Galaxy Clusters - Cosmological Laboratories for High-Energy Astrophysics

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in collaboration with

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Jan 16, 2010 / MIT Conference on Galaxy Clusters

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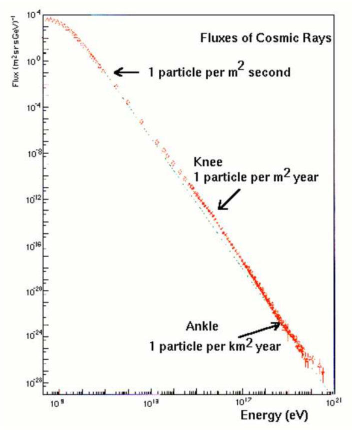
Galactic cosmic ray spectrum



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

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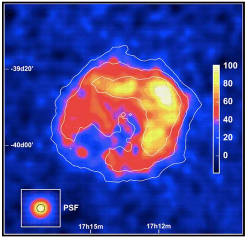
Supernova remnants

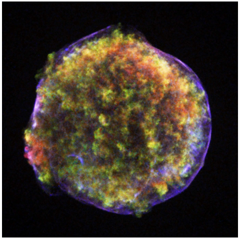
Properties of supernova remnants:

- 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)

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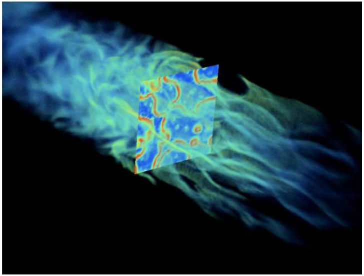
Collisionless shocks

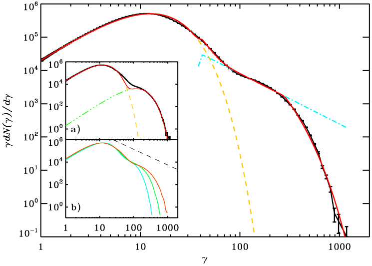
Astrophysical collisionless shocks can:

- 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

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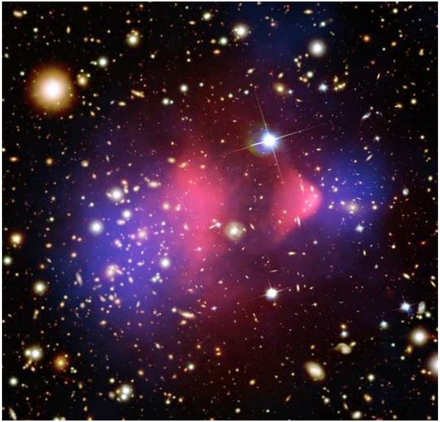
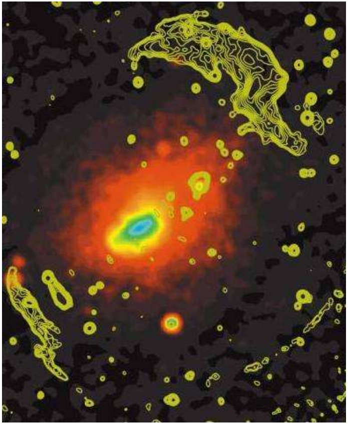
Shocks in galaxy clusters



1E 0657-56 (“Bullet cluster”)

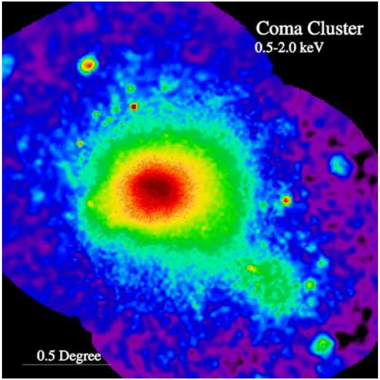
(X-ray: NASA/CXC/CfA/Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/Clowe et al.)



Abell 3667

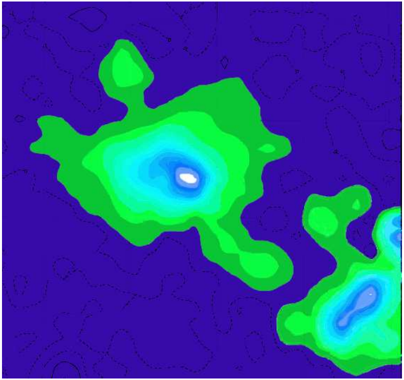
(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

Giant radio halo in the Coma cluster



thermal X-ray emission

(Snowden/MPE/ROSAT)



radio synchrotron emission

(Deiss/Effelsberg)

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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

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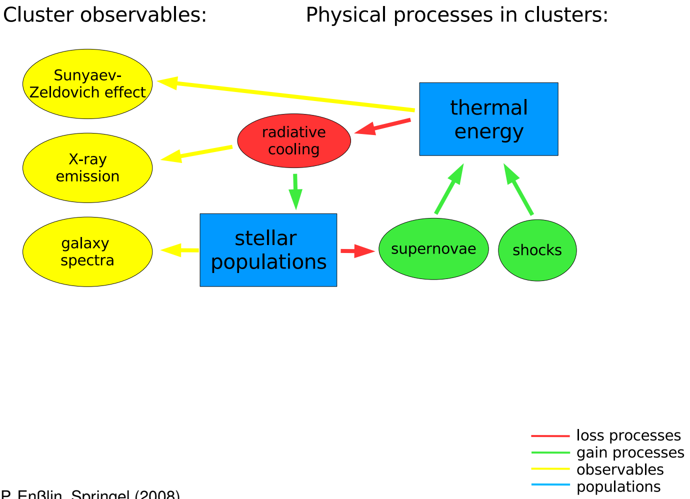
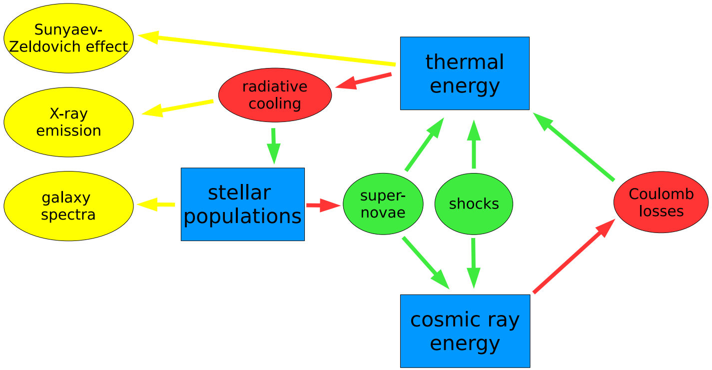
Radiative simulations – flowchart



CP, Enßlin, Springel (2008)

Radiative simulations with cosmic ray (CR) physics

Cluster observables: Physical processes in clusters:



loss processes
gain processes
observables
populations

CP, Enßlin, Springel (2008)

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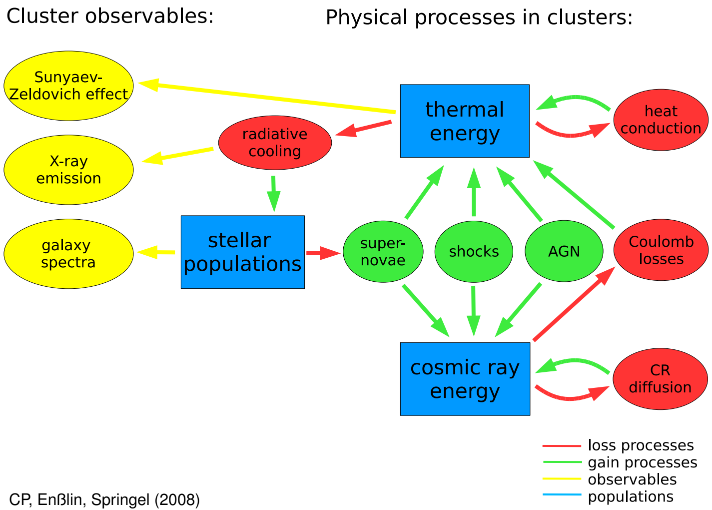
Radiative simulations with extended CR physics



CP, Enßlin, Springel (2008)

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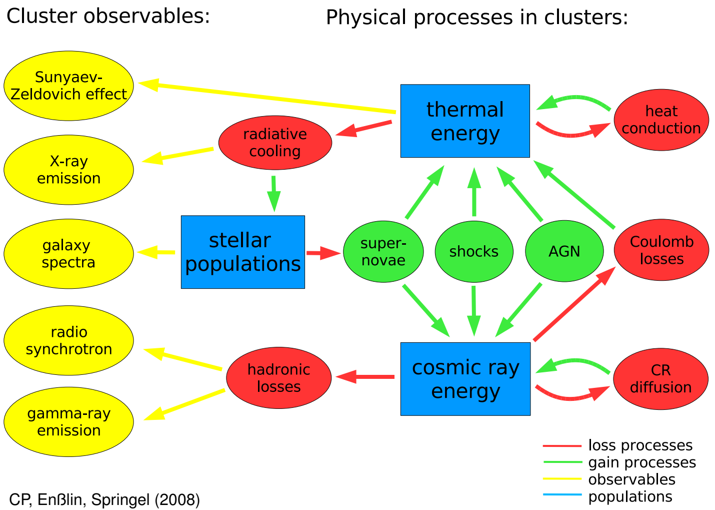
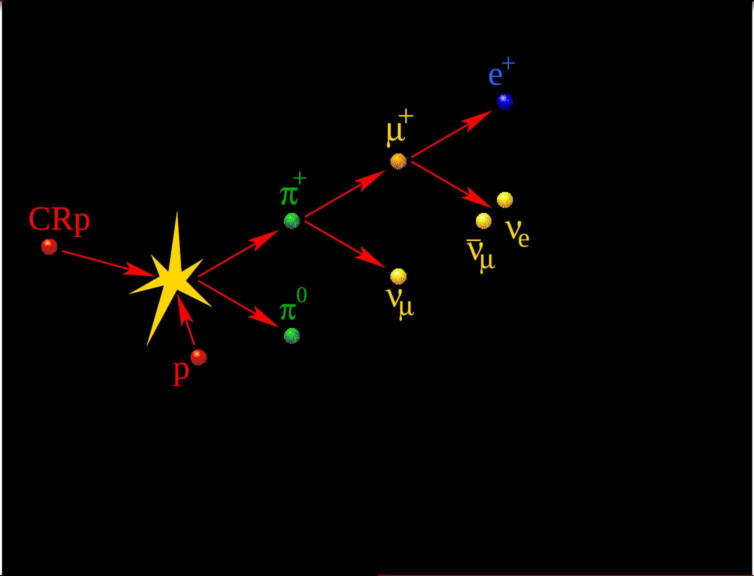


CP, Enßlin, Springel (2008)

Hadronic cosmic ray proton interaction



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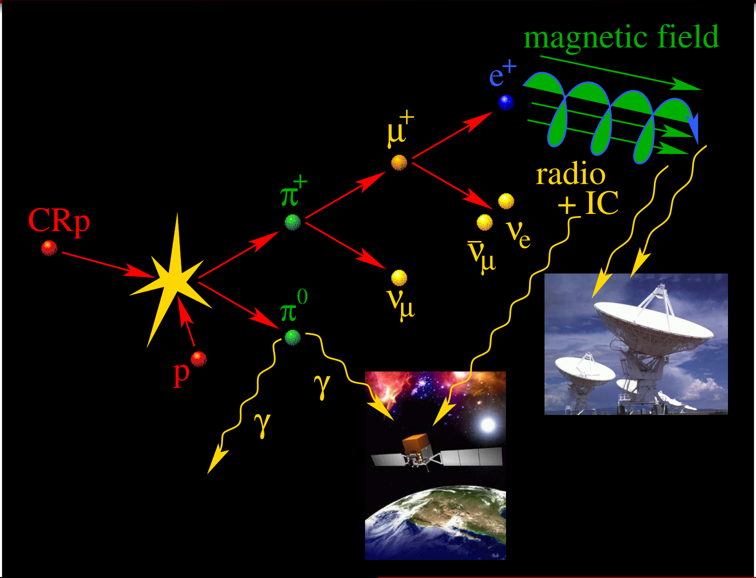


Our philosophy and description

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.

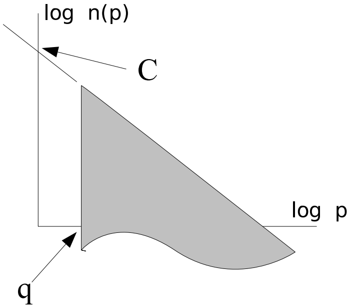
We seek a compromise between

- 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

CR spectral description



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

Enßlin, CP, Springel, Jubelgas (2007)

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

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

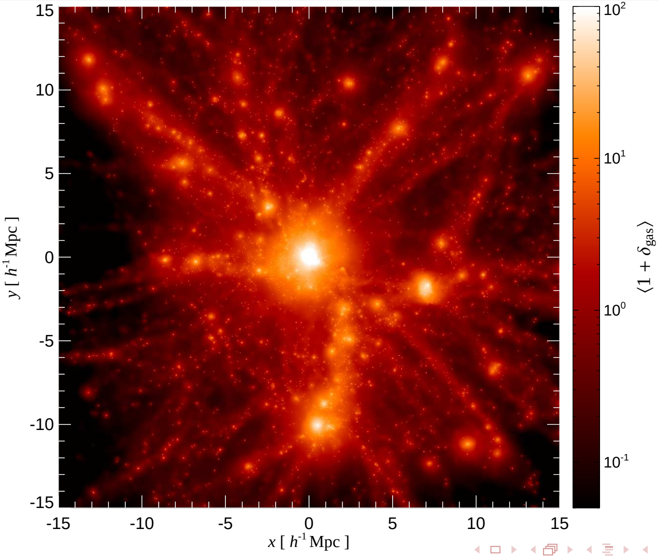
$$C(\rho) = \left(\frac{\rho}{\rho_0}\right)^{\frac{\alpha+2}{3}} C_0$$

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

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

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

Radiative cool core cluster simulation: gas density



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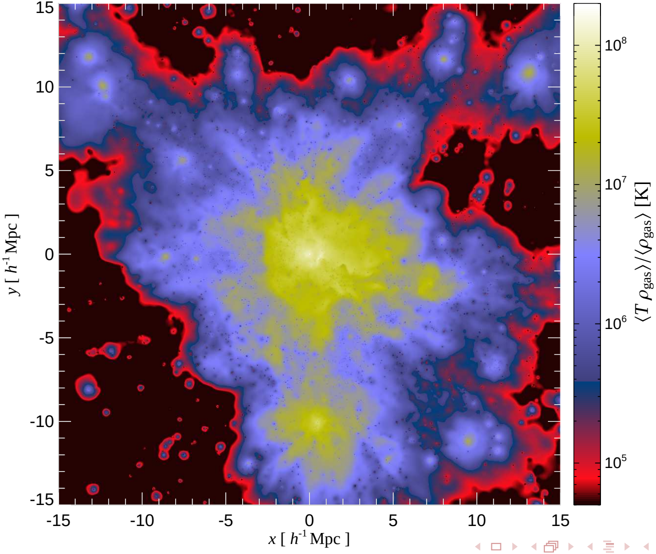
Mass weighted temperature



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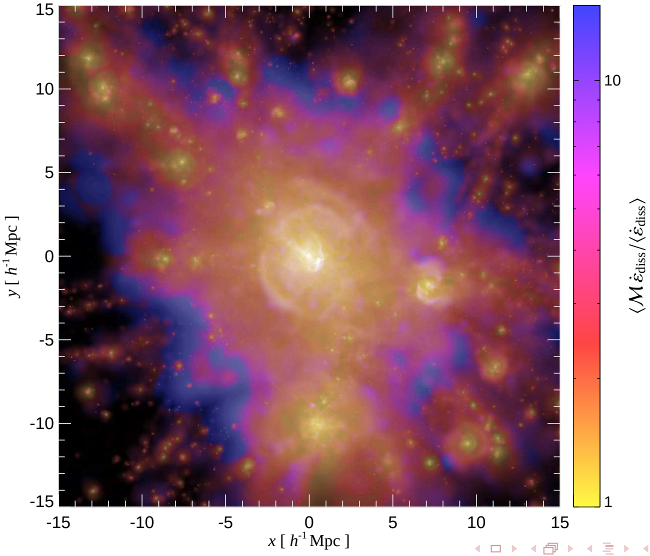
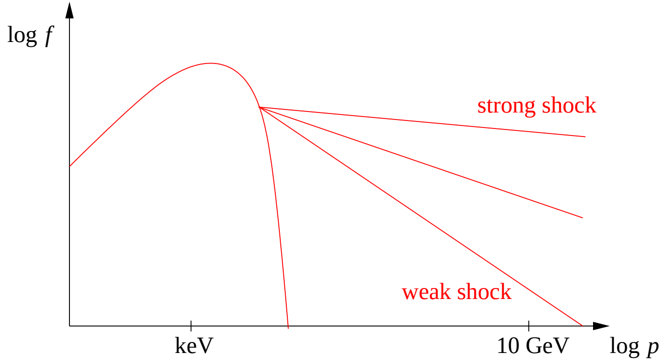
Mach number distribution weighted by $\varepsilon_{\rm diss}$



Diffusive shock acceleration – Fermi 1 mechanism

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



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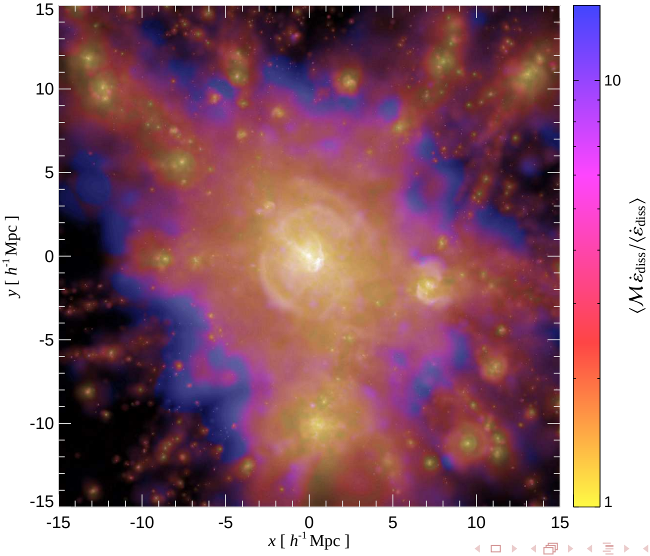

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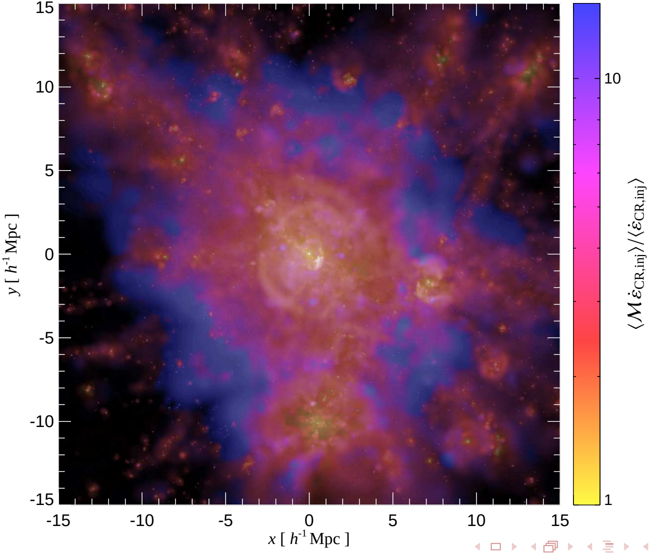
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



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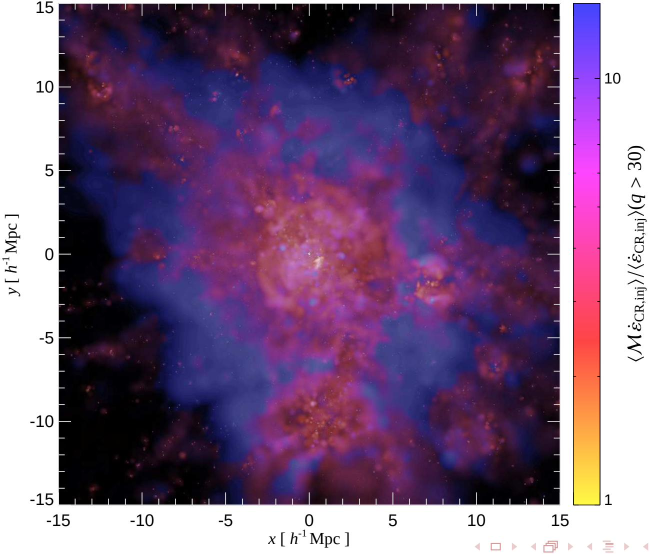
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}(q > 30)$



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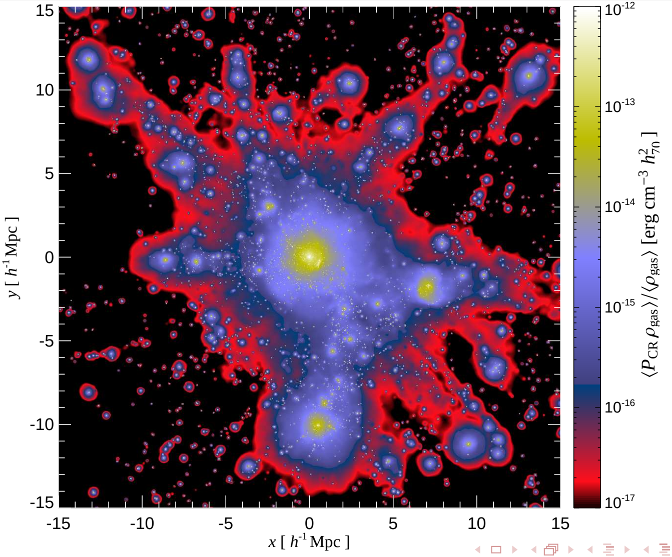
CR pressure P_{CR}



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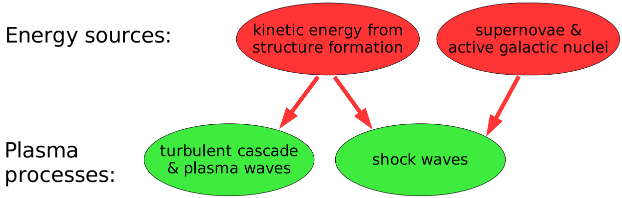
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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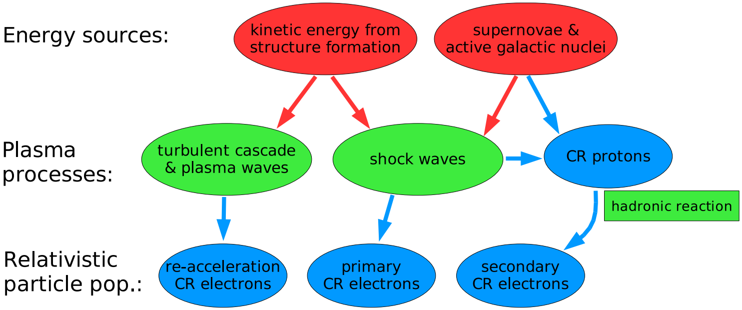

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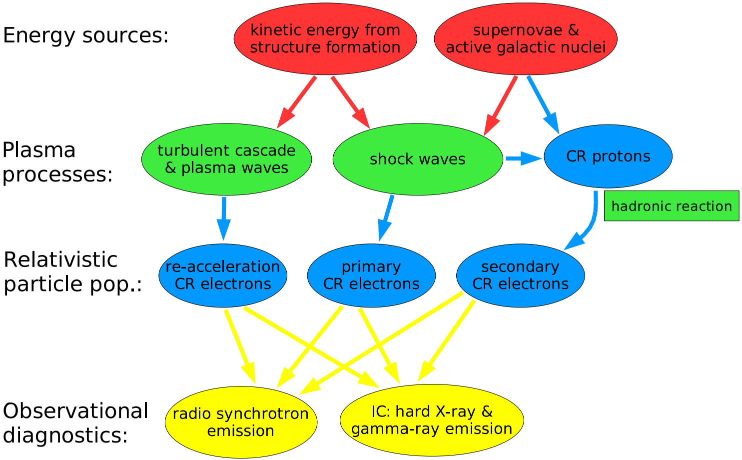

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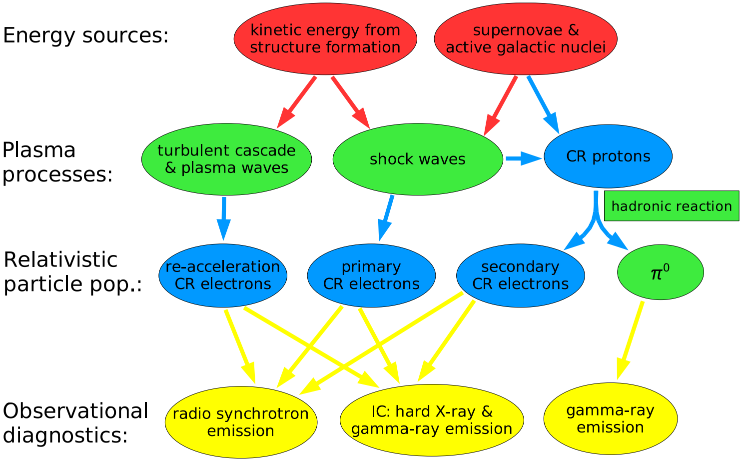
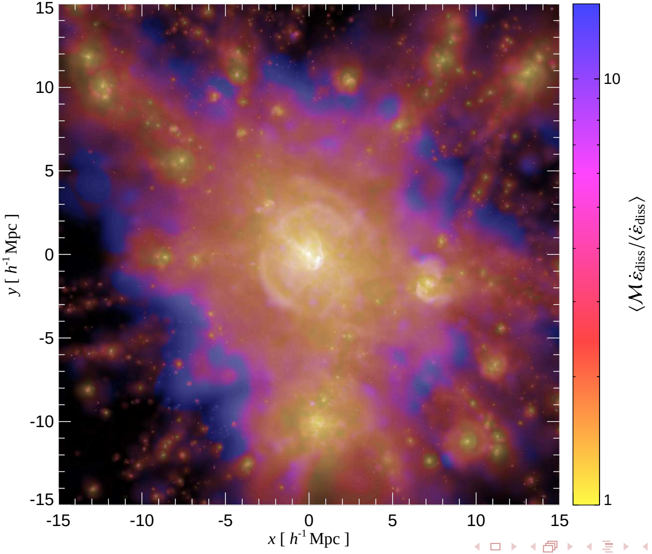


Cosmic web: Mach number



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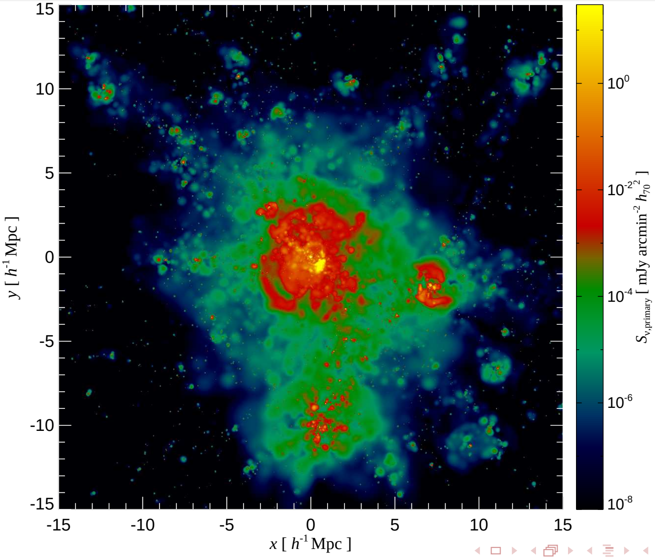
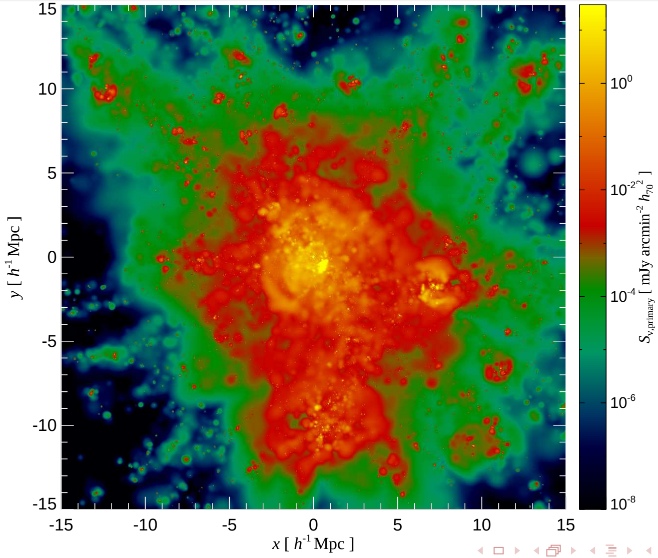
Radio gischt: primary CRe (150 MHz)



Radio gischt: primary CRe (150 MHz), slower magn. decline



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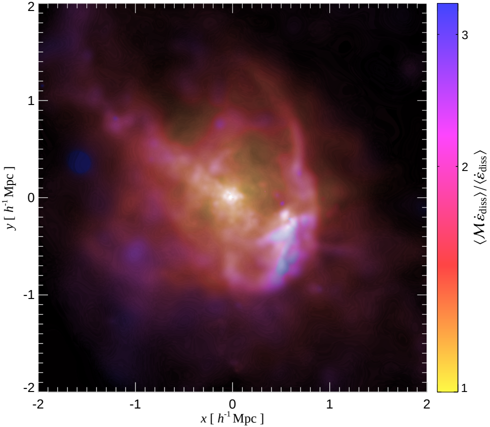
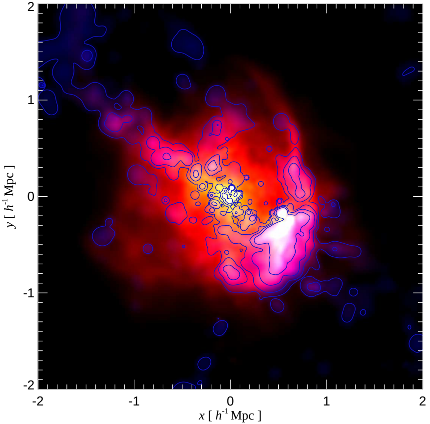
Radio gischt illuminates cosmic magnetic fields



Structure formation shocks triggered by a recent merger of a large galaxy cluster (Battaglia, CP, et al. 2008).



red/yellow: shock-dissipated energy, blue/contours: 150 MHz radio gischt emission from shock-accelerated CRe

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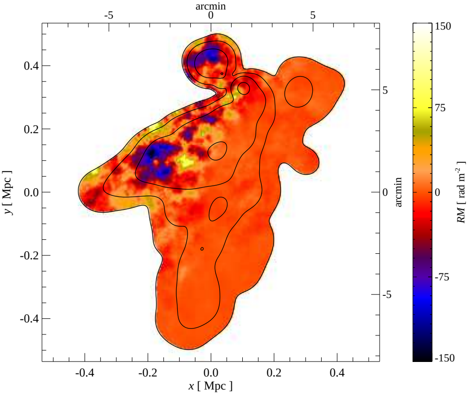
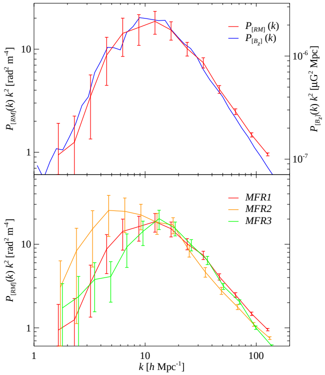
Rotation measure (RM)

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.

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Exploring the magnetized cosmic web

Cluster radio relic emission – an inverse problem

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,
- snapshots of current structure formation which enables reconstructing the recent history of clusters.

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

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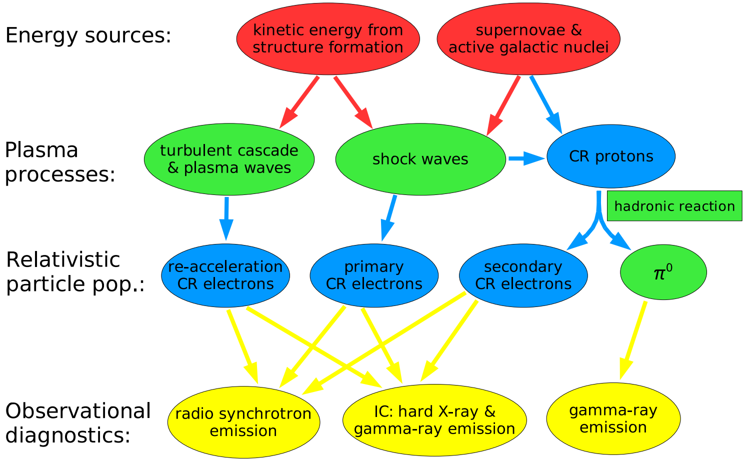

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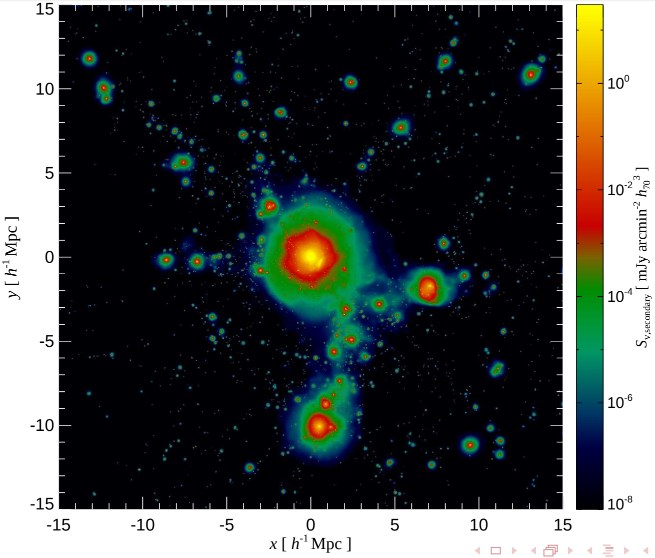
Cluster radio emission by hadronically produced CRe



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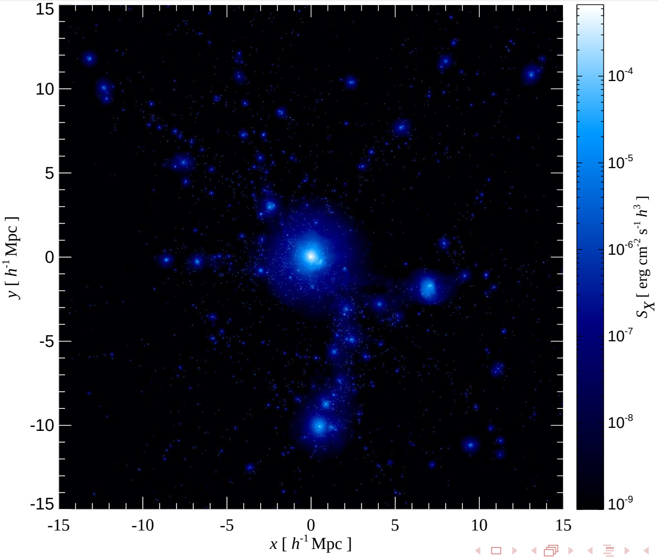
Thermal X-ray emission



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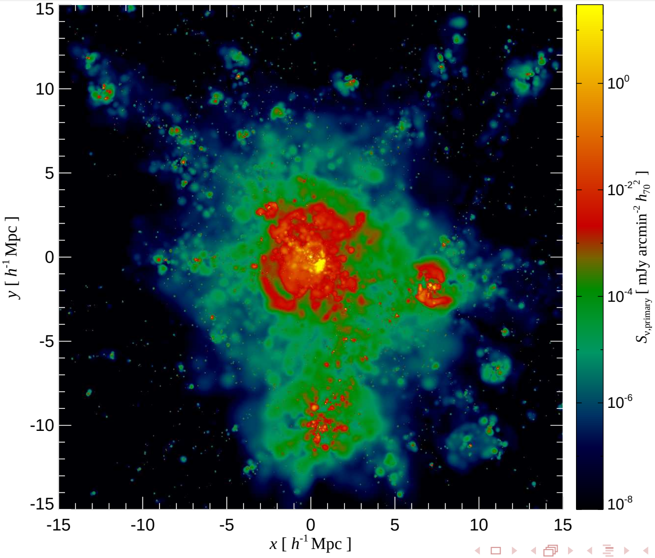

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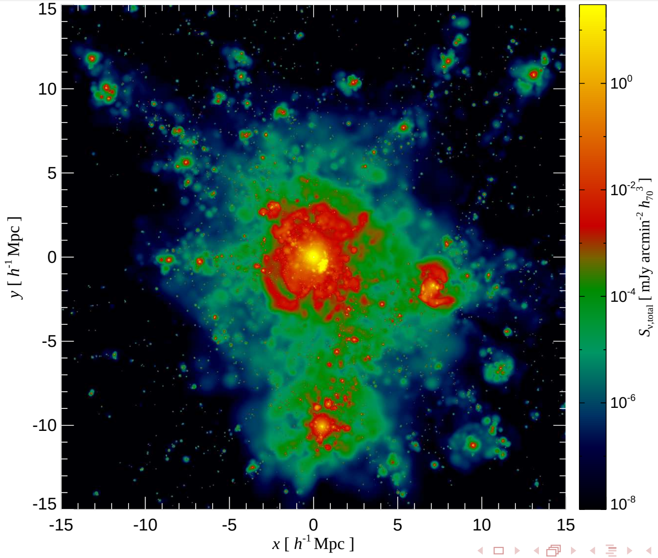
Radio gischt + central hadronic halo = giant radio halo



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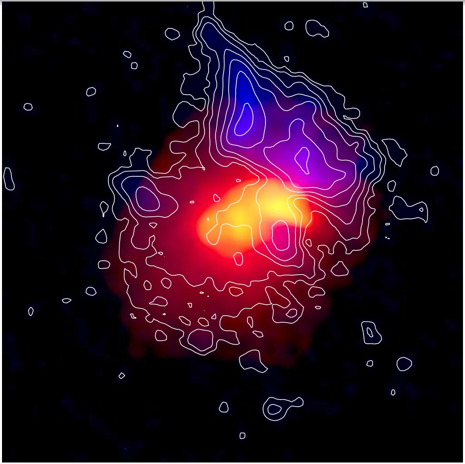
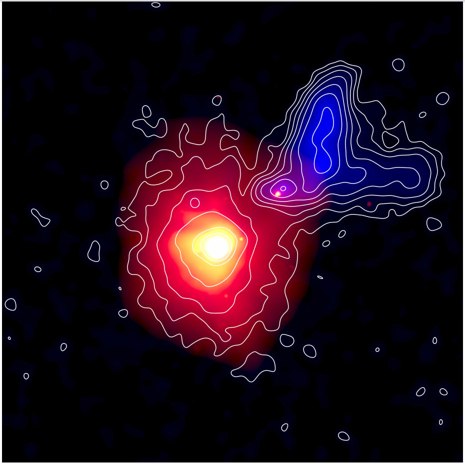
Which one is the simulation/observation of A2256?





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

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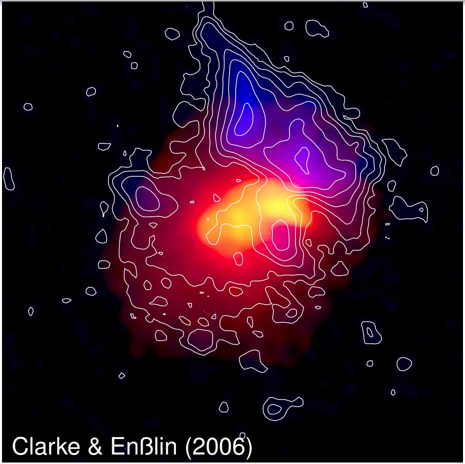
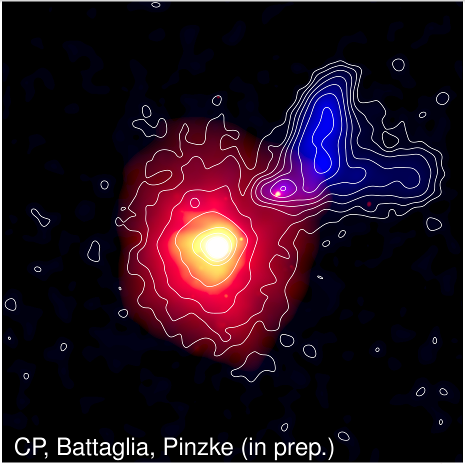
Observation – simulation of A2256





red/yellow: thermal X-ray emission,
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Unified model of radio halos and relics (CP, Enßlin, Springel 2008)

Cluster radio emission varies with dynamical stage of a cluster:

- Relaxed cluster with cool core: radio mini-halo due to hadronically produced CR electrons (cooling gas triggers radio mode feedback of AGN that outshines mini-halo → negative selection effect).
- Cluster experiences major merger: two leading shock waves 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 CR electron distribution, MHD turbulence amplifies B-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.

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Conclusions on 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)

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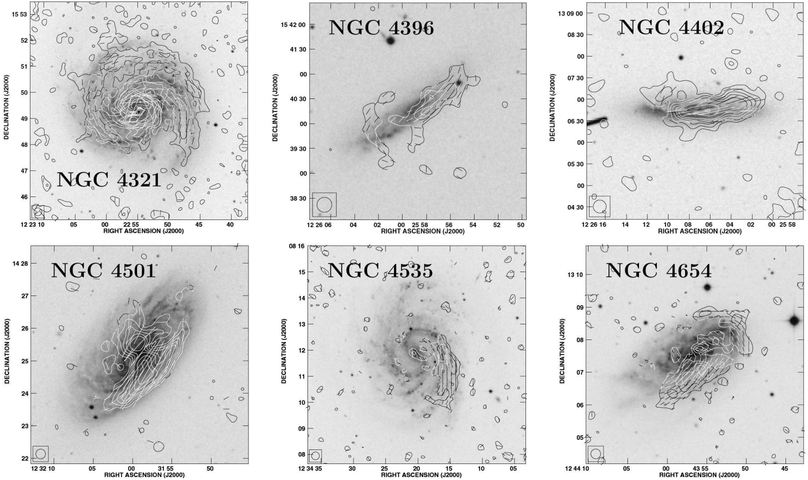
Magnetic draping at spiral galaxies – overview

Interesting blend of topics covered:

- Space Science: well understood effect, observed at planets, comets, and the coronal mass ejections of the sun
- Magneto-Hydrodynamics: suppression of Kelvin-Helmholtz instabilities, generation of vorticity/turbulence
- High-Energy Astrophysics: magnetic fields, acceleration and transport of CRs, radiative processes
- Cosmology: thermal evolution of galaxy clusters, interaction of galaxies with dense environments

CP & Dursi (2009), `arXiv:0911.2476`

Polarized synchrotron ridges in Virgo spirals



Vollmer et al. (2007): 6cm polarized intensity (contours), B-vectors, DSS b band (grey)

Observational evidence and model challenges

- asymmetric distributions of polarized intensity at the leading edge with extraplanar emission, sometimes also at the side
- coherent alignment of polarization vectors over ~ 30 kpc
- stars lead polarized emission, polarized emission leads gas
- HI gas only moderately enhanced (factor $\lesssim 2$), localized 'HI hot spot' smaller than the polarized emission region: $n_{\mathrm{compr}} \simeq n_{\mathrm{icm}}\, \upsilon_{\mathrm{gal}}^2 / c_{\mathrm{ism}}^2 \simeq 1\,\mathrm{cm}^{-3} \simeq \langle n_{\mathrm{ism}} \rangle$
- flat radio spectral index (similar to the Milky Way) that steepens towards the edges of the polarized ridge
- no or weak Kelvin-Helmholtz instabilities at interface detectable

$\rightarrow$ previous models that use ram-pressure compressed galactic magnetic fields fail to explain most of these points!

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Observational evidence and model challenges

- asymmetric distributions of polarized intensity at the leading edge with extraplanar emission, sometimes also at the side
- coherent alignment of polarization vectors over $\sim$ 30 kpc
- stars lead polarized emission, polarized emission leads gas
- HI gas only moderately enhanced (factor $\lesssim 2$), localized 'HI hot spot' smaller than the polarized emission region:
  $n_\mathrm{compr} \simeq n_\mathrm{icm}\, \upsilon_\mathrm{gal}^2 / c_\mathrm{ism}^2 \simeq 1\,\mathrm{cm}^{-3} \simeq \langle n_\mathrm{ism} \rangle$
- flat radio spectral index (similar to the Milky Way) that steepens towards the edges of the polarized ridge
- no or weak Kelvin-Helmholtz instabilities at interface detectable

$\rightarrow$ need to consider the full MHD of the interaction spiral galaxy and magnetized ICM !

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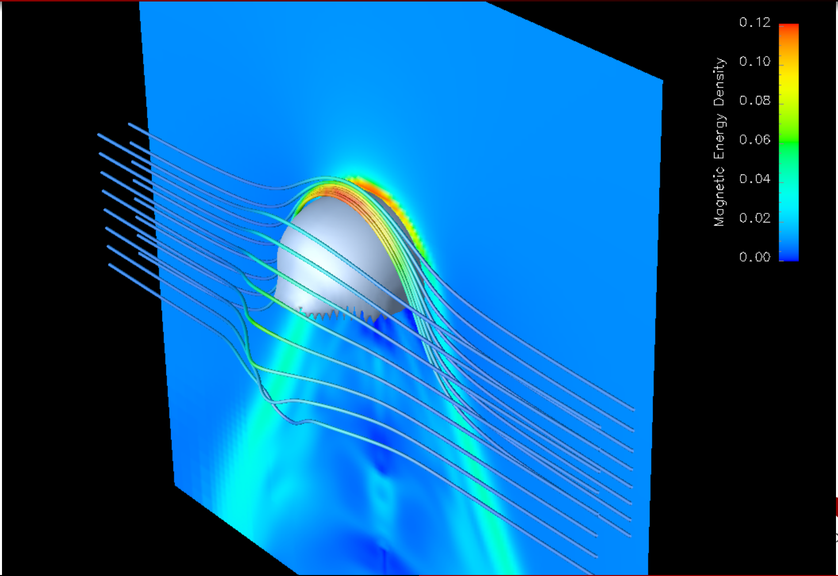
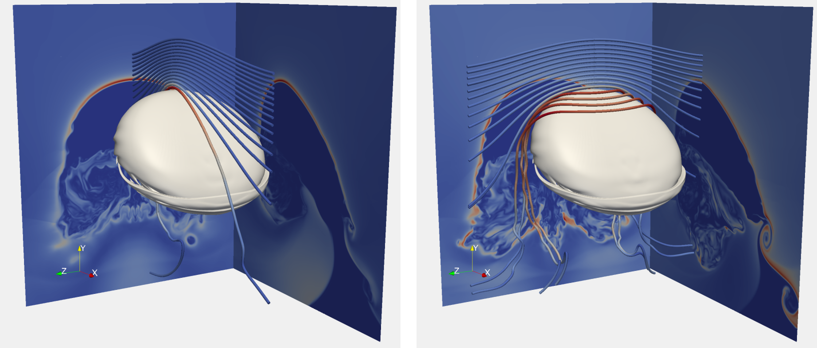
Draping field lines around a moving object



Magnetic draping around a spiral galaxy – MHD



Athena simulations of spiral galaxies interacting with a uniform cluster magnetic field. There is a sheath of strong field draped around the leading edge (field strength is color coded).

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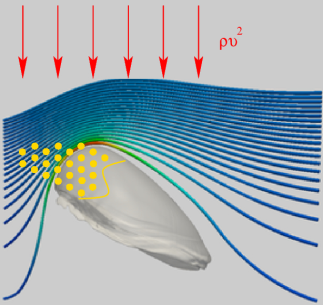
Magnetic draping around a spiral galaxy – physics



- the galactic ISM is pushed back by the ram pressure wind $\sim \rho \upsilon^2$
- the stars are largely unaffected and lead the gas
- the draping sheath is formed at the contact of ISM/ICM
- as stars become SN, their remnants accelerate CRes that populate the field lines in the draping layer

- CRes are transported diffusively (along field lines) and advectively as field lines slip over the galaxy
- CRes emit radio synchrotron radiation in the draped region, tracing out the field lines there $\rightarrow$ coherent polarized emission at the galaxies' leading edges

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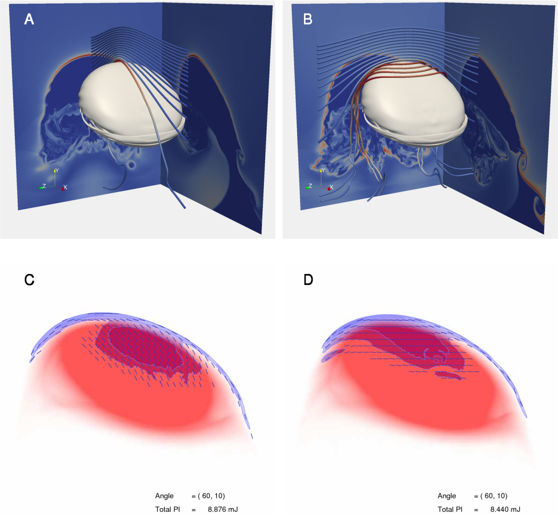
Magnetic draping and polarized synchrotron emission

Synchrotron B-vectors reflect the upstream orientation of cluster magnetic fields



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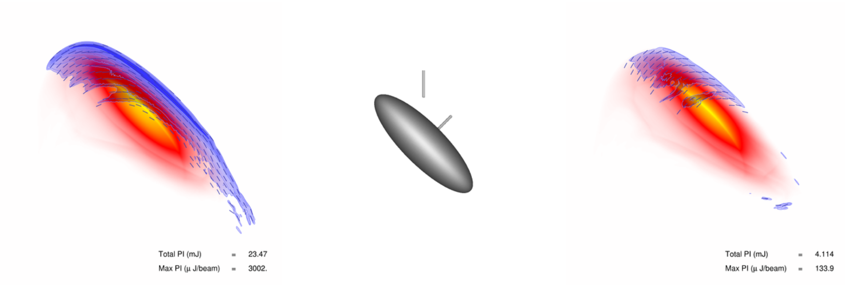
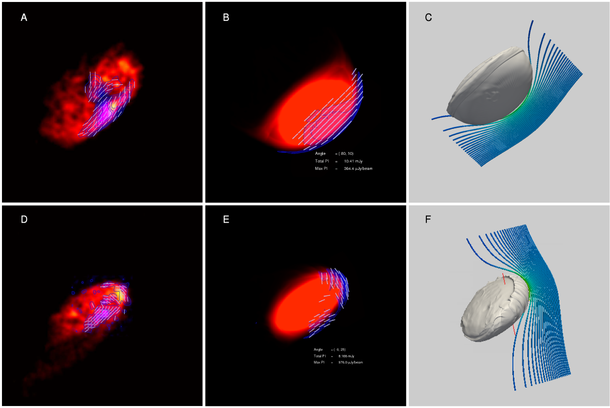
Simulated polarized synchrotron emission



Movie of the simulated polarized synchrotron radiation viewed from various angles and with two field orientations.

Observations versus simulations



HI emission of two spirals (red) is compared to the polarized radio synchrotron ridges at 6 cm (blue and contours) and B-vectors.

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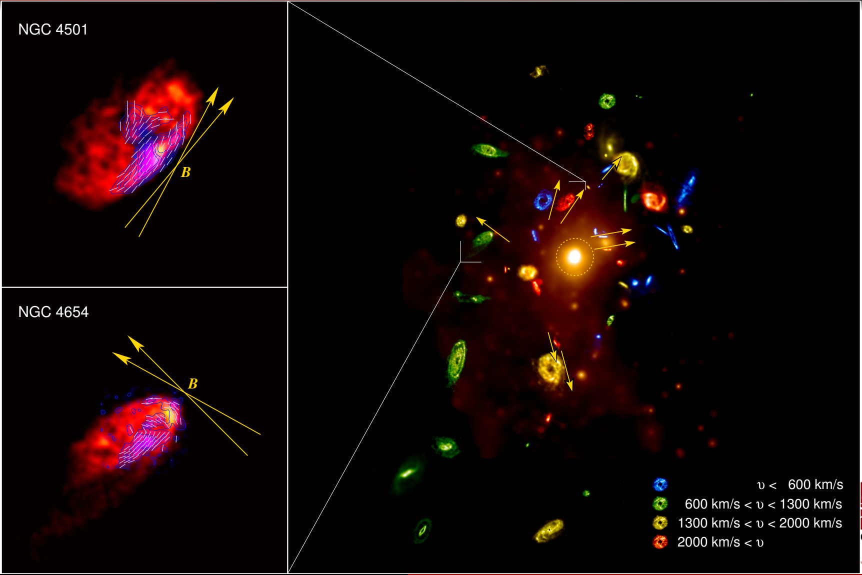
Mapping out the magnetic field in Virgo



Discussion of radial field geometry

- The alignment of the field in the plane of the sky is significantly more radial than expected from random chance. Considering the sum of deviations from radial alignment gives a chance coincidence of less than 1.7% ($\sim 2.2\,\sigma$).
- The isotropic distribution with respect to the centre (M87) is difficult to explain with the past activity of the central AGN.

$\rightarrow$ Which effect causes this field geometry?

The magneto-thermal instability: the idea

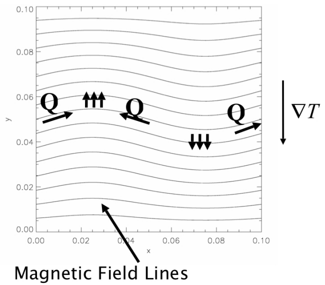


Figure from I. Parrish

Convective stability in a gravitational field:

- Classical Schwarzschild criterion: $\frac{\mathrm{d}S}{\mathrm{d}z} > 0$
- long MFP, Balbus criterion: $\frac{\mathrm{d}T}{\mathrm{d}z} > 0$
- new instability causes field lines to reorient radially $\rightarrow$ efficient thermal conduction radially (close to Spitzer)

The non-linear behavior of the MTI (Parrish & Stone 2007).

- Adiabatic boundary conditions for $T(r)$: the instability can exhaust the source of free energy $\rightarrow$ isothermal profile
- Fixed boundary conditions for $T(r)$: field lines stay preferentially radially aligned (35 deg mean deviation from radial)

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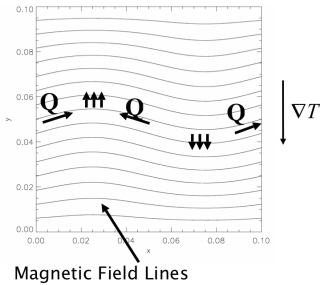
The magneto-thermal instability: the idea



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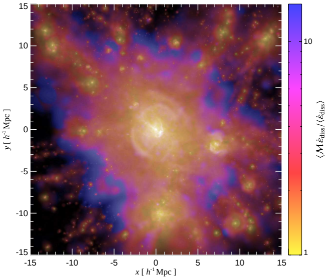
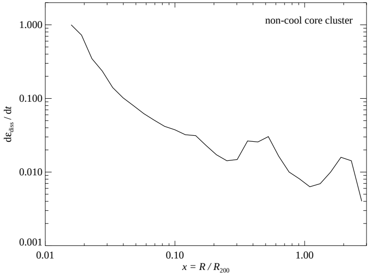
Gravitational shock wave heating

The observed temperature profile in clusters is decreasing outwards which is the necessary condition for MTI to operate → *gravitational heating can stabilize the temperature profile:*



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



Energy flux through shock surface $\dot{E}/A \sim \rho \upsilon^3$ → increase towards the center

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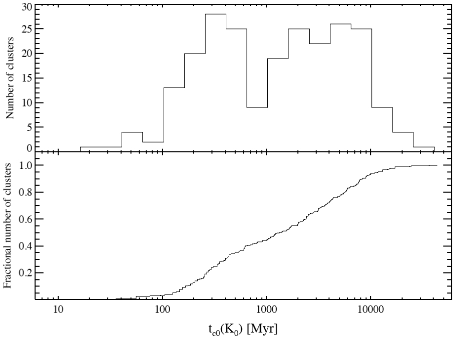
Implications for thermal stability of galaxy clusters



Cavagnolo et al. (2009)

- radial fields in non-cool core clusters (NCCs) imply efficient thermal conduction that stabilizes these systems against entering a cool-core state: $\tau_{\rm cond} = \lambda^2/\chi_{\rm C} \simeq 2.3\,{\rm Gyr}\,(\lambda/1\,{\rm Mpc})^2$, where $\chi_{\rm C}$ is the Spitzer thermal diffusivity
- current cosmological cluster simulations fail to reproduce NCCs that have no AGN activity → MHD + anisotropic conduction

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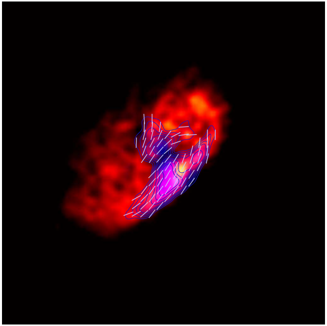
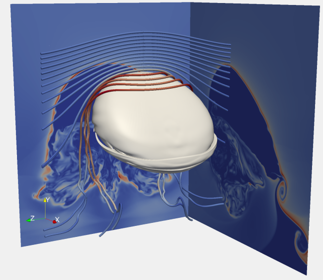
Conclusions on magnetic draping around galaxies



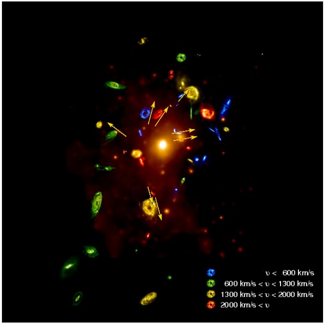
- draping of cluster magnetic fields naturally explains polarization ridges at Virgo spirals

Conclusions on magnetic draping around galaxies



- draping of cluster magnetic fields naturally explains polarization ridges at Virgo spirals
- this represents a new tool for measuring the in situ 3D orientation and coherence scale of cluster magnetic fields

Conclusions on magnetic draping around galaxies



- draping of cluster magnetic fields naturally explains polarization ridges at Virgo spirals
- this represents a new tool for measuring the in situ 3D orientation and coherence scale of cluster magnetic fields
- application to the Virgo cluster shows that the magnetic field is preferentially aligned radially

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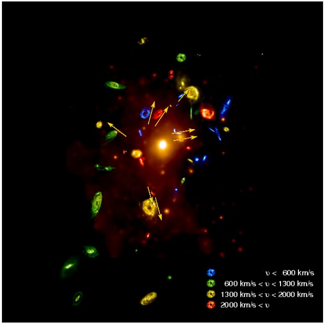
Conclusions on magnetic draping around galaxies



- draping of cluster magnetic fields naturally explains polarization ridges at Virgo spirals
- this represents a new tool for measuring the in situ 3D orientation and coherence scale of cluster magnetic fields
- application to the Virgo cluster shows that the magnetic field is preferentially aligned radially

- this finding is suggestive that the MTI may be operating and implies efficient thermal conduction close to the Spitzer value
- it also proposes that non-cool core clusters are stabilized by thermal conduction

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Final 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

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Literature for the talk

- Pfrommer & Dursi, submitted, arXiv:0911.2476, *Detecting the orientation of magnetic fields in galaxy clusters*
- Battaglia, Pfrommer, Sievers, Bond, Enßlin, 2009, MNRAS, 393, 1073, *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*

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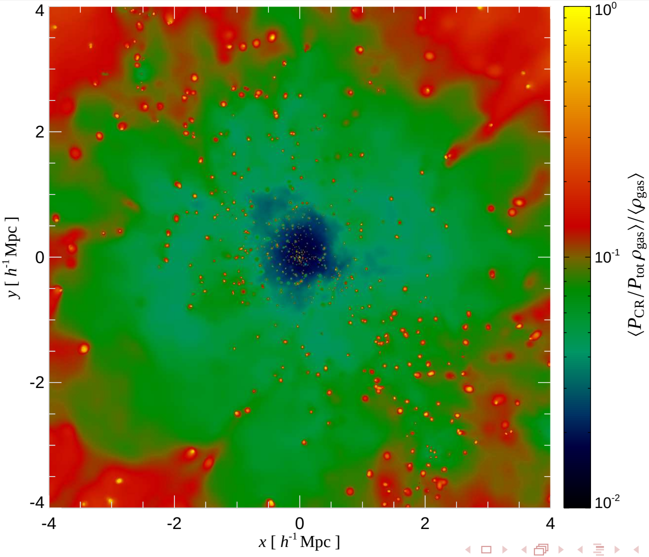
Relative CR pressure $P_{\mathrm{CR}}/P_{\mathrm{total}}$



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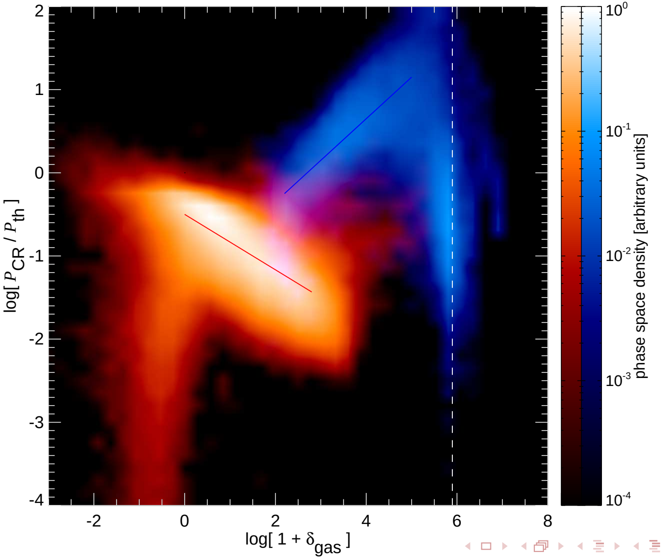
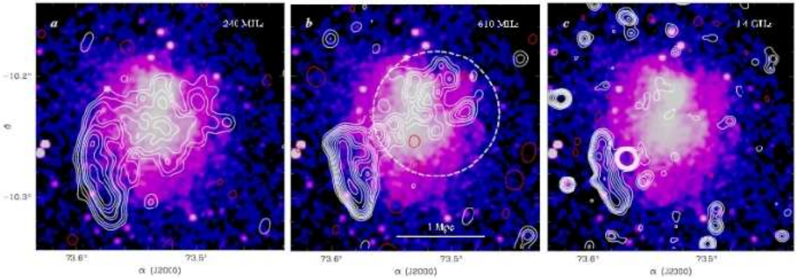
CR phase-space diagram: final distribution @ $z = 0$



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!