A Pedagogical Guide to Radio Phenomenon in Clusters

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in collaboration with

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Apr 21, 2011 / KITP program

Outline

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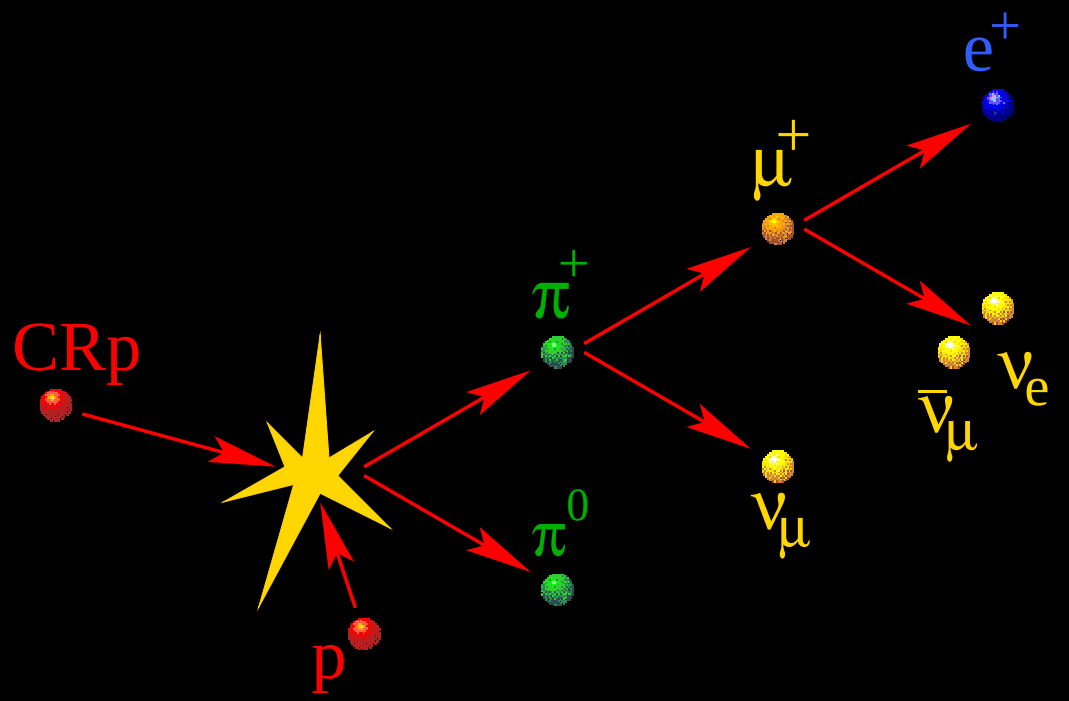
Hadronic cosmic ray proton interaction



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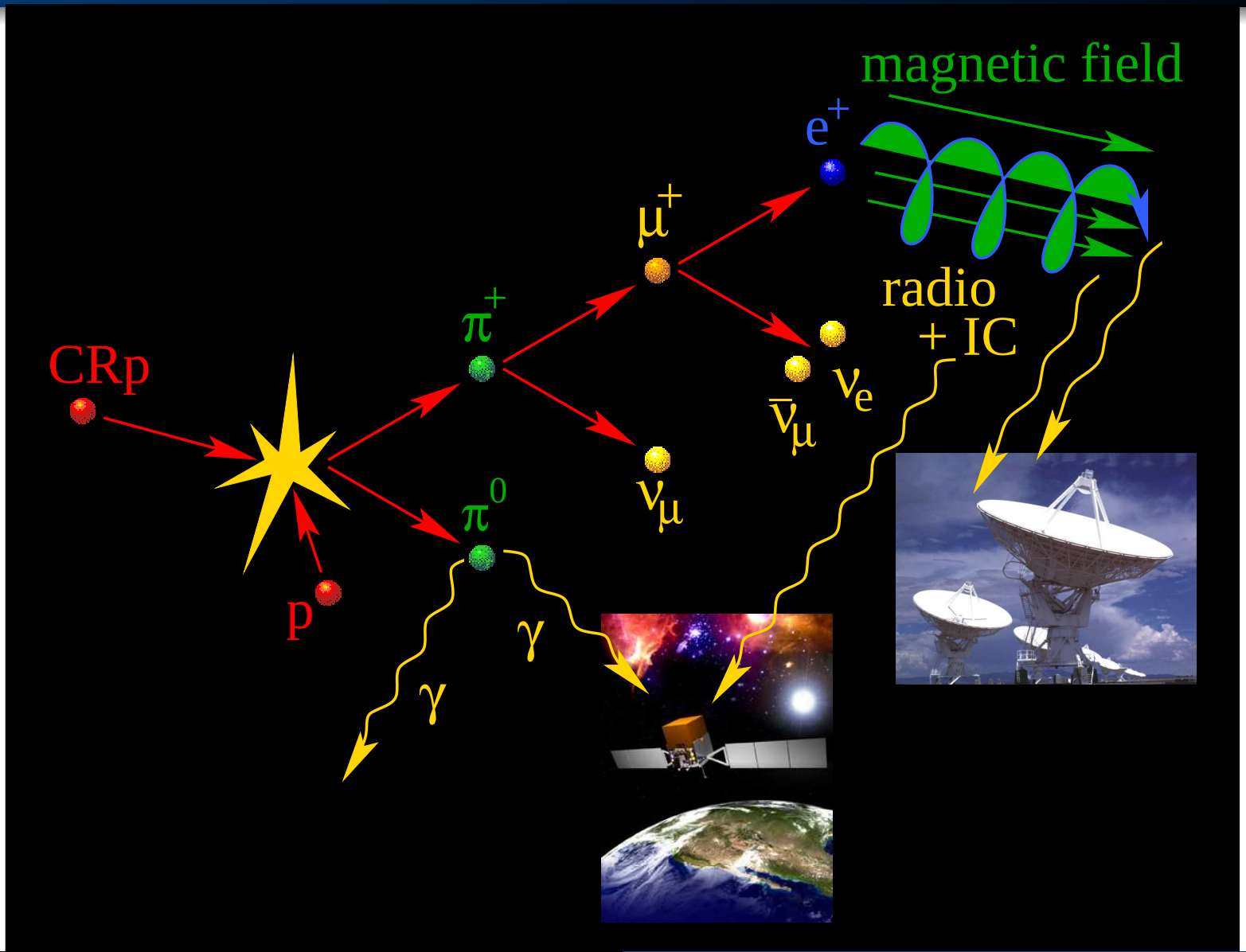
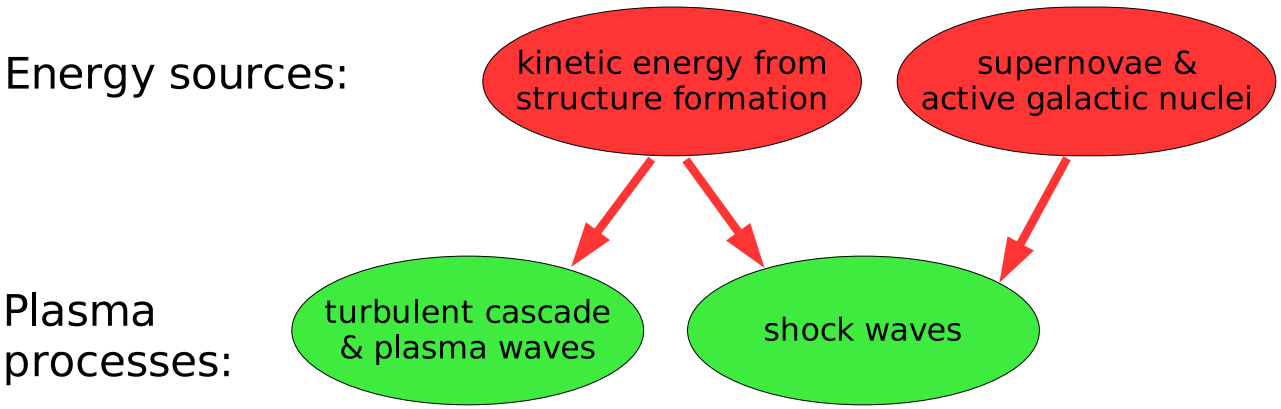


Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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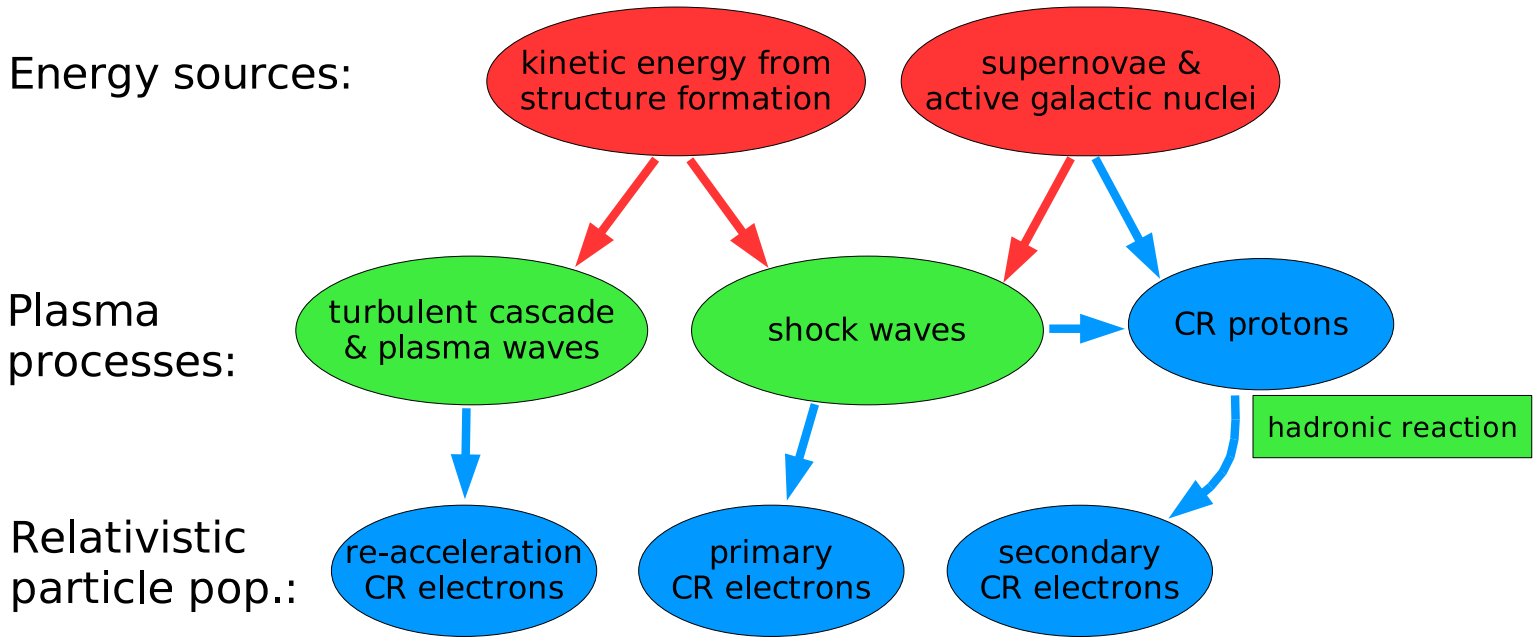

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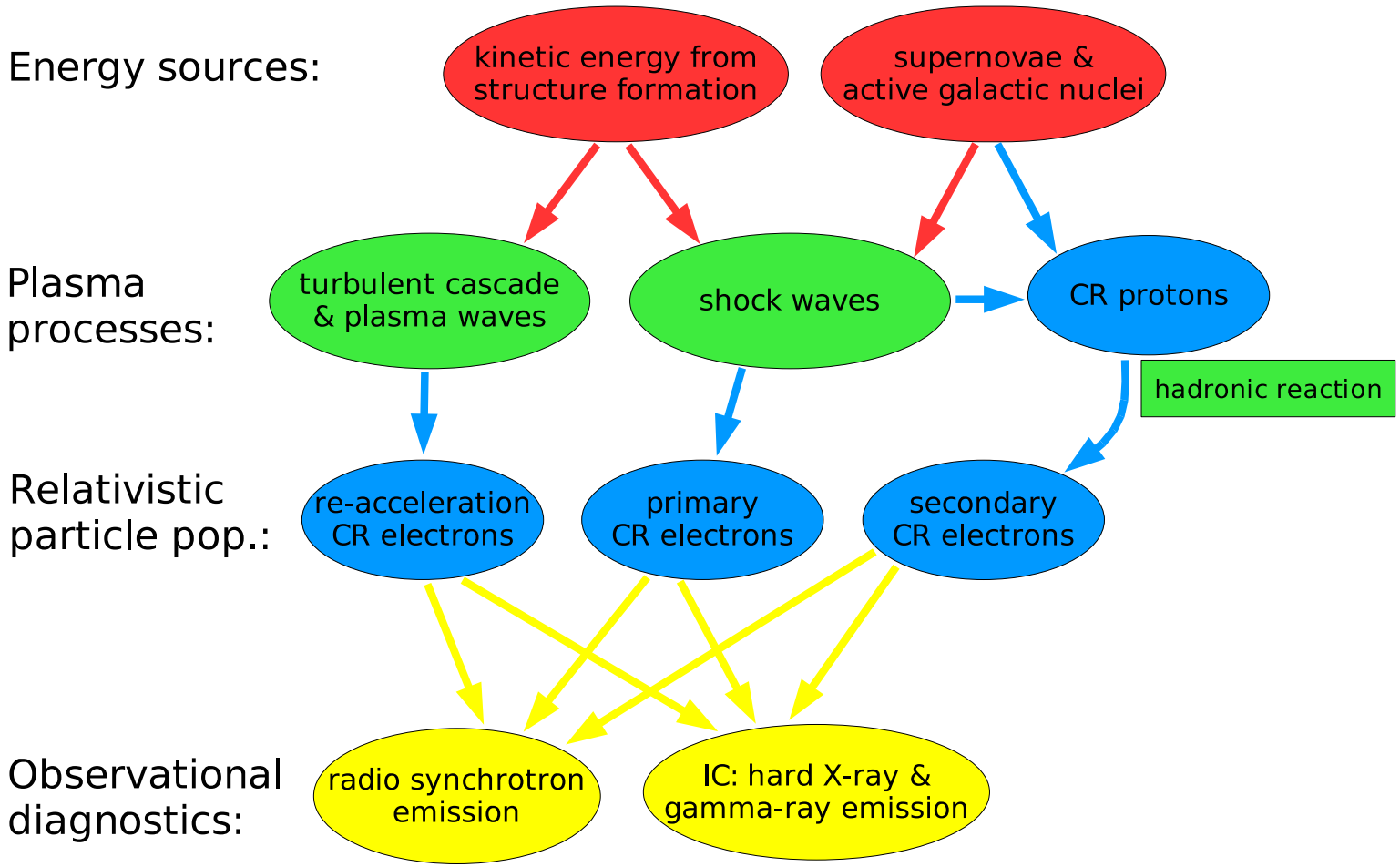

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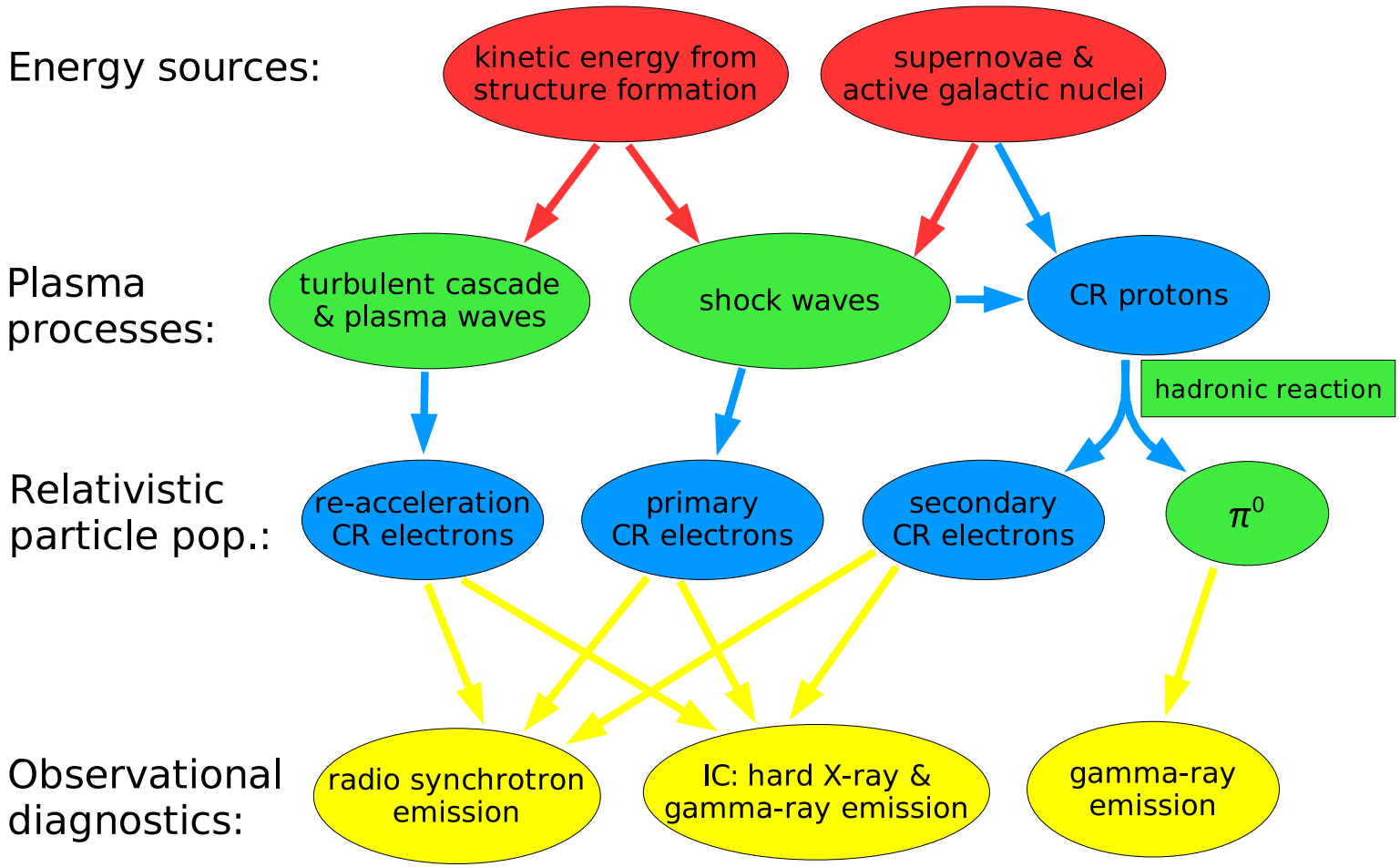

What we hope to learn from non-thermal emission

- plasma astrophysics:
  - shock and particle acceleration
  - large-scale magnetic fields
  - turbulence
- dynamical state $\rightarrow$ cosmology?
  - non-thermal pressure support: hydrostatics + SZE
  - history of individual clusters: cluster archeology
  - illuminating the process of structure formation
- consistent picture of non-thermal processes:
  radio, soft/hard X-rays, γ-rays

Overview of diffuse radio phenomenon

- radio relics: $\alpha_\nu \sim 1 - 2.5$, where $j_\nu \propto \nu^{-\alpha_\nu}$
  - radio relic bubble: aged radio cocoon, steep spectrum
  - radio phoenix: shock-revived bubble that has already faded out of the radio window $\rightarrow$ *adiabatic compression?*
  - radio gischt: irregular morphology, at cluster periphery ($<$ Mpc), in some cases coincident with weak X-ray shock, polarized $\rightarrow$ *diffusive shock acceleration (Fermi I)?*
- radio halos: centrally located, regular morphology, $\alpha_\nu \sim 1 - 1.5$, unpolarized $\rightarrow$ volume filling radio emission
  - giant radio halos: occur in merging clusters, $>$ 1 Mpc-sized, morphology similar to X-rays
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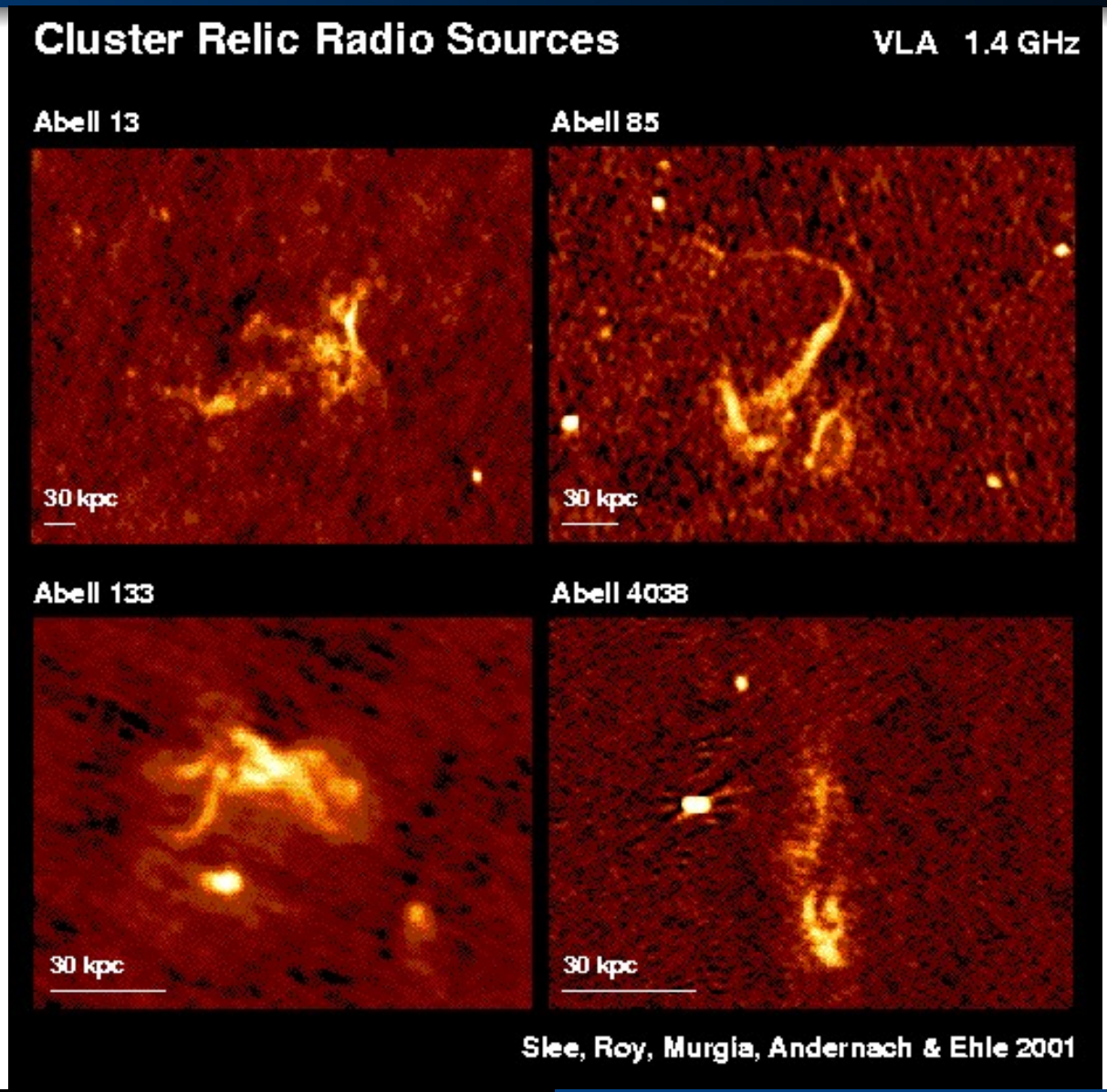
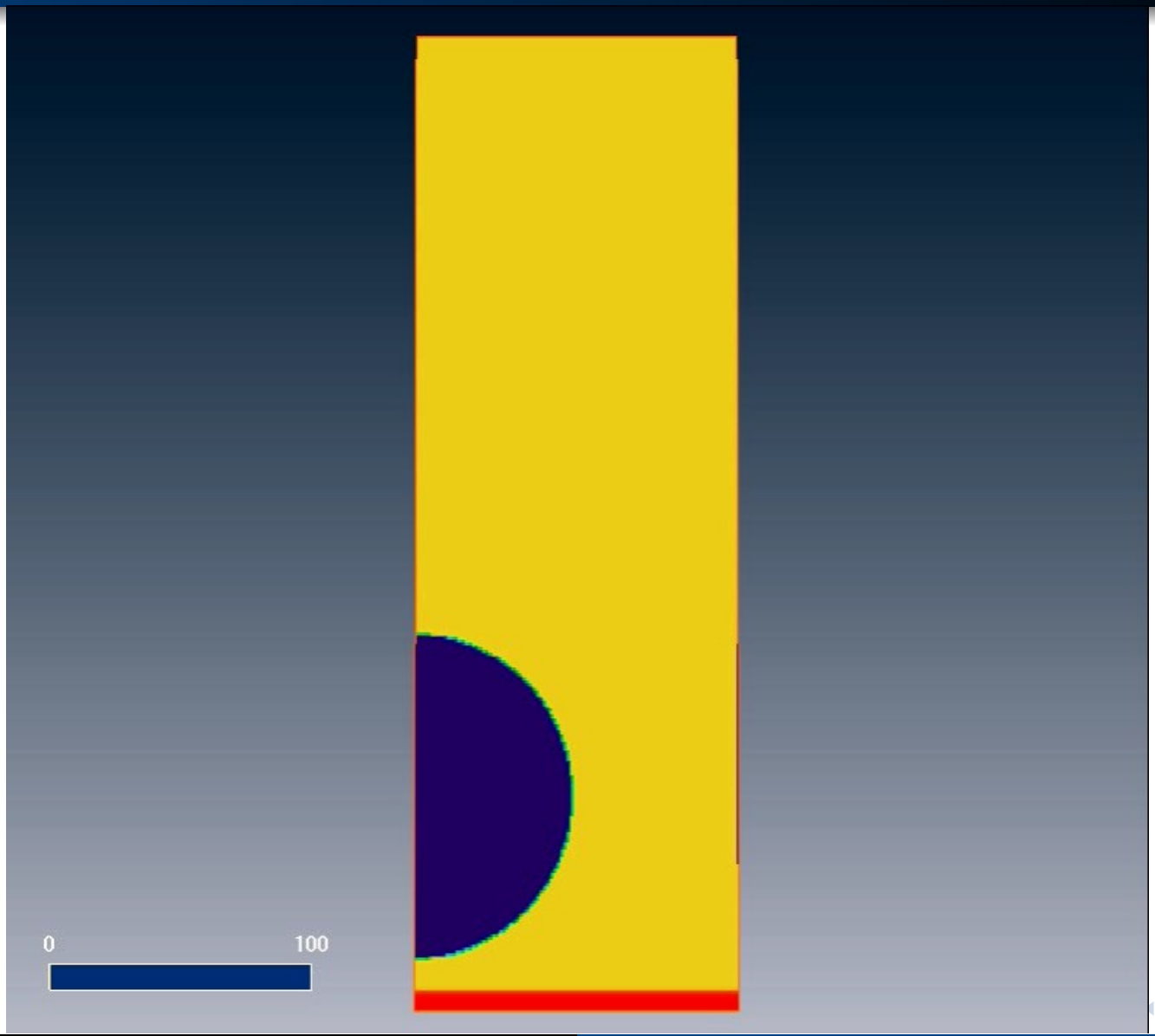
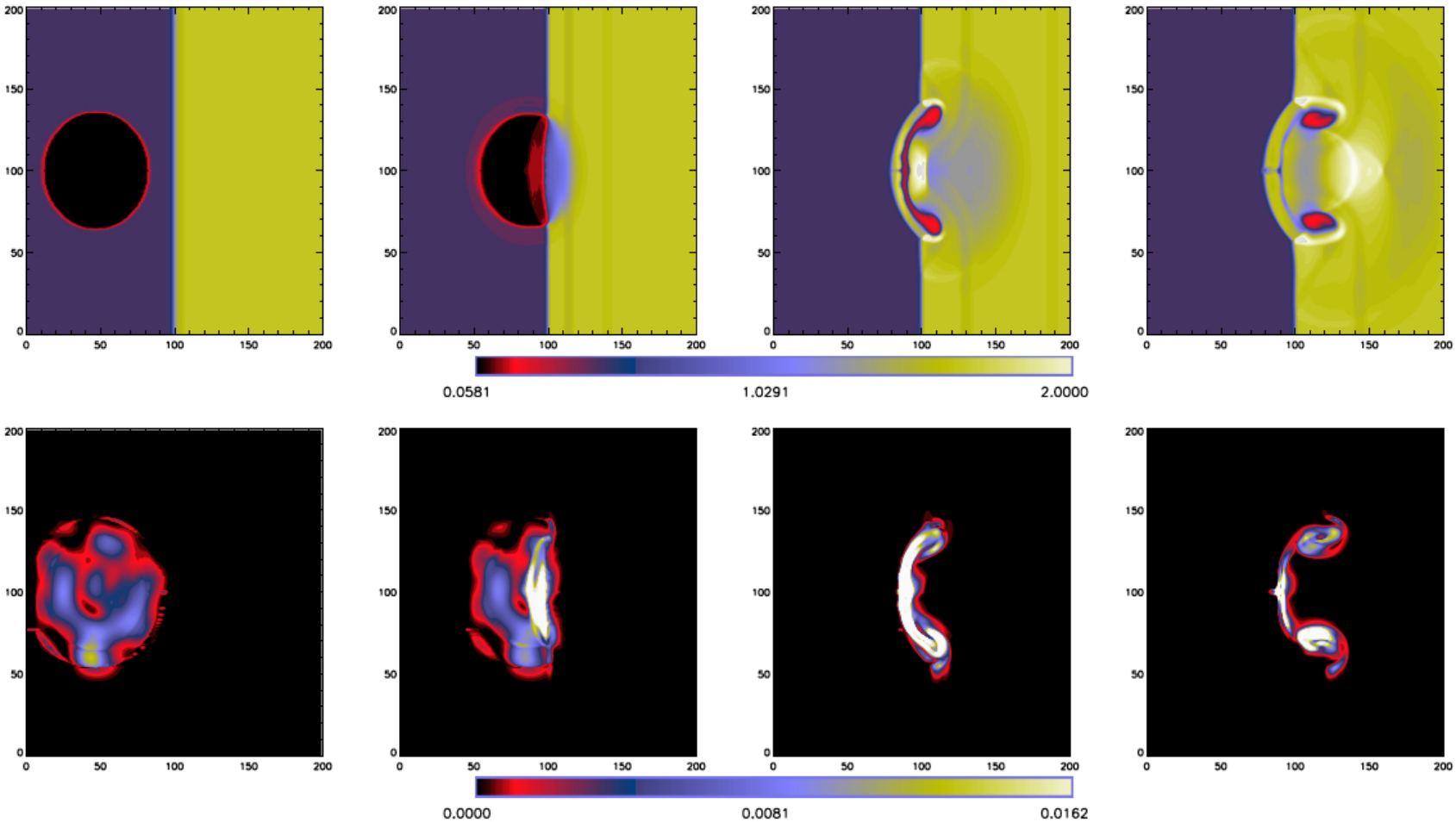
Radio phoenix



Shock overruns an aged radio bubble (C.P. & Jones 2011)

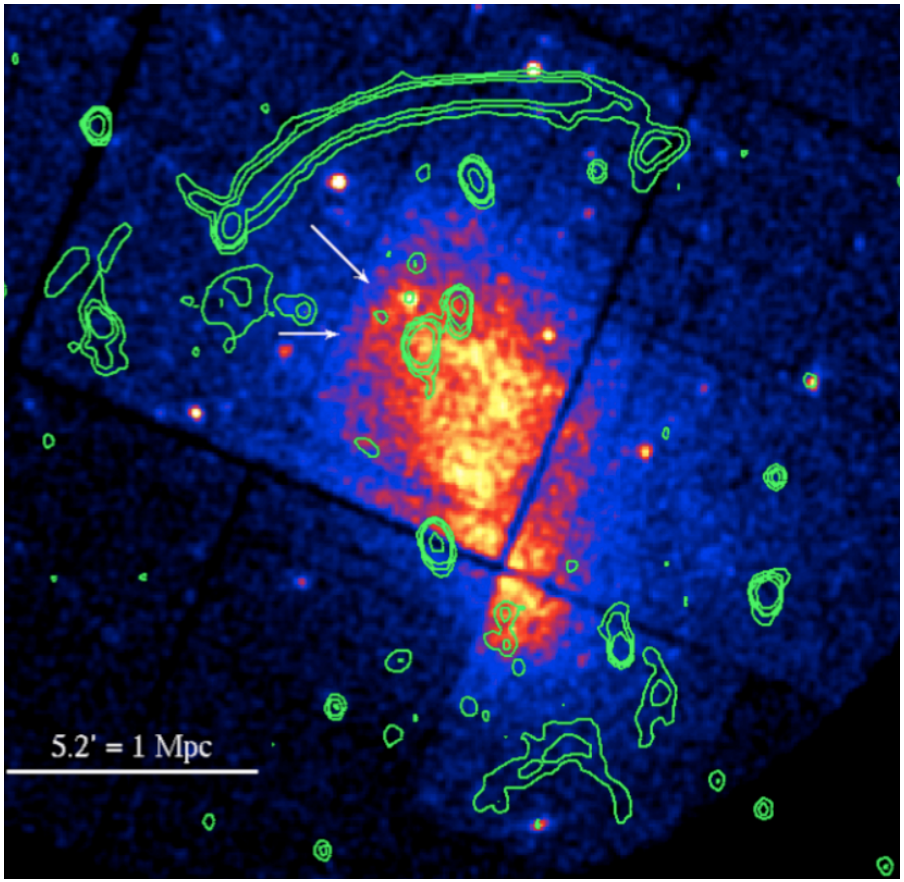


Bubble transformation to vortex ring



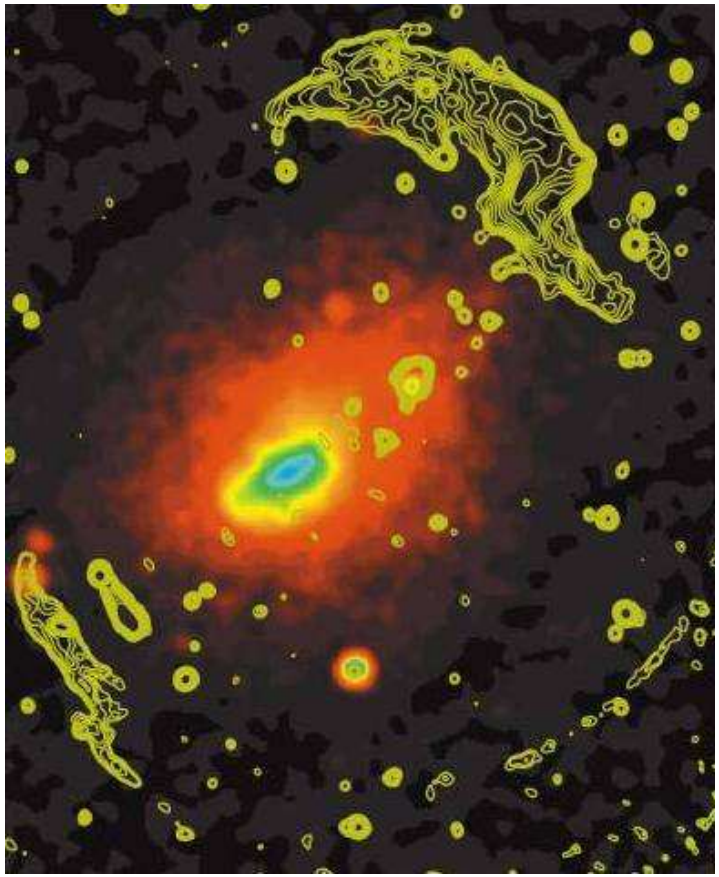
Enßlin & Brüggen (2002): gas density *(top)* and magnetic energy density *(bottom)*

Radio gischt: double relic sources



CIZA J2242.8+5301 (“sausage relic”)

(X-ray: XMM; radio: WSRT; Ogrean+ in prep.)



Abell 3667

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

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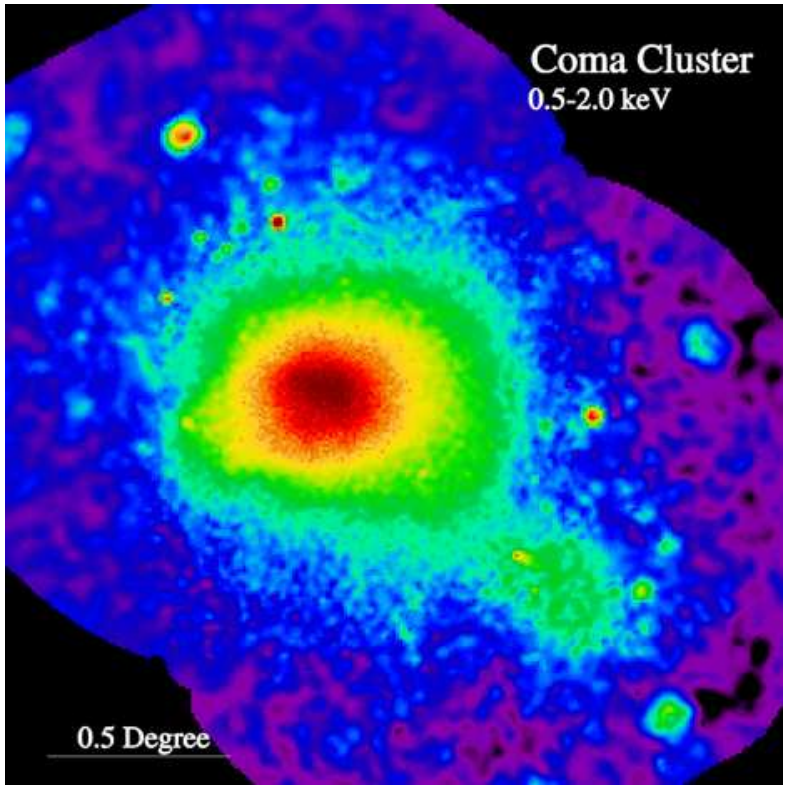
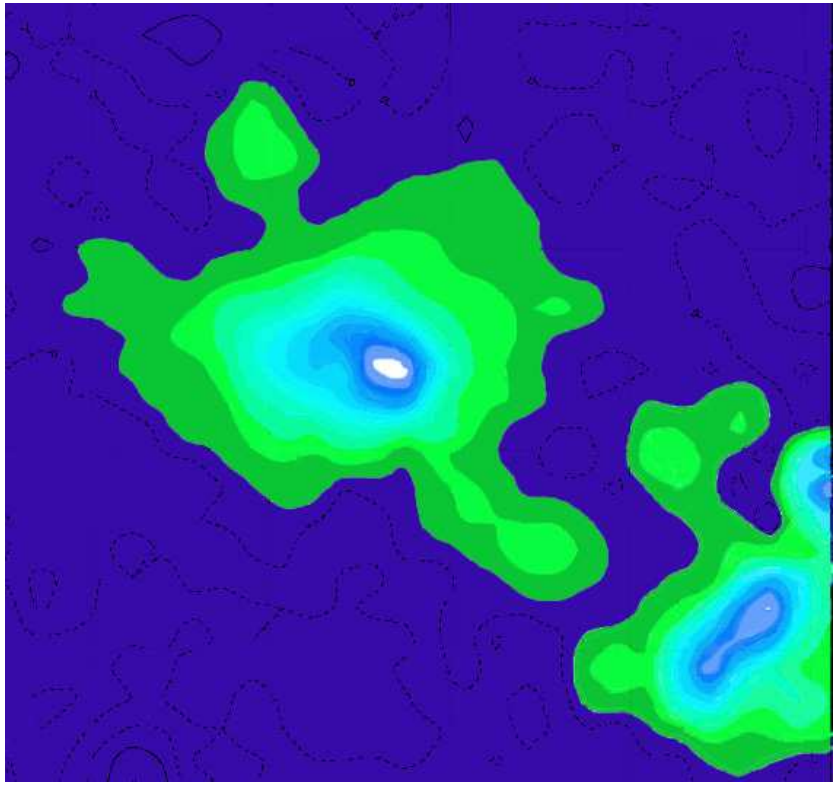
Giant radio halo in the Coma cluster



thermal X-ray emission

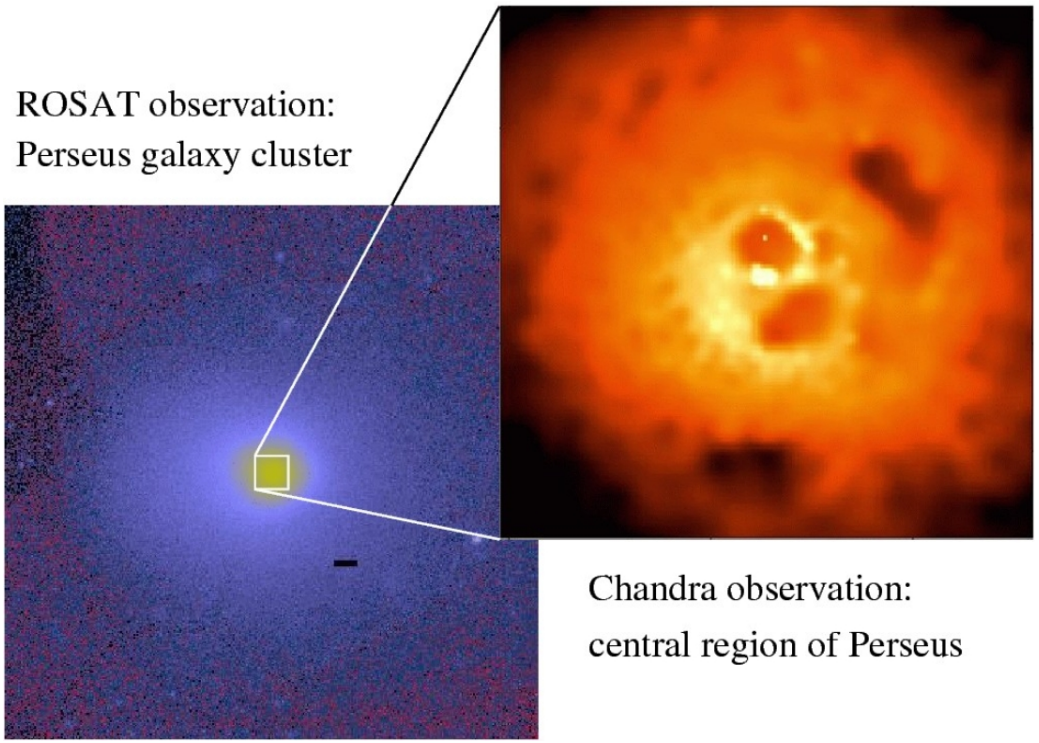
(Snowden/MPE/ROSAT)



radio synchrotron emission

(Deiss/Effelsberg)

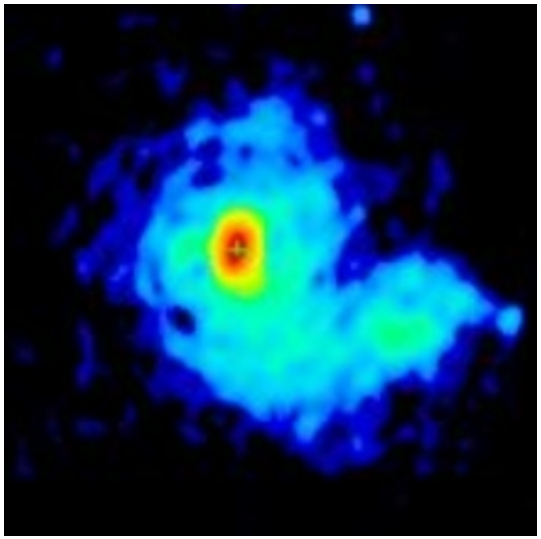
Radio mini halo in the Perseus cluster



thermal X-ray emission

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

Chandra observation:
central region of Perseus



radio synchrotron emission

(Pedlar/VLA)

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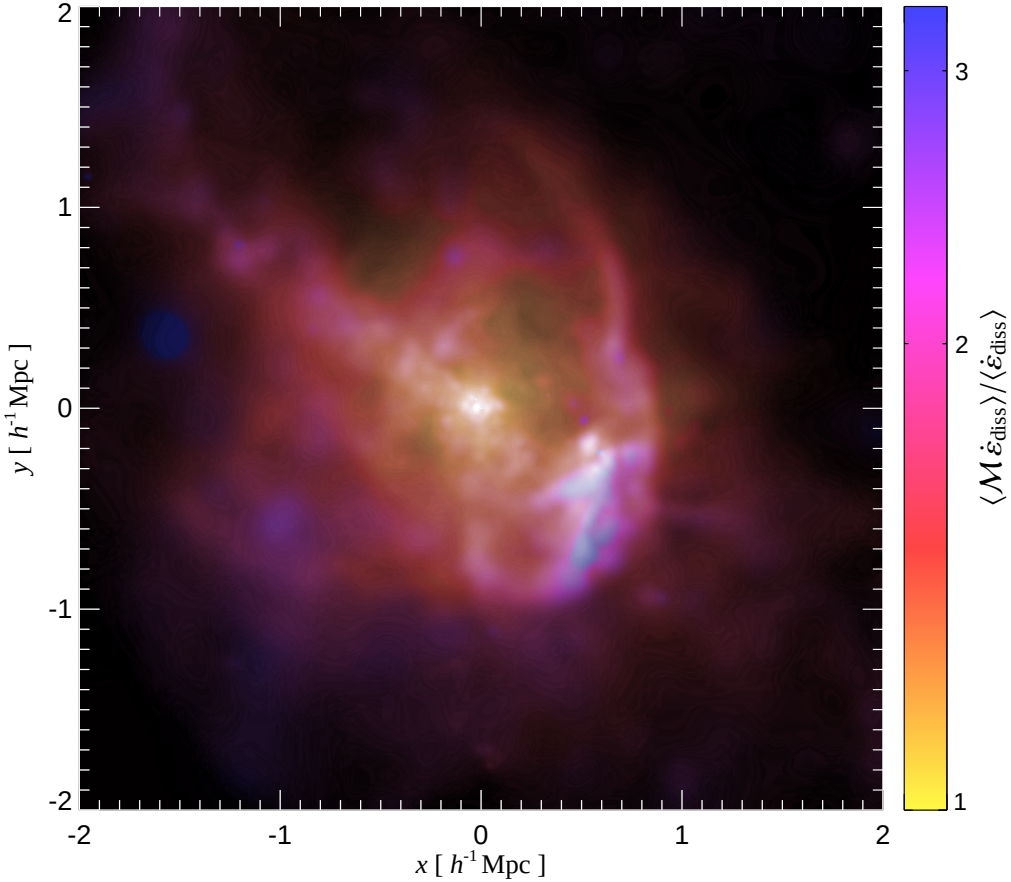
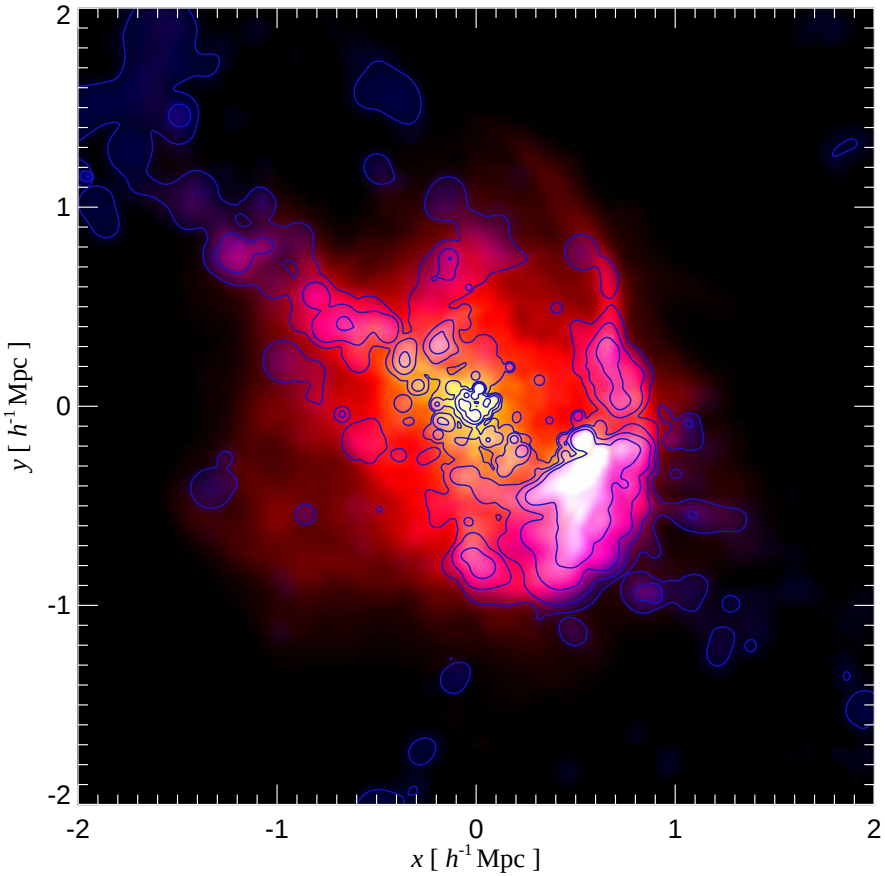
Radio gischt illuminates cluster shocks



Structure formation shocks triggered by a recent merger of a large galaxy cluster.



red/yellow: shock-dissipated energy,

blue/contours: 150 MHz radio gischt emission from shock-accelerated CRe

Diffuse cluster radio emission – an inverse problem

Exploring the magnetized cosmic web

Battaglia, C.P., Sievers, Bond, Enßlin (2009):

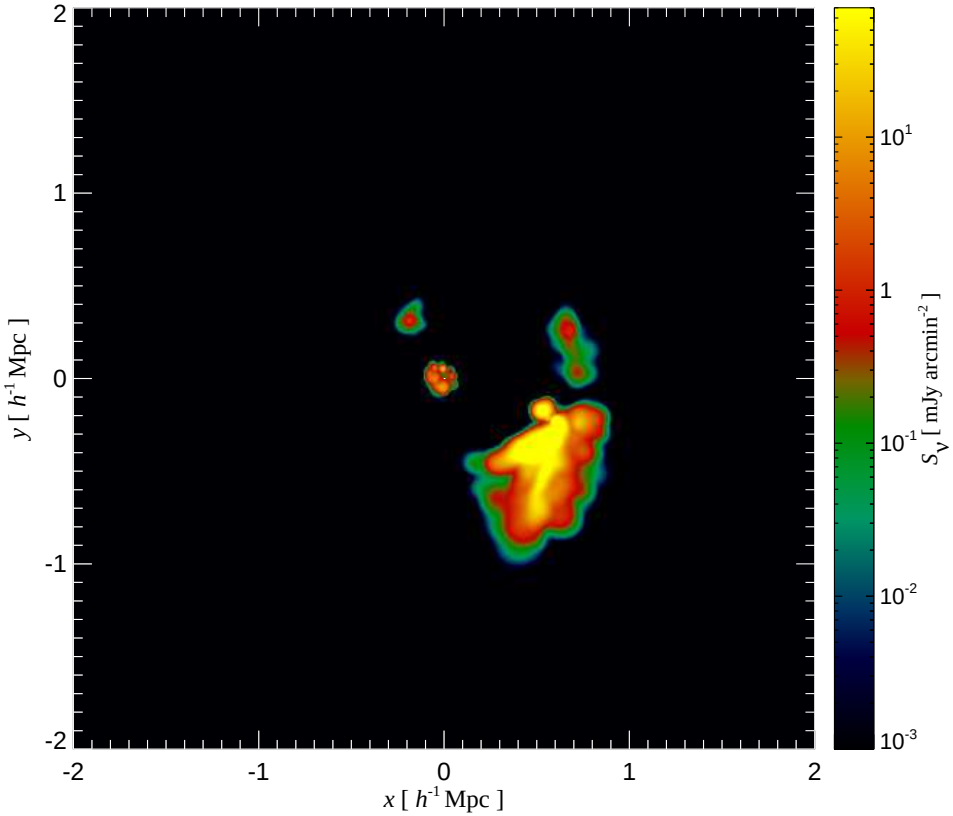
Combining the low-frequency radio observables of relics, we can probe

- strength and coherence scale of cluster magnetic fields
- diffusive shock acceleration of electrons
- existence and properties of the WHIM
- dynamical state of the cluster

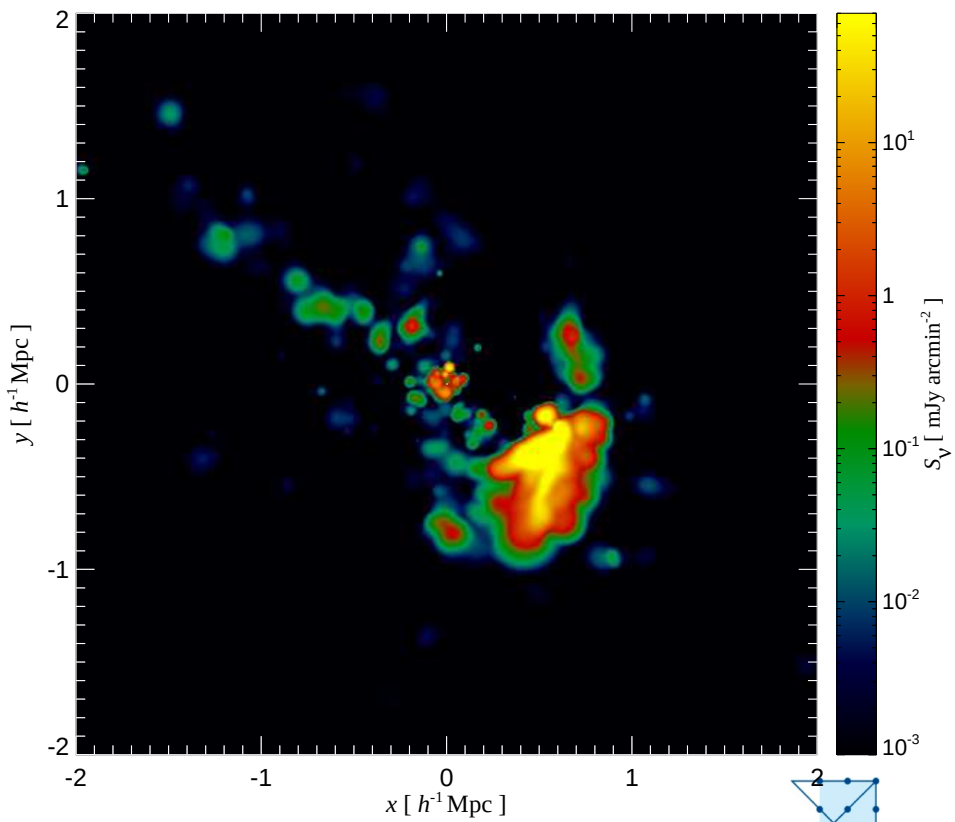
Population of faint radio relics in merging clusters

Probing the large scale magnetic fields

Finding radio relics with an FOF-finder that links radio emission instead of DM $\longrightarrow$ relic luminosity function:



radio map with GMRT emissivity threshold

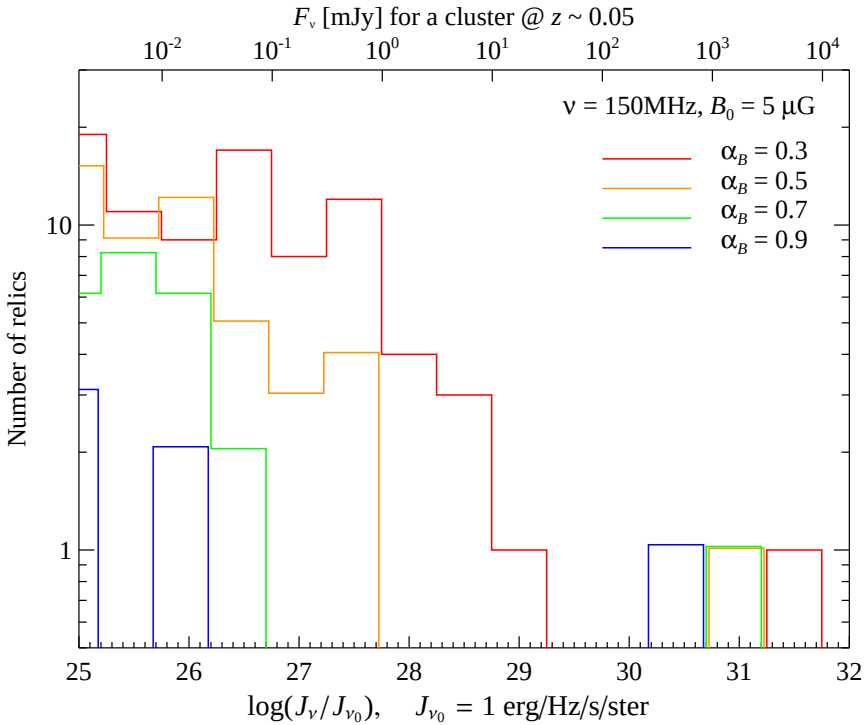


"theoretical" threshold (towards SKA)

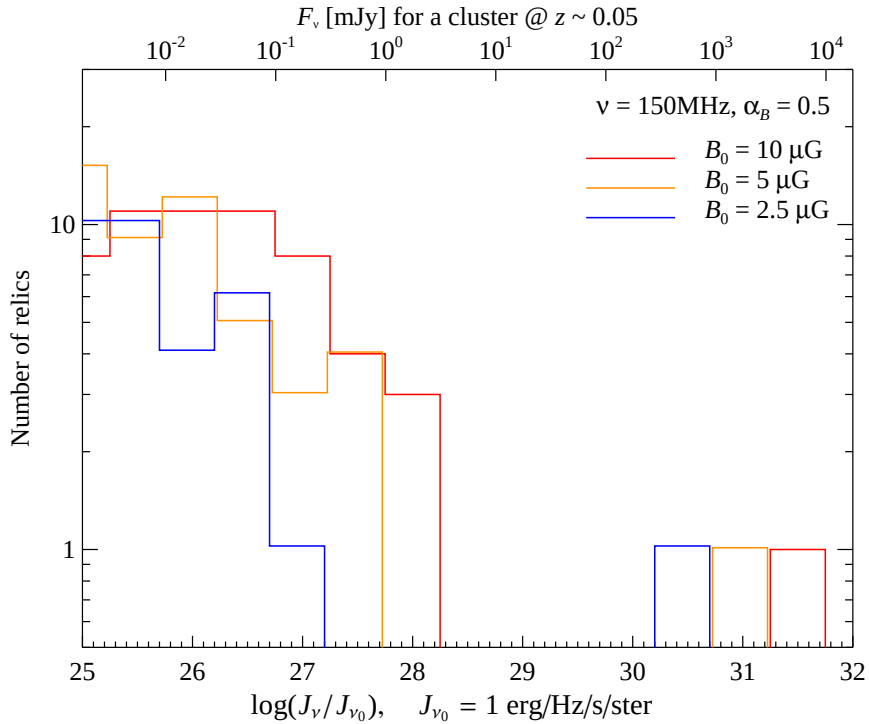
HITS

Relic luminosity function – theory

Relic luminosity function → magnetic field behaviour and dynamical state:



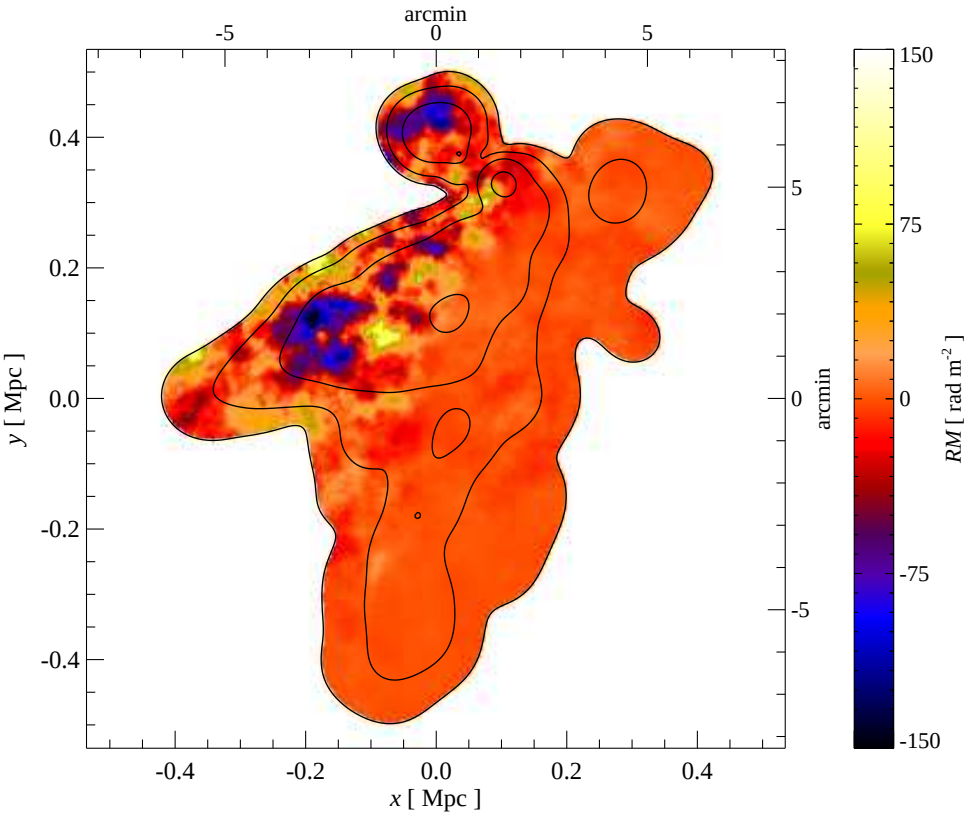
varying magnetic decline with radius

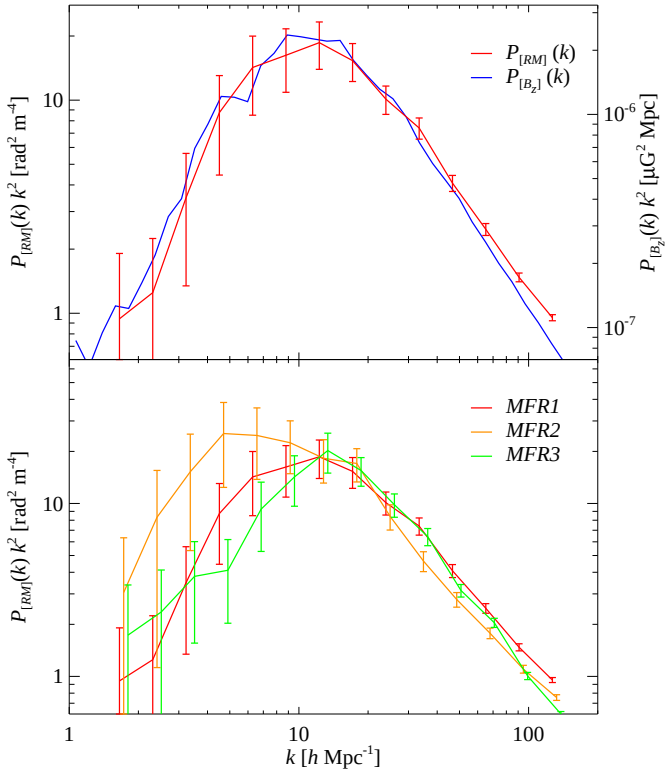


varying overall magnetic strength

Rotation measure (RM)

RM maps and power spectra have the potential to infer the magnetic pressure support and discriminate the nature of MHD turbulence in clusters:

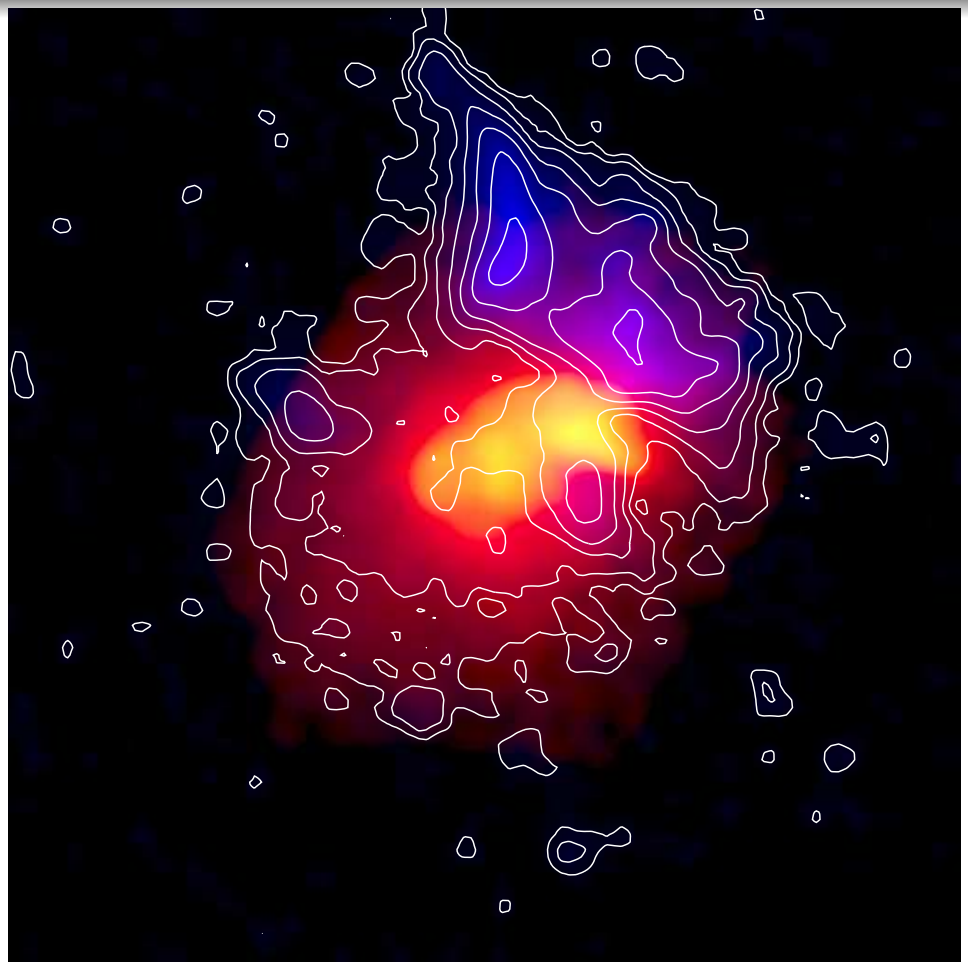


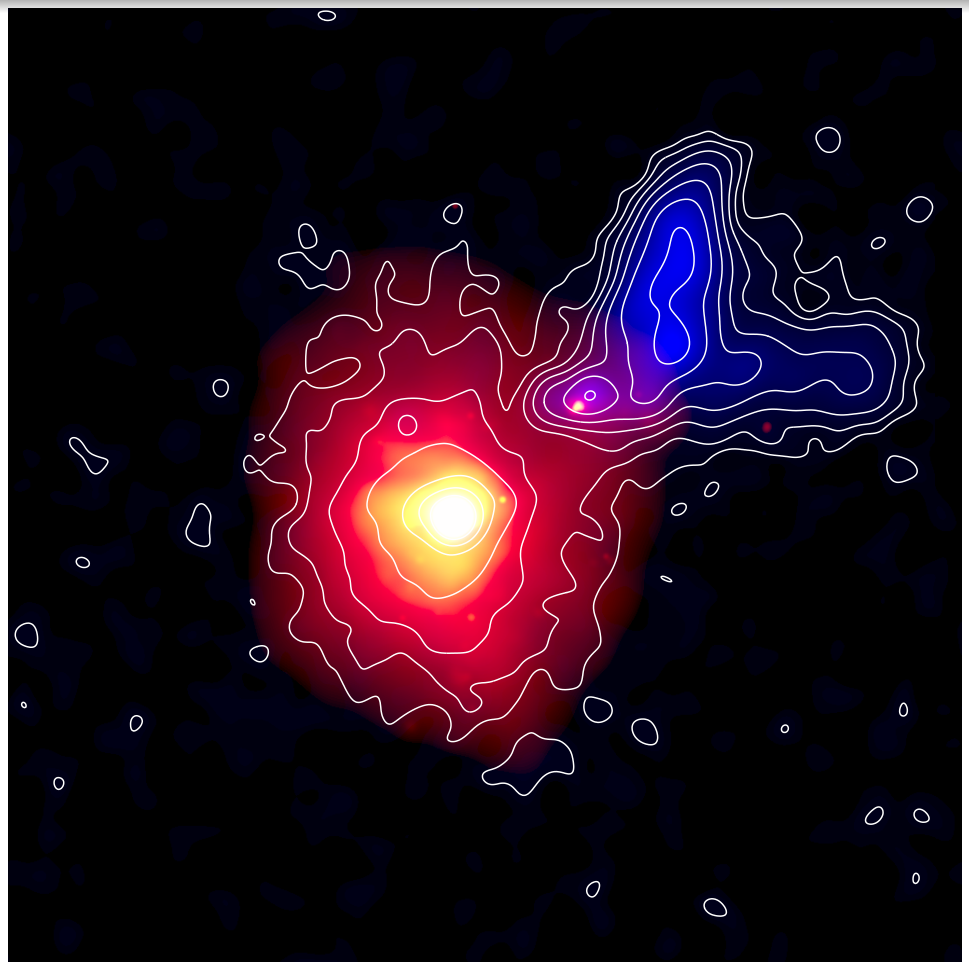


Left: RM map of the largest relic, *right:* Magnetic and RM power spectrum comparing Kolmogorow and Burgers turbulence models.

Outline

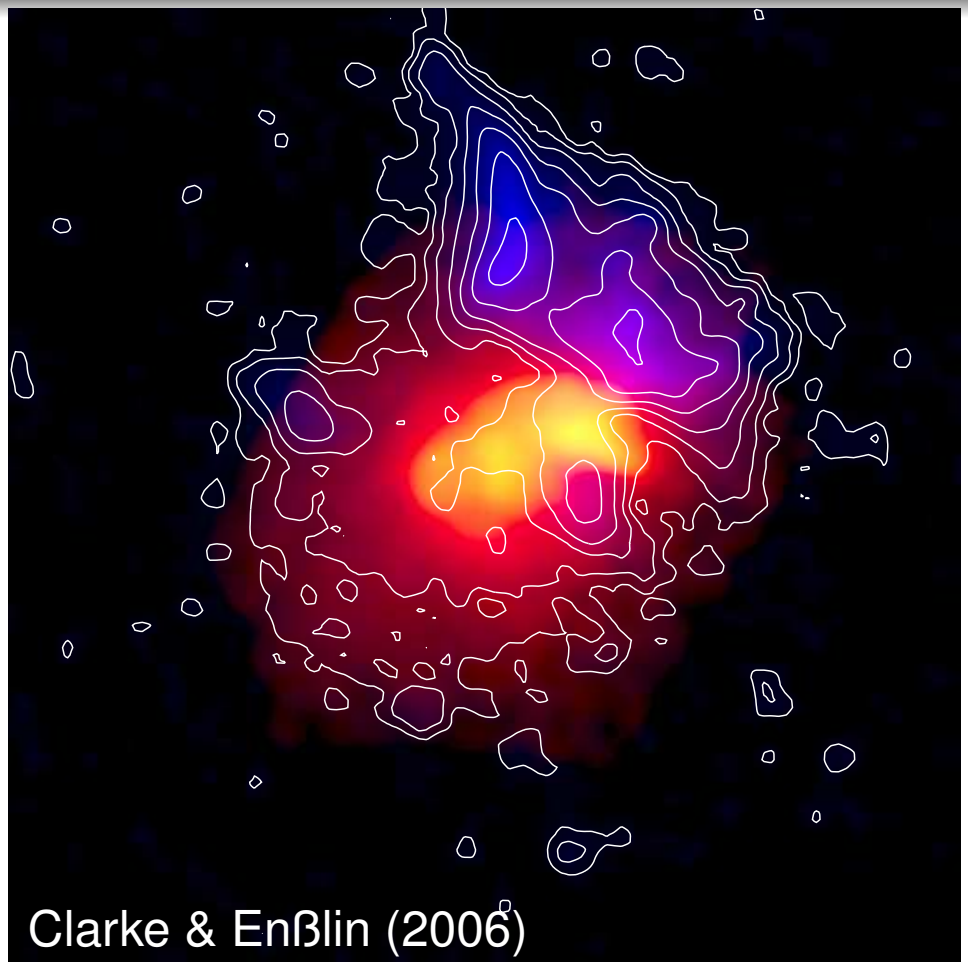
Which one is the simulation/observation of A2256?

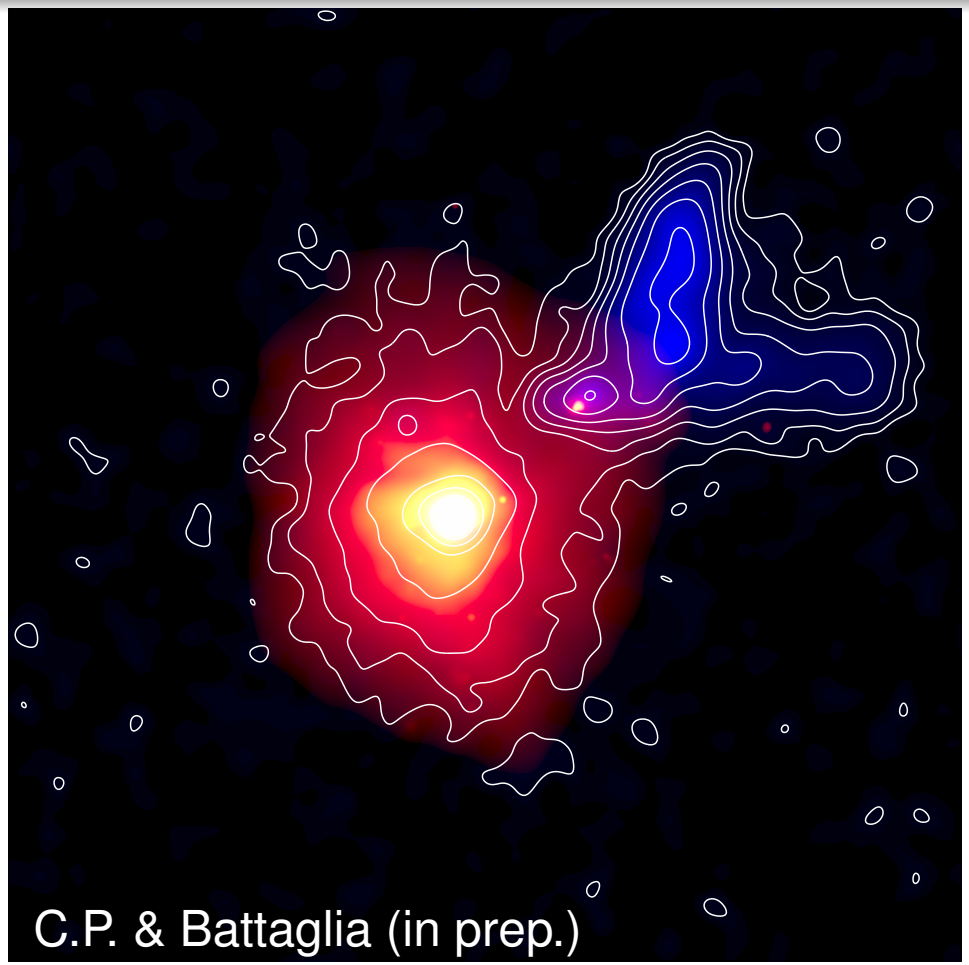




red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic

Observation – simulation of A2256





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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 morphologies as observed without tuning
- power-law spectra as observed

weakness:

- all clusters should have radio halos
- does not explain all reported spectral features
- ...

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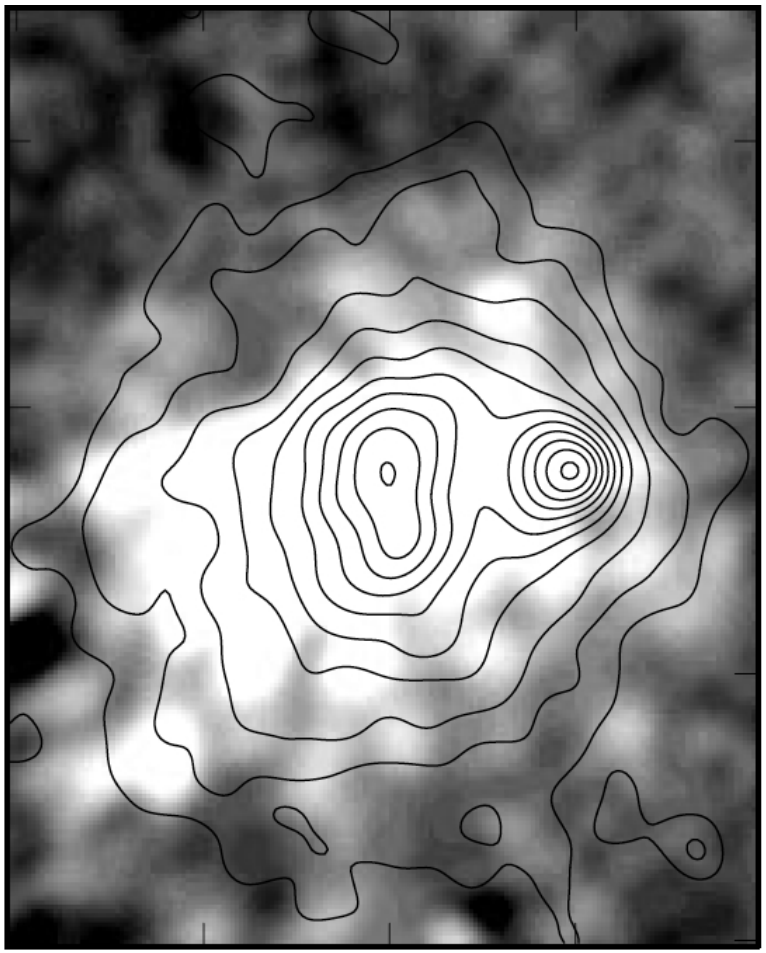
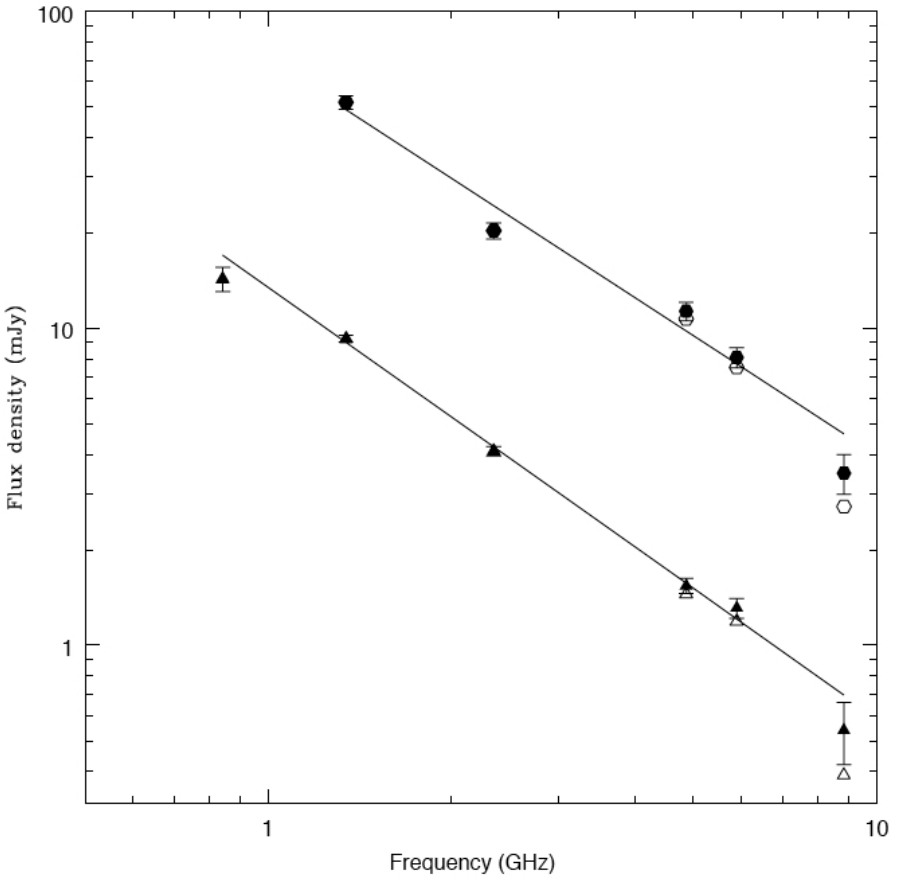
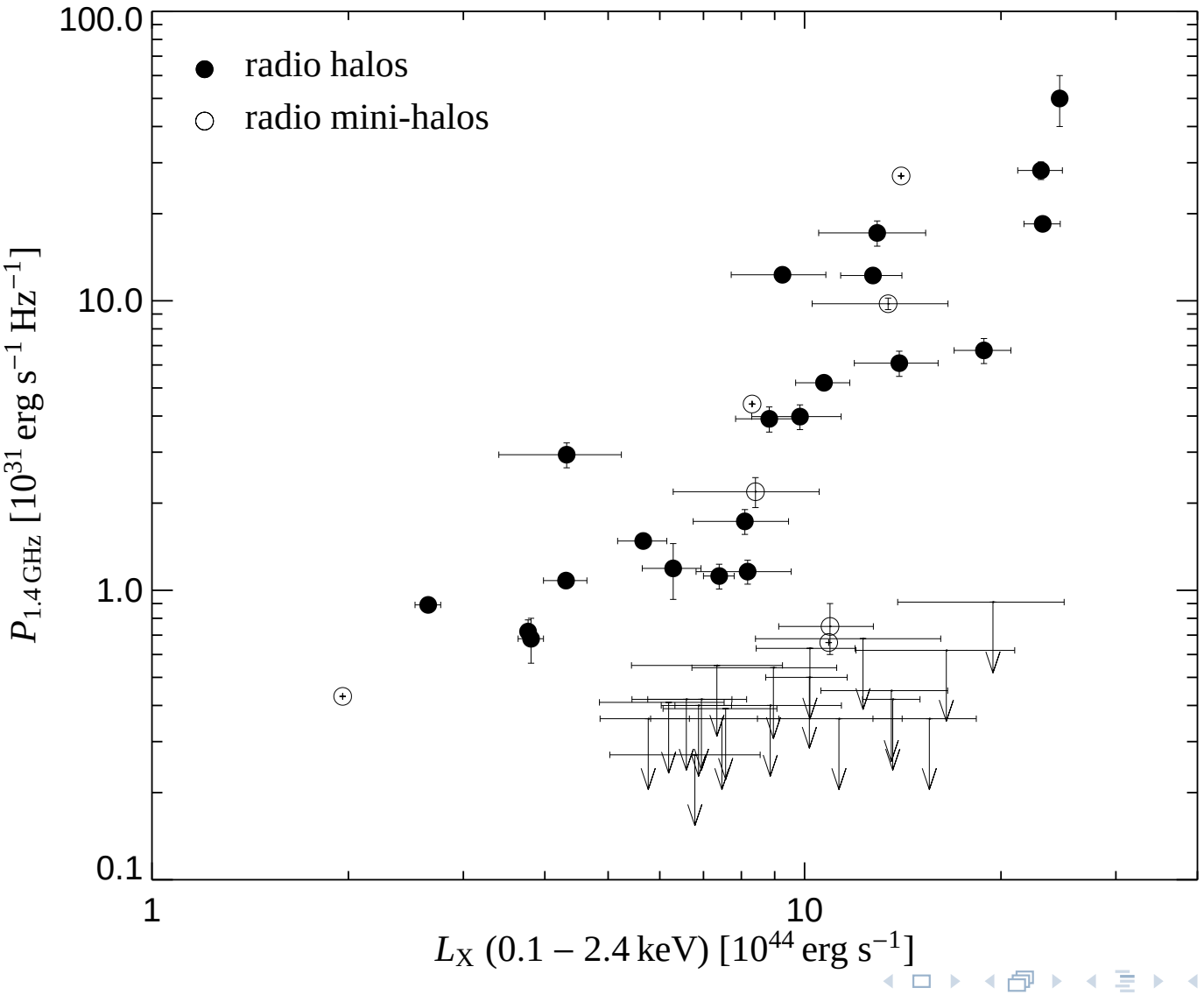
Radio halo and spectrum in the Bullet cluster





Liang et al. (2000): SZ-corrected

Radio luminosity - X-ray luminosity



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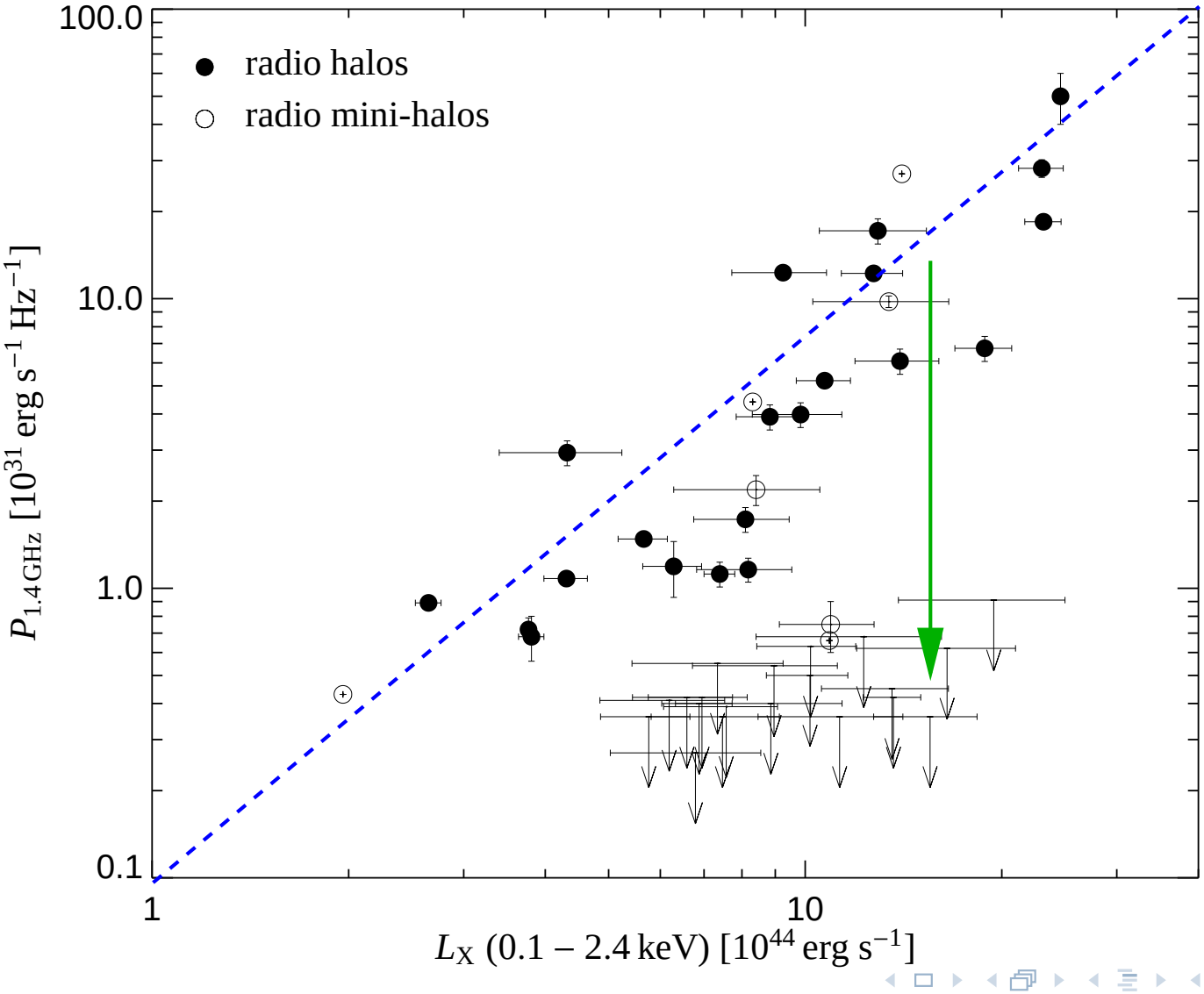

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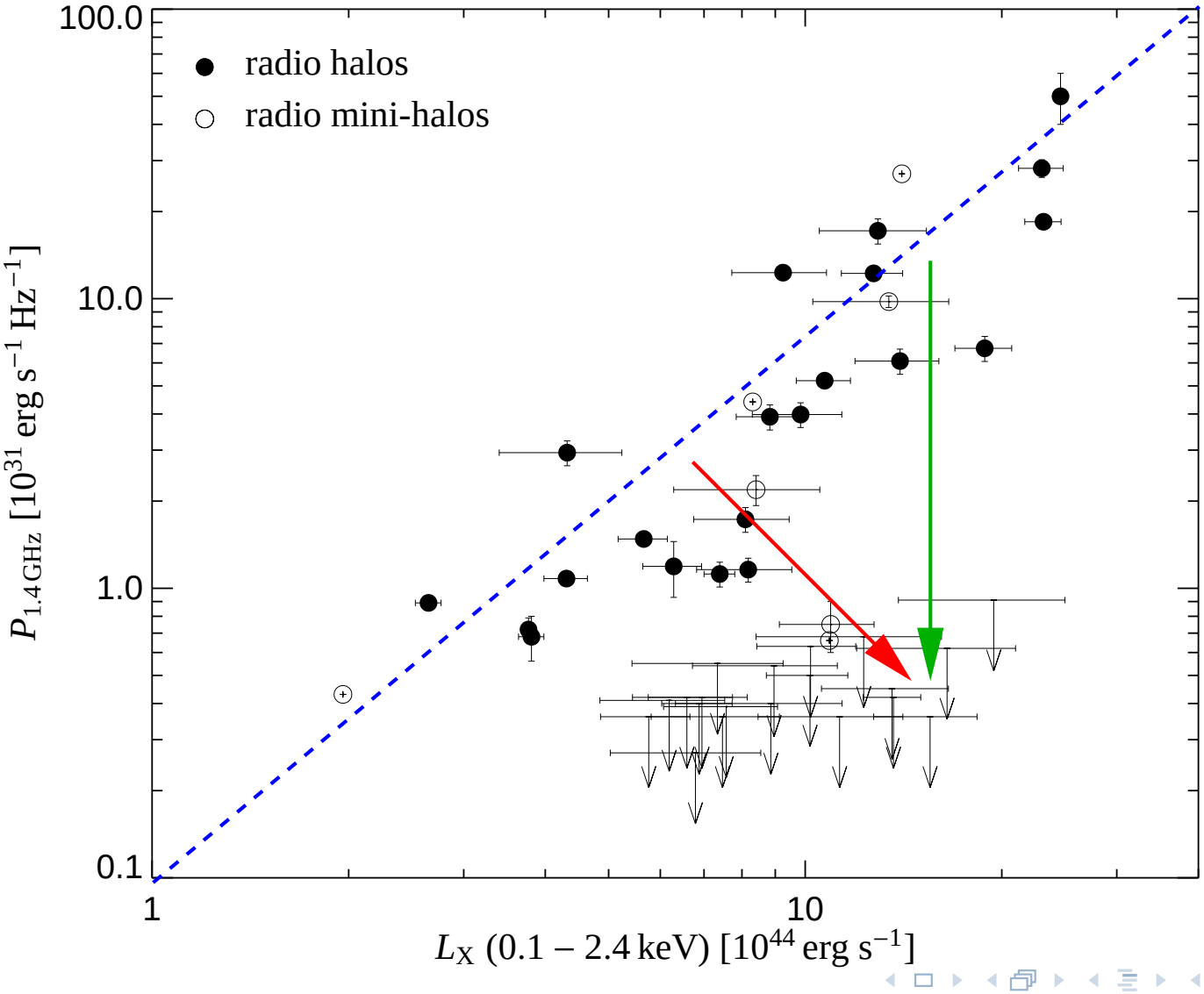
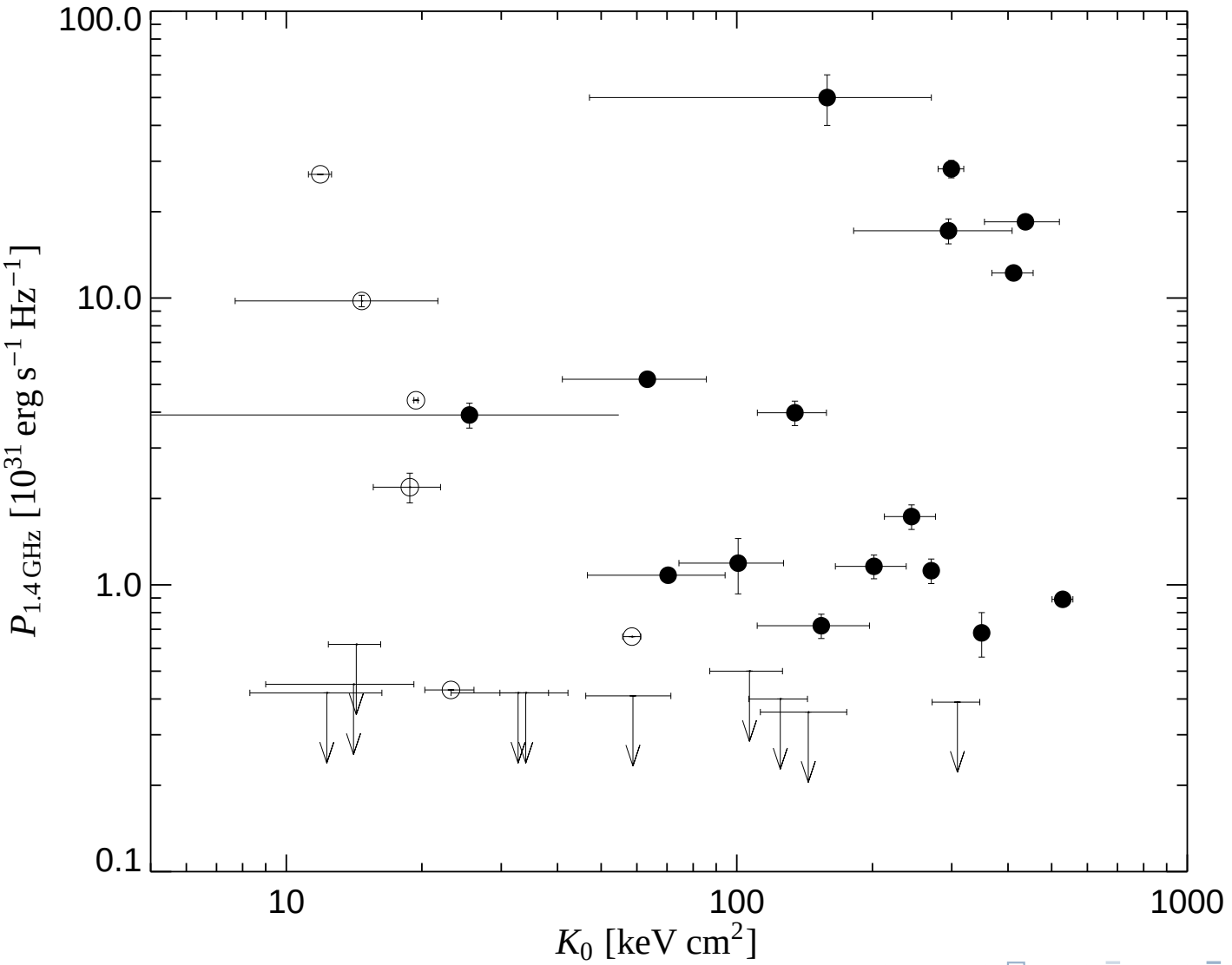


Radio luminosity - central entropy



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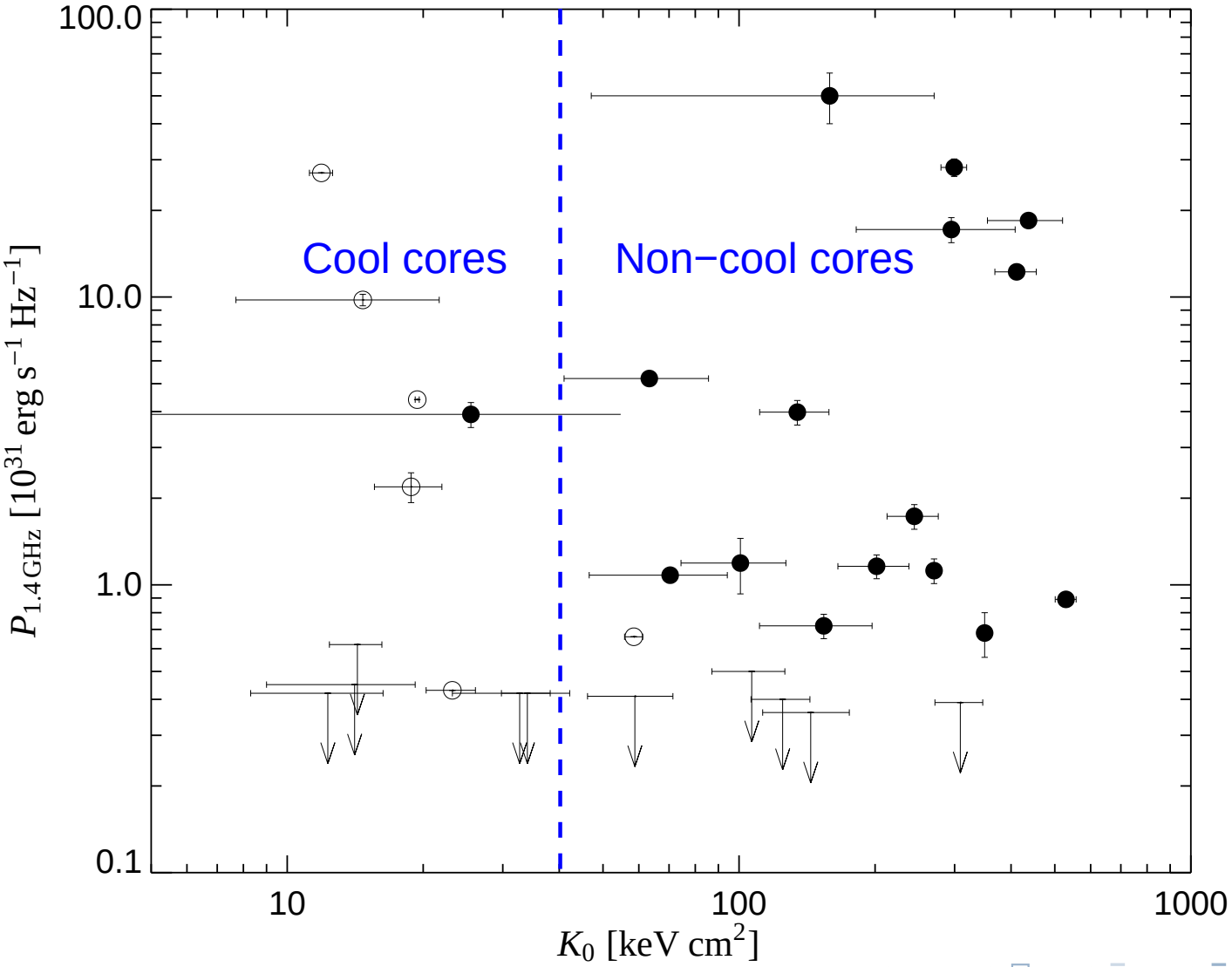

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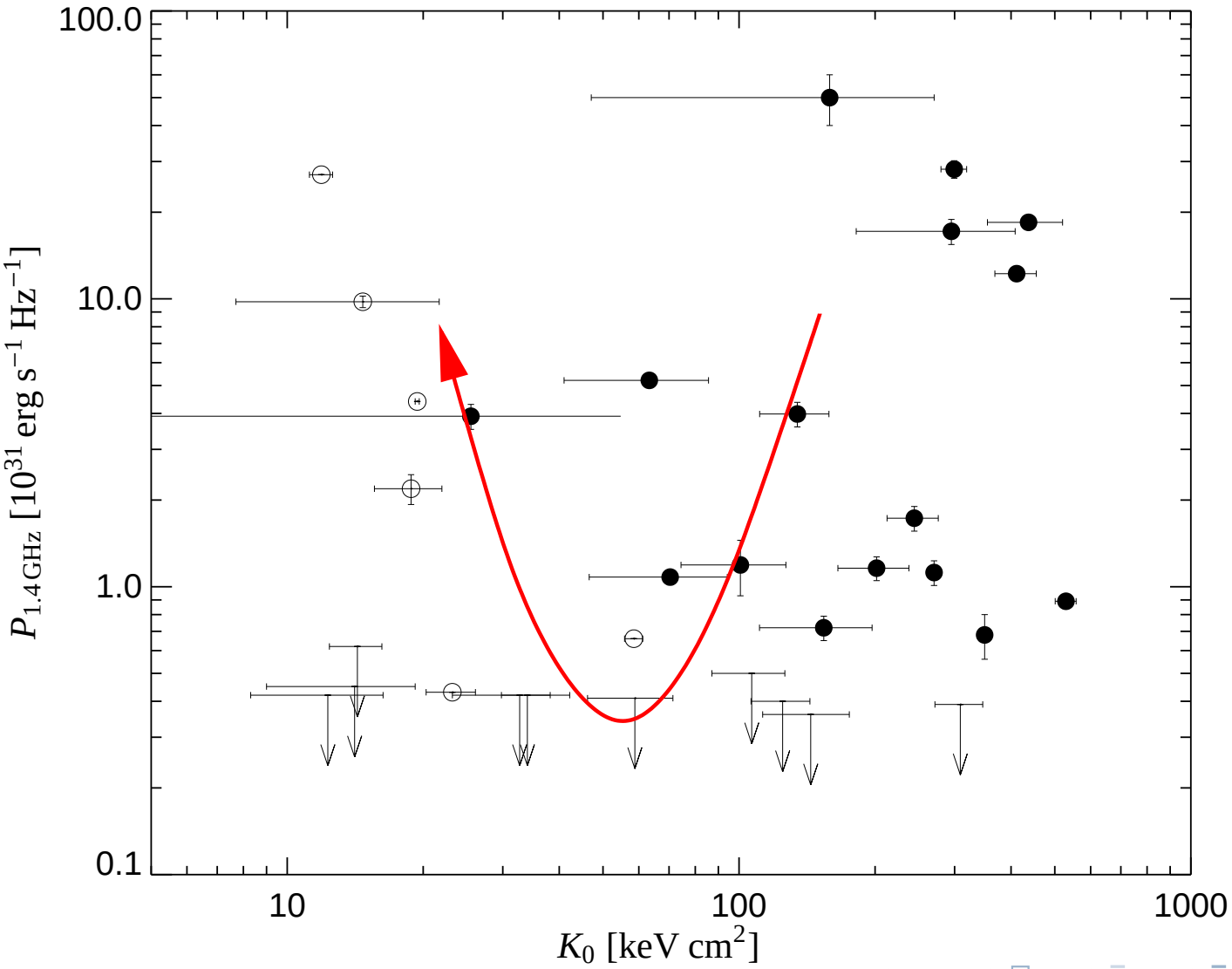

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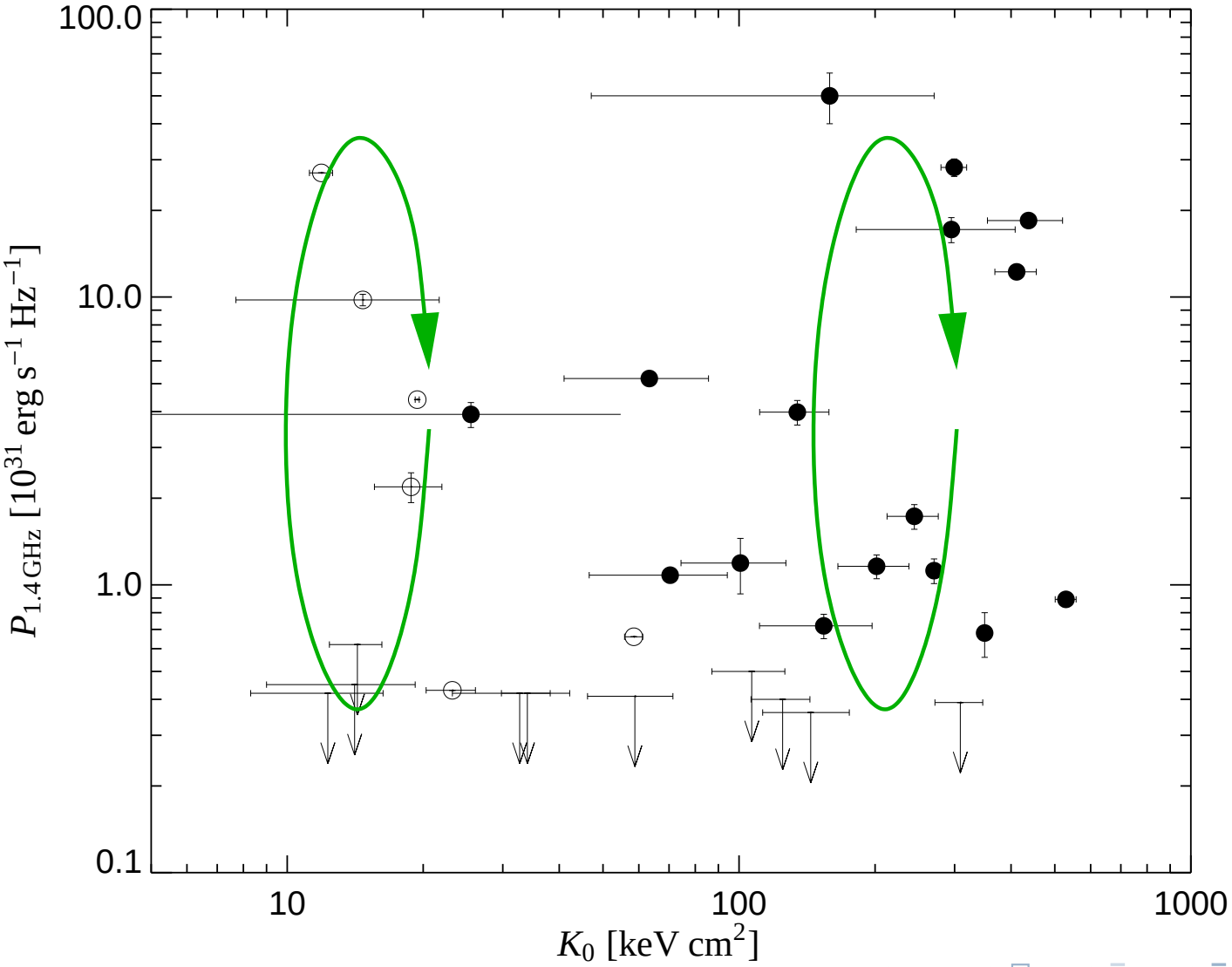
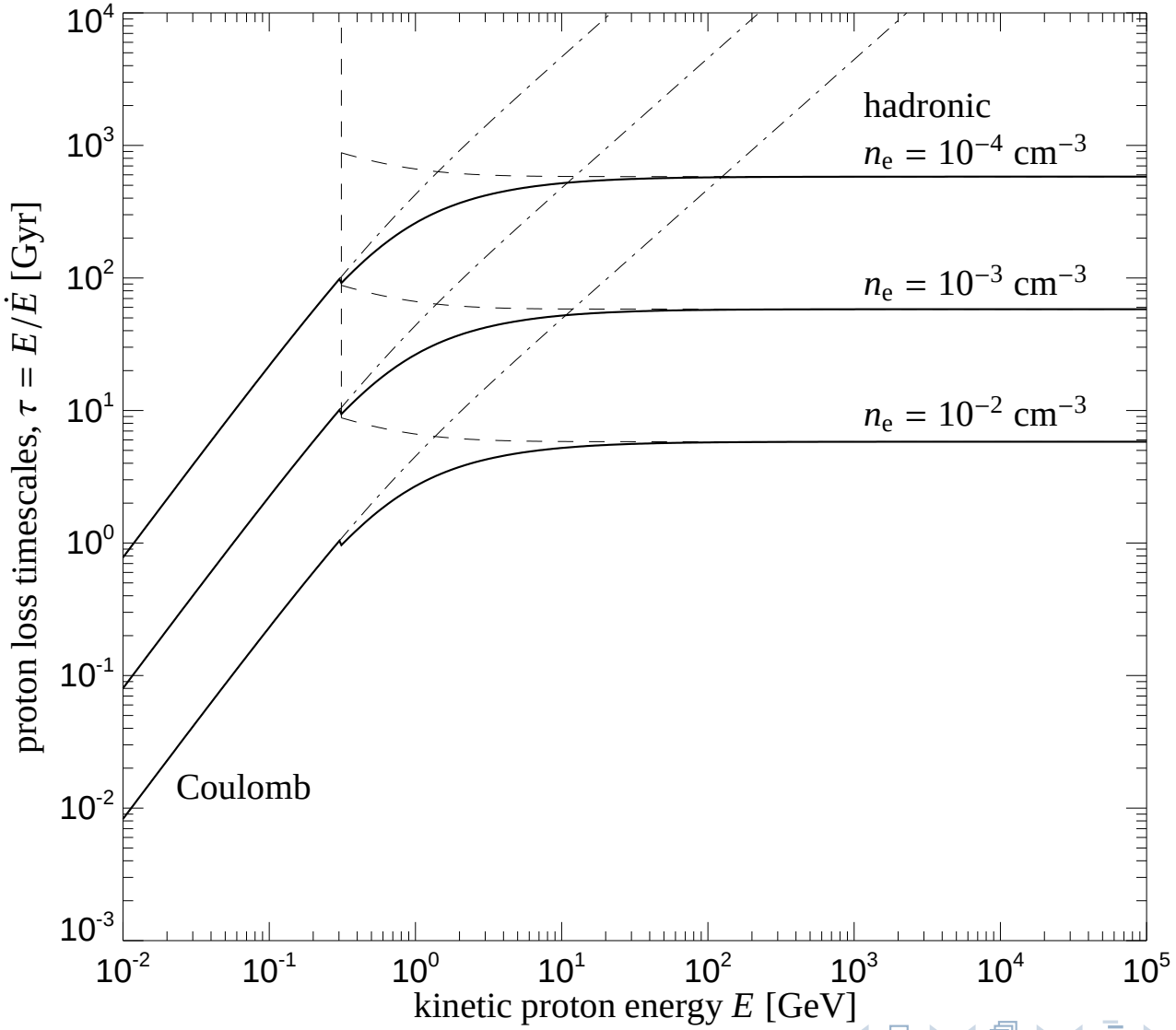


Proton cooling times



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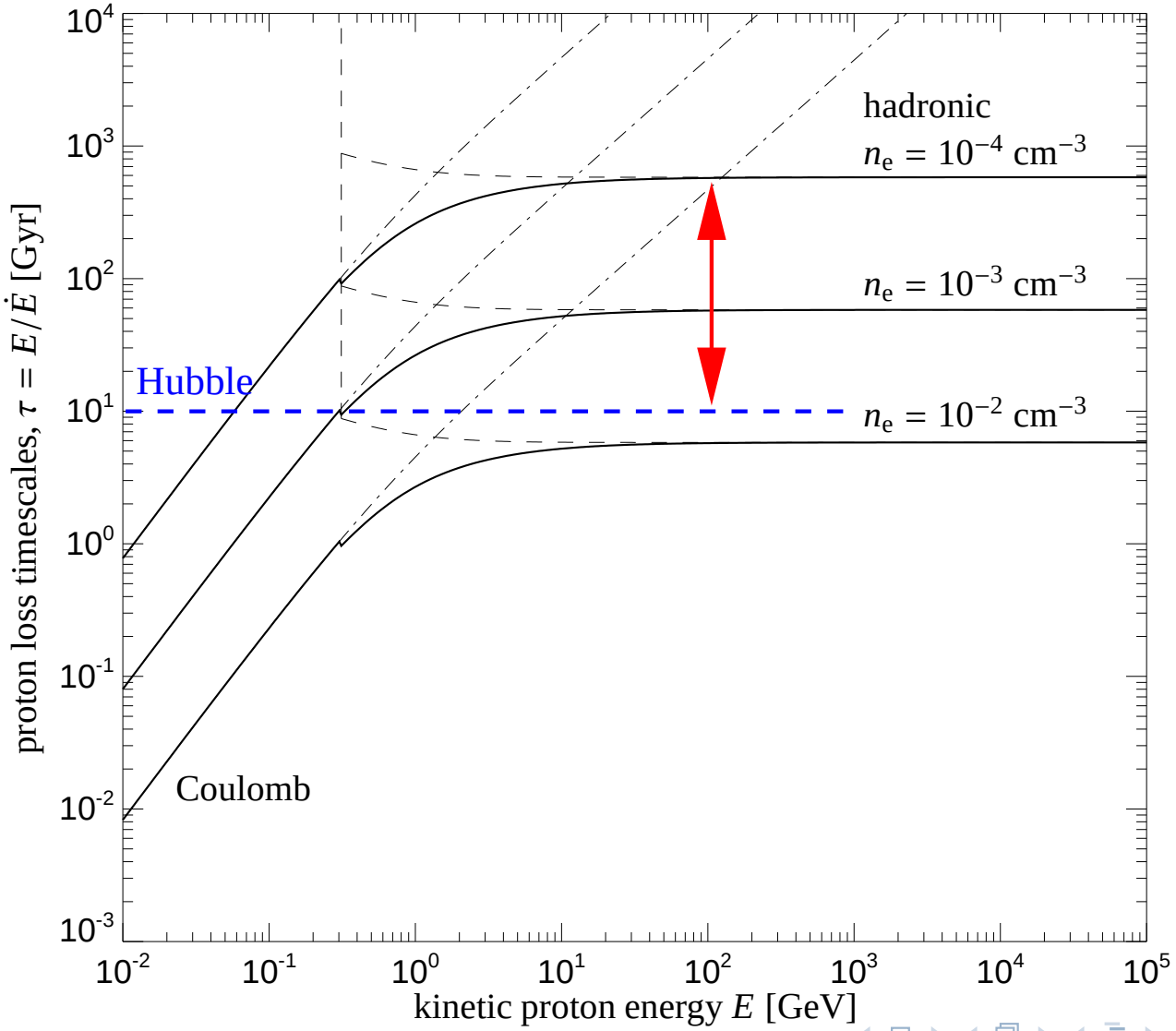

Radio halo theory – (ii) re-acceleration model

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

weakness:

- Fermi II acceleration is inefficient – CRe cool rapidly
- observed power-law spectra require fine tuning
- . . .

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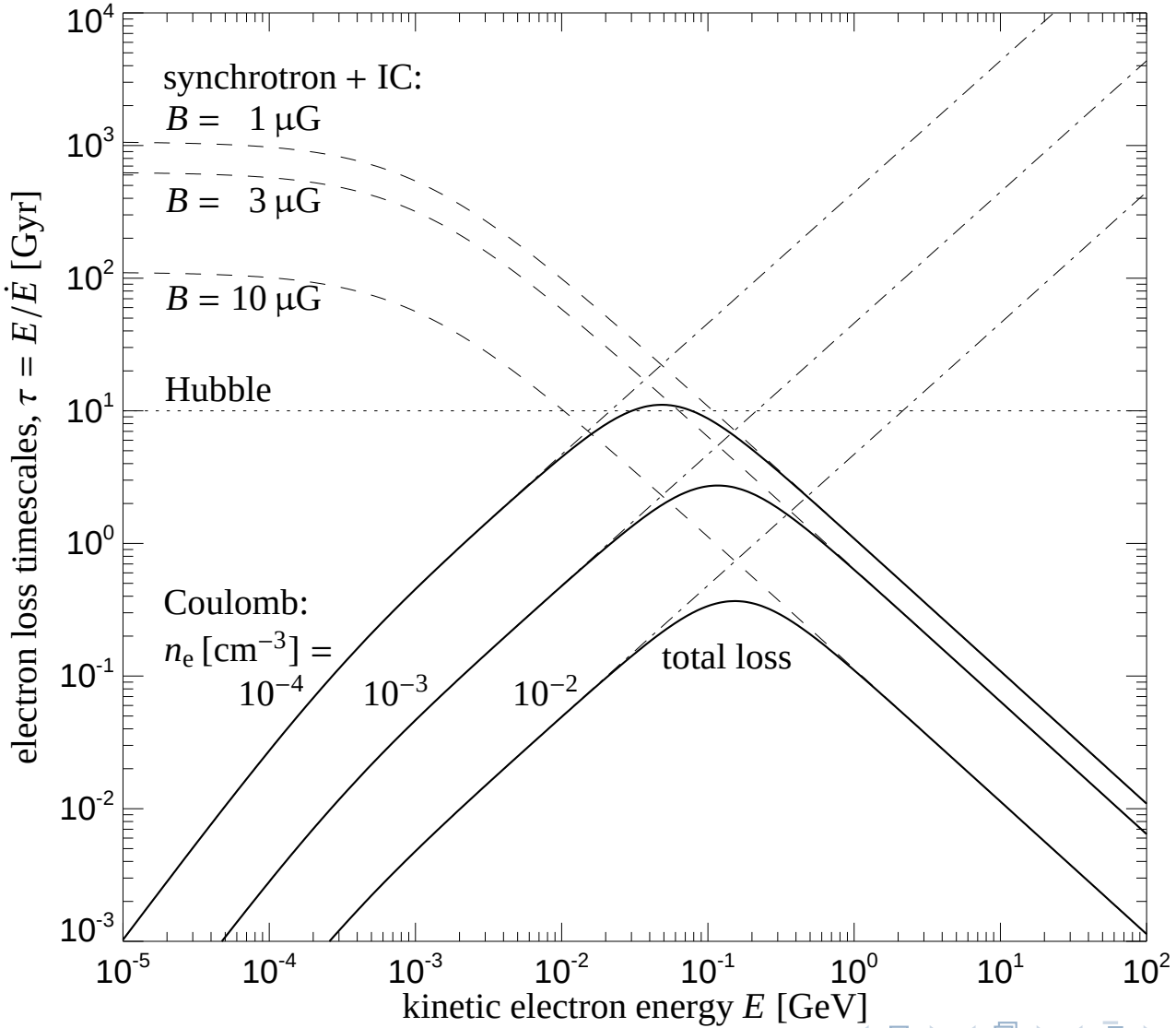

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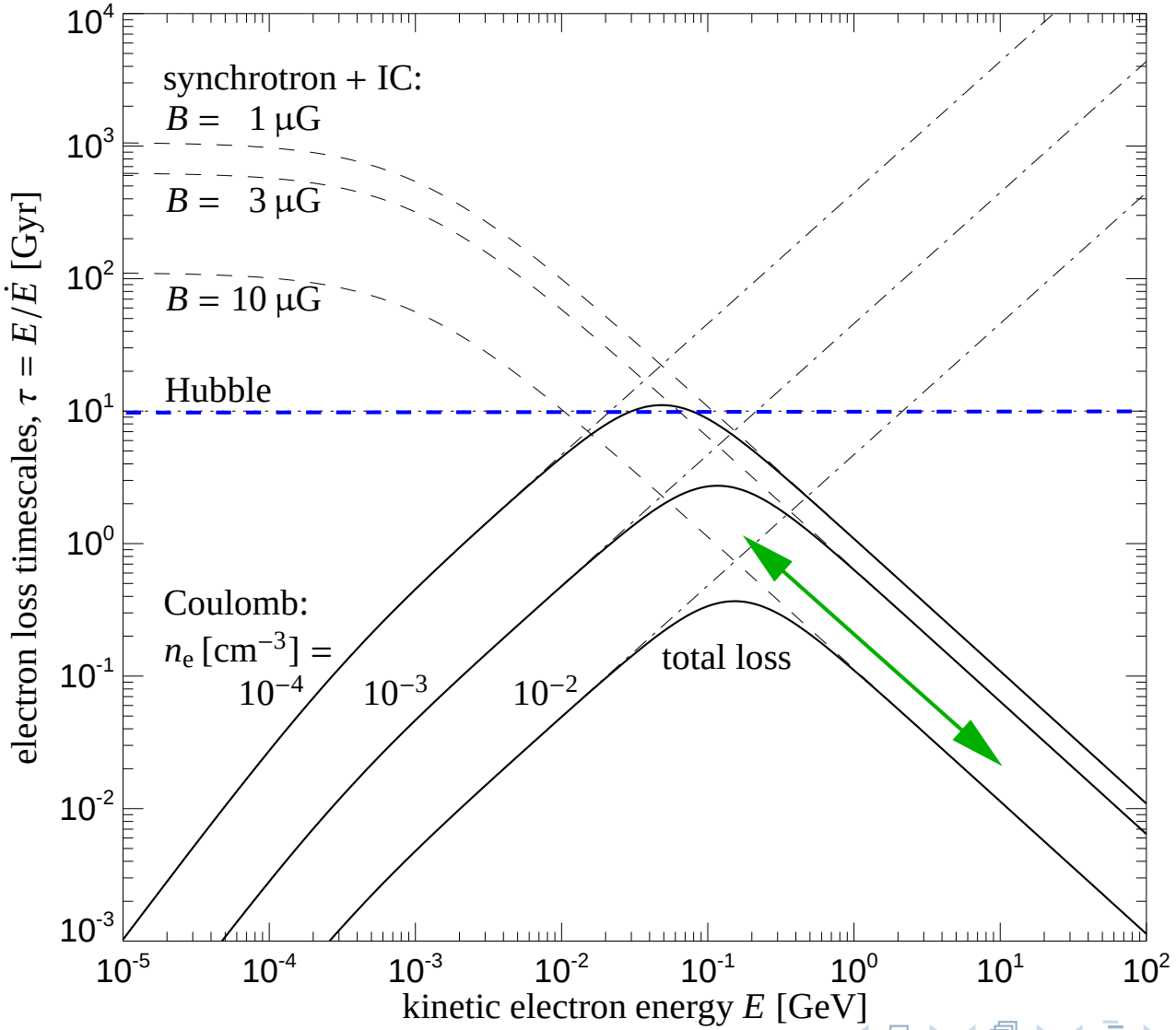

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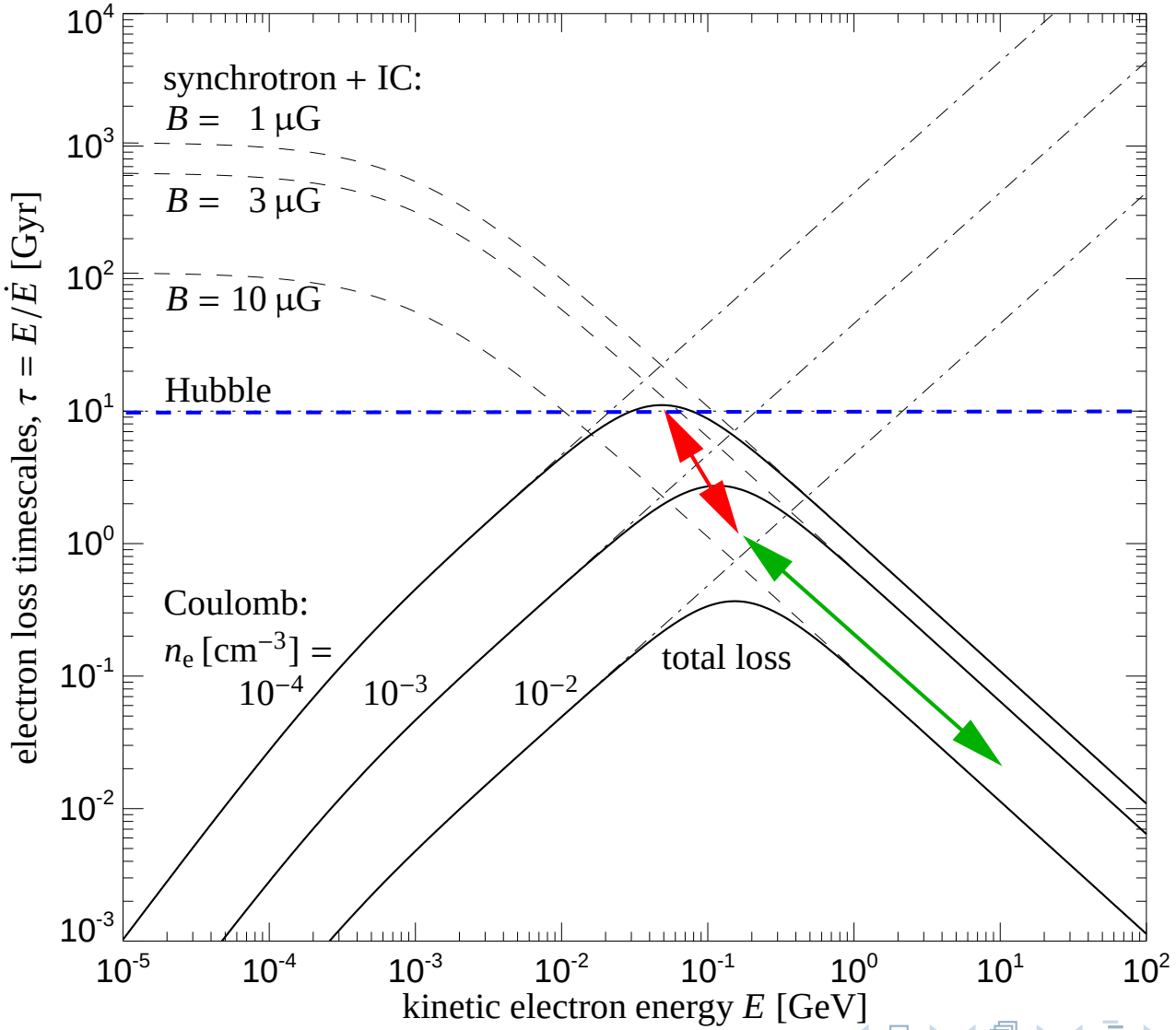
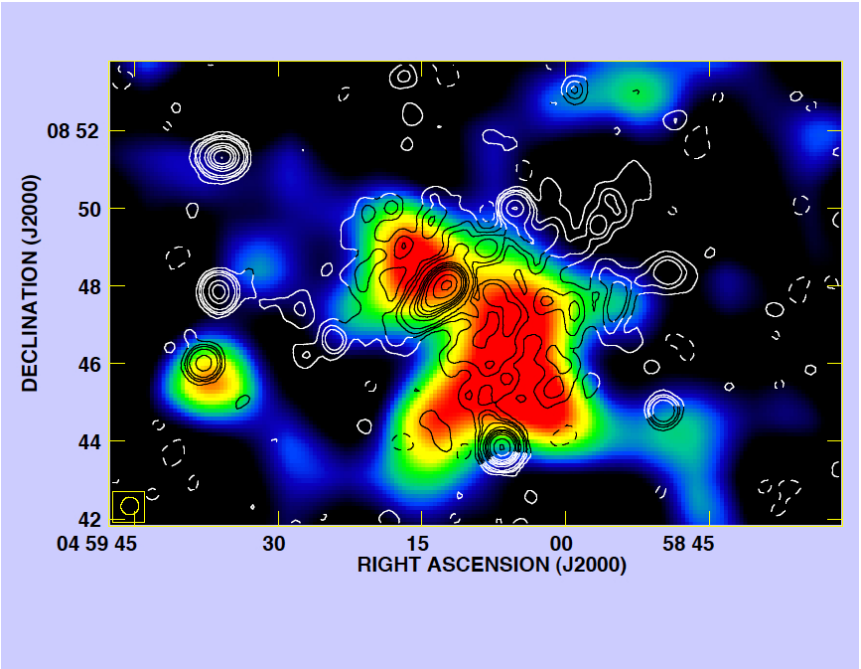
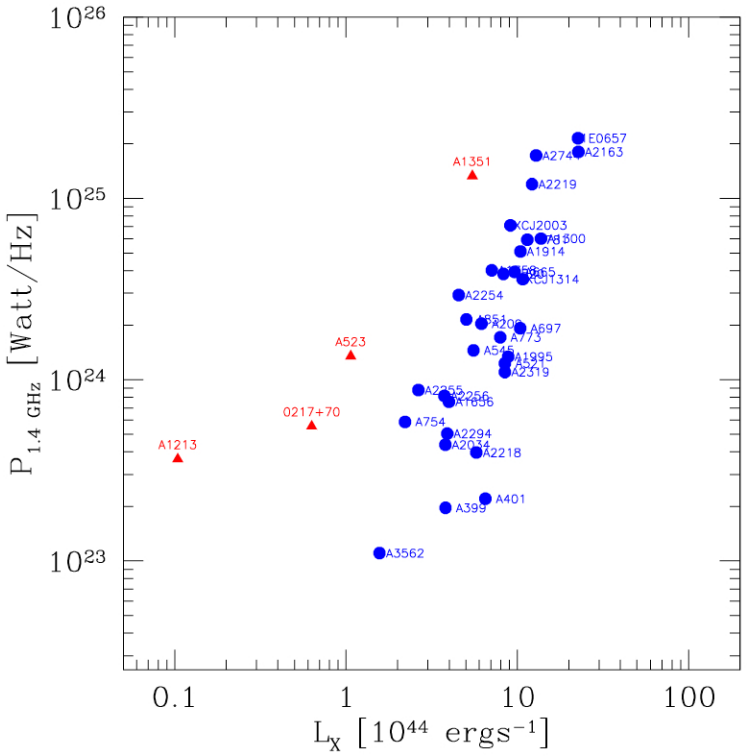


Radio halos in low-luminosity clusters

A challenge to the re-acceleration scenario or incomplete point source subtraction?



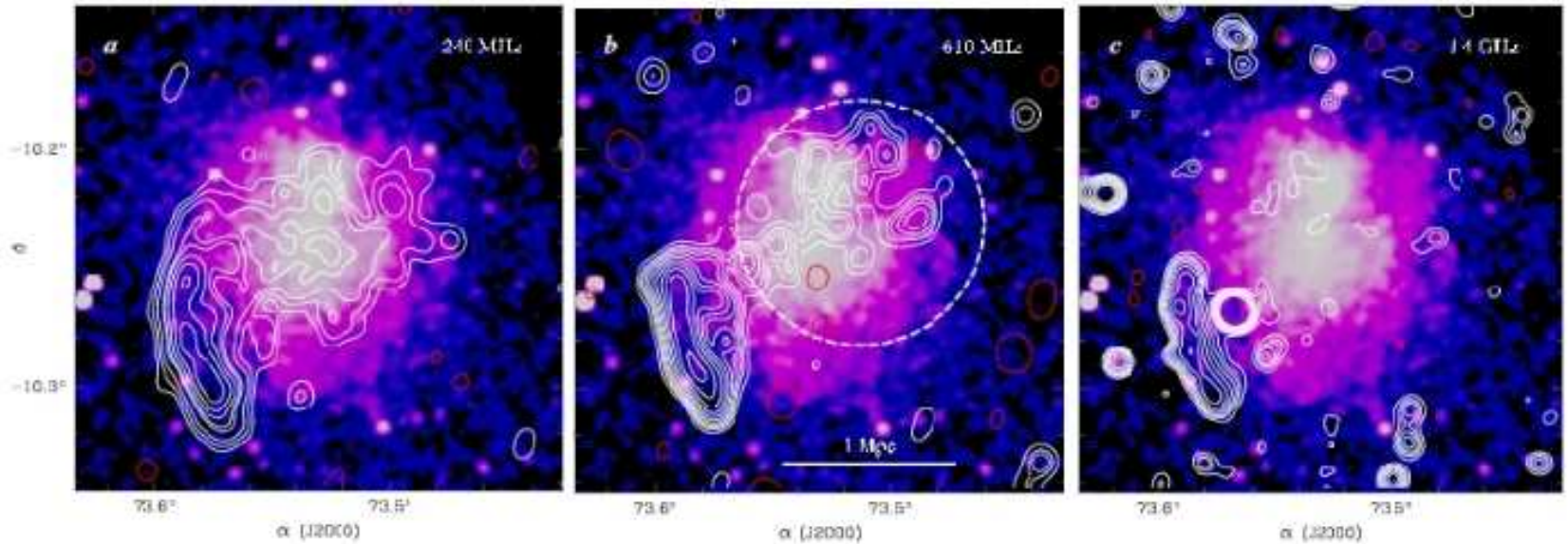
A523 at 1.4 GHz (Giovannini+ 2011)



$P_{1.4} - L_X$ relation with “outliers”

Particle acceleration by turbulence or shocks?

Diffuse low-frequency radio emission in Abell 521 (Brunetti et al. 2008)

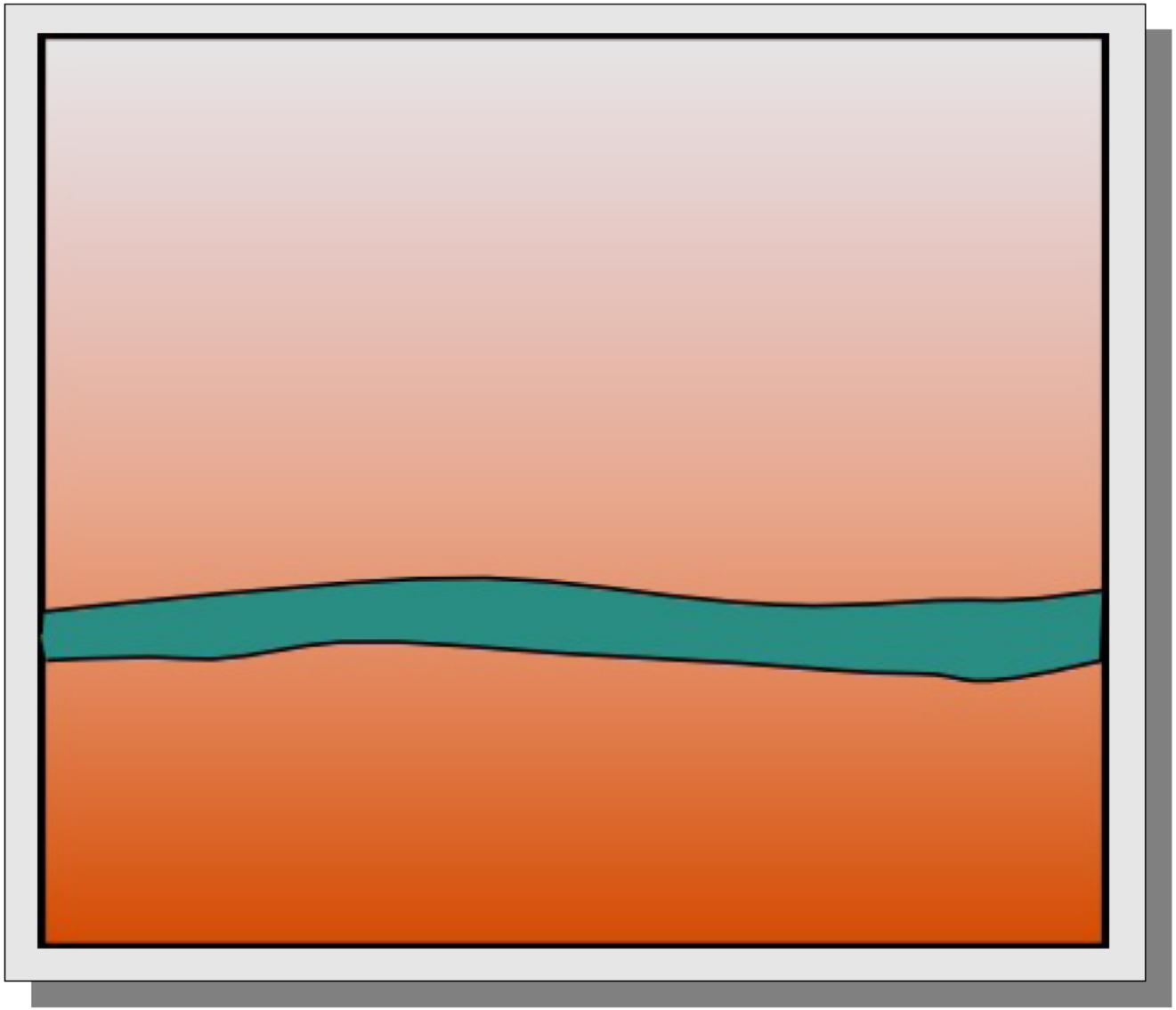


colors: thermal X-ray emission; contours: diffuse radio emission.

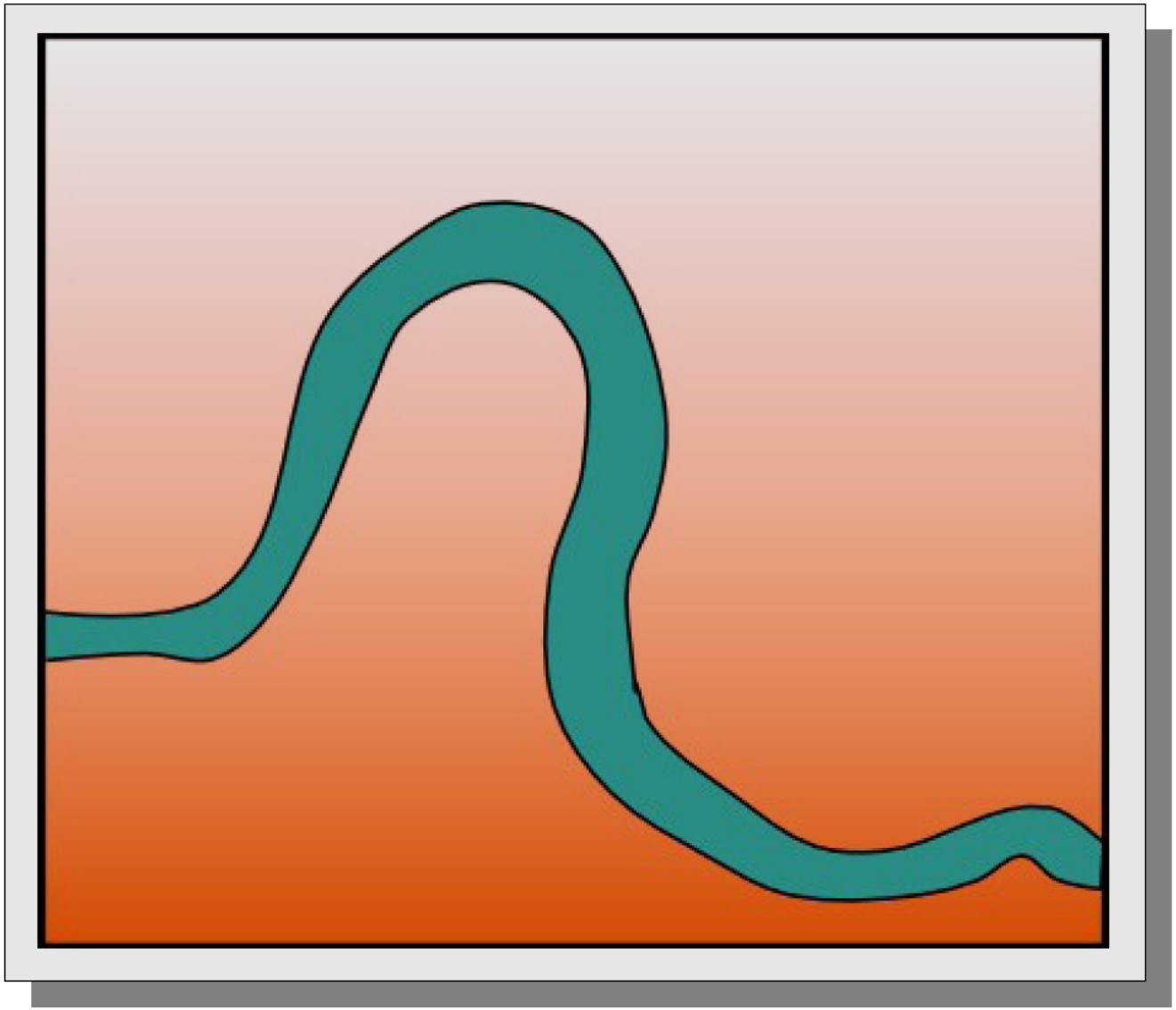
- "radio relic" interpretations with aged population of shock-accelerated electrons or shock-compressed radio ghosts (aged radio lobes),
- "radio halo" interpretation with re-acceleration of relativistic electrons through interactions with MHD turbulence.

→ synchrotron polarization is key to differentiate!

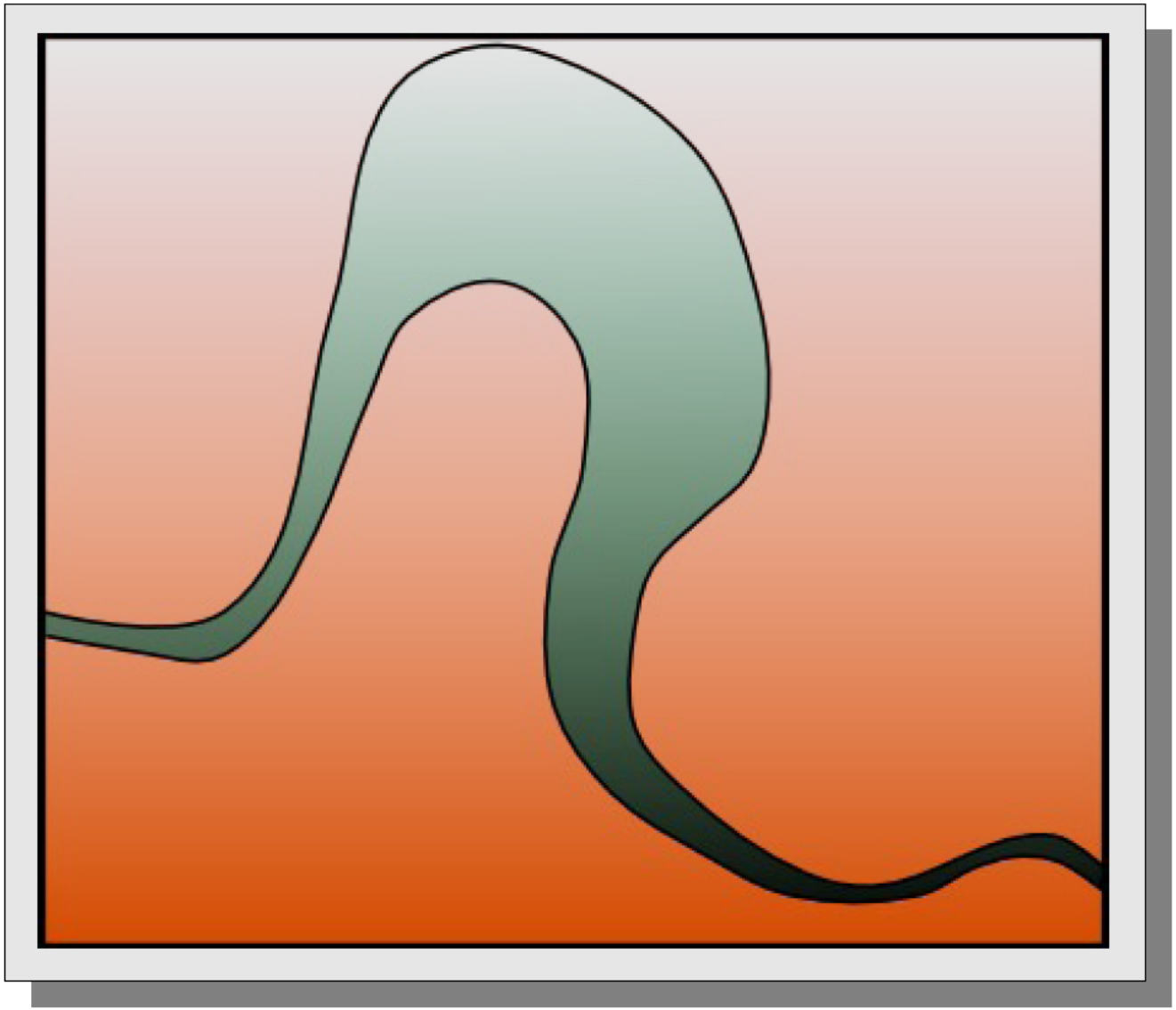
Cosmic ray transport – magnetic flux tube with CRs



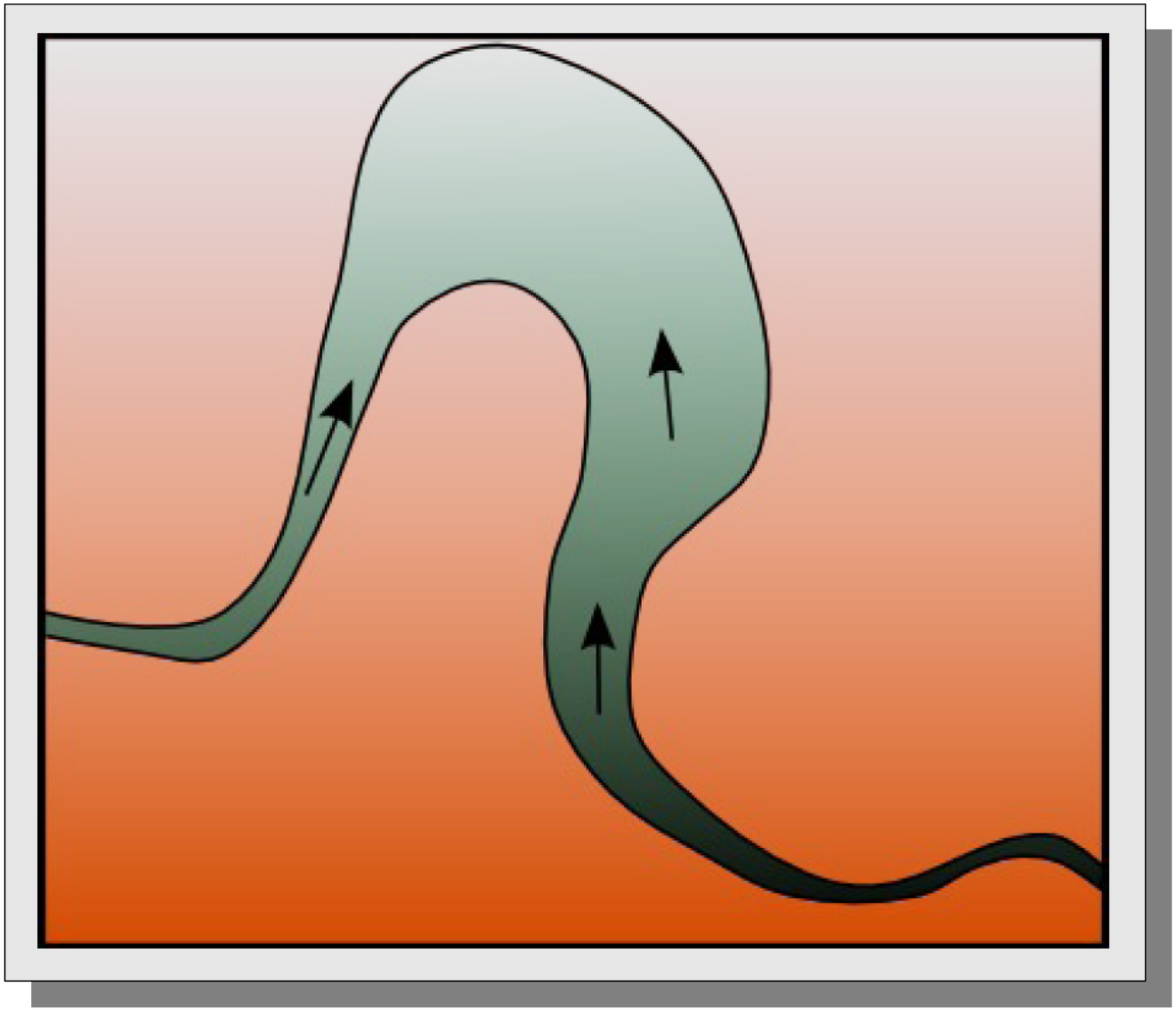
Cosmic ray advection



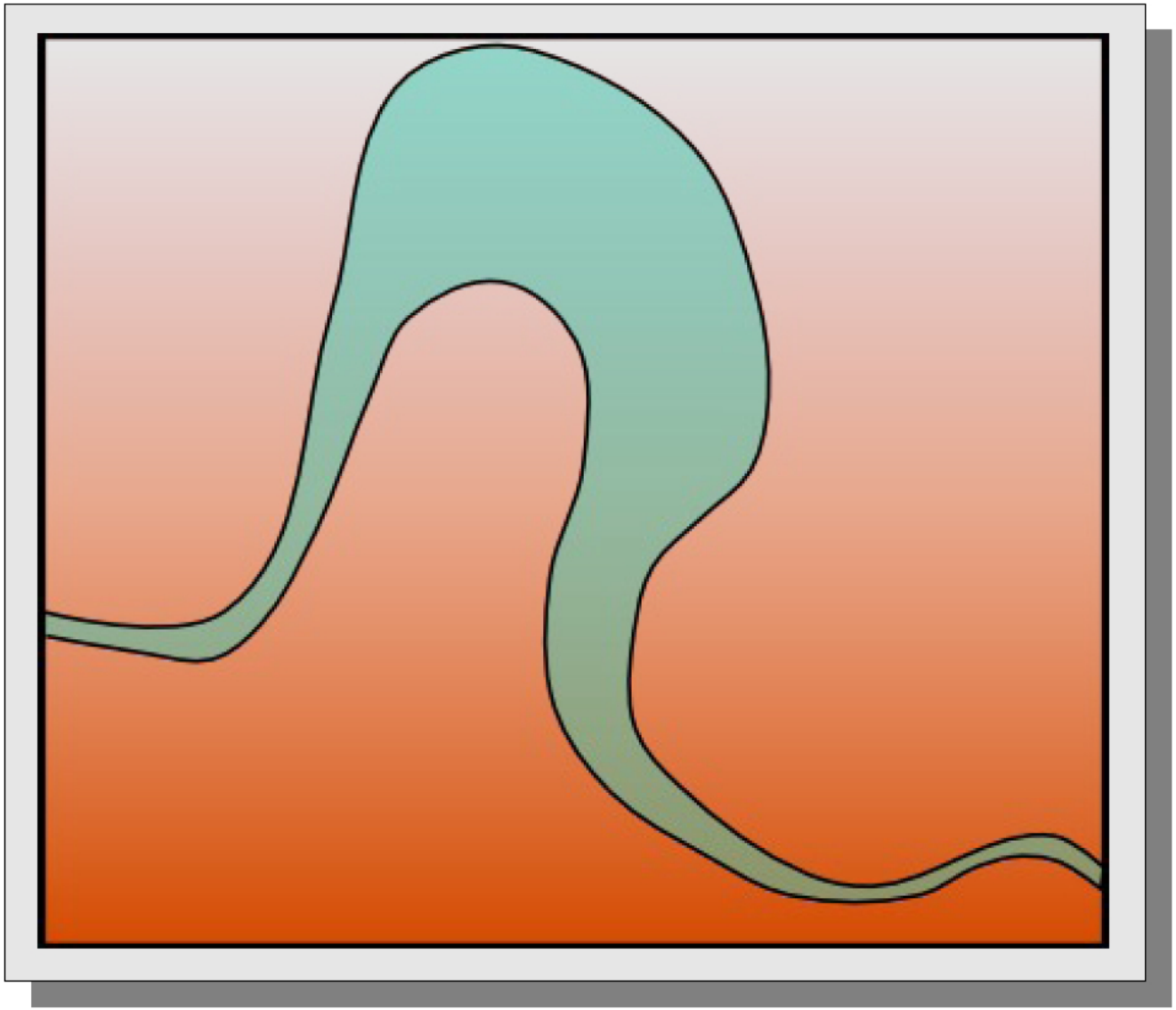
Adiabatic expansion and compression



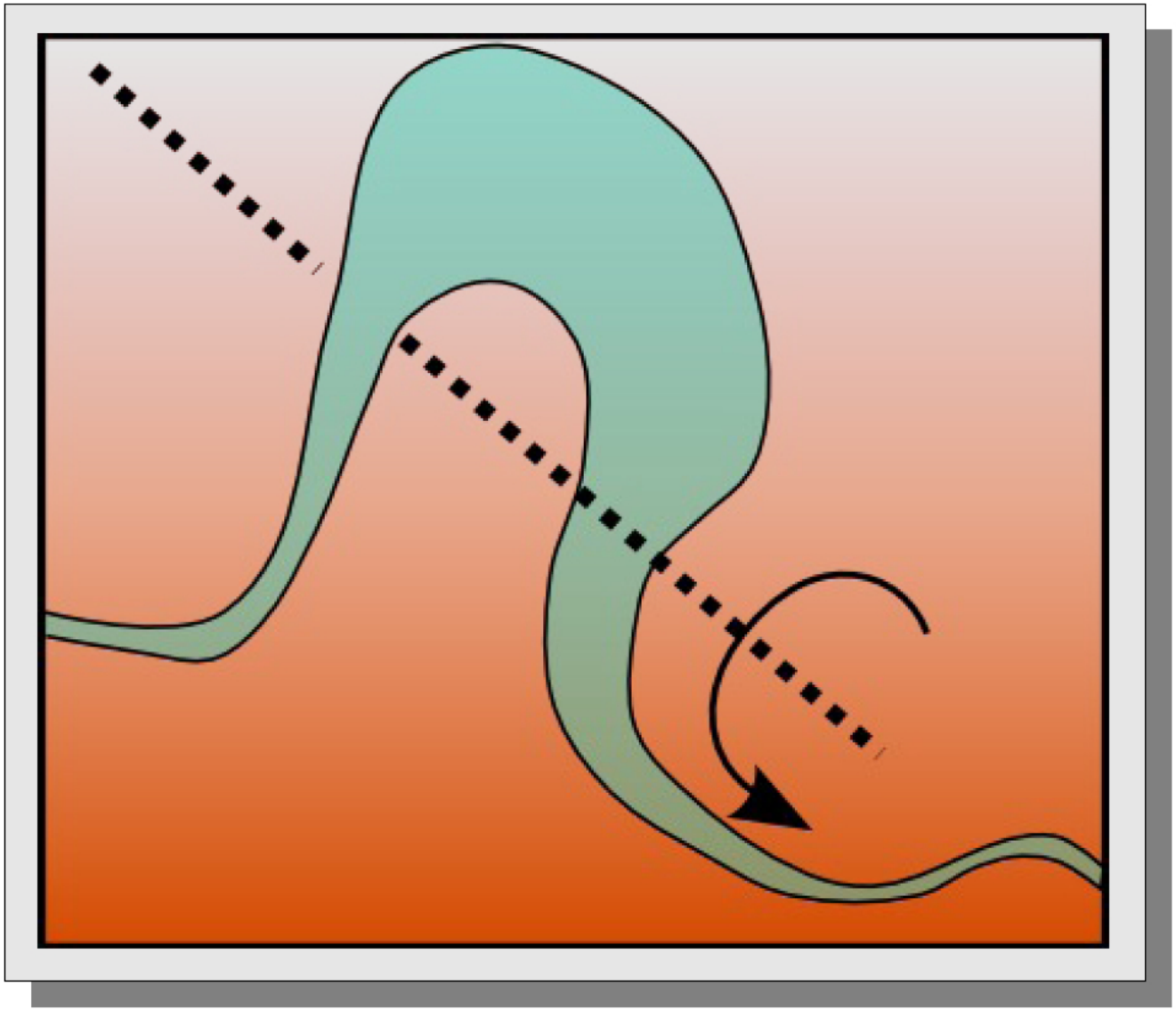
Cosmic ray streaming



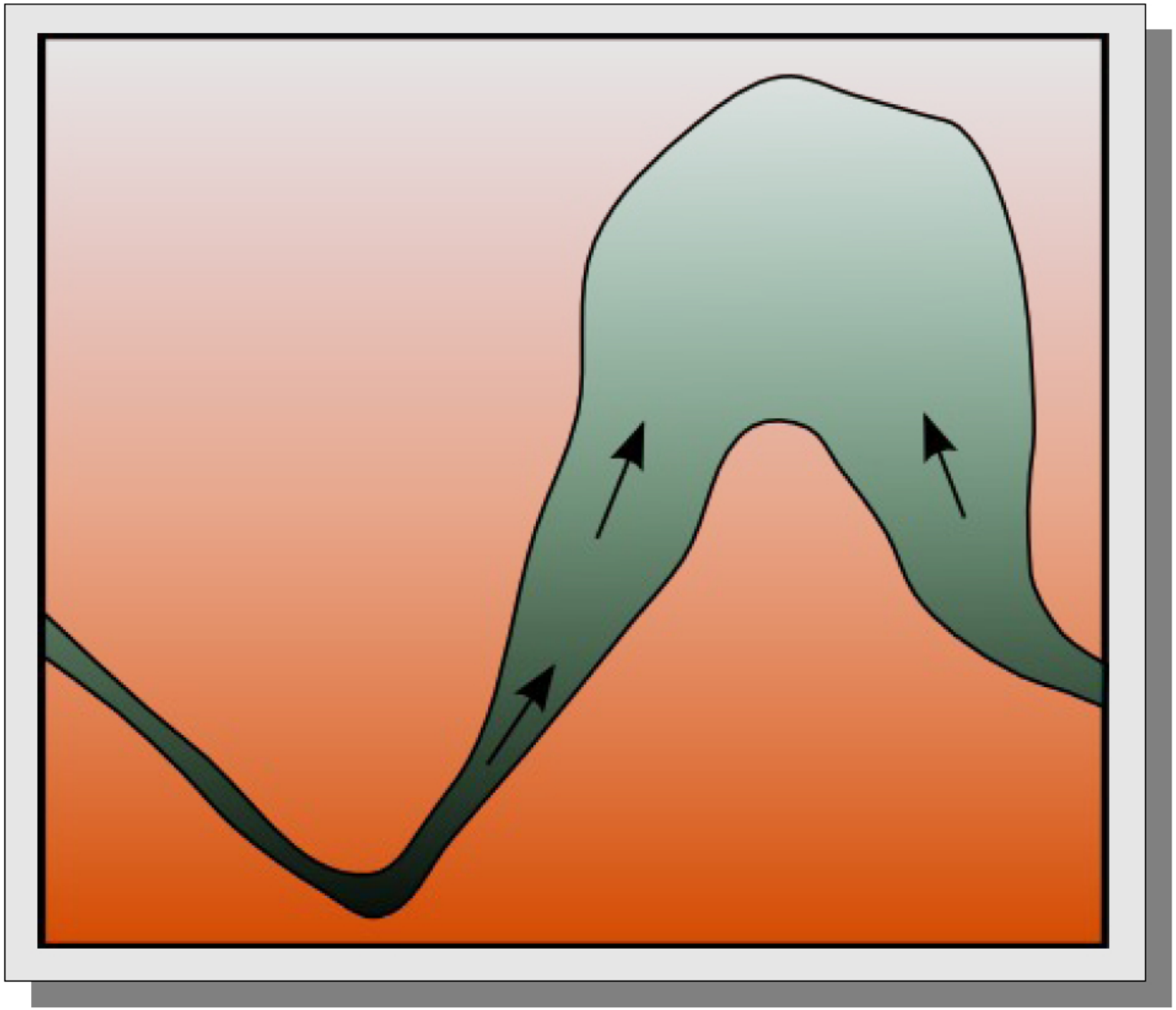
Expanded CRs



Turbulent pumping

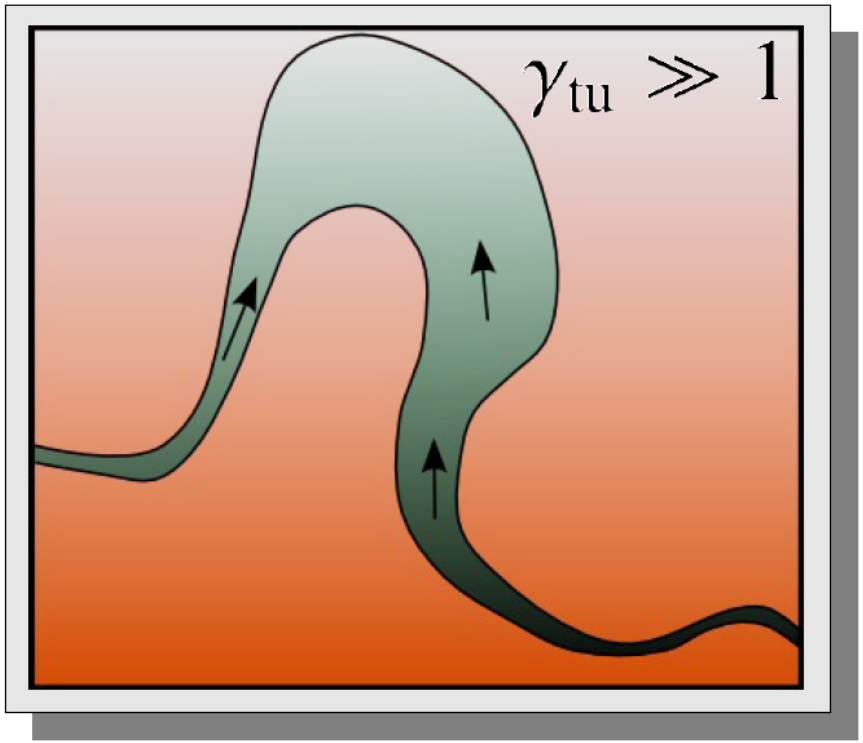


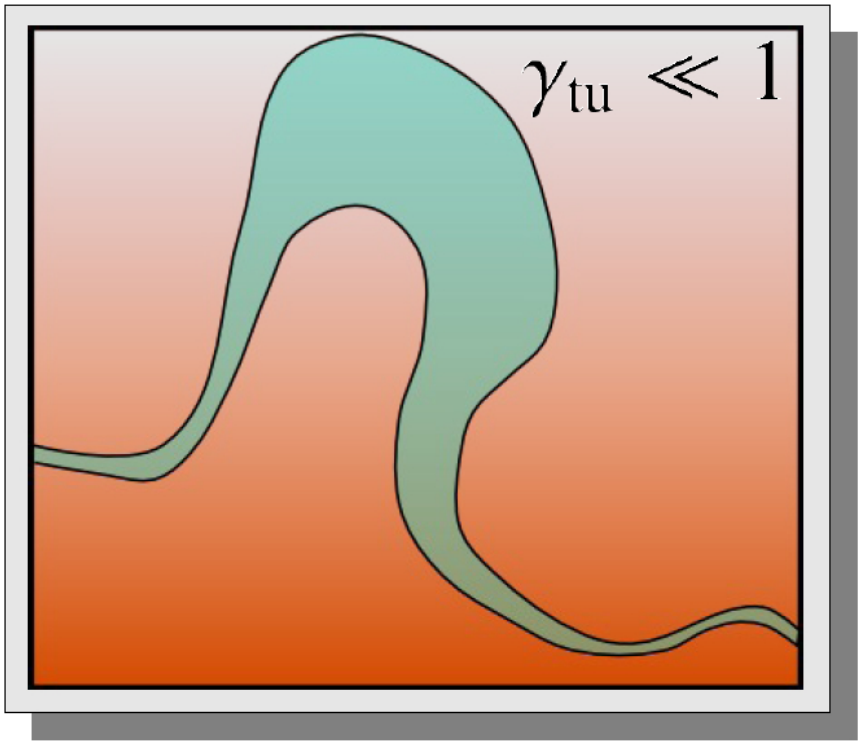
Turbulent pumping



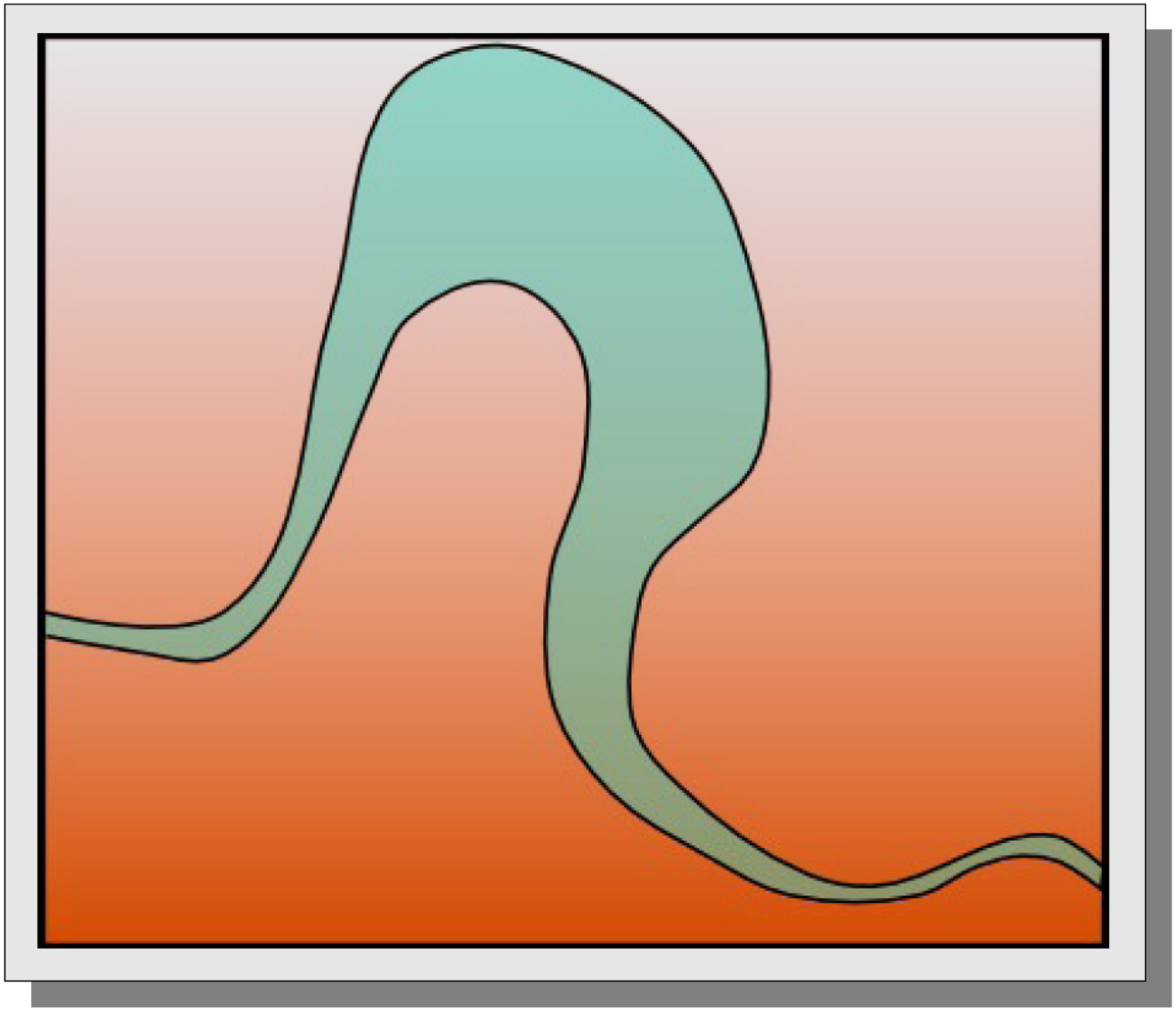
Turbulent-to-streaming ratio

$$\gamma_{\mathrm{tu}} = \frac{\upsilon_{\mathrm{tu}}}{\upsilon_{\mathrm{st}}}$$

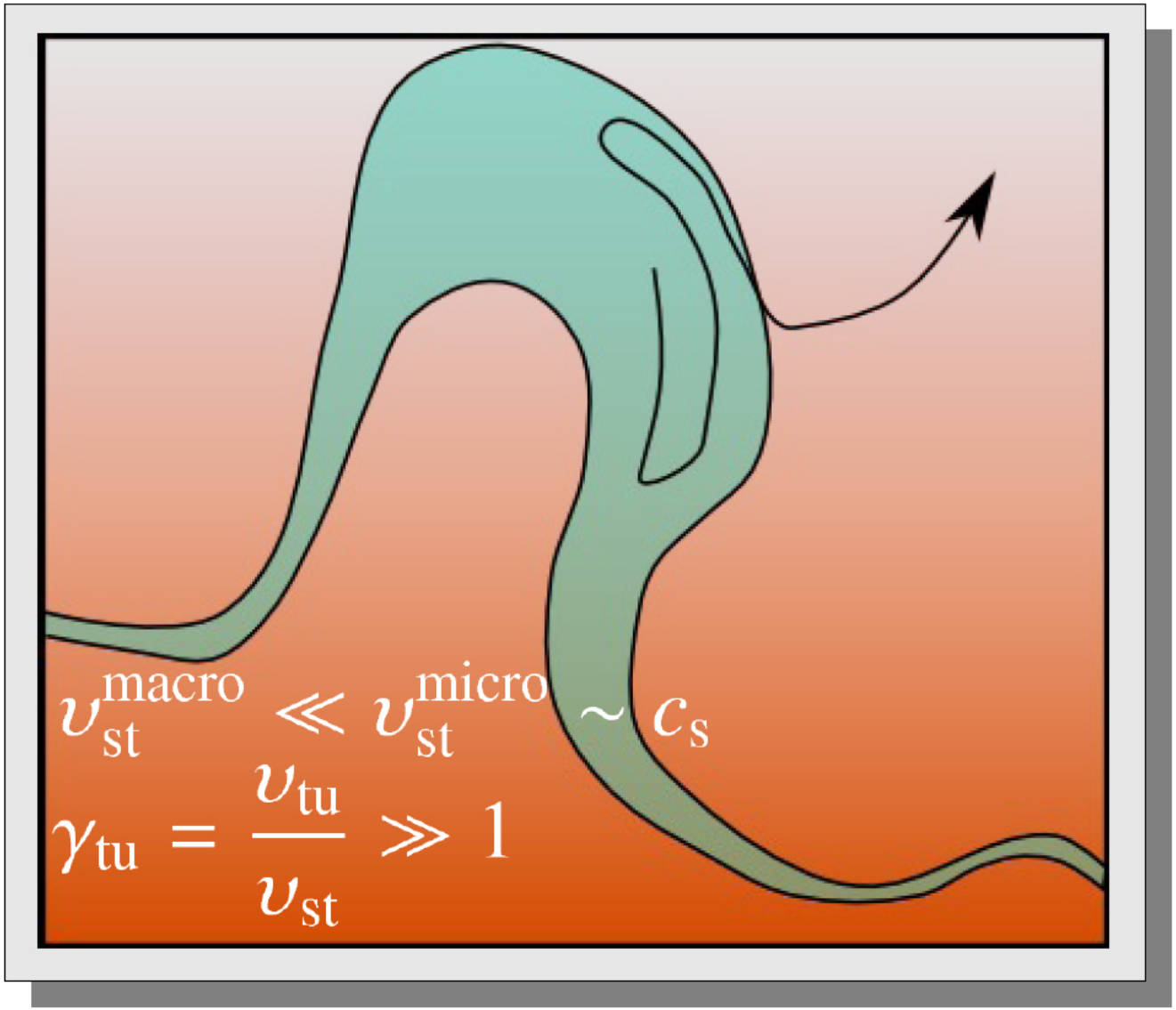




Are CRs confined to magnetic flux tubes?



Escape via diffusion: energy dependence



CR transport theory

CR continuity equation in the absence of sources and sinks:

$$\frac{\partial \varrho}{\partial t} + \vec{\nabla} \cdot (\boldsymbol{v}\, \varrho) = 0$$

$$\boldsymbol{v} = \boldsymbol{v}_{\mathrm{ad}} + \boldsymbol{v}_{\mathrm{di}} + \boldsymbol{v}_{\mathrm{st}}$$

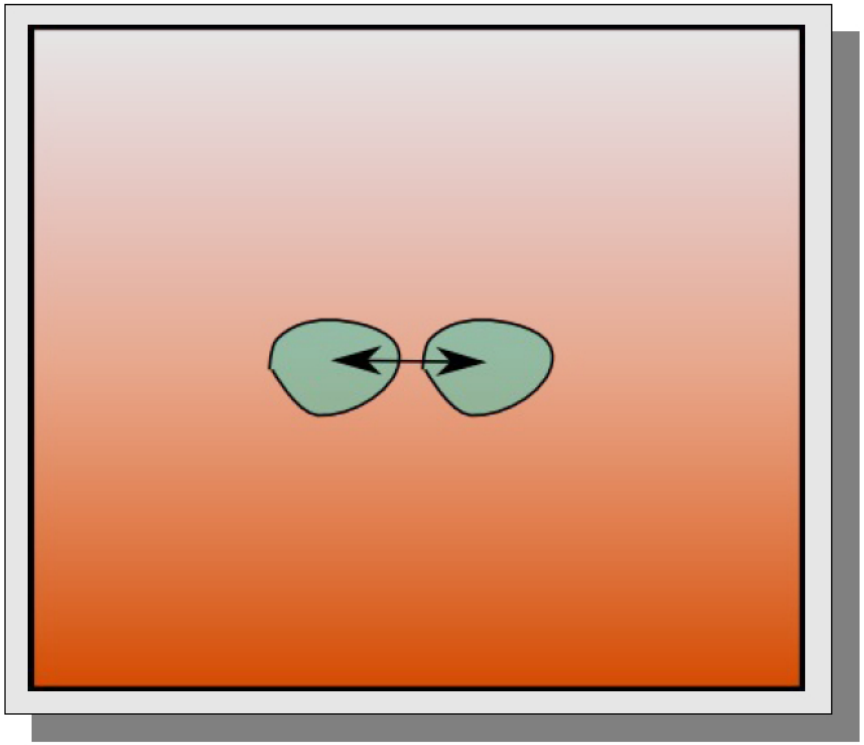
$$\begin{aligned}
\boldsymbol{v}_{\mathrm{st}} &= -v_{\mathrm{st}} \frac{\vec{\nabla}\, \varrho}{|\vec{\nabla}\, \varrho|} \\
\boldsymbol{v}_{\mathrm{di}} &= -\kappa_{\mathrm{di}}\, \frac{1}{\varrho}\, \vec{\nabla} \varrho \\
\boldsymbol{v}_{\mathrm{ad}} &= -\kappa_{\mathrm{tu}}\, \frac{\eta}{\varrho}\, \vec{\nabla} \frac{\varrho}{\eta}
\end{aligned}$$

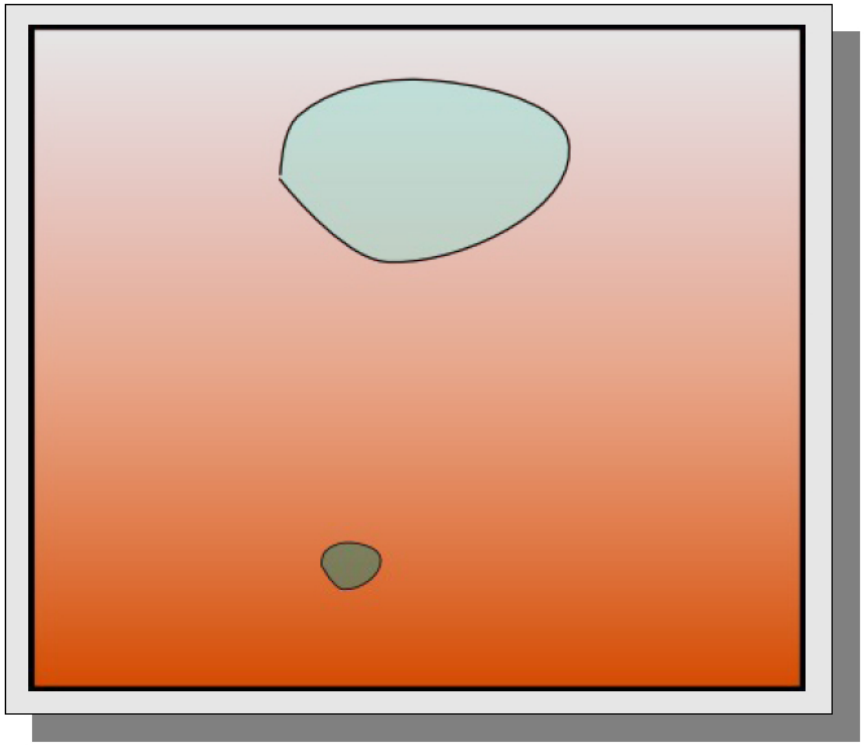
$$\kappa_{\mathrm{tu}} = \frac{L_{\mathrm{tu}}\, v_{\mathrm{tu}}}{3}$$

Enßlin, C.P., Miniati, Subramanian, 2011, A&A, 527, 99

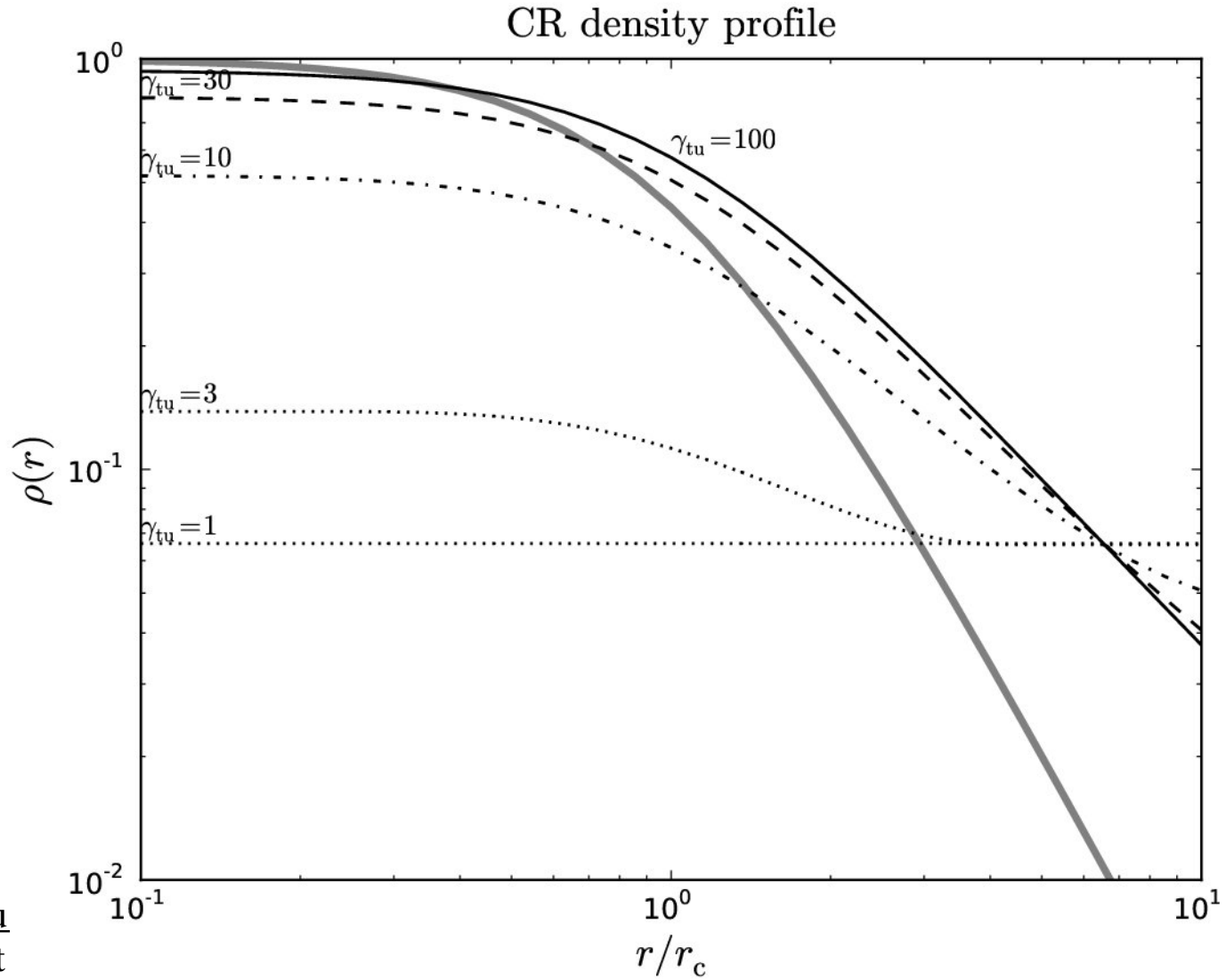
CR profile due to advection

$$\eta(r) = \left(\frac{P(r)}{P_0}\right)^{\frac{3}{5}}$$



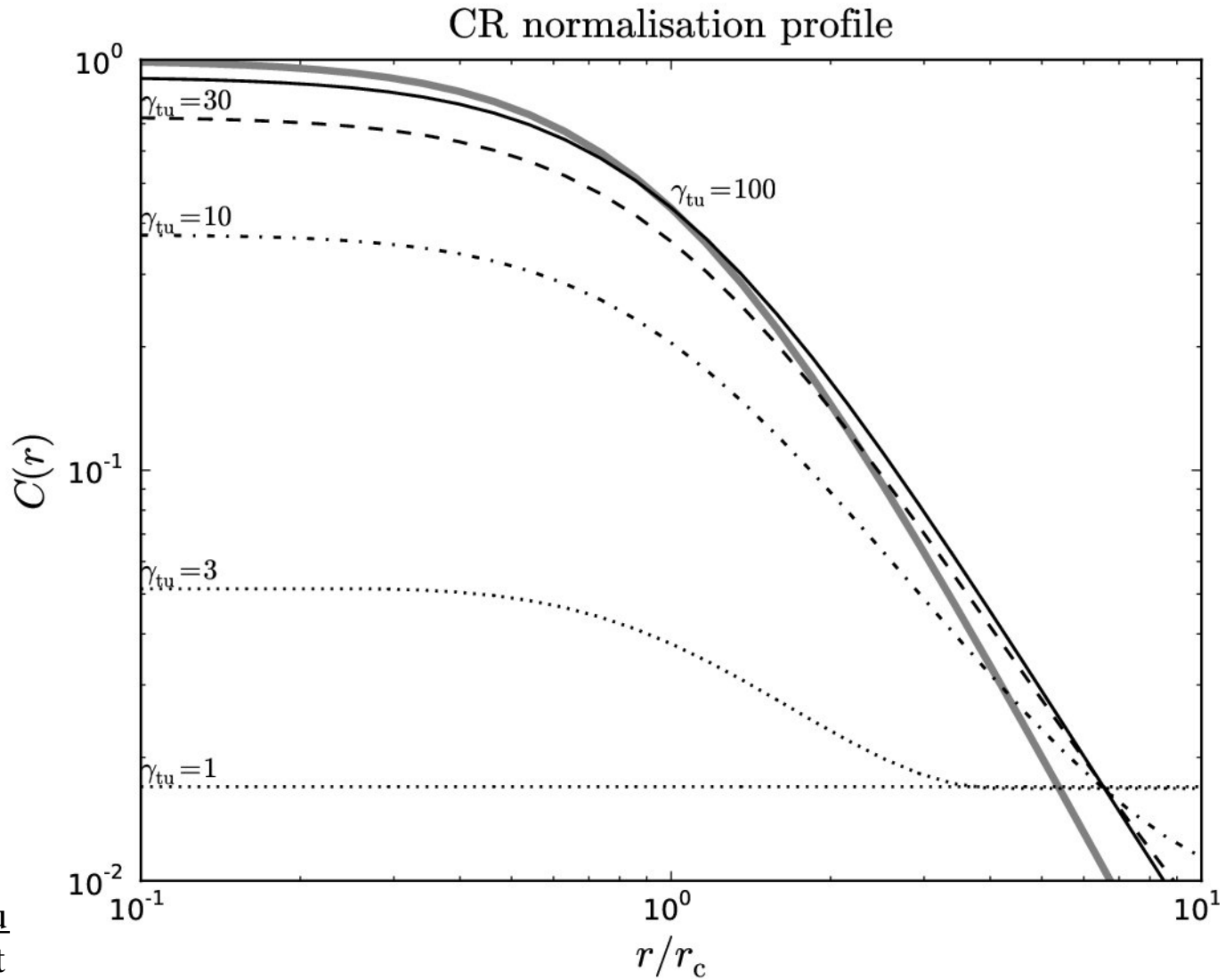


CR density profile



$$\gamma_{tu} = \frac{v_{tu}}{v_{st}}$$

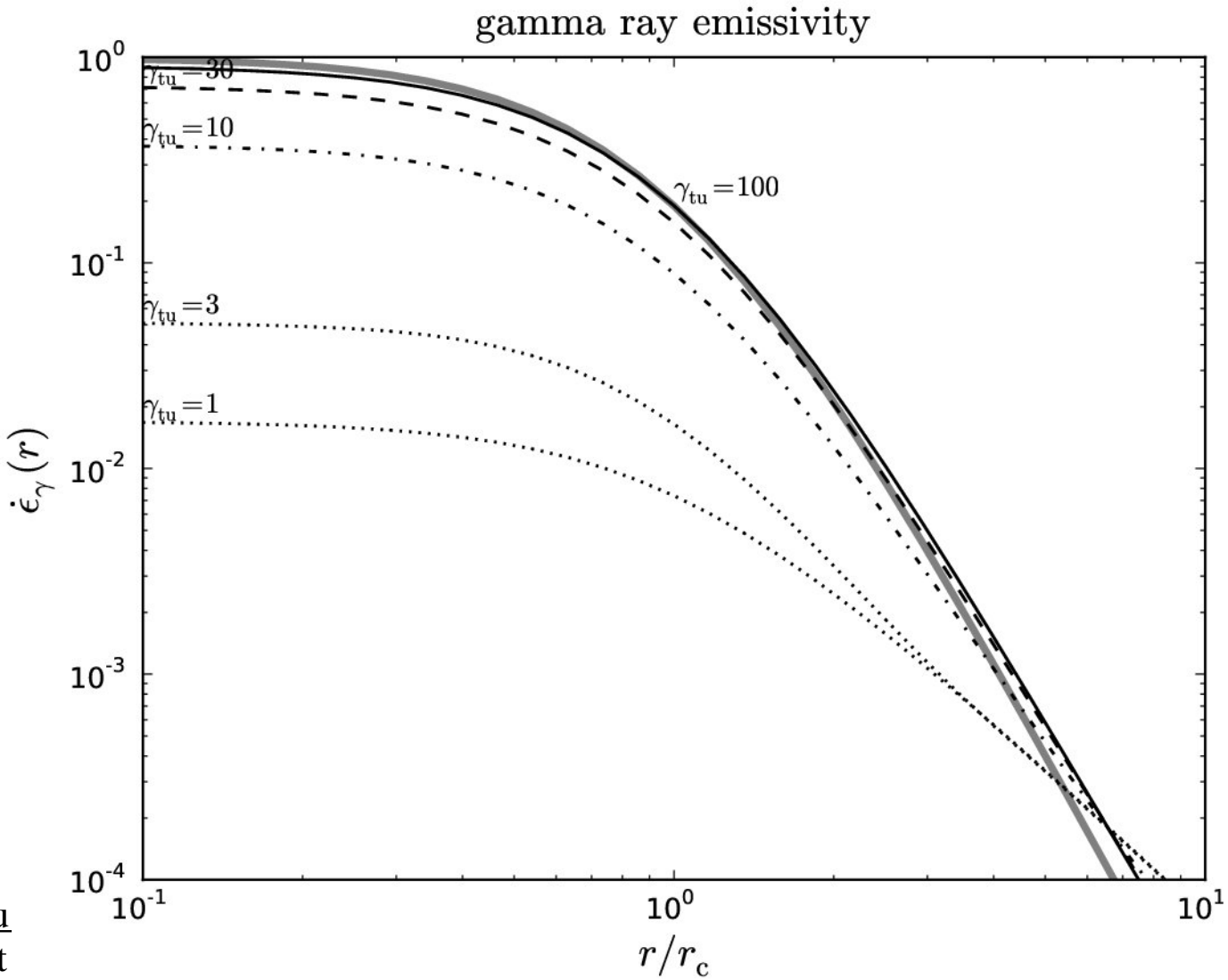
CR density at fixed particle energy



$$\gamma_{\rm tu} = \frac{v_{\rm tu}}{v_{\rm st}}$$

Gamma-ray emission profile

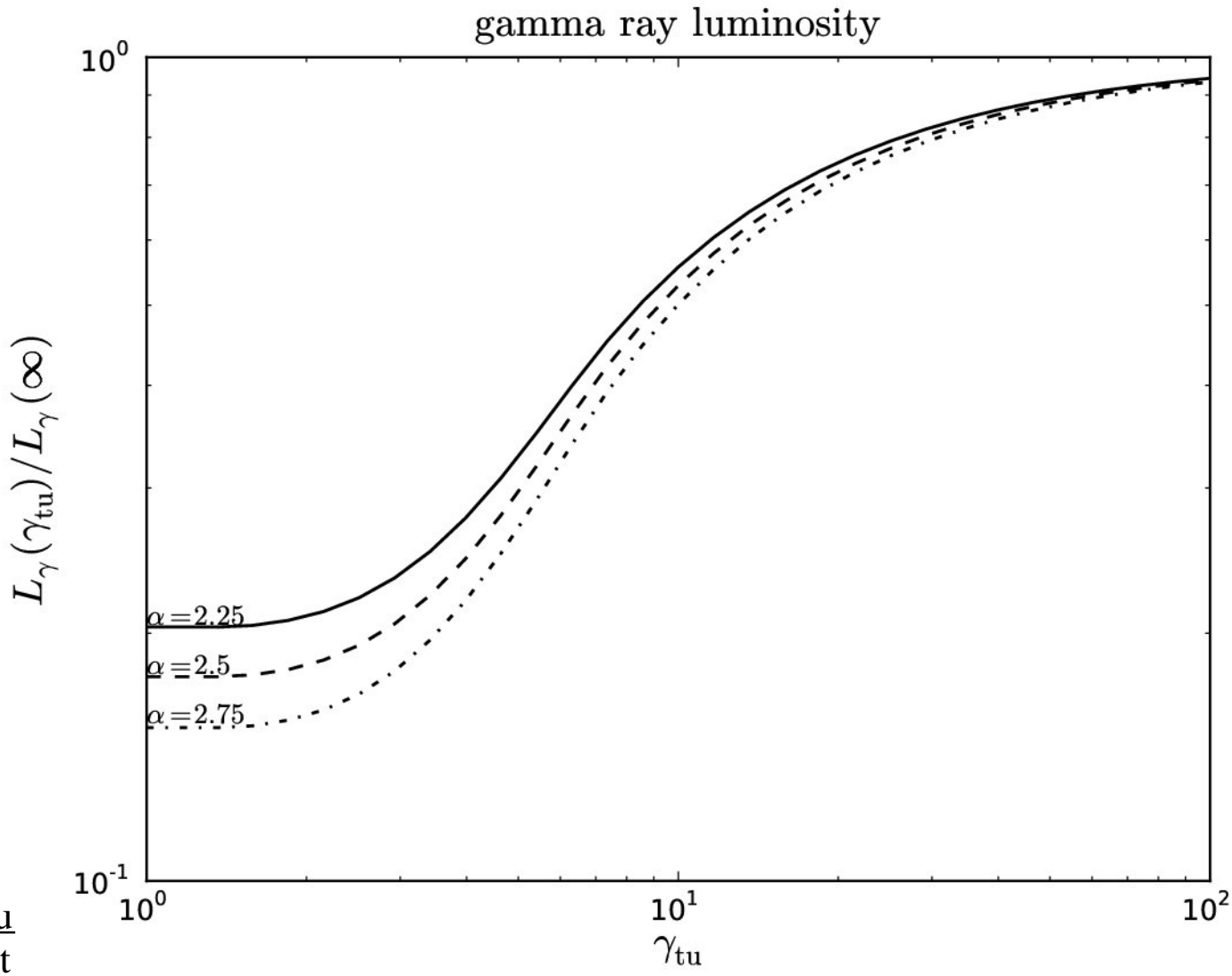
$p_{\mathrm{CR}} + p \rightarrow \pi^0 \rightarrow 2\gamma$



$$\gamma_{\mathrm{tu}} = \frac{v_{\mathrm{tu}}}{v_{\mathrm{st}}}$$

Gamma-ray luminosity

$p_{\mathrm{CR}} + p \rightarrow \pi^0 \rightarrow 2\gamma$



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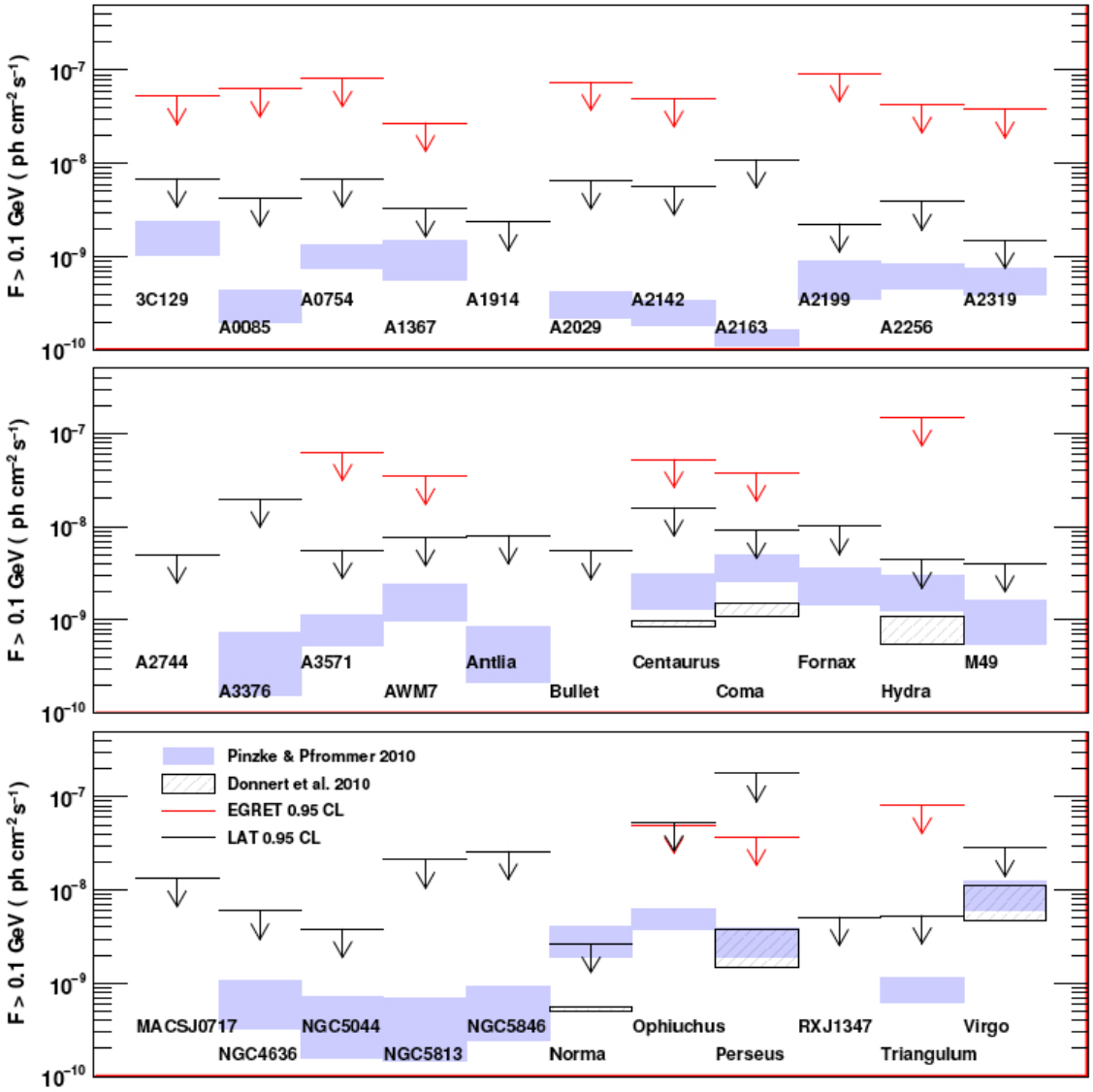
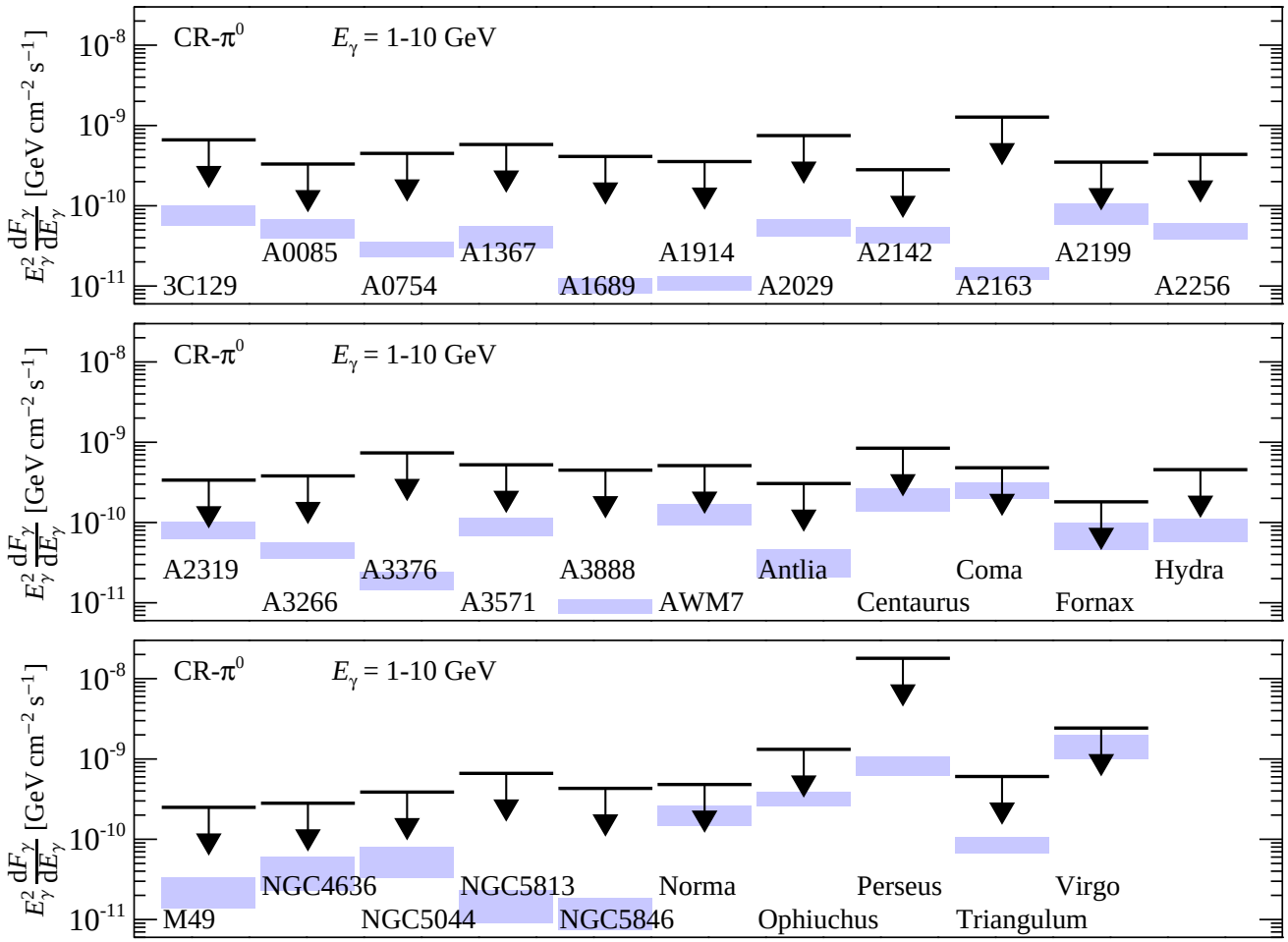
γ-ray limits and hadronic predictions (Ackermann et al. 2010)

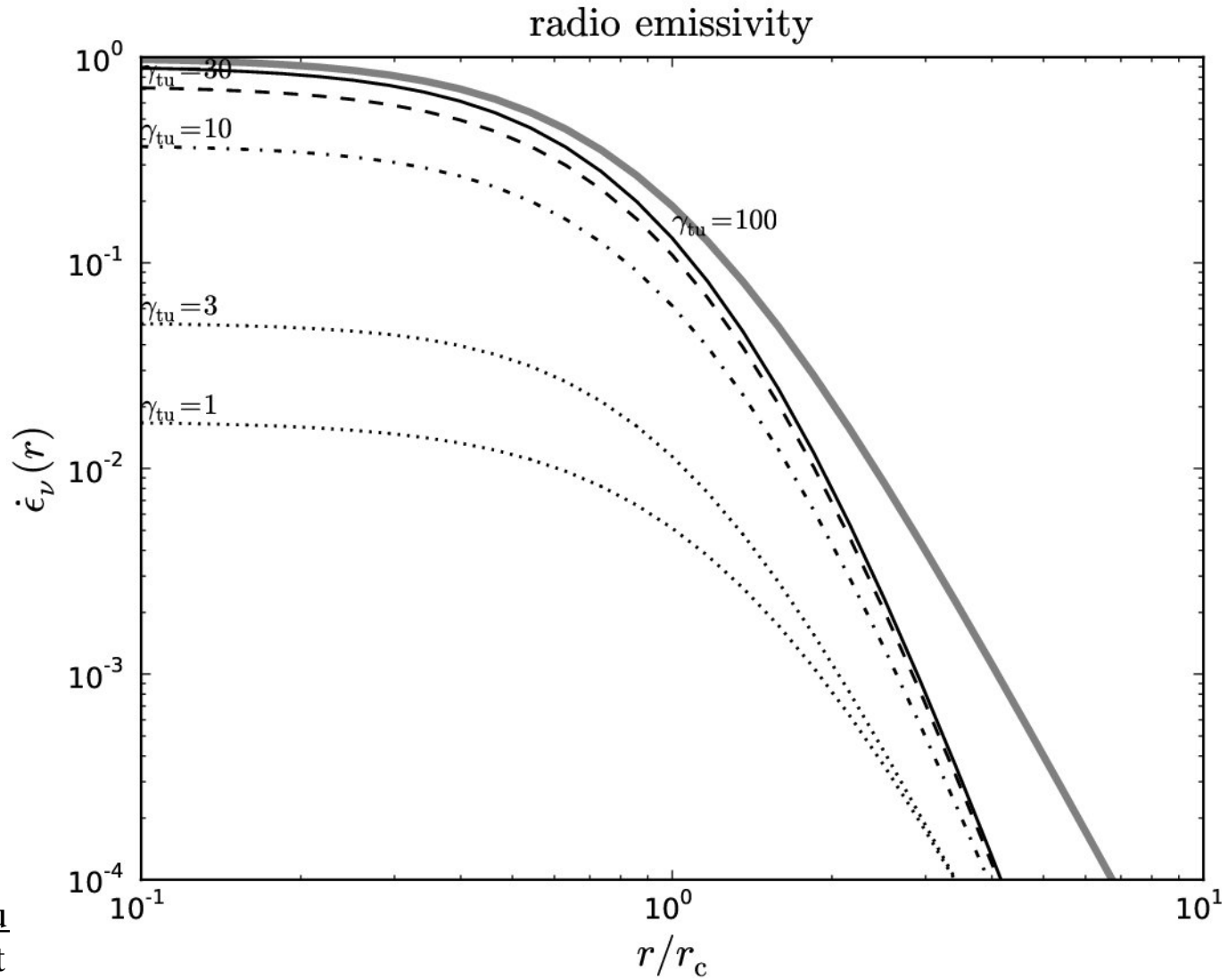


γ-ray limits and hadronic predictions (Pinzke et al. 2011)



Radio emission profile

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



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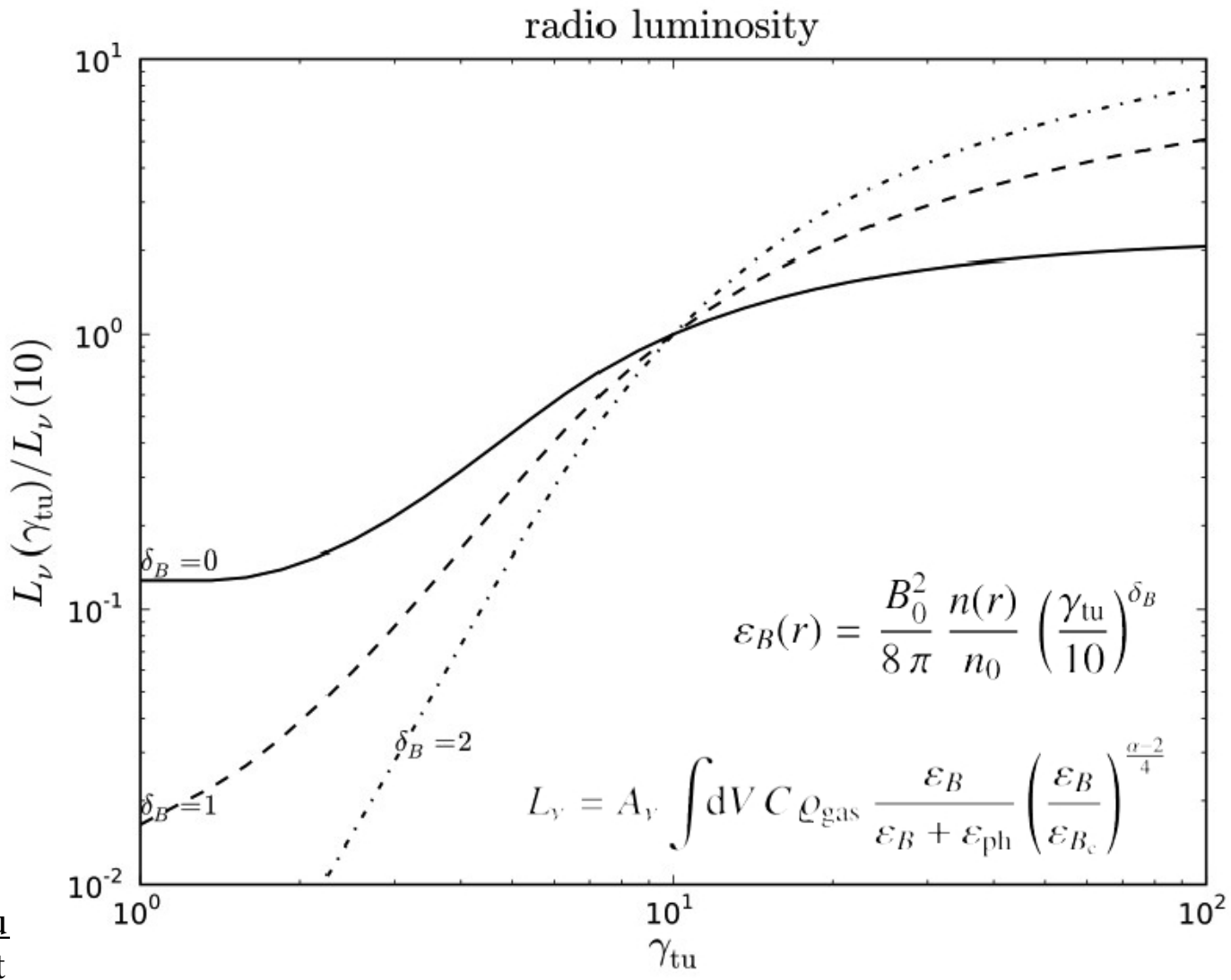

$$\gamma_{\mathrm{tu}} = \frac{\upsilon_{\mathrm{tu}}}{\upsilon_{\mathrm{st}}}$$

Conclusions on cosmic ray transport

- streaming & diffusion produce spatially flat CR profiles
  advection produces centrally enhanced CR profiles
  $\longrightarrow$ profile depends on advection-to-streaming-velocity ratio
- turbulent velocity $\sim$ sound speed $\leftarrow$ cluster merger
  CR streaming velocity $\sim$ sound speed $\leftarrow$ plasma physics
  $\longrightarrow$ peaked/flat CR profiles in merging/relaxed clusters
- energy dependence of $v_{\rm st}^{\rm macro}$ $\longrightarrow$ CR & radio spectral variations
  $\longrightarrow$ outstreaming CR: dying halo $\leftarrow$ decaying turbulence

$\longrightarrow$ bimodality of cluster radio halos & gamma-ray emission!

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Literature for the talk

- Enßlin, Pfrommer, Miniati, Subramanian, 2011, A&A, 527, 99,
  Cosmic ray transport in galaxy clusters: implications for radio halos, gamma-ray signatures, and cool core heating
- Battaglia, Pfrommer, Sievers, Bond, Enßlin, 2009, MNRAS, 393, 1073,
  Exploring the magnetized cosmic web through low frequency radio emission