Superradiance probe of neutrino moments

Anna John

IISER Berhampur

March 20, 2025

Vikram Discussion on Neutrino Astrophysics
Physical Research Laboratory, Ahmedabad

What is Superradiance?

- Superradiance - Spin or the angular velocity of a rotating compact object exceeds a certain limit and bosons condense and form a cloud like structure around it
- Clouds then grow exponentially by extracting rotational energy from the compact object

The bosonic cloud

- The bosonic cloud can be gravitationally bound to the BH which acts as the nuclei and form a "gravitational atom".
- The discrete bosonic states bound to the BH are characterized by the gravitational fine structure constant

$$\alpha_g = \frac{G M_{\mathsf{BH}} m_\psi}{\hbar c}$$

- Fixing the value of α_g at around 0.2 we get

$$m_{A'} M_{\mathsf{BH}} \approx 10^{-20}$$

here $m_{A'}$ is in GeV and M_{BH} is in $M_\odot$

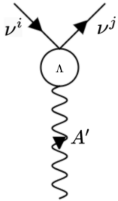
Neutrino Moments

- The idea of neutrinos having a magnetic moment was initially suggested by Pauli in 1930
- Spin flavor precession (SFP) of neutrinos due to electromagnetic moment was considered a solution to the solar neutrino problem.
- Neutrinos acquire magnetic moments within the standard model through quantum loop corrections
- The form factors involved in such loop level interactions are the neutrino electromagnetic moments

“ Connecting the Dots ”

- In our study we take the bosonic cloud to be a dark photon cloud
- Now consider loop level neutrino interactions with these dark photons
- The dark photon A' is the gauge field of the $U(1)'$ gauge symmetry indicating a dark sector, and $F'^{\mu\nu}$ is the field strength corresponding to A'

- The Feynman diagram for the interaction is



- The vertex function Λ seen above encompasses the electromagnetic properties of neutrinos and has the form,

$$\Lambda^{\mu}_{A'} = \left(\gamma^{\mu} - \frac{q^{\mu} q}{q^2}\right) [f_Q(q^2) + f_A(q^2) q^2 \gamma_5] - i\sigma^{\mu\nu} q_{\nu} [f_M(q^2) + i f_E(q^2) \gamma_5]$$

When $q^2 = 0$ these form factors in the expression above become the dark millicharge, dark anapole moment, dark magnetic dipole moment and dark electric dipole moment respectively

The Lagrangian

- The effective Lagrangian for the cases where the couplings are the anapole moment and the magnetic moment are*

$$\mathcal{L}_a = \frac{a_{ij}}{2}\bar{\nu_j}\gamma_\mu\gamma_5\nu_i\partial_\nu F'^{\mu\nu}$$

and

$$\mathcal{L}_\mu = \frac{\mu_{ij}}{2}\bar{\nu_j}\sigma_{\mu\nu}\nu_i F'^{\mu\nu}$$

Here a_{ij} and μ_{ij} are the anapole and magnetic moments respectively. ν_j and ν_i are the active neutrino states

*2406.08663

Neutrino Production

- Superradiance stops when $M_{\text{Cloud}} = 10\% M_{\text{BH}}$
- This is prevented if the bosons interact with fermions surrounding them and a **superradiance balance** is maintained
- These interactions ultimately lead to boosted fermion fluxes
- We consider the neutrino-dark photon interactions, in which the coupling is proportional to the anapole and magnetic moments of neutrinos

- The neutrino production happens through Schwinger pair production
- This process is supported only when

$$g_v E_{A'} \gg m_\nu^2$$

  where $E_{A'} \approx m_{A'}|\vec{A'}|$ is the strength of the electric field and g_v is the effective coupling
- Therefore it is important to look at the form of the field and the effective coupling!!!

The dark photon field

- The dark photon, from superradiance, is described by the field*;

$$A'^{\mu} = \Psi_0(t)e^{-\alpha_g^2 r/r_g}(\alpha_g \sin\theta \sin(m_A t - \varphi), \cos(m_A t), \sin(m_A t), 0)$$

  here Ψ_0 is the maximum field value*

- $$\Psi_0 = \left(\frac{\alpha_g}{0.2}\right)^2 \left(\frac{M_{\text{cloud}}}{10\% M_{BH}}\right)^{1/2} \times 8.7 \times 10^{16}\,\text{GeV}$$

- We take α_g to be 0.2
- Highest possible value M_{cloud} can take is 10% of M_{BH}
- All these factors considered we take $\Psi_0 \approx 10^{17}$ GeV

*2308.00741

The effective coupling

- Taking into consideration, the Lagrangians mentioned before and the form of the gauge field, the effective coupling would take the form

$$g_v = m_A^2 \, a + m_A \, \mu.$$

  Here m_A is the mass of the dark photon. a and μ are the anapole and magnetic moments.
- Here we consider only one active neutrino state - the lightest neutrino state

Boosted Neutrino Flux

- The neutrinos produced are then accelerated by the electric field to energies proportional to the effective coupling g_v^*

$$E_\nu \approx 0.35\, g_v \times 10^{26}\,\text{eV}$$

- The flux of these boosted neutrinos could be observed on earth through various detectors and neutrino telescopes. The differential flux, Φ is given as*

$$\Phi \approx 2.28 \times 10^{-7} \left(\frac{\Psi_0/\text{GeV}}{10^{14}}\right)\left(\frac{N_\nu}{1}\right)\left(\frac{10^{-12}}{m_{A'}/\text{eV}}\right)\left(\frac{g_v}{10^{-12}}\right) \times \left(\frac{0.3}{\alpha_g}\right)^3 \left(\frac{5}{d/\text{kpc}}\right)^2 \text{cm}^{-2}\,\text{s}^{-1}\,\text{GeV}^{-1}$$

Here d is the distance of the BH from the observer in kpc. N_ν is the number of neutrino mass/flavor eigenstates taken into consideration

*2308.00741

Superradiance Balance

- Superradiance balance in our study cannot be maintained solely by the dark photon neutrino interaction
- We suggest that the dark photon decays into a dark fermion(χ)-anti fermion($\bar{\chi}$) pair
- The amount of energy the dark photon cloud extracts from the black hole, is taken away by both neutrino generation and the decay of dark photon into dark fermions

Constraints on dark photon mass

- The bounds on the dark photon mass comes from 3 important conditions
  - The neutrino production criterion
  - From the lower bound on fermionic dark matter mass
  - The Non evaporation of black holes

1. Neutrino production condition

- Neutrinos can be produced through Schwinger pair production only when the criteria $g_v E_{A'} \gg m_\nu^2$ is met
- By taking into account that $E_{A'} \approx m_{A'} |\vec{A}'|$ and the form of the dark photon field we get
$$\sqrt{g_v \Psi_0 m_{A'}} \gg m_\nu$$
Thus we find that the dark photon mass must be much greater than 2.23×10^{-6} eV
- Here lightest neutrino mass is 10^{-12} GeV, the anapole is 7.45×10^{-5} GeV^{-2} and the magnetic moment is 5×10^{-9} GeV^{-1}

2. Limits from masses of associated fermions

- The dark photon in our case must decay into a dark fermion (and anti-fermion) pair
- If these dark fermions are not considered to be dark matter (*Cond-2a*), they can be light enough to facilitate the decay of dark photons with very low mass
- If these fermions are considered to be the dark matter, the picture changes (*Cond-2b*)
- Based on the analysis of eight dwarf spheroidal galaxies the lower bound on fermionic dark matter is updated to $190\,\mathrm{eV}$
- This implies that the dark photons should have at least double this mass.
- Therefore the renewed lower bound on the dark photon mass is $400\,\mathrm{eV}$.

3. Non-evaporation of black holes

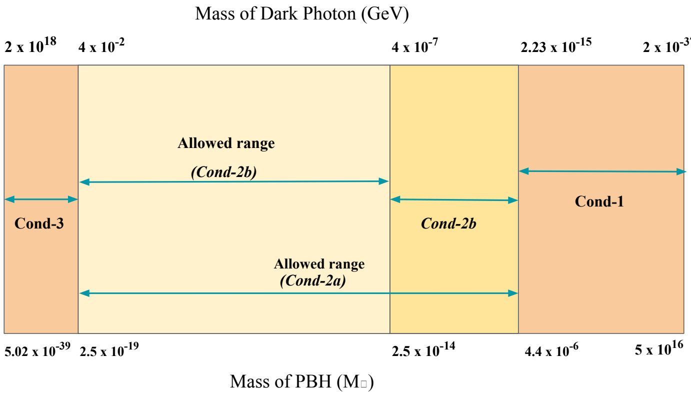
- The upper bound on the dark photon mass comes from the fact that black holes of mass less than $2.5 \times 10^{-19}\, M_{\odot}$ has already evaporated
- The product of the dark photon mass and the black hole mass obey the condition

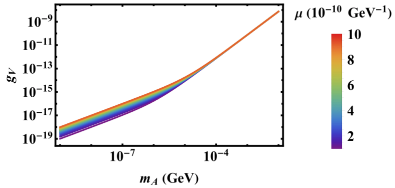
$$m_{A'} M_{\mathsf{BH}} \approx 10^{-20}$$

  Here M_{BH} is in Solar mass and $m_{A'}$ in GeV
- From this we get the upper bound on $m_{A'}$ to be $40\,\mathsf{MeV}$ by taking $M_{\mathsf{BH}} = 2.5 \times 10^{-19} M_{\odot}$
- From the above mentioned conditions we have put bounds on the dark photon mass under consideration to be $400\,\mathsf{eV} \leq m_{A'} \leq 40\,\mathsf{MeV}$

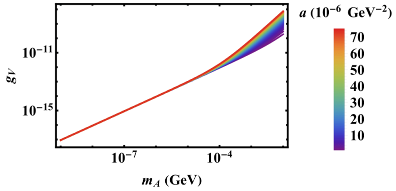
Schematic Diagram

The schematic diagram representing the bounds on the dark photon mass is given below

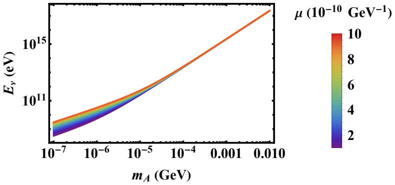




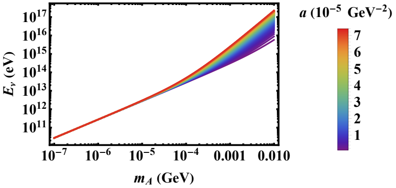
(a) Dependence of g_V on m_A for different μ when $a = 7.45 \times 10^{-5}\ \mathrm{GeV}^{-2}$.



(b) Dependence of g_V on m_A for different a when $\mu = 5 \times 10^{-9}\ \mathrm{GeV}^{-1}$.



(c) Dependence of E_ν on m_A for different μ when $a = 7.45 \times 10^{-5}\ \mathrm{GeV}^{-2}$.



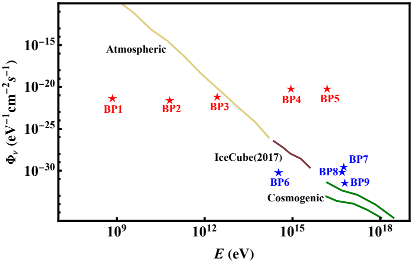
(d) Dependence of E_ν on m_A for different a when $\mu = 5 \times 10^{-9}\ \mathrm{GeV}^{-1}$.

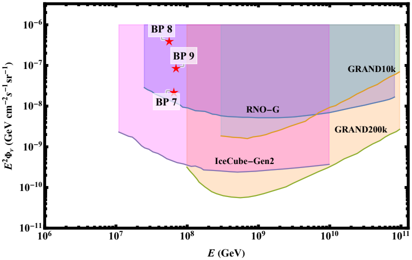
The efficiency of our complementary search is explained by a few bench mark parameters

BP	$M_{\rm BH}$ ($M_\odot$)	m_A (GeV)	a (GeV^{-2})	μ (GeV^{-1})	d (kpc)
1	2×10^{-14}	4×10^{-7}	2×10^{-5}	5×10^{-11}	1
2	1.43×10^{-15}	7×10^{-6}	4×10^{-7}	3×10^{-10}	3
3	5×10^{-16}	2×10^{-5}	7×10^{-5}	3×10^{-9}	7
4	1.67×10^{-17}	6×10^{-4}	7.2×10^{-5}	5×10^{-9}	8
5	3.3×10^{-18}	3×10^{-3}	5.5×10^{-5}	7×10^{-10}	15
6	1.6×10^{-17}	6×10^{-4}	3×10^{-5}	4×10^{-10}	5×10^{5}
7	2×10^{-18}	5×10^{-3}	7.45×10^{-5}	5×10^{-11}	10^{6}
8	5.5×10^{-19}	1.8×10^{-2}	5×10^{-6}	5×10^{-10}	10^{6}
9	5×10^{-19}	2×10^{-2}	5×10^{-6}	2×10^{-11}	5×10^{6}

Table 1: The benchmark parameters. BP1 to BP5 signify benchmark cases from within the milky way galaxy, whereas BP6 to BP9 denote the benchmark cases from far outside our galaxy.

The neutrino flux vs energy plots for the above benchmark parameters are given below





Summary

- Neutrino magnetic moments - (a bit?) mysterious, significant, interesting
- The effective interaction terms are versatile
- The versatility can be explored with neutrino flux created from BH superradiance
- The same term can also lead to other observables, e.g. cosmic birefringence
- Specific models can be explored, and constrained

Thank you