# Constraints on Astrophysical Limits of the SGR 1806-20

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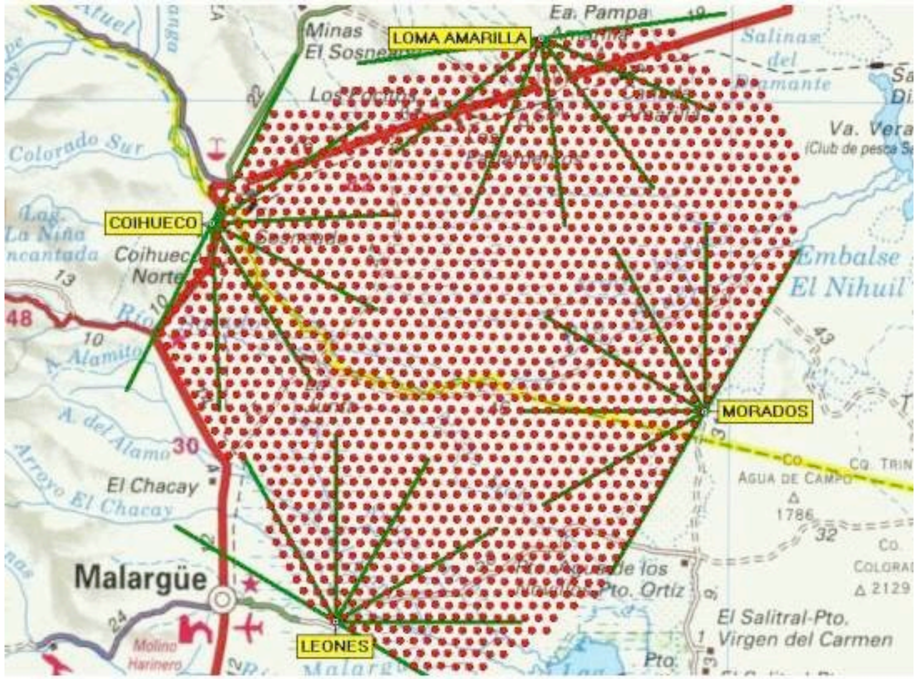
# Scientific Motivations

- Soft Gamma-ray Repeaters (SGRs) are candidates to accelerate ultra high-energy cosmic rays (UHECRs).
- It is believed that SGRs are directly associated to magnetars (magnetically powered neutron stars).
- On December 27, 2004 there was a giant flare from the SGR 1806-20.
- The arrival time of UHECRs depends on a large number of factors and it may be possible to detect UHECRs coming from this SGR in the interval ~ 0.6 years
- The main controversial questions between different models are related to the presence of a (relativistic ?) baryonic flow at the initial stage and the existence of a jet-collimated structure.
- It is very important to look for possible UHECRs from SGR 1806-20, since their observation with or without the low energy particle counterpart from this kind of cosmic event is a central key to answer these controversial questions.

# Pierre Auger Observatory

- The Pierre Auger Observatory was designed to study UHECRs, the most energetic and rare particles in the universe.
- Array of 1600 water-Cherenkov covering an area of approximately 3000 km$^2$, forming an equilateral triangular grid of 1.5 km, forming the surface detector (SD).
- 4 stations containing 6 telescope each, composing the fluorescence detector (FD).



# SGR 1806-20 and the flare

- Equatorial coordinates of the object: $(\alpha, \delta) = (272.16^\circ, -20^\circ)$.
- The giant flare was the most luminous transient cosmic ray event ever detected with isotropic-equivalent energy $E_\gamma \sim 10^{46-47}(d_{15})^2$ and peak luminosity in the first 125 ms $L_\gamma \sim 10^{47}$ erg $s^{-1}$, where $d_{15}$=d/15 kpc, where d is the distance to the source.
- Several models predict the production of UHECRs and high energy neutrinos with energies ~TeV and ~PeV resulting from the pion photoproduction.
- I) Detection of neutrinos would indicate the existence of non relativistic baryonic material in the initial stage of the flare, II) detection of UHECRs and no neutrino signal would indicate relativistic baryonic material in the intial stage and III) the absence of both neutrinos and UHECRs would favor pure radiation pair models (baryon poor).
- High energy neutrinos would be able to produce muons detectable by ground-based experiments such as AMANDA (Antarctic Muon and Neutrino Detector Array). Nevertheless AMANDA has reported no signal coming from the SGR 1806-20.
- Secondary neutrons can be produced in the interaction of relativistic protons and nuclei with photons in the flare environment. Those produced with energy above $E = 10^{18}$ eV have a boost large enough to survive from the production point to the Earth, providing information about their source. Due to the exponential depletion, about 20% of neutrons reach the Earth with $E = 10^{18}$ eV and about 58% with $E = 10^{18.5}$ eV.

# Upper limit on the particle flux

- In the case of a gaussian signal filter it is possible to model the distribution of the sum of the background and the signal, and derive an upper limit $\mu_{\beta,s}$ from this distribution.
- Using a gaussian approximation $N(n_{bg} + \mu_s , n_{bg}/2 + 2\mu_s/3)$ for the distribution of the total counting within a certain direction, the upper limit with a confidence level β of the counting from the source can be obtained from the expression below, where $n_{obs}$ is the observed counting from source direction, $n_{bg}$ is the expected counting obtained from the coverage map (the isotropic sky map as would be seen by the detector taking into account its acceptance), and $\mu_{\beta,s}$ the maximum counting estimated for the source. For a confidence level of 95% $C_\beta$ = 1.64.

$$n_{obs} - (n_{bg} + \mu_s^\beta) = C_\beta \sqrt{\frac{n_{bg}}{2} + \frac{2\mu_s^\beta}{3}},$$

- For a gaussian filter with parameter $\sigma_g$ the flux upper limit is given by

$$\Phi_s^\beta = \frac{4\mu_s^\beta \Phi_{CR} \pi \sigma_g^2}{n_{bg}}.$$

# Search of UHE neutrons in coincidence with the flare

- Time window for analysis: T = 5 min around the flare.
- Threshold energy: E > 1.1 EeV. This allows the detection of neutrons on Earth before their decay.
- Gaussian filter with dispersion 5° to extract the signal from the background.
- In this analysis we obtained $n_{obs} = 0$ from the data and $n_{bg} = 2.64\times10^{-3}$ from the coverage map (isotropic distribution of events convolved with the acceptance of the detector).
  since the overall flux of cosmic rays at the considered energies is $\Phi_{CR} = 7.05\times10^{-13}$, and using these values, we obtain using the previous equations $\mu_{\beta,s}$=1.40 and $\Phi_{95\%} = 3.87\times10^{-5}$ particles $m^{-2}sr^{-1}s^{-1}$, which is the upper limit for the neutron flux with 95% of confidence level.
- If the effective area of detection during the time interval T is $A_{eff}$ = 238 $km^2$, the maximum number of neutrons in coincidence with the flare is

$$N_n^{95\%} = \Phi_s^{95\%} A_{eff} T = 2.22$$

- This result can be further explored to constrain kinematic variables related to the initial stage of the giant flare.

# Limits for astrophysical variables

- According to Ioka *et al.* neutrons produced by p − γ interactions can reach us in a straight line without decaying if their energy is larger than ~ 1 EeV, and may be observed as coincident cosmic rays. Hence, the number of neutrons in coincidence with the flare that would be observed by the Pierre Auger Observatory for a baryon-rich scenario in the initial stage of the flare is

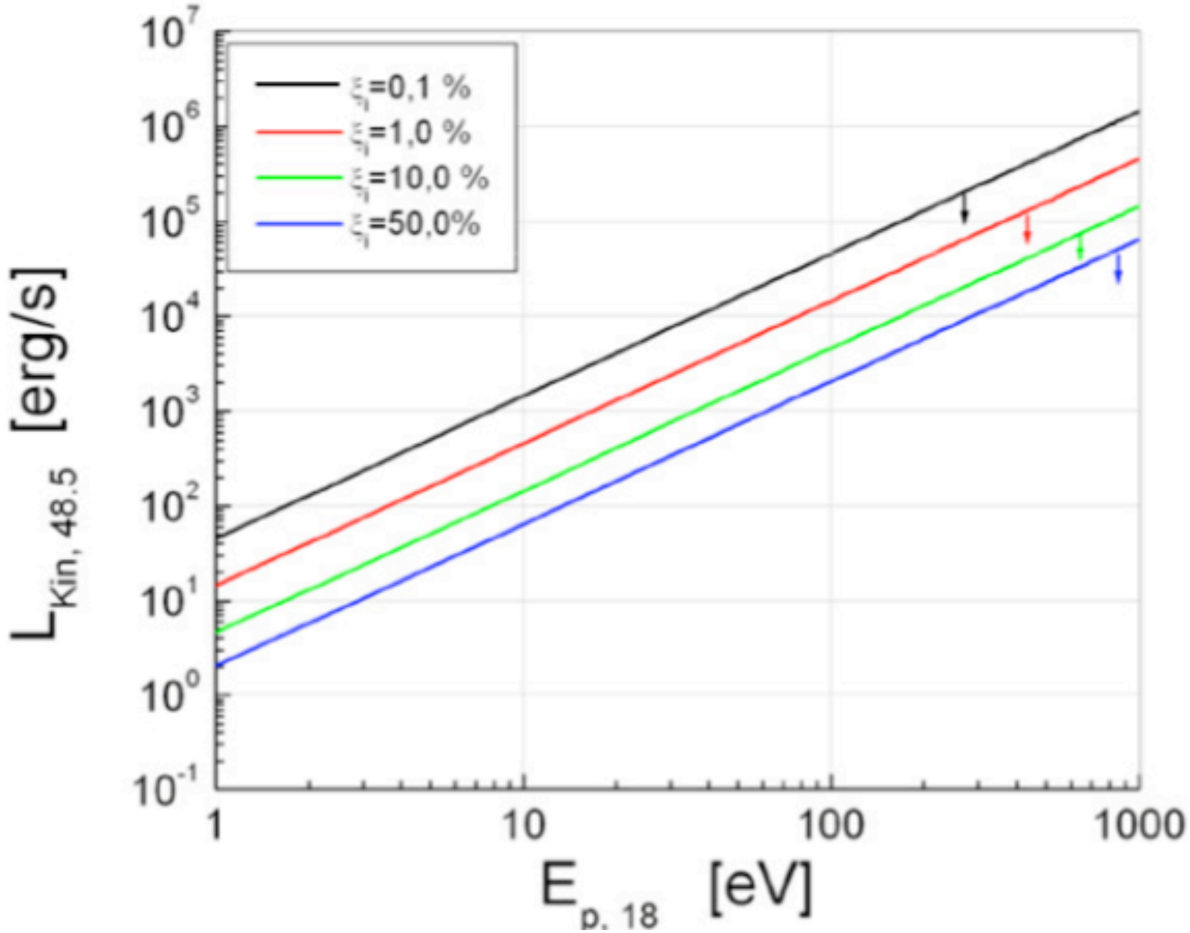
$$N_n \sim 1.06\epsilon_{p,18}^{-3}\xi_{i,-1}L_{kin,48.5}^{2}d_1^{-2}5\Delta t_{-1}^{-1} \leq 2.22$$

where $\varepsilon_p$ is the energy of the primary proton which gives rise to the neutron, $\xi_i$ is the conversion factor of kinetic energy into internal energy, $L_{kin}$ the kinetic luminosity and $\Delta t$ is the variability time scale. In this notation $X_n = X/10^n$ and for example $L_{kin,48.5}$ is the kinetic luminosity in units of $10^{48.5}$ erg $s^{-1}$.

- Since the variability time scale has to be smaller than the duration of the observed flare (~0.1s), it may be used to impose an upper limit for the luminosity of kinetic energy as a function of the proton energy and of the conversion factor of kinetic energy into internal energy

$$L_{kin,48.5(max)}^{2} \leq \frac{N_{n(max)}\Delta t_{-1(max)}}{1,06\xi_{i(min)}}\epsilon_{p,18}^{3} \leq \frac{2.094}{\xi_{i(min)}}\ \epsilon_{p,18}^{3}$$

# Limits for astrophysical variables




➡ The figure shows the upper limit for the luminosity of kinetic energy $L_{kin,48.5}$ as a function of the primary proton energy $\varepsilon_{p,18}$, for different values of $\xi$.

# Conclusion

- The absence of neutrons in our analysis in addition to the absence of high energy neutrinos from the SGR 1806-20 in AMANDA data favor models in which the giant flare arises from a baryon-poor initial stage. Otherwise, if the initial stage were baryon-rich, astrophysical variables related to the mechanism of production of the flare would be subject to the limits of 2.22 neutrons.
- Even though no flares were recorded in the recent past, the monitoring of the directions corresponding to the other magnetar candidates within our Galaxy could contribute to fill the absolute lack of information and for a better comprehension of these interesting objects that are relevant candidates to UHECRs sources, lying in our neighborhood.

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