Detecting TeV γ-rays from GRBs with km^3 neutrino telescopes

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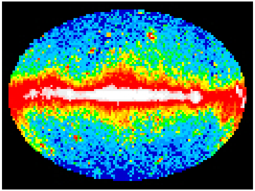
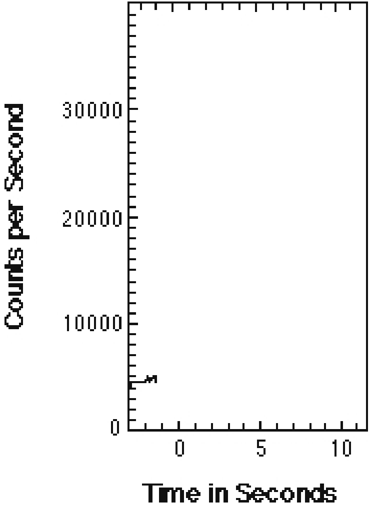
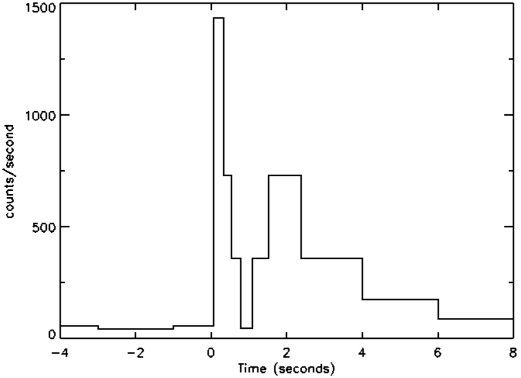
The most energetic event in the known universe



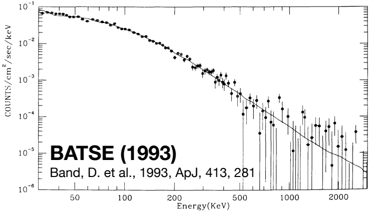


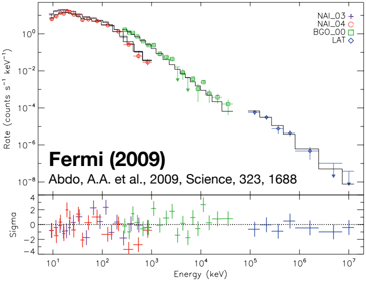
The serendipitous beginning

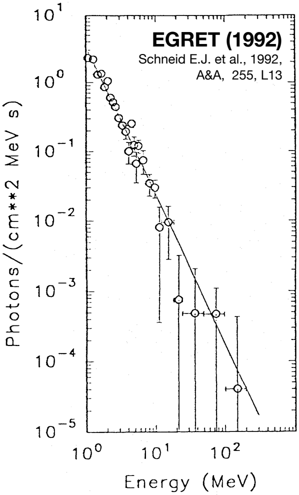
Vela satellite (1963) discovered the first GRB signal (1967)



It’s common now to see GeV photons from GRBs



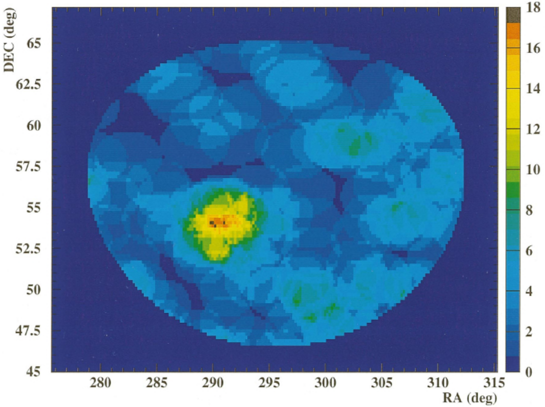




Do GRBs emit TeV photons?

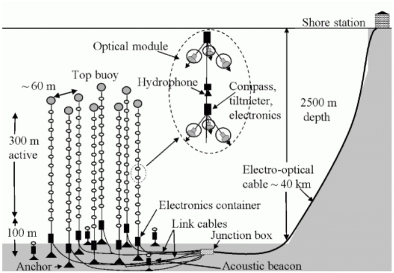
Milagrito observation of GRB 970417A

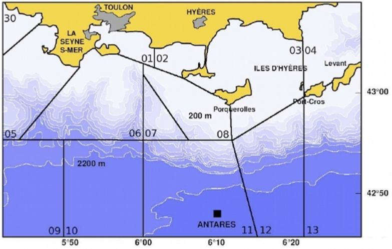
Atkins et al. 2000, ApJ 533: L119

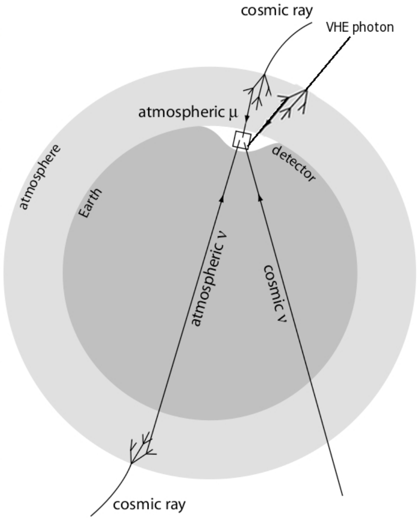


marginal detection significance at $\sim 3\sigma$

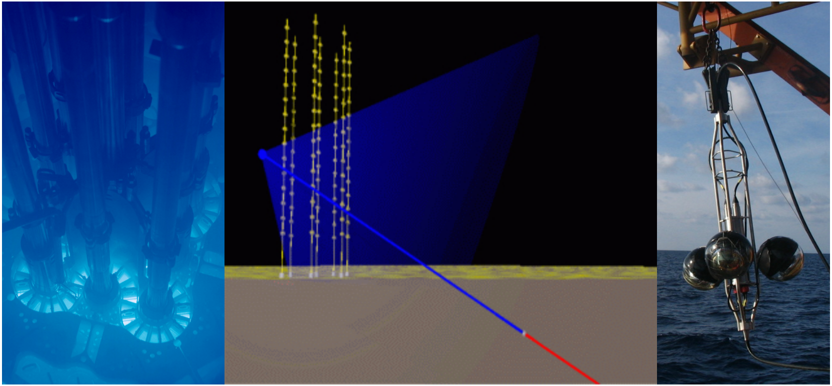
Potentials of undersea/ice neutrino telescopes







Potentials of undersea/ice neutrino telescopes



- Large collecting area: 0.01–$1\ \mathrm{km}^2$.
- Wide field ov view: $\sim \pi\ \mathrm{sr}$.
- 24/7 observation time: $\sim 95\%$ duty cycle.

The path of a TeV photons

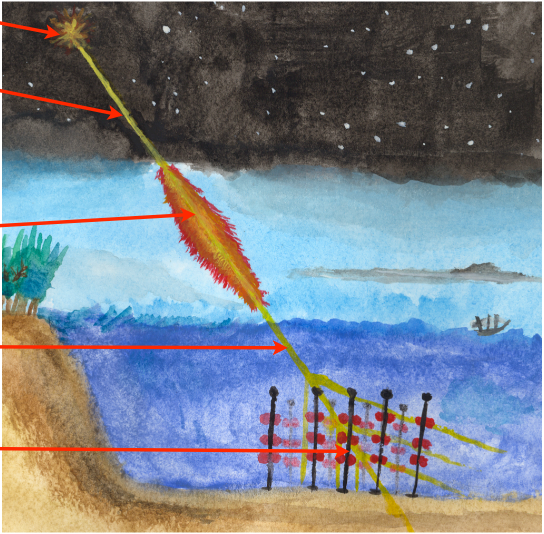
A GRB at redshift z takes place

TeV photons interact with ambient IR photons, annihilate themselves and produce pairs of electron-positron

The surviving photons initiate electromagnetic showers in the atmosphere and produce muons

As they traverse the seawater toward the detector, the muons lose energy

The Cherenkov light from the muons is detected by ANTARES and the muon track is reconstructed



Normalizing the photon spectrum

- The photon spectrum of a GRB can be modeled by a broken power law (Band function):

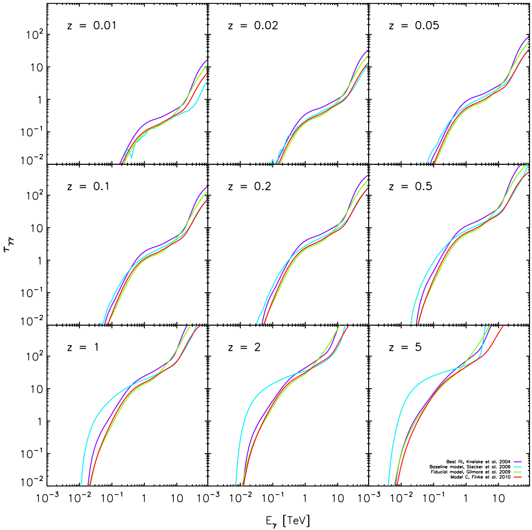
$$N(\epsilon) \propto \begin{cases} \exp\left[-(b-a)\frac{\epsilon}{\epsilon_{\rm bk}}\right]\left(\frac{\epsilon}{\epsilon_{\rm bk}}\right)^{-(a+1)} & \text{for } \epsilon < \epsilon_{\rm bk} \\ \left(\frac{\epsilon}{\epsilon_{\rm bk}}\right)^{-(b+1)} & \text{for } \epsilon \geq \epsilon_{\rm bk}, \end{cases}$$

- Let's assume that the spectrum extends to TeV the regime and normalize it using energy conservation:

$$L^{\rm iso}_{\rm bol*} = 4\pi r_c^2(z)(1+z)\Delta t \int_0^\infty d\epsilon N(\epsilon)\epsilon$$

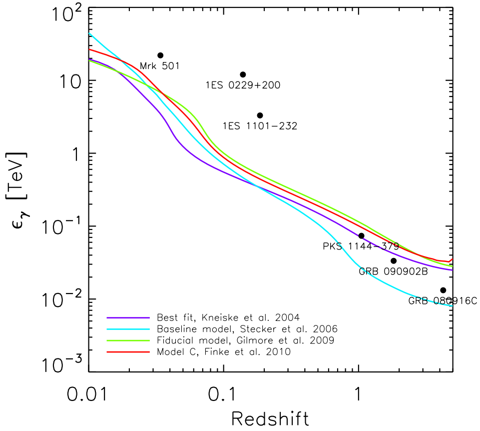
- Assume a cutoff $\epsilon_{\rm max*} = 300\ \rm TeV$ and that $a = 0$.
- Solving the integral, we can construct the photon spectrum of any GRB given $(L^{\rm iso}_{\rm bol*}, \epsilon_{\rm bk*}, z, \Delta t*, b)$.

Attenuation by ambient IR-photons



Attenuation by ambient IR-photons

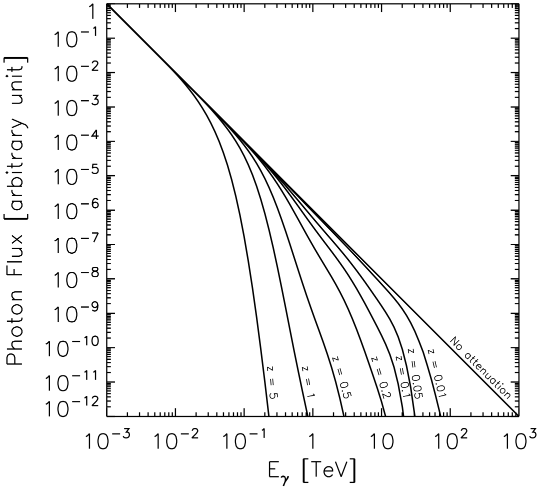
The Fazio–Stecker relation: $\tau(\epsilon_\gamma, z) = 1$



Later calculations will use the attenuation model of Finke et al. 2010

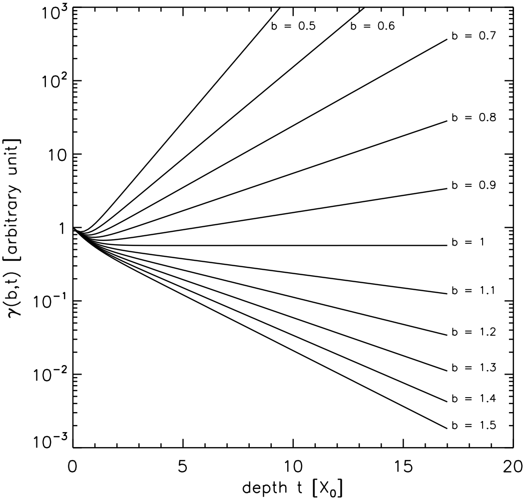
Effects of attenuation to the photon spectrum

$$\gamma_0(\epsilon_\gamma) = N(\epsilon_\gamma)\exp[-\tau(\epsilon_\gamma, z)]$$



The cascade equation

$$\gamma(\epsilon_\gamma, t) = \gamma_0(\epsilon_\gamma)\gamma_2(t)$$



Muon production (1): leptonic pion decay

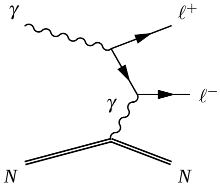
- Muons from this channel came from pion photoproduction and its subsequent decay into muons:

$$\gamma + N \to \pi + X,$$

$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\overline{\nu}_{\mu}),$$

- Solve the cascade equation for pions, and then use standard 2-body decay kinematics to obtain the muon spectrum (Drees et al. 1989, Halzen et al. 2009)

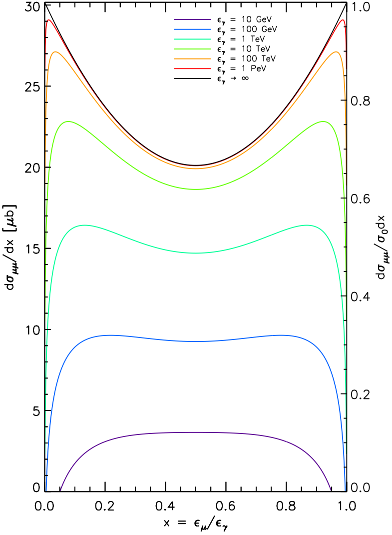
Muon production (2): direct pair production

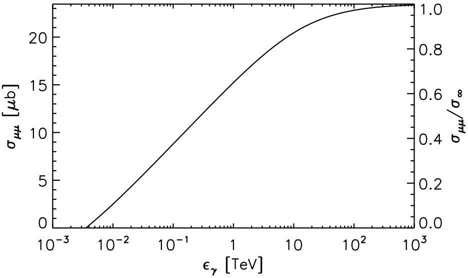


- Occurs when an impacting photon interacts with a photon in the electric field of a nucleus: $\gamma + N \rightarrow N + \mu^+ + \mu^-$
- Screening must to be taken into account since atoms are essentially neutral at large distances.
- Take the cross section formula from Bethe & Heitler (1934) and include elastic and inelastic form factors:

$$\frac{d\sigma}{dx}(x, E_\gamma) = 4\alpha Z^2 \left(r_0 \frac{m_e}{m_\mu} \right)^2 \left[1 - \frac{4}{3}x(1-x) \right] \left[\Phi_{\mathrm{el}}(\delta) + \frac{1}{Z}\Phi_{\mathrm{in}}(\delta) \right]$$

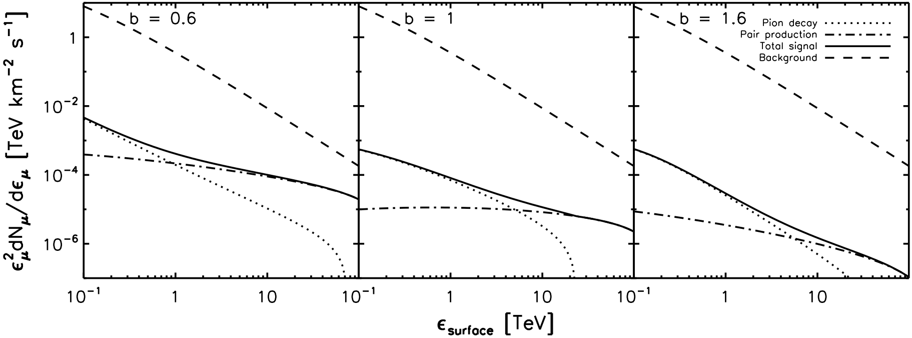
Muon production (2): direct pair production





A test source

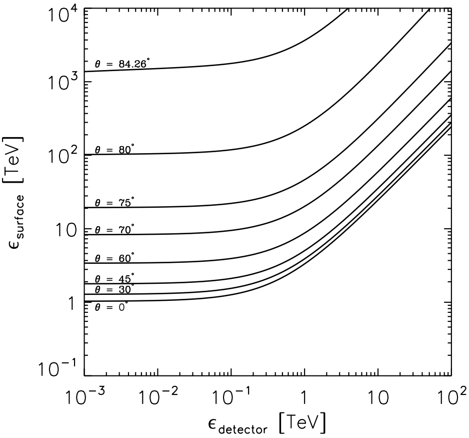
$N(\epsilon_\gamma) = 10^{-1} \left(\frac{\epsilon_\gamma}{1\ \mathrm{TeV}}\right)^{-(b+1)}\ \mathrm{TeV}^{-1}\ \mathrm{km}^{-2}\ \mathrm{s}^{-1}$
$\theta = 30°$
Background is estimated using the parametrization by Gaisser (1990).



The result is consistent with what was obtained by Halzen et al. 2009.

Muon energy loss

$$-\frac{d\epsilon}{dx} = a(\epsilon) + b(\epsilon)\epsilon \Rightarrow \int_{\epsilon_{\text{surface}}}^{\epsilon_{\text{detector}}} \frac{d\epsilon}{a(\epsilon)+b(\epsilon)\epsilon} + R = 0$$

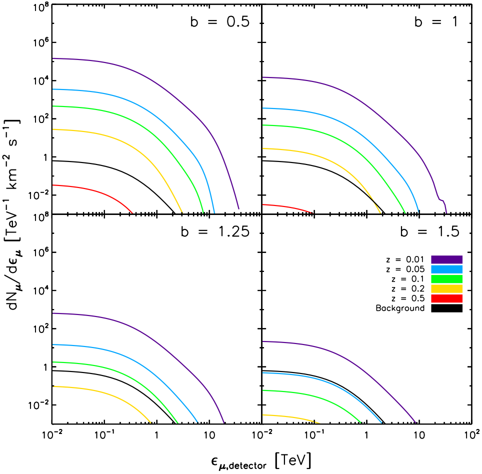


Calculated for seawater and ANTARES vertical depth of 2475 meter

The muon spectrum

$$L_{\mathrm{bol}*}^{\mathrm{iso}} = 8.9 \times 10^{52}\ \mathrm{erg},\ \epsilon_{\mathrm{bk}*} = (b-1)400\ \mathrm{keV},\ \Delta t_* = 10\ \mathrm{s}$$

$\theta = 0^\circ$ (Solid lines)



The muon spectrum

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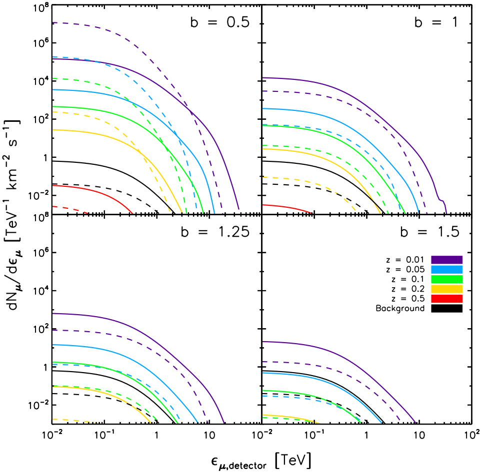
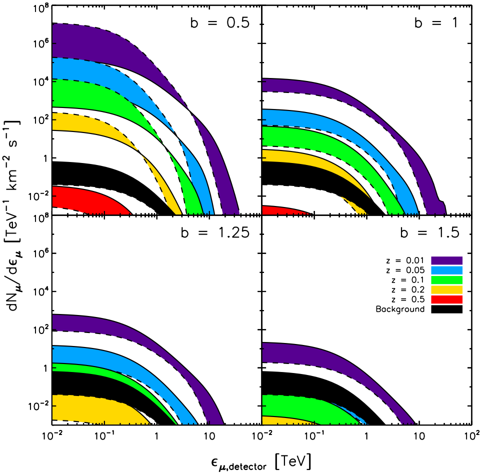
$\theta = 60^\circ$ (Dashed lines)



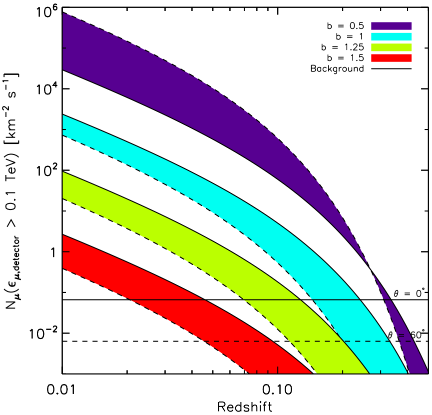
The muon spectrum

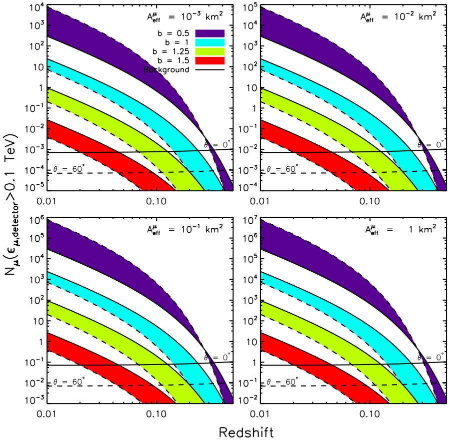
$L_{\text{bol}*}^{\text{iso}} = 8.9 \times 10^{52}$ erg, $\epsilon_{\text{bk}*} = (b-1)400$ keV, $\Delta t_* = 10$ s

$\theta = 0$–60° (Filled area)



Muon count as a function of redshift





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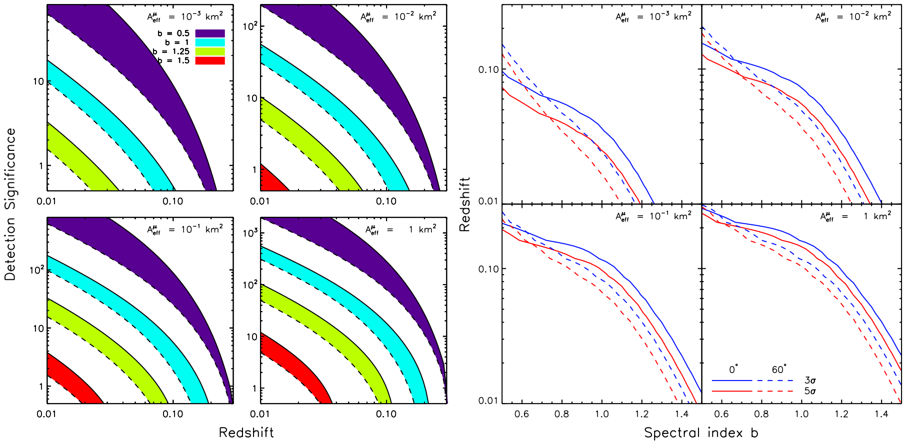
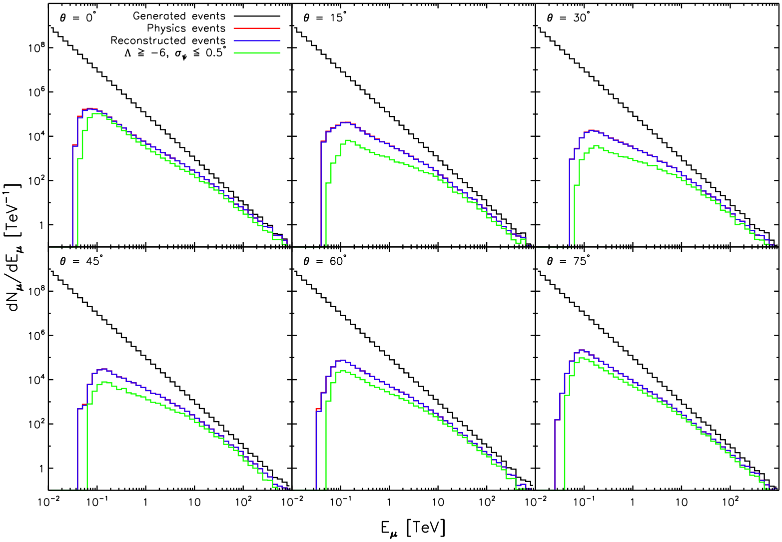


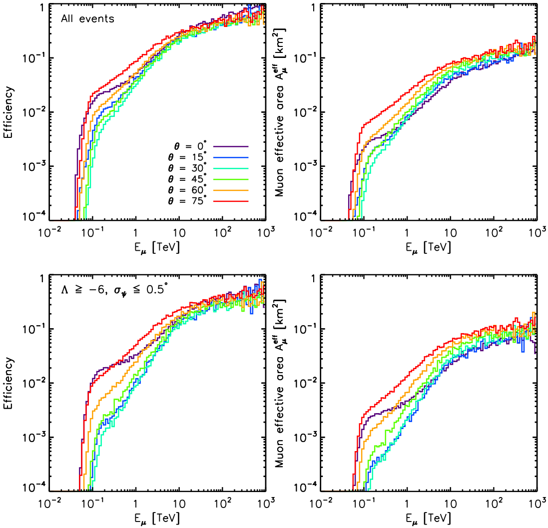
Conclusions

- Despite the many obstacles, in principle neutrino telescopes can observe TeV photons from GRBs.
- For an ANTARES-sized telescope, a typical GRB $(b = 1\text{–}1.25)$ must be located at $z \lesssim 0.06$ $(\sim\ 270\mathrm{Mpc})$ to allow a 3σ detection.
- A larger telescope with $A_{\mu}^{\mathrm{eff}} = 1\ \mathrm{km}^2$ can see further up to $z \lesssim 0.15$ $(\sim 700\ \mathrm{Mpc})$.
- Within *Swift* sample, 3 out of 144 GRBs with known redshift have $z \leq 0.15$. Nearby GRBs are rare events.
- A neutrino-telescope's secondary role as a γ-ray telescope is thus limited only to serendipity events.

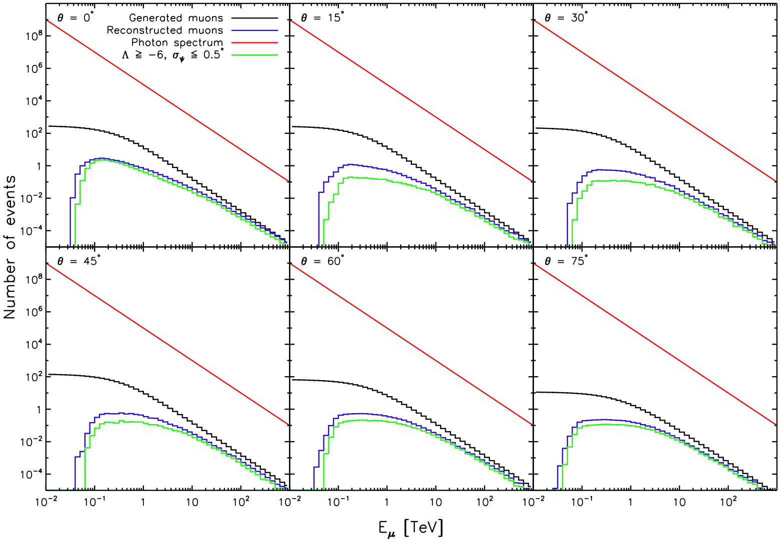
ANTARES muon effective area



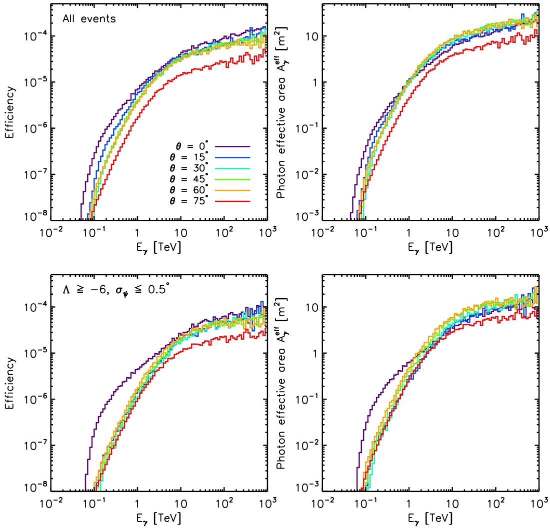
ANTARES muon effective area



ANTARES photon effective area



ANTARES photon effective area



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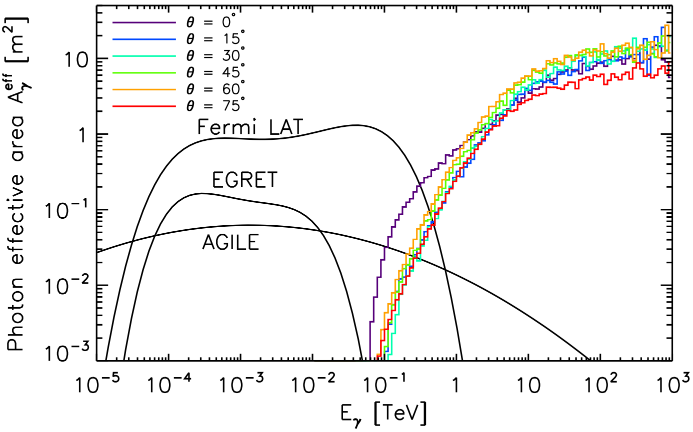

Parameters of effective area for other instruments are taken from Le & Dermer (2009).