Lorentz violations of cosmic particles from string theory model of space-time foam

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with Prof. MA Bo-Qiang (Peking Univ.)

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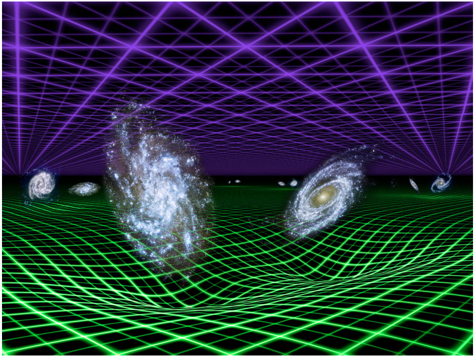
In a century from 1905



Einstein theory of time, space (SR) & gravity (GR)

Einstein theory of relativity

- relativistic principle
- constant speed of light

  <u>Lorentz symmetry as a foundation</u>

★ Triumphs of relativity

★ Whether it works at <u>every</u> scales

1. lengths $\lesssim 10^{-4}$ m $\to$ UV
2. beyond Solar system $\to$ IR

grand unification? Einstein's dream

Hints for a failure of exact Lorentz symmetry ?

- Noncompact group, QFT UV divergences, etc.
- Possible deformation (or reduction), and/or violation of Lorentz invariance (LV) within many well-motivated models for new physics beyond relativity

say, Quantum Gravity (QG)

- Dirac's new æther [Dirac'51]
- Wheeler's foam ($\delta\mathcal{E} \sim \hbar/\delta t$) [Wheeler'55, Hawking'78]

→ *foaminess ↔ quantum fluctuation of geometries ↔ "space-time foam"*

$$\delta g \sim \left(\frac{\ell_{\rm Pl}}{\ell}\right)^{\alpha} \sim \mathcal{O}(1) \text{ as } \ell \sim \ell_{\rm Pl}$$

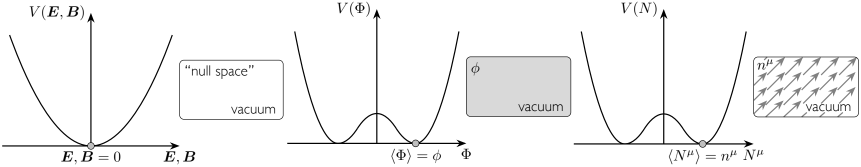
Wheeler's $\alpha = 1$, also for D-foam, holographic foam $\alpha = \frac{2}{3}$, random-walk $\alpha = \frac{1}{3}$, etc.

- QG with minimal length [Garay'95 IJMPA, see also Shao, Ma'11 SCPMA]
- discrete space-time ? (from entropy bounds) [Xu, Ma'11 MPLA]

$$\delta t \sim \delta\ell \geq \left(\frac{128}{3645\pi}\right)^{\frac{1}{2}} \ell_{\rm Pl} \simeq 0.1\ell_{\rm Pl}$$

Lorentz noninvariance [model-dep.]

- Lorentz-invariance violation from **strings** - **SLSB** by QG vacua
  - ∗ Tensor condensate in bosonic open-string field theory [Kostelecký, Samuel'89 PRD]



→ *effective target-space LV field theory - standard-model extension (SME)*
[Colladay, Kostelecký'97, 98 PRD, Myers, Pospelov'03 PRL]

$$\mathcal{L}_{\text{SM}} + \delta^{\text{LV}}\mathcal{L} \supset \delta^{\text{LV}}\mathcal{L}_\gamma^{\text{5d}} = -\frac{\xi}{M_{\text{Pl}}} n^\mu F_{\mu\sigma} n_\nu n\cdot\partial \widetilde{F}^{\nu\sigma} \quad \Rightarrow \quad \mathcal{E}^2 = \mathbf{k}^2 \pm \frac{2\xi}{M_{\text{Pl}}}\mathcal{E}^2|\mathbf{k}|$$

  - ∗ Gravitational defects from noncritical strings [Ellis+'92 PLB, Amelino-Camelia+'97 IJMPA]

$$\mathcal{S}_0 + \mathcal{S}_L\Big(\sim \int_\Sigma [(\pm)(\partial\phi)^2 - \mathcal{Q}\phi\mathcal{R}_{(2)}]\Big) + \int_\Sigma \sqrt{\widehat{\gamma}} g_L^i(\phi)\, V_i \quad \Rightarrow \quad \mathcal{E} \sim |\mathbf{k}| + \rho\mathbf{k}^2/M_{\text{Pl}}$$

→ *D-brane LV models of string cosmology - "stringy space-time (D-)foam"*

Lorentz noninvariance [model-indep.]

- Assume a Modified particle Dispersion Relation (MDR) w.r.t. $\mathcal{E}^2 = p^2 + m^2$

  e.g., photon (or ultrarelativistic neutrino)

$$\mathcal{E}^2 \simeq \mathbf{p}^2 - s_n \mathcal{E}^2 \left(\frac{|\mathbf{p}|}{E_{\mathrm{LV},n}} \right)^n \longrightarrow v = \frac{\partial \mathcal{E}}{\partial |\mathbf{p}|} \simeq 1 - s_n \frac{1+n}{2} \left(\frac{\mathcal{E}}{E_{\mathrm{LV},n}} \right)^n$$

- it gives birth to Quantum-Gravity (QG) Phenomenology via LVs [See Shao, Ma'10 MPLA, for a review]

1. *vacuum dispersion & birefringence (via long-baseline exp.s)*
2. *anomalous/peculiar threshold reactions*
3. *shifting of existing thresholds, etc.*

…but, suppressed by $E_{\mathrm{LV}} \sim \mathcal{O}(M_{\mathrm{Pl}})$ v.s. $\Lambda_{\mathrm{EW}}/M_{\mathrm{Pl}} \sim 10^{-16}$

[recall Bo-Qiang Ma's talk yesterday]

(LHC will probe Λ_{EW})

Can one see quantum gravity/space-time effect in the sky ?

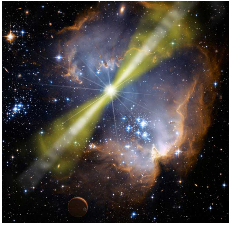
say, travel times affected by LV$_{n=1}$, $t_{\rm LV} = K_1 \dfrac{(1+z)s}{E_{\rm LV}} = t_o - (1+z)t_s$ (t_s - source-intrinsic lag)

$$K_1(z) = \frac{\mathcal{E}_h - \mathcal{E}_l}{(1+z)H_0} \int_0^z \frac{(1+\mathcal{Z})\mathrm{d}\mathcal{Z}}{\sqrt{\Omega_\Lambda + \Omega_{\rm M}(1+\mathcal{Z})^3}}$$

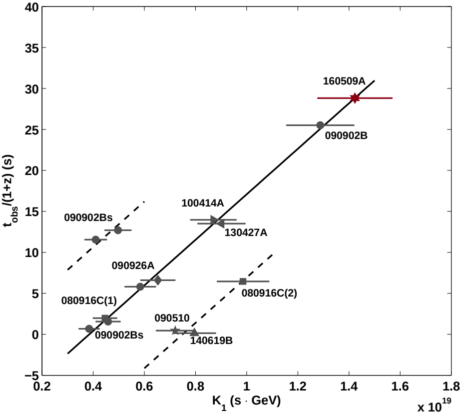
[Jacob, Piran'08 JCAP in ΛCDM, see also Zhu, Ma'22 PRD, for a derivation in Finsler cosmology]

luckily, astrophysics by means of (multi)messengers play a leading role in making that job e.g., energetic signal from cosmologically remote objects [Amelino-Camelia+, Nature393 (1998)]

bright Gamma-Ray Burst (GRB) v.s. *Active Galactic Nucleus (AGN)*



Light-speed variation in cosmic photons



[Xu, Ma'16 PLB, see also He, Ma'22 Universe, for a review on this suggestion]

- uncertainties: intrinsic lags $\mathcal{O}$(sec)

Analysis on FERMI multi-GeV data

- GRB γ time delay suggests:
  - ★ **light-speed variation**

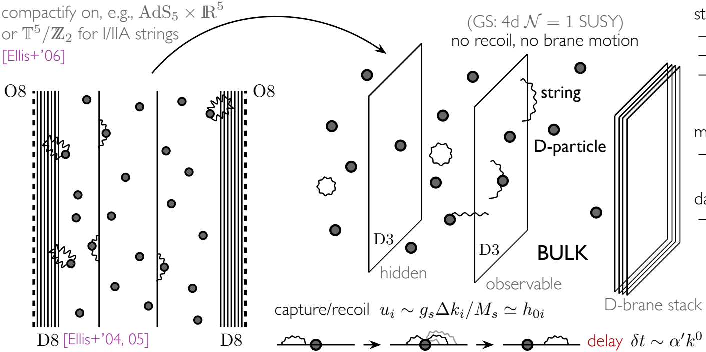
$$v_\gamma(\mathcal{E}) = 1 - \mathcal{E}/E_{\mathrm{LV}(\gamma)}$$

with $E_{\mathrm{LV}} \gtrsim 3.6 \times 10^{17}$ GeV
[Shao, Xiao, Ma'10, Zhang, Ma'15, Xu, Ma'16 APP]

- re-examination
  1. *"too rare to be accidental!"*
  [Amelino-Camelia+'17 Nature Astron.]
  2. *statistical significance 3-5σ*
  [Xu, Ma'18 JCAP, Liu, Ma'18 EPJC]
  3. *supports from AGNs & others*
  [Li, Ma'20 Sci. Bull., Zhu, Ma'21 PLB]

quantum space-time property, or just mimic?

D-brane/string inspired space-time foam



delay $\delta t \sim \alpha' k^0$ [Seiberg+'99, 00; Ellis+'08]

string/D-foam cosmology:
- dark energy budget
- inflation/early universe
- large-scale structure formation [Elghozi+'16; Mavromatos+'12, 13]

modified gravity:
- relativistic MOND (TeVeS-like models)

dark matter:
- sterile neutrino mass generation [Ellis+'19]
  $\Rightarrow$ tiny SM neutrino mass through seesaw [Mavromatos+'11, 17]

$$c_g \simeq 1 - 2g_s \frac{\zeta_D |\mathbf{k}|}{M_s} \simeq 1 - \mathcal{O}\left(\frac{n_D \mathcal{E}}{M_D}\right) \quad \xleftrightarrow[\text{refractive index}]{\zeta_D \,=\, \langle\!\langle \frac{\Delta k}{k} \rangle\!\rangle \,\geq\, 0} \quad \eta_{\mathrm{vac}(\gamma)} = 1 + \mathcal{O}\left(\sqrt{\alpha'}\zeta_D |\mathbf{k}|\right) \geq 1, \quad M_D = 1/(g_s\sqrt{\alpha'})$$

(a) $\delta c_g := \lvert c_g - 1\rvert$ scales linearly with energy	(c) photons are stable (i.e., do not decay away)
(b) subluminal refractive index $\eta_{\mathrm{vac}(\gamma)} - 1 > 0$	(d) helicity-blind/nonbirefringent foam vacuum

[**CL**, Ma, PLB 819(2021)136443, see also Results Phys. 26(2021)104380]

Recoil distortion & time delay

- Models with (type I/IIA) 0-brane [Ellis+'99, 00 PRD, Ellis+'04 PRD]
  - ∗ Deformed σ model for recoiling D-brane [Ellis+'98 IJMPA, Mavromatos, Szabo'99 PRD]
    - *impulse operator (of LCFT)* $V = \int_{\partial\Sigma} \epsilon u_i X^0 \Theta_\epsilon(X^0)\partial_n X^i \quad \Theta_{\epsilon\to 0^+}(t) := \frac{1}{\imath}\int_{-\infty}^{\infty} \frac{\mathrm{d}q}{q - \imath\epsilon}\mathrm{e}^{\imath q t}$
    - *dressing of Liouville to restore conformality (criticality)*

$$V^L \sim \int_\Sigma \mathrm{e}^{\alpha^L \phi(z,\bar{z})} \varepsilon_{\alpha\beta}\partial^\beta(\epsilon u_i X^0 \Theta_\epsilon(X^0)\partial^\alpha X^i) \supset -\epsilon^2 u_i \int_\Sigma \mathrm{e}^{\epsilon(\phi - X^0)} X^0 \Theta(X^0)\partial_\beta\phi\partial^\beta X^i$$

→ "foam-like" Finsler metrics $g_{0i}(X^0, u_i) \sim u_i\epsilon^2 X^0\Theta(X^0) \sim u_i \sim \zeta k_i/M_D \ (\zeta < 1)$

$$\mathbf{k}^2 - \mathcal{E}^2 \simeq 2\zeta_D g_s \ell_s \mathcal{E}\mathbf{k}^2 \quad \text{for} \quad \langle\langle u_i \rangle\rangle \neq 0 \quad \text{(anisotropic foam)}$$

  - ∗ Microscopic modeling of recoil/capture [Seiberg, Witten'99 JHEP, Susskind+'00 JHEP, Ellis+'08 PLB]

$$\delta t \sim \alpha' k^0/(1 - \mathbf{u}^2) \sim \mathcal{E}\alpha' \quad \text{as} \quad |u_i| \ll 1 \longrightarrow \text{reduced-Lorentz symmetry}$$

- IIB (super)string model with wrapped 3-brane [Li+'09 PLB, Li, Nanopoulos'12 EPJC]

$$\mathcal{A}_{\text{scat}} \ \text{comput} \longrightarrow \delta t \sim \mathcal{E}\ell_s^2$$

Light-speed variation in a D-foam

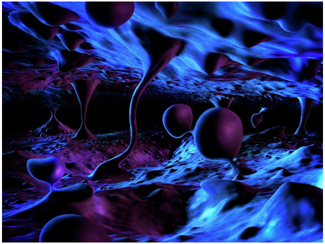
- D-particle foam as a (stringy) origin for <u>subluminal</u> LV$_\gamma$

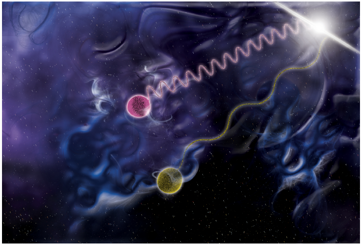
  e.g., constraint to QG-foam parameter/scale [**CL**, Ma 2105.06151 (**PLB**)]

$$\frac{\zeta_D g_s}{M_s} \simeq \frac{1}{2E_{\rm LV}} \lesssim 1.4 \times 10^{-18}\ {\rm GeV}^{-1}$$

$$M_s \gtrsim 7.2 \times 10^{26} \zeta_D g_s\ {\rm eV} \gtrsim \mathcal{O}({\rm TeV})$$

→ *light-speed variation of GRB/AGN, if plausible, supports stringy D(efect)-foam*





photons travel through "foamy space-time" at different speeds!
[Credit: Mark Garlick'16(left), NASA/Sonoma State Univ., Aurore Simonnet(right)]

Escaping from other tight bounds

- (i) Lorentz violating γ-decay, $\gamma \to ee^+$

  very-high-energy (VHE; $\mathcal{E} \gtrsim$ 0.1 TeV) γ-ray bounds superluminal LV$_\gamma$

  * Crab Nebula 50-80 TeV-γ: $E_{\rm LV} \gtrsim 10^{20}$ GeV [Martínez-Huerta, Peŕez-Lorenzana'17 PRD]
  * HAWC $\sim$ 100 TeV photons: $E_{\rm LV} > 2.2 \times 10^{22}$ GeV [Albert+(HAWC)'20 PRL]
  * Tibet ASγ Galactic γ-rays up to 957($^{+166}_{-141}$) TeV [Amenomori+(Tibet ASγ)'21 PRL]

$$E_{\rm LV}^{(\text{sup})} \gtrsim \mathcal{E}^3/(4m_e^2) \sim 8 \times 10^{23}\ \text{GeV}$$

  (ii) Vacuum birefringence - $\mathcal{O}(10^{11}) \times \gamma$-decay limit $\sim E_{\rm LV}^{(\text{bire})}$ for birefringent LV$_\gamma$

→ *complementary support to string/D-brane foam scenario* [**CL**, Ma'21 PLB & Results Phys.]

$$\underbrace{M_{\rm Pl} \ll E_{\rm LV}^{(\text{sup})}, E_{\rm LV}^{(\text{bire})}}_{\text{natural with D-foam}} \not\mapsto \frac{M_D}{\zeta_D}\ (\zeta_D > 0 \text{ for } \gamma_{R,L})$$

- Future improvements with HAWC, Tibet ASγ & **LHAASO**!!

Large High Altitude Air Shower Observatory

- China's 3G mountain observatory - LHAASO [See Cao'21 Nature Astron., Cao+'22 CPC, for LHAASO's objectives]

an ultrahigh-energy (UHE) cosmic-/γ-ray "hunter" set on Tibetan Plateau!

[Credit: Institute of High Energy Physics/Chinese Academy of Sciences (IHEP/CAS)]

How to receive messengers from the sky?

[Credit: IHEP/CAS]

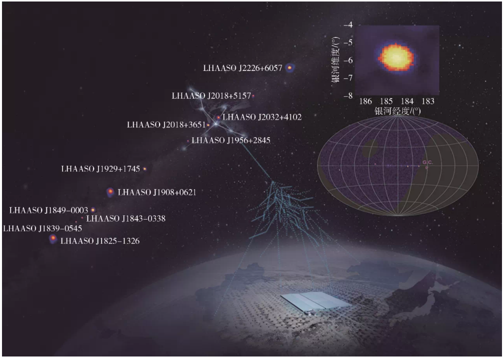
3 major components of LHAASO

Opening the UHE γ window

- Capture the *most-energetic* γ evt from the Cosmos! [Cao+(LHAASO), Nature594 (2021)]

  [See also **CL**, Ma, Sci. Bull. 66(2021)2254,
  for news & views, **李成翊**, **马伯强**, **现代物理知识**, 2022.34(1), p.33-37 (**科普**)]

Breakthrough discovery via LHAASO-KM2A



[Credit: LHAASO collab'21]

First results of LHAASO:

12 PeVatrons

- high significance $> 7\sigma$
- BG-free: CR BG rejection rate 10^{-5}
- large statistics: 530 UHE photons

★ LHAASO J2032+4102:

$$\mathcal{E}_{\text{max}} = 1.42 \pm 0.13 \text{ PeV}$$

the highest-energy γ ever observed!

- multiple types of candidates

[Cao+(LHAASO)'21 Nature]

the Universe (incl. the Milky Way) is full of PeVatrons!

Implications for γ Lorentz violation

- Probing LV$_\gamma$ via LHAASO PeV photon [**CL**, Ma, PRD 104(2021)063012]
  - *stringent constraint on γ self-decay due to superluminal LV$_\gamma$*
  - *support for threshold anomaly of $\gamma\gamma_{\rm b} \to ee^+$ induced by subluminal LV$_\gamma$*

active star-forming region of the Cygnus (?) [$d_{\rm Cy} \sim 2$ kpc *v.s.* $\bar{\lambda}_{\gamma\gamma_{\rm b}}({\rm PeV}) \sim 10$ kpc]

[LHAASO J2032+4102]

$\gamma\,({\rm PeV})$ $\dashrightarrow$ ee^+ $\xrightarrow{\text{if } \gamma \text{ decays}}$ (expected) spectral cutoff above $\mathcal{E} \simeq \left(4m_e^2 E_{\rm LV}^{\rm (sup)}\right)^{1/3}$

cosmic space

$\gamma_{\rm CMB}({\rm meV})$

$4\mathcal{E}\bar{\varepsilon}_{\rm CMB} \approx (2m_e)^2$

$\mathcal{E} \sim 4 \times 10^{14}$ eV

ee^+ in Special Relativity (SR)

no γ-decay !

LV threshold anomaly/shifting:

$$\varepsilon_{\rm b,thre} = \frac{m_e^2}{\mathcal{E}} + \boxed{\frac{1/4\,\mathcal{E}^2}{E^{\rm (sub)}_{\rm LV(\gamma)}}}$$

$\mathcal{E}_{\rm crit} = (2m_e^2 E_{\rm LV})^{1/3} \sim 6$ TeV $\longrightarrow$ for $\varepsilon^{\rm min}_{\rm b,thre}(\mathcal{E}_{\rm crit}) \gg \bar{\varepsilon}_{\rm CMB}$

observable 1.4 PeV LHAASO-γ !!

with subluminal LV$_\gamma$

The Universe is more transparent than that in SR ?!

[See also **CL**, Ma 2109.07794 (**Sci. Bull.**)]

- **Photon stability** against decay, $\gamma \to ee^+$

HAWC ∼ 100 TeV $E_{\mathrm{LV}\gamma} \gtrsim 2.2 \times 10^{22}$ GeV [Albert+(HAWC)'20 PRL]

Tibet ASγ up to sub-PeV scales $E_{\mathrm{LV}\gamma} \geq 8 \times 10^{23}$ GeV [**CL**, Ma 2105.06151 (**PLB**)]

LHAASO 1.4 PeV evt (yielding strongest bound ever reported) [**CL**, Ma 2105.07967 (**PRD**)]

$$E_{\mathrm{LV}\gamma}^{(\text{sup})} \gtrsim 9.57 \times 10^{32} \left(\frac{\mathcal{E}}{\mathrm{PeV}}\right)^3 \mathrm{eV} \approx 2.74 \times 10^{24}\ \mathrm{GeV}$$

→ *severely limits, e.g., SME* $[\xi \ll \mathcal{O}(1)]$ *v.s. supports string/D-brane foam !*

- **Necessity to modify $\gamma\gamma_{\mathrm{b}} \to ee^+$ kinematics ?** [**CL**, Ma'21 PRD]

$\gamma\gamma_{\mathrm{b}}$ threshold anomaly "protects" above-threshold photons of LHAASO !

sources: galactic or extragalactic ??

→ *extragalactic PeV γ as crucial test of subluminal LV$_\gamma$*

any observed γ of $\gtrsim$ 0.4 PeV from outside of our galaxy as signal for new physics !

[Li, Ma'21 JHEAp, 23 APP + EPJC, Wang, Ma'23 PRD: **new supports of either LV or Axion** by GRB221009A]

"optical transparency" - $E_{\mathrm{LV}\gamma}^{(\text{sub})} \lesssim \mathcal{O}(10^{23}\ \mathrm{GeV})$ **[Luohan Wang's talk]**

Petaelectronvolt γ from the "Standard Candle"

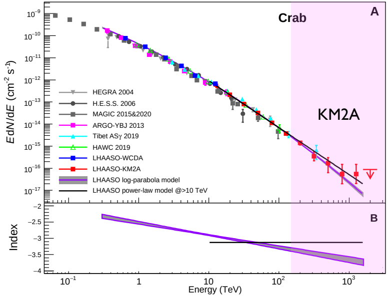
- Highest-energy messengers yet arrive from ancient Crab Nebula !

LHAASO measurement [Cao+(LHAASO), Science373 (2021) July 8th]

- *unique UHE SED; a PeVatron without ambiguity*
- *clear origin - a well-known Pulsar Wind Nebula (PWN)*
- *<u>record-breaking</u> Crab γ ($\gtrsim$ 100 TeV since 2019!)*

$$\mathcal{E}^{\rm Crab}_{\rm max} = \boxed{1.12} \pm 0.09 \; \boxed{\rm PeV}$$

remnant of SN explosion ("guest star") witnessed in 1054 AD



[Credit: NASA, ESA, NRAO/AUI/NSF, Buenos Aires Univ.(left), LHAASO collab'21(right)]

Does electron (or, its antiparticle counterpart) have nontrivial properties *in vacuo*?

say, it possesses a modified canonical dispersion relation [**CL**, Ma, PLB 829(2022)137034]

$$\mathcal{E}_e^2 = m_e^2 + \mathbf{p}_e^2\big(1+\delta_e^{(2)}\big) - s_{e,n}\mathcal{E}_e^2\left(\frac{|\mathbf{p}_e|}{E_{\mathrm{LV}e,n}}\right)^n \quad |\delta_e|^{\text{LEP}} \lesssim 10^{-15}$$ [Altschul'10 PRD]

so vacuum Čerenkov (VČ) effect by charged leptons, if being superluminal, occurs (e.g., efficient decay via VČ of electron/positron, $e \to e\gamma$) [Jacobson+'04 PRL]

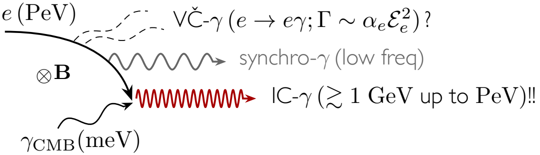
→ *electron of some high $\mathcal{E}_e$ is no longer stable in a vacuum!*

Stability against IC Čerenkov effect

→ *Crab Nebula as an ideal laboratory for constraining, or even ruling out LV_e*

- Assume an electronic origin (*synchro* + *inverse-Compton (IC)*) inside the nebula

no $e^{\mp}$ Čerenkov !



- **IC Čerenkov bound**

50 TeV photons $\quad E_{\mathrm{LV}e} \gtrsim 10^{21}$ GeV

HEGRA up to ~ 75 TeV $\quad$ strengthened by $(3/2)^3 \approx 3$

Tibet ASγ up to ~ 450 TeV (near-PeV $e^{\mp}$ is inferred) $\quad$ [**CL**, Ma 2204.02956]

$$E_{\mathrm{LV}e}^{(\mathrm{sup})} > 2\mathcal{E}_e^3/m_e^2 \sim 7 \times 10^{23}\ \mathrm{GeV}$$

Stability against IC Čerenkov effect

→ *Crab Nebula as an ideal laboratory for constraining, or even ruling out* LV_e

- **IC Čerenkov bound** via LHAASO [**CL**, Ma 2204.02956 (**PLB**)]

$$E_{\mathrm{LV}e}^{(\mathrm{sup})} \gtrsim 7.21 \times 10^{25} \left(\frac{\mathcal{E}^{\mathrm{Crab}}}{\mathrm{PeV}}\right)^{2.38} \mathrm{GeV} \sim 9.4 \times 10^{25}\ \mathrm{GeV}\ (\text{improved by} \gtrsim 10^4)$$

$$\geq \boxed{(7.7 \times 10^6)} \times M_{\mathrm{Pl}} \sim \mathcal{O}(10^{35}\ \mathrm{eV})$$

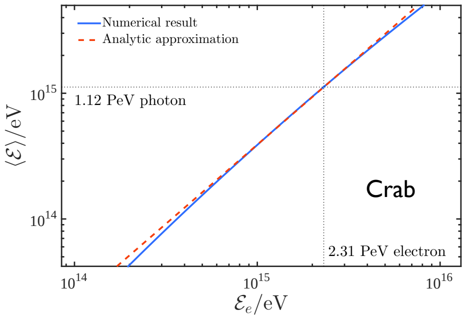
it severely limits, e.g., SME $\eta \ll \mathcal{O}(1)$

$$\delta^{\mathrm{LV}}\mathcal{L}_{\mathrm{QED}} \supset \frac{1}{M_{\mathrm{Pl}}} \overline{\psi}(\chi_1 \not{n} + \chi_2 \not{n}\gamma_5)(n \cdot \partial)^2 \psi$$

with $2(\chi_1 \pm \chi_2) =: \eta_{R/L} \lesssim 1.3 \times 10^{-7}$

[See also He, Ma'22 PLB, for a joint analy for param plane]

IC electron $\mathcal{E}_e/\mathrm{eV} \simeq 2.11(\mathcal{E}/\mathrm{PeV})^{0.79} \times 10^{15}$



Crab radiation & Quantum Gravity

- **Synchrotron constraint** [Jacobson+'03 Nature]

  critical freq $\omega_c = 3|e\mathbf{B}|\mathcal{E}_e^2/(2m_e^3)$ affected by subluminal LV$_e$

$$\omega_o \sim \mathcal{O}(.1\ \mathrm{GeV}) \lesssim \omega_c \leq \frac{5^{5/6}}{9\sqrt[3]{2}}\frac{|e\mathbf{B}|}{m_e}\left(m_e/E_{\mathrm{LVe}}^{(\mathrm{sub})}\right)^{-\frac{2}{3}} \qquad \boxed{E_{\mathrm{LVe}} \gtrsim 10^{24}\ \mathrm{GeV}}$$

maximal at $\mathcal{E}_e = (2m_e^2 E_{\mathrm{LVe}}/5)^{1/3}$ [Maccione+'07 JCAP]

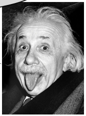
- Pheno preferred LV-feature$_{\mathrm{QED}}$

1. *In vacuo γ speed variation (as catalyzed by D-foam)*
2. *No electron/positron LV below Planck*

→ LV$_e$ may not be permitted by nature ?

[**CL**, Ma 2204.02956 (Phys. Lett. B)]

No $e^{\mp}$ Lorentz violation ?!



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$$\omega_o \sim \mathcal{O}(.1\ \mathrm{GeV}) \lesssim \omega_c \leq \frac{5^{5/6}}{9\sqrt[3]{2}}\frac{|e\mathbf{B}|}{m_e}\left(m_e/E^{(\text{sub})}_{\mathrm{LVe}}\right)^{-\frac{2}{3}} \qquad \boxed{E_{\mathrm{LVe}} \gtrsim 10^{24}\ \mathrm{GeV}}$$

- Pheno preferred LV-feature$_{\text{QED}}$
- **Crab discriminates between models of QG ?** [CL, Ma'22 PLB]

  * D-foam transparency to charged fields ! *D-particle: no "hair" - (electric) neutrality*

$$S_{\text{endpoint}} = \int_{\partial\Sigma} \mathrm{d}\tau A_a(X)(\mathrm{d}X^a/\mathrm{d}\tau)$$

[*"such a cutting is not allowed, due to charge conservation ($U(1)_{em}$ gauge inv.)"*, Ellis+'04 APP, Nature, IJMPA]

  - *no (tree-level) effect on probes carrying conserved charges (say, electric, or color flux)*
  - $e^{\mp}$ *has usual in-vacuo behavior* → evasion of any limit from soft/hard VČ

CPT violation in cosmic neutrinos

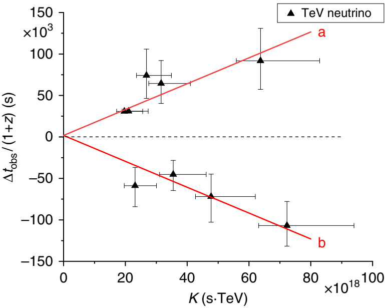
Analysis on IceCube TeV & PeV data [Huang, Ma'18 Commun. Phys.]

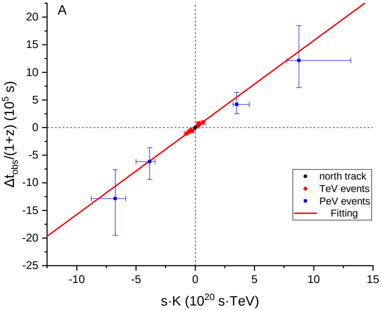
- association of ν evts with GRBs (<u>delay</u> + <u>advance</u>):

  ★ **neutrino-speed variation**

$$v_\nu(\mathcal{E}_\nu) = 1 \mp \mathcal{E}_\nu / E_{\mathrm{LV}\nu} \qquad E_{\mathrm{LV}\nu} \sim 6 \times 10^{17}\ \mathrm{GeV}$$

- additional supports [Huang, Li, Ma'19 PRD, see also Huang, Ma'22 Fund. Res.]





CPT breaking neutrino from strings

- Asymmetric $\nu/\overline{\nu}$-dispersion due to D-foam [**CL**, Ma, PLB 835(2022)137543]
  - isotropic $\langle\langle \frac{\Delta k}{k} \rangle\rangle = \langle\langle \zeta \rangle\rangle = 0$; but stochastic $\langle\langle \zeta^2 \rangle\rangle =: \mathring{\zeta}_D^2 < 1$ [Mavromatos, Sarkar'05 PRD]

$$\mathcal{E}_\nu(\mathbf{k}) = \sqrt{\mathbf{k}^2 + m_\nu^2}\left(1 + \frac{g_s^2}{2M_s^2}\mathring{\zeta}_D^2\mathbf{k}^2\right) - \mathring{\zeta}_D^2 g_s \frac{\mathbf{k}^2}{2M_s} + \mathcal{O}(1/M_D^4)$$

$$\mathcal{E}_{\overline{\nu}}(\mathbf{k}) = \underbrace{\sqrt{\mathbf{k}^2 + m_\nu^2}\left(1 + \frac{g_s^2}{2M_s^2}\mathring{\zeta}_D^2\mathbf{k}^2\right)}_{\text{geometric origin}} + \underbrace{\mathring{\zeta}_D^2 g_s \frac{\mathbf{k}^2}{2M_s}}_{\text{kinematic origin}} + \mathcal{O}(1/M_D^4)$$

- **CPT-violating (CPTV) neutrino propagation *in vacuo***
  - ∗ Only subluminal ν is present, while superluminality of $\overline{\nu}$ is established

$$\delta_{\overline{\nu}} := v_{\overline{\nu}} - 1 = \mathring{\zeta}_D^2|\mathbf{k}|/M_D > 0 \qquad \delta_\nu = -\mathring{\zeta}_D^2|\mathbf{k}|/M_D$$

→ different propagation properties between ν's & $\overline{\nu}$'s at IceCube!

[See also **CL**, Ma 2303.04765 (**JHEP**)]

$$\mathring{\zeta}_D^2 \simeq 1.6 \times 10^{-18}\left(\frac{M_s}{g_s}\right)\ \mathrm{GeV}^{-1}$$

Suppressing $\overline{\nu}$-decay

- Cohen-Glashow v.s. OPERA "phantom": $\nu \to \nu e e^+$ [Cohen, Glashow'11 PRL]

  e.g., limits on superluminal velocities

$$\delta_> := \mathcal{E}_\nu / E_{\mathrm{LV}\nu} < 10^{-18} \text{ to } \sim 5 \times 10^{-19} \quad \longrightarrow \quad E_{\mathrm{LV}\nu}^{(\mathrm{sup})} \geq (10^3 - 10^5) \times M_{\mathrm{Pl}}$$

- Plausible <u>violation of energy conservation</u> **inhibits** $\overline{\nu}$-decay**?** [**CL**, Ma'22 PLB, 23 JHEP]

  * Stochastic loss $\delta\mathcal{E}_D$ of $(\varsigma_I/M_D)p^2$ $(\varsigma_I > 0)$ in particle reaction in D-foam [Ellis+'01 PRD] affects decay threshold for, e.g., most efficient $\overline{\nu} \to \overline{\nu} e e^+$ channel:

$$\mathcal{E}_{\overline{\nu}} > \frac{2m_e}{\sqrt{\varDelta}} \qquad \varDelta := \left(1 - \frac{4\varsigma_I}{\mathring{\zeta}_D^2}\right) \delta_{\overline{\nu}}$$

  - for observing $\mathcal{O}(\mathrm{PeV})$ superluminal evt (#35, or #20)

$$(\mathring{\zeta}_D^2 - 4\varsigma_I) \lesssim \mathcal{O}(10^{-7}) \text{ or, with assignment } \varsigma_I \geq \mathring{\zeta}_D^2/2$$

Conclusions

Take home message

- Consistent LV_γ (incl. LHAASO obs) via D-foam [**CL**, Ma 2105.06151 (**PLB**) + 2105.07967 (**PRD**)]
- In accordance with Crab Nebula limits on LV_e [**CL**, Ma 2204.02956 (**PLB**)]
- CPTV for IceCube neutrino from strings [**CL**, Ma 2303.04765 (**JHEP**) + 2211.00900 (**PLB**)]

Open question

what is the fate of UV Lorentz symmetry *(say, LV as essential ingredient of nature ?)*

→ unraveling quantum gravity - "Holy Grail"

the situation starts to become exciting and,
time will show if QG can be finally confirmed by exp.s

Thanks for your attention !