Strong constraints on Lorentz violation using new γ-ray observations around PeV

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Outline

- Basic Idea
  - Quantum Gravity
  - Lorentz Violation & relics
- Ultra-high-energy photons test Lorentz Violation
  - Advantages of LHAASO
  - Modified Dispersion Relation
- Research Results
  - Constraints based on spectra cutoff
  - Constraint based on single event
  - Discussion
- Summary

- Back up

Basic - Quantum Gravity

$$\text{TOE}\begin{cases}\text{GUT}\begin{cases}\text{Strong}\\ \text{Weak}\\ \text{Electromagnetic}\end{cases} \rightarrow \text{Effective Field Theory} \rightarrow \text{Renomalizable}\begin{cases}\text{approximation under Energy cut}, \Lambda\\ \text{DoFs in specific scale}\end{cases}\\ \text{Gravity} \rightarrow \text{General Relativity (GR)} \rightarrow \text{Non Renormalizable} \rightarrow \Lambda \sim E_{Pl} \sim (1/G)^{\frac{1}{2}} \sim 10^{19}\text{GeV}\end{cases}$$

↓ Possible solution

$$\text{Quantum Gravity (QG)} \rightarrow \text{make GR Renormalizable, several attempts}\begin{cases}\text{SM extension}^{[1]}\\ \text{loop QG}^{[2]}\\ \text{string theory}^{[3]}\\ \text{space-time foam}^{[4]}\\ \ldots\end{cases}$$

↓ Predicts Lorentz Violation at high energies, $E_{LV} \lesssim E_{pl}$

Lorentz Violation (LV) → Lorentz Symmetry Breakdown

$E_{QG} \sim E_{Pl}$

↓

Trans-GZK cosmic ray $\sim 10^{11}$GeV

↓

LV cannot be verified or tested by UHECRs directly !

↓

LV relics → tiny LV effects can be accumulated and magnified through our universe

In the 1990s, Amelino-Camelia supposed to use GRBs photon flight time delay to test LV ![4]

Basic - Quantum Gravity

TOE: GUT (Strong, Weak, Electromagnetic) → Effective Field Theory → Renomalizable {approximation under Energy cut, Λ; DoFs in specific scale}

Gravity → General Relativity (GR) → Non Renormalizable → $\Lambda \sim E_{Pl} \sim (1/G)^{\frac{1}{2}} \sim 10^{19}\mathrm{GeV}$

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- SM extension[1]
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TOE
- GUT
  - Strong
  - Weak
  - Electromagnetic
- Gravity

Strong, Weak, Electromagnetic $\rightarrow$ Effective Field Theory $\rightarrow$ Renomalizable
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Lorentz Violation (LV) $\rightarrow$ Lorentz Symmetry Breakdown

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LV cannot be verified or tested by UHECRs directly !

$\downarrow$

LV relics $\rightarrow$ tiny LV effects can be accumulated and magnified through our universe

In the 1990s, Amelino-Camelia supposed to use GRBs photon wave dispersion to test LV ![4]

Basic - LV violation & relics

[5]

LV relics

- Purely photonic scenarios
  - Cummulative effects → Long baseline dispersion and vacuum birefringence (AGNs, GRBs ...)
  - Anmormalous threshold → Photon decay, vacuum Cherenkov effect
  - Non threshold effects → Photon splitting, helicity decay
- non photonic
  - Shifting of existing threshold reactions → Photon annihilation from BLs, GZK reactions
  - Maximum velocity → Synchrotron peak from SNRs, like radius and opening angles
  - Dynamicial Effects of LV bkg field → Gravitational coupling and additional wave modes
  - Sideral Variation of LV coupling → Lab coordinate moves with respect to a preferred frame or directions
  - ...

QED is well-understood

[6]

- QED vertex interactions
  - $e^- \to e^- + \gamma$ → Energy loss rate $\propto E^2$, cooling down rapidly 😐
  - $\gamma \to e^+ + e^-$ → Photon decay section $\Gamma \propto E$ above threshold with considerable rate 🙂
  - $e^+ + e^- \to \gamma$ → hardly distinguishable ☹
- $\gamma + \gamma \to e^+ + e^-$ → In ordinary QED, photon annihilation allowed, shifting lower threshold ☹ (Compton Scattering, Pair Production, ...)
- $\gamma \to N\,\gamma$ → Ordinary QED forbidden photon splitting , phase volume vanishes; 🙂 Modified QED allowed with finite rate
- Long baseline dispersion → Model dependence 😐
- Vacuum birefringence → Fine, but set poor constraint 😐

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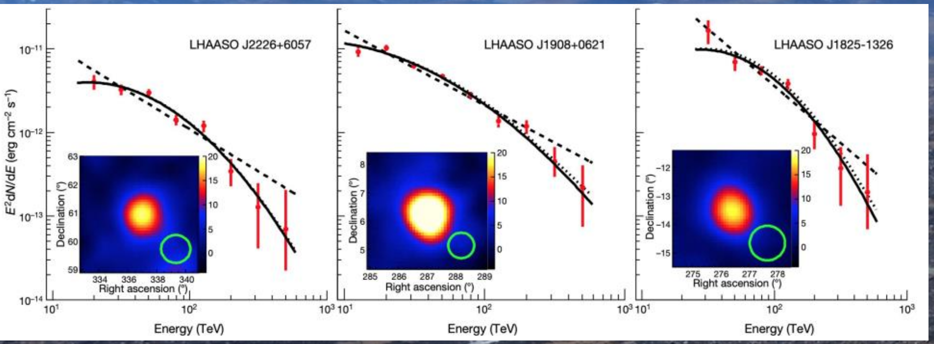
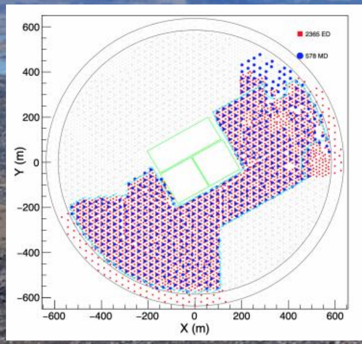
UHE photons test LV - Advantages of LHAASO

Half configuration, 2365EDs, 578MDs





- Most sensitive detector around hundred TeV energies:[8]
  $1.8 \times 10^{-13}\ erg \cdot cm^{-2} s^{-1}$ @[100, 178] TeV
- Rejection Power: $> 4 \times 10^3$ above 100 TeV
- Reported 3 galactic source spectra: [9]
  LHAASO J2226+6057, LHAASO J1908+0621, LHAASO J1825-1326
- Unveil UHE single photon event from Cygnus Region
  1.42±0.13 PeV non-rejection probability 0.028%

UHE photons test LV - Phenomenological Description

Modified Dispersions Relation (MDR) for photon

$$\omega^2(k) = k^2\left(1 \underbrace{\pm}_{\mathcal{A}} \underbrace{\xi_{n,}}_{\mathcal{B}}{}_{\underbrace{\pm}_{\mathcal{C}}} \frac{k^n}{E_{pl}^n}\right)$$

Mathematic Trick:

$$\omega^2 = k^2(1 + \alpha_n k^n)$$

$$\alpha_n = \xi_n / E_{pl}^n$$

$$\Big\downarrow E_{LV} \lesssim E_{pl}$$

$$E_{LV} = \alpha_n^{-1/n}$$

$\mathcal{A}$:

$+ \rightarrow$ superluminal

$- \rightarrow$ subluminal (radiative correction in EFT, hard to distinguish)[7]

$\mathcal{B}$: n−th order

$n = 0$, normal situation

$n = 1$, linear situation

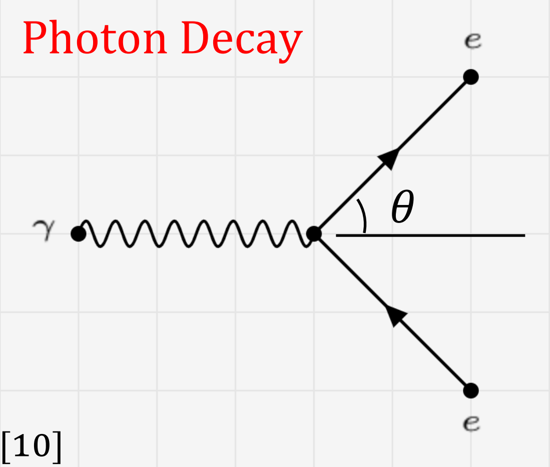
$n = 2$, quadratic situation

…

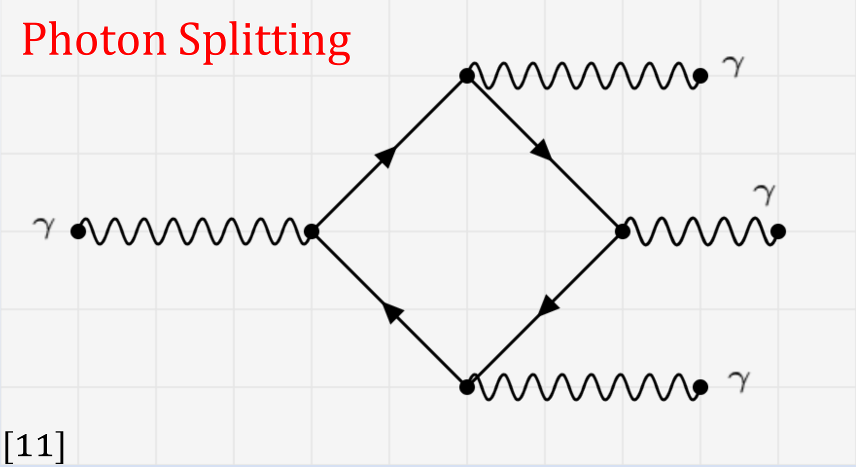
$\mathcal{C}$: polarization → Birefringence

$+ \rightarrow$ right circular polarization

$- \rightarrow$ left circular polarization



$$\mathcal{M} \rightarrow \text{Matrix element}$$
$$\Gamma \rightarrow \text{Scatter section}$$
$$\Gamma \sim \int |\mathcal{M}|^2 d\Omega$$



$$\Gamma_{\gamma\rightarrow e^+e^-} = \frac{e^2|\mathcal{M}|^2}{4\pi\cdot 4\omega}\int_0^{\pi}\sum_{\boxed{p=p_\pm}}\frac{p^2 sin\theta d\theta}{\left|(kcos\theta - p)E_e - p\sqrt{k^2+E_e^2-2kpcos\theta}\right|}$$

If $p_\pm$ exist,

then $\alpha_n^2 k^{2n+2}\cos^2\theta - 4(\sin^2\theta + \alpha_n k^n)(1+\alpha_n k^n)m_e^2 \geq 0$

$$a_n \leq \frac{4m_e^2}{k^n(k^2-4m_e^2)}$$

$$E_{LV}^{(1)} \geq 9.57\times 10^{23} eV\left(\frac{E_\gamma}{TeV}\right)^3$$

$$E_{LV}^{(2)} \geq 9.78\times 10^{17} eV\left(\frac{E_\gamma}{TeV}\right)^2$$

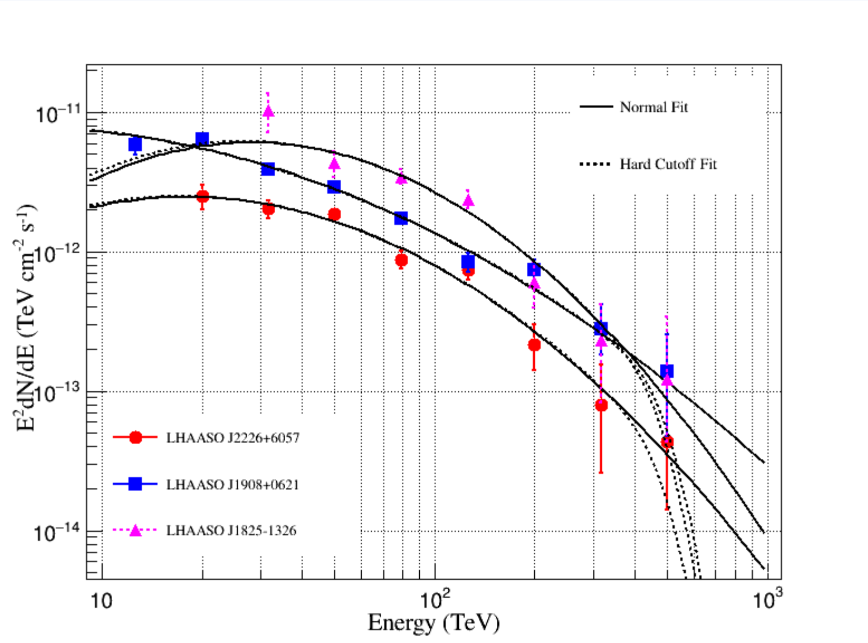
$$\Gamma_{\gamma\rightarrow 3\gamma} \cong 1.2\cdot 10^3\left(\frac{2\alpha_s}{45}\right)^2\frac{E^{19}}{2^8 3!\,\pi^4 m_e^8 E_{LV}^{10}}$$

$\gamma \rightarrow N\gamma$ $\Gamma_{\gamma\rightarrow 3\gamma} \propto E^{19}$
$N = 2$, Landau-Yang theorem
$N \geq 3$, Suppressed by vertexes, α_s^2

$$P_{\text{survival}} = e^{-\Gamma_{\gamma\rightarrow 3\gamma}\times L_{obs}} \rightarrow \Gamma_{\gamma\rightarrow 3\gamma}\times L_{obs} > 1$$

$$E_{LV}^{(2)} \geq 3.33\times 10^{19} eV\left(\frac{E_\gamma}{TeV}\right)^{1.9}\left(\frac{L_{obs}}{kpc}\right)^{0.1}$$

Research Results - Constraints based on spectra cutoff



Log parabola spectral model:

$$E^2\frac{dN}{dE} = E^2\Phi_0 \cdot \left(\frac{E}{E_0}\right)^{a+b\cdot log_{10}\left(\frac{E}{E_0}\right)}$$

Cutoff term: $\frac{1}{1+e^{\frac{E-E_{cut}}{0.11\cdot E_{cut}}}}$

Trick: $E_\gamma \sim E_{cut}$

$$\Delta\chi^2 = \chi^2(E_{cut}) - \chi^2(E_{cut} \to \infty)$$

one side confidence interval for Chi-square distribution
95% C.L. → 2.71

Source	E_{cut}/TeV	L_{obs}/kpc	$\alpha_0(10^{-18})$	$E_{LV}^1(10^{31}eV)$	$E_{LV}^2(10^{22}eV)$	$E_{LV(3\gamma)}^2\ (10^{24}eV)$
LHAASO J2226+6057	280.7	0.8	13.26	2.11	7.71	1.46
LHAASO J1908+0621	370.5	2.37	7.61	4.87	13.43	2.76
LHAASO J1825-1326	169.9	1.55	36.18	0.47	2.82	0.60
Combined sources	483.3	-	4.47	10.80	22.84	4.37

Research Results - Constraint based on single event

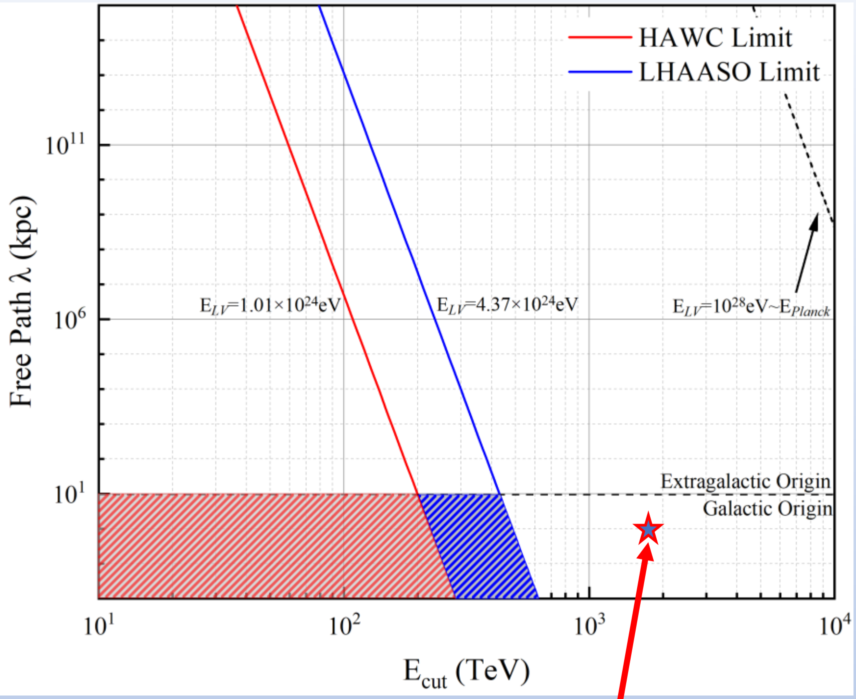
$\Gamma_{\gamma\to e^+e^-}, \Gamma_{\gamma\to 3\gamma} \propto E_\gamma^N$

Γ increases rapidly while E_γ is approximately E_{LV}.

Survival Probability, $P_{\text{survival}} = e^{-\Gamma\times L_{obs}}$ *decreases with the increment of* Γ.

BUT we still witness UHE photon events within galactic distance!

Counter example AGAINST low E_{LV} assumptions



UHE single photon

The energy of the UHE photon is 1.42±0.13 PeV, non-rejection probability 0.028%

$$E_{\gamma,low}^{95\%} = 1.21\ PeV$$

UHE single photon event originates from LHAASO J2032+4102.And the distance of possible astrophysical objects is 1.40±0.08 kpc

$$L_{obs,low}^{95\%} = 1.27\ kpc$$

	E_γ/PeV	L_{obs}/kpc	$\alpha_0(10^{-19})$	$E_{LV}^1(10^{33}eV)$	$E_{LV}^2(10^{24}eV)$	$E_{LV(3\gamma)}^2\ (10^{25}eV)$
UHE-event	1.21	1.27	7.13	1.70	1.43	2.45

Discussion

A. In 1990s, Amelino-Camelia supposed using GRBs photon flight time delay to test LV ! [4]

$$\Delta t_{LV} = \frac{1+n}{2\mathrm{H}_0}\xi_n \frac{(E_l^n - E_h^n)}{E_{pl}^n}\int_0^z \frac{(1+z')^n}{\sqrt{\Omega_A+\Omega_M(1+z')^3}}dz'$$

- Model dependence: GRB models, Hubble constant H_0, Cosmological constants Ω, photon propagation model(EBL CMB absorption…) + Theory
- Satellite-borne observation, and Fermi-LAT reported E_{LV} was 7.6 times greater than E_{pl}
- non-cumulative effect

B. Spectra Cutoff (Photon Decay & Photon Splitting)

- Photon's collective behavior
- Ground-based observation, HAWC and LHAASO report $E_{LV}s$ are 1800 and 8850 times of E_{pl}, respectively.
- Model dependence: intrinsic acceleration and radiation mechanisms, photon propagation model(EBL CMB absorption…) + Theory

C.UHE single photon event

- Model dependence: Theory
- The ONLY uncertainty that we should pay for: failure to reject a cosmic-ray event (rejection power 10^{-4} @ 100TeV)
- LHAASO reports E_{LV} is 139,000 times of E_{pl}

Summary

Bottom – up Interpretation:
UHE gamma-ray observation → test Lorentz Violation → narrow the parameter space → exclude QG theory candidates

LHAASO-KM2A advantages:

- Sensitivity above 100 TeV in Gamma
- Background Rejection Power
- Energy Resolution
- Angular Resolution

Endorse LHAASO – KM2A for functioning as a unique probe for Lorentz Violation physics

WCDA may have the capabilities of monitoring GRBs to set more stringent constraint on Lorentz violation based on photon flight time delay.

1st order $10^5 E_{Pl}$
2nd order $10^{-3} E_{pl}$

Collaboration:
Exploring Lorentz Invariance Violation from Ultra-high-energy Gamma Rays Observed by LHAASO(2106.12350)

arXiv:

1. Threshold anomalies of ultra-high energy cosmic photons due to Lorentz invariance violation(2105.06647)
2. Ultrahigh-energy photons from LHAASO as probes of Lorentz symmetry violations(2105.07967)
3. Two-sided constraints on Lorentz Invariance violation from Tibet-ASγ and LHAASO Very-High-Energy photon observations(2106.06393)
4. The implications of gamma-ray photons from LHAASO on Lorentz symmetry(2108.00869)
5. Modification of the mean free path of very high energy photons due to a relativistic deformed kinematics(2109.08402)

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[2] Alfaro J, Palma G. Loop quantum gravity and ultrahigh energy cosmic rays[J]. Physical Review D, 2003, 67(8): 083003.
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[10]Martínez-Huerta H, Pérez-Lorenzana A. Photon emission and decay from generic Lorentz Invariance Violation[C]. Journal of Physics: Conference Series. IOP Publishing, 2017, 866(1): 012006.
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Thanks!

Back up Slides

- For fermions

$$E^2(k) = m^2 + p^2\left(1 \pm \eta_{n,\pm}\frac{p^n}{E_{pl}^n}\right)$$

"helicity"

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

Helicity Decay or vacuum Cherenkov radiation
Cool down immediately, time scale $10^{-9}\ s$ for 10 TeV electron
Spectra structure

Effective but depends heavily on the acceleration capability of gamma-ray astrophysics sources

Jacobson T, Liberati S, Mattingly D. Threshold effects and Planck scale Lorentz violation: Combined constraints from high energy astrophysics[J]. Physical Review D, 2003, 67(12): 124011.

- Birefrigence → GRB 021206 $E_{LV} > 10^{14} eV$

Mitrofanov, I. G. (2003). A constraint on canonical quantum gravity?. *Nature*, *426*(6963), 139-139.

- Non-renormalizable Issue

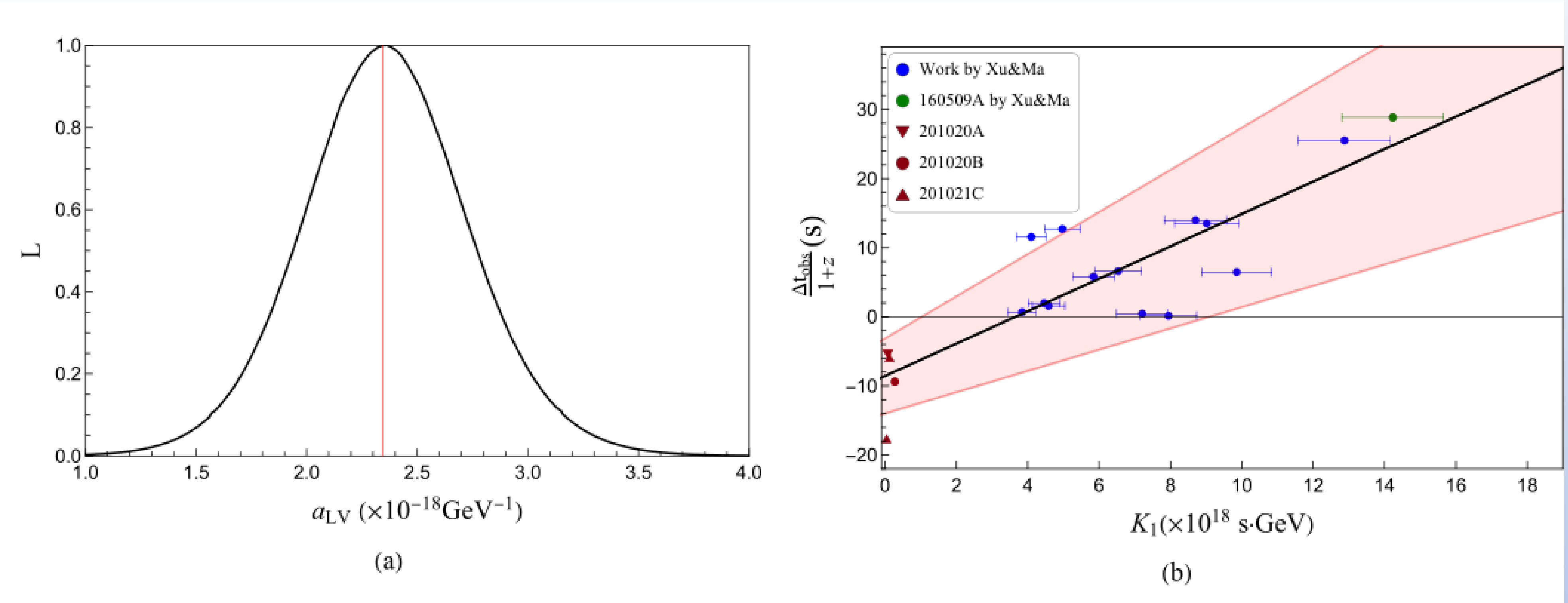
In the modern effective field theory point of view, there's nothing wrong with non-renormalizable theories. In fact, one may prefer a non-renormalizable theory inasmuch they tell you the point at which they fail (the energy cut-off).

To be concrete, consider an effective lagrangian expanded in inverse powers of the energy cut-off Λ

$$\mathcal{L}_{\text{eff}}(\Lambda) = \mathcal{L}_{\text{renorm}} + \sum_\alpha \frac{g_\alpha}{\Lambda^{\dim \mathcal{O}_\alpha - 4}} \mathcal{O}_\alpha$$

Gravity coupling constant g_{gravity} $\rightarrow$ Newton Constant $G \rightarrow [M]^{-2} \rightarrow$ dim (G) = -2

where L_{renorm} doesn't depend on Λ, $\mathcal{O}_\alpha$ are non-renormalizable operators (dim. > 4) and g_α are the corresponding coupling constants. Therefore, at very low energies $E \ll \Lambda$, the contributions from the non-renormalizable operators will be suppressed by powers of E/Λ.



$$\frac{\Delta t_{obs}}{1+z} = \boxed{\frac{\xi_n}{E_{LV,n}^n}} K_n + \Delta t_{in}$$

$$K_n = \frac{1+n}{2H_0}\frac{E_h^n}{1+z}\int_0^z \frac{(1+z')^n}{\sqrt{\Omega_\Lambda + \Omega_M(1+z')^3}}dz'$$

Light speed variation from gamma-ray bursts(1607.03203)

- GRBs test Lorentz Violation with light speed variation

A kind of "regression" method