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

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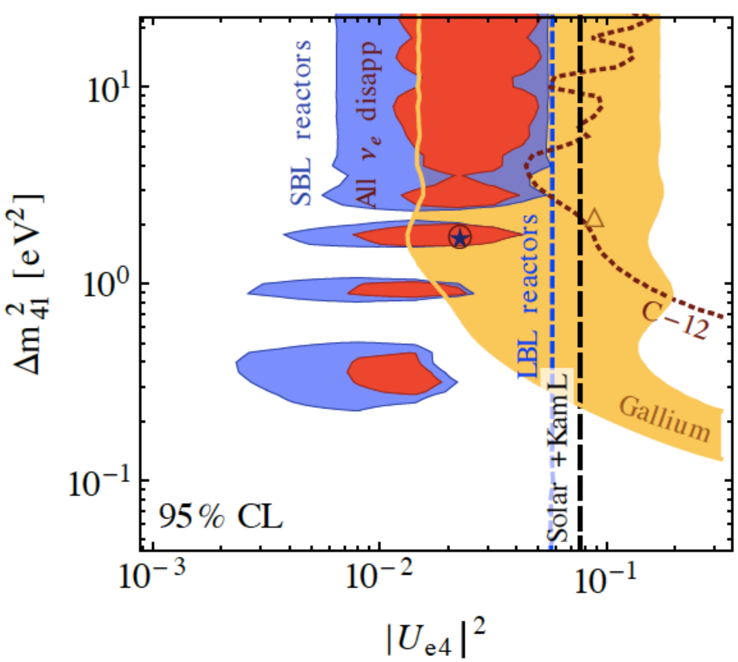
based on work with Y. S. Jeong, S. Palomares-Ruiz & I. Sarcevic
arXiv:1803.04541/JCAP 1806 (2018) 019

Work supported in part by the US Department of Energy

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

See, e.g., Kopp et al., JHEP 05 (2013) 050, Giunti et al., PRD 88 (2013) 073008.



Kopp et al., JHEP 05 (2013) 050

Example, allowed region for 3+1 at 95% CL, red is combined region

Introduce one sterile neutrino & new vector boson:

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

Cosmic eV-scale sterile neutrino background and supernova neutrinos

supernova neutrinos

sterile neutrino background

$$s = 2E_{\nu_s} m_s = m_\phi^2$$

$$E_{\nu_s} = 10 \text{ MeV},\ m_s = 1 \text{ eV} \implies m_\phi \simeq 5 \text{ keV}$$

It is possible to probe keV-scale gauge boson mediators with supernova neutrinos, through absorption dips.

Opportunity for DUNE measurements of physics beyond the standard model using SN neutrinos.

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

GZK neutrinos

neutrino background

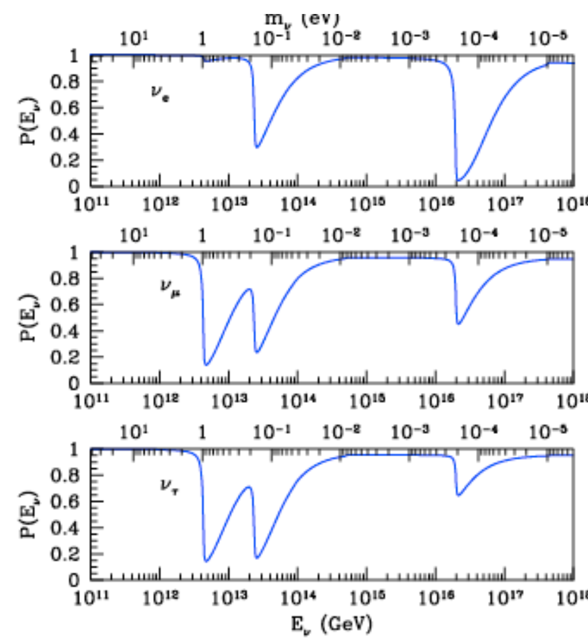
$$s = 2E_\nu m_\nu = m_Z^2$$

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

Other mass ranges, e.g.,

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

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~ 1 MeV).

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

- Later epochs, where CMB fluctuations can be modified by presence of massive neutrinos. Constraints on neutrino masses for standard model densities:

Need to satisfy these constraints to determine which (g_s, Mϕ) ranges are possible for consideration.

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.

Discussion here:

- Key feature with keV-scale gauge boson: a contact interaction is a bad approximation most of the time.

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

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

See recent work for QKE (using G_s)
by, e.g., Song, Gonzalez-Garcia & Salvado, 1805.08218.

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

BBN – first, no oscillations

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

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

$$\xi = \frac{T_s}{T_\nu}$$

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

$M_\phi \lesssim 1$ MeV

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

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

$M_\phi \gtrsim 1$ MeV

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

Active-sterile conversions

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

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

Matter effect including sterile neutrinos

Damping rate

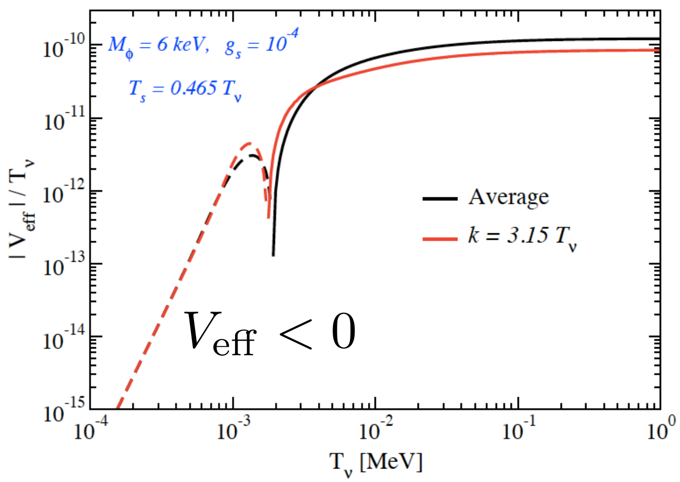
BBN – now with oscillations

BBN constraint, from expansion of the universe during nucleosyntheis:

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

In-medium mixing, active-sterile oscillations:

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

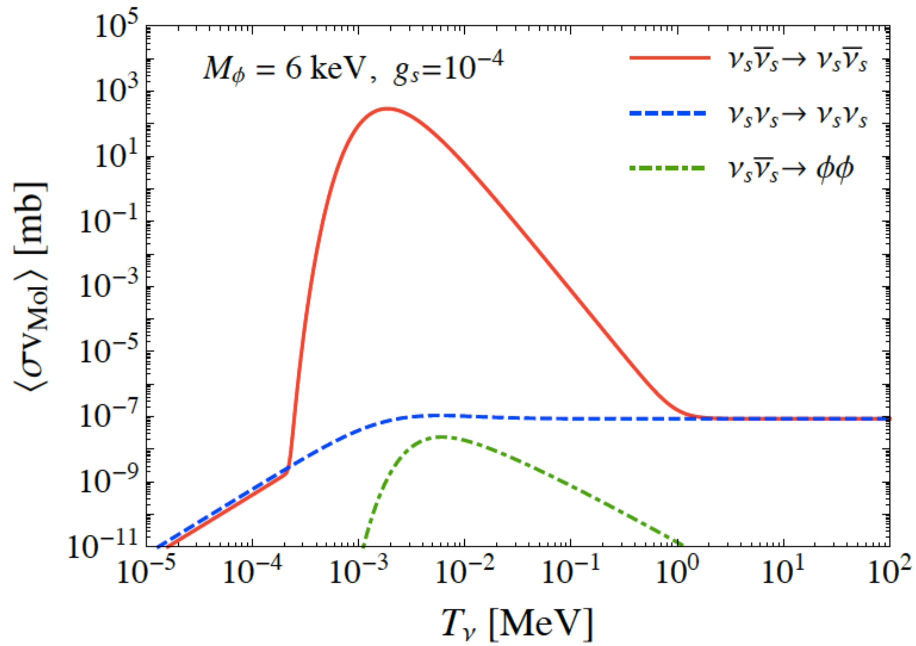


Contact interaction

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

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

Account for sterile neutrino interactions



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

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

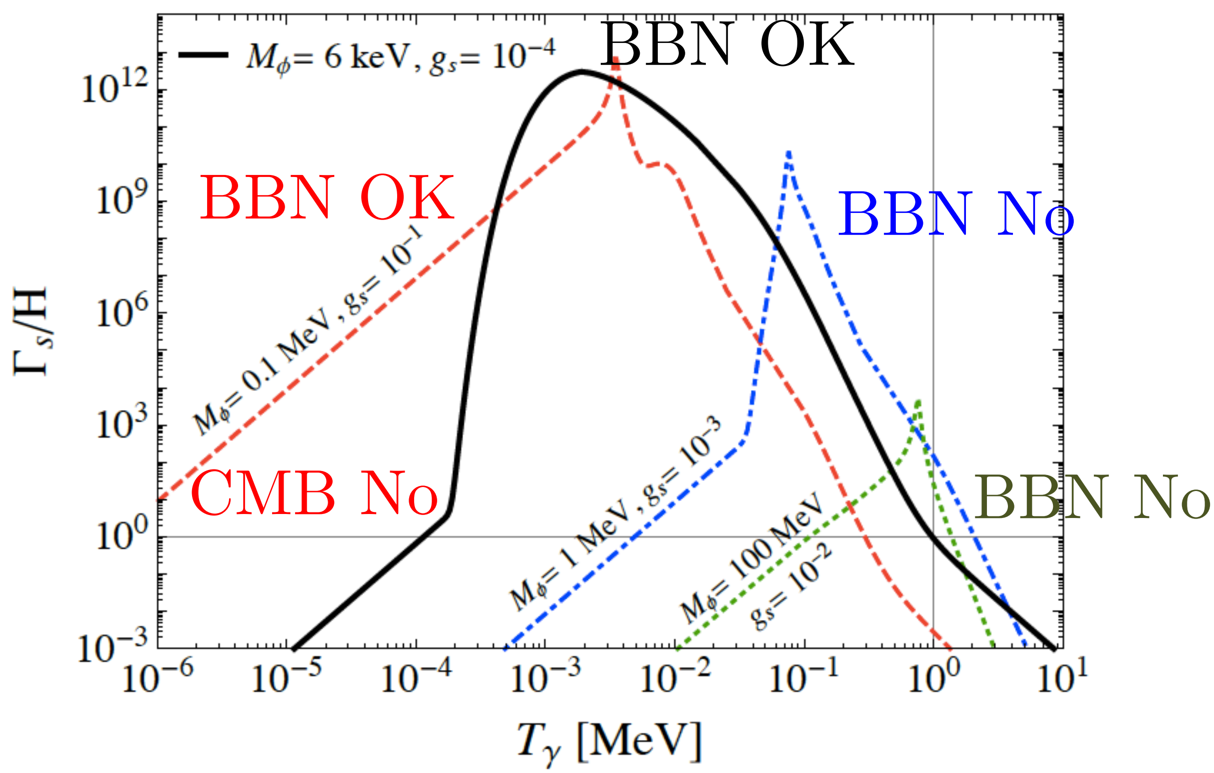
Resonance influences a wide range of temperatures due to thermal average.

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

Contact interaction

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

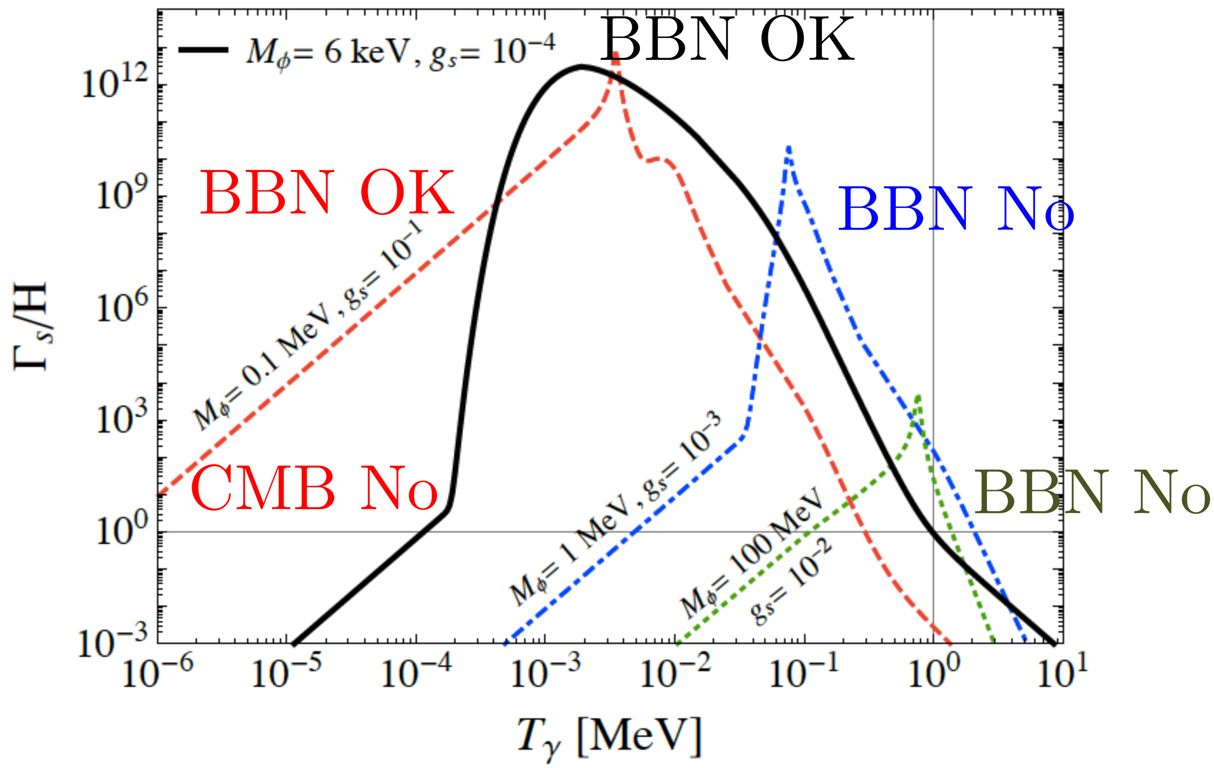
BBN sterile neutrino production rate constraint



Active-sterile recoupling after SM neutrino decoupling at 1 MeV.

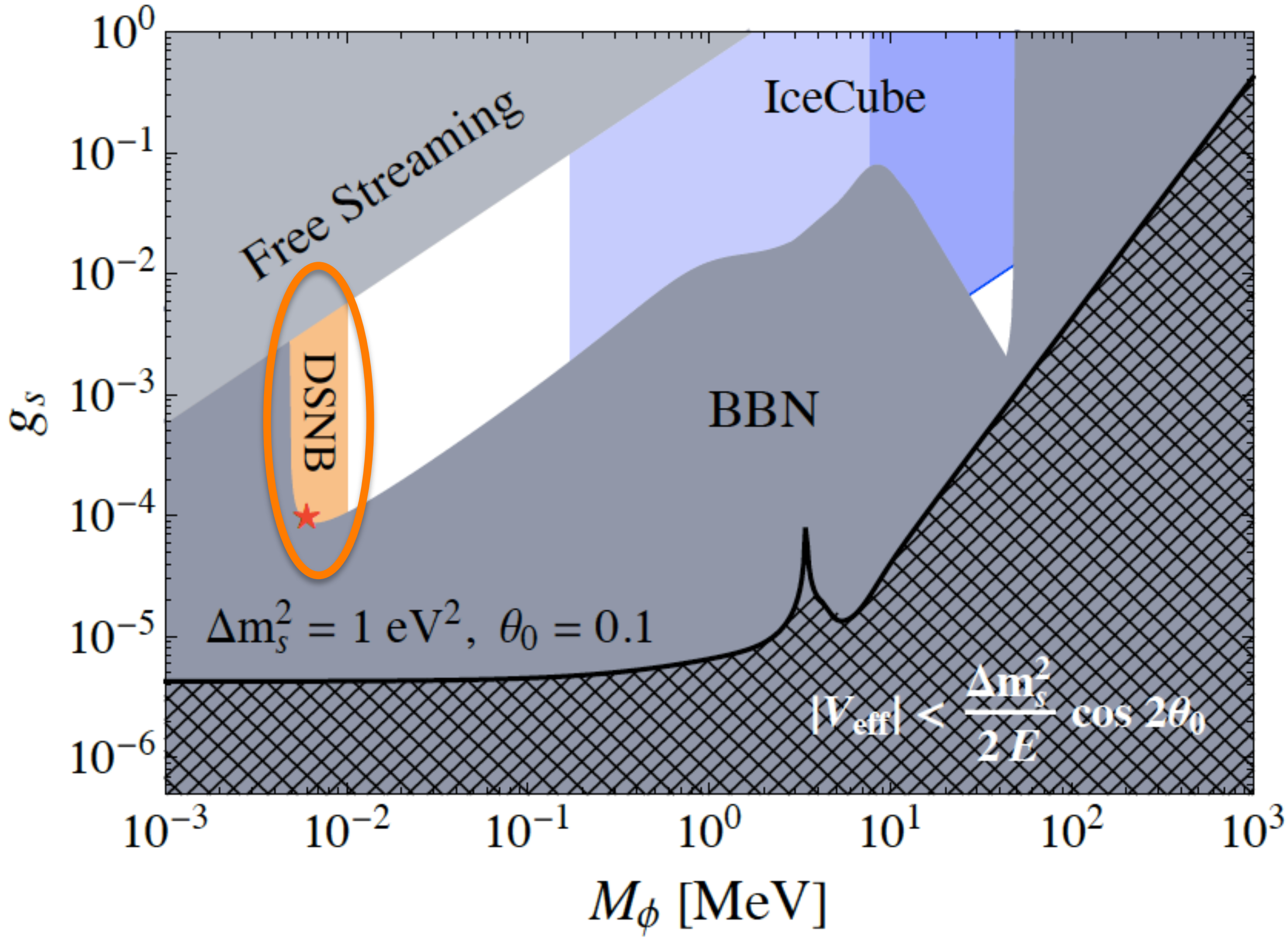
$$\Gamma_s/H < 1 \text{ for } T_\gamma > 1 \text{ MeV}$$

CMB sterile neutrino production rate constraint



Active-sterile recoupling after SM neutrino decoupling, must not occur after 1 eV.

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



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

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

See, however, Chu et al. 1806.10629, where they disagree about free-streaming constraints.

Spectrum of diffuse supernova background-ingredients

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

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

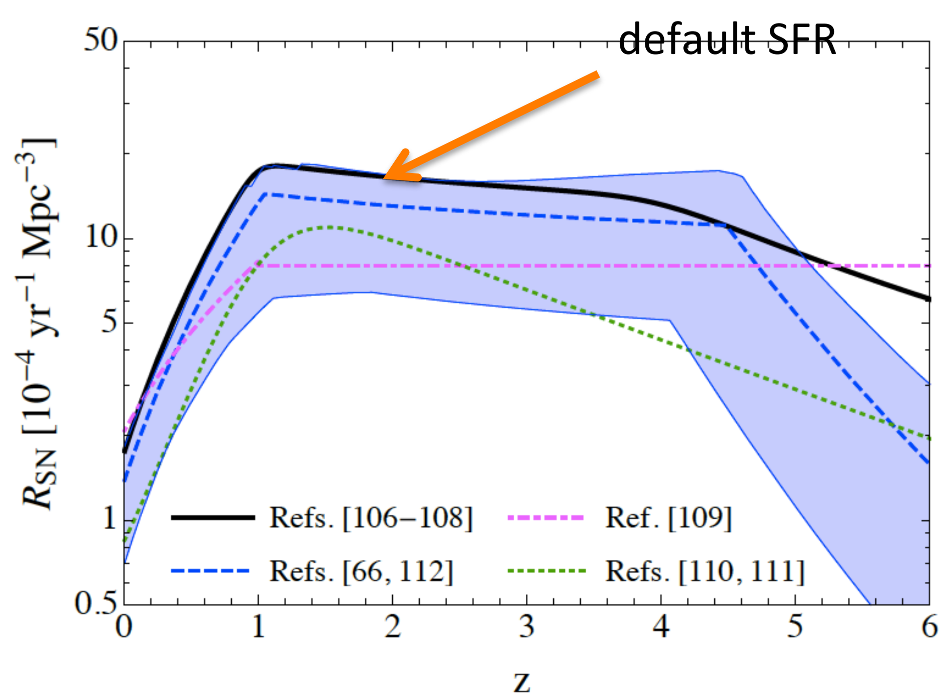
Energy emitted at redshift z, current energy.

$R_{\rm SN}(z)$

Supernova formation rate.

dN/dE_ν

Spectrum from generic supernova explosion.



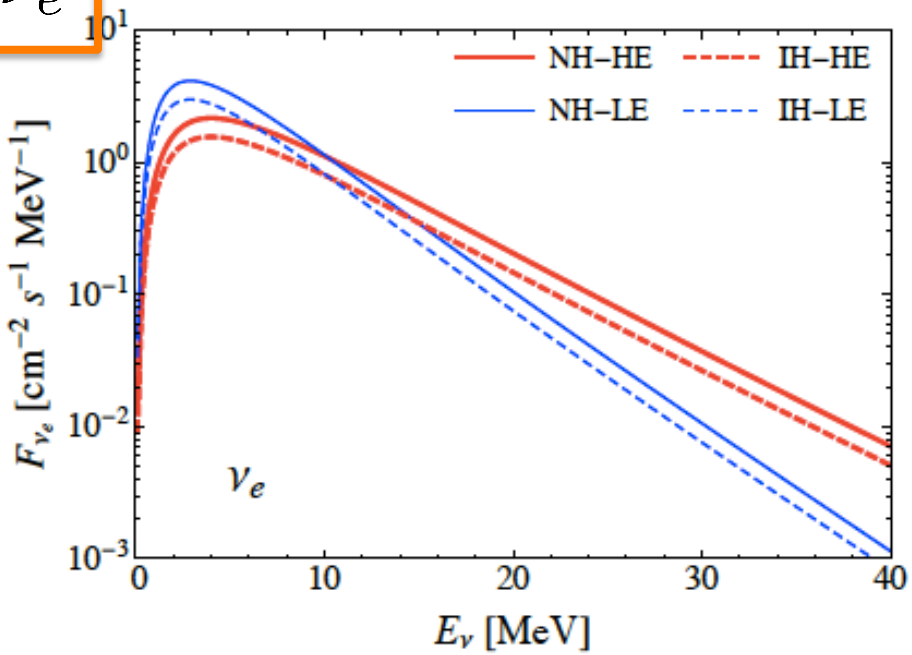
Yuksel et al., Ap. J. 683 (2008) L5, Kistler et al, arXiv: 1305.1630, Horiuchi et al., Ap. J. 738 (2011) 154.

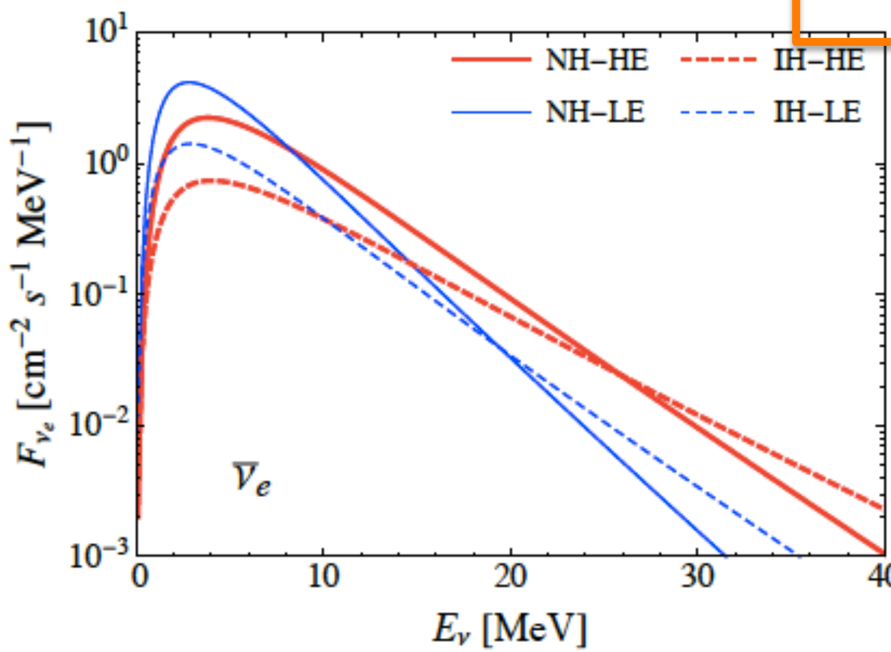
Diffuse supernova background fluxes, high energy (HE) and low energy (LE) models, no absorption

ν_e

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

$\bar{\nu}_e$



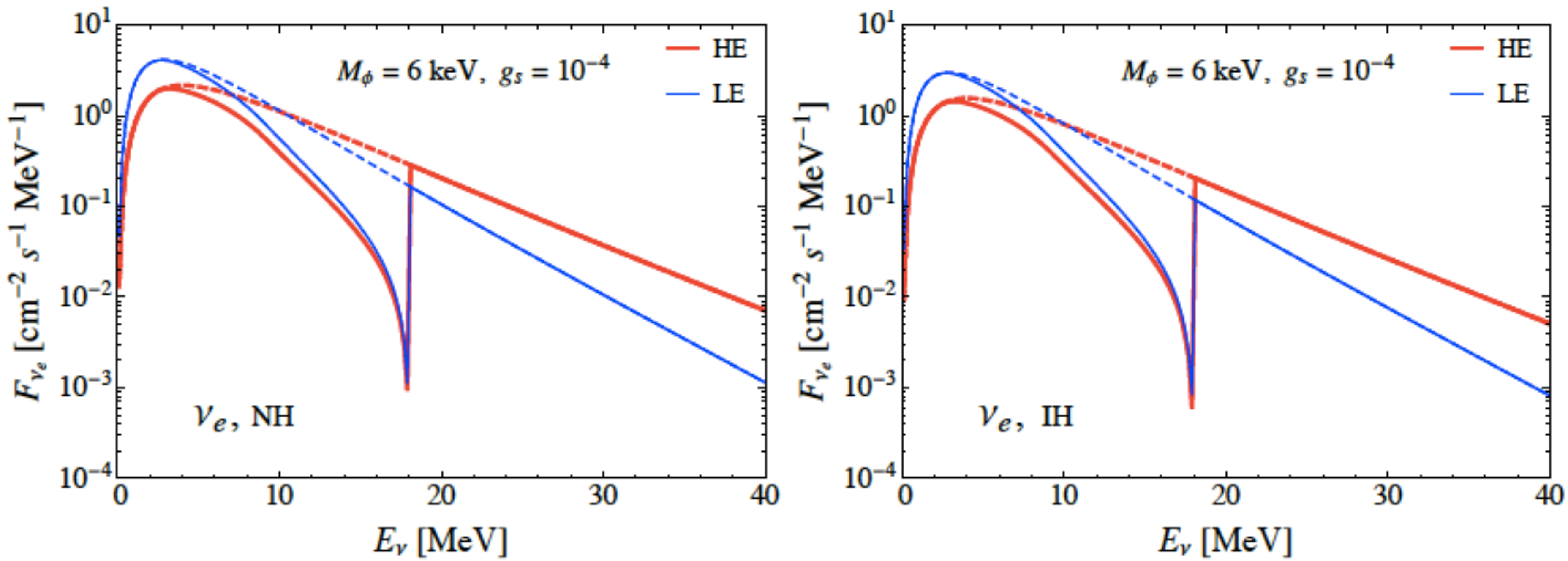


$$F_a(E_\nu) = \sum_{i=1}^{4} |U_{ai}|^2 F_i(E_\nu) = \sum_{i=1}^{4} |U_{ai}|^2 \int_0^{z_{\rm max}} dz\, R_{\rm SN}(z)\, F_i^0(E')\,(1+z)\left|\frac{dt}{dz}\right|$$

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

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

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

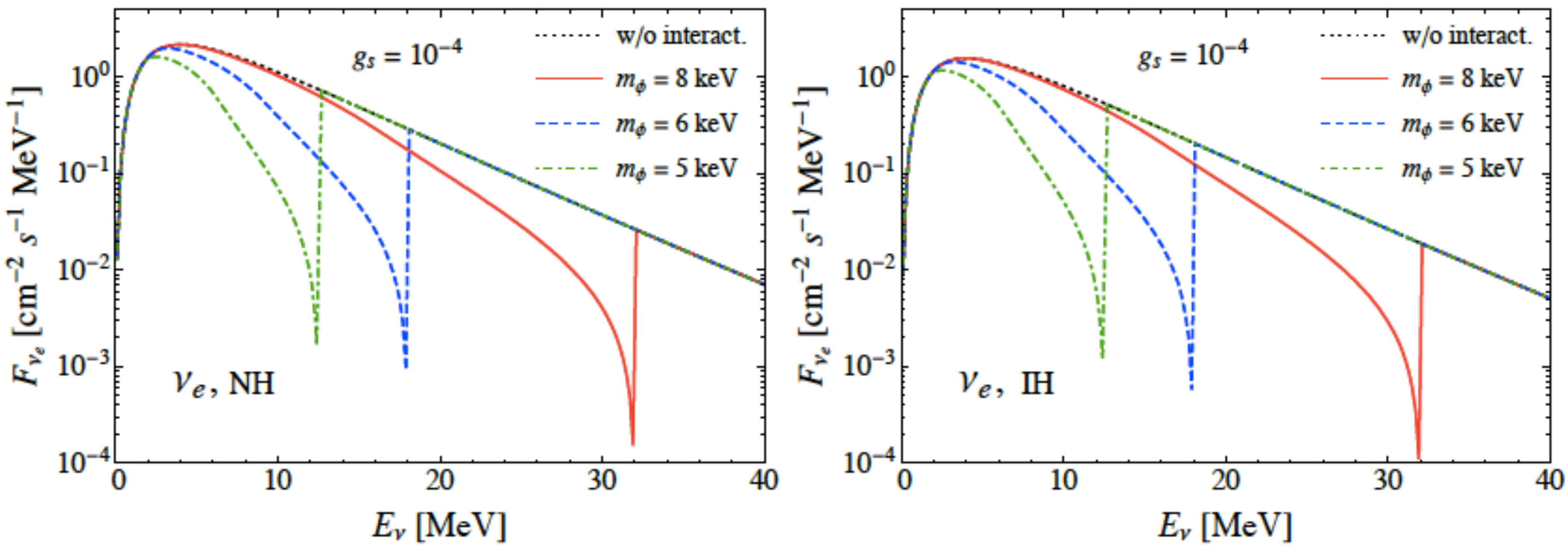


$M_\phi = 6$ keV, $g_s = 10^{-4}$, $m_s = 1$ eV and $\theta_0 = 0.1$

active-sterile mixing angle in resonant cross section

Diffuse supernova 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

Electron neutrino and antineutrino event rates in detectors

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

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

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

Energy resolution function

Cross sections

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

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

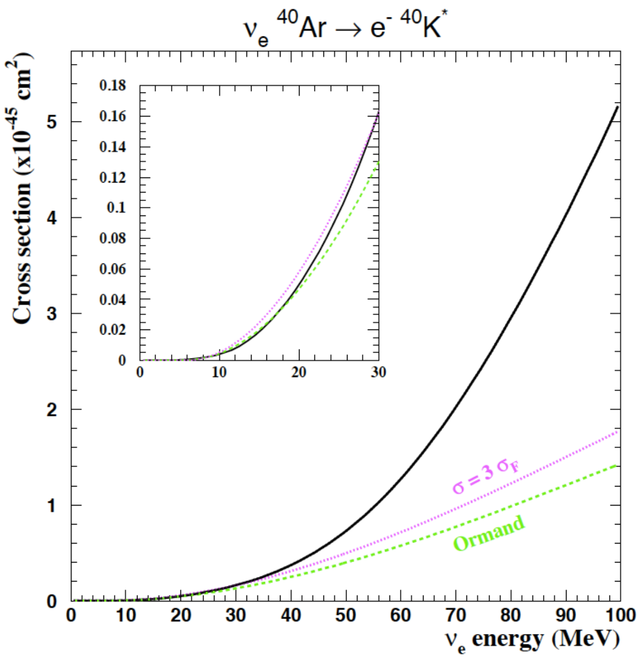


Fig. from Gil-Botella & Rubbia, JCAP 0310 (2003) 009.

Cross section: Kolbe, Langanke, Martinez-Pinedo & Vogel, J Phys CG 29 (2003) 2569.

In DUNE, use Gaussian energy distribution:

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

for 40 kton detector:

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

Cross sections

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

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

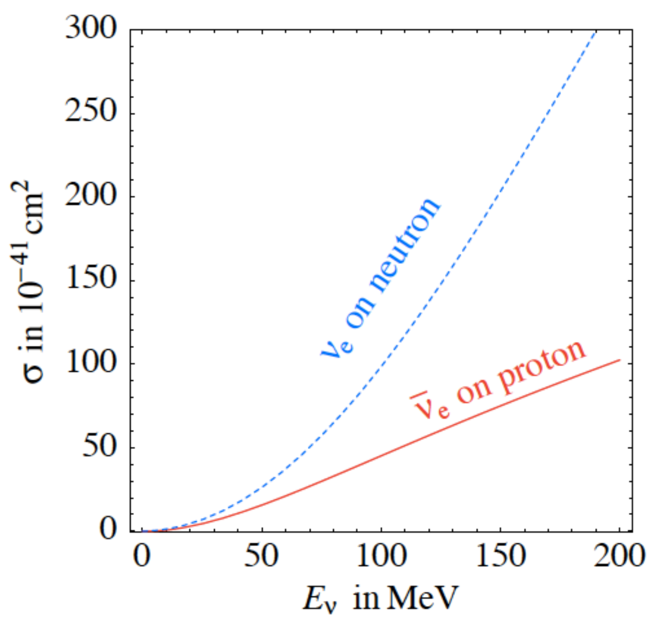


Fig. from Strumia & Vissani, PLB 564 (2003) 42.

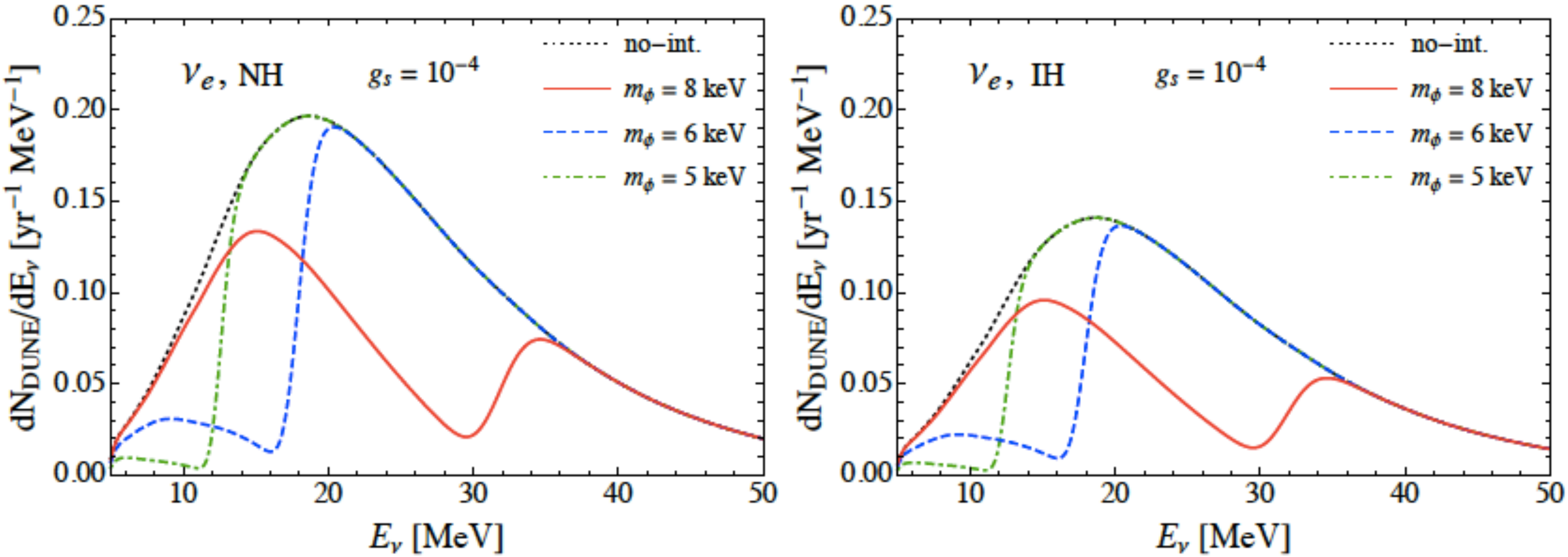
In HK, use Gaussian energy distribution:

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

for 2-187 kton tanks:

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

Dune differential event rates



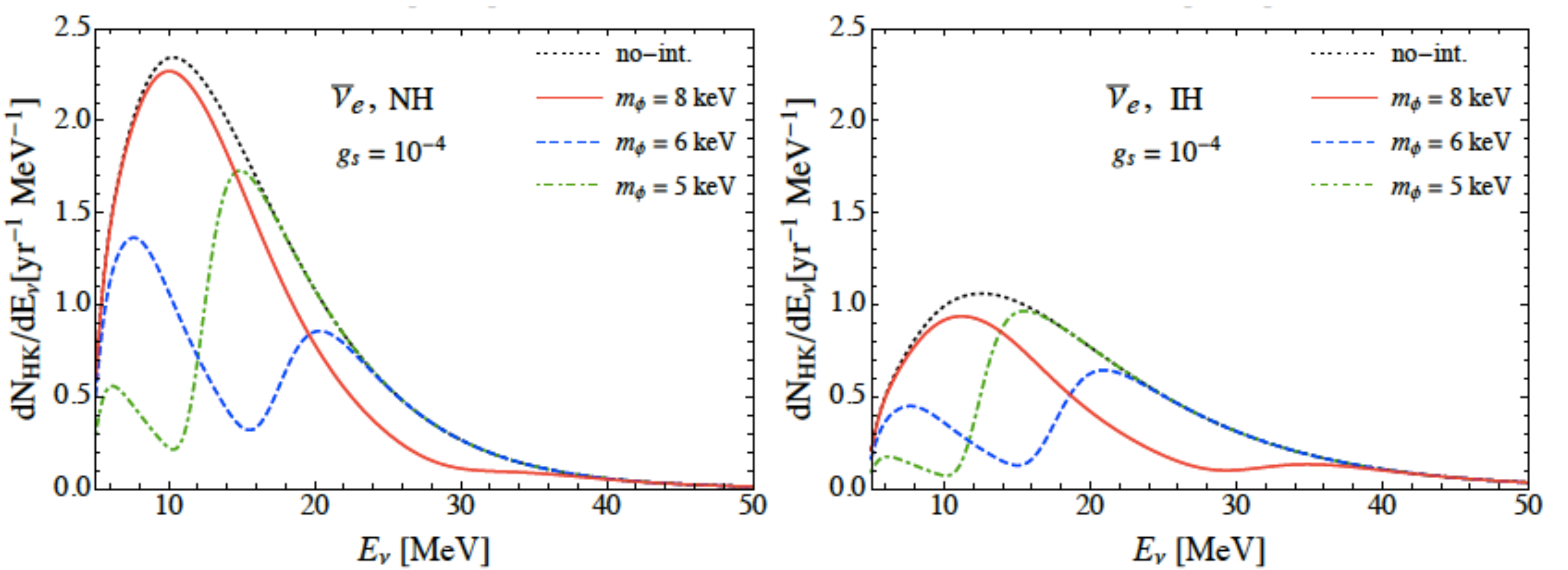
solar neutrinos an issue at lower energies

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

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

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

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

3 flavors

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

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

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

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

3 flavors

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

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
- Our conclusions different than Chu et al, 1806.10629, on cosmological acceptability. Mass sum, in particular, from CMB – a complicated issue given SM simulations input to CMB limits.