



Possible Evidence for Lorentz Invariance Violation in GRB 221009A

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Extragalactic Background Light (EBL)

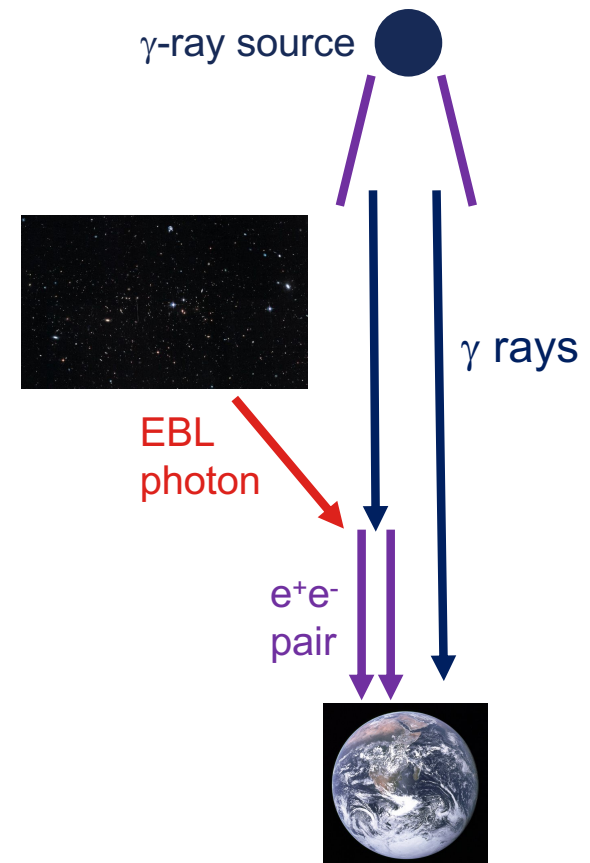
UV/optical/IR Extragalactic Background Light (EBL) from all the stars and dust that has existed in the observational universe.

Finke et al. (2022), *Astrophysical Journal*, 941, 33

<https://zenodo.org/record/7023073#.Y73cWi1h1N0>

Measurement of SFR, dust extinction, for 90% of the universe

Maybe some light galaxy surveys have missed





GRB 221009A

Brightest of all time (BOAT) GRB

Closest long GRB, $z=0.1505$ (Castro-Tirado et al. 2022; de Ugarte Postigo & Izzo (2022); Izzo et al. 2022)

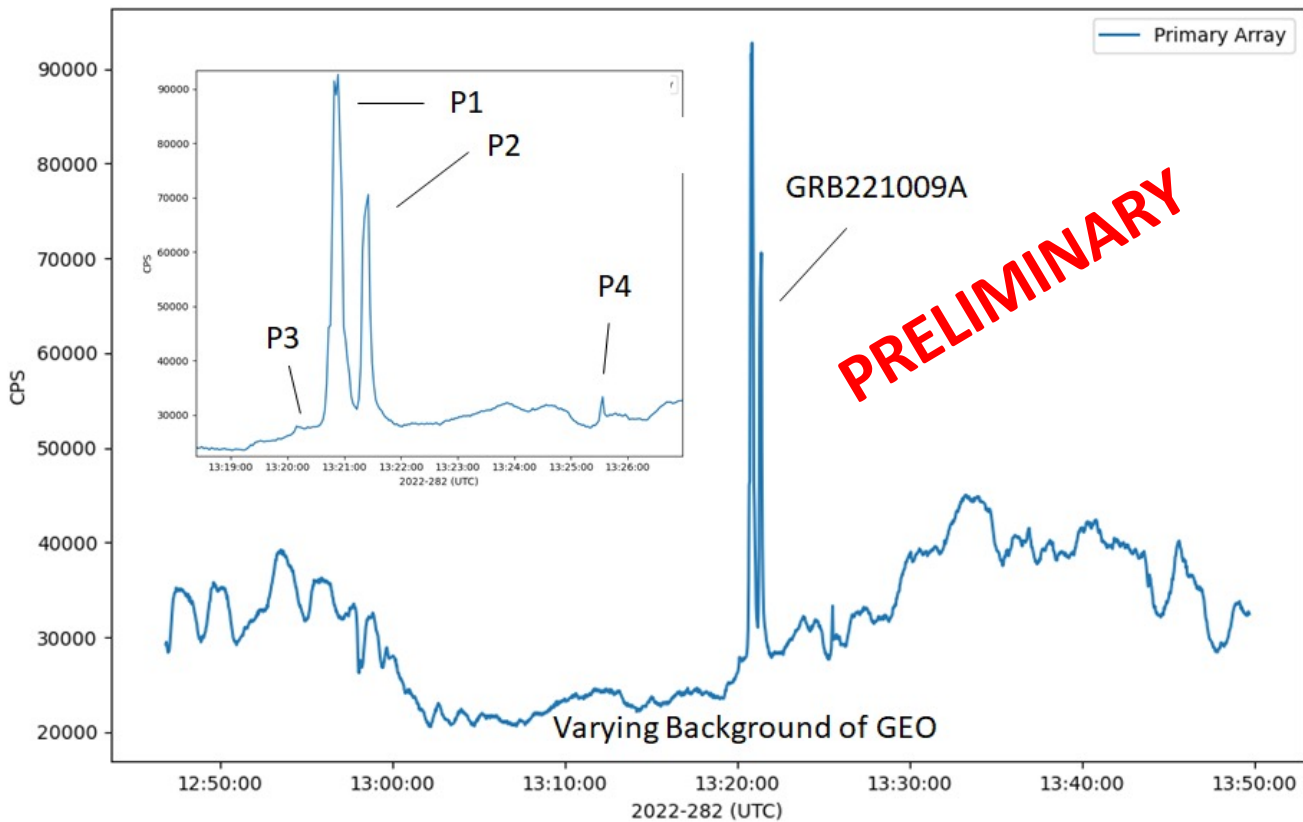
Detected by many instruments, including Fermi-GBM, Fermi-LAT, and SIRI-2

Reported VHE photons by LHAASO and Carpet 2





GRB 221009A with SIRI-2



SIRI-2 detected GRB 221009A! (GCN 32746)

SIRI-2: Seven SrI_2 scintillators on STP mission at GEO. 400-8000 keV. PI: Lee Mitchell (NRL)

Peaks aren't saturated!



Spectral Energy Distribution

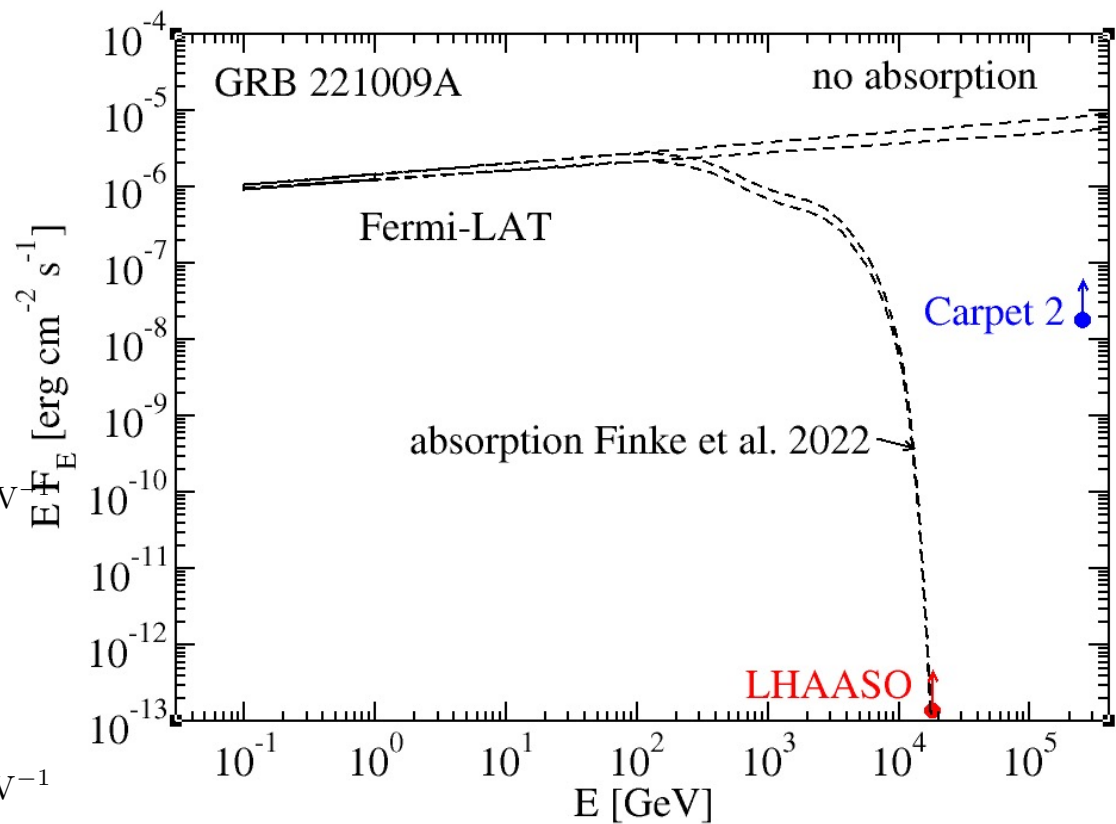
- LAT spectrum 200-800 s after burst (GCN 32658)
- LHAASO (Chinese) detect. up to 18 TeV within 2000 s (GCN 32677). A_{eff} , Implied 95% flux lower limit (Poisson statistics; Gehrels 1986):

$$\left. \frac{dN}{dE} \right|_{\text{obs}} (18 \text{ TeV}) \gtrsim \frac{5.13 \times 10^{-2}}{A_{\text{eff}} t E}$$

$$\gtrsim 2.9 \times 10^{-19} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ GeV}$$

- Carpet 2 (Russian) detect. of 251 TeV photon 4536 s after trigger (Atel 15669). $A_{\text{eff}} = 25 \text{ m}^2$. Implied 95% flux lower limit:

$$\left. \frac{dN}{dE} \right|_{\text{obs}} (251 \text{ TeV}) \gtrsim 1.8 \times 10^{-16} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ GeV}^{-1}$$





Comparison of EBL Models

EBL Model	τ_{18}	τ_{10}	$N_{\gamma,0.5}$	$N_{\gamma,18}$	$g_{a\gamma}$	$M_1(M_2)$
K&D2010	9.4	4.5	6700	1	-	- (-)
Fi2010	10.0	6.0	4162	0.9	-	- (-)
Gi2012	13.3	5.4	4500	2×10^{-2}	0.58	10.4 (2.6×10^{-7})
Do2011-	13.5	4.4	5800	1×10^{-2}	0.58	11.3 (2.8×10^{-7})
Gi2012f	13.9	5.6	5603	1×10^{-2}	0.58	10.1 (2.6×10^{-7})
Fr2008	18.3	6.8	5000	9×10^{-5}	0.59	8.4 (2.4×10^{-7})
SL2021	19.1	6.9	5200	4×10^{-5}	0.59	8.4 (2.4×10^{-7})
Do2011	19.2	6.1	4600	3×10^{-5}	0.59	9.1 (2.5×10^{-7})
Do2011+	27.1	7.8	4000	7×10^{-9}	0.59	7.5 (2.1×10^{-7})

Baktash et al. 2022 arXiv:2210.07172



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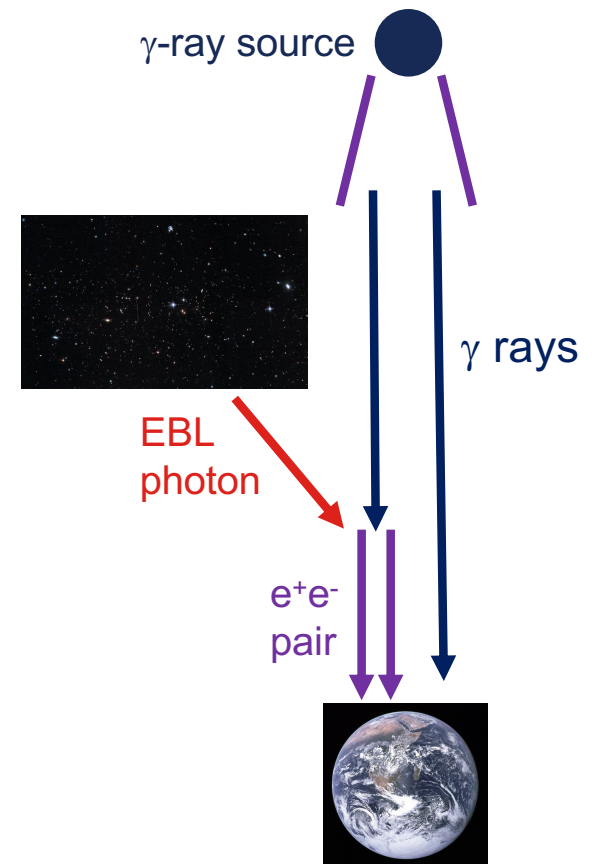
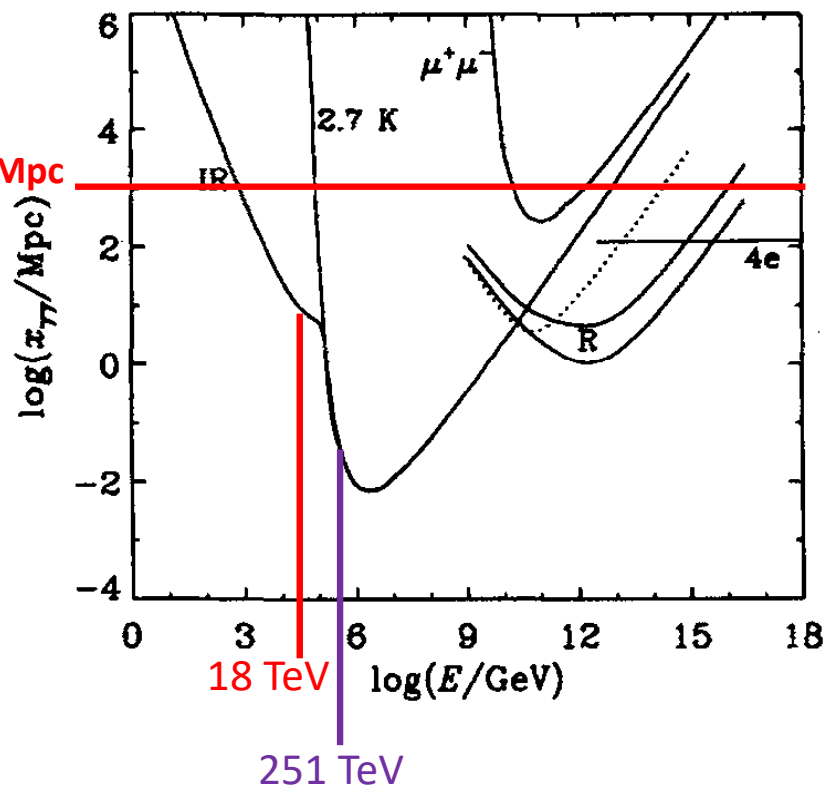
Are these EBL models ruled out?



Background Radiation Field Absorption

Protheroe & Biermann (1996)

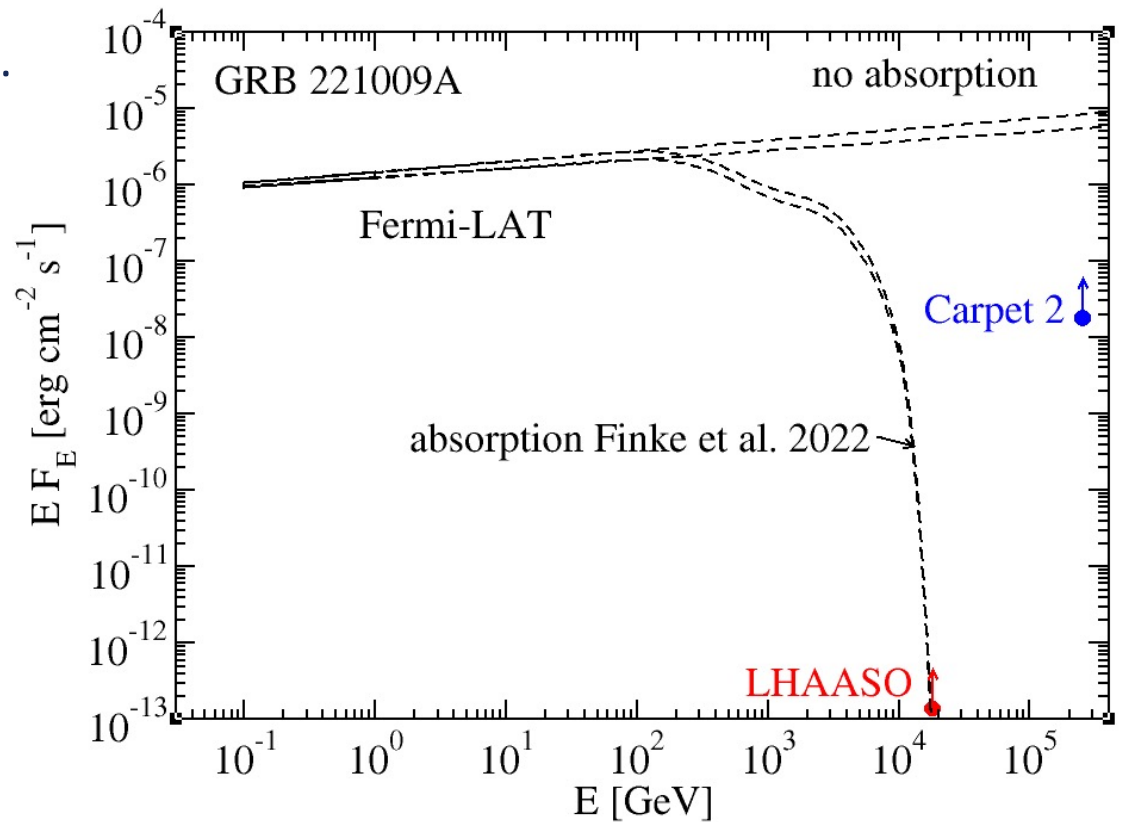
$z=0.15$
 $d_L=700$ Mpc





Spectral Energy Distribution

- 40% energy uncertainty for 18 TeV photons with LHAASO (Baktash et al. 2022)
- 18 TeV photon could be misidentified cosmic ray (Baktash et al. 2022)
- Excess absorption is still a problem for 251 TeV photon
- LHAASO and Carpet 2 photons' positions on sky are consistent with direction of known HAWC source seen up to 140 TeV (Atel 15675)!

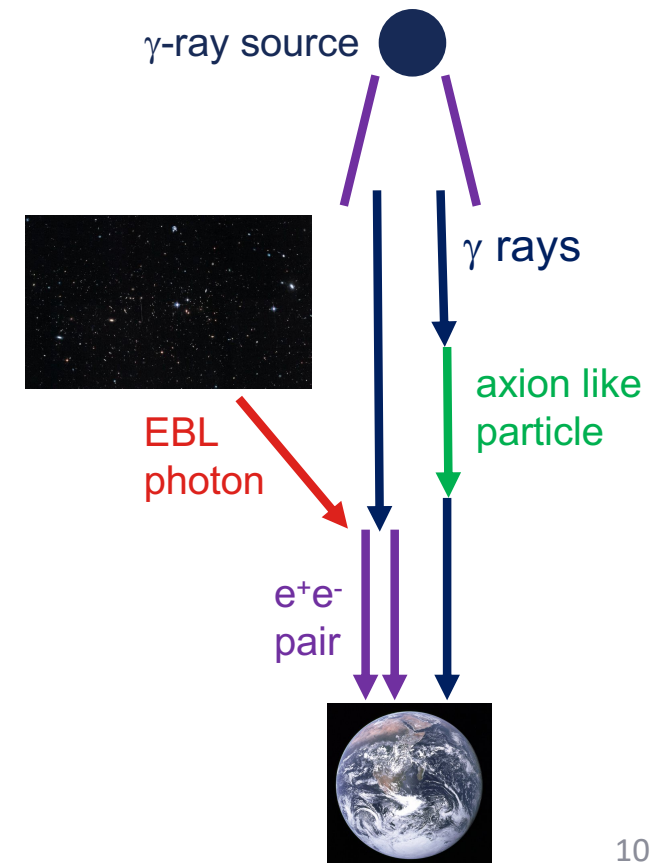




Extragalactic Background Light (EBL)

New physics possibilities!

1. VHE photons convert to axion like particles (ALPs) in B field to avoid γ -ray absorption (Baktash et al. 2022; Carena & Marsh 2022; Galanti et al. 2022; Nakagawa et al. 2022; Troitsky 2022; Zhang & Ma 2022).
2. Lorentz invariance violation could modify $\gamma + \gamma \rightarrow e^+ + e^-$ cross section (Dzhappuev et al. 2022; Baktash et al. 2022; Li & Ma 2022).





Extragalactic Background Light (EBL)

Violation of Lorentz invariance!

$$E^2 - p^2 c^2 = \pm E^2 \left(\frac{E}{E_{QG}} \right)^n$$

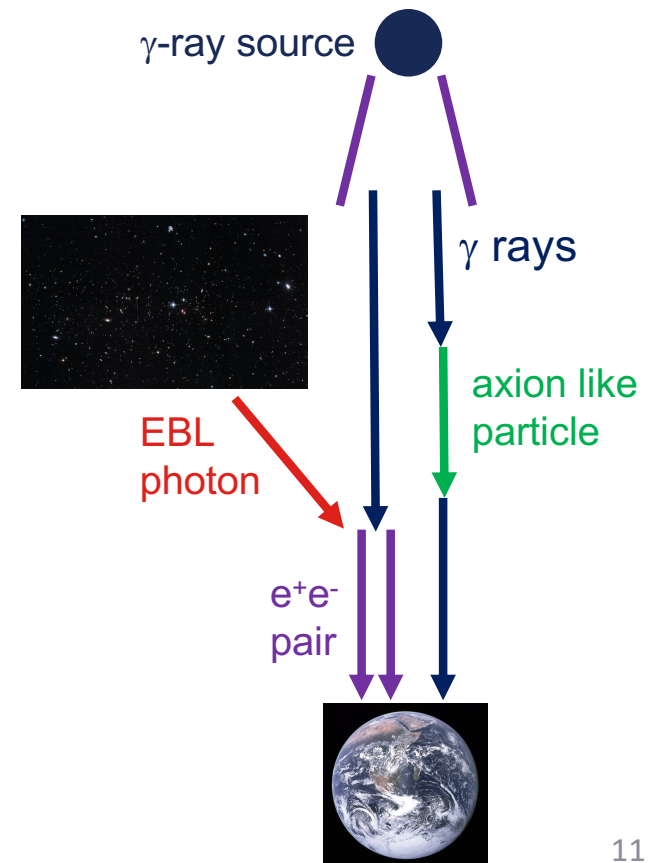
Predicted by some beyond Standard Model theories (e.g., Supersymmetry, String Theory)

Natural for $E_{QG} \sim E_{Planck} = 1.2 \times 10^{28}$ eV

Two relevant, potentially observable effects:

1. variation of speed of light as a function of photon energy
2. modification of $\gamma\gamma \rightarrow e^+e^-$ cross section

$$\epsilon_1 \rightarrow \frac{\epsilon_1}{1 + \frac{1}{4} \left(\frac{\epsilon_1 m_e c^2}{E_{QG}} \right)^n} \epsilon_1^2$$

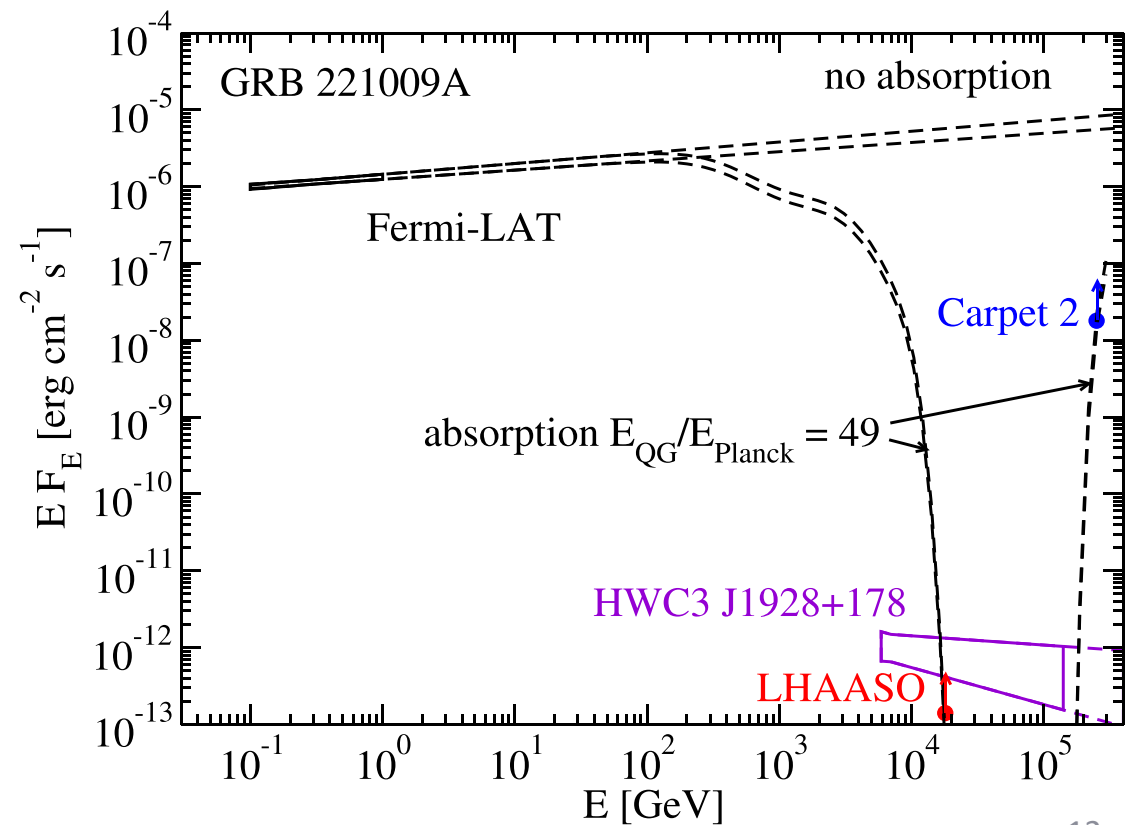




LIV constraint

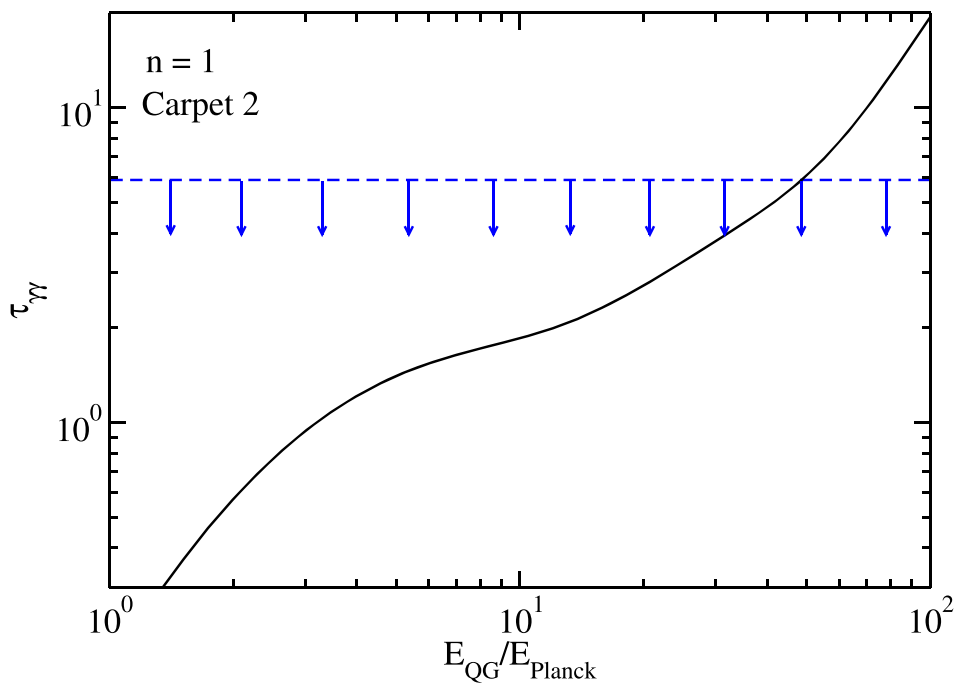
Carpenter 2 detection is not consistent with nearby HAWC source

LIV does allow LAT spectrum to be consistent with Carpet 2 photon!

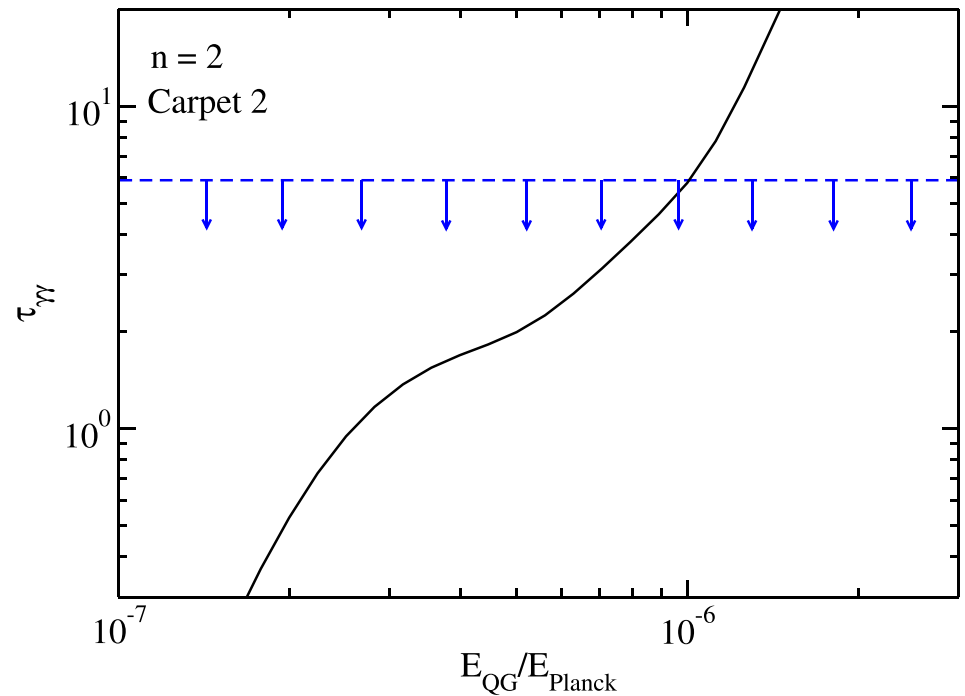




LIV constraint



$$E_{QG}/E_{Planck} \lesssim 49 \quad (n = 1)$$



$$E_{QG}/E_{Planck} \lesssim 1.0 \times 10^{-6} \quad (n = 2)$$



Summary

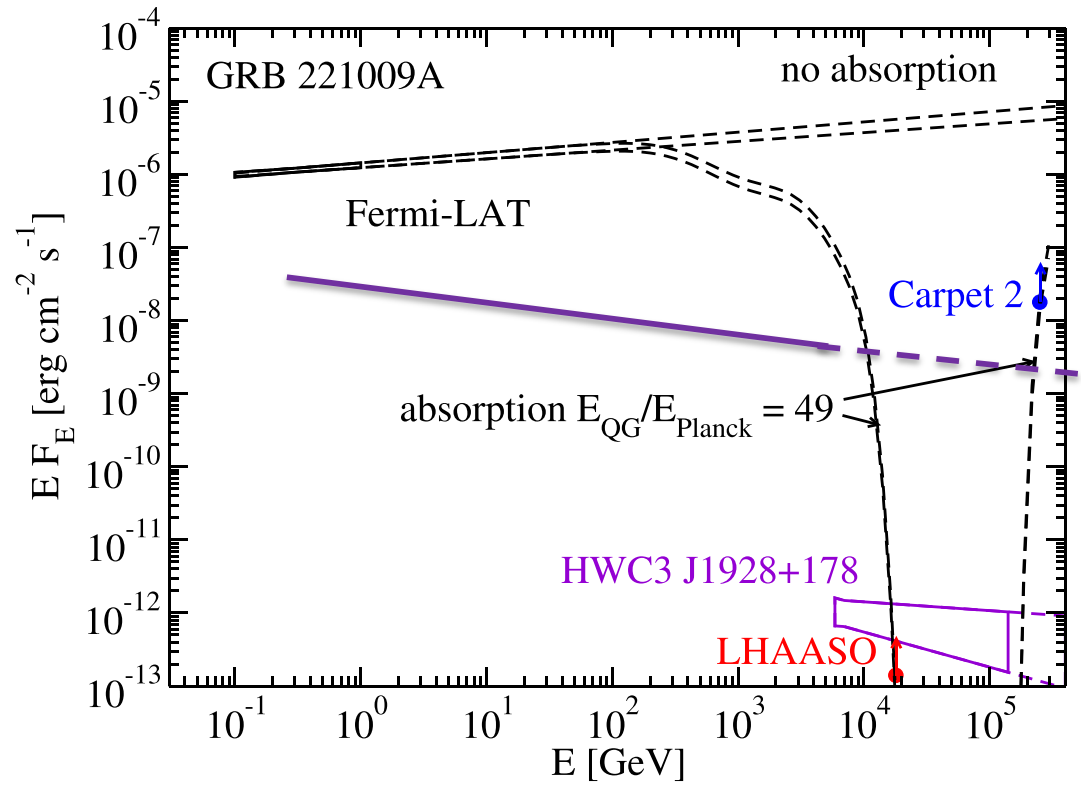
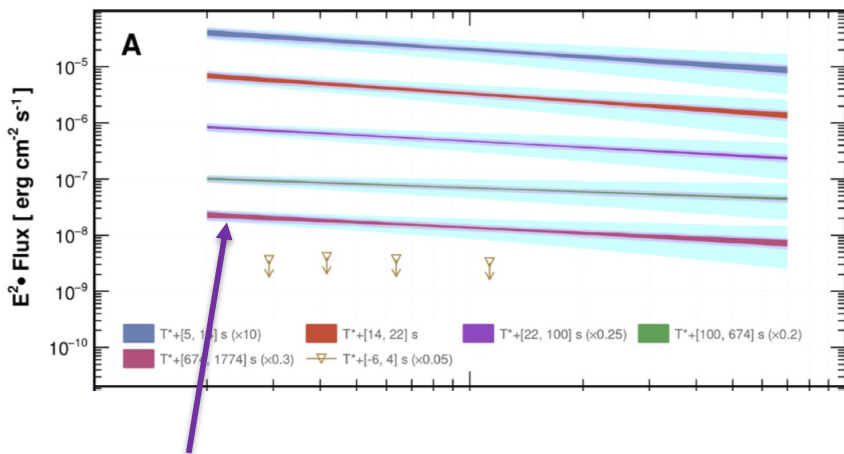
- An 18 TeV photon from GRB 221009A is consistent with some EBL models without resorting to post-Standard Model physics (ALPs, LIV) or from a nearby HAWC source.
- 251 TeV photon from GRB 221009A is consistent with $E_{\text{QG}} > 49 E_{\text{Planck}}$ and *is very unlikely to be from a nearby HAWC source or flaring Galactic source. **Could be the first evidence for LIV!***
- Consistent with all previous LIV constraints (n=1):
 - $10 < E_{\text{QG}}/E_{\text{Planck}}$ (VHE spectra; Lang et al. 2019)
 - $7.6 < E_{\text{QG}}/E_{\text{Planck}}$ (GRB time of flight; Vasileiou et al. 2013)
- But lots of caveats:
 - Could be evidence for ALPs instead
 - Could be mis-identified cosmic ray?
 - More detailed analysis by LHAASO and Carpet 2 collaborations needed.



Update

LHAASO WCDA publication on 221009A (LHAASO Collaboration 2023)

de-absorbed spectra





Acknowledgements

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