CAN QUANTUM GRAVITY SLOW DOWN NEUTRINOS AND HIGH-ENERGY PHOTONS?

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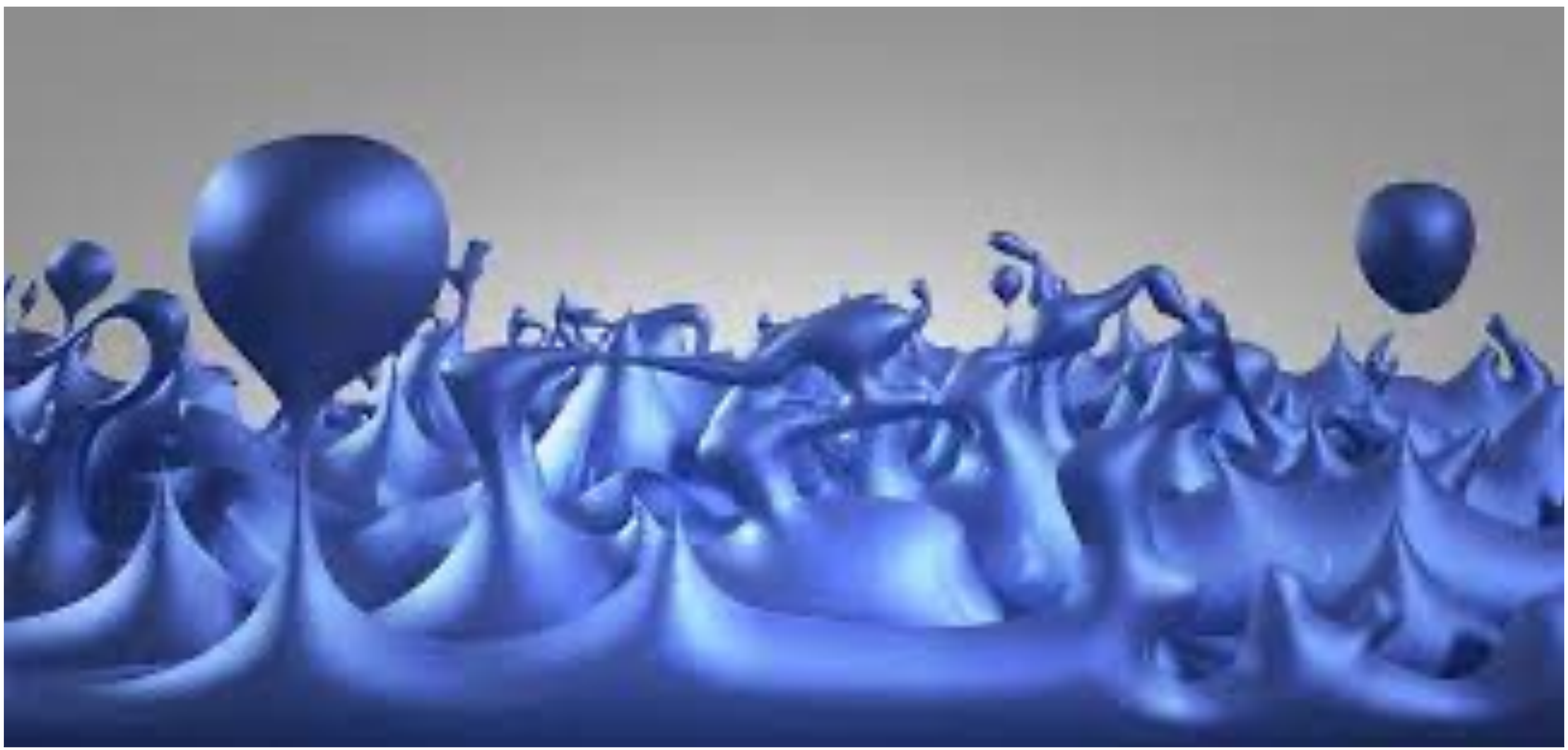
IFPU workshop “The New Era of Multi-Messenger Astroparticle Physics”

Propagation of particles in quantum spacetime

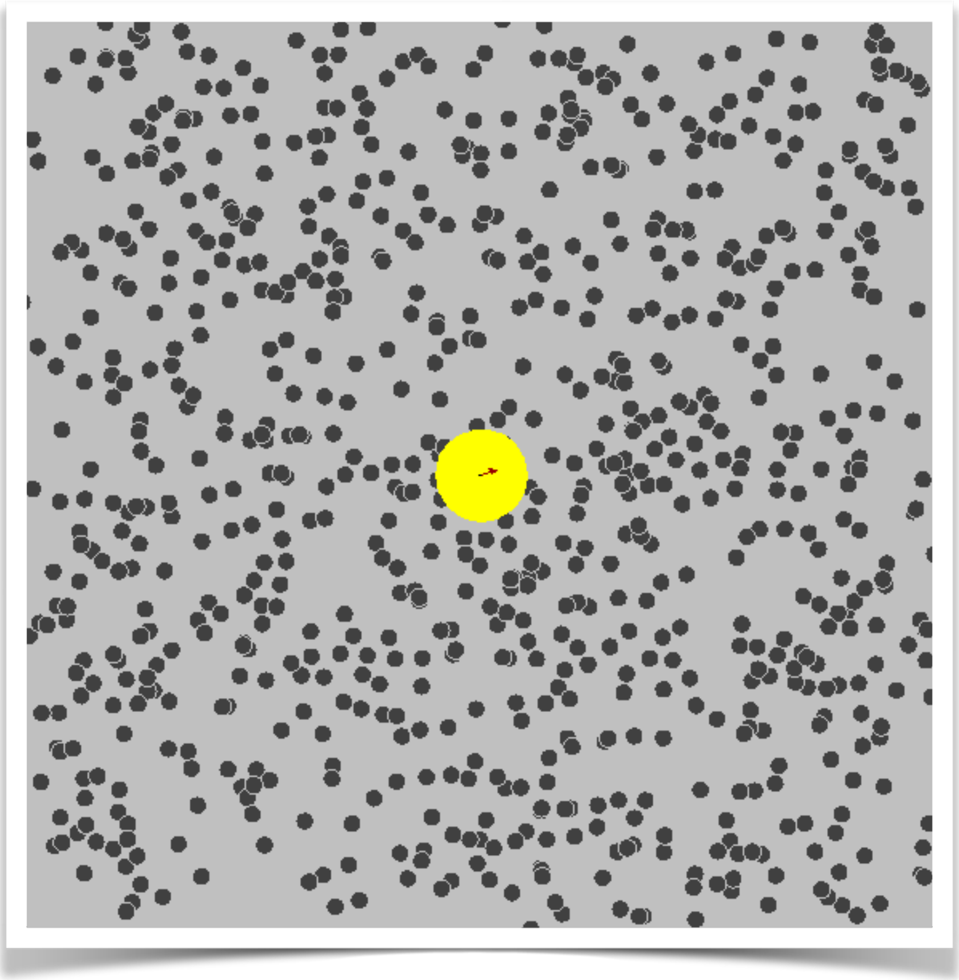
In quantum gravity research it is expected that spacetime shows quantum properties when tested at length scales of the order of the Planck length

$$L_P \sim 10^{-35}\text{m}$$



Propagation of particles in quantum spacetime

When particles travel in such quantum spacetime, anomalous propagation effects accumulate, with stronger effects for particles with smaller wavelengths



Propagation of particles in quantum spacetime - in vacuo dispersion

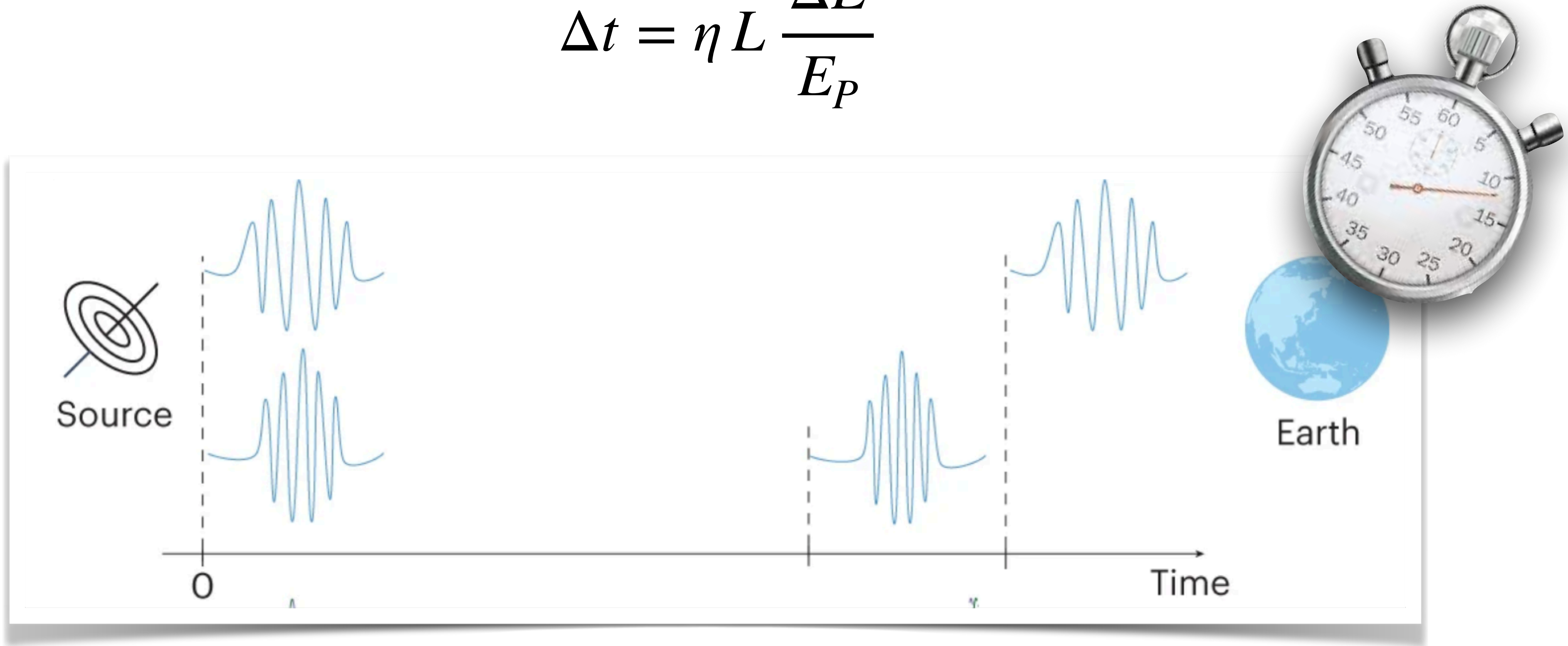
A possible anomalous propagation effect is in vacuo dispersion: the speed of massless particles acquires an energy dependence

$$v(E) = \left(1 + \eta \frac{E}{E_P}\right)$$

(Showing only the leading-order term in powers of the particle's energy over the Planck energy $E_P \sim 10^{19}\text{GeV}$)

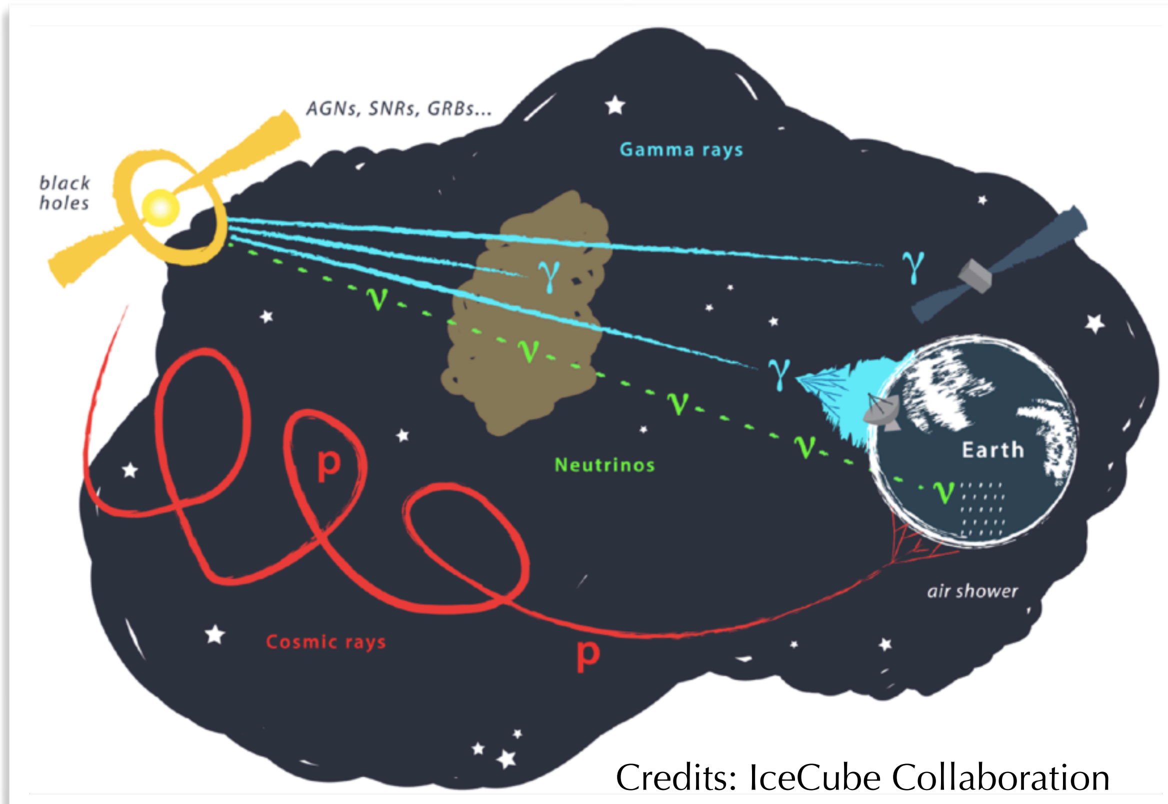
Particles with energy difference ΔE emitted simultaneously arrive at the detector with a time difference (in flat spacetime)

$$\Delta t = \eta L \frac{\Delta E}{E_P}$$



Implications for astrophysical messengers - time delays

Time delay effect can be tested by looking at high energy particles (photons, neutrinos) from astrophysical sources, so that the very long travel time can amplify even tiny propagation effects to a detectable level



flat spacetime:

$$\Delta t = \eta\, L\, \frac{\Delta E}{E_P}$$

FRW spacetime:

Jacob, Piran, JCAP 2008

$$\Delta t = \eta \frac{\Delta E}{E_P} D(z)$$

$$D(z) = \int_0^z d\zeta \frac{1+\zeta}{H_0\sqrt{\Omega_\Lambda + (1+\zeta)^3\Omega_m}}$$

→ Search for a correlation between energy, distance of the source and arrival time

Implications for astrophysical messengers - time delays

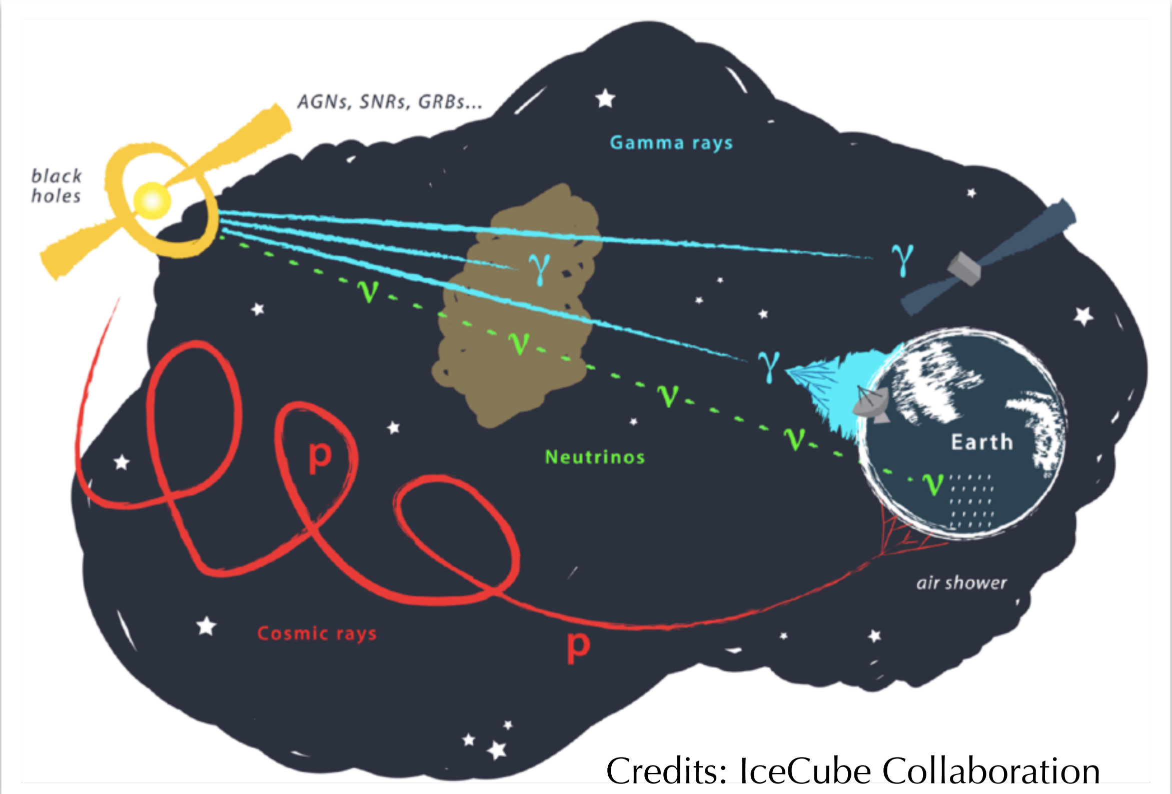
Using the FRW Jacob+Piran formula for time delays, assuming $\eta = 1$ and a source at redshift $z = 1$

For particles of energy ~10 GeV, one might expect a time difference w.r.t. low energy particles

$$\Delta t \sim 10^{-1} s$$

For particles of energy ~ few 100 TeV, one might expect a time difference w.r.t. to low energy particles

$$\Delta t \sim 1\,\text{day}$$

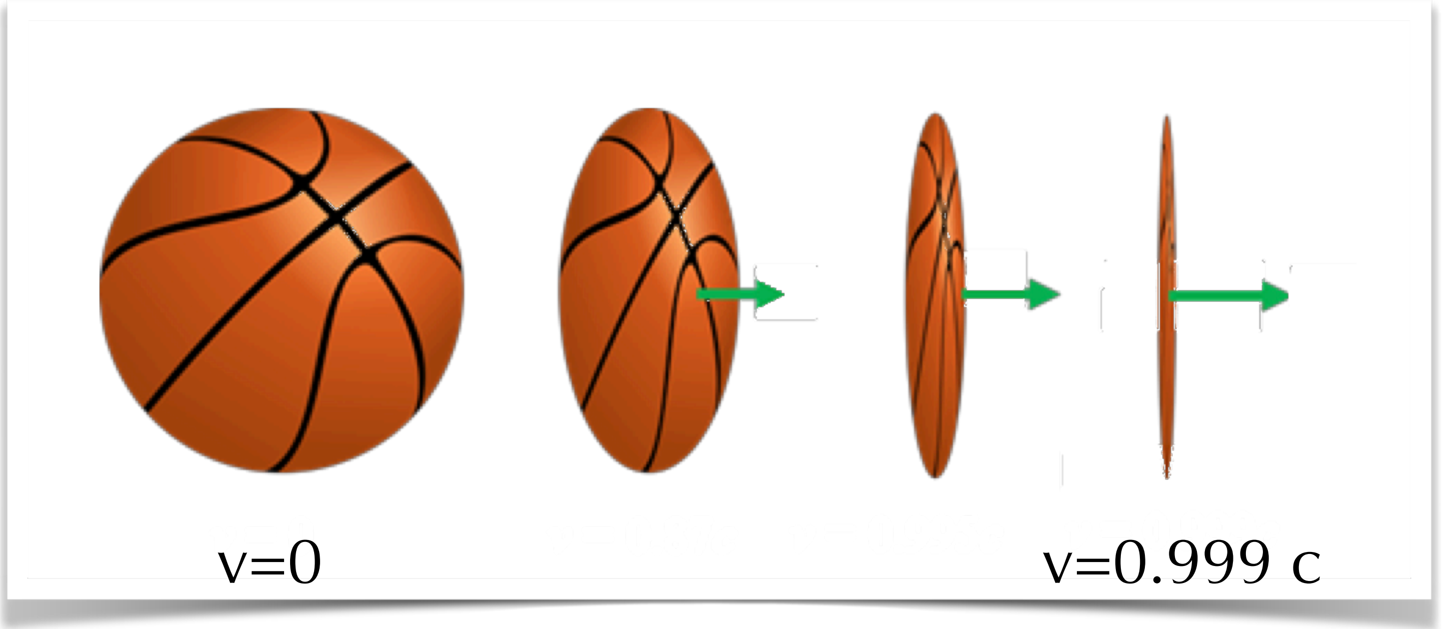


Credits: IceCube Collaboration

Challenges: intrinsic emission mechanisms at the source; identification of the source and its redshift; energy resolution - more later

Adding more complexity: theoretical modelling

The presence of a length/energy scale governing propagation anomalies implies a violation of Lorentz invariance.



Adding more complexity: theoretical modelling

The presence of a length/energy scale governing propagation anomalies implies a violation of Lorentz invariance.

Lorentz breaking

There is a ***preferred frame of reference*** where the propagation law takes the given form.

The most natural assumption is that energy and spatial momenta are conserved as usual. E.g. in a process $a + b \to c + d$

$$\begin{aligned} E_a + E_b &= E_c + E_d \\ \vec{p}_a + \vec{p}_b &= \vec{p}_c + \vec{p}_d \end{aligned}$$

The combination of modified dispersion relation and standard interaction produces strong ***implications for threshold reactions***, e.g. they allow for photon decay.

Carroll, Field, Jackiw, PRD 1990
Kostelecky, Mewes, PRD 2009

Lorentz deformation

The propagation law is the same in all reference frames, linked by ***deformed transformations.***

Conservation law are modified to be invariant under the deformed transformations. E.g. in a process $a + b \to c$

$$\begin{aligned} E_a &= E_b + E_c - \eta \vec{p}_b \cdot \vec{p}_c \\ \vec{p}_a &= \vec{p}_b + \vec{p}_c - \eta E_b \vec{p}_c - \eta E_c \vec{p}_b \end{aligned}$$

The interplay between MDR and modified conservation rules ***weakens the effects on threshold reactions,*** e.g. photon decay is forbidden.

Amelino-Camelia, IJMPD 2002, PLB 2001
Kowalski-Glikman, IJMPA 2001; Magueijo, Smolin, PRL 2002

Adding more complexity: theoretical modelling

The issue about Lorentz breaking/Lorentz deformation affects the possible redshift dependence of the time delay.

Lorentz breaking

The commonly used formula by Jacob+Piran is in fact just one of the possibilities. It assumes that the energy of the signal scales as usual with the redshift:

$$E_{source} = E_0(1+z) \longrightarrow \Delta t = \eta \frac{\Delta E}{E_p} \int_0^z d\zeta \frac{1+\zeta}{H_0\sqrt{\Omega_\Lambda + (1+\zeta)^3\Omega_m}}$$

However, once Lorentz invariance is broken, this does not need to be the case.

$$E_{source} = E_0(1+z) - \eta' \frac{E_0}{E_P}\frac{1}{1+z} \longrightarrow \Delta t = \frac{\Delta E}{E_p} \int_0^z d\zeta \frac{\eta(1+\zeta) + \frac{\eta'}{(1+\zeta)}}{H_0\sqrt{\Omega_\Lambda + (1+\zeta)^3\Omega_m}}$$

(In this example, when $\eta = -\eta'$ no time delay is expected for signals coming from sources at small redshifts)

In general, there is an **infinite array of possibilities** for the redshift dependence of the time delay

Amelino-Camelia, Bedic, Rosati, PLB 2021

Adding more complexity: theoretical modelling

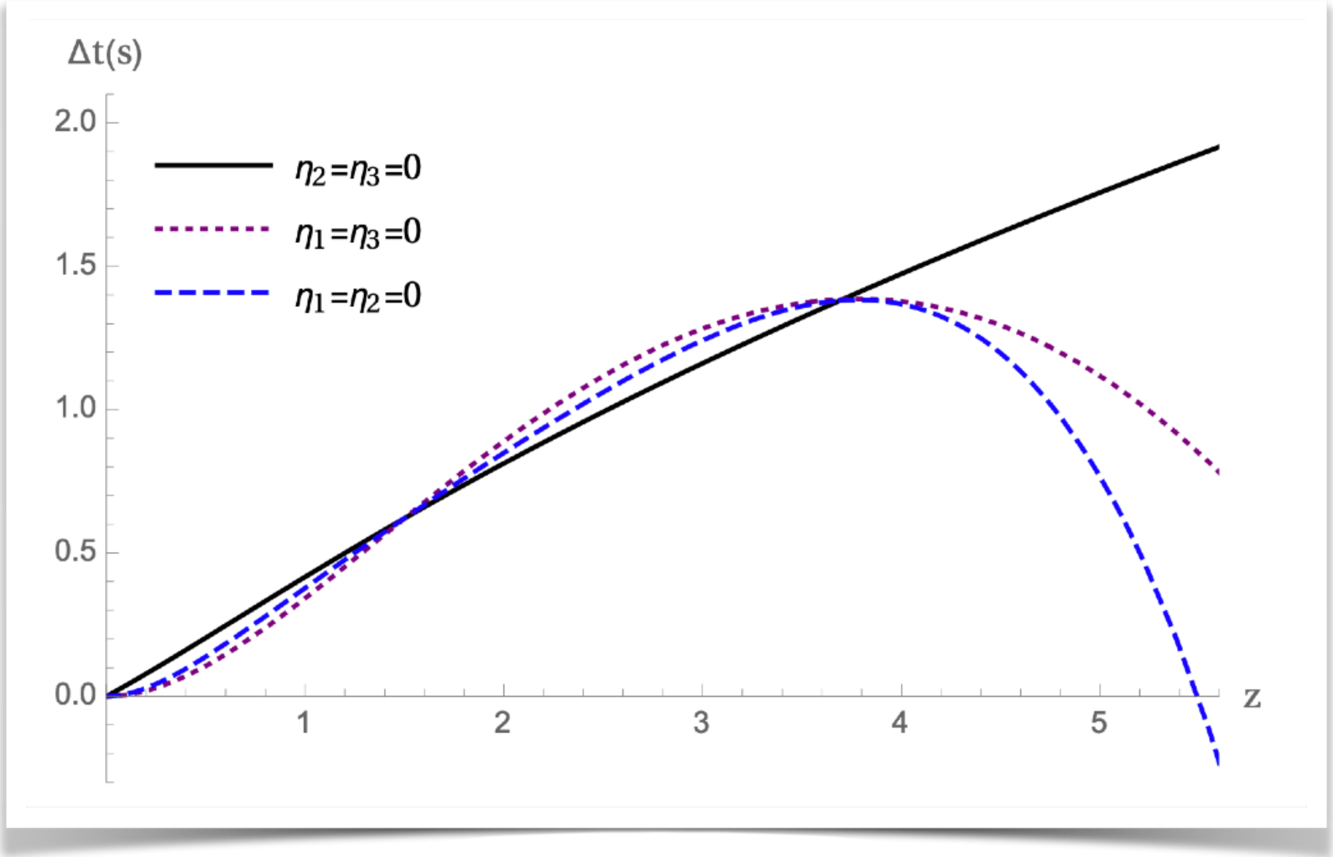
The issue about Lorentz breaking/Lorentz deformation affects the possible redshift dependence of the time delay.

Lorentz deformation

Relativistic invariance constrains the possible forms of the redshift dependence of the time delay, limiting it to just three free parameters:

$$\Delta t = \frac{\Delta E}{E_p} \int_0^z d\zeta \frac{(1+\zeta)}{H(\zeta)} \left[\eta_1 + \eta_2 \left(1 - \left(1 - \frac{H(\zeta)}{1+\zeta} \int_0^\zeta \frac{d\zeta'}{H(\zeta')} \right)^2 \right) + \eta_3 \left(1 - \left(1 - \frac{H(\zeta)}{1+\zeta} \int_0^\zeta \frac{d\zeta'}{H(z')} \right)^4 \right) \right]$$

Assuming ΔE = 10 GeV and fixing the parameters so that the time delays match at z = 1.5



Amelino-Camelia, Frattulillo, GG, Rosati, Bedic, JCAP 2024

Adding more complexity: theoretical modelling

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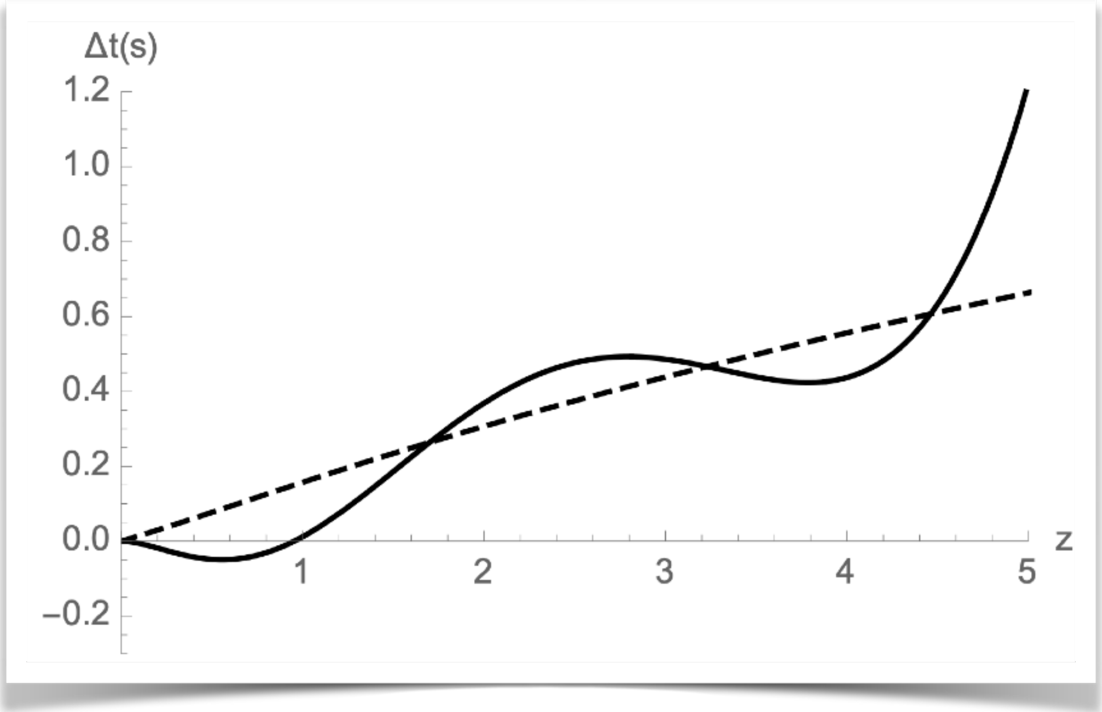
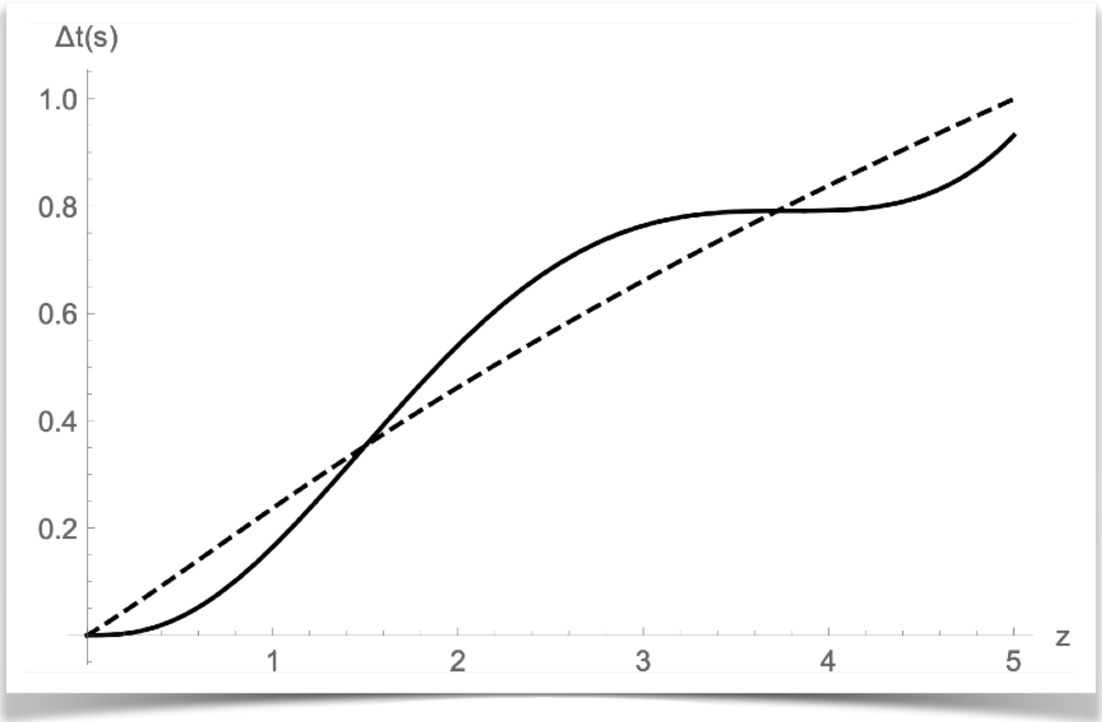
Lorentz deformation

Different combinations of the three parameters can produce a variety of different behaviours



Continuous line: ΔE = 10 GeV, $\eta_2 = 4$, $\eta_3 = -3$. Dashed line: ΔE = 10 GeV, η_1 fixed so that the time delays match at z = 1.5



Continuous line: ΔE = 10 GeV, $\eta_3 = -1$. Dashed line: ΔE = 10 GeV, η_1 fixed so that the time delays match at z = 1.5

Amelino-Camelia, Frattulillo, GG, Rosati, Bedic, JCAP 2024

Searches for energy-dependent time delays in GRBs

The use of GRBs for time of flight tests was suggested 25 years ago

letters to nature

Tests of quantum gravity from observations of γ-ray bursts

G. Amelino-Camelia, John Ellis, N. E. Mavromatos, D. V. Nanopoulos & Subir Sarkar

Nature **393,** 763–765 (1998)

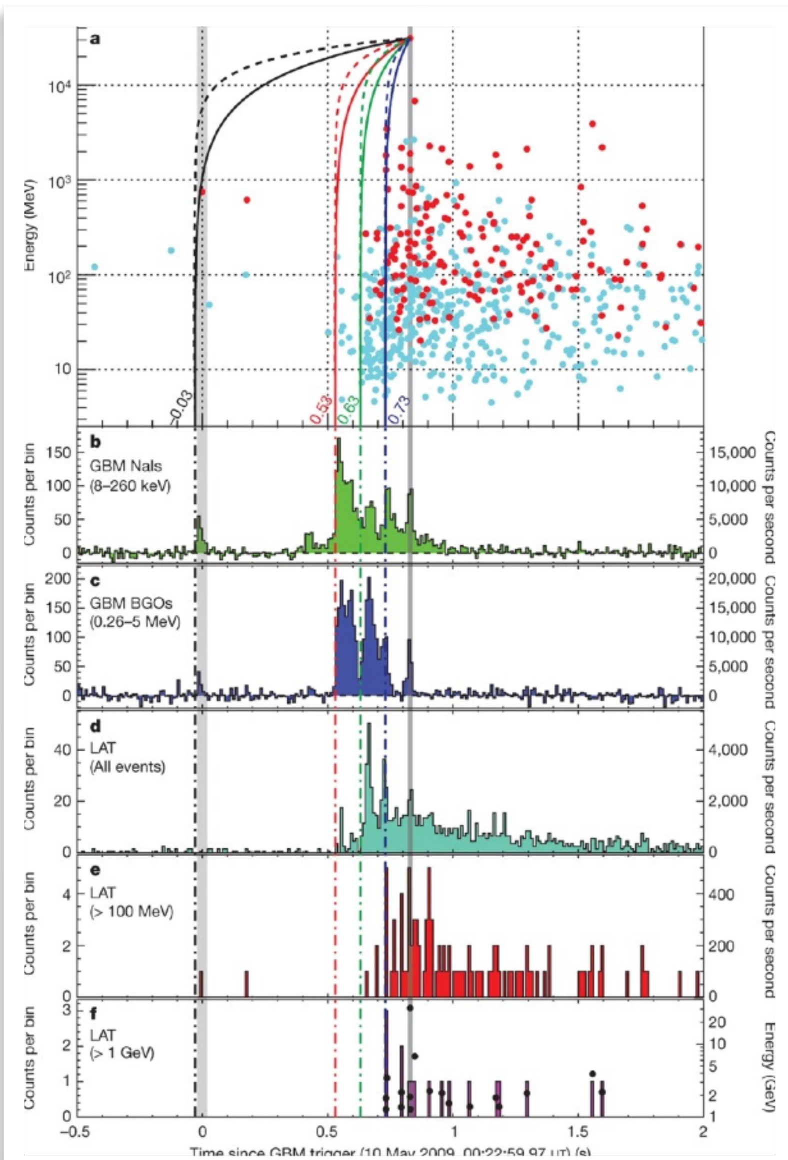
Nowadays these searches are routinely performed on new data

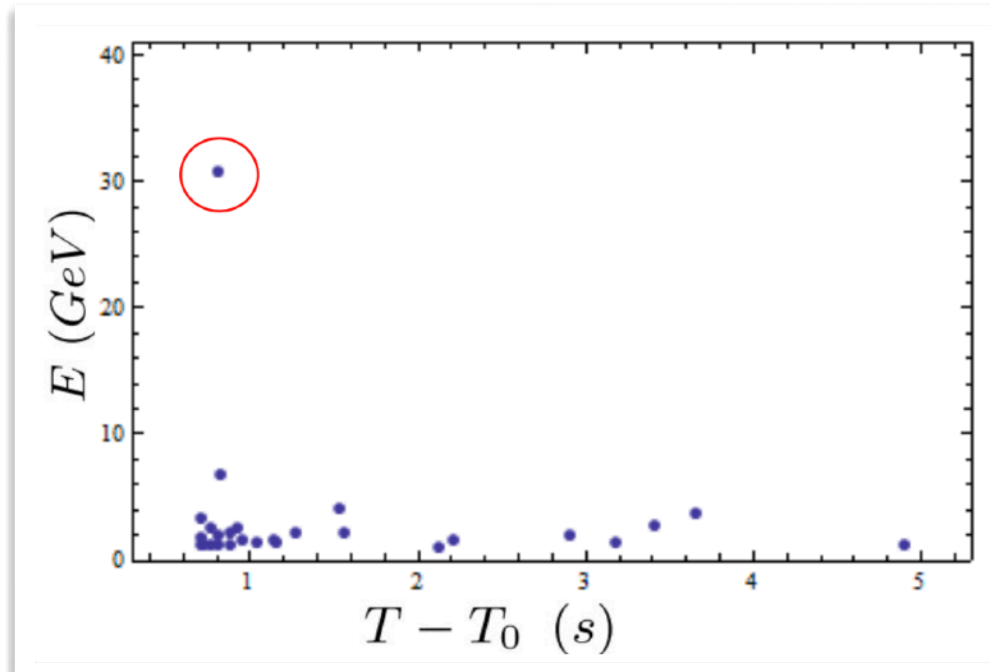
QUANTUM · GRAVITY · MULTI · MESSENGER

See the review *"Quantum gravity phenomenology in the multi-messenger approach"* by the COST Action CA18108, Prog. Part. Nucl. Phys. 125 (2022) 103948 arXiv: 2111.05659 [hep-ph]

Searches for energy-dependent time delays in GRBs- the pioneering era

Assume that the highest-energy photon (31 GeV) was not emitted before the first GBM pulse



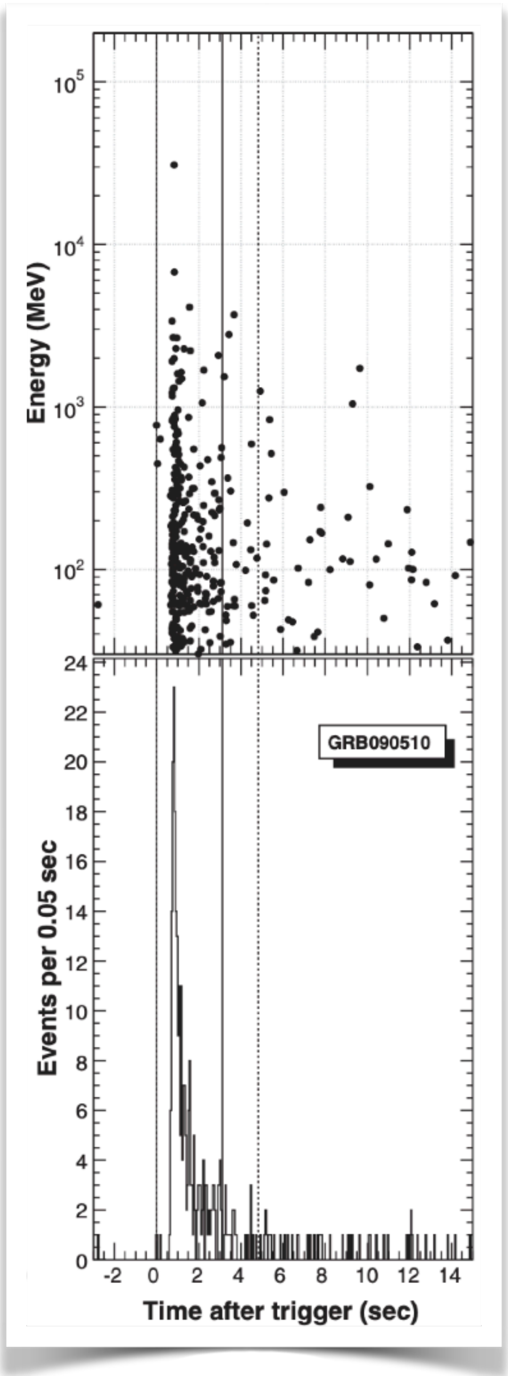


$$\eta < 0.8$$

FERMI Collaboration, Nature 462 (2009), based on GRB090510 (redshift 0.903)

Searches for energy-dependent time delays in GRBs- refining the analysis

The **Pair View method** studies the distribution of the time of arrival difference between all pairs of photons in a given pulse within the GRB.



Time and energy profiles of the detected events from GRB090510. Event energy versus event time scatter plot (top) and a light curve (bottom). The vertical lines denote the time intervals analyzed. The analyzed time intervals are chosen to correspond to the period with the highest temporal variability.

Vasieliou et al., PRD 87, 122001 (2013)

Searches for energy-dependent time delays in GRBs- refining the analysis

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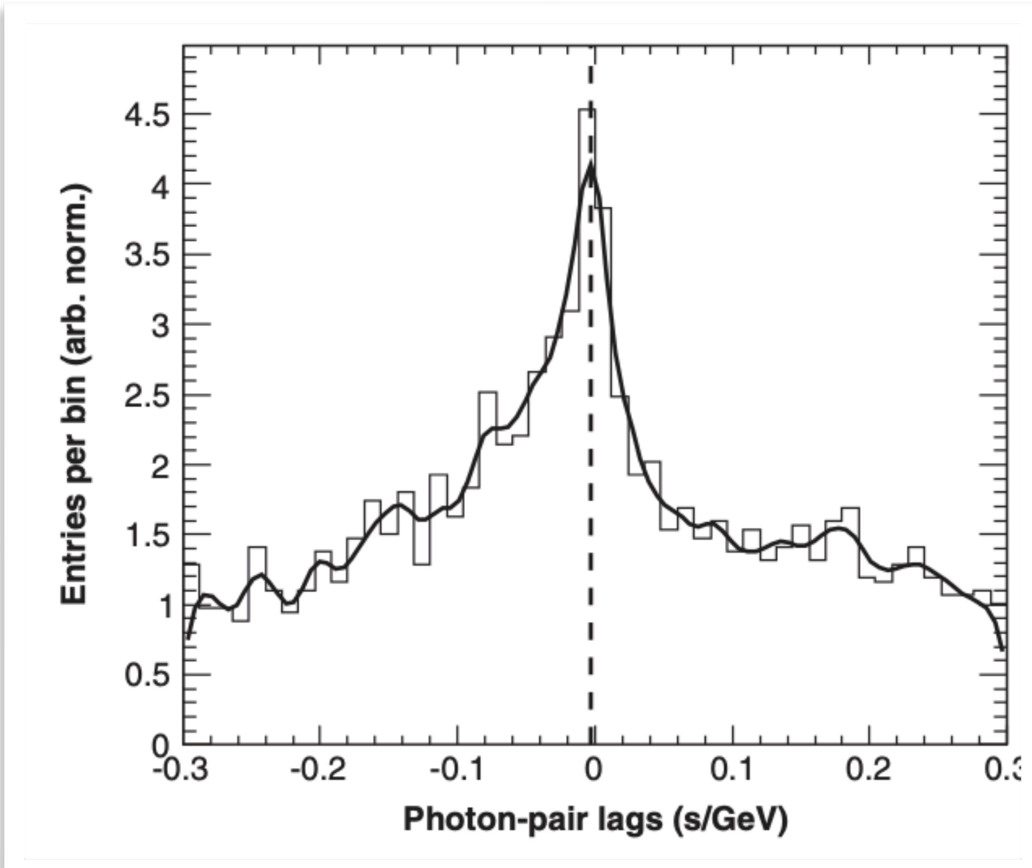

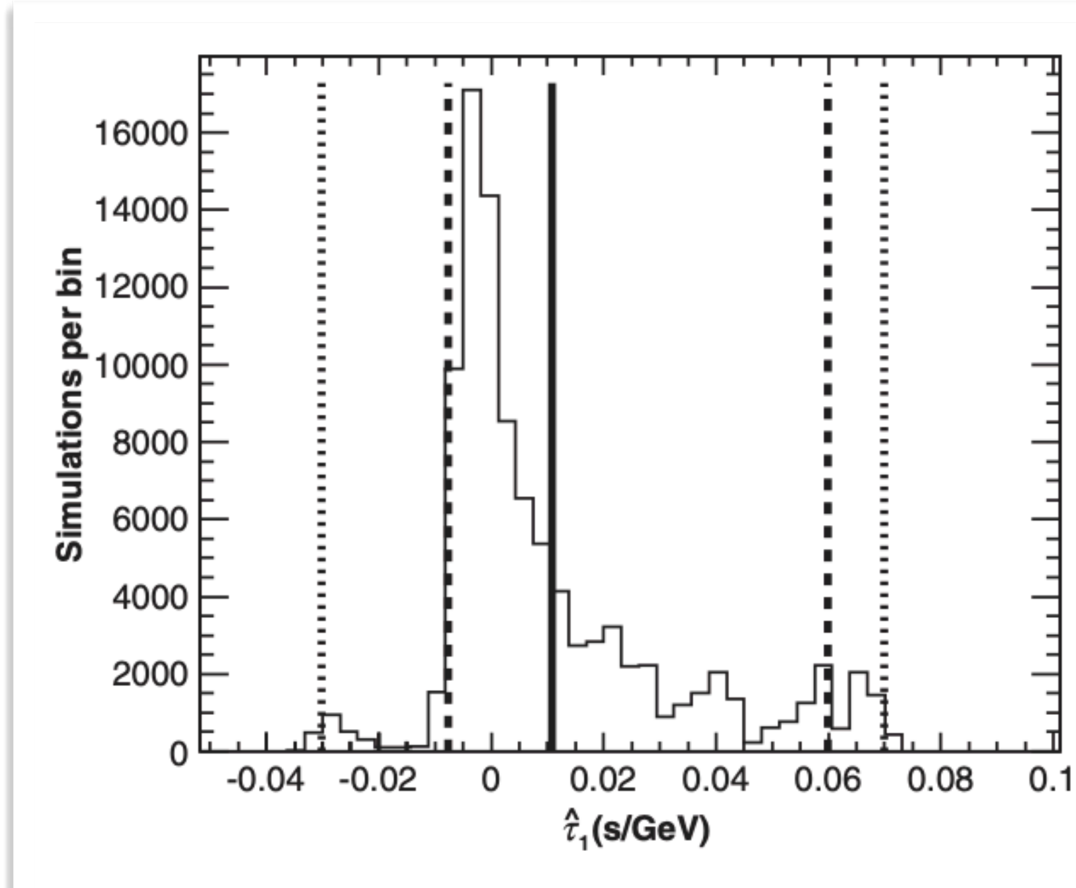

Left: distribution of photon-pair lags (histogram), KDE of the distribution (thick curve), location of the KDE's maximum used as ($\hat{\tau}_n$ by PV (vertical dashed line) for GRB090510
Right: distributions of the best estimates of the LIV parameter of the randomized data sets (histograms), 5% and 95% quantiles (dashed lines), 0.5% and 99.5% quantiles (dotted lines), and average value (central solid line)

$$\eta < 0.13$$ Not accounting for intrinsic lags

Vasieliou et al., PRD 87, 122001 (2013)

Searches for energy-dependent time delays in GRBs- refining the analysis

The **maximum likelihood** method relies on the low-energy observed light curve to infer the high-energy light curve (or on a theoretical modelling) and requires a model for EBL absorption

The probability distribution function for a signal event is

$$f_s(t, E_{est} | \eta, I) \propto \int dE\, \Phi_1(t - \Delta t(E, \eta))\, \Phi_2(E)\, F(E)\, A_{eff}(E)\, G(E_{est}, E)$$

Φ_1	Time-rescaled observed light curve
Φ_2	Observed Spectrum
F	EBL attenuation
A, G	Instrumental response functions

Martínez, Errando, ApP 2009

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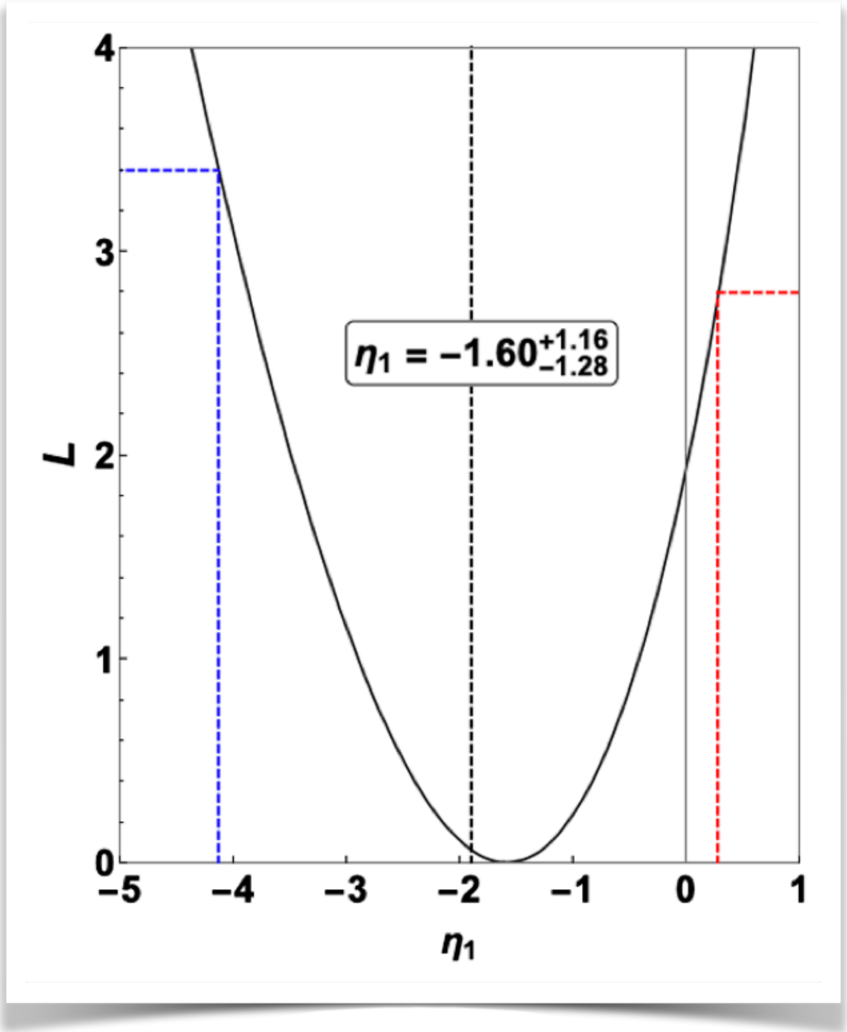
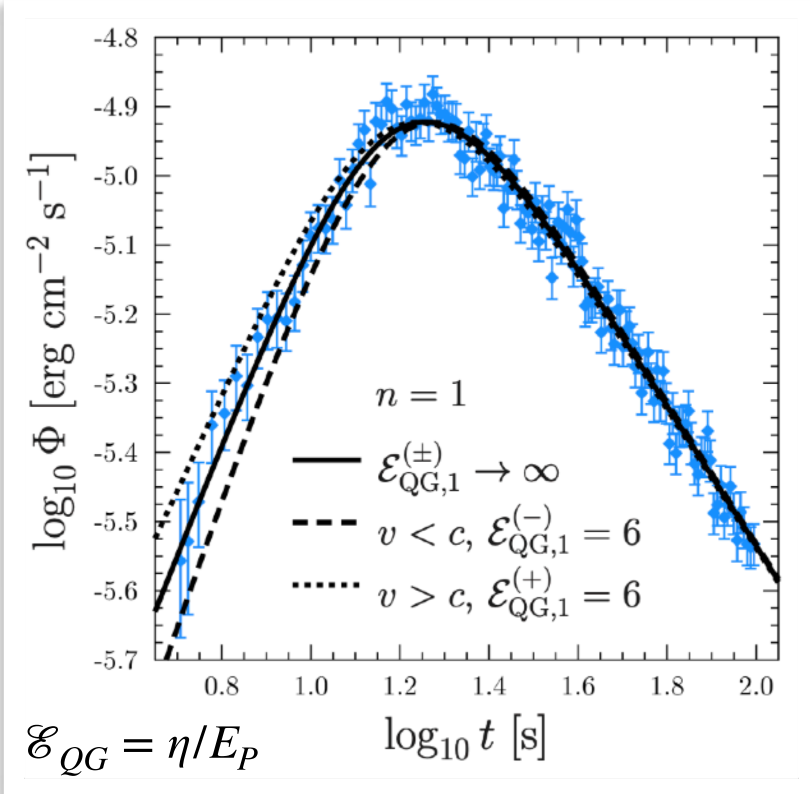


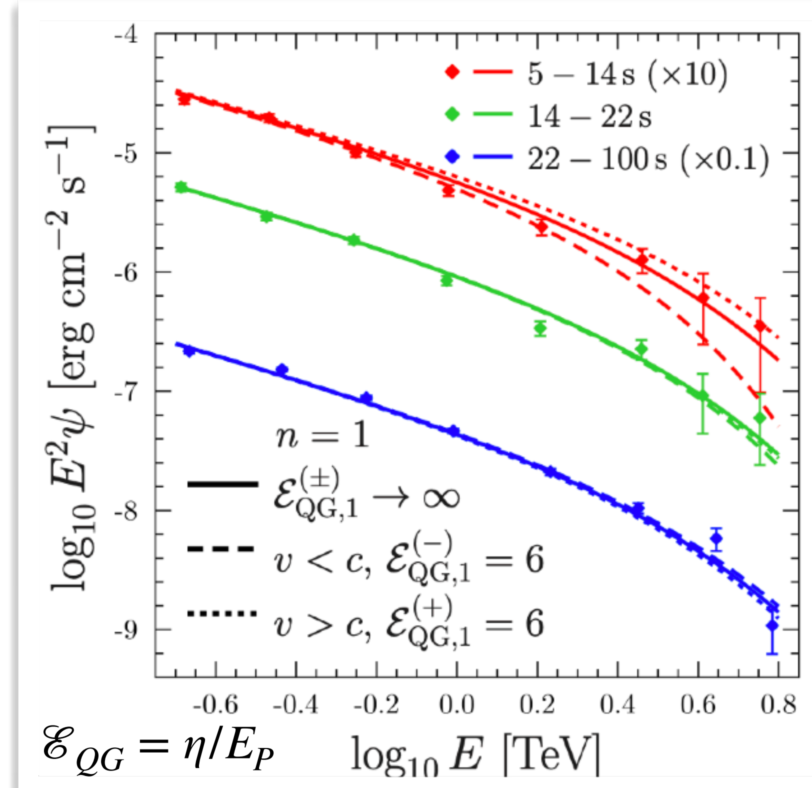
Likelihood profile for GRB190114C detected by MAGIC (redshift 0.42). The black dashed line represents the bias obtained from mock data sets.

$$\eta < 1.8$$

MAGIC Collaboration, PRL 2020

Searches for energy-dependent time delays in GRBs - GRB221009A





$$\Phi_{\mathrm{LIV}}(t, \mathcal{E}^{(\sigma)}_{\mathrm{QG,n}}) = \int_{0.3\,\mathrm{TeV}}^{5\,\mathrm{TeV}} F_{\mathrm{LIV}}(E, t; \mathcal{E}^{(\sigma)}_{\mathrm{QG,n}}) E\,\mathrm{d}E.$$

$$\psi^{(i)}_{\mathrm{LIV}}(E, \mathcal{E}^{(\sigma)}_{\mathrm{QG,n}}) = \frac{C_{\mathrm{a.c.}}}{t_{\mathrm{up}\,i} - t_{\mathrm{low}\,i}} \int_{t_{\mathrm{low}\,i}}^{t_{\mathrm{up}\,i}} F_{\mathrm{LIV}}(E, t; \mathcal{E}^{(\sigma)}_{\mathrm{QG,n}})\,\mathrm{d}t.$$

$$F_{\mathrm{LIV}}(E, t; \mathcal{E}^{(\sigma)}_{\mathrm{QG,n}}) = F\big(E, t + \delta t_{LIV, z=0.151}(E, \mathcal{E}^{(\sigma)}_{\mathrm{QG,n}})\big)$$

Simultaneous fit of the time-delay rescaled light curve and spectra using LHAASO data in the range 0.2-7 TeV

$$\eta < 0.17$$

Piran, Ofengeim, arXiv:2308.03031

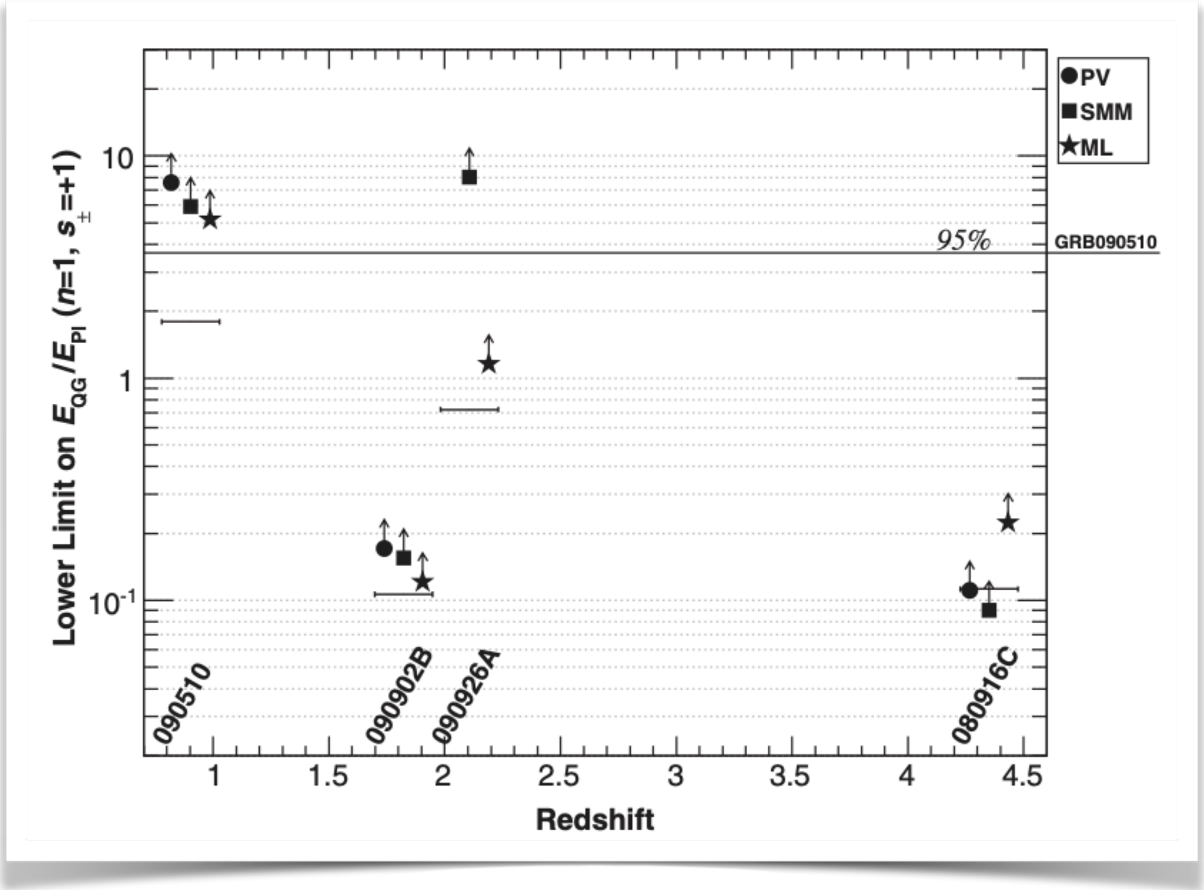
Searches for energy-dependent time delays in GRBs- challenges

EBL absorption

Intrinsic emission

Prompt vs Afterglow phases

Very few studies currently available that consider GRBs at different redshift.



Constraints were not combined, stating that the one from GRB090510 would dominate

Vasieliou et al., PRD 87, 122001 (2013)

Searches for energy-dependent time delays in GRBs- challenges

EBL absorption

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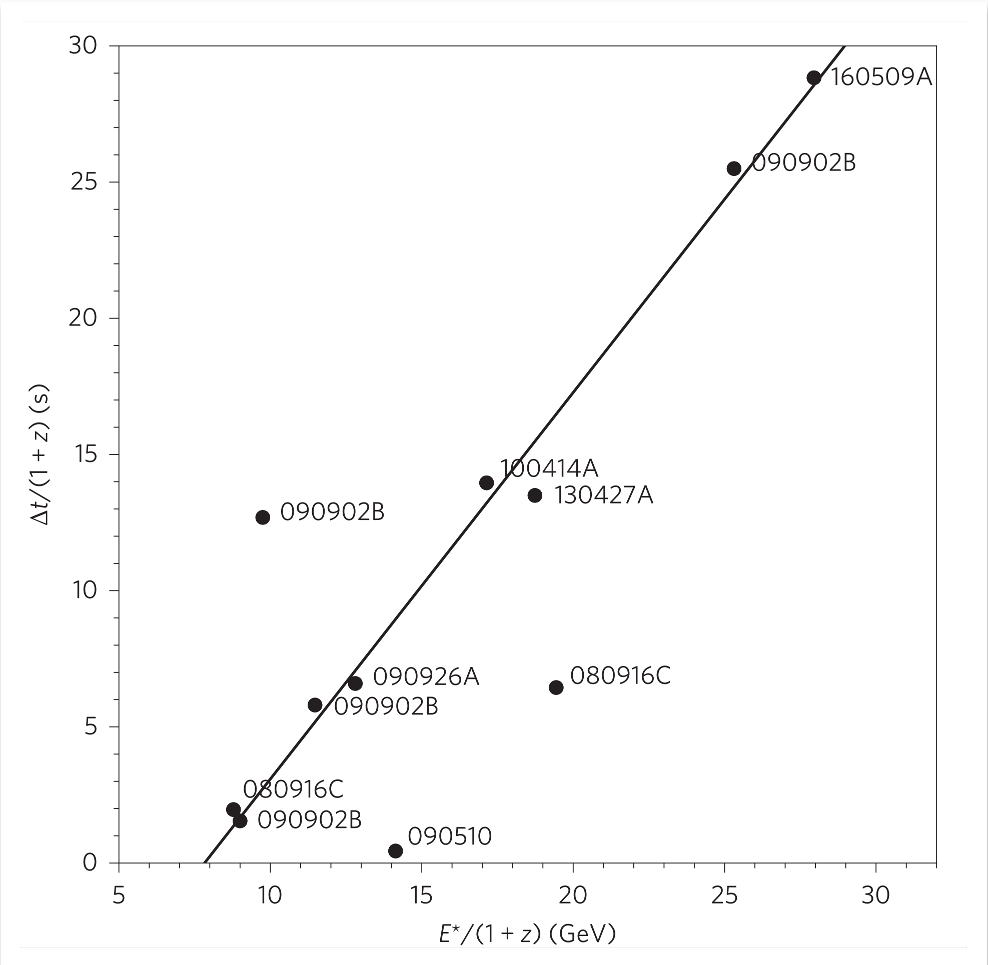


time delay of high-energy photons (>40 GeV at emission) with respect to the GBM peak of the relevant GRB

correlation 0.9959, ‘false alarm probability’ 0.0013%

Amelino-Camelia, D’Amico, Rosati, Loret. Nat. Astr. 2017

Multimessenger search for energy-dependent time delays

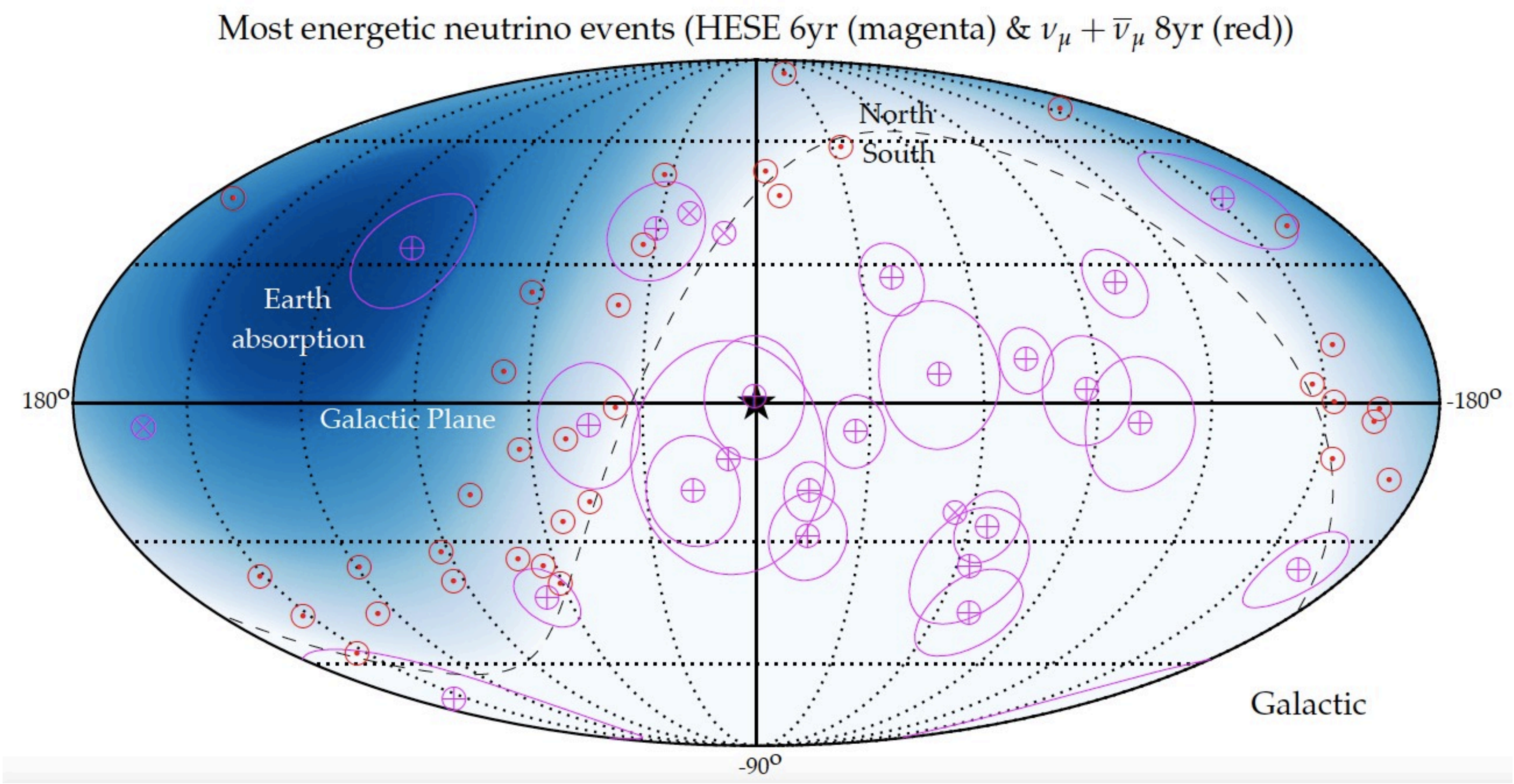
Advantages of using neutrinos:

- Neutrinos from distant sources can have higher energy than photons (the universe is transparent to neutrinos while being opaque for HE photons)
- Not affected significantly by astrophysical propagation effects (interaction with background, with extragalactic magnetic fields, etc.)
- Given the higher energy and thus larger possible time delay, less sensitive to intrinsic lags

Search for energy-dependent time delays in GRB-neutrinos - the pioneering era

Combine the data from the GRBs catalogue (Fermi, Swift, INTEGRAL, HESS, MAGIC…), with data from the ICECUBE neutrino detector
Search for a correlation between the time of arrival of GRB neutrino candidates and the corresponding low energy GRB signal

Jacob, Piran, Nature Physics 2007
Amelino-Camelia, Guetta, Piran, ApJ 2015
Amelino-Camelia, D'Amico, Rosati, Loret, Nat. Astr. 2017



Credits: IceCube Collaboration

Search for energy-dependent time delays in GRB-neutrinos - the pioneering era

Selection criteria of GRB neutrino candidates:

- 4y sample of ICECUBE cascade events (good energy resolution, $\sim 10\,\%$, poor angular resolution, $\sim 15°$), from the catalogue in Abbasi, R. et al. [IceCube collaboration] Phys. Rev. D 104, 022002 (2021)

- Neutrino energy $60\,\mathrm{TeV} < E_\nu < 500\,\mathrm{TeV}$

- GRB catalogue from icecube.wisc.edu/~grbweb_public/Summary_table.html

- Neutrino signal observed in a 3-day window w.r.t. the GRB and in spatial coincidence with the GRB (within a 3σ sigma region, $\sigma = \sqrt{\sigma^2_{GRB} + \sigma^2_\nu}$)

Redshift of the source is assigned based on the GRB redshift. For GRBs with unknown redshift this is estimated from GRBs with known redshift that find a neutrino match

Amelino-Camelia, Di Luca, GG, Rosati, D'Amico, Nat. Astr. 2023

Search for energy-dependent time delays in GRB-neutrinos

We consider separately the hypotheses $\eta < 0$ (early GRB neutrino signal) and $\eta > 0$ (late GRB neutrino signal)

- For $\eta < 0$ we find 3 candidate GRB neutrino out of 18 neutrino events

GRB	E_ν (TeV)	Δt (s)	z	GRB length
100605A	98.5	-113,050	–	L
120224B	186.6	-175,141	–	L
140219B	66.7	-234,884	–	L

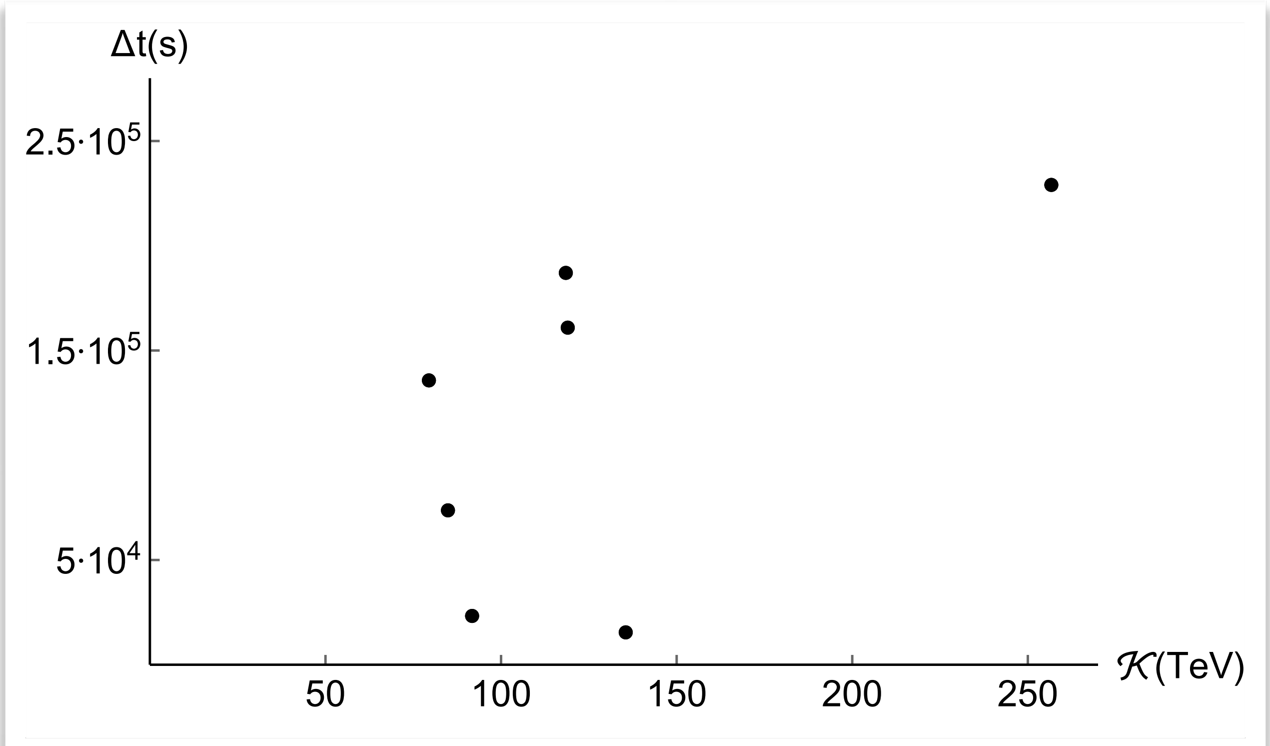
Probability of accidentally finding at least 3 such associations is 81% (using 10^5 simulations of the 18 neutrino events and the same selection criteria as for the real dataset), therefore we exclude this possibility

- For $\eta > 0$ we find 7 candidate GRB neutrino out of 18 neutrino events

GRB	E_ν (TeV)	Δt (s)	z	GRB length
100604A*	98.5	15,446	–	L
110625B*	86.5	160,909	–	L
111229A*	61.7	73,690	1.38	L
120121C	86.1	200,349	–	L
120121B	86.1	213,239	–	L
120121A*	86.1	187,050	–	L
120219A*	186.6	229,039	–	L
140129C*	134.2	135,731	–	S
140216A*	66.7	23,286	–	L

Probability of accidentally finding at least 7 such associations is 5% (using 10^5 simulations of the 18 neutrino events and the same selection criteria as for the real dataset), therefore we investigate this possibility

Characterisation of candidate late GRB-neutrino events



$$\mathcal{K}(E,z) = E\,D(z)/D(1)$$

$$D(z) = \int_0^z d\zeta \frac{1+\zeta}{H_0\sqrt{\Omega_\Lambda + (1+\zeta)^3\Omega_m}}$$

- When more than one GRB-neutrino association is found, we select the GRB that gives the highest correlation
- We estimate the background (i.e. number of neutrinos that accidentally find a GRB association) to be at least 1 with 83% probability, at least 2 with 39% probability and at least 3 with 18% probability
- Correlation of the data points is 0.56
- Probability of accidentally finding at least 7 GRB neutrino candidates (out of 18 neutrinos in the catalogue) with correlation at least 0.56 is 0.7% (using 10^5 simulations of the 18 neutrino events and the same selection criteria as for the real dataset)

Search for energy-dependent time delays in GRB-neutrino — including PeV neutrino

In order to extend the energy range of the analysis to PeV neutrino one would need to open the time window too much (tens of days), causing trouble in handling too many multiple GRB associations.

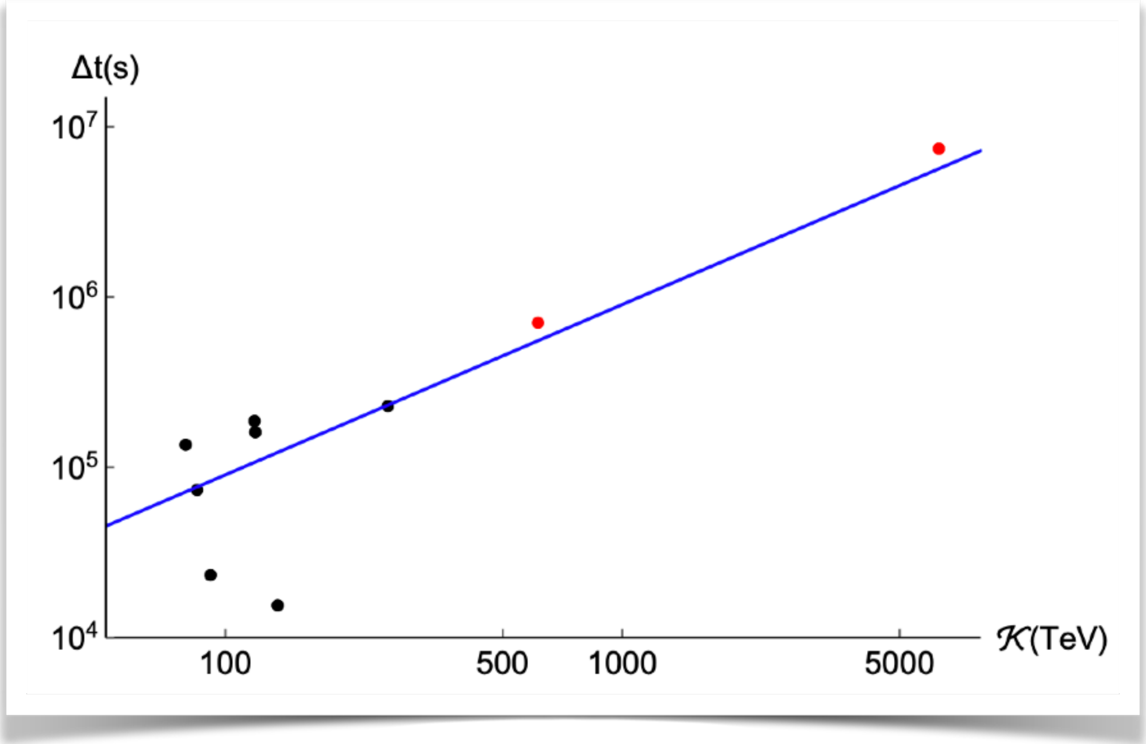
Instead, we use the 60 TeV - 500 TeV neutrinos to estimate $\eta = 21.7 \pm 9$ and use this information to search for candidate GRB neutrino in the PeV range in a restricted time window, asking that

$$|\,\Delta t - \eta \cdot \mathcal{K}(E,z)\,| < 2\,\delta\eta\,\mathcal{K}(E,z)$$

Of the 3 PeV neutrinos in our sample, we find 2 with a GRB association

	E_ν (TeV)	Δt (s)	z	GRB length
110801B*	1,035.5	706,895	–	S
110730A	1,035.5	907,892	–	L
110725A	1,035.5	1,320,217	–	L
120909A	1,800.0	7,435,884	3.93	L

Characterisation of candidate late GRB-neutrino events — including PeV neutrinos



Blue line corresponds to $\eta = 21.7$

$$\mathcal{K}(E, z) = E\, D(z)/D(1)$$

$$D(z) = \int_0^z d\zeta \frac{1+\zeta}{H_0\sqrt{\Omega_\Lambda + (1+\zeta)^3\Omega_m}}$$

- When more than one GRB-neutrino association is found, we select the GRB that gives the highest correlation
- Overall correlation of the data points is 0.9997
- Probability of accidentally finding at least 2 PeV GRB neutrino candidates (out of the 3 PeV neutrinos in the sample) within the time window specified by the lower-energy GRB neutrino candidates and with correlation at least 0.9997 is 0.005%

Search for energy-dependent time delays in GRB-neutrino — the way forward

Challenges of using neutrinos:

- Low statistics, large background - this will improve as more data is collected
- Large energy uncertainties
- GRB redshift uncertainty (which GRB population to use for estimating GRB redshift distribution?)
- Can we use other sources to search for neutrino-photon timed delays (e.g. blazars)?


THANK YOU