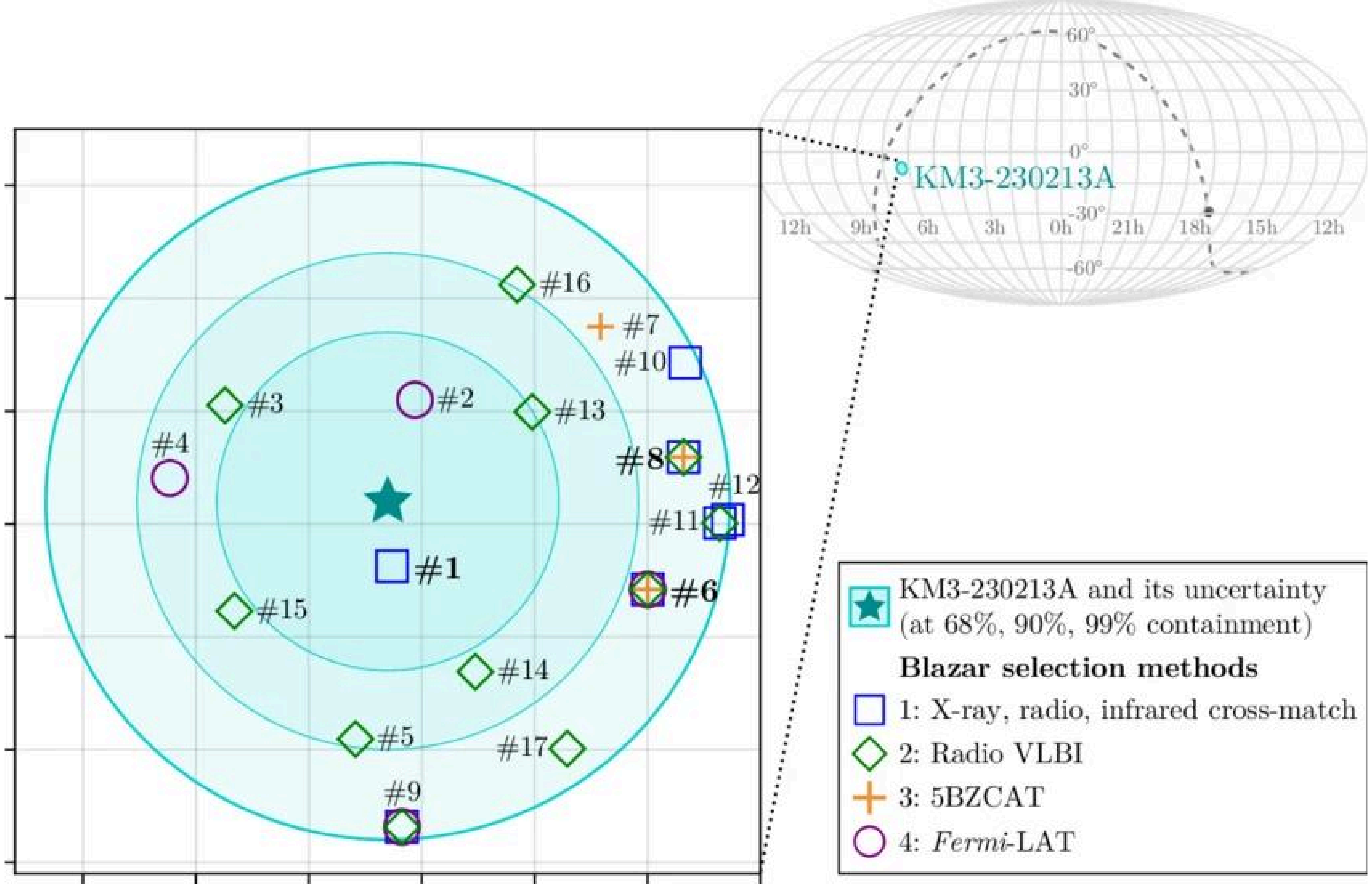
Can a gamma-ray dim radio blazar produce a 200-PeV neutrino? The case of PMN J0606−0724 and KM3-230213A

Polina Kivokurtseva

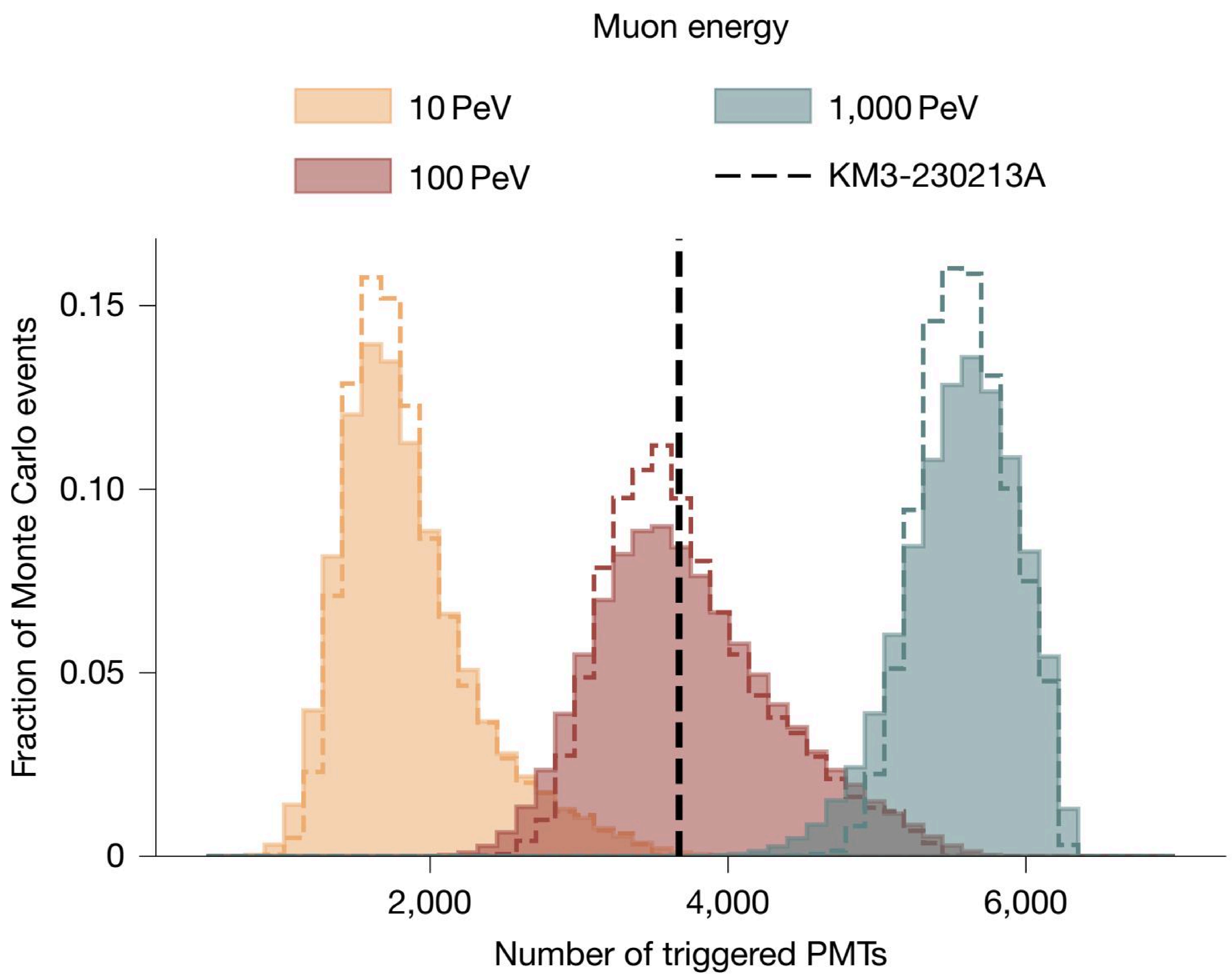


TeV Particle Astrophysics
TeVPA 2026
Tendo Japan
August 30 - September 4, 2026

The highest-energy muon ever detected: KM3 230213A

Muon energy:
120 PeV best-fit
(60-230) PeV 68% CL
(35-380) PeV 90% CL

Neutrino energy:
220 PeV best-fit
(110-790) PeV 68% CL
(72-2600) PeV 90% CL



The purpose of the present work is to study in more detail,whether this particular source, never detected in gamma rays, is capable of producing extremely energetic neutrinos.

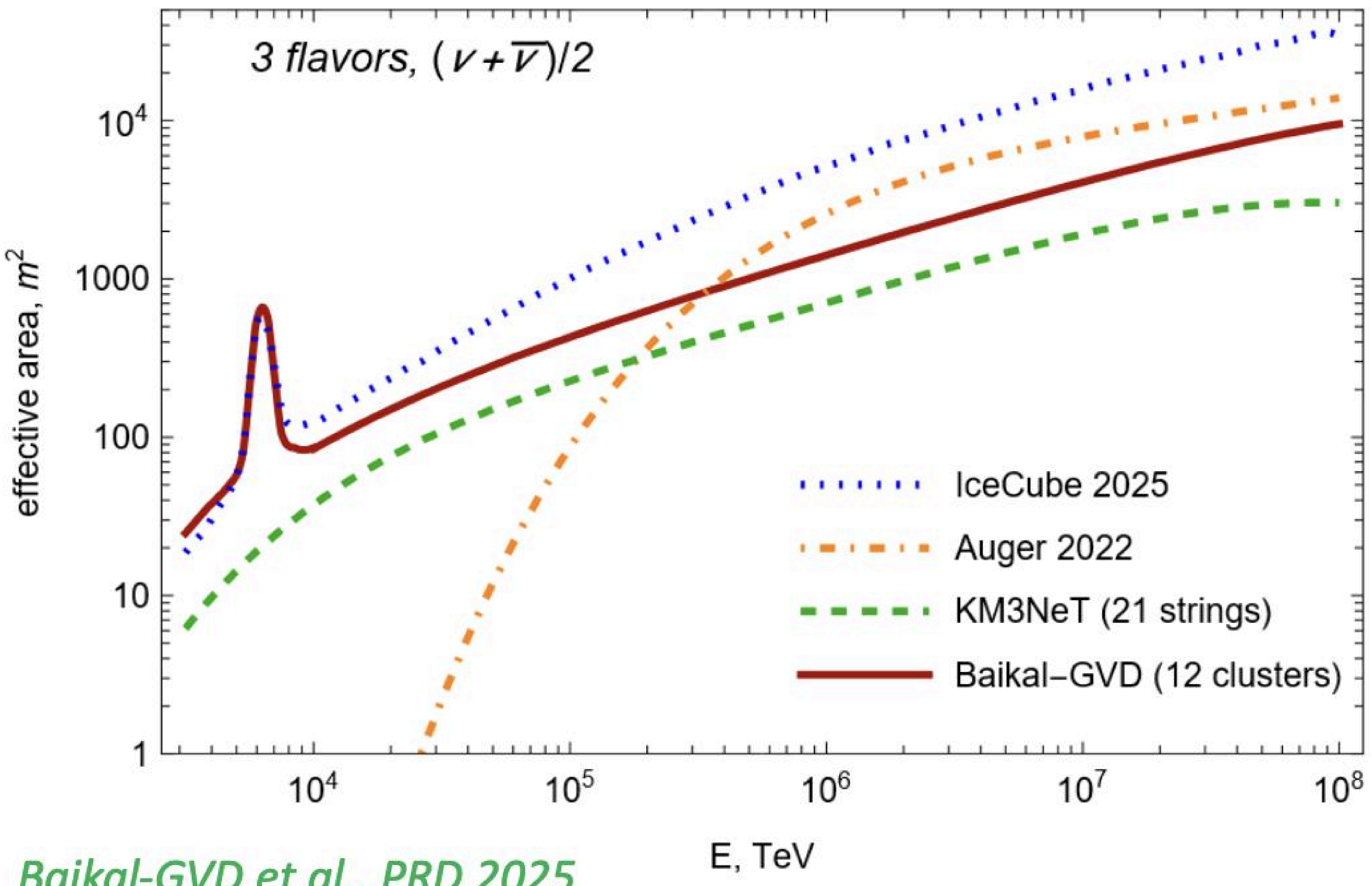
The highest-energy muon ever detected: KM3 230213A

During the time interval Δt of the flare, one event with the energy in the 90% CL interval ΔE, quoted above, was observed by KM3NeT.

$$\mathcal{F}_\nu = \frac{E_\nu^2\, N}{\Delta E_\nu\, \Delta t\, A}$$

$$A = A_{\rm KM3} + A_{\rm IC} + A_{\rm GVD} \approx (400 + 6000 + 1300)\ {\rm m}^2$$

$$\mathcal{F}_\nu = \left(\frac{\Delta t}{\rm yr}\right)^{-1} \left(1.3^{+1.8}_{-0.8}\right) \times 10^{-11}\ \frac{\rm erg}{{\rm cm}^2\,{\rm s}}$$



Baikal-GVD et al., PRD 2025

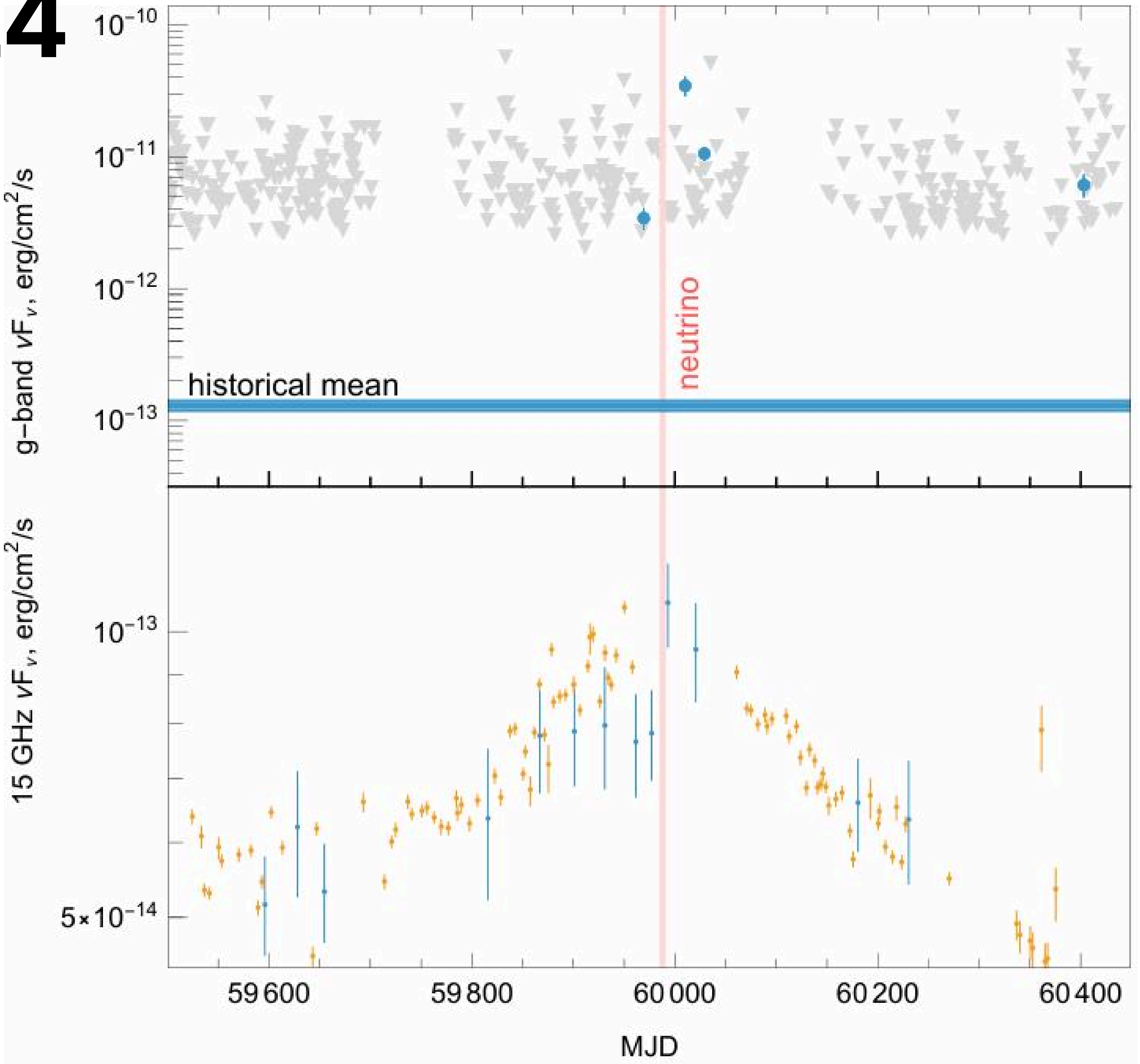
PMN J0606−0724

The origin of the neutrino is uncertain

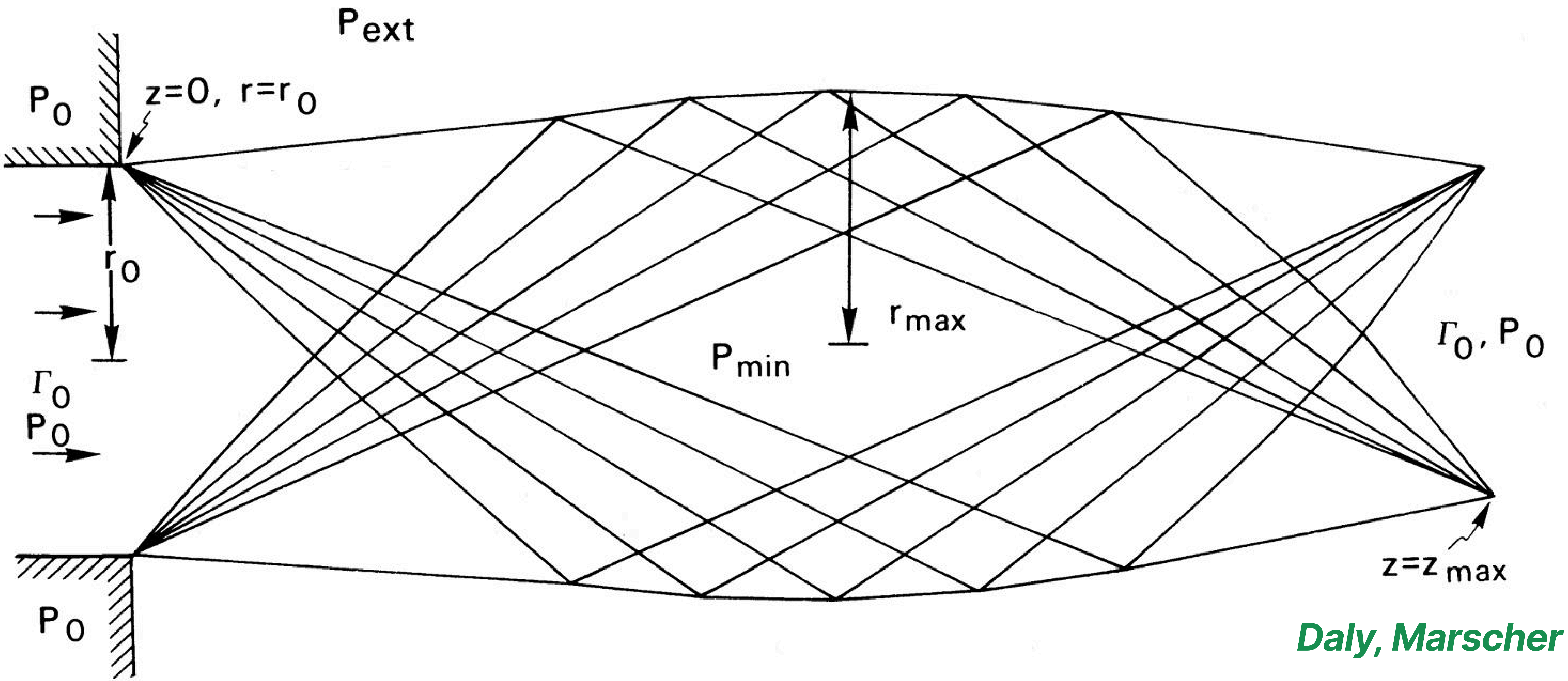
One of point sources within the large error circle

A purely diffuse component produced by interactions of energetic cosmic rays with ambient matter or radiation

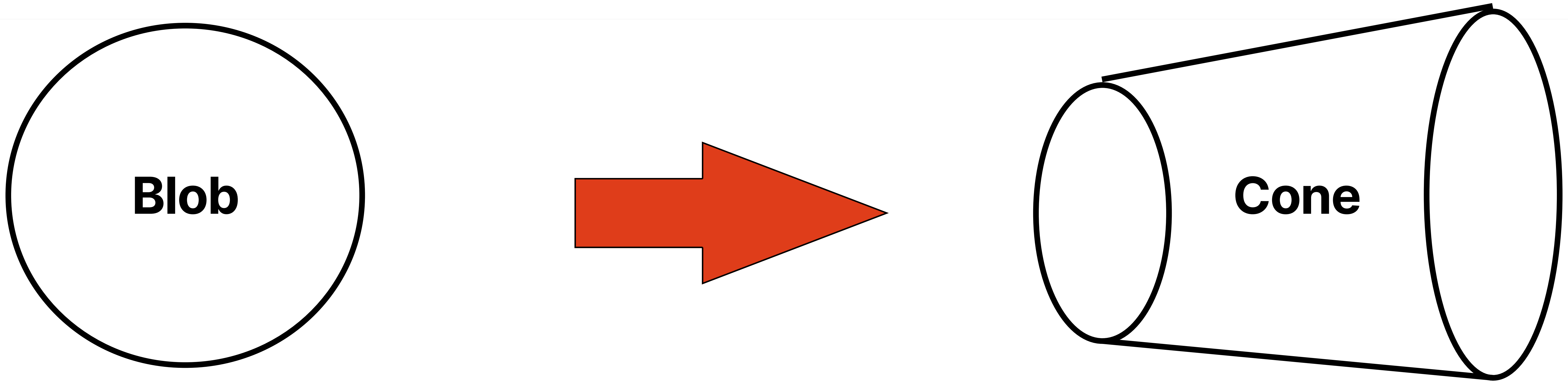
The probability of a chance coincidence of the event with the flare as 0.26%.



The shock model of the core

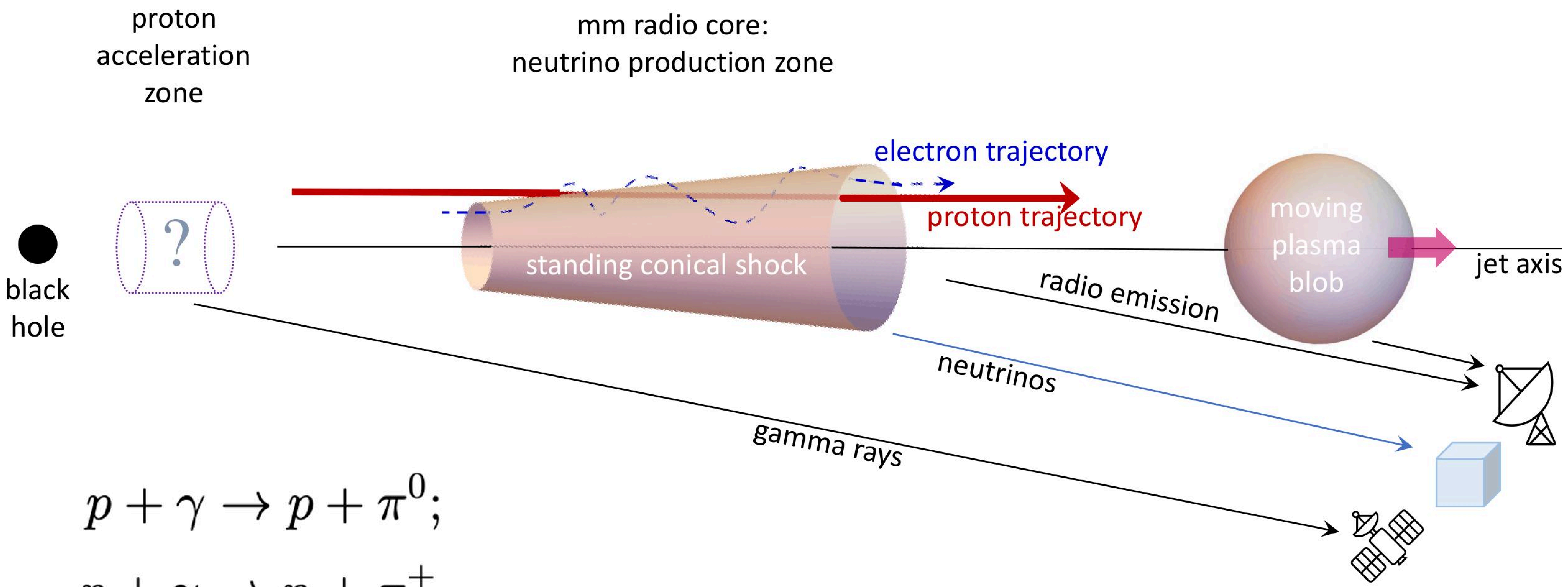


Daly, Marscher 1988



Mechanism of neutrino production

It is hard to explain the production of neutrinos in the radiative blazar zone, and suggested that multi-zone models may be required.



$$p + \gamma \to p + \pi^0;$$
$$p + \gamma \to n + \pi^+,$$

Kalashev, Kivokurtseva, Troitsky 2023

Estimates

Maximal energy of protons

Acceleration in the jet

$$\frac{0.05}{\delta_c} \lesssim \frac{B'}{\mathrm{G}} \lesssim 3.8\sqrt{\delta_c}$$

Acceleration before the jet launching

$$E_p^\star \sim 1.3 \times 10^{13}\ \mathrm{eV}\ M_8^{1/2}$$

We conclude that acceleration of protons to the energies required for producing a 220-PeV neutrino is possible in the jet of PMN~J0606-0724, but not in the magnetosphere vacuum gap of its black hole.

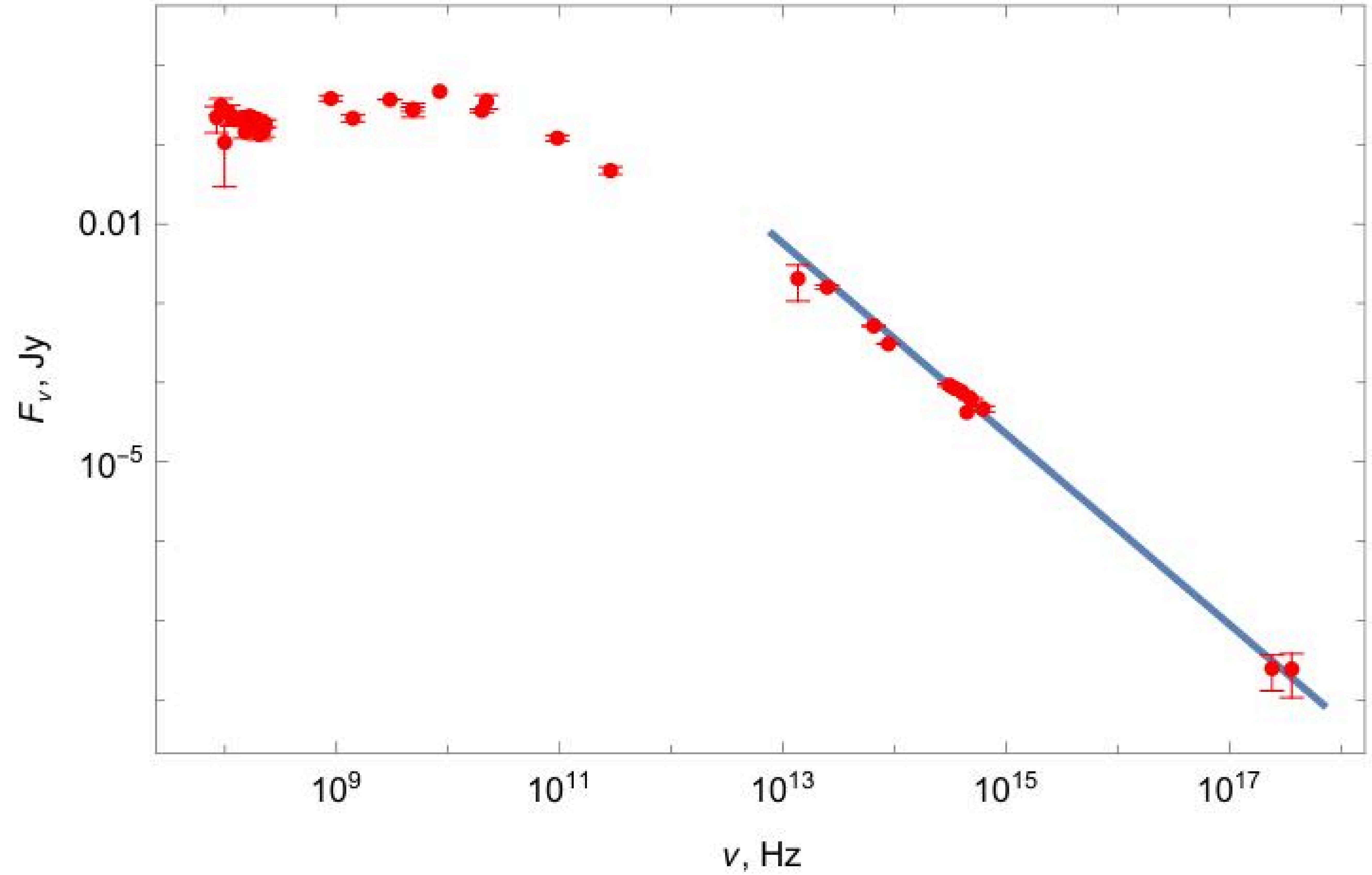
Estimates

Target photons

$$E'_\gamma n'_\gamma(E'_\gamma) = \frac{4d_L^2\mathcal{F}}{\delta_c^4 E'_\gamma r'^2}\left(\frac{r'}{l'}\right)^{2/3}$$

$$E'_\gamma n'_\gamma(E'_\gamma) = \frac{4d_L^2\mathcal{F}_0}{E_0(1+z)\delta_c^{5.4}E'_\gamma r'^2}\left(\frac{r'}{l'}\right)^{2/3}\left(\frac{E_{\gamma 0}}{E_0}\right)^{-1.2}$$

$$\approx \left(1.4^{+4.0}_{-0.8}\right)\times 10^{-11}\,\mathrm{cm}^{-3}\,\delta_c^{-5.4}\left(\frac{r'}{0.2\ \mathrm{pc}}\right)^{-2}\left(\frac{6r'}{l'}\right)^{2/3}$$



Time-averaged off-flare radio to X-ray SED of PMN J0606−0724.

Estimates

Gamma-ray opacity

$$E'_{\gamma 1} = \left(\frac{2.8}{\delta_c}\right)\left(3.6^{+10}_{-1.8}\right) \times 10^{17}\,\mathrm{eV}$$

Together with neutrinos, pγ interactions produce a number of energetic gamma rays coming from decays of neutral pions and having energies two times higher than neutrinos

The photons of interest, which may contribute to the putative Fermi-LAT signal either directly, or via intergalactic electromagnetic cascades on the cosmic background radiation, have energies

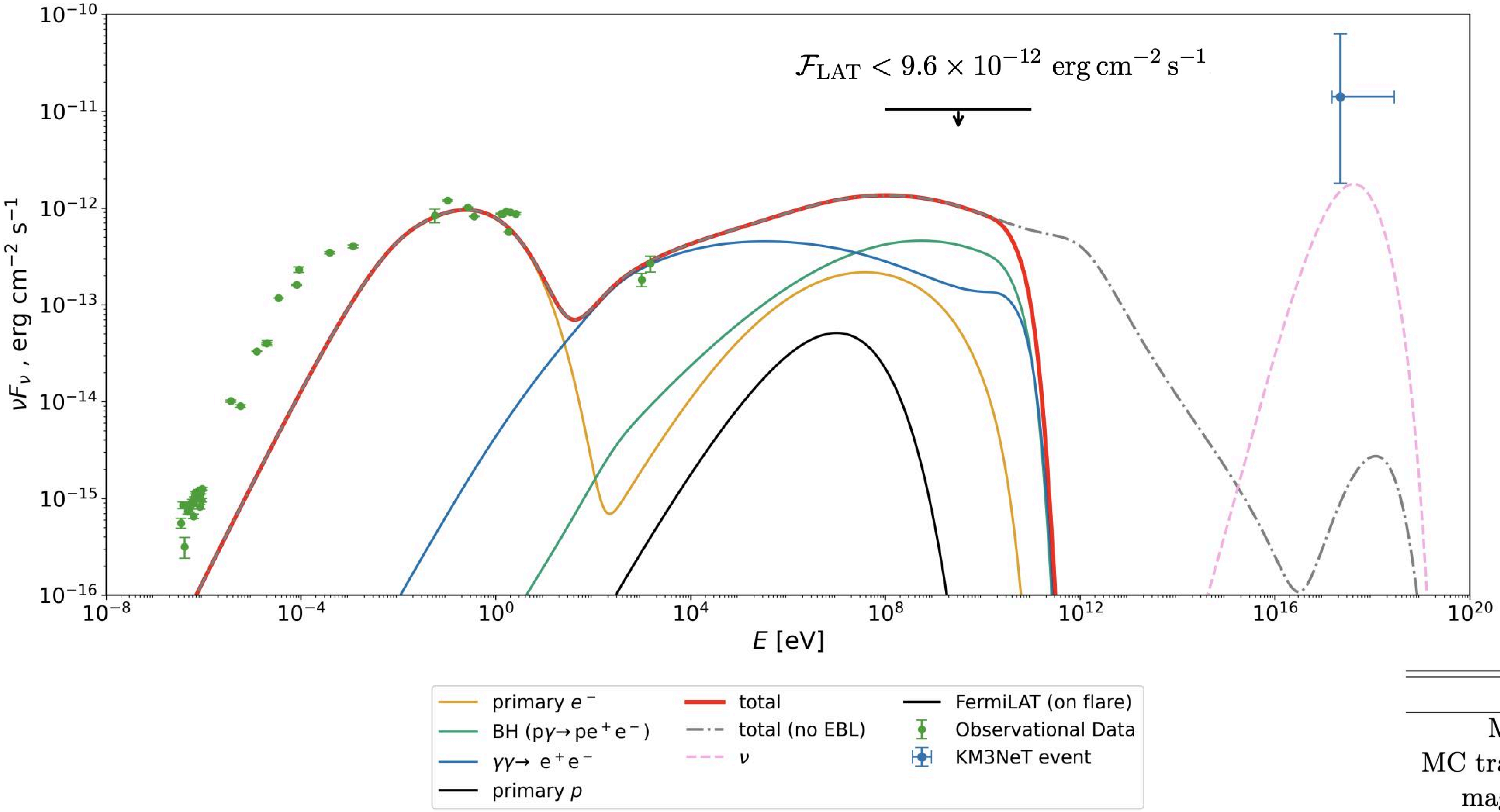
$$\frac{1+z}{\delta_c} \cdot 0.1\ \mathrm{GeV} \lesssim E'_{\gamma 1} \lesssim \frac{2.8}{\delta_c} \cdot 3.6 \times 10^{17}\ \mathrm{eV}.$$

$$L_{\mathrm{bol}} \approx \left(\frac{2.8}{\delta_c}\right)^4 1.5 \times 10^{45}\ \frac{\mathrm{erg}}{\mathrm{s}}.$$

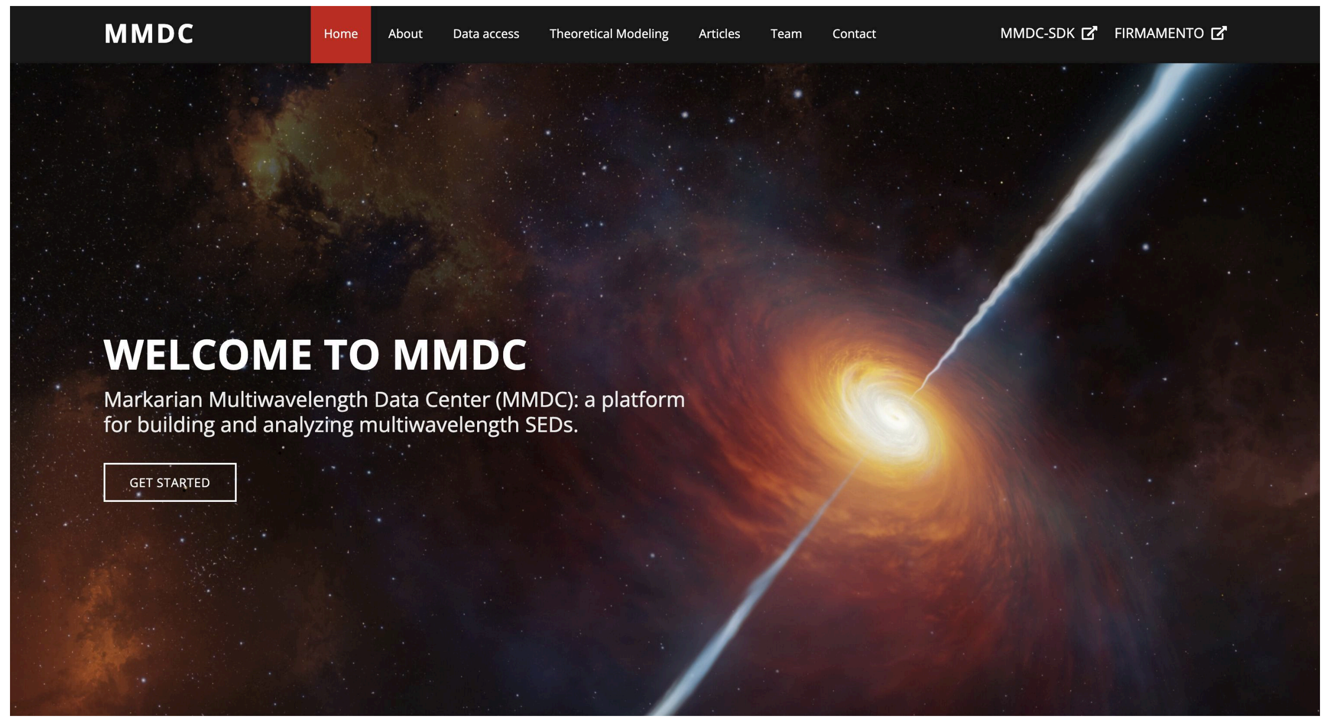
$$L_{\gamma 1} = \left(\frac{2.8}{\delta_c}\right)^4 \left(\frac{\mathrm{yr}}{\Delta t}\right)\left(6.0^{+15.7}_{-2.7}\right) \times 10^{46}\ \frac{\mathrm{erg}}{\mathrm{s}}$$

Like many other high-energy neutrino sources, PMN J0606−0724 is expected to be bright in MeV gamma rays, assuming that the neutrino was produced in pγ interactions in its MC

Numerical calculation



All data comes from MMDC



Parameter	Value	
MC length, l'	1.5 pc	
MC transverse radius, r'	0.6 pc	
magnetic field, B'	0.05 G	
Doppler factor, δ_c	5	
	Protons:	Electrons:
spectral index	1.0	1.8
minimal energy, E'_{min}	1×10^9 eV	1×10^9 eV
maximal energy, E'_{max}	2×10^{18} eV	10^{10} eV
total power, L'	5×10^{47} erg/s	5×10^{44} erg/s

Population of similar sources

duty cycle η

$$N_s$$

sources capable to produce neutrinos of these energies

Assuming identical sources, one estimates their contribution to the diffuse flux as

$$\mathcal{F}_{\text{diff}} \sim \frac{1}{4\pi} N_s \eta \mathcal{F}_\nu$$

90% CL upper limit

$$\mathcal{F}_{\text{diff}} < 8.4 \times 10^{-9}\ \text{GeV} \cdot \text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$

$$N_s \lesssim 220^{+310}_{-130}$$

The overall consistency (within 1.1σ) between the single detection from PMN J0606−0724 during the flare and non-detection of similar extremely energetic neutrinos from other blazars during the lifetime of all neutrino experiments.

Conclusions

Neutrinos at such energies can be produced in blazar PMN J0606−0724

We associate the neutrino production site with the millimeter radio core

Protons can be accelerated to the required energies in the millimeter radio core region and interact with soft photons

PMN J0606−0724 is not unique, the total very-high-energy neutrino emission from the population of similar sources remains below current upper limits on the diffuse neutrino flux at these extreme energies

Thank you!

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