Supernovae neutrino detection via coherent scattering off silicon nuclei

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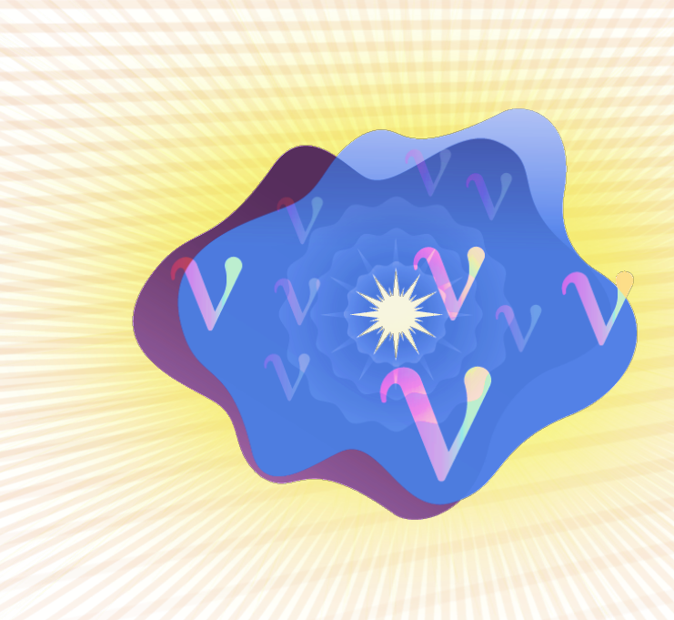


Introduction

Low-energy neutrinos are clean messengers from supernovae explosions and probably carry unique insights into the process of stellar evolution. We estimate the expected number of events considering coherent elastic scattering of neutrinos off silicon nuclei, as would happen in Charge Coupled Devices (CCD) detectors. The number of expected events, integrated over a window of about 18 s, is ~ 4 if we assume 10 kg of silicon and a supernovae 1 kpc away. For a distance similar to the red supergiant Betelgeuse, the number of expected events increases to ~ 30 – 120, depending on the supernovae model. We argue that silicon detectors can be effective for supernovae neutrinos and might possibly distinguish between models for certain target masses and distances.

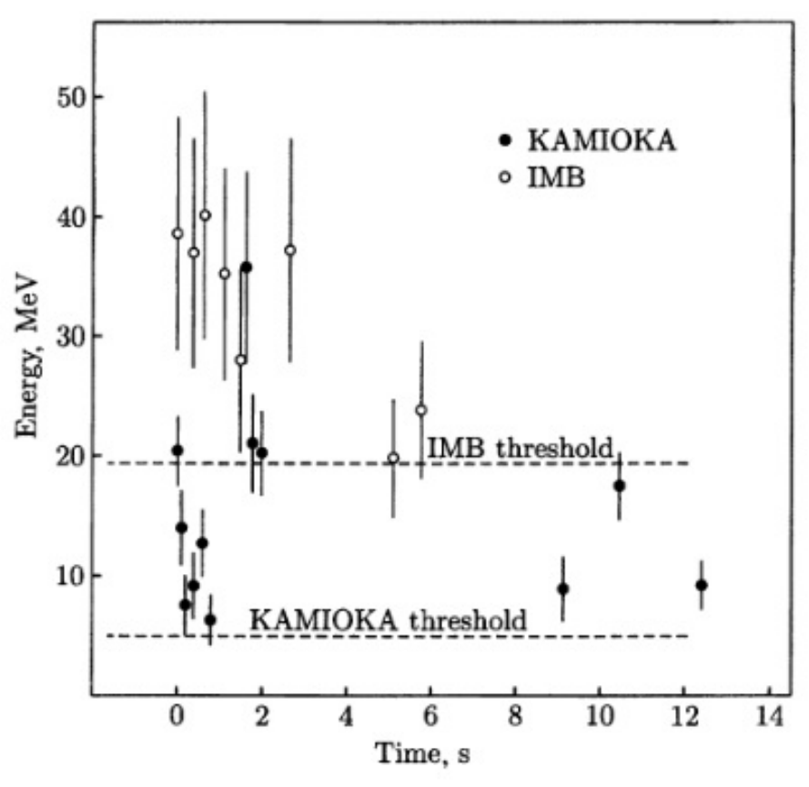
Supernova Neutrinos

The hydrostatic equilibrium of a star is maintained by the counterbalance of two opposite forces, gravity and the force generated from thermal pressure of fuel burning. If the star is massive enough, the burning proceeds to heavier elements, forming an onion shell structure inside the star. For stars heavier than $\sim 8\ M_\odot$, the gravitational force is strong enough to trigger **neutronization**, i.e. the process in which a proton captures an electron releasing a neutron and an electron neutrino via the inverse beta decay

$$p + e^- \rightarrow n + \nu_e$$

Due to their very weak interaction, neutrinos quickly escape from the star, creating a pressure gradient that leads to the instability and collapse with a potentially supernova explosion. These astronomical transient events are the most powerful **sources of MeV neutrinos** in the universe, that come in **all flavors** and are emitted over a timescale of **several tens of seconds**.

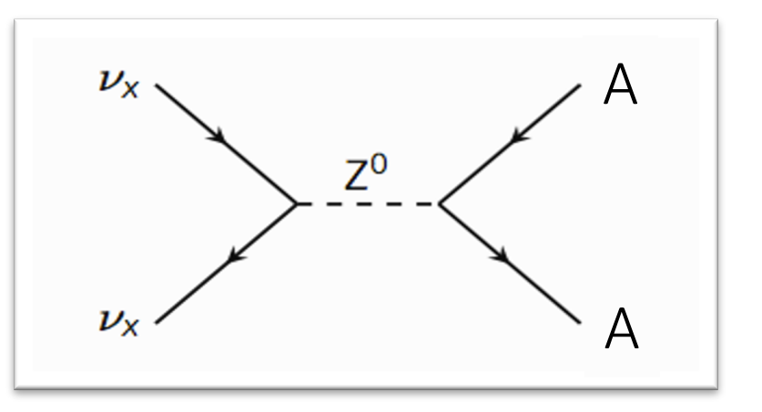
SN1987A: In 1987, the neutrinos coming from a supernova in the Large Magellanic Cloud arrived at Earth. In the brief period of ~13 seconds, 25 were detected by water Cherenkov and scintillator experiments. This was the **only supernova neutrino detection in the history of humanity.**



The well-known observed energy-time spectra of the SN 1987A neutrino events as published by Kamiokande and IMB. Extracted from ref. [1]

Coherent Elastic νN Scattering

Predicted for the first time in 1974, and recently measured by the COHERENT collaboration [2], the CEνNS is a **neutral current interaction** in which a neutrino of **any flavor** scatters off a nucleus transferring some energy in the form of a nuclear recoil. They are dominant for **low energy neutrinos** ($E_\nu < 50\ MeV$).



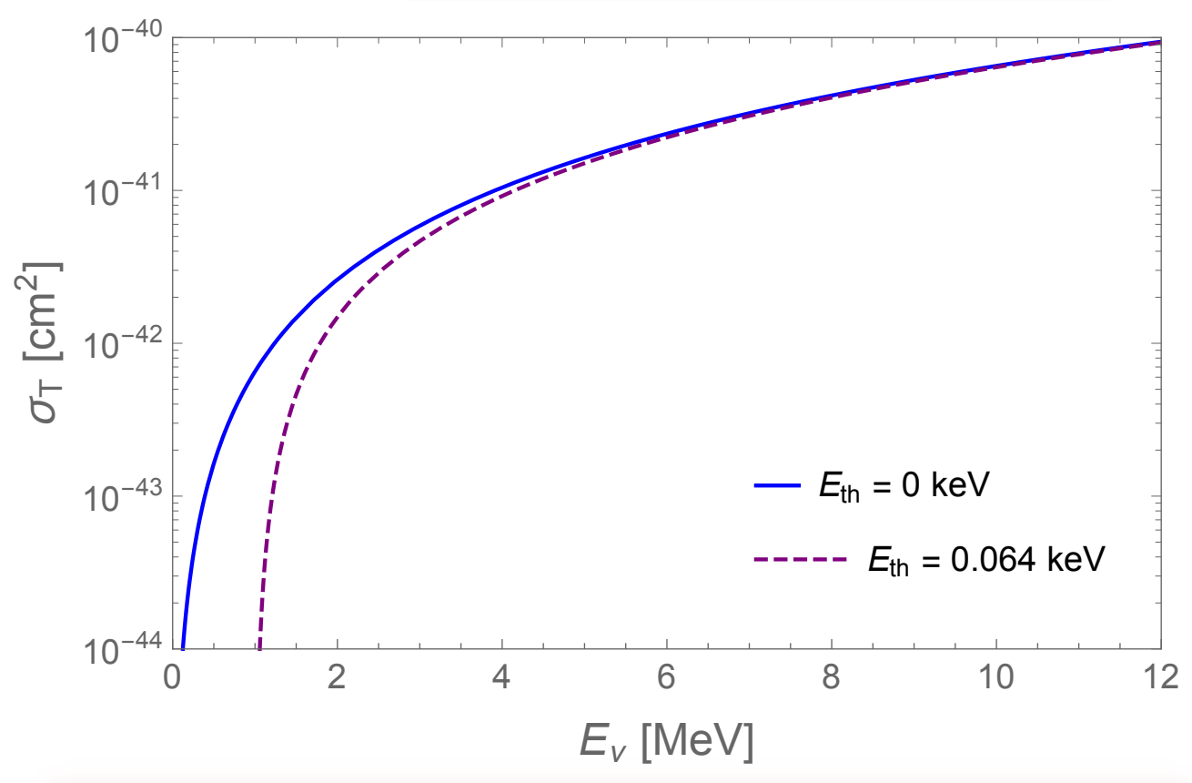
The differential cross section as a function of neutrino energy E_ν and nuclear recoil energy $E_{\rm nr}$ is

$$\frac{d\sigma}{dE_{nr}} = \frac{G_F^2}{8\pi} Q_W^2 \left[2 - \frac{2E_{nr}}{E_\nu} + \left(\frac{E_{nr}}{E_\nu}\right)^2 - \frac{ME_{nr}}{E_\nu^2} \right] M|F(q)|^2$$

where

$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

G_F = Fermi constant	Z = Number of protons	θ_W = Weak mixing angle
M = Target nuclear mass	N = Number of neutrons	$F(q^2)$ = Nuclear form factor



Total cross section σ_T of the coherent scattering of neutrinos off silicon nuclei as a function of the neutrino energy. E_{th} is the energy threshold of the detector.

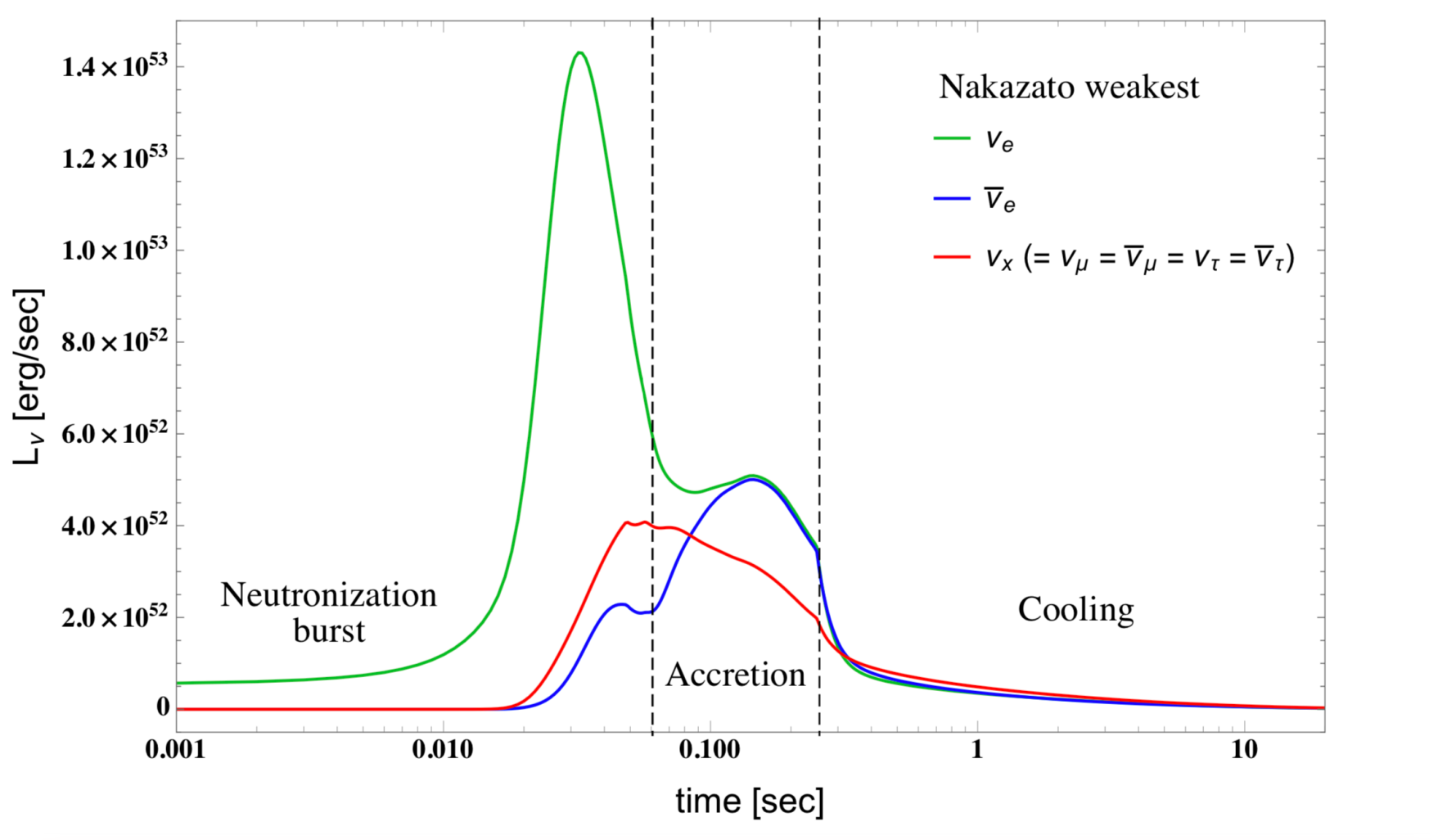
Supernova Model

Estimate the expected number of SNν events ⇒ SN neutrino spectrum ⇒ **SN numerical simulations**

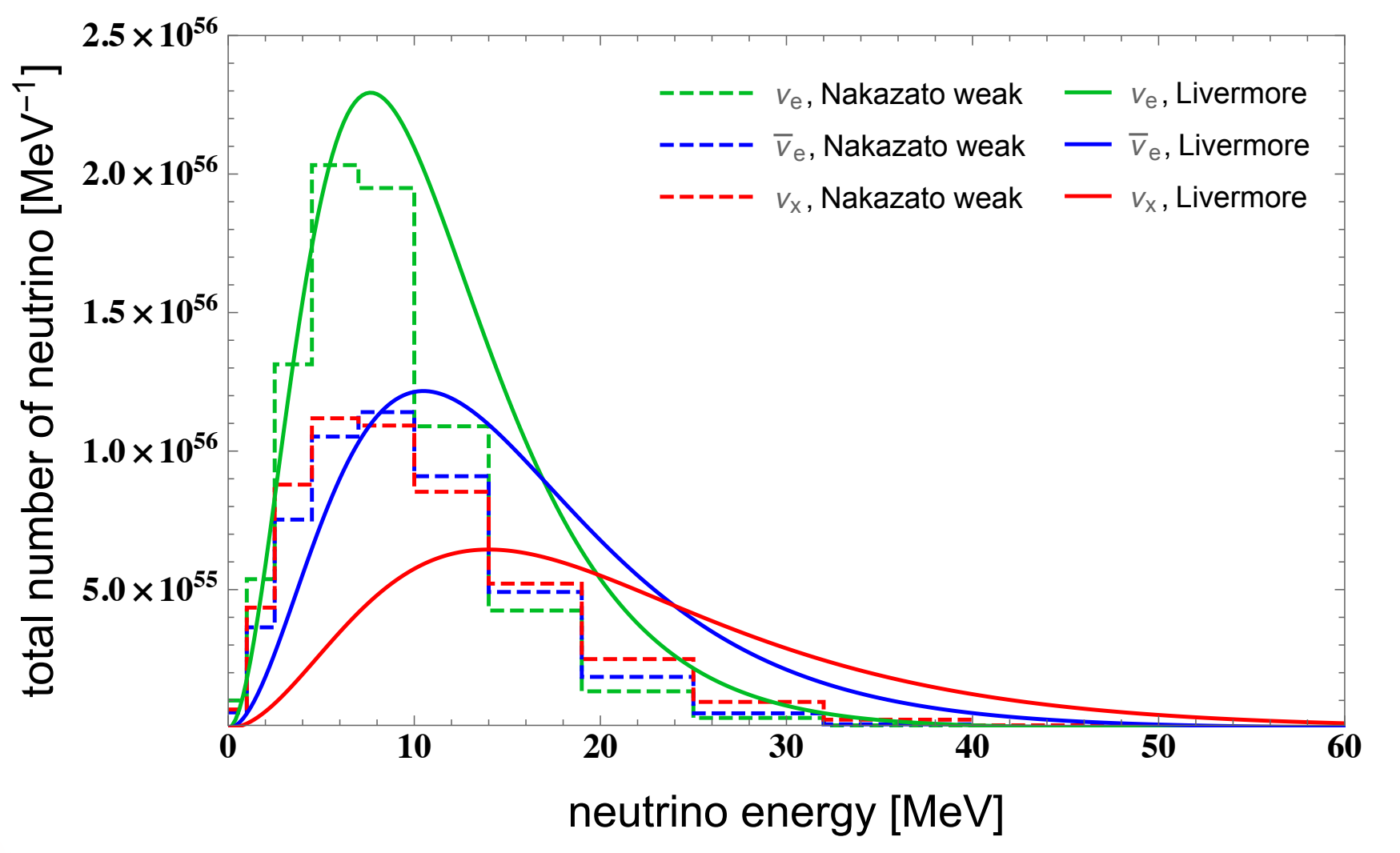
Livermore: one-dimensional numerical simulation based on SN1987A and performed from the onset of the collapse to 18 seconds after the core bounce. The progenitor is a main-sequence star of about 20 $M_\odot$ [3].

Nakazato: 1D simulations [4] performed from the core-collapse to ~20 seconds. The neutrino energy-spectra is available at a public database [5] for different mass progenitors M_p, galaxy metallicities Z and shock revival times t_{rev}. In the following study we considered 3 different Nakazato models:

- Nakazato weakest: $M_p = 20\ M_\odot$, $Z = 0.02$, $t_{rev} = 200\ ms$
- Nakazato brightest: $M_p = 30\ M_\odot$, $Z = 0.02$, $t_{rev} = 300\ ms$
- Nakazato black hole: $M_p = 30\ M_\odot$, $Z = 0.004$



Time profile of the neutrino luminosity considering Nakazato weakest simulation. The green peak signals the neutronization burst of electron neutrinos.



Total number of emitted neutrinos, integrated to about 18 s after the core bounce, as a function of the neutrino energy.

Event Rate

The differential event rate of SNν as a function of the nuclear recoil energy $E_{\rm nr}$ can be expressed as:

$$\frac{dR_0}{dE_{nr}}(E_{nr}) = \frac{M_{det}N_A}{A(4\pi d^2)} \sum_{i=\nu_e,\bar{\nu}_e,\nu_x} \int_{E_{min}}^{\infty} \frac{d\sigma}{dE_{nr}} f_i(E_\nu)dE_\nu$$

M_{det} = detector mass
d = supernova distance
N_A = Avogadro's number
A = atomic mass of silicon
$f_i(E_\nu)$ = neutrino energy spectra
$E_{\rm min}$ = minimal neutrino energy that can produce a nuclear recoil with energy E_{nr}

$$E_{min} = (E_{nr} + \sqrt{E_{nr}^2 + 2ME_{nr}})/2$$

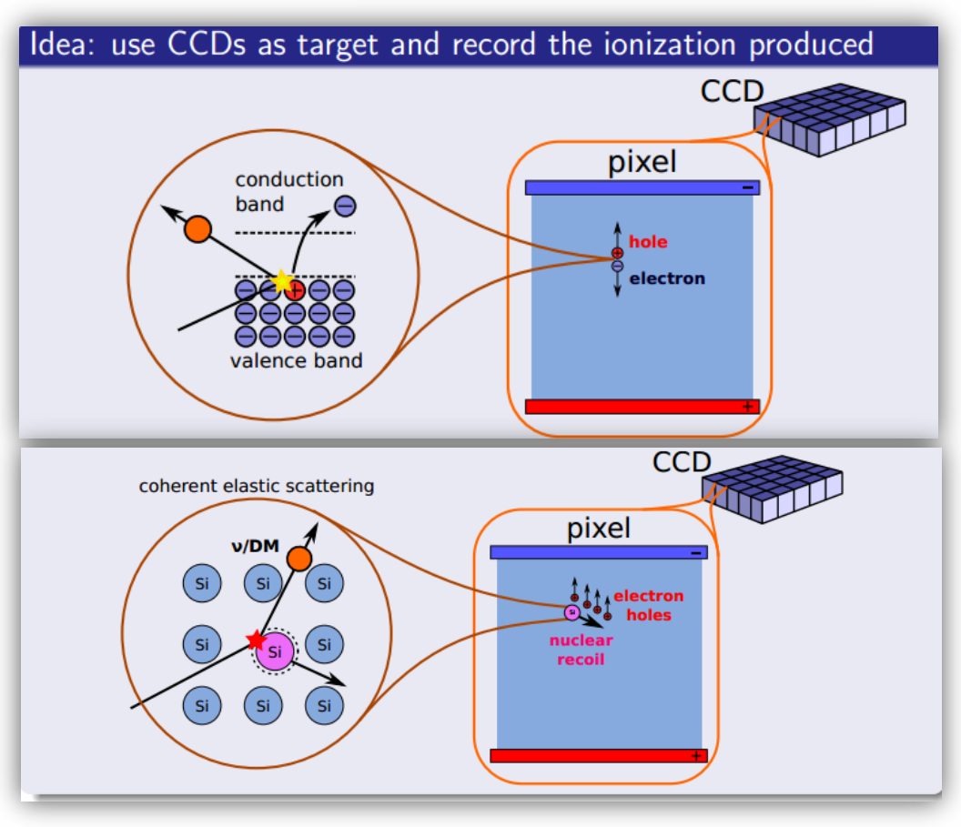
Energy deposition in CEνNS is very low (nuclear recoil energies are in the keV range) ⇒ Detection is experimentally very difficult ⇒ Very sensitive and low-noise detectors ⇒ Charge Coupled Devices (CCDs)!

The CONNIE Experiment

(Coherent Neutrino Nucleus Interaction Experiment) [6]

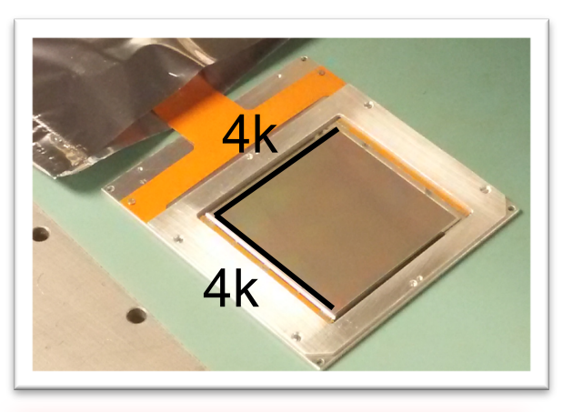
Motivation: Detection of Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)
- Irreducible background for WIMP detection in Dark Matter experiments
- MeV-neutrino physics has great relevance for energy transport in supernovae
- Opportunity to test physics beyond the Standard Model (see Ref. [7])

Detectors: Charge Coupled Devices (CCD's)
- Very low energy threshold silicon detectors: 5.5 eV
- "3D" information (diffusion): rejection of surface events



Location: Almirante Álvaro Alberto Nuclear Power Plant
- 30 meters from the Angra 2 core reactor
- 200 meters from the Angra 1 core reactor

Shielding: Reduces the Background contamination
- Polyethylene (for stopping neutrons)
- Lead (for stopping muons and gammas)



CONNIE 4k x 4k CCD

Quenching Factor and Efficiency

CCDs sensors measure the ionization energy E_I, i.e the fraction of the silicon nuclei recoil energy that is converted into charge carriers. In order to relate the true recoil energy into the observable ionization energy we need to use the quenching factor Q

$$Q = \frac{E_I}{E_{nr}} \quad \Rightarrow \quad \frac{dR_0}{dE_I}(E_I) = \frac{dR_0}{dE_{nr}}\frac{dE_{nr}}{dE_I} = \frac{dR_0}{dE_{nr}}\frac{1}{Q}\left(1 - \frac{E_I}{Q}\frac{dQ}{dE_I}\right)$$

For this purpose we employed the quenching factor measurements by Chavarria et al. [8].

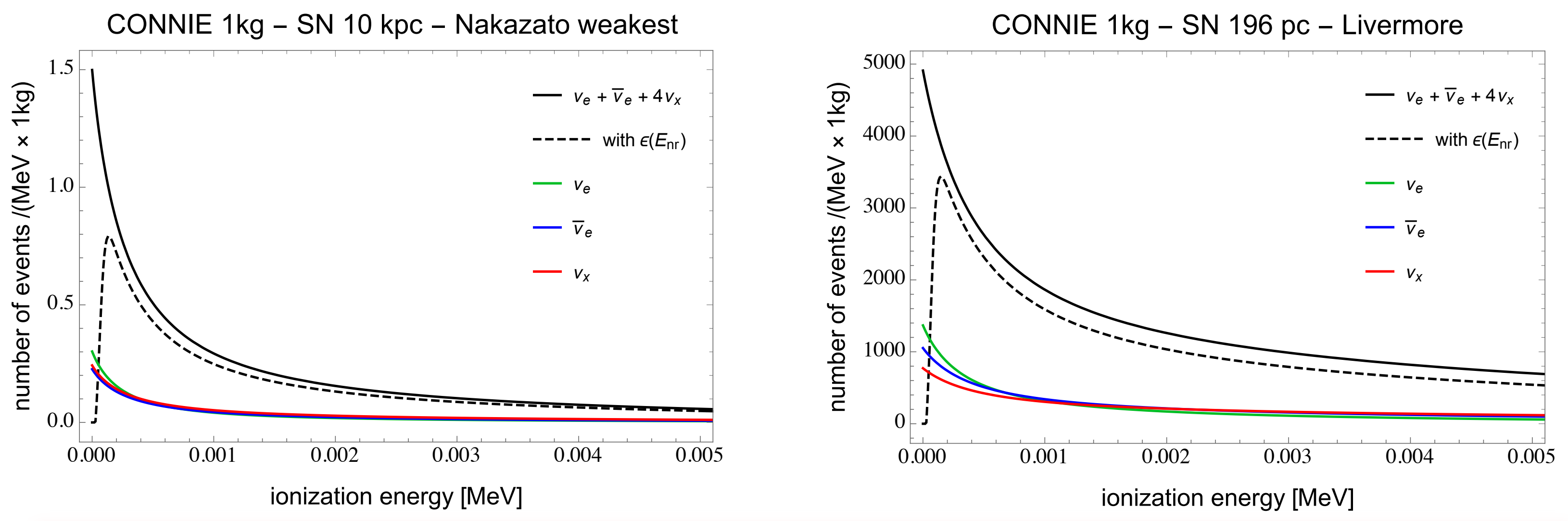
Finally, for a realistic event rate calculation, one must take into account the reconstruction efficiency $\epsilon(E_I)$ of the events registered in the CCDs:

$$\frac{dR}{dE_I} = \epsilon(E_I) \times \frac{dR_0}{dE_I}(E_I)$$

For the CONNIE processing tools, $\epsilon(E_I)$ has been evaluated in [6] using simulated events.

Results and Discussion

Event Rate Plots:



Energy spectrum as a function of the silicon ionization energy for the Nakazato weakest SN model (left) and the Livermore SN model (right). The SN distance was set to 10 kpc in the left panel and to 196 pc in the right panel. In both plots the detector mass is equal to 1 kg.

The total number of observable SN neutrino events of all flavors N_{obs} can be obtained by integrating the realistic differential event rate over all values of ionization energies:

$$N_{obs} = \int_{E_{th}}^{\infty} \frac{dR}{dE_I} dE_I$$

CONNIE E_{th} = 64 eV

		Supernova Model			
M_{det}[kg]	d[pc]	Livermore	Nakazato (weakest)	Nakazato (brightest)	Nakazato (black hole)
1	10^3	0.005	0.001	0.002	0.005
1	196	12.41	3.13	6.17	12.49
10	10^3	0.048	0.012	0.024	0.048
10	196	124.08	31.28	61.65	124.86
30	10^3	0.14	0.04	0.07	0.14
30	196	372.24	93.83	184.95	374.58

Number of observable SNν events calculated with CONNIE processing efficiency.

However, the CONNIE experiment is a surface detector close to a nuclear reactor ⇒ very high background contamination ~10 kdru (1 dru = 1 event/day/kg/keV).
Better choice: Underground Experiments

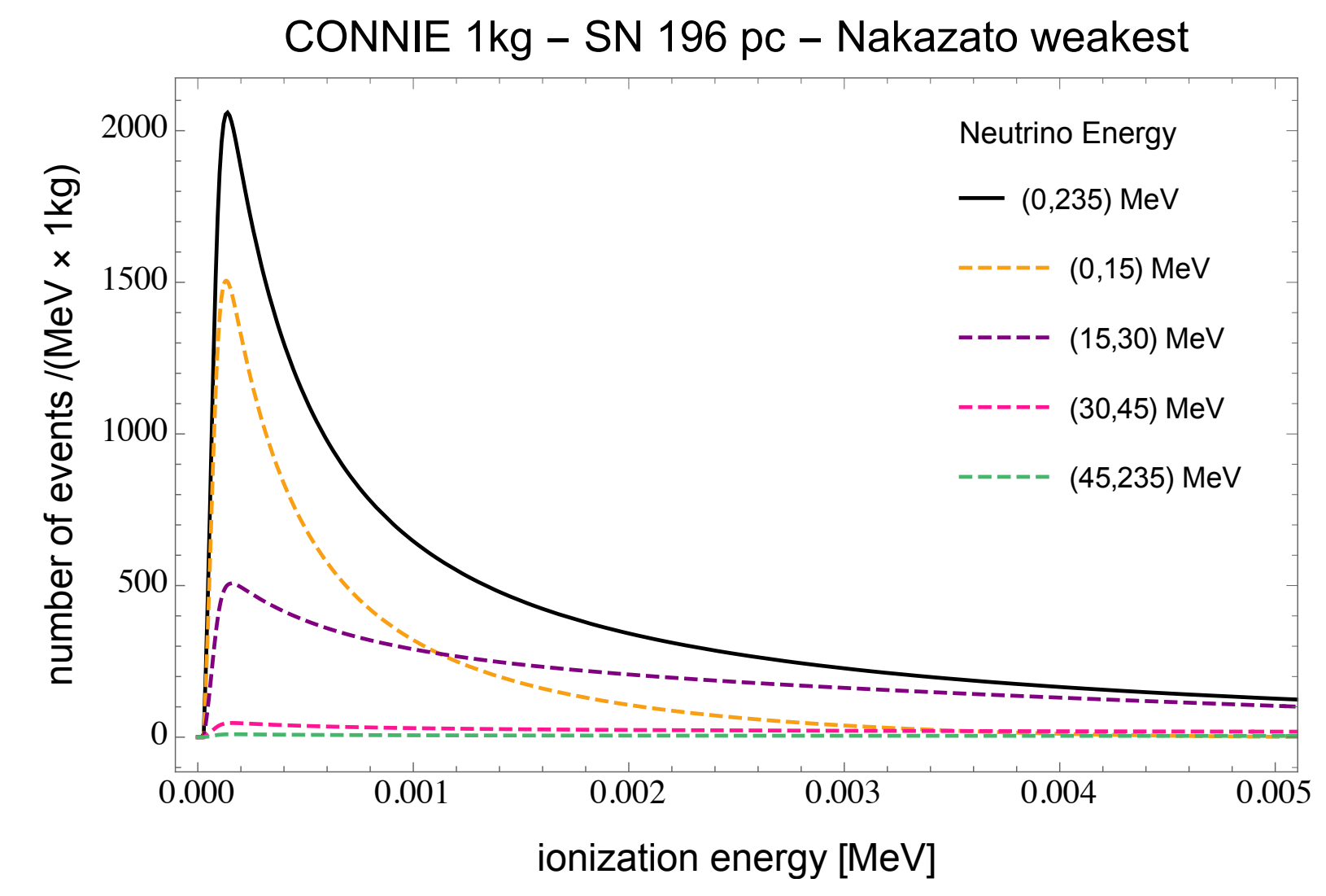
- SENSEI (Sub-Electron-Noise Skipper CCD Experimental Instrument) [9]
  - Skipper-CCD technology: non-destructive readout system (threshold of 15 eV)
  - A 100 g Skipper-CCD experiment is being assembled at SNOLAB with a background rate of 5 dru.
- DAMIC-M (DArk Matter In CCDs at Modane) [10]
  - 1 kg detector composed of 50 CCDs with Skipper technology
  - Background contamination of 0.1 dru
- OSCURA (Observatory of Skipper CCDs Unveiling Recoiling Atoms) [11]
  - 10 kg Skipper-CCD experiment with a projection of ~ 0.01 dru background

		Supernova Model			
M_{det} [kg]	d [pc]	Livermore	Nakazato (weakest)	Nakazato (brightest)	Nakazato (black hole)
0.1	10^3	0.0006	0.0002	0.0003	0.0006
0.1	196	1.50	0.39	0.76	1.48
1	10^3	0.006	0.002	0.003	0.006
1	196	15.00	3.92	7.62	14.85
10	10^3	0.06	0.02	0.03	0.06
10	196	150.02	39.2	76.24	148.48

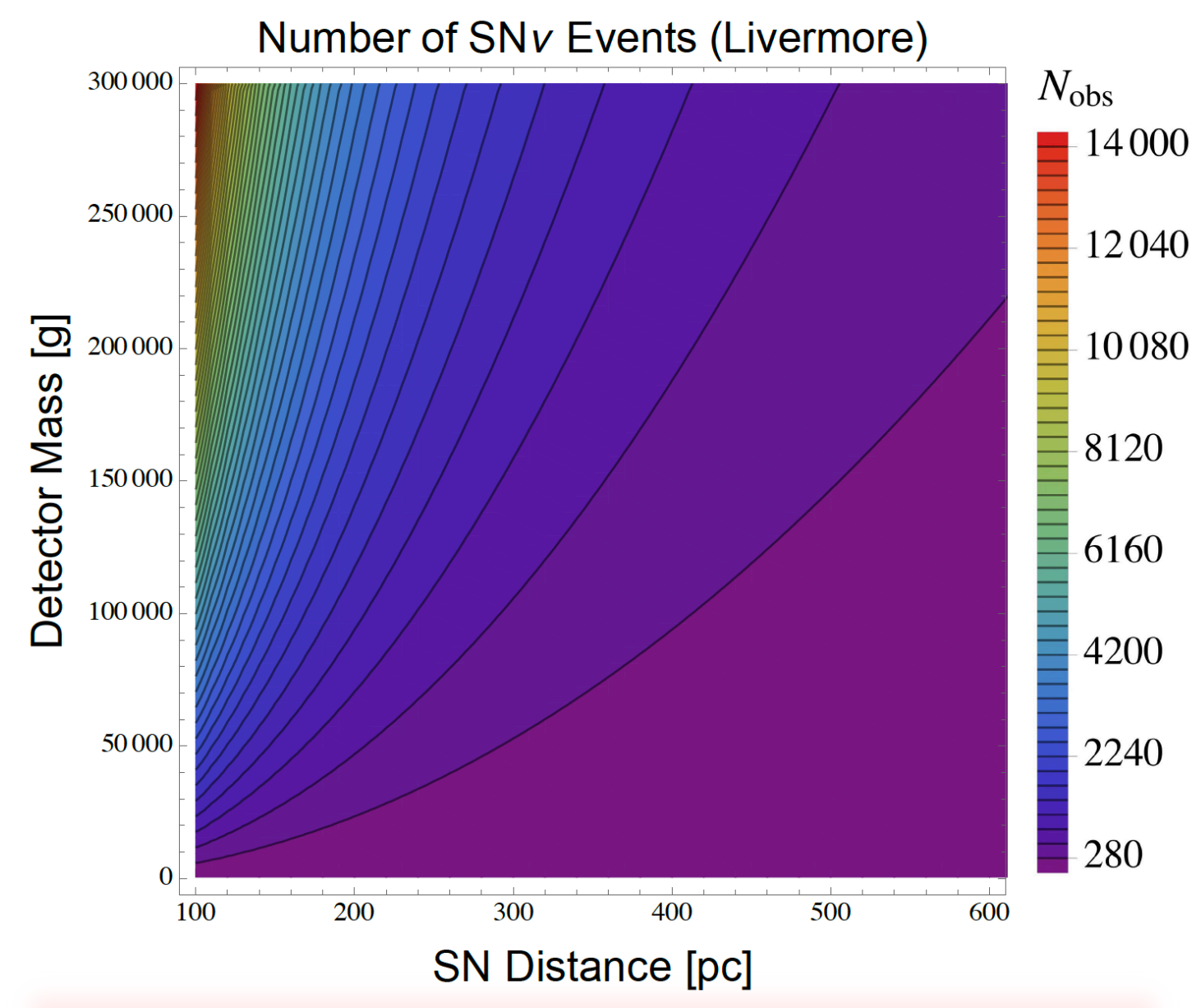
Number of observable SNν events considering the efficiency of Skipper-CCDs.

What are the advantages of SNν detection with CCDs?

Silicon can be used for detection of very low energy SN neutrinos while the noble liquid is mostly sensitive to neutrinos above 15 MeV.



Silicon detectors are sensitive exactly in this low-energy regime in which other types of detectors lack efficiency !



Contour plot of the number of observable SNν events considering a **wide range of values for the detector mass.**

References

[1] D. H. Perkins, *Introduction to High Energy Physics* (Cambridge University Press).
[2] D. Akimov *et al.*, *Science* **357** , 1123 (2017).
[3] T. Totani *et al., Astrophys. J.* **496** , 216 (1998)
[4] K.Nakazato *et al.*, *Astrophys. J. Suppl. Ser.* , **205**:2 (2013)
[5] Nakazato Supernova Neutrino Database: http://asphwww.ph.noda.tus.ac.jp/snn/
[6] A. Aguilar-Arevalo et al. (CONNIE), Phys. Rev. D **100**, 092005 (2019)
[7] A. Aguilar-Arevalo et al. (CONNIE), JHEP **04**, 054 (2019), arXiv:1910.04951 [hep-ex].
[8] A. Chavarria *et al.*, Phys. Rev. D **94**, 082007 (2016), arXiv:1608.00957 [astro-ph.IM].
[9] M. Crisler, *et al.*, Physical Review Letters **121**, 10.1103/physrevlett.121.061803 (2018).
[10] N.Castello-Mor (DAMIC-M),Nucl. Instrum. Meth. A **958**, 162933 (2020), arXiv:2001.01476
[11] OSCURA, https://astro.fnal.gov/science/dark-matter/oscura/ (2020)

Acknowledgments

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