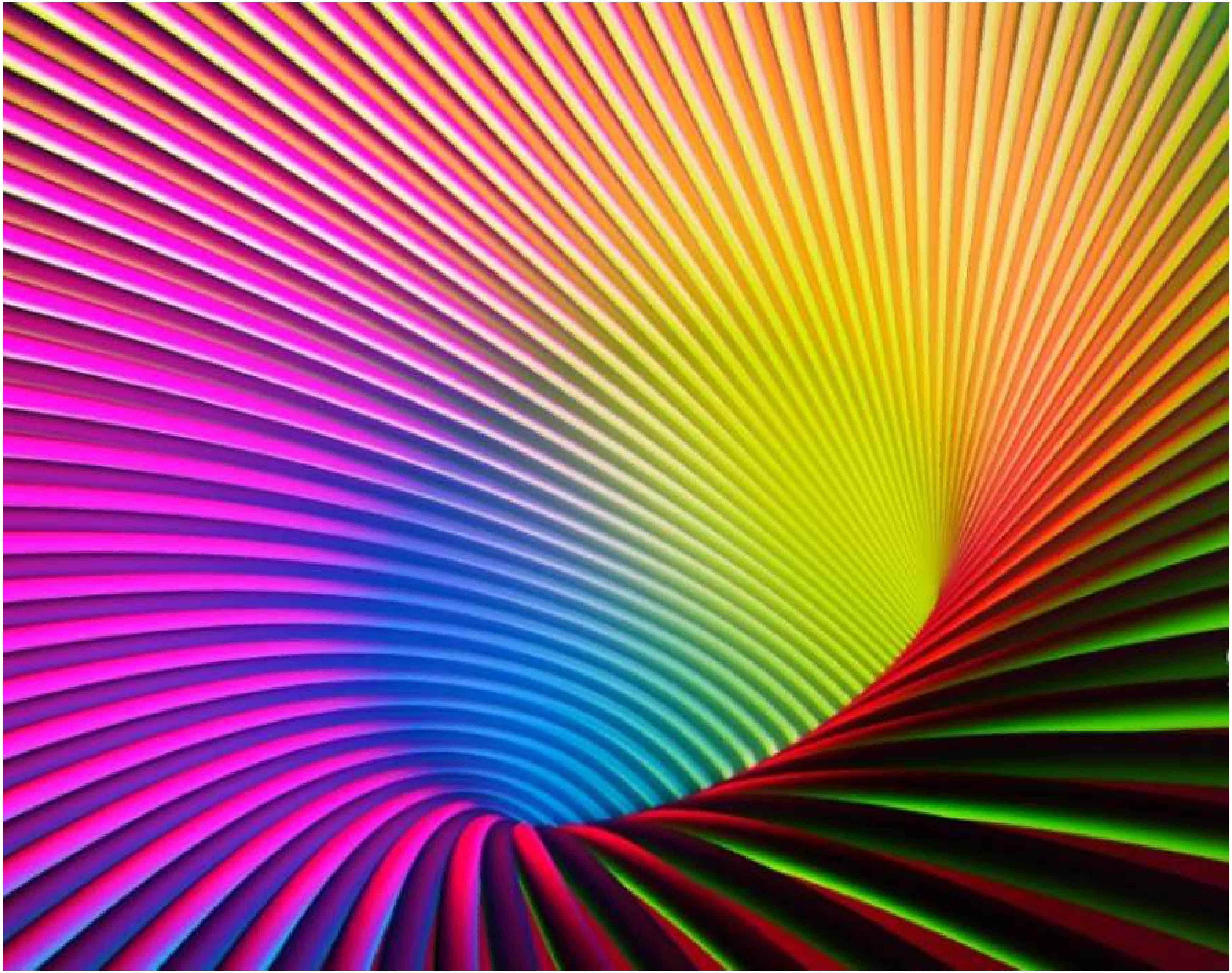
giovanni amelino-camelia

12.7.2023 Rijeka



CERN-TH/99-223
gr-qc/9910089

Are we at the dawn of quantum-gravity phenomenology?[1]

Giovanni AMELINO-CAMELIA[2]

Theory Division, CERN, CH-1211, Geneva, Switzerland

ABSTRACT

A handful of recent papers has been devoted to proposals of experiments capable of testing some candidate quantum-gravity phenomena. These lecture notes emphasize those aspects that are most relevant to the questions that inevitably come to mind when one is exposed for the first time to these research developments: How come theory and experiments are finally meeting in spite of all the gloomy forecasts that pervade traditional quantum-gravity reviews? Is this

C.J. Isham,
«Structural issues in quantum gravity»
gr-qc/9510063

The feature of quantum gravity that challenges its very right to be considered as a genuine branch of theoretical physics is the singular absence of any observed property of the world that can be identified *unequivocally* as the result of some interplay between general relativity and quantum theory. This problem stems from the fact that the natural Planck length—defined using dimensional analysis as $L_P := (G\hbar/c^3)^{\frac{1}{2}}$—has the extremely small value of approximately 10^{-35}m; equivalently, the associated Planck energy E_P has a value 10^{28}eV, which is well beyond the range of any foreseeable laboratory-based experiments. Indeed, this simple dimensional argument suggests strongly that the only physical regime where effects of quantum gravity might be studied directly is in the immediate post big-bang era of the universe—which is not the easiest thing to probe experimentally.

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at first only semi-heuristic estimates…

now actual derivations of effects in quantum-spacetime toy models (like kappa-minkowski) and mature phenomenological models

bottom-up approach is doing its thing, but still nothing from top-down…

C.J. Isham, «Structural issues in quantum gravity» gr-qc/9510063

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QGphen is now a broad field… I will focus on a few topics among the most studied…

wider perspective on QGphen in my "living review" :

GAC, LivingRev.Relativity16,5(2013)

www.livingreviews.org/lrr-2013-5

specifically for «QGphen in the multimessenger era» see the very recent review

Prog.Part.Nucl.Phys. 125, 103948 (2022)

www.sciencedirect.com/science/article/pii/S0146641022000096

menu:

in-vacuo dispersion (“dual-curvature redshift”)

dual-curvature lensing

threshold anomalies

IR/UV mixing

in-vacuo dispersion in flat spacetime

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

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

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)!!!

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)

"relative locality" and curvature of momentum space

mass of a particle with four-momentum p_μ is determined by the metric geodesic distance on momentum space from p_μ to the origin of momentum space

$$m^2 = d^2_\ell\,(p,0) = \int dt \sqrt{g^{\mu\nu}(\gamma^{[A;p]}(t))\dot{\gamma}^{[A;p]}_\mu(t)\dot{\gamma}^{[A;p]}_\nu(t)}$$

where $\gamma^{[A;p]}{}_\mu$ is the metric geodesic connecting the point p_μ to the origin of momentum space

$$\frac{d^2\gamma^{[A]}_\lambda(t)}{dt^2} + A^{\mu\nu}{}_\lambda \frac{d\gamma^{[A]}_\mu(t)}{dt}\frac{d\gamma^{[A]}_\nu(t)}{dt} = 0$$

with $A^{\mu\nu}{}_\lambda$ the Levi-Civita connection

the affine connection on momentum space determines the law of composition of momenta, through parrallel transport, and it might not be the Levi-Civita connection of the metric on momentum space (it is not in 3D quantum gravity and in all cases based on noncommutative geometry, where momentum space is a group manifold)

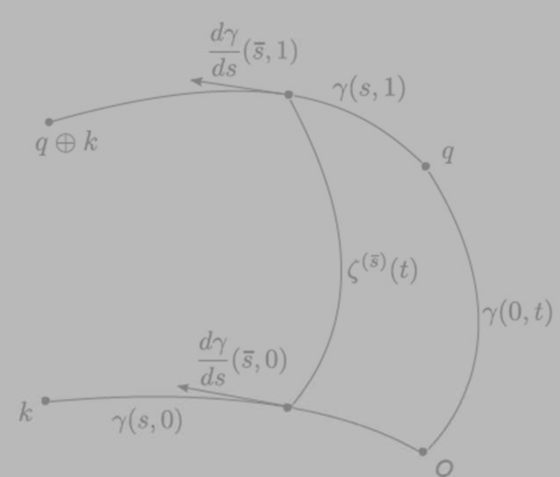


Figure 1. We determine the law of composition of momenta from the affine connection by associating to the points q and k of momentum space the connection geodesics $\gamma^{(q)}$ and $\gamma^{(k)}$ which connect them to the origin of momentum space. We then introduce a third curve $\bar{\gamma}(s)$, which we call the parallel transport of $\gamma^{(k)}(s)$ along $\gamma^{(q)}(t)$, such that for any given value $\bar{s}$ of the parameter s one has that the tangent vector $\frac{d}{ds}\bar{\gamma}(\bar{s})$ is the parallel transport of the tangent vector $\frac{d}{ds}\gamma^{(k)}(\bar{s})$ along the geodesic connecting $\gamma^{(k)}(\bar{s})$ to $\bar{\gamma}(\bar{s})$. Then the composition law is defined as the extremal point of $\bar{\gamma}$, that is $q \oplus_\ell k = \bar{\gamma}(1)$.

it is turning out that most models predicting in-vacuo dispersion are also models with curvature of momentum space (in the sense of the relative-locality framework) and that in-vacuo dispersion actually is dual-curvature lensing:

ordinary redshift in deSitter spacetime implies in particular that massless particles emitted with same energy but at different times from a distant source reach the detector with different energy

dual redshift in deSitter momentum space implies that massless particles emitted simultaneously but with different energies from a distant source reach the detector at different times

GAC+Barcaroli+Gubitosi+Loret, Classical&QuantumGravity30,235002 (2013)
GAC+Matassa+Mercati+Rosati, PhysicalReviewLetters106,071301 (2011)

solid understanding of implications of momentum-space curvature with 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 +Marciano+Matassa+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

$$\Delta t = \eta \frac{E}{E_P} \int_0^z d\zeta \frac{(1+\zeta)}{H(\zeta)}$$

$$H(\zeta) \equiv H_0 \sqrt{\Omega_\Lambda + (1+\zeta)^3 \Omega_m}$$

where as usual H_0 is the Hubble parameter, Ω_Λ is the cosmological constant and Ω_m is the matter fraction.

Several alternatives to Jacob-Piran formula are possible and are found in models

see, e.g., Rosati+GAC +Marciano+Matassa, PhysRevD92,124042(2015)

LIV

RodriguezMartinez+Piran,JCAP0604,006(2006)
Jacob+Piran, JCAP0801,031(2008)]
GAC +Rosati +Bedic, PhysLettB820,136595(2021)

$$\Delta t = \eta \frac{E}{E_P} \int_0^z d\zeta \frac{(1+\zeta)}{H(\zeta)} + \text{MANY OTHER TERMS}$$

CURVATURE-INDUCED LIV

GAC +Rosati +Bedic, PhysLettB820,136595(2021)

$$\Delta t = \gamma \frac{E}{E_P} \int_0^z d\zeta \frac{1}{H(\zeta)} \left(1 + \zeta - \frac{1}{1+\zeta}\right)$$

DSR (which is curvature-induced for β = - α, but not for generic α, β)

Rosati+GAC +Marciano+Matassa, PhysRevD92,124042(2015)

$$\Delta t = \alpha \frac{E}{E_P} \int_0^z d\zeta \frac{(1+\zeta)}{H(\zeta)}$$

$$+ \quad \beta \frac{E}{E_P} \int_0^z d\zeta \left(\sqrt{\frac{1+\zeta}{H(\zeta)}} - \sqrt{\frac{H(\zeta)}{1+\zeta}} \int_0^\zeta \frac{d\zeta'}{H(\zeta')} \right)^2$$

$+$ only one more term (see talk by Frattulillo)

$$H(\zeta) \equiv H_0 \sqrt{\Omega_\Lambda + (1+\zeta)^3 \Omega_m}$$

where as usual H_0 is the Hubble parameter, Ω_Λ is the cosmological constant and Ω_m is the matter fraction

different redshift dependence, different interplay between quantum properties of spacetime (curvature of momentum space) and spacetime curvature…

in characterizing the differences between alternative forms of redshift dependence it is emerging that the first feature that should be noticed is whether or not in-vacuo dispersion persists also in the flat-spacetime limit:
in some pictures the presence of in-vacuo dispersion requires the presence of spacetime curvature

this fits the intuition emerging from analyzing [GAC+Starodubtsev+Smolin,CQG(2004)] the role of the q-deSitter quantum group in some quantum-gravity studies: the quantum-group parameter q is given in terms of the Planck length and the cosmological constant $q = \exp(i\ell_P^2 \Lambda)$

so that when the curvature scale of the deSitter algebra is → 0 the deformation disappears
(the Inonu-Wigner constraction of the q-deSitter Holf algebra is just the Poincarè Lie algebra)

interestingly some semiheuristic arguments [see, e.g., Bianchi+Rovelli,PRD(2011)] on properties of the quantum-gravity regime lead to the emergence of quantum groups with quantum-group parameter q given by $q = \exp(i\ell_P^2 \Lambda)$

GAC+Rosati +Bedic, arXiv:2012.07790, PhysLettB820(2021)136595

This encourages to consider "curvature-induced" scenarios:

in-vacuo dispersion is not present in the flat (even non-commutative) limit, but only when spacetime curvature is significant.

GAC+Rosati +Bedic, arXiv:2012.07790, PhysLettB820(2021)136595

the on-shell relation in FRW which has been so far used is

$$E=\frac{p}{a\left(t\right)}\left(1-\frac{\lambda}{2}\frac{p}{a\left(t\right)}\right)\quad\longrightarrow\quad\Delta t=\lambda\Delta p\int_0^{z_{em}}\frac{dz}{H\left(z\right)}\left(1+z\right)$$

we focus on the alternative formula

$$E=\frac{p}{a\left(t\right)}\left(1-\frac{\lambda'}{2}p\,a\left(t\right)\right)$$

and consider a (toy) model

$$E=\frac{p}{a\left(t\right)}\left(1-\frac{\lambda}{2}\frac{p}{a\left(t\right)}-\frac{\lambda'}{2}p\,a\left(t\right)\right)$$

particle velocity

$\left(z=\frac{1}{a(t)}-1,\quad a(0)=1\right)$

$$v\left(z\right)=1+z-\left(\lambda+\lambda'+2\lambda z\left(1+\frac{1}{2}z\right)\right)p$$

for small t $\quad\simeq 1-H_0t-\left(\left(\lambda+\lambda'\right)-2\lambda H_0t\right)p$

for $\lambda'=-\lambda$ it is a pure "curvature-induced" correction

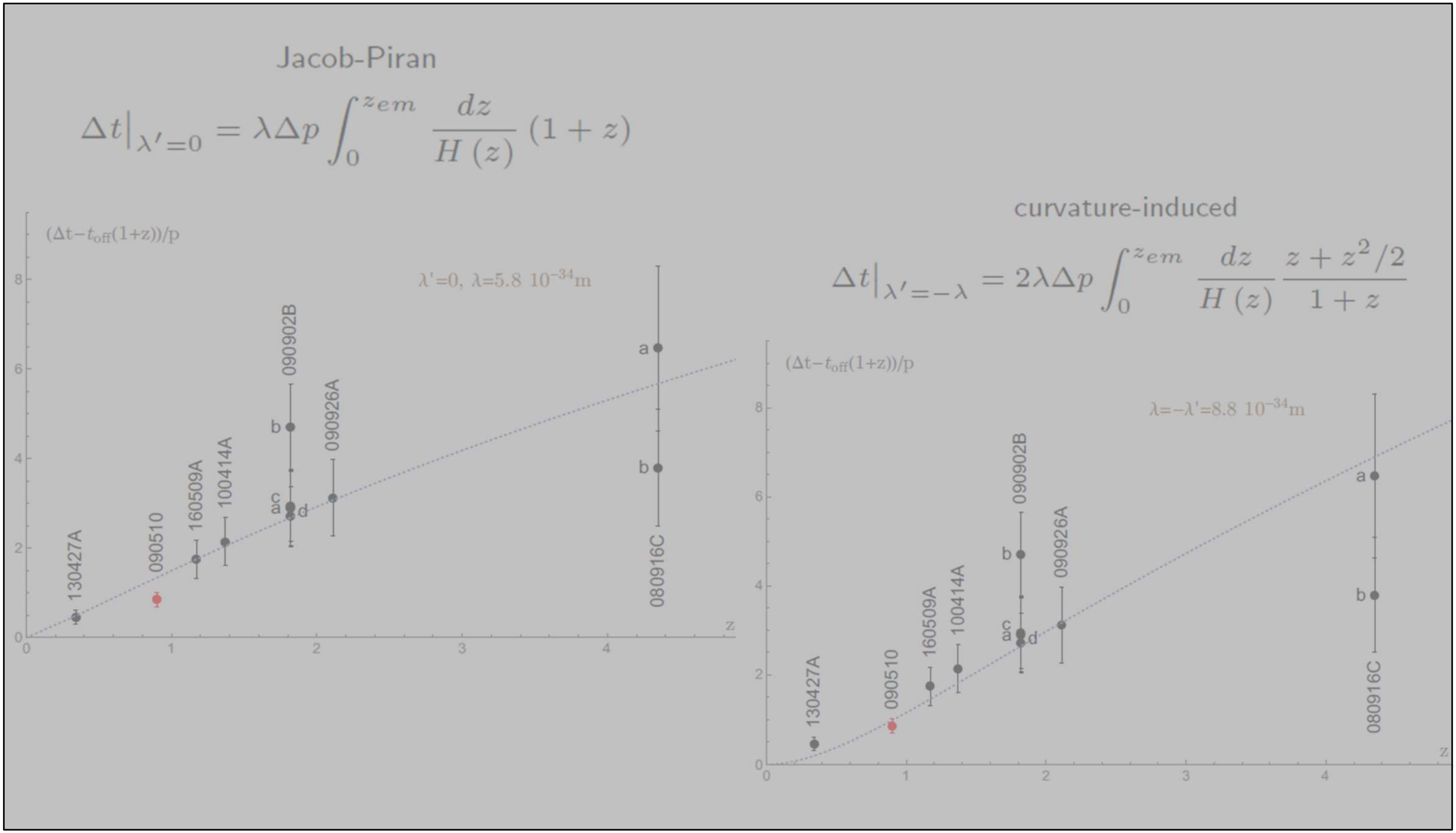
time delay

$$\Delta t=\Delta p\int_0^{z_{em}}\frac{dz}{H\left(z\right)}\left(\lambda\left(1+z\right)+\frac{\lambda'}{\left(1+z\right)}\right)$$

$$\Delta t\big|_{\lambda'=-\lambda}=2\lambda\Delta p\int_0^{z_{em}}\frac{dz}{H\left(z\right)}\frac{z+z^2/2}{1+z}$$

GAC+Rosati +Bedic, arXiv:2012.07790, PhysLettB820(2021)136595

- **note that the Jacob-Piran ansatz is such that dispersion is still present in the flat-spacetime limit**
- **when in-vacuo dispersion is "curvature induced" the onset of the effects at small redshift is of course much softer**



dual-curvature lensing

Freidel+Smolin,PhysRevD(2014)
GAC+Barcaroli+Loret,IJMPD(2017)
GAC +DiLuca +Frattulillo+Mercati, in preparation

$$\delta\theta \sim T^{n}\,\frac{E^{m+n}}{E_p^{m}}$$

N.B.: so far totally unexplored!!!

first meaningful limits with multisatellite telescopes like HERMES…

threshold anomaly for $\gamma\gamma \rightarrow e^+e^-$

assume the relevant photon and electrons are all governed by on-shellness

$$E^2 \approx m^2 + p^2 + \eta \frac{2}{n+1}\left(\frac{E}{M_P}\right)^n p^2$$

and make the additional assumption that energy-momentum is trivially conserved

$$E_1 + \epsilon = E_2 + E_3$$

$$p_1 - q = p_2 + p_3$$

-not what a nonprimitive coproduct suggests
-amplifier of this analysis is boost wrt COM frame
-requires breakdown (rather than deformation) of relativistic symmetries

and study the threshold-energy requirement (<u>head-on-collision</u>) for a hard photon to produce an electron-positron pair in interaction with a soft photon of energy ε

before

after

then, also assuming n=1

$$E_1+\epsilon=E_2+E_3$$

$$p_1-q=p_2+p_3$$

$$E=p+\frac{m^2}{2p}-\eta\frac{p^2}{M_p}$$

$$p_1-\eta\frac{p_1^2}{M_p}+q=2p_2+\frac{m^2}{p_2}-2\eta\frac{p_2^2}{M_p}$$

$$-\eta\frac{p_1^2}{M_p}+q=-q+\frac{2m^2}{p_1}-\frac{\eta}{2}\frac{p_1^2}{M_p}$$

$$2q=\frac{2m^2}{p_1}+\frac{\eta}{2}\frac{p_1^2}{M_p}$$

$$E_1\geq\frac{m^2}{\varepsilon}+\frac{\eta E_1^3}{4\varepsilon M_p}$$

threshold moves to higher values….
without the Mp effect photons with energies of about 10 TeV should be «absorbed» by the background of far-infrared photons…
data is presently unreliable but appears to show that absorption is somewhat suppressed…

threshold-anomaly issue possibly also for UHECRs

threshold anomaly for $p+\gamma \rightarrow p+\pi^0$

target photons would be CMBR photons

protons could have energy of about the GZK cutoff!!!

status of UHECRs at about the GZK cutoff stsill unclear….
are they protons or heavy ions?
from how far are we seeing them? (for a few years we thought we knew)

$\gamma\gamma \rightarrow e^{+}e^{-}$ **threshold-anomaly and LHAASO**

[don't know how far sources are but relevant photon background is well measured]

$\gamma\gamma \rightarrow e^{+}e^{-}$ **threshold-anomaly and TeV-blazars**

[we measure distance from the sources but FIR background is not well measured]

how far the TeV horizon extends?

how far the PeV horizon extends?

infrared/ultraviolet mixing

* Notice that Hawking's information paradox is an infrared issue!!!

* in some quantum spacetimes renormalization gets affected… prototypical case of canonical spacetime noncommutativity

$$[\hat{x}^\mu, \hat{x}^\nu] = i\theta^{\mu\nu}$$

$$\Delta x \geq \frac{\theta}{\Delta y}$$

$$-i\frac{\lambda}{6}\int \frac{d^4k}{(2\pi)^4}\left(2+\cos\left(p\times k\right)\right)\frac{i}{k^2-m^2} \quad ,$$

where p is the external momentum (the propagation momentum).

from planar diagrams

from nonplanar diagrams

infrared/ultraviolet mixing

modified propagator… once again the onshellness relation is affected, but in this case the IR form of the onshellness gets modified…

$$m^2 \simeq E^2 - p^2 + \frac{\zeta_\Phi}{\tilde{p}^2}$$

IR divergent, so it makes sense only with a IR cutoff…
peculiar phenomenology just looking for the IR cutoff…

$$m^2 \simeq E^2 - p^2 + \chi_\theta \, m^2 \log\left(\frac{E + \vec{p}\cdot\hat{u}_\theta}{m}\right)$$

for p<m the correction is linear in p…

$$m^2 \simeq E^2 - p^2 + \xi \frac{M_*}{m} p^2$$

mismatch between inertial mass and rest energy

implications for cold-atom interferometry!!!

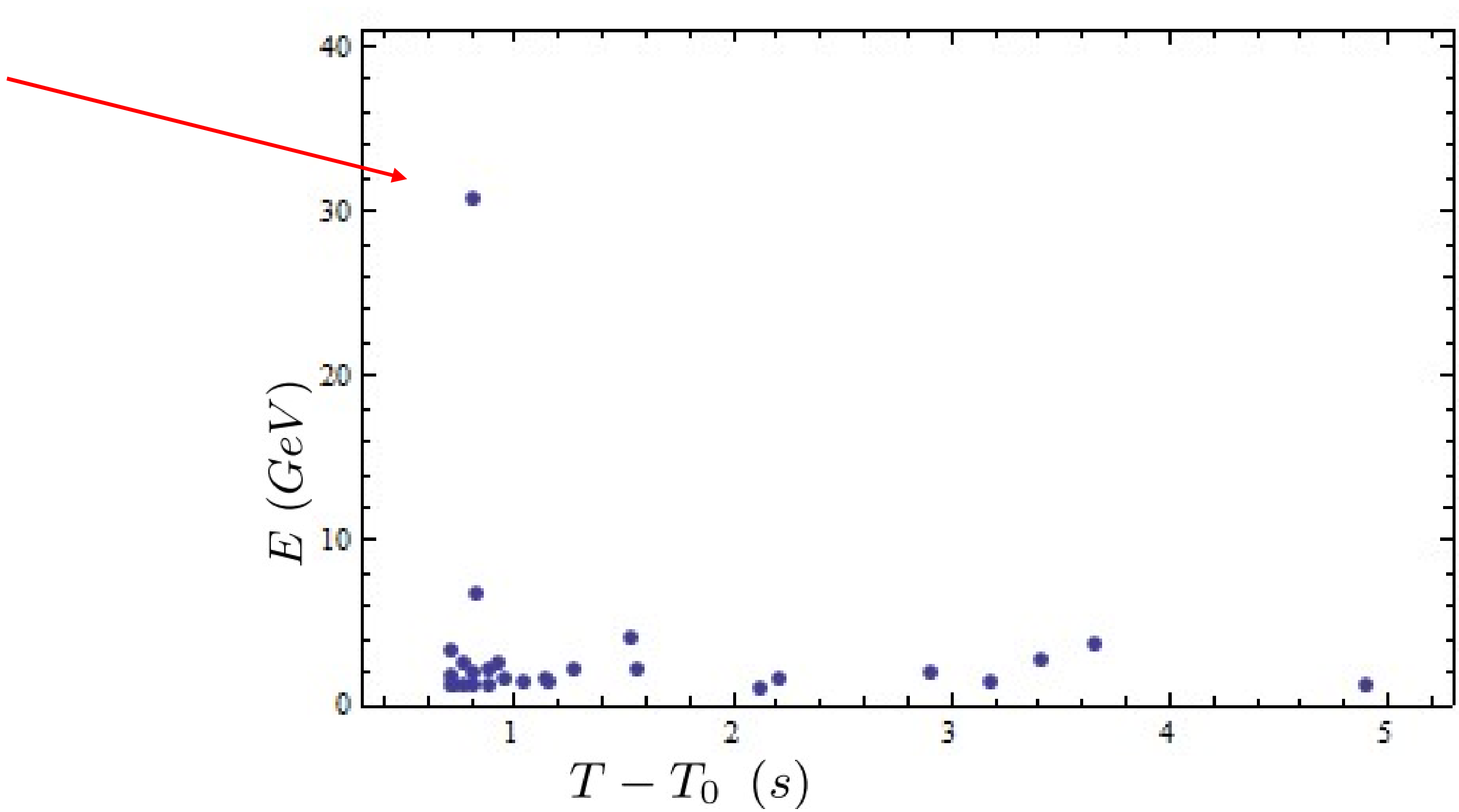
GAC+Laemmerzahl +Mercati +Tino,PhysicalReviewLetters103(2009)171302

also implications for astrophysics(Chandrasekhar model…)

in-vacuo dispersion for photons

first target for phenomenology has been testing the Jacob-Piran ansatz for the redshift dependence… for some GRBs one is led to experimental bounds of «Planckian sensitivity» by comparing the arrival time of the highest-energy photon with the arrival times of some lower-energy photons…

GRB090510



test in-vacuo dispersion statistically…

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)

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

Jacob+Piran [JCAP0801,031(2008)]

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

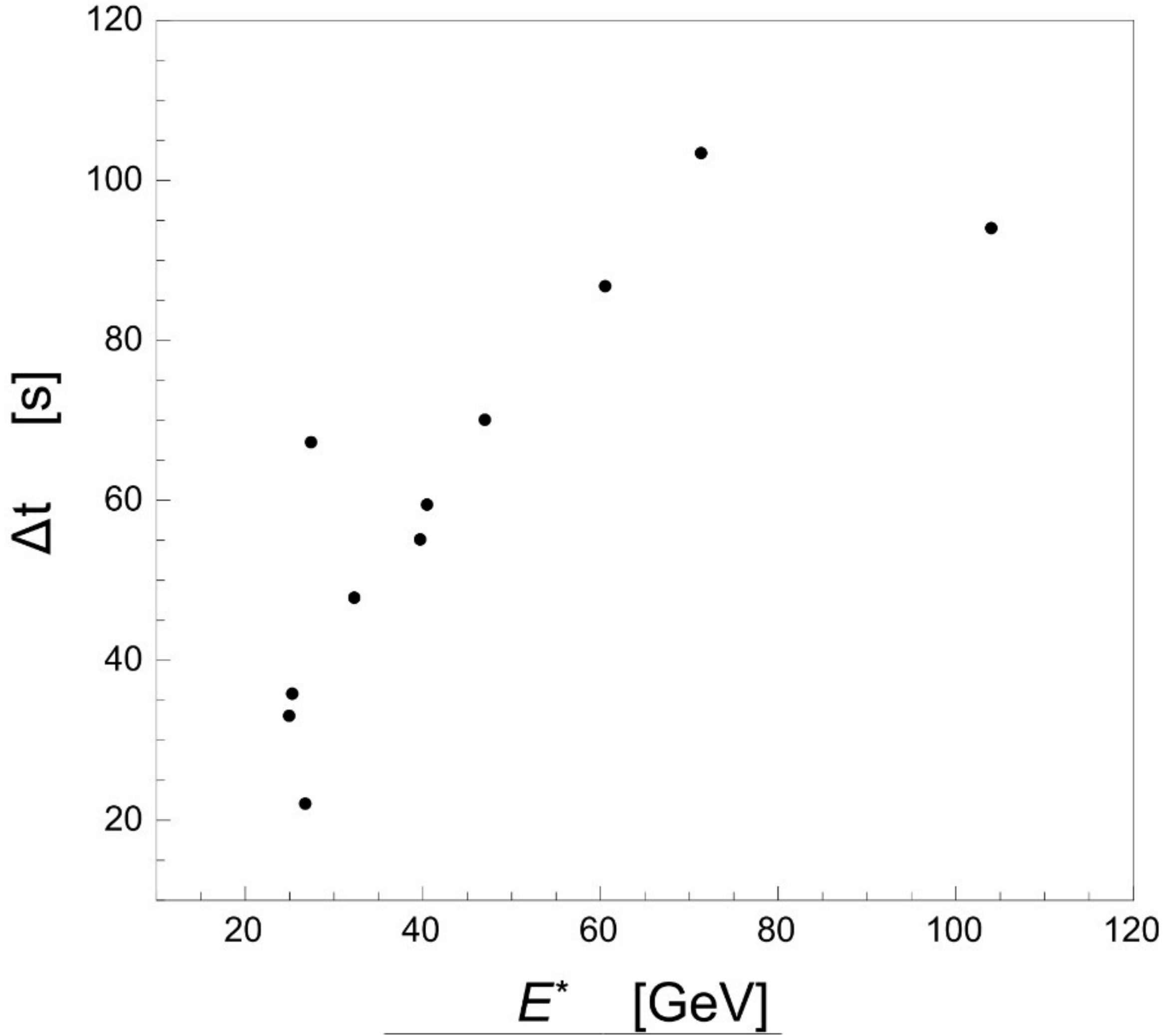
$$E^* \equiv E \frac{D(z)}{D(1)}$$

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

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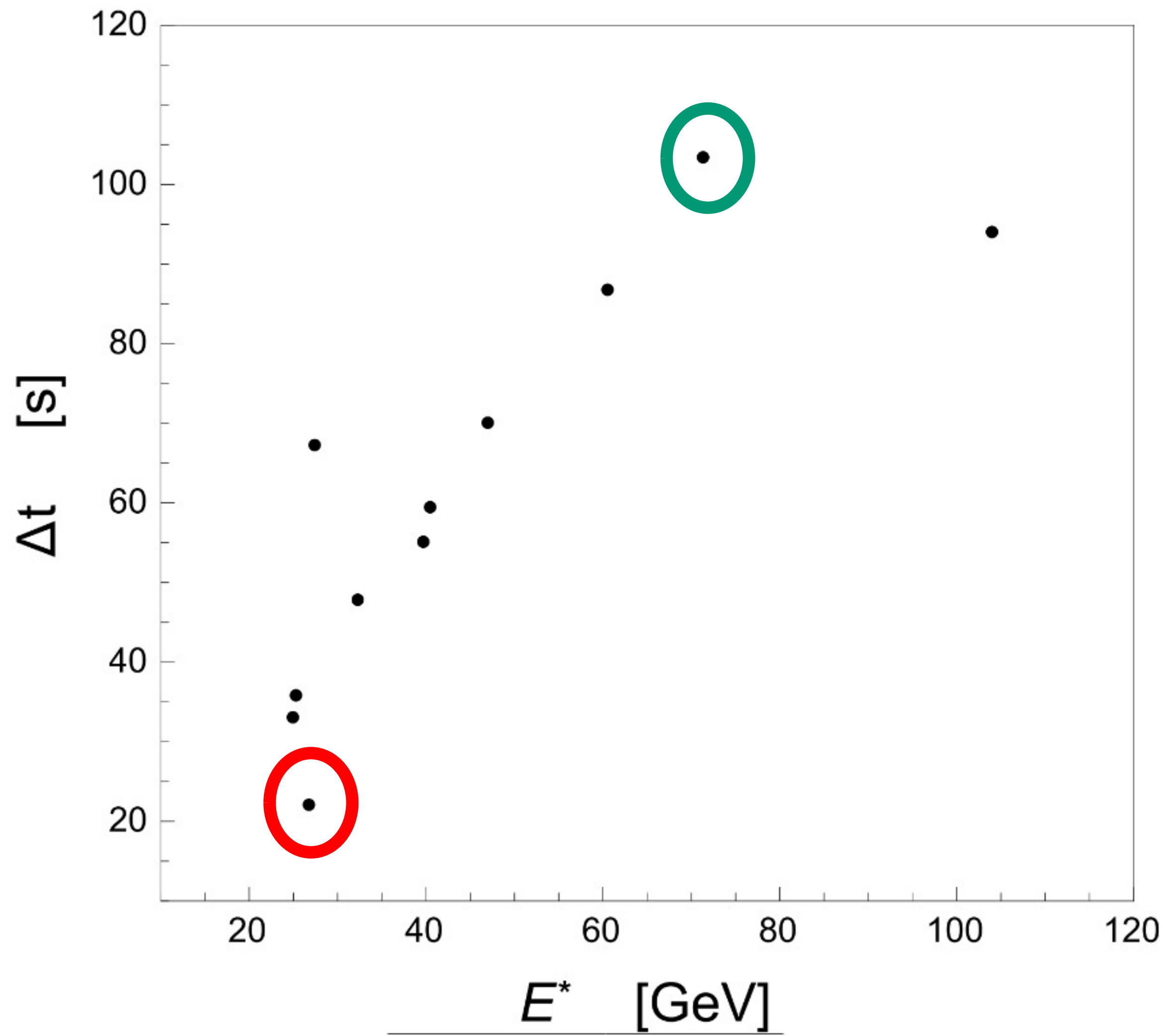

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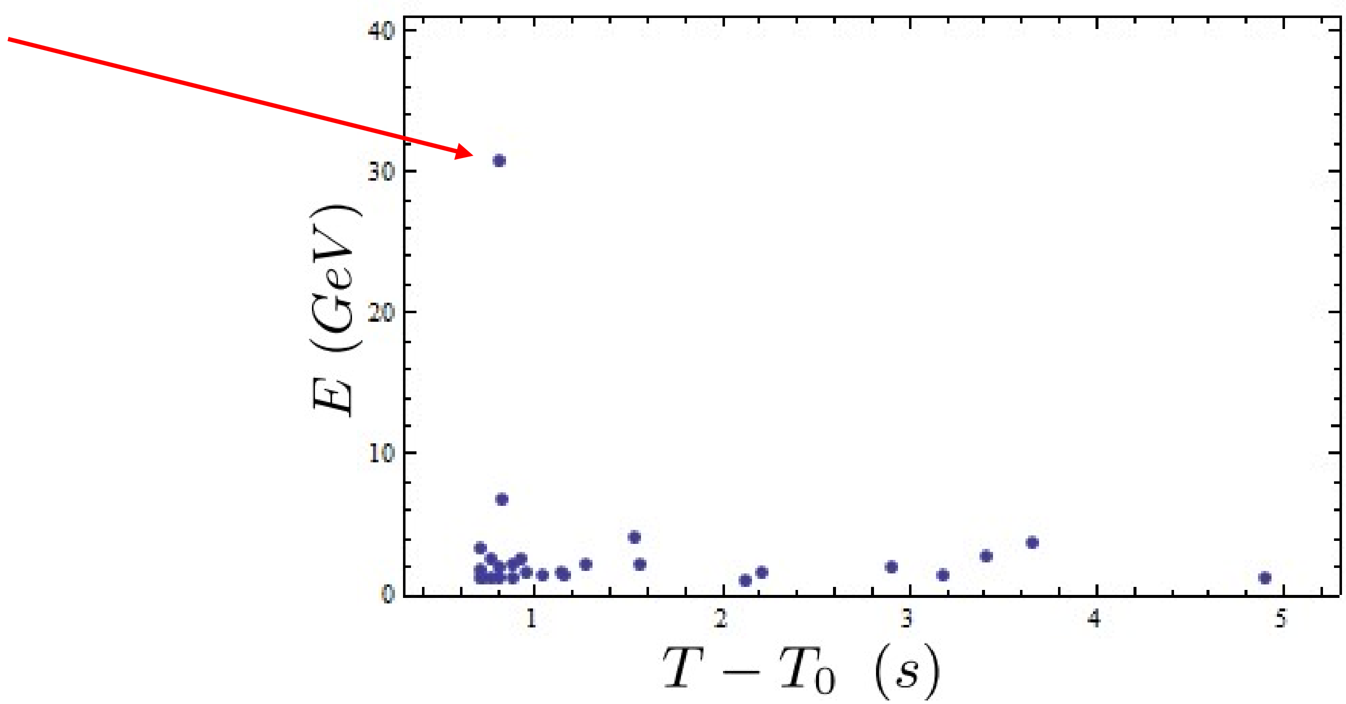


* **HERMES and other multisatellite telescopes**

* **CTA**

what about neutrinos???

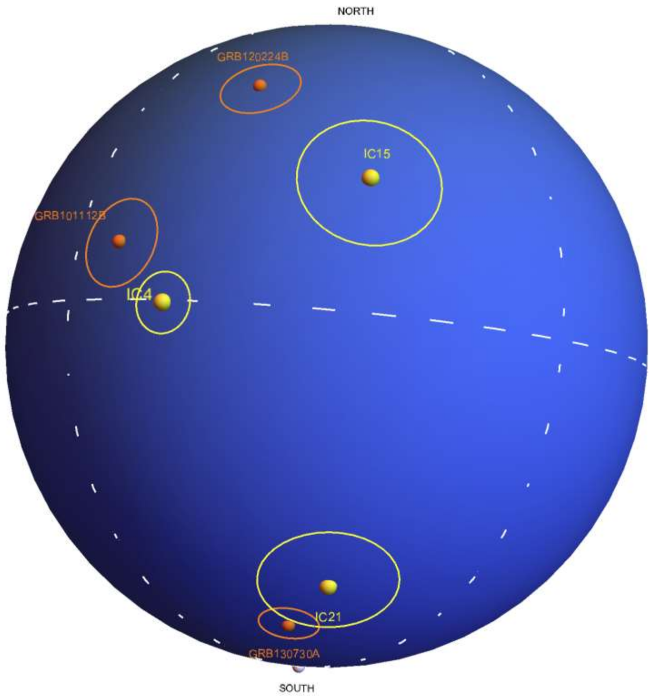
The prediction of a neutrino emission associated with Gamma Ray Bursts is generic within the most widely accepted astrophysical models

according to pre-IceCube predictions, IceCube should have seen a few GRB neutrinos in each year of operation but it has reported no GRB neutrinos!

most likely pre-IceCube models of neutrino production by GRBs were incorrect, but QG offers an alternative explanation:
typically IceCube looks for GRB neutrinos within a window of about 100 seconds of the GRB trigger…

GAC+D'Amico+Rosati +Loret, arXiv1612.02765, NatureAstronomy1,0139
GAC+Barcaroli+D'Amico+Loret+Rosati, arXiv1605.00496,PhysicsLettersB761(2016)318
GAC+DiLuca+Gubitosi+Rosati +D'Amico, arXiv2209.13726, NatureAstronomy(in press)

focus on "shower neutrinos" with energy between 60 and 500 TeV
("track neutrinos" have much worse energy estimation)



Assume once again validity of the Jacob-Piran ansatz

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

with

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

we should find that at least some of our GRB-neutrino candidates have difference of time of arrival with respect to the relevant GRB which grows linearly with energy, modulo the uncertainties in redshift

also for neutrinos we set up the analysis in terms of the relationship between Δt and E* (but we change notation from E* to K)

the large uncertainties in redshift will still be present, disguised as corresponding uncertainties for the determinations of E* (i.e. K) but at least we will be working with a linear relationship:

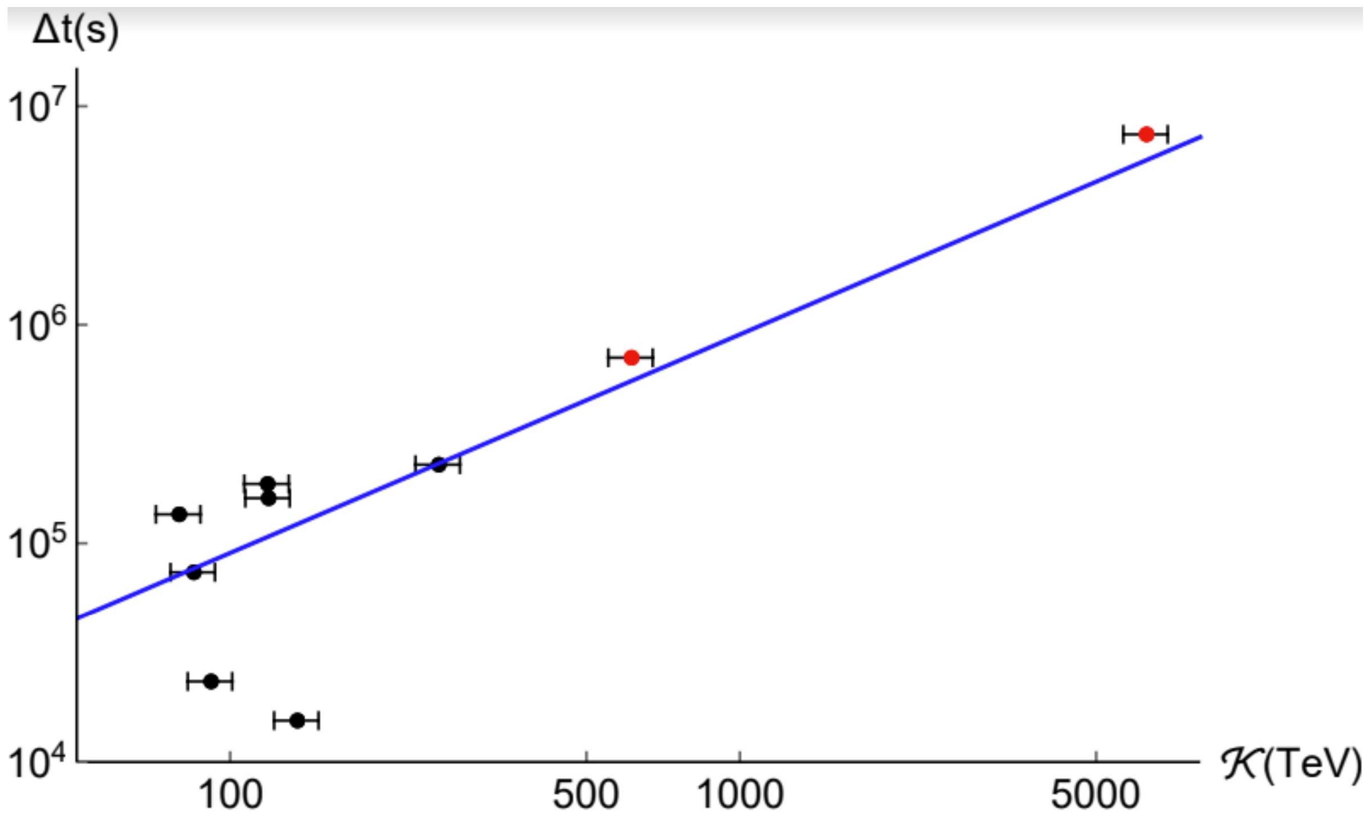
$$\Delta t = \eta \cdot D(1) \frac{E^*}{M_P}$$

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

Within the ICeCube data so far publicly available only 7 turned out to be "GRB-neutrino candidates" with our angular and temporal selection criteria.

So let's see if they provided some support for the linear dependence between Δt and K

GAC+DiLuca+Gubitosi+Rosati +D'Amico, arXiv2209.13726, NatureAstronomy(in press)



correlation visible in figure is remarkable especially considering that

- **our κ carries an additional uncertainty due to the limited knowledge about redshift of GRBs (error bars in figure take into account only uncertainty in energy)**
- **and especially considering that the expected number of background neutrinos that should sneak in our list of GRB-neutrino candidates is between 3 and 4**

<u>N.B. this is our updated analysis taking into account revised estimates of event directions and revised estimates of event energy made recently by IceCube, which were not known at the time of previous studies</u>

combining the photon analysis and the neutrino analysis