High Energy Astrophysics in Galaxy Clusters

Christoph Pfrommer

Canadian Institute for Theoretical Astrophysics, Canada

Dec 10, 2008 / 24th Texas Symposium, Vancouver

CITA–ICAT

Outline

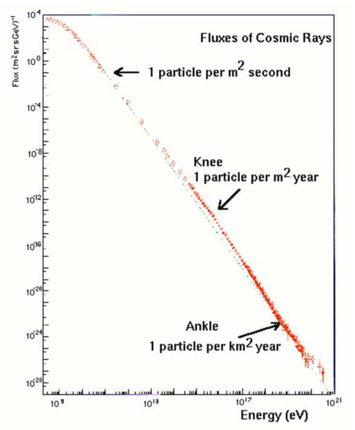
CITA–ICAT

Outline

1. Introduction and Motivation
   - Galactic high-energy processes
   - Shock waves in galaxy clusters
   - The big questions
2. Plasma processes in galaxy clusters
   - Cosmological galaxy cluster simulations
   - Shocks and particle acceleration
   - Turbulence and magnetic fields
3. Non-thermal emission from clusters
   - Radio emission by shocks and turbulence
   - Hadronically induced radio emission
   - High-energy γ-ray emission

CITA–ICAT

Galactic cosmic ray spectrum



data compiled by Swordy

Galactic CR all particle spectrum:

- spans $\sim$ 40 decades in flux when accounting for solar modulation that blocks low energy CRs
- ranges 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin

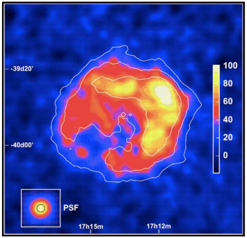
CITA–ICAT

Supernova remnants

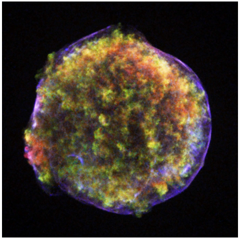
Properties of supernova remnants:

- Non-relativistic collisionless shocks ($\sim 10^3$ km/s)
- Class of young SNRs emitting synchrotron X-rays: direct evidence of electron acceleration to 50-100 TeV (Slane et al. 1999, 2001; Vink et al. 2006)
- 100 GeV-TeV emission (HESS sources): hadronic or IC leptonic?
- Cosmic ray protons modify shock dynamics – SNRs probably accelerate CRs; B field amplification (e.g. Vink & Laming 2003, Uchiyama et al. 2007)

SN 1006 X-rays (CXC/Hughes)



G347.3 HESS TeV (Aharonian et al. 2006)



Tycho X-rays (CXC)

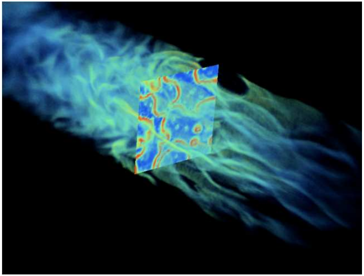
CITA–ICAT

Collisionless shocks

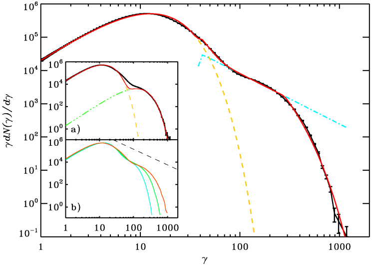
Astrophysical collisionless shocks can:

- accelerate particles
- amplify magnetic fields (or generate them from scratch)
- exchange energy between electrons and ions

Particle-in-cell simulations of unmagnetized, relativistic pair shocks that are mediated by the Weibel instability (Spitkovsky 2008)



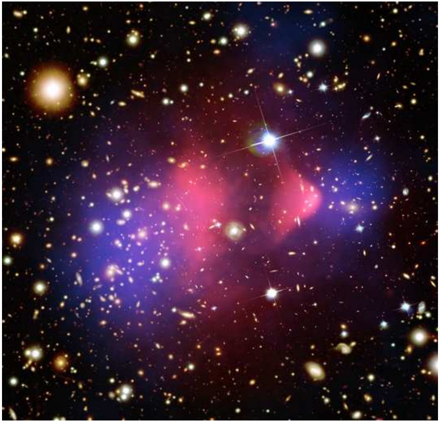
magnetic energy density (Spitkovsky 2008)



post-shock Maxwellian and accelerated CR power-law

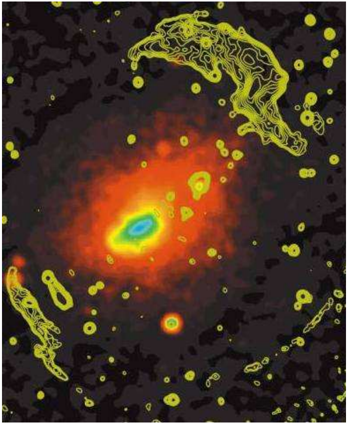
CITA–ICAT

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.)

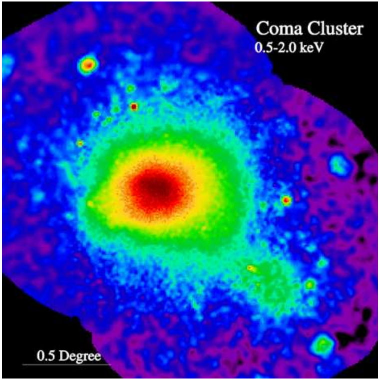


Abell 3667

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

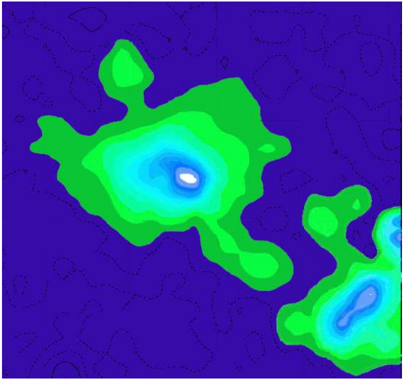
CITA–ICAT

Giant radio halo in the Coma cluster



thermal X-ray emission

(Snowden/MPE/ROSAT)



radio synchrotron emission

(Deiss/Effelsberg)

CITA–ICAT

High-energy astrophysics in galaxy clusters

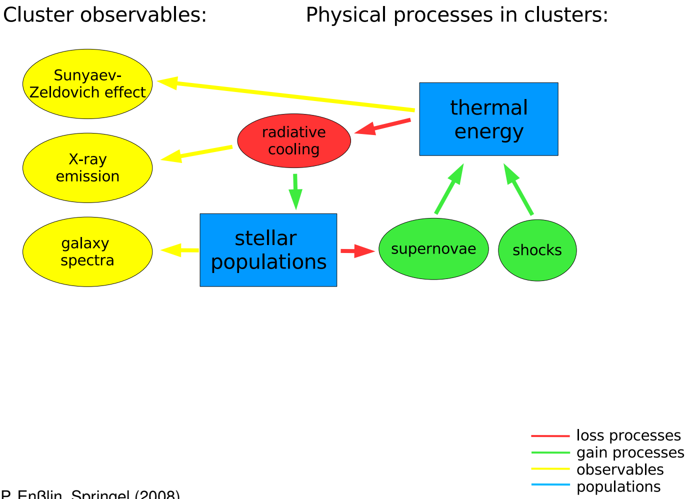
- consistent picture of non-thermal processes in galaxy clusters (radio, soft/hard X-ray, γ-ray emission)
  $\rightarrow$ illuminating the process of structure formation
  $\rightarrow$ history of individual clusters: cluster archeology
- understanding the non-thermal pressure distribution to address biases of thermal cluster observables
- gold sample of clusters for precision cosmology: using non-thermal observables to gauge hidden parameters
- 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

Outline

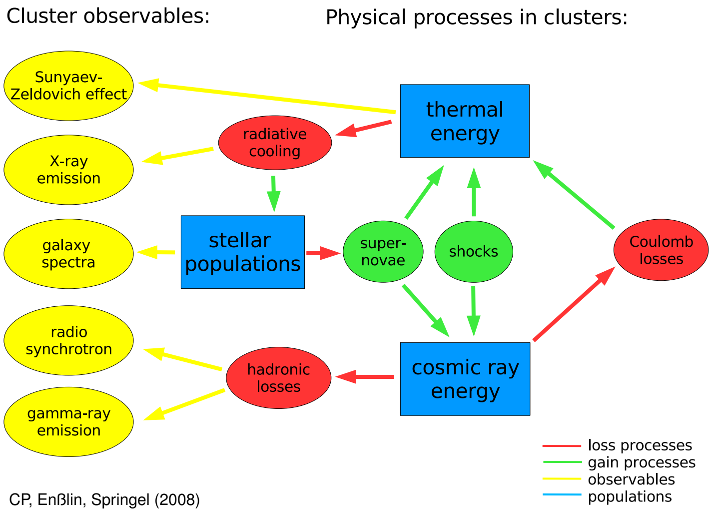
CITA–ICAT

Radiative simulations – flowchart



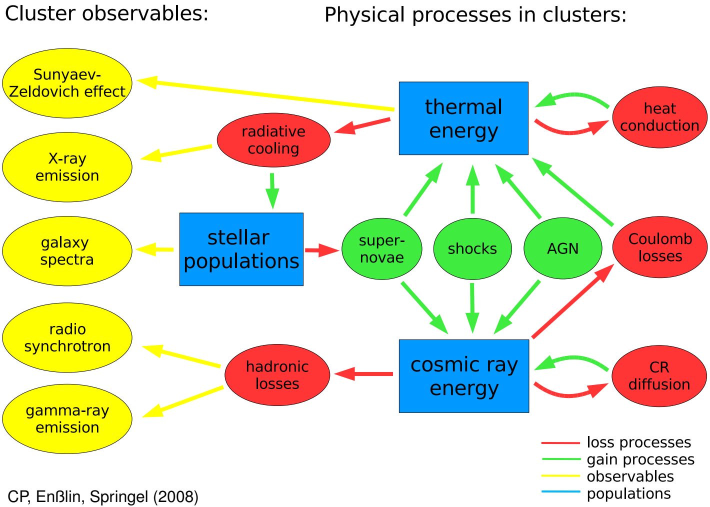
CP, Enßlin, Springel (2008)

Radiative simulations with cosmic ray (CR) physics



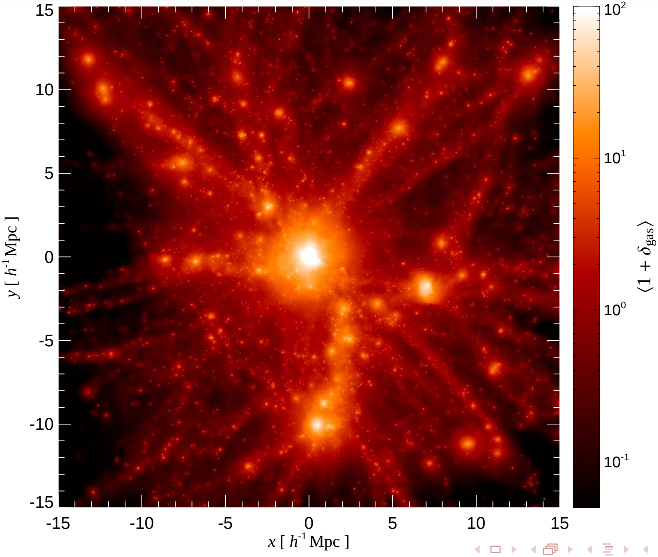
CP, Enßlin, Springel (2008)

Radiative simulations with extended CR physics



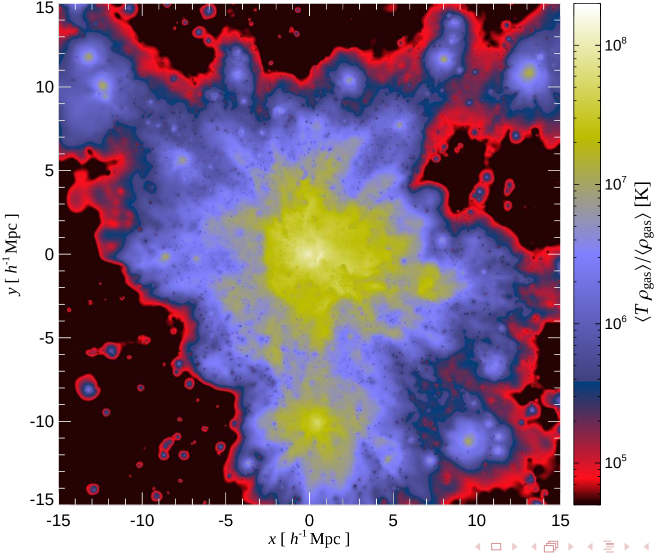
CP, Enßlin, Springel (2008)

Radiative cool core cluster simulation: gas density

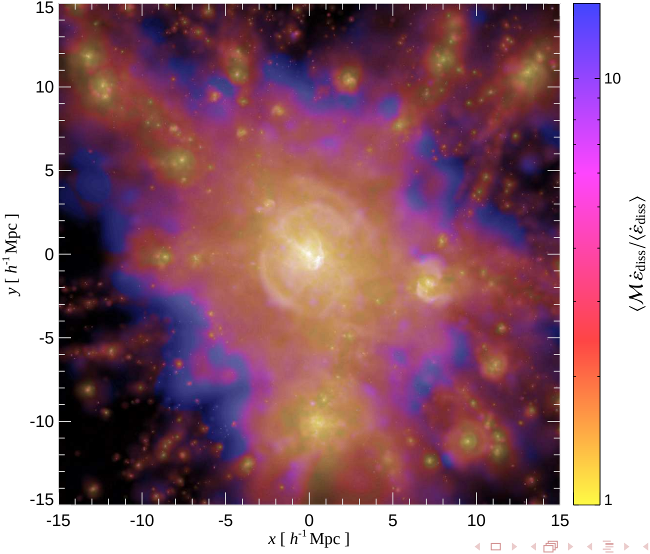


CITA–ICAT

Mass weighted temperature



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



CITA–ICAT

Diffusive shock acceleration – Fermi 1 mechanism (1)

conditions:

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

mechanism:

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

→ power-law CR distribution

CITA–ICAT

Diffusive shock acceleration – Fermi 1 mechanism (1)

conditions:

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

mechanism:

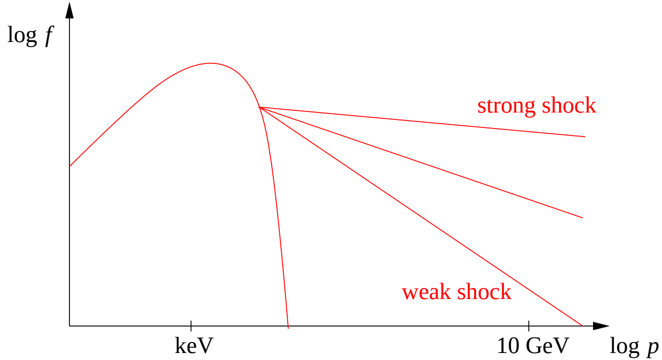
- supra-thermal particles diffuse upstream across shock wave
- each shock crossing energizes particles through momentum transfer from recoil-free scattering off macroscopic scattering agents
- momentum increases exponentially with number of shock crossings
- particle number decreases exponentially with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

$\longrightarrow$ power-law CR distribution

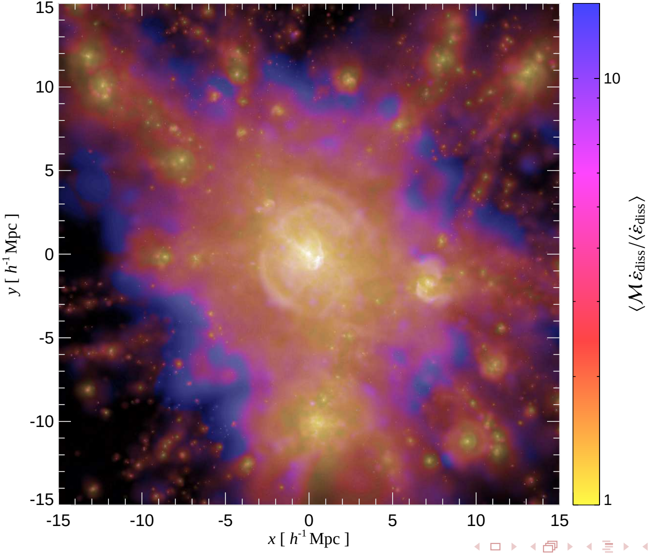
CITA–ICAT

Diffusive shock acceleration – Fermi 1 mechanism (2)

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

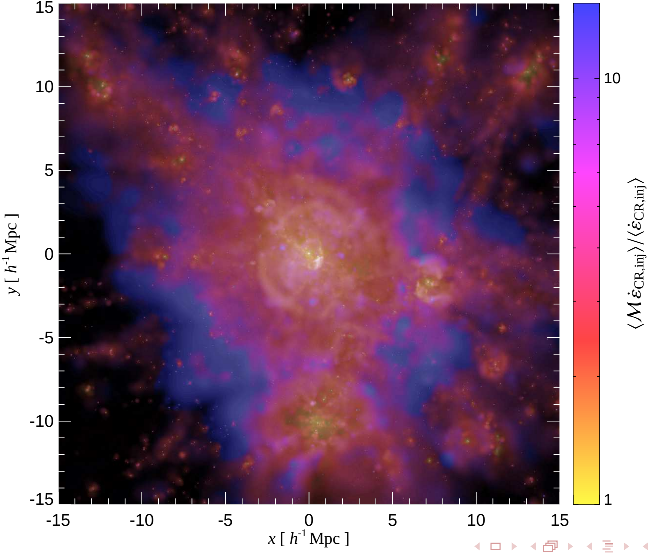


Mach number distribution weighted by $\varepsilon_{\rm diss}$



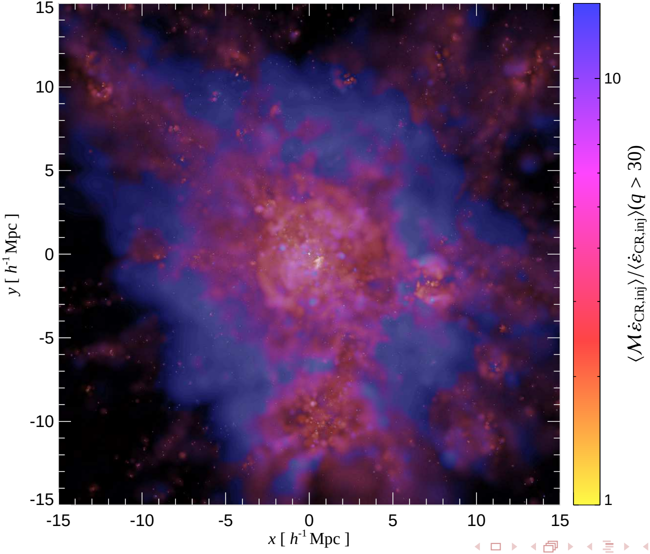
CITA–ICAT

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



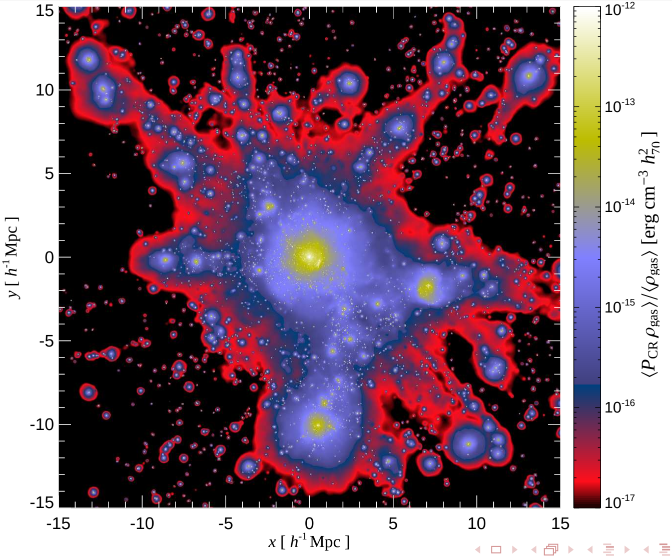
CITA–ICAT

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



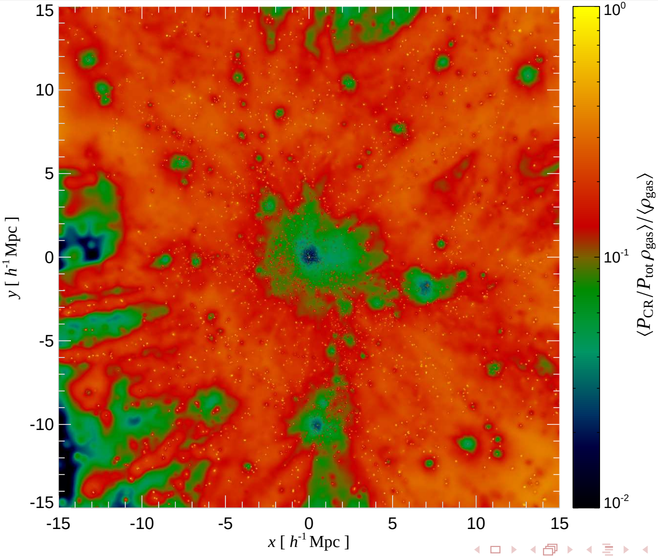
CITA–ICAT

CR pressure P_{CR}



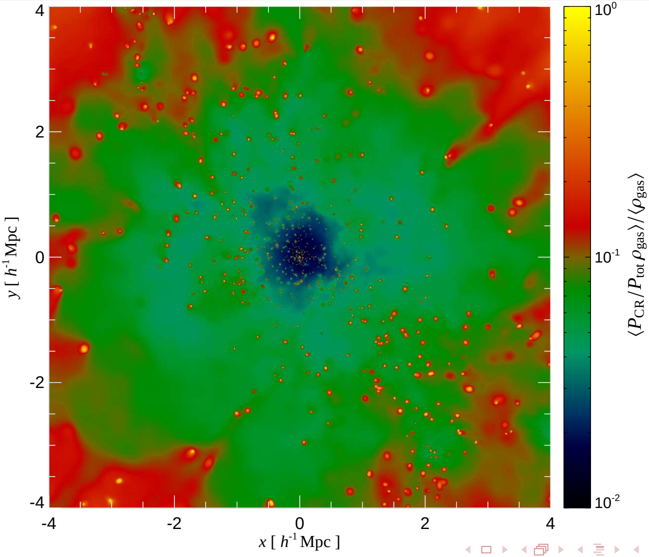
CITA–ICAT

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



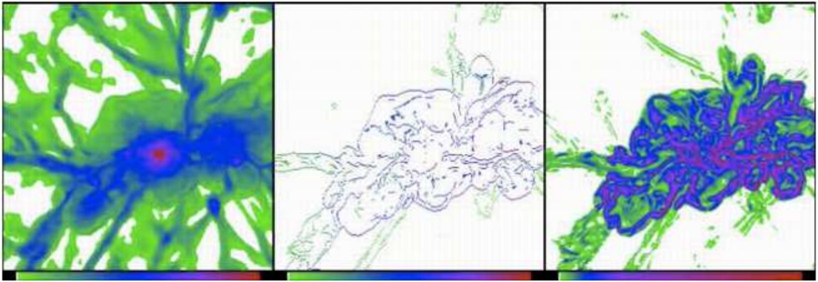
CITA–ICAT

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



CITA–ICAT

Nature and origin of turbulence and magnetic fields



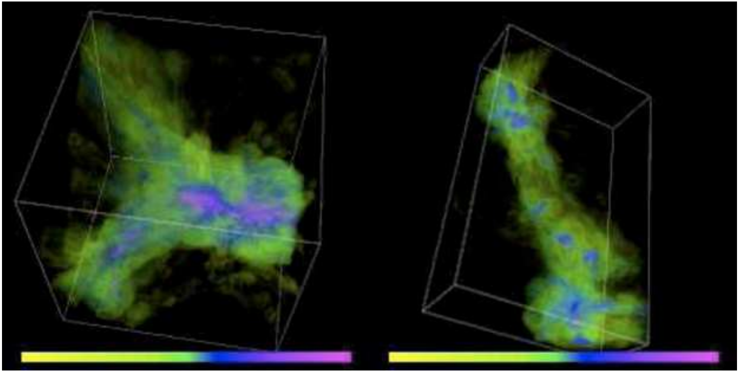
Gas density, locations of shocks, vorticity = curl of flow velocity (Ryu et al. 2008)

Model for the origin of intra-cluster magnetic fields:

- turbulent flow motions are induced via the cascade of the vorticity generated at cosmological shocks during the formation of the large scale structure
- the turbulence amplifies weak seed magnetic fields of any origin

CITA–ICAT

Volume rendered magnetic field strengths



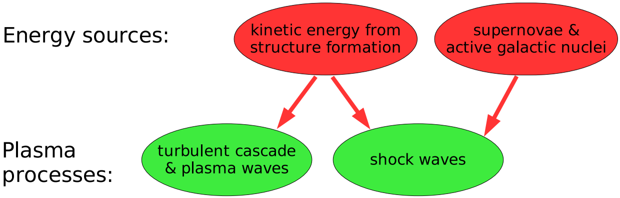
Spatial distribution of the resulting inter-galactic magnetic fields around a cluster complex and along a filament that includes a number of groups (Ryu et al. 2008).

Outline

CITA–ICAT

Multi messenger approach for non-thermal processes

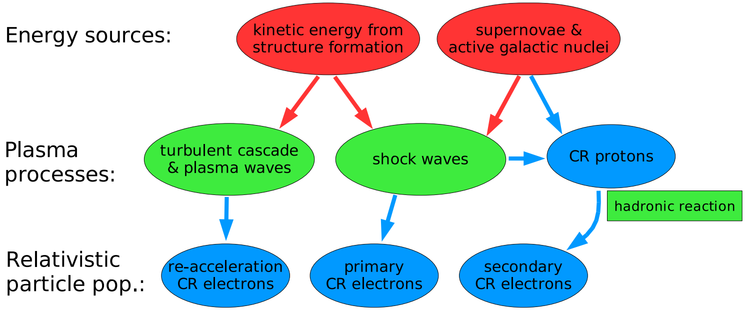
Relativistic populations and radiative processes in clusters:



CITA–ICAT

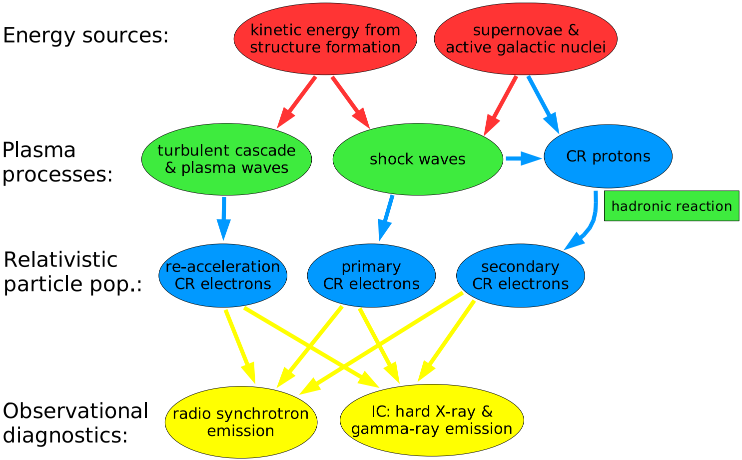
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



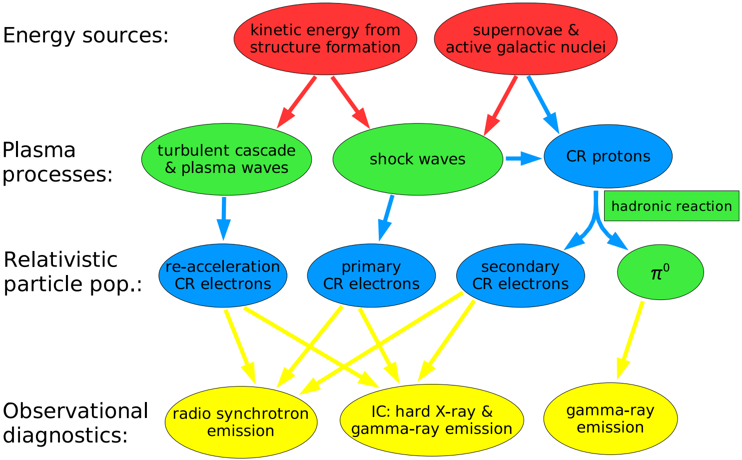
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:

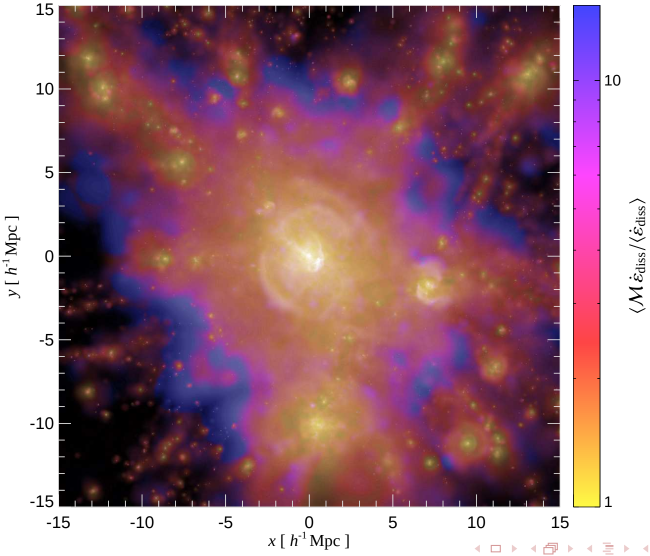


Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:

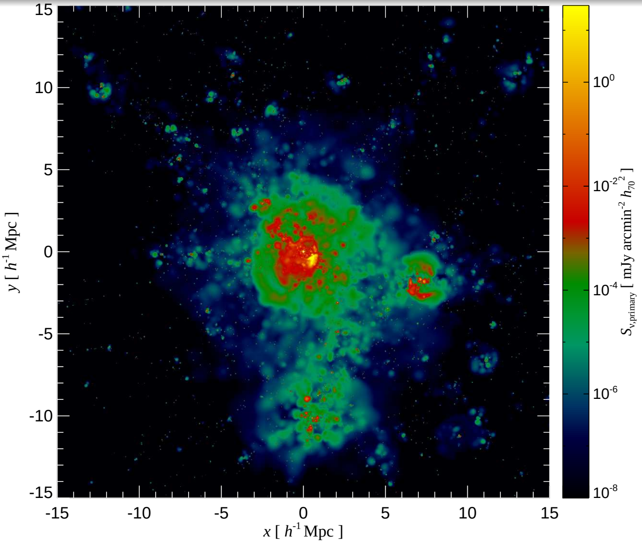


Cosmic web: Mach number



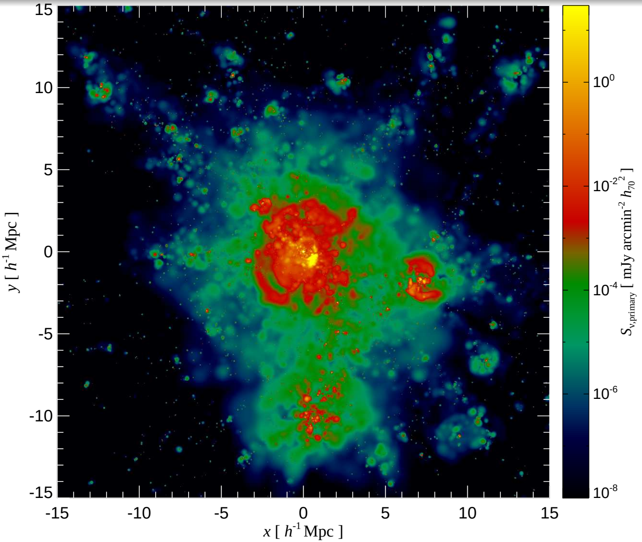
CITA–ICAT

Radio gischt (relics): primary CRe (1.4 GHz)



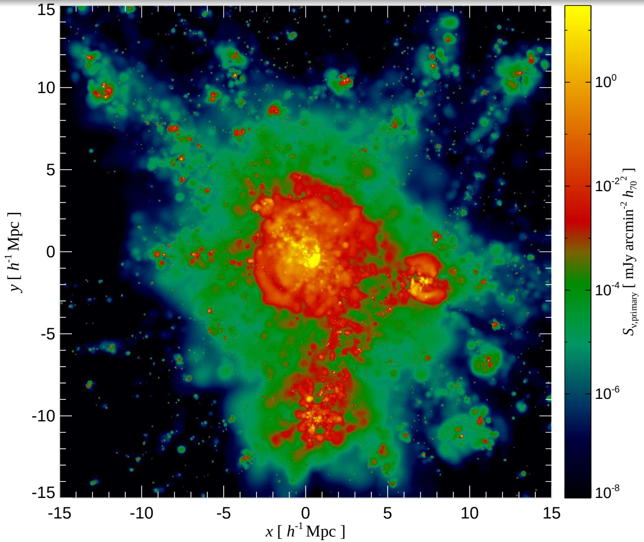
CITA–ICAT

Radio gischt: primary CRe (150 MHz)

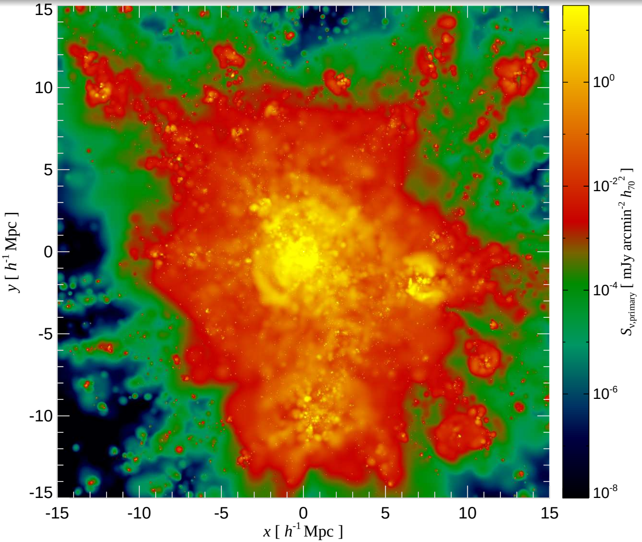


CITA–ICAT

Radio gischt: primary CRe (15 MHz)

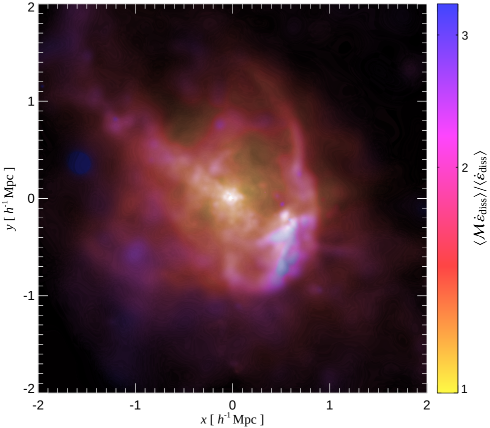


Radio gischt: primary CRe (15 MHz), slower magnetic decline

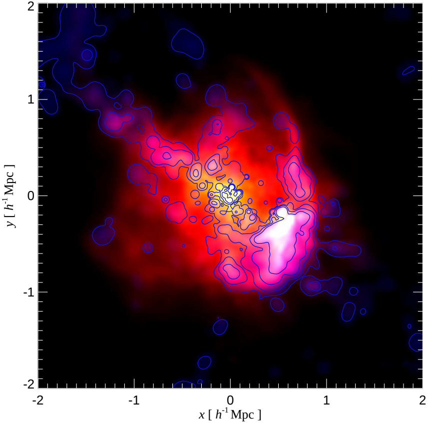


CITA–ICAT

Radio gischt illuminates cosmic magnetic fields



Structure formation shocks triggered by a recent merger of a large galaxy cluster.



red/yellow: shock-dissipated energy,

blue/contours: 150 MHz radio gischt emission from shock-accelerated CRe

CITA–ICAT

Diffuse cluster radio emission – an inverse problem

Exploring the magnetized cosmic web

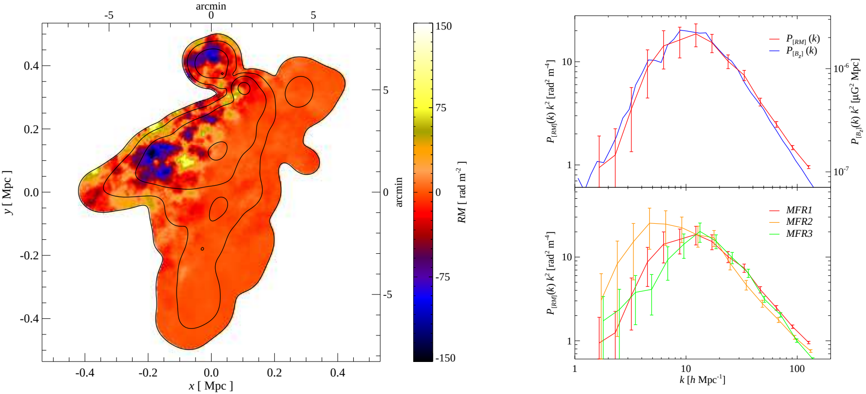
Battaglia, CP, Sievers, Bond, Enßlin (2008):

By suitably combining the observables associated with diffuse polarized radio emission at low frequencies ($\nu \sim 150$ MHz, GMRT/LOFAR/MWA/LWA), we can probe

- the strength and coherence scale of magnetic fields on scales of galaxy clusters,
- the process of diffusive shock acceleration of electrons,
- the existence and properties of the WHIM,
- the exploration of observables beyond the thermal cluster emission which are sensitive to the dynamical state of the cluster.

Rotation measure (RM)

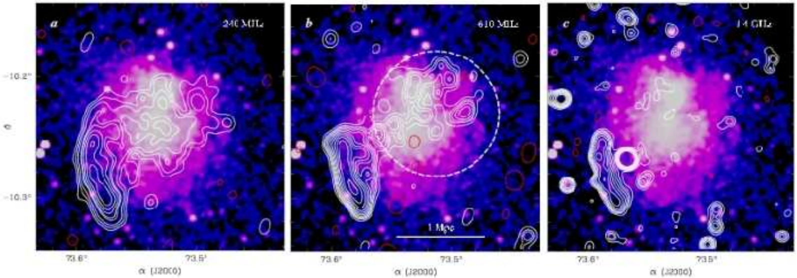
RM maps and power spectra have the potential to infer the magnetic pressure support and discriminate the nature of MHD turbulence in clusters:



Left: RM map of the largest relic, right: Magnetic and RM power spectrum comparing Kolmogorow and Burgers turbulence models.

Particle acceleration by turbulence or shocks?

Diffuse low-frequency radio emission in Abell 521 (Brunetti et al. 2008)



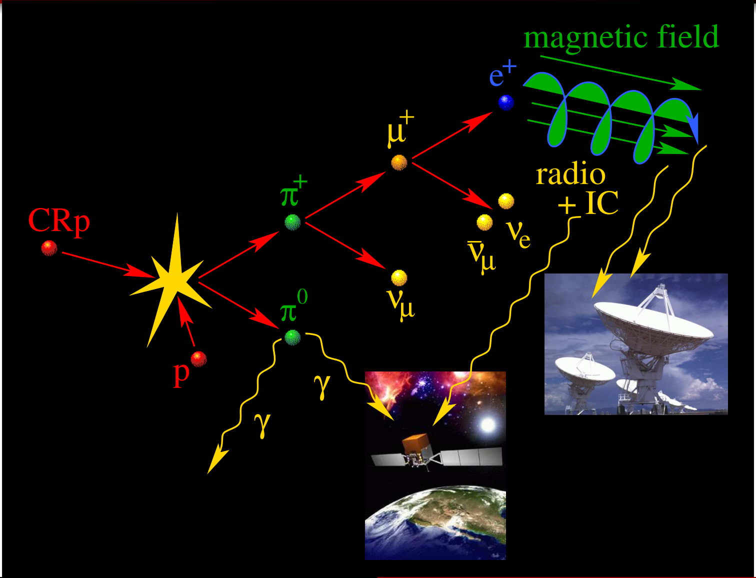
colors: thermal X-ray emission; contours: diffuse radio emission.

- “radio relic” interpretations with aged population of shock-accelerated electrons or shock-compressed radio ghosts (aged radio lobes),
- “radio halo” interpretation with re-acceleration of relativistic electrons through interactions with MHD turbulence.

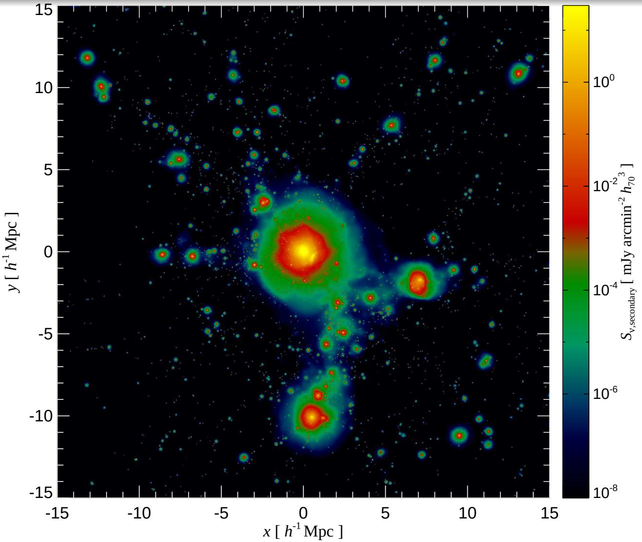
→ synchrotron polarization is key to differentiate!

CITA–ICAT

Hadronic cosmic ray proton interaction

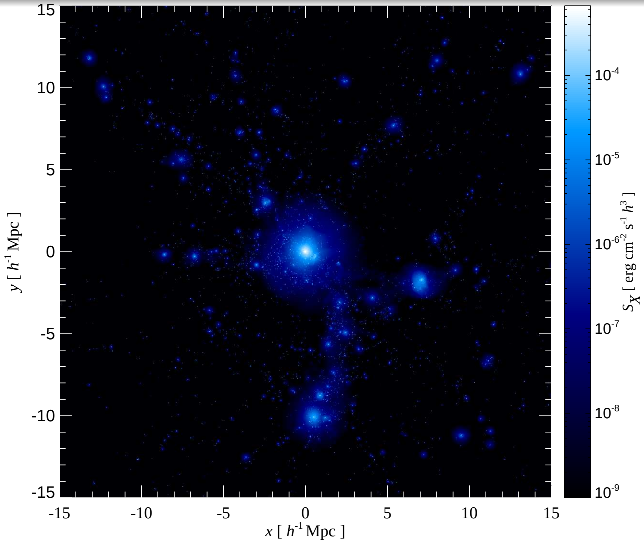


Cluster radio emission by hadronically produced CRe



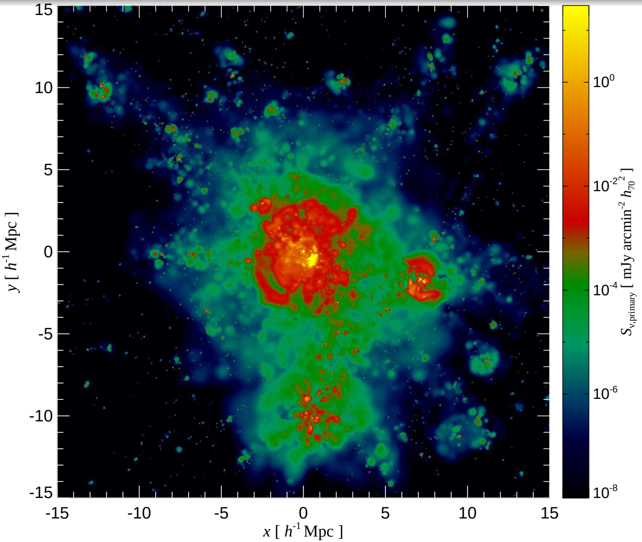
CITA–ICAT

Thermal X-ray emission



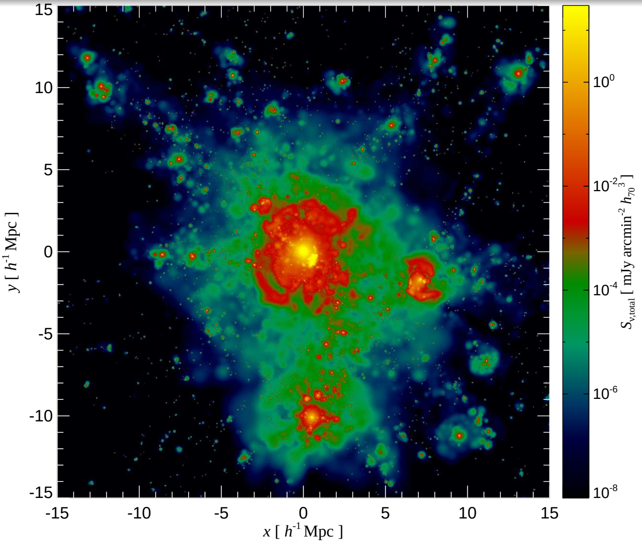
CITA–ICAT

Radio gischt: primary CRe (150 MHz)



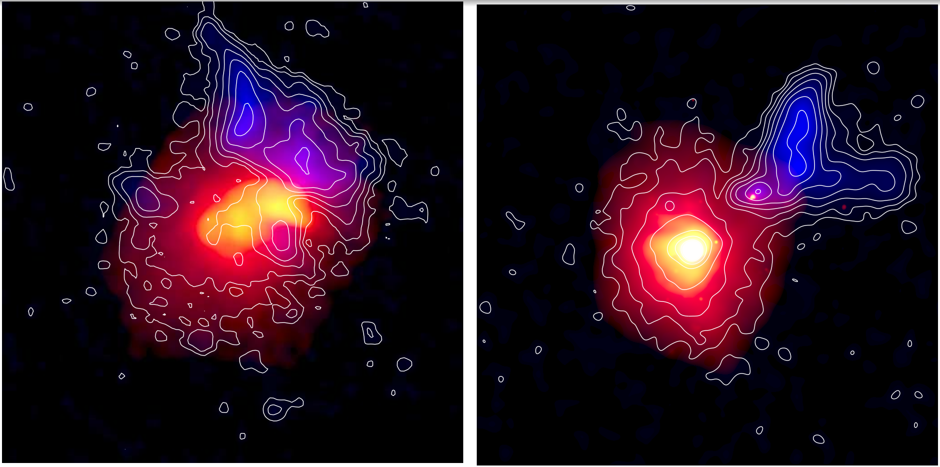
CITA–ICAT

Radio gischt + central hadronic halo = giant radio halo



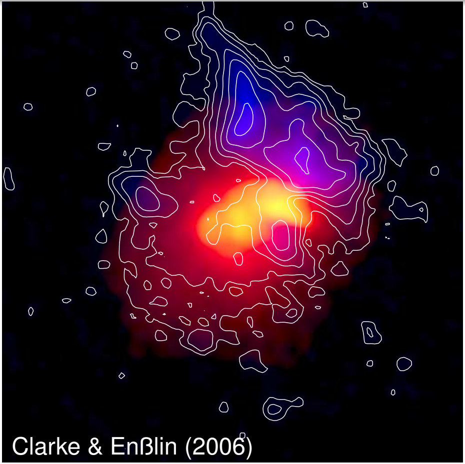
CITA–ICAT

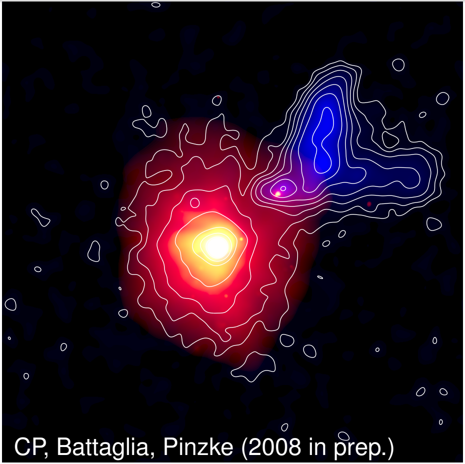
Which one is the simulation/observation of A2256?



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 $\rightarrow$ 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

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

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?
→ 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

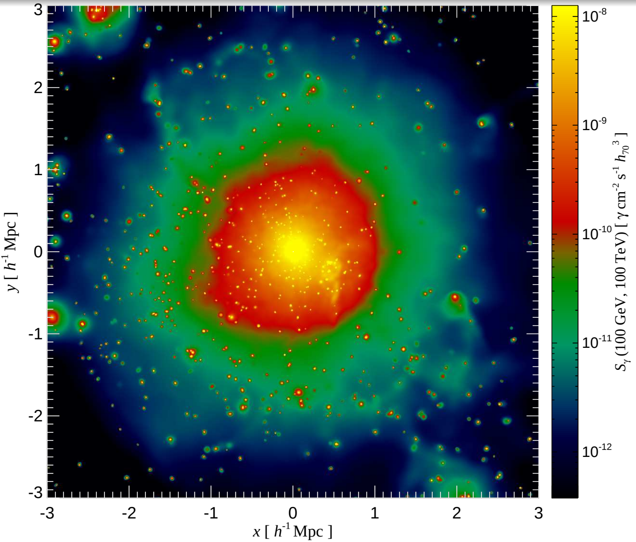
The quest for high-energy γ-ray emission from clusters

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

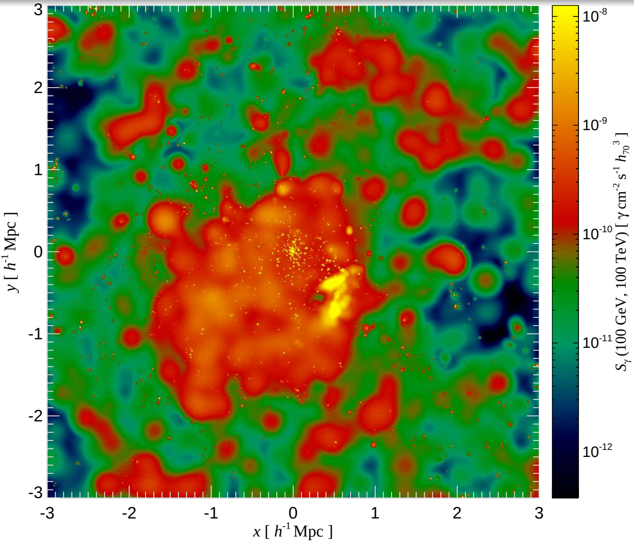
CITA–ICAT

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



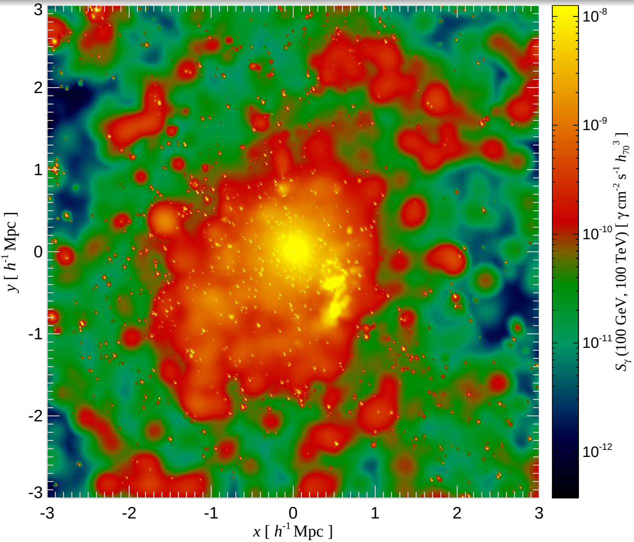
CITA–ICAT

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



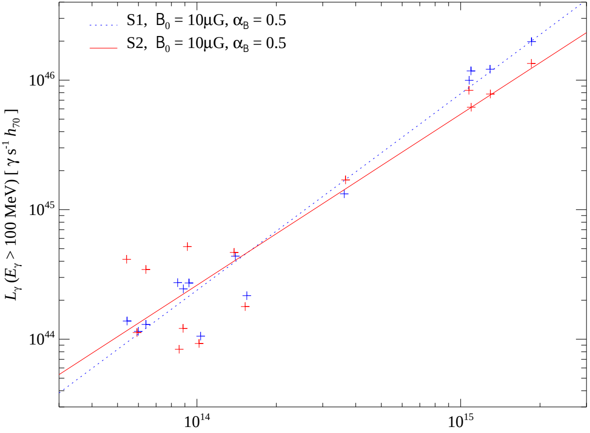
CITA–ICAT

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



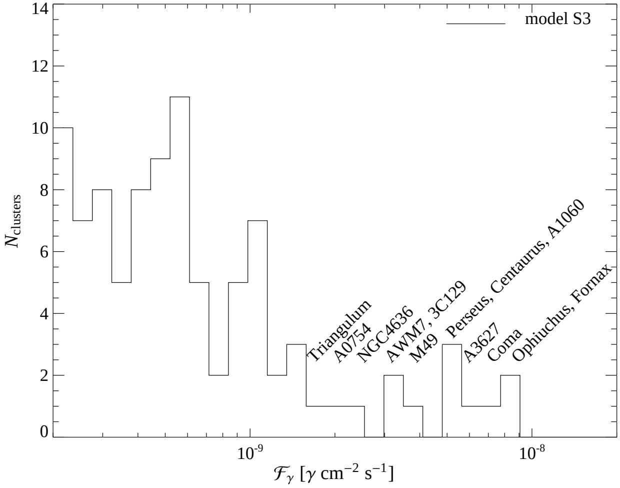
CITA–ICAT

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*



Conclusions

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

- Battaglia, Pfrommer, Sievers, Bond, Enßlin, 2008, MNRAS, in print, arXiv:0806.3272, *Exploring the magnetized cosmic web through low frequency radio emission*
- 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*
- Jubelgas, Springel, Enßlin, Pfrommer, A&A, , 481, 33, *Cosmic ray feedback in hydrodynamical simulations of galaxy formation*

CITA–ICAT