Radio Halos and Relics in Galaxy Clusters

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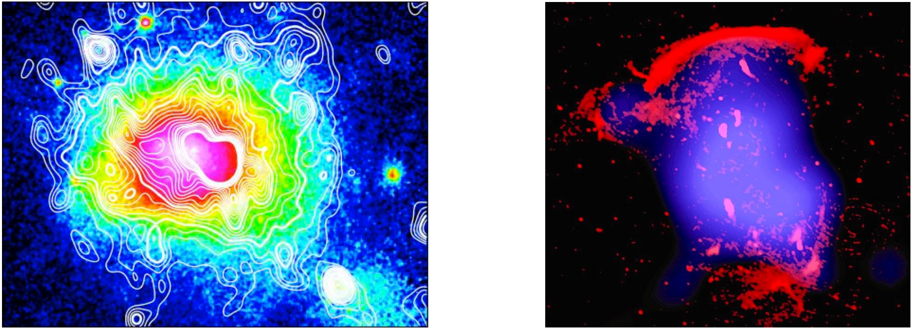
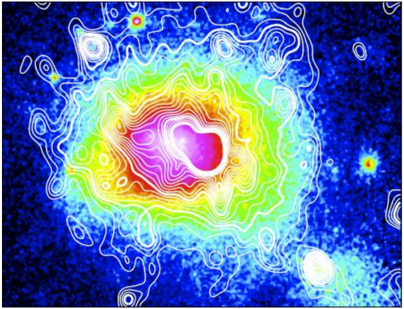
Jul 2, 2015 / Ringberg Castle: *Cosmic Magnetic Fields*

The origin of seed electrons in radio halos and relics



Giant radio halos in a nutshell



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

- present in > 30 clusters
- Mpc size
- trace X-ray emission
- unpolarized
- steep spectrum $\alpha_\nu \gtrsim 1$
- (sub) μJy$/$arcsec^2 surface brightness
- cluster merger connection

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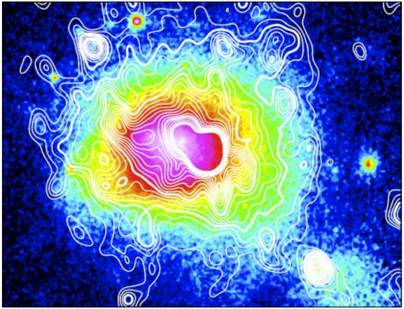

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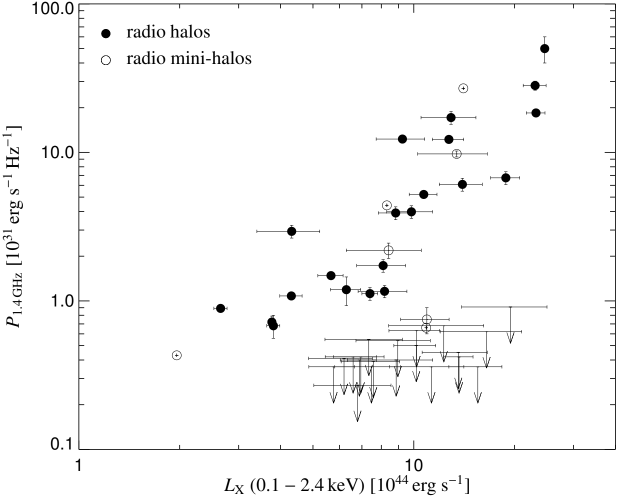
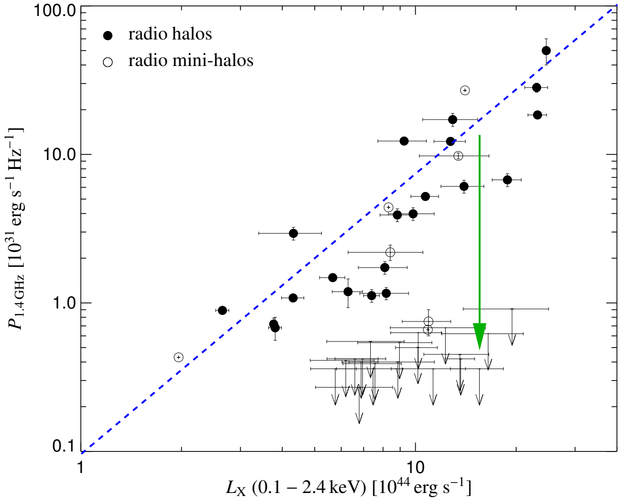
- evidence of volume-filling magnetic fields in clusters
- $\tau_{\text{syn}} \lesssim 100$ Myr $\to$ efficient in-situ electron acceleration

Radio vs. X-ray luminosity – two radio populations



Brunetti+ (2009), Enßlin+ (2011)

Radio luminosity - X-ray luminosity



Brunetti+ (2009), Enßlin+ (2011)

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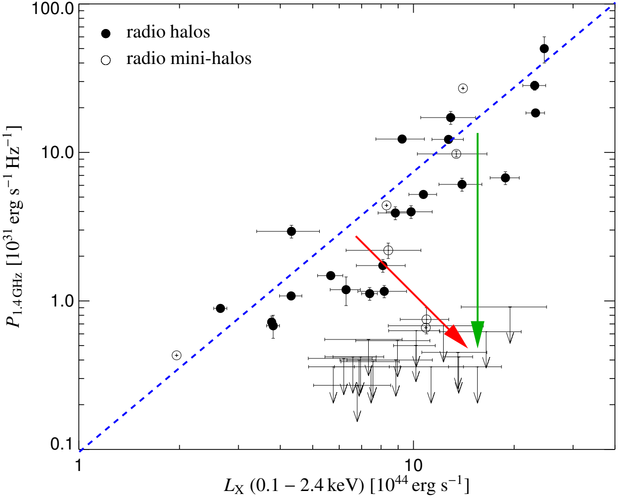


Brunetti+ (2009), Enßlin+ (2011)

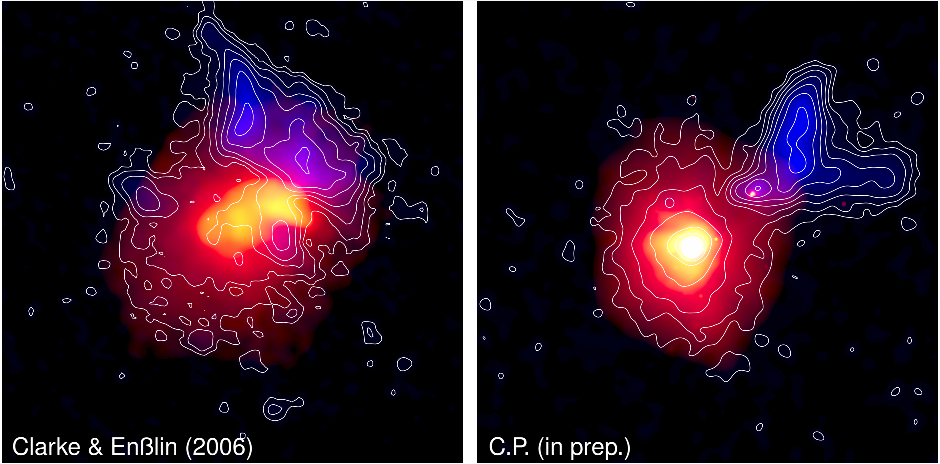
Radio halo theory – (i) hadronic model

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

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

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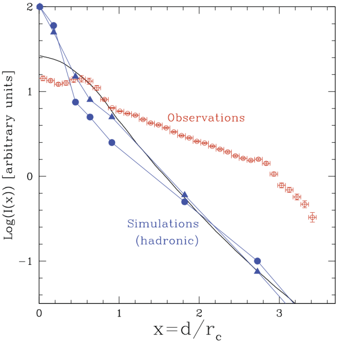
weakness:

- all clusters should have radio halos
  → putative solution: super-Alfvénic CR streaming (Enßlin+ 2011, Wiener+ 2013)
- does not explain spectral curvature and steep-spectrum sources
  → 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

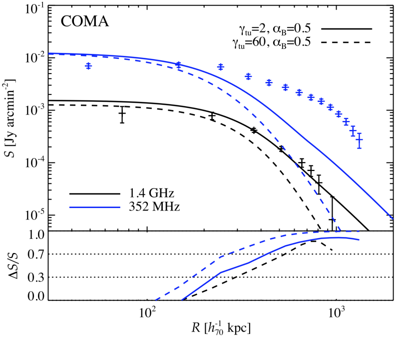
Challenging the hadronic model with extended radio halo profiles?

simulations: pure CR advection



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

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



Zandanel, C.P., Prada (2014)

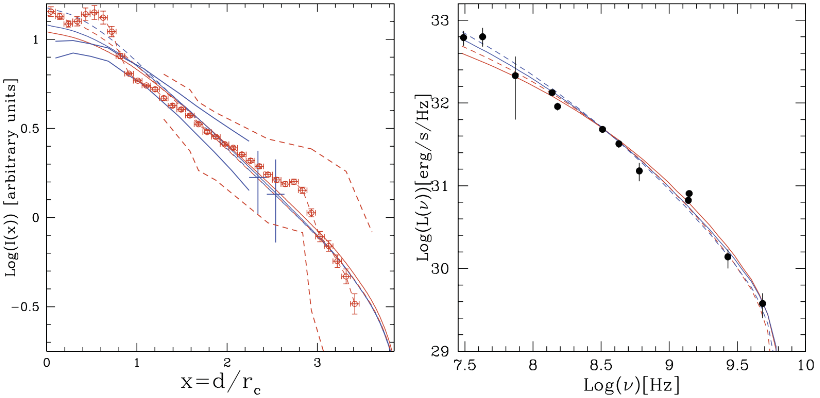
Radio halo theory – (ii) re-acceleration model

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)

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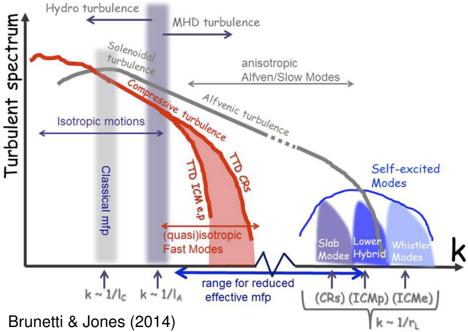
weakness:

- Fermi II acceleration is inefficient and scales as $(v/c)^2$
- plasma problem: CRe isotropization required by re-acceleration
  via transit time damping
- 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 $\Omega = eB/me$



Brunetti & Jones (2014)

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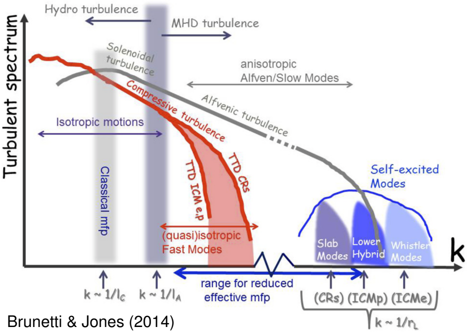
$$v_{\|} = \omega/k_{\|} = v_{\mathrm{ph},\|} \sim c_{\mathrm{s}}$$
→ only *large* pitch-angle CRs can “surf the waves”



Brunetti & Jones (2014)

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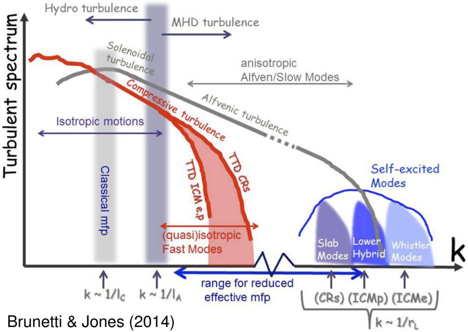
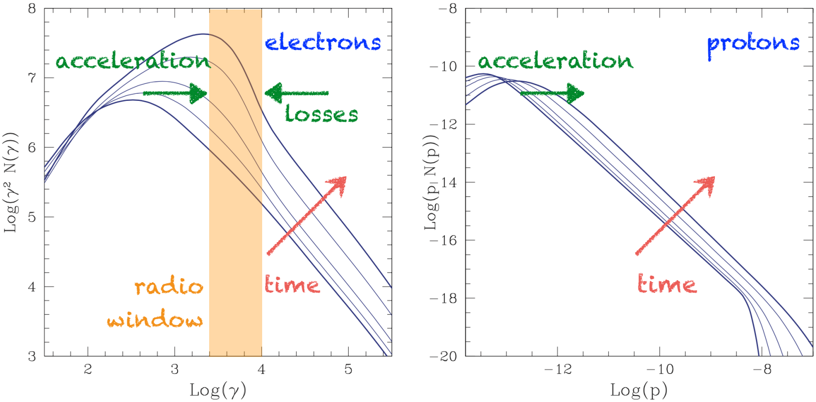
- transit time damping ($n = 0$):
$$v_{\|} = \omega/k_{\|} = v_{\mathrm{ph},\|} \sim c_\mathrm{s}$$
→ only *large* pitch-angle CRs can “surf the waves”
- only a fraction of $c_\mathrm{s}/c \sim 0.3\%$ goes into CRs, most energy ends up in thermal electrons
- **mechanism:** magnetic moment of CRs resonates with the time-varying magnetic field (from the fast modes)



Brunetti & Jones (2014)

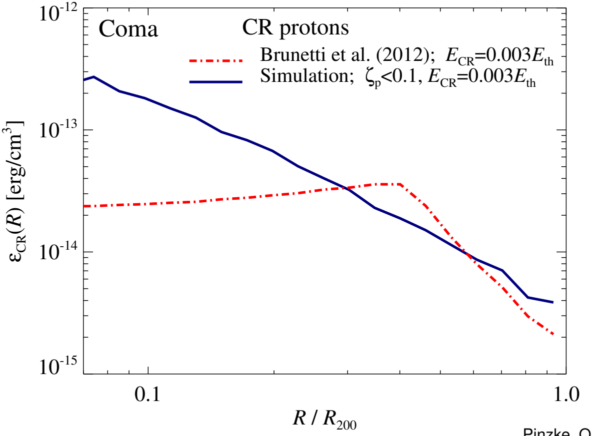
Turbulent re-acceleration: spectral evolution



Brunetti & Lazarian (2007, 2011)

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

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

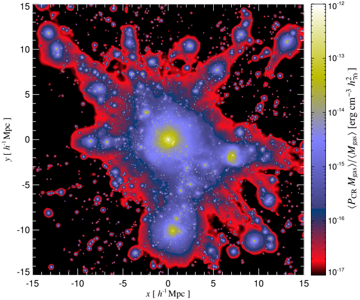


Pinzke, Oh, C.P. (2015)

- 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_{CR} in a cosmological zoom simulation of a galaxy cluster (C.P.+ 2008)

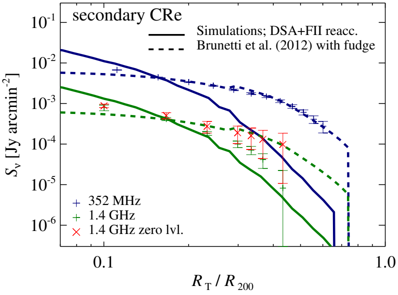
$$\frac{df_{\mathrm{e}}(p,t)}{dt} = \frac{\partial}{\partial p}\left\{ f_{\mathrm{e}}(p,t)\left[\left|\frac{dp}{dt}\right|_{\mathrm{C}} + \frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}\right) + \left|\frac{dp}{dt}\right|_{\mathrm{r}} - \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\right)\right]\right\}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

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

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

Coma radio halo: multifrequency profiles

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



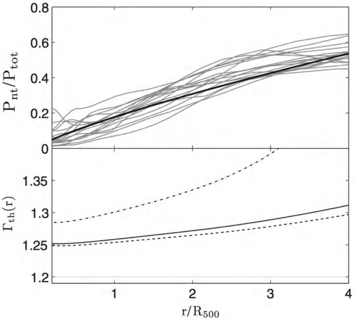
Pinzke, Oh, C.P. (2015)

possibilities:

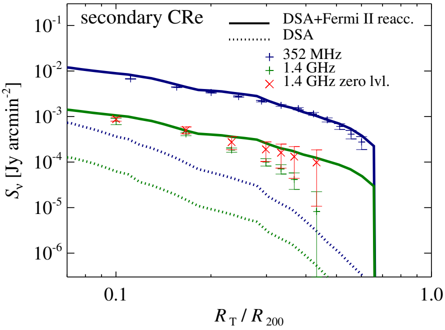
- 1.4 GHz zero-point too high
- observed *B*-field profile wrong
- new plasma physics

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

Solution I: changing the turbulent profile



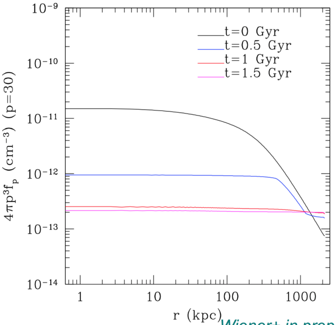
Shaw+ (2010)



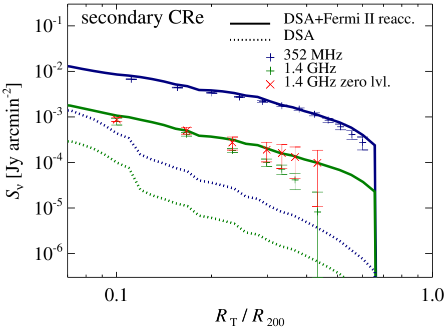
Pinzke, Oh, C.P. (2015)

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

Solution II: cosmic-ray streaming



Wiener+ in prep.



Pinzke, Oh, C.P. (2015)

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

Solution III: primary fossil electrons as seeds

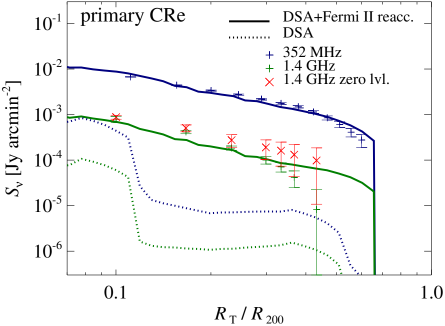
Need high electron acceleration efficiency

recent plasma simulations with PIC codes . . .

- . . . find electrons efficiently accelerated in perpendicular shocks

  (Guo, Sironi, Narayan 2015)

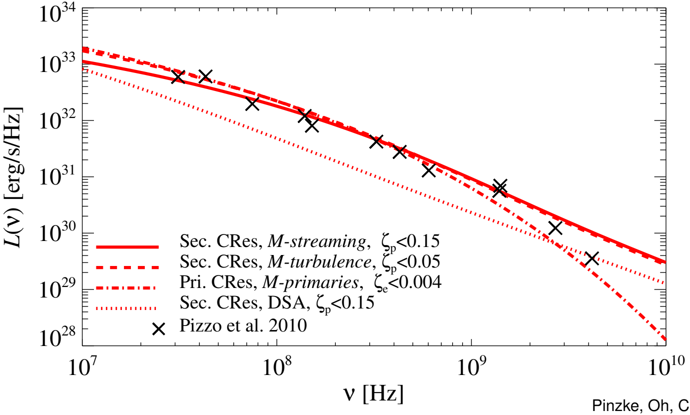
- . . . find ions efficiently accelerated in parallel shocks (Caprioli & Spitkovsky 2014)



Pinzke, Oh, C.P. (2015)

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

Coma radio spectrum

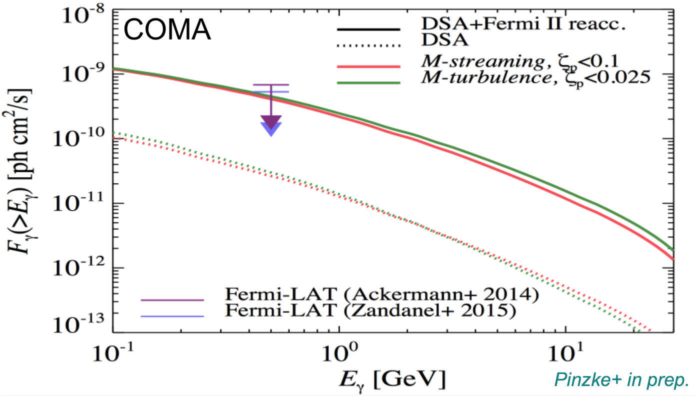


Pinzke, Oh, C.P. (2015)

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

How can we disentangle our models?

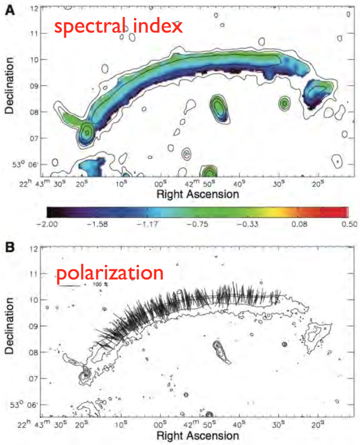
Gamma-ray observations by *Fermi*-LAT are the key



Pinzke+ in prep.

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

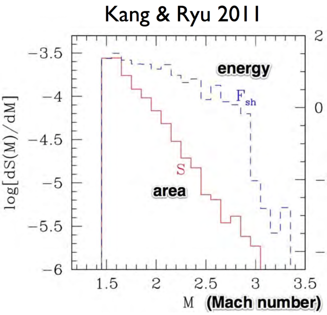
Radio relics – great tools for studying shock physics



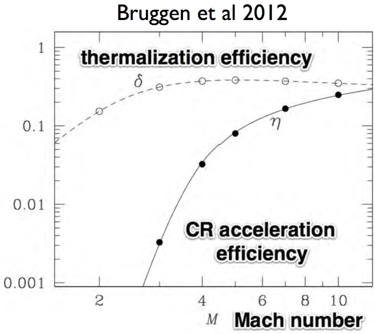
van Weeren+ (2010)

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

Biggest unknown: shock acceleration efficiency



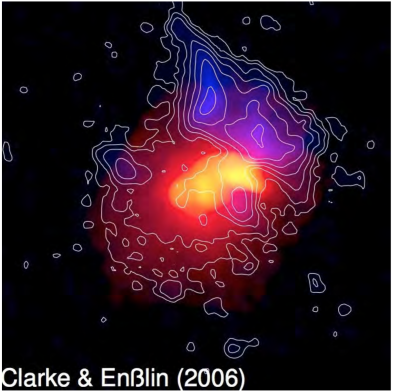
Kang & Ryu 2011

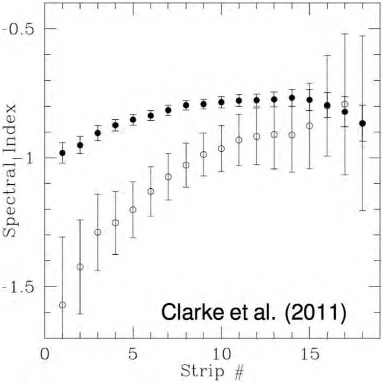


Bruggen et al 2012

- merging shocks dominated by low Mach number shocks
- these shocks have low acceleration efficiencies
- how many will LOFAR see?

A poster child: A2256


Clarke & Enßlin (2006)



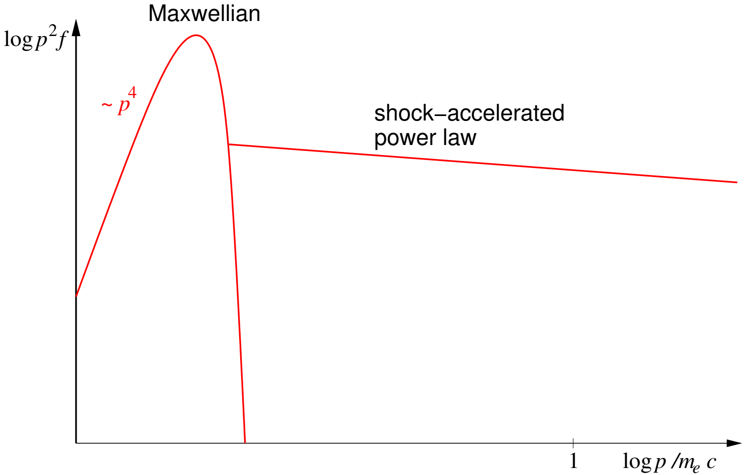
Clarke et al. (2011)

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

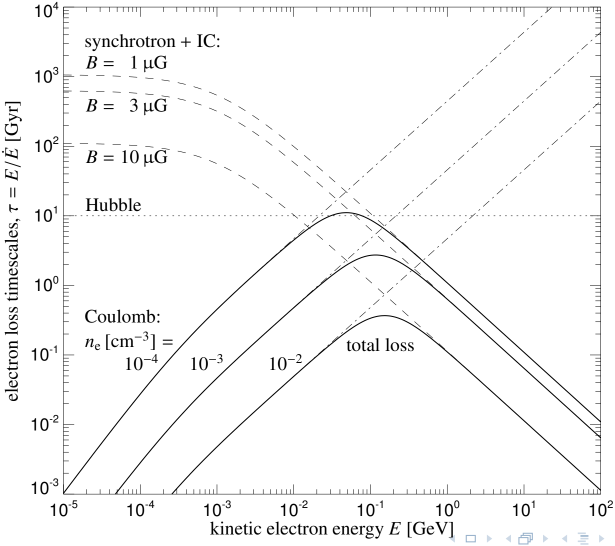
How is this possible?

Build-up of the fossil electron distribution

Strong structure formation shocks during the era of cluster formation



Electron cooling times



Build-up of the fossil electron distribution

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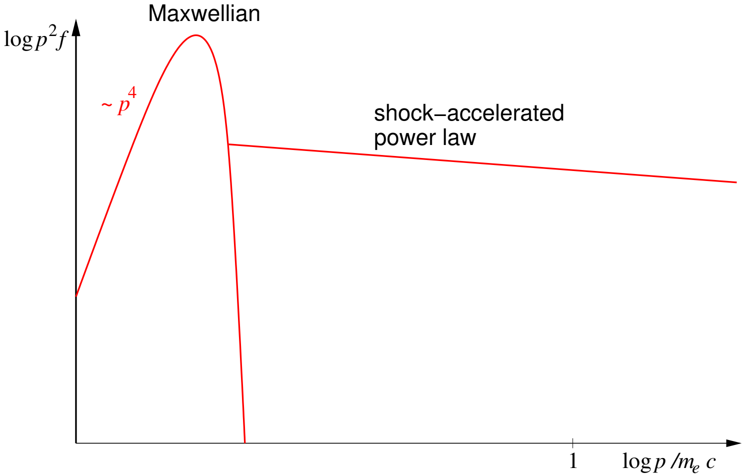

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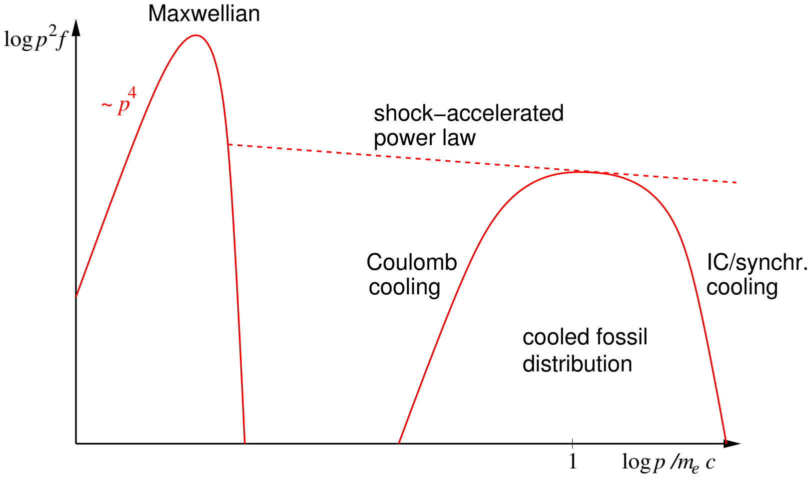

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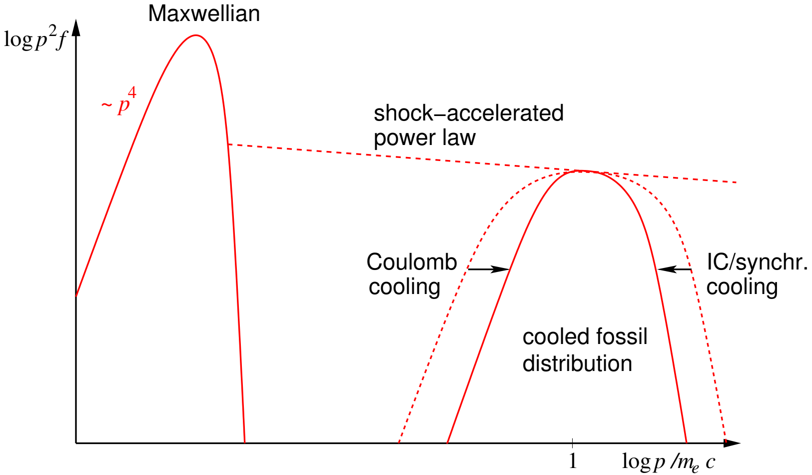
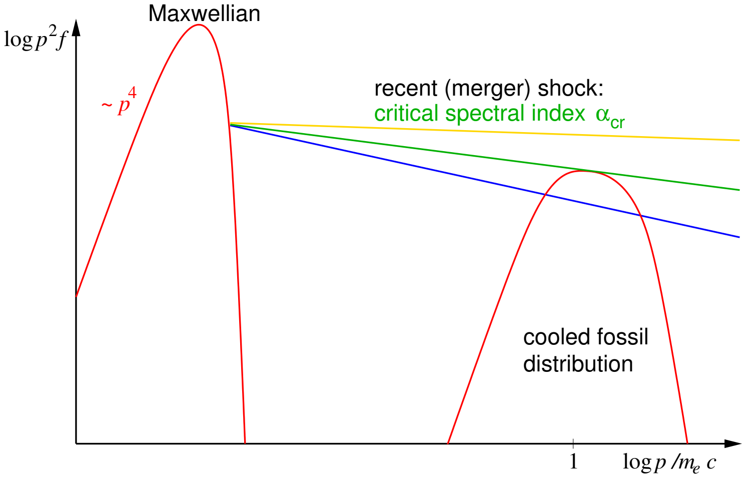


Illuminating radio relics

Re-acceleration of fossil electrons vs. primary acceleration



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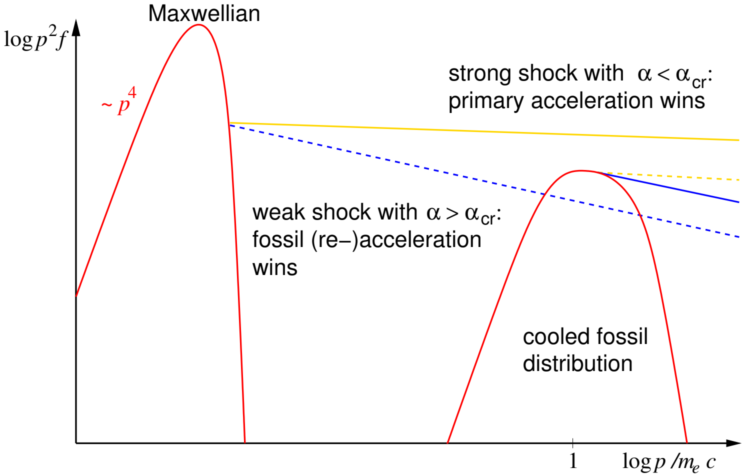

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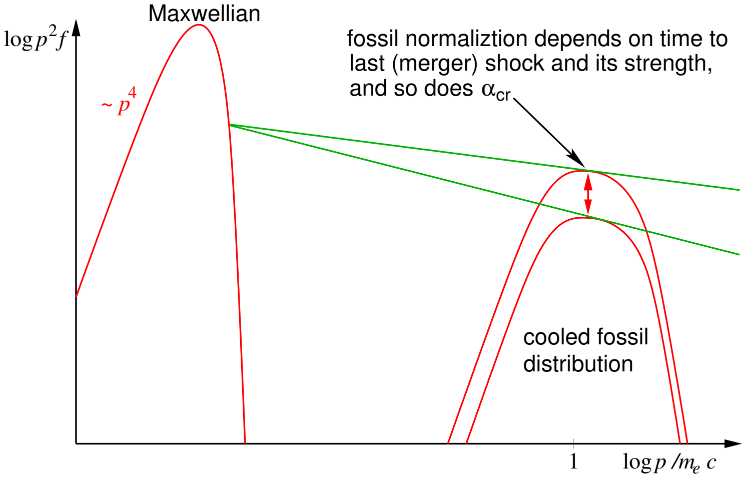
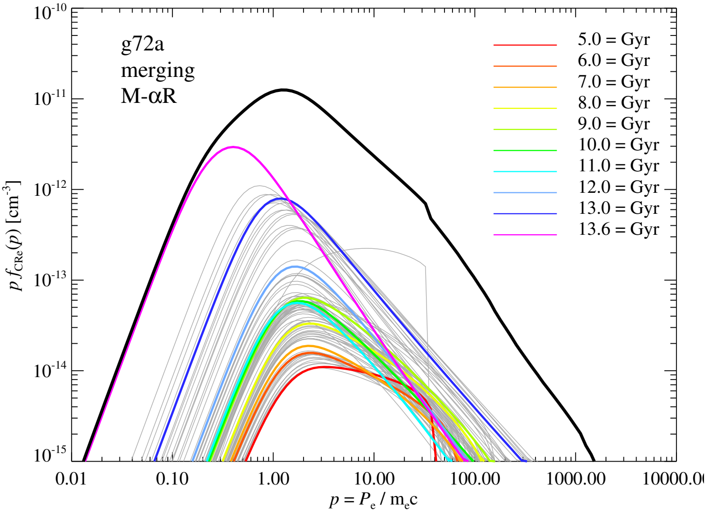
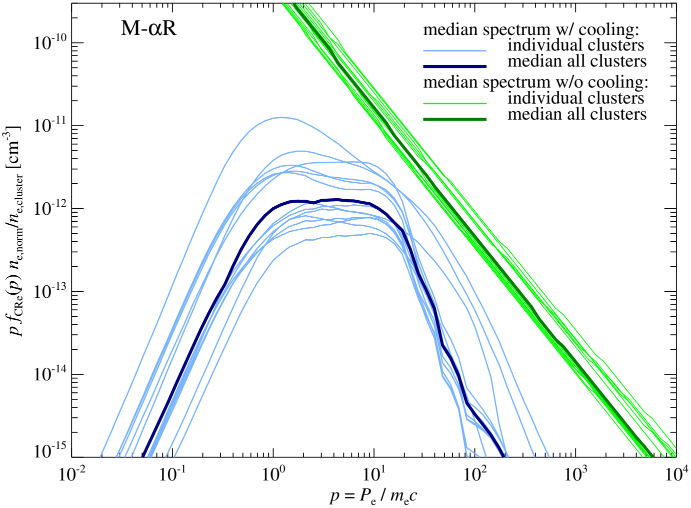


Time evolution of the fossil electron distribution



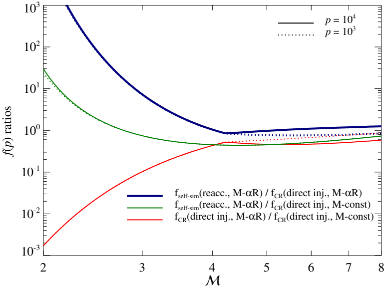
Pinzke, Oh, C.P. (2012)

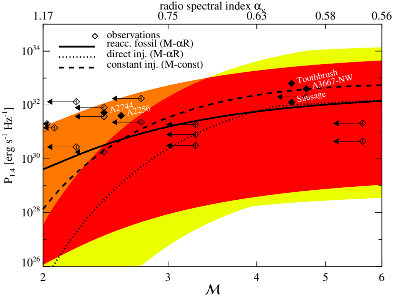
Fossil CR electron population



Pinzke, Oh, C.P. (2012)

Direct acceleration vs. Fermi-I re-acceleration



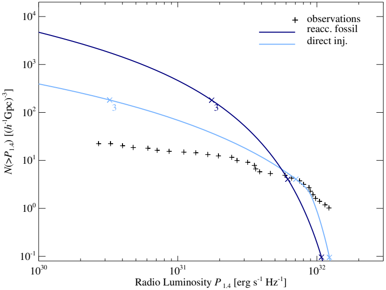


Pinzke, Oh, C.P. (2012)

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. (2012)

→ the relic luminosity function:

$$
\begin{aligned}
n(>P_{1.4}) &= \int \mathrm{d}P_{1.4}\,\frac{\mathrm{d}n}{\mathrm{d}P_{1.4}} \\
\frac{\mathrm{d}n}{\mathrm{d}P_{1.4}} &= \frac{\mathrm{d}n}{\mathrm{d}\mathcal{M}}\,\frac{\mathrm{d}\mathcal{M}}{\mathrm{d}P_{1.4}}
\end{aligned}
$$

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

Conclusions on radio halos and relics

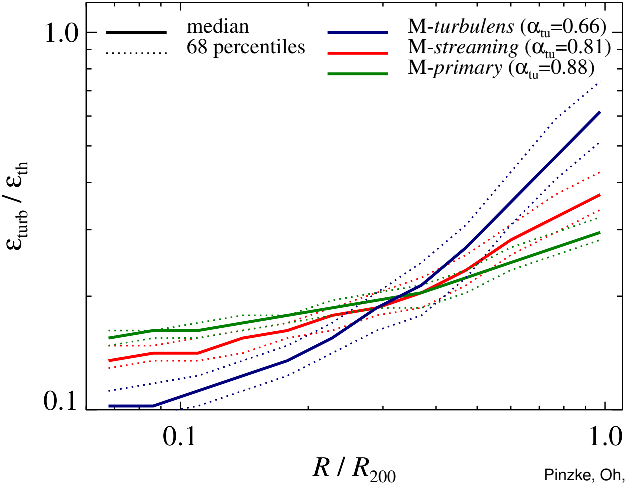
- **halos:** producing seed electrons for turbulent reacceleration require modifications to the standard picture:
  - flatter turbulent profile
  - CR streaming
  - high CRe/p injection
- **relics:** fossil electrons could allow radio relics to be seen at low Mach numbers

Literature for the talk

- A. Pinzke, S. P. Oh, C. Pfrommer, *Turbulence and particle acceleration in giant radio halos: the origin of seed electrons*, 2015, submitted, arXiv:1503.07870.
- A. Pinzke, S. P. Oh, C. Pfrommer, *Giant radio relics in galaxy clusters: re-acceleration of fossil relativistic electrons?*, 2013, *MNRAS*, 435, 1061.

Additional slides

Turbulent pressure profiles in our 3 models



Pinzke, Oh, C.P. (2015)