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Update on Supernova Neutrinos at ESSnuSB

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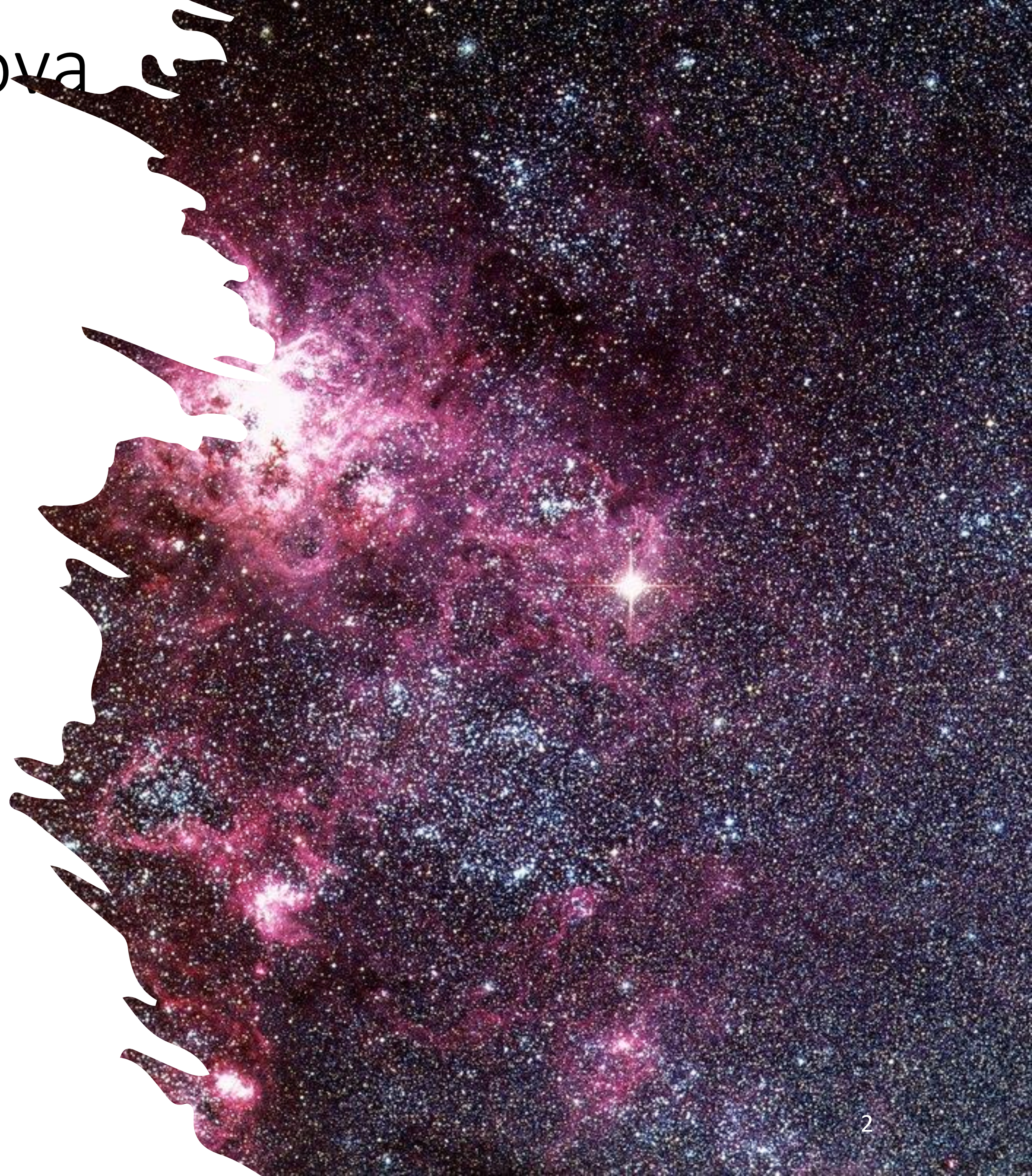
ESS neutrino Super Beam plus

Recap: Core Collapse Supernova

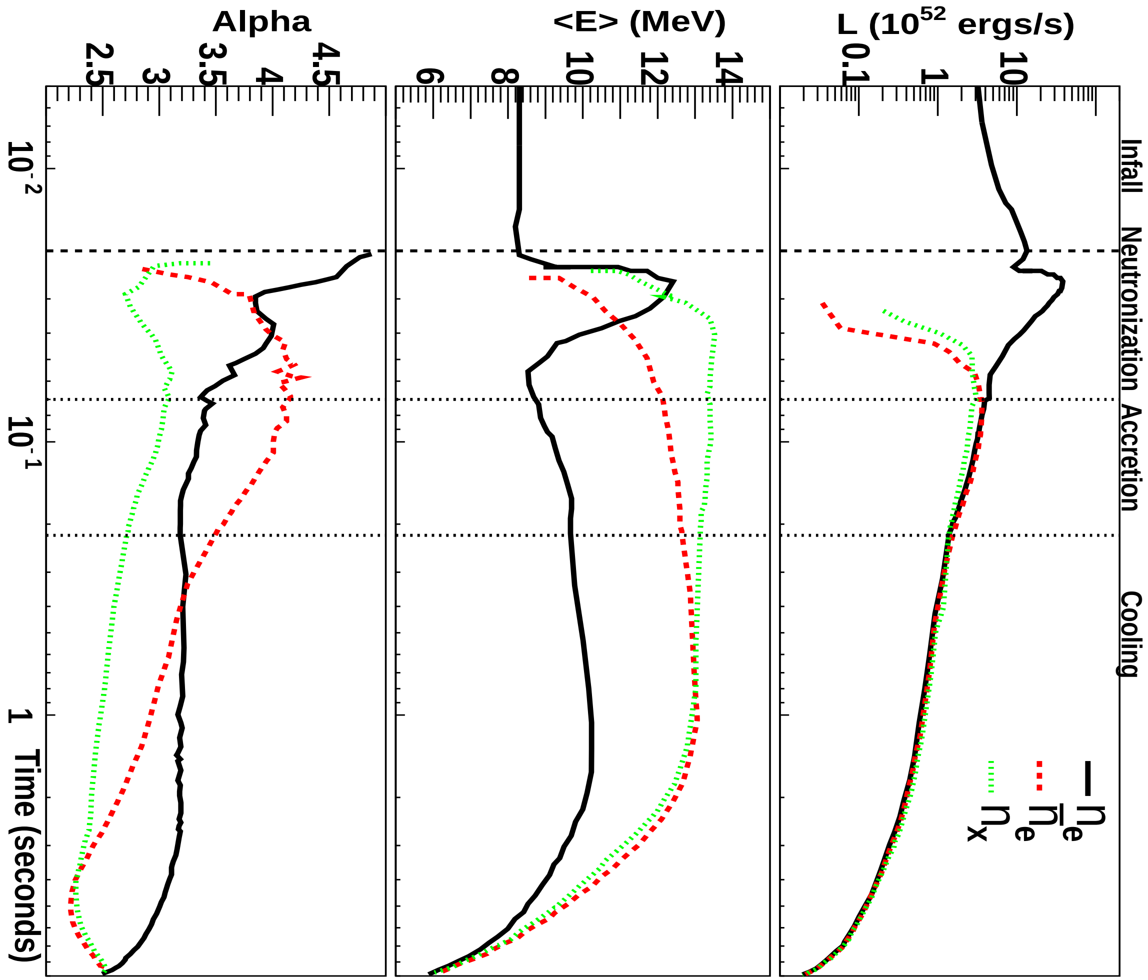
- When a star > 8 $M_{\odot}$ comes to the end of its life, often the core of the star collapses and it explodes with huge energy and luminosity.
- Neutrinos of different flavours are produced in the energy range around few tens of MeV
- Till now we are only able to detect neutrinos from SN1987A supernova occurred at a distance of 50 kpc from Earth
- Only 24 events are detected by:

  (i) water Cherenkov Kamiokande II,
  (ii) water Cherenkov Irvine-Michigan-Brookhaven (IMB)
  (iii) scintillator Baskan



Tarantula Nebula in the Large Magellanic Cloud. Supernova 1987A visible as the very bright star

Recap: Neutrino Flux



Primary neutrino spectra

$$\Phi_\nu(E)$$
$$= N \left(\frac{E_\nu}{\langle E_\nu \rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu \rangle}\right]$$

α = Pinching parameter

$$\mathrm{N} = \frac{(\alpha+1)^{\alpha+1}}{\langle E_\nu \rangle \Gamma(\alpha+1)}$$

$$F_\nu^0 = \frac{L_\nu}{\langle E_\nu \rangle} \Phi_\nu(E), \quad \mathrm{L} = \mathrm{Luminosity}$$

L and α are Model Dependent: Figure is for Garching Model

Many other models are available

Recap: Preliminary Study with ESSnuSB

Considered 3 supernova flux models and calculated events

Model 1: Livermore -> first ever supernova model with 1-D numerical simulation

Model 2: GKVM -> uses *S* matrix formalism as well as hydro dynamical density profiles

Model 3: Garching -> electron-capture model simulated in spherical symmetry framework

- Water Target: 538 kt
- Signal selection efficiency: 95%
- Gaussian energy resolution:

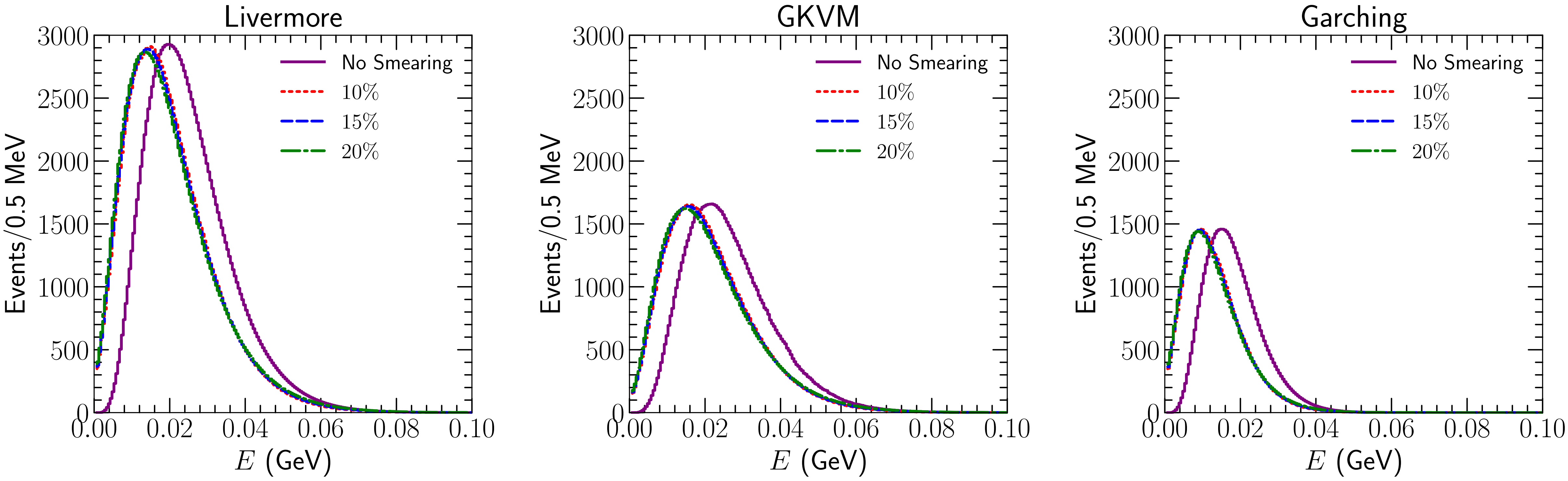
$$\frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(E-E')^2}{2\sigma^2}} \text{ with } \sigma = 0.10, 0.15, 0.20$$

T Astrophys. J. 496 (1998), 216-225, Phys. Rev. Lett. 103 (2009), 071101, , Phys. Rev. Lett. 104, 251101 (2010)

Recap: Results

Livermore	GKVM	Garching
148,686	88,528.8	51,068.7

$\boxed{\bar{\nu}_e + p \rightarrow n + e^+}$

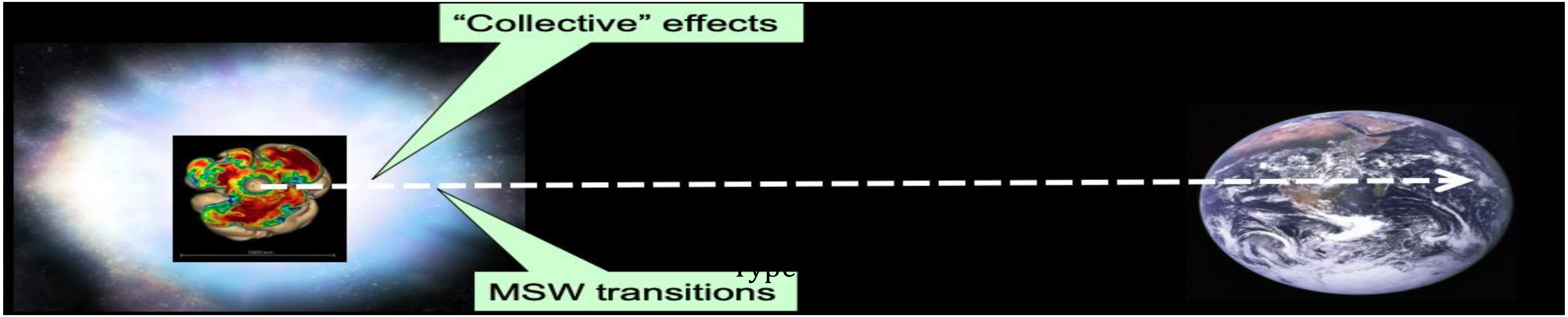


Calculated for 10 kpc

This talk

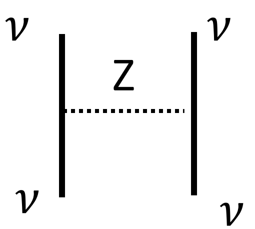
- Take Garching flux model – The one considered in DUNE analysis
- Consider ESSnuSB with 15% Gaussian energy resolution
- Include the effect of Oscillation
- Consider both standard and 3+1 scenario

Flavour Oscillations Inside Supernova

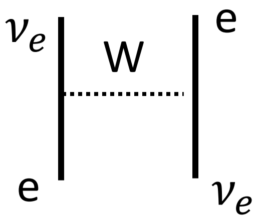


$$H = H_{vac} + H_{coll} + H_{MSW}$$

New Effect



Collective Effects: $\nu - \nu$ neutral current forward scattering



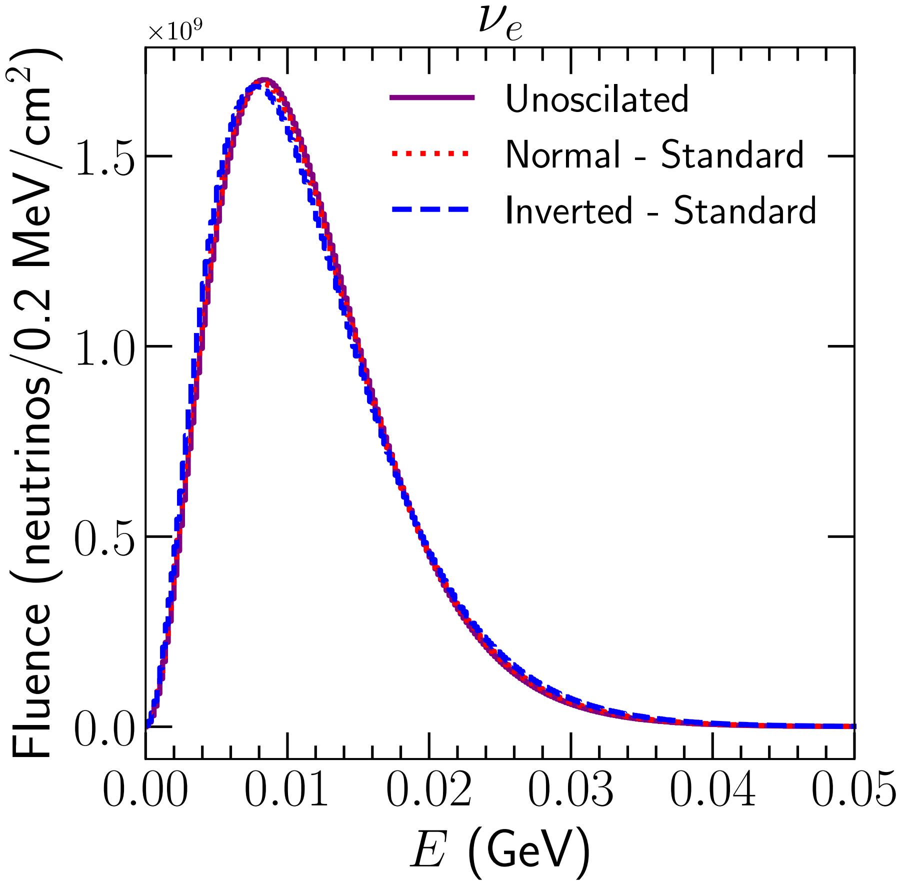
MSW Transitions: $\nu -$ e charged current forward exchange scattering

3 flavour MSW Transition

$$F_{\nu_e} = pF^0_{\nu_e} + (1-p)F^0_{\nu_x} \ ,$$
$$F_{\bar{\nu}_e} = \bar{p}F^0_{\bar{\nu}_e} + (1-\bar{p})F^0_{\nu_x} \ ,$$
$$2F_{\nu_x} = (1-p)F^0_{\nu_e} + (1+p)F^0_{\nu_x} \ ,$$
$$2F_{\bar{\nu}_x} = (1-\bar{p})F^0_{\bar{\nu}_e} + (1+\bar{p})F^0_{\bar{\nu}_x} \ ,$$

Ordering	p	$\bar{p}$
Normal	$sin^2\theta_{13}$	$cos^2\theta_{12}cos^2\theta_{13}$
Inverted	$sin^2\theta_{12}cos^2\theta_{13}$	$sin^2\theta_{13}$

F = Flux after MSW transition,
F^0 = Initial flux
p = Survival probability due to MSW transition



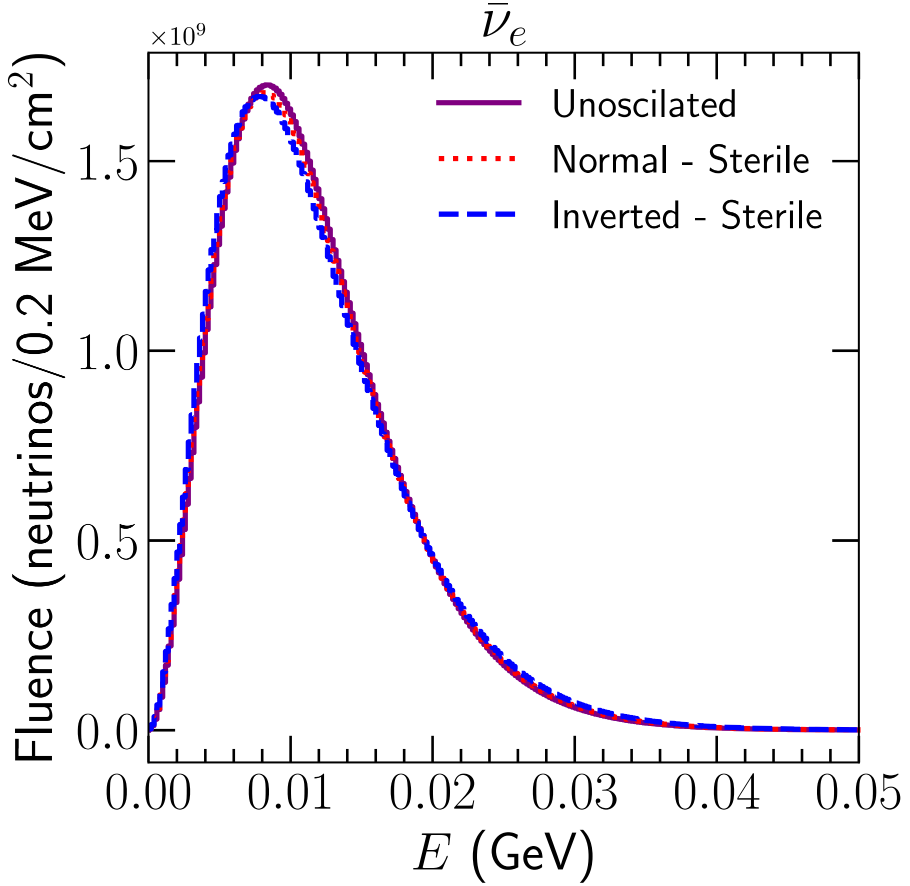
3+1 MSW Transition

Hierarchy	$a_{\alpha e}$	$a_{\alpha x}$	$b_{\alpha e}$	$b_{\alpha x}$
Normal	$\lvert U_{\alpha 4}\rvert^2$	$\lvert U_{\alpha 1}\rvert^2 + \lvert U_{\alpha 2}\rvert^2$	$\lvert U_{\alpha 1}\rvert^2$	$\lvert U_{\alpha 2}\rvert^2 + \lvert U_{\alpha 3}\rvert^2$
Inverted	$\lvert U_{\alpha 4}\rvert^2$	$\lvert U_{\alpha 1}\rvert^2 + \lvert U_{\alpha 3}\rvert^2$	$\lvert U_{\alpha 3}\rvert^2$	$\lvert U_{\alpha 1}\rvert^2 + \lvert U_{\alpha 2}\rvert^2$

$$
\begin{aligned}
F_{\nu_e} &= a_{ee}F^0_{\nu_e} + a_{ex}F^0_{\nu_x} + a_{es}F^0_{\nu_s}, \\
F_{\bar\nu_e} &= b_{ee}F_{\bar\nu^0_e} + b_{ex}F_{\bar\nu^0_x} + b_{es}F^0_{\bar\nu_s}, \\
2F_{\nu_x} &= (a_{\mu e} + a_{\tau e})F^0_{\nu_e} + (a_{\mu x} + a_{\tau x})F^0_{\nu_x} + (a_{\mu s} + a_{\tau s})F^0_{\nu_s}, \\
2F_{\bar\nu_x} &= (b_{\mu e} + b_{\tau e})F^0_{\bar\nu_e} + (b_{\mu x} + b_{\tau x})F^0_{\bar\nu_x} + (b_{\mu s} + b_{\tau s})F^0_{\bar\nu_s}, \\
F_{\nu_s} &= a_{se}F^0_{\nu_e} + a_{sx}F^0_{\nu_x} + a_{ss}F^0_{\nu_s}, \\
F_{\bar\nu_s} &= b_{se}F^0_{\bar\nu_e} + b_{sx}F^0_{\bar\nu_x} + b_{ss}F^0_{\bar\nu_s},
\end{aligned}
$$

$U = R_{14}\, R_{23}\, R_{13}\, R_{12}$

$$
U_{\alpha i} = \begin{pmatrix}
c_{12}c_{13}c_{14} & s_{12}c_{13}c_{14} & s_{13}c_{14} & s_{14} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} & 0 \\
s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} & 0 \\
-c_{12}c_{13}s_{14} & -s_{12}c_{13}s_{14} & -s_{13}s_{14} & c_{14}
\end{pmatrix}
$$



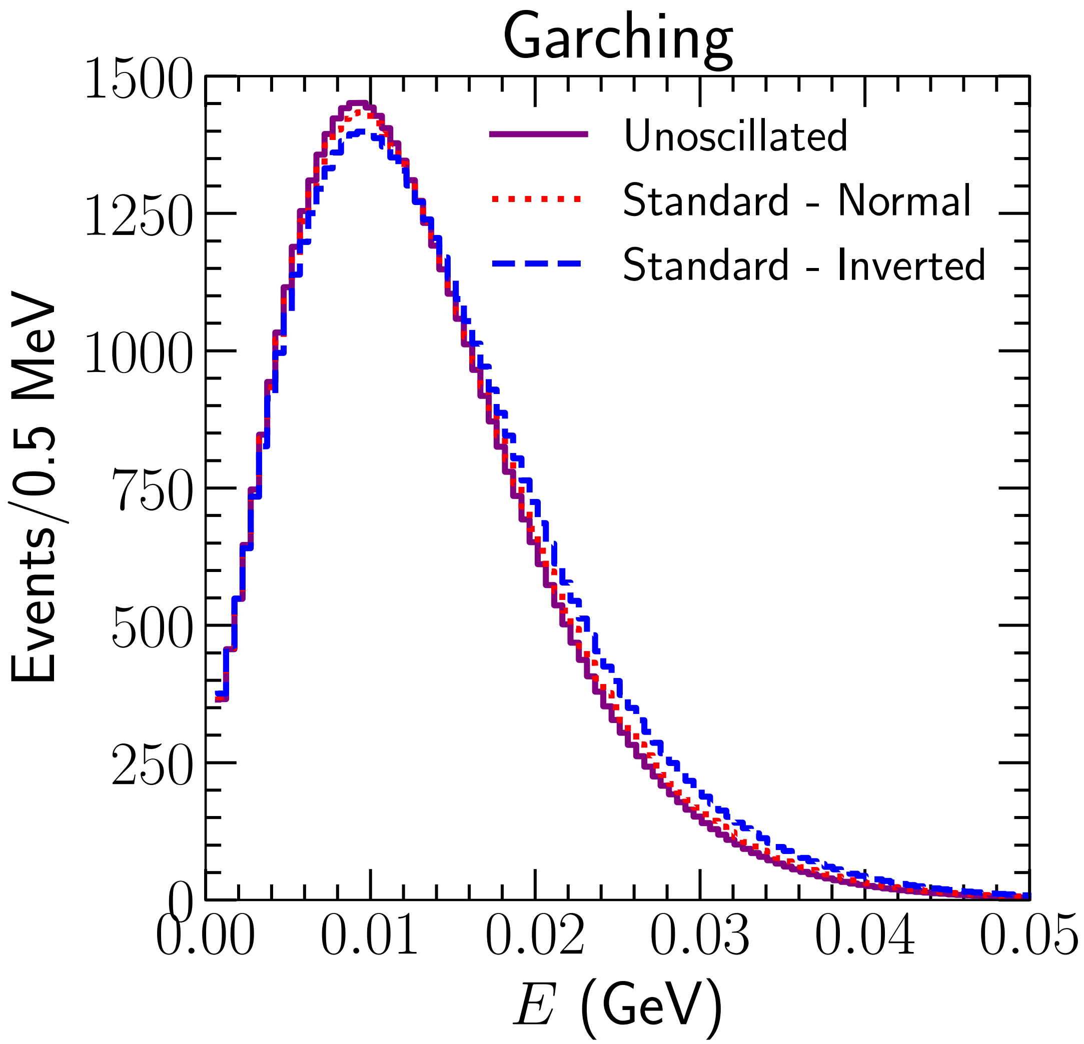
M. M. Saez, M. E. Mosquera and O. Civitarese, Int. J. Mod. Phys. E 31 (2022), 2250023, 2109.06244

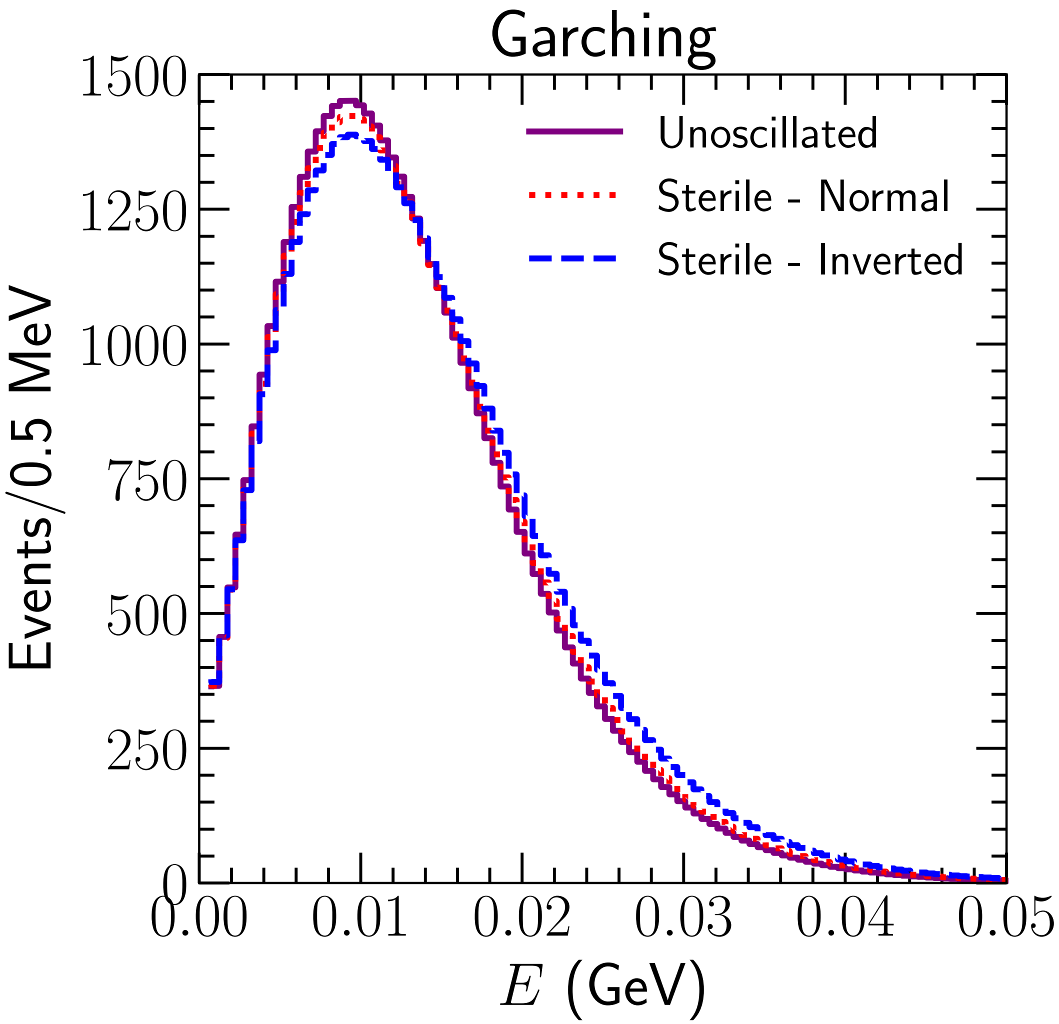
Collective effects

- Active area of research
- Its effect on neutrino flavour conversion is yet to be understood
- It was showed that modifications of the spectrum would get smeared out if time-integrated spectrum is taken
- Corrections are expected to be small

Recent studies (including analysis of T2HK and DUNE) does not consider collective effects

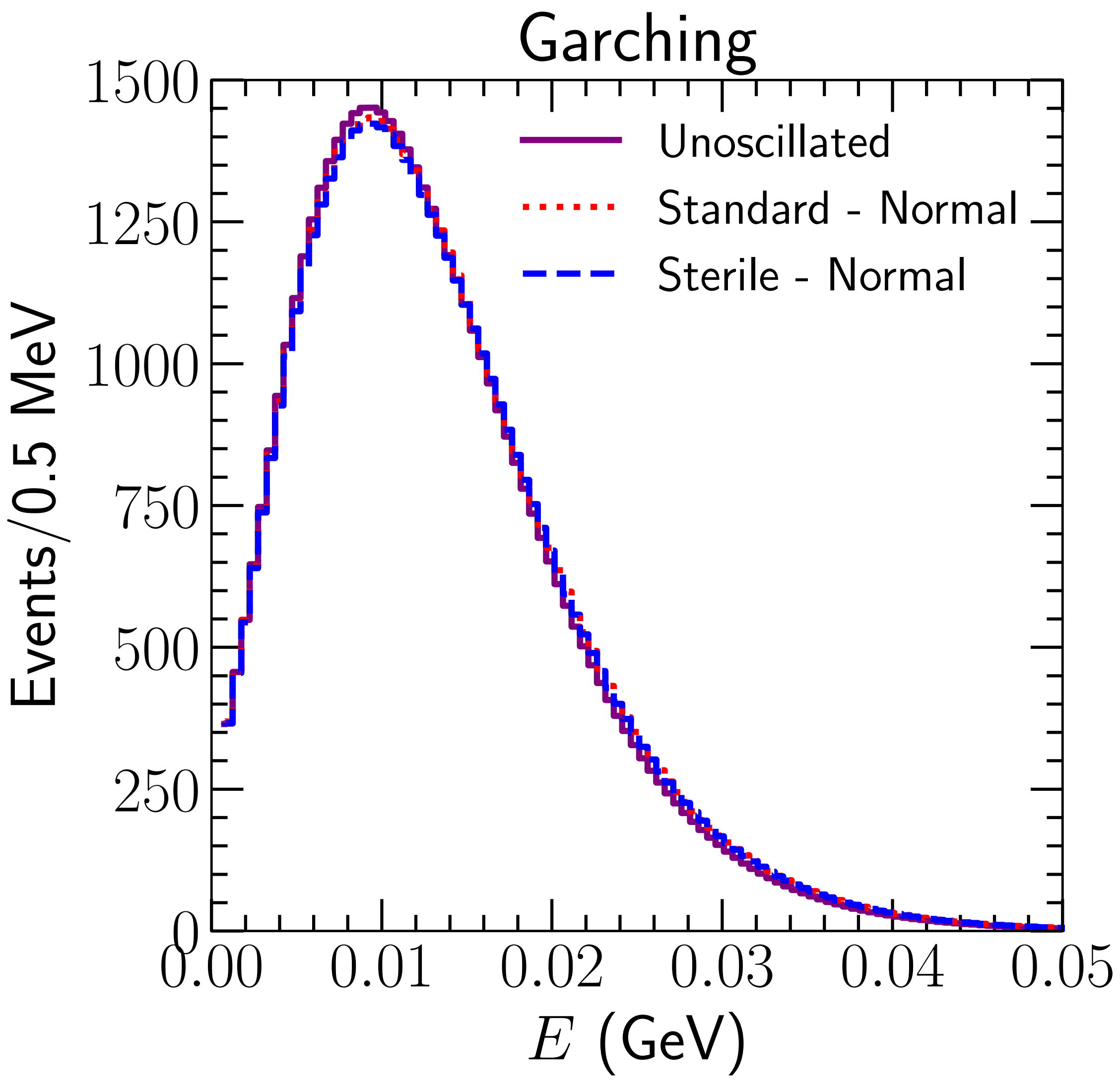
Results

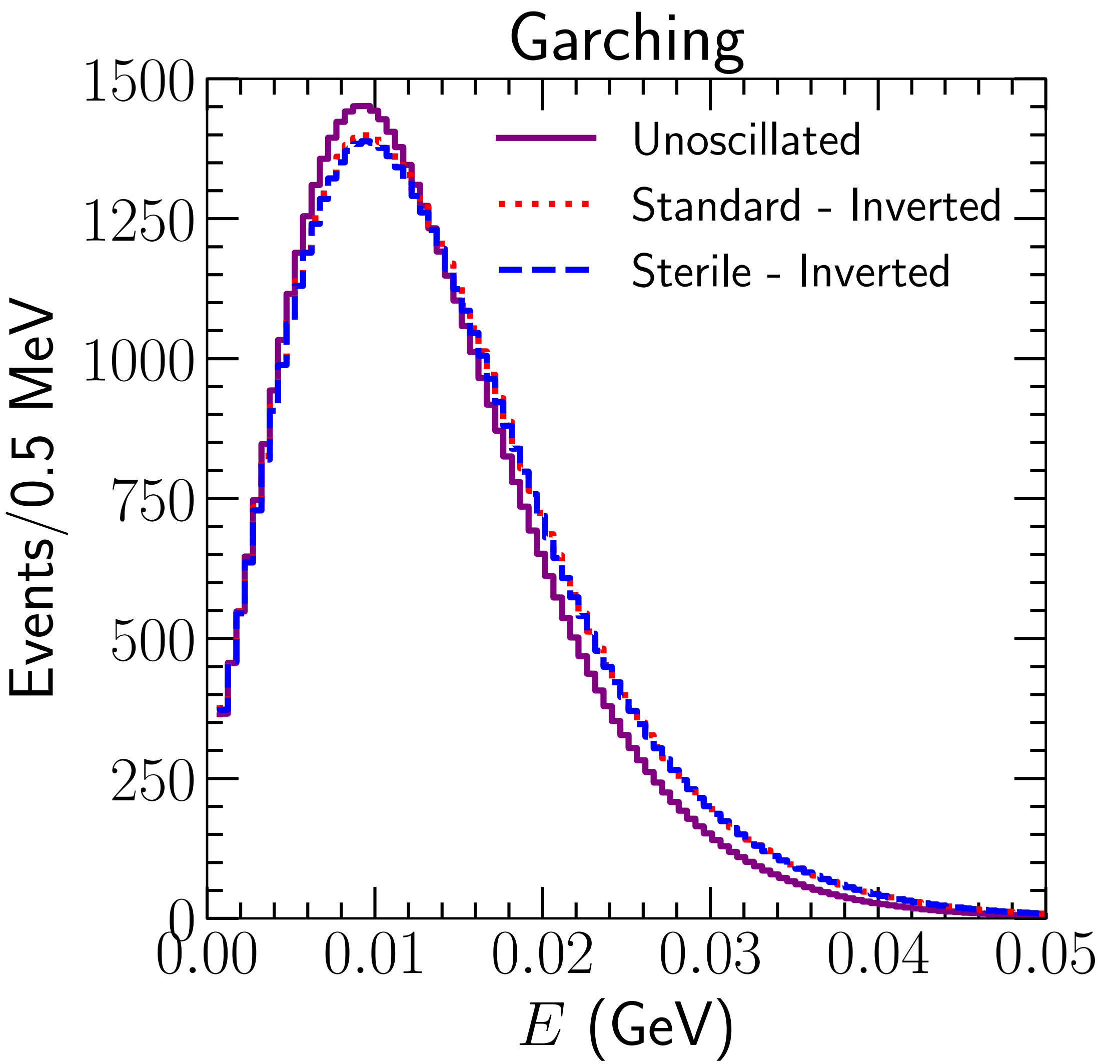




True ordering can be measured for both 3 and 3+1

Results





Difficult to disntinguish between 3 and 3+1

Futur Plans

- Better understand oscillation of supernova neutrinos
- Perform statistical analysis in terms of χ^2
- Look for physics problems which can be studied
- Estimate realitic efficincies and resolution (??)