# Introduction to astroparticle physics

Part 2, Exercises 3

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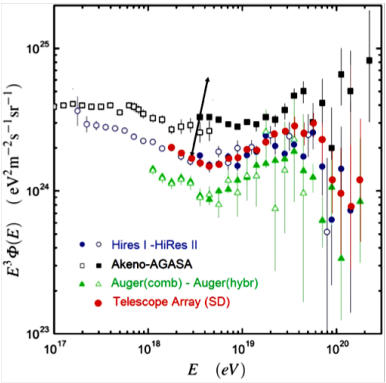
## 1 Beware of the Plots

The AGASA results suffer from a 25% systematic uncertainty on the estimated energy $E$. This implies that all the AGASA points can be shifted (choose one or more of the following options):

- ❑ right along x, and up along y.
- ❑ right along x, and down along y.
- ❑ left along x, and up along y.
- ❑ left along x, and down along y.

Estimate the amount of the possible shifts along x and along y.




## 2 GZK effect

Cosmic protons, during their propagation, can interact with the photons of the cosmic microwave background ($\gamma_{\rm CMB}$) leading to the so-called pion photo-production via the $\Delta(1232)^+$ resonance:

$$p + \gamma_{\rm CMB} \to \Delta(1232)^+ \to p + \pi^0$$
$$p + \gamma_{\rm CMB} \to \Delta(1232)^+ \to n + \pi^+$$

1. Compute the minimum energy ($E_{\rm thr}$) that a proton must have to induce this reaction.
2. Compute the mean free path ($\lambda$) for a cosmic proton, assuming that the cross section above threshold is $\sigma_{p\gamma} = 250$ µb and that the number density of CMB photons is $n_{\rm CMB} = 410.7$ cm$^{-3}$.
3. The produced $\pi^0$ will most likely decay into two photons. Compute the maximum and minimum energy of these photons in the laboratory frame in terms of the energy ($E$) and momentum ($p$) of the $\pi^0$. Show that the energy distribution ($dN_\gamma/dE_\gamma$) of these photons is flat i.e., it does not depend on the photon energy ($E_\gamma$).

## 3 What should happen to cosmic photons with $E > 100$ TeV?