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# Multi-Messenger Studies of Cosmic-Ray Acceleration in Galaxy Cluster Accretion Shocks

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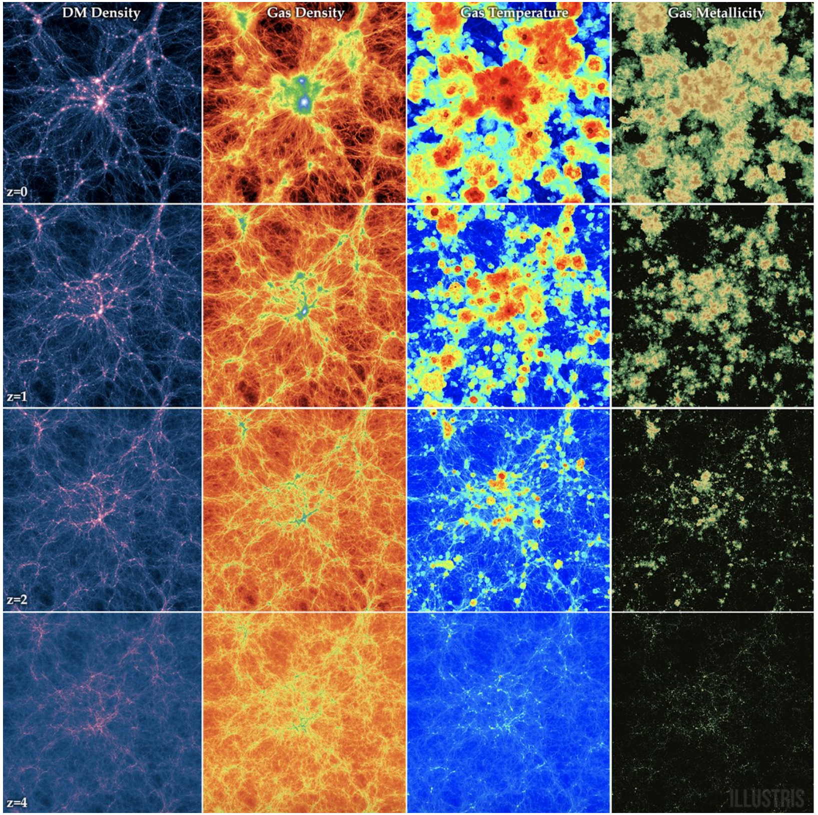


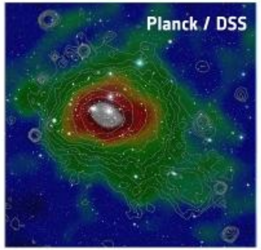

https://www.illustris-project.org

- Galaxy clusters - **largest gravitationally bound objects in the Universe**.
- We can learn about them from simulation and multiwavelength observations.
- Galaxy formation and evolution, dark matter, gravitational lensing, big bang and the evolution of the cosmos, chemistry …. and … particle acceleration.

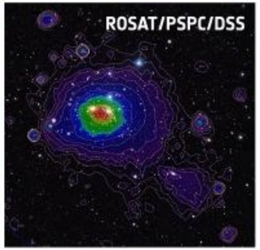
Coma cluster

Over 1000 galaxies
z=0.02 or 103 Mpc (336 Mly)

tSZ

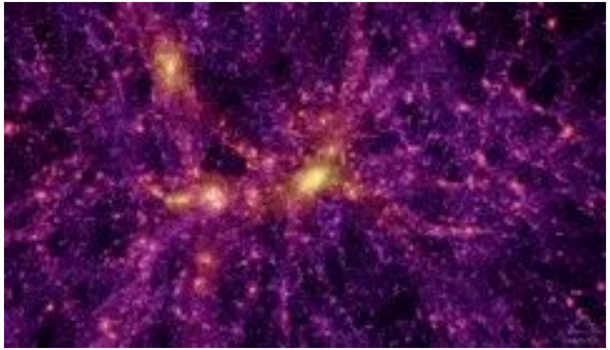


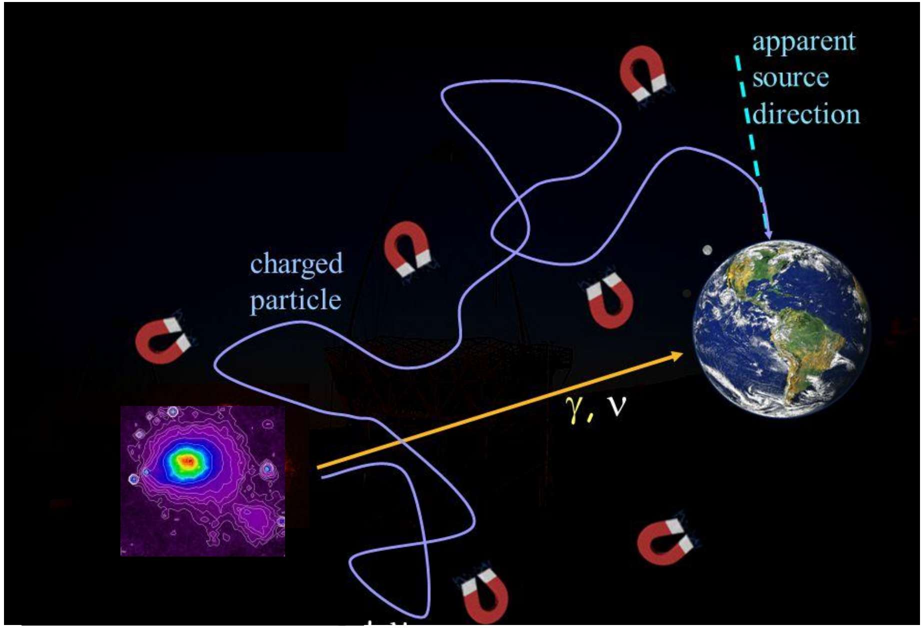

X-ray



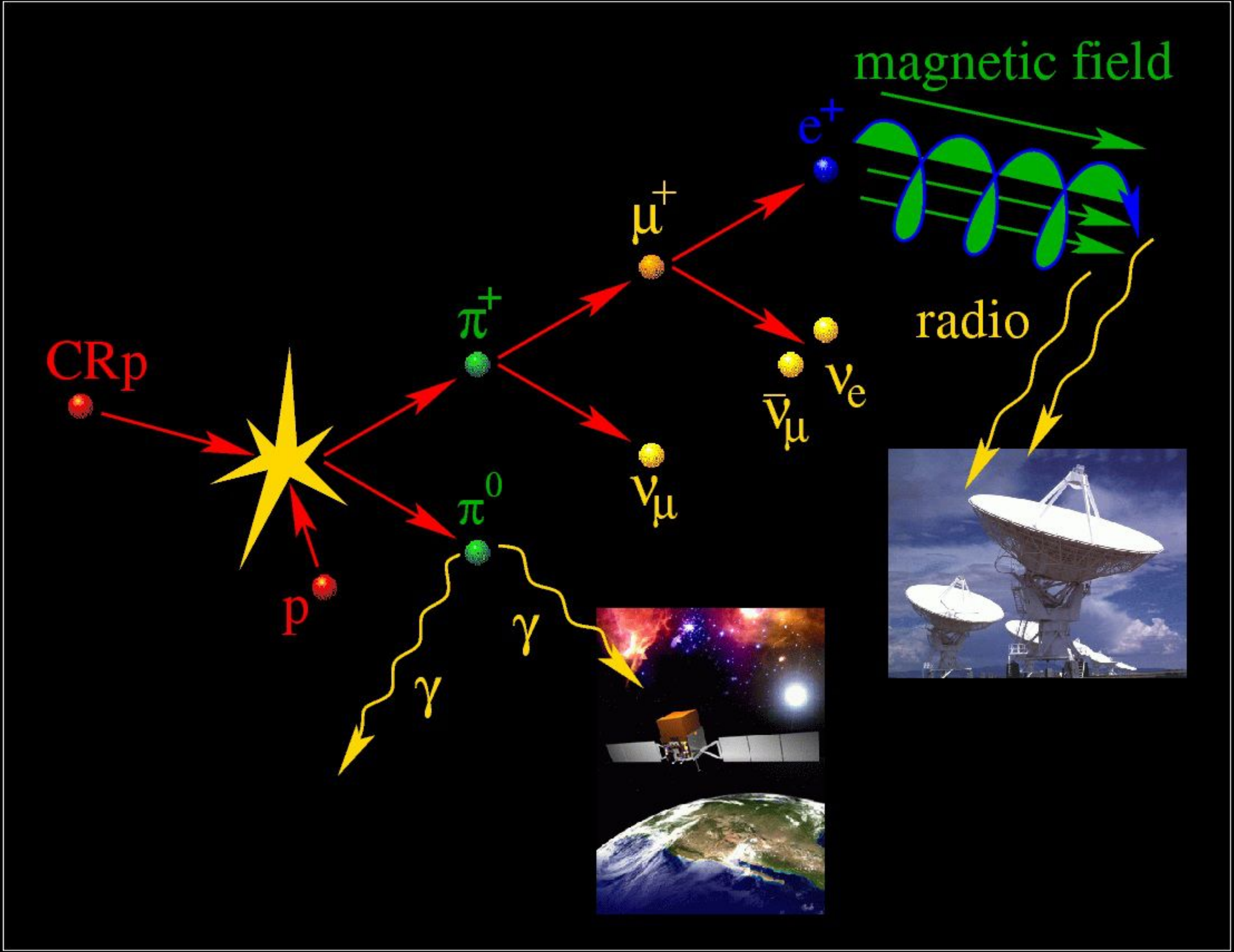
# Particle acceleration - Cosmic Rays

- Diffusive shock acceleration - origin of highest energy particles in the Universe (far above what we can produce in accelerators on Earth).
- **Recipe for particle acceleration - ingredients:** particles to accelerate, magnetic field, shock wave.
- Ingredients are present in different environments and scales - supernova remnants, Solar wind termination shock, ANGs, gamma-ray bursts … and … **large scale gas accretion**.



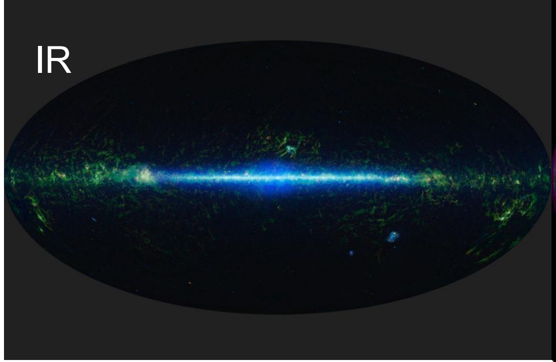


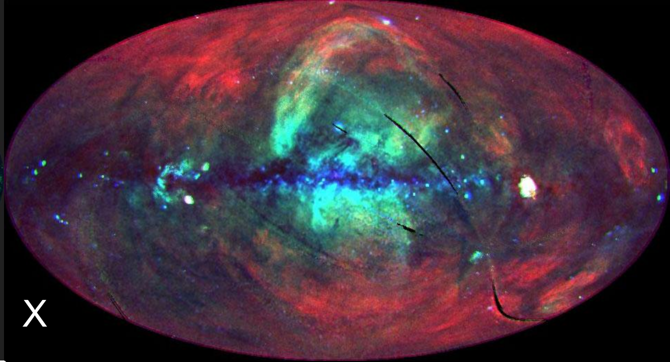

**How do we learn about the source using CRs?**

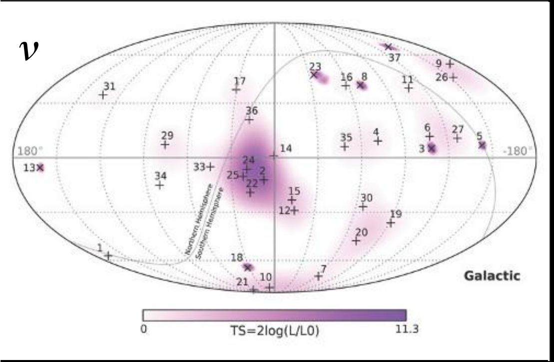


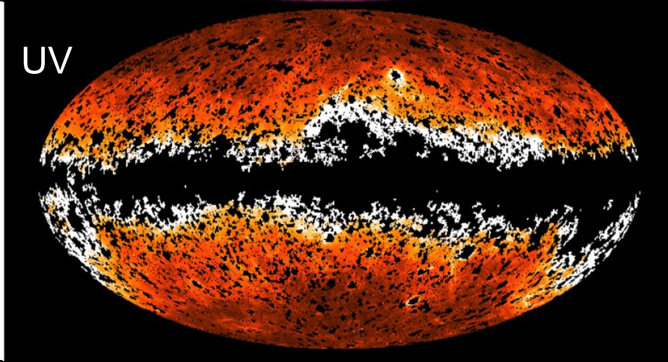
magnetic field
e+
μ+
π+
CRp
radio
νe
ν̄μ
νμ
π0
p
γ
γ

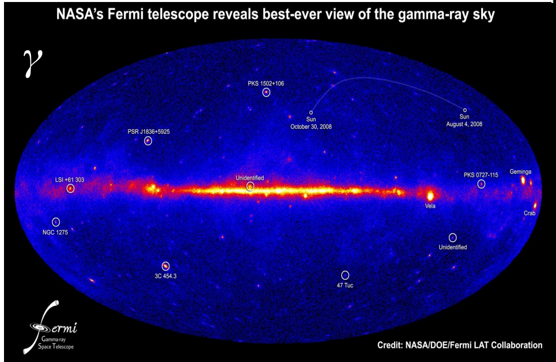
# What can background radiation tell us about galaxy clusters?

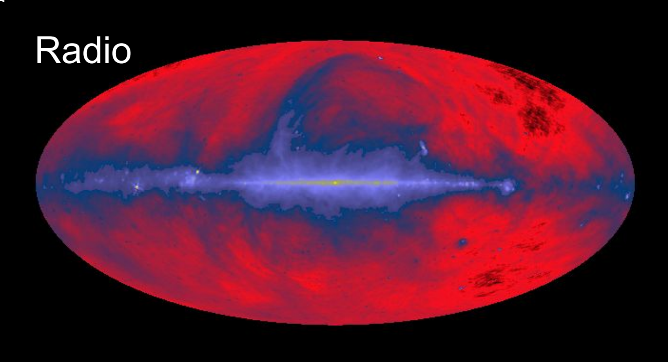


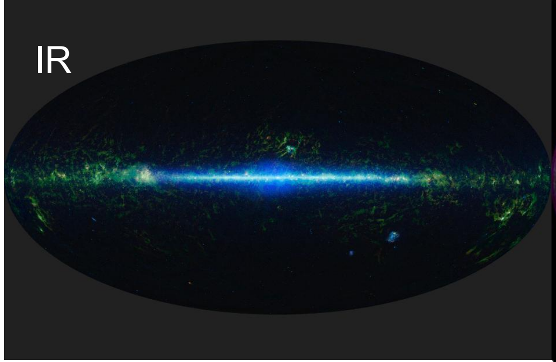



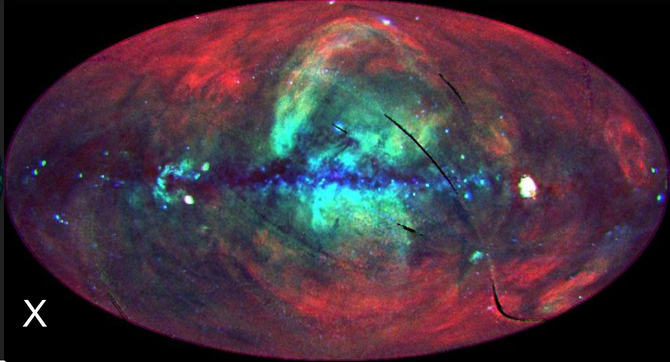



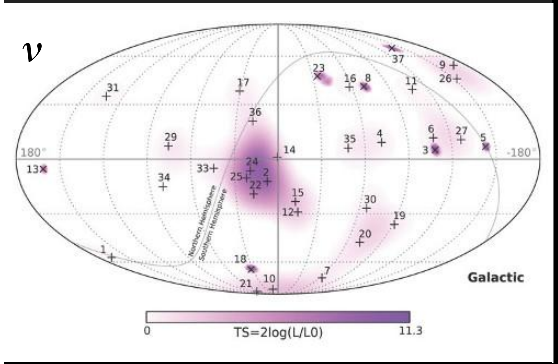



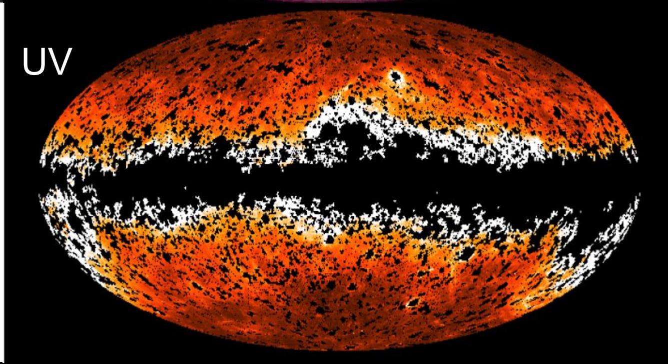
# What can background radiation tell us about galaxy clusters?

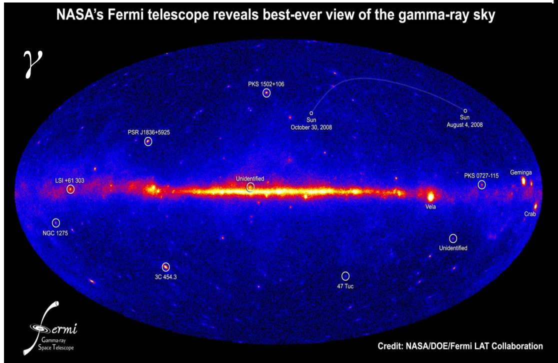
Unresolved galaxy clusters **contribute to diffuse background measurements on different wavelengths!**

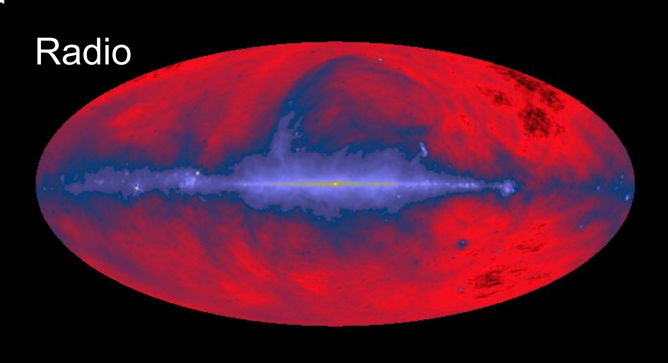


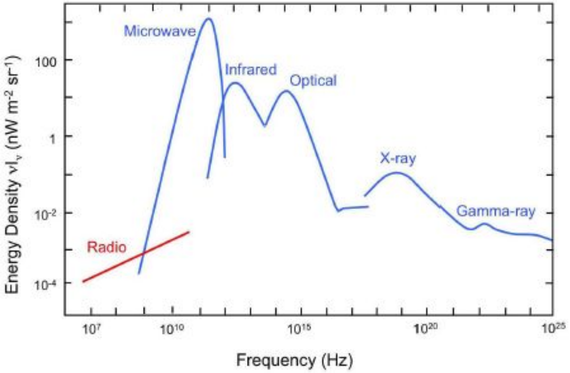



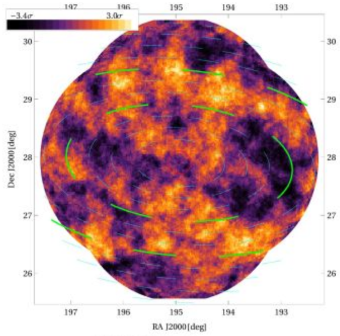
## Connecting the dots...

Gamma Rays + Neutrinos

Radio waves + tSZ

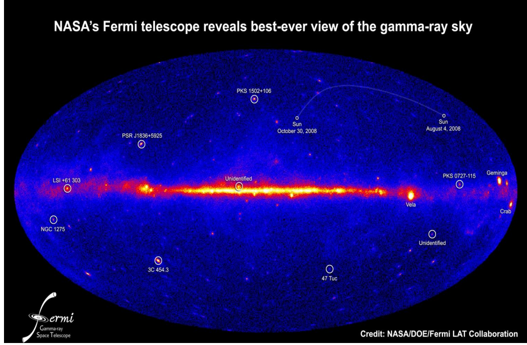
Conclusion

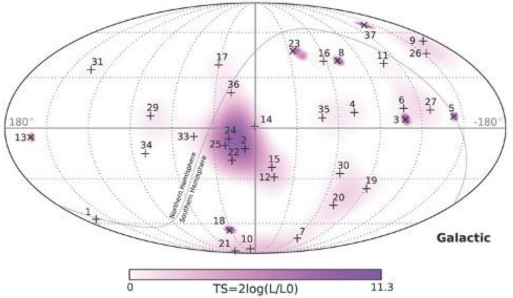


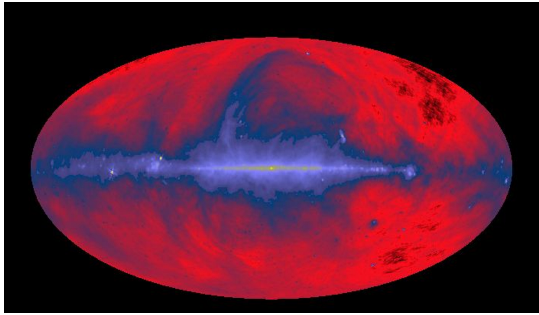



(a) VERITAS significance map

Gamma ring around Coma cluster
[Keshet, U. et al. 2017, ApJ, 845, 24]





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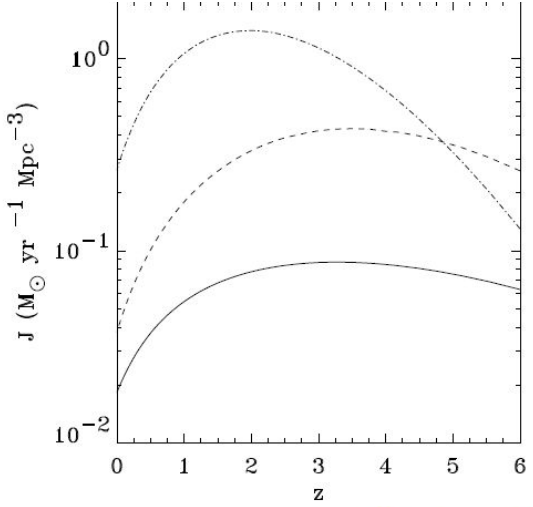
# Gamma-Rays and Neutrinos

$I_\gamma(E) \propto$ cosmology **x** cosmic accretion rate **x** gas fraction **x** gamma-ray spectrum **x** normalisation

$$\frac{dI_E}{d\Omega} = \frac{c}{4\pi H_0 J_0(z_0)} \int_0^{z_{\rm vir}} dz \frac{\dot{\rho}_{\rm sf}(z) L_{\gamma,0}[(1+z)E]}{\sqrt{\Omega_\Lambda + \Omega_{\rm m}(1+z)^3}} \times \left[ \frac{\epsilon}{\epsilon+1} + (\epsilon+1)^{-1} \frac{\int_{z_{\rm vir}}^{z} dz\,(dt/dz)\,\dot{\rho}_{\rm sf}(z)}{\int_{z_{\rm vir}}^{z_0} dz\,(dt/dz)\,\dot{\rho}_{\rm sf}(z)} \right]$$

- Differential intensity [$\mathrm{cm^{-2}\ s^{-1}\ GeV^{-1}\ sr^{-1}}$]
- Evolution of accretion shocks throughout the history of the Universe - analytical models [Pavlidou & Fields 2006, ApJ, 642, 734]
- Cosmic accretion rate - J or $\varrho_{\rm sf}$
- Unresolved galaxy clusters - **contribution to isotropic gamma-ray background (Fermi - LAT) + normalization using neutrinos (IceCube).**

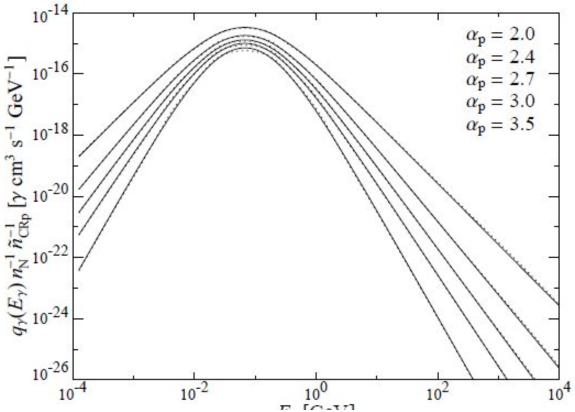


# Gamma-Rays and Neutrinos

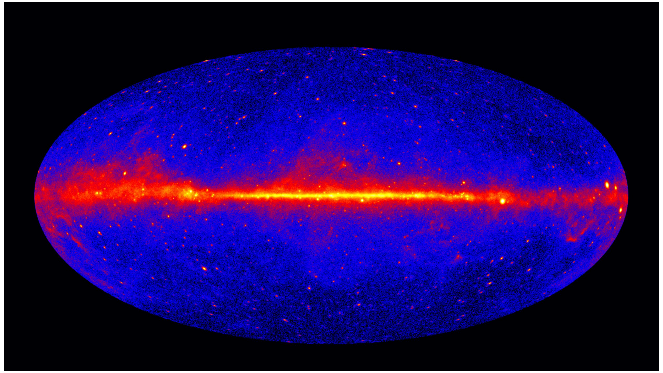
- **Assumption 1:** evolution of cosmic accretion rate directly translates to acceleration of CRs, and the resulting gamma-ray, neutrino, radio waves production etc.

- **Assumption 2**: gamma-rays are mostly from neutral pions - spectral shape is broken power law

[Pfrommer & Enlin 2003, A&A, 407, 73]

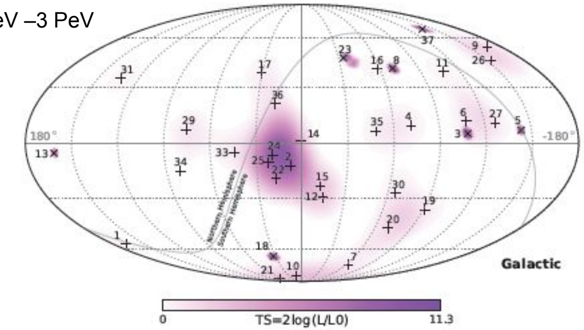



[Ackermann et al. 2015, ApJ, 799, 86]



[Aartsen et al. 2014, PhRvL, 113, 101101 ]
[Aartsen et al. 2015, PhRvD, 91, 022001]

0.06 TeV –3 PeV



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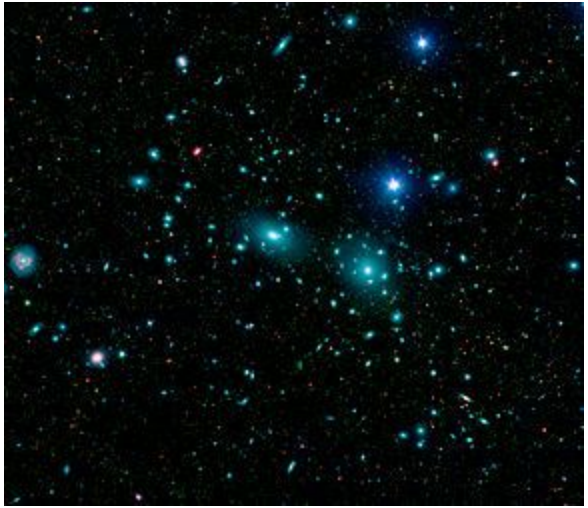
# Gamma-Rays and Neutrinos

- Neutrinos are produced via charged pion decay, while gamma rays have origin in neutral pion decay.
- Neutrino - gamma rays link is simple:

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} = \frac{2^\alpha}{6}\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}(E_0)$$

$$(\alpha = 2): \quad E^2\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}(E) = 2E^2\frac{\mathrm{d}N_{\nu_i}}{\mathrm{d}E_{\nu_i}}(E)|E = E_0$$

[Ahlers & Murase 2014, PhRvD, 90, 023010]
[Chang & Wang 2014, ApJ, 793, 131]





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# Gamma-Rays and Neutrinos

- If accretion shocks are predominantly strong neutrinos are much more constraining.
- **Accretion shocks can have possible non-negligible contribution to diffuse backgrounds.**

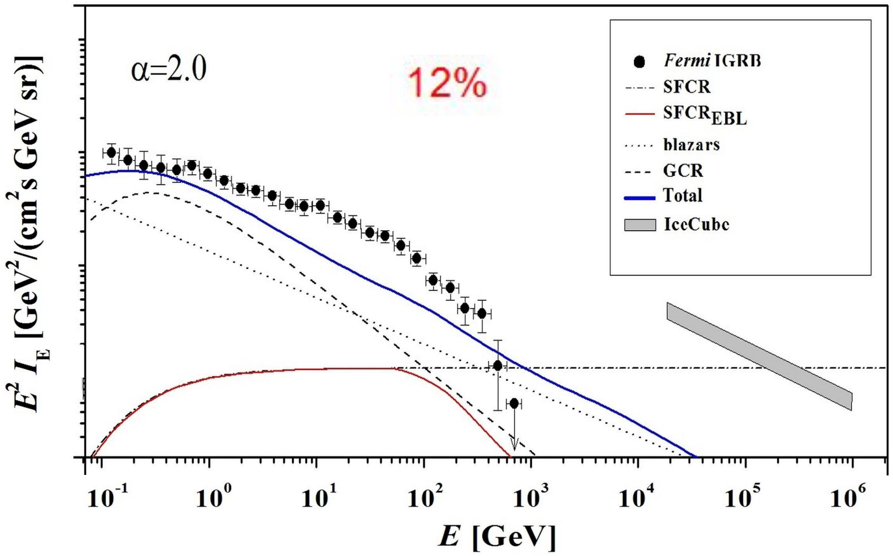
- Upper limits to clusters + SF galaxies IGRB contribution > 30-40% (100 GeV)

  [Murase, Ahlers & Lacki 2013, PhRvD, 88, 121301]

- Less than 20% of the neutrinos could be from clusters?

[Fang & Olinto, 2016, ApJ, 828, 37]
[Zandanel et al. 2015, A&A, 578, 32]

[Dobardžić & Prodanović 2014, ApJ, 782, 109]
[Dobardžić & Prdanović 2015, ApJ, 806, 184]



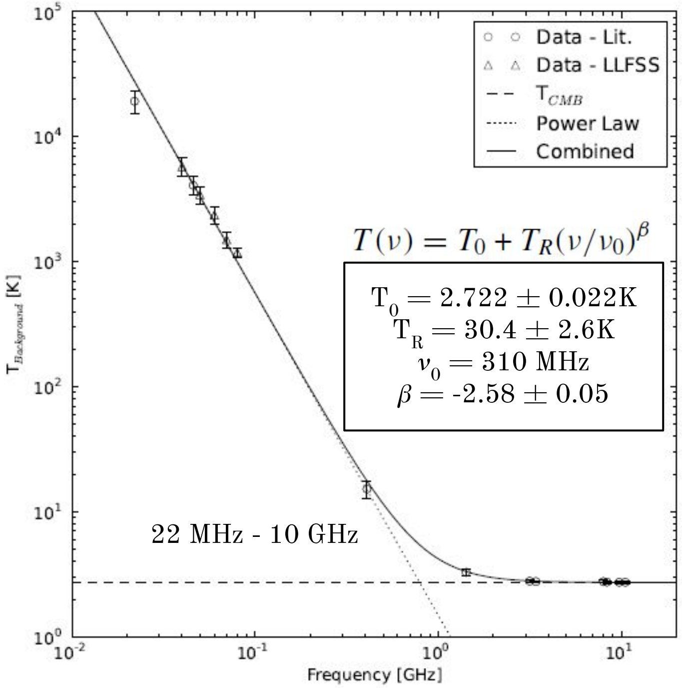
# Radio and tSZ

- **CR electrons produce synchrotron radiation in radio domain.**
- CRB spectrum is a power law with index -2.6.
- Regular galaxies, big radio galaxies, AGNs, quasars, galaxy clusters, radio supernovae, diffuse sources,dwarf galaxies, low surface brightness sources...

- **Managing to explain only 67% CRB at 1.4 GHz.** [Draper et al. 2011]

- We can use the same models as in case of gamma rays to get the contribution of galaxy clusters to the CRB.

Cosmic Radio Background - CRB




ARCADE 2 measurements
[Fixsen, D. J. et al. 2011, ApJ, 734, 5]

Long Wavelength Array
[Dowell & Taylor 2018]



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# Origin of high-energy CRs in galaxy clusters?

HADRONIC MODELS

$$p_{cr} + p \rightarrow \pi^{\pm} \rightarrow e^{\pm} + \nu_e/\bar{\nu}_e + \nu_{\mu} + \bar{\nu}_{\mu}$$

- CR accelerated in accretion shocks, AGNs….
- Power law spectrum.

REACCELERATION OF ELECTRONS

- Electrons that already exist in clusters with 0.1-10 GeV are accelerated above 10 GeV in turbulences during cluster interactions.
- But electrons lose energy fast and acceleration is not efficient.

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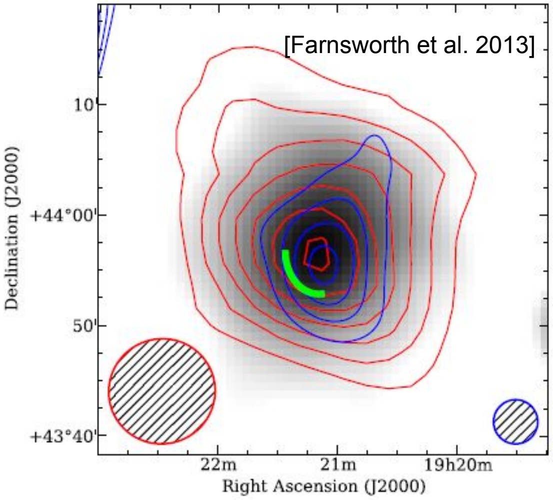


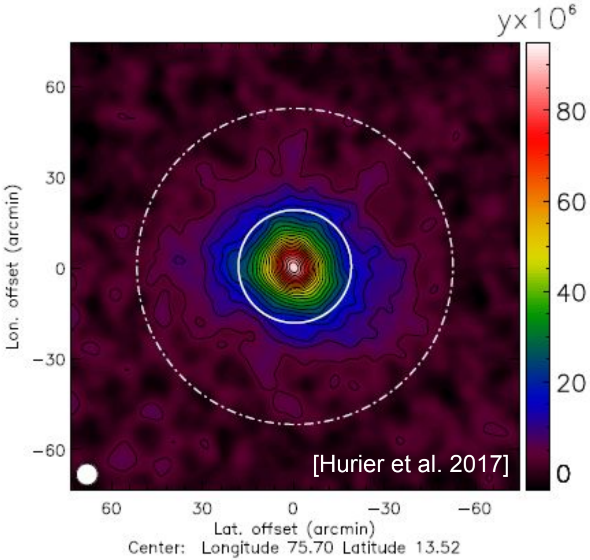

Green Bank Telescope 1.4 GHz
VLA 1.4 GHz

ROSAT All Sky Survey
XMM-Newton

Radio spectrum from observations
$L(\nu) = L_{1.4}(\nu/1.4\text{GHz})^{-\alpha}$

0.4 - 1.4 GHz
$\alpha = 1.2$
[Farnsworth et al. 2013]

$\alpha = 1.8$
[Feretti et al. 1997]




**tSZ** - location of the virial shock, current accretion rate
$R_v = (2.93 \pm 0.05) \times R_{500}$
$J_0 = (1.4 \pm 0.4) \times 10^5 M_{sun}\ yr^{-1}$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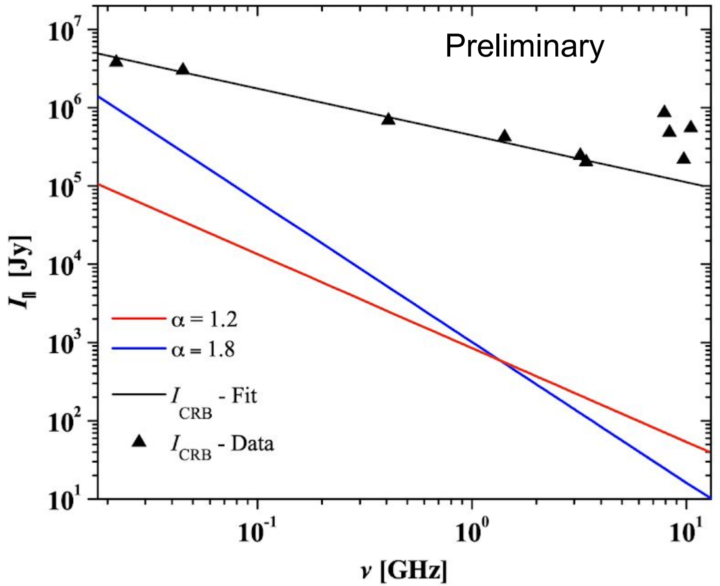
# Contribution of unresolved galaxy clusters to CRB

- A2319 was observed et several frequencies. Different authors derive slightly different power law spectra for A2319.

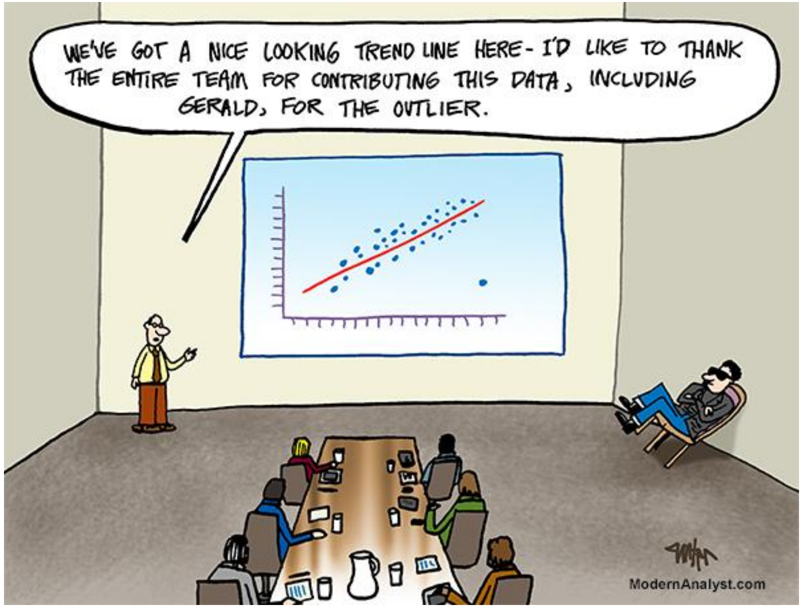
[Farnsworth, D. et al. 2013, ApJ, 779, 189]
[Feretti, L., Giovannini, G., Böhringer, H. 1997, NewA, 2, 501]

- **At 1.4 GHz the possible contribution of galaxy clusters is less than around 1%**, and in the 0.02-10 GHz, where CRB is measured, < 1-5%.
- If not all CR electrons located at the outskirts of the cluster are from virial shock than $J_0$ would be overestimated, but not for much since then we would overshoot the CRB at lowest frequencies.



# Conclusion

- Galaxy clusters are probes of large scale particle acceleration.
- Acceleration of particle in accretion shocks is still not well understood.
- Only by leveraging multi-messenger studies we'll be able to better understand processes that lead to CR acceleration, their properties and influence on evolution of astrophysical objects.
- We need new and better observations, and to find more visible galaxy clusters in different observations.




**Thank you!**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