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Axion-like Particles and Lorentz Invariance Violation

AVENGe – Advances in Very-High Energy Astrophysics with Next-Generation Cherenkov Telescopes

Roma, 31 May 2023

Outline

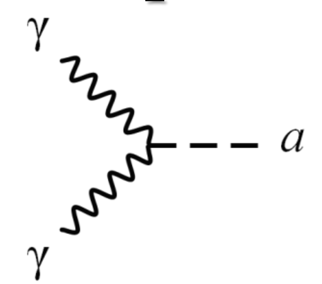
- Axion-like Particles
- ALPs with CTA & ASTRI
- Lorentz Invariance Violation
- LIV with CTA & ASTRI
- ASTRI & LHAASO and… the future
- Conclusions

Axion-like Particles

Axion-like Particles (ALPs)

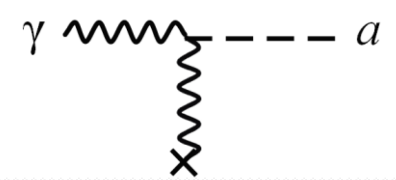
- Predicted by String Theory
- Very light particles ($m_a < 10^{-8}$ eV)
- Spin 0
- **Interaction with** two **photons** (coupling $g_{a\gamma\gamma}$)
- Interactions with other particles negligible
- Possible candidate for dark matter
- Induce the **change** of the **polarization state** of **photons**

Two photons

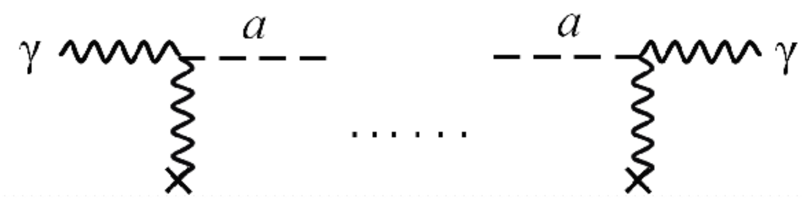


$$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$$

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

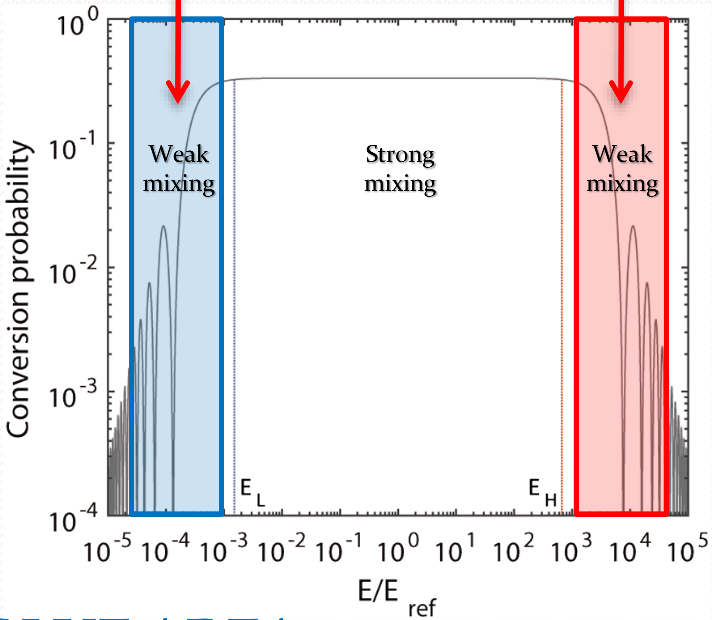
  - **Photon-ALP interaction** produces effective **photon absorption**

- 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 effects** 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, Phys. Rev. D 107, 103007 (2023).

RED AREA:

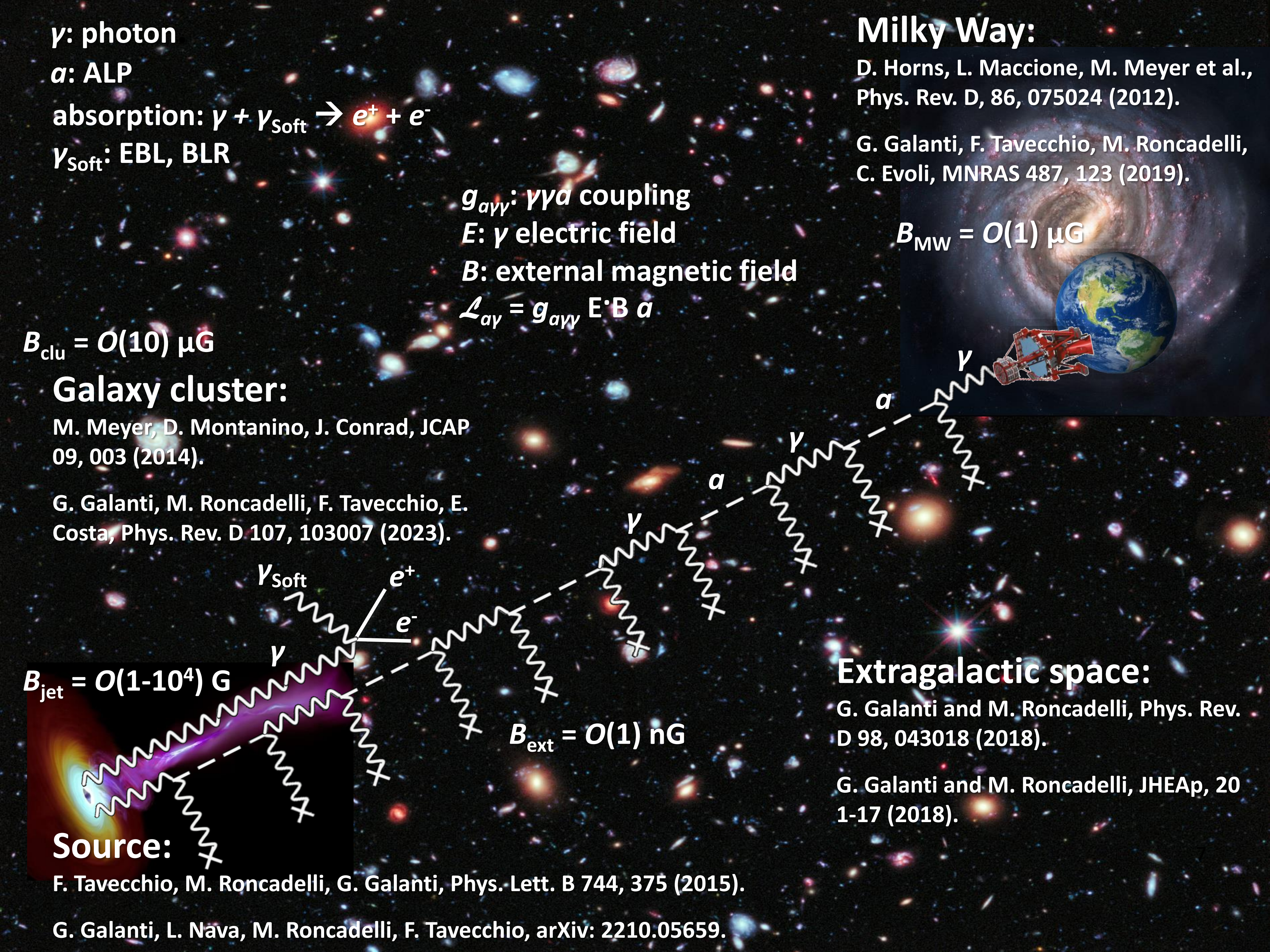
- Spectral effects investigated in:

  G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, MNRAS 487, 123 (2019).

  G. Galanti, F. Tavecchio, M. Landoni, MNRAS 491, 5268 (2020).

- Polarization effects studied in:

  G. Galanti, Phys. Rev. D 107, 043006 (2023).



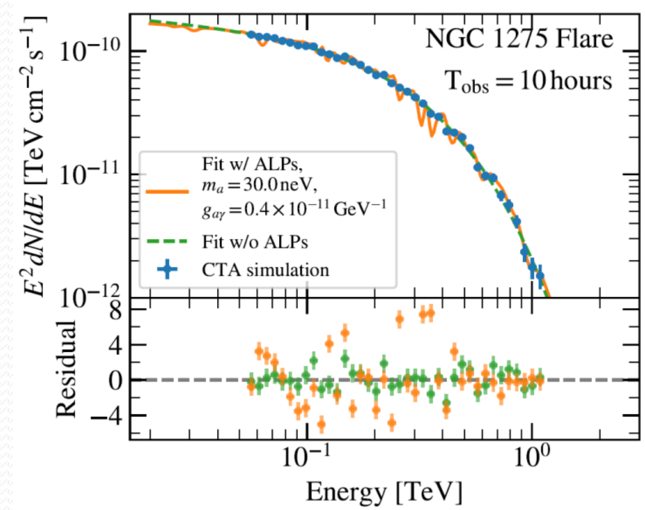
γ: photon
a: ALP
absorption: $\gamma + \gamma_{Soft} \rightarrow e^+ + e^-$
γ_{Soft}: EBL, BLR
$g_{a\gamma\gamma}$: $\gamma\gamma a$ coupling
E: γ electric field
B: external magnetic field
$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}\, \mathrm{E} \cdot \mathrm{B}\, a$
Milky Way:
D. Horns, L. Maccione, M. Meyer et al., Phys. Rev. D, 86, 075024 (2012).
G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, MNRAS 487, 123 (2019).
$B_{MW} = O(1)$ μG
$B_{clu} = O(10)$ μG
Galaxy cluster:
M. Meyer, D. Montanino, J. Conrad, JCAP 09, 003 (2014).
G. Galanti, M. Roncadelli, F. Tavecchio, E. Costa, Phys. Rev. D 107, 103007 (2023).
γ_{Soft}
e^+
e^-
γ
a
$B_{jet} = O(1\text{-}10^4)$ G
$B_{ext} = O(1)$ nG
Extragalactic space:
G. Galanti and M. Roncadelli, Phys. Rev. D 98, 043018 (2018).
G. Galanti and M. Roncadelli, JHEAp, 20 1-17 (2018).
Source:
F. Tavecchio, M. Roncadelli, G. Galanti, Phys. Lett. B 744, 375 (2015).
G. Galanti, L. Nava, M. Roncadelli, F. Tavecchio, arXiv: 2210.05659.

ALPs with CTA & ASTRI

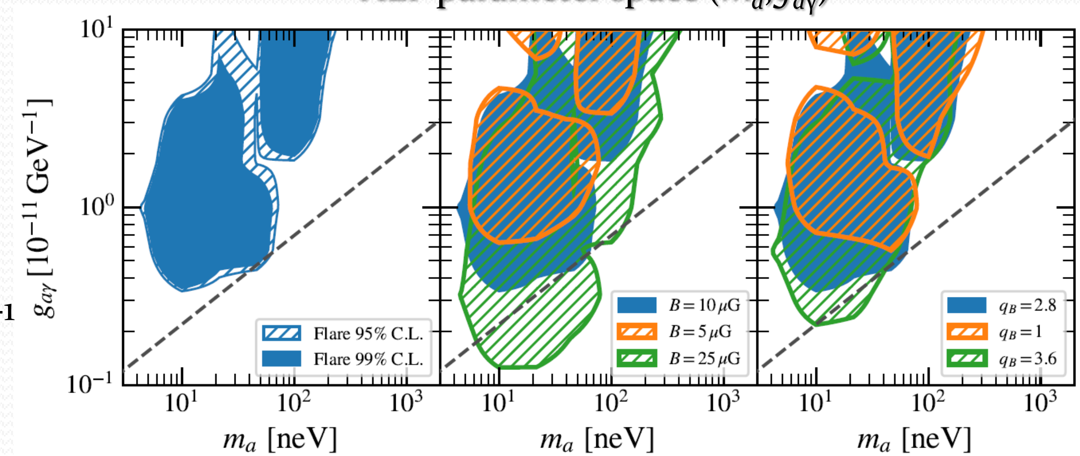
CTA

- **Perseus cluster** (z = 0.01756) -> emission from **NGC 1275**
- **High** ALP mass m_a -> γ-a conversion in the **low-energy weak mixing** regime around E_L (**BLUE AREA**, see before)
- γ->a in the cluster *turbulent* (q_B) magnetic field B
- a-> γ in the Milky Way
- Possible **bounds** on the **ALP parameter space**:
  - $m_a \in [5, 2\times10^2]$ neV
  - $g_{a\gamma} \in [0.2, 10]\times10^{-11}$ GeV^{-1}

NGC 1275 spectrum



ALP parameter space (m_a,$g_{a\gamma}$)

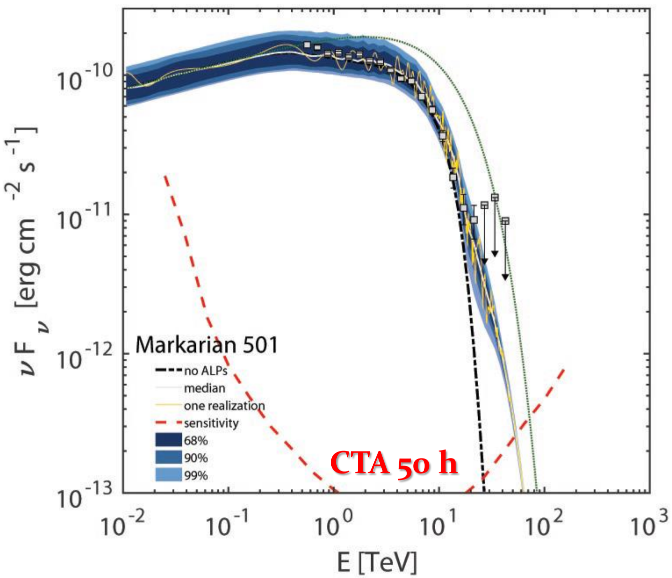


CTA Consortium, JCAP 02, 048 (2021)

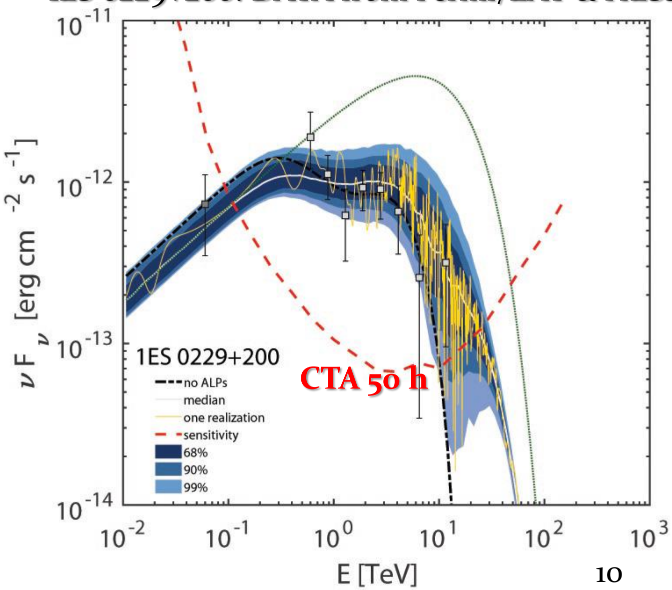
CTA (2)

- **Markarian 501** & **1ES 0229+200** -> emission in the jet
- **Low** ALP mass m_a -> γ-a conversion in the **high-energy weak mixing** regime around E_H (**RED AREA**, see before)
- γ<->a oscillations in the jet, host galaxy, extragalactic space & Milky Way
- $B_{jet,0} = 0.5$ G; $B_{ext} = 1$ nG
- $m_a = O(10^{-10})$ eV; $g_{a\gamma\gamma} = O(10^{-11})$ GeV^{-1}
- **Detectable ALP** induced **effects**:
  - **Spectral oscillations**
  - **Photon excess** above (10-20) TeV

Markarian 501: DATA from HEGRA



1ES 0229+200: DATA from Fermi/LAT & HESS

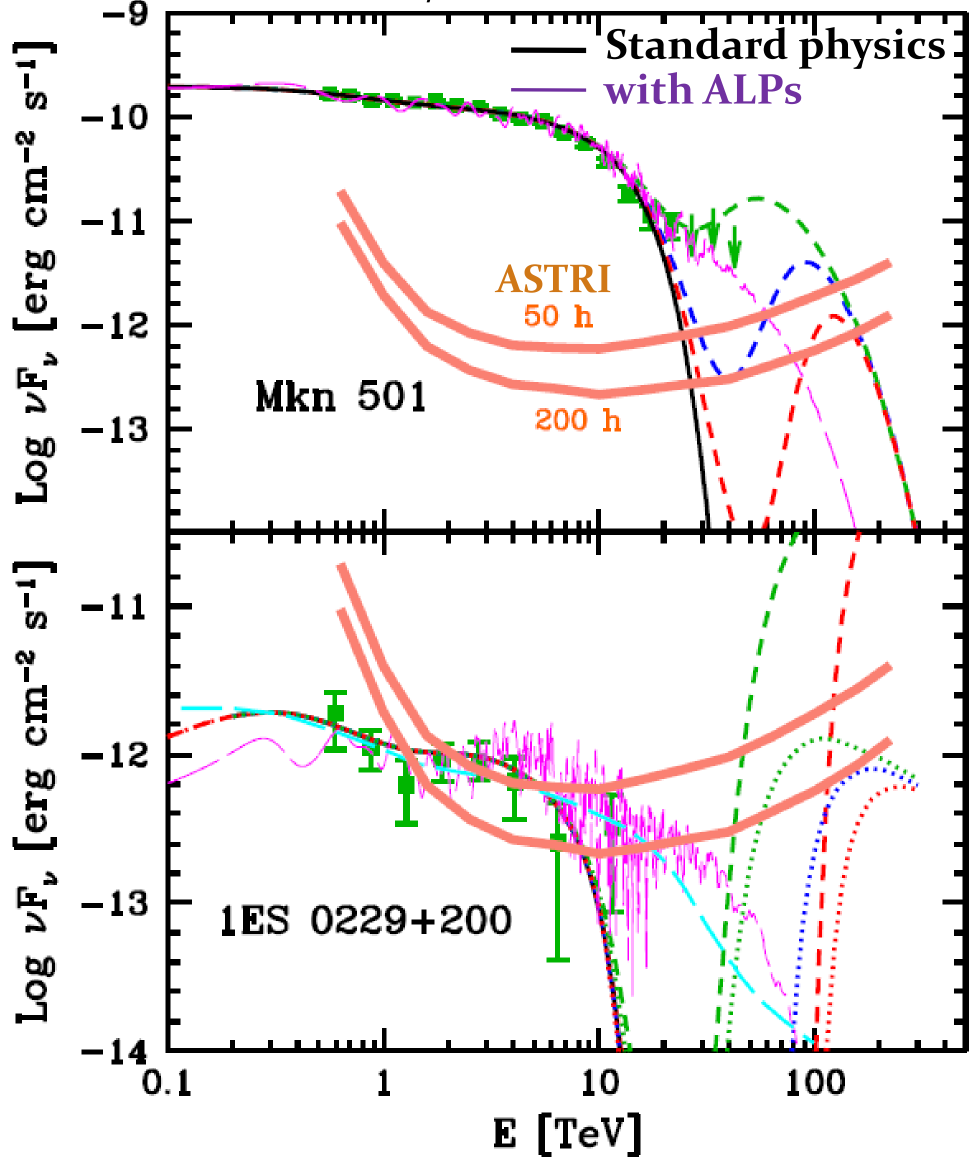


G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, MNRAS 487, 123 (2019)

ASTRI

- **ASTRI** will **detect** – before CTA – **ALP** induced **effects** (if present):
- **Photon excess**:
  - -> **for sure**
- **Spectral oscillations**:
  - -> **possible** (for close sources)

broken/dotted lines -> LIV



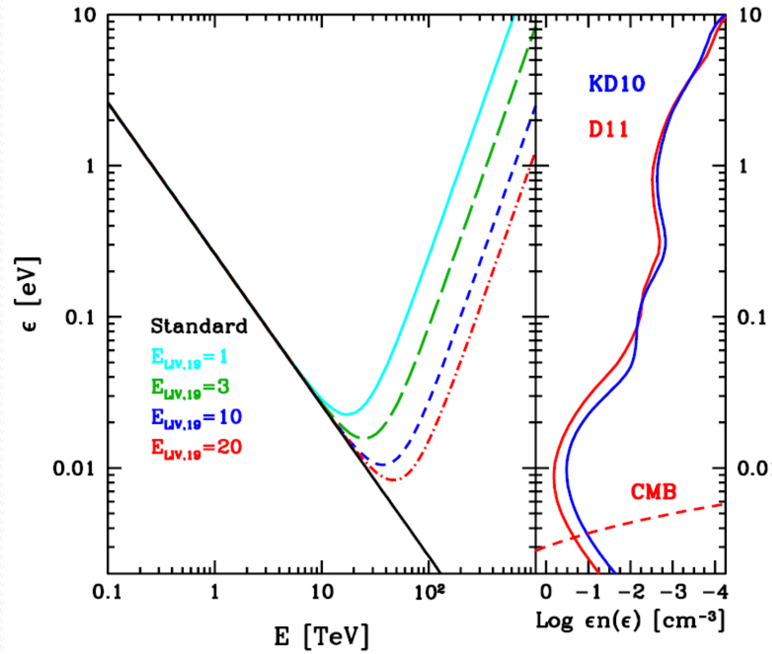
S. Vercellone et al. (ASTRI Collaboration), JHEAp 35, 1 (2022)

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**



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

- **Modified photon dispersion relation**

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

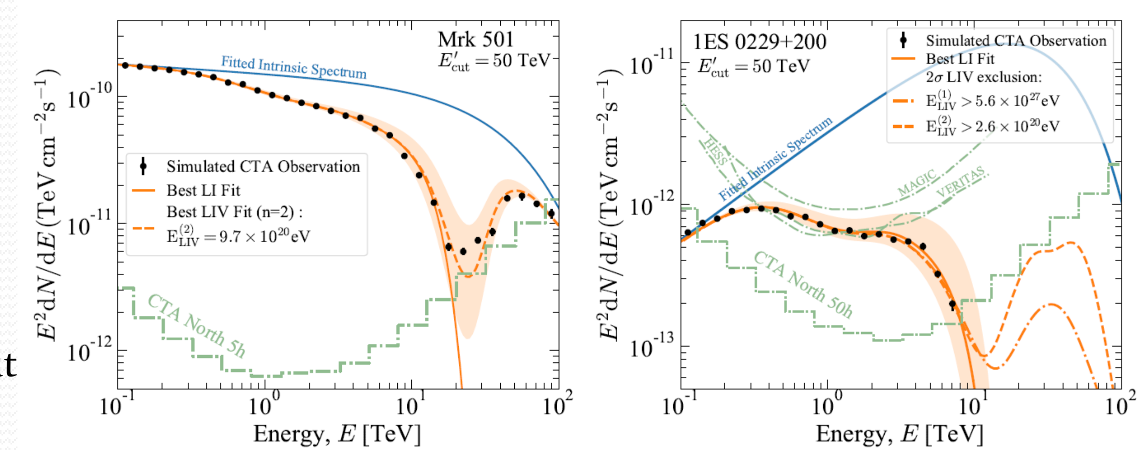
E -> energy
p -> momentum
E_{LIV} -> LIV parameter

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

LIV with CTA & ASTRI

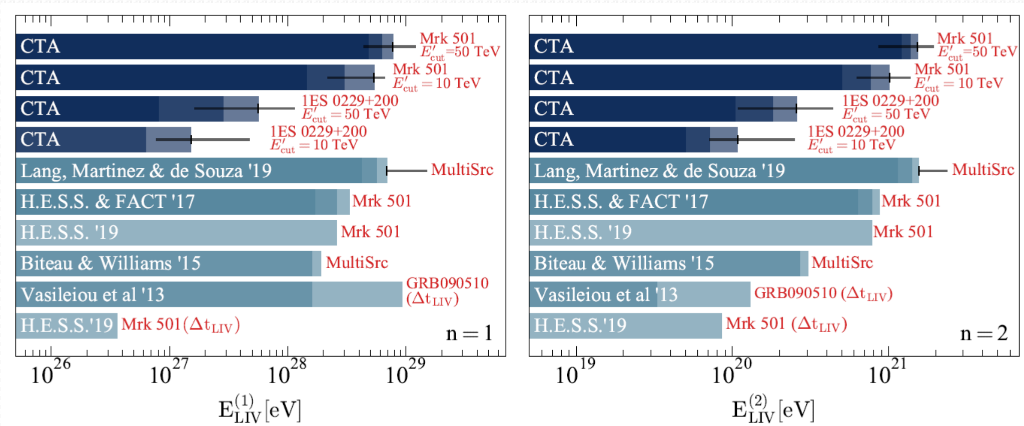
CTA

- **Markarian 501** & **1ES 0229+200**
- Emitted spectrum -> power law with exponential **cutoff** E'_{cut}



- E'_{cut} -> crucial parameter:
  - E'_{cut} = 10 TeV
  - E'_{cut} = 50 TeV

LIV parameter space: $E^{(1)}_{LIV}$; $E^{(2)}_{LIV}$



- Possible **bounds** on **LIV parameter**:
  - $E^{(1)}_{LIV} \gtrsim 7.7\times10^{28}$ eV
  - $E^{(2)}_{LIV} \gtrsim 1.5\times10^{21}$ eV

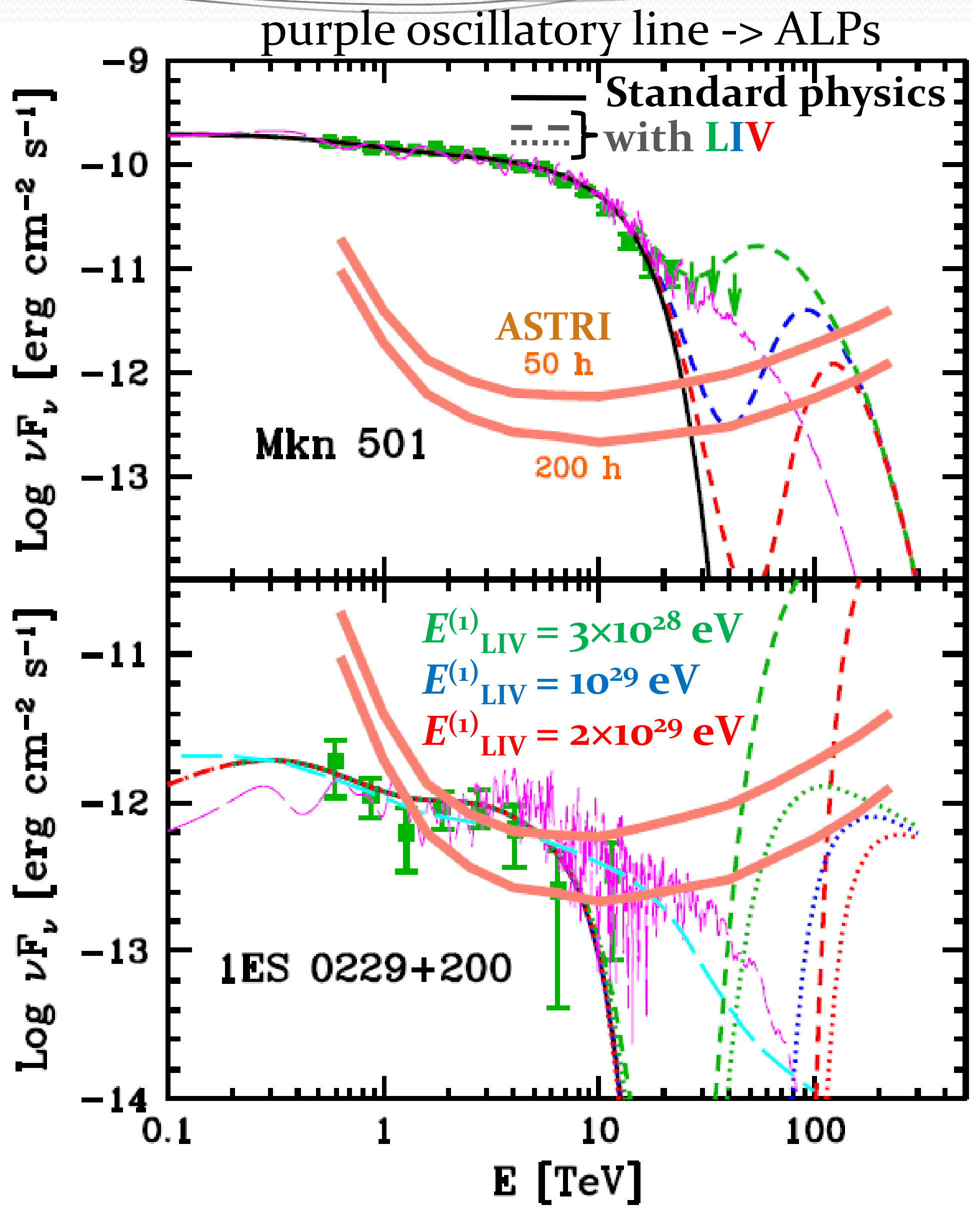
CTA Consortium, JCAP 02, 048 (2021)

ASTRI

- **ASTRI** will **detect** – before CTA – **LIV** induced **effects** (if present):

- **Markarian 501** emitted spectrum:
  - power law with exponential **cutoff**

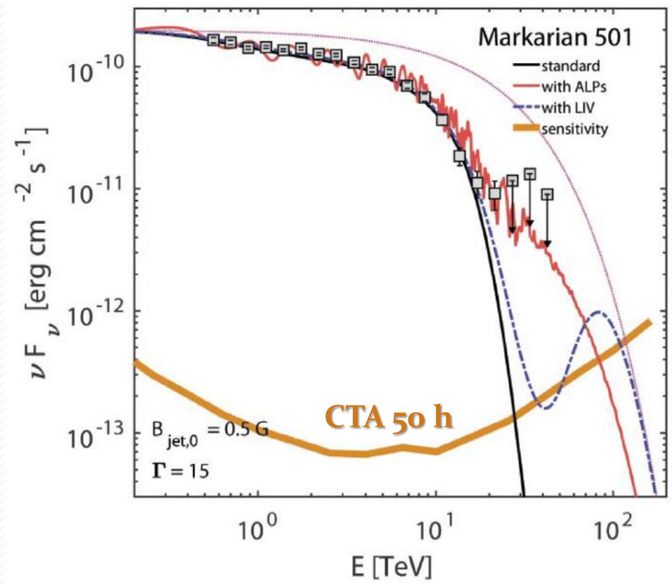
- **1ES 0229+200** emitted spectrum:
  - **unbroken** power law – – .
  - **broken** power law ....

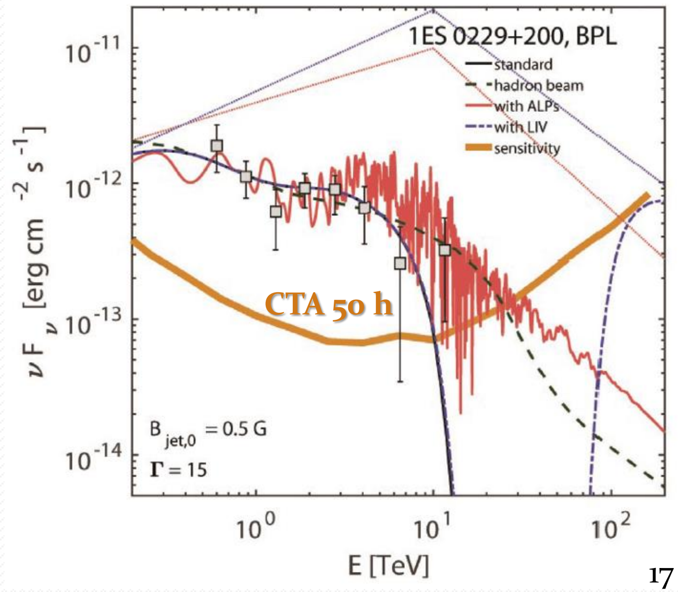


S. Vercellone et al. (ASTRI Collaboration), JHEAp 35, 1 (2022)

ALPs & LIV &… hadron beam

- **ASTRI** (and CTA) can **detect** the **effects** induced by several models:
  - **ALPs** -> *photon excess* (~30 TeV) & *spectral oscillations*
  - **LIV** -> *photon excess* (~100 TeV)
  - **hadron beam** (**HB**, EM cascade of hadrons on background photons) -> *photon excess* (~30 TeV)
- **Markarian 501** -> ALPs, LIV, no HB (too variable)
- **1ES 0229+200** -> ALPs, LIV, HB
- **ASTRI** (and more likely CTA) can **discriminate** among different models as **ALPs only** predict **spectral oscillations**





S. Galanti, F. Tavecchio, M. Landoni, MNRAS 491, 5268 (2020)

ASTRI & LHAASO and… the future

GRB 221009A

- Extremely luminous Gamma Ray Burst (GRB) at $z = 0.151$
- Observed by:
  - Fermi-GBM, Fermi-LAT, Swift
  - 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 $z = 0.151$ in 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}
D	12.7	3×10^{-6}	19.4	4×10^{-9}	350	2×10^{-152}	9654	~0
G	9.4	8×10^{-5}	13.1	2×10^{-6}	246	2×10^{-107}	9502	~0
FR	10.1	4×10^{-5}	14.1	7×10^{-7}	333	2×10^{-145}	15411	~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
D -> EBL model by Domínguez et al., 2011
G -> EBL model by Gilmore et al. 2012
FR -> EBL model by Franceschini & Rodighiero 2017
SL -> EBL model by Saldana-Lopez et al. 2021

QUESTION:

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

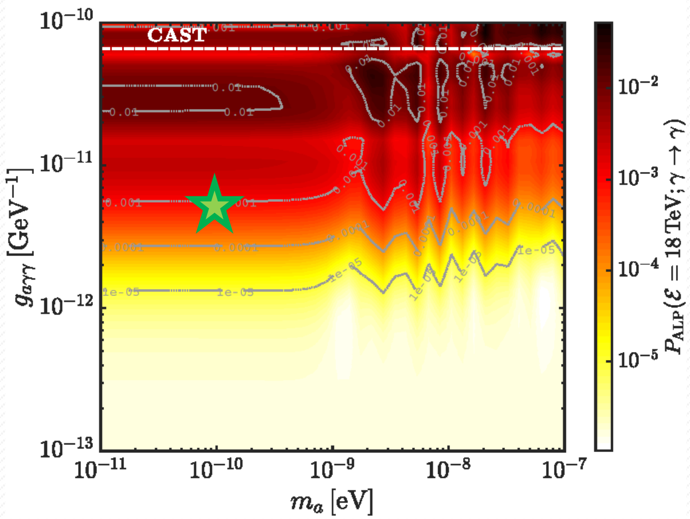
ANSWER:

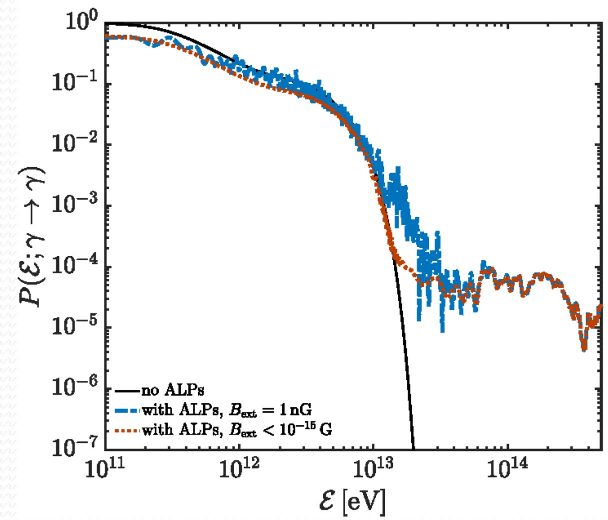
with **axion-like particles (ALPs)** !!!

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

ALP detection from GRB 221009A?

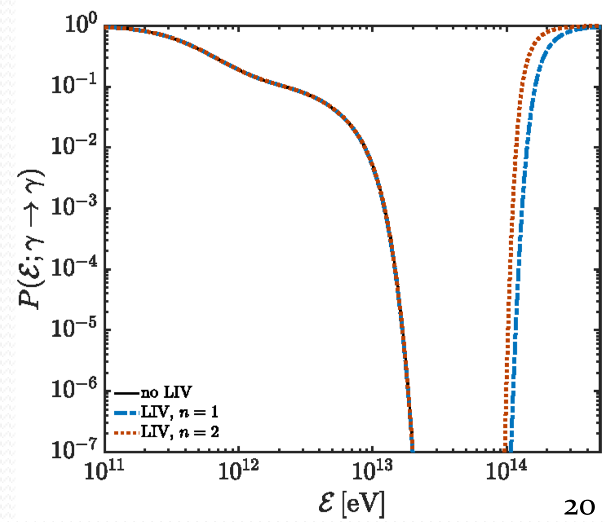
- **Photon-ALP mixing**
- $\mathcal{L}_{\rm ALP} = g_{a\gamma\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$
- $g_{a\gamma\gamma} = 5 \times 10^{-12}$ GeV^{-1}
- $m_a = O(10^{-10})$ eV





- **Lorentz Invariance Violation (LIV)**
- $E_{\rm LIV,\, n=1} = 3 \times 10^{29}$ eV
- $E_{\rm LIV,\, n=2} = 5 \times 10^{21}$ eV

- Photon-ALP mixing in all the possible crossed magnetic fields [source (negligible effect), host, extragalactic space*, Milky Way]
- $E = 18$ TeV $\rightarrow P_{\rm ALP}(\gamma \rightarrow \gamma) \simeq 9 \times 10^{-4}$
- $E = 251$ TeV $\rightarrow P_{\rm ALP}(\gamma \rightarrow \gamma) \simeq 5 \times 10^{-5}$
- **ALPs** can **explain both observations**
- **LIV** very good at 251 TeV, **fails at 18 TeV**
- Possible **ALP indirect detection**?!



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

The future

- **LHAASO** is expected to produce **new** exciting **observations** but with a **not so high energy resolution** (15%-30% above 10 TeV):
  - Blazars
  - GRBs
  - …

- **ASTRI** (and CTA) can work in **synergy** with **LHAASO** with a **better energy resolution** ($\lesssim$ 10%) at (1-100) TeV
  - GRB 221009A -> could have had a better spectral characterization -> **possible firm conclusions** on **ALPs**, **LIV**, **HB**
  - -> Important **focus on GRBs** for fundamental physics studies

- **Synergy** with **Fermi-LAT** & **Fermi-GBM** for a multi-wavelength analysis

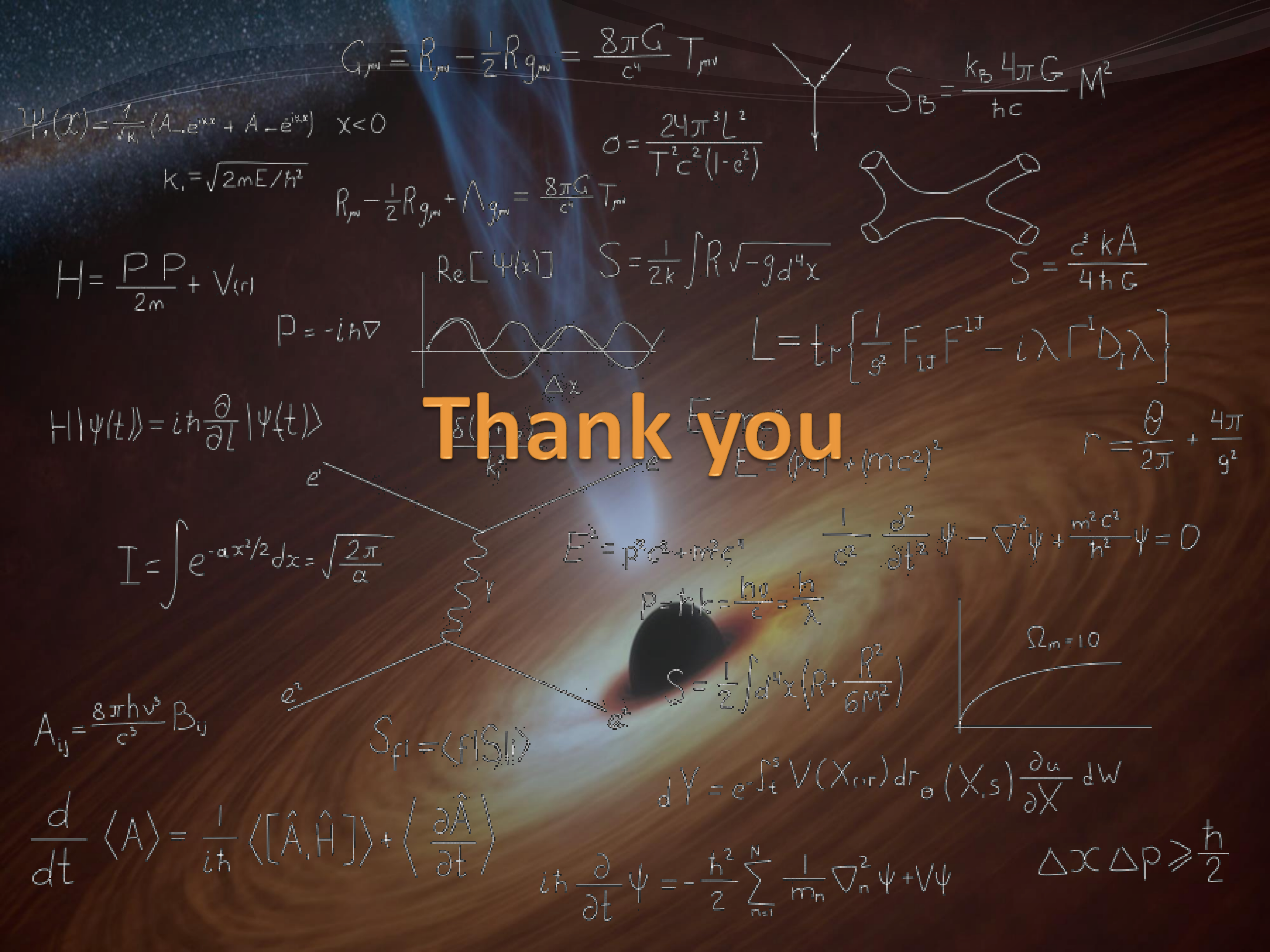
- Possible **synergy** with **IXPE** (eXTP, NGXP, …) and **COSI** (e-ASTROGAM, AMEGO) to strengthen spectral results -> **ALPs** & **LIV** produce detectable **polarization effects**

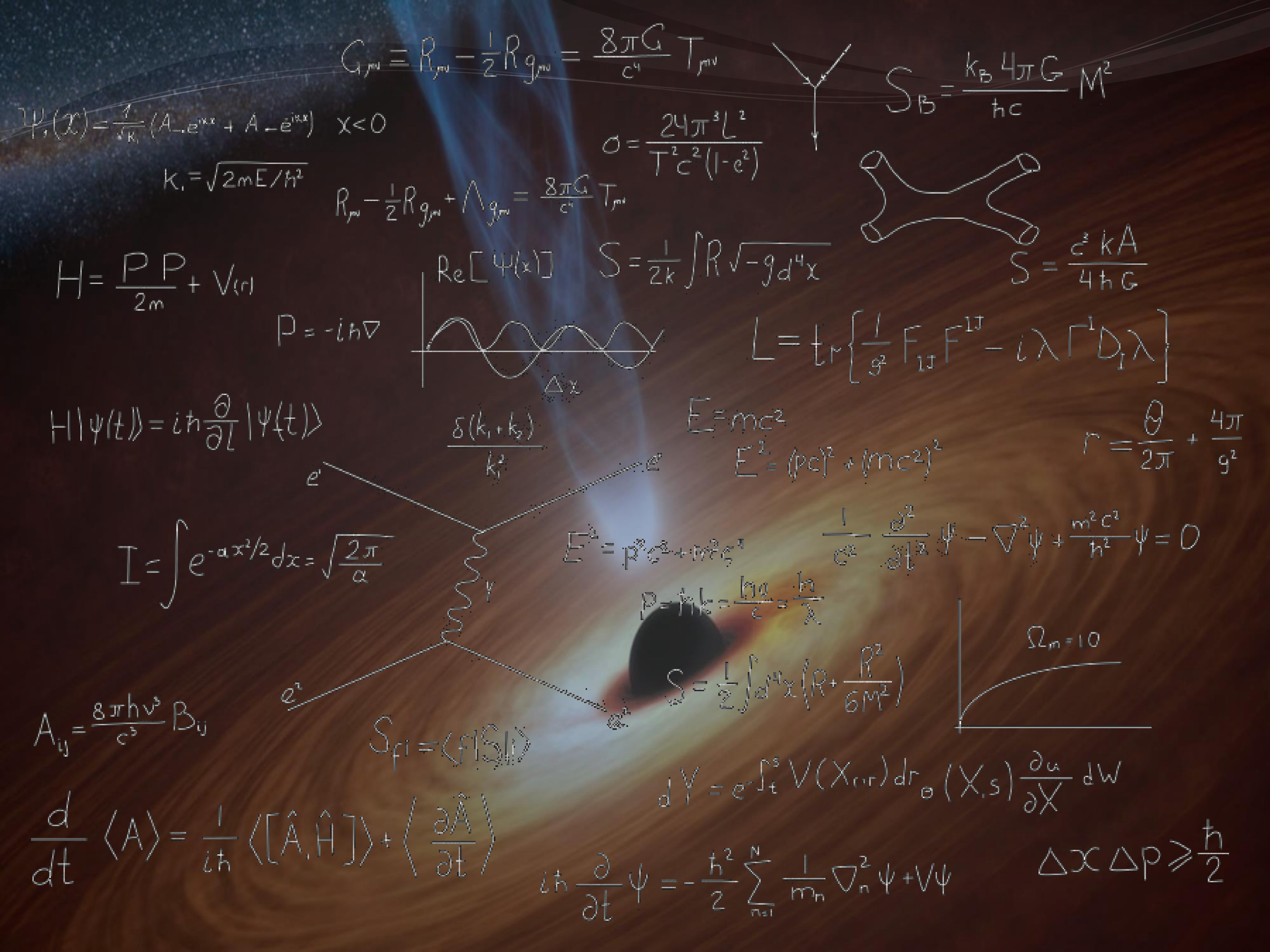
Conclusions

Conclusions

- **ASTRI** (and CTA) -> fantastic observatories to perform studies about **fundamental physics**
- They will likely give us a final answer about **ALPs**, **LIV**, **HB**
- **Synergies** with:
  - **LHAASO**
  - **Fermi-LAT** & **Fermi-GBM**
  - **IXPE** & **COSI**
- **ASTRI Pillar-2: cosmology and fundamental physics**
  - -> based on our proposal/expertise (concerning ALPs, LIV, HB, see before)
- Possible **leadership** also **inside CTA** concerning **fundamental physics** (?)
  - No dedicated observational campaigns needed -> existing KSP: AGN monitoring

Thank you





$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
$S_B = \frac{k_B 4\pi G}{\hbar c} M^2$
$x<0$
$k_1 = \sqrt{2mE/\hbar^2}$
$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
$S = \frac{1}{2k} \int R \sqrt{-g}\, d^4x$
$S = \frac{c^3 kA}{4\hbar G}$
$H = \frac{PP}{2m} + V(r)$
$P = -i\hbar\nabla$
$\mathrm{Re}[\Psi(x)]$
Δx
$H|\psi(t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle$
$E = mc^2$
$E^2 = (pc)^2 + (mc^2)^2$
$r = \frac{\theta}{2\pi} + \frac{4\pi}{g^2}$
$I = \int e^{-ax^2/2} dx = \sqrt{\frac{2\pi}{a}}$
$\frac{1}{c^2} \frac{\partial^2}{\partial t^2} \psi - \nabla^2 \psi + \frac{m^2 c^2}{\hbar^2} \psi = 0$
$\Omega_m = 1.0$
$A_{ij} = \frac{8\pi h \nu^3}{c^3} B_{ij}$
$S_{fi} = \langle f|S|i\rangle$
$\frac{d}{dt} \langle A \rangle = \frac{1}{i\hbar} \langle [\hat{A}, \hat{H}] \rangle + \left\langle \frac{\partial \hat{A}}{\partial t} \right\rangle$
$i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2} \sum_{n=1}^{N} \frac{1}{m_n} \nabla_n^2 \psi + V\psi$
$\Delta x \Delta p \geqslant \frac{\hbar}{2}$