Astrophysical Probes of New Physics:
From Neutron Stars to High-Energy Neutrinos

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Outline

- Neutron Star Eclipses as Axion Laboratories
  (VB, D. S. Chattopadhyay, arXiv:2504.02030)

- Does the 220 PeV Event at KM3NeT Point to New Physics?
  (VB, D. S. Chattopadhyay, arXiv:2502.21299)

Motivation: Strong CP Problem and Axion

- take QCD with 1 quark

$$\tilde{m} = e^{i\gamma_5\phi}$$

$$\mathcal{L}_{\not{C}\not{P}} \supset \frac{\theta}{32\pi^2}\epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma} - \bar{\psi}\tilde{m}\psi$$

- under chiral rotation $\psi' = \psi e^{\frac{i\alpha\gamma_5}{2}}$
  $\phi \to \phi' = \phi + \alpha$, $\theta \to \theta' = \theta - \alpha$
- $\bar{\theta} \equiv \theta + \phi$ is invariant and we can not rotate away the CP violation terms in the strong sector
- neutron electric dipole moment $\simeq 10^{-14}\bar{\theta}$ e cm and measurements give $|d_n| < 1.8 \times 10^{-26}$e cm
- $\bar{\theta} \lesssim 10^{-12}$ (strong CP problem)

- introduce $U(1)_{\mathrm{PQ}}$ symmetry which is spontaneously broken and generates axion

$$\mathcal{L}_a \supset \frac{a}{f_a}\frac{1}{32\pi^2}\epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma}$$

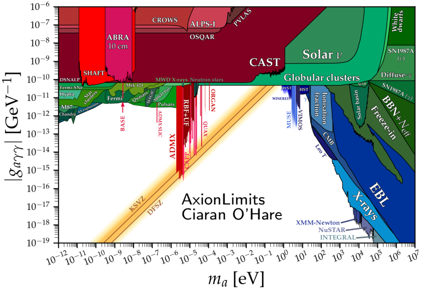
- from the axion potential we find that its VEV is $\langle a \rangle = -\bar{\theta} f_a$
- redefine $a_p = a - \langle a \rangle$; $\langle a_p \rangle = 0$
- we got $\mathcal{L}_a \supset -\bar{\theta}\frac{1}{32\pi^2}\epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma}$ which cancels $\not{C}\not{P}$ term in QCD $\mathcal{L}$
- in addition to solving the strong CP problem, axion is also a viable dark matter (DM) candidate

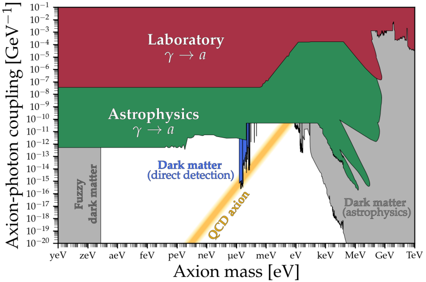
Axion-Photon Interaction

- axion's two-photon interaction plays a key role in the majority of the experimental searches

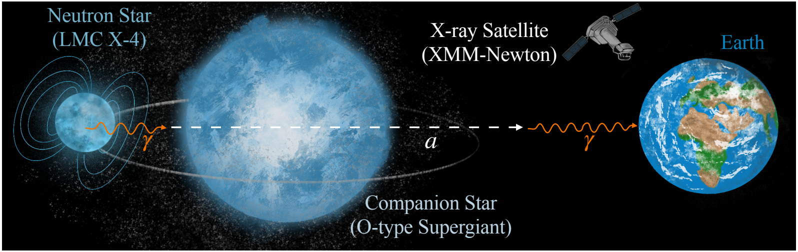
$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma}\, a\, F^{\mu\nu}\, \tilde{F}_{\mu\nu} = g_{a\gamma} \vec{E} \cdot \vec{B}$$

- here, $g_{a\gamma} \propto f_a^{-1}$ and $m_a f_a \approx m_\pi f_\pi \sim (100\,\mathrm{MeV})^2$
- fo the case of axion-like particles (ALPs), particle's mass and its decay constant are treated as independent parameters

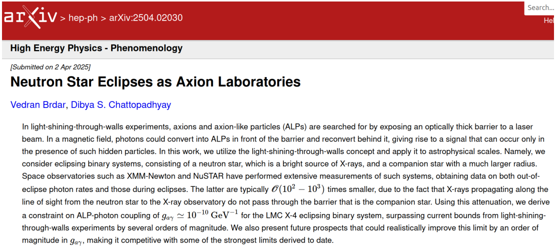




Neutron Star Eclipses as Axion Laboratories



Dibya Chattopadhyay



arXiv > hep-ph > arXiv:2504.02030

High Energy Physics - Phenomenology

[Submitted on 2 Apr 2025]

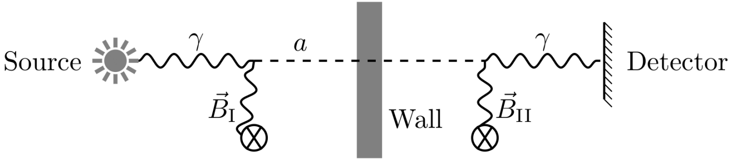
Neutron Star Eclipses as Axion Laboratories

Vedran Brdar, Dibya S. Chattopadhyay

In light-shining-through-walls experiments, axions and axion-like particles (ALPs) are searched for by exposing an optically thick barrier to a laser beam. In a magnetic field, photons could convert into ALPs in front of the barrier and reconvert behind it, giving rise to a signal that can occur only in the presence of such hidden particles. In this work, we utilize the light-shining-through-walls concept and apply it to astrophysical scales. Namely, we consider eclipsing binary systems, consisting of a neutron star, which is a bright source of X-rays, and a companion star with a much larger radius. Space observatories such as XMM-Newton and NuSTAR have performed extensive measurements of such systems, obtaining data on both out-of-eclipse photon rates and those during eclipses. The latter are typically $\mathcal{O}(10^2-10^3)$ times smaller, due to the fact that X-rays propagating along the line of sight from the neutron star to the X-ray observatory do not pass through the barrier that is the companion star. Using this attenuation, we derive a constraint on ALP-photon coupling of $g_{a\gamma} \simeq 10^{-10}\,\mathrm{GeV}^{-1}$ for the LMC X-4 eclipsing binary system, surpassing current bounds from light-shining-through-walls experiments by several orders of magnitude. We also present future prospects that could realistically improve this limit by an order of magnitude in $g_{a\gamma}$, making it competitive with some of the strongest limits derived to date.

Light-Shining-Through-Walls

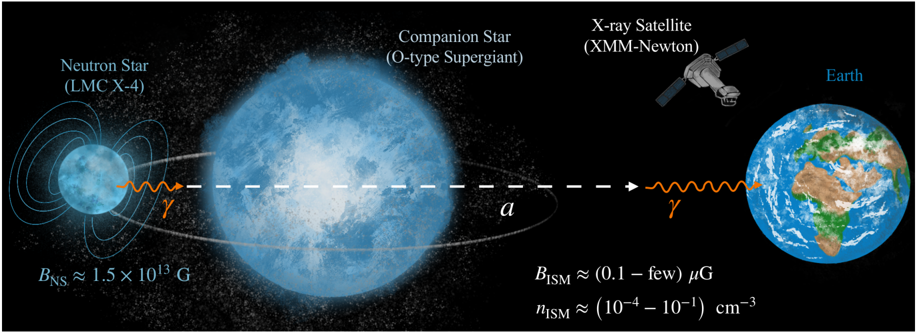
$$\mathcal{L} \supset -\frac{1}{4}\, g_{a\gamma}\, a\, F^{\mu\nu}\, \tilde{F}_{\mu\nu}$$



- Lab-based experiments: OSQAR, CROWS, ALPS ($g_{a\gamma} \simeq 10^{-7}\mathrm{GeV}^{-1}$)
  ALPS II (upcoming)

- we utilize the light-shining-through-walls concept and apply it to astrophysical scales (eclipsing binary system)

Schematic Diagram



- eclipsing binary system composed of:

  1) neutron star $\rightarrow$ bright source of X-rays
  2) larger companion star that serves as a "wall"

$\gamma \to a$ Transition Near Binary Systems

- 2-level system featuring ALP and photon states:

$$\mathcal{H}_{\text{eff}} = -\begin{pmatrix} \Delta_\gamma & \Delta_{a\gamma} \\ \Delta_{a\gamma} & \Delta_a \end{pmatrix}$$

$$\Delta_\gamma = -\frac{m_{\text{eff}}^2}{2E_\gamma} \qquad \Delta_a = -\frac{m_a^2}{2E_\gamma} \qquad \Delta_{a\gamma} = \frac{1}{2} g_{a\gamma} |\vec{B}_T|$$

effective photon mass: $m_{\text{eff}}^2(r) = \frac{4\pi\alpha}{m_e} n_e(r) - \frac{88\,\alpha^2 E_\gamma^2}{270\, m_e^4} B(r)^2$

- model the magnetic field like that of a dipole: $B(r) = B^{(0)}\,(r/10\,\text{km})^{-3}$
- $n_e(r) = n_e^{(0)}\,(r/10\,\text{km})^{-3}$
- $B^{(0)}$ and $n_e^{(0)}$ are magnetic field and electron number density at the surface of the neutron star

Finding the Ideal System: LMC X-4

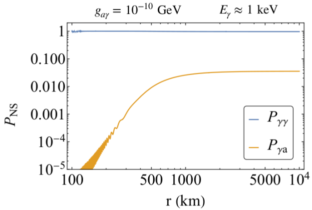
- Optimal candidate – high out-of-eclipse to eclipse flux ratio, large $B^{(0)}$, large distance from Earth

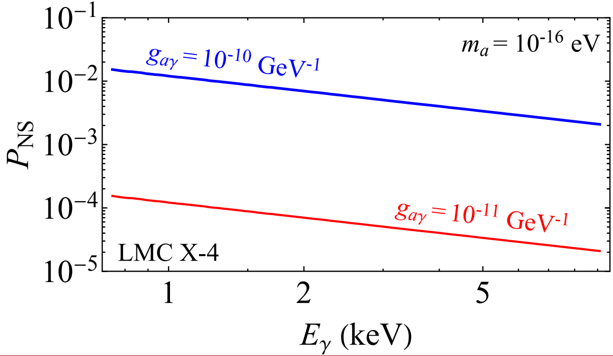
		Distance	NS Mag. field	Flux ratio	Location
HMXB	**LMC X-4**	~50 kpc	3×10^{13} G	**~237**	LMC
HMXB	**Vela X-1**	1.6 kpc	2.6×10^{12} G	**~100**	MW
HMXB	**Cen X-3**	~7.2 kpc	3×10^{12} G	**~70**	MW
LMXB	**MXB 1659-298**	9-15 kpc	$(10^8 - 10^9)$ G	~ **30**, 250	Towards GC
LMXB	**EXO 0748-676**	~7 kpc	$(10^8 - 10^9)$ G	~ **50**, 600	Galactic disk
LMXB	**XTE 1710-281**	12-16 kpc	$(10^8 - 10^9)$ G	**~129**, 500	Towards GC

90% LMXBs have weaker magnetic fields, while ~10% have magnetic field at ~10^{12} G

$\gamma \to a$ Process Near LMC X-4

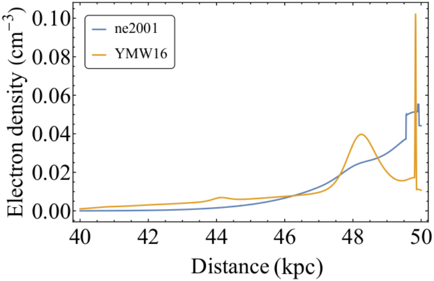
- solve $i\frac{d}{dr}\begin{pmatrix}\gamma(r)\\ a(r)\end{pmatrix} = \mathcal{H}_{\rm eff}\begin{pmatrix}\gamma(r)\\ a(r)\end{pmatrix}$ and compute $|a(r)|^2$
- the large transition probability, $P_{\rm NS}$, originates from the resonance achieved for $m_{\rm eff}^2 = m_a^2$

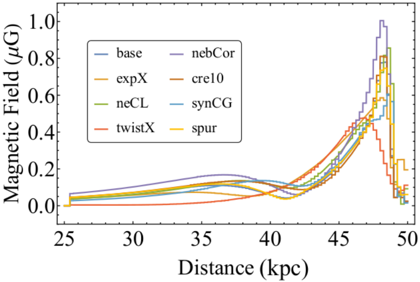




$a \to \gamma$ Transition in the Interstellar Medium (ISM)

- ISM n_e and B will affect the oscillation probabilities
- we use UF23 (x8) magnetic field, and the YMW16 electron density model



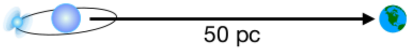


$$\Delta_\gamma \approx 1.1 \left(\frac{n_e}{10^{-2}\,\mathrm{cm}^{-3}}\right) \left(\frac{E_\gamma}{1\,\mathrm{keV}}\right)^{-1} \mathrm{kpc}^{-1}$$

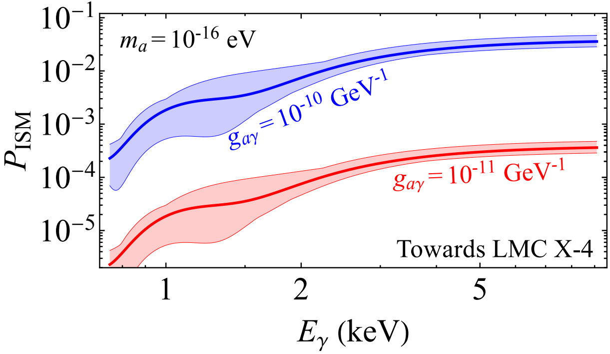
$$\Delta_{a\gamma} \approx 0.15 \left(\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right) \left(\frac{B_T}{1\,\mu\mathrm{G}}\right) \mathrm{kpc}^{-1}$$

$$P_{\mathrm{ISM}} = 4(\Delta_{a\gamma}^2/\Delta_\gamma^2)\sin^2(\tfrac{\Delta_\gamma L}{2})$$

$a \to \gamma$ Transition in the Interstellar Medium (ISM)



- $\sim$ kpc distances necessary for efficient transition probability P_{ISM}
- we consider conversion in Milky Way (LMC and IGMF not considered)

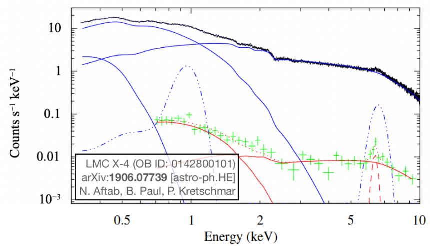


Constraining the ALP-Photon Coupling

- The total number of photons observed during the eclipse must exceed the number of photons produced through the γ-ALP-γ process

$$F_{\text{eclipse}} \gtrsim F_{\text{out-of-eclipse}}\, P_{\text{NS}}\, P_{\text{ISM}}$$

- we take that at least 80% of the observed photons during the eclipse are not arising from ALPs

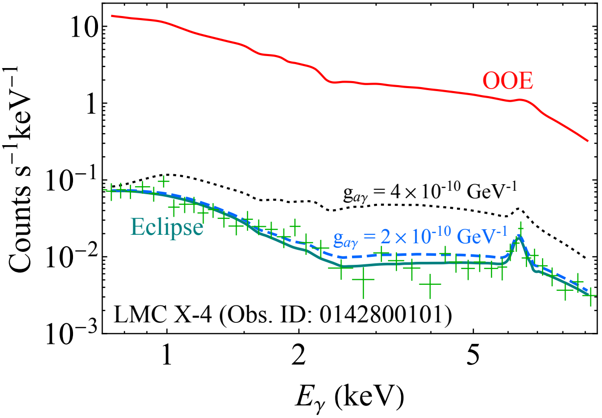


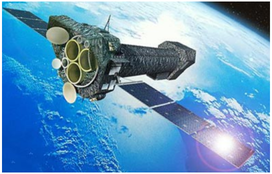
- to set the limit we use:

$$P_{\text{NS}}\, P_{\text{ISM}} = 0.2 F_{\text{eclipse}} / F_{\text{out-of-eclipse}}$$

Constraining the ALP-Photon Coupling

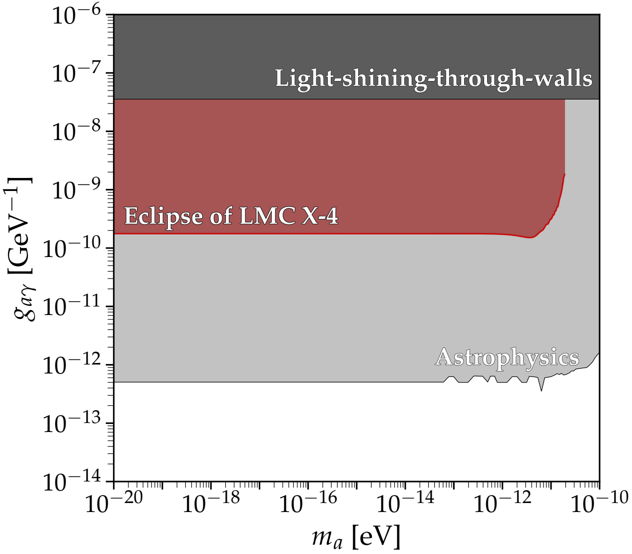
- $P_{\rm NS} P_{\rm ISM}$ is maximum in $E_\gamma \approx (3-6)$ keV range
- ISM conversion becomes inefficient at higher ALP masses
- bound at around $g_{a\gamma} \simeq 1.5 \times 10^{-10}\,\text{GeV}^{-1}$





XMM-Newton

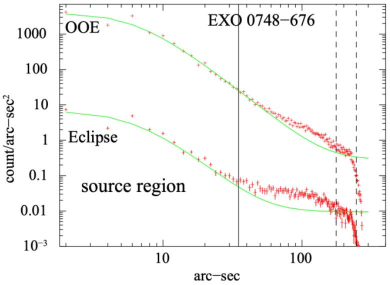
Constraining the ALP-Photon Coupling



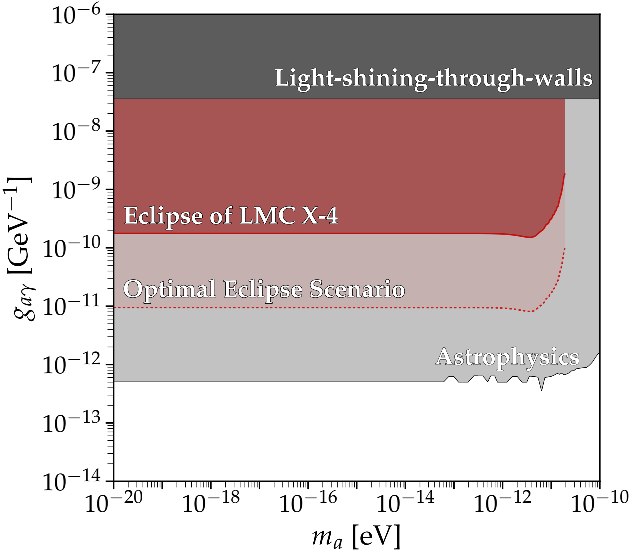
Towards the Ideal Candidate

- better understanding of the eclipsing system may constrain the contribution of the γ-ALP-γ process to at most a few %
- an eclipsing system located towards the Galactic Center would be ideal due to the stronger magnetic fields (factor of 10 in $P_{\rm ISM}$)
- a stronger magnetic field of the candidate neutron star (e.g., an eclipsing magnetar) could increase $P_{\rm NS}$ by $\mathcal{O}(10)$
- future observations may achieve unprecedented angular resolution for such a system, enhancing the out-of-eclipse to eclipse flux ratio by $\mathcal{O}(100)$

N. Aftab, B. Paul, [arXiv:2308.03916]

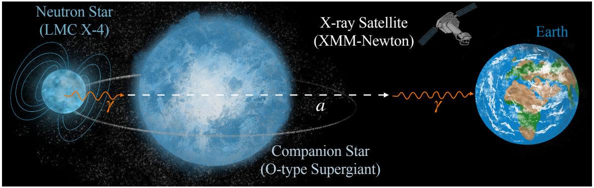


Constraining the ALP-Photon Coupling

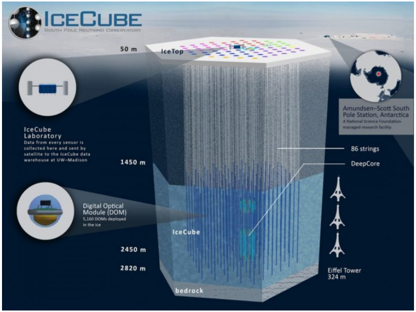


Take-Home Message

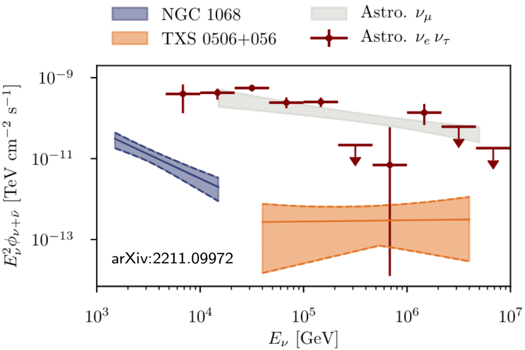
- Light-shining-through-walls in astrophysics
- Eclipsing neutron stars as a novel system to look for ALPs
- LMC X-4 system gives constraints of $g_{a\gamma} \sim 10^{-10}\,\mathrm{GeV}^{-1}$
- Optimal eclipse scenario can yield $g_{a\gamma} \sim 10^{-11}\,\mathrm{GeV}^{-1}$

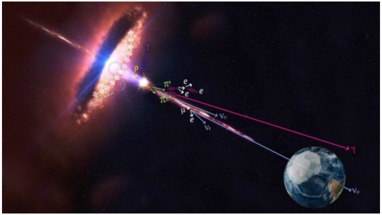


Neutrino Astronomy: IceCube

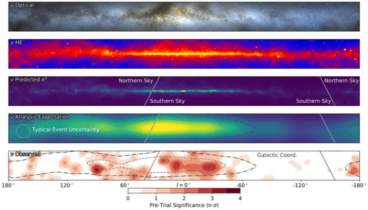


Neutrino Astronomy: IceCube



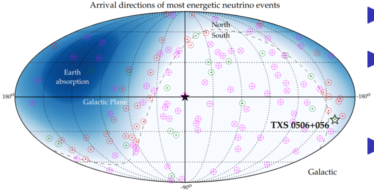


IceCube collaboration, Science 2023



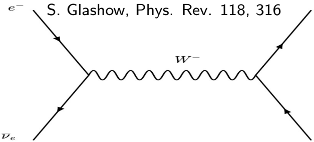
Former Energy Champion: Glashow Resonance at IceCube

Bull. Am. Astron. Soc. 51, 185 (2019)



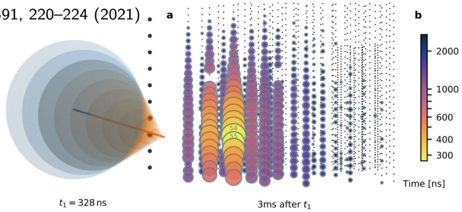
- $\mathcal{O}(100)$ upgoing tracks and HESE events
- Glashow resonance: cross section enhancement from on-shell W^- production
- $\sigma \propto \frac{1}{(E-E_0)^2+\Gamma^2}$, with $E_0 = \frac{M_W^2}{2m_e} \approx 6.3$ PeV

S. Glashow, Phys. Rev. 118, 316

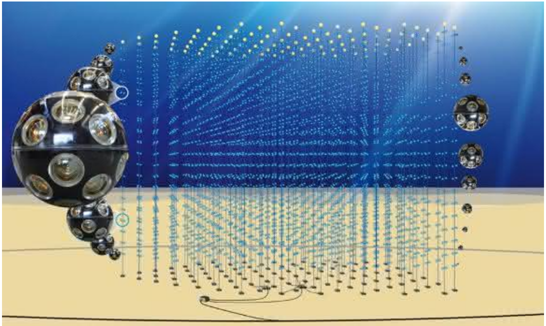


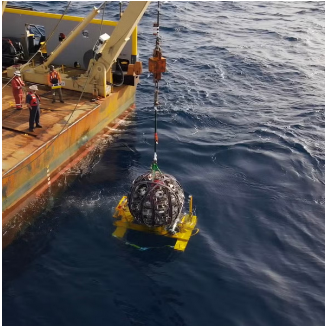
- shower with an energy of 6.05 ± 0.72 PeV
- presence of electron antineutrinos in the astrophysical flux $\rightarrow$ way to distinguish ν from $\bar{\nu}$

Nature 591, 220–224 (2021)



KM3NeT



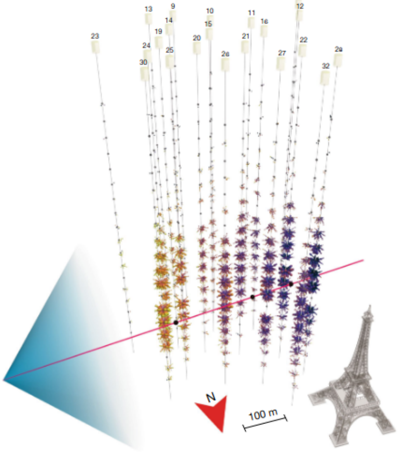


New Energy Champion: KM3-230213A Event

- The KM3NeT collaboration reported the detection of a ~ 120 PeV muon originating from a neutrino interaction with a median neutrino energy of 220 PeV

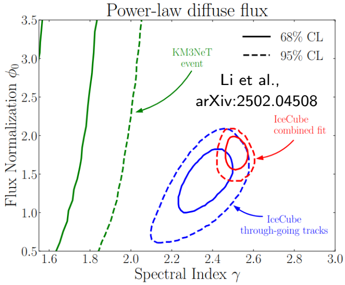
- This is the highest-energy neutrino ever detected, exceeding the Glashow resonance event in IceCube's dataset by a factor of $\mathcal{O}(10)$

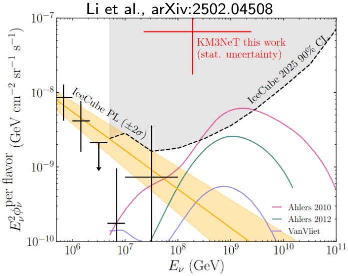
KM3NeT Collaboration, Nature (2025)



What about IceCube?

- IceCube has been operating with a much larger effective area for a longer time and has not observed neutrinos above ~ 10 PeV
- 2-3.5σ tension, depending on the neutrino source (Li et al., arXiv:2502.04508)
- Event such as KM3-230213A would be expected in 70 years of observation...an upward fluctuation at the level of 2.2σ (KM3NeT, Nature (2025))



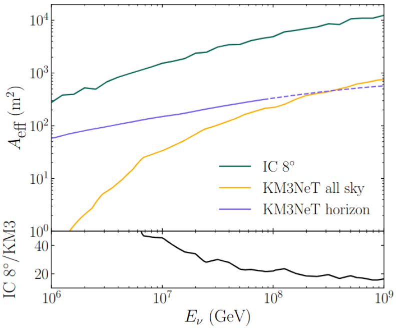


KM3NeT vs IceCube

$$\frac{dN(E_\nu)}{dE} = T \int d\Omega\, A_{\text{eff}}(E_\nu, \cos\theta)\, \Phi(E_\nu, \Omega)$$

- The difference in the effective areas between IceCube and KM3NeT is ~ 20
- To explain the tension, the neutrino flux at KM3NeT needs to be larger by a similar factor
- How to achieve that? $\Longrightarrow$ Sterile neutrinos partially converting into active neutrinos inside Earth

Li et al., arXiv:2502.04508

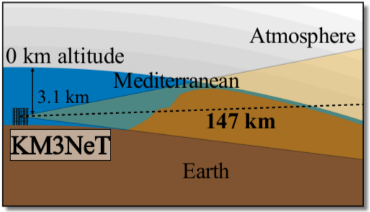


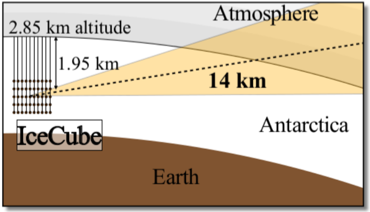
Sterile Neutrino Sources

- Lack of multi-messenger observations corresponding to KM3-230213A event

Speculations on sterile neutrino sources:

- A dense outer layer around the source - stops/downscatters SM particles
- AGN jets + dense matter blocking ultra high energy SM particles
- Dark sector stars





arXiv > hep-ph > arXiv:2502.21299

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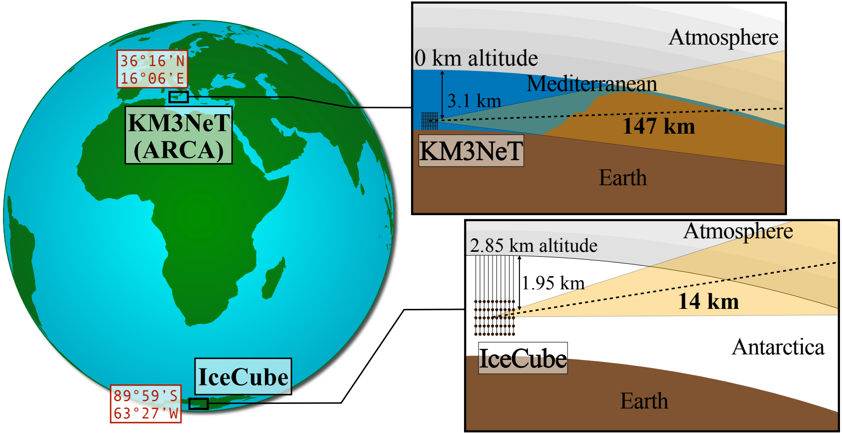
High Energy Physics - Phenomenology

[Submitted on 28 Feb 2025]

Does the 220 PeV Event at KM3NeT Point to New Physics?

Vedran Brdar, Dibya S. Chattopadhyay

The KM3NeT collaboration recently reported the observation of KM3-230213A, a neutrino event with an energy exceeding 100 PeV, more than an order of magnitude higher than the most energetic neutrino in IceCube's catalog. Given its longer data-taking period and larger effective area relative to KM3NeT, IceCube should have observed events around that energy. This tension has recently been quantified to lie between 2σ and 3.5σ, depending on the neutrino source. A $\mathcal{O}(100)$ PeV neutrino detected at KM3NeT has traversed approximately 147 km of rock and sea en route to the detector, whereas neutrinos arriving from the same location in the sky would have only traveled through about 14 km of ice before reaching IceCube. We use this difference in propagation distance to address the tension between KM3NeT and IceCube. Specifically, we consider a scenario in which the source emits sterile neutrinos that partially convert to active neutrinos through oscillations. We scrutinize two such realizations, one where a new physics matter potential induces a resonance in sterile-to-active transitions and another one where off-diagonal neutrino non-standard interactions are employed. In both cases, sterile-to-active neutrino oscillations become relevant at length scales of ~ 100 km, resulting in increased active neutrino flux near the KM3NeT detector, alleviating the tension between KM3NeT and IceCube. Overall, we propose the exciting possibility that neutrino telescopes may have started detecting new physics.



- $\mathcal{O}(100)$ PeV neutrino detected at KM3NeT has traversed $\sim$ 150 km of rock and sea en route to the detector
- Neutrinos arriving from the same location in the sky (angle of 8° w.r.t. horizon) would have only traveled through $\sim$ 14 km of ice before reaching IceCube

Neutrino production via non-standard interactions

- Consider the following Hamiltonian in the $(\nu_\mu,\, \nu_s)$ flavor basis

$$H = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & m_s^2/(2E_\nu) \end{pmatrix} \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} + \begin{pmatrix} V_{\rm NC} & \epsilon_{\mu s} V_{\rm CC} \\ \epsilon_{\mu s} V_{\rm CC} & 0 \end{pmatrix}$$

- NSI term arises from $\mathcal{L} \supset -2\sqrt{2} G_F \epsilon^f_{\mu s} \, (\bar{\nu}_s \gamma^\mu P_L \nu_\mu)(\bar{f}\gamma_\mu f)$

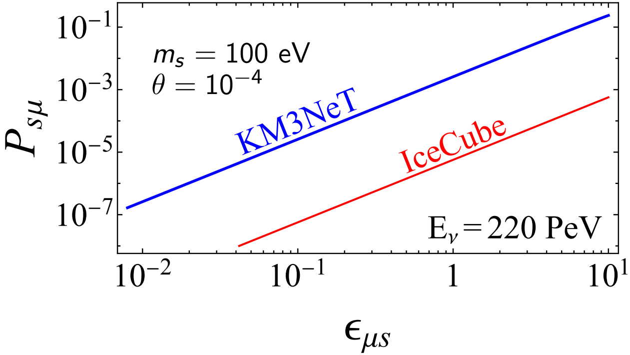
- The effective mixing angle and mass-squared difference in the limit of small θ:

$$\theta_m = \frac{1}{2}\tan^{-1}\left(\frac{4\epsilon_{\mu s} E_\nu V_{\rm CC}}{m_s^2 + E_\nu V_{\rm CC}}\right) \qquad \Delta m^2_{\rm eff} = \sqrt{(E_\nu V_{\rm CC} + m_s^2)^2 + 16\epsilon^2_{\mu s} E^2_\nu V^2_{\rm CC}}$$

- $\nu_s \to \nu_\mu$ conversion probability:

$$P_{s\mu} = \sin^2(2\theta_m)\sin^2\left[\Delta m^2_{\rm eff} L/(4E_\nu)\right]$$

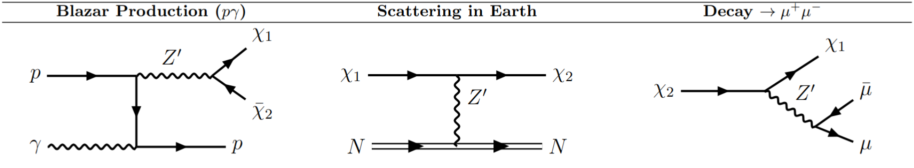
Neutrino production via non-standard interactions



- $\epsilon_{\mu s}$ values up to $\mathcal{O}(1–10)$ have a negligible effect on low-energy neutrino oscillations
- The difference in the propagation length between KM3NeT and IceCube leads to a difference in $P_{s\mu}$, which implies a larger active neutrino flux at KM3NeT, alleviating the tension

Alternative explanations for the tension

- in addition to oscillations, scattering in Earth is an option to explain the tension



(a) (b) (c)

arXiv > hep-ph > arXiv:2505.22754

High Energy Physics - Phenomenology

[Submitted on 28 May 2025]

`Dark' Matter Effect as a Novel Solution to the KM3-230213A Puzzle

P. S. Bhupal Dev, Bhaskar Dutta, Aparajitha Karthikeyan, Writasree Maitra, Louis E. Strigari, Ankur Verma

arXiv > hep-ph > arXiv:2505.22711

High Energy Physics - Phenomenology

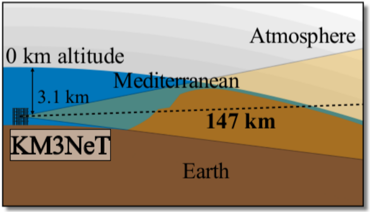
[Submitted on 28 May 2025]

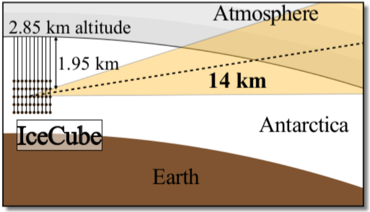
Astrophysical sources of dark particles as a solution to the KM3NeT and IceCube tension over KM3-230213A

Yasaman Farzan, Matheus Hostert

Take-Home Message

- KM3NeT collaboration observed highest-energy neutrino event exceeding $\mathcal{O}(100)$ PeV
- No such observation has been reported at IceCube, resulting in a tension of 2–3.5σ
- To alleviate the tension, we use the fact that the path through the Earth for KM3NeT is an order of magnitude longer than that for IceCube, leading to a larger $P(\nu_s \to \nu_\mu)$ and hence a higher flux of muon neutrinos at KM3NeT





BACKUP

Neutrino production through matter-induced resonance

- in a 2-flavor scenario (ν_μ and ν_s), MSW resonance is realized when $V = \cos 2\theta\, \Delta m^2/(2E_\nu)$
- in SM, matter potential V is $\sim 10^{-23}$ GeV; resonant oscillation length $L_{\rm res} \simeq \pi/(V \sin 2\theta)$ for $\theta^2 = 10^{-3}$ reads $L_{\rm res} = 10^5$ km
- for KM3NeT ($L \sim 100$ km), $L^2/L_{\rm res}^2 \simeq 10^{-6}$
- consider a large sterile neutrino matter potential ($V_s \gg V_{\rm SM}$) in order to have larger $\nu_s \to \nu_\mu$ transition probability
- model with spontaneously broken $U(1)_B$ (Pospelov, PRD 2011)

$$\mathcal{L} \supset g_b' \bar{\nu}_s \not{V} \nu_s + (g_b/3) \sum_q \bar{q} \not{V} q + \text{h.c.}$$

- EFT framework: $\mathcal{L}_{\rm eff} \supset \frac{g_b g_b'}{2m_V^2} \left[\bar{\nu}_s \gamma_\mu (1-\gamma_5)\nu_s\right]\left[\bar{p}\gamma^\mu p + \bar{n}\gamma^\mu n\right]$

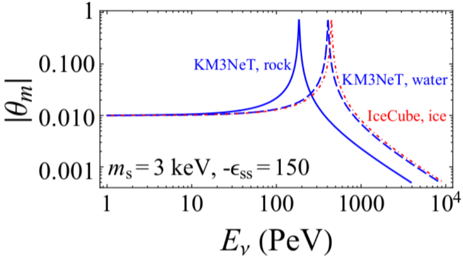
Sterile neutrino potential $V_s = \left[g_b g_b'/m_V^2\right](n_p + n_n) \equiv G_B(n_p + n_n)$

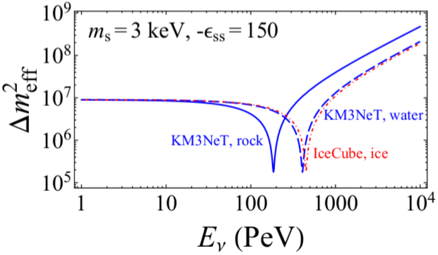
Neutrino production through matter-induced resonance

$$H = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & \frac{m_s^2}{2E_\nu} \end{pmatrix} \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} + \begin{pmatrix} V_{\rm NC} & 0 \\ 0 & V_s \end{pmatrix}$$

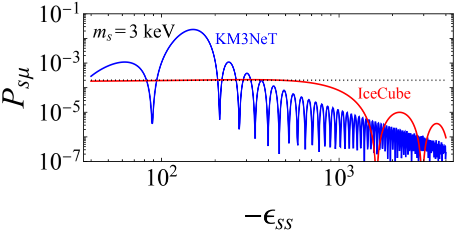
$$V_{\rm NC} = -(\sqrt{2}/2) G_F n_n \approx -(1/2) V_{\rm CC}$$

- $V_s = 2 G_F \epsilon_{ss} (n_n + n_p)$
- $\mathcal{O}(10^2 - 10^3)\, \epsilon_{ss}$ considered
- for $\mathcal{O}(100)$ PeV neutrino energy, resonance occurs for $\sqrt{\Delta m^2} \approx m_s \simeq 2 \times 10^{-1} \sqrt{\epsilon_{ss}}$ keV $\Rightarrow$ keV sterile neutrino

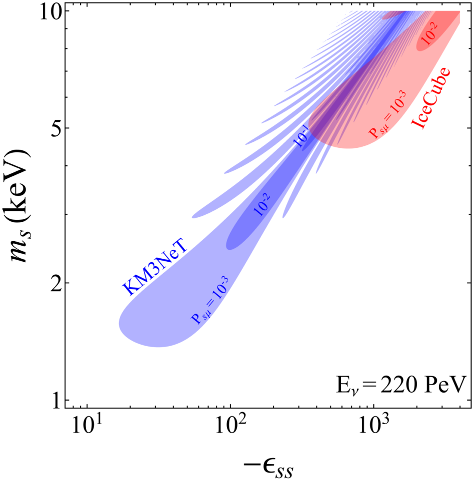




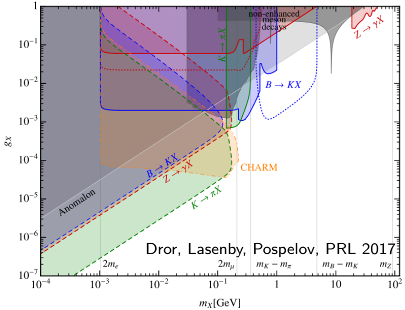
Neutrino production through matter-induced resonance



- The difference in $P(\nu_s \to \nu_\mu)$ implies a larger active neutrino flux at KM3NeT compared to that at IceCube, alleviating the tension

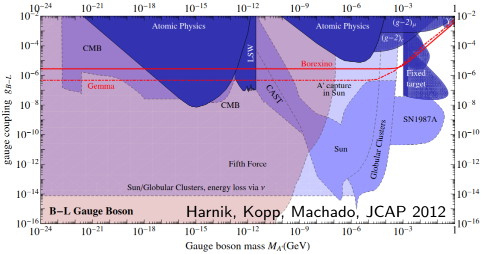


$U(1)_B$ Constraints



- we require $\epsilon_{ss} \simeq 100$

$$\left(\frac{g'}{g}\right)^2 \left(\frac{M_Z}{M_{Z'}}\right)^2 \simeq 100$$



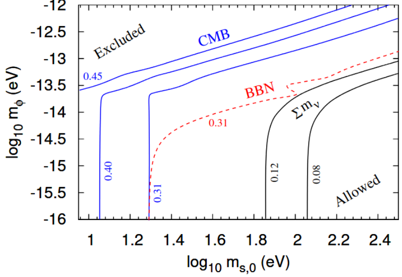
Harnik, Kopp, Machado, JCAP 2012

	$U(1)_{B-L}$ (vector couplings) (Model A)	Kinetically mixed (Model B)	$U(1)_B$ (vector couplings) (Model C)
$g-2$	✓	✓	✗
Fixed Target	✓	✓	✗[a]
Υ	✓	✓	✗[b]
Atomic physics	✓	✓	✗
Sun/Clusters/CAST	✓	✓	?
SN1987A	✓	✓	✓
LSW	✓	✓	✗
CMB	✓	✓	?
Borexino	✓	only if ν_s exist	✗
GEMMA	✓	✗	✗
Fifth force	✓	✗	✓

Alleviating Sterile Neutrino Constraints

- ν_s + secret self-interactions (1310.6337,1806.10629)
- ν_s with initially a very large mass generated by the VEV of a new scalar field (1806.10629)
- Yukawa coupling of ν_s to ultra-light scalar particle (dark matter) $\rightarrow$ large effective mass of ν_s in early Universe (1907.04271,1908.02278)
- Low reheating temperature (2501.01369)

1908.02278



2501.01369