ace on the river

Wroclaw
11.9.2015

not a talk about phenomenology vs pure theory

main point:
quantum-gravity problem is structurally different form other physics problems in such a way that the standard distinction between pure theory and phenomenology does not apply

I will take as working assumption today that the objective of physics research is not the one of looking smart, getting citations, going on TV…

objective of physics research: discovery of new phenomena
(with discovery meaning experimental observation!!)

ingredients for a (typical) discovery:
theory predicts an effect AND experiments find the effect

"winning probability" is product of probability the theory is "right" times probability the predicted measurement can be performed

$$P_{TH} \bullet P_{EXP}$$

ideally: maximize $P_{TH} \bullet P_{EXP}$ (roughly maximize P_{TH} and P_{EXP})

in the practice of other research areas: just maximize P_{TH} ($P_{EXP} \approx 100\%$)

quantum-gravity research first instance where maximizing P_{TH} is logically wrong ….P_{EXP} is very small in all but a few cases….
highest values of $P_{TH} \bullet P_{EXP}$ (not big anyway) come from cases where P_{TH} is not very large but P_{EXP} is large

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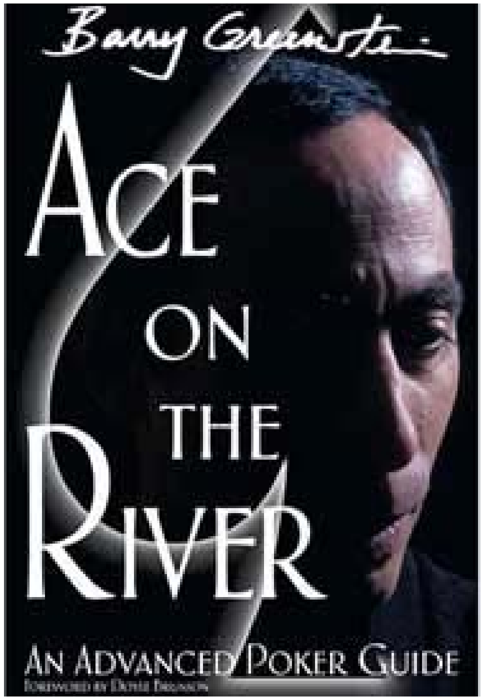

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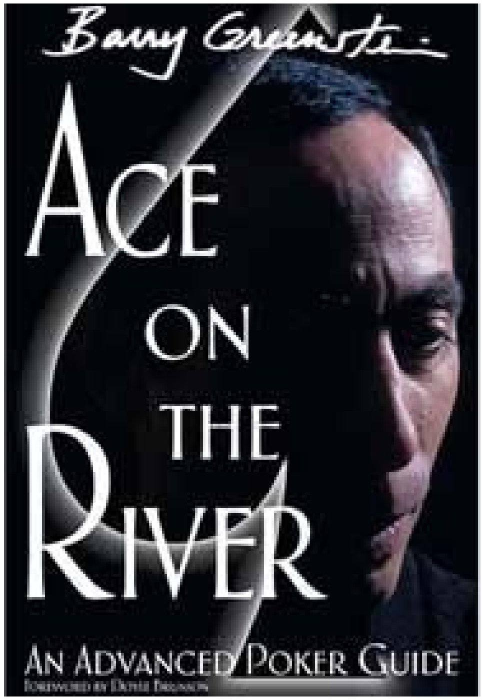
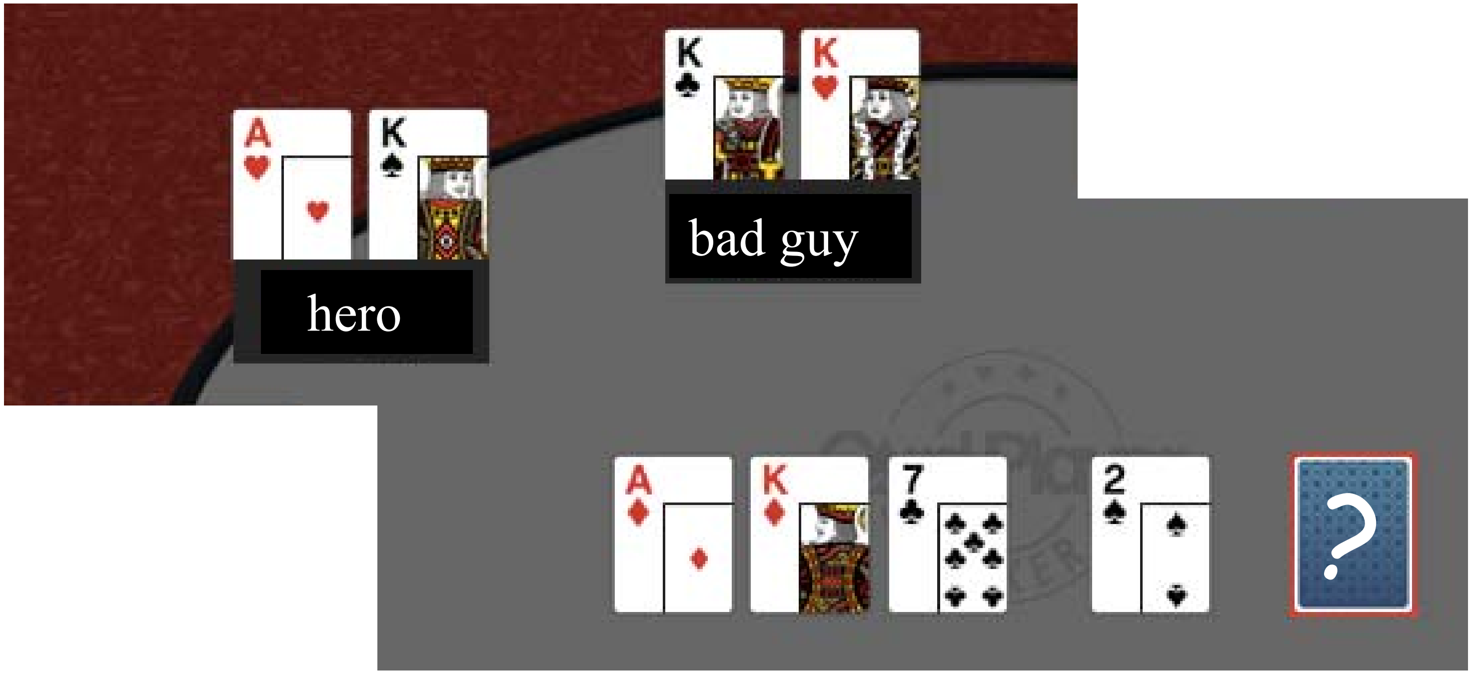




over the last 15 years a line of research adopting (in some cases consciously…in other cases subconsciously…) this strategic perspective on the quantum-gravity problem has grown very fast…

this line of research is now composed of very many proposals, which in particular involve several measurements which are possible "with Planck-scale sensitivity"…

A rather big field now the topic of a "living review"

GAC, Living Reviews in Relativity 16 (2013) 5

but today let me just look at one of these proposals from the viewpoint of P_{TH} and P_{EXP}

main claim of today's talk:

with the information presently available to us we should be assuming that $P_{TH} \bullet P_{EXP}$ is maximized in the case of effects providing departures from currently adopted relativistic laws

concerning P_{EXP}:
our most precise measurements concerns tests of currently-adopted special-relativistic laws

for example wavelength independence of speed of light is currently being tested with accuracy of 1 part in 10^{20} and accuracy of 1 part in 10^{30} is foreseeable

GAC+Ellis+Mavromatoos+Nanopoulos+Sarkar, Nature(1998)
GAC+Matassa+Mercati+Rosati, PhysicalReviewLetters (2011)

and in an appropriate sense the relativistic thresholds for certain particle-producing processes are being studied with accuracy of 1 part in 10^{24}

GAC+Piran, PhysicalReviewD (2001)

concerning P_{TH}:
P_{TH} cannot be estimated as reliably as P_{EXP}
each researcher must do subjective estimate of P_{TH}

of course if P_{TH} was 0 for departures from currently-adopted relativistic laws then the fact that P_{EXP} is high would be irrelevant

reasonable subjective estimates should conclude that P_{TH} is not 0:

spacetime noncommutativity, and in particular k-Minkowski (Wroclaw/Lukierski…)

3D quantum gravity [see, e.g. Freidel+Liivine, PhysicalReviewLetters(2006)]

Horava-Lifshitz

perhaps most notably it appears that dynamical dimensional reduction produces (nearly) inevitably departures from currently-adopted relativistic laws

GAC+Freidel+KowalskiGlikman+Smolin, PhysRevD84,084010 (2011)

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

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

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

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

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

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

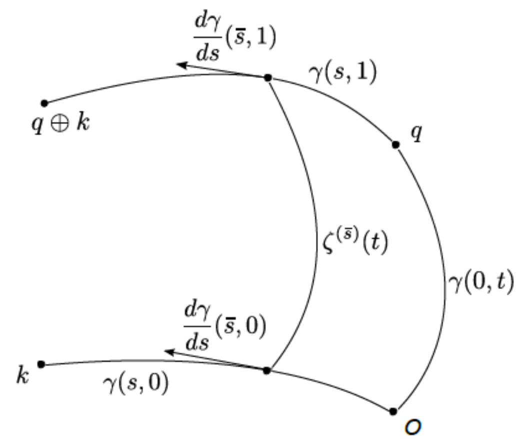


Figure 1. We determine the law of composition of momenta from the affine connection by associating to the points q and k of momentum space the connection geodesics $\gamma^{(q)}$ and $\gamma^{(k)}$ which connect them to the origin of momentum space. We then introduce a third curve $\bar{\gamma}(s)$, 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 $q \oplus_\ell k = \bar{\gamma}(1)$.

in this sort of framework DSR-relativistic invariance is possible if momentum space has some appropriate properties

GAC, PhysRevD85(2012)084034 (also see talks by Palmisano)

DSR-relativistic symmetries can be governed by Hopf-algebra mathematics (associativity) but can also involve nonassociative algebras

nonassociative??

Let's look back at the first "relativistic evolution", from Galilei to Einstein

"c" is scale of lightcone

lightcone structure is in "relativistic balance" with <u>relative simultaneity</u>

crucial for logical consistency of special relativity is the replacement of the Galileian composition of velocities V' = V + V*
with the special relativistic composition law

$$\mathbf{w} = \mathbf{v} \oplus \mathbf{u} \quad \textbf{with} \quad \begin{pmatrix} w_1 \\ w_2 \\ w_3 \end{pmatrix} = \frac{1}{1+\frac{v_1u_1+v_2u_2+v_3u_3}{c^2}} \left\{ \left[1 + \frac{1}{c^2}\frac{\gamma_{\mathbf{v}}}{1+\gamma_{\mathbf{v}}}(v_1u_1+v_2u_2+v_3u_3) \right] \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} + \frac{1}{\gamma_{\mathbf{v}}} \begin{pmatrix} u_1 \\ u_2 \\ u_3 \end{pmatrix} \right\}$$

which only for parallel velocities gives $$\frac{v+u}{1+(vu/c^2)}$$

A powerful perspective on previously-mentioned phenomenology:

Calculation of the energy dependence of speed of ultrarelativistic particles in a given model used to be troublesome and cumbersome.
Those calculations have ben streamlined now that we understand those results as dual redshift on Planck-scale-curved momentum spaces:

these results so far are fully understood for the case of
[maximally symmetric curved momentum space] ⊗ [flat spacetime]

it turns out that there is a duality between this and the familiar case of
[maximally-symmetric curved spacetime] ⊗ [flat momentum space]

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)

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

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

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

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

<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) <u>flat spacetime</u>

phenomenological opportunities are for propagation over cosmological distances, whose analysis requires <u>curved spacetime</u>

study of theories with <u>both curved momentum space and curved spacetime</u> 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.
However, it is now understood that Jacob-Piran formula implicitly assumes that space-and-time translation transformations and symmetries are unaffected by Planck-scale effects. <u>It is necessary to extend the scopes of this phenomenology</u> to include nontrivial effects in the translation sector because explicit models (such as kappa-Minkowski) suggest that the same effects affecting Lorentz sector also affect translation sector

Rosati + GAC +Marcianò +Matassa, arXiv:1507.02056

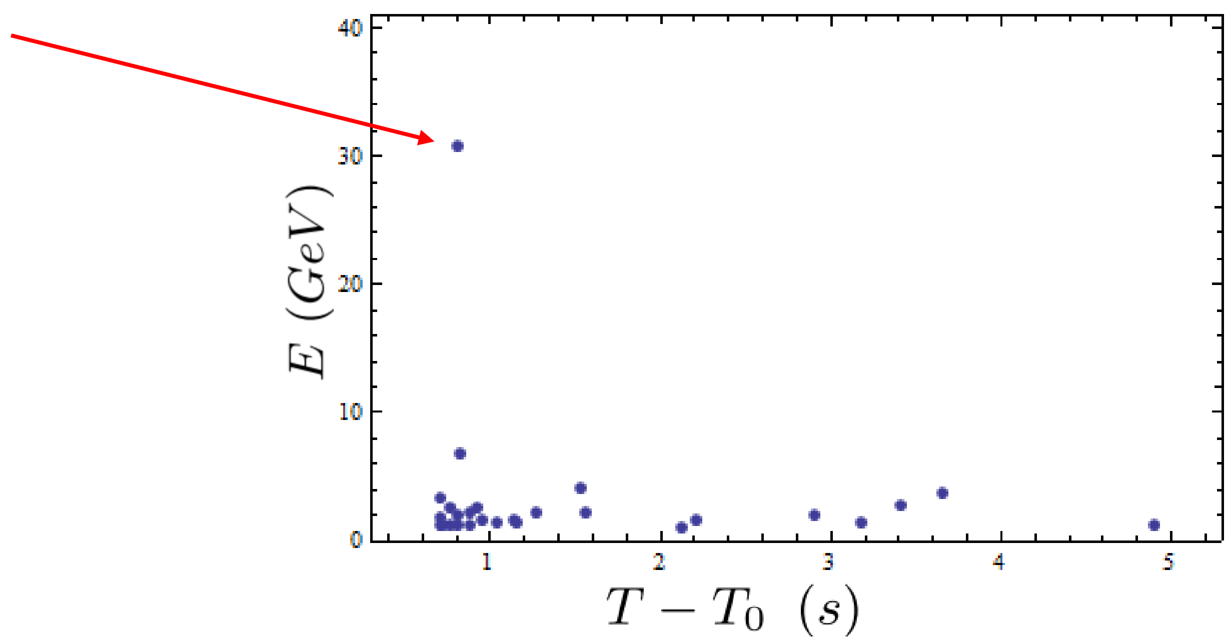
testing Jacob-Piran formula:

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

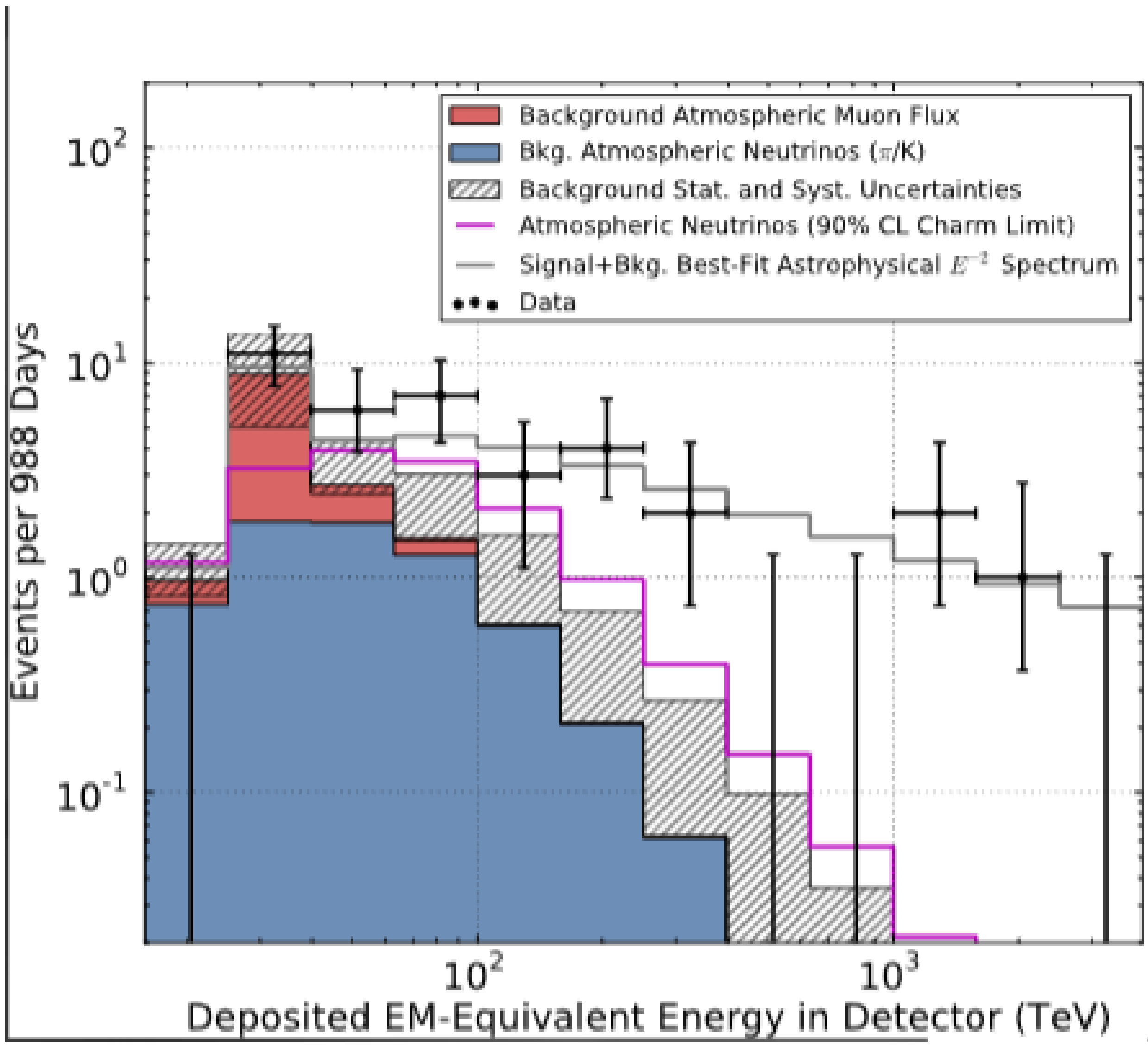


a test with accuracy of about one part in 10^{20}!!!

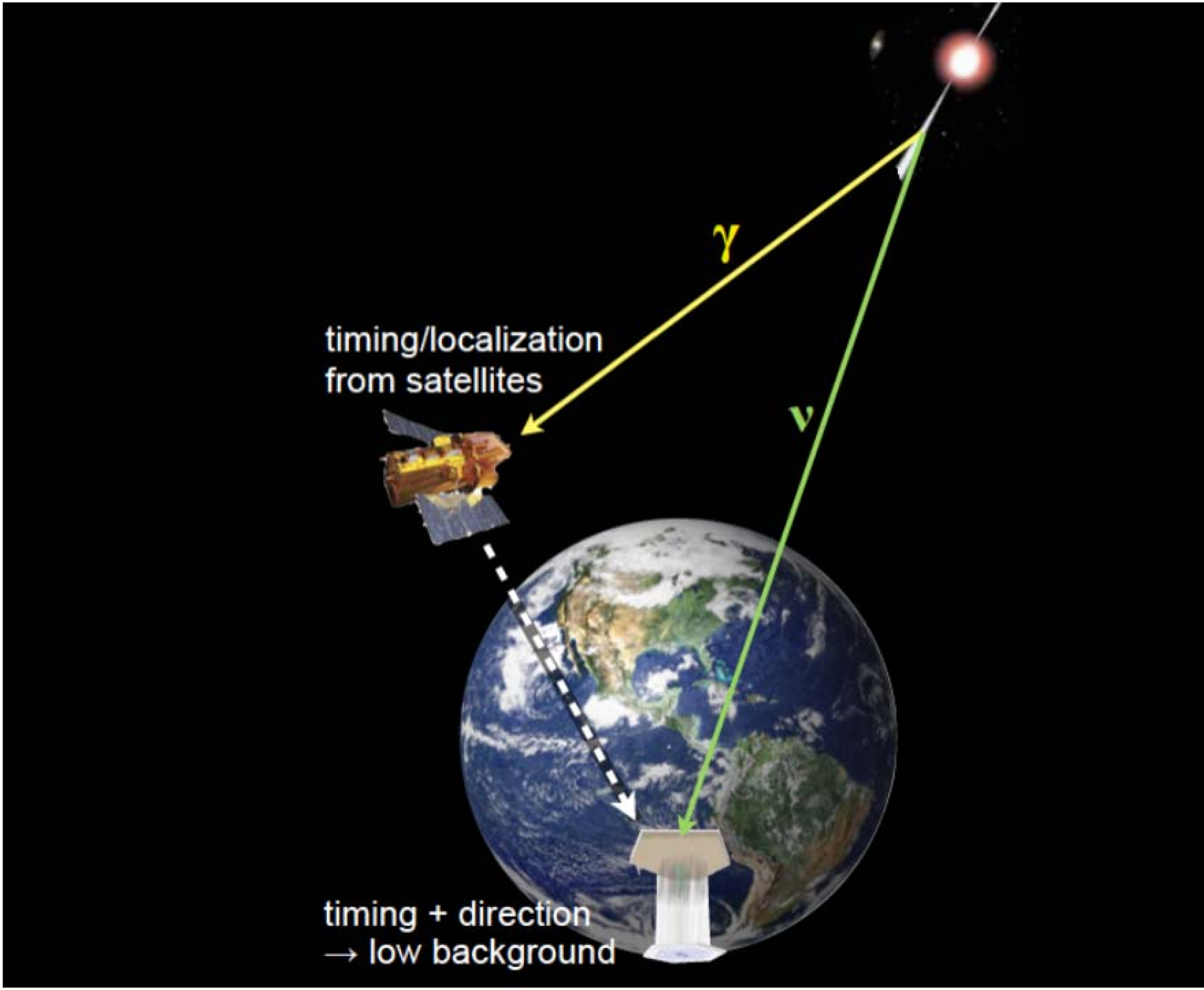
more excitement for this phenomenology forthcoming….

we see cosmological neutrinos!!!

GAC+Guetta+Piran, ApJ 806 (2015) 269



from talk by F. Halzen



slide from talk by F. Halzen

ALSO INTERESTING COSMOLOGY FROM PLANCK-SCALE MODIFICATIONS OF ON-SHELL RELATION

most of what I said so far implies that effectively the on-shell relation is affected by Planck-scale modification roughly of the type

$$E^2 \approx m^2 + p^2 + p^2 \left(\frac{p}{E_{Planck}} \right)^n$$

with n=1 or possibly n=2

There has been for a few years interest in the implications for cosmology of the Horava-Lifshitz scenario which corresponds to n=4

Magueijo, PhysRevLett100(2008)231302

that scenario however has no tangible implications for astrophysics and breaks relativistic invariance

We recently realized that one can have cosmology with most of the reasons of interest in HL scenario also within a case where relativistic invariance is DSR-deformed and n=1 for the leading order… de Sitter momentum space (exponentials of p/E_{planck})

GAC+Arzano+Gubitosi+Magueijo, PhysLettB736(2014)317

With a de Sitter momentum space one can have that the spectral dimension runs in the UV to 2, just like in the HL scenario and in several other quantum-gravity pictures…we have argued that the implications for cosmology when the UV spectral dimension is 2 are largely model independent

GAC+Arzano+Gubitosi+Magueijo, PhysRevD87(2013)123532

see talk by Gubitosi

but how long will it take?
I really don't know….preparation is only part of the task of being lucky the other part is pure luck…

it's something like taking the perfect snapshot

like that time at the building next to Perimeter Institute…that building is a museum, the "Canadian Clay and Glass Gallery"

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relative locality

proper introduction to the notion of relative locality would require a full talk…
famously from viewpoint of a "Galileian physicist" the fact that special relativity introduces an invariant velocity scale produces artifacts about the simultaneity (time coincidence) of events, that is "relative simultaneity"…
from viewpoint of "Einsteinian physicist" a relativistic theory which introduces also an invariant energy scale produces artifacts about the spacetime coincidence (locality) of events

GAC+Matassa+Mercati+Rosati, PhysicalReviewLetters106,07301
GAC+Freidel+Kowalski+Smolin, PhysicalReviewD84,087702

illustrative example: