Gamma-ray burst neutrino searches with ANTARES and KM3NeT

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On behalf of the ANTARES and KM3NeT Collaborations

Outline

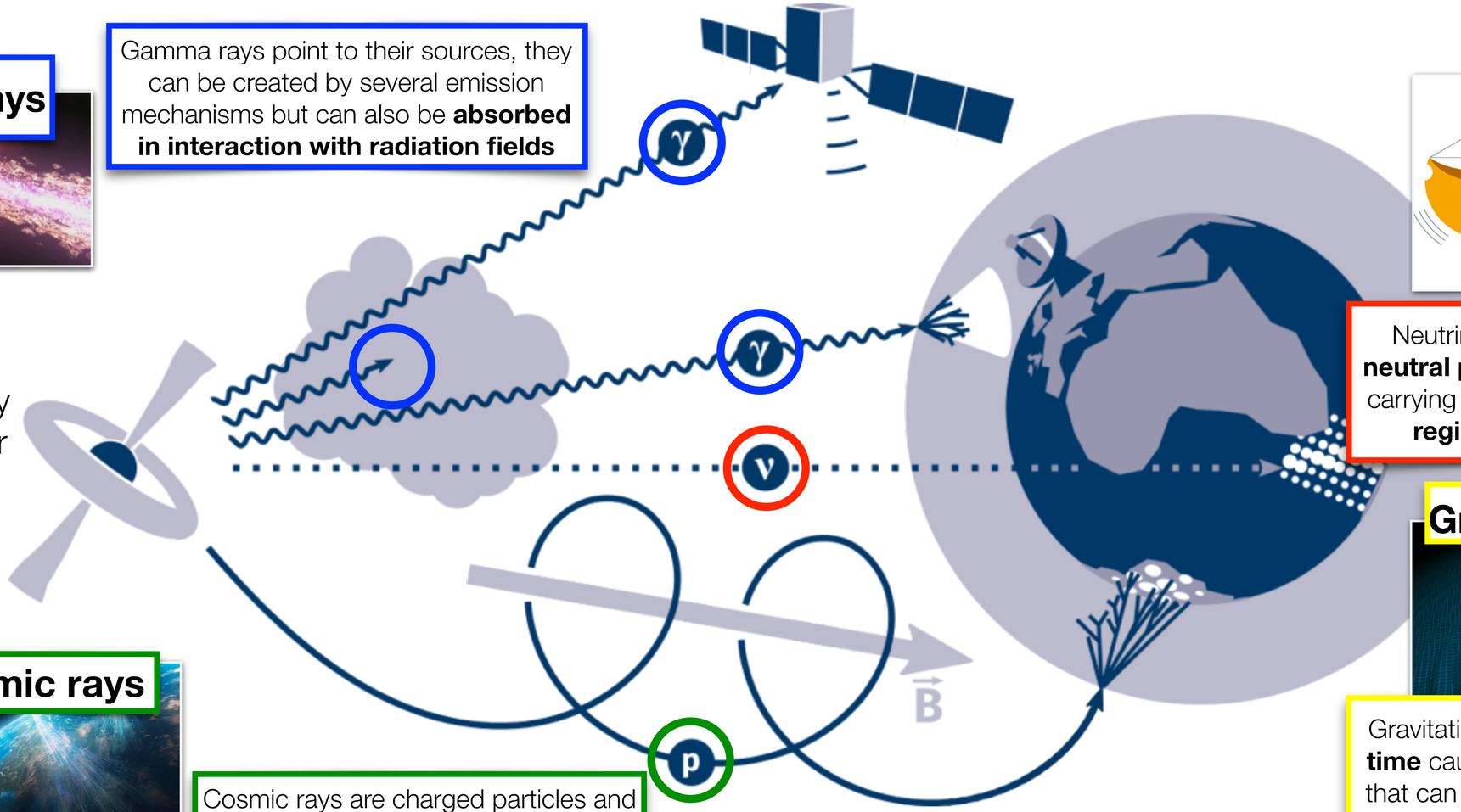
1. **INTRODUCTION**
    - Multi-messenger astronomy
2. **GAMMA-RAY BURSTS AND NEUTRINO PRODUCTION**
3. **HIGH-ENERY NEUTRINO TELESCOPES AND DETECTION PRINCIPLE**
4. **GRB NEUTRINO SEARCHES WITH ANTARES**
    - GRB stacking search with 10 years of data
    - Search for neutrinos from individual TeV emitting GRBs
5. **THE FUTURE WITH KM3NeT**
    - Detector sensitivity to transient neutrino sources

Multi-messenger astronomy

The exploration of the Universe using combined information from a multitude of cosmic messengers

Gamma rays

Gamma rays point to their sources, they can be created by several emission mechanisms but can also be **absorbed in interaction with radiation fields**

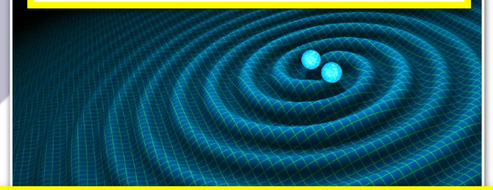


Cosmic-ray accelerator

Neutrinos

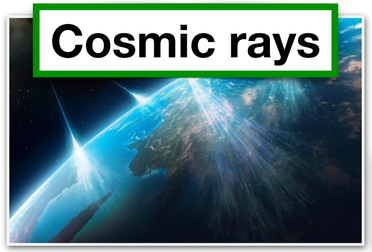
Neutrinos are **weakly interacting and neutral particles** that point to their sources carrying **information about deep opaque regions of extreme accelerators**

Gravitational Waves



Gravitational waves are **'ripples' in space-time** caused by **compact object mergers** that can lead to the **creation of relativistic jets** and therefore **particle acceleration**

Cosmic rays



Cosmic rays are charged particles and are **deflected by magnetic fields**

Multi-messenger astronomy

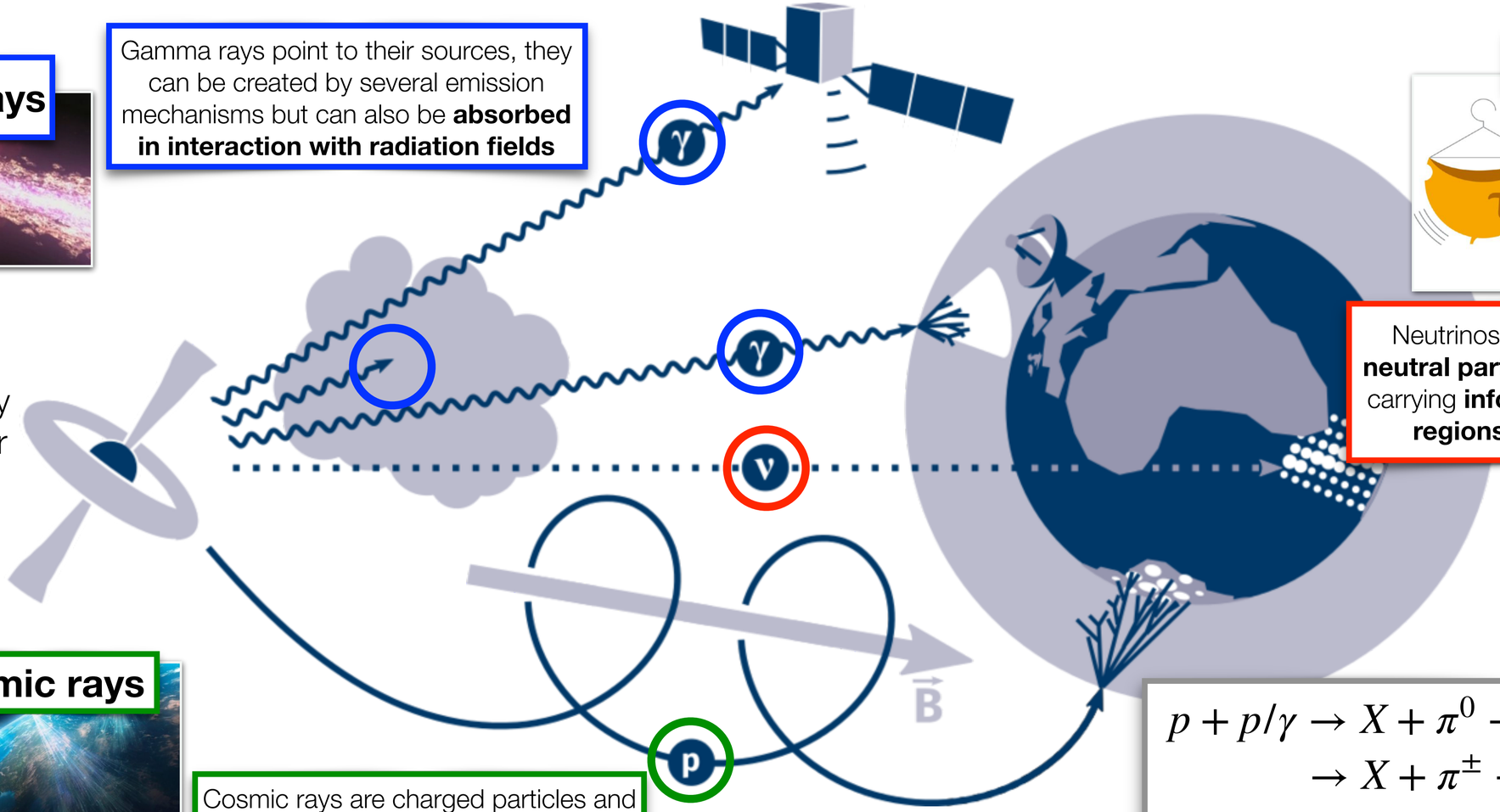
The exploration of the Universe using combined information from a multitude of cosmic messengers

Gamma rays

Gamma rays point to their sources, they can be created by several emission mechanisms but can also be **absorbed in interaction with radiation fields**

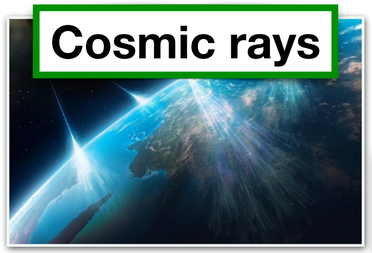
Neutrinos

Neutrinos are **weakly interacting and neutral particles** that point to their sources carrying **information about deep opaque regions of extreme accelerators**



Cosmic-ray accelerator

Cosmic rays



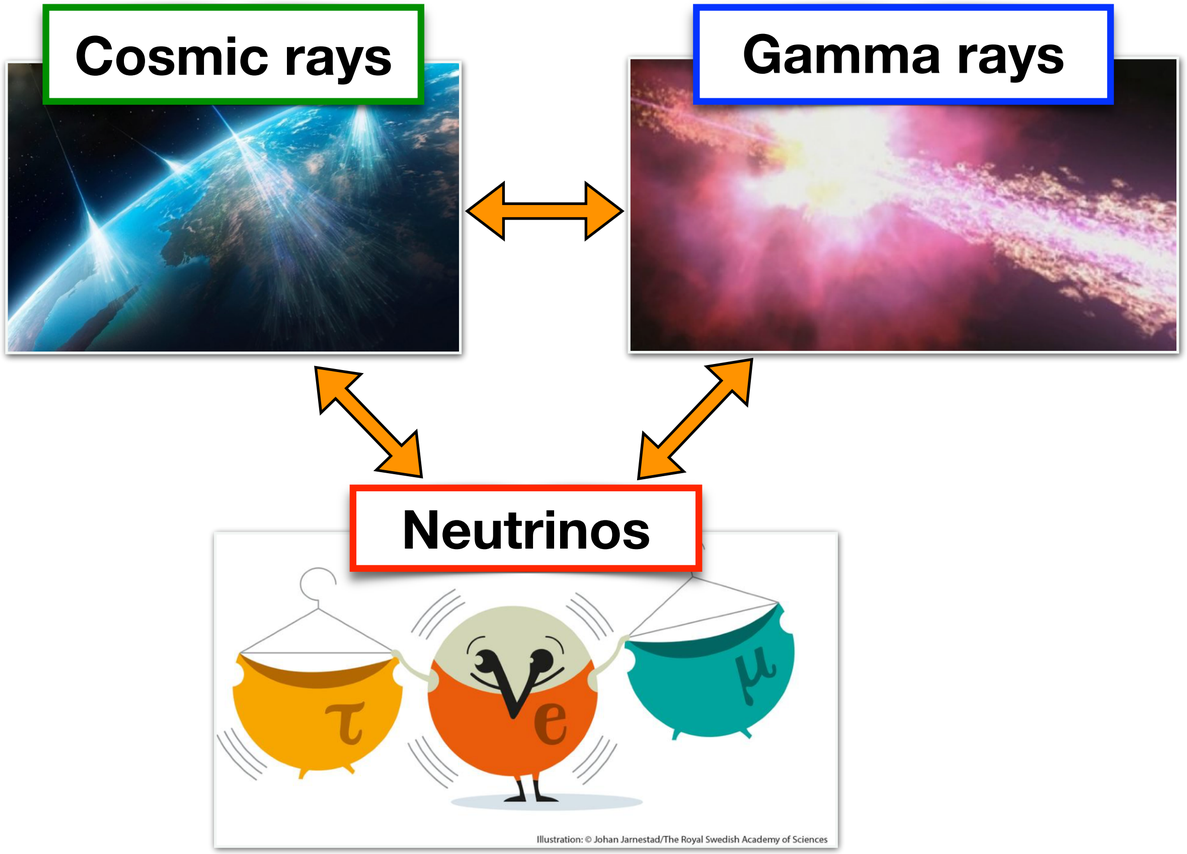
Cosmic rays are charged particles and are **deflected by magnetic fields**

HADRONIC scenario

$$p + p/\gamma \to X + \pi^0 \to \gamma\gamma$$
$$\to X + \pi^\pm \to \mu^\pm + \overset{(-)}{\nu}_\mu$$
$$\mu^\pm \to e^\pm + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu$$

Cosmic messengers

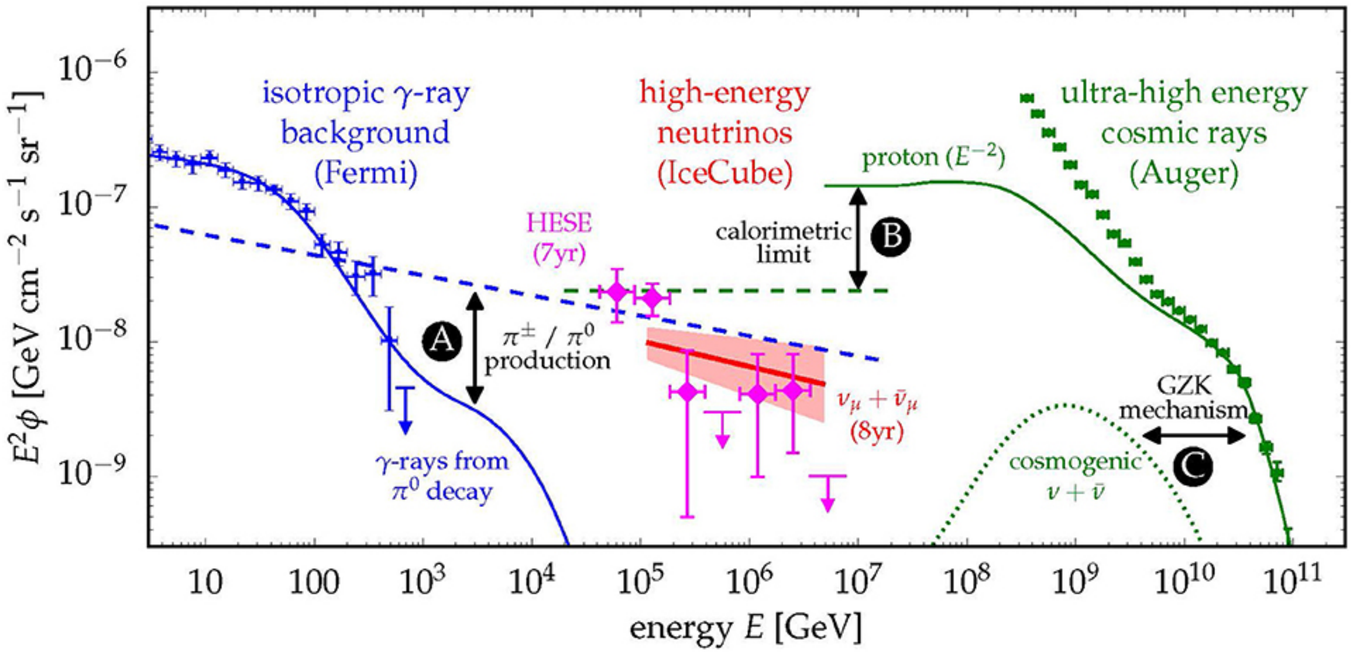
Spatial/temporal correlations between cosmic messengers can endorse the identification of acceleration process and interaction sites and shed the light on the cosmic accelerators processes



Extragalactic γ-ray background

TeV-PeV neutrinos whose origin has not yet been identified

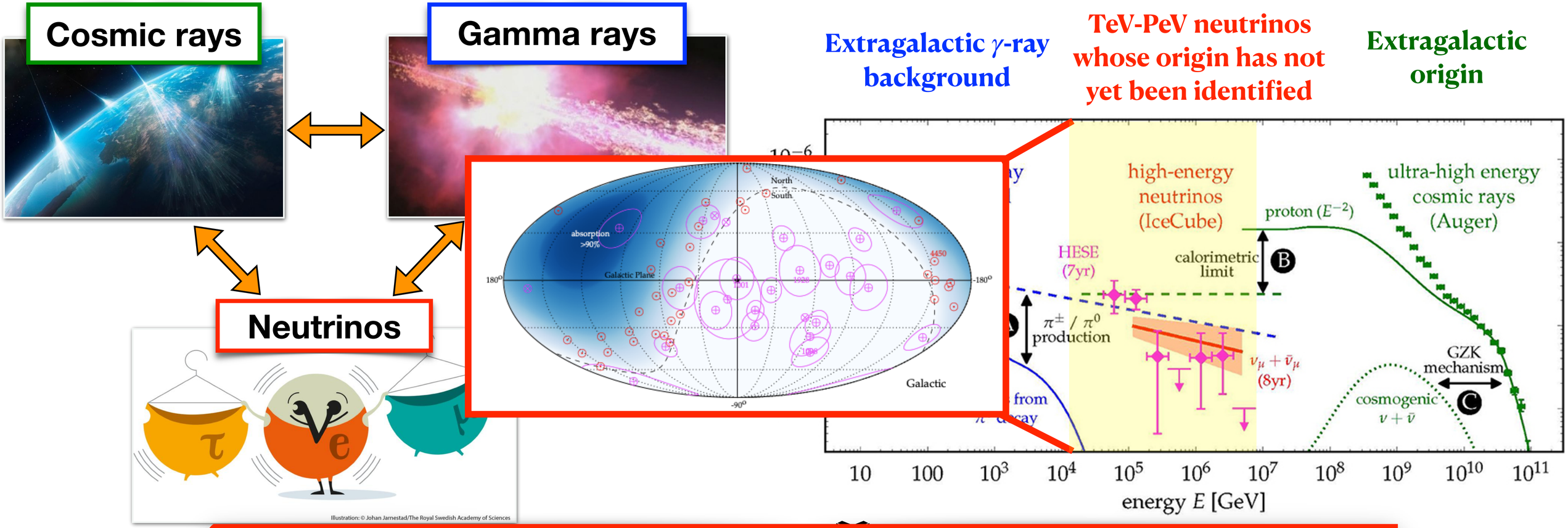
Extragalactic origin



Ahlers, M., and Halzen, F. (2018), *Prog. Part. Nucl. Phys.* 102, 73–88. doi: 10.1016/j.ppnp.2018.05.001

High-energy neutrinos

Spatial/temporal correlations between cosmic messengers can endorse the identification of acceleration process and interaction sites and shed the light on the cosmic accelerators processes

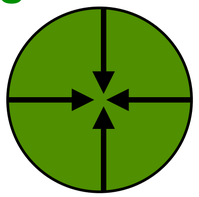


016/j.ppnp.2018.05.001

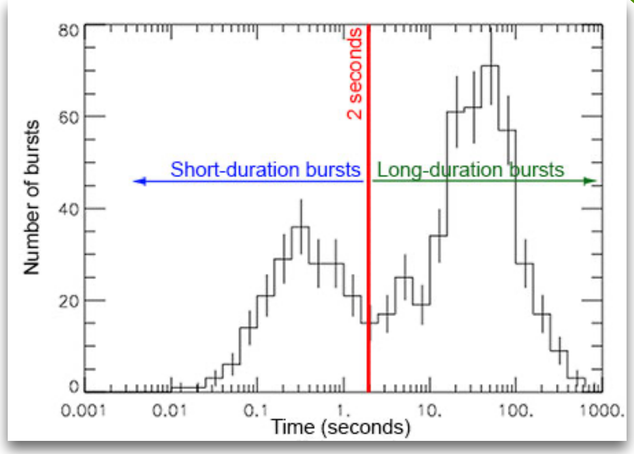
Several interesting neutrino candidates among **extragalactic high-energy sources**

Gamma-Ray Bursts: Fireball model and neutrino production

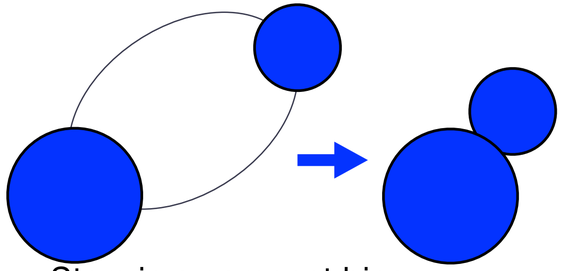
Long GRBs



Collapse of a very massive star



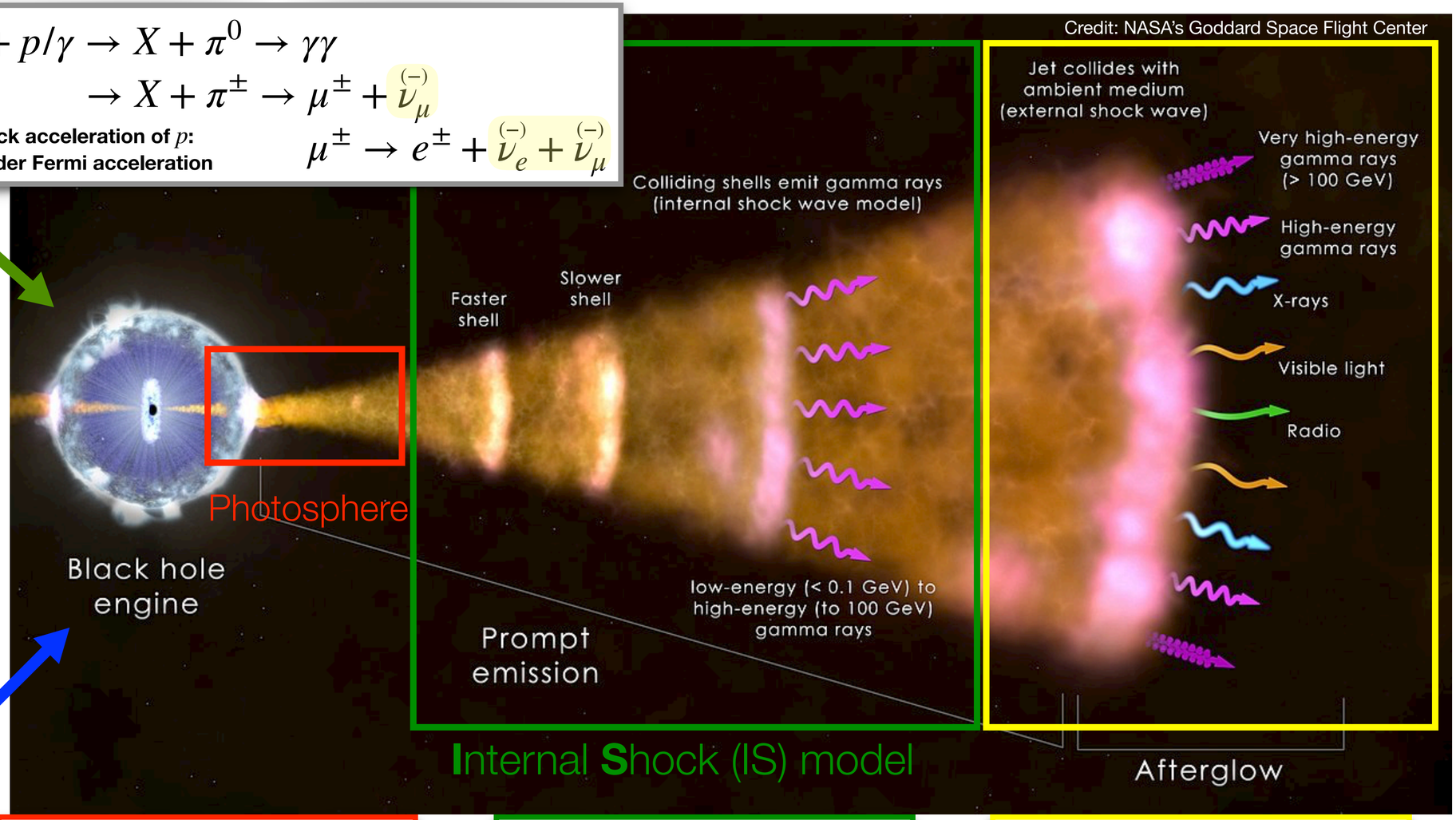
Short GRBs



Stars in a compact binary system inspiral and merge

$$p + p/\gamma \to X + \pi^0 \to \gamma\gamma$$
$$\to X + \pi^\pm \to \mu^\pm + \overset{(-)}{\nu}_\mu$$
$$\mu^\pm \to e^\pm + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu$$

Shock acceleration of p:
1st order Fermi acceleration

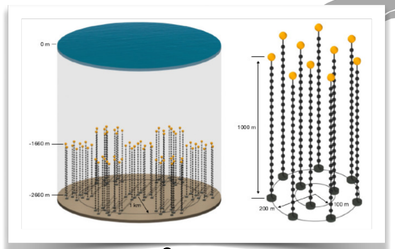


GeV-TeV neutrinos
Meszaros & Waxman 2001

TeV-PeV neutrinos
Waxman & Bahcall 1997

PeV-EeV neutrinos
Waxman & Bahcall 2000

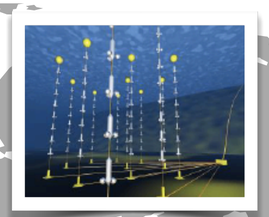
High-energy neutrino telescopes: World map



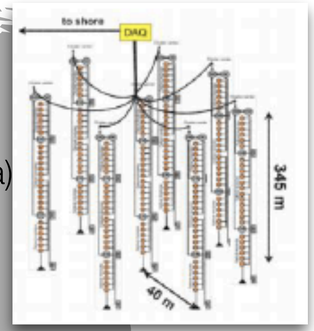
1 km^3, R&D

P-ONE (Canada)

ANTARES
>0.01 km^3, 2008-2022



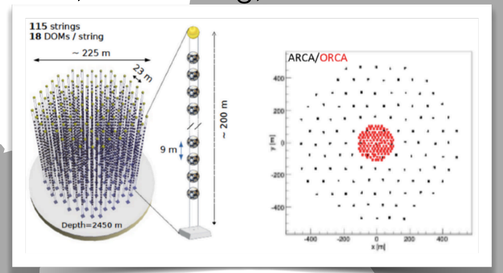
Baikal/GVD (Russia)
1 km^3, in construction



KM3NeT-ORCA (France)

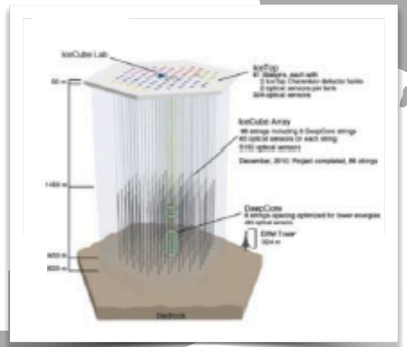
KM3NeT-ARCA (Sicily, Italy)

>1 km^3, data taking, in construction



IceCube
(South Pole)
1 km^3, 2011-data taking

IceCube-Gen2
(South Pole)
10 km^3, R&D

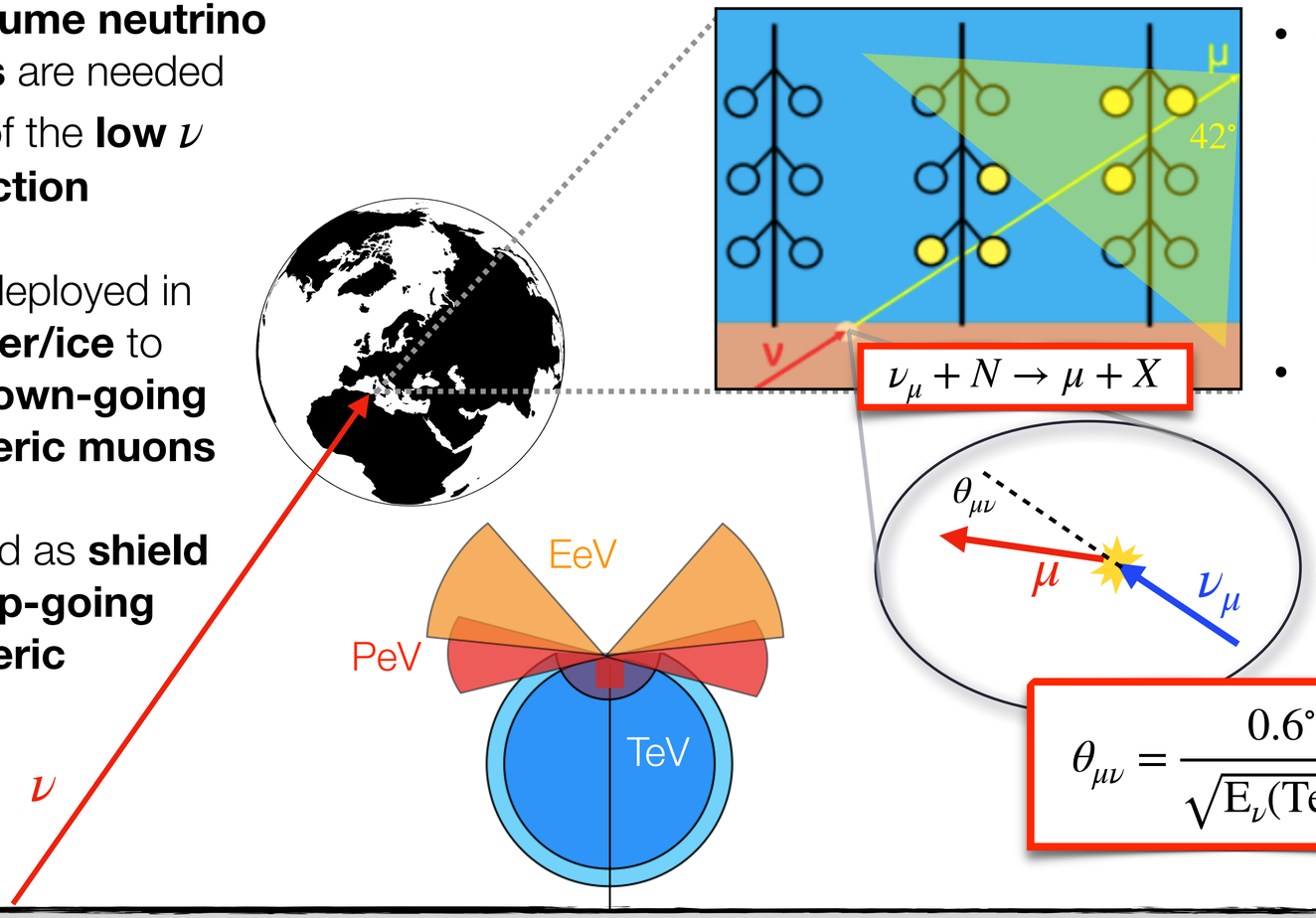


High-energy neutrino telescopes: detection principle

Neutrinos are challenging to be detected (large background contamination and low fluxes)

Reconstruction of $\mu(\sim \nu_\mu)$ trajectory from time, position and amplitude of PMT pulses

- **Large volume neutrino detectors** are needed because of the **low ν cross-section**
- Detector deployed in **deep water/ice** to **reduce down-going atmospheric muons**
- **Earth** used as **shield against up-going atmospheric muons**



- Cone of **Cherenkov light** originated **by muons** path in the medium and detected by **3D arrays of PMTs**

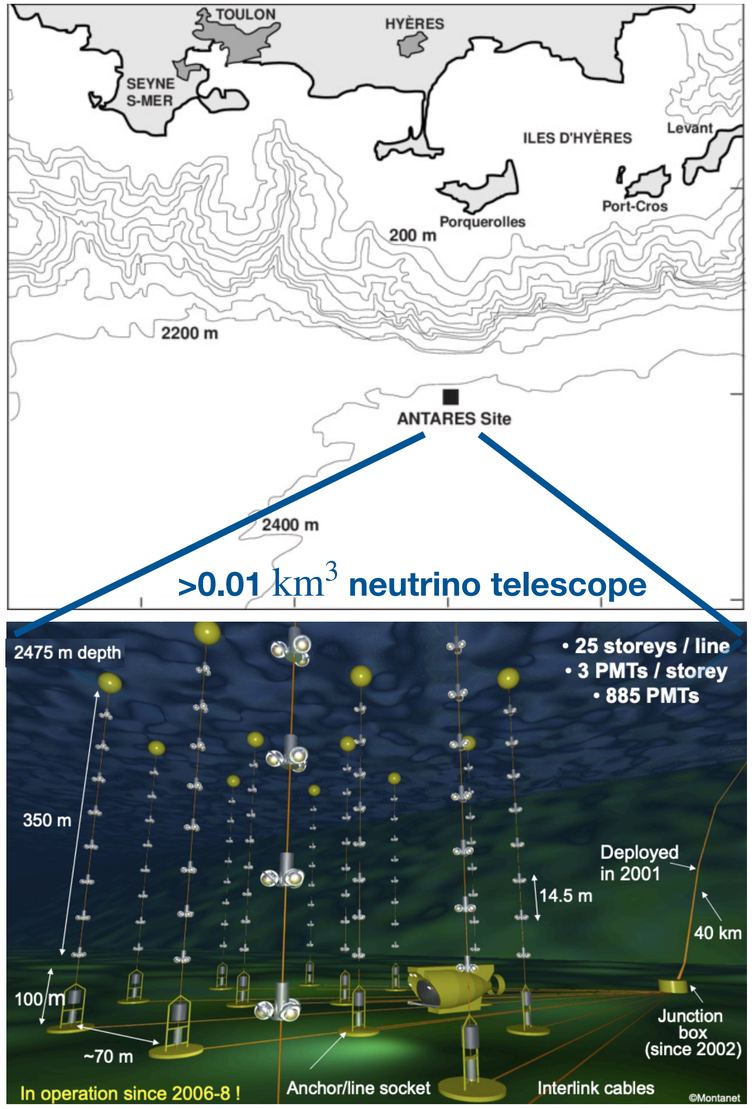
Cherenkov angle in water ~ 42°

- Either CC or NC interaction with quarks inside or nearby the detector volume

The higher the neutrino energy, the better its directional reconstruction

$$\theta_{\mu\nu} = \frac{0.6^\circ}{\sqrt{E_\nu(\mathrm{TeV})}}$$

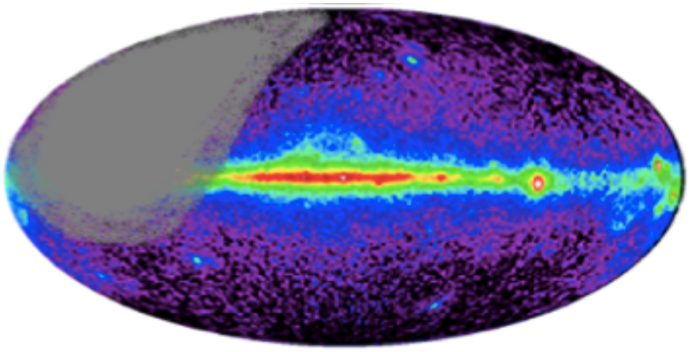
ANTARES neutrino telescope



First under-sea neutrino telescopes
(precursor of KM3NeT)

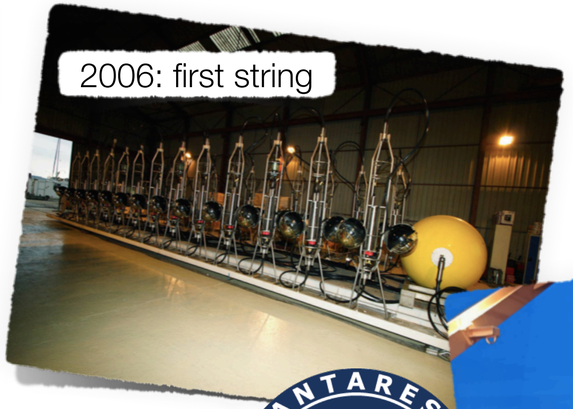
- 40 km offshore Toulon (France)
- 2006: first complete detector line
- 2008: detector with 12 lines completed
- 2022: Data taking terminated and detector decommissioned

~ 14 years of data taking



Sky visibility $\sim 3.5\pi$

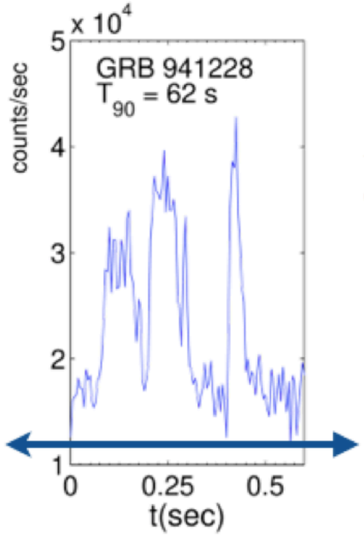
- 3D array of 885 PMTs
- 2475 m depth
- 12 vertical lines, 25 storeys,
- 3 PMTs per storey
- PMT facing 45° downwards

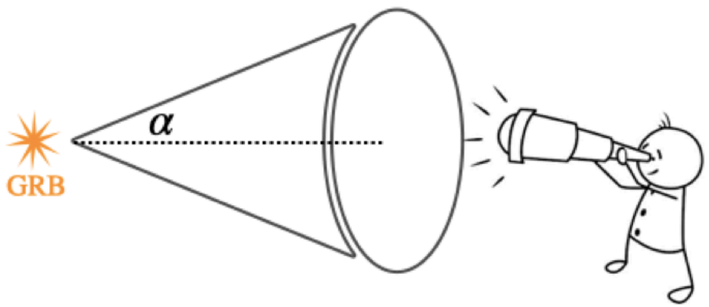


GRB neutrino searches: analysis method

Ansatz neutrinos come in coincidence with GRBs → **Methods**

- Individual GRBs
- Search for the overall flux from the cumulative signal of all observed GRBs (**stacking**)



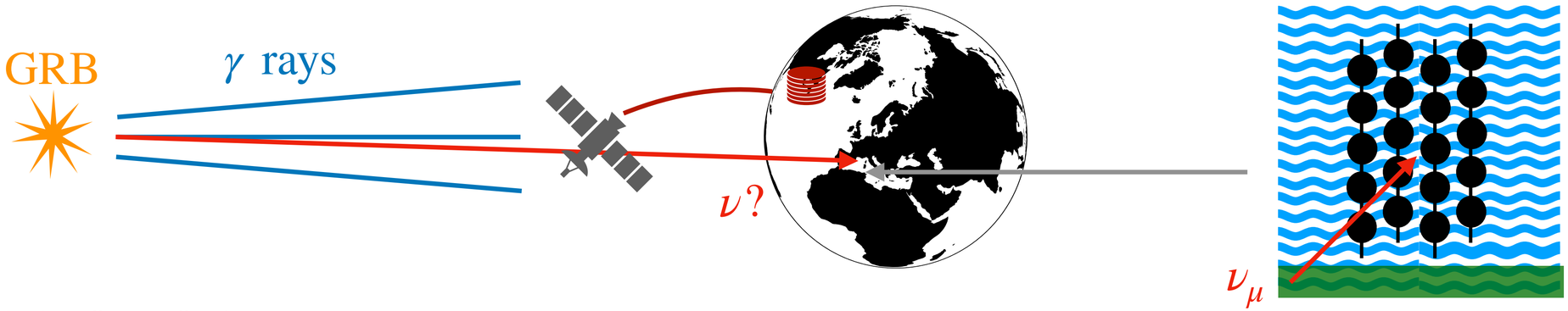


- Search time window slightly extended with respect to the gamma-ray duration of the burst (T_{90})
- Angular window of a suitable size around the satellite position

Analysis procedure

1. Expected neutrino signal from MC simulations
2. Background estimation from data and/or MC simulations
3. The **analysis** is **optimized** through various requirements, such as the **quality of the reconstruction**, allowing to **maximize the signal expectation having assumed a neutrino spectrum**

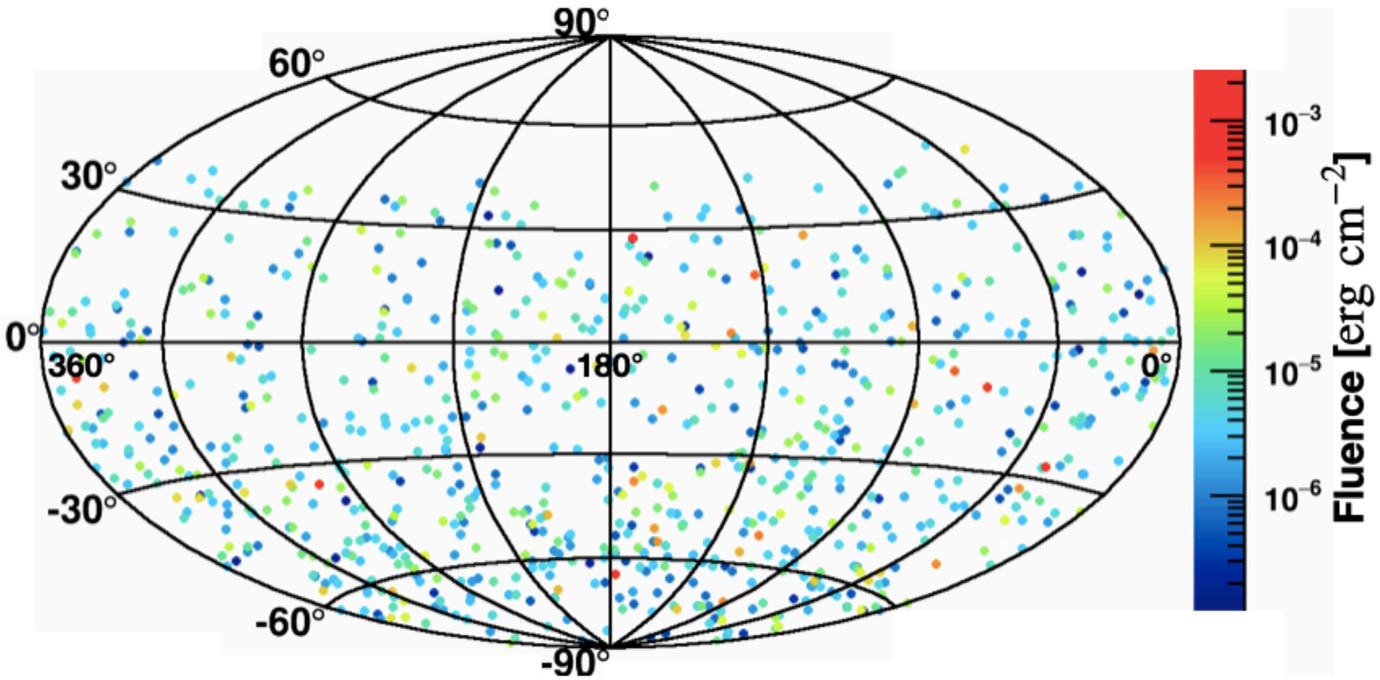
GRB stacking search with the ANTARES neutrino telescope



10 years of ANTARES data

SELECTION CRITERIA

- **Long bursts** in **2007-2017** from Fermi (GBM + LAT), Swift (BAT + XRT + UVOT) catalogs and Konus-Wind GCN (https://gcn.gsfc.nasa.gov/gcn3_archive.html);
- Spectrum is measured;
- T90 (~ duration) is measured;
- Position is measured and satellite angular uncertainty is less than 10 degrees;
- **Below ANTARES horizon at trigger time**;
- ANTARES taking data.

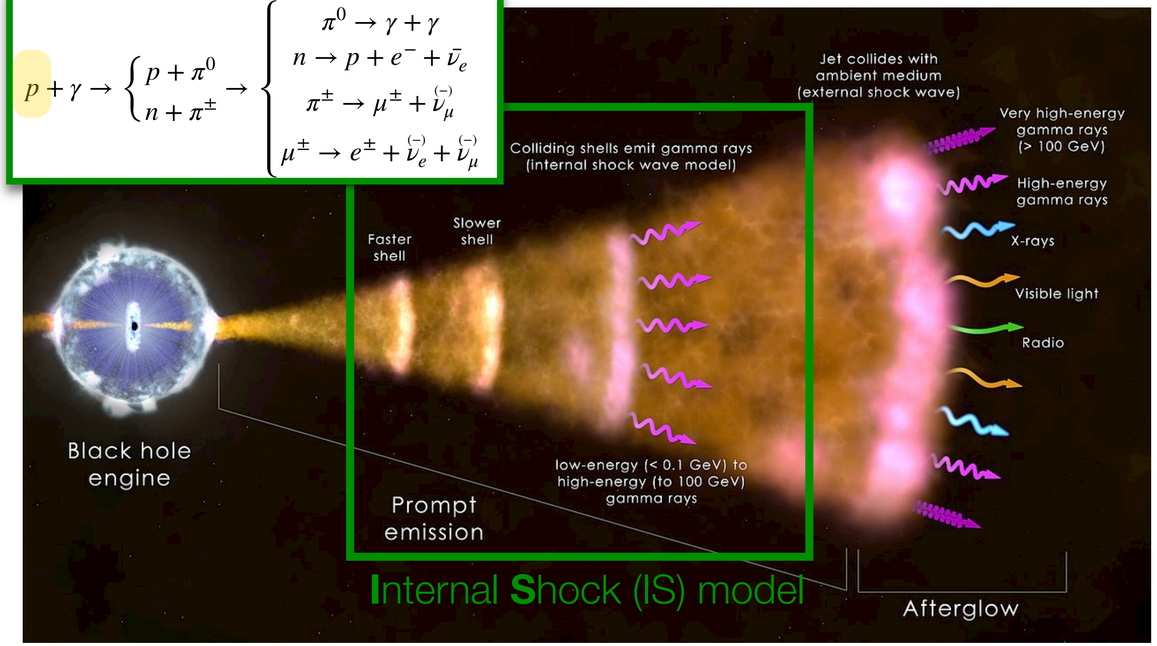


784 GRBs

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

GRBs: neutrino-gamma relation in IS model

$$p+\gamma \rightarrow \begin{cases} p+\pi^0 \\ n+\pi^{\pm} \end{cases} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma+\gamma \\ n \rightarrow p+e^- +\bar{\nu}_e \\ \pi^{\pm} \rightarrow \mu^{\pm}+\overset{(-)}{\nu}_{\mu} \\ \mu^{\pm} \rightarrow e^{\pm}+\overset{(-)}{\nu}_e+\overset{(-)}{\nu}_{\mu} \end{cases}$$



$< x_{p\rightarrow\pi} > = 0.2$ Average fraction of proton energy going into a pion per interaction

$f_p = 10$ Total energy in protons compared to the total energy in electrons

We want to know

$$\int_0^{+\infty} E_\nu F_\nu(E_\nu) dE_\nu = \frac{1}{8} f_p \left[1-(1-x_{p\rightarrow\pi})^{\frac{R}{\lambda_{p\gamma}}}\right] \int_{E_{min}}^{E_{max}} E_\gamma F_\gamma(E_\gamma) dE_\gamma$$

Proton converted energy

NEUTRINO FLUENCE

$$L_{\gamma,\mathrm{iso}} = 4\pi d_L^2(z) \frac{F_\gamma}{T_{90}}$$

$$\frac{R}{\lambda_{p\gamma}} = \left(\frac{L_{\gamma,\mathrm{iso}}}{10^{52}\mathrm{erg/s}}\right)\left(\frac{10^{2.5}}{\Gamma}\right)^4\left(\frac{0.01\mathrm{s}}{t_v}\right)\left(\frac{\mathrm{MeV}}{E_{\mathrm{peak}}}\right) = \tau_{p\gamma}$$

BULK LORENTZ FACTOR

MINIMUM VARIABILITY TIMESCALE

Unknown parameters of the model (intrinsic source characteristics)

Large parameter variability from burst to burst

(NeuCosmA model)

Hummer et al., Phys. Rev. Lett., 108, 231101, 2012

Neutrino-gamma relation in IS model

$$R_{\rm is} = 2\times 10^{13}\left(\frac{t_v}{0.01\ s}\right)\left(\frac{\Gamma}{10^{2.5}}\right)^2\left(\frac{3}{1+z}\right)\ {\rm cm}$$

t_v, Γ, and the redshift z of the source set the radial distance where shock collisions occur, having <u>large impact on neutrino flux expectations</u>

$< x_{p\to\pi} > = 0.2$ Average fraction of proton energy going into a pion per interaction

$f_p = 10$ Fraction of the total energy in protons compared to the total energy in electrons

BULK LORENTZ FACTOR

MINIMUM VARIABILITY TIMESCALE

<u>Unknown parameters of the model (intrinsic source characteristics)</u>

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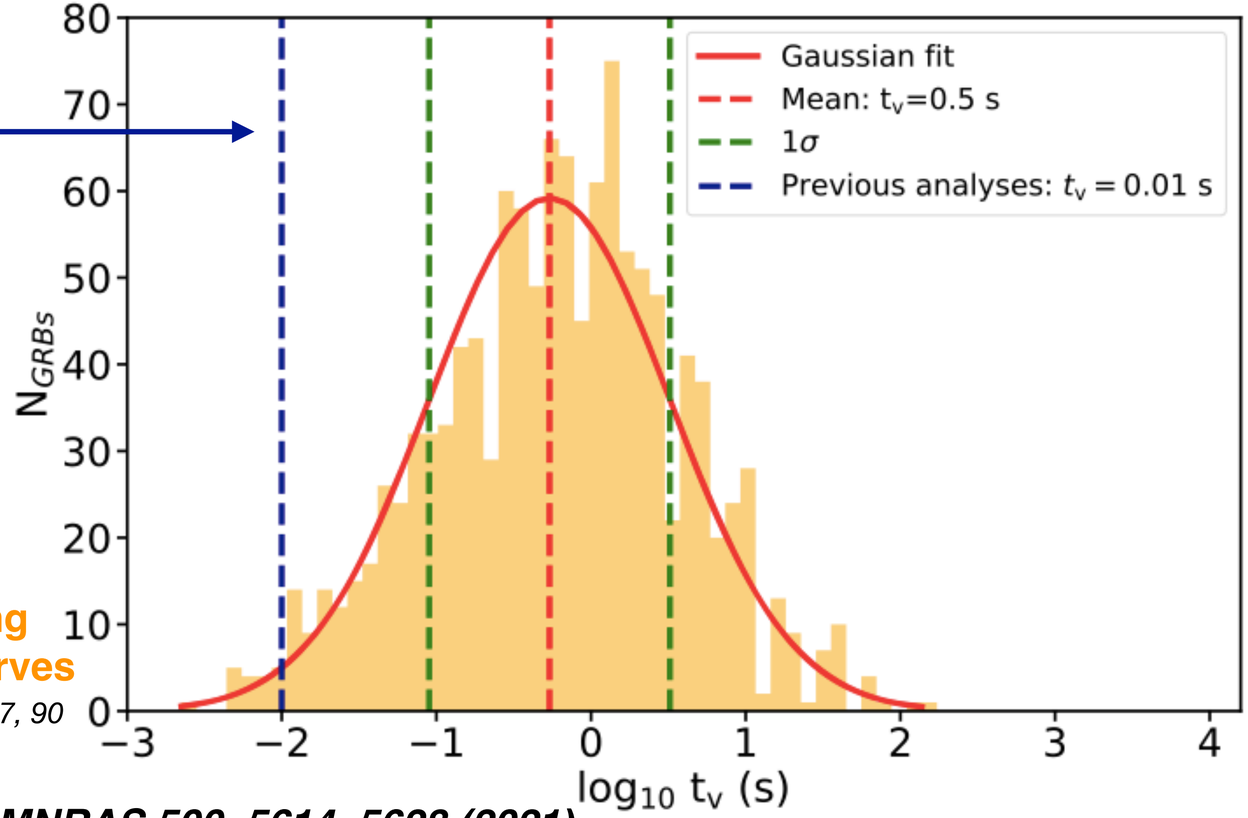
Hummer et al., Phys. Rev. Lett., 108, 231101, 2012

Parameter estimation: Minimum variability timescale

$$\frac{R}{\lambda_{p\gamma}} = \left(\frac{L_{\gamma,\mathrm{iso}}}{10^{52}\mathrm{erg/s}}\right)\left(\frac{10^{2.5}}{\Gamma}\right)^4\left(\frac{0.01\mathrm{s}}{t_\mathrm{v}}\right)\left(\frac{\mathrm{MeV}}{E_\mathrm{peak}}\right) = \tau_{p\gamma}$$

In the previous ANTARES analyses the minimum variability time scale was fixed at $t_\mathrm{v} = 10\ \mathrm{ms}$

1000 random extractions for each GRB with unknown minimum variability timescale (~70% of the sample)



Values obtained from post-processing Fourier analysis on the burst lightcurves

Golkhou, V. Zach & Butler, Nathaniel R. 2014, ApJ, 787, 90
Golkhou, V. Zach, et al. 2015, ApJ, 811, 93

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Parameter estimation: Bulk Lorentz factor and redshift

$$\frac{R}{\lambda_{p\gamma}} = \left(\frac{L_{\gamma,\mathrm{iso}}}{10^{52}\mathrm{erg/s}}\right)\left(\frac{10^{2.5}}{\Gamma}\right)^4\left(\frac{0.01\mathrm{s}}{t_\mathrm{v}}\right)\left(\frac{\mathrm{MeV}}{E_\mathrm{peak}}\right) = \tau_{p\gamma}$$

L_{iso} - Γ correlation

$$\Gamma = 249\left(\frac{L_{\gamma,\mathrm{iso}}}{10^{52}\mathrm{erg/s}}\right)^{0.30}$$

Lu et al., ApJ, 751, 49, 2012
https://doi.org/ 10.1088/0004-637X/751/1/49

Knowing L_{iso} we can infer Γ

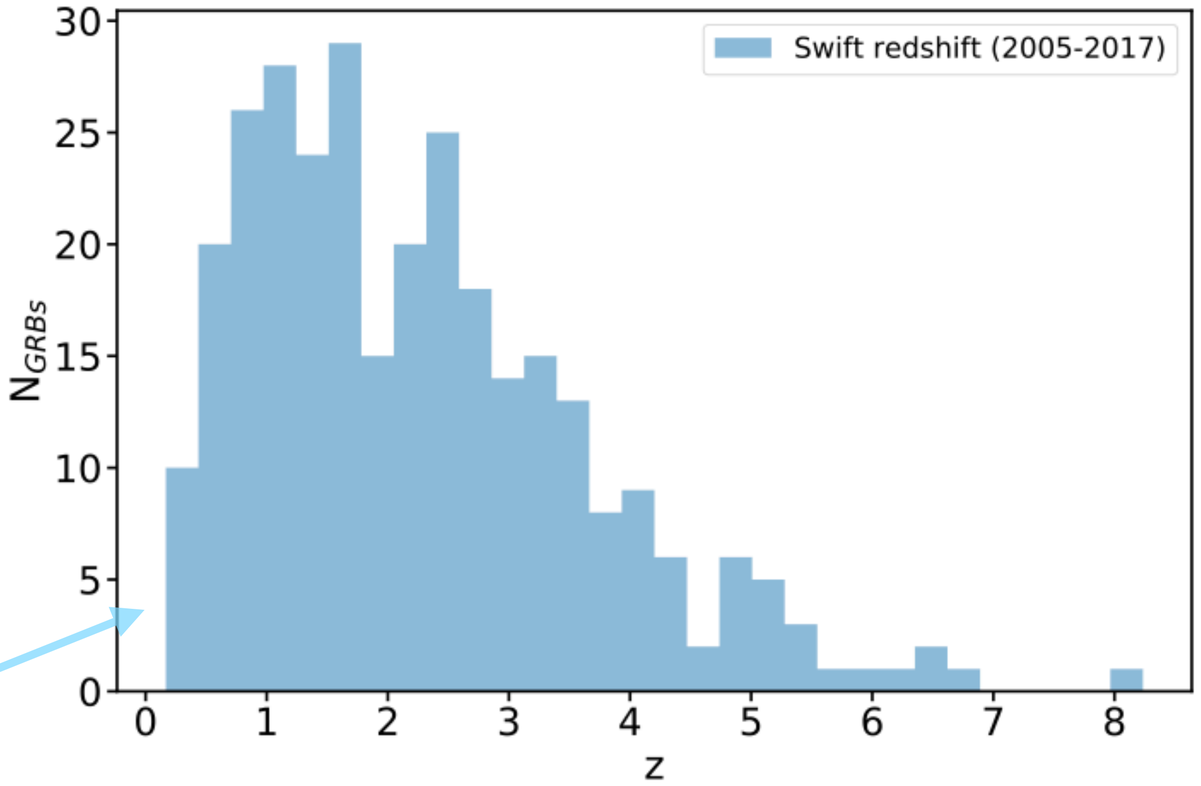
$$L_{\gamma,\mathrm{iso}}(z) = 4\pi d_L^2(z) F_\gamma / T_{90}$$

measured: F_γ

measured: T_{90}

To apply this correlation we need the redshift in order to evaluate the burst isotropic luminosity

1000 random extractions for each GRB with unknown redshift (~90% of the sample)



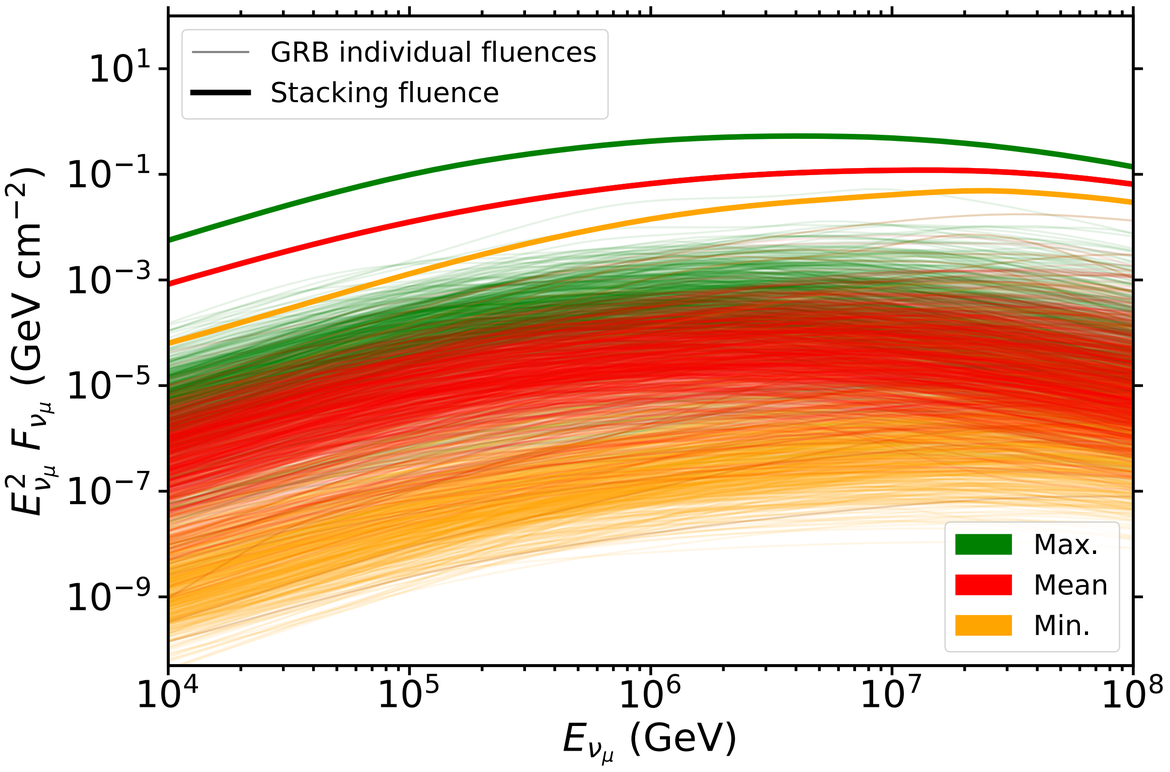
ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

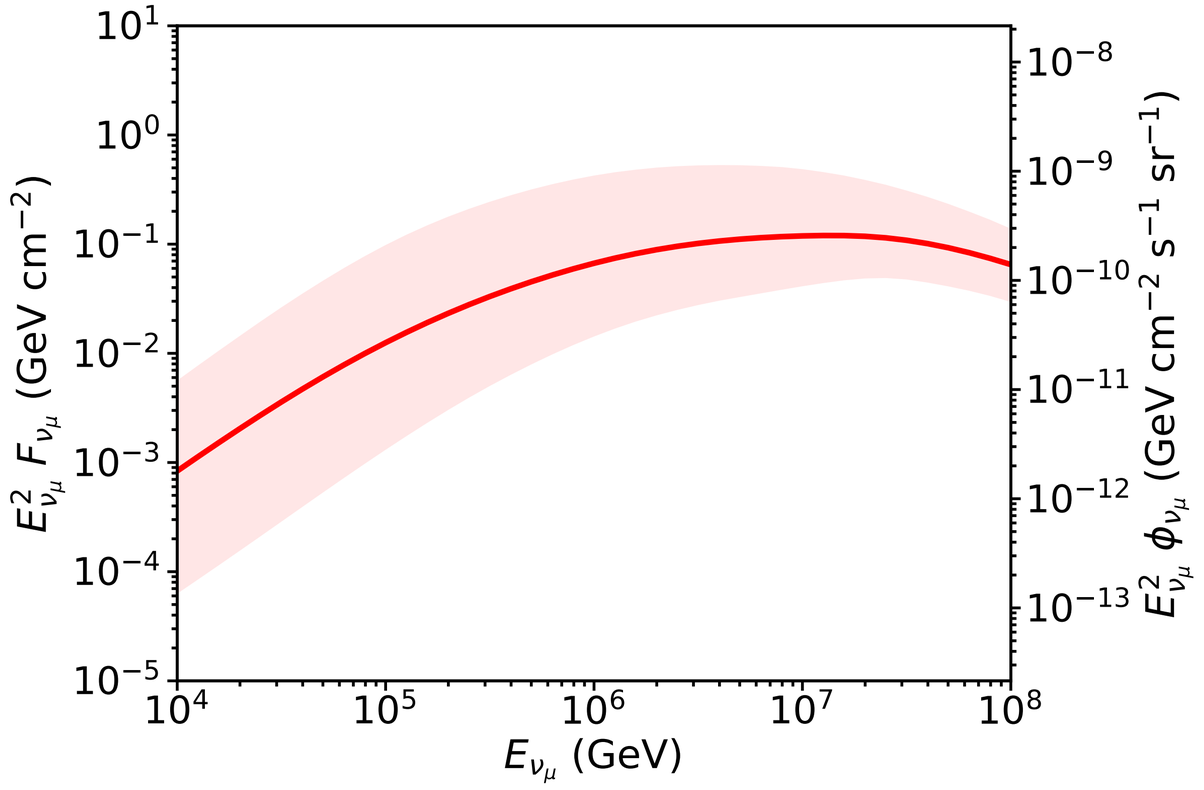
2007-2017 GRB stacked neutrino fluence (784 GRBs)

$$E^2_{\nu_\mu} F_{\nu_\mu} = \sum_{i=1}^{N_{GRB}=784} (E^2_{\nu_\mu} F_{\nu_\mu})^i$$

$$E^2_{\nu_\mu} \phi_{\nu_\mu} = \sum_{i=1}^{N_{GRB}} E^2_{\nu_\mu} F_{\nu_\mu} \frac{1}{4\pi} \frac{1}{N_{GRB}} 667 \mathrm{yr}^{-1}$$

Diffuse neutrino flux





ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Stacking search and optimization

ANTARES data were analyzed maximizing the discovery probability of the stacking sample through an **extended maximum likelihood strategy**

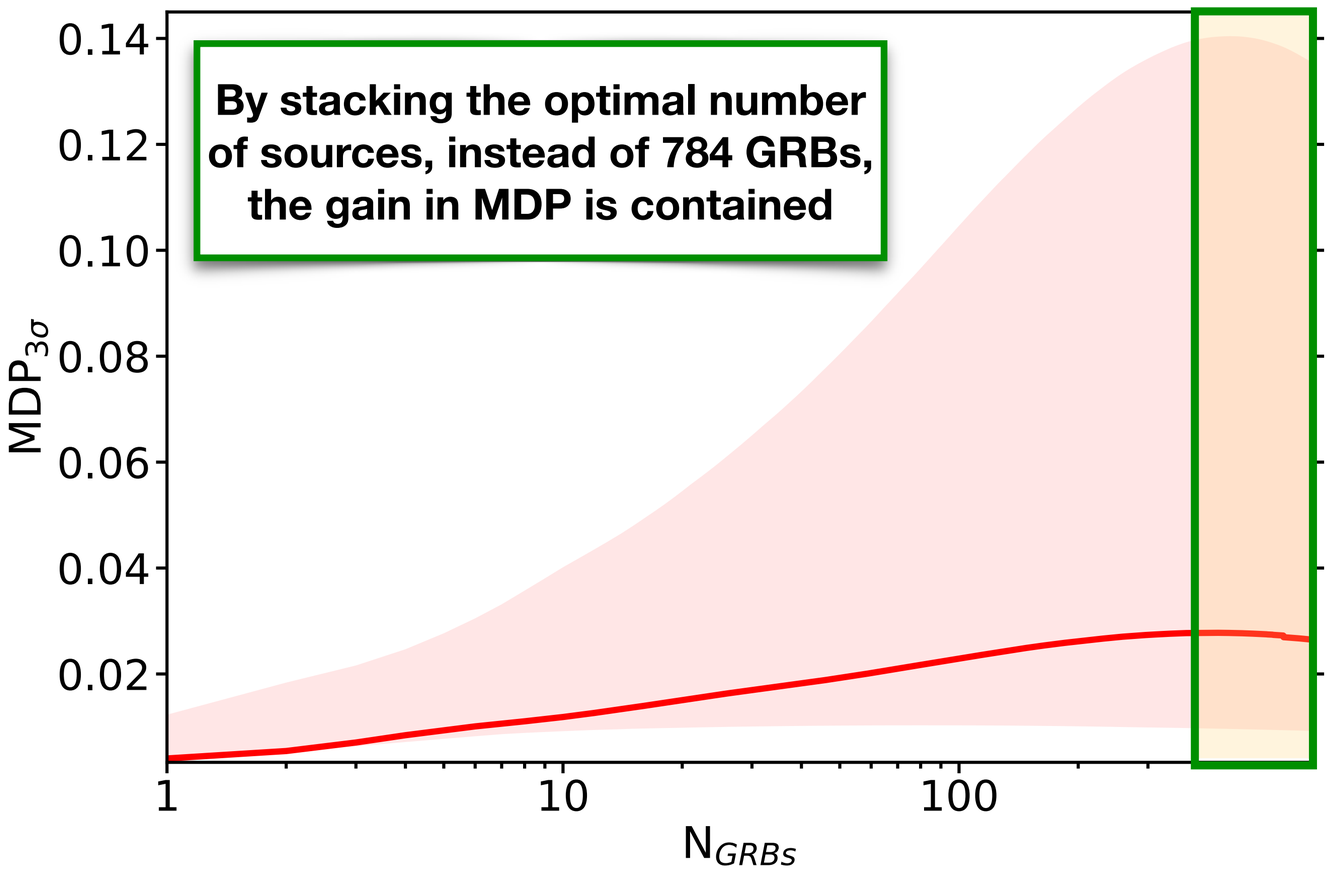
Barlow R., 1990, Nucl. Instr. Meth., A, 297, 496
Adrián-Martínez S. et al. (ANTARES Collaboration), 2013, A&A 559A

784 GRBs

for an equivalent lifetime of **T = 18.9 h** of data

The expected number of signal events from the total sample is:

$$n_s(N_{GRB} = 784) = 0.03^{+0.14}_{-0.02}$$



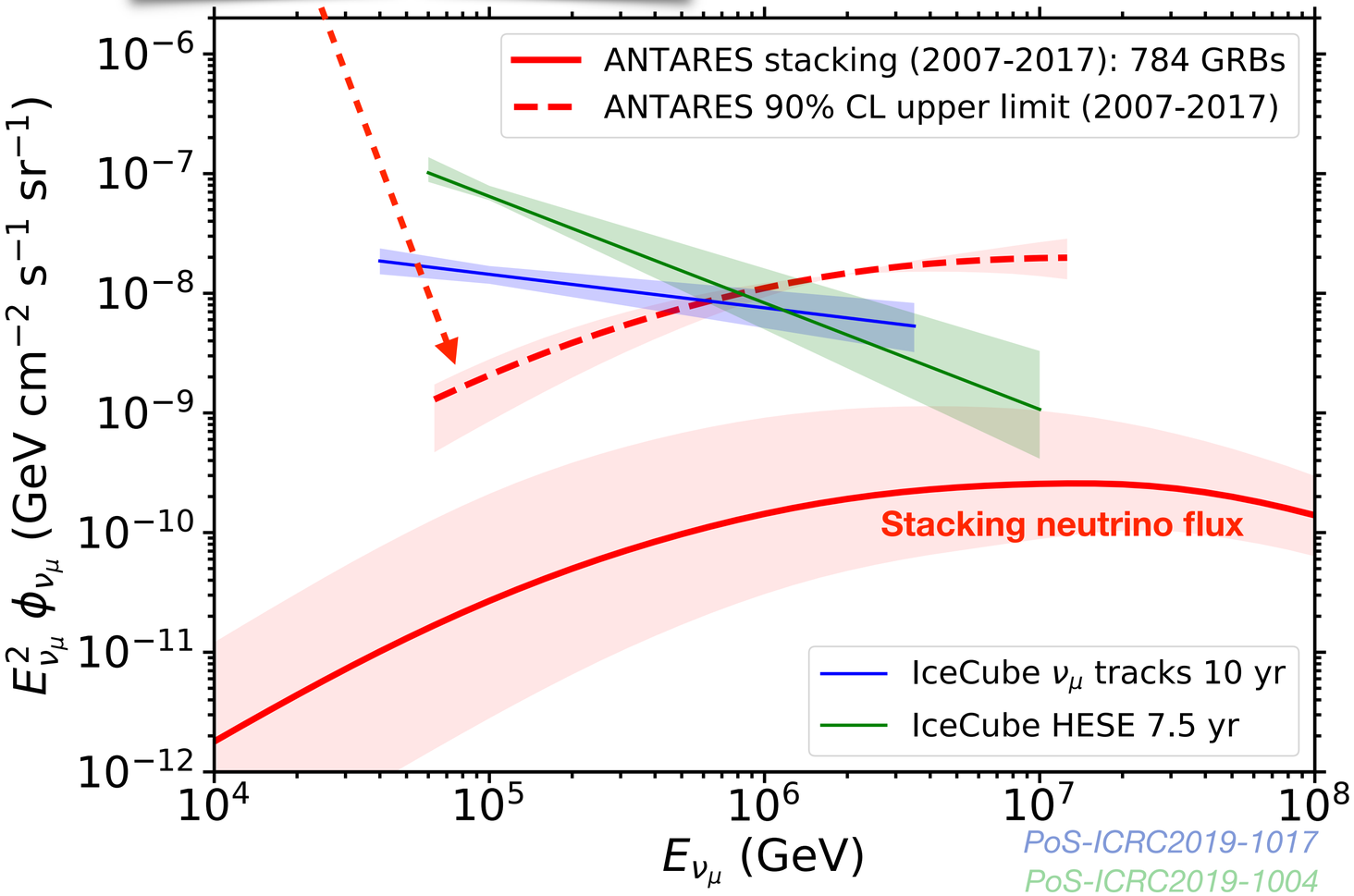
ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Constraining the HE diffuse neutrino flux from GRBs

NO neutrino events in ANTARES data found in spatial and temporal coincidence with the prompt phase of the GRB sample

- **GRBs are not the main contributors to the observed flux below ~ 1PeV,** within the NeuCosmA model framework with benchmark baryonic loading, $f_p = 10$
- **In the energy region where ANTARES is most sensitive (around 100 TeV), GRBs do not appear to contribute by more than 10%**

$$\phi_{\nu_\mu}^{90\%} = \phi_{\nu_\mu}\frac{n^{90\%}}{n_s} = \phi_{\nu_\mu}\frac{2.3}{n_s} = \phi_{\nu_\mu}\cdot 77^{+226}_{-64}$$



PoS-ICRC2019-1017
PoS-ICRC2019-1004

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Search for high-energy νs from (sub-)TeV GRBs with ANTARES

Dedicated offline searches from the first O(TeV) GRBs detected by the **I**maging **A**tmospheric **C**herenkov **T**elescopes (IACT) MAGIC and H.E.S.S. in the last few years

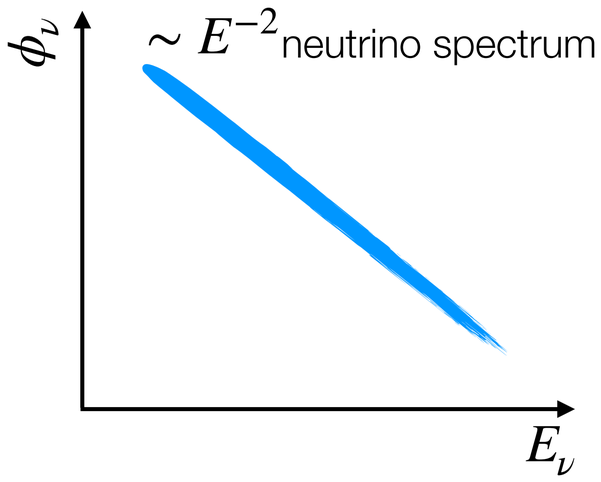
- ★ GRB 190114C
- ★ GRB 180720B
- ★ GRB 190829A

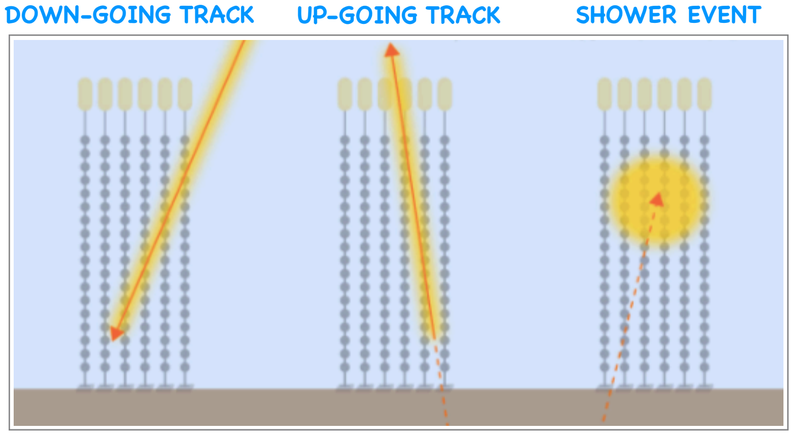
Search time windows

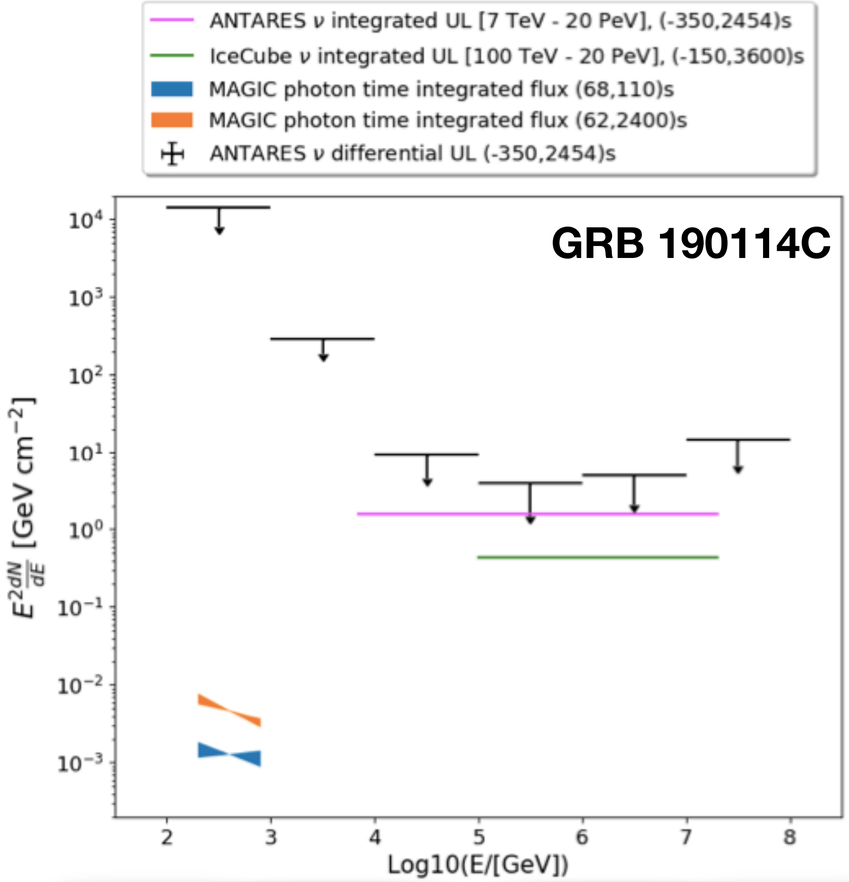
Event	$\delta t_{\mathrm{total}}$	δt_{up}	δt_{down}
GRB 180720B	12.1 h	7.7 h	4.4 h
GRB 190114C	2804 s	—	2804 s
GRB 190829A	8.1 h	2.85 h	5.25 h

PROMPT + AFTERGLOW

Space search region: optimized using ANTARES angular resolution (**~1°-2°** for **tracks** and **10°-20°** for **showers**)







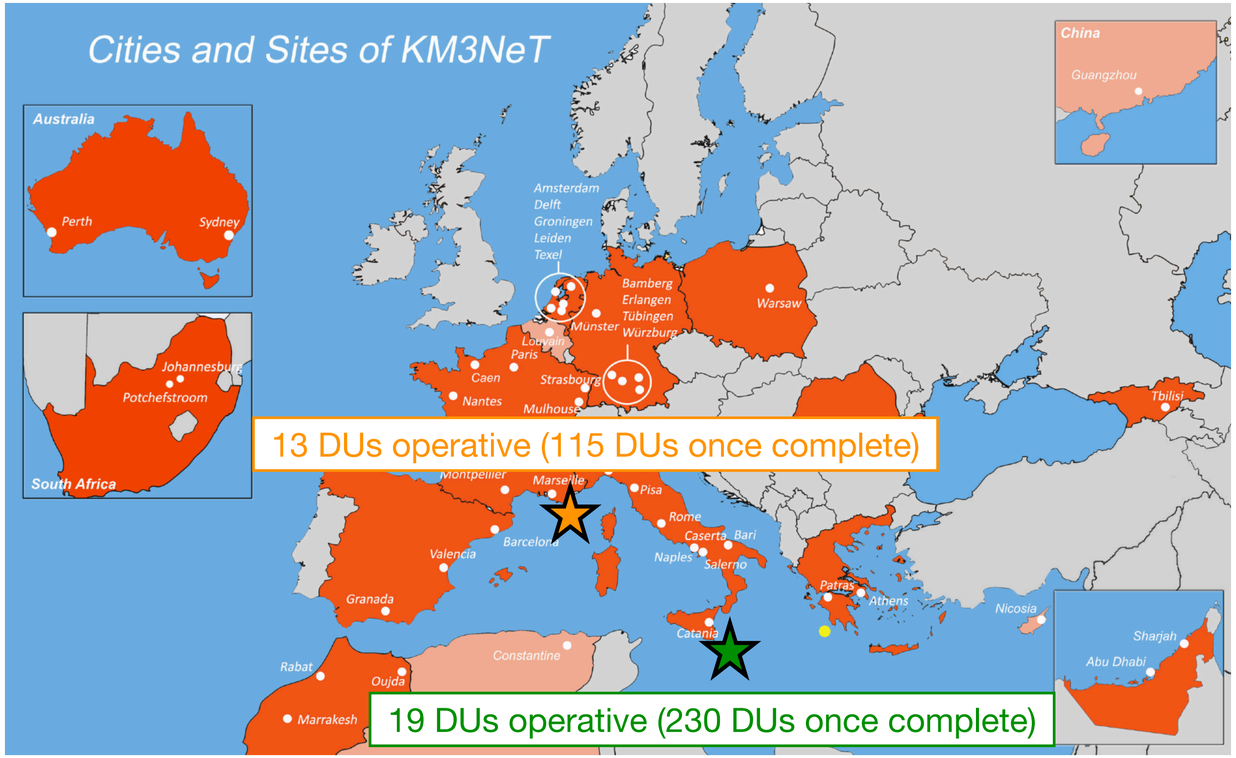
Upper limits on the total neutrino energy and neutrino spectral fluence

ANTARES Collaboration, JCAP(2021)092

KM3NeT neutrino telescope

- Deep infrastructure under construction in the Mediterranean Sea
- Two instrument sites: ORCA (France) and ARCA (Italy)

$> 1\ \mathrm{km}^3$ **neutrino telescope**



www.km3net.org

Designed for **low-energy** studies (**from MeV**)

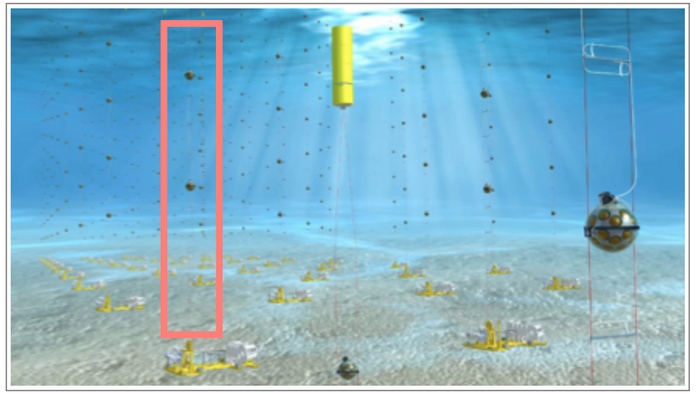
Oscillation
Research with
Cosmics in the
Abyss

Same technology used for both detectors but **different physics**

Astroparticle
Research with
Cosmics in the
Abyss

Designed for **high-energy** studies (**up to PeV**)

3D array of optical sensors

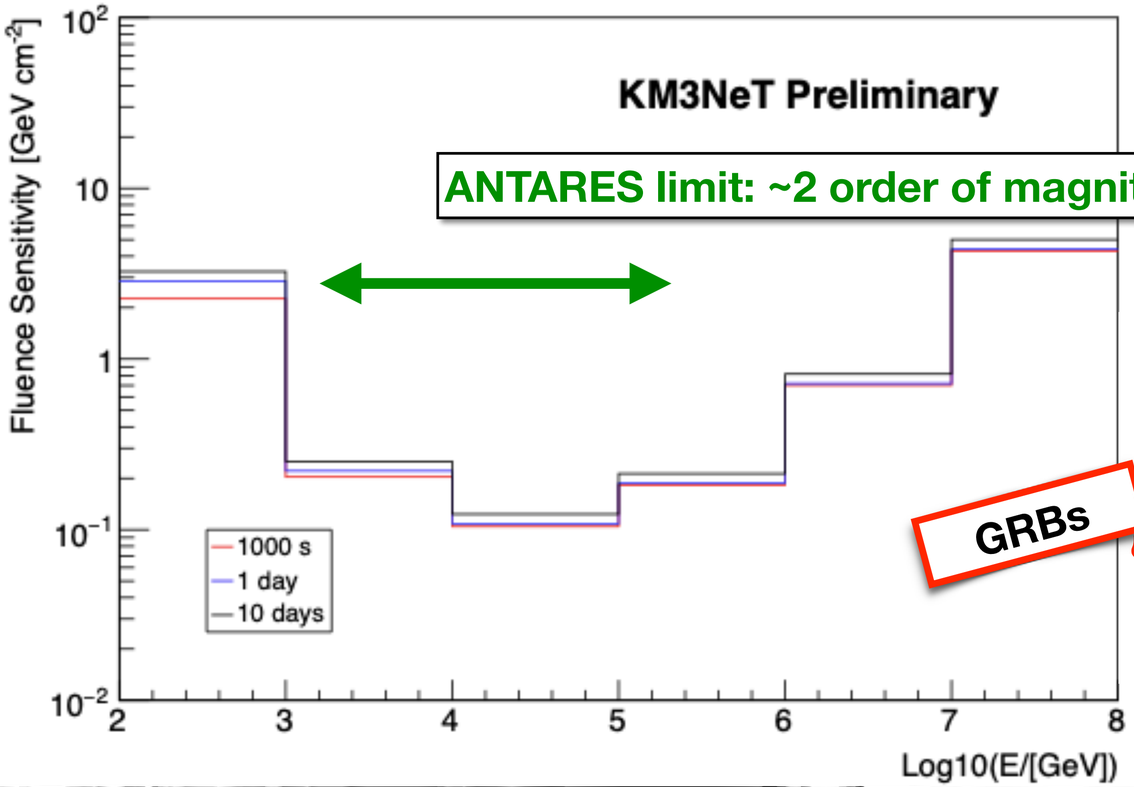


Digital **O**ptical **M**odule

Detection **U**nit

KM3NeT/ARCA sensitivity to transient neutrino sources

- A test source in the **up-going sky** (zenith=70° and azimuth=300°) has been considered for different time windows (**1000 s**, 1 day and 10 days) and with **spectrum** $\propto E^{-2}$ for cosmic neutrinos;
- Track-like events from ν_μ CC interactions;
- Sensitivity obtained by optimizing the model rejection potential to find the limit the would be placed on the neutrino flux if no true signal were present, and only the expected background of atmospheric neutrino (reduced through optimal cuts) events is observed. *Hill G.C.. & Rawling K., Astropart.Phys. 19(2003) 393-402*



ANTARES limit: ~2 order of magnitudes above KM3NeT

GRBs

Results for ARCA full detector (230 strings)

Ang. res. ~0.1° @100 TeV

Time window	Optimum RoI radius MRF	Expected background events	Fluence sensitivity (GeV · cm^{-2})	Discovery $N_{sg}^{5\sigma}$ (50%)
1000 s	6.5°	$1.2 \cdot 10^{-2}$	0.047	2.7
1 day	3.0°	$3.3 \cdot 10^{-2}$	0.050	3.6
10 days	2.0°	$1.2 \cdot 10^{-1}$	0.061	4.6

PoS(ICRC2021)1162

Summary and Conclusions

- **GRBs** have been considered **interesting candidates as UHECR accelerators and neutrino sources** for several years;

- To test these hypotheses, with the ANTARES neutrino telescope possible associations between neutrinos and GRBs have been searched for (both stacking and individual searches);

- By using **10 years of ANTARES data**, the **GRB contribution to the cosmic neutrino diffuse flux** is **constrained to be <10% at ~100 TeV** in the IS model hypothesis;

- From the **non-detection** of association between **high-energy neutrinos** and the recently discovered (**sub**-)**TeV GRBs** (**GRB 190114C**, **GRB 180720B**, and **GRB 190829A**), limits on the neutrino emission from such sources have been obtained; **hadronic models cannot be excluded**;

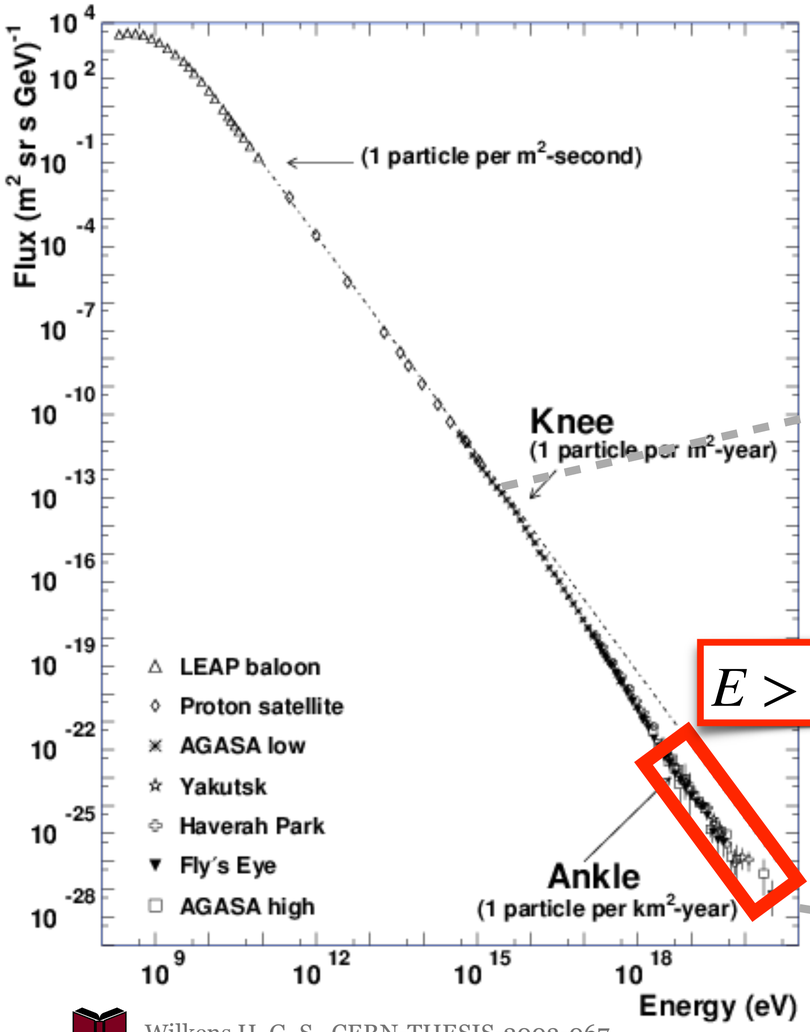
- Preliminary calculations of **KM3NeT** sensitivity to possible transient neutrino sources, as GRBs, indicate that the new-generation neutrino telescope will be able to set **more stringent limits with respect to ANTARES** (**~2 orders of magnitude**) in the **TeV-PeV** energy range for a classical neutrino spectrum $\propto E^{-2}$.

Backup slides

Mystery origin of Ultra High-Energy Cosmic Rays

Need for **extragalactic astrophysical accelerators** of **U**ltra **H**igh-**E**nergy **C**osmic **R**ays (UHECRs)

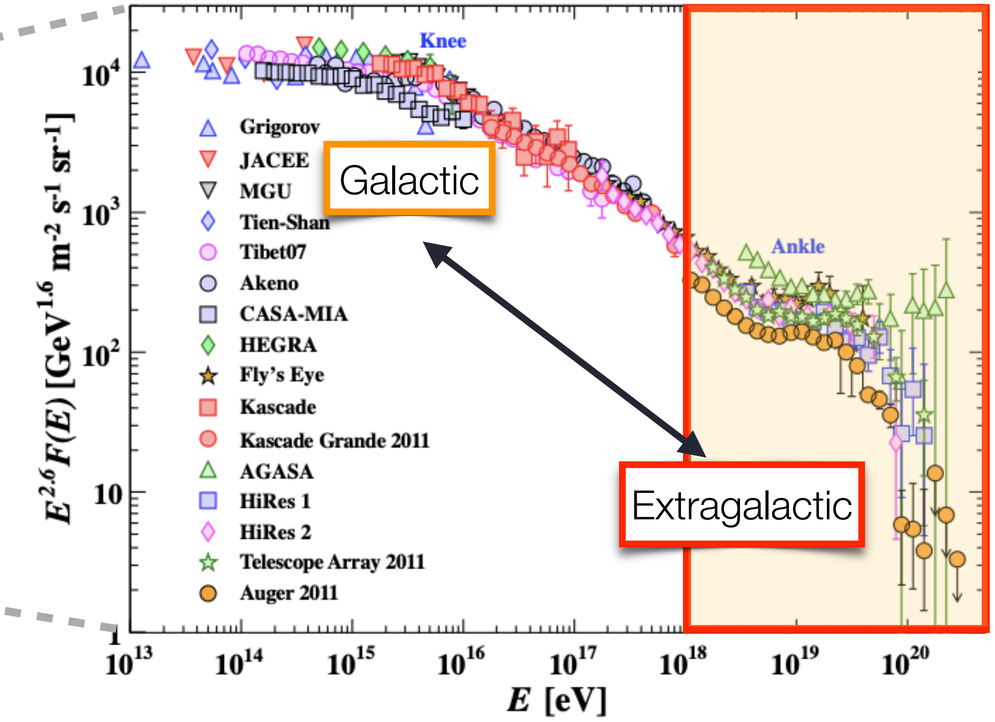
Energy density of extragalactic CRs $\rho_{\mathrm{CR_s}} \sim 10^{45}\ \mathrm{erg\ yr^{-1}\ Mpc^{-3}}$



$E > 10^{18}$ eV

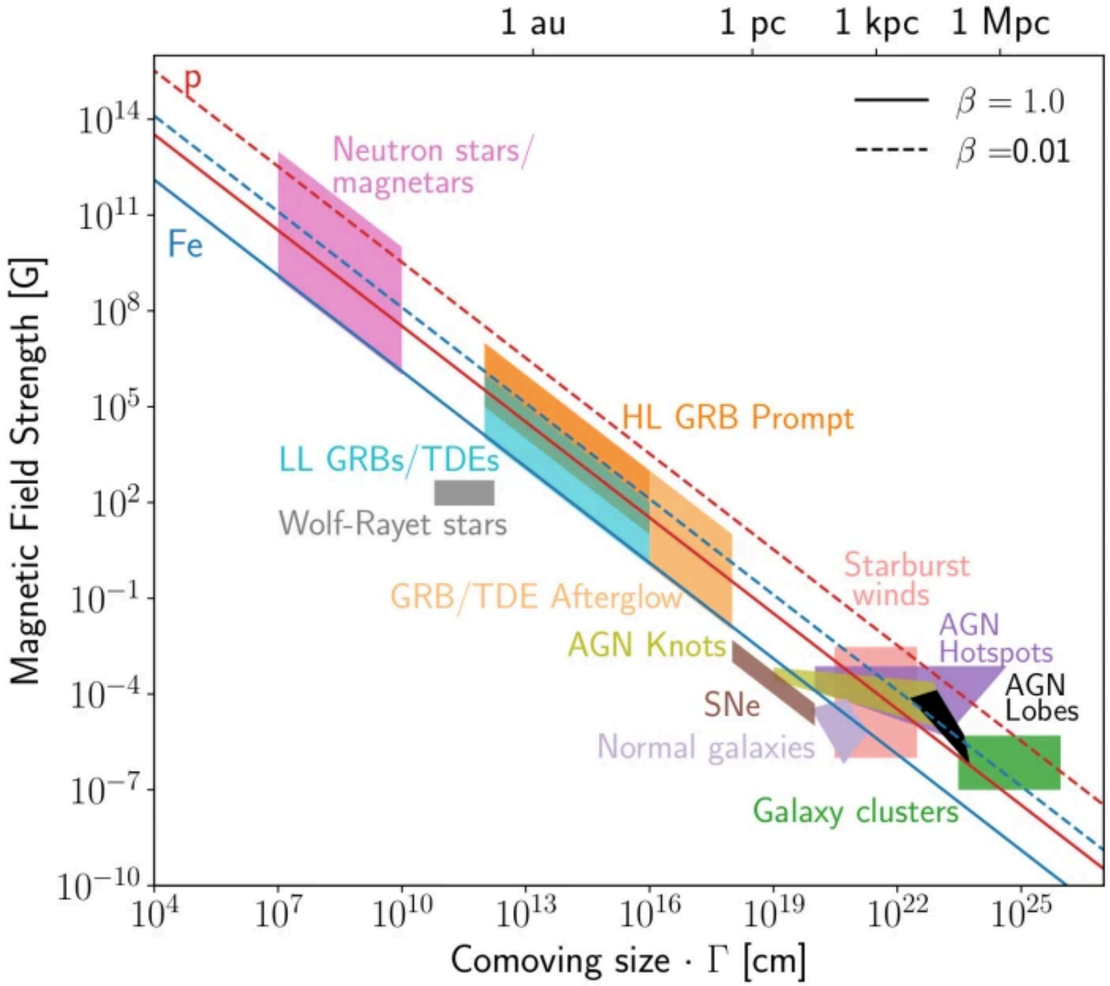
Wilkens H. G. S., CERN-THESIS-2003-067

Beringer J. et al., Phys. Rev. D86, 010001 (2012)



Hillas plot

The *Hillas condition* states that a necessary condition to accelerate particles to ultrahigh energy is that of confinement; particles can stay in the acceleration region as long as their Larmor radius is smaller than the size of the accelerator.



Maximum achievable energy

$$E_{\max} = \Gamma q B R$$

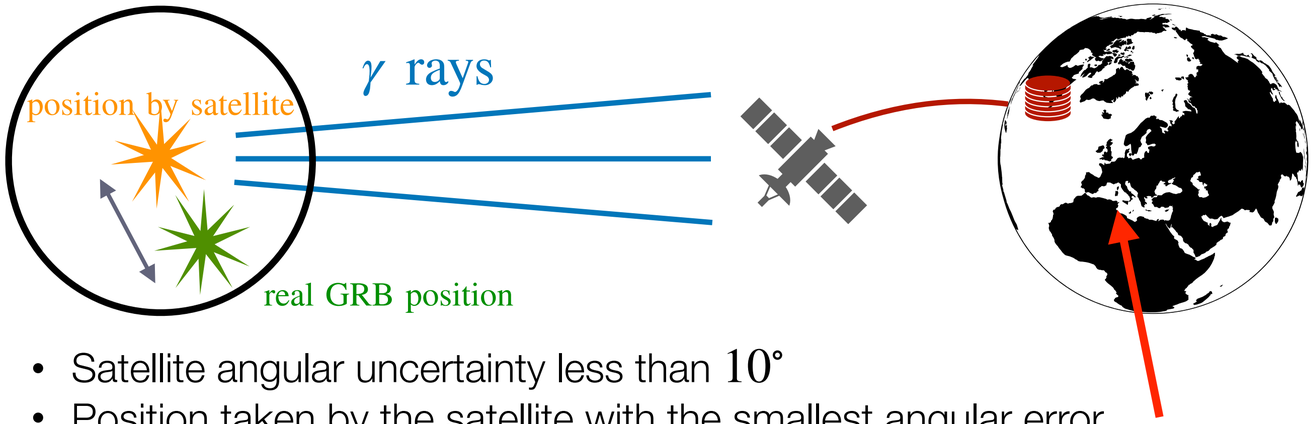
GRB stacking analysis: GRBs selection and parameters

From available catalogues:

- Time
- Direction
- Photon spectrum
- Fluence
- Redshift

GRB SEARCH

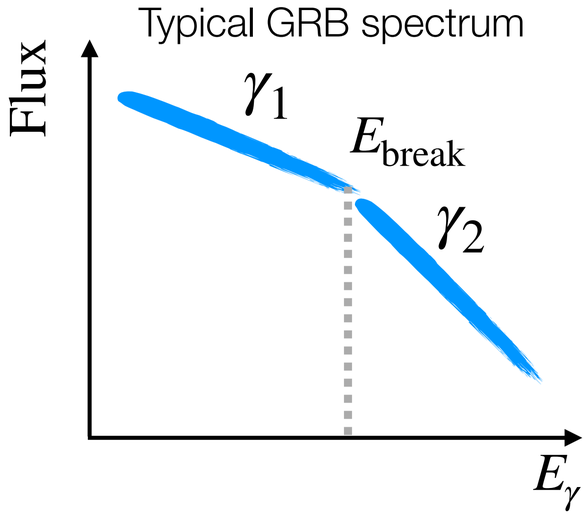
SIMULATION of the EXPECTED NEUTRINO FLUENCES



- Satellite angular uncertainty less than 10°
- Position taken by the satellite with the smallest angular error

Up-going muons

Only neutrino events below the ANTARES horizon at trigger time



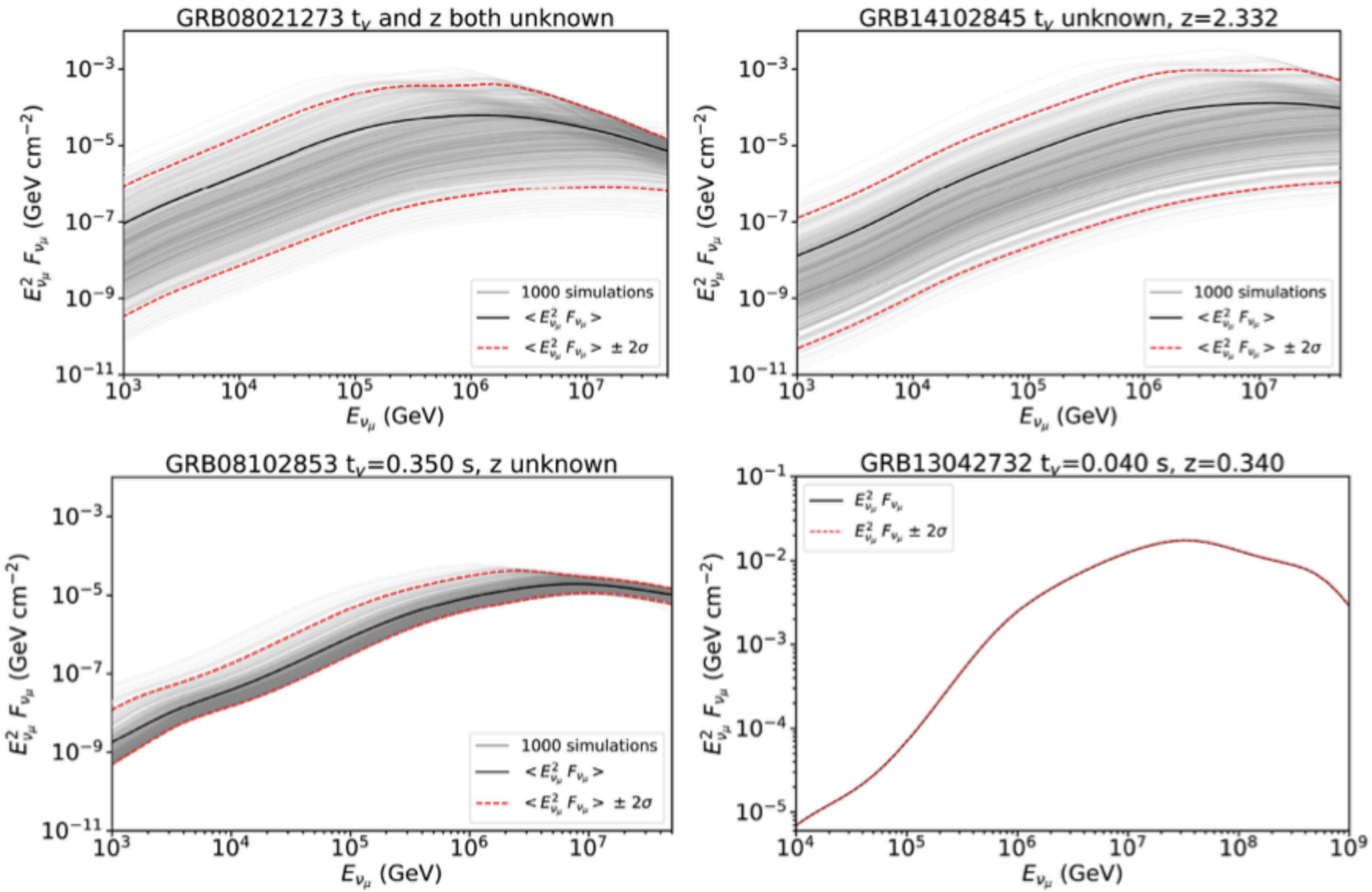
- We selected only GRBs with
  $\gamma_1 > -4$
  $\gamma_2 > -5$
- When γ_2 is not available from catalogues (1.4%):
  $\gamma_2 = \gamma_1 - 1$
- When $E_{\rm break}$ is not available from catalogues (33%):
  $E_{\rm break} = 200$ keV

Source	Position	Spectrum
Swift	29.9%	16.7%
Swift–BAT	9.3%	
Swift–UVOT	3.4%	
Swift–XRT	17.2%	
Fermi	68.8%	71.6%
Other (e.g. Konus-Wind)	1.3%	11.7%

- At least one parameter among fluence and redshift known in order to reduce the uncertainties on the neutrino fluence estimation ($L_{\gamma,\rm iso}$ depends both on z and F_γ)

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

GRB stacking analysis: systematic uncertainties on ν flux expectations



To evaluate the statistical uncertainty on the neutrino fluence, we:

1. Calculate the mean of these 1000 simulations;
2. Use percentiles to infer $\sigma(E^2_{\nu_\mu} F_{\nu_\mu})$;
3. Quote $E^2_{\nu_\mu} F_{\nu_\mu} \pm 2\sigma$.

The 2.28% of the values at the right and at the left of the $E^2_{\nu_\mu} F_{\nu_\mu}$ distributions have been excluded (in each energy bin)
-2σ is the 2.28th percentile
$+2\sigma$ is the 97.72nd percentile

The statistical error around the neutrino fluence of the GRBs with known values of t_ν and z were obtained by propagating t_ν and z uncertainties on $E^2_{\nu_\mu} F_{\nu_\mu}$

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Maximum likelihood and pseudo-experiments

Several pseudo-experiments with n_{tot} number of events are performed for several Λ_{cut} (from -5 to -5.8)

Cut on the quality parameter

Statistic test

$$Q = \log \mathscr{L}^{\max}_{\mathrm{s+b}} - \log \mathscr{L}_{\mathrm{b}} = \max_{\mu'_s \in [0, n_{\mathrm{tot}}]} \left(\sum_{i=1}^{n_{\mathrm{tot}}} \frac{\mu'_s S(\alpha_i) + \mu_b B(\alpha_i)}{\mu_b B(\alpha_i)} - \mu'_s \right) \rightarrow h_{n_s}(Q)$$

$$p = P(Q > Q^{\mathrm{th}} \,|\, \mu_b) = \int_{Q^{\mathrm{th}}}^{\infty} h_0(Q) \mathrm{d}Q$$

Λ_{cut} is optimized on each burst → The optimal cut is the one that maximizes the **M**odel **D**iscovery **P**otential for the value of μ_s predicted by NeuCosmA

$$\mathrm{MDP} = P(Q > Q^{\mathrm{th}} \,|\, \mu_s) = \sum_{n_s=0}^{\infty} \int P(n_s \,|\, \mu_s) G(\mu_s \,|\, \mu, \sigma_\mu) \mathrm{d}\mu_s \int_{Q^{\mathrm{th}}}^{\infty} h_{n_s}(Q) \mathrm{d}Q$$

Poissonian probability of injected signal n_s given the true signal μ_s

Acceptance systematics

Gaussian probability of true value of signal μ_s given the estimated value μ and its uncertainty $\sigma_\mu = 0.15$

S. Adrian-Martinez et al. (ANTARES Collaboration), Astrophys. J. 760 (2012) 53, arXiv:1207.3105

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Maximum likelihood and pseudo-experiments

The optimal number of sources to stack is found by ordering them in decreasing MDP.

$$p = 1 - \sigma \longrightarrow p = \frac{1-\sigma}{\boxed{\mathrm{TF}}}$$

To have the same overall probability of false discovery the p-value should be divided by the number of trials

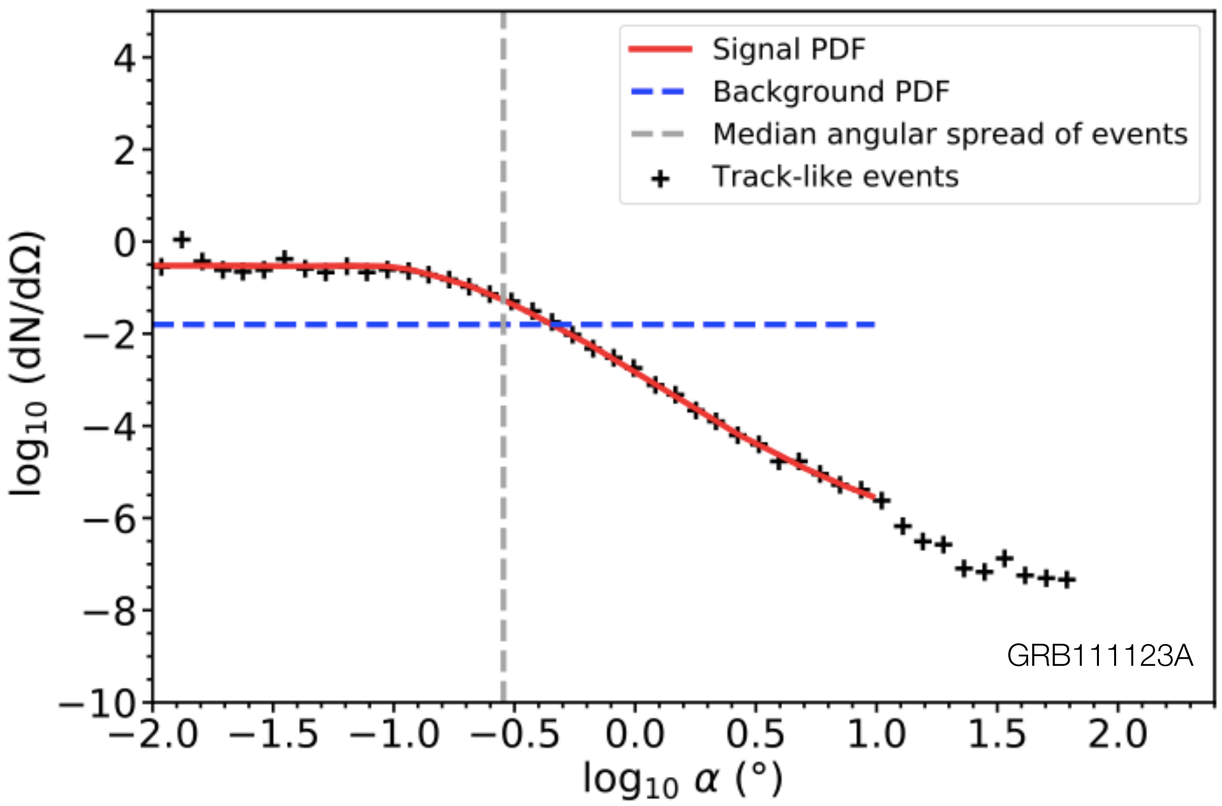
Total Model Discovery Potential

$$\mathrm{MDP}^p(\mathrm{N_{GRB}}) = 1 - \prod_{i=1}^{\mathrm{N_{GRB}}} (1 - \boxed{\mathrm{MDP}_i^p})$$

MDP of the single GRB at a given TF

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Signal and background Probability Density Functions

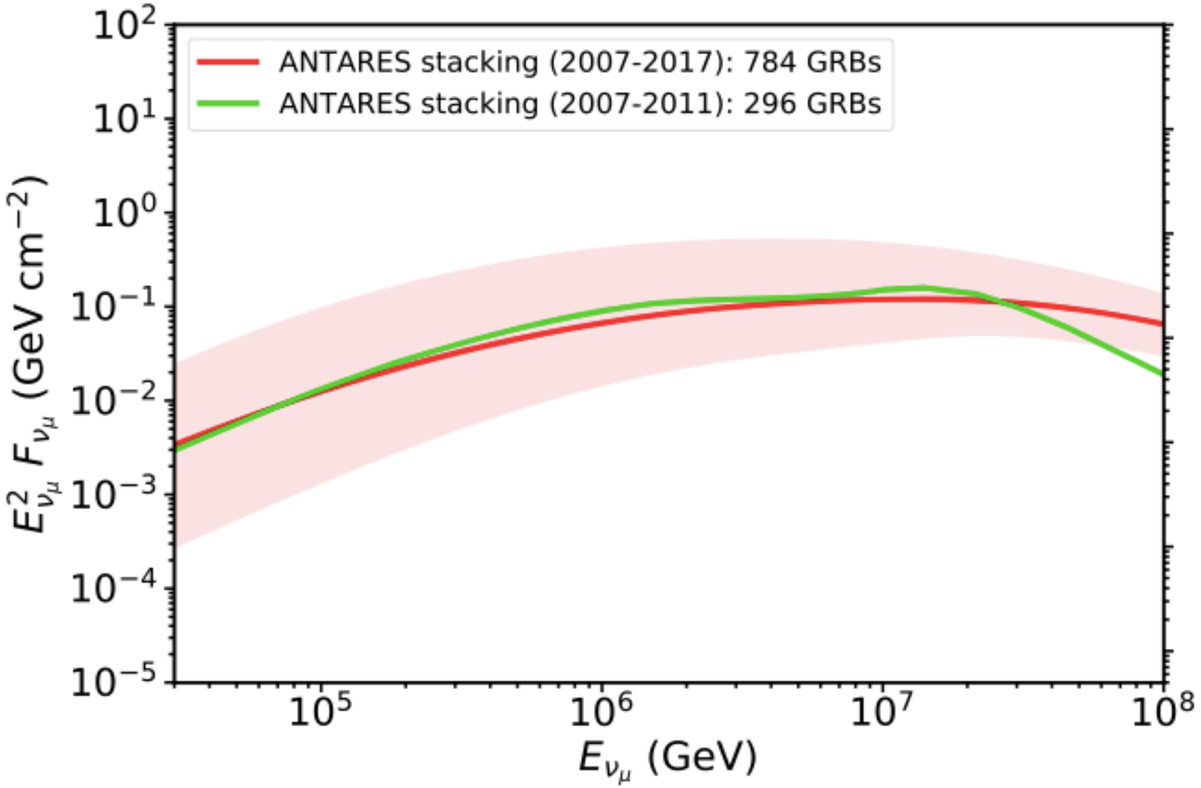


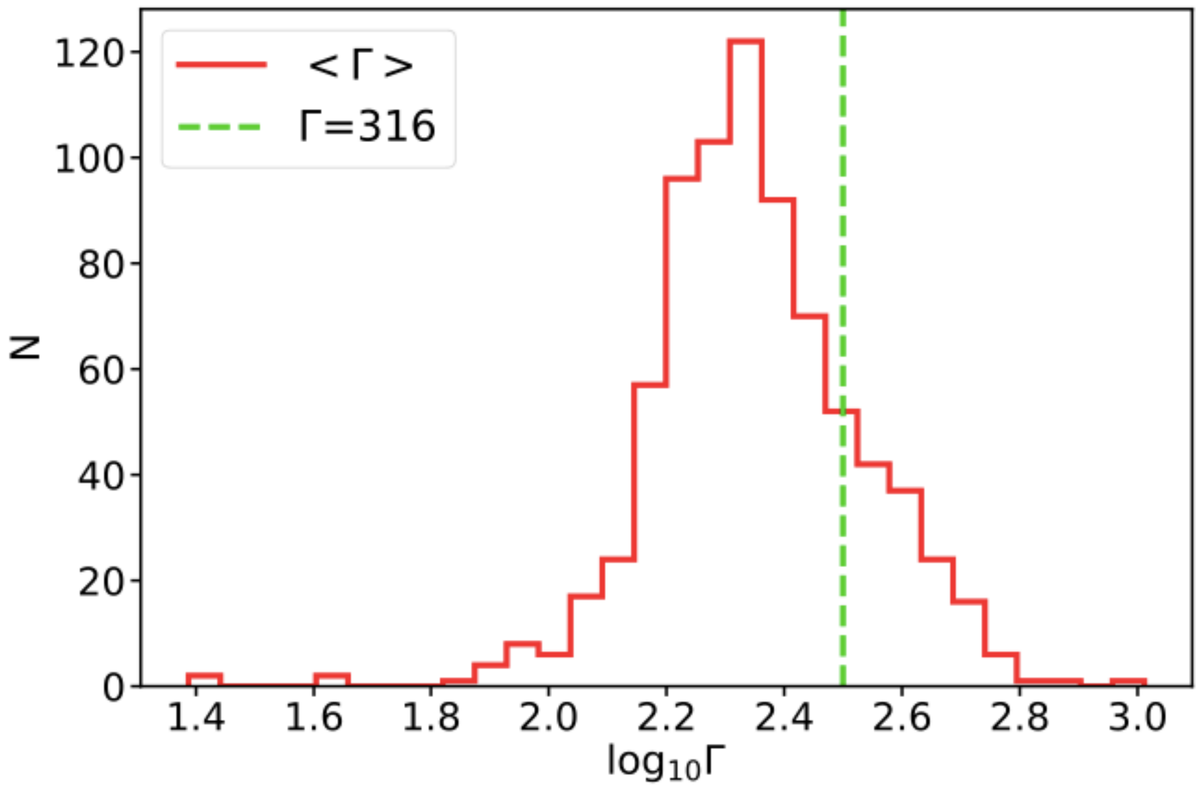
GRB111123A: reconstructed events from the MC signal simulation, per solid angle Ω as a function of the logarithm of the space angle α, obtained with tracks from ν_μ CC interactions and tracks from ν_μ NC and ν_e NC + CC interactions (all neutrino channels are shown in black), with $\beta < 1°$ and $\Lambda_{cut} = -5.2$. The vertical dashed line (in grey) indicates the median angular spread of events $\langle\alpha\rangle = 0.29°$; the horizontal dashed line (in blue) shows the flat background PDF $B(\alpha)$. The red curve is the signal Point Spread Function (PSF), inside the defined angular window, 10°, around the GRB position.

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Comparison with the previous ANTARES stacking GRB analysis

Adrián-Martínez S. et al. (ANTARES Collaboration), 2013, A&A 559A

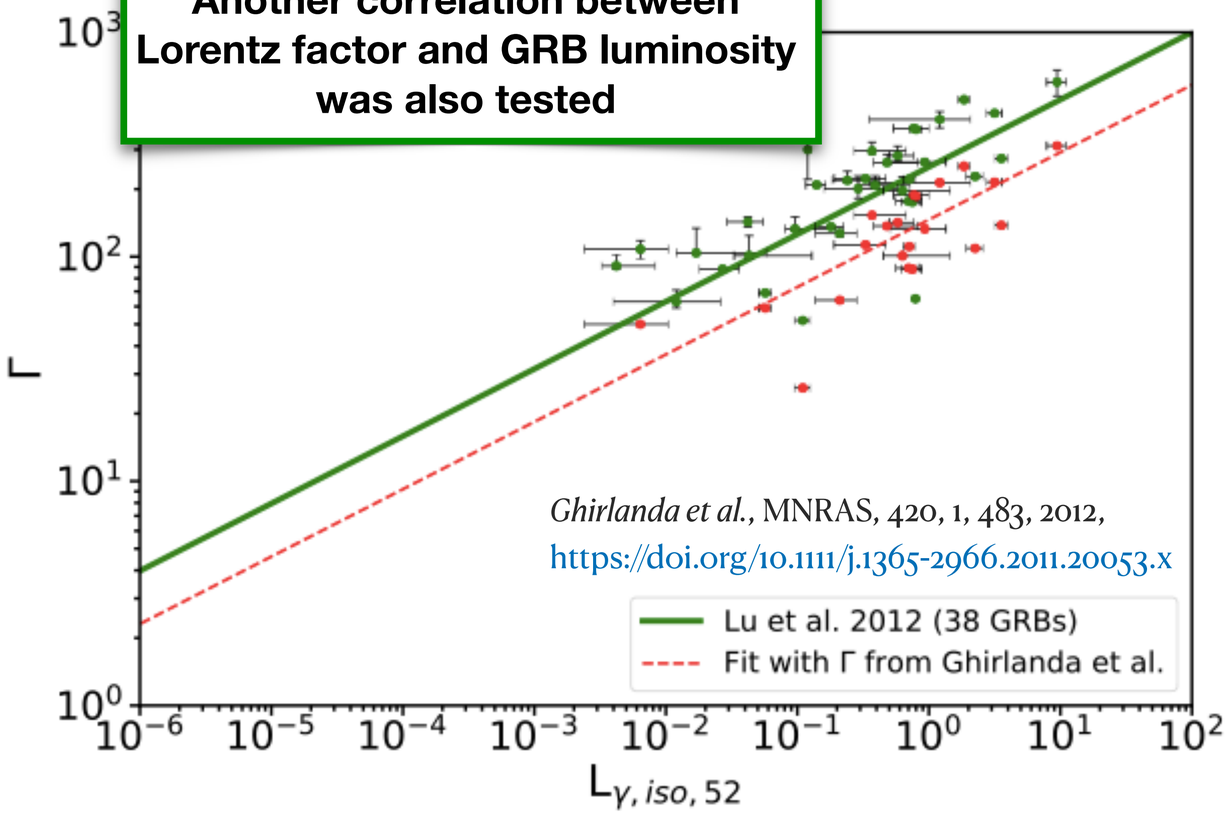




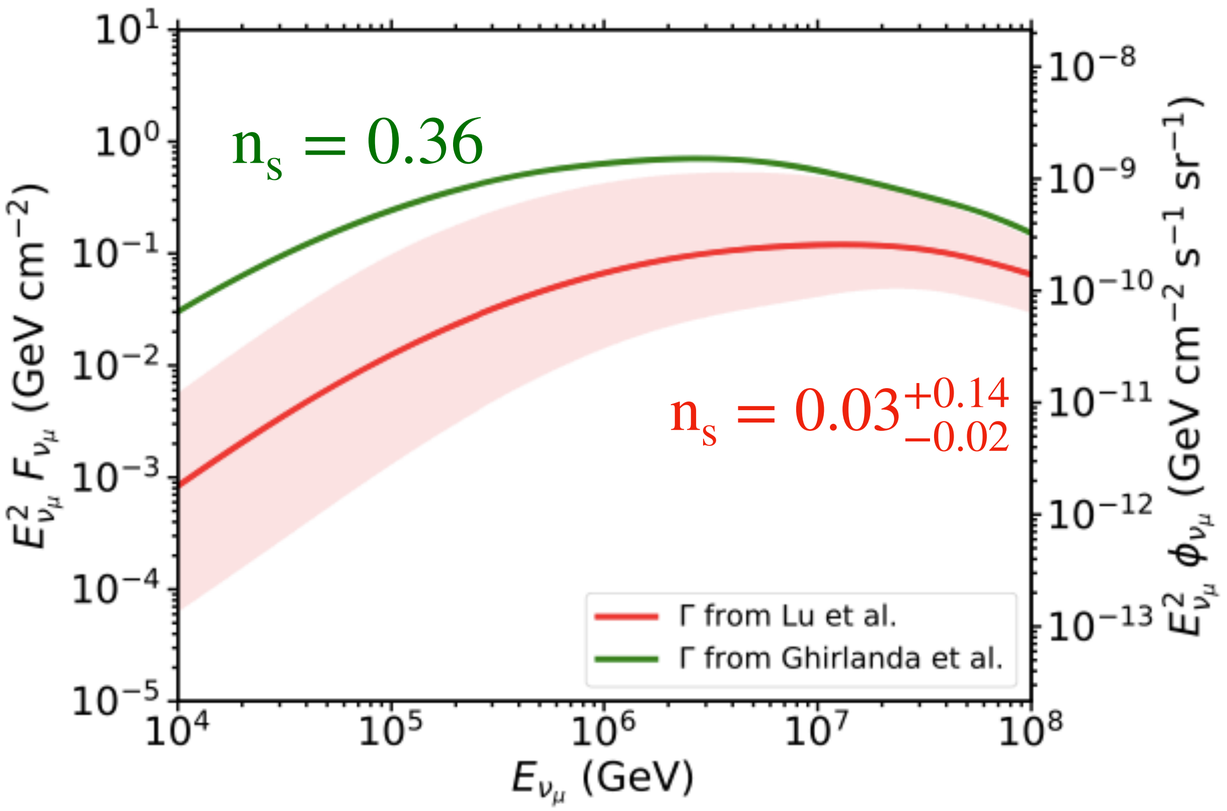
ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Systematics on treatment of Lorentz Factor Γ

Another correlation between Lorentz factor and GRB luminosity was also tested



Ghirlanda et al., MNRAS, 420, 1, 483, 2012, https://doi.org/10.1111/j.1365-2966.2011.20053.x



- By using the Ghirlanda et al. 2012 method to estimate Γ, **the stacking neutrino fluence would increase at lower energies;**
- The new analysis optimization results into an **expected number of neutrino events increased by a factor ~ 10.**

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

Search for high-energy νs from (sub-)TeV GRBs with ANTARES

	GRB 180720B	GRB 190114C	GRB 190829A
$\delta t_{\rm up}$	$[T_0-350$ s, $T_0+7.6$ h$]$	—	$[T_0-350$ s, $T_0+2.85$ h$]$
$\phi_0^{90\%}{}_{\rm up}$ (GeV·cm^{-2})	$\lesssim 1.5$	—	$\lesssim 1.4$
$\delta t_{\rm down}$	$[T_0+7.6$ h, $T_0+12.1$ h$]$	$[T_0-350$ s, T_0+2454 s$]$	$[T_0+2.85$ h, $T_0+8.1$ h$]$
$\phi_0^{90\%}{}_{\rm down}$ (GeV·cm^{-2})	$\lesssim 10$	$\lesssim 1.6$	$\lesssim 4$
$E^{\rm up}_{5-95\%}$	2.5 TeV – 4.0 PeV	—	2.5 TeV – 4.0 PeV
$E^{90\%}_{\nu,\rm iso}$ upgoing (erg)	$\lesssim 2\times10^{55}$	—	$\lesssim 2\times10^{53}$
$(\frac{f_\pi}{f_e})_{\rm up}$	$\lesssim 80$	—	$\lesssim 5\times10^4 - \lesssim 3\times10^3$
$E^{\rm down}_{5-95\%}$	20 TeV – 30 PeV	7 TeV – 20 PeV	15 TeV – 25 PeV
$E^{90\%}_{\nu,\rm iso}$ downgoing (erg)	$\lesssim 1\times10^{56}$	$\lesssim 8\times10^{54}$	$\lesssim 7\times10^{53}$
$(\frac{f_\pi}{f_e})_{\rm down}$	$\lesssim 600$	$\lesssim 2\times10^3$	$\lesssim 2\times10^5 - \lesssim 1\times10^4$
$E_{\gamma,\rm iso}$ (erg)	6×10^{53} [50; 300 keV]	2.5×10^{53} [1 keV; 10 MeV] 2×10^{52} [300 GeV; 1 TeV]	3×10^{50} [1 keV; 10 MeV] 2×10^{50} [50 keV; 300 keV]

Table 4. Upper limits on the neutrino spectral fluence, the total energy emitted in neutrinos within the 5–95% energy range of the analysis, and the fraction of energy going to pions to that going to electrons, f_π/f_e. Results are presented for the three GRB searches, separately for upgoing and downgoing events. The hyphen indicates that the corresponding GRB was not seen as upgoing during the gamma-ray emission. The systematic uncertainties on $\phi_0^{90\%}$ are reported in section 3. The last row shows the isotropic photon energy measured, $E_{\gamma,\rm iso}$. For event GRB 190829A, two $E_{\gamma,\rm iso}$ values in different energy ranges are considered to evaluate the f_π/f_e limits.

$$E_{\nu,\rm iso} = \frac{4\pi D_L(z)^2}{1+z}\int_{E^{5\%}}^{E^{95\%}} E_\nu^{-2}\phi_0^{90\%}E_\nu dE_\nu.$$

$$F_\nu = \frac{1}{12}\frac{f_\pi}{f_e}\frac{F_\gamma}{\ln(E_{\rm max,e}/E_{\rm min,e})},$$

$$\frac{f_\pi}{f_e} = 12\frac{1}{2}\ln\left(\frac{E_{\rm max,\gamma}}{E_{\rm min,\gamma}}\right)\frac{E_{\rm iso,\nu}}{E_{\rm iso,\gamma}}\frac{\ln(E_{\rm max,\gamma}/E_{\rm min,\gamma})}{\ln(E_{\rm max,\nu}/E_{\rm min,\nu})},$$

ANTARES Collaboration, JCAP(2021)092

Neutrino telescopes in the Mediterranean: science

KM3NeT-ORCA

KM3NeT-ARCA

ANTARES

Low-energy (MeV scale)

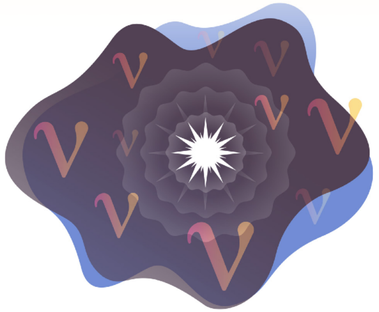
High-energy (PeV scale)

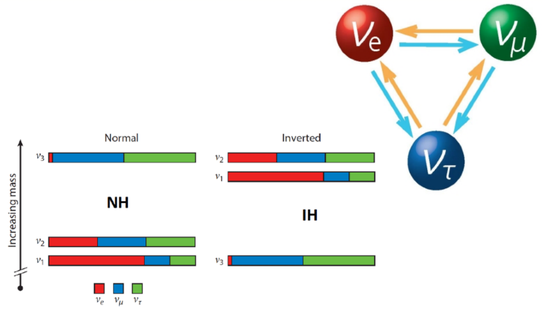
GeV

TeV

Supernova neutrinos

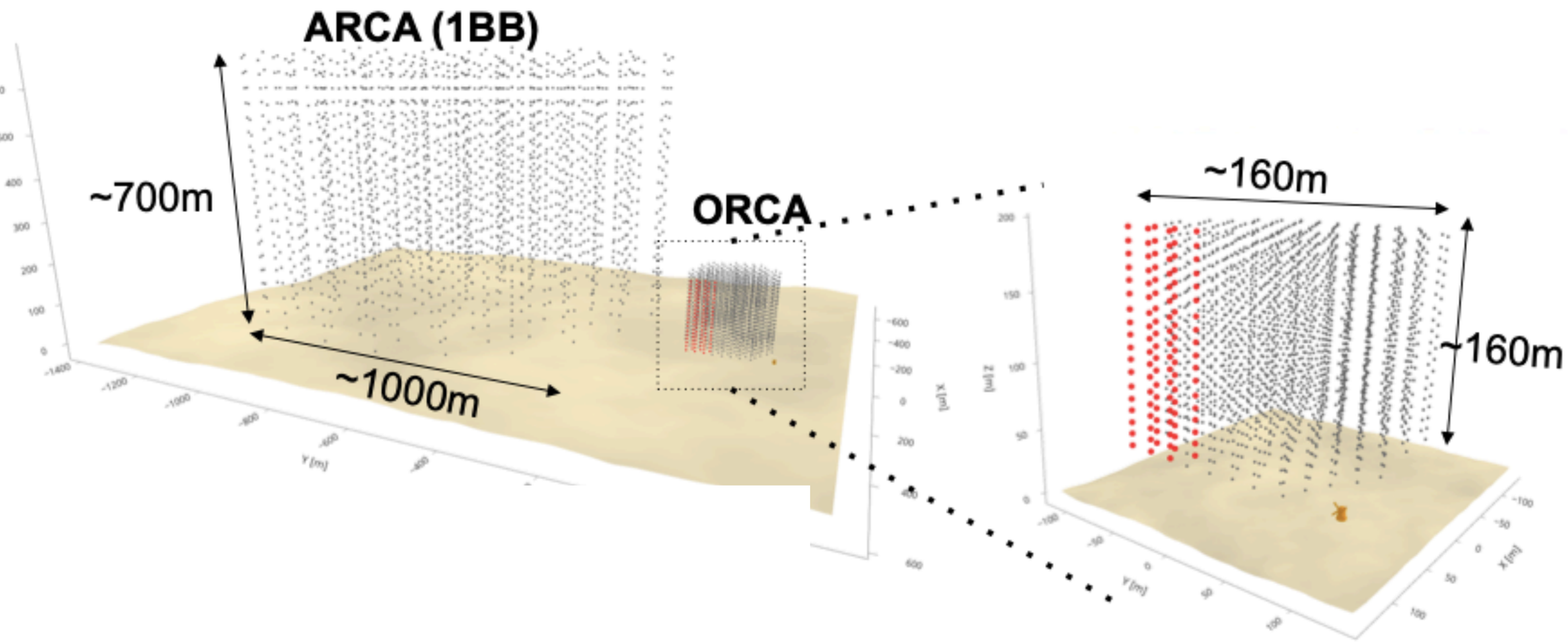
Neutrino mass hierarchy
Neutrino oscillations

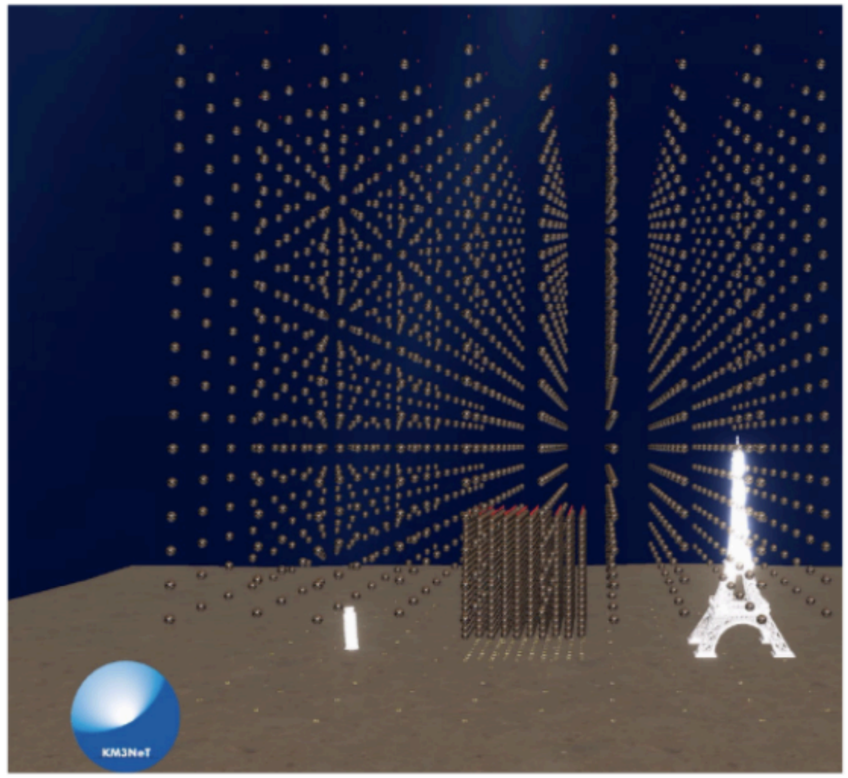




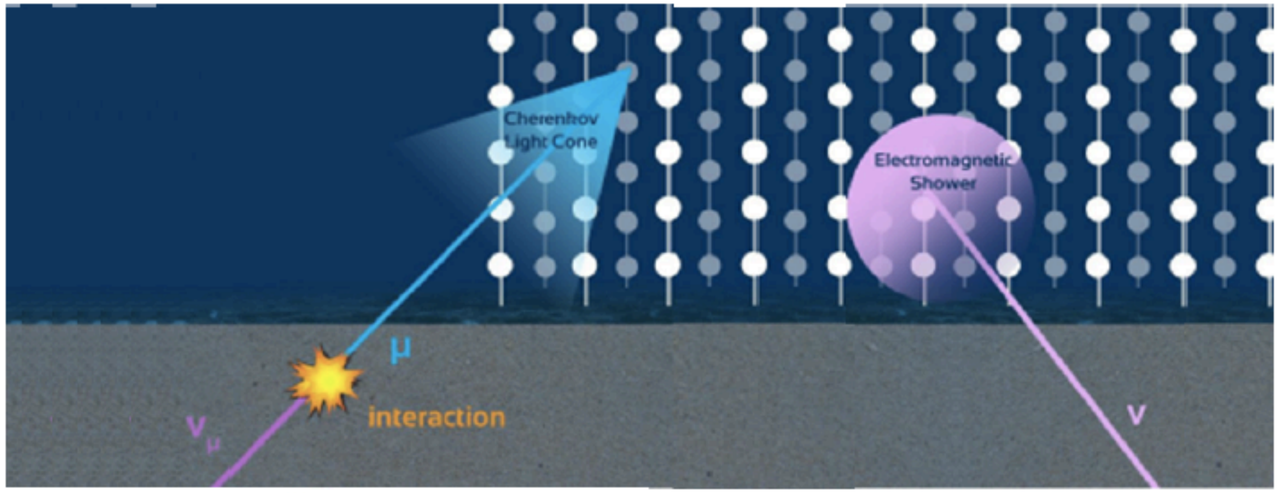
High-energy neutrinos
Neutrino astronomy

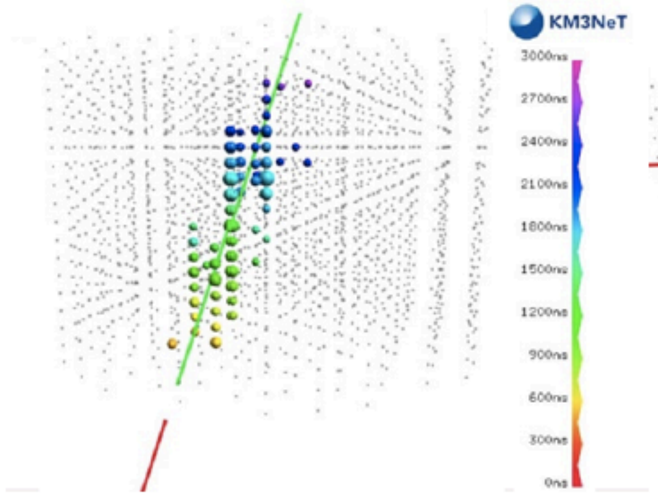
KM3NeT neutrino telescope

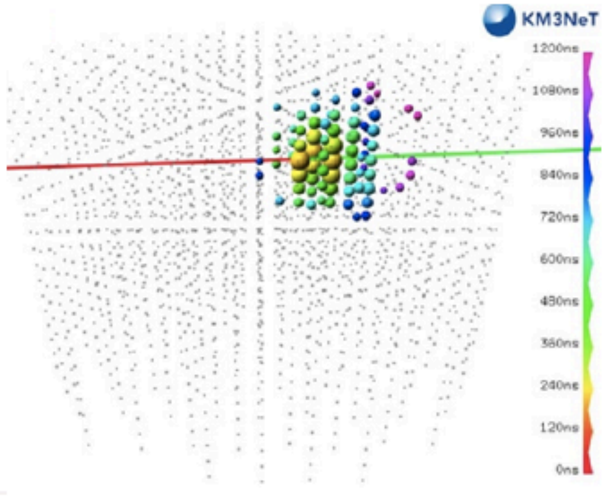


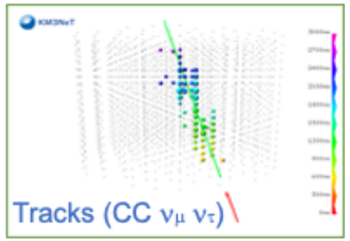


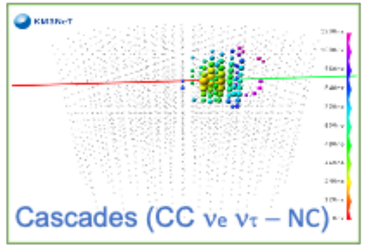
Event topologies and angular resolution



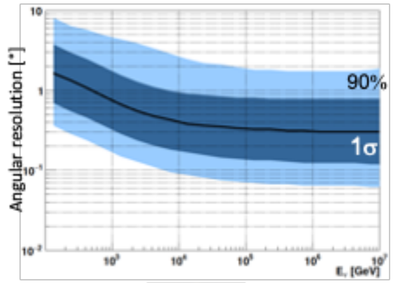




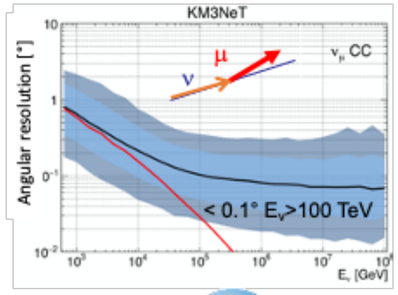


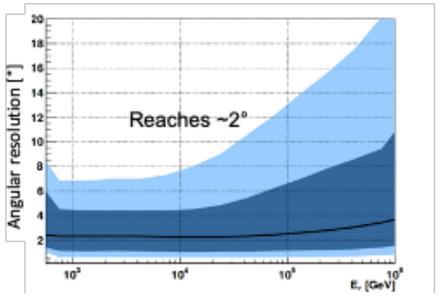


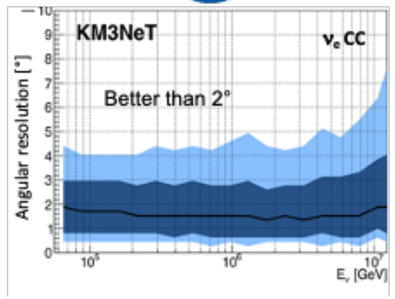
ANTARES

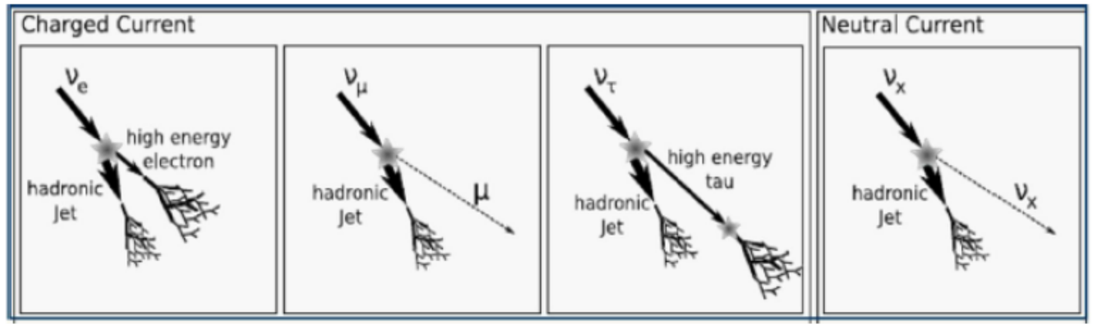


KM3NeT

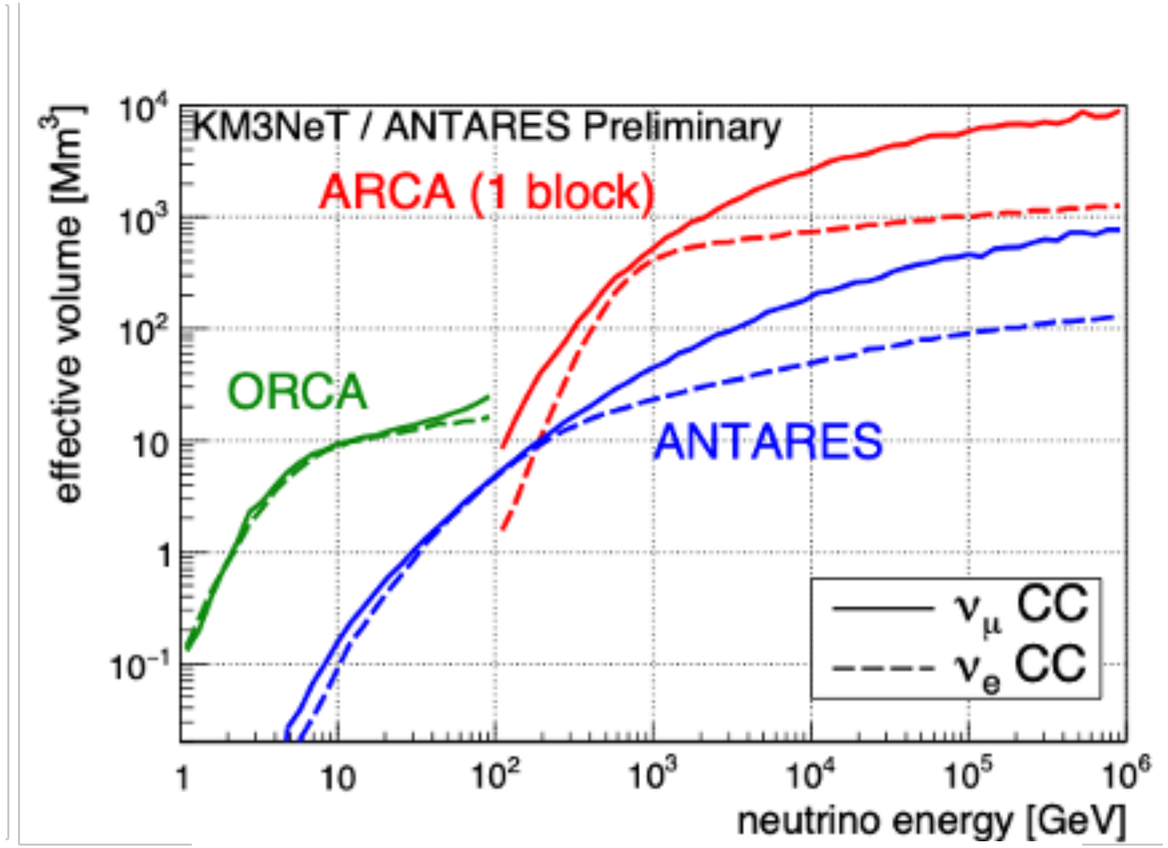






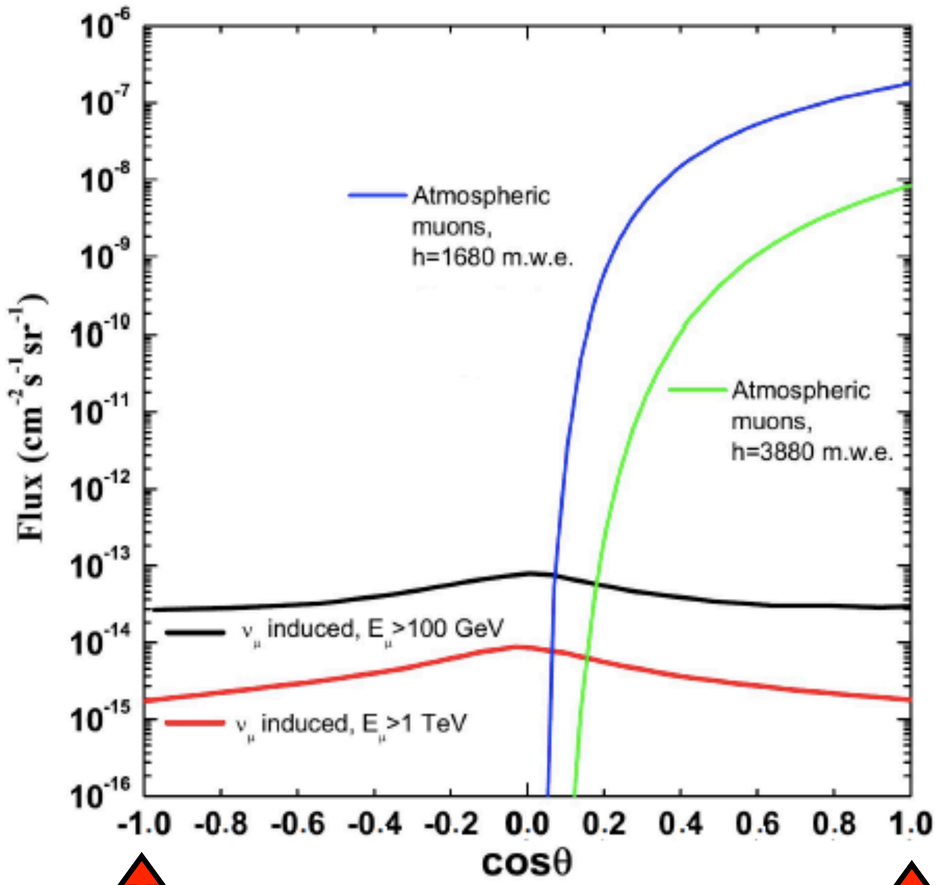


KM3NeT/ANTARES effective volumes comparison

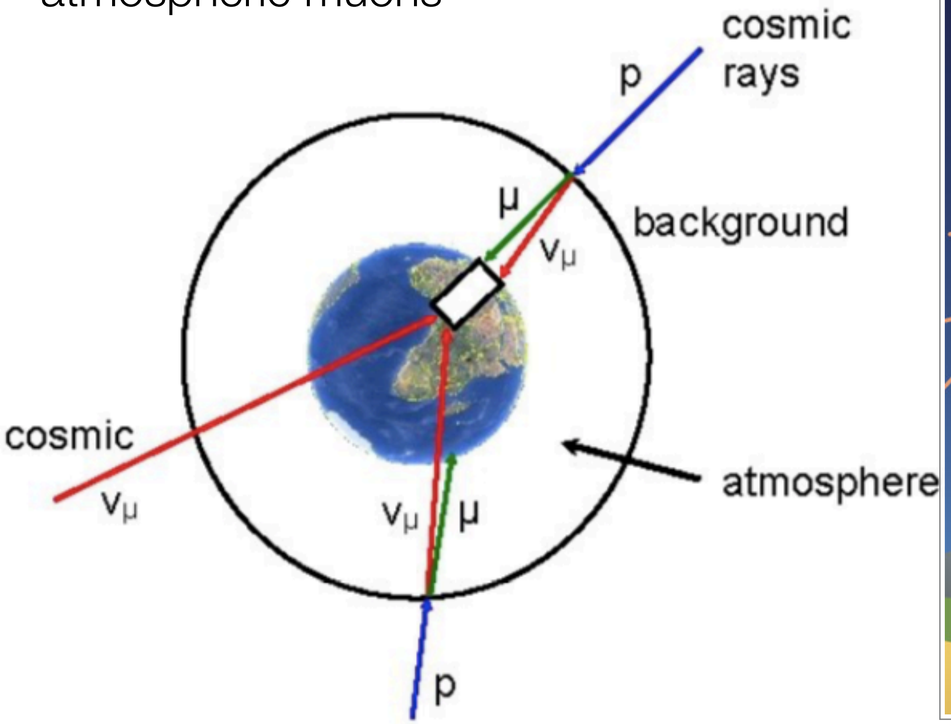


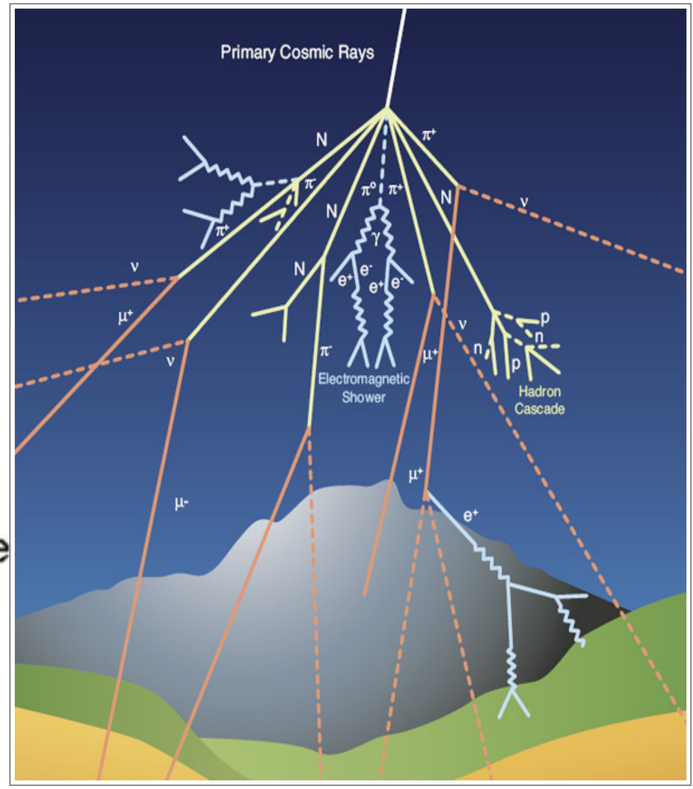
$$A_{eff}(E) = \sigma_{\nu_\mu^{CC}}(E)\rho N_A V_{eff}(E)$$

Background in neutrino detectors



The flux from above is dominated by atmospheric muons





Horizontal events

Up-going

Down-going

Neutrino telescopes are mainly sensitive to neutrinos from below