

Gamma-Ray Emission from Cosmic Rays in Galaxy Clusters

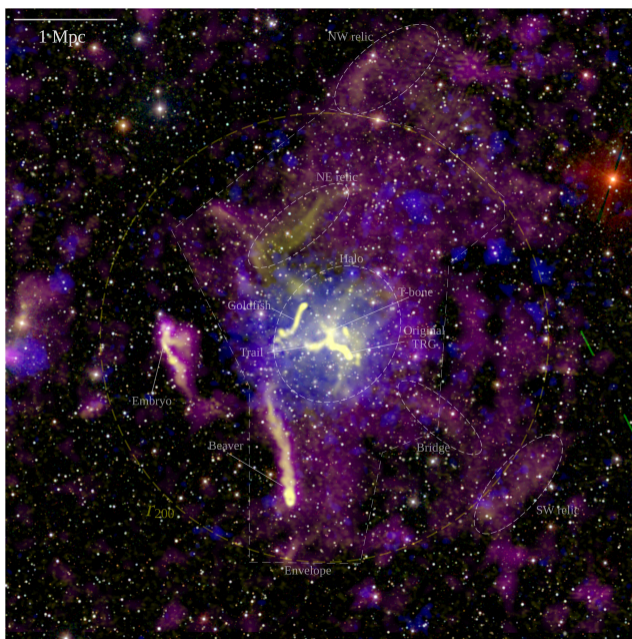
ORIGINS PhD Days 2025

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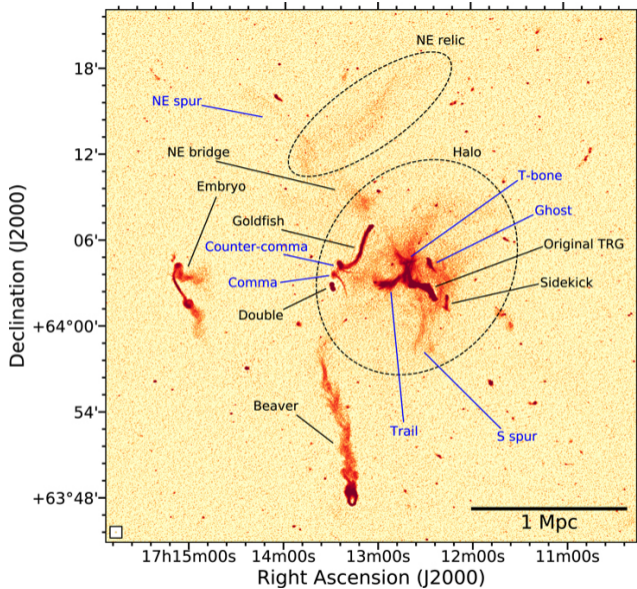




Main cosmic-ray sources:

- Large scale: weak shocks and turbulence in intracluster medium
- Small scale: supernovae and AGN in galaxies

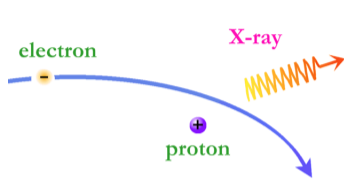
Galaxy cluster Abell 2255
 Radio emission from LOFAR is shown in yellow (145 MHz, at high resolution) and magenta (49 MHz, at low resolution). Blue: X-ray emission from ROSAT in the 0.1- to 2.4-keV band. Background: SDSS gri. (Botteon et al., 2022)



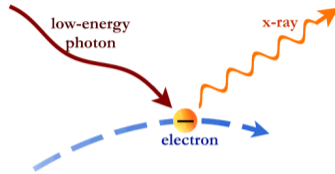
LOFAR image at 144 MHz of nearby galaxy cluster Abell 2255 at $z = 0.0806$ (Botteon et al., 2020)

What about protons? They do not radiate efficiently!

particle energy: $E = \gamma mc^2$



$$-\dot{\gamma} \propto \sigma_T \gamma \ln(\gamma)$$



$$-\dot{\gamma} \propto \sigma_T u_{\text{rad}} \gamma^2$$



$$-\dot{\gamma} \propto \sigma_T u_{\text{mag}} \gamma^2$$

<https://chandra.harvard.edu/resources/illustrations/x-raysLight.html>

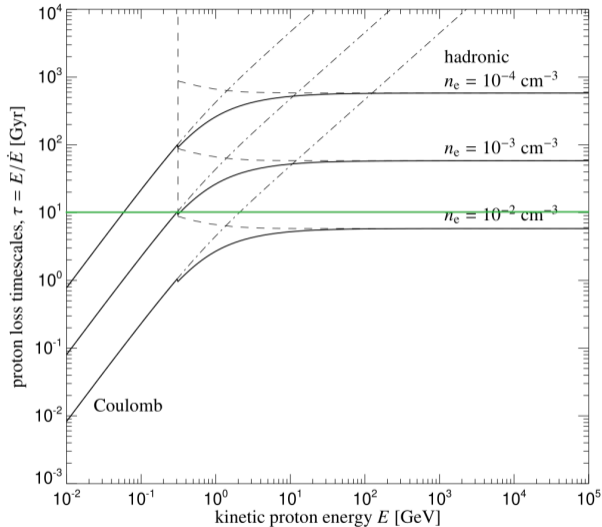
Bremsstrahlung, inverse Compton and synchrotron emission are suppressed by a factor

$$\frac{\sigma_{T,p}}{\sigma_{T,e}} = \left(\frac{m_e}{m_p} \right)^2 \approx 3.0 \cdot 10^{-7}$$

Protons should also be accelerated and accumulate in the cluster

- Long escape time (diffusive propagation + large cluster volume)
- Long cooling time

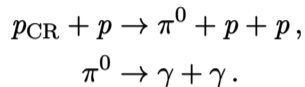
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Enßlin et al. (2011)

2 ways for producing γ -rays with protons

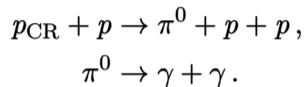
- 1 Neutral pions are produced and decay into γ -rays:



Threshold kinetic energy: 280 MeV (mildly relativistic protons!)

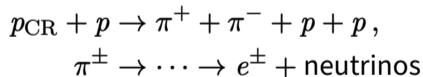
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- 1 Neutral pions are produced and decay into γ -rays:

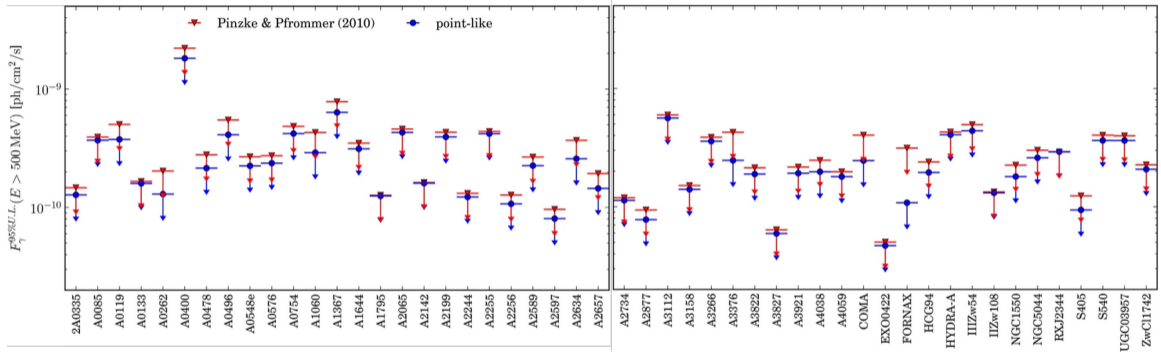


Threshold kinetic energy: 280 MeV (mildly relativistic protons!)

- 2 Secondary electrons: Charged pions decay into electrons, which IC upscatter background radiation:



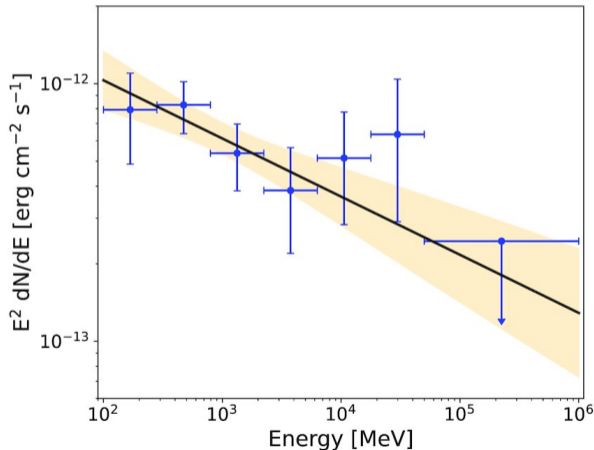
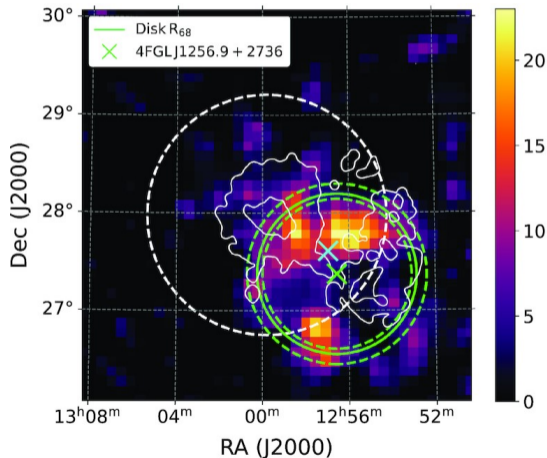
γ -ray observations of galaxy clusters: 4 years of FERMI-LAT data



Sample of 50 galaxy clusters from Ackermann et al. (2014)

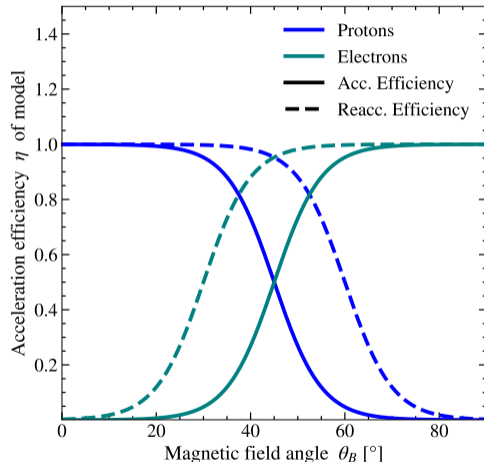
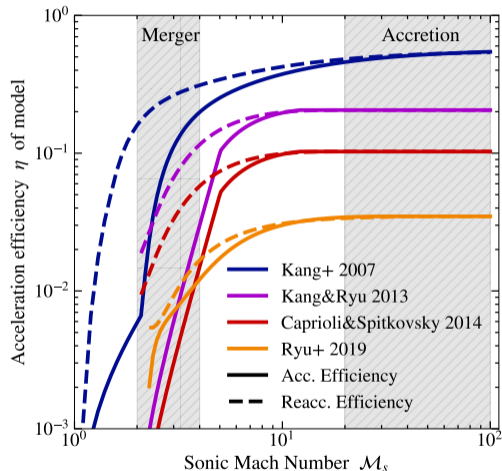
Coma cluster: 12.4 years of FERMI-LAT data (Baghmanyant et al., 2022)

5.4 σ -detection of diffuse γ -emission between 100 MeV and 1 TeV
Contributions from point-like and extended sources still unclear.



Missing γ -ray problem

Main explanation: Acceleration efficiency of weak shocks was overestimated in the past

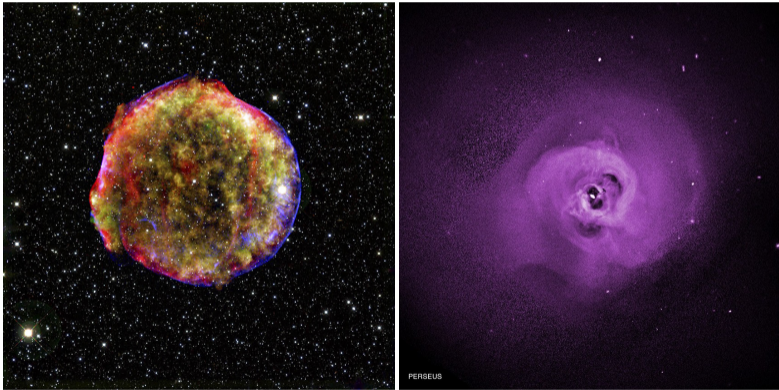


Efficiencies for diffusive shock acceleration (Böss et al., 2024)

Missing γ -ray problem

But what about...

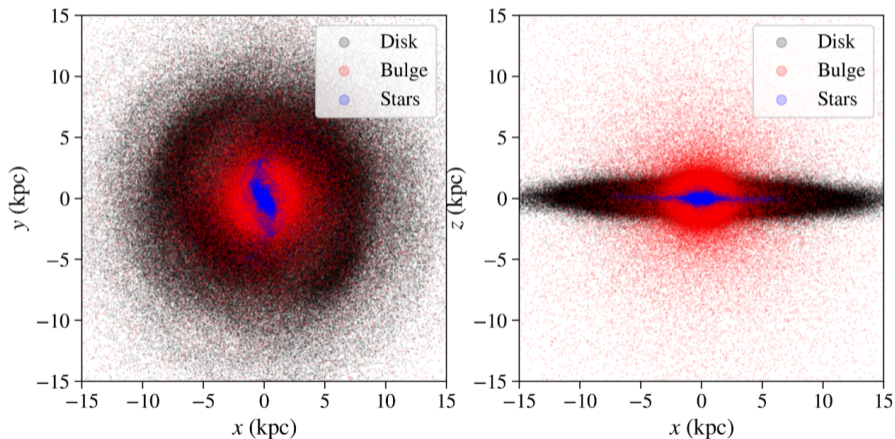
- additional, small-scale CR sources (supernova remnants, AGN)?
- transport processes (diffusion, streaming)?



Chandra X-ray observations of Tycho's supernova remnant (<https://chandra.harvard.edu/photo/2009/tycho/>) and the Perseus cluster (<https://chandra.harvard.edu/photo/2014/perseusvirgo/>)

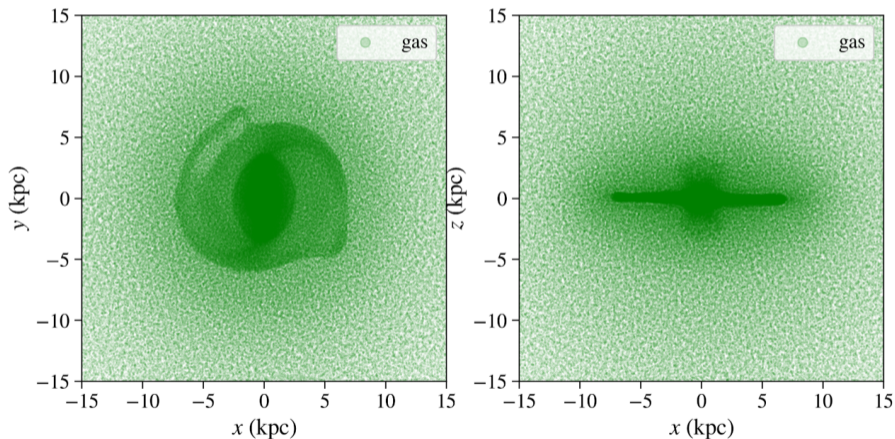
Numerical treatment

In our SPH code OpenGadget3 gas is represented by tracer particles. Each carries two spectra of the CR electron and proton population.



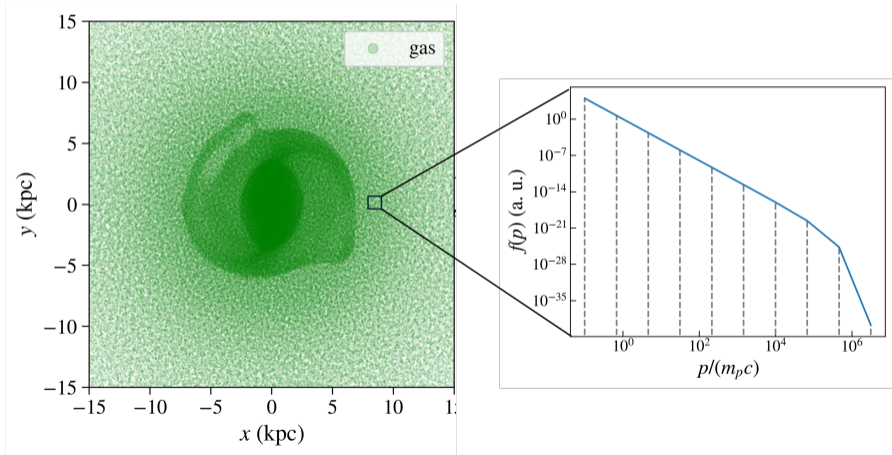
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Summary & Outlook

Take-home message

I investigate the non-thermal radiation from galaxy clusters by using a cosmological simulation code with a spectral cosmic ray model.

- Revisiting the “missing γ -ray problem”: Contributions from different CR sources
- How much do secondary electrons contribute to radio halos?
- Galaxy clusters are preferred targets for studying γ -ray signals from **decaying dark matter models** (e.g. annihilation of WIMPs) → sophisticated models for astrophysical background are needed!

References

Baghmany V., Zargaryan D., Aharonian F., Yang R., Casanova S., Mackey J., 2022, *MNRAS*, 516, 562

Böss L. M., Dolag K., Steinwandel U. P., Hernández-Martínez E., Khabibullin I., Seidel B., Sorce J. G., 2024, *A&A*, 692, A232

Botteon A., et al., 2020, *ApJ*, 897, 93

Botteon A., et al., 2022, *Science Advances*, 8, eabq7623

Enßlin T., Pfrommer C., Miniati F., Subramanian K., 2011, *A&A*, 527, A99

van Weeren R. J., de Gasperin F., Akamatsu H., Brüggén M., Feretti L., Kang H., Stroe A., Zandanel F., 2019, *Space Sci. Rev.*, 215, 16

Section 2

Backup Slides

Many challenges

- Supernovae:
 - Spectrum relatively well understood
 - How does the spectrum outside the galaxy (in ICM) look like?
- Active galactic nuclei:
 - Acceleration can happen “away from galaxy” in jet or termination shock
 - Shape of proton spectrum completely unclear
- Merger shocks in ICM:
 - Larger progress through PIC simulations in recent years
 - Acceleration efficiency depends on Mach number, shock obliquity, population of fossil CRs
- Turbulent re-acceleration:
 - Inefficient compared to shock acceleration, but still important in ICM
 - Complicated coupling to microphysical plasma turbulence (not resolved)

CR spectra are updated by evolving CR number and energy density

$$n_{\text{CR}} = \frac{4\pi}{\rho} \int_{p_i}^{p_{i+1}} f(p) p^2 dp$$

$$\varepsilon_{\text{CR}} = \frac{4\pi}{\rho} \int_{p_i}^{p_{i+1}} f(p) E_{\text{kin}}(p) p^2 dp$$

If distribution function $f(p)$ is a piecewise power-law, $f(p) = f_i \left(\frac{p}{p_i}\right)^{-q_i}$, and $E_{\text{kin}}(p) = pc$, then both integrals can be solved analytically (as in CRESCENDO).

The computation of n_{CR} and ε_{CR} should be accurate and fast!

CR spectra are updated by evolving CR number and energy density

With true kinetic energy $E_{\text{kin}}(p) = \sqrt{(pc)^2 + (mc^2)^2} - mc^2$ we get

$$\begin{aligned}\epsilon_{\text{CR}} &= \frac{4\pi}{\rho} \int_{p_i}^{p_{i+1}} f_i \left(\frac{p}{p_i} \right)^{-q_i} \left(\sqrt{(pc)^2 + (mc^2)^2} - mc^2 \right) p^2 dp \\ &= \frac{4\pi c (mc)^4 x_i^{q_i} f_i}{\rho} \int_{x_i}^{x_{i+1}} \left(\sqrt{x^2 + 1} - 1 \right) x^{2-q_i} dx ,\end{aligned}$$

where $x = p/(mc)$ is the dimensionless momentum.

Shocks

- Which shocks dominate CR production? Shocks in outskirts have higher Mach numbers -> higher acceleration efficiencies, can re-accelerate fossil CR population (long cooling time in low-density environment; need not start from thermal pool) but do not process so much material (again low density)
On the other hand, shocks closer to the cluster centre process more material, but have lower Mach numbers and a smaller acceleration efficiency.
- Two modes of diffusive shock acceleration: injection at single shock; re-acceleration of CR population by multiple shock crossings (not to confuse with turbulent reacceleration)