

Ultra high energy cosmic rays from very high energy gamma ray sources

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October 1, 2019

Outline

1. Introduction
2. Methods
3. Results
4. Conclusion

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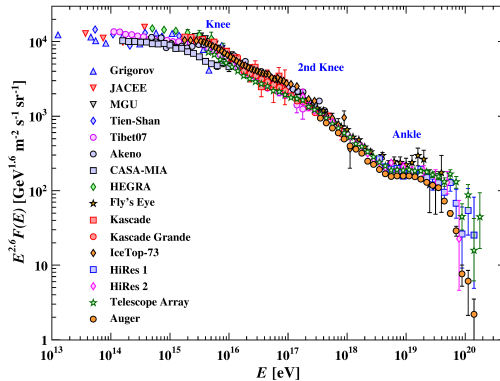
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Ultra High Energy Cosmic rays

- ▶ Ultra High Energy Cosmic Rays are extremely energetic particles hits the Earth for all direction with kinetic energy greater than 10^{18} eV.
- ▶ They are of mysterious origin. We still don't know where do they come from.

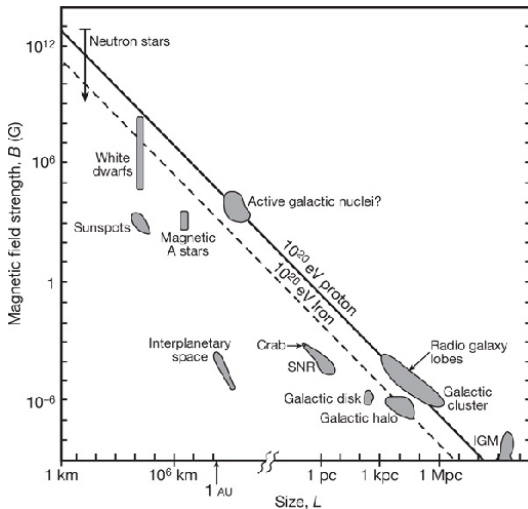
All-particle energy spectrum

[Patrignani et al. (Particle Data Group), 2016, Chin. Phys. C, 40, 100001]



Sources of UHE Cosmic Rays

[A. M. Hillas, Ann. Rev. Astron. Astrophys. 22 (1984) 425]



Major underway experiments



Figure : Pierre Auger Observatory (Argentina)



Figure : Telescope Array (TA) Experiment (USA)

Mass composition (> 10 EeV)

- ▶ **Auger:** heavy composition

[Auger Collab., 2014, Phys. Rev. D, 90, 122006]

- ▶ **TA:** light composition

[TA Collab., 2015, Astropart. Phys., 64, 49]

Gamma Ray Astronomy

- ▶ **High Energy Astrophysics** :
in the context of studies of high energy nonthermal processes in Universe.
- ▶ **Astroparticle Physics** :
as one of the cosmic messengers (together with cosmic rays, neutrinos, gravitational waves) as well as in the context of indirect search of Dark Matter, challenging basic laws in different areas of physics
- ▶ **Relativistic Astrophysics** :
the parents of gamma rays relativistic electrons, protons, nuclei are related, in one way or another, to particle acceleration close to relativistic objects: black holes, neutron stars/pulsars, SN explosions ...

Gamma Ray

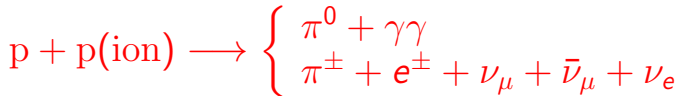
Gamma Rays(GR) : **unique carriers** of information about high energy processes in the Universe

- ▶ are effectively produced **in both electromagnetic and hadronic interactions.**
- ▶ penetrate (relatively) freely throughout **intergalactic and galactic magnetic and photon fields.**
- ▶ are effectively detected **by space based and ground based detectors**

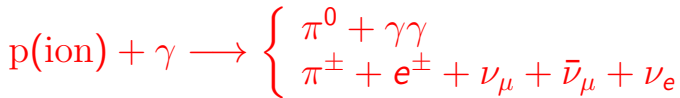
Gamma ray emission processes induced by cosmic rays

Hadronic processes :

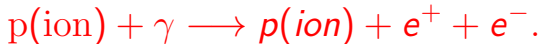
- ▶ Pion decay



- ▶ Photo-meson production :



- ▶ Bethe-Heitler pair production :



Gamma ray emission processes induced by cosmic rays

Leptonic processes :

- ▶ Inverse Compton :

$$e^* + \gamma \longrightarrow e + \gamma^*.$$

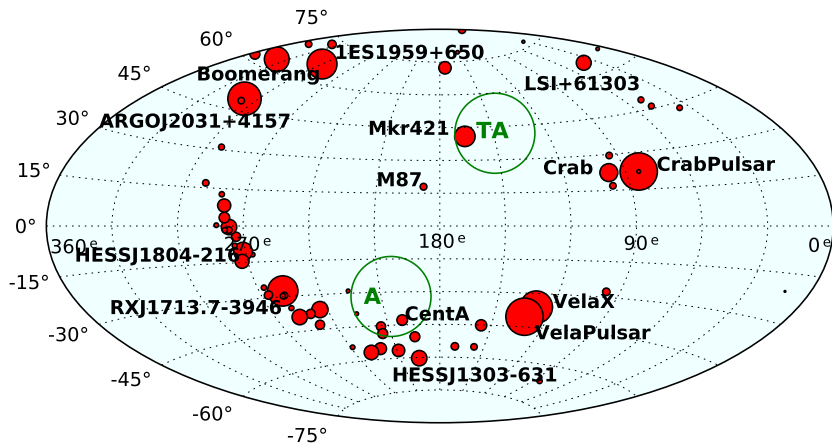
- ▶ Synchrotron radiation :

$$e^*(p^*) + B \longrightarrow e(p) + B\gamma^*.$$

- ▶ Bremsstrahlung :

$$e^* + p(\text{ion}) \longrightarrow e + p(\text{ion}) + \gamma^*.$$

Very High Energy Gamma Ray sources

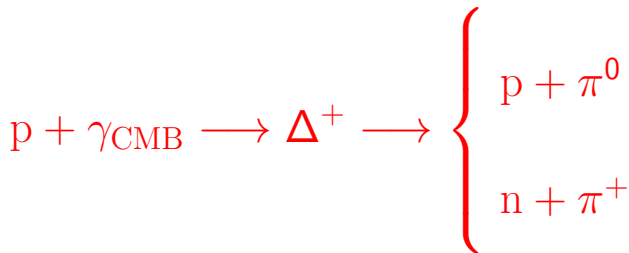


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GZK effect

[Greisen, 1966, PRL 16, 748; Zatsepin & Kuz'min, 1966, JETP Lett. 4, 78]



⇒ Threshold ~ 60 EeV

(1 EeV = 10^{18} eV)

⇒ Mean free path ~ 10 Mpc

(1 Mpc = 3.26×10^6 y)

Pair production



\Rightarrow Threshold ~ 0.40 EeV

(1 EeV = 10^{18} eV)

Propagation model: CRPropa 3

[Batista et al., 2016, J. Cosmol. Astropart. Phys. JCAP05, 038]

- ▶ Propagation of UHE cosmic-ray nuclei
- ▶ All relevant particle interactions
- ▶ 1D propagation mode (cosmological effects ...)
- ▶ 3D propagation mode (magnetic fields, sources ...)

Source model

- ▶ Injection energy spectrum:

$$\propto E^{-\gamma} e^{-E/E_{\text{cut}}}$$

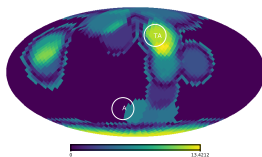
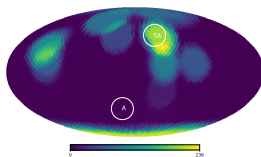
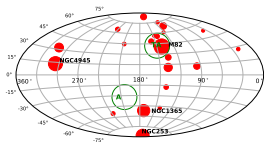
- ▶ Initial mass composition: pure proton

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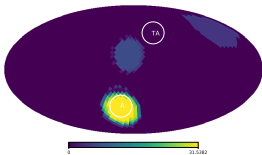
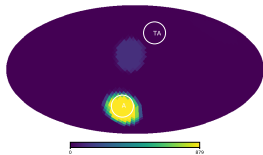
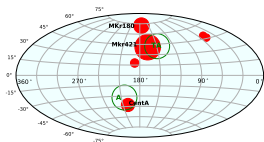
Extragalactic sources of UHE cosmic Rays

Starburst Galaxies :



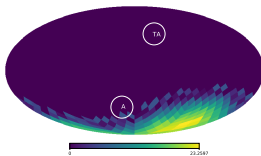
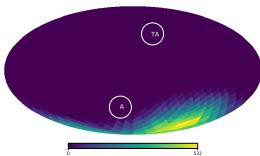
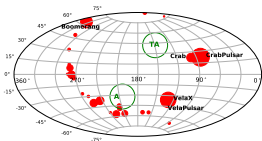
Extragalactic sources of UHE cosmic Rays

Active Galactic Nucleus :



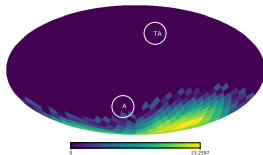
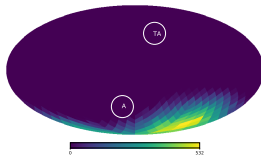
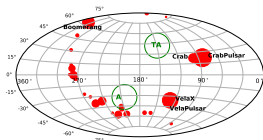
Galactic sources of UHE cosmic Rays

Pulsars :



Galactic sources of UHE cosmic Rays

SuperNova Remnants:



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Conclusion

- ▶ The observation of a hotspot near the direction of M82 puts forward the **starburst galaxy scenario**.
- ▶ The M82 starburst galaxy scenario **reproduces well observations**.
- ▶ The statistics are still not enough to draw any firm conclusion.

⇒ More data are greatly needed!

Thank you for your
attention!