Cosmological Simulations of Galaxy Clusters

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in collaboration with

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Outline

1. Galaxy cluster simulations
   - Observations and simulations
   - Shocks and cosmic rays
   - Non-thermal emission
2. AGN feedback in clusters
   - Observations
   - Isolated clusters
   - Cosmological simulations
3. Cluster cosmology
   - Sunyaev-Zel'dovich power spectrum
   - Scaling relations and number counts
   - Future challenges

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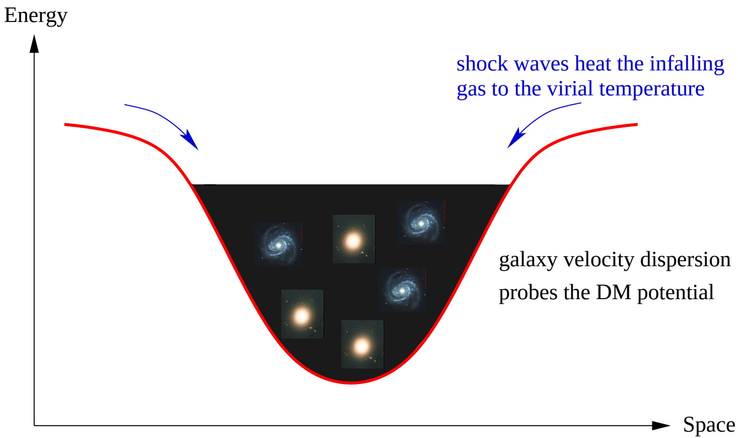
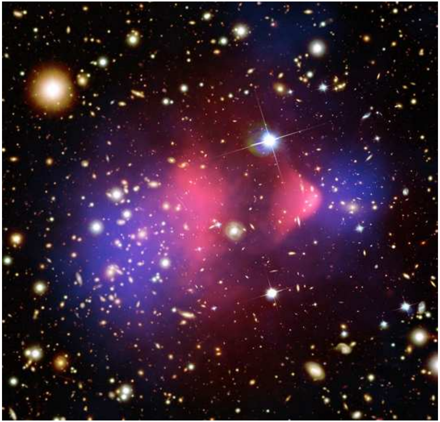
A theorist's perspective of a galaxy cluster . . .

Galaxy clusters are dynamically evolving dark matter potential wells:

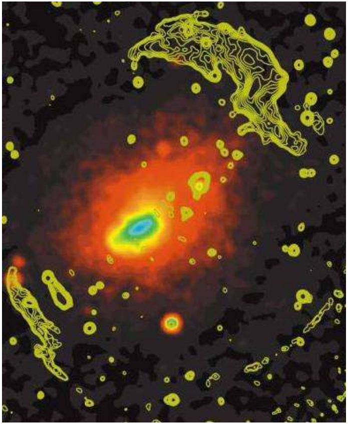


... and how the observer's Universe looks like



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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Galaxy clusters at the crossroads of astrophysics and cosmology
Metal enrichment as tracer of feedback processes

- clusters form at the intersection of the filamentary cosmic web: groups and (proto-)clusters harbour the most energetic cosmic beacons, which feedback to the surrounding IGM by galactic winds/AGN
- highly inhomogeneous enrichment of the primordial gas by metals, magnetic fields, cosmic rays; high-density peaks (proto-clusters) enrich earlier than low-density regions
- advective/turbulent transport adds complexity to the low-redshift metallicity observables
- understanding the map from initial to final distribution unveils
  - formation, evolution, and astrophysics of galaxy clusters
  - supermassive black holes
  - turbulence and plasma instabilities
  - magnetic fields and (ultra high-energy) cosmic rays

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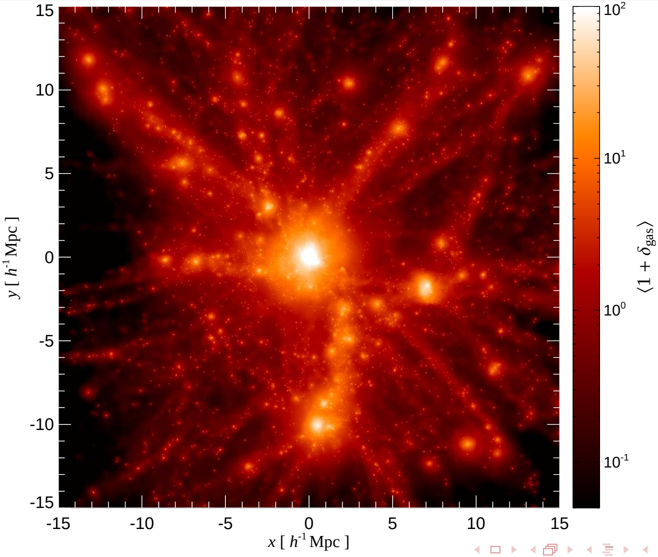
Radiative cool core cluster simulation: gas density



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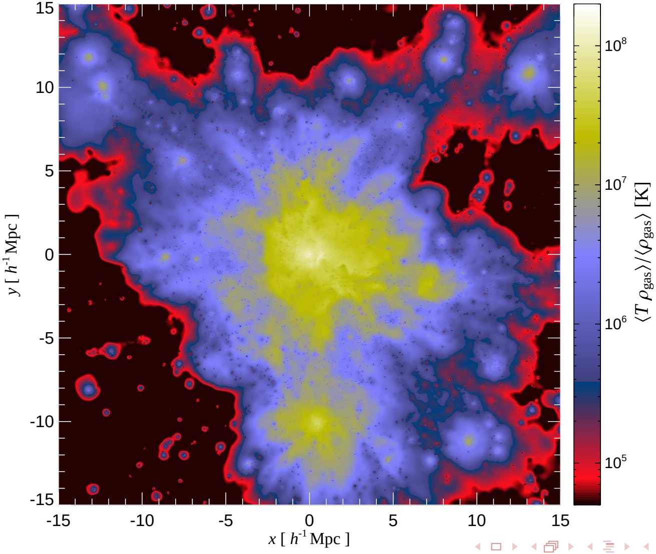
Mass weighted temperature



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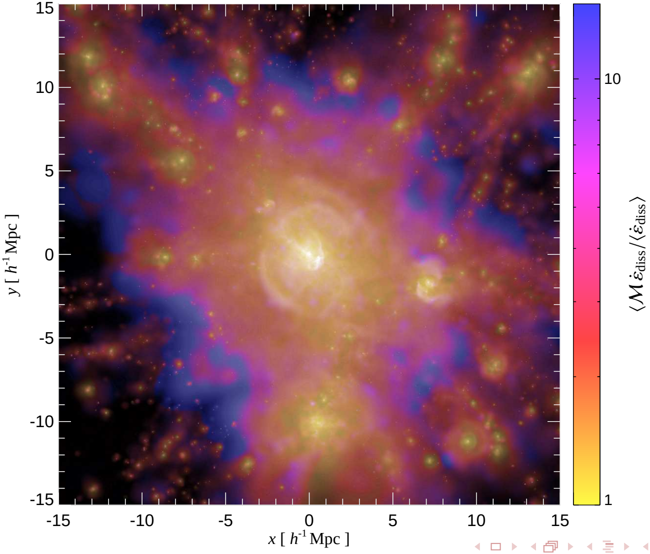
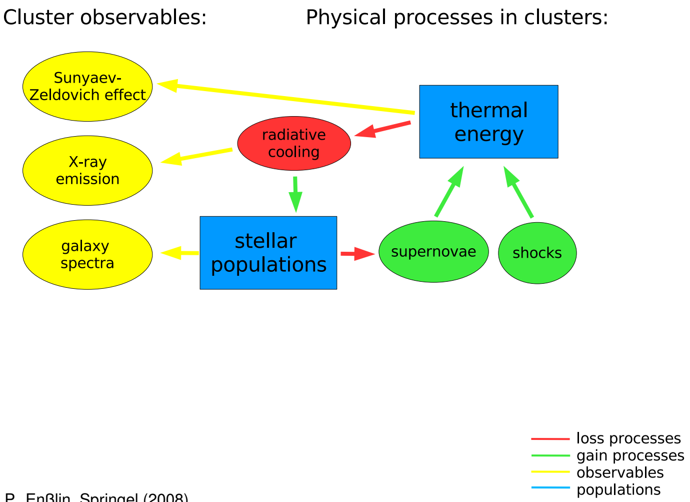
Mach number distribution weighted by $\varepsilon_{\text{diss}}$

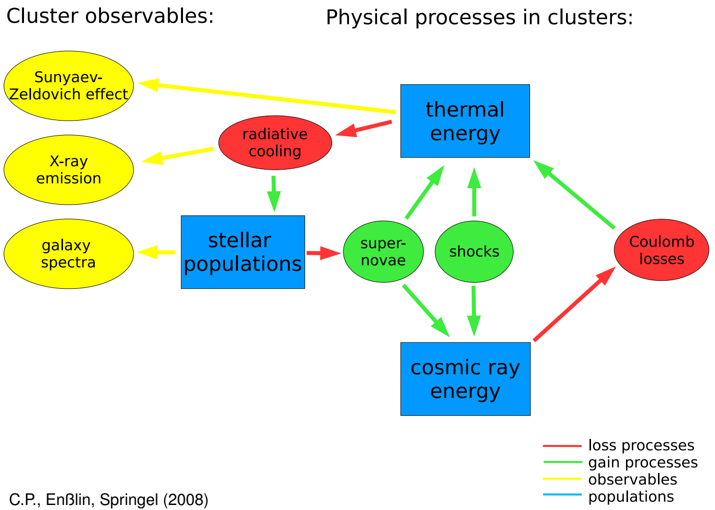


Radiative simulations – flowchart



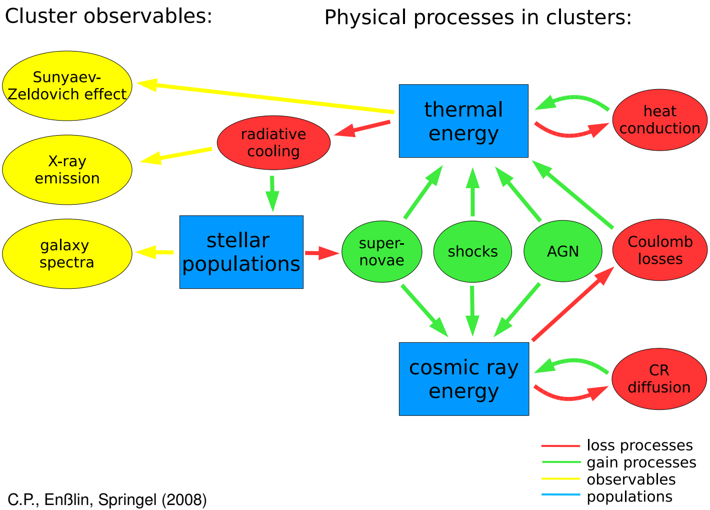
C.P., Enßlin, Springel (2008)

Radiative simulations with CR physics



C.P., Enßlin, Springel (2008)

Radiative simulations with extended CR physics



C.P., Enßlin, Springel (2008)

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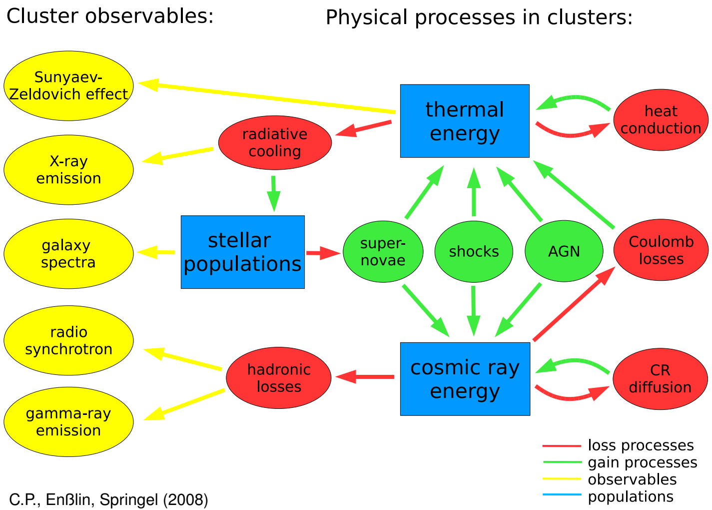
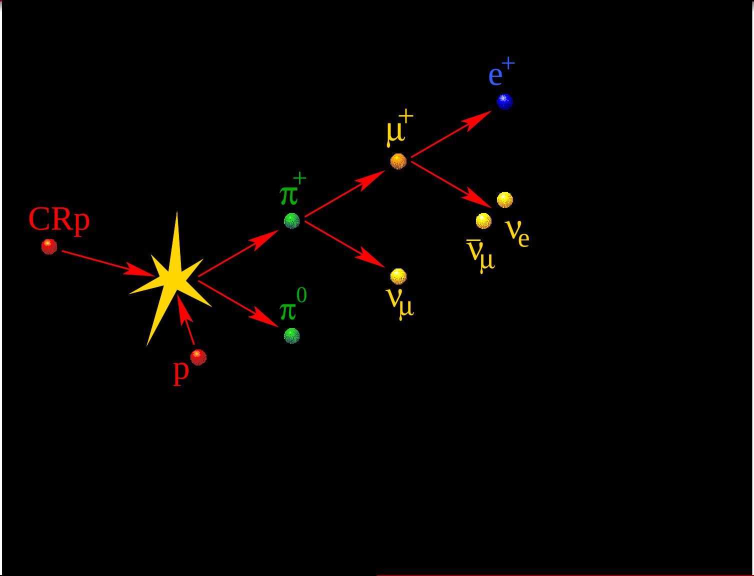


C.P., Enßlin, Springel (2008)

Hadronic cosmic ray proton interaction



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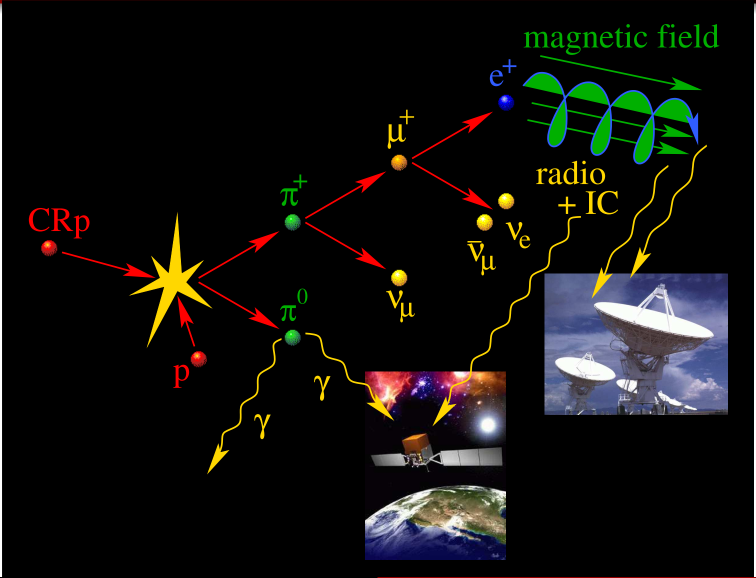

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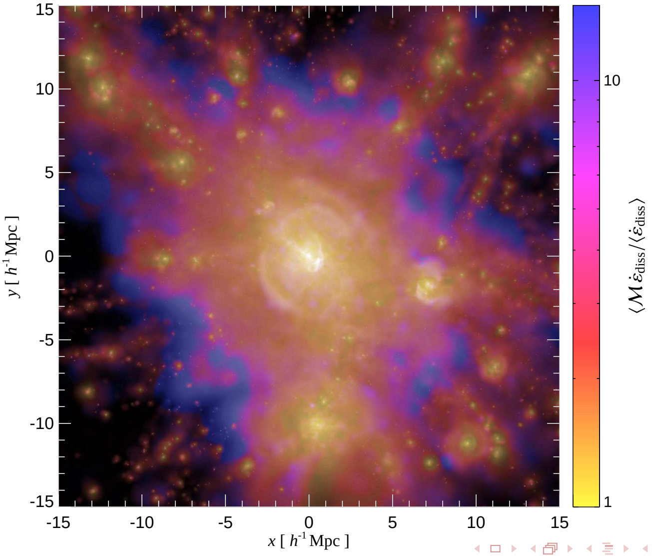

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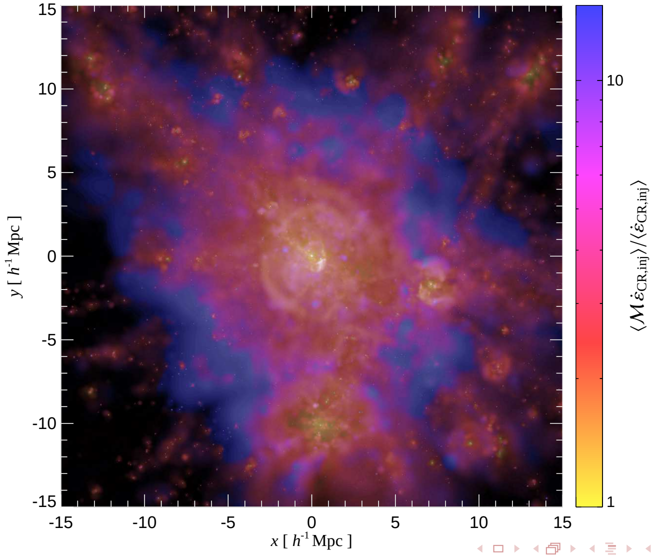
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



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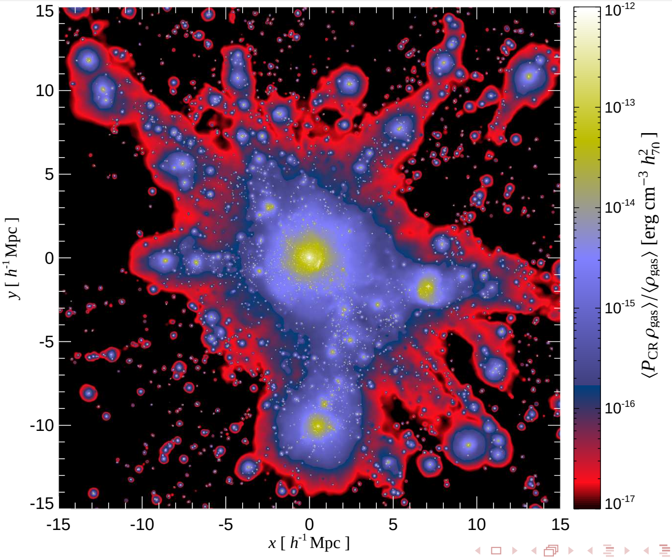
CR pressure P_{CR}



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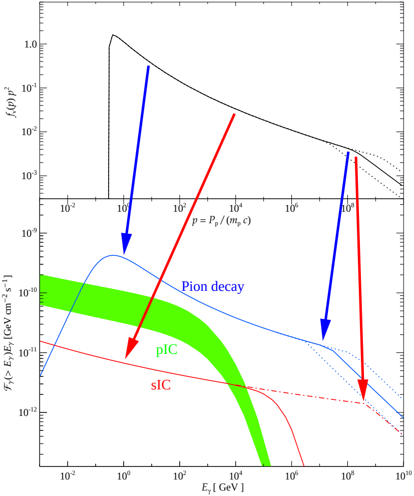
CR proton and γ-ray spectrum (Pinzke & CP 2009)



- normalized CR spectrum shows universal concave shape → governed mainly by hierarchical structure formation and adiabatic CR transport processes
- concave shape imprinted on dominating pion-decay γ-ray spectrum (blue)
- primary IC emission from shock-accelerated electrons (green) and secondary IC emission (red) subdominant

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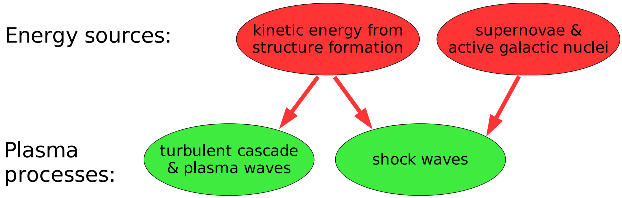
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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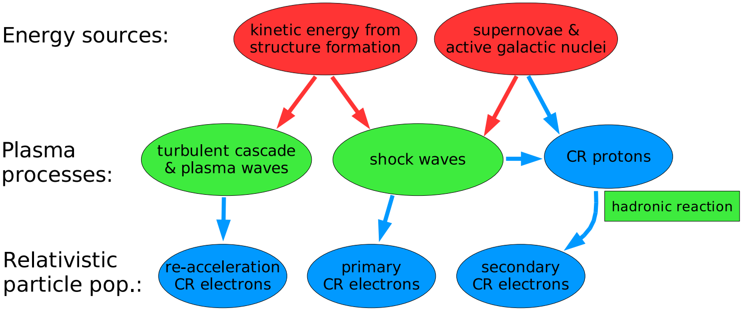

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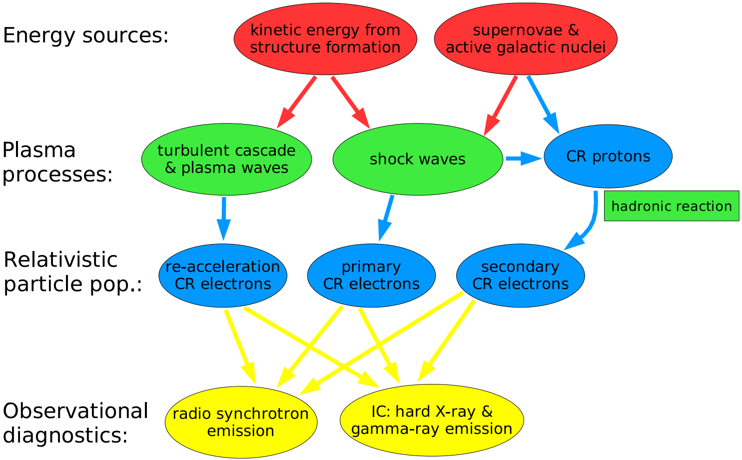

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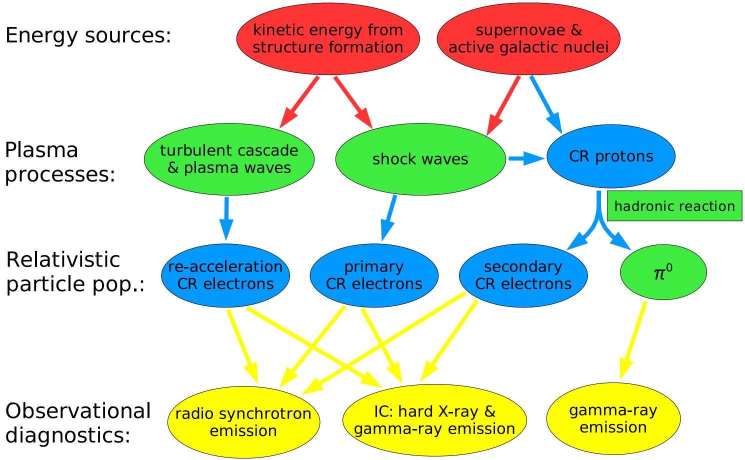
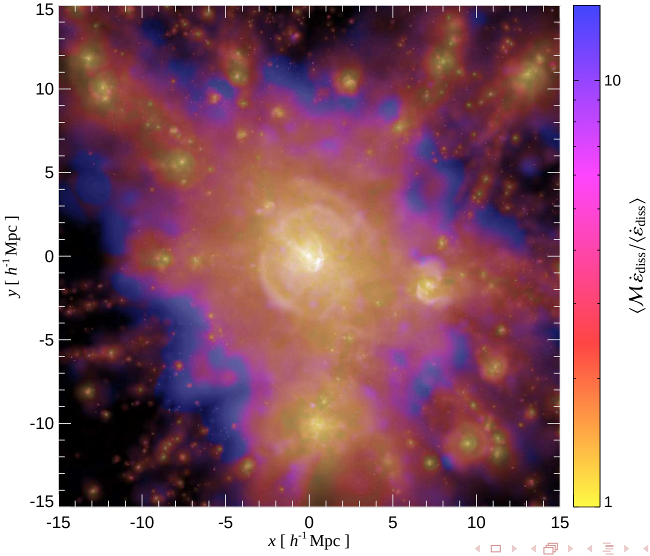


Cosmic web: Mach number



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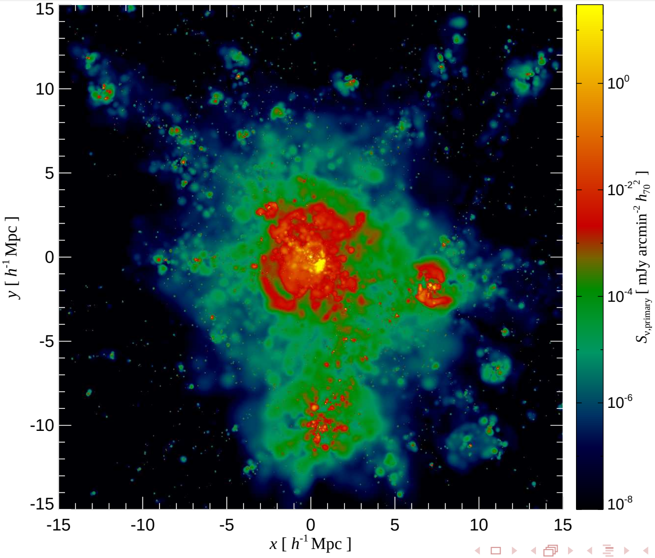
Radio gischt: primary CRe (150 MHz)



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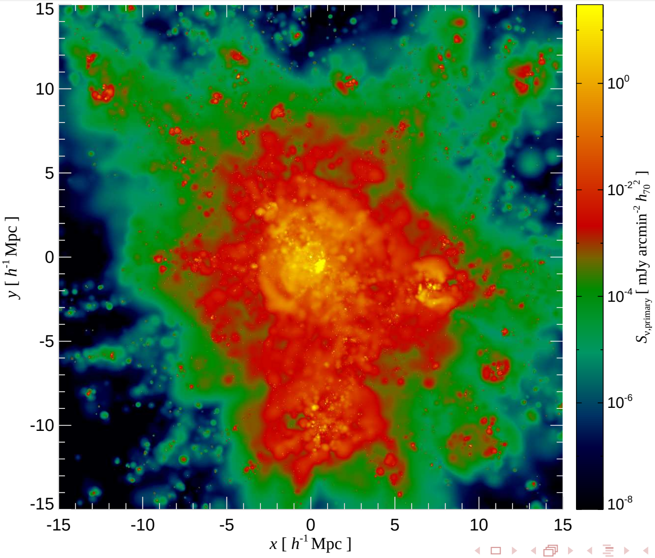
Radio gischt: primary CRe (150 MHz), slower magn. decline



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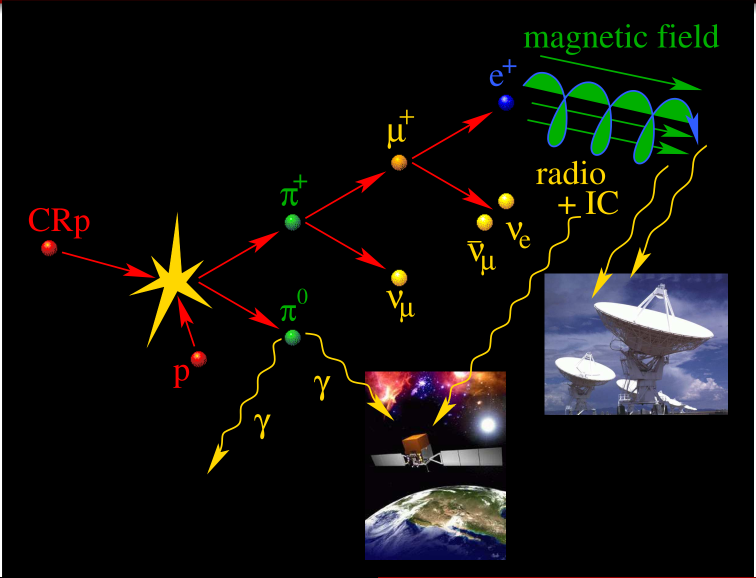
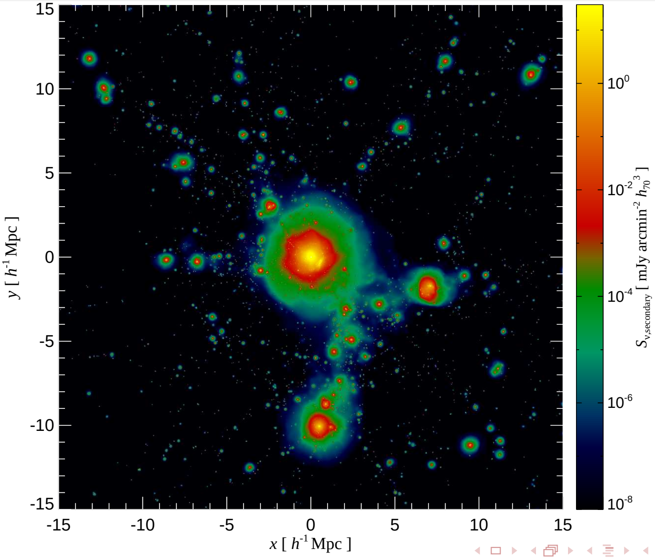
Hadronic cosmic ray proton interaction



Cluster radio emission by hadronically produced CRe



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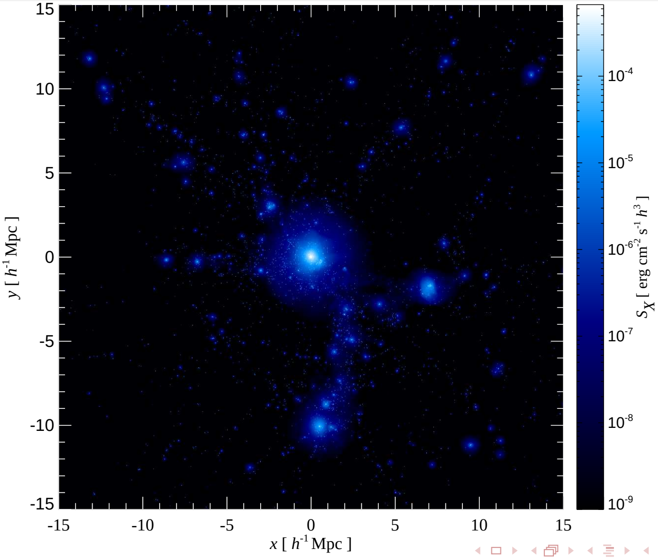
Thermal X-ray emission



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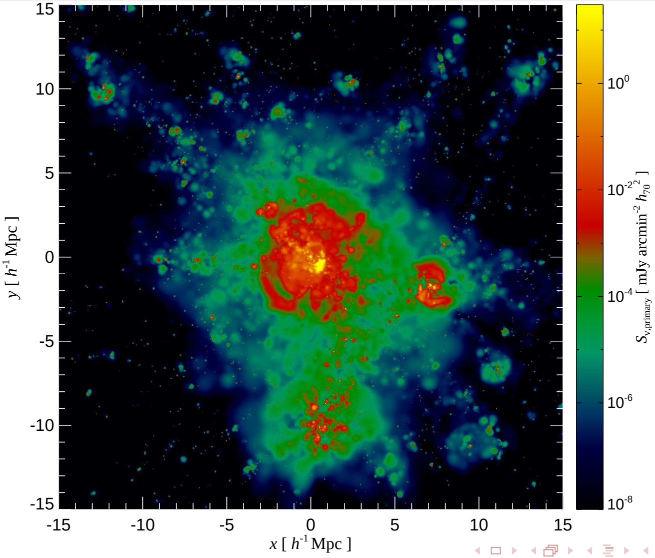

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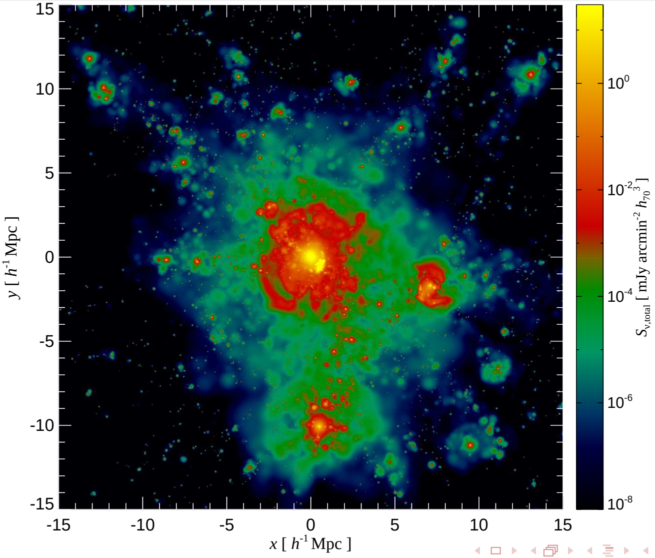
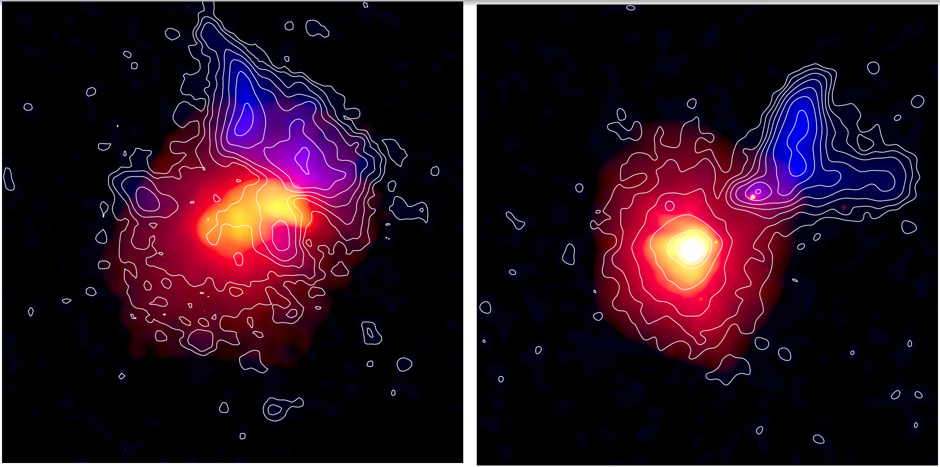
Radio gischt + central hadronic halo = giant radio halo

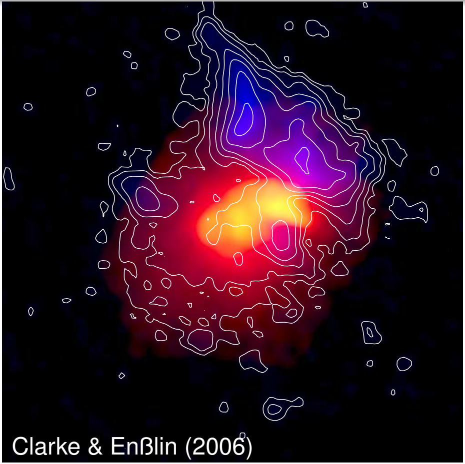


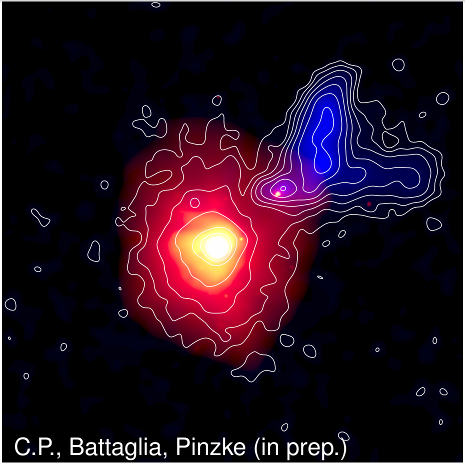
Which one is the simulation/observation of A2256?



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 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.:

- LOFAR, GMRT, MWA, LWA, SKA: interferometric array of radio telescopes at low frequencies ($\nu \simeq (15 - 240)$ MHz)
- NuSTAR, Xenia: future 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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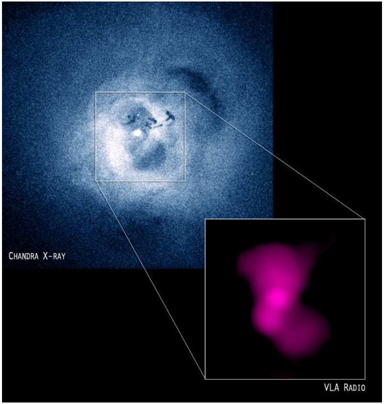
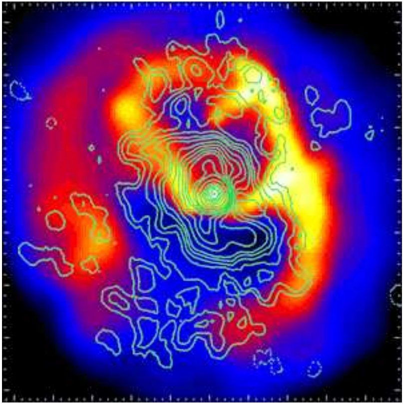
Plasma bubbles (1)



Perseus cluster

(NASA/IoA/A.Fabian et al.)



Abell 2052

(Blanton et al., 2001)

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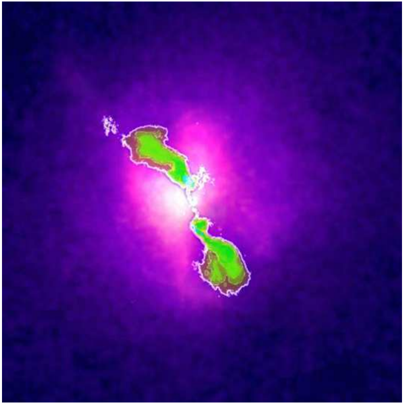
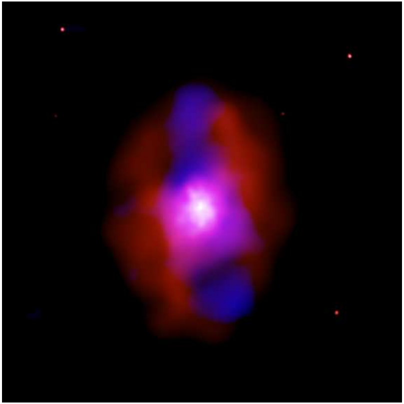
Plasma bubbles (2)



Hydra A cluster

(X-ray: NASA/CXC/SAO; Radio: NRAO)

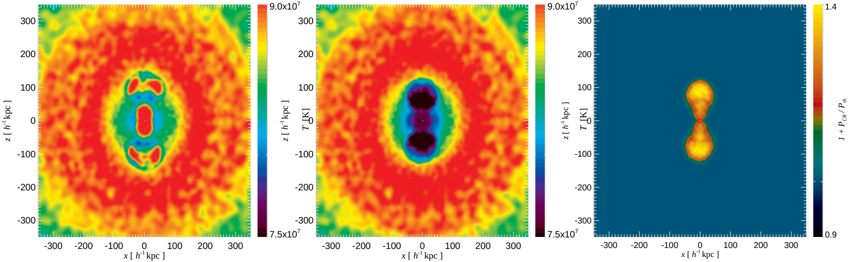


MS 0735 cluster

(X-ray: NASA/CXC/Ohio U./ B.McNamara et al.; Radio: NRAO/VLA)

CR feedback by AGN: isolated galaxy cluster

Isolated, non-cosmological cluster simulations: $t = 0.07 t_{\mathrm{H}}$



$\langle T \rangle_M$: without CRs

$\langle T \rangle_M$: with CRs

$1 + P_{\mathrm{CR}} / P_{\mathrm{th}}$

Sijacki, C.P., Springel, Enßlin (2008)

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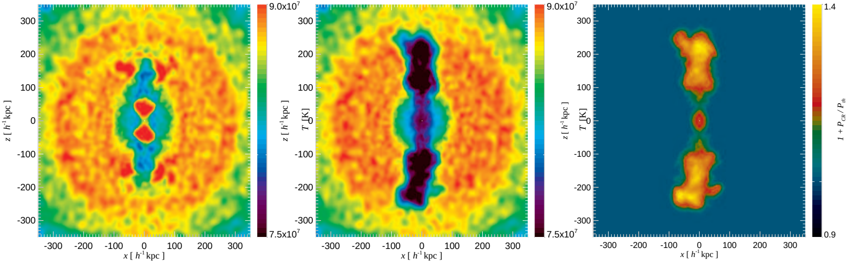
CR feedback by AGN: isolated galaxy cluster

Isolated, non-cosmological cluster simulations: $t = 0.12 t_{\mathrm{H}}$



$\langle T \rangle_M$: without CRs $\langle T \rangle_M$: with CRs $1 + P_{\mathrm{CR}} / P_{\mathrm{th}}$

Sijacki, C.P., Springel, Enßlin (2008)

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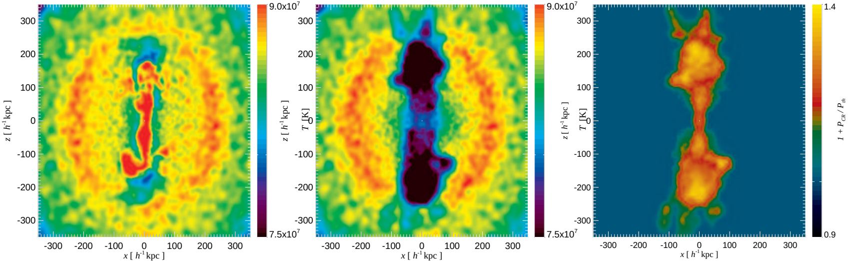
CR feedback by AGN: isolated galaxy cluster

Isolated, non-cosmological cluster simulations: $t = 0.24 t_H$



$\langle T \rangle_M$: without CRs

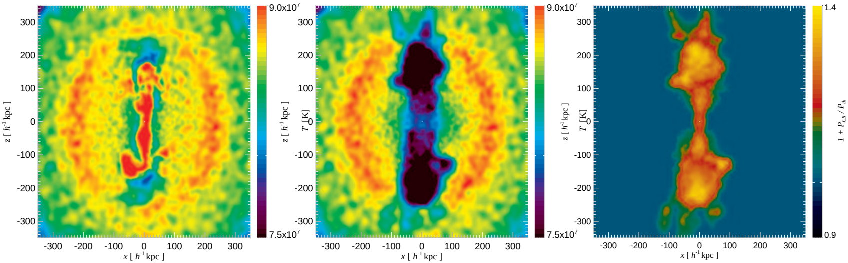
$\langle T \rangle_M$: with CRs

$1 + P_{CR}/P_{th}$

Sijacki, C.P., Springel, Enßlin (2008)

CR feedback by AGN: isolated galaxy cluster

Isolated, non-cosmological cluster simulations: $t = 0.24 t_{\mathrm{H}}$



$\langle T \rangle_M$: without CRs $\quad$ $\langle T \rangle_M$: with CRs $\quad$ $1 + P_{\mathrm{CR}}/P_{\mathrm{th}}$

$\rightarrow$ bubble dynamics, coherence and maximum cluster-centric distance reached are affected by the presence of a relativistic component filling the bubbles! (Sijacki, C.P., Springel, Enßlin 2008)

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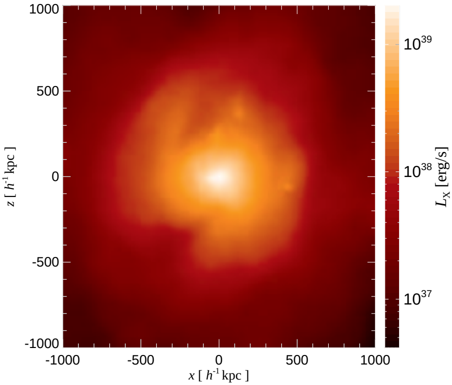
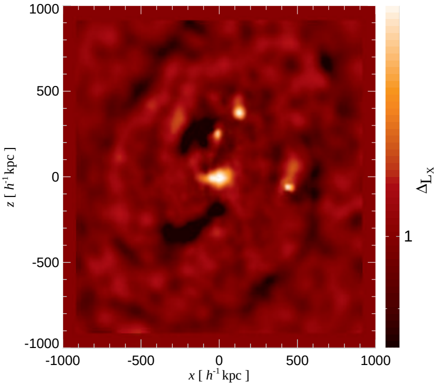
CR feedback by AGN: cosmological galaxy cluster

Ripples/weak shocks driven by AGN bubbles



X-ray brightness S_X, Virgo-like cluster



unsharp masked image ΔS_X

Sijacki, C.P., Springel, Enßlin (2008)

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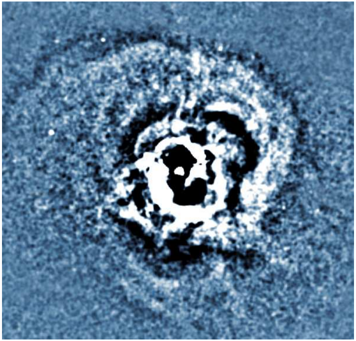
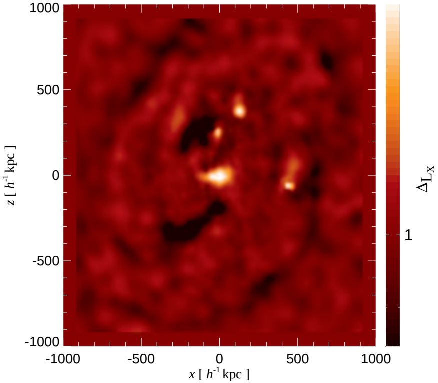
CR feedback by AGN: cosmological galaxy cluster

ΔS_X: observation vs. simulation





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

small cool core cluster, $M_{\rm vir} \simeq 10^{14} M_\odot / h$

Sijacki, C.P., Springel, Enßlin (2008)

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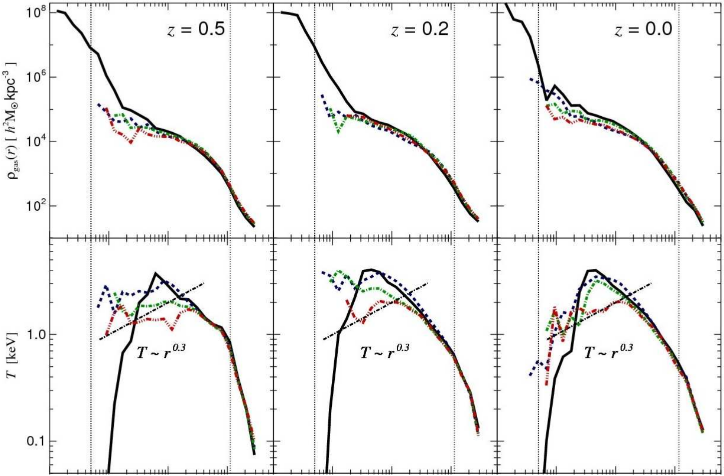
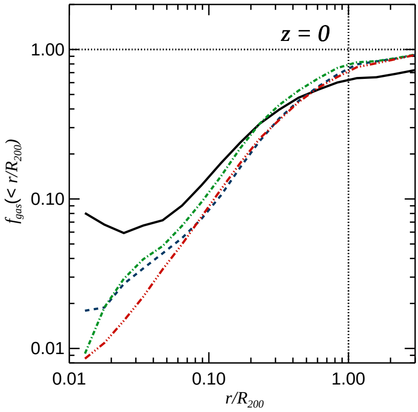
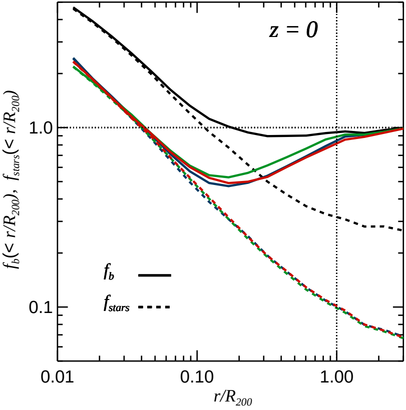
CR feedback by AGN: profiles of ρ and T



Sijacki, C.P., Springel, Enßlin (2008)

CR feedback by AGN: gas and baryon fraction





AGN feedback reduces the amount of formed stars to reconcile the observations! (Sijacki, C.P., Springel, Enßlin 2008)

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Sunyaev-Zel'dovich power spectrum

How to use galaxy clusters as cosmological tools!

- galaxy clusters are exponentially sensitive to new physics beyond the standard model:
  - testing Einstein's gravity on large scales
  - dark energy or Λ
  - non-Gaussianity
- Sunyaev-Zel'dovich power spectrum depends on cosmology and cluster physics:

$$C_\ell = g_\nu^2 \int_0^{z_{\max}} \mathrm{d}z \, \frac{\mathrm{d}V}{\mathrm{d}z} \int \mathrm{d}M \, \frac{\mathrm{d}n(z,M)}{\mathrm{d}M} \, |\tilde{y}_\ell(M,z)|^2$$

- amplitude of the SZ power spectrum $C_\ell \propto A_{\mathrm{SZ}} \propto \sigma_8^7$

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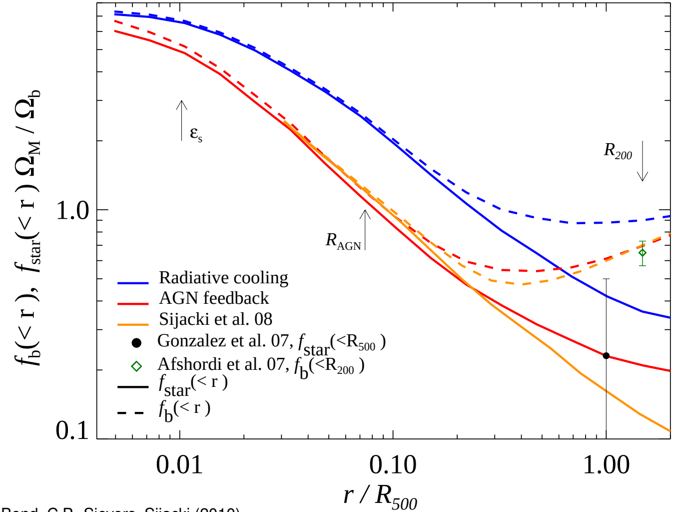
Baryon and stellar mass fraction

$f_{\mathrm{star}}(<r) = M_{\mathrm{star}}(<r)/M_{\mathrm{tot}}(<r)$ is reduced by AGN feedback to observed values



Battaglia, Bond, C.P., Sievers, Sijacki (2010)

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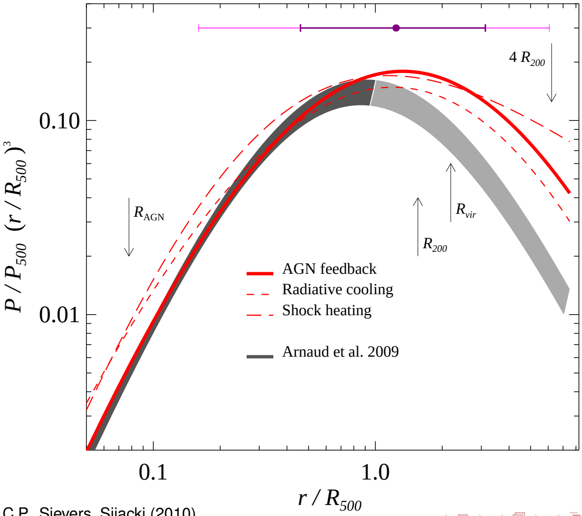
Stacked pressure profile

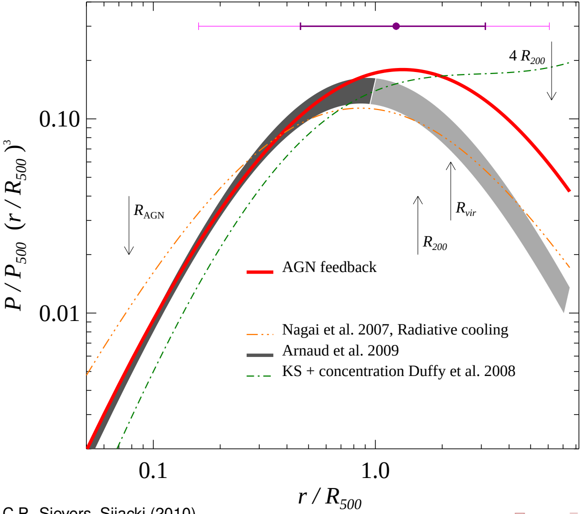
$P(r)r^3 \propto \mathrm{d}E/\mathrm{d}\log r$ peaks around virial radius with large convergence region



Battaglia, Bond, C.P., Sievers, Sijacki (2010)

Stacked pressure profile

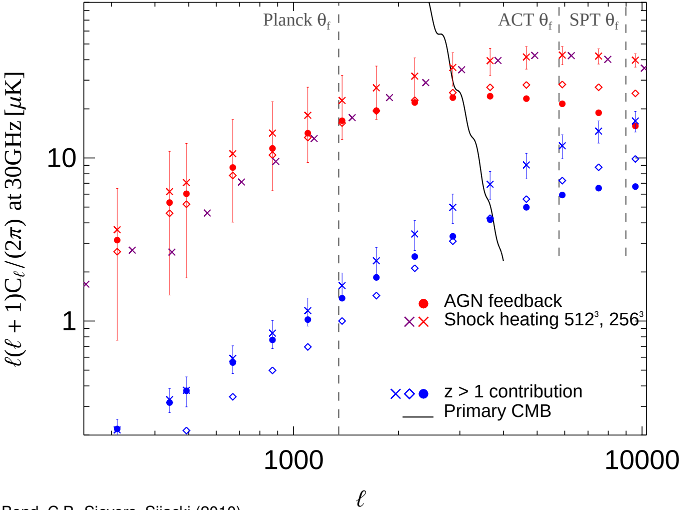
Analytic models and simulations without AGN feedback are in conflict with X-ray data



Battaglia, Bond, C.P., Sievers, Sijacki (2010)

SZ power spectrum with AGN feedback

Cosmological parameters: low-ℓ part, cluster astrophysics at $z \gtrsim 0.8$: high-ℓ part



Battaglia, Bond, C.P., Sievers, Sijacki (2010)

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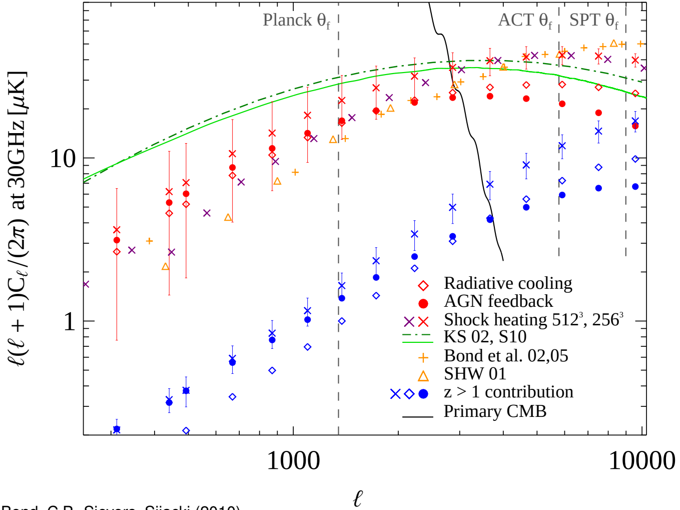
SZ power spectrum with AGN feedback

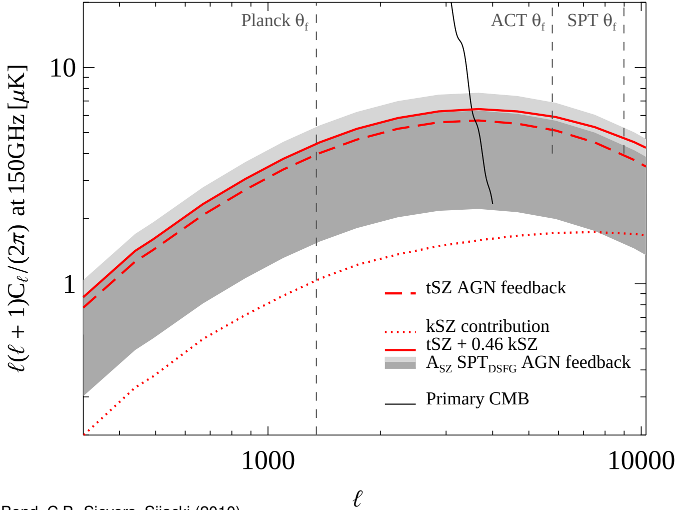
Importance of hydrodynamic simulations: effect of unvirialized motions/turbulence



Battaglia, Bond, C.P., Sievers, Sijacki (2010)

Cosmological constraints

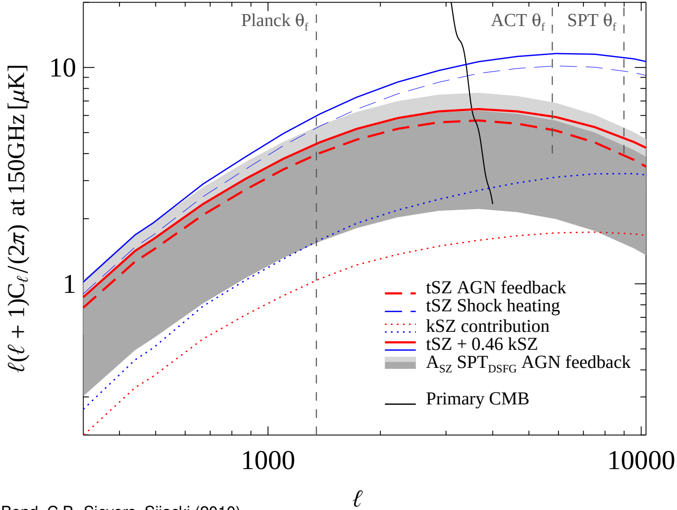
SPT data with WMAP $\sigma_8 = 0.8$ consistent with our AGN models



Battaglia, Bond, C.P., Sievers, Sijacki (2010)

Cosmological constraints

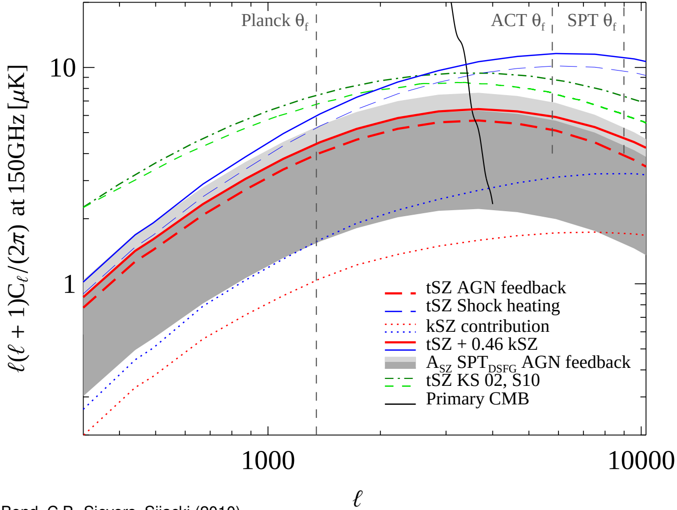
SPT data with WMAP $\sigma_8 = 0.8$ inconsistent with simple non-radiative models



Battaglia, Bond, C.P., Sievers, Sijacki (2010)

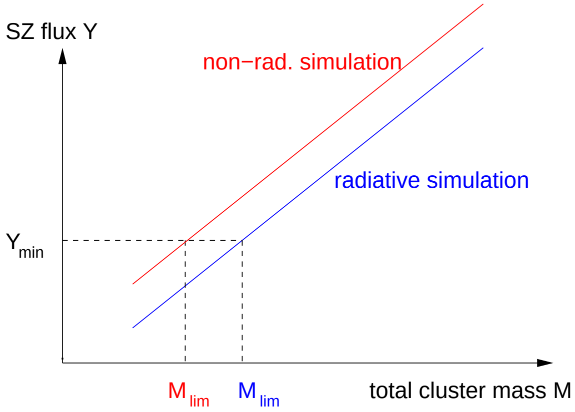
Cosmological constraints

SPT data with WMAP $\sigma_8 = 0.8$ inconsistent with (semi-)analytic models



Battaglia, Bond, C.P., Sievers, Sijacki (2010)

How cluster physics changes scaling relations (1)



→ cooling and star formation depletes the gas reservoir, which decreases the SZ flux and increases the effective mass threshold for an SZ flux−limited cluster sample

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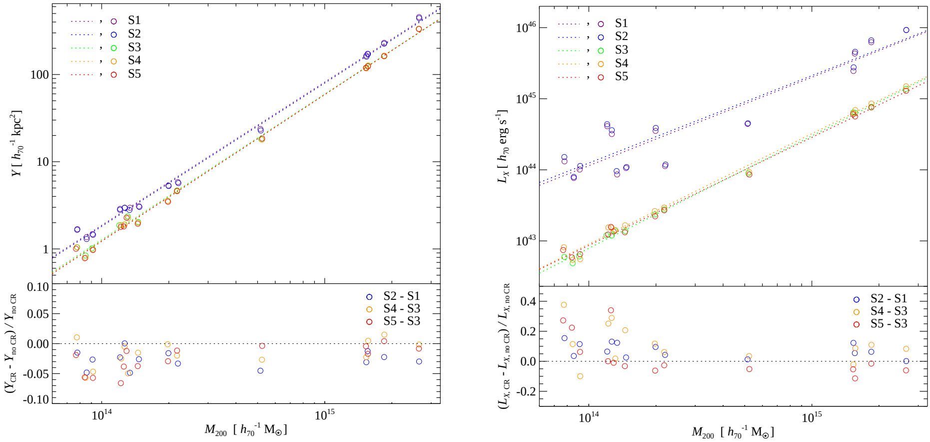
How cluster physics changes scaling relations (2)



top: scaling relations of non-radiative/radiative simulations, $Y(M_{200})$ vs. $L_X(M_{200})$

bottom: relative diff. due to CR feedback → system. negative (positive) bias for Y (L_X)!

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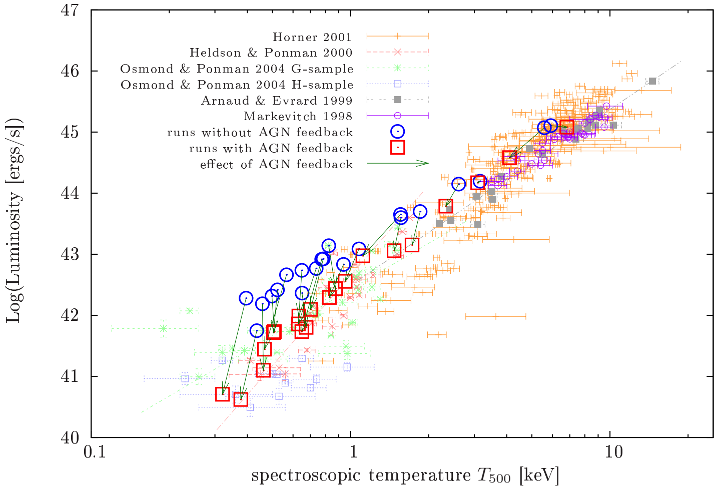
$L_X - T$ scaling relation: impact of AGN feedback



Puchwein, Sijacki, Springel (2008)

Degeneracies of the cluster redshift distribution (1)

- The number density of massive clusters is exponentially sensitive to the amplitude of the initial Gaussian fluctuations, whose normalization we usually describe using σ_8, the *rms* fluctuations of overdensity within spheres of 8 h^{-1} Mpc.
- The cluster redshift distribution $\mathrm{d}n/\mathrm{d}z$ is increased by a lower effective mass threshold M_{lim} in a survey or by increasing σ_8 respectively Ω_m $\rightarrow$ degeneracies of cosmological parameters with respect to cluster physics.

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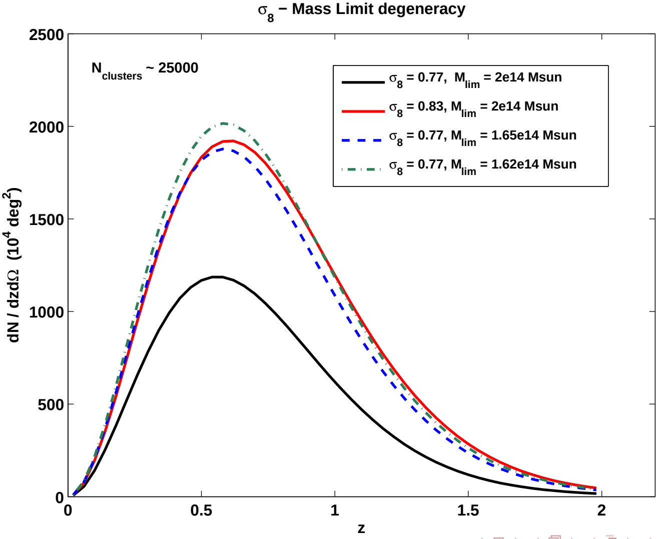
Degeneracies of the cluster redshift distribution (2)



Conclusions on cluster cosmology

- crucial to *separate effects* of cluster physics from cosmology or physics beyond the standard model
- inhomogeneous, localized and self-regulated feedback by AGN . . .
    - solves over-cooling and recovers observed stellar mass fractions
    - brings simulated X-ray profiles/scaling relations in agreement with observations
    - brings simulated SZ power spectra in agreement with observations (for σ_8 from primordial CMB fluctuations)

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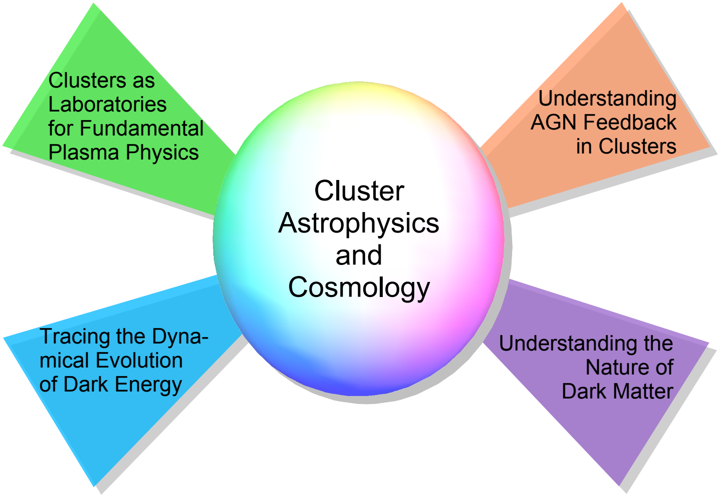
Future perspectives and directions



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Literature for the talk

- Battaglia, Bond, Pfrommer, Sievers, Sijacki, 2010, submitted, arXiv:1003.4256, *Simulations of the Sunyaev-Zel'dovich Power Spectrum with AGN Feedback*
- Pinzke & Pfrommer, 2010, submitted, arXiv:1001.5023, *Simulating the gamma-ray emission from galaxy clusters: a universal cosmic ray spectrum and spatial distribution*
- Sijacki, Pfrommer, Springel, Enßlin, 2008, MNRAS, 387, 1403, *Simulations of cosmic ray feedback by AGN in galaxy clusters*
- Pfrommer, 2008, MNRAS, 385, 1242 *Simulating cosmic rays in clusters of galaxies – III. Non-thermal scaling relations and comparison to observations*
- Pfrommer, Enßlin, Springel, 2008, MNRAS, 385, 1211, *Simulating cosmic rays in clusters of galaxies – II. A unified scheme for radio halos and relics with predictions of the γ-ray emission*
- Pfrommer, Enßlin, Springel, Jubelgas, Dolag, 2007, MNRAS, 378, 385, *Simulating cosmic rays in clusters of galaxies – I. Effects on the Sunyaev-Zel'dovich effect and the X-ray emission*
- Pfrommer, Springel, Enßlin, Jubelgas, 2006, MNRAS, 367, 113, *Detecting shock waves in cosmological smoothed particle hydrodynamics simulations*
- Enßlin, Pfrommer, Springel, Jubelgas, 2007, A&A, 473, 41, *Cosmic ray physics in calculations of cosmological structure formation*

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