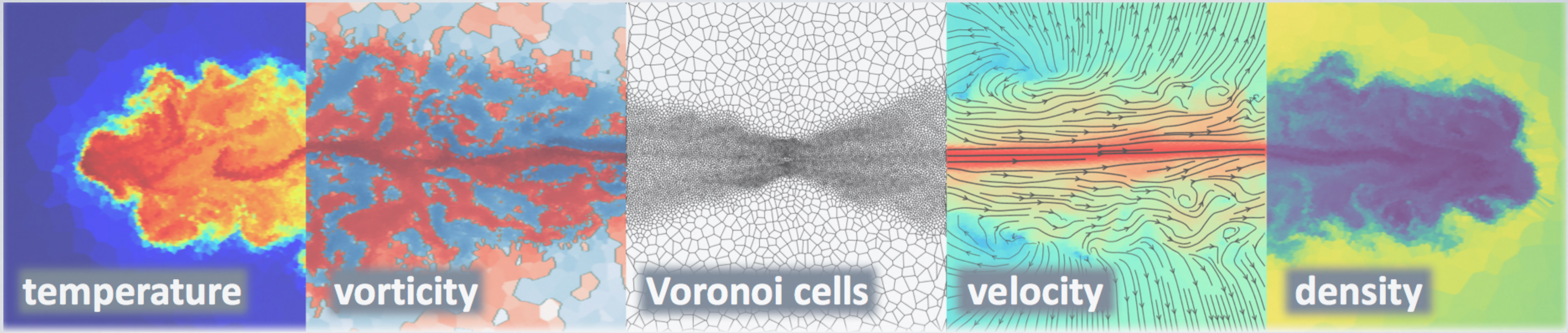
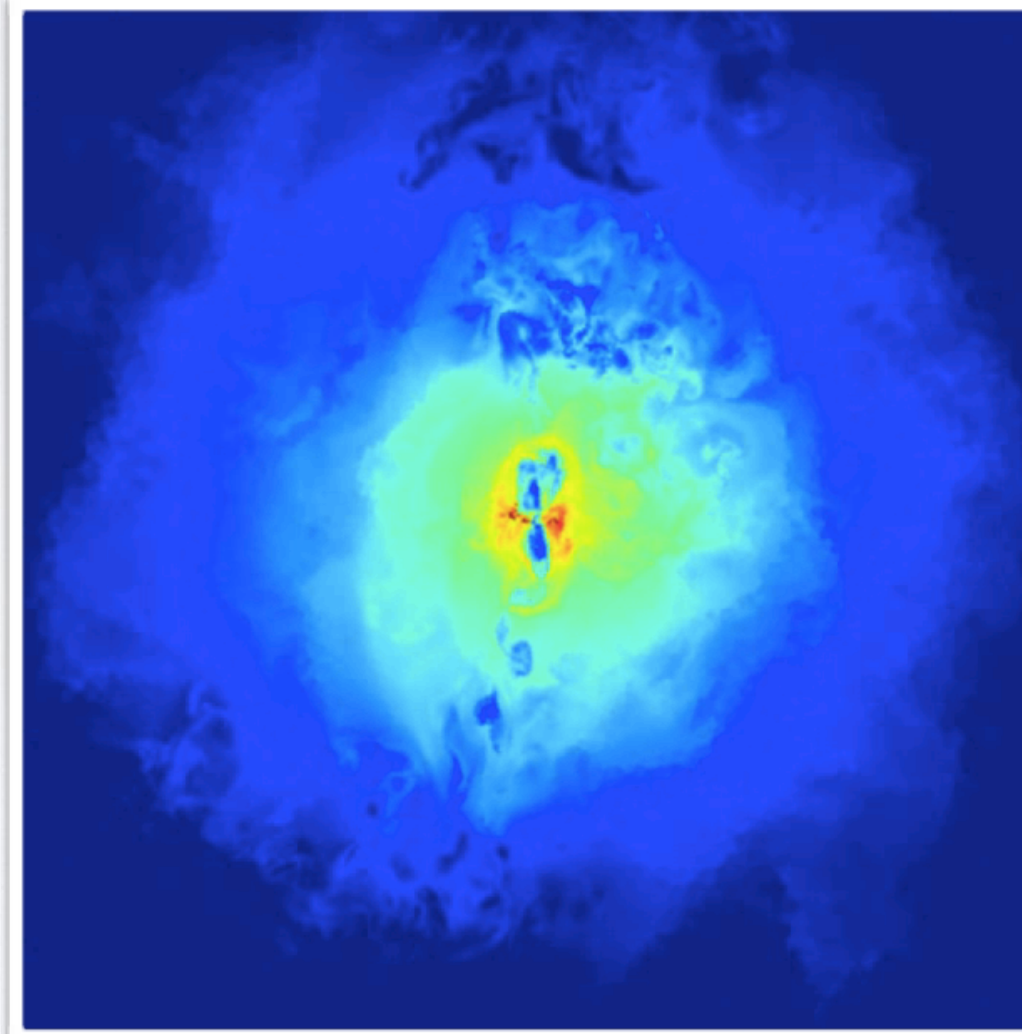


JET FEEDBACK IN GALAXY CLUSTERS



Martin Bourne

Collaborators: Debora Sijacki & Ewald Puchwein

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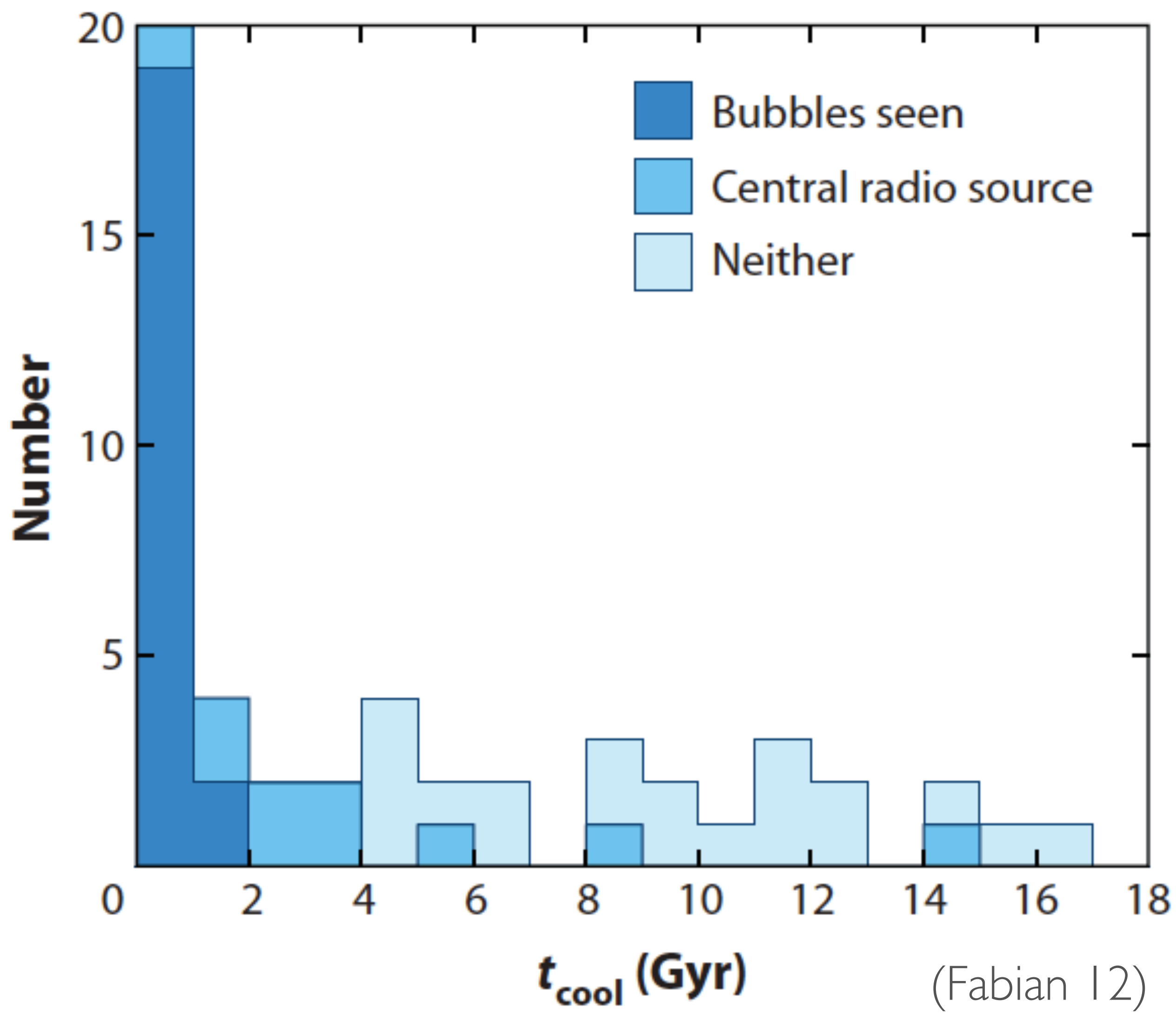
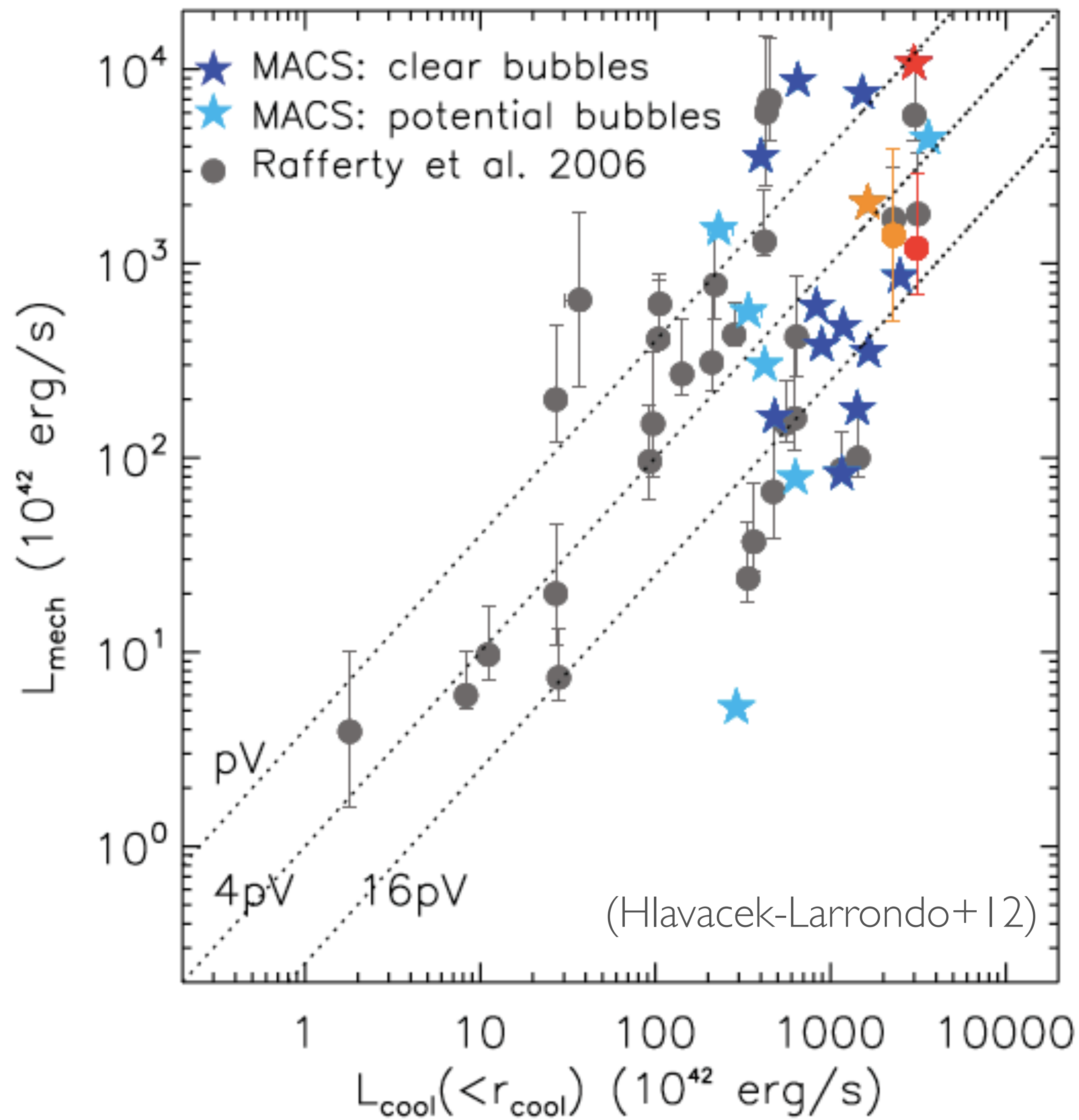
GALAXY CLUSTERS

(Image: Fabian+11)

FEEDBACK IN GALAXY CLUSTERS



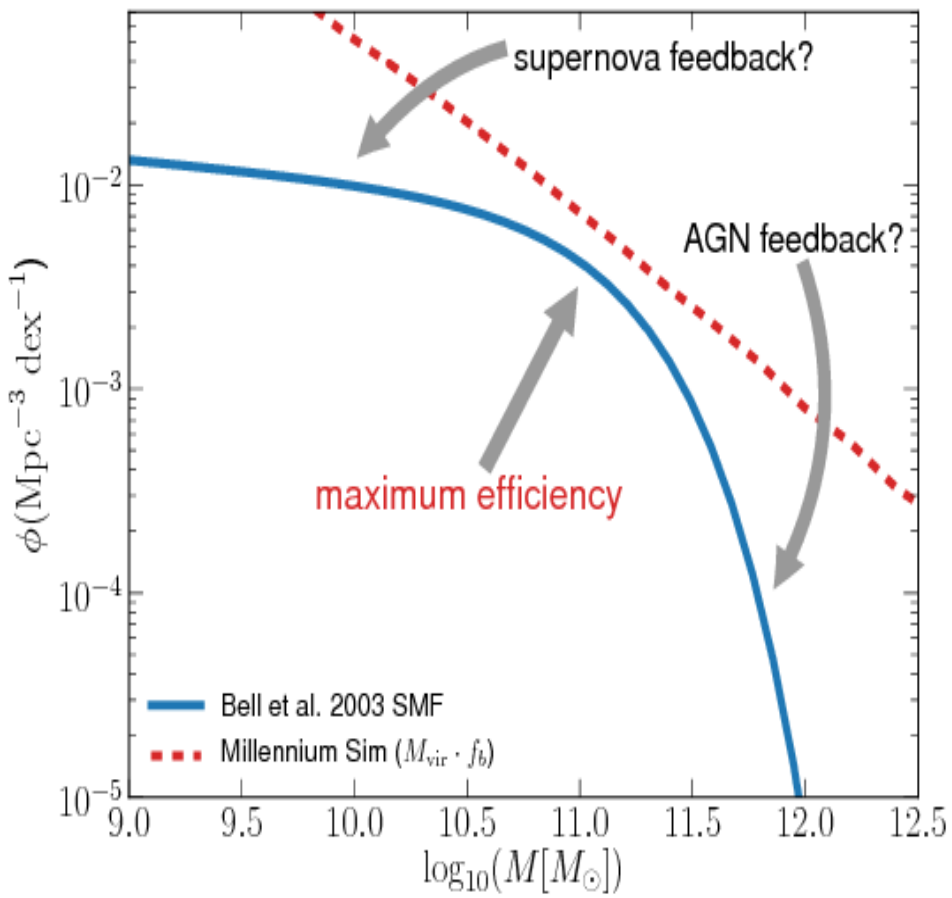
(Fabian 12)



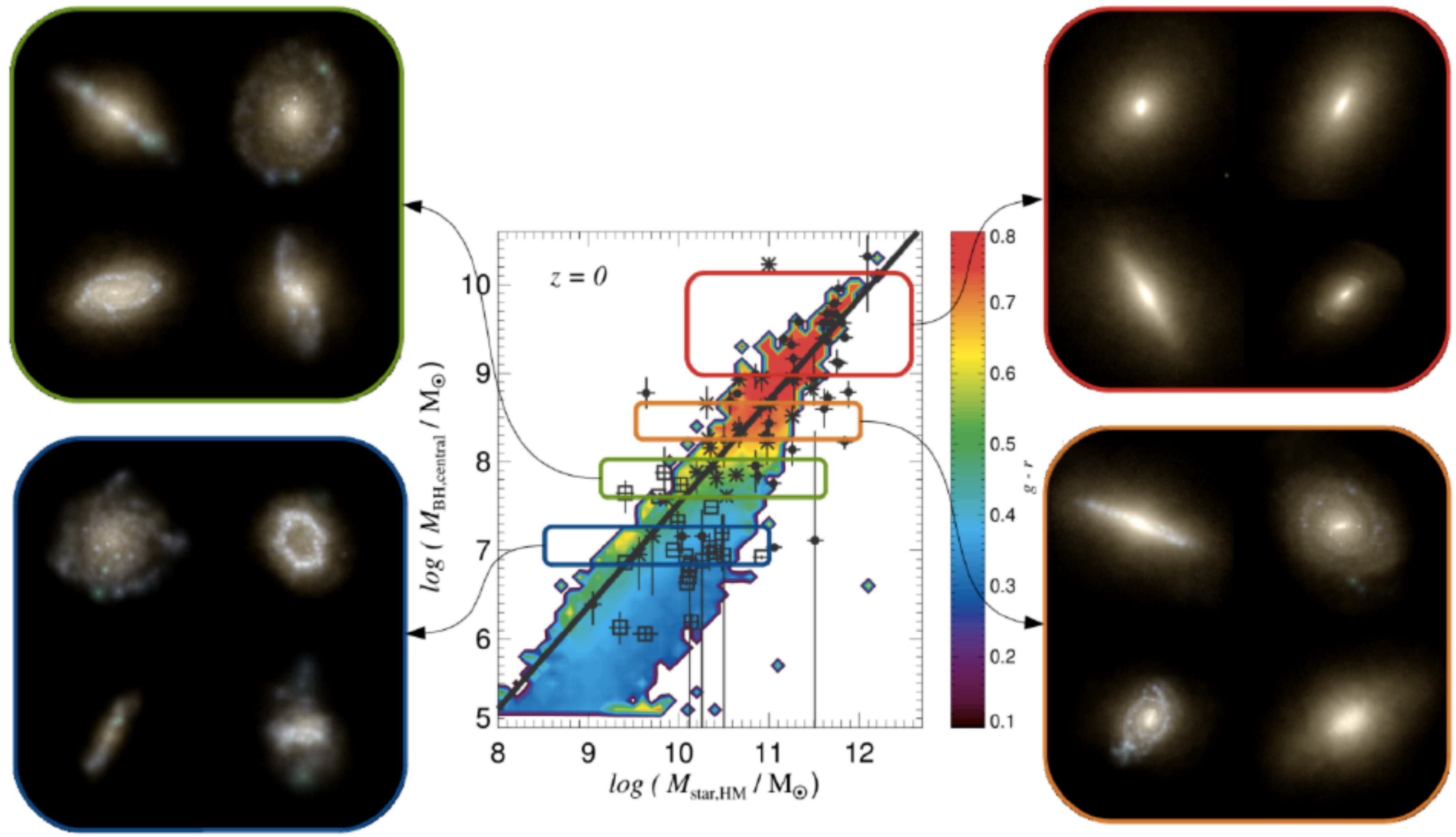
(Hlavacek-Larrondo+12)

A NECESSARY INGREDIENT

(Fig: Mutch+ 13)



(Fig: Sijacki+ 15)



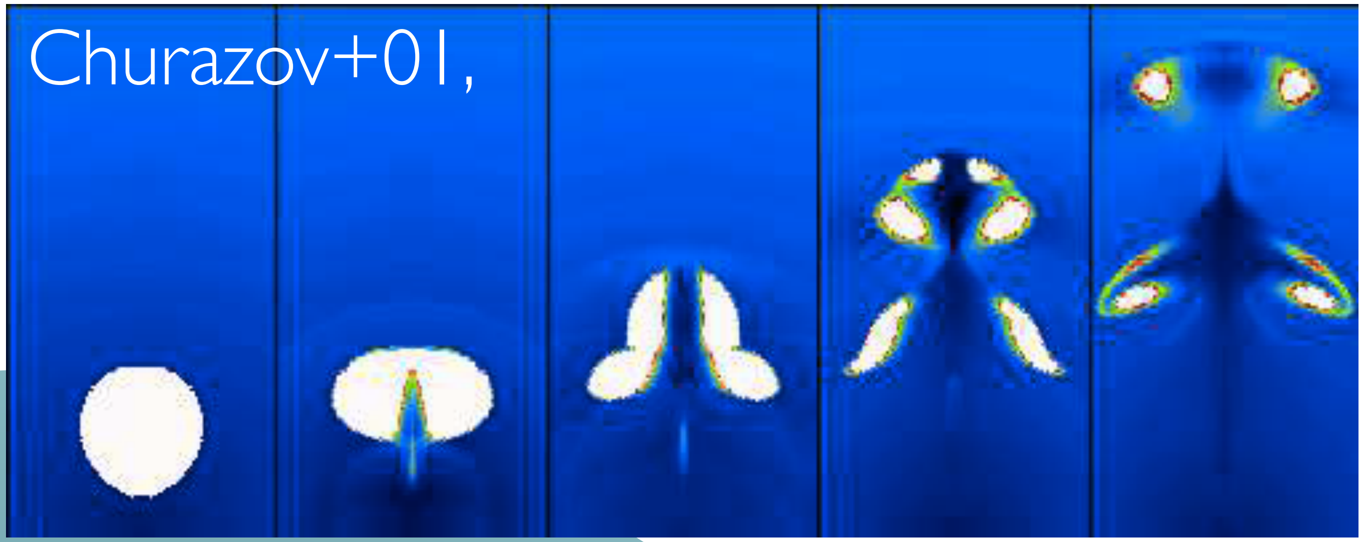
Quench star formation

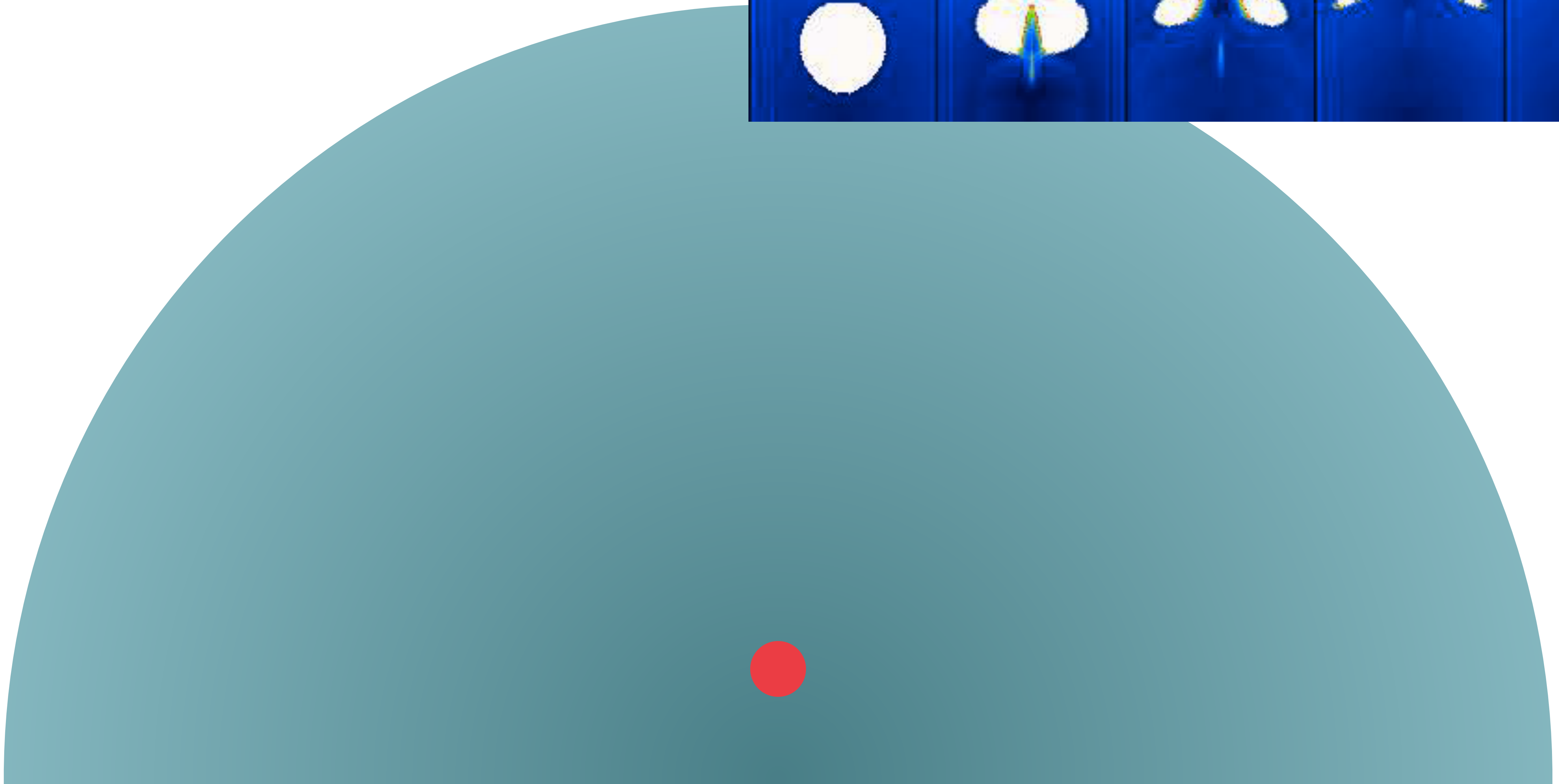
Regulate black hole growth

Produce realistic galaxies

BUBBLES AND LOBE INFLATION

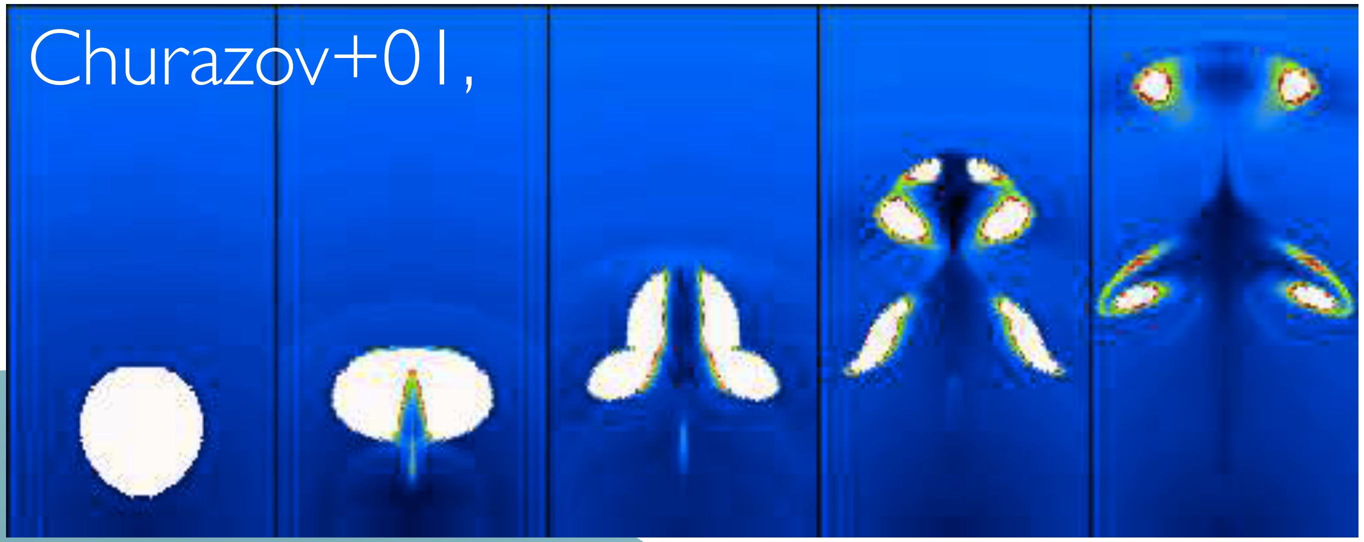
- Mimic effect of jets - hot bubbles
  (e.g. Churazov+01, Quilis+01, Sijacki+07)

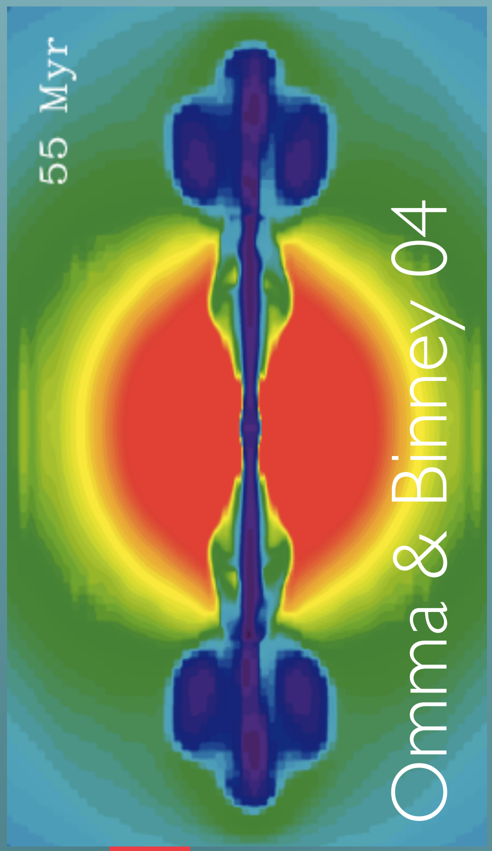


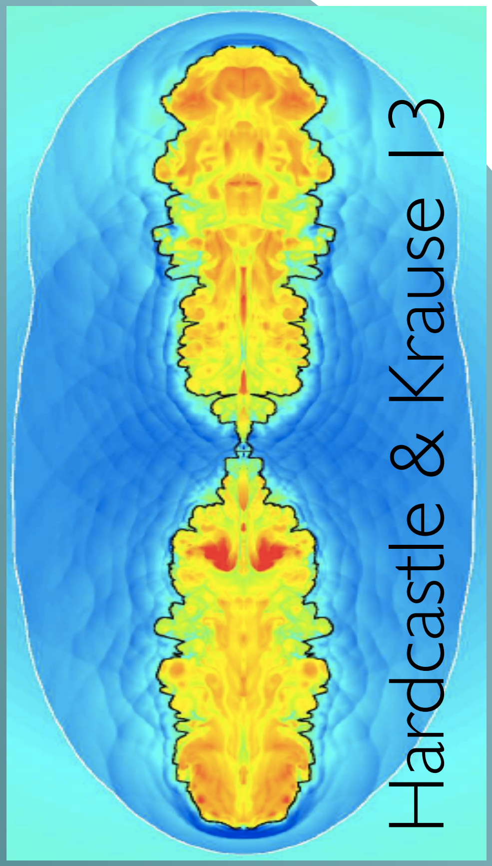


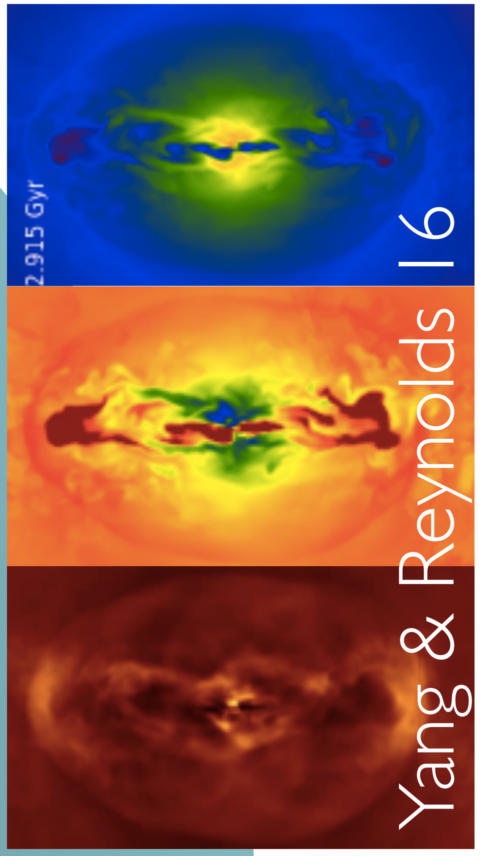
BUBBLES AND LOBE INFLATION

- Mimic effect of jets - hot bubbles (e.g. Churazov+01, Quilis+01, Sijacki+07)
- Inject jet momentum, energy & mass (e.g. Omma+04, Cattaneo+07, Gaspari+11, Li+14, Yang+16)
- Define thermodynamic & kinetic state (e.g.Krause+12, Hardcastle & Krause 13, Weinberger+17)



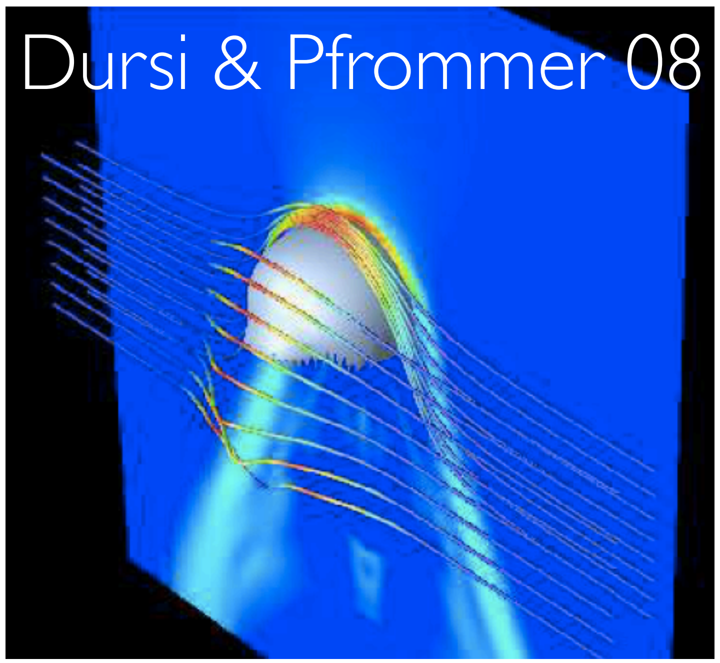






“ADDITIONAL” PHYSICS

MHD



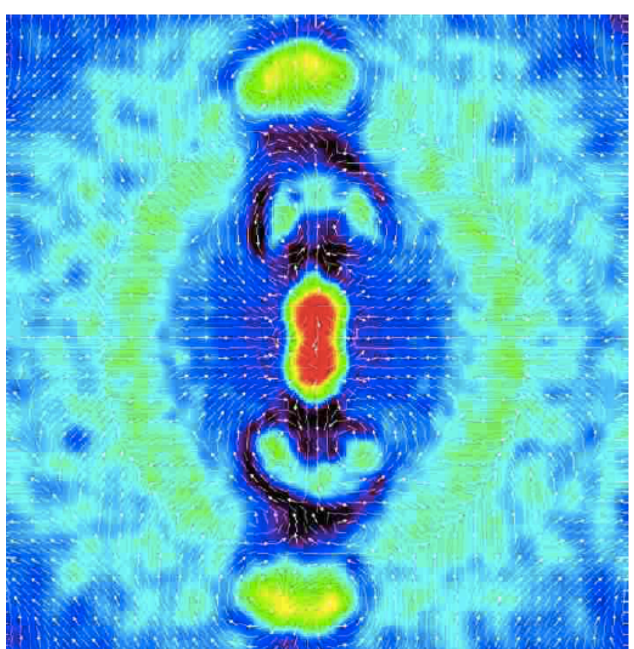
(also e.g. Ruszkowski+07, Hardcastle & Krause 14)

Cosmic Ray Physics
e.g. Weinberger+17

Relativistic Effects
e.g. English+16

Thermal Conduction
e.g. Yang&Reynolds 16, Kannan+17

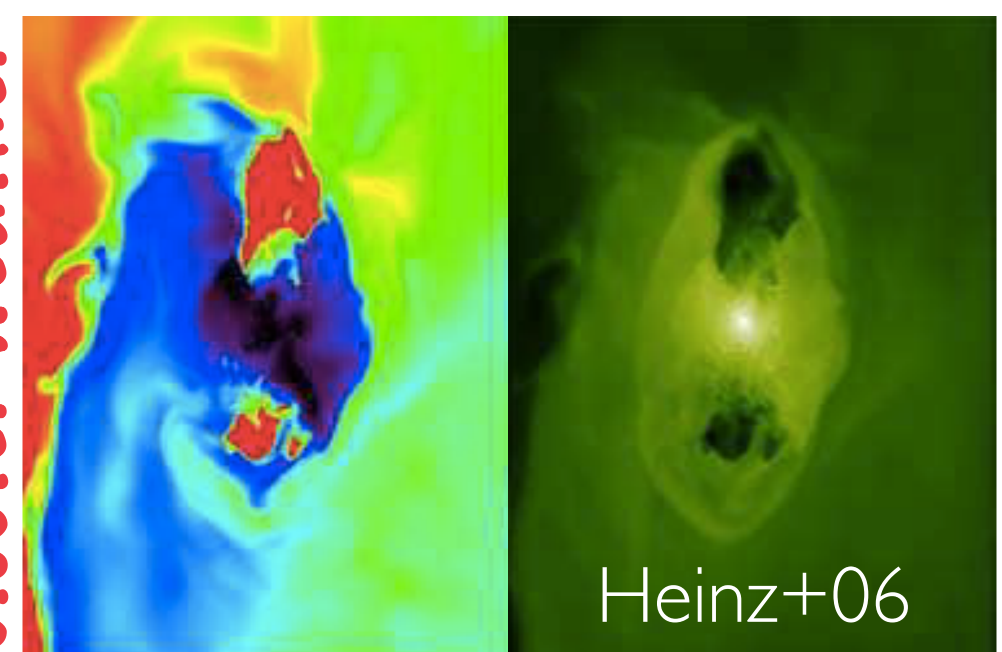
Viscosity



Sijacki & Springel 06

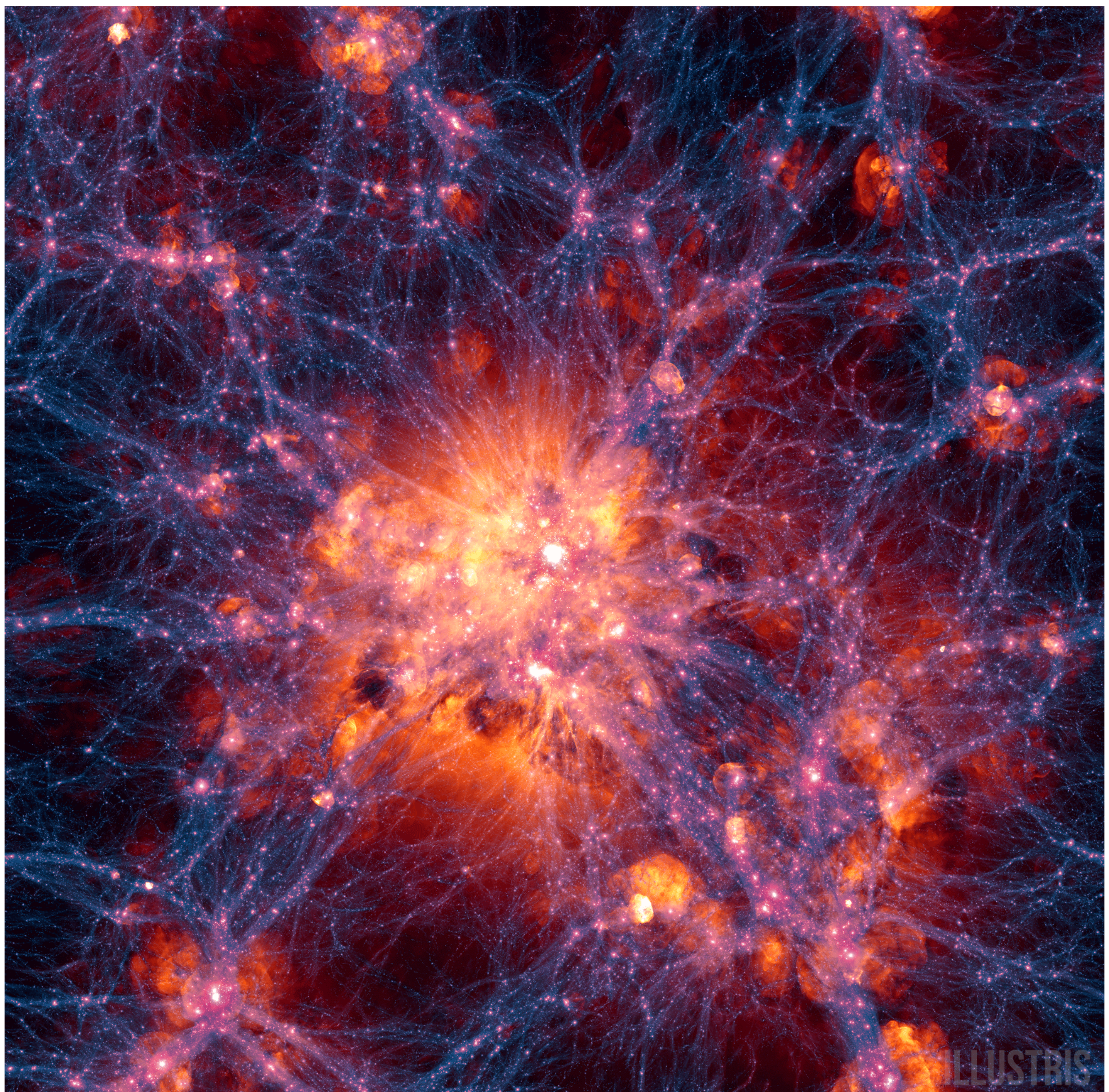
(also e.g. Ruszkowski+04)

Cluster weather



(also e.g. Mendygral+12)

"JET" MODE FEEDBACK IN LARGE SCALE SIMULATIONS



$$\chi = \dot{M}_{\rm BH}/\dot{M}_{\rm Edd}$$
$$\chi < \chi_{radio}$$

Bubbles - Illustris
(Sijack+15)

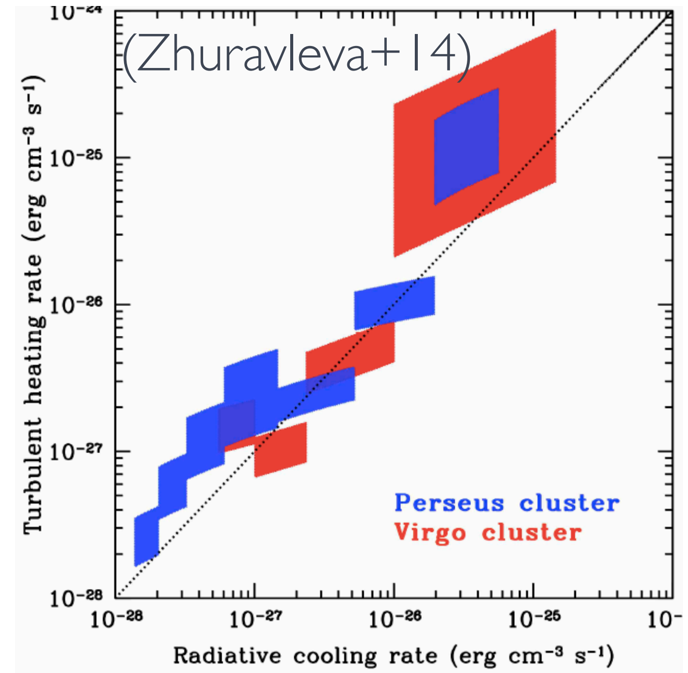
Collimated kinetic outflow - Horizon AGN
(Dubois+16)

$$\chi < min\left[0.002\left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)^2, 0.1\right]$$

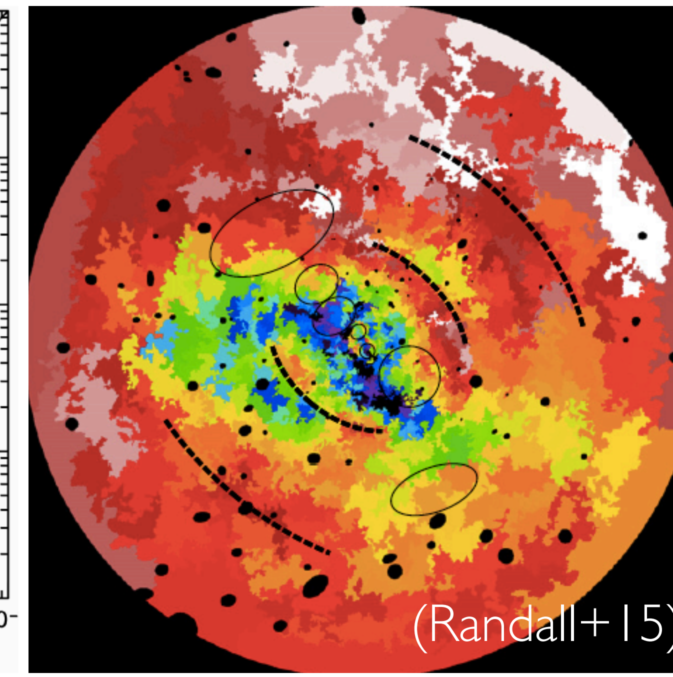
Stochastically directed kinetic injection - Illustris TNG
(Weinberger+18)

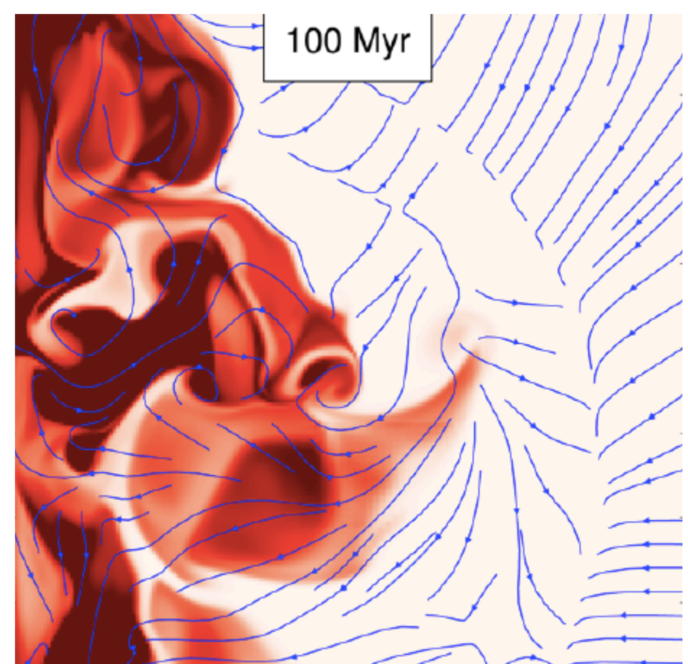
ENERGY TRANSFER MECHANISMS

- 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)

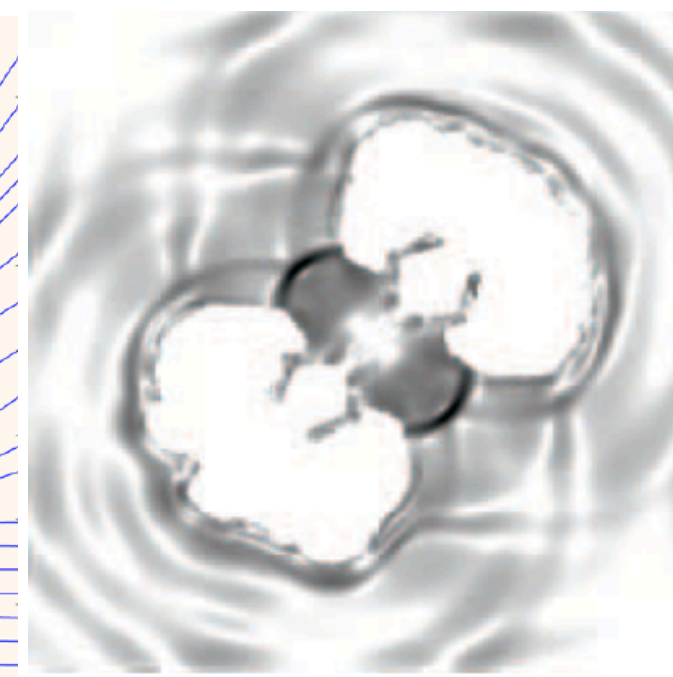


(Zhuravleva+14)


(Randall+15)

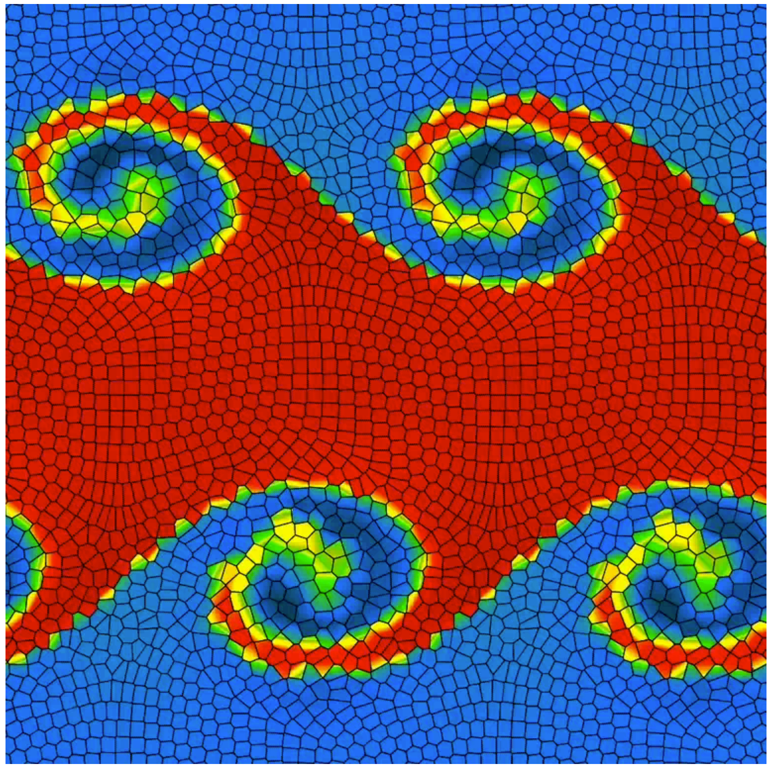


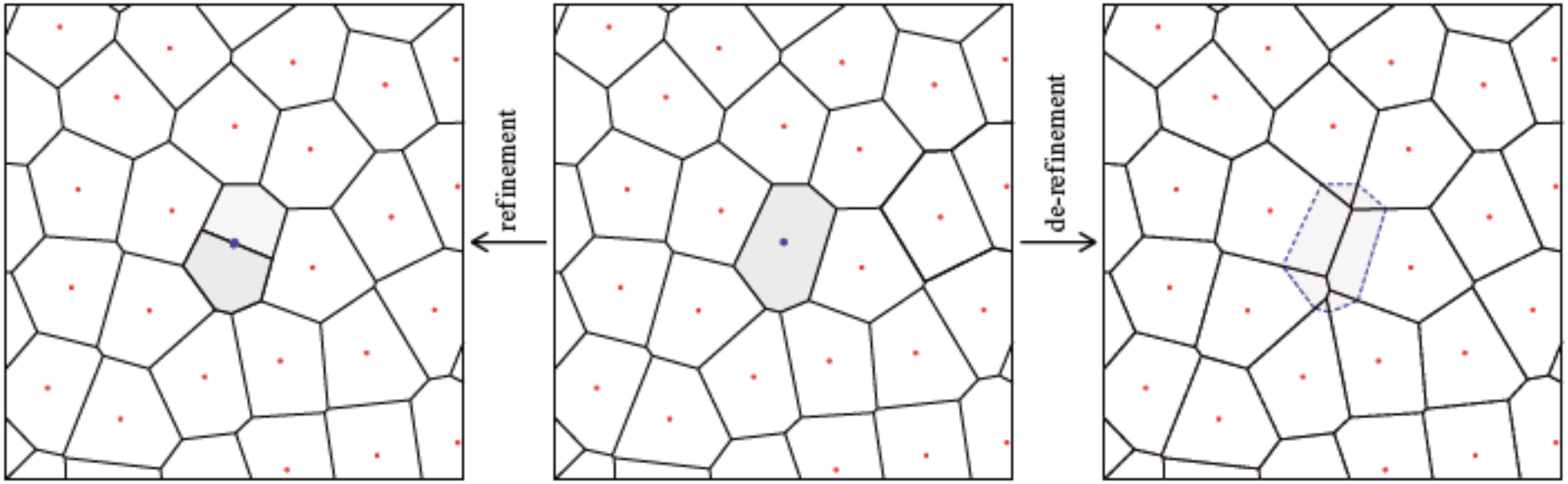
(Hillel & Soker 16)


(Ruszkowski+04)

AREPO (Springel 2010)

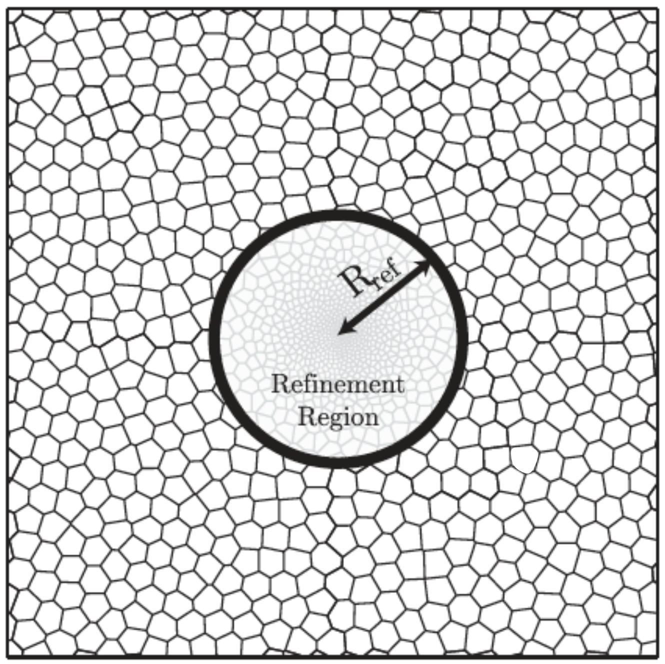
- Moving mesh - Voronoi cells with fixed target mass
- Lagrangian/Eulerian hybrid
- Super-Lagrangian refinement method
- Primordial radiative cooling
- Sub-grid ISM and star formation model (Springel & Hernquist 03)
- Modified black hole feedback and accretion



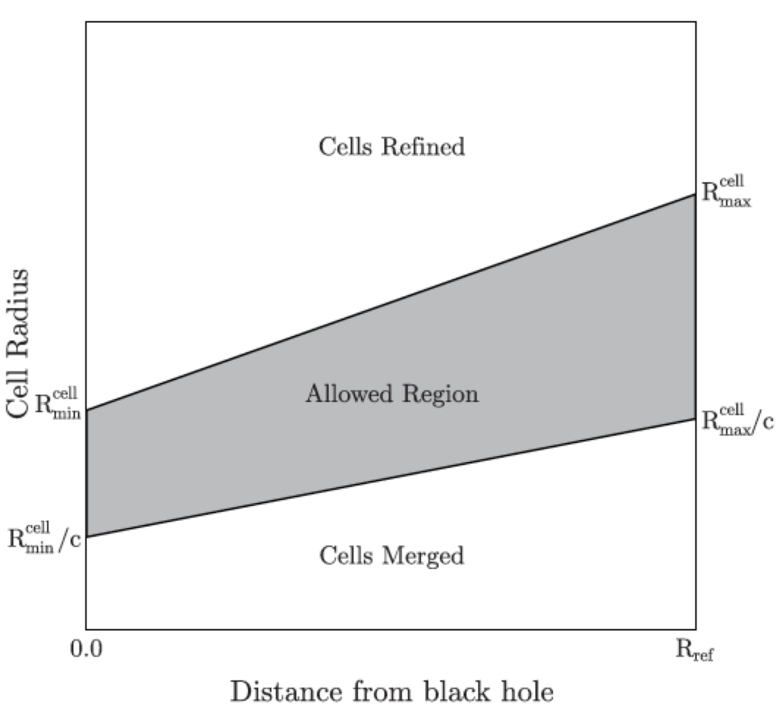


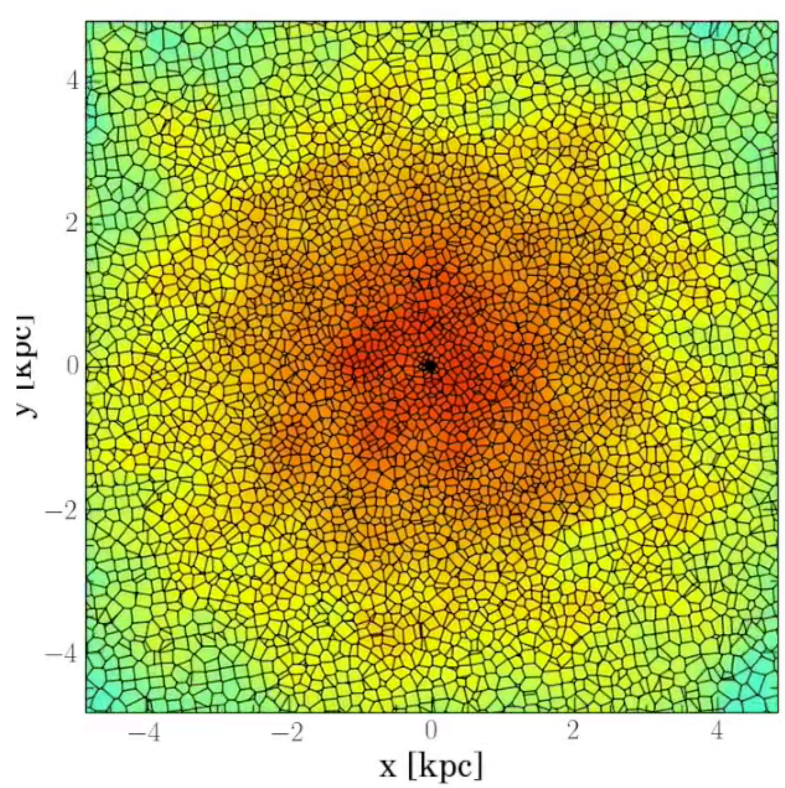
BLACK HOLE REFINEMENT SCHEME

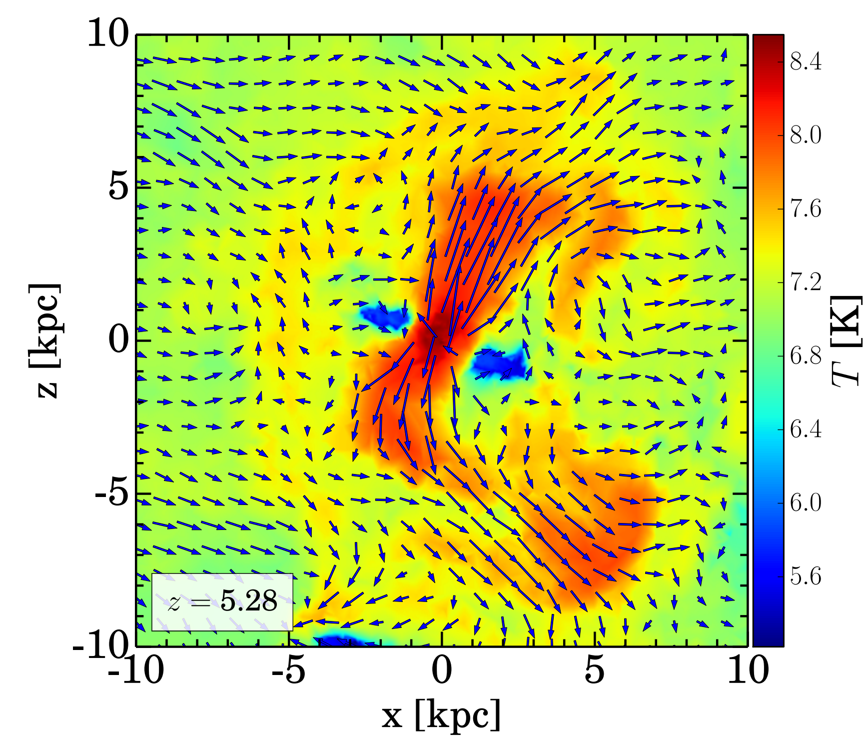
(Curtis & Sijacki 15, 16)



- 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





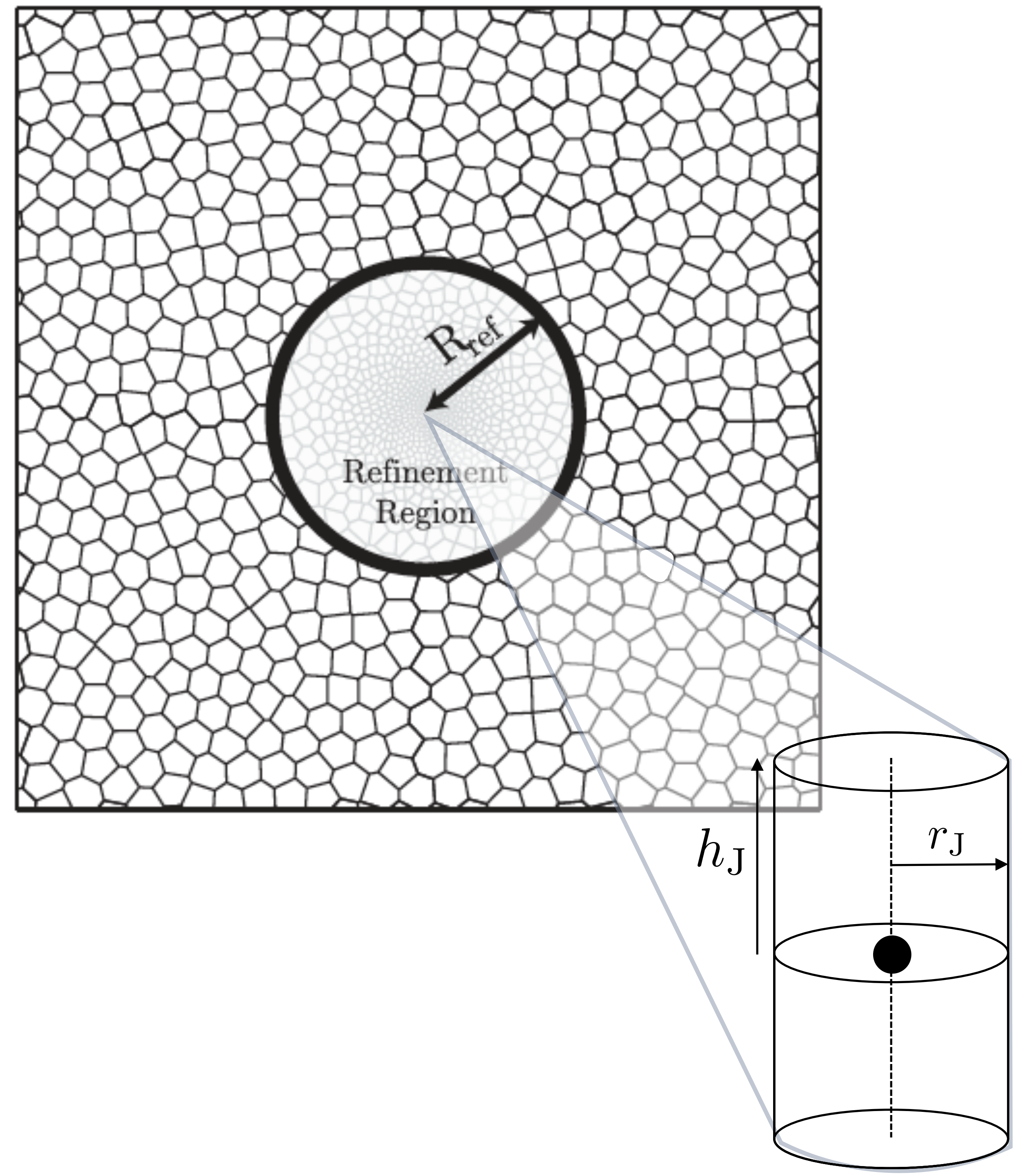


INJECTING THE JET

Define a cylinder of fixed mass (or volume)

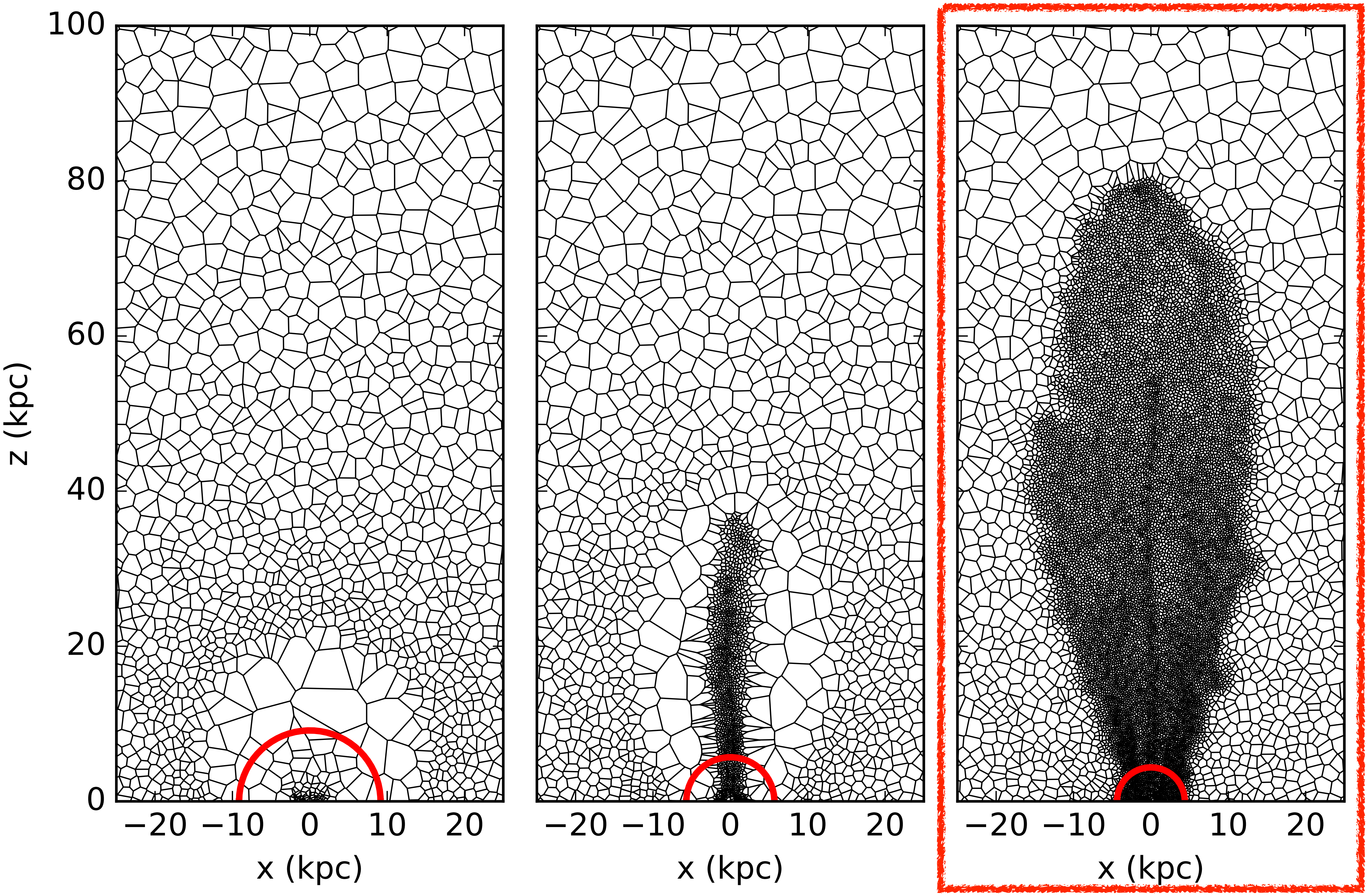
Inject mass, momentum and energy into cells within the cylinder

(e.g. Cattaneo & Teyssier 07, Dubois+10, Yang+12)



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

REFINEMENT



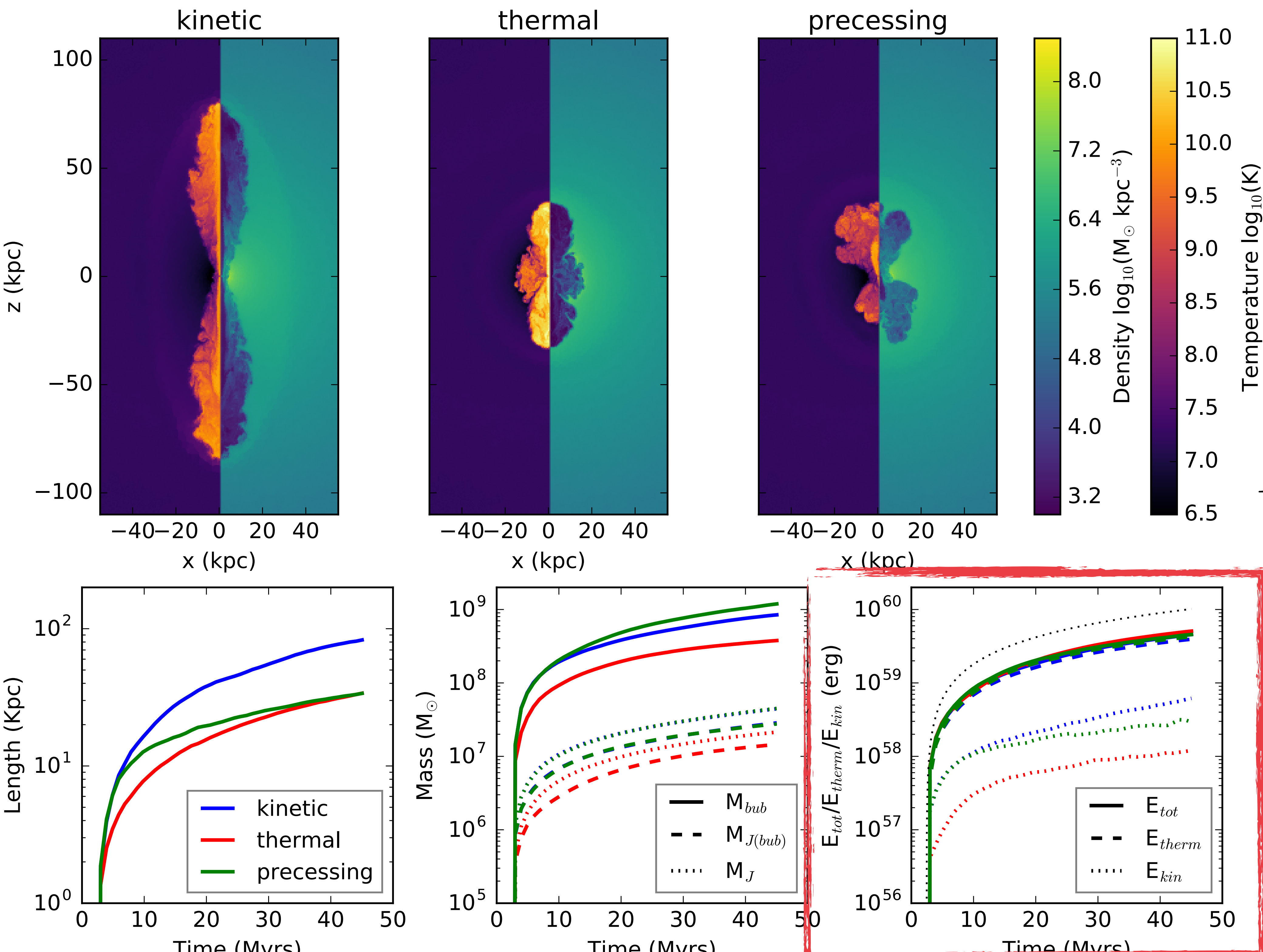
smallest cell
~ 10 pc

R_{vir}
~750 kpc

Less harsh de-refinement

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

INJECTION METHOD



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

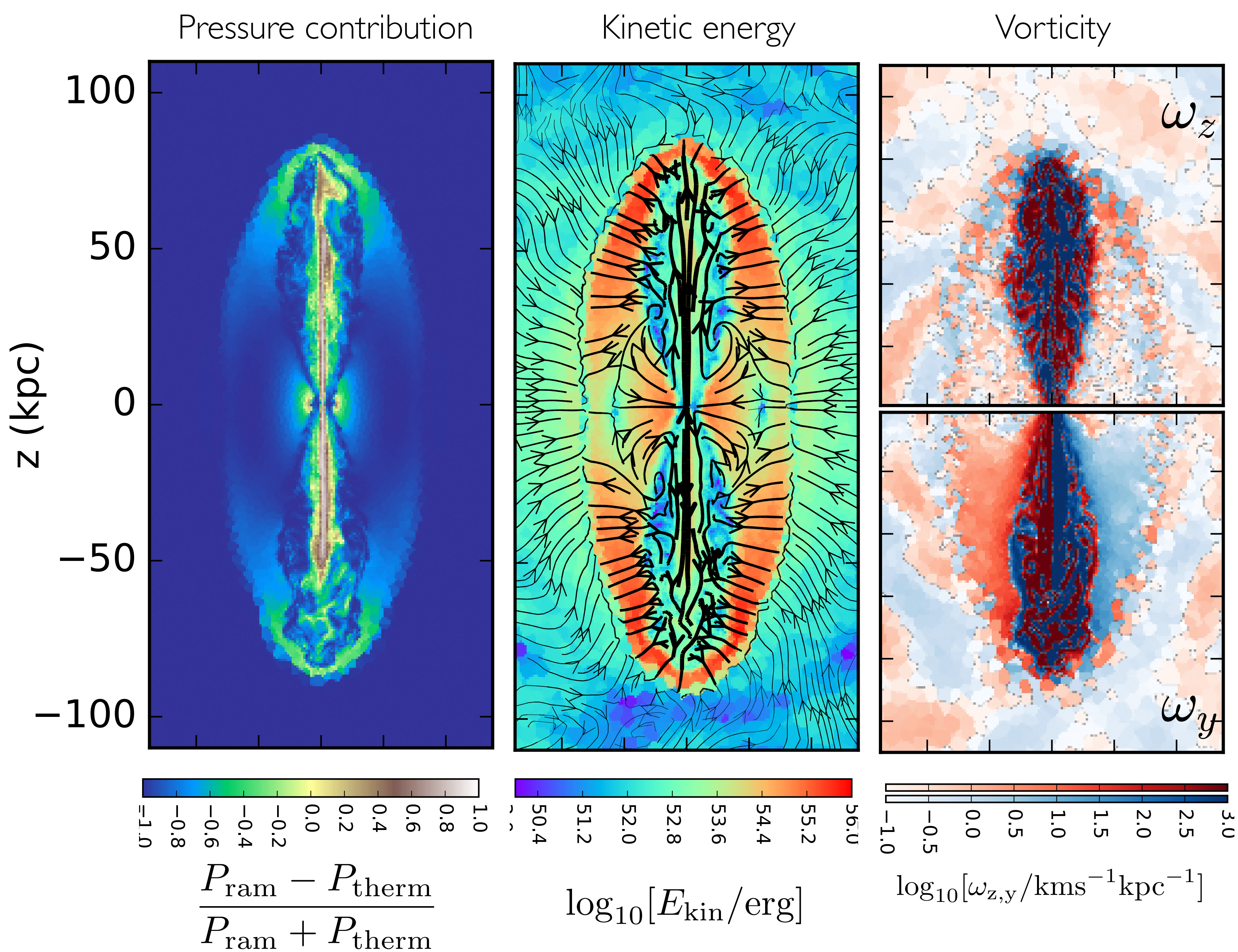
$$M_{\rm BH,0} = 10^{9} M_\odot$$

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

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

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

JET INFLATION AND GAS FLOWS



Bow shock persists

Perpendicular shock broadens into sound wave

Shell:

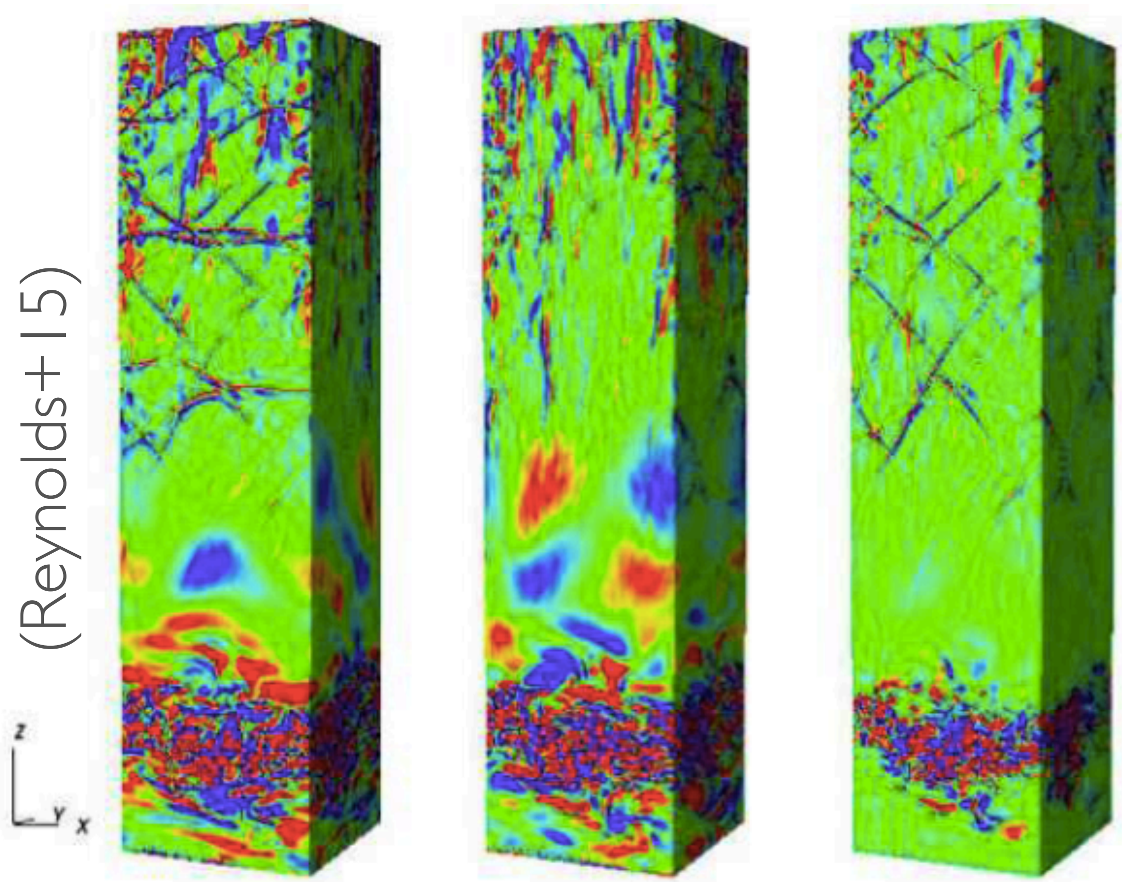
$E_k \sim 10\% \ E_{Inj}$

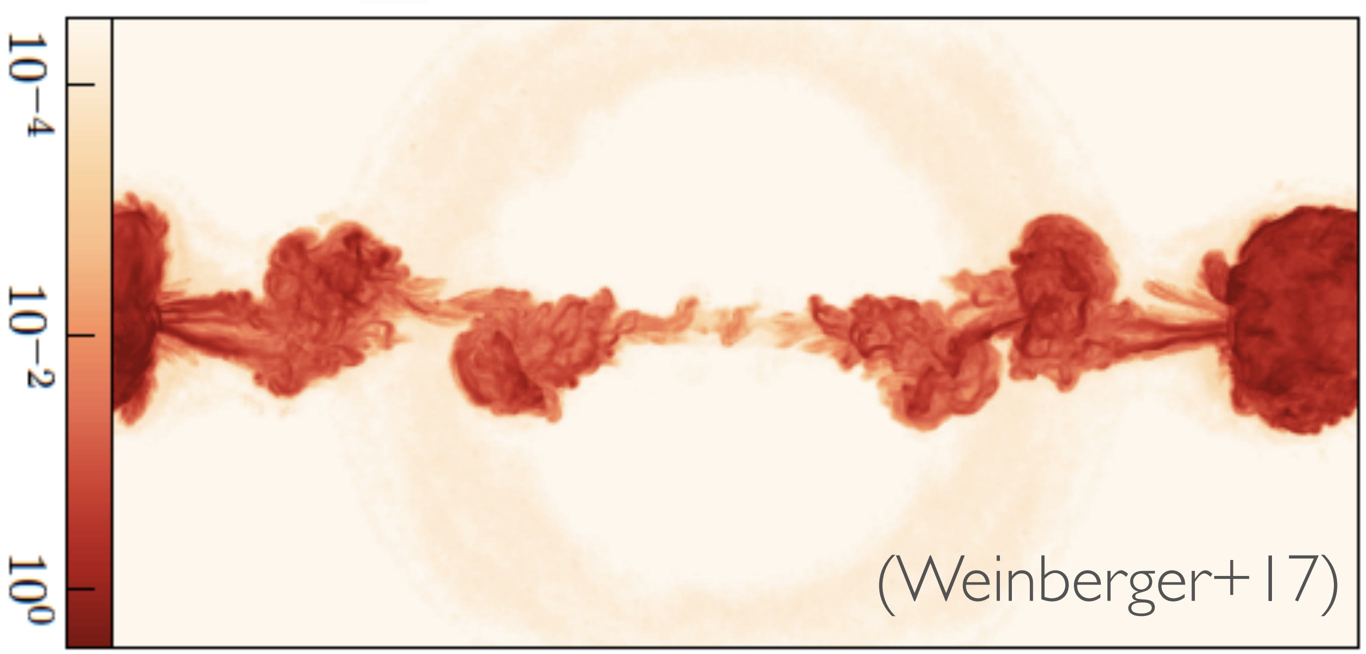
Lobe displaces ~ 10^{10}-10^{11} M_{sol}

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

VORTICITY GENERATION

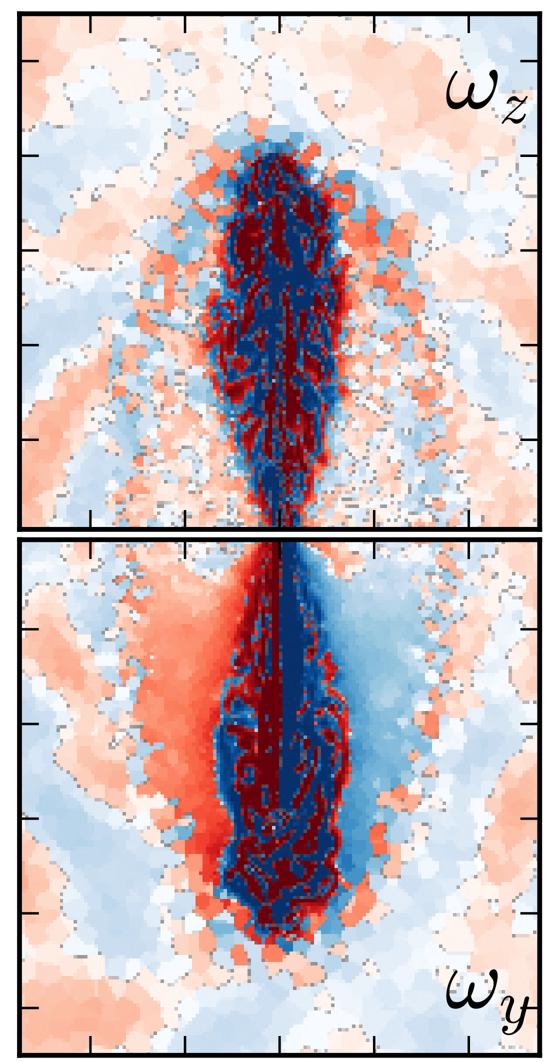
(Reynolds+15)





(Weinberger+17)

Vorticity



$$E_{\rm turb}^{\rm lobe} < E_{\rm kin}^{\rm lobe}$$

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:

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

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

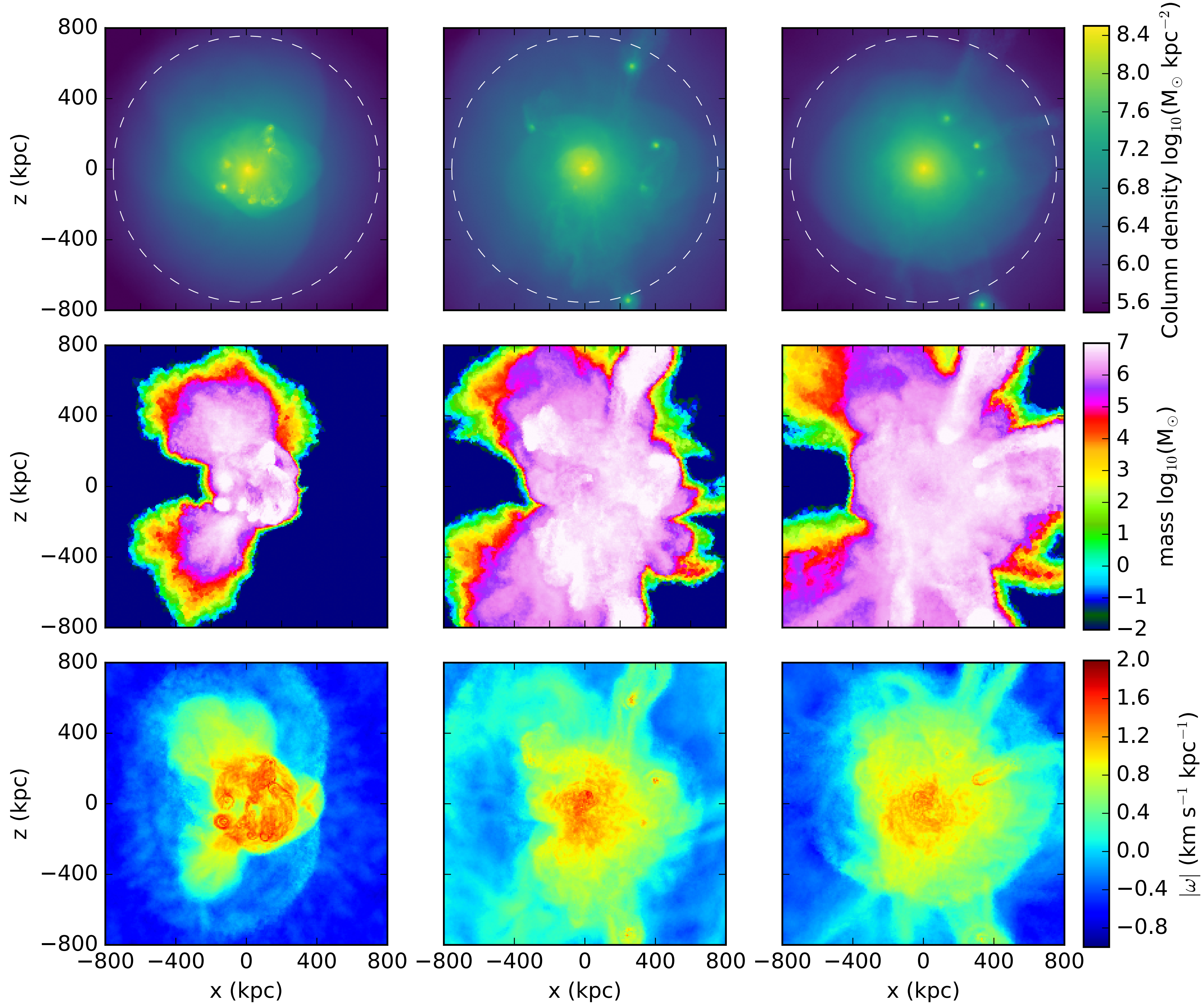
TURBULENCE IN THE ICM

Observations - ICM contains a *small* turbulent component

(e.g., Sanders+11,12,13, Pinto+15, Hitomi+16)

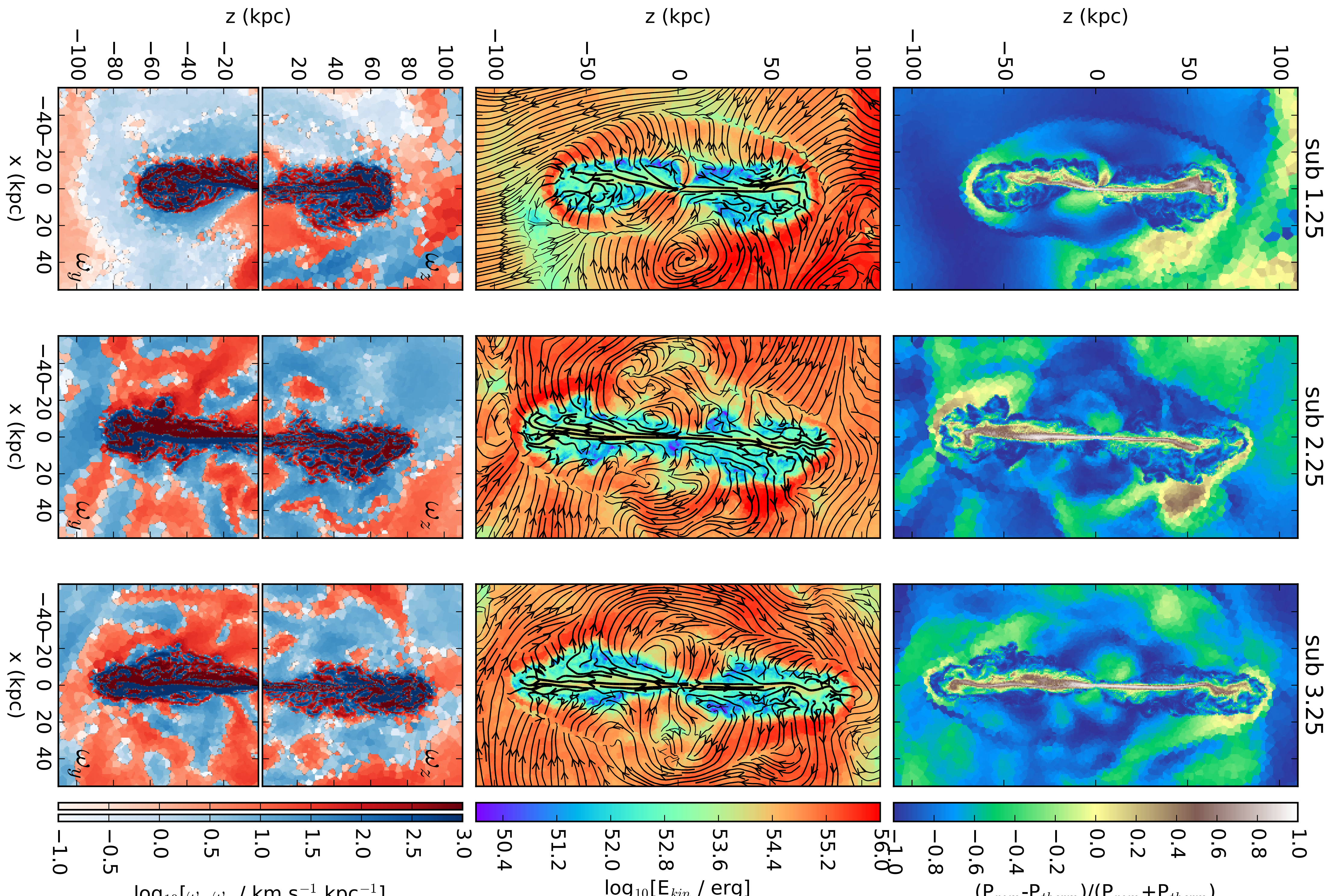
Add sub halos by hand to stir ICM

Produce turbulence and vorticity



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

JETS IN A TURBULENT ICM



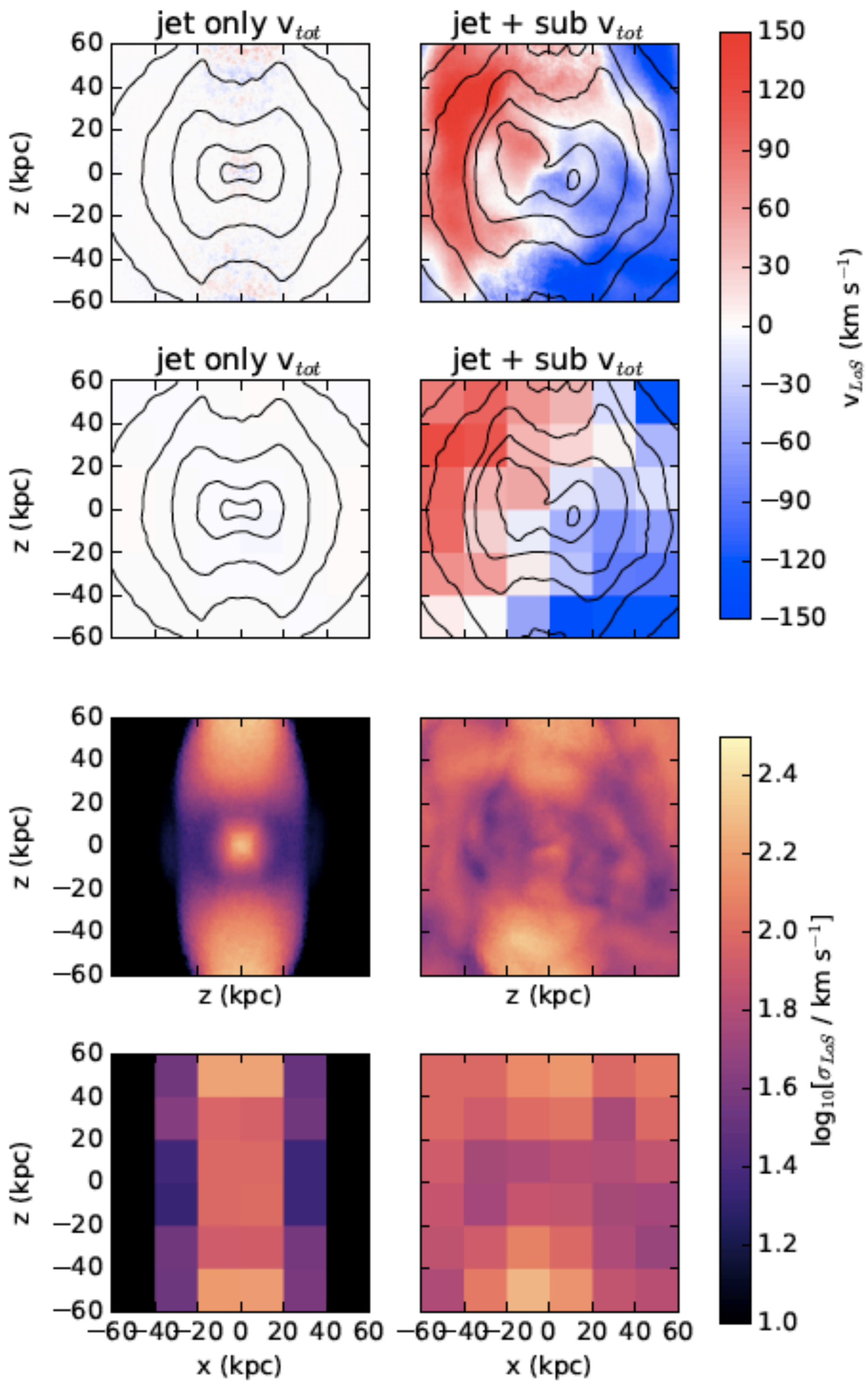
Pre-existing motions disrupt the jet cocoon

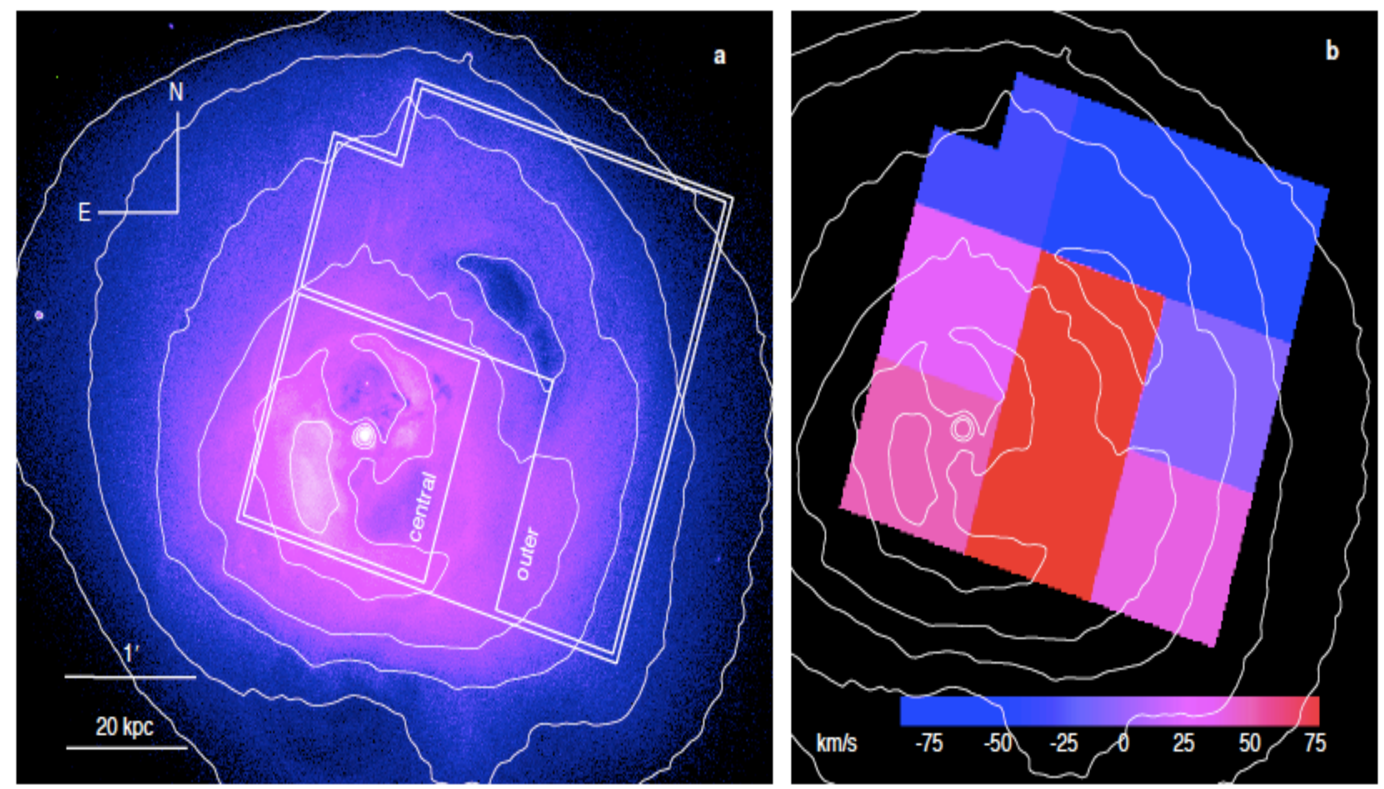
High levels of existing vorticity/turbulence

(Bourne & Sijacki, 17)

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

SUBSTRUCTURE MOTIONS & COMPARISON WITH HITOMI



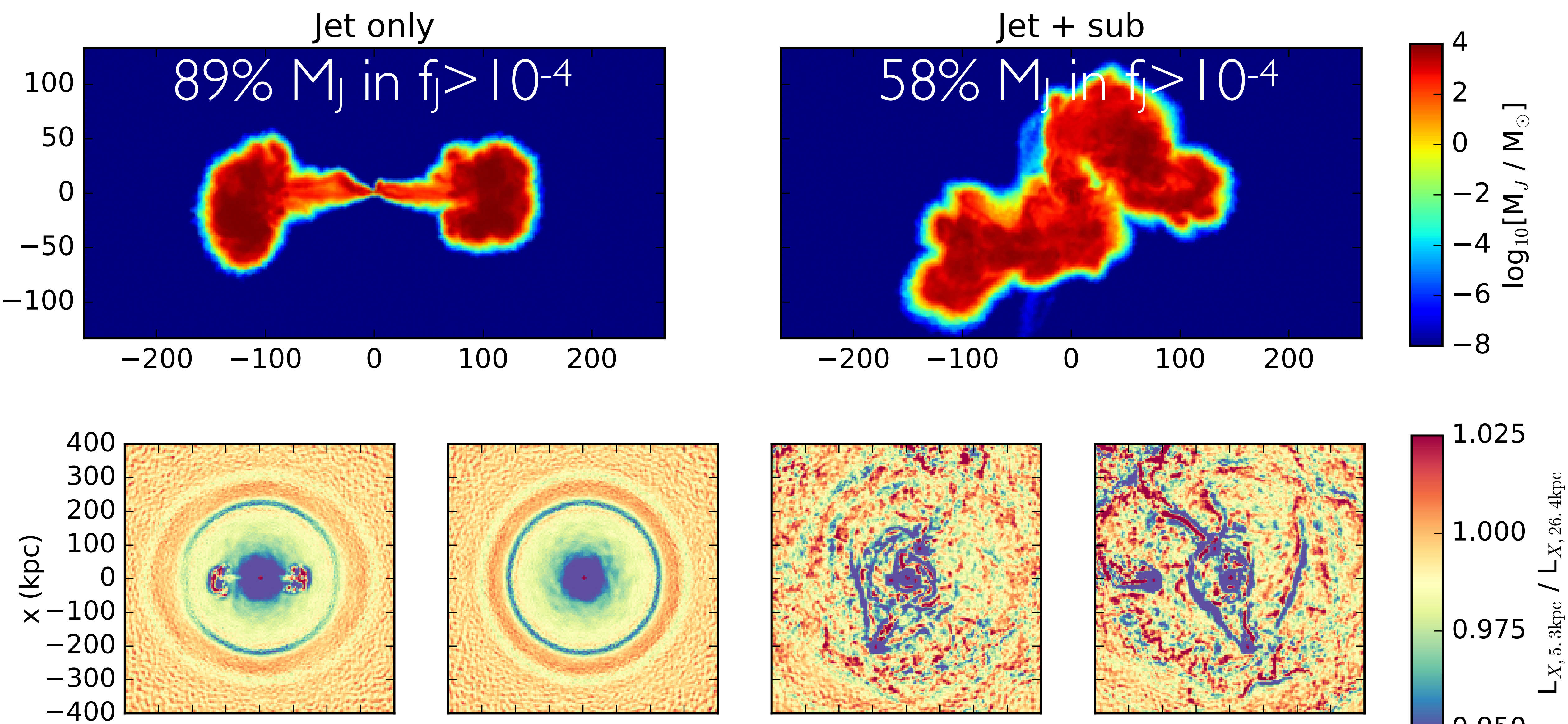


(Fig: Hitomi Collaboration 16)

Able to reproduce kinematics and X-ray features consistent with Hitomi when a jet and substructure motions are included

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

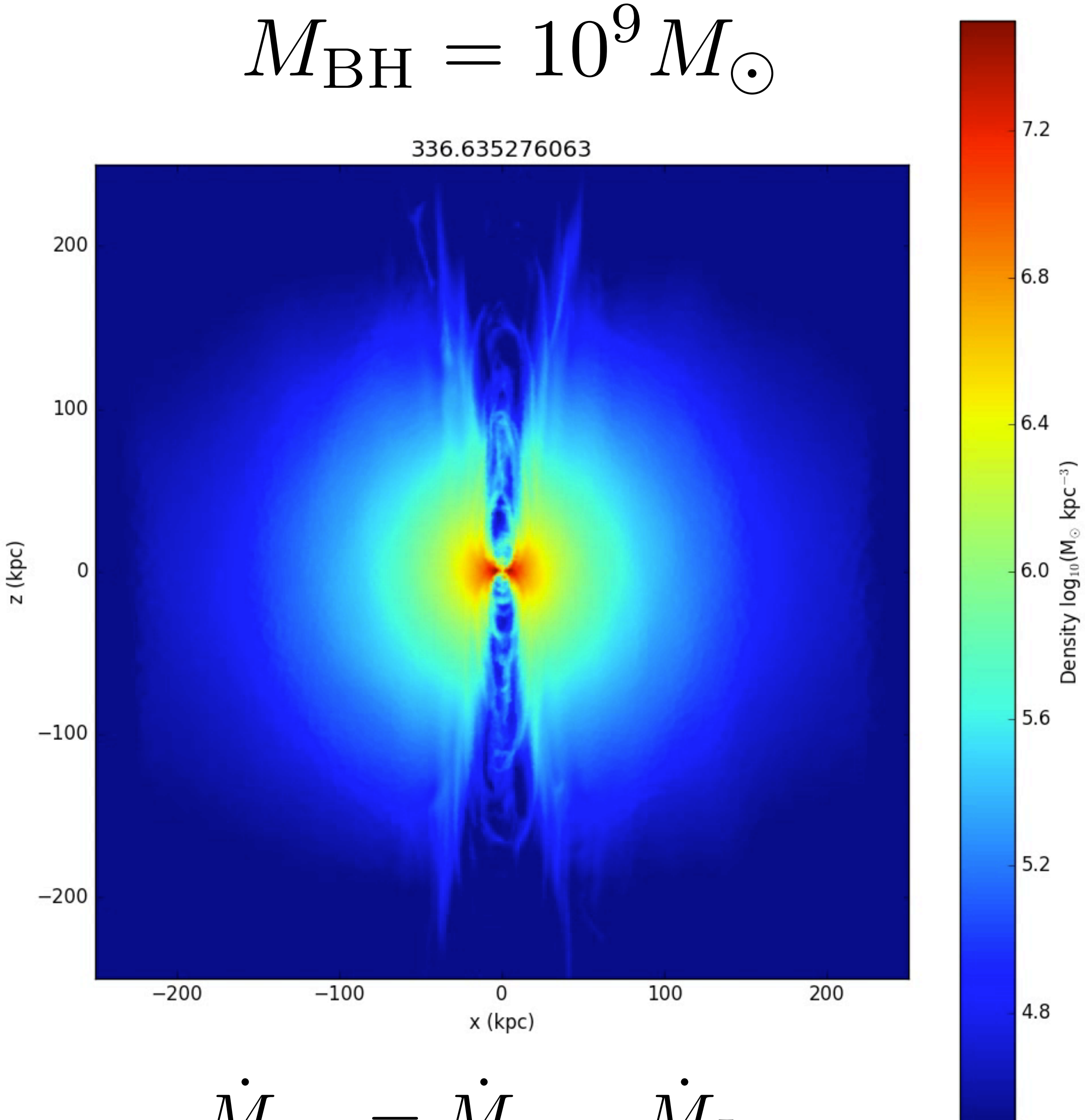
LONG TERM EVOLUTION, MIXING AND SOUND WAVES

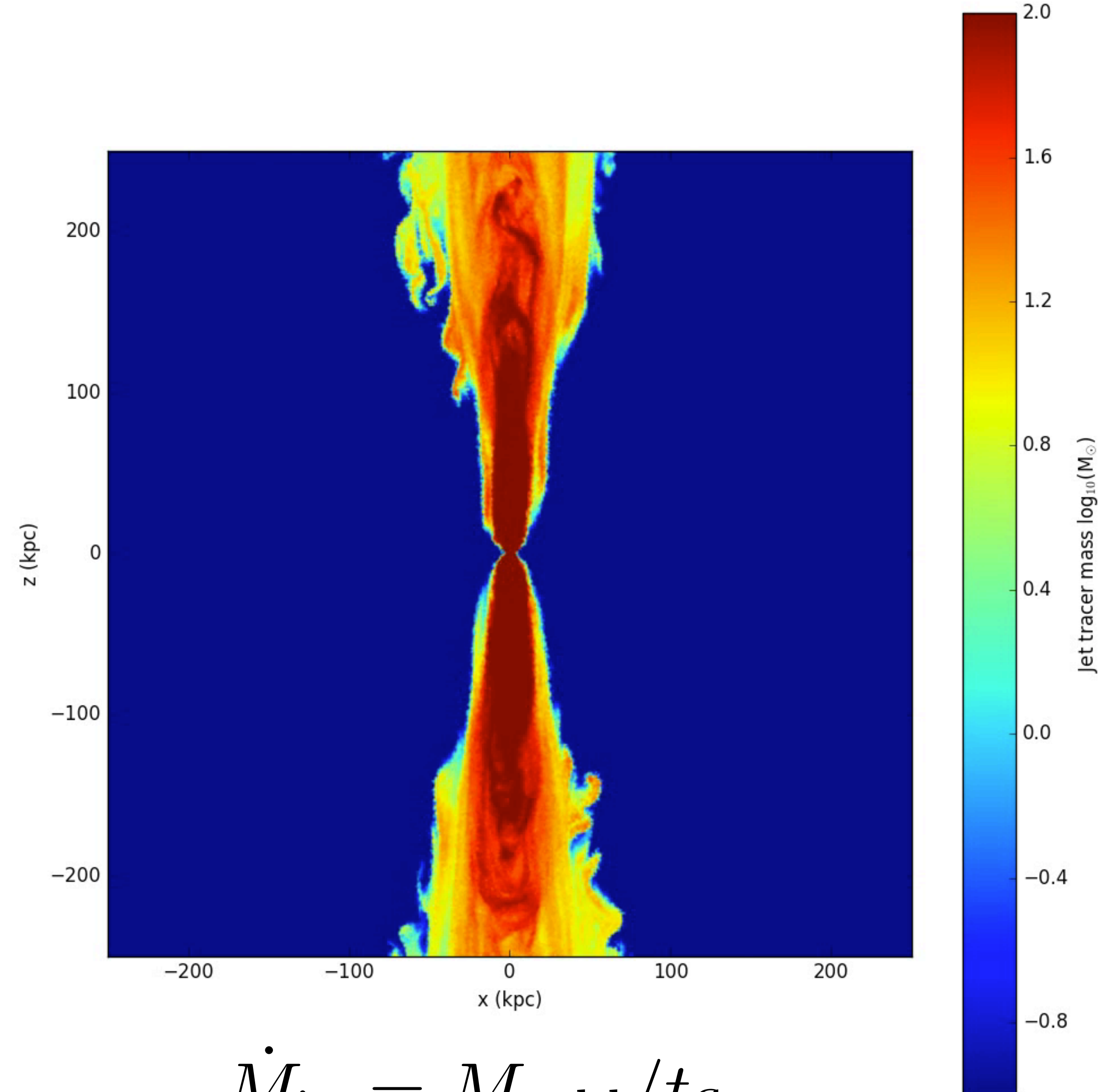


ACCRETION & FEEDBACK

(PRELIMINARY)

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





$$\dot{M}_{\rm acc} = \dot{M}_{\rm in} - \dot{M}_{\rm J}$$

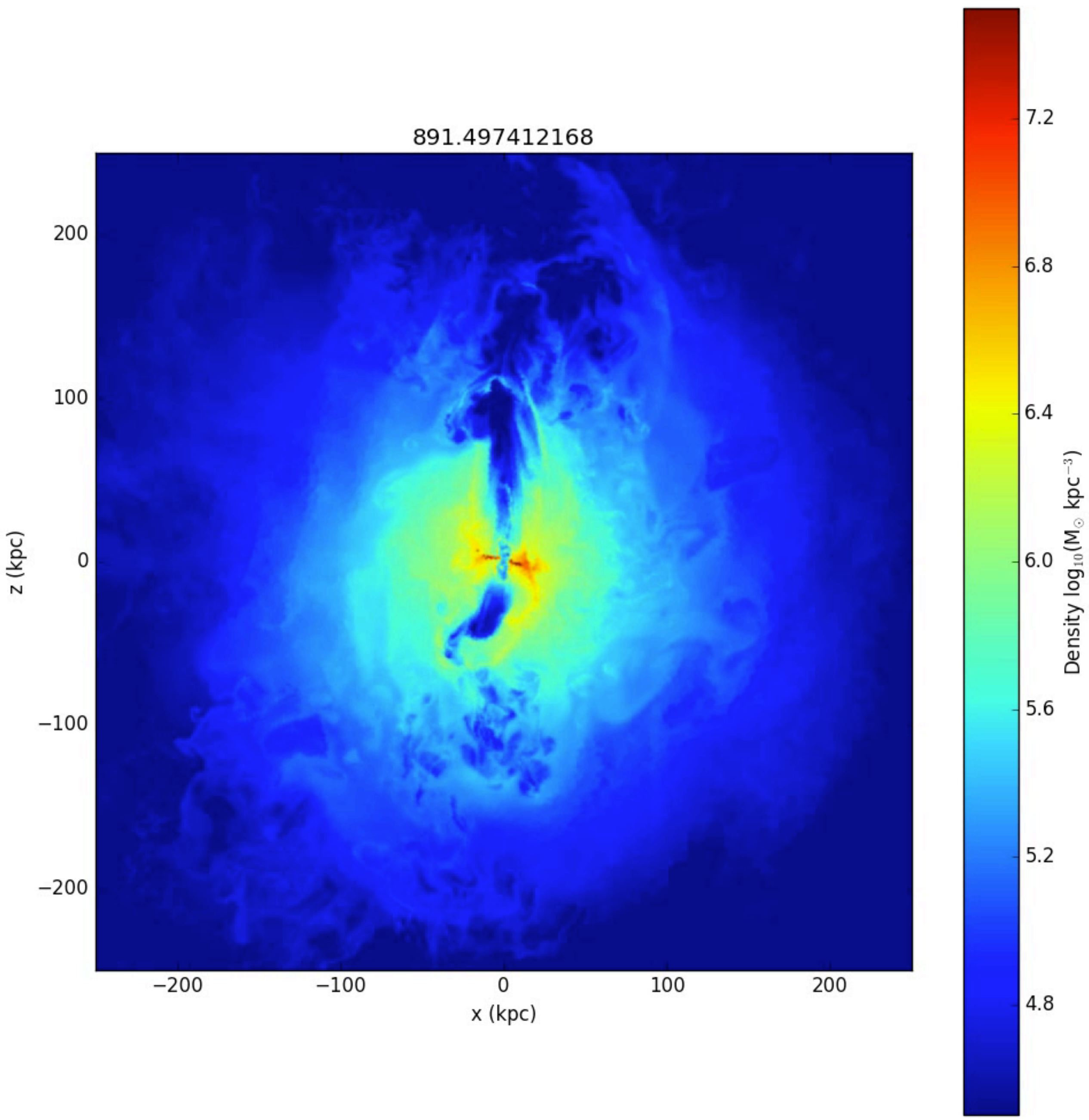
$$\eta_{\rm J} = \dot{M}_{\rm J}/\dot{M}_{\rm acc} = 1$$

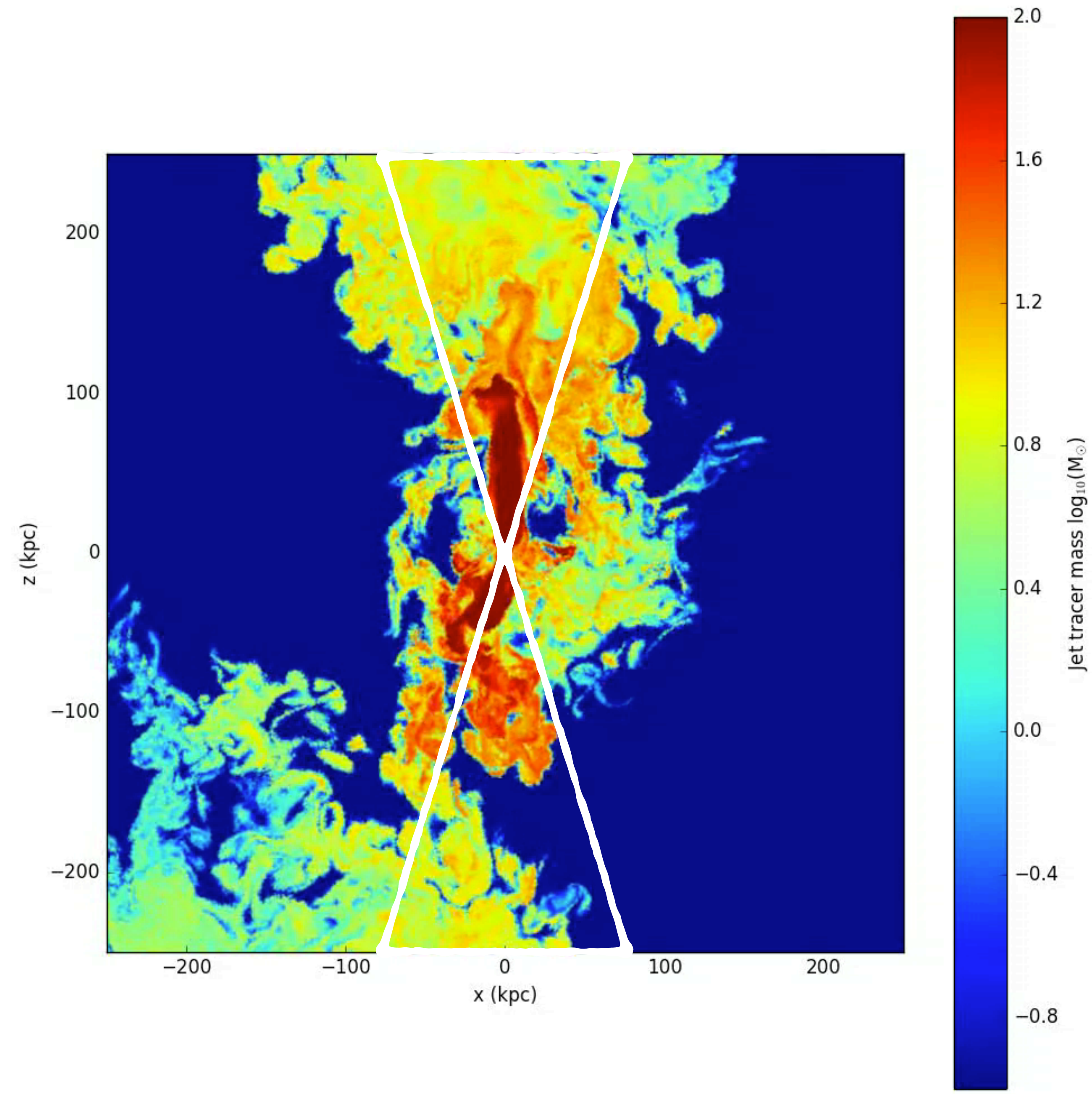
(e.g. Ostriker+10)

$$\dot{M}_{\rm in} = M_{\rm cold}/t_{\rm flow}$$

(e.g. Yang & Reynolds 16)

ACCRETION & FEEDBACK
(PRELIMINARY)

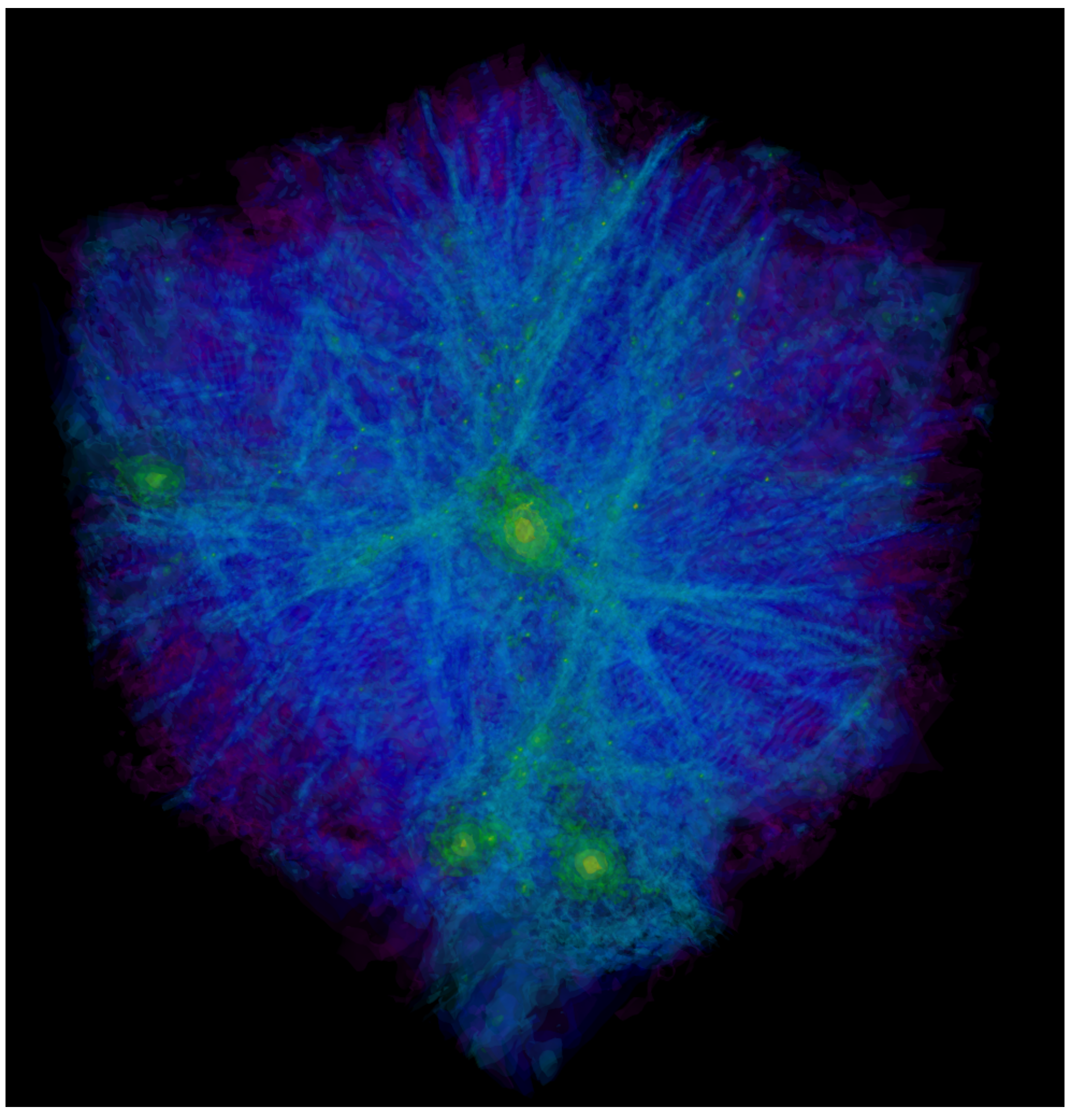




COSMOLOGICAL CLUSTER

(PRELIMINARY)

$z = 0.1$



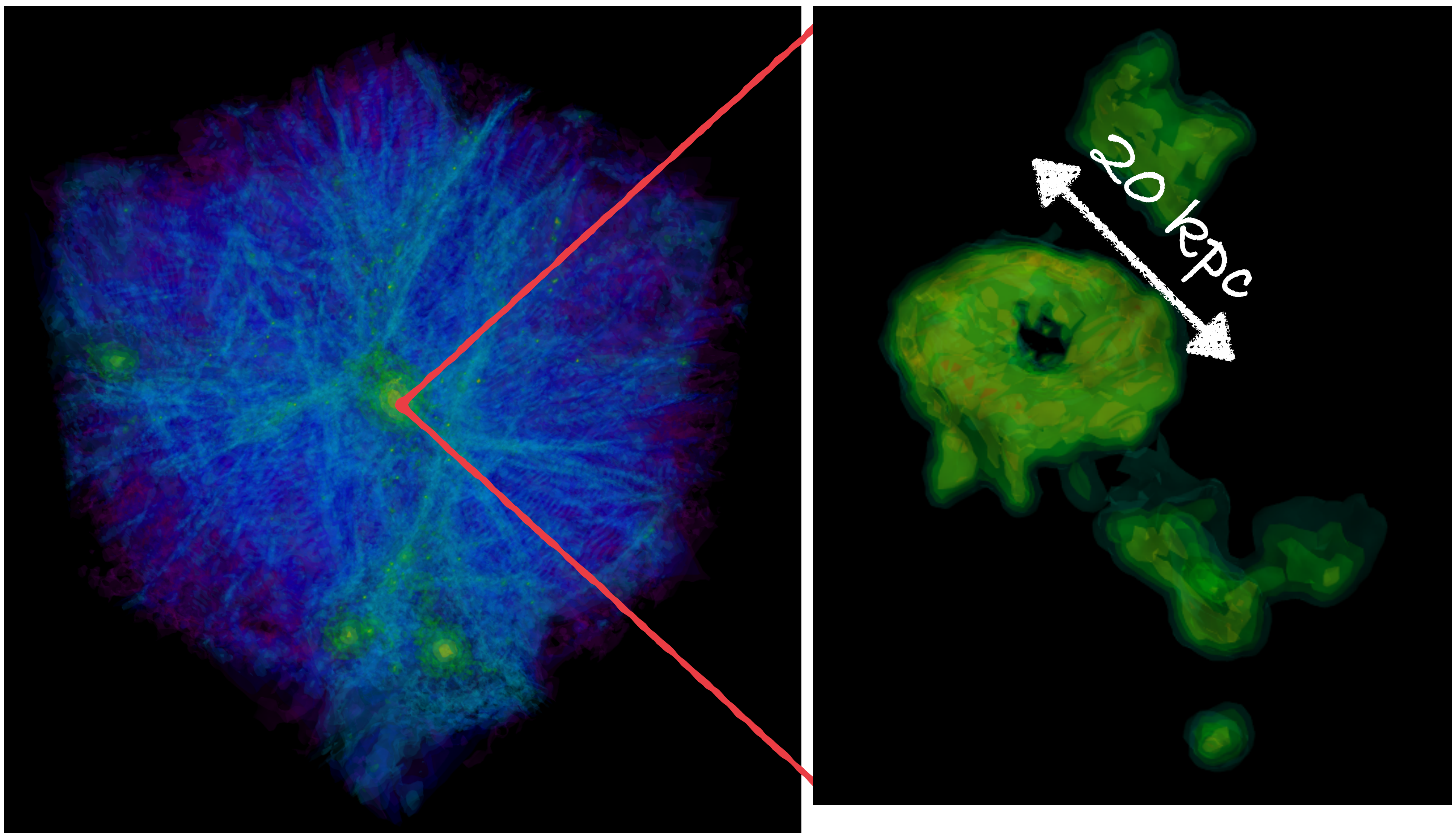
$$M_{200} \sim 4 \times 10^{14} M_{\odot}$$

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

COSMOLOGICAL CLUSTER

(PRELIMINARY)

$z = 0.1$



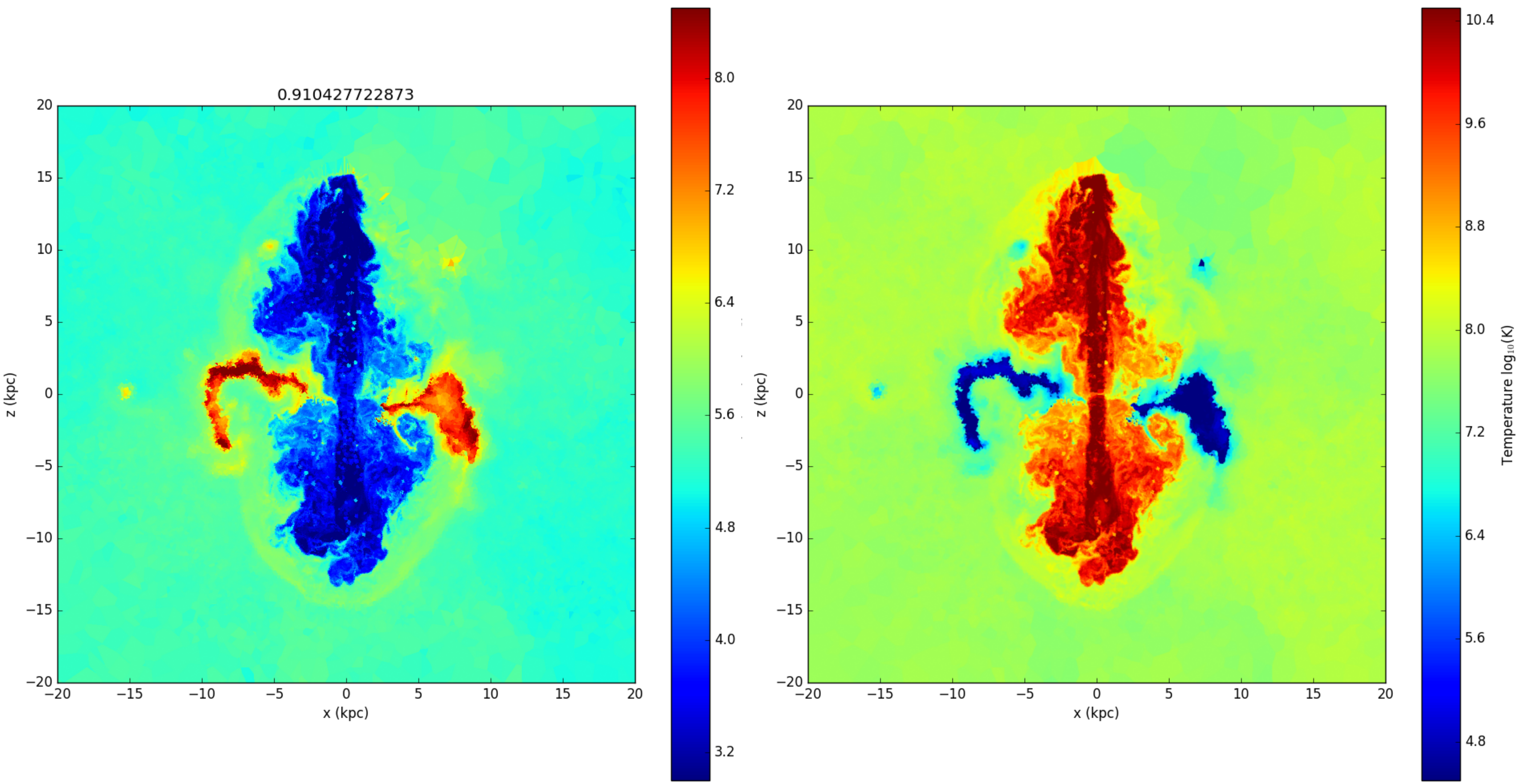
$M_{200} \sim 4 \times 10^{14} M_\odot$

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

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

COSMOLOGICAL CLUSTER

(PRELIMINARY)

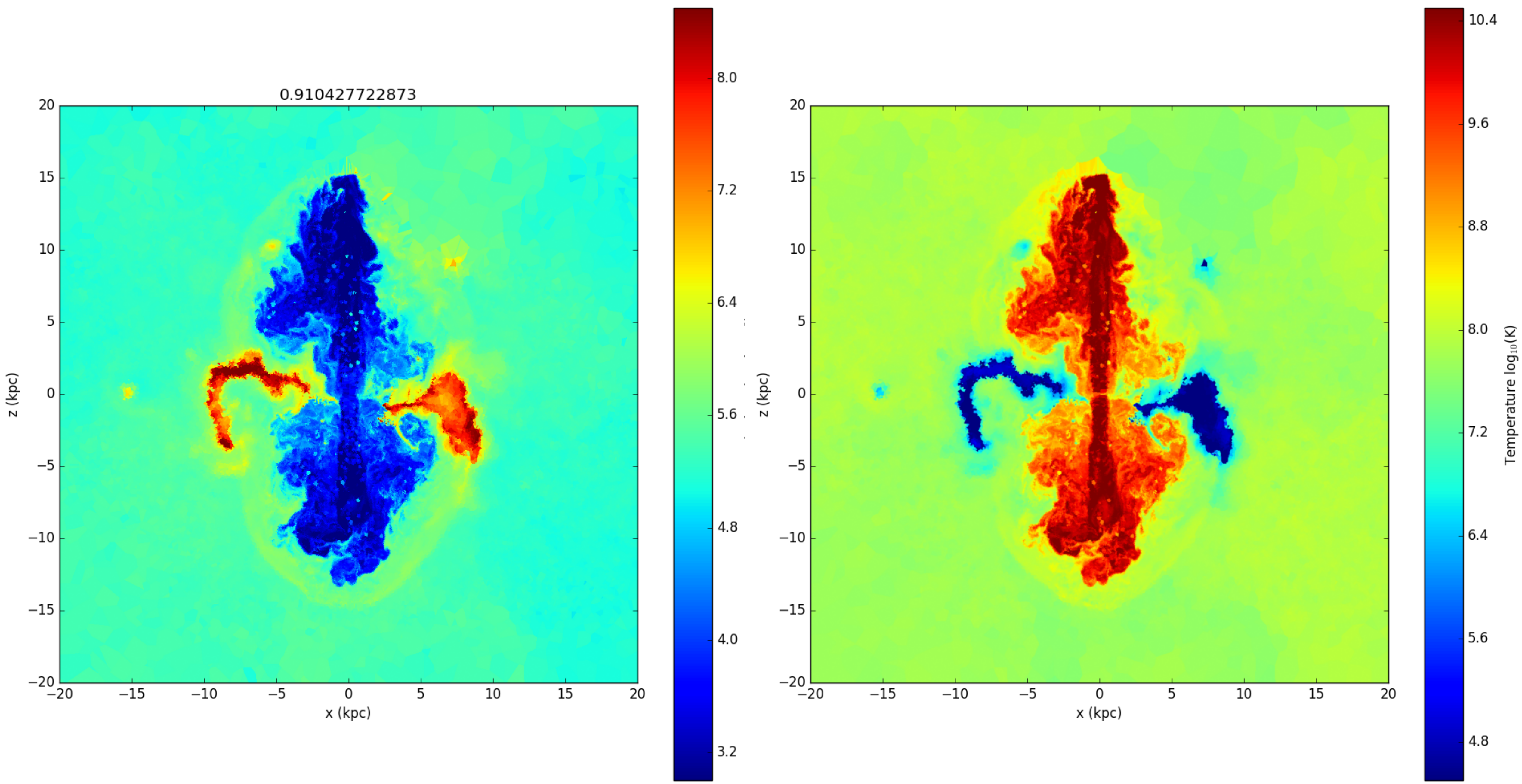


$$\dot{M}_{\rm acc} = 10^{-4}\dot{M}_{\rm Edd}$$

$$\dot{E}_{\rm J} \simeq 3.3 \times 10^{44} {\rm erg/s}$$

COSMOLOGICAL CLUSTER

(PRELIMINARY)



Trigger star formation?

(e.g. Zubovas & Bourne 17)

SUMMARY

- AGN feedback is an important ingredient in simulations of galaxy formation in order to reproduce a number of observational properties and a realistic galaxy population.
- Jets can alter the central energy budget through a number of processes. However, while significant vorticity is generated within the lobes, the jets are unable to drive turbulence in the ICM
- Substructure motions stir the ICM and generate turbulence, which can interact with and disrupt the jet cocoons, provide additional pressure support to ICM gas, and in the long term displace jet lobe positions and promote mixing of jet material with the ICM.
- Substructure motions and a jet are able to produce line-of-sight velocity kinematics consistent with those observed in the Perseus cluster by Hitomi.
- Currently modelling self-consistent feedback and accretion in idealised systems and fixed power jets in cosmological cluster simulations.