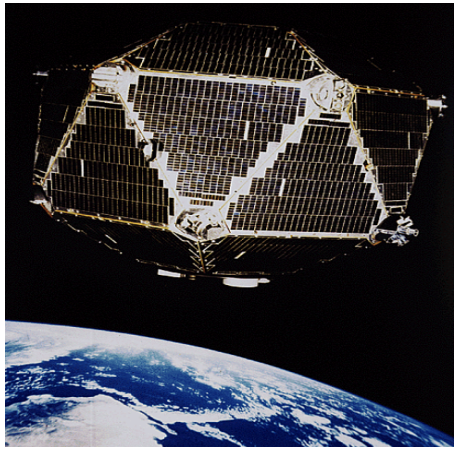
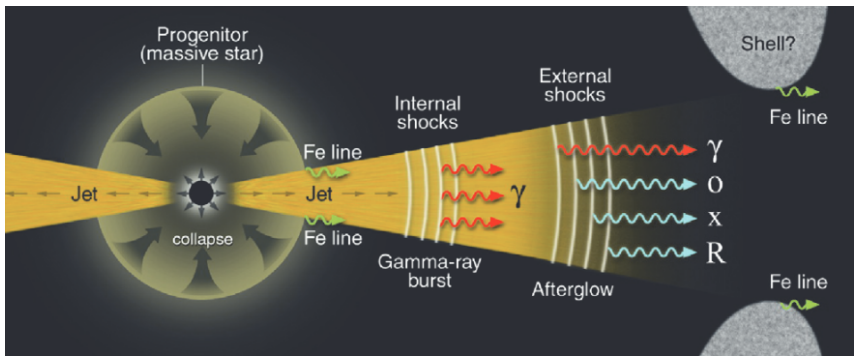
Very-High-Energy Gamma-Ray Burst: BSM Explanations of GRB 221009A

Vedran Brdar

Gamma-Ray Bursts (GRBs)

- in the 70s, Vela satellites discovered unexpected γ-ray flashes coming from the outer space
- in 1991, GRB detections by BATSE (on board of Compton-GRO) indicated that the bursts are distributed uniformly over the sky
- GRBs are broadly classified into two categories based on the duration (long $t \gtrsim 2$ s ; short $t \lesssim 2$ s)
- origin: core-collapse of a massive star (GRB 980425) or mergers of binary systems (GRB 170817A)





GRB 221009A Discovery

TITLE: GCN CIRCULAR
NUMBER: 32635
SUBJECT: GRB 221009A: Swift detected transient may be GRB
DATE: 22/10/09 20:44:25 GMT
FROM: Jamie Kennea at Penn State U <jak51@psu.edu>

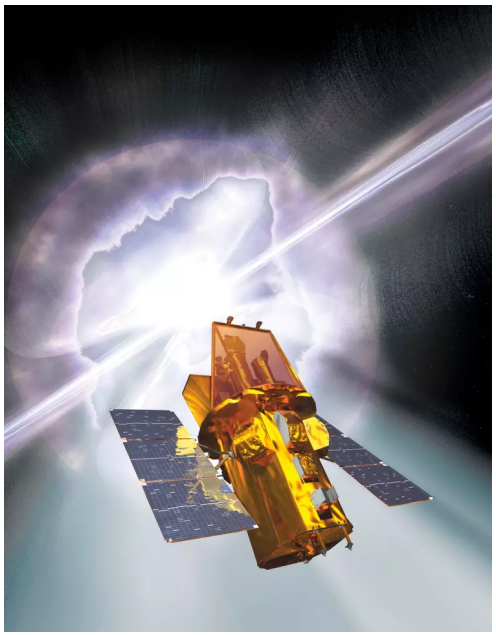
J. A. Kennea and M. Williams (PSU) report on behalf of the Swift Team:

We provide an update on the BAT trigger 1126853, AKA Swift J1913.1+1946 (GCN #32632). Examination of XRT data from this trigger shows strong fading. We also note that Fermi/LAT has triggered on the same location. There is also a possible association with a Fermi/GBM trigger @ 13:16:59UT. Given this, we believe that this source is now likely a Gamma-Ray Burst and not a Galactic Transient. If the GBM trigger is the same source, this would suggest a highly energetic outburst, and therefore we strongly encourage follow-up of this usual event.

TITLE: GCN CIRCULAR
NUMBER: 32642
SUBJECT: GRB 221009A: Fermi GBM observation
DATE: 22/10/10 04:04:41 GMT
FROM: Stephen Lesage at Fermi-GBM Team <sjl0014@uah.edu>

S. Lesage (UAH), P. Veres (UAH), O.J. Roberts (USRA),
E. Burns (LSU), and E. Bissaldi (Politecnico and INFN Bari)
report on behalf of the Fermi GBM Team:

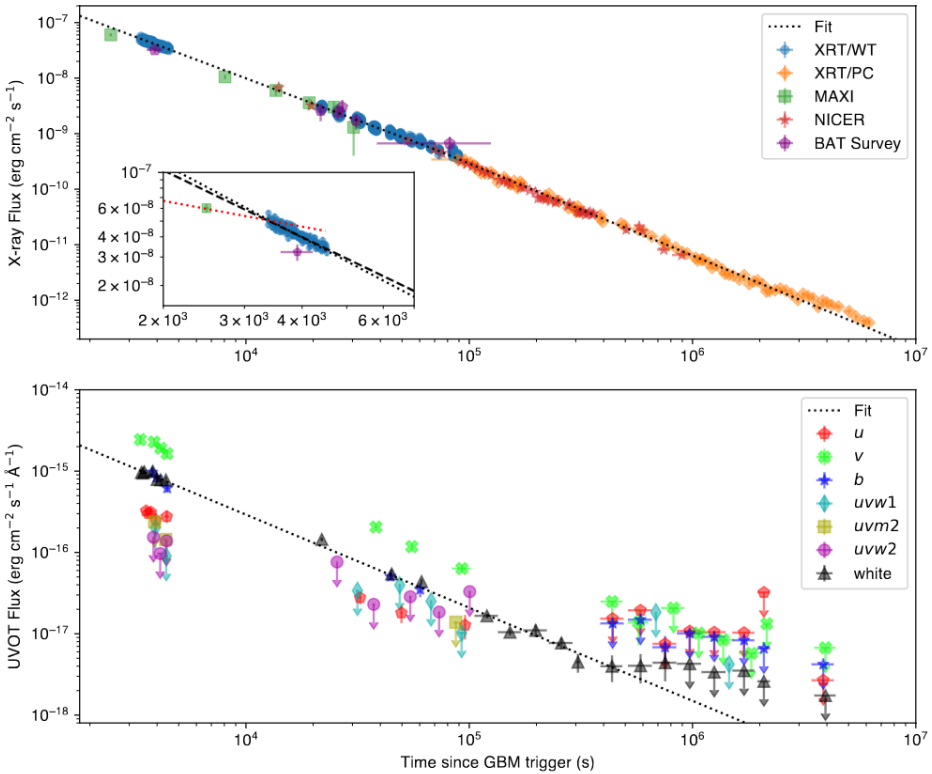
"At 13:16:59.99 UT on 09 October 2022, the Fermi Gamma-Ray Burst Monitor triggered and located GRB 221009A (trigger 687014224/221009553) which was also detected by Swift-BAT (S. Dichiara, et al. 2022, GCN 32632; J. A. Kennea, et al. 2022, GCN 32635), Fermi-LAT (E. Bissaldi et al. 2022, GCN 32637), INTEGRAL (SPI-ACS), Konus-Wind, and triangulated by IPN (D. Svinkin et al. 2022, GCN 32641). The GBM on-ground location (GCN 32636) is
consistent with the Swift-BAT and Fermi-LAT locations and the IPN localization.



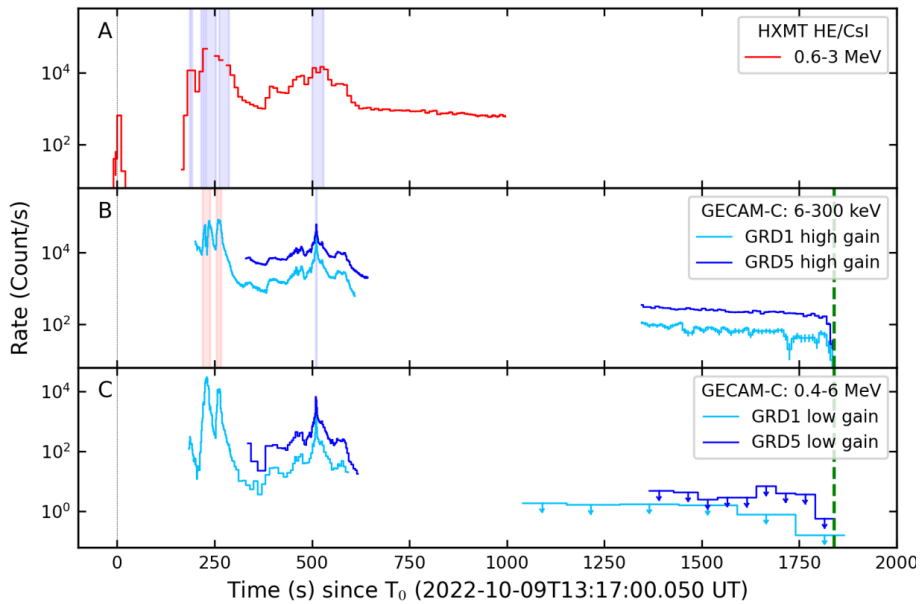
GRB 221009A Discovery

- Detection by HXMT, JWST, AGILE, KONUS-Wind, GECAM-C, GRANDMA, SIRI-2, BepiColombo, Voyager 1 and many others

Williams et al., 2302.03642

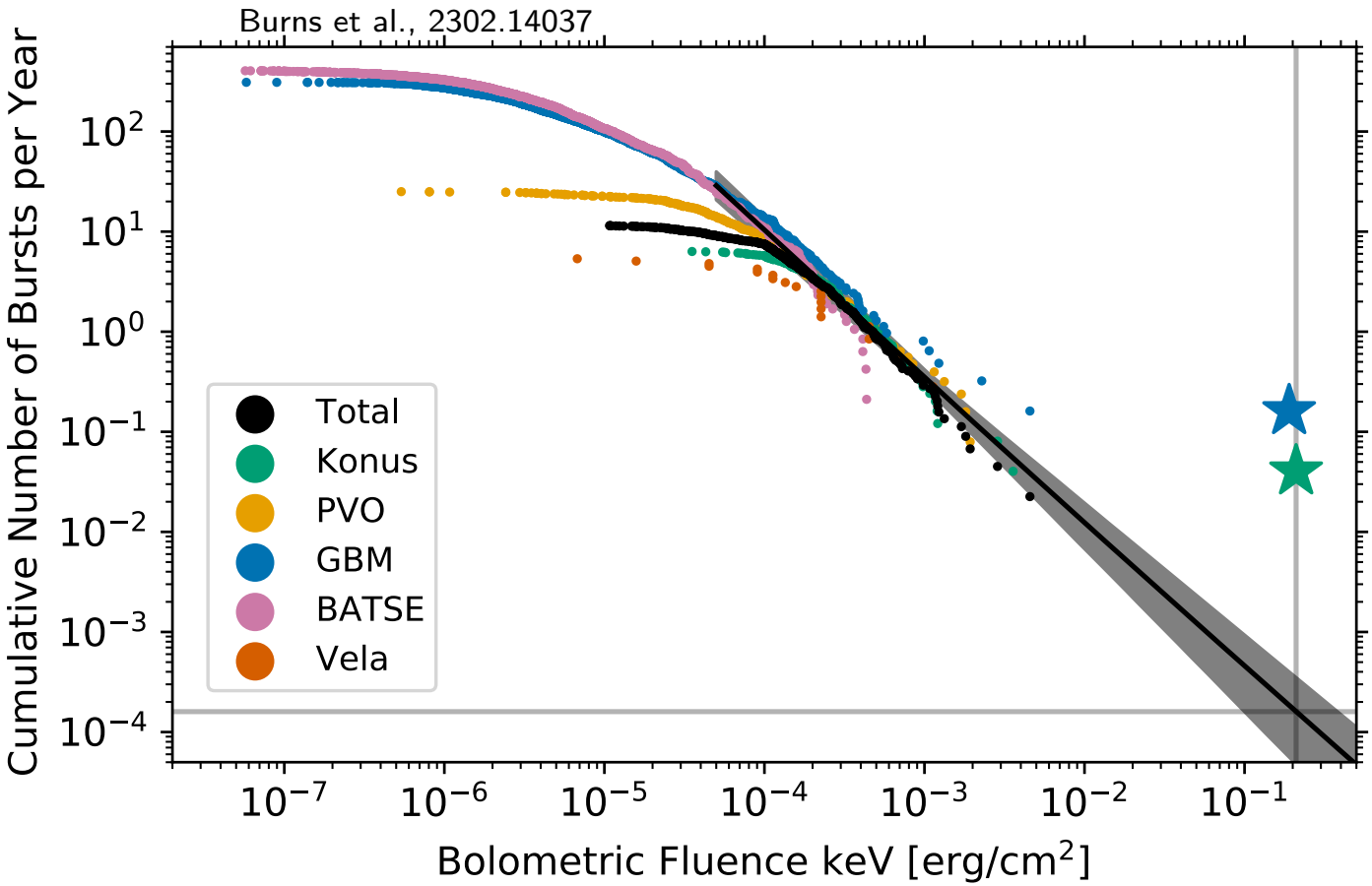


An et al., 2303.01203

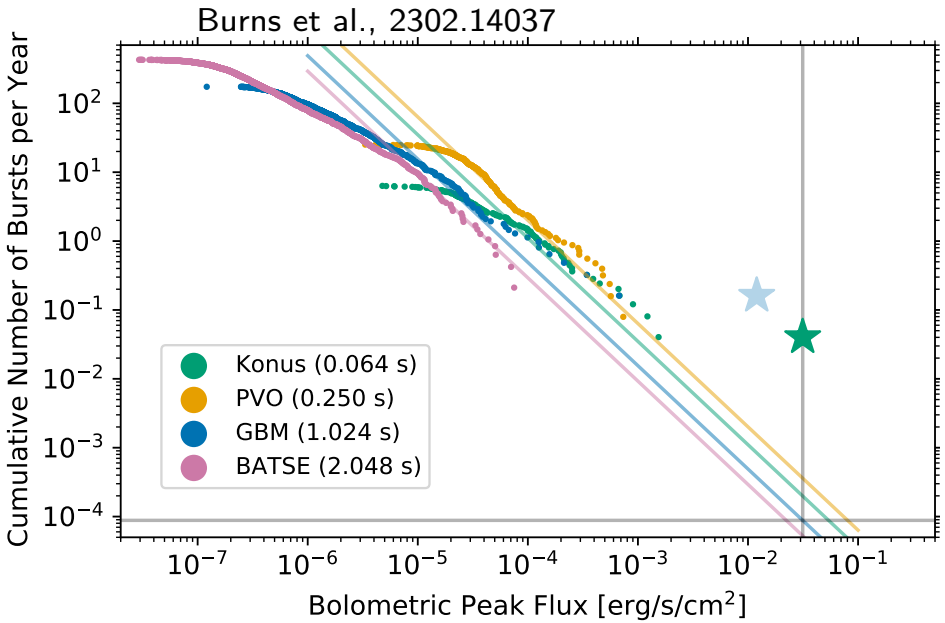


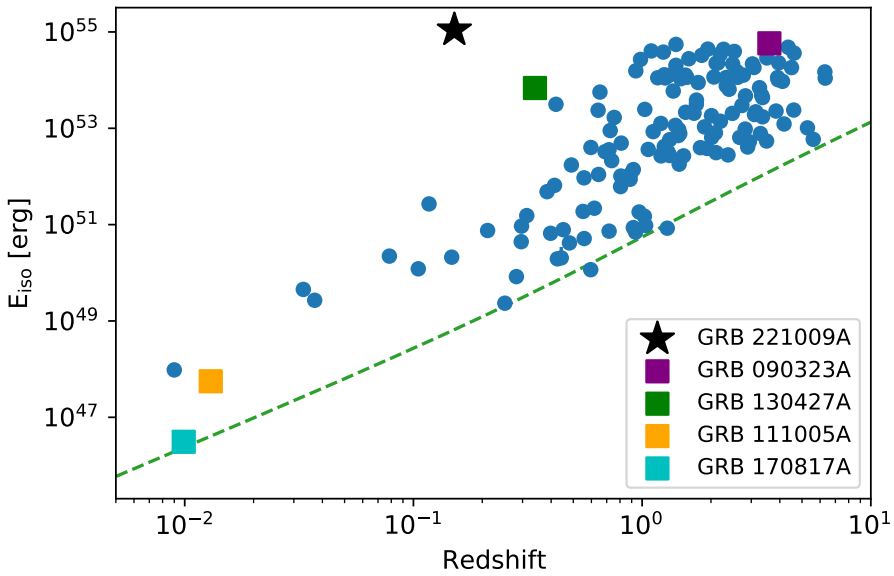
GRB 221009A Properties

- GRB 221009A was truly exceptional: by a large margin, it is the GRB with the highest fluence and peak flux ever recorded



GRB 221009A Properties





Very-High-Energy Photons from GRB 221009A

TITLE: GCN CIRCULAR
NUMBER: 32677
SUBJECT: LHAASO observed GRB 221009A with more than 5000 VHE photons up to around 18 TeV
DATE: 22/10/11 09:21:54 GMT
FROM: Judith Racusin at GSFC <judith.racusin@nasa.gov>

Yong Huang, Shicong Hu, Songzhan Chen, Min Zha, Cheng Liu, Zhiguo Yao and
Zhen Cao report on behalf of the LHAASO experiment

We report the observation of GRB 221009A, which was detected by Swift (Kennea
et al. GCN #32635), Fermi-GBM (Veres et al. GCN #32636, Lesage et al. GCN #32642),
Fermi-LAT (Bissaldi et al. GCN #32637), IPN (Svinkin et al. GCN #32641) and so on.

GRB 221009A is detected by LHAASO-WCDA at energy above 500 GeV, centered at
RA = 288.3, Dec = 19.7 within 2000 seconds after T0, with the significance above
100 s.d., and is observed as well by LHAASO-KM2A with the significance about 10 s.d.,
where the energy of the highest photon reaches 18 TeV.

This represents the first detection of photons above 10 TeV from GRBs.

The LHAASO is a multi-purpose experiment for gamma-ray astronomy (in the energy
band between 10^11 and 10^15 eV) and cosmic ray measurements.

Swift J1913.1+1946/GRB 221009A: detection of a 250-TeV photon-like air shower by Carpet-2

ATel #15669; *D. D. Dzhappuev, Yu. Z. Afashokov, I. M. Dzaparova, T. A. Dzhatdoev, E. A. Gorbacheva, I. S. Karpikov, M. M. Khadzhiev, N. F. Klimenko, A. U. Kudzhaev, A. N. Kurenya, A. S. Lidvansky, O. I. Mikhailova, V. B. Petkov, E. I. Podlesnyi, N. A. Pozdnukhov, V. S. Romanenko, G. I. Rubtsov, S. V. Troitsky, I. B. Unatlokov, I. A. Vaiman, A. F. Yanin, K. V. Zhuravleva (Carpet-2 group, INR RAS)*
on 12 Oct 2022; 13:56 UT
Credential Certification: Sergey Troitsky (st@ms2.inr.ac.ru)

Subjects: VHE, UHE, Gamma-Ray Burst, Transient

Referred to by ATel #: 15675

Tweet

The X-ray and optical transient Swift J1913.1+1946 (ATel #15650; GCN #32632) is possibly associated with a gamma-ray burst GRB 221009A (Fermi GBM alert, GCN #32635, #32636). This bright transient has been observed by numerous instruments in optical, X-ray and gamma-ray bands (ATel #15651, #15653, #15655, #15656, #15660, #15661, #15662, #15663, #15664, #15665; GCN #32634 - #32671, #32676 - #32679, #32683 - #32686, #32688, #32690 - #32695 and counting). Tentative redshift from the observation of the afterglow emission is z=0.151 (GCN #32648, #32686). In case the GRB association is true, this event produced the most energetic GRB photon ever seen by Fermi LAT (ATel #15656), that of 99 GeV. Moreover, the same transient was detected by LHAASO during 2000 sec after the GRB trigger with photons up to 18 TeV, highest energies ever detected from a GRB (GCN #32677).

In a follow-up analysis of Carpet-2 data, we found an air shower consistent with being caused by a photon of 251 TeV energy, giving zero hits in the 175 m^2 muon detector. This event was detected at 14:32:35 UT, that is 1338 sec after the SWIFT trigger and 4536 sec after the GBM trigger. The reconstructed arrival direction is RA=289.51 deg, DEC=18.44 deg, that is 1.78 deg from the transient direction, well within the Carpet-2 angular resolution of 4.7 deg (90% CL).

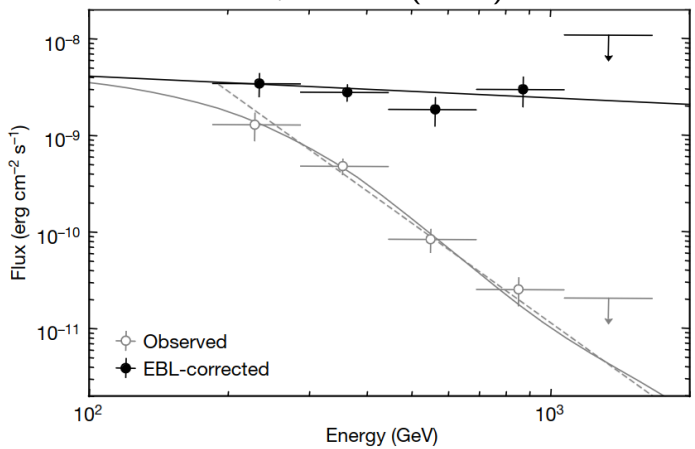
- 18 TeV γ detected by LHAASO,
  251 TeV γ detected by CARPET-2 (?!)

Swift J1913.1+1946/GRB 221009A: Galactic sources of > 100 TeV-photon in spatial coincidence with the 250-TeV photon-like air shower reported by Carpet-2

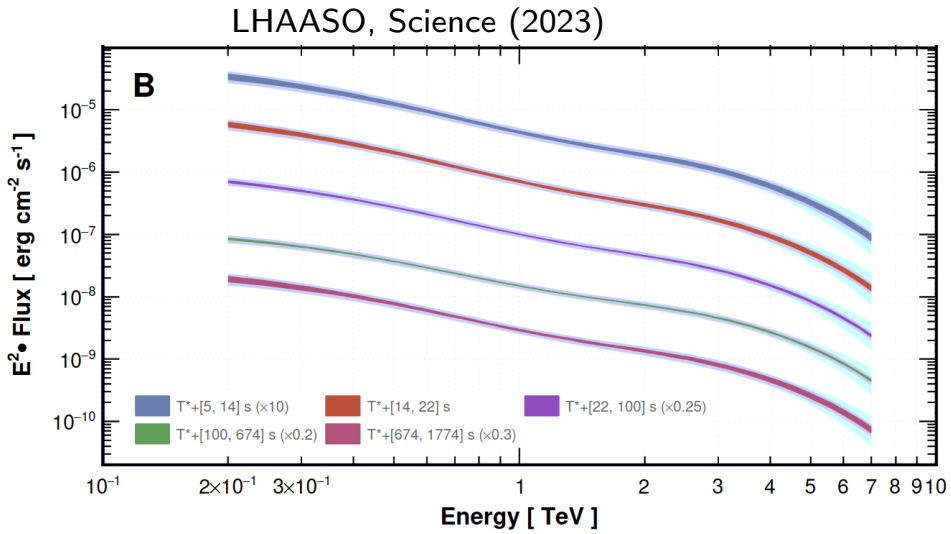
ATel #15675; *Nissim Fraija (UNAM), Magda Gonzalez(UNAM), for the HAWC Collaboration*
on 13 Oct 2022; 19:30 UT

- previous record holder – TeV γ from GRB 190114C

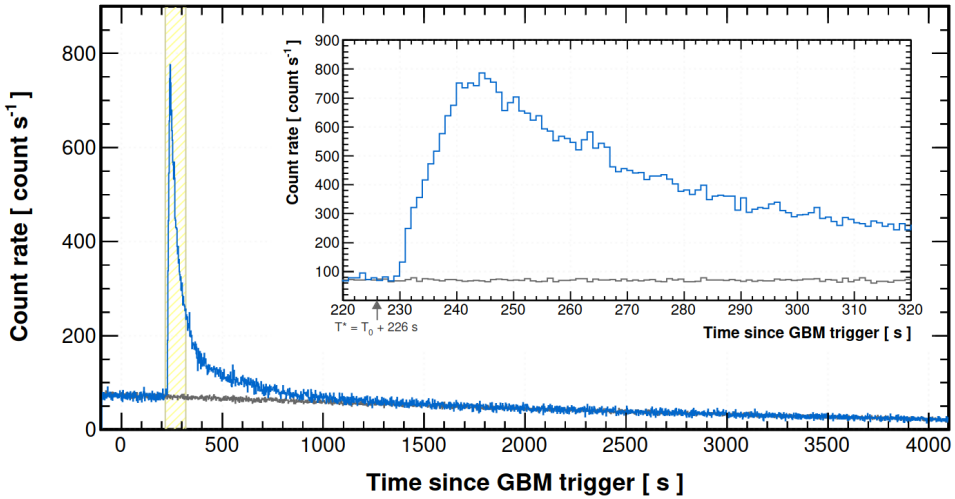
MAGIC, Nature (2019)



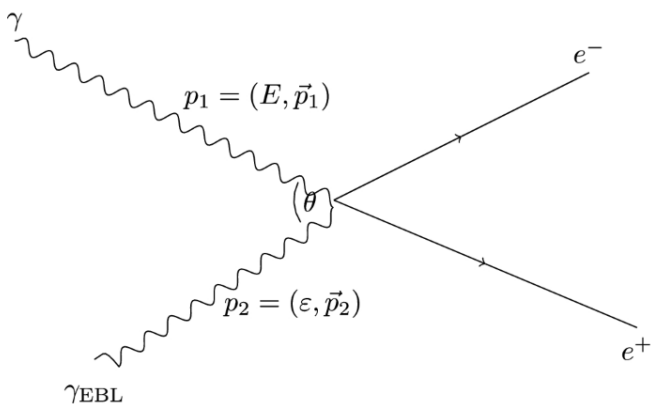
LHAASO Observation of GRB 221009A



- 6000 s long observation
- LHAASO Water Cherenkov Detector Array (WCDA) detected $\gtrsim 6 \times 10^4$ photons in [0.2,7] TeV
- 18 TeV γ is from LHAASO-KM2A



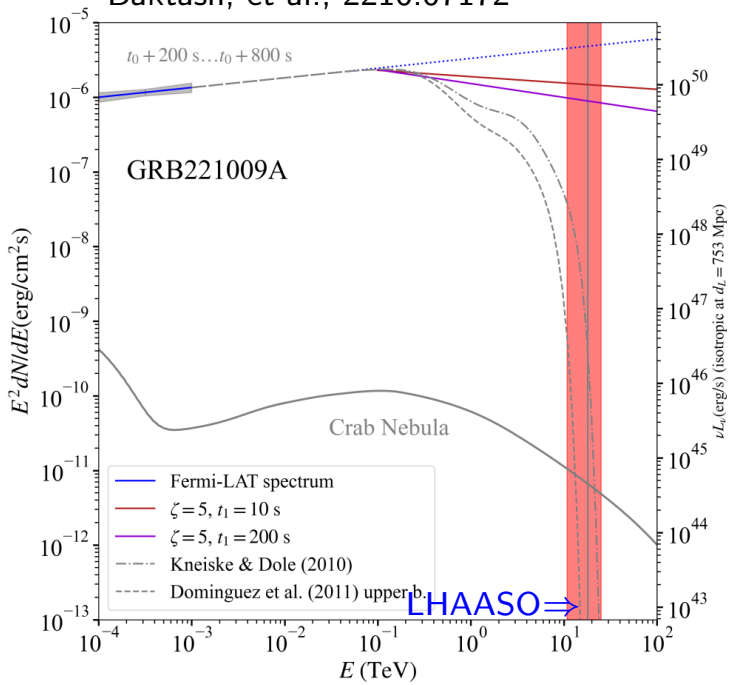
SM Explanation of the 18 TeV Photon?



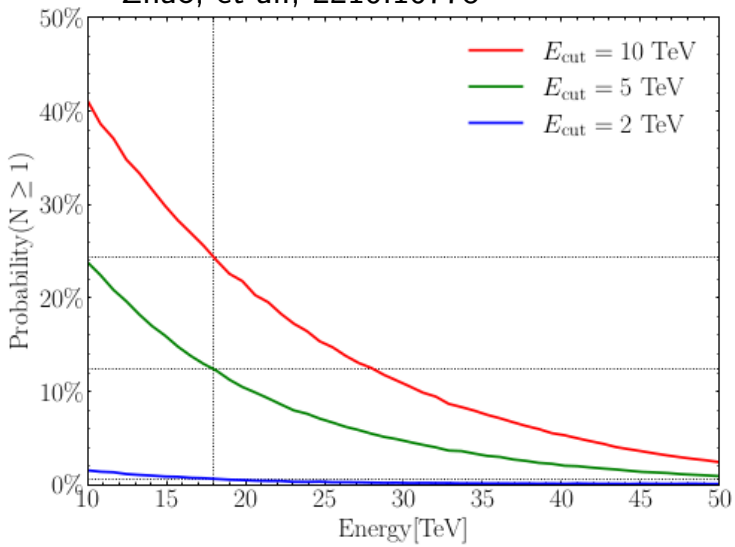
$$\Phi = \Phi_0 \, \mathrm{Exp}[-\tau(E, z)]$$

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., 2210.07172



Zhao, et al., 2210.10778

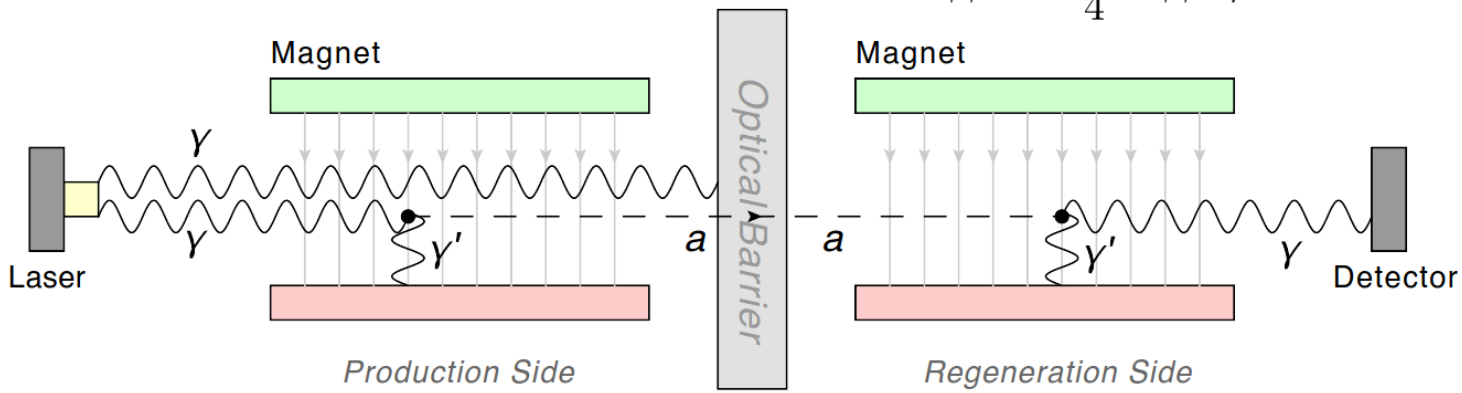


BSM Explanations

- BSM can come in handy for effective reduction of the optical depth τ

- analogy with light-shining-through-walls experiments

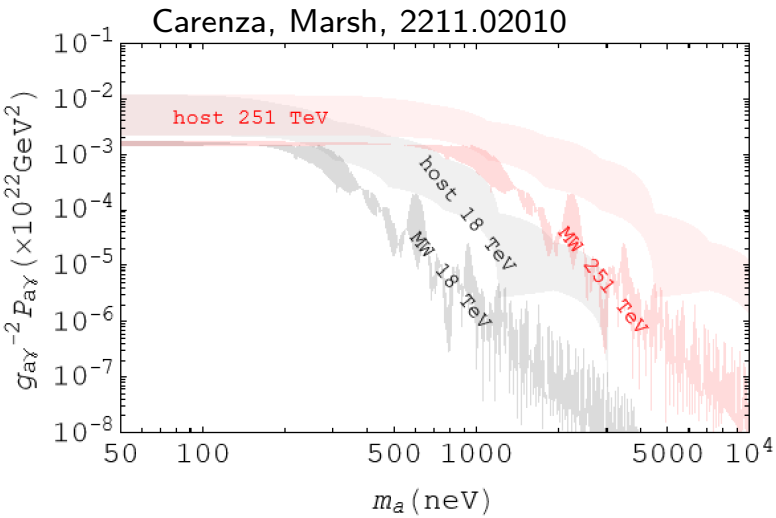
$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4}\, g_{a\gamma\gamma}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu}\, a = g_{a\gamma\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$$



BSM Explanations

- ALPs: 2210.05659, 2210.08841, 2210.10022, 2210.13120, 2210.15857, 2210.07172, 2211.02010, 2211.06935, 2304.01819, 2305.05145, 2307.08313, 2307.10382
- Sterile Neutrinos: 2210.14178, 2211.00634, 2211.02028
- LIV: 2210.06338, 2210.11261, 2211.01836, 2212.02436, 2306.02962, 2307.14256, 2308.03031
- Others: 2212.03477, 2301.02258, 2308.06172

ALPs

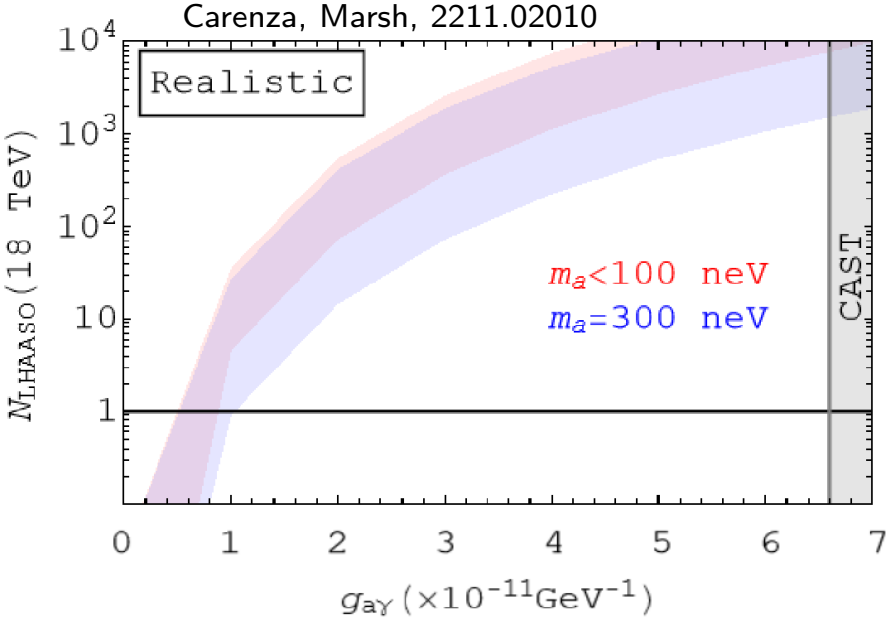


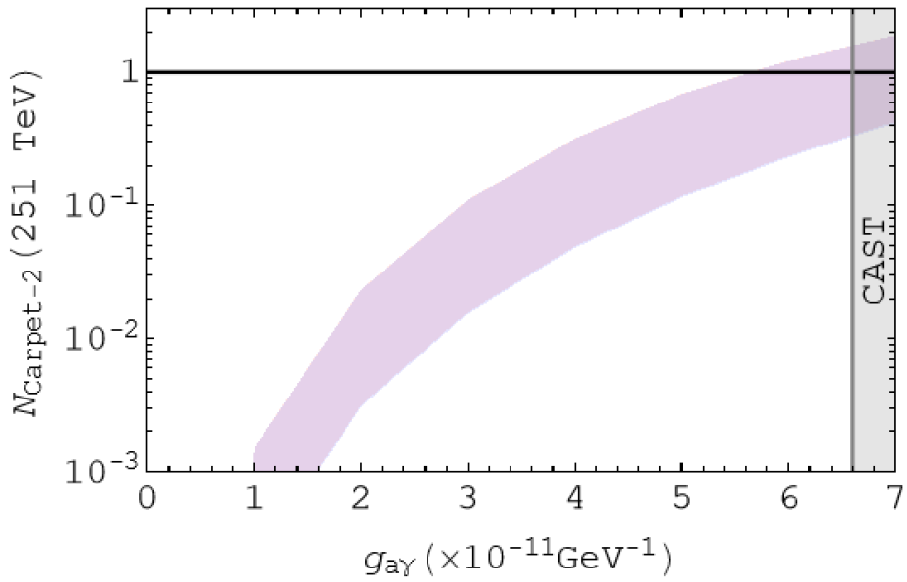
- γ to ALP conversion
  - in the jet
  - in the host galaxy
  - in the extragalactic space
- ALP to γ conversion in the Milky Way

- various scenarios involving ALPs reviewed in 2211.02010 and 2211.06935

ALPs

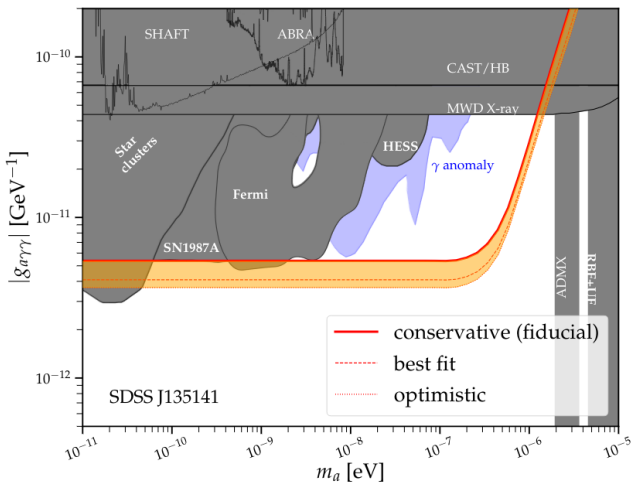
Carenza, Marsh, 2211.02010





- extrapolation of the flux measured by Fermi to higher energies
- time dependence of the flux during observations?
- LHAASO-KM2A and CARPET-2 flux measurements are essential

2203.04319



Sterile Neutrino

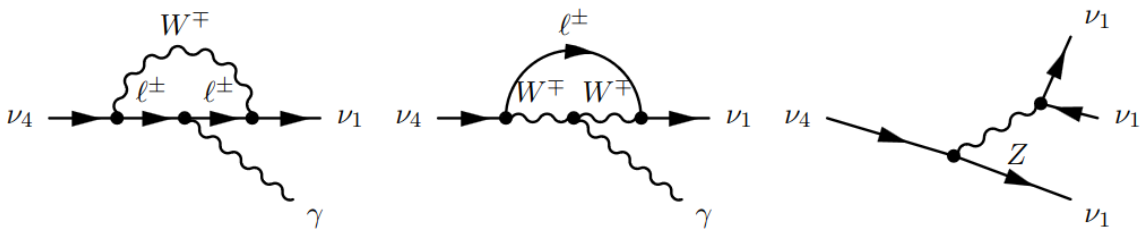
- neutrino origin of high-energy GRB γ
- IceCube set constraints on the ν flux

TITLE: GCN CIRCULAR
NUMBER: 32665
SUBJECT: GRB 221009A: Upper limits from a neutrino search with IceCube
DATE: 22/10/10 16:43:52 GMT
FROM: Jessie Thwaites at IceCube/U Wisc-Madison <thwaites@wisc.edu>

The IceCube Collaboration (http://icecube.wisc.edu/) reports:

IceCube has performed a search for track-like muon neutrino events arriving from the direction of GRB 221009A (GCN Circular 32632<https://gcn.gsfc.nasa.gov/gcn3/32632.gcn3> (Swift); 32636<https://gcn.gsfc.nasa.gov/gcn3/32636.gcn3> (Fermi-GBM)) in a time range of -1 hour/+2 hours from the initial trigger reported by Fermi-GBM (T0=2022-10-09 13:16:59.99 UTC) during which IceCube was collecting good quality data. Zero track-like events are found coincident with the position of the GRB. We accordingly derive a time-integrated muon-neutrino flux upper limit for this source of E^2 dN/ dE = 3.9 x 10^-2 GeV cm^-2 at 90% CL, under the assumption of an E^-2 power law. 90% of events IceCube would detect from a source at this declination with an E^-2 spectrum have energies in the approximate energy range between 800 GeV and 1 PeV.

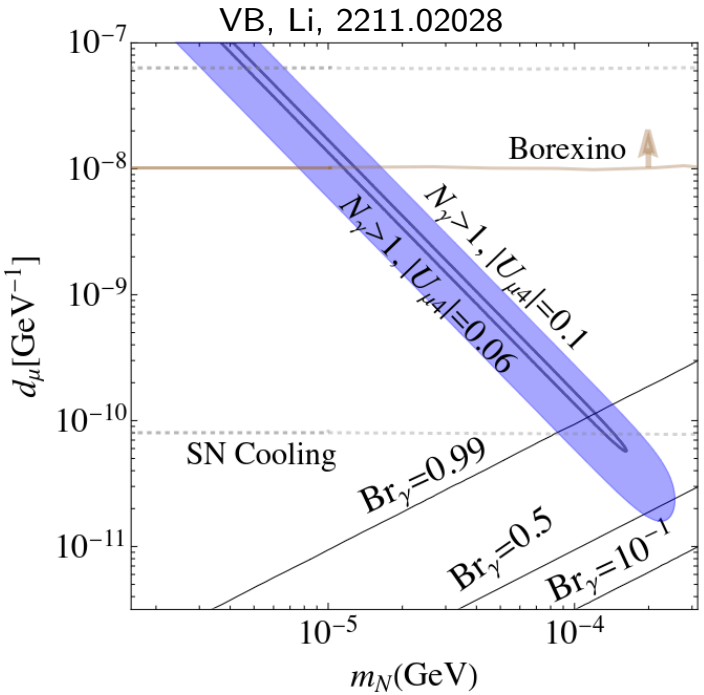
- ν_s flux suppressed by $\sin^2\theta$ with respect to the active one
- ν_s decay to a neutrino and a photon in the Milky Way
- scenario with $\mathcal{O}$(MeV) ν_s studied in 2211.00634
- additional BSM that increases $Br(\nu_s \to \nu\gamma)$ required (left-right, Zee?) for explaining 18 TeV LHAASO event

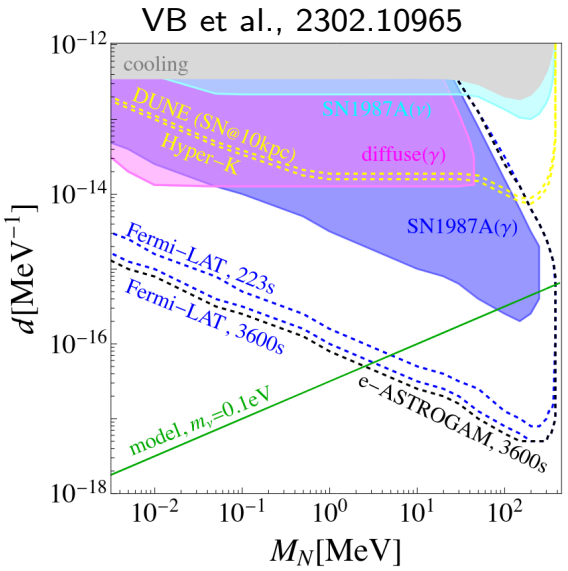


Sterile Neutrino

- scenario with sub-MeV ν_s studied in 2211.02028
- additional BSM required $\Rightarrow$ utilize different ν_s mass dependence in Γ

$$\mathcal{L} \supset d_\mu \overline{\nu_{\mu L}} \sigma_{\mu\nu} F^{\mu\nu} N + \frac{1}{2} m_N \overline{N}^c N + y \overline{L_\mu} \tilde{H} N + \text{h.c.}$$

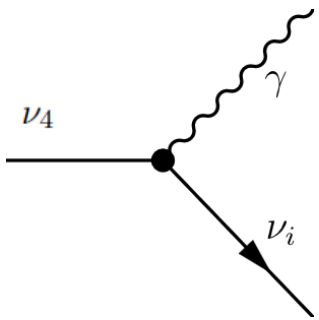




$$\Gamma_N^{(3,U_{\mu4})} \approx \frac{G_F^2 m_N^5}{64\pi^3} |U_{\mu4}|^2 ,$$

$$\Gamma_N^{(2,U_{\mu4})} \approx \frac{9\alpha G_F^2 m_N^5}{512\pi^4} |U_{\mu4}|^2 ,$$

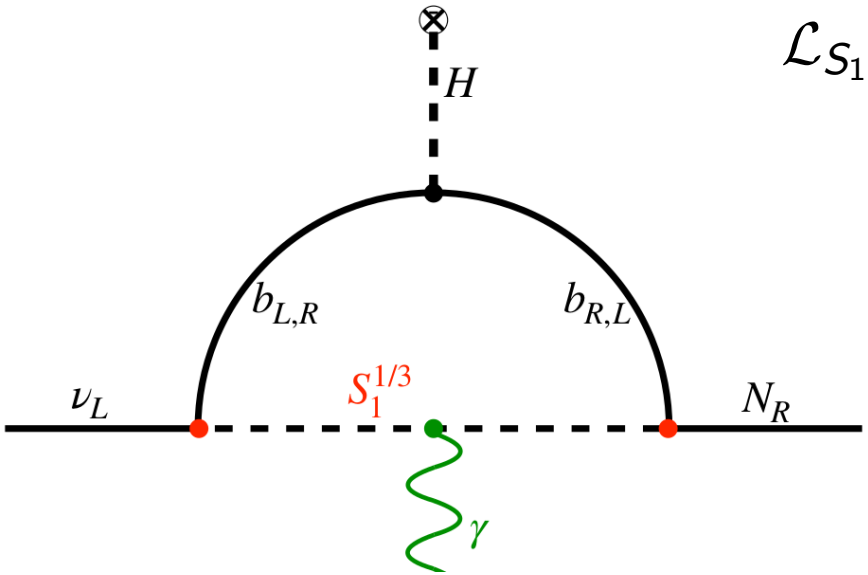
$$\Gamma_N^{(2,d_\mu)} \approx \frac{|d_\mu|^2 m_N^3}{4\pi} .$$



- non-standard cosmology required (to address $\sin^2\theta \lesssim 10^{-2}$)

The Model

- consider TeV-scale scalar leptoquark $S_1 \sim (\bar{3}, 1, 1/3)$
- assume dominant coupling with the third family of quarks
- benefits: (i) avoiding large Yukawa suppression in radiatively induced μ_ν
  (ii) addressing flavor anomalies



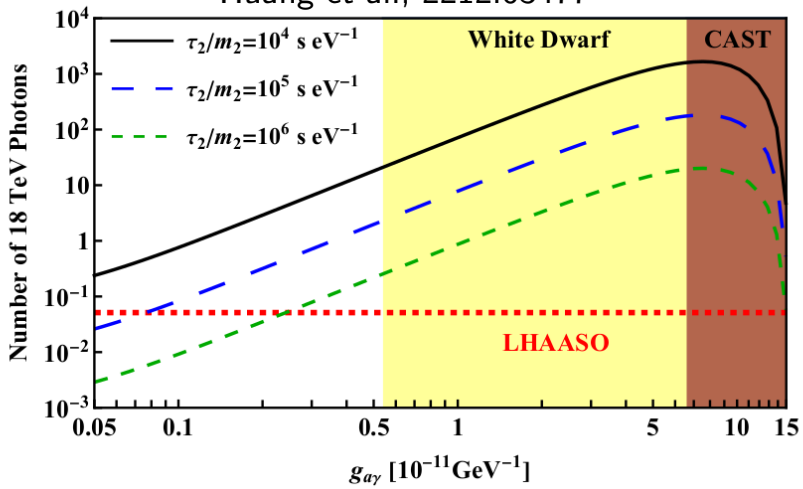
$$\mathcal{L}_{S_1} \supset y_1 \, \overline{b_R^c} \, N_R \, S_1 + y_2 \, \overline{Q_L^3} \, L_L^{i\,c} \, S_1^\dagger + \text{h.c.}$$

$$d \approx \frac{e\, y_1 y_2}{8\pi^2 m_{LQ}^2} \, m_b \log \frac{m_b^2}{m_{LQ}^2}$$

ALP & Neutrino

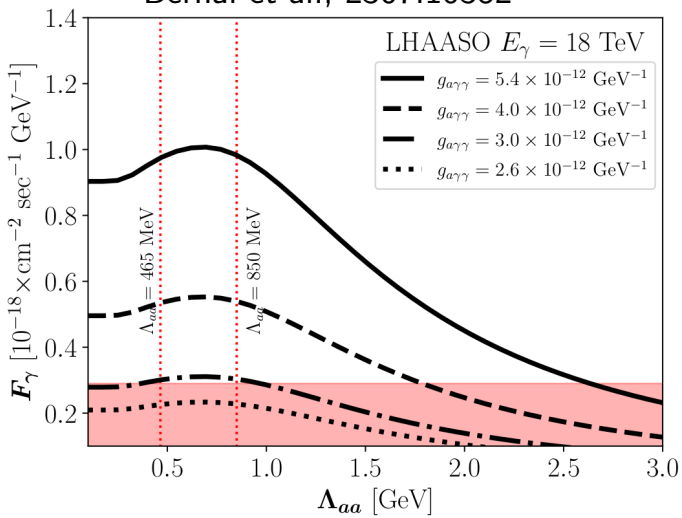
- ν from GRB 221009A decays to ALPs
- ALP converts to γ in the galactic magnetic field

Huang et al., 2212.03477



- neutrino scatters on CνB ($\nu\nu \to aa$)
- ALP converts to γ in the galactic magnetic field

Bernal et al., 2307.10382



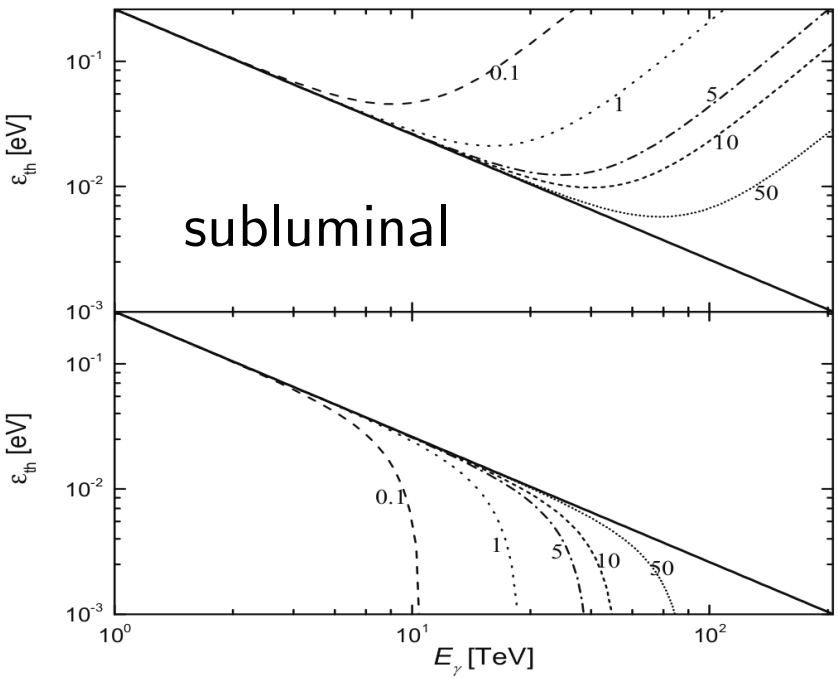
Lorentz Invariance Violation (LIV)

$$E^2 - p^2c^2 - m^2c^4 \simeq \pm E^2 \left(\frac{E}{\xi_n E_{\rm Pl}}\right)^n$$

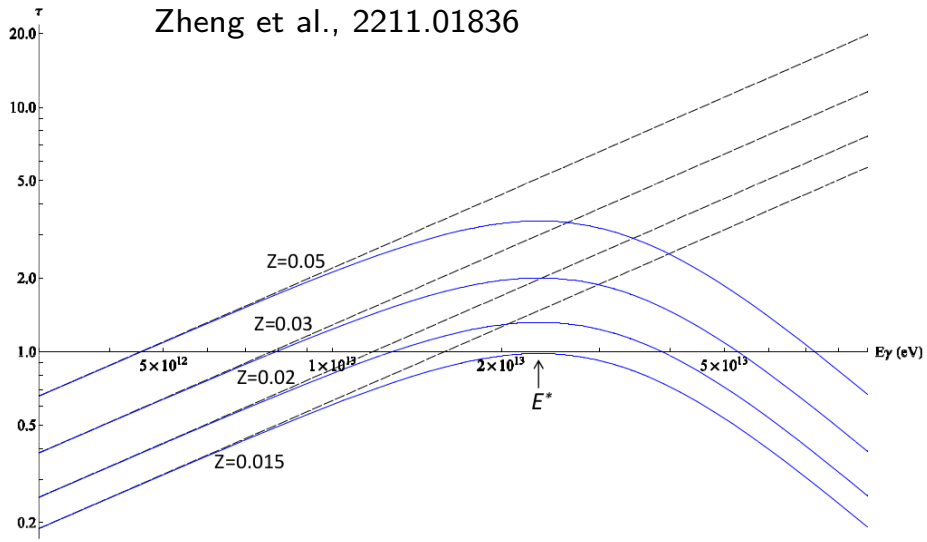
- modification of the threshold for the $\gamma\gamma$ pair production interaction $(\gamma + \gamma \to e^+ + e^-)$

$$E_{\rm thr} = \frac{m_e^2}{E_\gamma} \mp \frac{1}{4}(1 - 2^{-n}) \left(\frac{E_\gamma}{\xi_n E_{\rm Pl}}\right)^n E_\gamma$$

Jacob and Piran, 0810.1318



Zheng et al., 2211.01836



Summary

- among all detected GRBs to date, GRB 221009A broke the record for both the highest flux and the highest photon energy detected
- given the distance of the source and the $\gtrsim 10$ TeV energies involved, the optical depth, τ, may appear too large $\Rightarrow$ attenuation of the γ flux
- while the no-new-physics explanation is by no means strongly disfavored, several BSM explanations aid in the reduction of τ
- these new physics scenarios involve ALPs, sterile neutrinos and models with Lorentz invariance violation