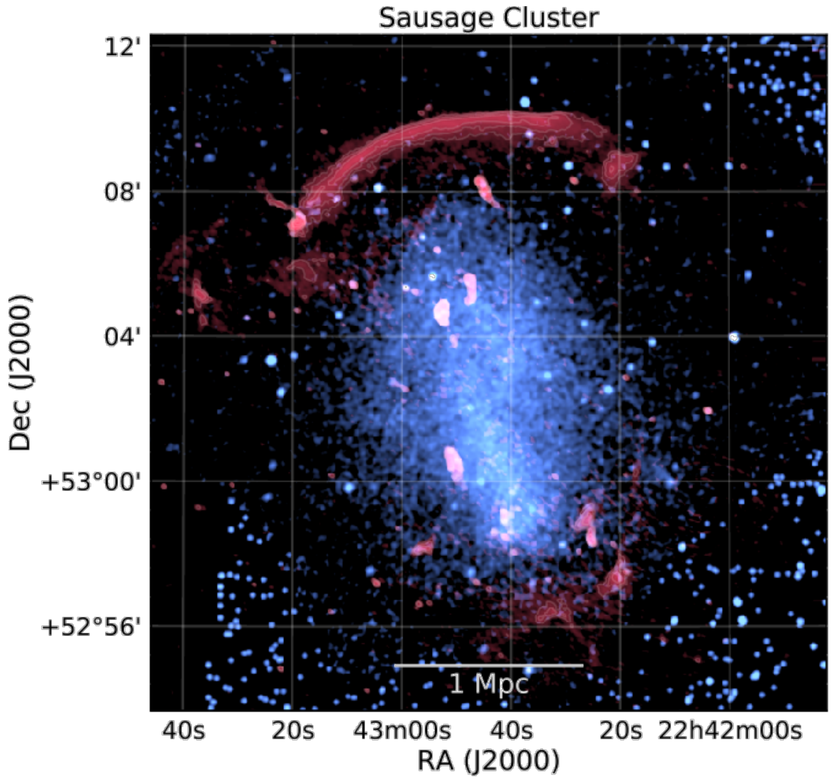
The interaction between merger-driven gas motions and AGN feedback in clusters of galaxies

John ZuHone (CfA), Maxim Markevitch (NASA/GSFC),
Rainer Weinberger (CITA), Paul Nulsen (CfA),
Kristian Ehlert (AIP), Christoph Pfrommer (AIP),
Andrew Fabian (IoA), Stephen Walker (U of Alabama—Huntsville)

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Radio Relics

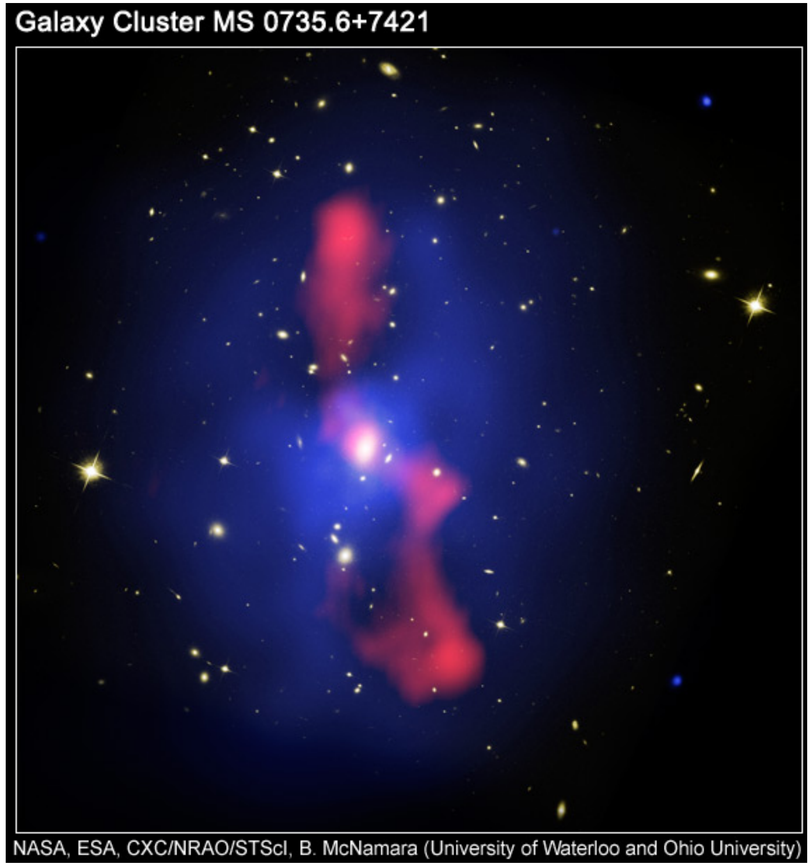
- Diffuse, elongated, polarized radio emission seen in clusters with evidence of merging activity
- In the simplest models, they originate from shocks which accelerate uniformly distributed e^- from the ICM or re-accelerate pre-existing CRe
- Curiosities:
  - Not all radio relics are aligned with ICM shocks on the sky
  - How do you produce the highly-ordered B-field required for polarization from shock compression alone?
- What if these features are characteristics of the pre-shock CRe material instead?



van Weeren et al. 2010; Ogrean et al. 2014; van Weeren et al. 2019

ICM Motions Spreading CRe from AGNs

- AGN inject CRe which can persist for many Gyr after cooling to $\gamma \sim 100$
- Such CRe can be advected by gas motions in the ICM plasma: bulk motions and turbulence
- Questions:
  - What are the spatial distributions of CRe produced by advection?
  - In the CRe-enriched regions, what is the distribution of magnetic field?



Simulations

- MHD idealized cluster merger simulations performed with AREPO
- ~10^{15} $M_\odot$ cluster, two different mergers (one minor, one major)
- Jet Physics:
  - t ~ 3.5 Gyr after merger, fire a jet in opposite directions with $E_{jet} \sim 10^{61}$ ergs from center of cluster
  - Jet material is magnetized with $\beta \sim 1$, injects thermal, kinetic, magnetic energy (Weinberger et al. 2017, 2018)
  - Fired along three principal simulation axes: x, y, z (merger is in x-y plane)
- In these first simulations, the “CRe” are represented by a passive tracer field that is advected along with the gas (but we’ll change this later)

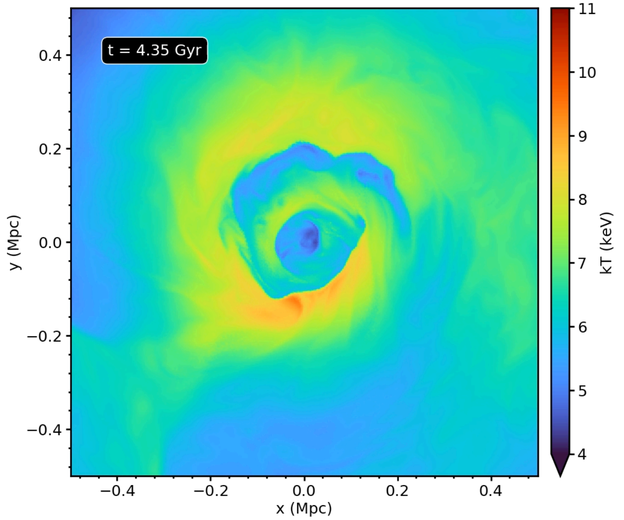
ZuHone et al. (2021a)

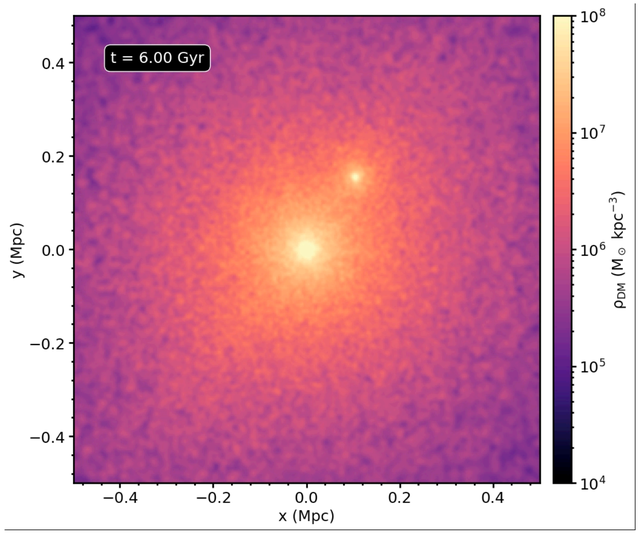
kT (keV)

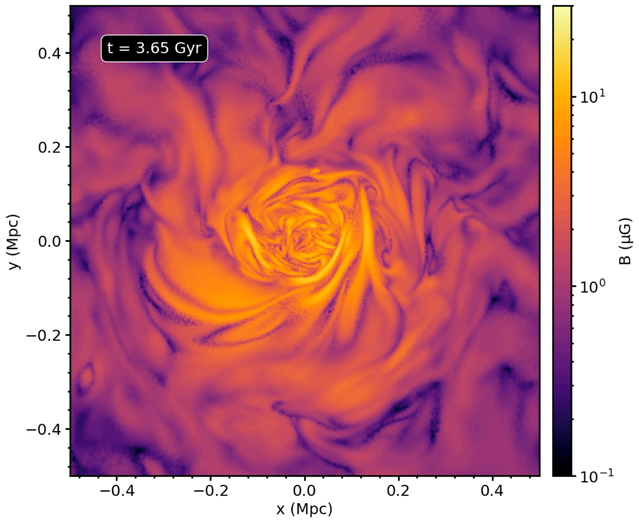
$\rho_{\rm DM}$ ($M_\odot$ $\rm kpc^{-3}$)

B (μG)

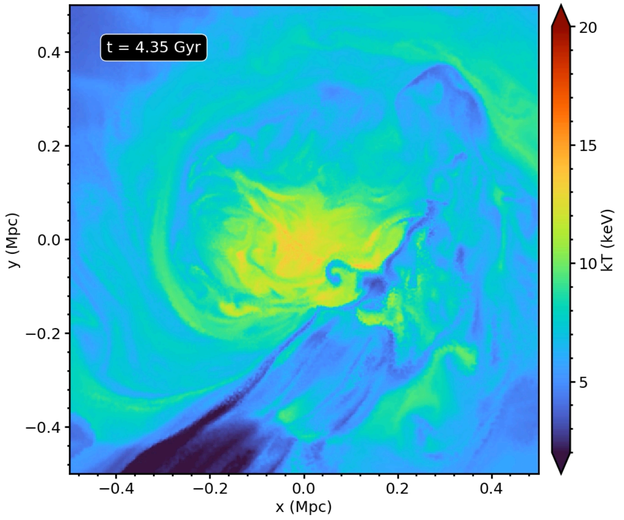
Merger1 Simulation

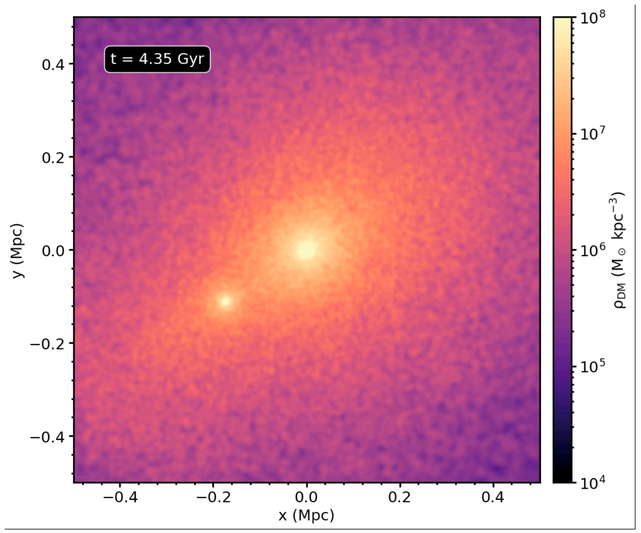


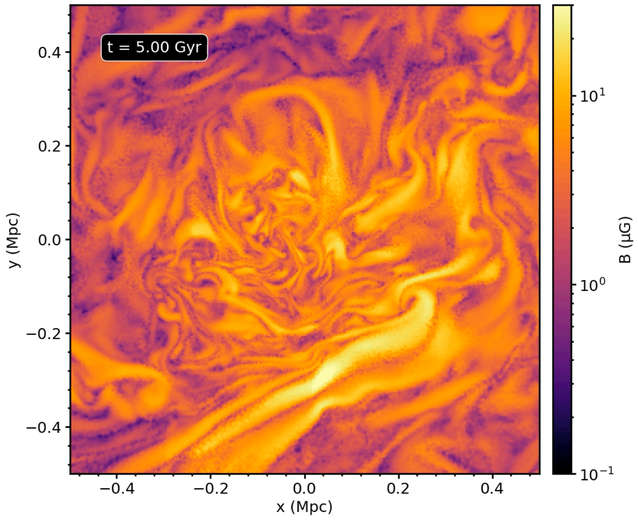




Merger2 Simulation

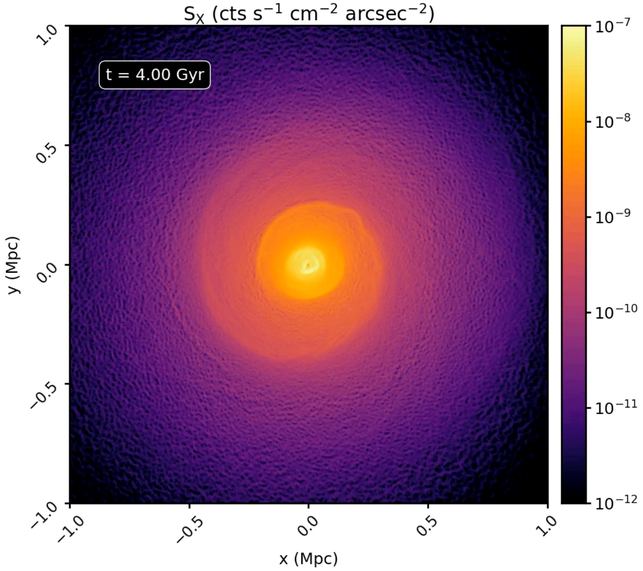


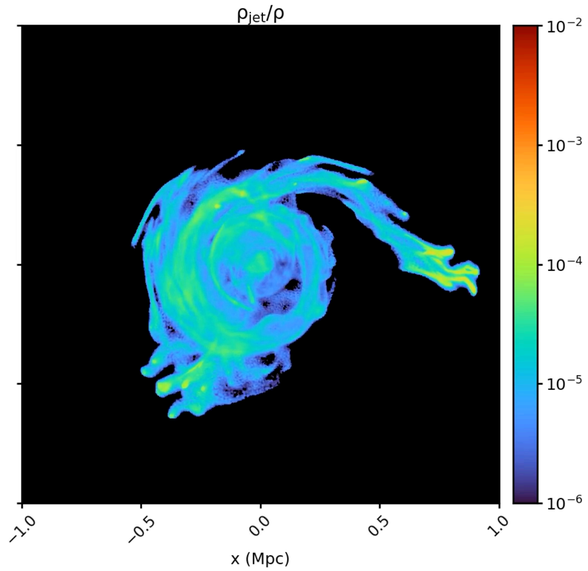


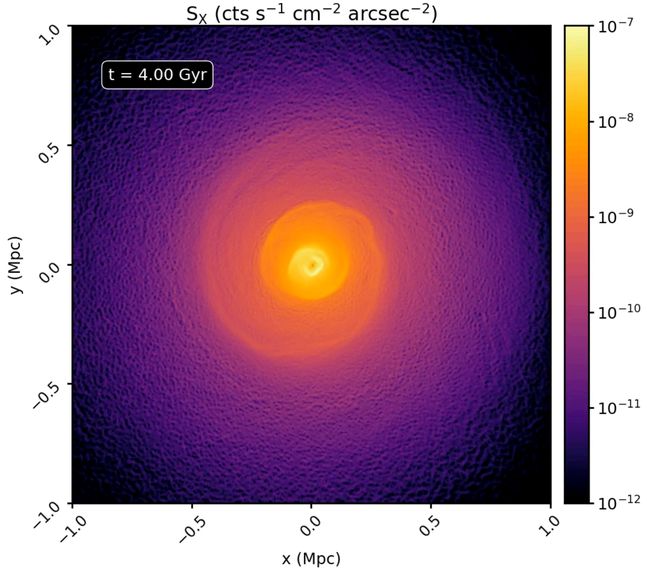


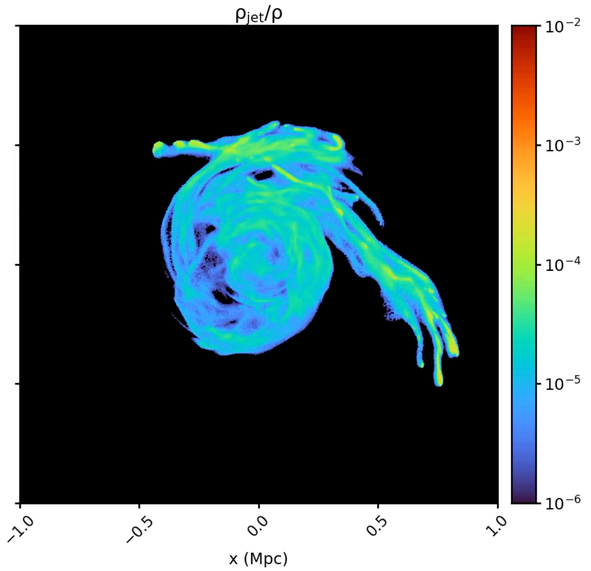
ZuHone et al. (2021a)

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN



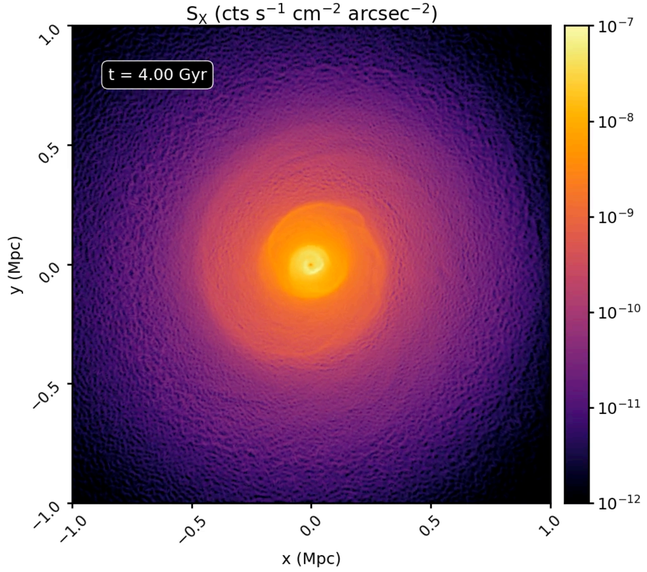


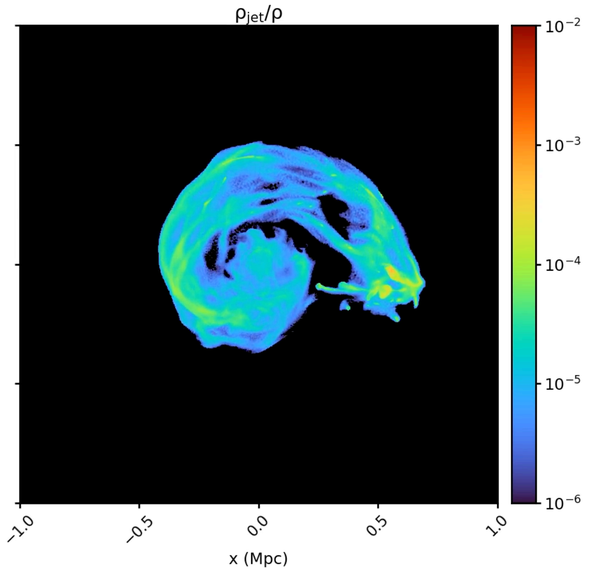




Merger1 Simulation, In-Plane Jets

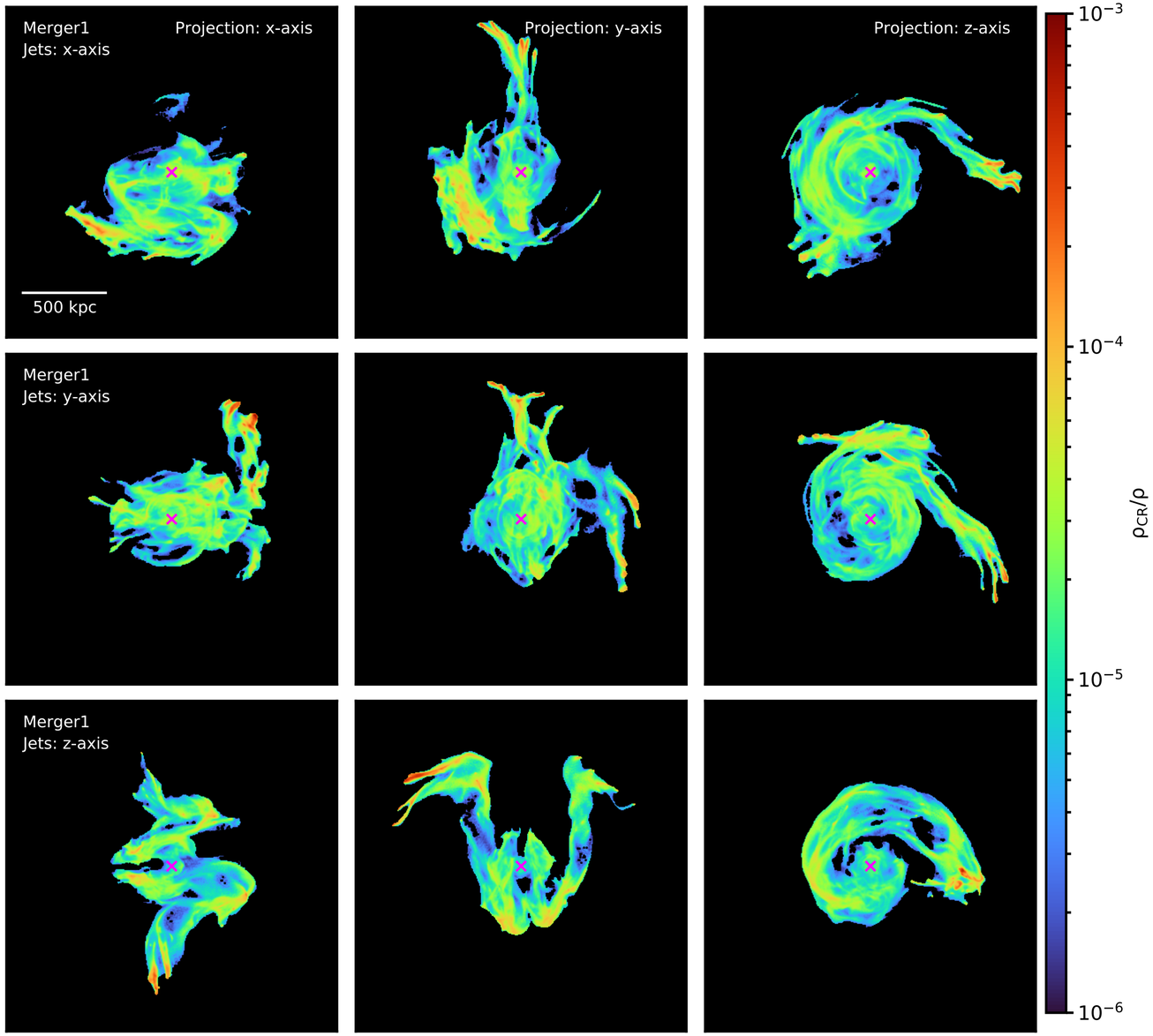
ZuHone et al. (2021a)



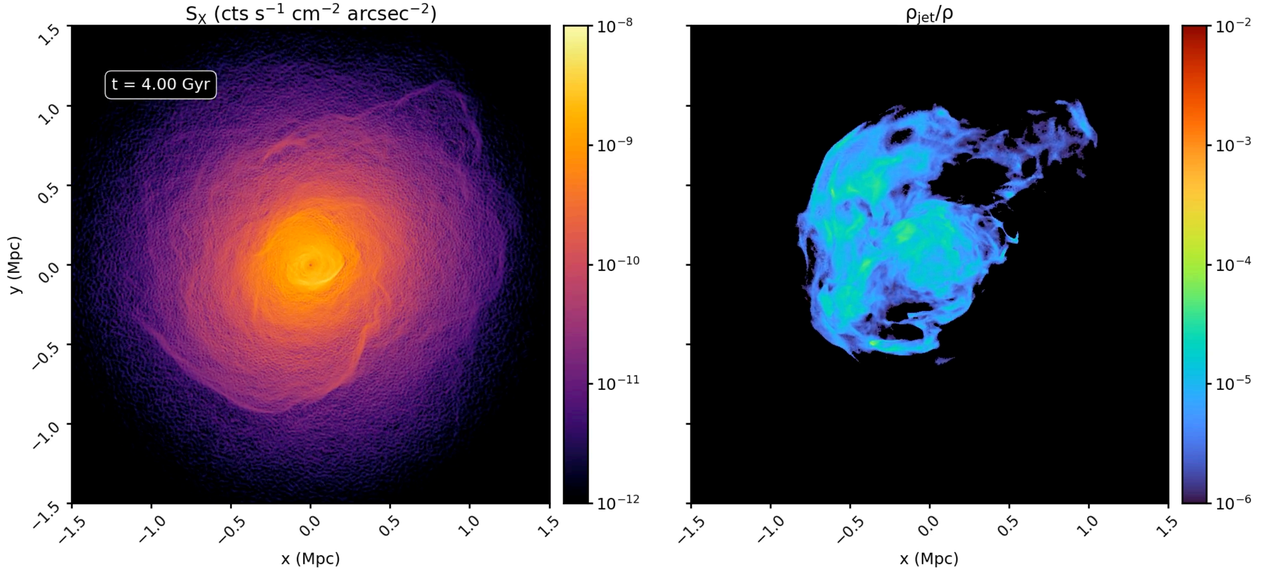


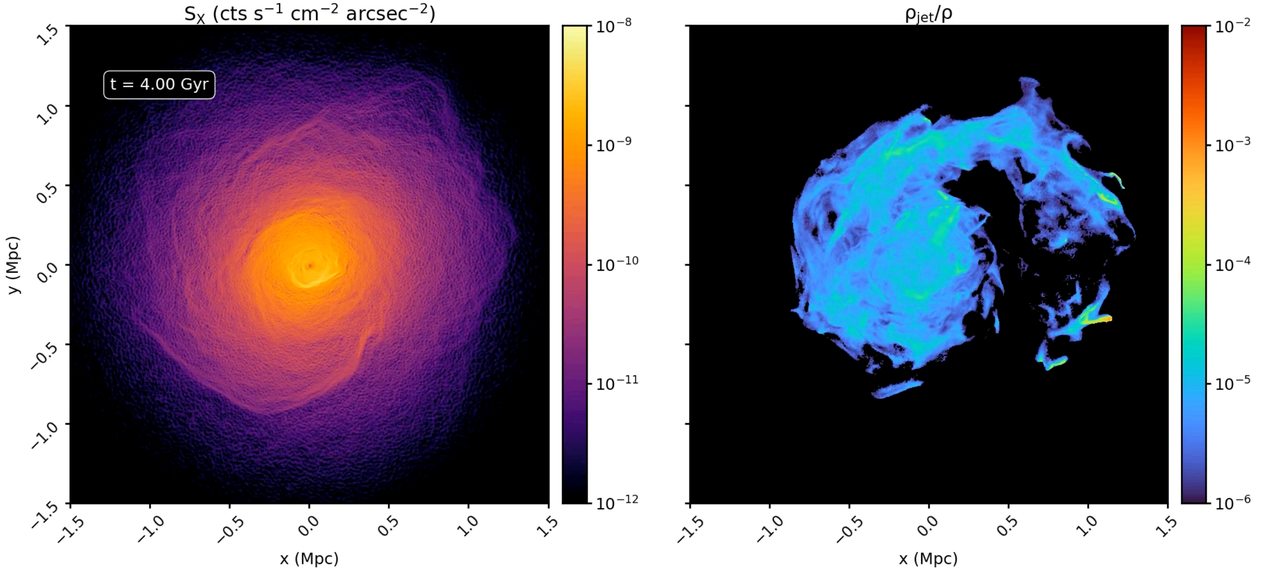
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Different Axis Projections: Merger1 Simulation



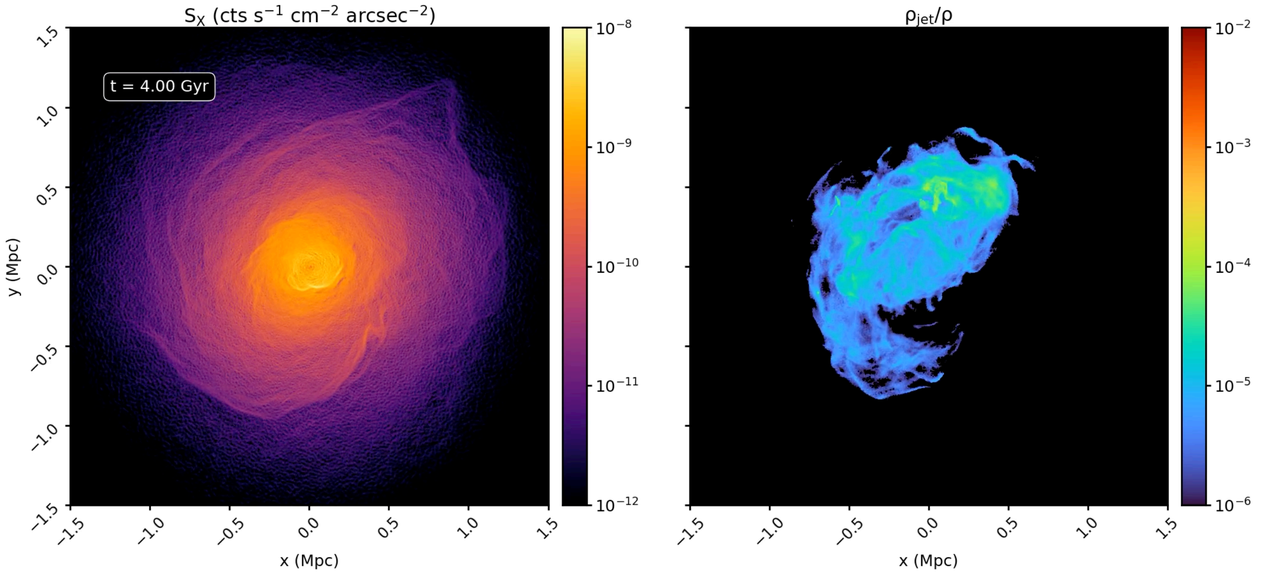
ZuHone et al. (2021a)





Merger2 Simulation, In-Plane Jets

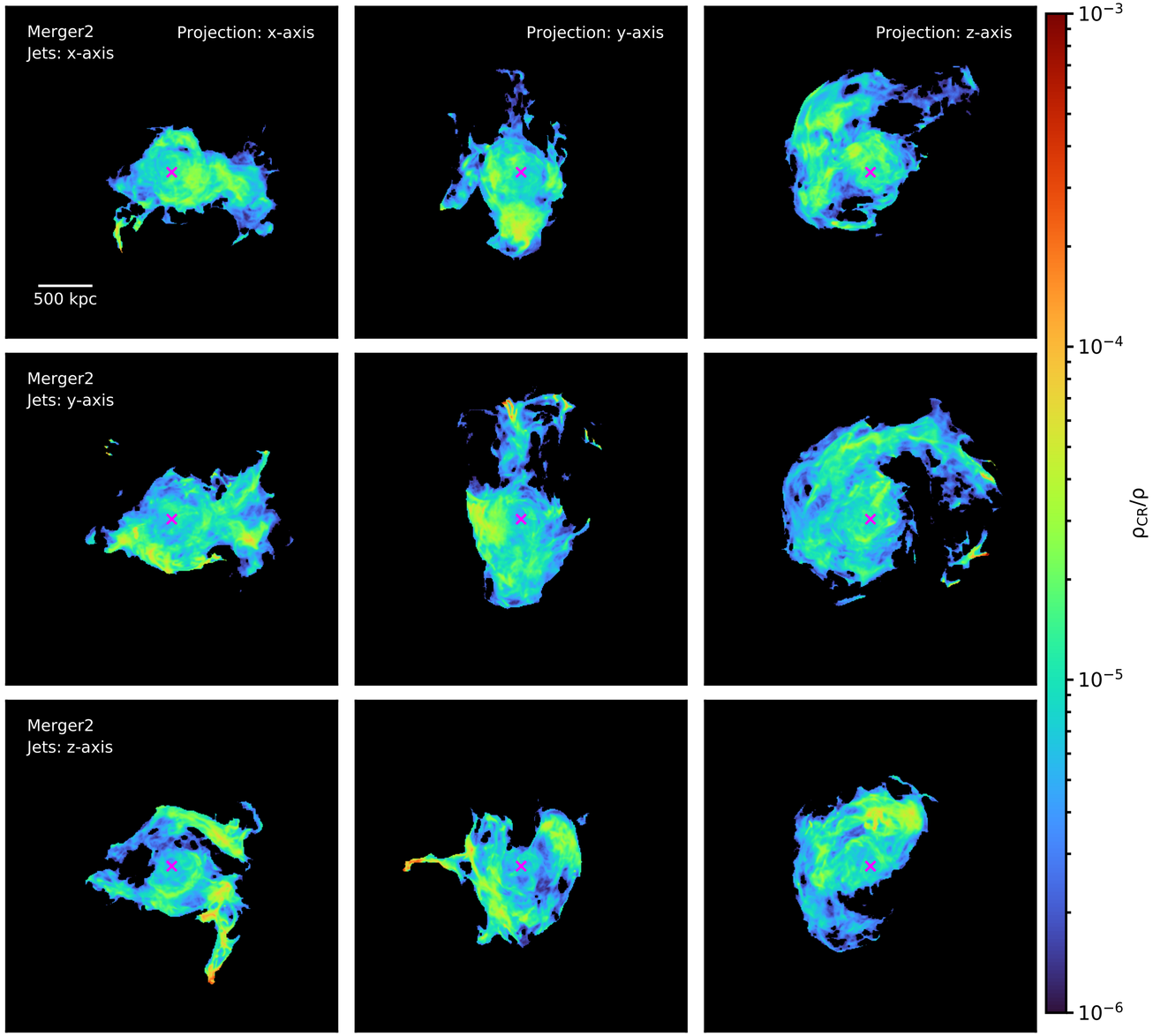
ZuHone et al. (2021a)



CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

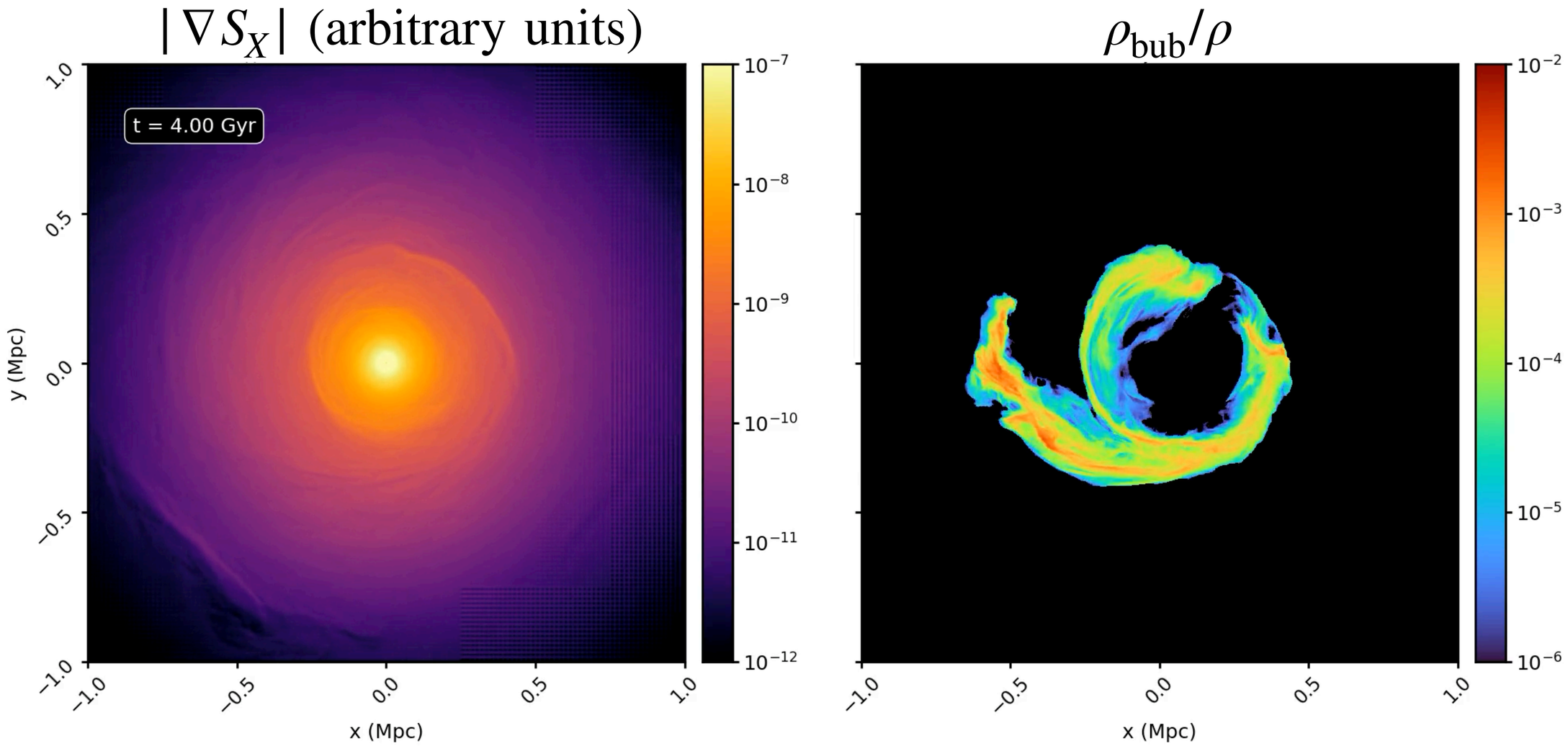
Different Axis Projections: Merger2 Simulation

ZuHone et al. (2021a)



CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

An Isolated Bubble Simulation



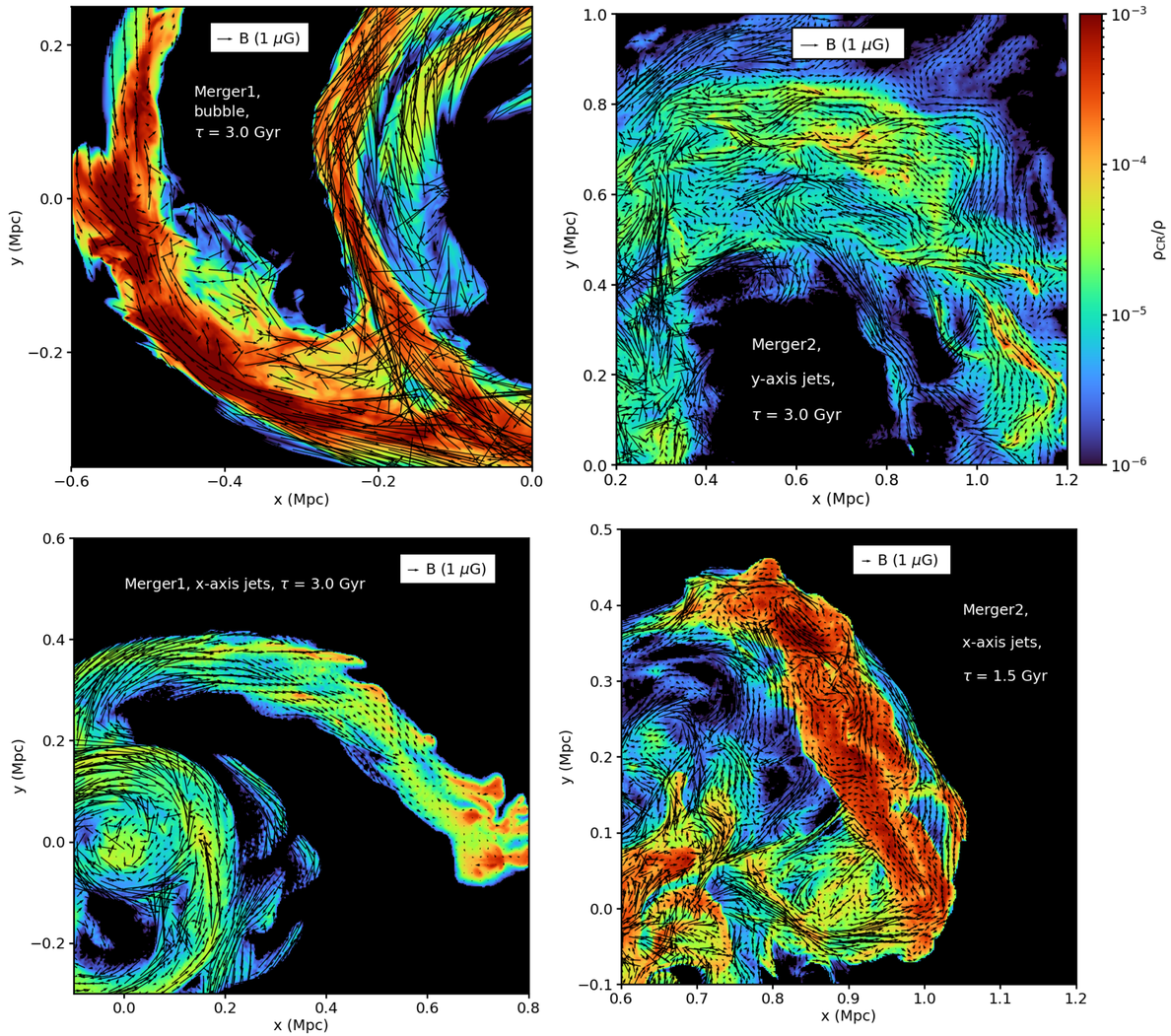
Wonki Lee will give another example on Friday

ZuHone et al. (2021a)

Aligned Magnetic Fields—Potential Explanation for Polarization?

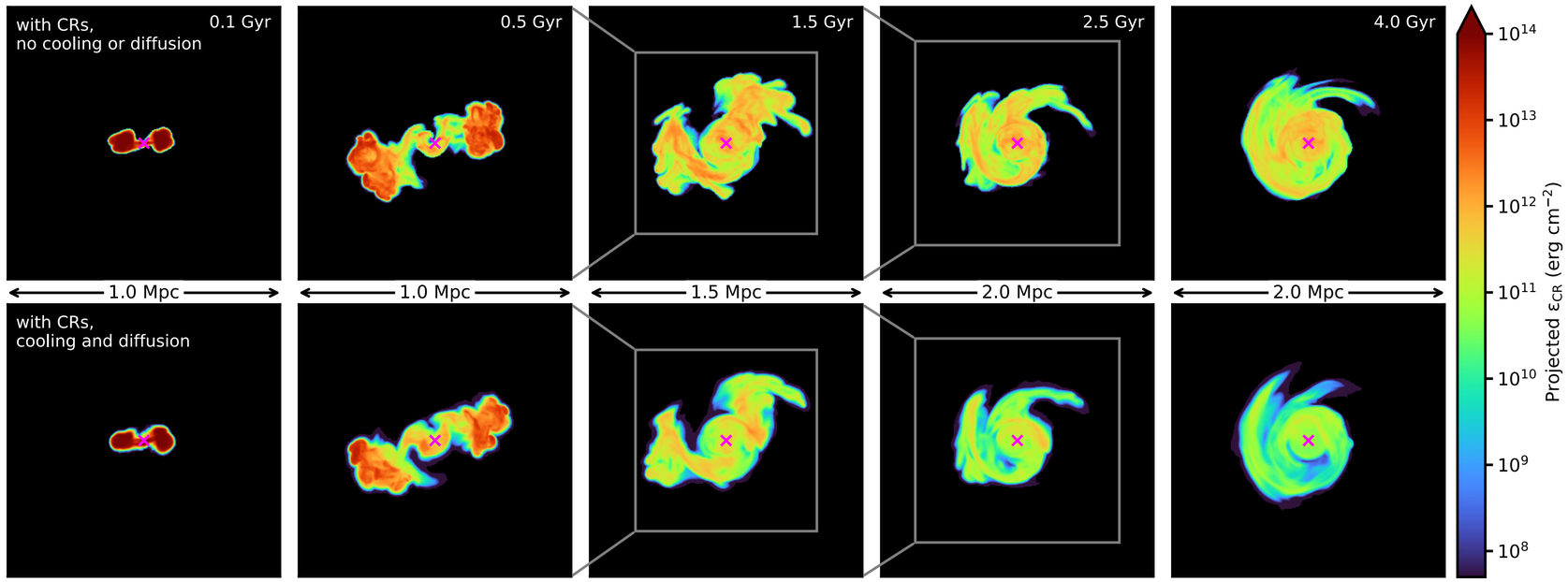
- The same gas motions which spread the material from the bubbles stretch and amplify magnetic fields in the same direction
- Results in highly ordered fields in the location of CRe-enriched plasma
- "Emission-weighted" plane-of-sky B-field vectors ($\propto B^2\epsilon_{\rm CR}$) to show which fields would actually be measured

ZuHone et al. (2021a)



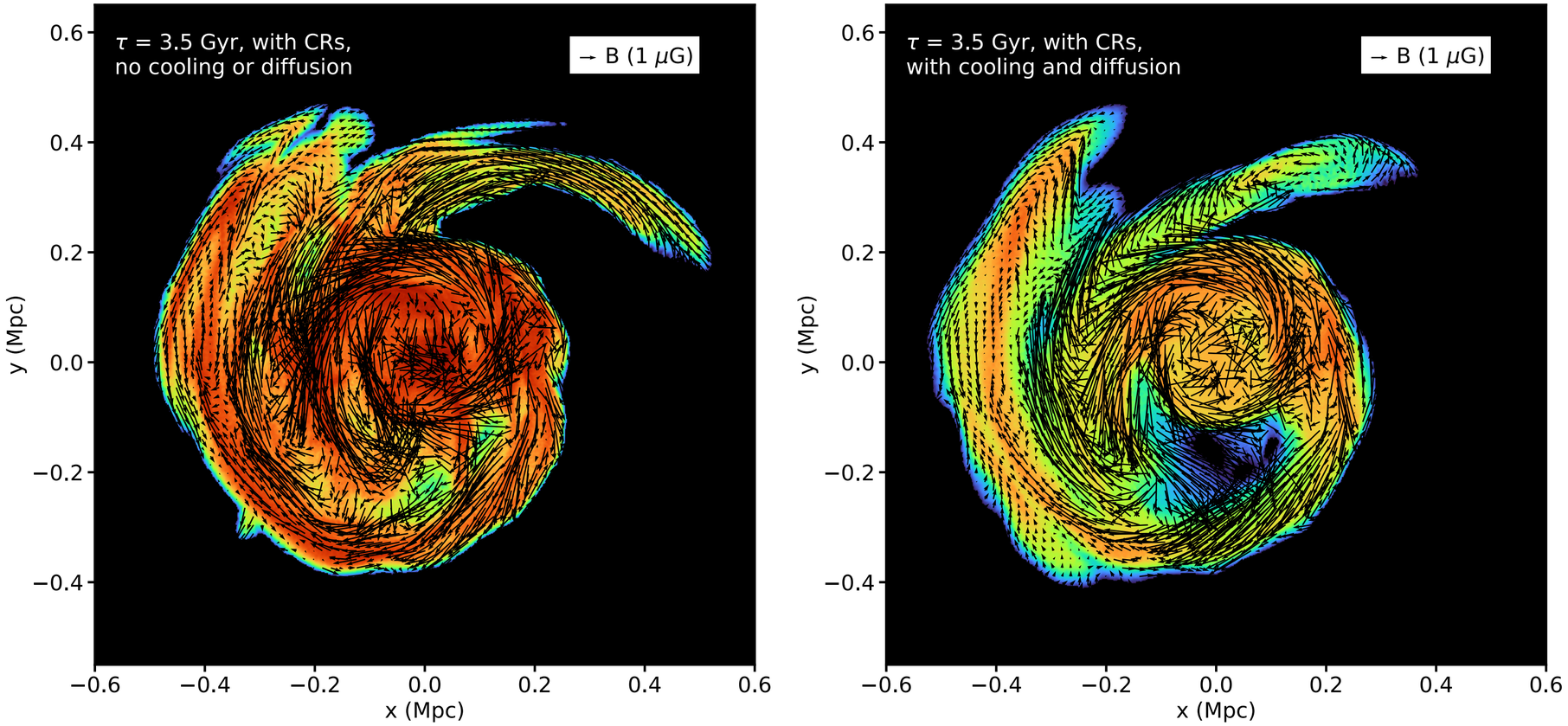
Enhancing CR Physics

- The next step is to improve the CR physics included in the simulation:
  - Model CRs as separate fluid with Γ = 4/3
  - CR spatial diffusion (parallel to B) and Alfvén losses



ZuHone et al. (2021b)

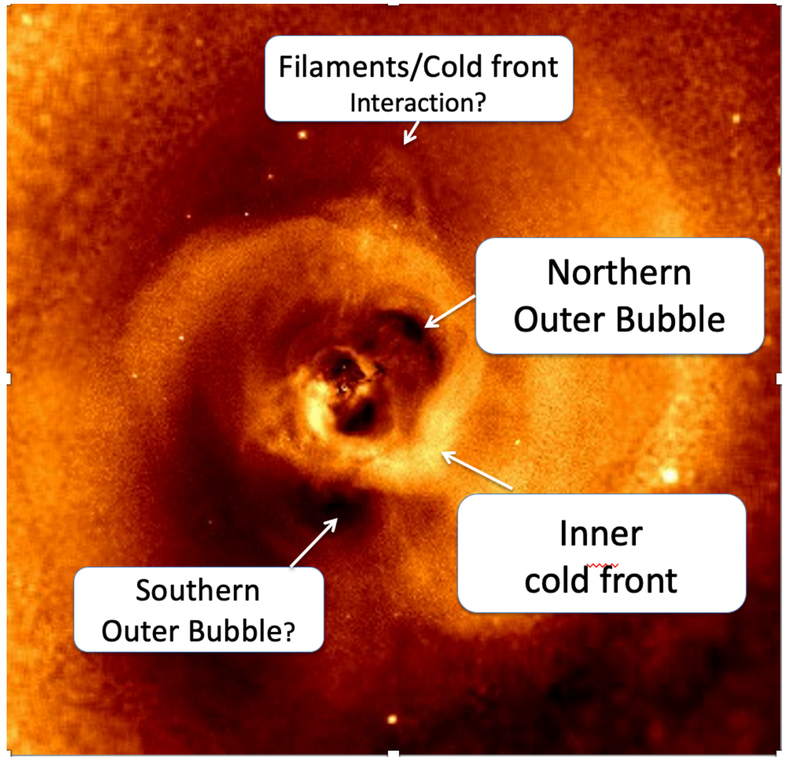
Effect of CR Physics on Observed B-field



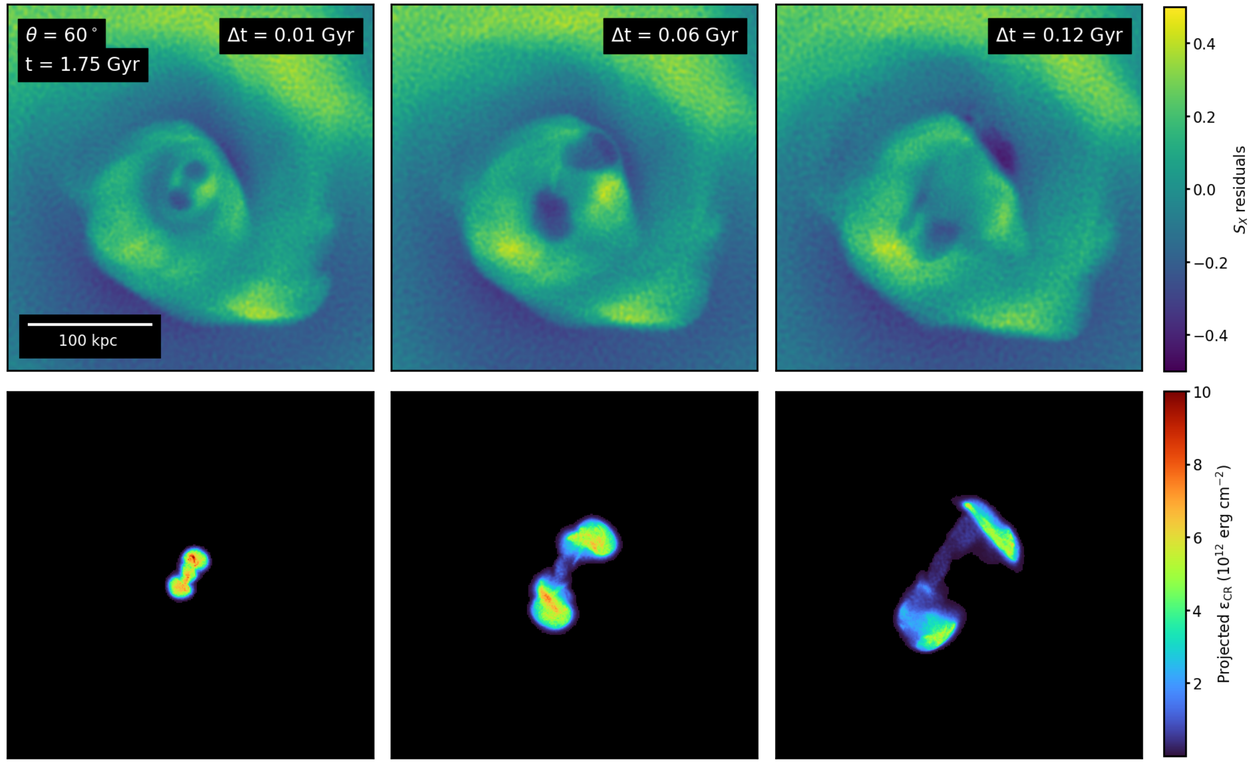
ZuHone et al. (2021b)

Other Effects of Core Gas Motions on AGN Bubbles

These cold fronts go to large radii—see Elena Bellomi's talk in less than an hour



X-ray surface brightness residuals

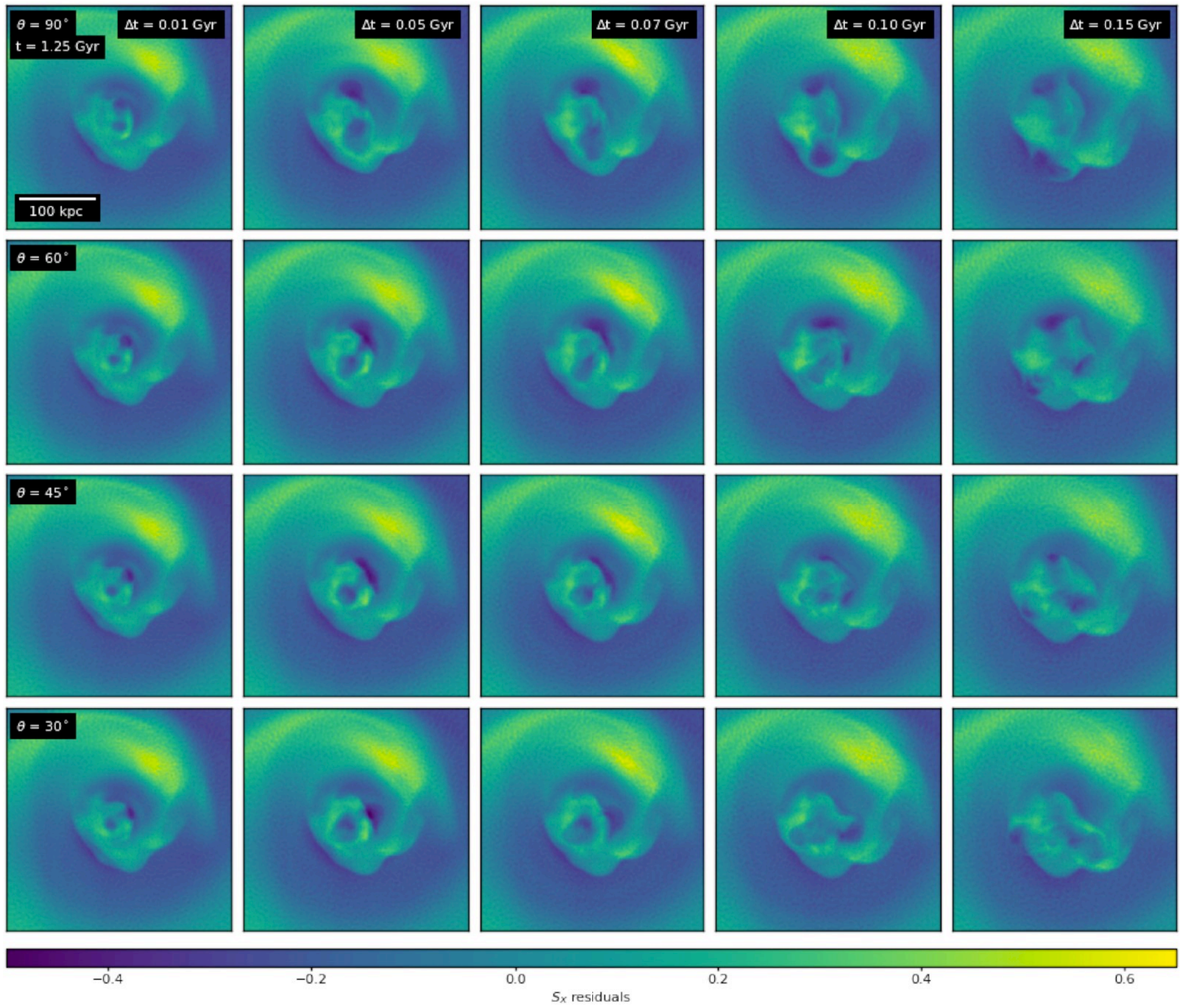


Projected CRe energy density

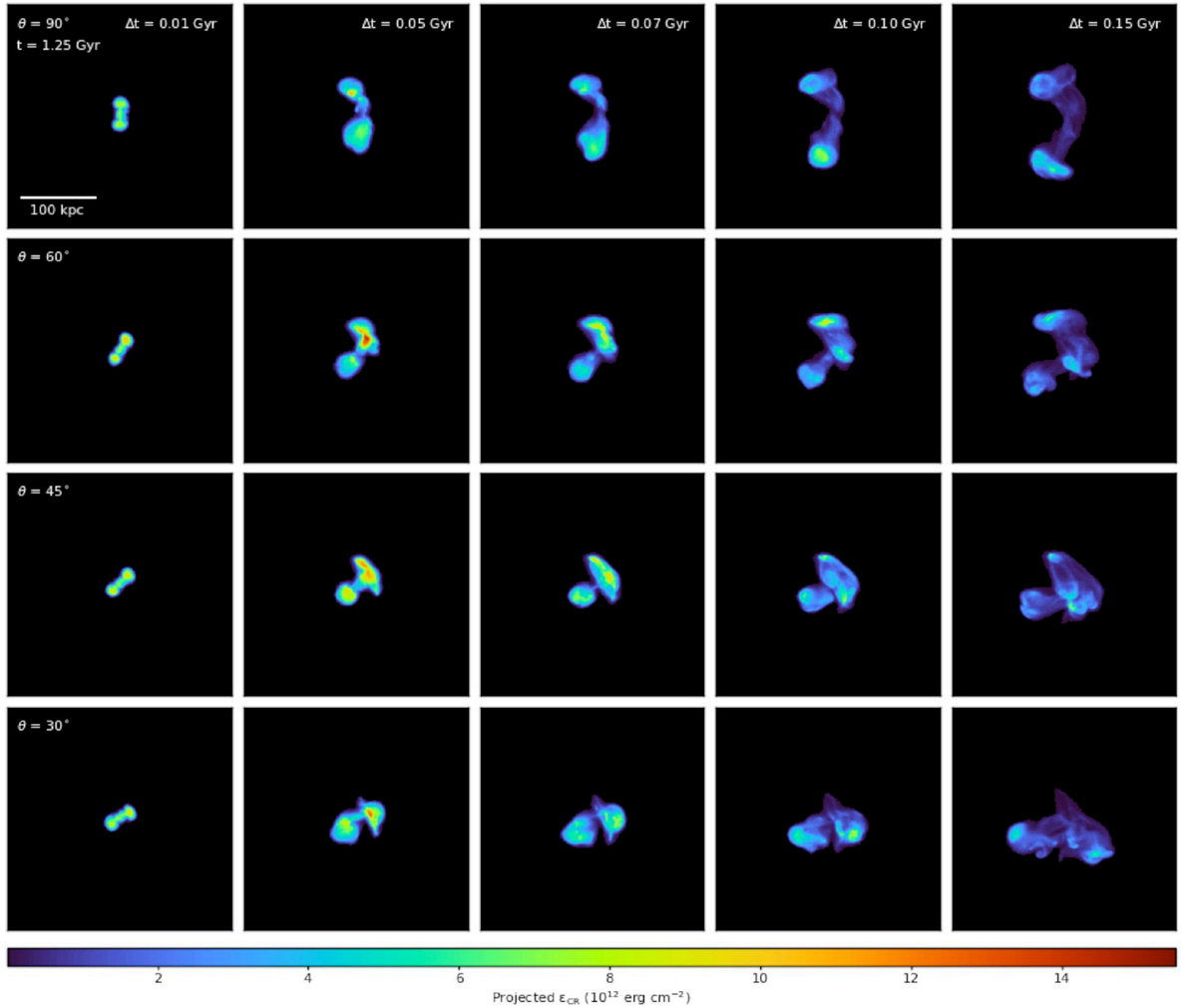
flattened, distorted, and pushed bubbles

Fabian et al. (2022)

X-ray surface brightness residuals



Projected CRe energy density



Fabian et al. (2022)

Summary

- Bulk motions and turbulence can transport CRe from AGN bubbles to radii large enough to produce radio relics, and they can produce the elongated, mostly tangentially oriented features which are similar in appearance
- Sloshing motions driven by minor mergers can produce straight, thin regions of plasma enriched by CRe with lengths ~1 Mpc
- Major mergers produce more turbulent motions, which result in wider and more diffuse CRe distributions, but also tend to produce faster bulk motions which can move the CRe around more quickly and to larger radii
- The magnetic fields produced in these CRe-enriched regions are largely oriented along the long axis of these features, potentially explaining the polarization of radio relic features
- CR diffusion and cooling can complicate this picture by reducing CR energy
- In the early stages of an AGN cycle, fast sloshing can distort, stretch, and move bubbles, as seen in Perseus