Axion-like particle impact in high-energy astrophysics

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8th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy

Milano, 2 September 2024

Outline

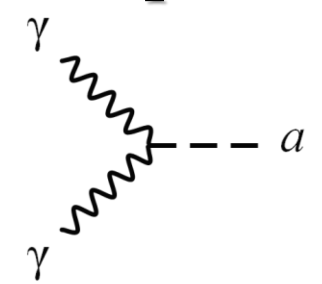
- Axion-like particles
- ALP impact in high-energy astrophysics
- Conclusions

Axion-like particles

Axion-like particles (ALPs)

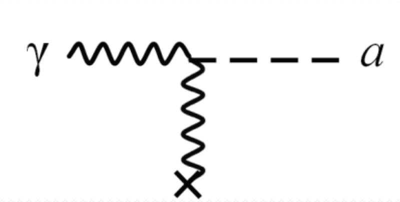
- Predicted by **String Theory**
- Very light particles ($m_a < 10^{-8}$ eV)
- Spin 0
- **Interaction with** two **photons** (coupling $g_{a\gamma\gamma}$)
- Subdominant interactions with other particles
- Possible candidate for dark matter
- Produce **spectral** and **polarization effects**

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

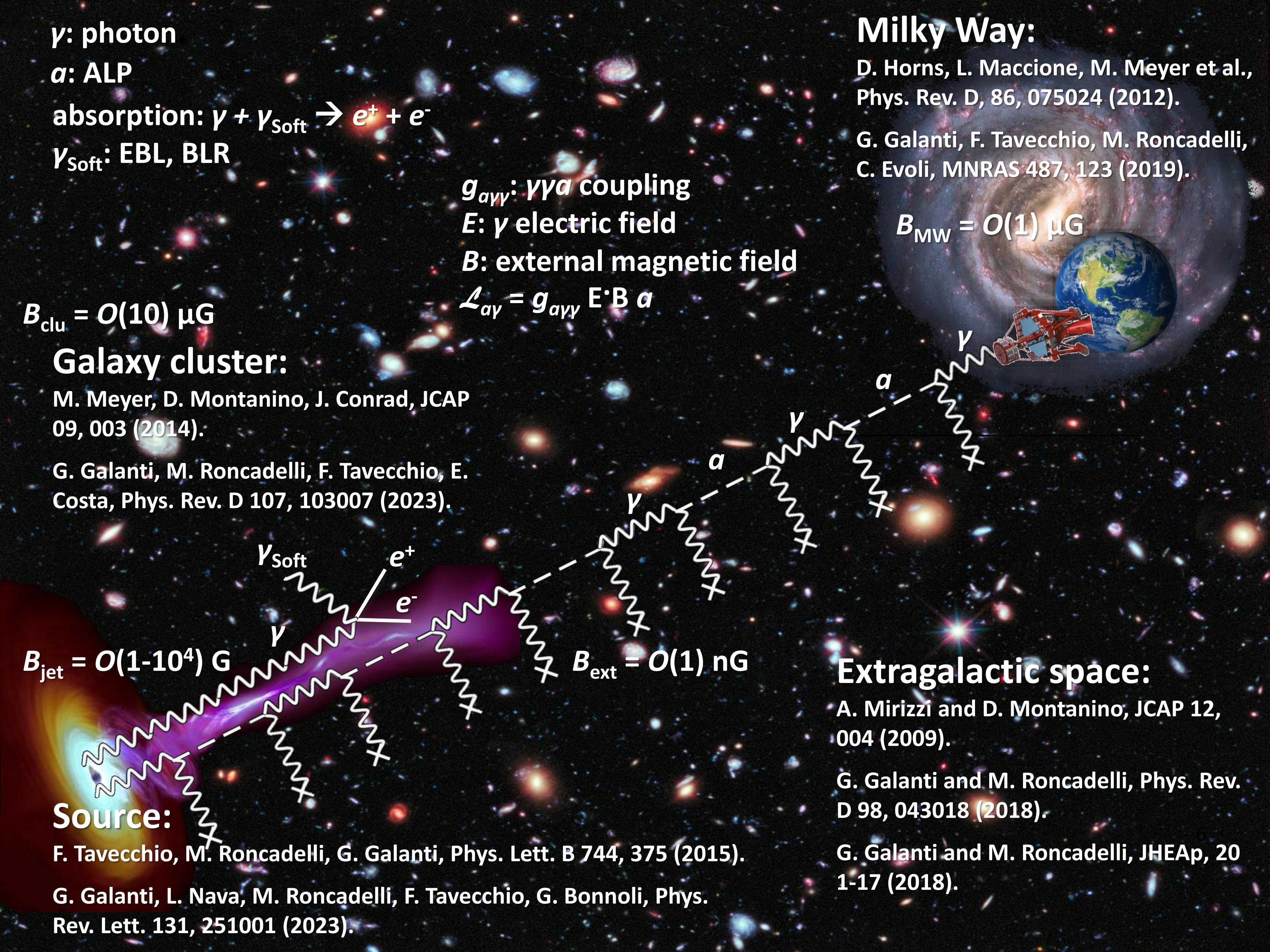
- ALPs very **elusive** in laboratory experiments (low coupling) → **astrophysical environment** is the **best opportunity** to study ALPs and ALP effects (*for free*)

- Photon/ALP beam with energy $E >> m_a$

- ALPs induce **modifications to astrophysical spectra**
  - 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**

- ALPs induce **modifications to photon polarization** (*birefringence*, *dichroism*)

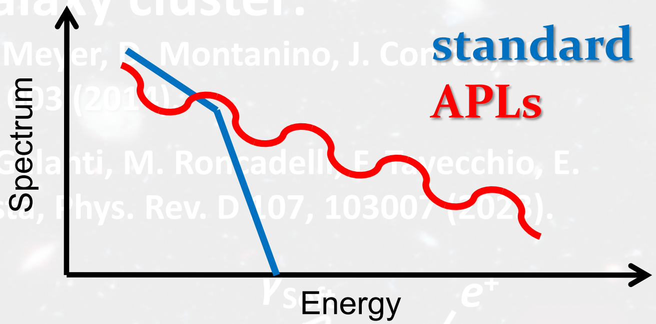
- **HINTS** at ALP existence:
  - Explain how flat spectrum radio quasars (FSRQs) can emit up to 400 GeV
    F. Tavecchio, M. Roncadelli, G. Galanti and G. Bonnoli, Phys. Rev. D, 86, 085036 (2012).
  - Solve the anomalous redshift dependence of blazar spectra
    G. Galanti, M. Roncadelli, A. De Angelis and G. F. Bignami, MNRAS 493, 1553 (2020).
  - GRB 221009A
    G. Galanti, L. Nava, M. Roncadelli, F. Tavecchio and G. Bonnoli, Phys. Rev. Lett. 131, 251001 (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
$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}\, E \cdot B\, a$
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
a
γ
a
γ
γ_{Soft}
e^+
e^-
γ
$B_{jet} = O(1\text{-}10^4)$ G
$B_{ext} = O(1)$ nG
Extragalactic space:
A. Mirizzi and D. Montanino, JCAP 12, 004 (2009).
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, G. Bonnoli, Phys. Rev. Lett. 131, 251001 (2023).

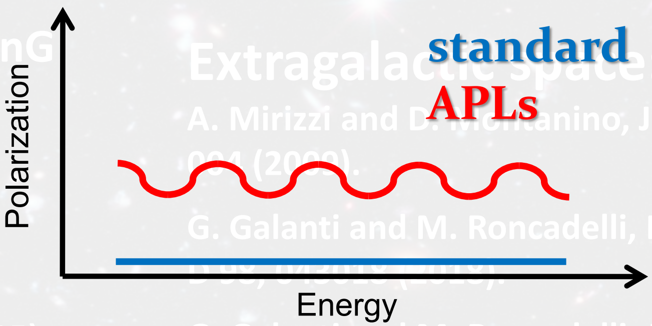
SPECTRA

- **Standard physics**
  - photon absorption
- **With ALPs**
  - lower photon absorption
  - spectral irregularities



POLARIZATION

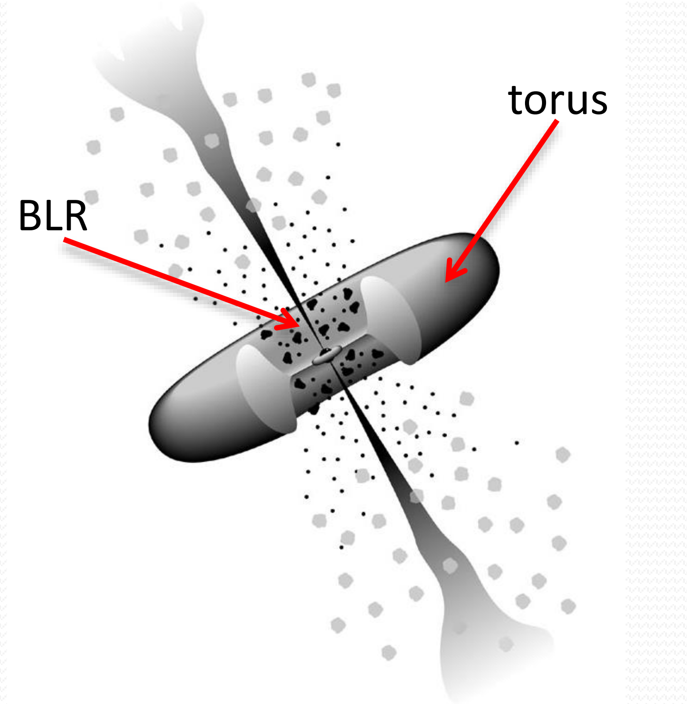
- **Standard physics**
  - unpolarized photon case
- **With ALPs**
  - modified polarization
  - partially polarized photons



ALP impact in high-energy astrophysics

Active Galactic Nuclei (AGN)

- Super massive black holes ($10^6 - 10^9\ M_\odot$)
- Accretion disk
- Collimated jets (if towards us -> **blazars**)
- Photons produced at the jet base

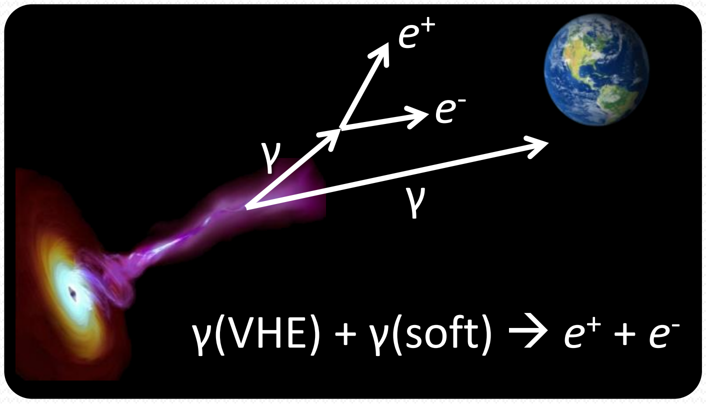


BL Lacs:

- No broad line region (BLR)
- No dusty torus
- Absorption due to the extragalactic background light (EBL) for $E > 100$ GeV

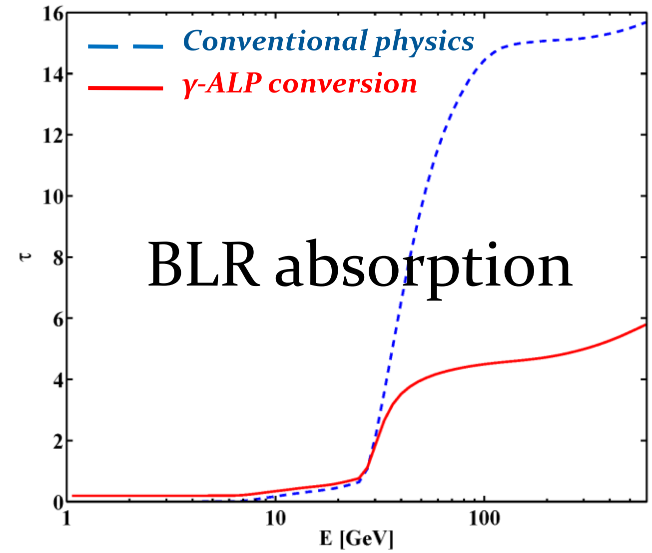
Flat spectrum radio quasars (FSRQs):

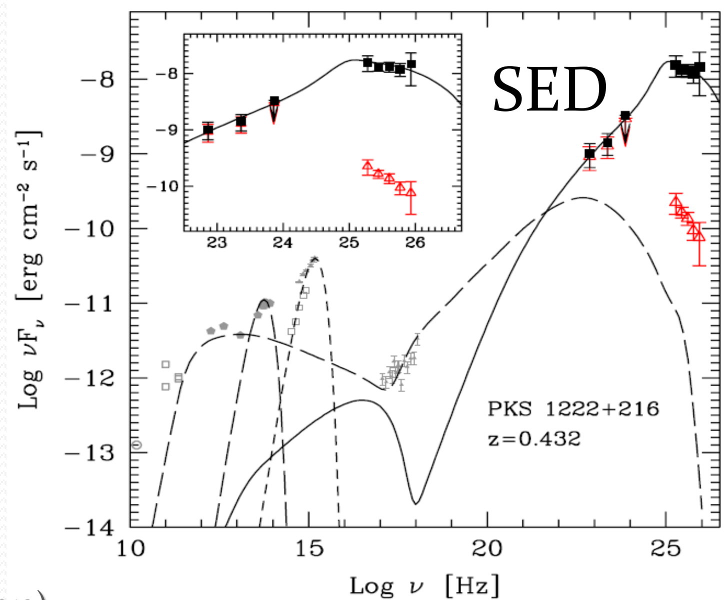
- Absorption due to the BLR for $E > 20$ GeV
- Absorption due to the dusty torus for $E > 300$ GeV
- Absorption due to the EBL for $E > 100$ GeV



ALPs in FSRQs

- **High BLR absorption** → no photons with $E > 20$ GeV predicted **BUT**
- **Photons observed up to 400 GeV**
- **Why?** Photon/ALP conversions?
  - $B_{\text{jet}} = 0.2$ G and scales as $1/y$
  - $g_{a\gamma\gamma} = O(10^{-11})$ GeV^{-1}, $m_a < O(10^{-10}$ eV$)$
  - BLR $n_{e,\text{BLR}} = 10^{10}$ cm^{-3}
- Photon-ALP **conversion** before the BLR – **reconversion** outside the BLR
- -> BLR absorption **REDUCED**
- Physically motivated flux (SED)
- **First hint** at **ALP existence**





F. Tavecchio, M. Roncadelli, G. Galanti, G. Bonnoli, Phys. Rev. D, 86, 085036 (2012).

Anomalous z dependence of Blazars

- We consider all BL Lacs (HBL and IBL) with strong VHE spectrum:
  - In flare
  - $E > 100$ GeV
  - redshift up to $z = 0.6$

- Emitted spectra → **power law**

$$\Phi_{\rm em}(E) = \hat{K}_{\rm em}\, E^{-\Gamma_{\rm em}}$$

- Observed spectrum → **power law**

$$\Phi_{\rm obs}(E_0, z) = \hat{K}_{\rm obs}(z)\, E_0^{-\Gamma_{\rm obs}(z)}$$

- Emitted – observed spectrum relation

$$\Phi_{\rm obs}(E_0, z) = P_{\gamma \to \gamma}(E_0, z)\, \Phi_{\rm em}\big(E_0(1+z)\big)$$

- We **deabsorb** the **observed spectrum**:
  - if no ALPs → EBL absorption only
  - **with ALPs** → EBL absorption and photon-ALP oscillations

G. Galanti, M. Roncadelli, A. De Angelis, G. F. Bignami, MNRAS 493, 1553 (2020).

Anomalous z dependence of Blazars (2)

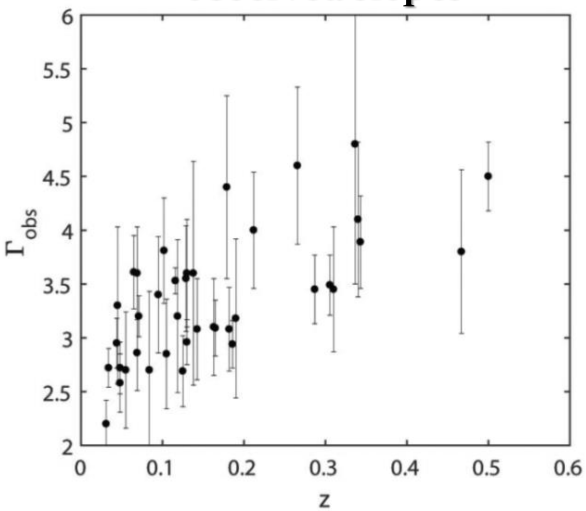
Conventional Physics (CP):

- **Anomalous redshift dependence** of blazar spectra

$$\Phi^{\rm CP}_{\rm em}\big(E_0(1+z)\big) = e^{\tau^{\rm FR}_{\gamma}(E_0,z)}\, K_{\rm obs}(z)\left(\frac{E_0}{E_{0,*}}\right)^{-\Gamma_{\rm obs}(z)}$$

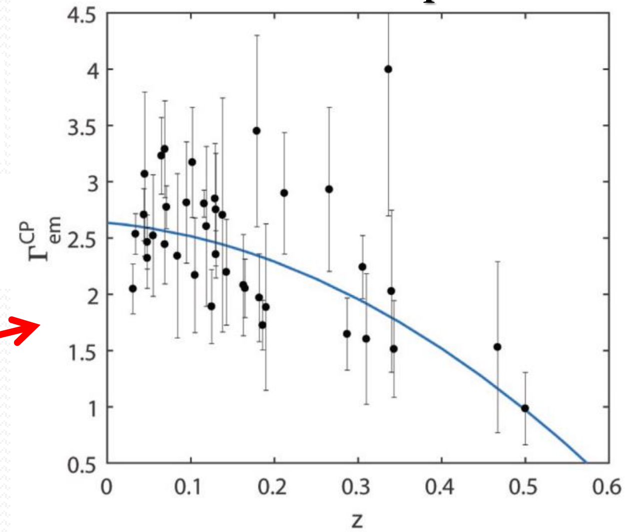
$$\Phi^{\rm CP,BF}_{\rm em}\big(E_0(1+z)\big) = K^{\rm CP}_{\rm em}(z)\left(\frac{E_0(1+z)}{E_{0,*}}\right)^{-\Gamma^{\rm CP}_{\rm em}(z)}$$

observed slopes

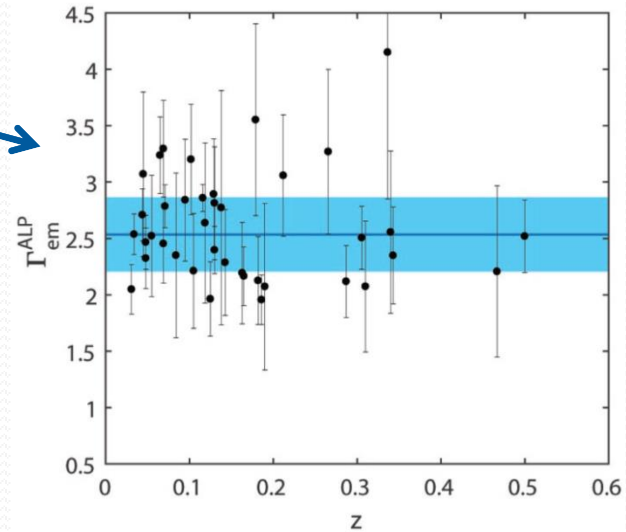


CP

emitted slopes



ALP



With ALPs:

$$\Phi^{\rm ALP}_{\rm em}\big(E_0(1+z)\big) = \left(P^{\rm ALP}_{\gamma\to\gamma}(E_0,z)\right)^{-1} K_{\rm obs}(z)\left(\frac{E_0}{E_{0,*}}\right)^{-\Gamma_{\rm obs}(z)}$$

- Anomaly **SOLVED**

$$\Phi^{\rm ALP,BF}_{\rm em}\big(E_0(1+z)\big) = K^{\rm ALP}_{\rm em}(z)\left(\frac{E_0(1+z)}{E_{0,*}}\right)^{-\Gamma^{\rm ALP}_{\rm em}(z)}$$

Second hint at **ALP existence** (a new study gets similar results, see Dong+2023)

G. Galanti, M. Roncadelli, A. De Angelis, G. F. Bignami, MNRAS 493, 1553 (2020).

GRB 221009A

- Extremely luminous Gamma Ray Burst (GRB) at redshift z = 0.151
- Observed by:
  - Fermi-GBM, Fermi-LAT (Fermi 2023), Swift (Williams+2023)
  - **LHAASO** at $E \simeq$ (13-18) TeV within 2000 s after the initial burst (LHAASO 2022, 2023a,b)

BUT **strong EBL absorption** for $E \gtrsim$ 10 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

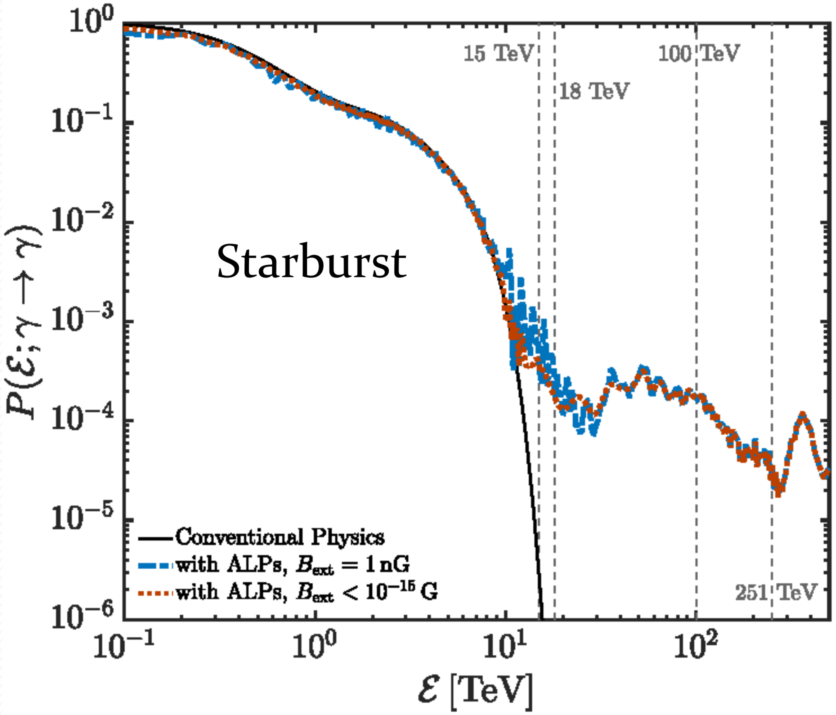
QUESTION:
How can we have detected this GRB up to $E \simeq$ (13-18) TeV?

→

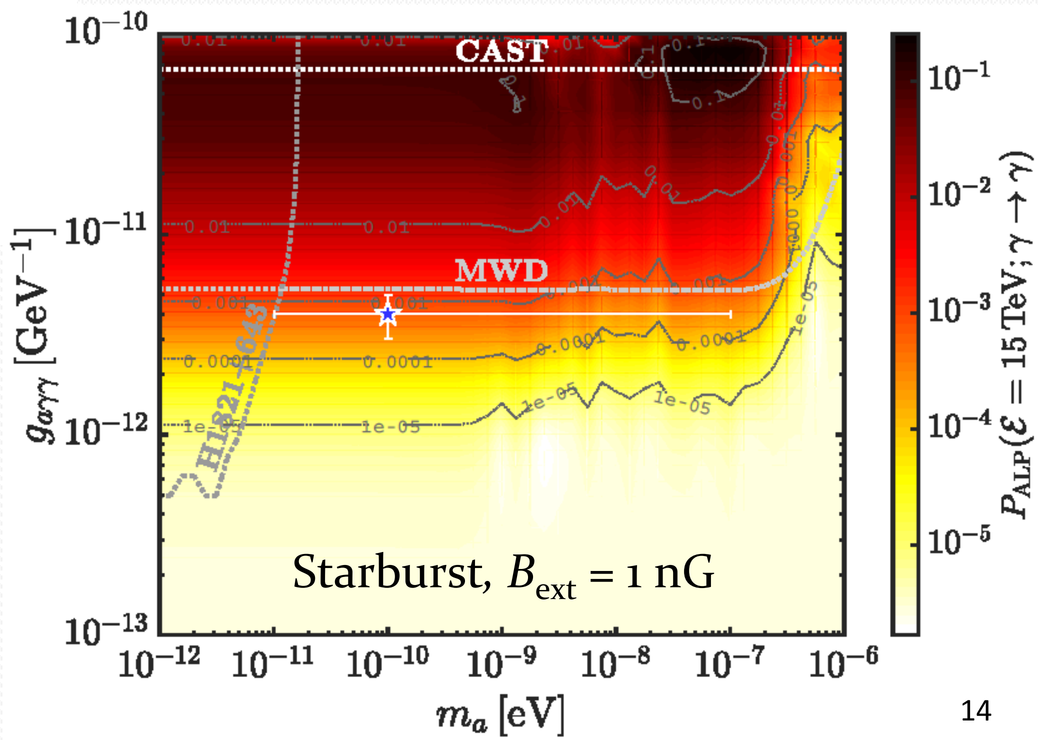
ANSWER:
with **axion-like particles (ALPs)** !!!

G. Galanti, L. Nava, M. Roncadelli, F. Tavecchio, G. Bonnoli, Phys. Rev. Lett. 131, 251001 (2023).

Photon survival probability



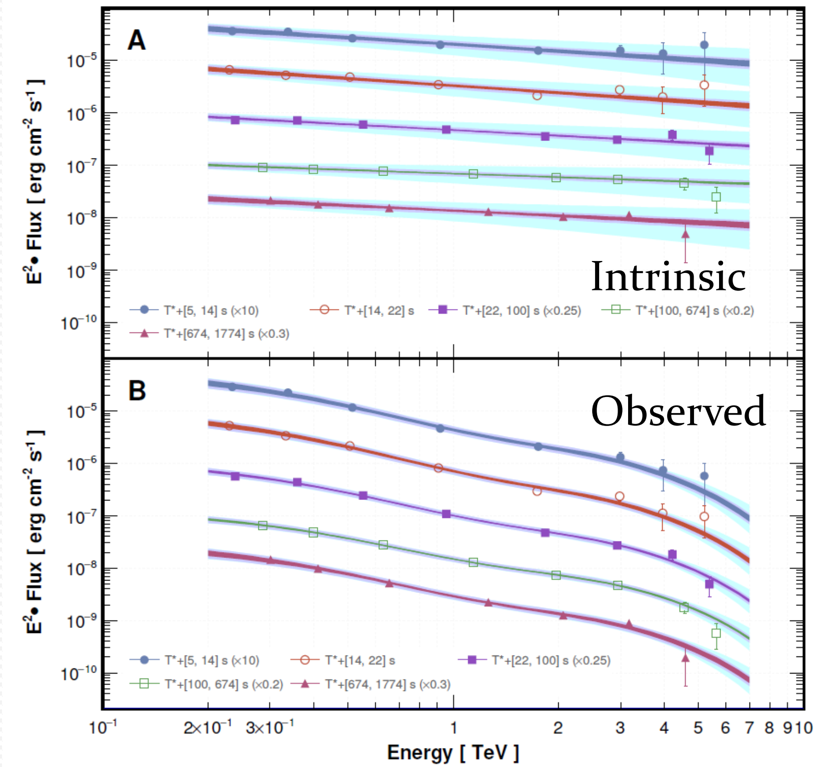
- $P_{CP}(E, \gamma \to \gamma)$:
  - @ 15 TeV → ~3×10^{-6}
  - @ 18 TeV → ~1×10^{-8}
  - @ 100 TeV → ~3×10^{-96}
  - @ 251 TeV → ~0
- $P_{ALP}(E, \gamma \to \gamma)$:
  - @ 15 TeV → ~$\mathbf{6 \times 10^{-4}}$
  - @ 18 TeV → ~$\mathbf{3 \times 10^{-4}}$
  - @ 100 TeV → ~2×10^{-4}
  - @ 251 TeV → ~3×10^{-5}



- We take $g_{a\gamma\gamma} = (3 - 5) \times 10^{-12}$ GeV^{-1}; $m_a = (10^{-11} - 10^{-7})$ eV
- Within all most stringent ALP bounds (Sisk-Reynés+2022; Dessert+2022)
- **Explain LHAASO**
- **Compatible with other ALP hints**

G. Galanti, L. Nava, M. Roncadelli, F. Tavecchio, G. Bonnoli, Phys. Rev. Lett. 131, 251001 (2023).

GRB 221009A spectrum



Adapted from LHAASO Collaboration, Science 380, 1390 (2023).

- **LHAASO spectrum** (only **WCDA**):
  - E = (0.2 – 7) TeV
  - In 5 time intervals Δt_i
- **Intrinsic** spectrum -> power law with **no cutoff**:

$$\mathcal{F}_i(\mathcal{E}) \equiv \frac{\mathrm{d}N}{\mathrm{d}\mathcal{E}} = A\left(\frac{\mathcal{E}}{\mathrm{TeV}}\right)^{-\gamma}$$

- **Average** intrinsic spectrum

$$\mathcal{F}_{\rm int} \equiv \langle \mathcal{F}_i \rangle = \frac{1}{T}\sum_{i=1}^{5} \Delta t_i \mathcal{F}_i$$

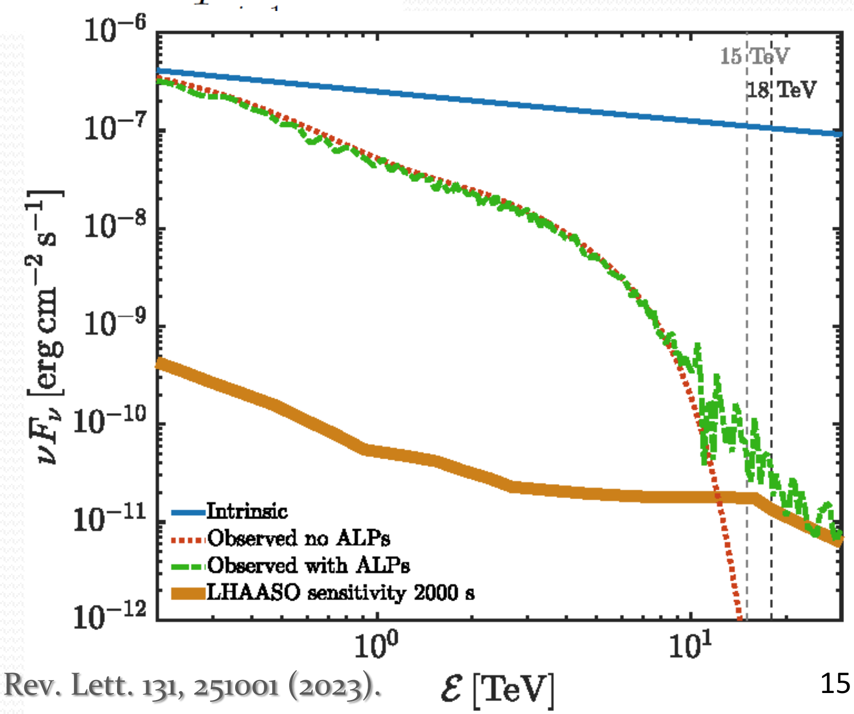
T -> total duration

- **Observed** spectrum -> extended to ~20 TeV:

$\mathcal{F}_{\rm obs}(\mathcal{E}) = P(\mathcal{E};\gamma \to \gamma)\mathcal{F}_{\rm int}(\mathcal{E})$ with $P = P_{\rm CP}$ or $P_{\rm ALP}$

$\nu F_\nu = \mathcal{E}^2 \mathcal{F}_{\rm obs}$

- **CP does NOT work** for E above ~10 TeV
- **ALPs solve** the **problem** -> **Third hint**



G. Galanti, L. Nava, M. Roncadelli, F. Tavecchio, G. Bonnoli, Phys. Rev. Lett. 131, 251001 (2023).

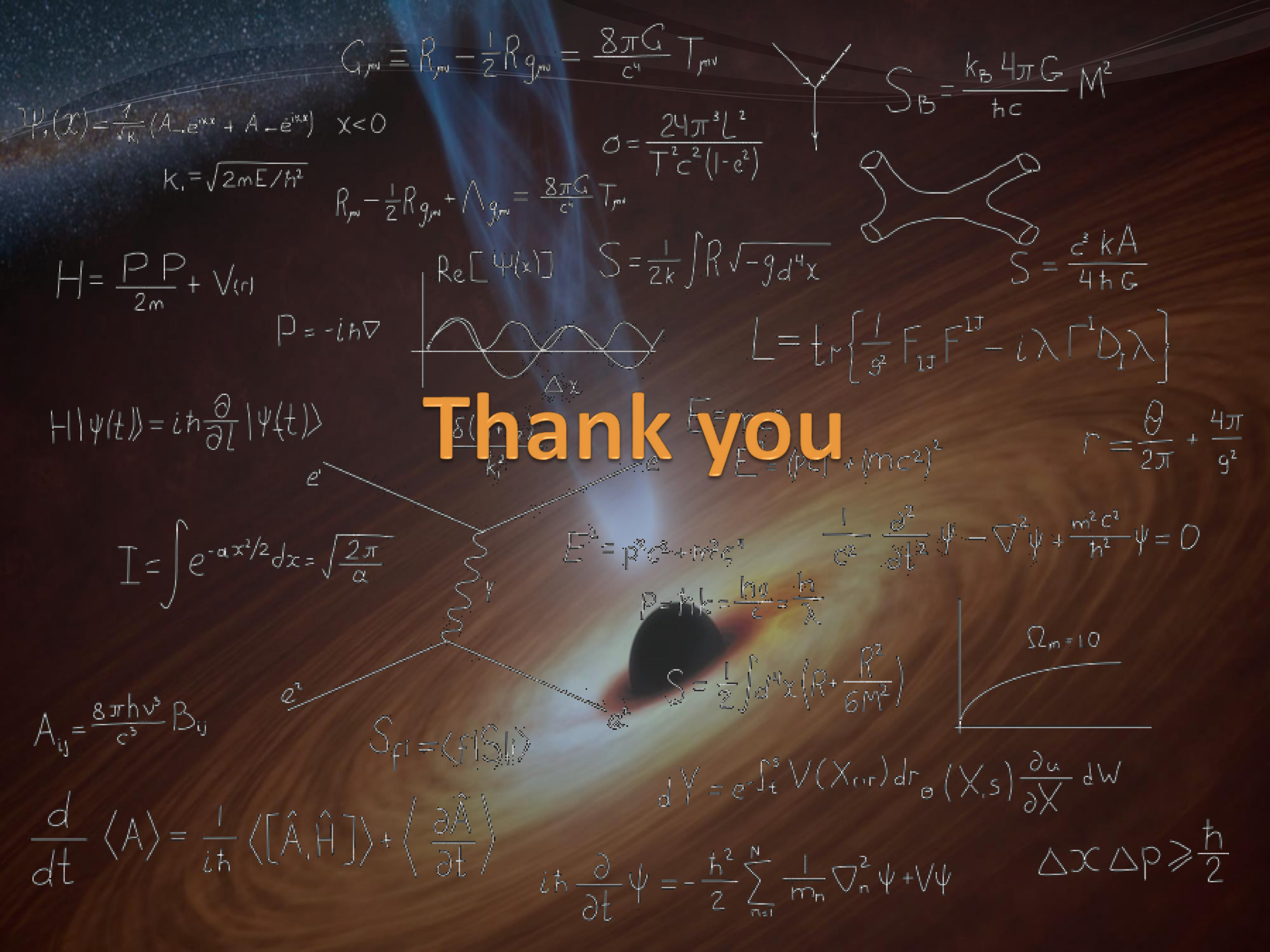
Conclusions

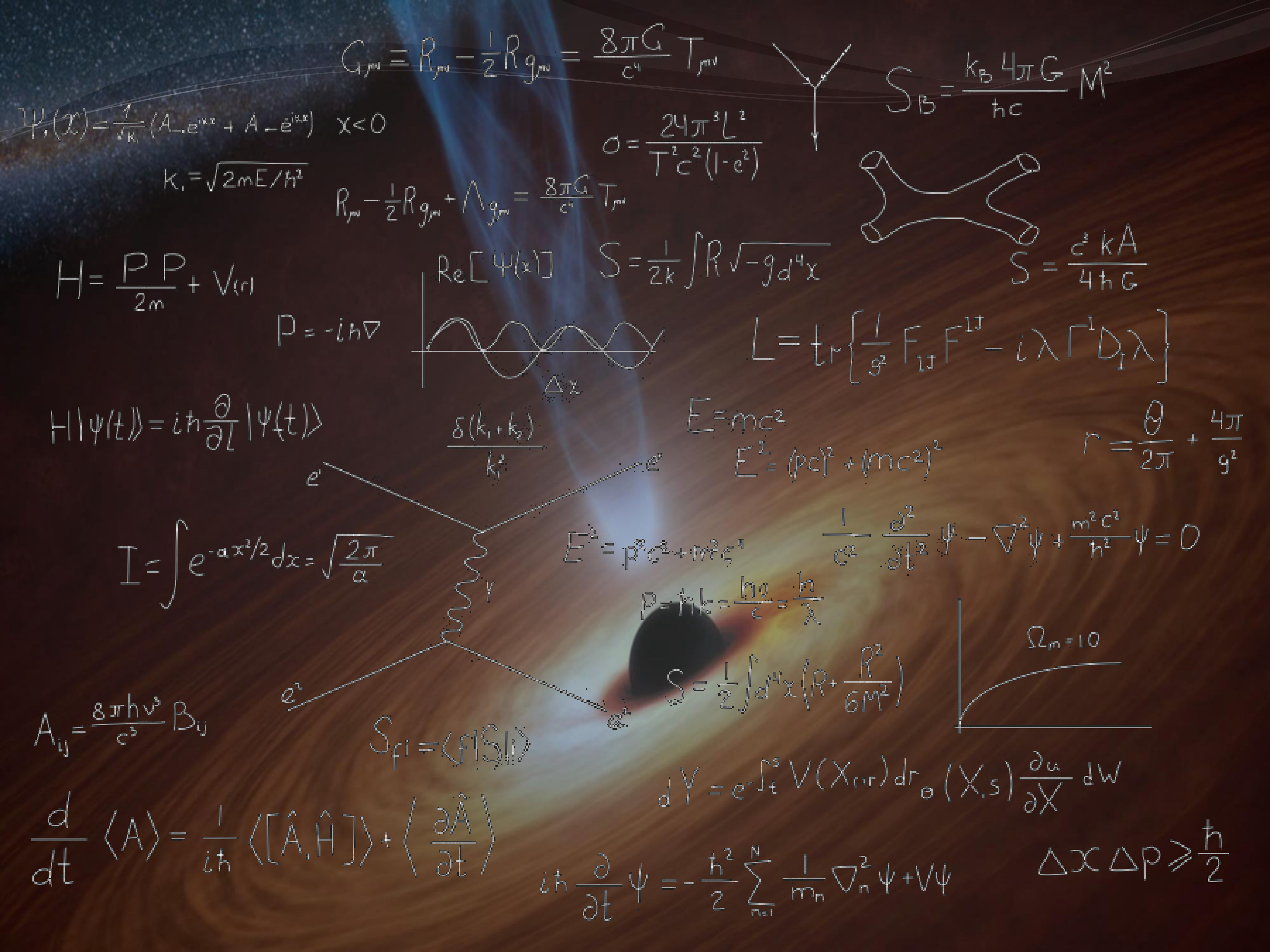
DO ALPs EXIST?

- **Three hints** from astrophysical spectra with **same ALP parameters**
  - **Two indications** from **blazars**
  - The most recent and **strongest one** from **GRB 221009A**
- Additional hints from **photon polarization** expected
  - Photons diffusely emitted by galaxy clusters are **unpolarized** within standard physics
  - ALPs make them **partially polarized** (see Galanti+2023): if detected -> **ALP hint**

FINAL ANSWER:

- Within few years
- **Confirmed** or **disproved**:
  - From new spectral data by ASTRI, CTA, LHAASO
  - Possible polarization data from IXPE, NGXP, COSI, AMEGO
  - From laboratory experiments such as ALPSII, IAXO


Thank you



G_μν = R_μν − ½ R g_μν = 8πG/c⁴ T_μν
S_B = k_B 4πG / ħc M²
k₁ = √(2mE/ħ²)
R_μν − ½ R g_μν + Λ g_μν = 8πG/c⁴ T_μν
H = P·P/2m + V(r)
S = 1/2k ∫ R √(−g) d⁴x
S = c³kA / 4ħG
p = −iħ∇
Re[ψ(x)]
Δx
H|ψ(t)⟩ = iħ ∂/∂t |ψ(t)⟩
E = mc²
E² = (pc)² + (mc²)²
I = ∫ e^(−αx²/2) dx = √(2π/α)
S_fi = ⟨f|S|i⟩
dY = e^(−∫ V(X,r) dr) σ(X,s) ∂u/∂X dW
d/dt ⟨A⟩ = 1/iħ ⟨[Â, Ĥ]⟩ + ⟨∂Â/∂t⟩
iħ ∂/∂t ψ = −ħ²/2 Σ 1/m_n ∇_n² ψ + Vψ
ΔxΔp ≥ ħ/2
Ω_m = 1.0