Dips in the Diffuse Supernova Neutrino Background

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Outline

- Motivation: SLIM scenario linking DM with neutrino mass
- Phenomenological effects of MeV DM coupled to neutrinos
- Propagation of SN neutrino across universe
- Dips in the spectrum of DSNB
- Conclusions

Freeze-out scenario

$$\Omega_{DM} = \frac{nm}{\rho_c} \propto \frac{m/T_f}{\langle \sigma v \rangle}$$

- m/T_f has a value between 10 to 30. So, the DM density is practically independent of the mass of the DM candidate and is solely determined by its annihilation cross-section.

A scenario Linking these two problems

- New fields:
- Majorana Right-handed neutrino
- SLIM=Scalar as LIght as MeV

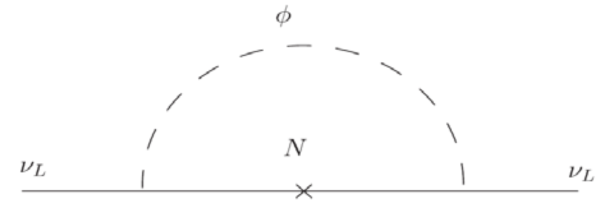
$$\mathcal{L}_I \supset g \phi \bar{N} \nu$$

Boehm, Y. F., Hambye, Palomares-Ruiz and Pascoli, PRD 77 (08) 43516

$$g \quad m_\phi \quad m_N$$

neutrino masses

- In this scenario, SLIM does not develop any VEV so the tree level neutrino mass is zero.
- Radiative mass in case of real scalar:



- Ultraviolet cutoff Λ
- Majorana mass:

$$m_\nu = \frac{g^2}{16\pi^2} m_N \left[\ln\left(\frac{\Lambda^2}{m_N^2}\right) - \frac{m_\phi^2}{m_N^2 - m_\phi^2} \ln\left(\frac{m_N^2}{m_\phi^2}\right) \right]$$

SLIM as a real field

- For $m_N > m_\phi$, SLIM plays the role of dark matter candidate. Imposing a Z_2 symmetry, the SLIM can be made stable and a potential dark matter candidate:

$$\mathcal{L} = g\phi\bar{N}\nu + (\frac{m_N}{2}NN + H.c) + \frac{m_\phi^2}{2}\phi^2 + \ldots$$

- Z_2 symmetry:

$$\phi \rightarrow -\phi \ , \qquad N \rightarrow -N$$

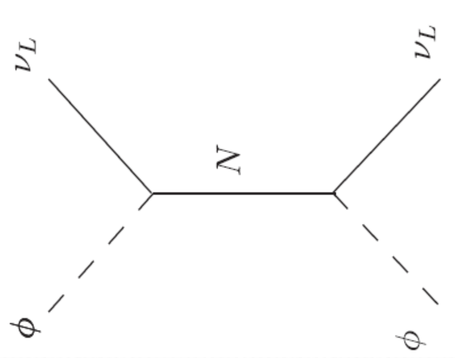
$$\cancel{\bar{N}L\cdot H}$$

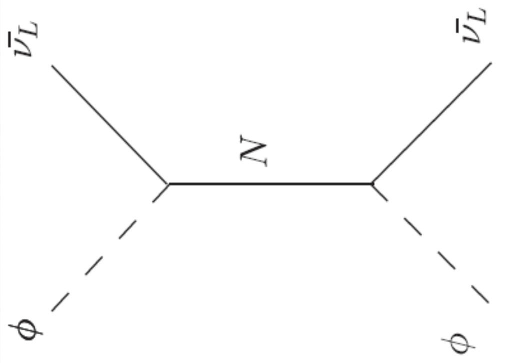
- SLIM is stable but the right handed neutrino decays:

$$\Gamma_N = g^2 m_N^2/(16\pi E_N)$$

Annihilation cross-section

- Pair Annihilation:





$$\langle \sigma(\phi\phi \to \nu\nu)\mathrm{v}_r\rangle = \langle \sigma(\phi\phi \to \bar{\nu}\,\bar{\nu})\mathrm{v}_r\rangle$$

$$\simeq \frac{g^4}{4\pi}\frac{m_N^2}{(m_\phi^2 + m_N^2)^2},$$

$$g \simeq 10^{-3}\sqrt{\frac{m_N}{10\ \mathrm{MeV}}}\left(\frac{\langle \sigma\nu_r\rangle}{10^{-26}\ \mathrm{cm}^3/\mathrm{s}}\right)^{1/4}\left(1 + \frac{m_\phi^2}{m_N^2}\right)^{1/2}$$

Linking dark matter and neutrino mass

$$m_\nu \simeq \sqrt{\frac{\langle \sigma v_r \rangle}{128\pi^3}} m_N^2 \left(1 + \frac{m_\phi^2}{m_N^2}\right) \ln\left(\frac{\Lambda^2}{m_N^2}\right)$$

$$\langle \sigma v_r \rangle \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}.$$

$$\Lambda \sim E_{\mathrm{electroweak}} \sim 200\ \mathrm{GeV}$$

$$0.05\ \mathrm{eV} < m_\nu < 1\ \mathrm{eV},$$

$$O(1)\ \mathrm{MeV} \lesssim m_N \lesssim 10\ \mathrm{MeV}.$$

Bounds on SLIM mass

- Upper bound: $m_\phi < M_N$

- Lower bound: Lyman alpha

Realization of the scenario

- For real SLIM, m_N <10 MeV ➡ N has to be singlet.
- Therefore, $\mathcal{L}_I \supset g\phi\bar{N}\nu$ must be effective and can obtain this form only after electroweak symmetry breaking.
- By promoting ϕ to be a doublet one can complete.
- E. Ma, Annales Fond. Broglie 31 (06) 285;
- E. Ma, PRD73 (2006).

An economic model embedding *real* SLIM

YF, "*Minimal model linking two great mysteries: Neutrino mass and dark matter*", PRD 80 (2009) 073009

Field content

1) An electroweak singlet scalar, $\eta;$
2) Two (or more) Majorana right-handed neutrinos N_i
3) A scalar electroweak doublet, $\Phi^T = [\phi^0 \ \phi^-]$

- With $\phi^0 \equiv (\phi_1 + i\phi_2)/\sqrt{2}$

- We impose a Z_2 symmetry under which all the new particles are odd.

Light and heavy

- Light sector: Dark matter candidate δ_1 and N_1
- (similar to what we had in the SLIM scenario)
- Heavy sector: δ_2 ϕ_2 ϕ^- ⇓

Lepton Flavor Violating rare decays, $\mu \to e\gamma$, $\tau \to \mu\gamma$ and $\tau \to e\gamma$

Magnetic dipole moment of the muon

- **Production at LHC**

MeV Dark matter

$$\langle \rho_{DM} \rangle \sim \frac{keV}{cm^3}$$

$$\langle n_{DM} \rangle \sim \frac{0.001}{cm^3} \sim \frac{1000}{m^3}$$

$$\rho_{DM}^{local} \sim 0.4\frac{GeV}{cm^3}$$

$$n_{DM}^{local} \sim \frac{400}{cm^3} \sim \frac{10^8}{m^3}$$

These particles should affect neutrinos travelling cosmic distance:

Neutrinos from supernovae at cosmic distances

YF and S. Palomares-Ruiz, arXiv:1401.7019

Coupling in general

$$gN_R^\dagger \nu_L \phi$$

a Z_2 symmetry ($N \to -N$, $\phi \to -\phi$ and SM$\to$SM),

Eight general possibility

$Case\ m_N < m_\phi$

$Case\ m_\phi < m_N$

$-\ \ Real\ \phi\ \ and\ Dirac\ N$

$-\ \ Real\ \phi\ \ and\ \ Majorana\ \ N$

$-\ \ Complex\ \phi\ \ and\ Dirac\ N$

$-\ \ Complex\ \phi\ \ and\ \ Majorana\ \ N$

Freeze-out scenario

$Case\ m_N < m_\phi$ $\quad$ $Real\ \phi\ and\ Dirac\ N:$

$$\sigma(N\,N \to \nu\,\nu) = \sigma(\bar{N}\,\bar{N} \to \bar{\nu}\,\bar{\nu}) = \frac{g^4}{4\pi}\frac{m_N^2}{(m_N^2 + m_\phi^2)^2}$$

$$\langle\sigma(N\bar{N} \to \nu\bar{\nu})v\rangle = \frac{g^4 m_N^2}{4\pi(m_N^2 + m_\phi^2)^2}$$

Freeze-out scenario

$Case\ m_N < m_\phi$

$Real\ \phi\ and\ Majorana\ N$

$$\sigma(N\,N \to \nu\,\nu) = \frac{g^4}{4\pi}\frac{m_N^2}{(m_N^2 + m_\phi^2)^2}$$

Freeze-out scenario

$Case\ m_N < m_\phi$

$Complex\ \phi\ and\ Dirac\ N$

$$\langle \sigma(N\bar{N} \to \nu\bar{\nu})v \rangle = \frac{g^4 m_N^2}{4\pi(m_N^2 + m_\phi^2)^2}$$

Freeze-out scenario

Case $m_N < m_\phi$ *Complex* ϕ *and Majorana* N

$$\langle \sigma(NN \to \nu\bar{\nu})v \rangle = \frac{4\,g^4}{3\pi} \frac{m_N^4 + m_\phi^4}{(m_N^2 + m_\phi^2)^4}\, p_{\rm DM}^2$$

where $p_{\rm DM}$ is the momentum of the DM at freeze-out: $p_{\rm DM}^2 \sim m_N^2/20$.

Freeze-out scenario for Pseudo-Dirac N

- N_1 and N_2

  small mass splitting $\Delta m_N = m_L + m_R$.

  scatter off ϕ and ν $\Gamma_{\rm scat} \sim g^4 T/4\pi$.

For $\Delta m_N/\Gamma_{\rm scat} \gg 1$, coherence is lost. They will behave like Majorana particles at freeze-out. Both annihilation and co-annihilation

Bound from freeze-out scenario

- Total annihilation cross section~1 pb

In all cases with N as DM

$$g < \mathcal{O}(0.01)$$

Freeze-out for scalar as DM

- SLIM was an example:

$$m_N \simeq m_R \sim 1 - 10 \text{ MeV, from } \sigma(\phi\phi \to \overset{(-)}{\nu}\overset{(-)}{\nu}) \sim 1 \text{ pb},$$

$$3 \times 10^{-4} < g < 10^{-3}$$

The only case which allows large coupling within freeze-out scenario:

Real scalar and (pseudo-)Dirac N

Emphasis on pseudo-Dirac case

- Connection to neutrino mass

Emphasis on pseudo-Dirac case

- Connection to neutrino mass: An example

Emphasis on pseudo-Dirac case

- Connection to neutrino mass: An example

$U(1) \times U(1) \times U(1)$ flavor symmetry softly broken only by $(m_R)_{\alpha\beta}$.

$m_{N_\alpha} \bar{N}_\alpha N_\alpha$

coupling g_α.

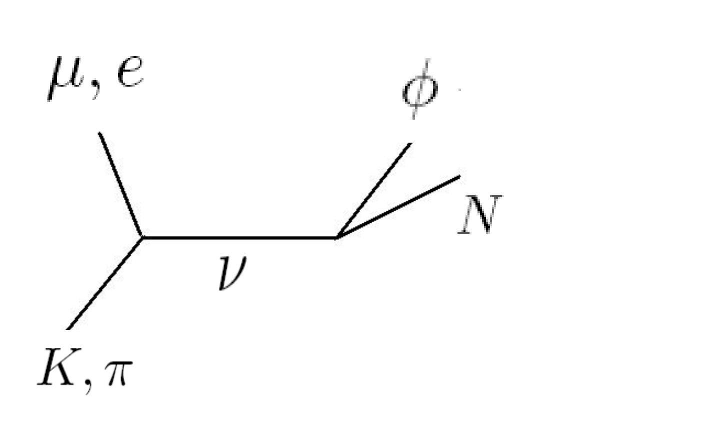
$$(m_\nu)_{\alpha\beta} \simeq \frac{g_\alpha g_\beta}{16\pi^2}(m_R)_{\alpha\beta} \log(\frac{\Lambda^2}{m_{\phi,N}^2})$$

Relevant low energy effects

1) New rare meson decay modes
2) Nucleosynthesis
3) Supernova evolution

Potential signature

- Missing energy in Pion and Kaon decay
- Lessa and Peres PRD (07) 94001, Britton et al., PRD 49 (94) 28; Barger et al., PRD 25 (82) 907;Gelmini et al., NPB209 (82) 157



- Barger et al., PRD 25 (82) 907
- More recent data:
- Lessa and Peres , PRD75

$$g \lesssim 10^{-2}$$

- PANG et al., PRD8 (1973!!!) 1989
- KLOE collaboration,EPJC 64 (09) 627

$$\max\{m_\phi^2, m_N^2\} \ll m_{K,\pi}^2,$$

$$|g_e|^2 < 10^{-5} \qquad |g_\mu|^2 < 10^{-4}$$

Bounds on coupling

$$m_K < m_\phi + m_N < m_D,$$

$$|g_e| < 0.4$$

Large coupling

In fact g_τ can be as large as $O(1)$.

- In our analysis of DSNB, we consider only one right-handed neutrino exclusively coupled to tau neutrino.
- We focus on real phi as dark matter and a Dirac N. But other 7 cases show similar effect on DSNB

Neutrino mass flavor structure

- Pseudo-Dirac N

$$(m_\nu)_{\alpha\beta} \simeq \frac{g_\alpha g_\beta}{16\pi^2}(m_R)_{\alpha\beta}\log(\frac{\Lambda^2}{m^2_{\phi,N}})$$

Notice that even with $g_\mu \ll g_\tau$, we can obtain $(m_\nu)_{\mu\mu} \sim (m_\nu)_{\tau\tau}$ provided that $(m_R)_{\mu\mu} \gg (m_R)_{\tau\tau}$.

Nucleosynthesis

- For masses above ~10 MeV, there is no effect on BBN.

- For 1 MeV $< m_\phi <$ 10 MeV, the SLIM density is suppressed at the time of nucleosynthesis but its annihilation to neutrinos increases the entropy and thus the temperature of the neutrino which affects nucleosynthesis.

Stronger bound from Planck

- Boehm et al, JCAP 1308 (13) 41 Lower bound on mass (MeV)

	Planck	Y_p	D/H
Real scalar	-	-	-
Complex scalar	3.9	-	-
Majorana N	3.5	-	-
Dirac N	7.3	0.8	3.3

Supernova Bounds

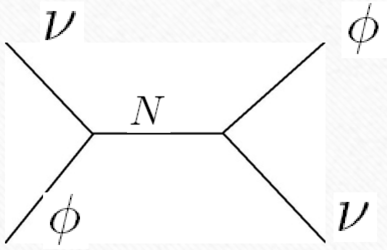
- Energy loss consideration: binding energy

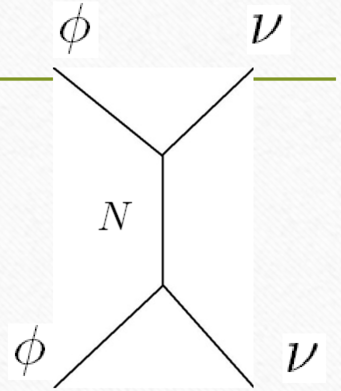
$$E_b = (1.5 - 4.5) \times 10^{53} \text{ erg},$$ Sato and Suzuki, PLB196 (87)

- Majoron can carry away energy leaving no energy for neutrinos which is in contradiction with SN1987a.
- Choi and Santamaria, PRD42 (90)293; Berezhiani and Smirnov
- PLB 220 (89)279; Kachelriess, Tomas and Valle, PRD 62 (00) 23004; Giunti et al., PRD45 (92) 1556; Grifols et al, PLB215 (88) 593.

Thermalization

- SLIMs will be trapped in the core.





- In the outer core with T~30 MeV
- Mean free path of SLIM<< Mean free path of neutrinos in SM
- The effect of SLIMs on cooling can be tolerated within present uncertainties of supernova models.

Diffuse Supernova Neutrino Background

- Neutrinos from supernovas happening during the course of universe

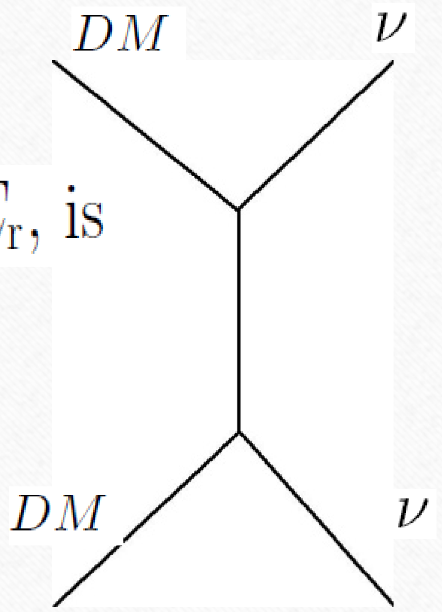
- Most contribution comes from SN at $z \sim 1$

Resonance scattering of SN neutrinos at propagation

$gN_R^\dagger \nu_L \phi$

The resonance neutrino energy in the laboratory frame, E_r, is

$$E_\mathrm{r} = \frac{m_\mathrm{r}^2 - m_\mathrm{DM}^2}{2\, m_\mathrm{DM}} = E_0\,(1 + z_\mathrm{r})$$



Optical depth

$$\tau = \int \frac{c\,dt}{\lambda_\nu} = \int dz\,\frac{dt}{dz}\,n(z)\,\sigma(z)\,,$$

$$dt/dz \;=\; -((1\;+\;z)\,H(z))^{-1}$$

$$H(z) \simeq H_0\sqrt{\Omega_\Lambda + \Omega_{\mathrm{m},0}(1+z)^3}$$

Optical depth

$$\tau = \int \frac{c\,dt}{\lambda_\nu} = \int dz\,\frac{dt}{dz}\,n(z)\,\sigma(z)\,,$$

$$n(z) = n_0\,(1+z)^3 = \frac{\Omega_{\mathrm{DM},0}\,\rho_c}{m_{\mathrm{DM}}}\,(1+z)^3 \simeq 1.26\,\left(\frac{\mathrm{keV}}{m_{\mathrm{DM}}}\right)\,(1+z)^3\,\mathrm{cm}^{-3}$$

Differential cross section

$$\frac{d\sigma^p_{ij}}{dE'} = \frac{d\sigma^p_{ij}}{d\cos\theta}\,\frac{2E_\nu + m_{\rm DM}}{E_\nu^2}$$

$$\frac{m_{\rm DM}}{2E_\nu + m_{\rm DM}} E_\nu < E'_\nu < E_\nu$$

Differential cross section

$$\frac{d\sigma_{ij}^{p}}{dE'} = \frac{d\sigma_{ij}^{p}}{d\cos\theta}\,\frac{2E_\nu + m_{\rm DM}}{E_\nu^2}$$

- Close to the resonance:

$$\frac{d\sigma_{ij}^{\rm LC}}{d\cos\theta} = \frac{g_i^2 g_j^2}{32\pi}\,\frac{(m_{\rm r}^2 - m_{\rm DM}^2)^2}{(m_{\rm r}^2 + m_{\rm DM}^2)}\,\frac{1+\cos\theta}{(s-m_{\rm r}^2)^2 + \Gamma_{\rm r}^2\, m_{\rm r}^2}$$

Close to the resonance, the total LC cross section is given by

$$\sigma_{ij}(s) \simeq \frac{g_i^2 g_j^2}{16\pi} \frac{(m_\mathrm{r}^2 - m_\mathrm{DM}^2)^2}{m_\mathrm{r}^2 + m_\mathrm{DM}^2} \frac{1}{(s - m_\mathrm{r}^2)^2 + \Gamma_\mathrm{r}^2 m_\mathrm{r}^2} \, .$$

$$\Gamma_\mathrm{r} = \sum_i \frac{g_i^2}{16\pi} \frac{(m_\mathrm{r}^2 - m_\mathrm{DM}^2)^2}{m_\mathrm{r}^3}$$

Narrow width approximation

For $\Gamma_{\rm r} \ll m_{\rm r}$, it is convenient to use the narrow width approximation limit

$$\begin{aligned}
\sigma_{ij}(s) &\simeq \frac{g_i^2 g_j^2}{\sum_k g_k^2}\pi \frac{m_{\rm r}^2}{m_{\rm r}^2 + m_{\rm DM}^2}\delta\left(s - m_{\rm r}^2\right) \\
&= \frac{g_i^2 g_j^2}{\sum_k g_k^2}\pi \frac{1+z}{m_{\rm r}^2 - m_{\rm DM}^2}\,\frac{m_{\rm r}^2}{m_{\rm r}^2 + m_{\rm DM}^2}\,\delta\left((1+z) - \frac{m_{\rm r}^2 - m_{\rm DM}^2}{2m_{\rm DM}E_0}\right)
\end{aligned}$$

Optical depth

For $E_0 \leq E_{\rm r}$, we have

$$\begin{aligned}\tau_i(z_{\rm r}) &= \sum_j \frac{g_i^2 g_j^2}{\sum_k g_k^2}\left(\frac{\pi}{m_{\rm r}^2 - m_{\rm DM}^2}\right)\left(\frac{m_{\rm r}^2}{m_{\rm r}^2 + m_{\rm DM}^2}\right)\left(\frac{n_0}{H_0}\right)\left(\frac{\Omega_{\rm DM}(z_{\rm r})}{\Omega_{\rm DM,0}}\right)\\ &\simeq 5\times 10^2\, g_i^2 \left(\frac{20\ {\rm MeV}}{E_{\rm r}}\right)\left(\frac{\rm MeV}{m_{\rm DM}}\right)^2\left(\frac{E_{\rm r} + m_{\rm DM}/2}{E_{\rm r} + m_{\rm DM}}\right)\left(\frac{\Omega_{\rm DM}(z_{\rm r})}{\Omega_{\rm DM,0}}\right)\end{aligned}$$

where $\Omega_{\rm DM}(z) = \Omega_{\rm DM,0}(1+z)^3/\sqrt{\Omega_\Lambda + \Omega_{\rm m,0}(1+z)^3}$.

$$f_{\mathrm{abs}} = 1 - e^{-\tau}$$

$$f_{\mathrm{abs}} = 10\%,$$

$$g_i^2 > 2 \times 10^{-4} \left(\frac{E_{\mathrm{r}}}{20\ \mathrm{MeV}} \right) \left(\frac{m_{\mathrm{DM}}}{\mathrm{MeV}} \right)^2 \left(\frac{\Omega_{\mathrm{DM},0}}{\Omega_{\mathrm{DM}}(z_{\mathrm{r}})} \right) \left(\frac{E_{\mathrm{r}} + m_{\mathrm{DM}}}{E_{\mathrm{r}} + m_{\mathrm{DM}}/2} \right)$$

Resonant scattering at galaxy

- Milky way $\left(E_{\mathrm{r}} - \Gamma_{\mathrm{r}}\, m_{\mathrm{r}}/2m_{\mathrm{DM}},\; E_{\mathrm{r}} + \Gamma_{\mathrm{r}}\, m_{\mathrm{r}}/2m_{\mathrm{DM}}\right)$
- Host galaxy $\dfrac{E_r}{1+z} \pm \dfrac{\Gamma_r}{1+z}\dfrac{m_r}{2m_{DM}}$

Resonant scattering at galaxy

- Milky way $(E_{\mathrm{r}} - \Gamma_{\mathrm{r}}\, m_{\mathrm{r}}/2m_{\mathrm{DM}},\ E_{\mathrm{r}} + \Gamma_{\mathrm{r}}\, m_{\mathrm{r}}/2m_{\mathrm{DM}})$
- Host galaxy $\dfrac{E_r}{1+z} \pm \dfrac{\Gamma_r}{1+z}\dfrac{m_r}{2m_{DM}}$
- Redshift-integrated effect for DSNB

$$\text{all energies between } E_{\mathrm{r}} \text{ and } E_{\mathrm{r}}/(1+z)$$

Flux

$$F_i(t, E_\nu) \equiv \frac{d\Phi_i}{dE_\nu}(t, E_\nu)$$

Flux propagation

$$\frac{\partial F_i(t,E_\nu)}{\partial t} = -3H(t)F_i(t,E_\nu) + \frac{\partial}{\partial E_\nu}\left(H(t)E_\nu F_i(t,E_\nu)\right) - \frac{1}{\lambda_i(t,E_\nu)}F_i(t,E_\nu)$$
$$+\sum_j \int_{E_\nu}^{\infty} dE'_\nu \left[\mathcal{T}_{ji}^{\mathrm{LC}}(t,E'_\nu,E_\nu)\,F_j(t,E'_\nu) + \mathcal{T}_{ji}^{\mathrm{LV}}(t,E'_\nu,E_\nu)\,F_{\bar{j}}(t,E'_\nu)\right]$$
$$+\mathcal{L}_i(t,E_\nu)/a^3(t)\,,$$

Mean free path

$$\lambda_i(t, E_\nu) \equiv \frac{1}{\sum_{p,j} n(t)\, \sigma_{ij}^{p}(E_\nu)}$$

$$\sigma_{ij}(s) \simeq \frac{g_i^2 g_j^2}{\sum_k g_k^2} \pi \frac{m_{\mathrm{r}}^2}{m_{\mathrm{r}}^2 + m_{\mathrm{DM}}^2} \delta\left(s - m_{\mathrm{r}}^2\right)$$

$g_1 = g_\tau U_{\tau 1}$ $\quad$ $g_2 = g_\tau U_{\tau 2}$ $\quad$ $g_3 = g_\tau U_{\tau 3}$

Flux propagation

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$$+\mathcal{L}_i(t,E_\nu)/a^3(t)\,,$$

$$\mathcal{T}_{ji}^{\mathrm{LC}}(t, E'_\nu, E_\nu) \equiv n(t)\,\frac{d\sigma_{ji}^{\mathrm{LC}}}{dE_\nu}(E'_\nu, E_\nu)$$

$$\mathcal{T}_{ji}^{\mathrm{LV}}(t, E'_\nu, E_\nu) \equiv n(t)\,\frac{d\sigma_{ji}^{\mathrm{LV}}}{dE_\nu}(E'_\nu, E_\nu)$$

Flux propagation

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$$+\mathcal{L}_i(t,E_\nu)/a^3(t)\,,$$

The comoving luminosity of the source of neutrinos of flavor α at redshift z, $\mathcal{L}_\alpha(z, E_\nu)$,

$$\mathcal{L}_\alpha(z, E_\nu) = R_{\mathrm{SN}}(z)\, F_\alpha^{\mathrm{SN}}(E_\nu)$$

$R_{\mathrm{SN}}(z)$ represents the SN rate per comoving volume at redshift z.

$F_\alpha^{\mathrm{SN}}(E_\nu)$ is the number spectrum of neutrinos of flavor α emitted by a typical SN

Canonical parameterization of optically thin Supernova

$$R_{\rm SN}(z) = 0.0088\, M_\odot^{-1}\ \dot{\rho}_0 \left[(1+z)^{a\,\zeta} + \left(\frac{1+z}{B}\right)^{b\,\zeta} + \left(\frac{1+z}{C}\right)^{c\,\zeta}\right]^{1/\zeta}$$

A. M. Hopkins and J. F. Beacom, Astrophys. J. **651**, 142 (2006) [astro-ph/0601463]

S. Horiuchi, J. F. Beacom, C. S. Kochanek, J. L. Prieto, K. Z. Stanek and T. A. Thompson, Astrophys. J. **738**, 154 (2011)

M. D. Kistler, H. Yuksel and A. M. Hopkins, arXiv:1305.1630

Canonical parameterization of optically thin Supernova

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with $\dot{\rho}_0 = 0.02\, M_\odot\, \mathrm{yr}^{-1}\, \mathrm{Mpc}^{-3}$, $a = 3.4$, $b = -0.3$, $c = -2.5$, $\zeta = -10$, $B = (1+z_1)^{1-a/b}$ and $C = (1+z_1)^{(b-a)/c}\,(1+z_2)^{1-b/c}$ in which $z_1 = 1$ and $z_2 = 4$.

Neutrino spectrum from SN

$$F_\alpha^{\mathrm{SN}}(E_\nu) = \frac{(1+\beta_{\nu_\alpha})^{1+\beta_{\nu_\alpha}}\, L_{\nu_\alpha}}{\Gamma(1+\beta_{\nu_\alpha})\,\overline{E}_{\nu_\alpha}^2} \left(\frac{E_\nu}{\overline{E}_{\nu_\alpha}}\right)^{\beta_{\nu_\alpha}} e^{-(1+\beta_{\nu_\alpha})E_\nu/\overline{E}_{\nu_\alpha}}$$

	$\overline{E}_{\nu_e}$ [MeV]	$\overline{E}_{\bar{\nu}_e}$ [MeV]	$\overline{E}_{\nu_x}$ [MeV]	β_{ν_e}	$\beta_{\bar{\nu}_e}$	β_{ν_x}
Model A [19]	11.2	15.4	21.6	2.8	3.8	1.8
Model B [31, 32]	10	12	15	3	3	2.4

$$L_{\nu_e} = L_{\bar{\nu}_e} = L_{\nu_x} = 5.0 \times 10^{52} \text{ ergs.}$$

Adiabatic conversion

- Normal ordering

$$F^{\mathrm{SN}}_{\bar{\nu}_1}(E_\nu) = F^{\mathrm{SN}}_{\bar{\nu}_e}\ ; \quad F^{\mathrm{SN}}_{\bar{\nu}_2}(E_\nu) = F^{\mathrm{SN}}_{\nu_x}\ ; \quad F^{\mathrm{SN}}_{\bar{\nu}_3}(E_\nu) = F^{\mathrm{SN}}_{\nu_x}$$

$$F^{\mathrm{SN}}_{\nu_1}(E_\nu) = F^{\mathrm{SN}}_{\nu_x}\ ; \quad F^{\mathrm{SN}}_{\nu_2}(E_\nu) = F^{\mathrm{SN}}_{\nu_x}\ ; \quad F^{\mathrm{SN}}_{\nu_3}(E_\nu) = F^{\mathrm{SN}}_{\nu_e}$$

Dighe and Smirnov, PRD 62 (2000) 033007

Adiabatic conversion

- Inverted ordering

$$F^{\rm SN}_{\bar\nu_1}(E_\nu) = F^{\rm SN}_{\nu_x}\ ; \quad F^{\rm SN}_{\bar\nu_2}(E_\nu) = F^{\rm SN}_{\nu_x}\ ; \quad F^{\rm SN}_{\bar\nu_3}(E_\nu) = F^{\rm SN}_{\bar\nu_e}$$

$$F^{\rm SN}_{\nu_1}(E_\nu) = F^{\rm SN}_{\nu_x}\ ; \quad F^{\rm SN}_{\nu_2}(E_\nu) = F^{\rm SN}_{\nu_e}\ ; \quad F^{\rm SN}_{\nu_3}(E_\nu) = F^{\rm SN}_{\nu_x}$$

Dighe and Smirnov, PRD 62 (2000) 033007

Neutrino-neutrino collective

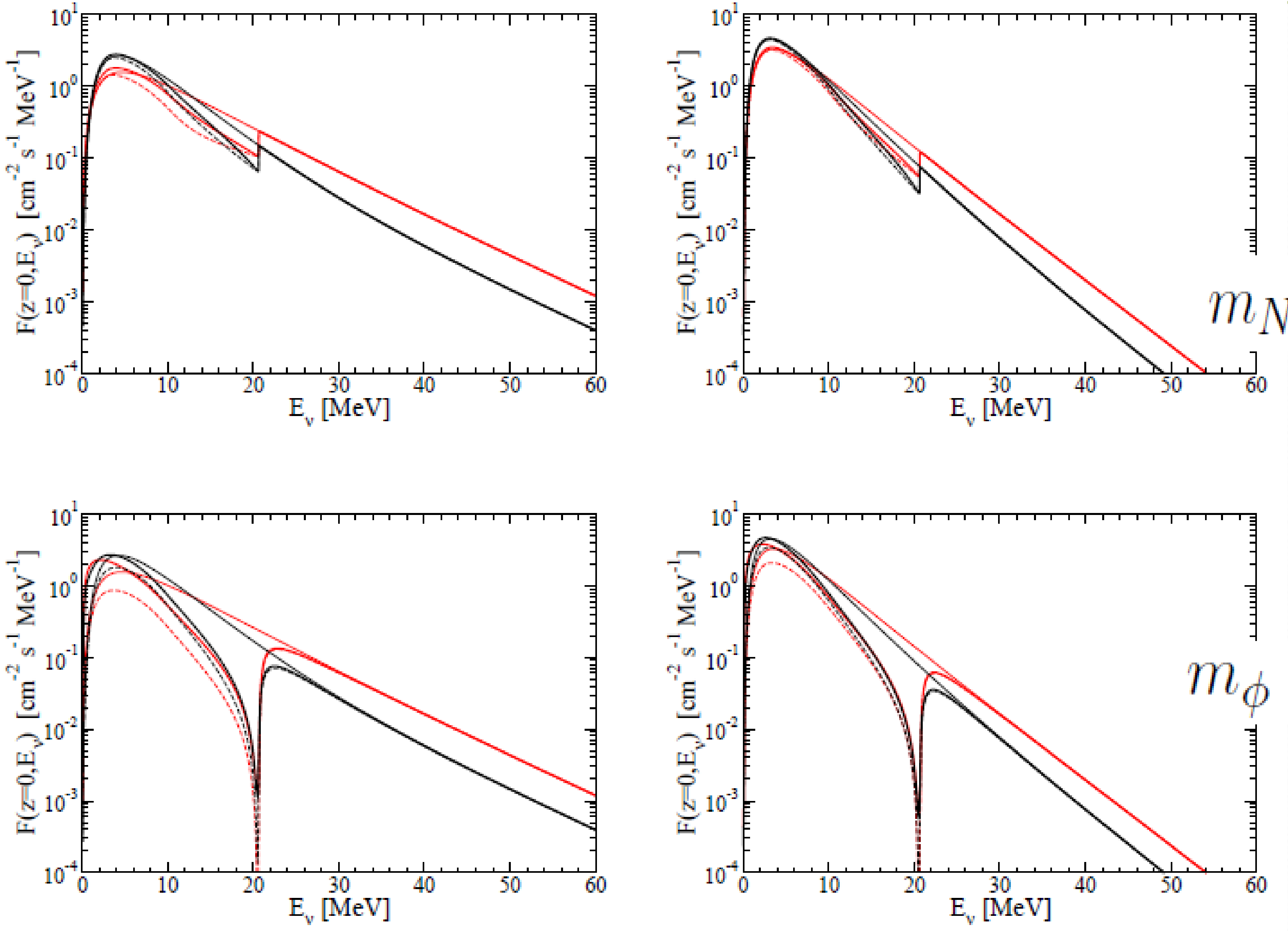
- Lunardini and Tamborra, JCAP 1207 (2012) 12
- Smearing over time and over the SN population
- Collective effects below 10% for DSNB

Detection

- Inverse beta decay events: $(\bar{\nu}_e + p \to e^+ + n)$

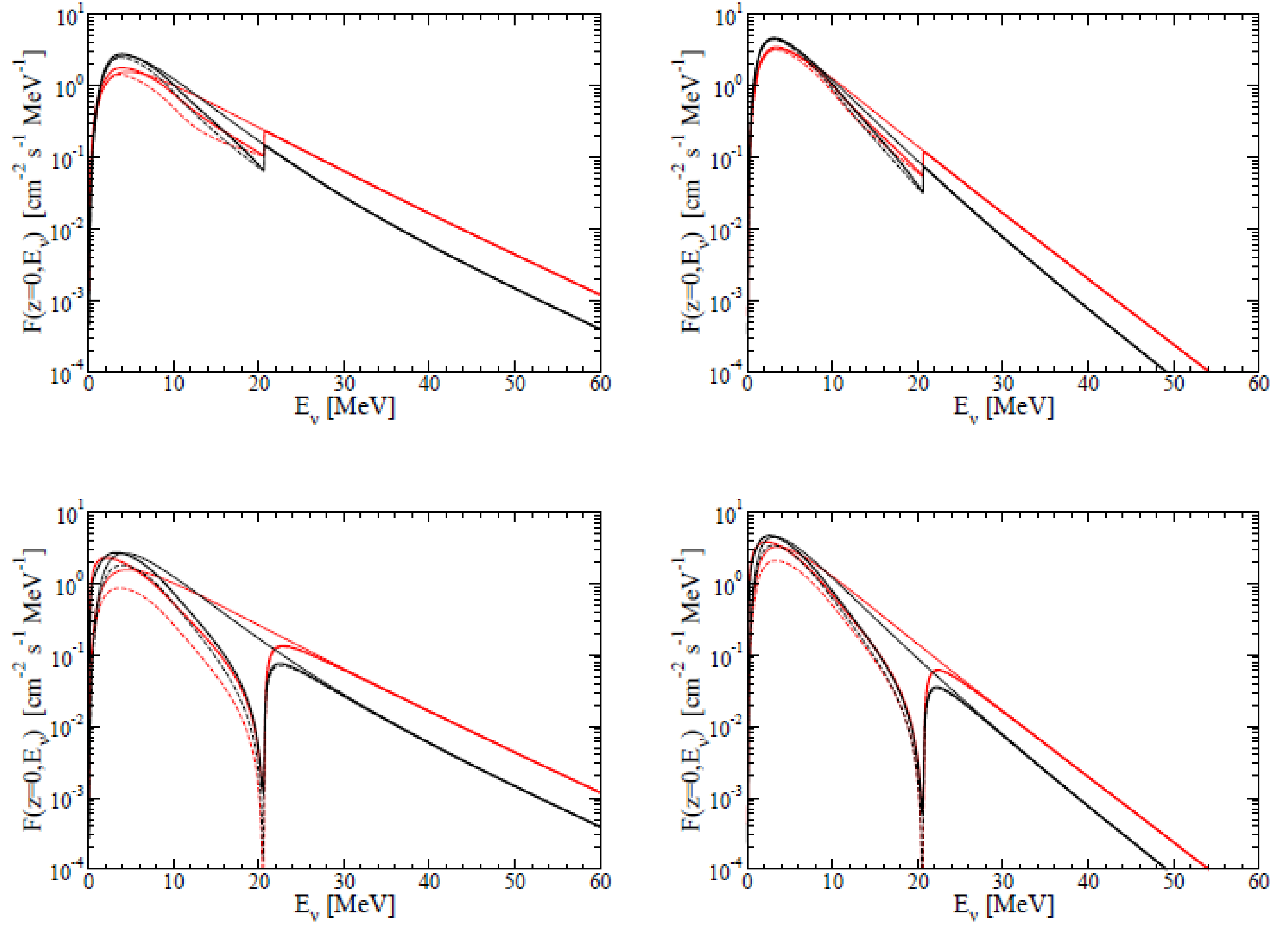
the interactions of ν_e and $\bar{\nu}_e$ off Oxygen nuclei.

- For IO, we shall have higher statistics for E>10 MeV



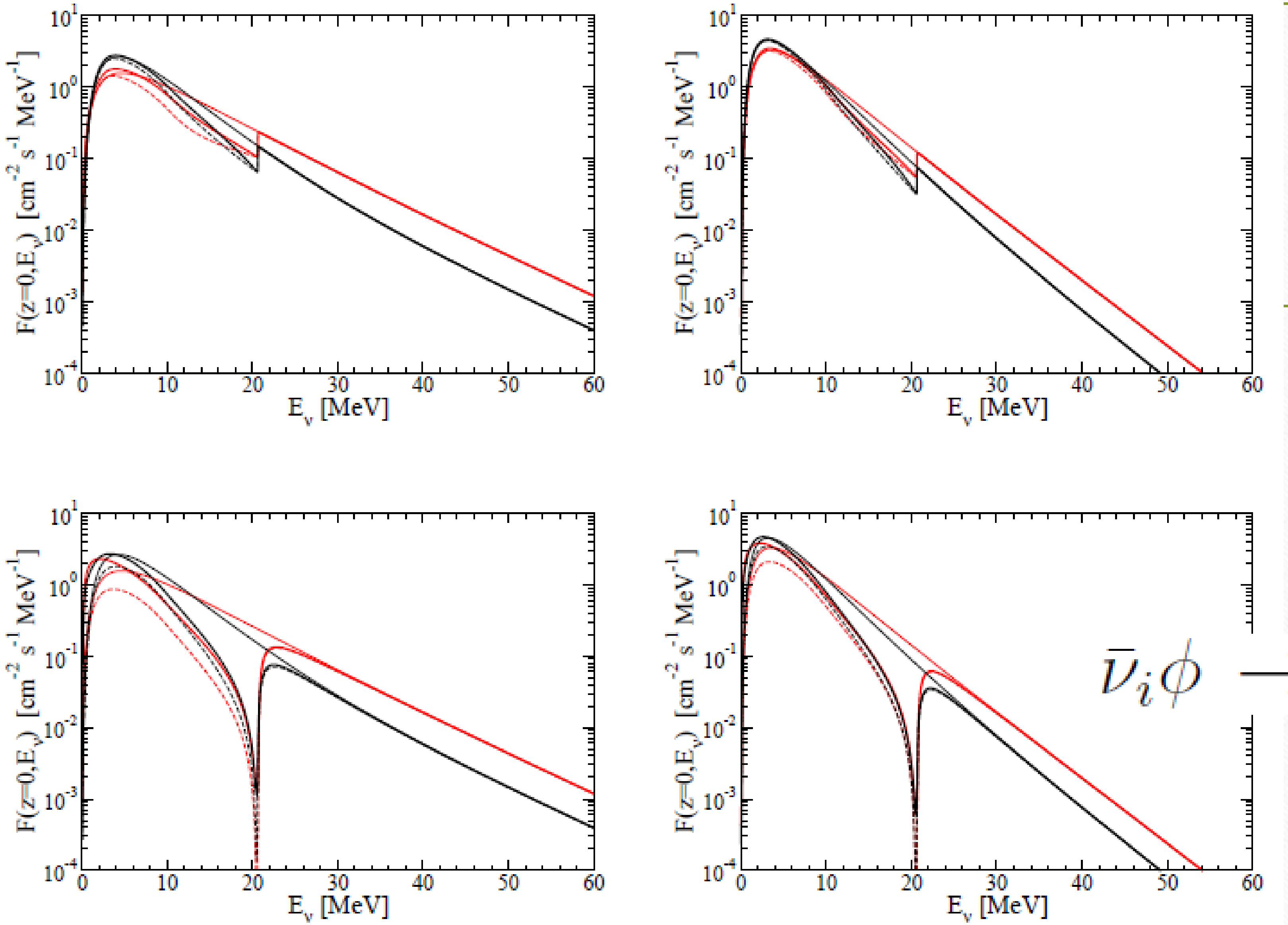
$$m_N = m_{\mathrm{r}} = 6.5\ MeV$$

$$m_\phi = m_{\mathrm{DM}} = 1\ MeV$$



$g_\tau = 0.1$

$g_\tau = 0.5$



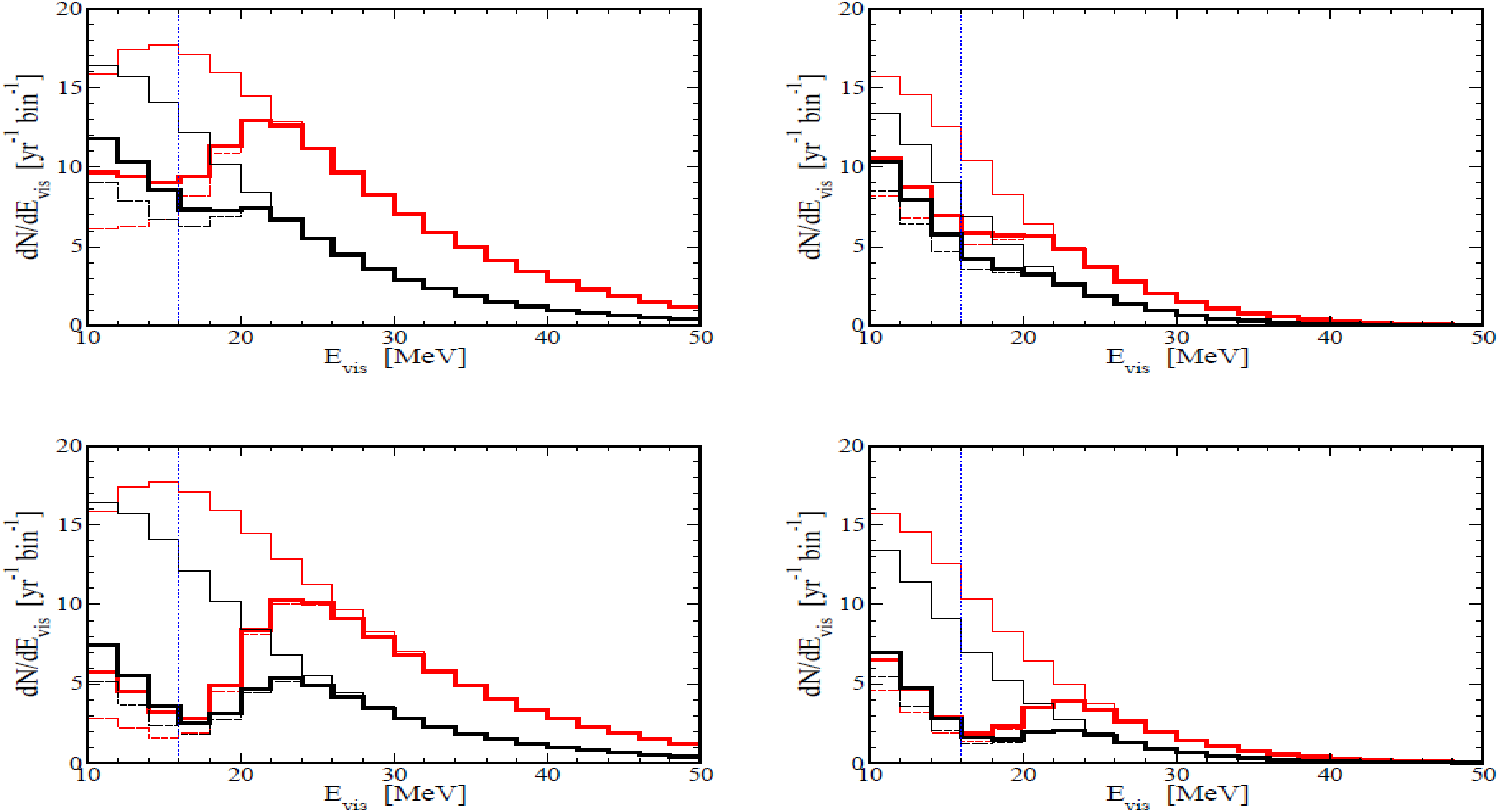
$$\bar{\nu}_i \phi \;\to\; N \;\to\; \bar{\nu}_s \phi$$

Number of events

- Hyper-Kamiokande
- 25 times SK

fiducial volume of 562.5 kton

- Detection efficiency of 90 % and energy resolution of 10 %



20
15
10
5
0
10
20
30
40
50
dN/dE$_{vis}$ [yr^{-1} bin^{-1}]
E$_{vis}$ [MeV]

What else?

- Let us suppose that dip is established.
- Can we make sure this mechanism is at work?
- Resonance scattering en route, but …..

What else?

- Let us suppose that dip is established.
- Can we make sure this mechanism is at work?
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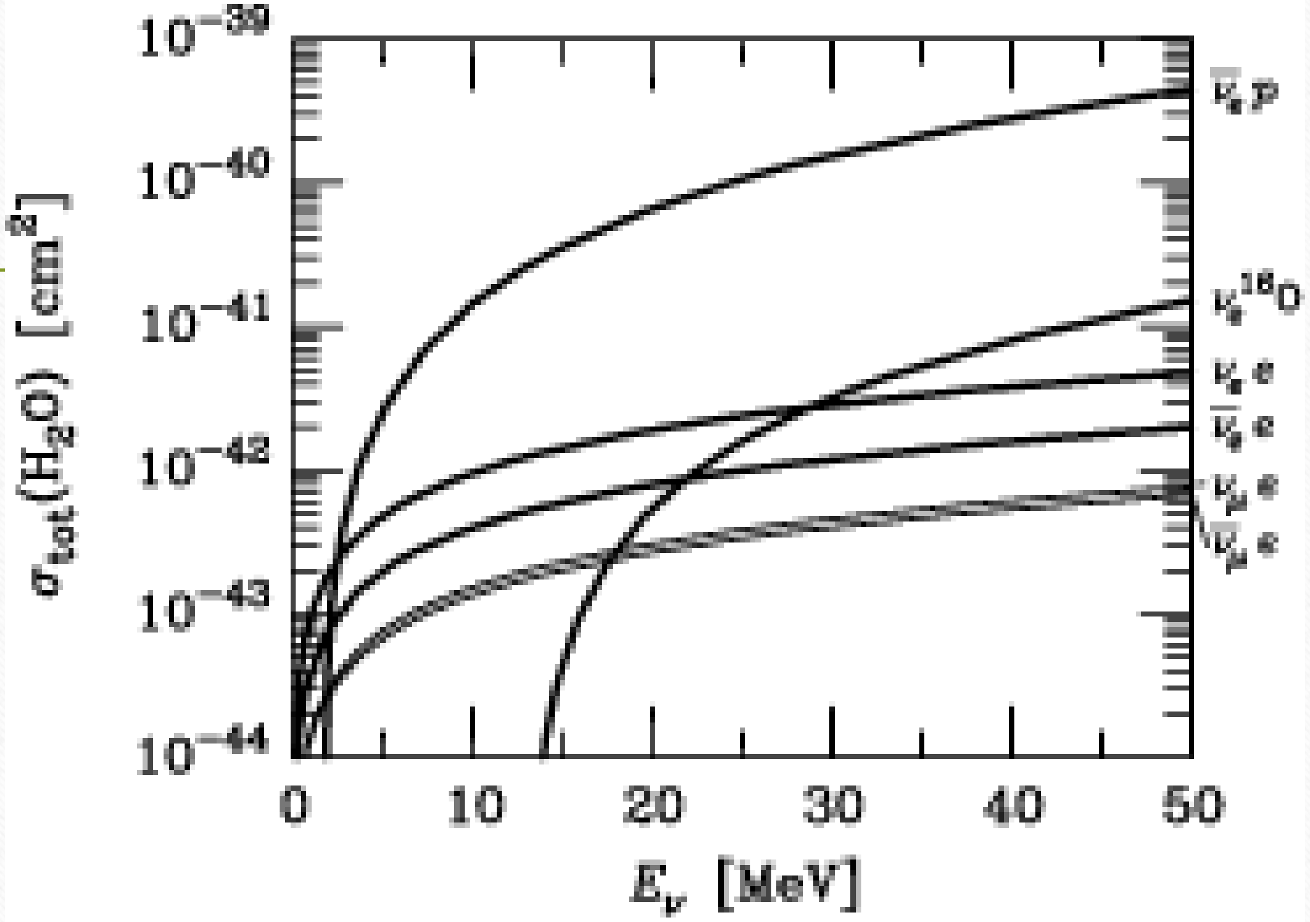
$$\nu + \nu \to Z'$$

relic neutrinos

Conclusion

- For $E_{\mathrm{r}} \sim 20\ \mathrm{MeV}$ and $g > 0.1$, distortion of DSNB spectrum is significant.
- For IH, the dip can be established by HK after a few years.
- For NH, dip might be mimicked by shifting average energies to lower values.

Backup



10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
$\sigma_{tot}(H_2O)$ [cm^2]
0
10
20
30
40
50
E_ν [MeV]
$\bar{\nu}_e p$
$\nu_e {}^{16}O$
$\nu_e e$
$\bar{\nu}_e e$
$\nu_\mu e$
$\bar{\nu}_\mu e$