



Lorentz invariance violation search with very-high-energy gamma-rays

Fundamental physics Île-de-France meeting – Sept. 2026

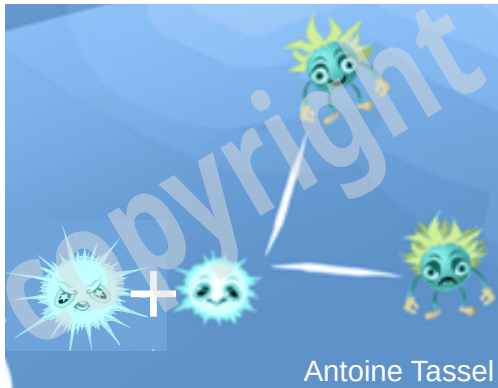
Cyann Plard



Symmetry of relativity

Energy-momentum dispersion relation

$$E^2 = m_0^2 c^4 + p^2 c^2$$

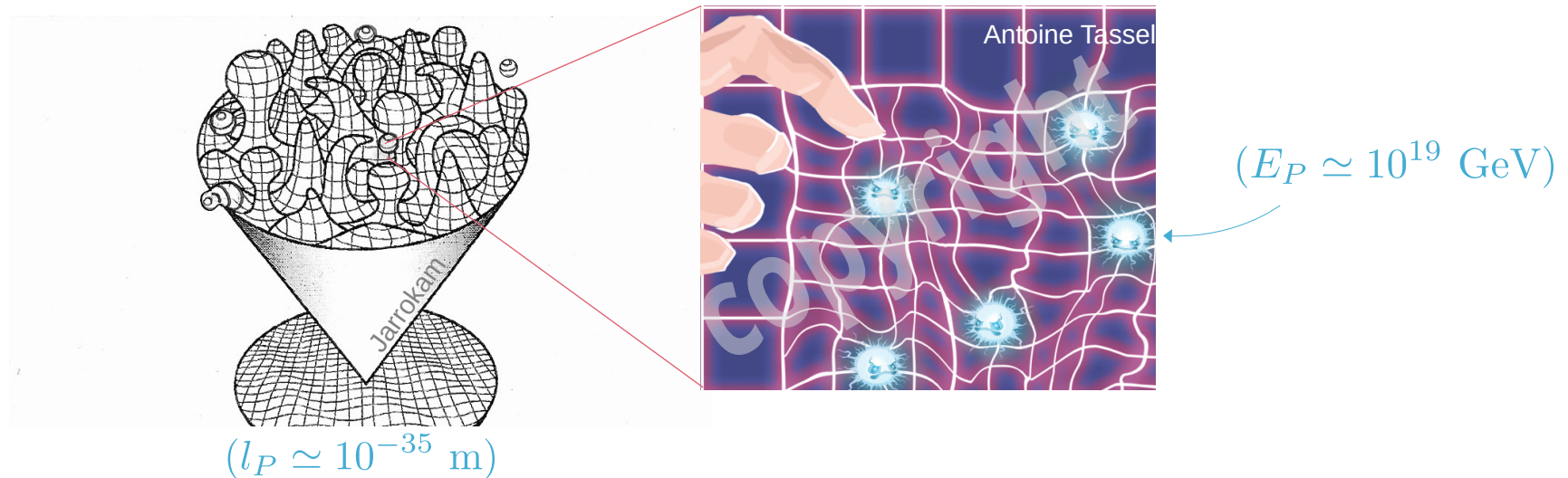


Dispersion relation of photons

$$E^2 = p^2 c^2$$



Quantum gravity and “foaming” spacetime

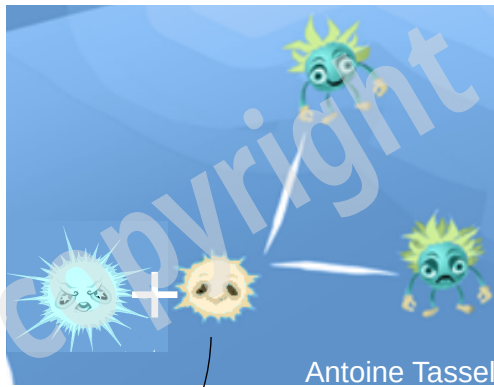


Modified energy-momentum dispersion relation

$$E^2 = m_0^2 c^4 + p^2 c^2 \left[1 \pm \sum_{n=1}^{\infty} \left(\frac{pc}{E_{\text{LIV},n}} \right)^n \right]$$

Some things that we can look for using VHE gamma-rays

Interaction thresholds



$$E \geq \frac{m_e^2 c^2}{E_\gamma} \mp \left(\frac{E_\gamma}{E_{\text{LIV},n}} \right)^n E_\gamma$$

Time delays between γ & [γ or neutrino]



$$\Delta t_n = \pm \frac{n+1}{2} \frac{\Delta E^n}{E_{\text{LIV},n}^n} \times \frac{\kappa_n(z)}{H_0}$$

No detection → lower limit on the characteristic energy E_{LIV}



1. LIV with energy thresholds (spectral)

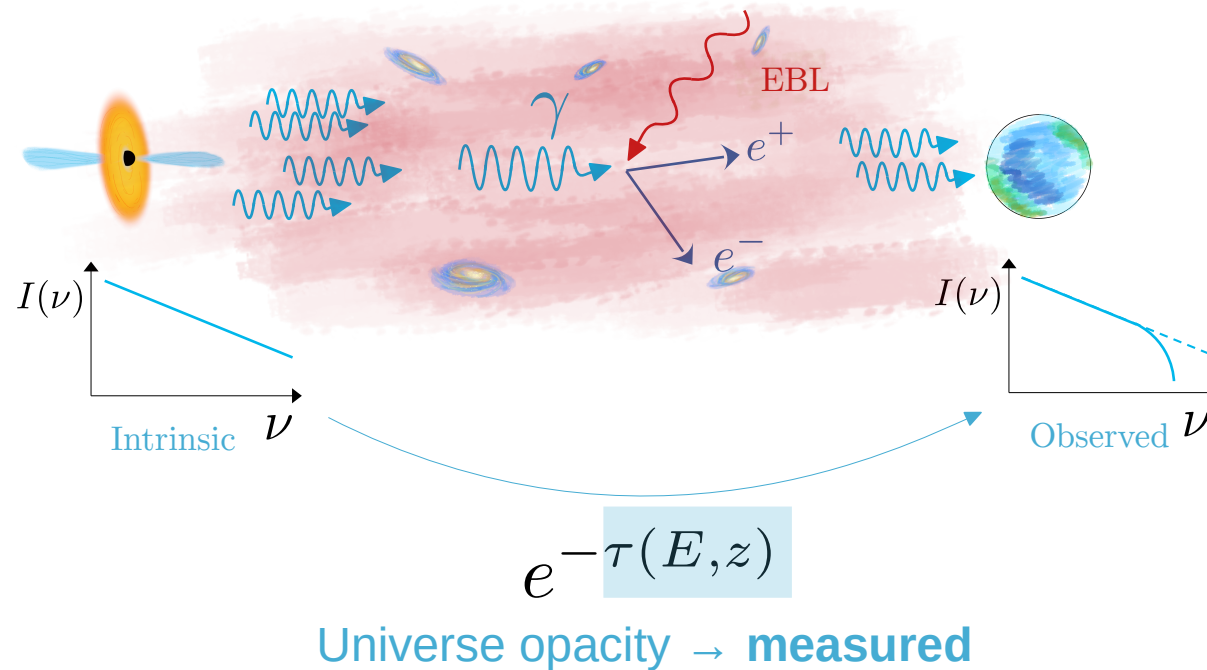


2. LIV with time delays between photons (temporal)

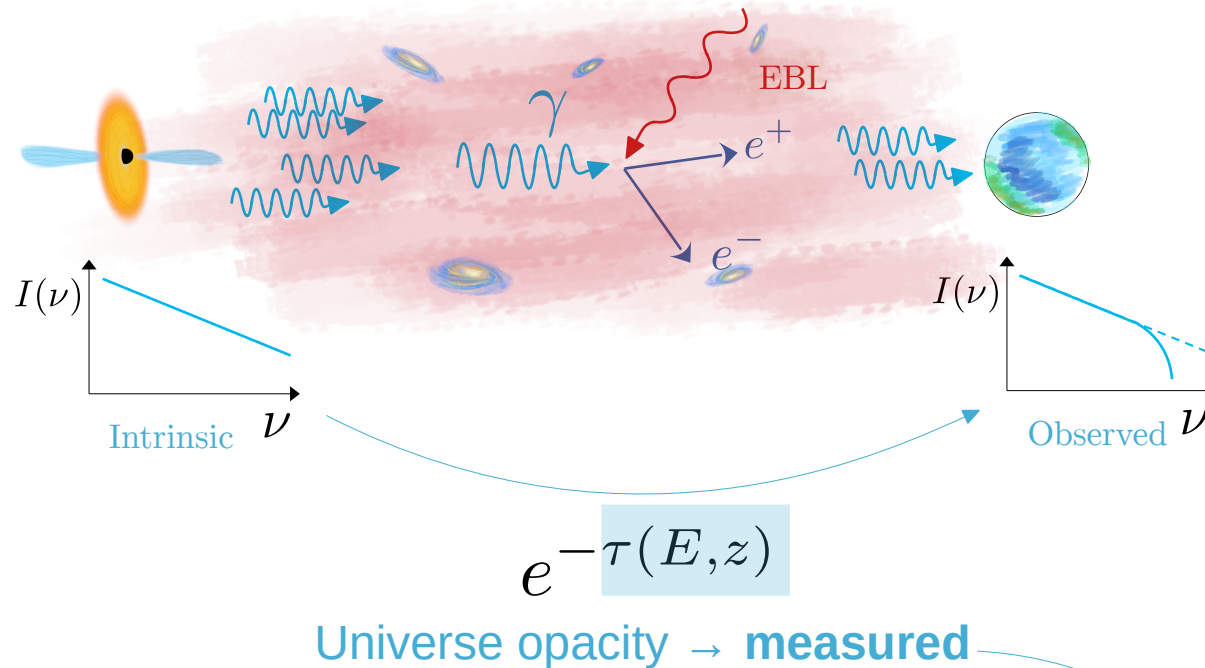


3. LIV with time delays between photons & neutrinos (correlations)

Measuring the extragalactic background light (EBL)



Measuring the extragalactic background light (EBL)



$$\tau(E, z) = \int_0^z \frac{dl'}{dz'} dz' \int_{-1}^1 d \cos \theta \frac{1 - \cos \theta}{2} \int_{\epsilon_{\text{th}}}^{\infty} d\epsilon' \sigma_{\gamma\gamma}(\beta') n(\epsilon', z')$$

Density of EBL photons/energy $\rightarrow$ **derived**

$$\tau(E, z) = \int_0^z \frac{dl'}{dz'} dz' \int_{-1}^1 d \cos \theta \frac{1 - \cos \theta}{2} \int_{\epsilon_{\text{th}}}^{\infty} d\epsilon' \sigma_{\gamma\gamma}(\beta') n(\epsilon', z')$$

Depends on cosmological
parameters, like H_0

Depends on an eventual
LIV effect

Density of EBL
photons/energy

$$\tau(E, z) = \int_0^z \frac{dl'}{dz'} dz' \int_{-1}^1 d \cos \theta \frac{1 - \cos \theta}{2} \int_{\epsilon_{th}}^{\infty} d\epsilon' \sigma_{\gamma\gamma}(\beta') n(\epsilon', z')$$

Depends on cosmological parameters, like H_0

Depends on an eventual LIV effect

Density of EBL photons/energy

Fixed cosmology

No LIV

EBL measurement

H_0 measurement

No LIV

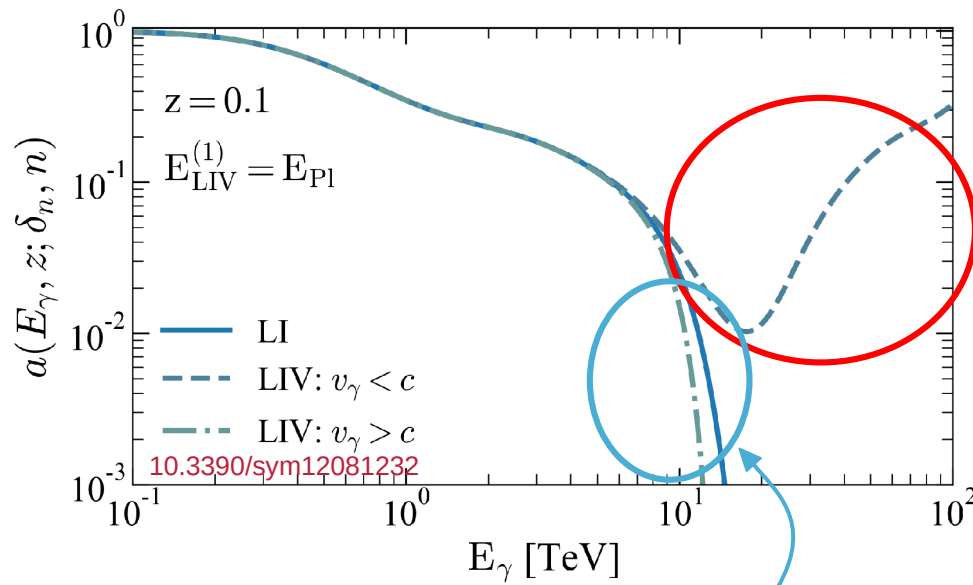
Measured independently

Fixed cosmology

LIV research

Measured independently

$$\tau(E, z) = \int_0^z \frac{dl'}{dz'} dz' \int_{-1}^1 d \cos \theta \frac{1 - \cos \theta}{2} \int_{\epsilon_{\text{th}}}^{\infty} d\epsilon' \sigma_{\gamma\gamma}(\beta') n(\epsilon', z')$$



$$E \geq \frac{m_e^2 c^2}{E_\gamma} \mp \left(\frac{E_\gamma}{E_{\text{LIV},n}} \right)^n E_\gamma$$

Subluminal (+) means less opacity

Highest constraint (Lang et al., 2019):

$$E_{\text{LIV},n=1} > 1, 2 \times 10^{20} \text{ GeV}$$

Supraluminal (-) means more opacity

$$\tau(E, z) = \int_0^z \frac{dl'}{dz'} dz' \int_{-1}^1 d \cos \theta \frac{1 - \cos \theta}{2} \int_{\epsilon_{th}}^{\infty} d\epsilon' \sigma_{\gamma\gamma}(\beta') n(\epsilon', z')$$

Depends on cosmological parameters, like H_0

Depends on an eventual LIV effect

Density of EBL photons/energy

Current work:

project with Lucas Gréaux (IJCLab → Bochum, Germany) & Guillaume Grolleron (LPNHE → LAPP)

- Method independent of spectral modelization & EBL model
- Largest dataset possible from Cherenkov telescopes, with IRF

Part of a taskforce with members of several Cherenkov telescope collaborations



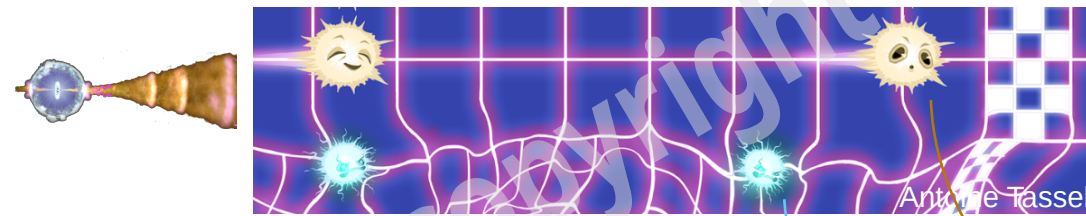
1. LIV with energy thresholds (spectral)



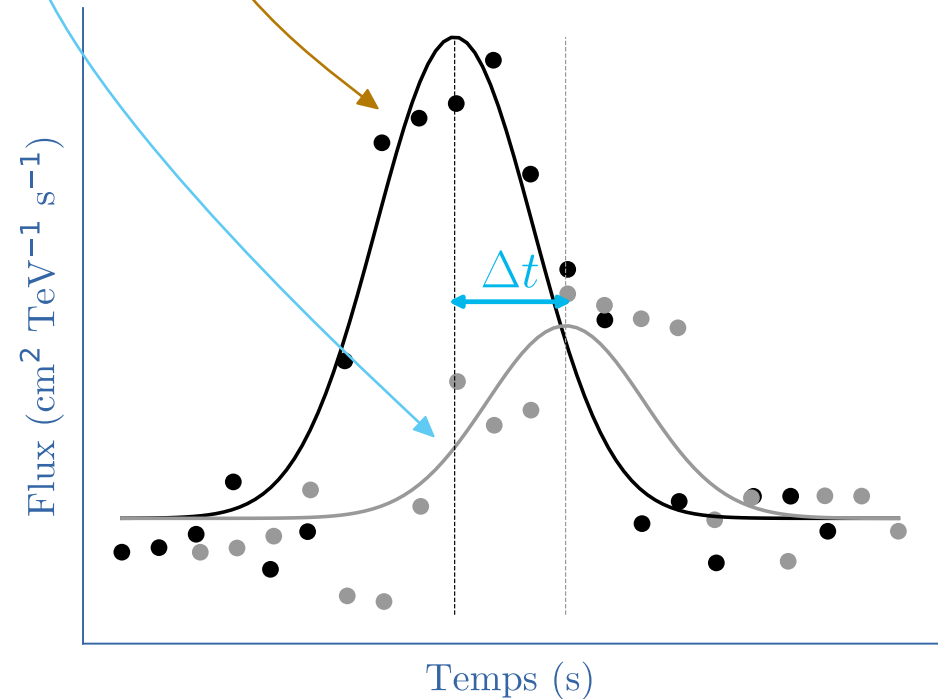
2. LIV with time delays between photons (temporal)



3. LIV with time delays between photons & neutrinos (correlations)

$$\Delta t_n = \pm \frac{n+1}{2} \frac{\Delta E^n}{E_{\text{LIV},n}^n} \times \frac{\kappa_n(z)}{H_0}$$


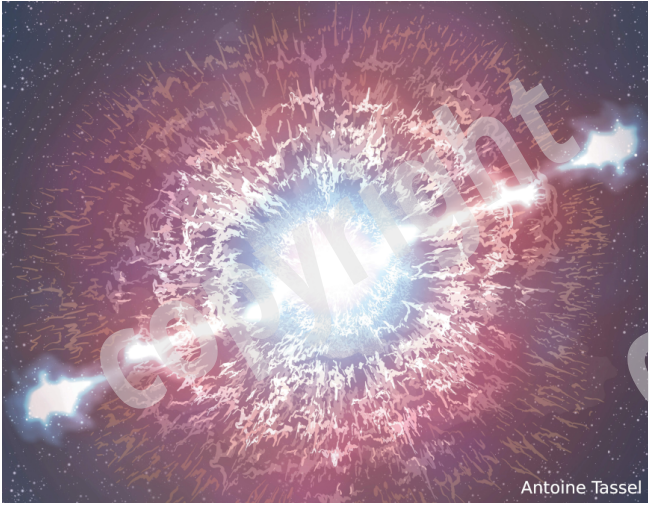
“Looking for an offset between light curves of two energy bins”



$$\Delta t_n = \pm \frac{n+1}{2} \frac{\Delta E^n}{E_{\text{LIV},n}^n} \times \frac{\kappa_n(z)}{H_0}$$



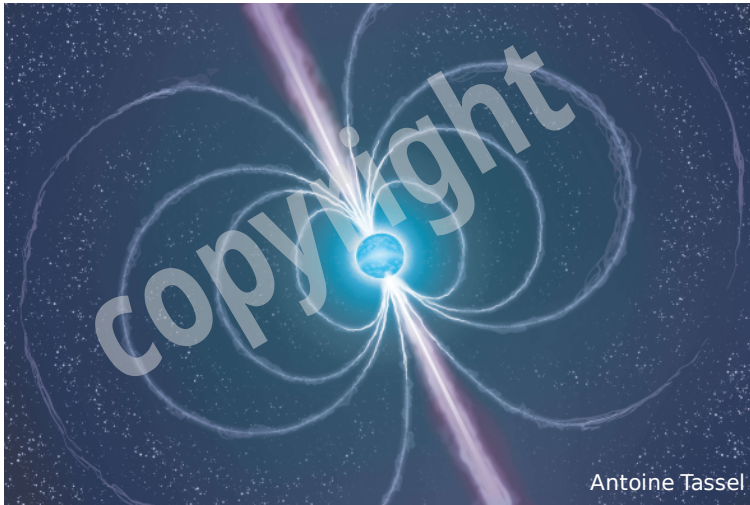
Gamma-ray bursts



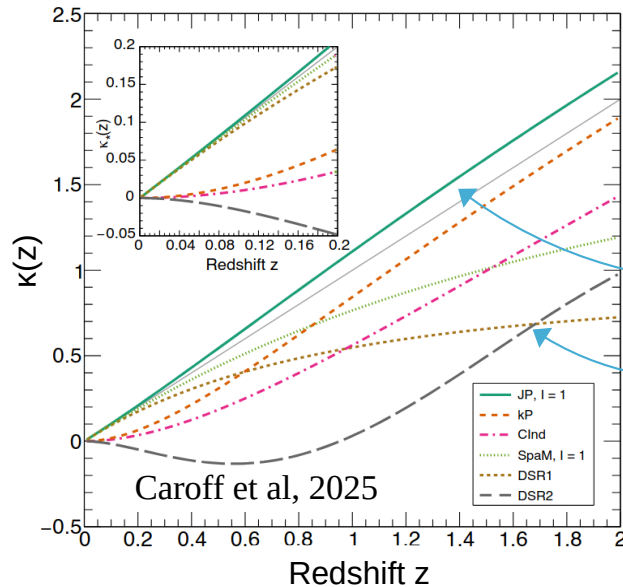
Blazars (flaring AGN)



Pulsars



Problem 1: Freedom of choice for modelisation of propagation



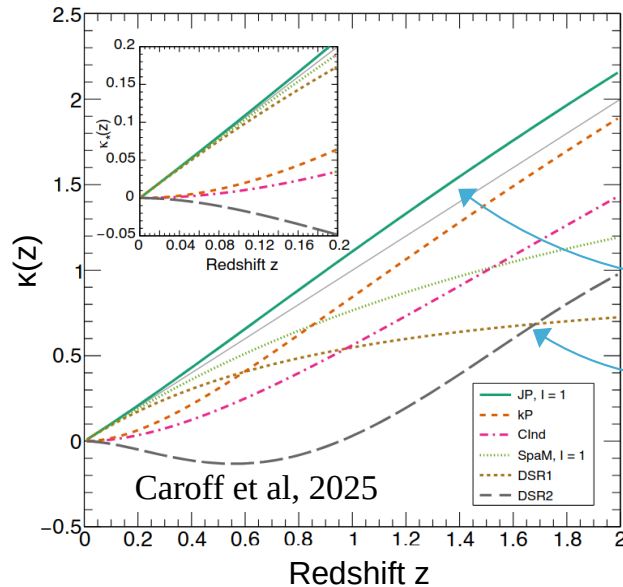
$$\Delta t_n = \pm \frac{n+1}{2} \frac{\Delta E^n}{E_{\text{LIV},n}^n} \times \frac{\kappa_n(z)}{H_0}$$

Needs to be “chosen”

$\kappa_n^{\text{JP}}(z)$ Jacob & Piran, 2008

$\kappa_{n=1}^{\text{DSR2}}(z, \alpha_1, \alpha_2, \alpha_3)$ Doubly special relativity

Problem 1: Freedom of choice for modelisation of propagation



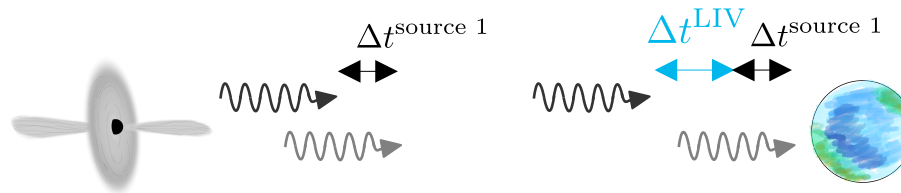
$$\Delta t_n = \pm \frac{n+1}{2} \frac{\Delta E^n}{E_{\text{LIV},n}^n} \times \frac{\kappa_n(z)}{H_0}$$

Needs to be “chosen”

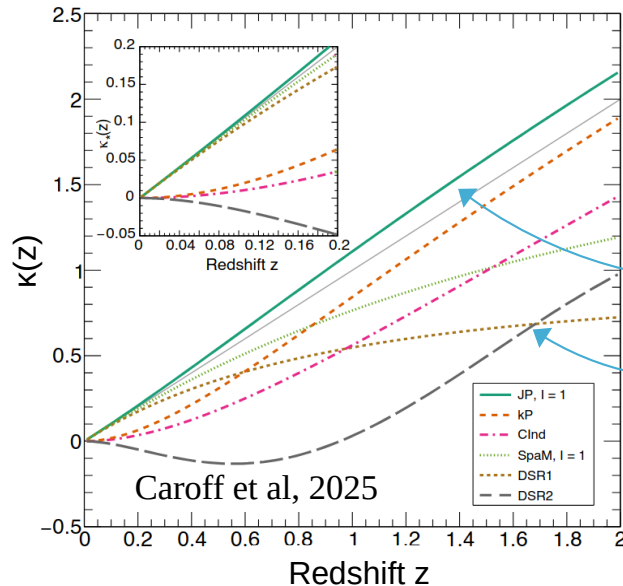
$\kappa_n^{\text{JP}}(z)$ Jacob & Piran, 2008

$\kappa_{n=1}^{\text{DSR2}}(z, \alpha_1, \alpha_2, \alpha_3)$ Doubly special relativity

Problem 2: Intrinsic source delays may appear



Problem 1: Freedom of choice for modelisation of propagation



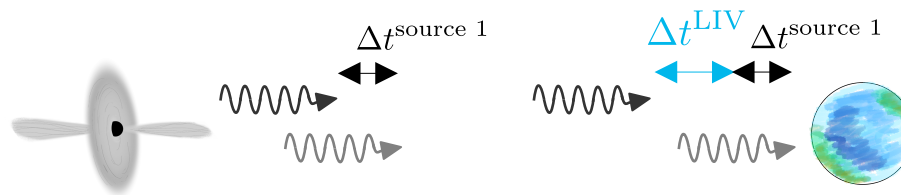
$$\Delta t_n = \pm \frac{n+1}{2} \frac{\Delta E^n}{E_{\text{LIV},n}^n} \times \frac{\kappa_n(z)}{H_0}$$

Needs to be “chosen”

$\kappa_n^{\text{JP}}(z)$ Jacob & Piran, 2008

$\kappa_{n=1}^{\text{DSR2}}(z, \alpha_1, \alpha_2, \alpha_3)$ Doubly special relativity

Problem 2: Intrinsic source delays may appear



- Combination of sources distributed over a large range of redshifts
- Combination of various sources (and flares) and various types of sources

Combination of Cherenkov telescopes data

LIV – Spectral – Temporal – Correlations

H.E.S.S.



MAGIC



VERITAS



Ugo Pensac & Julien Bolmont (LPNHE)

Tomislav Terzic (Croatia)

Samantha Wong (Canada)

γ -LIV WG sample

LST-1 (CTAO)



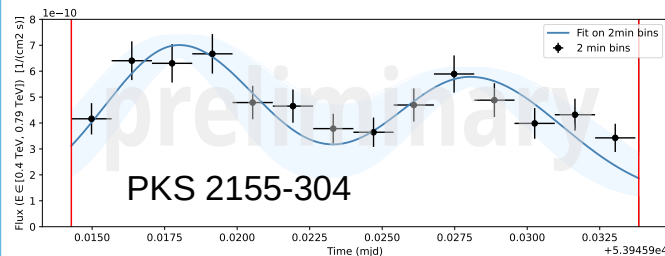
Me & Sami Caroff (LAPP)

Combination of Cherenkov telescopes data

LIV – Spectral – Temporal – Correlations

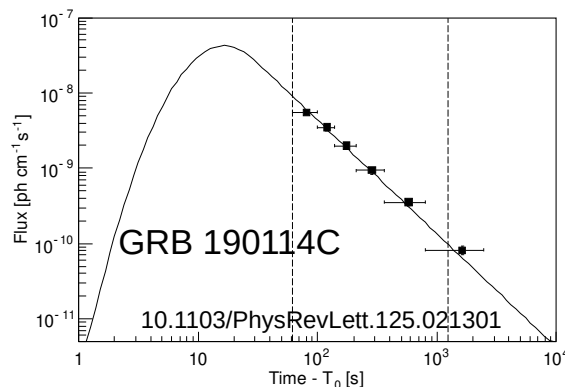
H.E.S.S.

1 AGN flare ($z=0.11610$)



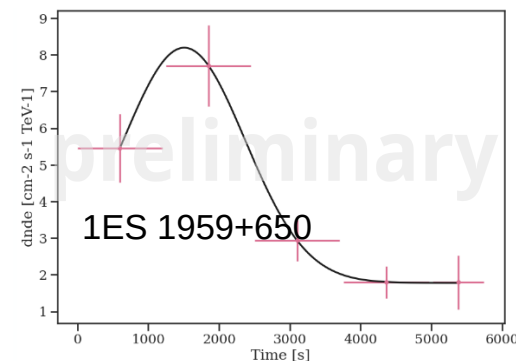
MAGIC

1 GRB ($z=0.425$)



VERITAS

1 AGN flare ($z=0.047$)



Ugo Pensac & Julien Bolmont (LPNHE)

Tomislav Terzic (Croatia)

Samantha Wong (Canada)

1 GRB + 7 AGN flares (4 different redshifts)

LST-1 (CTAO)

All flares within all suitable AGN observations: 5 flares of 1 AGN ($z=0.069$, BL Lacertae)

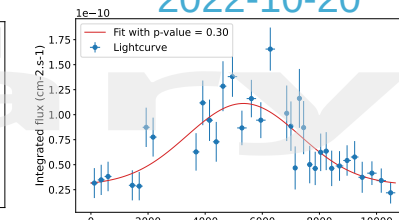
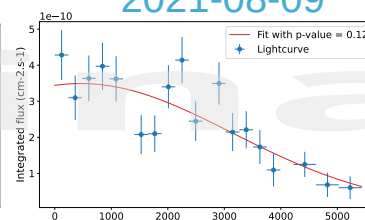
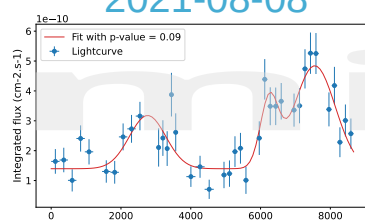
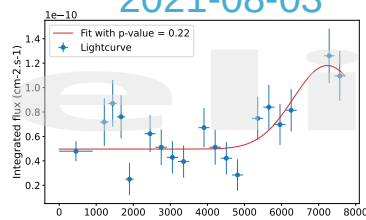
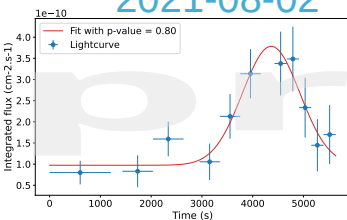
2021-08-02

2021-08-03

2021-08-08

2021-08-09

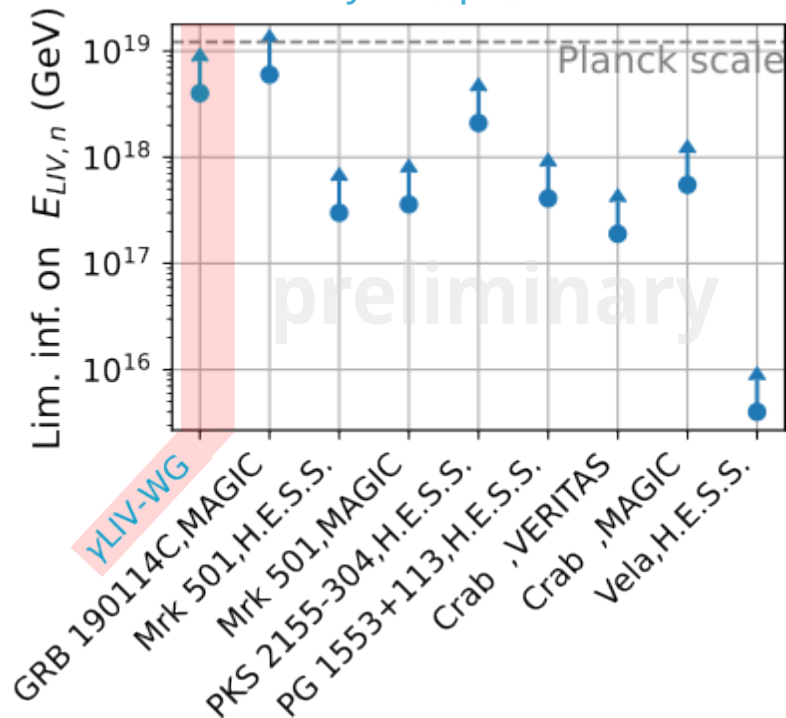
2022-10-20



Me & Sami Caroff (LAPP)

Results & comparison

Likelihood minimisation
→ delay compatible with 0



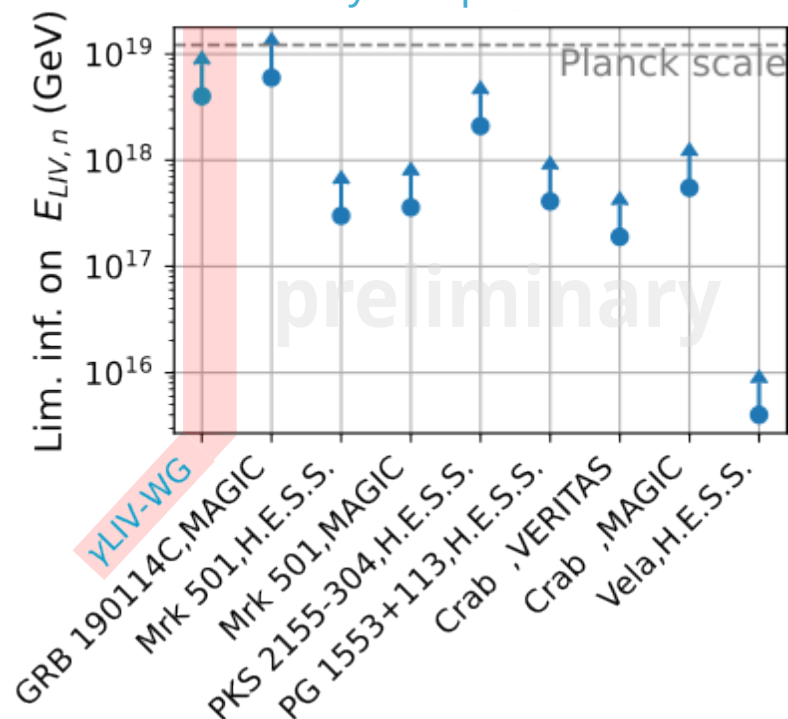
First analysis combining different types of sources & taking into account the largest set of uncertainties sources

Combination of Cherenkov telescopes data

LIV – Spectral – Temporal – Correlations

Results & comparison

Likelihood minimisation
→ delay compatible with 0

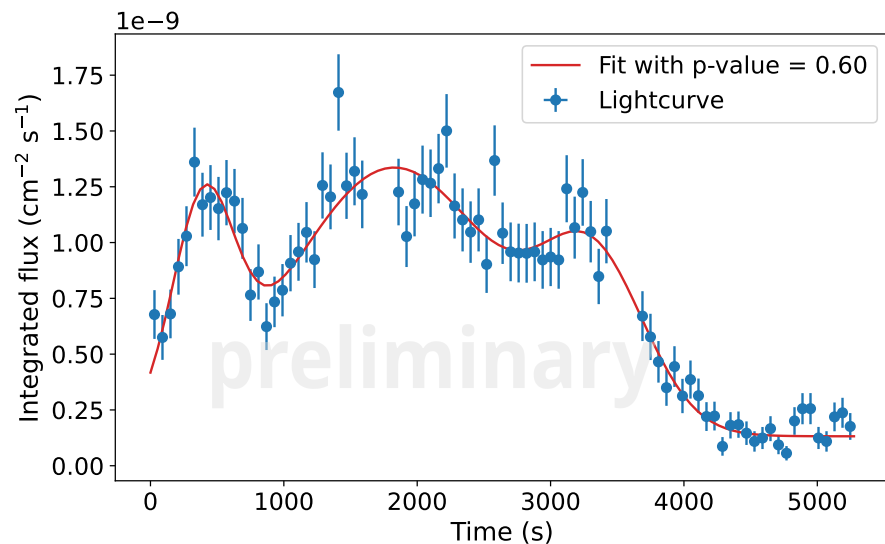


First analysis combining different types of sources & taking into account the largest set of uncertainties sources

Current work: more sources!

After LST-1, scan of H.E.S.S. data!

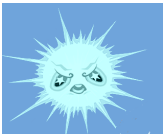
Already implemented the “big flare” of PKS 2155-304.



Goal: catalog of AGN variability in H.E.S.S.



1. LIV with energy thresholds (spectral)



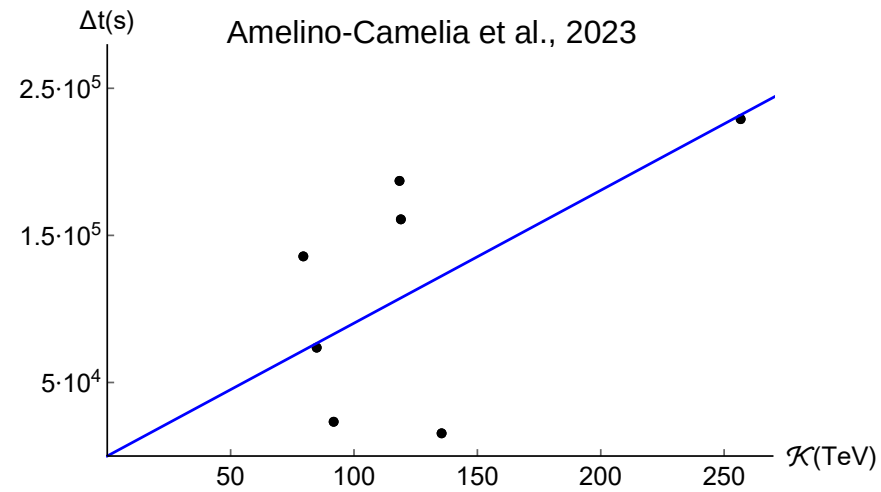
2. LIV with time delays between photons (temporal)

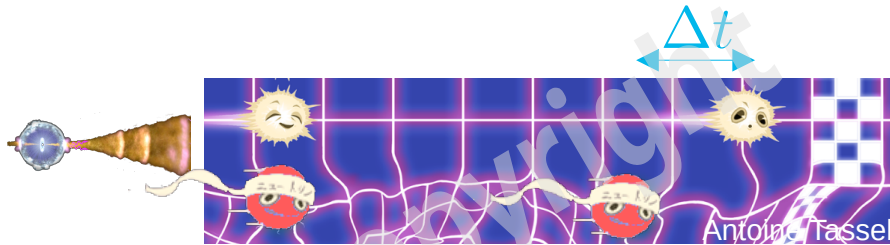


3. LIV with time delays between photons & neutrinos (correlations)



$$\Delta t = \pm \frac{\kappa_n^*(E, z)}{E_{\text{LIV}}} = \pm \frac{\kappa_n^*(E, z)\eta}{E_P}$$

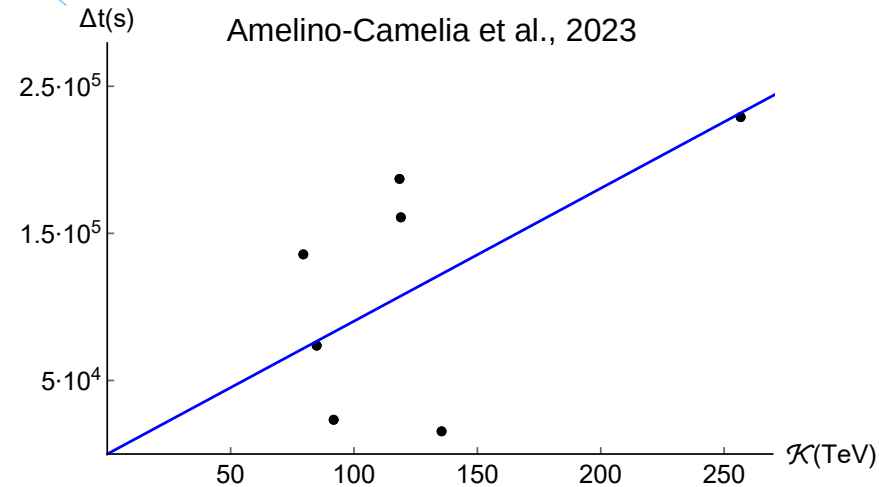


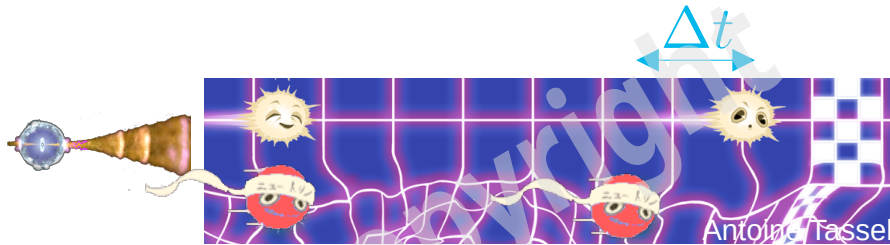


$$\Delta t = \pm \frac{\kappa_n^*(E, z)}{E_{\text{LIV}}} = \pm \frac{\kappa_n^*(E, z)\eta}{E_P}$$

Correlation between neutrinos & GRB triggers.

- Found 10 candidates using 7.5 years of IceCube data (HESE) based on temporal window & cartesian distance window.
- Excluded the supraluminal case and kept only the 7 candidates for subluminal case.

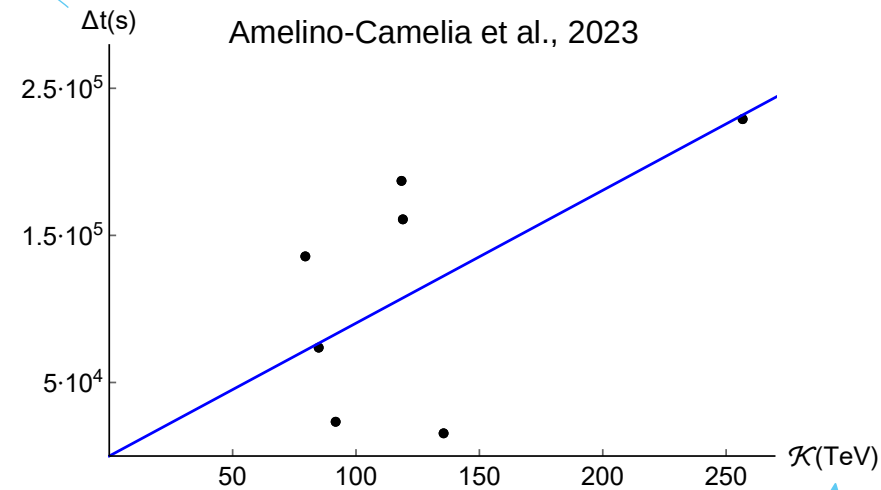




$$\Delta t = \pm \frac{\kappa_n^*(E, z)}{E_{\text{LIV}}} = \pm \frac{\kappa_n^*(E, z)\eta}{E_P}$$

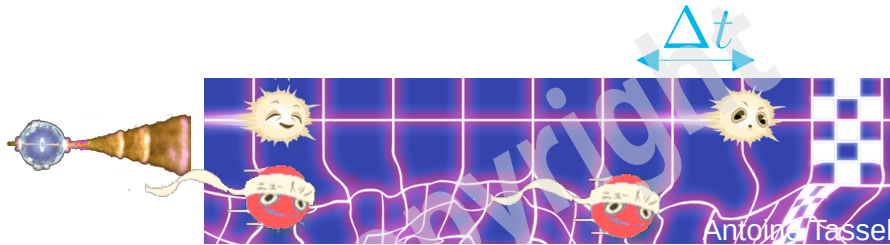
Correlation between neutrinos & GRB triggers.

- Found 10 candidates using 7.5 years of IceCube data (HESE) based on temporal window & cartesian distance window.
- Excluded the supraluminal case and kept only the 7 candidates for subluminal case.



Compute the energy-model function $\kappa(E, z)$
 → need to estimate the redshift

- Only 1 GRB has measured redshift.
- Assigned fixed values to the 6 remaining.



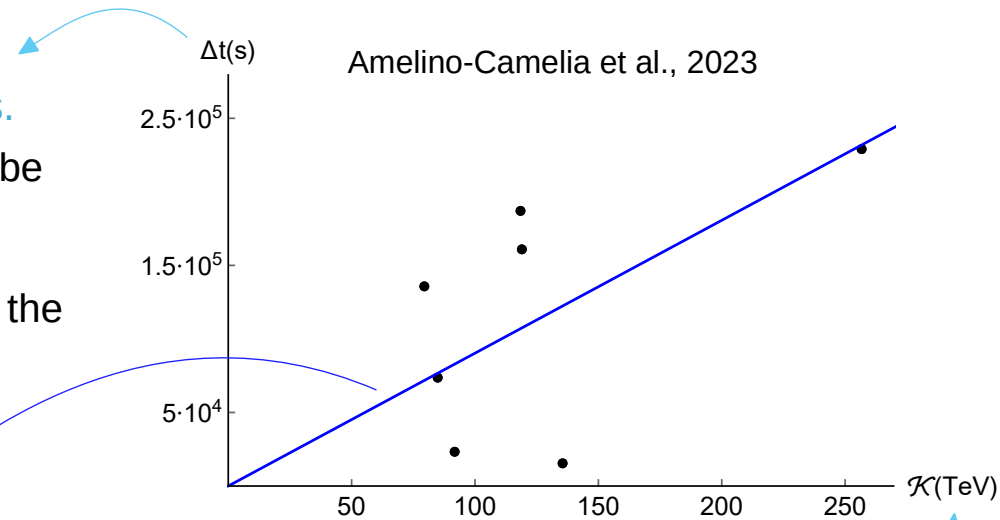
$$\Delta t = \pm \frac{\kappa_n^*(E, z)}{E_{\text{LIV}}} = \pm \frac{\kappa_n^*(E, z)\eta}{E_P}$$

Correlation between neutrinos & GRB triggers.

- Found 10 candidates using 7.5 years of IceCube data (HESE) based on temporal window & cartesian distance window.
- Excluded the supraluminal case and kept only the 7 candidates for subluminal case.

From the linear fit, get E_{LIV}

Found significant result of $\eta = 21.7 \pm 4.5$.
They have “detected” an LIV effect!!!!!!



Compute the energy-model function $\kappa(E, z)$
→ need to estimate the redshift

- Only 1 GRB has measured redshift.
- Assigned fixed values to the 6 remaining.



$$\Delta t = \pm \frac{\kappa_n^*(E, z)}{E_{\text{LIV}}} = \pm \frac{\kappa_n^*(E, z)\eta}{E_P}$$

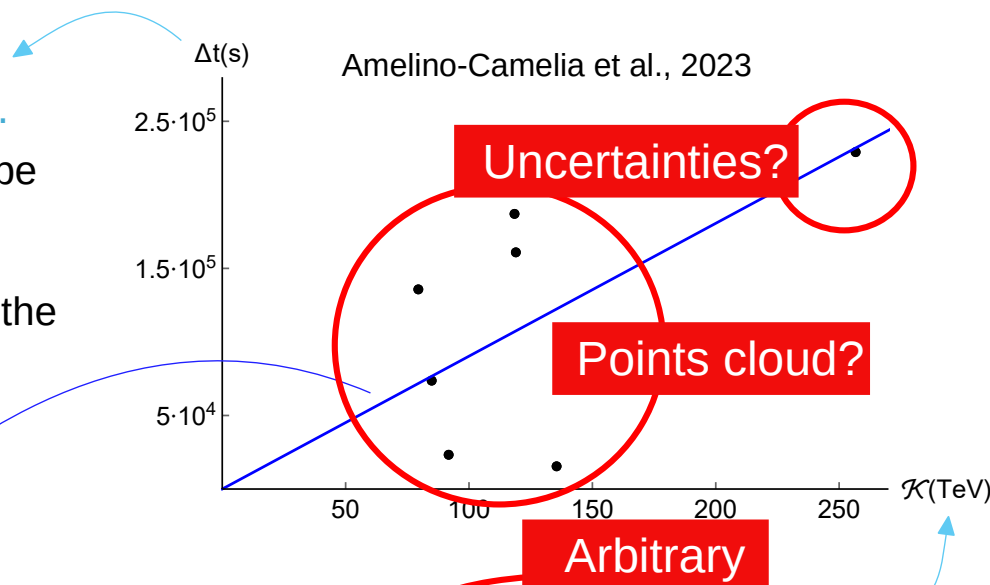
Correlation between neutrinos & GRB triggers.

- Found 10 candidates of IceCube
- Approx. (ESE) based on temporal window & cartesian distance window.
- Excluded the supraluminal case and kept only the 7 candidates for subluminal case.

Offset?

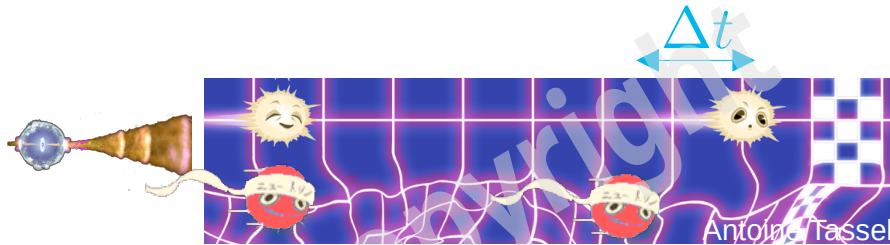
From the linear fit get E_{LIV}

Found significant result of $\eta = 21.7 \pm 4.5$.
They have "???" an LIV effect!!!!!!



Compute the energy-model function $\kappa(E, z)$
→ need to estimate the redshift

- GRB has measured redshift.
- Assigned fixed values to the 6 remaining.



$$\Delta t = \pm \frac{\kappa_n^*(E, z)}{E_{\text{LIV}}} = \pm \frac{\kappa_n^*(E, z)\eta}{E_P}$$

Internship of Debasish Chabanya co-supervised with Rafel Alves Batista

1. Correlation between neutrinos & GRB triggers.

→ Found **13 candidates** using **12 years** of IceCube data (HESE) with **spherical geometry**.

2. Estimate the redshift of GRB (mostly unknown).

→ Only 2 GRB have measured redshift.

→ For the 11 remaining, used **probability density functions** from Wanderman & Piran (2010, 2015)

3. Compute the energy-model function $\kappa(E, z)$

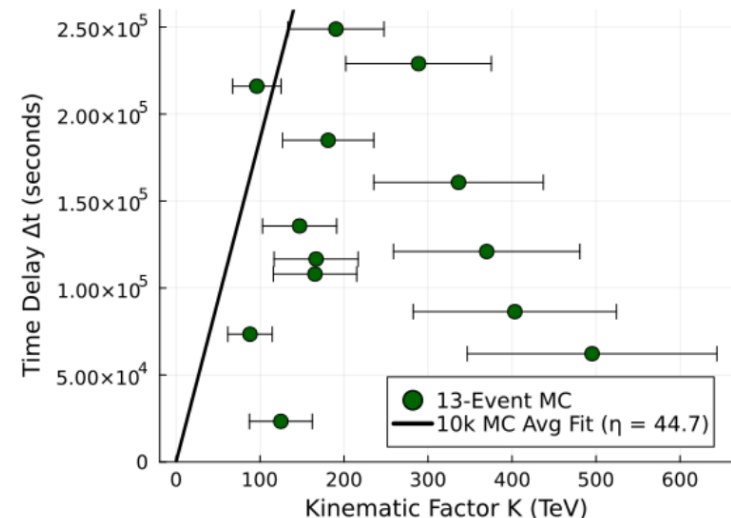
→ **Energy uncertainty** is of $\pm 30\%$.

→ **Redshift uncertainty** estimated from 10,000 MC.

4. From the linear fit, get E_{LIV}

→ Reprocessing of previous dataset gives $\eta = 40 \pm 1100$!

→ Debasish's new dataset gives $\eta = 45 \pm 700$ → **no LIV**.

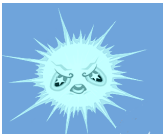


Lorentz invariance violation (LIV)



1. LIV with energy thresholds (spectral)

Using pair-production between γ -rays & EBL photons
→ opacity of the Universe in AGN **spectra**



2. LIV with time delays between photons (temporal)

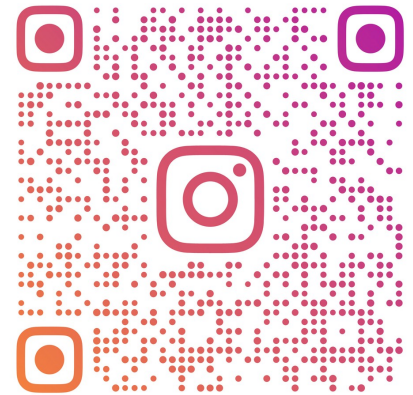
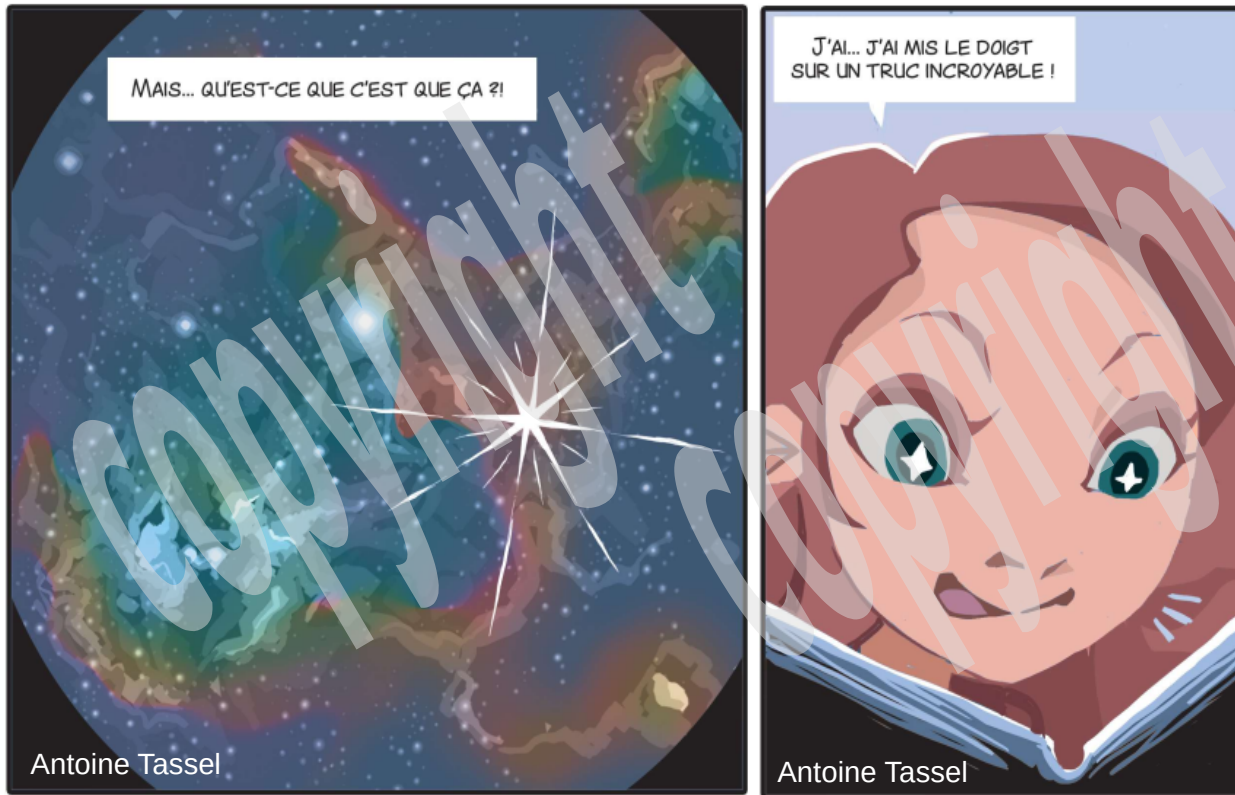
AGN, GRB & pulsar combination
→ energy-dependency of their **light curves**



3. LIV with time delays between photons & neutrinos (correlations)

Pair of neutrino detection & GRB triggers
→ linear dependency of the delays vs energy

L'odyssée cosmique de Pénélope



Sortie en novembre 2026 avec CNRS édition !