EstrellaNueva: An Open-source Software to Study the Interactions and Detection of Neutrinos Emitted by Supernovae

Osmany Ignacio González-Reina and Eric Vázquez-Jáuregui

Instituto de Física - UNAM

August 3, 2022

EstrellaNueva

EstrellaNueva is designed to calculate interaction rates of neutrinos emitted by supernovae with target particles in the active volume of detectors.

Input:

- the supernova model,
- the neutrino mass ordering [1],
- the distance to the supernova,
- the mass of the active volume of the detector,
- the chemical composition of the material, and
- the detection channels.

Output:

- the interaction rates with respect to the incoming neutrino energy; the time; and in case of elastic scattering interactions, the interaction rates with respect to the kinetic energy and the scattering angle of the recoil particle;
- the fluences; and
- the total number of interactions.

Published on The Astrophysical Journal: O. I. González-Reina et al. 2022, ApJ, 932, 125
Software package available at: https://doi.org/10.5281/zenodo.6412768

[1] The neutrino mass ordering is required for the adiabatic MSW effect in the supernova matter.

Software structure

The software package, stored in the directory "EstrellaNueva", contains the following items:

- The main file "EstrellaNueva.py": main script to execute the software. This Python script uses Python 3 as interpreter, from the directory "EstrellaNueva". The command line for execution is: "`python3 EstrellaNueva.py`".
- The configuration file "`config.json`": JSON file for setting the configuration parameters, before executing the main script.
- The sub-directory "data": contains the data of the supernova models, as well as some of the implemented cross sections which were taken from the SNOwGLoBES repository in form of data files. These cross sections correspond to the interactions with ^{12}C, ^{16}O, and ^{208}Pb.
- The sub-directory "out": will contain the output files once the code is executed. The output consists of data files with the number of interactions per channel, interaction rates, and fluences.
- The sub-directory "src": contains the EstrellaNueva libraries. The cross sections implemented analytically are located in this directory.
- The sub-directory "doc": contains the user manual.

Flavor fluxes and the adiabatic MSW effect

Primary fluxes at the neutrino-sphere [2]:

$$F_\nu^0(E,t) = \mathcal{L}_\nu(t)\frac{(1+\beta_\nu(t))^{1+\beta_\nu(t)}}{\Gamma(1+\beta_\nu(t))}\frac{E^{\beta_\nu(t)}}{(\langle E_\nu\rangle(t))^{\beta_\nu(t)+2}} \times \exp\left[-(\beta_\nu(t)+1)\frac{E}{\langle E_\nu\rangle(t)}\right],$$

where

$$\beta_\nu(t) = \frac{2(\langle E_\nu\rangle(t))^2 - \langle E_\nu^2\rangle(t)}{\langle E_\nu^2\rangle(t) - (\langle E_\nu\rangle(t))^2}.$$

Transformed fluxes in vacuum following the adiabatic MSW effect:

(NO)

$$\begin{aligned}
F_{\nu_e} &= |U_{e1}|^2 F^0_{\nu_x} + |U_{e2}|^2 F^0_{\nu_x} + |U_{e3}|^2 F^0_{\nu_e},\\
F_{\nu_\mu} &= |U_{\mu1}|^2 F^0_{\nu_x} + |U_{\mu2}|^2 F^0_{\nu_x} + |U_{\mu3}|^2 F^0_{\nu_e},\\
F_{\nu_\tau} &= |U_{\tau1}|^2 F^0_{\nu_x} + |U_{\tau2}|^2 F^0_{\nu_x} + |U_{\tau3}|^2 F^0_{\nu_e},\\
F_{\bar\nu_e} &= |U_{e1}|^2 F^0_{\bar\nu_e} + |U_{e2}|^2 F^0_{\nu_x} + |U_{e3}|^2 F^0_{\nu_x},\\
F_{\bar\nu_\mu} &= |U_{\mu1}|^2 F^0_{\bar\nu_e} + |U_{\mu2}|^2 F^0_{\nu_x} + |U_{\mu3}|^2 F^0_{\nu_x},\\
F_{\bar\nu_\tau} &= |U_{\tau1}|^2 F^0_{\bar\nu_e} + |U_{\tau2}|^2 F^0_{\nu_x} + |U_{\tau3}|^2 F^0_{\nu_x};
\end{aligned}$$

(IO)

$$\begin{aligned}
F_{\nu_e} &= |U_{e1}|^2 F^0_{\nu_x} + |U_{e2}|^2 F^0_{\nu_e} + |U_{e3}|^2 F^0_{\nu_x},\\
F_{\nu_\mu} &= |U_{\mu1}|^2 F^0_{\nu_x} + |U_{\mu2}|^2 F^0_{\nu_e} + |U_{\mu3}|^2 F^0_{\nu_x},\\
F_{\nu_\tau} &= |U_{\tau1}|^2 F^0_{\nu_x} + |U_{\tau2}|^2 F^0_{\nu_e} + |U_{\tau3}|^2 F^0_{\nu_x},\\
F_{\bar\nu_e} &= |U_{e1}|^2 F^0_{\nu_x} + |U_{e2}|^2 F^0_{\nu_x} + |U_{e3}|^2 F^0_{\bar\nu_e},\\
F_{\bar\nu_\mu} &= |U_{\mu1}|^2 F^0_{\nu_x} + |U_{\mu2}|^2 F^0_{\nu_x} + |U_{\mu3}|^2 F^0_{\bar\nu_e},\\
F_{\bar\nu_\tau} &= |U_{\tau1}|^2 F^0_{\nu_x} + |U_{\tau2}|^2 F^0_{\nu_x} + |U_{\tau3}|^2 F^0_{\bar\nu_e}.
\end{aligned}$$

[2] The primary fluxes coming from the neutrino-sphere are $F^0_{\nu_e}$, $F^0_{\bar\nu_e}$, and $F^0_{\nu_x}$, where $\nu_x = (\nu_\mu, \nu_\tau, \bar\nu_\mu, \bar\nu_\tau)$.

Interaction rates with respect to E, t, and T

Interaction rate with respect to time t and neutrino energy E:

$$\frac{d^2N_\nu}{dEdt}(E,t) = \frac{N_t}{4\pi d^2}\sigma_\nu(E)F_\nu(E,t) \qquad (\sigma_\nu : \text{total cross section}, \nu = (\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau)).$$

Fluence:

$$\lambda_\nu(E) = \frac{1}{4\pi d^2}\int_{t_0}^{t_{end}} F_\nu(E,t)dt.$$

Then, the interaction rates with respect to E and t are

$$\frac{dN_\nu}{dE}(E) = \int_{t_0}^{t_{end}} dt \left[\frac{d^2N_\nu}{dEdt}(E,t)\right] = N_t\sigma_\nu(E)\lambda_\nu(E), \qquad \frac{dN_\nu}{dt}(t) = \int_0^\infty dE \left[\frac{d^2N_\nu}{dEdt}(E,t)\right].$$

In case of elastic scattering interactions, we can define the interaction rate with respect to E, t, and the recoil particle energy T:

$$\frac{d^3N_\nu}{dEdTdt}(E,T,t) = \frac{N_t}{4\pi d^2}\frac{d\sigma_\nu}{dT}(E,T)F_\nu(E,t) \qquad \frac{d\sigma_\nu}{dT} : \text{differential cross section with respect to } T.$$

Then, the interaction rate with respect to T is

$$\frac{dN_\nu}{dT}(T) = \int_{t_0}^{t_{end}} dt \int_{E_{min}(T)}^\infty dE \left[\frac{d^3N_\nu}{dEdTdt}(E,T,t)\right] = N_t \int_{E_{min}(T)}^\infty dE \left[\frac{d\sigma_\nu}{dT}(E,T)\lambda_\nu(E)\right],$$

$$E_{min}(T) = \frac{T + \sqrt{T(T+2m)}}{2}.$$

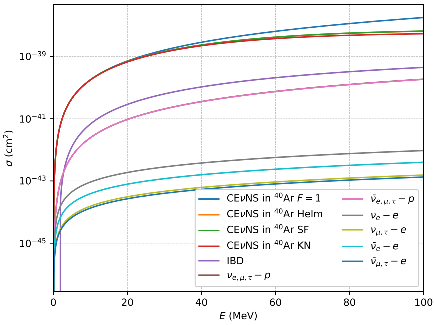
Supernova models

Model	Progenitor mass [$M_\odot$]	EoS	Time interval [s]
LS220-s11.2	11.2	LS220	-0.170092974551 – 0.500004733154
LS220-s11.2c	11.2	LS220	-0.170092974551 – 7.600478503686
LS220-s12.0	12.0	LS220	-0.187296800690 – 0.497543448537
LS220-s15.0	15.0	LS220	-0.304032523673 – 0.498446483650
LS220-s15s7b2	15.0	LS220	-0.221282374565 – 0.496251020000
LS220-s17.6	17.6	LS220	-0.284925820013 – 0.498178366419
LS220-s17.8	17.8	LS220	-0.279131376354 – 0.500068432690
LS220-s20.0	20.0	LS220	-0.256519704513 – 0.499980285627
LS220-s20.6	20.6	LS220	-0.412889509135 – 0.500009131565
LS220-s25.0	25.0	LS220	-0.455379448410 – 0.499728493980
LS220-s27.0	27.0	LS220	-0.344627618270 – 0.497878869527
LS220-s27.0c	27.0	LS220	-0.344627618270 – 8.350202515285
LS220-s27.0co	27.0	LS220	-0.349455361517 – 15.439433579436
LS220-z9.6co	9.6	LS220	-0.233381022196 – 11.999932339246
LS220-s40.0c	40.0	LS220	-0.408731709799 – 2.105601215751
LS220-s40s7b2c	40.0	LS220	-0.408737176878 – 0.567932280255
SFHo-s27.0co	27.0	SFHo	-0.292910194783 – 11.169139356183
SFHo-z9.6co	9.6	SFHo	-0.242266894100 – 13.622987243331
Shen-s8.8	8.8	Shen	-0.0636472236 – 8.90975001
Shen-s11.2	11.2	Shen	-0.136560972782 – 0.495312224658
Shen-s12.0	12.0	Shen	-0.144379115573 – 0.495545475007
Shen-s15.0	15.0	Shen	-0.211057570069 – 0.499739838584
Shen-s15s7b2	15.0	Shen	-0.167861670324 – 0.500369261592
Shen-s17.6	17.6	Shen	-0.199208094334 – 0.498790872514
Shen-s17.8	17.8	Shen	-0.190373490538 – 0.498689914046
Shen-s20.0	20.0	Shen	-0.187767329639 – 0.500071977502
Shen-s20.6	20.6	Shen	-0.254702334699 – 0.499291328668
Shen-s25.0	25.0	Shen	-0.275634063374 – 0.496790109348
Shen-s27.0	27.0	Shen	-0.227437666075 – 0.496242346477
Shen-s40.0	40.0	Shen	-0.254058543569 – 0.500396111047

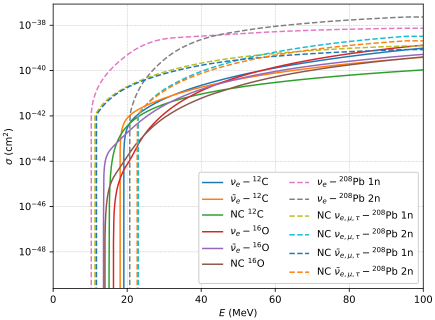
Supernova models from the Core-Collapse Modeling Group at the Max Planck Institute for Astrophysics, available in the software EstrellaNueva. Also, it is possible to define time-independent models in the software EstrellaNueva.

Detection channels

EstrellaNueva has implemented the cross sections for the principal detection channels for materials used in current an future detectors.



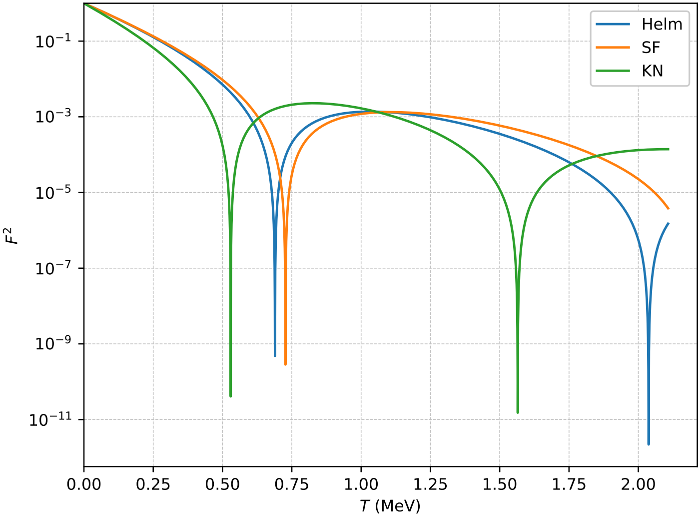
(a) Analytically implemented.



(b) Taken from the SNOwGLoBES repository.

As an example for CEνNS, the cross sections for ^{40}Ar are shown.

Nuclear form factors for ^{40}Ar.



Recent updates

Implementing the interaction rates with respect to the scattering angle for elastic scattering interactions ($\nu - e$, $\nu - p$, and CEνNS).

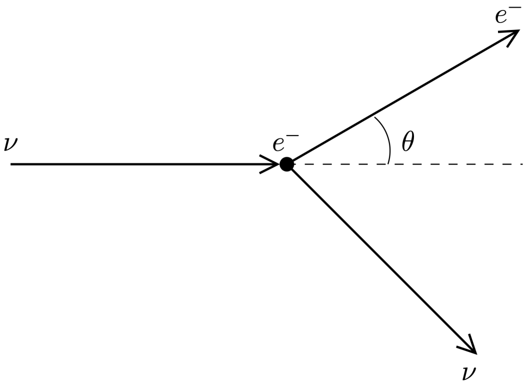


Figure: $\nu - e$ in the laboratory frame. Figure taken from Giunti & Wook (2007).

Interaction rates with respect to $\cos\theta$

We can define the interaction rate with respect to E, $\cos\theta$, and t:

$$\frac{d^3N_\nu}{dEd(\cos\theta)dt}(E,\cos\theta,t) = \frac{N_t}{4\pi d^2}\frac{d\sigma_\nu}{d(\cos\theta)}(E,\cos\theta)F_\nu(E,t),$$

where $\frac{d\sigma_\nu}{d(\cos\theta)}$ is the differential cross section with respect to $\cos\theta$.
Then, the interaction rate with respect to $\cos\theta$ is

$$\begin{aligned}\frac{dN_\nu}{d(\cos\theta)} &= \int_0^\infty dE \int_{t_0}^{t_{\text{end}}} dt \left[\frac{d^3N_\nu}{dEd(\cos\theta)dt}(E,\cos\theta,t)\right] \\ &= N_t \int_0^\infty dE \left[\frac{d\sigma_\nu}{d(cos\theta)}(E,\cos\theta)\lambda_\nu(E)\right].\end{aligned}$$

Differential cross section with respect to $\cos\theta$

Differential cross section with respect to $\cos\theta$:

$$\frac{d\sigma_\nu}{d(\cos\theta)}(E,\cos\theta) = \frac{d\sigma_\nu}{dT}(E,\, T(E,\cos\theta))\frac{dT}{d(\cos\theta)}(E,\cos\theta),$$

where $\frac{dT}{d(\cos\theta)}$ is the derivative of T with respect to $\cos\theta$.
Kinematic relation between the recoil particle energy T and the scattering angle θ for a given neutrino energy E:

$$T(E,\cos\theta) = \frac{2mE^2\cos^2\theta}{(m+E)^2 - E^2\cos^2\theta},$$

then,

$$\frac{dT}{d(\cos\theta)}(E,\cos\theta) = \frac{4mE^2(m+E)^2\cos\theta}{\left[(m+E)^2 - E^2\cos^2\theta\right]^2}.$$

Finally,

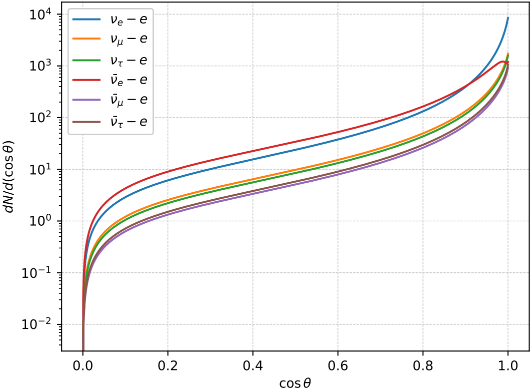
$$\frac{dN_\nu}{d(\cos\theta)}(\cos\theta) = N_t\int_0^\infty dE\left[\frac{d\sigma_\nu}{dT}(E,\, T(E,\cos\theta))\frac{dT}{d(\cos\theta)}(E,\cos\theta)\lambda_\nu(E)\right].$$

Interaction rates for $\nu - e$ in a 100 kiloton detector using LAB

Configuration

- model: LS220-s15.0,
- MSW: NO,
- distance: 10 kpc,
- material: LAB,
- detector mass: 100 kton

Channel	Events
$\nu_e - e$	212.21
$\nu_\mu - e$	59.94
$\nu_\tau - e$	53.30
$\bar{\nu}_e - e$	135.64
$\bar{\nu}_\mu - e$	31.53
$\bar{\nu}_\tau - e$	35.93
Total	528.55

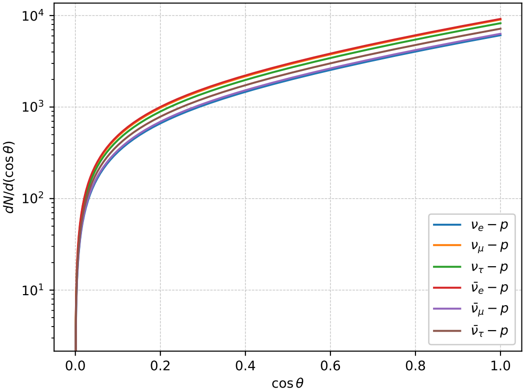


Interaction rates for $\nu - p$ in a 100 kiloton detector using LAB

Configuration

- model: LS220-s15.0,
- MSW: NO,
- distance: 10 kpc,
- material: LAB,
- detector mass: 100 kton

Channel	Events
$\nu_e - p$	2324.08
$\nu_\mu - p$	3440.57
$\nu_\tau - p$	3140.95
$\bar{\nu}_e - p$	3507.25
$\bar{\nu}_\mu - p$	2414.84
$\bar{\nu}_\tau - p$	2743.40
Total	17571.10

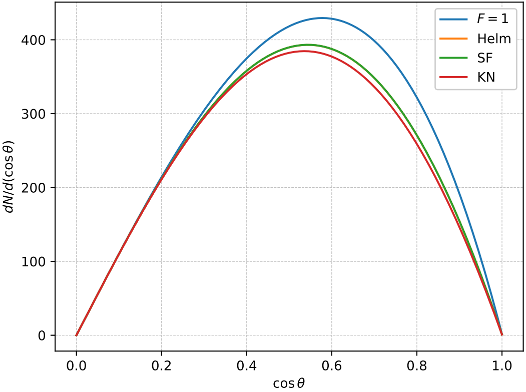


Interaction rates for CEνNS in a 100 ton detector using Liquid Argon (pure ^{40}Ar)

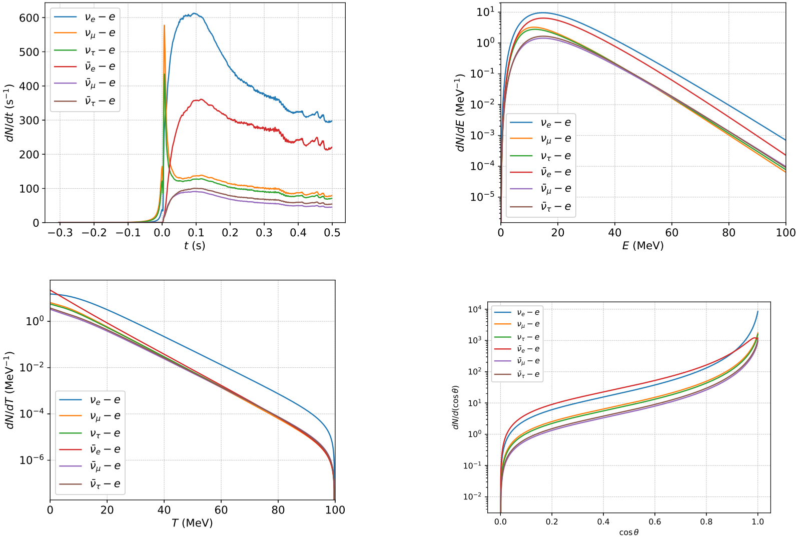
Configuration

- model: LS220-s15.0,
- MSW: off,
- distance: 10 kpc,
- material: Argon,
- detector mass: 100 ton

Form Factor	Events
$F = 1$	279.13
Helm	255.11
SF	255.17
KN	249.34



Complete set of interaction rates for $\nu - e$ in 100 kton of LAB, model: LS220-s15.0, distance: 10 kpc, MSW: NO



Final remarks

- EstrellaNueva provides a useful and friendly tool to study the interactions and detection of neutrinos emitted by supernovae; calculating fluences, interaction rates, and total number of interactions.
- The principal detection channels for materials used in current and future detectors, such as $\nu - e$, $\nu - p$, IBD, CEνNS, and the interactions with ^{12}C, ^{16}O and ^{208}Pb, are implemented.
- The Helm, Klein-Nystrand, and symmetrized Fermi nuclear form factors, for CEνNS interactions have been implemented. A nuclear form factor equal to one can also be assumed.
- The adiabatic MSW effect for flavor transformations in the supernova matter is also implemented.
- Several supernova models simulated by the Core-Collapse Modeling Group at the Max Planck Institute for Astrophysics are considered. In addition, the primary flux parameters can be considered constant in time, which is useful to study soft regions of the supernova neutrino spectrum.
- Published on The Astrophysical Journal: O. I. González-Reina et al. 2022, ApJ, 932, 125
- Software package available at: `https://doi.org/10.5281/zenodo.6412768`

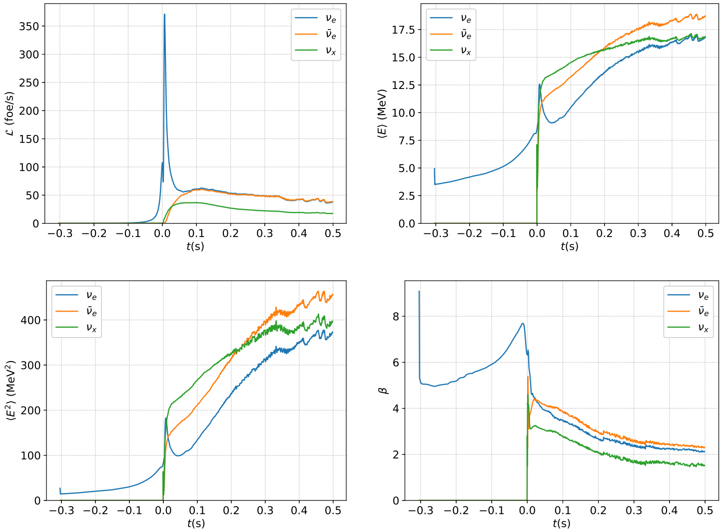
Next steps:

- Adding the experimental characteristics of the detectors to simulate the expected signal: efficiency and resolution.
- Implementing other supernova models: Princeton models as well as other Garching models.
- Integrating EstrellaNueva with SNEWPY.

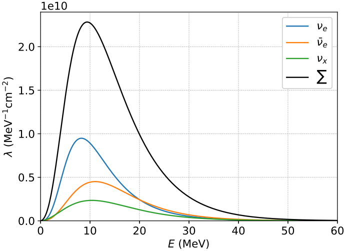
Thank you!

Primary flux parameters corresponding to the supernova model LS220-s15.0:

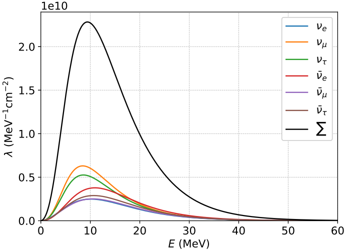
$$F_\nu^{\mathbf{0}}(E,t) = \mathcal{L}_\nu(t)\,\frac{(1+\beta_\nu(t))^{\mathbf{1}+\beta_\nu(t)}}{\Gamma\left(1+\beta_\nu(t)\right)}\,\frac{E^{\beta_\nu(t)}}{\left(\langle E_\nu\rangle\,(t)\right)^{\beta_\nu(t)+\mathbf{2}}} \times \exp\left[-\left(\beta_\nu(t)+1\right)\frac{E}{\langle E_\nu\rangle\,(t)}\right].$$



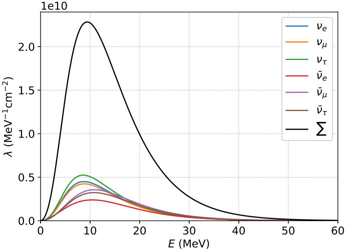
Fluences corresponding to the supernova model LS220-s15.0 for a distance of 10 kpc:



(a) No flavor transformations.



(b) Adiabatic MSW effect with NO.



(c) Adiabatic MSW effect with IO.

Cross section of CEνNS

$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2 M}{4\pi} q_W^2 \left(1 - \frac{MT}{2E^2}\right) F^2(q^2), \qquad q_W = N - \left(1 - 4\sin^2\theta_W\right) Z, \qquad q^2 \approx 2MT.$$

Form factors

- $F_{\text{Helm}}(q^2) = 3\frac{j_1(qR_0)}{qR_0} e^{-(qs)^2/2}$,
- $F_{\text{SF}}(q^2) = \frac{3}{qc[(qc)^2+(\pi qa)^2]} \left[\frac{\pi qa}{\sinh(\pi qa)}\right] \left[\frac{\pi qa \sin(qc)}{\tanh(\pi qa)} - qc\cos(qc)\right]$
- $F_{\text{KN}}(q^2) = \frac{4\pi\rho_0}{Aq^3}(\sin(qR_A) - qR_A\cos(qR_A))\frac{1}{1+(qa_k)^2}$

Parameters

- $s = 0.9$ fm (nuclear surface thickness)
- $R_0 = \sqrt{c^2 + \frac{7}{3}\pi^2 a^2 + s^2}$ (diffraction radius)
- $c = 1.23A^{1/3} - 0.60$ fm (half density radius)
- $a = 0.52$ fm (diffuseness)
- $a_k = 0.7$ (range of the Yukawa potential)
- $R_A = A^{1/3} r_0$ (effective nuclear radius)
- $r_0 = 1.3$ fm (proton radius)
- $\rho_0 = \frac{3}{4\pi r_0^3}$ (nuclear density)