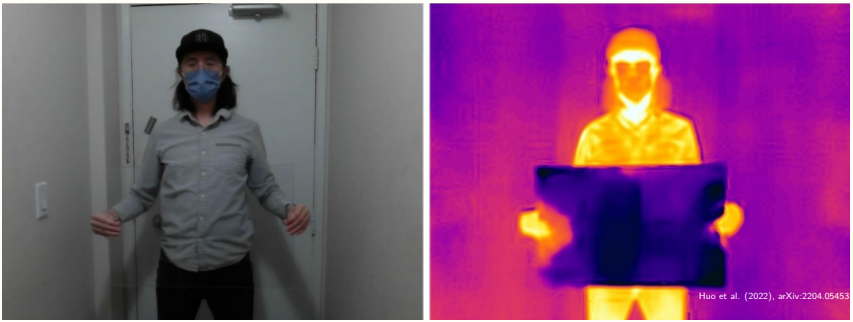
TeV gamma ray as probes of axions and neutrinos

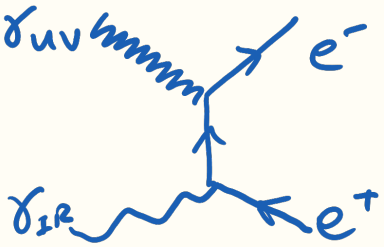
Chen Sun, UCAS-HIAS

September 10, 2026

w/ Shengyi Liu (HKUST), Hyeonseok Seong (HKUST→TDLI),
Seokhoon Yun (Kyungpook National U.); to appear


Huo et al. (2022), arXiv:2204.05453

How transparent is the universe at TeV scale?



$$\sigma_{\gamma\gamma\to e^+e^-}(s) \simeq \begin{cases} 0, & s < 4m_e^2, \\ \dfrac{\pi\alpha^2}{m_e^2}\sqrt{1-\dfrac{4m_e^2}{s}}, & s \gtrsim 4m_e^2, \\ \dfrac{4\pi\alpha^2}{s}\left[\ln\left(\dfrac{s}{m_e^2}\right)-1\right], & s \gg m_e^2. \end{cases}$$

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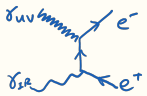

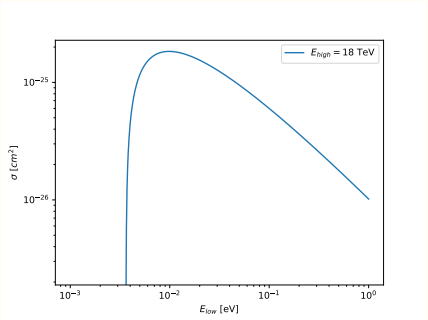

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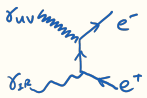

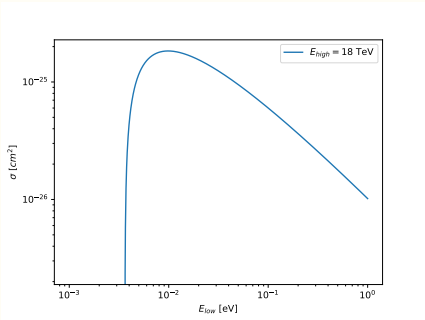

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$$\begin{aligned} s &= 2E_{\rm UV}E_{\rm IR}(1-\cos\theta) \\ &\sim \left(\frac{E_{\rm UV}}{10\,\text{TeV}}\right)\left(\frac{E_{\rm IR}}{0.1\,\text{eV}}\right)\text{MeV}^2 \gtrsim m_e^2 \end{aligned}$$

CORE IDEA

IF

BSM physics supplies
enough **soft photons**

$E_{\text{soft}} \gtrsim 0.01\,\text{eV}$

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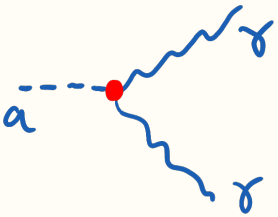
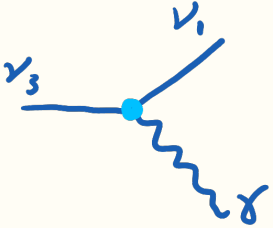
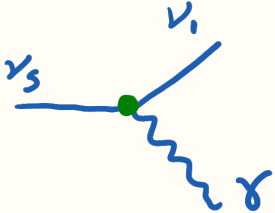
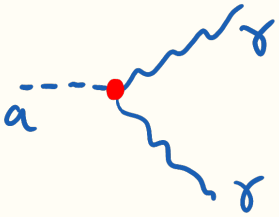
Multi-TeV γ rays probe **BSM-induced light at** 0.01–$0.1\,\text{eV}$.


a
γ
γ

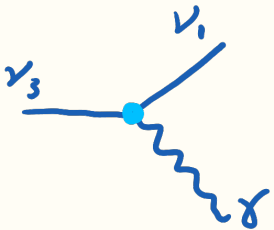

ν1
ν3
γ


ν1
ν3
γ

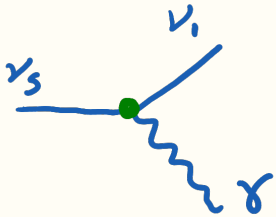
What new physics generates soft photons, the “EBL”



$m_a \sim \mathcal{O}(0.1)\,\mathrm{eV}$



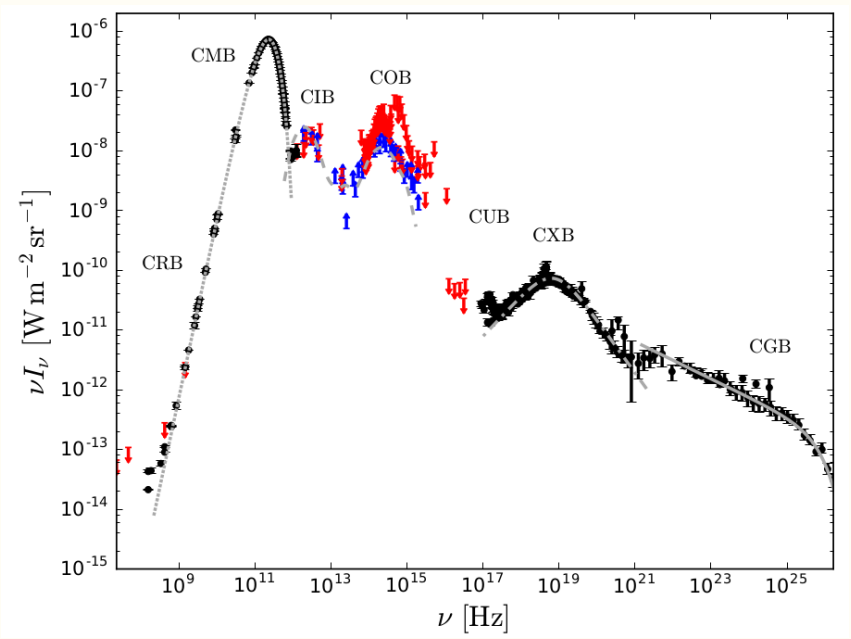
$\sqrt{\Delta m^2_{\mathrm{atm}}} = 0.05\,\mathrm{eV}$



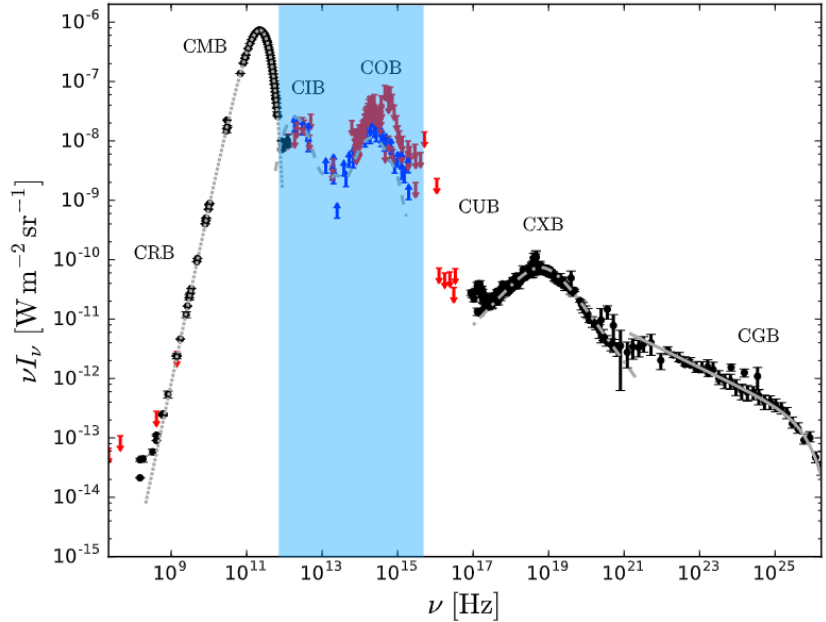
$\sqrt{\Delta m^2_{41}} \sim \mathcal{O}(\mathrm{eV})$

Use the E&M spectrum to constrain New Physics is not very new. Why –

- do we choose to work on this specific energy range,
- through such a very specific channel?


CMB
CIB
COB
CUB
CXB
CGB
CRB
νI_ν [W m^{-2} sr^{-1}]
ν [Hz]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{9}
10^{11}
10^{13}
10^{15}
10^{17}
10^{19}
10^{21}
10^{23}
10^{25}

R. Hill, K. W. Masui, D. Scott, [1802.03694]



How do we measure the EBL?

The same background light leaves three different observables.

01

Direct light

Measure the total
night-sky glow.

$$I_{\mathrm{sky}} = I_{\mathrm{EBL}} + I_{\mathrm{foregrounds}}$$

What it gives

an upper bound (barring foreground subtraction)

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Galaxy counts

Add the light from resolved galaxies.

$$\sum_{\text{galaxies}} F_\nu \longrightarrow I_{\text{EBL}}$$

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03

γ-ray shadow

Infer the light from absorbed TeV spectra.

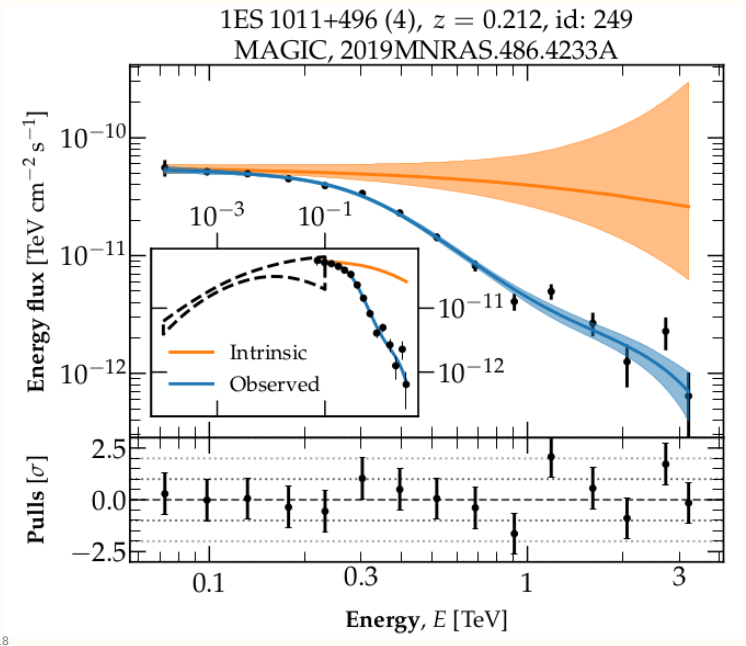
$$\Phi_{\mathrm{obs}} = \Phi_{\mathrm{int}} e^{-\tau_{\mathrm{EBL}}}$$

Main challenge

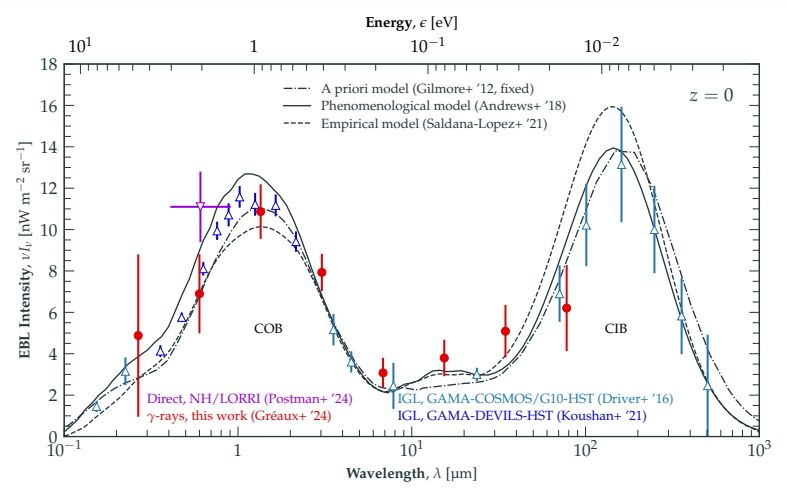
intrinsic source spectrum

Counts set the **floor**; direct light and γ rays test what lies **above it**.

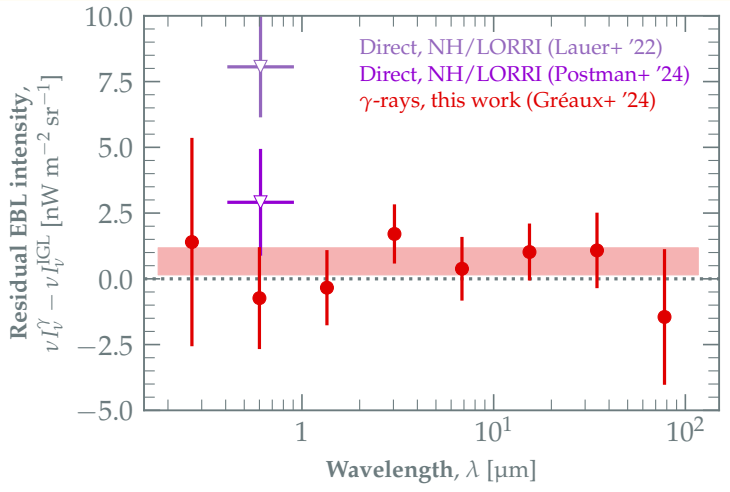
The Data


1ES 1011+496 (4), $z = 0.212$, id: 249
MAGIC, 2019MNRAS.486.4233A
Energy flux [TeV cm^{-2} s^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-3}
10^{-1}
Intrinsic
Observed
Pulls [σ]
2.5
0.0
−2.5
0.1
0.3
1
3
Energy, E [TeV]

γ rays reconstruct the total EBL

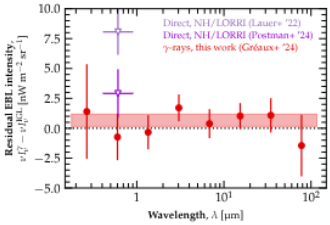


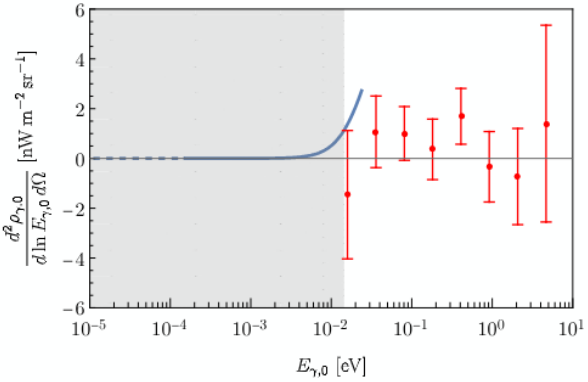
No significant EBL excess above galaxy counts



Gréaux et al. 2024 ApJL 975 L18

STeVECat, >260 TeV spectra


Direct, NH/LORRI (Lauer+ '22)
Direct, NH/LORRI (Postman+ '24)
γ-rays, this work (Gréaux+ '24)
Residual EBL intensity, $\nu I_\nu^{\rm res} = \nu I_\nu^{\rm EBL}$ [nW m^{-2} sr^{-1}]
Wavelength, λ [μm]


$\frac{d^2\rho_{\gamma,0}}{d\ln E_{\gamma,0}\, d\Omega}$ [nW m^{-2} sr^{-1}]
$E_{\gamma,0}$ [eV]

The brightest burst ever crossed a nearly opaque Universe

GRB 221009A

$z = 0.151$ | $d \simeq 750\,\mathrm{Mpc}$

142
events above 3 TeV

> 10 TeV
photons detected

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EXPECTED SURVIVAL AT 10 TeV

$0.05\text{–}0.5\%$

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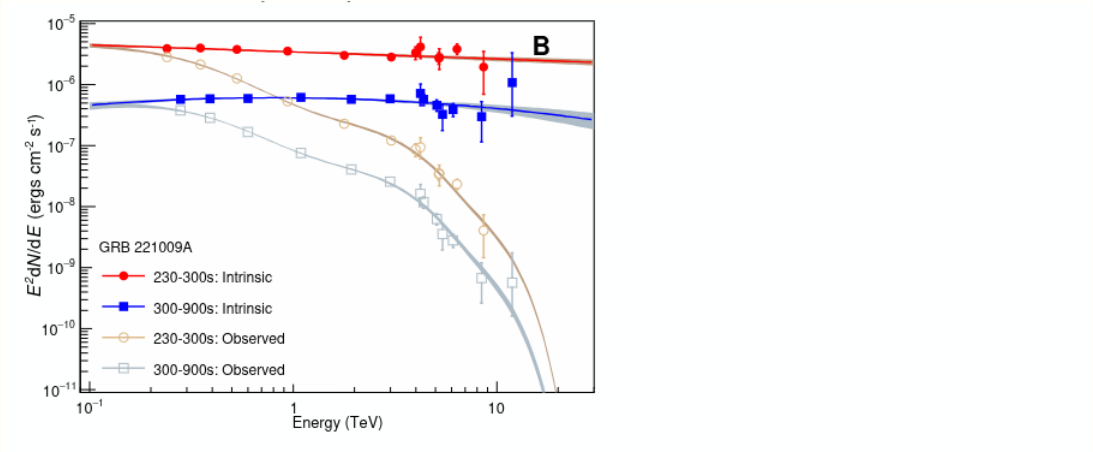
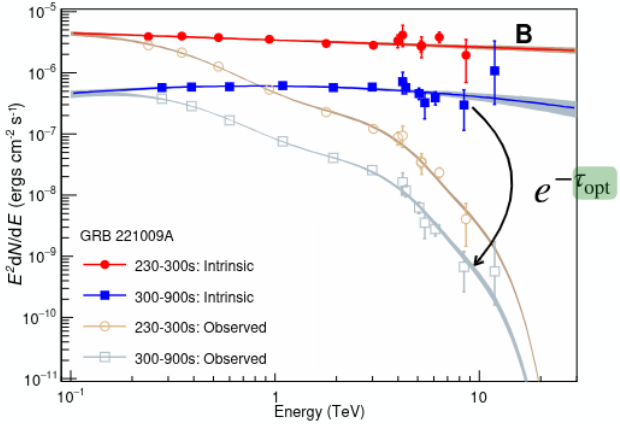
Assume an intrinsic spectrum Φ_{int}: the missing photons become an EBL measurement.

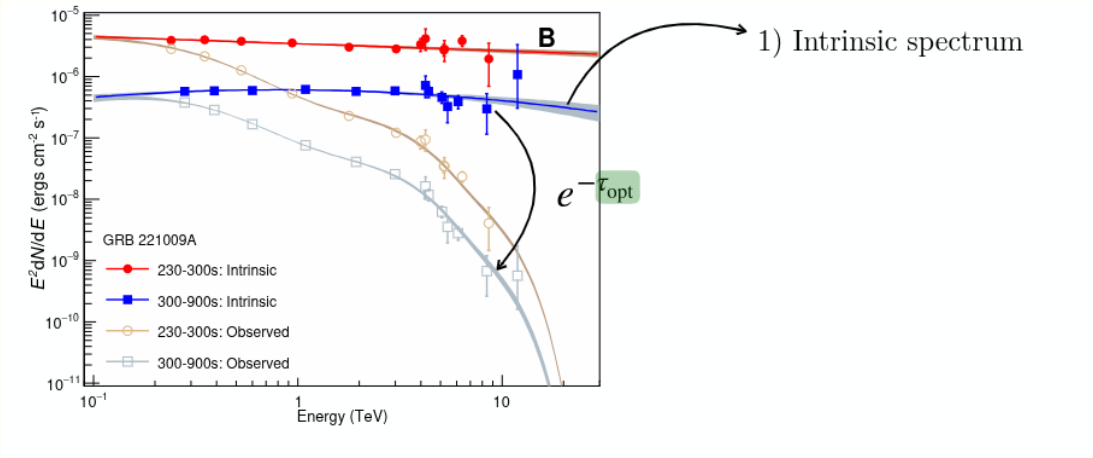
Far-IR intensity $\longrightarrow$ **close to the galaxy-count floor.**

LHAASO, *Sci. Adv.* 9, eadj2778 (2023)

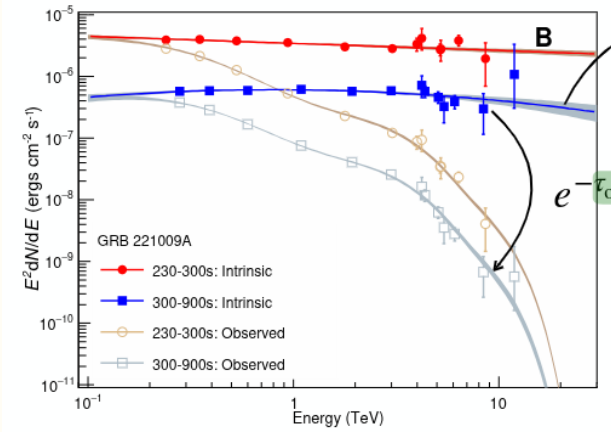


LHAASO, Sci.Adv. 9 (2023) 46


B
$e^{-\tau_{\rm opt}}$
GRB 221009A
230-300s: Intrinsic
300-900s: Intrinsic
230-300s: Observed
300-900s: Observed
E^2dN/dE (ergs cm^{-2} s^{-1})
Energy (TeV)



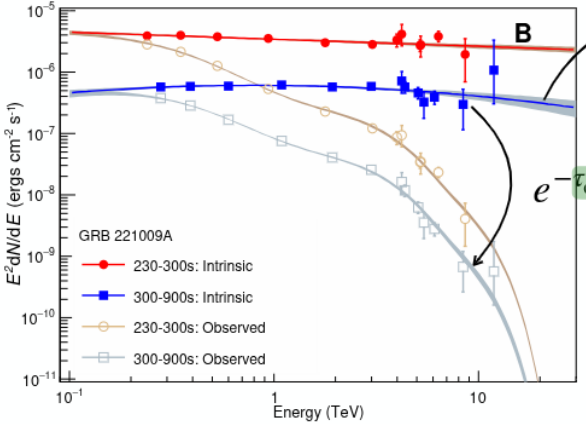
LHAASO, Sci.Adv. 9 (2023) 46



1) Intrinsic spectrum

2) Calculate $\tau_{\rm opt} \propto n_{\rm EBL}\sigma_{\gamma\gamma\to e^+e^-} l_{\rm path}$

$e^{-\tau_{\rm opt}}$



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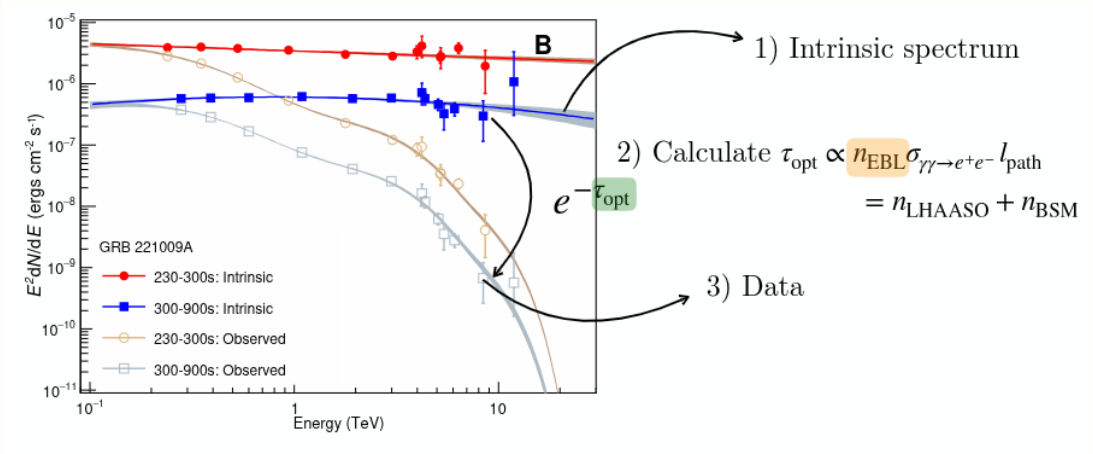
$= n_{\rm LHAASO} + n_{\rm BSM}$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$e^{-\tau_{\rm opt}}$
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GRB 221009A
230-300s: Intrinsic
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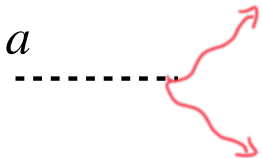
230-300s: Observed
300-900s: Observed
E^2dN/dE (ergs cm^{-2} s^{-1})
Energy (TeV)

EBL Model	τ_{18}	τ_{10}	$N_{\gamma,0.5}$	$N_{\gamma,18}$	$g_{a\gamma}$	$M_1(M_2)$	$N_{\rm cr}$
Fr2008	18.2	6.7	4900	6×10^{-4}	0.45	$9.8(2.7\times10^{-7})$	
SL2021	19.1	6.9	5100	3×10^{-4}	0.45	$9.8(2.6\times10^{-7})$	
K&D2010	9.2	4.5	6800	5	–	–	
Fi2010	9.9	6.0	4000	3	–	–	
Do2011	19.2	6.1	4500	2×10^{-4}	0.45	$10.5(2.7\times10^{-7})$	2...3
Do2011+	27.1	7.8	3900	9×10^{-8}	0.45	$8.7(2.5\times10^{-7})$	
Do2011-	13.5	4.4	5800	7×10^{-2}	0.44	$13.1(3.1\times10^{-7})$	
Gi2012	13.3	5.4	4500	9×10^{-2}	0.43	$12.3(2.9\times10^{-7})$	
Gi2012f	13.8	5.6	5600	5×10^{-2}	0.44	$11.8(2.9\times10^{-7})$	

The BSM Constraints

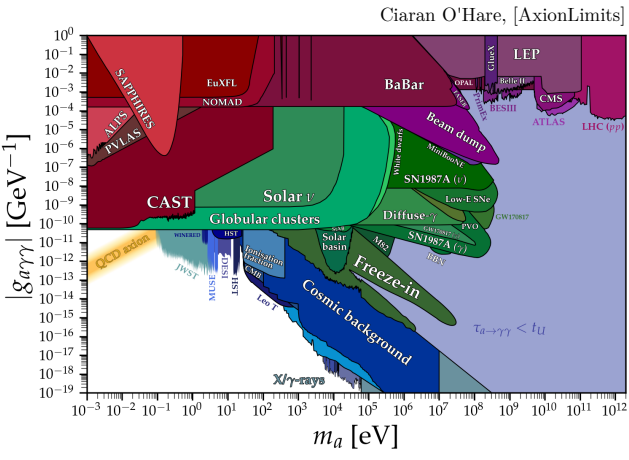
Axions



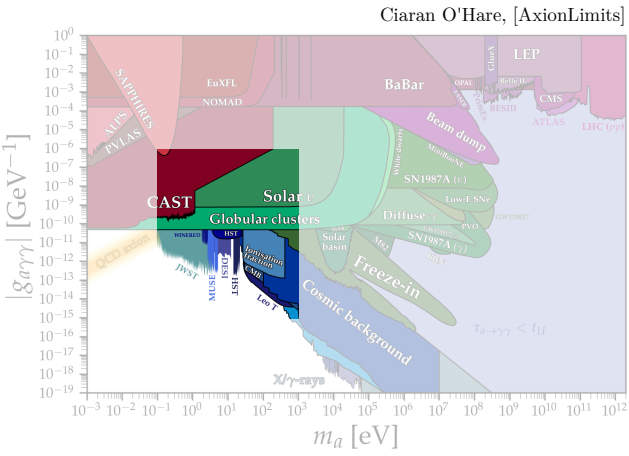
A. Caputo, M. Regis, M. Taoso, and S. J. Witte, [1811.08436]

$$\frac{d^2 n_{\gamma,0}}{df_0\, d\Omega} = \frac{1}{2\pi} \frac{\Gamma_a (1+2f_\gamma)}{H(z=z_{\rm init})} \frac{n_a(z=z_{\rm init})}{(1+z_{\rm init})^3} \frac{1}{f_0} \Theta(f_\star - f_0)$$

Axion-photon coupling



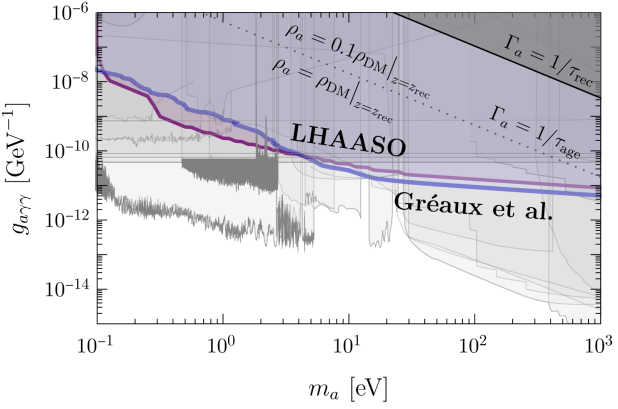
Axion-photon coupling

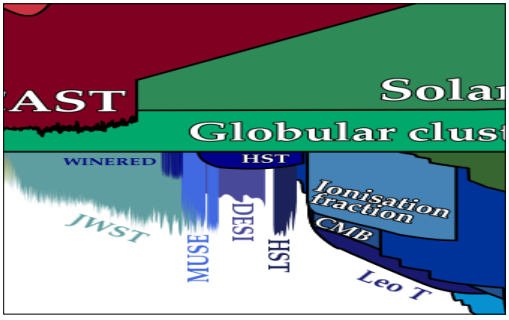


Axion-photon coupling

J. L. Bernal, G. Sato-Polito, and M. Kamionkowski, [2203.11236]
J. L. Bernal, A. Caputo, G. Sato-Polito. J. Mirocha. and M. Kamionkowski. [2208.13794]
S. Liu, H. Seong, CS, and S. Yun 2026

95% C.L. Exclusion Region





Neutrinos

$$\mathscr{L}_{\text{eff}} \supset \frac{1}{2}\bar{\nu}^j \sigma_{\mu\nu}(\mu_{ij} + \epsilon_{ij}\gamma_5)\nu^i F^{\mu\nu} \; + \; \textbf{h.c.}$$

ν^i : mass eigenstates

μ_{ij} : magnetic moments

ϵ_{ij} : electric moments

$\sigma_{\mu\nu} \propto [\gamma_\mu, \gamma_\nu]$

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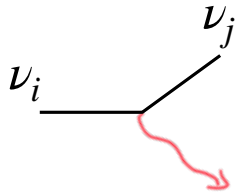
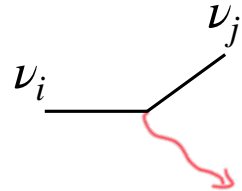


Neutrinos

$$\mathscr{L}_{\text{eff}} \supset \frac{1}{2}\bar{\nu}^j \sigma_{\mu\nu}(\mu_{ij} + \epsilon_{ij}\gamma_5)\nu^i F^{\mu\nu} + \textbf{h.c.}$$



ν^i : mass eigenstates

μ_{ij} : magnetic moments

ϵ_{ij} : electric moments

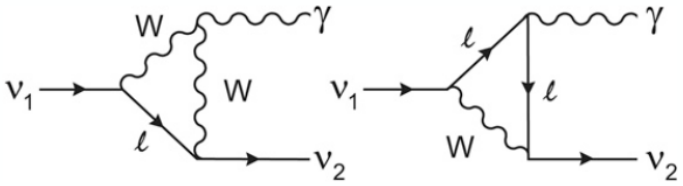
$\sigma_{\mu\nu} \propto [\gamma_\mu, \gamma_\nu]$

G. G. Raffelt, [Stars as laboratories]

$$\Gamma_{i\to j} = \frac{|\mu_{ij}|^2 + |\epsilon_{ij}|^2}{8\pi}\left(\frac{m_i^2 - m_j^2}{m_i}\right)^3$$

$$\simeq 5.3\times 10^{-23}\,\text{s}^{-1}\frac{|\mu_{ij}|^2 + |\epsilon_{ij}|^2}{\left(10^{-10}\,\mu_\text{B}\right)^2}\left(\frac{m_i^2 - m_j^2}{m_i^2}\right)^3\left(\frac{m_i}{0.1\,\text{eV}}\right)^3$$

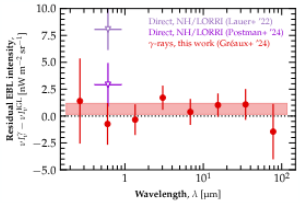
R. Cowsik, PRL '77
A. de Rujula and S.L. Glashow, PRL '80
P. B. Pal and L. Wolfenstein, PRD '82

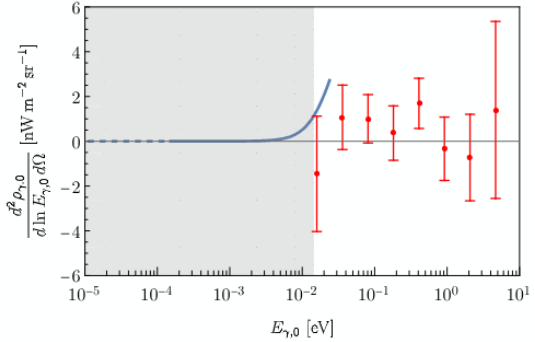


J. M. Overduin and P. S. Wesson, [astro-ph/0407207]

$$\tau_{\text{decay}} \gg t_{\text{age}} \ \textbf{(SM)}$$

$$\frac{d^2 n_{\gamma,0}}{df_0\, d\Omega} = \frac{1}{4\pi}\,\frac{\Gamma_{i\to j}}{H(z=z_{\rm init})}\,\frac{n_{\nu,i}(z=z_{\rm init})}{(1+z_{\rm init})^3}\,\frac{1}{f_0}\,\Theta(f_\star - f_0)$$



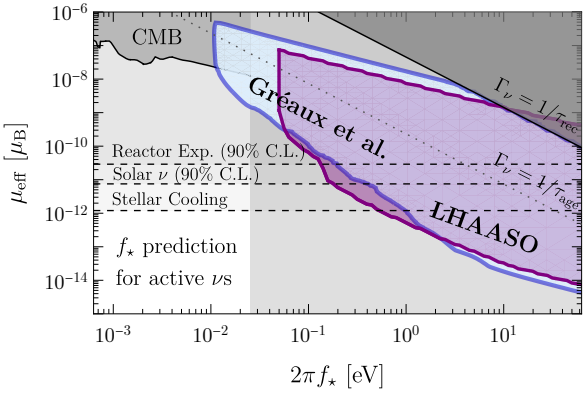


S. Liu, H. Seong, CS, and S. Yun 2026

Neutrino electromagnetic (transition) moments

J. L. Bernal, A. Caputo, F. Villaescusa-Navarro. and M. Kamionkowski. [2103.12099]
S. Liu, H. Seong, CS, and S. Yun 2026

95% C.L. Exclusion Region



Caveat: For reactor and solar neutrino constraints, $\mu_{\rm eff}$ has a different dependence on the electric and magnetic moments, such as their relative sign and probability weights.

Neutrinos

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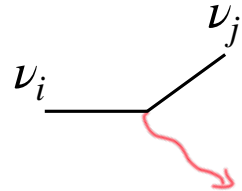

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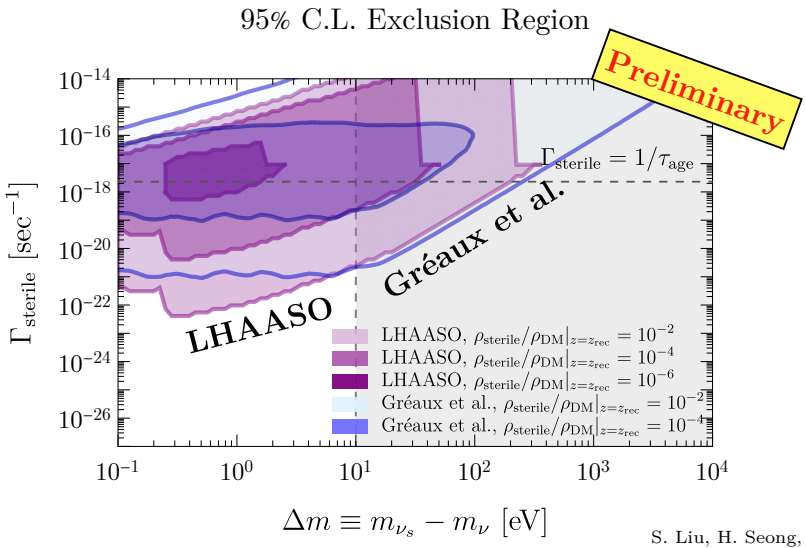
Sterile neutrino decay rate



S. Liu, H. Seong, CS, and S. Yun 2026

Transparency turns TeV photons into a soft-light probe

01 WINDOW

10 TeV γ rays select 0.01–0.1 **eV** light.

02 DATA

EBL reaches the **galaxy-count floor**.

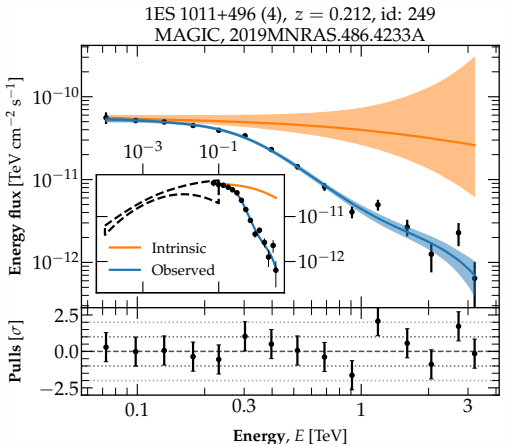
03 PHYSICS

No excess $\Longrightarrow$ limits on $a \to \gamma\gamma$ **and** $\nu_i \to \nu_j \gamma$.

observed transparency $\longrightarrow$ less hidden light $\longrightarrow$ **stronger decay bounds**

Backup slides

How to anchor the intrinsic spectrum



Gréaux et al. 2024 ApJL 975 L18

1. Fermi-LAT: shape anchor

0.1–100 GeV with $\tau_{\rm EBL} \simeq 0$

$$(\widehat{\Gamma}, \widehat{\beta}, \mathrm{Cov})_{\rm LAT} \longrightarrow \underbrace{p(\Gamma, \beta)}_{\text{Gaussian prior}}$$

2. MAGIC + shared EBL

MAGIC fits $\Phi_{\rm obs} = e^{-\tau_{\rm EBL}} \Phi_{\rm int}$, with one EBL spectrum shared across all 268 observations.

Posterior-inferred, not independently measured.

LAT fixes the shape, not the normalization (variability).