Looking for "the old quantum-gravity theory" with gamma rays and cosmic rays

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Main purpose: a common language and hopefully shared objectives

how many quantum-gravity theories?

1??

what is the value of the quantum-gravity scale?

$=1.2208916 \bullet 10^{19}$GeV ???

limit on energy dependence of speed of light?

LIV? or DSR?

a perspective on theory and data on

* **Fuzziness**
* **Birefringence**
* **Anomalous Kinematics thresholds (absorption of gamma rays, GZK cosmic rays)**

Can't do no wrong (Testing Lorentz symmetry with or without quantum gravity)

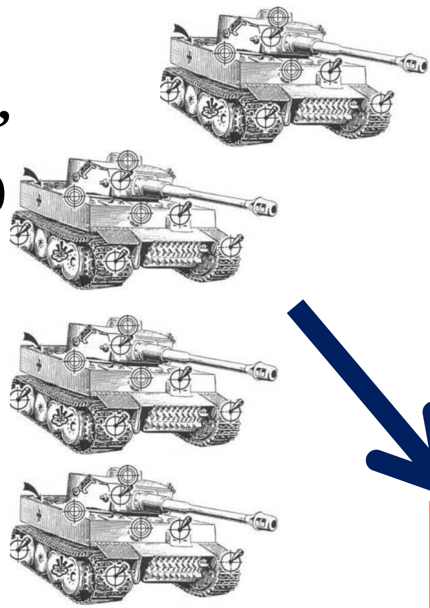
detailed review covering QGphen:
arXiv:0806.0339

many QuantumGravity theories:
PhysRevD80, 084017 [arXiv:0906.3731]
(with Smolin)

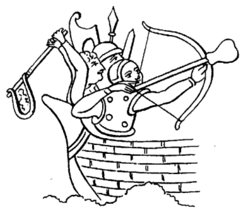
DSR is not like LIV:
arXiv:1006.0007
(with Marciano+Matassa+Rosati)

traditional strategy

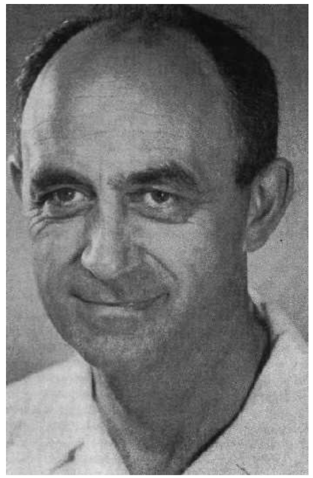
“wanna be like Einstein”
(one big jump to get to GR)
we’ll get ourselves a
Theory Of Everything



quantum-gravity problem



the “old quantum-gravity theory” strategy:
but probably QG requires a totally new paradigm...
must come about more like Quantum Mechanics...
necessarily first the old quantum theory....and think of the century-long story of weak interactions....
brilliant partial solutions helped us along the way...



how many QG theories are there?

∞: "youguys of QG research don't even know what you're talking about...
you are wasting taxpayer's money!!!"

1: "QG is String Theory" ("Moses told me"...but which one?)
[∞ again.....]

1: "QG is a single theory combining the claims in all papers on the QG problem, even though they used completely different formalisms"
[dispersion+birefringence+fuzziness+GUP+GZK ??<u>definitely not!!!!</u>]

several:"it could be EITHER string theory OR loopQG
OR spacetime noncommutativity OR..."

<u>healthy perspective:</u> we cannot look for QG right now....
we can look for "the old QG theory"...
so we need several "QG theories of NOT everything"

but how do we figure out which models are “good”?

hopefully soon with data....

...but for now:

* analysis of the structure of the QG problem
  (see, e.g., comments on fuzziness, later)

* and...hmmmm....well....
  string theory, loopQG and spacetime noncommutativity
  (so “business as usual”.....only nearly....)

great!!! and what do they say???

<u>mainstream string theory</u> (critical, SUSY...)

could be one day turned into beautiful phenomenology of NOT everything,
but presently not useful for Planck-scale-phenomenology (infinitely many theories...)

<u>loop Quantum Gravity</u>

probably predictive
<u>main feature is discreteness of spacetime observables</u>...
but presently unmanageable for phenomenology...
still it does inspire some "quantum-gravity theories of NOT everything"
(see below..semiheuristic arguments of Gambini+Pullin, Urrutia+...)

<u>spacetime noncommutativity</u>

N.B. "Connes noncommutativity" predicts...the Standard Model!!!!
"quantum-group noncommutativity" is <u>tangibly predictive</u>,
but not that much simpler than loopQG
and far too many options
[by the way....q-GNC is my preferred formalism...and it stinks!!!]

<u>out-of-mainstrem string theory(like model of QG foam of Ellis+Mavromatos+Nanopulos)</u>

impossible to make computations....therefore not predictive...but suitable for
beautiful semi-heuristic analyses with of course <u>predictive (but "flexible") outcome</u>

ok, then just tell us the value of the Quantum-Gravity scale…

E_{QG} =E_{Planck}=$1.2208916 \bullet 10^{19}$GeV (“we predict dispersion at the Planck scale...”)

$E_{QG} \sim 10^{3}$ GeV (large extra dimensions...)

$E_{QG} \sim 10^{19}$ GeV

and it is only rough order-of-magnitude estimate at best

mainly comes from observing that at the Planck scale

$$\lambda_{compton} \sim \lambda_{schwartzschild}$$

and assumes that G does not run at all!!!!!!!!!

but it runs!!!

and it should run!!!!

PART II

outline:

dispersion

fuzziness

birefringence

$$\textbf{threshold anomalies}\begin{cases} \gamma\,\gamma \rightarrow e+\ e- & \textbf{(TeV gamma rays, AGNs....)} \\ p\,\gamma \rightarrow p\,\pi & \textbf{(GZK, cosmic rays...)} \end{cases}$$

in-vacuo dispersion

spacetime noncommutativity: in most (but not all) models

loop QG: "expected" by many experts

<u>other models</u> of spacetime foam: likely

linear or quadratic

$$m^2 = E^2 - p^2 + \lambda E p^2$$

$$m^2 = E^2 - p^2 + \lambda^2 E^2 p^2$$

but apparently not quartic (which would be otherwise feared)

in-vacuo dispersion

1998:

$$m^2 = E^2 - p^2 + \lambda E p^2$$

GAC+Ellis+Mavromatos+Nanopoulos+Sarkar, Nature(1998)

$$v_\gamma \simeq 1 - \lambda |p|$$

where λ is λ_{LIV} a <u>preferred-frame</u> picture (LIVpicture, i.e. LSB picture, i.e. preferred frame) and it was formalized only for <u>flat spacetime</u> initially

2000:

$$m^2 = E^2 - p^2 + \lambda_{DSR} E p^2$$

GAC, arXiv:grqc0012051;
IntJournModPhysD11,35;
Nature418,34

$$v_\gamma \simeq 1 - \lambda_{DSR} |p| \ .$$

with λ_{DSR} <u>no preferred frame</u>
but was formalized only for <u>flat spacetime</u> initially

2008: consensus emerges for formalization in expanding spacetimes of LIV case

$$v_\gamma \simeq \left(1 - \lambda_{\rm LIV} \frac{|p|}{a(\eta)}\right)$$

$$\Delta t \simeq \frac{1}{H_0} \lambda_{\rm LIV} \Delta p \int_0^z \frac{(1+z')dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

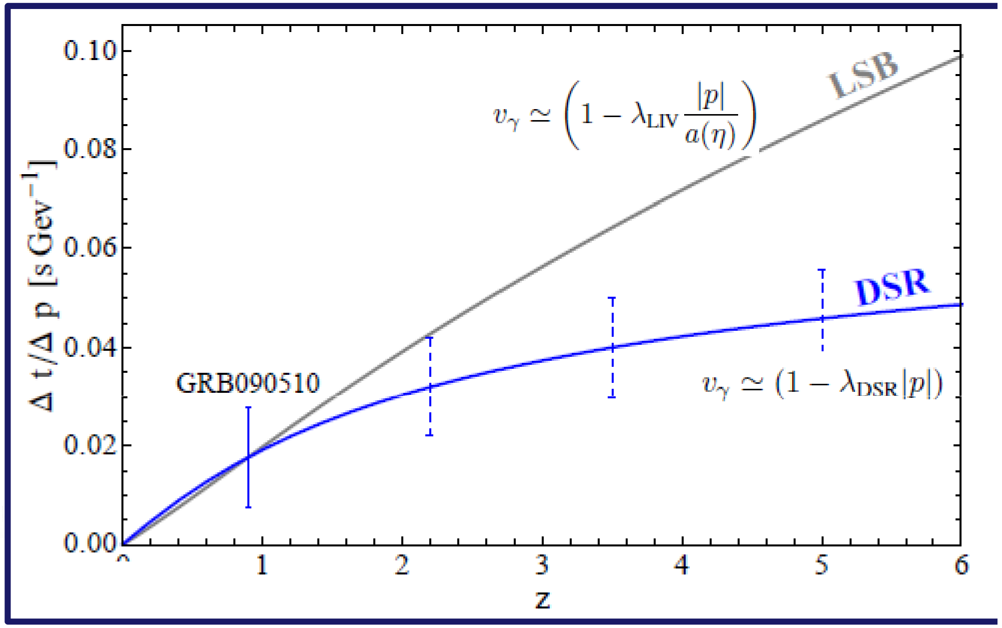
Jacob+Piran , JCAP0801,031
Ellis+Mavromatos+Nanopoulos+Sakharov+Sarkisyan, Astropart.Physics29,158

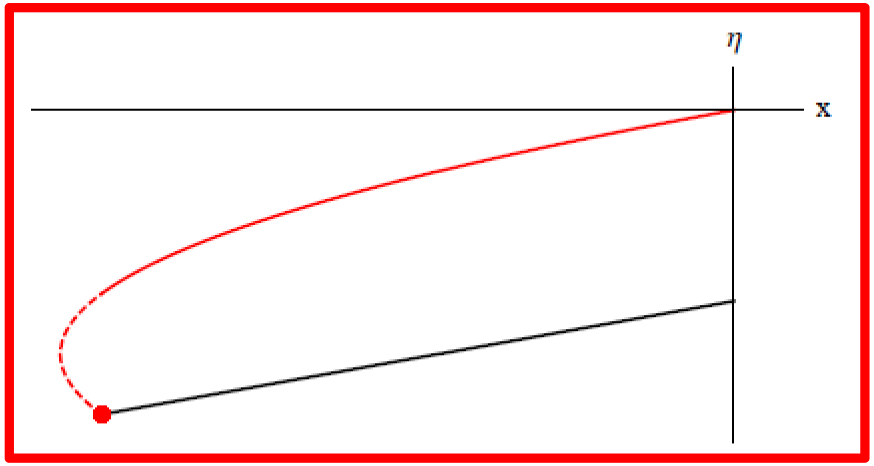
a DSR theory compatible with spacetime expansion
arXiv:1006.0007
GAC+Marciano+Matassa+Rosati)

$$v_\gamma \simeq (1 - \lambda_{\mathrm{DSR}} |p|)$$

$$\Delta t \simeq \frac{1}{H_0} \lambda_{\mathrm{DSR}} \Delta p \int_0^z \frac{dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

$$G_N = x(1 - H\eta)\partial_\eta + \left(\frac{1-(1-H\eta)^2}{2H} - \frac{H}{2} x^2 \right) \partial_x + $$
$$+ \lambda_{\mathrm{DSR}} \left(\frac{1+H\eta}{2} x\, \partial_x - (1-H\eta)\, \eta\, \partial_\eta + \frac{H\eta}{2} \right) \partial_x$$



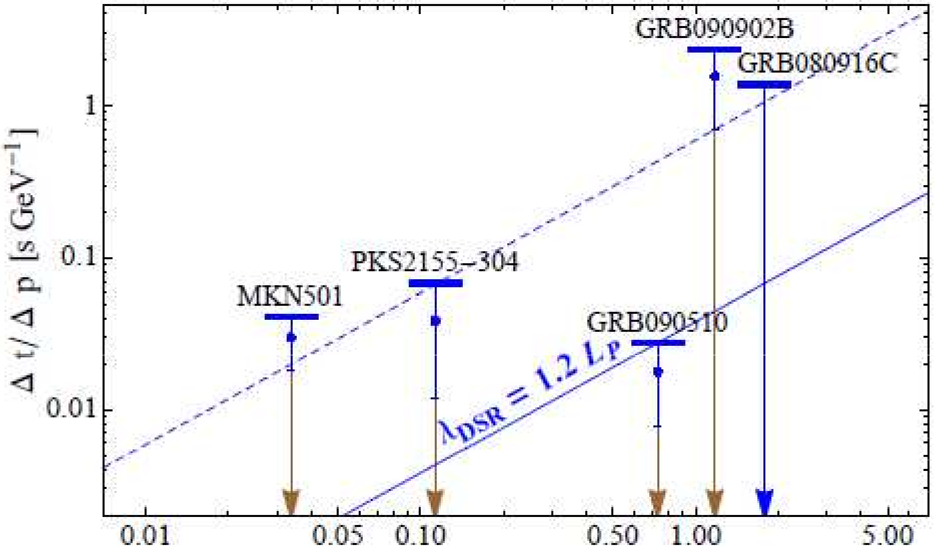


a DSR theory compatible with spacetime expansion

$$v_\gamma \simeq (1 - \lambda_{\rm DSR}|p|)$$

$$\Delta t \simeq \frac{1}{H_0}\lambda_{\rm DSR}\Delta p \int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$$

$$G_N = x(1-H\eta)\partial_\eta + \left(\frac{1-(1-H\eta)^2}{2H} - \frac{H}{2}x^2\right)\partial_x + $$
$$+ \lambda_{\rm DSR}\left(\frac{1+H\eta}{2}\,x\,\partial_x - (1-H\eta)\,\eta\,\partial_\eta + \frac{H\eta}{2}\right)\partial_x$$



$$K_{\rm DSR}(z) = \int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$$

in the "Minkowski limit of quantum gravity" (clearly a <u>theory of not everything</u>) one might have noncommuting spacetime coordinates

Let us consider the example of kappaMINKOWSKI spacetime

$$[x_j, t] = i\lambda x_j$$

$$[x_j, x_m] = 0$$

Lukierski+Nowicki+Ruegg+Tolstoy,PLB(1991)
Nowicki+Sorace+Tarlini,PLB(1993)
Majid+Ruegg,PLB (1994)
Lukierski+Ruegg+Zakrzewski, AnnPhys(1995)

It would seem that translation and boost symmetries are lost….but our intuition only really reliable for "recognizing symmetries at first sight" when the algebra of fields is commutative….

Consider for example the following action for "kappa-Klein-Gordon fields":

$$S = \frac{1}{2} \int d^4x \, \Phi(x) \, \Box_\lambda \, \Phi(x)$$

where

$$\Phi(x,t) = \int d^4k \left(\varphi(k) e^{ikx} e^{ik_0 t} \right)$$

$$\Box_\lambda \Phi(x) \equiv \left[- \left(\frac{2}{\lambda} \right)^2 \sinh^2 \left(\frac{\lambda P_0}{2} \right) + e^{\lambda P_0} |\vec{P}|^2 \right] \Phi(x)$$

$$P_\mu \left(e^{ikx} e^{ik_0 t} \right) = k_\mu \left(e^{ikx} e^{ik_0 t} \right)$$

many familiar "symmetry tests" are successful assuming P_μ generate translation symmetries
and similar results found for candidate rotation/boost generators (see later)

But $\Box_\lambda$ is a "deformed box", non-special-relativistic….

Noether analysis of Hopf-algebra symmetries of field theories in noncommutative spacetime

PLB671(2009)298, PRD78(2008) 025005 ,MPLA22(2007)1779
(with Arzano,Gubitosi,Marciano',Martinetti,Mercati)

Translation generators in kappa-Minkowski:

$$P_\mu\left(e^{ikx}\,e^{ik_0t}\right)=k_\mu\left(e^{ikx}\,e^{ik_0t}\right)$$

classical action

$$[x_j, t] = i\lambda x_j \qquad [x_j, x_m] = 0$$

$$\Rightarrow \quad e^{ikx}e^{ik_0t}e^{iKx}e^{iK_0t} = e^{i(k+e^{\lambda k_0}K)x}e^{i(k_0+K_0)t}$$

then

$$P_\mu\left(e^{ikx}\,e^{ik_0t}e^{iKx}\,e^{iK_0t}\right)=P_\mu\left(e^{i(k+e^{\lambda k_0}K)x}\,e^{i(k_0+K_0)t}\right)$$

$$=\left(k_\mu+e^{-\lambda k_0}K_\mu\right)\left(e^{ikx}\,e^{ik_0t}e^{iKx}\,e^{iK_0t}\right)$$

$$=\left[P_\mu\left(e^{ikx}\,e^{ik_0t}\right)\right]\left(e^{iKx}\,e^{iK_0t}\right)+\left[e^{-\lambda P_0}\left(e^{ikx}\,e^{ik_0t}\right)\right]P_\mu\left(e^{iKx}\,e^{iK_0t}\right)$$

Nontrivial coproduct!!
Translations are not classical in kappa-Minkowski

It appeared to us that the most criticizeable assumption made in previous failed attempts of Noether analysis was

$$f \to f + df \qquad \text{with} \qquad df(x) = i a_\mu P_\mu f(x)$$

and <u>transformation parameters</u> a_μ <u>that were “as usual” ordinary real numbers</u>.

IDEA: transformation parameters ε_μ must be based on the (noncommutative!) differential calculus on the noncommutative spacetime

$$[\varepsilon_0, x_\mu] = 0; [\varepsilon_i, x_l] = 0; [\varepsilon_i, x_0] = i\lambda\varepsilon_i$$

Sitarz, PhysLettB349(1995)42 Majid+Oeckl, math.QA/9811054

so that in particular $x_\mu+\varepsilon_\mu$ obeys the kappa-Minkowski commutation relations.

When we then used

$$df(x) = i\varepsilon_\mu P_\mu f(x)$$

in the Noether analysis no further obstacles were encountered

For the mentioned example of action for kappa-Klein-Gordon fields one arrives at explicit form for the charges

$$Q_j = \int d^3x J_{0j} = \frac{1}{2}\int d^3x [(\tilde{P}_0 e^{-\lambda P_0/2}\Phi)(P_j\Phi) + (P_j\Phi)\tilde{P}_0 e^{-\lambda P_0/2}\Phi]$$

$$\tilde{P}_0 = \left(\frac{2}{\lambda}\right)\sinh(\lambda P_0/2)$$

whose t-independence (on solutions of the EoM) is easily verified

Fuzziness

$$[x_\mu, x_\nu] = i\theta_{\mu\nu}(\{x_\alpha\})$$ → points are not "point-like"…..
roughly like position in phase space….

very general prediction of QG problem….
more general than dispersion(!!)….
and "seen" in most QG formalisms…
but how big is this fuzziness??
an ansatz

$$v_\gamma(p) \simeq 1 - \frac{p}{M_{QG}} \pm \eta_f \frac{p}{M_{QG}}$$

Ng+VanDam,ModPhysLett(1994)
GAC,ModPhysLettA(1994)
Garay,IntJournModPhysA(1995)
Ford,PhysRevD(1995)

GAC+Smolin,PhysRevD(2009)

N.B. dispersion → fuzziness (but not necessarily same order)
but fuzziness does not imply dispersion, so it is possible

$$v_\gamma(p) \simeq 1 \pm \eta_f \frac{p}{M_{QG}}$$

surely testable with bursts of γ-rays…
can't say if it can compete with other
bound-setting strategies

Lieu+Hillman, Astrophys.Journ.(2003)
Ng+VanDam+Christiansen, Astrophys.Journ.(2003)

birefringence

$$[x_\mu, x_\nu] = i\theta_{\mu\nu}$$

~loopQG

→ birefringence

Gambini+Pullin,PhysRevD(1999)
Myers+Pospelov, PhysRevLett(2003)

nothing in QG problems points to birefringence
but it is <u>strikingly easy to get out of Quantum Field Theory</u>
[still….QFT prediction of cosmological constant
is a bit off…and the prediction that there is no gravity
is also questionable…]

linear effect extremely well constrained

Gleiser+Kozameh,PhysRevD(2001)
Mattingly, Living RevRel(2005)
GAC, arXiv:0806.0339

it would be exciting if we could aim for quadratic effect

threshold anomalies

N.B.:
*MDR does not imply ThresholdAnomalies
*ThresholdAnomalies do not require MDR

Kifune, AJL 518(1999)L21
Kluzniak, AP11(1999)117
Protheroe+Meyer, PhysLettB493(2000)1
GAC, Nature408(2000)661
GAC+Piran, PhysRevD64(2001)036005

IFF mod disp rel THEN appears to be inevitable in the LIV case but forbidden in the DSR case
(where energy-momentum charges must be consistently deformed)

GAC, arXiv:grqc0012051;
IntJournModPhysD11,35;
Nature418,34

......LIV scenario is now restricted to photons!!!!!???

example: $\gamma\gamma \rightarrow e^+ e^-$

using $m^2 = E^2 - p^2 + \lambda E p^2$ one finds that the process is only allowed if

$$E - \frac{\lambda E^3}{8\epsilon} \gtrsim \frac{m_e^2}{\epsilon}$$

analogous prediction for $p\,\gamma \rightarrow p\,\pi$ is in trouble with GZK cutoff story...
this is why LIV is being restricted to photons...
for LIV case even quadratic in Planck length is starting to be in trouble with GZK story...
but it is intriguing to think of all this in relation to observations of γ-rays from AGNs...

absorption of TeV photons

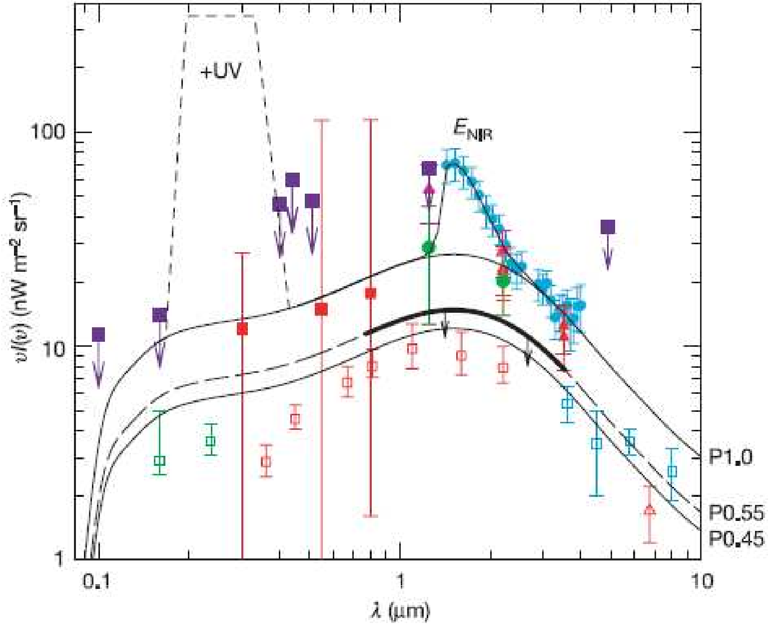


Figure 1 | SED of the EBL in the wavelength band most affecting these HESS data (0.1–10 μm). The EBL data are from a review compilation[1] (errors 1σ), unless otherwise stated. Open symbols correspond to the integrated light from galaxy counts, and thus must be considered lower limits for the EBL: in the UV–O range, from Hubble data (green, red[8]); in the NIR, from Spitzer (blue[28]) and ISO data. We note that these data are also lower limits for the total emission from galaxies, because of various observational and selection effects in the detection and counting of faint galaxies. The possible missed light in the the UV–O band has been estimated[29] to be $\lesssim$(2–3) nW m^{-2} sr^{-1}. The upper limits (purple) are 2σ estimates[1]. Direct measurements are shown as filled symbols: IRTS data from the NIR spectrometer[16] (blue), and data from COBE/DIRBE (green[15], magenta[17] and red triangles). Red squares correspond to tentative detections in the optical[26] with corrections according to ref. 30. The curves show the EBL shapes used to reconstruct the intrinsic spectra. P1.0 gives 26, 23 and 14 nW m^{-2} sr^{-1} at 1.25, 2.2 and 3.5 μm, respectively. The thick line shows the range most effectively constrained by the HESS data.

Aharonian et al
Nature 440, 1018 (2006)

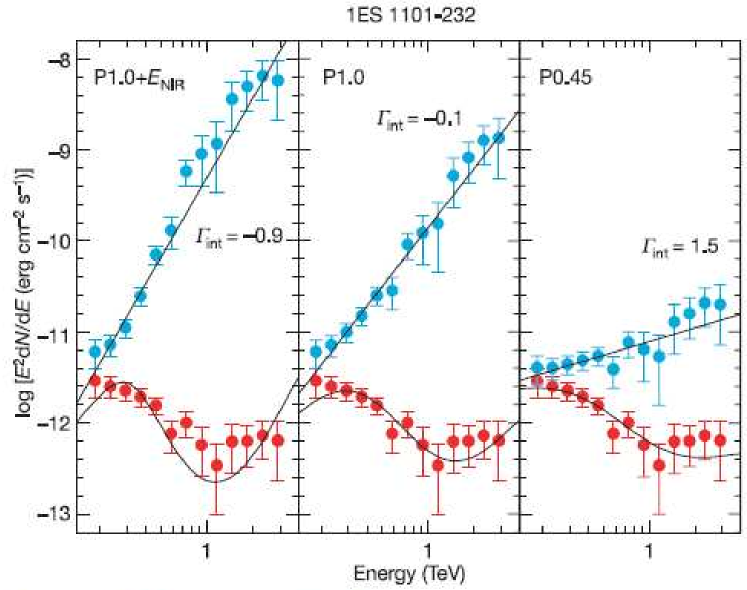


Figure 2 | The HESS spectra of 1ES 1101−232, corrected for absorption with three different EBL SED values, as labelled in Fig. 1. Red, observed data; blue, absorption-corrected data. The data points are at the average photon energy in each bin, also used to calculate the optical depth for reconstruction. For the calculation, a flat Λ-dominated cosmology was adopted, with $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$. Error bars are 1σ s.d., statistical errors only. Between 1.3 and 3.3 TeV, the overall detection is 4σ. The lines show the best-fit power laws to the reconstructed spectrum ($dN/dE = N_0E^{-\Gamma_{int}}$), where E is measured in TeV, and the corresponding shapes after absorption. The χ^2_{red}/d.o.f. (calculated by integrating the

Therefore, the conservative and self-consistent assumptions of both not-unusual blazar spectra ($\Gamma_{int} \geq 1.5$) and a galaxy-like EBL spectrum allow the EBL flux around 1–2 μm to be constrained at the level of $\lesssim$(14 ± 4) nW m^{-2} sr^{-1} (that is, $\lesssim$0.55 ± 0.15 × P1.0). This corresponds to P(0.45 + 0.1) to allow for galaxy evolution effects. Coupled with the lower limits derived from galaxy counts given by the Hubble Space Telescope[8] ($\sim 9.0 - 9.7^{+3.0}_{-1.9}$ nW m^{-2} sr^{-1}), the HESS spectra lead us to conclude that more than two-thirds of the EBL in the O–NIR band is resolved into single sources. This result is independent of any 'direct' measurement of the EBL. Remarkably, it is in severe conflict with the claims of high EBL flux at NIR wavelengths[16,17] and, to a lesser extent, with the reported detections at 2.2 and 3.5 μm (refs 1, 15). The HESS upper limits agree instead with the most recent theoretical calculations[23] of the EBL, as well as with recent theoretical arguments[24,25] against high EBL fluxes due to population III stars.

absorption of TeV photons

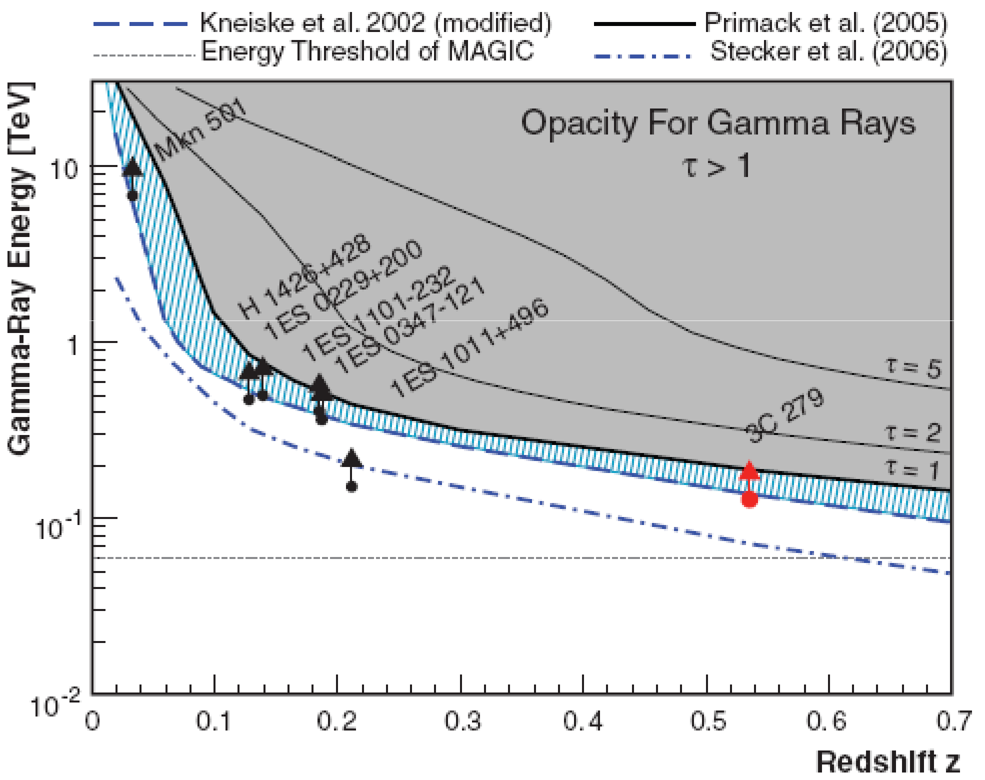


Fig. 3. The gamma-ray horizon. The redshift region over which the gamma-ray horizon can be constrained by observations has been extended up to $z = 0.536$. The prediction range of EBL models is illustrated by (*8*) (thick solid black line) and (*11*) (dashed-dotted blue line). The tuned model of (*14*) (dashed blue line) represents an upper EBL limit based on our 3C 279 data, obtained on the assumption that the intrinsic photon index is ≥1.5 (red arrow). Limits obtained for other sources are shown by black arrows, most of which lie very close to the model (*14*). The narrow blue band is the region allowed between this model and a maximum possible transparency (i.e., minimum EBL level) given by (*8*), which is nearly coincident with galaxy counts. The gray area indicates an optical depth $\tau > 1$, i.e., the flux of gamma rays is strongly suppressed. To illustrate the strength of the attenuation in this area, we also show energies for $\tau = 2$ and $\tau = 5$ (thin black lines), again with (*8*) as model.

Albert et al,
Science 320, 1752 (2008)

testing Lorentz symmetry with or without QG

N.B.: DSR theory showed on previous slides is
first ever test theory of SR without a preferred frame!!

IFF one adopts formalism of effective low-energy Quantum Field Theory (not obvious!!)
THEN (from a QG perspective) situation of SR tests looks something like

advantage of SME: many more possible effects violating SR monitored
(now infinitely many parameters!!)
disadvantage of SME: very many effects violating SR monitored

scope of QGphen from the narrow SRtest perspective:
*set priorities from QG perspective
*expose lack of generality of searches (nonpowercountingREN, DSR, defHeisenberg…)

warning: sometimes difficult to compare
(focus still mostly on original$_{\text{minimal}}$ SME…no Planck-scale effects in the sense of QGphen)
…quadratic dispersion and linear birefringence are in the generalized SME

detailed review covering QGphen:
arXiv:0806.0339

many QuantumGravity theories:
PhysRevD80, 084017 [arXiv:0906.3731]
(with Smolin)

DSR is not like LIV:
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CONCLUSIONS:

we are in the (slow but certain) process of starting to understand <u>noteverything</u>

Einstein's theory-of-everything utopia :
"<u>I would like to state a theorem…: there are no arbitrary constants ... that is to say, nature is so constituted that it is possible logically to lay down such strongly determined laws that within these laws only rationally completely determined constants occur…</u>"