# 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

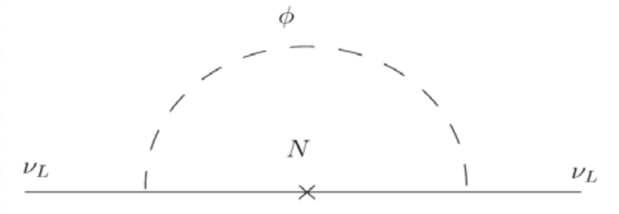
$$\mathcal{L}_I \supset g\phi\bar{N}\nu$$

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 $\Lambda$
- 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:

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

- $Z_2$ symmetry:

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

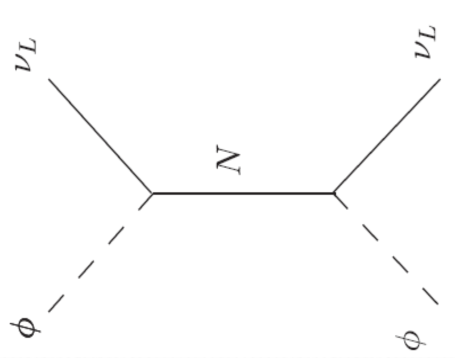
$$\bar{N}L \cdot H$$

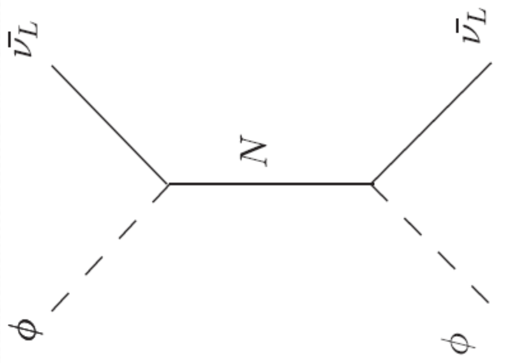
- SLIM is stable but the right handed neutrino decays:

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

# 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

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

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

$$\Lambda \sim \mathrm{E}_{\mathrm{electroweak}} \sim 200\ \mathrm{GeV}$$

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

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

# 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 $\phi$ 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 $\delta_1$ and $N_1$
- (similar to what we had in the SLIM scenario)
- Heavy sector: $\delta_2$ $\phi_2$ $\phi^-$ ⇩

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

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

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

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

# Freeze-out scenario

$Case\ m_N < m_\phi$ $\quad$ $Real\ \phi\ \ and\ \ Majorana\ \ N$

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

# 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* $\phi$ *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 $\phi$ and $\nu$ $\Gamma_{\rm scat} \sim g^4 T/4\pi.$

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:

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

$$\Downarrow$$

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

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

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- Connection to neutrino mass: An example

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- 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 $g_\alpha$.

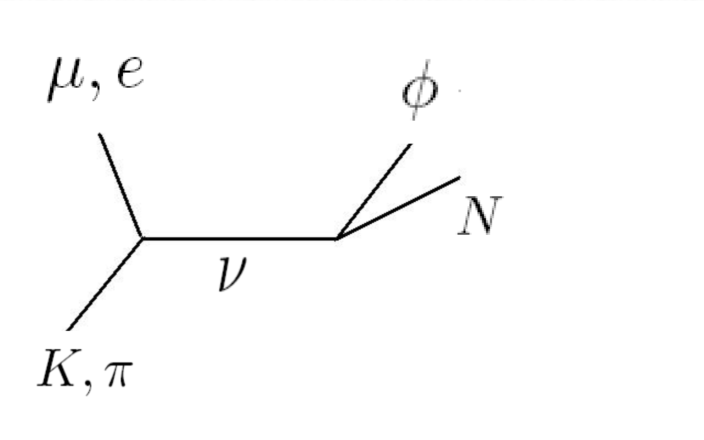
$$(m_\nu)_{\alpha\beta} \simeq \frac{g_\alpha g_\beta}{16\pi^2} (m_R)_{\alpha\beta} \log\left(\frac{\Lambda^2}{m^2_{\phi,N}}\right)$$

# 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 $g_\tau$ 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

$$(m_\nu)_{\alpha\beta} \simeq \frac{g_\alpha g_\beta}{4\pi}(m_R)_{\alpha\beta}\log(\frac{\Lambda^2}{m^2_{\phi,N}})$$

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

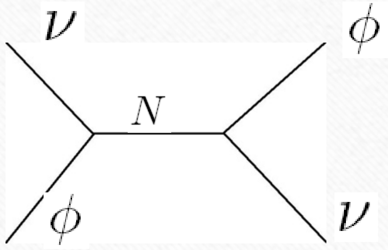
- Energy loss consideration: binding energy

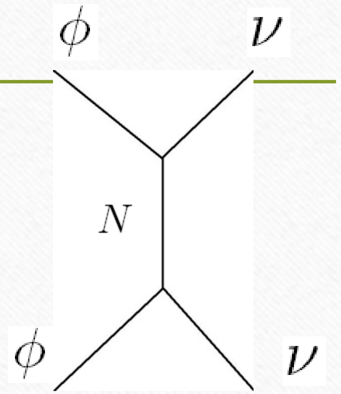
$E_b = (1.5 - 4.5) \times 10^{53}$ erg. Sato and Suzuki, PLB196 (87)

- 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.



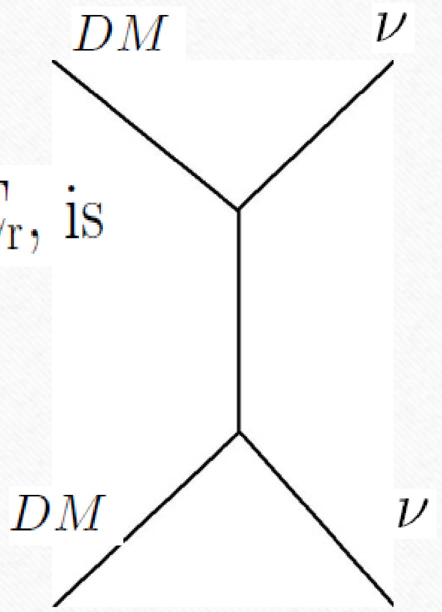

- In the outer core with T~30 MeV
- Mean free path: $(\sigma n_\nu)^{-1} = 10 \text{ cm}$
- The effect of SLIMs on cooling can be tolerated within present uncertainties of supernova models.

# Resonance scattering of SN neutrinos at propagation

$g N_R^\dagger \nu_L \phi$

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

$$E_r = \frac{m_r^2 - m_{DM}^2}{2\, m_{DM}} = E_0\,(1 + z_r)$$



# 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

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

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

# 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

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

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

# Narrow width approximation

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

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

# Optical depth

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

$$\tau_i(z_{\rm r}) = \sum_j \frac{g_i^2 g_j^2}{\sum_k g_k^2} \left(\frac{\pi}{m_{\rm r}^2 - m_{\rm DM}^2}\right) \left(\frac{m_{\rm r}^2}{m_{\rm r}^2 + m_{\rm DM}^2}\right) \left(\frac{n_0}{H_0}\right) \left(\frac{\Omega_{\rm DM}(z_{\rm r})}{\Omega_{\rm DM,0}}\right)$$

$$\simeq 5 \times 10^2\, g_i^2 \left(\frac{20\ {\rm MeV}}{E_{\rm r}}\right) \left(\frac{\rm MeV}{m_{\rm DM}}\right)^2 \left(\frac{E_{\rm r} + m_{\rm DM}/2}{E_{\rm r} + m_{\rm DM}}\right) \left(\frac{\Omega_{\rm DM}(z_{\rm r})}{\Omega_{\rm DM,0}}\right)$$

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

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

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

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

# 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 $\frac{E_r}{1+z} \pm \frac{\Gamma_r}{1+z}\frac{m_r}{2m_{DM}}$

# Resonant scattering at galaxy

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

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

# Flux

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

# Flux propagation

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

# 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

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

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

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

# Flux propagation

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

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

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

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

$F_\alpha^{\rm SN}(E_\nu)$ is the number spectrum of neutrinos of flavor $\alpha$ 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 $\dot\rho_0 = 0.02\, M_\odot\, {\rm yr}^{-1}\, {\rm Mpc}^{-3}$, $a = 3.4$, $b = -0.3$, $c = -2.5$, $\zeta = -10$, $B = (1+z_1)^{1-a/b}$ 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] | $\beta_{\nu_e}$ | $\beta_{\bar{\nu}_e}$ | $\beta_{\nu_x}$ |
|---|---|---|---|---|---|---|
| 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

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

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

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

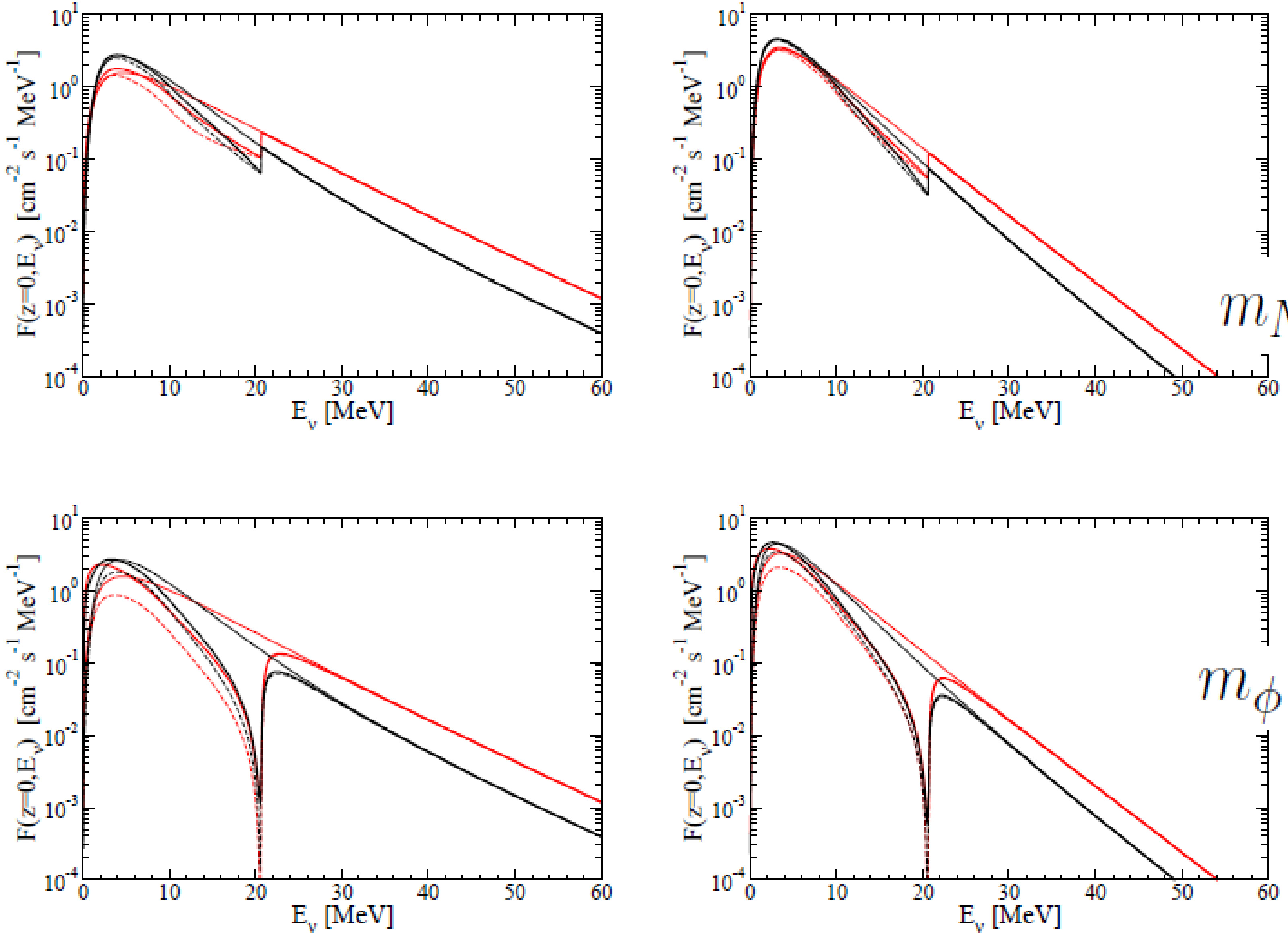
- Lunardini and Tamborra, JCAP 1207 (2012) 12
- Smearing over time and over the SN population
- Collective effects below 10% for DSNB

# Detection

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

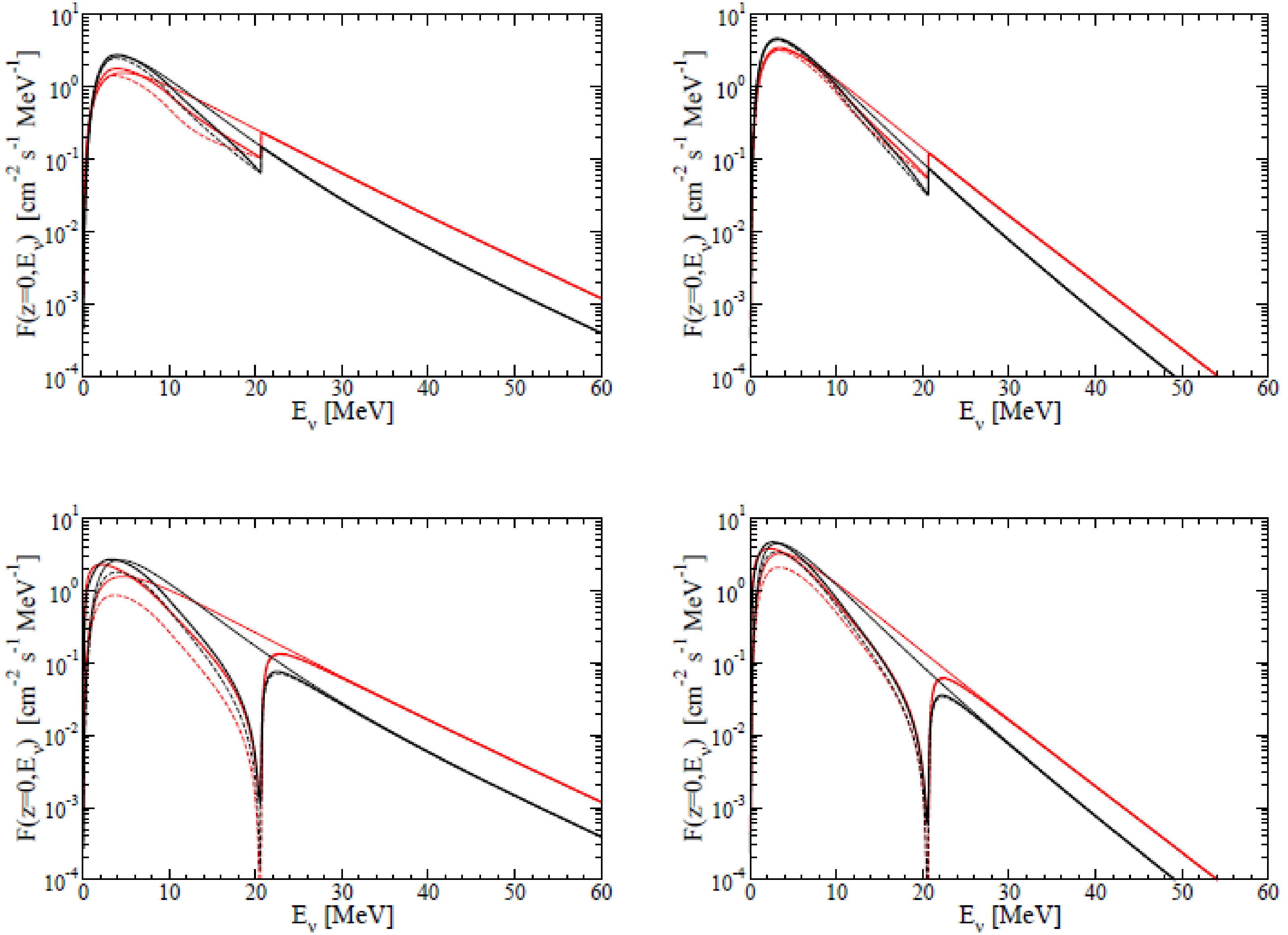
the interactions of $\nu_e$ and $\bar{\nu}_e$ off Oxygen nuclei.

- For IH, we shall have higher statistics foe E>10 MeV



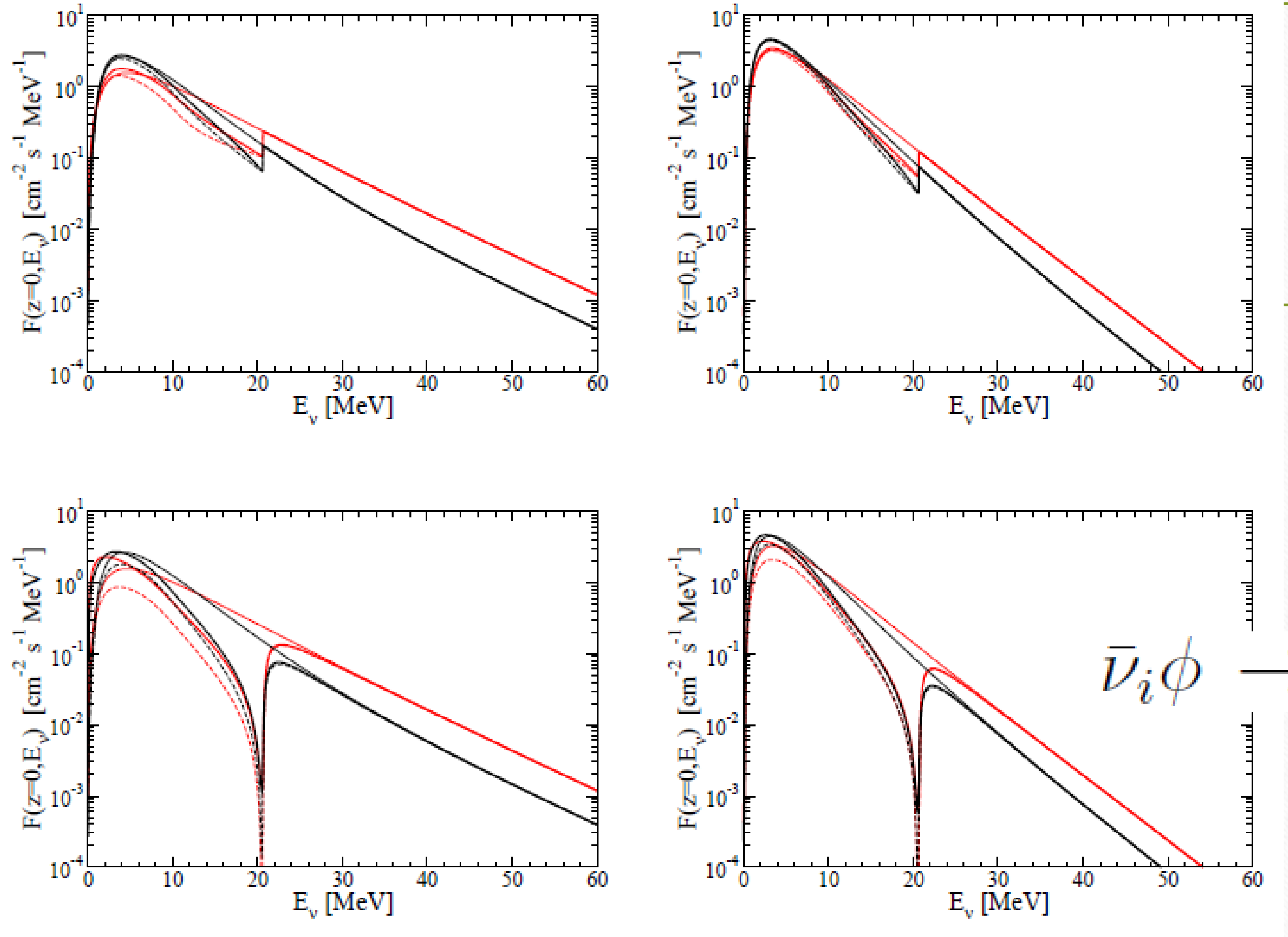

$$m_N = m_{\rm r} = 6.5\ MeV$$

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




$g_\tau = 0.1$

$g_\tau = 0.5$



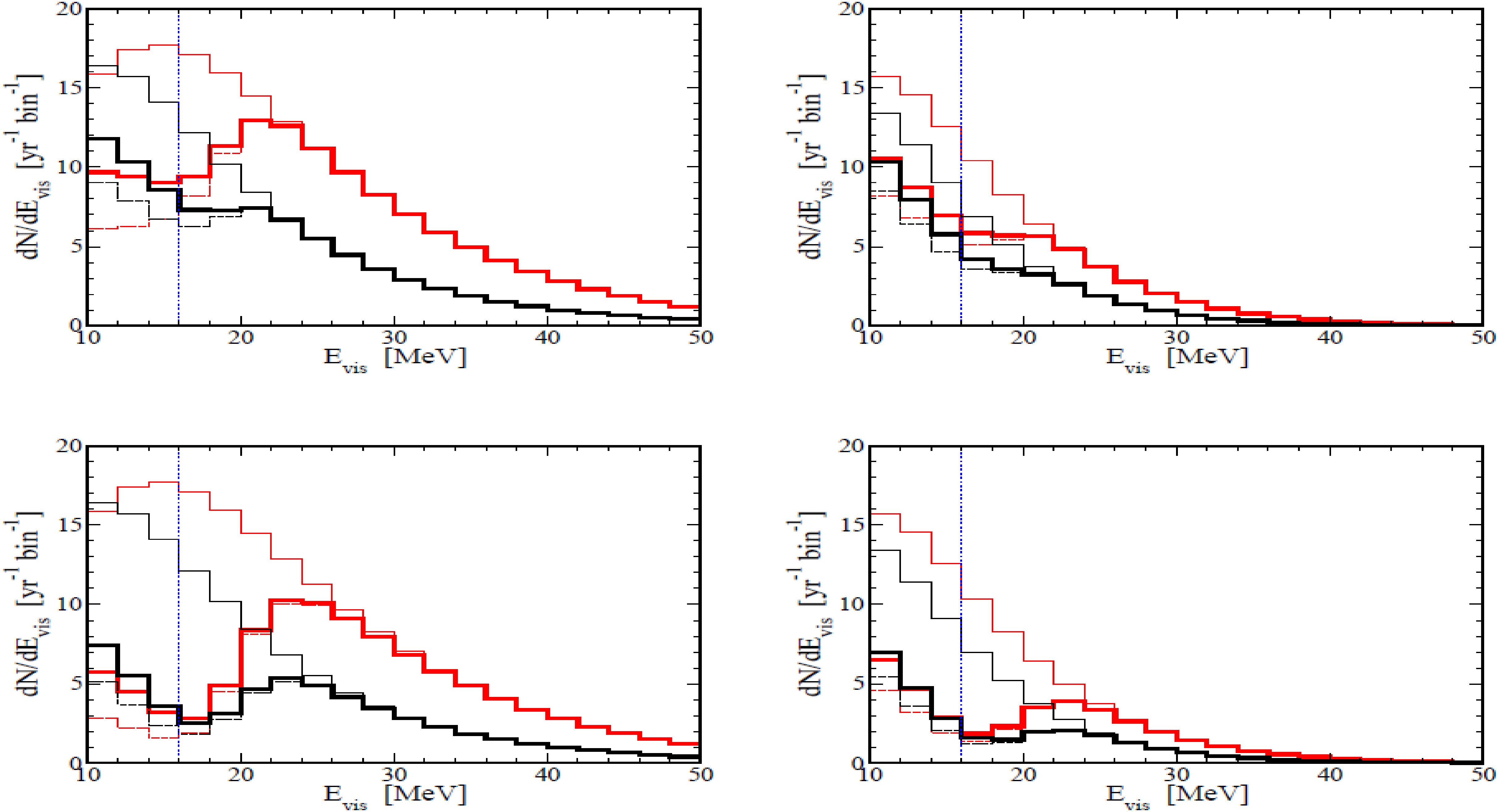

$$\bar{\nu}_i \phi \rightarrow N \rightarrow \bar{\nu}_s \phi$$

# Number of events

- Hyper-Kamiokande
- 25 times SK

fiducial volume of 562.5 kton

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



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 …..

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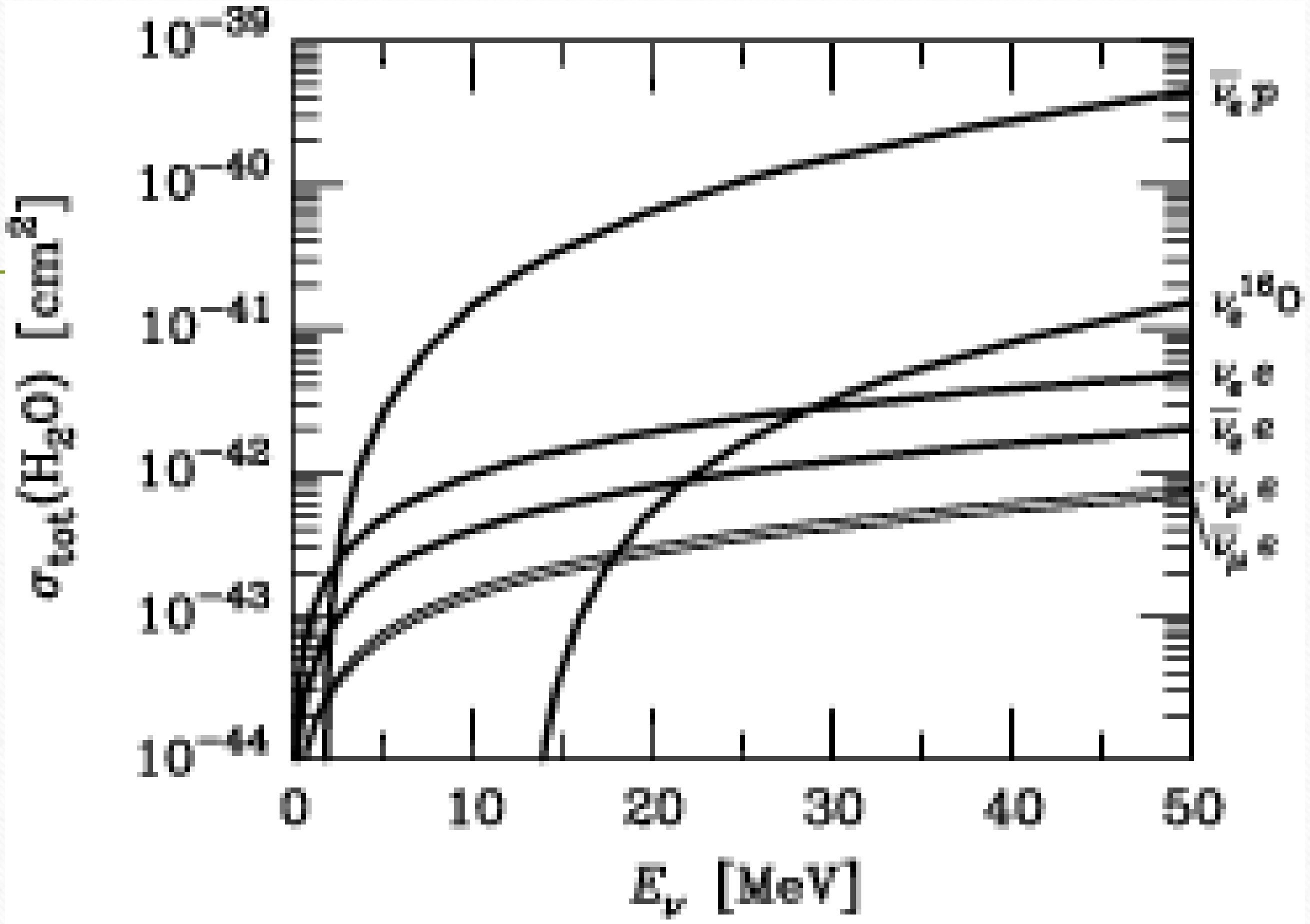
- Let us suppose that dip is established.
- Can we make sure this mechanism is at work?
- Resonance scattering en route, but …..   $\nu + \nu \to Z'$

relic neutrinos

# Conclusion

- For $E_{\rm r} \sim 20$ 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
$E_\nu$ [MeV]
$\bar{\nu}_e p$
$\nu_e {}^{16}O$
$\nu_e e$
$\bar{\nu}_e e$
$\nu_\mu e$
$\bar{\nu}_\mu e$