Alexander von Humboldt Stiftung/Foundation

MAX-PLANCK-GESELLSCHAFT

Diffuse Supernova Neutrinos

Irene Tamborra

von Humboldt Research Fellow at the MPI for Physics, Munich

INT 12-2a, Nuclear and Neutrino Physics in Stellar Core Collapse
University of Washington, Seattle
July 6, 2012

Outline

- ★ Cosmological supernova rate
- ★ Neutrino oscillations in supernovae
- ★ Reference neutrino signal
- ★ Diffuse supernova neutrino background (DSNB)
- ★ Conclusions

This talk is based on work in collaboration with Cecilia Lunardini, JCAP 07 (2012) 012.

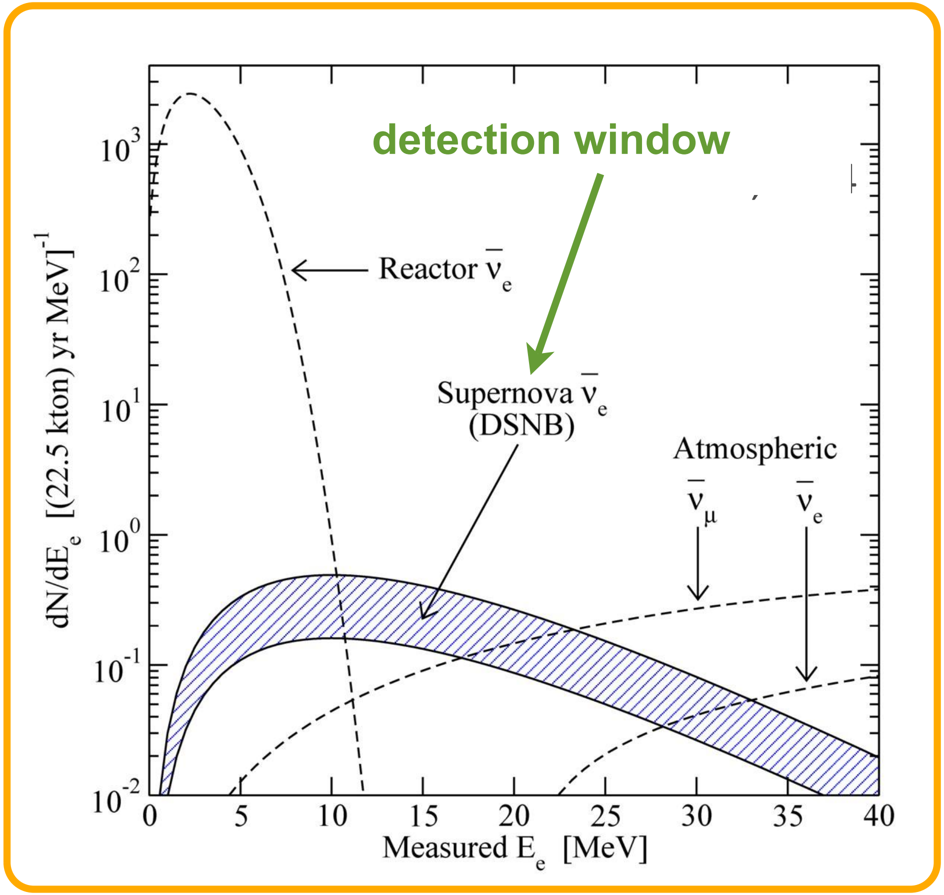
Why the DSNB?

Galactic supernova maybe rare but supernova explosions are quite common.
On average there is one supernova explosion every second somewhere in the universe and these produce a diffuse supernova neutrino background (DSNB).

★ Detectable $\bar{\nu}_e$ flux at the Earth mostly from redshift z ~ 1

★ Test of supernova astrophysics

★ New frontiers for neutrino astronomy



* Beacom and Vagins, arXiv: hep-ph/0309300

DSNB Detection Perspectives

The DSNB has not been observed yet, the most stringent limit is from Super-Kamiokande (SK):

$$\phi_{\bar{\nu}_e} \leq 2.8 - 3.0 \text{ cm}^{-2}\text{s}^{-1}$$

computed for energies above 17.3 MeV.

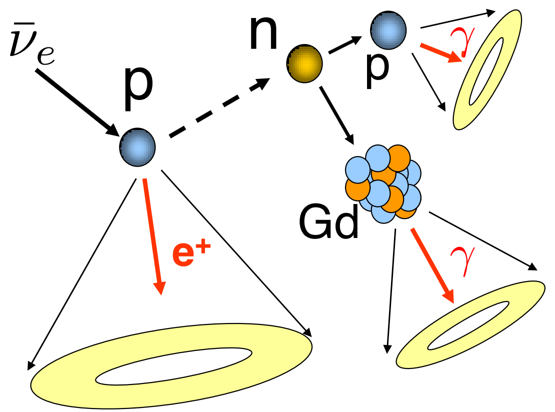
Concept	energy window (MeV)	detection processes	experiment (location)	fiducial mass (kt)	events per year
H_2O	19.3 - 30 $[17.3 - 30]$	$\bar{\nu}_\mathbf{e}\ (\mathbf{p},\mathbf{n})\mathbf{e}^+$ $\nu_e\ (^{16}O, X)e^-$ $\bar{\nu}_e\ (^{16}O, X)e^+$ $\nu_w(e^-, e^-)\nu_w$ $\nu_w(p,p)\nu_w$ $\nu_w(^{16}O, X)\nu_w$	SK (Japan)	22.5	0.25 - 1.40
			DUSEL WC (USA)	300	3.3 - 18.7
			MEMPHYS (Europe)	440	4.9 - 27.5
			Hyper-K (Japan)	500	5.5 - 31.2
			Deep-TITAND (Japan)	$5\ 10^3$	55 - 312
$H_2O + Gd$	11.3 - 30	same as H_2O	GADZOOKS (Japan)	22.5	0.97 - 2.8
			DUSEL WC+Gd	300	12.9 - 37.2
			MEMPHYS+Gd	440	18.9 - 54.6
			Hyper-K+Gd	500	21.5 - 62.0
Scintillator	$\sim 8 - 30$	$\bar{\nu}_\mathbf{e}\ (\mathbf{p},\mathbf{n})\mathbf{e}^+$ $\nu_e\ (^{12}C, X)e^-$ $\bar{\nu}_e\ (^{12}C, X)e^+$ $\nu_w(e^-, e^-)\nu_w$ $\nu_w(p,p)\nu_w$ $\nu_w(^{12}C, X)\nu_w$	LENA (Europe)	50	1.9 - 5.4
			Hano Hano (USA)	10	0.3 - 1.1
Argon	$\sim 18 - 30$	$\nu_\mathbf{e}\ (^{40}\mathbf{Ar},\mathbf{X})\mathbf{e}^-$ $\bar{\nu}_e\ (^{40}Ar, X)e^+$ $\nu_w(e^-, e^-)\nu_w$ $\nu_w(^{40}Ar, X)\nu_w$	LANNDD (USA)	< 100	< 3.3
			GLACIER (Europe)	100	0.9 - 3.3

For details see: C. Lunardini, arXiv: 1007.3252.

DSNB Detection

Neutron tagging in Gd-enriched WC detector (Super-K with 100 tons Gd to trap neutrons)

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

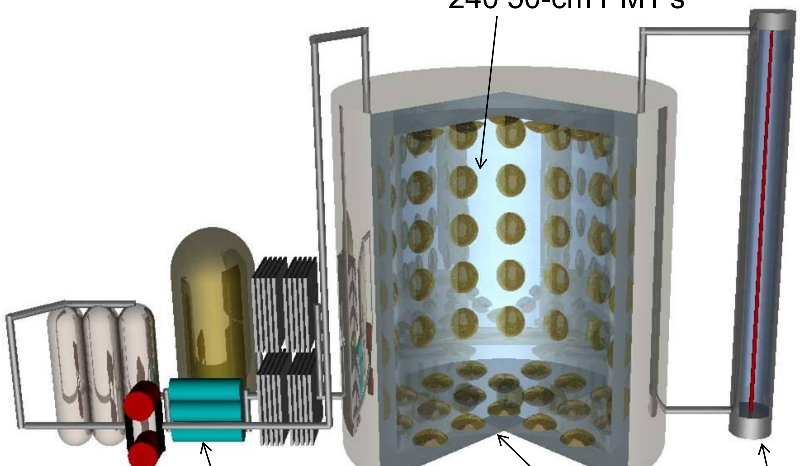


Positron and gamma ray vertices are within ~50cm.

$\bar{\nu}_e$ can be identified by delayed coincidence

spatial and temporal separation between prompt positron Cherenkov light and delayed Gd neutron capture gamma cascade

few clean events/yr in Super-K with Gd



*See talks by Vagins at Hanse 2011 and by Beacom at Neutrino 2012.

Ingredients

$$\Phi(E) = \frac{c}{H_0}\int_0^{z_{max}} R_{SN}(z)\frac{dN(E')}{dE'}\frac{dz}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

cosmological supernova rate

oscillated neutrino flux corrected by redshift
[$E' = E(1+z)$]

cosmology

Cosmological Supernova Rate

Cosmological Supernova Rate (SNR)

$$R_{\rm SN}(z,M) = \frac{\int_{8M_\odot}^{125M_\odot} dM\ \eta(M)}{\int_{0.5M_\odot}^{125M_\odot} dM\, M\eta(M)}\dot{\rho}_\star(z)$$

initial mass function
(mass distribution of stars at birth)

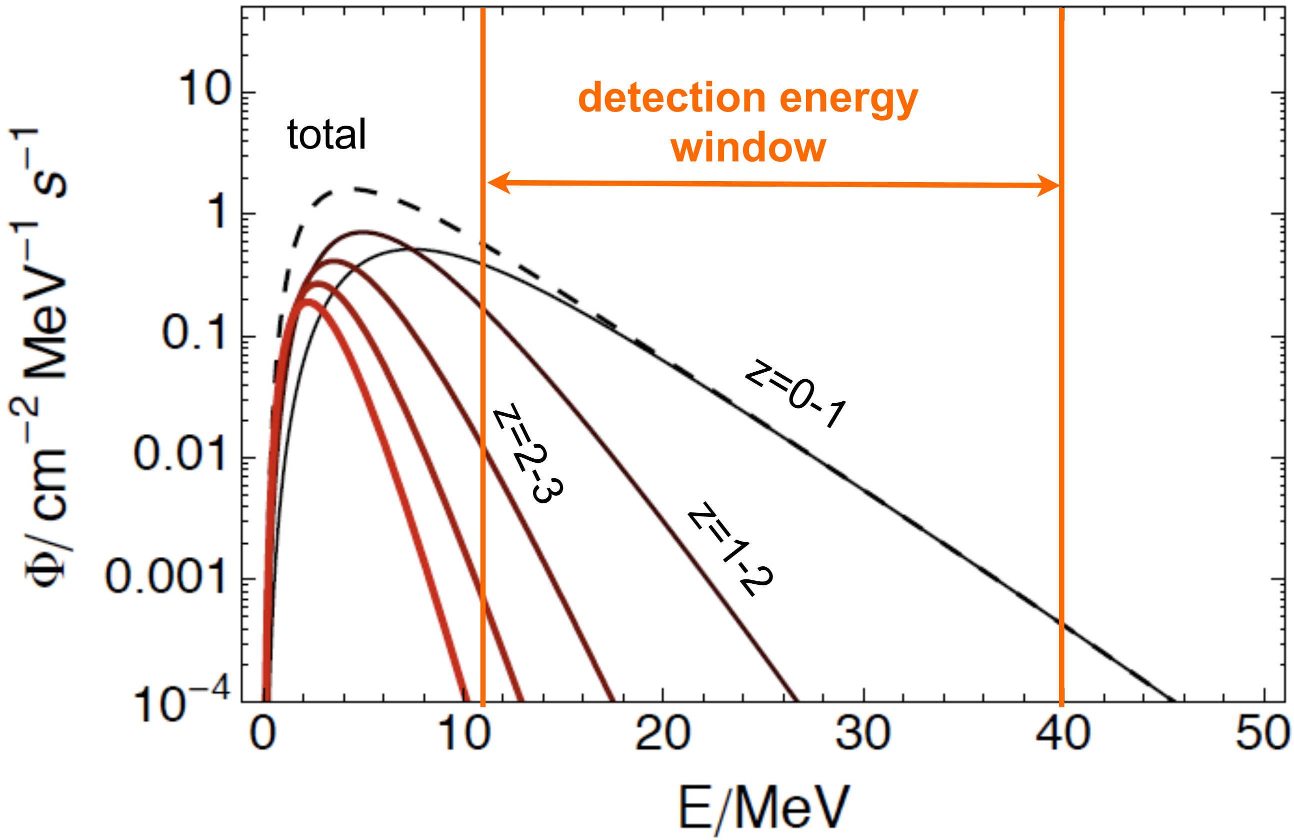
star formation rate

The initial mass function $\eta(M) \propto M^{-2.35}$. Therefore the flux is dominated by low mass stars.

The DSNB is dominated by the contribution of the closest ($z \leq 1$) and least massive ($M \simeq 8M_\odot$) stars and it depends only weakly on $M_{\rm max}$ and $z_{\rm max} \simeq 5$.

Cosmological Supernova Rate (SNR)

The redshift correction of energy is responsible for accumulating neutrinos of higher redshift at lower energies. Therefore the diffuse flux is dominated by the low z contribution ($z \leq 1$) in the energy window relevant for experiments (11 <E< 40 MeV).



See for details Ando, Sato, PLB 559 (2003) 113; Lunardini, arXiv: 1007.3252.

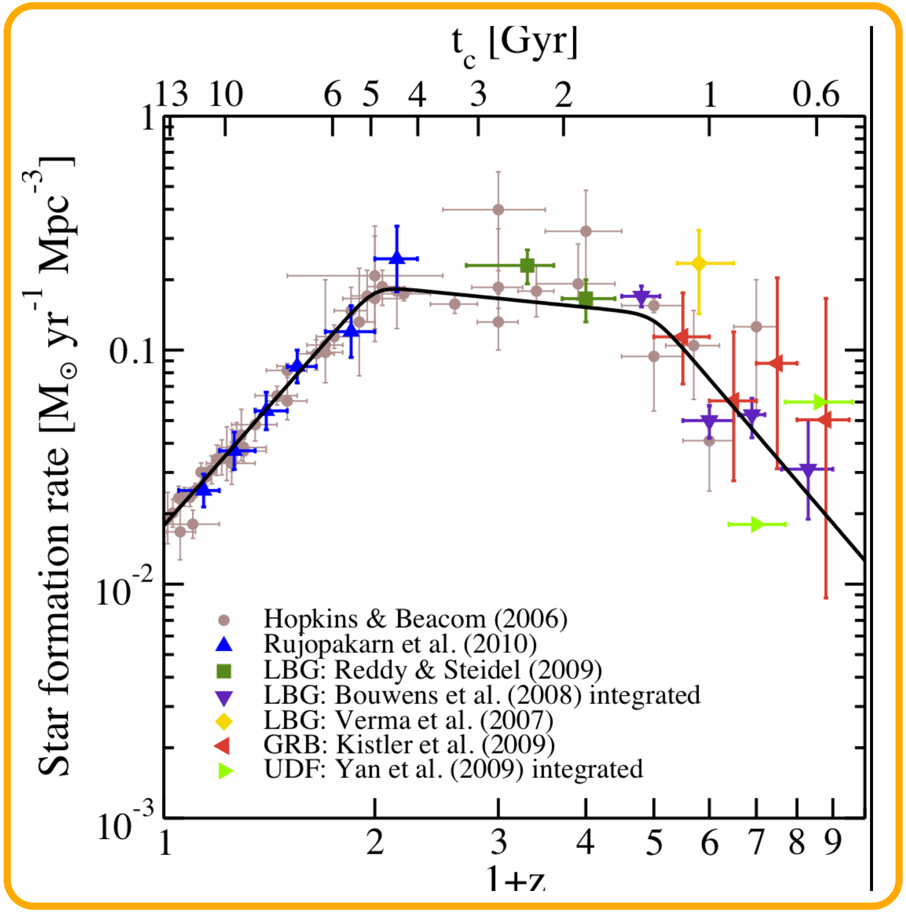
SNR: Predictions From Star Formation Rate

The SNR is proportional to the star formation rate (SFR), mass that forms stars per unit time per unit volume:

$$\dot{\rho}_\star \propto \begin{cases} (1+z)^\delta & z < 1 \\ (1+z)^\alpha & 1 < z < 4.5 \\ (1+z)^\gamma & 4.5 < z \end{cases}$$

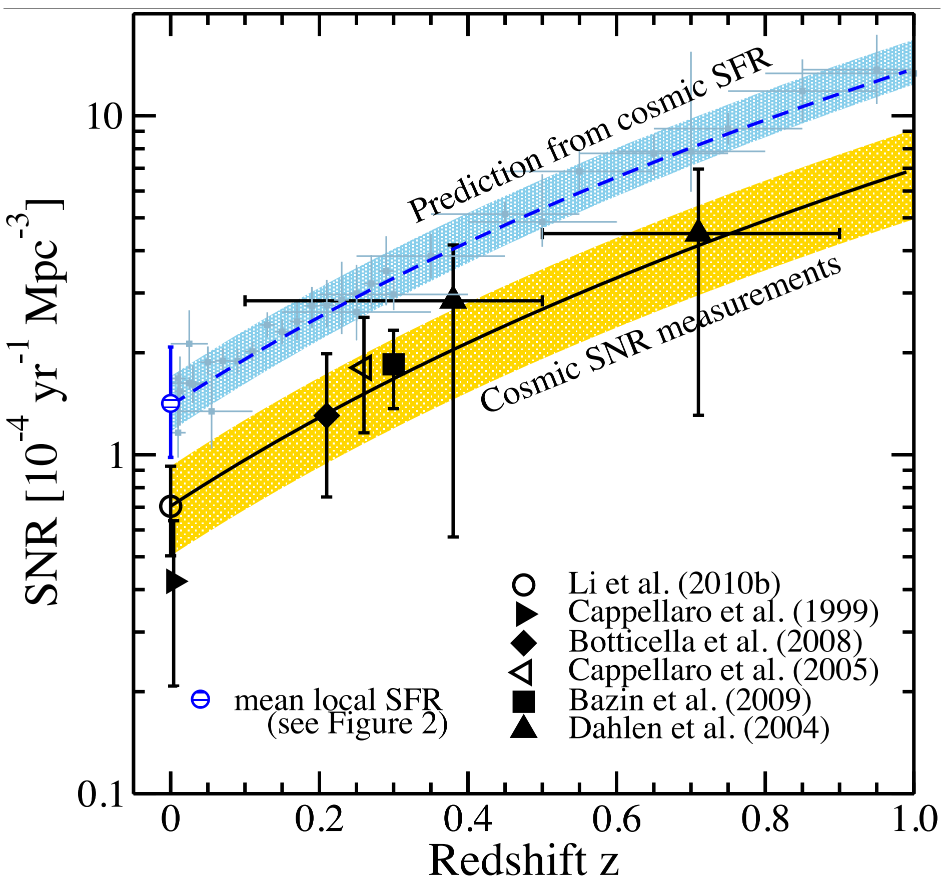
The most precise way to measure the SNR is from data on the SFR.

The cosmic star formation history as a function of the redshift is pretty well known from data in the ultraviolet and far-infrared. Impressive agreement among results from different groups.



See for details Horiuchi, Beacom, arXiv: 1006.5751; Hopkins, Beacom, arXiv: astro-ph/0601463.

SNR: Measured Supernova Rate



The SNR is also given by direct SN observations.

Surprisingly, **the normalization from direct SN observations is lower than that from SFR data by a factor ~ 2** and by a smaller factor at higher z.

Why? There are missing SNe - they are faint, obscured, or dark.

↓

The existing measurements of the SNR and their uncertainties are dominated by normalization errors.

See Horiuchi et al., arXiv: 1102.1977; Botticella et al., arXiv: 1111.1692.

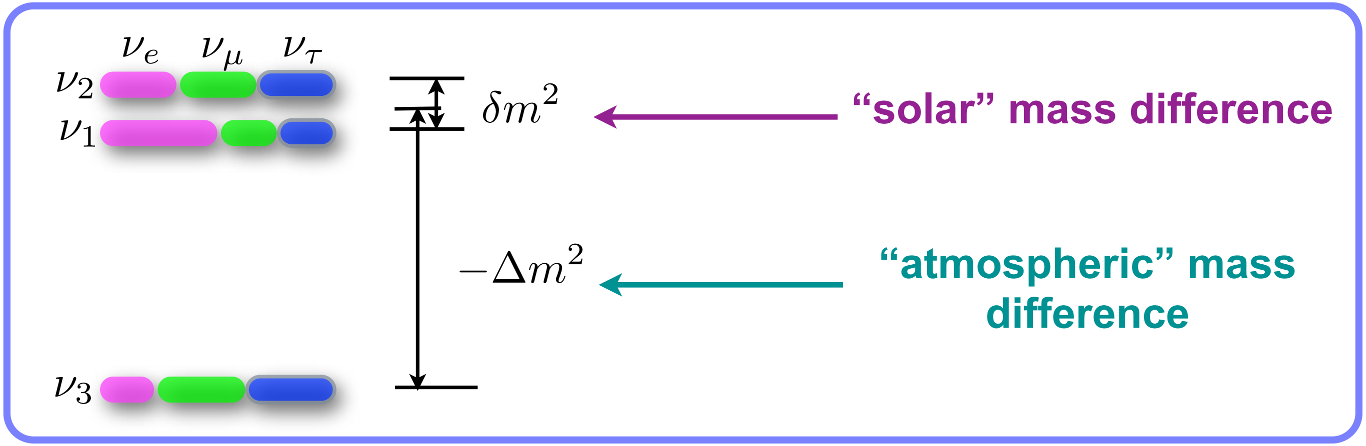
Neutrino Mixing

Neutrino Masses and Neutrino Flavors

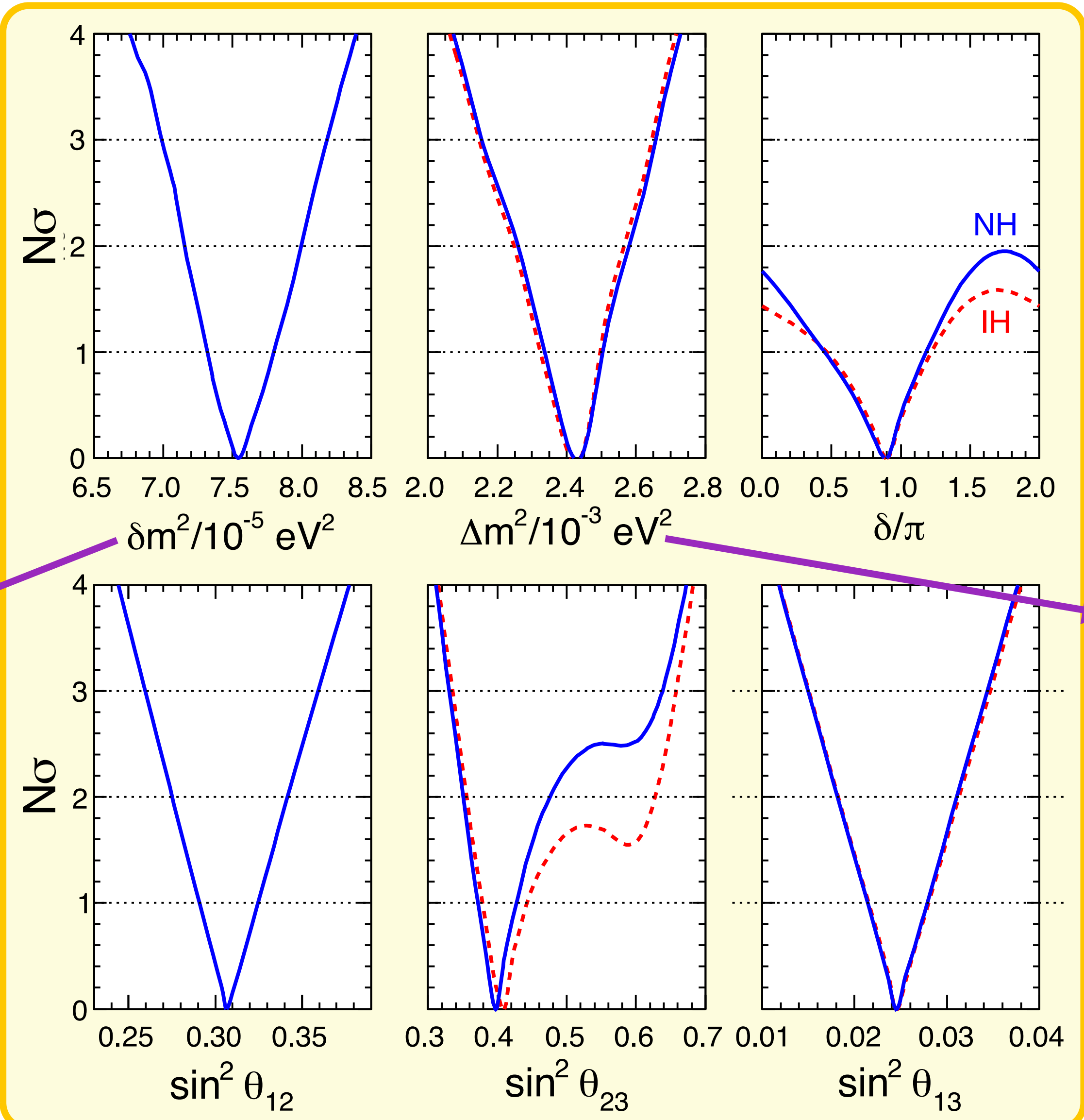
Neutrino flavor eigenstates are linear combinations of mass eigenstates by means of three mixing angles and one CP-phase

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino mass eigenstates differ by two mass differences. The sign of the biggest one is still unknown [normal hierarchy: $+\Delta m^2$, inverted hierarchy: $-\Delta m^2$].
For example, in inverted hierarchy:



Neutrino Masses and Mixing Angles



"solar" mass difference

"atmospheric" mass difference

mixing angles

* G.L. Fogli et al., arXiv: 1205.5254.

Neutrino Masses and Mixing Angles

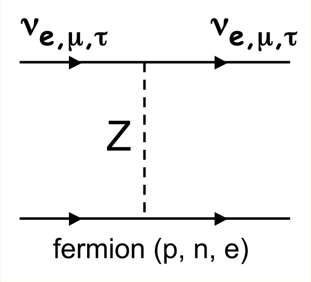
Parameter	Best fit	1σ range
$\delta m^2/10^{-5}\ \mathrm{eV}^2$ (NH or IH)	7.54	7.32 – 7.80
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25
$\Delta m^2/10^{-3}\ \mathrm{eV}^2$ (NH)	2.43	2.34 – 2.50
$\Delta m^2/10^{-3}\ \mathrm{eV}^2$ (IH)	2.42	2.32 – 2.49
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.45	2.14 – 2.79
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.46	2.15 – 2.80
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.98	3.72 – 4.28
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.08	3.78 – 4.43
δ/π (NH)	0.89	0.45 – 1.18
δ/π (IH)	0.90	0.47 – 1.22

* G.L. Fogli et al., arXiv: 1205.5254.

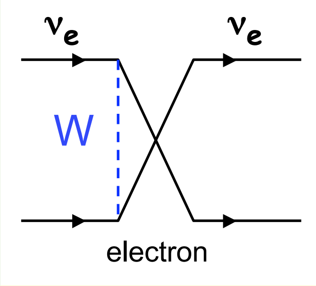
Neutrino Oscillations in Supernovae

Neutrino Interactions

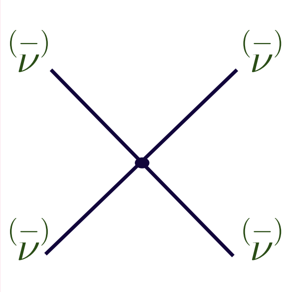
Neutrinos interact with matter and among themselves...



Neutral current (NC) interactions with matter background



e-flavor has charged current (CC) interactions too



$\nu - \nu$ interactions

Equations of Motion

The equations of motion for neutrinos and antineutrinos describing the time evolution in a homogeneous medium for each energy mode E and angle ϑ are

$$i\,\dot{\varrho}_{E,\vartheta} = [\mathsf{H}_{E,\vartheta}, \varrho_{E,\vartheta}] \quad \text{and} \quad i\,\dot{\bar{\varrho}}_{E,\vartheta} = [\bar{\mathsf{H}}_{E,\vartheta}, \bar{\varrho}_{E,\vartheta}]$$

with the neutrino Hamiltonian defined as

$$\mathsf{H}_{E,\vartheta} = \frac{\mathsf{U}\mathsf{M}^2\mathsf{U}^\dagger}{2E} + \sqrt{2}G_\mathrm{F}\ \mathsf{N}_l + 2\pi\sqrt{2}G_\mathrm{F}\int dE\ \int d\cos\vartheta'\ \left(\varrho_{E',\vartheta'} - \bar{\varrho}_{E',\vartheta'}\right)(1-\cos\vartheta\cos\vartheta')$$

vacuum term (with opposite sign for antineutrinos)

matter term

$\mathsf{N}_\ell = \mathrm{diag}(n_e - n_{\bar{e}}, n_\mu - n_{\bar{\mu}}, n_\tau - n_{\bar{\tau}})$

$\nu-\nu$ interaction term

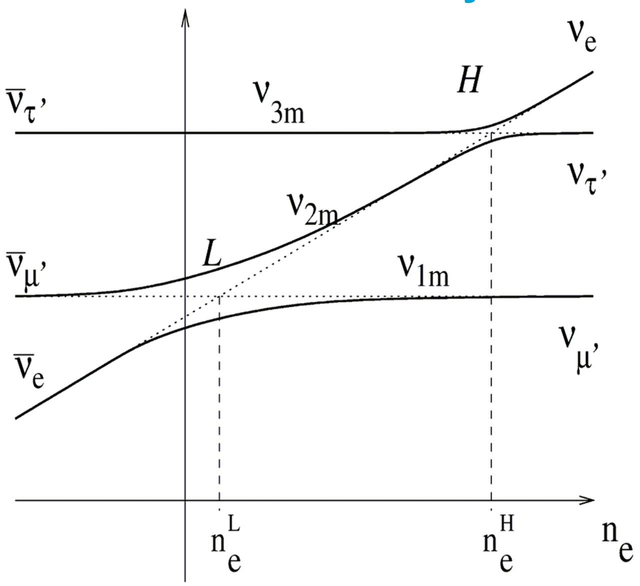
The Hamiltonian for antineutrinos has the vacuum term with opposite sign.

Neutrino Interactions with Matter (MSW)

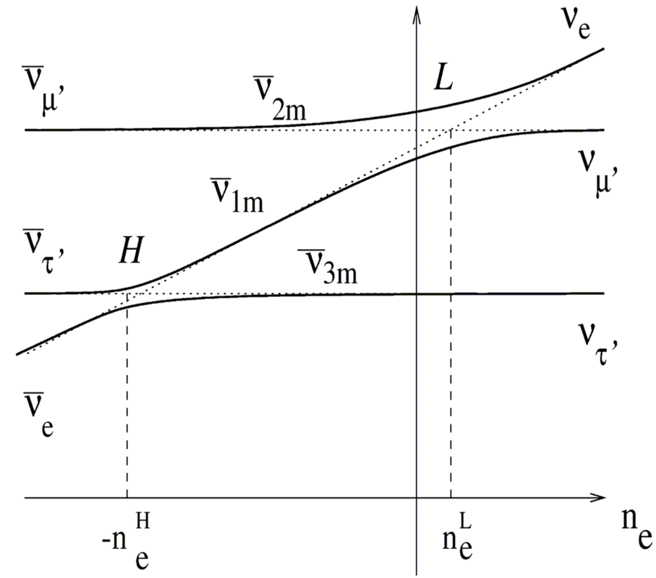
When the vacuum term is in resonance with the matter term maximal flavor conversions occur (MSW effect).

Level-Crossing diagrams in a supernova

Normal hierarchy



Inverted hierarchy



Δm^2 resonance for neutrinos
δm^2 resonance for neutrinos

Δm^2 resonance for antineutrinos
δm^2 resonance for neutrinos

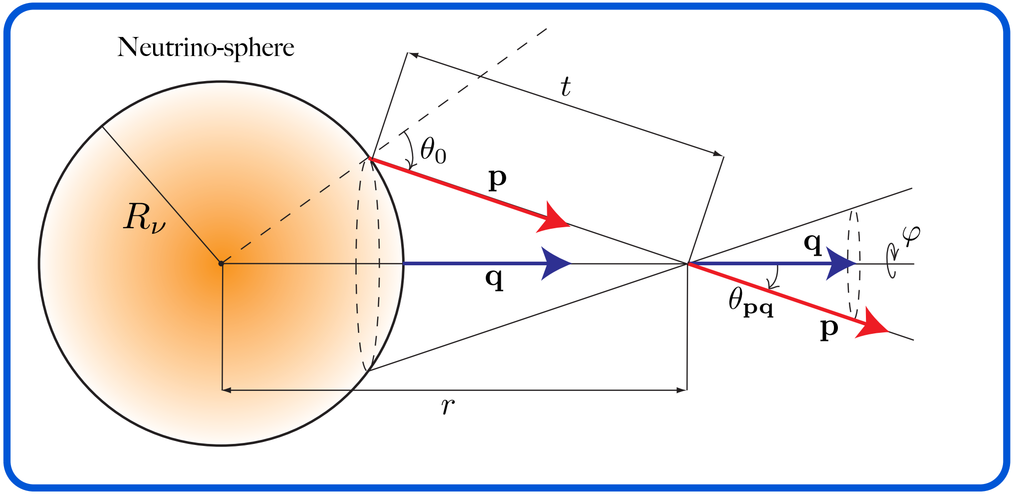
* For details see: A. Dighe and A. Yu. Smirnov, arXiv: hep-ph/9907423

Neutrino-neutrino Interactions

The $\nu - \nu$ term is non linear and it depends on the relative angle between colliding neutrinos

$$\mathsf{H}_{E,\vartheta} = \frac{\mathsf{UM}^2\mathsf{U}^\dagger}{2E} + \sqrt{2}G_\mathrm{F}\ \mathsf{N}_l + 2\pi\sqrt{2}G_\mathrm{F}\int dE' \int d\cos\vartheta' \ \ (\varrho_{E',\vartheta'} - \bar{\varrho}_{E',\vartheta'})\,(1-\cos\vartheta\cos\vartheta')$$

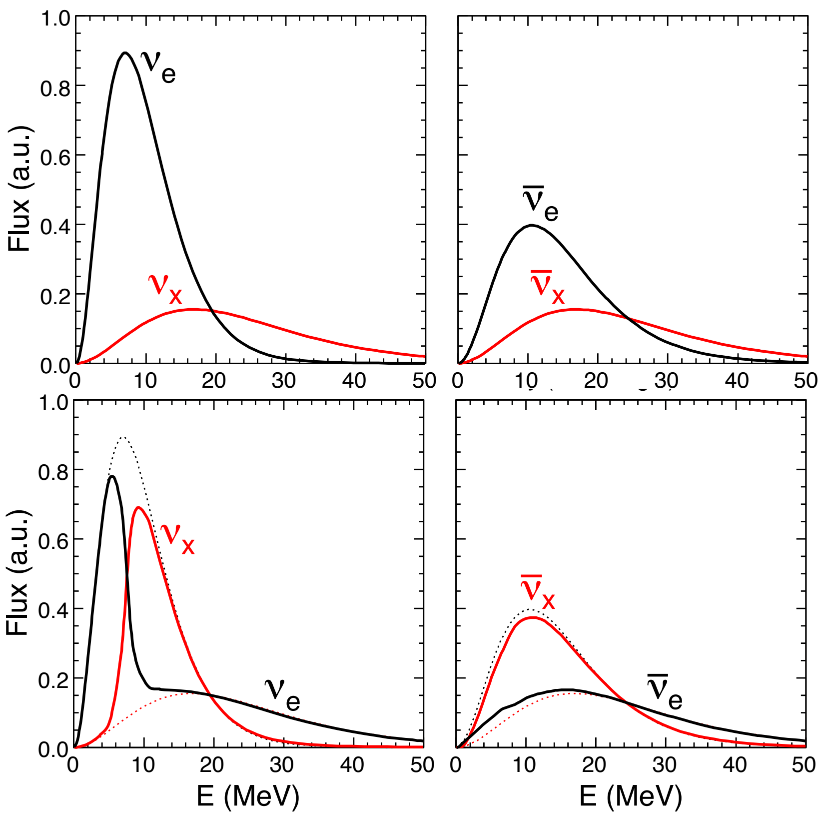
We assume the "bulb model"*: the neutrino-sphere emits neutrinos of all flavors from each point in the forward solid angle uniformly and isotropically.



Only lately, we are learning to appreciate the role of the angle among colliding neutrinos.

* For details see: H. Duan et al., arXiv: astro-ph/0606616.
For realistic angular distributions see S. Sarikas, G.G. Raffelt, L. Huedepohl, H.-T. Janka, arXiv: 1109.3601

Spectral Splits



The immediate signature of collective effects is the "**spectral split**": for energies above a critical value, a full flavor swap occurs*.

← **non-oscillated fluxes**

← **fluxes after collective effects in *inverted hierarchy***

fluxes after collective effects = non-oscillated fluxes in *normal hierarchy*

The appearance and the number of splits are strictly dependent on:

★ the ratio among the fluxes of different flavors

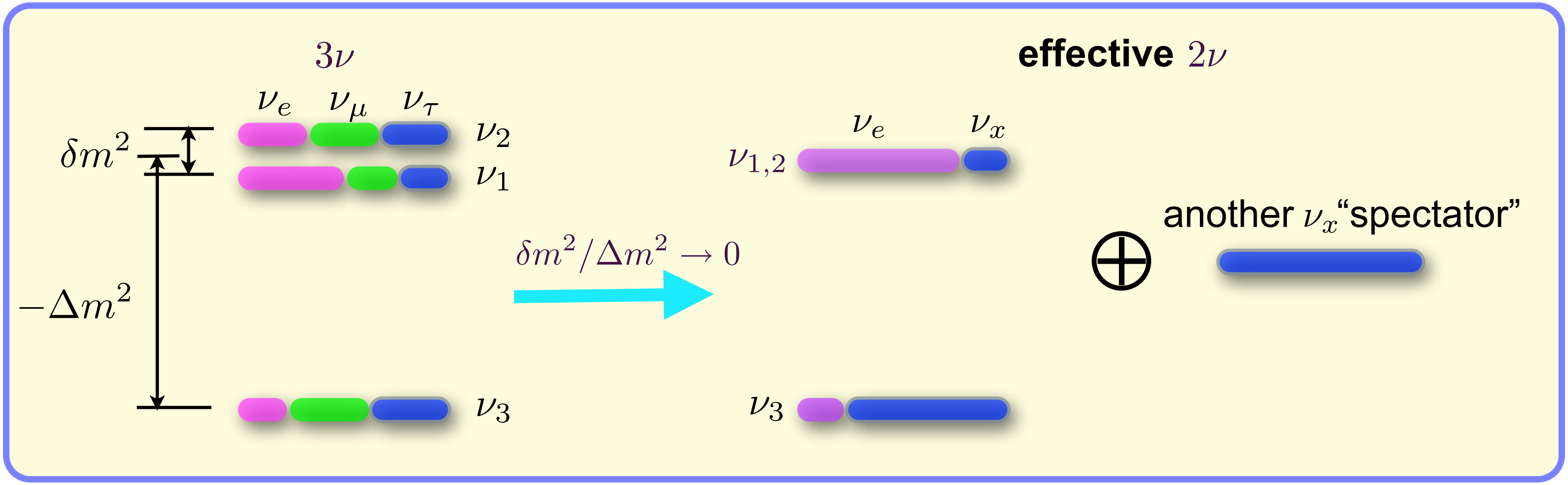
★ the geometry of the neutrino angular emission

★ the neutrino mass hierarchy.

* For details see: G.L. Fogli, E. Lisi, A. Marrone, A. Mirizzi, I. Tamborra arXiv: 0707.1998, 0808.0807
G.G. Raffelt and A. Yu. Smirnov, arXiv: 0705.1830, 0709.4641, H. Duan et al., arXiv: 0706.4293

$3\nu = 2\nu \oplus 1\nu$ approximation

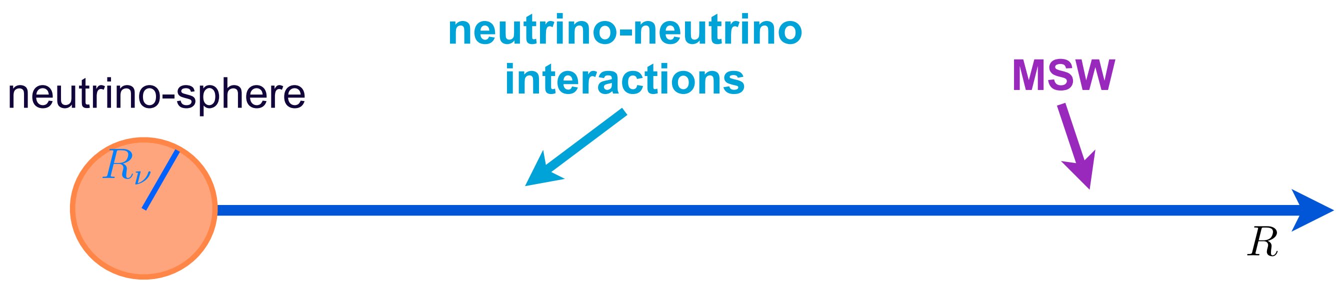
Typical supernova neutrino energies are below threshold for μ and τ production via CC. ν_μ and ν_τ behave in a similar way and are often denoted by ν_x.
Generally, one may use an effective 2-flavor approximation as far as $\delta m^2/\Delta m^2 \to 0$.*



The effects on collective oscillations induced by the third flavor are of the nature of a subtle correction, negligible for our purposes. In what follows, we will treat collective oscillations in the two flavor approximation and the only way the "spectator" ν_x will affect the final spectra will be by MSW transitions.

* B. Dasgupta, A. Dighe, arXiv: 0712.3798 [hep-ph]

Oscillated Fluxes at the Earth



For large θ_{13} the oscillated fluxes are:

$$
\begin{aligned}
F_{\nu_e}^{\rm NH} &= \sin^2\theta_{12}[1-P_c(F^c_{\nu_e},F^c_{\bar\nu_e},E)](F^0_{\nu_e}-F^0_{\nu_y})+F^0_{\nu_y}\\
F_{\bar\nu_e}^{\rm NH} &= \cos^2\theta_{12}\bar P_c(F^c_{\nu_e},F^c_{\bar\nu_e},E)(F^0_{\bar\nu_e}-F^0_{\nu_y})+F^0_{\nu_y}\ ,\\
F_{\nu_e}^{\rm IH} &= \sin^2\theta_{12}P_c(F^c_{\nu_e},F^c_{\bar\nu_e},E)(F^0_{\nu_e}-F^0_{\nu_y})+F^0_{\nu_y}\ ,\\
F_{\bar\nu_e}^{\rm IH} &= \cos^2\theta_{12}[1-\bar P_c(F^c_{\nu_e},F^c_{\bar\nu_e},E)](F^0_{\bar\nu_e}-F^0_{\nu_y})+F^0_{\nu_y}
\end{aligned}
$$

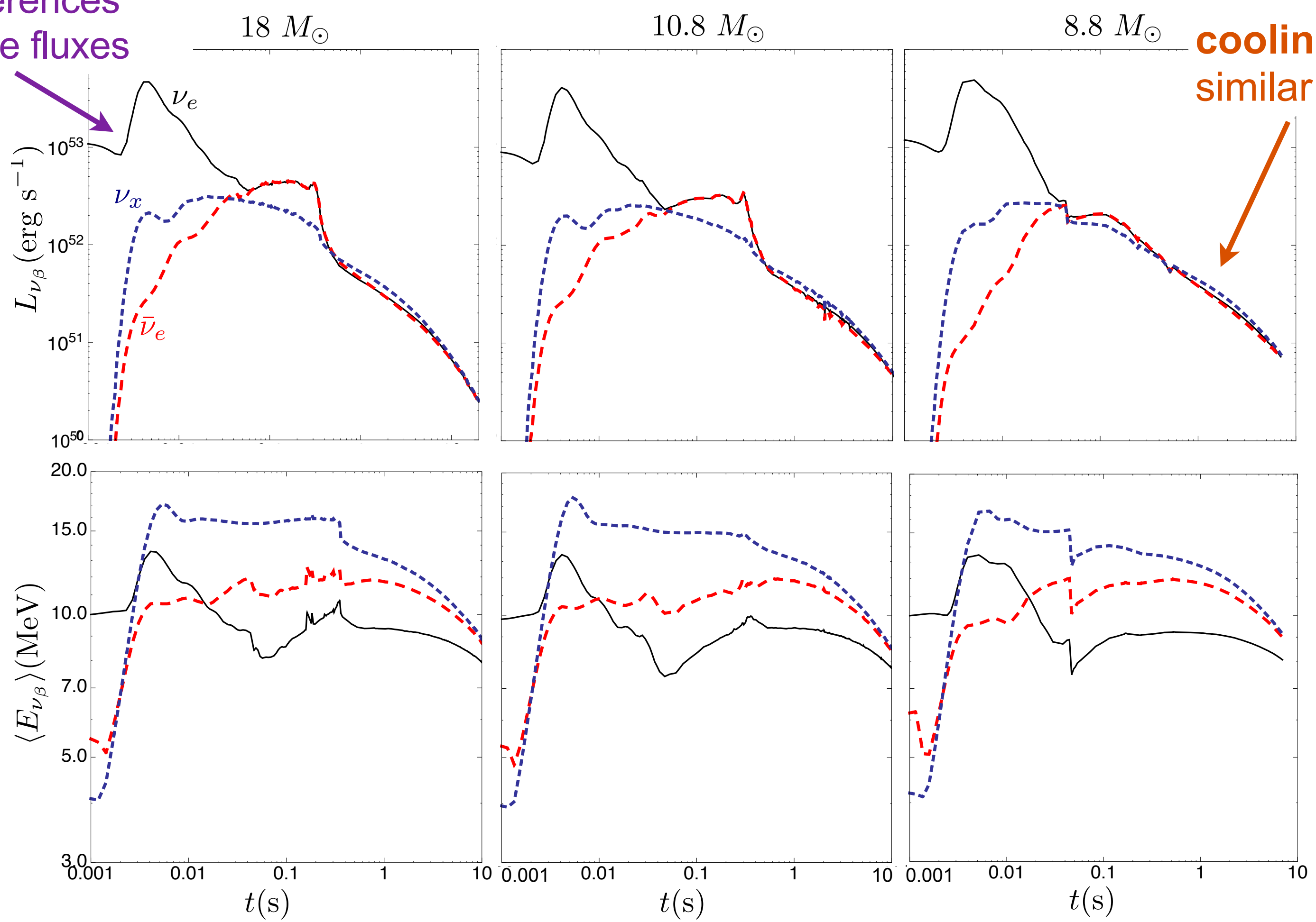
Since self-induced flavor conversions and MSW resonances occur in well separated regions in most of the cases, we choose to factorize both the effects and treat them separately.

Reference Neutrino Signal

Reference Neutrino Signal

accretion:
large differences among the fluxes

cooling:
similar fluxes



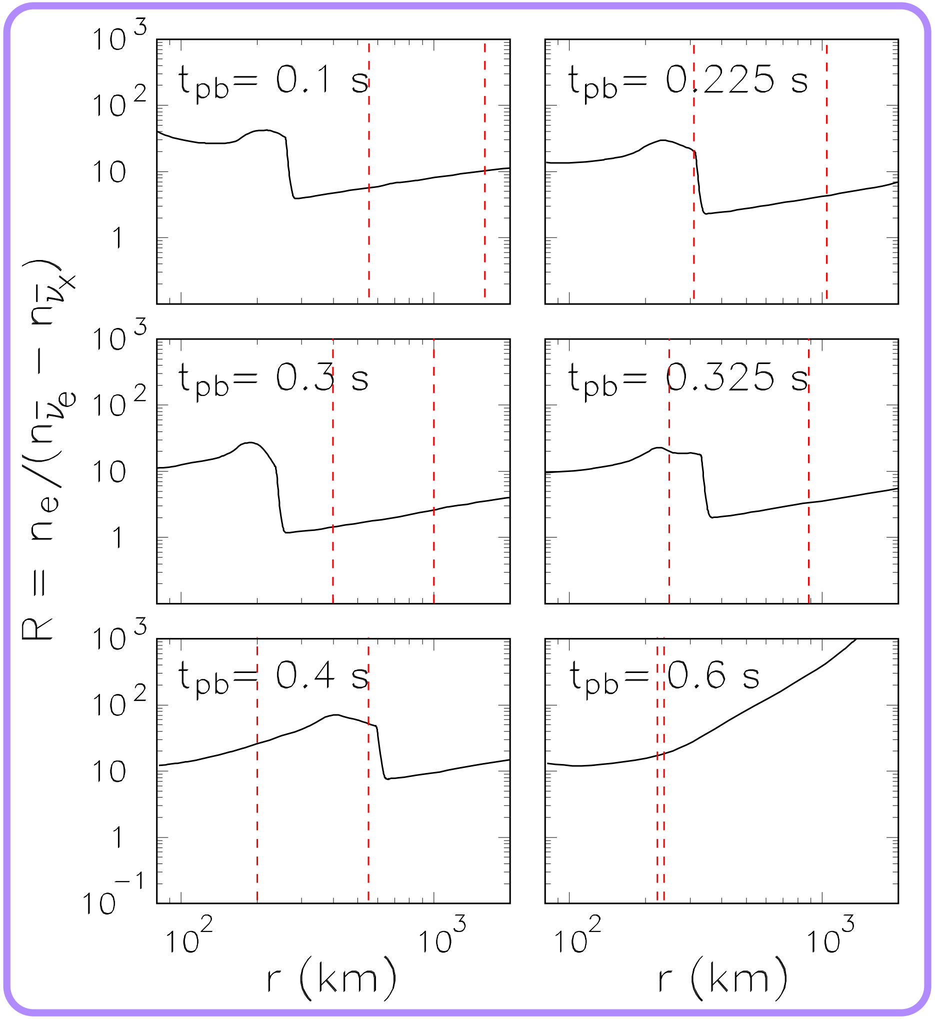
We adopt SN simulations* consistently developed over 10s for three different SN masses.

* Fisher et al. (Basel group), arXiv: 0908.1871 [astro-ph.HE]

Oscillations During the Accretion Phase

Accretion Phase

Matter density during the accretion phase vs. neutrino density for a $10.8\ M_\odot$ SN (Basel model)



During the **accretion phase** the matter density is always larger than the neutrino one.
Then, one could expect multi-angle matter suppression of collective flavor conversions at small radii.
Does this happen?

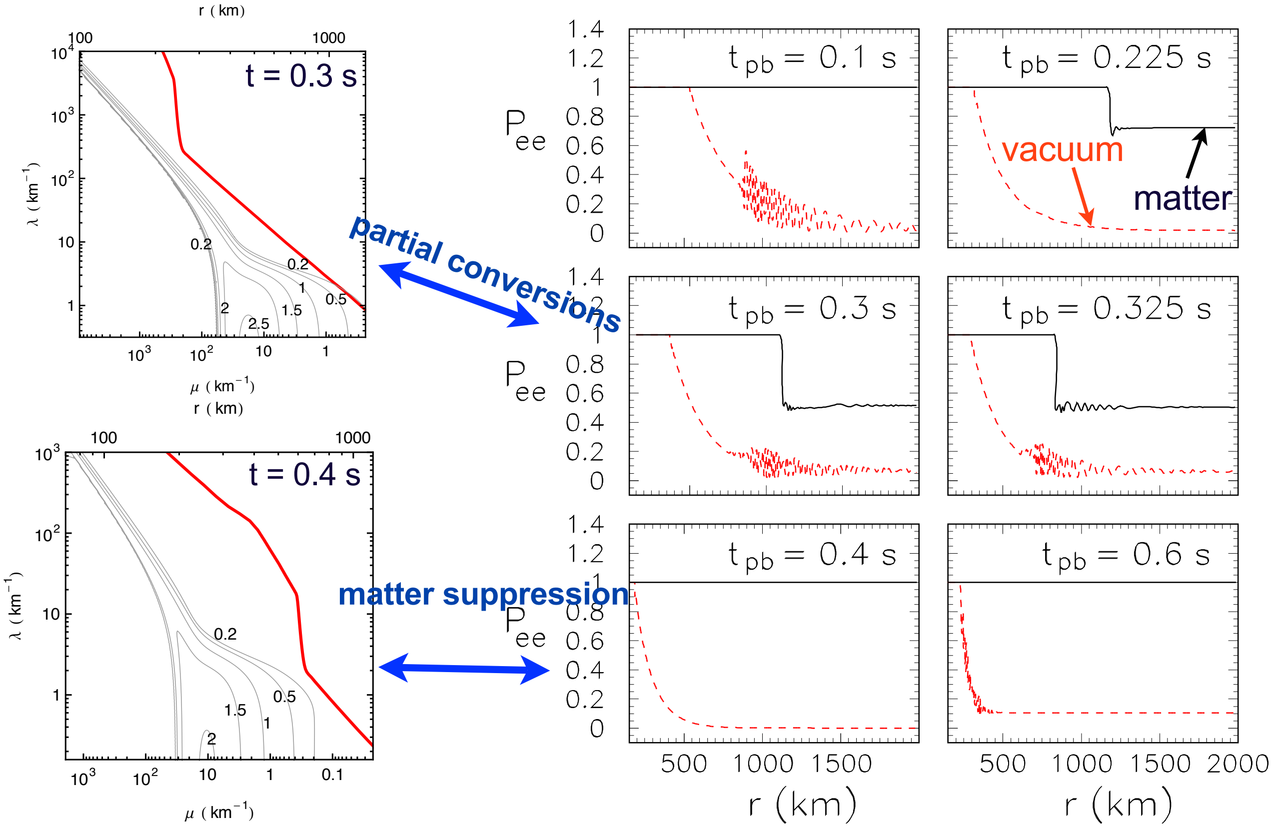
[See talk by G. Raffelt]

* For details see: S. Chakraborty et al., arXiv: 1104.4031, arXiv: 1105.1130, S. Sarikas, G.G. Raffelt, arXiv: 1109.3601

Accretion Phase: Flavor Evolution

Stability analysis
[See talk by G. Raffelt]

Electron survival probability for one energy mode (IH,$10.8\ M_{\odot}$)



Matter suppression of collective effects during the accretion -only MSW-

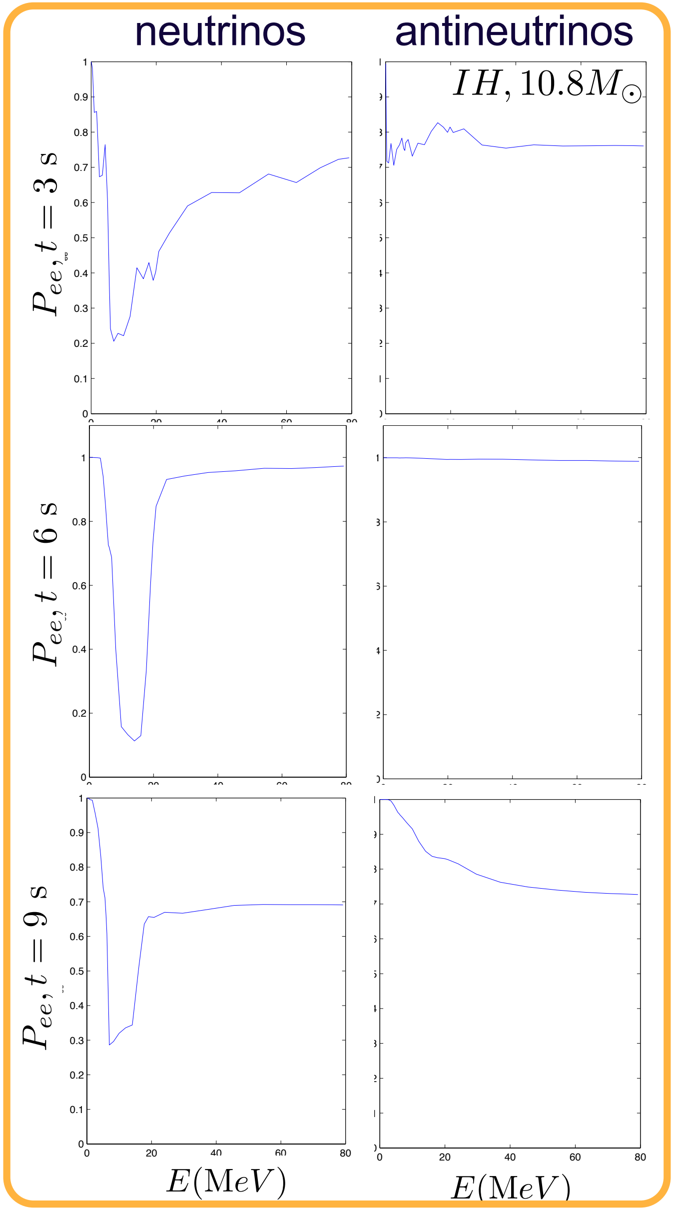
The high electron density suppresses collective flavor oscillations (no splits) during the accretion phase for the three considered progenitors ($P_c \simeq 1$). Only MSW occurs.

The angular distribution is crucial for the flavor-oscillation suppression!

* For details see: S. Chakraborty et al., arXiv: 1104.4031, arXiv: 1105.1130, S. Sarikas et al., arXiv: 1110.5572

Oscillations During the Cooling Phase

Cooling Phase: Flavor Evolution



During the **cooling phase** multiple spectral splits are expected. We numerically solve the evolution equations for discrete time slices. The spectral splits are smeared and their size is reduced due to similarity of the un-oscillated flavor spectra and due to multi-angle effects.

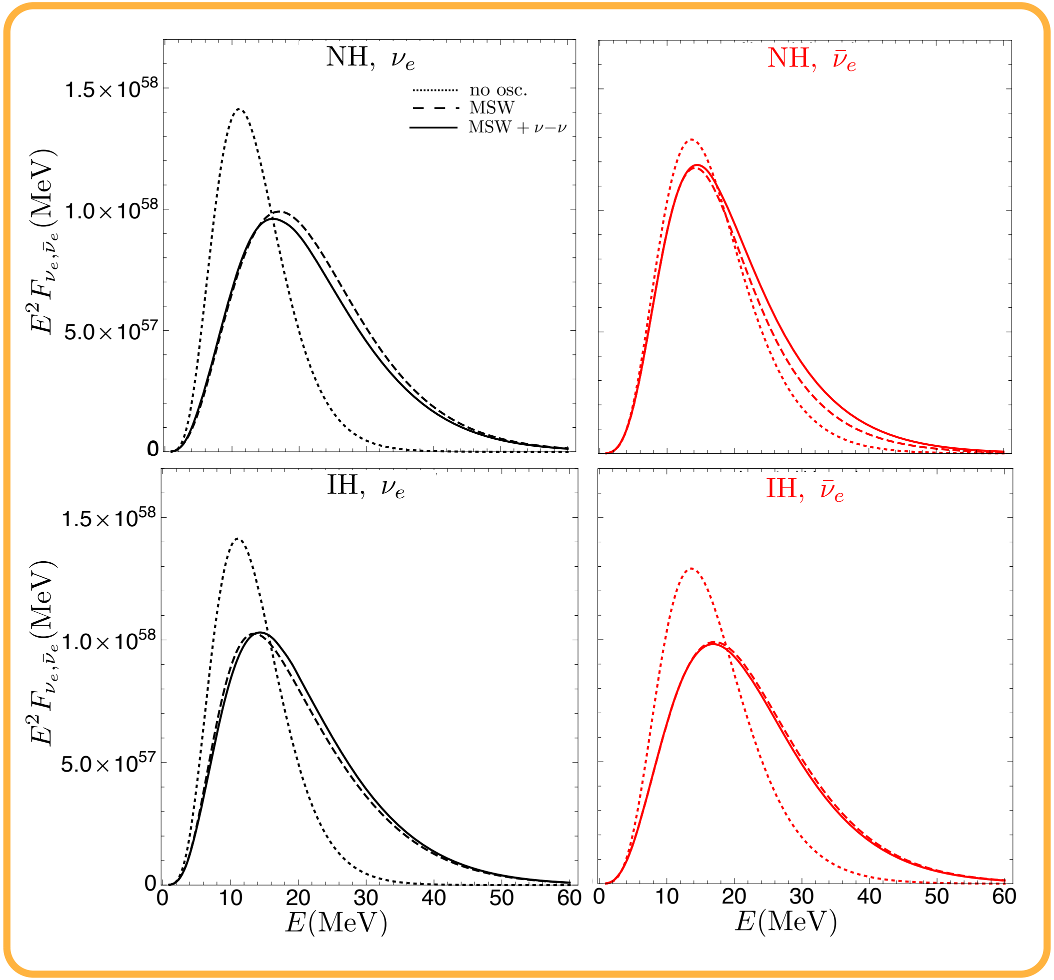
Only partial conversion is realized.
For NH, $P_c \geq 0.6$ for high energies and $P_c \leq 0.3$ for low energies with transition energy increasing with time for energies from 15 to 35 MeV. A similar behavior is observed for antineutrinos for E > 5 MeV.

For IH, $P_c \sim 0.1 - 0.3$ for E < 15-20 MeV to $P_c > 0.6$ at higher energies.
For antineutrinos $\bar{P}_c > 0.7$ at all times and at all energies.

* For details see: Fogli, Lisi, Marrone, Tamborra, arXiv: 0907.51515; Mirizzi and Tomàs, arXiv: 1012.1339.

Diffuse Supernova Neutrino Background

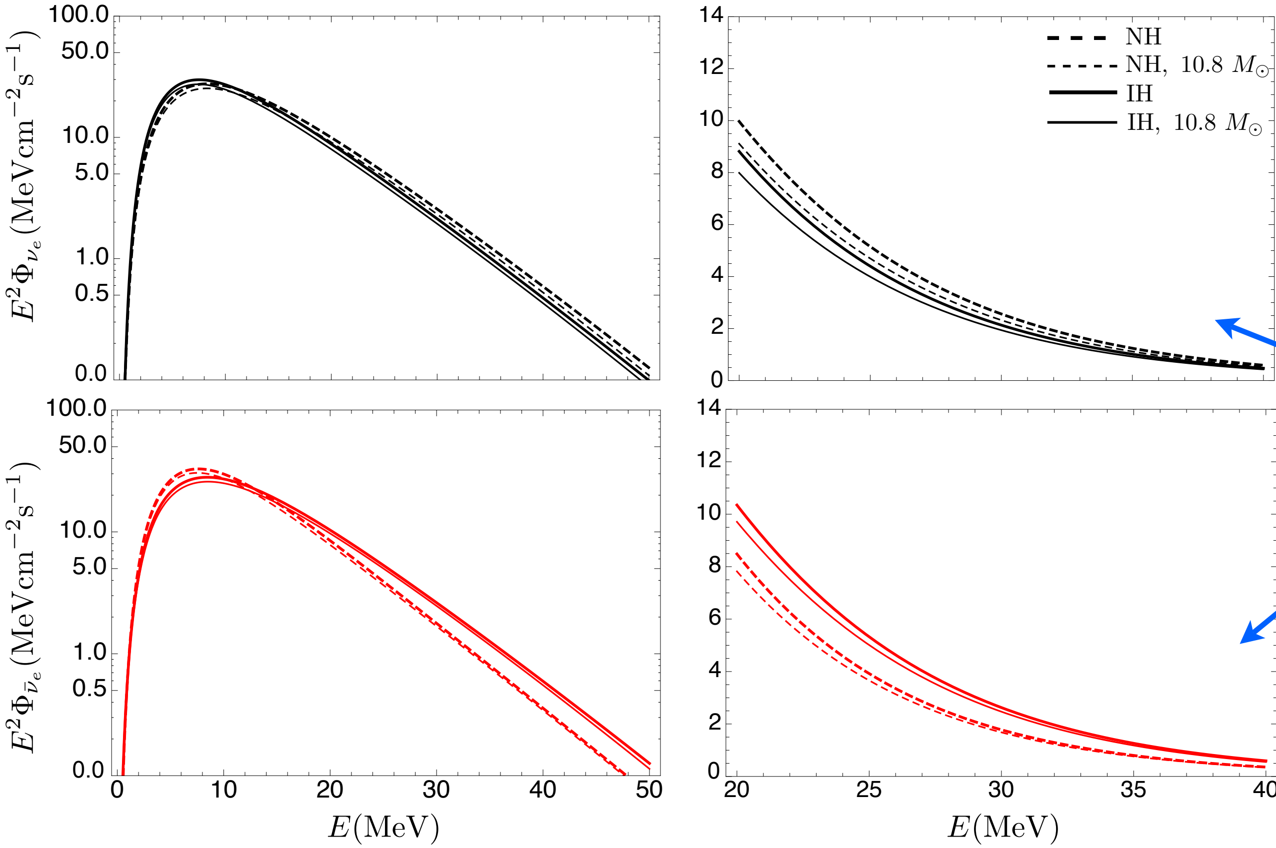
Time-integrated Neutrino Fluxes ($10.8\ M_{\odot}$)



The MSW effect is large and it generates hotter fluxes. Collective effects produce a slight hardening or softening of the fluxes depending on the mass hierarchy. No signature of the spectral splits.

For details see: C. Lunardini and I. Tamborra, arXiv: 1205.6292.

Diffuse Supernova Neutrino Background

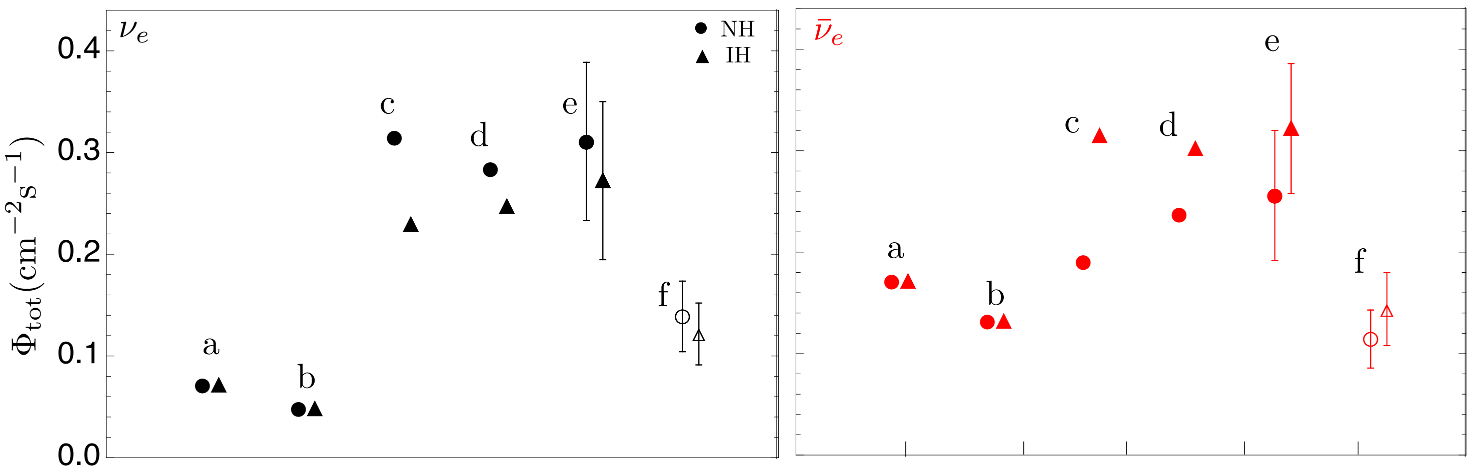


region of interest for Super-Kamiokande detection

A maximum variation of 10-20% (at $E \simeq 20$ MeV) is related to the mass hierarchy.

For details see: C. Lunardini and I. Tamborra, arXiv: 1205.6292.

Estimate of the Different Contributions



Compared to static spectra (a), the effect of time-dependence of the spectra over 10 s is responsible for a variation of 6% (b). The MSW effects (c) are the largest source of variation of the DSNB with respect to the case without oscillations and it is 50-60%. Neutrino-neutrino interactions (d) are responsible for a variation of 5-10%. The stellar population (e) is responsible for a variation of 5-10% due to the more luminous fluxes of the massive stars.

$$\Phi_{tot}^{\nu_e,NH} = 0.31\ cm^{-2}s^{-1} \text{ and } \Phi_{tot}^{\nu_e,IH} = 0.27\ cm^{-2}s^{-1}$$
$$\Phi_{tot}^{\bar{\nu}_e,NH} = 0.26\ cm^{-2}s^{-1} \text{ and } \Phi_{tot}^{\bar{\nu}_e,IH} = 0.32\ cm^{-2}s^{-1}$$

For details see: C. Lunardini and I. Tamborra, arXiv: 1205.6292.

Conclusions

★ The inclusion of time-dependent neutrino spectra is responsible for colder neutrino spectra in the DSNB (error ~5%).

★ The largest effect of flavor oscillations is due to MSW resonances (~50-60%), neutrino-neutrino interactions contribute at 5-10%. No energy-dependent signature of collective oscillations.

★ The dependence on the mass hierarchy is ~10-20% and it is stronger for antineutrinos.

★ Combining results for different progenitor stars (instead of using $10.8 M_\odot$ spectra for all stars), increases the DSNB by 5-10%.

★ The DSNB is mainly affected by MSW effects and it can be used to extract astrophysical quantities.

★ The forthcoming detection of the DSNB will be an excellent benchmark to test models of neutrino spectra/emission and SNR.

Thank you

for your attention!