Cold Gas and AGN Feedback In Galaxy Clusters

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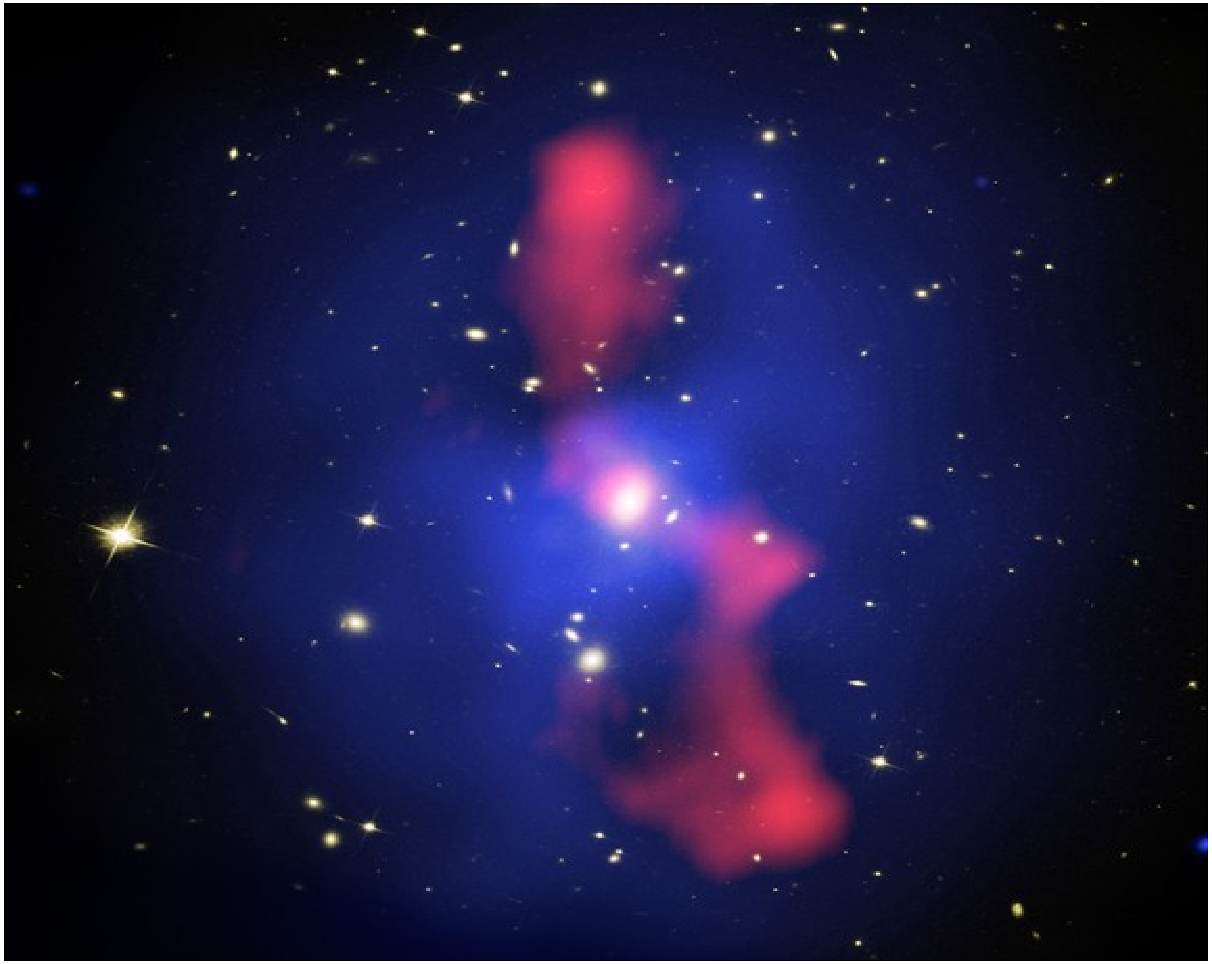
Introduction



MS0735.6+7421;
McNamara & Nulsen,
2007, ARAA

How AGN heating can keep pace with cooling that increases rapidly with increasing core density? → Not completely clear.

Feedback Cycle

Dense core is highly susceptible to condensation

↓

Formation of multiphase medium

↓

In-fall and accretion of cold gas clumps

↓

AGN outbursts

↓

Heating of the cluster cores

↓

Accretion rate low

↓

Low jet power

↓

Cooling starts again

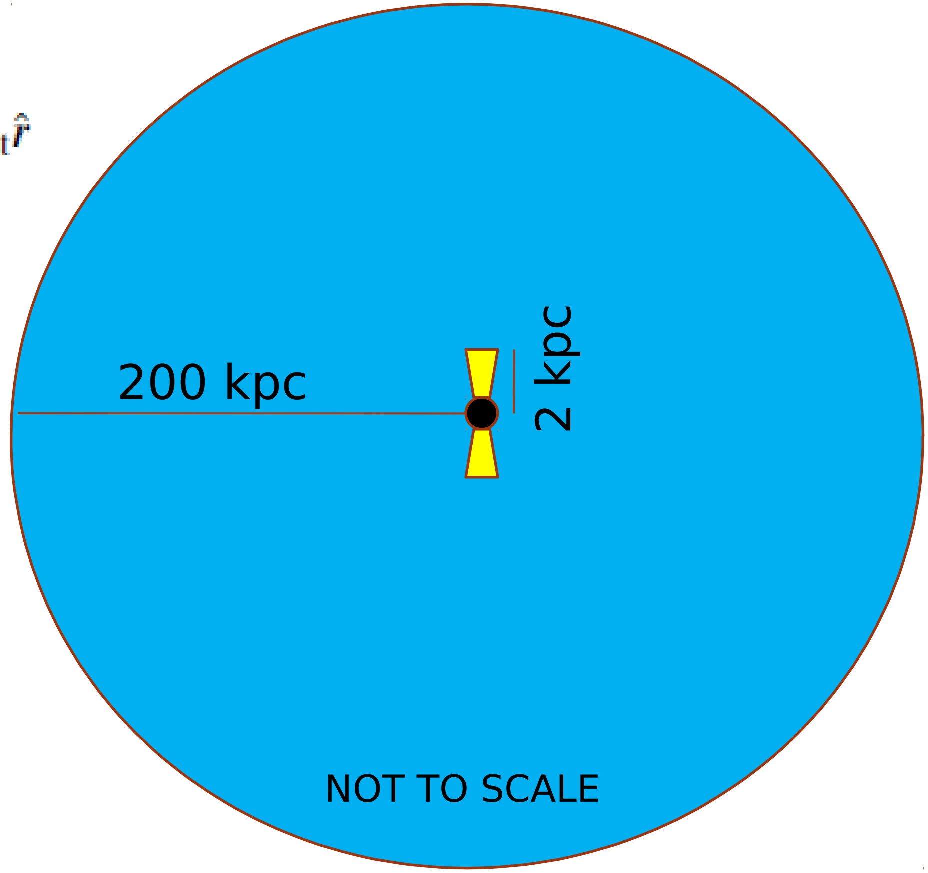
Numerical Setup

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = S_\rho$$

$$\frac{\partial \rho v}{\partial t} + \nabla . (\rho v \otimes v) = -\nabla p - \rho \nabla \Phi + S_\rho v_{\mathrm{jet}} \hat{r}$$

$$e \frac{d}{dt} \ln(p/\rho^{\gamma}) = -n_e n_i \Lambda(T)$$

S_ρ → source term

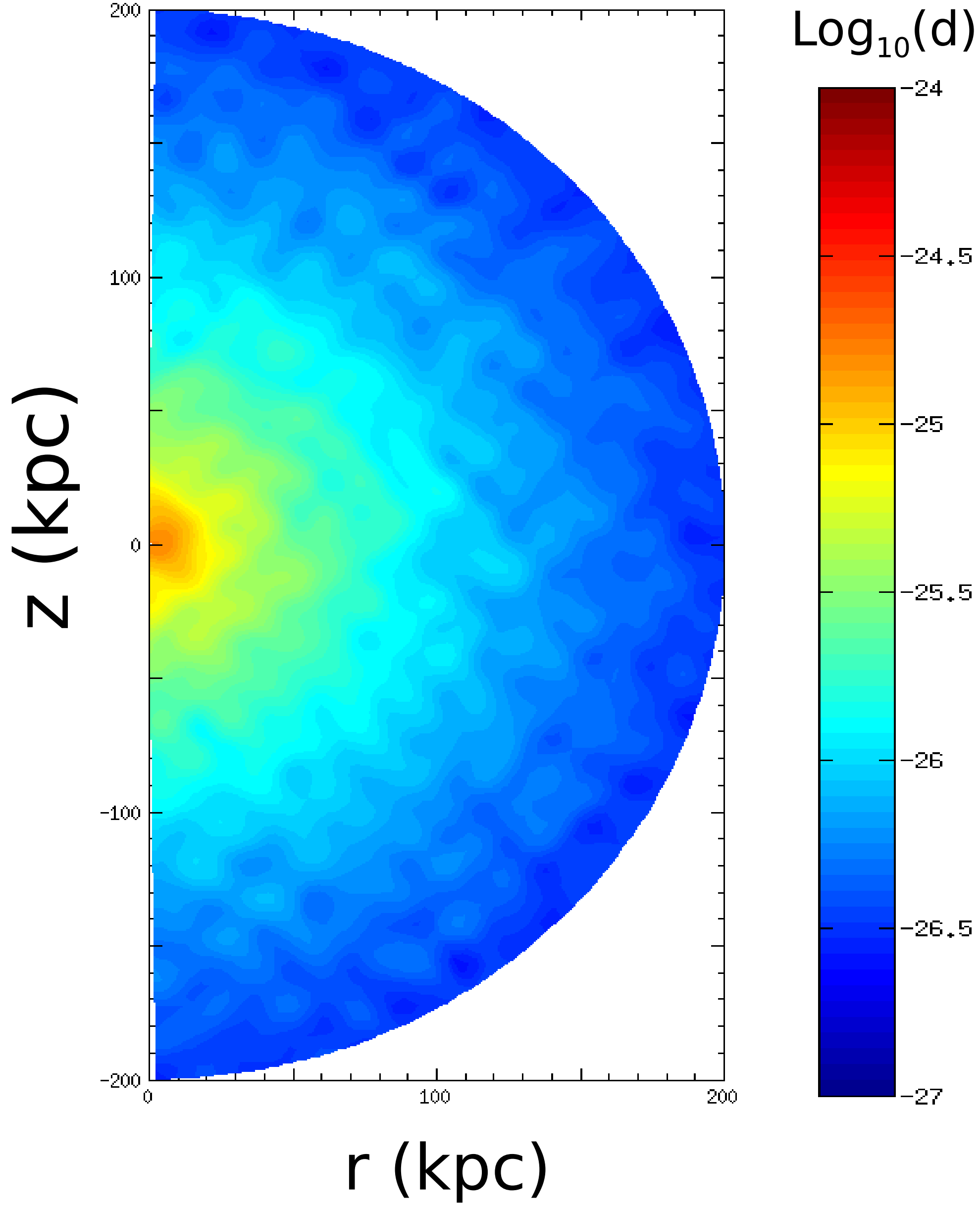


Jet mass loading factor

$$\dot{M}_{\mathrm{jet}} v_{\mathrm{jet}}^2 = \epsilon \dot{M}_{\mathrm{acc}} c^2$$

where, ε → accretion efficiency; v_{jet} = 0.1 c.

Initial Setup



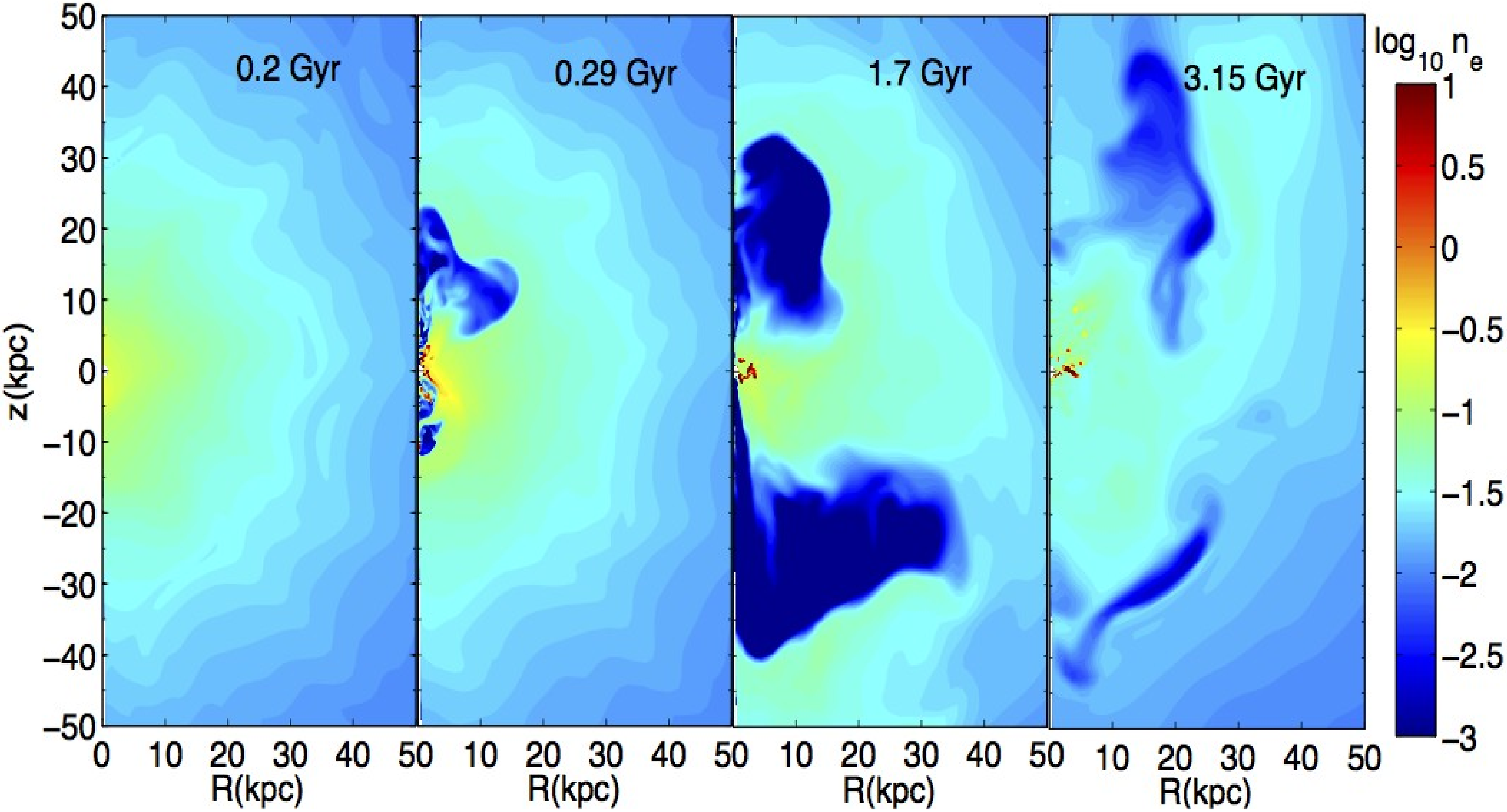
Fiducial 3D run:

$\varepsilon = 6 \times 10^{-5}$

Resolution at inner radii

~ few 10s of pc

Jets, Bubbles and Multiphase Gas



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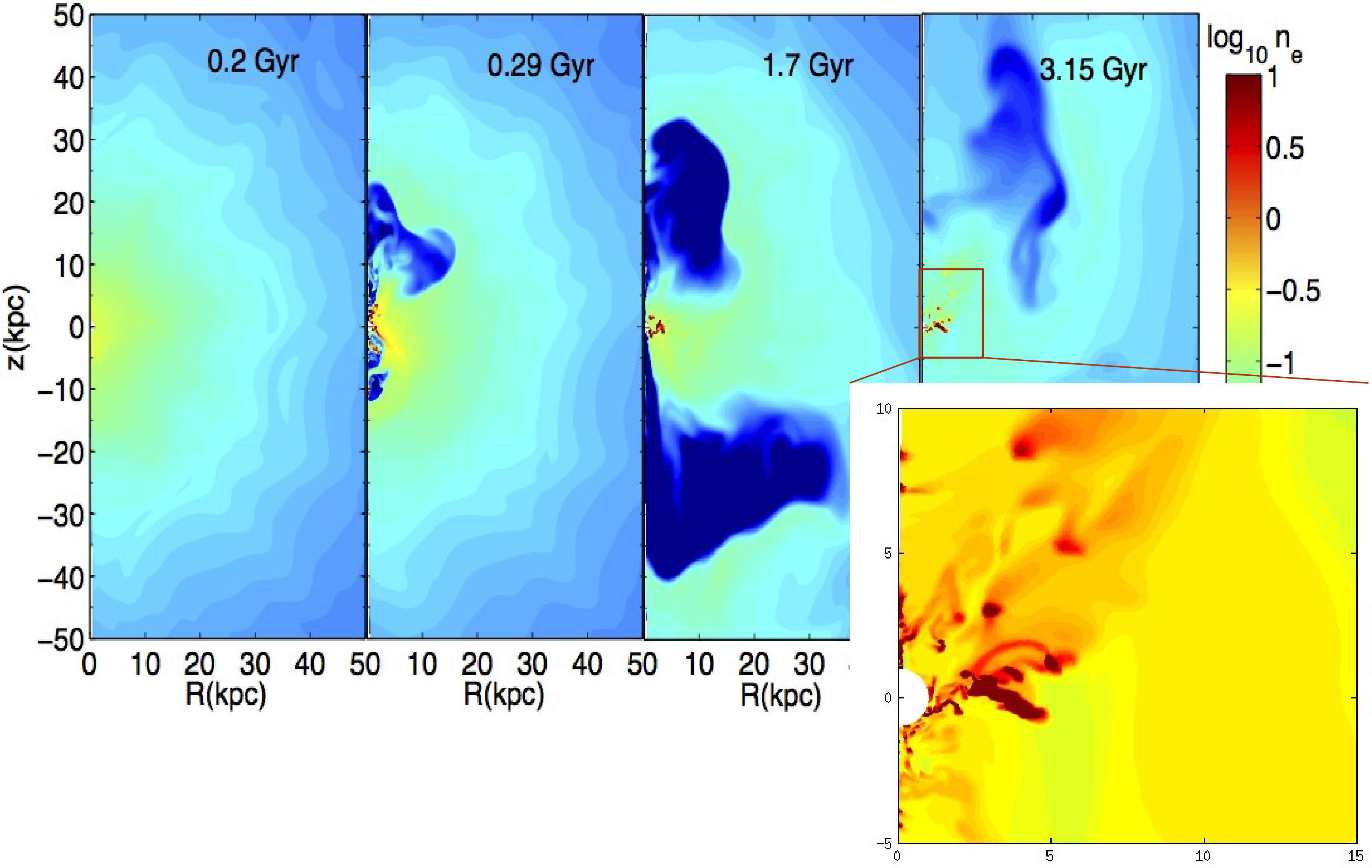

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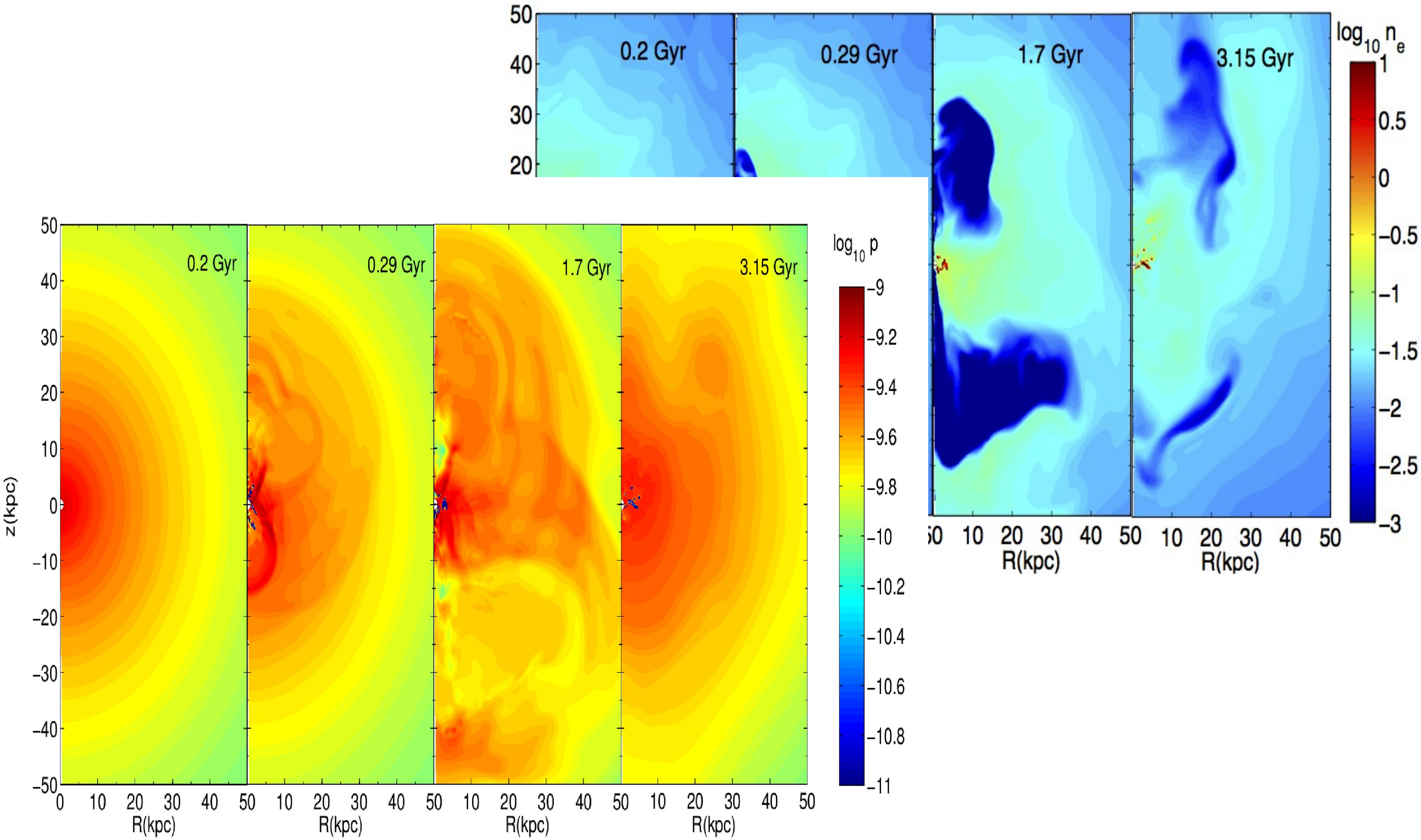

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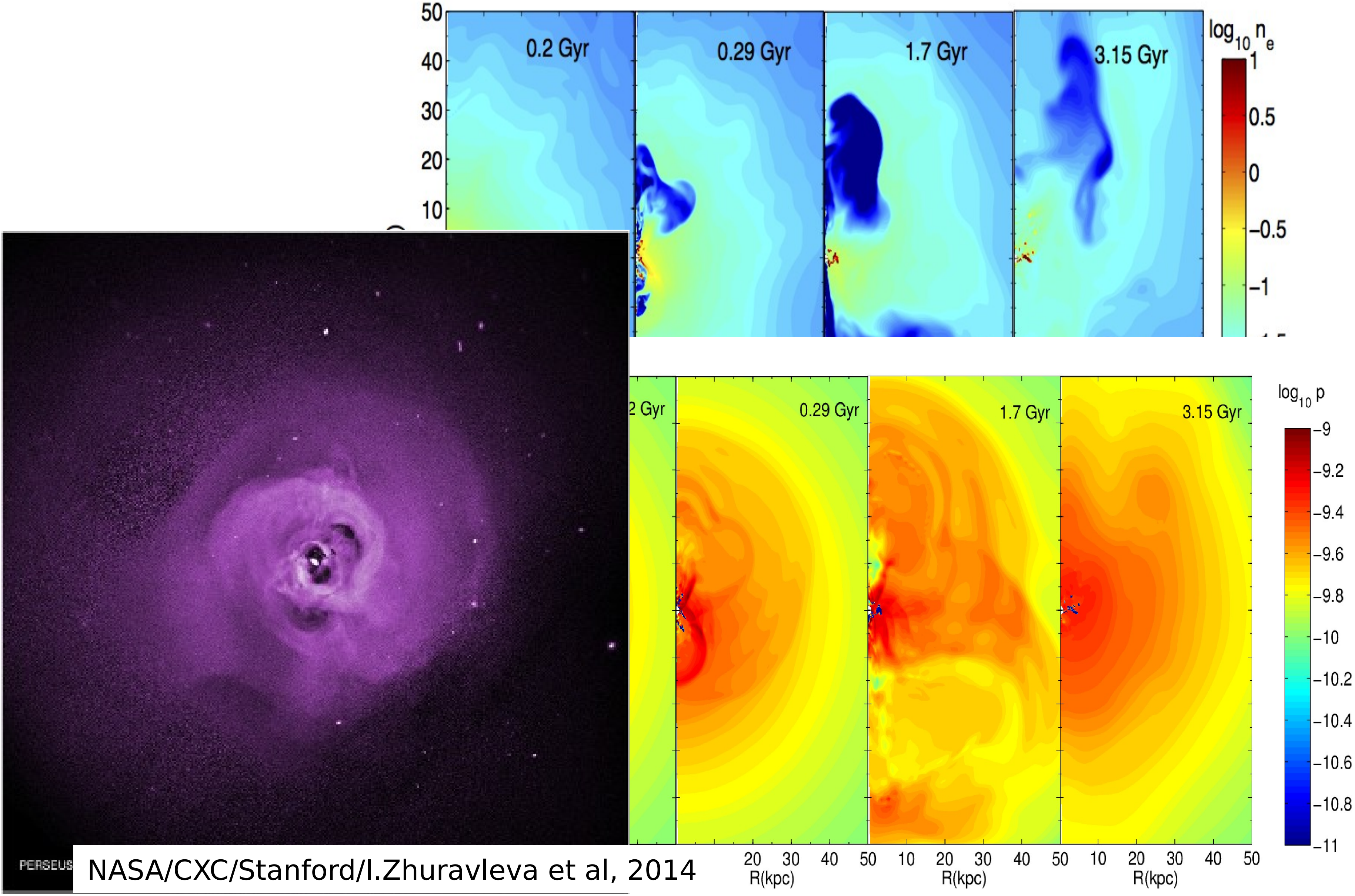
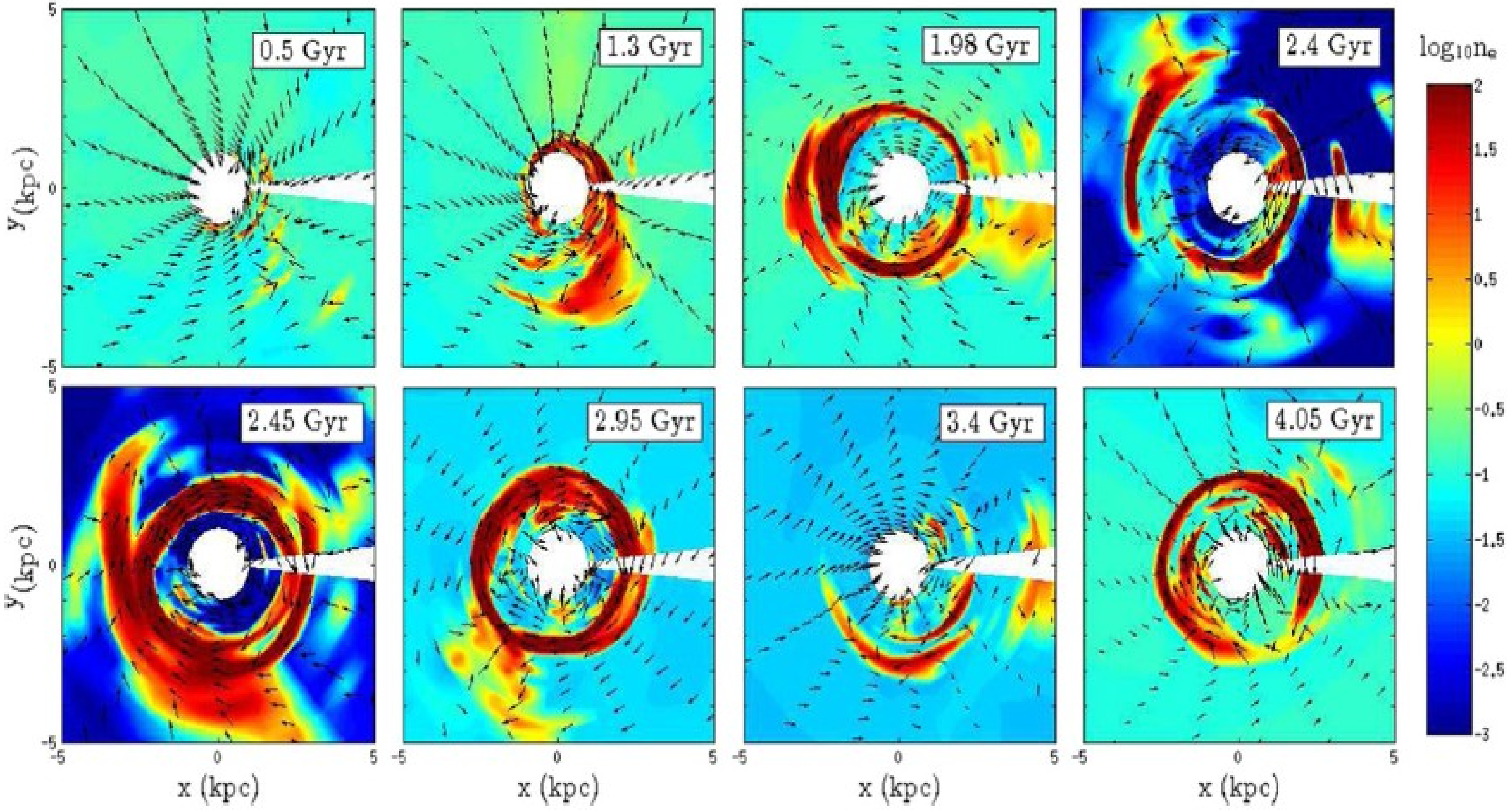


NASA/CXC/Stanford/I.Zhuravleva et al, 2014

The Cold Torus



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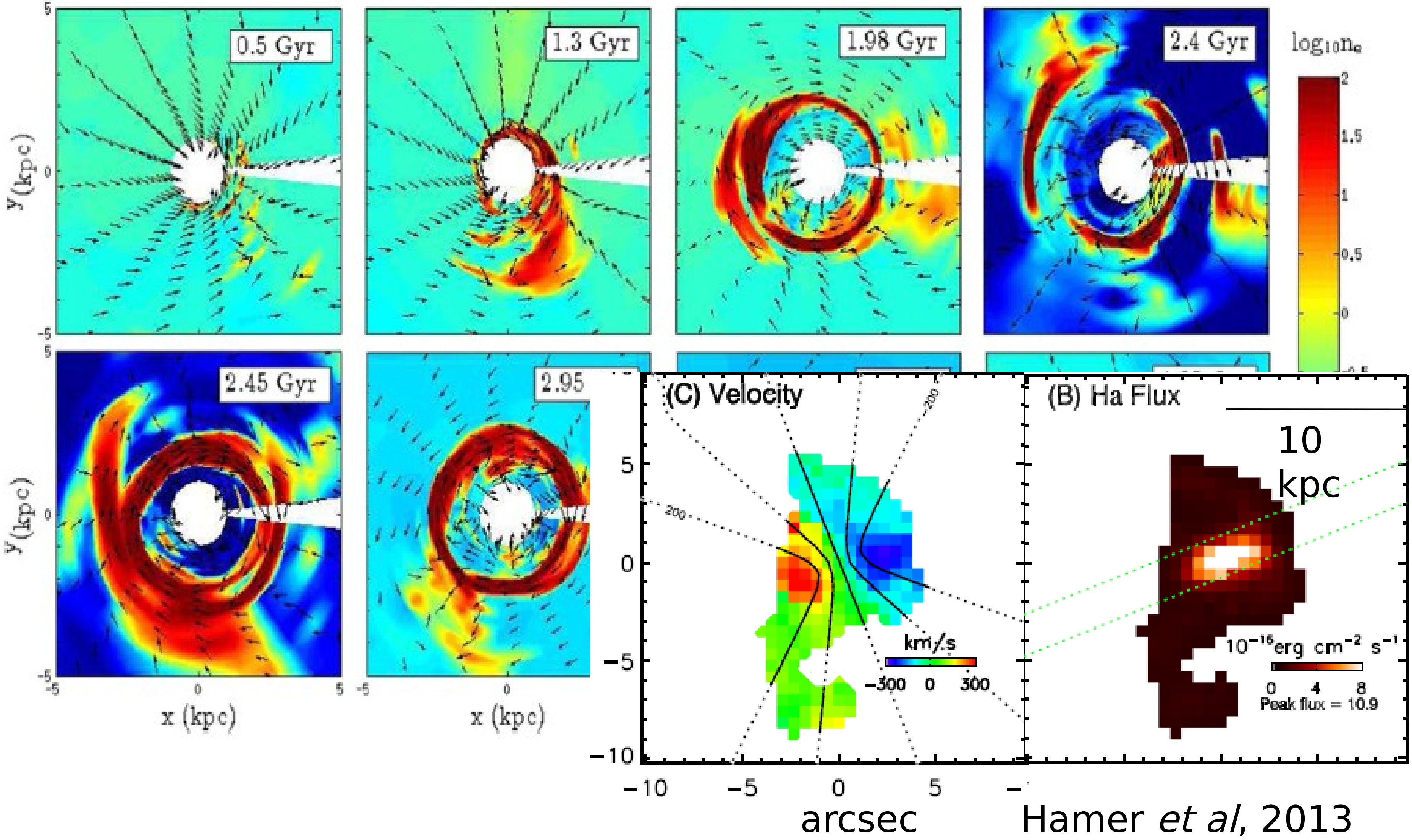
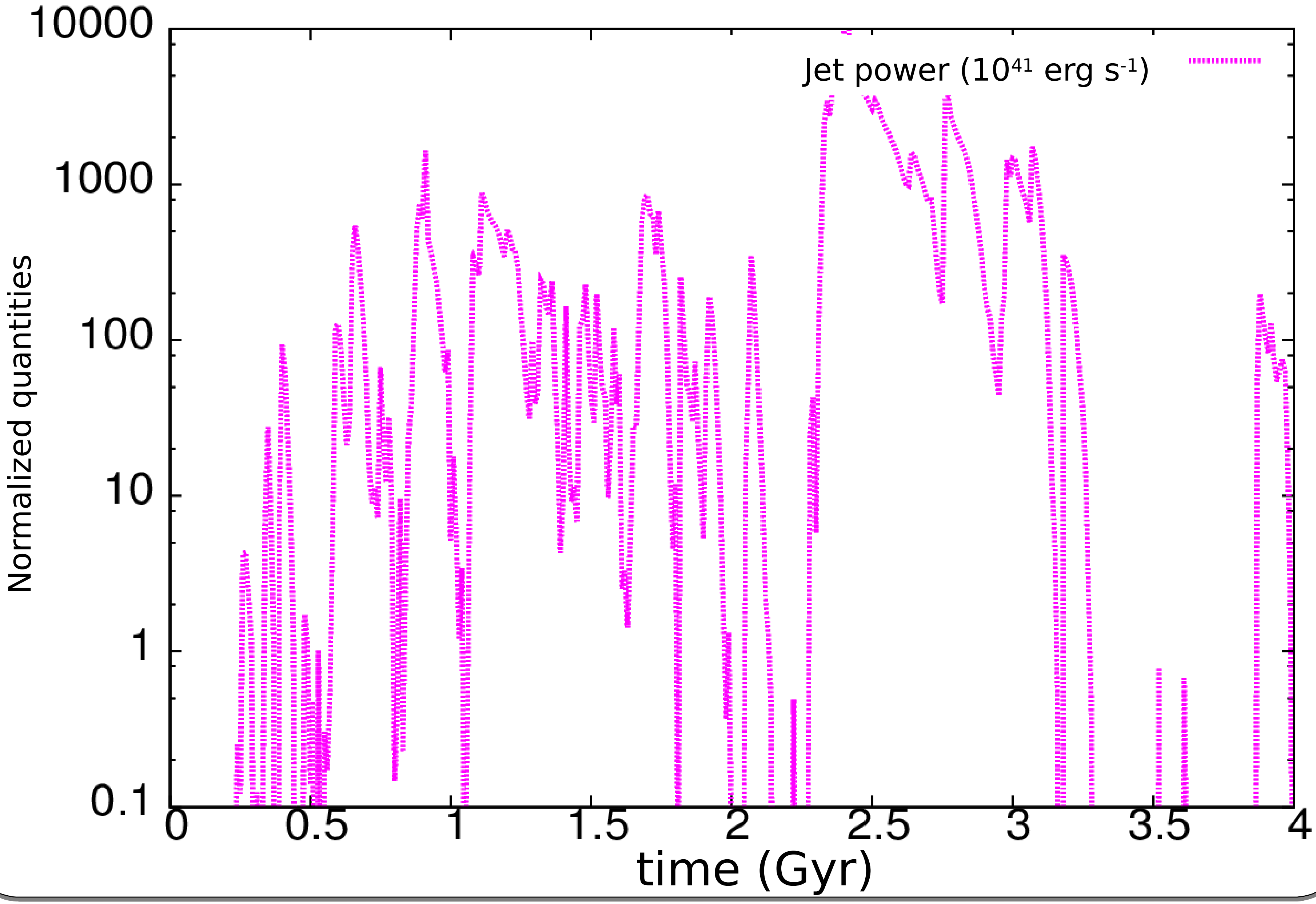


Hamer *et al*, 2013

AGN Jets as source of fast outflows



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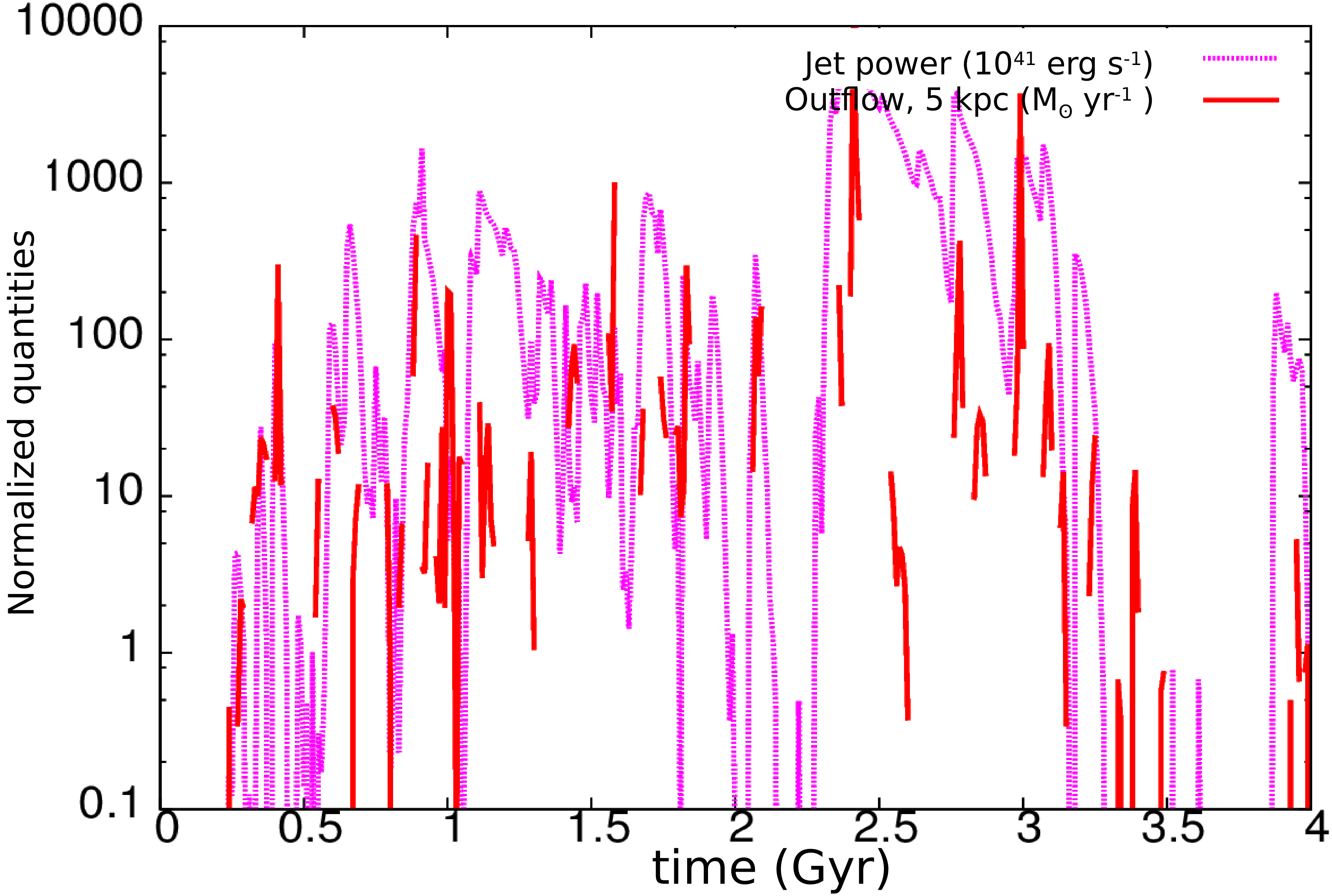

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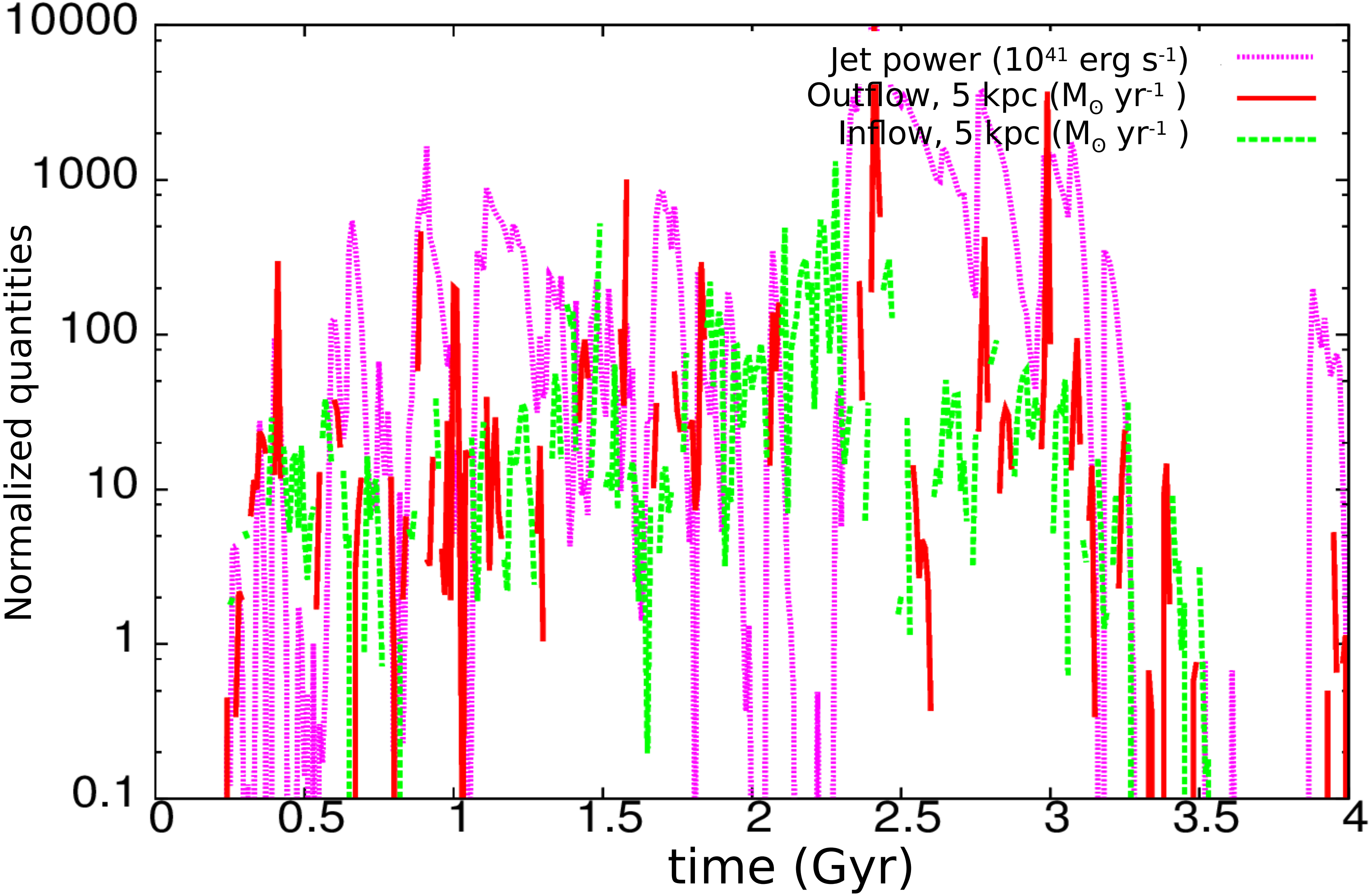

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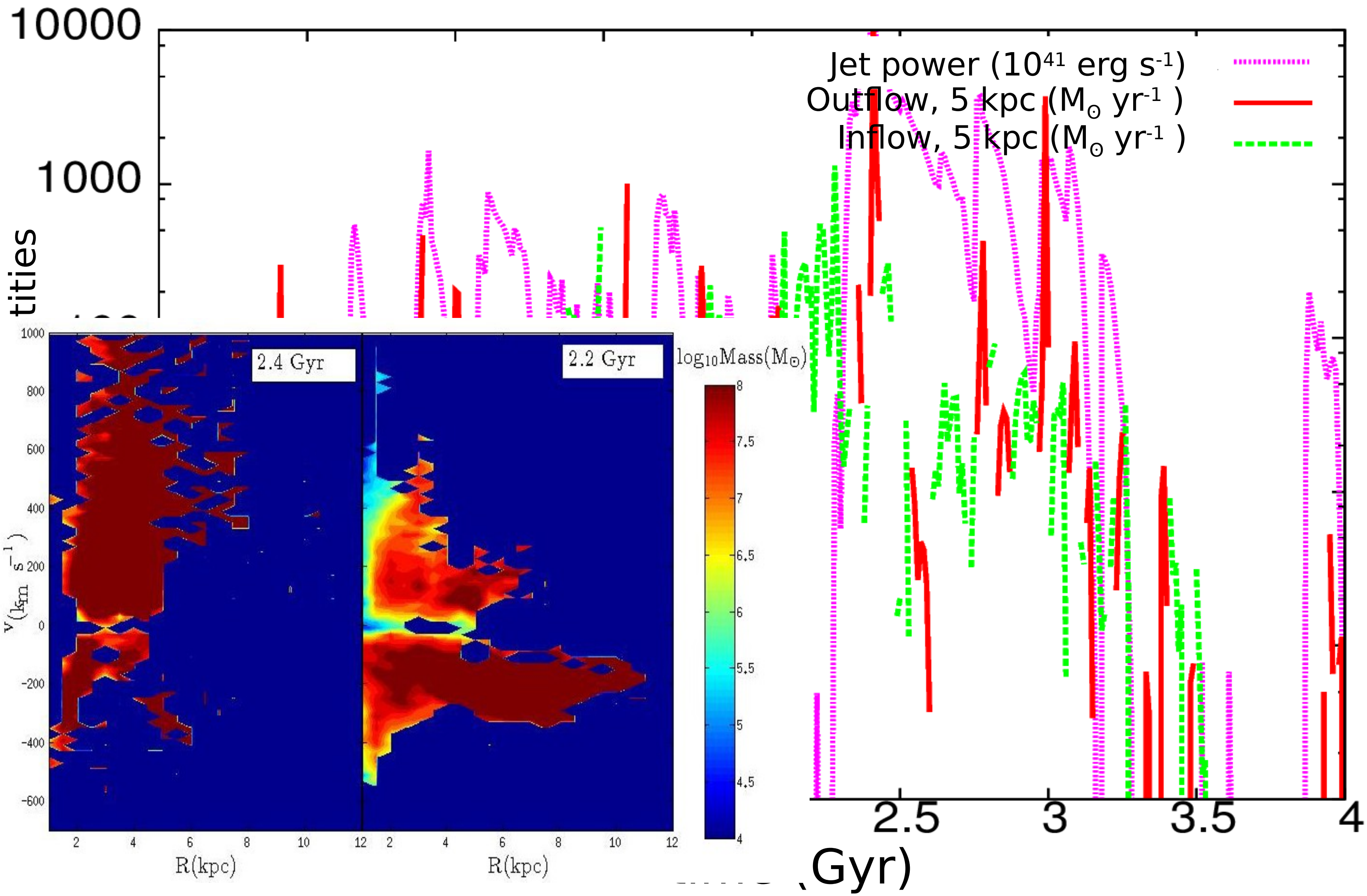

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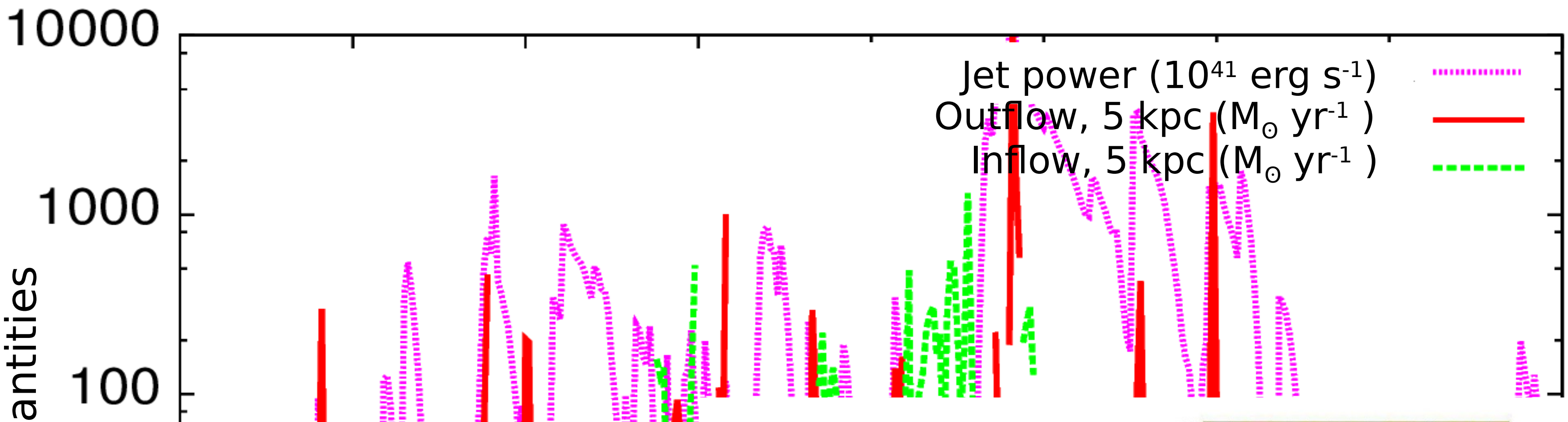

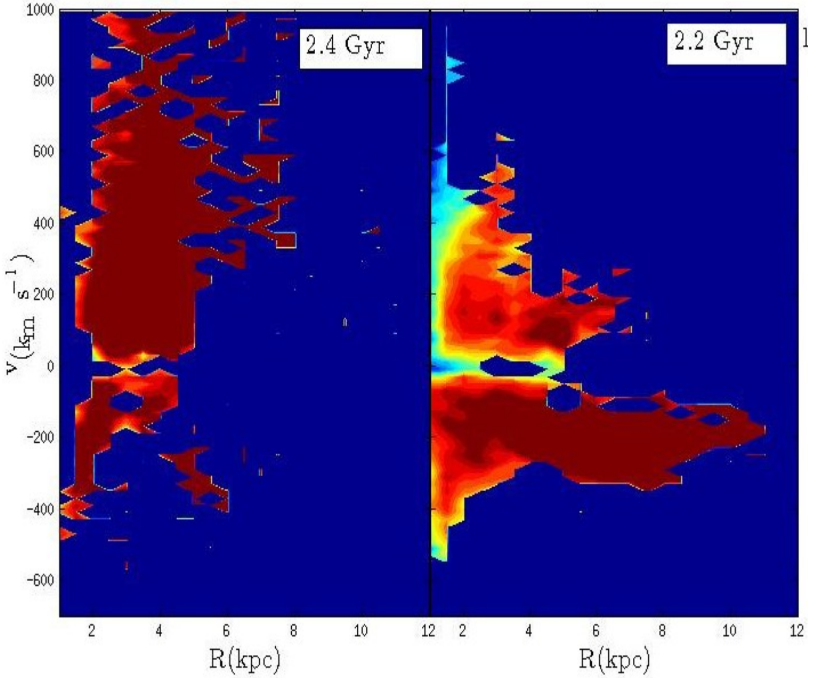

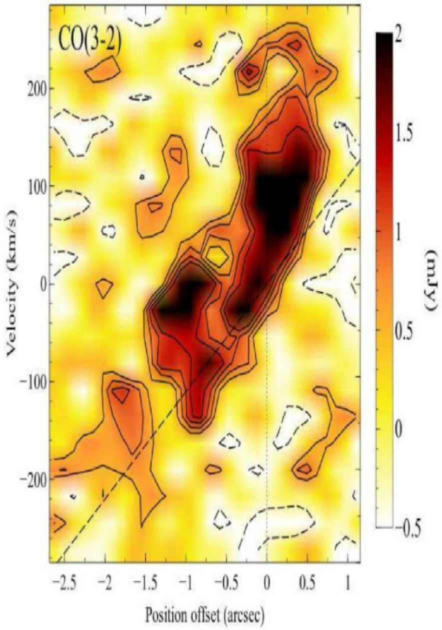

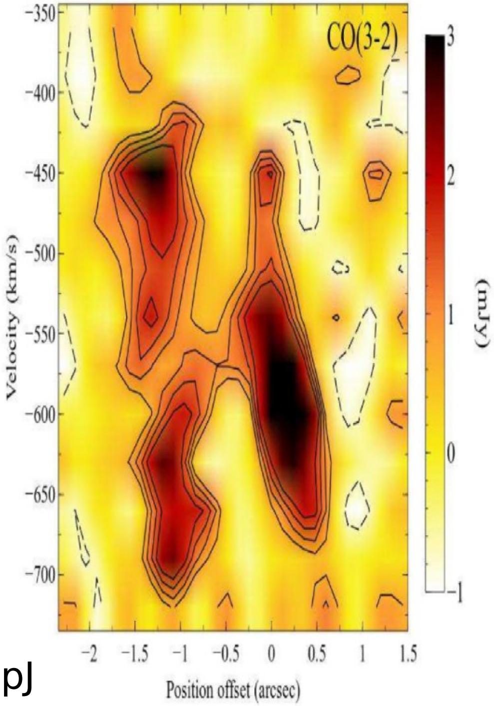

Russell et al, 2014, ApJ

Conclusion

- Cold mode feedback control the catastrophic cooling flow in cluster cores.

- Cold gas in our 3D simulation has two distinct components:
  (a) a centrally concentrated rotationally supported torus.
  (b) extended cold gas outgoing to 30 kpc.

- Massive torus is decoupled from the feedback loop.

- Radially dominant in-falling cold gas closes the feedback cycle.

THANK YOU

Cross-Correlations

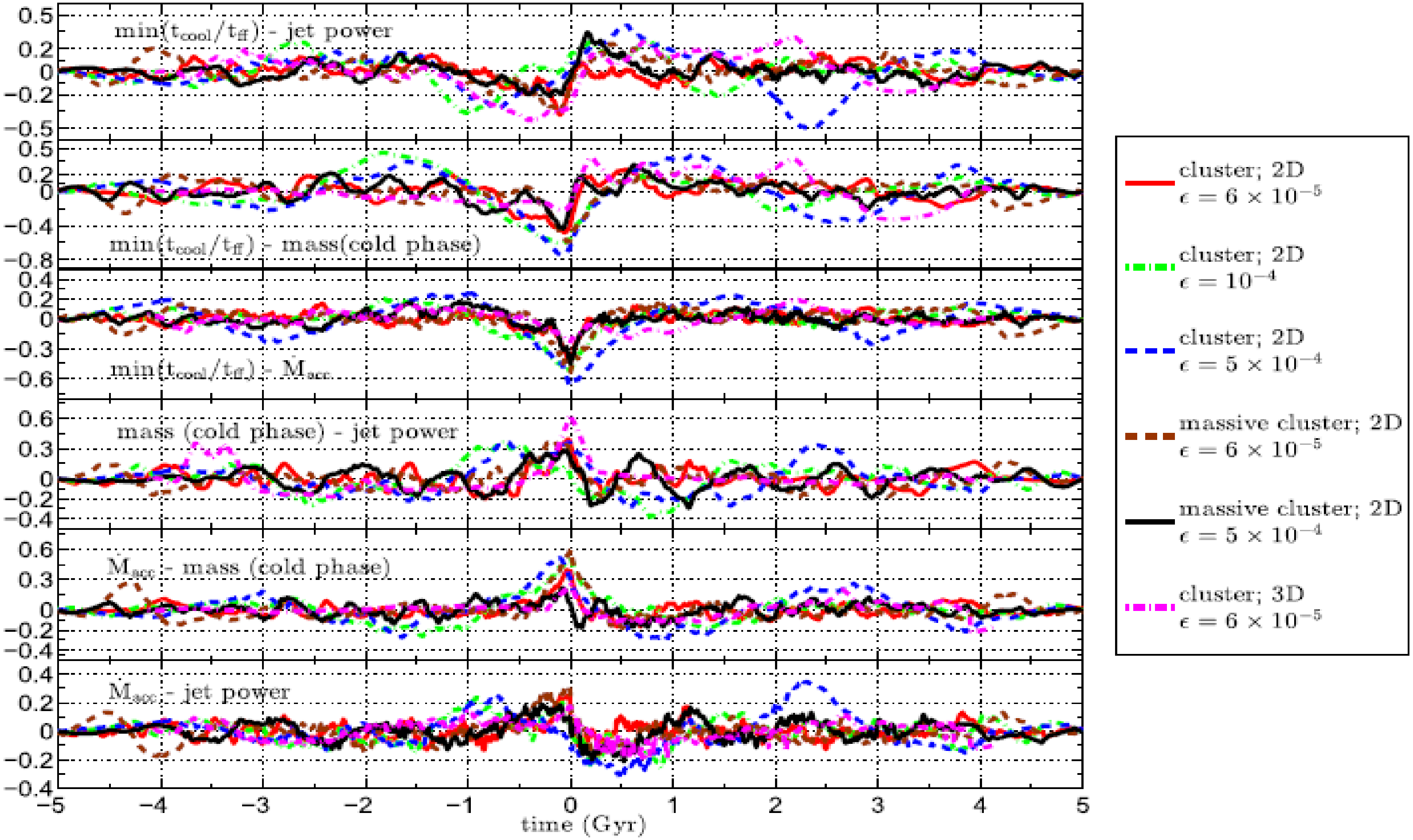

Figure 15. Cross-covariance of various quantities (min[$t_{\rm cool}/t_{\rm ff}$], jet energy, mass in cold phase, $\dot{M}_{\rm acc}$) as a function of time lag to show temporal relationship between these various quantities. Cross covariance between two quantities as a function of time, as used here, is defined as: $\mathrm{cov}(a, b; \tau) = \int_0^{T-|\tau|} [\delta a(t+\tau)\delta b(t)dt] \Big/ \left[\sqrt{\int_0^T |\delta a(t)|^2 dt \int_0^T |\delta b(t)|^2 dt}\right]$, where $-T \leqslant \tau \leqslant T$ is the time lag and δa and δb are mean-subtracted quantities. Since there is a large variation in various quantities (see Figures 13 and 14), we take log before evaluating cross-covariance. For the 3D cluster run we have used the radially dominant cold gas mass; the cross-covariance is much weaker if we use total cold gas mass.

Various Correlations