Non-thermal processes in galaxy clusters (1)

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Canadian Institute for Theoretical Astrophysics, Canada

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Plan of the lectures

- Thermal plasma in clusters: simulations, observables
- Cosmic rays: acceleration, transport, cooling
- Magnetic fields: generation, transport, MHD turbulence
- Non-thermal radiative processes in clusters

Emphasis on theory, simulations with a connection to observations.

`www.cita.utoronto.ca/~pfrommer/Talks`

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Outline

1. Thermal plasma in galaxy clusters
    - Introduction and simulations
    - Structure formation shock waves
    - Thermal cluster observables
2. Cosmic rays in galaxy clusters
    - Cosmic ray physics
    - Simulating cosmic rays
    - Particle acceleration processes

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Outline

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Dynamical picture of cluster formation

- structure formation in the ΛCDM universe predicts the hierarchical build-up of dark matter halos from small scales to successively larger scales
- clusters of galaxies currently sit atop this hierarchy as the largest objects that have had time to collapse under the influence of their own gravity
- cluster are dynamically evolving systems that have not finished forming and equilibrating, $\tau_{\text{dyn}} \sim 1$ Gyr

→ two extreme dynamical states of galaxy clusters: **merging clusters** and **cool core clusters**, which are relaxed systems where the central gas develops a dense cooling core due to the short thermal cooling times

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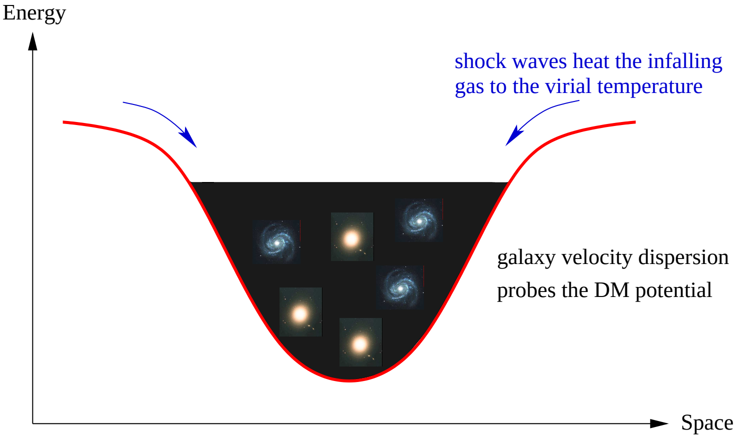
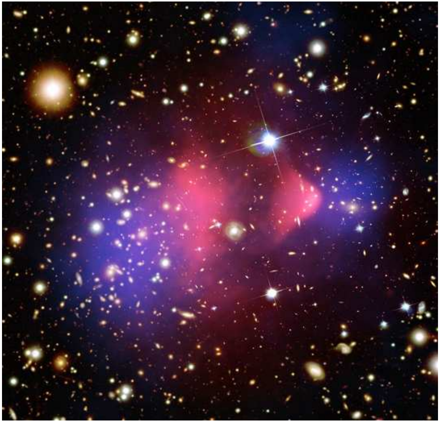
A theorist's perspective of a galaxy cluster . . .

Galaxy clusters are dynamically evolving dark matter potential wells:

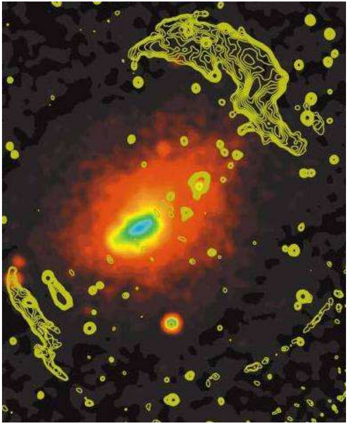


. . . and how the observer's Universe looks like



1E 0657-56 (“Bullet cluster”)

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



Abell 3667

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

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Numerically modeling clusters – Dark matter (DM)

- Non-interacting DM is described by the collisionless Boltzmann equation coupled to the Poisson equation in an expanding background Universe:

  $$\frac{\mathrm{d}}{\mathrm{d}t} f(\boldsymbol{r},\boldsymbol{v},t) \equiv \dot{f} + (\boldsymbol{v}\nabla)f - \nabla\Phi\nabla_{\boldsymbol{v}} f = 0,$$

  $$\nabla^2\Phi(\boldsymbol{r},t) = 4\pi G \int f(\boldsymbol{r},\boldsymbol{v},t)\mathrm{d}\boldsymbol{v},$$

  $f(\boldsymbol{r},\boldsymbol{v},t)$ denotes the distribution function in phase space.
- *N-body simulations* are particularly suited to solve these equations since phase space density is sampled by a large number N of tracer particles which are integrated along characteristic curves of the collisionless Boltzmann equation. The accuracy of this approach depends on a sufficiently high number of particles.

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Numerically modeling clusters – gas (1)

WMAP-5y: $\frac{\Omega_b}{\Omega_m} = 0.165$: why bothering about the gas?

- Gas has different dynamics compared to collisionless fluid:
  - Gas can shock and convert bulk kinetic energy into thermal energy.
  - Gas pressure is isotropic; hence gas can not have anisotropic support.
  - Gas flows can not interpenetrate.
- Gas can cool or heat through radiative processes.
- We observe gas directly!

→ In the simplest form, the intra-cluster medium (ICM) is modeled as an ideal inviscid gas which is coupled to dark matter through its gravitational interaction.

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Numerically modeling clusters – gas (2)

- 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:

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

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

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

  $\Lambda(u,\rho)$ 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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Numerically modeling clusters – gas (3)

- Cluster are dynamically evolving, non-linear objects → requires 3D simulations of the hydrodynamics coupled with N-body techniques for the DM.
- Numerical discretization requires compromises to solve for the hydrodynamics:
  1) Discretizing space to calculate fluid properties on regular grid of points using finite differences → Eulerian approach: adaptive mesh refinement (AMR) simulations
  2) Discretizing mass to model the fluid as a collection of fluid elements represented by N particles → Lagrangian approach: smoothed particle hydrodynamics (SPH) simulations
- Each method has its drawbacks and limitations → choose the better suited method for the problem under consideration!
- None of these methods is ‘better’ or superior over the other!

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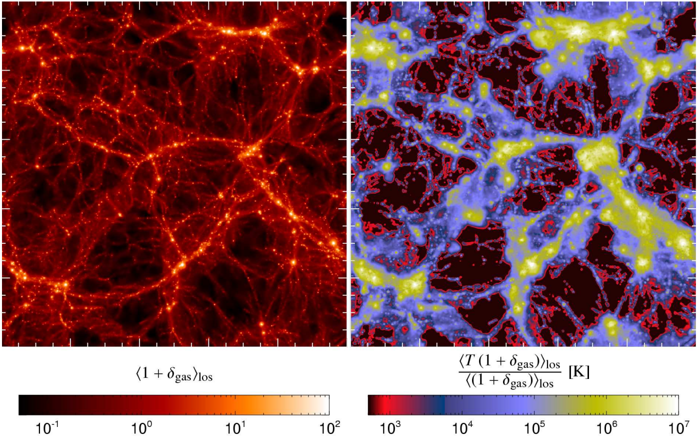
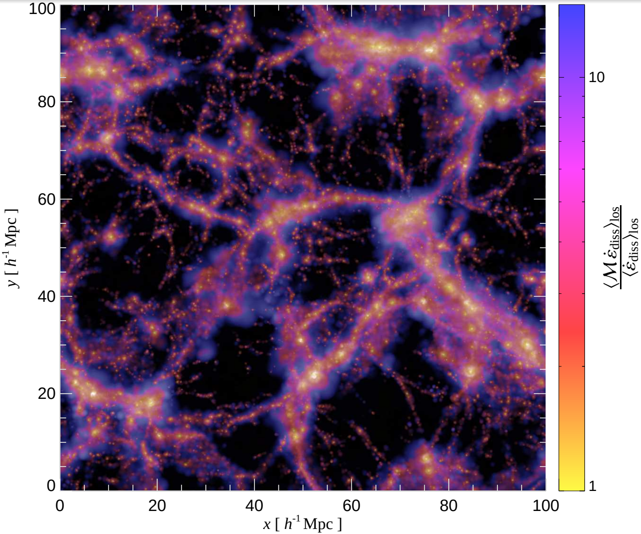
Gravitational heating by shocks



The "cosmic web" today. *Left:* the projected gas density in a cosmological simulation. *Right:* gravitationally heated intra-cluster medium through cosmological shock waves.

Cosmological Mach numbers: weighted by $\varepsilon_{\mathrm{diss}}$



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Volume rendered shock surfaces

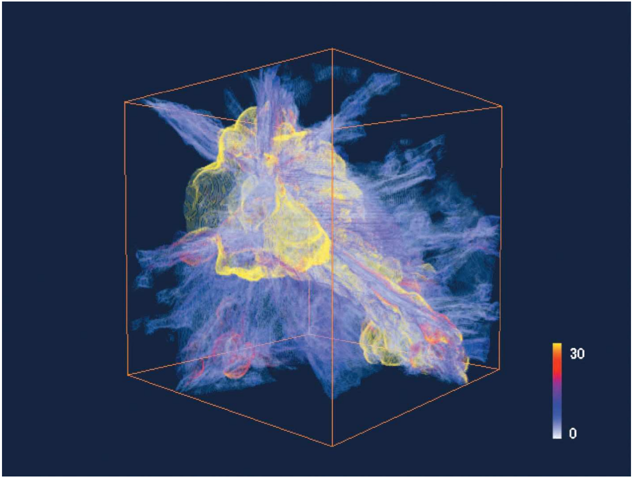
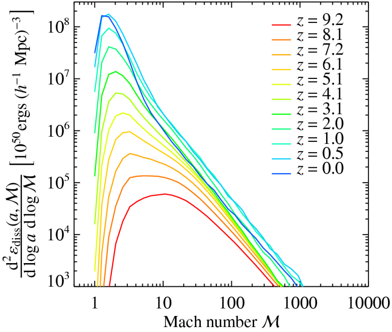


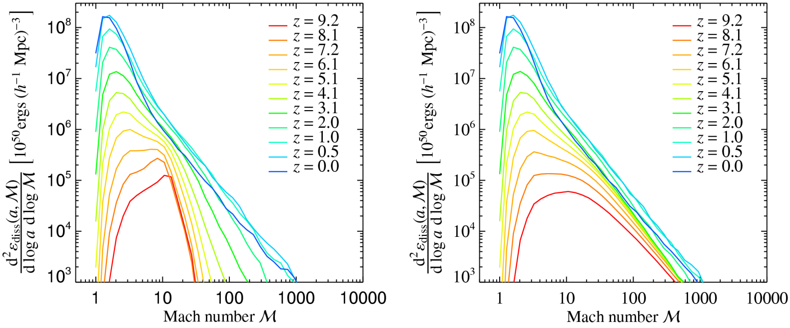
Figure: from Ryu et al. (2003)

Cosmological Mach number statistics



- more energy is dissipated in weak shocks internal to collapsed structures than in external strong shocks
- more energy is dissipated at later times
- mean Mach number decreases with time

Cosmological statistics: influence of reionization



- re-ionisation epoch at $z_{\mathrm{reion}} = 10$ suppresses efficiently strong shocks at $z < z_{\mathrm{reion}}$ due to jump in sound velocity
- cosmological constant causes structure formation to cease

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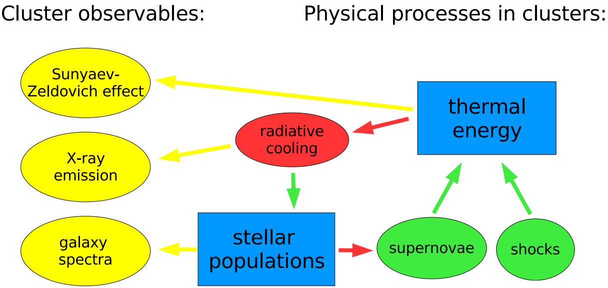
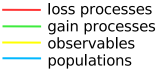
Radiative processes in simulations – flowchart





Cluster scaling relations

- Observable-mass relations are one of the key ingredients for deriving cosmological constraints using upcoming large cluster surveys.
- X-ray and SZE observable-mass relations ($\Delta = 200$):

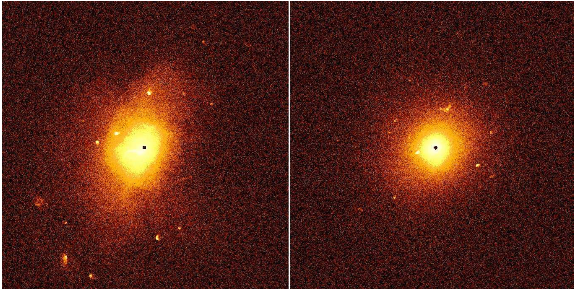
$$\begin{aligned} T_\text{gas} &\propto M_\Delta / R_\Delta \propto M_\Delta^{2/3}\, E(z)^{2/3}, \\ SZ\ flux &\propto \int P_\text{gas}\, \mathrm{d}l\, \mathrm{d}\Omega \propto f_\text{gas}\, M_\Delta^{5/3}\, E(z)^{-2/3}, \end{aligned}$$

using $M_\Delta \equiv (4\pi/3)\, R_\Delta^3 \Delta\, \rho_\text{crit}(z)$, $E(z) \equiv H(z)/H_0$

- Questions:
  How does galaxy formation affect global cluster properties?
  How do simulations compare to observations?

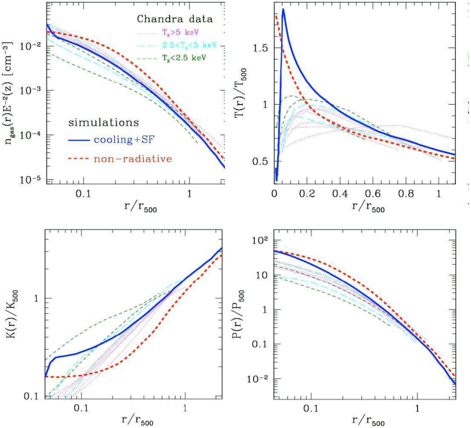
Chandra mock observations

- Generate ‘Chandra data’ for clusters from high-resolution simulations and reduce with real data analysis pipeline (Rasia et al. 2005, Nagai et al. 2006)
- Results:
  $\longrightarrow$ hydrostatic mass biased low at R_{500} due to turbulent pressure
  $\longrightarrow$ temperatures accurate to $\sim 10\%$



unrelaxed versus relaxed cluster (Nagai, Kravtsov, & Vikhlinin 2006)

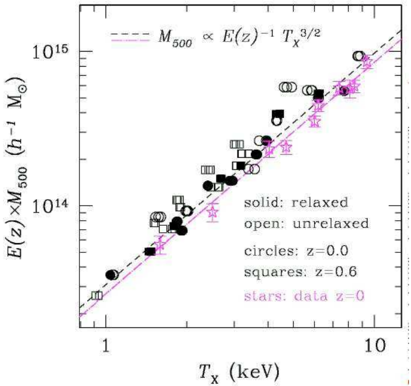
Profiles of the intra-cluster medium

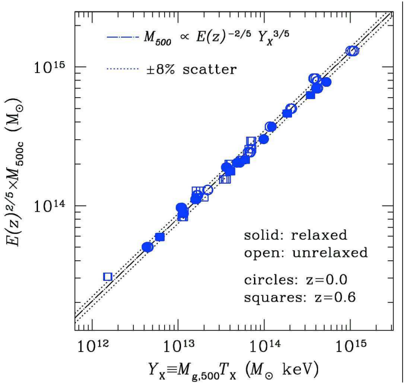


- red line: mean profile for relaxed clusters in non-radiative simulations
- blue band: mean profile for relaxed clusters in simulations with cooling and star formation
- thin dashed lines: profiles of Chandra clusters of different temperatures

  (Nagai, Kravtsov, & Vikhlinin 2006)

X-ray scaling relations





Scatter in $M - T_X$ is $\sim$ 20% in mass at a given T_X (driven by unrelaxed systems).

Scatter in $M - Y_X$ is $\sim$ 8% $\longrightarrow$ why is there an anti-correlation between $M_{\mathrm{gas},500}$ and T_X?

Problems

Current Lagrangian (SPH) as well as Adaptive Eulerian (AMR) approaches face the same problems → lack of our physical understanding

- over-cooled cluster core regions out to $r \simeq 0.2\, R_{200}$
- too numerous gaseous substructures
- external regions: non-thermal pressure support (CRs, turbulence)
- influence of the clusters dynamical state on the scaling properties (especially the nature of the scatter)

Cluster self-calibration in its most general approach won't allow us to improve on statistical uncertainties of cosmological parameters.

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Solution

Hybrid self-calibration:

- Combining thermal and non-thermal observables simultaneously in observation space to solve for the virial mass.
- Imposing Bayesian priors on the functional properties of the scaling relations and the non-cosmological redshift evolution derived from hydrodynamical simulations.

→ cosmological motivation to study and understand feedback processes

Outline

Why should we care about cosmic rays in clusters?

It allows us to explore complementary windows to cluster cosmology

1. Is high-precision cosmology possible using clusters?
    - Non-equilibrium processes such as cosmic ray pressure and turbulence possibly modify thermal X-ray emission and Sunyaev-Zel'dovich effect.
    - Cosmic ray pressure can modify the scaling relations → bias of cosmological parameters, or increase of the uncertainties if we marginalize over the 'unknown cluster physics' (cluster self-calibration)
2. What can we learn from non-thermal cluster emission?
    - Estimating the cosmic ray pressure contribution.
    - Constructing a 'gold sample' for cosmology using orthogonal information on the dynamical cluster activity.
    - Fundamental physics: diffusive shock acceleration, large scale magnetic fields, and turbulence.

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Quasilinear theory for cosmic ray transport (1)

Starting point: relativistic Vlasov equation for a particle population described by its distribution function, $f(t, \boldsymbol{x}, \boldsymbol{p})$ and the equations of motion:

$$\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \nabla f + \dot{\boldsymbol{p}} \cdot \nabla_p t = s(t, \boldsymbol{x}, \boldsymbol{p}),$$

$$\dot{\boldsymbol{p}} = q \left[\boldsymbol{E}(\boldsymbol{x}, t) + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B}(\boldsymbol{x}, t) \right],$$

$$\dot{\boldsymbol{x}} = \boldsymbol{v} = \frac{\boldsymbol{p}}{\gamma m},$$

s denotes sources/sinks of particles.

→ particles in a collisionless plasma interact with collective electromagnetic forces and waves!

Quasilinear theory for cosmic ray transport (2)

Fokker-Planck equation describes the transport of the isotropic part of the comic ray distribution $F(x, p, t)$, assuming weak anisotropy:

$$\frac{\partial}{\partial t} F - s(x,p,t) = \frac{\partial}{\partial z}\left[D_{\|}(x,p)\frac{\partial}{\partial x}F - uF\right] - \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\Gamma(x,p)\frac{\partial}{\partial p}F + \frac{p^3}{3}\frac{\partial u}{\partial x}F - p^2\dot{p}\,F\right] - \frac{F}{T_{\mathrm{c}}}$$

rhs: spatial diffusion and advection, momentum diffusion (Fermi II), momentum advection (Fermi I), continuous and catastrophic loss processes.

def: x along the mean magnetic field, $u = u(x, p, t)$ is the CR bulk speed, $D_{\|}$ and Γ are the spatial/momentum diffusion coefficients.

CR protons vs. CR electrons

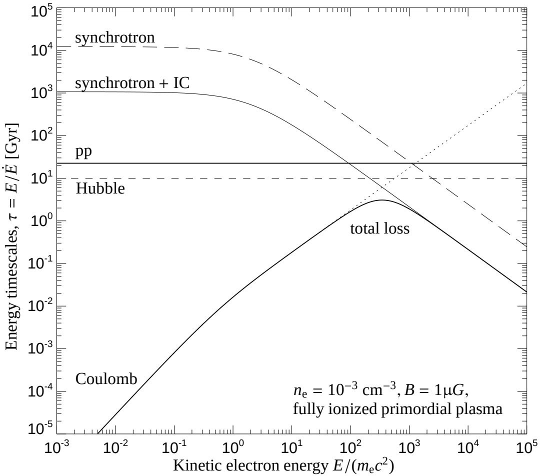
CR protons:

- acceleration by shocks, MHD wave interactions
- can potentially provide substantial pressure support → hydrodynamic interaction with gas, modified shocks
- radiative losses negligible – suppressed by $(m_\mathrm{e}/m_\mathrm{p})^2$,
- Coulomb/MHD wave interactions → modifies thermal gas content

CR electrons:

- acceleration by shocks, MHD wave interactions, hadronic injection
- negligible pressure support
- radiative losses important: we can observe them!

Cooling time scales of CR electrons



Equilibrium distribution of CR electrons

- CR electron injection balances IC/synchrotron cooling:
$$\frac{\partial}{\partial E_\mathrm{e}}\left[\dot{E}_\mathrm{e}(E_\mathrm{e}) f_\mathrm{e}(E_\mathrm{e})\right] = s_\mathrm{e}(E_\mathrm{e})\,.$$
- For $\dot{E}_\mathrm{e}(p) < 0$, this equation is solved by
$$f_\mathrm{e}(E_\mathrm{e}) = \frac{1}{|\dot{E}_\mathrm{e}(E_\mathrm{e})|}\int_{E_\mathrm{e}}^{\infty} \mathrm{d}E_\mathrm{e}'\, s_\mathrm{e}(E_\mathrm{e}')\,.$$
- At high energies, IC/synchrotron losses dominate:
$$-\dot{E}_\mathrm{e}(E_\mathrm{e}) = \frac{4\,\sigma_\mathrm{T}\,c}{3\,m_\mathrm{e}^2\,c^4}\left[\varepsilon_B + \varepsilon_\mathrm{ph}\right]\,E_\mathrm{e}^2.$$
- CR electrons can either be produced by structure formation shocks, or in hadronic CR proton interactions → source function s_e.

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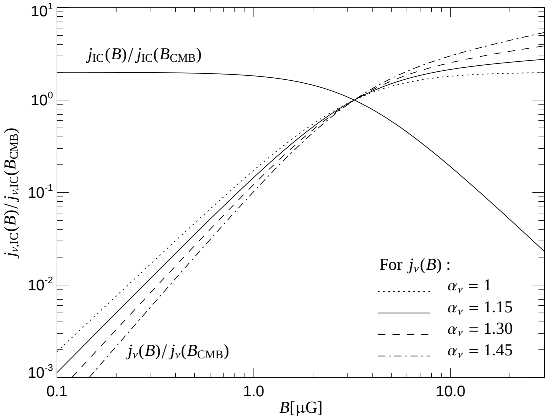
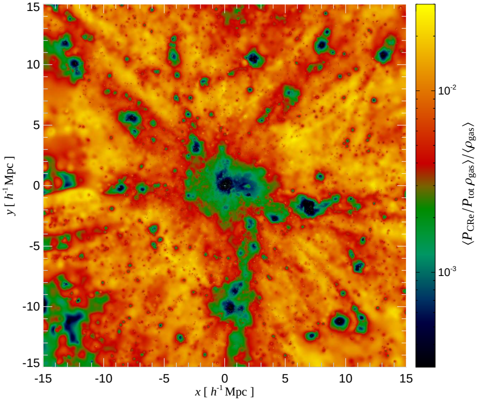
Synchrotron versus IC emissivity



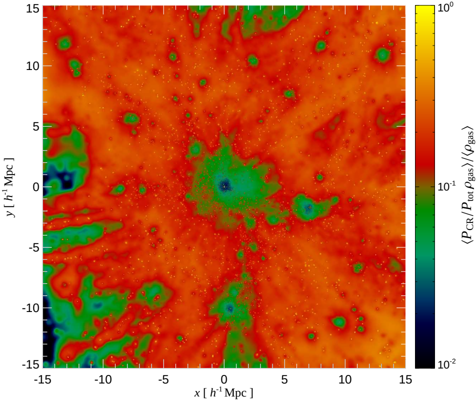
IC cooling regime: leftwards of $B_{\mathrm{CMB}} \simeq 3.2\,(1+z)^2\;\mu\mathrm{G}$,

synchrotron cooling regime: rightwards of B_{CMB}.

CR electron versus CR proton pressure



Relative pressure of primary CR electrons.



Relative pressure of CR protons.

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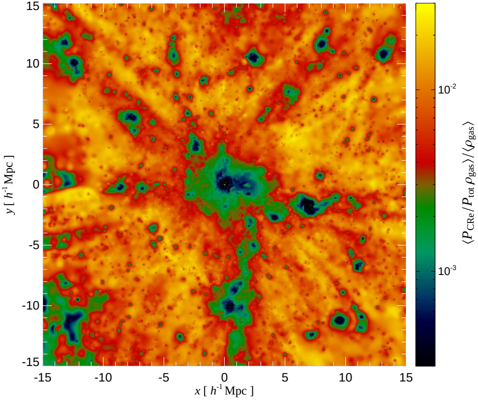
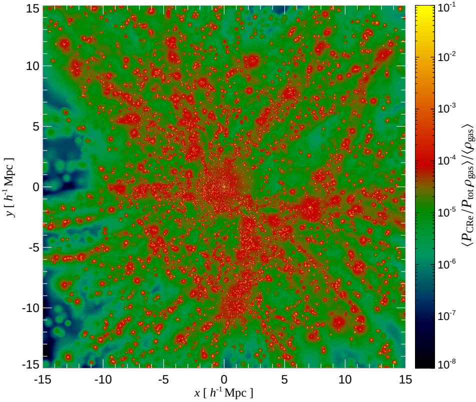
Primary versus secondary CR electrons



Relative pressure of *primary* CR electrons.



Rel. pressure of *secondary* CR electrons.

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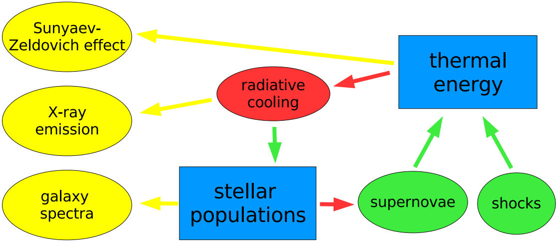
Radiative simulations – flowchart

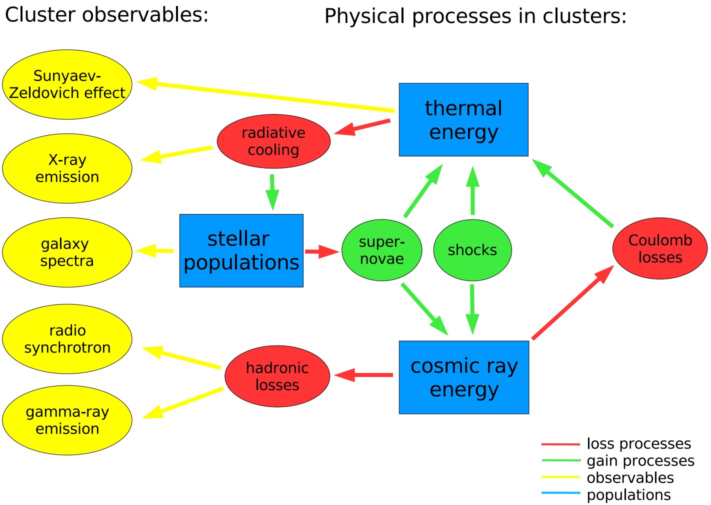
Cluster observables:

Physical processes in clusters:

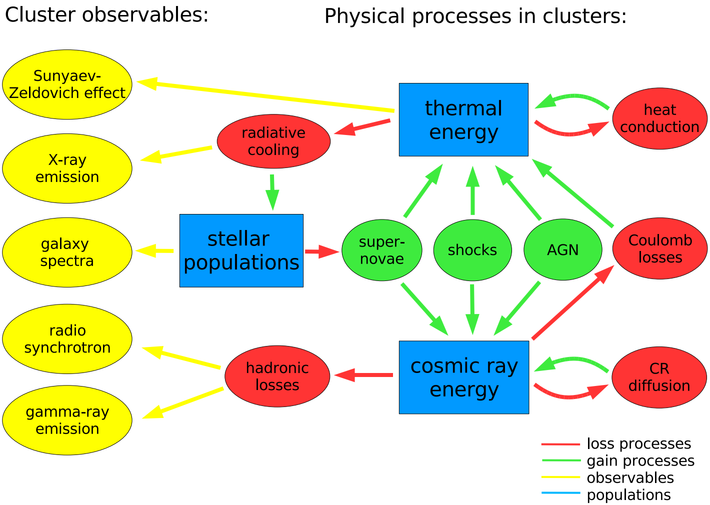


- 🟥 loss processes
- 🟩 gain processes
- 🟨 observables
- 🟦 populations

Radiative simulations with cosmic ray (CR) physics



Radiative simulations with extended CR physics



Philosophy and description

An accurate description of CRs should follow the evolution of the spectral energy distribution of CRs as a function of time and space, and keep track of their dynamical, non-linear coupling with the hydrodynamics.

We seek a compromise between

- capturing as many physical properties as possible
- requiring as little computational resources as necessary

Assumptions:

- protons dominate the CR population
- a momentum power-law is a typical spectrum
- CR energy & particle number conservation

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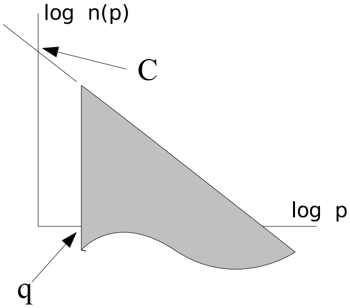
CR spectral description



$$p = P_\mathrm{p}/m_\mathrm{p}\, c$$

$$f(p) = \frac{dN}{dp\, dV} = C\, p^{-\alpha}\theta(p-q)$$

$$q(\rho) = \left(\frac{\rho}{\rho_0}\right)^{\frac{1}{3}} q_0$$

$$C(\rho) = \left(\frac{\rho}{\rho_0}\right)^{\frac{\alpha+2}{3}} C_0$$

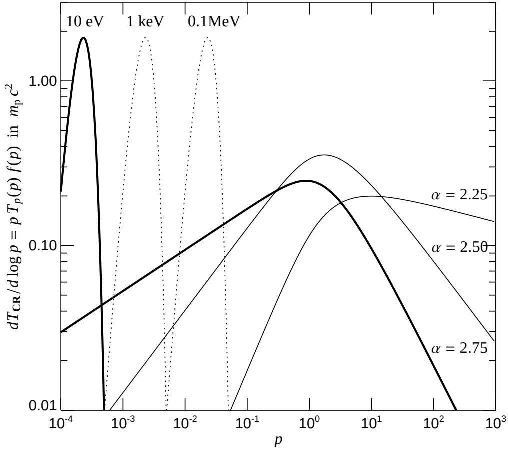
$$n_\mathrm{CR} = \int_0^\infty \mathrm{d}p\, f(p) = \frac{C\, q^{1-\alpha}}{\alpha-1}$$

$$P_\mathrm{CR} = \frac{m_\mathrm{p} c^2}{3}\int_0^\infty \mathrm{d}p\, f(p)\, \beta(p)\, p$$

$$= \frac{C\, m_\mathrm{p} c^2}{6}\, \mathcal{B}_{\frac{1}{1+q^2}}\left(\frac{\alpha-2}{2}, \frac{3-\alpha}{2}\right)$$

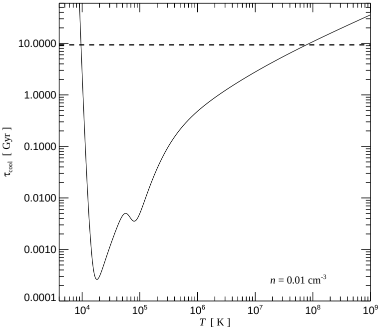
Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:

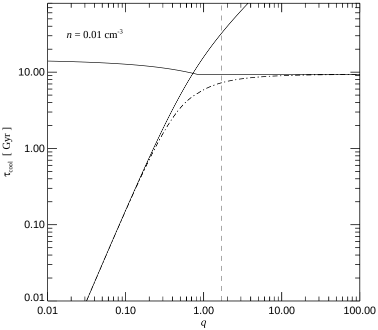


Cooling time scales of CR protons

Cooling of primordial gas:

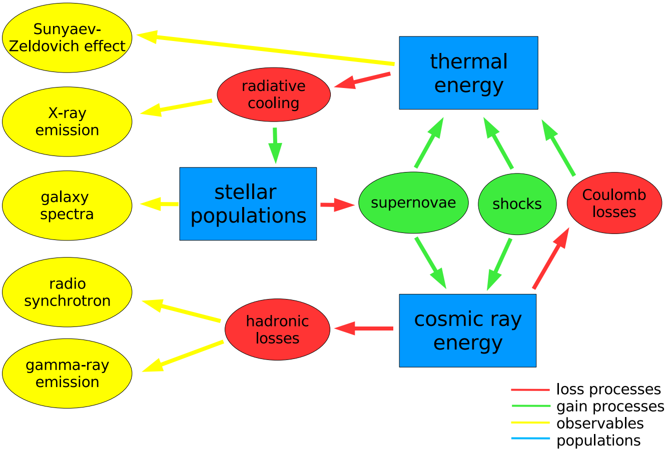


Cooling of cosmic rays:

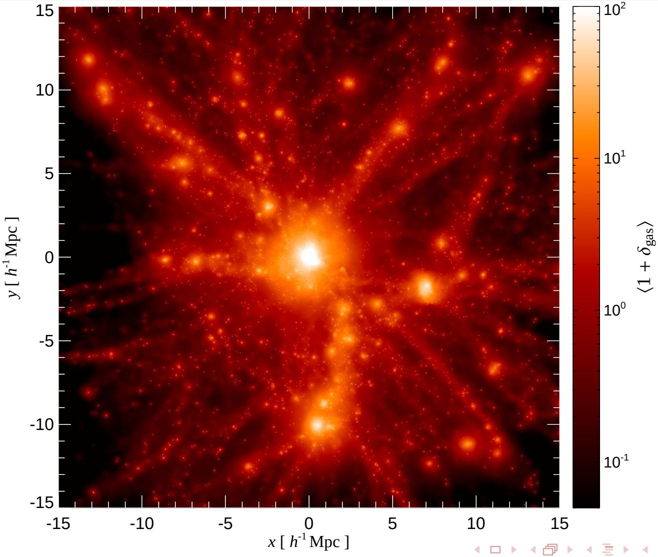


Radiative simulations with CR physics

Cluster observables: Physical processes in clusters:



Radiative cool core cluster simulation: gas density



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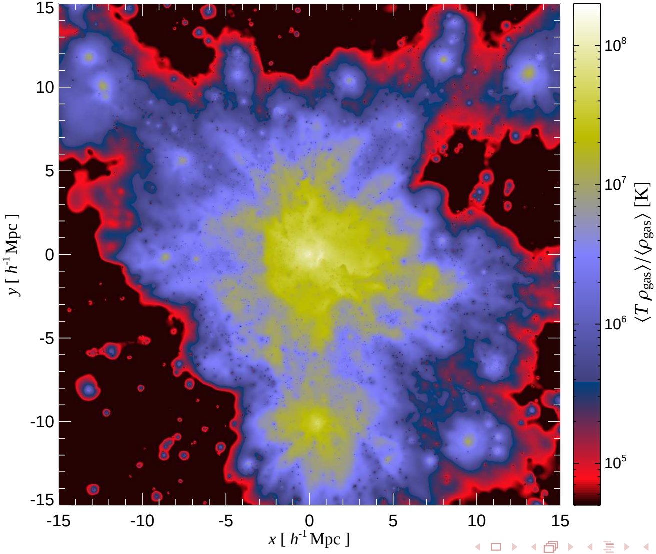
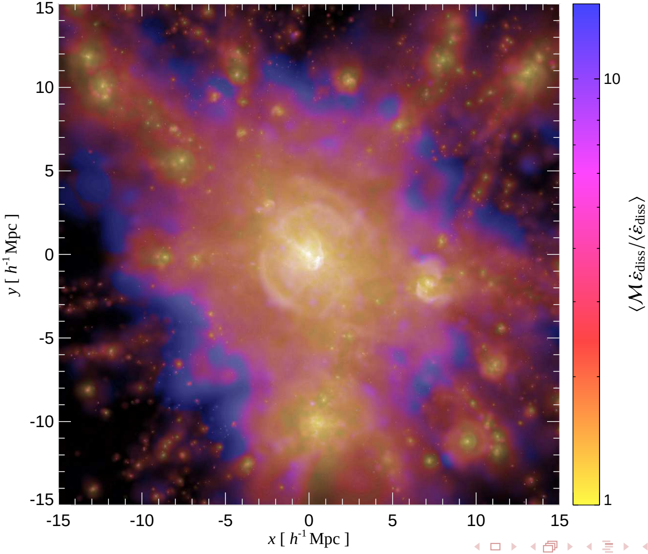
Mass weighted temperature



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



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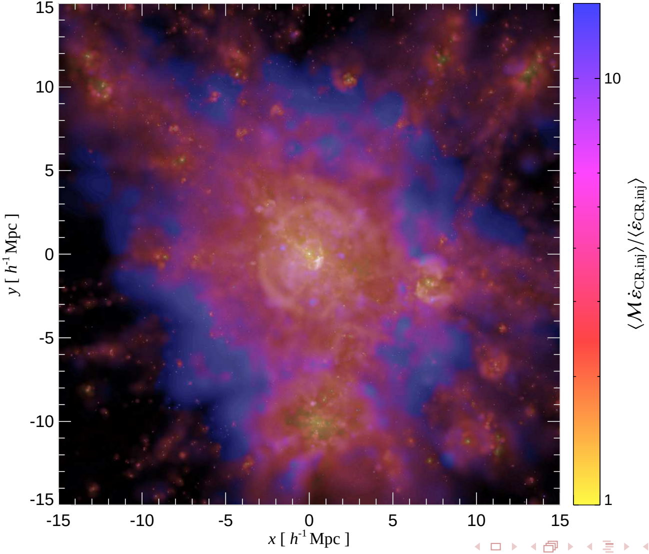
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



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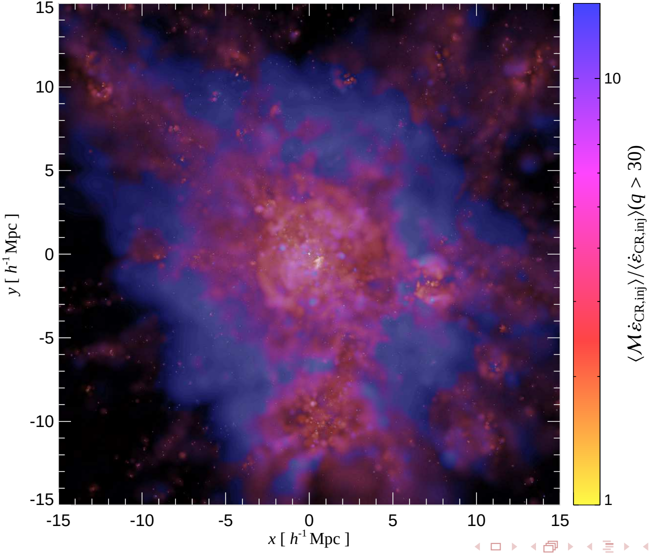
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}(q > 30)$



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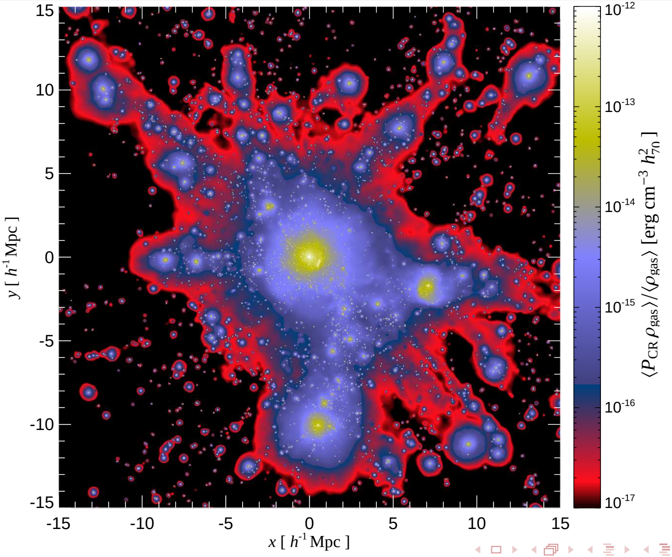
CR pressure P_{CR}



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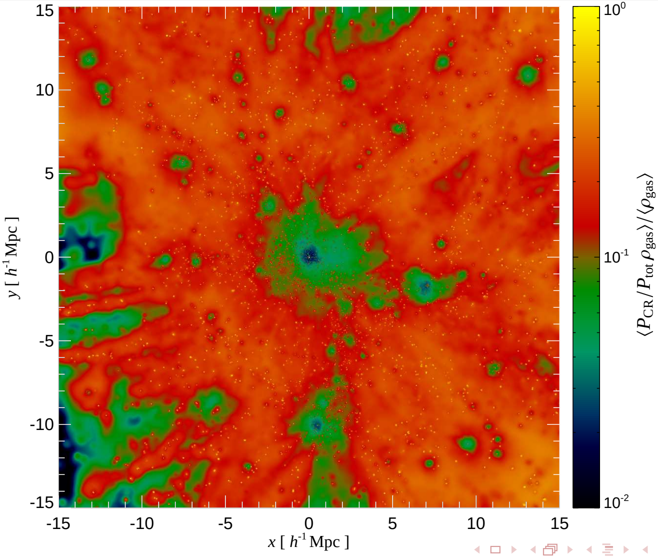
Relative CR pressure $P_{\mathrm{CR}}/P_{\mathrm{total}}$



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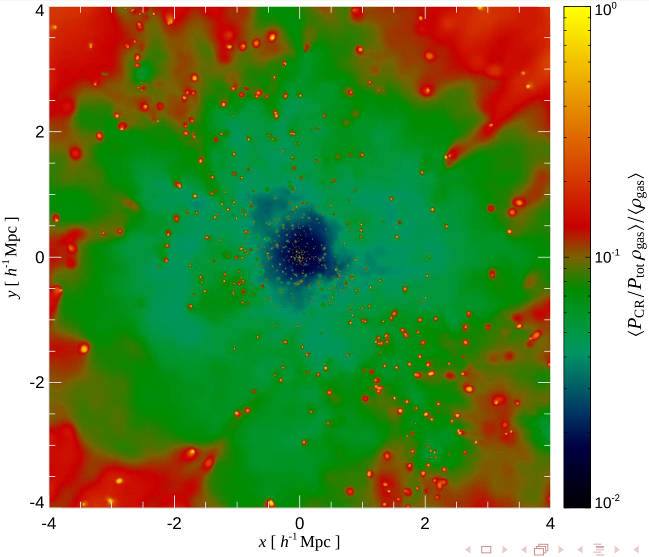

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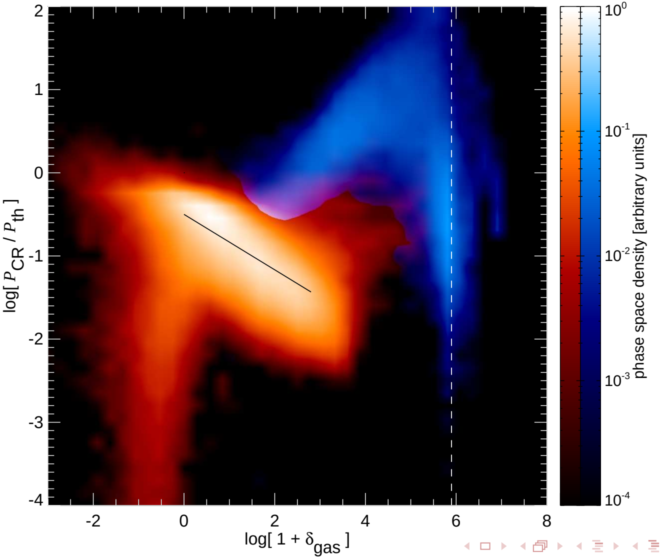
CR phase-space diagram: final distribution @ $z = 0$



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Outline

1. Thermal plasma in galaxy clusters
   - Introduction and simulations
   - Structure formation shock waves
   - Thermal cluster observables
2. Cosmic rays in galaxy clusters
   - Cosmic ray physics
   - Simulating cosmic rays
   - Particle acceleration processes

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Particle acceleration processes

particles are accelerated via:

- adiabatic compression
- diffusive shock acceleration (Fermi I)
- stochastic acceleration by plasma waves (Fermi II)
- particle reactions (pp $\to \pi \to \mu\nu \to e\nu\nu$)

particles are decelerated via:

- adiabatic expansion
- radiative cooling (synchrotron, inverse Compton, bremsstrahlung, hadronic interactions)
- non-radiative cooling (Coulomb interactions)

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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 the macroscopic scattering agents
- momentum increases exponential with number of shock crossings
- number of particles decreases exponential with number of crossings

→ power-law CR distribution

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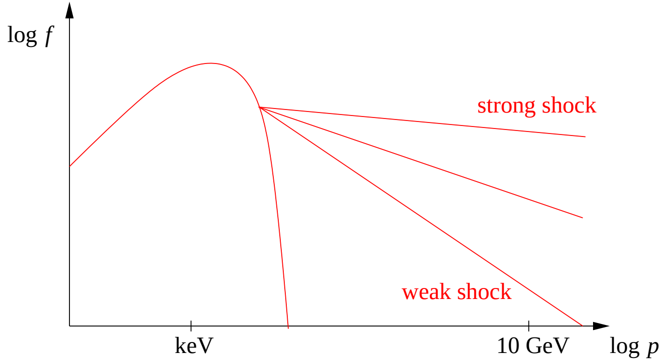
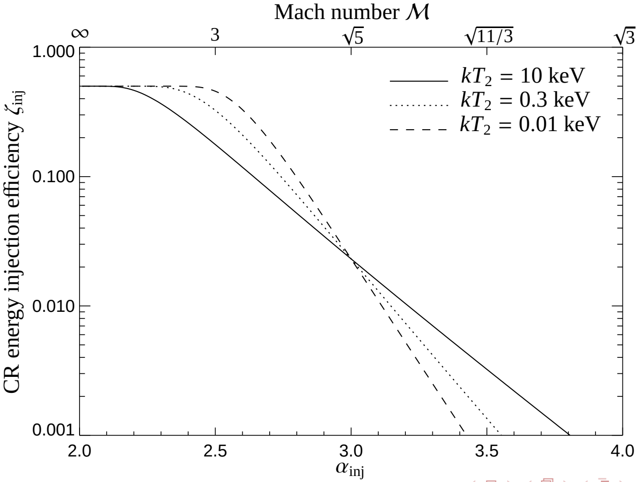
Diffusive shock acceleration – Fermi 1 mechanism (2)

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, $\zeta_{\text{inj}} = \varepsilon_{\text{CR}}/\varepsilon_{\text{diss}}$:



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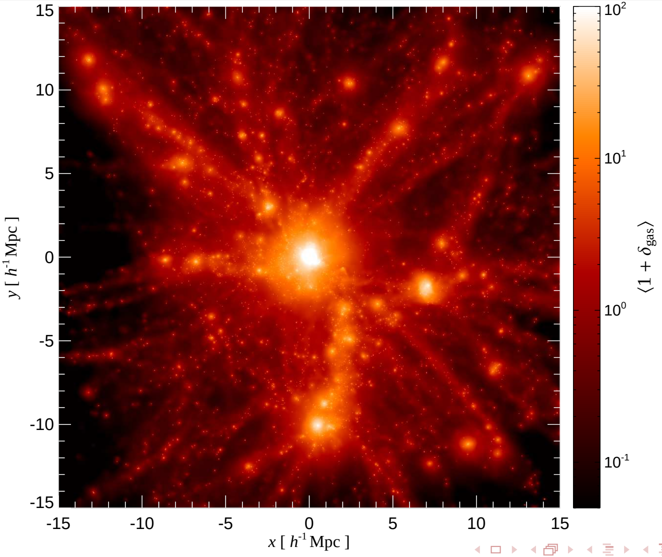
Radiative cool core cluster simulation: gas density



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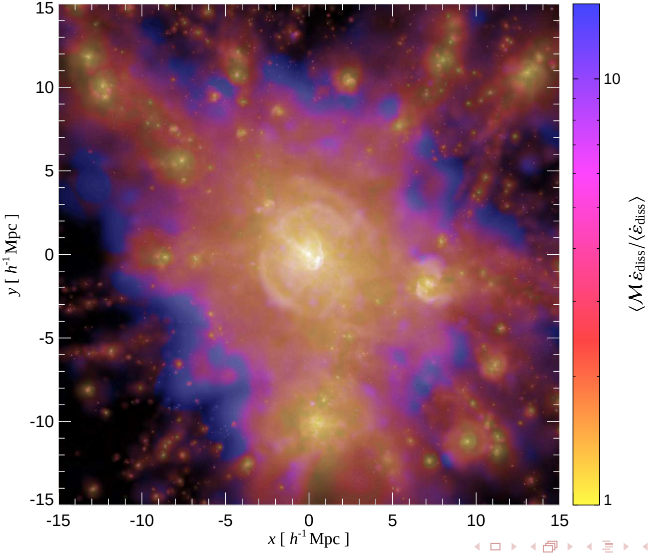
Cosmic web: Mach number



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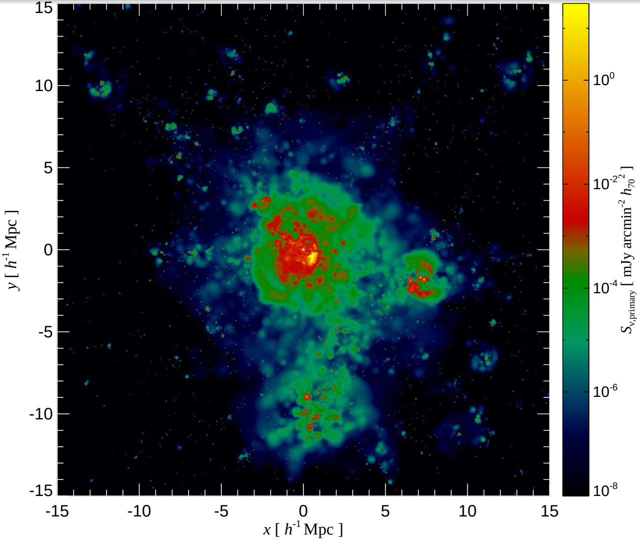
Radio web: primary CRe (1.4 GHz)



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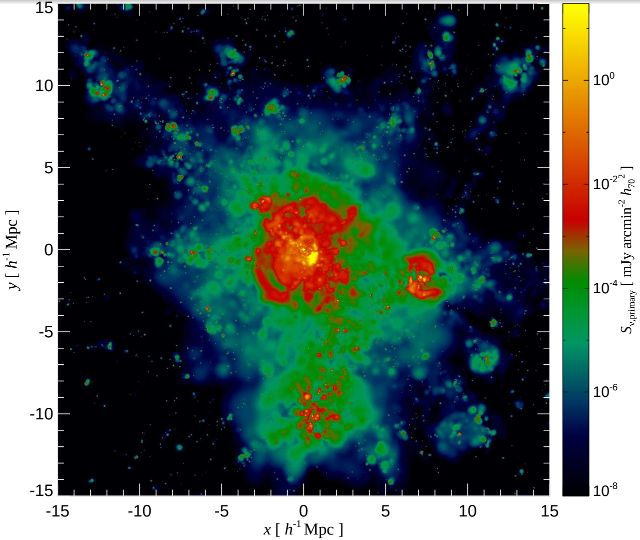
Radio web: primary CRe (150 MHz)



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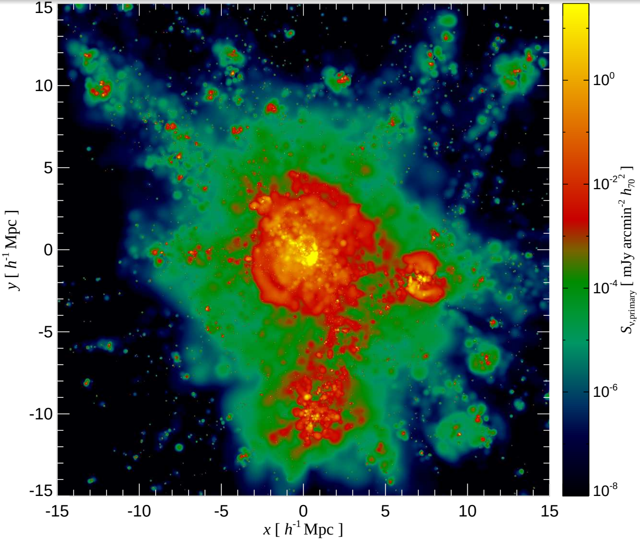
Radio web: primary CRe (15 MHz)



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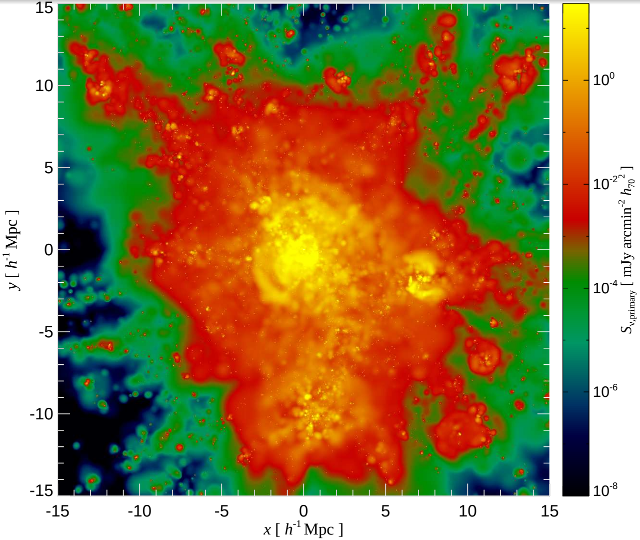
Radio web: primary CRe (15 MHz), slower magnetic decline



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Stochastic acceleration: recipe (1)

conditions:

- super-thermal or better relativistic particles
- magnetic fields to confine them
- high level of plasma waves to scatter them via gyro-resonances

mechanism:

- head on wave-particle collision energises particle
- tail on wave-particle collision de-energise particle
- statistically more head-on than tail-on collisions

→ net energy gain due to diffusion in momentum space
advantage: plasma waves are everywhere!

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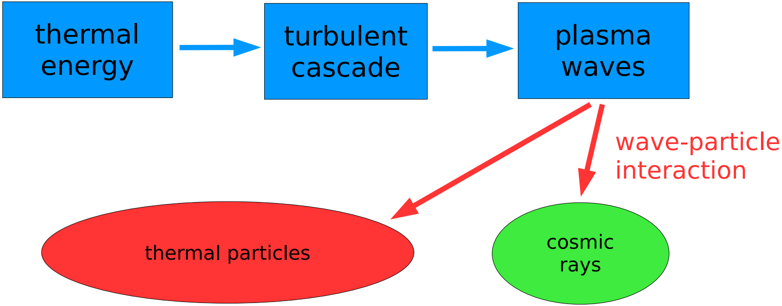
Stochastic acceleration: cartoon (2)


thermal energy

turbulent cascade

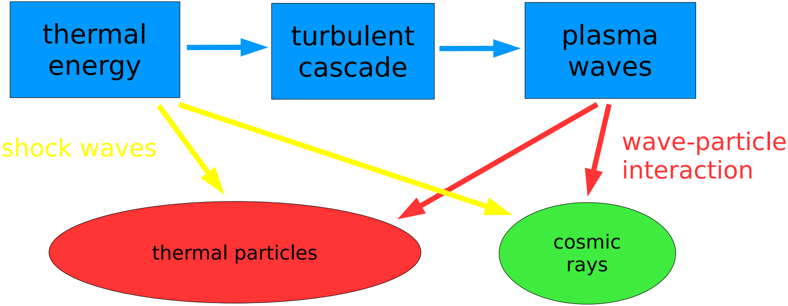
plasma waves

wave-particle interaction

thermal particles

cosmic rays

Stochastic acceleration: cartoon (2)



Stochastic acceleration: problems (3)

problems:

- low efficiency (2^{nd} order in ratio of wave to particle velocity)
- waves like to cascade to small scales
- small-scale waves dissipate into the thermal pool
- wave energy budget is usually tight
- at locations with high wave density (e.g. shocks), more efficient acceleration mechanism may be in operation (e.g. DSA)

Particle reactions

relativistic proton populations can often be expected, since

- acceleration mechanisms work for protons . . .
    - . . . as efficient as for electrons (adiabatic compression) or
    - . . . more efficient than for electrons (DSA, stochastic acc.)
- galactic CR protons are observed to have 100 times higher energy density than electrons
- CR protons are very inert against radiative losses and therefore long-lived ($\sim$ Hubble time in galaxy clusters, longer outside)

$\longrightarrow$ an energetic CR proton population should exist in clusters

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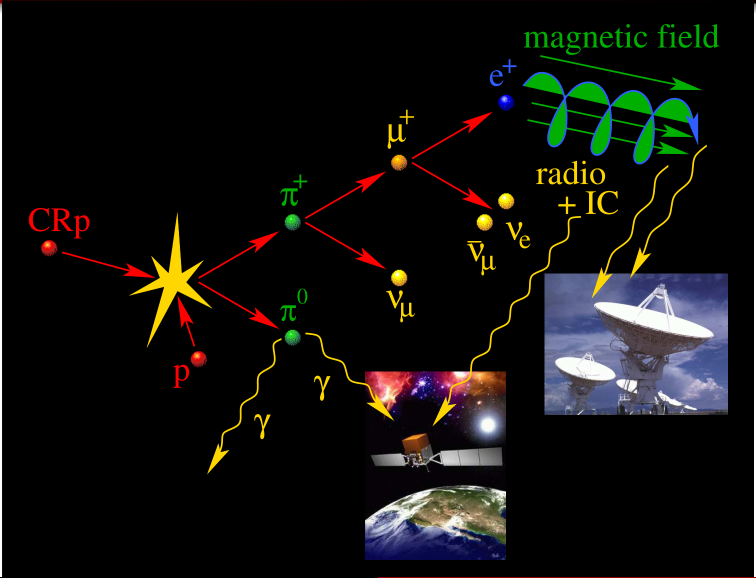
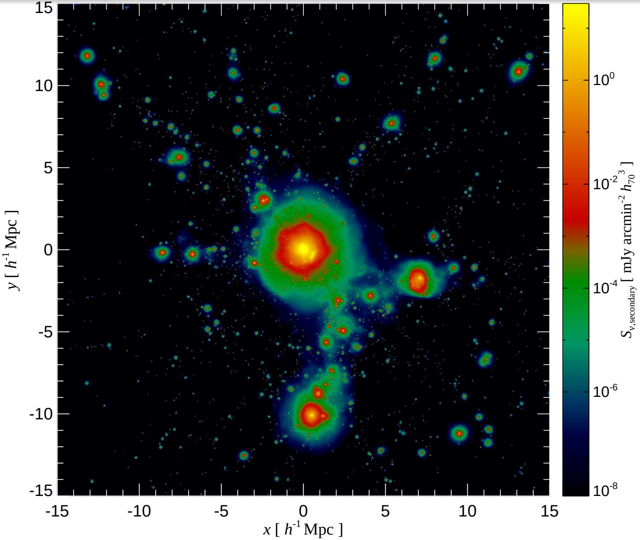
Hadronic cosmic ray proton interaction



Cluster radio emission by hadronically produced CRe



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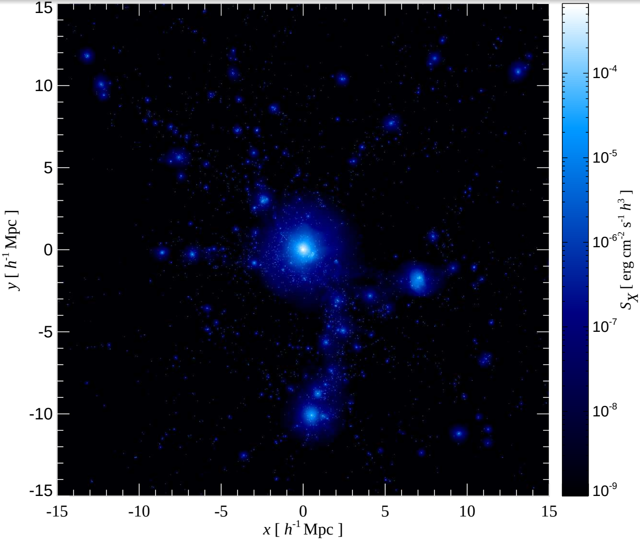
Thermal X-ray emission



Literature for the CR part of the lectures

- 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, and 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, and Jubelgas, 2007, A&A, 473, 41, *Cosmic ray physics in calculations of cosmological structure formation*
- Jubelgas, Springel, Enßlin, and Pfrommer, A&A, in print, astro-ph/0603485, *Cosmic ray feedback in hydrodynamical simulations of galaxy formation*