Detection of a Muon Burst Coincident with KM3-230213A

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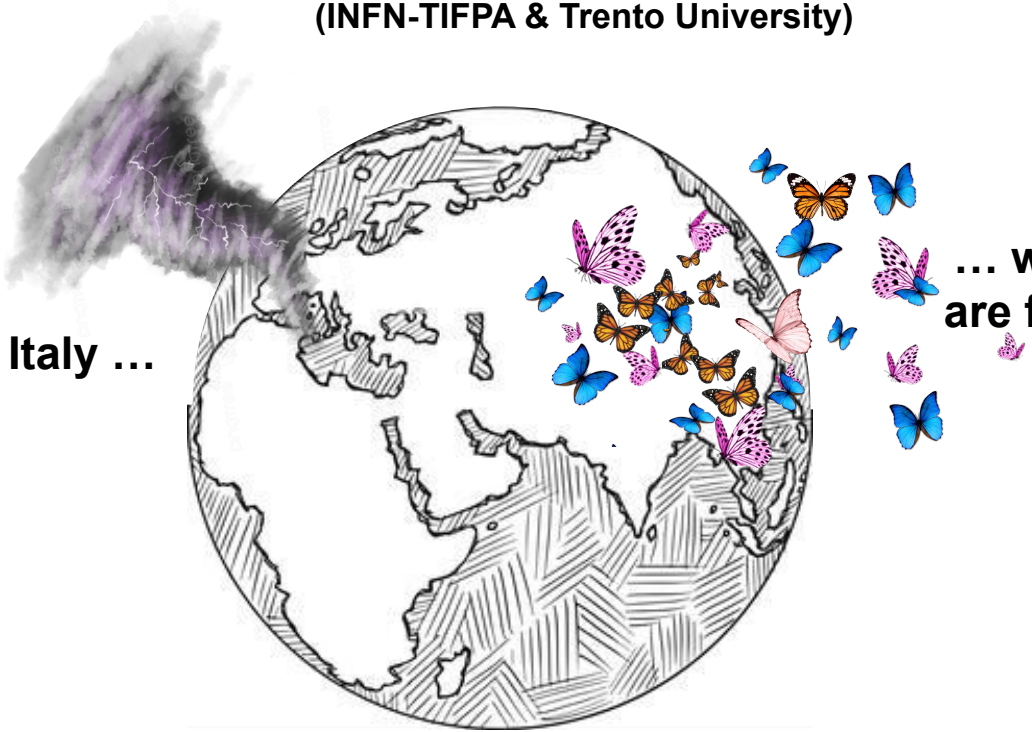
a Tornado in Italy …



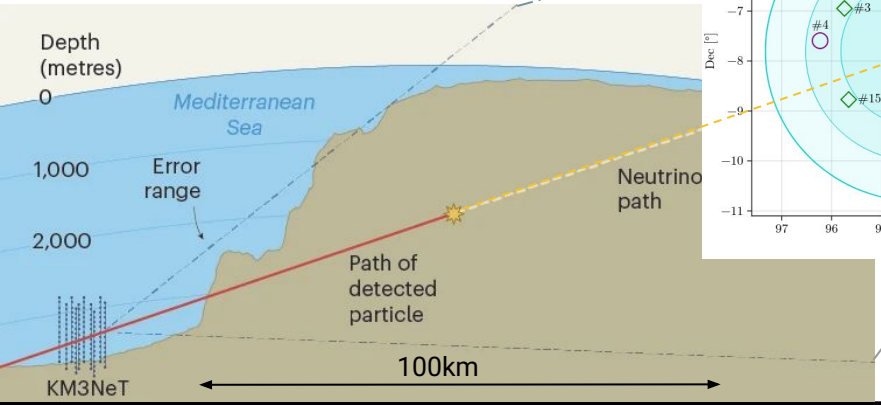
… while butterflies' wings are flapping in China

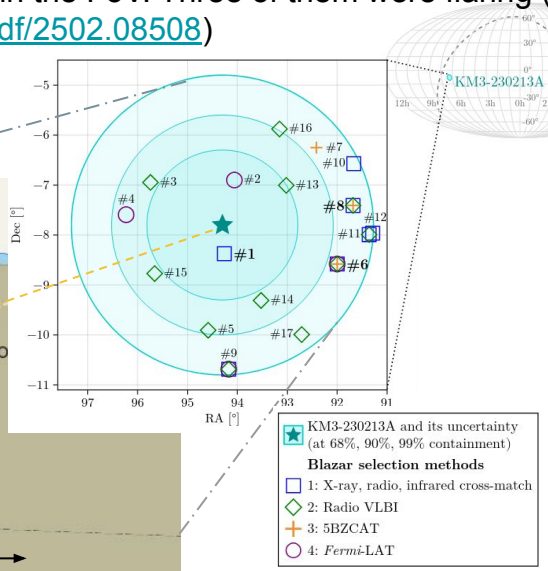
KM3-230213A: a brief summary

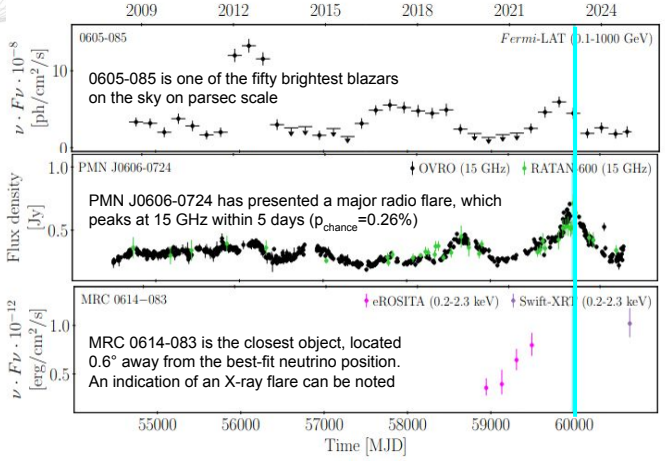
On 2023 February 13 at 01:16:47, KM3NeT/ARCA detected an “horizontal” muon with energy in the range 35-380 PeV (90% C.L.) most likely it was originated by a neutrino with energy roughly 200 PeV arriving from (RA = 94.3°,Dec = −7.8°) with 1.5° uncertainty
Regarding its origin:

- Apparent 2.5-3σ tension with null observations from IceCube and Pierre Auger (https://arxiv.org/abs/2502.08173)
- An interaction of a cosmic-ray particle with even higher energy in the atmosphere is considered implausible
- No plausible galactic source. Few Blazars are in the FoV. Three of them were flaring (https://arxiv.org/abs/2502.08484)
- Potential cosmogenic origin (https://arxiv.org/pdf/2502.08508)

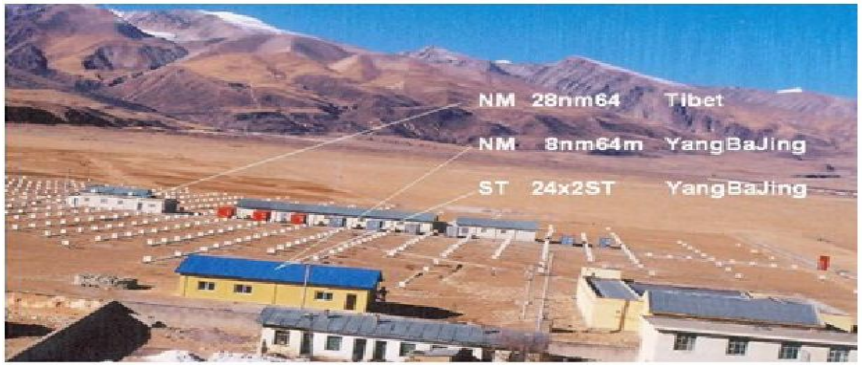
(confirmation of a multi-messenger correlation would rule out the latter possibility)



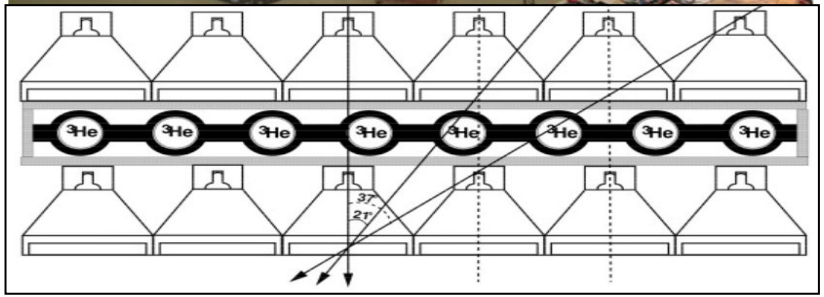


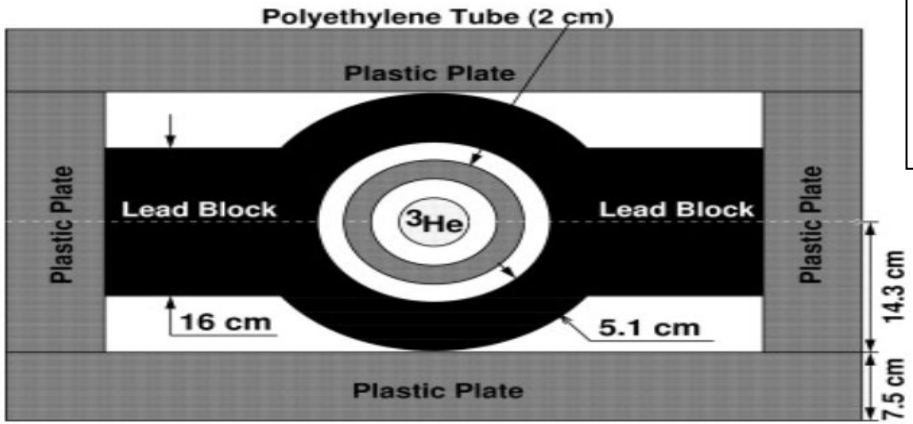


The Yangbajing μ/n telescope



Yangbajing Int. Cosmic Ray Obs. 4300m
90°E 30°N located 140° from KM3-230213A

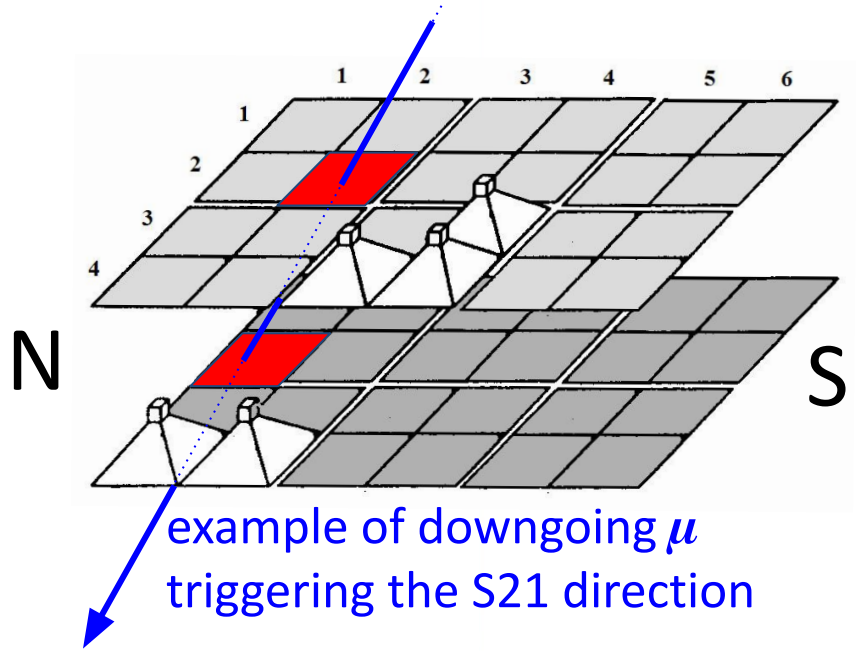




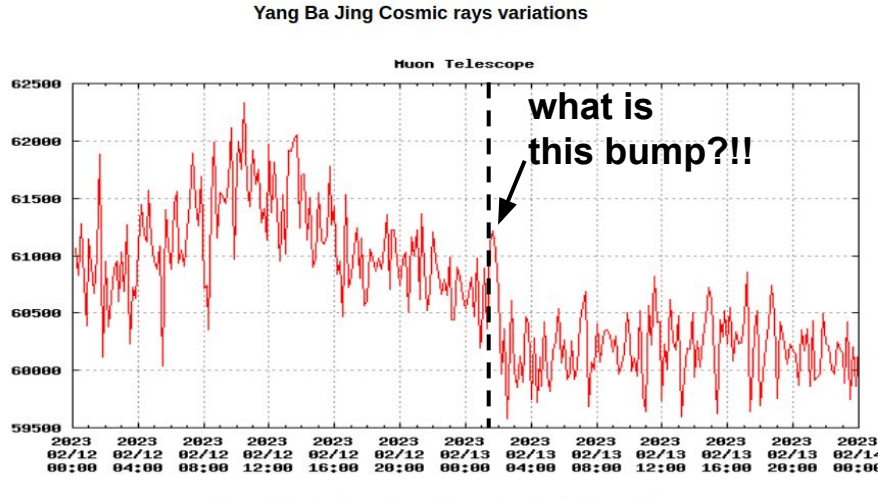
-two 2 x 3 m^2 layers of plastic scintillators
-vertically separated by 130 cm
-each layer is made of 24 tiles 50x50x5 cm^3
-Lead plates absorb the soft component of cosmic rays, resulting in an **energy threshold of 300 MeV** for μ.

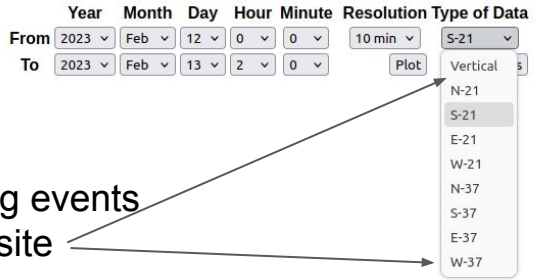
NIMA 623 (2010) 1030 + PoS(ICRC2015)353 + Network CR Stations

the Yangbajing Data Center: http://ybjnm.ihep.ac.cn/mu/



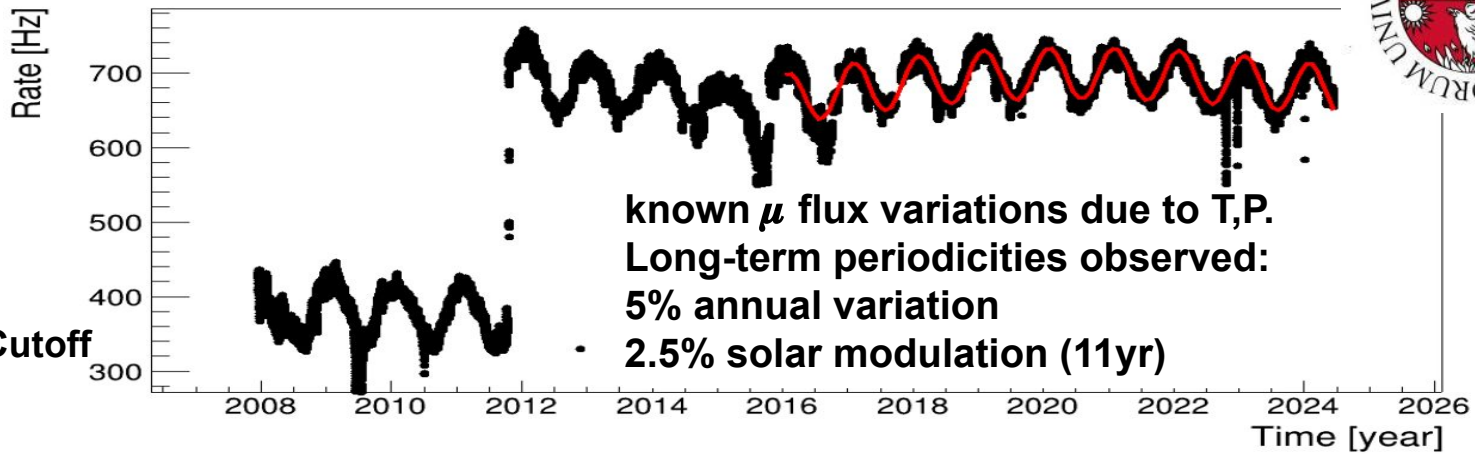
example of downgoing μ triggering the S21 direction





The gate is 50-200 ns, it is impossible to classify downgoing vs upgoing events
There are 77 directional components, only 9 are published on the website
The best time resolution of the published data is 1 minute

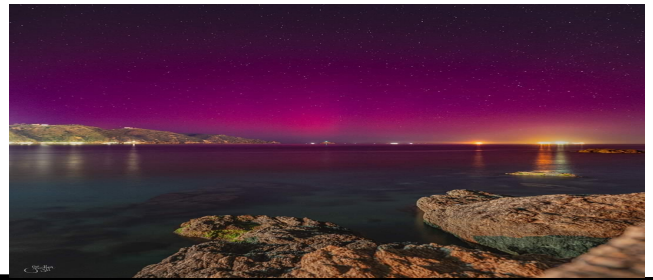
time variations of μ measured by YBJ

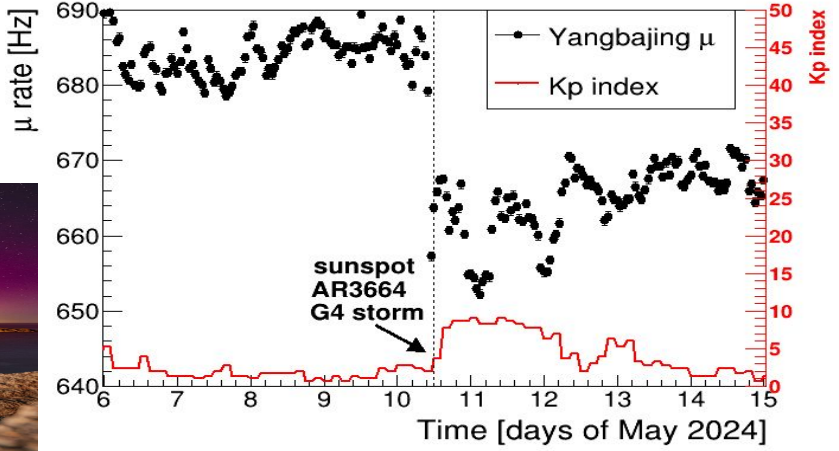


YBJ site:
14.1GV Rigidity Cutoff

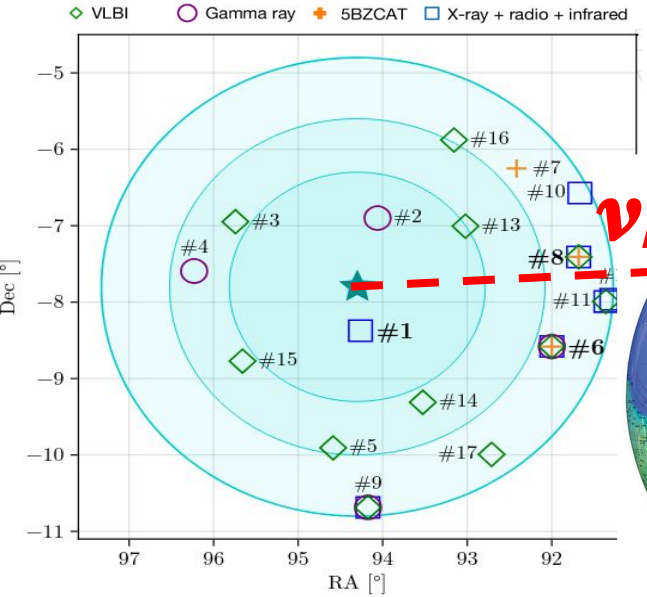
known μ flux variations due to T,P.
Long-term periodicities observed:
5% annual variation
2.5% solar modulation (11yr)

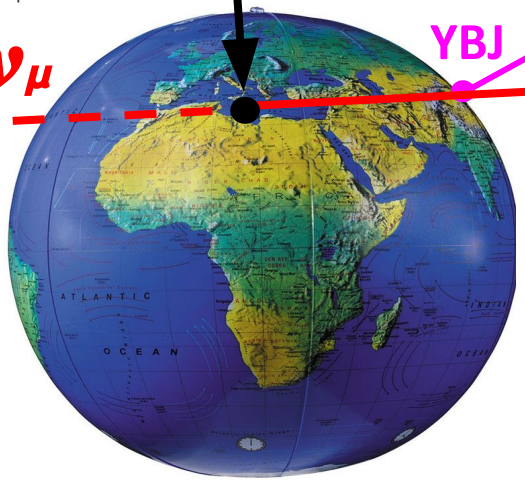
The time series also shows many spikes and steps, most of which are caused by detector upgrades, maintenance (or possibly malfunctions); however, some transients are related to genuine astrophysical phenomena.
Example:
Forbush decrease caused by the G4 geomagnetic storm 10/05/2024 (aurorae were visible from Algeria after the Sun CME)

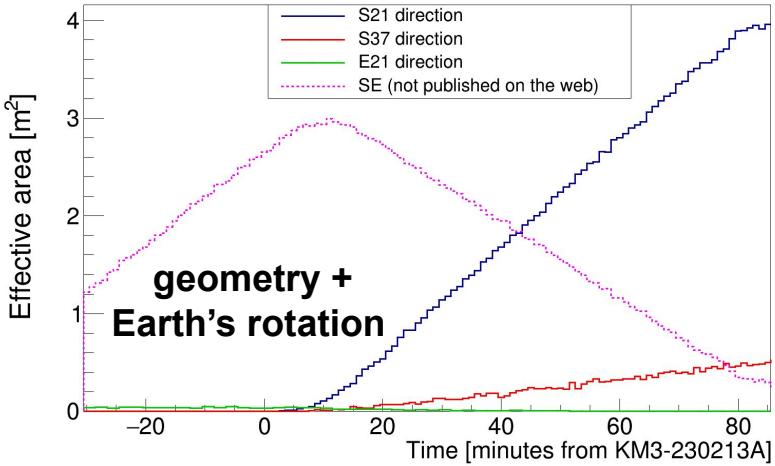




Investigation of KM3-230213A @ YBJ



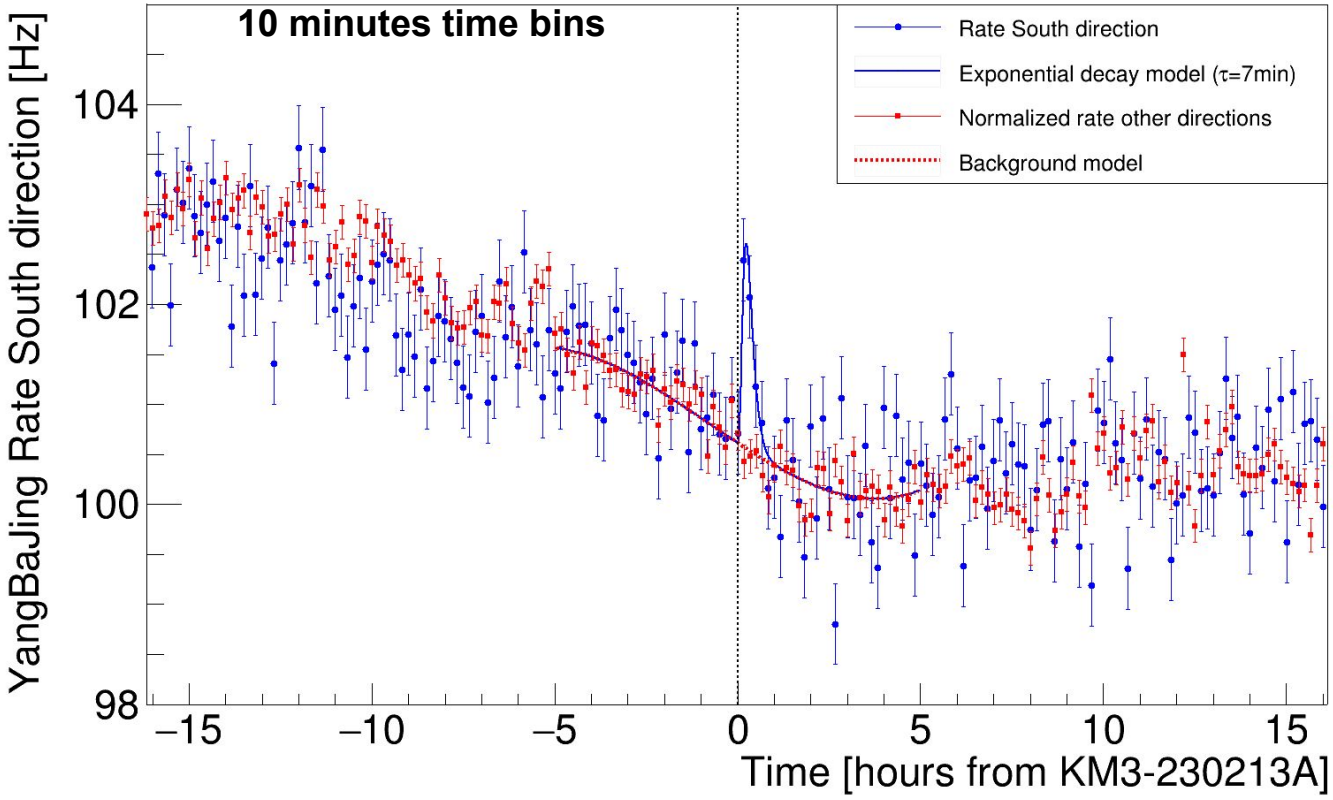




Considering the data published on YBJ website

- **only southern directions have KM3-230212A in the FoV**
- **the rates of the other published directions can be used as a control/bkg sample**

a μ excess associated to KM3-230213A?



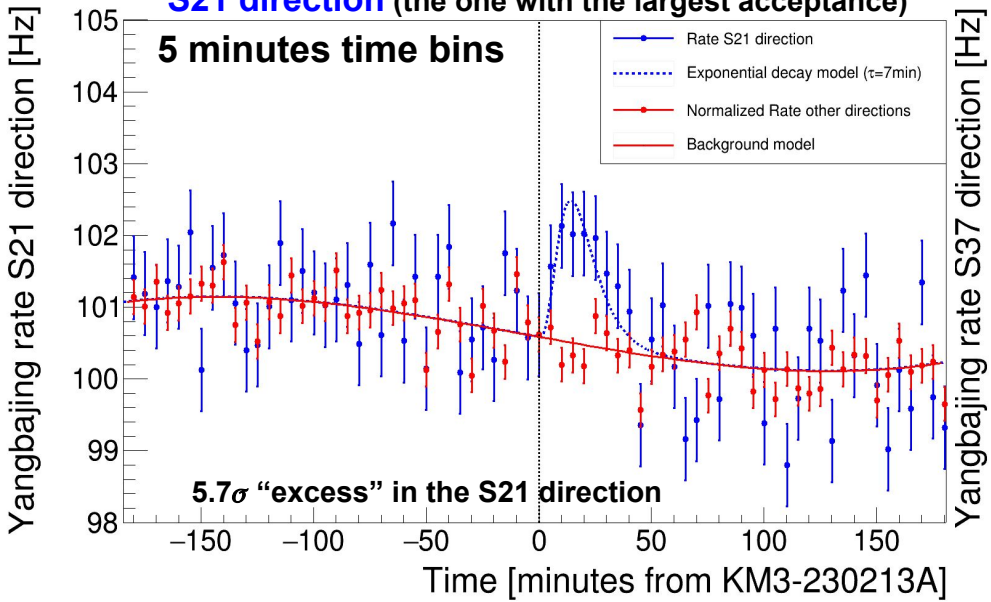
The "other directions" sample is useful to model the time variations of the downgoing muon background.

A peak "coincident" with KM3-230213A is observed only in the "south direction" which has the source direction in the FoV.

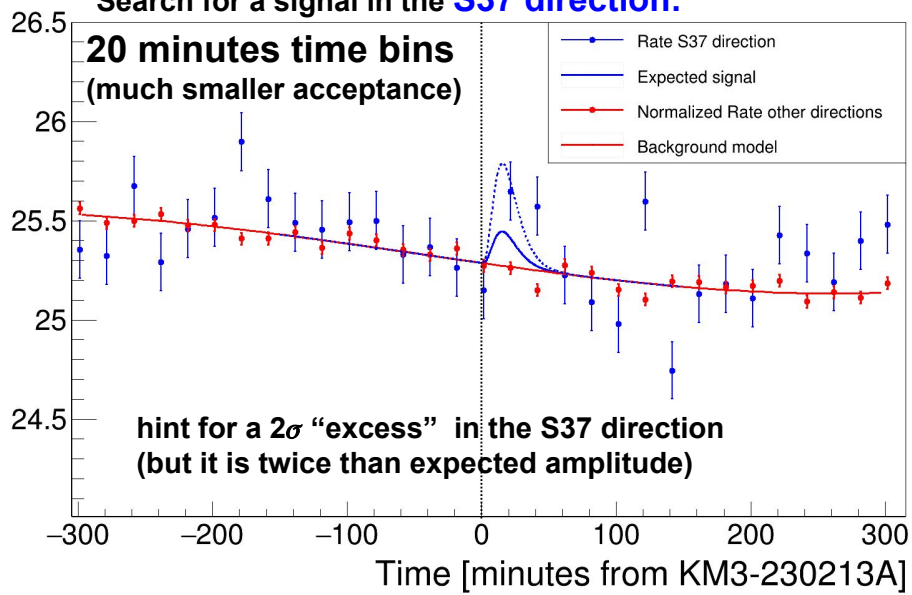
Considering Earth's rotation (time evolving acceptance) the excess behaviour is compatible with exponential decay of the flaring source having τ =7.0 ± 1.5 minutes.

investigation of the μ excess

S21 direction (the one with the largest acceptance)



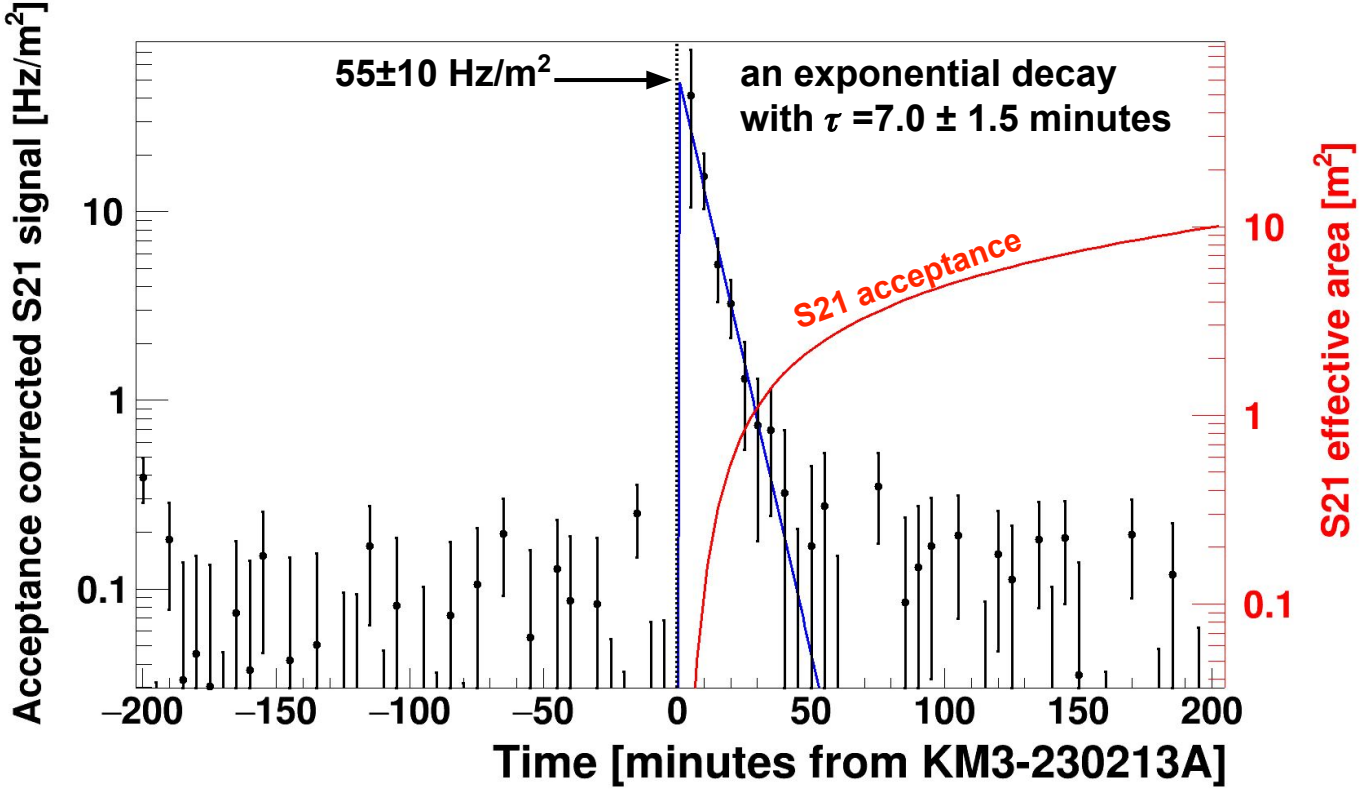
Search for a signal in the **S37 direction:**



It will be very useful to analyze the (unpublished) SE direction rates: a large peak is expected

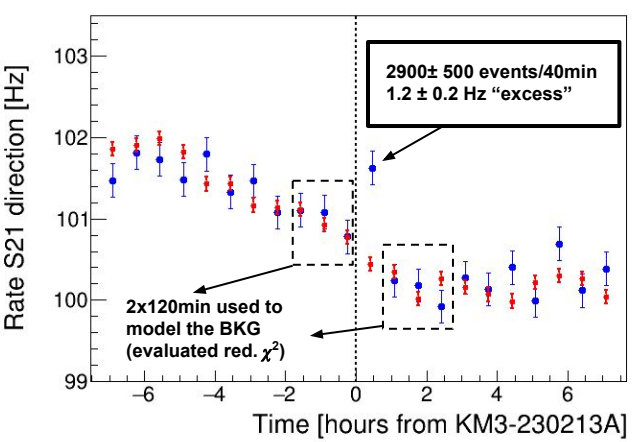
temporal shape of the μ excess

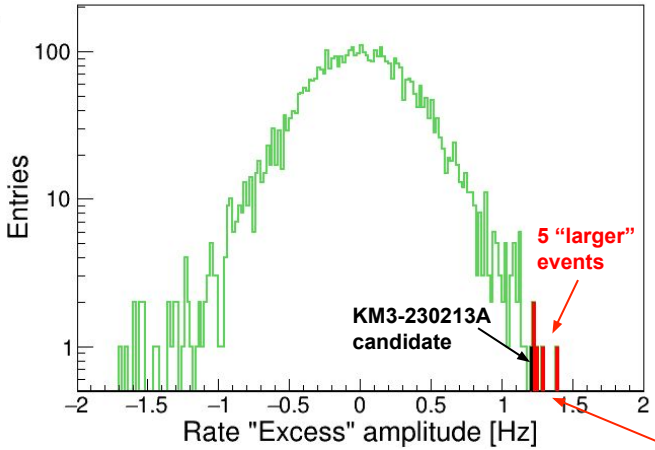
including the geometrical acceptance to residuals of the S21 rate:

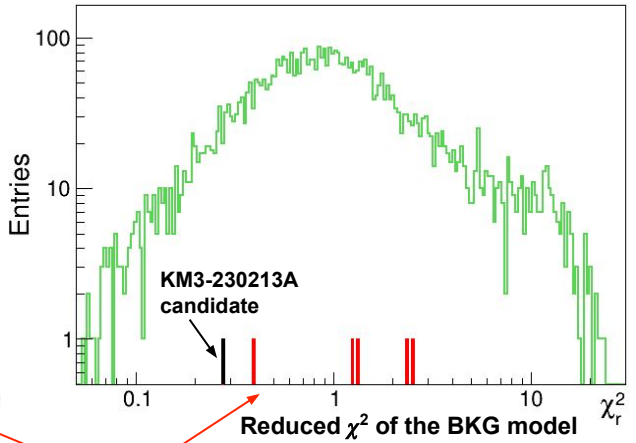


chance coincidence probability

analysis with bins of 40 minutes performed for the first 4 months of 2023







5 bins found with an "excess" amplitude larger than 2900 events

Probability of a chance coincidence < 1.1 x 10^{-3}
(this evaluation is cautious not using the temporal shape of the excess and the directional signature)

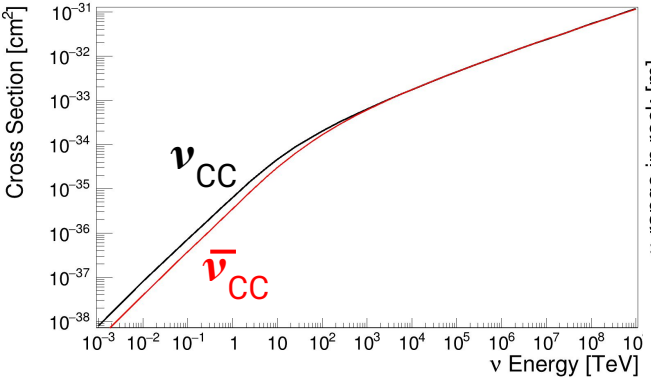
Inferring the neutrino flux (1/2)

$$\frac{1}{A}\frac{dN_\mu}{dt} = \sum_{\nu_i=(\nu,\bar{\nu})_{e,\mu,\tau}} \int \Phi_{\nu_i}(E_\nu) \cdot \frac{A^{\nu_i}_{eff}(E_\nu)}{A} dE_\nu$$

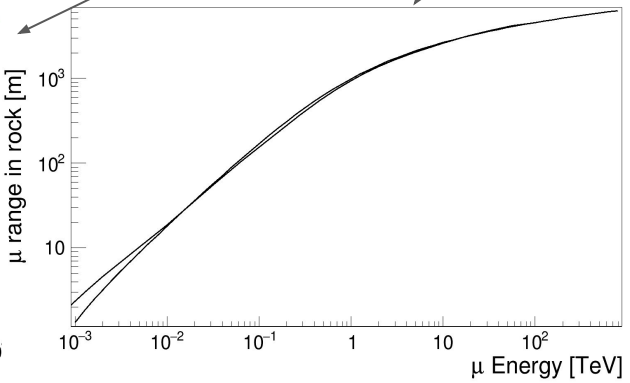
example: contribution of $\bar{\nu}_\mu + N \rightarrow \mu^+ + X$ → other muons from X hadronic shower

$$\int \Phi_{\bar{\nu}_\mu}(E_\nu) \cdot \frac{A^{\bar{\nu}_\mu}_{eff}(E_\nu)}{A} dE_\nu \simeq \int \Phi_{\bar{\nu}_\mu}(E_\nu) \left[\rho_N \cdot \sigma^{CC}_{\bar{\nu}_\mu N}(E_\nu) \cdot R(E_\mu) + \frac{A^{\bar{\nu}_\mu \rightarrow had.}_{eff}}{A} \right] dE_\nu$$

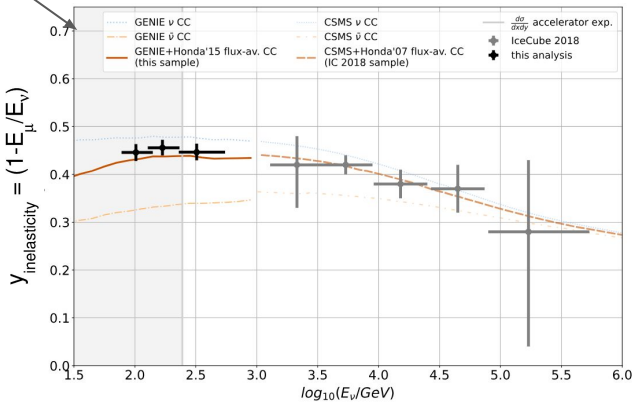
≈40% of ν energy into had. shower



Gandhi et al. PRD 58 093009 (1998)



At. Data & Nucl. Data Tables 78 (2001)

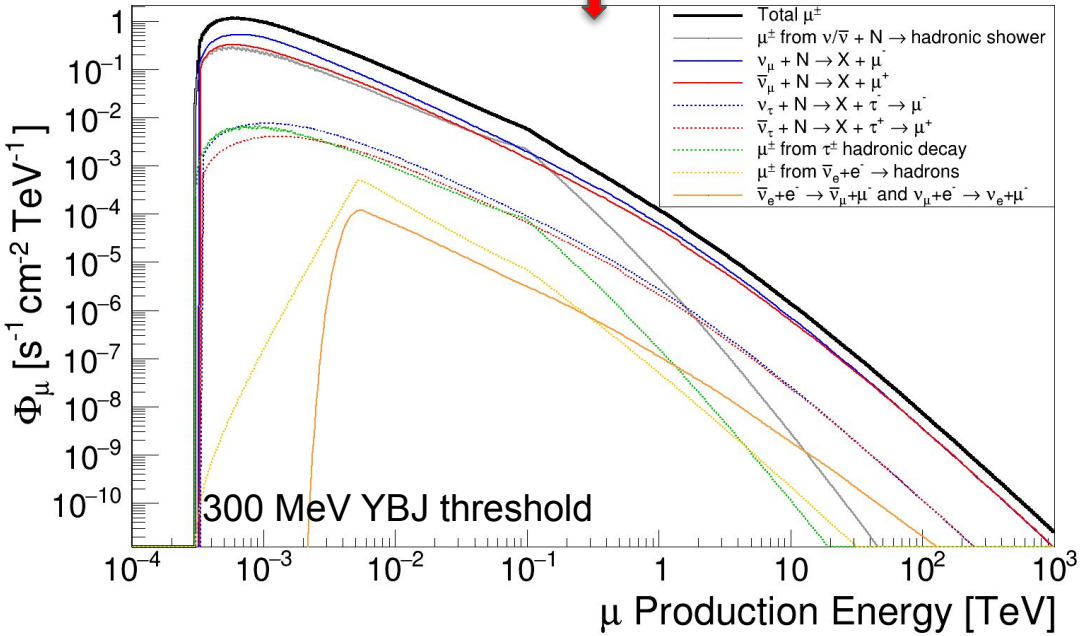


IceCube: PRD 111 112001 (2025)

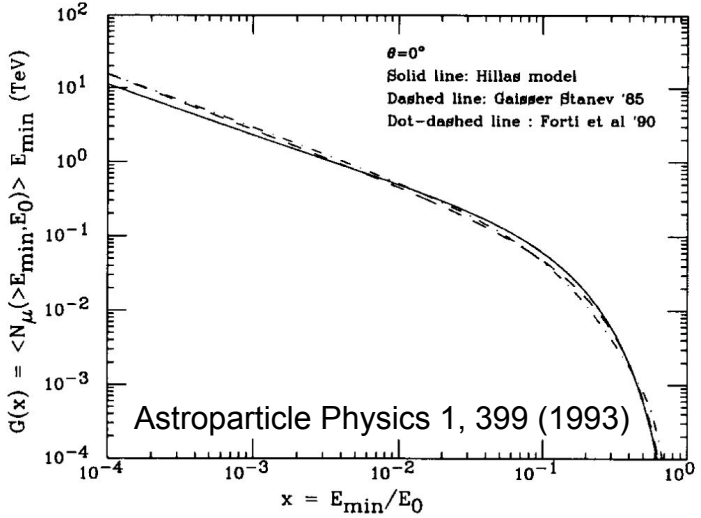
Inferring the neutrino flux (2/2)

$$\frac{A_{eff}^{\bar{\nu}_\mu \to had.}}{A} \simeq \rho_N \int \sigma_{\bar{\nu}_\mu N}^{(CC+NC)} \frac{dn_\mu}{dE_\mu} \cdot R(E_\mu)\, dE_\mu$$

Assuming:
- γ = 3.2 power-law spectrum
- same abundances for $(\nu,\bar{\nu})_{e,\mu,\tau}$
- μ rate @ ignition 55±10 Hz/m^2



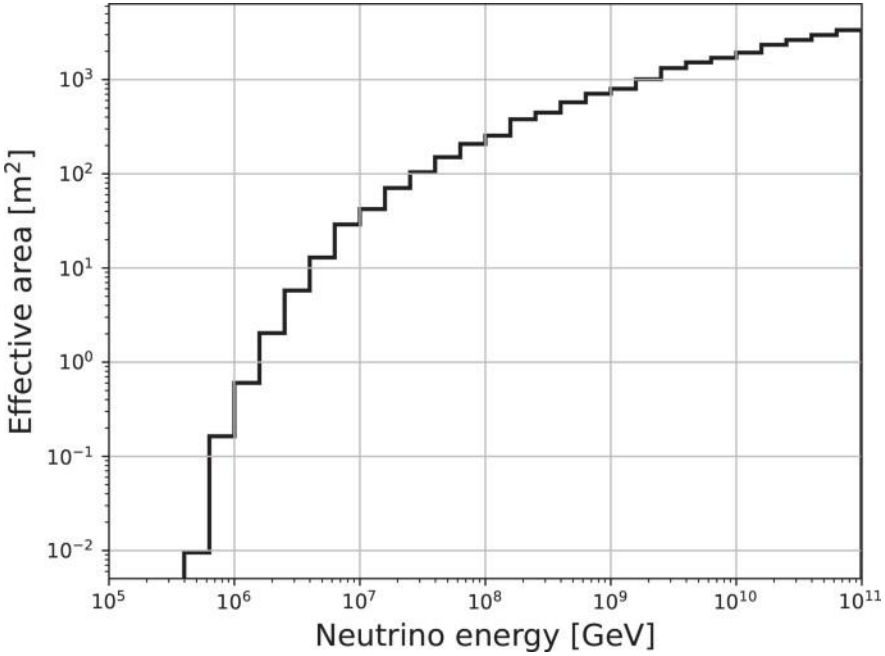
≈15% of had. shower energy into $\mu^\pm$



-average production energy of the detected muons ≈ 200 GeV
-average energy of detected ν ≈ 8 TeV

comparison with KM3-230213A flux

Assuming the KM3NeT/ARCA effective area:
Nature 638 (2025) 376



the evaluated neutrino flux by Yangbajing:

$$\Phi_{\nu_i} = (9.2 \pm 1.7)\, e^{-t/\tau} \left(\frac{E}{\mathrm{TeV}}\right)^{-3.2} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$$

τ =7.0 ± 1.5 minutes

predicts the detection of 1.4 ± 0.3 neutrinos with E>72 PeV by KM3NeT/ARCA

… very reasonable agreement …

assuming the association of the two events we can infer: γ = 3.2 ± 0.1 for the source that is typical for CR in the 100 PeV range

Summary/Conclusion

KM3-230213A is an exceptionally large energy event:
it deserves detailed investigations from the multimessenger point of view.

- **YangBaJing μ telescope detects a 5.7σ excess (2300±400 evts) in 30min. following the event**
- **signal is present only in the published direction S21, having KM3-230213A in the FoV**
- **signal is compatible with a pure exponential decay with τ=7.0±1.5 minutes**
- **chance coincidence probability < 10^{-3}**
- **a 2σ hint for a signal is present for S37 direction having KM3-230213A partially in the FoV**

This represents a very intriguing "excess".
It is very important to investigate the rate of SE direction (not published on YBJ web page)
and the rate of Nagoya muon telescope (rates with granularity below 1h are not published)
and rate of other underground detectors (Super-K, LVD, etc…)

Assuming the signal can be attributed to KM3-230213A:

- **the signal is not due to a cosmological ν but possibly emitted from a flaring source**
- **τ=7.0±1.5 minutes represents the duration of the flare**
- **power law γ = 3.2±0.1 accommodates both YBJ excess and the KM3-230213A event**