Violations of Lorentz invariance and Opera

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Outline

- Motivations for LIV - Theory
- Motivations for LIV - Experiments
- Opera results vs our established physics description
- Opera results and new descriptions of physics world
- Final questions (rather than conclusions)

Why testing Lorentz invariance?

- Lorentz invariance is assumed to be a fundamental symmetry of nature. It is rooted via the equivalence principle in GR and it is a fundamental pillar in the SM. The more fundamental is an ingredient of your theory, the more it needs to be tested observationally.

- Several ideas related to quantum gravity have suggested violations of Lorentz invariance

- This is one of the few cases in which our sensitivity can constrain new physics at the Planck scale, so tests of Lorentz invariance can be used to rule out QG models.

Why LV?

Known theories of gravity rest on Einstein's equivalence principle → local Lorentz invariance

Principle of relativity — Implies the group structure

Isotropy — Implies reciprocity together with Principle of Relativity

Homogeneity — Implies linearity of coordinate transformations

Pre-causality — Implies a notion of past and future

Lorentz invariance

von Ignatowski (1910-1911)

Modified dispersion relations

Many QG models have led to modified dispersion relations

From a purely phenomenological point of view, the general form of Lorentz invariance violation (LIV) is encoded into the dispersion relations

$$E^2 = p^2 + m^2 + \Delta(p, M)$$

$M \equiv$ spacetime structure scale, generally assumed $\approx M_{\text{Planck}} = 10^{19}$ GeV

Assuming rotation invariance
we can expand this as

$$E^2 = p^2 + m^2 + M\eta^{(1)}|p| + \eta^{(2)}p^2 + \eta^{(3)}|p|^3/M \quad \ldots$$

Theoretical frameworks

Of course to cast constraints on LIV using these phenomena one needs more than just the kinematics information provided by the modified dispersion relations, one also often needs to compute reaction rates and decay times, i.e. a dynamical framework…

Explicit Lorentz symmetry violation

EFT+LV

Renormalizable, or higher dimension operators

Introduce a preferred reference frame

Deformed/Doubly SR paradigm

Non-critical Strings

Non-commutative spacetime
Finsler geometry

Preserve relativity principle - no preferred frames

Windows on Quantum Gravity

$M_{Pl} \sim 10^{19}$ GeV $\sim 10^{8}$ E_{UHECR}

At energies << M_{Pl} only **tiny effects** are expected.

BUT there are **special situations** where these tiny corrections can be magnified to sizable effects

- **Cumulative effects**
  (e.g. color dispersion & birefringence)
- **Anomalous threshold reactions**
  (e.g. forbidden if LI holds, e.g. gamma decay, Vacuum Cherenkov)
- **Shift of standard threshold reactions**
  (e.g. gamma absorption or GZK)
- **new threshold phenomenology**
  (asymmetric pair creation and upper thresholds)
- **LV induced decays not characterized by a threshold**
  (e.g. decay of particle from one helicity to the other or photon splitting)
- **Reactions affected by "speed limits"**
  (e.g. synchrotron radiation)

Threshold reactions

Key point: the effect of the non LI dispersion relations can be important at energies well below the fundamental scale

$$E^2 = c^2 p^2 \left(1 + \frac{m^2 c^2}{p^2} + \eta \frac{p^{n-2}}{M^{n-2}} \right)$$

Corrections start to be relevant when the last term is of the same order as the second.
If η is order unity, then

$$\frac{m^2}{p^2} \approx \frac{p^{n-2}}{M^{n-2}} \Rightarrow p_{crit} \approx \sqrt[n]{m^2 M^{n-2}}$$

n	p_{crit} for ν_e	p_{crit} for e^-	p_{crit} for p^+
2	$p \approx m_\nu$~1 eV	$p \approx m_e$=0.5 MeV	$p \approx m_p$=0.938 GeV
3	~1 GeV	~10 TeV	~1 PeV
4	~100 TeV	~100 PeV	~3 EeV

Existence of new thresholds however can occur only with explicitly broken Lorentz symmetry through preferred reference frames (Amelino-Camelia et al, 2000-2011)

Applications: QED with LV at O(E/M)

Dimension 5 Standard Model Extension: include dimension 5 LV operators in the SM preserving gauge and rotation invariance and quadratic in the fields

Myers & Pospelov, 2003

Contribution at order p^3/M to the MDR.

$$L = L_{QED} - \frac{\xi}{2M} u^m F_{ma} (u \cdot \partial)(u_n \tilde{F}^{na}) + \frac{1}{2M} u^m \bar{\psi} \gamma_m (\varsigma_1 + \varsigma_2 \gamma_5)(u \cdot \partial)^2 \psi$$

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Warning: CPT violated!

$$\text{electrons} \quad E^2 = m^2 + p^2 + \eta_\pm (p^3/M_{\rm Pl})$$

$$\text{photons} \quad \omega^2 = k^2 \pm \xi (k^3/M_{\rm Pl})$$

$$\eta_\pm = 2(\zeta_1 \pm \zeta_2)$$

electron helicities have independent LIV coefficients

photon helicities have opposite LIV coefficients

	Positive helicity	Negative helicity
Electron	η_+	η_-
Positron	$-\eta_-$	$-\eta_+$

correspondence relation between LV coeff for electrons and positrons

Astrophysical constraints: LV QED (n=3)

Gamma decay

- Lorentz violation allows the conservation of energy-momentum.
- Well above threshold it is very fast as the decay rate goes like $\Gamma \gg E^2/M$.
- 10 TeV photons would decay in approximately 10^{-8} seconds.
- If we see very high energy gamma rays from distant sources at least one photon polarization must travel on cosmological distances. I.e. they must be below threshold.
- If $|\xi| \ll |\eta|$ the constraint has the form

$$|\eta_\pm| \lesssim 6\sqrt{3} m^2 M / k_{\rm th}^3$$

Vacuum Cherenkov (Helicity Decay)

- Depending on parameters one can have emission of soft or hard photon.
- Once the reaction can happen it is very fast as the rate of energy loss goes like $dE/dt \approx E^3/M \Rightarrow$ 10 TeV electron would lose most of its energy in $\approx 10^{-9}$ seconds.
- The observation of the propagation of some high energy electrons implies that at least one helicity state cannot decay in either of the photon helicities.
- Hence the constraint can be worked out for one of the $\pm\eta_\pm$ and ξ.

$$p_{\rm th} = \left(m^2 M / 2\eta\right)^{1/3}$$

LIV: end of the story?

- QG phenomenology of Lorentz and CPT violations is a a success story in physics. We have gone in few years (1997->2010) from almost no tests to tight, robust constraints on EFT models.
- In summary for EFT with LIV:
  - **Photons**: $O(10^{-14})$ on dim 5 (no birefringence from GRB), $O(10^{-8})$ on dim 6 op (CR)
  - **Electron/Positron**: up to $O(10^{-22})$ on dim 4, up to $O(10^{-5})$ on dim 5 op (Crab) and up to $O(10^{-8})$ on dim 6 op (CR)
  - **Hadronic sector**: up to $O(10^{-46})$ on dim 3, $O(10^{-27})$ on dim 4, $O(10^{-14})$ on dim 5, up to $O(10^{-6})$ on dim 6 op (CR)
  - **Neutrinos oscillations**: up to $O(10^{-28})$ on dim 4, $O(10^{-8})$ and expected up to $O(10^{-14})$ on dim 5 (ICE^3), expected up to $O(10^{-4})$ on dim 6 op.
  - **Neutrino vs Light**: Delta c/c < 10^{-8} at 10 MeV for electronic antineutrinos from SN1987.

- If there is Lorentz violation, and it is described by the same modified dispersion relation at all energies then its scales seems required to be well beyond the Planck scale...

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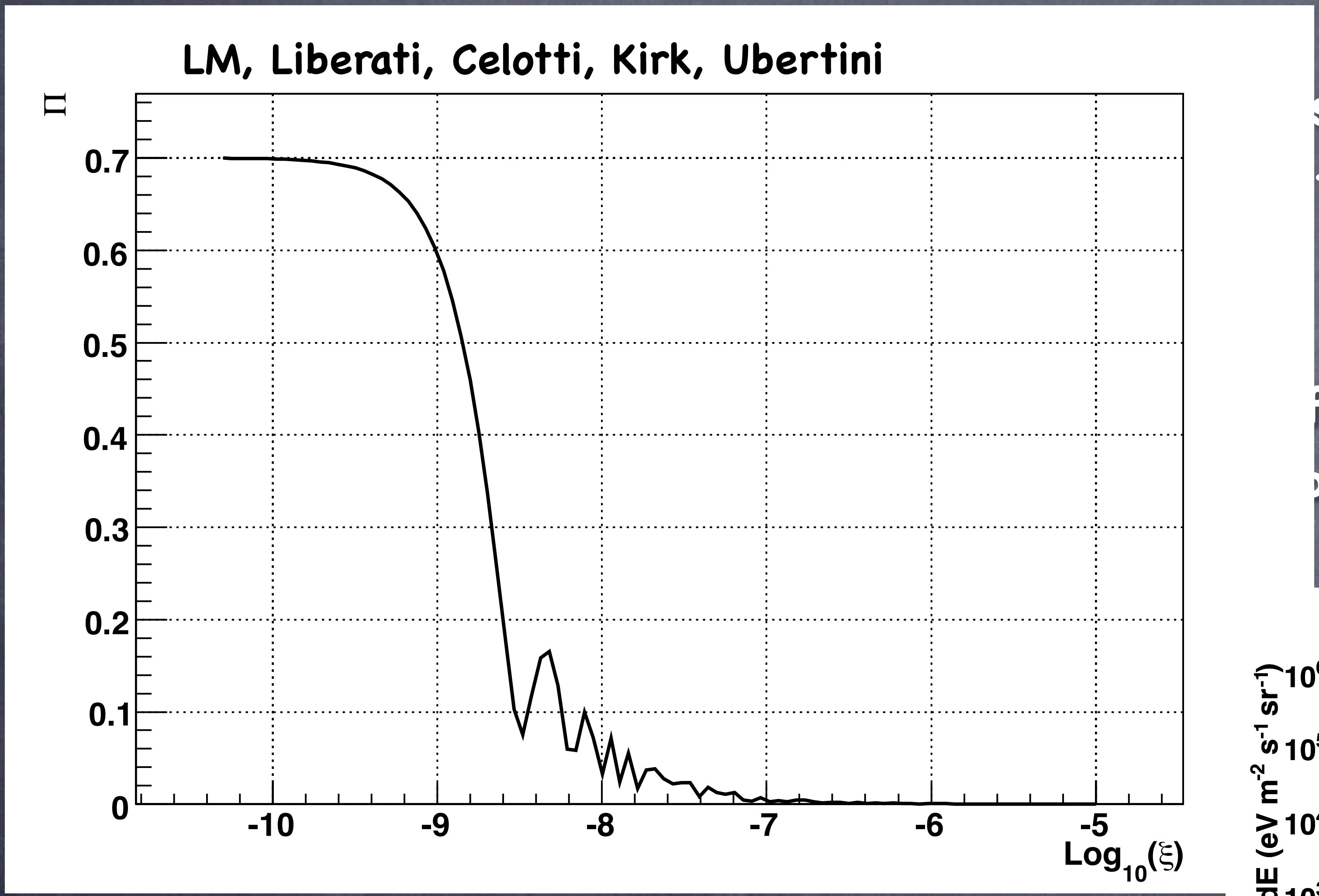

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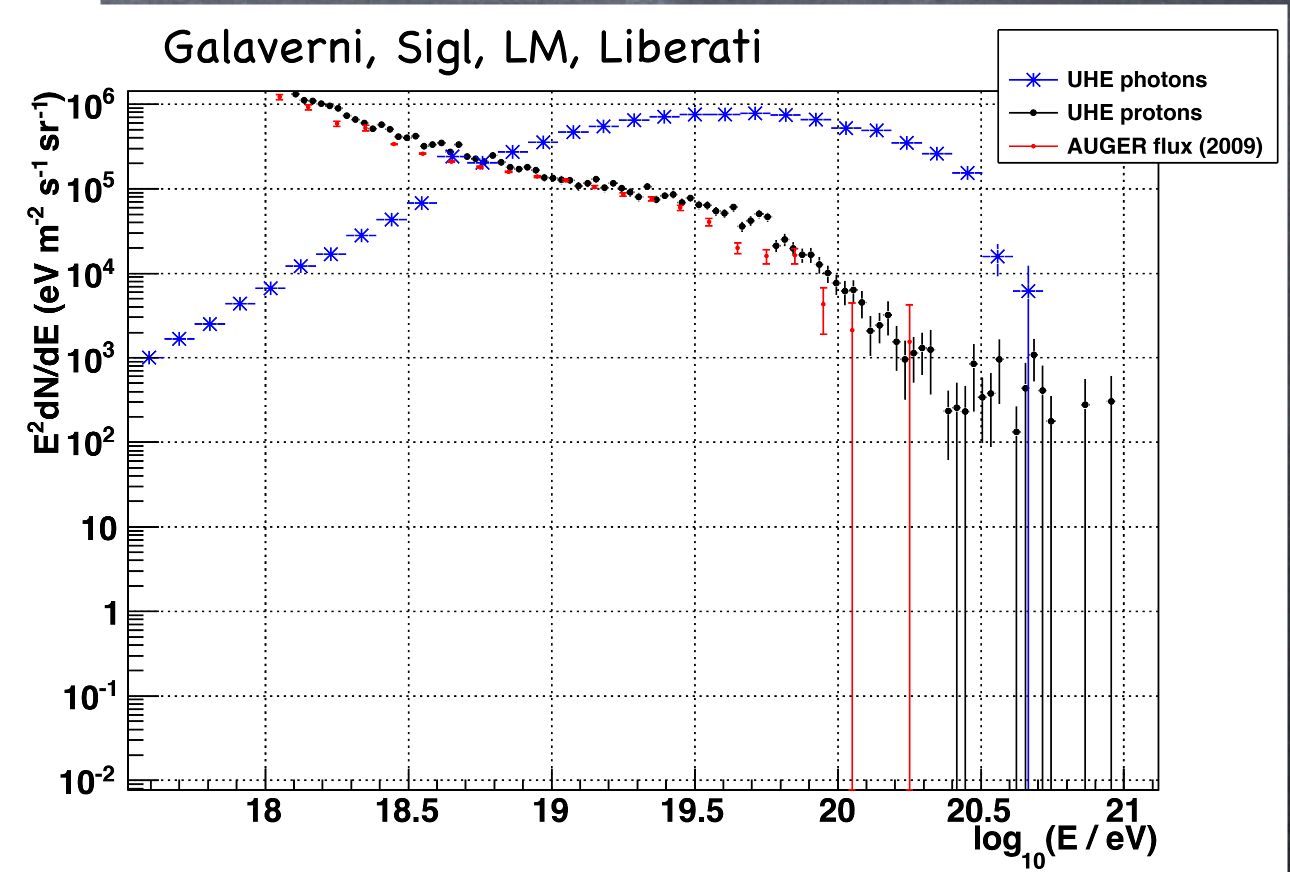

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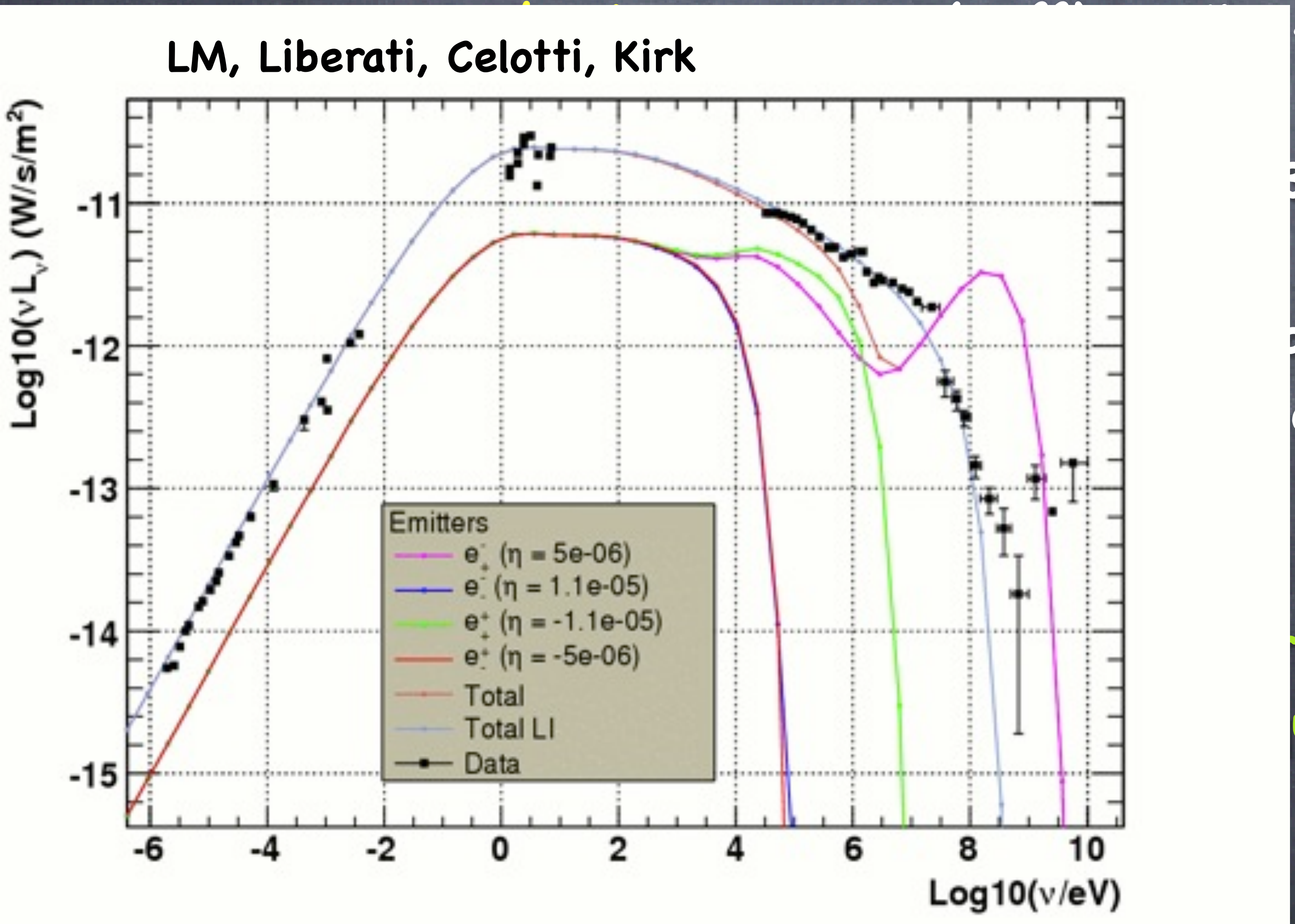

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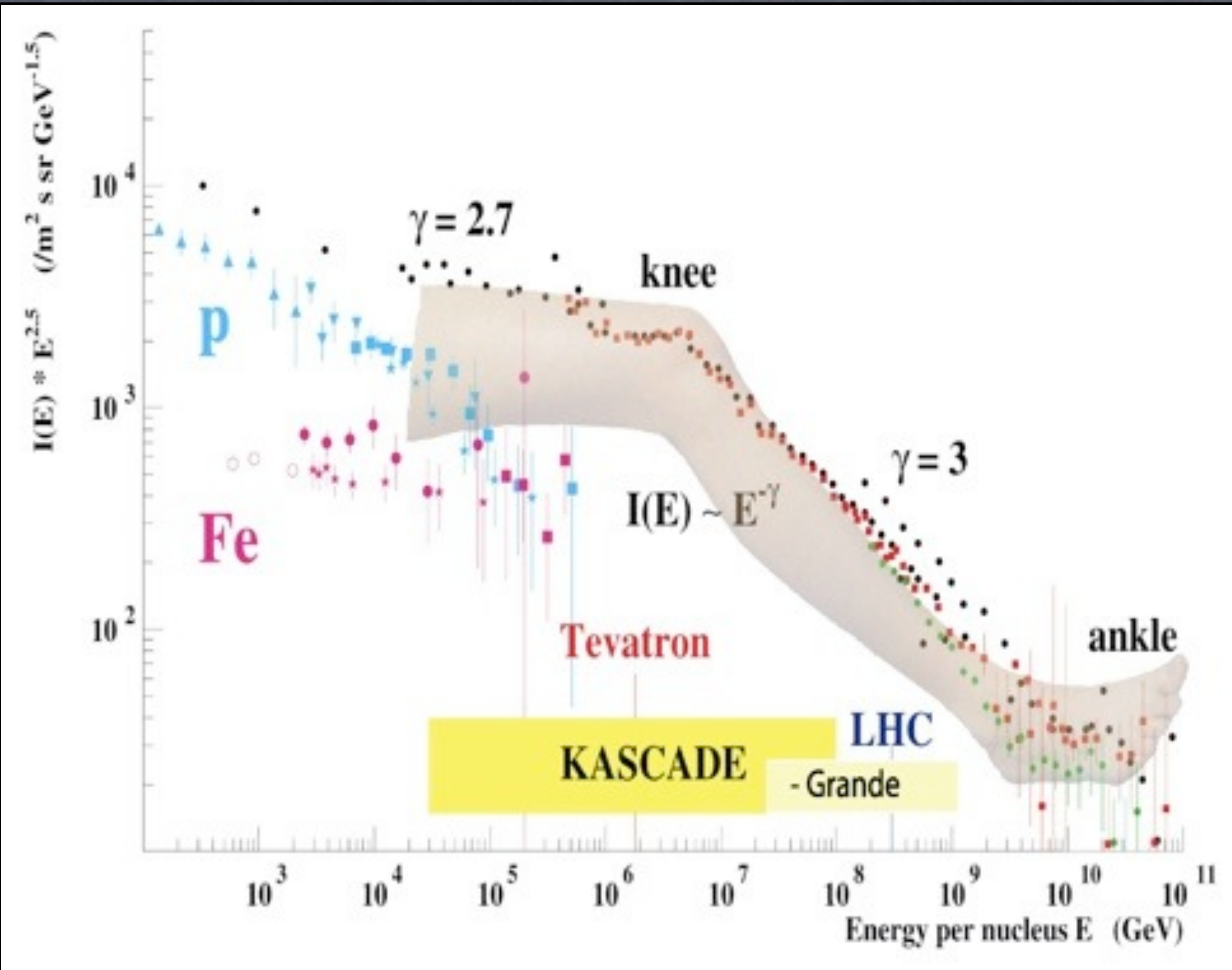

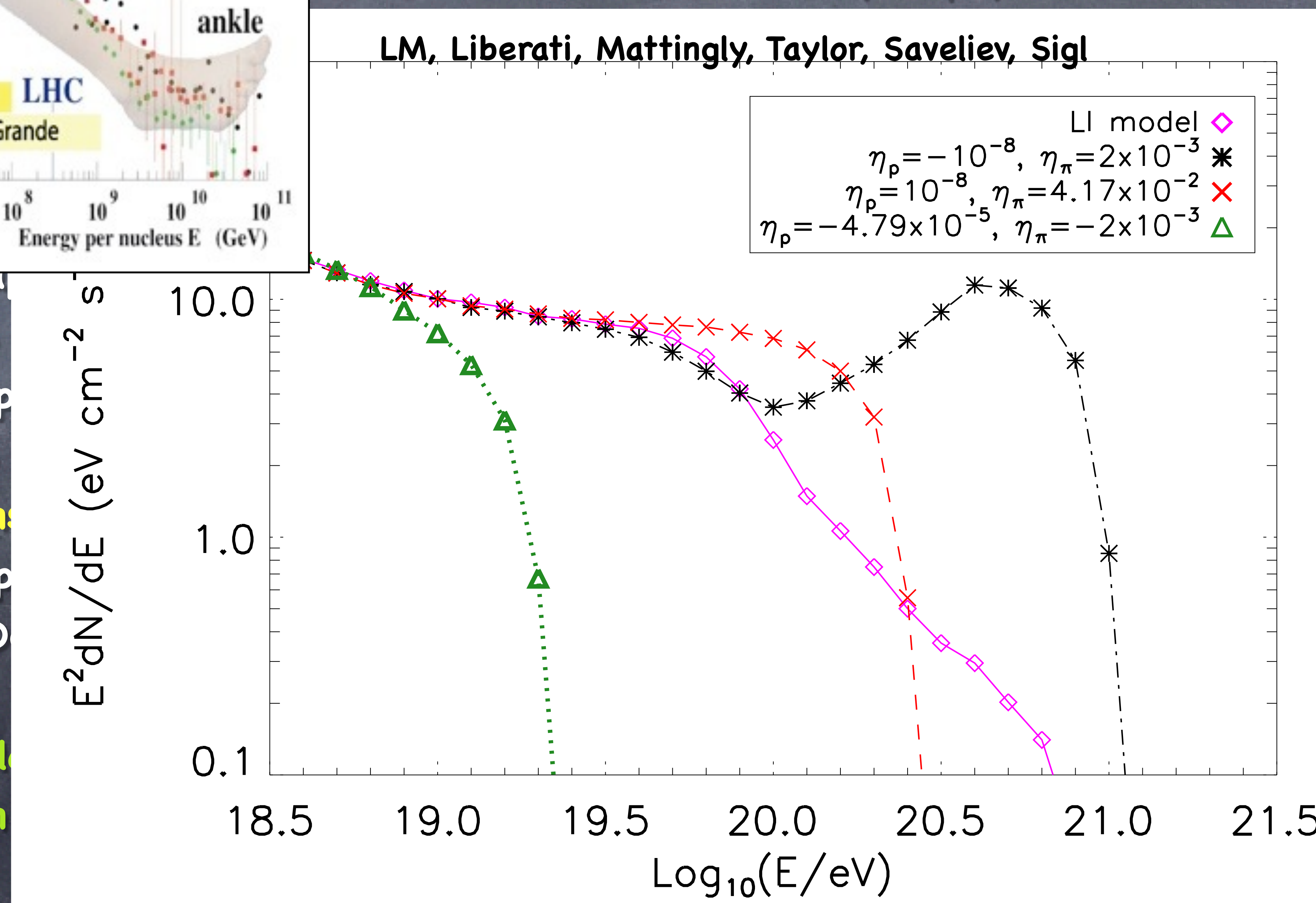

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- Hadronic sector: up
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  dim 5 (ICE^3), exp
- Neutrino vs Light: D

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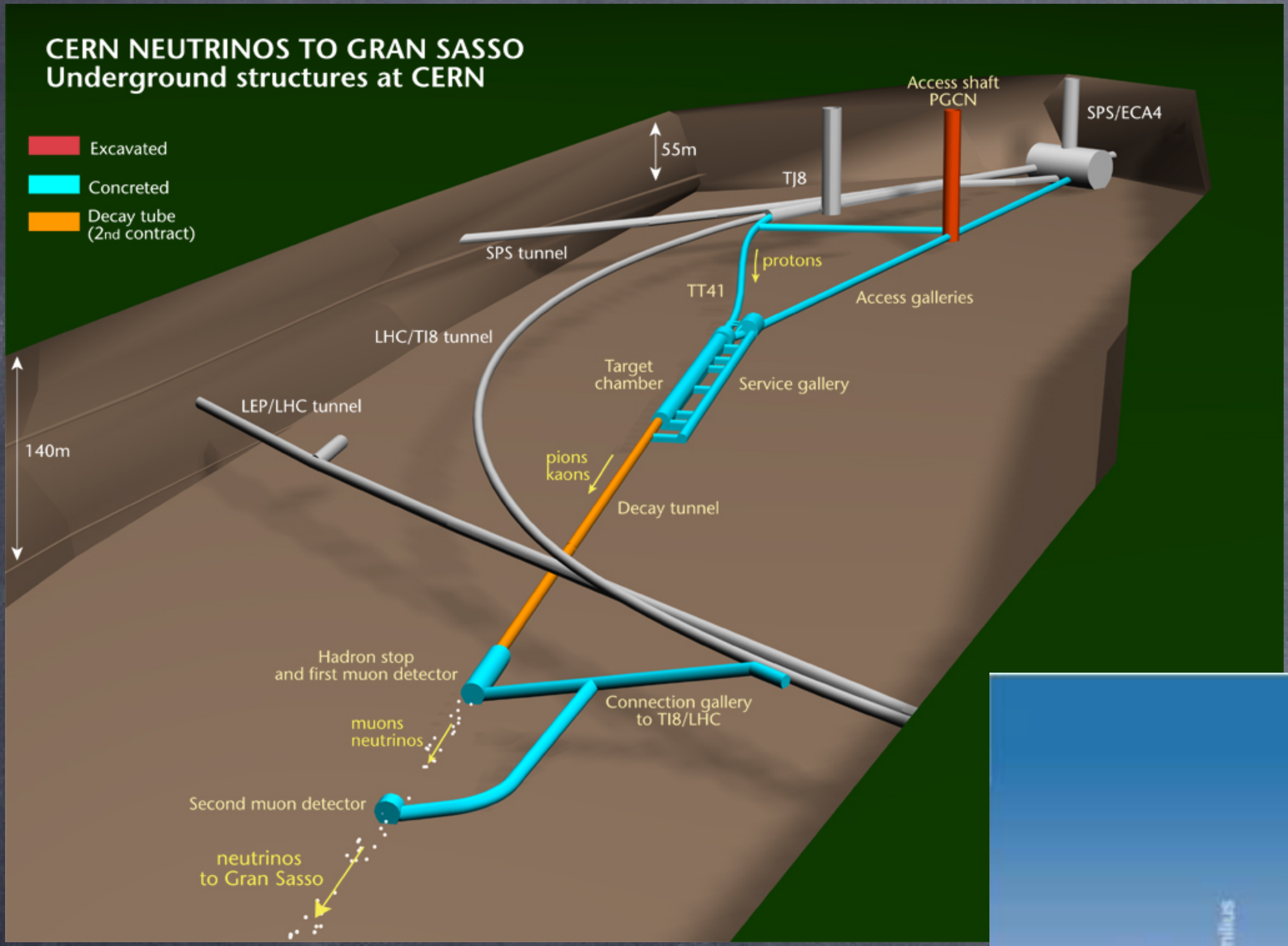
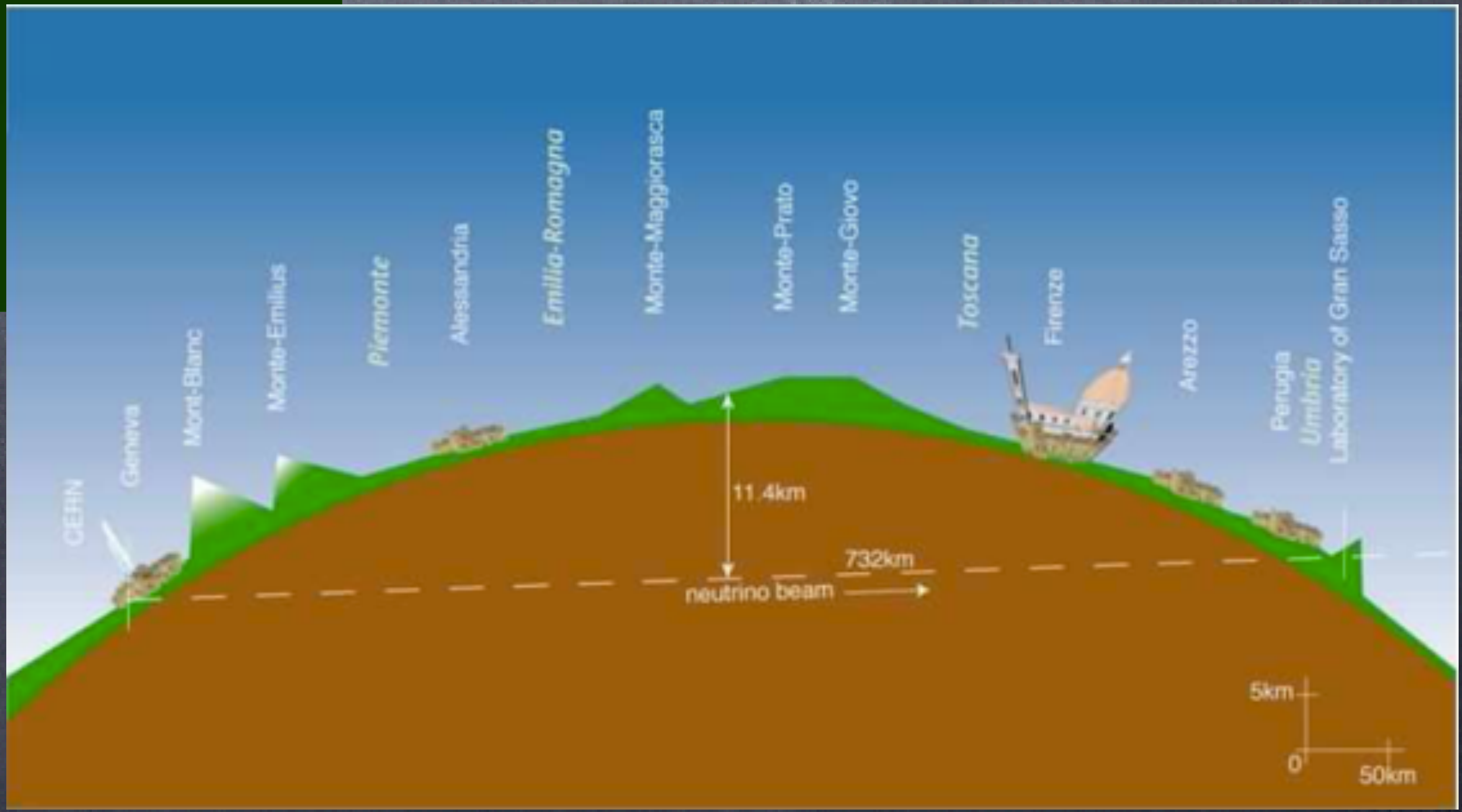
Neutrino LIV after Opera



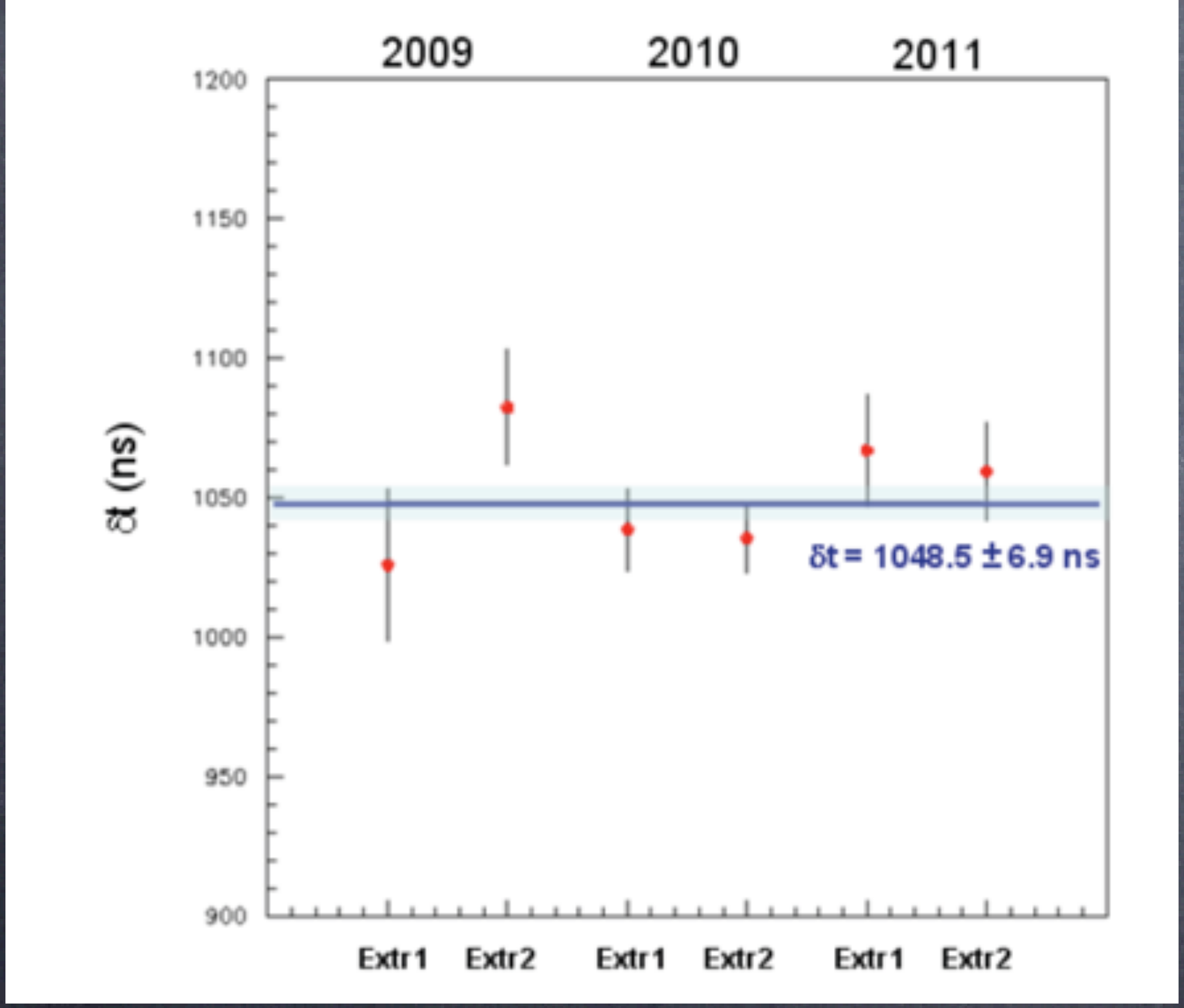


The claim by Opera

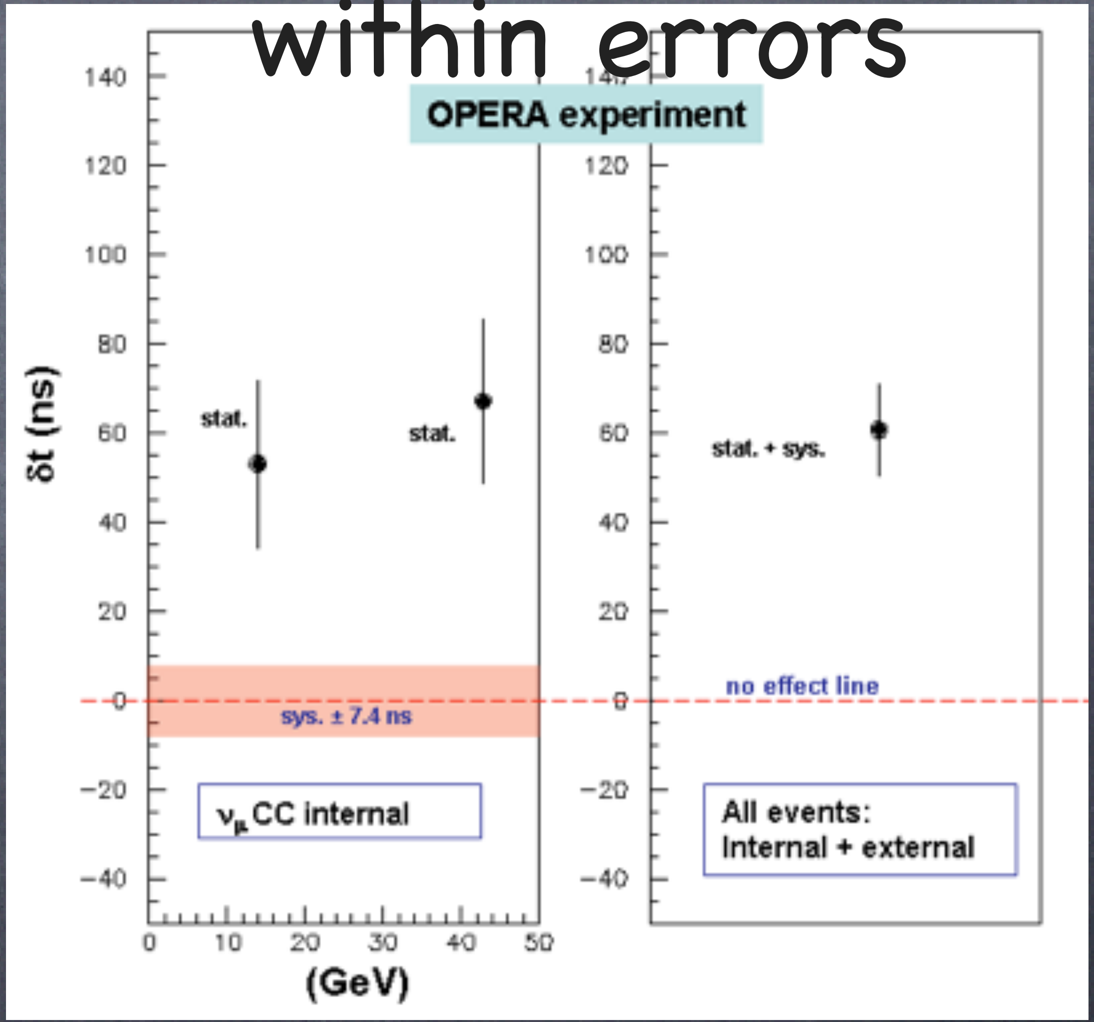
Opera "rocked the world" by announcing the detection at 6 sigma of faster than light neutrinos

$$(v_{\nu_\mu} - c)/c = (2.48 \pm 0.28\,(\mathrm{stat}) \pm 0.30\,(\mathrm{sys})) \times 10^{-5}$$

No sidereal variation



No energy dependence within errors



Note: Previously, the MINOS Collaboration reported $\Delta c/c \lesssim (5.1 \pm 2.9) \times 10^{-5}$ for 3 GeV ν_μ, compatible with 0 within 2σ.

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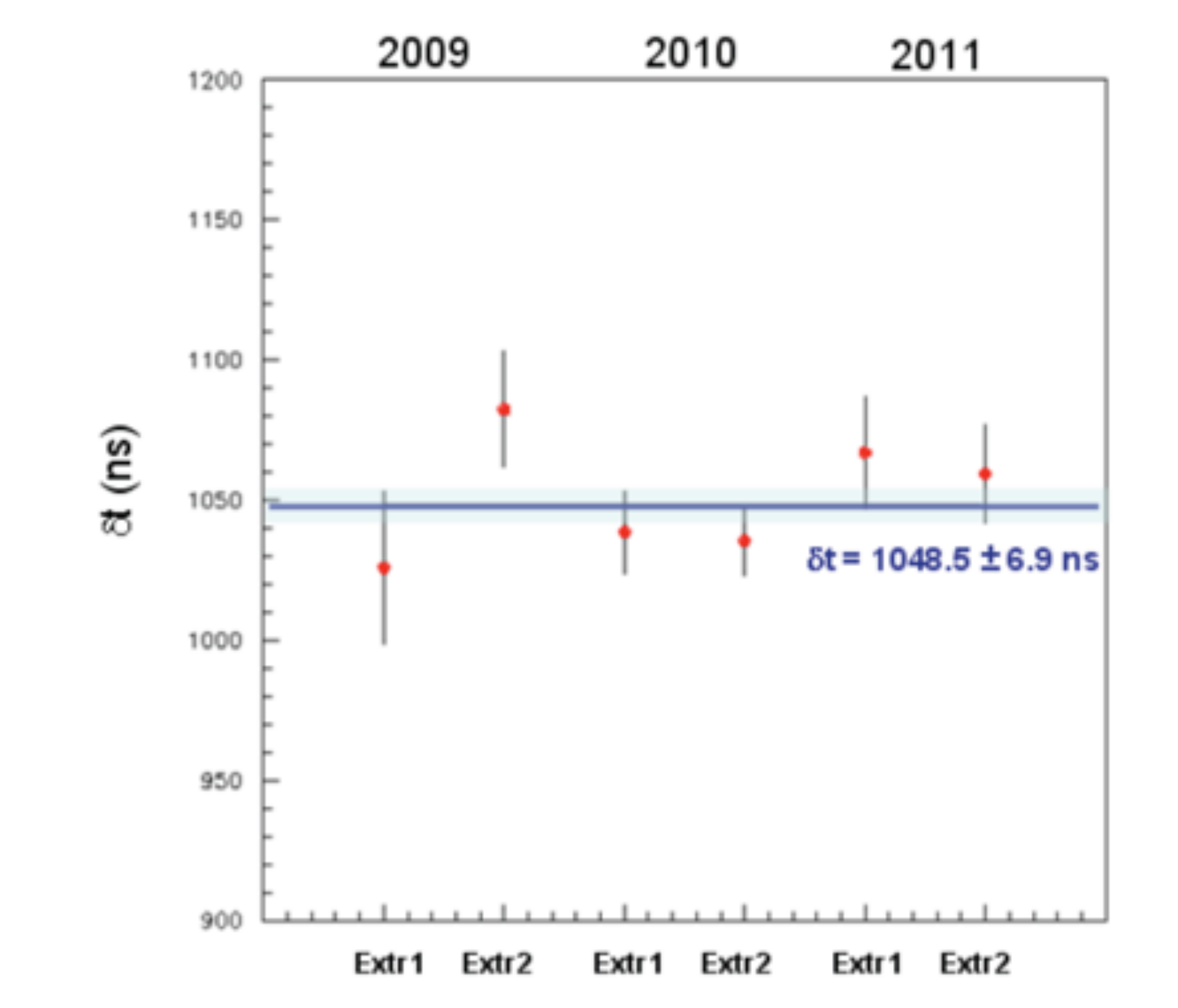

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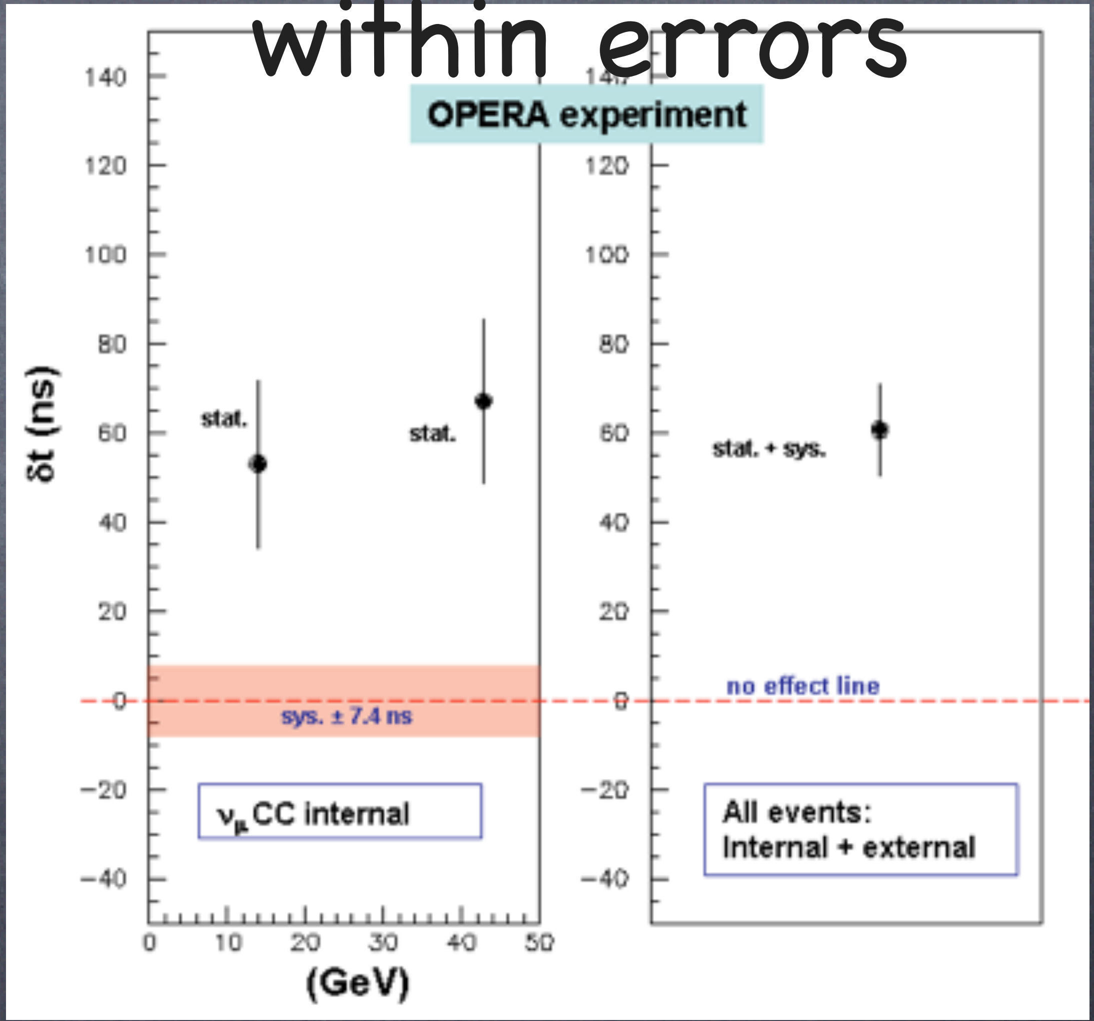

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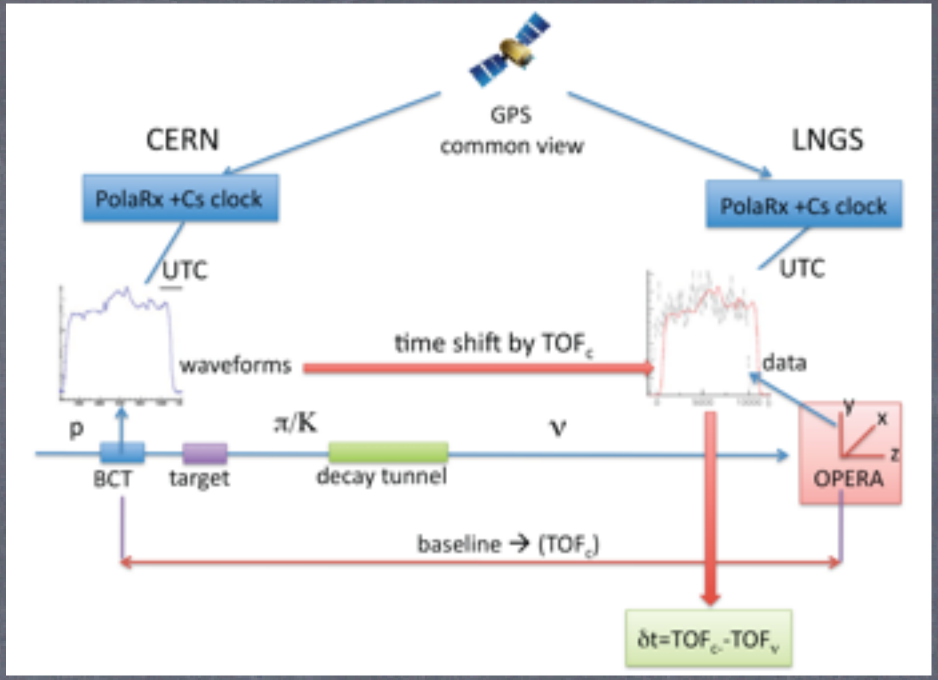
Facts about Opera



- The experiment is a time of flight measurement but a tricky one: the time of flight of single CNGS neutrinos cannot be precisely measured at the single interactions (first version).

- So they do it statistically by reconstructing the probability density distribution (PDF) of the time of emission of the neutrinos.

- This measurement (first version) does not rely on the difference between a start and a stop signal but on the comparison of two event time distributions.

- The PDF can then be compared with the time distribution of the interactions detected in OPERA, in order to measure TOFν.

- The deviation

  Observed advance   Explained advance

  δt = TOFc − TOFν=1048.5 ns - 987.8 ns=

  = (60.7 ±6.9 (stat) ±7.4 (sys)) ns

  is obtained by a maximum likelihood analysis of the time tags of the OPERA events with respect to the PDF, as a function of δt.

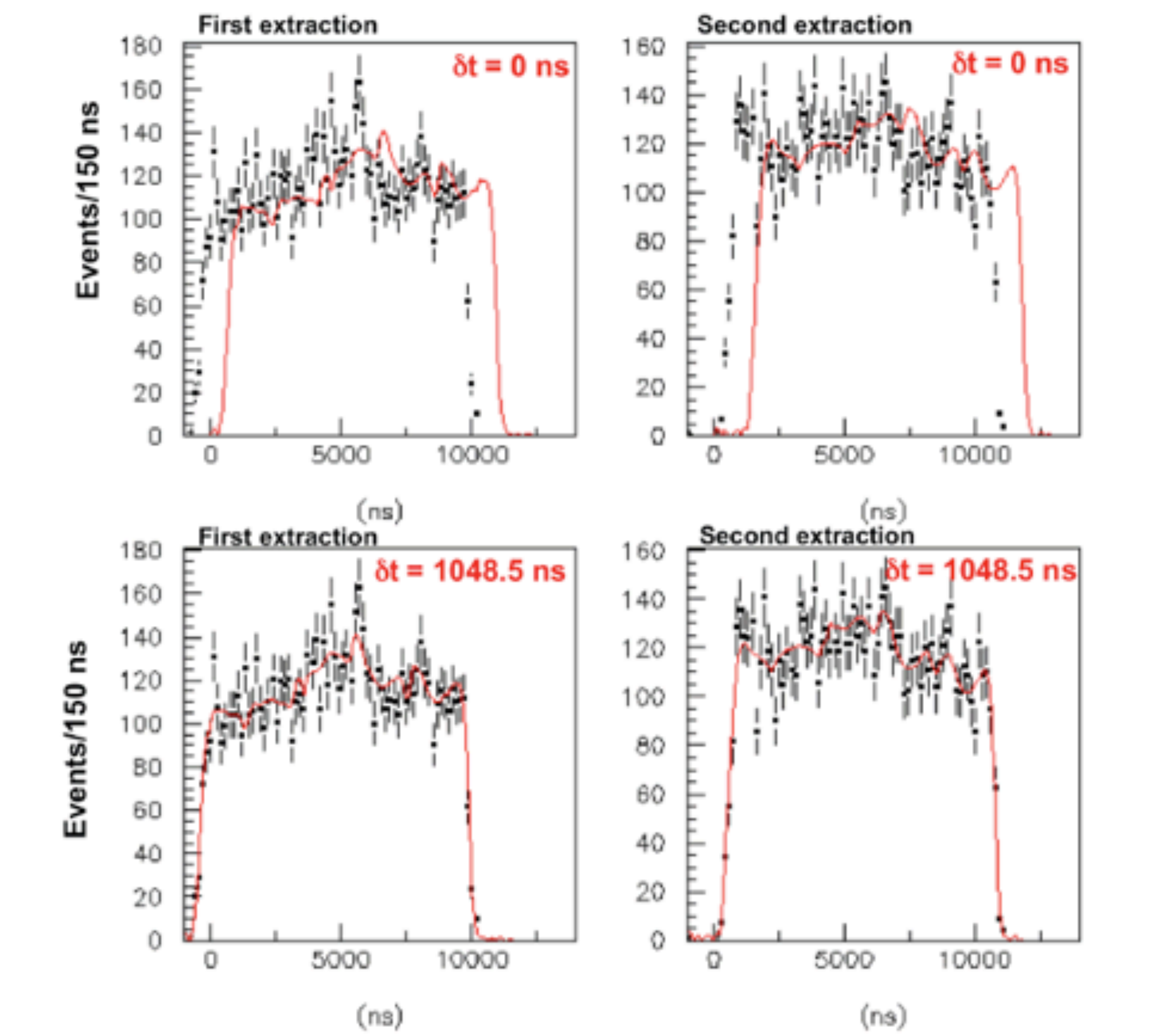
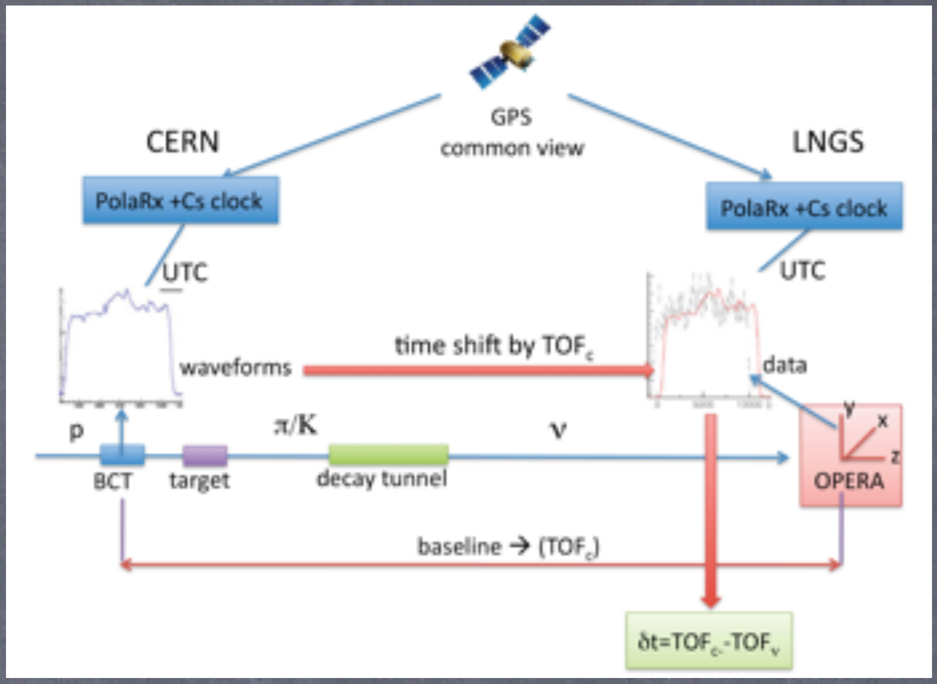


Fig. 11: Comparison of the measured neutrino interaction time distributions (data points) and the proton PDF (red line) for the two SPS extractions before (top) and after (bottom) correcting for δt (blind) resulting from the maximum likelihood analysis.

Facts about Opera



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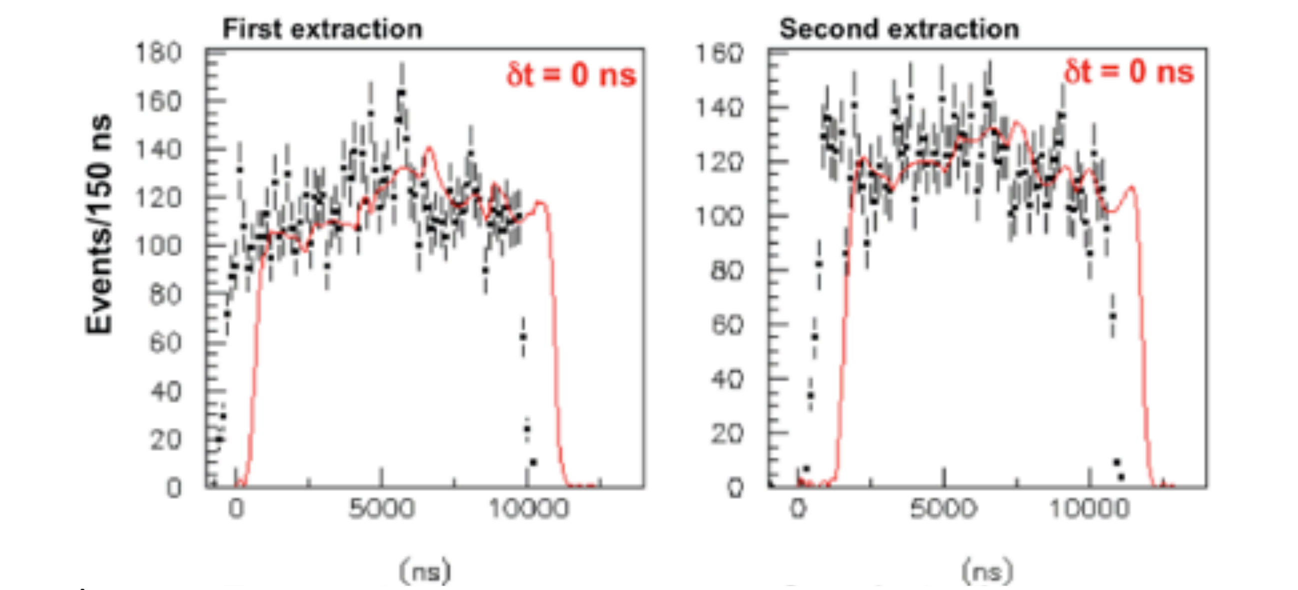
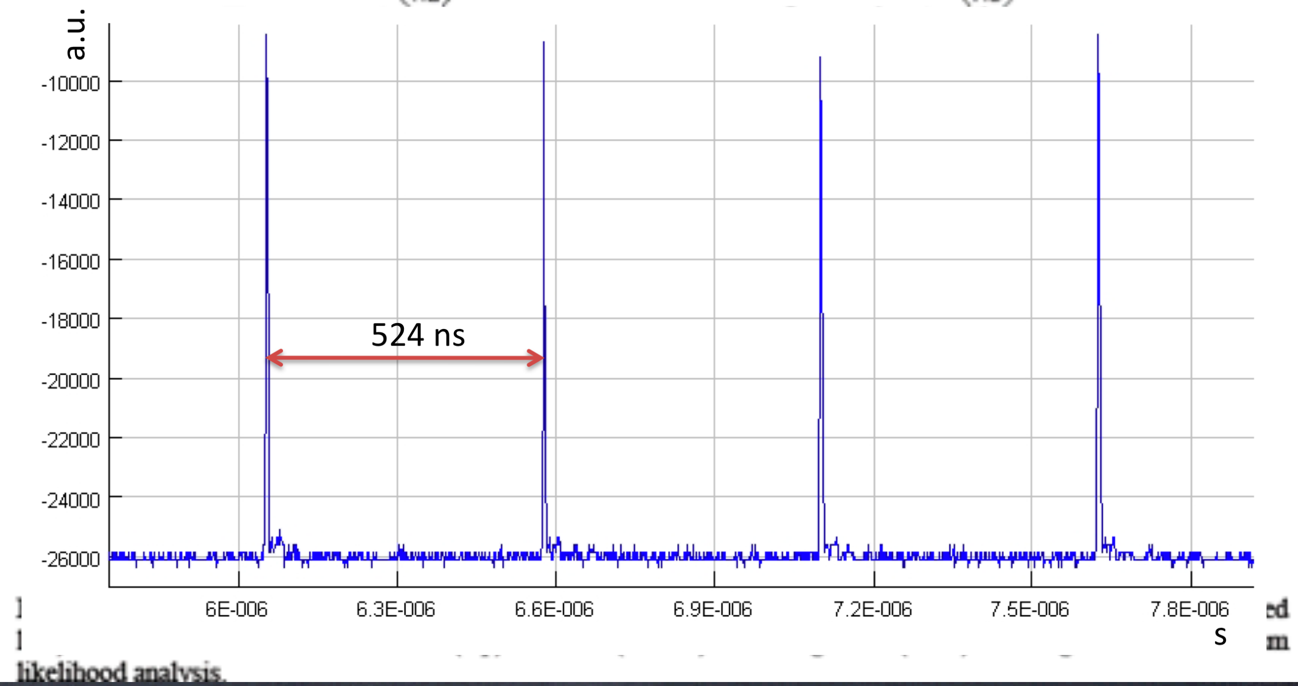




Disclaimer:

it is not the job of the theorist to either confirm or disprove an experimental fact.
In the following I will take the Opera result as firmly established, and try to sketch how many of our prejudices it ruins

Opera vs what we know

Let us start assuming that

- Opera claim is not flawed (systematic error, alternative explanation, etc…)
- Once you choose a power-law dispersion relation this is it at all energies: no smartly "designed" Lorentz violation in finite range of energy for the moment.
- EFT holds (no models like space-time foam …)
- energy-momentum conservation as usual

Let's consider as a case study with n=2,3,4

$$E^2 = p^2 + m_i^2 + \xi_i \frac{p^n}{M^{n-2}}$$

- n=2 (rot invariant SME dim 4 or Coleman-Glashow model) = constant shift in the speed of light
- n=3 LIV shift = p/M energy dependent LIV but mild scaling with energy
- n=4 LIV shift = p^2/M^2 energy dependent LIV but faster scaling with energy

We can now look at three different kinds of constraints

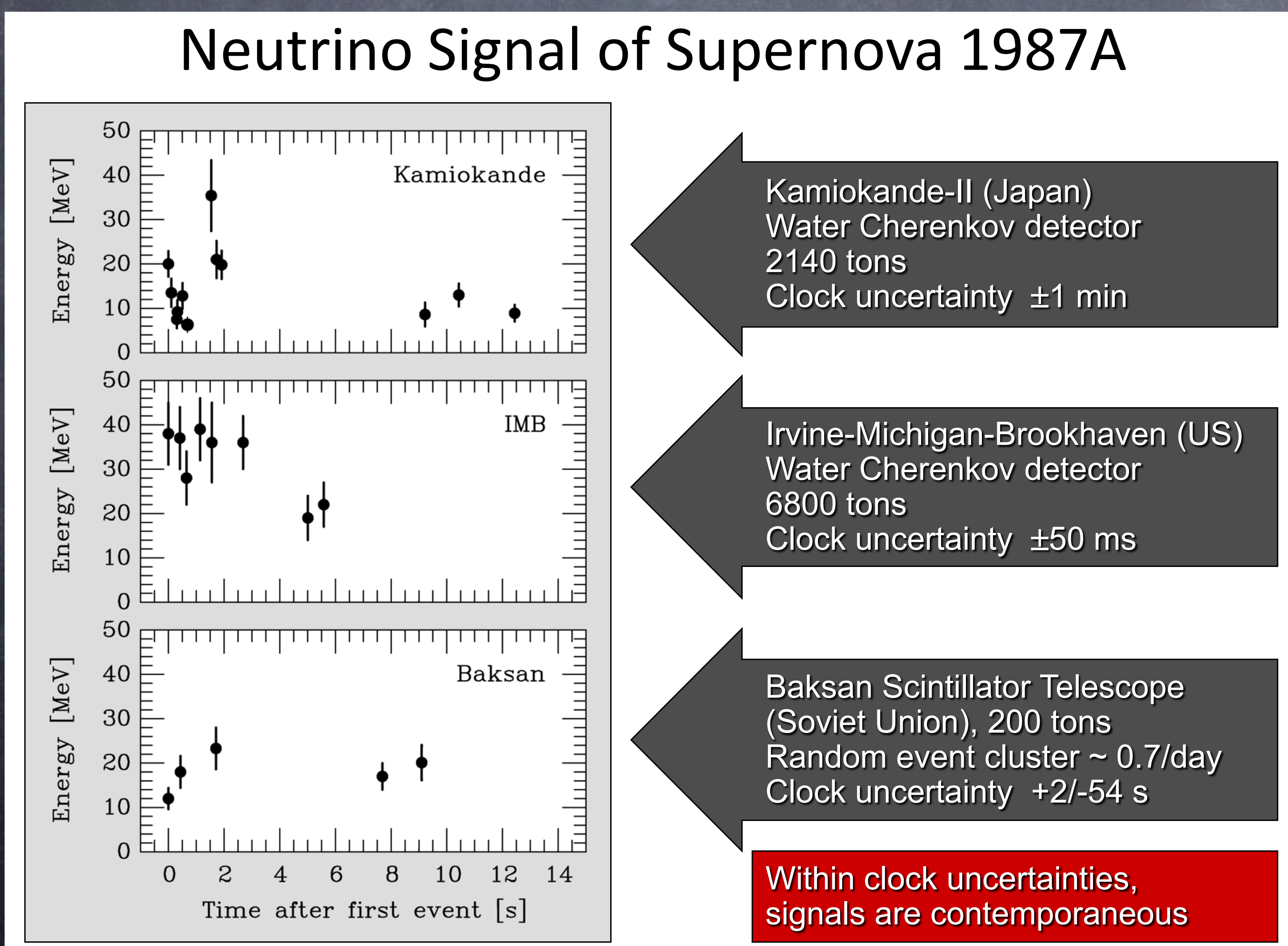
- **Neutrino oscillations**
- **Time of Flight**
- **Threshold reactions**

Time of Flight constraints

Caveat: We will attribute a definite velocity to the neutrino flavor eigenstates (like everybody does without questioning), although they are not energy eigenstates. However, given that we are considering ultra-relativistic neutrinos, for which the mass term is negligible, then we can safely discuss about the velocity of a neutrino flavor eigenstate.

$$\frac{\Delta c^{TOF}}{c}_{(n)} = \frac{v(p)-c}{c} = -\frac{m^2}{2p^2} + \xi \frac{n-1}{2}\left(\frac{p}{M}\right)^{n-2}$$

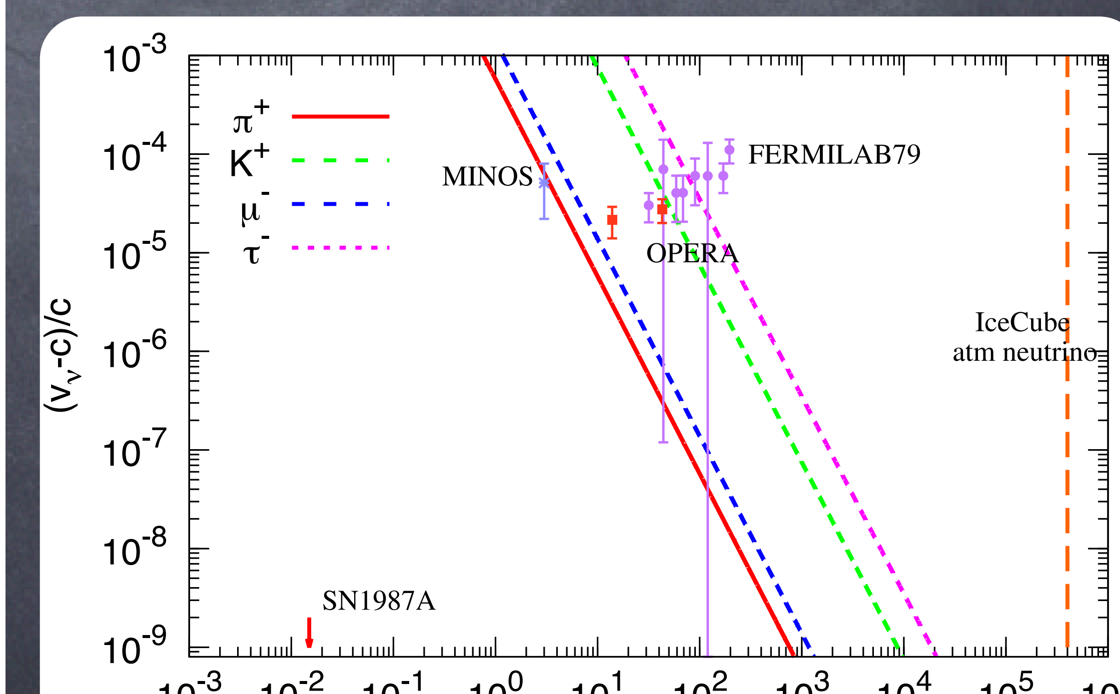
$$M = p \times \left(\frac{\Delta c^{TOF}}{c}_{(n)} + \frac{m^2}{2p^2}\right)^{-1/(n-2)}$$



courtesy, A. Mirizzi

$$\frac{v_\nu - c}{c} \lesssim 10^{-8} \div 10^{-12}$$

Longo (1989)
Ellis et al. PRD (2008)



Bi et al.

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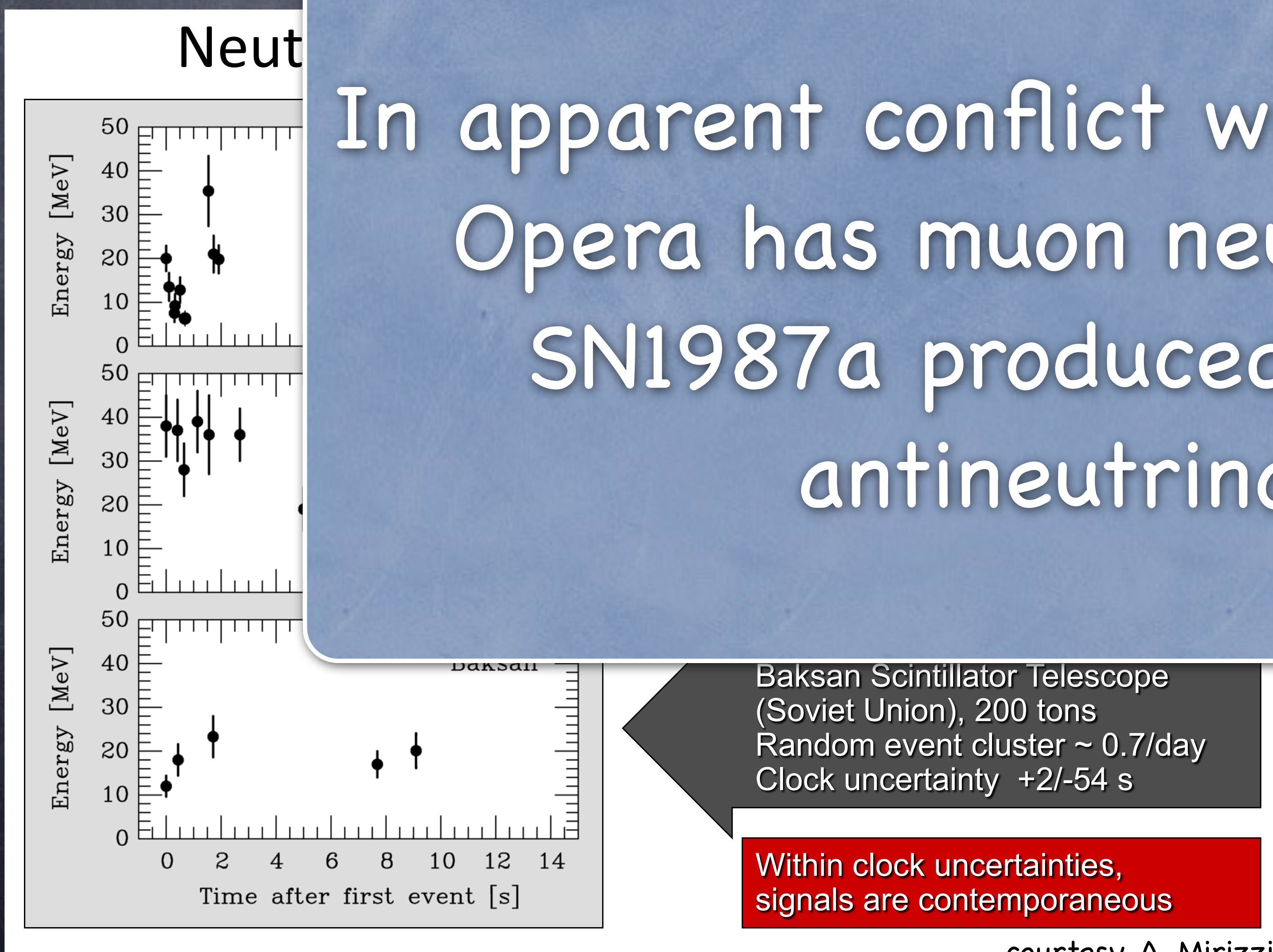

$\div 10^{-12}$

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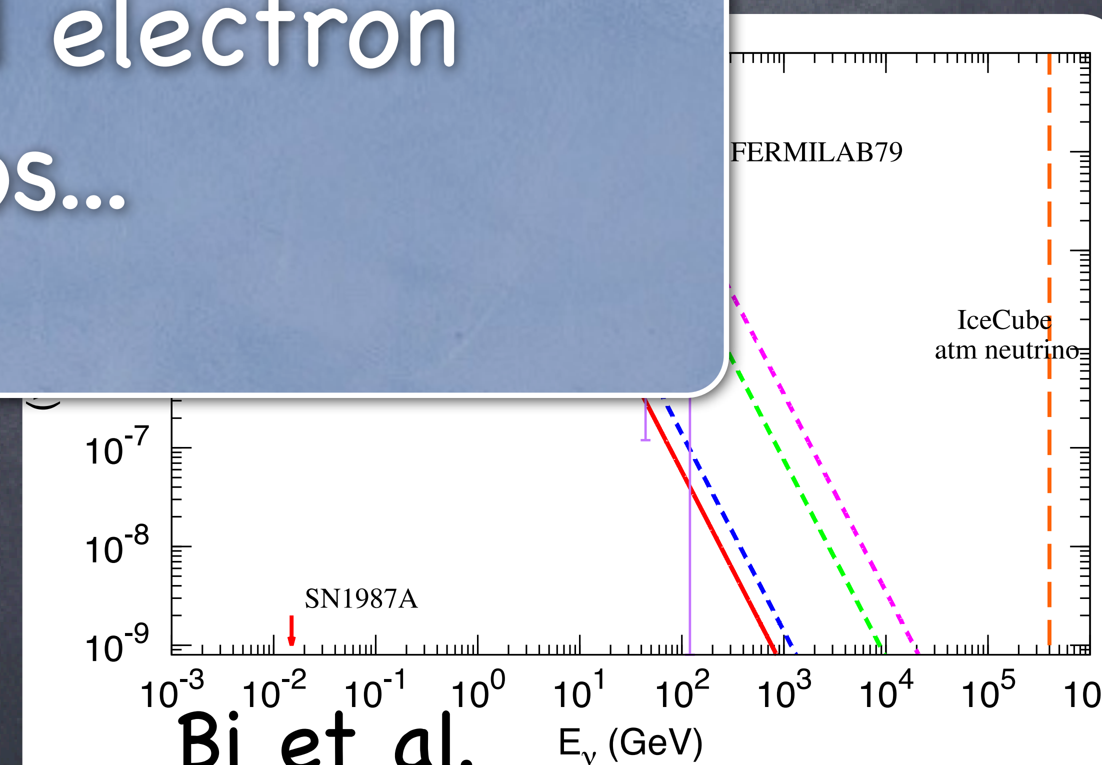
l. PRD (2008)



In apparent conflict with Opera, but Opera has muon neutrinos, the SN1987a produced electron antineutrinos...

Neutrino Oscillations

Neutrino flavor oscillations yield constraints on LIV differences within the neutrino sector. Neutrino oscillations depend on the differences in E−p between different neutrino eigenstates.
In standard neutrino oscillations, this difference is governed by the squared mass differences between the energy eigenstates. With LV oscillations are governed by the differences in the effective mass squared

$$N_i^2 = m_i^2 + \xi_i p^n / M_i^{n-2}$$

The transition probability between two flavors I,J is then ruled by the factor

$$\delta N_{ij}^2 = \Delta m_{ij}^2 + p^2 \left(\frac{\Delta c}{c}\right)_{ij}^{LIV} \qquad \left(\frac{\Delta c}{c}\right)_{ij}^{LIV} = \xi_i \left(\frac{p}{M_i}\right)^{n-2} - \xi_j \left(\frac{p}{M_j}\right)^{n-2}$$

Solar neutrinos: E~MeV, messy physics, no constraints

Atmospheric neutrinos: E~MeV—TeV, (Delta c/c)$\nu_\mu \nu_\tau$ AMANDA-IceCube

Reactors antineutrinos: E~MeV, (Delta c/c) $\nu_e \nu_\mu$ KamLAND

Accelerators neutrinos: E>1 GeV, (Delta c/c) $\nu_e \nu_\mu$ or (Delta c/c)$\nu_\mu \nu_\tau$ or (Delta c/c) $\nu_e \nu_\tau$

The best constraint to date comes from survival of atmospheric muon neutrinos observed by the former IceCube detector AMANDA-II in the energy range 100 GeV ÷ 10 TeV, and reads $(\Delta c/c)_{\nu_\mu \nu_\tau} \leq 2.8 \times 10^{-27}$ at 90% CL. Given that IceCube does not distinguish neutrinos from antineutrinos, the same constraint applies to the corresponding antiparticles.

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If we have LIV in neutrinos it must be ~ flavor independent

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Atmospheric

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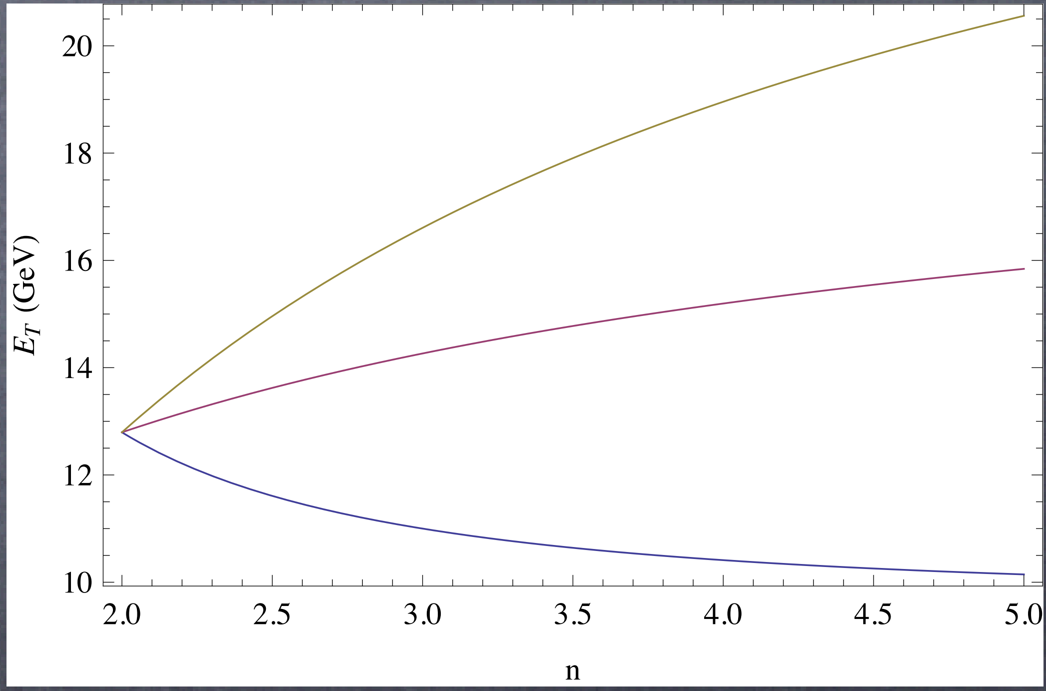
Neutrinos threshold reactions

- Vacuum Cherenkov: $\nu \rightarrow \nu\gamma$
  - Too suppressed: relevant only above ~10^{19} eV
- Neutrino splitting: $\nu \rightarrow \nu\nu\bar{\nu}$
- Neutrino decay by pair creation: $\nu \rightarrow \nu e^{+} e^{-}$
  (Idea and n=2 worked out in Cohen-Glashow 2011)

$$\tau_{\nu-\text{pair}} \simeq \frac{m_Z^4 \cos^2\theta_w}{g^4 E^5}\left(\frac{M}{E}\right)^{3(n-2)}$$



Rests on a few assumptions:
✓ a preferred frame exists
✓ energy-momentum conservation laws are linear
✓ hamiltonian dynamics is preserved
✓ electrons are not superluminal
✓ the asymptotic electron states are free and on-shell in vacuum

Cohen and Glashow, 2011,
LM, Liberati, Mattingly, 2011
J. Evslin, 2011
Villante and Vissani, 2011

Constraints

MDR n=2

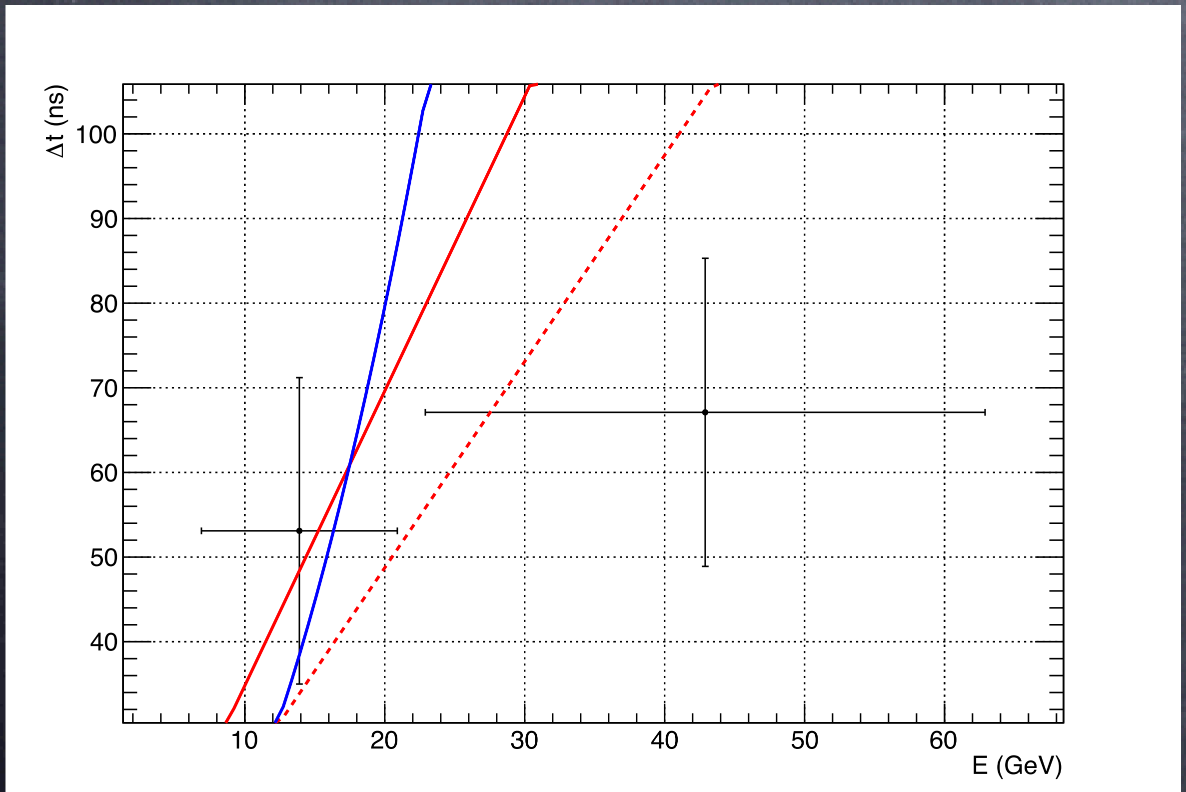
- Ruled out by SN1987 if flavour independent
- Ruled out by neutrino pair creation (Cohen-Glashow) at Opera energies
  - Note: this rules out n=2 even for flavor dependent LIV models with MDR only at Opera energies

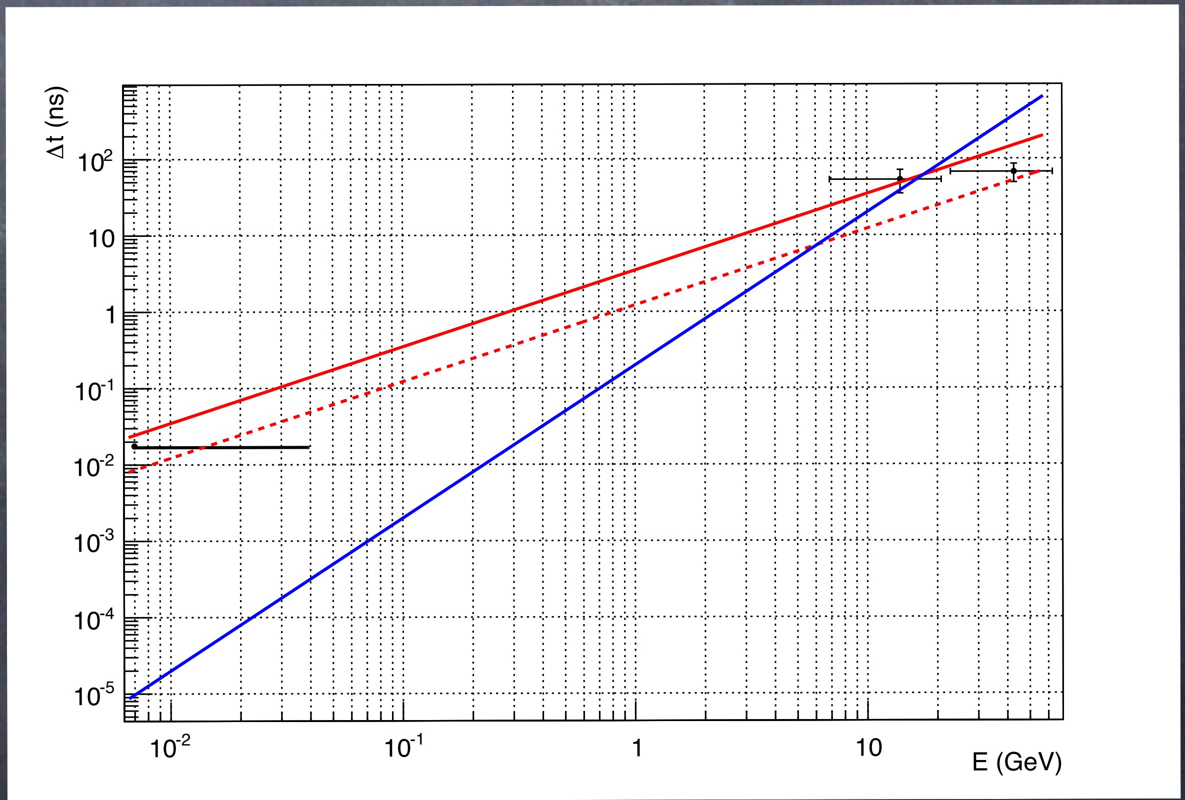
MDR n=3

- Compatible at 2σ with SN1987 and Opera with M~1000 TeV
- Ruled out by neutrino pair creation (Cohen-Glashow) at Opera energies and neutrino splitting by observation 100-400 TeV

MDR n=4

- Incompatible with the constraints on energy dependence of Opera.





Constraints

MDR n=2

- Ruled out by SN1987 if flavour independent
- Ruled out by neutrino pair creation (Cohen-Glashow) at Opera energies
  - Note: this rules out n=2 even for flavor dependent LIV models with MDR only at Opera energies

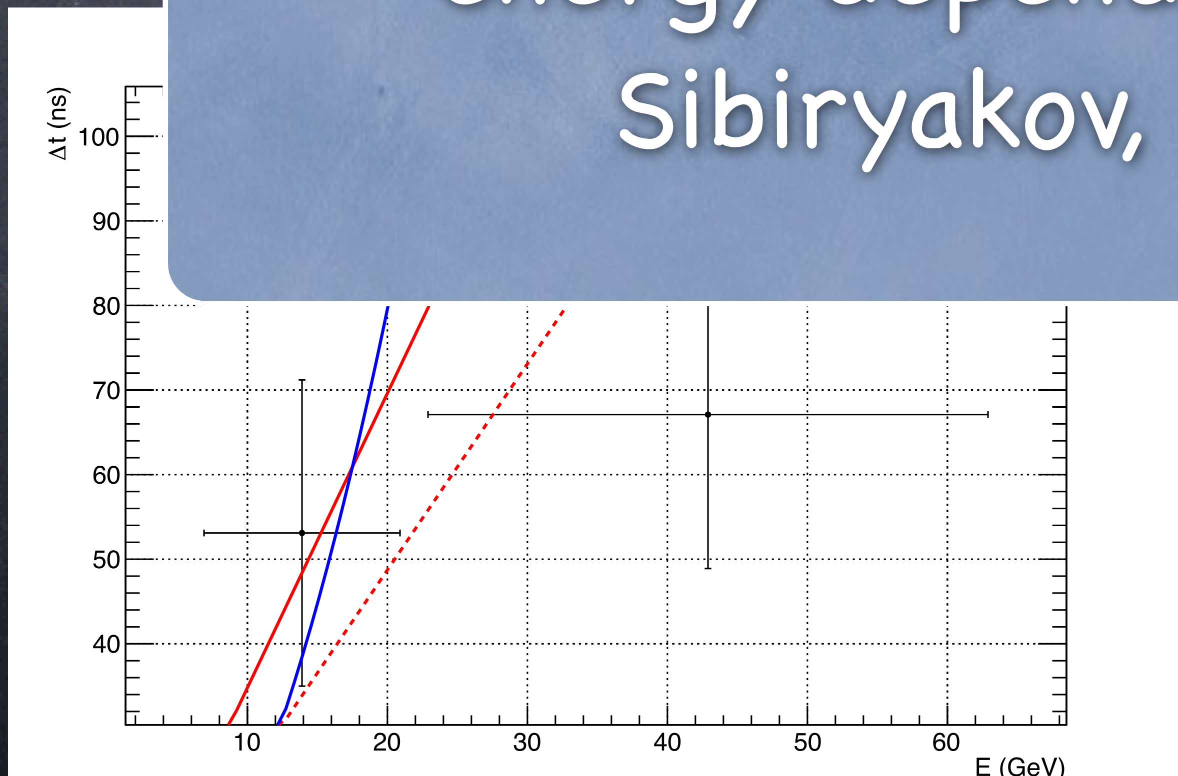
MDR n=3

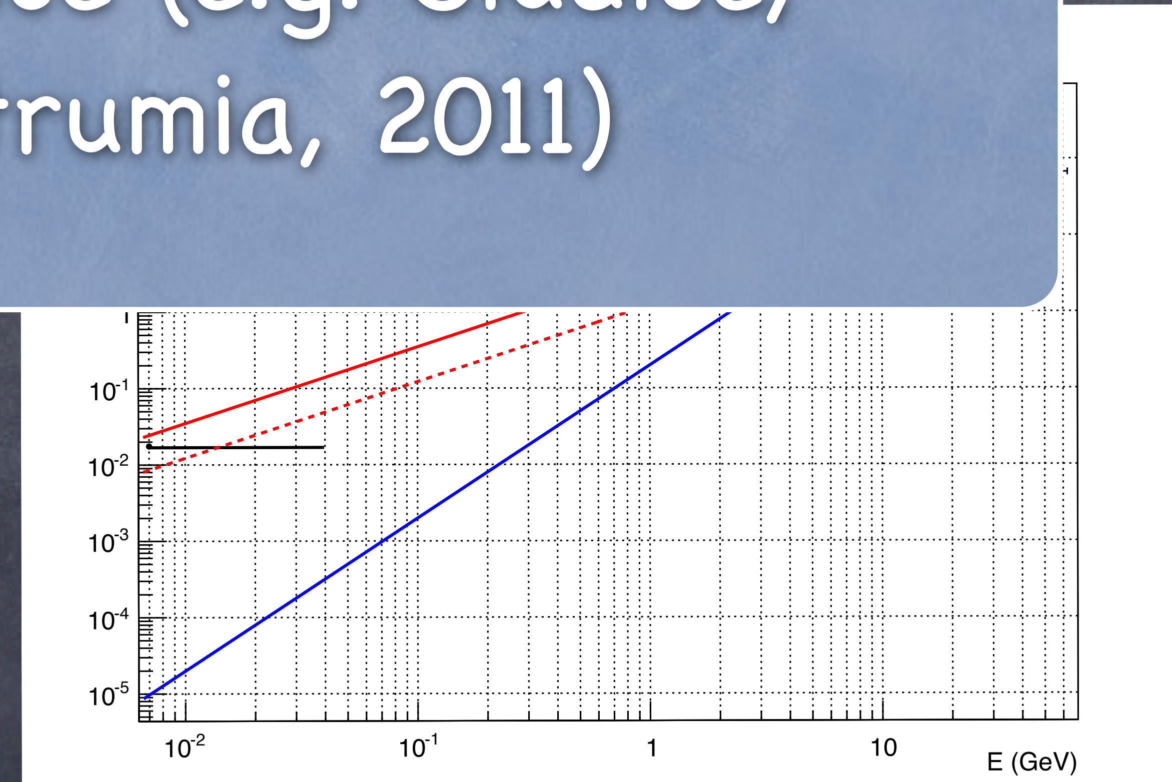
- Compatible at 2σ with SN1987 and Opera with M~1000 TeV

ies

MDR

Challenges also models with non-trivial energy dependence (e.g. Giudice, Sibiryakov, Strumia, 2011)





What about pion decay?

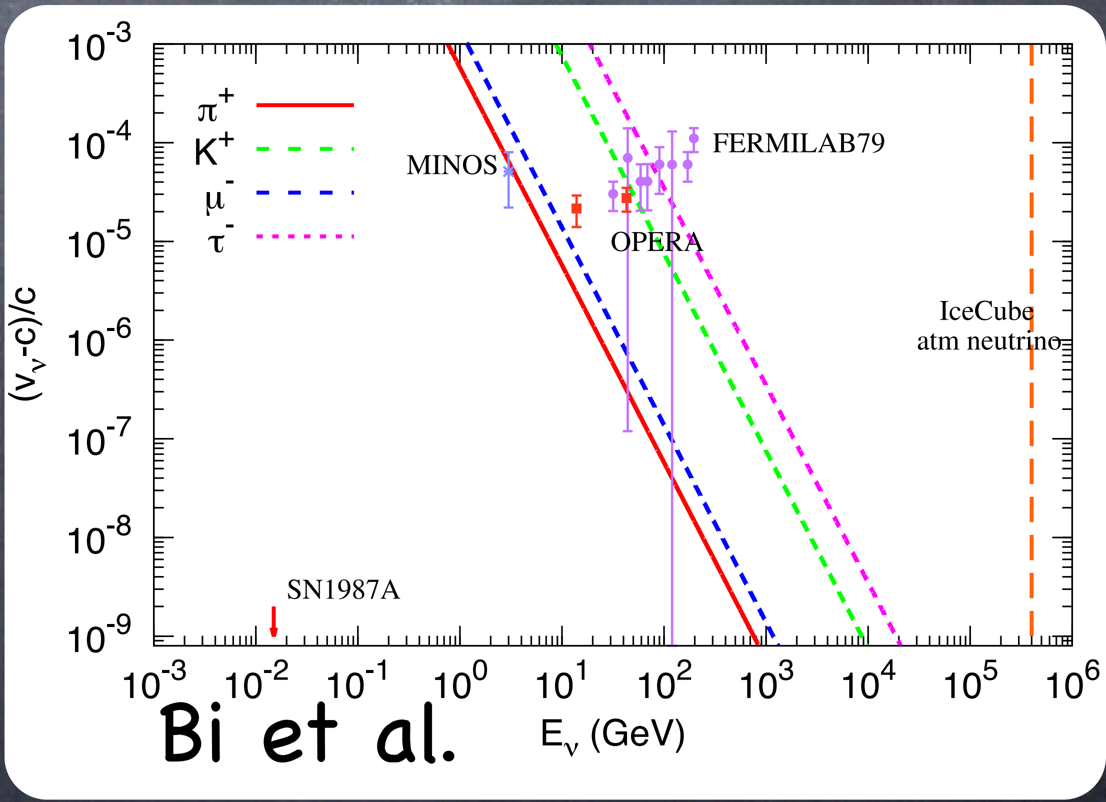
Gonzales-Mestres
Bi, Yin, Yu, Yuan
Klinkhamer, Altschul

Pion decay can be forbidden if LIV in neutrino sector

$$p_\nu^2 \leq m_\pi^2 (2\delta c(\nu))^{-1} \lesssim 20 \text{ GeV}$$ if LIV as required by OPERA

Assuming subluminal muons does not solve (due to spontaneous photon decay)

Assuming also LIV for the pion would solve the issue, but would bring LIV in the hadronic sector, triggering cosmic ray constraints:
- suppression of proton flux above ~700 GeV
- suppression of gamma-ray flux above ~1 TeV (due to proton-antiproton radiation)



Conclusions

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Measured something else

Did OPERA take into account the motion and geology of the Earth?

Clearly, the Earth is spinning so the target was not stationary. Moreover, the beam travelled underground.

Markus G. Kuhn

C. S. Unnikrishnan

R. A. J. van Elburg

Dominique Monderen

Jean-Paul Mbelek

Juan Manuel Garcia-Islas

Did OPERA synchronize the clocks properly?

How about the statistical analysis?

Dado & Dar: measured energy deposition effects in target: the progressive reduction in the target effective column density during the pulse reduces the neutrino production rate per incident proton. Efficiency of late protons is reduced --> mean neutrino production time is advanced. A 7% effect is enough to achieve 60 ns advance.

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Environmental effects

Dvali & Vikman

Most LIV tests/computations are done in vacuum,
but Opera neutrinos propagate in Earth (dense medium)

extra-field sourced (e.g.) by the Earth
- must have spin-2 $h_{\mu\nu}$
- must have non-universal coupling
- $10^{-10}\ \mathrm{M_{Pl}} < M_* < 10^{-6}\ \mathrm{M_{Pl}}$

Basically boils down to
bimetric theories
(J. Moffat, several papers)

However it does not
solve automatically
the CG problem
(check the couplings)

Deformed special relativity?

Amelino-Camelia, Freidel, Kowalski-Glikman, Smolin et al.
Huo, Li, Nanopoulos et al.

energy-momentum relations and conservation laws and Poincare' transformations get non-linear, in such a way that relativity of inertial frames is preserved

→

Hence stable particles cannot "decay" because of superluminality : threshold energy would be infinite

$$[\mathcal{N}_j, p_0^2 - \mathbf{p}^2 + \Delta(E, \mathbf{p}; M_*)] = 0 \, .$$

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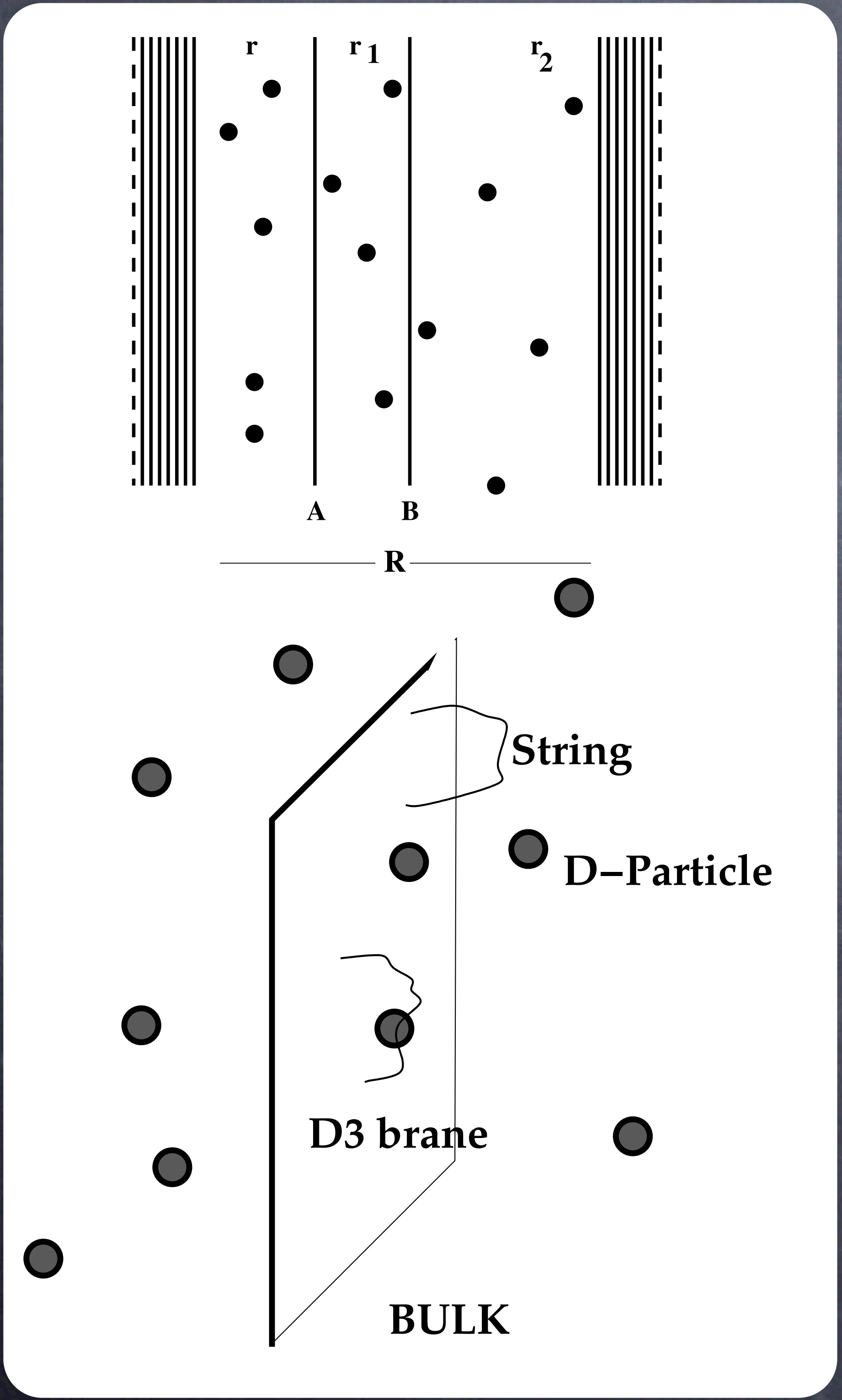
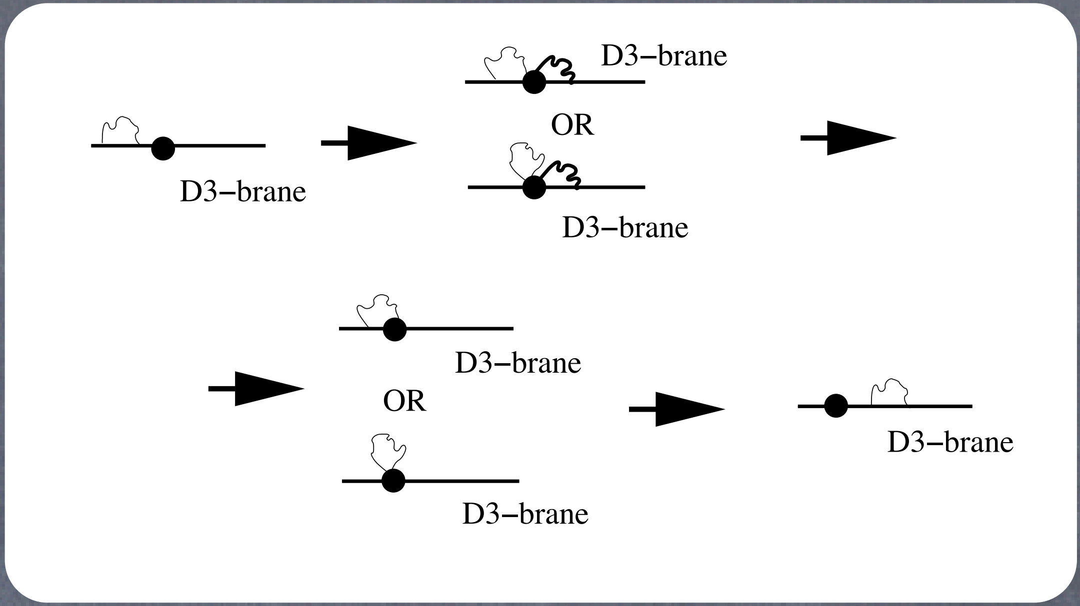
In this framework the CG effect is forbidden, yet neutrinos can be superluminal

String theory to rescue?

Ellis, Mavromatos, Li, Nanopoulos et al.





QG medium as oscillators that absorb and emit photons/neutrinos
Oscillators are D-particles flashing in the space-time

Photon/neutrino absorption and re-emission: D-particles and photons form a compound state that stretches in between D3-branes and D-particles, and eventually decays. The D-particle recoils
D-particles are neutral: charged particles do not feel their presence.

Adding specific derivative couplings to background (axial) vectors leads to superluminal propagation

$$\frac{1}{M^{n-1}}\overline{\psi}(i\vec{D}_5 \cdot \vec{\gamma})^n \psi \qquad n \geq 2,$$

Can apparent superluminal neutrino speeds be explained as a quantum weak measurement?

M V Berry[1], N Brunner[1], S Popescu[1] & P Shukla[2]

[1]H H Wills Physics Laboratory, Tyndall Avenue, Bristol BS8 1TL, UK

[2] Department of Physics, Indian Institute of Technology, Kharagpur, India

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Abstract

Probably not.

Way out of the puzzle?

Way out of the puzzle?

?

Way out of the puzzle?

As theorists, we know that if the experimental result will be confirmed experimentally, we will have no other way than rethinking the fundaments of our theories

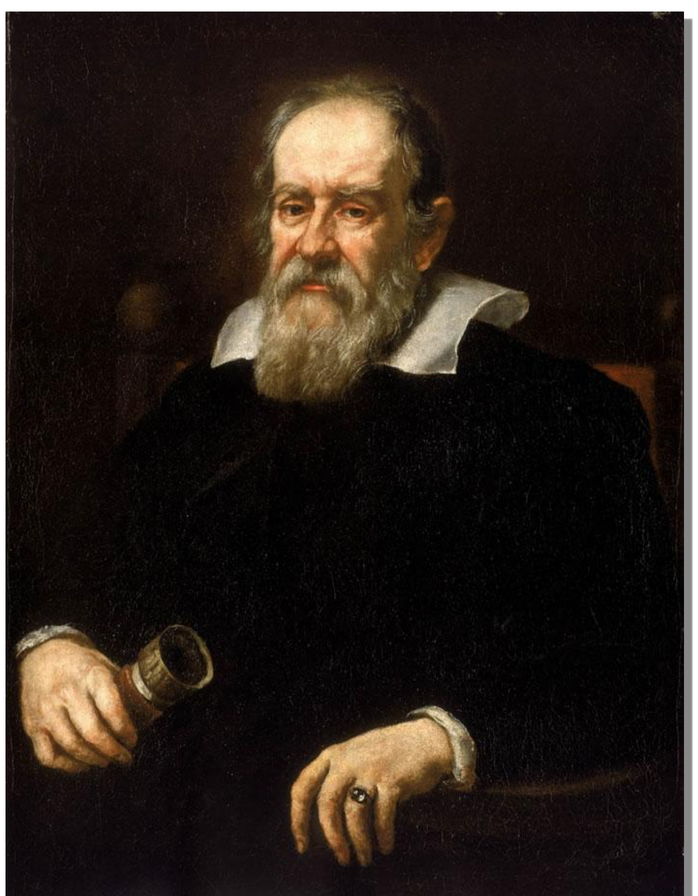
How?

- Study bimetric theories (and Finsler geometry and so on...)
- Study deformed special relativity
- String theory?
- Go for preferred frame, but find some smart way to avoid the CG effect
- ....

Galileo gave a course of three lectures in Padua upon SN 1604 to a great audience. The main point he brought out concerning the new star was that it upset the received Aristotelian doctrine of the immutability of the heavens.

"Che ha a che fare la filosofia col misurare? Che importa al matematico se il cielo sia corruttibile e generabile? Se anche la nuova stella fosse di polenta, chi vieta ai matematici di osservarla e misurarla? Canchero, l'ha avuto torto questa stella a rovinare così la filosofia di costoro"

G. Galilei, Dialogo de Cecco Ronchitti da Bruzene in perpuosito de la Stella Nuova

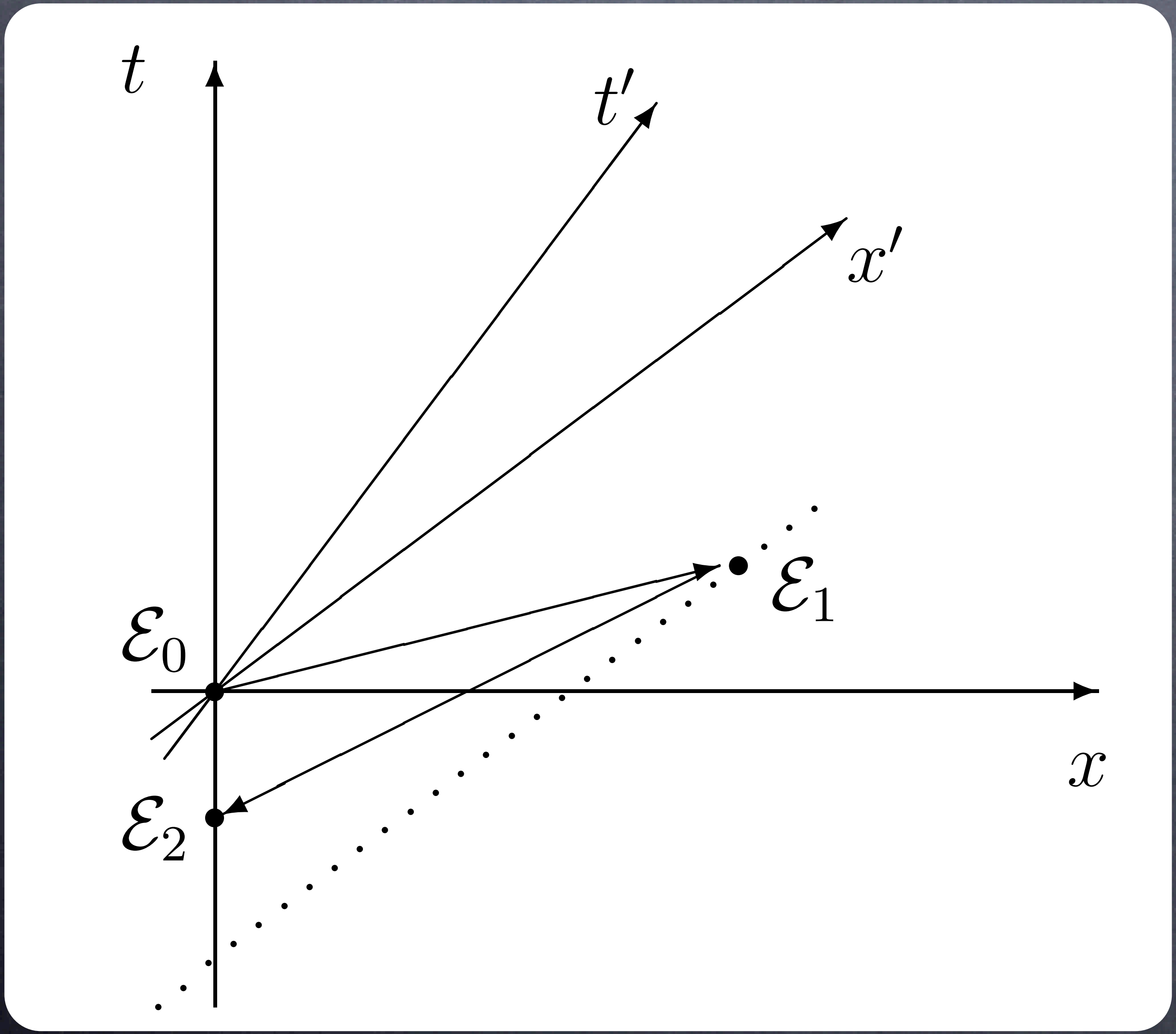


courtesy, A. Mirizzi

Backup

Superluminal propagation and time machines

Liberati, Sonego, Visser, 2001



At 0 a tachyon is sent to 1. In the primed reference frame t1 < t0. Now 1 sends back a tachyon to 0. This tachyon will arrive at 2, where t2 < t0.

However, to cause a trouble, tachyons must be able to travel backward in time in arbitrary reference frames. No trouble if in ONE reference frame there are tachyons moving only forward in time. This picks out a preferred reference frame.