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Lorentz-Invariance Violation with neutrinos and gamma-ray bursts

TeVPA 2026

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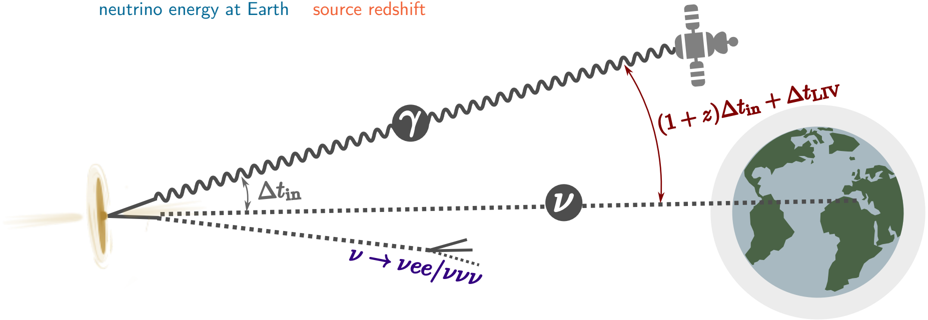
ANTARES results on behalf of the ANTARES collaboration

Credit (original picture): Soheb Mandhai

- Lorentz Invariance Violation (LIV) may arise from **deviations from Special Relativity**.
- If present in the neutrino sector, LIV would **affect astrophysical neutrino propagation**.
- Assuming first order LIV correction and LIV scale $\Lambda_{\rm LIV} = M_P/\eta$ [1]:

$$\frac{v_\nu}{c} = 1 \mp \eta \frac{E_\nu}{M_P} \rightarrow \begin{cases} \Delta t_{\rm LIV}(E_\nu, z_{\rm src}, \eta) \approx \pm 1\,\text{h} \times \frac{E_\nu}{100\,\text{TeV}} \times \eta \times J(z_{\rm src}, 1) & \left(J(z,u) = \int_0^z \frac{\mathrm{d}\zeta (1+\zeta)^u}{\sqrt{\Omega_m (1+\zeta)^3 + \Omega_\Lambda}} \right) \\ \mathcal{P}_{\rm surv}(E_\nu, z_{\rm src}, \eta) = \exp\left[-C \left(\frac{E_\nu}{E_{\rm eff}(\eta)} \right)^8 J(z_{\rm src}, 7) \right] & \text{for superluminal neutrinos} \end{cases}$$

neutrino energy at Earth — source redshift



Using gamma-ray bursts as probe of LIV

- Gamma-ray bursts (GRBs) are candidate neutrino emitters.
- The expected intrinsic time delay at the source Δt_{in} is small: $-350 < \Delta t_{\mathrm{in}} < +150\,\mathrm{s}$.
- All searches for a prompt neutrino signal (time window of a few minutes) from GRBs may be unsuccessful due to the presence of LIV shifting the neutrino signal.

Search for neutrino–GRB coincidences using both **energy-spatial** and **temporal** (delay) information.

Past studies

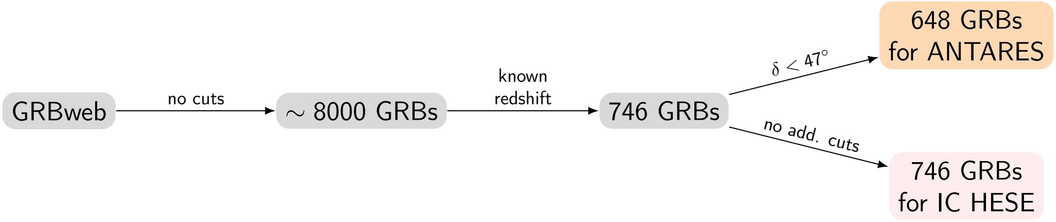
- Several studies using IceCube High-Energy Starting Events (HESE) and GRB catalogues report hints for LIV with $\eta \sim 20$ [2,3], but have limited treatment of instrumental response functions.
- Previous ANTARES search (5-yr dataset) [4] found no significant excess.

This study

1. Define catalogue of GRB with known redshift and list of neutrino candidates.
2. Compute test statistic to compare $H_{\text{no LIV}}$ and H_{LIV} hypotheses.
3. Repeat analysis with ANTARES dataset (internal) and with IceCube HESE 12-yr public dataset.

GRB inputs and modeling

- We use GRB catalogue from GRBweb [5].
- Final catalog is reduced to all GRBs with known redshift and crossing the visible sky for the chosen neutrino dataset (ANTARES = upgoing, HESE = full-sky).

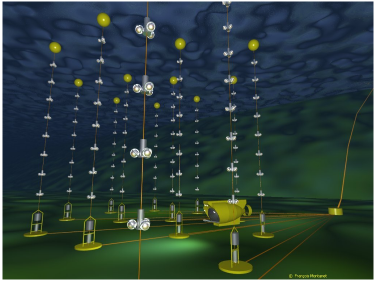


- No specific modeling is assumed for neutrino emission from GRBs:
  - All GRBs are attributed equal weight in the study.
  - We assume E^{-2} spectrum for the neutrinos.

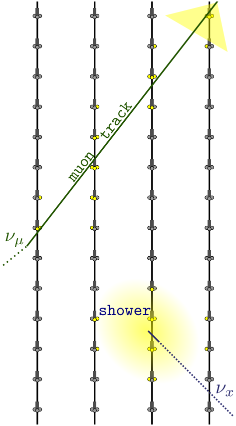
$\Rightarrow$ The analysis is **not equivalent** to a dedicated study of GRB neutrino emission processes.

Cherenkov light induced by charged particles from ν interactions ($\nu_\mu + N \to \mu^- + X$, $\nu_x + N \to \text{shower} + X$).

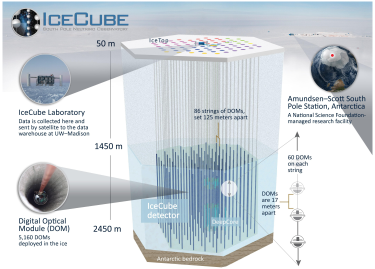
ANTARES



- In the depths of Mediterranean Sea.
- 12 lines in operation in 2007–2022.



IceCube



- Located at the South Pole.
- 86 strings spanning 1 km^3 of ice.

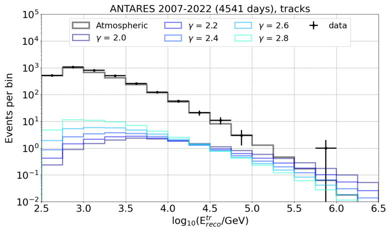
Additionally, KM3NeT, the successor of ANTARES, is under construction but already taking data with 51 out of about 200 lines (ARCA site). LIV-GRB analysis not performed yet.

[8] JCAP 08 (2024) 038
[9] IceCube HESE 12-year data release
[10] PRD 104, 022002

ANTARES data samples

- Full ANTARES dataset: 2007–2022
- Event selection used in diffuse flux analysis [8]
- Information used:
  - *data:* time, reco energy, RA, Dec
  - background IRFS: data-driven
  - signal IRFs: derived from MC simulations

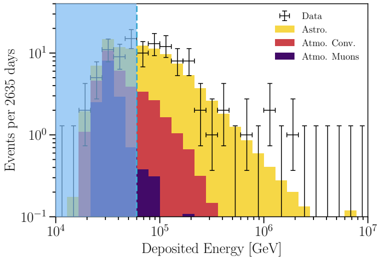
3392 tracks + 187 showers



IceCube HESE public dataset

- 12-yr dataset: 2010–2022 [9,10]
- Information used:
  - *data:* time, reco energy, RA, Dec
  - angular error as Fisher-Bingham parameters
  - energy error: 30% (11%) for tracks (showers)

55 tracks + 109 showers



Statistical test

fraction of events from GRBs in data

$1/N_{\rm GRBs}$

GRB weighting

$[B_{\rm time}(t_i) \times B_{\rm ang}(\mathrm{dir}_i) \times B_{\rm ene}(E_{\rm rec,i})]$

background term

$$\mathcal{L}(f_{\rm sig}, \eta; \mathrm{data}) = \prod_i \left[f_{\rm sig} \times \sum_g w_g \times S_{i,g} + (1 - f_{\rm sig}) \times B_i \right]$$

LIV scale

signal term

$[S_{\rm time}(t_i; \eta, t_g, z_g, E_{\rm rec,i}) \times S_{\rm ang}(\mathrm{dir}_i; \mathrm{dir}_g, E_{\rm rec,i}) \times S_{\rm ene}(E_{\rm rec,i})]$

We compare the signal+LIV hypothesis $f_{\rm sig} > 0, \eta > 0$ with the no-neutrino hypothesis ($f_{\rm sig} = 0$):

$$TS = 2 \times \left[\log \mathcal{L}(\hat{f}_{\rm sig}, \hat{\eta}) - \log \mathcal{L}(f_{\rm sig} = 0, \eta = 0) \right]$$

values maximising the likelihood

- TS background distribution estimated from scrambled data. The TS from real data can be compared to this background distribution to get a p-value.
- $\mathcal{L}$ can be used to derive best-fit values in data and confidence intervals (using Wilks' theorem).

Signal time PDF

$$\Delta t \equiv t_\nu - t_g = (1+z)\Delta t_{\text{in}} \pm \eta \times E_\nu \times f(z) \qquad \left(f(z) = J(z,1) \times \frac{1\,\text{h}}{100\,\text{TeV}} \right)$$

Several ingredients:

- Takes into account unknown **intrinsic delay** ($(t_\nu - t_g)_{\text{source}} \in [-350, +150]\,\text{s}$).
- Effect of detector **energy resolution**.
- **Survival probability** of superluminal neutrinos.
- For the ANTARES study: **Selection efficiency** varies with time (visibility + detector performance).
- **Normalisation** computed with Monte Carlo integration (ensuring $\int \frac{\mathrm{d}P}{\mathrm{d}t_\nu}\mathrm{d}t_\nu = 1$).

normalisation term

assumed uniform between $\tau_- = -350\,\text{s}$ and $\tau_+ = 150\,\text{s}$

$$\frac{\mathrm{d}P}{\mathrm{d}t_\nu} = C \times \varepsilon(t_\nu, \Omega_g) \int \frac{\mathrm{d}P}{\mathrm{d}\Delta t_{\text{in}}}(\Delta t_{\text{in}}) \frac{\mathrm{d}P}{\mathrm{d}E_\nu}\left(E_\nu(\Delta t, \Delta t_{\text{in}}, z)\right) \mathcal{P}_{\text{surv}}(E_\nu(\Delta t, \Delta t_{\text{in}}, z), \eta, z)\, \mathrm{d}\Delta t_{\text{in}}$$

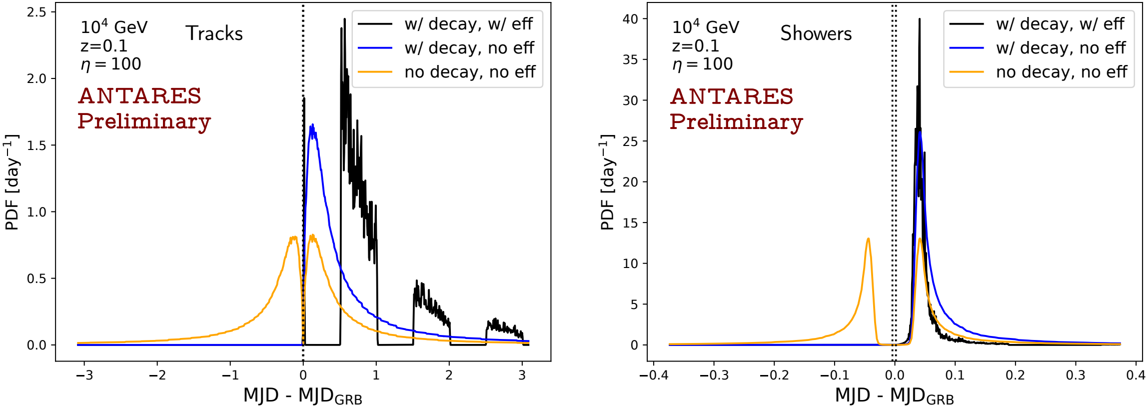
signal efficiency

energy resolution

decay of superluminal component

$$= \frac{1}{\eta f(z)} |\Delta t - (1+z)\Delta t_{\text{in}}|$$

Illustration of signal time PDF

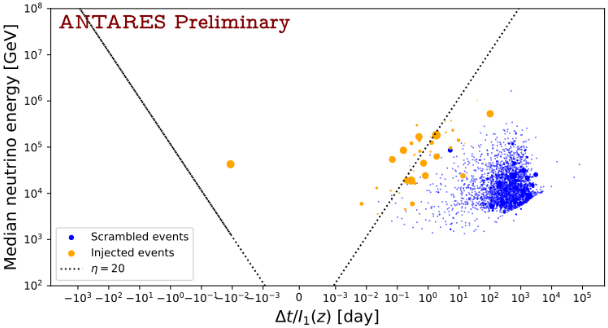


*Signal time PDF distribution for tracks (left) and showers (right). In **orange**: assuming $P_{\rm surv} = 1$ (no decay) and $\varepsilon = 1$ (no efficiency variation). In **blue**: assuming $\varepsilon = 1$. In **black**: including all effects.*

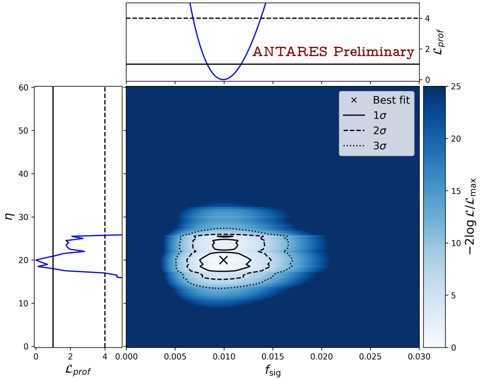
Better energy resolution for showers reflects into a more peaked time PDF.

Tests with signal injection for ANTARES

Example injection with $\eta = 100$ and $f_{\mathrm{sig}} = 10^{-2}$ in the ANTARES dataset.



Time delay vs median neutrino energy estimate for all events in the simulated dataset. The size of markers indicates the value of the signal angular PDF term.

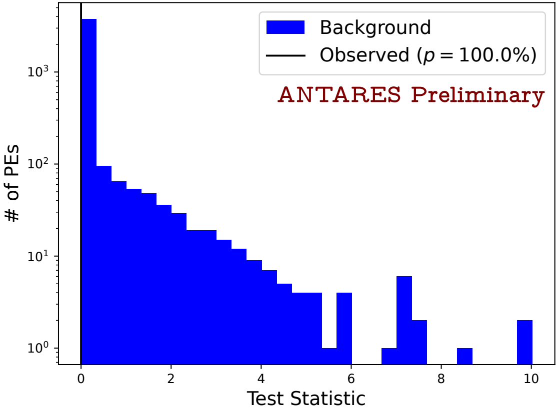


Likelihood distribution and corresponding $1-2-3\sigma$ contours assuming Wilks' theorem.

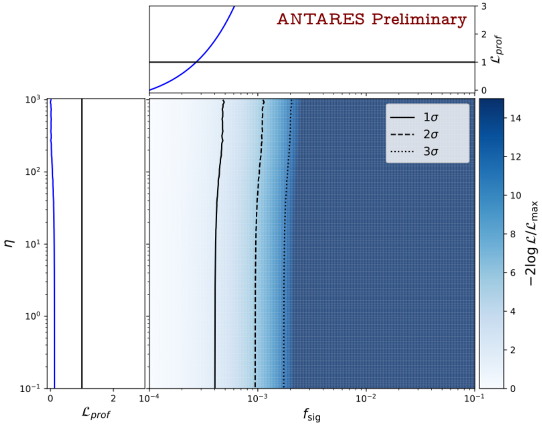
Results with ANTARES

No excess observed: $\hat{f}_{\text{sig}} = 0,\ \hat{\eta} = 0,$ p-value $= 100\%$.

Background TS distribution

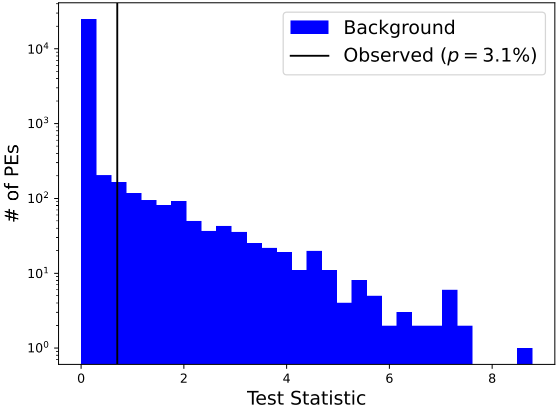


Likelihood contour

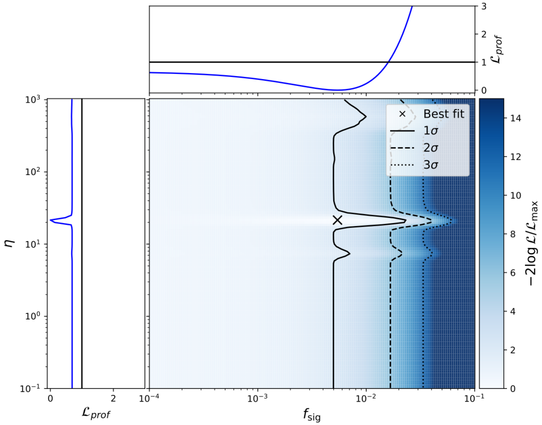


Best-fit point with real data: $\hat{f}_{\text{sig}} = 6.1 \times 10^{-3}$, $\hat{\eta} = 21.0$, p-value $= 3.1\%$.

Background TS distribution



Likelihood contour

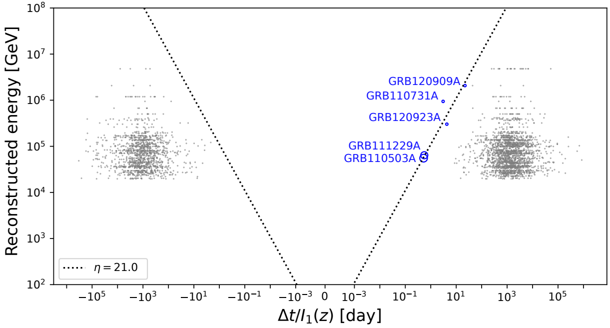


Results with IceCube (2)

[2] JCAP 02 (2026) 035

Top associations:

#	Associated GRB	E_{rec} [TeV]	Δt [d]	$\Delta t_{\mathrm{LIV}}^{\eta=21}$ [d]
1	GRB110503A	55	0.93	0.89
2	GRB111229A	64	0.85	0.89
3	GRB120909A	2075	86	73
4	GRB120923A	302	28	18
5	GRB110731A	943	9	25

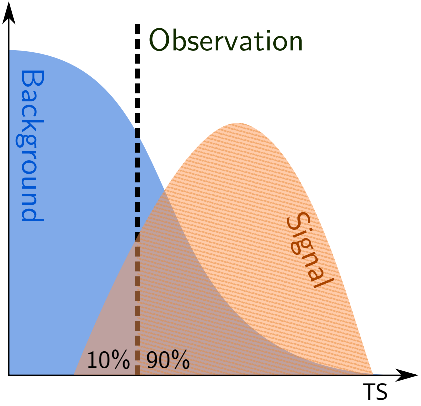


Best-fit point consistent with [2], but different significance.

Results	η	p
[2]	21.7	0.006
This study	21.0	0.031

Cannot compare values of $f_{\rm sig}$ for IceCube (IC) and ANTARES (A), as the samples have different sizes and compositions, and they do no probe the same GRB population.

- IceCube best fit is $\hat{f}_{\rm sig,IC} = 6.1 \times 10^{-3}$, $\hat{\eta} = 21.0$
- For $\eta = 21.0$, we can derive upper limit on $f_{\rm sig,A}$ based on the observed TS: $f_{\rm sig,A} < 9.2 \times 10^{-4}$ at 90% C.L.
- Constraints on $f_{\rm sig,\{A,I\}}$ can be converted to ones on the total per-flavour $\nu + \bar{\nu}$ flux from gamma-ray bursts.
- Assuming E^{-2} and for $\eta = 21.0$, we get:
  - IceCube: $E^2 \mathrm{d}N/\mathrm{d}E = 0.2\,\mathrm{GeV\,cm^{-2}}$ (per-GRB: 3×10^{-4})
  - ANTARES: $E^2 \mathrm{d}N/\mathrm{d}E < 5.3\,\mathrm{GeV\,cm^{-2}}$ (per-GRB: 8×10^{-3})



Outlook and plans

- LIV may be detected through **time delays** between neutrinos and **gamma-ray bursts**.
- **Analysis ingredients:**
  - GRB with known redshifts from GRBweb $\rightarrow$ 648 (746) sources for the ANTARES (IceCube) analysis.
  - ANTARES (IceCube) neutrino list with tracks+showers: 3.6k (164) events.
  - Unbinned likelihood approach with specific time PDF accounting for LIV time delay.
- **Results:**
  - ANTARES: $\boxed{\text{no excess observed}}$
  - IceCube: $\boxed{1.9\sigma \text{ excess at } \eta = 21}$ (consistent with Amelino-Camelia et al)

  $\rightarrow$ Intriguing but not yet at discovery level
- **Outlooks:**
  - Analyses with additional data (KM3NeT, other IceCube datasets).
  - Joint analyses between different detectors.
  - Incorporating more detailed astrophysical priors (e.g., GRB modeling).

Amelino-Camelia 2025
IC-HESE 12yr — $\eta = 21.7$, 2.5σ

This work
IC-HESE 12yr — $\eta = 21.0$, excess of 1.9σ

This work
ANTARES 15yr — $f_{\rm sig} < 9.2 \times 10^{-4}$ for $\eta = 21$

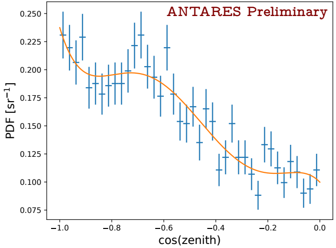
Future studies
- Other IceCube datasets
- KM3NeT data
- Combined analyses

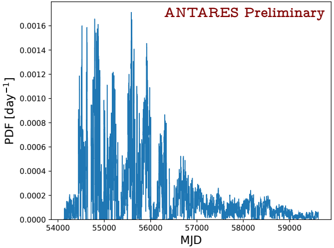
Supplementary slides

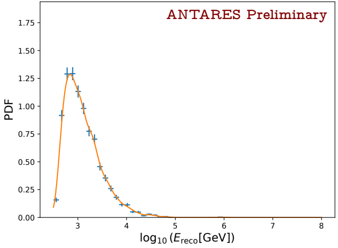
ANTARES – Background PDFs from data

Zenith | Time (MJD) | Reco energy

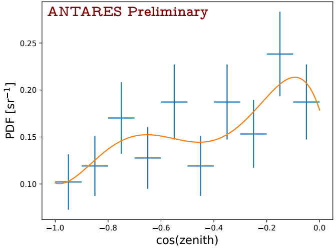
Tracks

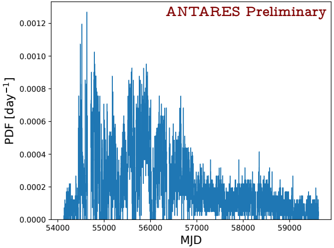


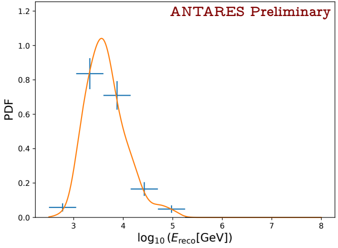




Showers



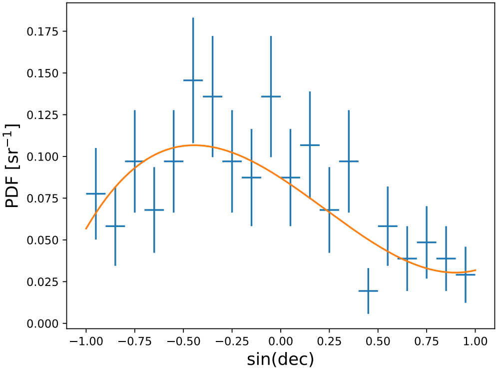




IceCube – Background PDFs

Given the limited statistics and the absence of public MC simulations

- **Declination PDF:** extracted from data, summing over tracks and showers.
- **Time PDF:** assumed to be uniform between min(MJD) and max(MJD).
- **Reconstructed energy PDF:** not included in the likelihood.



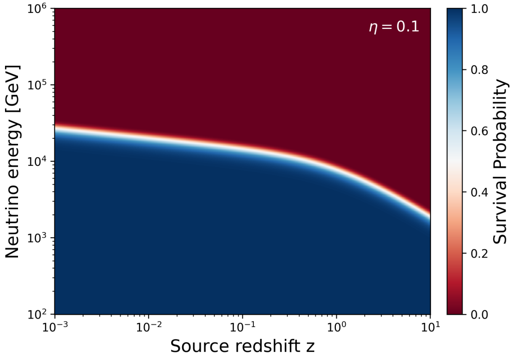
Survival probability

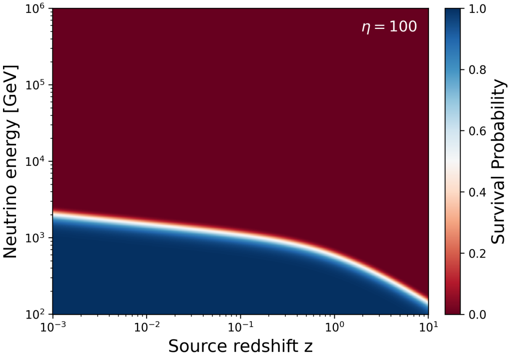
- Total decay width ($\nu_\alpha \to \nu_\alpha + \nu_\beta + \bar{\nu}_\beta$ & $\nu_\alpha \to \nu_\alpha + e^- + e^+$)

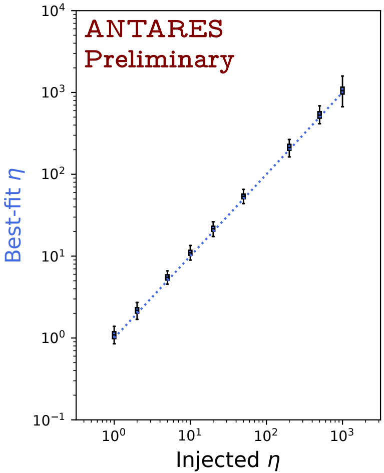
$$\Gamma_\alpha(E) = \left[\kappa_\alpha^{(\mathrm{NSpl})} + \kappa_\alpha^{(\mathrm{VPE})}\theta\left(E - E_{\mathrm{th}}^{(\mathrm{VPE})}\right)\right] \frac{G_F^2}{192\pi^3} E^8 \Lambda^{-3}$$

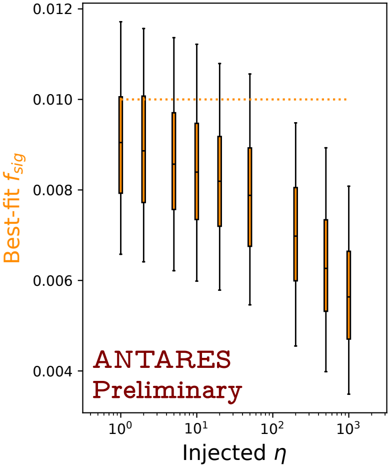
- Survival probability for a given line of sight and final neutrino energy

$$f_{\mathrm{surv}}(E_\nu, z_g) = e^{-\tau(E_\nu, z_g)} \quad \text{where} \quad \tau(E_\nu, z_g) = \int_0^{z_s} dz \frac{\Gamma_\alpha((1+z)E_\nu)}{(1+z)H(z)}$$





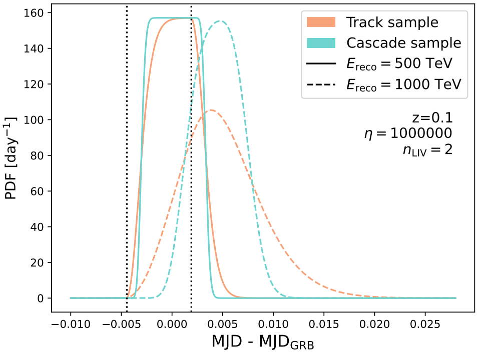


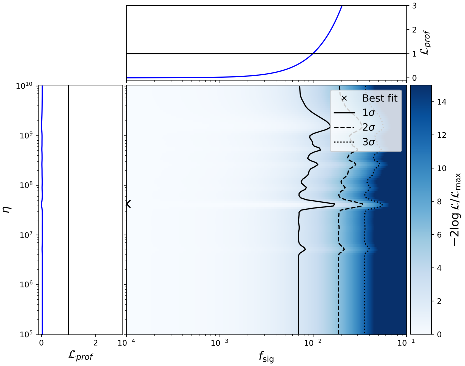


Bias on the fitted values of η *(left) and* f_{sig} *(right) as a function of the injected LIV scale, assuming* $f_{\mathrm{sig}}^{\mathrm{inj}} = 10^{-2}$, *for the ANTARES dataset.*

Results for second-order LIV

- **Time delay:** $\Delta t \equiv t_\nu - t_g = (1+z)\Delta t_{\rm in} \pm (5\,{\rm ns}) \times \eta^2 \times \left(\frac{E_\nu}{1\,{\rm PeV}}\right)^2 \times J(z,2)$
- Both neutrinos and antineutrinos are sub- *or* superluminal $\rightarrow$ consider **subluminal (no decay)**.





No significant excess (p-value: 100%), best fit: $\eta = 0$