Illuminating cosmological formation shocks

Christoph Pfrommer

in collaboration with

T. Enßlin, V. Springel

Heidelberg Institute for Theoretical Studies, Germany

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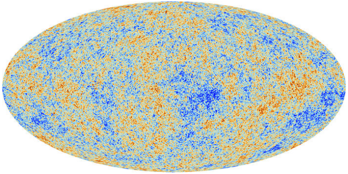
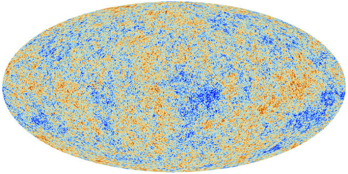
Cosmological structure formation



ESA/Planck Collaboration (2013)

- small fluctuations in cosmic microwave background are initial conditions for structure formation

Cosmological structure formation

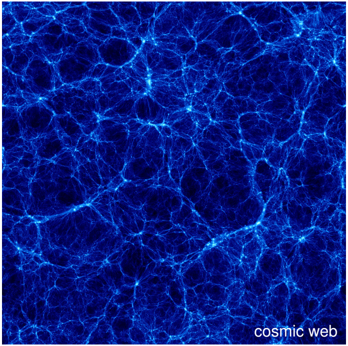


ESA/Planck Collaboration (2013)

dropping pebbles into the pond generates expanding waves that interfere with each other

- small fluctuations in cosmic microwave background are initial conditions for structure formation
- galaxies and clusters form at sites of constructive interference of those primordial waves

Cosmological structure formation



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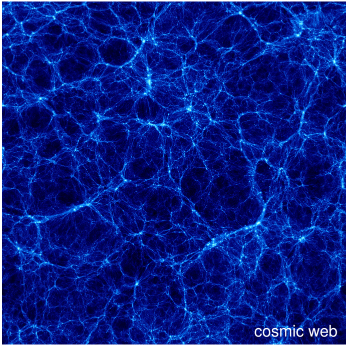
- galaxies and clusters form at sites of constructive interference of those primordial waves
- cosmic matter assembles in the “cosmic web” through gravitational instability
- galaxies form as “beats on a string” along the cosmic filaments
- galaxy clusters form at the knots of the cosmic web by mergers of galaxies and galaxy groups

Cosmological structure formation



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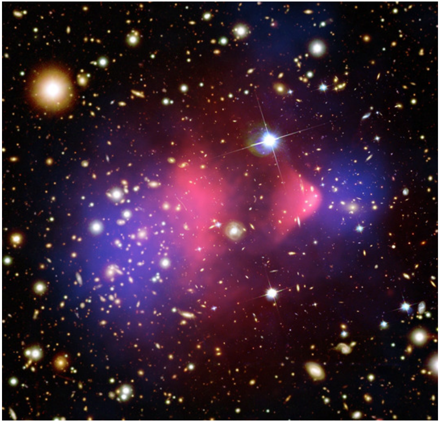
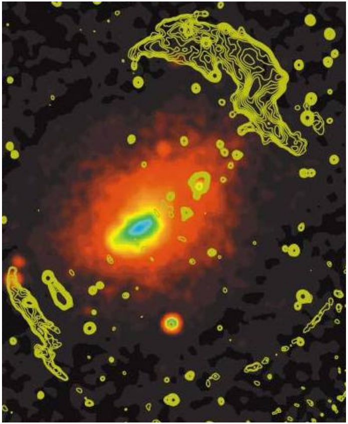
Shocks in galaxy clusters



1E 0657-56 (“Bullet cluster”)

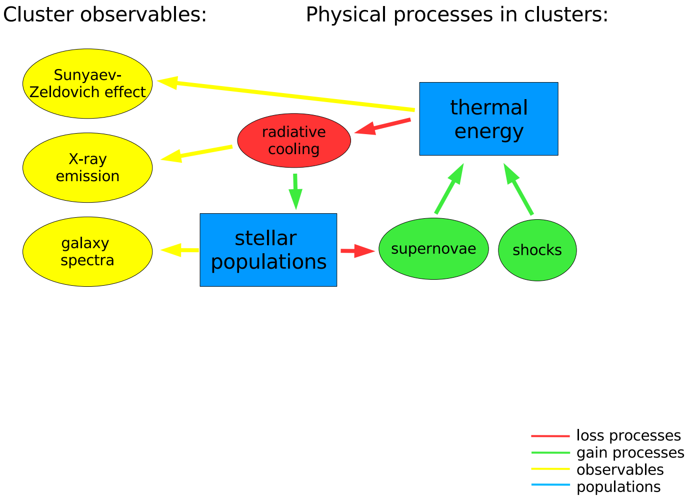
(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)



Abell 3667

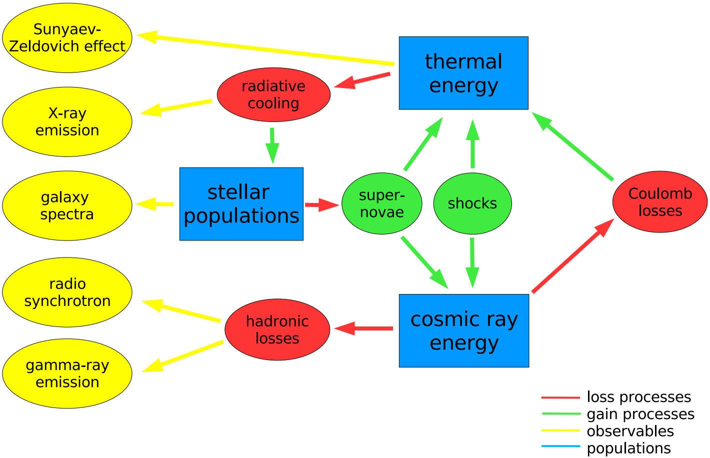
(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

Radiative simulations – flowchart

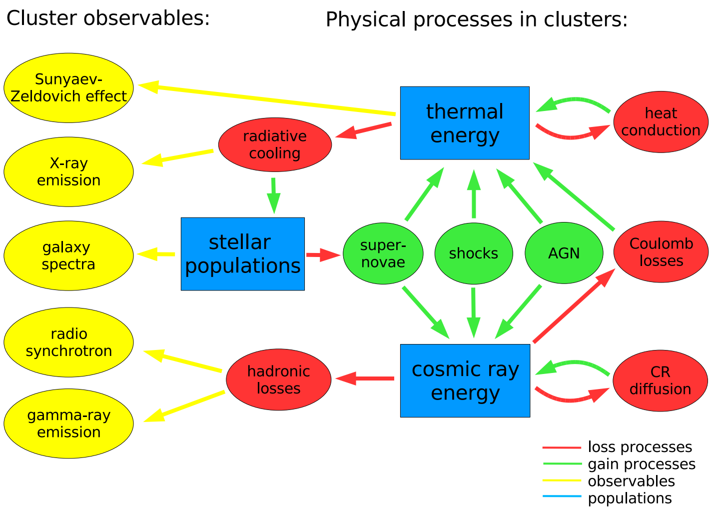


Radiative simulations with cosmic ray (CR) physics

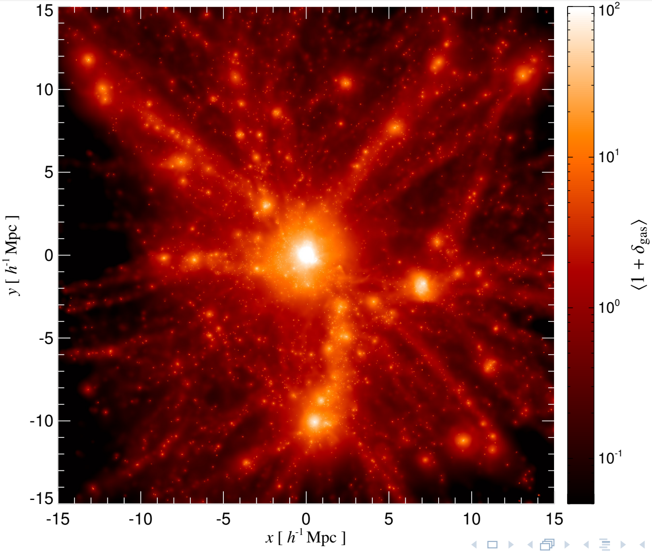
Cluster observables: Physical processes in clusters:



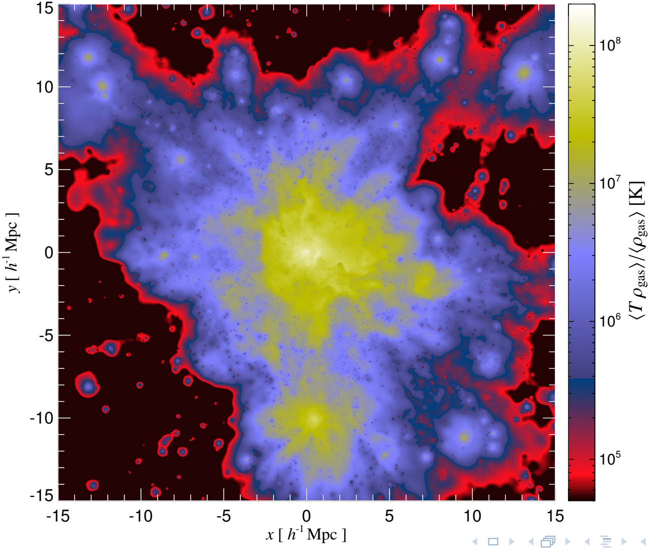
Radiative simulations with extended CR physics



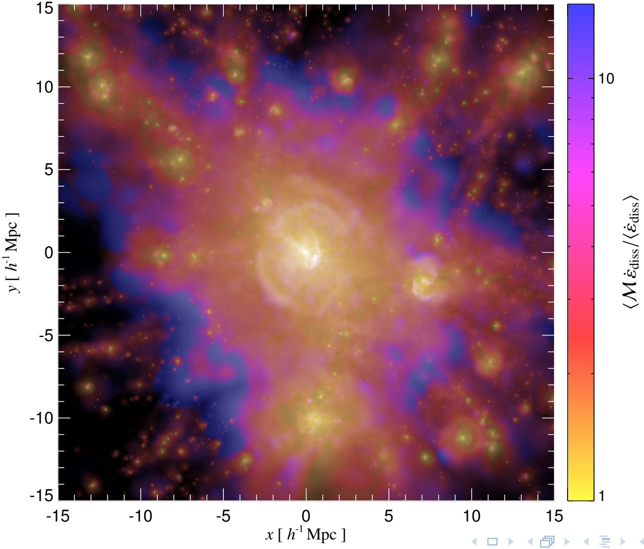
Radiative cool core cluster simulation: gas density



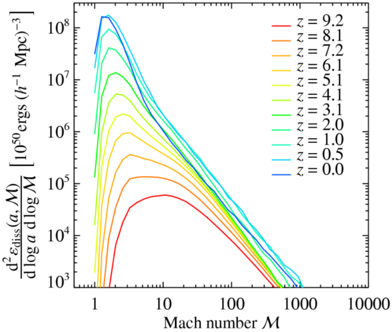
Mass weighted temperature



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

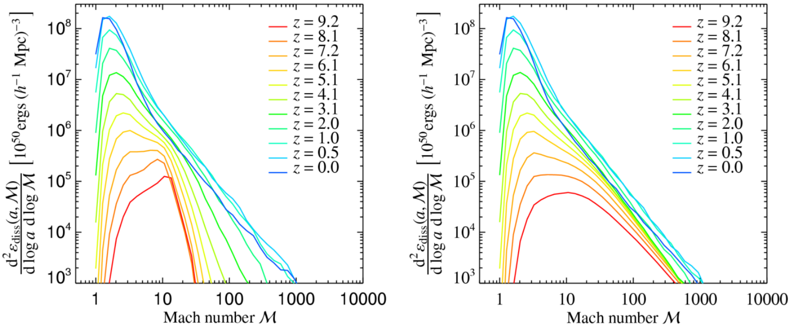


Cosmological shock statistics



- more energy is dissipated at later times
- mean Mach number decreases with time

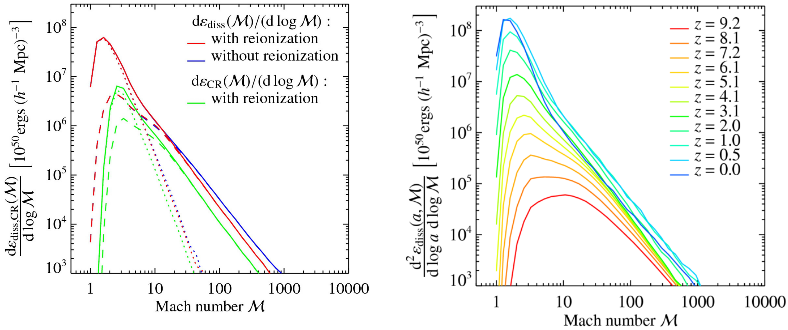
Cosmological shock statistics: influence of reionization



- reionization epoch at $z_{\text{reion}} = 10$ suppresses efficiently strong shocks at $z < z_{\text{reion}}$ due to jump in sound velocity
- cosmological constant causes structure formation to cease

HITS

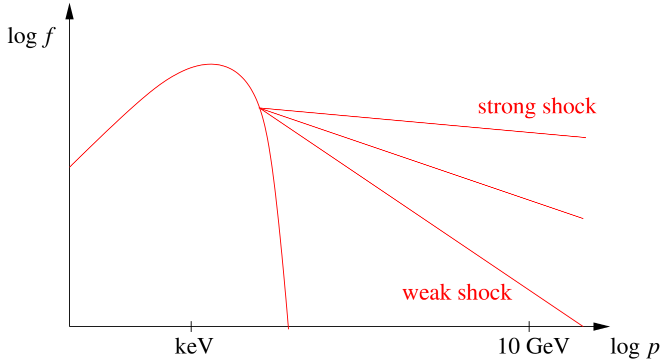
Cosmological shock statistics: CR injection



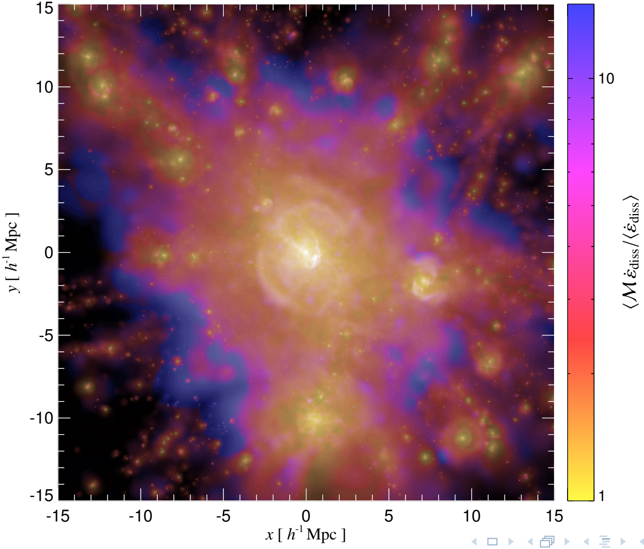
- Mach number dependent injection efficiency of CRs favors medium Mach number shocks ($\mathcal{M} \gtrsim 3$) for the injection
- more energy is dissipated in weak shocks internal to collapsed structures than in external strong shocks

Diffusive shock acceleration – Fermi 1 mechanism

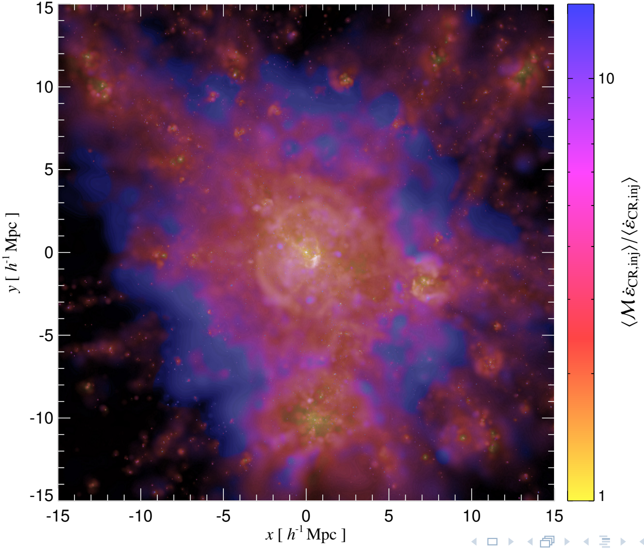
Spectral index depends on the Mach number of the shock, $\mathcal{M} = \upsilon_{\mathsf{shock}} / c_{\mathsf{s}}$:



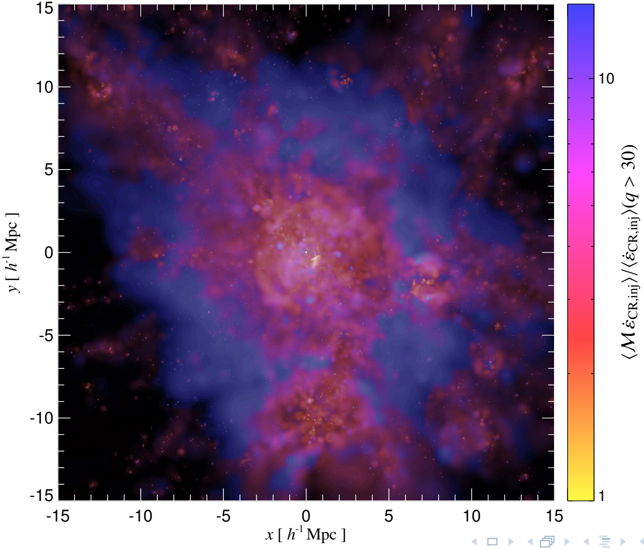
Mach number distribution weighted by $\varepsilon_{\rm diss}$



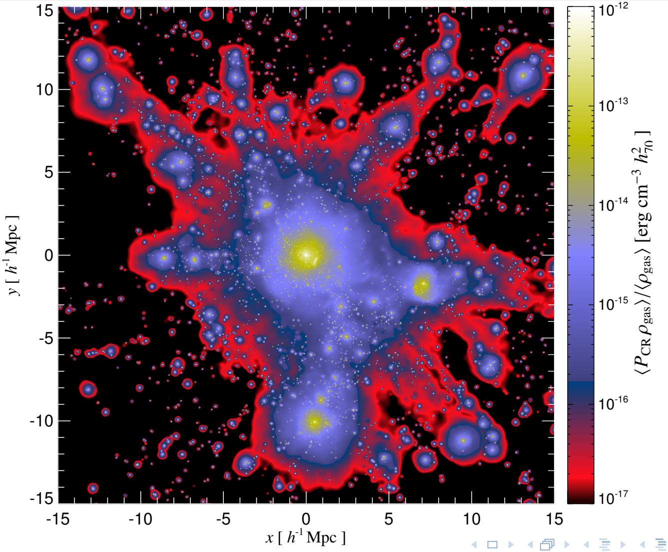
Mach number distribution weighted by $\varepsilon_{\rm CR,inj}$



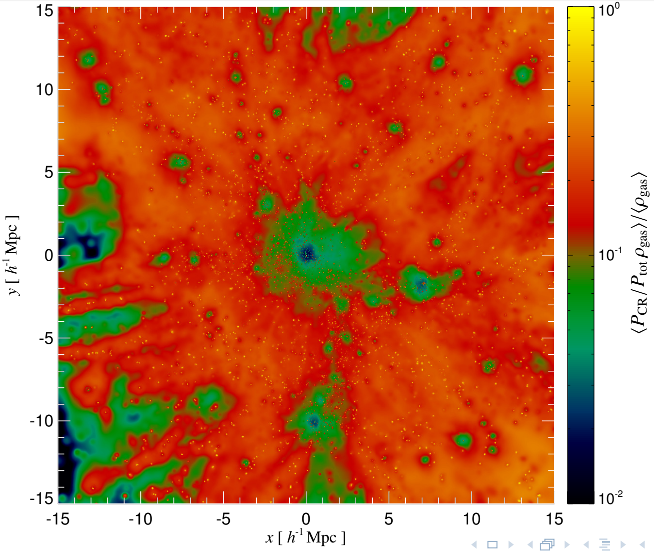
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}(q > 30)$



CR pressure $P_{\rm CR}$



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



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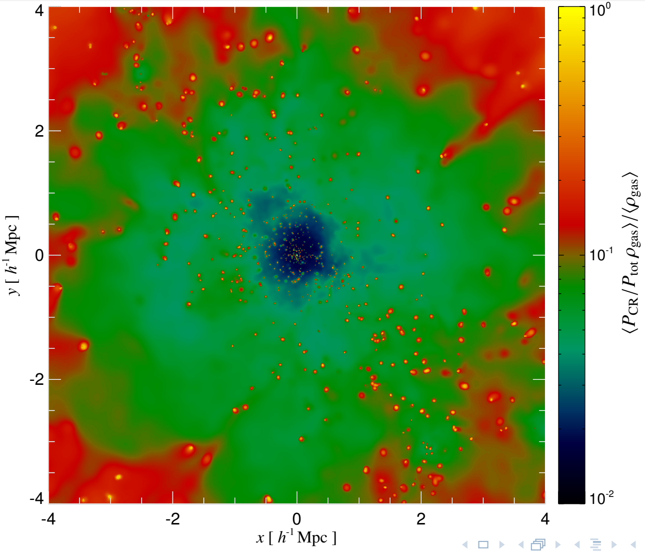
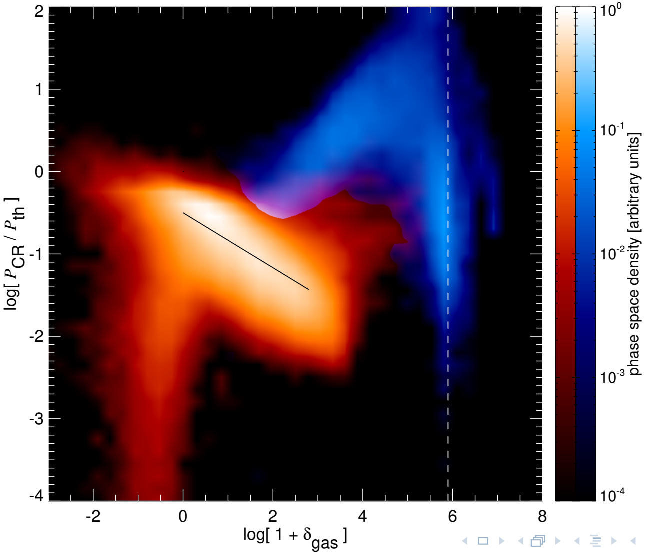


CR phase-space diagram: final distribution @ $z = 0$



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

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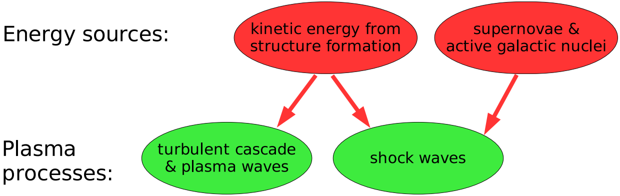
How can we read out this information about non-thermal populations?
$\rightarrow$ new era of multi-frequency experiments, e.g.:

- LOFAR, GMRT, MWA, LWA: interferometric array of radio telescopes at low frequencies ($\nu \simeq (15 - 240)$ MHz)
- Jansky VLA: array of radio telescopes ($\nu \simeq (0.07 - 50)$ GHz)
- *Fermi*: γ-ray space satellite ($E \simeq (0.1 - 300)$ GeV)
- Imaging air Čerenkov telescopes ($E \simeq (0.1 - 100)$ TeV)

Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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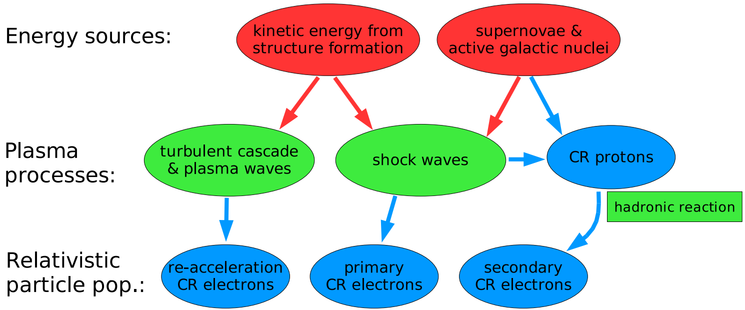

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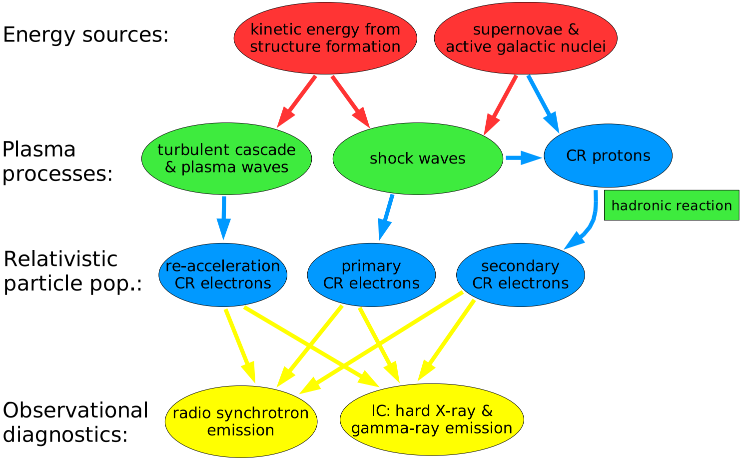

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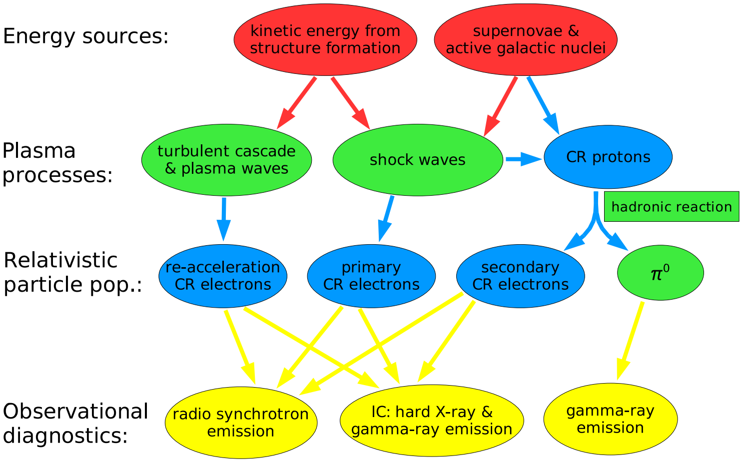
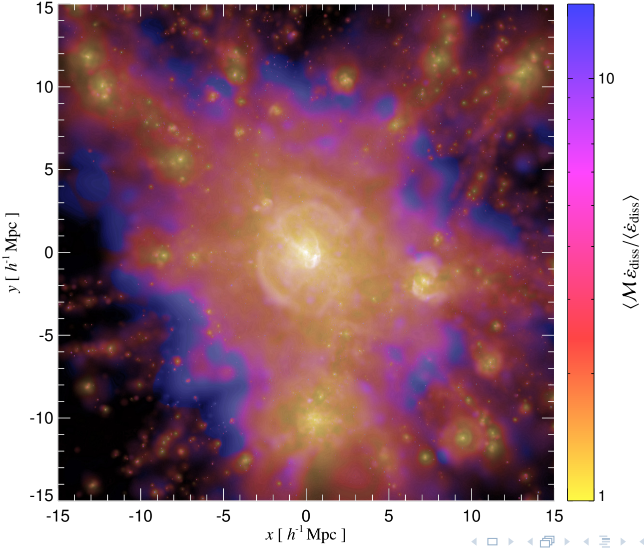
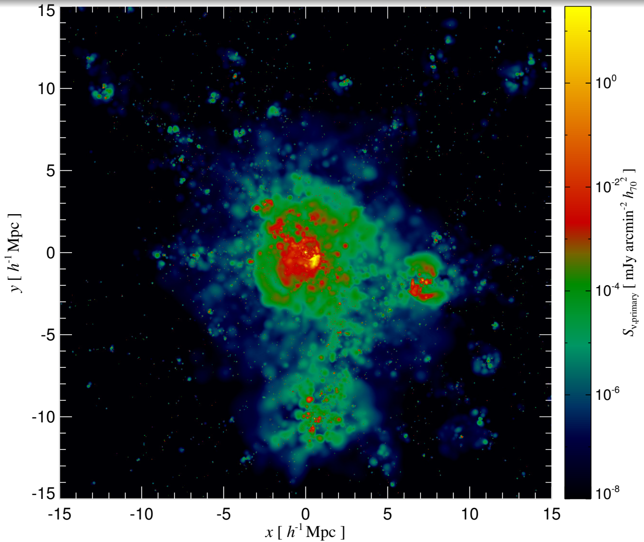


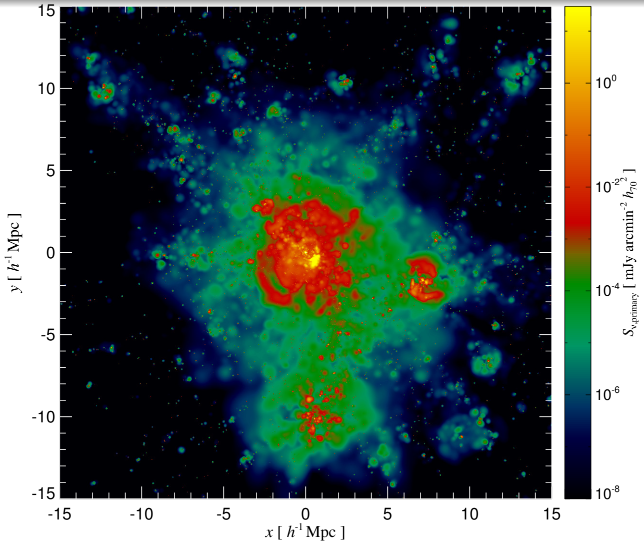
Cosmic web: Mach number



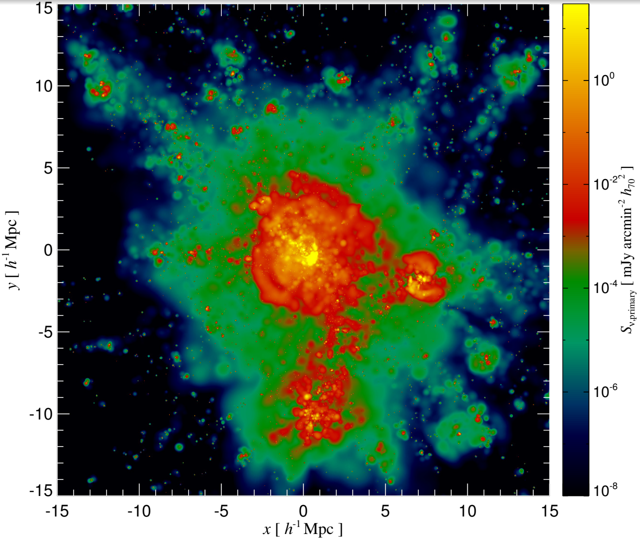
Radio gischt (relics): primary CRe (1.4 GHz)



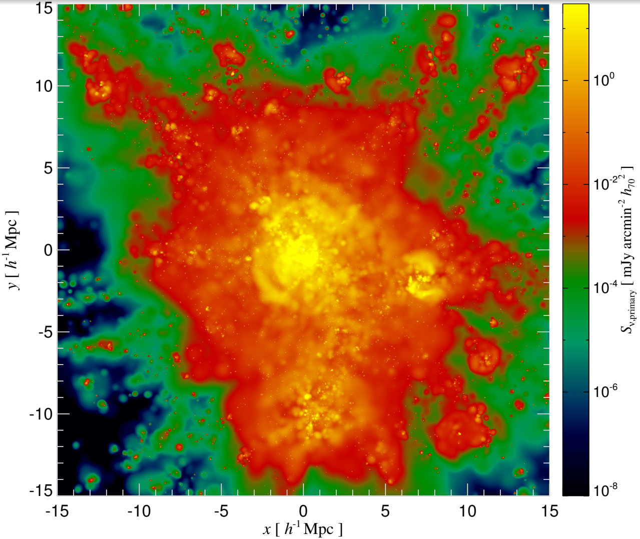
Radio gischt: primary CRe (150 MHz)



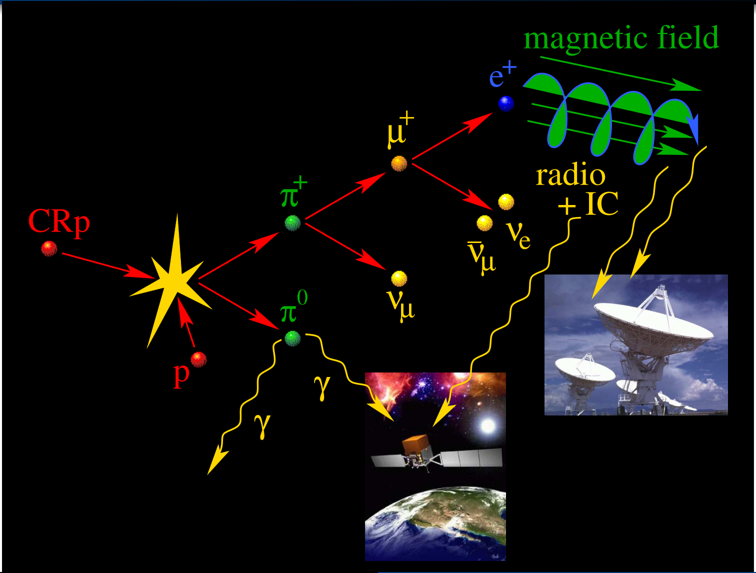
Radio gischt: primary CRe (15 MHz)



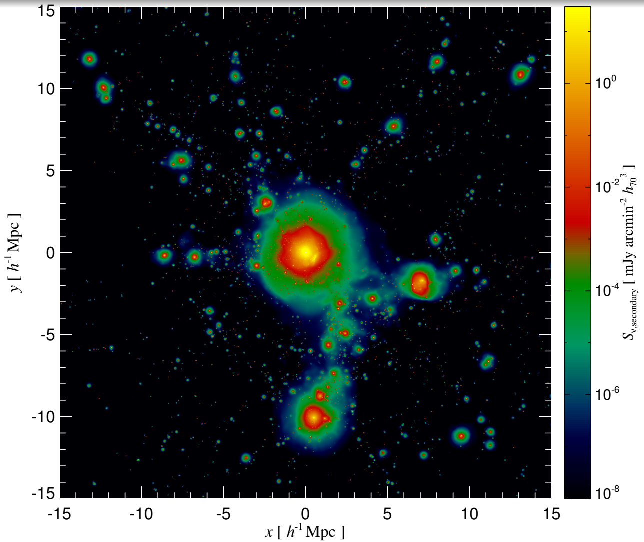
Radio gischt: primary CRe (15 MHz), slower magnetic decline



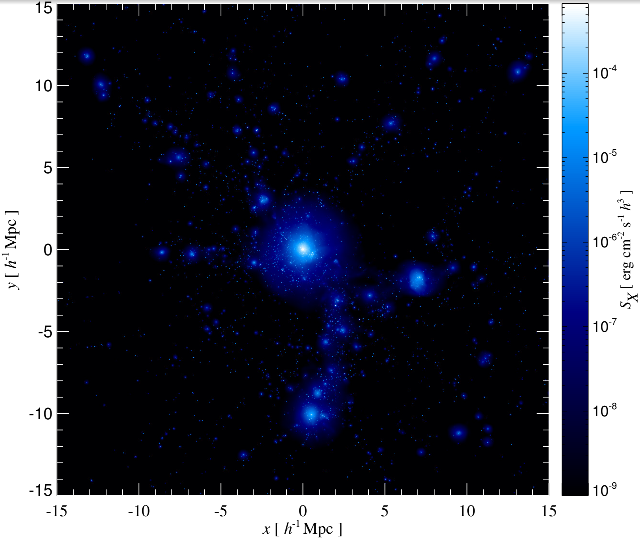
Hadronic cosmic ray proton interaction



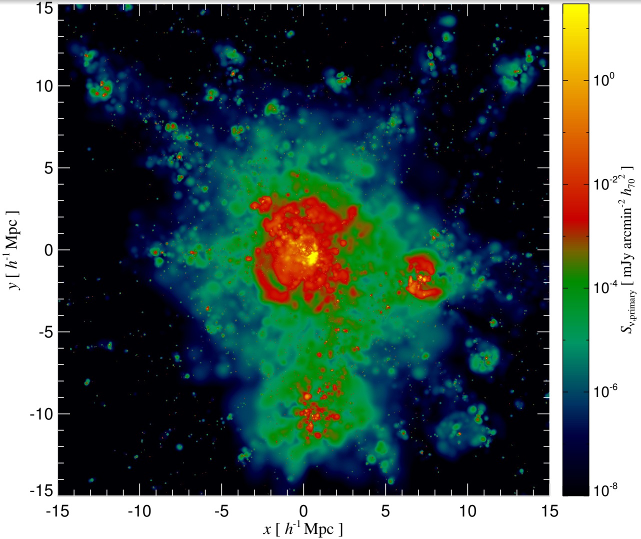
Cluster radio emission by hadronically produced CRe



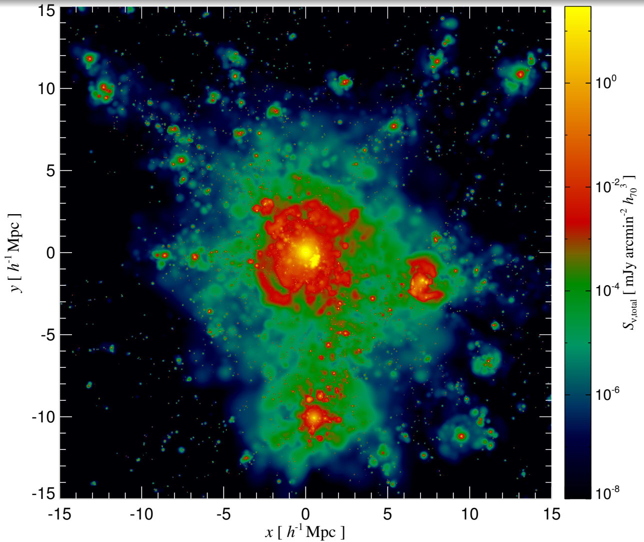
Thermal X-ray emission



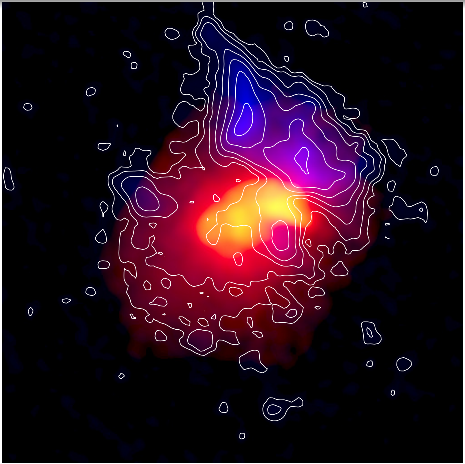
Radio gischt: primary CRe (150 MHz)

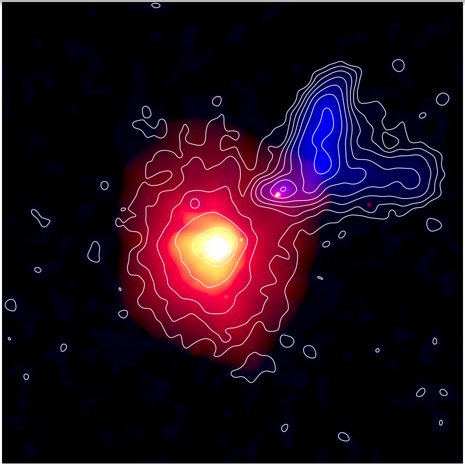


Radio gischt + central hadronic mini-halo



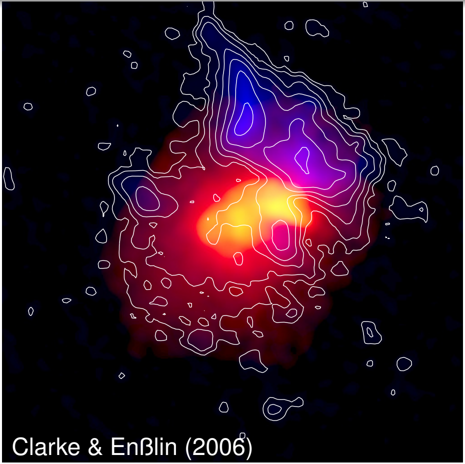
Which one is the simulation/observation of A2256?

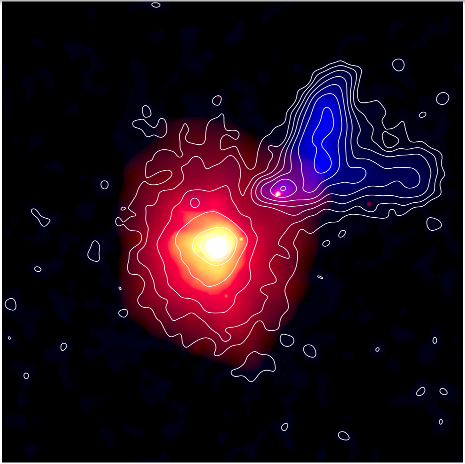




red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic

Observation – simulation of A2256





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Conclusions

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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, X-ray, and γ-ray emission:
    - plasma physics: diffusive shock acceleration, large scale magnetic fields, and turbulence
    - nature of dark matter
    - gold sample of cluster for precision cosmology

CRAGSMAN: The Impact of Cosmic RAys on Galaxy and CluSter ForMAtioN

This project has received funding from the European Research Counsil (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No CRAGSMAN–646955).

Literature for the talk

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- 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*
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