Testing in-vacuo dispersion with GRB neutrinos

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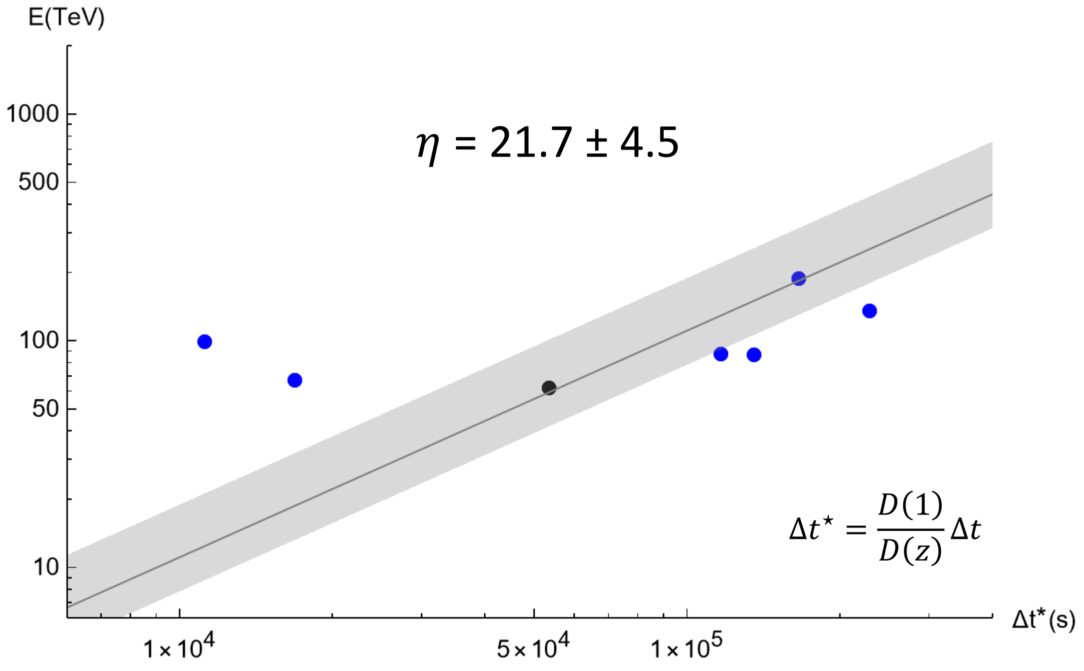
INTRODUCTION

- Theoretical models commonly predict neutrino emission from GRBs, yet after $\sim$15 years IceCube (IC) has reported not a single GRB neutrino:

- an intriguing explanation is that in principle our failure to observe GRB neutrinos could be attributed to some quantum properties of spacetime (in-vacuo dispersion):

- $\Delta t = \eta \frac{E}{M_{Pl}} D(z),$ where $D(z) = \int_0^z dx \frac{1+x}{H_0\sqrt{\Omega_\Lambda + (1+x)^3\Omega_M}}$

INTRODUCTION (2)



Amelino-Camelia et al., Nat. Astro (2017),
Amelino-Camelia et al., Nat. Astro (2023)

- HESE sample (2010-2014) → it is the least contaminated by atmospheric neutrinos.
- Shower events since track events have very poor energy estimates.
- GRBs of known and unknown redshift, roughly estimating the redshift when this is unknown.

IC NEUTRINOS and GRBs OF KNOWN REDSHIFT

- HESE sample (2010-2022).
- We restricted to shower events.
- We restricted to GRBs of known redshift instead of making assumptions to roughly estimate the redshifts as in previous works [*Amelino-Camelia et al., Nat. Astro (2017), Amelino-Camelia et al., Nat. Astro (2023)*].

*Amelino-Camelia, D'Amico, D'Esposito, Fabiano, **DF**, Gubitosi, Guetta, Moia, Rosati, arXiv:2501.13840*

GRB-NEUTRINO CANDIDATES

TEMPORAL COMPATIBILITY

- We take the result of [*Amelino-Camelia et al., Nat. Astro (2023)*], η = 21.7 ± 4.5, as a starting point for our analysis:

- any GRB and neutrino times of arrival are regarded as compatible if they satisfy $\Delta t = \eta \frac{E}{M_{Pl}} D(z)$ for some $\eta \in [12.7, 30.7]$ within two standard deviations in the neutrino energy.

ANGULAR COMPATIBILITY

- Neutrino directional information provided by IC in terms of FB8 distributions (not gaussians).

- $S_{dir} = \int P_\nu(\Omega) P_{GRB}(\Omega) d\Omega$, where $P_\nu(\Omega)$ and $P_{GRB}(\Omega)$ are the angular distributions of the neutrino and the GRB.

- The directions of a GRB-neutrino pair as compatible if the corresponding S_{dir} satisfies $S_{dir} \geq S_{dir}^{cut}$

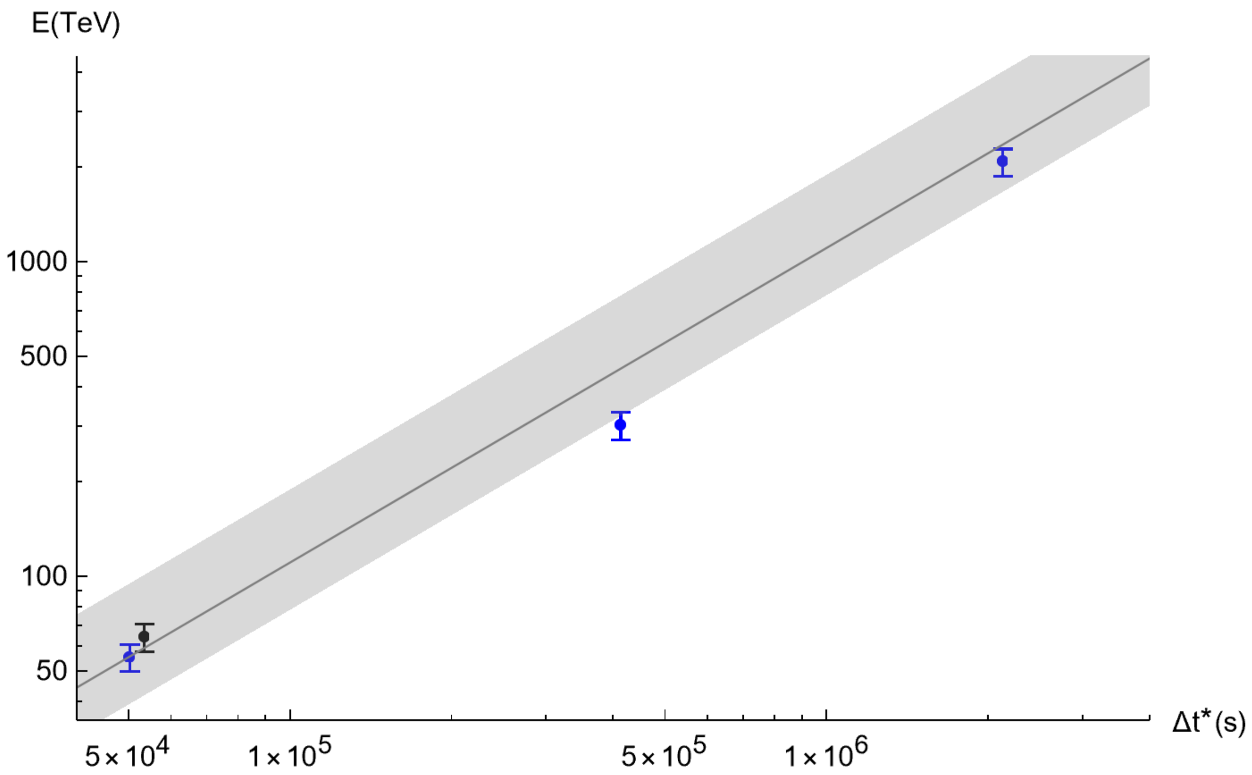
PROPERTIES OF S_{dir}

- S_{dir} can be computed for angular distributions of arbitrary shape.

- Its value increases as the overlap between the two angular distributions increases $\Rightarrow$ it is a good measure of angular compatibility, reflecting how likely it is for two directions to coincide [*Abbott et al. Astrophys. J. Lett. (2017)*] .

- In the main analysis we adopted $S_{dir}^{cut} = \frac{1}{4\pi}$ which is the value taken by S_{dir} whenever one of the distributions is the uniform distribution on the sphere (using simulated data, we checked that this choice for S_{dir}^{cut} entails a 7.8% probability of accidental directional association between a neutrino and a GRB).

MAIN ANALYSIS



- 4 GRB-neutrino candidates with correlation r between $\Delta t^{\star}$and E r =0.9985

- FAP of finding at least 4 GRB-neutrino candidates with correlation greater than 0.9985 is $\mathrm{P_r} = 0.6\% \ (2.8\sigma)$.

THE NEUTRINO EVENT KM3-230213A

- Track event observed by ARCA on 13 February 2023 at 01:16:47 UTC
- Median energy 220 PeV; 110–790 PeV at 68% confidence; 72 PeV–2.6 EeV at 90% confidence
- J2000 coordinates of 230213A are RA = $94.3°$, decl = $-7.8°$ with containment radius R(68%) = $1.5°$

S. Aiello et al. [KM3NeT], Nature 638 (2025)

POSSIBLE ASTROPHYSICAL SOURCES

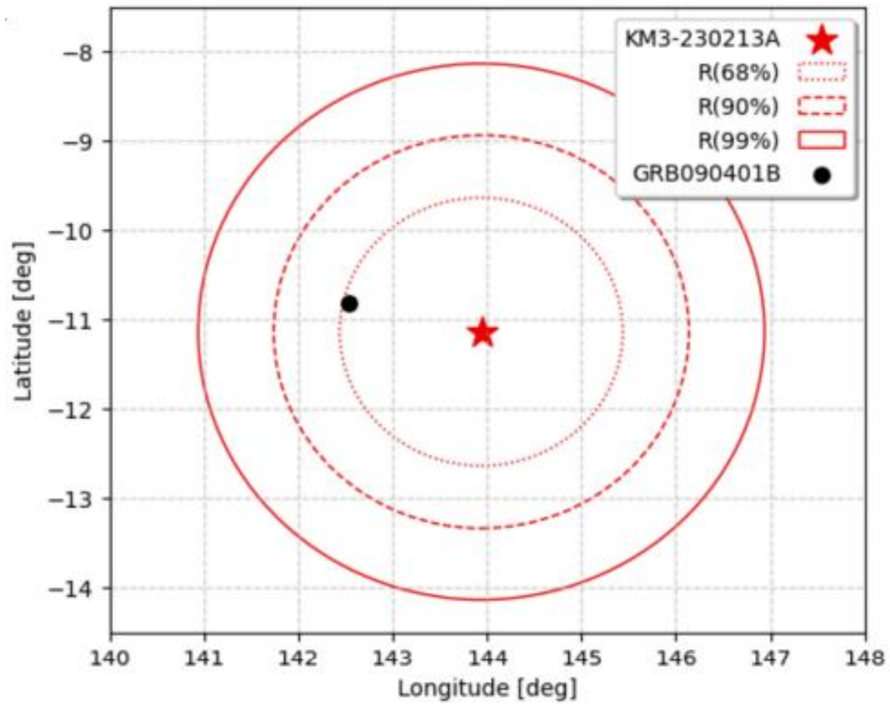
- Bounds set by IC on the flux of cosmogenic neutrinos → a cosmogenic origin for 230213A is regarded as very unlikely; [*S. Aiello et al. [KM3NeT], Nature 638 (2025); S. W. Li et al. (2025), arXiv:2502.04508*]

- Blazars are not expected to have enough fire power for the observation of such a high-energy neutrino; [*O. Adriani et al. (2025), arXiv:2502.08484*]

- A GRB origin for 230213A would make observational and theoretical sense [*A. Neronov et al. (2025), arXiv:2502.12986*]:

1. no GRB in good directional and close temporal coincidence with 230213A;
2. a 220 PeV GRB neutrino could be delayed by several years, even assuming that the QG scale is rather close to the Planck scale → opportunity to test the predictive power of our previous picture.

GRB090401B



*Amelino-Camelia, D'Amico, Fabiano, **DF**, Gubitosi, Moia, Rosati,* arXiv:2502.13093

- J2000 coordinates are RA = $95.088°$, decl = − $8.972°$ with an angular uncertainty of $0.000065°$
- Measured redshift z= 3.1
- Long GRB (T90 = 183 s) observed by Swift on 01 April 2009 at 08:35:25 UTC
- 14-year separation between the two observations !

- unsurprising from an in-vacuo-dispersion standpoint, considering the very high energy of 230213A and the relatively high redshift of 090401B.

S_{dir} and S_E

- S_{dir} to quantify the directional agreement between the GRB and the neutrino;

- New indicator S_E to quantify the agreement between the experimental information on the energy of the neutrino and the range of energies that in-vacuo dispersion would predict for such a delayed neutrino observation assuming it has been emitted at the GRB redshift:

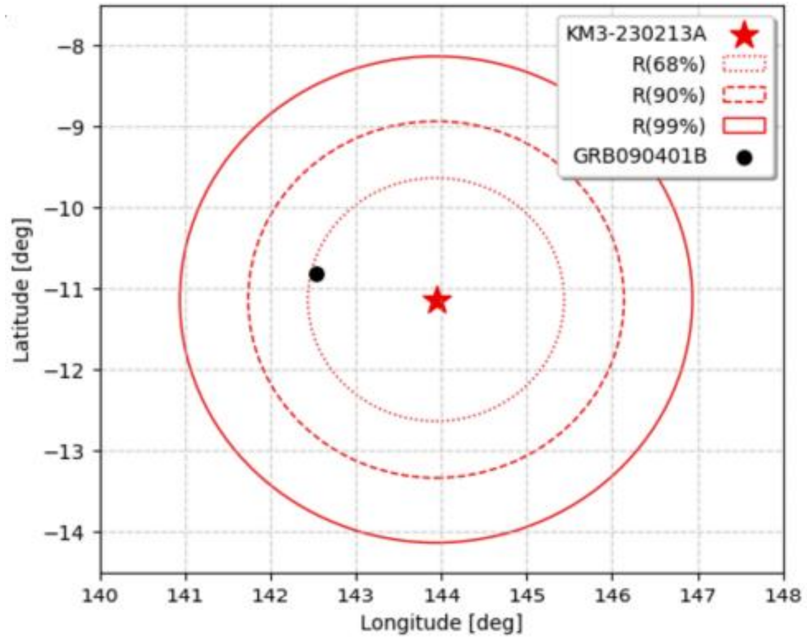
- $$S_E = \int_{E_{min}}^{E_{max}} \frac{\rho_\nu(E)}{E_{max}-E_{min}}\, dE$$

where:

1. $\rho_\nu(E)$ is the energy distribution of 230213°;
2. Using $\Delta t, z$ we convert the range $\frac{1}{\mathrm{M_{pl}}} \cdot [12.7, 30.7]$ into a range $[E_{min}, E_{max}]$ for the inferred energy of 230213°.

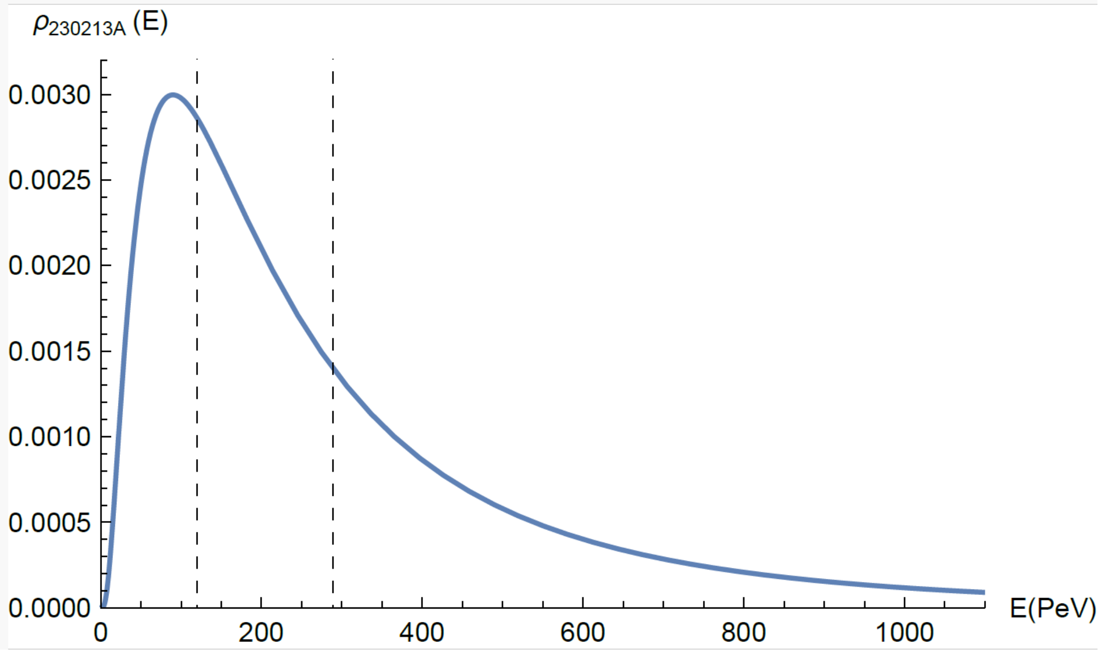
THE 090401B-230213A PAIR

ANGULAR COMPATIBILITY



S_{dir}=194

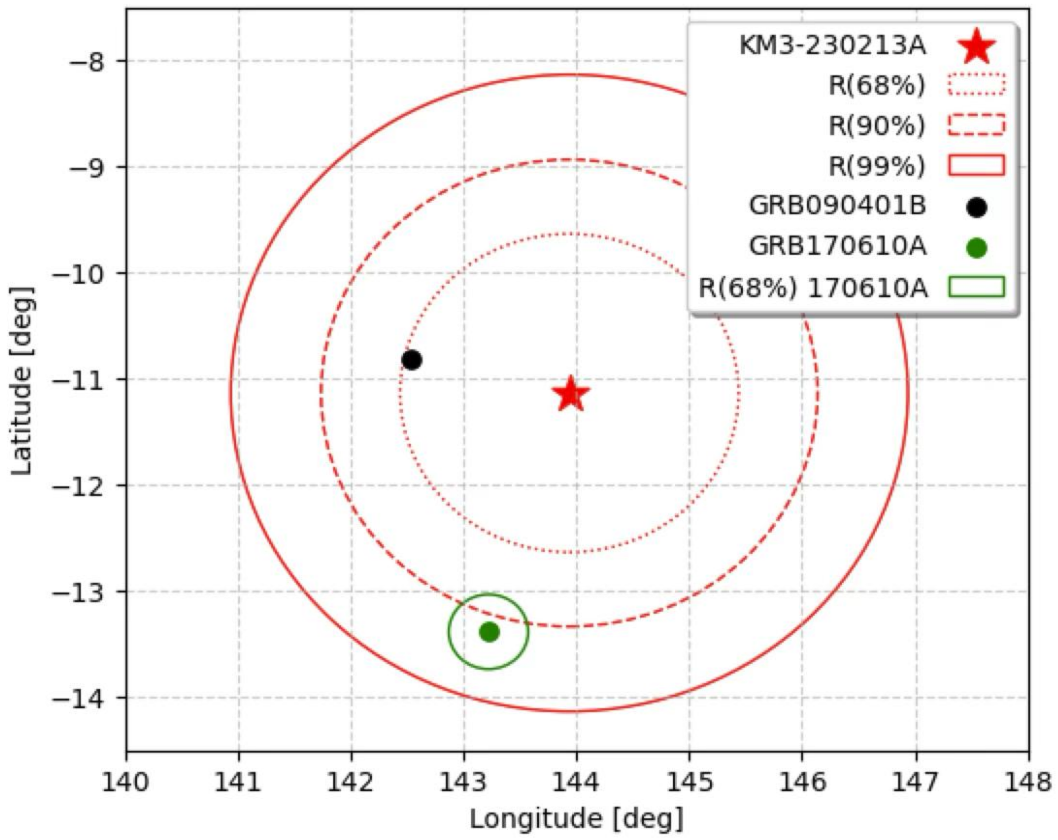
TEMPORAL (ENERGY) COMPATIBILITY



S_E =0.00209 PeV^{-1}

- FAP of finding a GRB that produces S_{dir} ≥194 and S_E ≥0.00209 PeV^{-1} , $p = 1.5\%$ (2.4σ).

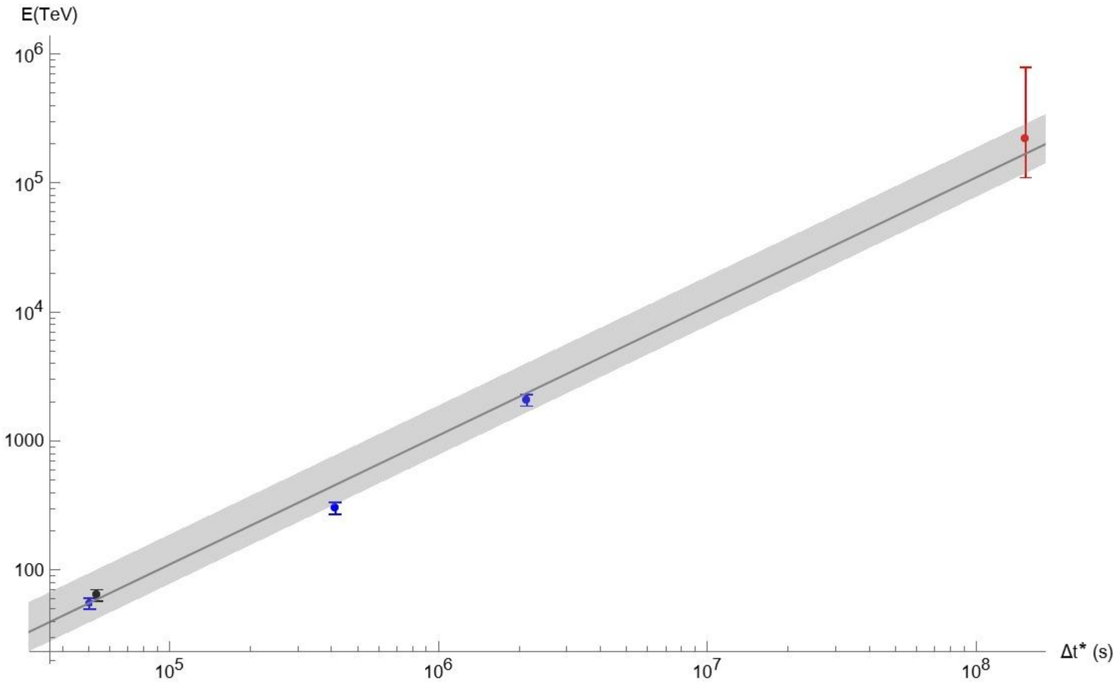
GRBs OF UNKOWN REDSHIFT



- 090401B is the GRB with the best directional agreement with 230213A, even including GRBs of unknown redshift: for all of them, the value of S_{dir} is significantly smaller than 194.

- The directional compatibility between GRB170610A and 230213A corresponds to S_{dir} = 36.

OUTLOOK

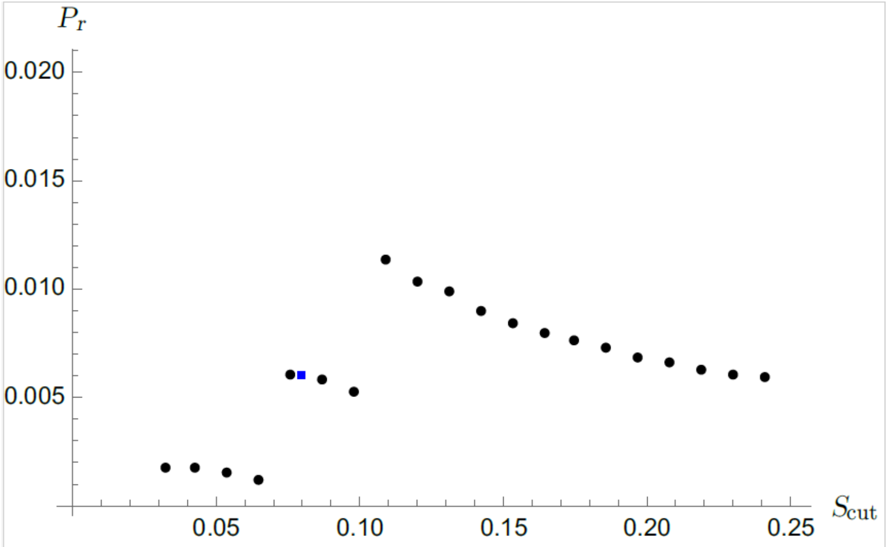


- Combined statistical significance for in-vacuo dispersion of all five GRB-neutrino candidates?
- How to upgrade our statistical approach to include also IC track GRB-neutrino candidates?

Thank you!

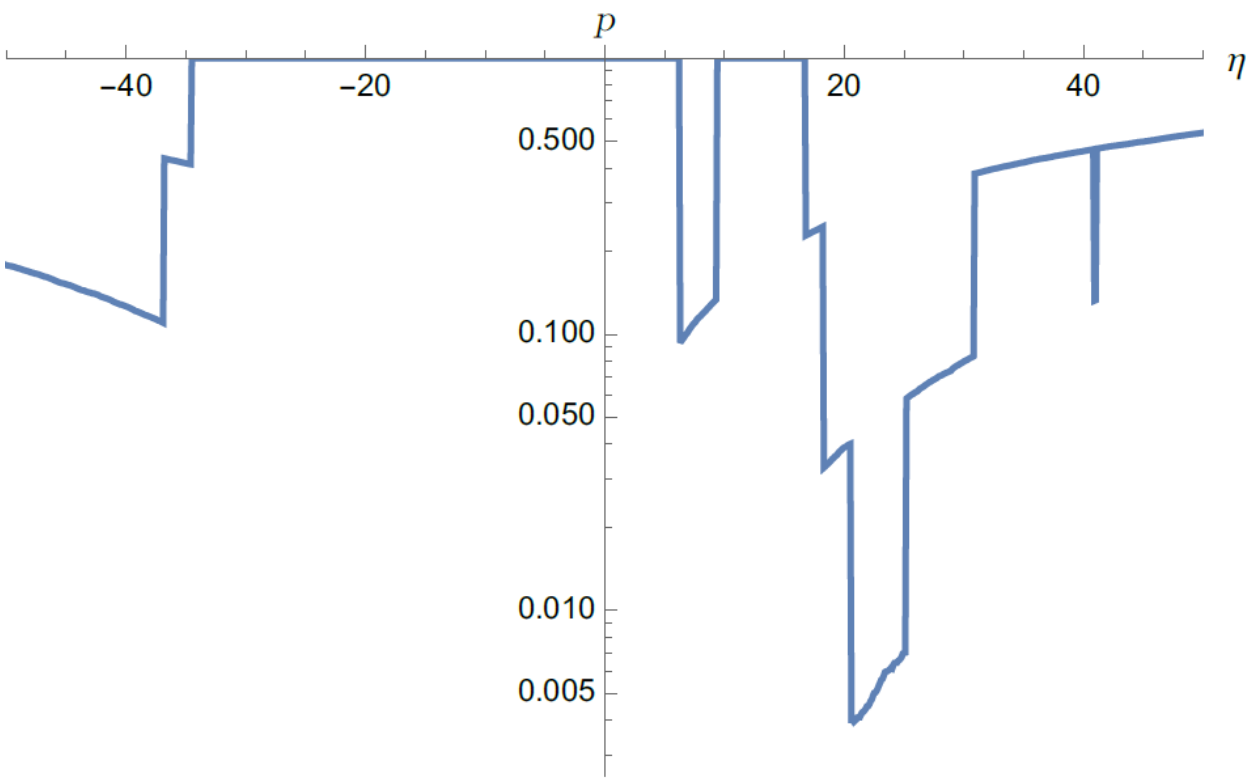
AVENUES FOR REFINING THE STRATEGY OF ANALYSIS

1. Alternative choices of Scut: our main result $\mathrm{P_r}$ does not depend strongly on the choice of S_{dir}^{cut};



2. Improved correlation r_0 (sensitive to the fact that one should have $\Delta t^{\star} \rightarrow 0$ for E → 0: $\mathrm{P_{r_0}} = 0.4\%$

p-CURVE FOR $\eta \in$ [-50, 50]



FAKE DATA and FAP

- Simulated data obtained from the real data performing the following independent manipulations:

1. random permutation and a random periodic time translation of neutrino observation times;
2. random rotation around the Earth's axis of neutrino directions;
3. random permutation and a random rotation around the Galactic axis of GRB directions.

- FAP of finding at least 4 GRB-neutrino candidates with correlation greater than 0.9985 is $\mathrm{P_r} = 0.6\%\ (2.8\sigma)$.

FAKE DATA and FAP

- Simulated data obtained from true data acting on the GRB directions with a random permutation and a random rotation around the Galactic axis.

- FAP of finding a GRB that produces S_{dir} ≥194 and S_E ≥0.00209 PeV^{-1} , $p = 1.5\%\ (2.4\sigma)$.