In-vacuo-dispersion-like spectral lags in gamma-ray bursts

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TeVPA 2018, Berlin

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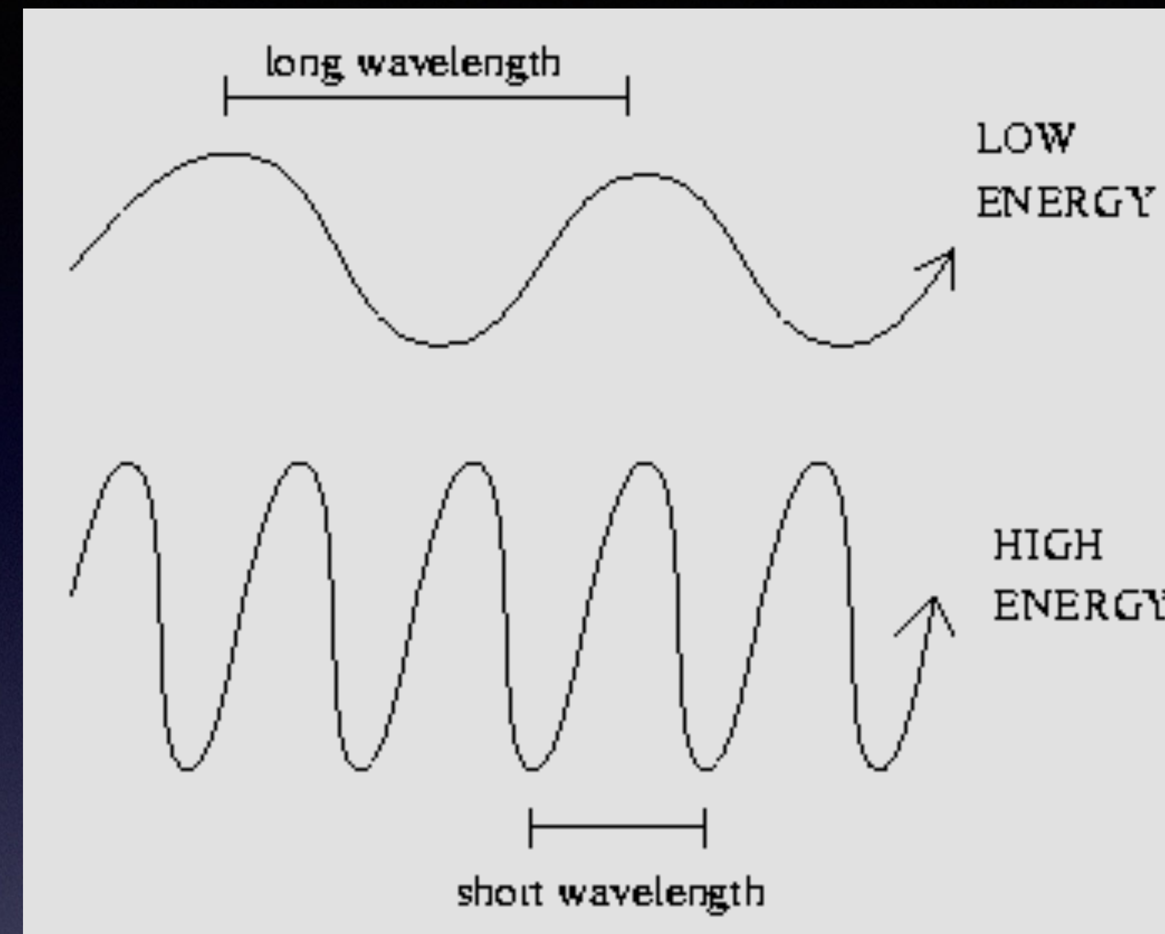
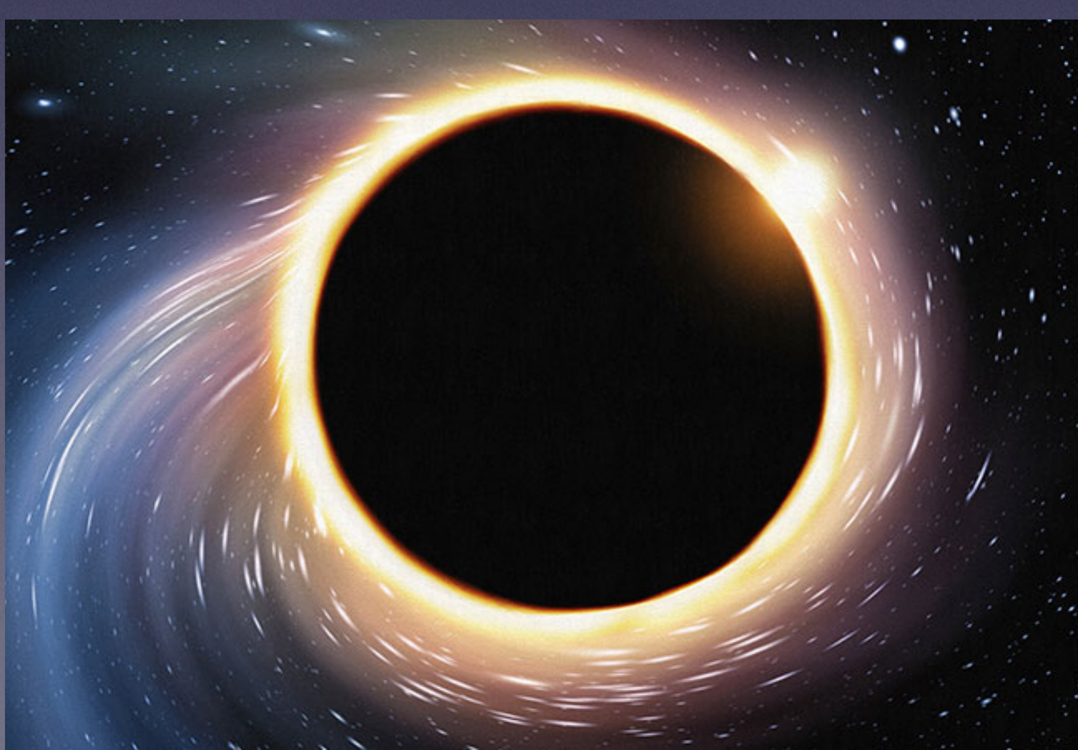
"QM + GR"

$$\lambda_C \sim \frac{\hbar c}{E}$$



$$\lambda_C \sim \lambda_S \sim \frac{GE}{c^4}$$



$$\lambda \gtrsim \sqrt{\frac{G\hbar}{c^3}} = \ell_{\rm Pl} \approx 10^{-35}\ \rm m$$

- Doubly (or Deformed) Special Relativity (and Relative Locality):

Amelino-Camelia, Int. J. Mod. Phys. D11 (2002); Amelino-Camelia, Phys. Lett. B510 (2001); Magueijo, Smolin, Phys. Rev. Lett. 88 (2002); Kowalski-Glikman, Nowak, Phys. Lett. B539 (2002); Freidel, Kowalski-Glikman, Smolin, Phys. Rev. D69 (2004); Amelino-Camelia, Freidel, Kowalski-Glikman, Smolin, Phys. Rev. D 84 (2011).

- Quantum Groups and Non-commutative Geometry:

Majid, Ruegg, Phys. Lett. B334 (1994); Lukierski, Ruegg, Tolstoi, Phys. Lett. B264 (1991); Lukierski, Nowicki, Ruegg, Phys. Lett. B293 (1992); Amelino-Camelia, Majid, Int. J. Mod. Phys. A15 (2000).

- Loop Quantum Gravity (and 3D Quantum Gravity):

Gambini, Pullin, Phys. Rev. D59 (1999); Alfaro, Morales-Tecotl, Urrutia, Phys. Rev. Lett. 84 (2000); Alfaro, Morales-Tecotl, Urrutia, Phys. Rev. D65 (2002); Bojowald, Morales-Tecotl, Sahlmann, Phys. Rev. D71 (2005); Girelli, Livine, Oriti, Nucl. Phys. B708 (2005); Girelli, Hinterleitner, Major, SIGMA 8 (2012); Amelino-Camelia, da Silva, MR, Cesarini, Lecian, Phys. Rev. D95 (2017); Brahma, MR, Amelino-Camelia, Marciano, Phys. Rev. D95 (2017); Freidel, Livine, Phys. Rev. Lett. 96 (2006); Brahma, MR, Phys.Lett. B778 (2018).

- String Theory:

Veneziano, Europhys. Lett. 2 (1986); Konishi, Paffuti, Provero, Phys. Lett. B234 (1990); Ellis, Mavromatos, Nanopoulos, Phys. Rev. D65 (2002); Magueijo, Smolin, Phys. Rev. D71 (2005); Freidel, Leigh, Minic, Phys. Rev. D94 (2016).

- Horava-Lifshitz Gravity:

Magueijo, Phys. Rev. Lett. 100 (2008); Vacaru, Gen. Rel. Grav. 44 (2012); Amelino-Camelia, Gualtieri, Mercati, Phys. Lett. B686 (2010).

- Asymptotic Safety:

Girelli, Liberati, Percacci, Rahmede, Class. Quant. Grav. 24 (2007); Calmet, Hossenfelder, Percacci, Phys. Rev. D82 (2010).

- Causal Dynamical Triangulations:

Mielczarek, arXiv:1503.08794; Coumbe, Int. J. Mod. Phys. D26 (2017).

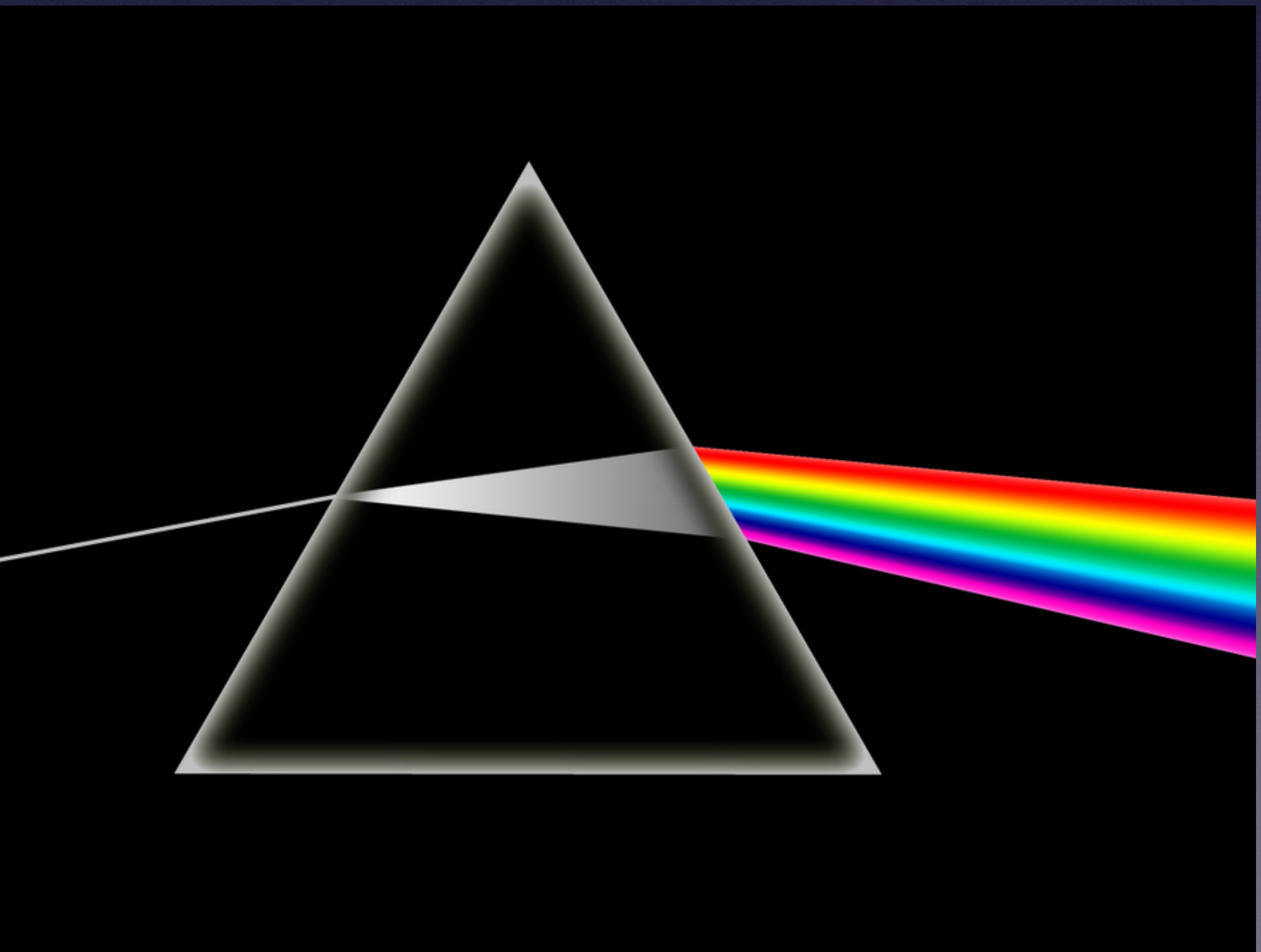
… too many models to test!!

A heuristic approach: MDR

$$E_P = \frac{1}{\ell_{\rm Pl}}\frac{\hbar}{c} \simeq 10^{19}\ \ {\rm GeV}$$

$$H^2 = m^2c^4 + p^2c^2 \to m^2c^4 + p^2c^2\left(1 + \eta\frac{E}{E_P} + \dots\right)$$

$$v = \frac{\partial H}{\partial p} \simeq c\left(1 + \eta\frac{E}{E_P} + \dots\right)$$



$$\frac{E}{E_P} \approx 10^{-15} - 10^{-6}$$

...extremely small effect, how can we detect it?

Cumulative time lags over cosmological distances

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

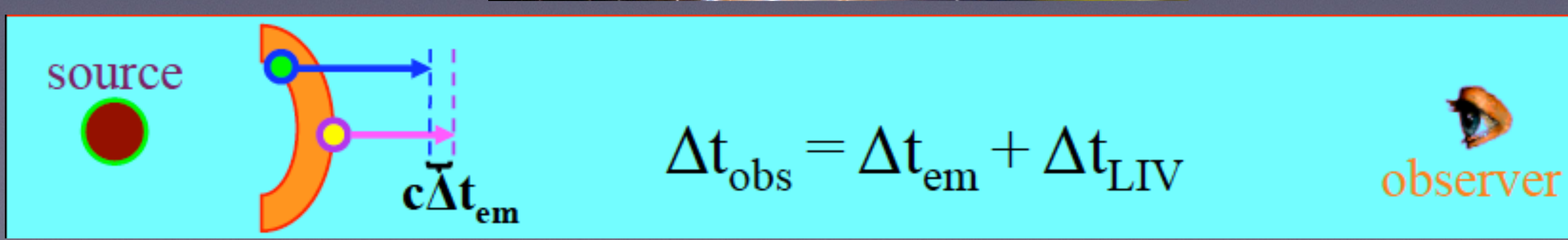
$$D(z) = \int_0^z d\zeta \frac{(1+\zeta)}{H_0\sqrt{\Omega_\Lambda + (1+\zeta)^3\Omega_m}}$$

Jacob, Piran, arXiv:0712.2170

Gamma ray bursts

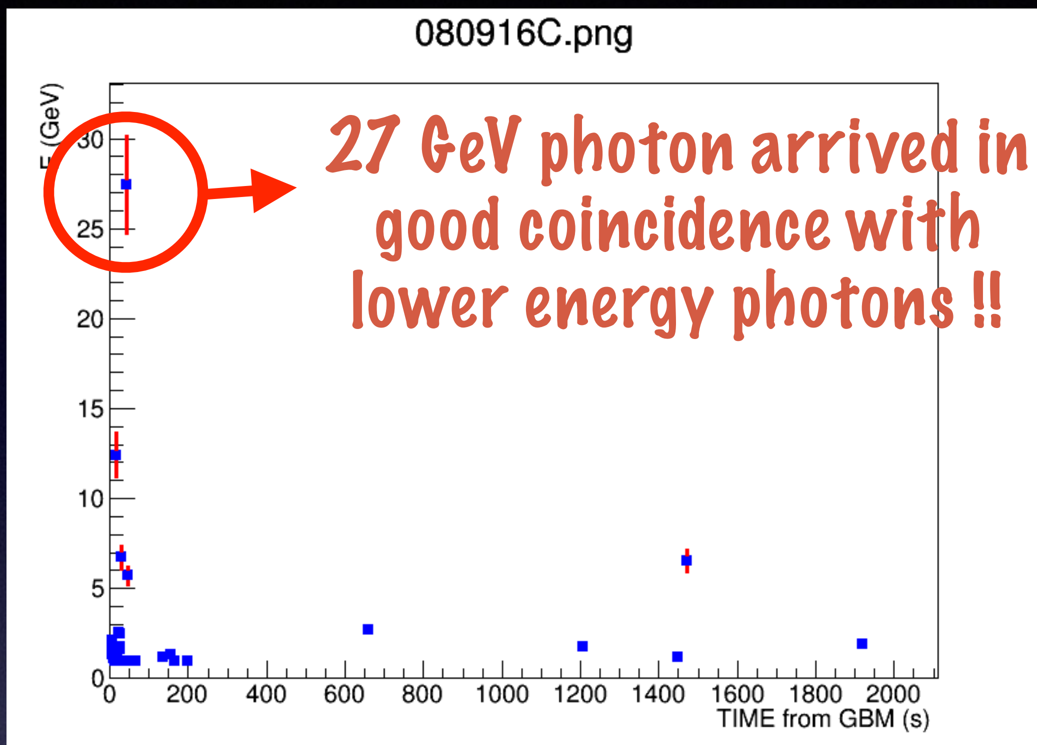
- High energy emission
- Time variability
- Cosmological distances (z>0)

Emission mechanism??



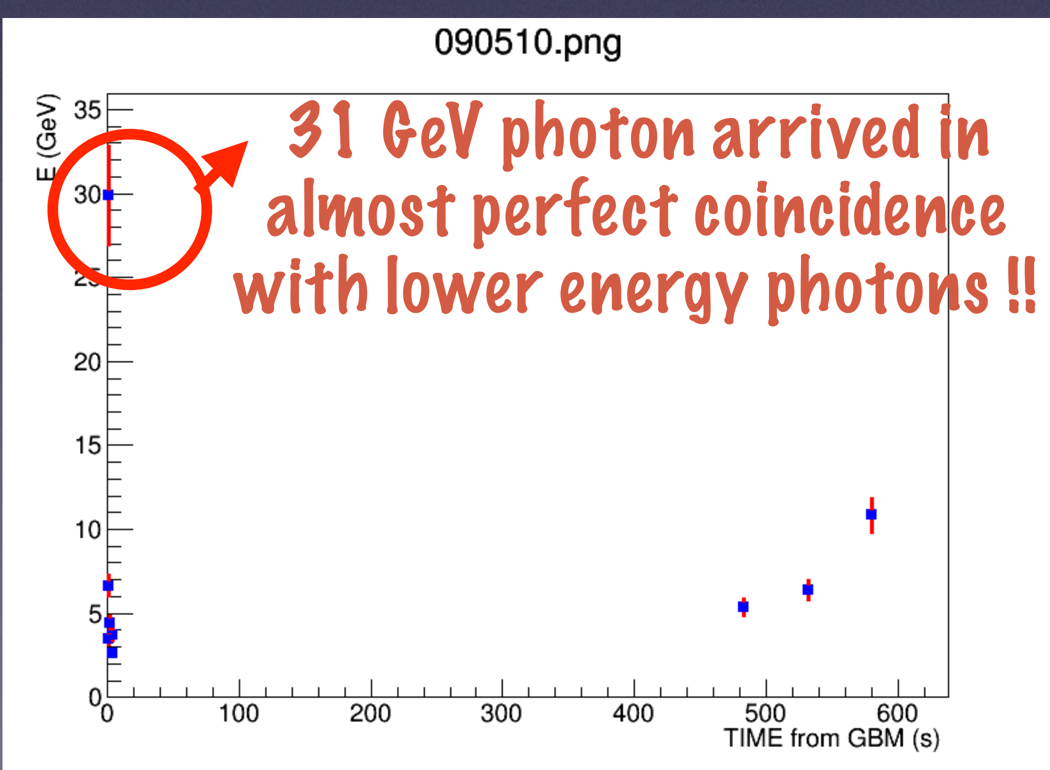
Single-burst analyses

GRB080916C: Fermi-LAT and GBM Collaborations, Science 323 (2009)



$$M_{QG} \gtrsim 10^{-1} M_P$$

GRB090510: Fermi-LAT and GBM Collaborations, Nature 462 (2009)

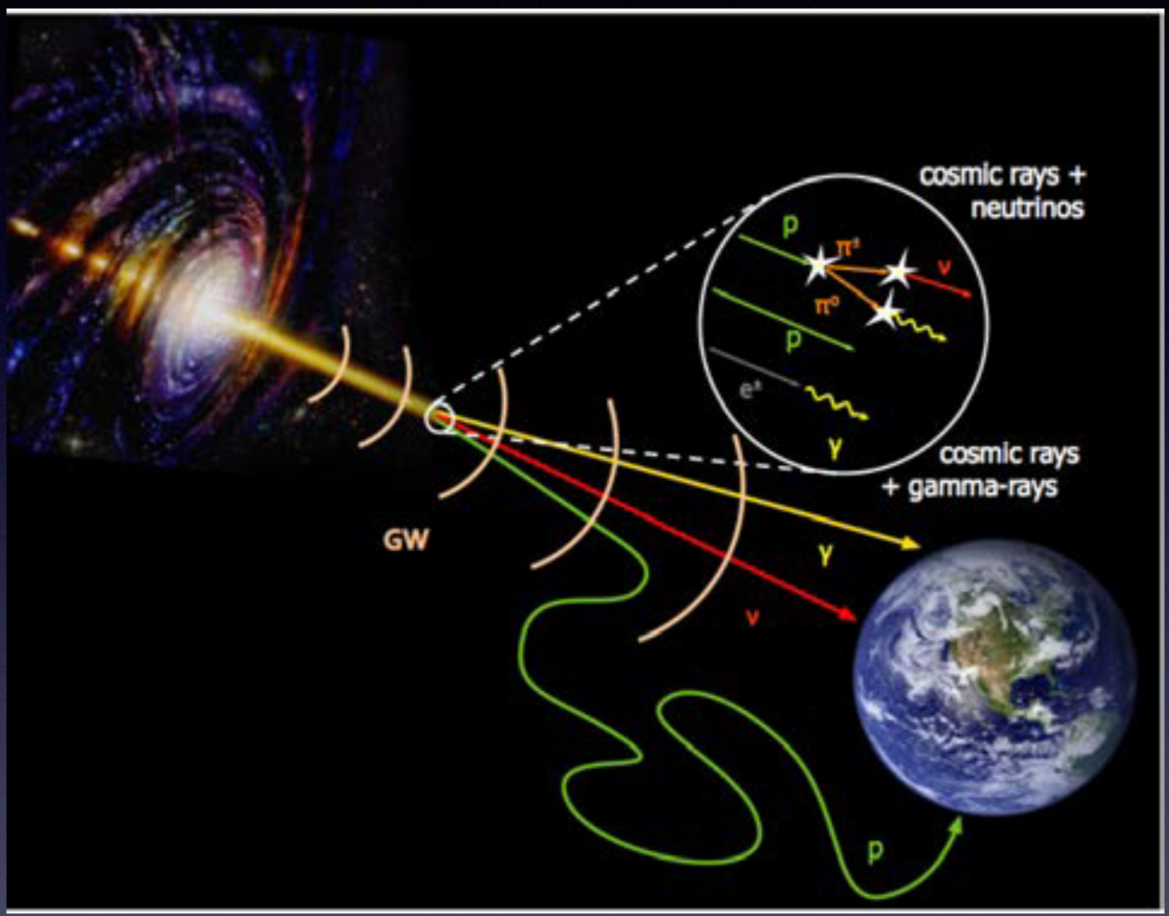


$$M_{QG} \gtrsim M_P$$

Experimental analyses for n=1
LIV reached the Planck scale!!!

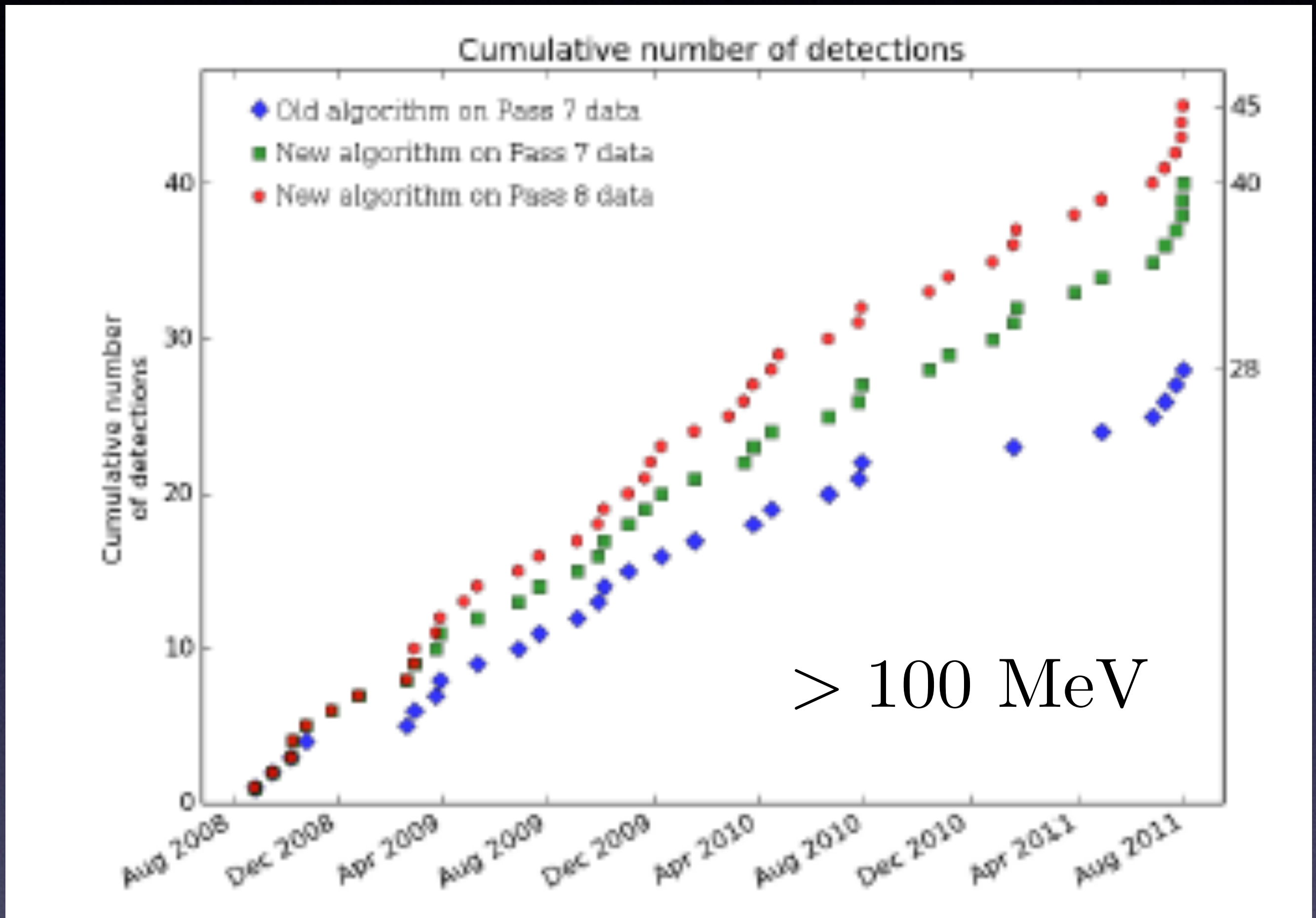
Forthcoming improvements

Multi-messenger



Amelino-Camelia, D'Amico, Rosati, Loret, Nature Astron. 1 (2017)

More statistics



Nava, arXiv:1804.01524

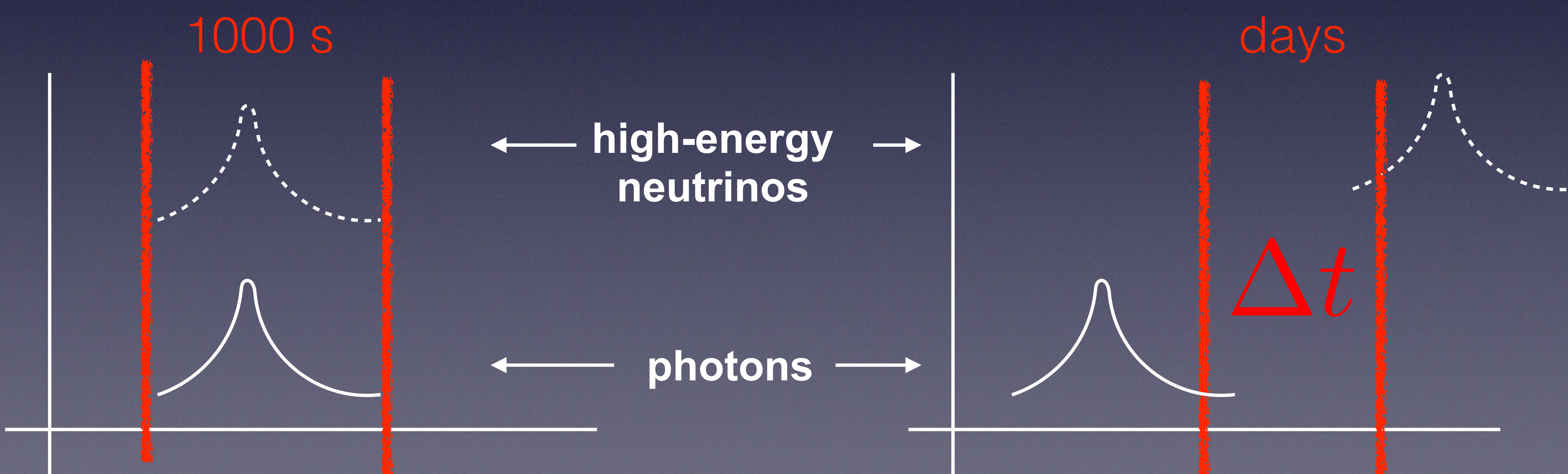
Amelino-Camelia, D'Amico, Fiore, Puccetti, MR, arXiv: 1707.02413

Neutrinos from GRBs?

All proposed models for GRB-emission mechanism (e.g. fireball) requires the production of neutrinos: we expect to detect 10 neutrinos per 1000 GRBs in a 1 Km cube detector (IceCube, Km3Net)

IceCube detected no GRB neutrinos so far!!
(2008-2017)

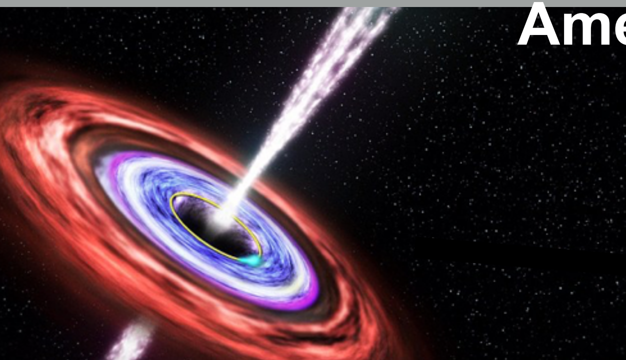
No LIV — LIV



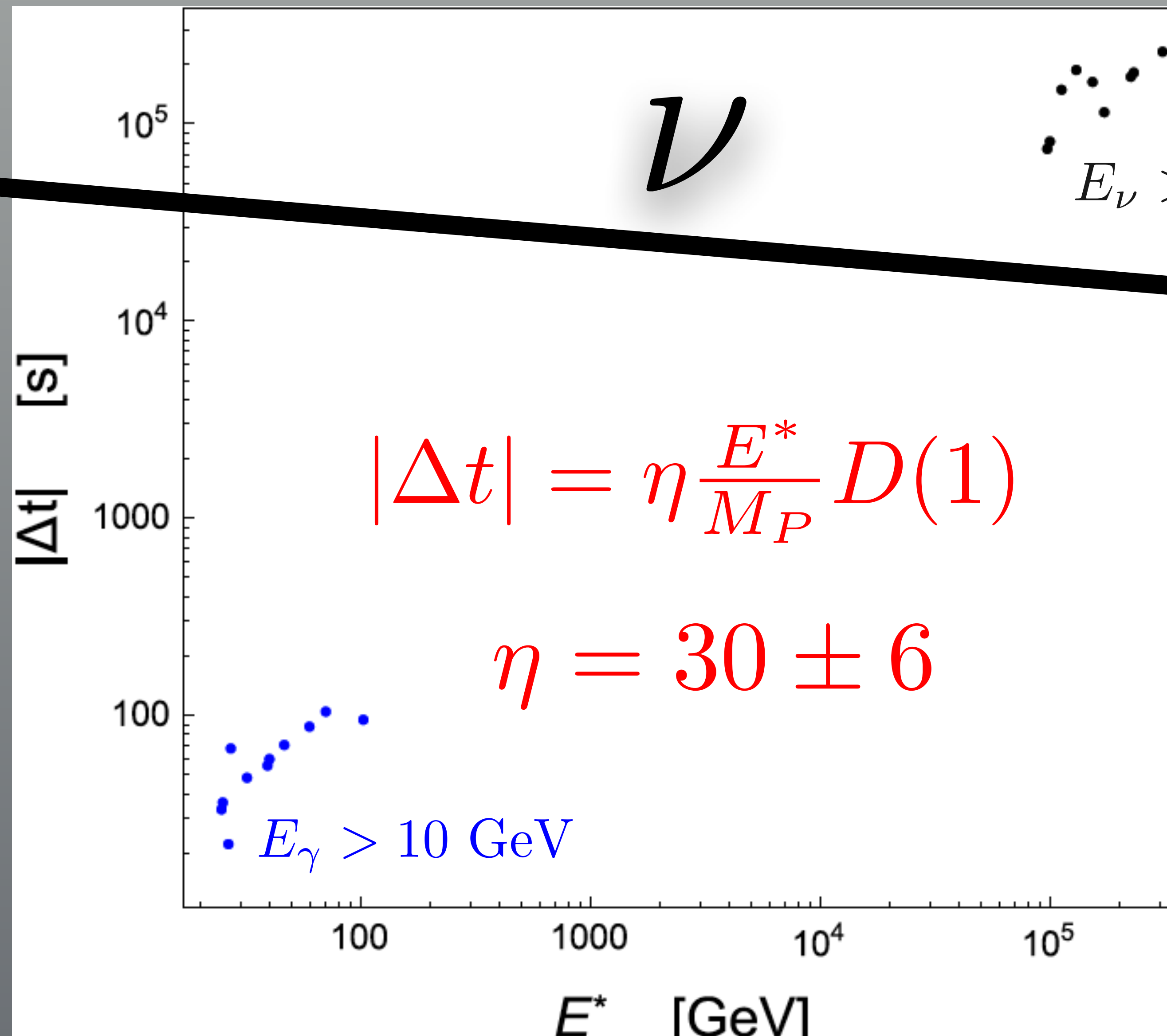
Time coincidence! — Time delay!

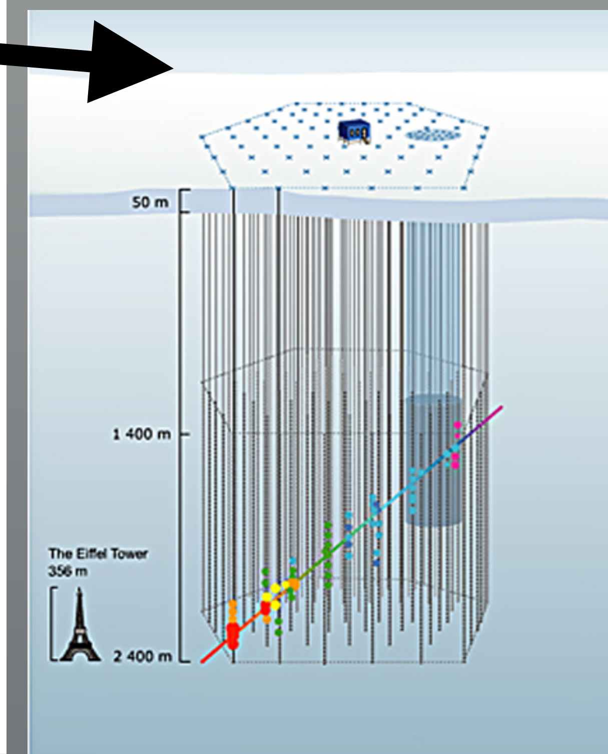
Hints of LIV??

Amelino-Camelia, D'Amico, Rosati, Loret, Nature Astron. 1 (2017)



ν





IceCube

γ

Fermi-LAT

in-vacuo dispersion-like feature:

time difference with respect to the first GBM peak

$$|\Delta t| = \eta \frac{E^*}{M_P} D(1) \quad \text{with} \quad E^* = E\frac{D(z)}{D(1)}$$

Increase statistics

Amelino-Camelia, D'Amico, Fiore, Puccetti, MR, arXiv:1707.02413

Selection criteria:

- known redshift z
- $E \times (1+z) > 5$ GeV

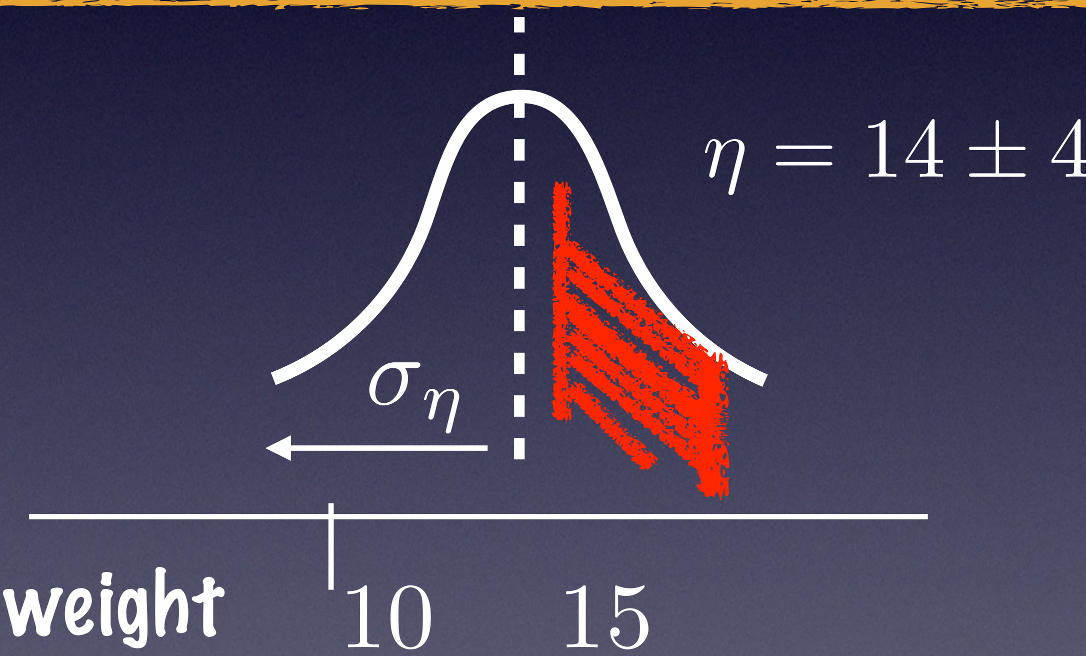
→

Data sample:
7 GRBs (080916C, 090510, 090902B, 090926A, 100414A, 130427A, 160509A) detected by FermiLAT, 148 photons analysed in total

For each pair of photons we compute:

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

10% error on energies considered with Gaussian weight



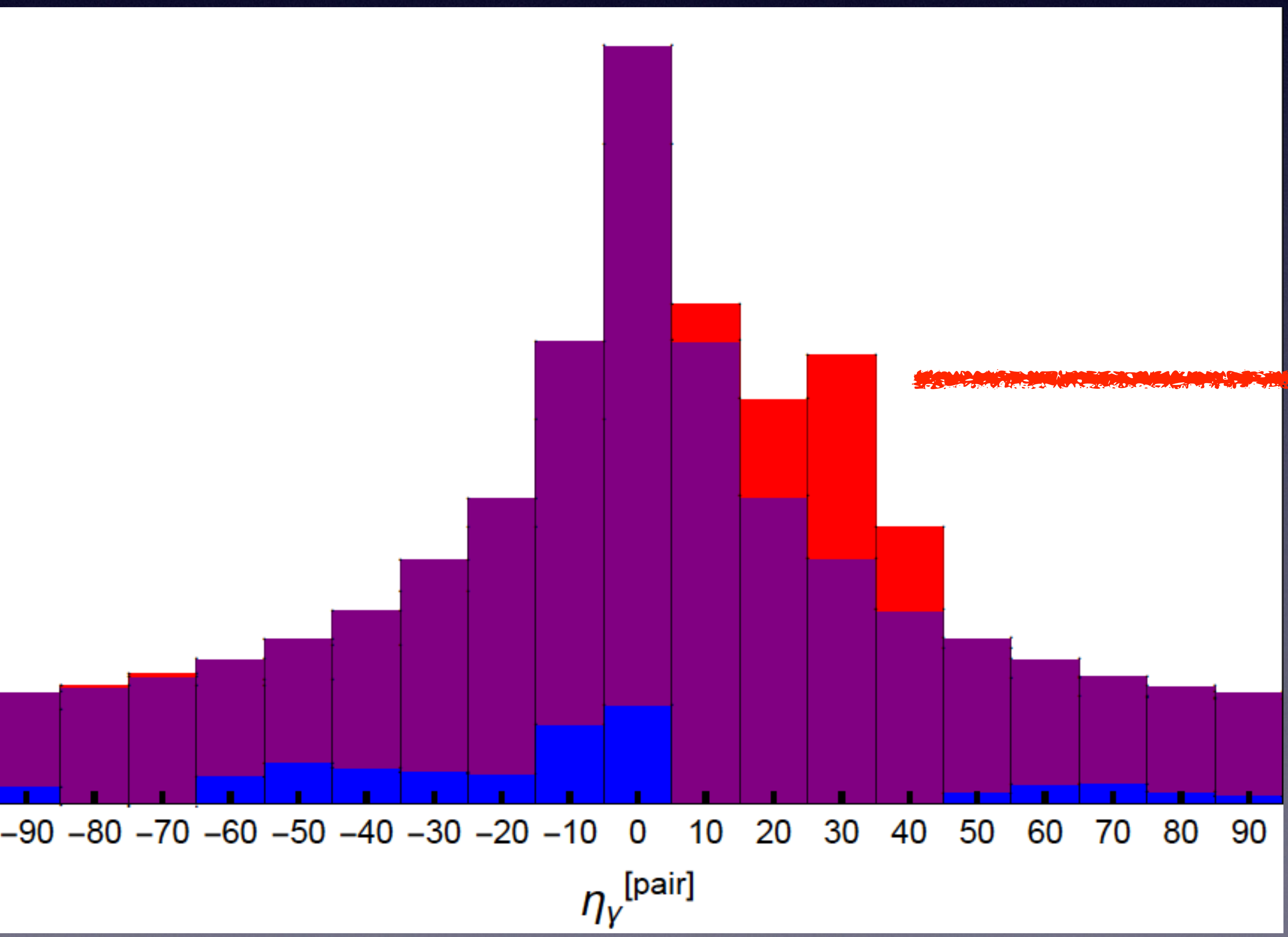
Frequent non-zero value compatible with 30!?

All-pairs analysis

Purple bars: simulated data distribution

Blue bars: defect in real data

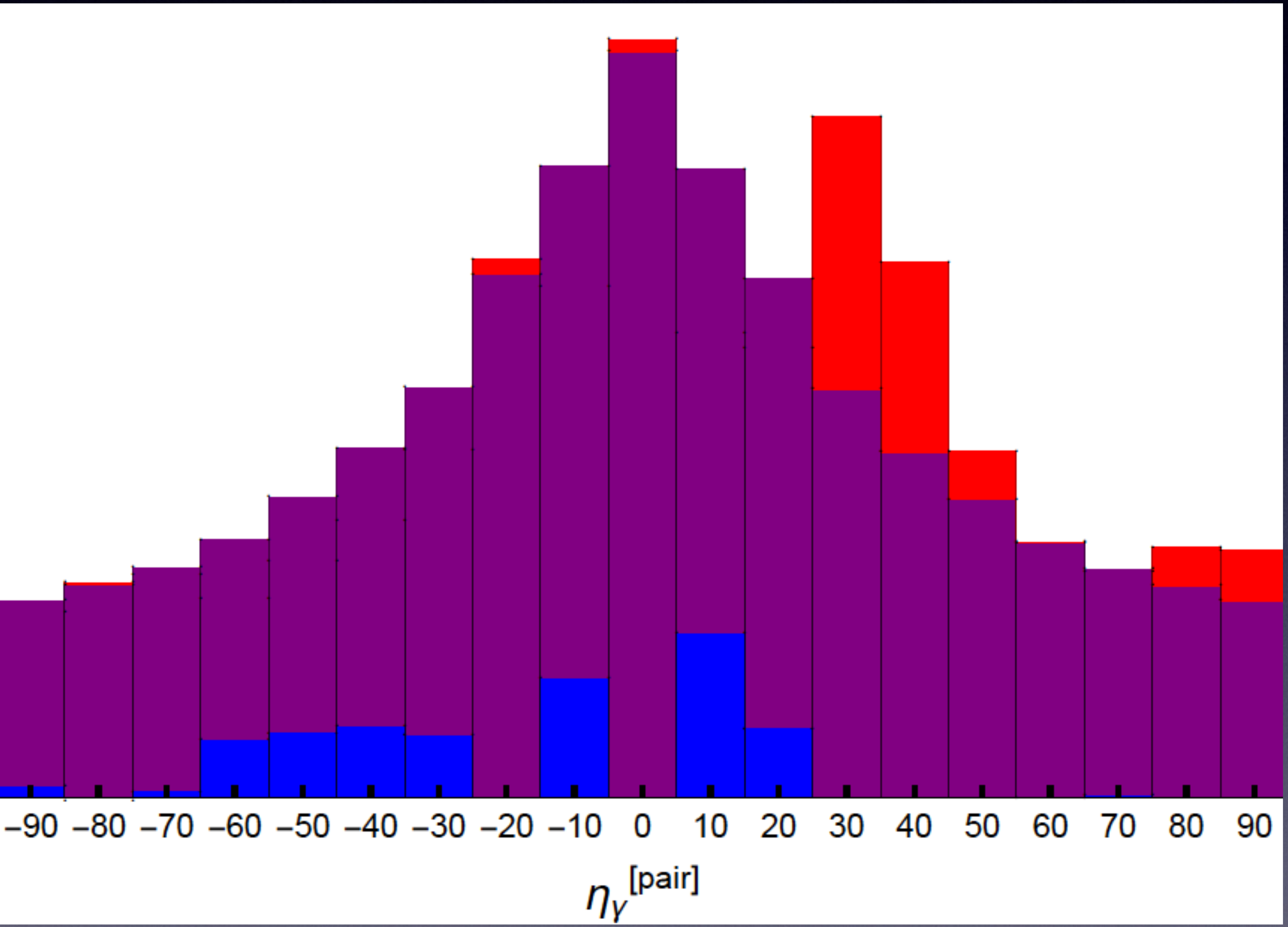
Red bars: excess in real data



Over 10^5 simulated data (reshuffling times) the observed peak for $25 < \eta < 35$ is reproduced in less than 0.5% of cases!!!

Data samplings

no-high pairs



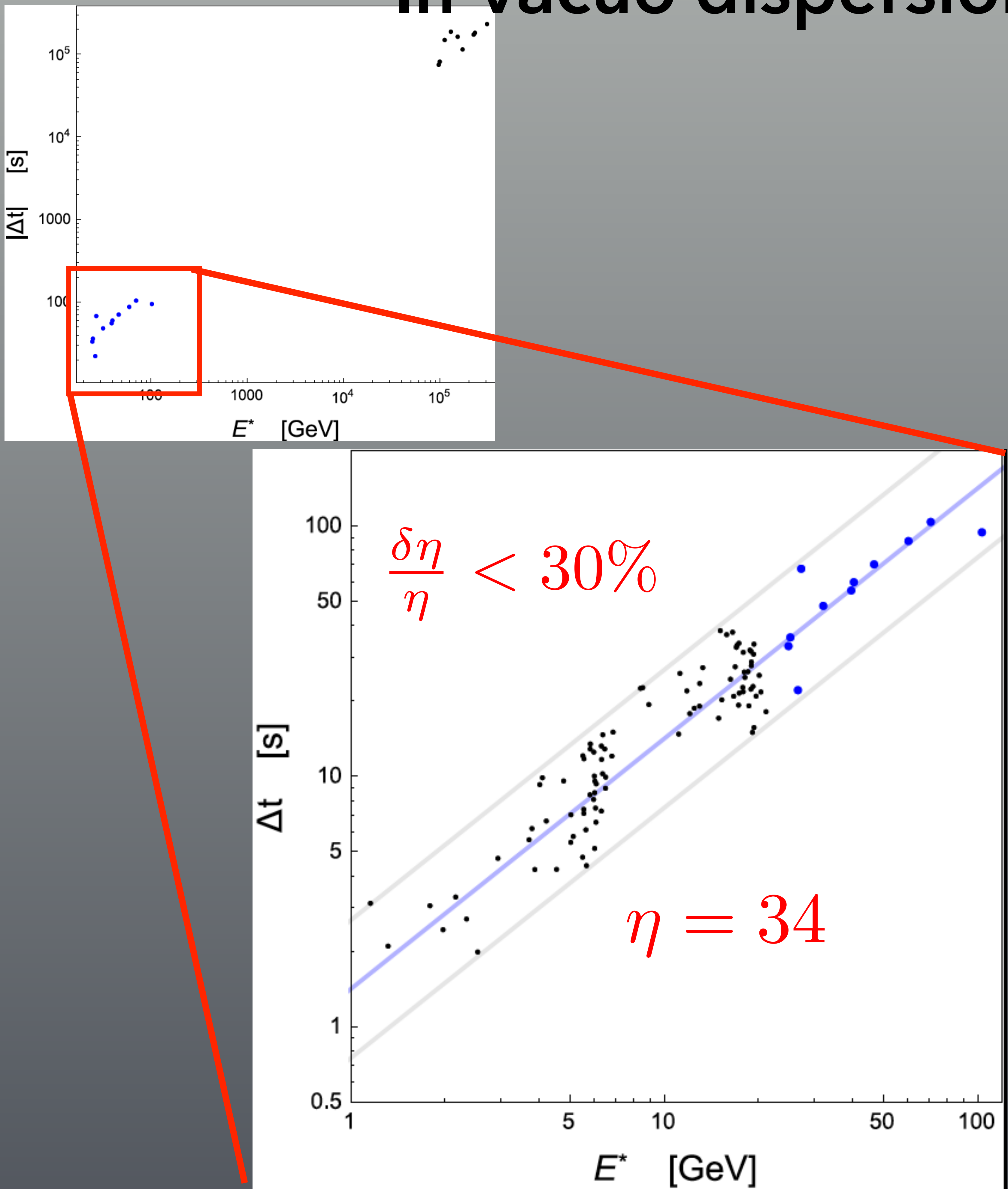
Pairs constituted by all photons with:

$$5 \text{ GeV} < E \times (1+z) < 40 \text{ GeV}$$

(excluding the energy range analysed by previous analyses)

Peak at $25 < \eta < 35$ appears accidentally only in 0.6 % of cases!

In-vacuo dispersion-like feature



- **BLUE POINTS: GRB photons with energy at the emission greater than 40 GeV**
- **BLACK POINTS: GRB photons with energy at the emission between 5 GeV and 40 GeV**

Consistency between the E>40GeV analysis and the 5GeV<E<40GeV analysis!!!

Summary and Outlook

Spectral time lags are observed in all GRBs

In-vacuo-dispersion like spectral lags in 7 GRBs but yet they might be manifestations of intrinsic GRB physics

Quantity and quality of Fermi-LAT data finally allow to pass from single-burst analyses to statistical analyses over collections of GRBs!

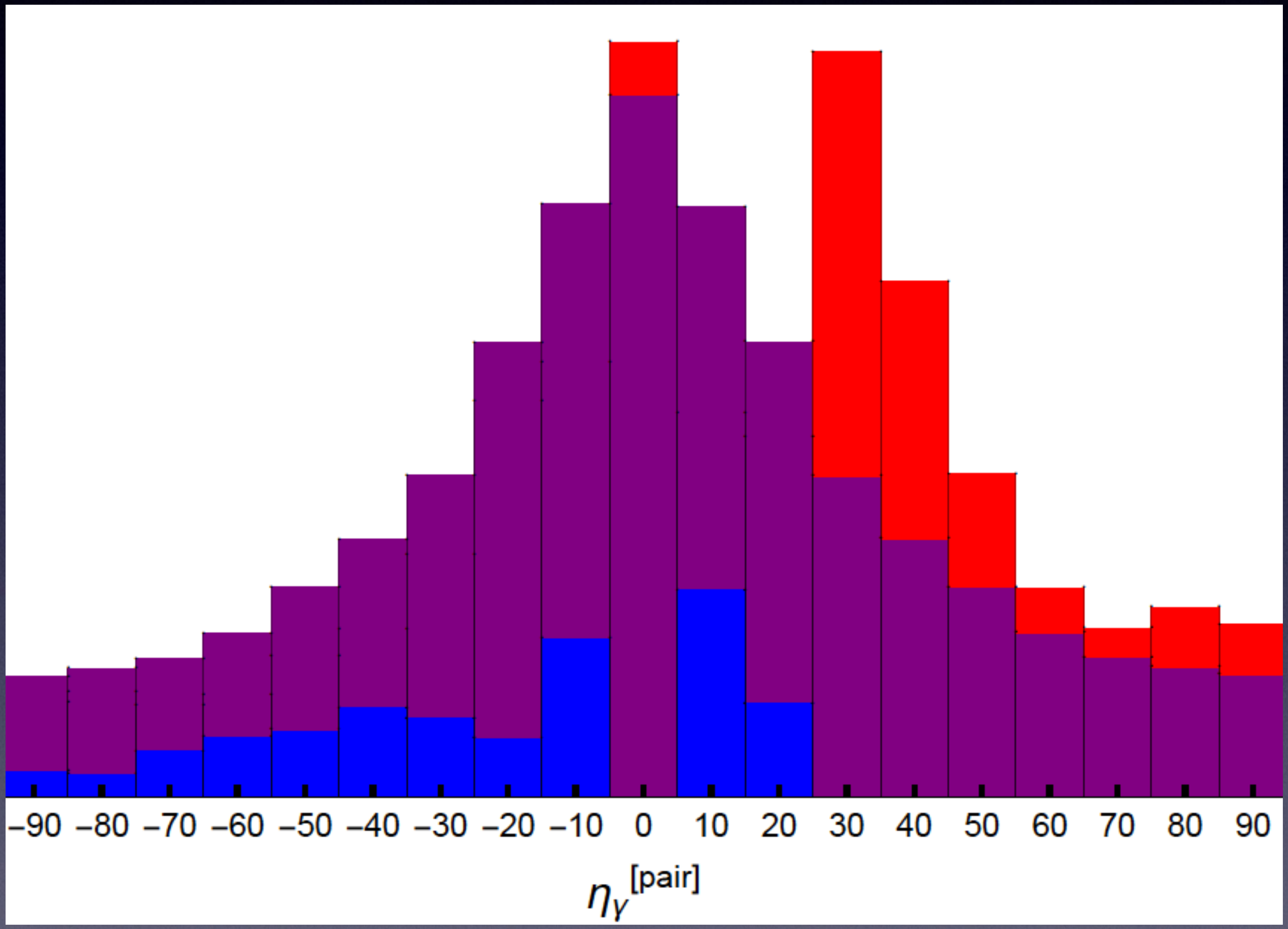
To decouple intrinsic from LIV effects:

- **Study the dependence on the redshift (population studies)**
- **Combine different sources (e.g. AGNs+GRBs)**
- **Multi-messenger analyses**
- **Model time variability at the emission**
- **Increase statistics in the GeV range**

Thanks for your attention!

Data samplings

medium-low pairs



Pairs constituted by:

1. **"Low" photon with**

$$5\ \mathrm{GeV} < E \times (1+z) < 15\ \mathrm{GeV}$$

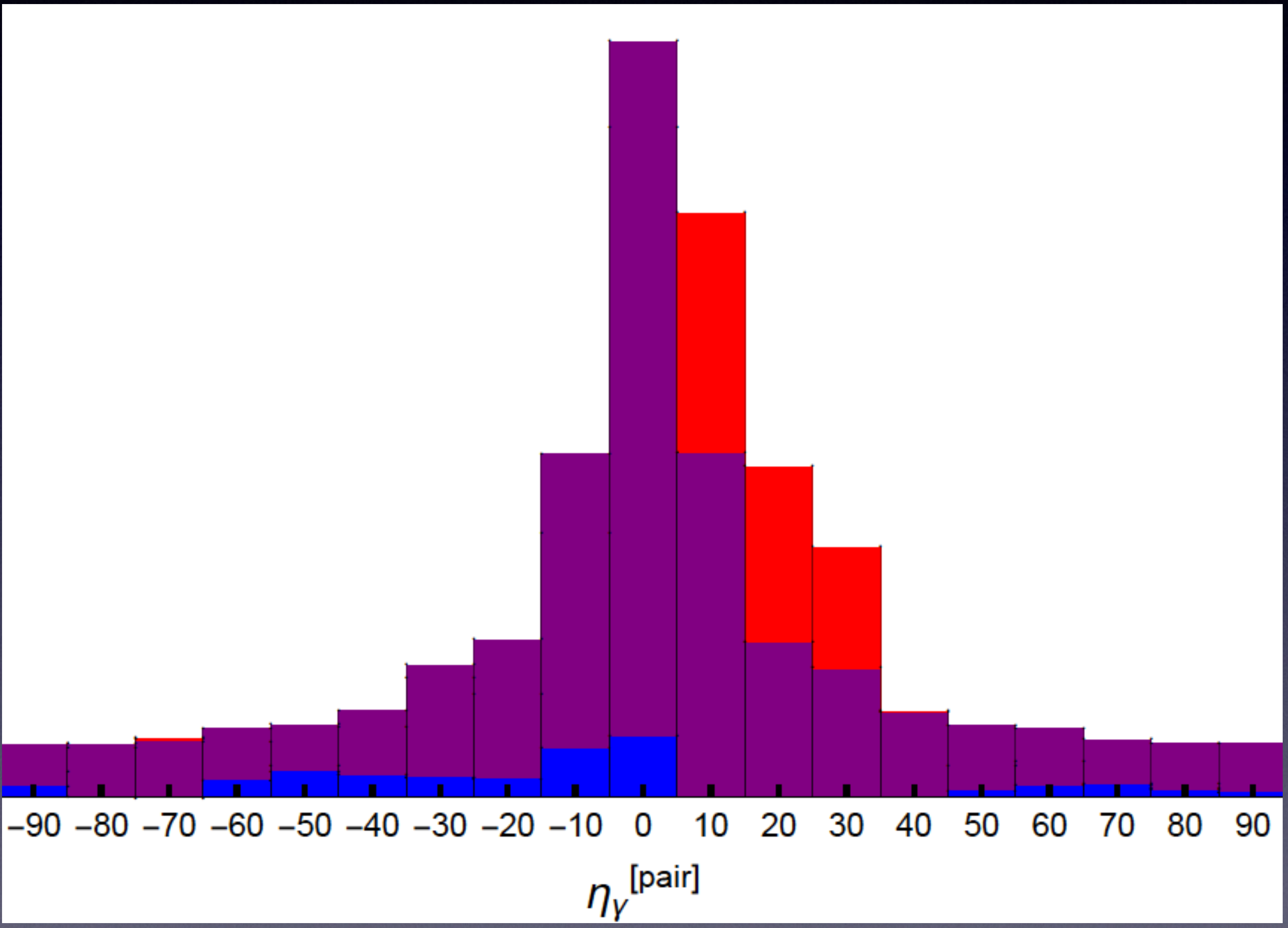
2. **"Medium" photon with**

$$15\ \mathrm{GeV} < E \times (1+z) < 40\ \mathrm{GeV}$$

False alarm probability = 0.2 %!

Data samplings

high-low pairs



Pairs constituted by:

1. **"Low" photon with**

$$5\ \mathrm{GeV} < E \times (1+z) < 15\ \mathrm{GeV}$$

2. **"High" photon with**

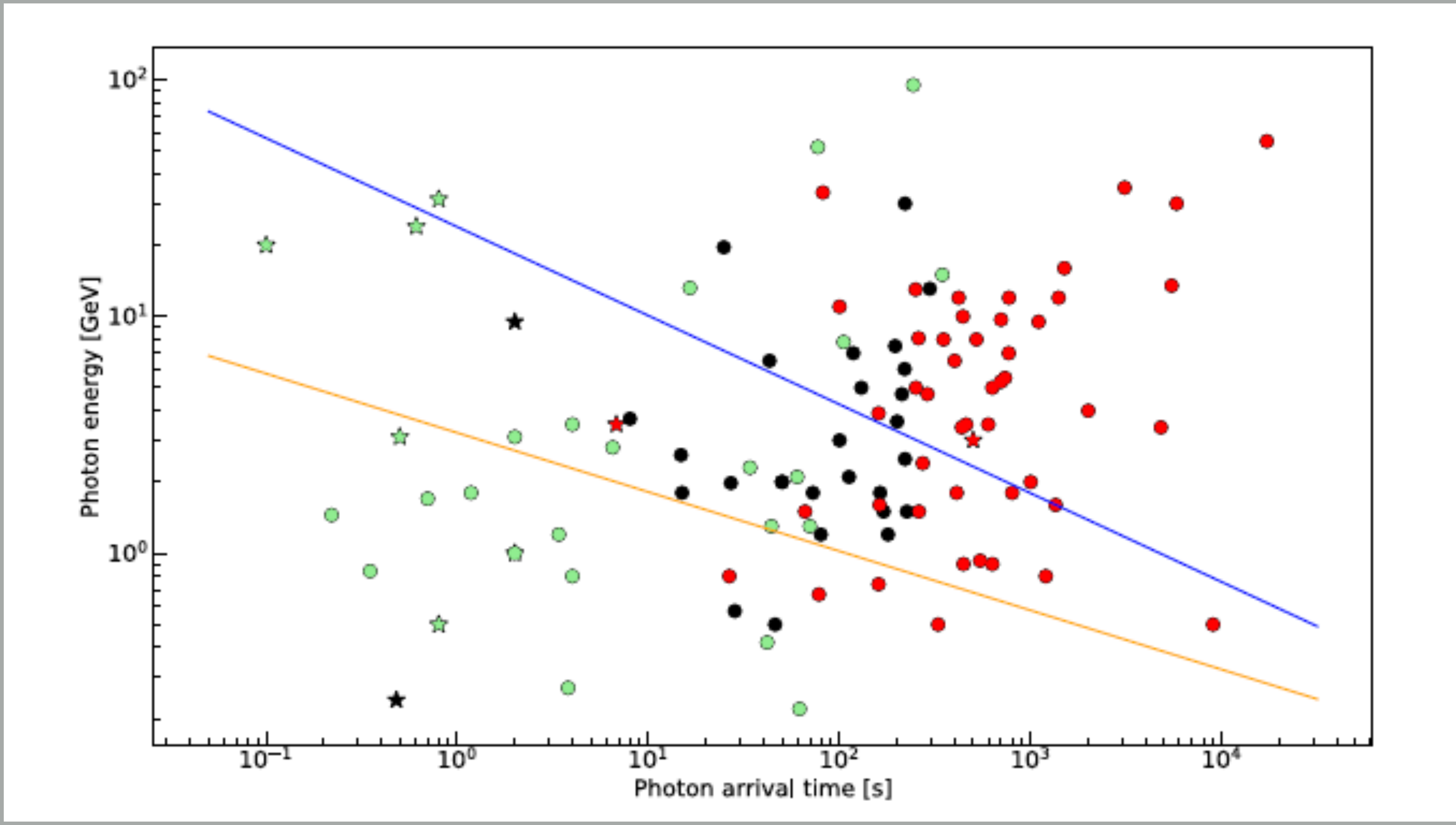
$$E \times (1+z) > 40\ \mathrm{GeV}$$

False alarm probability = 14 %!

How to explain delayed GeV component?

Nava, arXiv:1804.01524

- **BLUE LINE: homogenous medium**
- **ORANGE LINE: wind-like medium**



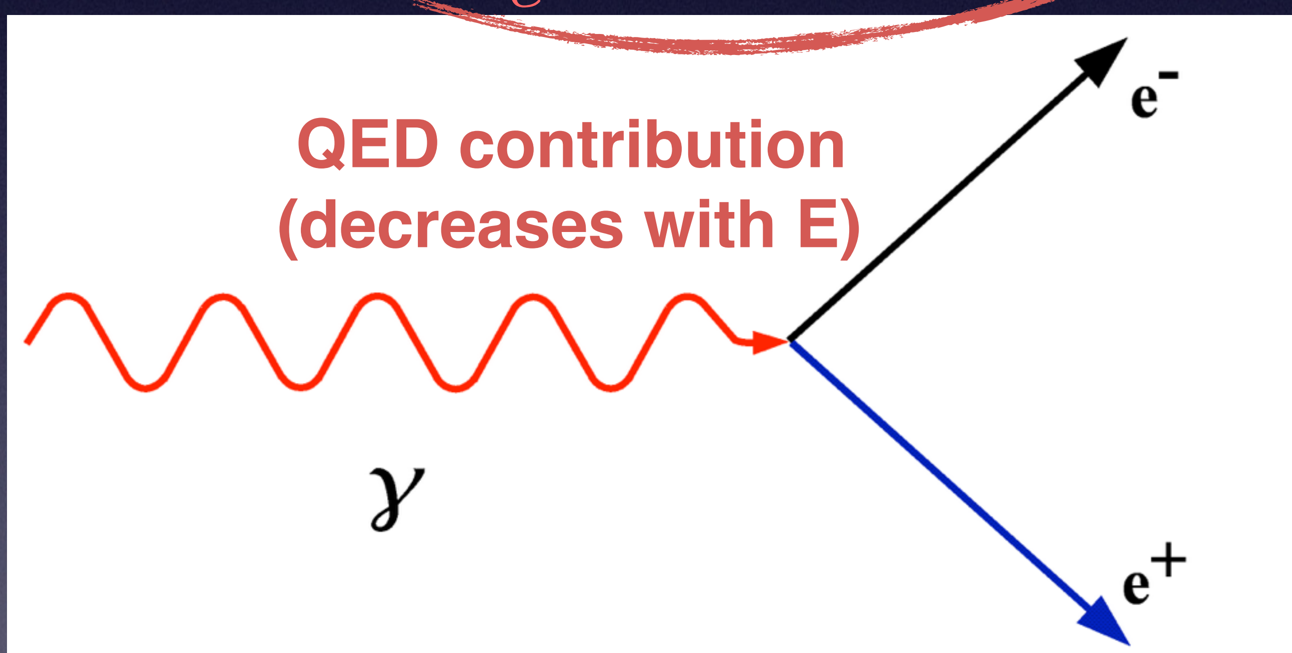
$$E_{max}^{syn} = \frac{50\,\mathrm{MeV} \times \Gamma}{1+z}$$

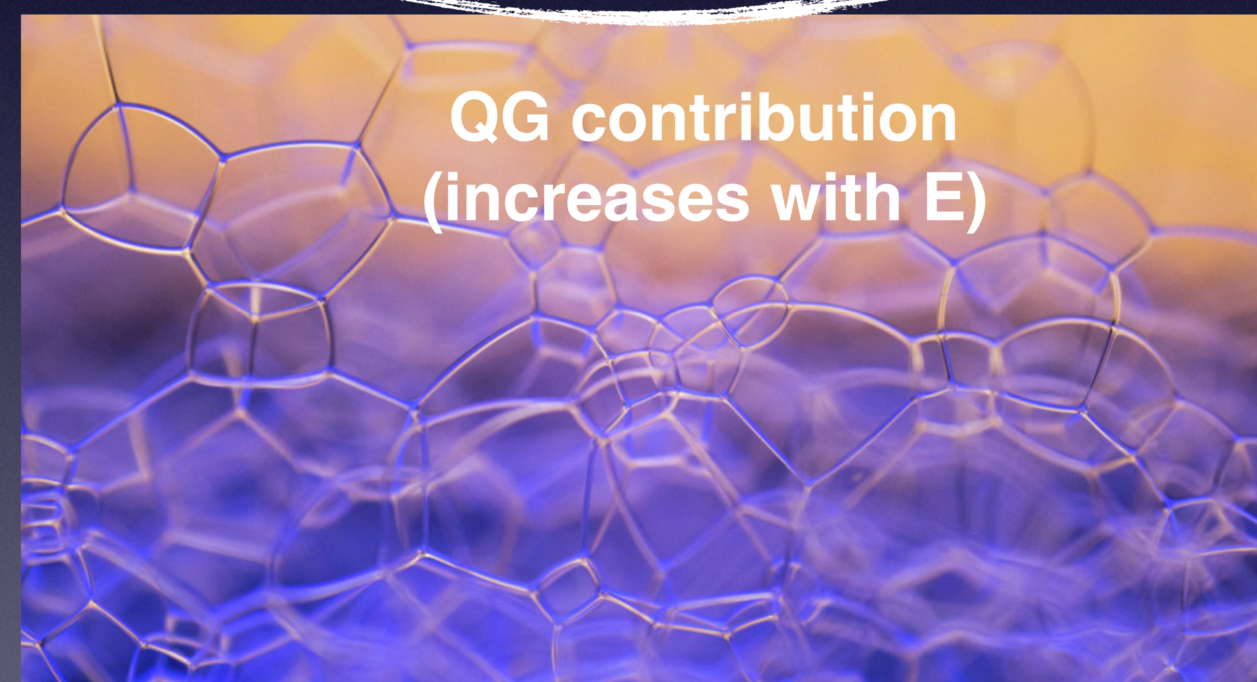
No simple explanation in terms of synchrotron radiation!!

QG vs Standard physics

$$E \sim 1\text{MeV} \qquad m_e \sim 0.5\text{MeV} \qquad N_b \sim 0.25\ \text{m}^{-3}$$

$$\Delta t \propto \frac{N_b}{m_e E^2} L \simeq 10^{-40} L \quad \ll \quad \frac{E}{M_P} L \simeq 10^{-20} L$$





At high energies (linear) QG-induced delays dominates over conventional in-medium physics effects!!

Jacob-Piran formula

Jacob, Piran, arXiv:1707.02413

$$H^2 = p^2c^2\left(1+\eta\frac{pc}{E_P}\right) \quad \xrightarrow{\text{pass to comoving momenta to account for universe expansion}} \quad H = \frac{pc}{a}\sqrt{1+\eta\frac{pc}{aE_P}}$$

$$v = \frac{\partial H}{\partial p} \quad \longrightarrow \quad x(t,p) = \int_0^t \frac{c}{a(t')}\left(1+\eta\left(\frac{pc}{a(t')E_P}\right)\right)dt'$$

turning to redshift variable z:

$$x(z,E_0) = \frac{c}{H_0}\int_0^z \left(1+\eta\left(\frac{E_0}{E_P}(1+z')\right)\right)\frac{dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$$

Taking into account that the comoving distance is the same for a high-energy and a low-energy (i.e. no in-vacuo dispersion) photon:

$$\Delta t = \frac{1}{H_0}\frac{\eta E_0}{E_P}\int_0^z \frac{(1+z')dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}} = \eta\frac{E_0}{E_P}D(z)$$

MDR: kappa-Poincaré

kappa-Minkowski non-commutative space

$$[\mathbf{x}_0, \mathbf{x}_j] = -i\lambda x_j$$

+

duality relations

$$< \mathbf{x}_\mu, P_\nu >= -i\eta_{\mu\nu}$$

kappa-Poincaré Hopf algebra

deformed commutators:

$$\begin{aligned}
[\mathcal{P}_\mu, \mathcal{P}_\nu] &= 0 \\
[M_j, \mathcal{P}_k] &= i\epsilon_{jkl}\mathcal{P}_l \\
[M_j, P_0] &= 0 \\
[\mathcal{N}_j, \mathcal{P}_k] &= i\delta_{jk}\left(\frac{1}{2\lambda}(1 - e^{-2\lambda P_0}) + \frac{\lambda}{2}\mathcal{P}^2\right) - i\lambda\mathcal{P}_j\mathcal{P}_k \\
[\mathcal{N}_j, P_0] &= i\mathcal{P}_j
\end{aligned}$$

deformed coproducts:

$$\begin{aligned}
\Delta P_0 &= P_0 \otimes 1 + 1 \otimes P_0 \\
\Delta M_j &= M_j \otimes 1 + 1 \otimes M_j \\
\Delta \mathcal{P}_j &= \mathcal{P}_j \otimes 1 + e^{-\lambda P_0} \otimes \mathcal{P}_j \\
\Delta \mathcal{N}_j &= \mathcal{N}_j \otimes 1 + e^{-\lambda P_0} \otimes \mathcal{N}_j - \lambda\varepsilon_{jkl}\mathcal{P}_k \otimes M_l
\end{aligned}$$

deformed mass Casimir

$$C_\lambda(\mathcal{P}) = \frac{e^{\lambda P_0} + e^{-\lambda P_0} - 2}{\lambda^2} - \vec{\mathcal{P}}^2 e^{\lambda P_0} \xrightarrow{\lambda=0} P_0^2 - \vec{P}^2$$

MDR: multi-fractional spaces

multi-scale measure

$$d^4q(x) = dq^0(t)\, dq^1(x^1) \cdots dq^3(x^3)$$

geometrical and physical coordinates

$$q^i(x^i) = x^i + \frac{\ell_*}{\alpha}\left|\frac{x^i}{\ell_*}\right|^{\alpha} F_\omega(x^i)\,,$$

$$q^0(t) = t + \frac{t_*}{\alpha_0}\left|\frac{t}{t_*}\right|^{\alpha_0} F_\omega(t)\,,$$

geometrical and physical momenta

$$p^\mu(k^\mu) := \frac{1}{q^\mu(1/k^\mu)}$$

$$[p^0(E)]^2 = |\mathrm{p}|^2 + m^2 = \sum [p^i(k^i)]^2 + m^2$$

$$|\mathrm{p}|^2 \simeq \sum_i k_i^2 \left[1 - \frac{2}{\alpha}\left|\frac{k_i}{k_*}\right|^{1-\alpha} F_\omega(k_i)\right]$$

modified dispersion!!

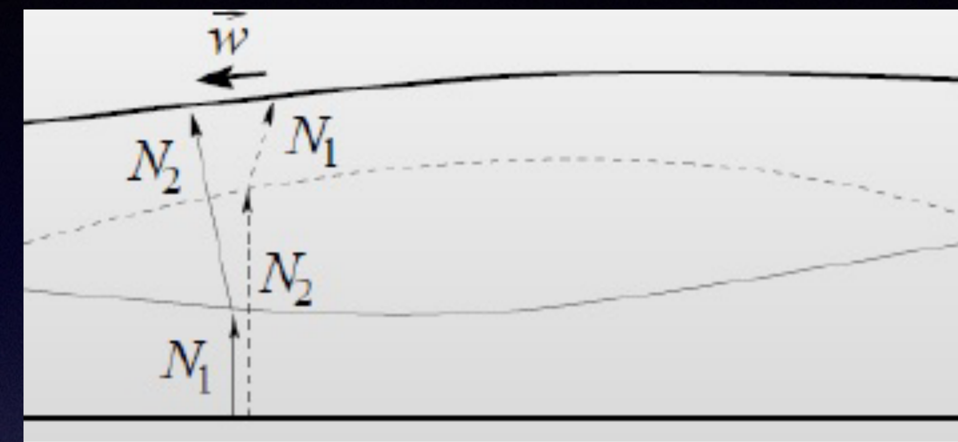
MDR: effective LQG

Brahma, MR, arXiv: 1801.09417

Hypersurface-deformation algebra:

$$\{D[M^k], D[N^j]\} = D[\mathcal{L}_{\vec{M}} N^k],$$
$$\{D[N^k], H[M]\} = H[\mathcal{L}_{\vec{N}} M],$$
$$\{H[N], H[M]\} = D[h^{jk}(N\partial_j M - M\partial_j N)],$$

generate hypersurface deformations!



LQG corrections to diffeomorphisms!!

$$\{D[M^a], D[N^a]\} = D[\mathcal{L}_{\vec{M}} N^a],$$
$$\{D[N^a], H^Q[M]\} = H^Q[\mathcal{L}_{\vec{N}} M],$$
$$\{H^Q[M], H^Q[N]\} = D[\beta h^{ab}(M\partial_b N - N\partial_b M)].$$

Minkowski/Poincaré limit:

$$N^k(x) = \delta^k + \epsilon^{kij}\varphi_i x_j, \quad N(x) = \delta + \alpha_i x^i$$

$$P_0^2 = \int \beta(P_r) P_r dP_r\,,$$

modified dispersion!!