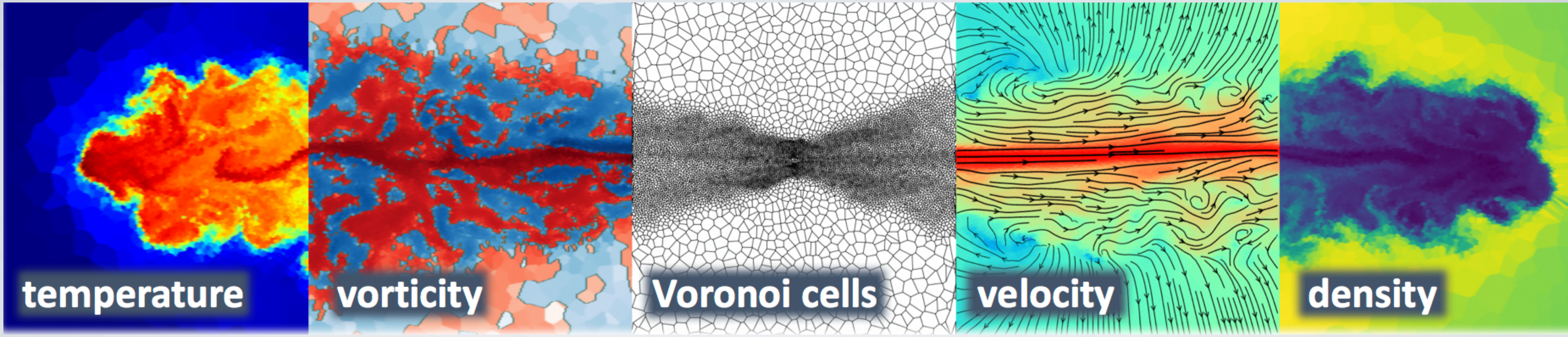
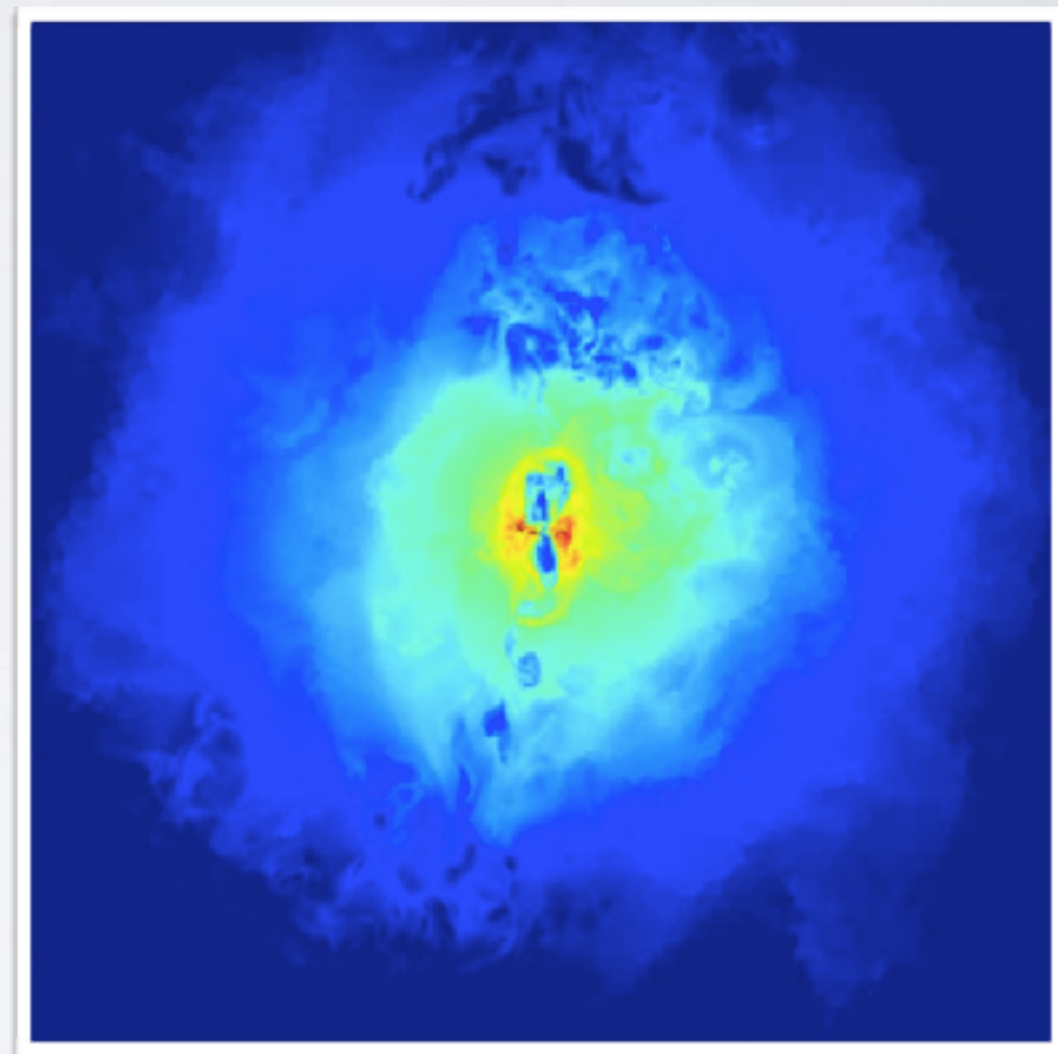


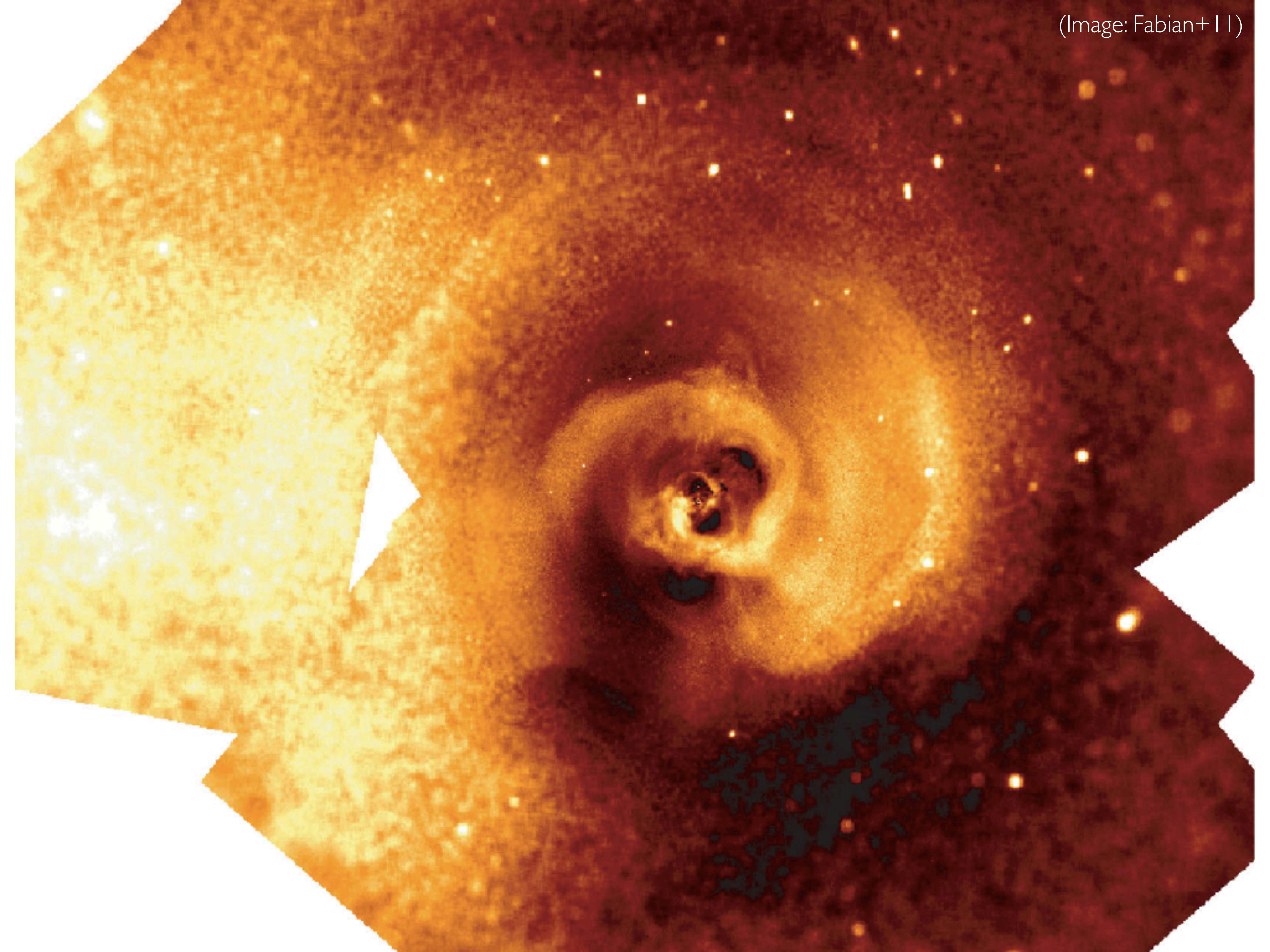
SIMULATION OF

AGN FEEDBACK
IN
GALAXY CLUSTERS



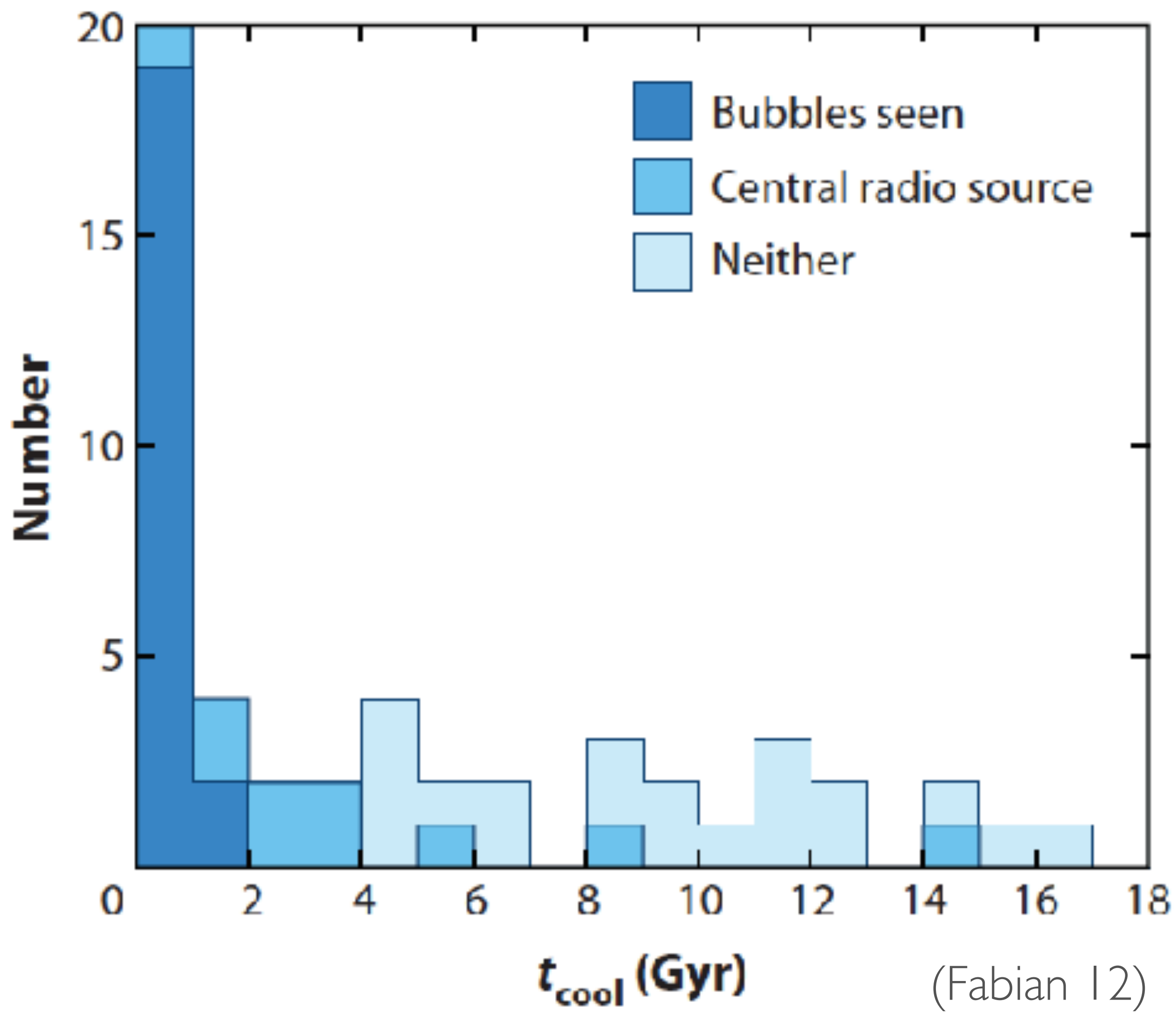
Martin Bourne

Collaborators: Debora Sijacki & Ewald Puchwein

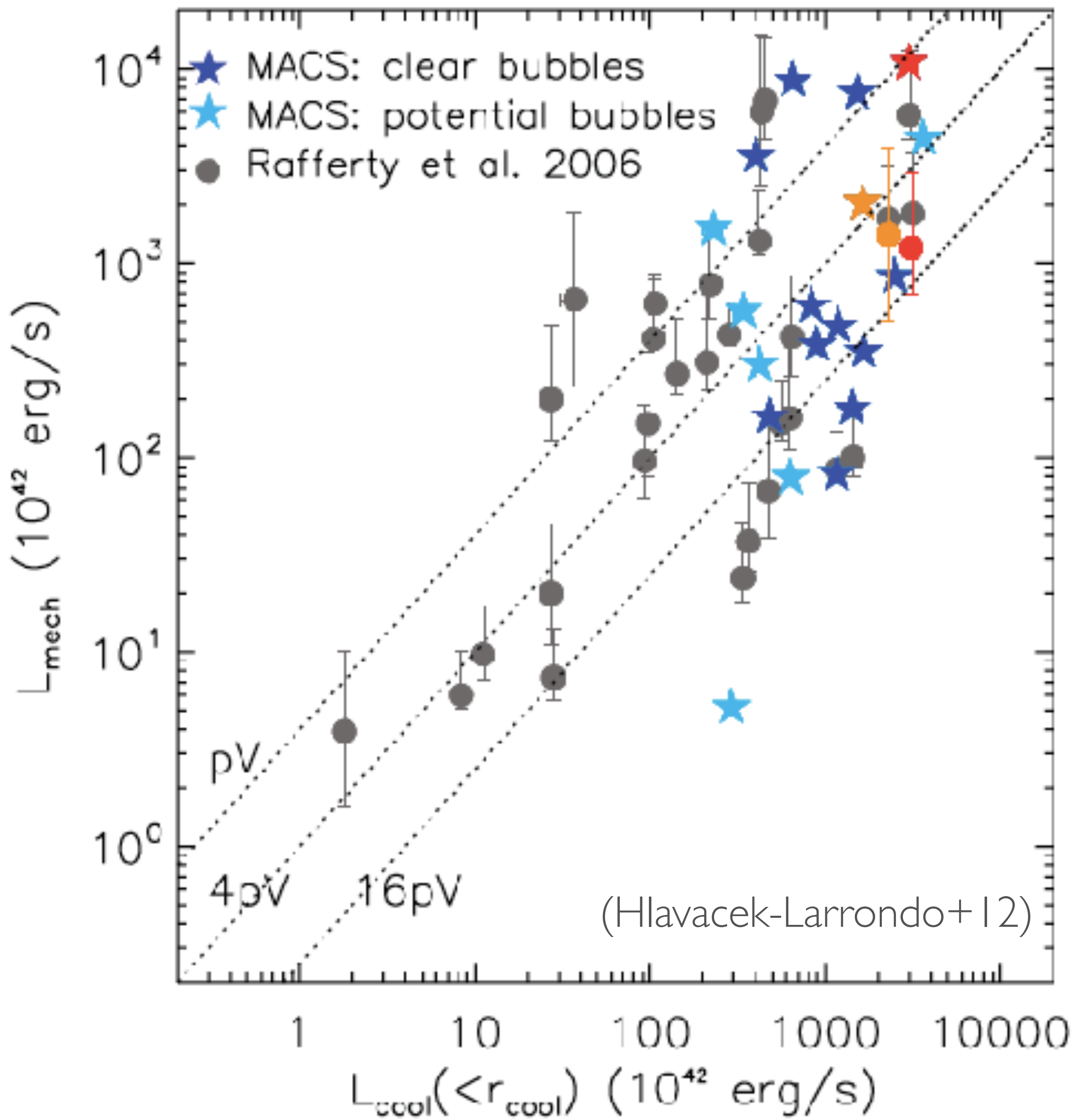


(Image: Fabian+11)

FEEDBACK IN GALAXY CLUSTERS



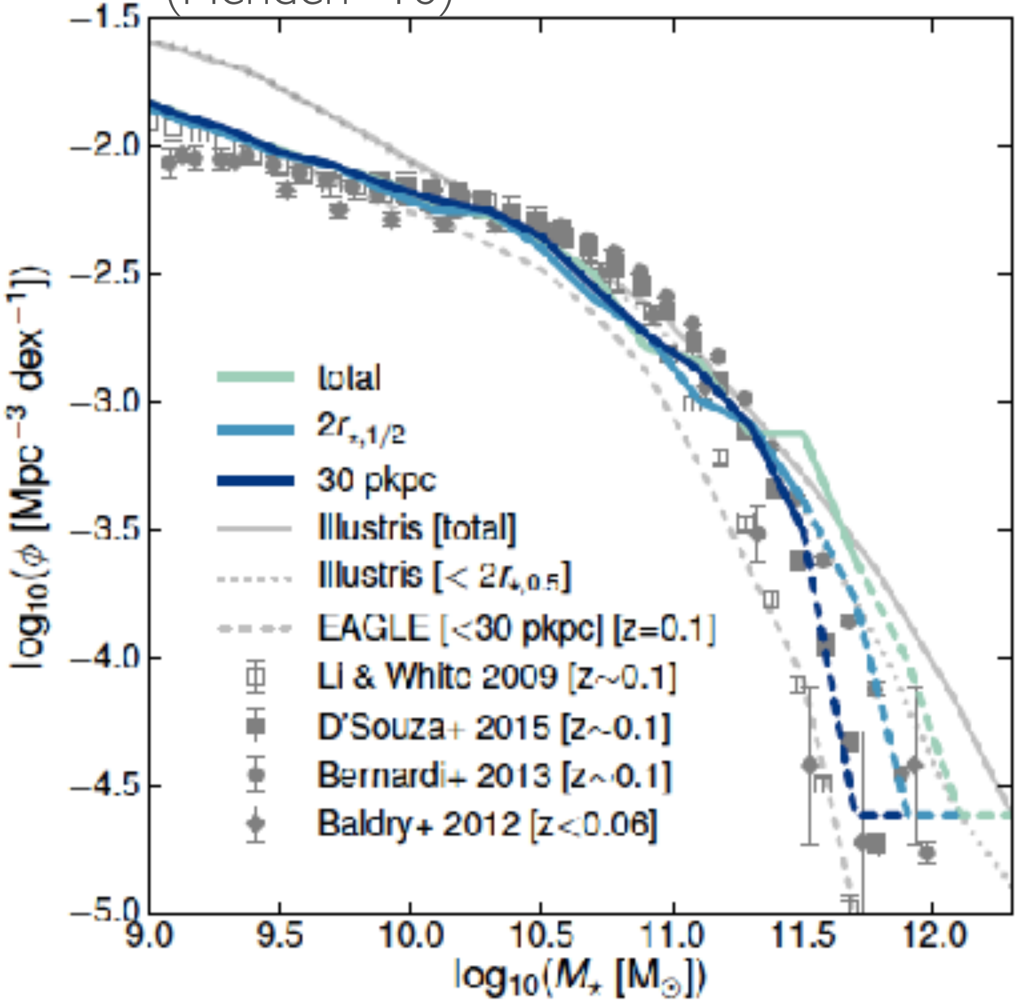
(Fabian 12)



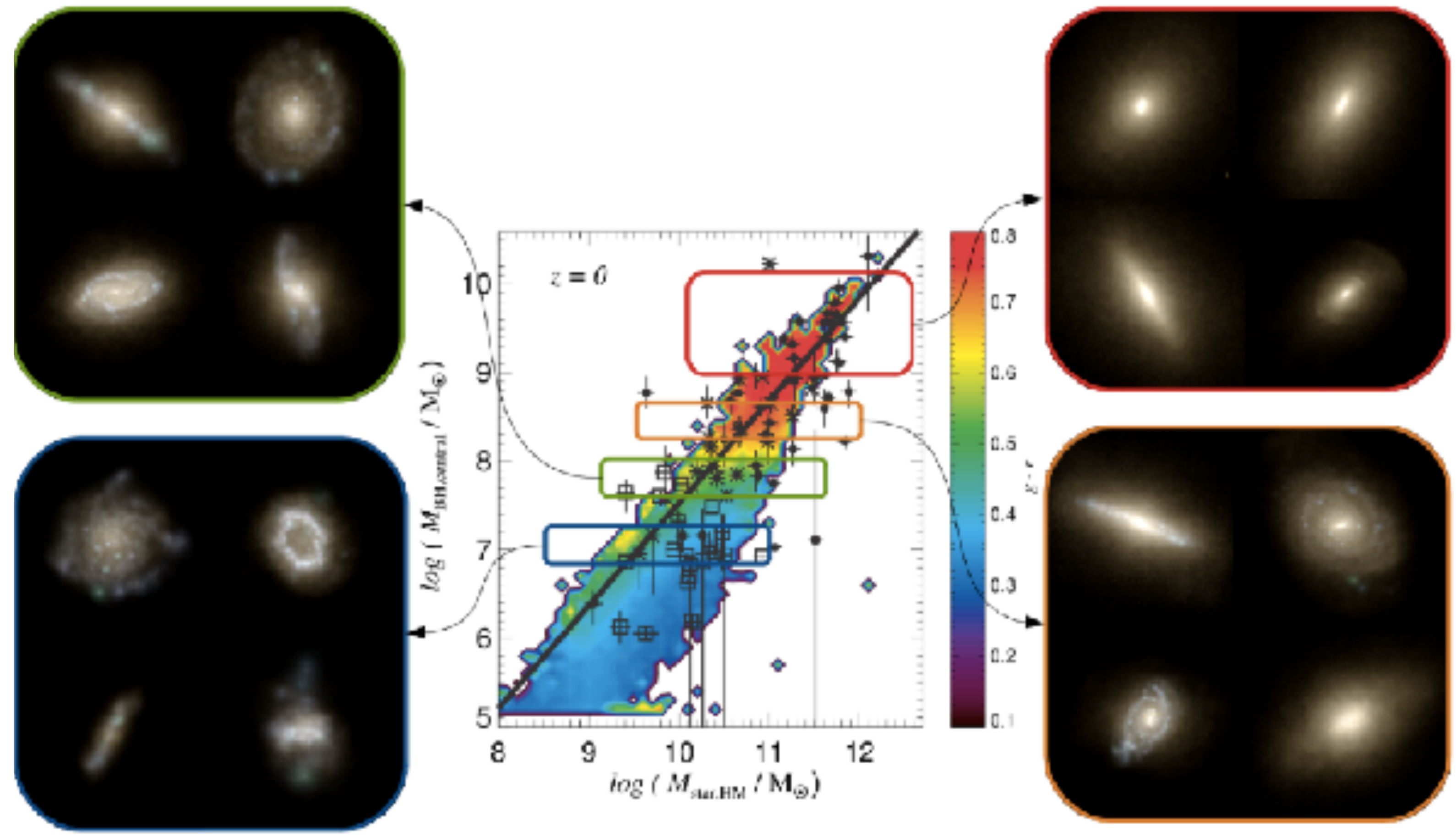
(Hlavacek-Larrondo+12)

A NECESSARY INGREDIENT IN COSMOLOGICAL SIMULATIONS

(Henden+18)



Quench star formation



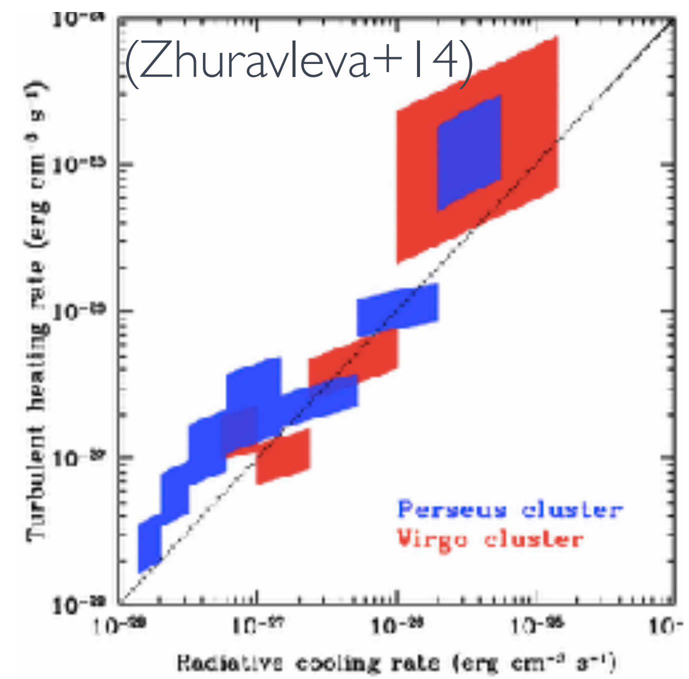
(Fig: Sijacki+15)

Regulate black hole growth

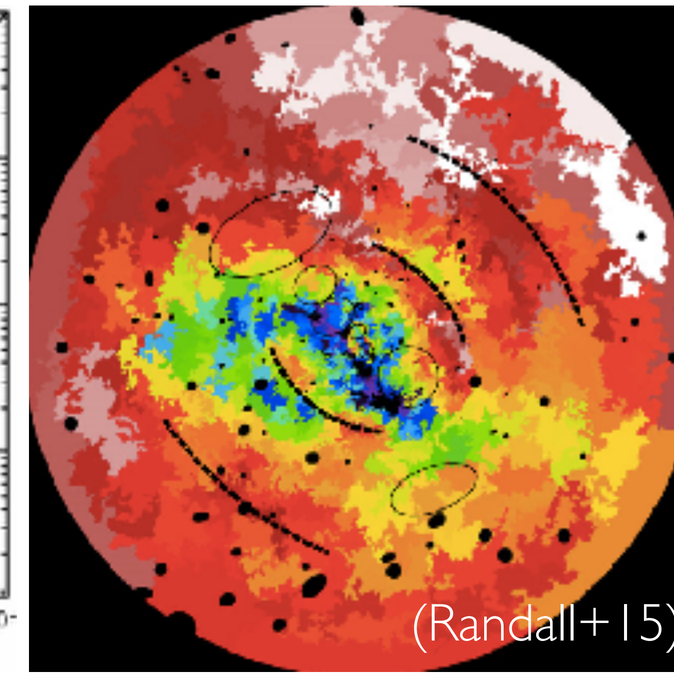
Produce realistic galaxies

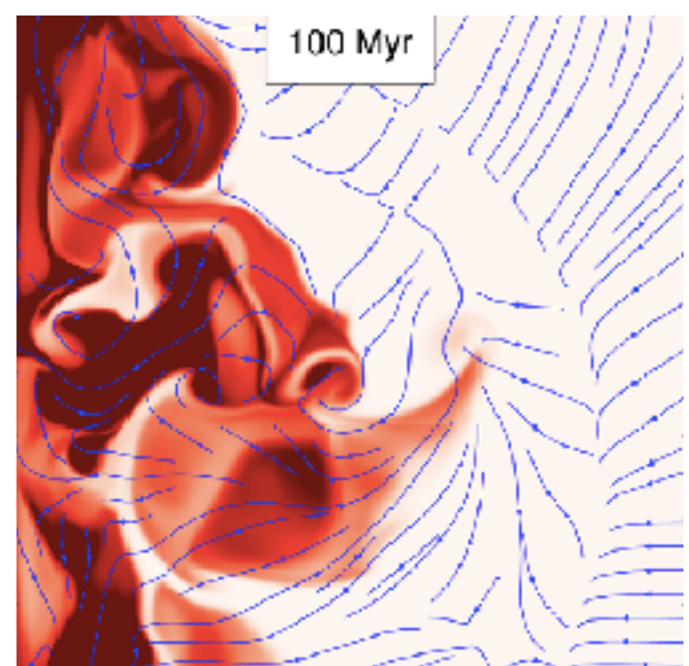
ENERGY TRANSFER MECHANISMS

- Shocks
  (e.g. Fabian+03, Randall+15, Li+16)
- Sound waves
  (e.g. Fabian+03, 05, 17, Ruszkowski+04)
- Mixing
  (e.g. Hillel & Soker 16)
- Turbulence
  (e.g. Banerjee & Sharma 2014, Zhuravleva+14)
- Cavity heating
  (e.g. Churazov+02, Birzan+04)
- Cosmic rays
  (e.g. Sijacki+08, Pfrommer 13)

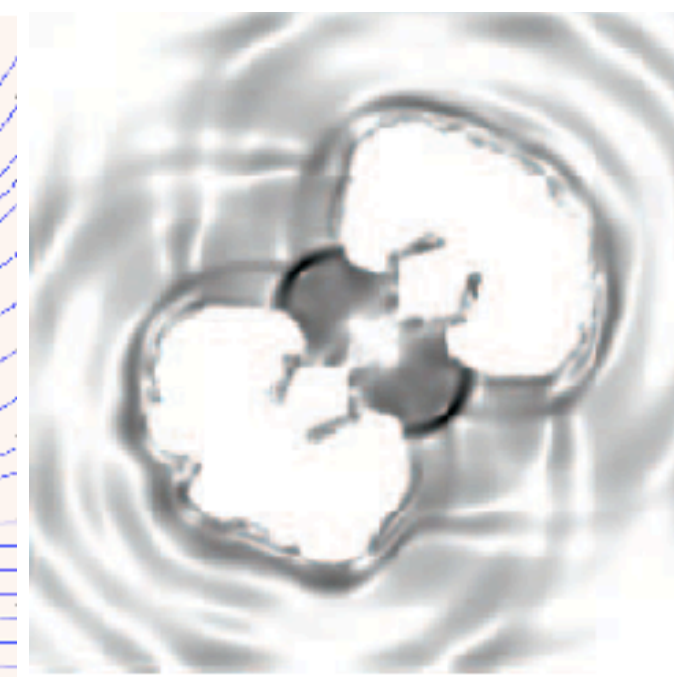


(Zhuravleva+14)

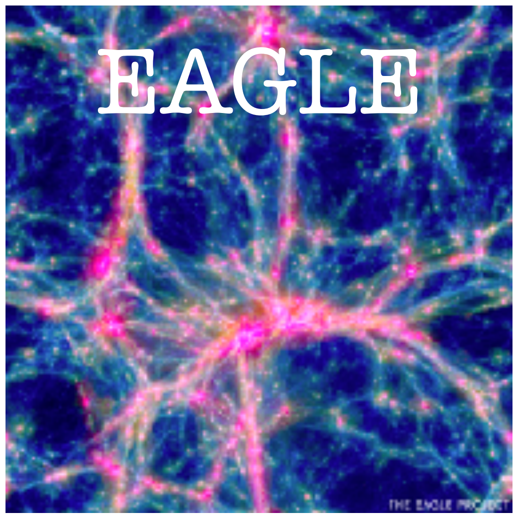

(Randall+15)

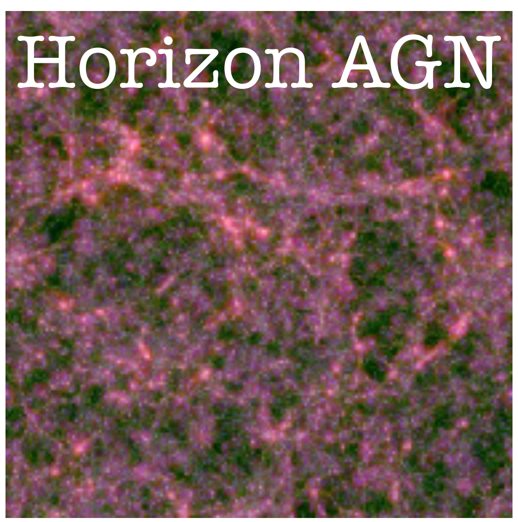


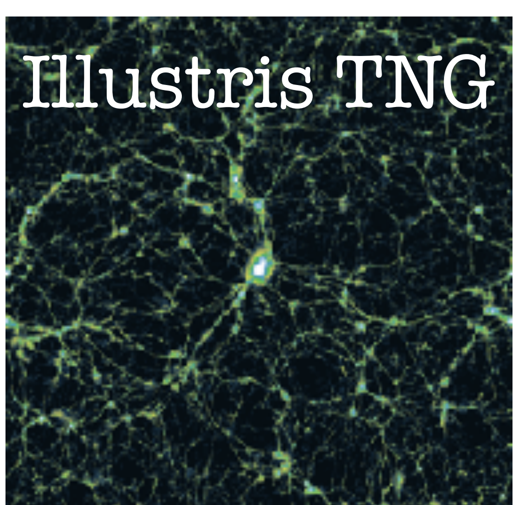
(Hillel & Soker 16)

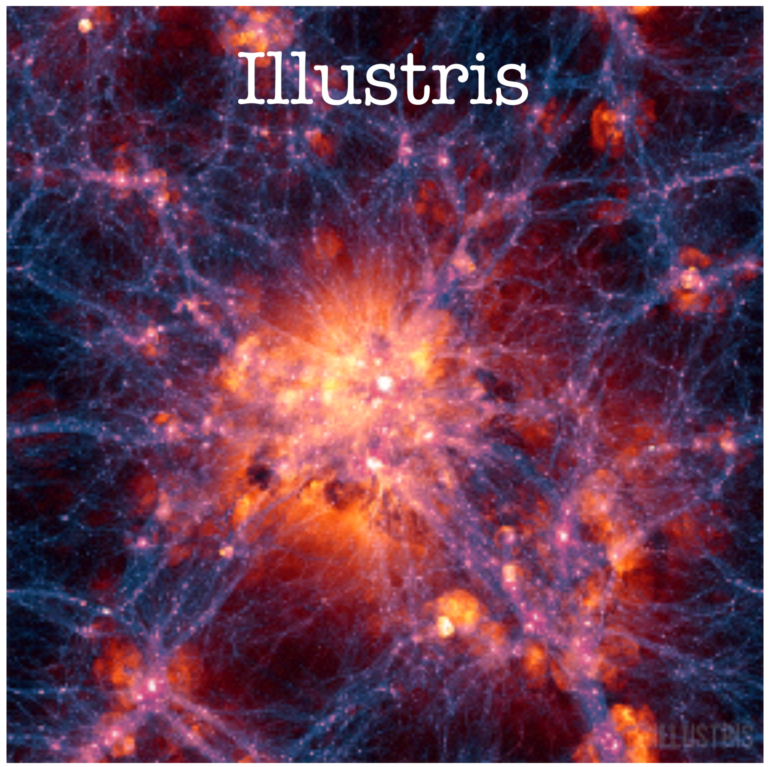

(Ruszkowski+04)

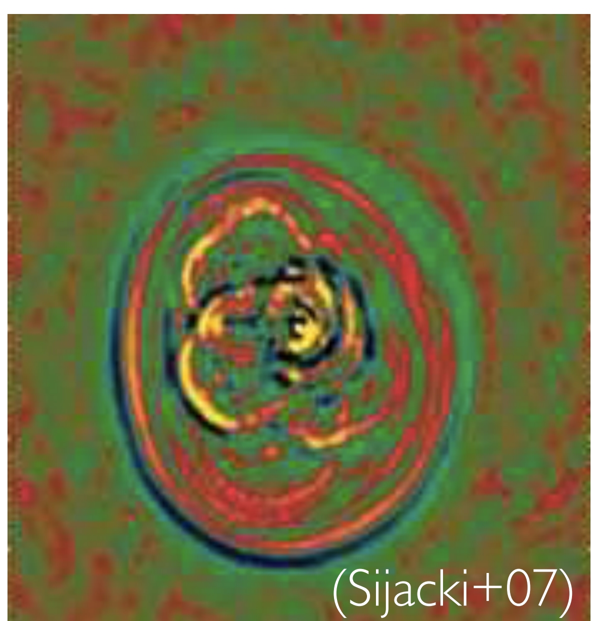
SIMULATING JET MODE FEEDBACK IN CLUSTERS

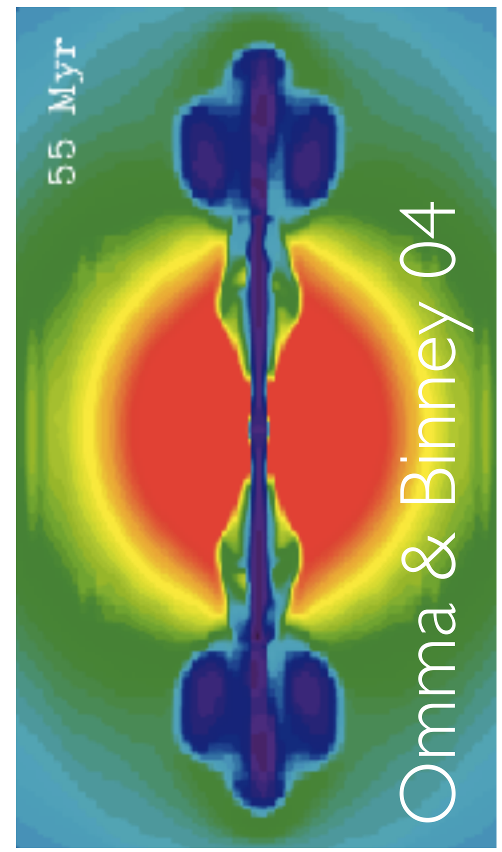


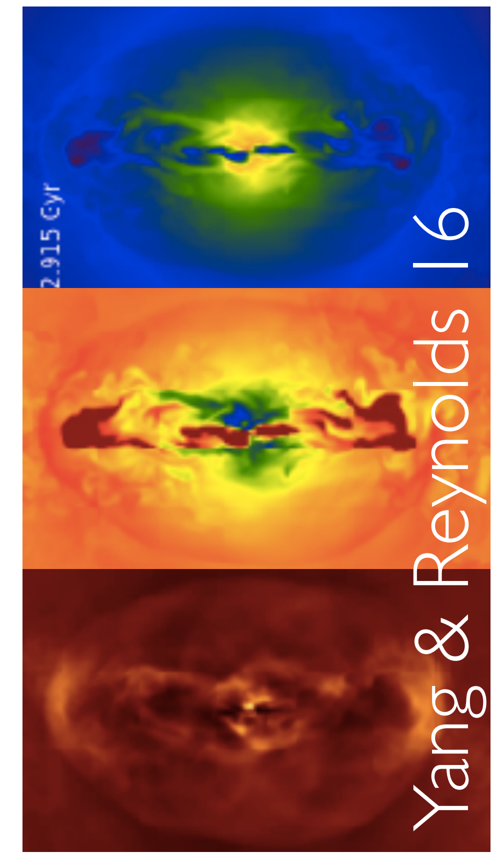


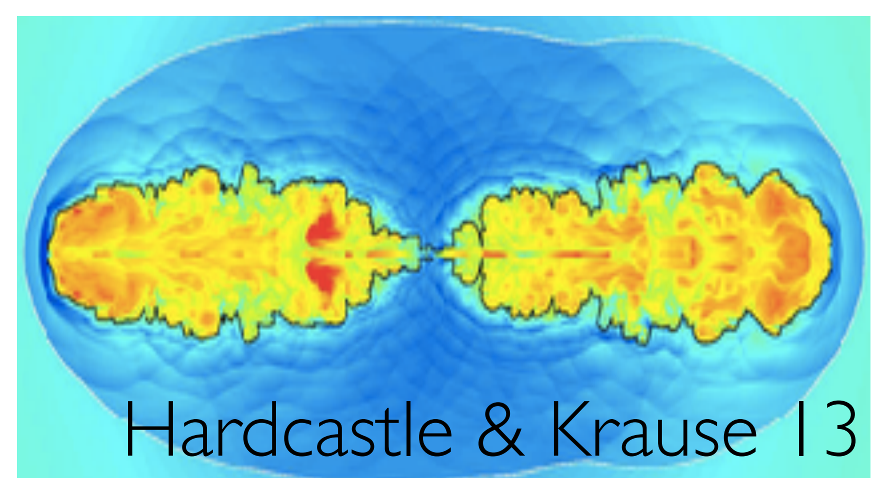






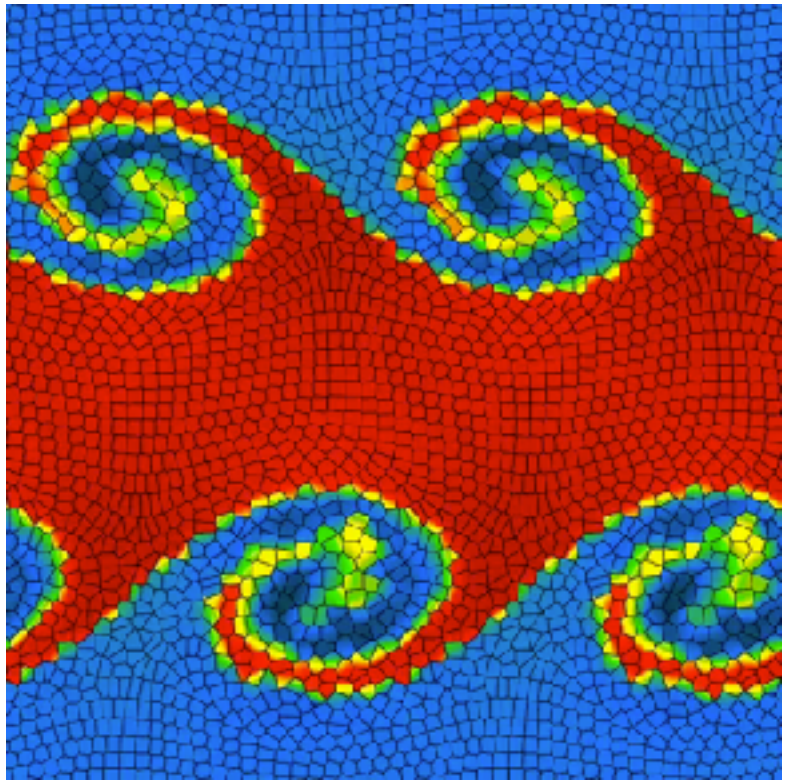


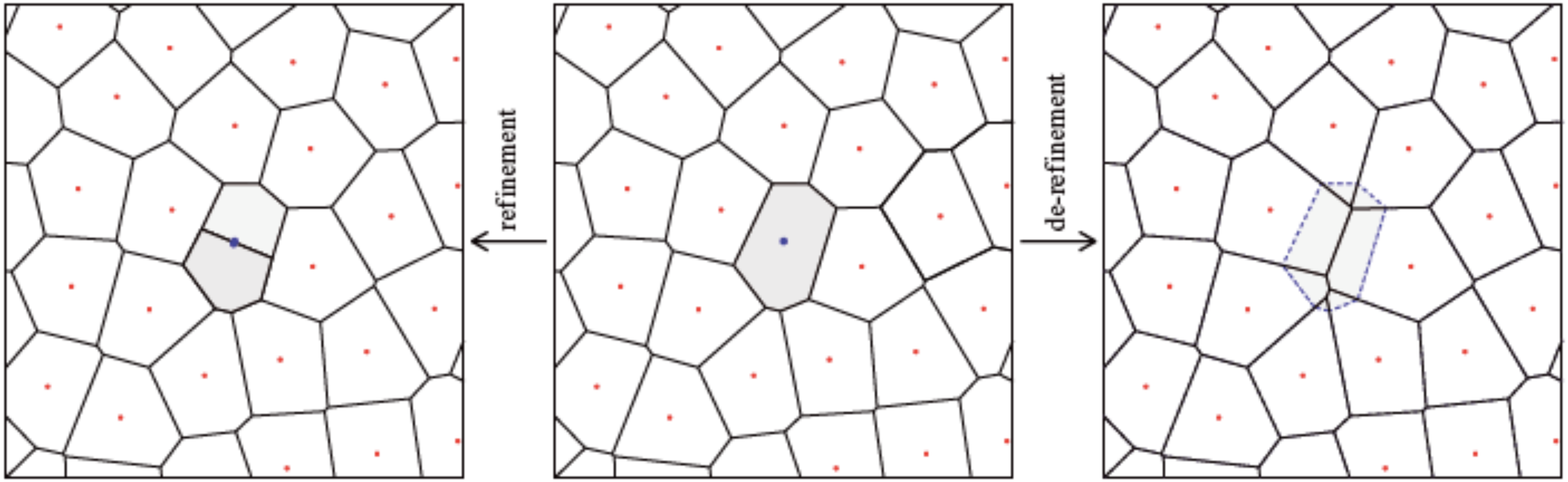




AREPO (Springel 2010)

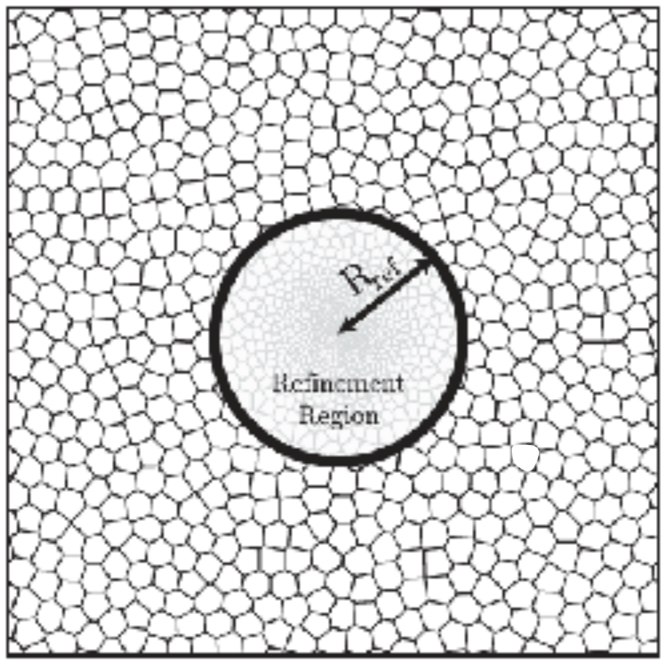
- Moving mesh - Voronoi cells with fixed target mass
- Lagrangian/Eulerian hybrid
- Super-Lagrangian refinement method
- Primordial radiative cooling
- Sub-grid ISM and star formation model (Springel & Hernquist 03)
- Modified black hole feedback and accretion



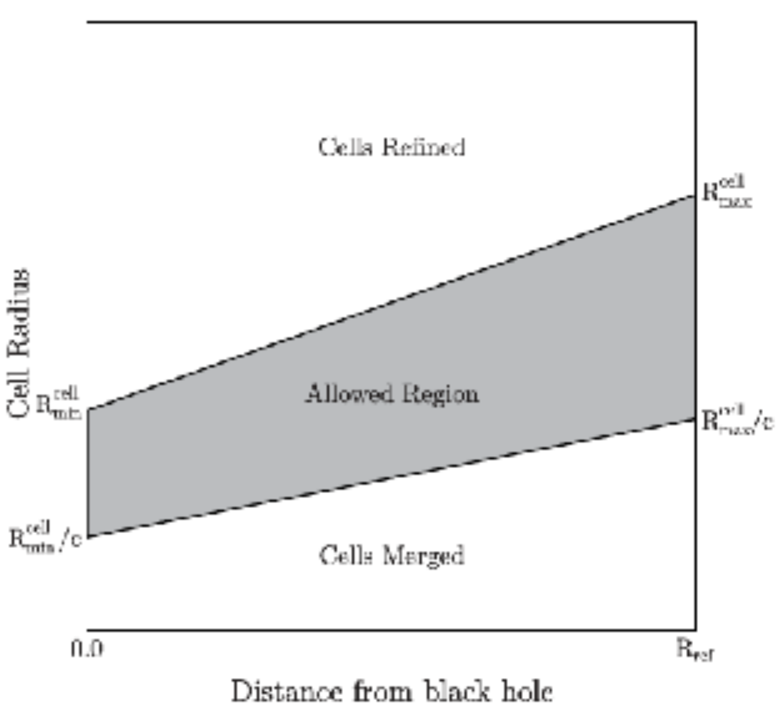


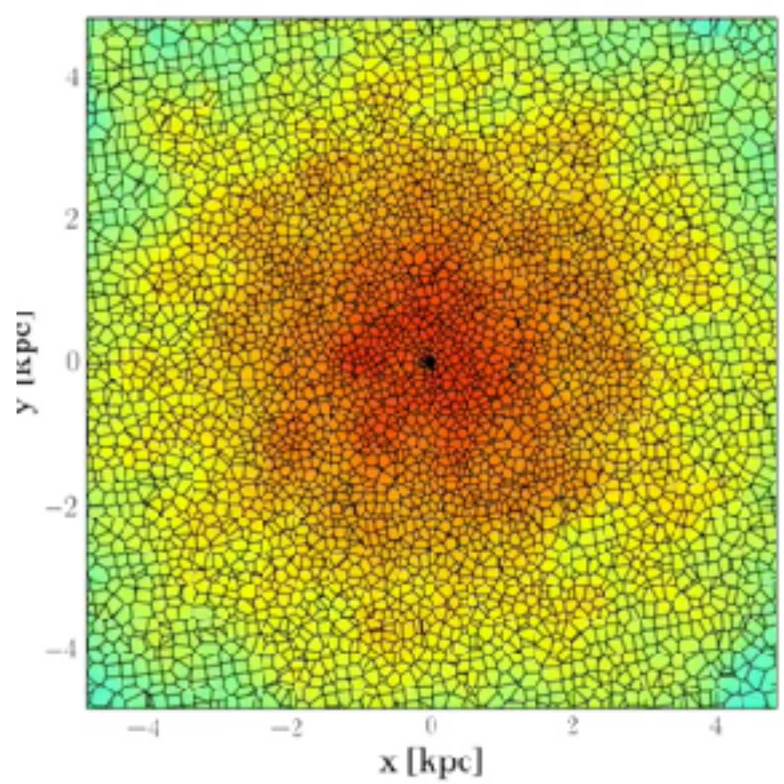
BLACK HOLE REFINEMENT SCHEME

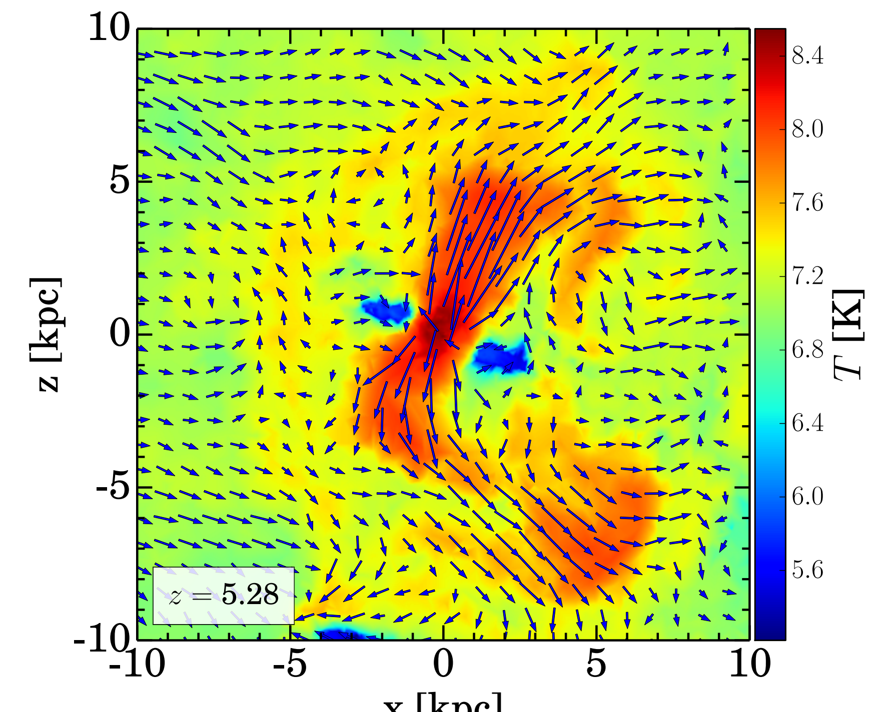
(Curtis & Sijacki 15, 16)



- Better capture gas dynamics close to the BH to improve accretion rate estimates
- More accurate modelling of outflow-ISM interface
- Ability to resolve vorticity distribution of gas close to black hole - include effects of angular momentum on gas accretion rates



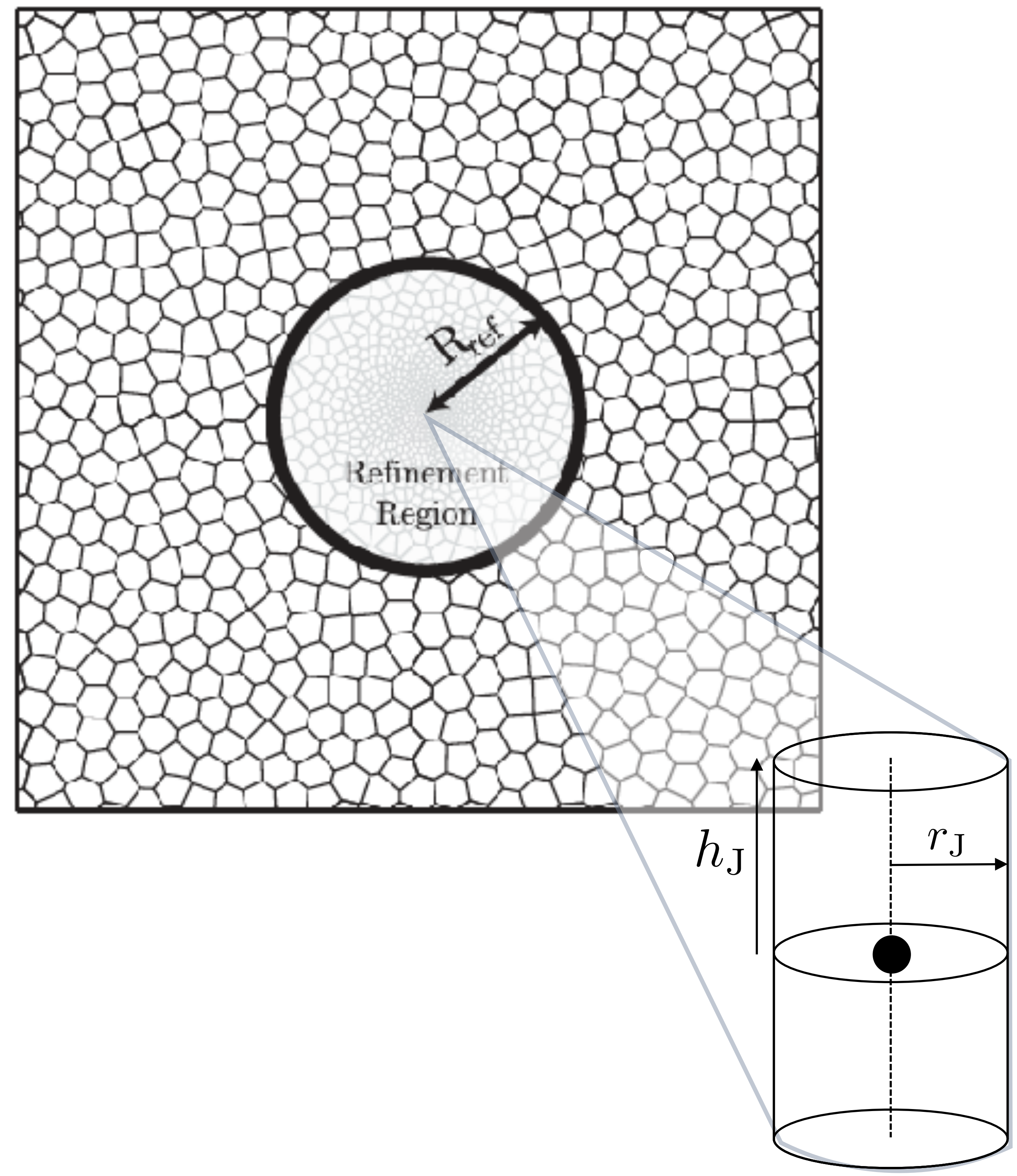




INJECTING THE JET

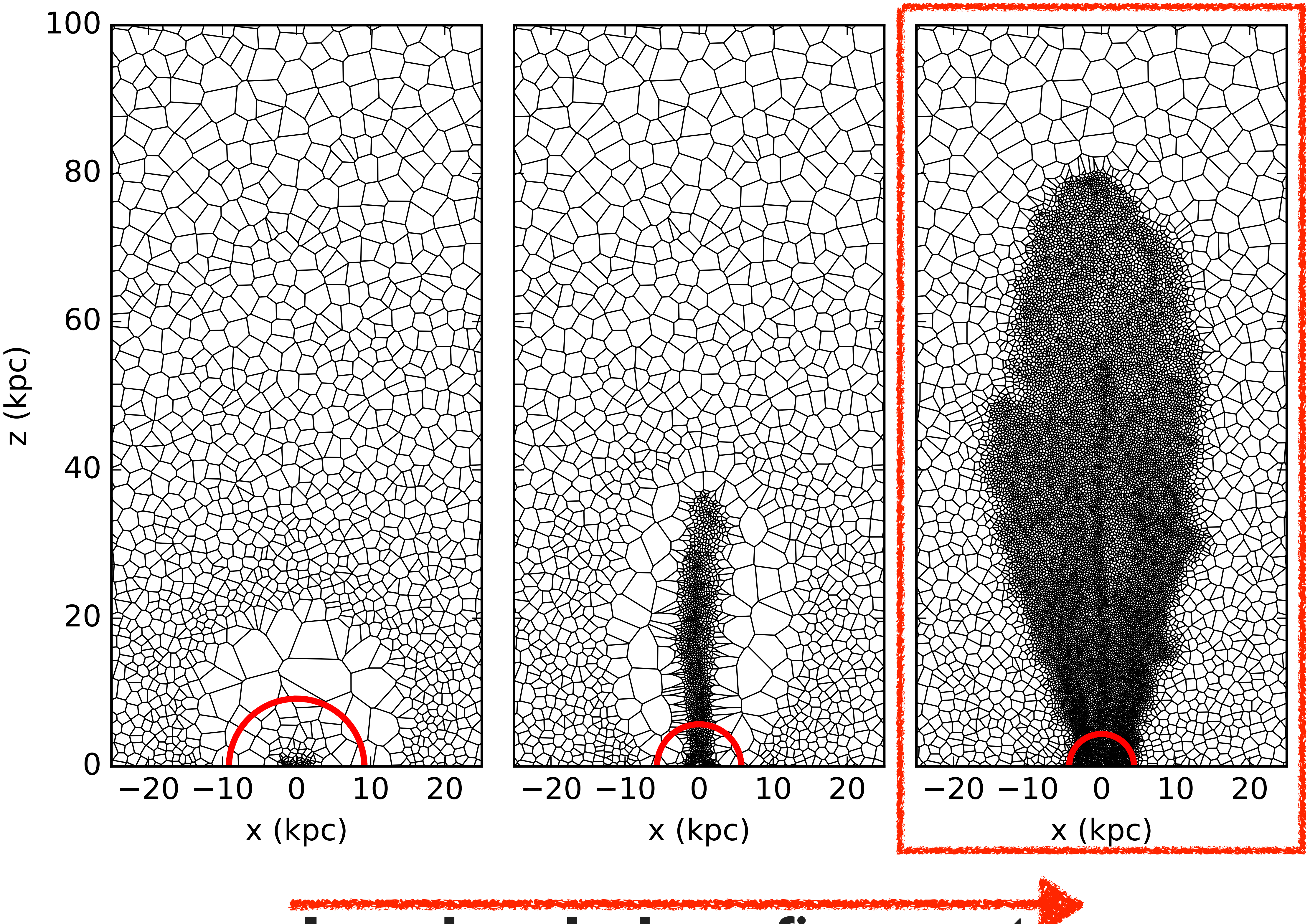
Define a cylinder of fixed mass

Inject mass, momentum and energy into cells within the cylinder
(e.g. Cattaneo & Teyssier 07, Dubois+10, Yang+12)



(Bourne & Sijacki, 17, MNRAS, arXiv:1705.07900)

REFINEMENT



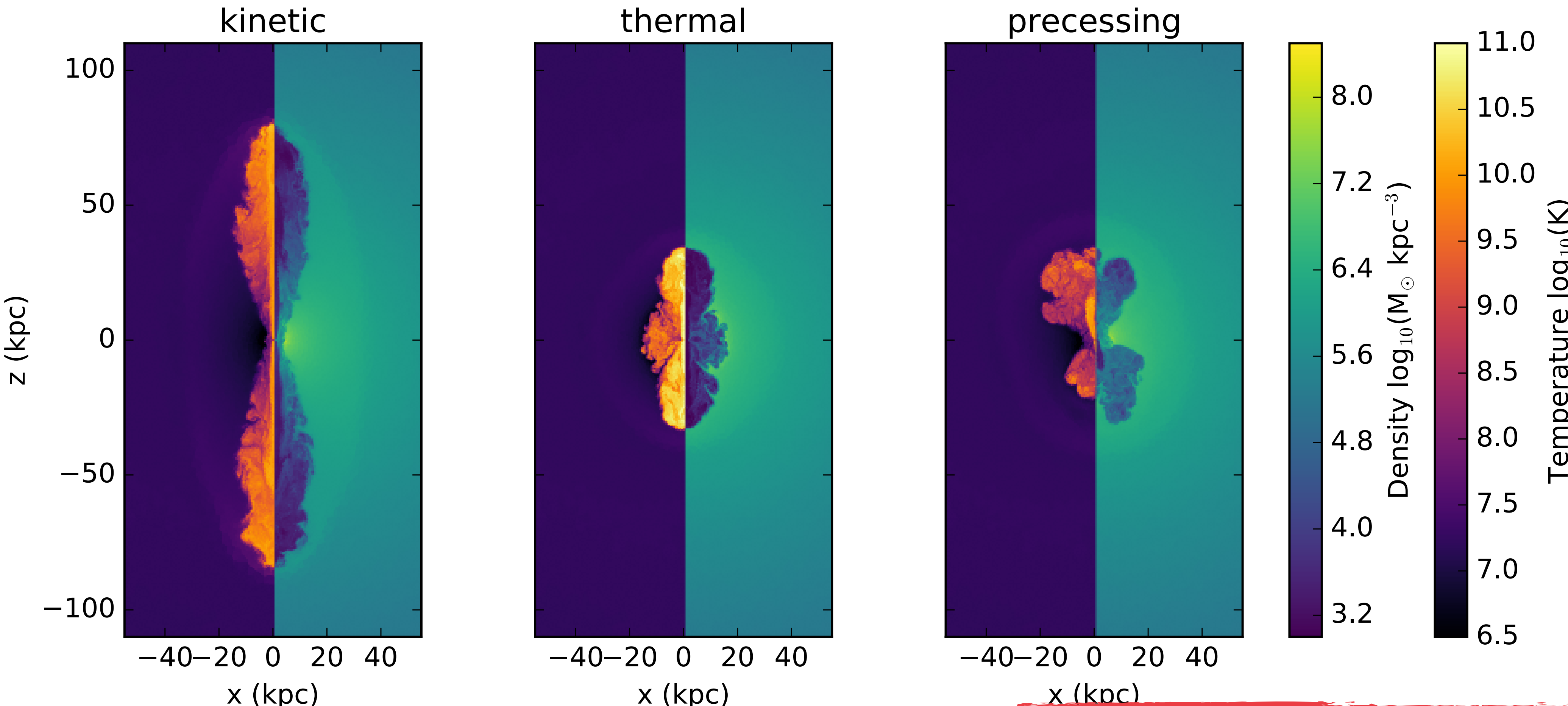
smallest cell
~ 10 pc

R_{vir}
~750 kpc

Less harsh de-refinement

(Bourne & Sijacki, 17, MNRAS, arXiv:1705.07900)

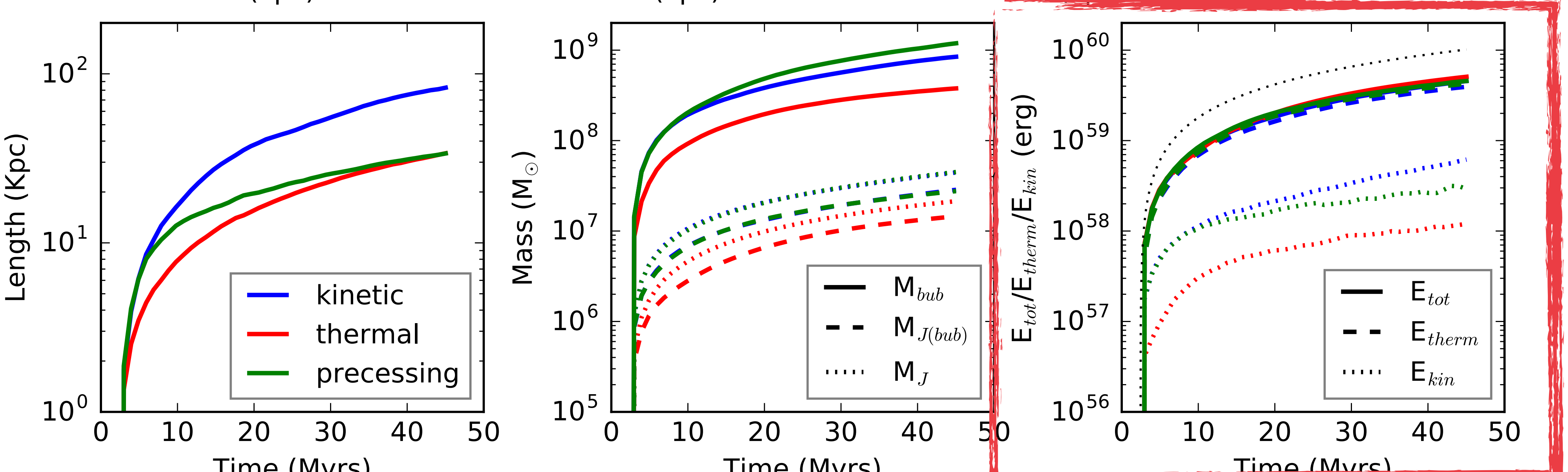
INJECTION METHOD



$$M_{\rm Cluster} = 10^{14} M_\odot$$

$$M_{\rm BH,0} = 10^{9} M_\odot$$

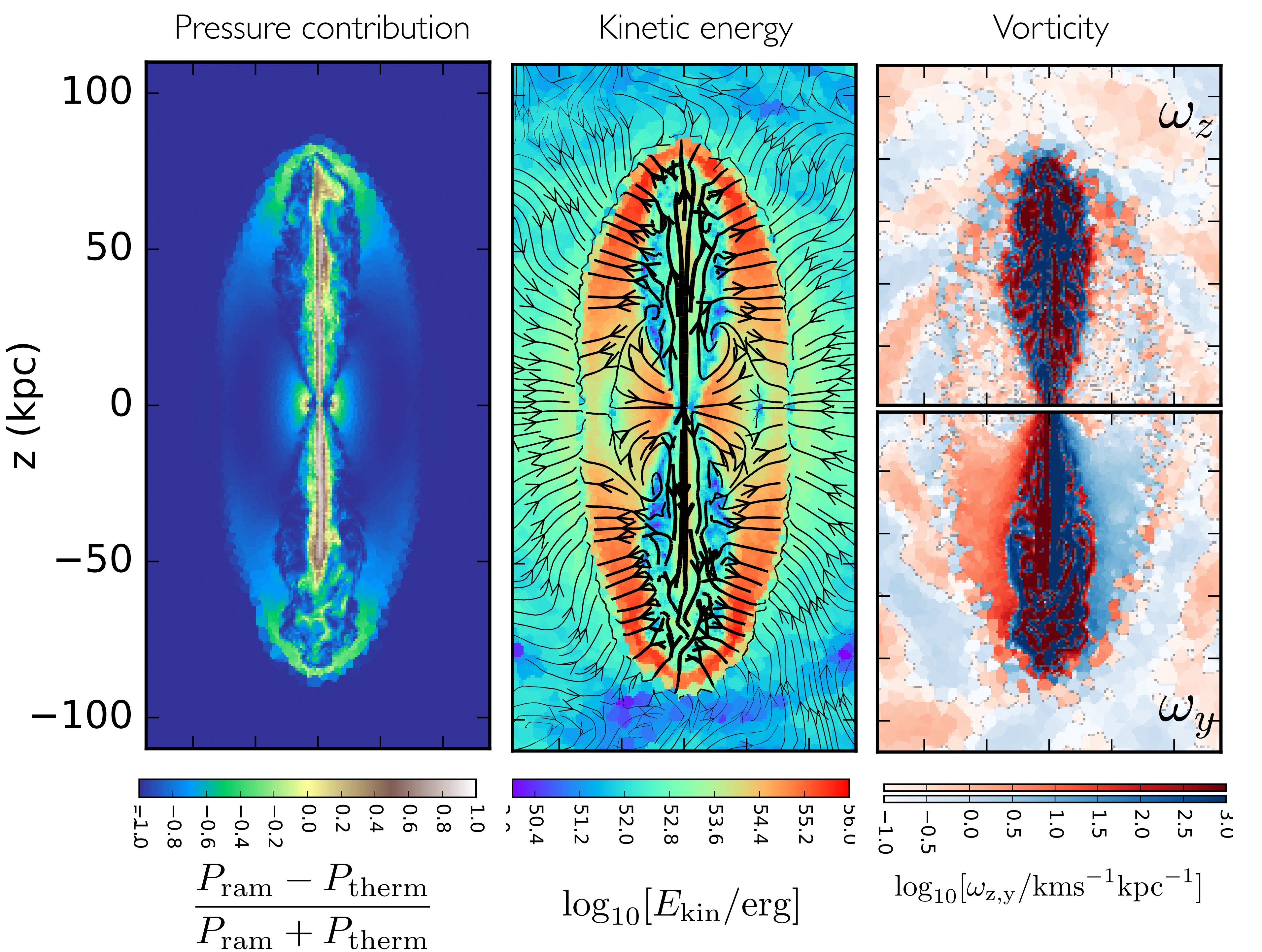
$$\dot{E}_{\rm Jet} \sim 10^{45} {\rm erg/s}$$



$E_{kin} < 0.13\ E_{bub}$

(Bourne & Sijacki, 17, MNRAS, arXiv:1705.07900)

JET INFLATION AND GAS FLOWS



Bow shock persists

Perpendicular shock broadens into sound wave

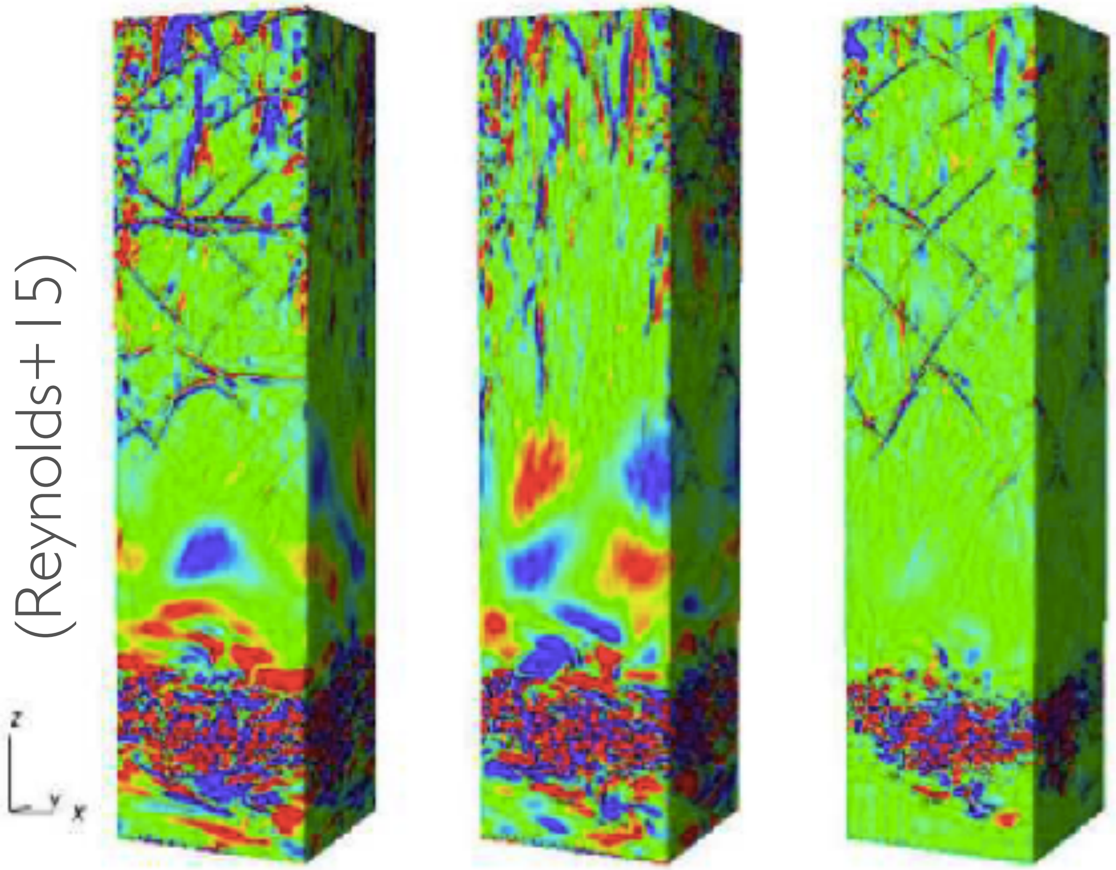
Shell:

$E_k \sim 10\%\ E_{Inj}$

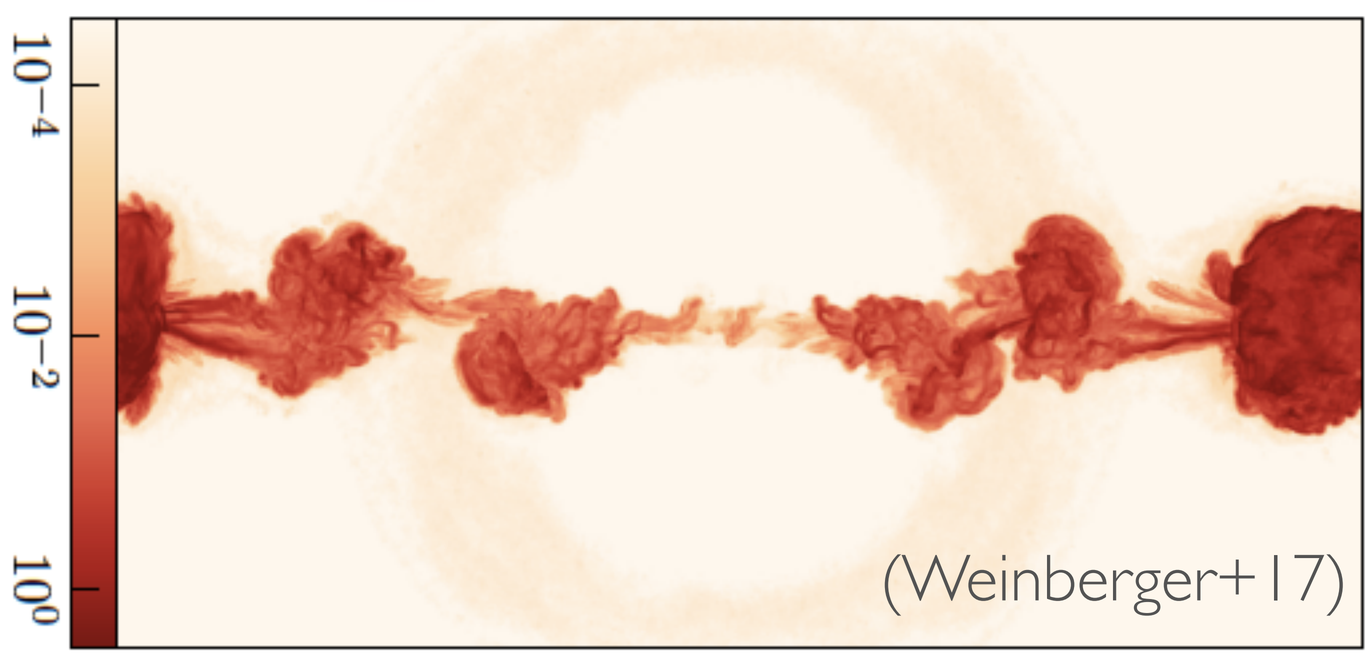
Lobe displaces ~ 10^{10}-10^{11} M_{sol}

(Bourne & Sijacki, 17, MNRAS, arXiv:1705.07900)

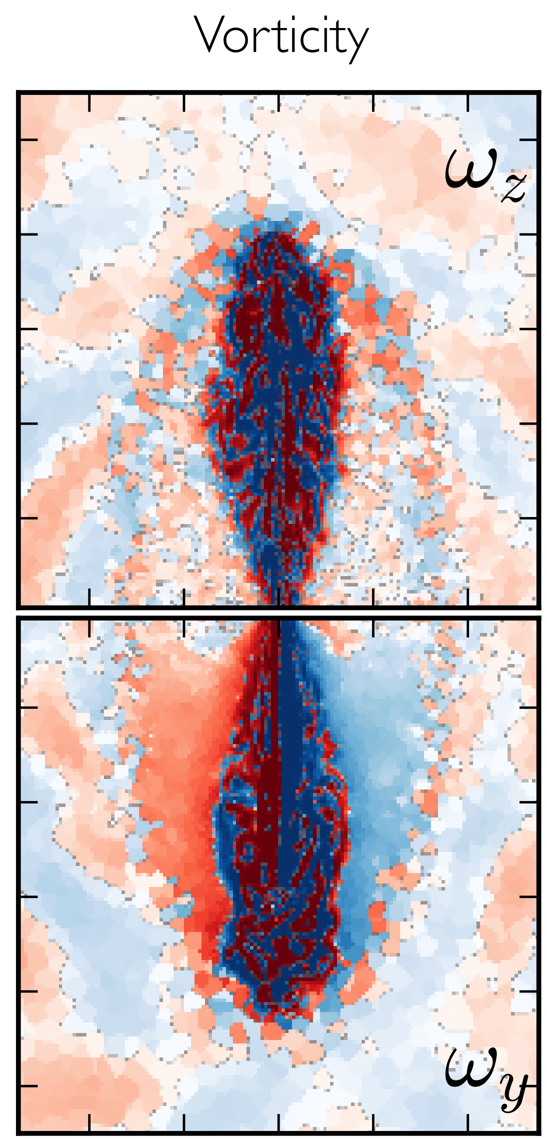
VORTICITY GENERATION



(Reynolds+15)



(Weinberger+17)



Compressive ratio:

$$r_{\rm cs} = \frac{\langle|\nabla\cdot\mathbf{v}|^2\rangle}{\langle|\nabla\cdot\mathbf{v}|^2\rangle + \langle|\nabla\times\mathbf{v}|^2\rangle}$$

Jet lobe:

$$r_{\rm cs} \simeq 0.03$$

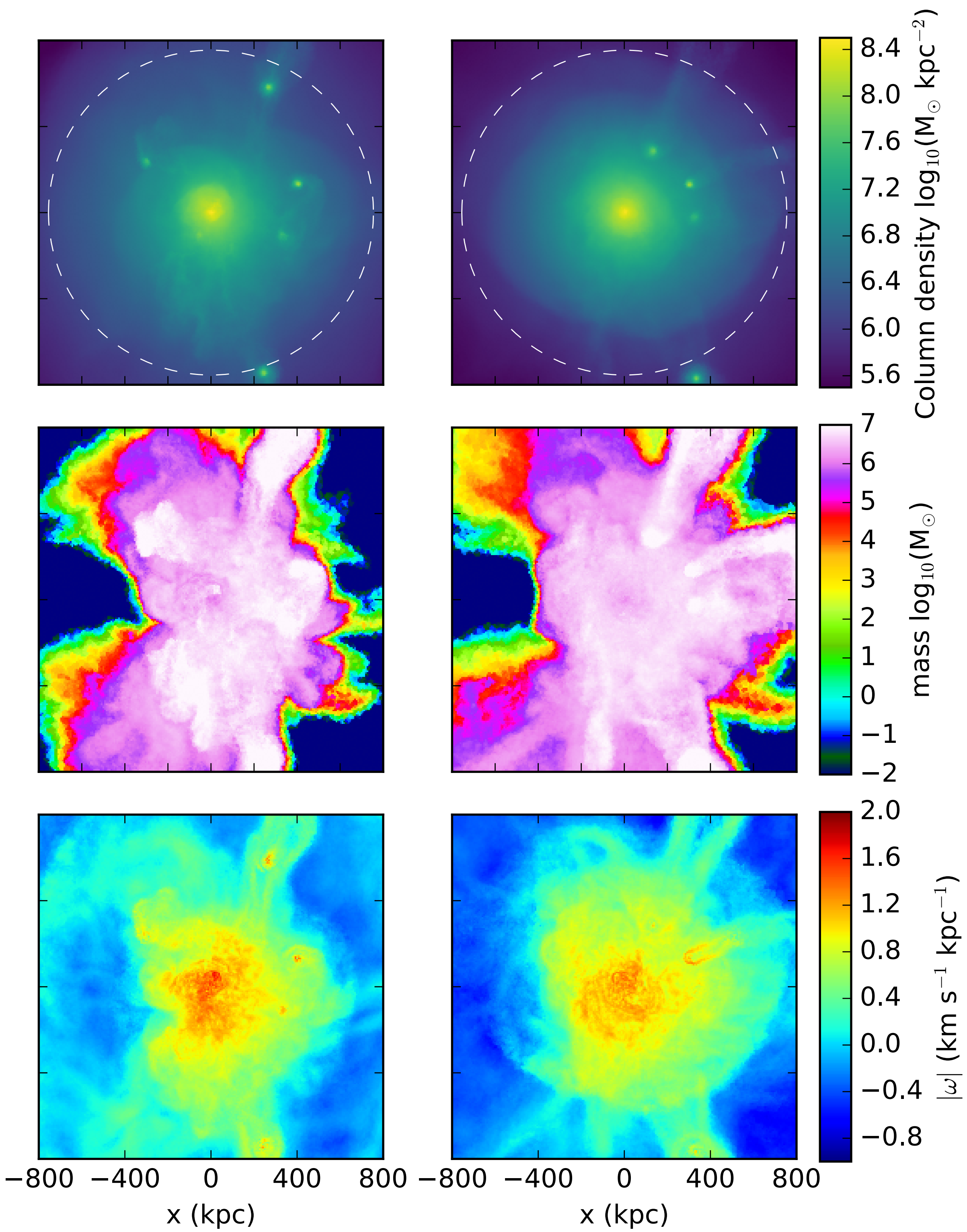
Expanding cocoon:

$$r_{\rm cs} \simeq 0.85$$

see also:
Yang&Reynolds 16, Bambic+18

(Bourne & Sijacki, 17, MNRAS, arXiv:1705.07900)

JETS IN A TURBULENT ICM



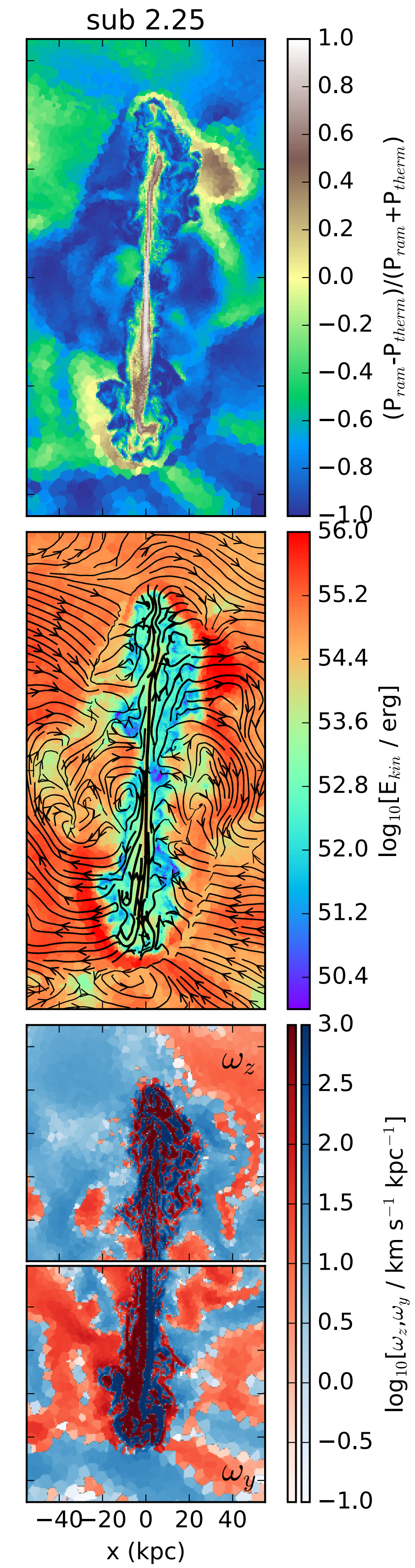
Observations - ICM contains a *small* turbulent component (e.g., Sanders+11, Pinto+15, Hitomi+16)

Add sub halos by hand to stir ICM

Produce turbulence and vorticity

Pre-existing motions disrupt the jet cocoon

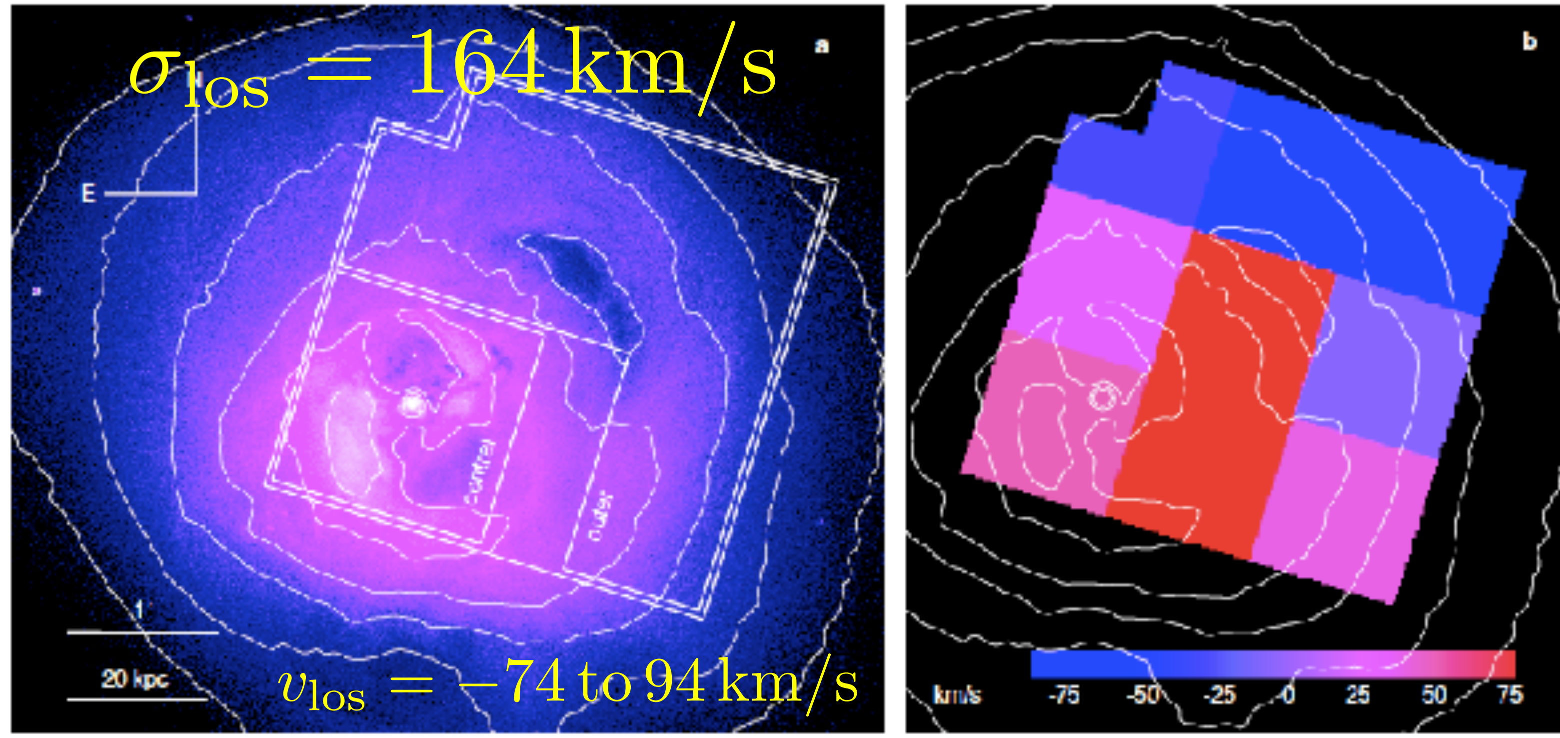
High levels of existing vorticity/ turbulence



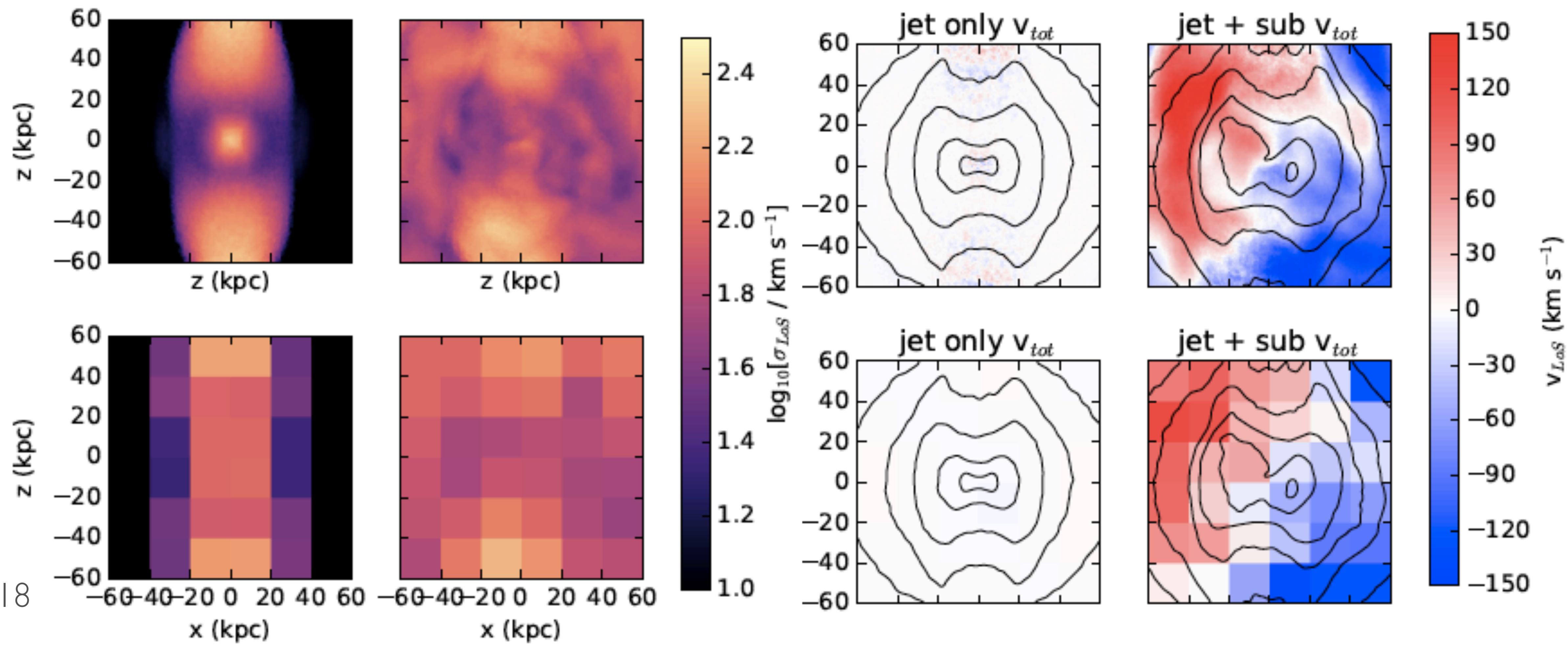
(Bourne & Sijacki, 17, MNRAS, arXiv:1705.07900)

COMPARISON WITH HITOMI

Able to reproduce kinematic features consistent with Hitomi when a jet and substructure motions are included



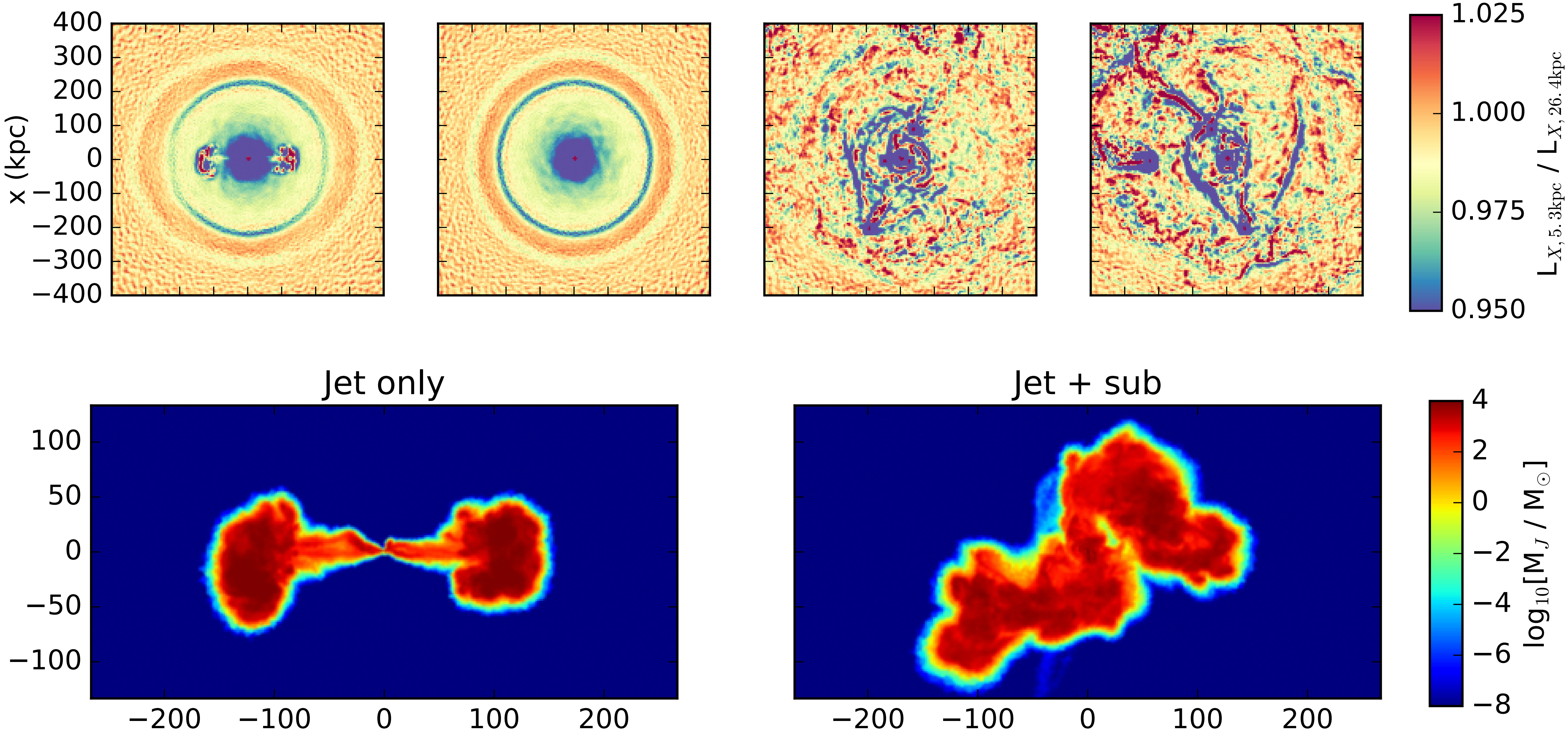
(Hitomi Collaboration 16)



see also: Lau+18, ZuHone+18

(Bourne & Sijacki, 17, MNRAS, arXiv:1705.07900)

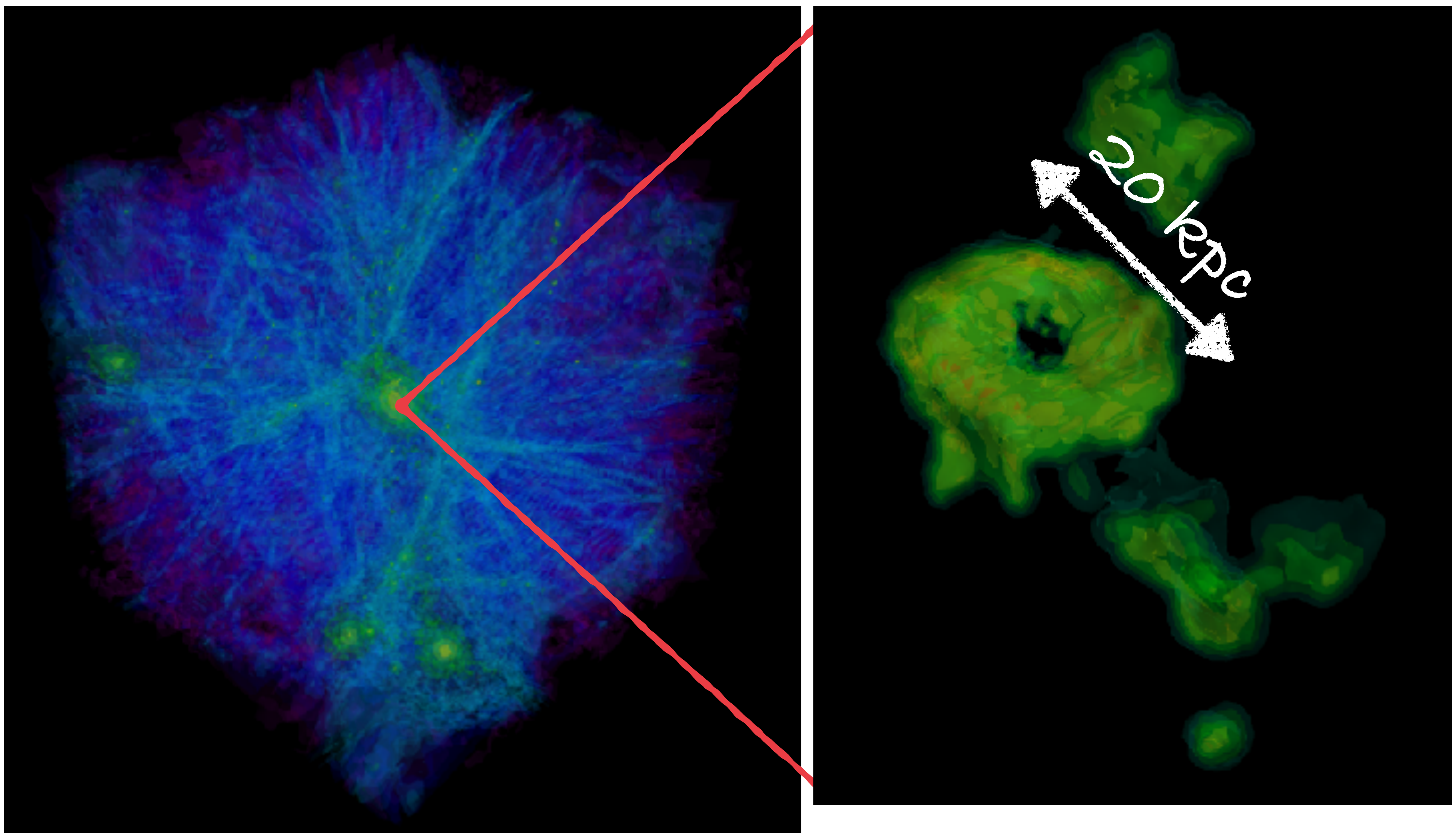
LONG TERM EVOLUTION, MIXING AND SOUND WAVES



COSMOLOGICAL CLUSTER

(PRELIMINARY)

$z = 0.1$

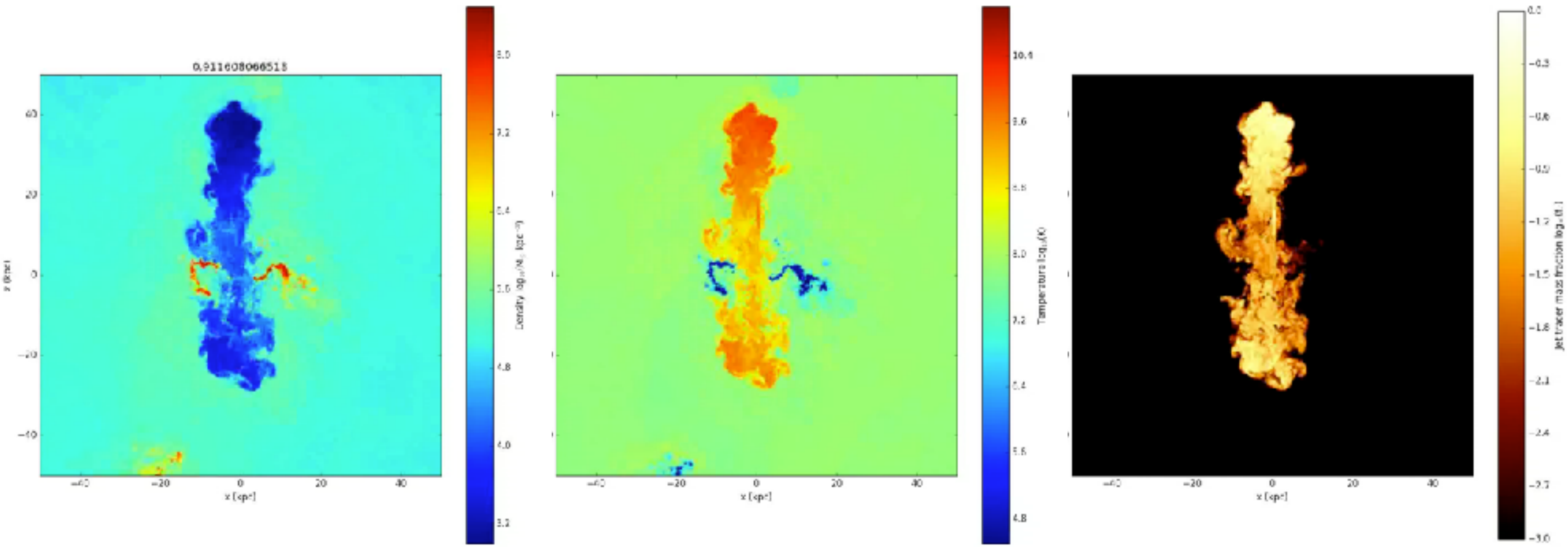


$M_{200} \sim 4 \times 10^{14} M_{\odot}$

$R_{200} \sim 1.3 \mathrm{Mpc}$

$M_{\mathrm{BH}} = 2.64 \times 10^{10} M_{\odot}$

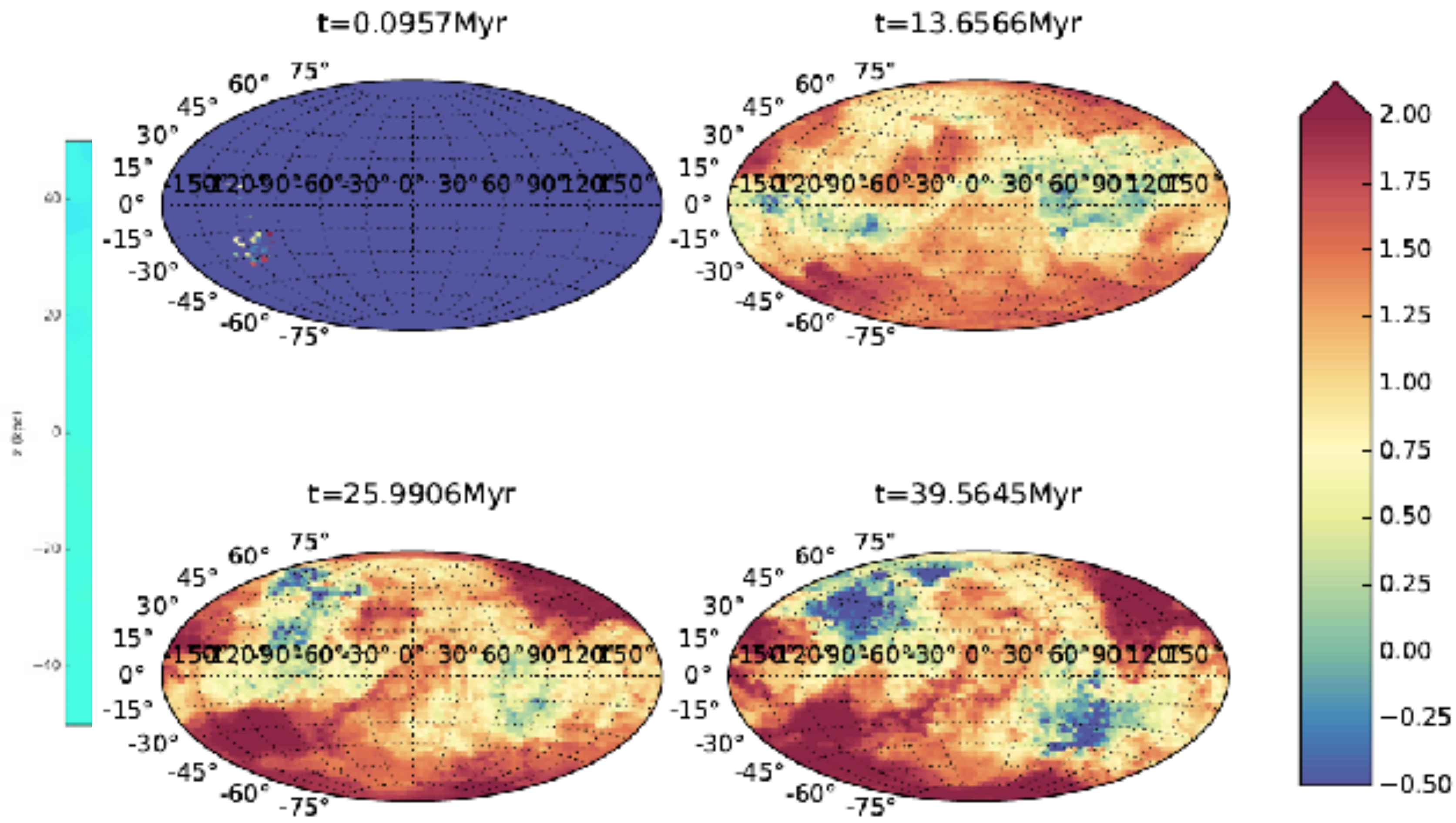
COSMOLOGICAL CLUSTER
(PRELIMINARY)

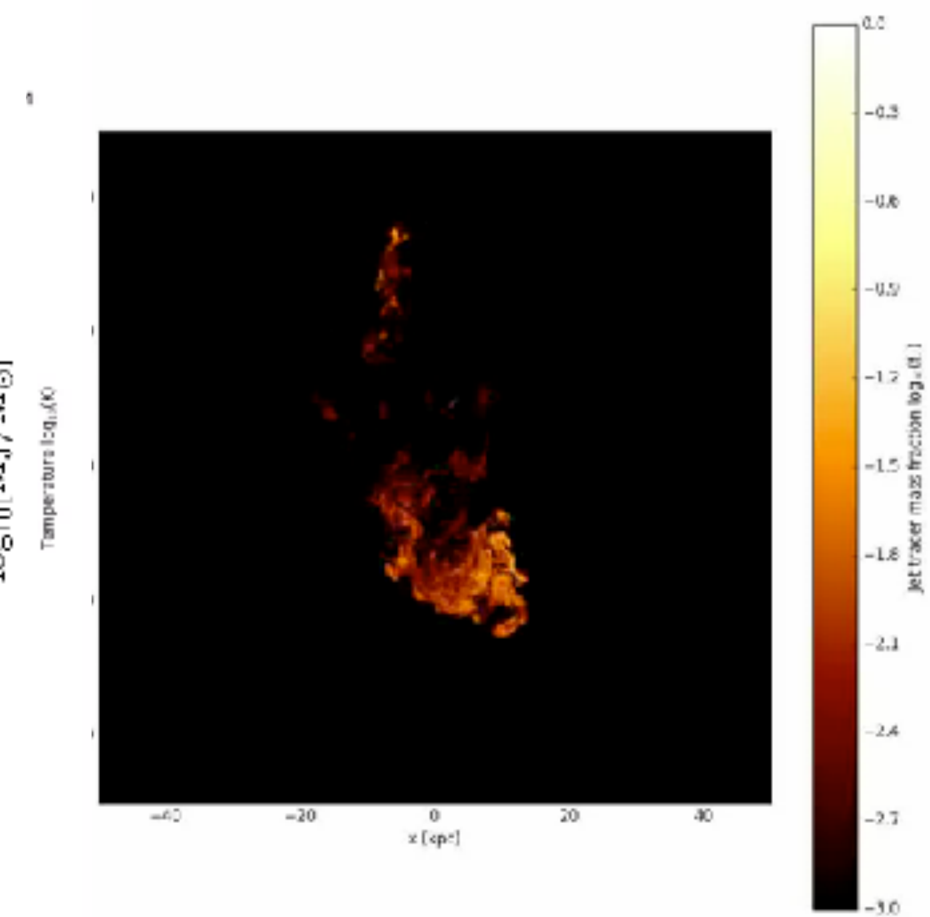


$$M_{200} \sim 4 \times 10^{14} M_{\odot}$$
$$R_{200} \sim 1.3\mathrm{Mpc}$$

$$M_{\mathrm{BH}} = 2.64 \times 10^{10} M_{\odot}$$
$$\dot{M}_{\mathrm{acc}} = 10^{-4} \dot{M}_{\mathrm{Edd}}$$
$$\dot{E}_{\mathrm{J}} \simeq 3.3 \times 10^{44} \mathrm{erg/s}$$

COSMOLOGICAL CLUSTER
(PRELIMINARY)

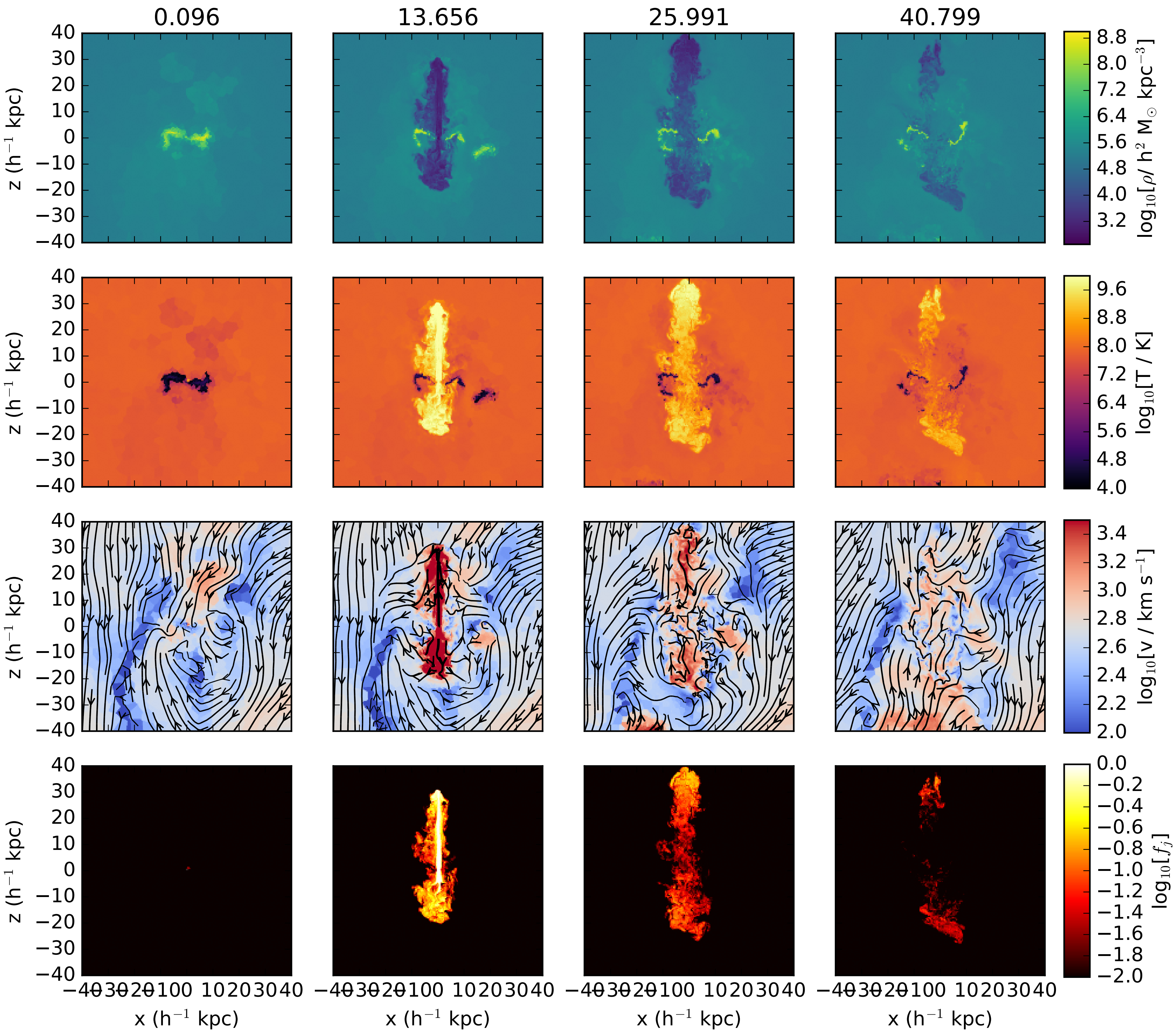




$$M_{200} \sim 4 \times 10^{14} M_\odot$$
$$R_{200} \sim 1.3\mathrm{Mpc}$$

$$M_{\rm BH} = 2.64 \times 10^{10} M_\odot$$
$$\dot{M}_{\rm acc} = 10^{-4} \dot{M}_{\rm Edd}$$
$$\dot{E}_{\rm J} \simeq 3.3 \times 10^{44} \mathrm{erg/s}$$

COSMOLOGICAL CLUSTER

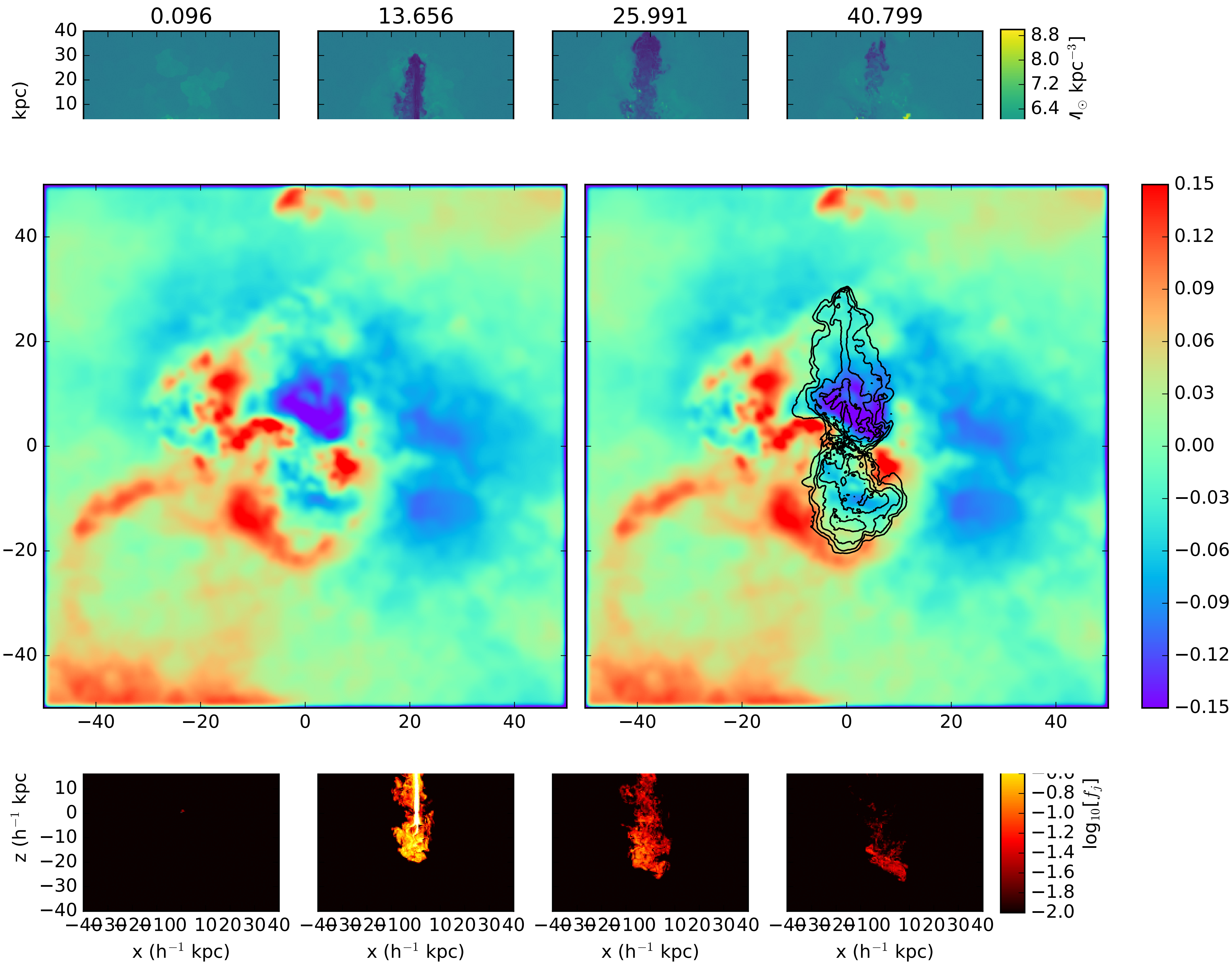


Lobes should be X-ray faint

No strong ICM shocks

Turbulence confined to jet material

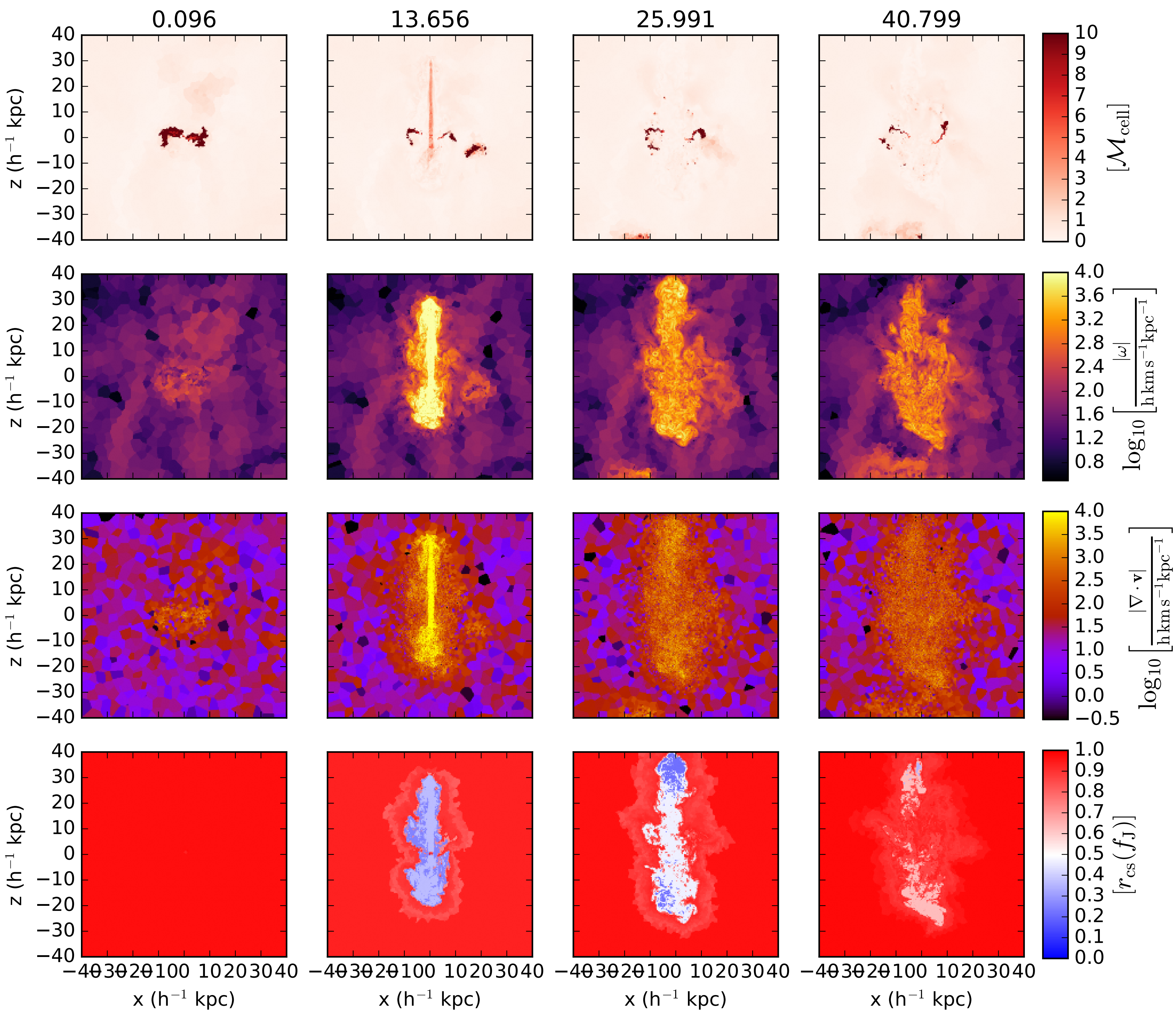
COSMOLOGICAL CLUSTER



No strong ICM shocks

Turbulence confined to jet material

COSMOLOGICAL CLUSTER

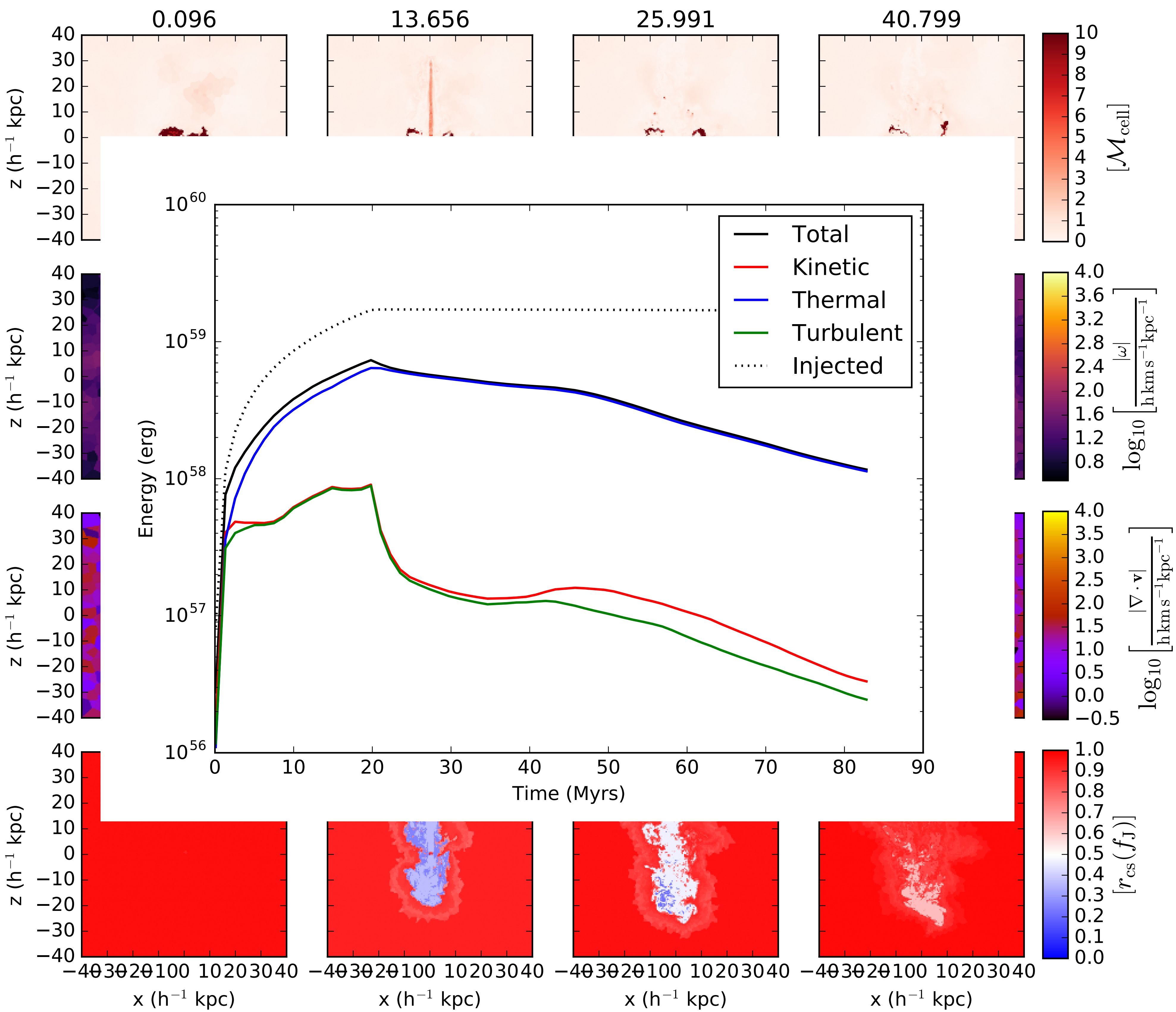


Lobes should be X-ray faint

No strong ICM shocks

Turbulence confined to jet material

COSMOLOGICAL CLUSTER



Lobes should be X-ray faint

No strong ICM shocks

Turbulence confined to jet material

SUMMARY

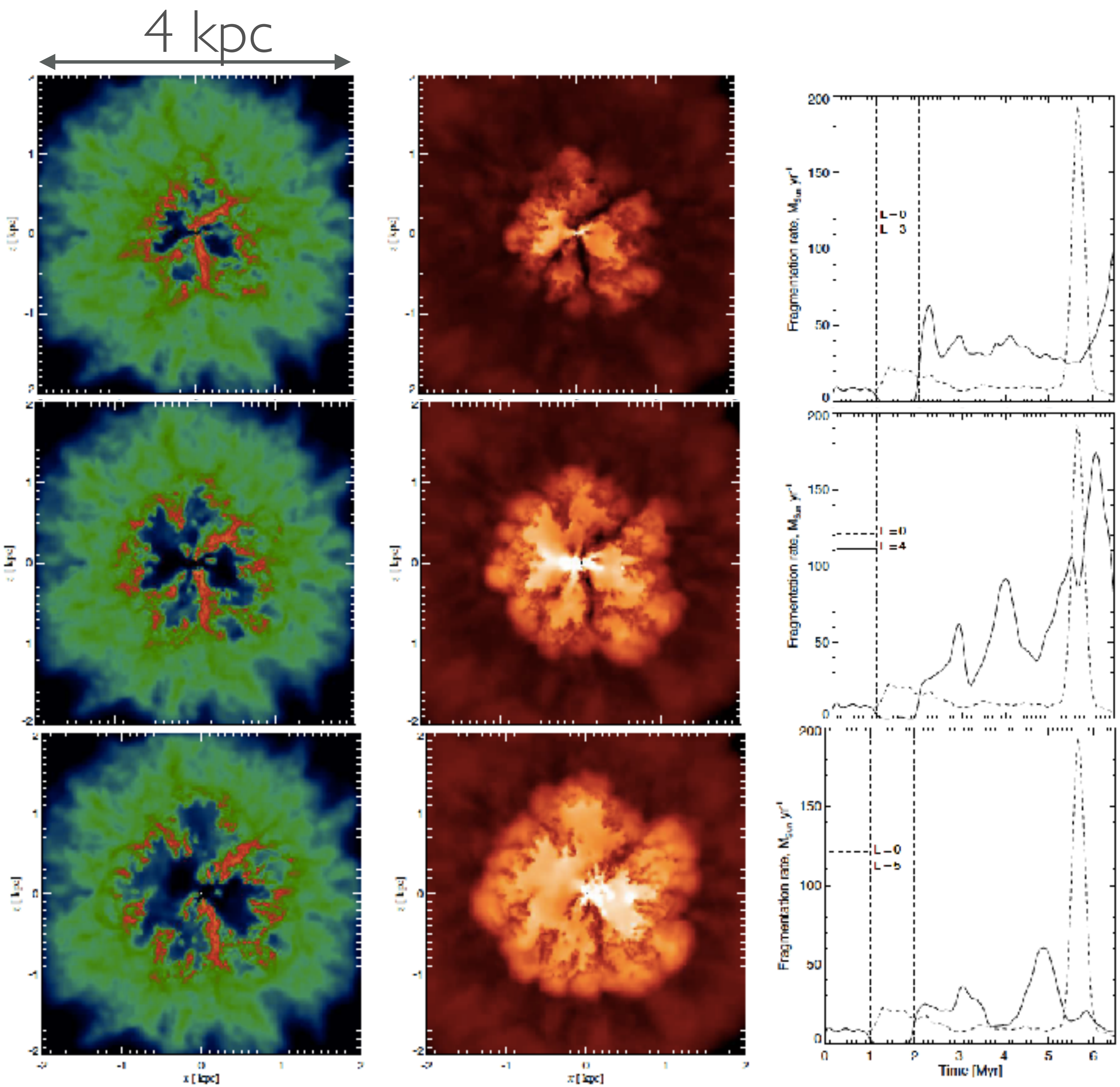
- AGN feedback is an important ingredient in simulations of galaxy formation, however, the large dynamic range in processes governing AGN feeding and feedback means simplifications need to be made - we are developing techniques to help ``bridge the gap''.

- We have developed a new model for Jet feedback in the moving mesh code AREPO, which allows the production of high resolution jets in coarser resolution simulations. We have considered the interaction of the jet lobes with the intracluster medium, including heating processes and the generation of turbulence (which is largely confined to the jet lobes).

- Substructure motions stir the ICM and generate turbulence, which can interact with and disrupt the jet cocoons and in the long term displace jet lobe positions and promote mixing. Such substructure motions and a jet are able to produce line-of-sight kinematics consistent with those observed in the Perseus cluster by Hitomi.

- Our new models are allowing us to include jet feedback in cosmological cluster simulations in order to consider lobe inflation and evolution in realistic cluster environments.

TRIGGERING STAR FORMATION



Consider wind feedback at different luminosities on turbulent gas distribution

Find a 'sweet spot' luminosity which results in maximum gas fragmentation

Find enhanced SF in filaments/clumps and at bubble edge

Observational signatures: enhanced star formation along edge of feedback bubbles, hyper-velocity stars, stars with radial orbits?

(Zubovas & Bourne, 2017)