Title: Gravity in (and with) Quantum Spacetime

Date: Sep 30, 2010 01:00 PM

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Abstract: Over the last decade there has been strong interest in the theory and phenomenology of particle propagation in quantum spacetime. The main results concern possible Planck-scale modifications of the "dispersion" relation between energy and momentum of a particle. I review results establishing that these modifications can be tested using observations of gamma rays from sources at cosmological distances. And I report recent progress in the understanding of the implications of spacetime expansion for such studies. I also discuss recent preliminary results suggesting that the same Planck-scale modifications of the dispersion relation might have an unexpected role in gravitational collapse.

[redacted]

gravity in (and with) quantum spacetime

PI 30·9·2010

Giovanni Amelino-Camelia
University of Rome "La Sapienza"

a perspective on recent results in quantum-spacetime research, with emphasis on issues for which gravity plays a significant role

which quantum gravity?

traditional strategy

find solution of "quantum-gravity problem"
in one big jump...........possibly get ourselves
a Theory Of Everything....

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but if quantum-gravity really requires a new paradigm...
"old quantum-gravity theory strategy"....
....same relationship between "Quantum Mechanics"
and the "Old Quantum Theory"....
similar story for weak interactions....

over the last decade several research lines have adopted
(often implicitly) this perspective

let me focus initially on the most studied scenario
which works well as an <u>illustrative example</u> of how
pieces of the Old Quantum Gravity Theory might be discovered:

attempts to model "quantum spacetime"
(using "noncommutative geometry" or adopting
certain perspective on the description of the semiclassical
limit of Loop Quantum Gravity)
have stumbled upon modifications of the energy-momentum
(on-shell) dispersion relation

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

striking!!!
but λ is expected of the order of the Planck length...
so, no chance?

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

GAC,Nature408,661 (2000)

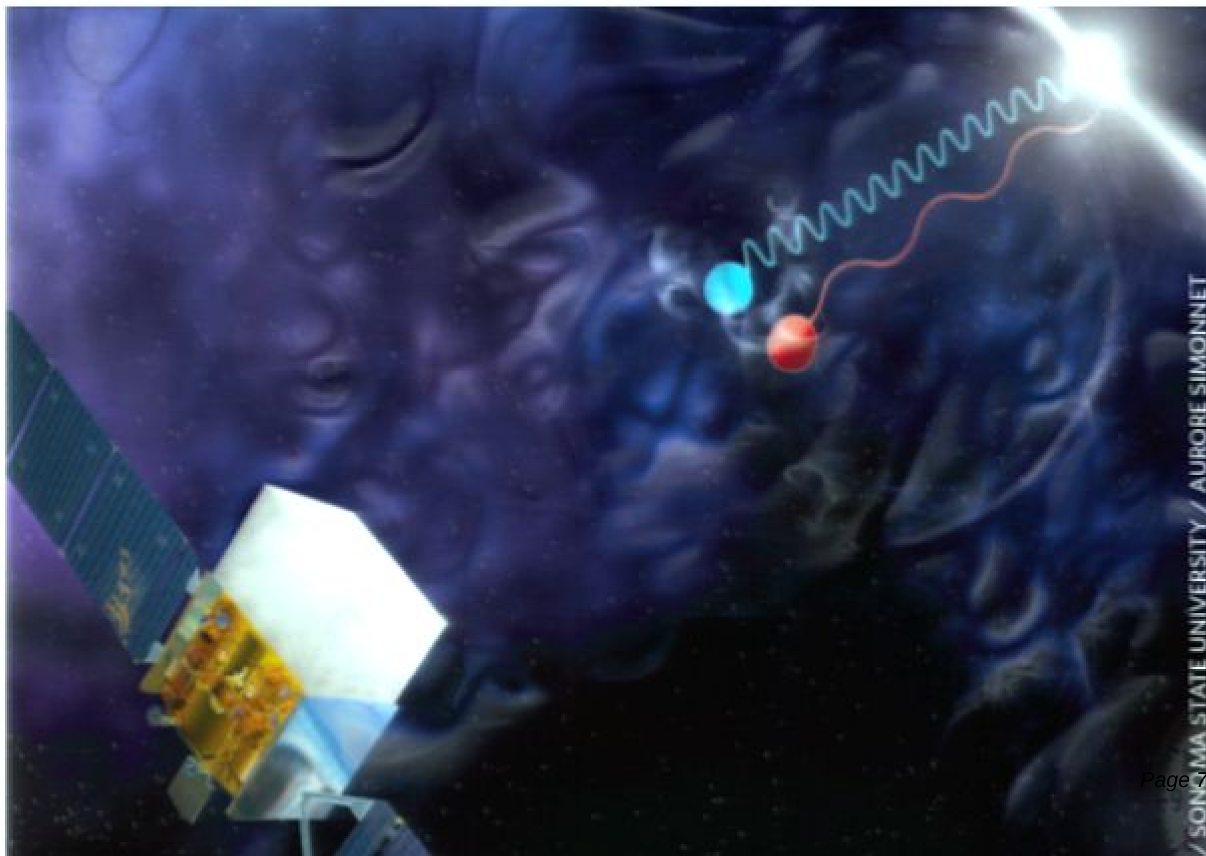
<u>effects are indeed completely negligible on terrestrial scales</u>

but Nature provides a nearly ideal laboratory: GRBs

•photons observed up to ~100 GeV

•emission of photons simultaneous on a time scale of seconds....possibly milliseconds if one can associate photons to microbursts with the burst...

* distance established (redshift>1 !!!) for many such highenergy GRBs



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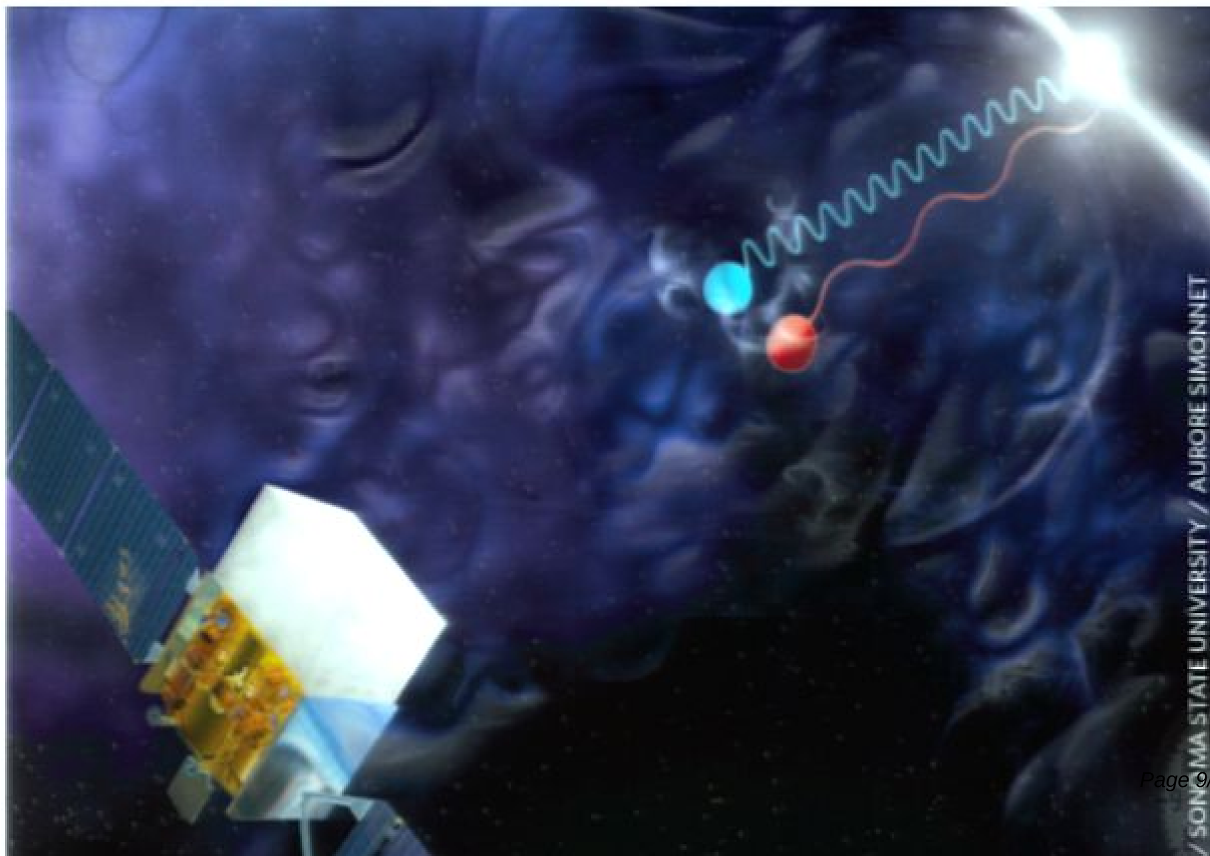


from modification of dispersion relation

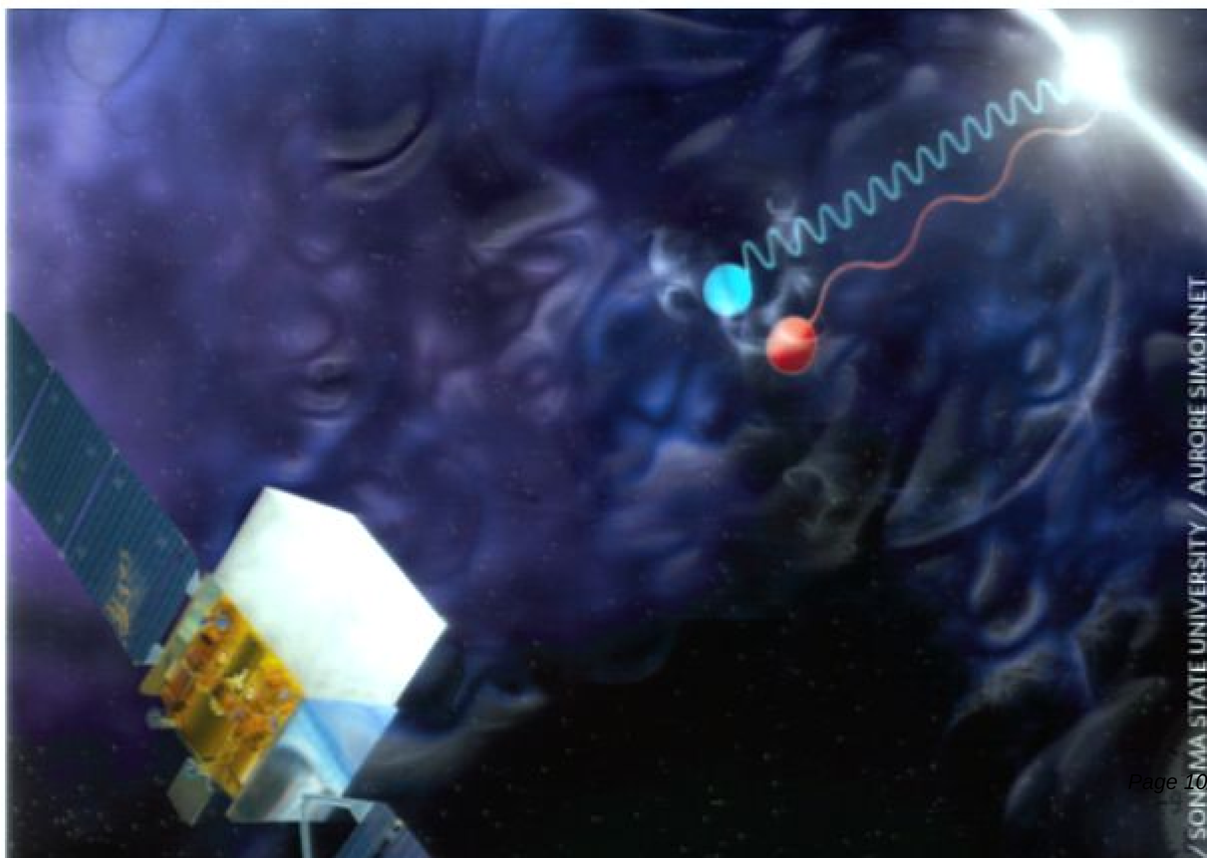
$$m^2 = E^2 - p^2 + \lambda E p^2$$

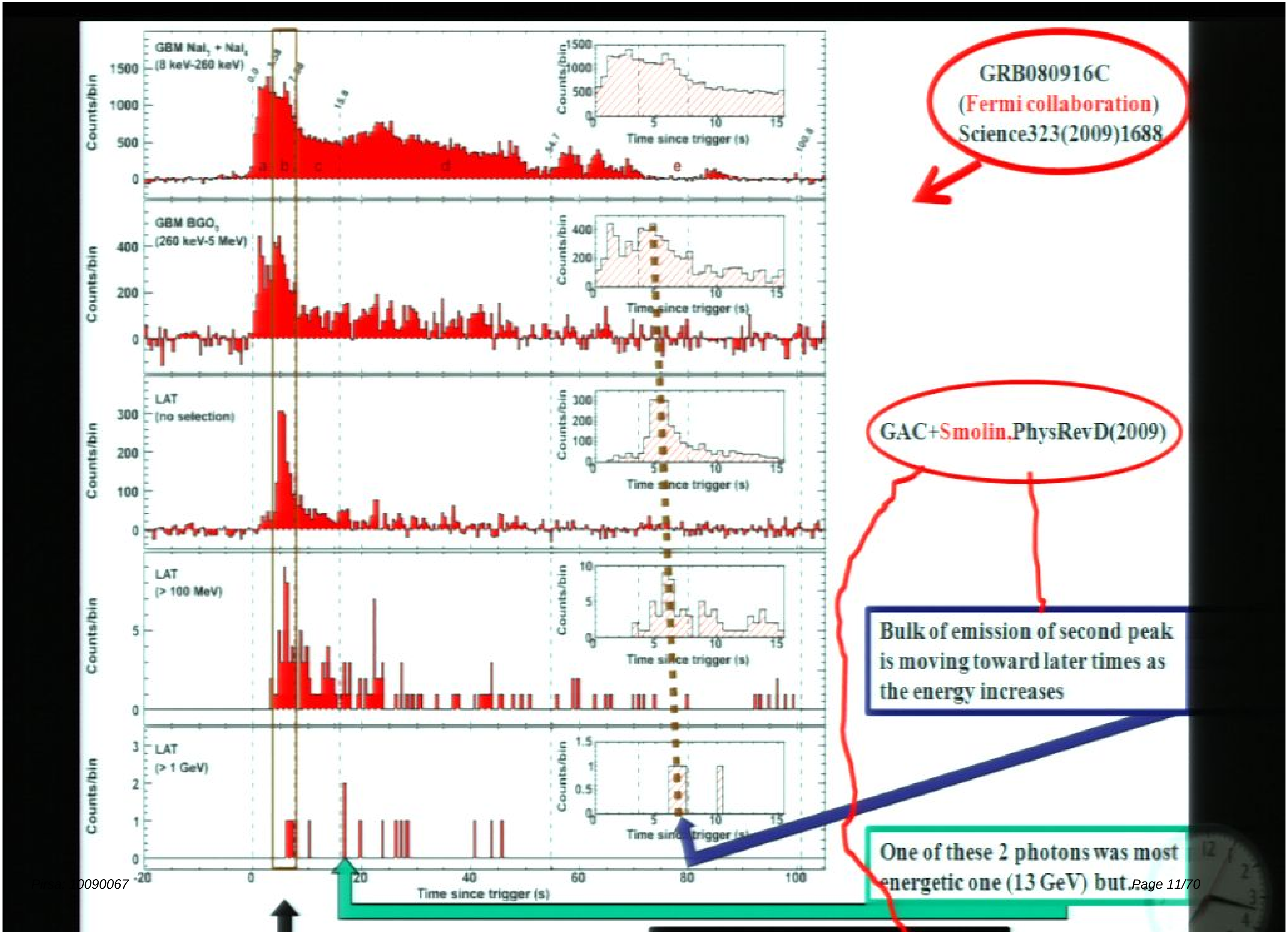
it follows that

$$v_\gamma \simeq c(1 - \lambda|p|)$$

and

$$\Delta T_{propag} = (\lambda E) T_{propag} \approx 1s$$ [Planck length 100GeV 10^{17}s]




GRB080916C
(Fermi collaboration)
Science323(2009)1688
GAC+Smolin.PhysRevD(2009)
Bulk of emission of second peak is moving toward later times as the energy increases
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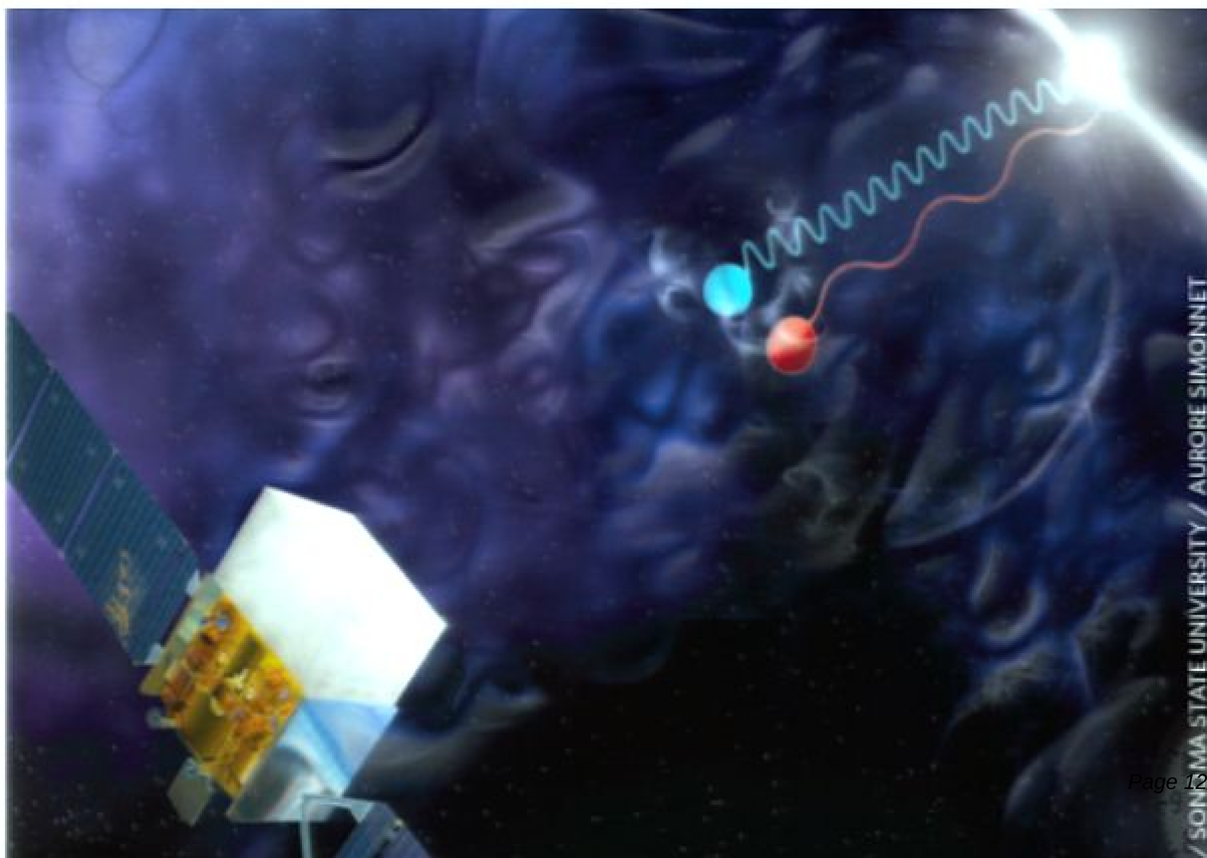

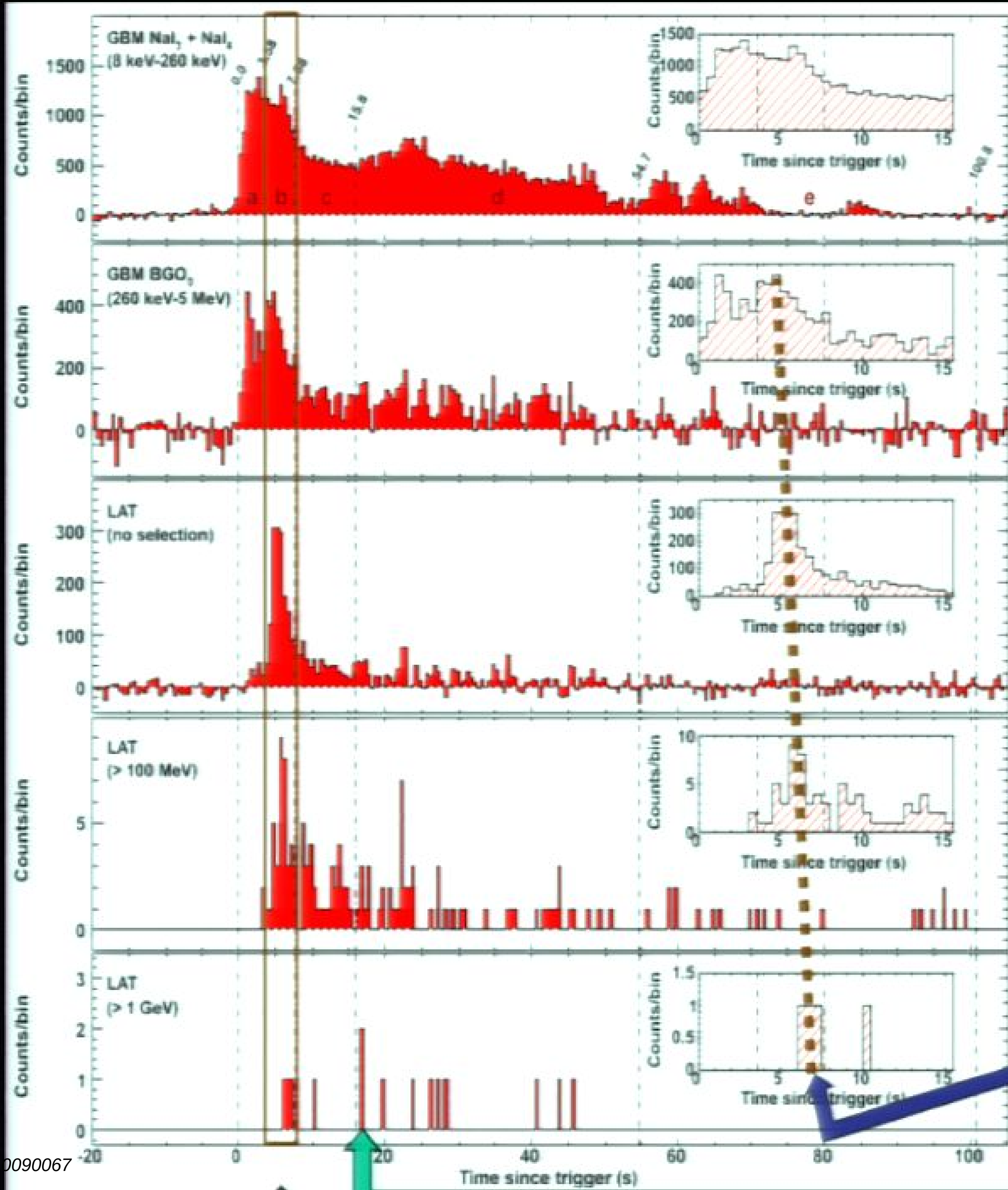

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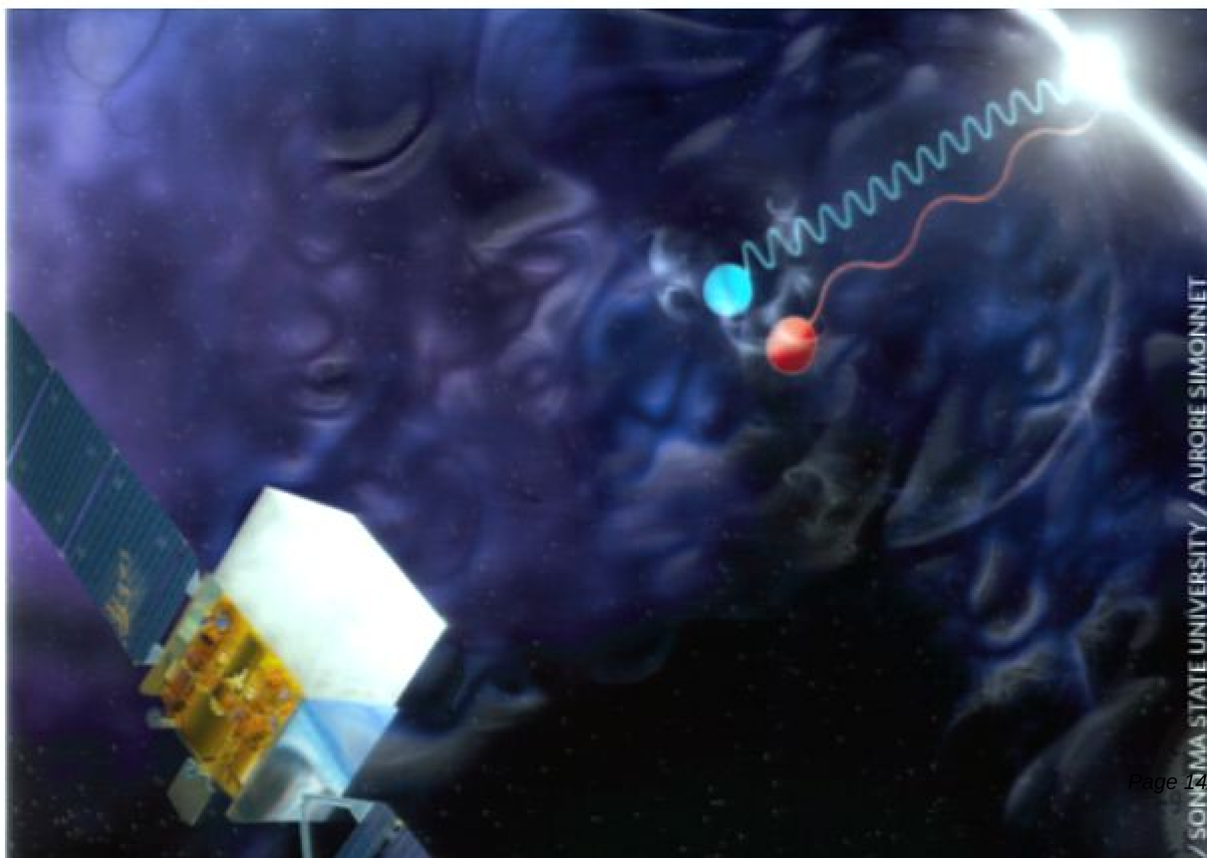
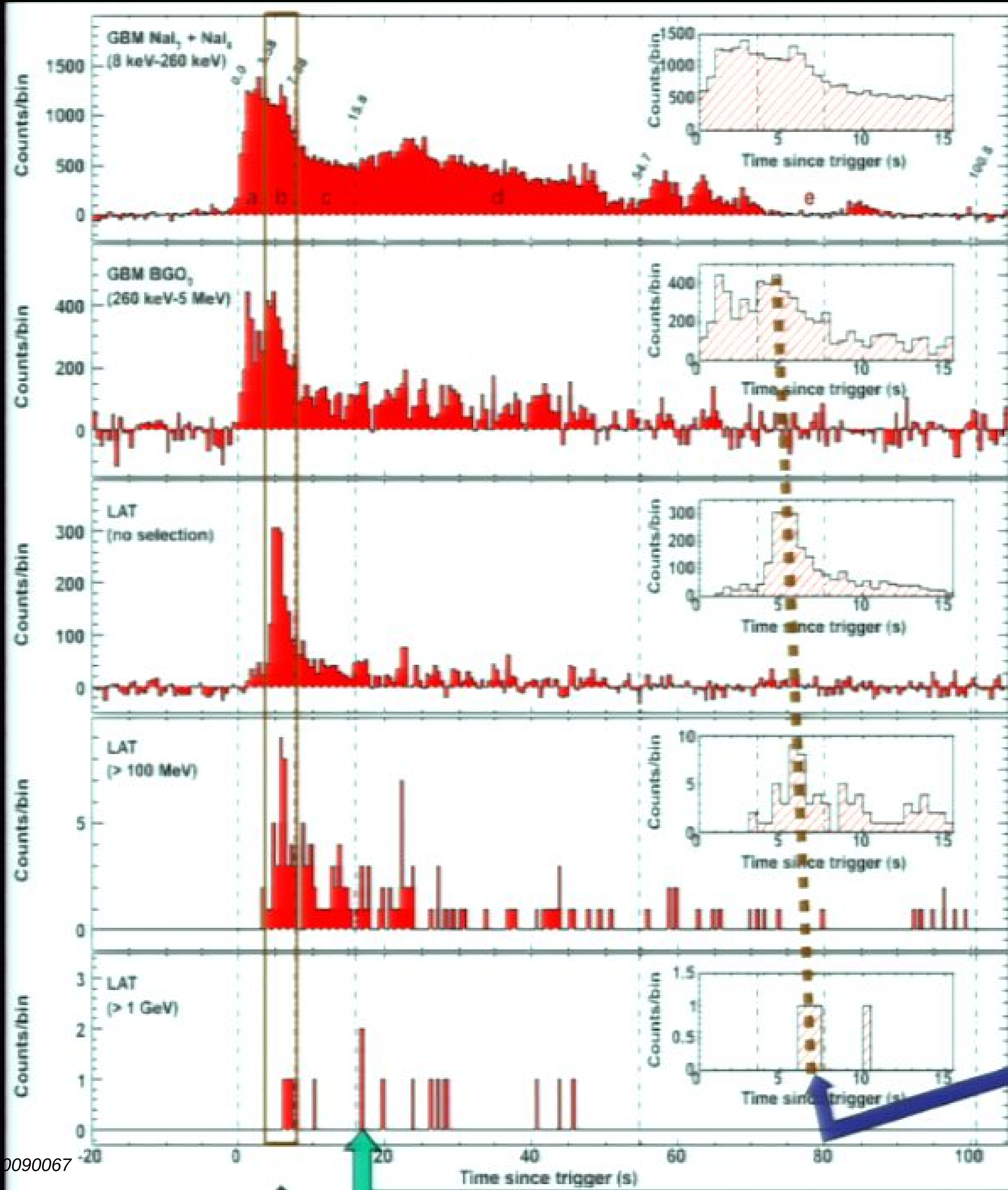
then we could even probe to some extent the case of analogous effects suppressed quadratically by the quantum-gravity scale

$$v \approx c(1 - \lambda^2 p^2)$$





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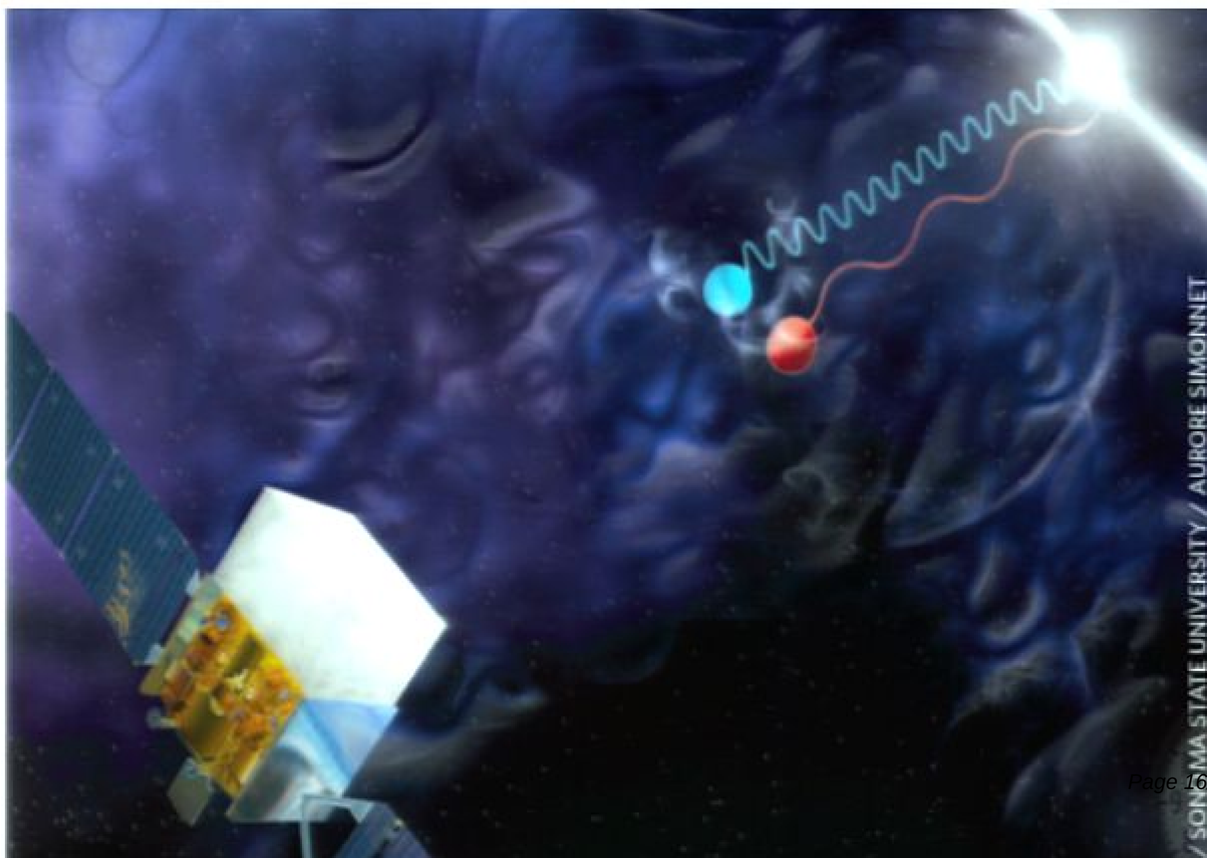
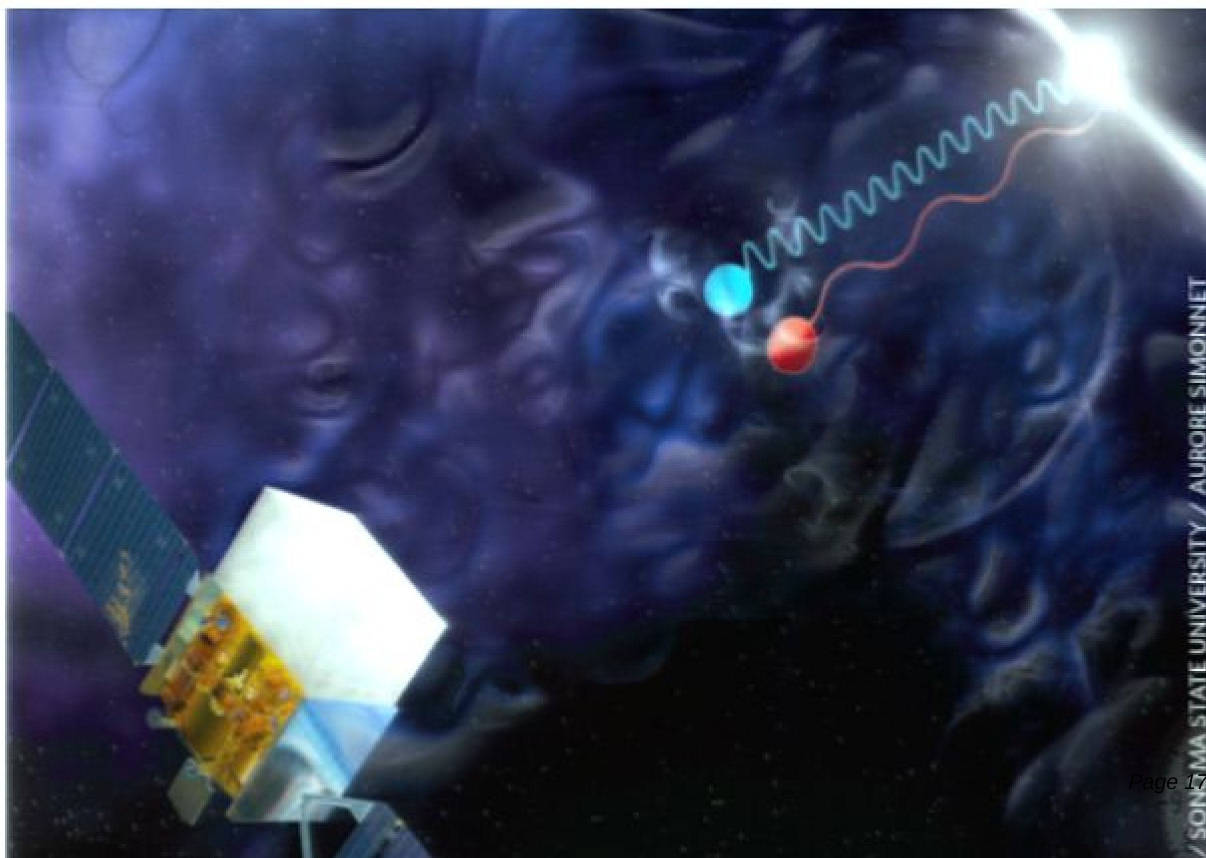


is our ignorance of the source engine a problem?

of course it is....one more reason to make vigorous effort to improve reliability of GRB models....but even without knowing anything about the source engine the analysis can be successful

$$\Delta T_{observed} = \Delta T_{emission} + \Delta T_{propag} = \Delta T_{emission} + (\lambda E) T_{propag}$$

[and $\Delta T_{emission}$ should not depend significantly on $T_{propagation}$]



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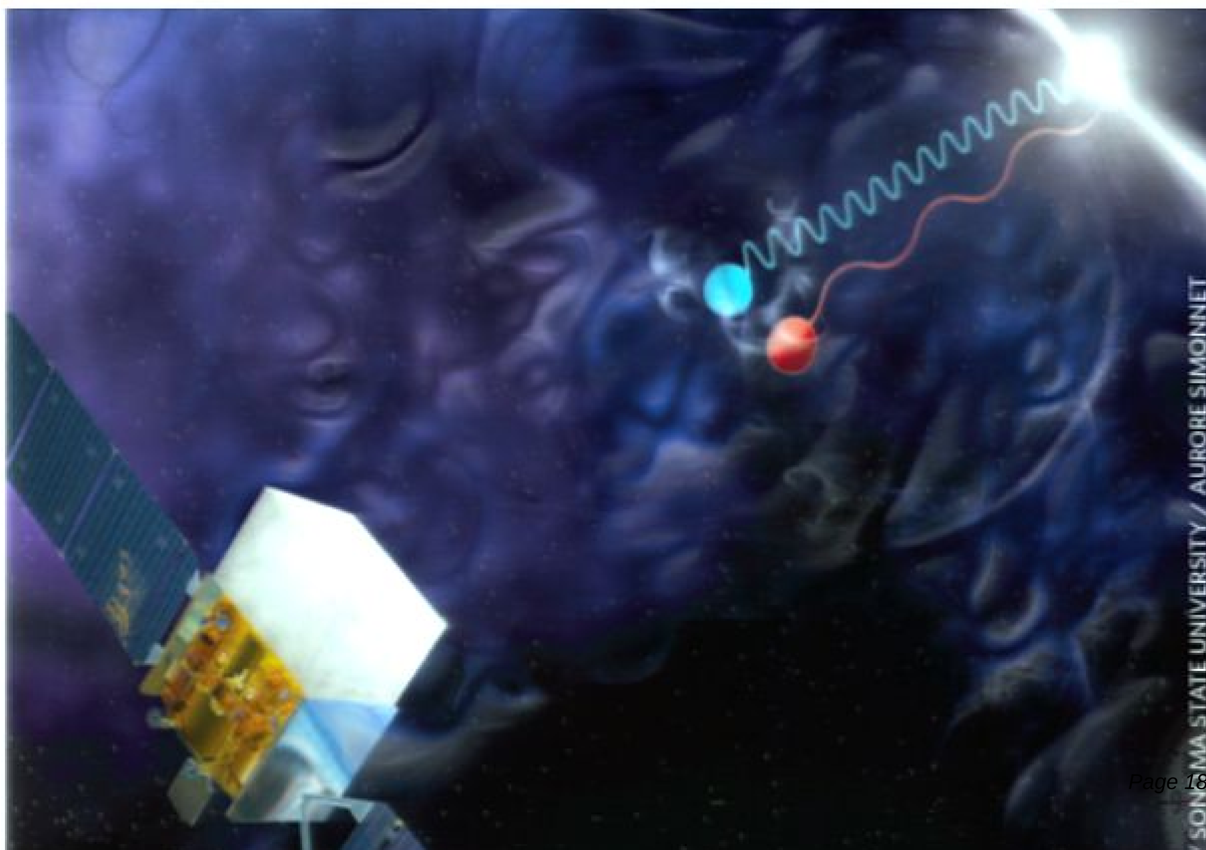

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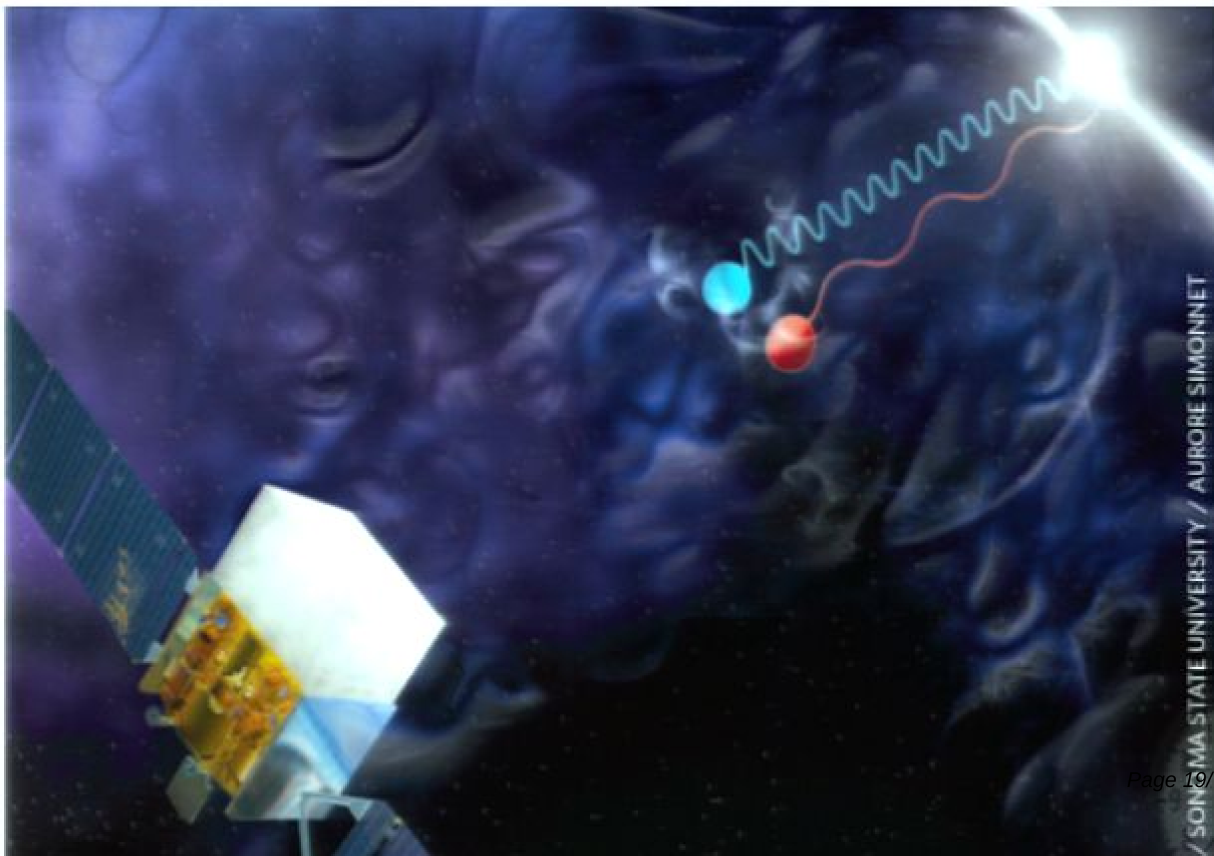

and is curvature/expansion a problem?

these opportunities in phenomenology have motivated much work on momentum dependence of the speed of photons....

but nearly all analyses and arguments <u>only apply to flat (Minkowski-like) spacetime</u>

now we have "good" data but are we ready?

z>1 ......

how does the expansion of a spacetime affect the momentum dependence of speed of light ?

issue only discussed in exploratory papers

by Ellis+Mavromatos+Nanopoulos+Sakharov+Sarkisyan

and by Jacob+Piran

which eventually led to the adoption of a description based on

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"canonical energy" "canonical momentum"

$$v_\gamma \simeq \ 1 - \lambda(1 - H\eta)\Pi$$

specializing formulas to the insightful case of deSitter spacetime in <u>conformal coordinates</u>

$$ds^2 = \frac{1}{(1 - H\eta)^2}\left(d\eta^2 - dx^2\right)$$

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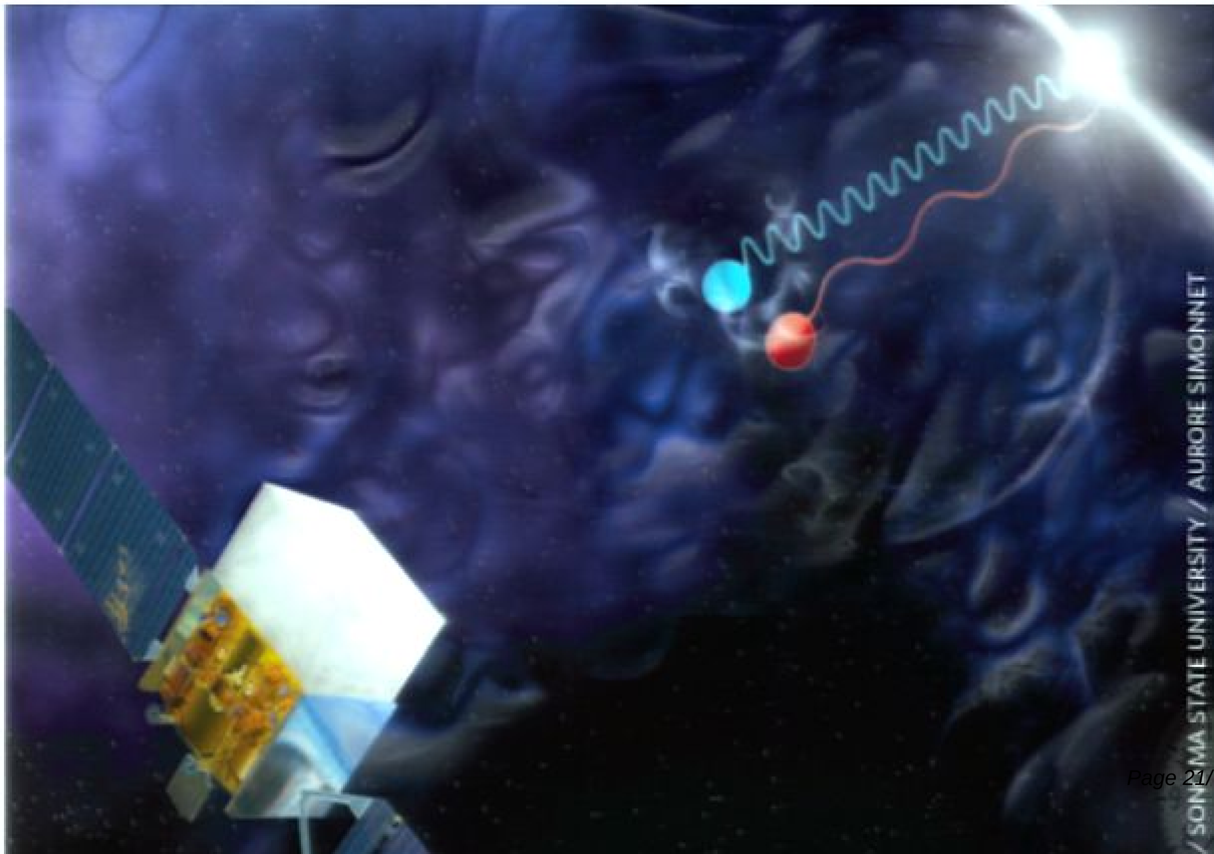

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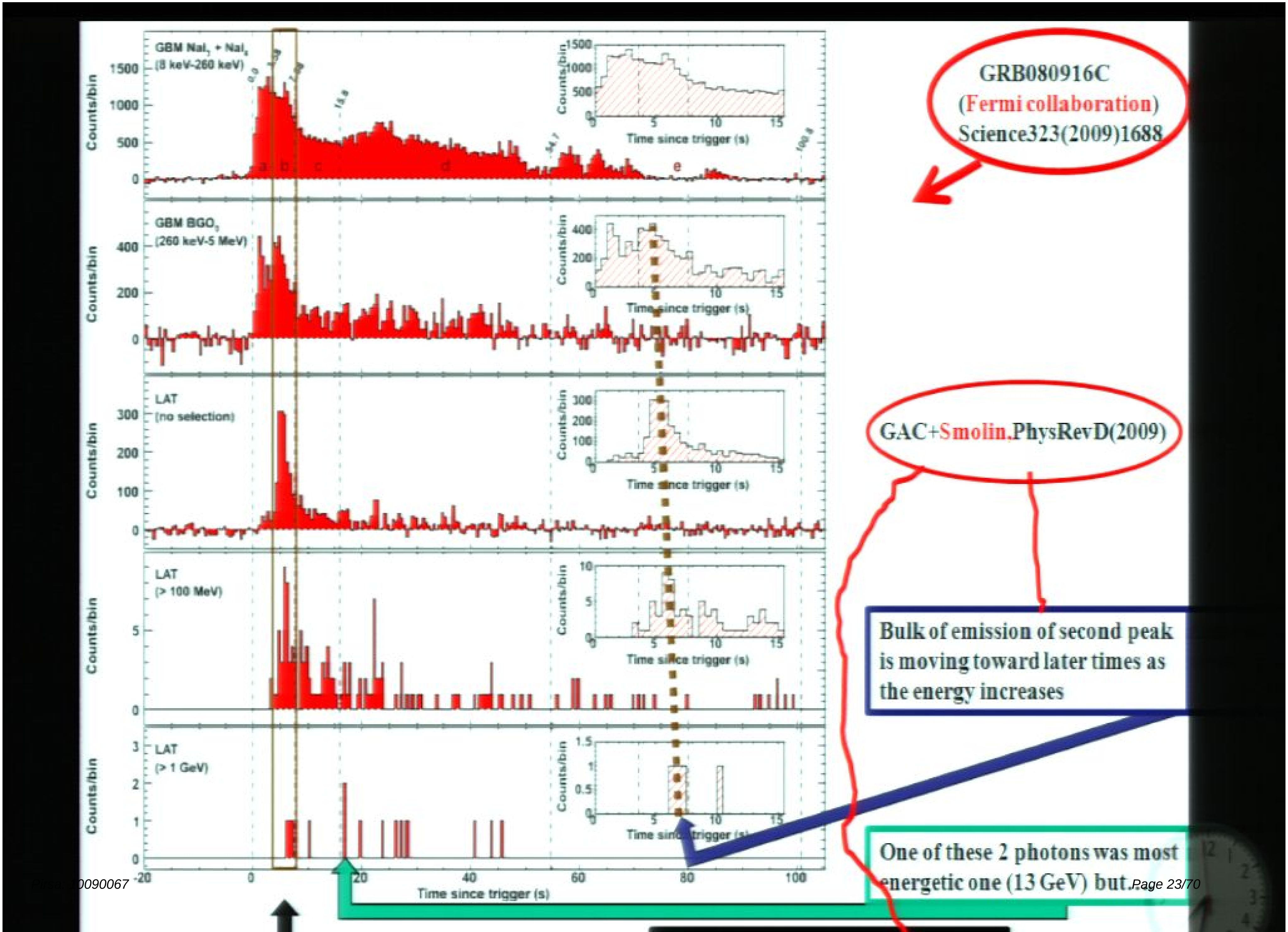

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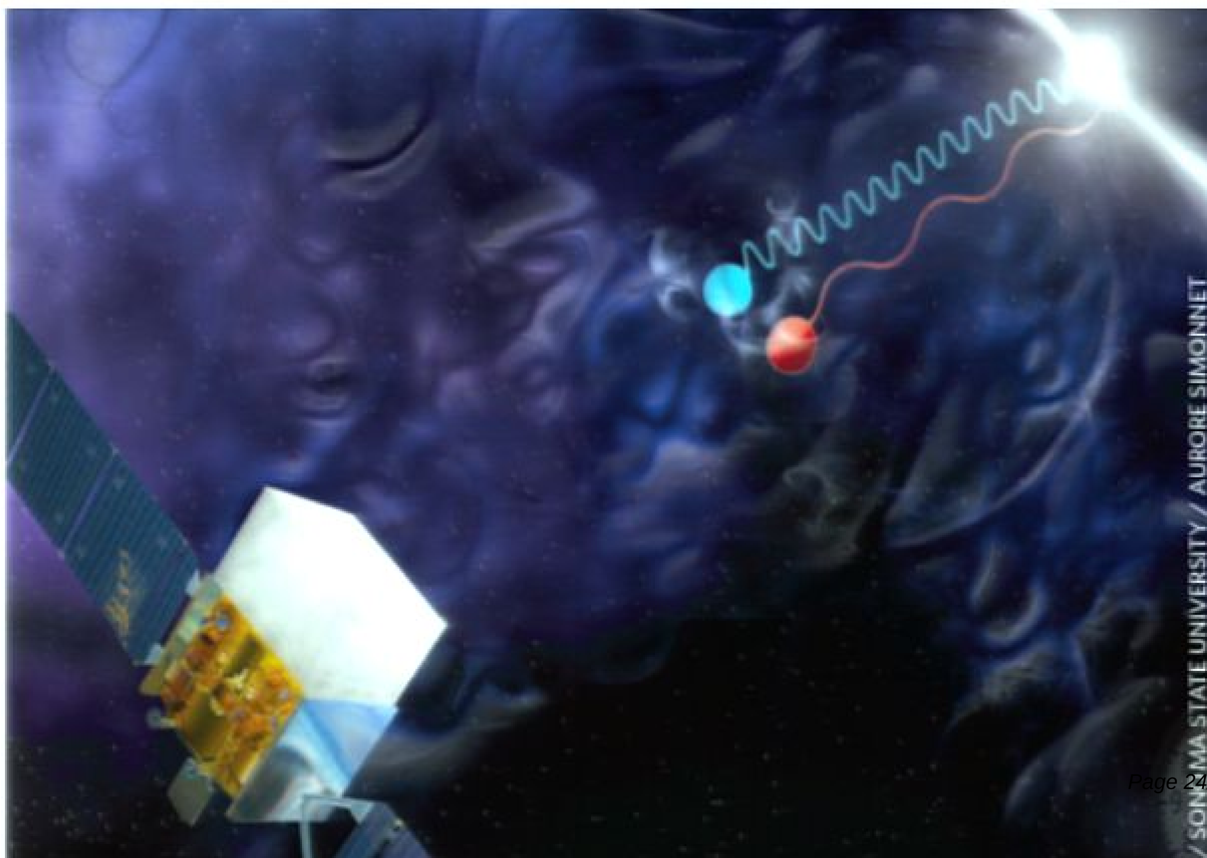

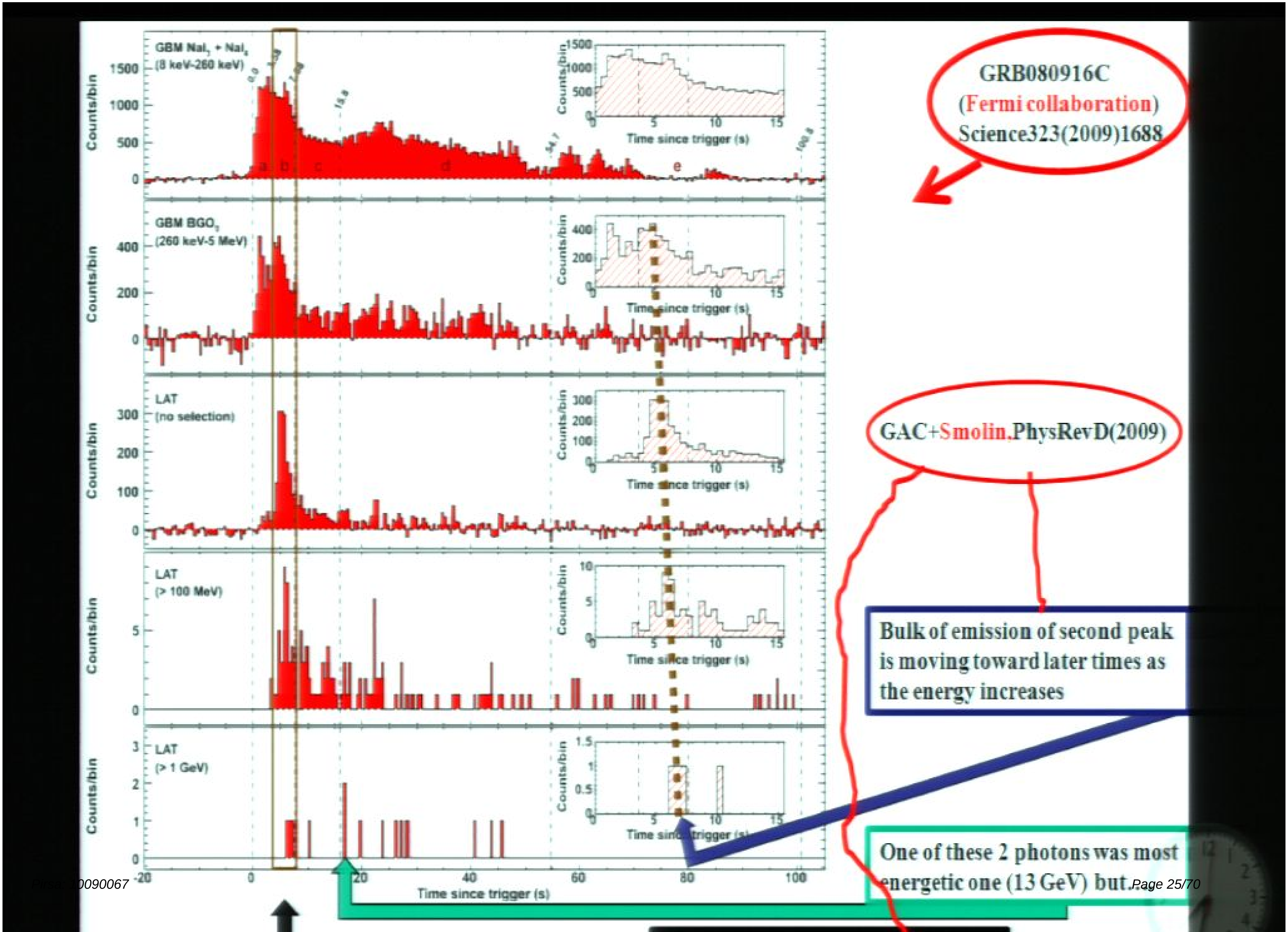
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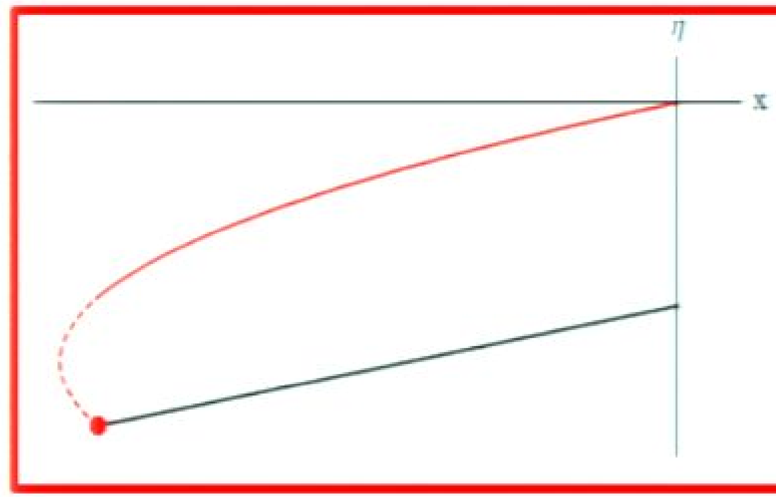

coordinate artifact?

artifact of leading-order truncation?

a "feature" due to preferred frame?

arXiv:1006.0007

but does this require a preferred-frame formulation?

first phenomenology based on results on
modified dispersion relations in quantum spacetime
<u>assumed a preferred frame</u>
But there is a viable alternative which
requires implementing the relativity principle
with two nontrivial relativistic invariants
(a large speed and a small length)

GAC, IJMPD11(2002)
PhysLettB510(2001)
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Kowalski-Glikman,PhysLettA286(2001)
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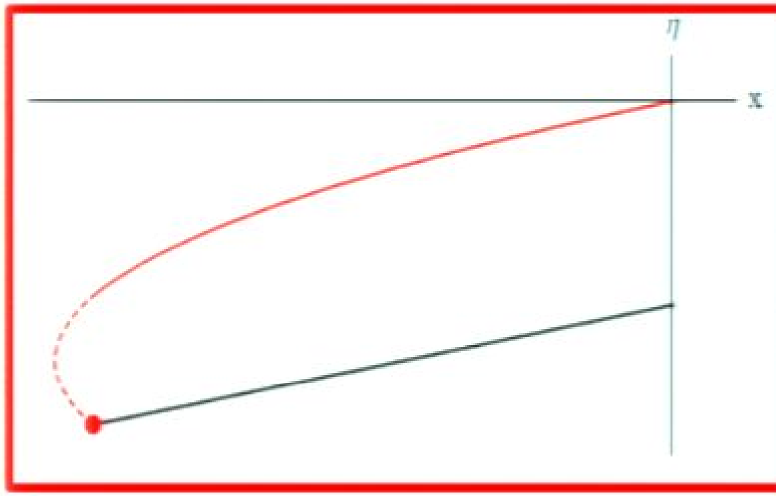

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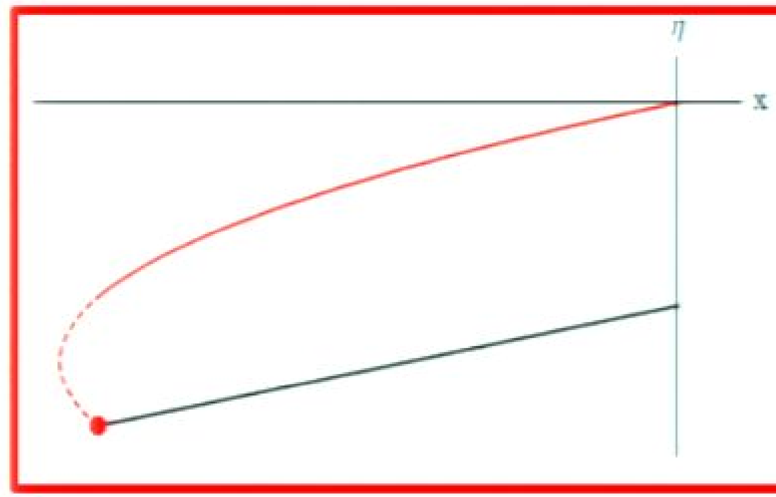

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a DSR framework compatible with spacetime expansion

GAC+Marciano+Matassa+Rosati, arXiv:1006.0007

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$$\{\Pi, x\} = -1\ , \qquad \{\Omega, \eta\} = 1$$

$$G_N = x(1 - H\eta)\partial_\eta + \left(\frac{1-(1-H\eta)^2}{2H} - \frac{H}{2}x^2\right)\partial_x + + \lambda_{\rm DSR}\left(\frac{1+H\eta}{2}x\,\partial_x - (1-H\eta)\,\eta\,\partial_\eta + \frac{H\eta}{2}\right)\partial_x\ .(11)$$

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

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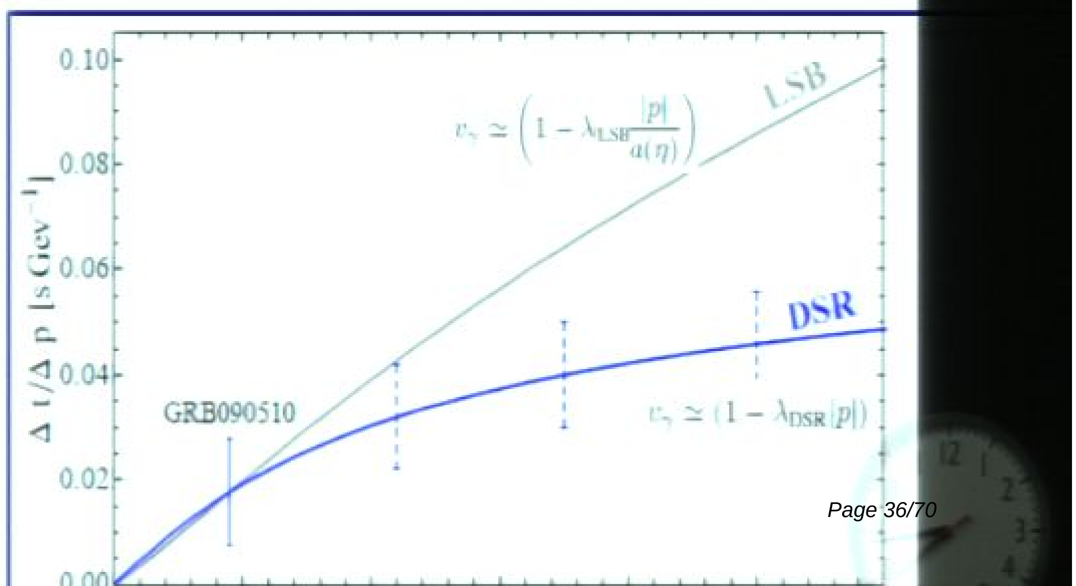

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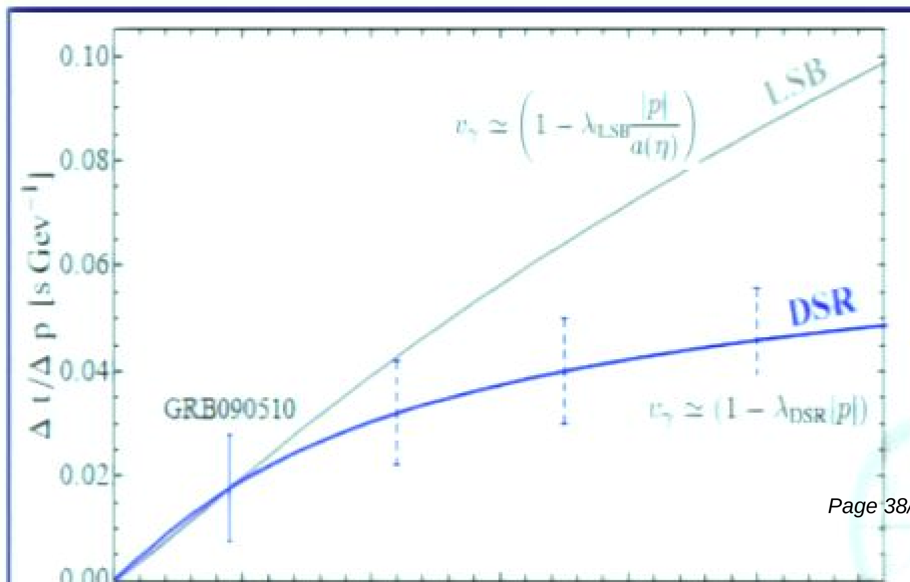

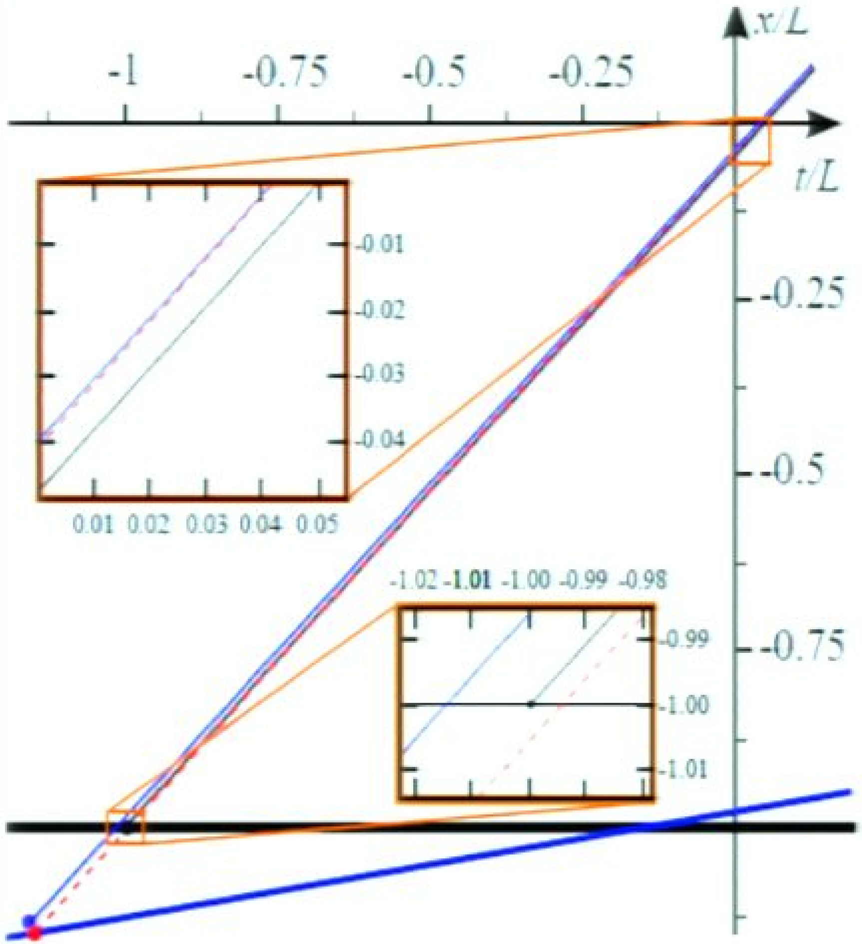

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of course this DSR scenario has no pathologies of the type shown before

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Note that observer s loose the objectivity of distant simultaneity BUT PRESERVE OBJECTIVITY OF LOCAL SIMULTANEITY (quite different from what was envisaged on the basis of naive arguments)

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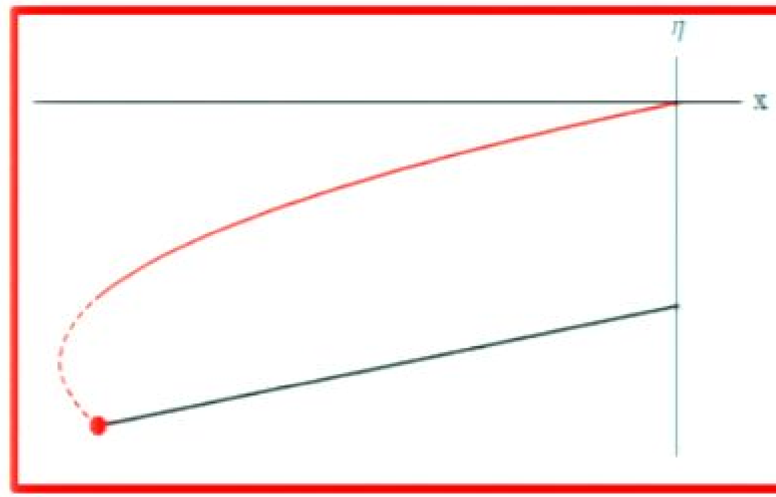


coordinate artifact?

artifact of leading-order truncation?

a "feature" due to preferred frame?

arXiv:1006.0007

but does this require a preferred-frame formulation?

first phenomenology based on results on modified dispersion relations in quantum spacetime <u>assumed a preferred frame</u>
But there is a viable alternative which requires implementing the relativity principle with two nontrivial relativistic invariants (a large speed and a small length)

GAC, IJMPD11(2002)
PhysLettB510(2001)
Nature418(2002)
Kowalski-Glikman,PhysLettA286(2001)
Kowalski-Glikman+Nowak,IJMPD12(2003)
Magueijo+Smolin,PhysRevLett88(2002)
PhysRevD67(2003)

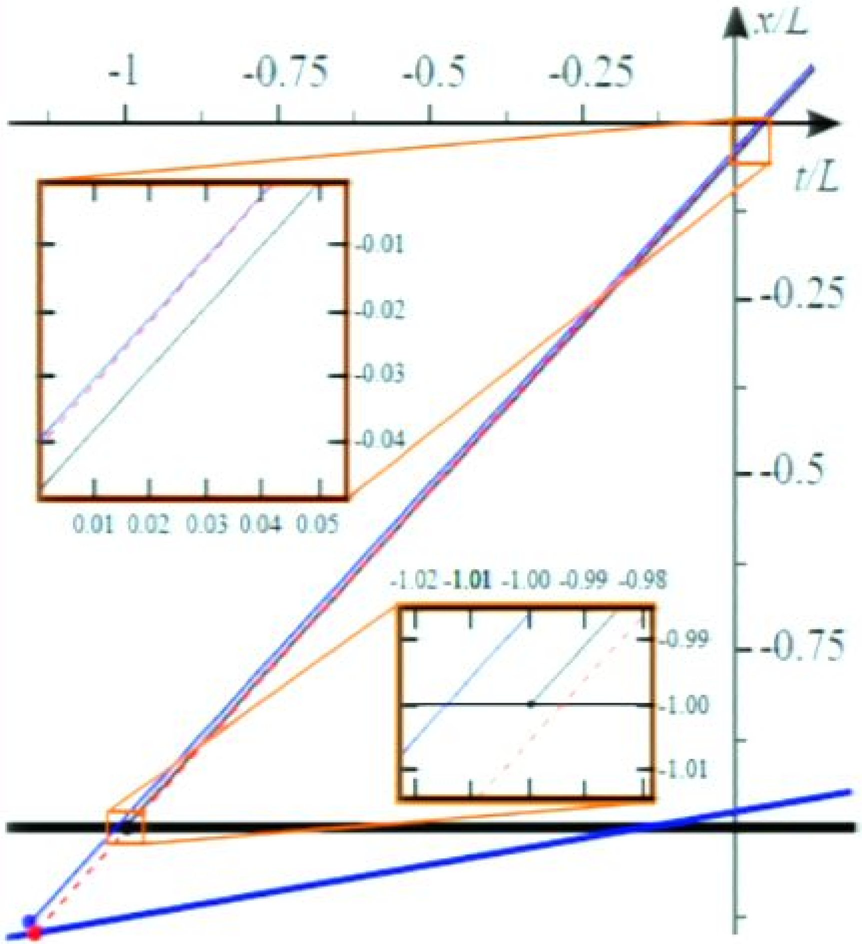
This is the idea that inspires the search of "DSR-deformed" boost transformations (still looking for a fully satisfactory implementation....mathematics of Hopf algebras is usually considered most promising direction....)

!!!

<u>there is no</u> deformed deSitter boost compatible with the invariance of the previously adopted

$$m^2 = (1 - H\eta)^2(\Omega^2 - \Pi^2 + \lambda(1 - H\eta)\Pi^3)$$

arXiv:1006.0007
GAC+Marciano+Matassa+Rosati)



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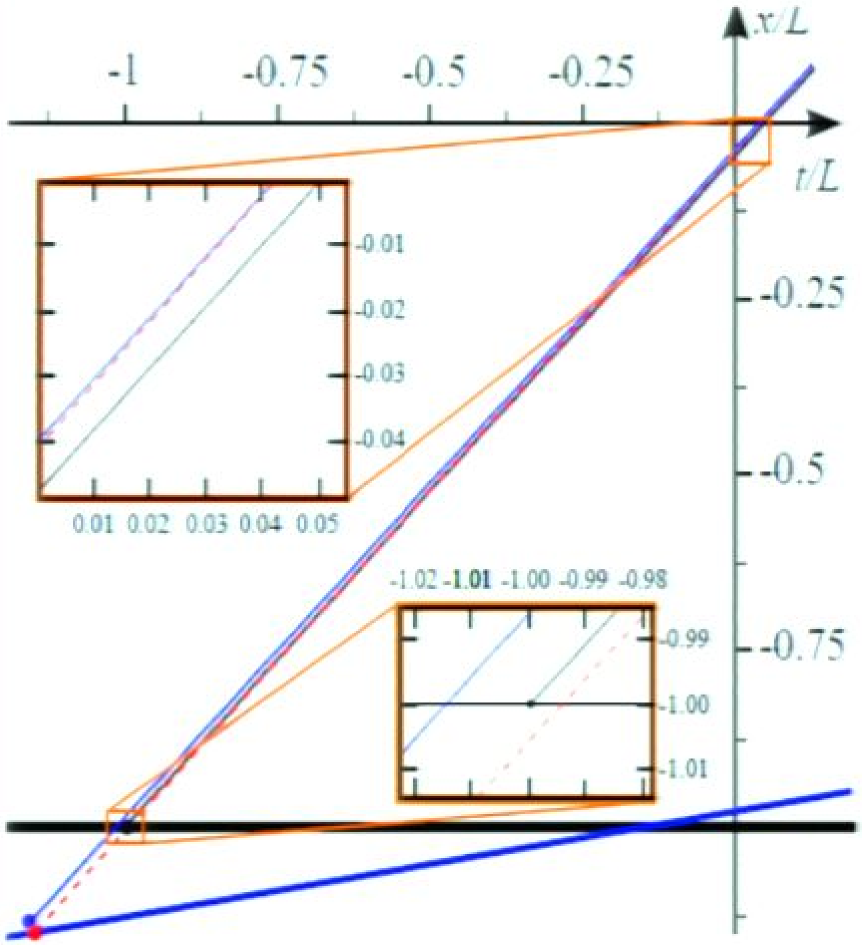

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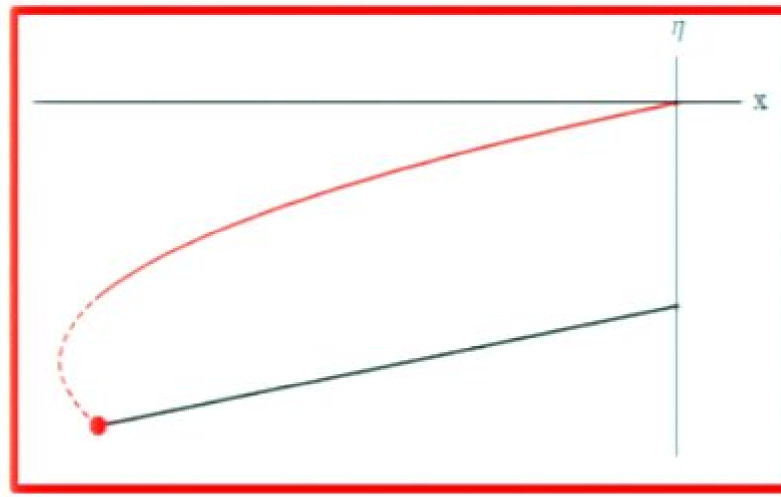

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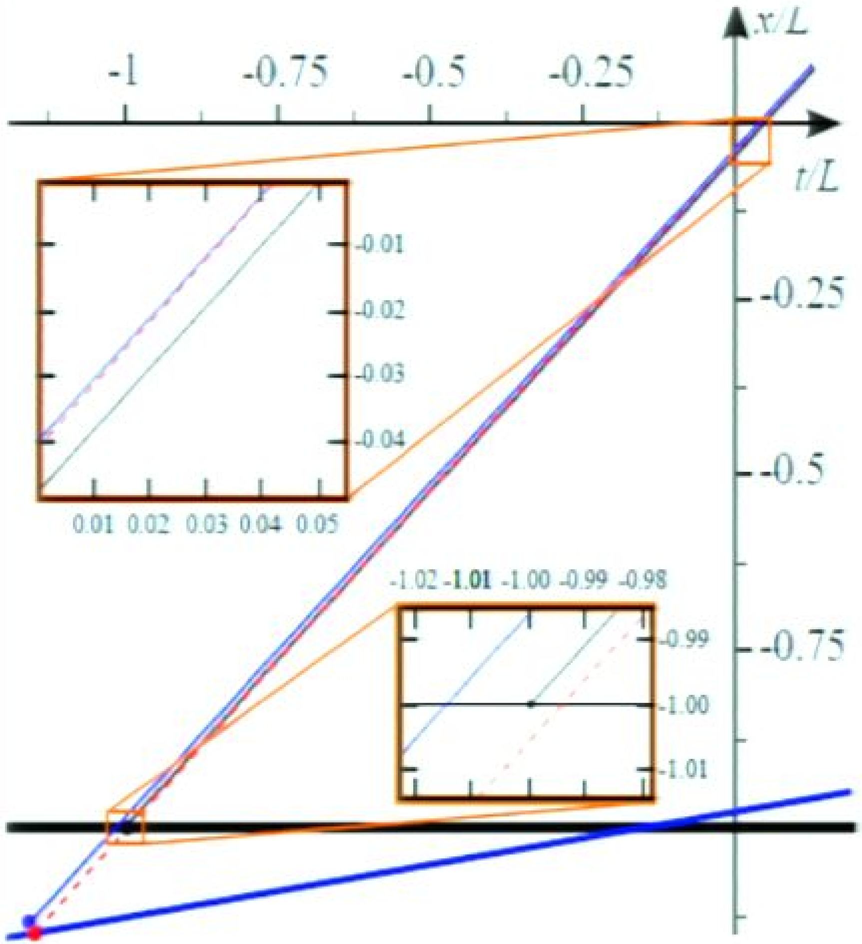

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quantum-gravity phenomenology with macroscopic objects?

[well, so far Landau model of stars....]

The other feature concerns a modification of the Fermi pressure: the L_P-modified dispersion relation (4) is such that more energy is needed (with respect to the $L_P \to 0$ classical-spacetime case) in order to "squeeze" the system by pushing more fermions to states with ultrashort wavelength. As a result we find that for the case $n = 1$ the dependence of the "speed of sound"[19] on the radius of the system R is

$$v_s^2 = \frac{\partial P}{\partial \epsilon} \simeq \frac{1}{3} + \frac{\eta}{3}(3\pi)^{2/3} L_P \frac{N^{1/3}}{R} \tag{5}$$

This means that, unlike the classical-spacetime case, in these quantum-spacetime pictures one has violations of the $v_s^2 \leq 1/3$ constraint[19]. And it is noteworthy that the Planck-length correction is "amplified" by the number N of fermions in the system. This is due to the Pauli exclusion principle, which implies that some fermions have Planckian momentum (the Fermi momentum p_F is $\sim 1/L_P$) even when the average momentum in the system is below the Planck scale.

arXiv:1007.0851

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Livello batteria in riserva

Collegarsi alla rete elettrica o trovare un'altra fonte di alimentazione

La batteria è quasi scarica (7%). Collegare il computer alla rete elettrica immediatamente. In caso contrario, il computer verrà messo in stato di ibernazione automaticamente.

OK

arXiv:1007.0851

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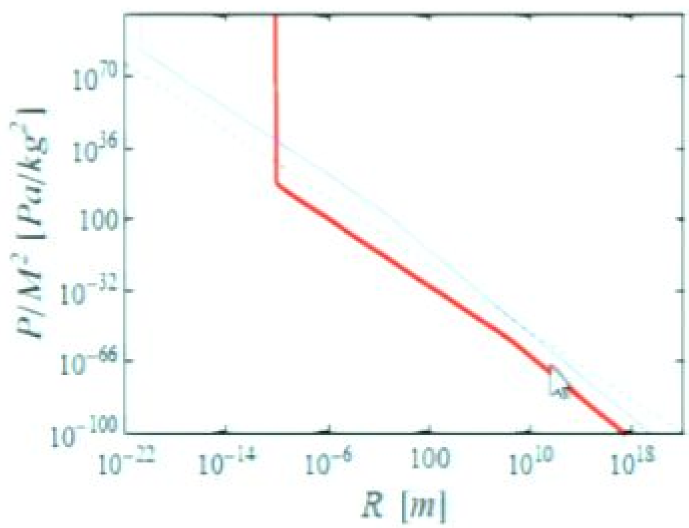

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2. IR/UV mixing

GAC+Laemmerzahl+Mercati+Tino, PhysRevLetters103(2009)171302

GAC+Mercati, arXiv:1004.3352

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Matusis+Susskind+Toumbas,JHEP(2000)

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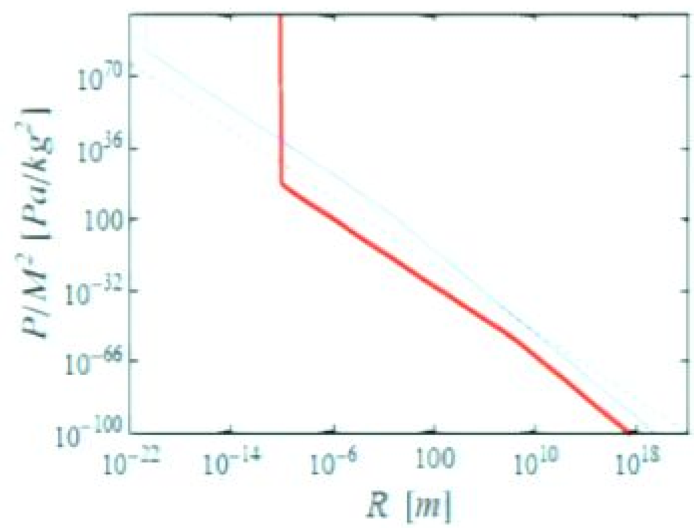

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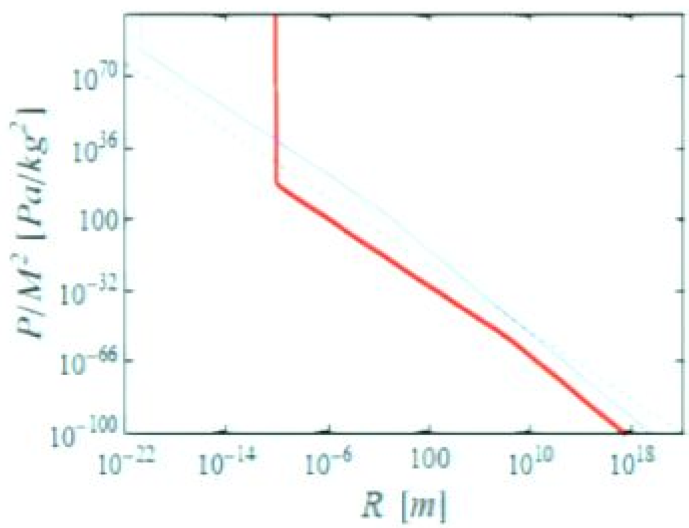

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modifications of type ξ_1 (linear in momentum) also necessarily produce modifications of the relationship between transferred momentum and recoil energy in a "two-photon Raman transition"

GAC+Laemmerzahl+Mercati+Tino, PhysRevLetters103(2009)171302

$$\frac{\Delta\nu}{2\nu_*(\nu_* + p/h)} = \frac{h}{m} .$$

~10^{-17} ~10^{8}

$$\frac{\Delta\nu}{2\nu_*(\nu_* + p/h)}\left[1 - \xi_1\left(\frac{m}{M_P}\right)\left(\frac{m}{h\nu_* + p}\right)\right]$$

and modifications of type ξ_1 (linear in momentum) also necessarily produce modifications of the nonrelativistic deBroglie relation

$$\lambda\vec{v} = \frac{h}{m_n}\hat{p} - \xi_1\frac{\lambda}{2}\hat{p}$$

GAC+Mercati, arXiv:1004.3352

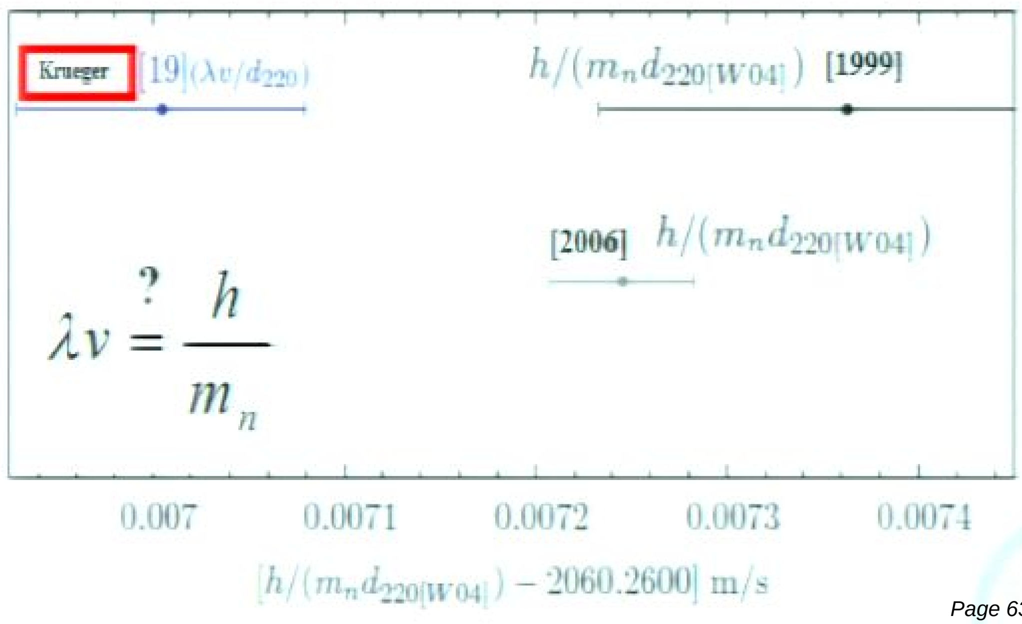
QG-deformed deBroglie relation

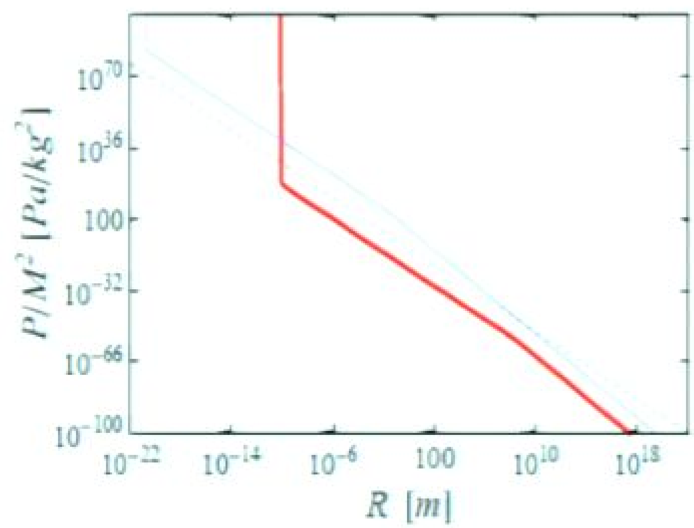
GAC+Mercati, arXiv:1004.3352

- deformations of the deBroglie relation are "natural" (naturally considered) in quantum gravity…..e.g. can be used to introduce a minimum wavelength principle…

- we have good data on this from cold neutrons and of course deBroglie relation for cold neutrons

- measurement of Krueger et al (done between 1995 and 1999) determined λv/d220 which can be compared to independent measurements of $h/(m_n d_{220[W04]})$





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arXiv:1007.0851

a DSR framework compatible with spacetime expansion

GAC+Marciano+Matassa+Rosati, arXiv:1006.0007

but there is a consistent picture with
DSR-deformed deSitter boosts:

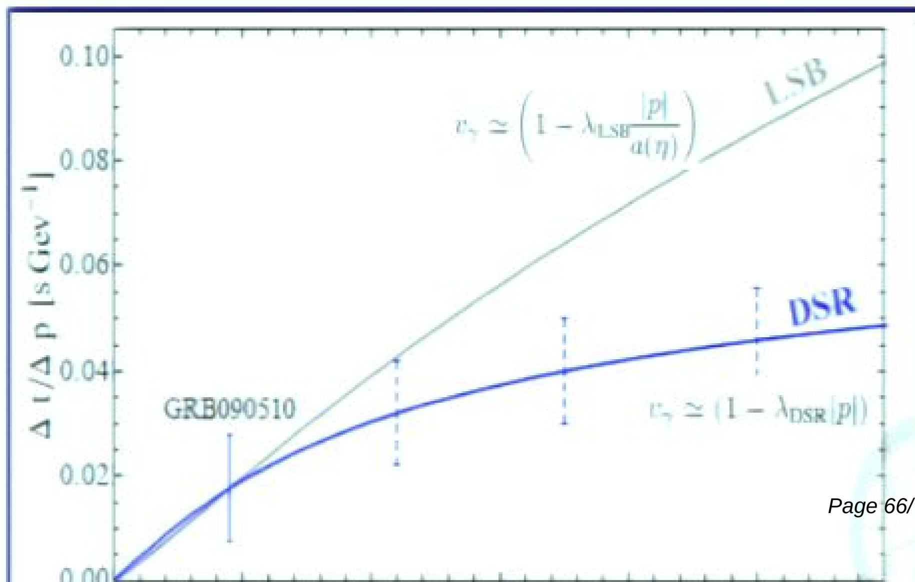
$$m^2 = (1 - H\eta)^2(\Omega^2 - \Pi^2 + \lambda_{\rm DSR}\Omega\Pi^2)$$

$$\{\Pi, x\} = -1\,, \qquad \{\Omega, \eta\} = 1$$

$$G_N = x(1 - H\eta)\partial_\eta + \left(\frac{1-(1-H\eta)^2}{2H} - \frac{H}{2}x^2\right)\partial_x + \lambda_{\rm DSR}\left(\frac{1+H\eta}{2}x\,\partial_x - (1-H\eta)\,\eta\,\partial_\eta + \frac{H\eta}{2}\right)\partial_x\,. \quad (11)$$

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

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



and is curvature/expansion a problem?

these opportunities in phenomenology have motivated much work on momentum dependence of the speed of photons....

but nearly all analyses and arguments only apply to flat (Minkowski-like) spacetime

now we have "good" data but are we ready?

z>1 ......

how does the expansion of a spacetime affect the momentum dependence of speed of light ?

issue only discussed in exploratory papers

by Ellis+Mavromatos+Nanopoulos+Sakharov+Sarkisyan

and by Jacob+Piran

which eventually led to the adoption of a description based on

$$m^2 = (1 - H\eta)^2(\Omega^2 - \Pi^2 + \lambda(1 - H\eta)\Pi^3)$$

"canonical energy" "canonical momentum"

$$v_\gamma \simeq 1 - \lambda(1 - H\eta)\Pi$$

specializing formulas to the insightful case of deSitter spacetime in conformal coordinates

$$ds^2 = \frac{1}{(1 - H\eta)^2}(d\eta^2 - dx^2)$$

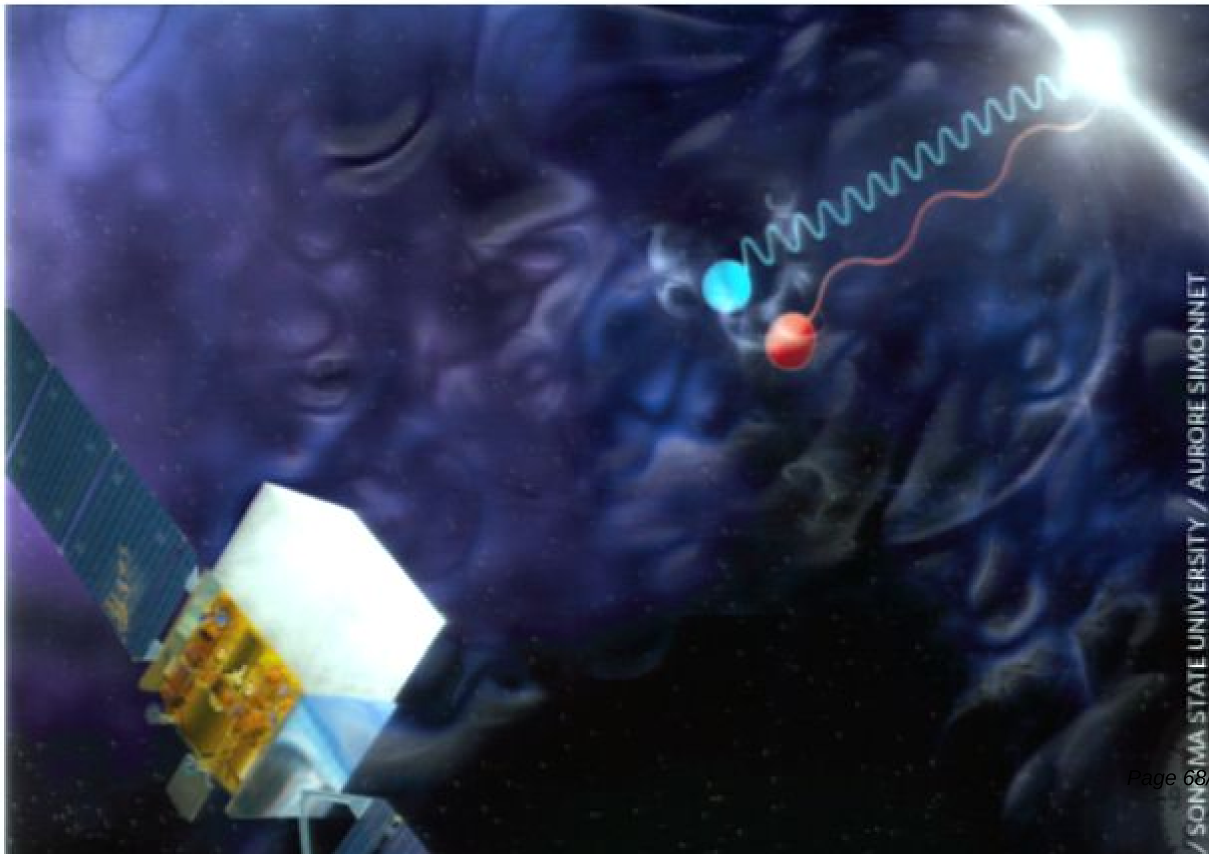
all this ASSUMES "Lorentz-invariance violation" ("LIV" or LSB for Lorentz-sym breakdown),

is our ignorance of the source engine a problem?

of course it is....one more reason to make vigorous effort to improve reliability of GRB models.... but even without knowing anything about the source engine the analysis can be successful

$$\Delta T_{observed} = \Delta T_{emission} + \Delta T_{propag} = \Delta T_{emission} + (\lambda E) T_{propag}$$

[and $\Delta T_{emission}$ should not depend significantly on $T_{propagation}$]



from modification of dispersion relation

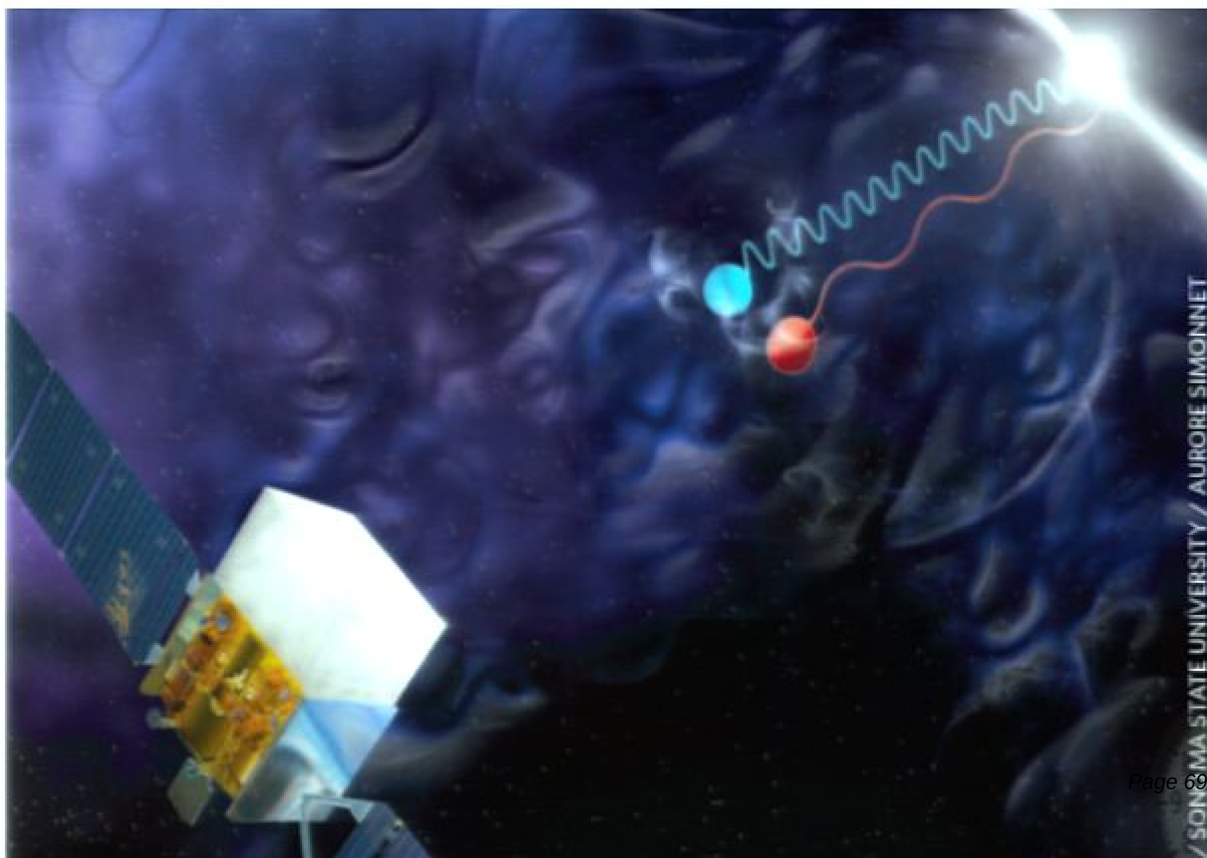
$$m^2 = E^2 - p^2 + \lambda E p^2$$

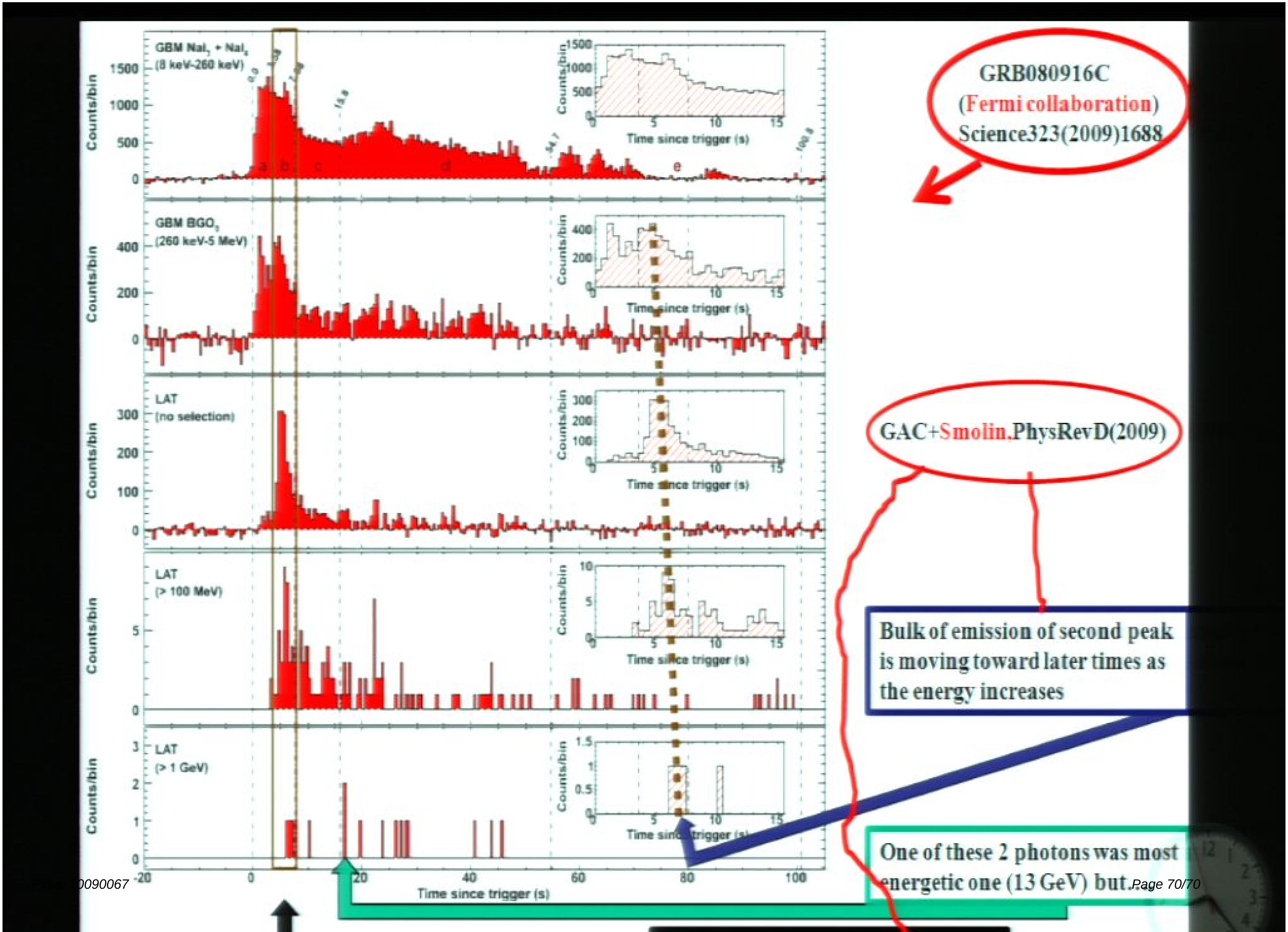
it follows that

$$v_\gamma \simeq c(1 - \lambda|p|)$$

and

$$\Delta T_{propag} = (\lambda E) T_{propag} \approx 1s$$ **[Planck length 100GeV 10^{17}s]**




GRB080916C
(Fermi collaboration)
Science323(2009)1688
GAC+Smolin.PhysRevD(2009)
Bulk of emission of second peak is moving toward later times as the energy increases
One of these 2 photons was most energetic one (13 GeV) but...
GBM NaI + NaI (8 keV-260 keV)
GBM BGO (260 keV-5 MeV)
LAT (no selection)
LAT (> 100 MeV)
LAT (> 1 GeV)
Counts/bin
Time since trigger (s)