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INAF – IASF-MI

GRB multi-TeV detection: Beyond standard physics?

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ASTRI and LHAASO Workshop

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Outline

- GRB 221009A
- Axion-like particles
- Results with ALP model
- Lorentz Invariance Violation
- Results with LIV model
- Conclusions

GRB 221009A

GRB 221009A

- Extremely luminous Gamma Ray Burst (GRB) at $z = 0.151$
- Observed by:
  - Swift, Fermi
  - LHAASO at $E \simeq 18$ TeV within 2000 s after the initial burst
  - Carpet-2 at $E \simeq 251$ TeV at 4536 s after Fermi-GBM trigger

BUT **strong EBL absorption** for $E \gtrsim 14$ TeV at $z = 0.151$ within Conventional Physics (CP)

EBL	15 TeV		18 TeV		100 TeV		251 TeV	
	τ_{CP}	P_{CP}	τ_{CP}	P_{CP}	τ_{CP}	P_{CP}	τ_{CP}	P_{CP}
FR	10.1	4×10^{-5}	14.1	7×10^{-7}	333	2×10^{-145}	15411	~0
G	9.4	8×10^{-5}	13.1	2×10^{-6}	246	2×10^{-107}	9502	~0
SL	12.8	3×10^{-6}	18.3	10^{-8}	220	3×10^{-96}	>9251	~0

τ_{CP} -> optical depth; P_{CP} -> photon survival probability
FR -> EBL model by Franceschini & Rodighiero 2017
G -> EBL model by Gilmore et al. 2012
SL -> EBL model by Saldana-Lopez et al. 2021

Warning!!!

- Our **results** are **based on**:
  - **LHAASO** event @ 18 TeV
  - Possible **Carpet-2** event @ 251 TeV

More **solid conclusions** will be drawn **when** the **SED** is **known**

QUESTION:

How can we have detected this GRB at $E \simeq 18$ TeV, 251 TeV?

ANSWER:

with **axion-like particles (ALPs)** !!!

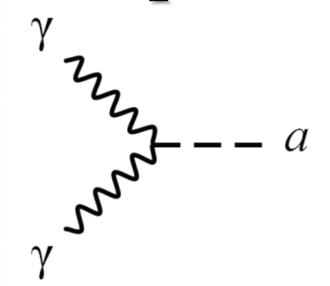
G. Galanti, L. Nava, M. Roncadelli and F. Tavecchio, arXiv:2210.05659

Axion-like particles

Axion-like particles (ALPs)

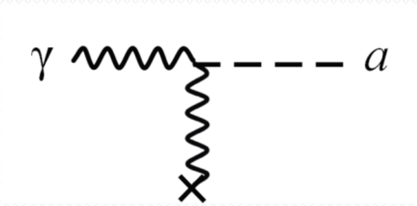
- Predicted by String Theory
- Very light particles a ($m_a < 10^{-8}$ eV)
- Spin 0
- **Interaction with** two **photons** (coupling $g_{a\gamma\gamma}$)
- Interactions with other particles discarded
- Possible candidate for dark matter
- Induce the **change of the polarization state** of photons

Two photons



$$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$$

In an external B field

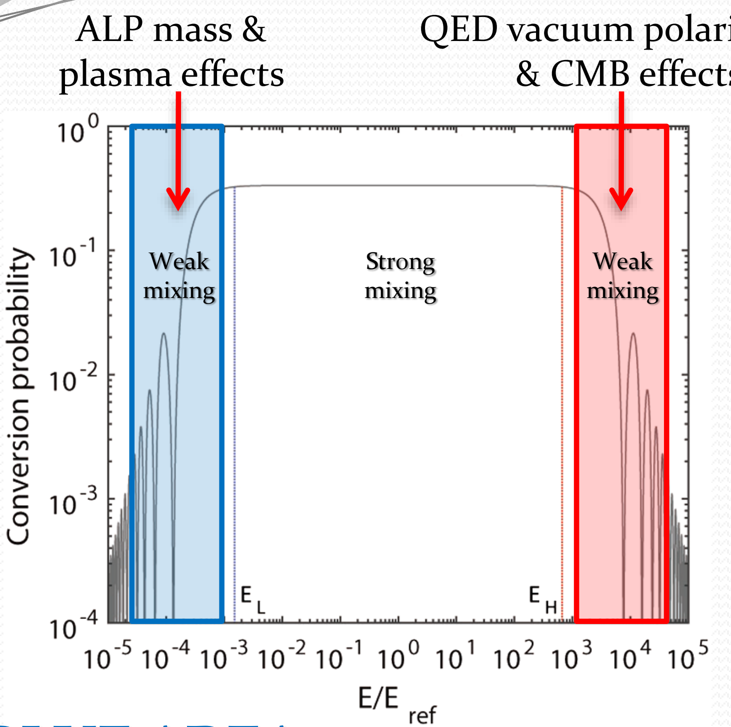


Photon-ALP oscillations

ALPs in astrophysical contest

- ALPs very **elusive** in laboratory experiments (low coupling) → **astrophysical environment** is the **best opportunity** to study ALPs and ALP effects (*for free*)
- Photon/ALP beam in the VHE band $E >> m_a$
- For E < 10 GeV → negligible photon absorption due to EBL
  - **Photon-ALP interaction** produces effective **photon absorption**
- For E > 10 GeV → photons absorbed by EBL ($\gamma\gamma \rightarrow e^+e^-$), **ALPs** are **not absorbed**
  - **Photon-ALP oscillations increase medium transparency**
- **HINTS** at ALP existence:
  - Explain how flat spectrum radio quasars (FSRQs) can emit up to 400 GeV
    F. Tavecchio, M. Roncadelli, G. Galanti and G. Bonnoli, Phys. Rev. D, 86, 085036 (2012) [arXiv: 1202.6529].
  - Solve the anomalous redshift dependence of blazar spectra
    G. Galanti, M. Roncadelli, A. De Angelis, G. F. Bignami, MNRAS 493, 1553 (2020) [arXiv: 1503.04436].
  - GRB 221009A?
    G. Galanti, L. Nava, M. Roncadelli and F. Tavecchio, arXiv:2210.05659.

ALP-induced irregularities



- Photon-ALP conversion probability $P_{\gamma\to a}(E, m_a, g_{a\gamma\gamma}, B)$

- Highlighted zones predict **spectral irregularities** and **polarization features** in observational data

- Constraints on $g_{a\gamma\gamma}$ and m_a but the firmest is $g_{a\gamma\gamma} < 6.6 \times 10^{-11}$ GeV^{-1} for $m_a < 0.02$ eV (CAST collaboration, 2017)

BLUE AREA:

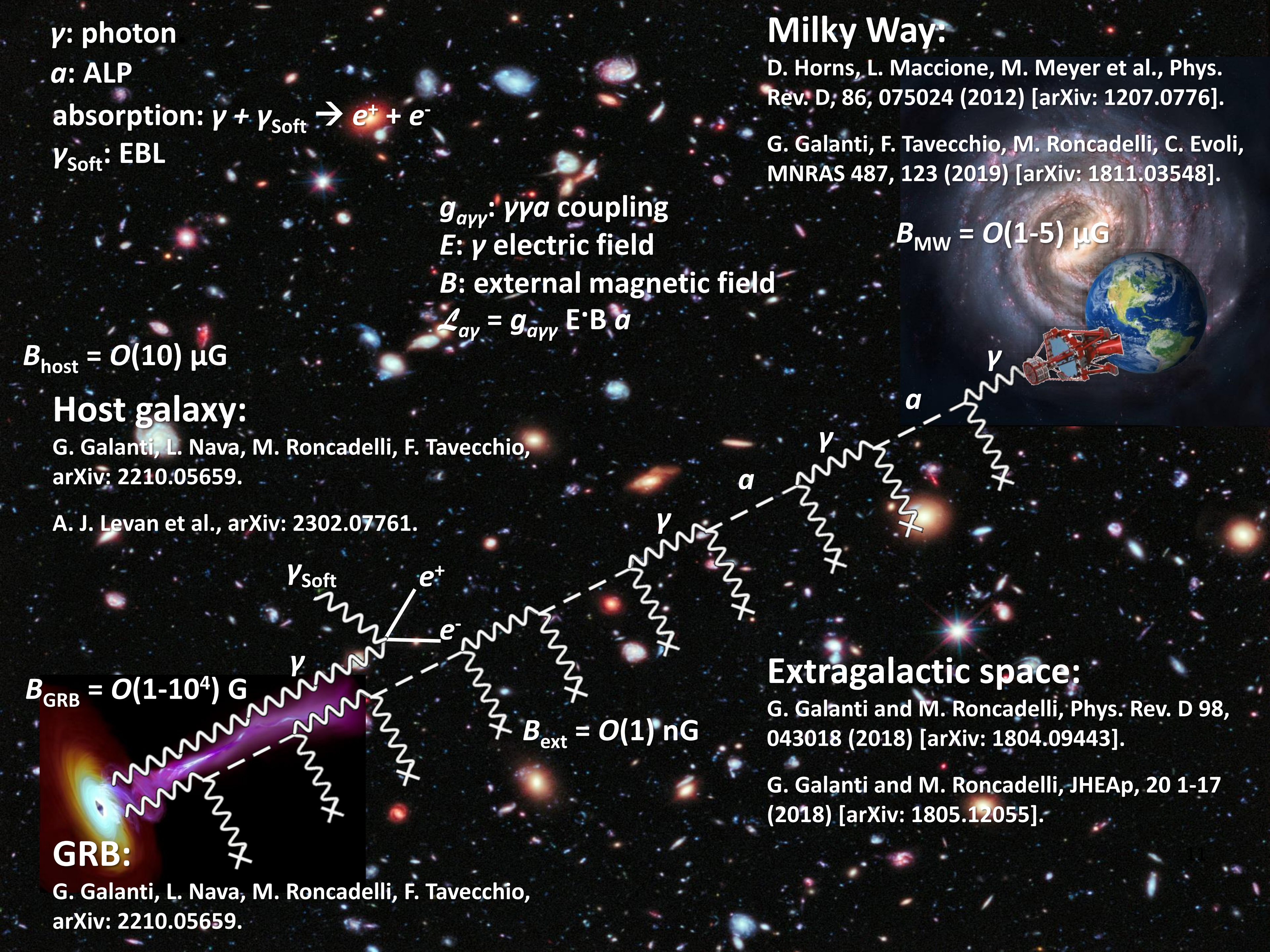
- Spectral effects investigated in:
  D. Wouters, P. Brun, Phys. Rev. D 86, 043005 (2012).
  Fermi-LAT Collaboration, Phys. Rev. Lett. 116, 161101 (2016).
  CTA Consortium, JCAP 02, 048 (2021).

- Polarization effects studied in:
  G. Galanti, Phys. Rev. D 107, 043006 (2023).
  G. Galanti, M. Roncadelli, F. Tavecchio, E. Costa, arXiv:2202.12286.

RED AREA:

- Spectral effects investigated in:
  G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, MNRAS 487, 123 (2019) [arXiv:1811.03548].
  G. Galanti, F. Tavecchio, M. Landoni, MNRAS 491, 5268 (2020) [arXiv:1911.09056].

- Polarization effects studied in:
  G. Galanti, Phys. Rev. D 107, 043006 (2023) [arXiv:2202.11675].



γ: photon
a: ALP
absorption: $\gamma + \gamma_{Soft} \rightarrow e^{+} + e^{-}$
γ_{Soft}: EBL
$g_{a\gamma\gamma}$: $\gamma\gamma a$ coupling
E: γ electric field
B: external magnetic field
$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}\, \mathrm{E} \cdot \mathrm{B}\, a$
Milky Way:
D. Horns, L. Maccione, M. Meyer et al., Phys. Rev. D, 86, 075024 (2012) [arXiv: 1207.0776].
G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, MNRAS 487, 123 (2019) [arXiv: 1811.03548].
$B_{MW} = O(1\text{-}5)\ \mu G$
$B_{host} = O(10)\ \mu G$
Host galaxy:
G. Galanti, L. Nava, M. Roncadelli, F. Tavecchio, arXiv: 2210.05659.
A. J. Levan et al., arXiv: 2302.07761.
γ_{Soft}
e^{+}
e^{-}
γ
a
$B_{GRB} = O(1\text{-}10^{4})$ G
$B_{ext} = O(1)$ nG
Extragalactic space:
G. Galanti and M. Roncadelli, Phys. Rev. D 98, 043018 (2018) [arXiv: 1804.09443].
G. Galanti and M. Roncadelli, JHEAp, 20 1-17 (2018) [arXiv: 1805.12055].
GRB:
G. Galanti, L. Nava, M. Roncadelli, F. Tavecchio, arXiv: 2210.05659.

γ-ALP conversion for GRB 221009A

GRB:

- **Negligible** γ-ALP conversion even with parameters maximizing $P_{\gamma \to a}$
  - B'_{GRB} = 2 G, distance $R = 2 \times 10^{17}$ cm, $\Gamma = 45$ at $t \sim 2000$ s
  - → γ-ALP beam propagation length $\Delta R' \sim R/\Gamma \sim 5 \times 10^{15}$ cm

Host Galaxy:

- **Disk-like galaxy** observed **edge-on** with **GRB** in the **center** (Levan+2023). We take:
  - i) **Starburst** galaxy -> M82 as a model (Lopez-Rodriguez+2021) -> $B_{host} = O(20\text{-}50)$ μG
  - ii) **Spiral** galaxy (Beck2016) -> $B_{host} = O(5\text{-}10)$ μG

Extragalactic space:

- **Domain-like model** for B_{ext} (Galanti & Roncadelli, 2018) -> limits: 10^{-7} nG < B_{ext} < 1.7 nG on $L_{dom} = O(1)$ Mpc (Pshirkov+2016). We take:
  - i) **B_{ext} = 1 nG** with 0.2 Mpc < L_{dom} < 10 Mpc: **favored** by (Rees & Setti, 1968; Kronberg+1999)
  - ii) **$B_{ext} < 10^{-15}$ G** -> very **conservative** scenario

Milky Way:

- B_{MW} **map by Jansson & Farrar** (Jansson & Farrar, 2012a,b)

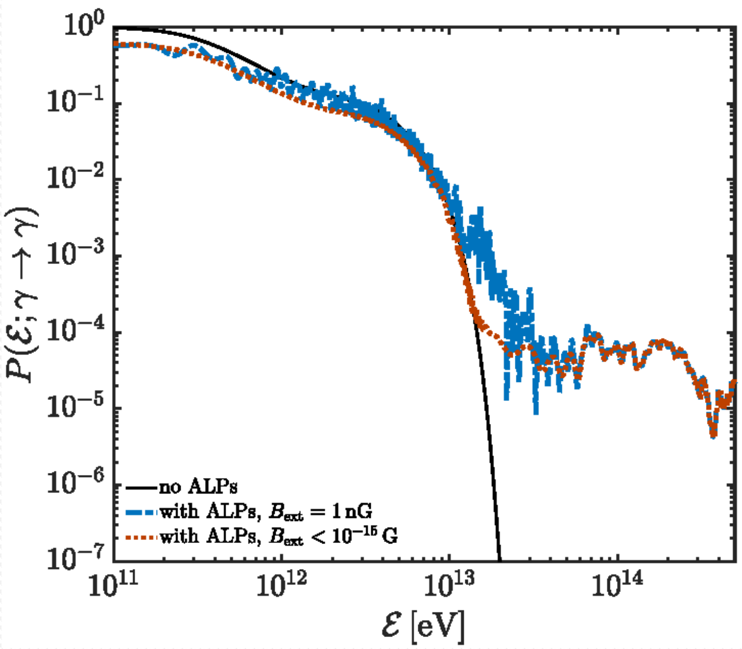
Total Effect:

- γ–ALP interaction in **all media** → **final photon survival probability** P_{ALP}

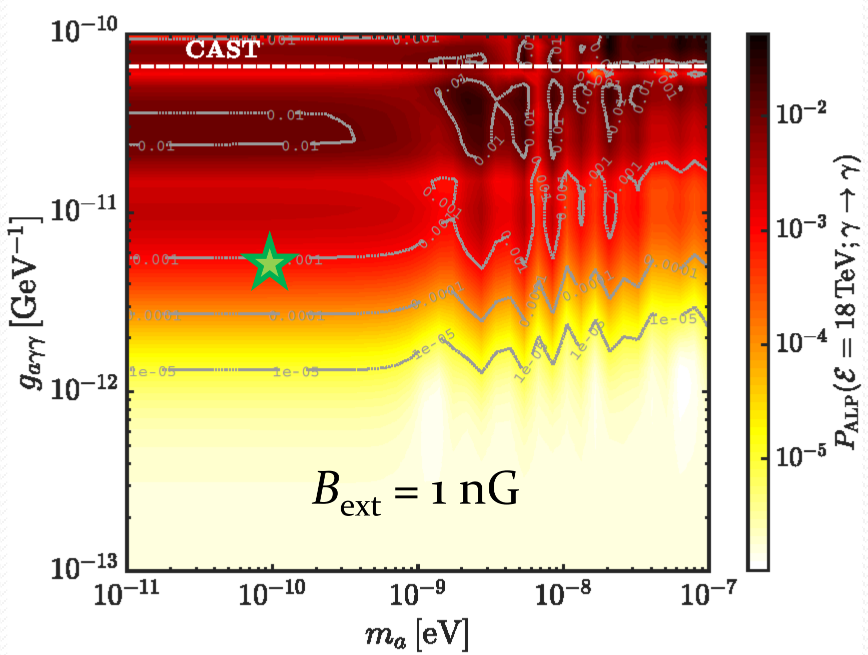
G. Galanti, L. Nava, M. Roncadelli and F. Tavecchio, arXiv:2210.05659

Results with ALP model

ALP effect – Starburst galaxy



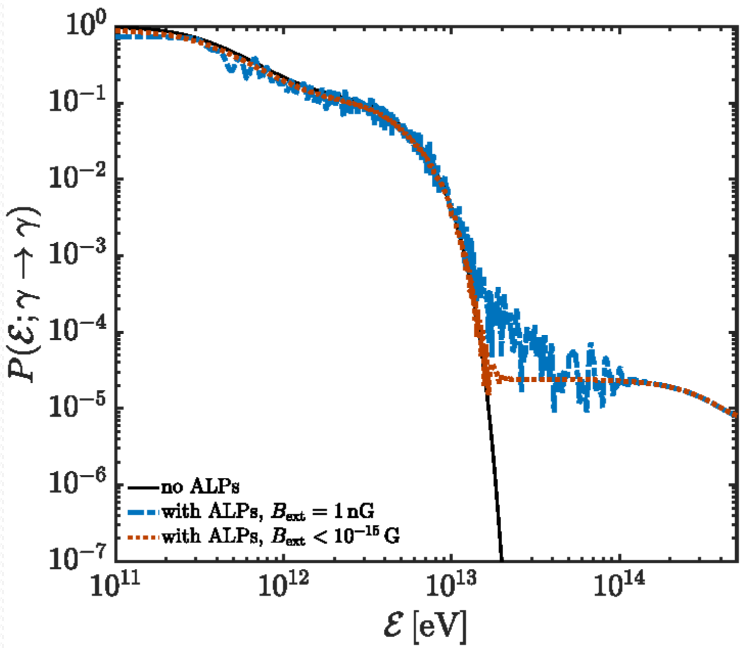
- $P_{\rm CP}(E, \gamma \to \gamma)$:
  - @ 15 TeV → ~4 x 10^{-4}
  - @ 18 TeV → ~7 x 10^{-7}
  - @ 100 TeV → ~2 x 10^{-145}
  - @ 251 TeV → ~0
- $P_{\rm ALP}(E, \gamma \to \gamma)$:
  - @ 15 TeV → ~**3 x 10^{-3}**
  - @ 18 TeV → ~**9 x 10^{-4}**
  - @ 100 TeV → ~7 x 10^{-5}
  - @ 251 TeV → ~5 x 10^{-5}



- CAST bound (CAST collaboration, 2017)
  - $g_{a\gamma\gamma} < 6.6 \times 10^{-11}$ GeV^{-1} for $m_a < 0.02$ eV
- Most stringent bound (Dessert+2022)
  - $g_{a\gamma\gamma} < 5.4 \times 10^{-12}$ GeV^{-1} for $m_a < 3 \times 10^{-7}$ eV
- We take $g_{a\gamma\gamma} = 5 \times 10^{-12}$ GeV^{-1}; $m_a = 10^{-10}$ eV
  - **Explain** both **LHAASO** and **Carpet-2**
  - **Compatible with other ALP hints**

G. Galanti, L. Nava, M. Roncadelli and F. Tavecchio, arXiv:2210.05659

ALP effect – Spiral galaxy



- $P_{\rm CP}(E, \gamma \to \gamma)$:
  - @ 15 TeV → ~4 x 10^{-4}
  - @ 18 TeV → ~7 x 10^{-7}
  - @ 100 TeV → ~2 x 10^{-145}
  - @ 251 TeV → ~0
- $P_{\rm ALP}(E, \gamma \to \gamma)$:
  - @ 15 TeV → ~**3 x 10^{-4}**
  - @ 18 TeV → ~**2 x 10^{-4}**
  - @ 100 TeV → ~3 x 10^{-5}
  - @ 251 TeV → ~2 x 10^{-5}

- CAST bound (CAST collaboration, 2017)
  - $g_{a\gamma\gamma} < 6.6 \times 10^{-11}$ GeV^{-1} for $m_a < 0.02$ eV
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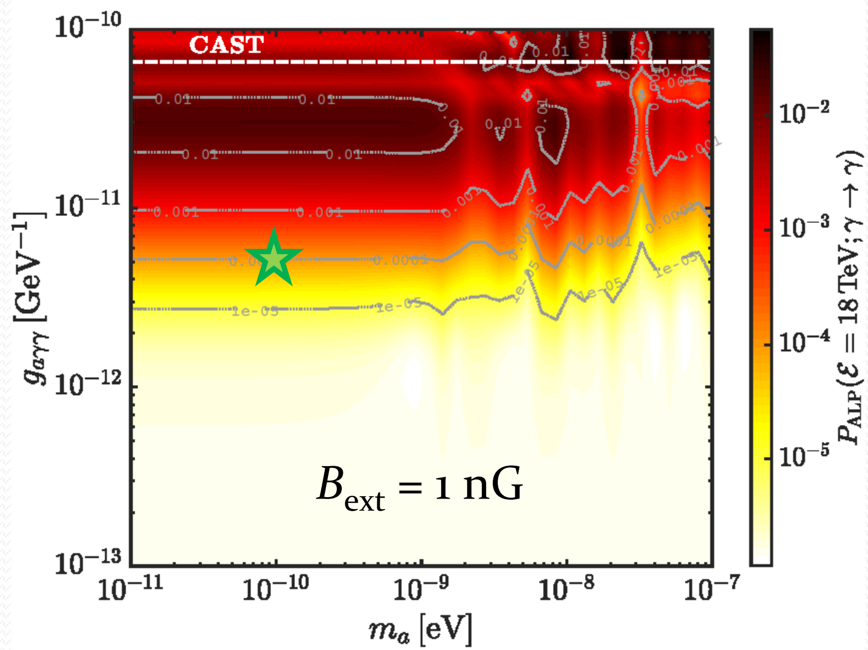


G. Galanti, L. Nava, M. Roncadelli and F. Tavecchio, arXiv:2210.05659

Lorentz Invariance Violation

Lorentz Invariance Violation (LIV)

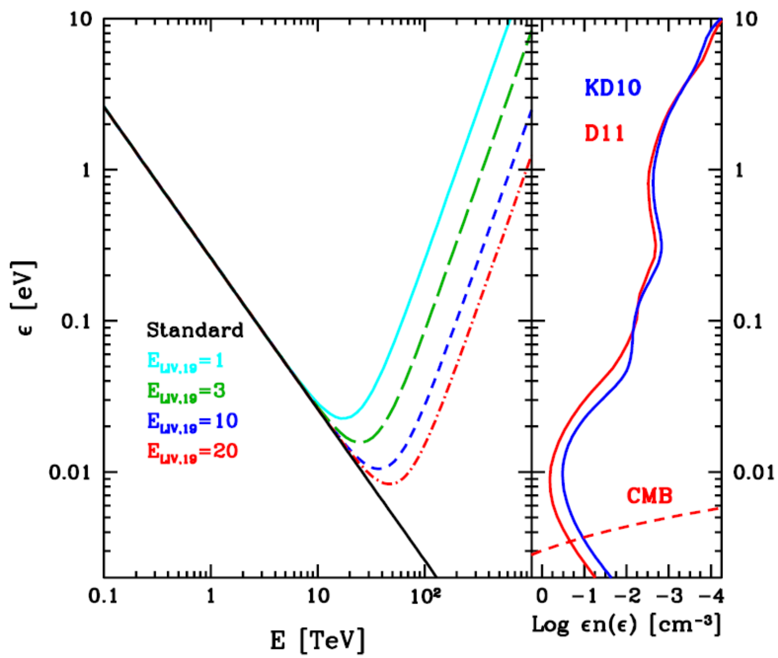
- Predicted by quantum gravity models for $E > 10^{19}$ GeV (Mattingly 2005)

- Effects on standard physics processes (Coleman&Glashow 1999; Jacobson+2003; Liberati 2013):
  - Photon decay
  - Photon splitting
  - **Modification of dispersion relations**

- **Modified photon dispersion relation**

$$E^2 - p^2 = -\frac{E^{n+2}}{E_{\mathrm{LIV}}^n}$$

E -> energy
p -> momentum
E_{LIV} -> LIV parameter

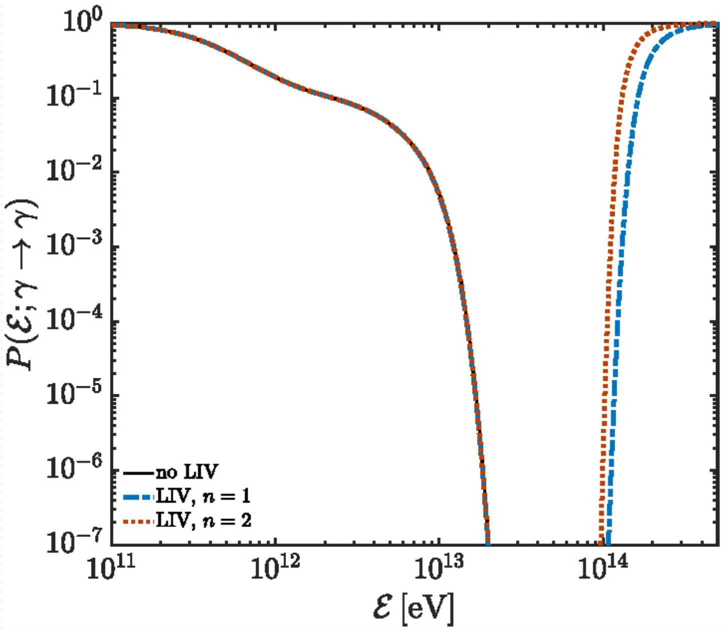


F. Tavecchio and G. Bonnoli, A&A 585, A25 (2016)

- → **Modification** of the **threshold** of the γγ → e^+e^- process
  - Hundreds-TeV photons interact with optical/UV photons
  - **Smaller** photon absorption

Results with LIV model

LIV effect



- $P_{CP}(E, \gamma \rightarrow \gamma)$:
  - @ 15 TeV → ~4 x 10^{-4}
  - @ 18 TeV → ~7 x 10^{-7}
  - @ 100 TeV → ~2 x 10^{-145}
  - @ 251 TeV → ~0
- $P_{\mathrm{LIV},\, n=1}(E, \gamma \rightarrow \gamma)$:
  - @ 15 TeV → ~ as in CP
  - @ 18 TeV → ~ as in CP
  - @ 100 TeV → ~5 x 10^{-10}
  - @ 251 TeV → **~0.68**
- $P_{\mathrm{LIV},\, n=2}(E, \gamma \rightarrow \gamma)$:
  - @ 15 TeV → ~ as in CP
  - @ 18 TeV → ~ as in CP
  - @ 100 TeV → ~2 x 10^{-6}
  - @ 251 TeV → **~0.91**

- LIV bounds (Lang+2019)
  - $E_{\mathrm{LIV},\, n=1} > 10^{20}$ GeV
  - $E_{\mathrm{LIV,\, n=2}} > 2 \times 10^{12}$ GeV
- We take
  - $E_{\mathrm{LIV},\, n=1} = 3 \times 10^{20}$ GeV
  - $E_{\mathrm{LIV,\, n=2}} = 5 \times 10^{12}$ GeV

- LIV-induced modifications sizable above ~40 TeV
  - **cannot explain LHAASO** event
  - effective to **explain Carpet-2** event (if real event not too far from E ~ 251 TeV)

G. Galanti, L. Nava, M. Roncadelli and F. Tavecchio, arXiv:2210.05659

Conclusions

Conclusions

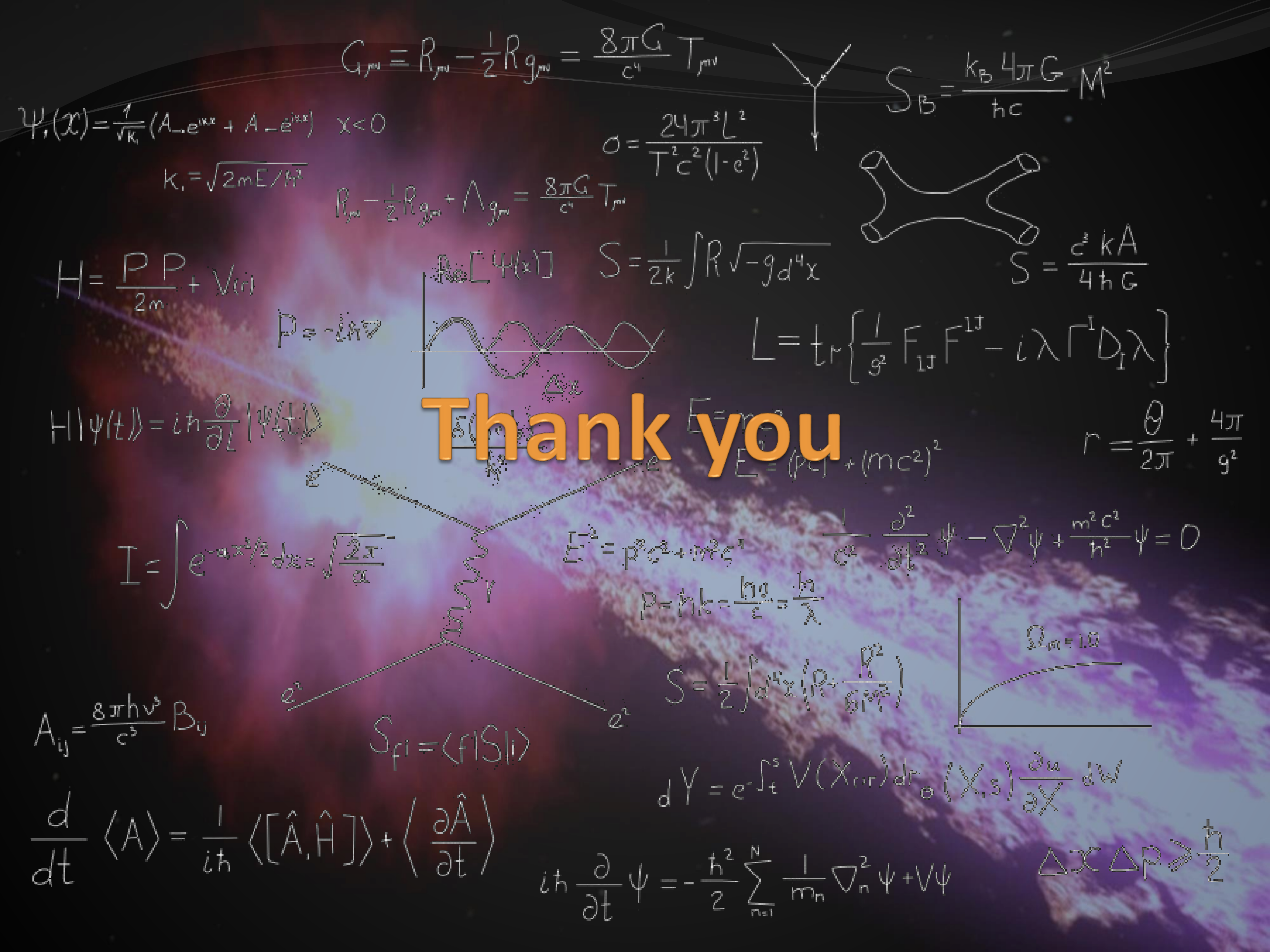
- **GRB 221009A challenges conventional physics** (CP)
  - Event @ 18 TeV (**LHAASO**) → **very problematic** within CP
  - Event @ 251 TeV (**Carpet-2**) → **unexplainable** by CP

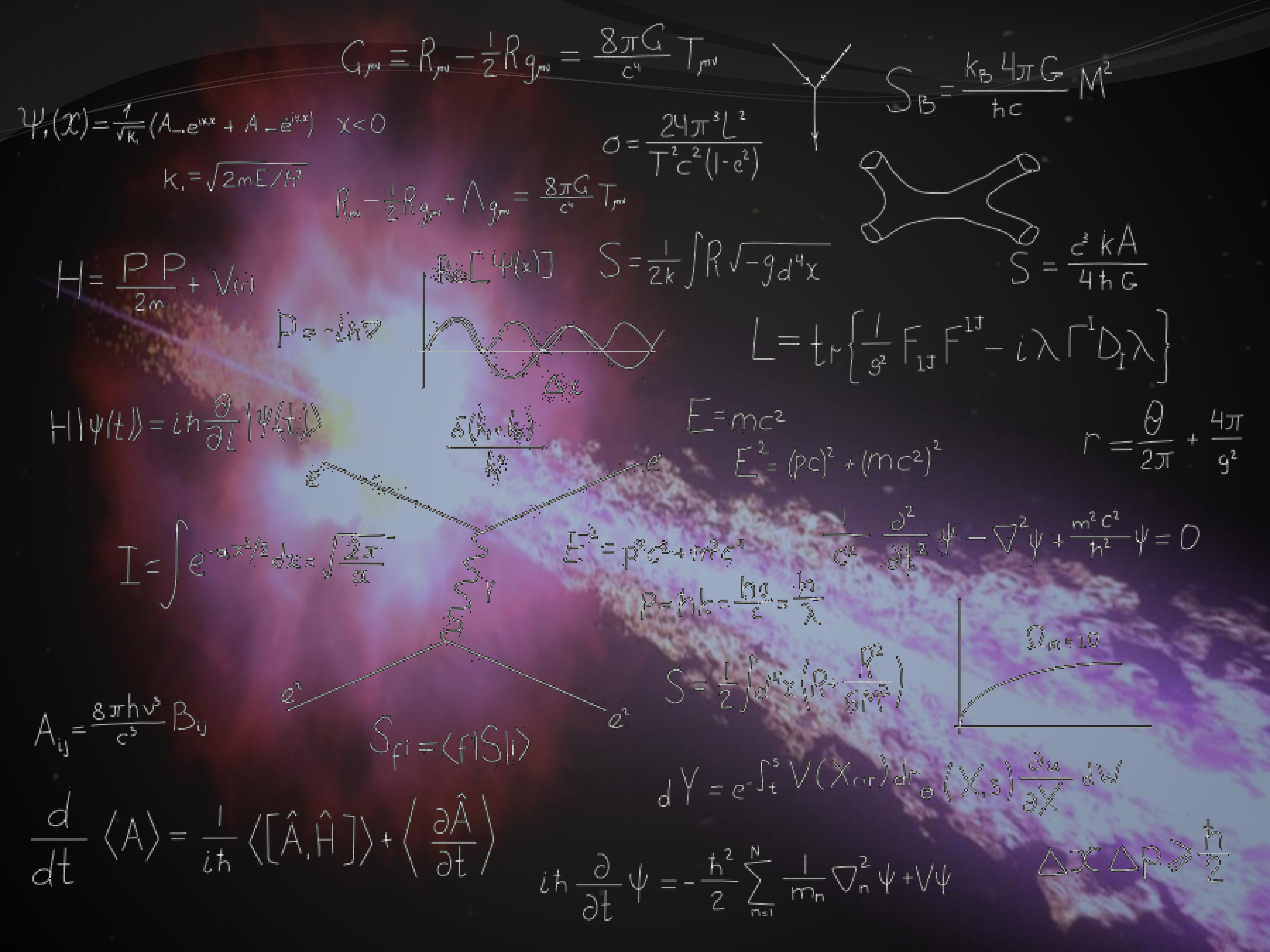
- **ALPs** can **explain both the detections**
  - Within current bounds about $g_{a\gamma\gamma}$ and m_a
  - Same ALP parameters used in previous hints at ALPs

- **LIV not satisfactory**
  - **Cannot explain LHAASO** detection
  - Very effective to **justify Carpet-2** event

- **FINAL QUESTION:** Possible first **ALP indirect detection**?

Thank you





$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
$S_B = \frac{k_B 4\pi G}{\hbar c} M^2$
$x < 0$
$k_1 = \sqrt{2mE/\hbar^2}$
$\sigma = \frac{24\pi^3 L^2}{T^2 c^2 (1-e^2)}$
$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
$S = \frac{1}{2k} \int R \sqrt{-g} d^4x$
$S = \frac{c^3 kA}{4\hbar G}$
$H = \frac{P P}{2m} + V(r)$
$L = tr\{\frac{1}{g^2} F_{IJ} F^{IJ} - i\lambda \Gamma^I D_I \lambda\}$
$E = mc^2$
$E^2 = (pc)^2 + (mc^2)^2$
$r = \frac{\theta}{2\pi} + \frac{4\pi}{g^2}$
$\frac{1}{c^2} \frac{\partial^2}{\partial t^2} \psi - \nabla^2 \psi + \frac{m^2 c^2}{\hbar^2} \psi = 0$
$A_{ij} = \frac{8\pi h \nu^3}{c^3} B_{ij}$
$S_{fi} = \langle f | S | i \rangle$
$\frac{d}{dt} \langle A \rangle = \frac{1}{i\hbar} \langle [\hat{A}, \hat{H}] \rangle + \langle \frac{\partial \hat{A}}{\partial t} \rangle$
$i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2} \sum_{n=1}^{N} \frac{1}{m_n} \nabla_n^2 \psi + V\psi$
$\Delta x \Delta p \geq \frac{\hbar}{2}$