Probing secret interactions of eV-scale sterile neutrinos with the diffuse supernova neutrino background

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LSND and reactor anomalies

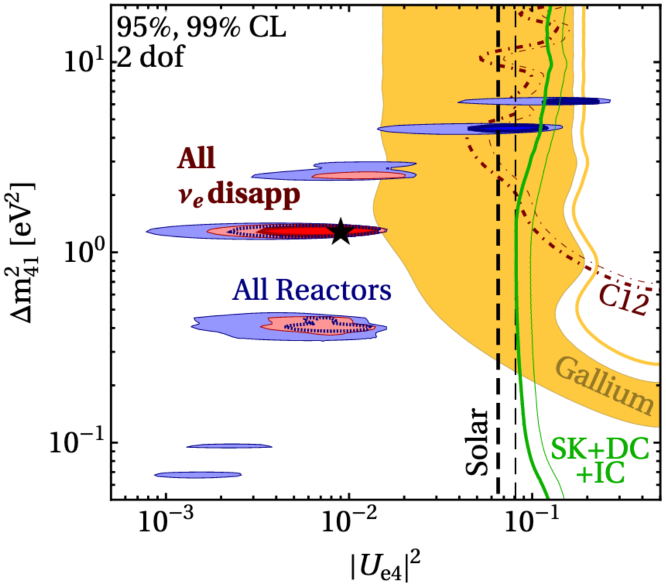


Figure from Dentler et al., JHEP 08 (2018) 010.

True, there are tensions between the anomalies in appearance and disappearance experiments.

LSND and reactor anomalies suggest there could be another (sterile) neutrino with an eV scale mass and a mixing with active neutrinos of order $\vartheta_0 \cong 0.1$.

Introduce one sterile neutrino and a new vector boson:

$$\mathcal{L}_s = g_s \, \bar{\nu}_s \gamma_\mu P_L \, \nu_s \, \phi^\mu$$

ϕ is the “secret interaction” mediator.

Cosmic eV-scale sterile neutrino background and supernova neutrinos

supernova neutrinos

sterile neutrino background

$$s = 2E_\nu m_s = m_\phi^2$$

$$E_\nu = 10\ \mathrm{MeV},\ m_s = 1\ \mathrm{eV} \Rightarrow m_\phi \simeq 5\ \mathrm{keV}$$

It is possible to probe keV-scale gauge boson mediators with supernova neutrinos, in particular the diffuse supernova neutrino background flux, through absorption dips.

Opportunity for DUNE and HyperK measurements of physics beyond the standard model using supernova (SN) neutrinos.

Cosmic eV-scale sterile neutrino background and supernova neutrinos – analogy with Z-bursts

GZK neutrinos

neutrino background

$$s = 2E_\nu m_\nu = m_Z^2$$

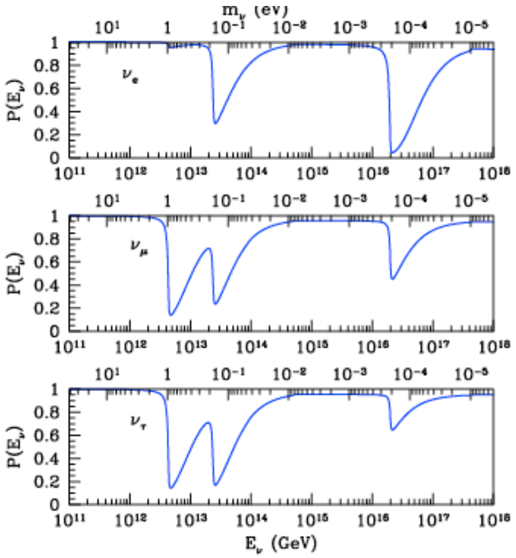
$$E_\nu \sim 10^{13}\ \mathrm{GeV},\ m_\nu = 0.1\ \mathrm{eV} \implies m_Z \simeq 90\ \mathrm{GeV}$$

Other mass ranges, e.g.,

Cherry, Friedland & Shoemaker, 1411.1071,1605.06506, Hooper, PRD 75 (2007) 123001, Ng & Beacom, PRD 90 (2014) 065035

Z-bursts: Weiler, PRL 49 (1982) 234, Ap. J. 28 (1984) 295.

Survival probabilities for NH, Barenboim, Mena & Quigg, PRD 71 (2005) 083002



Where could this go wrong?

Cosmological constraints:

- Big bang nucleosynthesis (BBN), affects the expansion rate of the universe at a critical time/temperature ($T\sim1$ MeV).

$$N_{\rm eff}^{\rm BBN} < 3.2$$

- Later epochs, where CMB fluctuations can be modified by presence of massive neutrinos ($T\sim1$ eV).

Need to satisfy these constraints to determine which (g_s, $M\phi$) ranges are possible for consideration.

$$\mathcal{L}_s = g_s\,\bar{\nu}_s\gamma_\mu P_L\,\nu_s\,\phi^\mu$$

Topic of recent interest, for cosmological implications, e.g.,

Hannestad, Hansen & Tram, PRL 112 (2014) 031802; Dasgupta & Kopp, PRL 112 (2014) 031803; Mirizzi et al, PRD 91 (2015) 025019; Cherry, Friedland & Shoemaker, arXiv:1411.1071, 1605,06506; Chu, Dasgupta & Kopp, JCAP 10 (2015) 011.

Our discussion here:

- Key feature with keV-scale gauge boson: a contact interaction is a bad approximation most of the time since we are looking at keV scale mediators.

$$\frac{g_s^4}{(Q^2+M_\phi^2)^2} \not\Longrightarrow G_s^2$$

$$\frac{g_s^4}{(s-M_\phi^2)^2} \not\Longrightarrow G_s^2$$

See recent work for QKE (using G_s)
by, e.g., Song, Gonzalez-Garcia & Salvado, JCAP 10 (2018) 055.

- Revisit cosmological constraints.
- Signals at DUNE (and HyperK).

BBN – first, no oscillations

BBN constraint, from expansion of the universe during nucleosyntheis, the effective number of neutrinos: $N_{\rm eff}^{BBN} \lesssim 3.2$

Depends on the sterile and active neutrino temperatures: $\xi = \dfrac{T_s}{T_\nu}$

We assume sterile neutrinos and ϕ decouple at the TeV scale where the number of degrees of freedom is $g_* \sim 106.7$.

ϕ relativistic
at BBN $M_\phi \lesssim 1$ MeV

$$\xi_{\rm rel} = \left(\frac{10.75}{106.75}\right)^{1/3} \simeq 0.465$$

$$N_{\rm eff}^{\rm rel} = N_{\nu_a} + \frac{g_{\nu_s}\cdot 7/8 + g_\phi}{g_{\nu_a}\cdot 7/8}\,\xi_{\rm rel}^4 \simeq 3.17 \quad \checkmark$$

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ϕ non-relativistic

at BBN $M_\phi \gtrsim 1$ MeV

$$\xi_{\rm nr} = \left(\frac{10.75}{106.75}\right)^{1/3}\left(\frac{2\cdot 7/8+3}{2\cdot 7/8}\right)^{1/3} \simeq 0.649$$

$$N_{\rm eff}^{\rm nr} = N_{\nu_a} + \xi_{\rm nr}^4 \simeq 3.22\ , \quad \checkmark$$

Cosmological constraints applied here

Require that sterile neutrinos do not recouple to active neutrinos at temperatures higher than 1 MeV (before BBN) to keep $N_{\rm eff}^{BBN} \lesssim 3.2$.

Allow recoupling at later times (secret interactions will do it).

Require that sterile neutrinos decouple before $T = 1$ eV so that active neutrinos are free streaming (so CMB fluctuations are not affected). The sterile neutrinos are non-relativistic at this point.

Active-sterile conversions/recoupling & decoupling

$$\Gamma_{\nu_s}(\nu_a \to \nu_s) = \frac{\Gamma_{\rm int}}{2}\,\langle P(\nu_a \to \nu_s)\rangle \qquad D_{\rm int} = \frac{\Gamma_{\rm int}}{2}$$

$$\langle P(\nu_a \to \nu_s)\rangle \simeq \frac{1}{2}\,\frac{\frac{\Delta m_s^2}{2E}\,\sin^2 2\theta_0}{(\frac{\Delta m_s^2}{2E}\,\cos 2\theta_0 + V_{\rm eff})^2 + \frac{\Delta m_s^2}{2E}\,\sin^2 2\theta_0 + D_{\rm int}^2}$$

Matter effect including sterile neutrinos with effective potential (SM and sterile interactions).

Damping rate D_{int} accounts for loss of coherence due to collisions.

If active-sterile conversions are large, sterile neutrinos will be in equilibrium with active neutrinos too soon and ruin BBN.

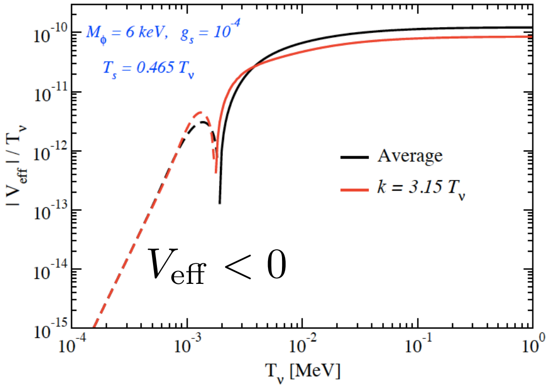
Standard model effective potential, see, e.g., Notzold and Raffelt, Nucl. Phys. B 307 (1988) 924.

BBN – now with oscillations – effective *V*

In-medium mixing, active-sterile oscillations:

$$\langle P(\nu_a \to \nu_s)\rangle \simeq \frac{1}{2}\frac{\frac{\Delta m_s^2}{2E}\sin^2 2\theta_0}{\left(\frac{\Delta m_s^2}{2E}\cos 2\theta_0 + V_{\rm eff}\right)^2 + \frac{\Delta m_s^2}{2E}\sin^2 2\theta_0 + D_{\rm int}^2}$$

Effective potential from interactions in the sterile sector, in the low- and high-temperature limits (E is neutrino energy):

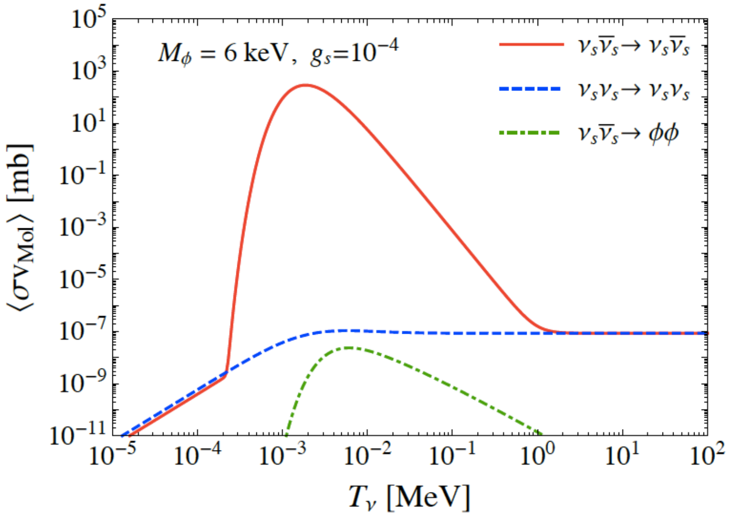


Contact interaction

$$V_{\rm eff,s}(E,T_s) \simeq \begin{cases} -\frac{7\pi^2 g_s^2}{45}\frac{E\,T_s^4}{M_\phi^4} & \text{for} \quad T_s \ll M_\phi \\ \frac{g_s^2}{8}\frac{T_s^2}{E} & \text{for} \quad T_s \gg M_\phi \end{cases}$$

See also Dasgupta & Kopp, PRL 112 (2014) 031803.

BBN – now with oscillations – interactions Γ_{int}



Thermal average of t-channel limit at high energy is constant.

See, e.g., Cherry, Friedland, Shoemaker, 1411.1071, 1605.06506

Resonance influences a wide range of temperatures due to thermal average.

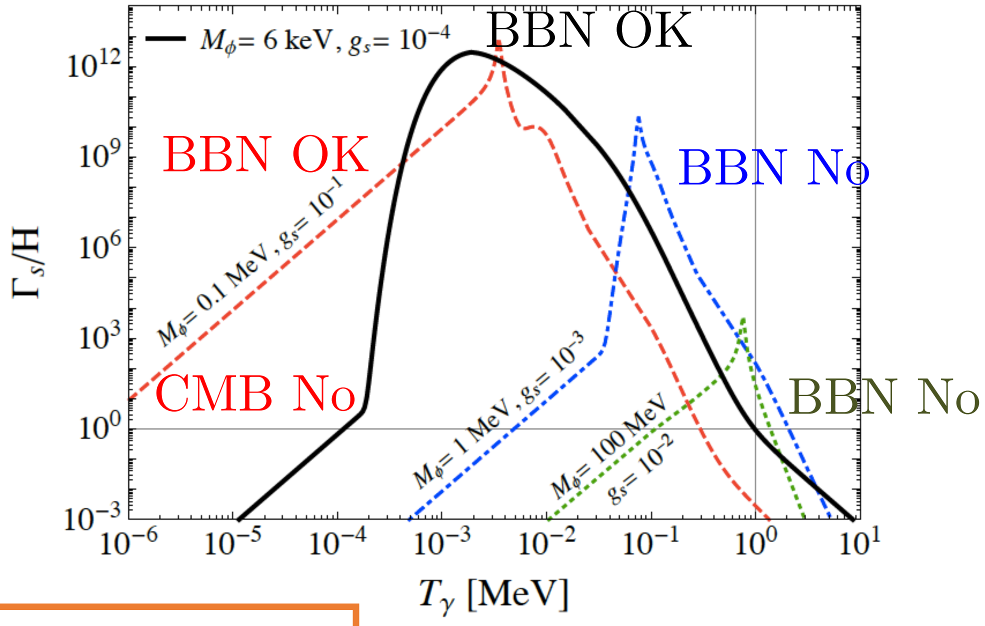
$$\sigma_s \equiv \sigma(\nu_s\,\bar{\nu}_s \to \nu_s\,\bar{\nu}_s) = \begin{cases} \dfrac{g_s^4}{4\,\pi\,M_\phi^2} & \text{for} \quad s > M_\phi^2 \\ \dfrac{g_s^4}{12\,\pi}\,\dfrac{s}{\left(s - M_\phi^2\right)^2 + M_\phi^2\,\Gamma_\phi^2} & \text{for} \quad s \sim M_\phi^2 \\ \dfrac{g_s^4}{3\,\pi\,M_\phi^4}\,s & \text{for} \quad s < M_\phi^2 \end{cases}$$

Contact interaction

For example, thermal average of sterile neutrino cross sections [Gondolo & Gelmini, Nucl. Phys. B 360 (1991) 145].

$$\Gamma_\phi = \frac{g_s^2\,M_\phi}{24\,\pi}\,.$$

BBN & CMB sterile neutrino production rate and Hubble expansion rate *H* constraint



Black curve: example of active-sterile recoupling after SM neutrino decoupling at 1 MeV.

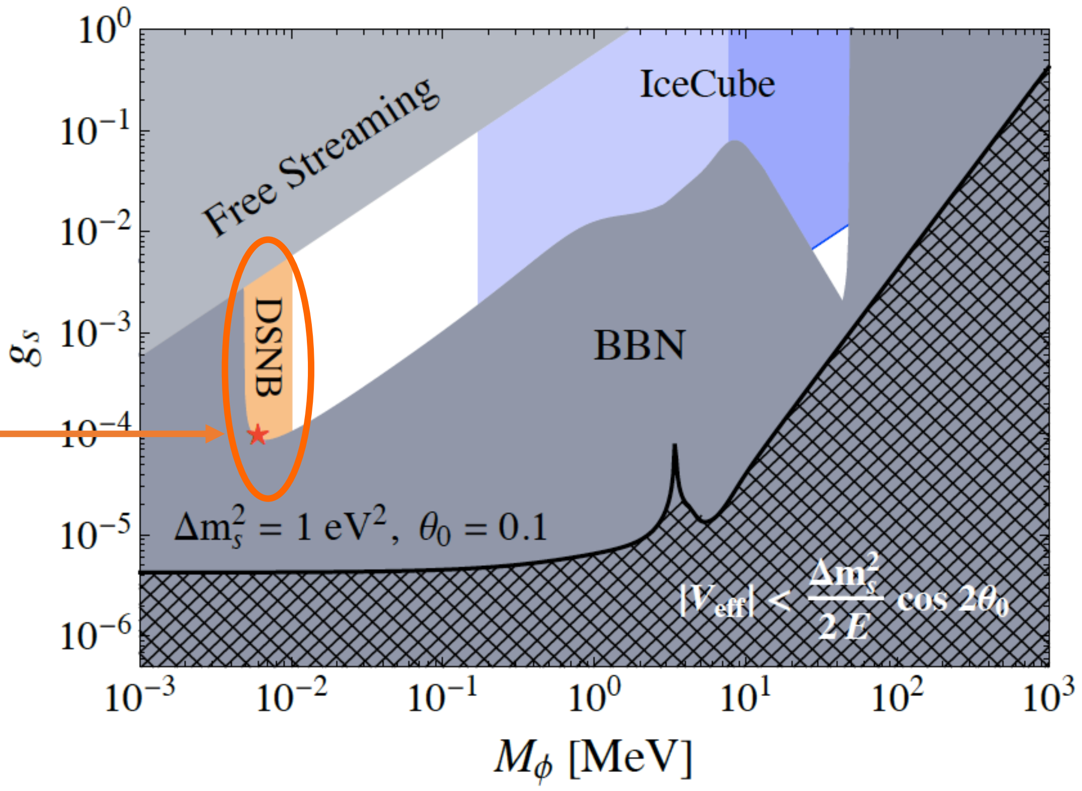
Blue and green: recoupling before BBN – excluded.

Red: sterile neutrinos aren't decoupled before T=1 eV (recombination).

$$\Gamma_s/H < 1 \text{ for } T_\gamma > 1 \text{ MeV}$$
$$\Gamma_s/H < 1 \text{ for } T_\gamma < 1 \text{ eV}$$

allowed

We are interested in this mass range because of absorption dips in the diffuse SN neutrino background (DSNB) flux.



Bounds on the mass of new vector boson and gauge coupling of hidden sector interactions. Red star is our canonical choice.

$$g_s = 10^{-4} \qquad M_\phi = 4 - 8\ \mathrm{keV}$$

Spectrum of diffuse SN background- ingredients

$$F_a(E_\nu) = \int_0^{z_{\max}} dz\, R_{\rm SN}(z)\, \frac{dN_a(E'_\nu)}{dE'_\nu}\, (1+z) \left| \frac{dt}{dz} \right|$$

$$E'_\nu = E_\nu\,(1+z)$$

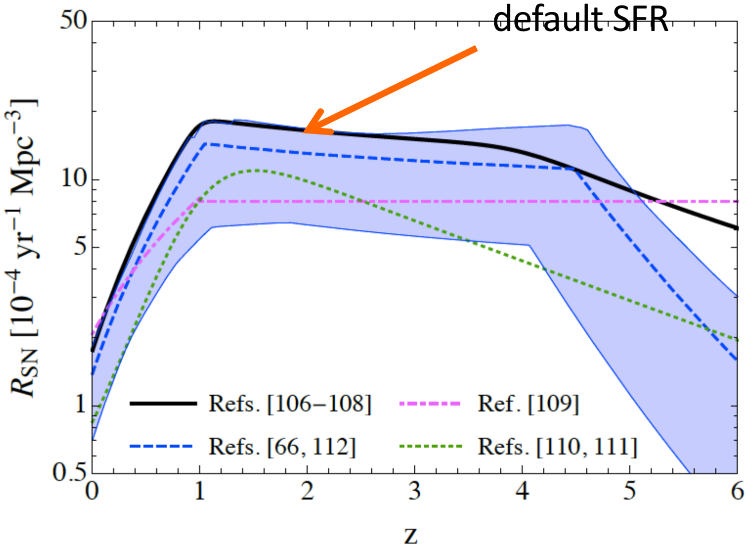
Energy emitted at redshift z, current energy.

$$R_{\rm SN}(z)$$

Supernova formation rate.

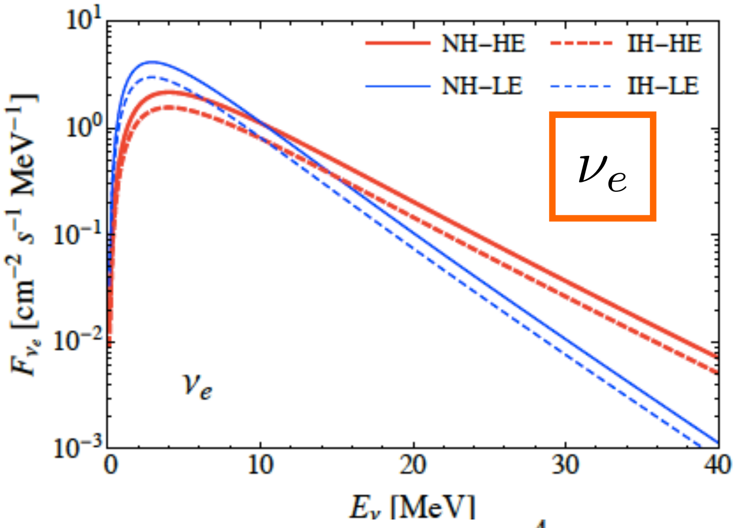
$$dN/dE_\nu$$

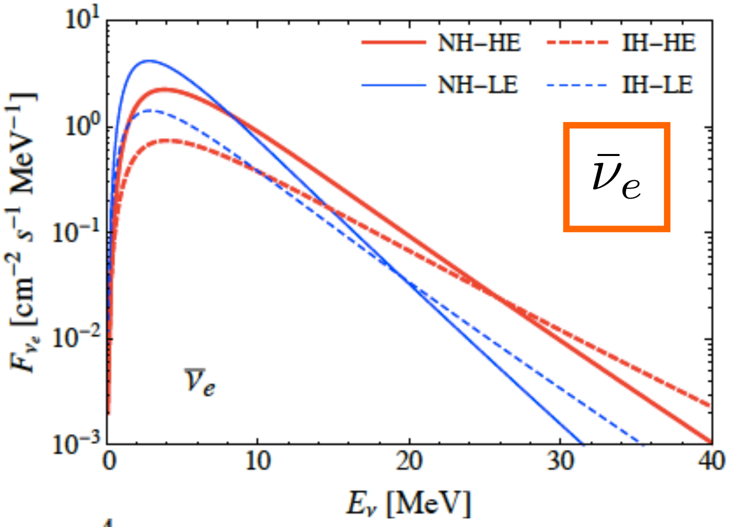
Spectrum from generic supernova explosion.



Yuksel et al., Ap. J. 683 (2008) L5, Kistler et al, arXiv:1305.1630, Horiuchi et al., Ap. J. 738 (2011) 154.

Diffuse SN background fluxes, high energy (HE) and low energy (LE) SN models, no absorption





Lunardini, Astropart. Phys. 79 (2016) 49, Esmaili et al, PRD 90 (2014) 033013

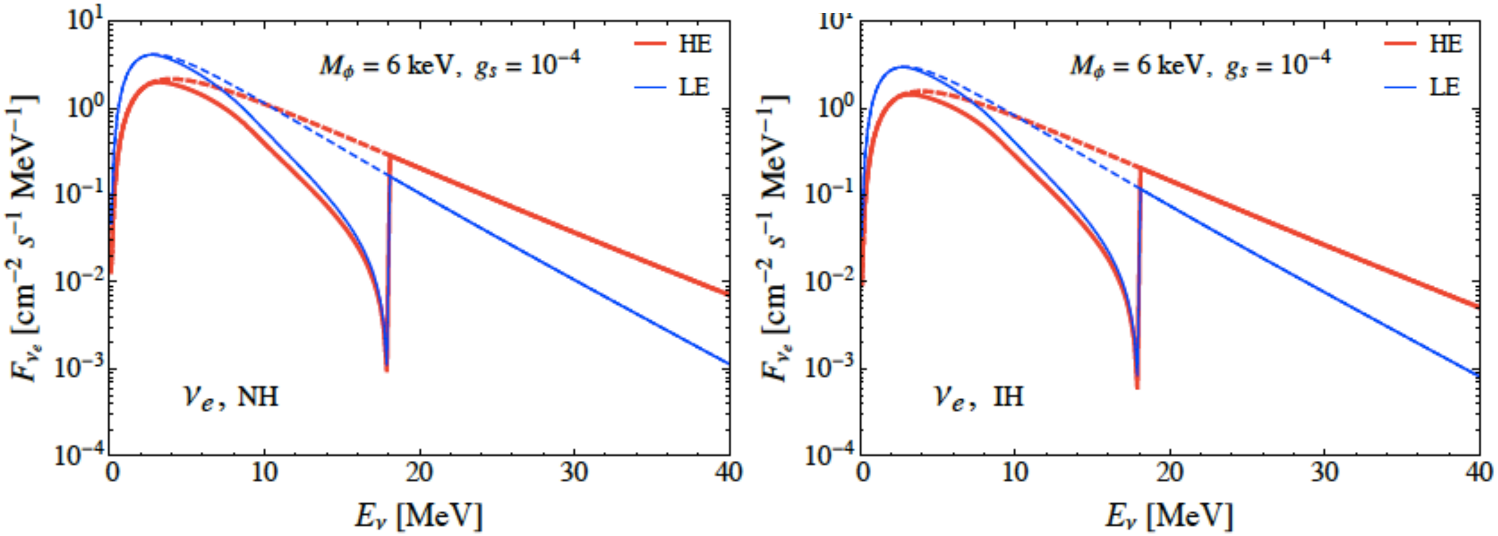
$$F_a(E_\nu) = \sum_{i=1}^{4} |U_{ai}|^2 \, F_i(E_\nu) = \sum_{i=1}^{4} |U_{ai}|^2 \int_0^{z_{\max}} dz \, R_{\rm SN}(z) \, F_i^0(E') \, (1+z) \left| \frac{dt}{dz} \right|$$

⇒

$$F_a(E_\nu) = \sum_{i=1}^{4} |U_{ai}|^2 \int_0^{z_{\max}} dz \, P_i(E_\nu, z) \, R_{\rm SN}(z) \, F_i^0(E') \, (1+z) \left| \frac{dt}{dz} \right|$$

Diffuse SN background fluxes, high energy (HE) and low energy (LE) SN models, with absorption

$$E_{\rm res} = \frac{M_\phi^2}{2\,m_s} = 18\ {\rm MeV}\left(\frac{M_\phi}{6\ {\rm keV}}\right)^2\left(\frac{1\ {\rm eV}}{m_s}\right)$$

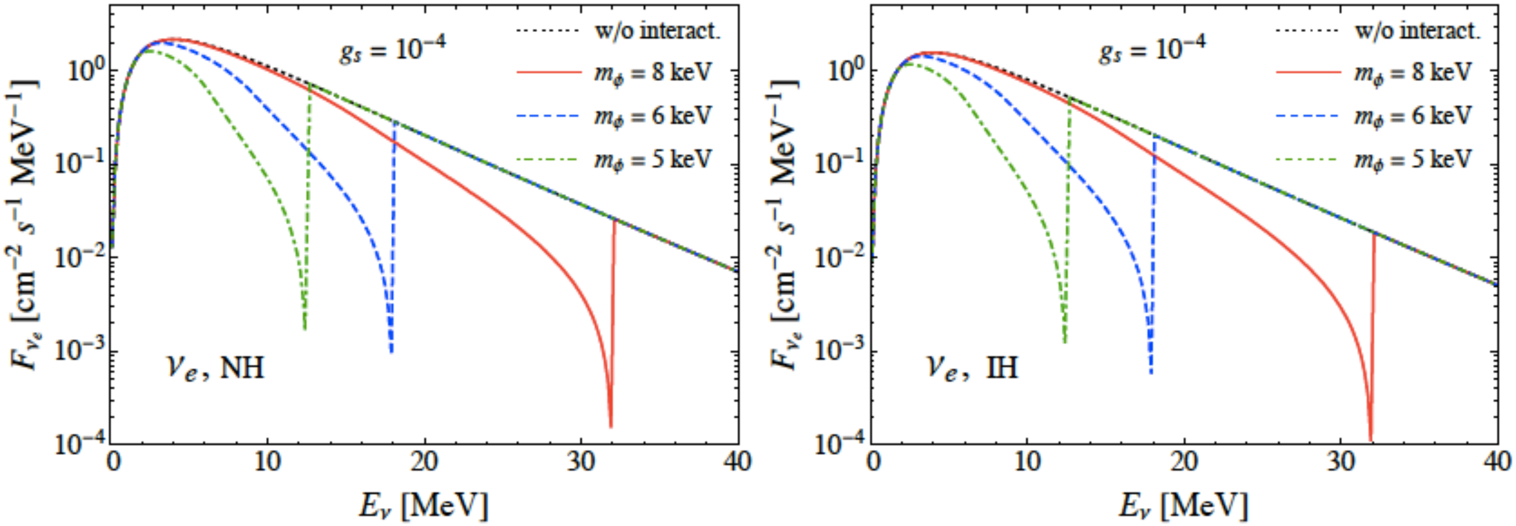


$$M_\phi = 6\ {\rm keV},\ g_s = 10^{-4},\ m_s = 1\ {\rm eV\ and}\ \theta_0 = 0.1$$

active-sterile mixing angle in resonant cross section

Diffuse SN background fluxes, high energy (HE) and low energy (LE) models, with absorption

$$E_{\rm res} = \frac{M_\phi^2}{2\,m_s} = 18\ {\rm MeV}\left(\frac{M_\phi}{6\ {\rm keV}}\right)^2\left(\frac{1\ {\rm eV}}{m_s}\right)$$



$g_s = 10^{-4}$, $m_s = 1$ eV and $\theta_0 = 0.1$

active-sterile mixing angle in resonant cross section, three masses

Electron neutrino and antineutrino event rates in detectors

DUNE detection: $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$

Water-Cherenkov detection: $\bar{\nu}_e + p \rightarrow e^+ + n$

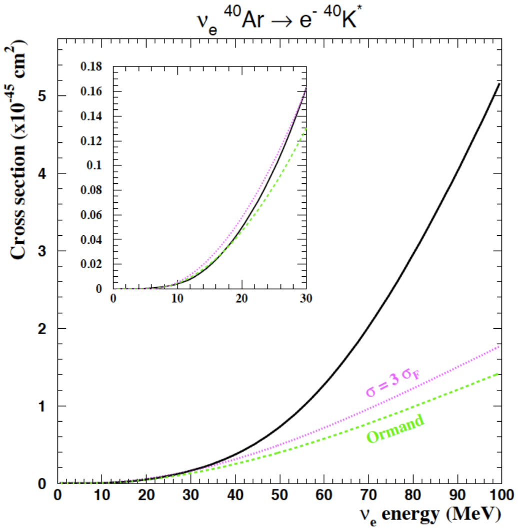
$$\frac{dN_a}{dE_\nu} = N_T \int dE'_\nu \, R(E_\nu, E'_\nu)\, F_a(E'_\nu)\, \sigma_a(E'_\nu)$$

Energy resolution function

Cross sections

DUNE detection: $\nu_e + ^{40}\mathrm{Ar} \rightarrow e^- + ^{40}\mathrm{K}^*$

Water-Cherenkov detection: $\bar{\nu}_e + p \rightarrow e^+ + n$



In DUNE, use Gaussian energy distribution:

$$\frac{\sigma}{E_\nu} = 0.05$$

for 40 kton detector:

$$N_{\mathrm{Ar}} = 6 \times 10^{32}$$

Fig. from Gil-Botella & Rubbia, JCAP 0310 (2003) 009.
Cross section: Kolbe, Langanke, Martinez-Pinedo & Vogel, J Phys CG 29 (2003) 2569.

Cross sections

DUNE detection: $\nu_e + {}^{40}\mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^*$

Water-Cherenkov detection: $\bar{\nu}_e + p \to e^+ + n$

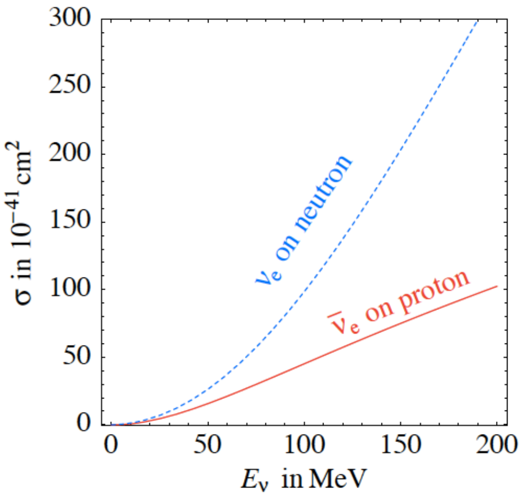


Fig. from Strumia & Vissani, PLB 564 (2003) 42.

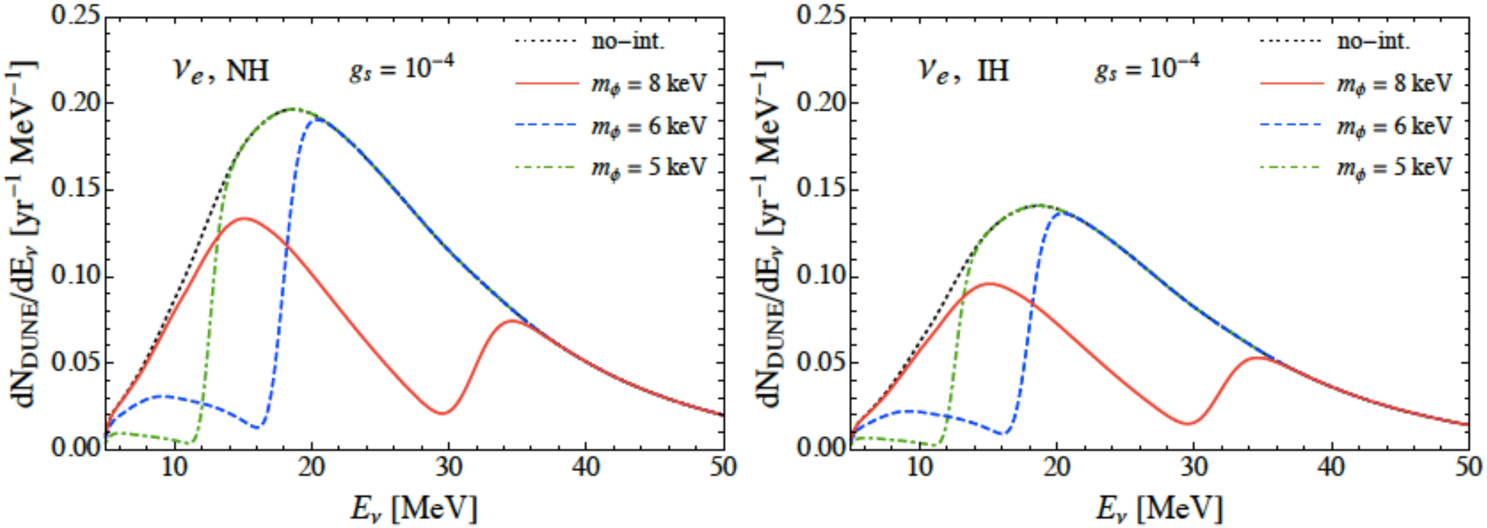
In HK, use Gaussian energy distribution:

$$\frac{\sigma}{E_\nu} = 0.10$$

for 2-187 kton tanks:

$$N_{\rm HK} = 1.25 \times 10^{34} \text{ free protons}$$

DUNE differential event rates



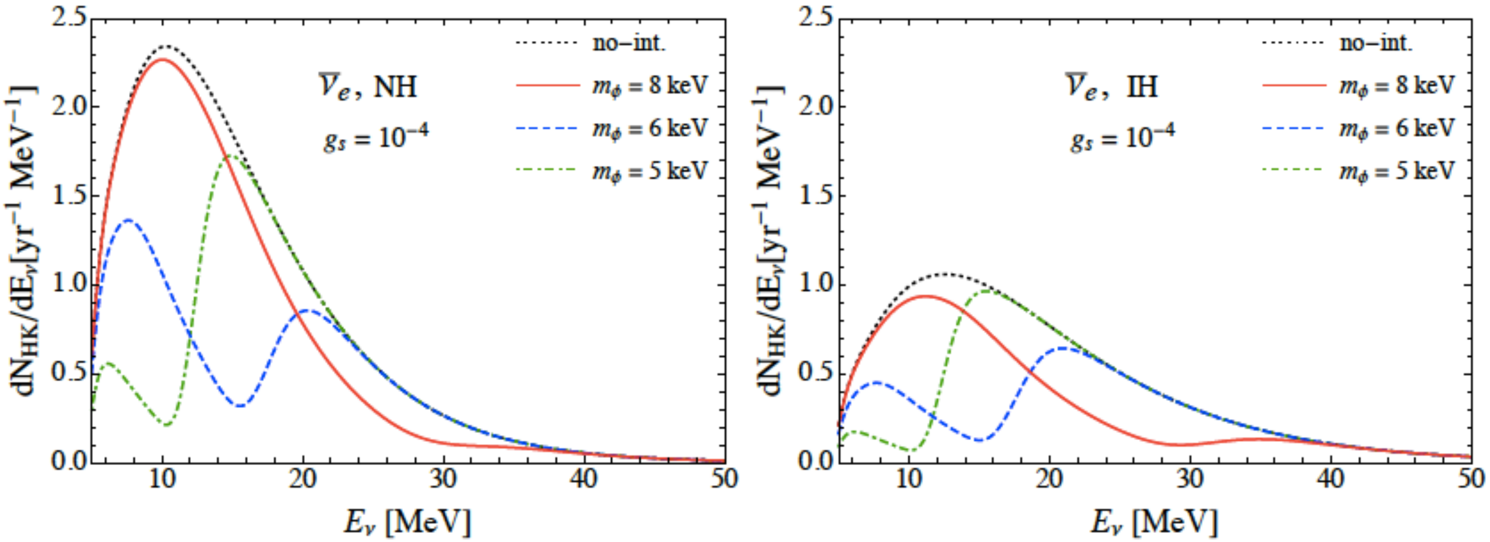
solar neutrinos an issue at lower energies

$$g_s = 10^{-4}$$

40 kton DUNE LAr detector

ν_e charged-current interactions off ^{40}Ar,

HyperK differential event rates

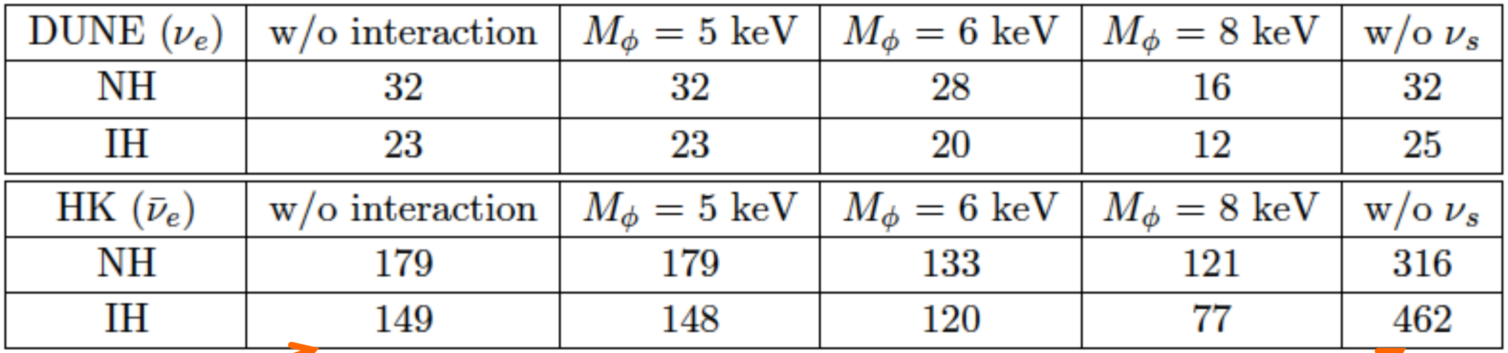


$$g_s = 10^{-4}$$

187 kton HK tank

$\bar{\nu}_e$ inverse beta decay off water

Number of events in 10 years from diffuse supernova flux



DUNE (ν_e)	w/o interaction	$M_\phi = 5$ keV	$M_\phi = 6$ keV	$M_\phi = 8$ keV	w/o ν_s
NH	32	32	28	16	32
IH	23	23	20	12	25

HK ($\bar{\nu}_e$)	w/o interaction	$M_\phi = 5$ keV	$M_\phi = 6$ keV	$M_\phi = 8$ keV	w/o ν_s
NH	179	179	133	121	316
IH	149	148	120	77	462

4 flavors, φ not in interesting range for absorption dips

$$16\ \mathrm{MeV} \leq E_\nu \leq 40\ \mathrm{MeV}$$

$$g_s = 10^{-4}$$

3 flavors

$$400\ kT \cdot yr\ (\mathrm{DUNE}),\ 2.6\ MT \cdot yr\ (\mathrm{HK})$$

Number of events in 10 years from diffuse supernova flux

DUNE (ν_e)	w/o interaction	$M_\phi = 5$ keV	$M_\phi = 6$ keV	$M_\phi = 8$ keV	w/o ν_s
NH	32	29	21	17	32
IH	23	21	15	12	27

HK ($\bar{\nu}_e$)	w/o interaction	$M_\phi = 5$ keV	$M_\phi = 6$ keV	$M_\phi = 8$ keV	w/o ν_s
NH	337	252	164	273	528
IH	209	170	111	133	642

solar neutrinos an issue at lower energies

4 flavors, φ not in interesting range for absorption dips

$$10\ \mathrm{MeV} \leq E_\nu \leq 30\ \mathrm{MeV}$$

$$g_s = 10^{-4}$$

3 flavors

$$400\ kT \cdot yr\ (\mathrm{DUNE}),\ 2.6\ MT \cdot yr\ (\mathrm{HK})$$

Conclusions

- Suppression in the event rates, spectral features from BSM physics with keV scale mediators and eV scale sterile neutrinos.
- For DUNE, the nominal event rate is small…
- Uncertainties in inputs could increase the event rate by as much as an order of magnitude:
  - neutrino cross section
  - SN energy spectra
  - SN formation rate (SNR)
  - other sources of 10’s of MeV neutrinos, e.g., failed SN (stellar collapse to black holes)

    Lundardini, PRL 102 (2009) 231101
- Mass sum, in particular, from CMB – a complicated issue given SM simulations input to CMB limits. Our conclusions different than, e.g., Chu et al, JCAP 11 (2018) 049, on cosmological acceptability for CMB.