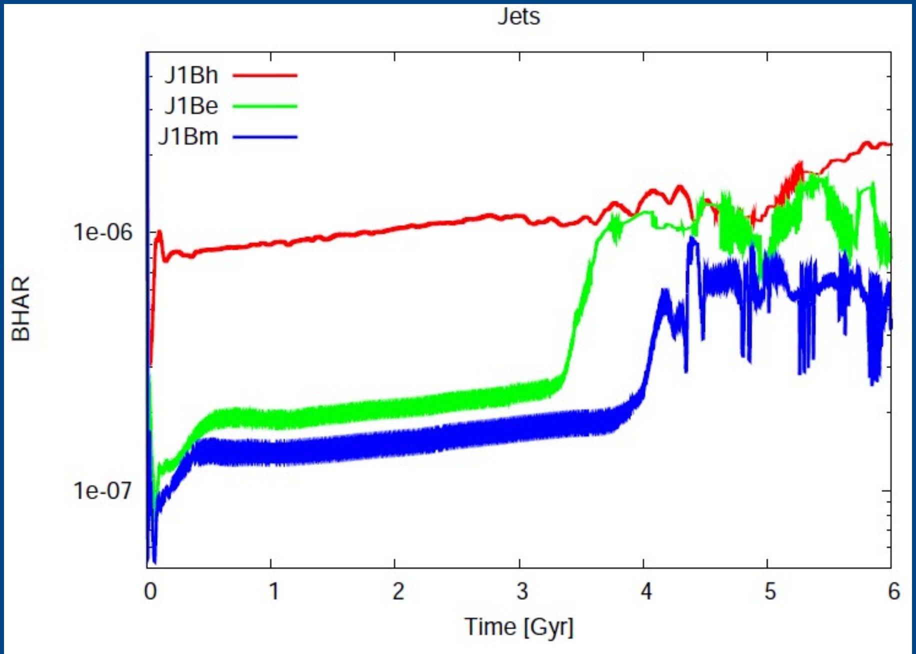
Parameter survey – jets

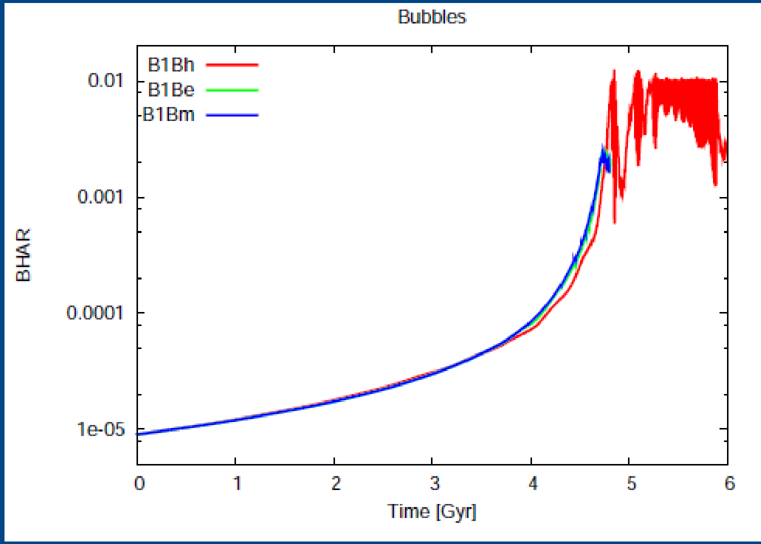
Designation	Δx	α	h_{ej}	r_{ej}	R_{acc}	R_{dep}	Outflow types
			Varying Resolution				
J1A	0.50	1	2.0	2.5	2.0	2.0	m
J1B	1.00	-	-	-	-	-	h,e,m
			Scaling Jet Size with Resolution				
J2A	-	-	4.0	5.0	-	-	m
J2B	2.00	-	8.0	10.0	-	-	m
J2C	4.00	-	16.0	20.0	-	-	m
J2D	-	-	8.0	10.0	-	-	m
			Varying Alpha				
J3A	0.50	100	2.0	2.5	-	-	m
J3B	1.00	-	-	-	-	-	m
J3C	-	300	-	-	-	-	m
			Varying Accretion and Depletion Radii				
J4A	-	1	-	-	1.0	1.0	m
J4B	-	-	-	-	4.0	4.0	m
J4C	-	-	-	-	2.0	0.0	m

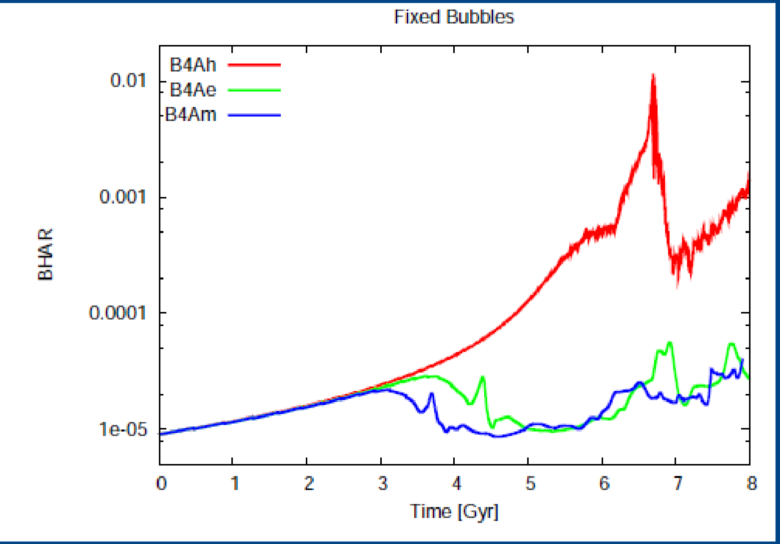
Parameter survey – bubbles

Designation	Δx	α	$R_{\rm dis}/R_{\rm bub}$	Outflow types
Varying Resolution				
B1A	0.50	1	1.0	m
B1B	1.00	-	-	h,e,m
B1C	2.00	-	-	m
B1D	4.00	-	-	m
B1E	8.00	-	-	m
Varying Alpha				
B2A	2.00	100	-	m
B2B	-	300	-	m
Scaling Alpha with Resolution				
B3A	0.50	50	-	m
B3B	4.00	300	-	m
Fixing Bubble Position				
B4A	1.00	1	0.0	h,e,m

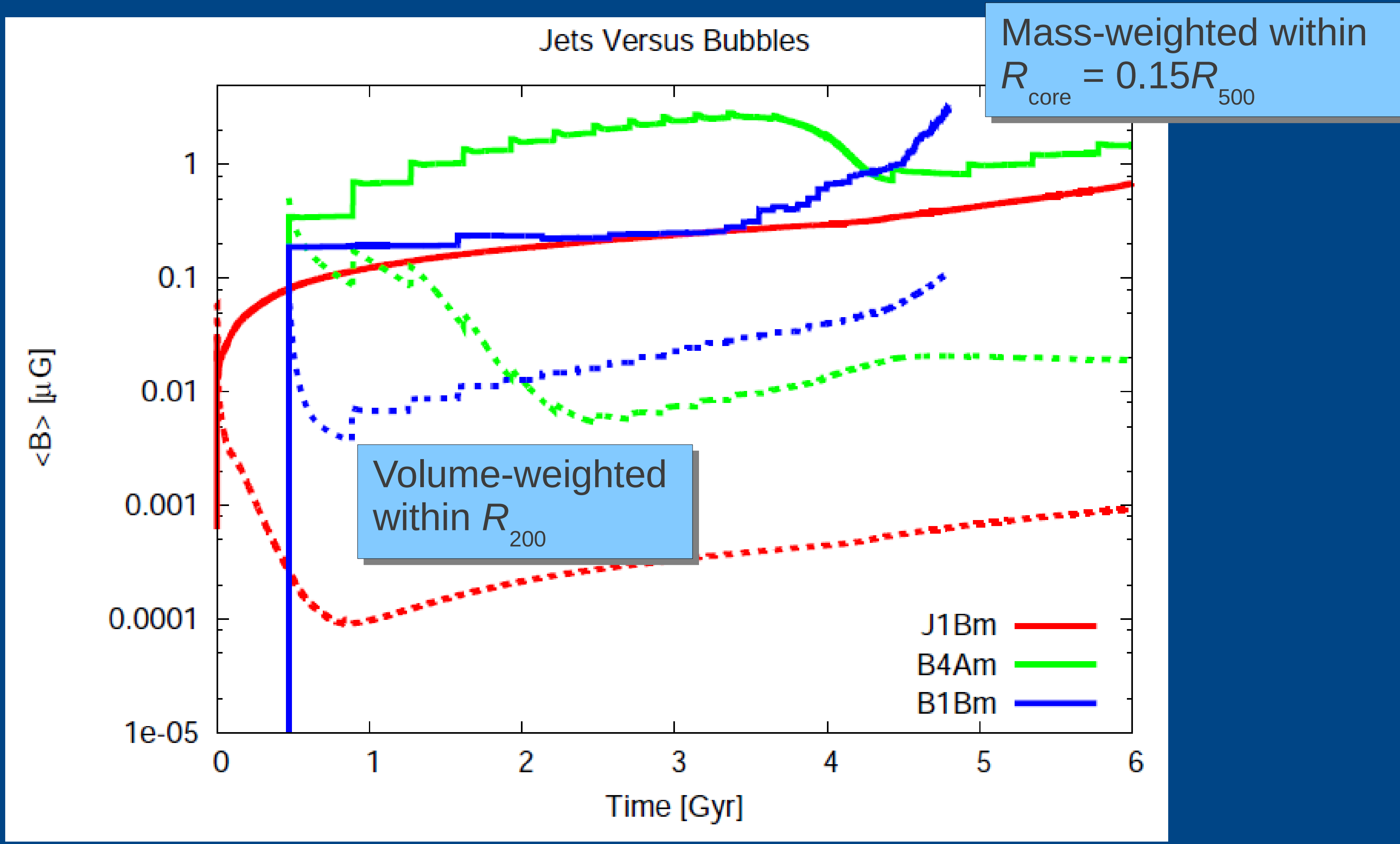
Black hole accretion rate (BHAR)



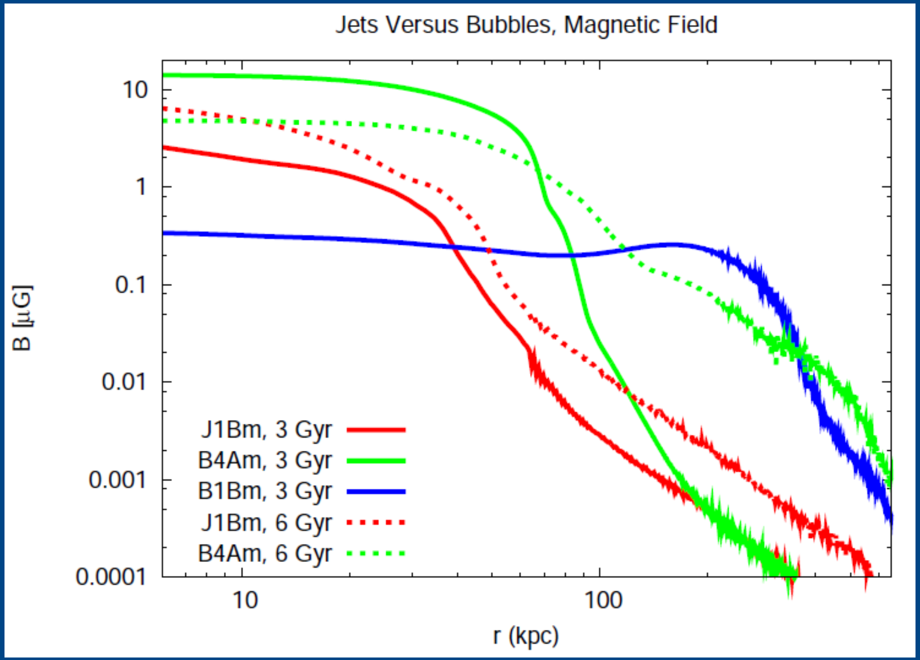


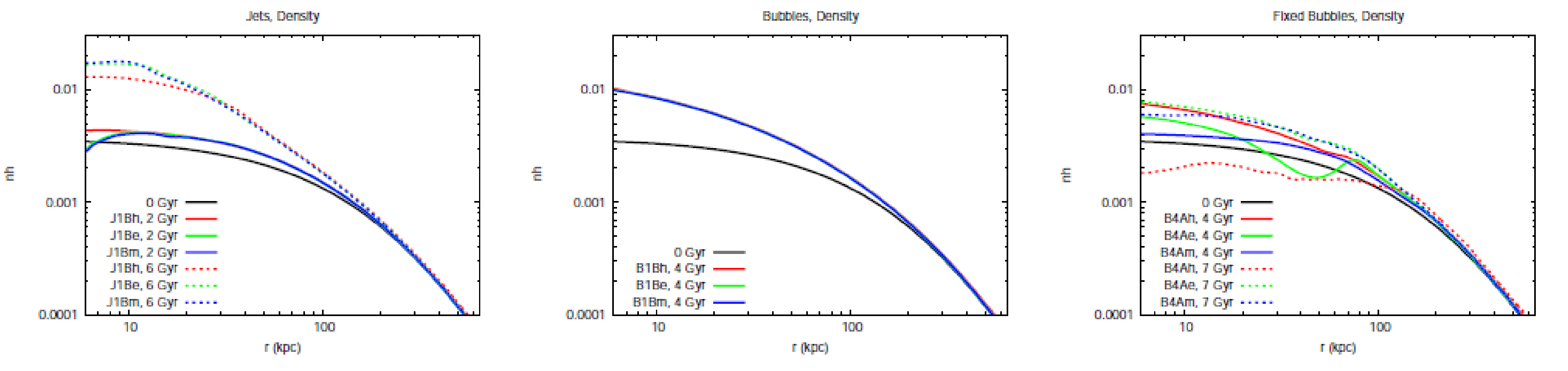


Magnetic field strength

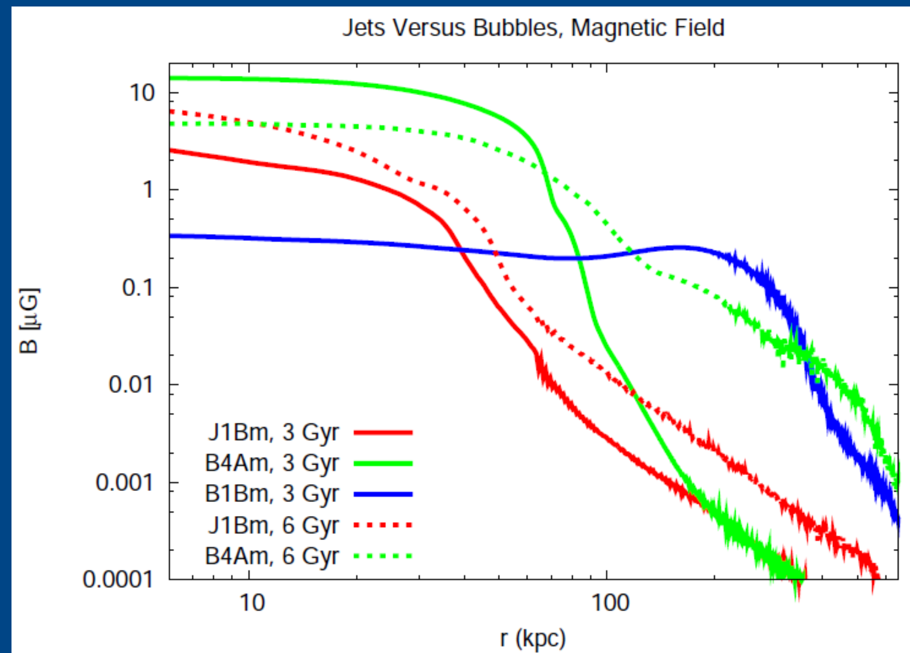


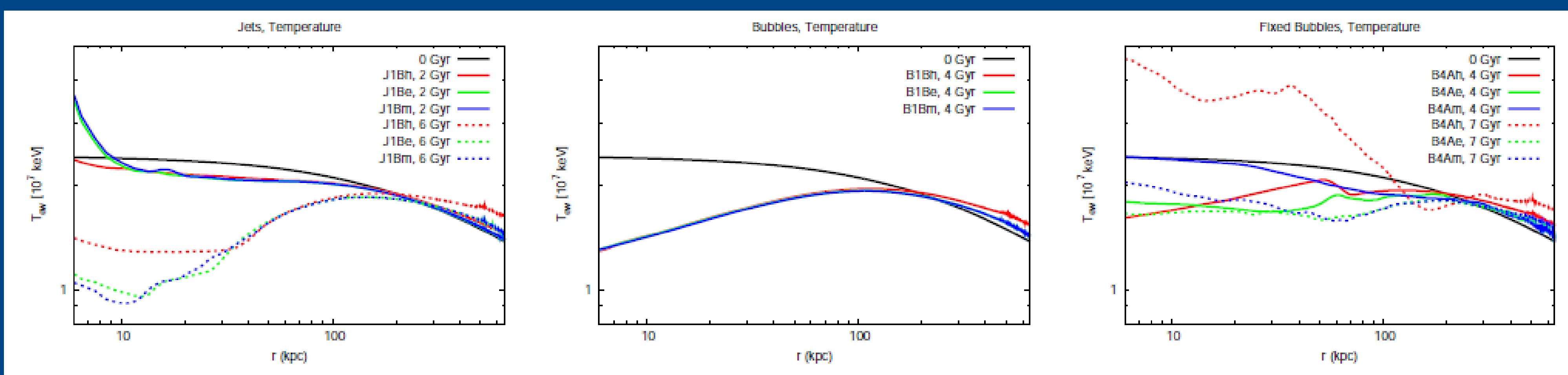
Magnetic field and density



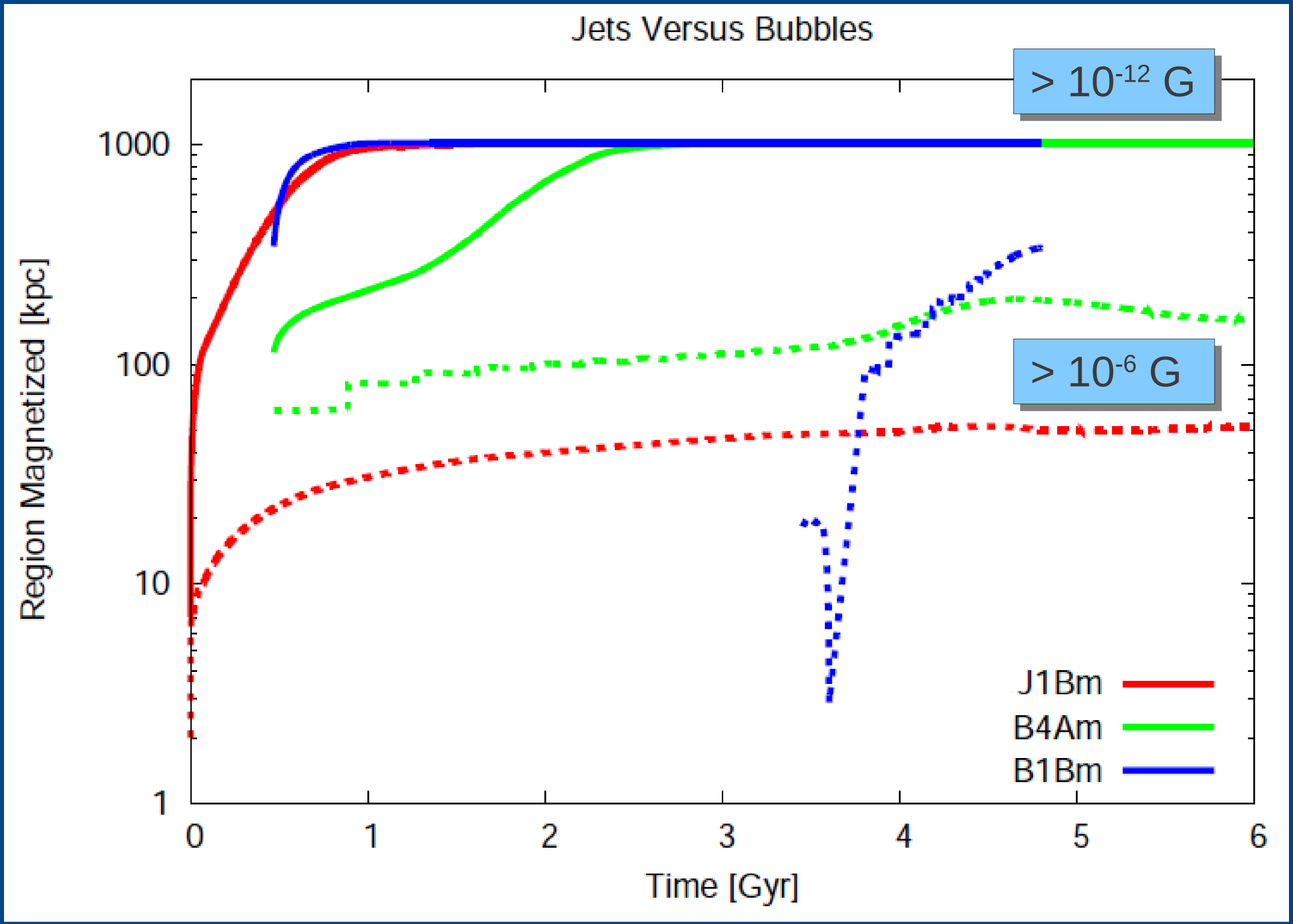


Magnetic field and temperature

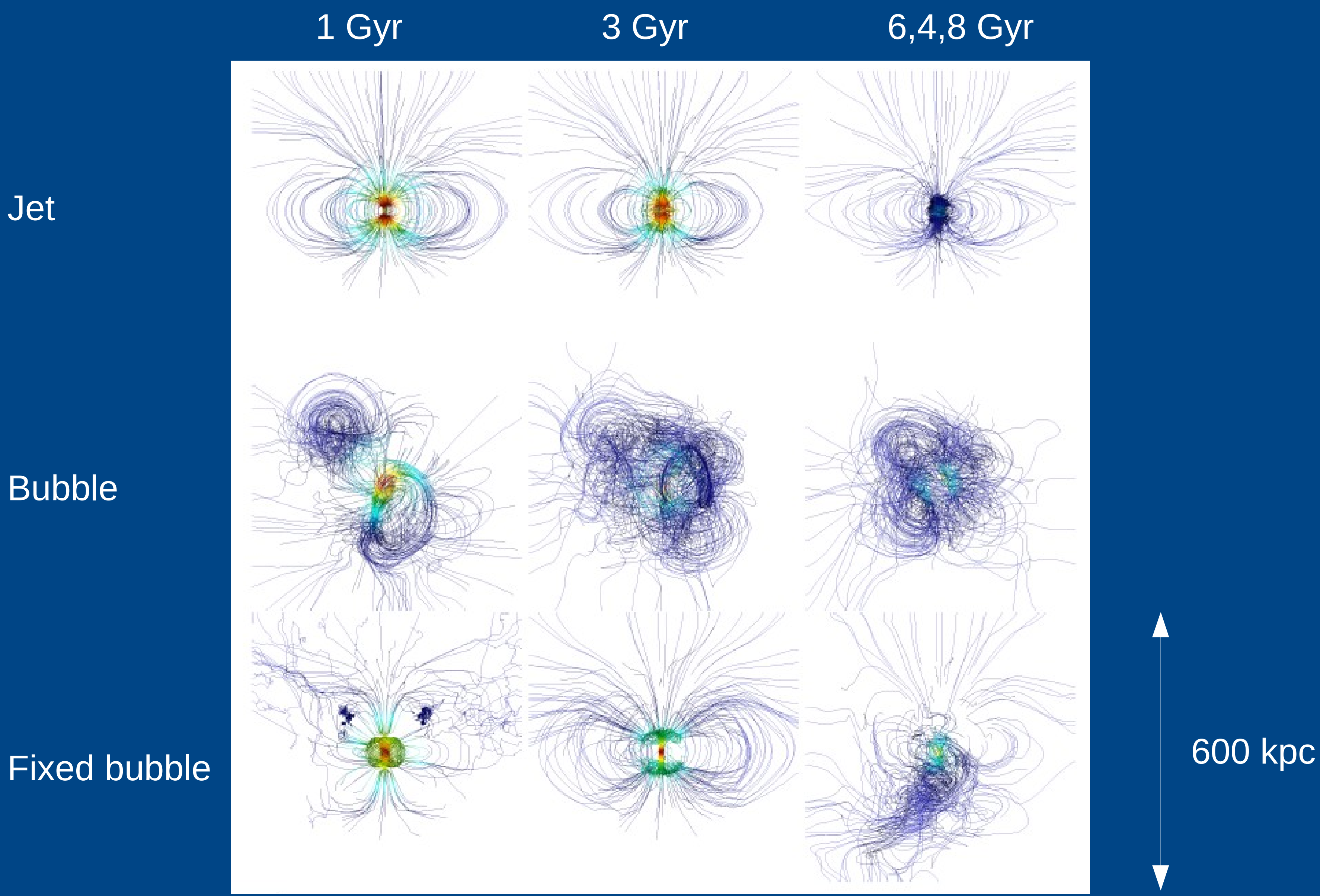




Size of region magnetized



Magnetic field structure

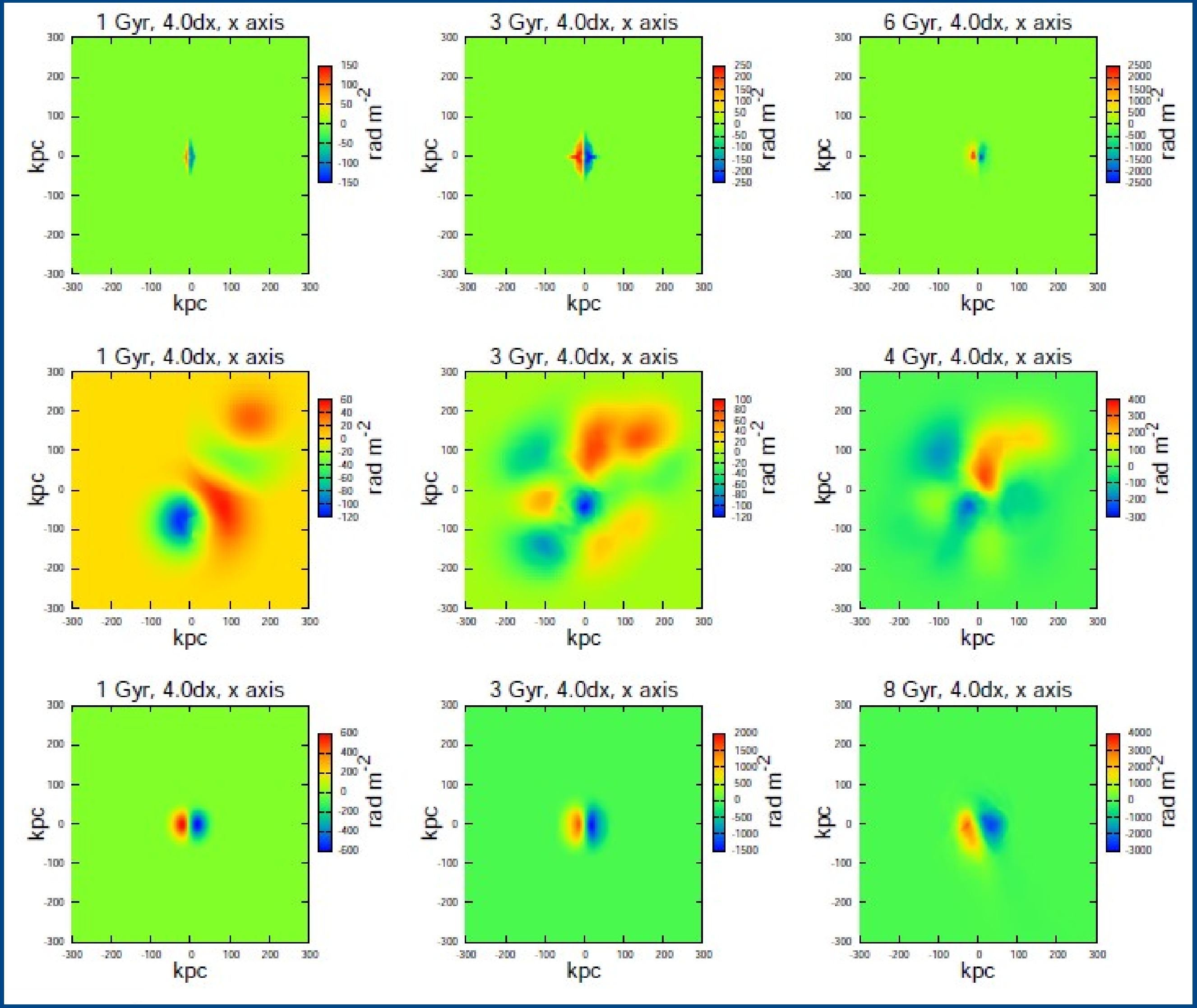


Magnetic field structure – RM maps

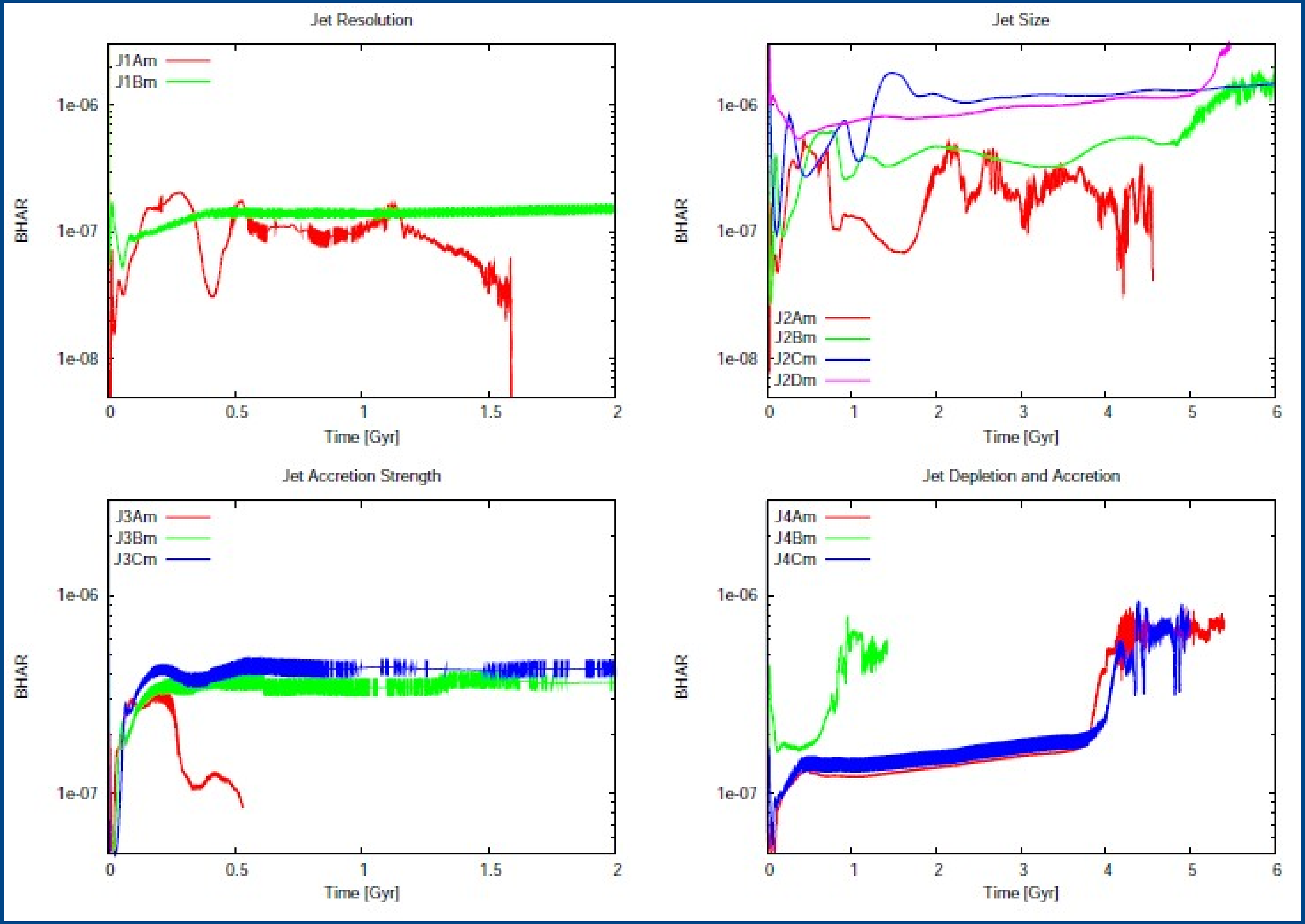
Jet

Bubble

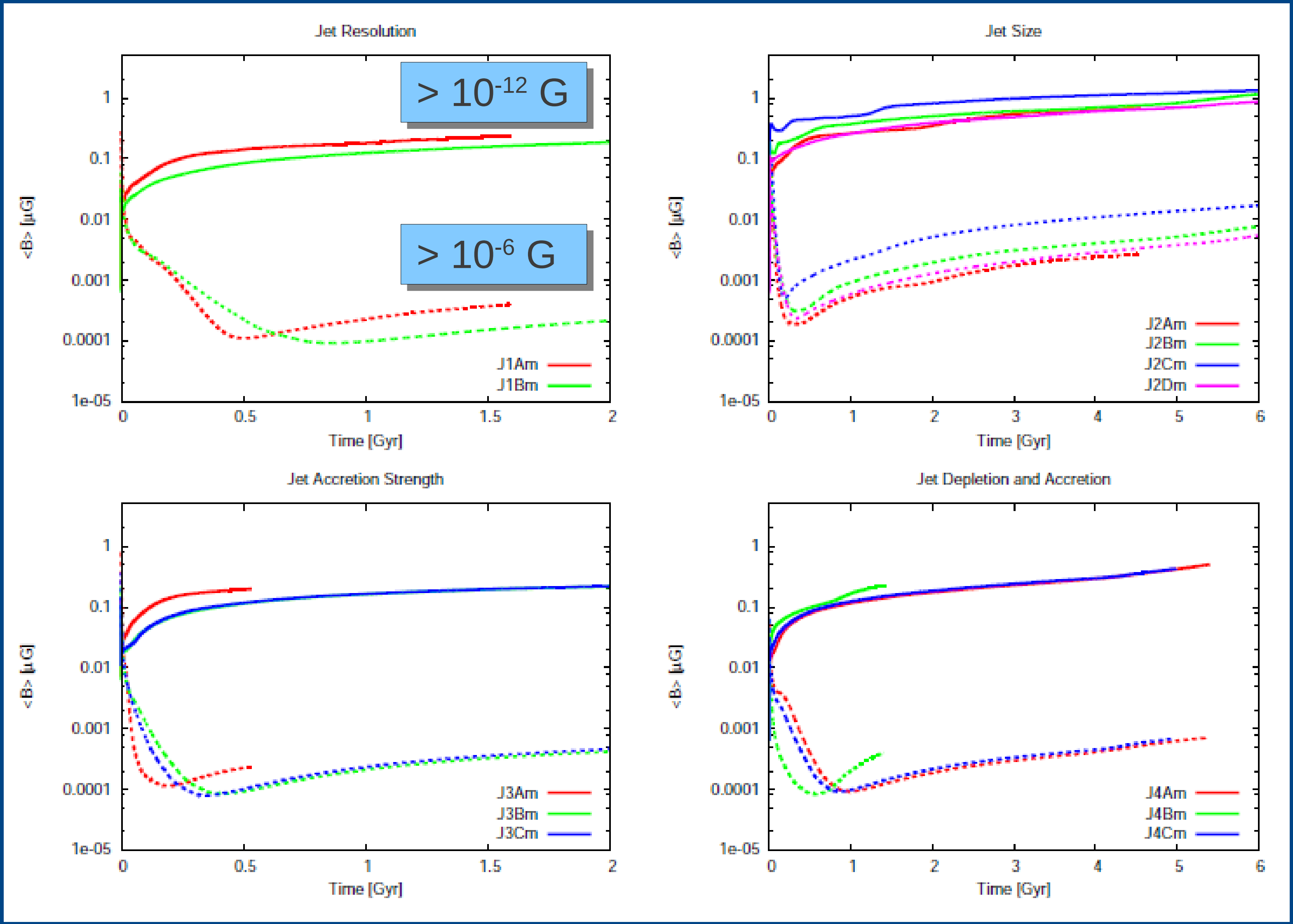
Fixed bubble



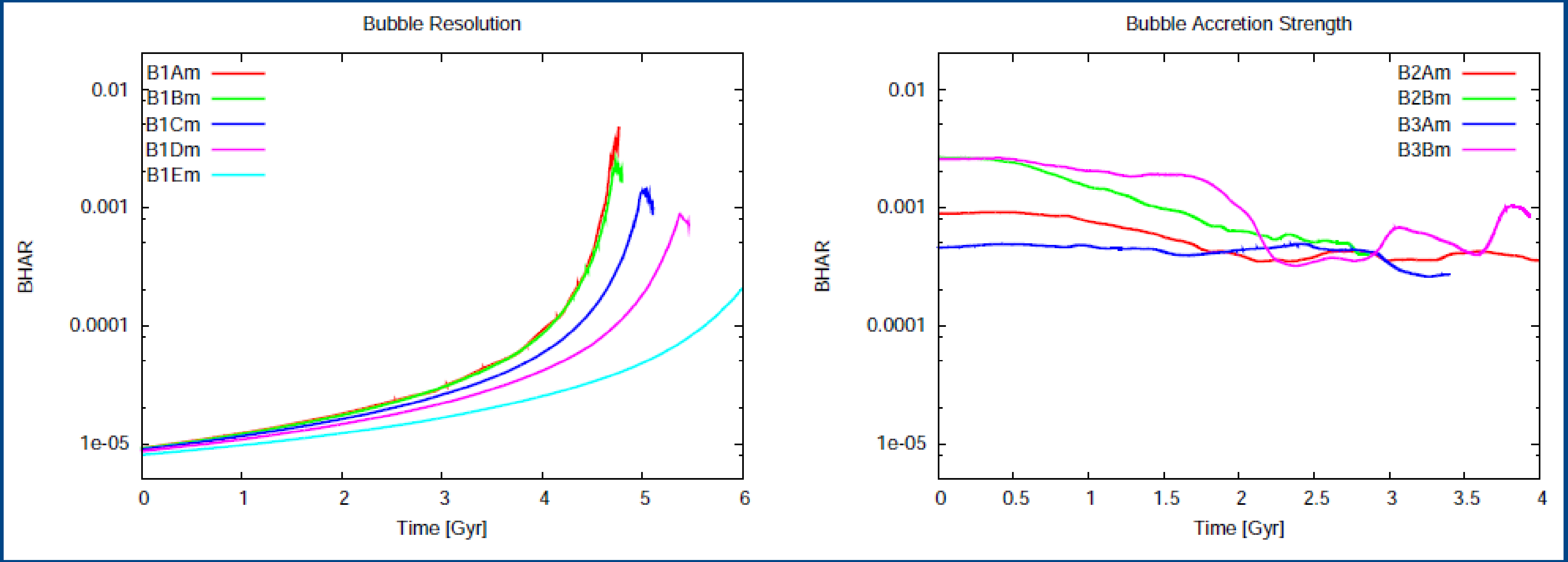
Parameter study – jets – BHAR



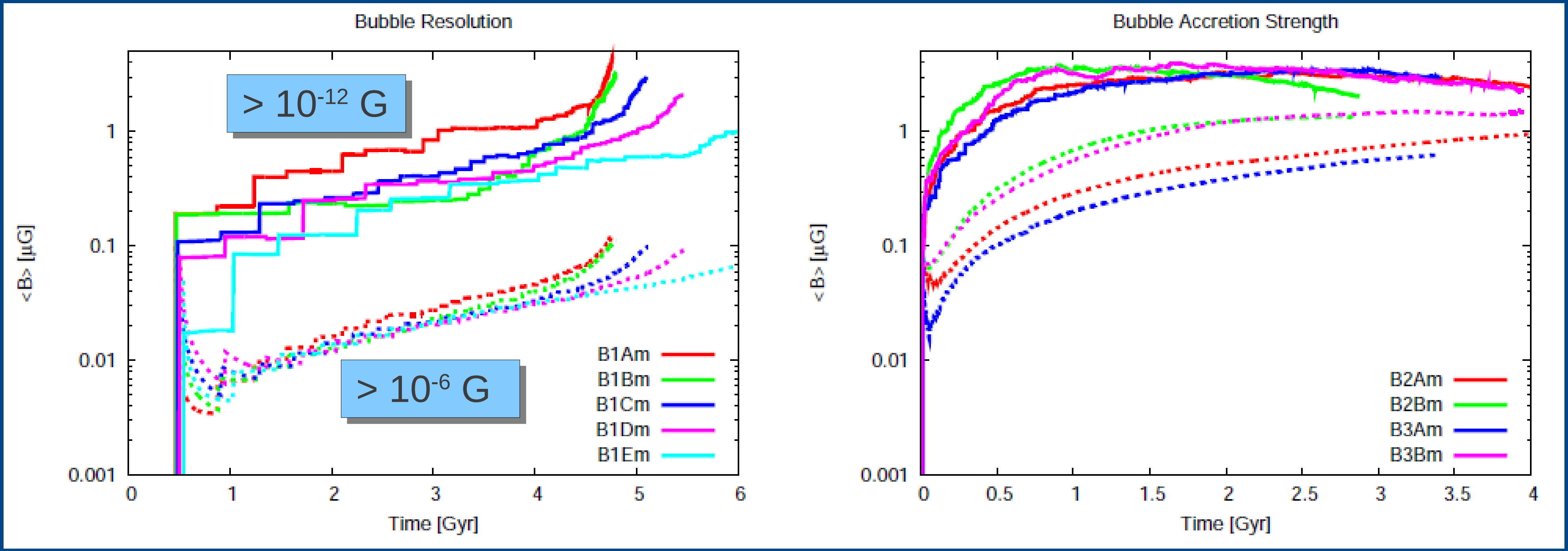
Parameter study – jets – <B>



Parameter study – bubbles – BHAR



Parameter study – bubbles – <B>



Conclusions

- AGN can magnetize the ICM through injected field and/or induced turbulence – reproducing strength, extent, and scale dependence
- Difference between equipartition and magnetically dominated feedback is slight
- Strength and structure of field, and effect on BHAR, sensitive to choice of AGN subgrid model
- Outcomes in “cosmological” clusters likely depend on specific merger histories – need cosmological simulations to investigate