Shocking Astrophysics in Galaxy Clusters

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in collaboration with

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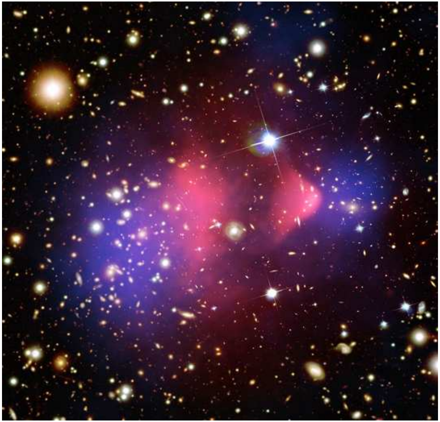
Outline

1. Non-thermal emission
   - Introduction
   - Physical processes
   - Radio halos and relics
2. Cosmic ray transport
   - Observations and models
   - CR pumping, streaming, and diffusion
   - Radio and gamma-ray bimodality
3. Probes of accretion shocks
   - A puzzling radio galaxy
   - Radio galaxy-bubble system
   - Radio gischt emission

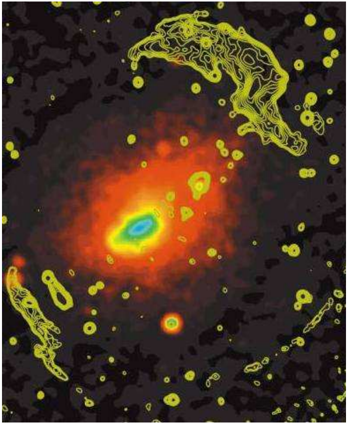
Outline

Shocks in galaxy clusters



1E 0657-56 (“Bullet cluster”)

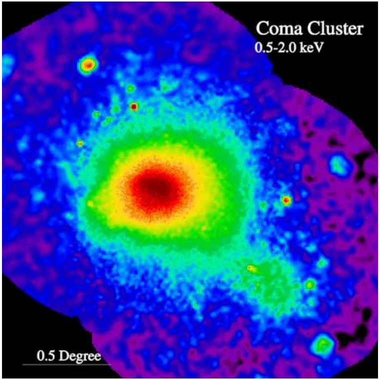
(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)



Abell 3667

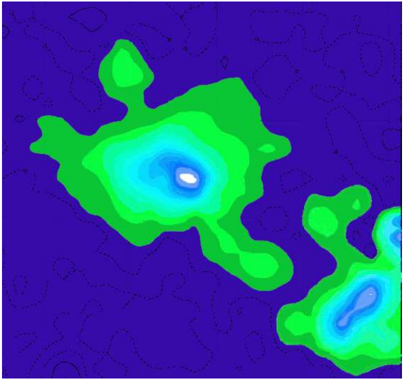
(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

Giant radio halo in the Coma cluster



thermal X-ray emission

(Snowden/MPE/ROSAT)



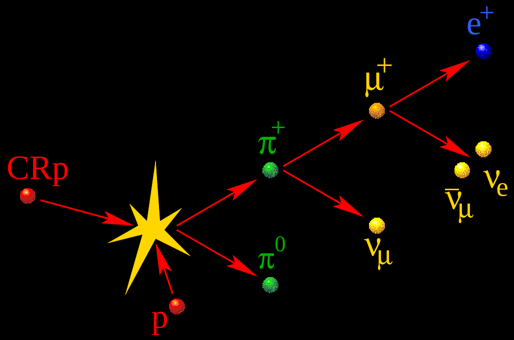
radio synchrotron emission

(Deiss/Effelsberg)

What can we learn from non-thermal emission?

- plasma astrophysics:
  - shock and particle acceleration
  - large-scale magnetic fields
  - turbulence
- dynamical state → 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

Hadronic cosmic ray proton interaction



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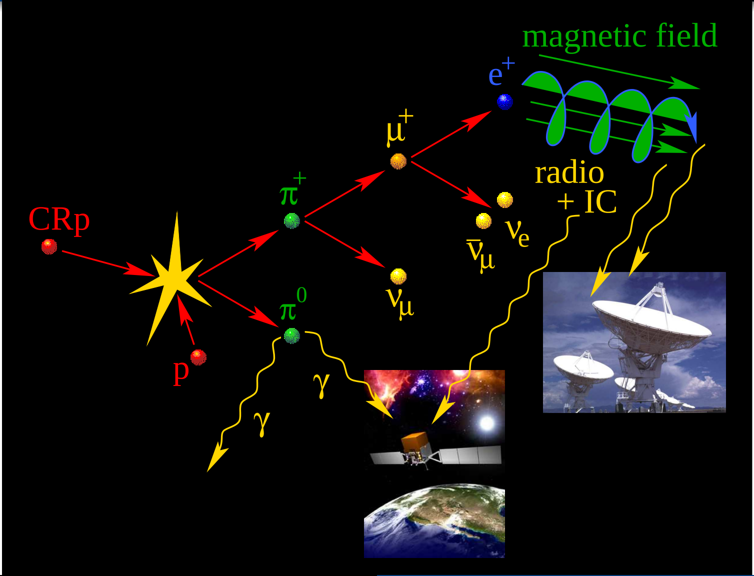
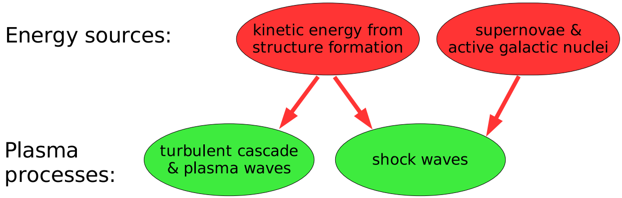


Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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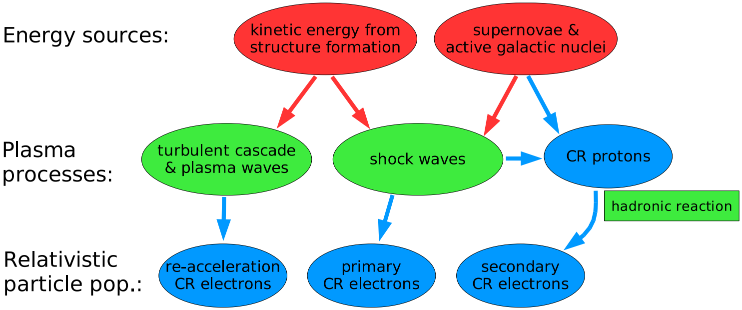

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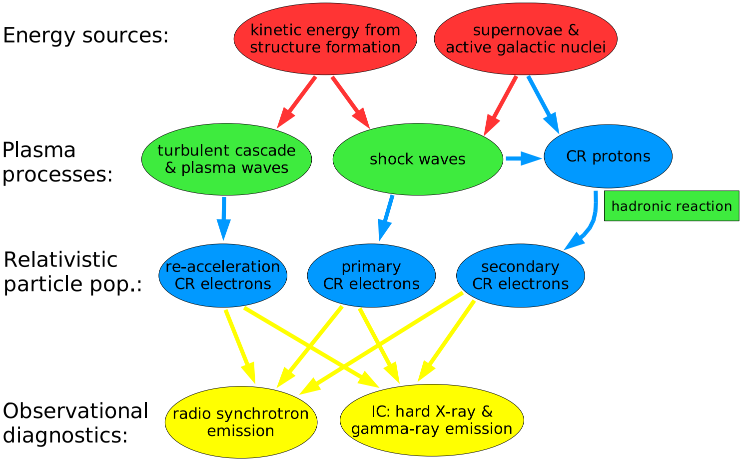

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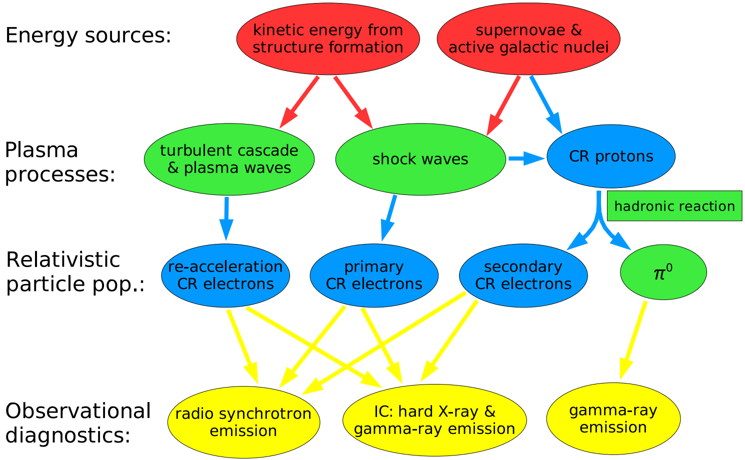
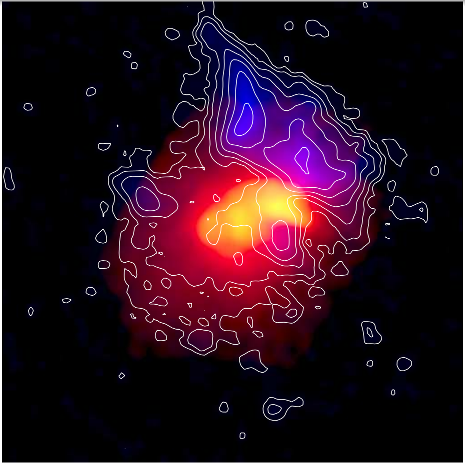
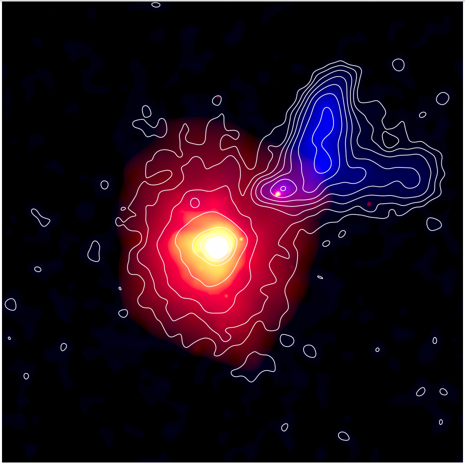


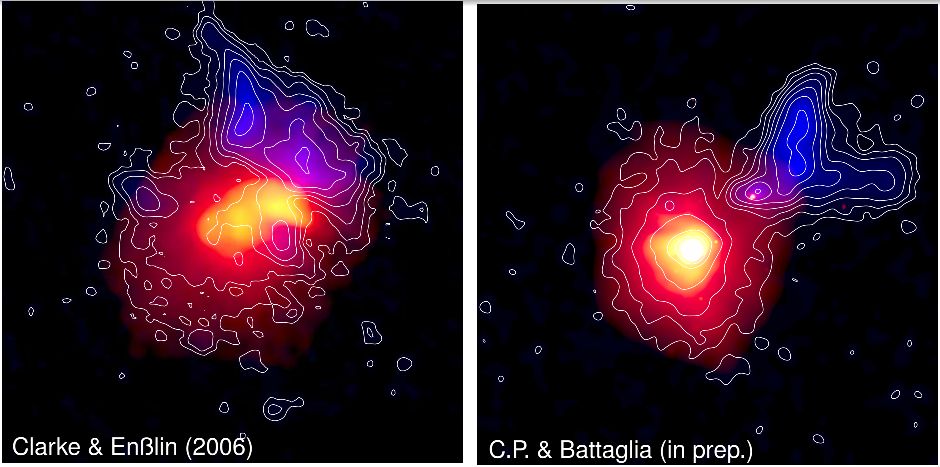
Which one is the simulation/observation of A2256?





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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Outline

Radio halo theory – (i) hadronic model

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

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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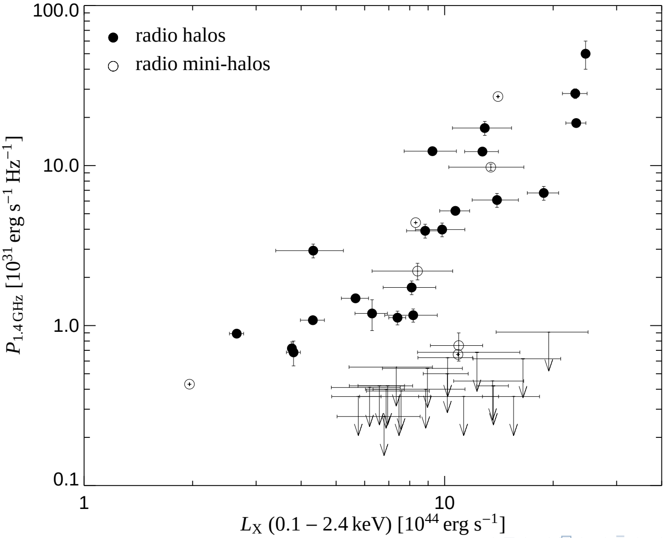
Radio luminosity - X-ray luminosity



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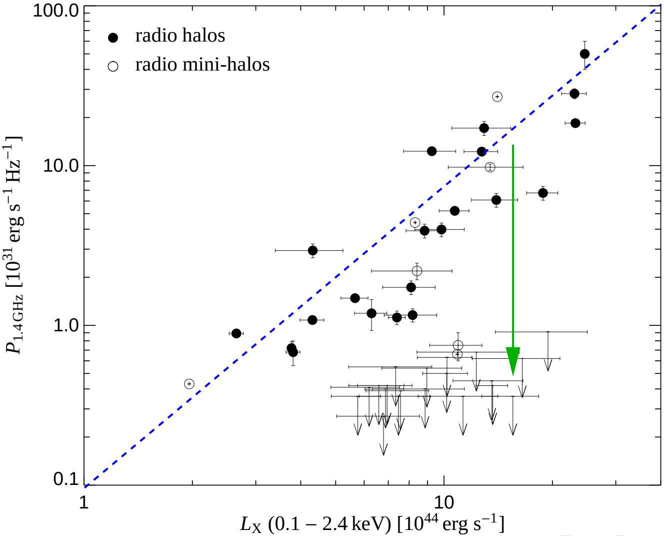

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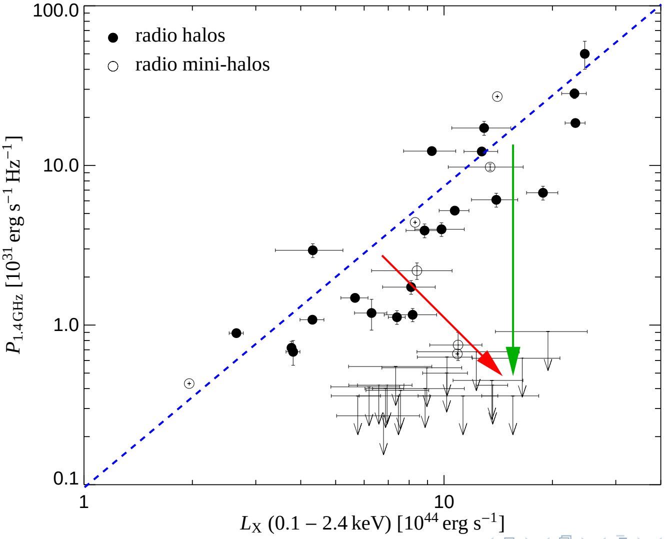
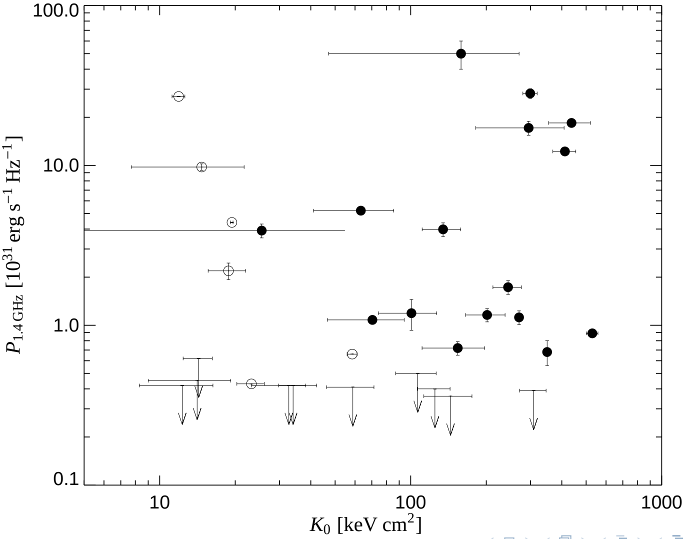


Radio luminosity - central entropy



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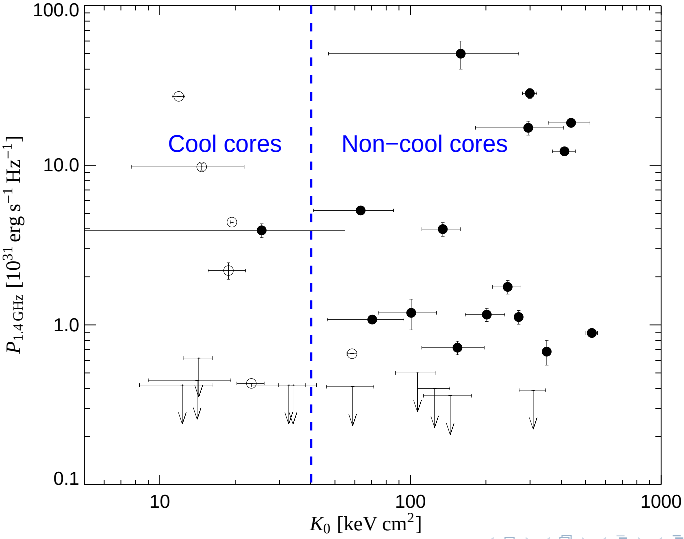

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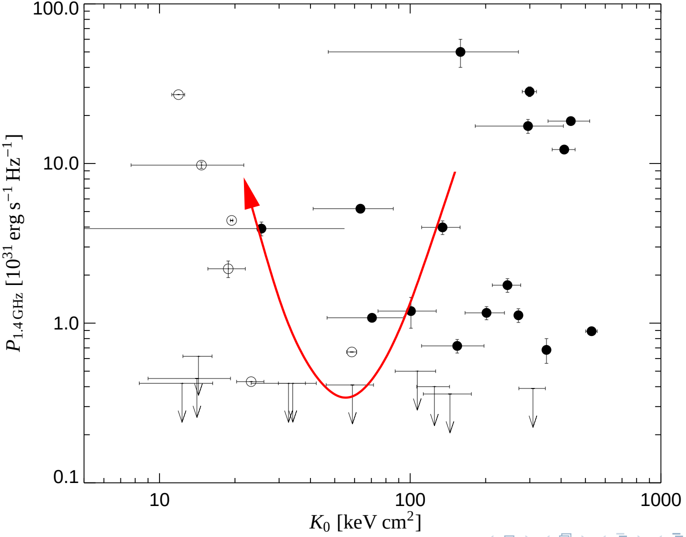

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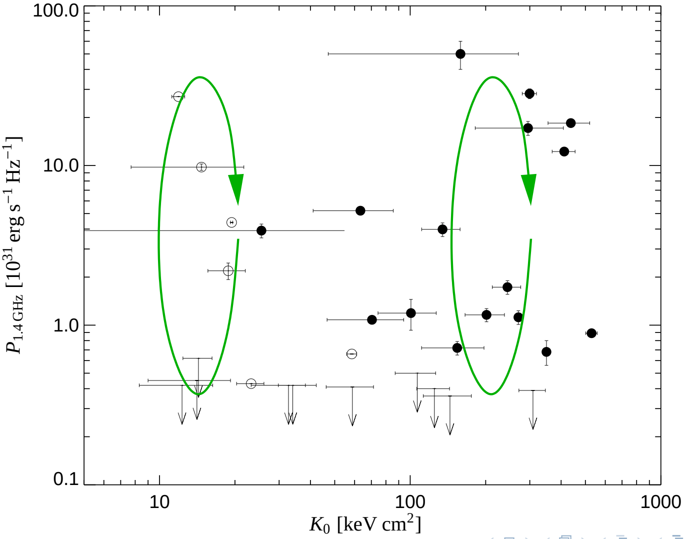
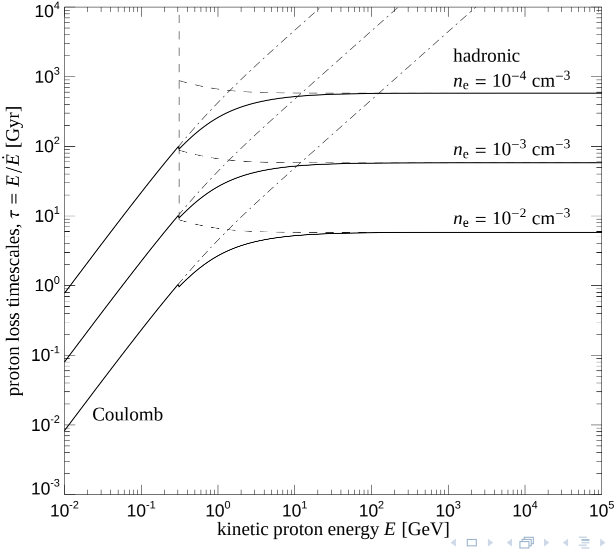


Proton cooling times



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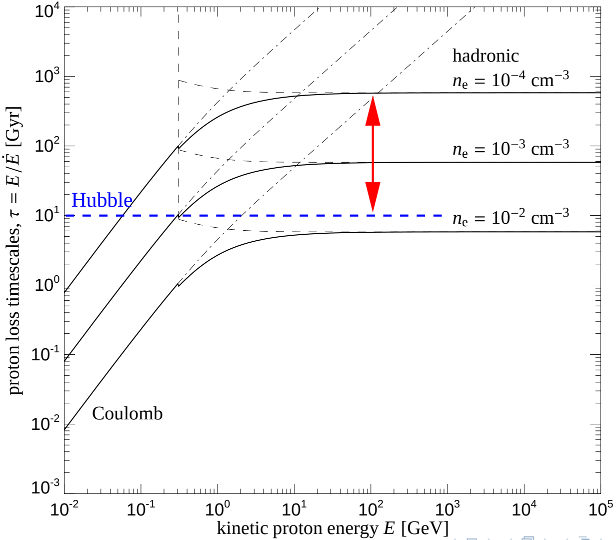

Radio halo theory – (ii) re-acceleration model

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- reported complex radio spectra emerge naturally
- clusters without halos $\leftarrow$ less turbulent

weakness:

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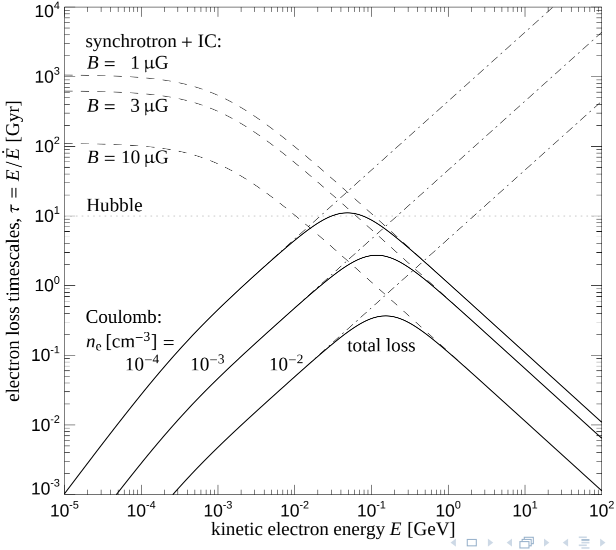
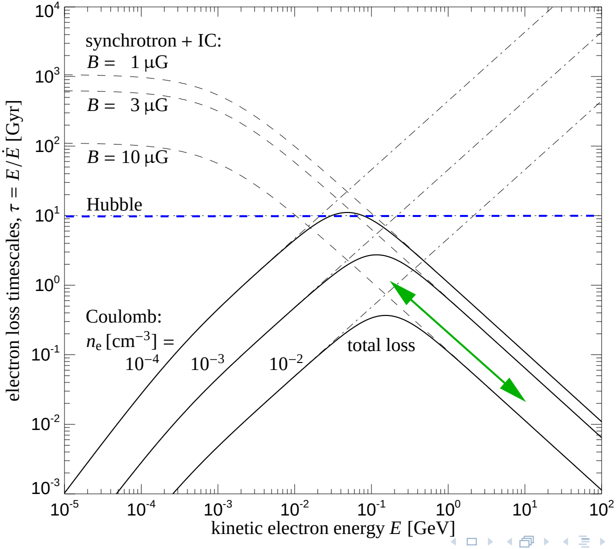
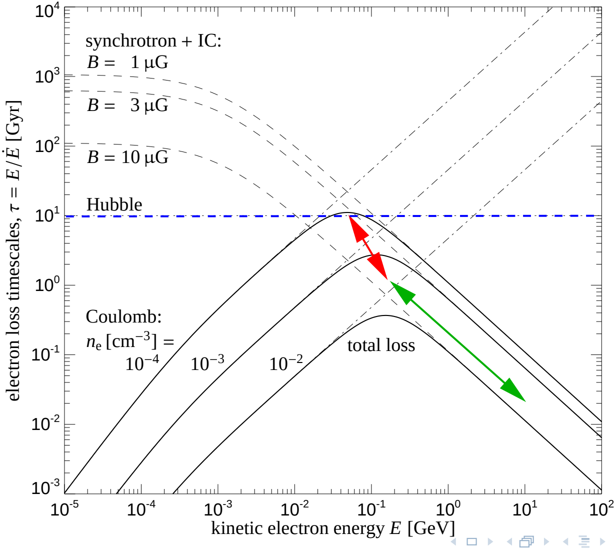
Electron cooling times



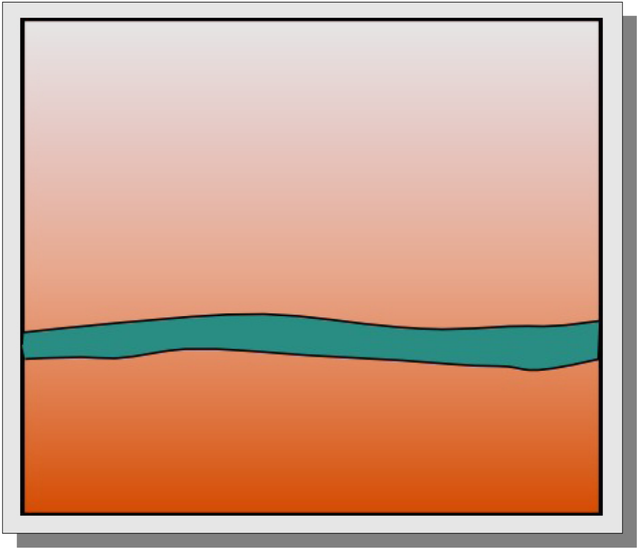
Electron cooling times



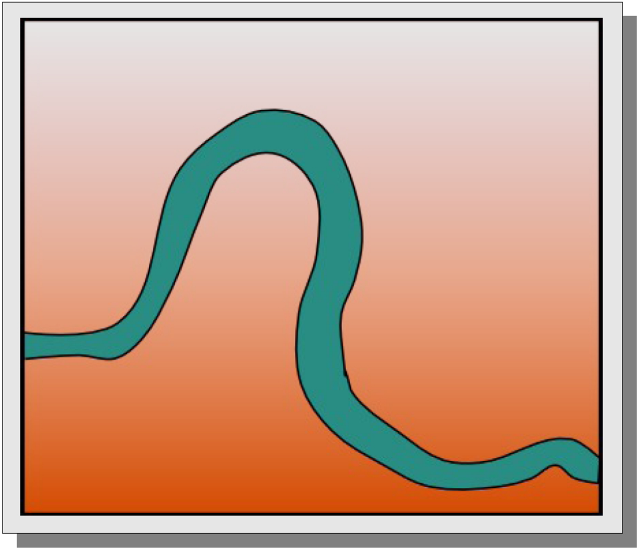
Electron cooling times



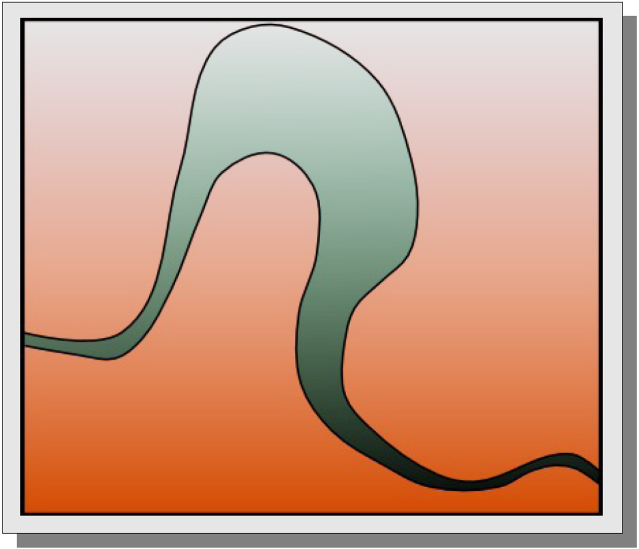
Cosmic ray transport – magnetic flux tube with CRs



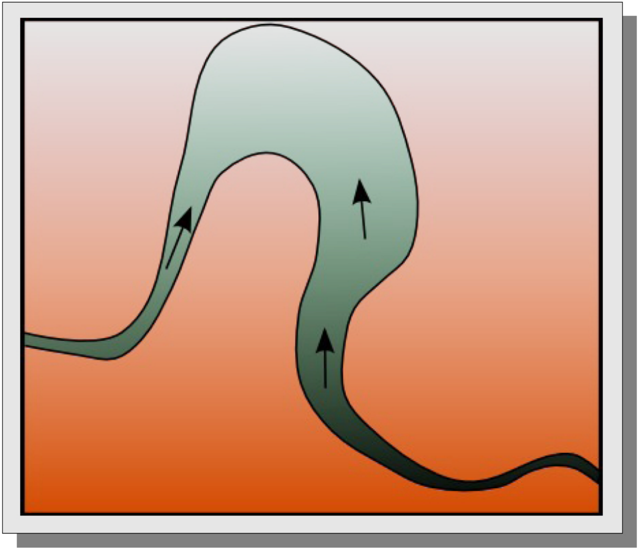
Cosmic ray advection



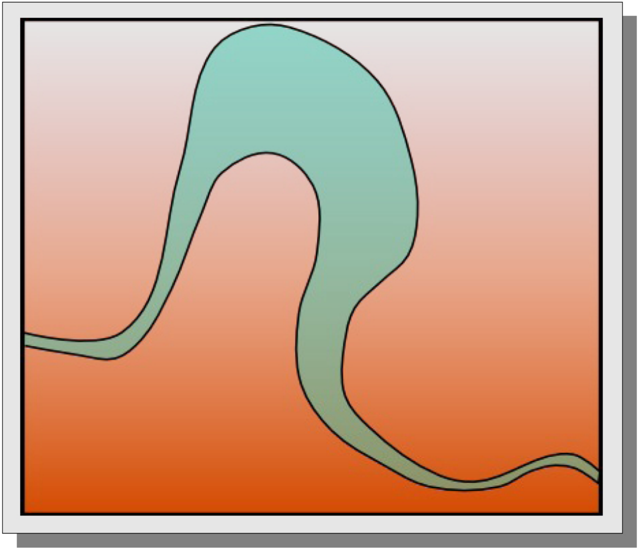
Adiabatic expansion and compression



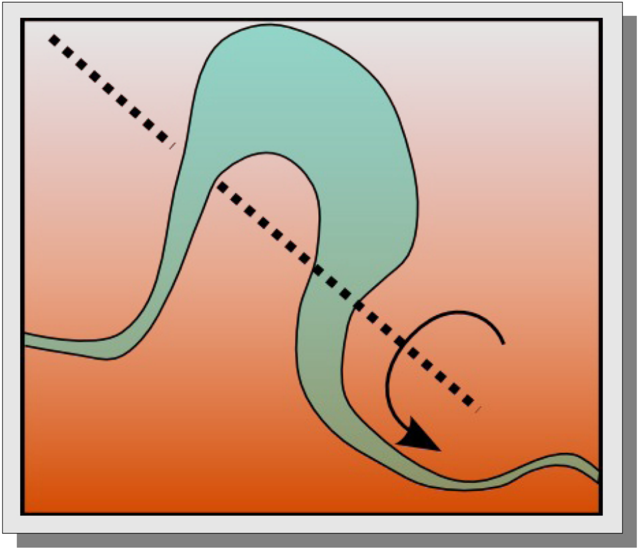
Cosmic ray streaming



Expanded CRs



Turbulent pumping



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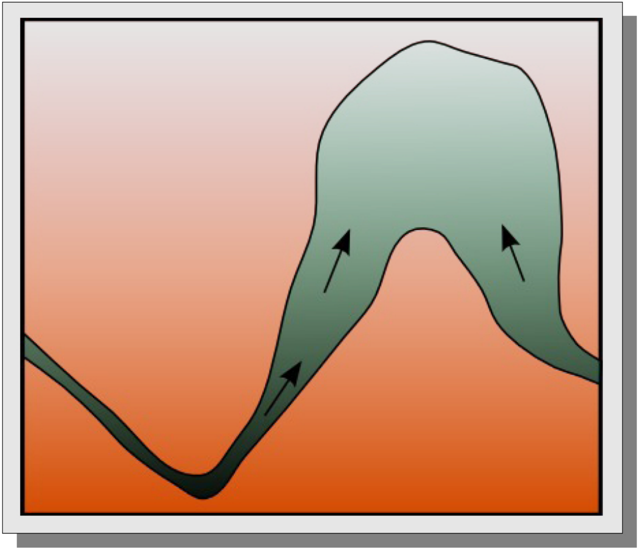
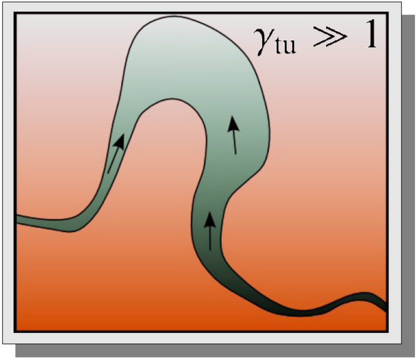
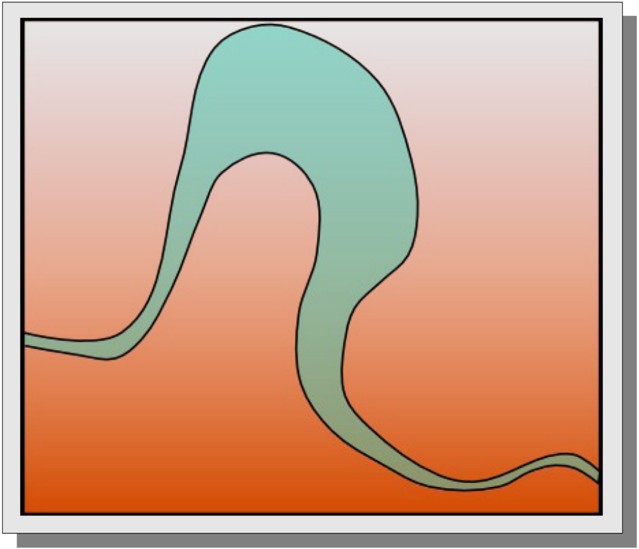


Turbulent-to-streaming ratio

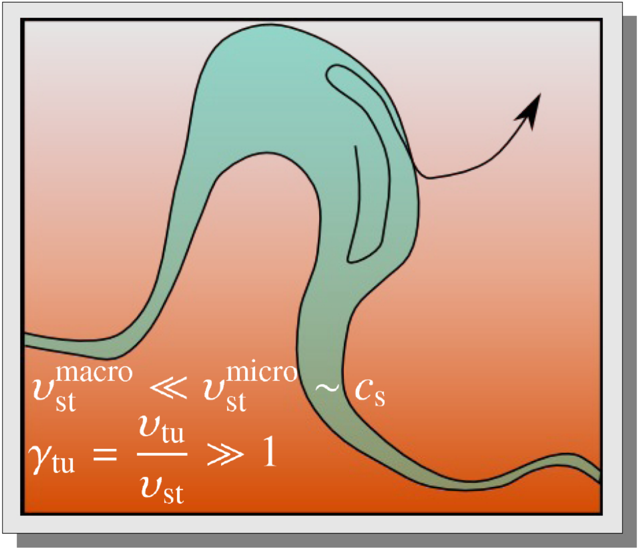
$$\gamma_{\rm tu} = \frac{\upsilon_{\rm tu}}{\upsilon_{\rm st}}$$



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:

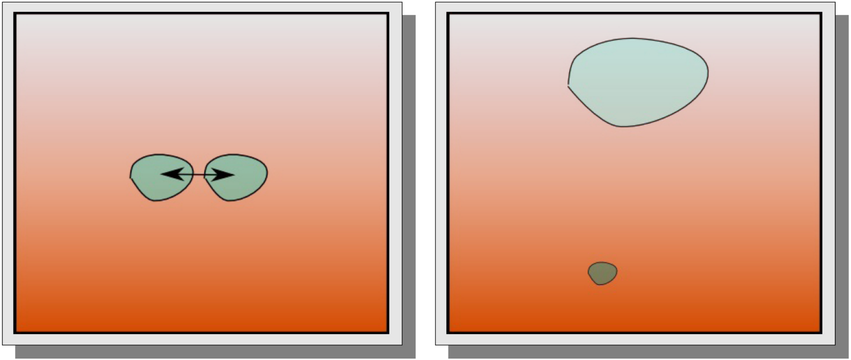
$$\frac{\partial \varrho}{\partial t} + \vec{\nabla} \cdot (\boldsymbol{v}\, \varrho) = 0 \qquad \boldsymbol{v} = \boldsymbol{v}_{\rm ad} + \boldsymbol{v}_{\rm di} + \boldsymbol{v}_{\rm st}$$

$$\begin{aligned} \boldsymbol{v}_{\rm st} &= -v_{\rm st} \frac{\vec{\nabla}\, \varrho}{|\vec{\nabla}\, \varrho|} \\ \boldsymbol{v}_{\rm di} &= -\kappa_{\rm di} \frac{1}{\varrho} \vec{\nabla} \varrho \\ \boldsymbol{v}_{\rm ad} &= -\kappa_{\rm tu} \frac{\eta}{\varrho} \vec{\nabla} \frac{\varrho}{\eta} \end{aligned} \qquad \kappa_{\rm tu} = \frac{L_{\rm tu}\, v_{\rm tu}}{3}$$

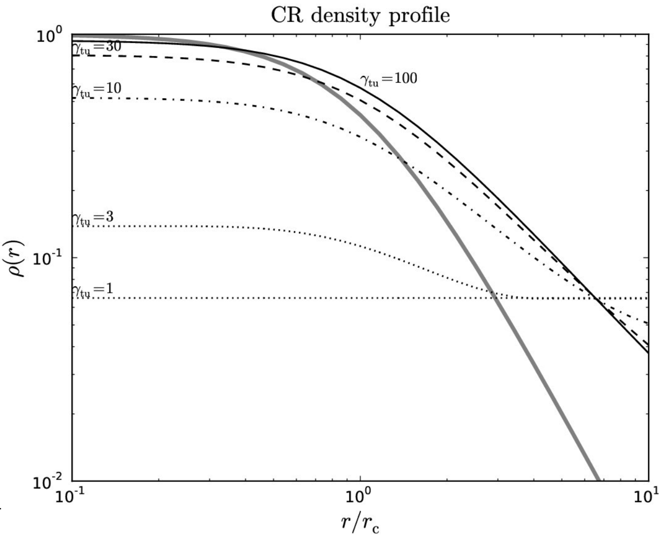
Enßlin, C.P., Miniati, Subramanian, 2011, A&A, 527, 99

CR profile due to advection

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

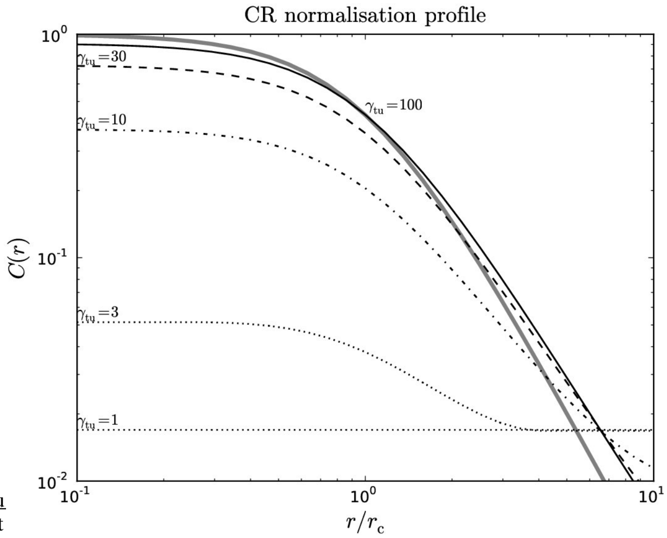


CR density profile



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

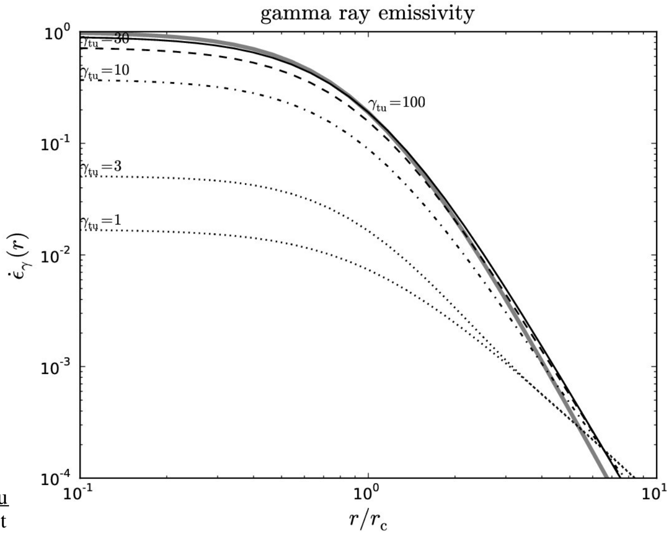
CR density at fixed particle energy



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

Gamma-ray emission profile

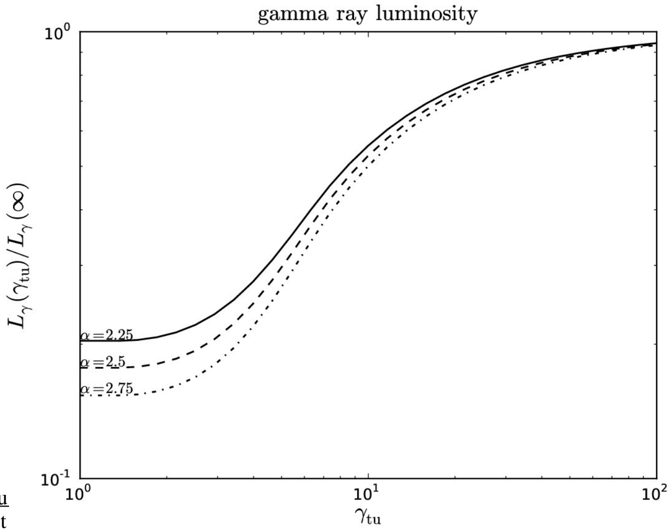
$p_{CR} + p \rightarrow \pi^0 \rightarrow 2\gamma$



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

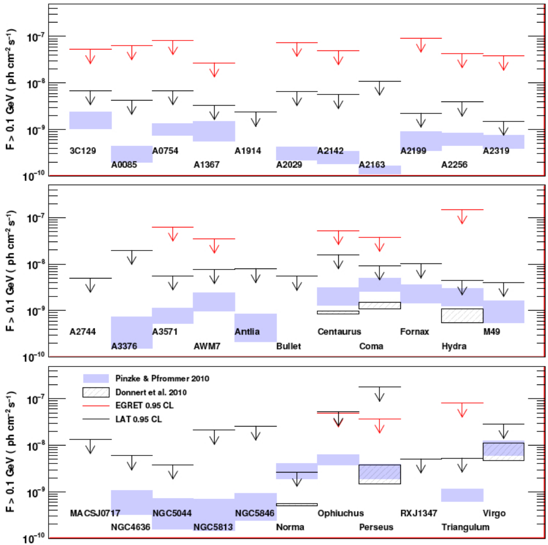
Gamma-ray luminosity

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



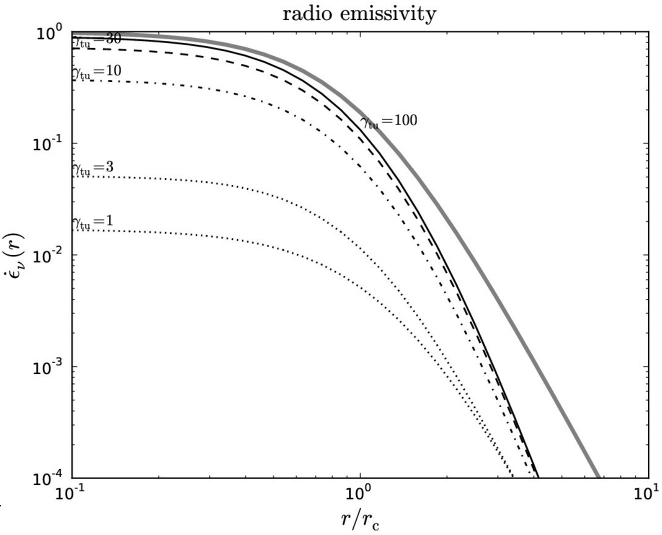
$$\gamma_{\mathrm{tu}} = \frac{\upsilon_{\mathrm{tu}}}{\upsilon_{\mathrm{st}}}$$

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



Radio emission profile

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



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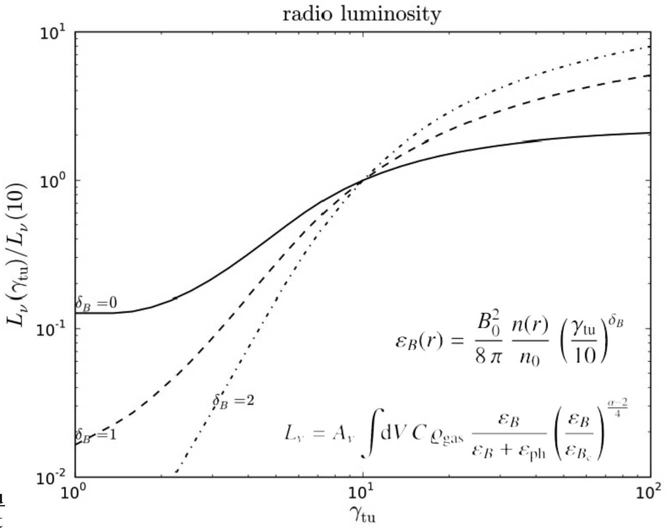

$$\gamma_{\rm tu} = \frac{\upsilon_{\rm tu}}{\upsilon_{\rm st}}$$

Conclusions on cosmic ray transport

- streaming & diffusion produce spatially flat CR profiles
  advection produces centrally enhanced CR profiles
  $\rightarrow$ 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
  $\rightarrow$ peaked/flat CR profiles in merging/relaxed clusters
- energy dependence of $v_{\mathrm{st}}^{\mathrm{macro}}$ $\rightarrow$ CR & radio spectral variations
  $\rightarrow$ outstreaming CR: dying halo $\leftarrow$ decaying turbulence

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

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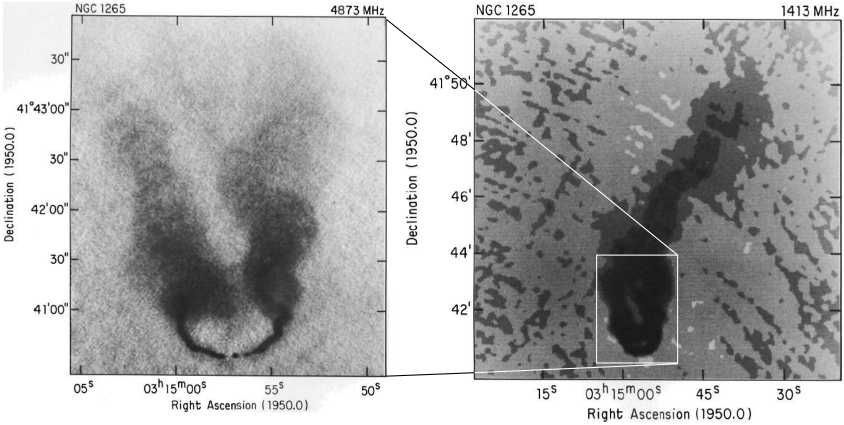
Outline

Wish list for shocks

What we would like to measure and hope to infer:

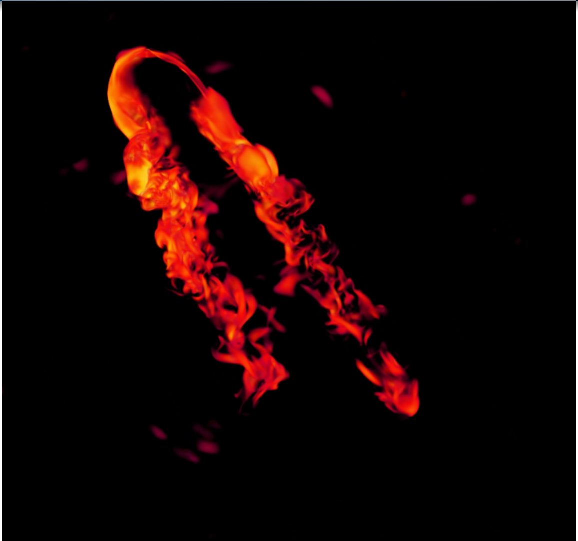
- jump conditions: shock strength
- upstream properties: infalling WHIM
- post- and pre-shock conditions: geometry, obliquity
- shock curvature: vorticity and B field generation
- post-shock turbulence: power spectrum, non-thermal pressure support
- ...

Total synchrotron intensity of NGC 1265



O'Dea & Owen (1986): 4.9 GHz *(left)* and 1.4 GHz *(right)*

Bipolar AGN jets in an ICM wind: magnetic field



credit: Porter, Mendygral & Jones

Bipolar AGN jets in an ICM wind: synthetic radio

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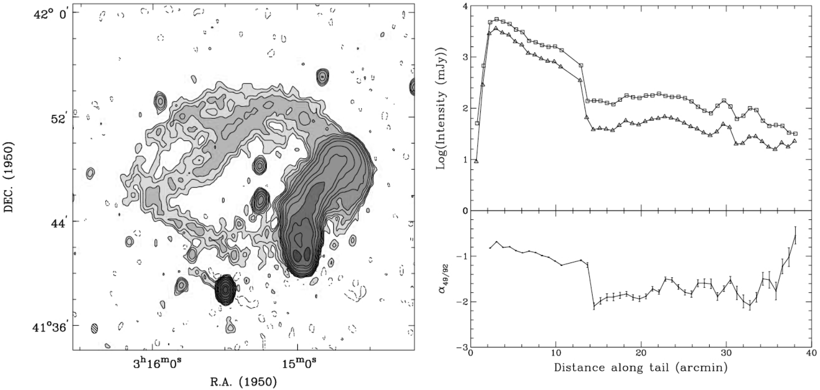
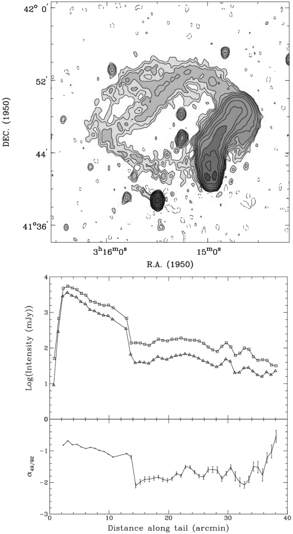
Radio properties of NGC 1265



Sijbring & de Bruyn (1998), *left:* radio intensity $I_{600\,\mathrm{MHz}}$; *right:* variations of $I_{600\,\mathrm{MHz}}$ *(triangles)*, $I_{150\,\mathrm{MHz}}$ *(squares)* and spectral index *(bottom)* along the tail

Requirements for any model of NGC 1265

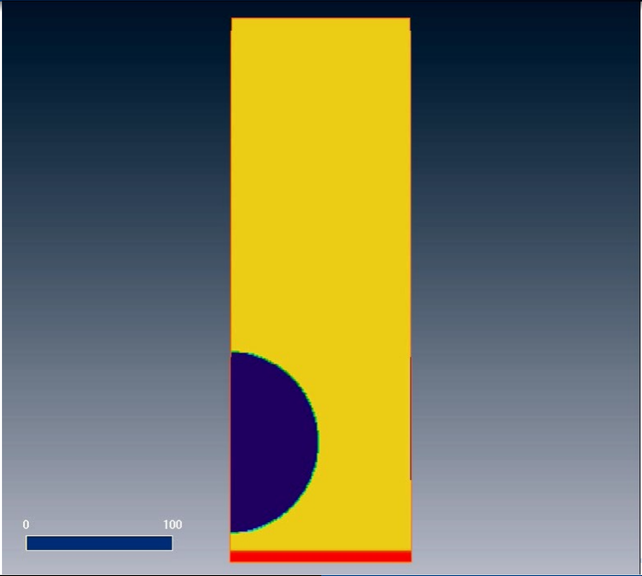


- bright narrow angle tail radio jet: synchrotron cooling
- transition region: change of winding direction and sharp drop in S_ν and α
- coherent properties along the dim radio ring, confined morphology

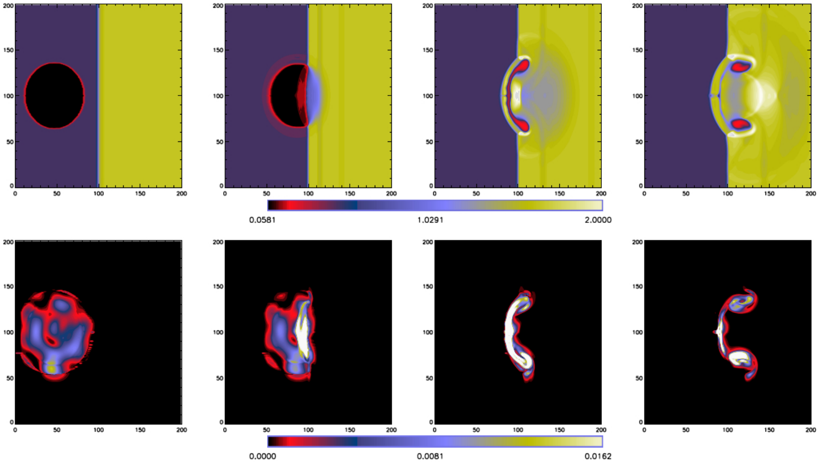
$\rightarrow$ *we are looking at 2 electron populations in projection possibly suggesting 2 different epochs of feedback:*

$\rightarrow$ active jet + detached radio bubble that recently got energized coherently across 300 kpc $\rightarrow$ shock?

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

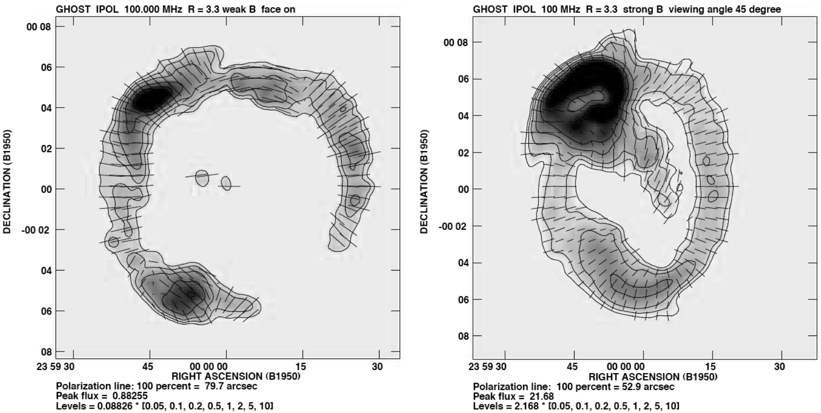


Bubble transformation to vortex ring



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

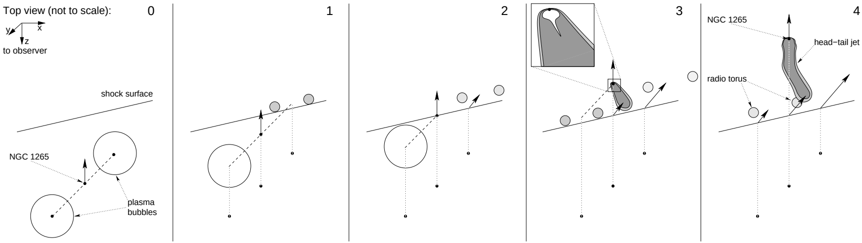
Synthetic radio emission of shock-transformed bubble



Enßlin & Brüggen (2002): total 100 MHz intensity and polarization E-vectors, strong shock/weak *B (left)* and strong shock/strong *B* model *(right)*

Cartoon of the time evolution of NGC 1265

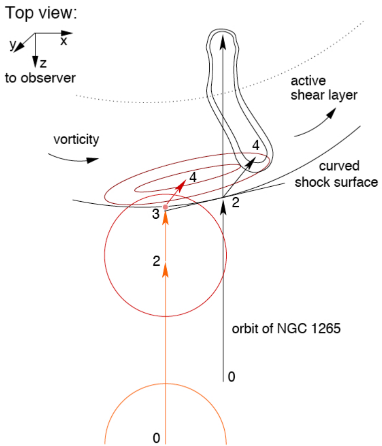
C.P. & Jones (2011):

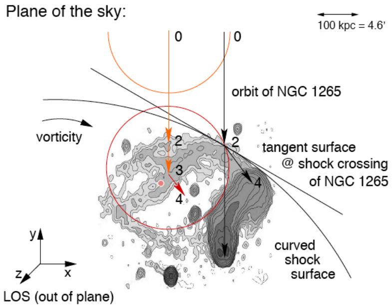


NGC 1265 as a perfect probe of a shock

- **idea:**
  - galaxy velocity not affected by shock
    $\rightarrow$ pre-shock conditions
  - tail & torus as tracers of the post-shock flow
- **assumptions:**
  - shock surface $\parallel$ gravitational equipotential surface of Perseus
  - recent jet launched shortly after shock crossing
- **method:**
  - extrapolating position and velocity back in time
  - employing conservation laws at oblique shock
  - iterate until convergence

Derived geometry for NGC 1265





C.P. & Jones (2011)

Shock strength and jump conditions

- shock compresses relativistic bubble adiabatically: $P_2/P_1 = C^{4/3}$
- bubble compression factor:

$$C = \frac{V_\mathrm{bubble}}{V_\mathrm{torus}} = \frac{\frac{4}{3}\pi R^3}{2\pi^2 R r_\mathrm{min}^2} = \frac{2}{3\pi}\left(\frac{R}{r_\mathrm{min}}\right)^2 \simeq 10$$

- assuming pressure equilibrium → shock jumps:

$$\frac{P_2}{P_1} \simeq 21.5, \quad \frac{\rho_2}{\rho_1} \simeq 3.4, \quad \frac{T_2}{T_1} \simeq 6.3, \quad \text{and } \mathcal{M} \simeq 4.2$$

C.P. & Jones (2011)

Perseus accretion shock and WHIM properties

- jet has low Faraday RM → NGC 1265 on near side of Perseus
  NGC 1265 redshifted w/r to Perseus → infalling system
  → shock likely the accretion shock
- extrapolating X-ray n- and T-profiles to R_{200} & shock jumps:
  → upper limits on infalling warm-hot intergalactic medium

$$\begin{aligned} kT_1 &\lesssim 0.4\,\mathrm{keV} \\ n_1 &\lesssim 5\times10^{-5}\,\mathrm{cm}^{-3} \\ P_1 &\lesssim 3.6\times10^{-14}\,\mathrm{erg\,cm}^{-3} \end{aligned}$$

C.P. & Jones (2011)

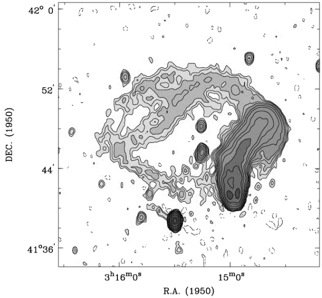
Shear flows and shock curvature

- ellipticity of radio torus (magnitude and orientation) & bending direction of tail
  $\rightarrow$ excludes projection effects
  $\rightarrow$ evidence for post-shock shear flow
- shock curvature injects vorticity that shears the gas westwards:

$$\frac{\varepsilon_{\rm shear}}{\varepsilon_{\rm th,2}} = \frac{\mu m_{\rm p} v_\perp^2}{3kT_2} \simeq 0.14,$$

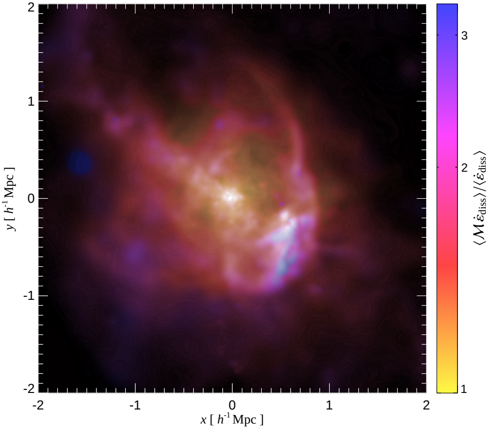
with $kT_2 \simeq 2.4\,\mathrm{keV}$ and $v_\perp \simeq 400\,\mathrm{km/s}$.

C.P. & Jones (2011)

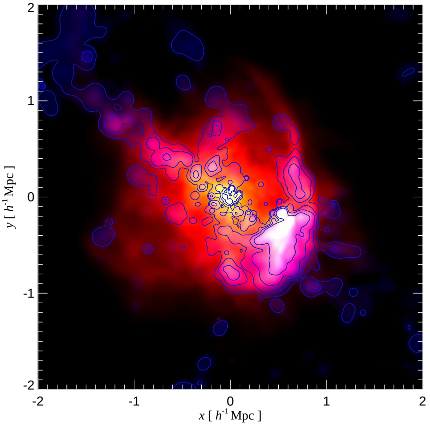


Sijbring & de Bruyn (1998)

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):

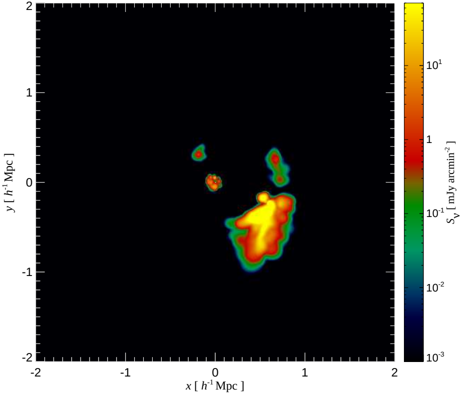
Combining the low-frequency radio observables of relics, we can probe

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

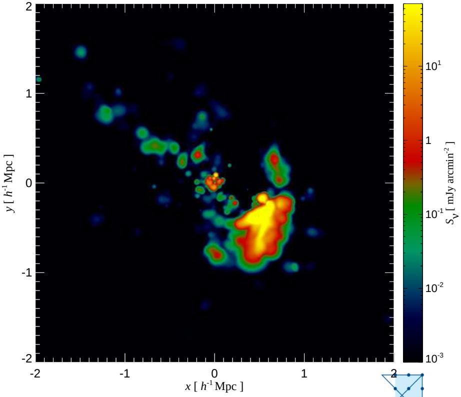
Population of faint radio relics in merging clusters

Probing the large scale magnetic fields

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



radio map with GMRT emissivity threshold

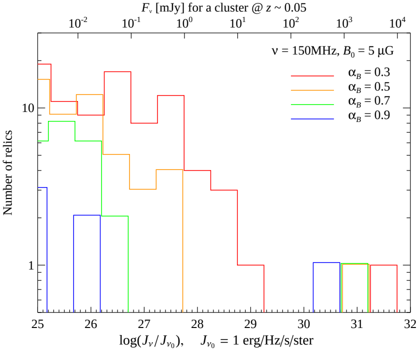


“theoretical” threshold (towards SKA)

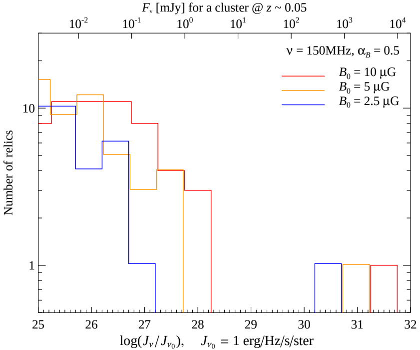
HITS

Relic luminosity function – theory

Relic luminosity function → magnetic field behaviour and dynamical state:



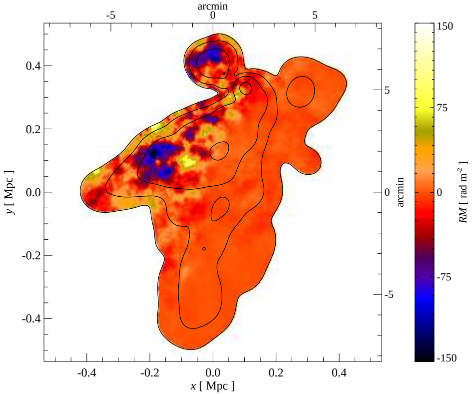
varying magnetic decline with radius

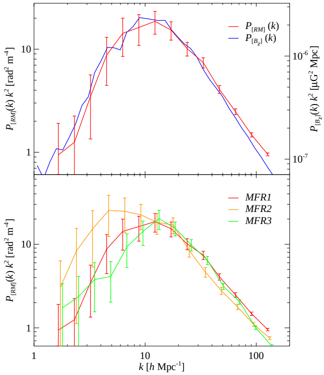


varying overall magnetic strength

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.

Conclusions on probes of accretion shocks

- **radio galaxies are perfect probes of pre- and post-shock flows:**
  - hydrodynamic jumps and Mach numbers
  - statistical properties of the infalling WHIM (+ X-rays)
  - estimating the curvature radius of shocks and induced shear flows
- **radio gischt emission in cluster outskirts probes**
  - strength and coherence scale of magnetic fields
  - diffusive shock acceleration of electrons
  - nature of magnetic and hydrodynamic turbulence
  - dynamical cluster state

Literature for the talk

- Pfrommer & Jones, 2011, ApJ, 730, 22, *Radio Galaxy NGC 1265 unveils the Accretion Shock onto the Perseus Galaxy Cluster*
- 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*
- Pinzke & Pfrommer, 2010, MNRAS, 409, 449, *Simulating the gamma-ray emission from galaxy clusters: a universal cosmic ray spectrum and spatial distribution*
- Battaglia, Pfrommer, Sievers, Bond, Enßlin, 2009, MNRAS, 393, 1073, *Exploring the magnetized cosmic web through low frequency radio emission*
- Pfrommer, 2008, MNRAS, 385, 1242, *Simulating cosmic rays in clusters of galaxies – III. Non-thermal scaling relations and comparison to observations*
- Pfrommer, Enßlin, Springel, 2008, MNRAS, 385, 1211, *Simulating cosmic rays in clusters of galaxies – II. A unified scheme for radio halos and relics with predictions of the* γ*-ray emission*