Feedback in galaxy clusters - a progress report

Christoph Pfrommer

Canadian Institute for Theoretical Astrophysics, Canada

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Outline

1. Feedback processes in the ICM
   - AGNs and cosmic rays
   - Magnetic fields and turbulence
   - Galactic outflows and transport processes
2. AGN feedback revisited
   - General considerations
   - Physics of AGN bubbles
   - Impact on cluster environment

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2. AGN feedback revisited
   - General considerations
   - Physics of AGN bubbles
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Feedback

feedback n -s often attrib:

1. the return to the input of a part of the output of a machine, system, or process
2. the partial reversion of the effects of a given process to its source or to a preceding stage so as to reinforce or modify it
3. the solution of all problems in galaxy formation and cluster physics

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3. the solution of all problems in galaxy formation and cluster physics

What is the future potential for studying clusters?

Why do we study feedback?

- We want to understand their formation, evolution, and structure and to solve open observational puzzles.
- The ICM is an ideal plasma (cleaner than most other astrophysical plasmas). Hence we can use them (individually or an ensemble) as laboratories to study . . .
  - the nature of dark matter,
  - CR acceleration,
  - MHD turbulence,
  - plasma instabilities,
  - microscopic transport processes (anisotropic conduction/diffusion),
  - the applicability of MHD as supposed to kinetic theory.
- “Calibrate” or select them: “gold” sample for cosmology

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Different feedback processes in the ICM

Incomplete and biased list of cluster feedback processes in addition to the usually considered cooling and star formation:

1. AGN ‘radio mode’ feedback
2. cosmic ray (CR) pressure
3. magnetic fields
4. turbulence
5. galactic outflows
6. physical viscosity
7. heat conduction
8. . . .

Different feedback processes in the ICM

1. AGN ‘radio mode’ feedback:
   where: cluster center/cD galaxy
   what: quenching of cooling flows (e.g., Churazov et al. 2001, Sijacki & Springel 2006, Heinz et al. 2006), suppression of the high-mass end of the luminosity function, down-sizing and color bimodality of galaxies (Croton et al. 2006, de Lucia & Blaizot 2006)
2. cosmic ray (CR) pressure
3. magnetic fields
4. turbulence
5. galactic outflows
6. physical viscosity
7. heat conduction
8. . . .

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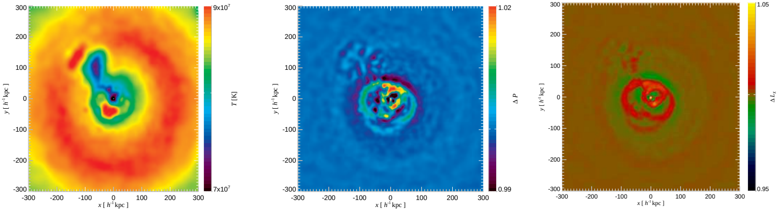
AGN ‘radio mode’ feedback

Mass-weighted temperature, pressure, X-ray brightness (unsharp masked):



- central bubbles have mushroom-like morphologies and are uplifting residual cool material
- bubbles generate sound waves and weak shocks

(Sijacki & Springel 2006)

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Different feedback processes in the ICM

1. AGN 'radio mode' feedback
2. cosmic rays (CR):
   where: cluster center and outskirts, WHIM
   what: bias of X-ray emission (Pfrommer et al. 2007), possibly responsible for radio halo emission (Dennison 1980, Pfrommer et al. 2008), excitation of Hα-filaments (Ruszkowski et al. 2007), suppression of the low-mass end of the galaxy luminosity function (Jubelgas et al. 2007)
3. magnetic fields
4. turbulence
5. galactic outflows
6. physical viscosity
7. heat conduction
8. ...

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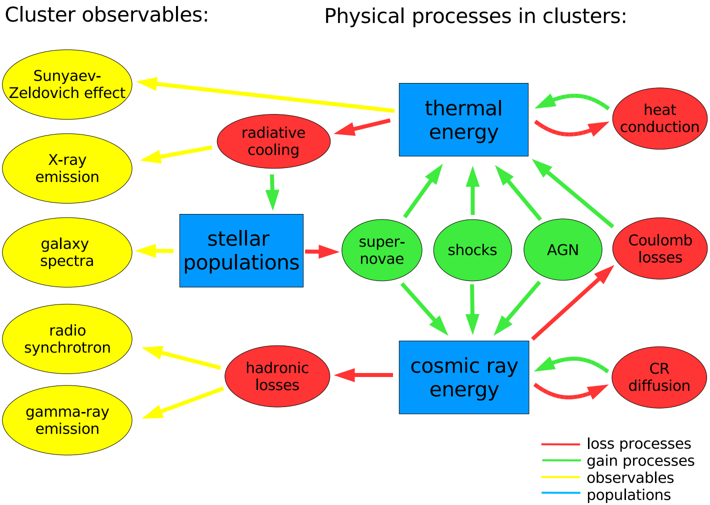
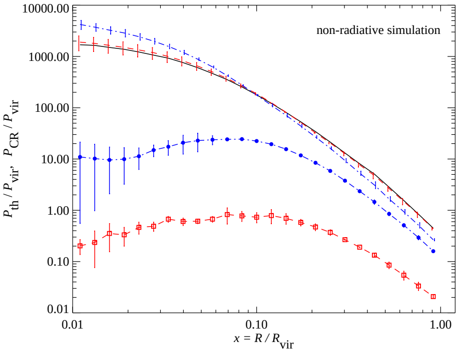
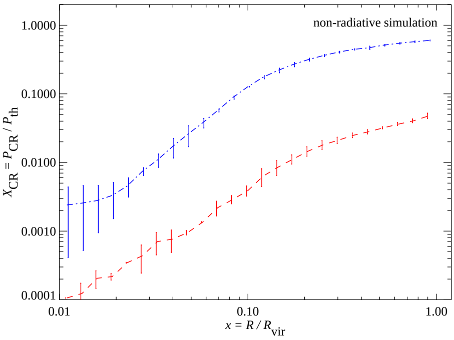
Radiative simulations with extended CR physics



Profiles: non-radiative simulations



Thermal & CR pressure



Relative CR pressure, $X_{CR} = P_{CR}/P_{th}$.

red: Mach number dependent CR injection,

blue: fixed acceleration efficiency (too simplistic).

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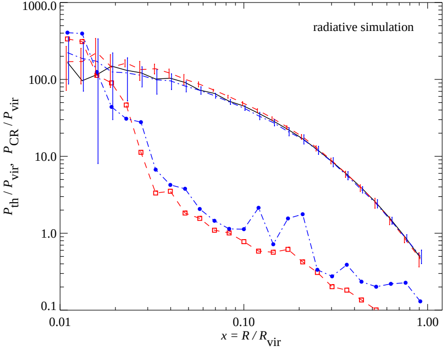
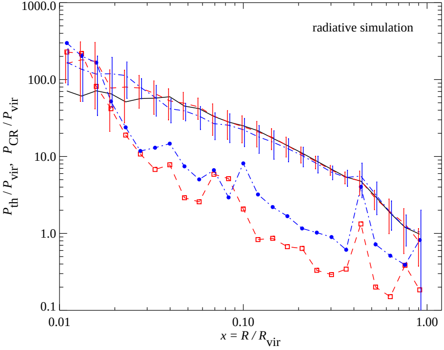
Radiative simulations: pressure profile





Cool core cluster sample.

Merging cluster sample.

red: only structure formation shock CRs,

blue: structure formation & SNe CRs.

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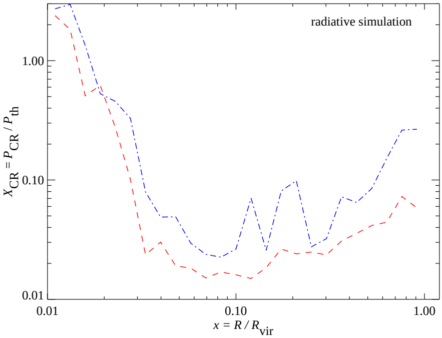
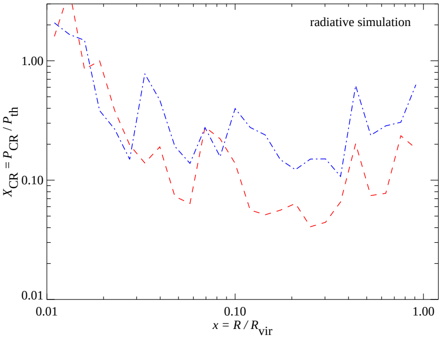
Radiative simulations: relative CR pressure profile





Cool core cluster sample.

Merging cluster sample.

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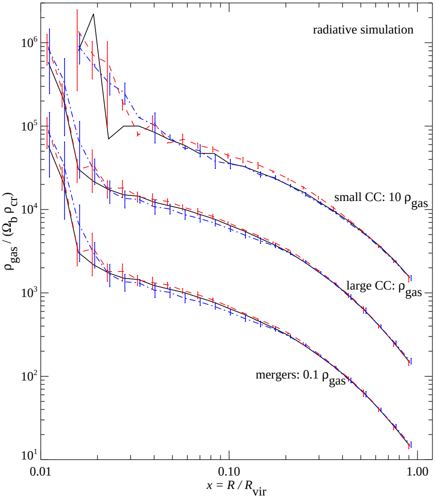
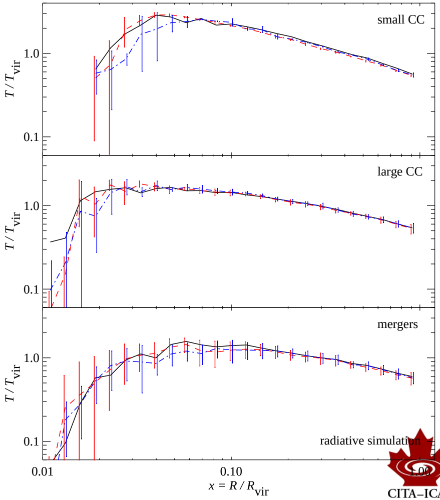
Radiative simulations: density and temperature profile





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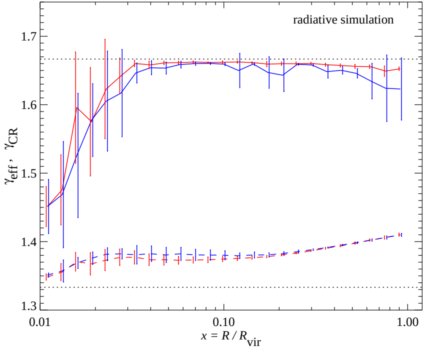
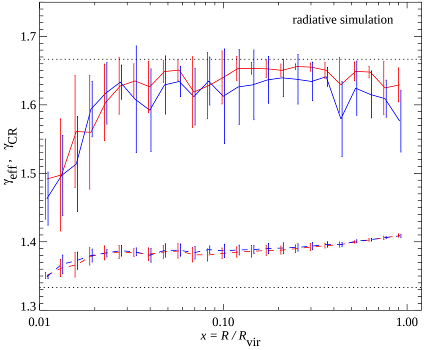
Radiative simulations: adiabatic index profile





Cool core cluster sample.

Merging cluster sample.

red: only structure formation shock CRs,

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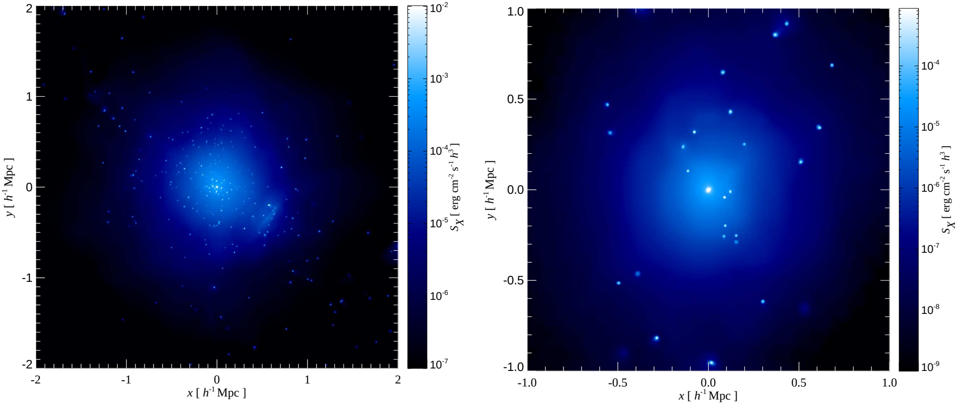
Thermal X-ray emission



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

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

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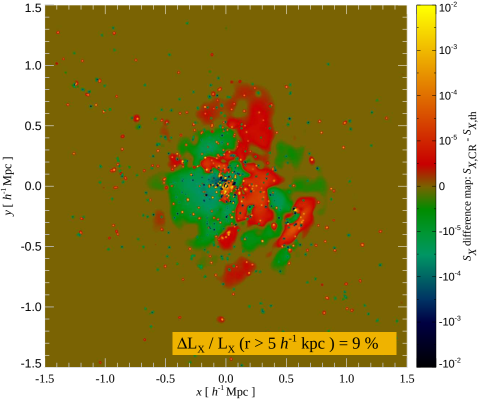
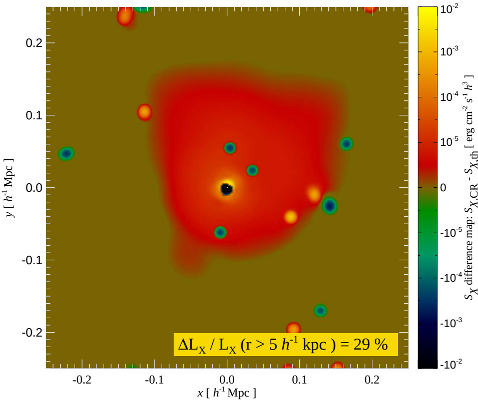
Difference map of S_X: $S_{X,CR} - S_{X,th}$





large merging cluster, $M_{vir} \simeq 10^{15} M_\odot / h$
→ contributes to the scatter in the $M - L_X$ scaling relation

cool core cluster, $M_{vir} \simeq 10^{14} M_\odot / h$
→ systematic increase of L_X for small cool core clusters

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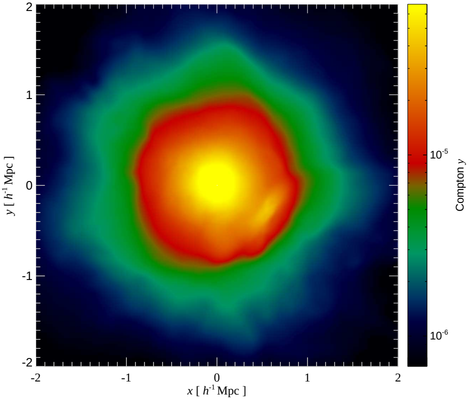
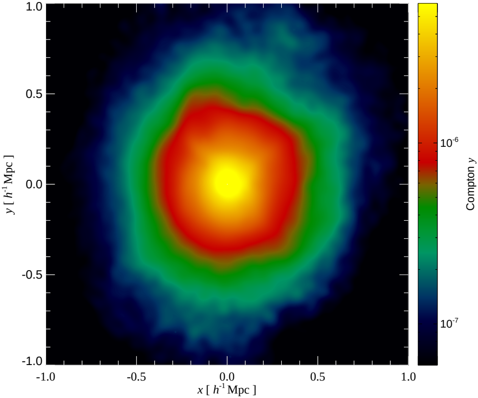
Compton y parameter in radiative cluster simulation



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



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

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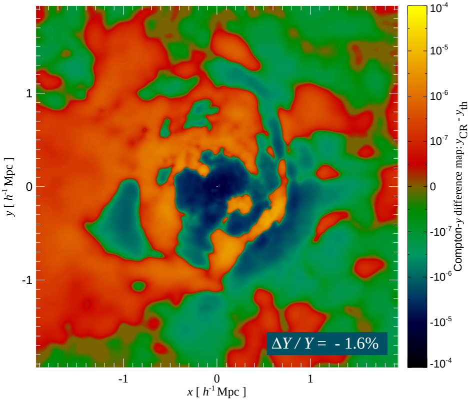
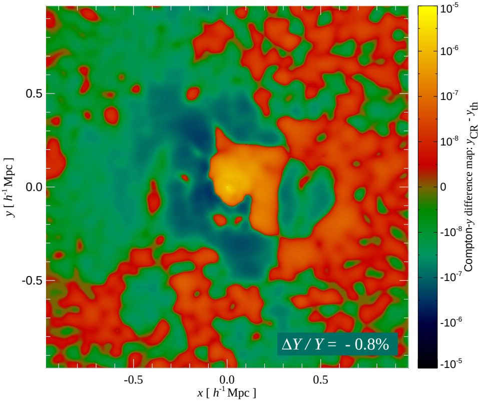
Compton y difference map: $y_{\rm CR} - y_{\rm th}$



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



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

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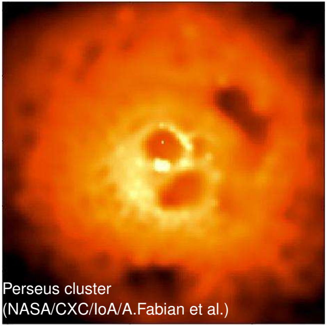
Different feedback processes in the ICM

1. AGN ‘radio mode’ feedback
2. cosmic ray (CR) pressure
3. magnetic fields:
   where: at the interface of different phases of the ICM (bubbles, cold fronts) and in the bulk of the ICM
   what: suppresses hydrodynamic instabilities (Kelvin-Helmholtz, Rayleigh-Taylor) and transport processes across interface (Asai et al. 2007, Lyutikov 2007, Ruszkowski et al. 2007, Dursi & Pfrommer 2008), magneto-thermal instabilities enhance or suppress heat conduction (Balbus 2000, Quataert 2007)
4. turbulence
5. galactic outflows
6. physical viscosity
7. heat conduction
8. . . .

Sharp interfaces in the ICM

- Radio Bubbles, seen as cavities in X-rays, are observed out to large distances and have very sharp interfaces.
- ‘Cold fronts’ show very sharp gradients in density and temperature.



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

Hydrodynamic instabilities should disrupt them, conduction should dissipate the interfaces in $\sim 10^8$ yrs.

Could bubble/core motions sweep up enough field to suppress instabilities and conduction?

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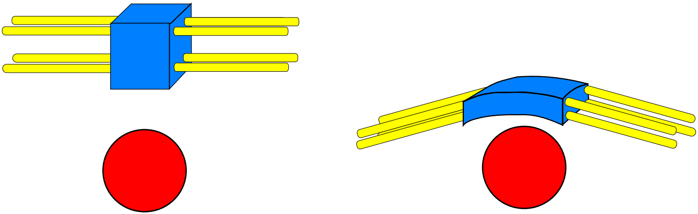
Magnetic draping: cartoon



A cartoon showing the distortion of incoming fluid elements and stretching of field lines as a red spherical projectile moves upwards through the ambient medium.

Magnetic draping: some analytics

- The magnetic field should exert a significant back-reaction when the resulting magnetic pressure is comparable to the ram pressure of the incoming material, $B^2/8\pi \sim \rho_0 u^2$.
- The magnetic layer is very thin, with $L \sim R/\mathcal{M}_A^2$, where $\mathcal{M}_A = u/v_A \sim 10 \ldots 100$ is the Alfvénic Mach number of the core, $v_A^2 = B_0^2/4\pi\rho_0$ is the ambient Alfvén speed.
- Sweeping up such a magnetic field will occur on a timescale $t/t_c \sim (L/R)\mathcal{M}_A \sim \mathcal{M}_A^{-1}$, where $t_c = 2R/u$ is the projectile's own crossing time
  $\rightarrow$ because the magnetic layer is very thin, a strong field can be built up extremely quickly!

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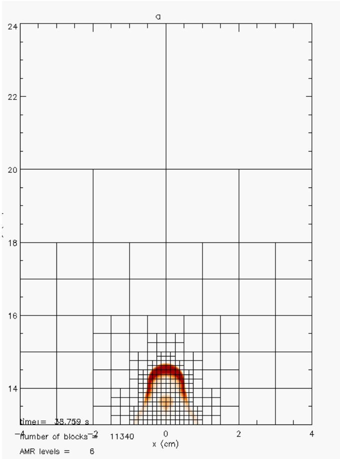
Magnetic draping: 3D simulations with FLASH

- AMR very useful for focusing resolution in near draped layer
- large dynamic range between size of traversed region and thickness of layer
- magnetic dynamics relatively straightforward



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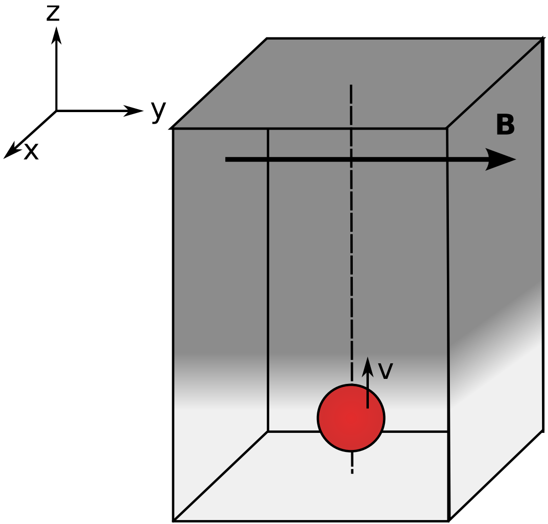
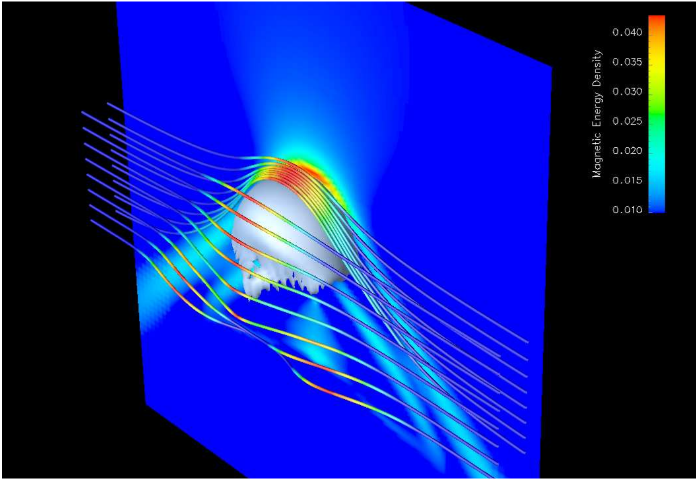
Magnetic draping: simulation setup



Magnetic draping: simulations



Draping: opening angle $\theta \simeq v_A / u$ (Dursi & Pfrommer 2008)

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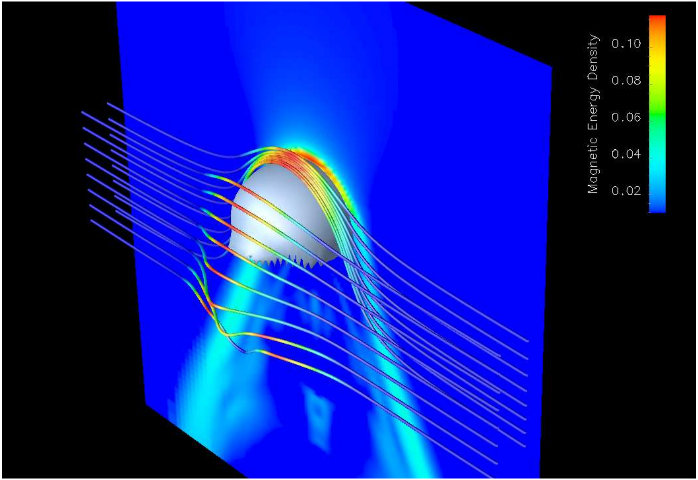
Magnetic draping: simulations



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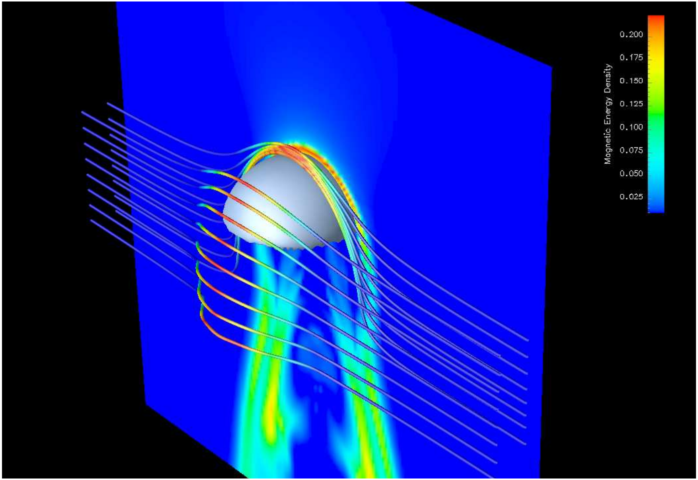

Draping: opening angle $\theta \simeq v_{\rm A}/u$ (Dursi & Pfrommer 2008)

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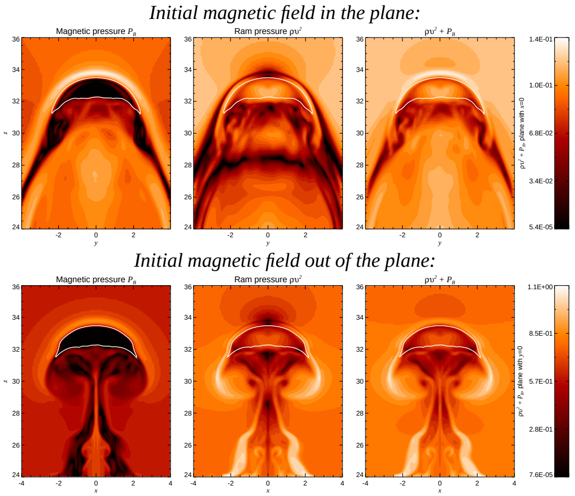
Magnetic draping: simulations



Draped magnetic pressure vs. ram pressure (Dursi & Pfrommer 2008)

Exact MHD solution: kinetic approximation

- Solve for viscous and incompressible flow around the sphere – potential flow with $\nabla^2\phi = 0$ and $\boldsymbol{v} = \nabla\phi$:
  $$\boldsymbol{v} = -\boldsymbol{u} + \frac{R^3}{2r^3}\,[3\boldsymbol{e}_r(\boldsymbol{u}\cdot\boldsymbol{e}_r) - \boldsymbol{u}].$$
- Equations of ideal MHD with infinity conductivity:
  $\mathrm{curl}(\boldsymbol{v}\times\boldsymbol{B}) = \boldsymbol{0}$ and $\mathrm{div}\,\boldsymbol{B} = 0$.
- Complicated solutions, approximations near the sphere:

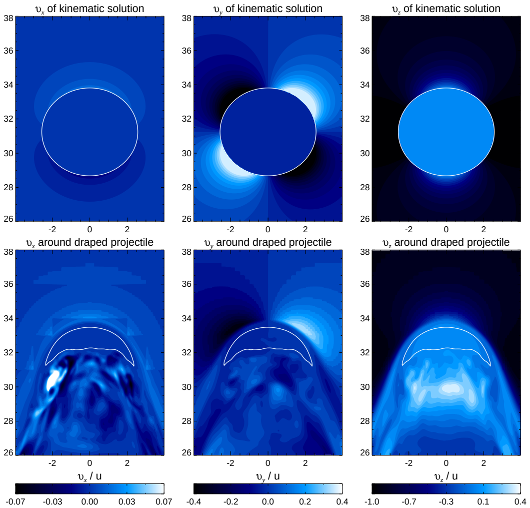
$$B_r = \frac{2}{3}B_0\sqrt{\frac{3s}{R}}\,\frac{\sin\theta}{1+\cos\theta}\,\sin\phi,$$
$$B_\theta = B_0\sin\phi\sqrt{\frac{R}{3s}},$$
$$B_\phi = B_0\cos\phi\sqrt{\frac{R}{3s}} \qquad \text{and } s = r - R.$$

Magnetic draping: comparison to theory

Potential flow around a solid sphere

3d AMR results

(Dursi & Pfrommer 2008)



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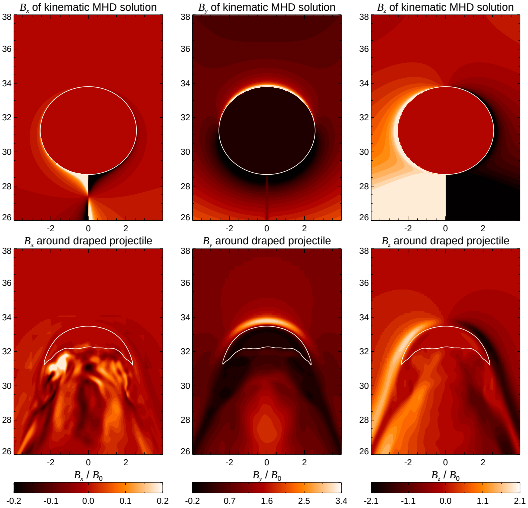
Magnetic draping: comparison to theory

Potential flow around a solid sphere

3d AMR results

(Dursi & Pfrommer 2008)

Initial magnetic field in the plane:



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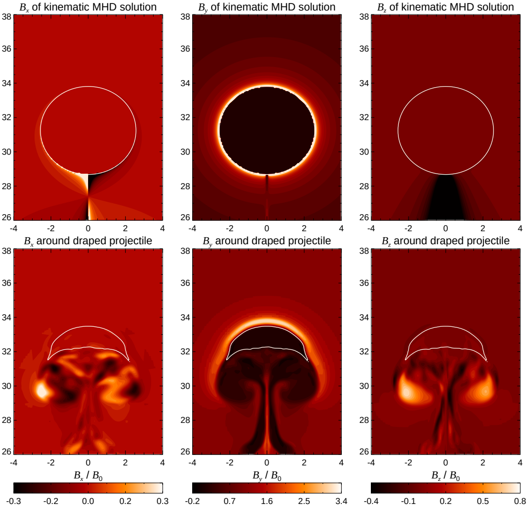
Magnetic draping: comparison to theory

Potential flow around a solid sphere

3d AMR results

(Dursi & Pfrommer 2008)

Initial magnetic field out of the plane:



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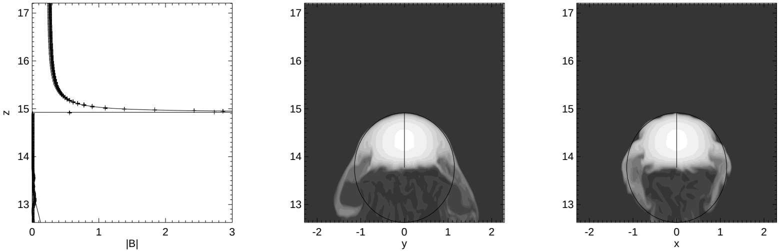
Magnetic draping: comparison to theory



Left: magnetic field along the stagnation line in the simulation and a fitted theory prediction.

Right: cut-planes along and across the initial magnetic field of the density of the projectile. The circle indicates the curvature at the working surface of the projectile (radius obtained from fit, left).

(Dursi & Pfrommer 2008)

Different feedback processes in the ICM

1. AGN 'radio mode' feedback
2. cosmic ray (CR) pressure
3. magnetic fields
4. turbulence:
   where: ICM, at particular at outskirts (stronger shocks)
   what: magnetic field growth by turbulent dynamos (Subramanian 2003, Schekochihin & Cowley 2006), bias of hydrostatic masses (Rasia et al. 2005, Kravtsov et al. 2006), quenching of cooling flows (Enßlin & Vogt 2006), source of CRs through Fermi II acceleration (Brunetti & Lazarian 2007)
5. galactic outflows
6. physical viscosity
7. heat conduction
8. ...

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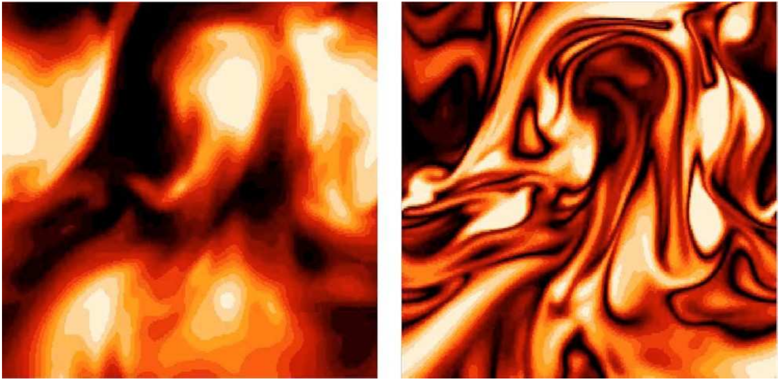
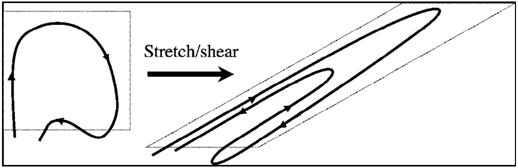
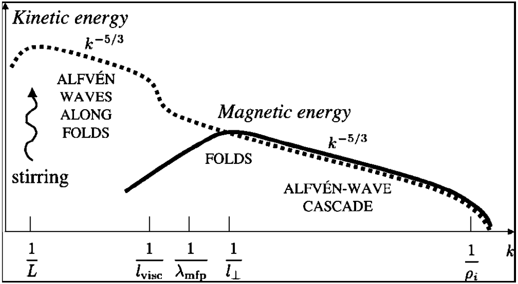
MHD turbulence in clusters



cross-section of $|\boldsymbol{u}|$ and $|\boldsymbol{B}|$ in the saturated dynamo state (Schekochihin & Cowley 2006)

MHD turbulence in clusters





(Schekochihin & Cowley 2006)

Different feedback processes in the ICM

1. AGN 'radio mode' feedback
2. cosmic ray (CR) pressure
3. magnetic fields
4. turbulence
5. galactic outflows:
   where: cluster center & around galaxies
   what: metal enrichment of the IGM (Springel & Hernquist 2002), injection of magnetic fields into the IGM (Bertone et al. 2006), entropy source of the ICM
6. physical viscosity
7. heat conduction
8. ...

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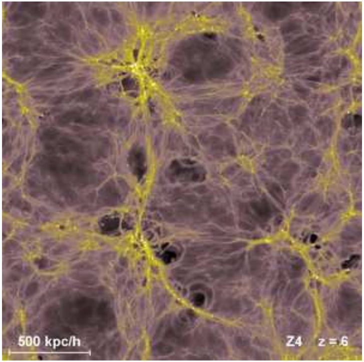
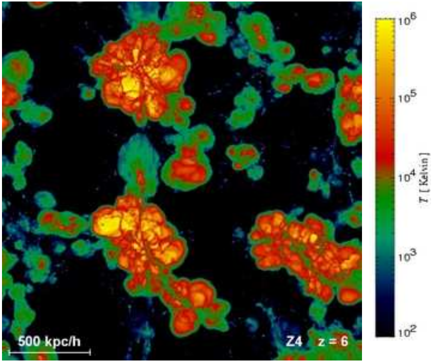
Galactic Outflows





A galactic outflow seen at high redshift. Left: the projected gas density around some of the first star forming galaxies. Right: generated bubbles of hot gas, as seen in the temperature map (Springel & Hernquist 2002).

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Different feedback processes in the ICM

1. AGN ‘radio mode’ feedback
2. cosmic ray (CR) pressure
3. magnetic fields
4. turbulence
5. galactic outflows
6. physical viscosity:
   where: ICM
   what: change of bubbles properties, additional entropy generation mode, effective gas stripping (Sijacki & Springel 2006)
7. heat conduction
8. . . .

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ICM as ideal gas – Euler equation

- The hydrodynamics of the gas is governed by the continuity equation (mass conservation), the Euler equation (momentum conservation), and the conservation equation for the thermal energy u:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\nabla\boldsymbol{v} = 0,$$

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho} - \nabla\Phi,$$

$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho}\nabla\boldsymbol{v} - \frac{\Lambda(u,\rho)}{\rho}, \qquad \text{and} \quad \frac{\mathrm{d}}{\mathrm{d}t} \equiv \frac{\partial}{\partial t} + \boldsymbol{v}\cdot\nabla$$

  $\Lambda(u,\rho)$ describes external sinks or sources of heat for the gas.

- The equation of state and the Poisson equation close the above system of coupled differential equations:

$$P = (\gamma - 1)\rho u,$$

$$\nabla^2\Phi = 4\pi G\rho_{\mathrm{tot}}.$$

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$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho}\nabla \boldsymbol{v} - \frac{\Lambda(u,\rho)}{\rho}, \qquad \text{and} \quad \frac{\mathrm{d}}{\mathrm{d}t} \equiv \frac{\partial}{\partial t} + \boldsymbol{v}\cdot\nabla$$

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- The equation of state and the Poisson equation close the above system of coupled differential equations:

$$P = (\gamma - 1)\rho u,$$

$$\nabla^2\Phi = 4\pi G\rho_{\mathrm{tot}}.$$

Physical viscosity – Navier Stokes equation

- Unlike ideal gases which are isentropic outside of shock waves, entropy conservation does not hold for viscous fluids: Euler equation → generalized Navier-Stokes equation:
  $$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho} - \nabla\Phi + \frac{\nabla\hat{\boldsymbol{\sigma}}}{\rho},$$
  where the viscous stress tensor, or 'rate-of-strain tensor' is
  $$\hat{\sigma}_{ik} = \eta\left(\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i} - \frac{2}{3}\delta_{ik}\frac{\partial v_l}{\partial x_l}\right) + \zeta\delta_{ik}\frac{\partial v_l}{\partial x_l},$$
  η is the coefficient of shear viscosity, and ζ represents the bulk viscosity coefficient.
- Energy conservation law → general heat transfer equation:
  $$\rho T\frac{\mathrm{d}S}{\mathrm{d}t} = \nabla(\kappa\nabla T) + \frac{1}{2}\eta\,\hat{\sigma}_{\alpha\beta}\hat{\sigma}_{\alpha\beta} + \zeta(\nabla\boldsymbol{v})^2$$
  This equation expresses how much entropy is generated by the internal friction of the gas and by the heat conducted into the considered volume element.

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Physical viscosity – Navier Stokes equation

- Unlike ideal gases which are isentropic outside of shock waves, entropy conservation does not hold for viscous fluids: Euler equation → generalized Navier-Stokes equation:
$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho} - \nabla\Phi + \frac{\nabla\hat{\boldsymbol{\sigma}}}{\rho},$$
where the viscous stress tensor, or 'rate-of-strain tensor' is
$$\hat{\sigma}_{ik} = \eta\left(\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i} - \frac{2}{3}\delta_{ik}\frac{\partial v_l}{\partial x_l}\right) + \zeta\delta_{ik}\frac{\partial v_l}{\partial x_l},$$
η is the coefficient of shear viscosity, and ζ represents the bulk viscosity coefficient.
- Energy conservation law → general heat transfer equation:
$$\rho T\frac{\mathrm{d}S}{\mathrm{d}t} = \nabla(\kappa\nabla T) + \frac{1}{2}\eta\,\hat{\sigma}_{\alpha\beta}\hat{\sigma}_{\alpha\beta} + \zeta(\nabla\,\boldsymbol{v})^2$$
This equation expresses how much entropy is generated by the internal friction of the gas and by the heat conducted into the considered volume element.

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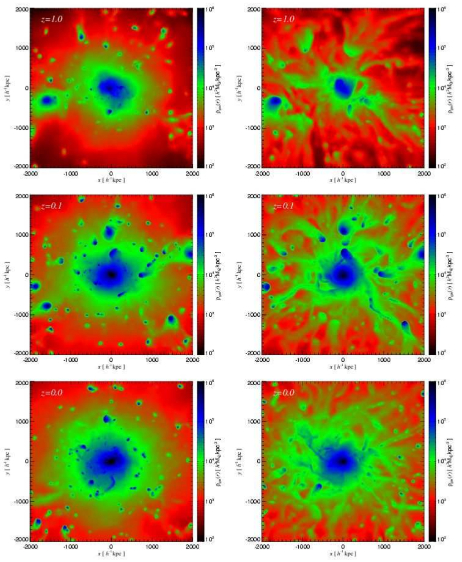
Gas stripping in viscous medium

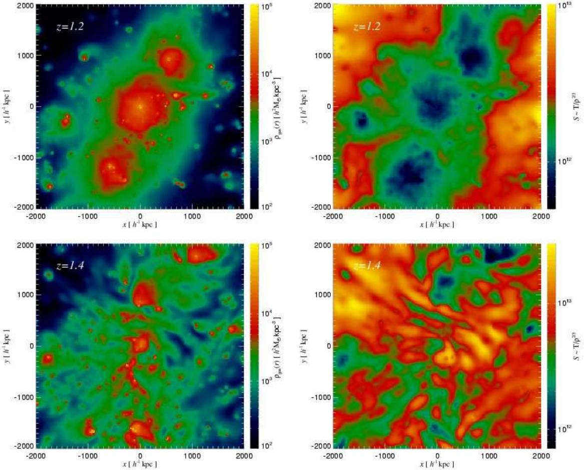


- Projected gas density maps of a non-radiative cluster simulation at redshifts $z = 1.0$, $z = 0.1$ and $z = 0.0$
- left: no physical viscosity, right: including Braginskii shear viscosity suppressed by a factor 0.3
- friction forces induced by viscosity remove more gas from infalling structures when they enter the massive halo $\rightarrow$ pronounced gaseous tails

(Sijacki & Springel 2006)

Generation of entropy bridges in viscous medium

Gas density and entropy in radiative cluster simulation:



(Sijacki & Springel 2006)

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Different feedback processes in the ICM

1. AGN ‘radio mode’ feedback
2. cosmic ray (CR) pressure
3. magnetic fields
4. turbulence
5. galactic outflows
6. physical viscosity
7. heat conduction:
   where: ICM
   what: re-distribution of thermal energy, quenching of cooling flows (Narayan & Medvedev 2001, Jubelgas et al. 2004, Dolag et al. 2004)
8. . . .

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Outline

1. Feedback processes in the ICM
   - AGNs and cosmic rays
   - Magnetic fields and turbulence
   - Galactic outflows and transport processes
2. AGN feedback revisited
   - General considerations
   - Physics of AGN bubbles
   - Impact on cluster environment

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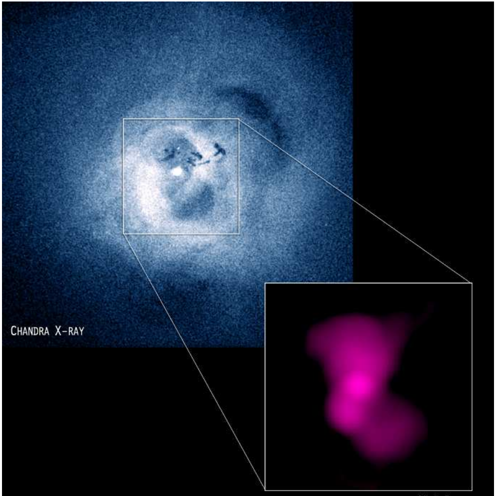
Steps towards understanding AGN feedback

Super massive black holes (SMBHs) with $M \sim 10^9 M_\odot$ live in their hosting cD galaxies at the centers of galaxy clusters. They co-evolve with the surrounding ICM and provide self-regulated energetic feedback to balance cooling. Open questions:

1. launching the jet from the SMBH-accretion disk system: requires understanding of accretion (Narayan & McClintock 2008) and GRMHD simulations (McKinney 2007)
2. jet-ICM interaction and rising of the bubbles: CR confinement vs. entrainment of ICM gas, duty cycle
3. heating mechanism: cavity heating through releasing potential energy, weak shocks, sound damping, . . . (McNamara & Nulsen 2007)

AGN feedback at work: combing X-ray and radio



Perseus cluster (NRAO/VLA/G. Taylor)

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AGN feedback – energetics

Gravitational binding energy $E_{\mathrm{grav}} = M\sigma^2$,
$M_{\mathrm{BH}} \sim M/500$ from the $M - \sigma$ relation.

Hence the available energy to be extracted from the BH is
$E \sim 0.1 M_{\mathrm{BH}} c^2$.

It follows

$$\frac{E}{E_{\mathrm{grav}}} = 0.1\,\frac{M_{\mathrm{BH}}}{M}\left(\frac{c}{\sigma}\right)^2 \sim 200\left(\frac{300\ \mathrm{km/s}}{\sigma}\right)^2.$$

There is more than enough energy available for feedback from the BH!

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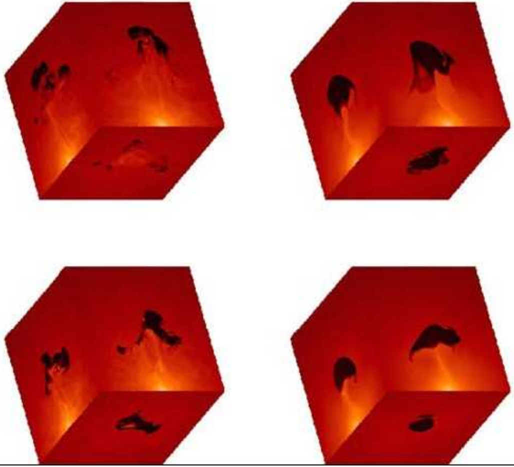
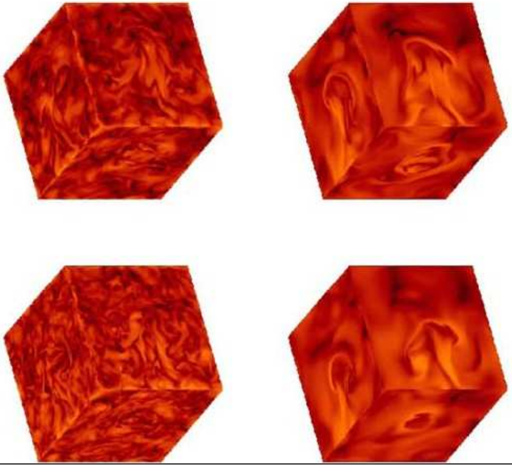
Magnetic draping at bubbles: density



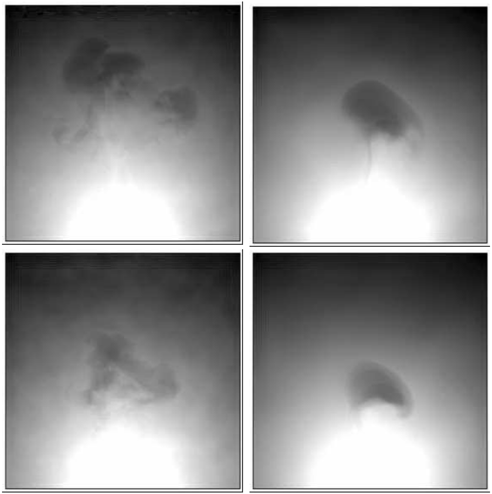
log ρ, non-draping versus draping case (Ruszkowski et al. 2007)

Magnetic draping at bubbles: magnetic pressure



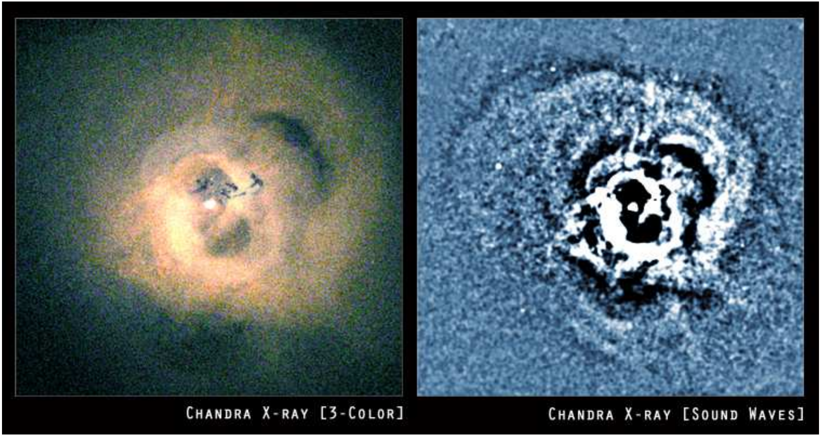
log B^2, non-draping versus draping case (Ruszkowski et al. 2007)

Magnetic draping at bubbles: X-ray emission



S_X, non-draping versus draping case (Ruszkowski et al. 2007)

X-ray observations



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

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X-ray observations: weak shocks and sound waves

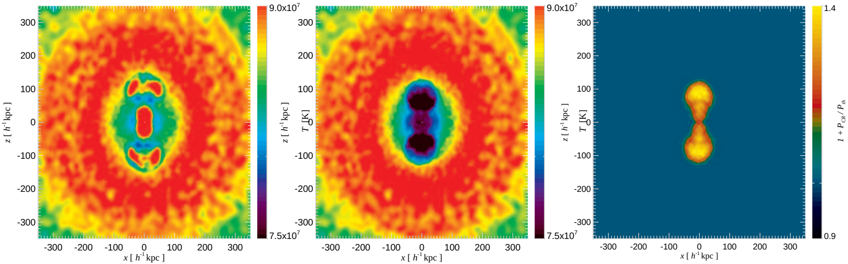
- Substantial energy, comparable to the cavity enthalpy, is required to drive the weak shocks seen in association with AGN outbursts in some clusters → much of the shock energy ends up as additional potential energy in the gas.
- Viscous damping of sound waves generated by repeated AGN outbursts may represent a significant source of heating (Fabian et al. 2003).

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

Dissipation of sound depends on the transport coefficients, but shock heating does not → distinct spatial distributions of heating.

CR feedback by AGN in galaxy clusters

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, Pfrommer, Springel, Enßlin (2008)

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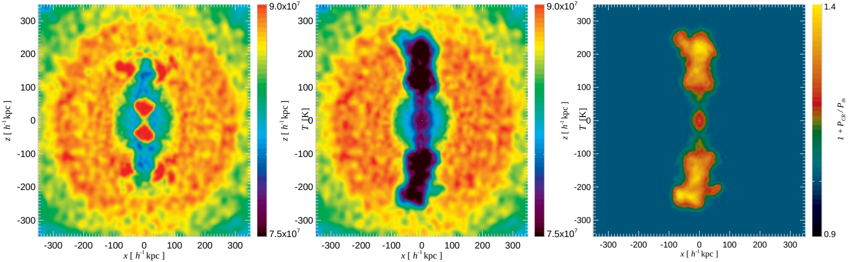
CR feedback by AGN in galaxy clusters

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



$\langle T \rangle_M$: without CRs

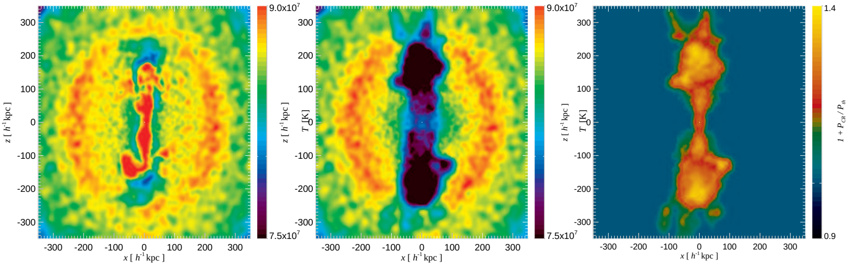
$\langle T \rangle_M$: with CRs

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

Sijacki, Pfrommer, Springel, Enßlin (2008)

CR feedback by AGN in galaxy clusters

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



$\langle T \rangle_M$: without CRs

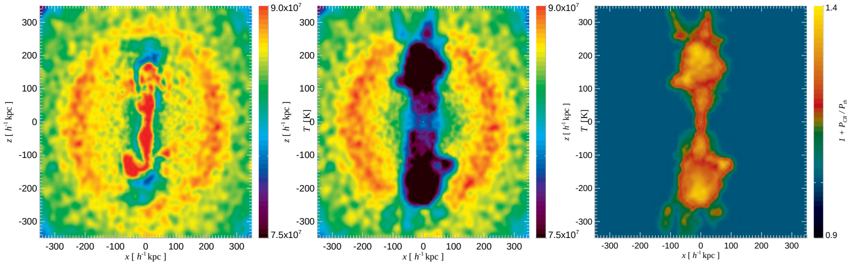
$\langle T \rangle_M$: with CRs

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

Sijacki, Pfrommer, Springel, Enßlin (2008)

CR feedback by AGN in galaxy clusters

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



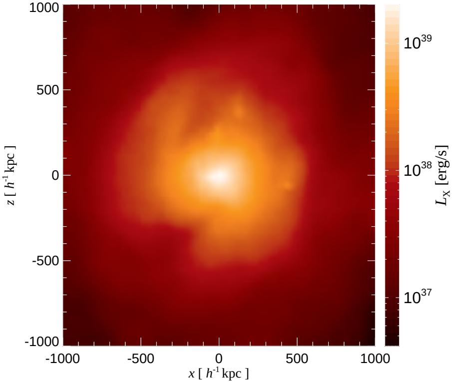
$\langle T \rangle_M$: without CRs

$\langle T \rangle_M$: with CRs

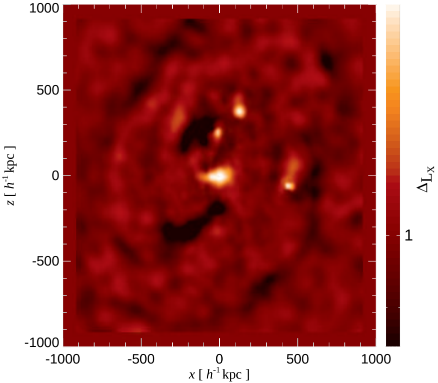
$1 + P_{\mathrm{CR}}/P_{\mathrm{th}}$

→ bubble dynamics, coherence and maximum cluster-centric distance reached are affected by the presence of a relativistic component filling the bubbles! (Sijacki, Pfrommer, Springel, Enßlin 2008)

CR feedback by AGN in cosmological galaxy clusters



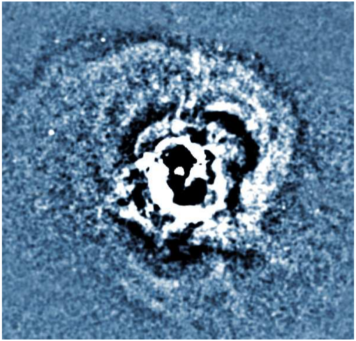
X-ray brightness S_X, Virgo-like cluster

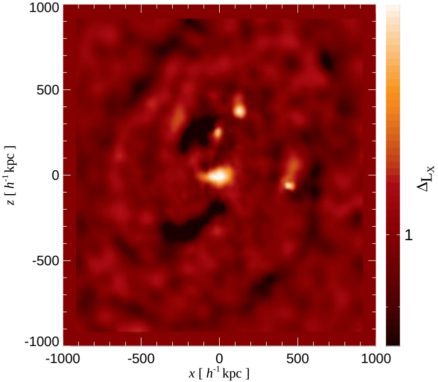


unsharp masked image ΔS_X

Sijacki, Pfrommer, Springel, Enßlin (2008)

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, Pfrommer, Springel, Enßlin (2008)

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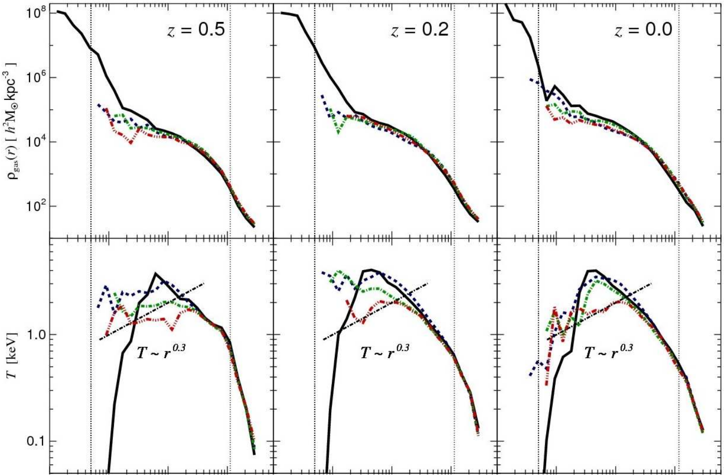
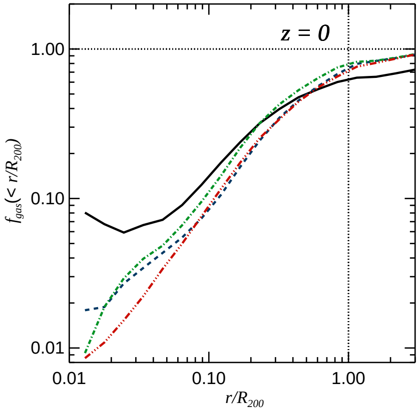
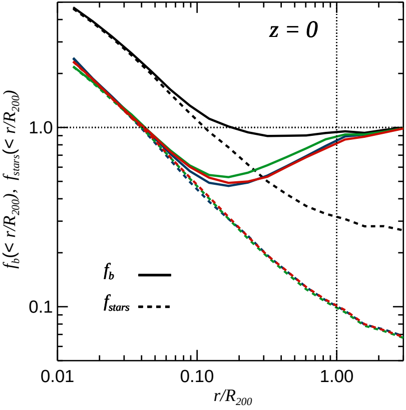
CR feedback by AGN: profiles of ρ and T



Sijacki, Pfrommer, Springel, Enßlin (2008)

CR feedback by AGN: gas and baryon fraction





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

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Conclusions

There is exciting and interesting physics in clusters (nature of dark matter, AGN, CRs, magnetic fields, MHD turbulence, plasma instabilities, transport processes, . . .):

- For precision cosmology with clusters, we have to (1) understand these effects sufficiently well, or (2) parametrize them to marginalize over the unknowns.
- We can learn fundamental plasma physics (CR acceleration, large scale magnetic fields, and turbulence), accretion and jet physics.

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