Galaxy Clusters - Cosmological Laboratories for High-Energy Astrophysics

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in collaboration with

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Outline

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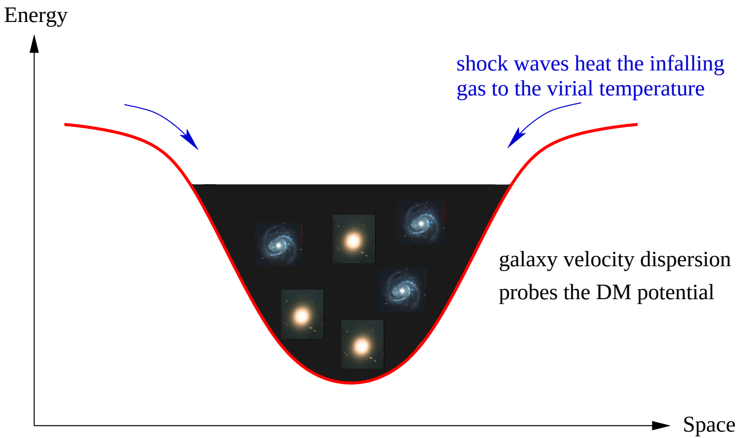
A theorist's perspective of a galaxy cluster . . .

Galaxy clusters are dynamically evolving dark matter potential wells:



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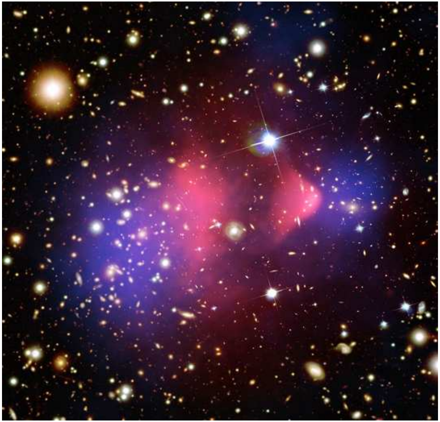
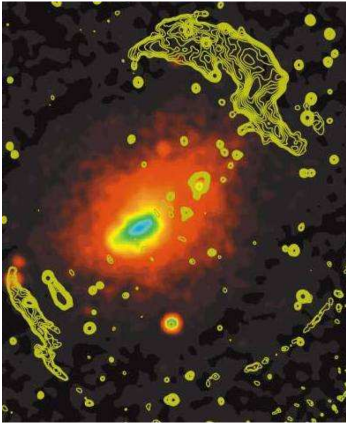
. . . and how the observer's Universe looks like



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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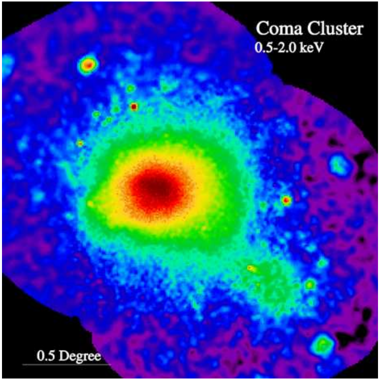
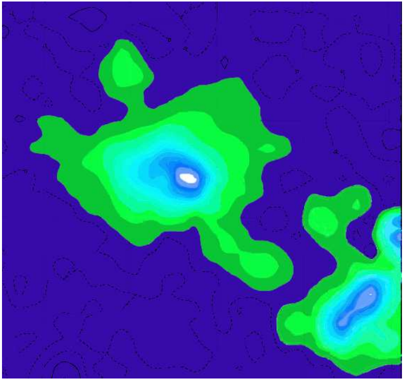
Giant radio halo in the Coma cluster



thermal X-ray emission

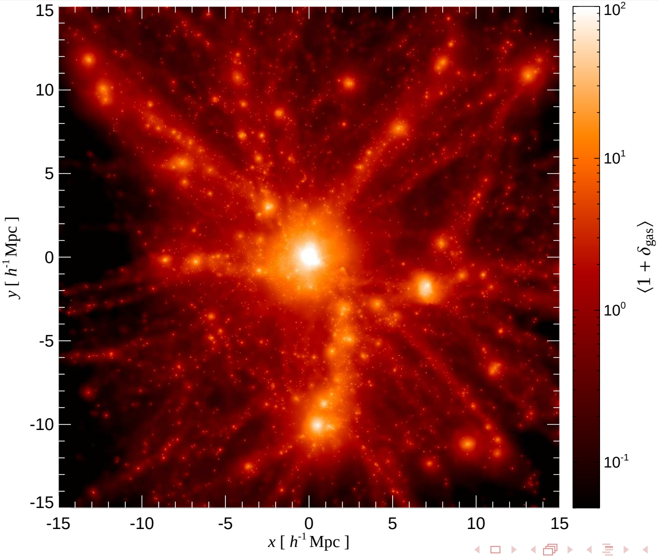
(Snowden/MPE/ROSAT)



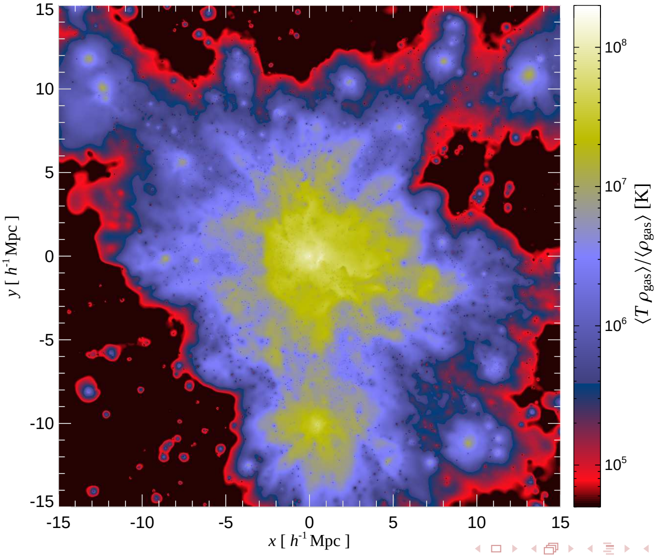
radio synchrotron emission

(Deiss/Effelsberg)

Radiative cool core cluster simulation: gas density



Mass weighted temperature



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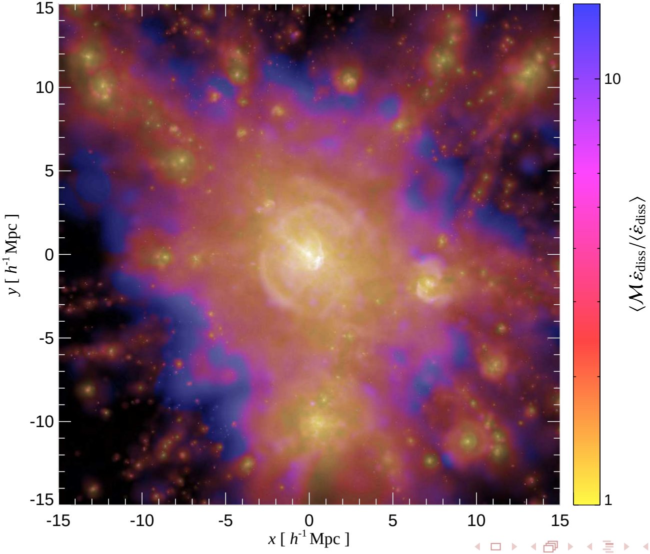
Mach number distribution weighted by $\varepsilon_{\text{diss}}$



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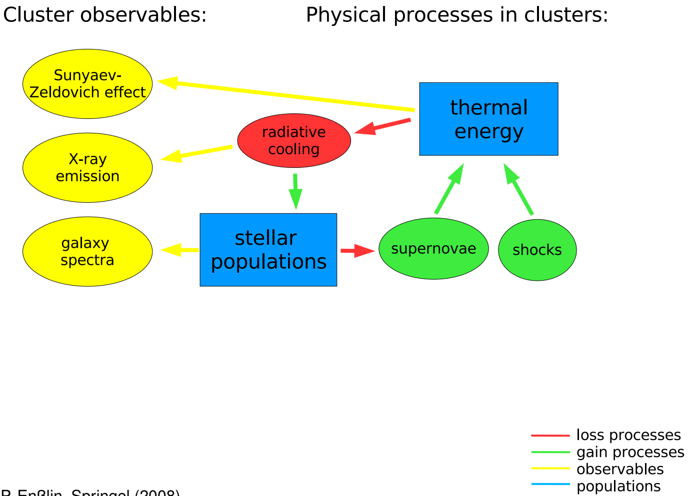
Radiative simulations – flowchart



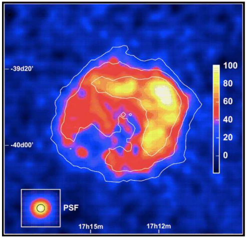
CP, Enßlin, Springel (2008)

Collisionless shocks at supernova remnants

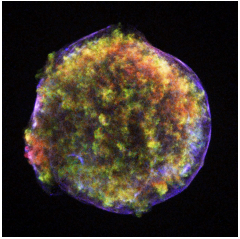
Astrophysical collisionless shocks can:

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

SN 1006 X-rays (CXC/Hughes)



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



Tycho X-rays (CXC)

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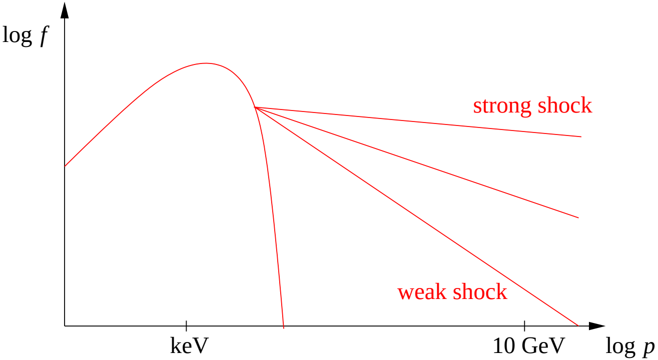
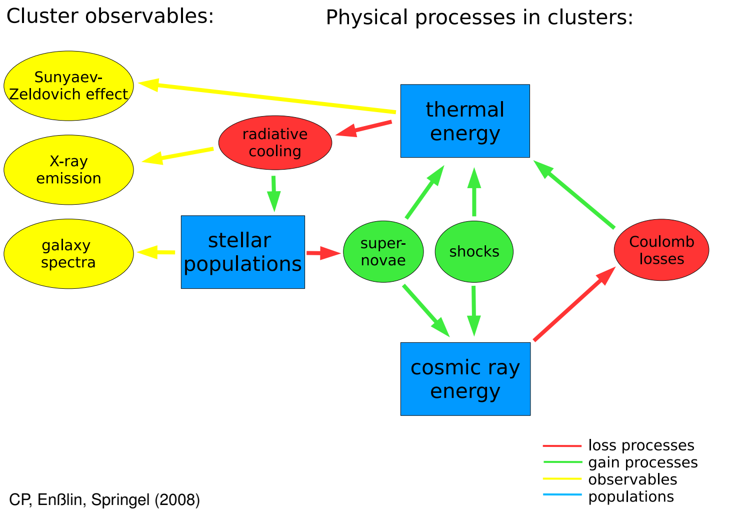
Diffusive shock acceleration – Fermi 1 mechanism

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

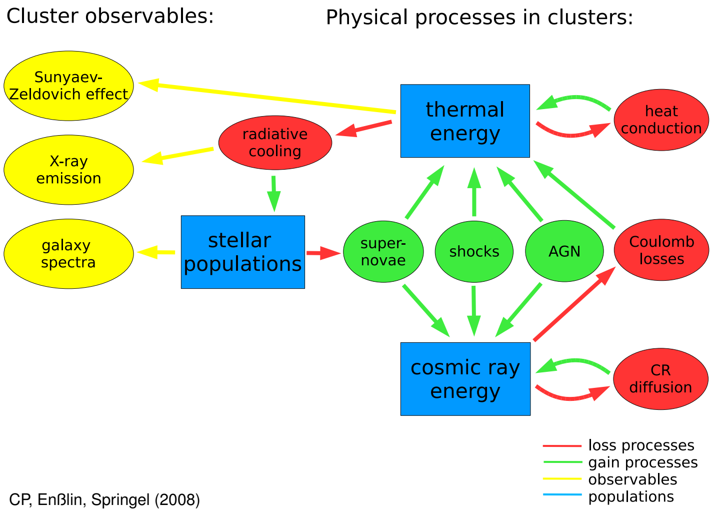


Radiative simulations with cosmic ray (CR) physics



CP, Enßlin, Springel (2008)

Radiative simulations with extended CR physics



CP, Enßlin, Springel (2008)

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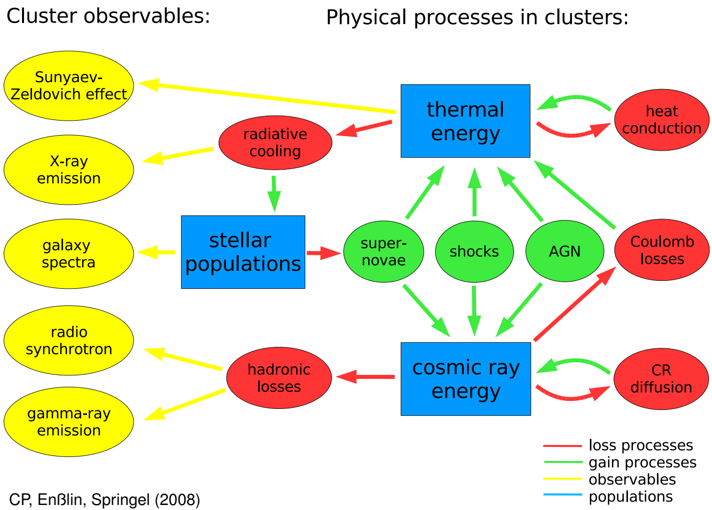
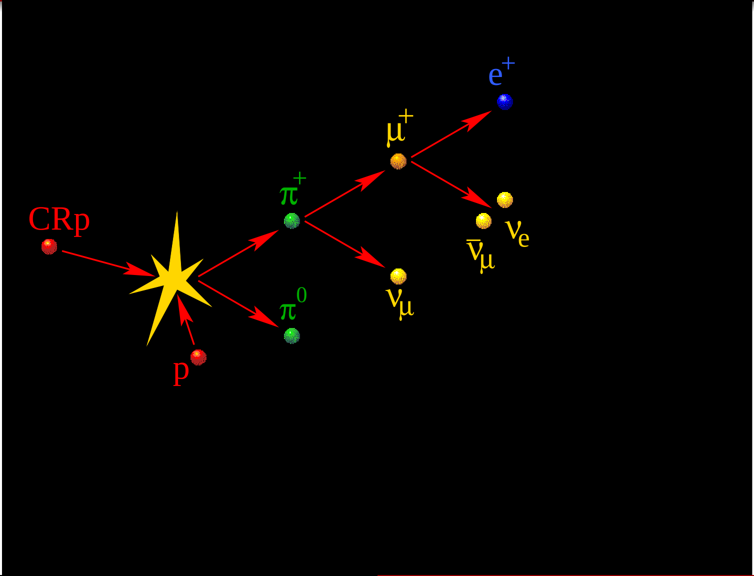
Radiative simulations with extended CR physics



CP, Enßlin, Springel (2008)

Hadronic cosmic ray proton interaction



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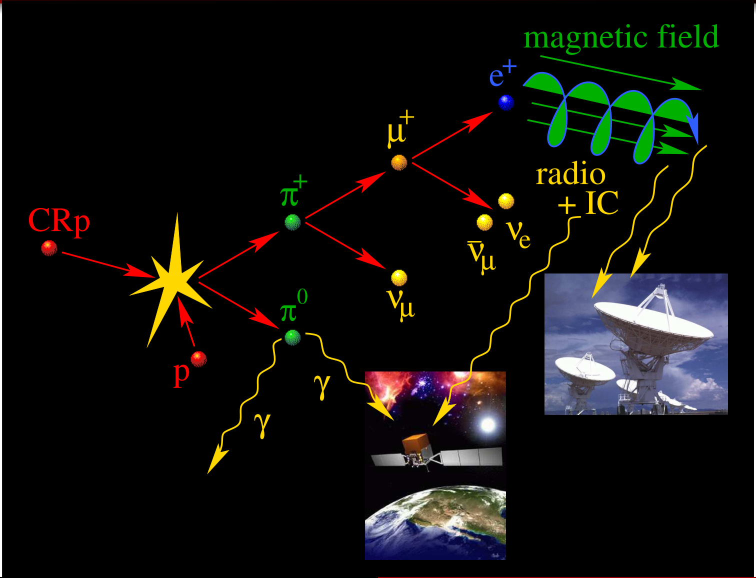
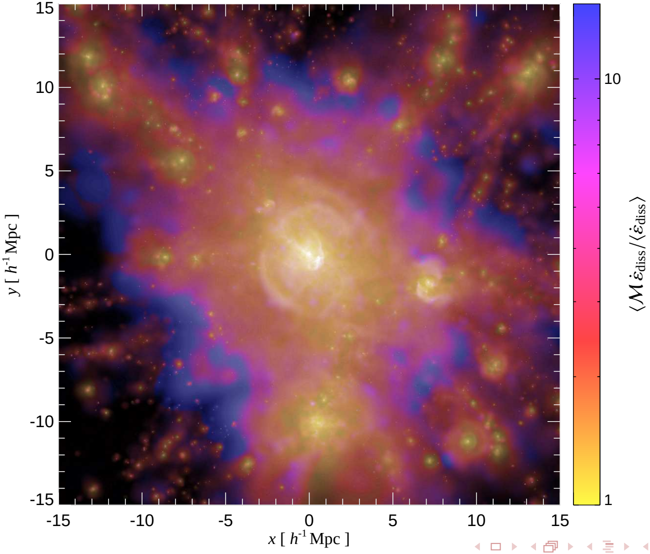


Mach number distribution weighted by $\varepsilon_{\rm diss}$



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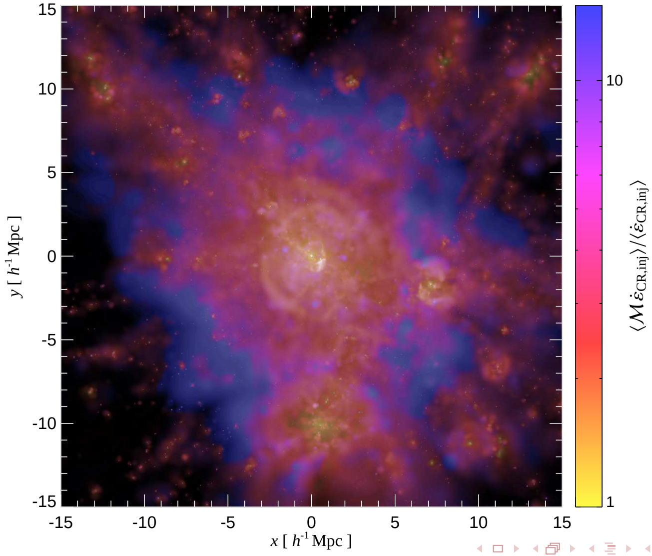
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



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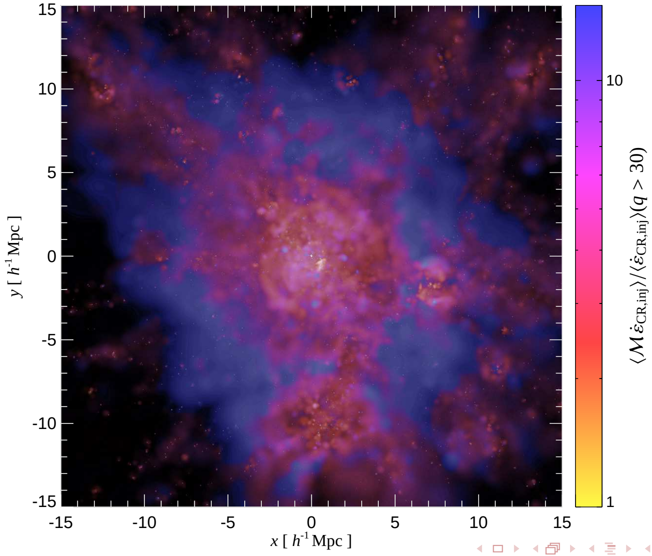
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}(q > 30)$



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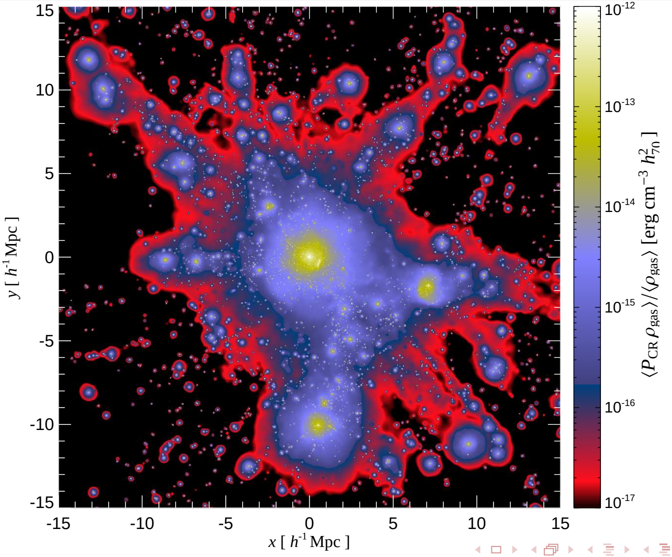
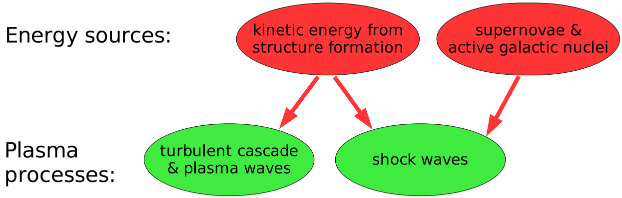
CR pressure P_{CR}



Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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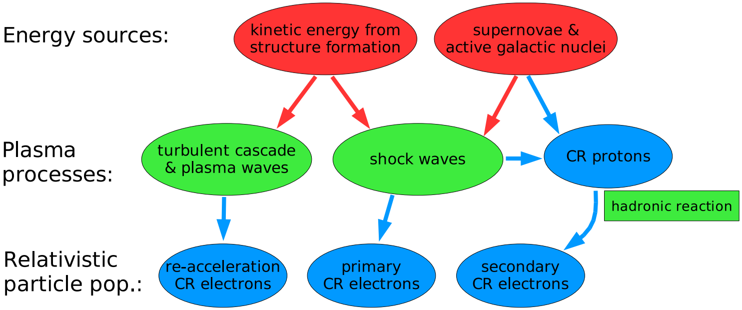

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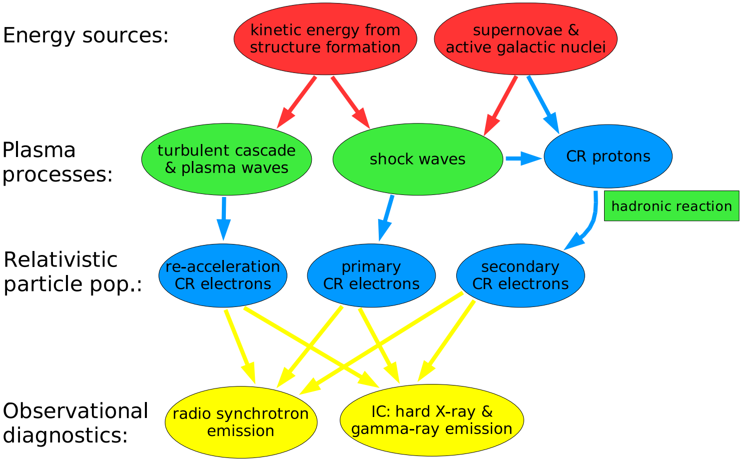

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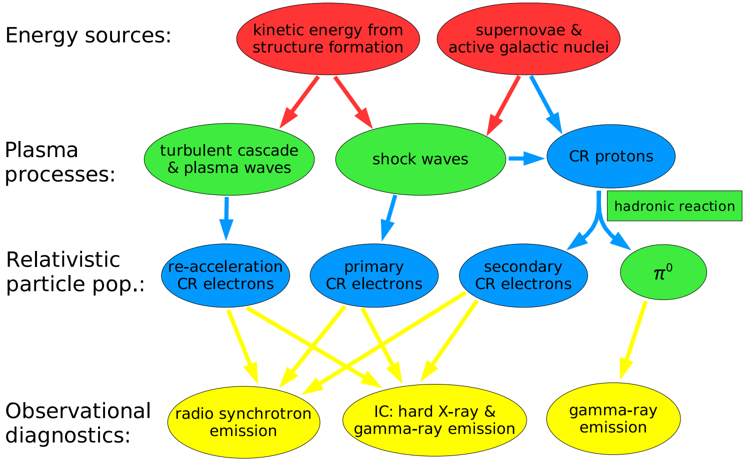

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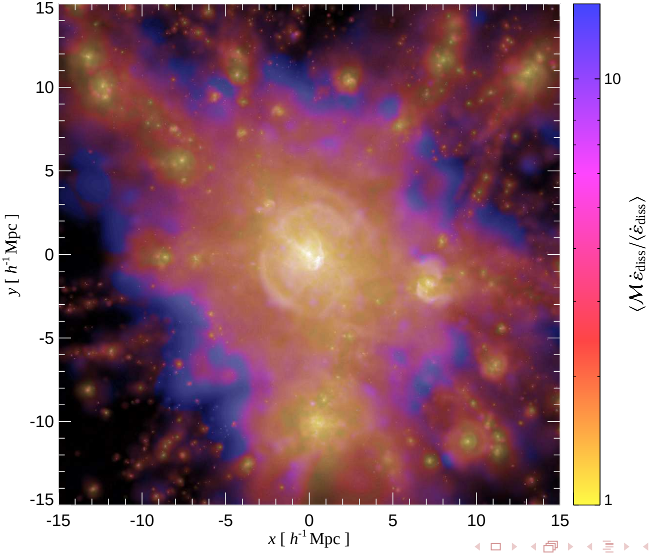
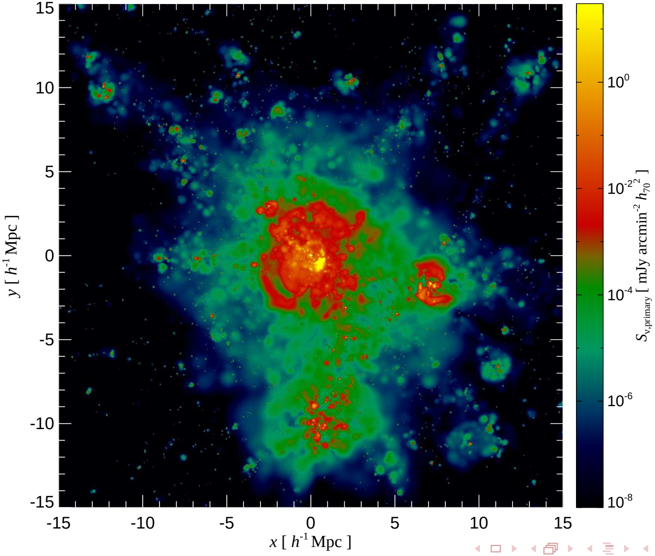
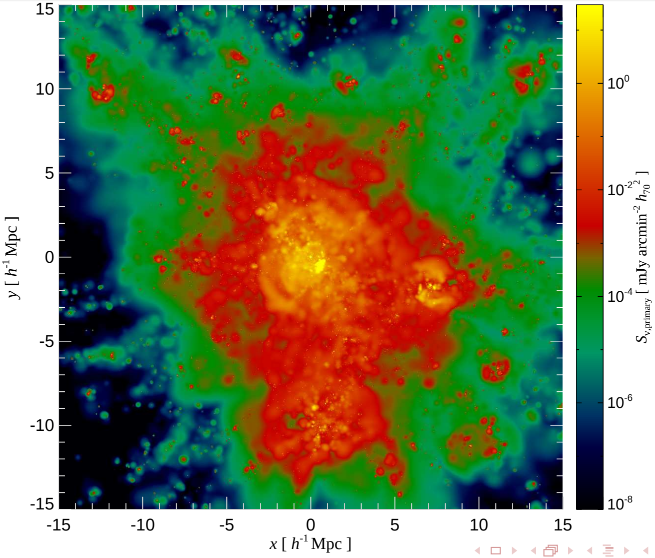
Cosmic web: Mach number



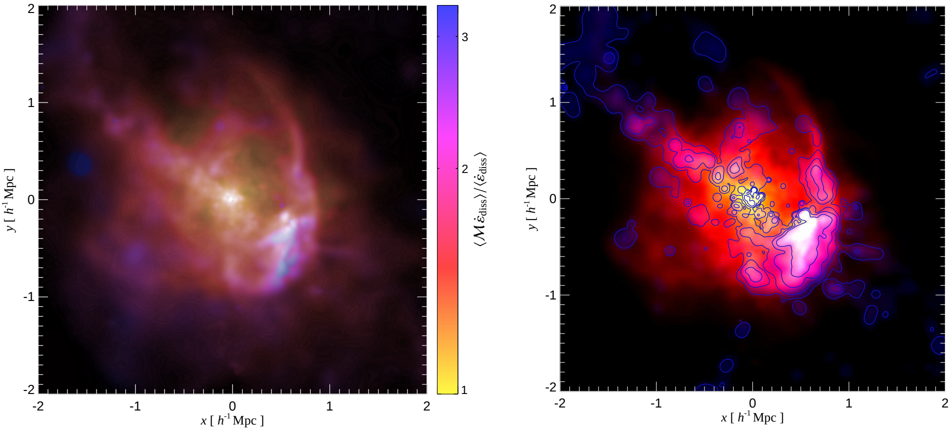
Radio gischt: primary CRe (150 MHz)



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



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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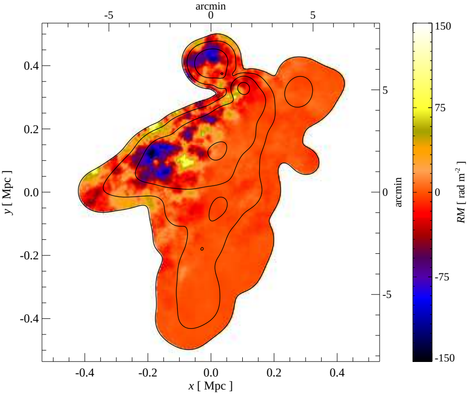
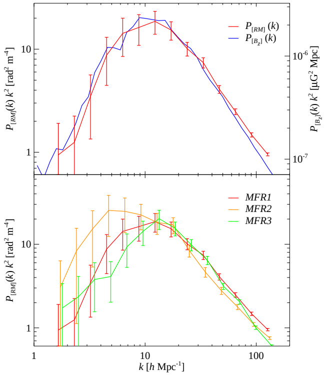
Rotation measure (RM)

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.

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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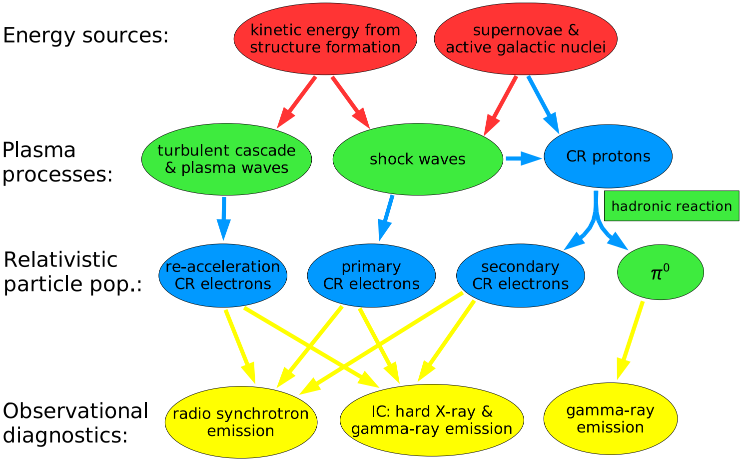
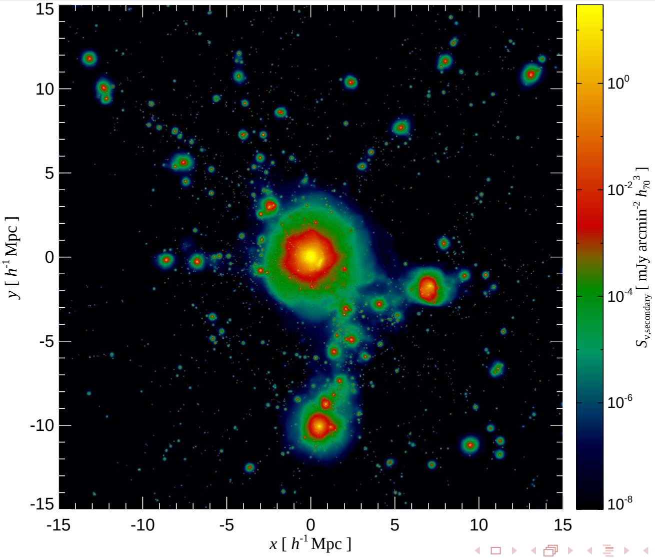


Cluster radio emission by hadronically produced CRe



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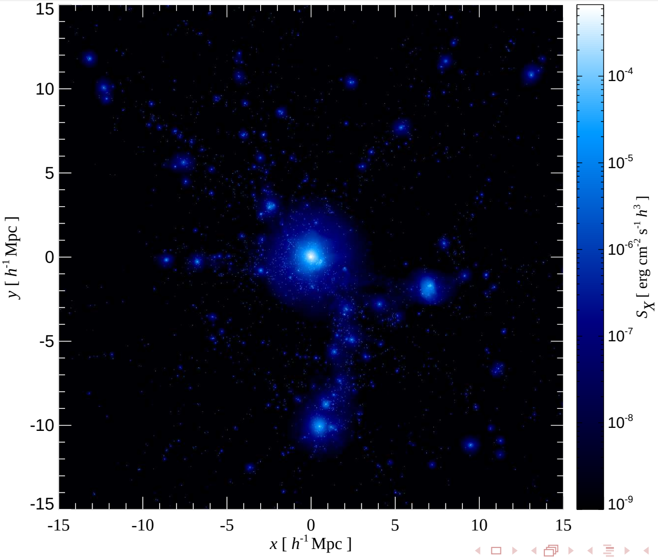
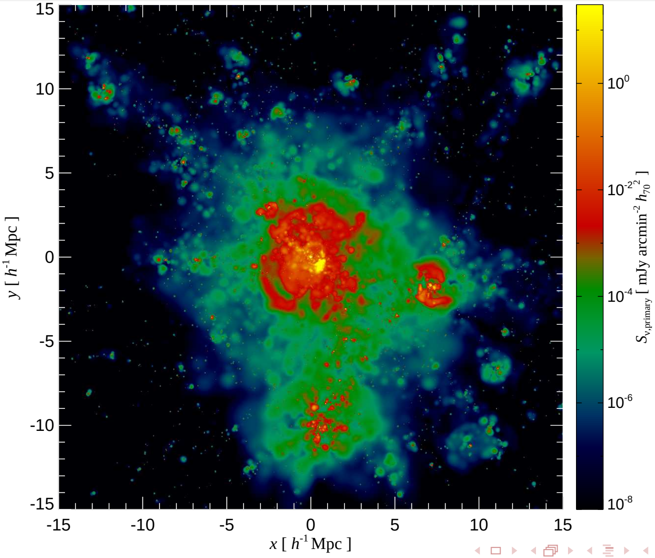
Thermal X-ray emission



Radio gischt: primary CRe (150 MHz)



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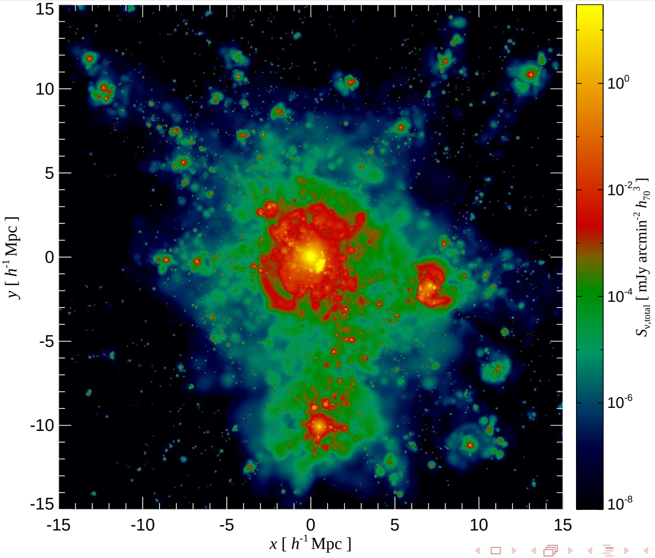
Radio gischt + central hadronic halo = giant radio halo



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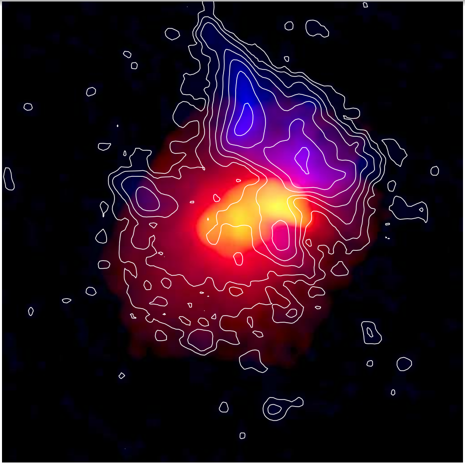
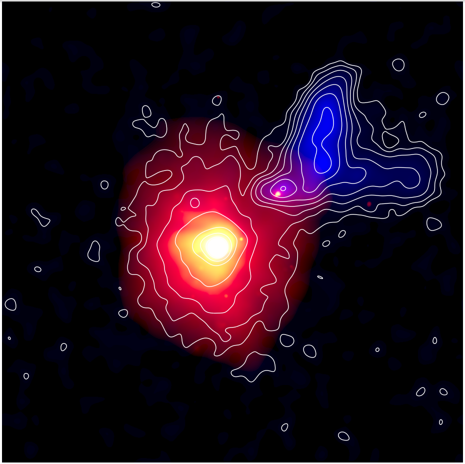
Which one is the simulation/observation of A2256?





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

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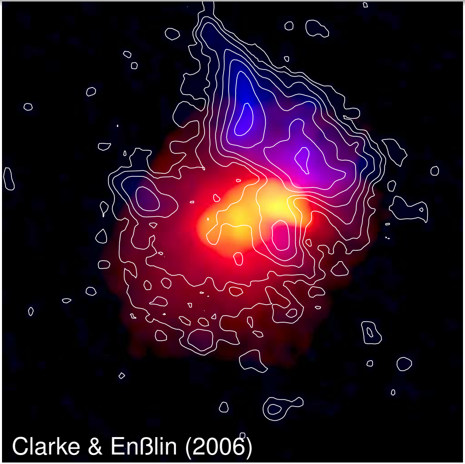
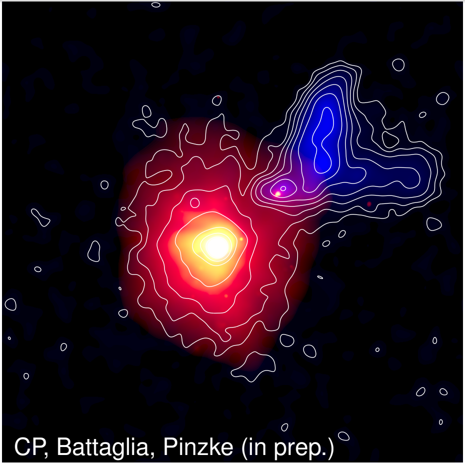
Observation – simulation of A2256





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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`

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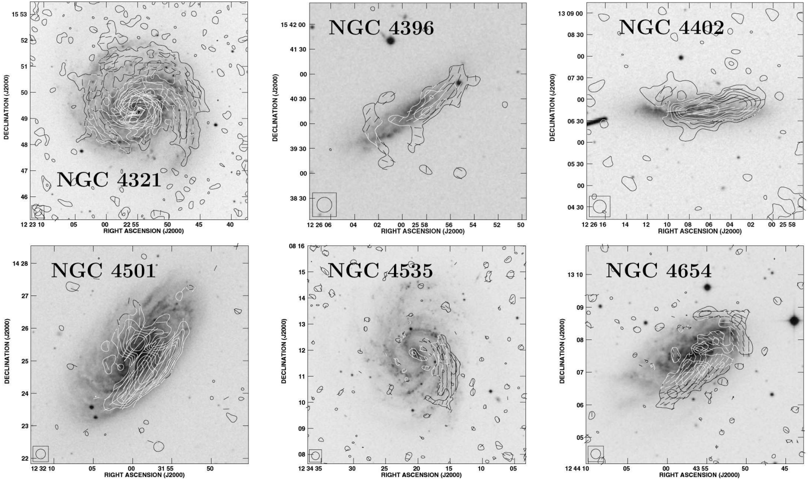
Polarized synchrotron ridges in Virgo spirals



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

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

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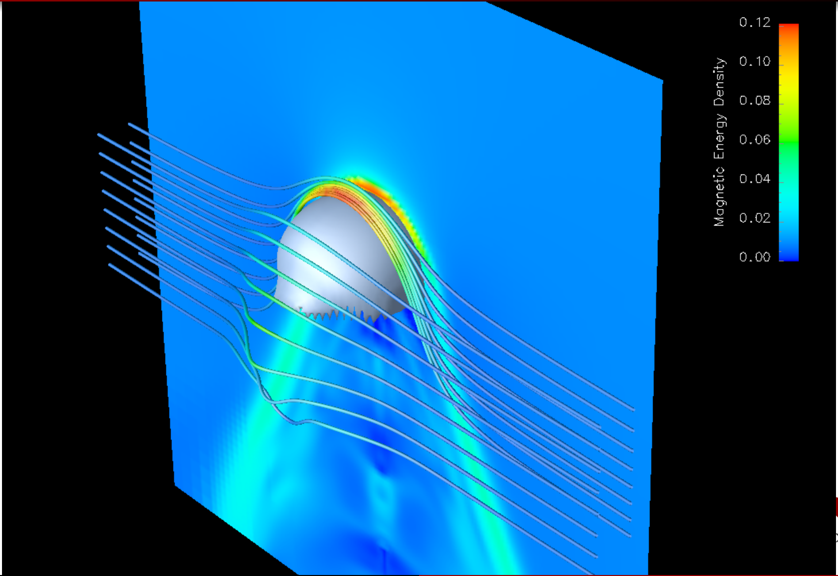
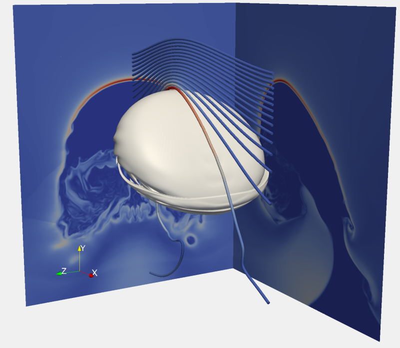
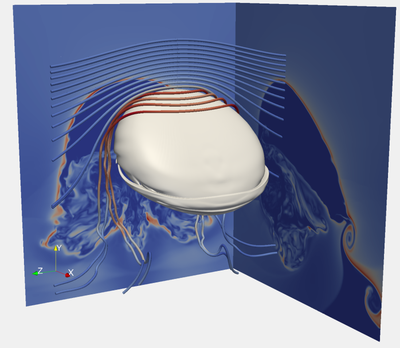
Draping field lines around a moving object



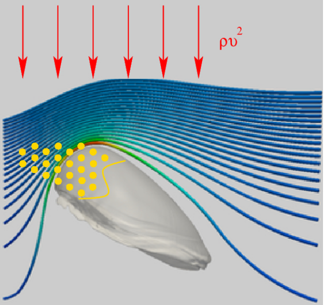
Magnetic draping around a spiral galaxy – MHD





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).

Magnetic draping around a spiral galaxy – physics



- the galactic ISM is pushed back by the ram pressure wind $\sim \rho v^2$
- 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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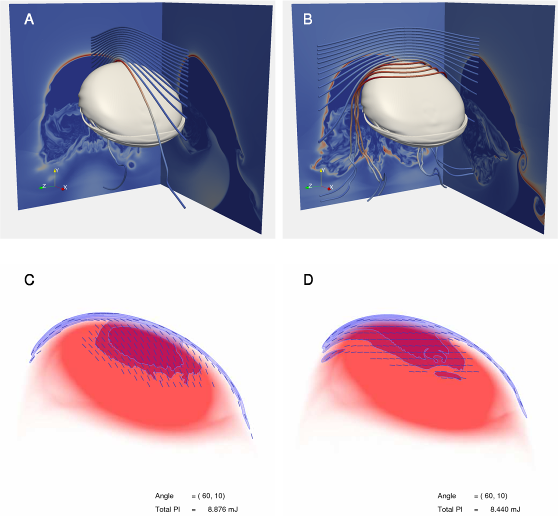
Magnetic draping and polarized synchrotron emission

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



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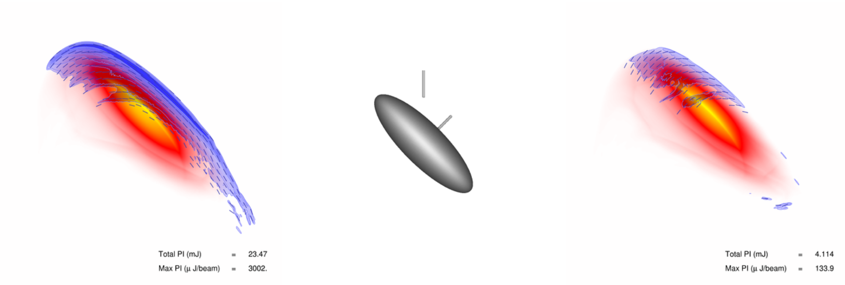
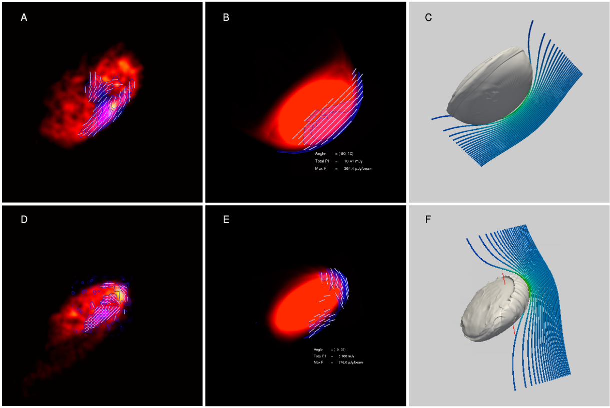
Simulated polarized synchrotron emission



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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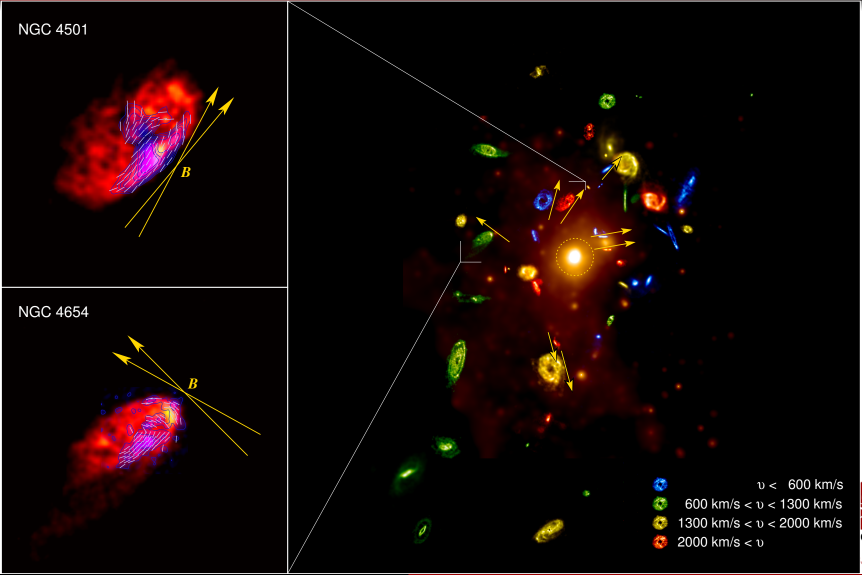
Mapping out the magnetic field in Virgo



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

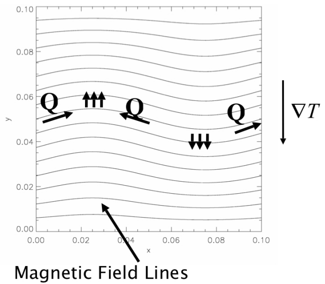


Figure from I. Parrish

Convective stability in a gravitational field:

- Classical Schwarzschild criterion: $\frac{dS}{dz} > 0$
- long MFP, Balbus criterion: $\frac{dT}{dz} > 0$
- new instability causes field lines to reorient radially → 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 → isothermal profile
- Fixed boundary conditions for $T(r)$: field lines stay preferentially radially aligned (35 deg mean deviation from radial)

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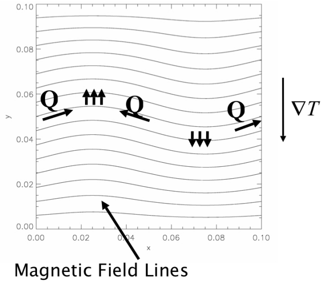
The magneto-thermal instability: the idea



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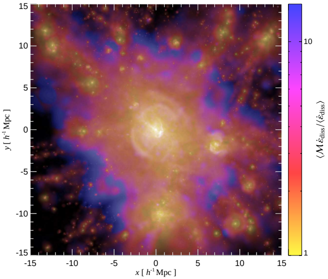
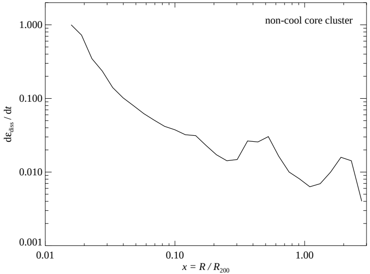
Gravitational shock wave heating

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 $\varepsilon_{\text{diss}}$.



Energy density flux through shock surface $\sim \rho v^3$ → increase towards the center

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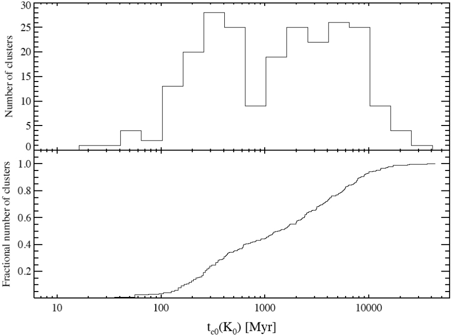
Implications for thermal stability of galaxy clusters



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: $\tau_\mathrm{cond} = \lambda^2/\chi_\mathrm{C} \simeq 2.3\,\mathrm{Gyr}\,(\lambda/1\,\mathrm{Mpc})^2$, where χ_C is the Spitzer thermal diffusivity
- current cosmological cluster simulations fail to reproduce NCCs that have no AGN activity $\rightarrow$ MHD + anisotropic conduction

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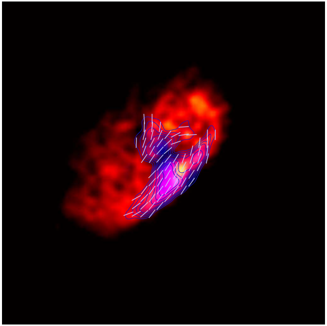
Conclusions on magnetic draping around galaxies



- **draping of cluster magnetic fields naturally explains polarization ridges at Virgo spirals**
- 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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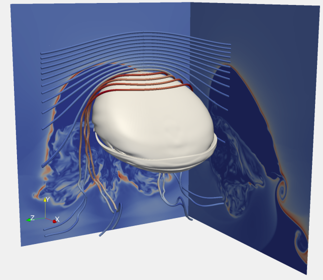
Conclusions on magnetic draping around galaxies



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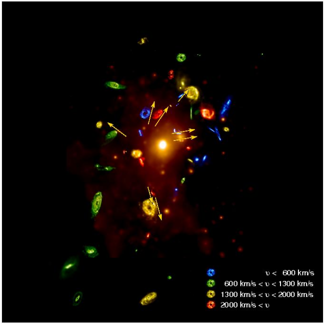

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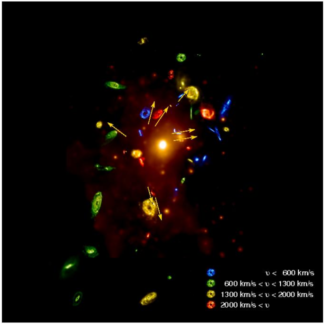

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Outline

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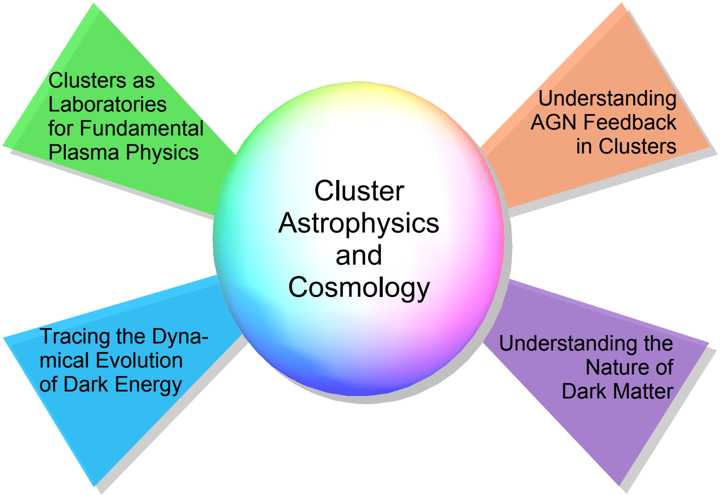
Future perspectives and directions



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Clusters as laboratories for plasma physics

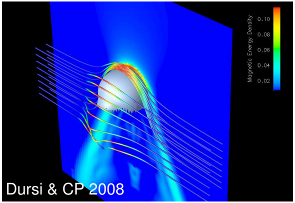
Opening up the radio and γ-ray window for the "non-thermal Universe"

- plasma processes (acceleration, turbulence, instabilities, anisotropic transport)
- cosmic rays (including ultra-high energy CRs)
- magnetic fields – origin, growth
- feedback processes (AGN, galaxies)

goal: connecting multi-frequency observables (LOFAR, MAGIC) to high-resolution simulations → fundamental plasma astrophysics

large scales: cluster "cluster archeology", cosmological surveys (eROSITA, ACT)

small scales: solving riddles (cold fonts, bubble stability) → new effects (magnetic draping)



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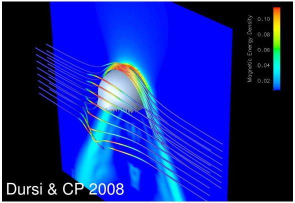

Dursi & CP 2008

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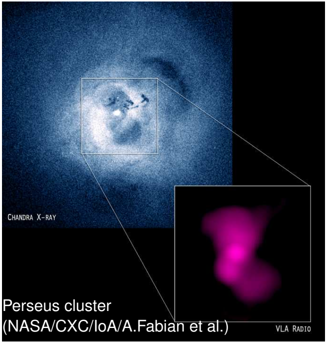
Understanding AGN feedback in clusters

The intertwined lives of supermassive black holes and cluster cores

1. AGN accretion, jet launch, bubble formation: magnetic fields, cosmic rays, and turbulence play crucial role
2. heating mechanism: cavity heating through releasing potential energy, weak shocks, sound damping, . . .

   (McNamara & Nulsen 2007)
3. cosmological impact: role in galaxy and cluster evolution



Perseus cluster
(NASA/CXC/IoA/A.Fabian et al.)

→ understanding both the detailed plasma physics and the statistical properties of the AGN feedback in the cosmological context

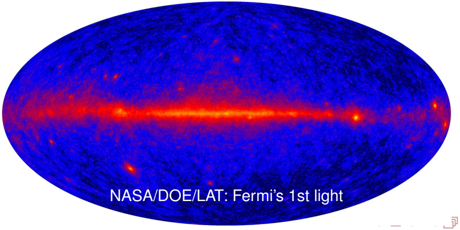
→ high-performance simulations of the involved physics and new observational strategies to elucidate the properties of the interaction

Understanding the nature of dark matter

Unveiling dark matter annihilation in the presence of astrophysical foregrounds

- disentangling the γ-ray emission resulting from dark matter (DM) annihilation from the cosmic ray induced signal
- electrons/positrons from DM annihilations vs. CR interactions: modified synchrotron emission and local particle spectra

self-consistent cosmic ray simulations (galaxy clusters, our Galaxy) and modeling of spectral and spatial emission characteristics necessary to discover the properties of dark matter



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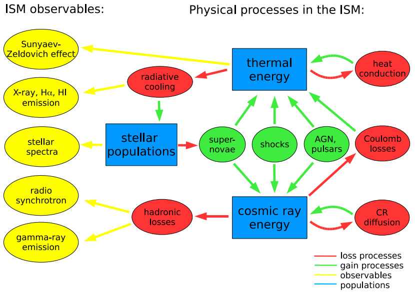
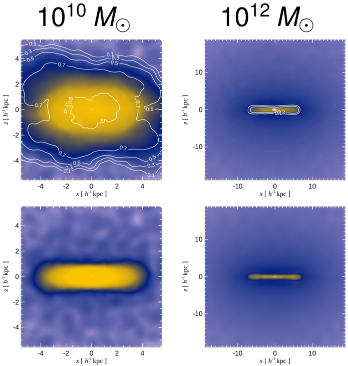
Modelling non-thermal processes in galaxies





Jubelgas, Springel, Enßlin, CP (2008)

interesting astrophysics associated with dynamically modeling non-thermal processes in the ISM

→ timely projects of γ-ray (MAGIC, Fermi) and radio emission (LOFAR)

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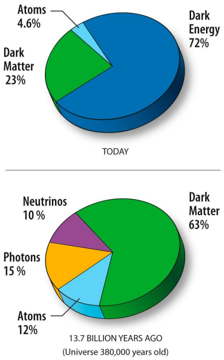
Tracing the dynamical evolution of dark energy

Joint analysis of simulated cluster surveys

- accelerated expansion of the Universe caused by either a cosmological fluid (scalar field, vacuum energy) or by modification of General Relativity for small curvature
- this causes modified evolution of the signal from cosmological standard candles (SNe) / yard sticks (baryon acoustic oscillations) or a different growth of structure (weak lensing, cluster surveys) → complementary probes of precision cosmology



(NASA/WMAP Science Team)

→ study of the influence of different physical processes on cluster mock catalogues in the X-rays (eROSITA) and the Sunyaev-Zel'dovich effect (Planck, SPT, ACT)

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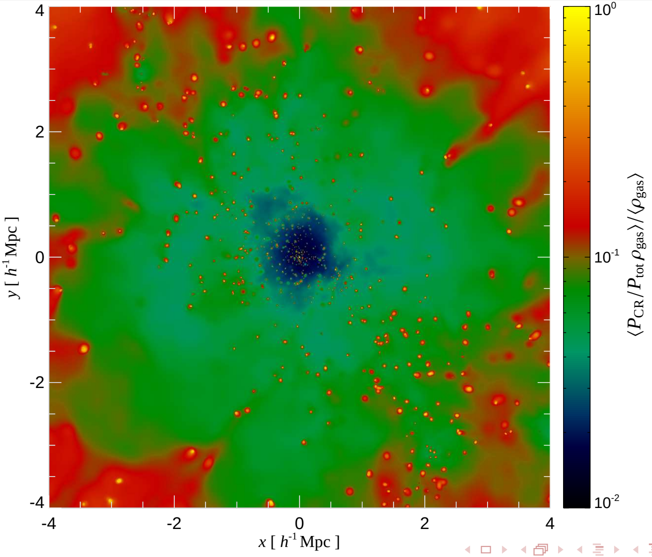
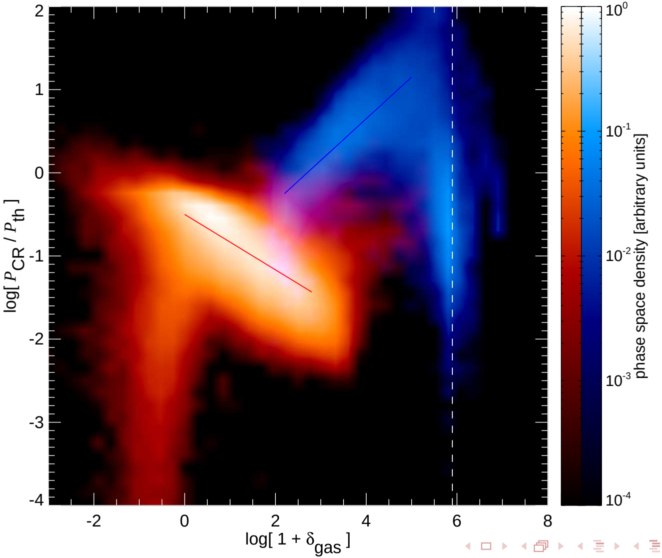
Relative CR pressure P_{CR}/P_{total}

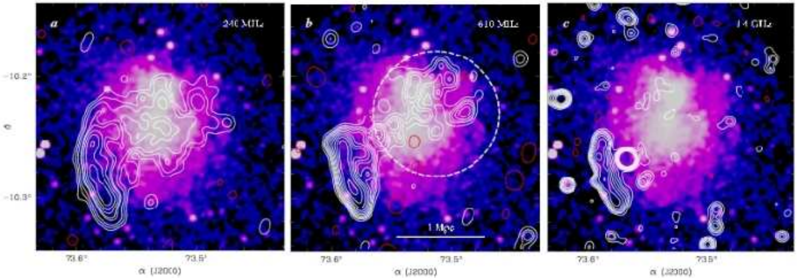


CR phase-space diagram: final distribution @ $z = 0$



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!

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