The imprint of cluster physics on the SZ effect: from bubbles to cosmological parameters

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in collaboration with

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Outline

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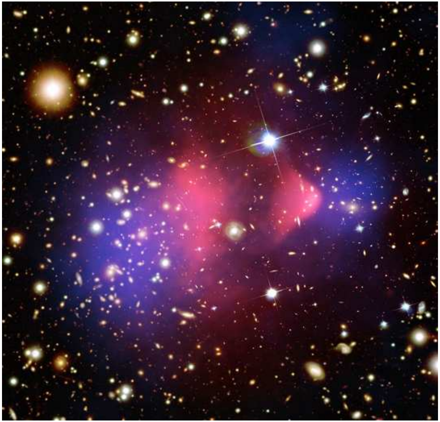
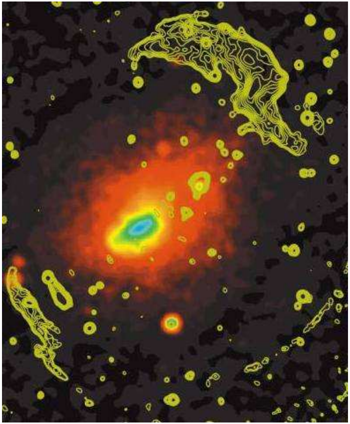
1. Galaxy cluster gastrophysics
   - Cosmological galaxy cluster simulations
   - Cosmic ray acceleration and transport
   - Imprint on the Sunyaev-Zel'dovich effect
2. Galaxy cluster cosmology
   - Scaling relations
   - Bias of cosmological parameters
   - Hydrostatic cluster masses and non-thermal processes
3. Sunyaev-Zel'dovich bubbles
   - Unveiling the bubbles' composition
   - Cosmological simulations of AGN feedback
   - Conclusions

Shocks in galaxy clusters



1E 0657-56 ("Bullet cluster")

(X-ray: NASA/CXC/CfA/Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/Clowe et al.)



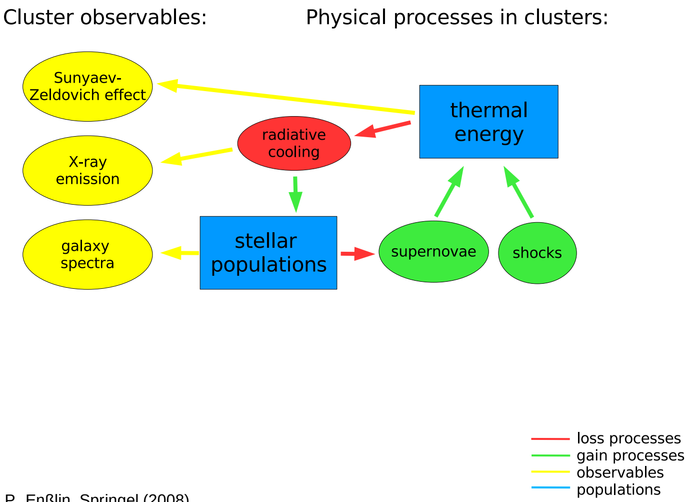
Abell 3667

(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

Sunyaev-Zel'dovich astrophysics and cosmology

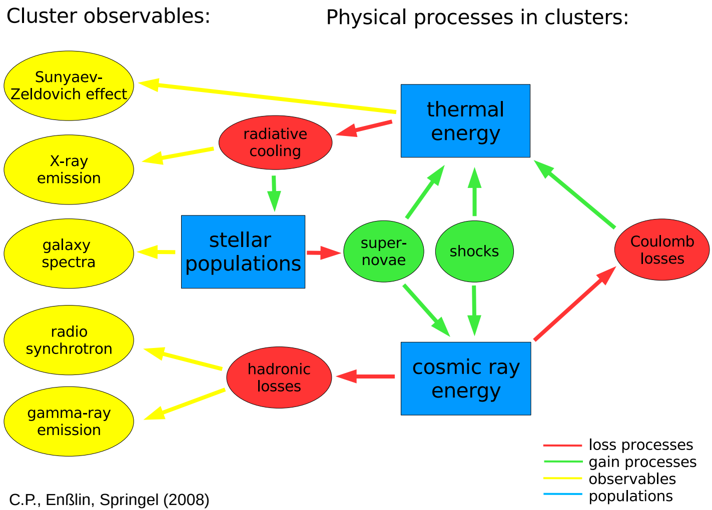
- How does cluster physics (cooling & star formation, turbulence, cosmic rays, AGN feedback) impact on the thermal pressure distribution?
  $\longrightarrow$ how are SZ scaling relations and hydrostatic masses biased?
  $\longrightarrow$ do we understand our numerical methods well enough to trust these answers?
- How does this propagate into uncertainties of cosmological parameters (Ω_8, w) and possibly bias their mean?
- How can the SZ effect help in solving the cooling flow problem and shape our understanding of cluster evolution?

Radiative simulations – flowchart



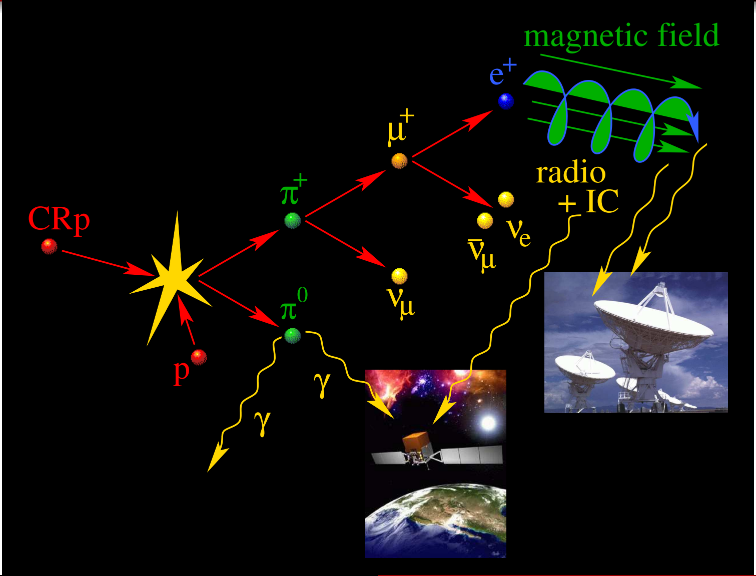
C.P., Enßlin, Springel (2008)

Radiative simulations with cosmic ray (CR) physics

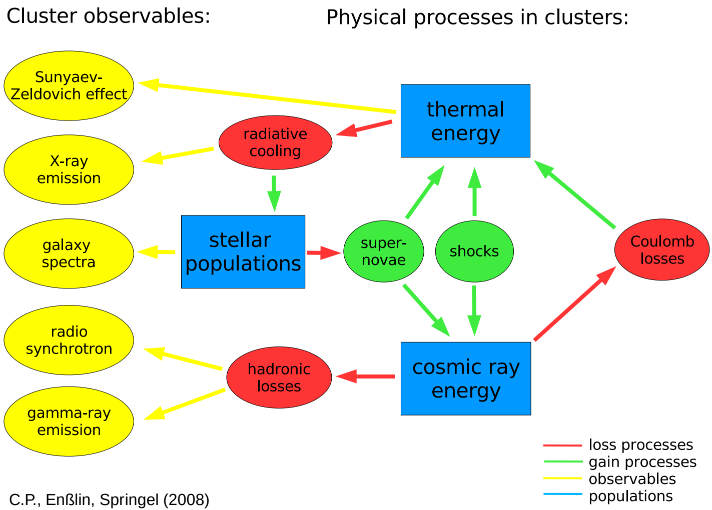


C.P., Enßlin, Springel (2008)

Hadronic cosmic ray proton interaction

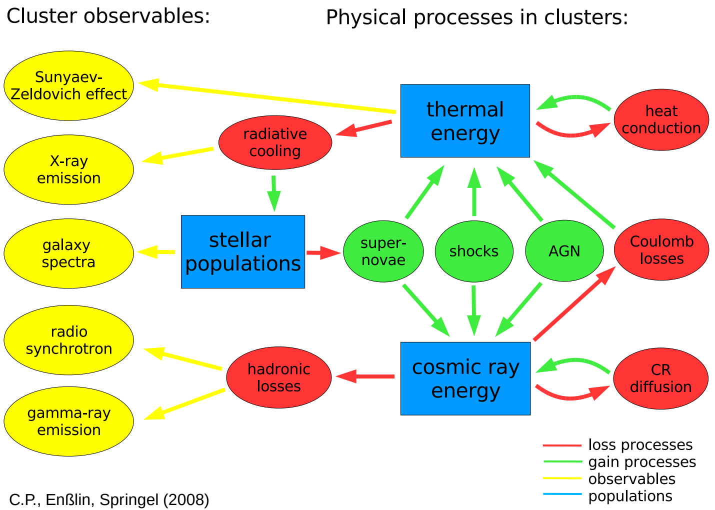


Radiative simulations with cosmic ray (CR) physics



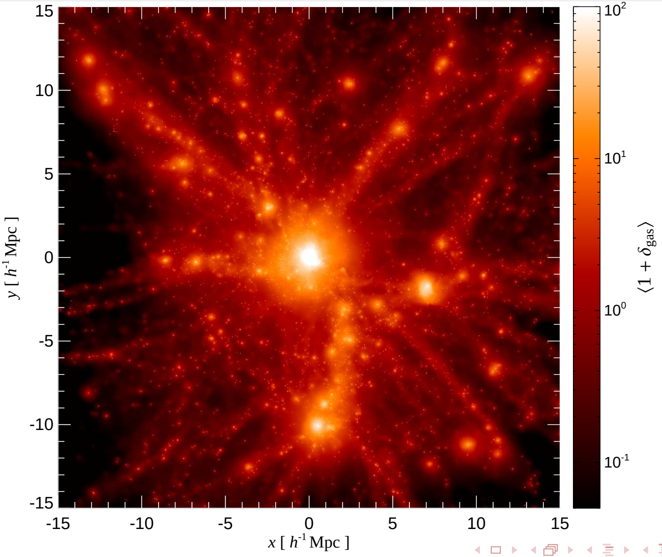
C.P., Enßlin, Springel (2008)

Radiative simulations with extended CR physics

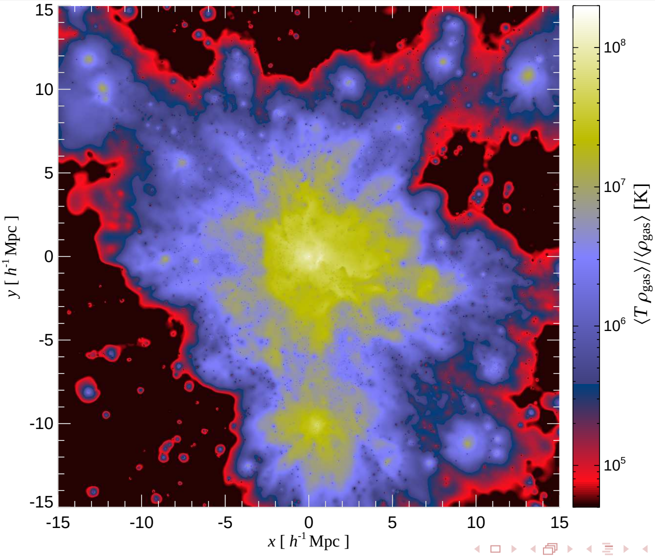


C.P., Enßlin, Springel (2008)

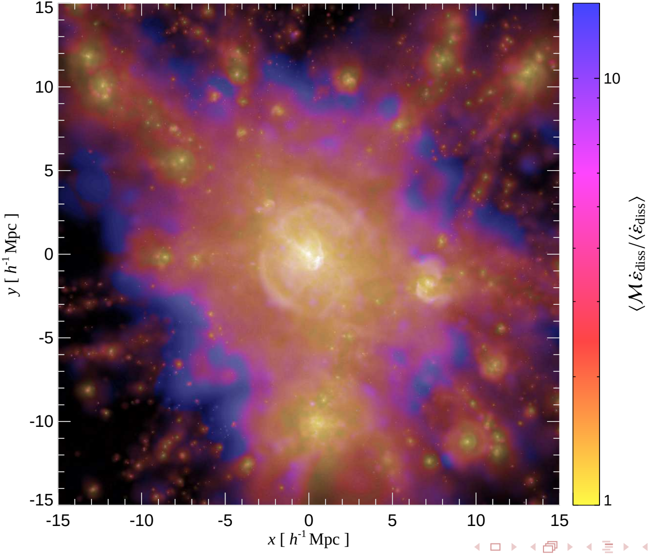
Radiative cool core cluster simulation: gas density



Mass weighted temperature



Mach number distribution weighted by $\varepsilon_{\mathrm{diss}}$



Diffusive shock acceleration – Fermi 1 mechanism (1)

conditions:

- a collisionless shock wave
- magnetic fields to confine energetic particles
- plasma waves to scatter energetic particles → particle diffusion
- supra-thermal particles

mechanism:

- supra-thermal particles diffuse upstream across shock wave
- each shock crossing energizes particles through momentum transfer from recoil-free scattering off macroscopic scattering agents
- momentum increases exponentially with number of shock crossings
- particle number decreases exponentially with number of crossings

→ power-law CR distribution

Diffusive shock acceleration – Fermi 1 mechanism (1)

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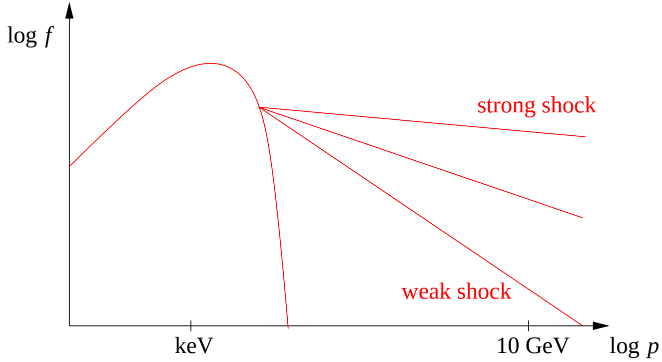
$\longrightarrow$ power-law CR distribution

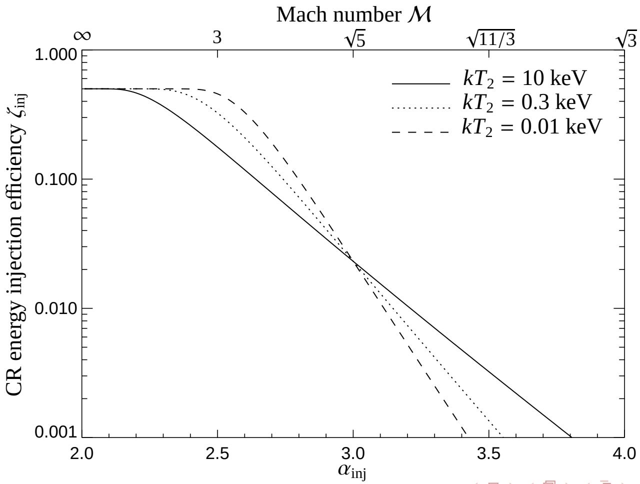
Diffusive shock acceleration – Fermi 1 mechanism (2)

Spectral index depends on the Mach number of the shock, $\mathcal{M} = \upsilon_\text{shock}/c_\text{s}$:

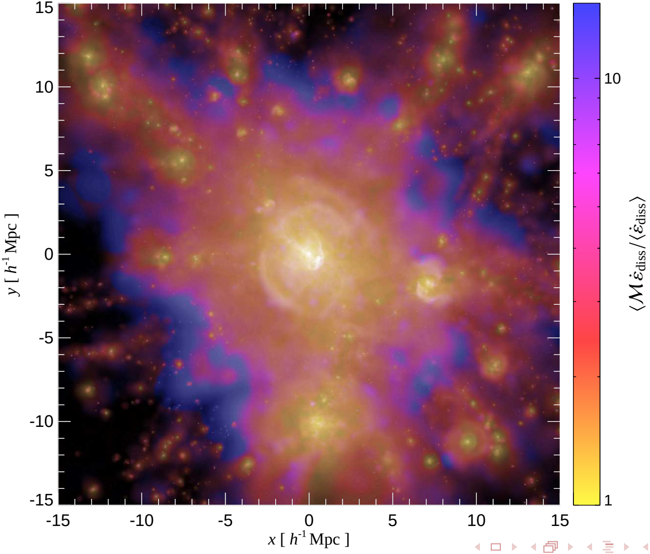


Diffusive shock acceleration – efficiency (3)

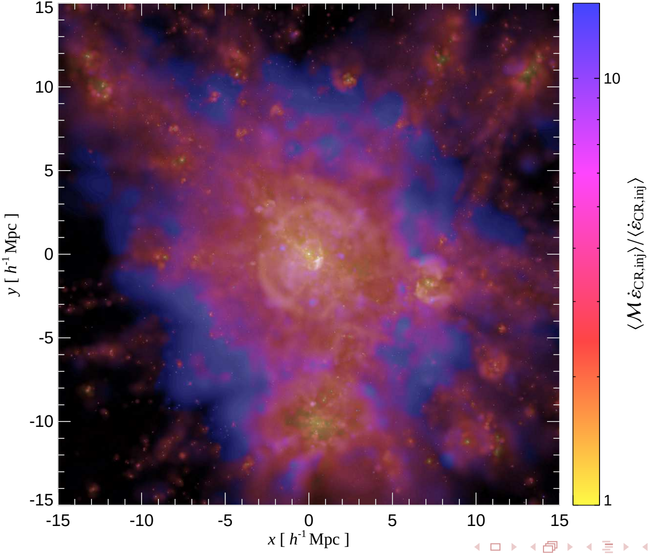
CR proton energy injection efficiency, $\zeta_{\rm inj} = \varepsilon_{\rm CR}/\varepsilon_{\rm diss}$:



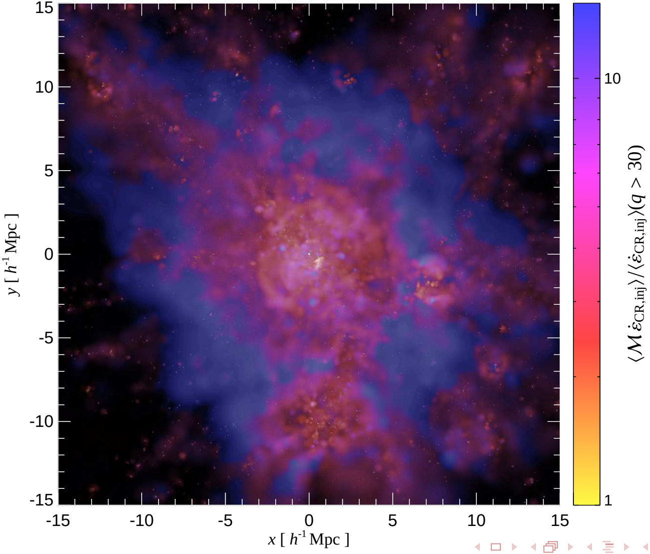
Mach number distribution weighted by $\varepsilon_{\rm diss}$



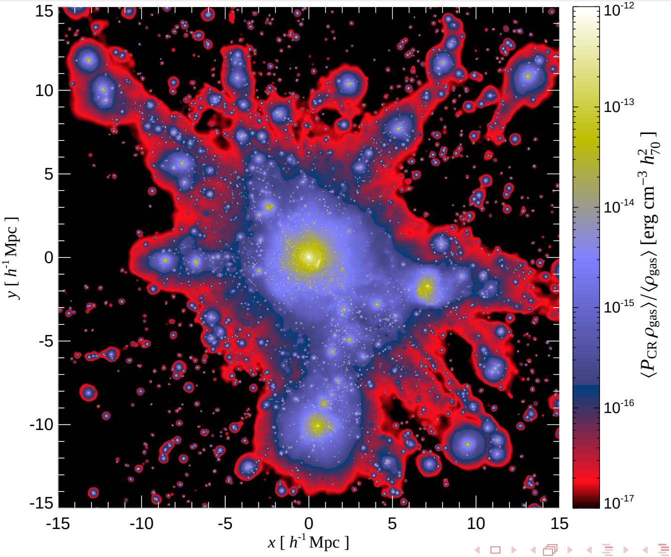
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



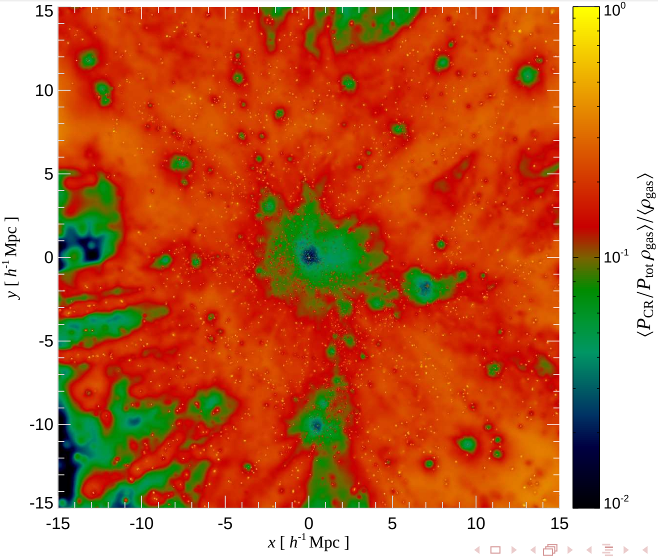
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}(q > 30)$



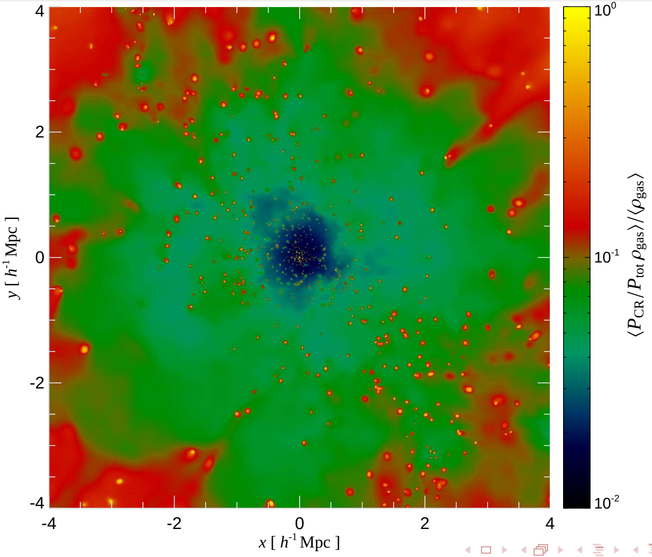
CR pressure $P_{\rm CR}$



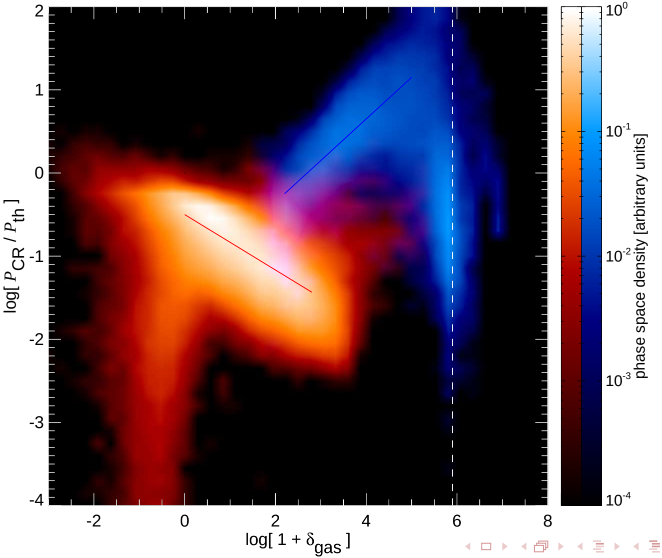
Relative CR pressure $P_{\rm CR}/P_{\rm total}$



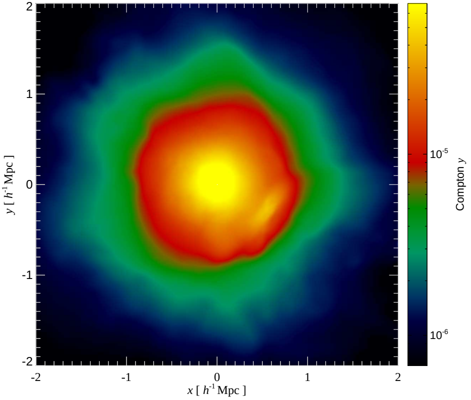
Relative CR pressure $P_{\rm CR}/P_{\rm total}$



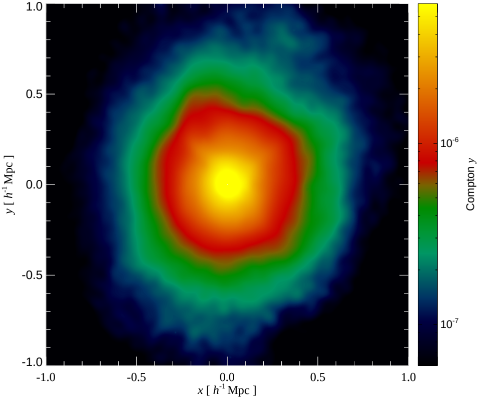
CR phase-space diagram: final distribution @ $z = 0$



CR impact on SZ effect: Compton y parameter

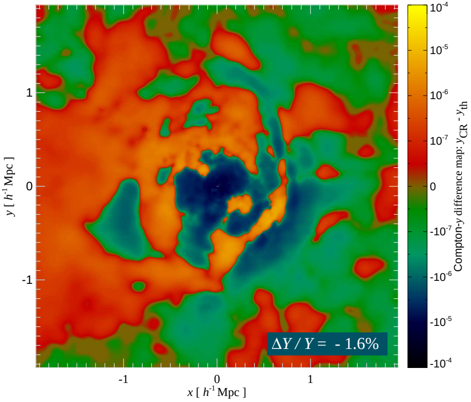


large merging cluster, $M_{\rm vir} \simeq 10^{15} M_\odot / h$

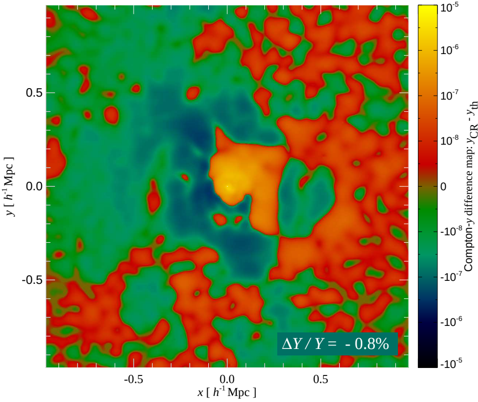


small cool core cluster, $M_{\rm vir} \simeq 10^{14} M_\odot / h$

Compton y difference map: $y_{CR} - y_{th}$



large merging cluster, $M_{\mathrm{vir}} \simeq 10^{15} M_\odot / h$



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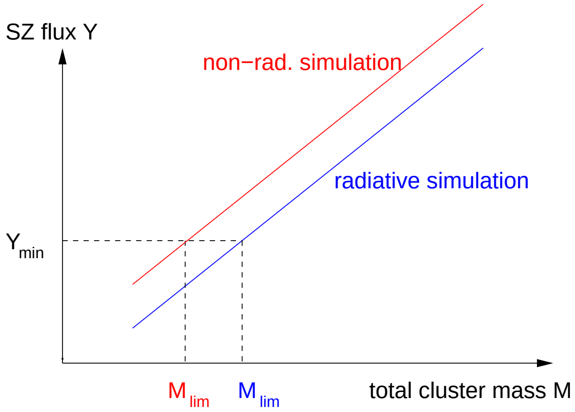
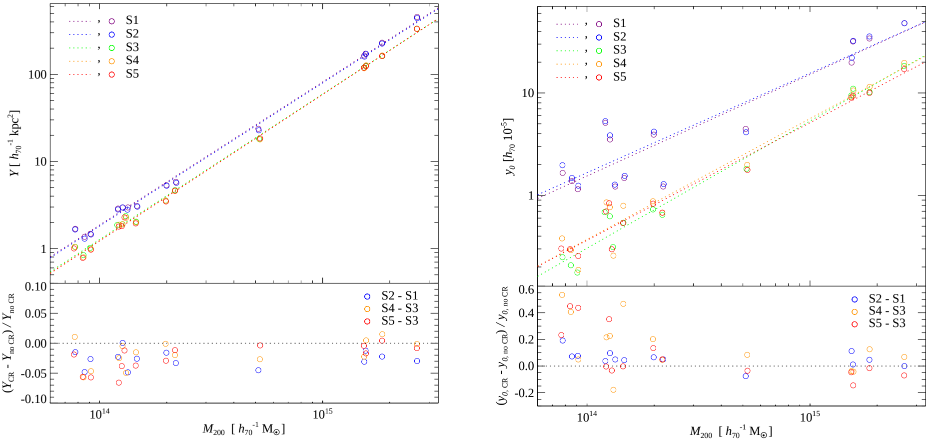
How cluster physics changes scaling relations (1)



→ cooling and star formation depletes the gas reservoir, which decreases the SZ flux and increases the effective mass threshold for an SZ flux−limited cluster sample

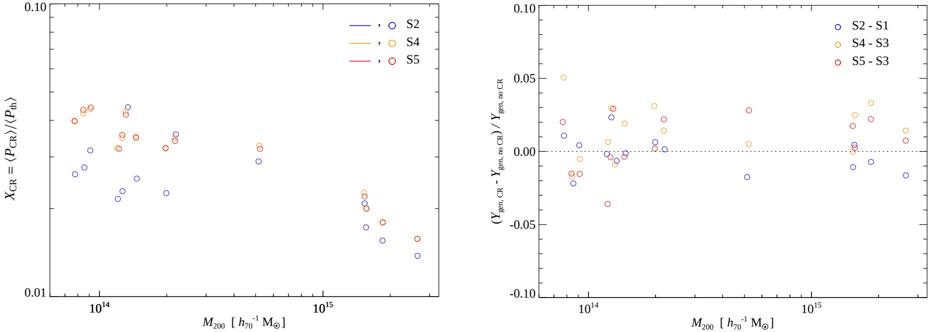
How cluster physics changes scaling relations (2)



top: scaling relations of non-radiative/radiative simulations, $Y(M_{200})$ vs. $y_0(M_{200})$

bottom: relative diff. due to CR feedback → system. negative (positive) bias for Y (y_0)!

Quantifying the CR pressure bias

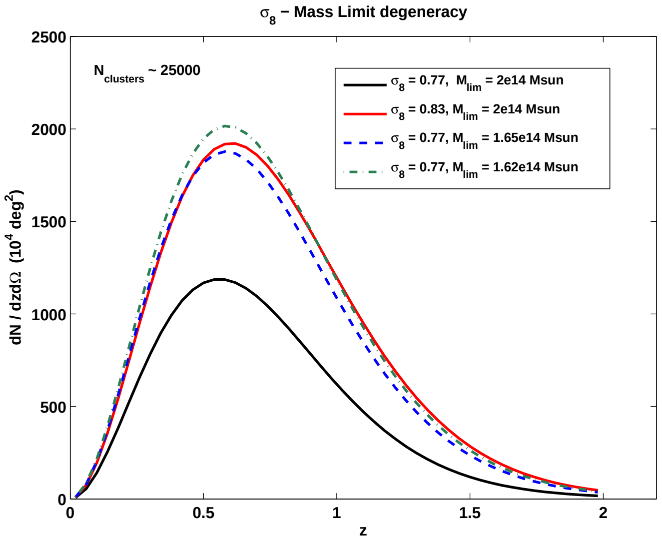


- Relative CR pressure $X_{CR} \sim 0.02 \ldots 0.04$ decreases for more massive clusters, is larger for radiative simulations due to the small thermal cooling time scale.
- Relative difference due to CR feedback of $Y_{general} \propto \int dV (P_{th} + P_{CR})$, that accounts for the unobservable CR pressure contribution and explicitly shows the origin of the cluster mass dependent bias of Y

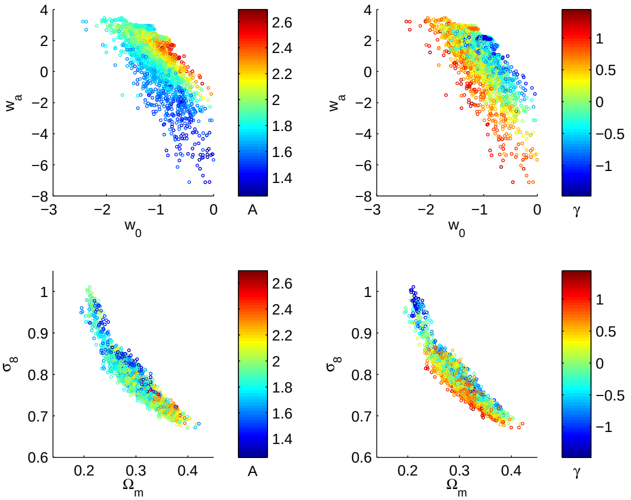
Degeneracies of the cluster redshift distribution (1)

- The number density of massive clusters is exponentially sensitive to the amplitude of the initial Gaussian fluctuations, whose normalization we usually describe using σ_8, the *rms* fluctuations of overdensity within spheres of $8\,h^{-1}$ Mpc.
- The cluster redshift distribution $\mathrm{d}n/\mathrm{d}z$ is increased by a lower effective mass threshold M_{lim} in a survey or by increasing σ_8 respectively Ω_{m} $\rightarrow$ degeneracies of cosmological parameters with respect to cluster physics.

Degeneracies of the cluster redshift distribution (2)



Bias of cosmological parameters using SZ surveys (1)

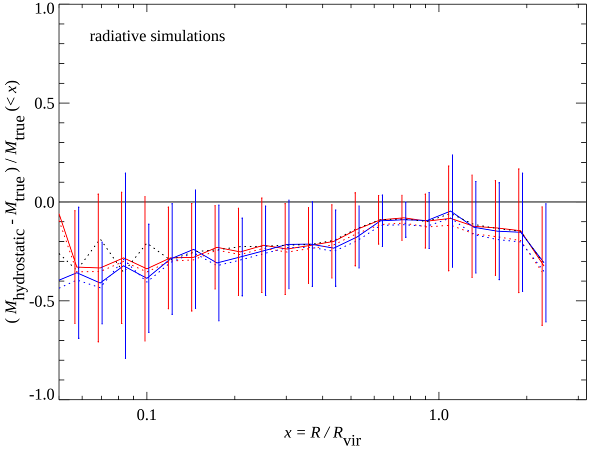


Bias of cosmological parameters using SZ surveys (2)

C.P. & Majumdar in prep:

- self-calibration around the (correct) radiative model with CR physics yields unbiased parameters, however at the expense of large uncertainties of $\Delta\Omega_\mathrm{m} = 0.038$, $\Delta\sigma_8 = 0.057$, and $\Delta\omega = 0.37$.
- wrong Bayesian prior put on our non-radiative model with CR physics $\rightarrow$ biases on the 1σ level
- SPT-like survey ($F_\mathrm{lim} = 5\mathrm{mJy}$, $4000\ \deg^2$), assuming WMAP5: radiative model yields 1.5×10^4 clusters, the non-radiative 2.2×10^4

Influence of CR pressure and turbulence on $M_{\text{hydrostatic}}$

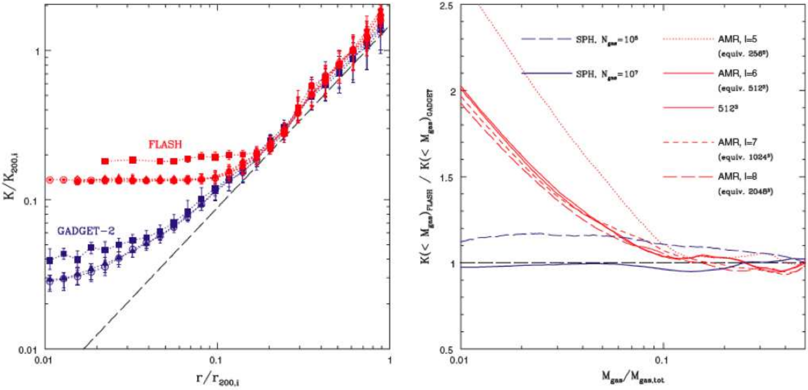


$$\rho_{\text{gas}}^{-1} \frac{\mathrm{d}P_{\text{tot}}}{\mathrm{d}r} = -\frac{G\,M(<r)}{r^2}, \text{ where } P_{\text{tot}} = P_{\text{th}} + P_{\text{nth}},$$

C.P. & Majumdar in prep.

Difference in hydrostatic masses: AMR vs. SPH (1)

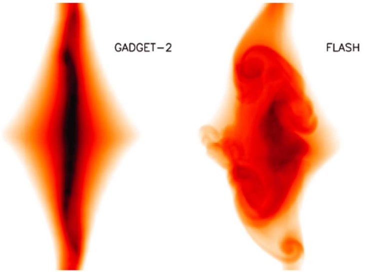
Origin of entropy cores in non-radiative simulations (Mitchell et al. 2009)



Difference in hydrostatic masses: AMR vs. SPH (2)

Exploring possible causes of the differences (Mitchell et al. 2009)

- difference in gravity solvers
- Galilean non-invariance of mesh codes
- 'pre-shocking' in the SPH runs due artificial viscosity
- difference in the amount of mixing in SPH and mesh codes

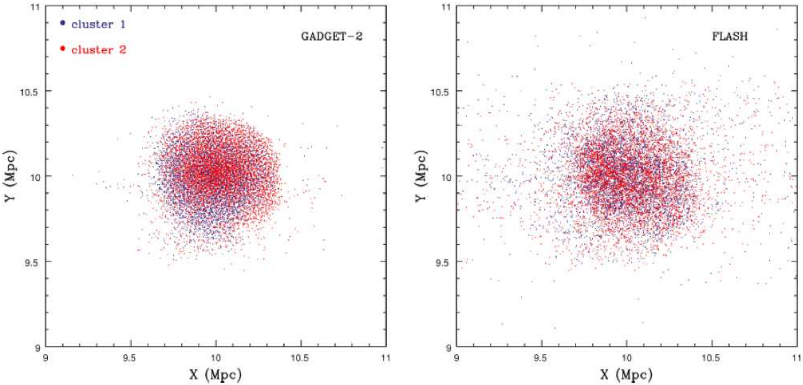


Mitchell et al. 2009: projected entropy maps during core collision suggests different treatment of vorticity in the simulations → mixing!

Ascasibar & Markewitch (2006) reproduce long-lived spiral X-ray structures with an SPH code; these features are absent in AMR calculations due to efficient mixing.

Difference in hydrostatic masses: AMR vs. SPH (3)

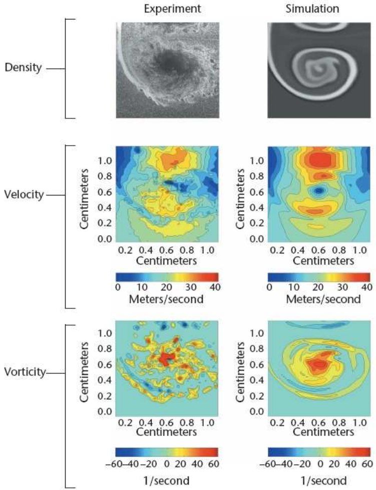
The final spatial distribution of particles: difference in mixing (Mitchell et al. 2009)



Shock-accelerated fluid interfaces

Validating models and codes with experiments (Benjamin 2004)

- LANL code validation program of an AMR code with single cylinder experiments: testing the onset of turbulence with the Richtmyer-Meshkov instability
- collaborative, iterative approach in both calculations and experiments was needed
- large-scale density and vorticity fields agree between experiment and simulation, significant differences at smaller spatial scales → crucial for understanding mixing!



Take home messages (1)

- SZ scaling relation $Y = Y_0 M_{15}^{\text{slope}}$ is affected by
  - cooling & star formation: slope $\simeq 5/3$ very weakly modified, amplitude Y_0 reduced by (up to) 30%, the answer depends on our ability to accurately model metal cooling star formation, feedback ...
  - cosmic rays from shocks: slope very weakly modified, amplitude Y_0 only slightly reduced by $2 \ldots 4\%$
- large scatter in y_0 but total Compton-y dominated by the exterior parts (uncertainties in cores less severe, apart from integral effect on overall gas fraction) $\rightarrow$ lesson to go out to $\sim R_{\text{vir}}$
- hybrid self-calibration with weak simulation biases might be the way to go...

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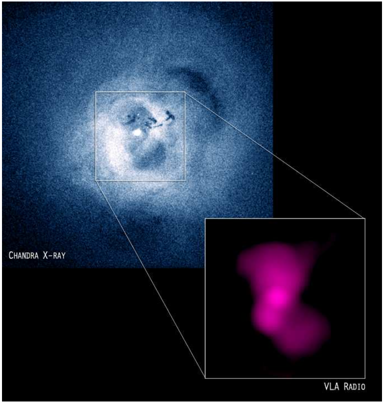
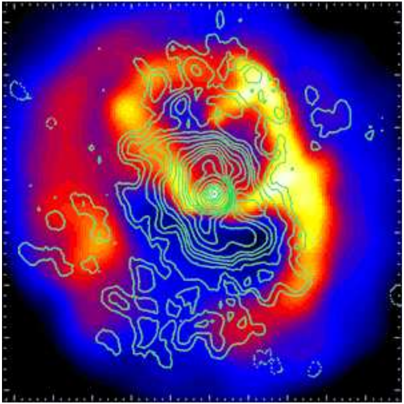
Plasma bubbles (1)



Perseus cluster

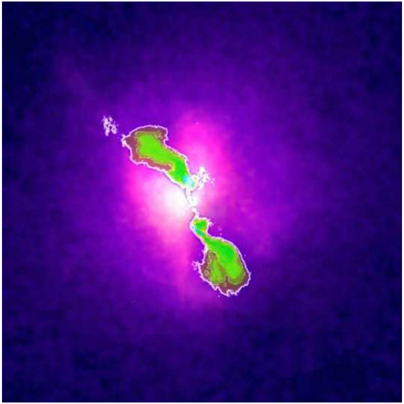
(NASA/IoA/A.Fabian et al.)



Abell 2052

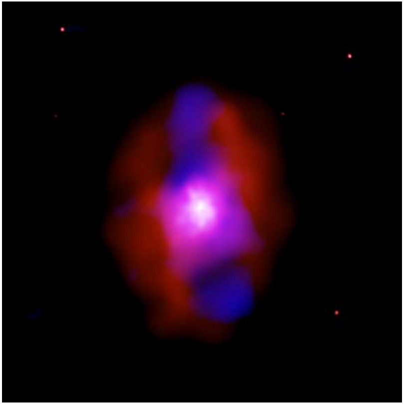
(Blanton et al., 2001)

Plasma bubbles (2)



Hydra A cluster

(X-ray: NASA/CXC/SAO; Radio: NRAO)



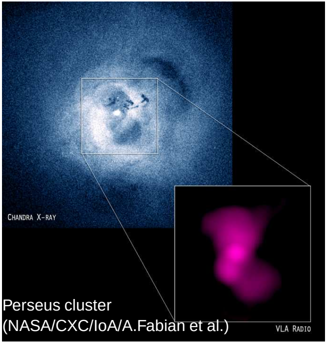
MS 0735 cluster

(X-ray: NASA/CXC/Ohio U./ B.McNamara et al.; Radio: NRAO/VLA)

Understanding AGN feedback in clusters

The intertwined lives of supermassive black holes and cluster cores

1. Heating mechanism: cavity heating through releasing potential energy, weak shocks, sound damping, . . .
   (McNamara & Nulsen 2007)
2. Minimum energy arguments of radio bubbles: $\varepsilon_{\rm CRe} \simeq 0.1\varepsilon_{\rm th}$ $\rightarrow$ where is the 'missing' pressure?
3. AGN accretion and jets: what is the composition of AGN jets – hadronic/leptonic scenario?



Perseus cluster (NASA/CXC/IoA/A.Fabian et al.)

$\rightarrow$ new observational strategies needed to elucidate the properties of the interaction $\rightarrow$ understanding of the detailed plasma physics!

This work: C.P., Torsten Enßlin, & Craig Sarazin, 2005, A&A, 430, 799

Idea of SZ bubble observations

Disadvantages of bubble X-ray observations: $L_X \propto n_e^2 \sqrt{kT_e}$

- very hot, dilute gas barely contributes to X-ray luminosity
- projected foreground and background emission contaminates weak signal
- projected substructure in outer regions could mock signal

Advantages of bubble SZ observations:

$$y \propto \int n_e k T_e \mathrm{d}l = \int P_e \mathrm{d}l$$

- SZ effect measures directly the 'missing' quantity pressure
- possibility of bubble detections in outer cluster regions
- relativistic SZ effect sensitive to (trans-)relativistic bubble fillings

SZ effect

Planckian distribution function of the CMB $I(x)$:

$$I(x) = i_0 i(x) = \frac{2(kT_{\rm CMB})^3}{(hc)^2} \frac{x^3}{e^x - 1},$$

The relative change $\delta i(x)$ in flux density as a function of dimensionless frequency $x = h\nu/(kT_{\rm CMB})$ for a line-of-sight through a galaxy cluster is given by

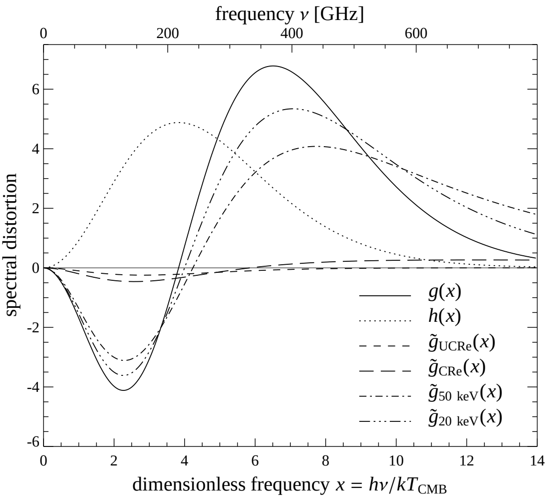
$$\delta i(x) = g(x)\, y_{\rm gas} - h(x)\, w_{\rm gas} + [j(x) - i(x)]\, \tau_{\rm rel}$$

thermal SZ effect

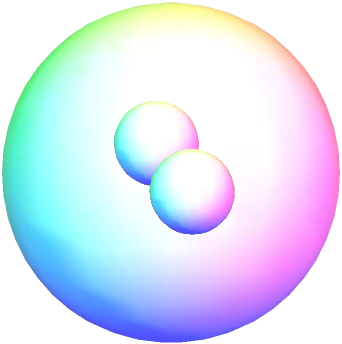
relativistic SZ effect

kinetic SZ effect

Spectral distortions



Bubble model: visual



Pressure of the cooling core cluster is described by a multiple β-model, radio plasma bubbles are spheres cutting out the thermal pressure.

Bubble model: mathematical

- Unperturbed line-of-sight (not intersecting the bubble), the observed thermal Comptonization parameter reads

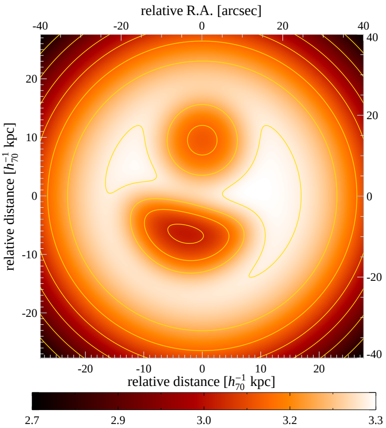
$$y_{\mathrm{cl}}(x_1, x_2) = \sum_{i=1}^{N} y_i \left(1 + \frac{x_1^2 + x_2^2}{r_{y,i}^2}\right)^{-(3\beta_{y,i}-1)/2}$$

where $y_i = \sigma_{\mathrm{T}}(m_{\mathrm{e}}c^2)^{-1} P_i r_{y,i} \mathcal{B}\left(\frac{3\beta_{y,i}-1}{2}, \frac{1}{2}\right)$.

- In the case of a line-of-sight intersecting the surface of the bubble, the area covered by the bubble reads

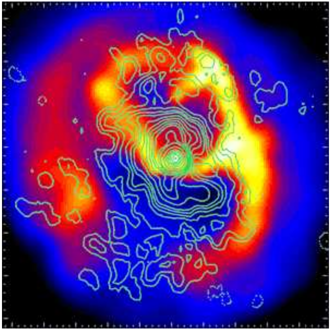
$$\begin{aligned} y_{\mathrm{b}}(x_1, x_2) &= y_{\mathrm{cl}}(x_1, x_2) - \sum_{i=1}^{N} y_i \left(1 + \frac{x_1^2 + x_2^2}{r_{y,i}^2}\right)^{-(3\beta_{y,i}-1)/2} \\ &\quad \times \left[\frac{\mathrm{sgn}(z)}{2} \mathcal{I}_{q_{y,i}(z)}\left(\frac{1}{2}, \frac{3\beta_{y,i}-1}{2}\right)\right]_{z_-}^{z_+} \end{aligned}$$

A2052: SZE versus thermal X-rays



'simulated' GBT observation

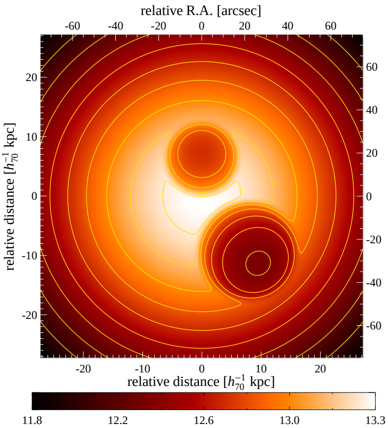
$\nu = 90$ GHz, size: $80'' \times 80''$



Chandra: $76'' \times 76''$

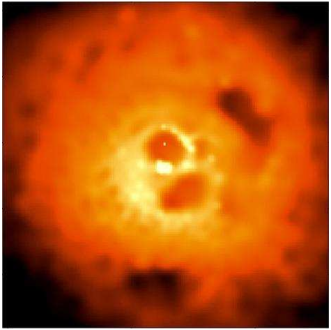
(Blanton et al., 2001)

Perseus: SZE versus thermal X-rays



'simulated' ALMA observation

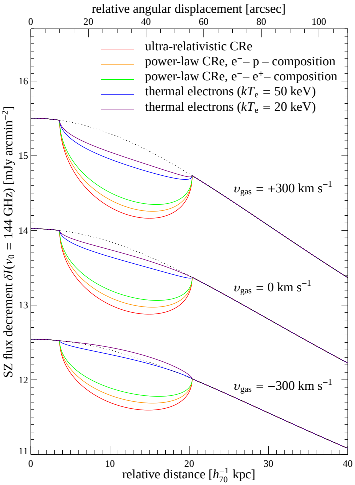
$\nu = 144$ GHz, size: $2.5' \times 2.5'$

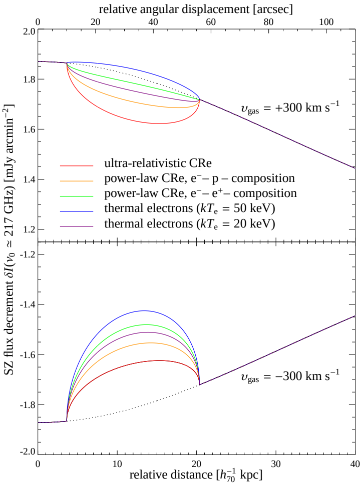


Chandra: $6' \times 6'$

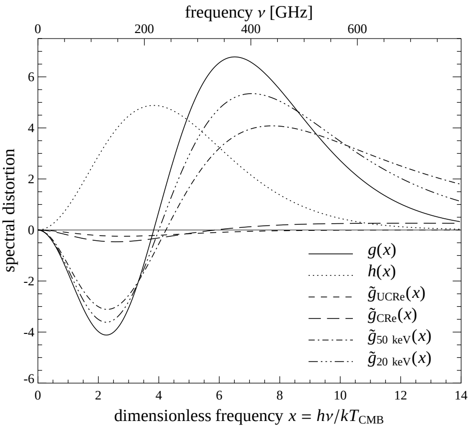
(NASA/IoA/A.Fabian et al.)

Unveiling the composition of bubbles





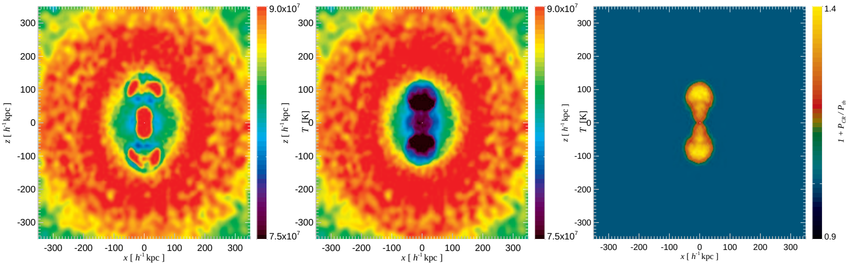
Spectral distortions – recap



→ detailed observations will reveal the dynamically dominant composition (relativistic electrons/protons, magnetic fields, hot thermal gas)

CR feedback by AGN: isolated galaxy cluster (1)

Isolated, non-cosmological cluster simulations: $t = 0.07 t_{\mathrm{H}}$



$\langle T \rangle_M$: without CRs

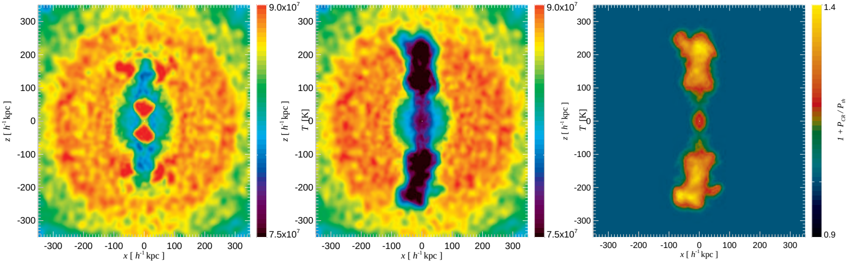
$\langle T \rangle_M$: with CRs

$1 + P_{\mathrm{CR}}/P_{\mathrm{th}}$

Sijacki, C.P., Springel, Enßlin (2008)

CR feedback by AGN: isolated galaxy cluster (2)

Isolated, non-cosmological cluster simulations: $t = 0.12 t_{\mathrm{H}}$



$\langle T \rangle_M$: without CRs

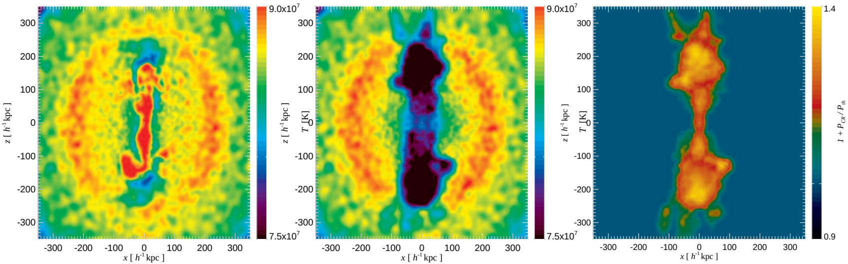
$\langle T \rangle_M$: with CRs

$1 + P_{\mathrm{CR}}/P_{\mathrm{th}}$

Sijacki, C.P., Springel, Enßlin (2008)

CR feedback by AGN: isolated galaxy cluster (3)

Isolated, non-cosmological cluster simulations: $t = 0.24 t_{\rm H}$



$\langle T \rangle_M$: without CRs

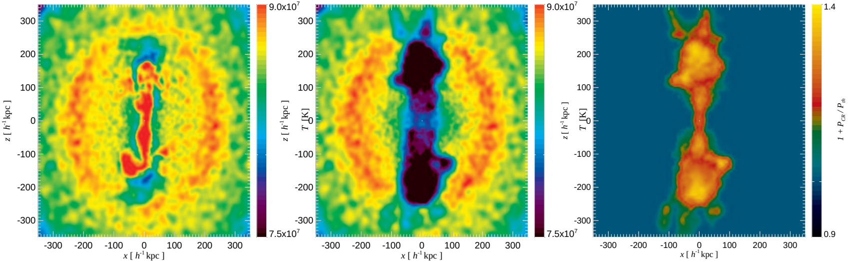
$\langle T \rangle_M$: with CRs

$1 + P_{\rm CR}/P_{\rm th}$

Sijacki, C.P., Springel, Enßlin (2008)

CR feedback by AGN: isolated galaxy cluster (4)

Isolated, non-cosmological cluster simulations: $t = 0.24t_{\mathrm{H}}$

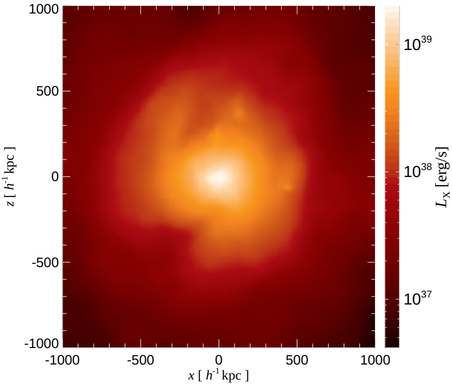


$\langle T \rangle_M$: without CRs $\quad$ $\langle T \rangle_M$: with CRs $\quad$ $1 + P_{\mathrm{CR}}/P_{\mathrm{th}}$

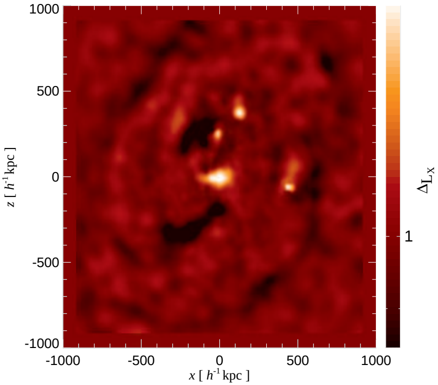
$\rightarrow$ bubble dynamics, coherence and maximum cluster-centric distance reached are affected by the presence of a relativistic component filling the bubbles! (Sijacki, C.P., Springel, Enßlin 2008)

CR feedback by AGN: cosmological galaxy cluster (1)

Ripples/weak shocks driven by AGN bubbles



X-ray brightness S_X, Virgo-like cluster

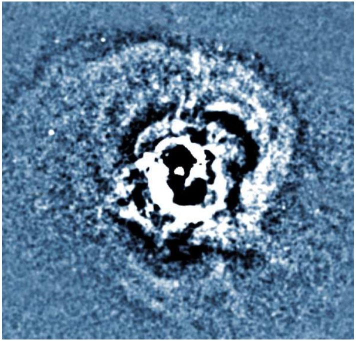


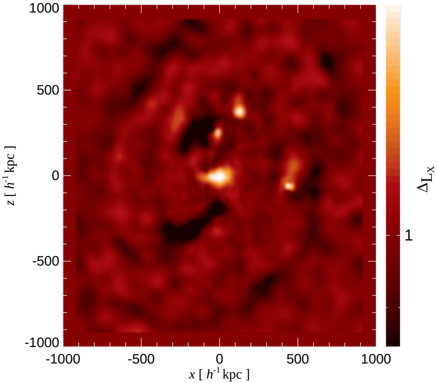
unsharp masked image ΔS_X

Sijacki, C.P., Springel, Enßlin (2008)

CR feedback by AGN: cosmological galaxy cluster (2)

ΔS_X: observation vs. simulation



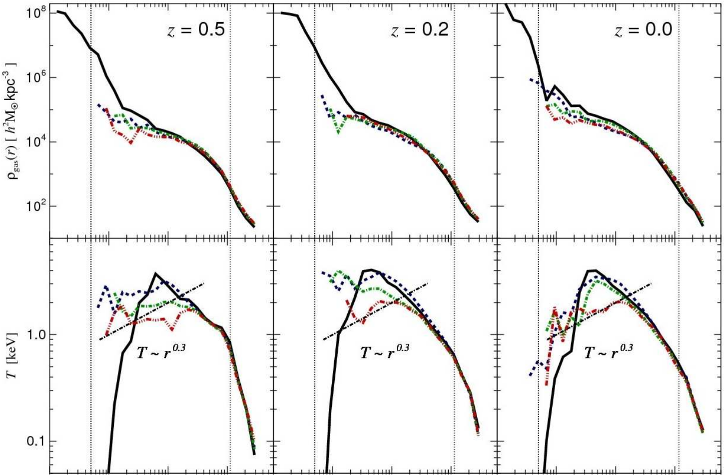


Perseus cluster (NASA/CXC/IoA/A.Fabian et al.)

small cool core cluster, $M_{\rm vir} \simeq 10^{14} M_\odot / h$

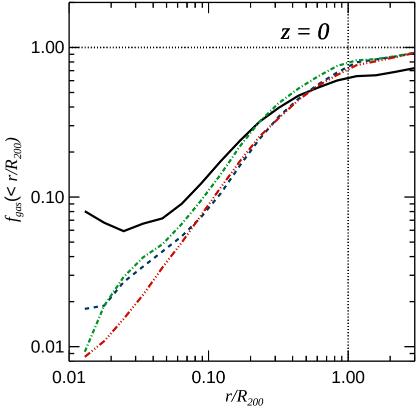
Sijacki, C.P., Springel, Enßlin (2008)

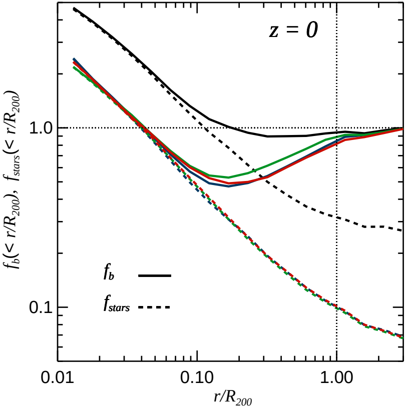
CR feedback by AGN: profiles of ρ and T



Sijacki, C.P., Springel, Enßlin (2008)

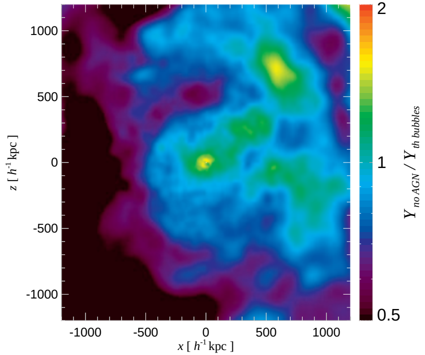
CR feedback by AGN: gas and baryon fraction



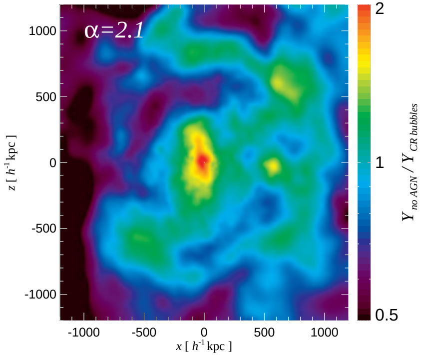


AGN feedback reduces the amount of formed stars to reconcile the observations! (Sijacki, C.P., Springel, Enßlin 2008)

CR feedback by AGN: Influence on the SZ effect



thermal AGN feedback



AGN feedback with CR-filled bubbles

$\rightarrow$ AGN feedback lowers the central Compton-y parameter and pushes the gas beyond R_{vir} (importance at high-z!)

Sijacki, C.P., Springel, Enßlin 2008

Take home messages (2)

- CR feedback by AGN is a promising solution to the over-cooling problem:
  - for the first time, temperature profiles and gas fractions in cosmological simulations are in agreement with observation
  - successful reproduction of observational features such as X-ray ripples and bubble morphologies
- high-resolution SZ observations of bubbles with GBT/ALMA can elucidate the dynamical component of bubbles → important for solving the cooling flow problem

→ exciting first results: interplay of SZ observations and simulations provide great promises for understanding clusters and (to some degree) cosmology!

Literature for the talk

- Sijacki, Pfrommer, Springel, Enßlin, 2008, MNRAS, 387, 1403, *Simulations of cosmic ray feedback by AGN in galaxy clusters*
- Pfrommer, 2008, MNRAS, 385, 1242 *Simulating cosmic rays in clusters of galaxies – III. Non-thermal scaling relations and comparison to observations*
- Pfrommer, Enßlin, Springel, 2008, MNRAS, 385, 1211, *Simulating cosmic rays in clusters of galaxies – II. A unified scheme for radio halos and relics with predictions of the γ-ray emission*
- Pfrommer, Enßlin, Springel, Jubelgas, Dolag, 2007, MNRAS, 378, 385, *Simulating cosmic rays in clusters of galaxies – I. Effects on the Sunyaev-Zel'dovich effect and the X-ray emission*
- Pfrommer, Springel, Enßlin, Jubelgas, 2006, MNRAS, 367, 113, *Detecting shock waves in cosmological smoothed particle hydrodynamics simulations*
- Enßlin, Pfrommer, Springel, Jubelgas, 2007, A&A, 473, 41, *Cosmic ray physics in calculations of cosmological structure formation*