# AGN heating with CRs in a magnetized, turbulent ICM

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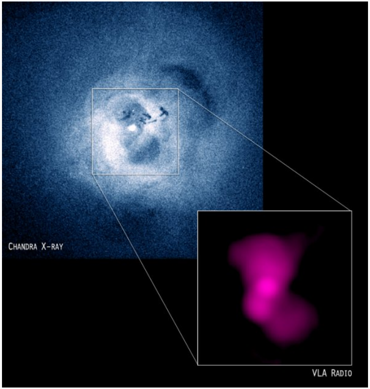
March 6, 2019

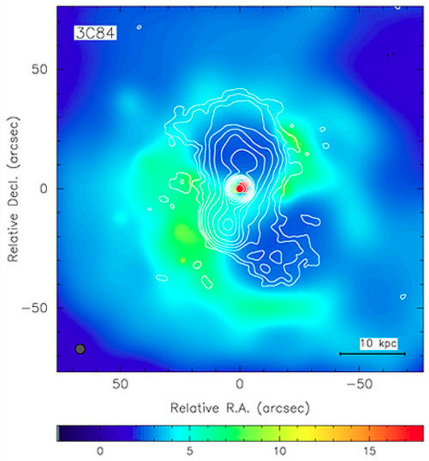
# Cooling flow problem

- Heating clusters with cosmic rays (Ehlert et al., 2018)
- Simulations of the Sunyaev-Zel'dovich of bubbles (Ehlert et al., 2019)



# CRs in lobes

- missing pressure in lobes; at most $5 - 10\%$ of pressure due to magnetic field & CR electrons




X-ray image with radio contours of Perseus jet help to constrain the contents of bubbles assuming equipartition (Fabian et al., 2011)

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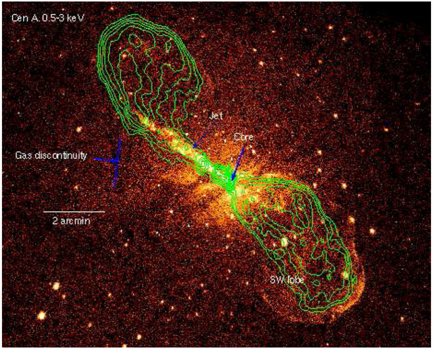
- linked to hotspots observationally




X-ray image with radio contours of the jet of Centaurus A (Worrall, 2009). Multitude of X-rays cores detectable within the jet.

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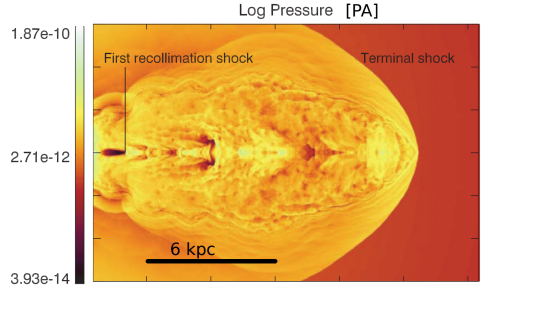
- linked to hotspots observationally
- simulations: collision of internal shocks




Relativistic jet simulation (Perucho and Martí, 2007) with developing shock fronts.

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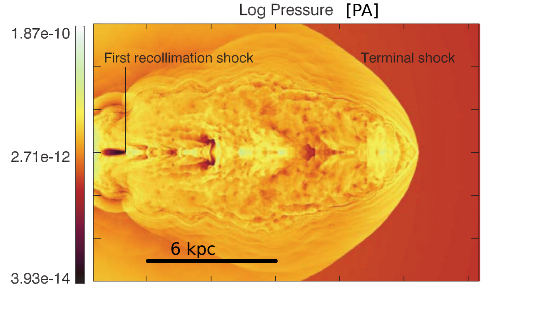
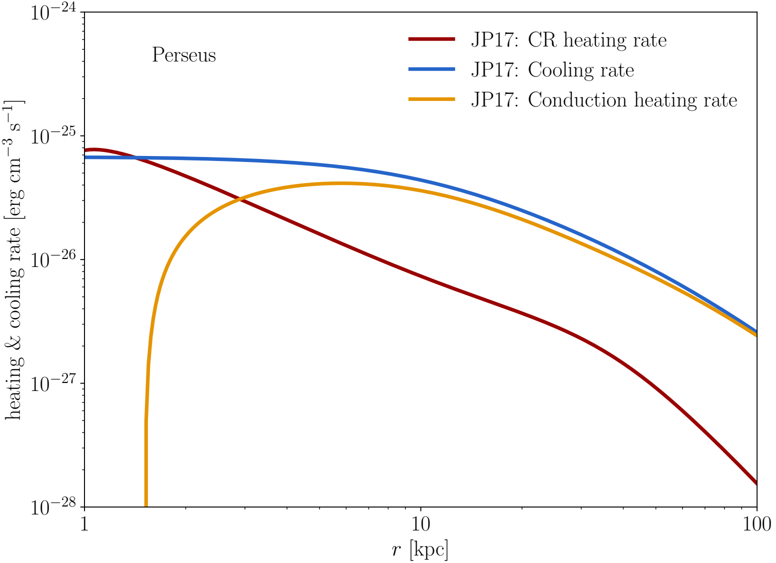


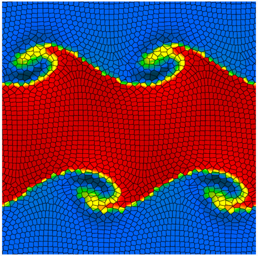

Relativistic jet simulation (Perucho and Martí, 2007) with developing shock fronts.

→ significant CR proton population!

# Heating and cooling rates: Perseus



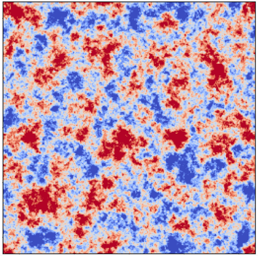
# Moving to MHD jet simulations



AREPO: unstructured-mesh

- MHD moving-mesh code AREPO
- NFW cluster potential

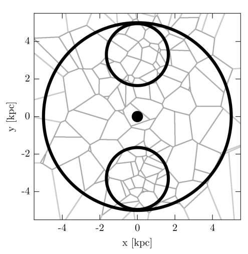
# Moving to MHD jet simulations



Initial magnetic field

- MHD moving-mesh code AREPO
- NFW cluster potential
- External turbulent magnetic field (Kolmogorov)

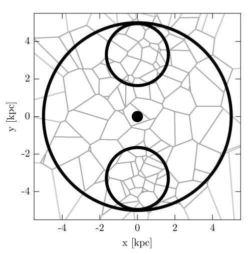
# Moving to MHD jet simulations




AREPO: Jet injection region (Weinberger et al., 2017)

- MHD moving-mesh code AREPO
- NFW cluster potential
- External turbulent magnetic field (Kolmogorov)
- Jet module
  - Prepare low-density state in pressure equilibrium
  - Inject kinetic energy
  - Initial magnetic field & CRs
  - Refine to sustain density contrast

# CR treatment




AREPO: Jet injection region (Weinberger et al., 2017)

- Subgrid CR acceleration:
  - Reality: Internal shocks
  - Code: $E_{\rm cr}/E_{\rm th} \geq 0.5$

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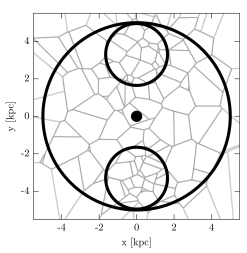
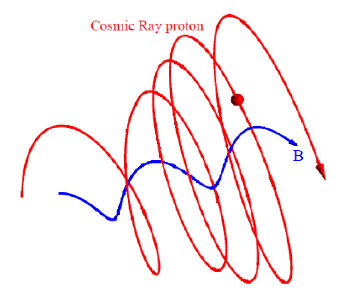



AREPO: Jet injection region (Weinberger et al., 2017)

- Subgrid CR acceleration:
  - Reality: Internal shocks
  - Code: $E_{\mathrm{cr}}/E_{\mathrm{th}} \geq 0.5$
- CR transport:
  - CRs are advected
  - Emulate CR streaming $\approx$ anisotropic CR diffusion & Alfvén cooling

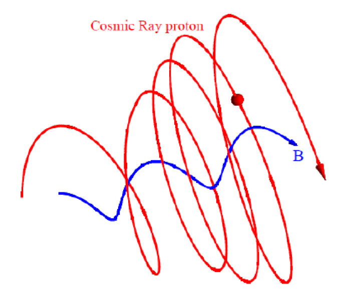
# Streaming cosmic rays




Scattered CR proton on magnetic field perturbations

- CRs excite Alfvén waves

# Streaming cosmic rays




Scattered CR proton on magnetic field perturbations

- CRs excite Alfvén waves
- CRs self-confined via scattering on Alfvén waves
- In clusters: $\mathbf{v}_{\rm st} \approx -\mathbf{v}_{\rm A} \frac{\mathbf{b}\cdot\nabla P_{\rm cr}}{|\mathbf{b}\cdot\nabla P_{\rm cr}|}$

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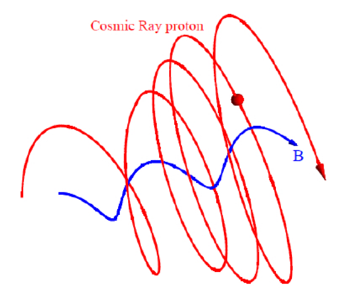


Scattered CR proton on magnetic field perturbations

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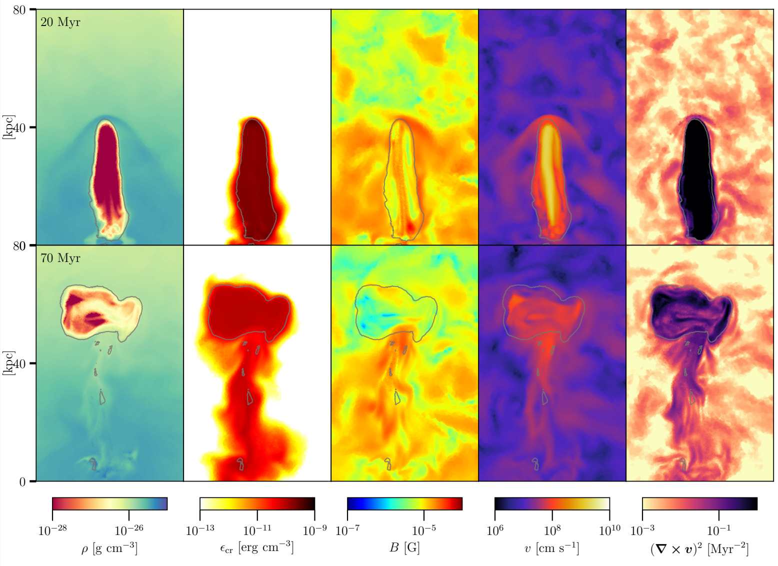
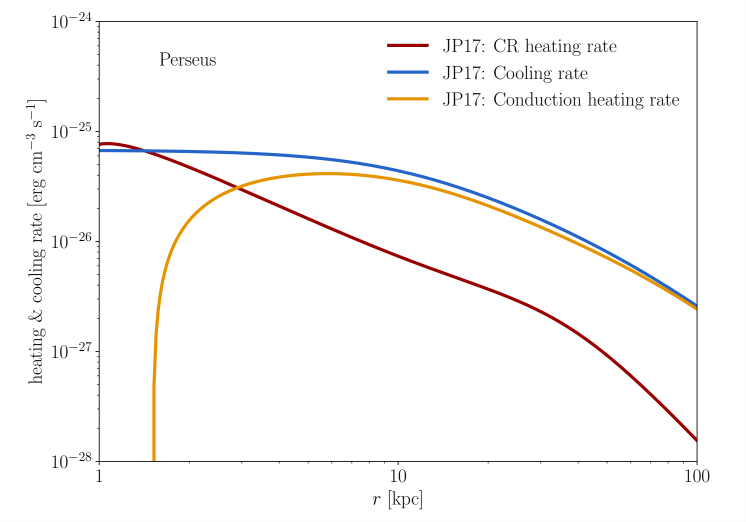
- In clusters: $\mathbf{v}_{\rm st} \approx -\mathbf{v}_{\rm A} \frac{\mathbf{b}\cdot\nabla P_{\rm cr}}{|\mathbf{b}\cdot\nabla P_{\rm cr}|}$
- Alfvén waves partially damped
- Transfer of CR to thermal energy via Alfvén wave damping: $\mathcal{H}_{\rm cr} = |\mathbf{v}_{\rm A} \cdot \nabla P_{\rm cr}|$

# Bubble evolution



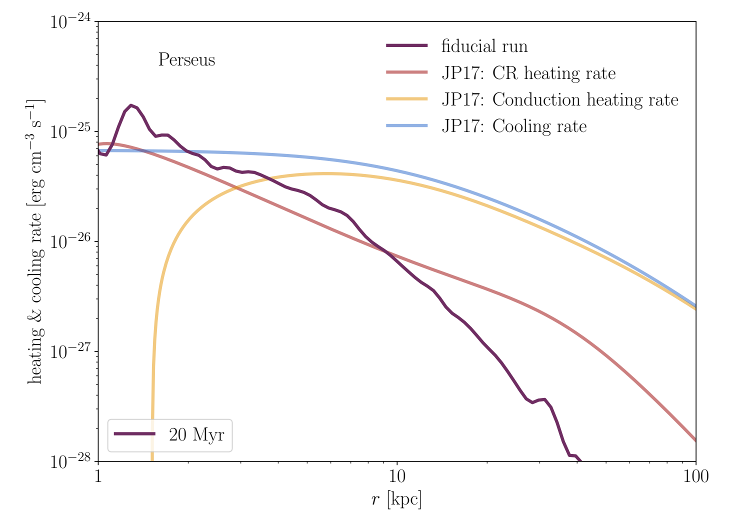

Bubble evolution in a turbulent cluster

# Heating and cooling rates: Steady-state model



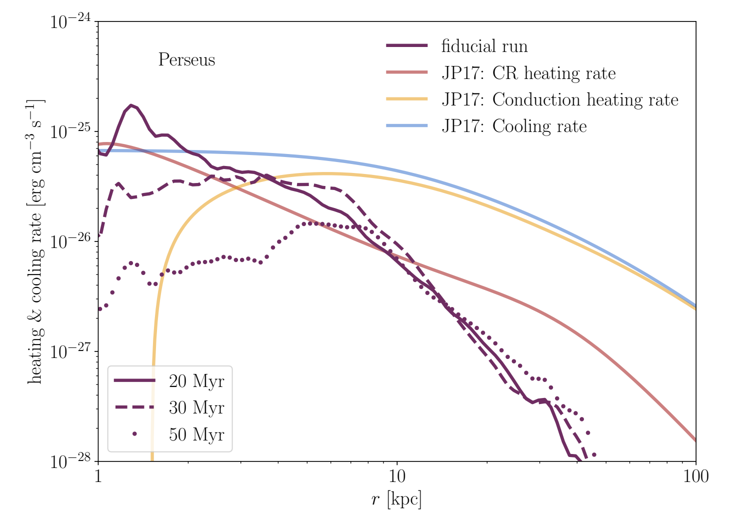

cooling ≈ conduction + CR heating (Jacob and Pfrommer, 2017)

# Heating and cooling rates: Simulation



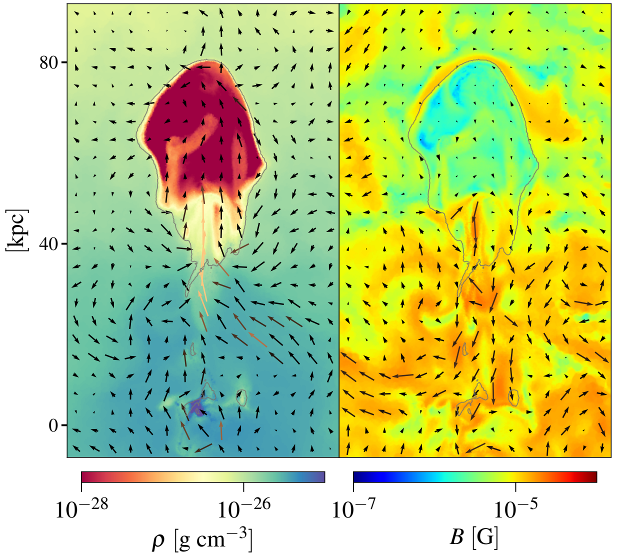

Correct profile at 20 Myr and high central isotropy within 15 kpc

# Heating and cooling rates: Simulation



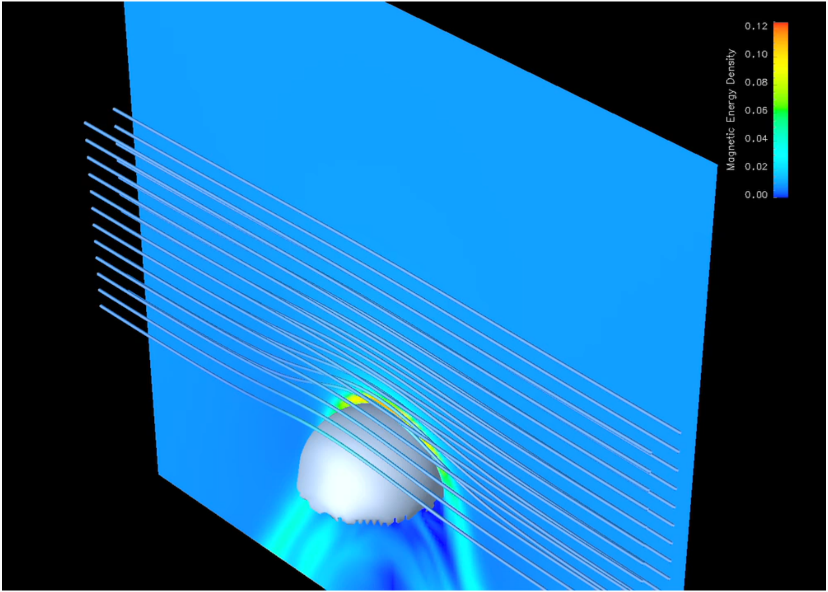

Require new duty cycle at later times

# Magnetic draping

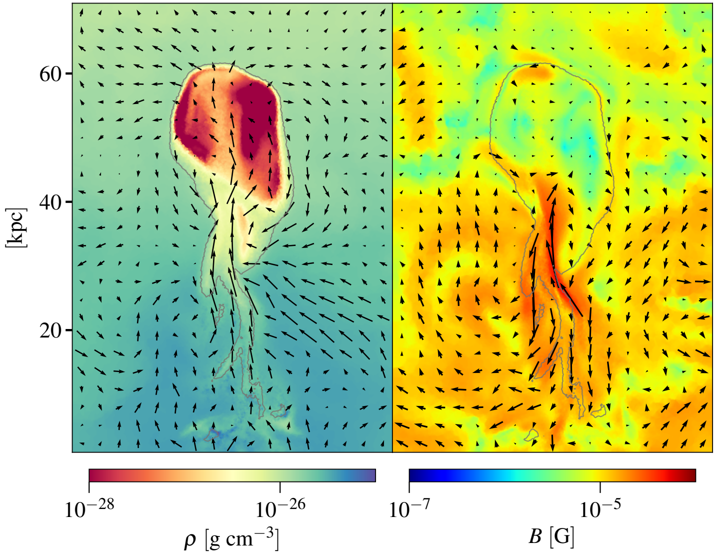



Draping active $\Rightarrow$ stabilizes bubble

# Draping by Dursi and Pfrommer (2008)

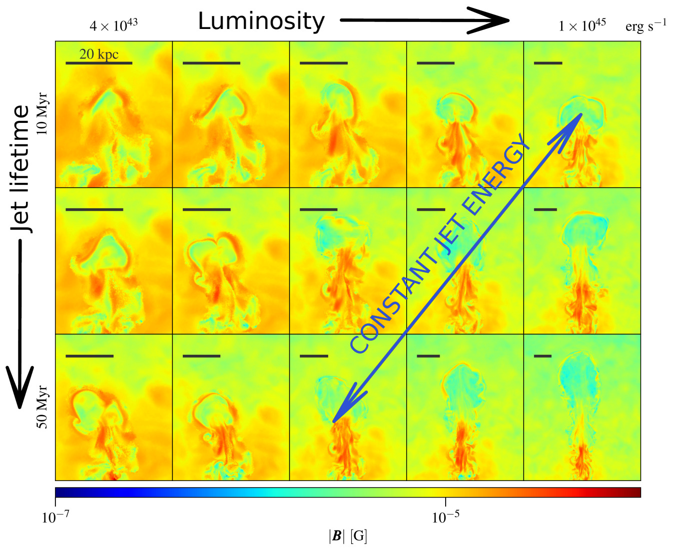


# Magnetic enhancement in the wake



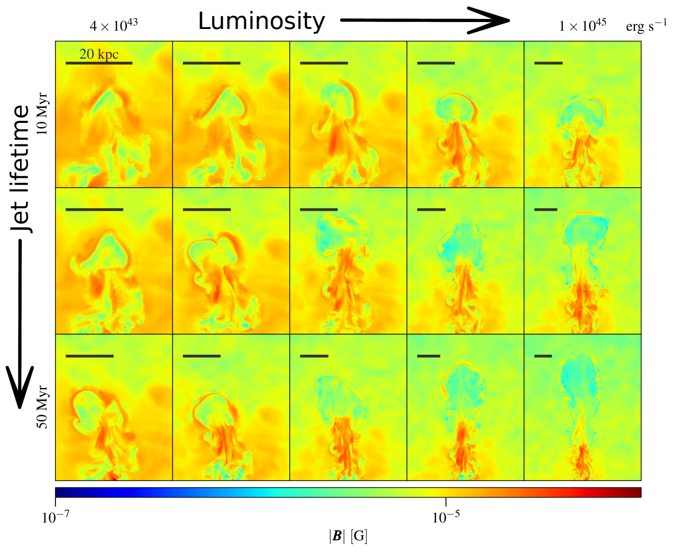

Enhanced magnetic field in wake helps CRs escape

# Magnetic field structure



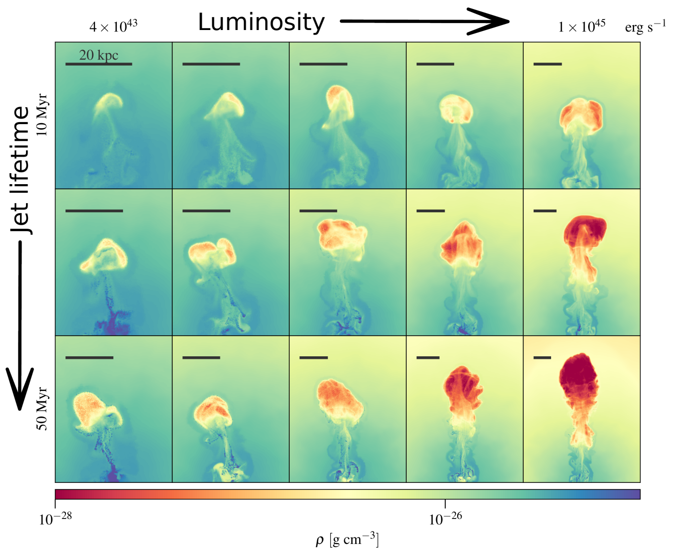

Magnetic enhancement and draping general feature

# Magnetic field structure



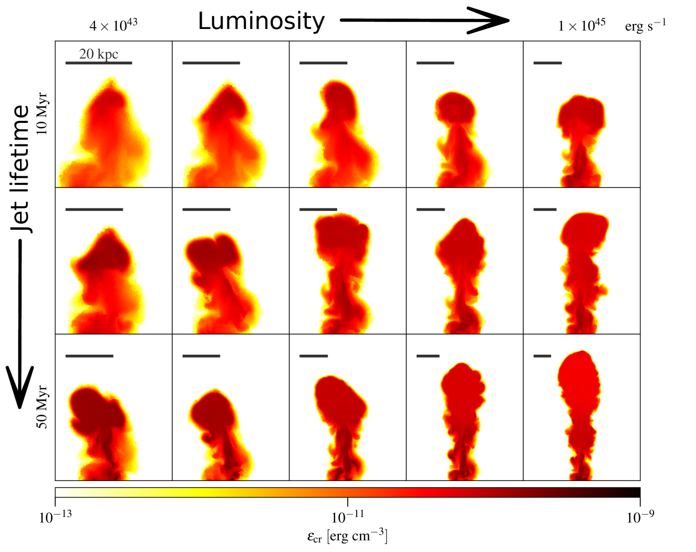

Magnetic enhancement and draping general feature

# Jet morphology



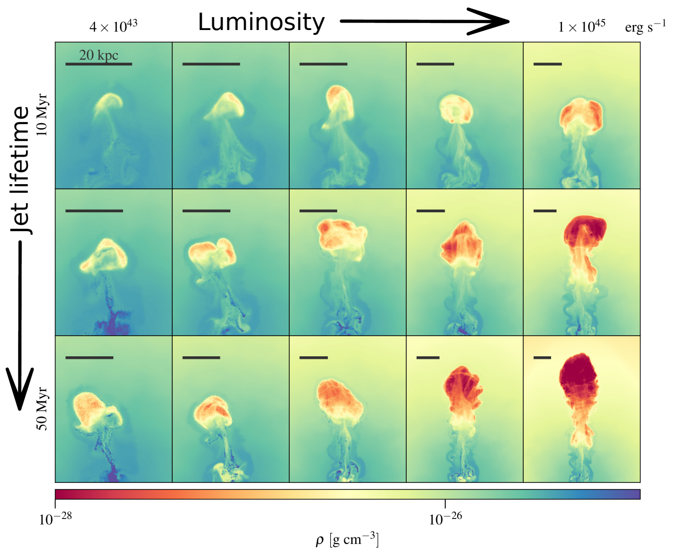

Low energy/power jets mix more efficiently

# CR distribution



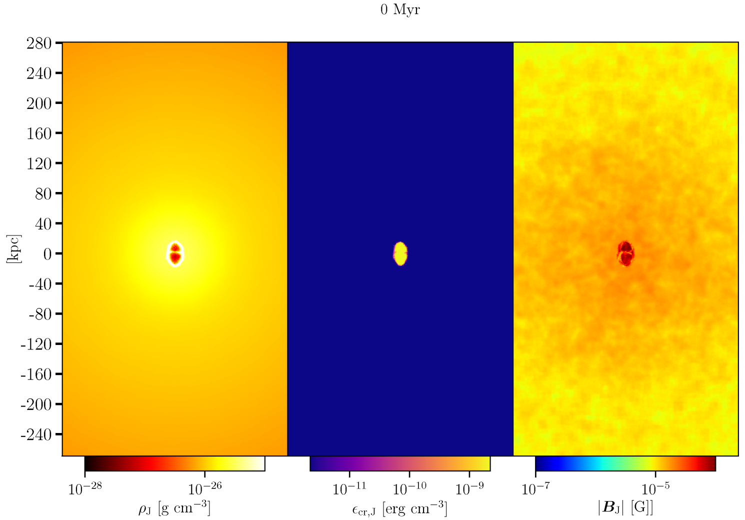

CRs still present

# Jet morphology



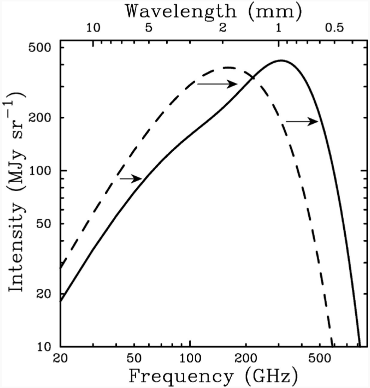

Even though bubbles become invisible in X-ray observations

# Bubble dynamics



# Sunyaev-Zel'dovich effect depends on electron properties

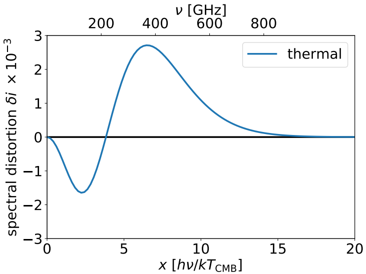
- frequency dependant shift of CMB spectrum to higher frequencies




Thermal SZ effect for 1000 times more massive typical cluster (Carlstrom et al., 2002)

# Sunyaev-Zel'dovich effect depends on electron properties

- frequency dependant shift of CMB spectrum to higher frequencies
- thermal electrons from cluster up-scatter CMB photons
  - $\delta i_{\rm th}(x) = g(x) y_{\rm gas}$
  - $y_{\rm gas} \propto \int {\rm d}z \; n_{\rm e,gas} k T_{\rm e}$




Spectral distortion due to thermal SZ effect (blue) for reference cluster.

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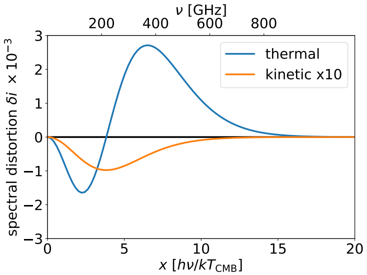
  - $\delta i_{\mathrm{th}}(x) = g(x) y_{\mathrm{gas}}$
  - $y_{\mathrm{gas}} \propto \int \mathrm{d}z \; n_{\mathrm{e,gas}} k T_{\mathrm{e}}$
- if cluster moves (kinetically) relative to CMB; Doppler boosted CMB
  - $\delta i_{\mathrm{kin}}(x) = -h(x) w_{\mathrm{gas}}$
  - $w_{\mathrm{gas}} \propto \int \mathrm{d}z \; n_{\mathrm{e,gas}} \frac{v_{\mathrm{gas},z}}{c}$




Spectral distortion due to kinetic SZ effect (orange) for reference cluster.

# Sunyaev-Zel'dovich effect depends on electron properties

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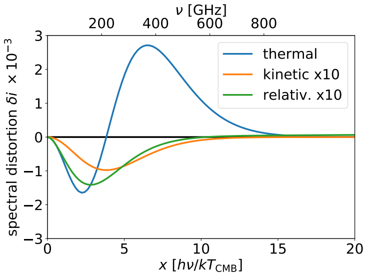
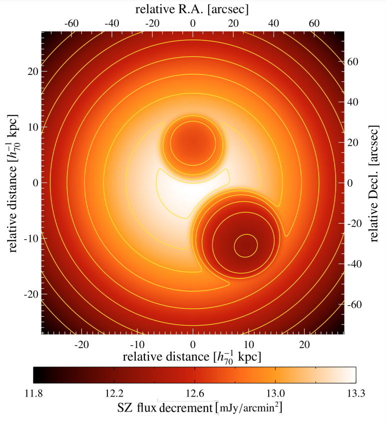
- if cluster moves (kinetically) relative to CMB; Doppler boosted CMB
  - $\delta i_{\mathrm{kin}}(x) = -h(x) w_{\mathrm{gas}}$
  - $w_{\mathrm{gas}} \propto \int \mathrm{d}z \; n_{\mathrm{e,gas}} \frac{v_{\mathrm{gas},z}}{c}$
- if relativistic particles in AGN bubble; CMB photons IC scattered out of microwave band
  - $\delta i_{\mathrm{rel}}(x) = [j(x) - i(x)] \tau_{\mathrm{rel}}$
  - $w_{\mathrm{gas}} \propto \int \mathrm{d}z \; n_{\mathrm{e,rel}}$




Spectral distortion due to relativistic SZ effect (green) for reference cluster.

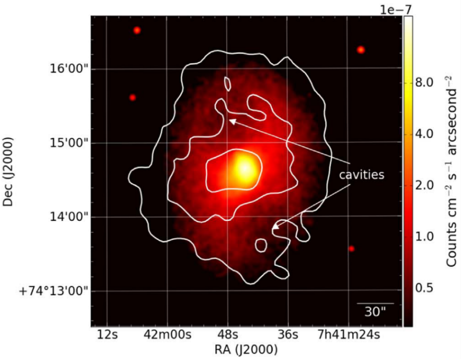
# Unveiling composition of bubbles with SZ effect

- Assume model for bubble morphology: Ellipsoid
- Fill bubbles with thermal electrons of certain temperature to match observational SZ signal




Mock observations with ALMA of Perseus by Pfrommer et al. (2005)

# CARMEN observations of the SZ signal in MS0735




*Chandra* X-ray

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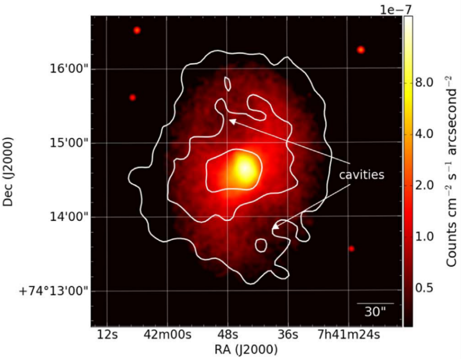


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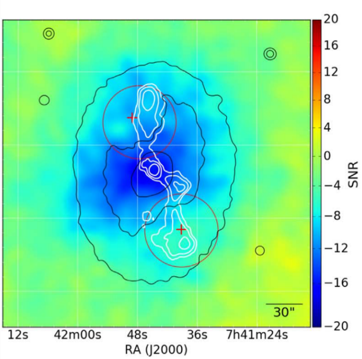
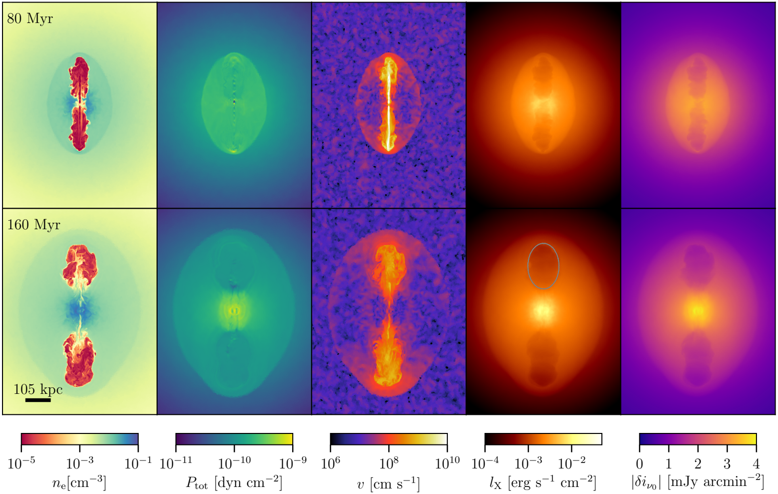


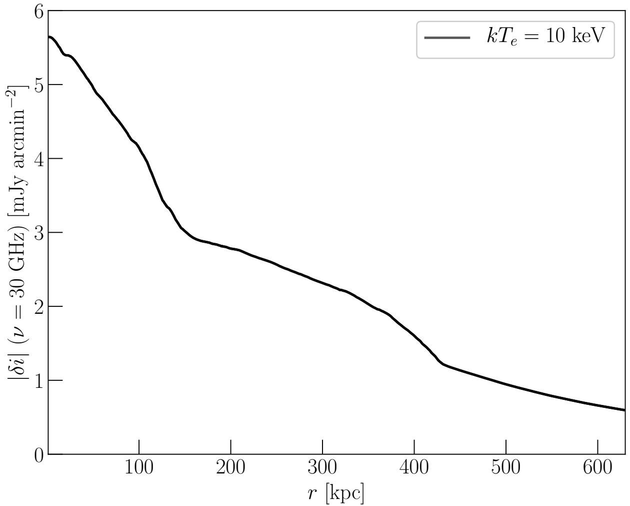

SZ signal after central point source subtraction
(Abdulla et al., 2019)

# Simulating the bubbles of MS0735



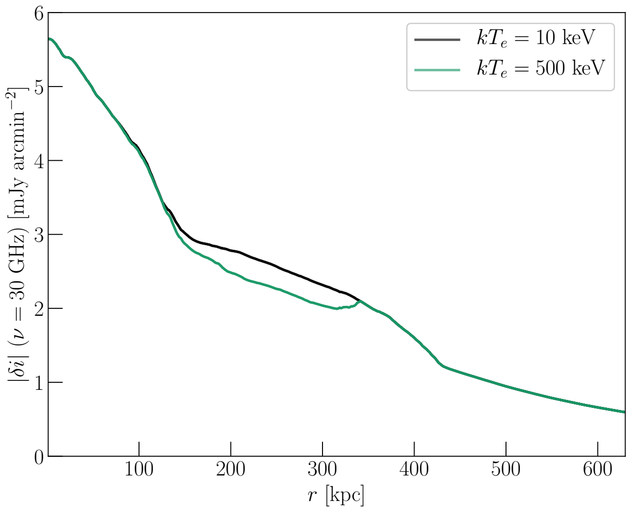

Thermal Sunyaev Zel'dovich effect in turbulent MS0735-like cluster

# Thermal and relativistic bubbles



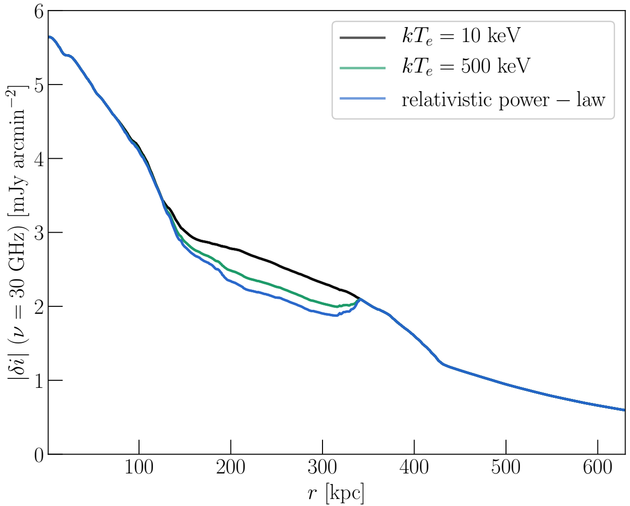

Thermal bubbles leave no SZ imprint

# Thermal and relativistic bubbles



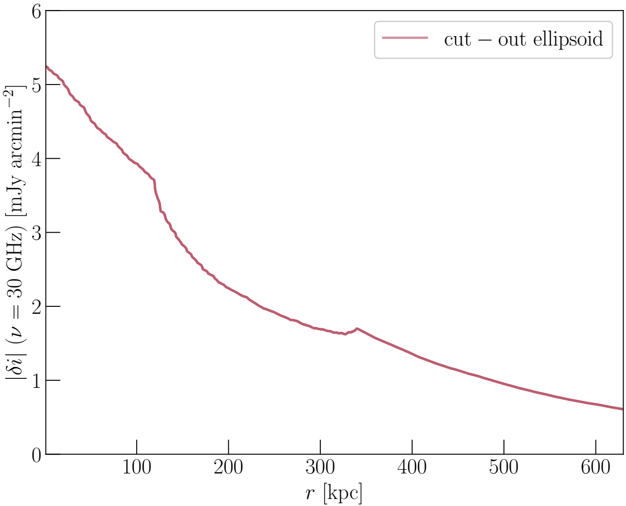

Very hot bubbles are detectable as troughs in the SZ signal

# Thermal and relativistic bubbles



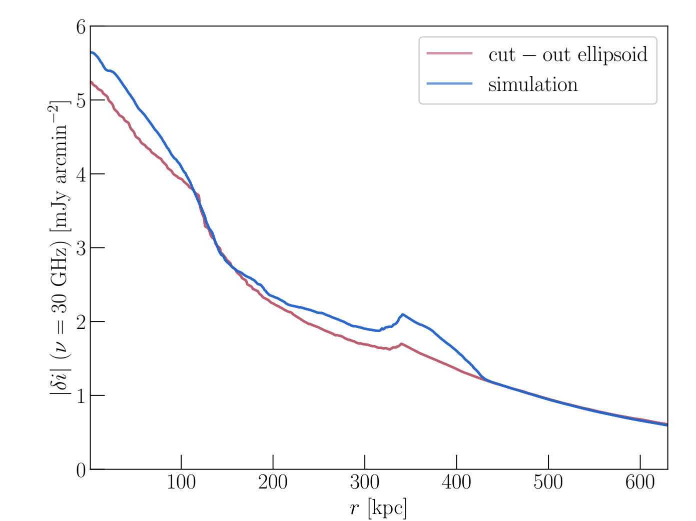

.. relativistic bubbles also show troughs in the SZ signal

# Comparison with simulations



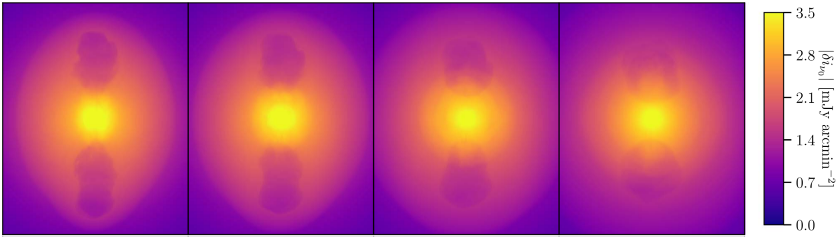

Relativistic ellipsoidal bubble inserted in initial conditions

# Comparison with simulations




Shocked cocoon modifies profile significantly

# Significance of observationally unconstrained inclination



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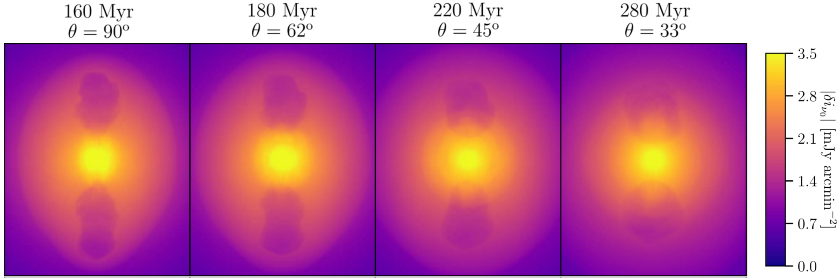

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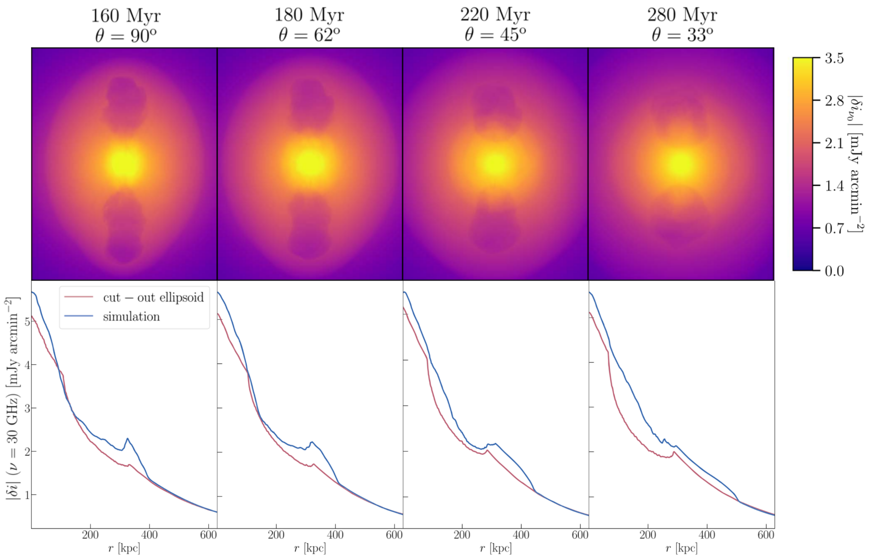

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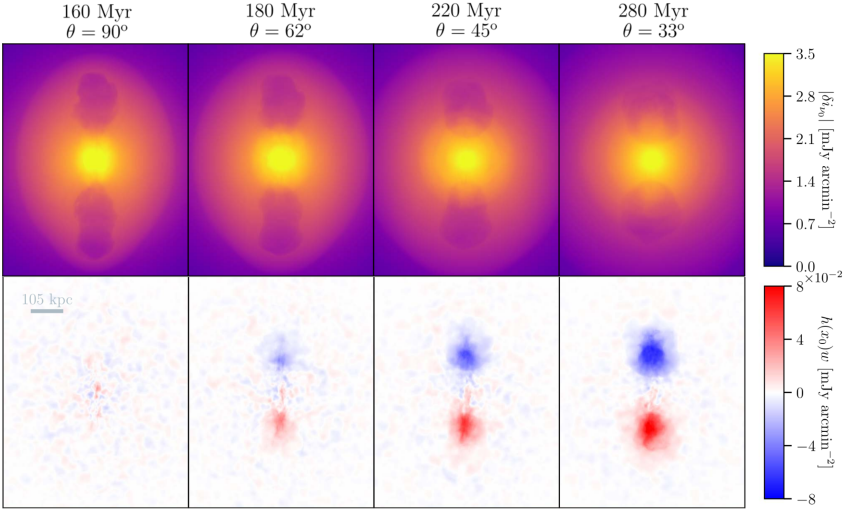

# Summary

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- Magnetic draping confines CRs and stabilizes bubbles
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Outlook

- Simulations with cooling and accretion $\rightarrow$ self-regulated evolution?
- Cosmological simulations for more realistic environment

# References


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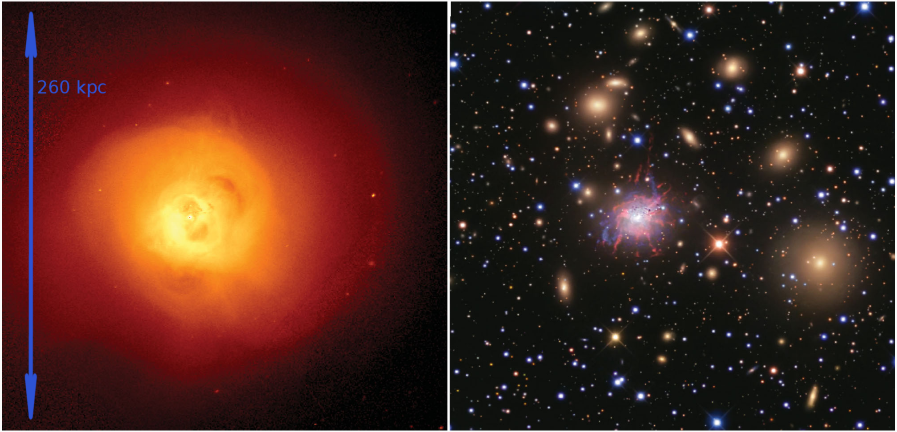
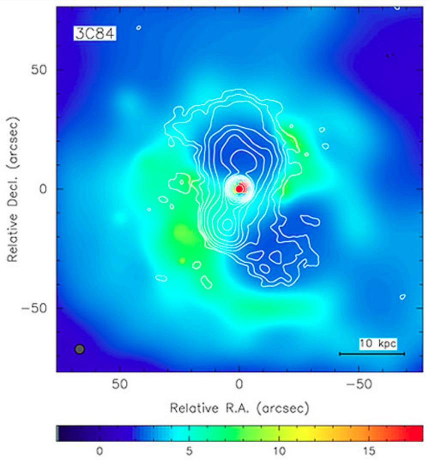
# Perseus Cluster




X-ray (Chandra composite) and optical (Blackbird observatory) images of the Perseus cluster (adopted from Fabian et al., 2011)

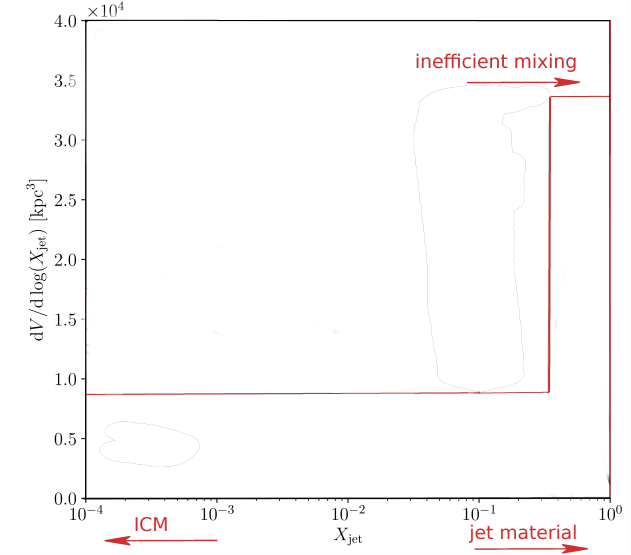
# Cool core clusters



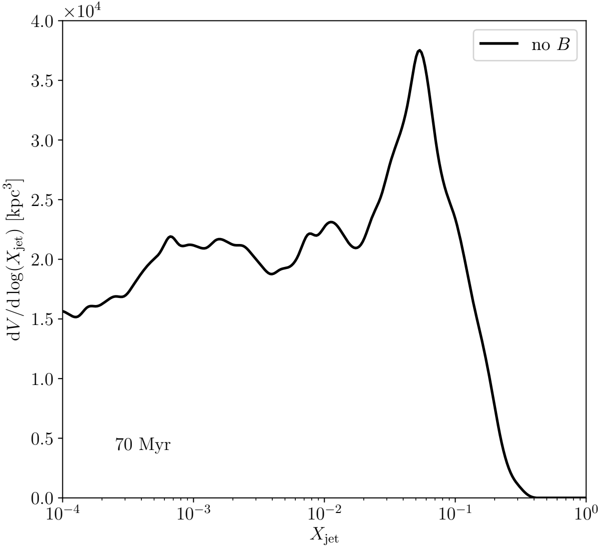

(Fabian et al., 2011)

- $t_{\text{cool}} < 1$ Gyr
- relatively low SF
- no cooling flows
- jet power correlates with cooling power
- jet power suffices to halt cooling flow

# Histogram of jet tracers

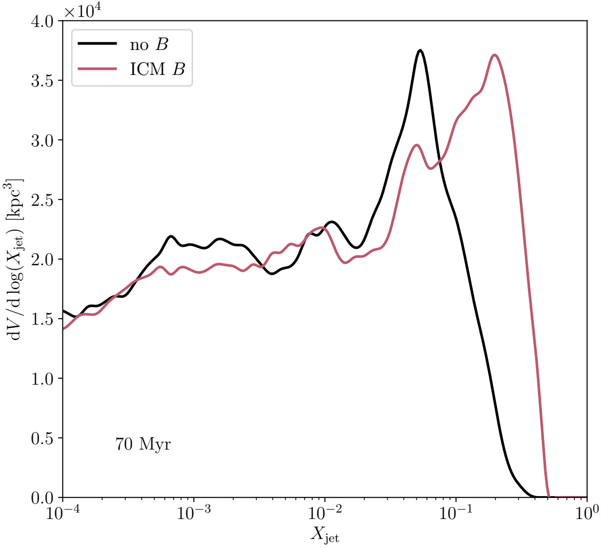


# Bubble stability: Magnetic field



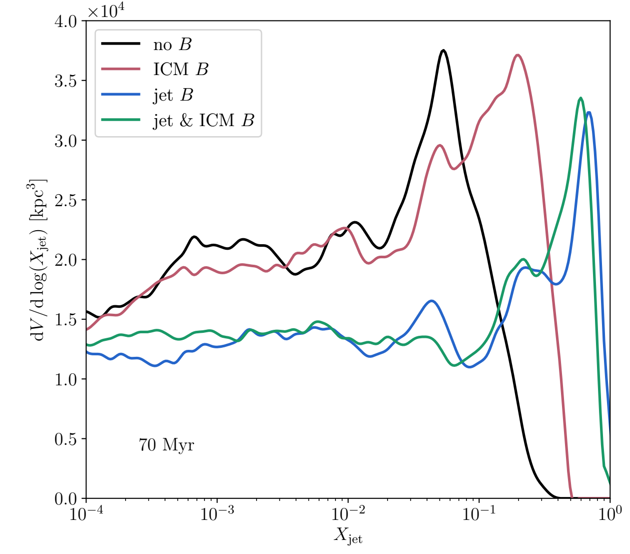

Efficient mixing for unmagnetized jet and ICM

# Bubble stability: Magnetic field



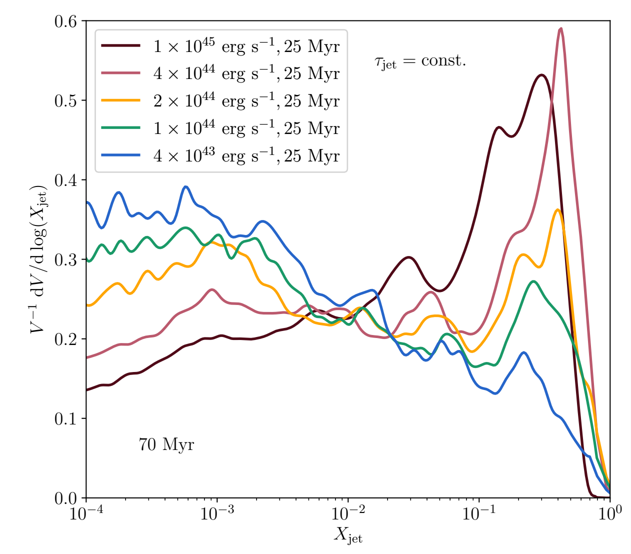

Draping suppresses mixing

# Bubble stability: Magnetic field



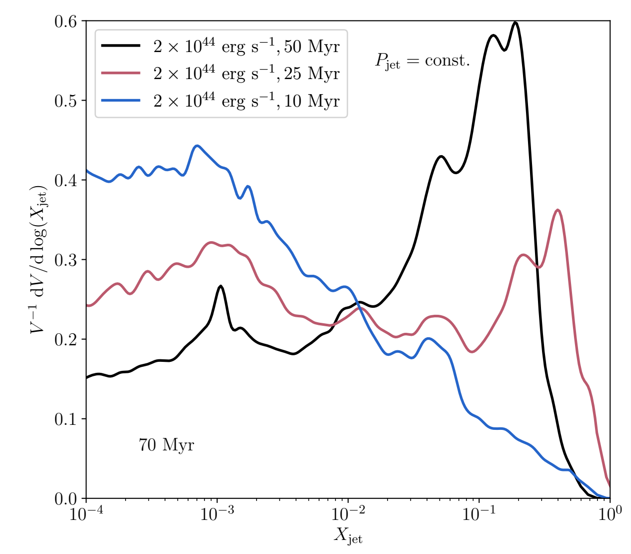

Internal magnetic fields stabilize the bubble additionally

# Bubble stability: Power



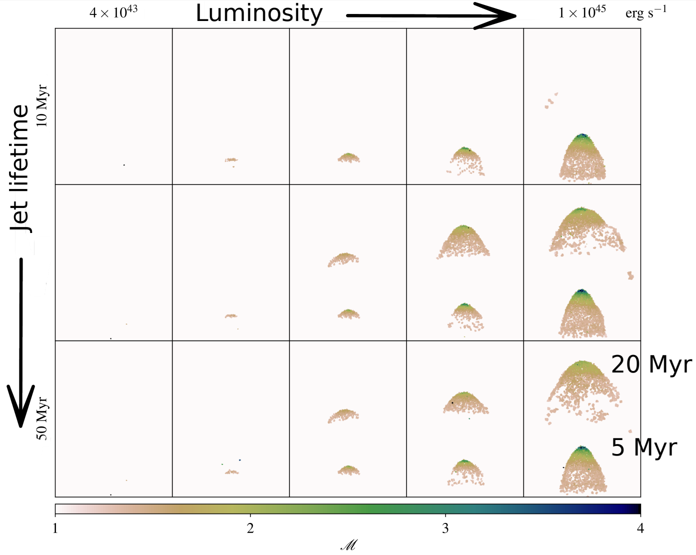

Increasing jet power **decreases** mixing efficiency

# Bubble stability: Energy



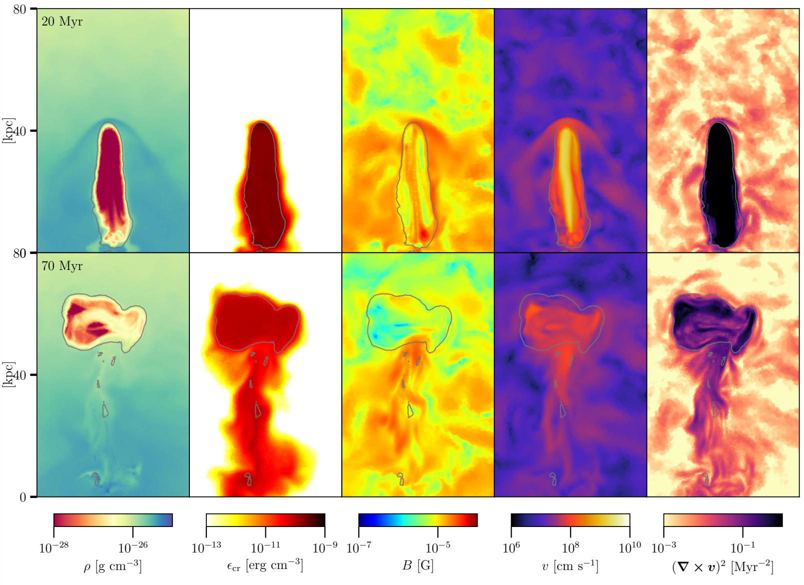

Increasing jet energy **decreases** mixing efficiency

# Jet Mach numbers

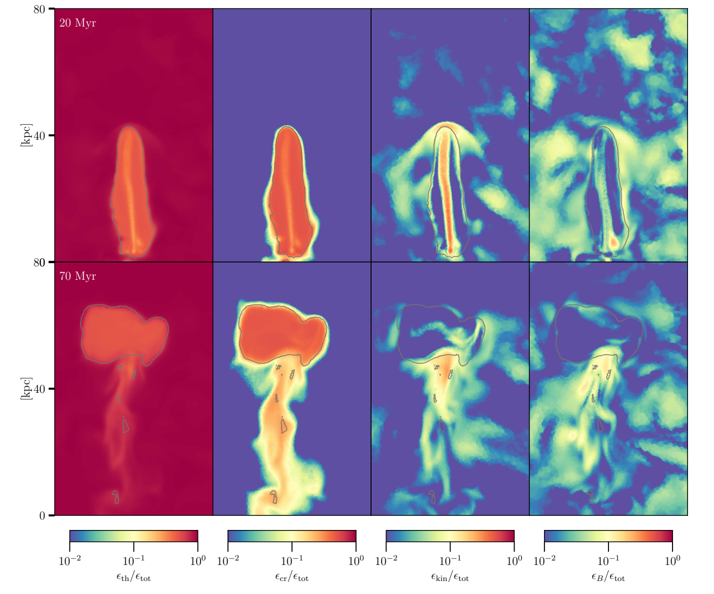



Mach numbers generally low

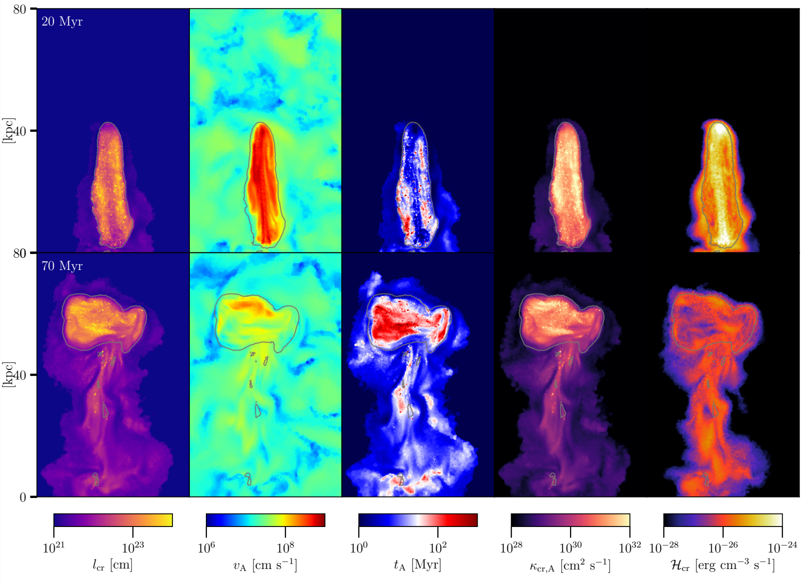
# Bubble evolution



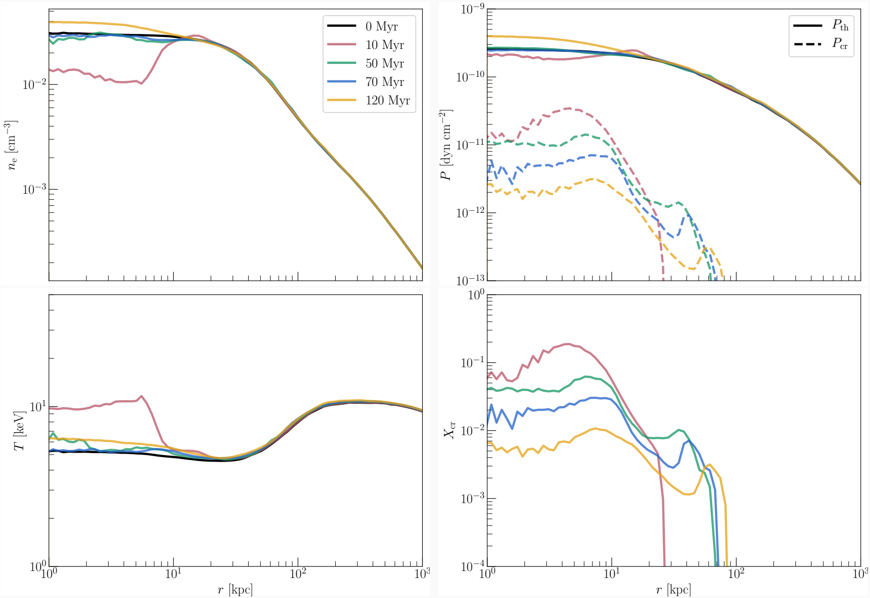
# Bubble energy evolution



# Bubble CRs



20 Myr
70 Myr
80
40
0
[kpc]
$10^{21}$
$10^{23}$
$l_{cr}$ [cm]
$10^{6}$
$10^{8}$
$v_A$ [cm s$^{-1}$]
$10^{0}$
$10^{2}$
$t_A$ [Myr]
$10^{28}$
$10^{30}$
$10^{32}$
$\kappa_{cr,A}$ [cm$^2$ s$^{-1}$]
$10^{-28}$
$10^{-26}$
$10^{-24}$
$\mathcal{H}_{cr}$ [erg cm$^{-3}$ s$^{-1}$]


0 Myr
10 Myr
50 Myr
70 Myr
120 Myr
$n_e$ [cm$^{-3}$]
$P_{th}$
$P_{cr}$
$P$ [dyn cm$^{-2}$]
$T$ [keV]
$X_{cr}$
$r$ [kpc]
$r$ [kpc]