

New ν -Background from Black Hole Superradiance

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Superradiance

- ▶ Consider an object scattering off a stationary cylinder. Friction at the surface (dissipation) leads to loss of energy and angular momentum of the object.
- ▶ What happens if the cylinder is rotating?
- ▶ If $\Omega_c > v_\phi$, the object extracts energy and angular momentum, i.e. “dissipation” leads to enhancement.
- ▶ Superradiance: dissipative mechanism leading to the enhancement of energy.

Superradiance: Wave analogue

- ▶ Consider a wave incident on a rotating dissipative surface.
- ▶ The wave extracts energy and will grow in amplitude if $\Omega_c > \omega/m$, where m is the angular momentum quantum number.
- ▶ In the language of QFT, a growth in amplitude corresponds to particle creation.

(Vanilla) Black Hole Superradiance

- ▶ Consider a spinning black hole. When the spin exceeds a certain limit, bosonic particles are spontaneously produced through vacuum fluctuations forming a cloud around the black hole.
- ▶ $\implies$ reduction in the angular momentum & energy of the black hole.
- ▶ Superradiant shutdown : In the vanilla scenario, bosonic cloud grows exponentially till the black hole spin decreases to a value at which the superradiance process is not sustainable anymore.
- ▶ This creates a “gravitational atom” characterized by the gravitational fine structure constant, $\alpha_g = GM_{\text{BH}}m_b/(\hbar c)$.

Boson Cloud

- ▶ Ground states in superradiance exhibit the fastest growth rates.
- ▶ In Boyer-Lindquist coordinates (t, r, θ, ϕ) , these states of the scalar and vector fields are

$$\Phi(\vec{r}, t) = \Psi_0(t) e^{1-\alpha_g^2 r/2r_g} \frac{\alpha_g^2 r}{2r_g} \sin \theta \cos(m_\Phi t - \phi),$$

$$A^\mu(\vec{r}, t) = \Psi_0(t) e^{-\alpha_g^2 r/r_g} \left\{ \alpha_g \sin \theta \sin(m_A t - \phi), \cos(m_A t), \sin(m_A t), 0 \right\}.$$

where $r_g = GM_{\text{BH}}$ is the gravitational radius and Ψ_0 is the peak field value.

- ▶ The mass of the bosonic cloud is given by

$$M_c = \begin{cases} \frac{186\Psi_0^2}{\alpha_g^3 m_\phi}, & \text{scalar,} \\ \frac{\pi\Psi_0^2}{\alpha_g^3 m_A}, & \text{vector.} \end{cases}$$

Superradiant Shutdown

- ▶ When M_c exceeds 10% of M_{BH} , the spin of the black hole decreases and superradiance shuts down.
- ▶ The threshold is given by,

$$\alpha_g < \frac{\alpha_J}{2 \left(1 + \sqrt{1 - \alpha_J^2} \right)},$$

where α_J is the spin of the black hole.

- ▶ The peak field value at the threshold is

$$\psi_0^{10\%} = \begin{cases} 2.75 \times 10^{26} \alpha_g^2 \text{ eV}, & \text{for the scalar,} \\ 2.175 \times 10^{27} \alpha_g^2 \text{ eV}, & \text{for the vector.} \end{cases}$$

Reviving Superradiance: Quenched Superradiance

- ▶ If sufficient amount of energy is lost from the cloud, superradiance will sustain for longer.
- ▶ Facilitated by any model that allows for fermion flux production from the bosonic cloud.
- ▶ Ensures M_c stays the same for much longer as compared to the vanilla case.
- ▶ This mechanism is called “**Quenched Superradiance**”.

Timeline & phases of Quenched Superradiance

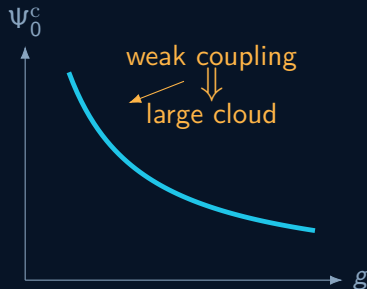
1. Growth Phase →	2. Balanced Phase →	3. Depletion Phase
▶ The cloud grows by extracting energy from the BH. ▶ $M_c \ll M_{\text{BH}}$. Thus the BH spin is nearly constant.	▶ Fermion production quenches further cloud growth. ▶ $M_c \simeq \text{const.}$ ▶ Spin evolution: $\frac{d\alpha_J}{dt} = -\frac{m_{\phi/A} \Gamma_{\text{SR}} M_c}{\alpha_g^2}$	▶ Superradiance shuts off. ▶ Fermion production continues from the remaining cloud as long as the production criteria are satisfied.

$$\frac{dM_c}{dt} = \underbrace{\Gamma_{\text{SR}} M_c}_{\text{growth}} - \underbrace{2E_f \int \Gamma_{s/v} d^3x}_{\text{fermion production}} - \underbrace{\frac{dE_{\text{GW}}}{dt}}_{\text{GW emission}}$$

Balanced Phase

- In the balanced phase, superradiant growth rate, Γ_{SR} , and the fermion production rate, $\Gamma_{s/v}$, match. Equating them gives the critical field value,

$$\psi_0^c \approx \begin{cases} 4.8 \times 10^{16} \left(\frac{3}{N_f}\right)^2 \left(\frac{m_\phi/\text{eV}}{10^{-12}}\right) \left(\frac{\alpha_g}{0.3}\right)^{16} \left(\frac{10^{-7}}{g_s}\right)^5 \left(\frac{\alpha_J}{0.9}\right) \text{eV}, & \text{scalar,} \\ 5.7 \times 10^{23} \left(\frac{1}{N_f}\right) \left(\frac{m_A/\text{eV}}{10^{-12}}\right) \left(\frac{\alpha_g}{0.3}\right)^6 \left(\frac{10^{-12}}{g_v}\right)^3 \left(\frac{\alpha_J}{0.9}\right) \text{eV}, & \text{vector.} \end{cases}$$



Balanced Phase: A Summary in Picture



Balance: Energy loss stabilizes growth

Neutrino Production

Scalar: Parametric Excitation

$$\mathcal{L} \supset g_s \phi \bar{\nu}_s \nu_s$$

$$\Gamma_s = \frac{g_s^2 \phi_0^2 m_\phi^2}{48\pi^3} \sqrt{\frac{m_\phi}{g_s \phi_0}}$$

- ▶ Production of sterile neutrinos which then undergo active-sterile oscillation.
- ▶ Production condition: $g_s \Psi_0 \gg m_\nu$.

Vector: Schwinger Pair Production

$$\mathcal{L} \supset g_v A^\mu \bar{\nu} \gamma_\mu \nu$$

$$\Gamma_\nu = \frac{g_v^2 E_A^2}{48\pi}$$

- ▶ Direct production of active neutrinos.
- ▶ Production condition: $g_v E_A \gg m_\nu^2$.

Neutrino Energy and Flux from a Point Source

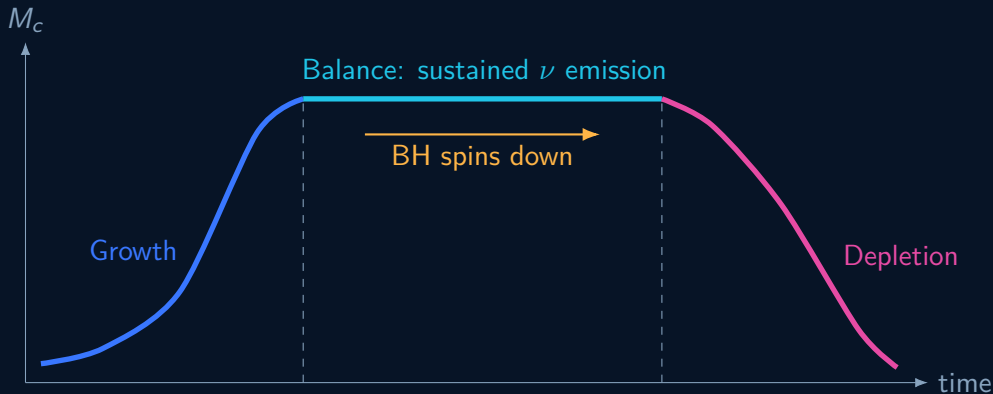
- ▶ Neutrinos produced are immediately accelerated to higher energies due to Pauli blocking. This leads to a detectable flux of high energy neutrinos.
- ▶ Energy and differential flux of these neutrinos from a point black hole source are,

$$E_\nu \approx \begin{cases} 0.27 g_s \Psi_0, & \text{scalar,} \\ 0.35 g_\nu \Psi_0, & \text{vector.} \end{cases}$$

and

$$\frac{d\Phi_\nu}{dE} \approx \begin{cases} 1.2 \times 10^{-17} \text{ cm}^{-2} \text{ s}^{-1} \text{ eV}^{-1} \left(\frac{\Psi_0/\text{GeV}}{4.8 \times 10^7} \right)^{1/2} \left(\frac{N_\nu}{3} \right) \left(\frac{10^{-12}}{m_\phi/\text{eV}} \right) \left(\frac{\alpha_g}{0.3} \right)^3 \\ \quad \times \left(\frac{g_s}{10^{-8}} \right)^{1/2} \left(\frac{5}{d/\text{kpc}} \right)^2, & \text{scalar} \\ 1.3 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \text{ eV}^{-1} \left(\frac{\Psi_0/\text{GeV}}{5.7 \times 10^{14}} \right) \left(\frac{N_\nu}{1} \right) \left(\frac{10^{-12}}{m_A/\text{eV}} \right) \left(\frac{\alpha_g}{0.3} \right)^3 \\ \quad \times \left(\frac{g_\nu}{10^{-12}} \right) \left(\frac{5}{d/\text{kpc}} \right)^2, & \text{vector.} \end{cases}$$

Quenched Superradiance: A Summary in Picture



$\Gamma_{\text{SR}} M_c$ dominates

$dM_c/dt \simeq 0$; source is long-lived

production drains the cloud

Diffuse Quenched Superradiance ν Background

- ▶ We now consider a population of spinning primordial black holes (PBH) which would give us a diffuse ν -background from quenched superradiance.
- ▶ Upper bound on the background $\implies$ lower bound on boson-neutrino coupling.
- ▶ The diffuse ν flux has two components.

Extragalactic component

- ▶ PBHs enter the balanced phase at very high redshift.
- ▶ Thus this component is produced throughout cosmic history.
- ▶ Therefore the energy and flux are strongly redshifted.

Galactic component

- ▶ Cosmological redshift is negligible.
- ▶ Relevant only if PBHs are still in the balanced phase today.
- ▶ Not included in cosmological bounds that we study.

Extragalactic DQS $_{\nu}$ B

- ▶ Observed energy and flux which are redshifted from those at the source are

$$E_{\text{obs}} = \frac{E_s}{1+z}, \quad R_{\text{obs}} = \frac{R_s}{1+z}$$

where $R_s = E_{\nu} \frac{d\Phi}{dE_s} (4\pi d^2) \delta(E_s - E_{\nu})$.

- ▶ We also define,

$$z_* \equiv \frac{E_{\nu}}{E_{\text{obs}}} - 1.$$

- ▶ Diffuse flux from the cosmological PBH population is obtained by integrating R_{obs}

$$\frac{d\Phi_{\text{obs}}}{dE} = c \int_{z_{\text{lower}}}^{z_{\text{upper}}} \left| \frac{dt}{dz} \right| n_{\text{PBH}}(z) R_{\text{obs}} dz,$$

where n_{PBH} is the PBH number density.

Extragalactic DQS ν B contd ...

- ▶ Computing the integral we get the total extragalactic flux to be,

$$\frac{d\Phi_{\text{obs}}^{\text{EG}}}{dE} = \begin{cases} cn_{\text{PBH},0} \frac{1+z_*}{H(z_*)} \frac{R_{\text{tot}}}{E_{\text{obs}}} & z_{\text{lower}} \leq z_* \leq z_{\text{upper}} \\ 0 & \text{everywhere else.} \end{cases}$$

where z_{upper} is the redshift at the end of PBH formation and growth phase and z_{lower} is the redshift at the end of balanced phase.

- ▶ Substituting for the expression of z_* in the range $z_{\text{lower}} \leq z_* \leq z_{\text{upper}}$, we get the diffuse flux energy range to be

$$\frac{E_\nu}{1+z_{\text{upper}}} \leq E_{\text{obs}} \leq \frac{E_\nu}{1+z_{\text{lower}}}.$$

Galactic Component

- ▶ For the calculation of galactic flux, we ignore the redshift dependence. Instead, the spatial distribution of dark-matter in the Milky Way must be taken into account.
- ▶ To model this, we assume the standard Navarro–Frenk–White (NFW) profile,

$$n_{\text{PBH}}(r) = \frac{f_{\text{PBH}}}{M_{\text{PBH}}} \rho_{\text{NFW}}(r).$$

- ▶ The energy integrated diffuse flux over the full sky is given by,

$$\Phi_{\text{Tot}}^{\text{Ga}} = \frac{f_{\text{PBH}}}{4\pi M_{\text{PBH}}} R_{\text{tot}} J_{\text{tot}}.$$

where $J_{\text{tot}} = 2.8 \times 10^{32} \text{eV cm}^{-2}$.

Total Flux: Summary

- ▶ **Extragalactic:** Redshifted continuum.
- ▶ **Galactic:** An unredshifted line and contributes only if the balanced phase survives until today.
- ▶ The total flux gets contributions from the galactic and extragalactic components,

$$\Phi_{\text{total}} = \Phi_{\text{EG}}^{\text{tot}} + \Theta(t_0 - t_{\text{start}})\Theta(t_{\text{end}} - t_0)\Phi_{\text{Ga}}^{\text{tot}}$$

where

$$t_{\text{start}} = t_{\text{PBH form}} + \tau_{\text{growth}}, \quad t_{\text{end}} = t_{\text{start}} + \tau_{\text{balanced}}$$

and $t_0 = 4.41 \times 10^{17}$ s is the age of the universe.

Constraining the Neutrino Background

- ▶ We constrain the neutrino background cosmologically and from the terrestrial Super-Kamiokande experiment.
- ▶ For the cosmological constraints, we only include the extra galactic component while both galactic and extra galactic components are included for the bounds from experiments.

Bounds from ΔN_{eff}

- ▶ The no: of relativistic d.o.f in the early universe contributing to radiation energy density is given by N_{eff} .
- ▶ Planck (2018) data obtained $N_{\text{eff}} = 2.99 \pm 0.17$ (at 68% CL). On the other hand the standard model predicted value is 3.046.
- ▶ This mismatch, ΔN_{eff} , quantifies the excess radiation energy density arising from any generic mechanism.
- ▶ The expression for ΔN_{eff} is

$$\Delta N_{\text{eff}} = \frac{8}{7} \left(\frac{11}{4} \right)^{\frac{4}{3}} \frac{\rho_{\nu}^{\text{extra,now}}}{\rho_{\gamma}^{\text{now}}}, \text{ where, } \rho_{\nu}^{\text{extra,now}} = \frac{4\pi}{c} \int_0^{\infty} E \frac{d\Phi_{\text{pre}}}{dE} dE.$$

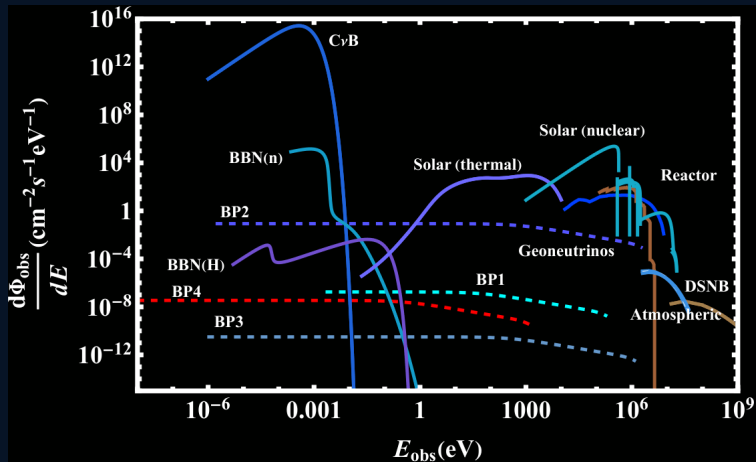
- ▶ By requiring that at 95% C.L., $\Delta N_{\text{eff}} \leq 0.3$, we obtain bounds on our background.

Bounds from Super-Kamiokande

- ▶ At 90% C.L. a combined SK I-IV analysis constrains the flux with energies greater than 17.3 MeV to $2.5 - 2.8 \text{ cm}^{-2}\text{s}^{-1}$.
- ▶ We take into consideration the SK-I upper limit of $2.3 \text{ cm}^{-2}\text{s}^{-1}$.
- ▶ By integrating our flux over energy and using the above mentioned constraints, we obtain bounds on the background.

From the constraints on the backgrounds from cosmology and Super-Kamiokande, we obtain lower bounds on the boson-neutrino couplings.

Results: Extragalactic Benchmark Spectra

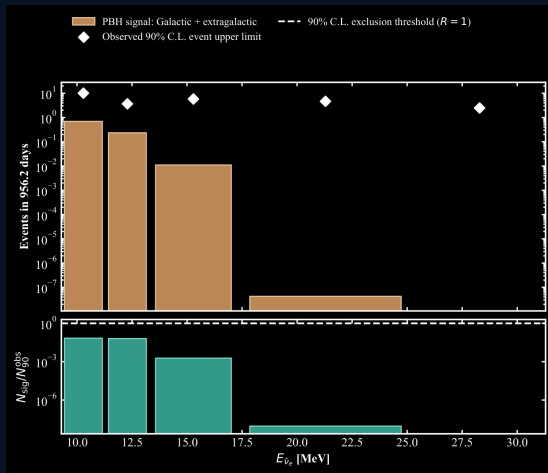


BP	m_{boson}	g
1	10^{-14} eV	10^{-10}
2	10^{-6} eV	3.16×10^{-7}
3	10^{-3} eV	10^{-4}
4	10^2 eV	10^{-2}

► BP1-2: vector.

► BP3-4: scalar.

Results: Super-Kamiokande-Gd Event Yield

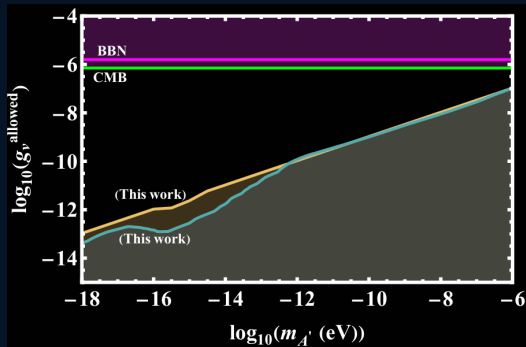


SK-Gd analysis

- ▶ Predicted Ga + EG flux folded with σ_{IBD} , detector energy response and tagging efficiencies.
- ▶ SK published flux limits, converted to 90% C.L. event upper limits in each energy bin.
- ▶ Representative vector benchmark

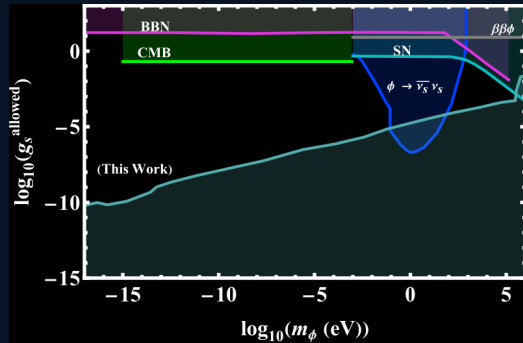
$$m_A = 10^{-14} \text{ eV}, g_\nu = 1.40 \times 10^{-11},$$
$$\alpha_g = 0.3, \alpha_J = 0.9, f_{\text{PBH}} = 8.35 \times 10^{-7}$$

Results: Lower Bounds on Couplings



Vector mediator

- ▶ Lower bounds from both ΔN_{eff} and Super-Kamiokande.



Scalar mediator

- ▶ Lower bound arises from ΔN_{eff} .
- ▶ Active–sterile mixing of $|U_{s\alpha}| \sim 10^{-3}$ assumed to obtain active neutrino-boson coupling bounds.

Conclusions

1. Quenched superradiance of spinning PBHs can generate a new **diffuse neutrino background**: the $DQS\nu B$.
2. Its spectrum can cover an exceptionally **large energy range** and remains nearly flat, distinguishing it from $C\nu B$, BBN and DSNB backgrounds.
3. Cosmology and neutrino experiments convert the absence of an excessive $DQS\nu B$ into **lower bounds on exotic couplings**:
 - vector case: $\Delta N_{\text{eff}} + \text{Super-Kamiokande}$,
 - scalar case: primarily ΔN_{eff} .

Provides a new probe for BSM neutrino interactions using **black hole physics**

Thank You!