# Cosmic ray feedback in hydrodynamical simulations of galaxy and cluster formation

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in collaboration with

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*Cosmic Frontiers*, Durham University

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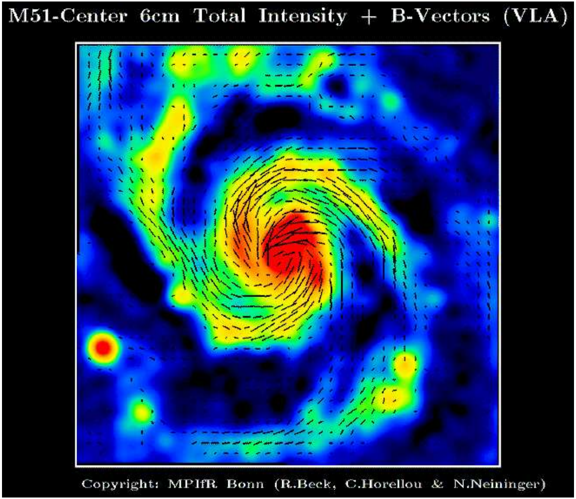
# Outline

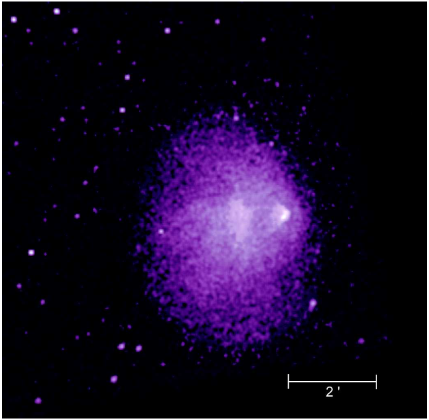
1. Motivation and introduction
   - Cosmic rays in galaxies and clusters
   - Cosmic rays in GADGET
2. Cosmic rays and galaxy formation
   - Cosmic rays in isolated galaxies
   - Dwarf galaxy formation
3. Cosmic rays in galaxy clusters
   - Radiative high-resolution cluster simulations
   - Enhanced X-ray emission
   - Modified Sunyaev-Zel'dovic effect

# M51: cosmic ray electron population



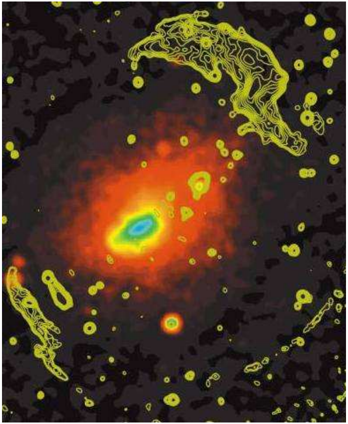

Fletcher, Beck, Berkhuijsen und Horellou, in prep.

# Observations of cluster shock waves




1E 0657-56 (“Bullet cluster”)

(NASA/SAO/CXC/M.Markevitch et al.)



Abell 3667

(Radio: Austr.TC Array. X-ray: ROSAT/PSPC.)

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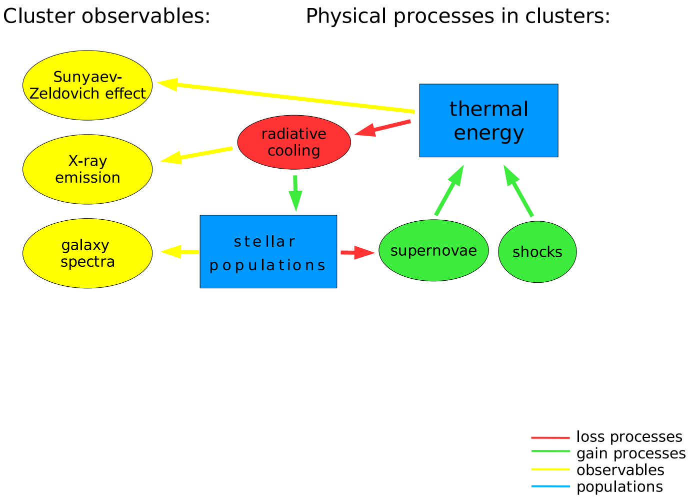
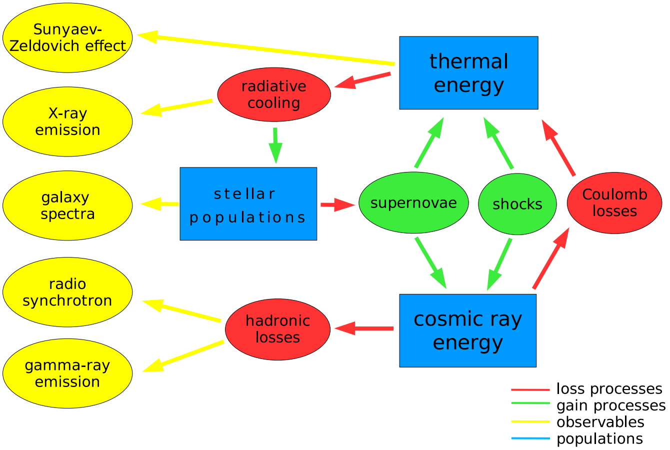
# Radiative simulations – flowchart



# Radiative simulations with cosmic rays

Cluster observables: Physical processes in clusters:



# 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 possible

**Assumptions:**

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

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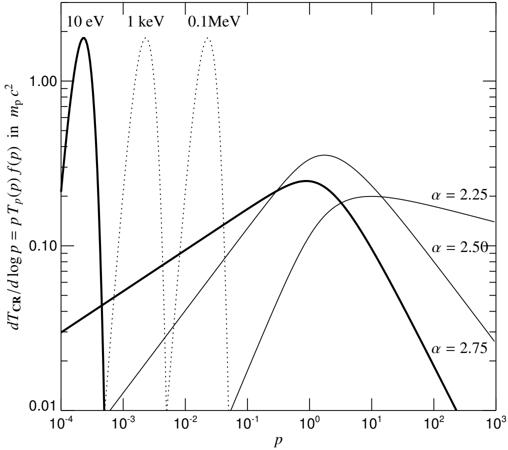
# Thermal & CR energy spectra

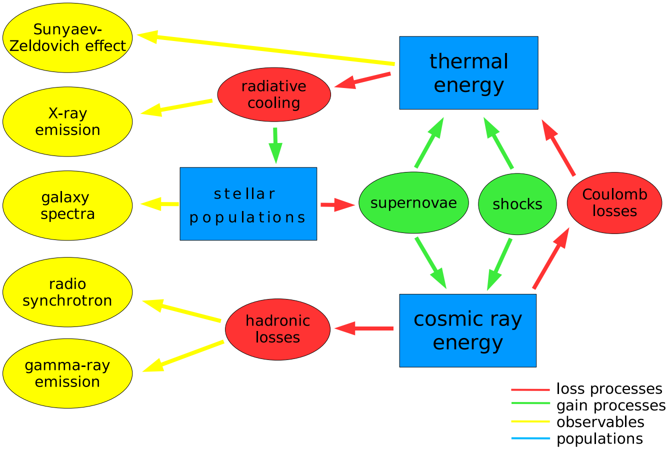
Kinetic energy per logarithmic momentum interval:



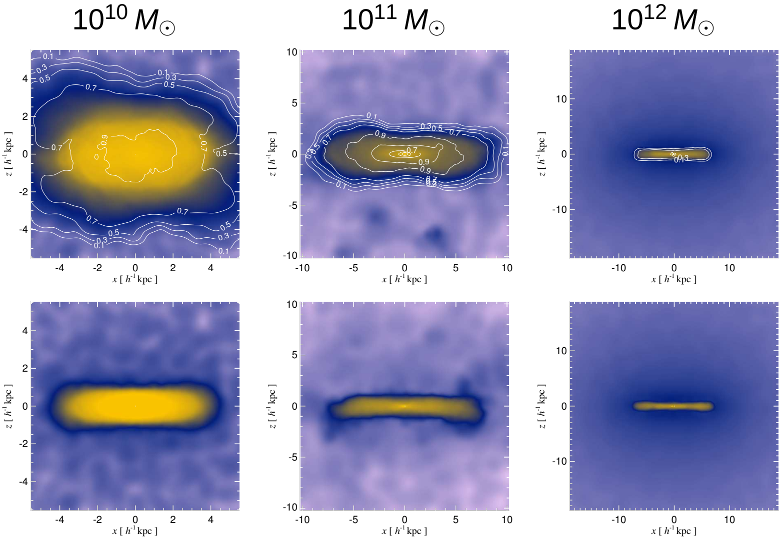
# Cosmic rays and galaxy formation

Cluster observables:

Physical processes in clusters:



# Isolated galaxies – projections

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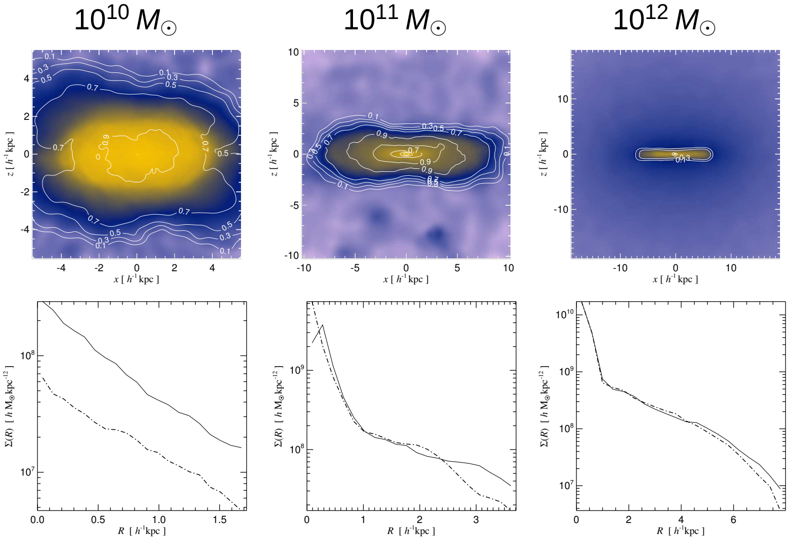
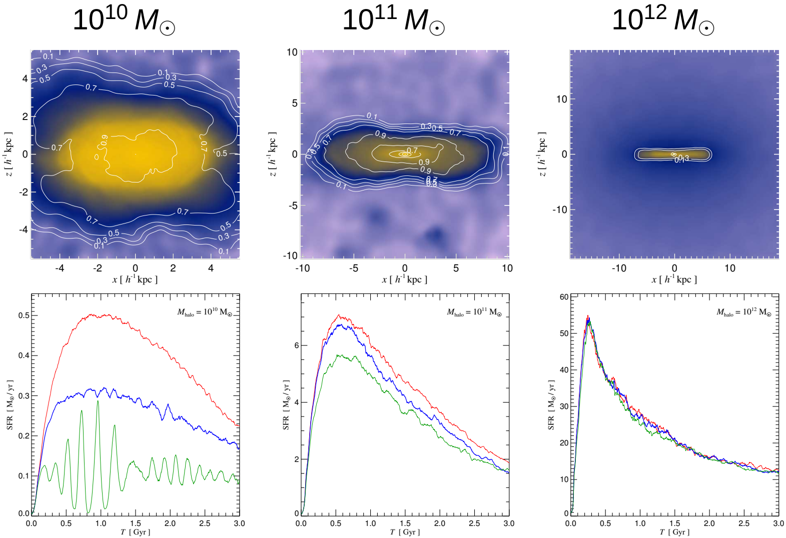
# Isolated galaxies – stellar profiles



# Isolated galaxies – star formation history

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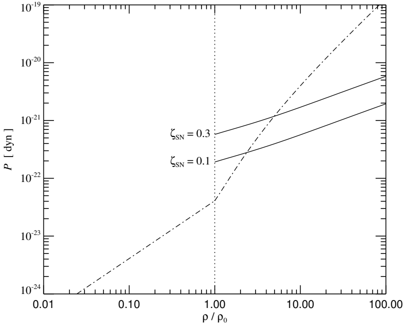
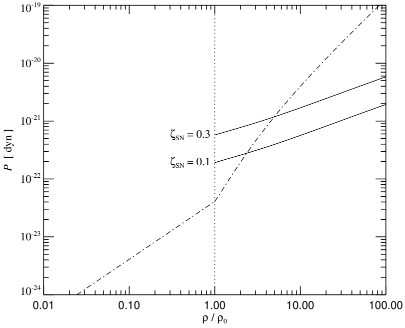
# Effective equation of state

Supernova heating balances cooling

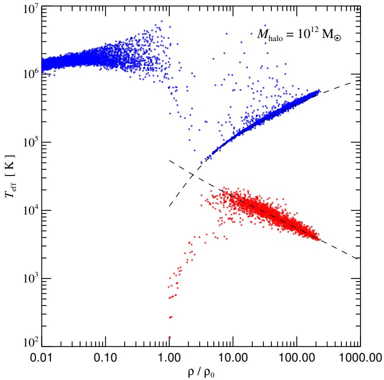


# Effective equation of state & phase space distribution

## Supernova heating balances cooling

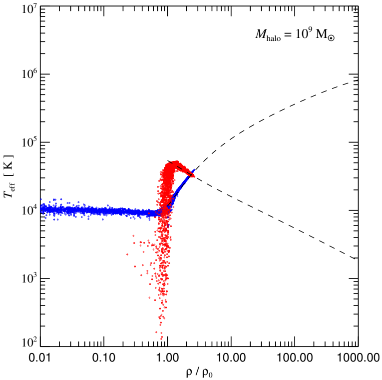



## $10^{12}\,M_\odot$ galaxy

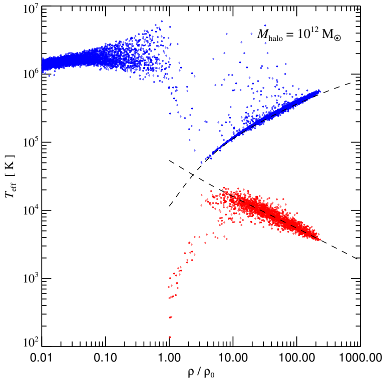


# Effective equation of state & phase space distribution

## $10^9\,M_\odot$ galaxy




## $10^{12}\,M_\odot$ galaxy

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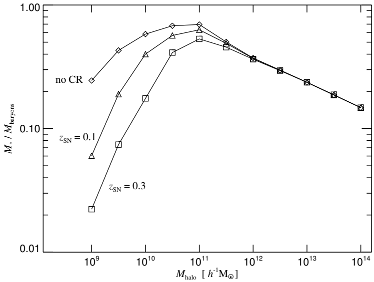
# Quenching of dwarf galaxies

Star formation efficiency suppressed in small halos:

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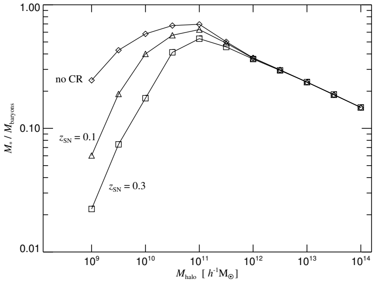
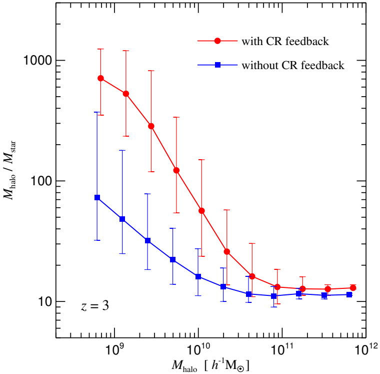



Averaged mass-to-light ratio:

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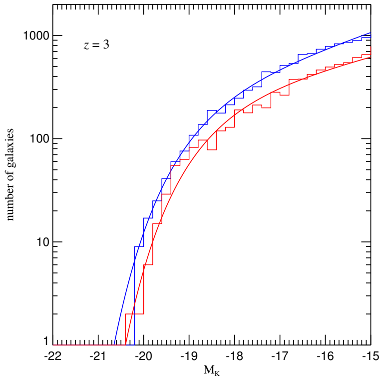
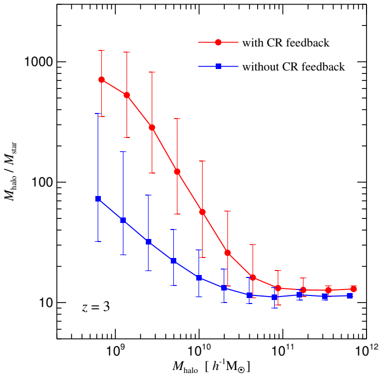
# Quenching of small galaxies

## Luminosity function (z=3):




## Averaged mass-to-light ratio:

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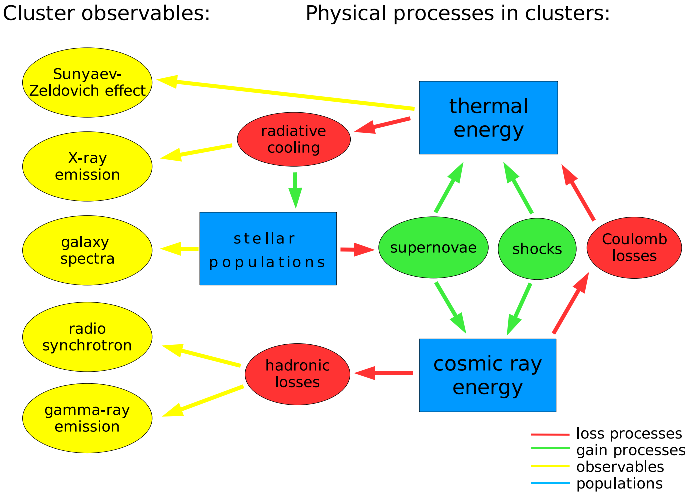
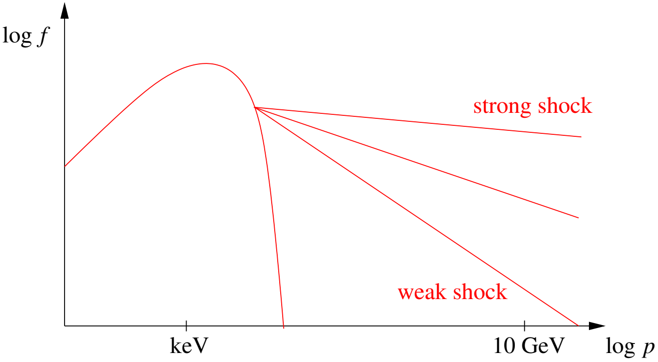
# Cosmic rays in galaxy clusters

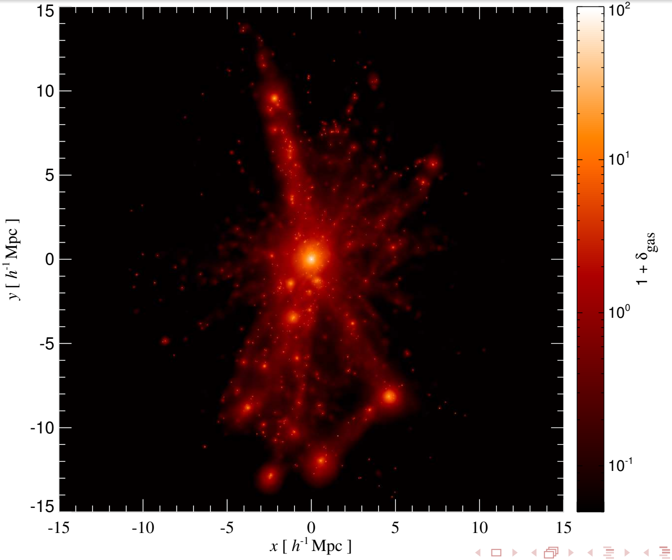


# Diffusive shock acceleration – Fermi 1 mechanism

Cosmic rays gain energy $\Delta E/E \propto \upsilon_1 - \upsilon_2$ through bouncing back and forth the shock front. Accounting for the loss probability $\propto \upsilon_2$ of particles leaving the shock downstream leads to power-law CR population.



# Radiative cluster simulation: gas density

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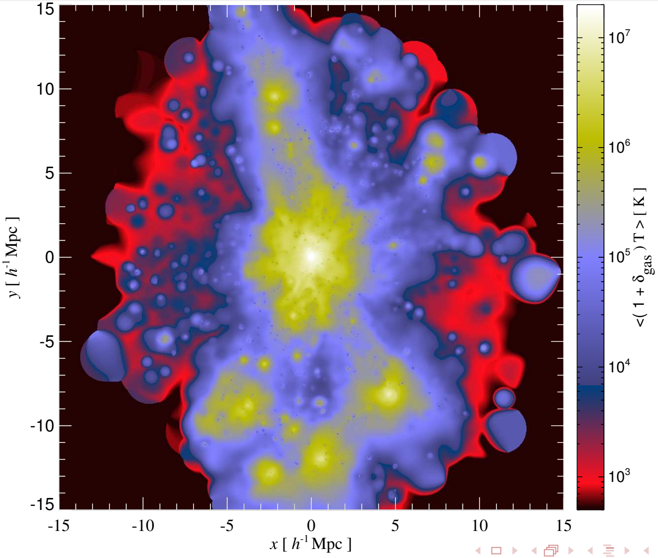
# Mass weighted temperature

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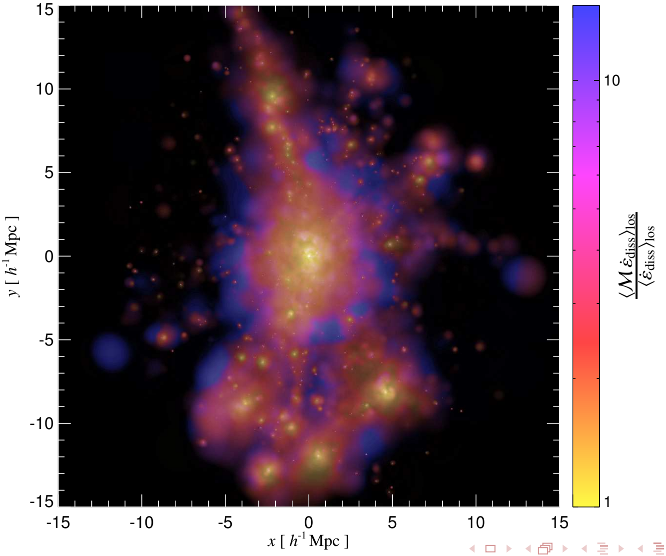
# Mach number distribution weighted by $\varepsilon_{\text{diss}}$

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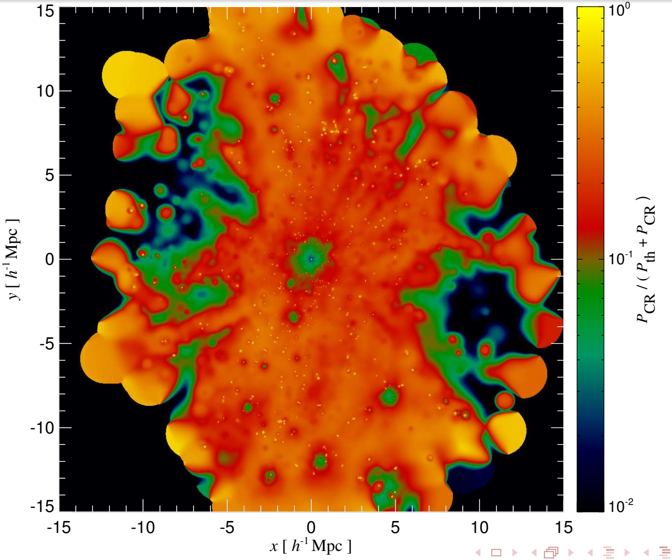
# Relative CR pressure $P_{CR}/P_{total}$

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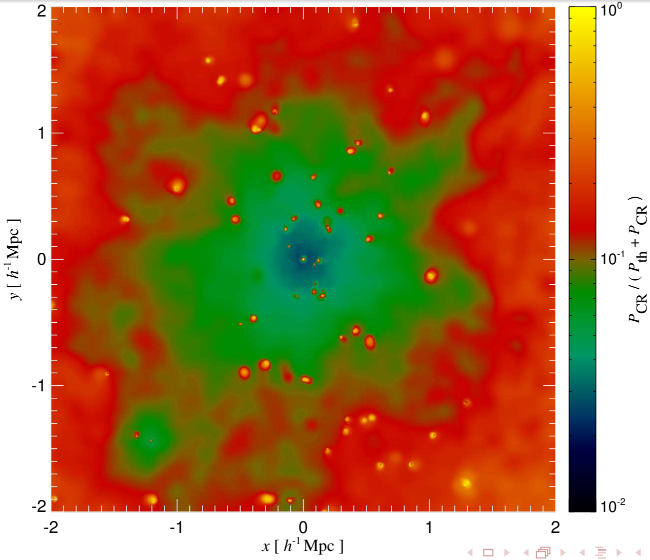
# Relative CR pressure $P_{\mathrm{CR}}/P_{\mathrm{total}}$

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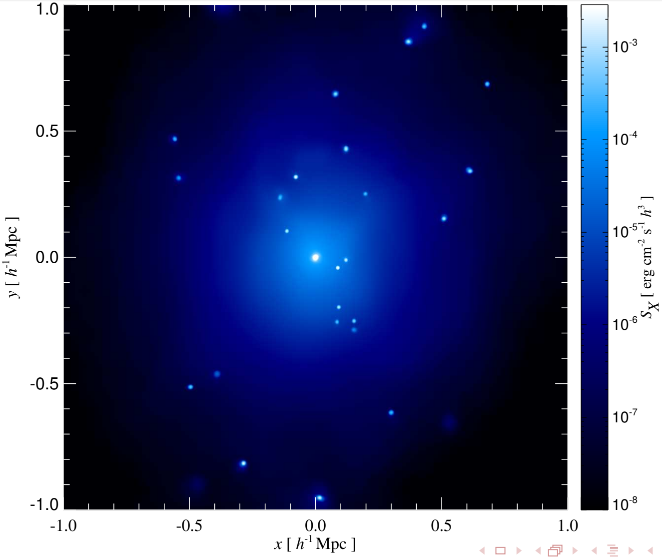
# Thermal X-ray emission

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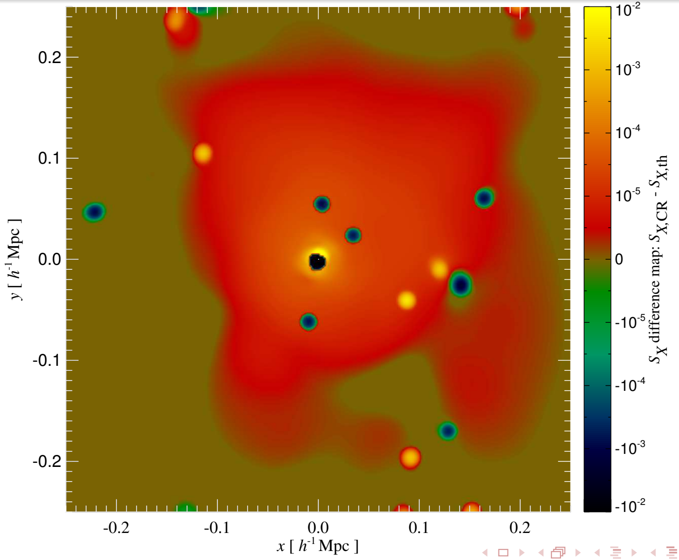
# Difference map of $S_X$: $S_{X,\mathrm{CR}} - S_{X,\mathrm{th}}$

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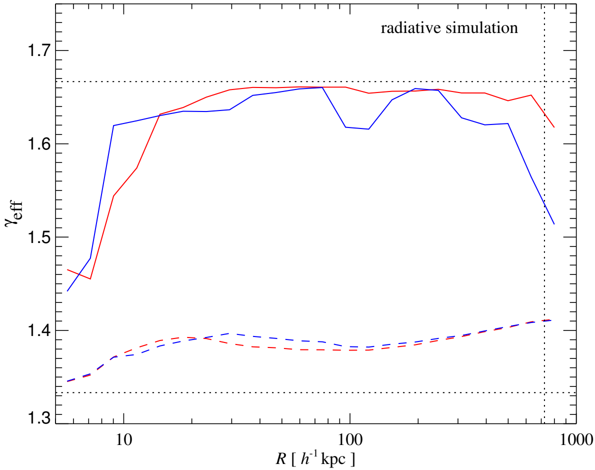
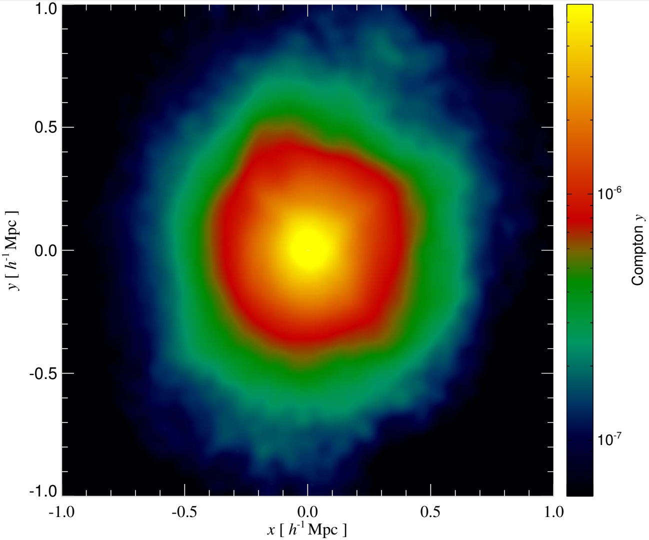
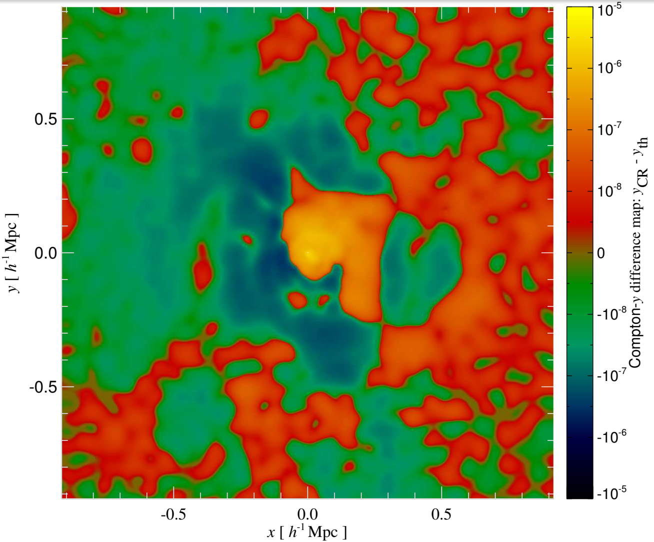
# Softer effective adiabatic index of composite gas



# Compton $y$ parameter in radiative cluster simulation



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

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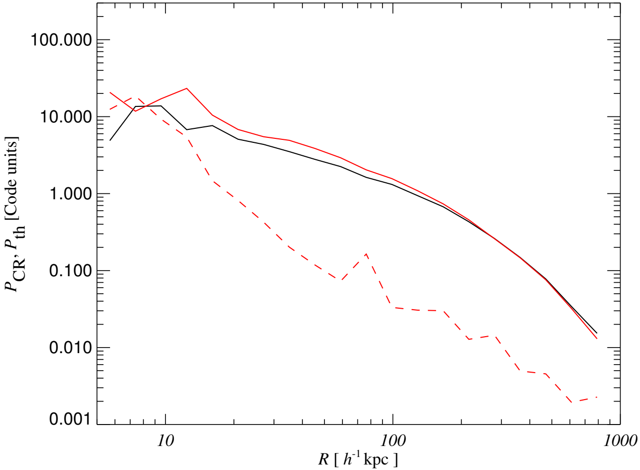
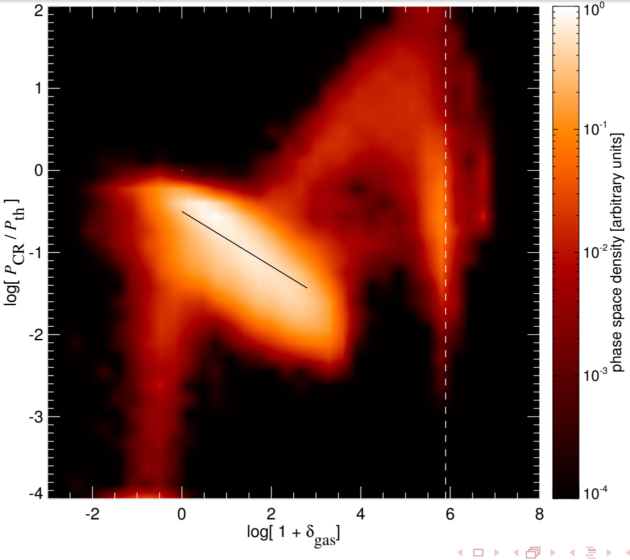
# Pressure profiles with and without CRs



# Phase-space diagram of radiative cluster simulation

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# Summary

- Galaxy evolution: CRs significantly reduce the star formation efficiency in small galaxies.
- Galaxy cluster X-ray emission is enhanced up to 35%, predominantly in low-mass cooling core clusters.
- Integrated Sunyaev-Zel'dovich effect remains largely unchanged while the Compton-$y$ profile is more peaked.
- Understanding non-thermal processes is crucial for using clusters as cosmological probes (high-$z$ scaling relations).

- Outlook
  - Huge potential and predictive power of cosmological CR simulations $\rightarrow$ provides detailed $\gamma$-ray/radio emission maps
  - Galaxy evolution: CRs might influence energetic feedback, galactic winds, and disk galaxy formation

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