

SIMULATION OF  
JET FEEDBACK  
IN  
REALISTIC CLUSTER  
ENVIRONMENTS

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CAMBRIDGE

DiRAC



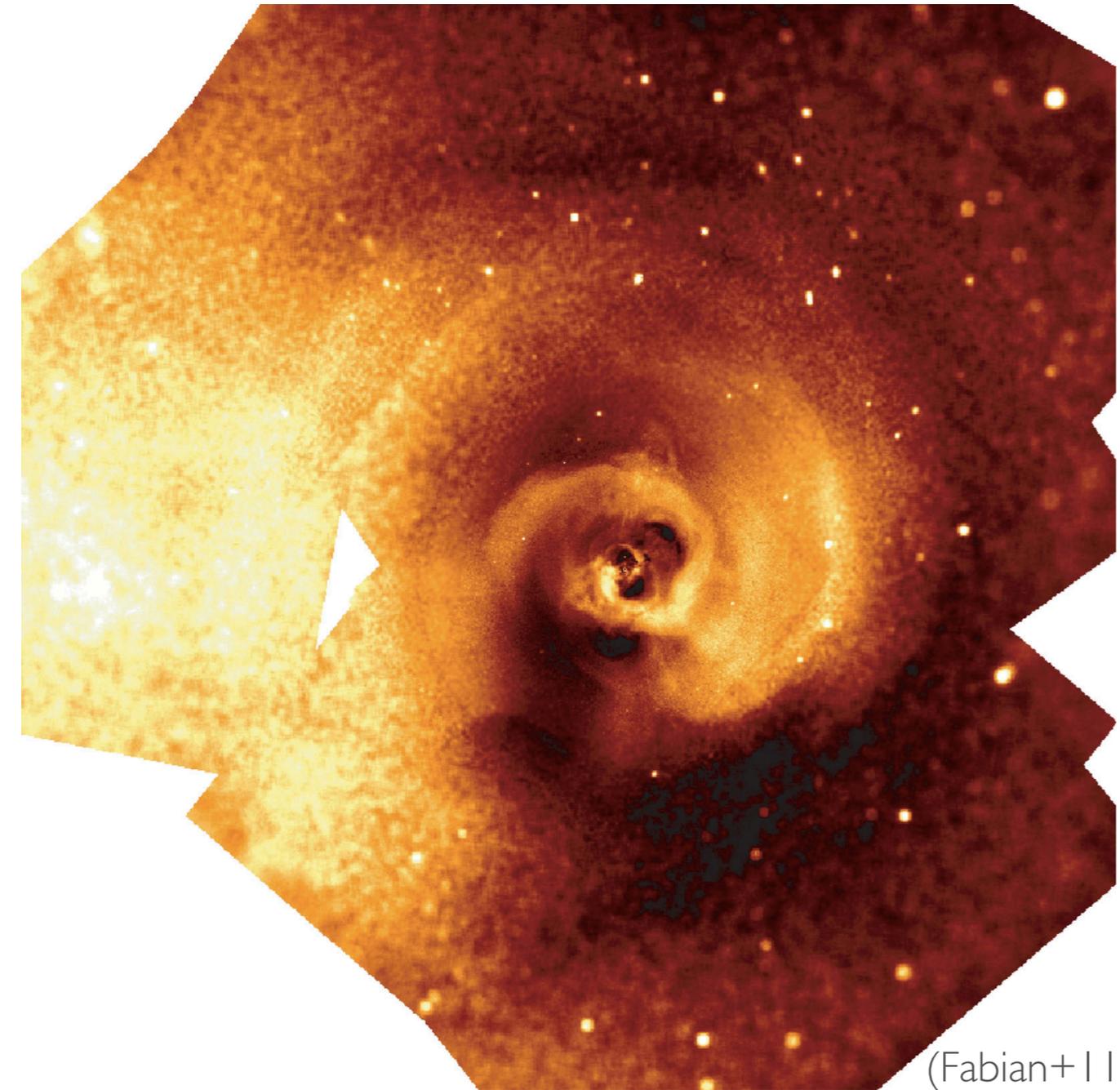
# SIMULATING GALAXY CLUSTERS

time since Big Bang  
9.5 Gyr

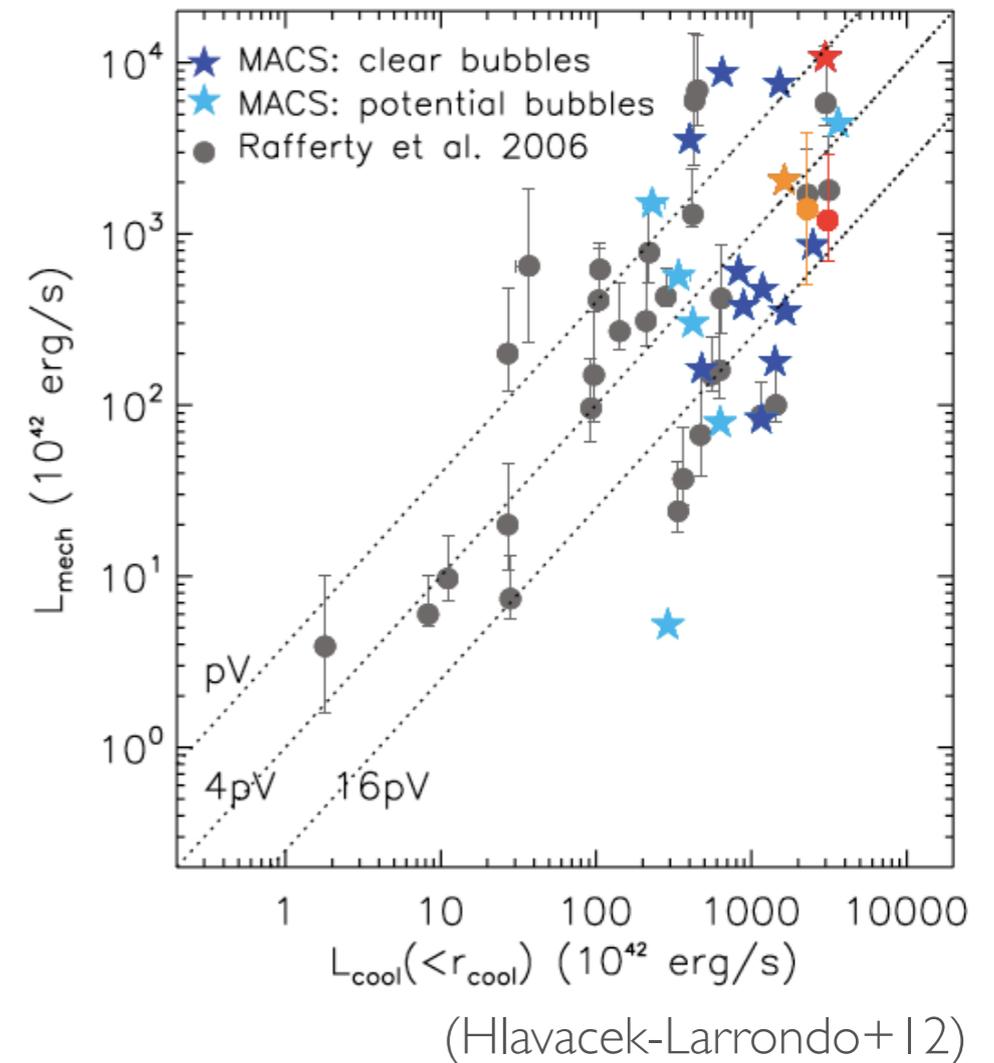
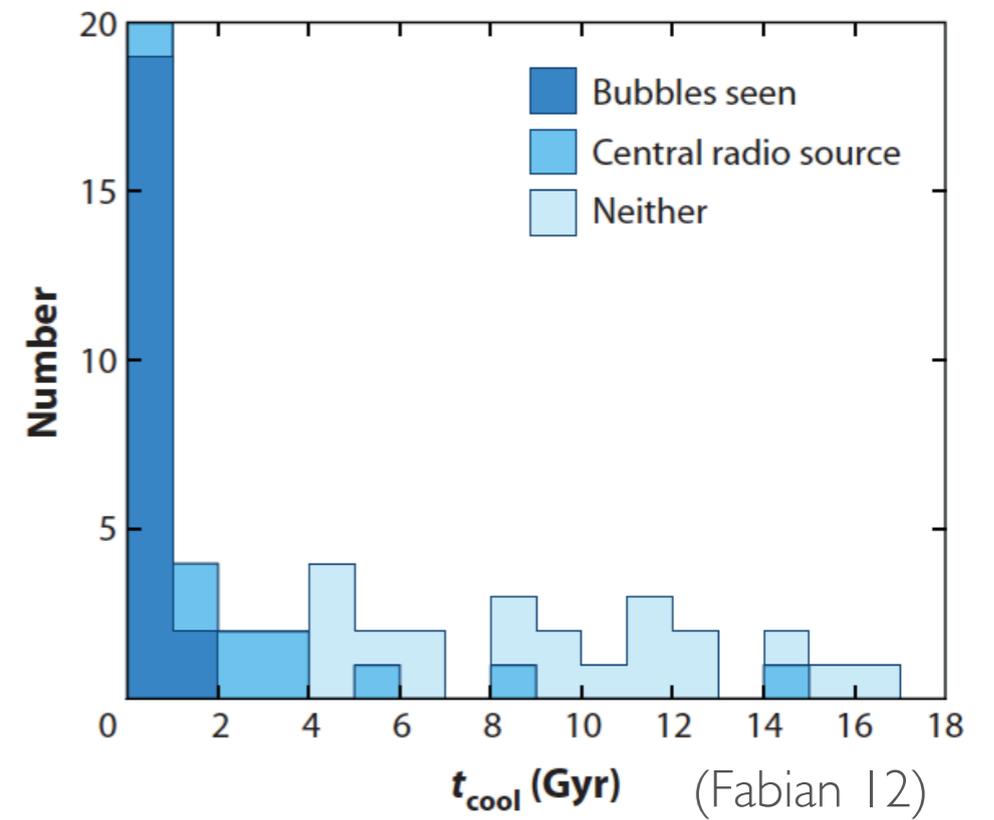
1 cMpc  
—

Fable Simulations: movie courtesy of Nick Henden

# FEEDBACK IN GALAXY CLUSTERS

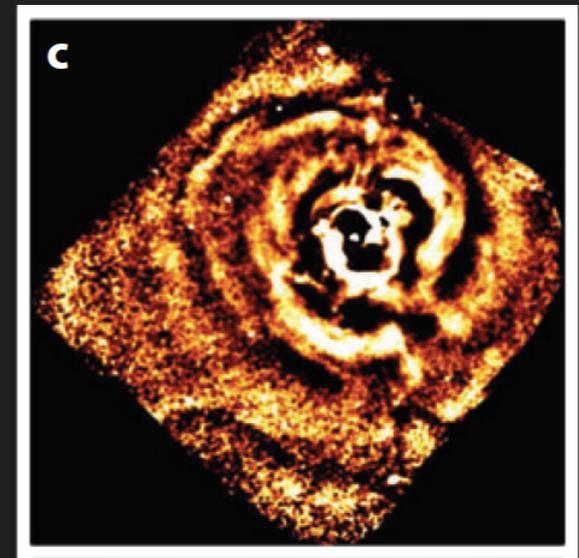


(Fabian+11)



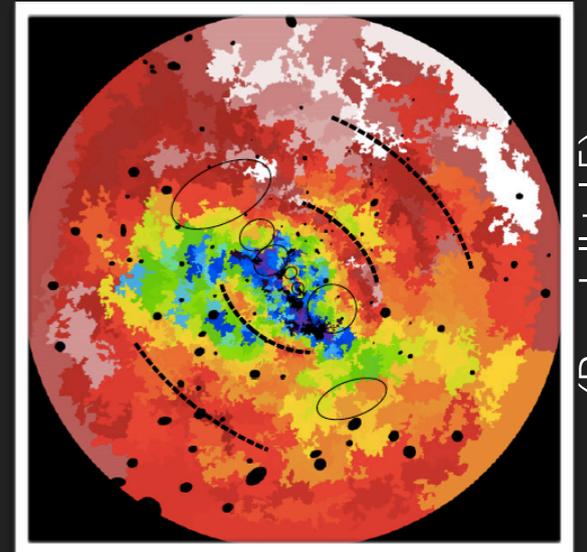
(Hlavacek-Larrondo+12)

# How does the jet heat the ICM?



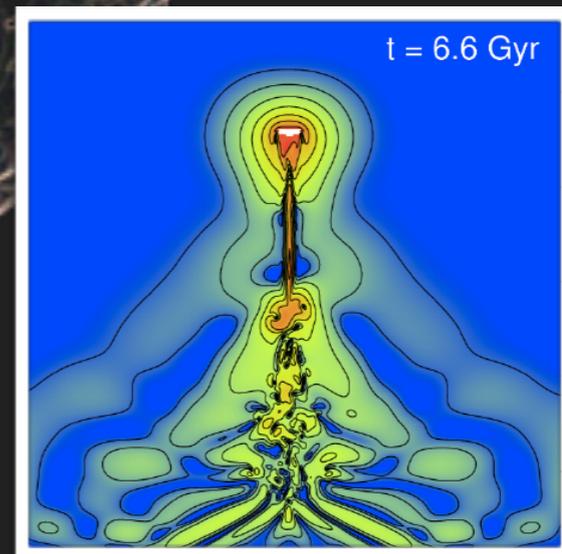
(Fabian 12)

Sound waves



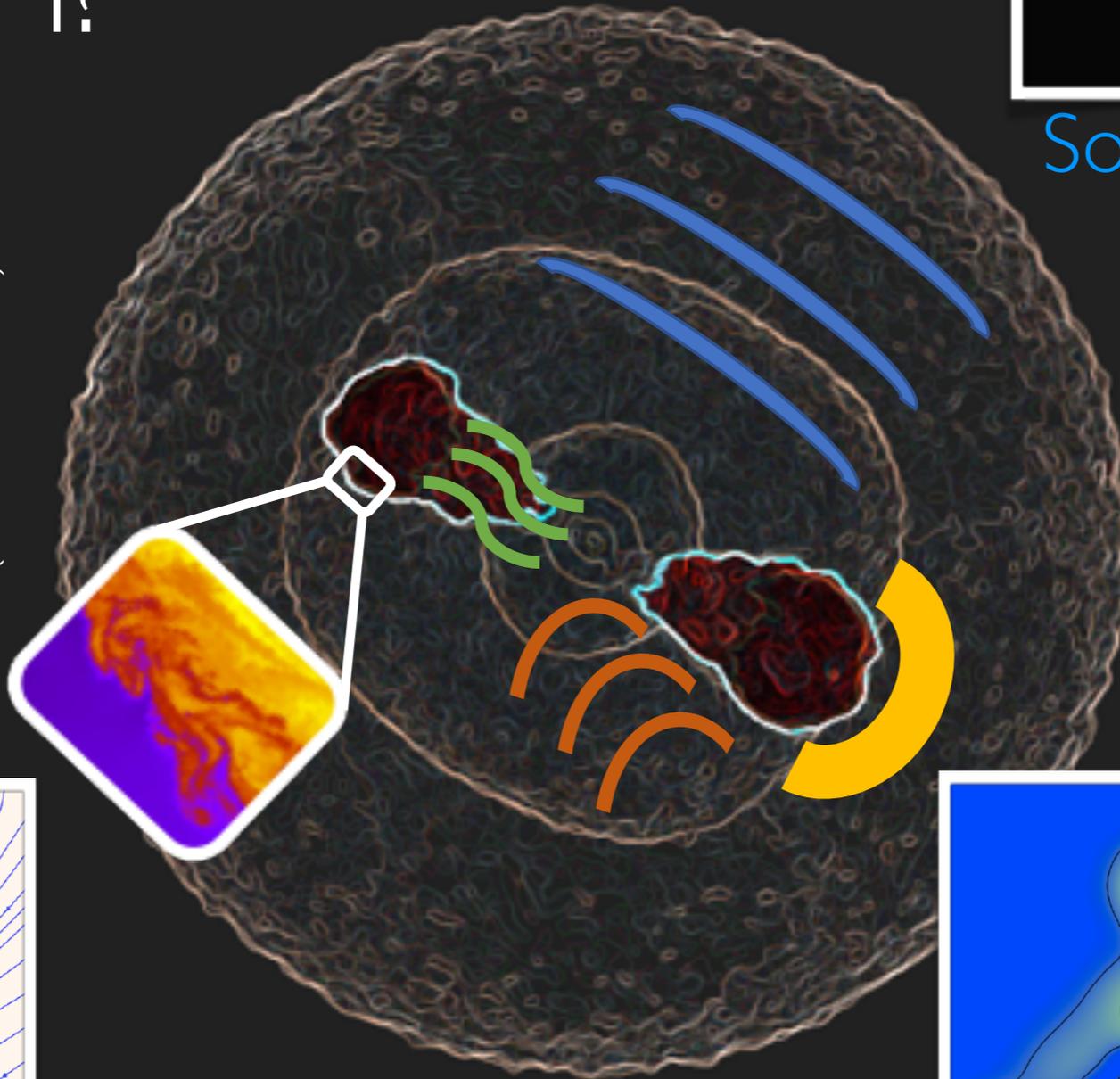
(Randall+15)

Shocks



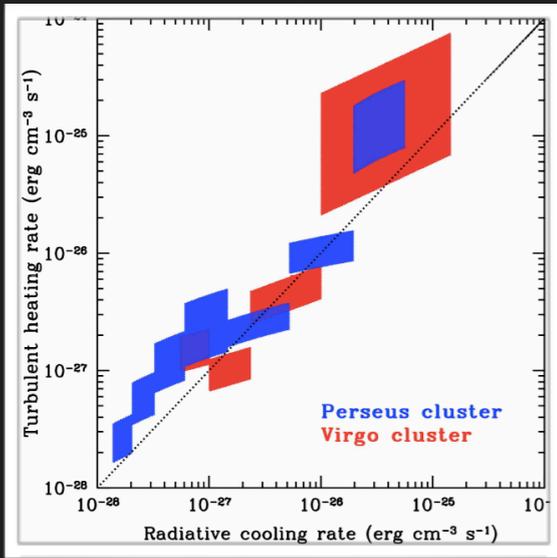
(Zhang+18)

Gravity waves

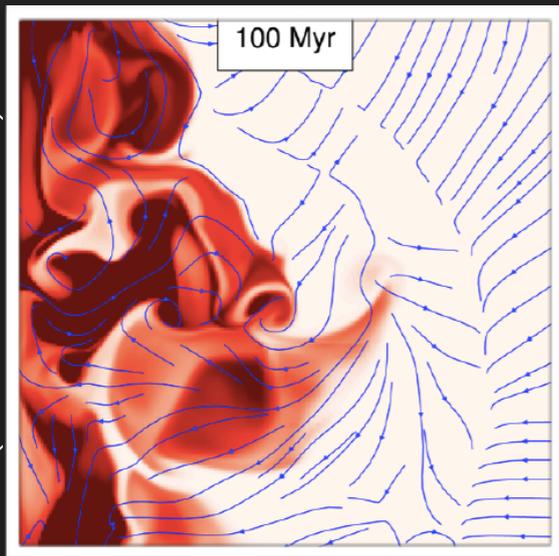


(Zhuravleva+14)

Cavity heating, cosmic rays, circulation...



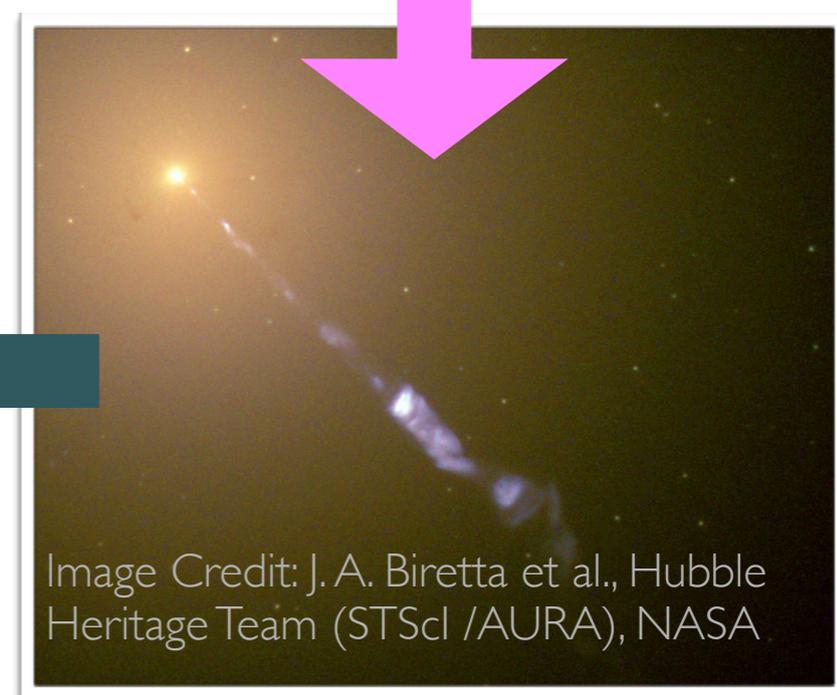
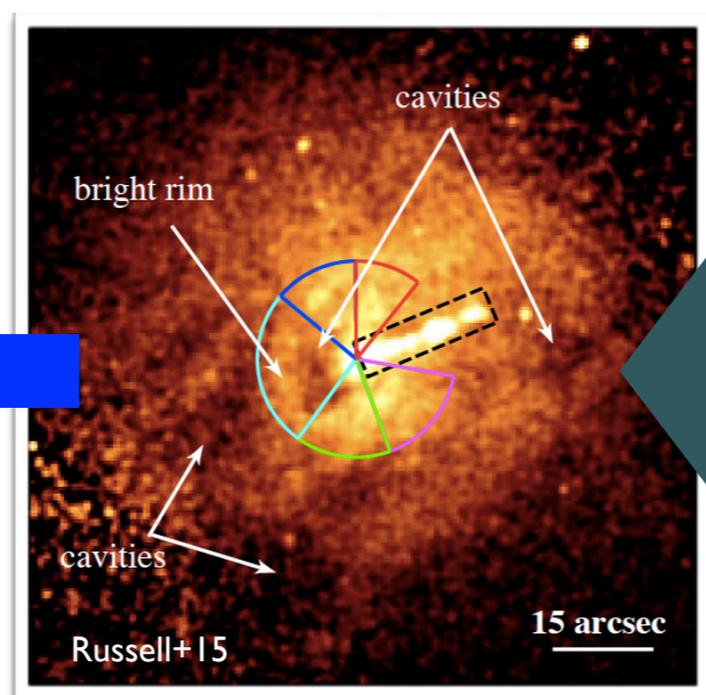
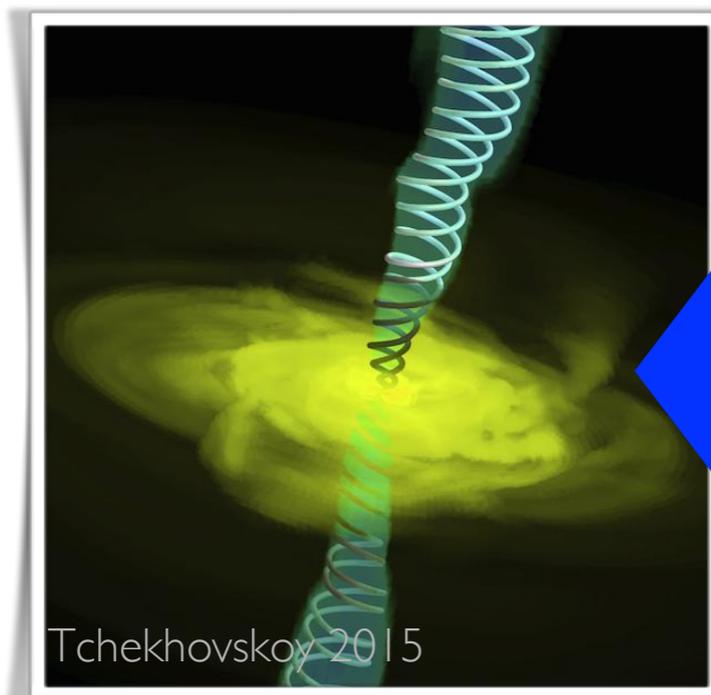
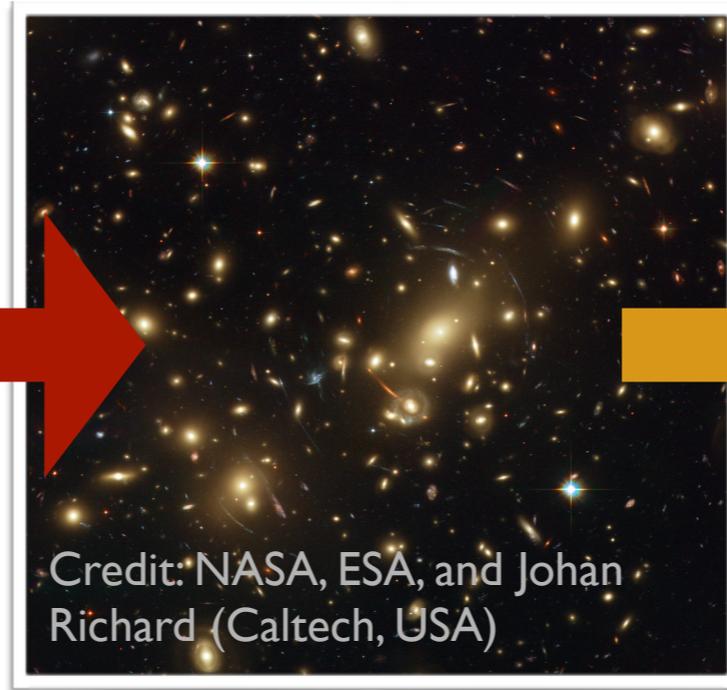
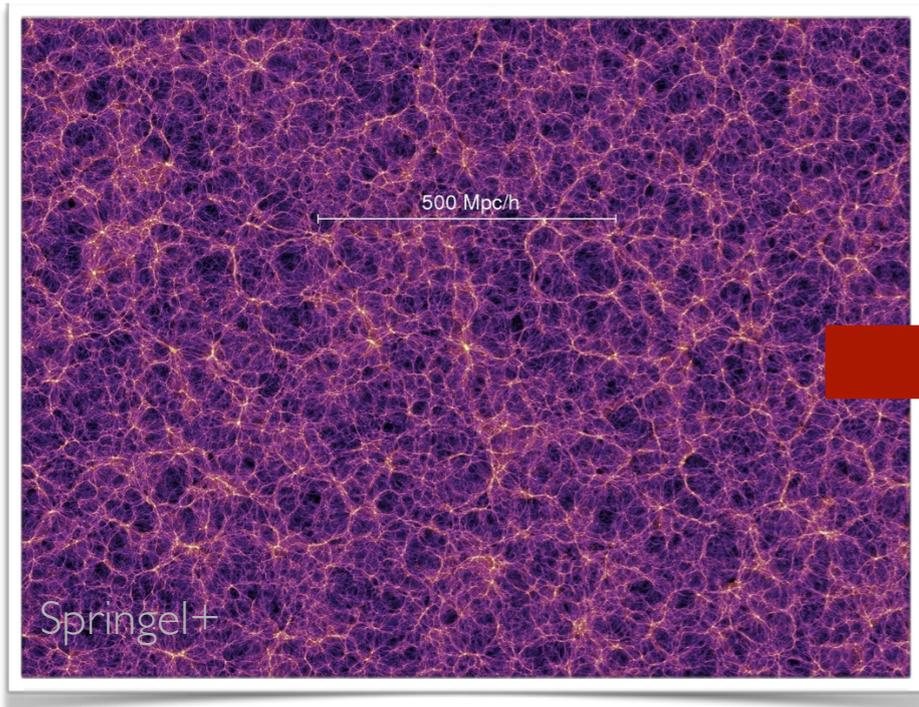
Turbulence



(Hillel&Soker 16)

Mixing

# BRIDGING THE GAP



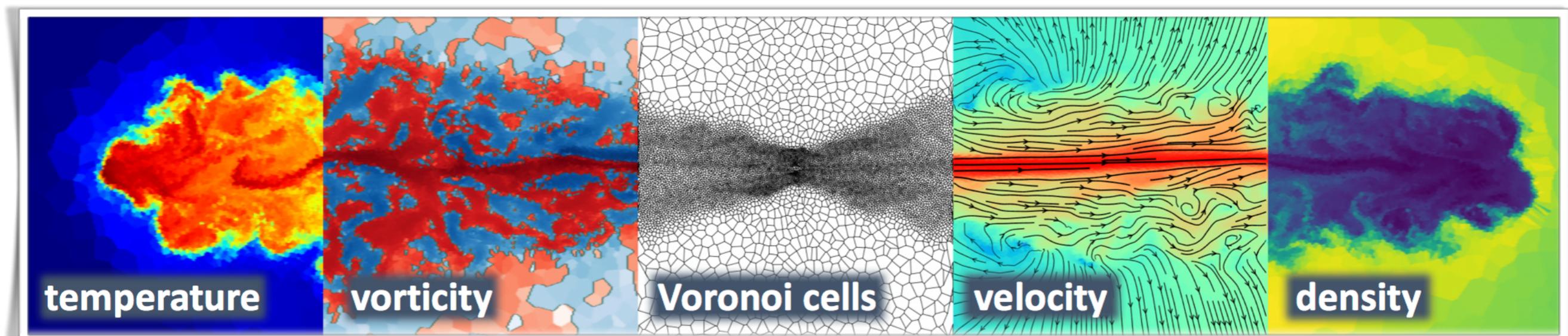
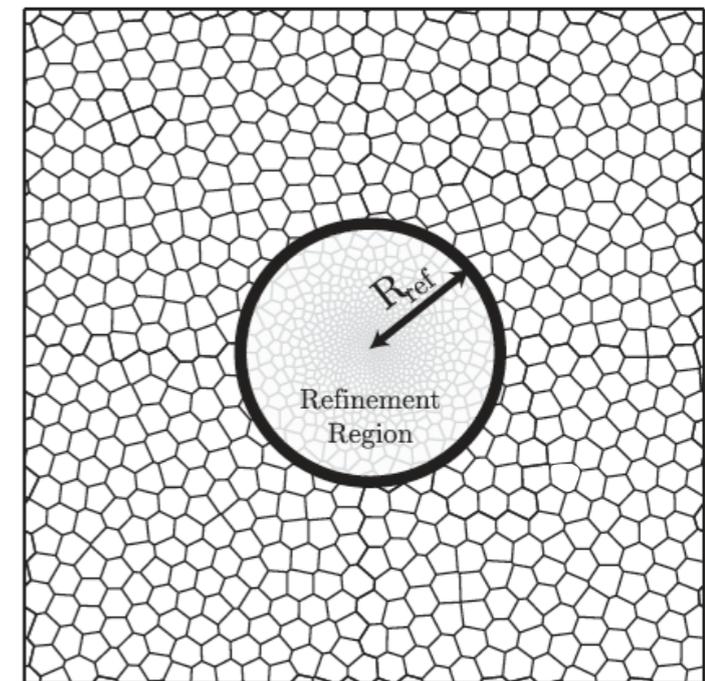
# AREPO (Springel 2010)

AND

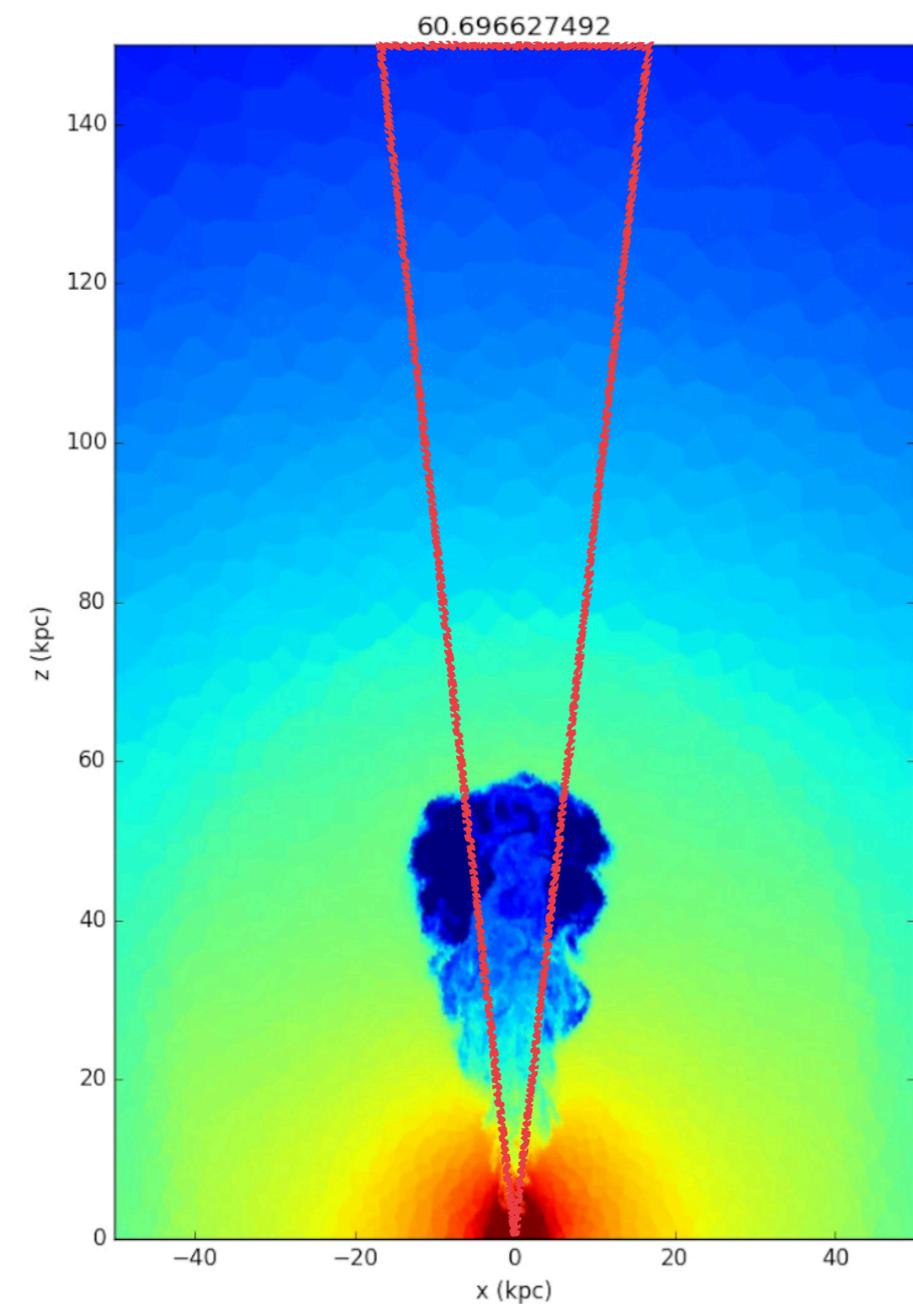
# SUPER-LAGRANGIAN REFINEMENT

(Curtis & Sijacki 15, 16)

- 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

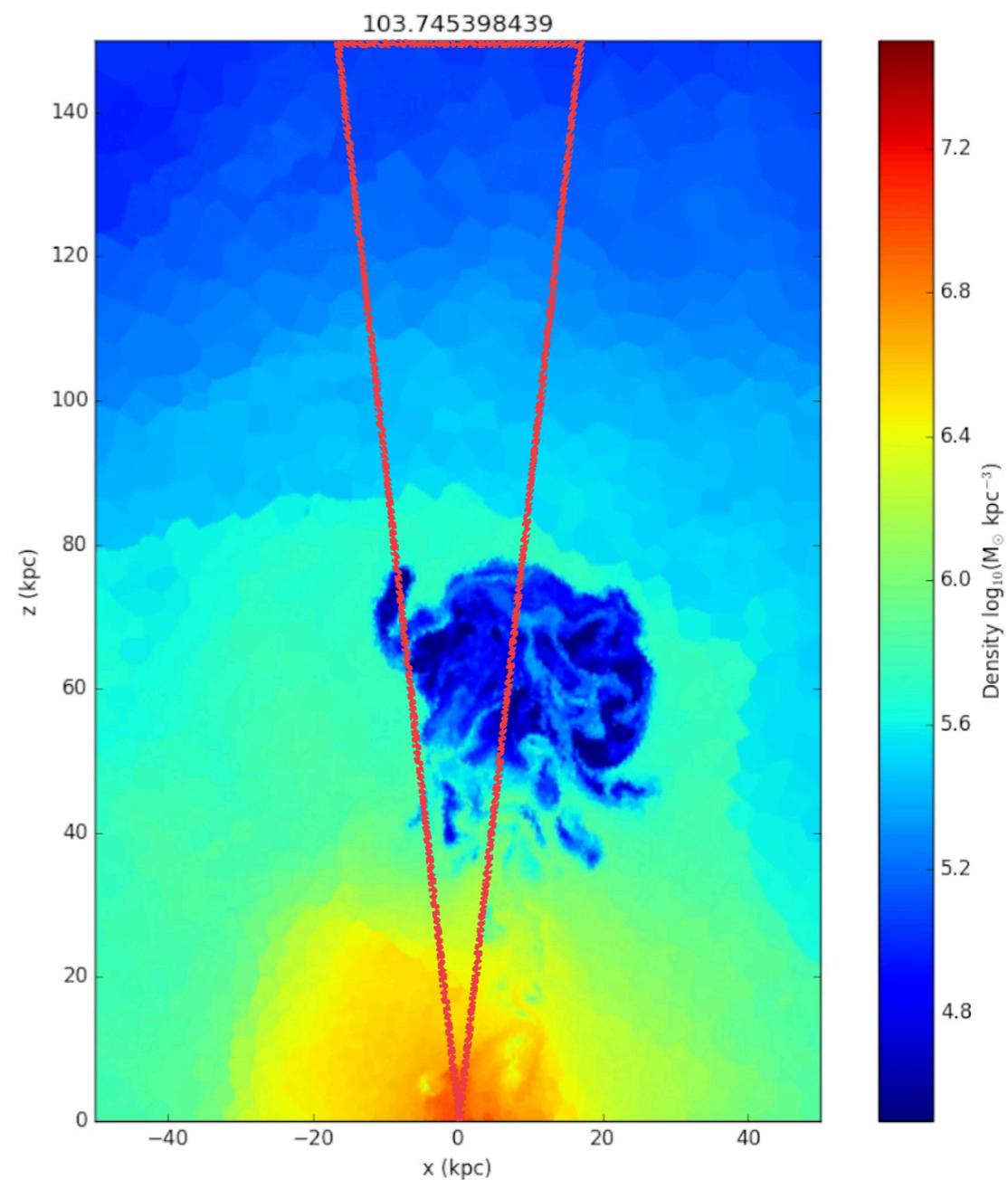


# Hydrostatic ICM



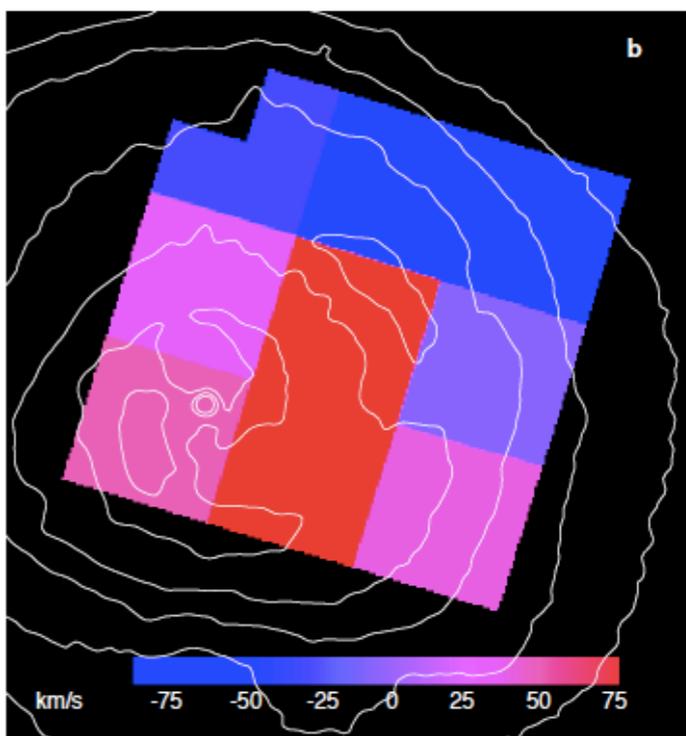
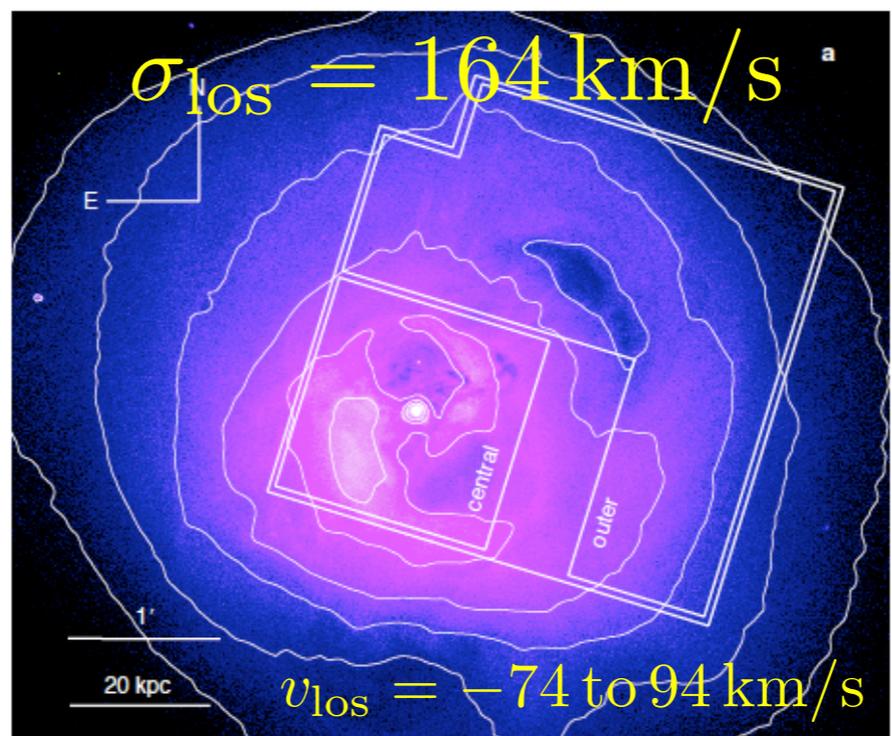
# IMPACT OF STIRRING BY SUBSTRUCTURES

# Stirred ICM

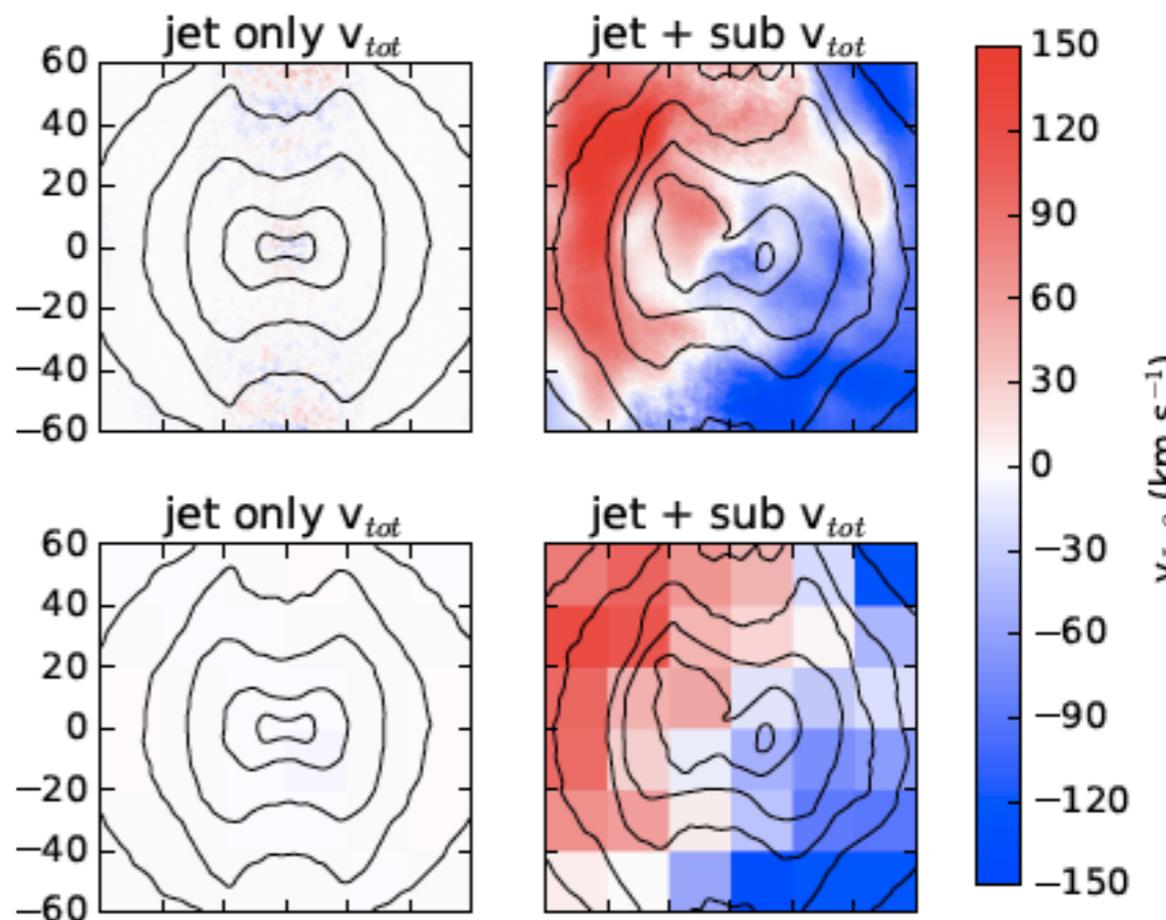
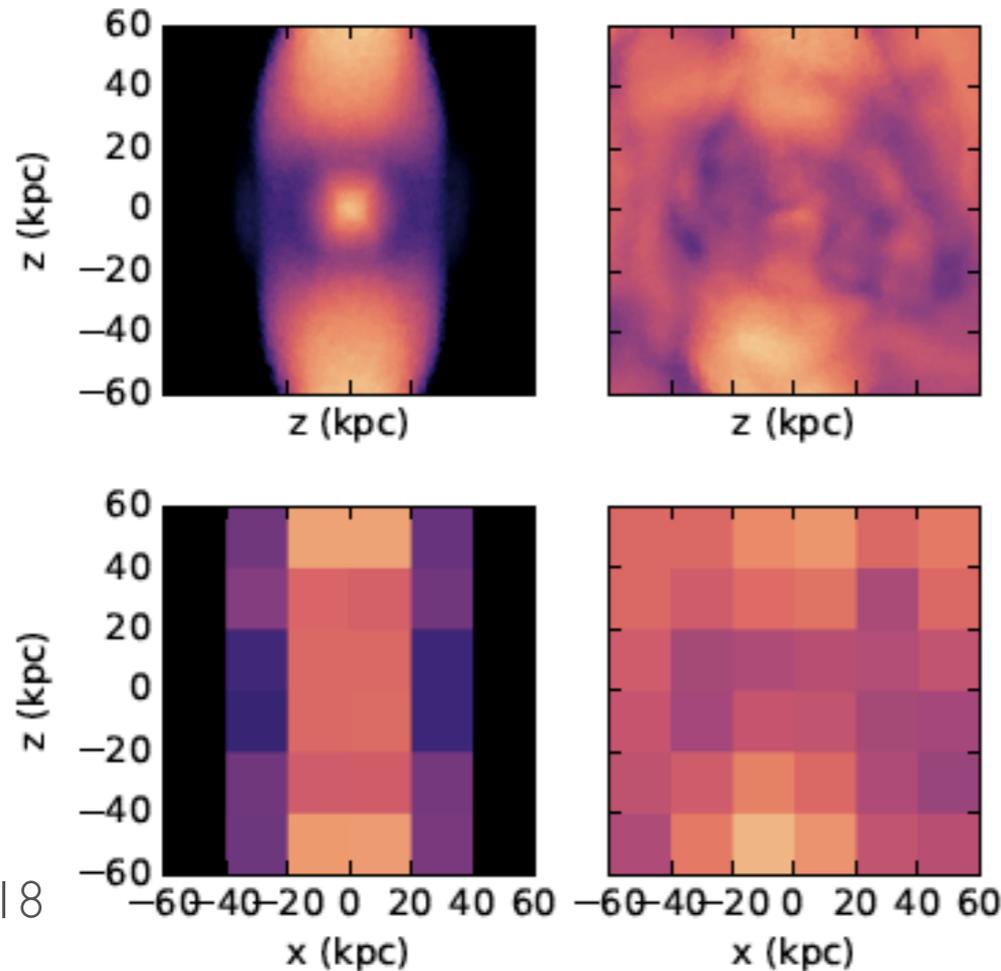


# COMPARISON WITH HITOMI

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

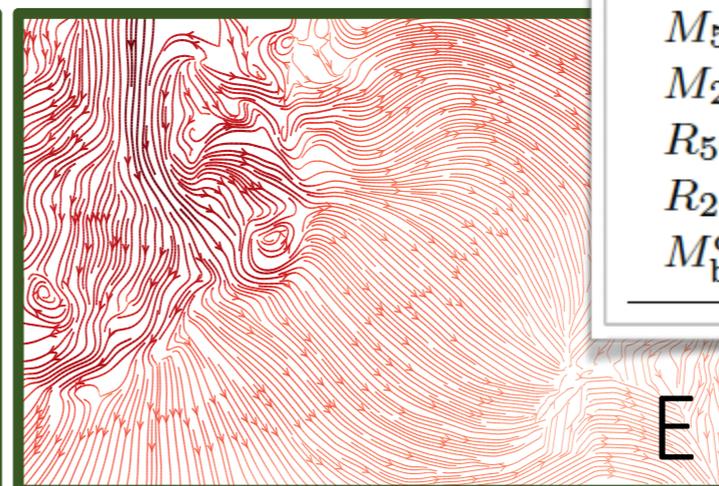
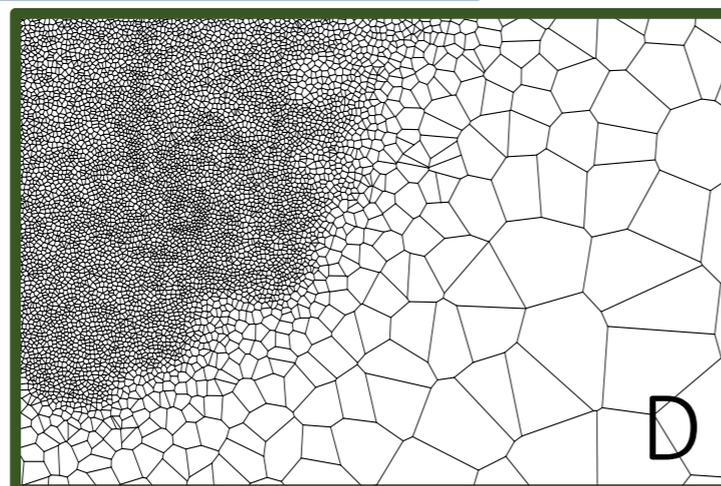
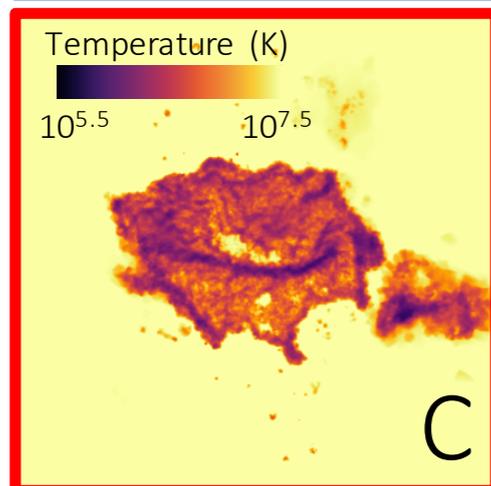
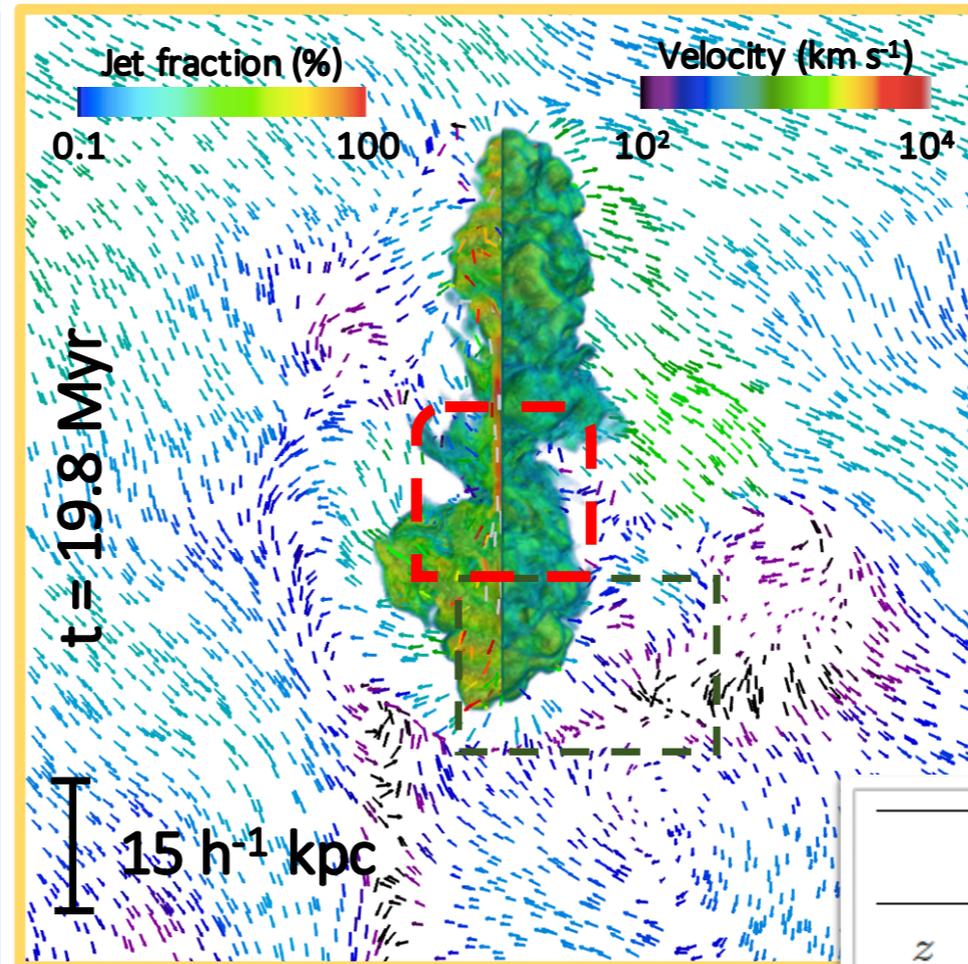
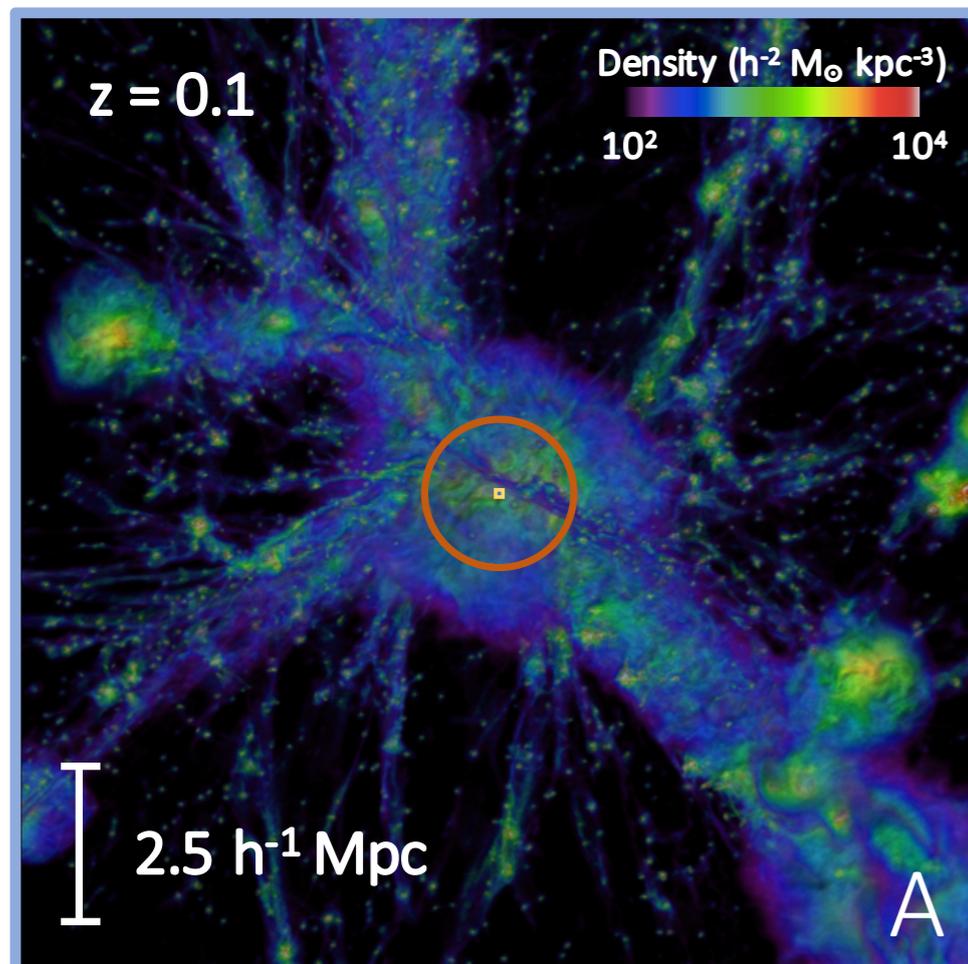


(Hitomi Collaboration 16)



see also:  
Lau+18,  
ZuHone+18

# COSMOLOGICAL CLUSTER SIMULATION

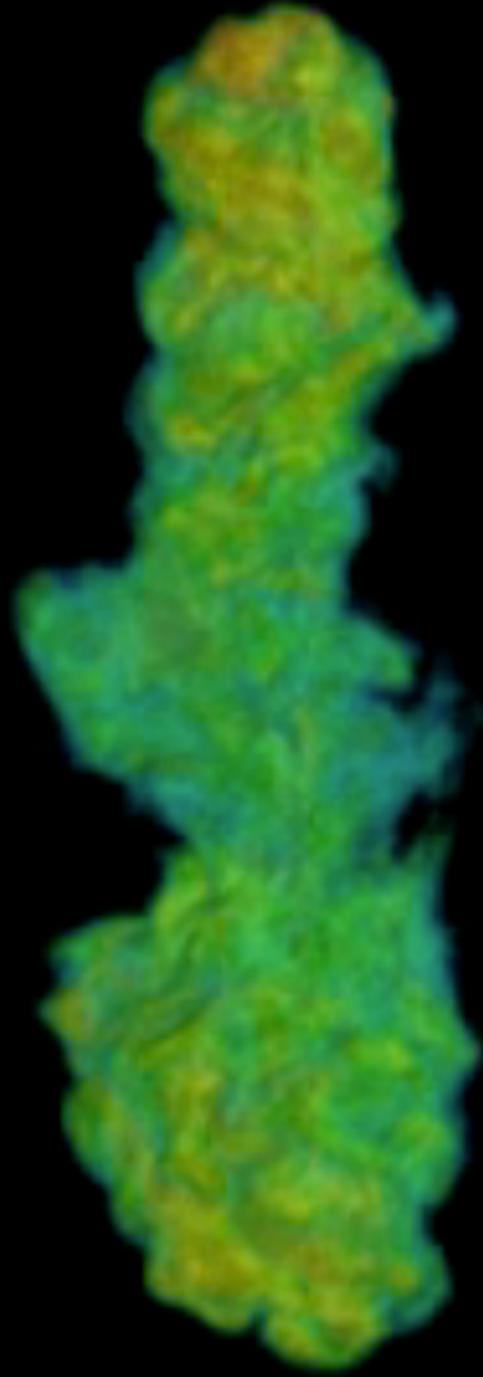


Initial properties	
$z$	0.0989
$M_{500}$	$2.82 \times 10^{14} h^{-1} M_{\odot}$
$M_{200}$	$4.14 \times 10^{14} h^{-1} M_{\odot}$
$R_{500}$	$763.6 h^{-1} \text{ kpc}$
$R_{200}$	$1117 h^{-1} \text{ kpc}$
$M_{\text{bh}}^{\text{central}}$	$2.17 \times 10^{10} h^{-1} M_{\odot}$

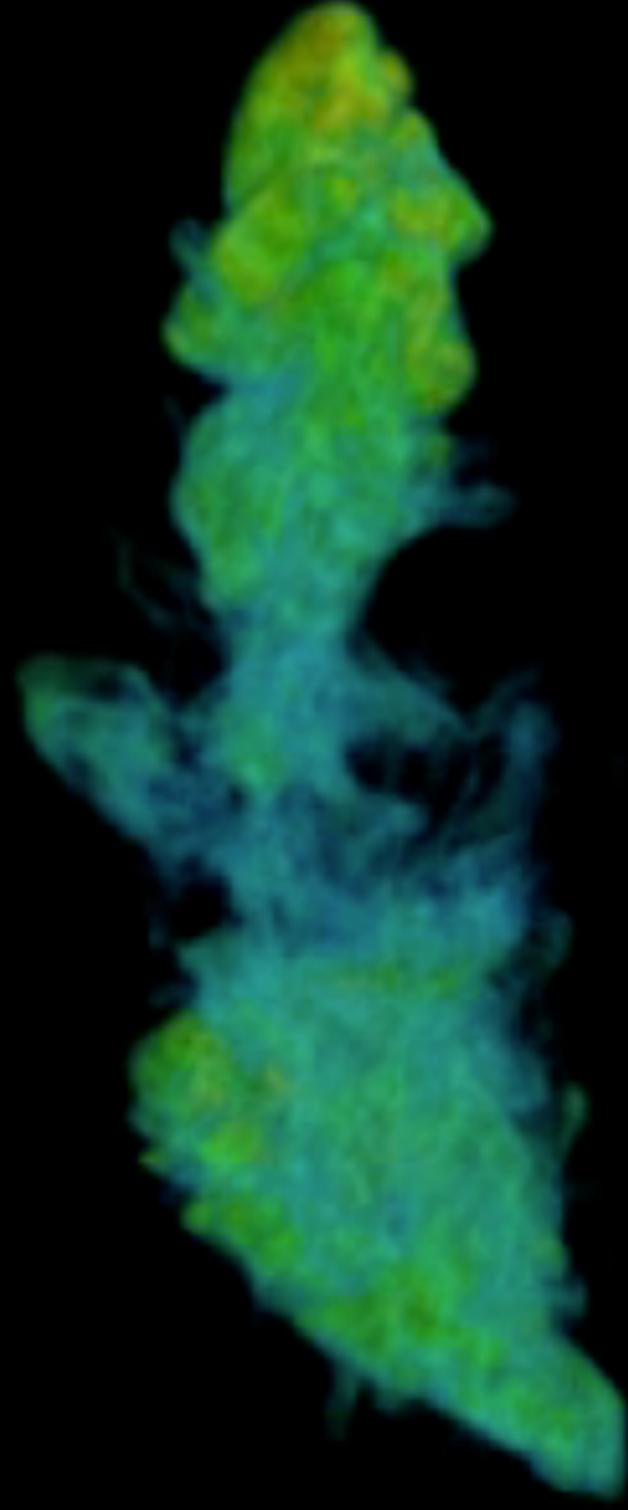
# LOBE INFLATION AND ICM INTERACTION

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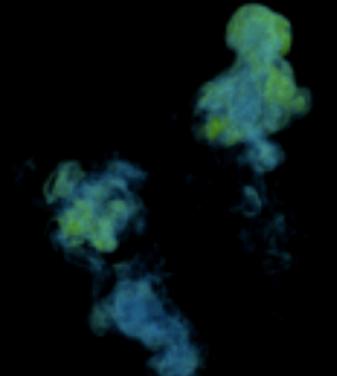
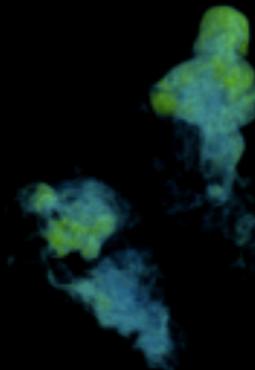
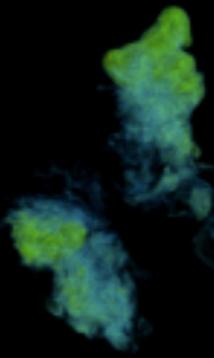
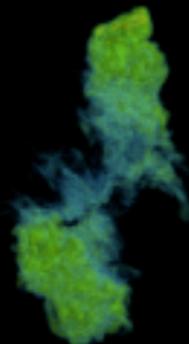
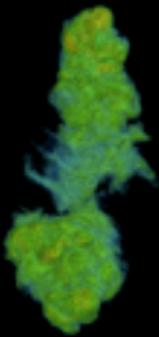
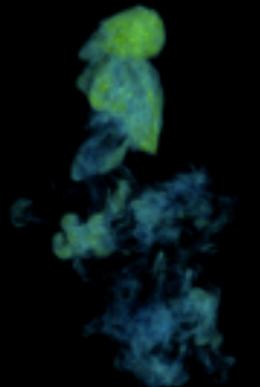
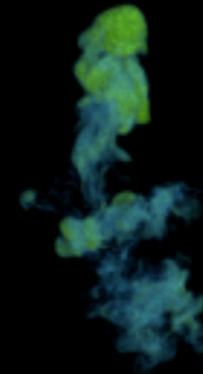
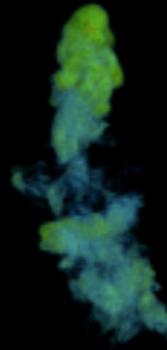
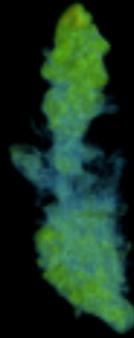
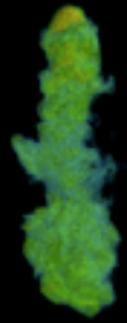
25.99 Myr

40.8 Myr

54.38 Myr

69.2 Myr

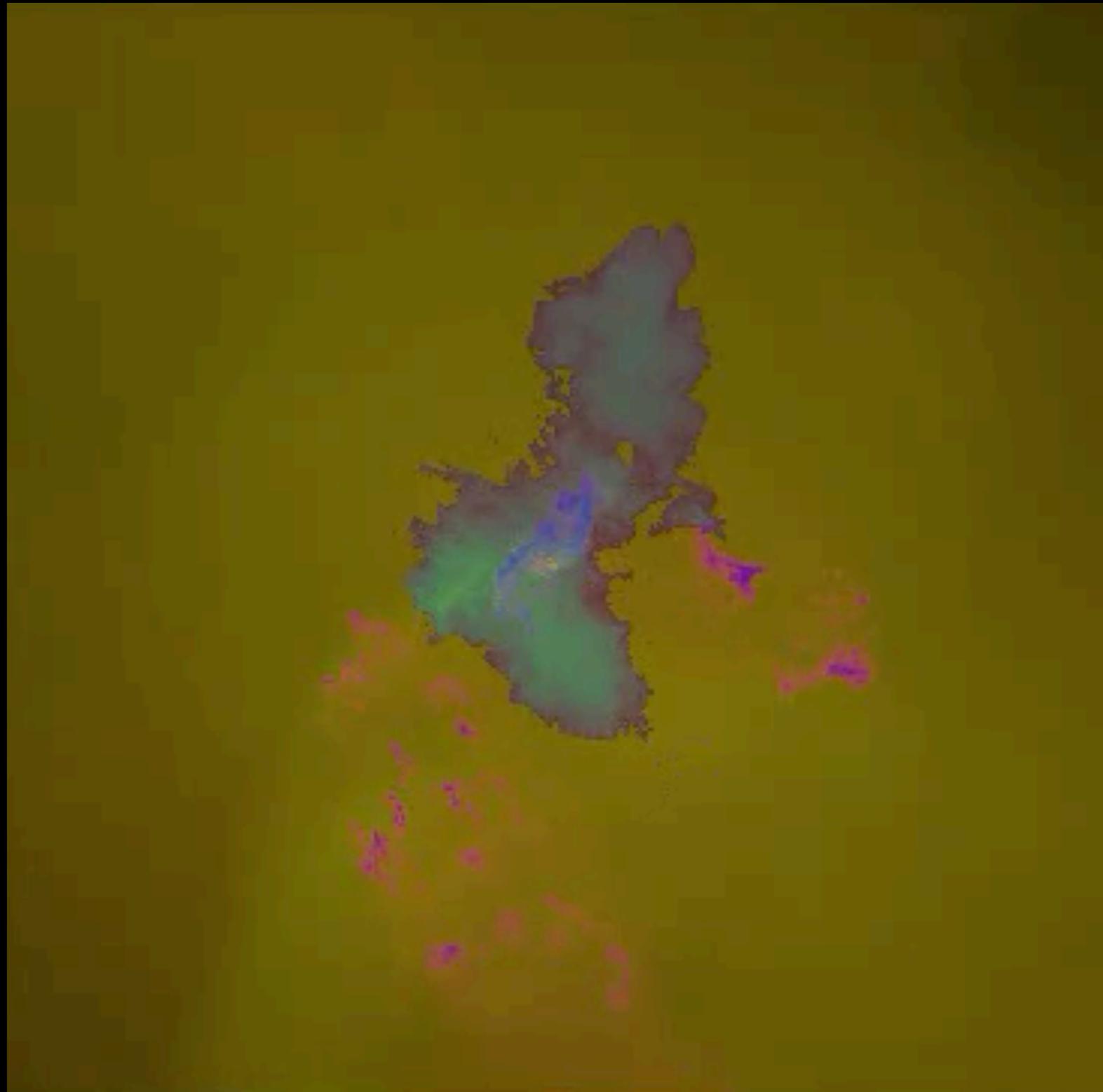
82.8 Myr



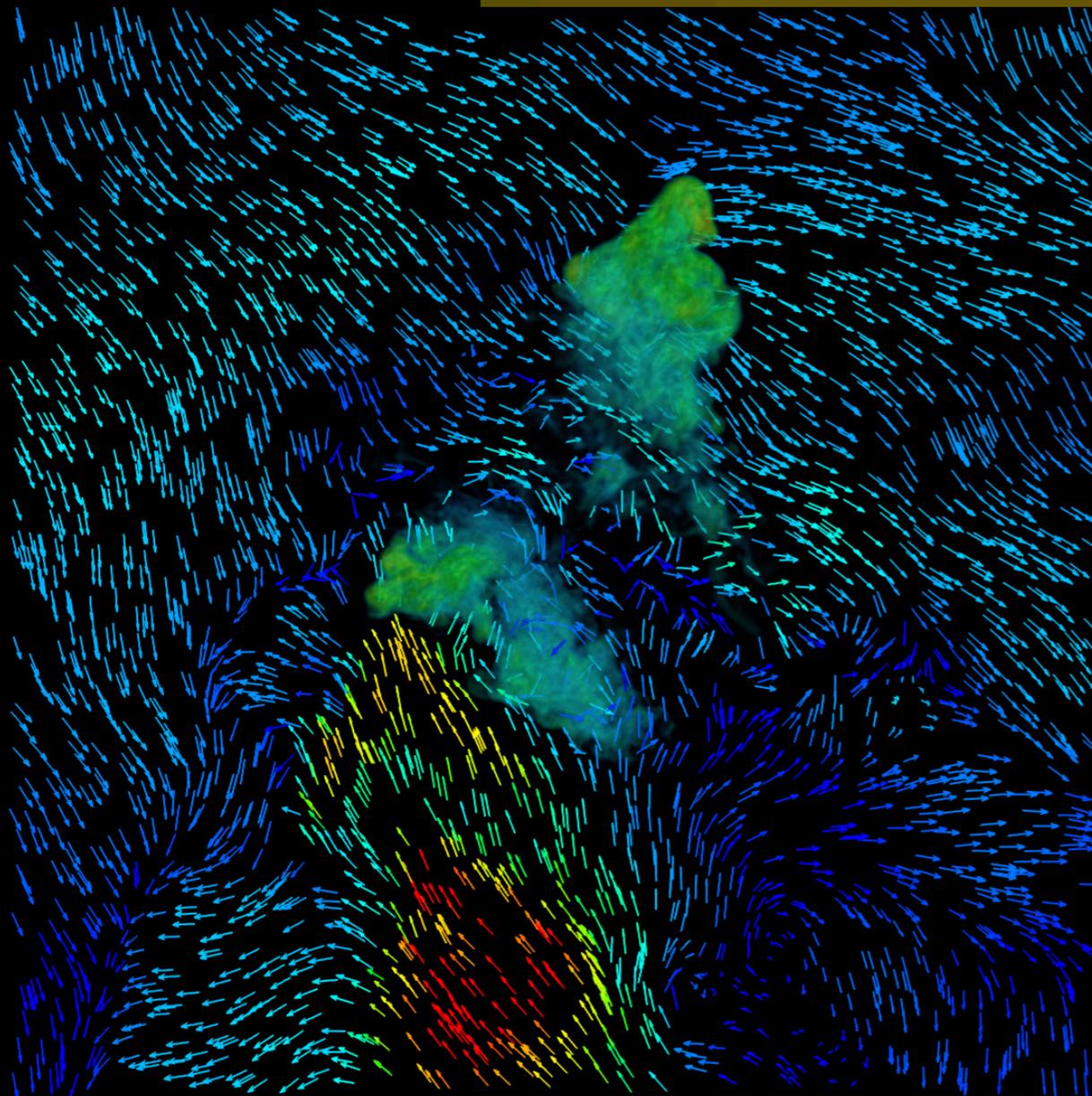
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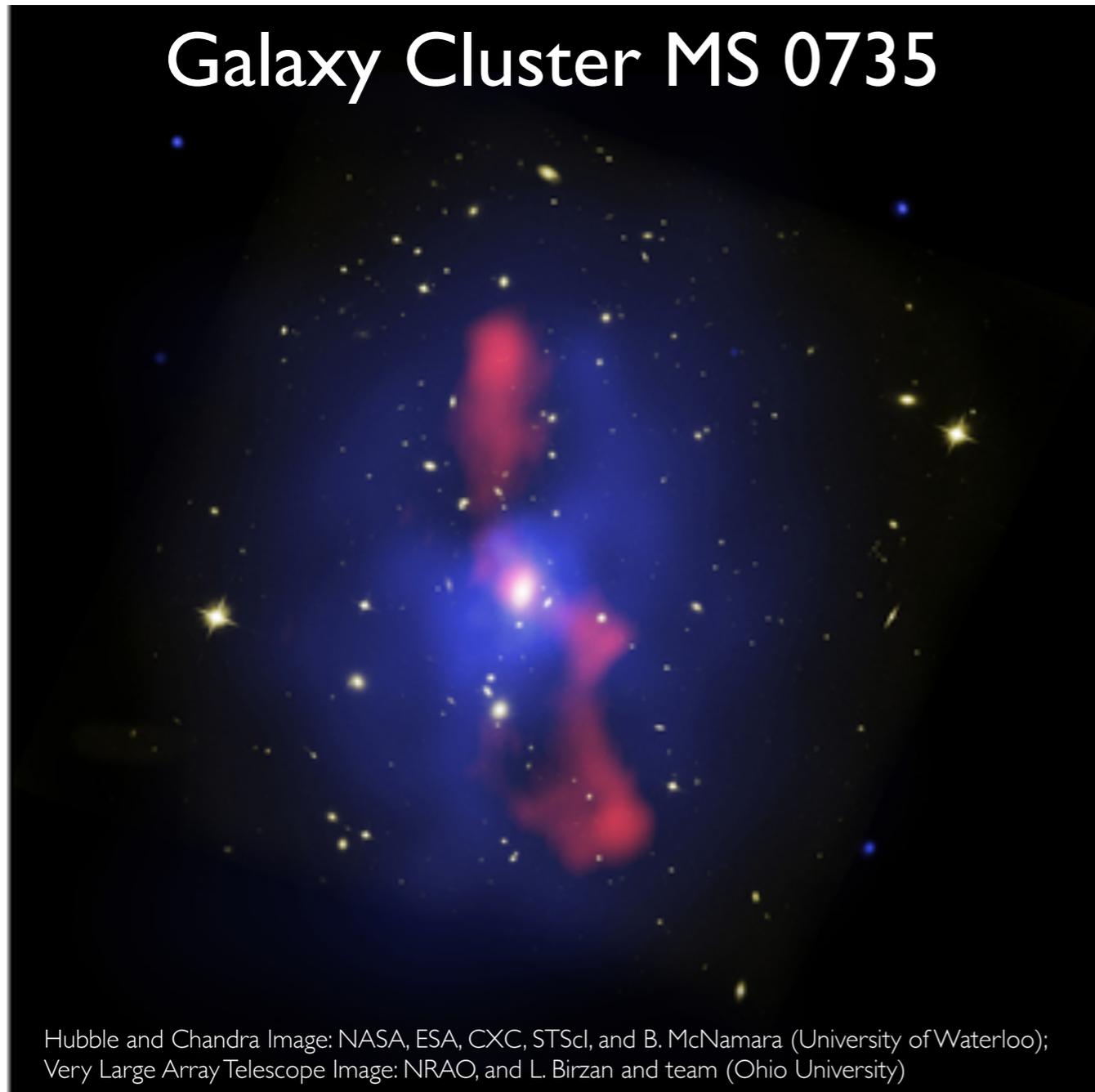


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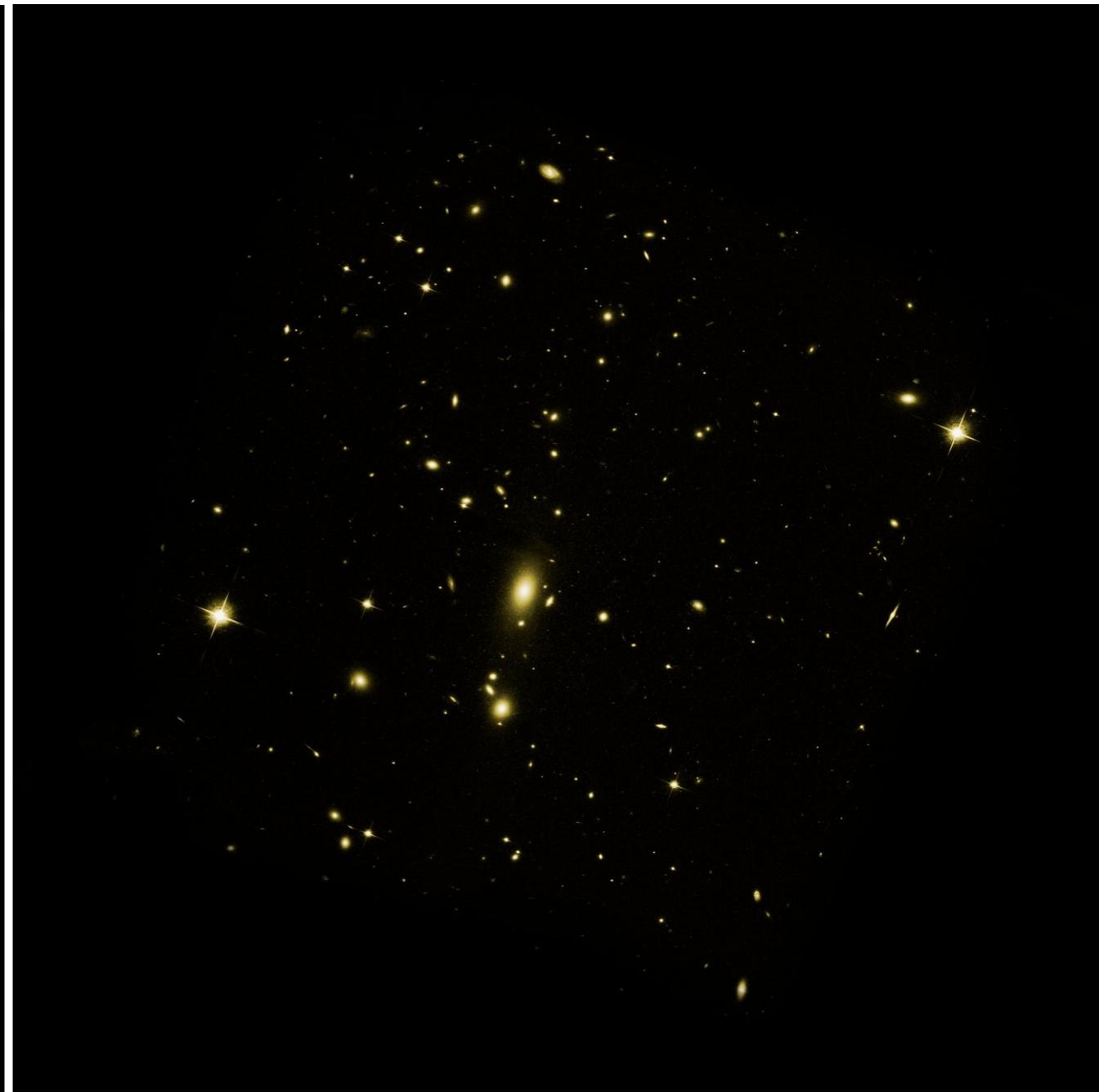


# COMPARING TO REAL SYSTEMS

## Galaxy Cluster MS 0735

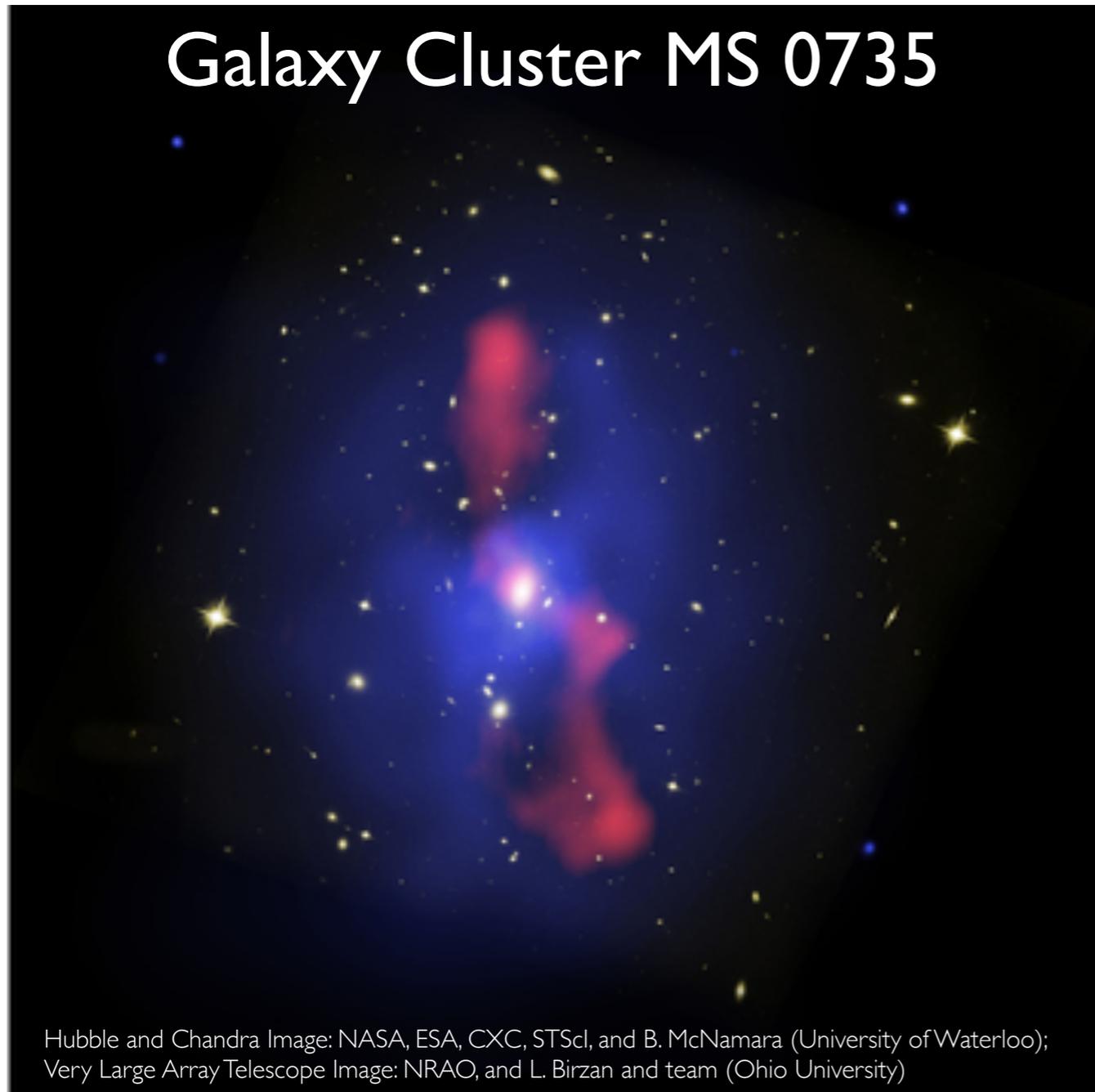


Hubble and Chandra Image: NASA, ESA, CXC, STScI, and B. McNamara (University of Waterloo);  
Very Large Array Telescope Image: NRAO, and L. Birzan and team (Ohio University)



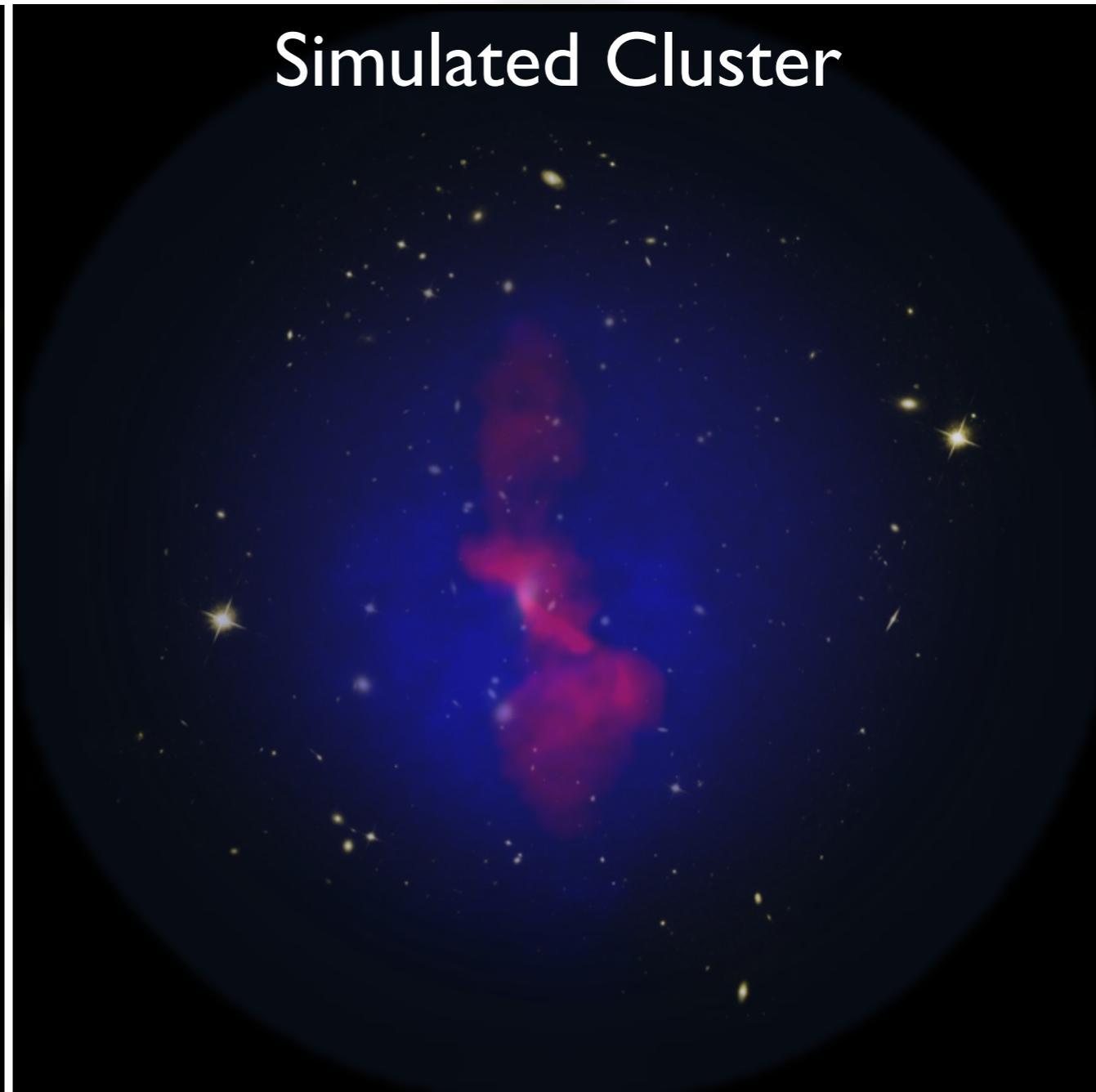
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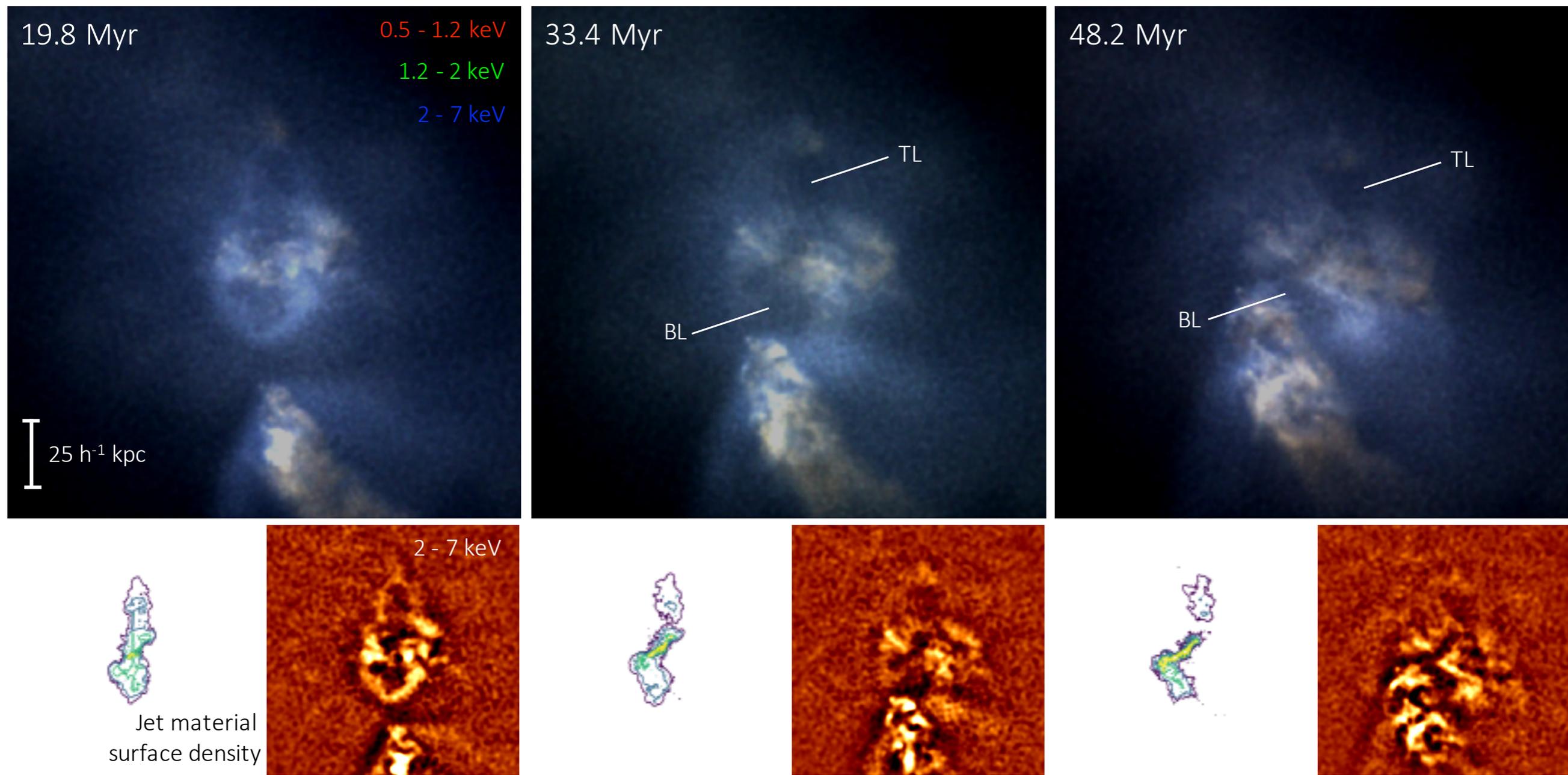


Hubble and Chandra Image: NASA, ESA, CXC, STScI, and B. McNamara (University of Waterloo);  
Very Large Array Telescope Image: NRAO, and L. Birzan and team (Ohio University)

Simulated Cluster



# MOCK X-RAY MAPS

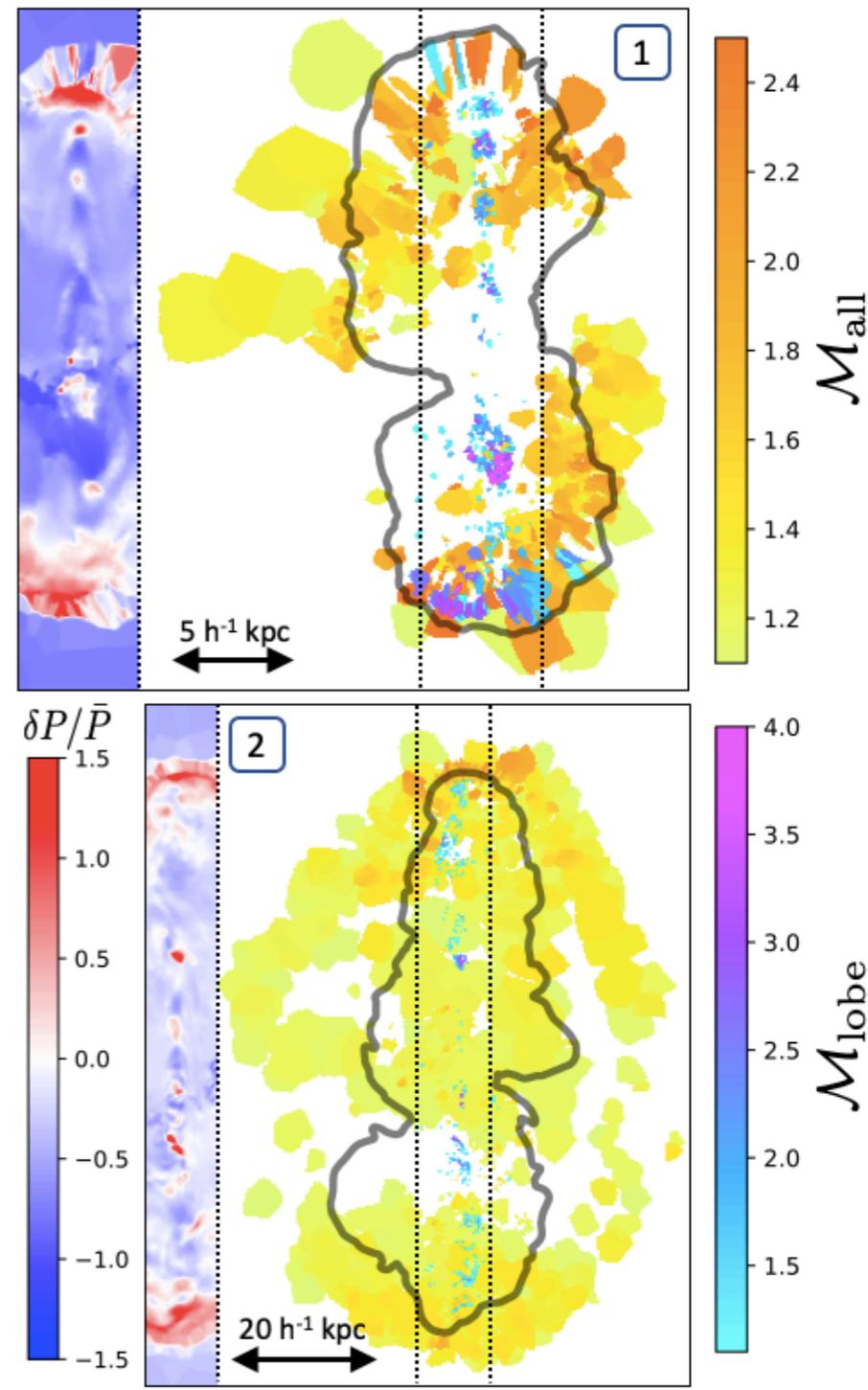
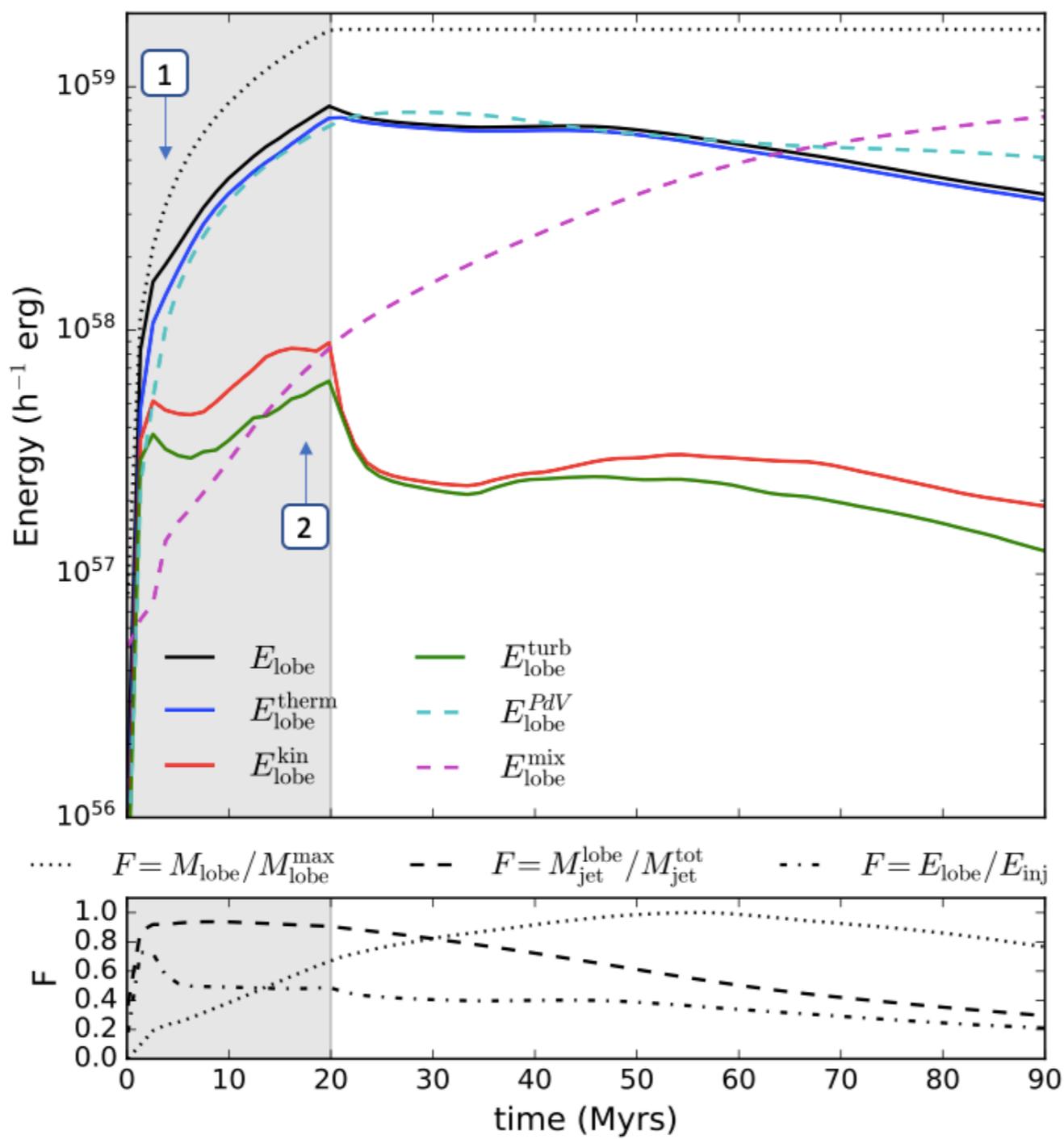


Lobe asymmetry  
Abel 4059, Abel 2052

(used PYXSIM, ZuHone+14)

# WHERE DOES THE ENERGY GO?

**During inflation**  
 50% in lobe  
 40% into PdV  
**After 90 Myrs**  
 20% in lobe  
 40% mixed into ICM



# WHERE DOES THE ENERGY GO?

During  
inflation

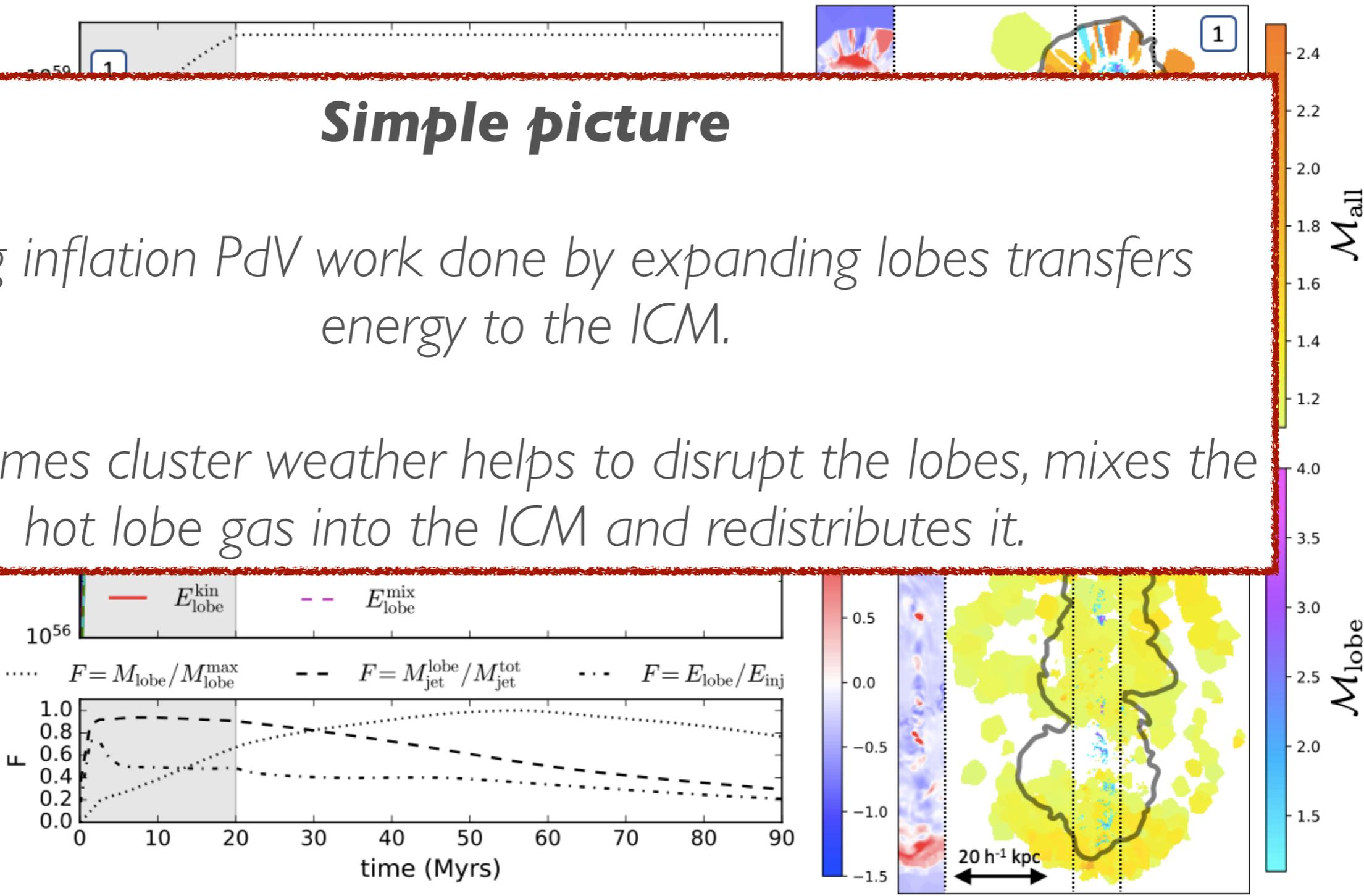
5  
40

## Simple picture

During inflation PdV work done by expanding lobes transfers energy to the ICM.

At later times cluster weather helps to disrupt the lobes, mixes the hot lobe gas into the ICM and redistributes it.

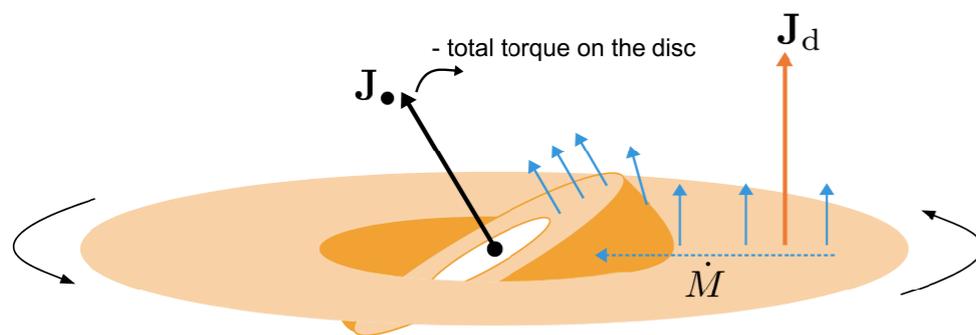
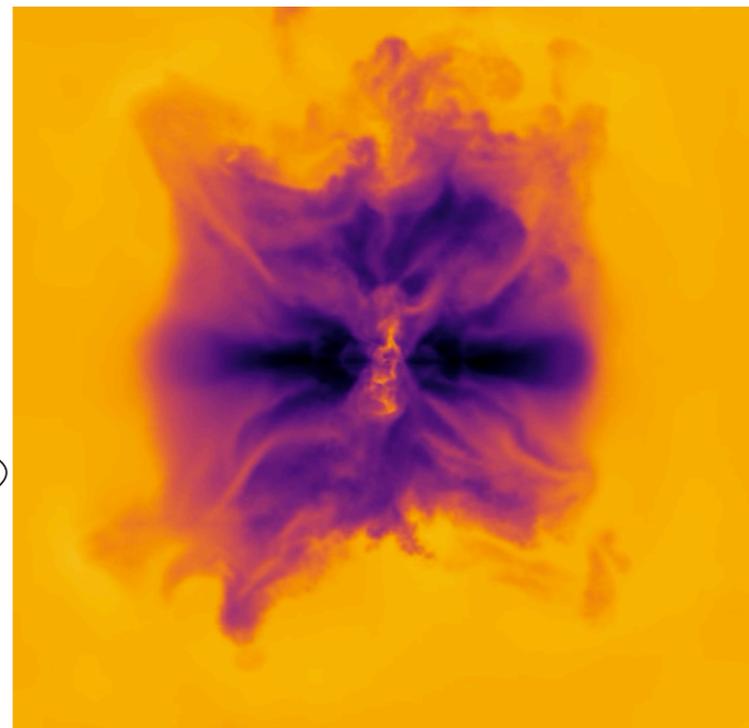
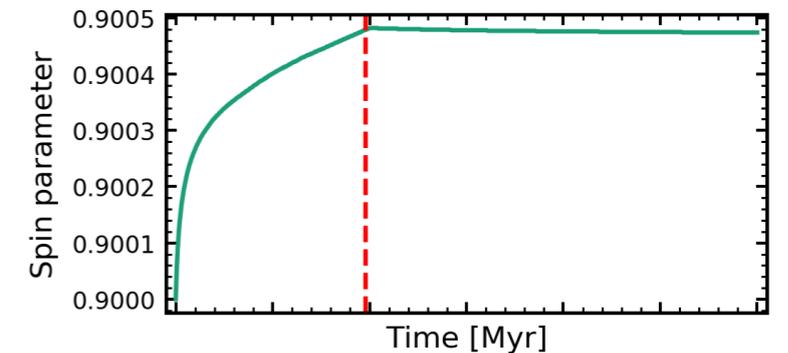
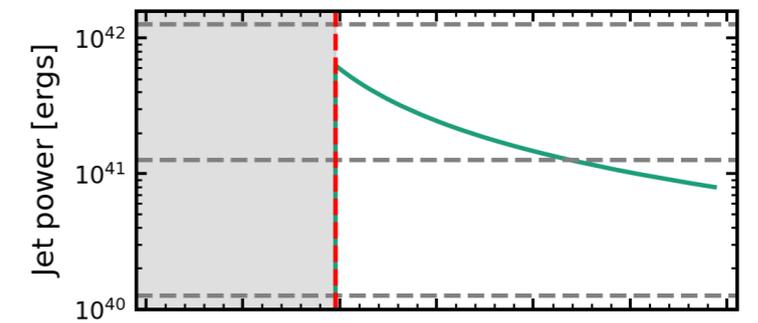
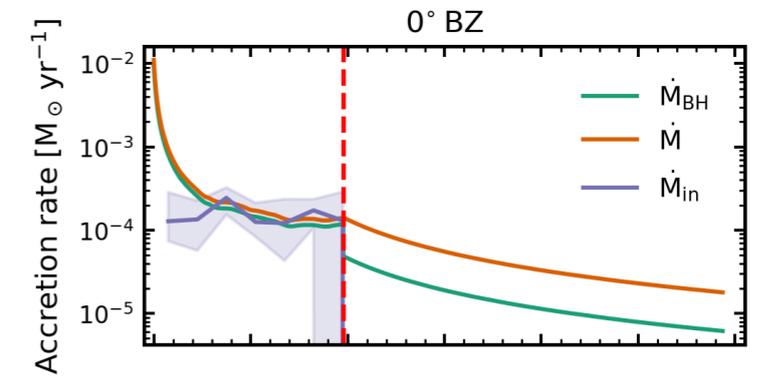
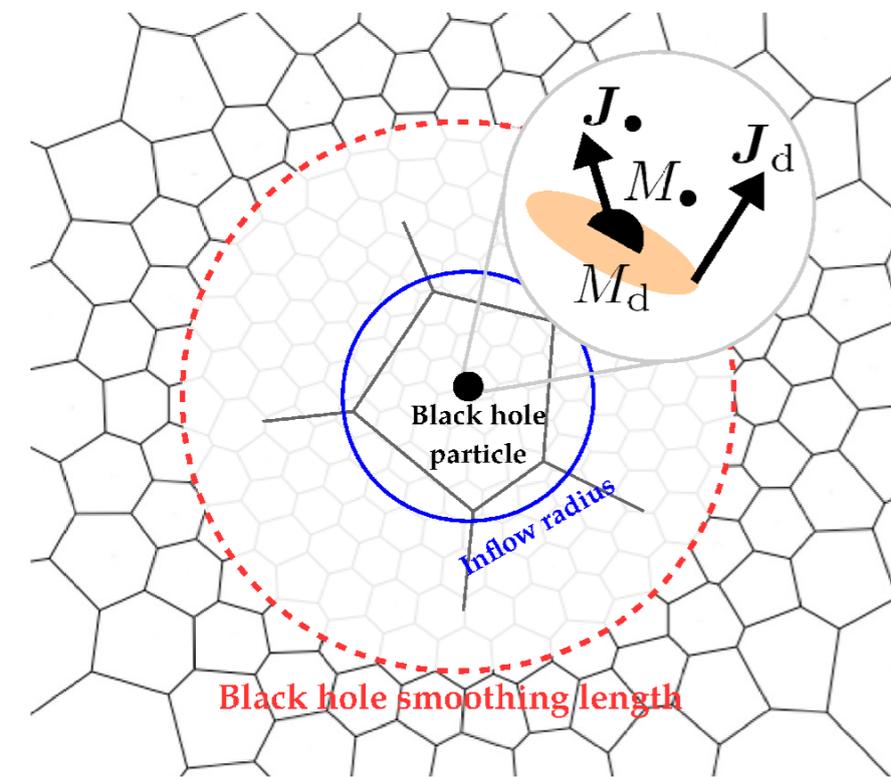
20% in  
lobe  
40%  
mixed  
into ICM



# COMPLETING THE FEEDBACK LOOP

Work led by PhD student Rosie Talbot

Sub-grid accretion  
disc model



Fiacconi+18

Assume BZ model to link  
spin and jet power

# SUMMARY

- **Done so far:**

- New techniques are allowing us to push the resolutions limits within our simulations, invoking more sophisticated feedback models and bridging the gap between between SMBH and cluster environment.
- We have incorporated our jet feedback model into a full cosmological run of a galaxy cluster allowing us to study the interaction of the jet lobes with their environment, finding that energy is transferred mainly via PdV work and cluster weather aided mixing.

- **In progress:**

- Coupling the jet feedback direction and power to a sub grid accretion disc model that tracks accretion rates, disc angular momentum and black hole spin.
- Also test jets in high redshift proto-clusters to explore differences in the action of the feedback mechanism.

