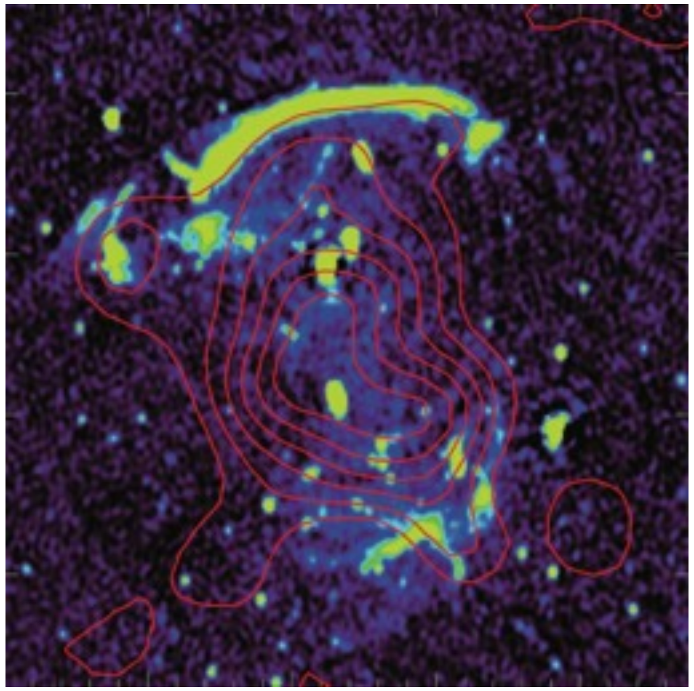
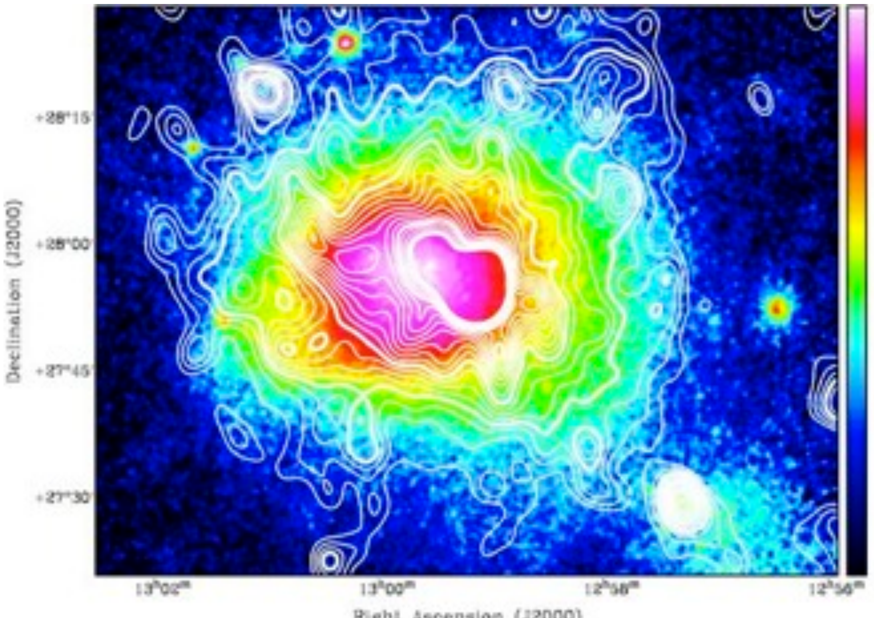


Turning Radio Relics On and Radio Halos Off



Peng Oh
UCSB

The Switches

Josh Wiener (UCSB)

Anders Pinzke
(UCSB)

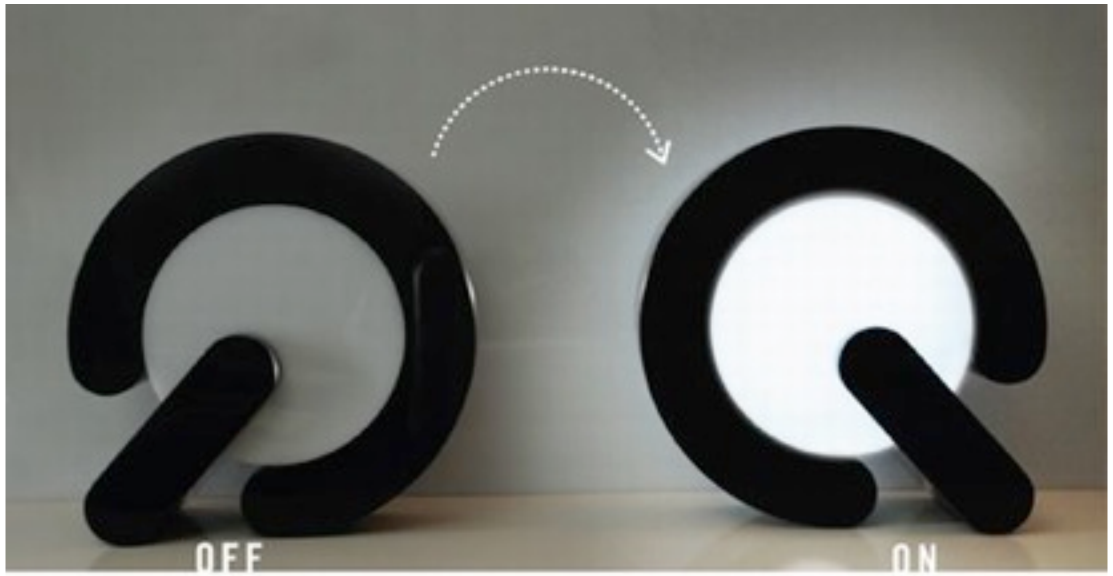
Fulai Guo
(Santa Cruz)

Christoph Pfrommer

(Heidelberg)

Why you should care

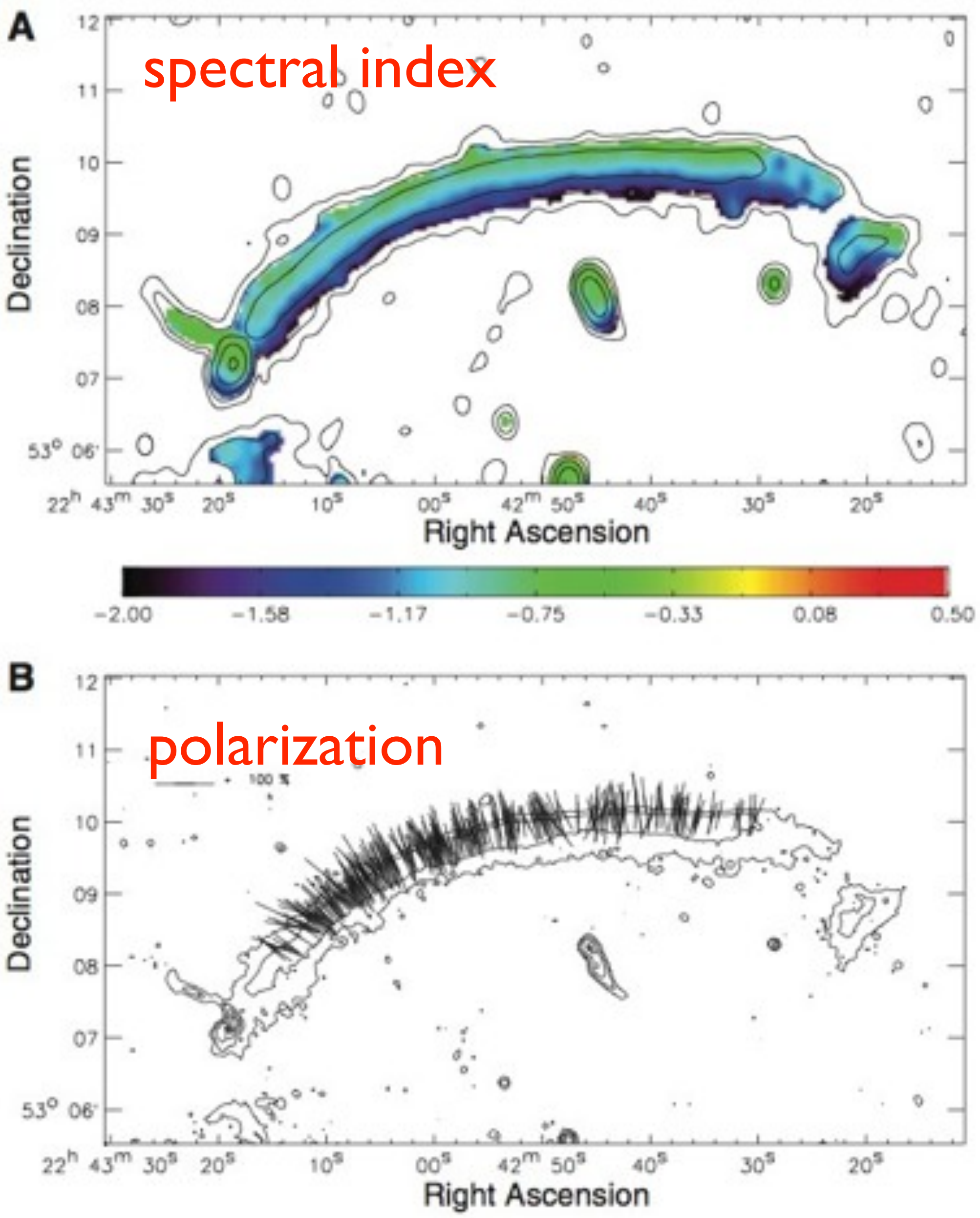
LOFAR could really shake things up!



Turning Radio Relics On with Fossil Electrons

Pinzke, Oh, Pfrommer, 2012, in prep

Radio Relics: Awesome!

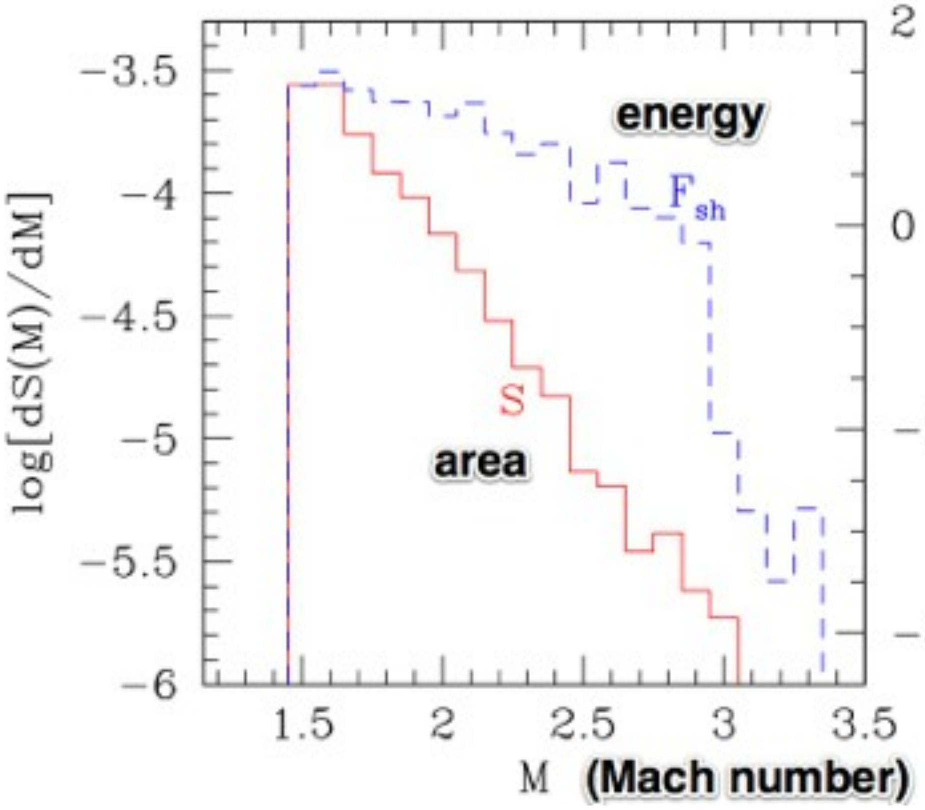


van Weeren et al, 2010

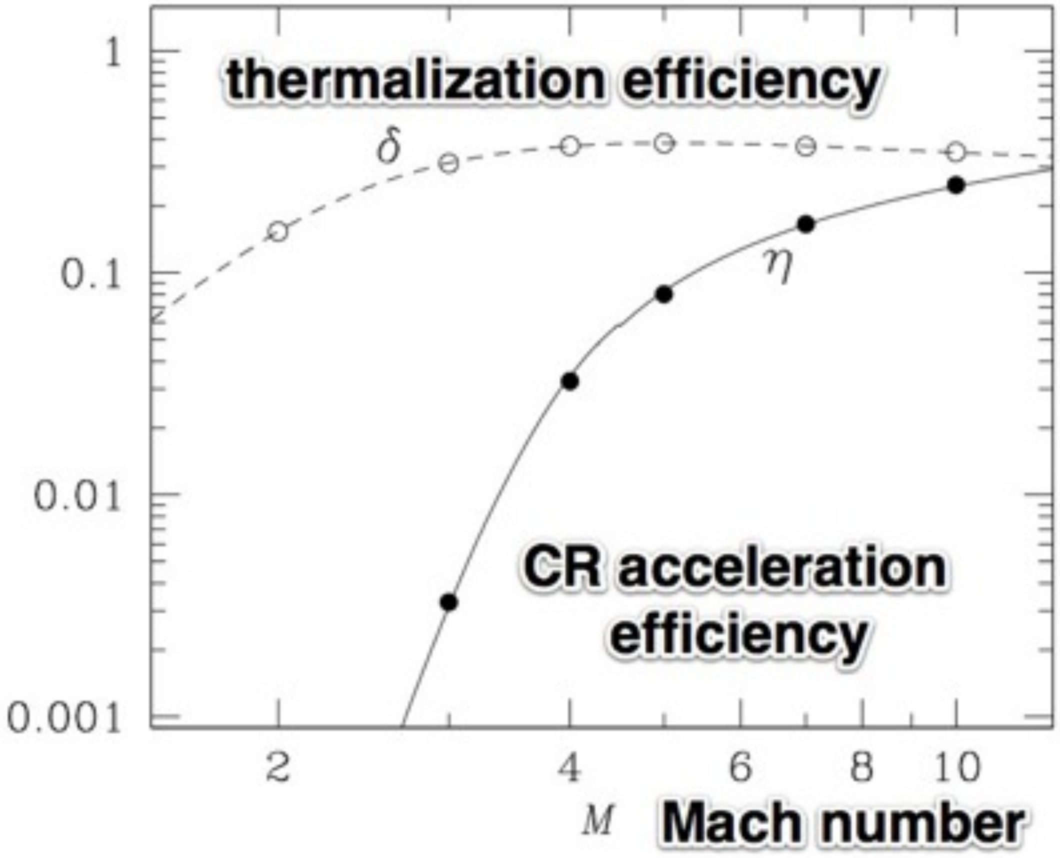
- Trace shocks in cluster outskirts
- Spectral index: shock Mach number
- Spectral ageing: B-field strength
- Polarization: B-field orientation

Biggest unknown: shock acceleration efficiency

Kang & Ryu 2011



Bruggen et al 2012

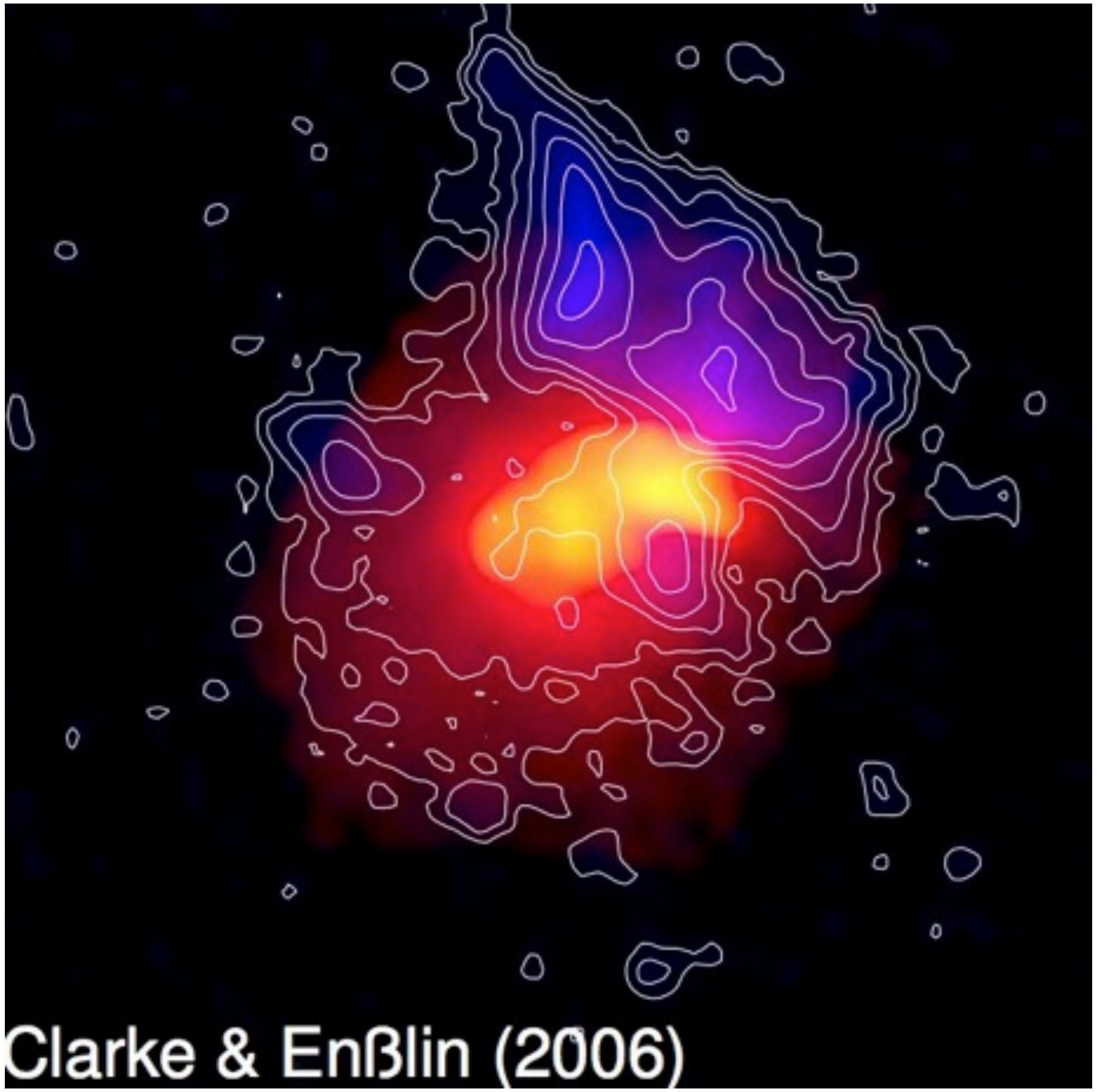


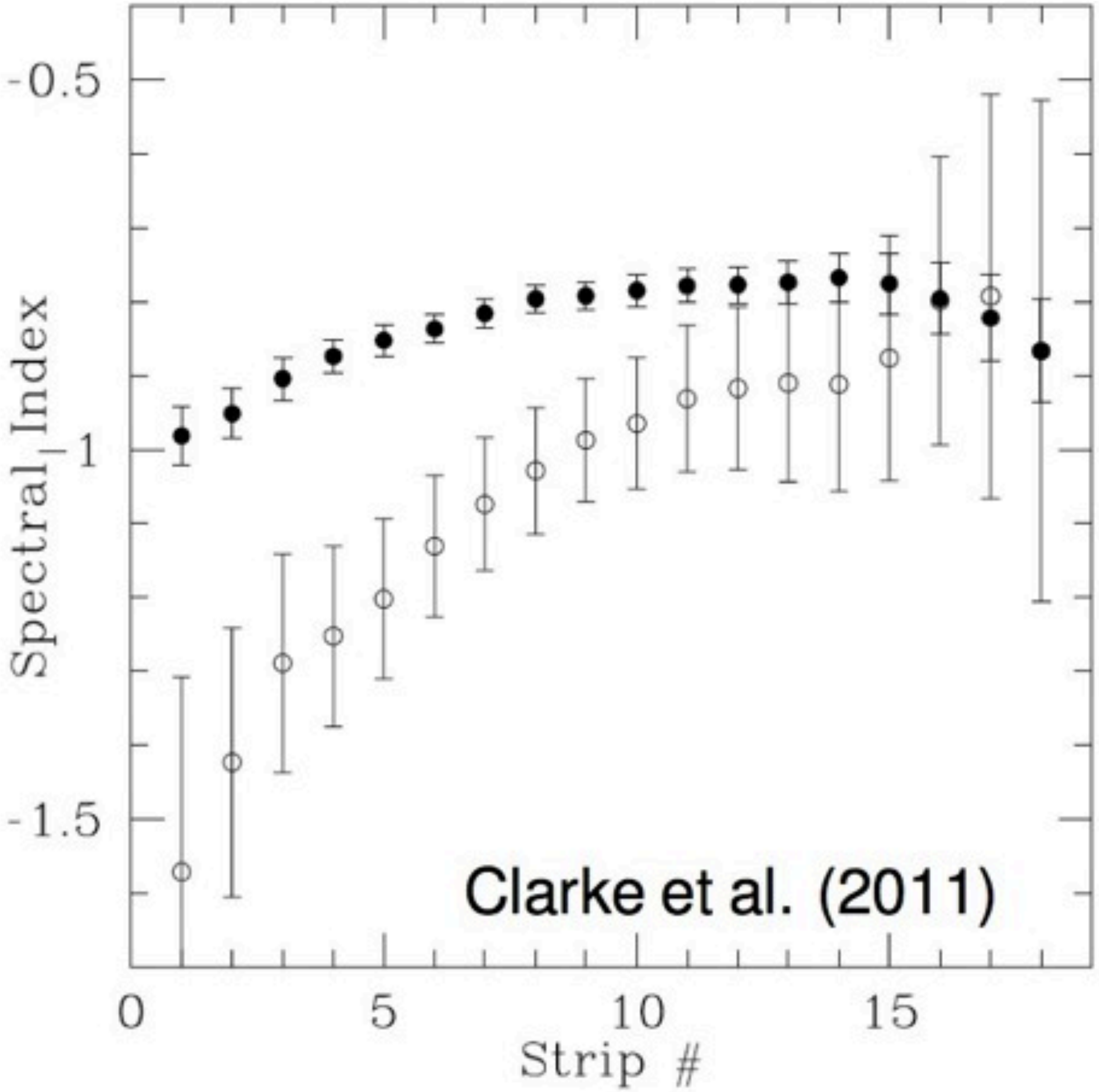
Outskirts dominated by low Mach number shocks

These shocks have low acceleration efficiency

How many will LOFAR see?

A poster child: A2256


Clarke & Enßlin (2006)

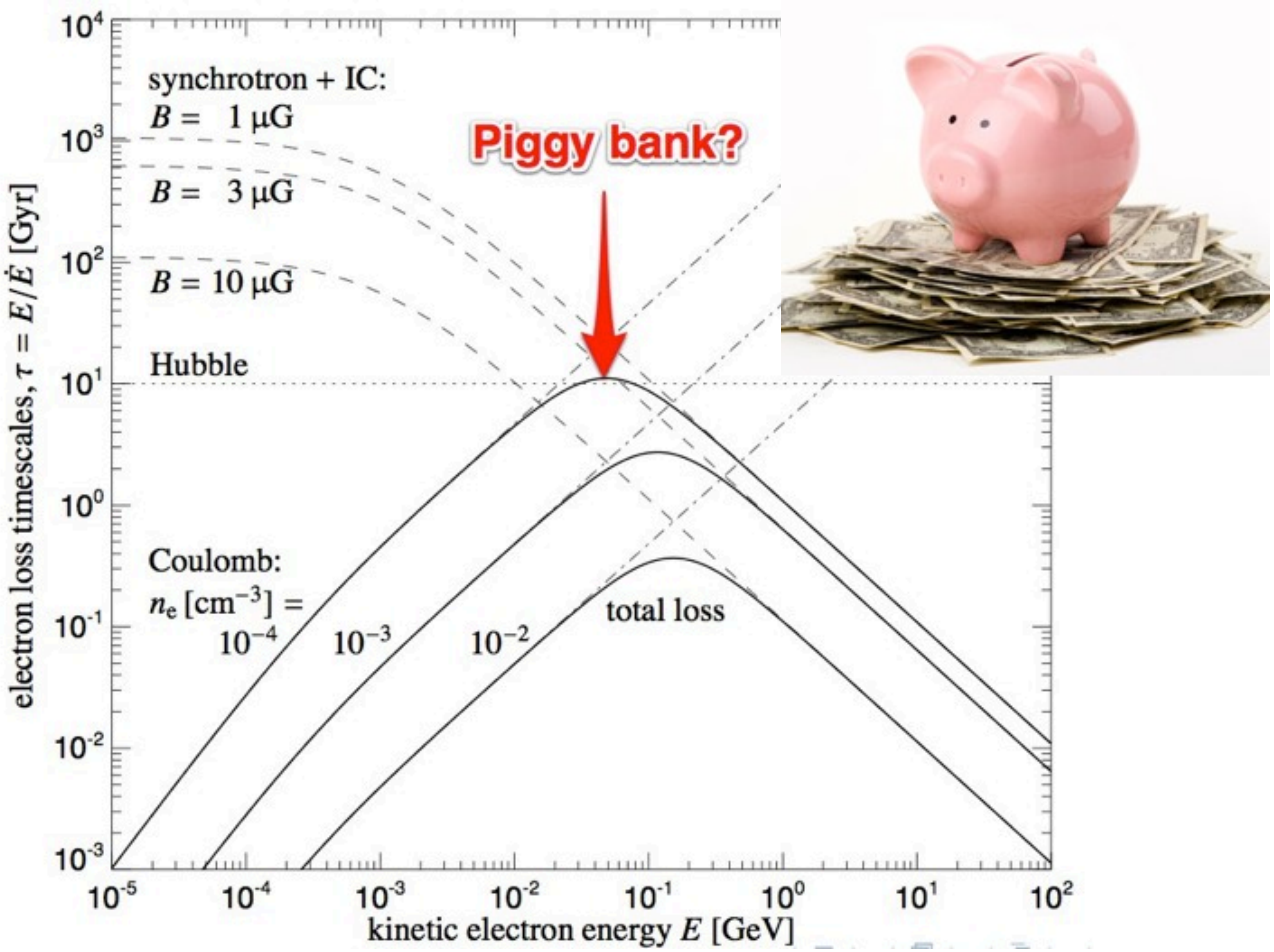


Clarke et al. (2011)

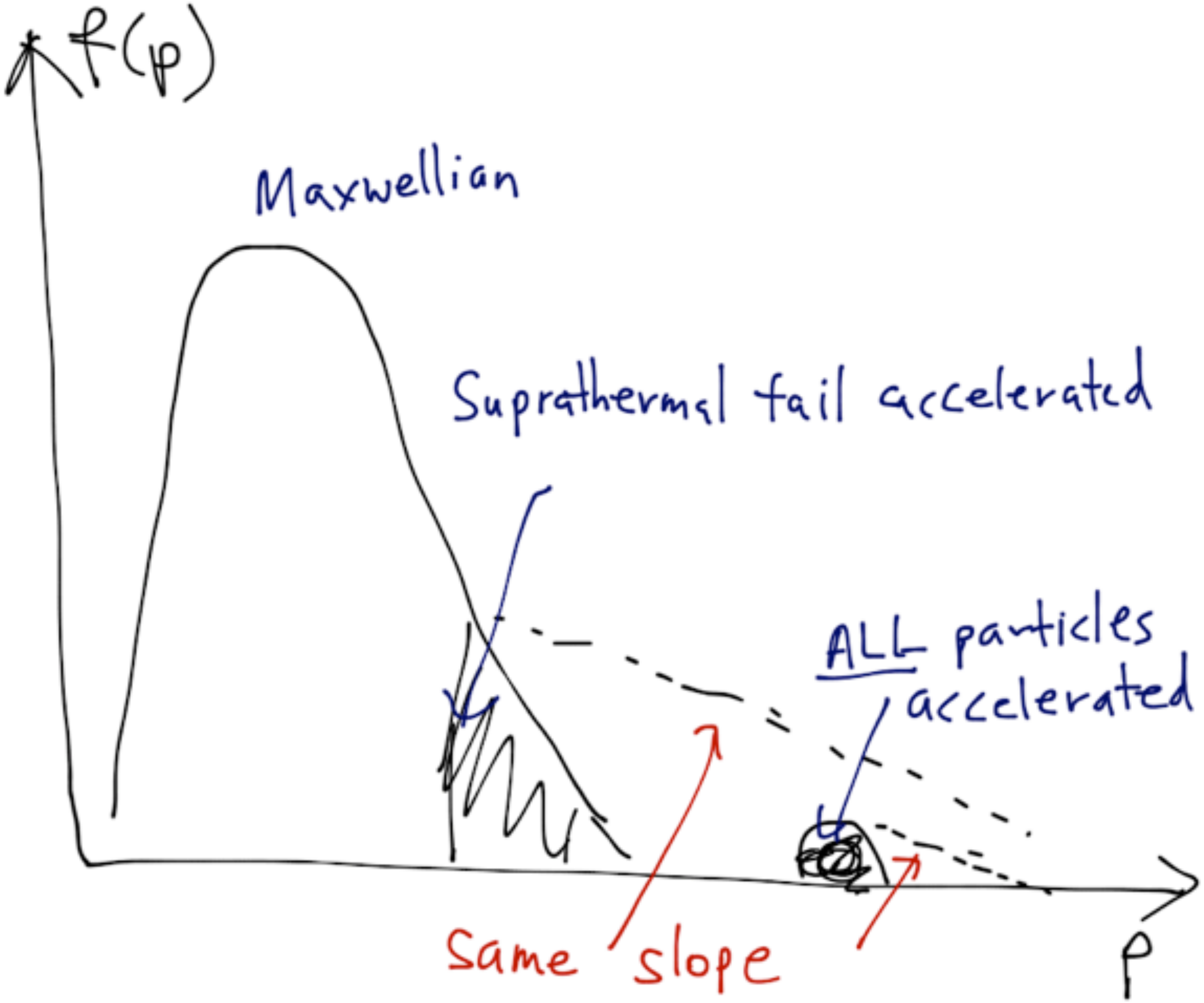
$$\alpha_\nu = 0.85 \quad \rightarrow \quad \mathcal{M} = 2.6:$$

How is this possible?

Could fossil electrons be responsible?



How would relic reacceleration work?



Could this beat direct injection?

Ultimately, we care about $f(p_{\rm emit})$ where $p_{\rm emit} \approx 10\,{\rm GeV}$

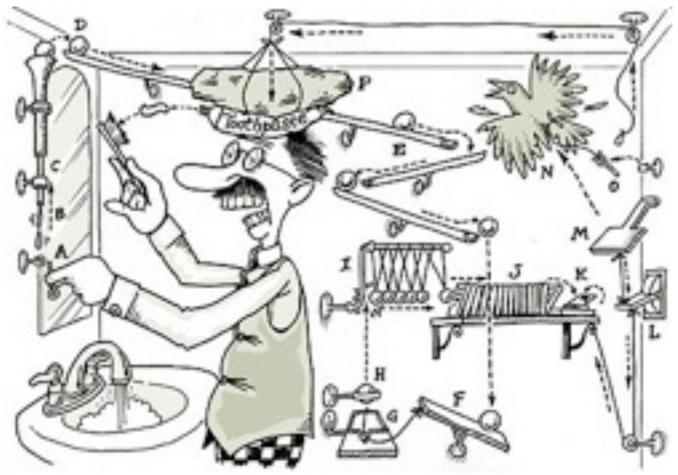
Can show that this is approximately:

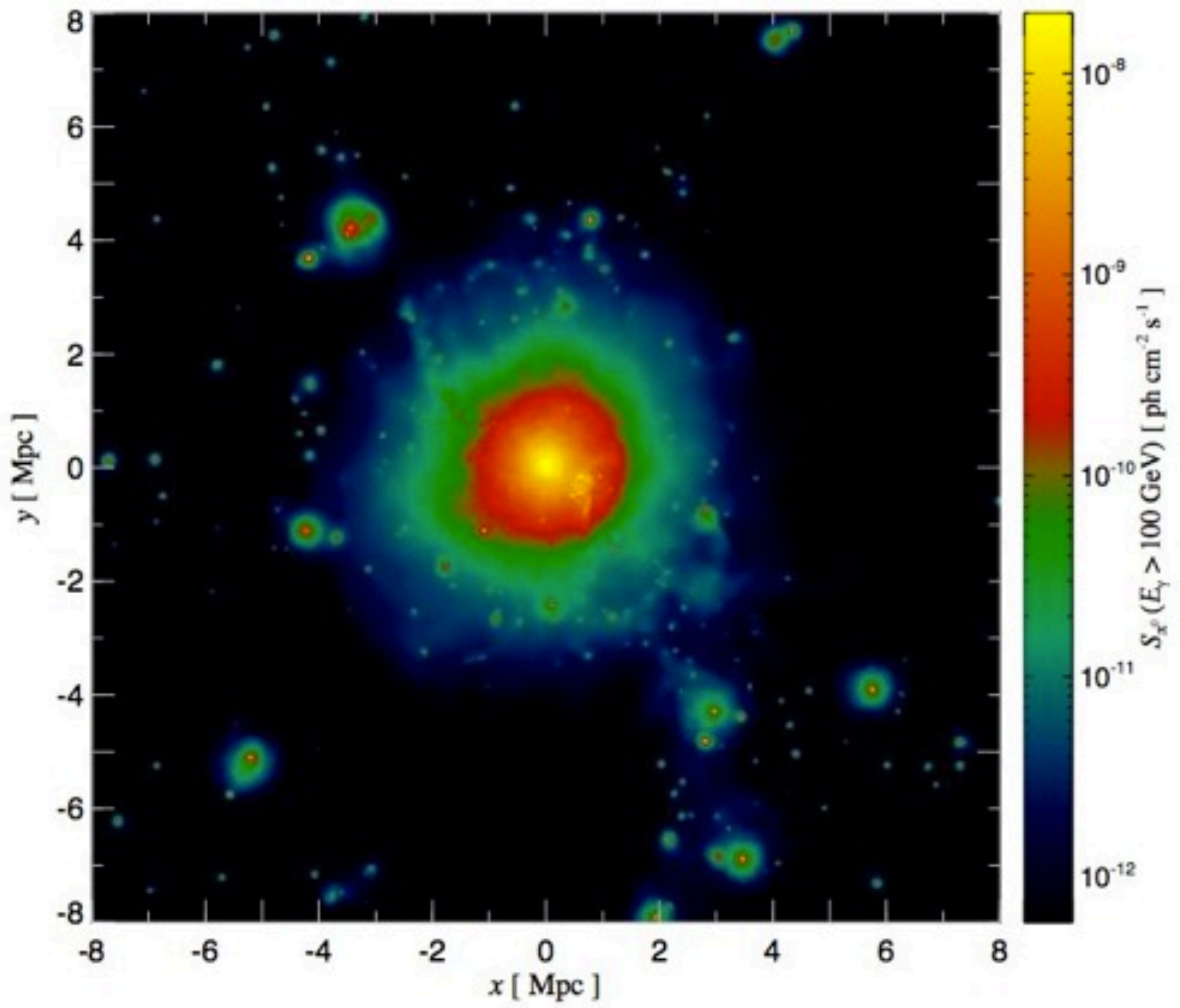
$$f_2(p_{\rm emit}) \approx q\frac{n_{\rm o}(p > p_*)}{4\pi p_*^3}\left(\frac{p_{\rm emit}}{p_*}\right)^{-q}$$

where p_* is where number density peaks

So just need to figure out $p_*, n(p > p_*)$

Method





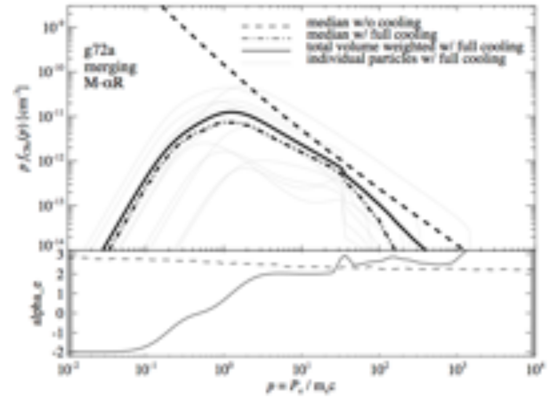
Pinzke & Pfrommer 2010

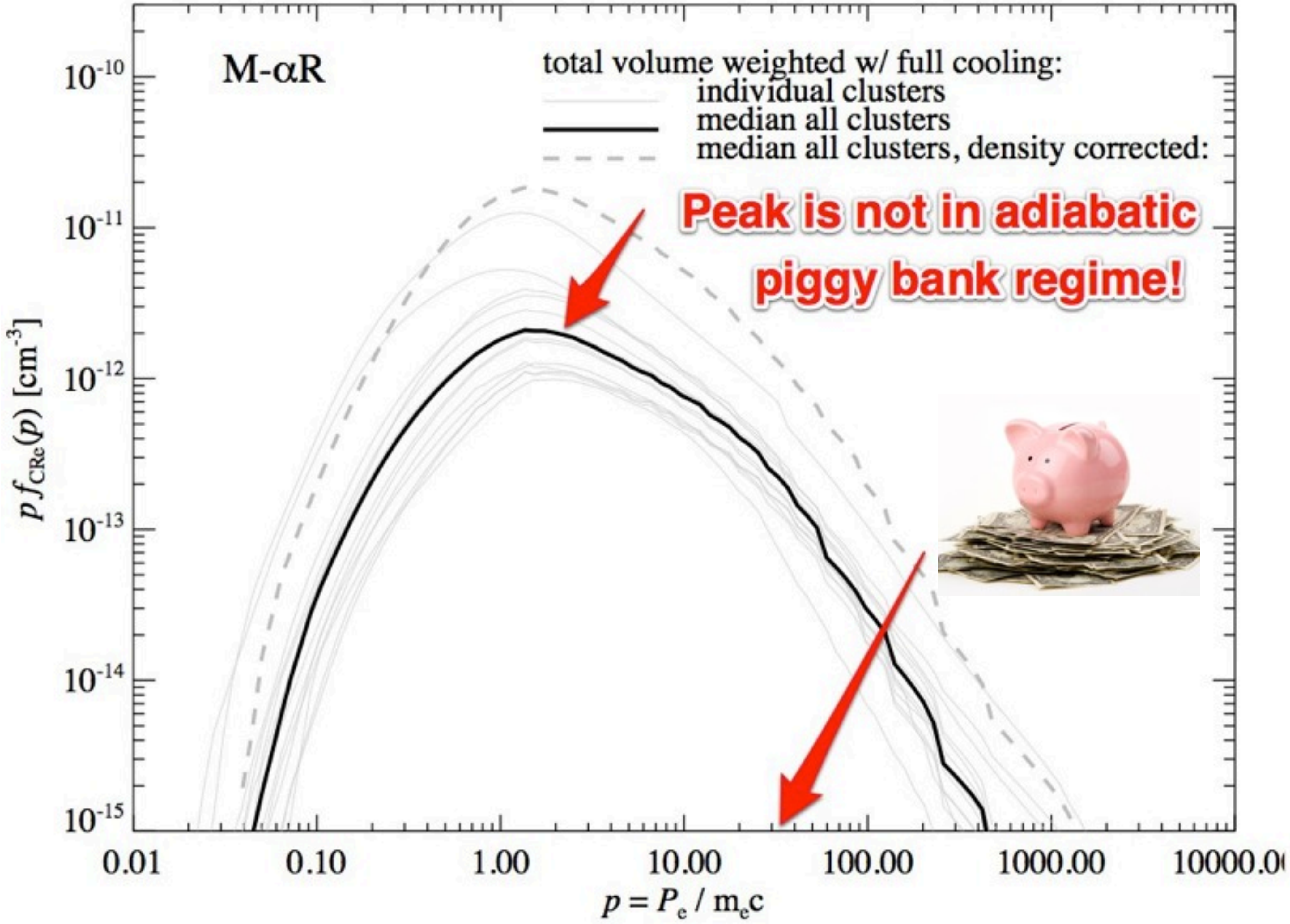
Use previous CR proton sims: (time resolution: ~100 Myr, 1 Gyr)

Now inject CR electrons with e/p ~ 0.01

Track Coulomb + synchrotron/inverse Compton cooling

Result

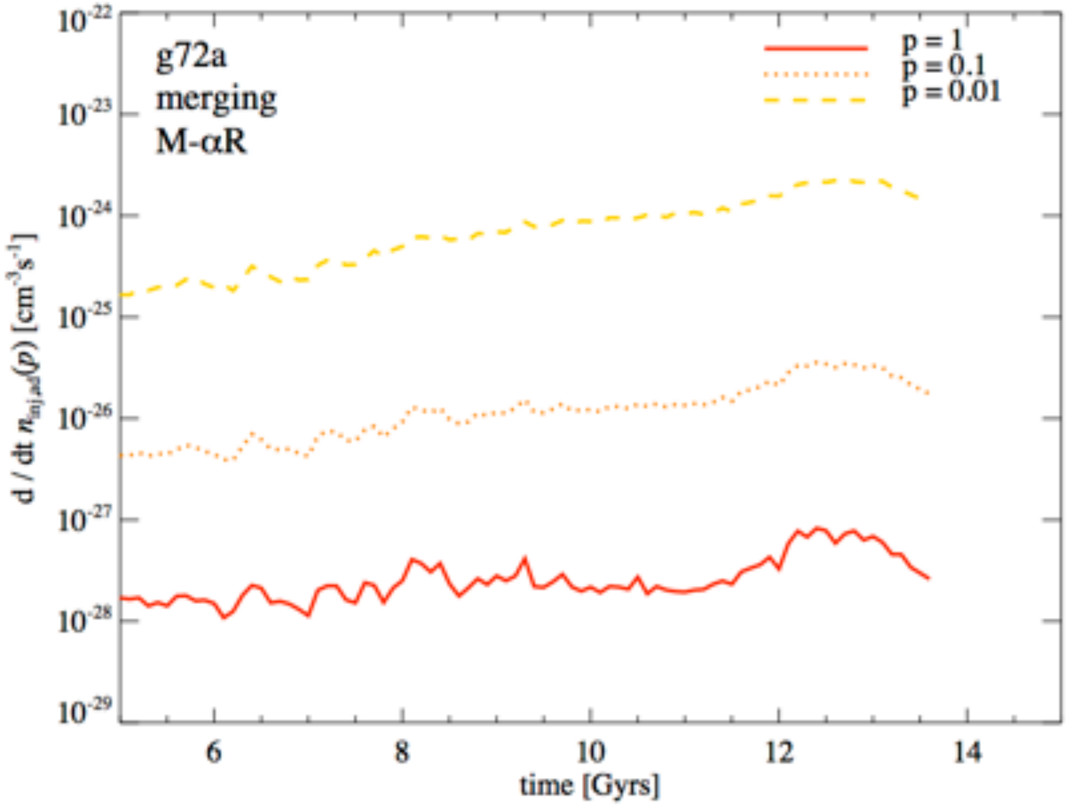




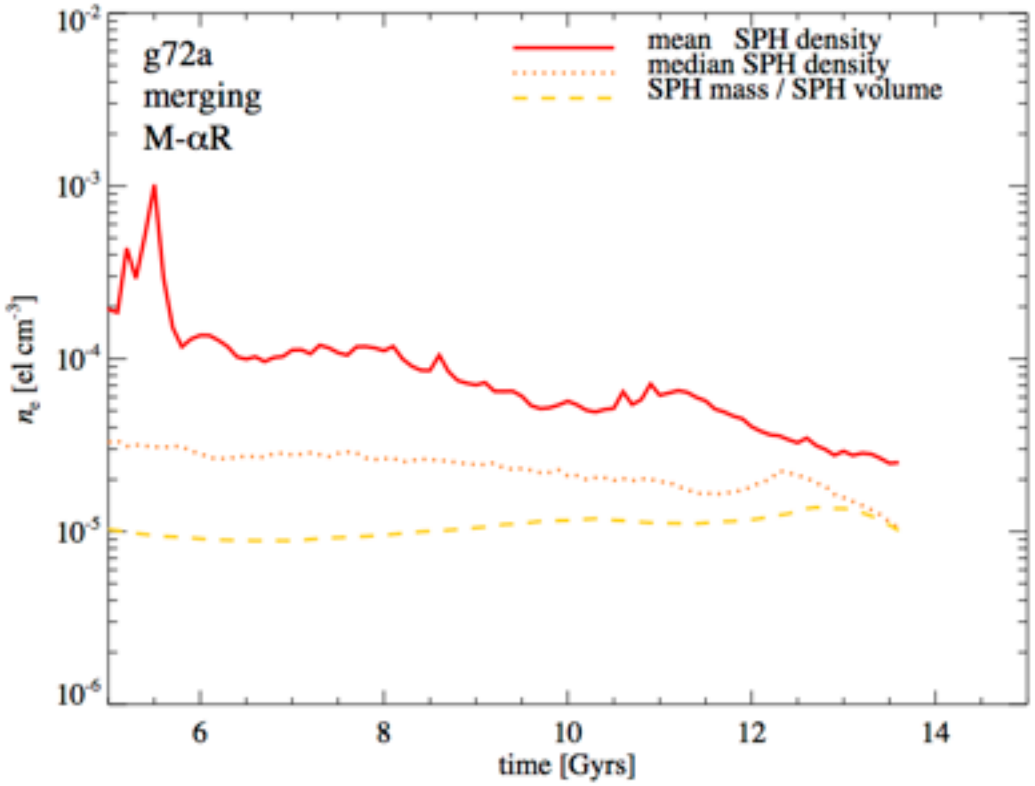
Peak is not in adiabatic piggy bank regime!

How to understand it

We only care about injection and Coulomb cooling



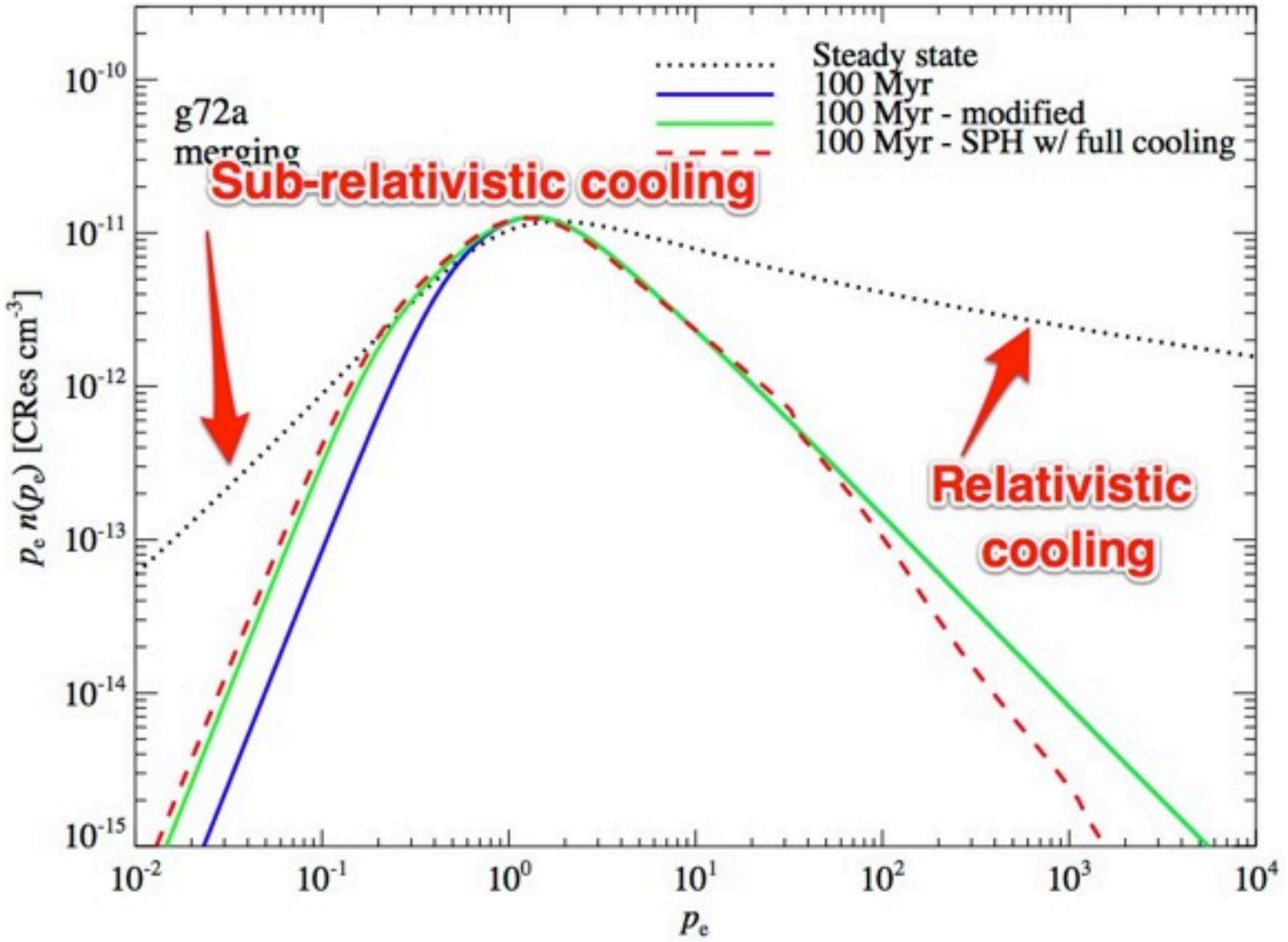
Injection is fairly steady, not impulsive



Density (and hence cooling) is fairly constant

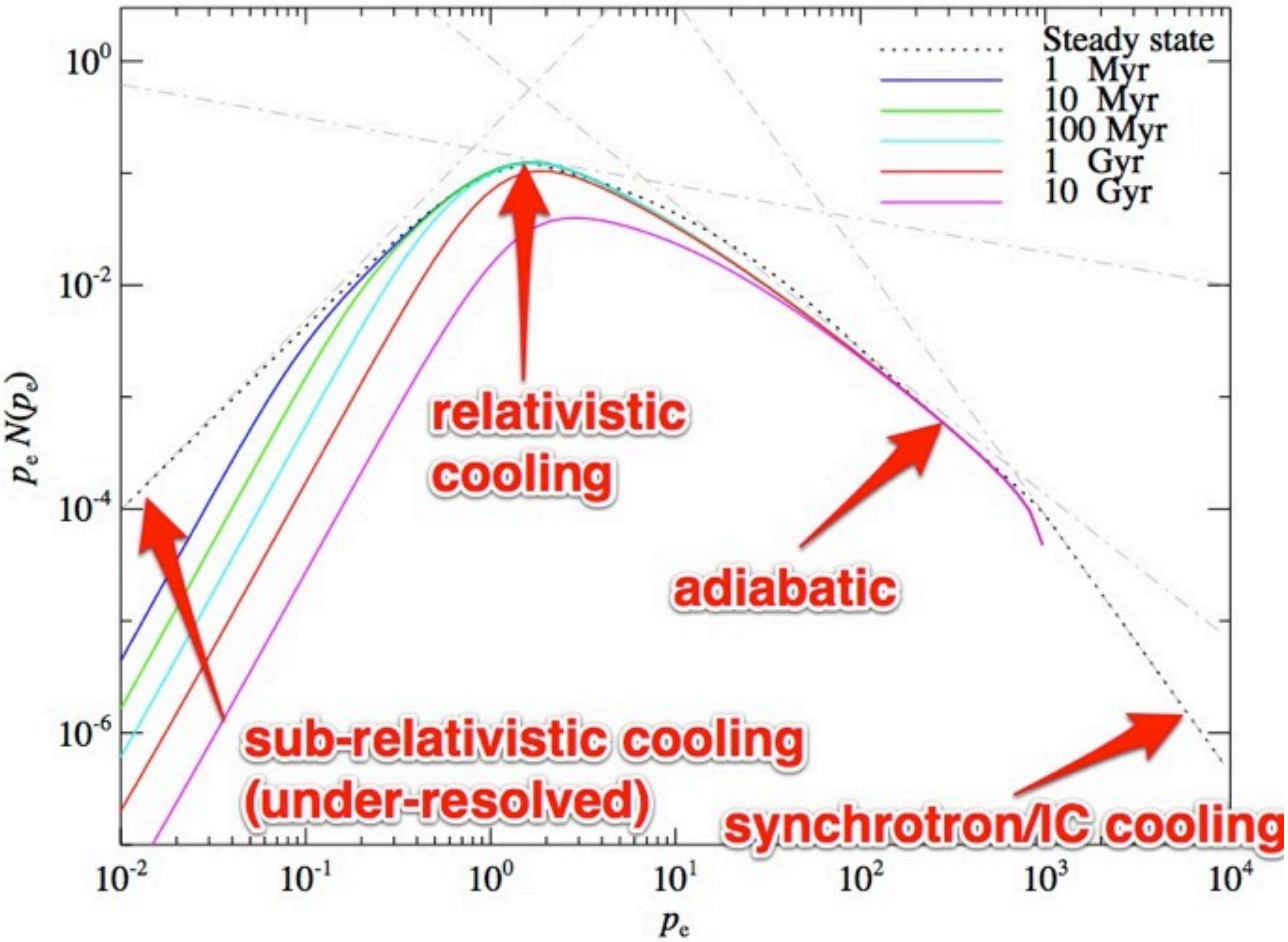
…so it's in steady state

this means you can calculate analytic models!



The peak looks good…why is the rest a terrible fit?

Time Resolution

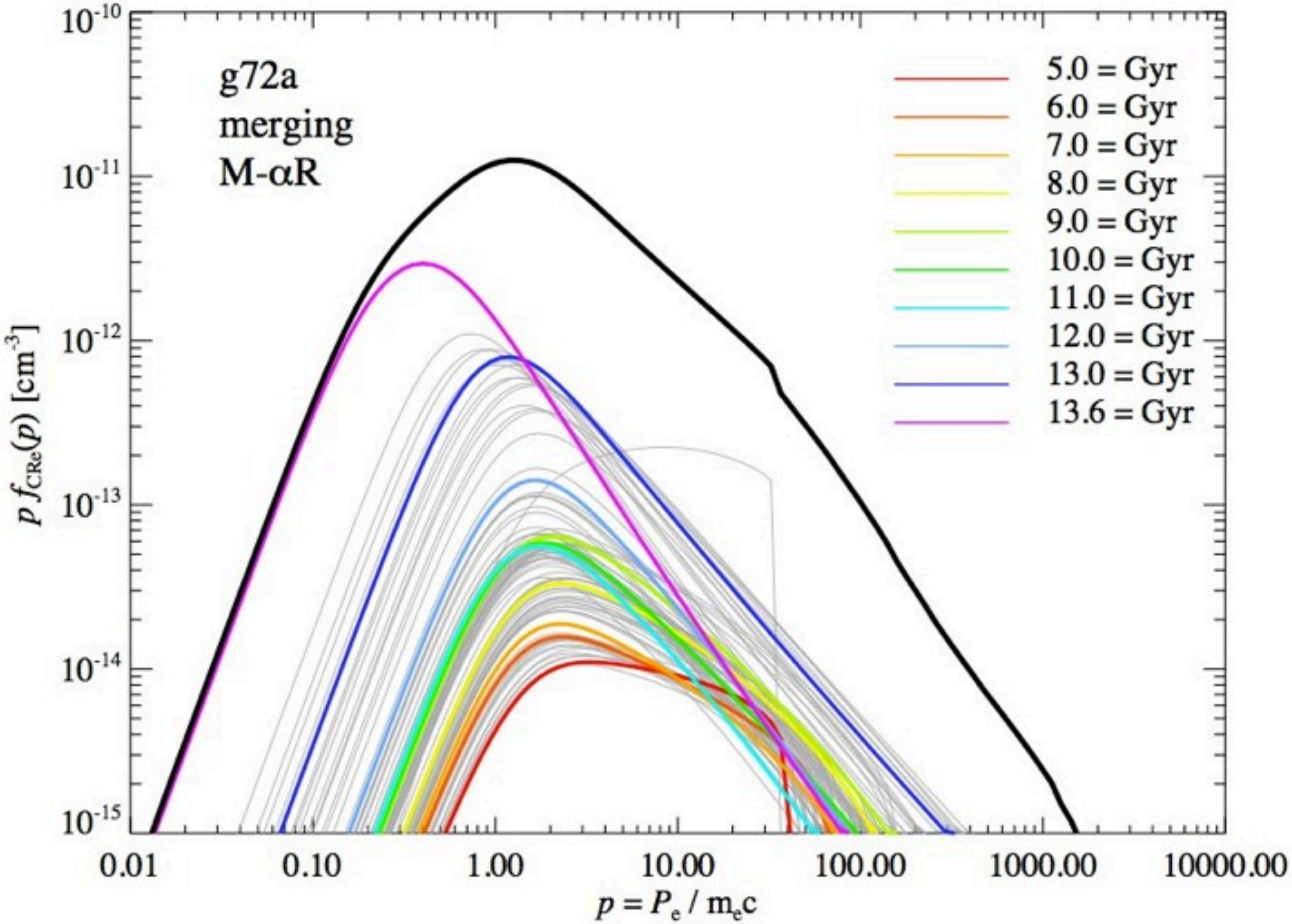


We only resolve portion where

$$\Delta t < t_{\rm cool}$$

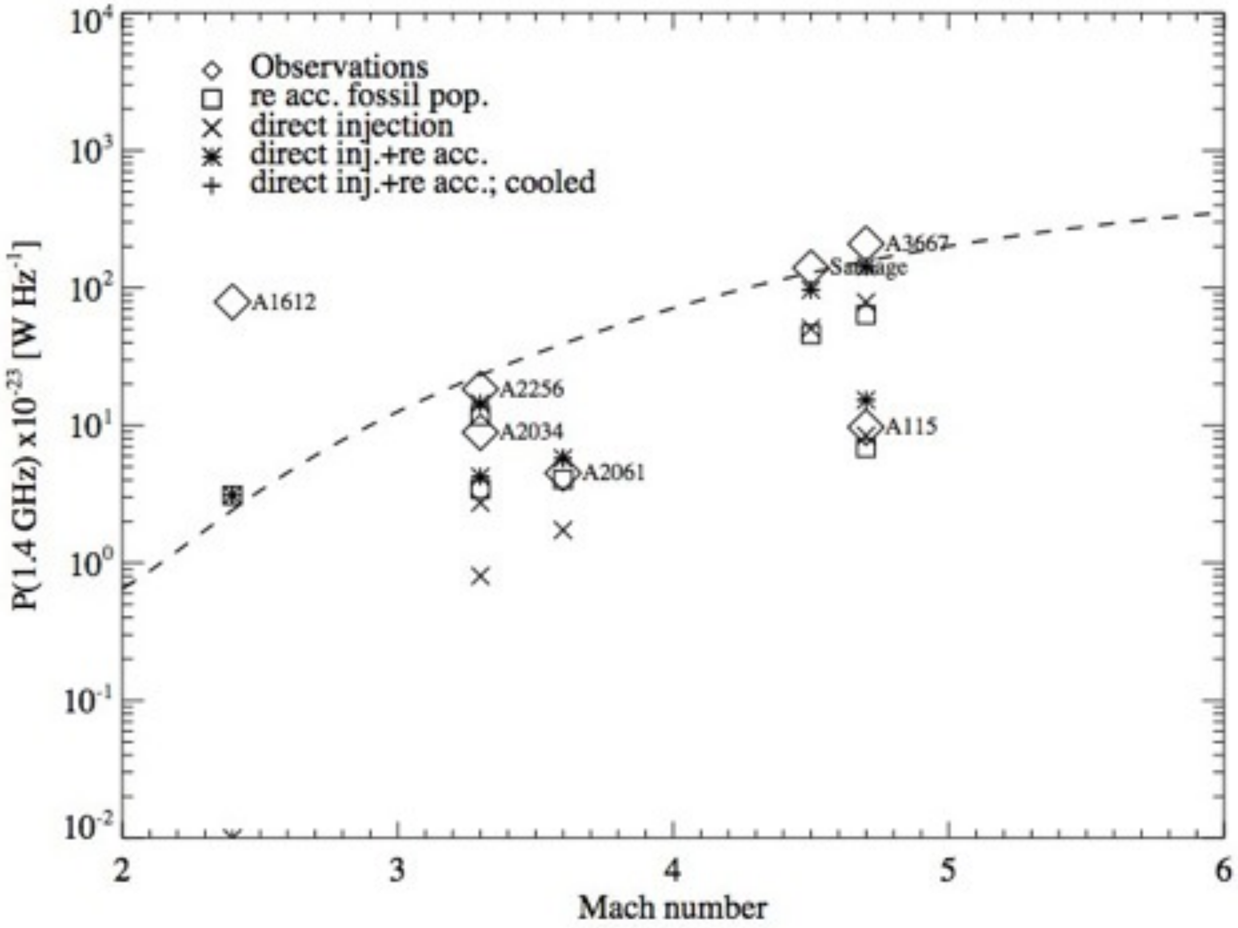
But we resolve the crucial peak

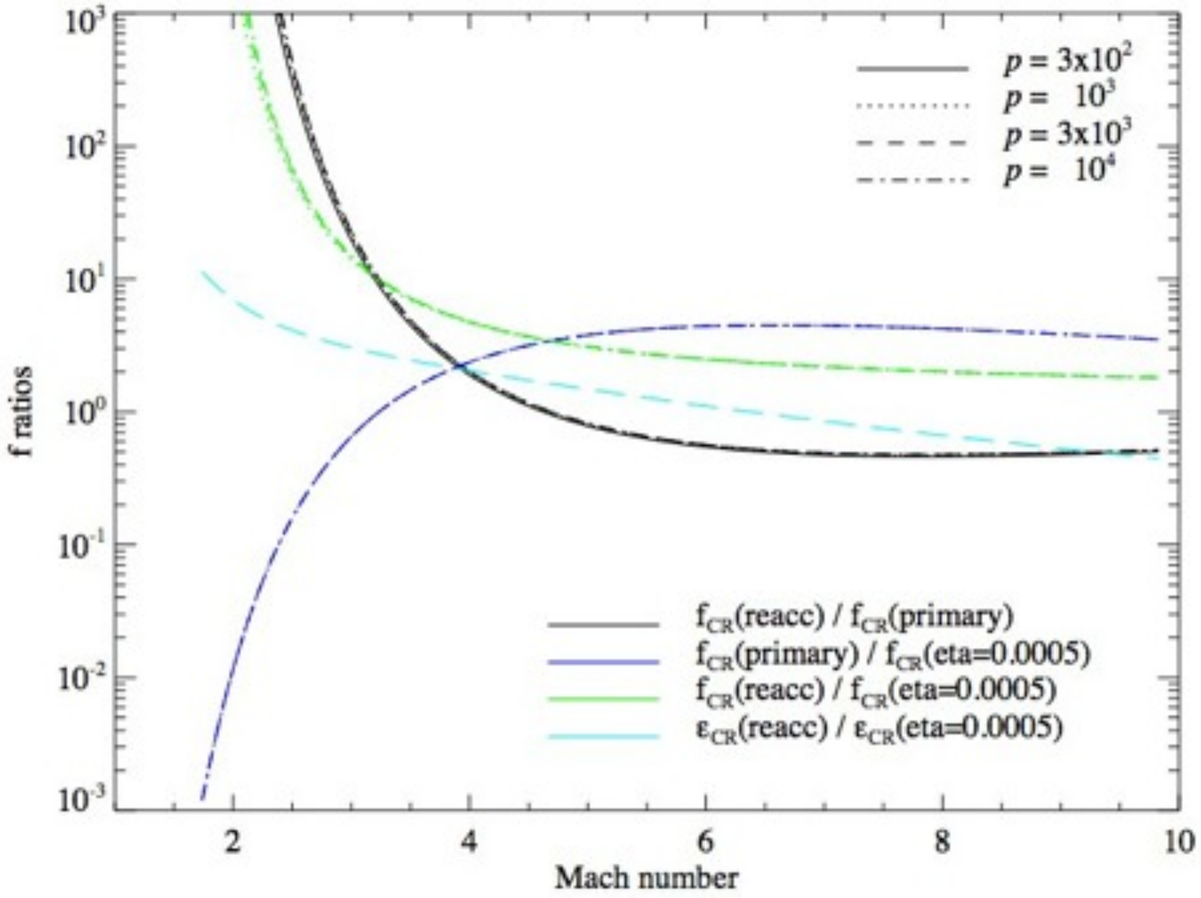
Stochasticity



Contribution heavily weighted toward late times: recent merger history matters...

The Bottom Line

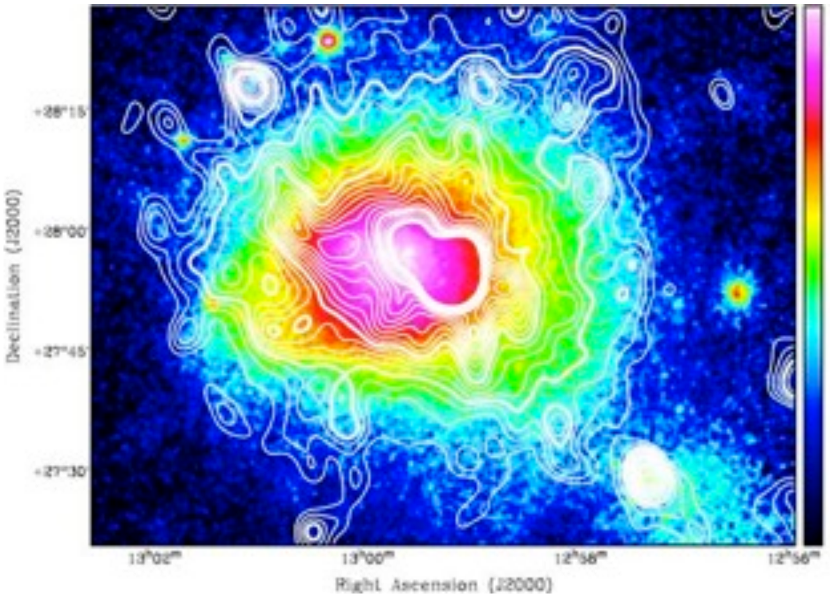




Fossil contribution comparable to direct injection at high $\mathcal{M}$

Dominates at low $\mathcal{M}$

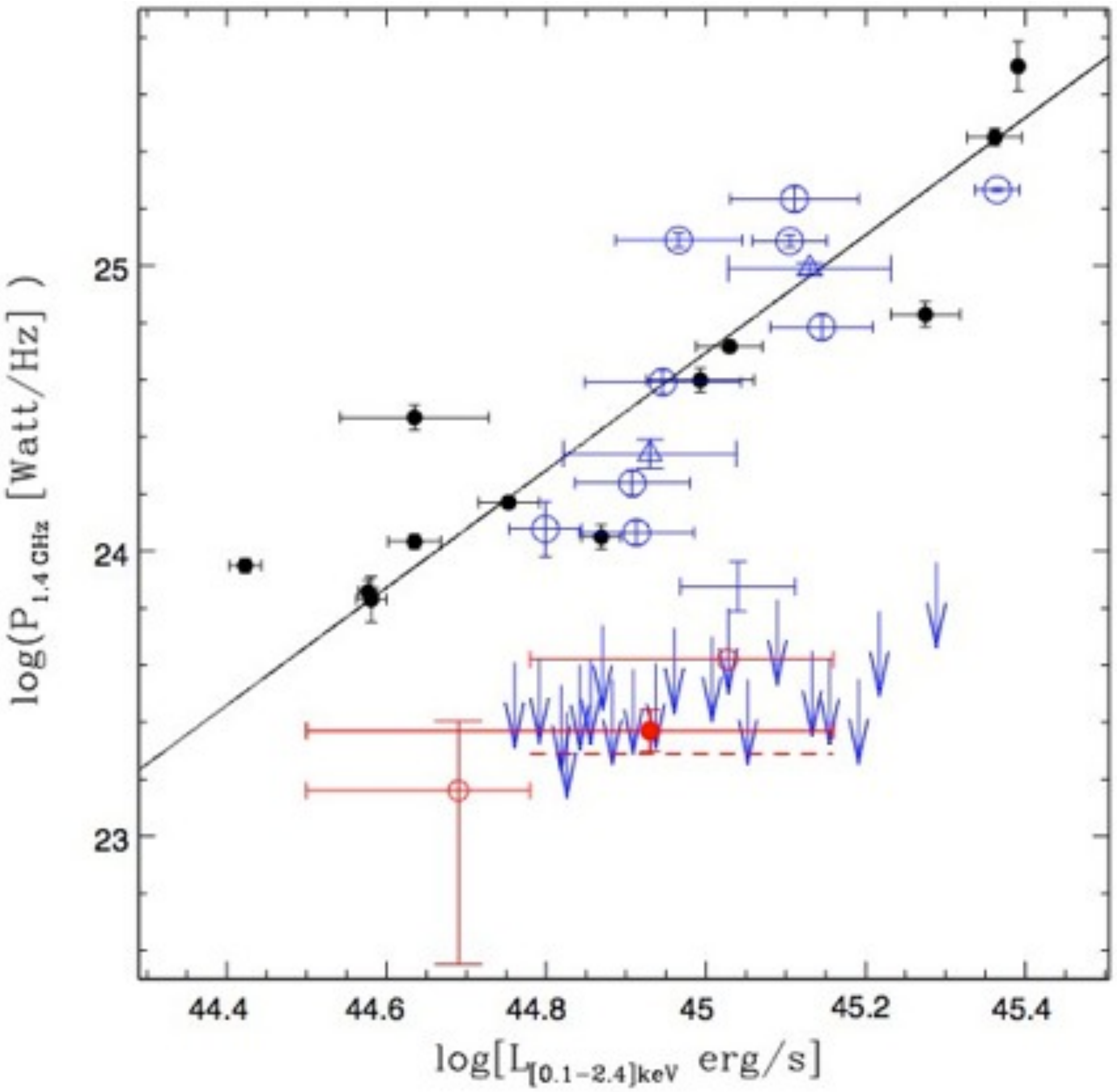
N.B. Fossils needed even more for radio halos....



Turning Radio Halos Off with Cosmic Ray Streaming

Wiener, Oh & Guo, 2012, in prep

Radio Halos: Two classes



Brown et al 2011
Brunnetti et al 2009

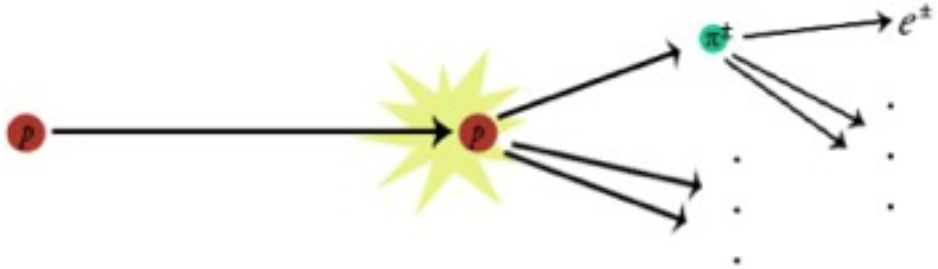
They are either ON
or OFF

ON: recent or ongoing merger

OFF: Stacked images show faint emission (Brown et al 2011)

Radio Halos: Two models

Hadronic Model



The good:
Well-known physics
Produces nice smooth halos

The bad:
Can't produce spectral curvature
Can't produce bimodality

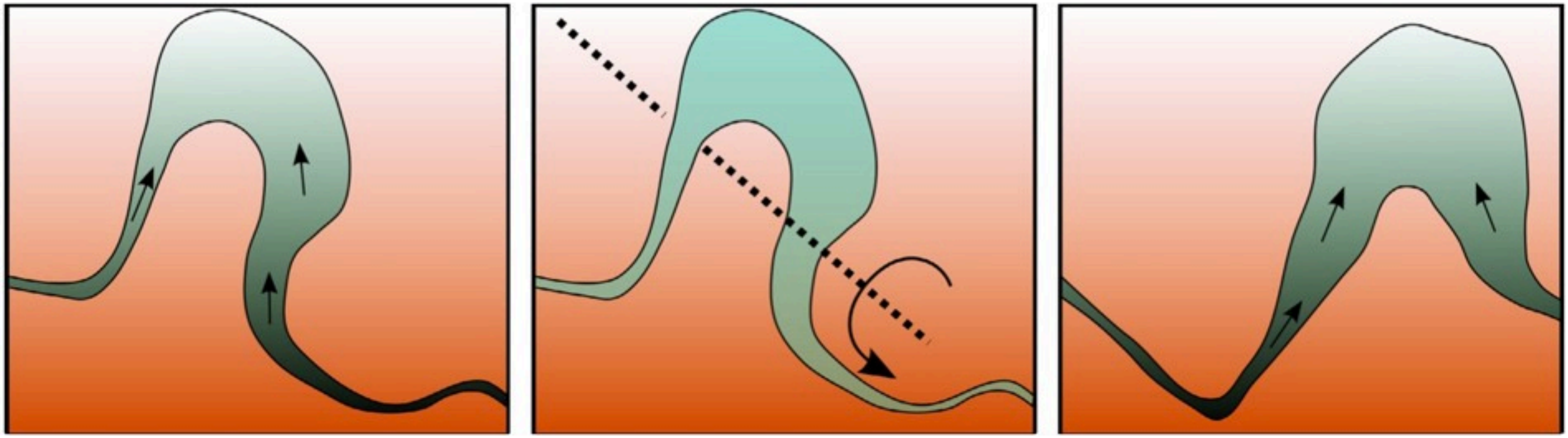
Turbulent Reacceleration

The good:
Bimodality is natural
Produces spectral curvature

The bad:
Acceleration efficiency hard to predict
Need fossil electrons

Super-Alfvenic streaming

Could it turn off radio halos?



Ensslin, Pfrommer, Miniati, Subramaniam 2011

For this to work, need $v_\mathrm{D} \sim c_\mathrm{S}$

Check this!

Cosmic Ray Speed Limits

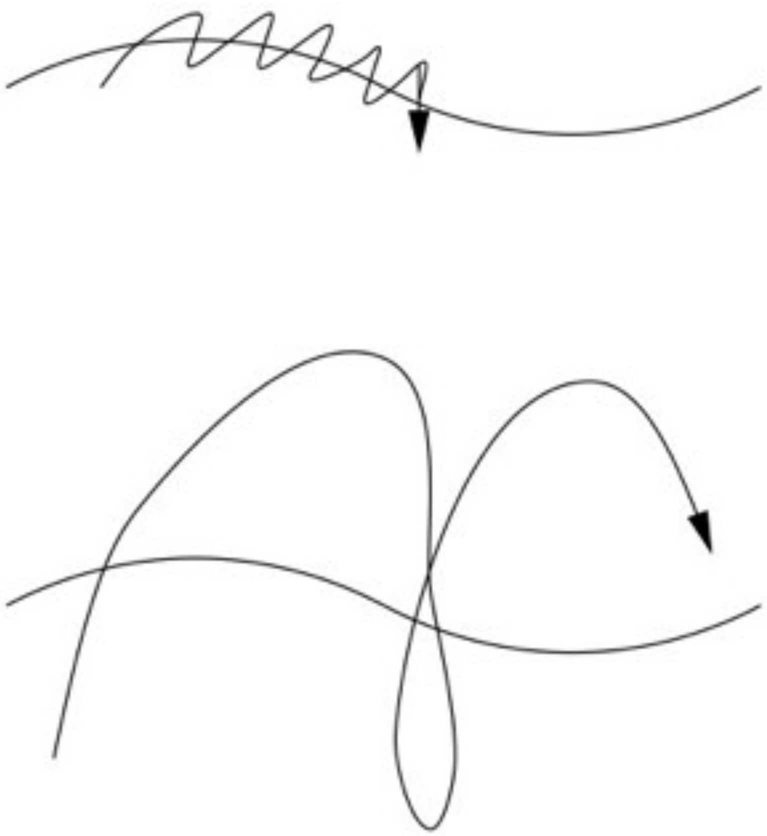
In our Galaxy, $v_{\rm D} \sim v_{\rm A} \ll c_{\rm S}$

Consistent with observed isotropy $\delta \sim 10^{-4} \sim \frac{v_{\rm D}}{c}$

and confinement times of $\sim 3 \times 10^6\,{\rm yr}$ from spallation

Can be explained from CR
self-confinement

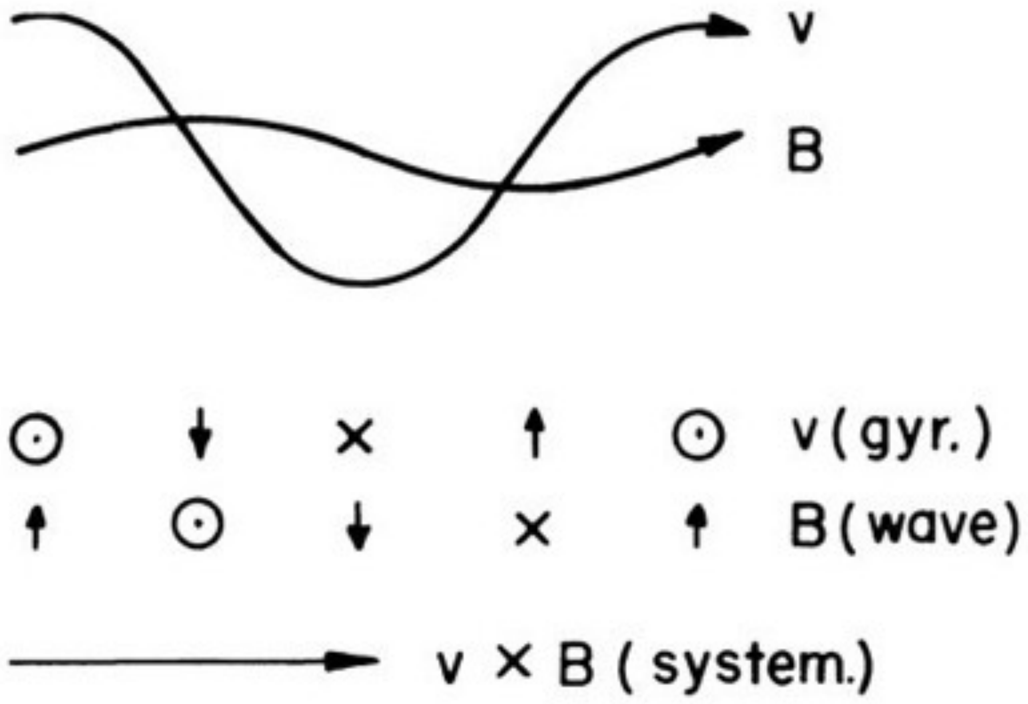
Resonant wave growth



Kulsrud 2006

Resonance condition

$$k_{\|} \sim \frac{1}{\mu r_{\mathrm{L}}}$$



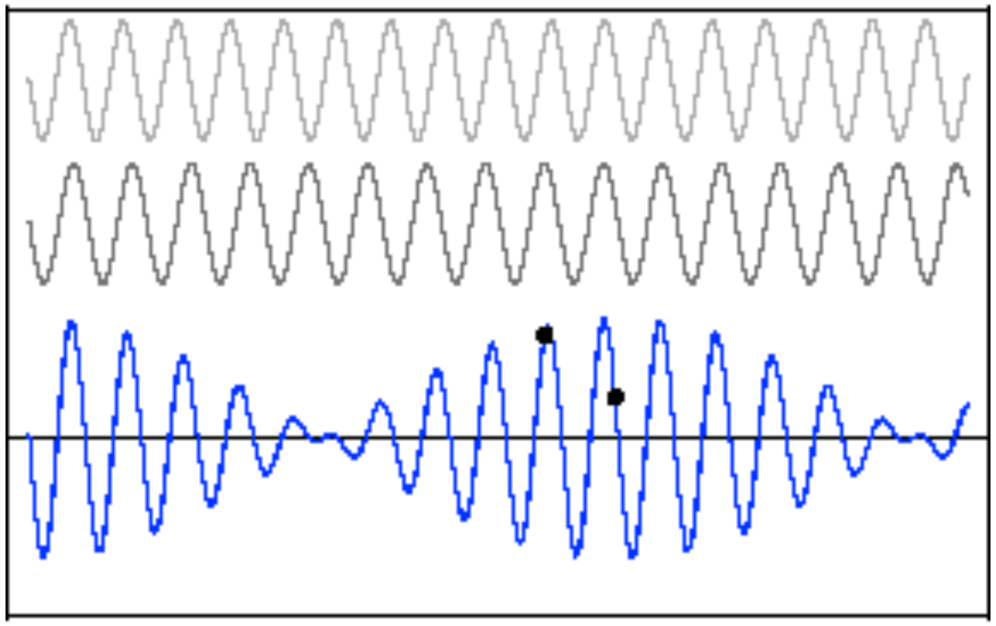
Wentzel 1972

Steady Lorentz force

Wave growth rate

$$\Gamma_{\mathrm{CR}}(k_{\|}) \sim \Omega_0 \frac{n_{\mathrm{CR}}(>\gamma)}{n_{\mathrm{i}}} \left(\frac{v_{\mathrm{s}}}{v_{\mathrm{A}}} - 1 \right)$$

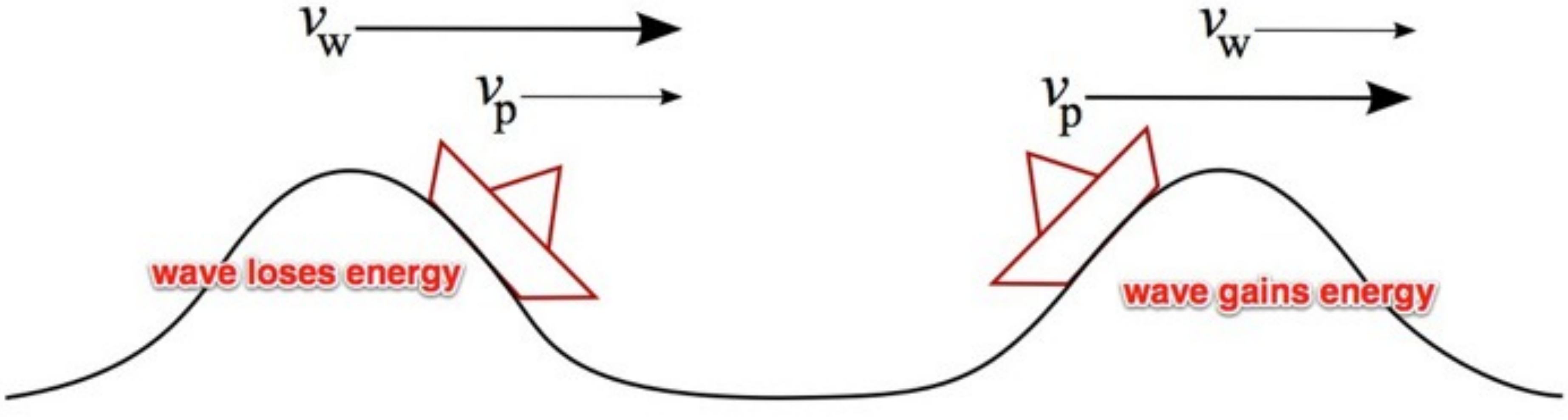
Non-linear Landau damping



Alfven waves make a beat wave

Damping rate:

$$\Gamma \sim \frac{v_i}{v_A}\omega\left(\frac{\delta B}{B}\right)^2$$



Thermal particles surf and extract energy

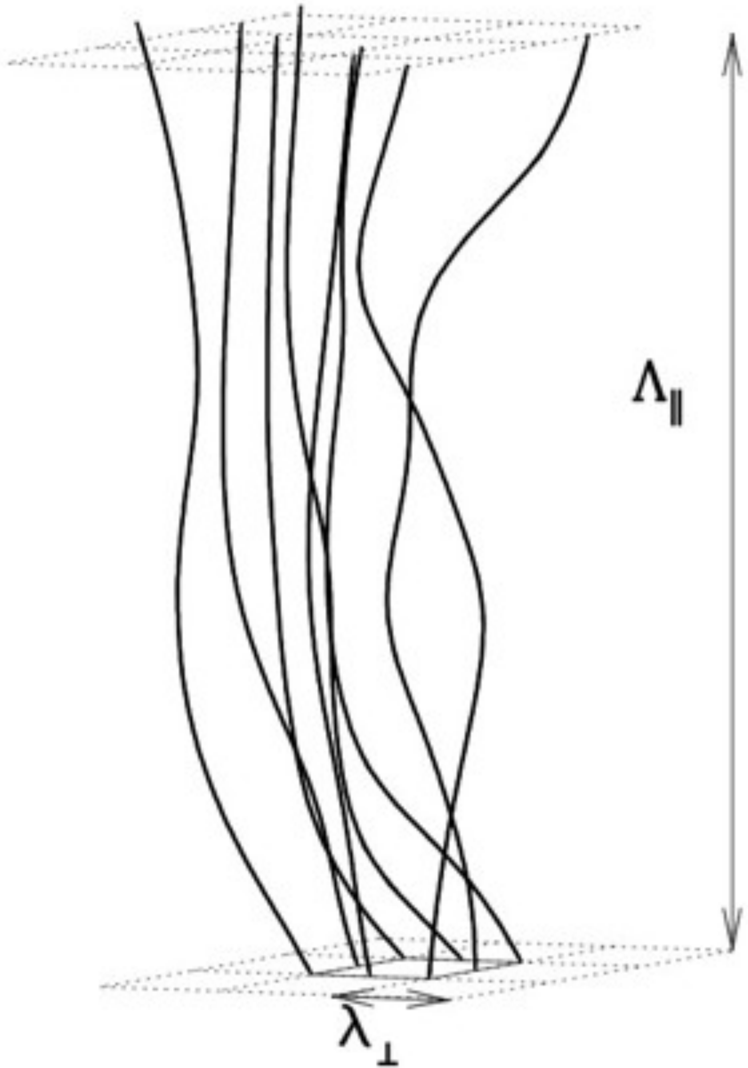
Turbulent Damping

MHD turbulence is anisotropic

Cascade is primarily transverse to field

Eddy destroyed by cascading to smaller scales

Lithwick & Goldreich 2001



Damping rate

$$\Gamma_{\rm turb,min} \sim \left(\frac{\epsilon}{r_{\rm L} v_{\rm A}}\right)^{1/2}$$

Farmer & Goldreich 2004

where

$$\epsilon \sim \frac{v_{\rm A}^3}{L}$$

Streaming speeds

Set $\Gamma_{\rm grow} = \Gamma_{\rm damp}$

Get (for 100 GeV protons):

$$v_{\rm D} = v_{\rm A} \left(1 + 2.4 \frac{T_{4\,{\rm keV}}^{1/4}}{B_{\mu{\rm G}} L_{{\rm z},100}^{1/2} (n_{-10}^{\rm CR})^{1/2} (n^{i}_{-3})^{3/4}} \gamma_{100}^{(n-3)/2} 100.^{(n-3)/2-0.8} \right)$$

Non-linear Landau damping

$$v_{\rm D} = v_{\rm A} \left(1 + 1.6 \frac{B_{\mu{\rm G}}^{1/2} n_{i,-3}^{1/2}}{L_{{\rm MHD},50}^{1/2} n_{{\rm CR},-10}} \gamma_{100}^{n-3.5} 100^{\frac{n-3.5}{1.1}} \right)$$

Turbulent damping

Pretty much still Alfvenic! But note different functional forms... (streaming speed evolves)

Simulate this!

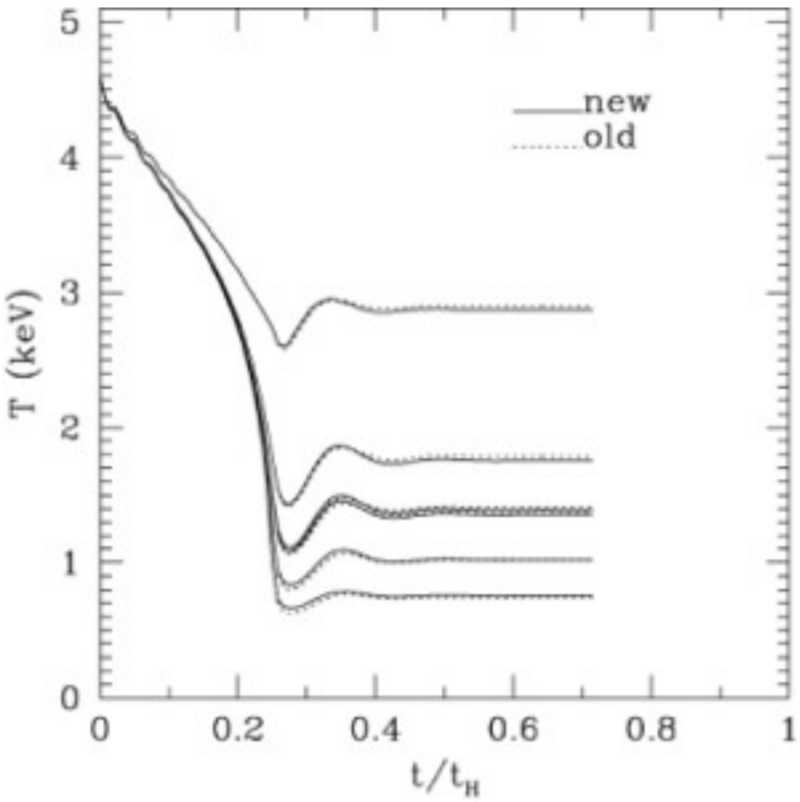
Solve CR equation in spherical symmetry

$$\frac{\partial \bar{f}_p}{\partial t} + (\mathbf{u} + \mathbf{v}_A) \cdot \nabla \bar{f}_p = \nabla \cdot (\kappa \mathbf{n}\mathbf{n} \cdot \nabla \bar{f}_p) + \frac{1}{3} p \frac{\partial \bar{f}_p}{\partial p} \nabla \cdot (\mathbf{u} + \mathbf{v}_A) + \bar{Q}$$

where diffusion is

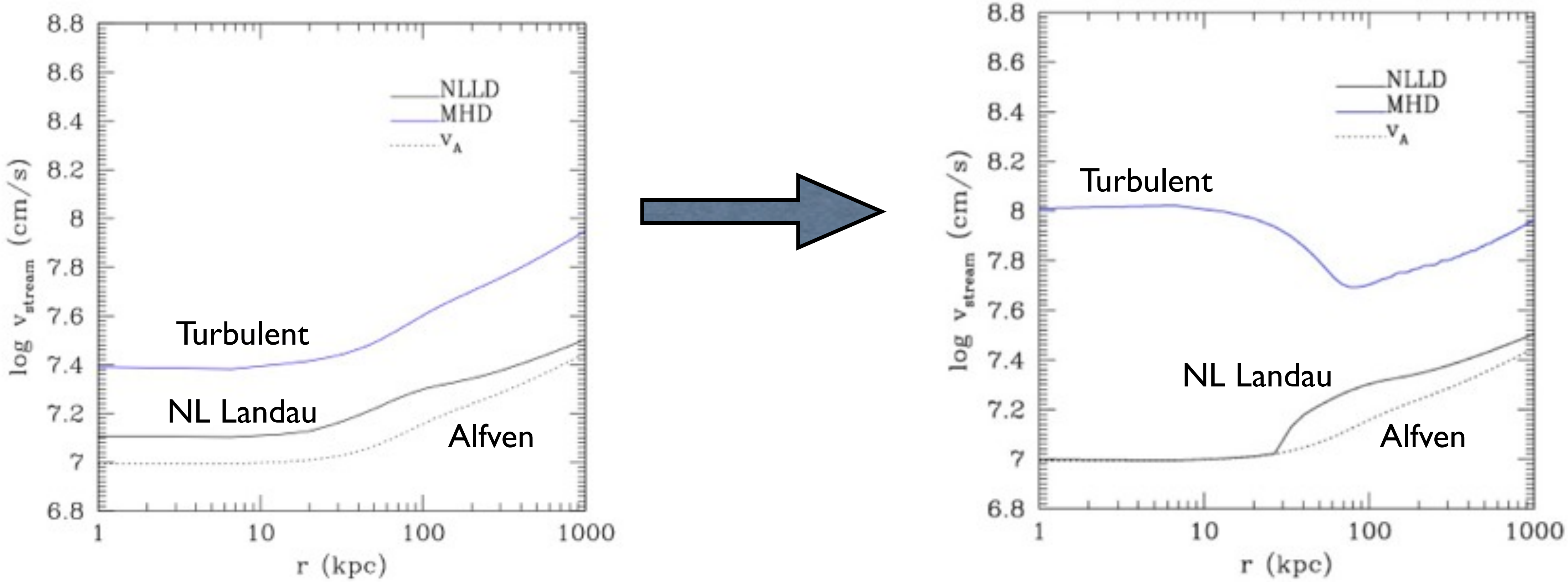
$$\kappa = c^2 \langle \frac{1 - \mu^2}{\nu(\mu, \gamma)} \rangle \approx L_z (v_{\rm D} - v_{\rm A})$$

Compare against Guo & Oh (2008) when solve for CRs in fluid approximation: good agreement!

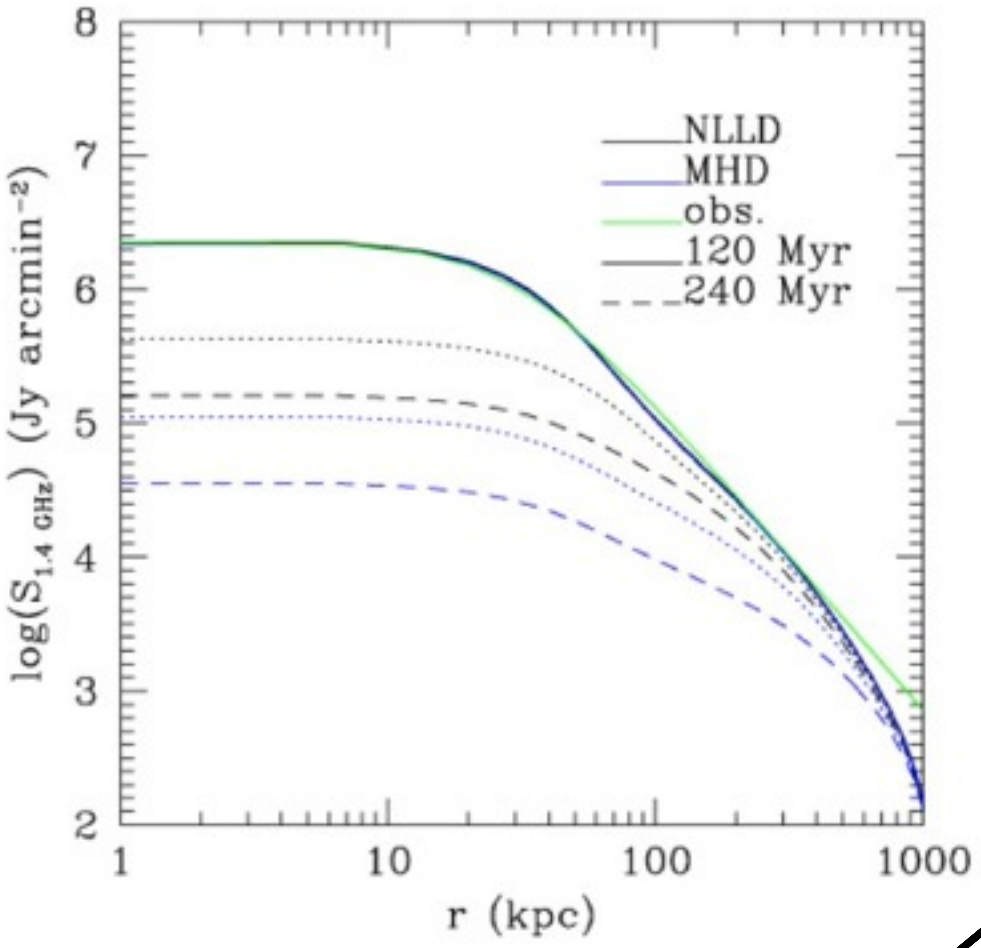


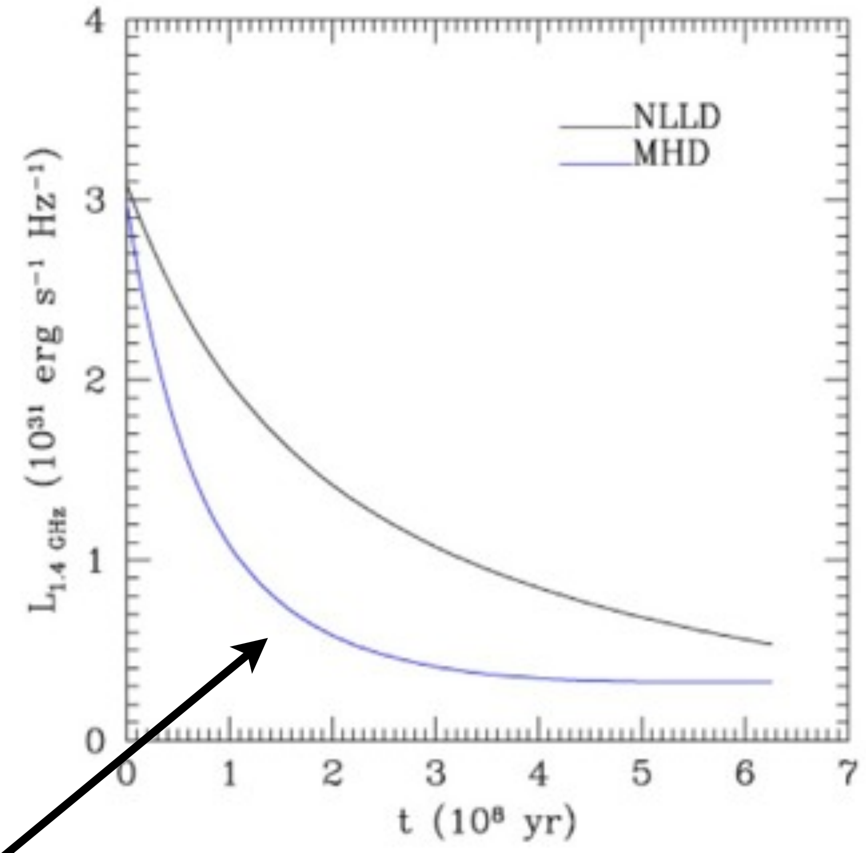
Results for Perseus

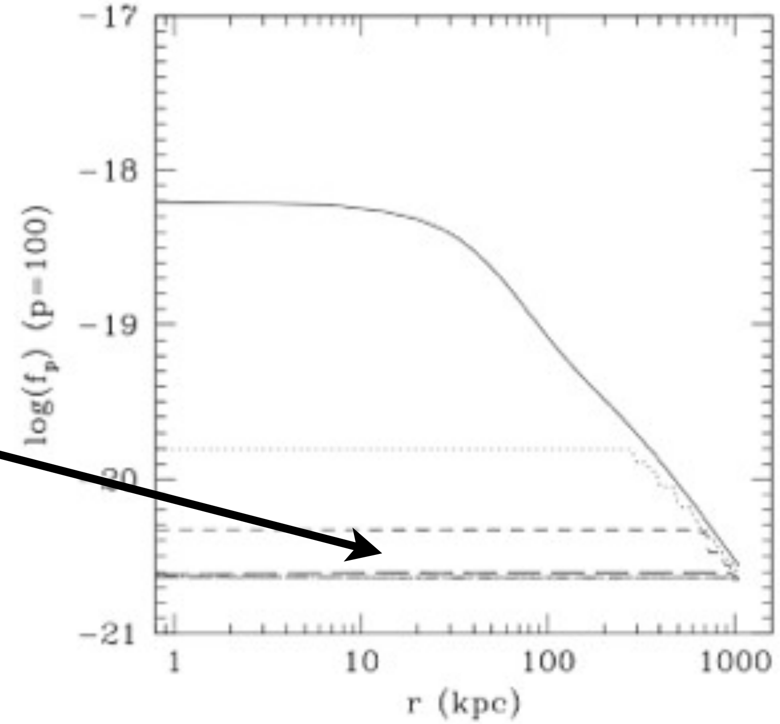
Initialize halo with CR profile needed to reproduce observations (Zandanel et al 2012). Then sit and wait...



Very different evolution in streaming speed for turbulent and non-linear Landau damping



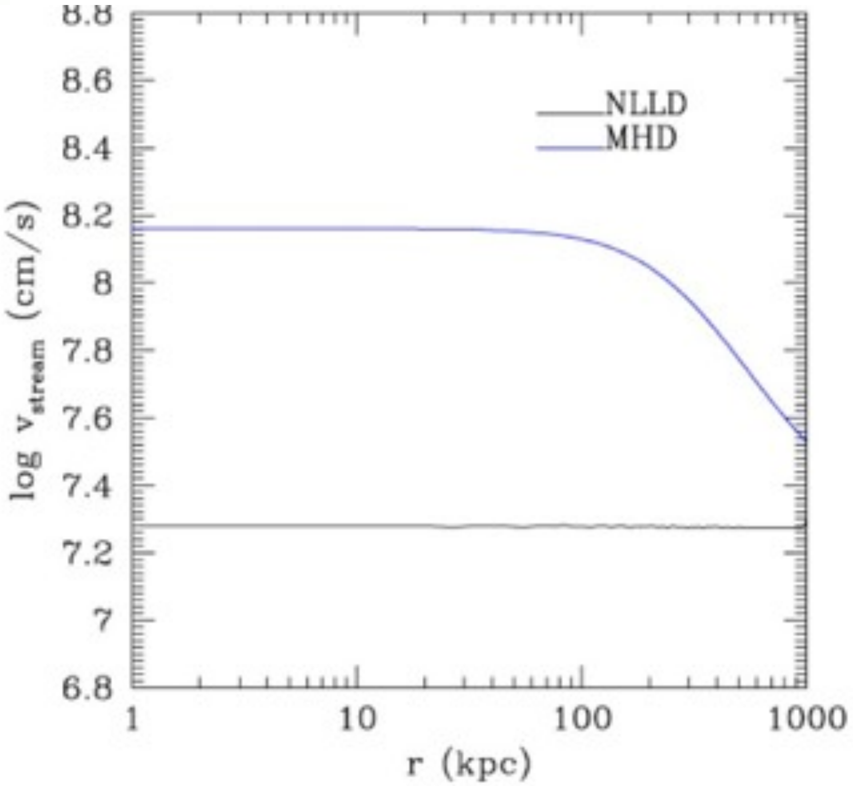


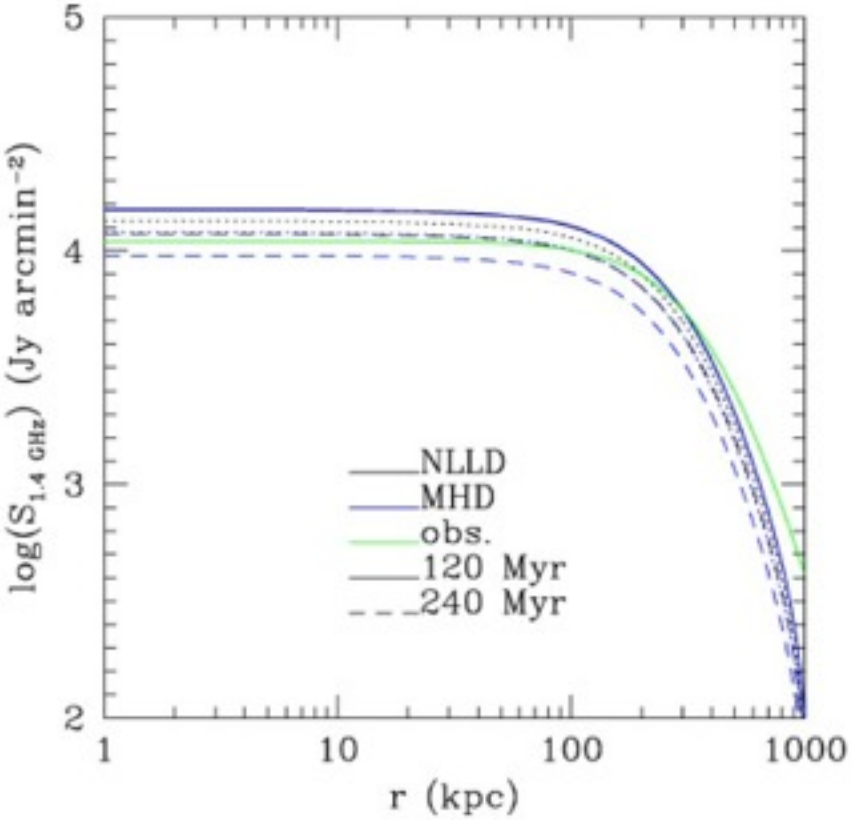


Streaming slows down as CR profile flattens

Factor of ~6 change in radio luminosity might be possible with turbulent damping

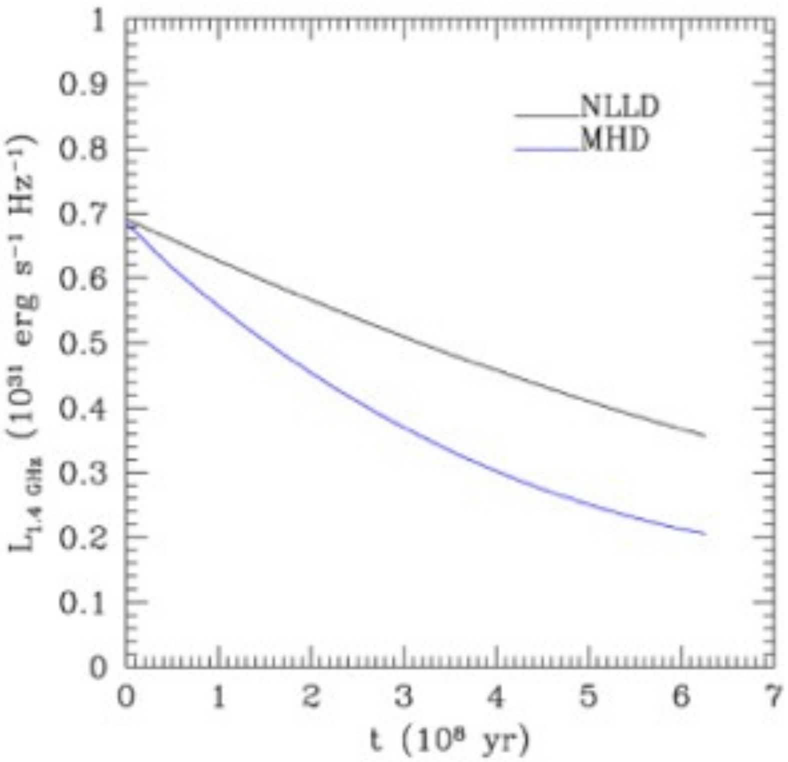
Results for Coma





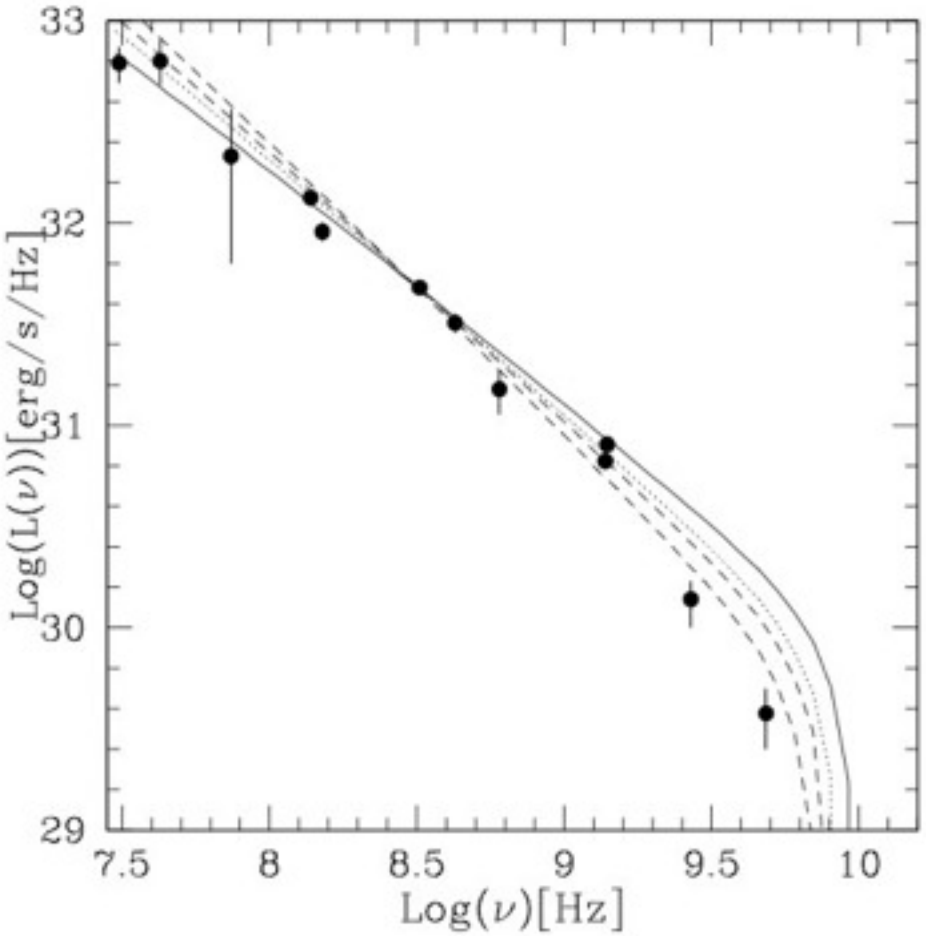
Coma has a much larger extent and a flat CR profile as inferred from observations

Diffusion time is long, streaming has a small effect.

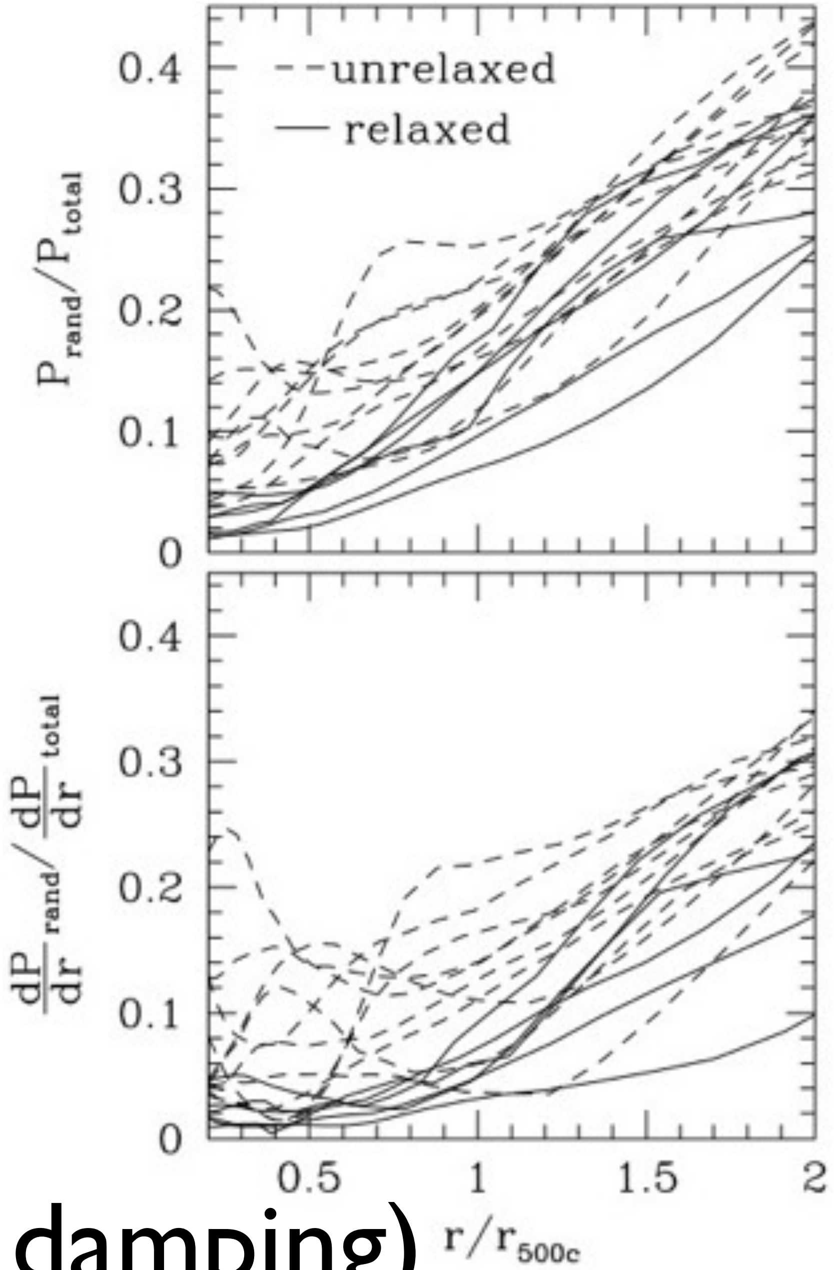


In Progress

Spectral curvature



Brunetti et al 2012



Turbulent diffusion

(should use same velocity profile as for damping)

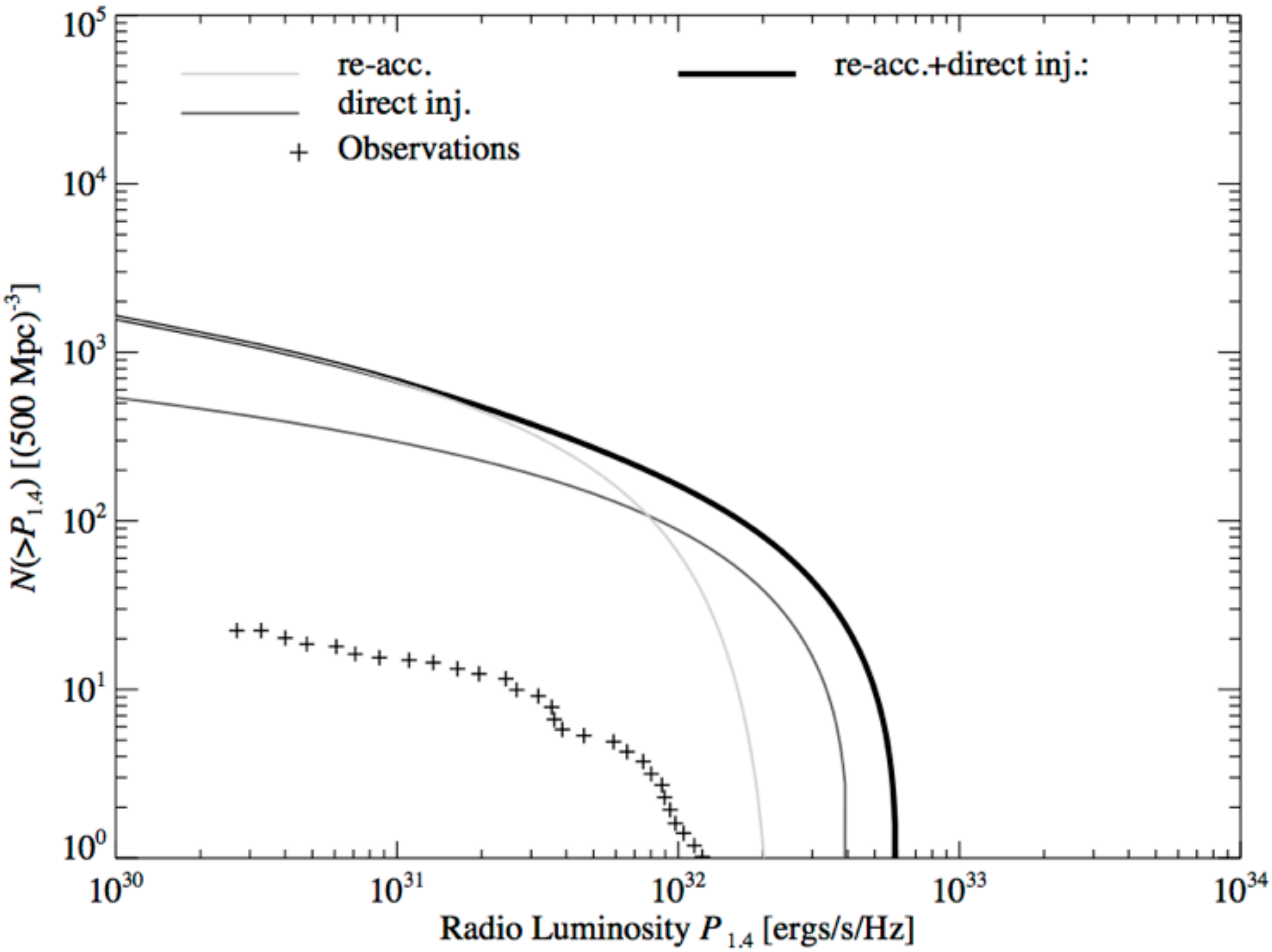
Lau et al 2009

Take Home

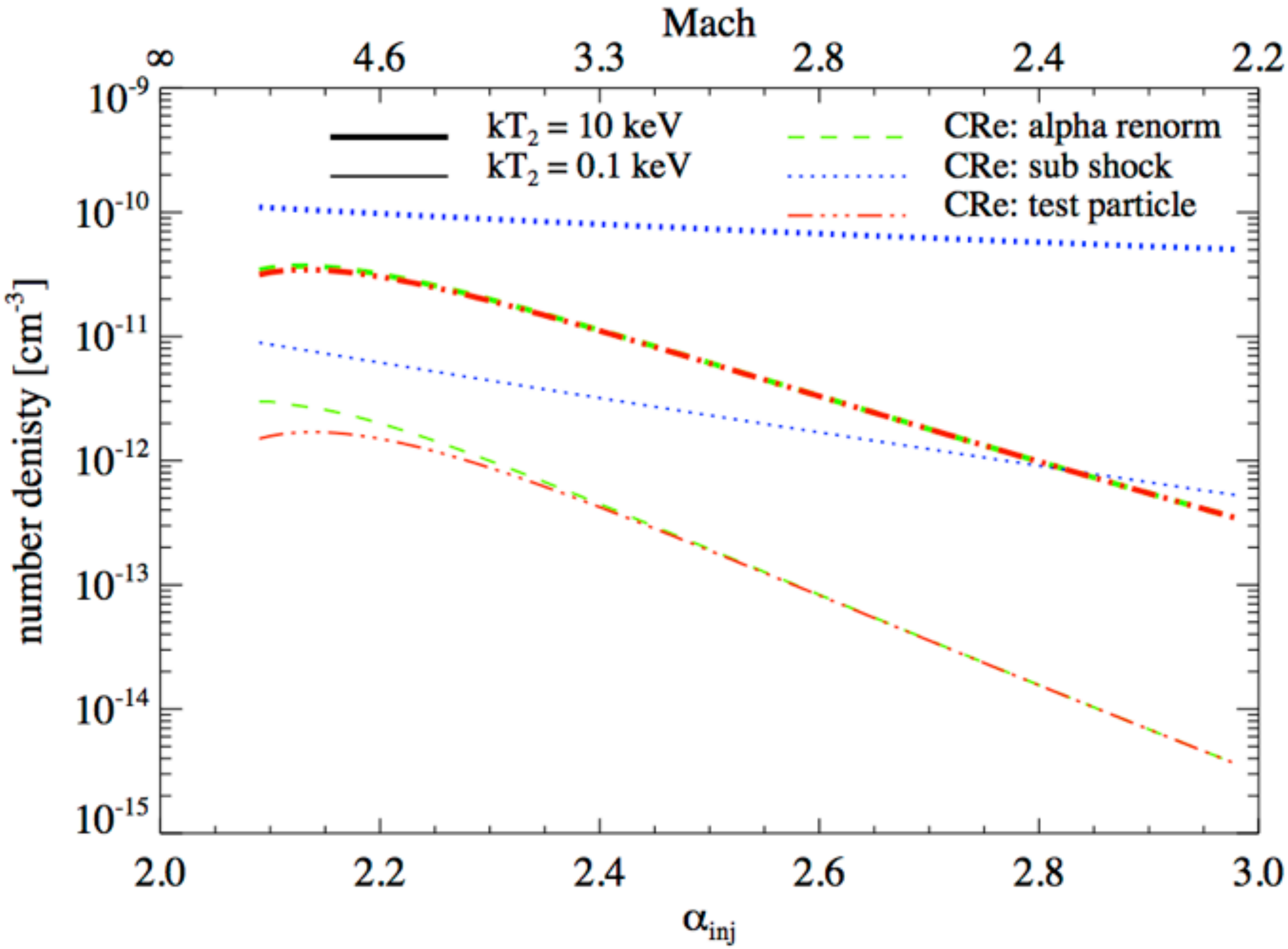
Fossil electrons could allow radio relics to be seen at low Mach numbers

Streaming of cosmic rays might play a role in radio mini-halos, but unlikely in giant radio halos

Relic Counts Predictions



Model Dependence



Different shock acceleration models can be characterized by the injected number density