DEVELOPMENT OF A FRAMEWORK FOR MULTI-MESSENGER OBSERVATIONS WITH THE AUGER OBSERVATORY

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LIP Summer Internship 2018

MULTI-MESSENGER ASTRONOMY

Observation of different signals emitted by the same Event.

Types of signals:

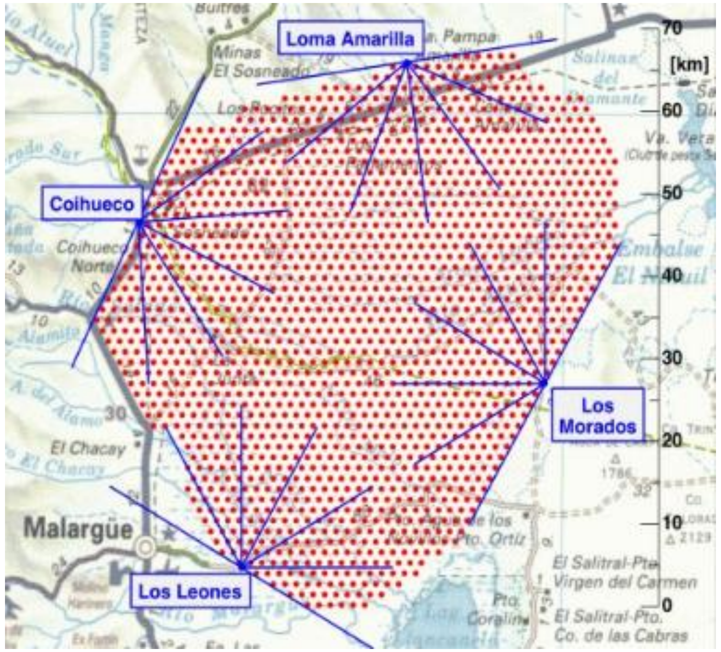
- Electromagnetic Radiation
- Gravitational Waves
- Neutrinos
- Cosmic Rays (mainly high-energy protons and atomic nuclei)

} Same Source

THE PIERRE AUGER OBSERVATORY

A Cosmic Ray and Neutrino observatory located in Argentina.

The size of the Auger Observatory over a satellite image of Lisbon.

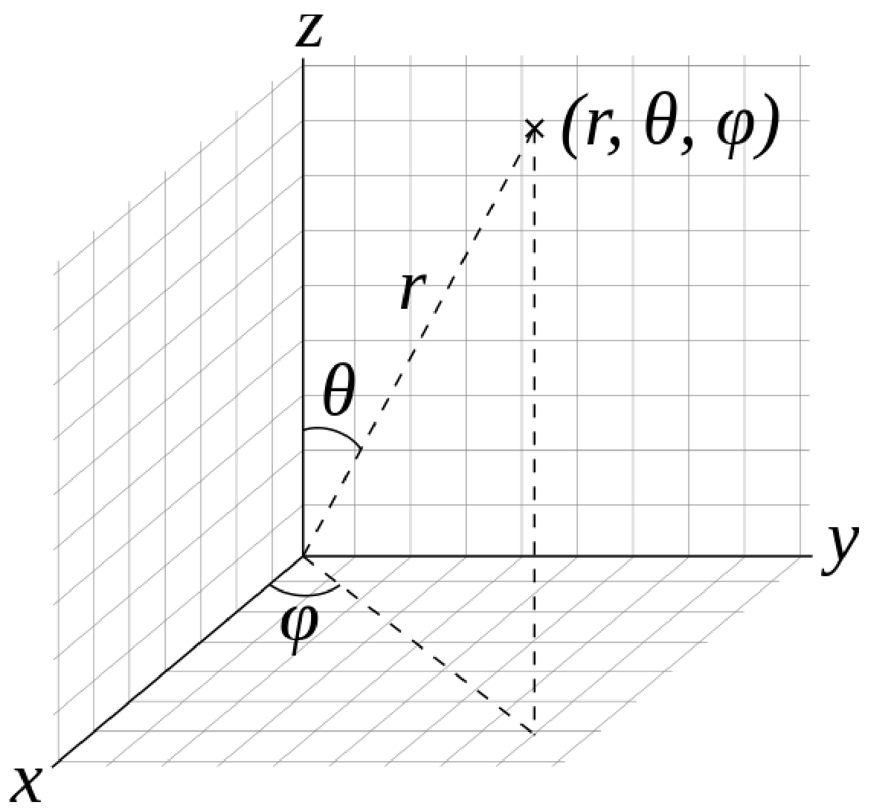


Position of the Auger Observatory and it's detectors.

A typical detector in the Auger Observatory.

PARTICLE DETECTION AT THE PIERRE AUGER OBSERVATORY

The detection of particles depends on the angle of arrival.



$\theta < 60°$:

Showers produced by Cosmic Rays

$60° < \theta < 75°$:

Showers produced by Cosmic Rays

Downward-going low angle Neutrinos

$75° < \theta < 90°$:

downward-going high angle Neutrinos

$90° < \theta < 95°$:

Earth-skimming neutrinos

THE OBJECTIVE

Creating software that allows the plotting of the sky at Auger and specific events.

Utility:

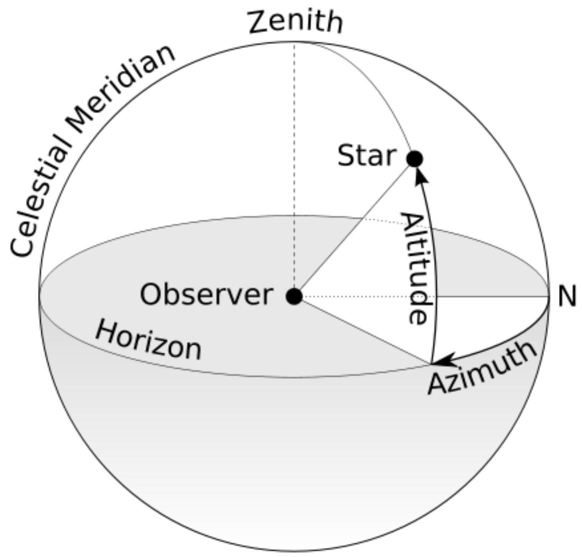
- Usage at the IST Control Room
- Studying Astronomical Events
- Know if an event was visible to the Auger Observatory

What to represent:

- Auger's field-of-view at a specific time
- The main sources visible in Auger's sky at that specific time
- Astronomical Events

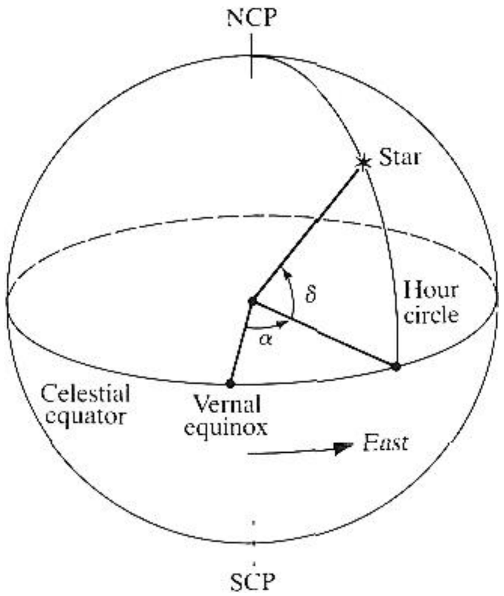
COORDINATE SYSTEMS

Systems of coordinates used to represent the Celestial Sphere.



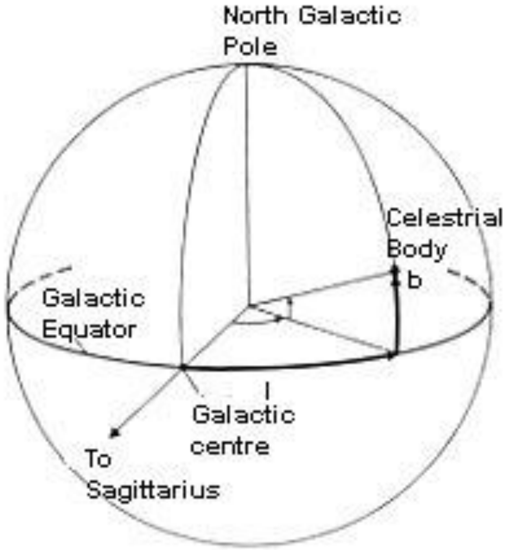
Horizontal Coordinates

(Azimuth, Altitude)
Depends on location and time



Equatorial Coordinates

(Right Ascension, Declination)
Does not depend on location and time

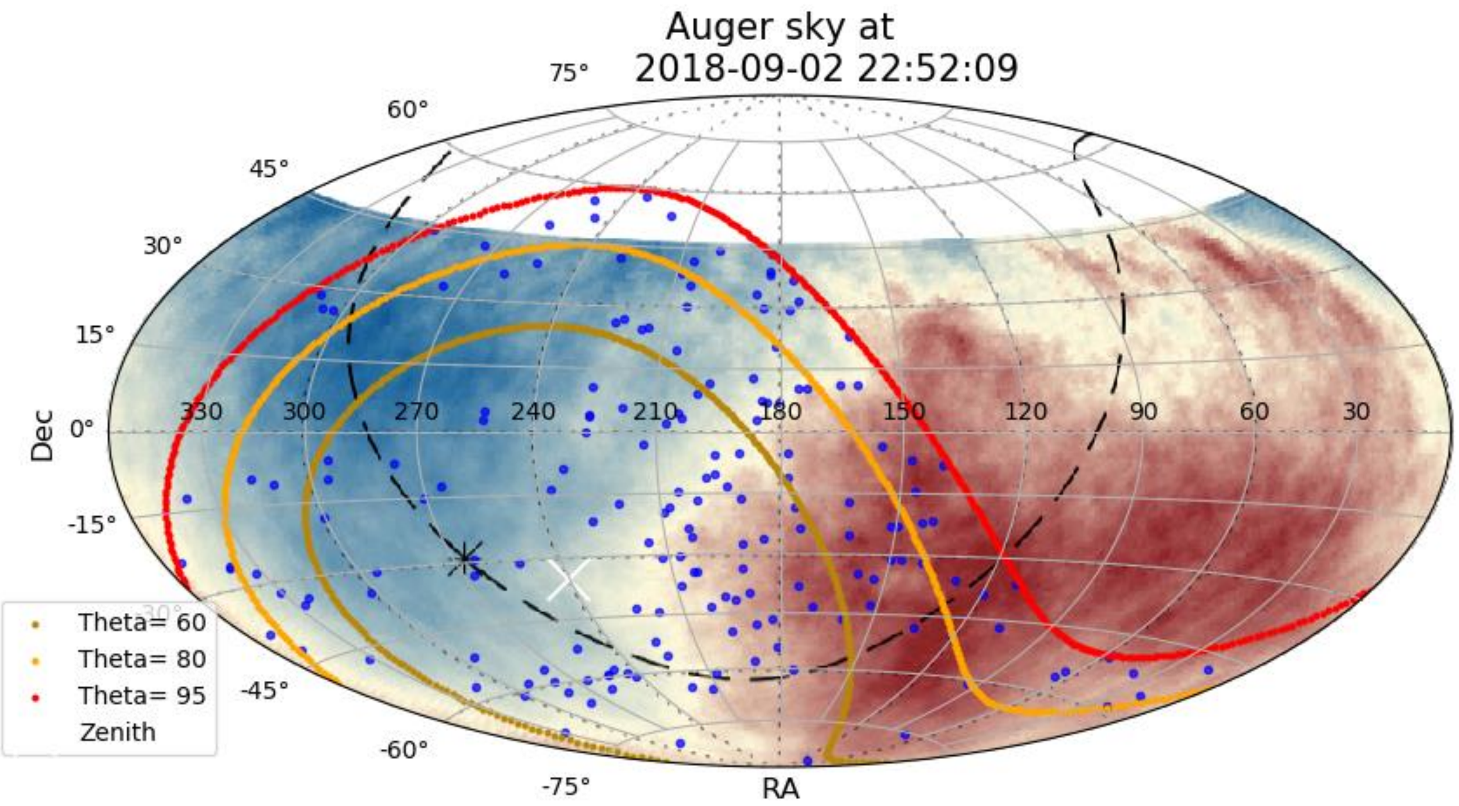


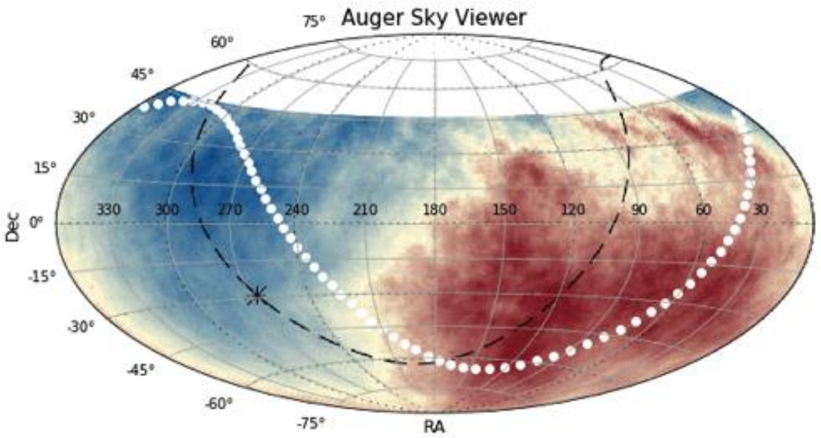
Galactic Coordinates

(Latitude, Longitude)
Does not depend on location and time

AUGER'S FIELD-OF-VIEW AND POSSIBLE SOURCES

http://www.lip.pt/~ev18117/equatorial.html

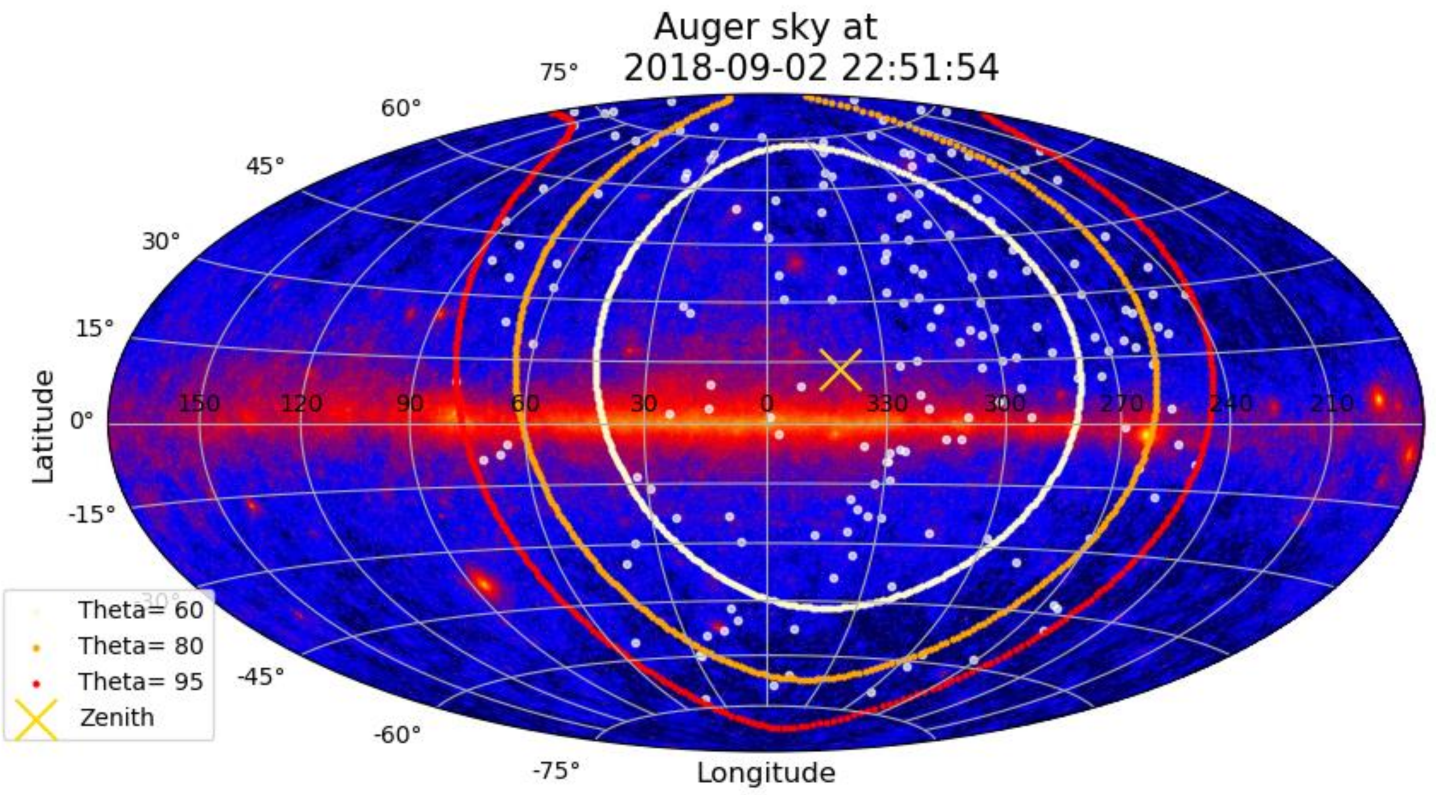


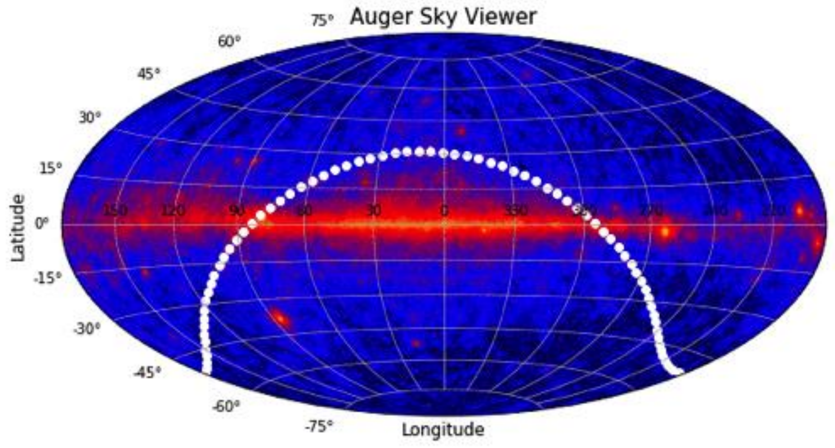


	Angle < 60	60 < Angle < 80	80 < Angle < 95
0	CenA	NGC4388	NGC4151
1	IC4329A	MCG-05-23-016	MCG+04-48-002
2	NGC4945	NGC7172	NGC7314
3	CircinusGalaxy	Mrk509	2MASSJ07594181-3843560
4	NGC5506	NGC3281	Fairall9
5	NGC4507	NGC3081	Mrk1498
6	NGC3783	NGC7582	MCG-01-24-012
7	AXJ1737.4-2907	NGC5548	Mrk417
8	NGC5252	NGC4992	Mrk915
9	ESO103-035	Mrk501	NGC4138

AUGER’S FIELD-OF-VIEW AND POSSIBLE SOURCES

http://www.lip.pt/~ev18117/galatica.html





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THE HUNT FOR HIGH-ENERGY PARTICLES

Neutral

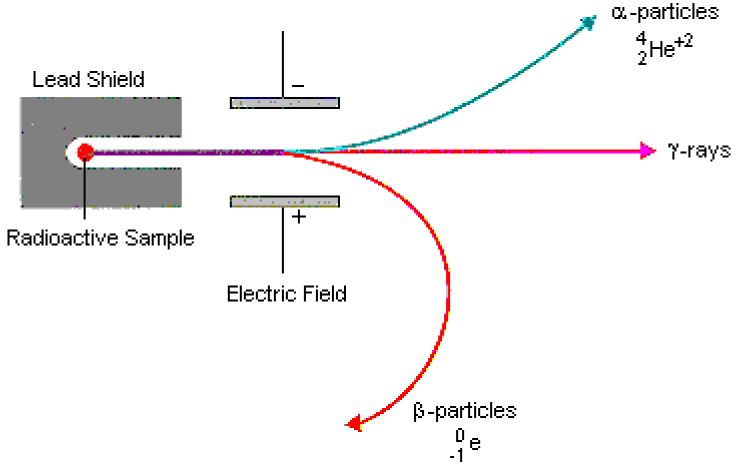
- Photons
- Neutrinos
- Neutrons

Charged

- Protons
- Iron nuclei

FACING THE PROBLEMS

- Time delay
- Deviation angles
- GZK effect

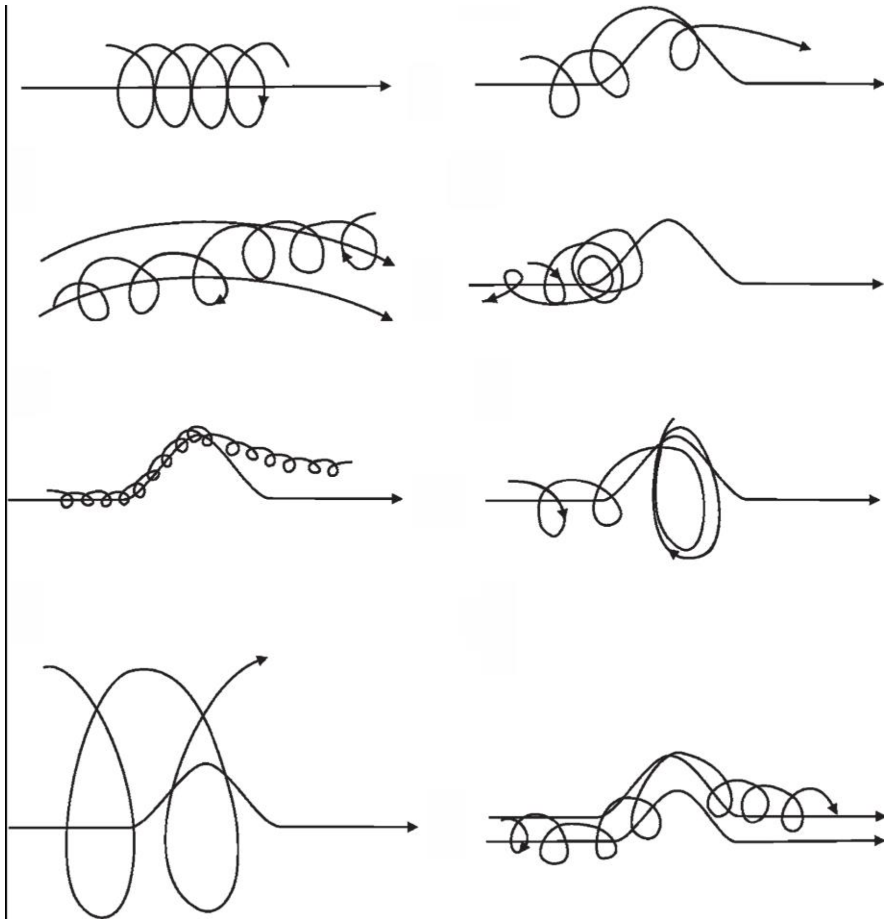


BUT FIRST…GYRATION RADIUS

$$r[m] = 3.33795\ \frac{E\ [GeV]}{Z\ B[T]}$$

- A very big energy or a very small magnetic field is needed in order to far away particles reach us.

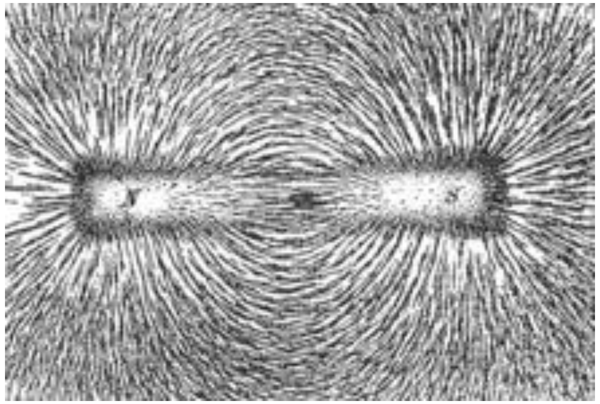
- Particles with small gyration radius get trapped in magnetic fields.



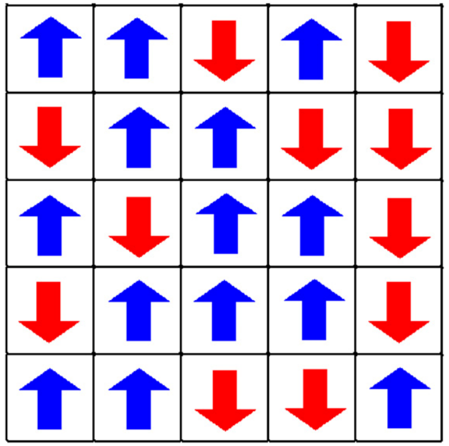
"*Cosmic Rays and Particle Physics*", Gaisser, Engel and Resconi, 2nd Edition, Cambridge University Press

BUT FIRST…MAGNETIC FIELDS

- Two **ordered** magnetic fields
  - Extragalactic
    - Magnitude $B_{IGM} \sim 10^{-11}$G
    - Important at distances > 10-100 Mpc
  - Galactic
    - Magnitude $B_{gal} \sim 10^{-6}$G
    - Important at distances < 100 kpc



- One **random** magnetic field
  - Magnitude $B_r \sim 10^{-9}$G
  - Important at distances > 10 Mpc



KINEMATIC DELAY OF NEUTRAL PARTICLES

- The easy one

- $t_{unc}[s] = \frac{d}{2c}\left(\frac{m}{E}\right)^2 = 5.14294 \times 10^7 d[pc]\left(\frac{m}{E}\right)^2$

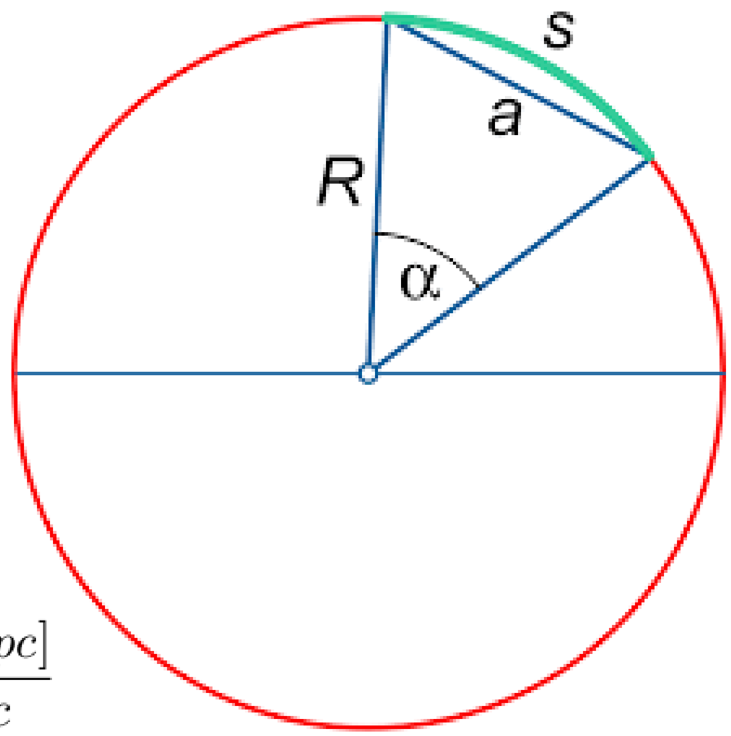
- At energies $E > 10^{18} eV$ is negligible

TIME DELAY OF CHARGED PARTICLES

$$t_{gal}\,[yr] = \frac{\Delta x}{c} \approx 3.262 \times 10^{6}\, R\,[Mpc]\,(\alpha - 2\sin(\alpha/2))$$

$$t_{IGM}\,[yr] \approx 1200\, Z^2 \left(\frac{D\,[Mpc]}{100\, Mpc}\right)^3 \left(\frac{10^{20}}{E\,[eV]}\right)^2 \left(\frac{B_{IGM}\,[G]}{10^{-11}\, G}\right)^2$$

$$t_r\,[yr] \approx 3.1 \times 10^5\, Z^2 \left(\frac{D\,[Mpc]}{100\, Mpc}\right)^2 \left(\frac{10^{20}}{E\,[eV]}\right)^2 \left(\frac{B_r\,[G]}{10^{-9}\, G}\right)^2 \frac{l_{coh}\,[Mpc]}{1\, Mpc}$$

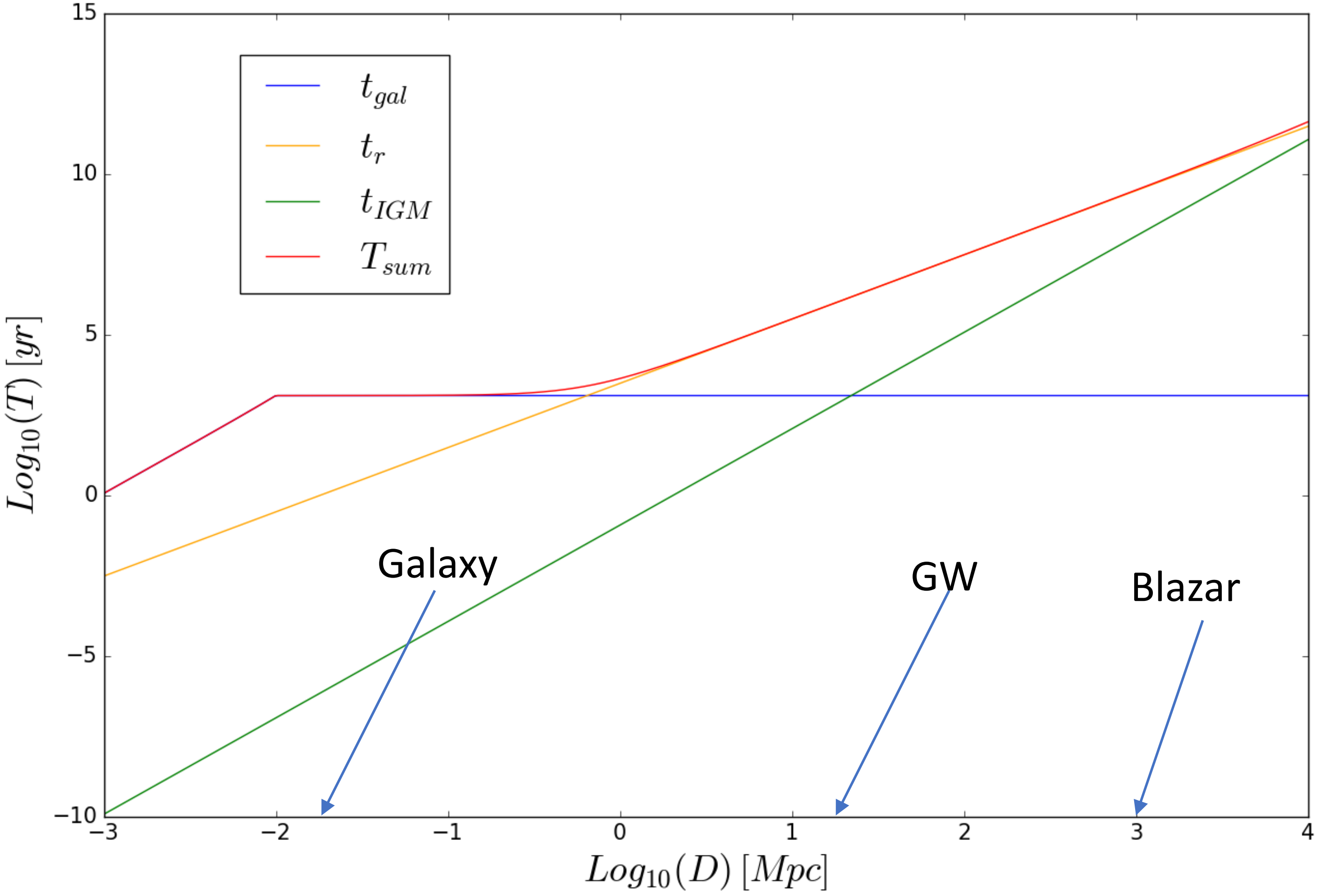


TIME DELAY OF CHARGED PARTICLES

Conclusions

- Dependence with Z^2

- In general, big time delays are obtained



Time delay of charged particle (yr) in function of distance (Mpc) for $E = 10^{19} eV$

DEVIATION ANGLES

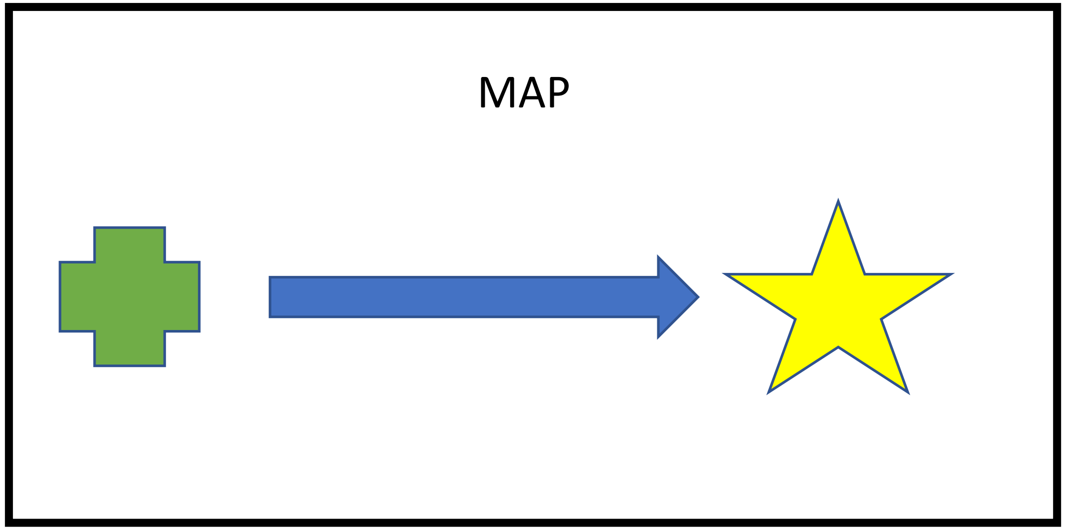
- Ordered

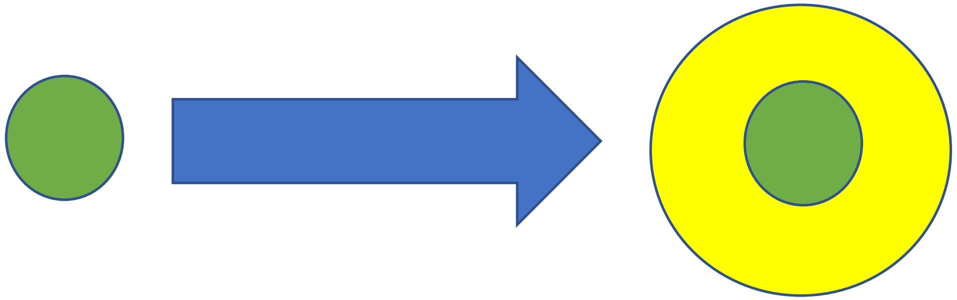
$$\Delta\theta_{gal} \approx 15.87990739^{\circ}\, Z\, B_{\mu G} \frac{d\,[kpc]}{30\,kpc} \frac{10^{20}}{E\,[eV]}$$

$$\Delta\theta_{IGM} \approx 0.53^{\circ}\, Z \frac{10^{20}}{E\,[eV]} \frac{D\,[Mpc]}{100\,Mpc} \frac{B_{IGM}\,[G]}{10^{-11}\,G}$$

- Random

$$\Delta\theta_{r} \approx 3.5^{\circ}\, Z \frac{B_r\,[G]}{10^{-9}\,G} \frac{10^{20}}{E\,[eV]} \left(\frac{l_{coh}}{1\,Mpc} \frac{D\,[Mpc]}{100\,Mpc}\right)^{1/2}$$



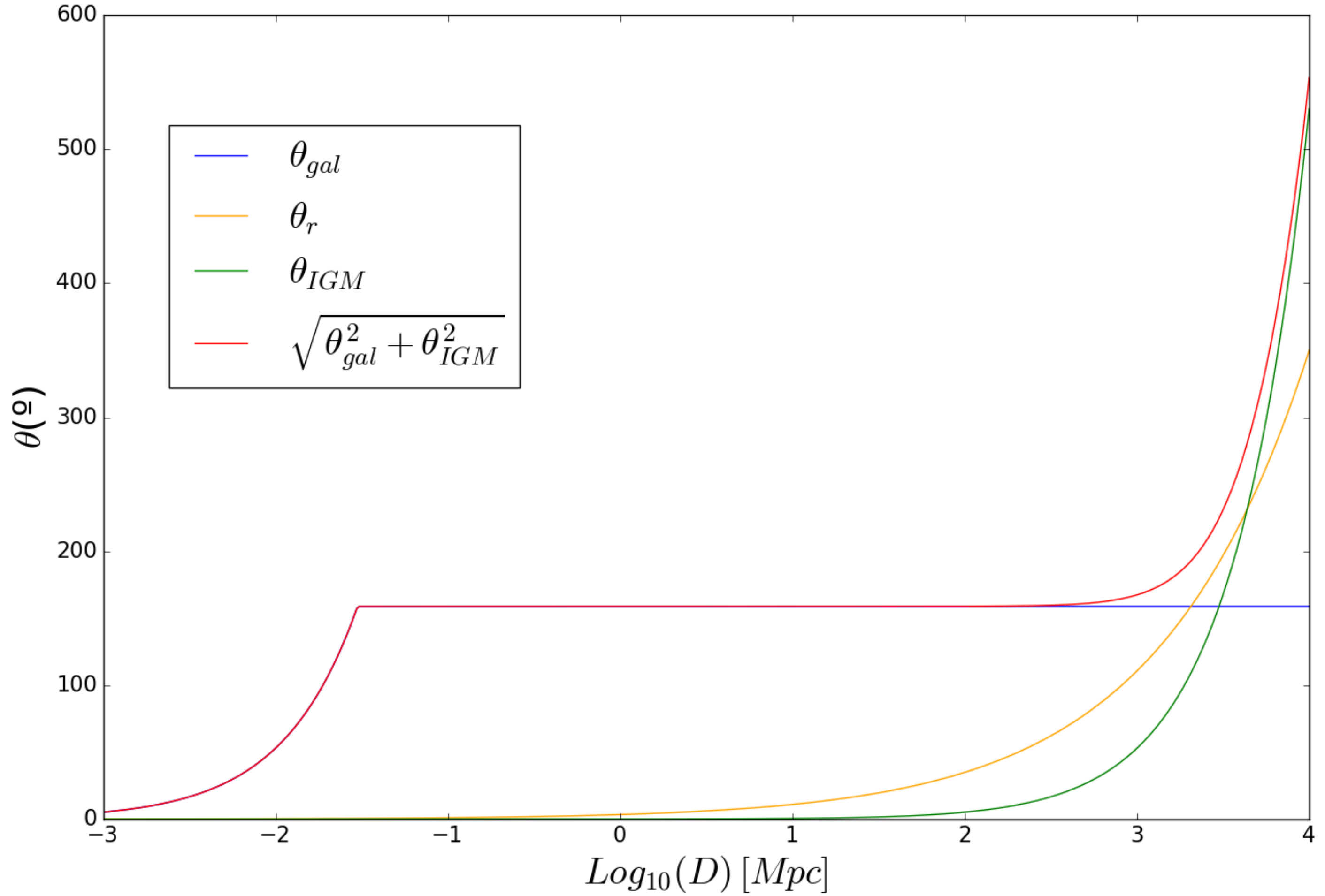


DEVIATION ANGLES

Conclusions

- Major influence from galactic magnetic field

- In general, for large distances (> 1 Gpc) we obtain unphysical deviation angles



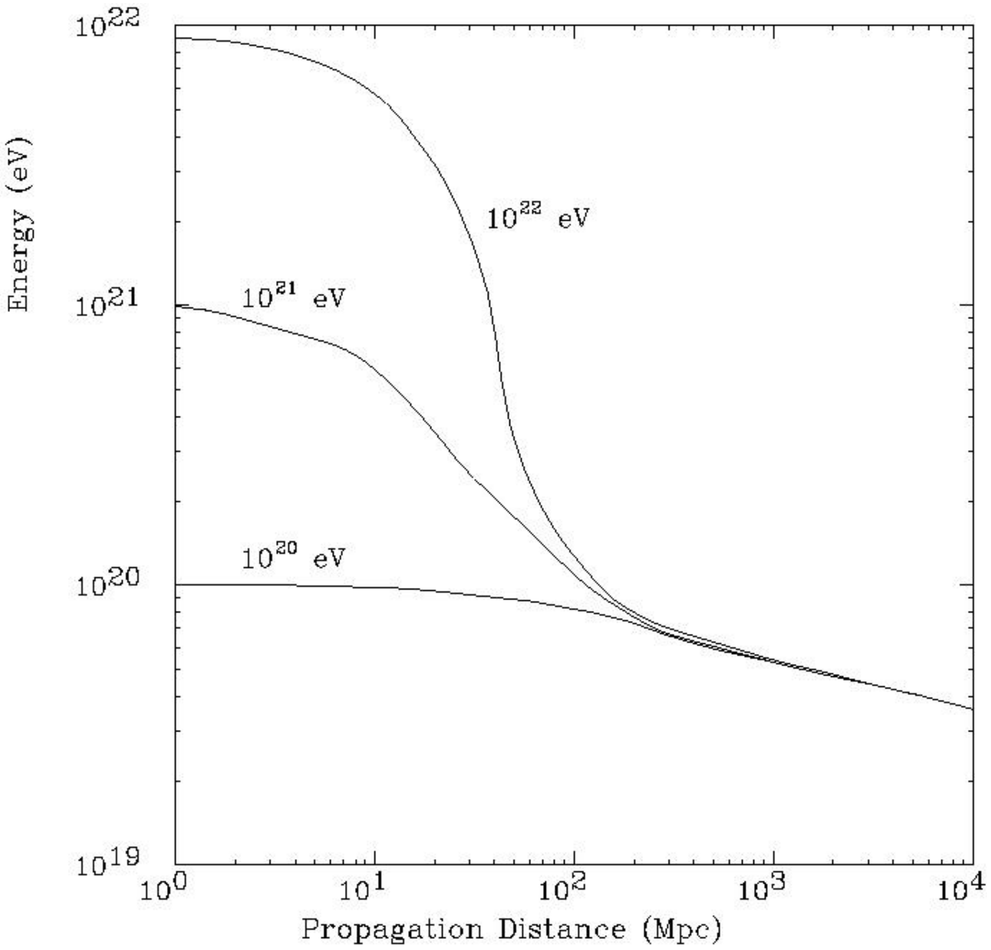
Deflection angles (º) as function of the distance to the source (in Mpc), for $E = 10^{19} eV$

GZK EFFECT

- For energies above the GZK threshold ($E > 10^{19.5} eV$), the protons interact with the CMB photons

$$p + \gamma \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \quad (\gamma)$$
$$n + \pi^{+} \quad (\nu)$$

- The mean free path is ≈10 Mpc, and protons lost approximately 20% of their energy



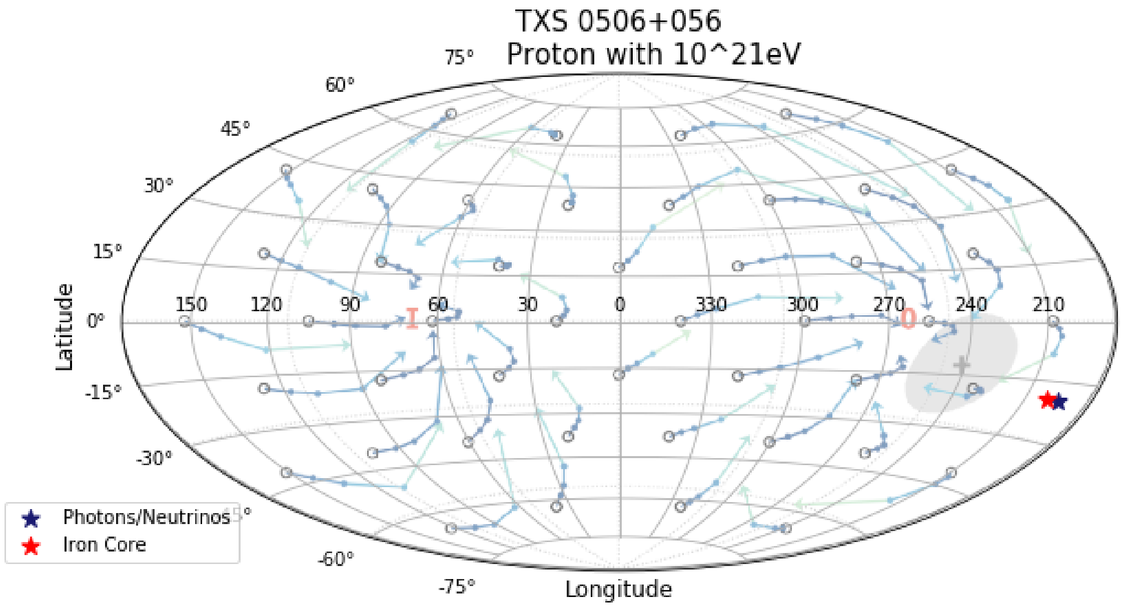
Taken from http://apcauger.in2p3.fr/Public/Presentation/Images/GZK_proton.jpg

BLAZAR TXS 0506+056

Distance ≈1.1 Gpc

Observed in 2017 by IceCube, with a 290 TeV neutrino

Particle	Horizon (pc)	Energy (eV)	r_G (pc)	$\Delta\theta$ (°)	$\sigma\theta$ (°)	ΔT
n	$9.121 * 10^3$	10^{18}	-	-	-	0.05 (s)
	$9.121 * 10^6$	10^{21}	-	-	-	5×10^{-8} (s)
	$9.121 * 10^9$	10^{24}	-	-	-	5×10^{-14} (s)
p		10^{18}	1.08×10^6	1691.62	1160.80	3.91×10^{11} (yr)
		10^{21}	1.08×10^9	5.25	1182.17	3.91×10^5 (yr)
		10^{24}	1.08×10^{12}	5.16	803.29	0.391 (yr)
Fe		10^{18}	4.16×10^4	43982.17	30180.87	2.64×10^{14} (yr)
		10^{21}	4.16×10^7	136.44	799143.59	2.64×10^8 (yr)
		10^{24}	4.16×10^{10}	134.27	543024.03	264.365 (yr)

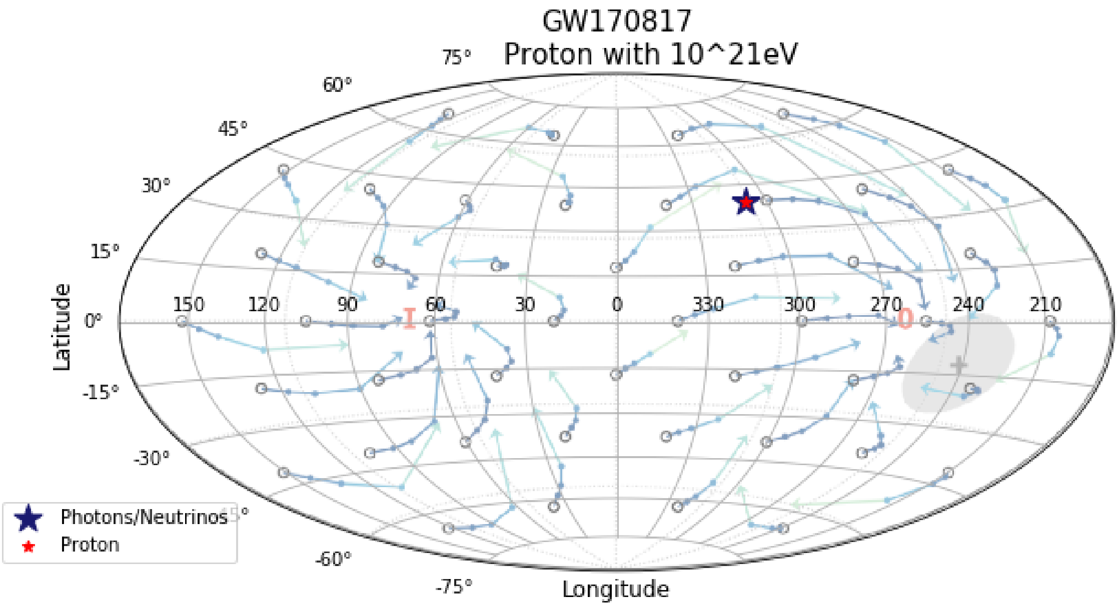


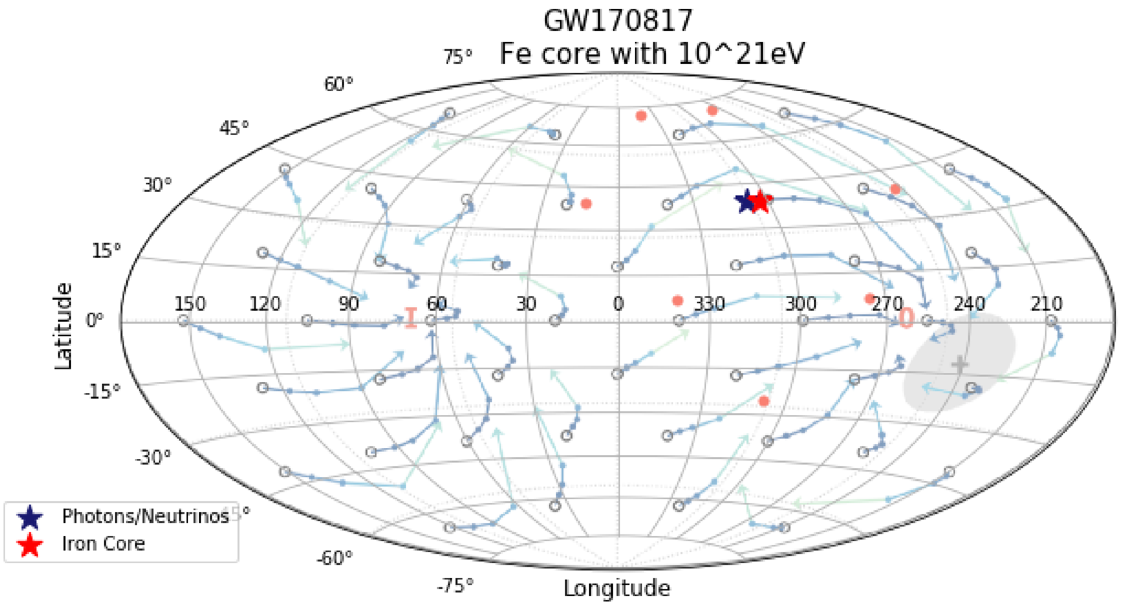
GW170817

Distance ≈39.85 Mpc

Observed in 2017 by LIGO and VIRGO

Particle	Horizon (pc)	Energy (eV)	r_G (pc)	$\Delta\theta$ (°)	$\sigma\theta$ (°)	ΔT
n	$9.121 * 10^3$	10^{18}	-	-	-	1.81×10^{-3} (s)
	$9.121 * 10^6$	10^{21}	-	-	-	1.81×10^{-9} (s)
	$9.121 * 10^9$	10^{24}	-	-	-	1.81×10^{-15} (s)
p		10^{18}	1.08×10^6	1588.13	220.86	4.93×10^8 (yr)
		10^{21}	1.08×10^9	0.164	0.096	493.05 (yr)
		10^{24}	1.08×10^{12}	1.64×10^{-4}	9.58×10^{-8}	4.93×10^{-4} (yr)
Fe		10^{18}	4.16×10^4	41291.17	5742.38	3.33×10^{11} (yr)
		10^{21}	4.16×10^7	4.26	64.75	3.33×10^5 (yr)
		10^{24}	4.16×10^{10}	4.26×10^{-3}	6.47×10^{-5}	0.333 (yr)





SUPERNOVA 1987a

Distance ≈51.4 kpc

Observed in 1987 by Kamiokande II, IMB and Baksan in neutrinos

Particle	Horizon (pc)	Energy (eV)	r_G (pc)	$\Delta\theta$ (°)	$\sigma\theta$ (°)	ΔT
n	$9.121 * 10^3$	10^{18}	-	-	-	2.33×10^{-6}
	$9.121 * 10^6$	10^{21}	-	-	-	2.33×10^{-12}
	$9.121 * 10^9$	10^{24}	-	-	-	2.33×10^{-18}
p		10^{18}	1.08×10^6	1587.99	5.12	819 (yr)
		10^{21}	1.08×10^9	1.59	5.12×10^-3	0.117 (yr)
		10^{24}	1.08×10^{12}	1.59×10^{-3}	5.12×10^{-6}	1.17×10^{-7}(yr)
Fe		10^{18}	4.16×10^4	41287.76	133.12	553650 (yr)
		10^{21}	4.16×10^7	41.29	0.133	79.614 (yr)
		10^{24}	4.16×10^{10}	0.0413	1.33×10^{-4}	7.91×10^{-5} (yr)