Cosmological simulations of clusters

Christoph Pfrommer

Leibniz Institute for Astrophysics Potsdam (AIP)

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Outline

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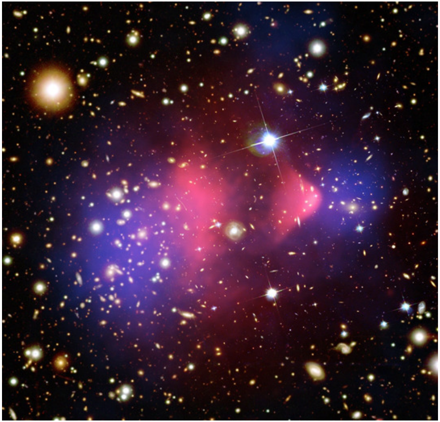
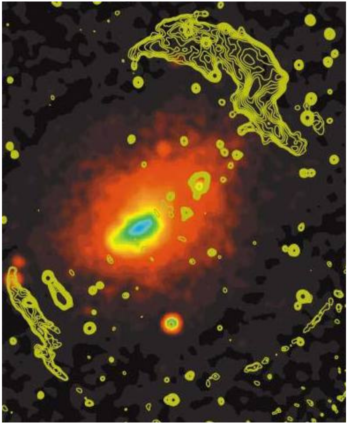
Outline

Cluster mergers: *the* most energetic cosmic events



1E 0657-56 (“Bullet cluster”)

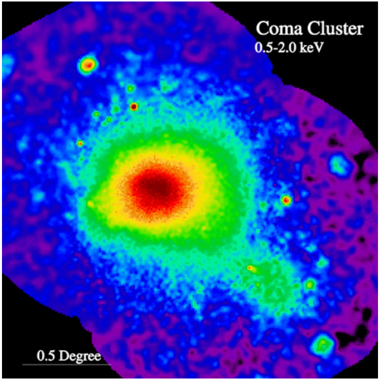
(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)



Abell 3667

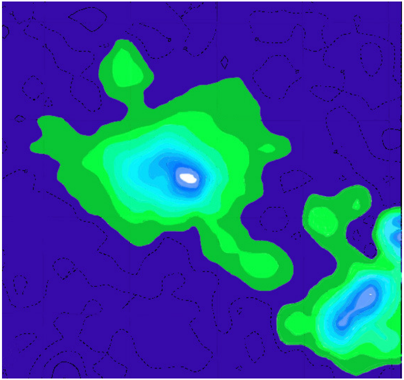
(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

Giant radio halo & relic in the Coma cluster



thermal X-ray emission

(Snowden/MPE/ROSAT)

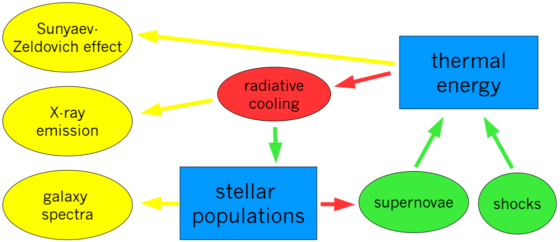


radio synchrotron emission

(Deiss/Effelsberg)

Cosmological simulations – flowchart

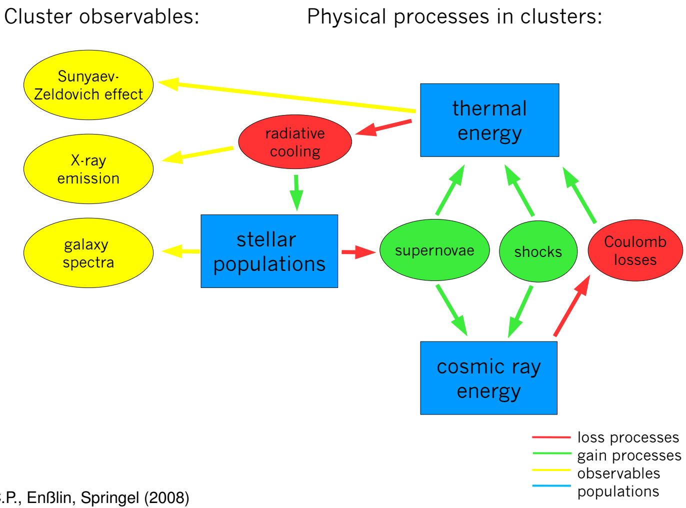
Cluster observables: Physical processes in clusters:



loss processes
gain processes
observables
populations

C.P., Enßlin, Springel (2008)

Cosmological simulations with cosmic ray physics



C.P., Enßlin, Springel (2008)

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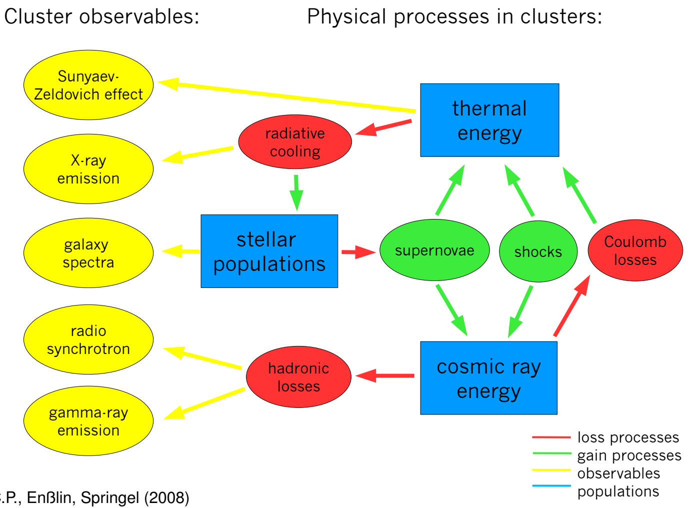
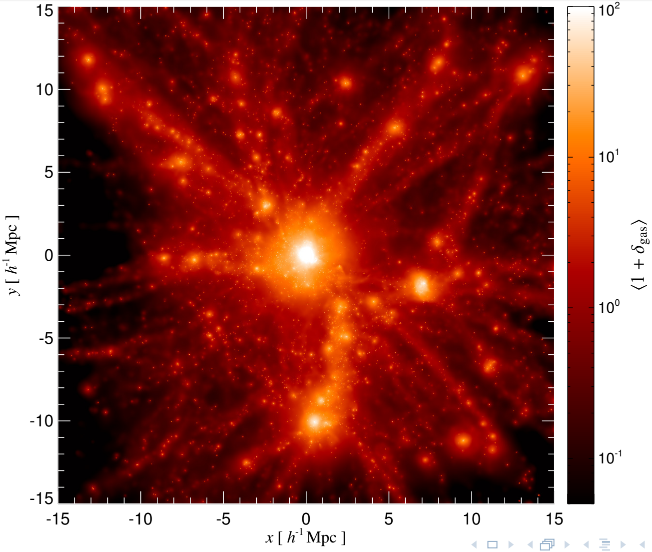
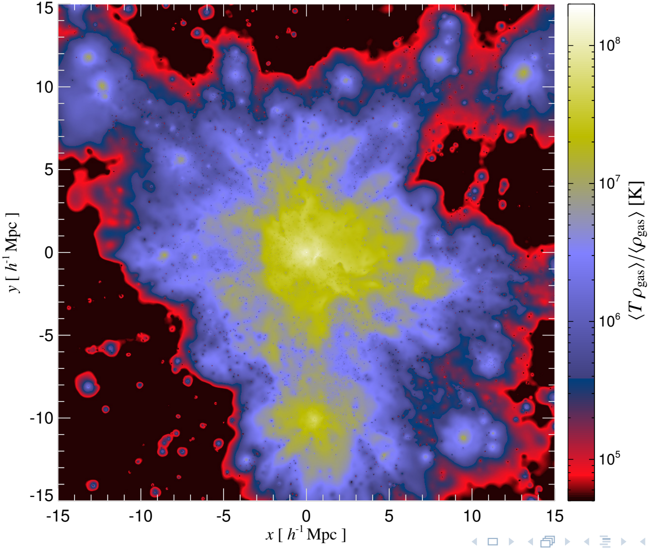


C.P., Enßlin, Springel (2008)

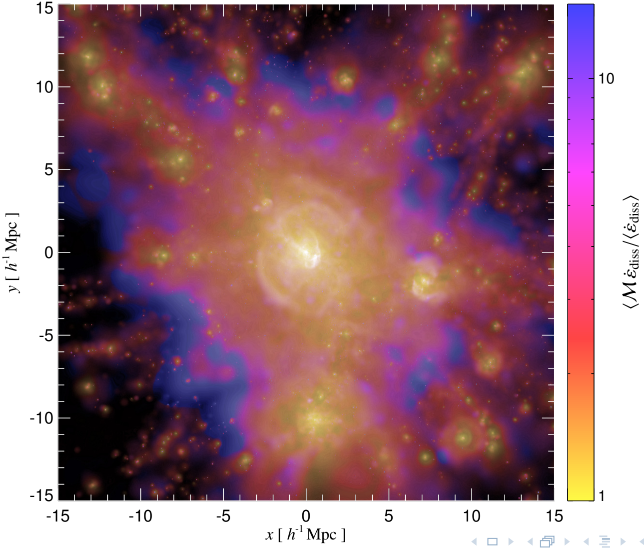
Cosmological cluster simulation: gas density



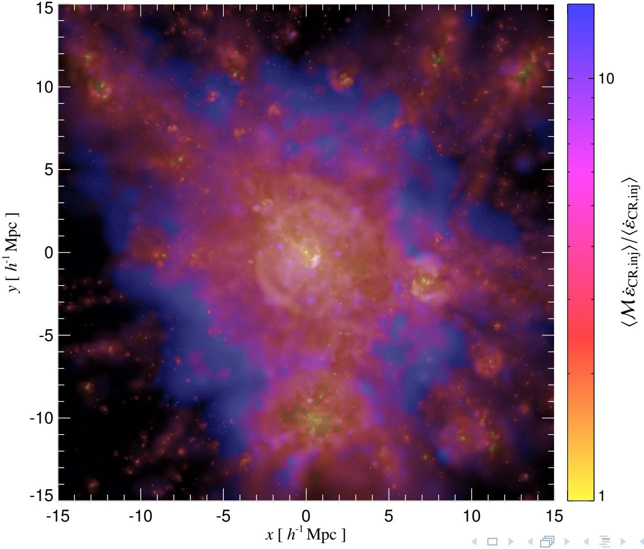
Mass weighted temperature



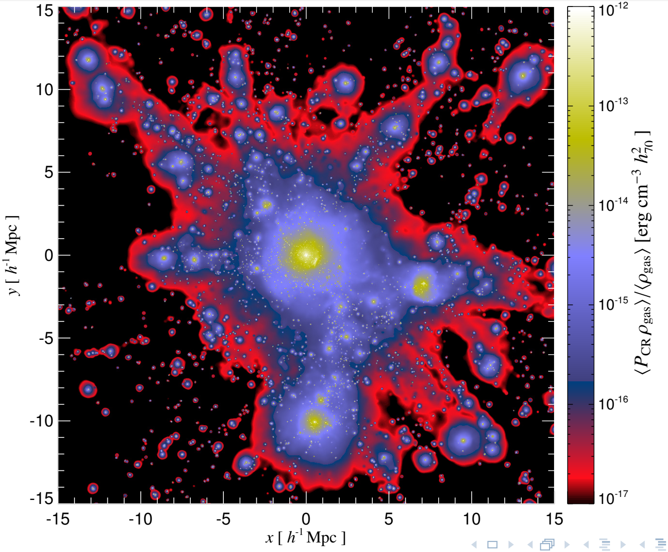
Shock strengths weighted by dissipated energy



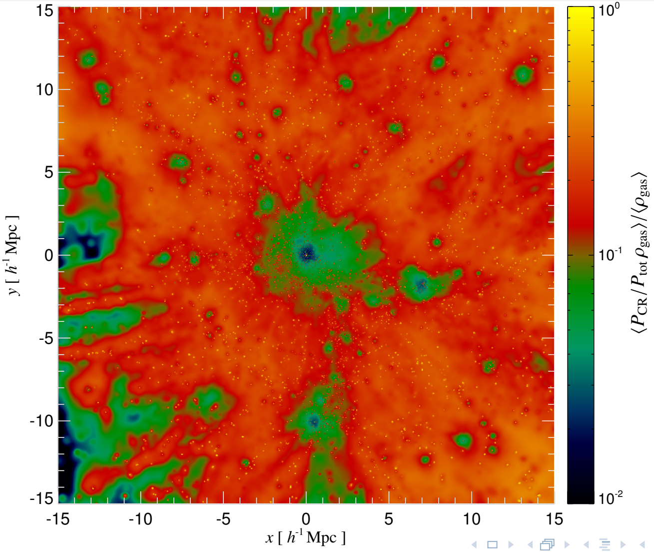
Shock strengths weighted by injected CR energy



Evolved CR pressure

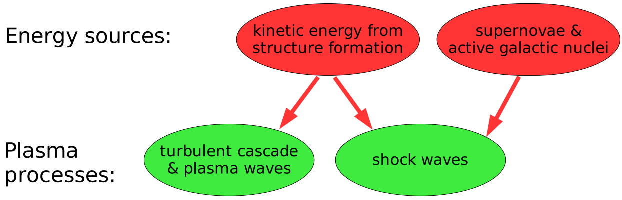


Relative CR pressure $P_{\rm CR}/P_{\rm total}$



Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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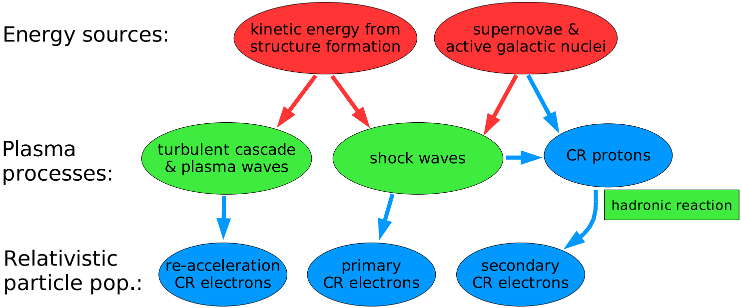

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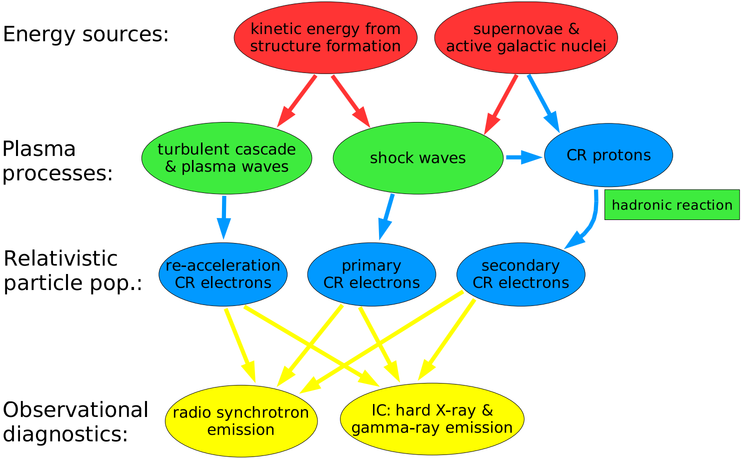

Multi messenger approach for non-thermal processes

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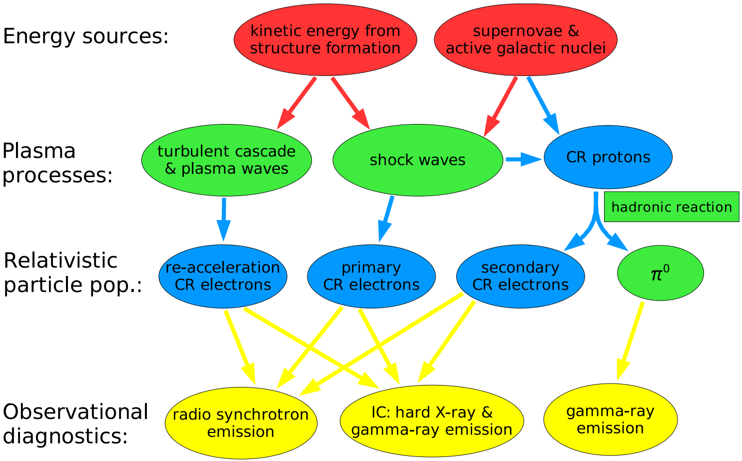
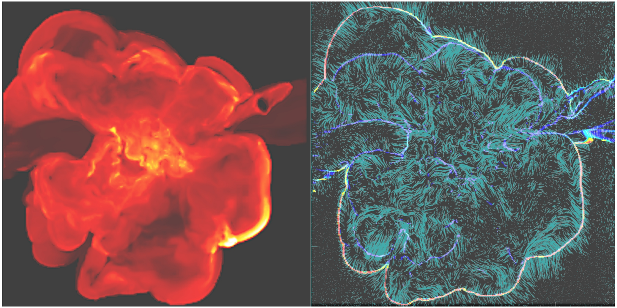


Outline

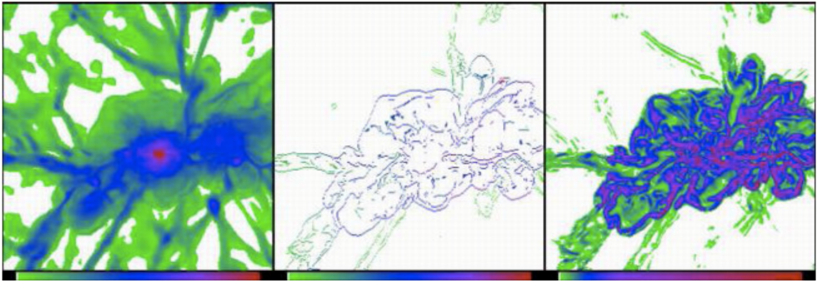
Major challenges – physics



Temperature, Mach number & turbulence with AMR (credit: Vazza)

- strength and properties of magnetic fields: in ICM and at shocks
- properties of cluster turbulence: MHD to kinetic scales
- cosmic ray transport properties

Nature and origin of turbulence and magnetic fields

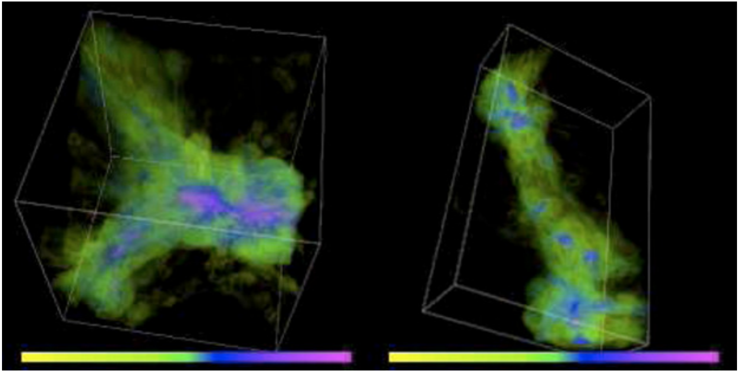


Gas density, locations of shocks, vorticity = $\nabla \times \vec{v}$ (Ryu+ 2008)

Model for the origin of intra-cluster magnetic fields:

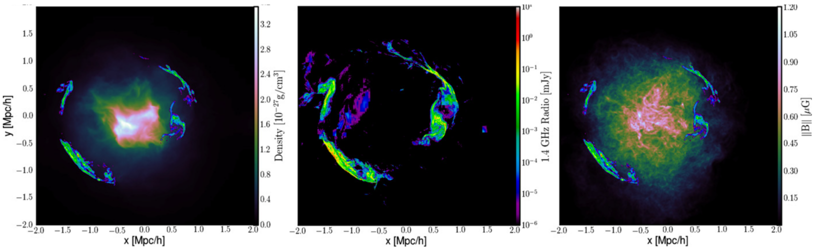
- large scale structure formation $\rightarrow$ curved shocks $\rightarrow$ injection of vorticity and turbulent flow motions
- turbulence amplifies weak seed magnetic fields of any origin

Volume rendered magnetic field strengths



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

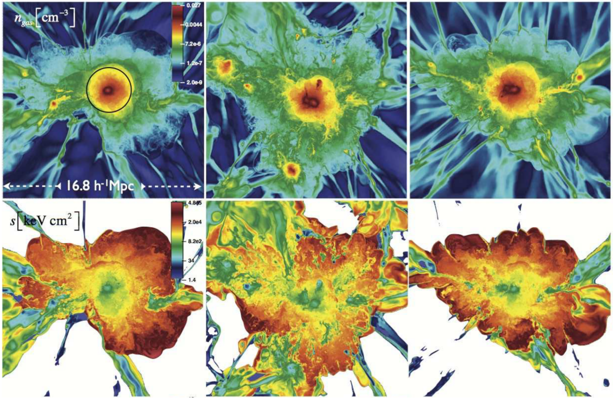
Problem of magnetic fields at relics



Density, radio intensity, magnetic field strength with AMR (Skillman+ 2013)

- relics trace merger shocks
- simulated $B \lesssim 0.1\ \mu$G at relic position
- observed $B \approx 3\ \mu$G at relic position
  (Finoguenov+ 2010, van Weeren+ 2012)

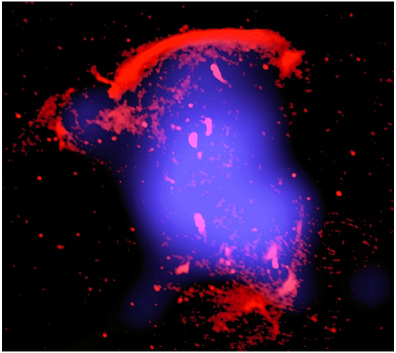
Turbulence properties



Three different density (top) and specific entropy (bottom) slices (Miniati+ 2014)

- $r < R_{\mathrm{vir}}/3$: mostly solenoidal (Kolmogorov) turbulence
- consistent with fully developed, homogeneous and isotropic turbulence
- towards R_{vir}: flow becomes more compressional

Major challenges – giant relics

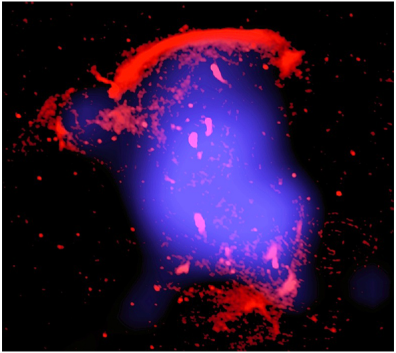


CIZA J2242.8+5301, sausage relic,
X-ray and radio
X-ray: XMM-Newton; radio: van Weeren

what we know (not contentious):

- trace shocks in cluster outskirts
- energy source: hierarchical growth $\rightarrow$ cluster mergers
- diffusive shock acceleration at merger shocks

Major challenges – giant relics



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what we know (not contentious):

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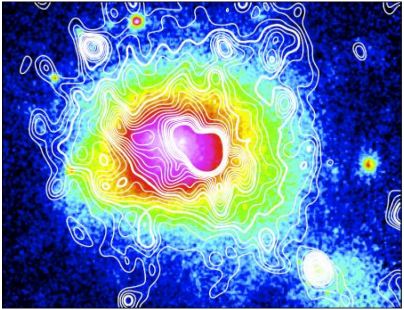
- diffusive shock acceleration at merger shocks

challenges:

- weak shocks: electron acceleration mechanism?
- explain magnetic properties (strength, orientation)

Major challenges – giant halos



Coma cluster, color: X-ray, contours: radio
X-ray: Snowden/MPE/ROSAT; radio: Brown/Westerbork

what we know (not contentious):

- energy source: hierarchical growth $\rightarrow$ cluster mergers
- volume filling synchrotron emission in turbulent fields
- fields have likely grown via small-scale dynamo

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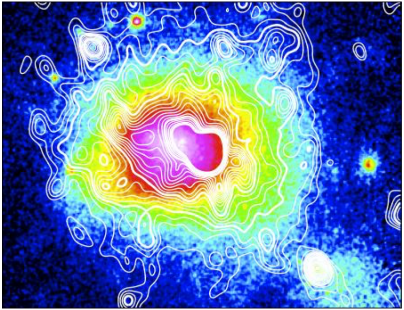
Major challenges – giant halos



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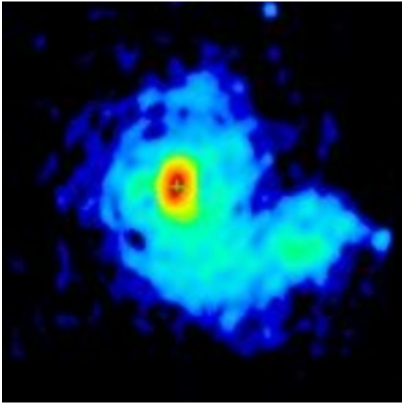
what we know (not contentious):

- energy source: hierarchical growth $\rightarrow$ cluster mergers
- volume filling synchrotron emission in turbulent fields
- fields have likely grown via small-scale dynamo

challenges:

- $\tau_{\rm syn} \lesssim 100$ Myr $\rightarrow$ requires efficient in-situ electron acceleration – which?
- robust prediction? ways forward to test?

Major challenges – mini halos

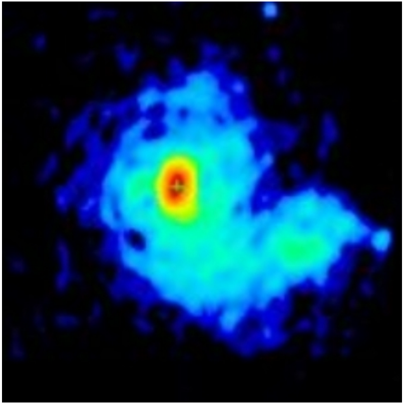


Perseus cluster, radio mini halo
Pedlar+ (1990)

what we know (not contentious):

- occurence in strong cool core clusters (large SFR, cooling radii)
- volume filling synchrotron emission in turbulent fields

Major challenges – mini halos



Perseus cluster, radio mini halo
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what we know (not contentious):

- occurence in strong cool core clusters (large SFR, cooling radii)
- volume filling synchrotron emission in turbulent fields

challenges:

- energy source: AGN feedback or sloshing?
- acceleration mechanism: hadronic or re-acceleration

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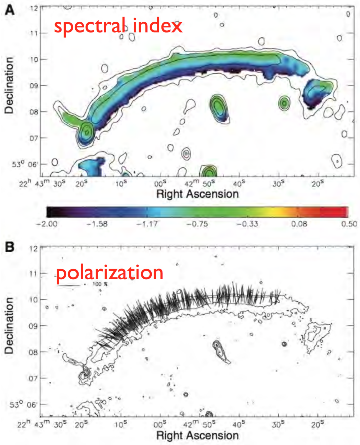
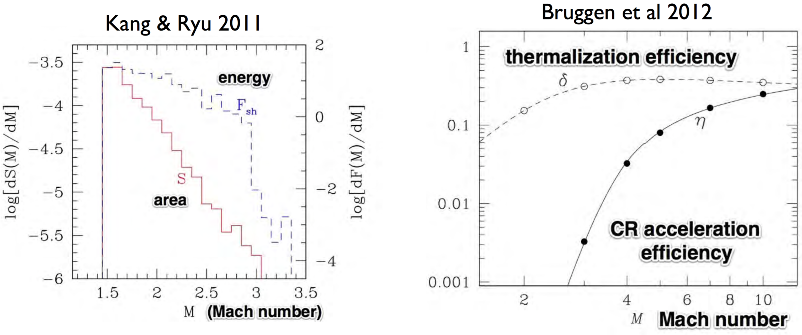
Radio relics – great tools for studying shock physics



van Weeren+ (2010)

- trace shocks in cluster outskirts
- spectral index: shock Mach number → projection?
- spectral ageing: B-field strength → reacceleration?
- polarization: B-field orientation

Biggest unknown: shock acceleration efficiency



- merging shocks dominated by low Mach number shocks
- these shocks have low acceleration efficiencies

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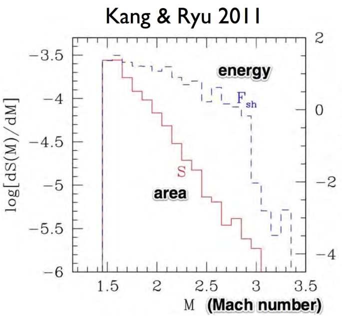
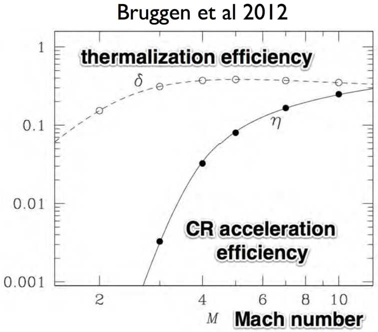
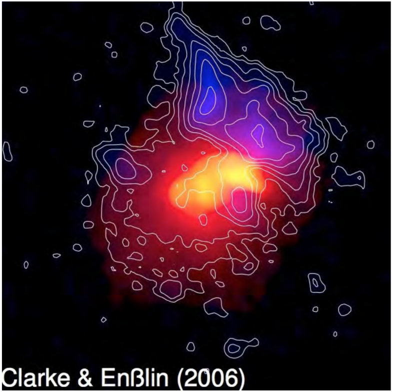
Biggest unknown: shock acceleration efficiency

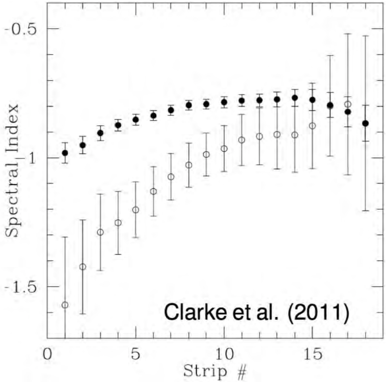




- merging shocks dominated by low Mach number shocks
- these shocks have low acceleration efficiencies
  → electron preheating via shock-drift/-surfing acceleration at weak perpendicular shocks possible (Guo+ 2014, Park+ 2015)

A poster child: A2256



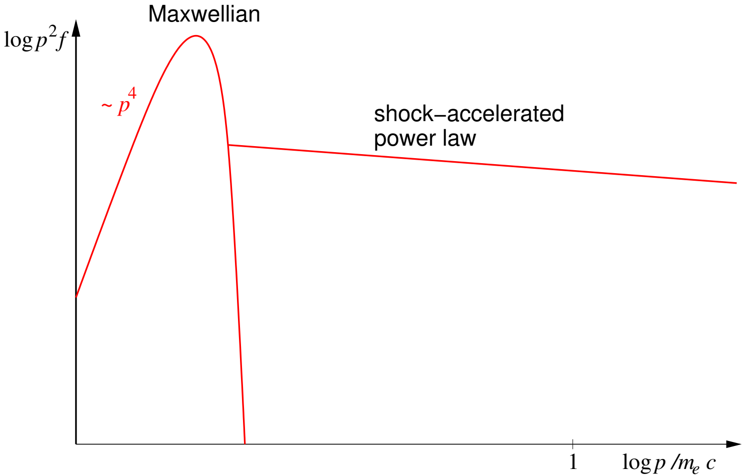


$$\alpha_\nu = 0.85 \quad \rightarrow \quad \mathcal{M} = 2.6:$$

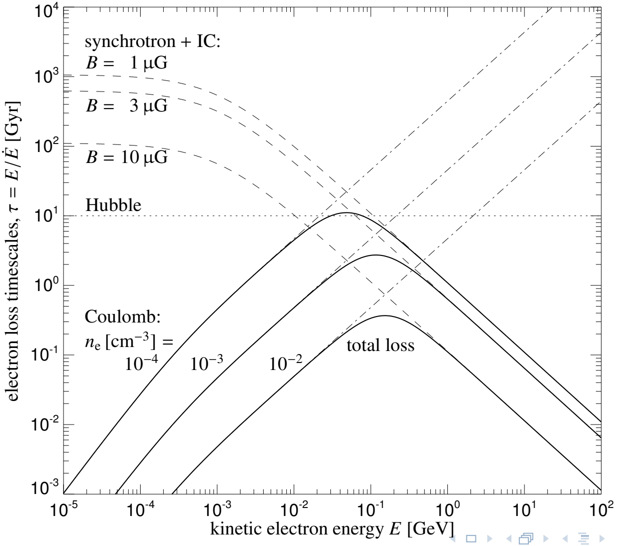
How is this possible?

Build-up of the fossil electron distribution

Strong structure formation shocks during the era of cluster formation



Electron cooling times



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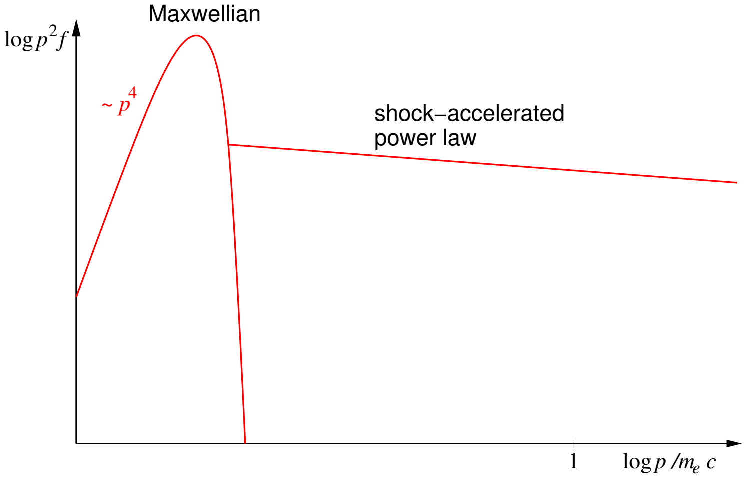

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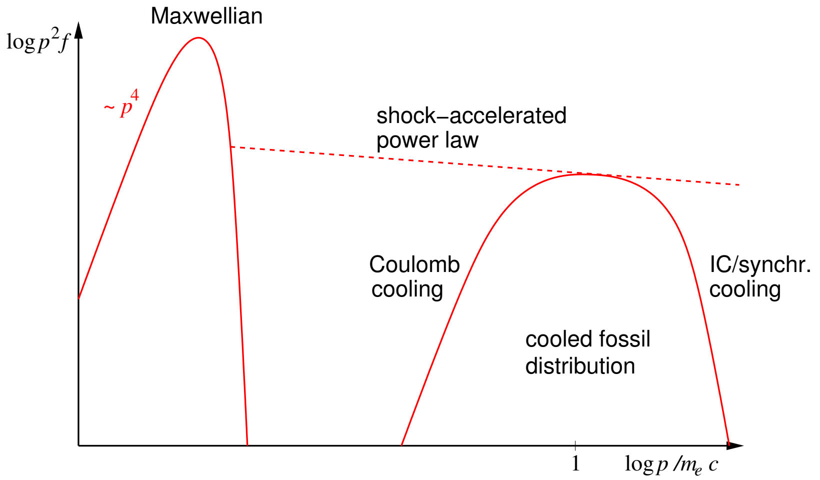

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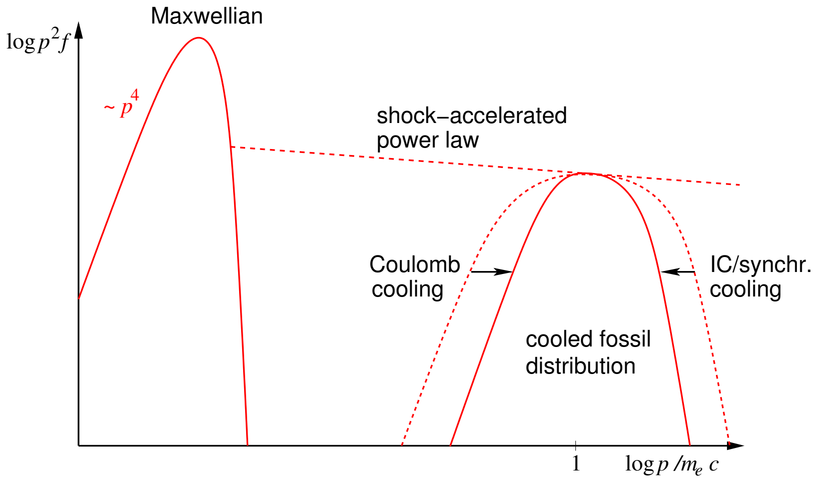
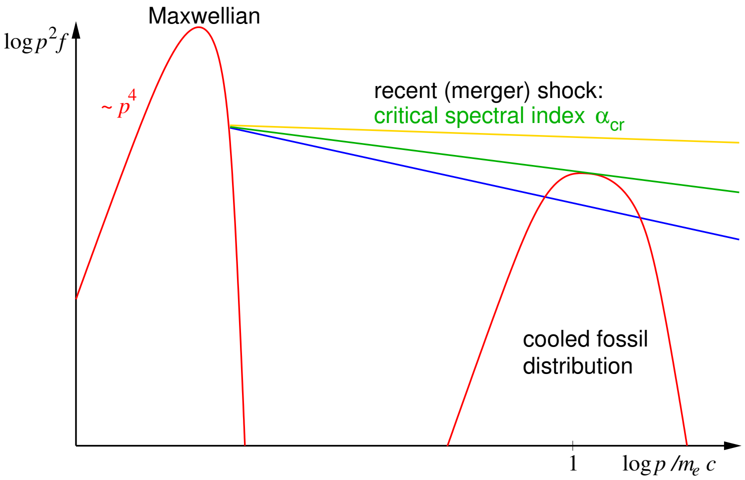


Illuminating radio relics

Re-acceleration of fossil electrons vs. primary acceleration



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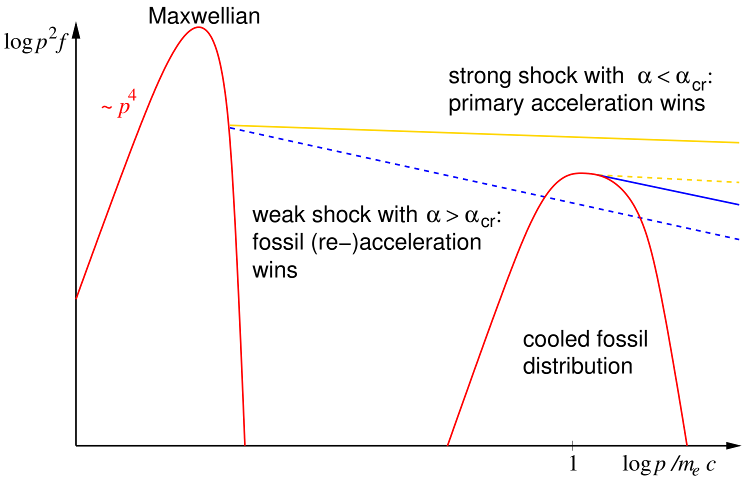

Illuminating radio relics
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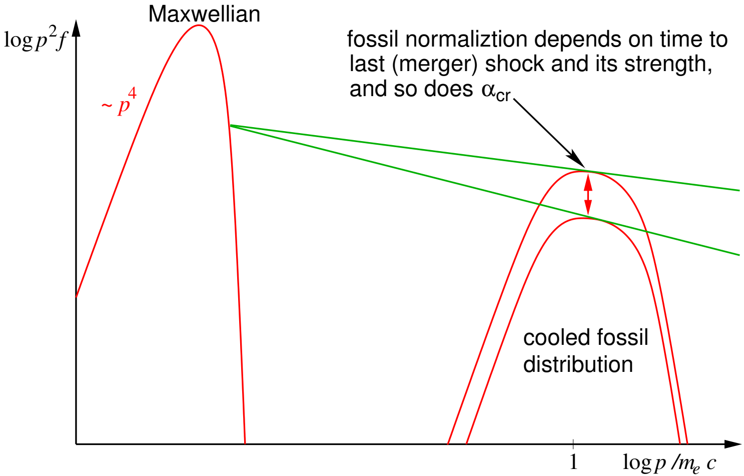
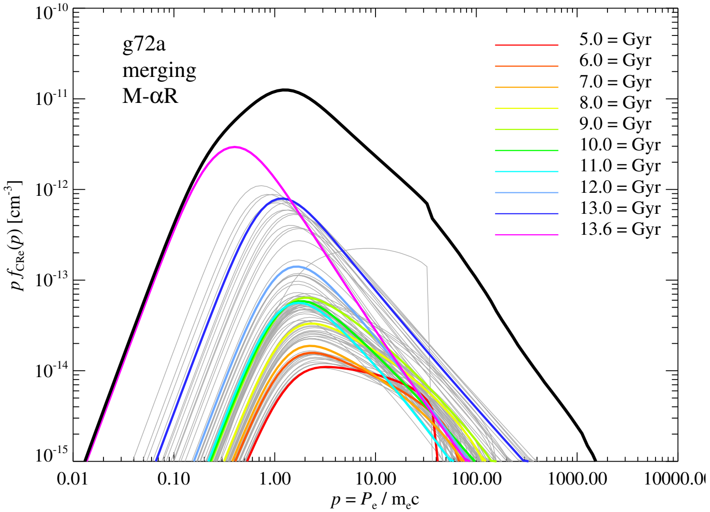
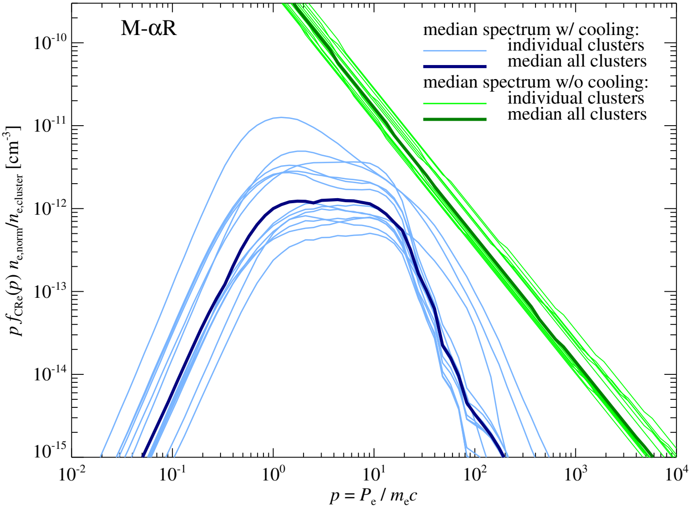


Time evolution of the fossil electron distribution



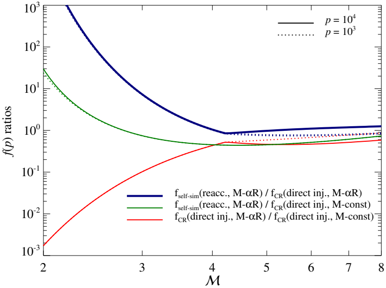
Pinzke, Oh, C.P. (2013)

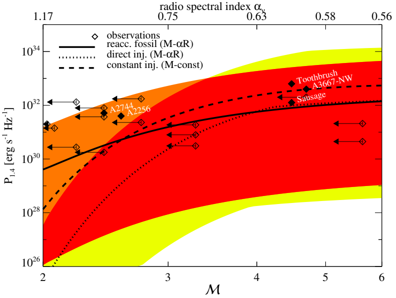
Fossil CR electron population



Pinzke, Oh, C.P. (2013)

Direct acceleration vs. Fermi-I re-acceleration



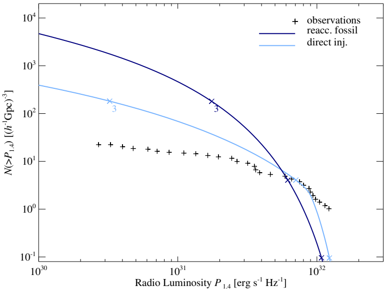


Pinzke, Oh, C.P. (2013)

the bottom line:

- fossil contribution comparable to direct injection at high $\mathcal{M}$
- fossils dominate at low $\mathcal{M}$

Radio relics – the future



Pinzke, Oh, C.P. (2013)

→ **the relic luminosity function:**

$$n(>P_{1.4}) = \int \mathrm{d}P_{1.4}\,\frac{\mathrm{d}n}{\mathrm{d}P_{1.4}}$$

$$\frac{\mathrm{d}n}{\mathrm{d}P_{1.4}} = \frac{\mathrm{d}n}{\mathrm{d}\mathcal{M}}\,\frac{\mathrm{d}\mathcal{M}}{\mathrm{d}P_{1.4}}$$

depends on the Mach number distribution and the $\mathcal{M} - P_{1.4}$ relation!

bright prospects for LOFAR:

- Fermi-I reacceleration predicts a few 1000 radio relics per Gpc^3
- direct injection predicts a few 100 luminous radio relics

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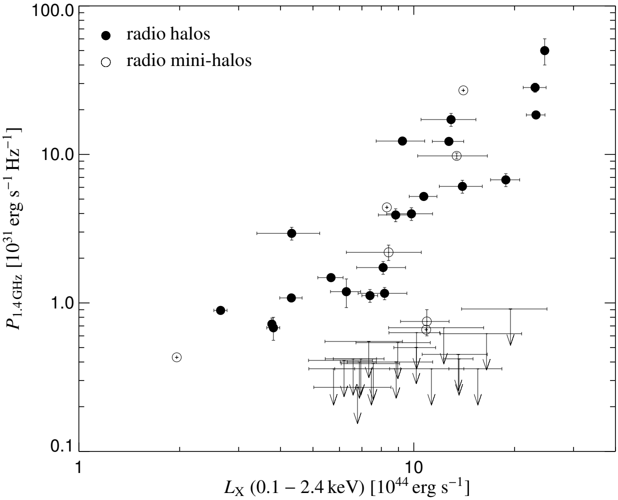
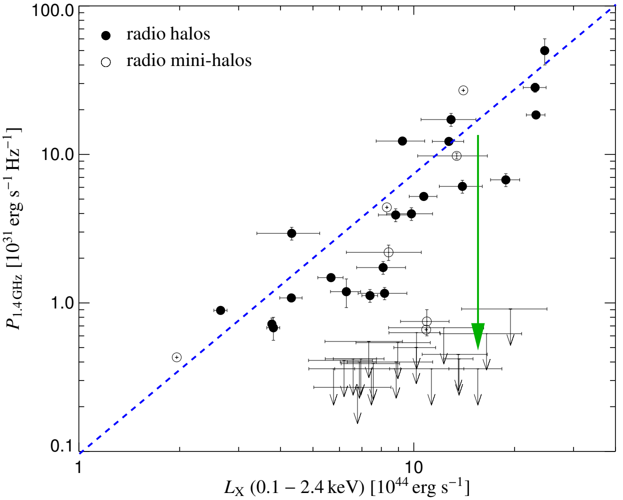
Radio vs. X-ray luminosity – two radio populations



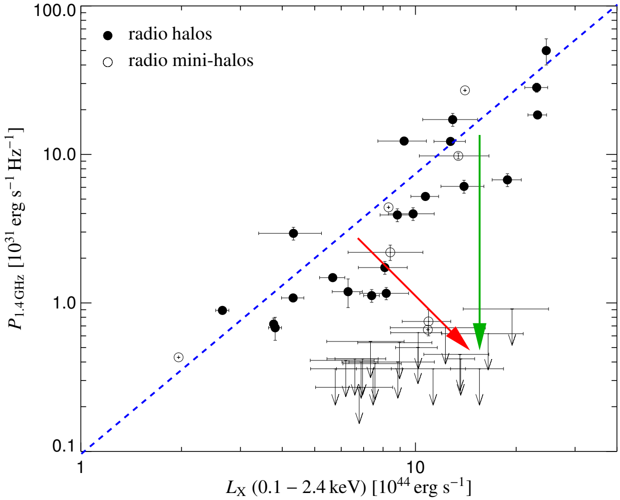
Brunetti+ (2009), Enßlin+ (2011)

Radio luminosity - X-ray luminosity



Brunetti+ (2009), Enßlin+ (2011)

Radio luminosity - X-ray luminosity



Brunetti+ (2009), Enßlin+ (2011)

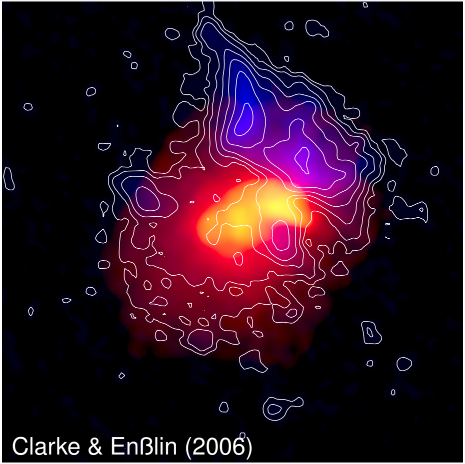
Radio halo theory – (i) hadronic model

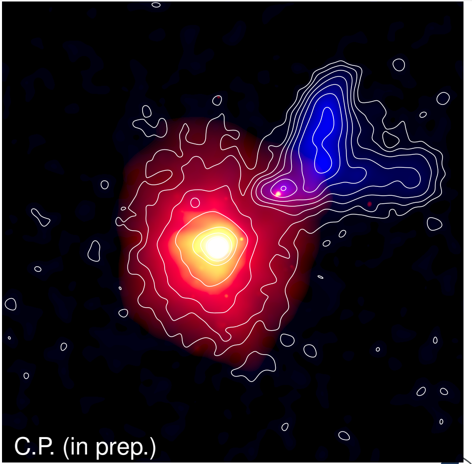
$$p_{\mathrm{CR}} + p \rightarrow \pi^{\pm} \rightarrow e^{\pm}$$

strength:

- all required ingredients available:
  shocks to inject CRp, gas protons as targets, magnetic fields
- predicted luminosities and overall morphologies match observations without tuning

Observation – simulation of A2256





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

Radio halo theory – (i) hadronic model

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strength:

- all required ingredients available:
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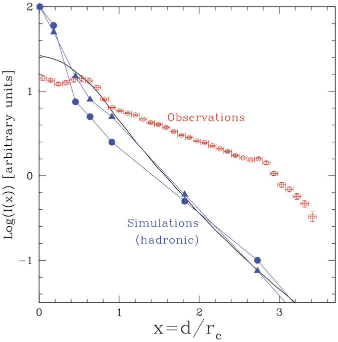
weakness:

- all clusters should have radio halos
  $\rightarrow$ putative solution: super-Alfvénic CR streaming (Enßlin+ 2011, Wiener+ 2013)
- does not explain spectral curvature and steep-spectrum sources
  $\rightarrow$ putative sol.'n: energy-dependent CR diffusion (Enßlin+ 2011, Wiener+ 2013)
- requires increasing CR pressure toward the outskirts of Coma
  (Brunetti+ 2013, Zandanel+ 2014)

Coma radio halo: surface brightness profile

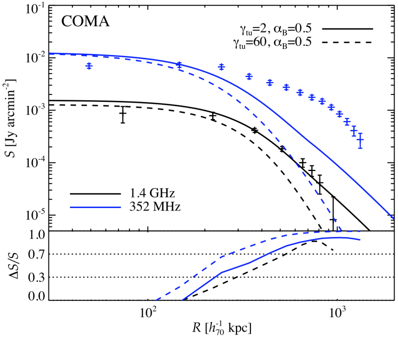
Challenging the hadronic model with extended radio halo profiles?

simulations: pure CR advection



C.P.+ (2008), Pinzke & C.P. (2010), Brunetti+ (2013)

solid: CR streaming $\rightarrow P_{CR} \sim$ const.



Zandanel, C.P., Prada (2014)

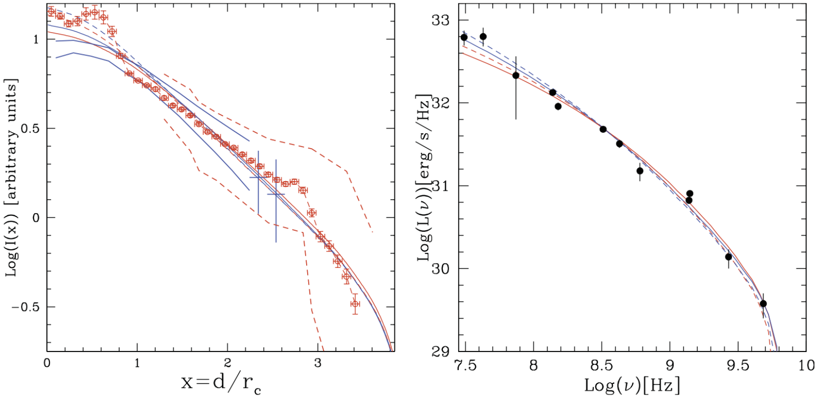
Radio halo theory – (ii) re-acceleration model

strength:

- all required ingredients available:
  radio galaxies & relics to inject CRe, plasma waves to re-accelerate, ...
- reported complex radio spectra emerge naturally
- clusters without halos ← less turbulent

Coma radio halo: re-acceleration model

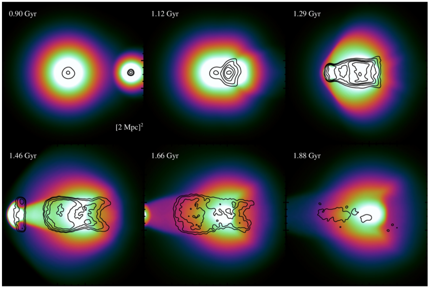
Good fit to profile and spectrum, **but** many free parameters and assumptions!



Brunetti+ (2013)

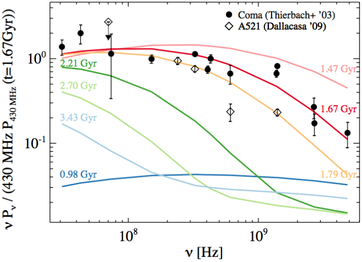
Rise and fall of re-accelerated radio halos

X-ray/radio surface brightness



colour: X-rays, contours: radio (Donnert+ 2013)

radio spectrum



radio spectral evolution (Donnert+ 2013)

- first idealized merger simulation that demonstrated the success of the re-acceleration model

Radio halo theory – (ii) re-acceleration model

strength:

- all required ingredients available:
  radio galaxies & relics to inject CRe, plasma waves to re-accelerate, . . .
- reported complex radio spectra emerge naturally
- clusters without halos $\leftarrow$ less turbulent

weakness:

- Fermi II acceleration is inefficient and scales as $(v/c)^2$
  comparably flat turbulent (Kraichnan) spectrum required
- CRe cool rapidly: seed population for re-acceleration?

The physics of turbulent re-acceleration

- compressible turbulence can energize particles via gyroresonant interactions

$$\omega - k_{\|} v_{\|} = n\Omega/\gamma, \qquad n = \pm 1, \pm 2, \dots$$

wave vector $k_{\|}$ and particle velocity $v_{\|}$ are parallel to B and $\Omega = eB/me$

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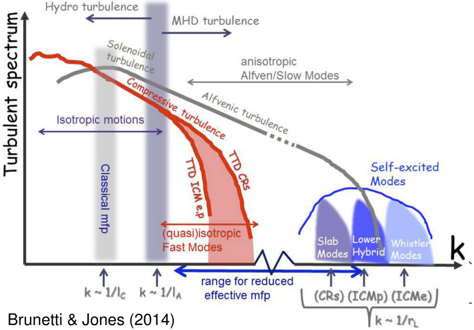
- transit time damping ($n = 0$):

$$v_{||} = \omega/k_{||} = v_{\mathrm{ph},||} \sim c_s$$

$\rightarrow$ only *large* pitch-angle CRs can "surf the waves"



Brunetti & Jones (2014)

The physics of turbulent re-acceleration

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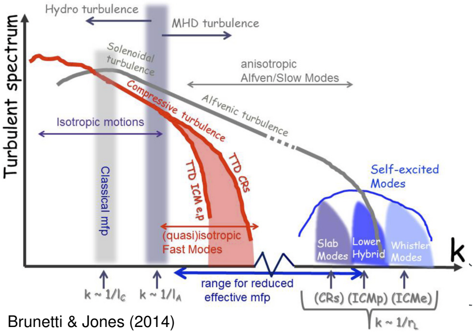
$$v_{\|} = \omega/k_{\|} = v_{\mathrm{ph},\|} \sim c_{\mathrm{s}}$$
$\rightarrow$ only *large* pitch-angle CRs can "surf the waves"

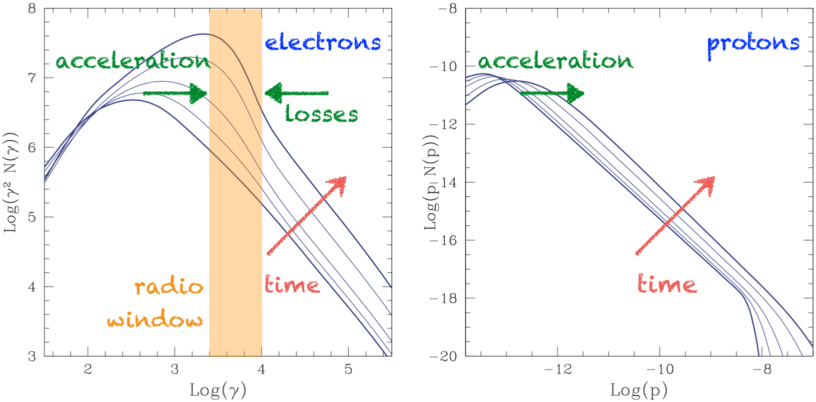
- only a fraction of $c_{\mathrm{s}}/c \sim 0.3\%$ goes into CRs, most energy ends up in thermal electrons

- **mechanism:** magnetic moment of CRs resonates with the time-varying magnetic field (from the fast modes)



Brunetti & Jones (2014)

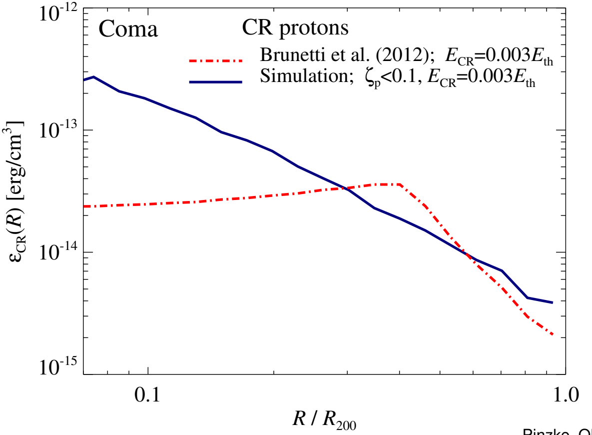
Turbulent re-acceleration: spectral evolution



Brunetti & Lazarian (2007, 2011)

But the re-acceleration model has a missing link . . .

. . . it needs seed electrons, which have never been calculated

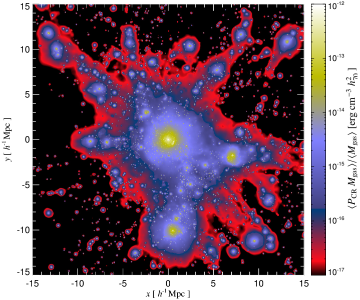


Pinzke, Oh, C.P. (2017)

- cosmological simuations do not reproduce the required population of seed electrons

Method

→ integrate Fokker-Planck equation to follow momentum diffusion in a cosmological simulation with CR proton/electron physics:



$P_{\rm CR}$ in a cosmological zoom simulation of a galaxy cluster (C.P.+ 2008)

$$\frac{df_{\rm e}(p,t)}{dt} = \frac{\partial}{\partial p}\left\{ f_{\rm e}(p,t)\left[\left|\frac{dp}{dt}\right|_{\rm C} + \frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}\right) + \left|\frac{dp}{dt}\right|_{\rm r} - \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\right)\right]\right\} - \left(\vec{\nabla}\cdot\vec{v}\right) f_{\rm e}(p,t) + \frac{\partial^2}{\partial p^2}\left[D_{pp} f_{\rm e}(p,t)\right] + Q_{\rm e}\left[p,t; f_{\rm p}(p,t)\right]$$

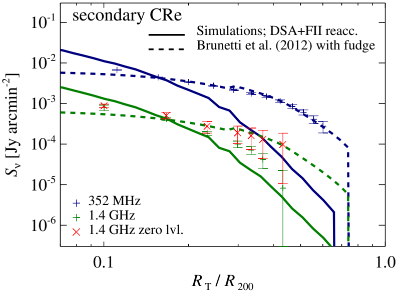
$$D_{pp}(p,t) = \frac{\pi}{16}\frac{p^2}{c\,\rho}\left\langle \frac{\beta |B_k|^2}{16\pi\, W}\right\rangle I_\theta \int_{k_{\rm cut}} \mathcal{W}(k) k\, dk,$$

$$\mathcal{W}(k) = \sqrt{2/7\, I_0\, \rho\, \langle V_{\rm ph}\rangle}\, k^{-3/2}$$

AIP

Coma radio halo: multifrequency profiles

even idealized models (Brunetti+ 2013) **have problems:**
→ spectral steepening with radius seen in observations not reproduced with models



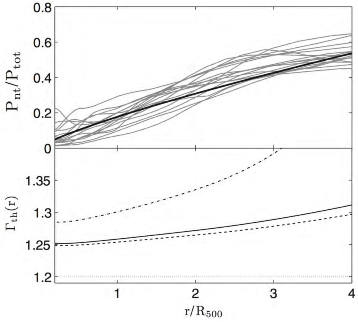
Pinzke, Oh, C.P. (2017)

possibilities:

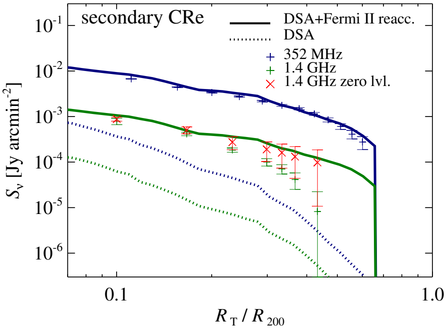
- 1.4 GHz zero-point too high
- observed *B*-field profile wrong
- new plasma physics

→ can we match the more reliable 352 MHz data? (Brown & Rudnick 2011)

Solution I: changing the turbulent profile



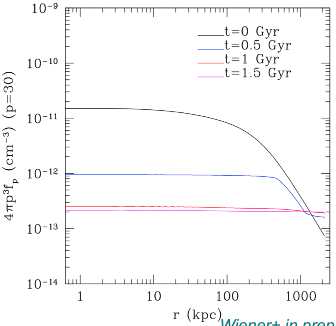
Shaw+ (2010)



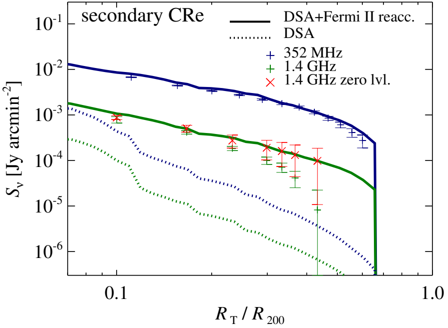
Pinzke, Oh, C.P. (2017)

note: in practice we have to separate compressible turbulence from bulk motions!

Solution II: cosmic-ray streaming



Wiener+ in prep.



Pinzke, Oh, C.P. (2017)

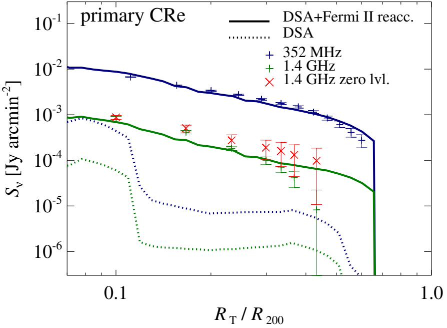
note: in practice we have to simultaneously simulate cosmic-ray streaming and turbulent re-acceleration!

Solution III: primary fossil electrons as seeds

Need high electron acceleration efficiency

recent plasma simulations with PIC codes . . .

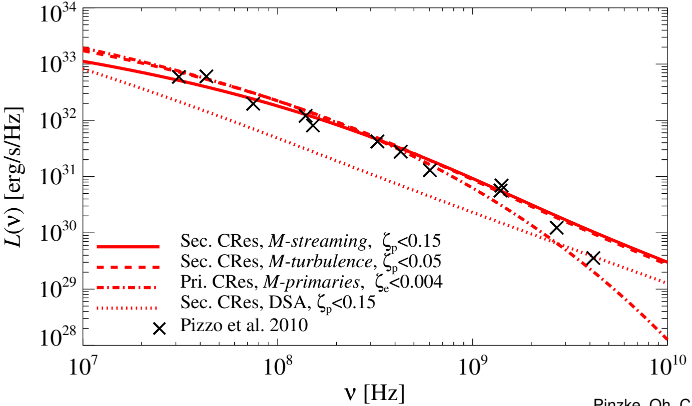
- . . . find electrons efficiently accelerated in perpendicular shocks (Guo, Sironi, Narayan 2015)
- . . . find ions efficiently accelerated in parallel shocks (Caprioli & Spitkovsky 2014)



Pinzke, Oh, C.P. (2017)

→ so quasi-perpendicular shock regions might satisfy our requirements!

Coma radio spectrum



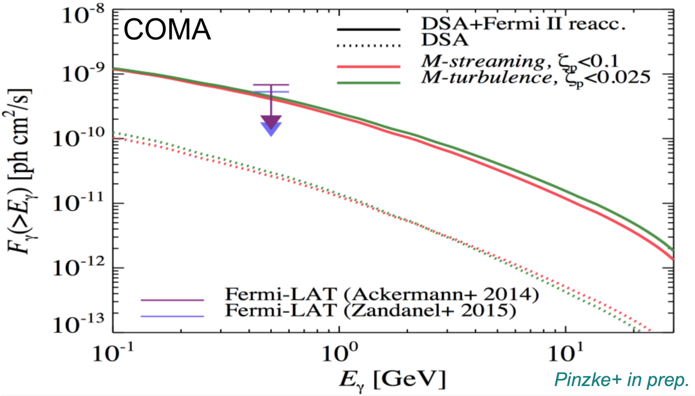
Pinzke, Oh, C.P. (2017)

- all 3 models match the observed radio spectrum
- pure hadronic model fails (only DSA, no turbulent re-acceleration)

AIP

How can we disentangle our models?

Gamma-ray observations by *Fermi*-LAT are the key

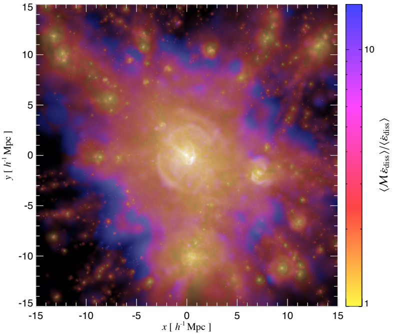


Pinzke+ in prep.

Fermi-LAT can probe M-streaming and M-turbulence in near future!

MERGHERS

Meerkat Extended Relics, Giant Halos, and Extragalactic Radio Sources survey



Cosmological shocks, C.P.+ (2008)

Statistical diffuse radio emission survey of few hundred SZ-selected galaxy clusters (PI Knowles)

Key questions:

- cosmological evolution
- formation impact of cluster mass/merger properties
- cosmic ray transport & (re-)energising mechanisms
- lots of other radio science (AGN, BCGs, radio galaxies, . . .)

Conclusions on radio halos and relics

- **halos:** producing seed electrons for turbulent reacceleration require modifications to the standard picture:
  - flatter turbulent profile
  - CR streaming
  - high CRe/p injection
- **relics:** fossil electrons could allow radio relics to be seen at low Mach numbers

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

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