Supernova Constraints on Dark Flavored Sectors

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1. Introduction

The observation of SN 1987A has helped to confirm the standard picture of core-collapse SN. An experimental limit on *dark luminosity* stems from the observation of a neutrino pulse, sustained over $\sim 10\,\mathrm{s}$ in coincidence with SN 1987A. Exotic cooling would shorten the neutrino signal, leading to the classical bound [1],

$$L_{\rm d} \lesssim 3\times 10^{52}\ \ \mathrm{erg\ s}^{-1}, \tag{1}$$

at $\sim 1\,\mathrm{s}$ after bounce. The proto-neutron star (PNS) forming during core-collapse supernovae reaches temperatures and densities that enable the production of Λ hyperons which can contribute to the dark luminosity through the decay $\Lambda \to nX^0$ if X^0 interact with strange quarks.

2. Emission rate and reabsorption

The spectrum of the emission rate per unit volume that is induced by this process in the medium is given by

$$\frac{d\mathcal{N}_{\rm em}}{d\omega} = \frac{m_\Lambda^2\Gamma}{2\pi^2\bar\omega}\int_{E_0}^{\infty} dE\, f_\Lambda(1-f_n), \tag{2}$$

where ω (E) is the energy of the X^0 (Λ) in the PNS's rest frame, $E_0 = m_\Lambda(\omega^2+\bar\omega^2)/(2\omega\bar\omega)$ is the minimal energy of the Λ required to produce an X^0 with energy ω and Γ is the width of the decay $\Lambda \to nX^0$ for a massless X^0, in vacuum.
The emitted X^0 can get reabsorbed by the stellar medium if their mean-free path is shorter than the size of the PNS. The main absorption mechanism is the inverse of production, $X^0 n \to \Lambda$.
The total dark luminosity of the PNS can be then written as,

$$L_{\rm d} = \int d^3\vec{r}\int_0^\infty d\omega \frac{dQ(r)}{d\omega}e^{-\tau(\omega,r)}, \tag{3}$$

where τ is the optical depth.

5. An example: The Dark Photon

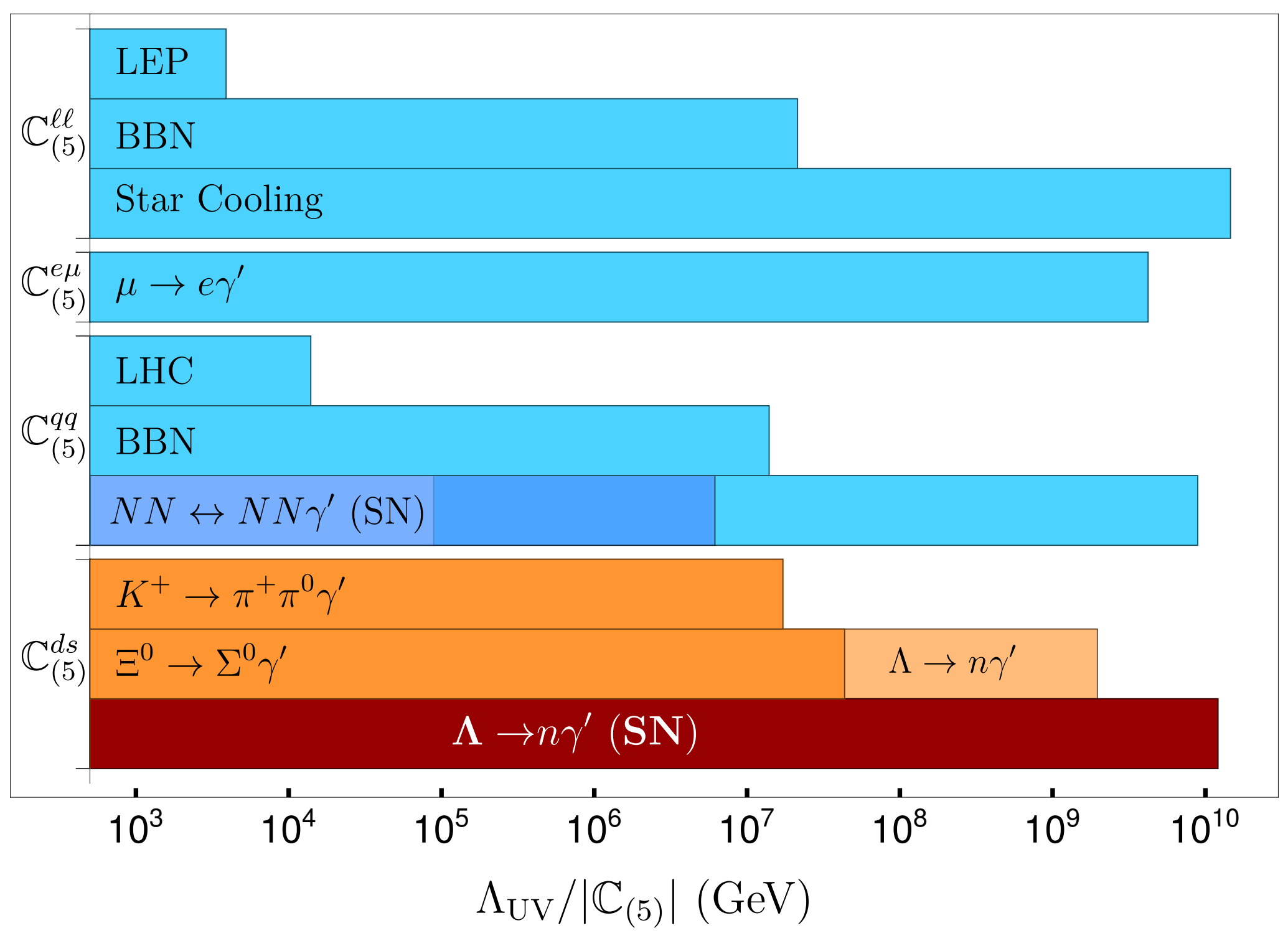
In order to apply our result to the massless dark photon case we consider the dimension-five operator

$$\mathcal{L}_{\gamma'} = \frac{1}{\Lambda_{\rm UV}}\bar\psi_i\sigma^{\mu\nu}\left(\mathbb{C}^{ij}+i\,\mathbb{C}_5^{ij}\gamma_5\right)\psi_j F'_{\mu\nu}. \tag{5}$$

Taking the upper limit on $\mathrm{BR}(\Lambda\to nX^0)$ by SN given in Eq. (4) we can set the lower limit,

$$\Lambda_{\rm UV} \gtrsim 1.2\times 10^{10}\ \mathrm{GeV}, \tag{6}$$

assuming order-one couplings.



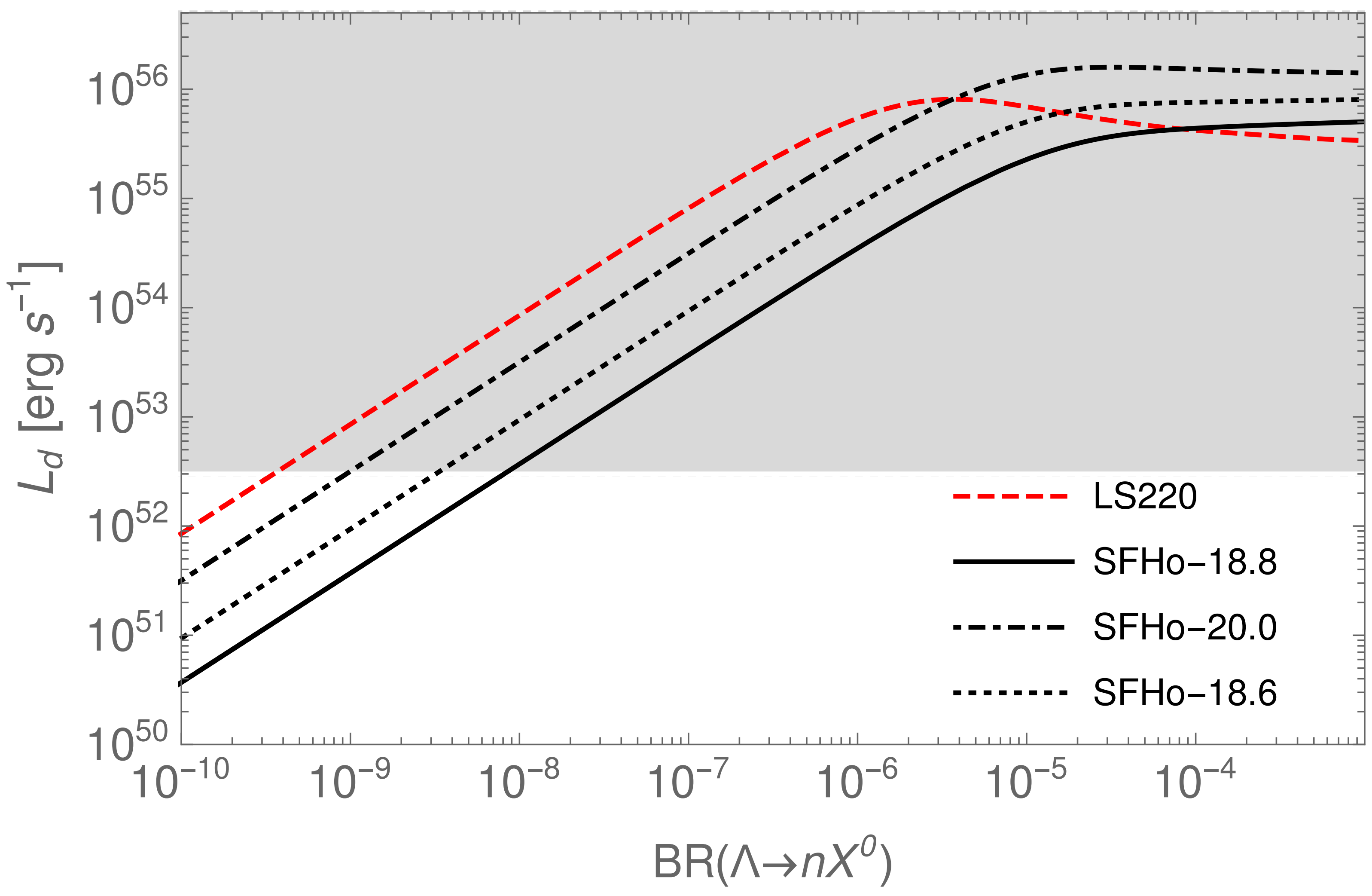
We see that the SN analysis done in this work sets the strongest limit on dark photon couplings, along with star cooling constraints on lepton couplings.

3. Simulations and EoS

We use recent SN simulations including muons that were developed specifically to constrain the axion-muon coupling using the neutrino data from SN 1987A [2]. Two EoS are employed for nuclear matter, SFHo and LS220.
Hyperons can be added indirectly through the nuclear EoS because the models used in the simulations have been extended with Λ's as explicit degrees of freedom; these EoS are called SFHoY and LS220Λ.
We use the radial profiles of density, temperature and proton fraction from the simulations as inputs to obtain the radial profiles of the other relevant thermodynamical quantities, which are derived from interpolation tables generated by the CompOSE database [3].

4. Model independent results

Combining all the previous ingredients we compute the dark luminosity of SN 1987A as a function of $\Gamma(\Lambda\to nX^0)$. Comparing this to the bound in luminosity shown in Eq. (1) (grey band) allows us to set an upper limit on the branching fraction of the decay $\Lambda \to nX^0$.



The flattening of the curves at large coupling (or branching ratio) reflects the behavior in the trapping regime. Given all the above, the SN 1987A bound is,

$$\mathrm{BR}(\Lambda\to nX^0) \lesssim 8.0\times 10^{-9}, \tag{4}$$

and it applies to any ultralight dark particle inducing the Λ decay and long-lived enough to leave the PNS.

6. Summary and conclusions

- We have studied in detail a novel SN bound on dark flavored sectors.
- We get a model independent upper limit $\mathrm{BR}(\Lambda\to nX^0)\lesssim 8.0\times 10^{-9}$.
- This leads to the strongest bounds that have been derived so far on the couplings of the massless dark photon to quarks.
- This analysis also sets strong constraints on flavor-violating axion models [4], and can be readily extended to other flavored dark sectors.

7. References

[1] G.G. Raffelt. *Stars as laboratories for fundamental physics: The astrophysics of neutrinos, axions, and other weakly interacting particles.* 5 1996.

[2] Robert Bollig, William DeRocco, Peter W. Graham, and Hans-Thomas Janka. Muons in supernovae: implications for the axion-muon coupling. *Phys. Rev. Lett.*, 125(5):051104, 2020.

[3] CompStar Online Supernovae – Equations of State: https://compose.obspm.fr/.

[4] J. Martin Camalich et al. Quark Flavor Phenomenology of the QCD Axion. *Phys. Rev. D*, 102(1):015023, 2020.