large variety of phenomenological models

*** quantum-gravity scale could be bigger or smaller than E_{planck}**

*** can be brokenSR or deformedSR**

- **notice that no quantum-spacetime picture has been shown rigorously to lead to brokenSR**
- **notice that threshold anomalies (e.g. anomalous transparency…$\gamma\gamma \rightarrow e^+e^-$) are only possible with brokenSR (protected by a theorem in any deformedSR scenario, GAC,PhysRevD85,084034)**
- **for time-of-flight analyses techniques borrowed from propagation of light in media might not apply to deformedSR**

***the redshift dependence may be different from the Jacob-Piran ansatz**

***the effects can be spin/helicity/polarization dependent**

***the effects can be particle-type dependent (different for photons and neutrinos)**

***the effects should be fuzzy but theory work at present only provides essentially the deformation of the lightcone, without being able to establish the fuzziness of the deformed lightcone**

dual redshift on Planck-scale-curved momentum spaces (but with flat spacetime) produces time-of-arrival effects which at leading order are of the form ($n \in \{1,2\}$)

$$\Delta T = \left(\frac{E}{E_P} \right)^n T$$

and could be described in terms of an energy-dependent "physical velocity" of ultrarelativistic particles

$$\mathrm{v} = c + s_{\pm} \left(\frac{E}{E_P} \right)^n c$$

<u>these are very small effects but (at least for the case n=1) they could cumulate to an observably large ΔT if the distances travelled T are cosmological and the energies E are reasonably high (GeV and higher)!!!</u>

GRBs are ideally suited for testing this:
cosmological distances (established in 1997)
photons (and neutrinos) emitted nearly simultaneously
with rather high energies (GeV…..TeV…100 TeV…)

GAC+Ellis+Mavromatos+Nanopoulos+Sarkar, Nature393,763(1998)
GAC, NaturePhysics10,254(2014)

problem:

solid theory is for (curved momentum space and) flat spacetime

phenomenological opportunities are for propagation over cosmological distances, whose analysis requires curved spacetime

study of theories with both curved momentum space and curved spacetime still in its infancy

GAC+Rosati, PhysRevD86,124035(2012)
KowalskiGlikman+Rosati,ModPhysLettA28,135101(2013)
Heckman+Verlinde,arXiv:1401.1810(2014)

Jacob and Piran [JCAP0801,031(2008)] used a compelling heuristic argument for producing a formula of energy-dependent time delay applicable to FRW spacetimes, which has been the only candidate so far tested

$$\Delta T = -s_{\pm} \frac{E}{M_{QG}} \frac{c}{H_0} \int_0^z d\zeta \frac{(1+\zeta)}{\sqrt{\Omega_\Lambda + (1+\zeta)^3 \Omega_m}}$$

where as usual H_0 is the Hubble parameter, Ω_Λ is the cosmological constant and Ω_m is the matter fraction.
Jacob-Piran formula is surely not the most general possibility.
It is important for phenomenology to understand this issue, but it requires handling the interplay between curvature of spacetime and curvature of momentum space in subtle ways

GAC+Rosati, PhysRevD

Jacob-Piran formula in dS spacetime (it actually assumes modification only affects boosts, with translations unaffected…not what we see in explicit quantum-spacetime models…GAC+Marcianò+Matassa+Rosati,PhysRevD86,124035)

$$\Delta t = \ell |p| \frac{z + \frac{z^2}{2}}{H}$$

example of logically-consistent alternative

$$\Delta t = \ell |p| \ \frac{\ln(1+z)}{H}$$

and combinations are also logically consistent

$$\Delta t = \ell |p| \left(\alpha \frac{\ln(1+z)}{H} + \beta \frac{z + \frac{z^2}{2}}{H} \right)$$

this is for deSitter expansion…we reported observations relevant for FRW expansion in Rosati+GAC+Marcianò+Matassa, arxiv:1507.02056, Phys.Rev. D92 (2015) 124042

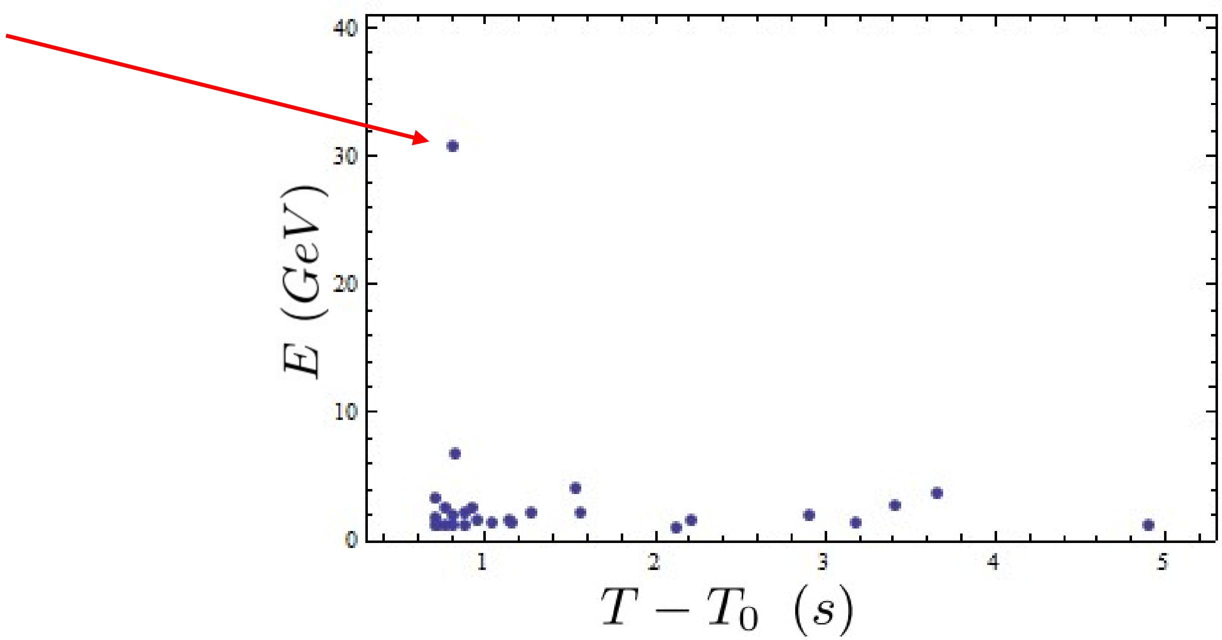
testing Jacob-Piran formula:

focus on n=1 case (sensitivity to the n=2 case still far beyond our reach presently but potentially within reach of future neutrino astrophysics)

first came GRB080916C data providing a limit of $M_{QG}>10^{-1}M_{planck}$ for hard spectral lags and $M_{QG}>10^{-2}M_{planck}$ for soft spectral lags

analogous studies of blazars lead to comparable limits

then came GRB090510 (magnificent short burst) allowing to establish a limit at M_{planck} level on both signs of dispersion (soft and hard spectral lags)



a test with accuracy of about one part in 10^{20}!!!

this Planck-scale sensitivity is illustrative of how we have learned over this past decade that there are ways for achieving in some cases sensitivity to Planck-scale-suppressed effects,
<u>something that was thought to be impossible up to the mid 1990s</u>

Quantum-Gravity Phenomenology exists!!!

a collection of other plausible quantum-gravity effects and of some associated data analyses where <u>Planck-scale sensitivity</u> was achieved (or is within reach) can be found in my "living review"

GAC, LivingRev.Relativity16,5(2013)

http://www.livingreviews.org/lrr-2013-5

still makes sense to test in-vacuo dispersion statistically…
our "quantum-gravity phenomenological models" will turn out to be (at best!!) like the Bohr-Somerfeld quantization…

in order to best setup the statistical analysis it is convenient to notice that we are testing a linear relationship between Δt and the product of energy and the redshift-dependent function D(z)

$$\Delta t = \eta \frac{E}{M_P} D(z) \qquad \text{with} \qquad D(z) = \int_0^z d\zeta \frac{(1+\zeta)}{H_0 \sqrt{\Omega_\Lambda + (1+\zeta)^3 \Omega_m}}$$

we can absorbe the redshift dependence into an "accordingly rescaled energy", which we call E^*

$$E^* \equiv E \frac{D(z)}{D(1)}$$

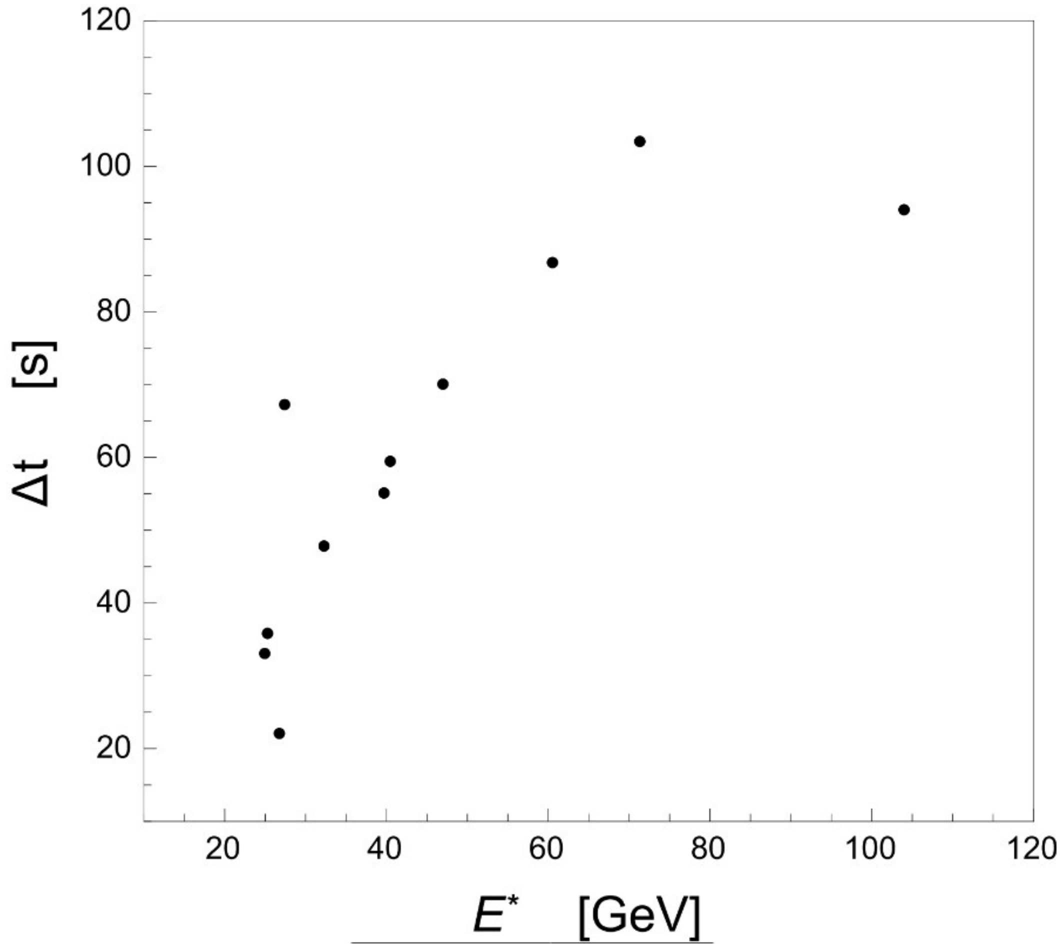
This then affords us the luxury of analysing data in terms of a linear relationship between Δt and E^*

$$\Delta t = \eta \, D(1) \frac{E^*}{M_P}$$

H.Xu+B.Q.Ma, PhysLettB760(2016)602
GAC+G.D'Amico+G.Rosati +N.Loret, arXiv:1612.02765, NatureAstronomy1,0139

criteria:
- focus on photons whose energy at emission was greater than 40 GeV
-take as **Δt** the time-of-observation difference between such high-energy photons and the first peak of the (mostly low-energy) signal

[note that this makes sense only for photons which were emitted in (near) coincidence with the first peak…not all those with >40GeV will …and surely only a rather small percentage of all photons…]



in order to get a sense of how striking this data situation is one can ask how often such high correlation between Δt and E^* would occur if the pairing of values of Δt and E^* was just random: overall having such high correlation would happen in less than 0.1% of cases, and correlation as high as seen for the best 8 out of 11 in 0.0013% of cases

H.Xu+B.Q.Ma, PhysLettB760(2016)602
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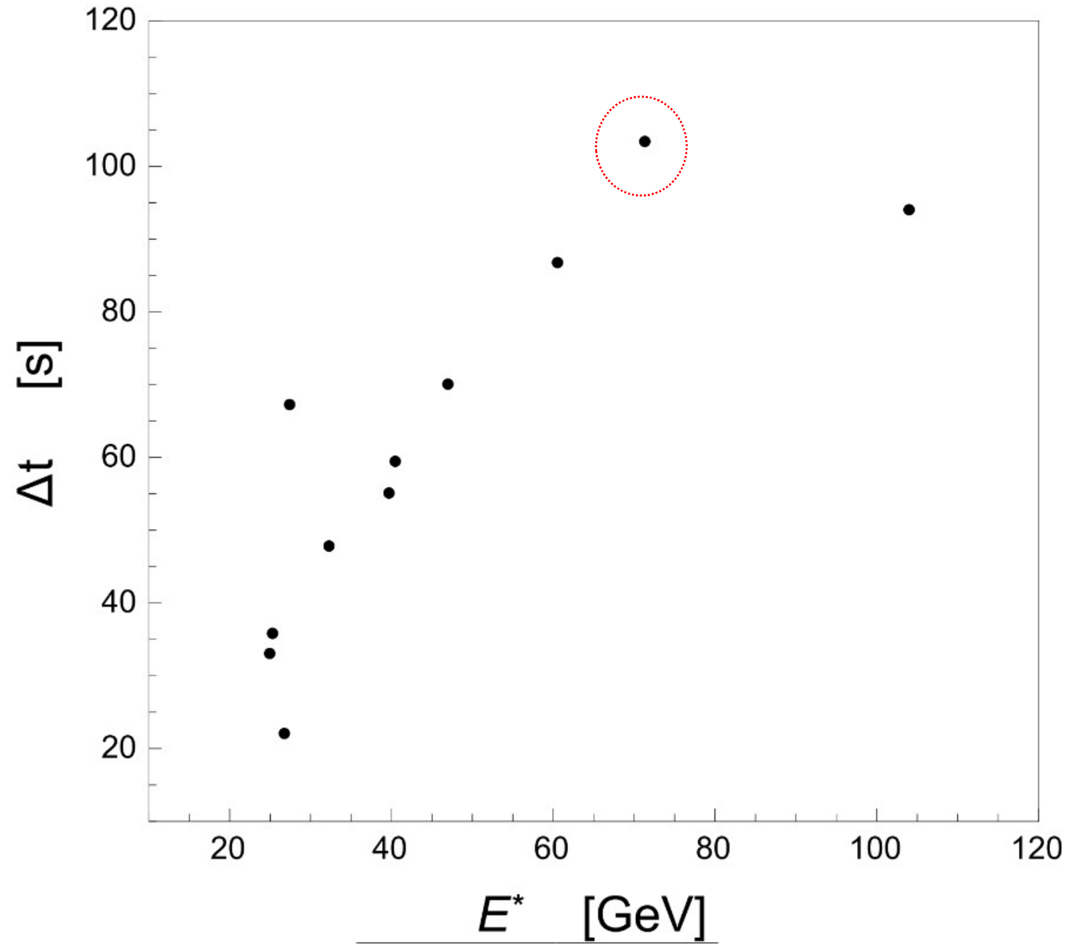

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GAC+Barcaroli+D'Amico+Loret+Rosati, arXiv1605.00496, PhysicsLettersB761,318
GAC+D'Amico+Rosati +Loret, arXiv:1612.02765, NatureAstronomy1,0139
[these use latest data release by IceCube....also see previous exploratory analysis on 2008-2010 IceCube data GAC+Guetta+Piran, Astrophys.J.806,269]

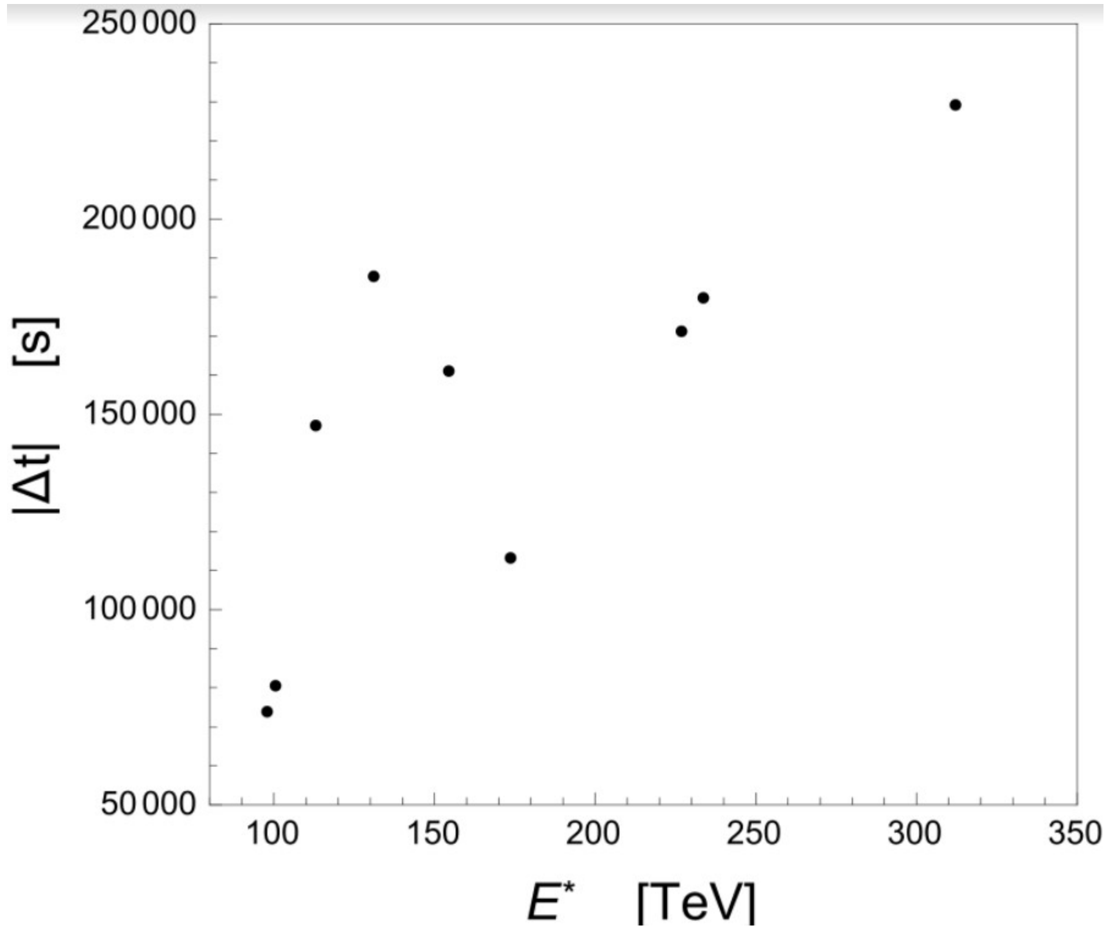
IceCube still found no GRB neutrinos (expected at least a dozen at this point)

If effect is of seconds for GeV photons it can be very large for 300TeV neutrinos…the time window adopted by IceCube would never catch such GRB neutrinos…

IceCube has reported so far 21 shower neutrinos with energy between 60 and 500 TeV

we found that 9 of them could be "GRB-neutrino candidates" (direction compatible with the GRB direction and time of observation within 3 days of the GRB)
so let's see if they provided some support for the linear dependence between Δt and E*

GAC+Barcaroli+D'Amico+Loret+Rosati, arXiv1605.00496, PhysicsLettersB761(2016)318

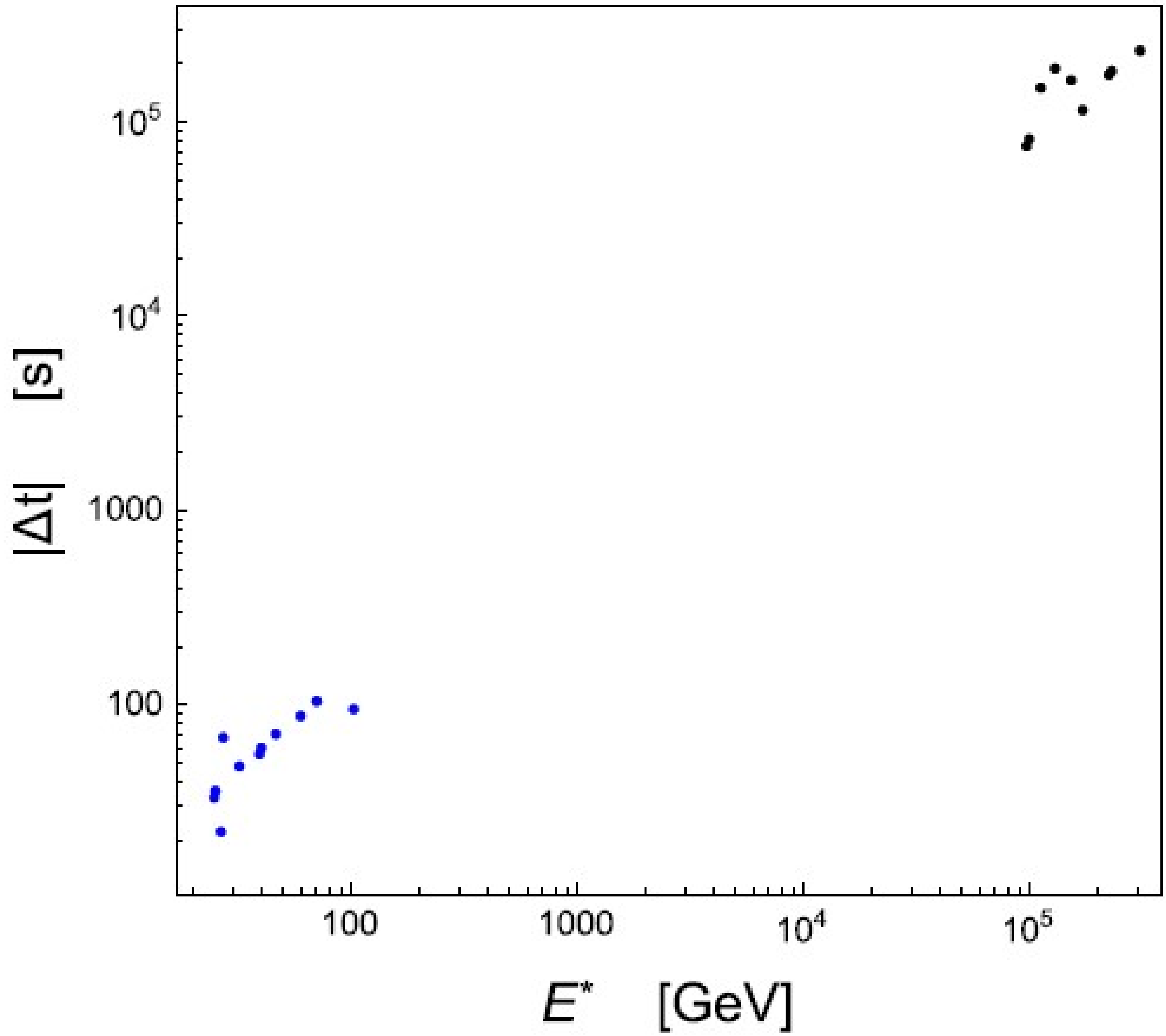


<u>the correlation found in data is 0.95</u>

particularly amazing considering that we can independently estimate (even if there was in-vacuo dispersion, and therefore some of these are GRB neutrinos) that most likely 3 or 4 of our 9 neutrinos must be background neutrinos, unrelated to GRBs

the false alarm probability is 0.5% (probability of finding such a high correlation if all neutrinos are background neutrinos that happened to fit by accident our GRB-neutrino selection criteria)

GAC+D'Amico+Rosati +Loret, arXiv:1612.02765, NatureAstronomy1,0139



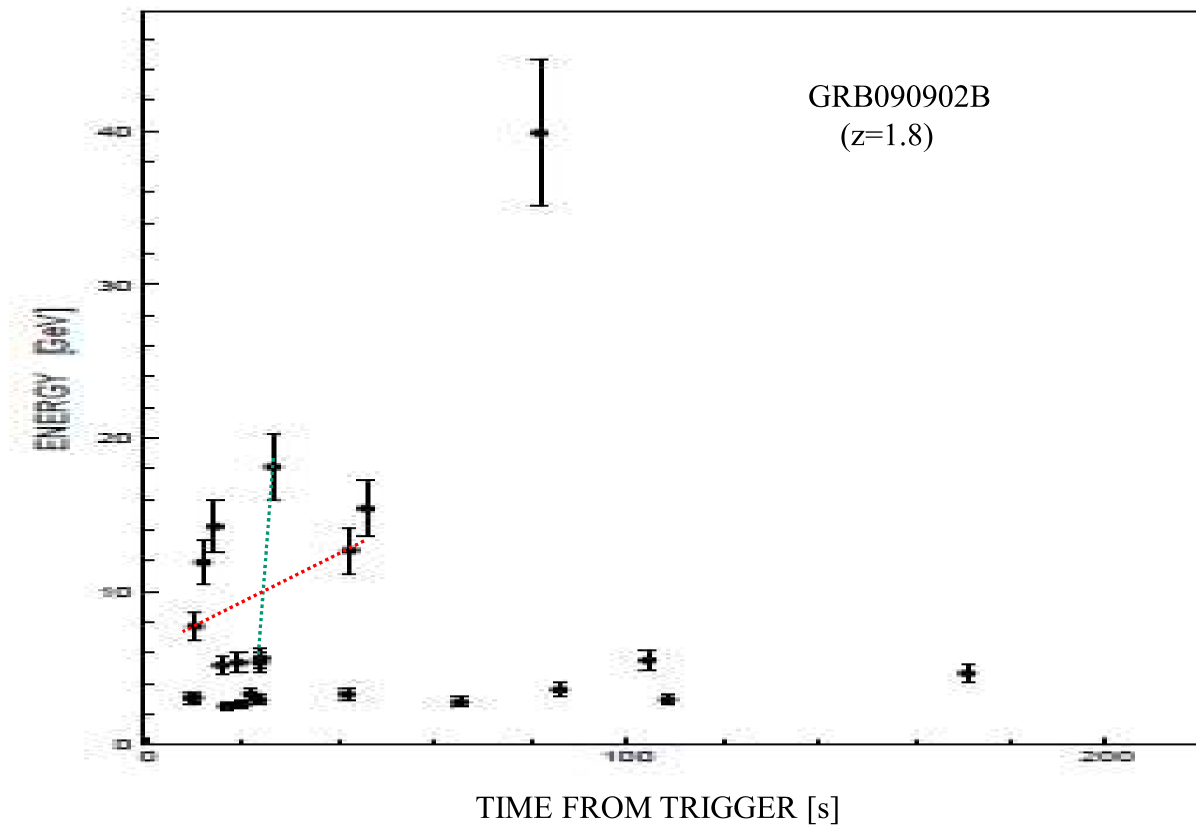
NEW

GAC+D'Amico+Fiore+Puccetti+Ronco, arXiv:1707.02413

there is no reason to dwell much on statistical significance since more data will be available in a rather near future…

actually we already have more data to analyse, the GRB photons with energy at emission lower than 40 GeV, but for those it would be absurd to assume emission in near coincidence with the first peak of the GRB

previous graph gives η_γ of 30 ± 6
and note that each pair of photons in a GRB nominally determines a value of η_γ, though the large majority of them will be "spurious" for our analysis (photons emitted in different phases of the GRB)
we can still see if the frequency of occurrence of η_γ of about 30 is particularly high



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for bins where the observed population is higher than expected we color the bar in purple up to the level expected, showing then the excess in red;
for bins where the observed population is lower than expected the bar height gives the expected population, while the blue portion of the bar quantifies the amount by which the observed population is lower than expected