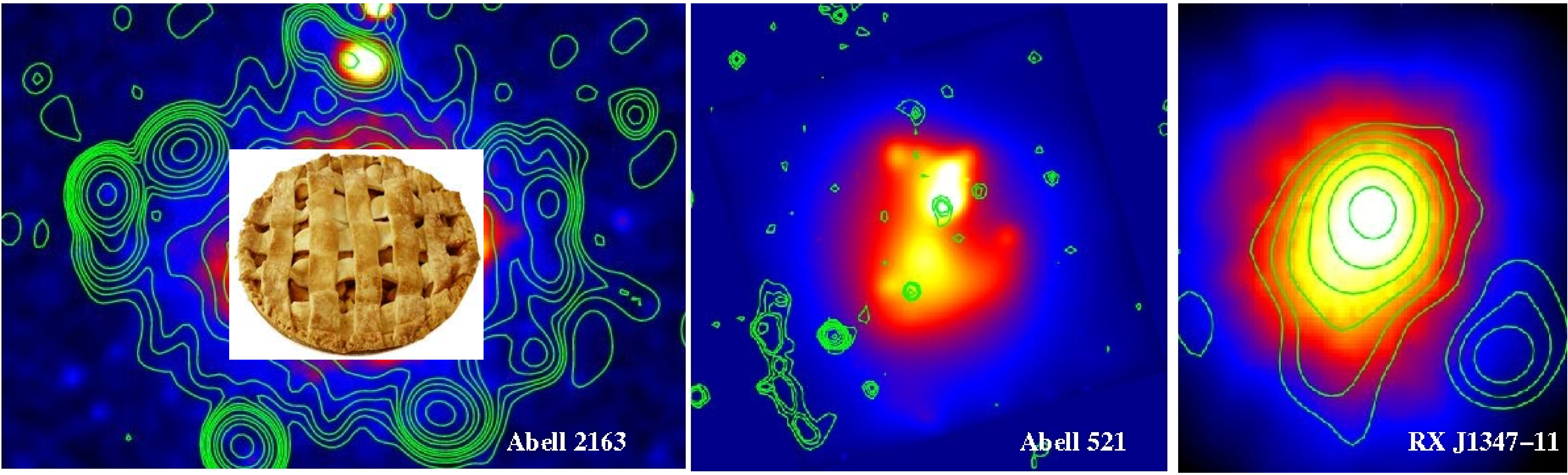
Fermi I and II (re)acceleration of cosmic rays in the ICM



Anders Pinzke

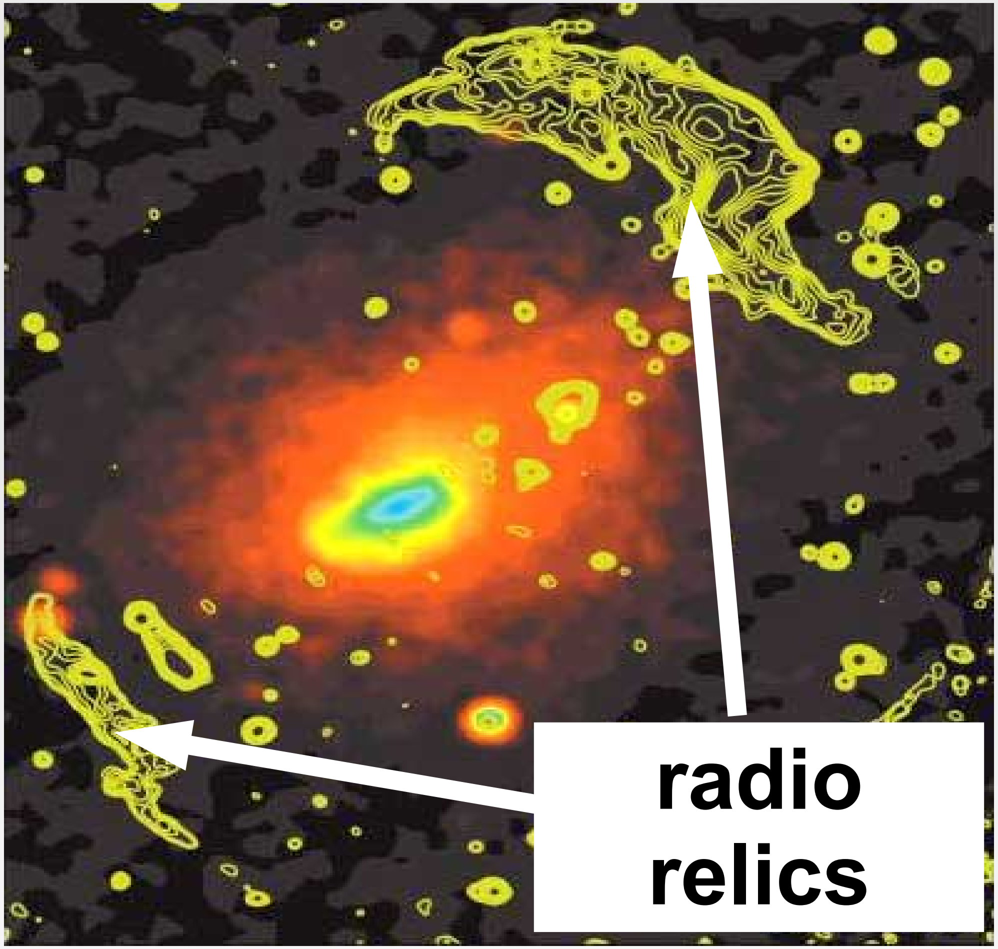
Collaborators: **C. Pfrommer (Heidelberg), P. Oh (Santa Barbara), and J. Wiener (Santa Barbara)**

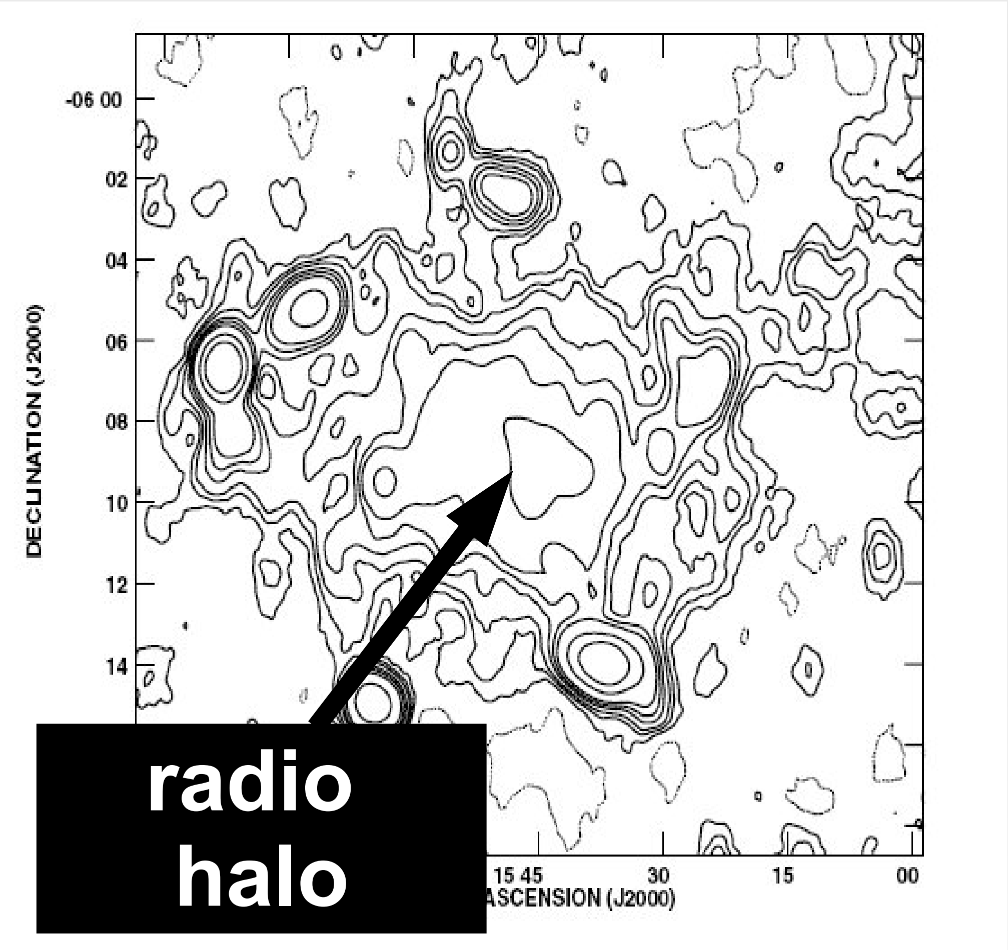
Dark Cosmology Centre

Stockholm University

Garching, Germany ***June 15-17, 2015***

Signs of non-thermal activity in galaxy clusters





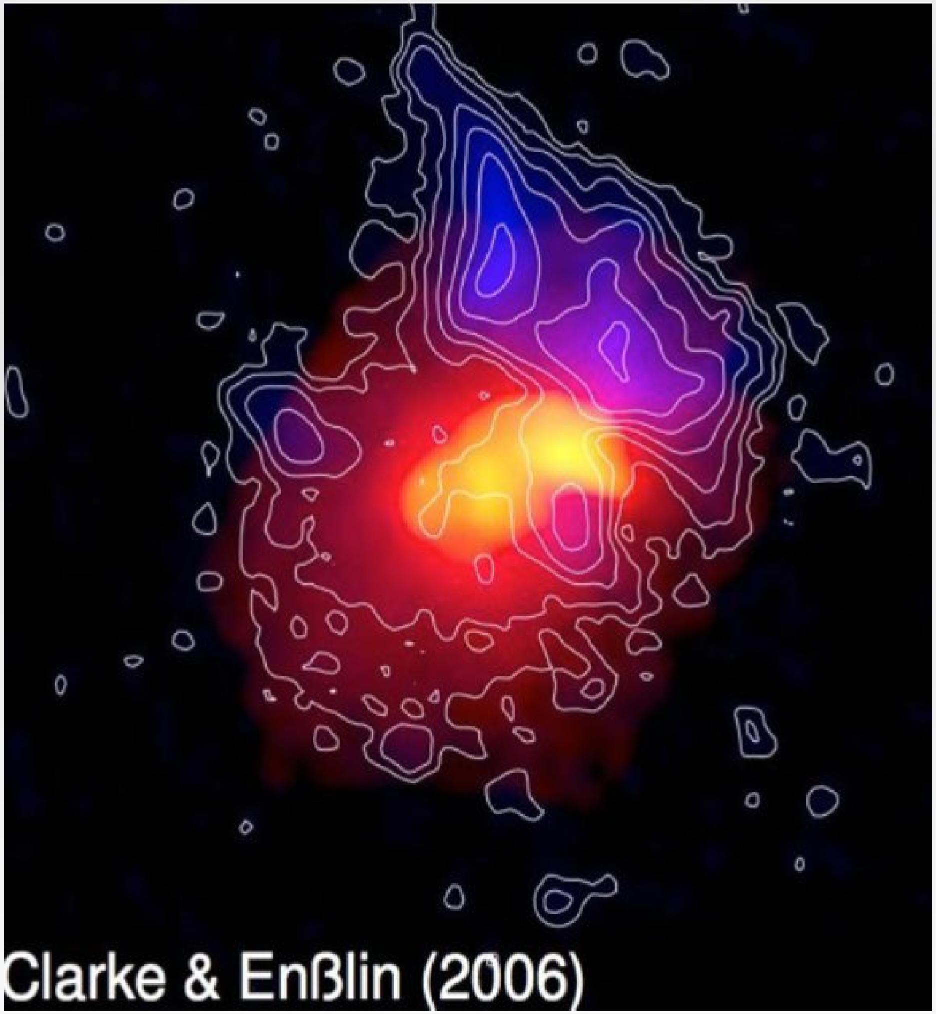
A 3667

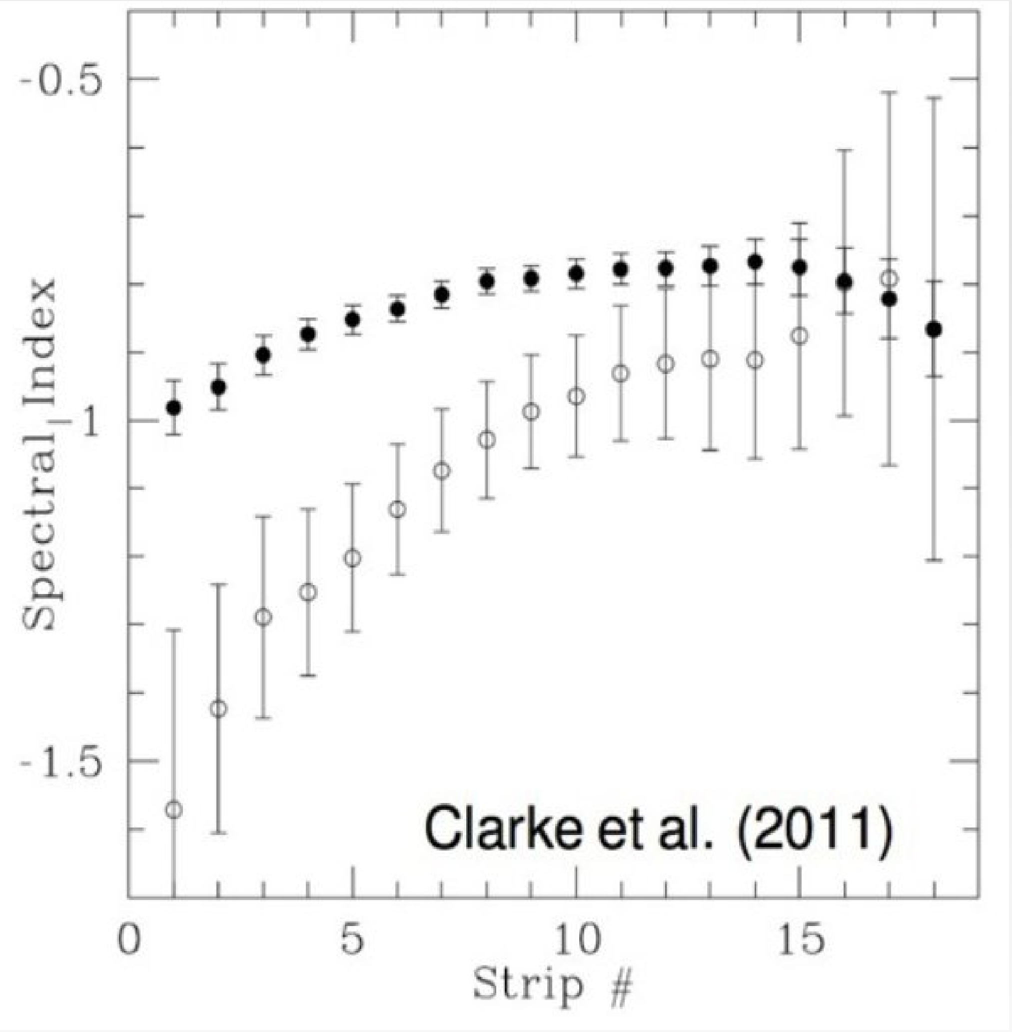
Radio: *Johnston-Hollitt.;*
X-ray:*ROSAT/PSPC.*

A 2163

Radio: *Feretti at al, 2004*

A radio relic poster child: A2256

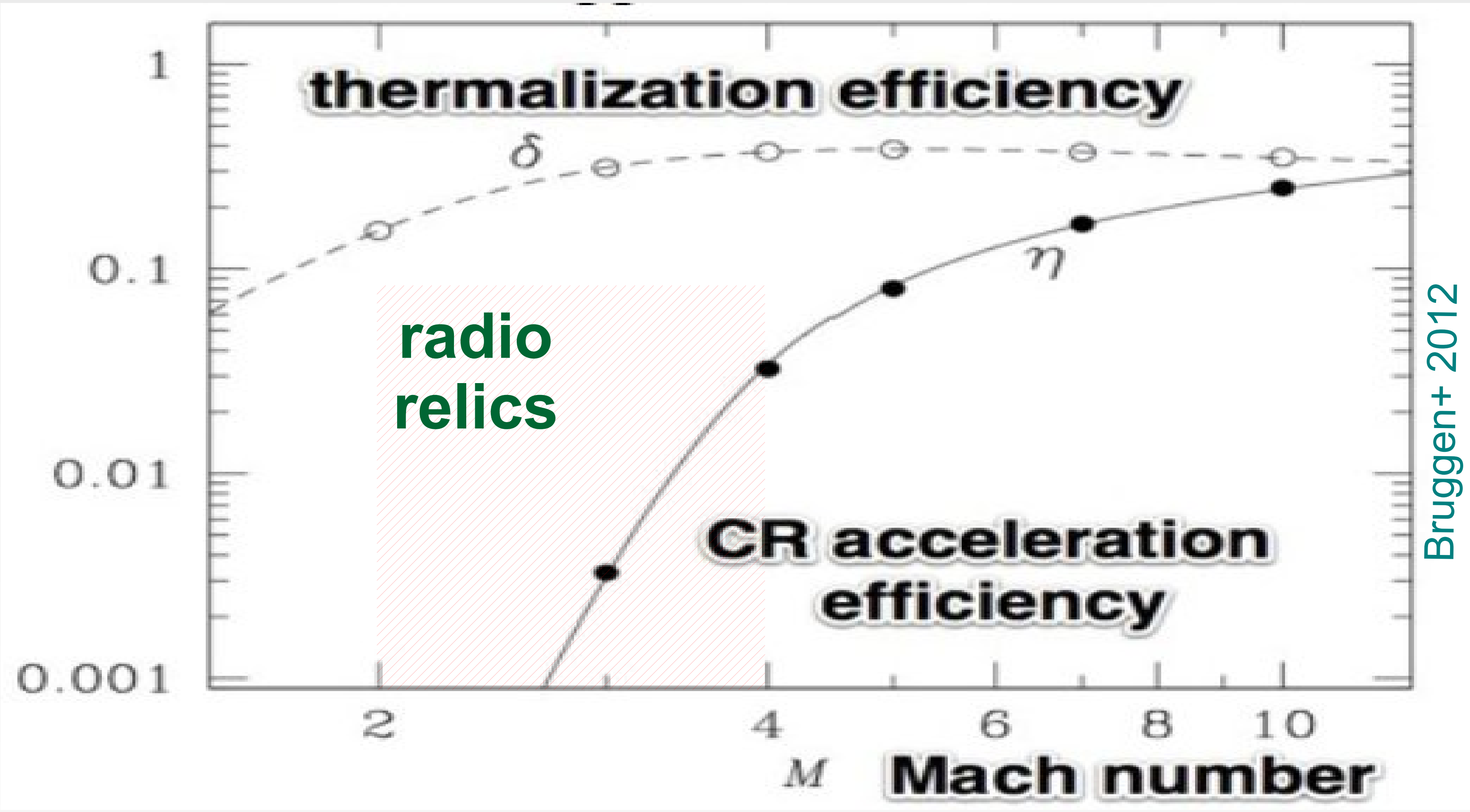




$\alpha_\nu = 0.85 \rightarrow$ Mach = 2.6

How is this possible???

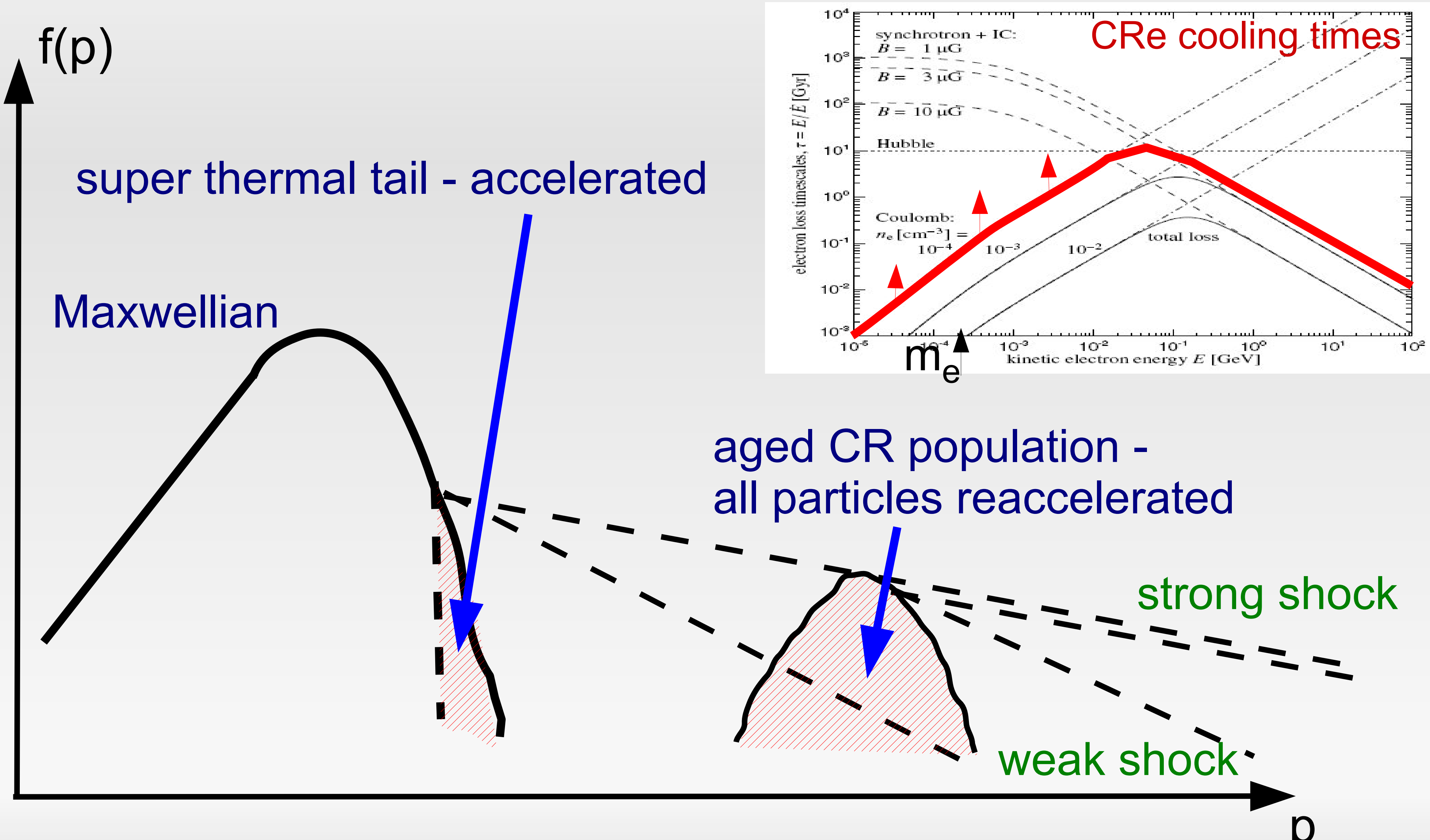
Biggest unknown:
Shock acceleration efficiency



Outskirts dominated by low Mach number shocks.

These shocks have low acceleration efficiency.

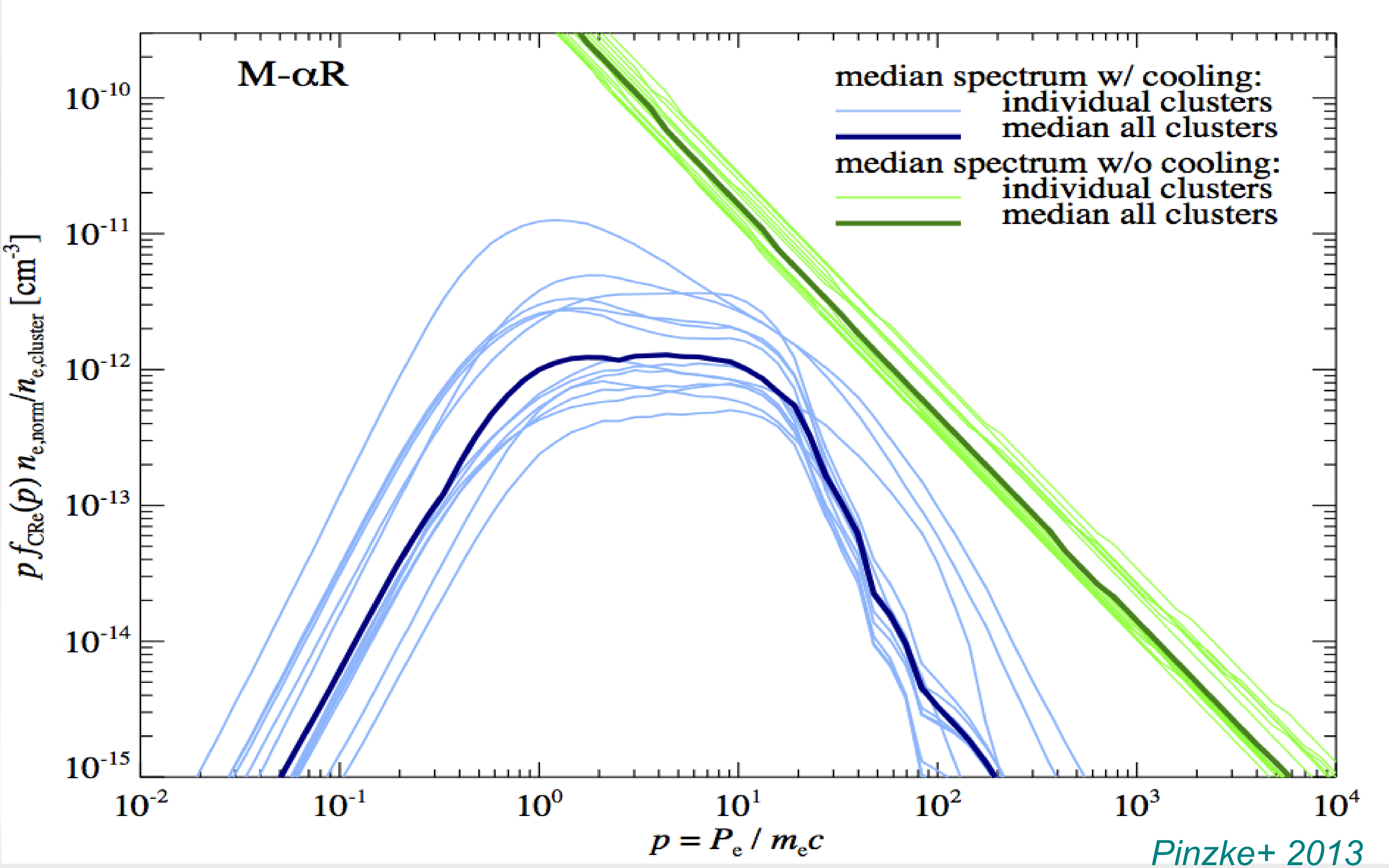
Diffusive shock acceleration – reacceleration through Fermi I



Fermi I reacceleration:

e.g. Kang and Ryu, 2011, Kang+ 2012, Pinzke+ 2013, Bonafede+ 2014, Vazza+ 2014

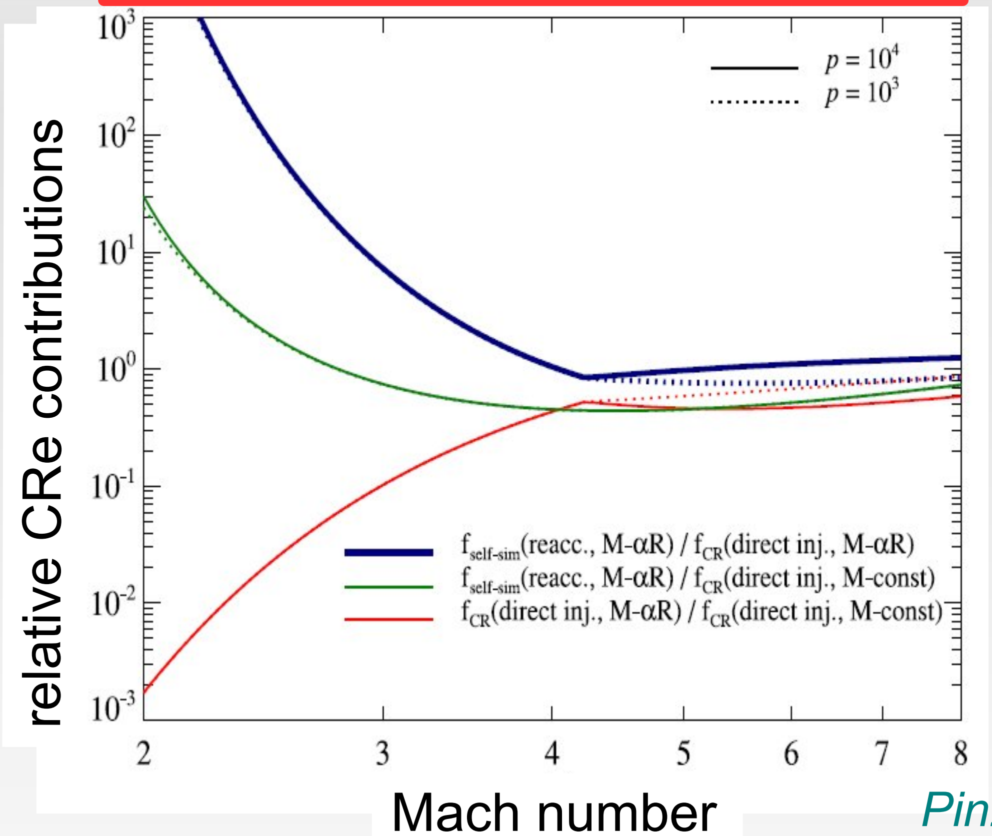
Fossil CR electron population

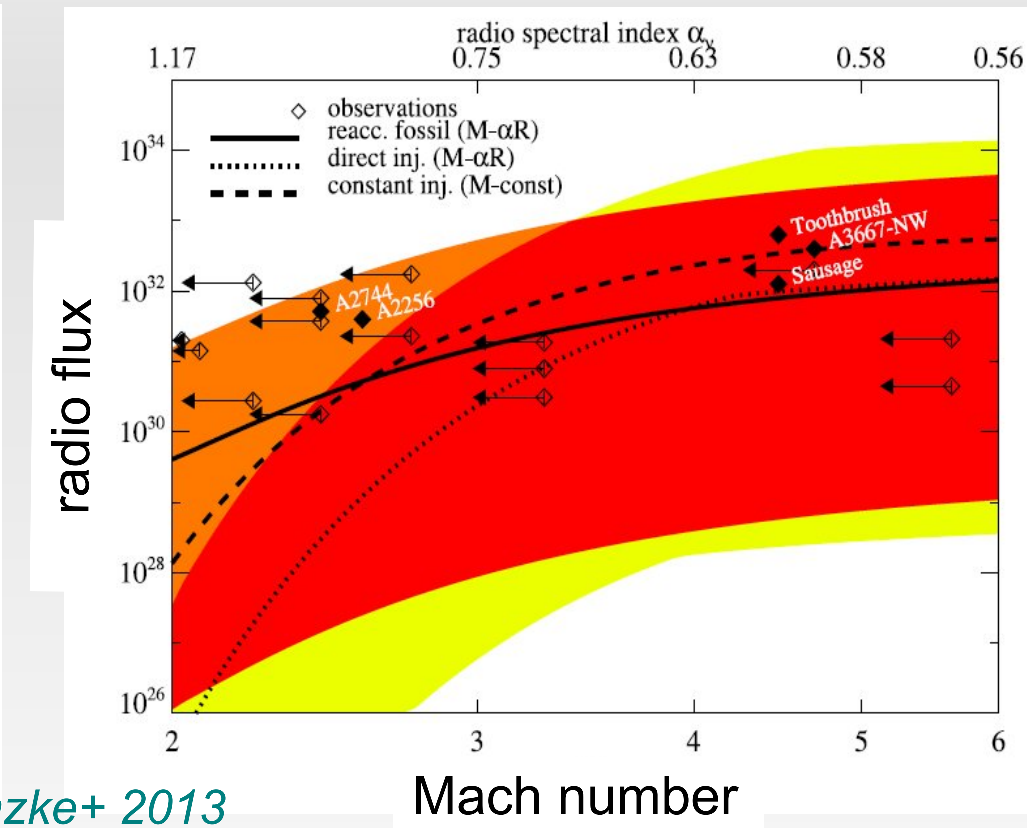


Pinzke+ 2013

Fermi-I re-acceleration in radio relics

$$f_2^{\mathrm{reaccel}}(p) = \int_{p_{\mathrm{inj}}}^{\infty} (\alpha+2)\left(\frac{p}{p'}\right)^{-\alpha} f_0(p') H(p-p') \mathrm{d}(\log p')$$





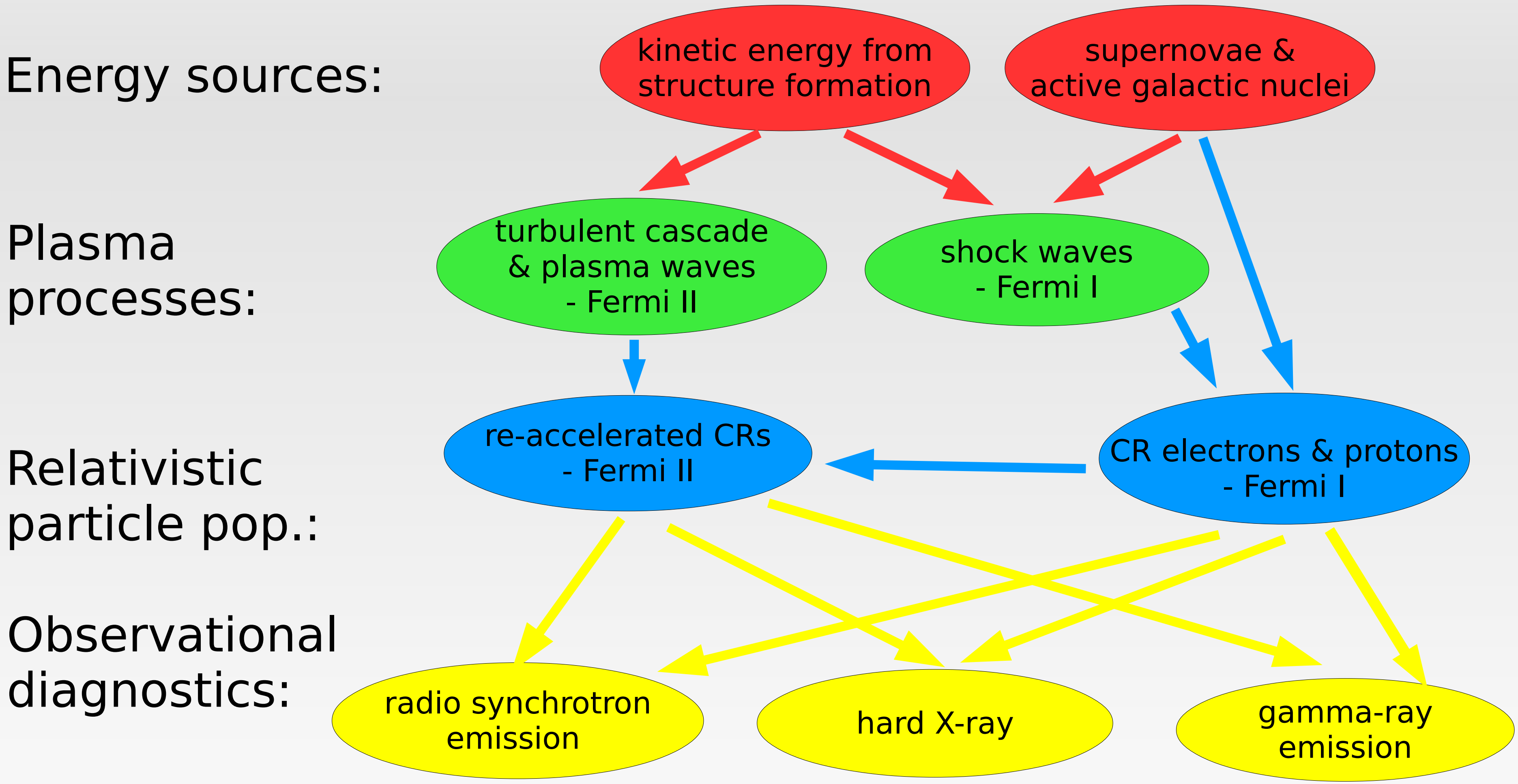
Pinzke+ 2013

Fossil contribution comparable to direct injection at high M

Dominates at low M !

Giant radio halo – Fermi II reacc.

Relativistic populations and radiative processes in clusters:



Hadronic: *e.g. Ensslin+ 2011, Wiener+ 2013, Zandanel+ 2013, Zandanel and Ando 2014, Pfrommer+ 2004,2008, Pinzke and Pfrommer 2010, Pinzke+ 2012*

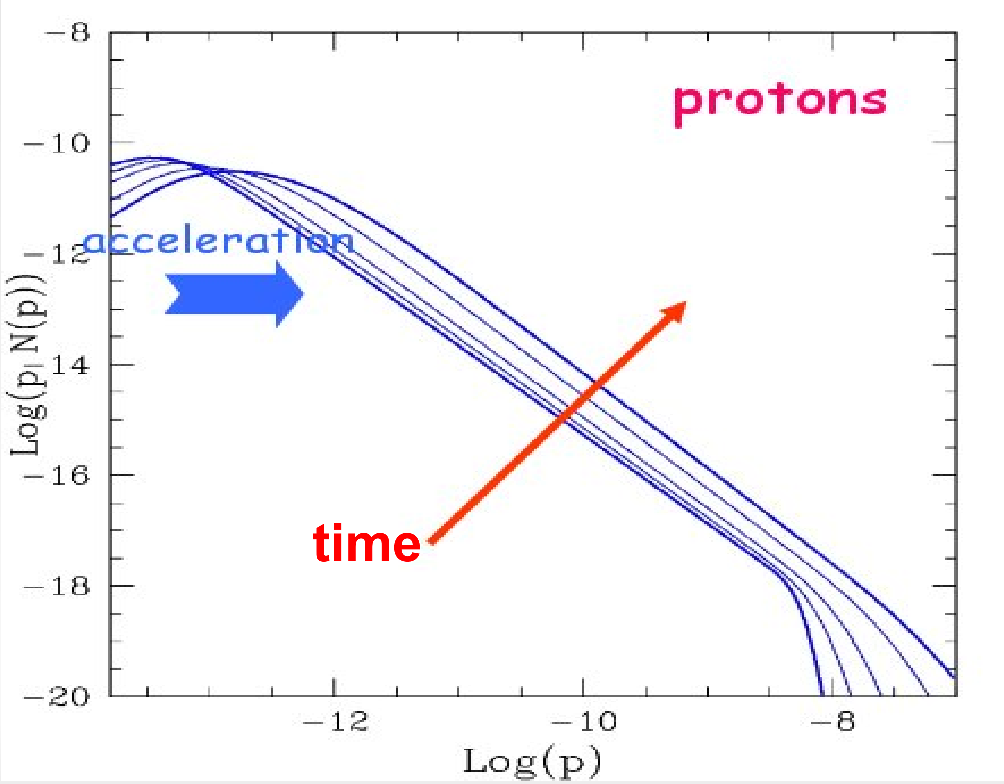
Fermi II reacceleration: *e.g. Brunetti+ 2001,2004,2012, Brunetti and Lazarian 2007, 2011, Petrosian 2001, Cassano and Brunetti 2005*

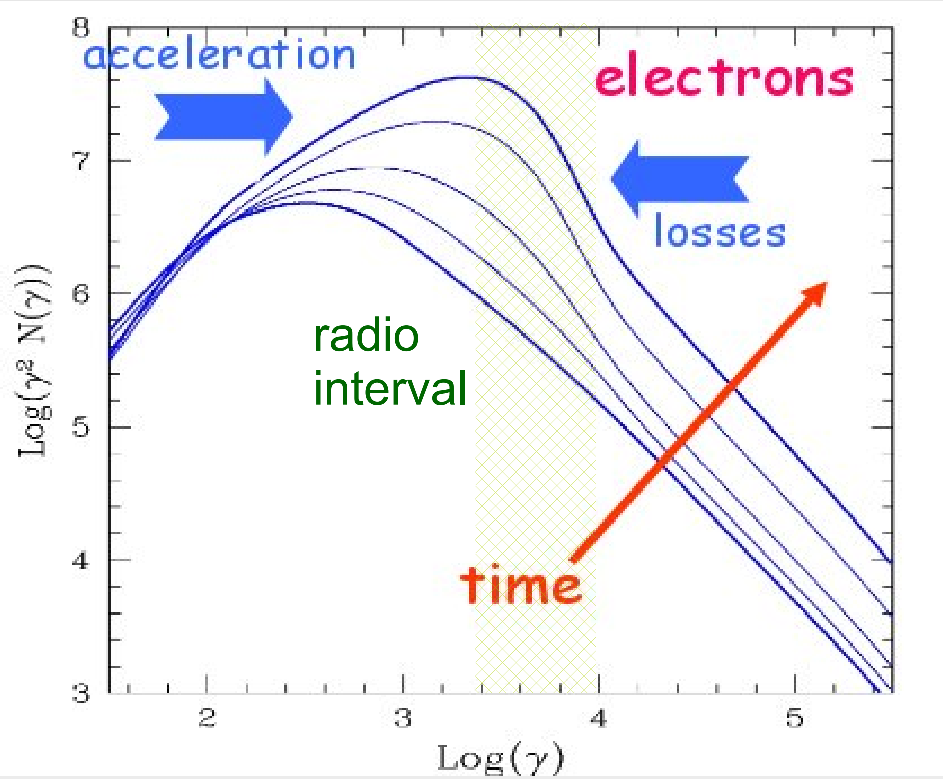
Fermi II reacc. - CRs

Acceleration mechanism: Compressible MHD turbulence

L_{inj} = 300 kpc, $(V_{turb}/C_s)^2$=0.22, τ_{reacc} = 650 Myr, isotropic Kraichnan turbulence

$$D_{pp}(p,t) = \frac{\pi}{8}\frac{p^2}{c}\langle\frac{\beta_{pl}|B_k|^2}{16\pi W}\rangle\frac{1}{c_s^2}\left(\frac{2I_o\langle V_{\rm ph}\rangle}{7\rho}\right)^{\frac{1}{2}} k_{cut}(t)^{\frac{1}{2}}\int_0^{\pi/2} d\theta V_{\rm ph}^2\frac{\sin^3(\theta)}{|\cos(\theta)|}\mathcal{H}\left(1-\frac{V_{\rm ph}/c}{\cos\theta}\right)\left(1-(\frac{V_{\rm ph}/c}{\cos\theta})^2\right)^2$$

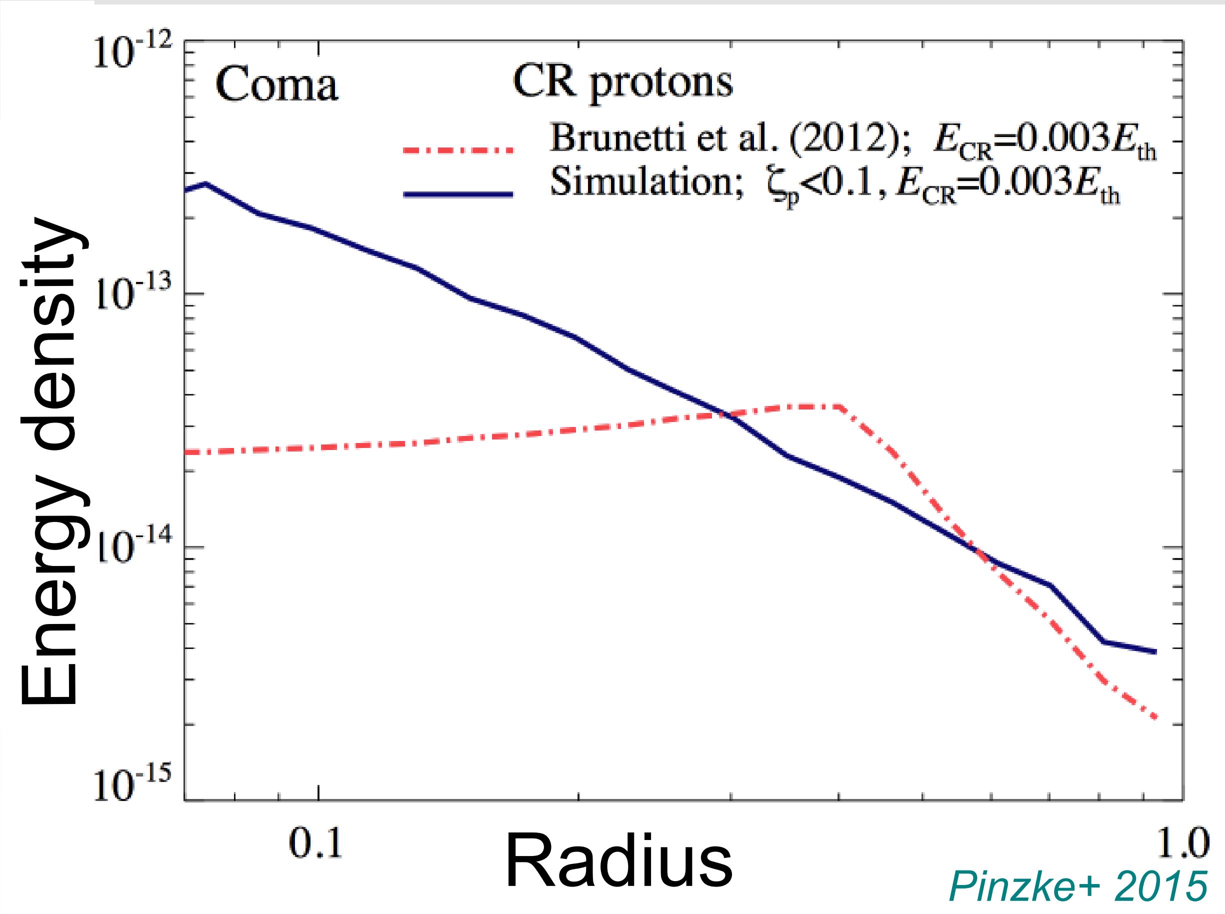




Brunetti and Lazarian 2007, 2011, Brunetti+ 2012

Fermi II reacc. - uncertainties

- flat CR profile (out to ~0.4 R_{200})
  - strong tension with simulations



possible solutions:

- CRp streaming
- $d\epsilon_{turb}/dR << d\epsilon_{th}/dR$
- primary CRes
- alpha_B << 0.5

Fermi II reacc. - uncertainties

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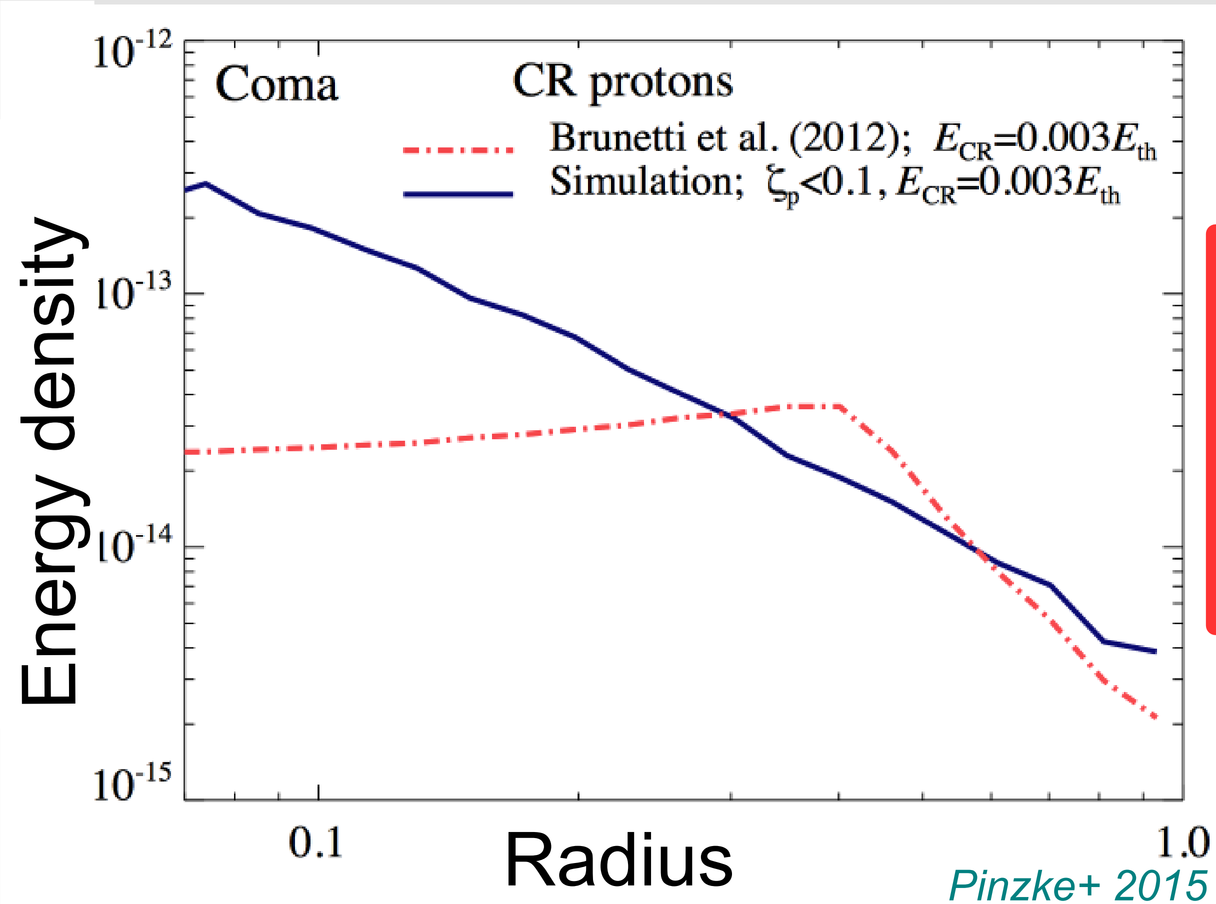


Pinzke+ 2015

possible solutions:

- CRp streaming
- $d\epsilon_{turb}/dR \ll d\epsilon_{th}/dR$
- primary CRes
- alpha_B << 0.5

Realistic cluster simulations with relevant physics need to fully establish Fermi II reacceleration models!

Streaming and diffusion – CR protons

Ensslin+ 2011, Zandanel+ 2013, 2014, Wiener+ 2013

Small anisotropy in CRs (frame of waves)
⇒ momentum transfer CRs → waves
⇒ wave growth rate

$$\Gamma_{\rm CR}(k_\parallel) \sim \Omega_0 \frac{n_{\rm CR}(>\gamma)}{n_{\rm i}} \left(\frac{v_{\rm s}}{v_{\rm A}} - 1\right) \qquad k_\parallel \sim \frac{1}{\mu r_{\rm L}}$$

Kulsrud and Pearce 1969

⇒ grows until scattering renders CRs isotropic, $V_D \sim V_A$

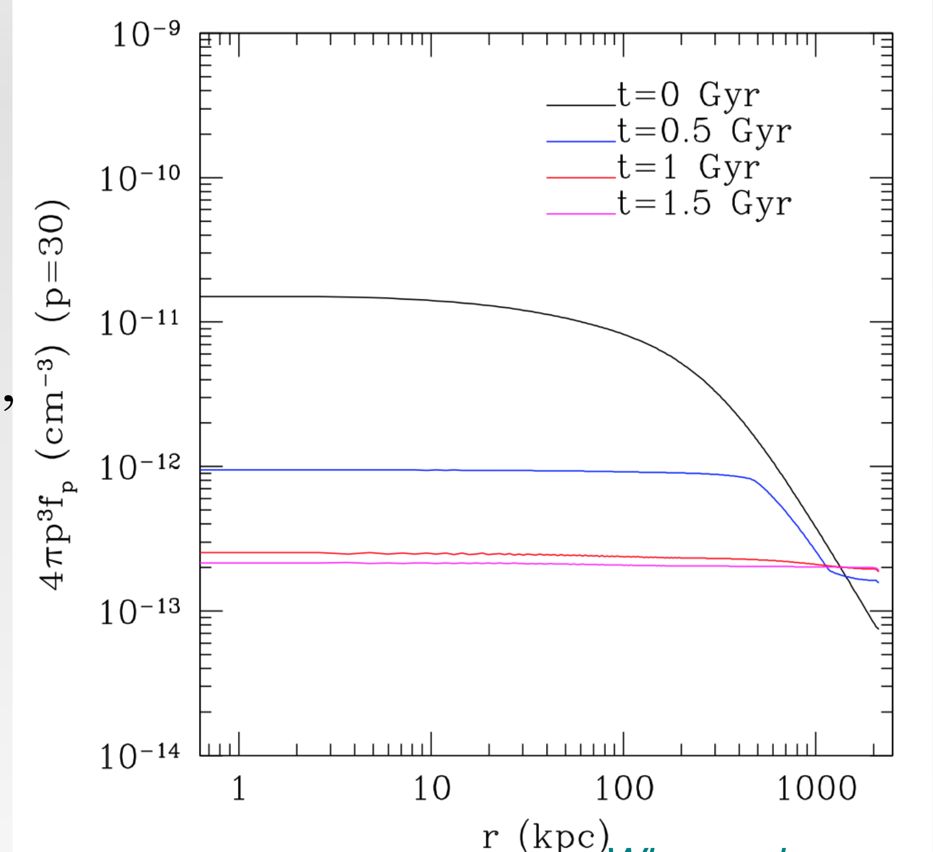
⇒ self-confinement

Turbulence damps growth of waves since waves cascade to smaller scales before scattering CRs *Farmer and Goldreich 2004*

Adopt steady state, $\Gamma_{\rm grow} = \Gamma_{\rm damp}$

$$v_{\rm D} = v_{\rm A}\left(1 + 1.2 \frac{B_{\mu G}^{1/2} n_{i,-3}^{1/2}}{L_{\rm MHD,100}^{1/2} n_{\rm CR,-10}} \gamma_{100}^{n-3.5} 10^{2(n-4.6)}\right)$$

Wiener+ 2013



Wiener+ in prep.

CR protons in clusters stream outward faster than inward turbulent advection

Fermi II reacc. - three scenarios

1) Flat turbulent profile (M-*turbulence*, $\alpha_{tu} = 0.66$)

– secondary CRes and CRps, reaccelerated by flat turbulent profile
– $\alpha_{tu} < 1$ motivated by cosmological simulations, *Lau et al. 2009; Shaw et al. 2010; Battaglia et al. 2012*

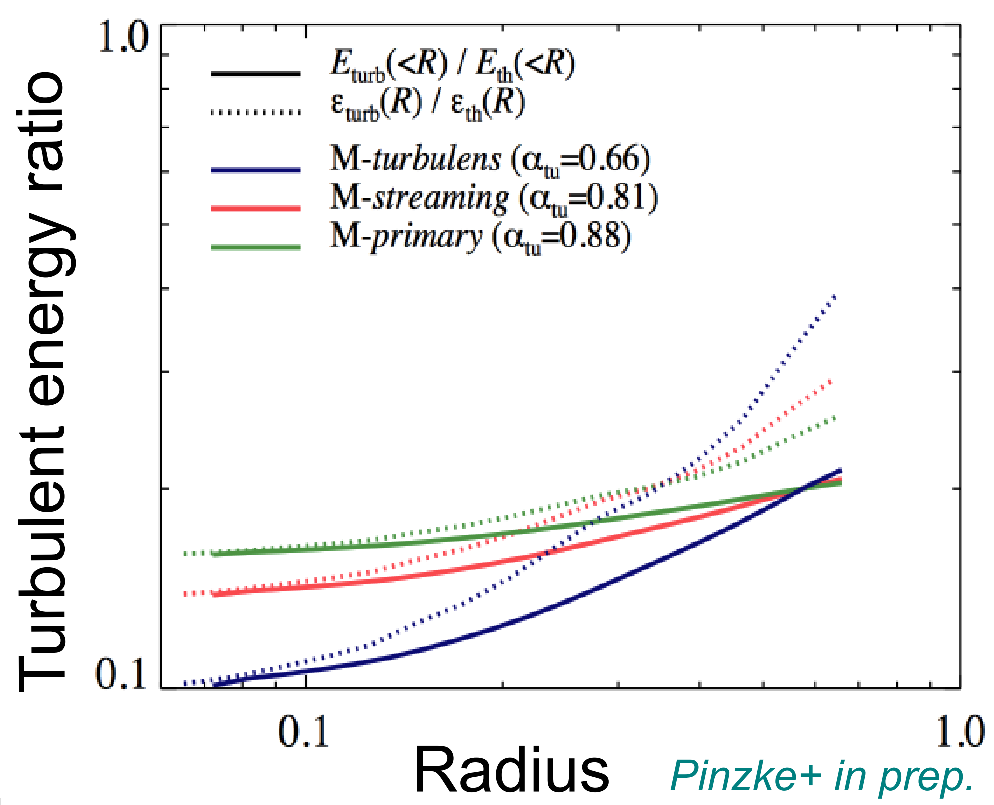
2) Streaming CRps (M-*streaming*, $\alpha_{tu} = 0.81$)

– secondary CRes and streamed CRps, reaccelerated
– CRp streaming needed in hadronic model, unexplored for ICM, *Ensslin+ 2011, Zandanel+ 2013, 2014, Wiener+ 2013, Pinzke+15*

3) Primary CRes (M-*primary*, $\alpha_{tu} = 0.88$)

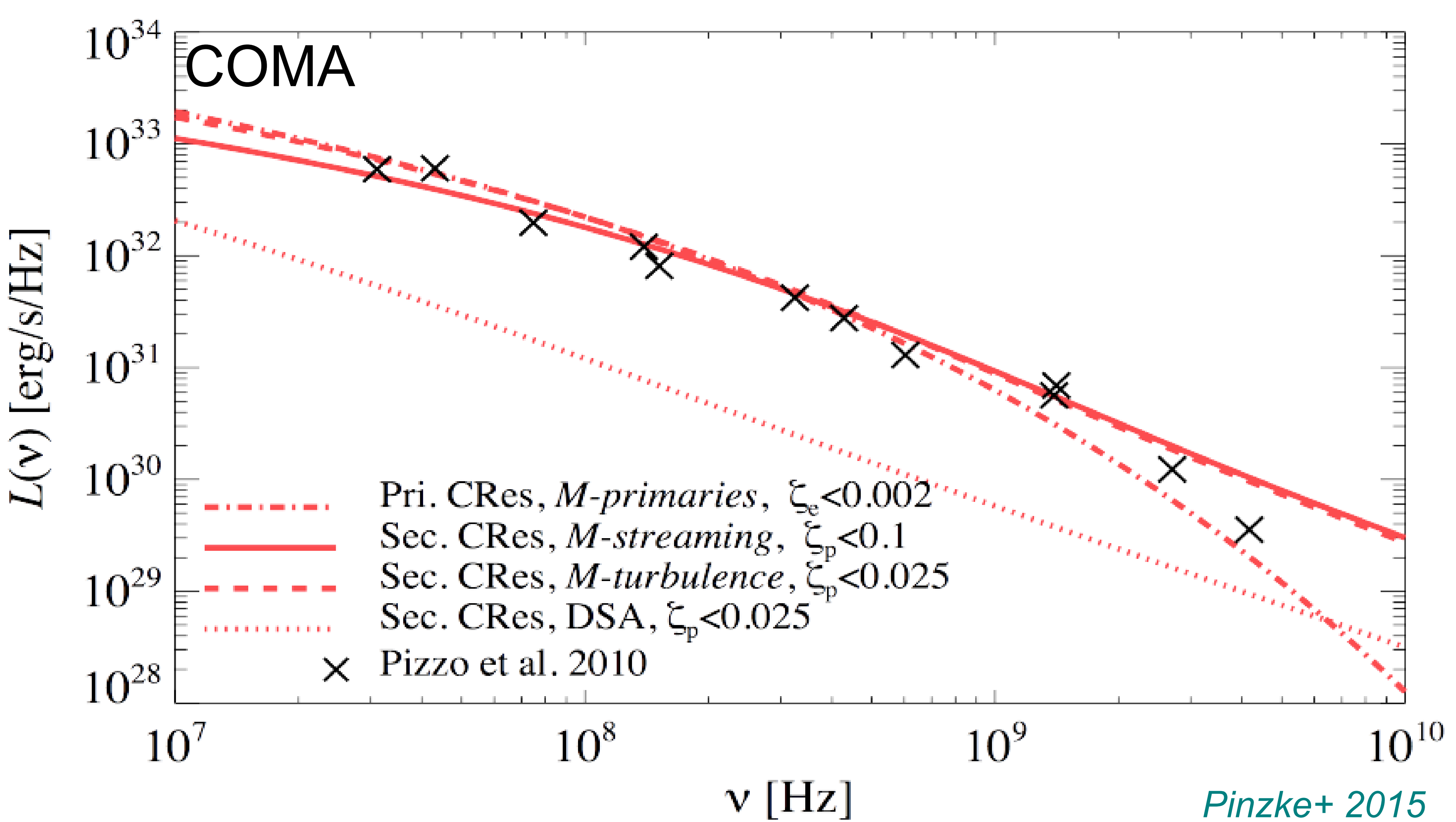
– *primary CRes with $K_{ep} = 0.1$, reaccelerated*
– *high K_{ep} motivated by radio relics and lack of γ-ray emission,* *e.g. Vazza & Brüggen 2014*

$$\epsilon_{turb}(R) \propto \epsilon_{th}^{\alpha_{tu}}(R)$$
$$E_{turb}(< R_{RH}) = 0.2 E_{th}(< R_{RH})$$



Pinzke+ in prep.

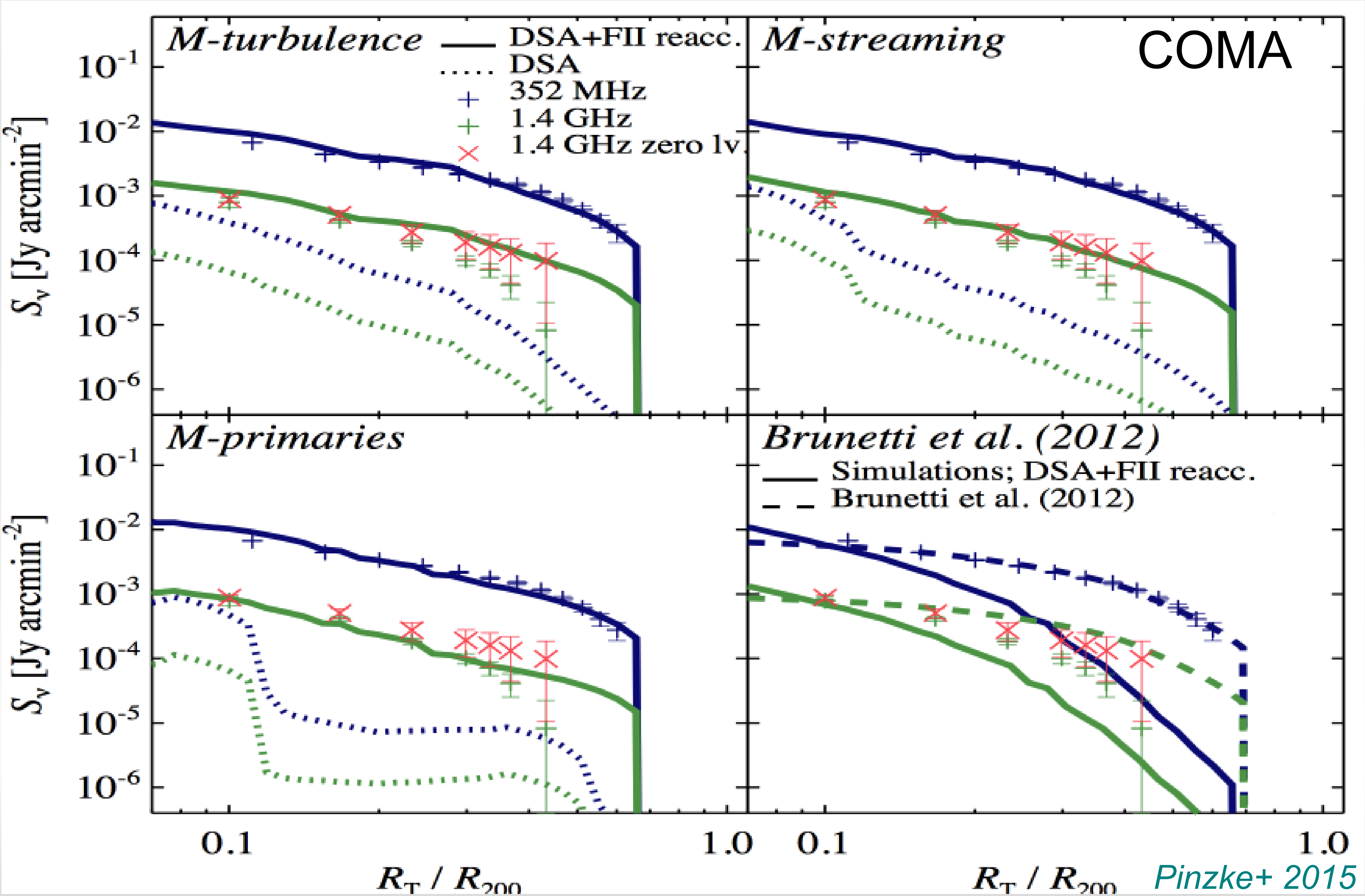
Fermi II reacc. – radio spectrum



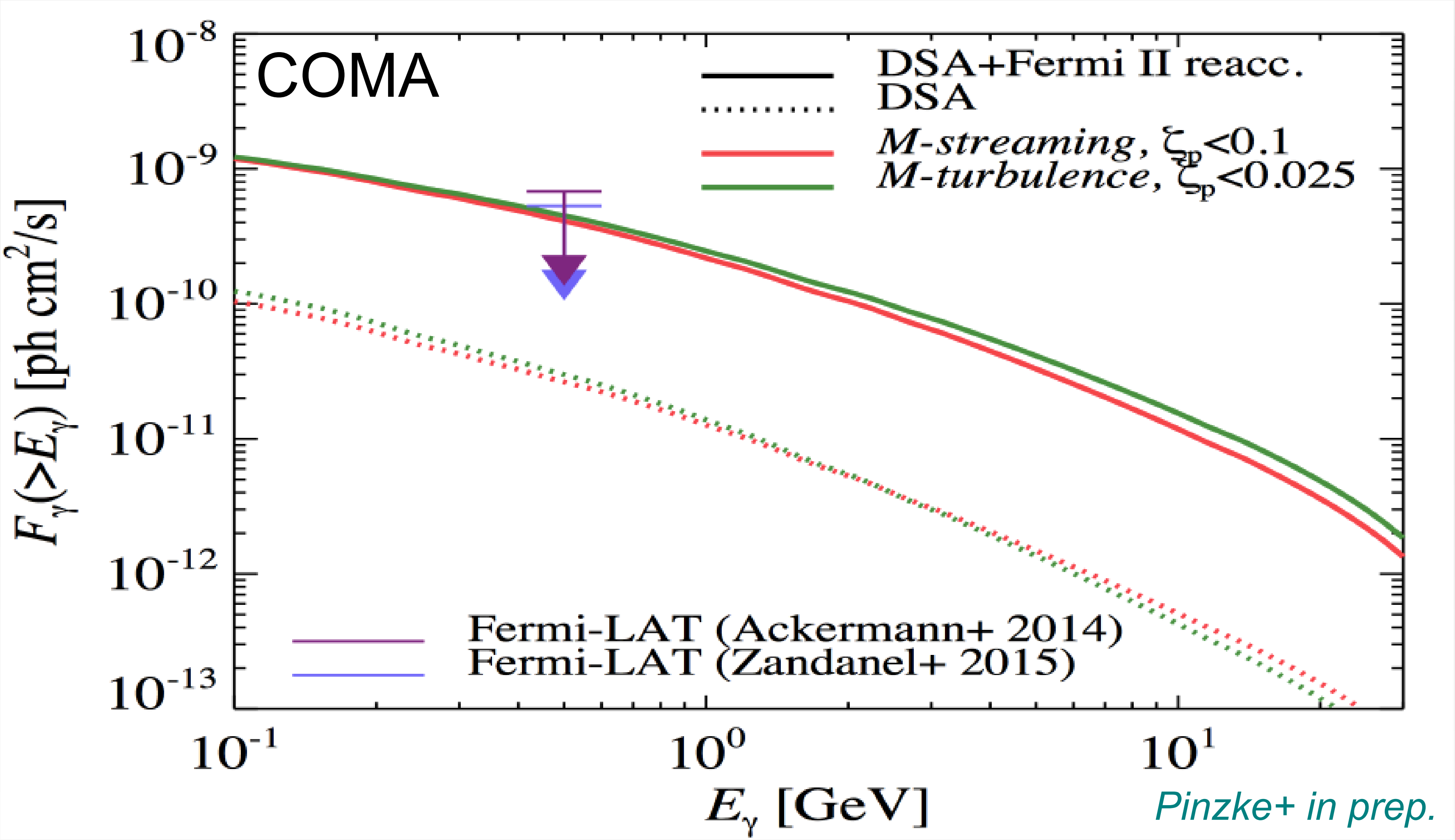
Pinzke+ 2015

- ✔ All three proposed scenarios reproduce observed radio spectrum
- ✖ Pure hadronic model (DSA only) can not reproduce spectrum

Fermi II reacc. – radio profiles



Fermi II reacc. – gamma-rays



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

Take home messages

Radio relics

- *Fermi I reaccelerated* fossil CR electrons in cluster outskirts can explain radio emission from low Mach number shocks

Giant radio halos

- *Classical hadronic models* ruled out by radio observations
- *Fermi II reacceleration* preferred, however, tension between initial CR distribution and simulations

  → 3 different solutions to the problem

  – *primary CRes* (large K_{ep})
  – *streaming CRps* that produce secondary CRes
  – CRps and secondary CRes reaccelerated by *flat turbulent profile*

Fermi I & II reacc. can reproduce both radio and gamma-ray observations in halos and relics!

Thank You