Non-thermal processes in galaxy clusters – How reliable is the Sunyaev-Zel'dovich effect?

Christoph Pfrommer[1]

in collaboration with

Nick Battaglia[1], Jon Sievers[1], Dick Bond[1],
Anders Pinzke[2], Torsten Enßlin[3], Volker Springel[3]

[1]Canadian Institute for Theoretical Astrophysics, Canada
[2]Stockholm University, Sweden
[3]Max-Planck Institute for Astrophysics, Germany

Mar 7, 2009 / CIfAR meeting, Mont-Tremblant

CITA–ICAT

Outline

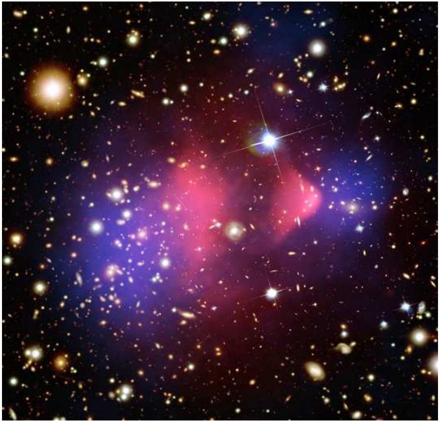
1. Introduction and motivation
   - Observations
   - The big questions
   - Cosmological simulations
2. Galaxy cluster thermodynamics
   - Cosmological galaxy cluster simulations
   - Cosmic ray acceleration and transport
   - Effect on the Sunyaev-Zel'dovich effect
3. Non-thermal emission from clusters
   - General picture
   - Cluster radio halos
   - High-energy γ-ray emission

CITA–ICAT

Outline

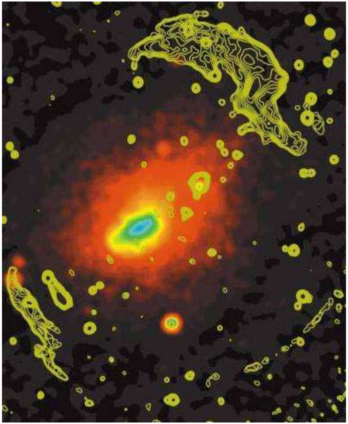
CITA–ICAT

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.)

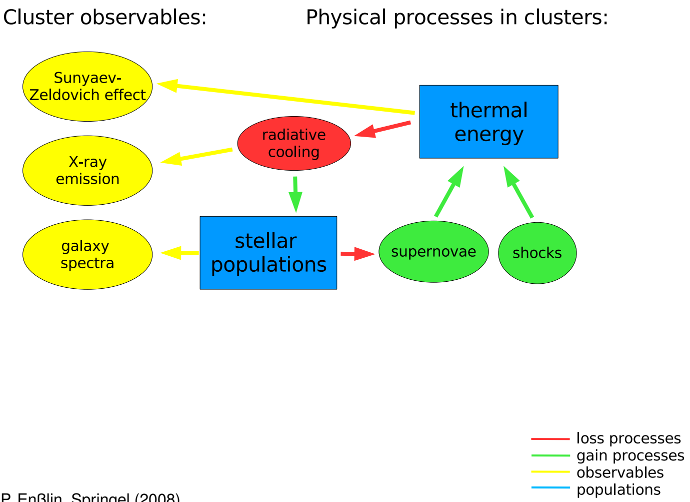
CITA–ICAT

High-energy astrophysics in galaxy clusters

- understanding the non-thermal pressure distribution from cosmic rays, turbulence: what is the bias on the SZ effect?
- consistent picture of non-thermal processes in galaxy clusters (radio, soft/hard X-ray, γ-ray emission)
  $\rightarrow$ illuminating the process of structure formation
  $\rightarrow$ history of individual clusters: cluster archeology
- nature of dark matter: annihilation signal vs. cosmic ray (CR) induced γ-rays
- fundamental plasma physics:
  - diffusive shock acceleration in high-β plasmas
  - origin and evolution of large scale magnetic fields
  - nature of turbulent models

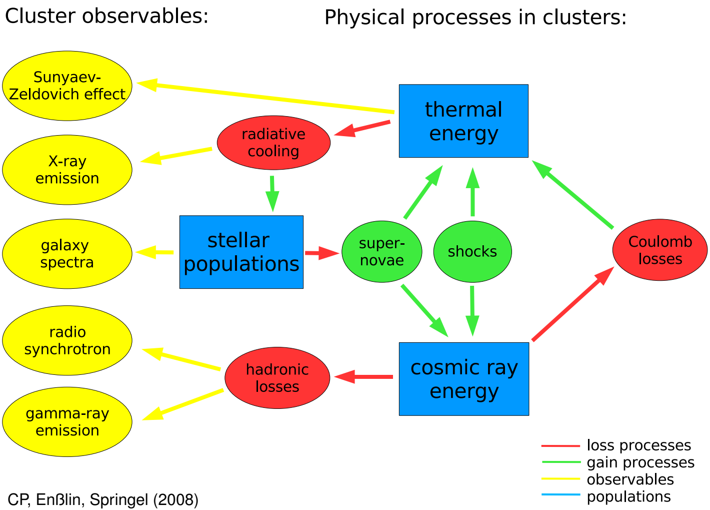
CITA–ICAT

Radiative simulations – flowchart



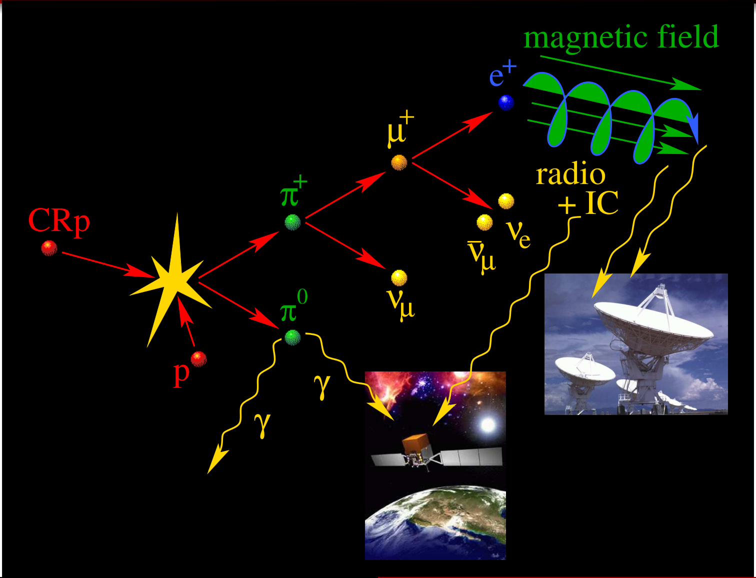
CP, Enßlin, Springel (2008)

Radiative simulations with cosmic ray (CR) physics

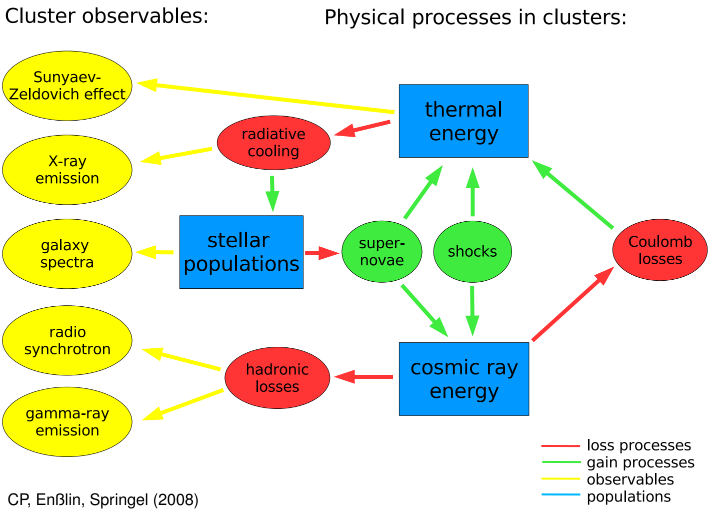


CP, Enßlin, Springel (2008)

Hadronic cosmic ray proton interaction

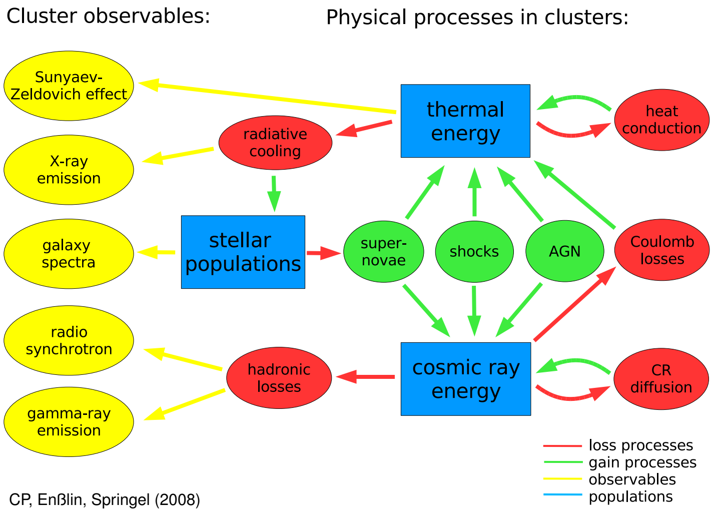


Radiative simulations with cosmic ray (CR) physics



CP, Enßlin, Springel (2008)

Radiative simulations with extended CR physics

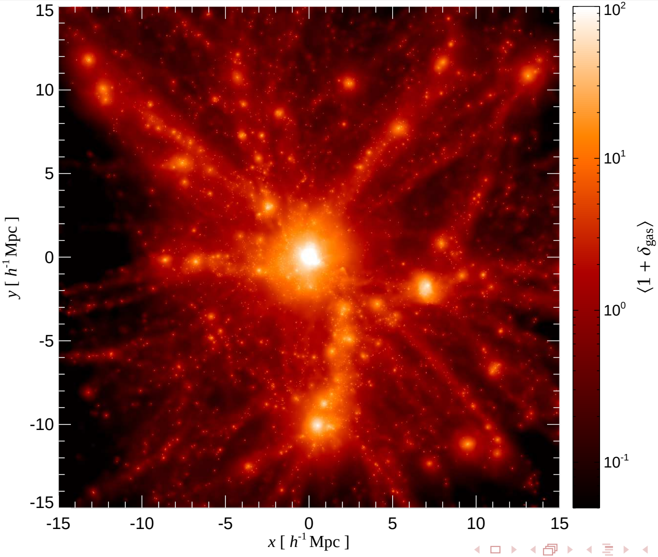


CP, Enßlin, Springel (2008)

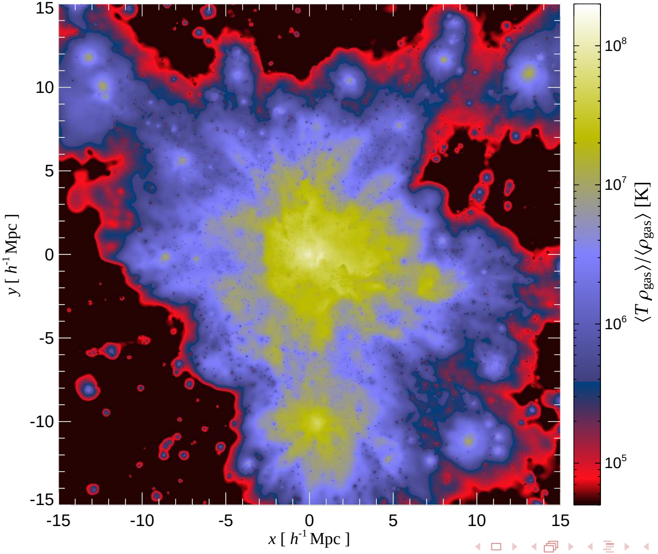
Outline

CITA–ICAT

Radiative cool core cluster simulation: gas density

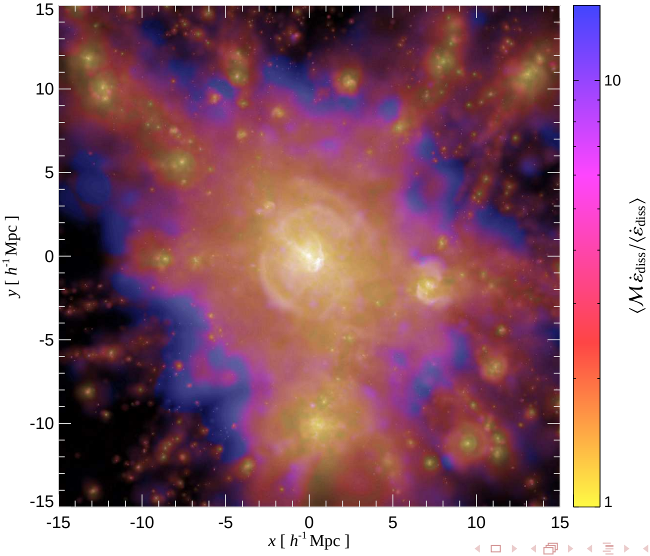


Mass weighted temperature



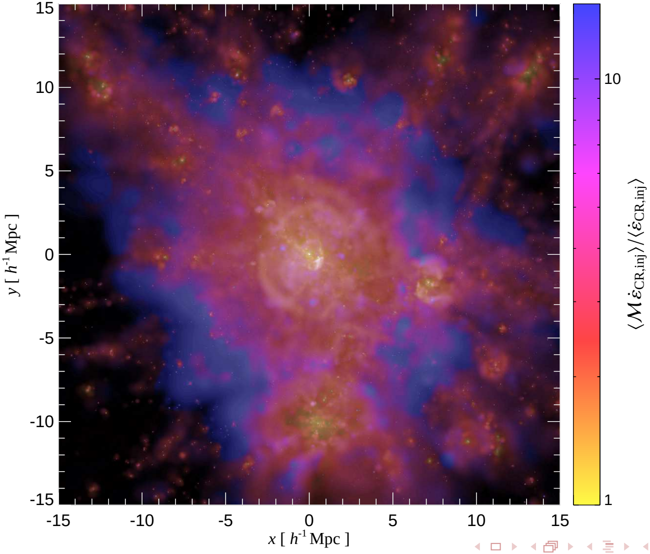
CITA–ICAT

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



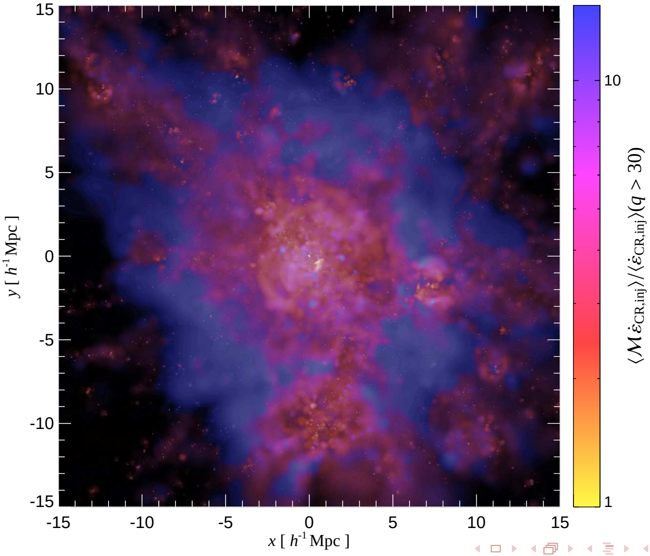
CITA–ICAT

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



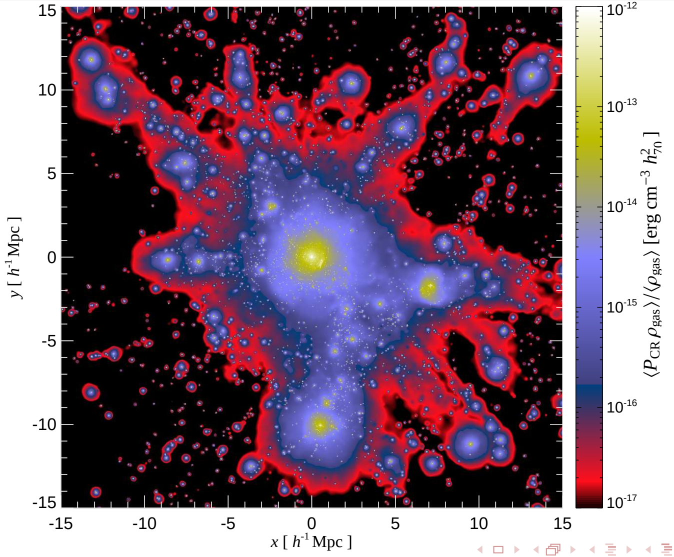
CITA–ICAT

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



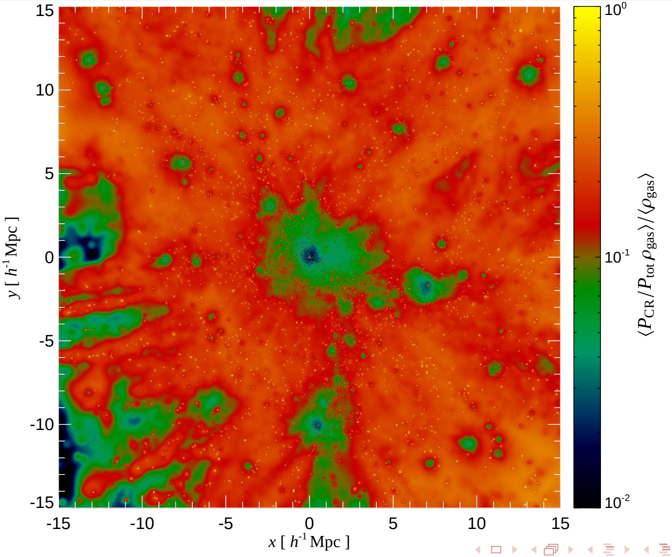
CITA–ICAT

CR pressure P_{CR}

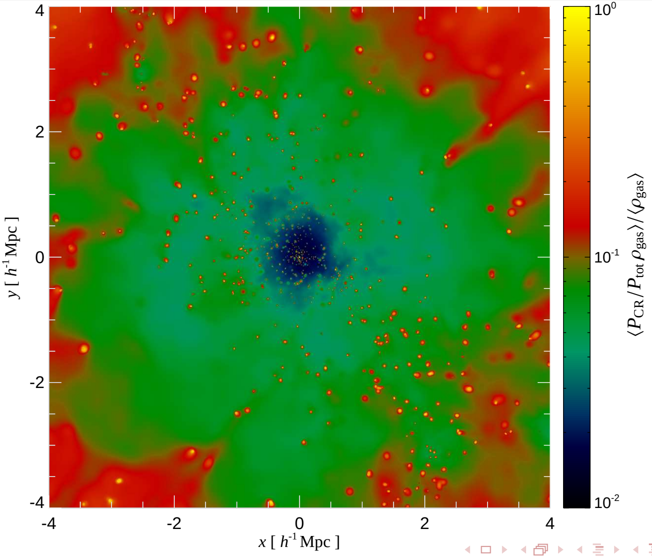


CITA–ICAT

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

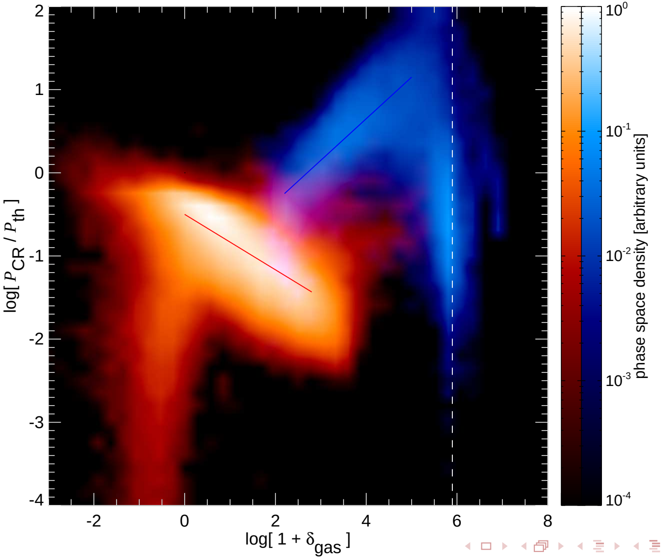


Relative CR pressure $P_{\rm CR}/P_{\rm total}$

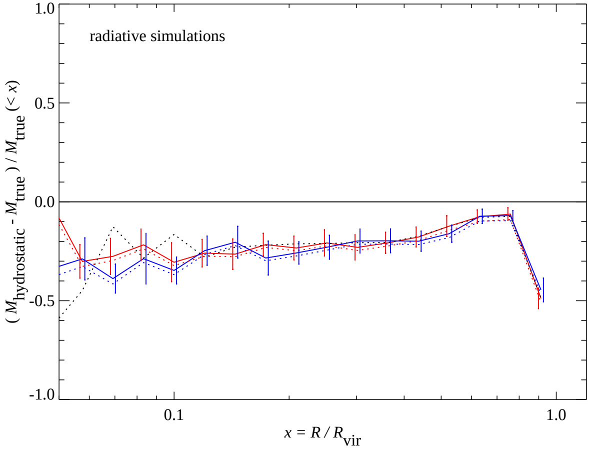


CITA–ICAT

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



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

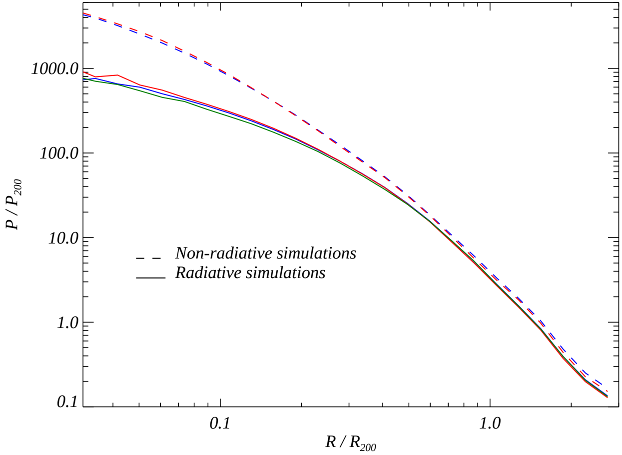


$$\rho_{\mathrm{gas}}^{-1} \frac{\mathrm{d}P_{\mathrm{tot}}}{\mathrm{d}r} = -\frac{G\,M(< r)}{r^2}, \text{ where } P_{\mathrm{tot}} = P_{\mathrm{th}} + P_{\mathrm{nth}},$$

CP in prep.

CITA–ICAT

Influence of cooling, star formation and CRs on $P(r)$

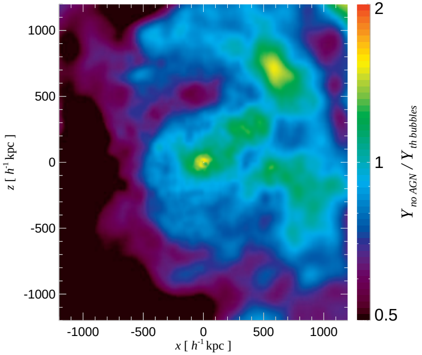


$$y \propto \int \mathrm{d}l \, P_{\mathrm{e,th}},$$

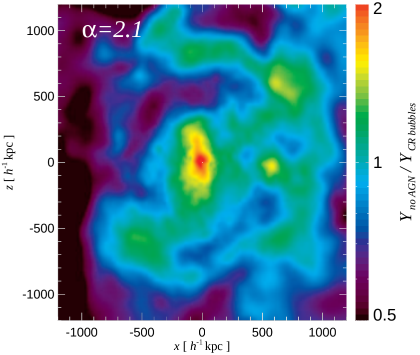
CP et al. 2007; Battaglia, Bond, CP, Sievers in prep.

CITA–ICAT

Influence of AGN feedback on the SZ effect



thermal AGN feedback



AGN feedback with CR-filled bubbles

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

Sijacki, CP, Springel, Enßlin 2008

CITA–ICAT

Take home messages (1)

1. non-radiative simulations overestimate central pressure by a factor of ~ 10 and the total Compton-y parameter by $\sim 33\%$
   - transforming baryons into stars
   - radiative cooling removes low-entropy ($S \sim T/\rho^{2/3}$) gas which is replaced by high-S gas that has a lower initial pressure $P \sim S\rho^{5/3}$
2. feedback by CRs, galactic winds modify the SZ effect only on the per cent level
3. total Compton-y dominated by the exterior parts (uncertainties in cores less severe, apart from integral effect on overall gas fraction), but turbulence effects on the order of $\sim 10 - 20\%$

$\rightarrow$ huge effort to investigate these problems and its influence on the C_ℓ's systematically using large cosmological box simulations.

CITA–ICAT

Outline

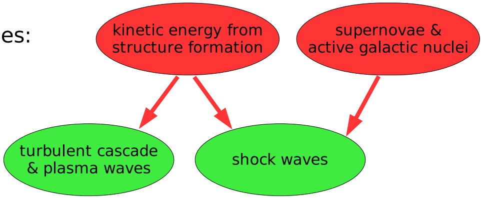
CITA–ICAT

Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:

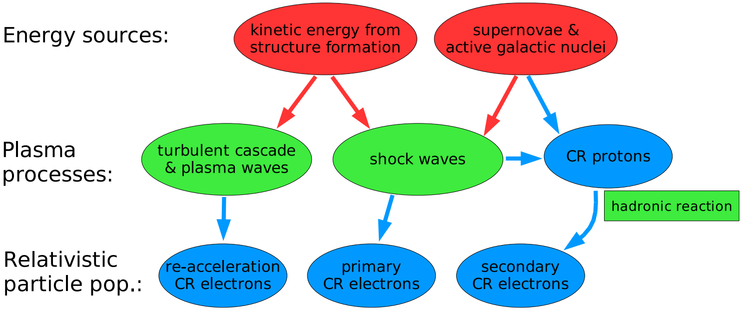
Energy sources:

Plasma processes:



Multi messenger approach for non-thermal processes

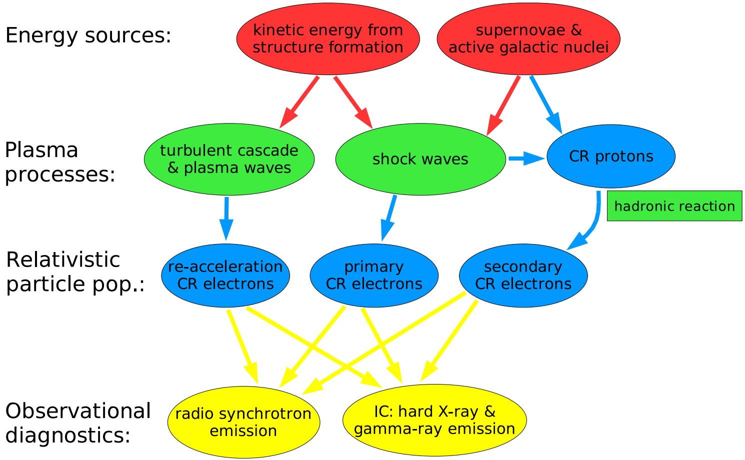
Relativistic populations and radiative processes in clusters:



CITA–ICAT

Multi messenger approach for non-thermal processes

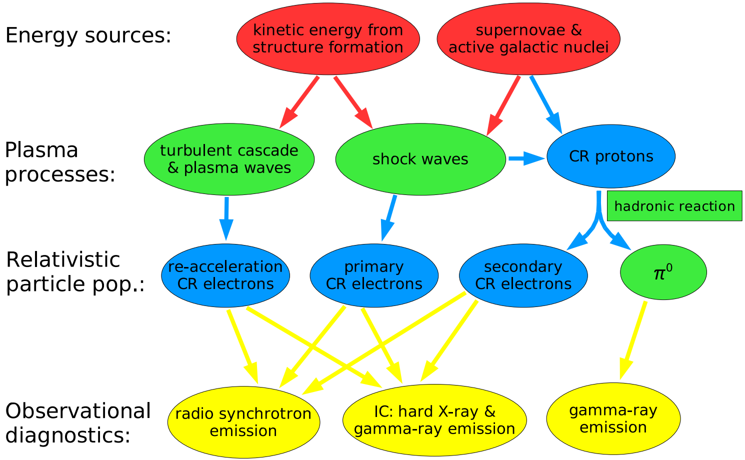
Relativistic populations and radiative processes in clusters:



CITA–ICAT

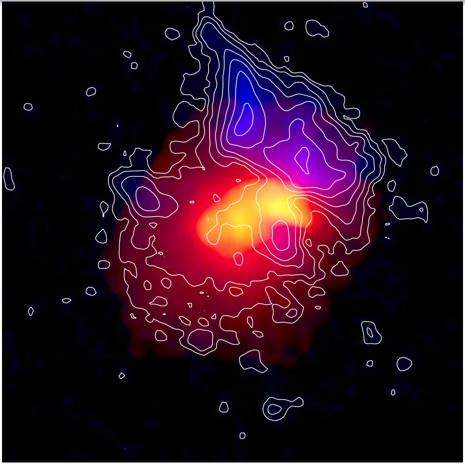
Multi messenger approach for non-thermal processes

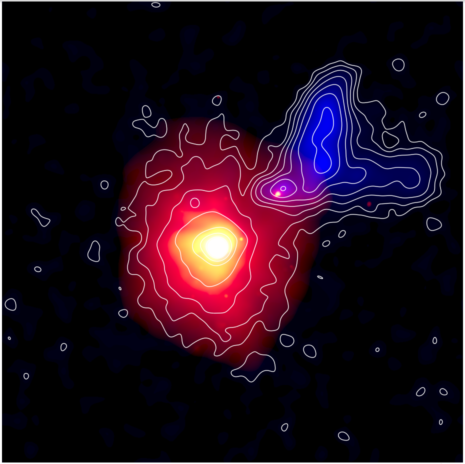
Relativistic populations and radiative processes in clusters:



CITA–ICAT

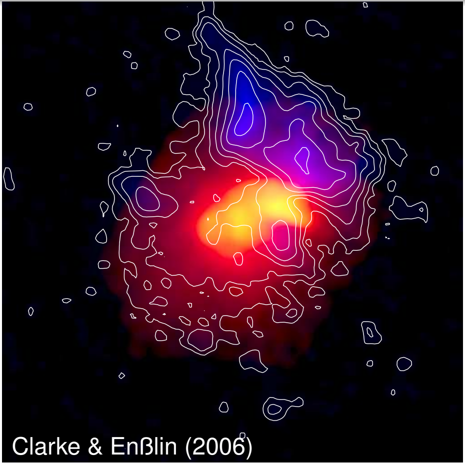
Which one is the simulation/observation of A2256?

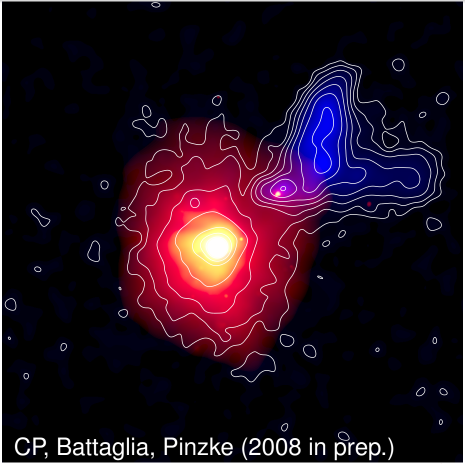




red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic

Observation – simulation of A2256





red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic

CITA–ICAT

Unified model of radio halos and relics (CP, Enßlin, Springel 2008)

Cluster radio emission varies with dynamical stage of a cluster:

- Cluster relaxes and develops cool core: radio mini-halo develops due to hadronically produced CR electrons, magnetic fields are adiabatically compressed (cooling gas triggers radio mode feedback of AGN that outshines mini-halo → selection effect).
- Cluster experiences major merger: two leading shock waves are produced that become stronger as they break at the shallow peripheral cluster potential → shock-acceleration of primary electrons and development of radio relics.
- Generation of morphologically complex network of virializing shock waves. Lower sound speed in the cluster outskirts lead to strong shocks → irregular distribution of primary electrons, MHD turbulence amplifies magnetic fields.
- Giant radio halo develops due to (1) boost of the hadronically generated radio emission in the center (2) irregular radio 'gischt' emission in the cluster outskirts.

CITA–ICAT

Unified model of radio halos and relics (CP, Enßlin, Springel 2008)

Cluster radio emission varies with dynamical stage of a cluster:

- Cluster relaxes and develops cool core: radio mini-halo develops due to hadronically produced CR electrons, magnetic fields are adiabatically compressed (cooling gas triggers radio mode feedback of AGN that outshines mini-halo $\rightarrow$ selection effect).
- Cluster experiences major merger: two leading shock waves are produced that become stronger as they break at the shallow peripheral cluster potential $\rightarrow$ shock-acceleration of primary electrons and development of radio relics.
- Generation of morphologically complex network of virializing shock waves. Lower sound speed in the cluster outskirts lead to strong shocks $\rightarrow$ irregular distribution of primary electrons, MHD turbulence amplifies magnetic fields.
- Giant radio halo develops due to (1) boost of the hadronically generated radio emission in the center (2) irregular radio 'gischt' emission in the cluster outskirts.

CITA–ICAT

Non-thermal emission from clusters

Exploring the memory of structure formation

- primary, shock-accelerated CR electrons resemble current accretion and merging shock waves
- CR protons/hadronically produced CR electrons trace the time integrated non-equilibrium activities of clusters that is modulated by the recent dynamical activities

How can we read out this information about non-thermal populations?
$\rightarrow$ new era of multi-frequency experiments, e.g.:

- GMRT, LOFAR, MWA, LWA, SKA: interferometric array of radio telescopes at low frequencies ($\nu \simeq (15 - 240)$ MHz)
- Simbol-X/NuSTAR: future hard X-ray satellites ($E \simeq (1 - 100)$ keV)
- Fermi γ-ray space telescope ($E \simeq (0.1 - 300)$ GeV)
- Imaging air Čerenkov telescopes ($E \simeq (0.1 - 100)$ TeV)

CITA–ICAT

Non-thermal emission from clusters

Exploring the memory of structure formation

- primary, shock-accelerated CR electrons resemble current accretion and merging shock waves
- CR protons/hadronically produced CR electrons trace the time integrated non-equilibrium activities of clusters that is modulated by the recent dynamical activities

How can we read out this information about non-thermal populations?
$\rightarrow$ new era of multi-frequency experiments, e.g.:

- GMRT, LOFAR, MWA, LWA, SKA: interferometric array of radio telescopes at low frequencies ($\nu \simeq (15 - 240)$ MHz)
- Simbol-X/NuSTAR: future hard X-ray satellites ($E \simeq (1 - 100)$ keV)
- Fermi γ-ray space telescope ($E \simeq (0.1 - 300)$ GeV)
- Imaging air Čerenkov telescopes ($E \simeq (0.1 - 100)$ TeV)

CITA–ICAT

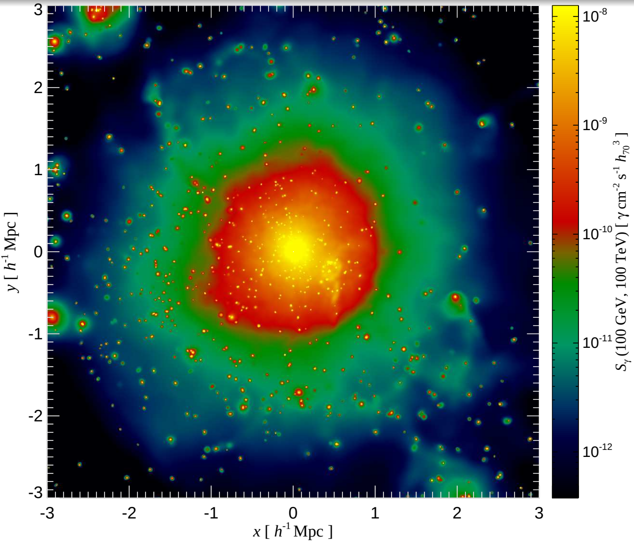
The quest for high-energy γ-ray emission from clusters

Multi-messenger approach towards fundamental astrophysics

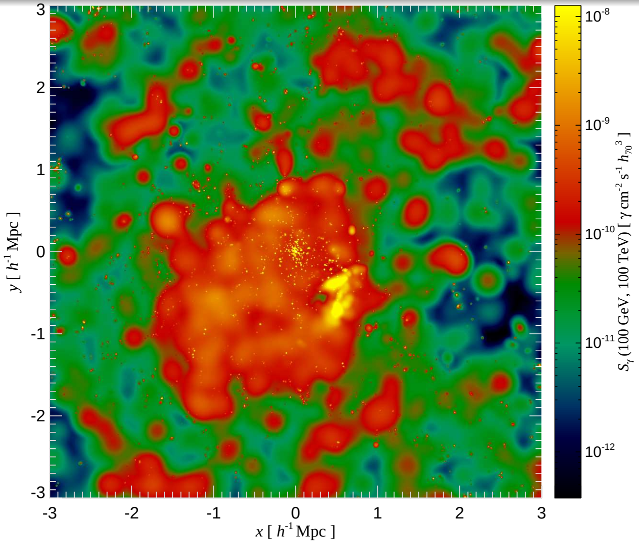
1. complements current non-thermal observations of galaxy clusters in radio and hard X-rays:
   - identifying the nature of emission processes
   - unveiling the contribution of cosmic ray protons
2. elucidates the nature of dark matter:
   - disentangling annihilation signal vs. CR induced γ-rays
   - spectral and morphological γ-ray signatures $\rightarrow$ DM properties
3. probes plasma astrophysics such as macroscopic parameters for diffusive shock acceleration

CITA–ICAT

Hadronic γ-ray emission, $E_\gamma > 100$ GeV

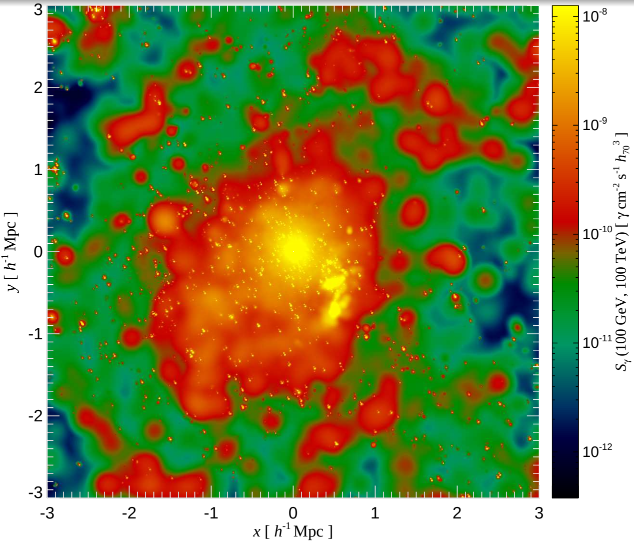


Inverse Compton emission, $E_{\mathrm{IC}} > 100$ GeV



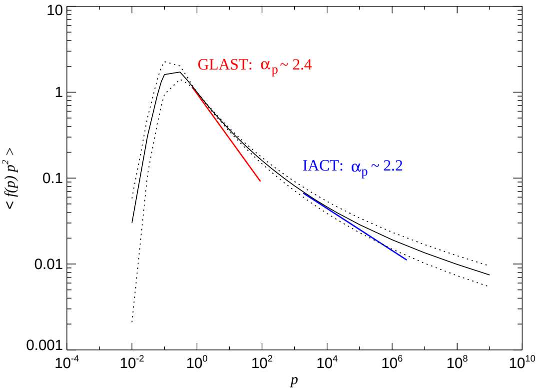
CITA–ICAT

Total γ-ray emission, $E_\gamma > 100$ GeV



CITA–ICAT

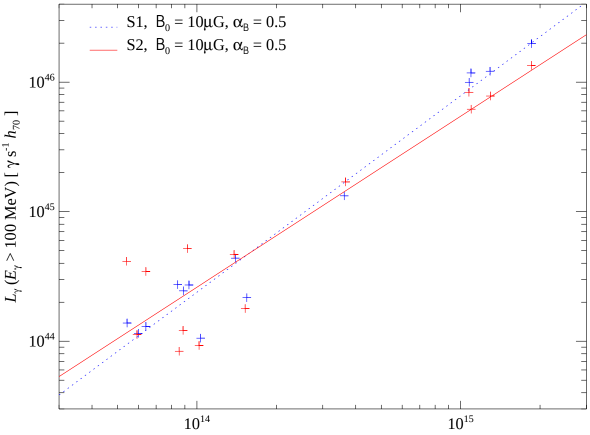
Universal CR spectrum in clusters



Normalized CR spectrum shows universal concave shape → governed mainly by hierarchical structure formation and adiabatic CR transport processes. (Pinzke & CP, in prep.)

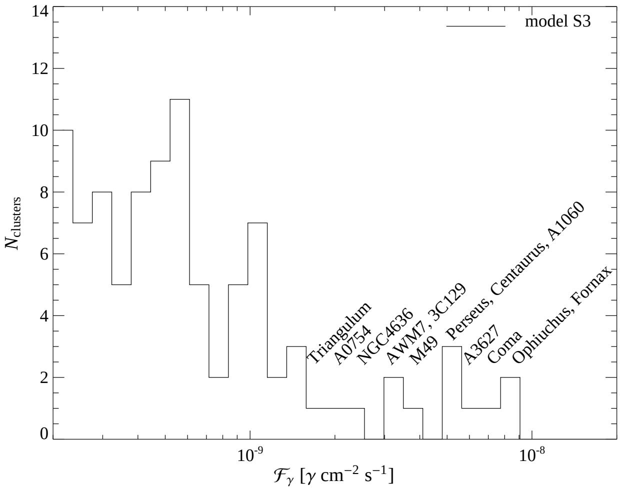
→ very promising for disentangling the dark matter annihilation signal!

Gamma-ray scaling relations



Scaling relation + complete sample of the brightest X-ray clusters (extended HIFLUCGS) → predictions for *Fermi* (CP 2008)

Predicted cluster sample for *Fermi*



CITA–ICAT

Take home messages (2)

In contrast to the thermal plasma, the non-equilibrium distributions of CRs preserve the information about their injection and transport processes and provide thus a unique window of current and past structure formation processes!

1. Cosmological hydrodynamical simulations are indispensable for understanding non-thermal processes in galaxy clusters
   $\rightarrow$ illuminating the process of structure formation
2. Multi-messenger approach including radio synchrotron, hard X-ray IC, and HE γ-ray emission:
   - fundamental plasma physics: diffusive shock acceleration, large scale magnetic fields, and turbulence
   - nature of dark matter
   - gold sample of clusters for precision cosmology

CITA–ICAT

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*

CITA–ICAT