Neutrino Interaction Rate in CUTE

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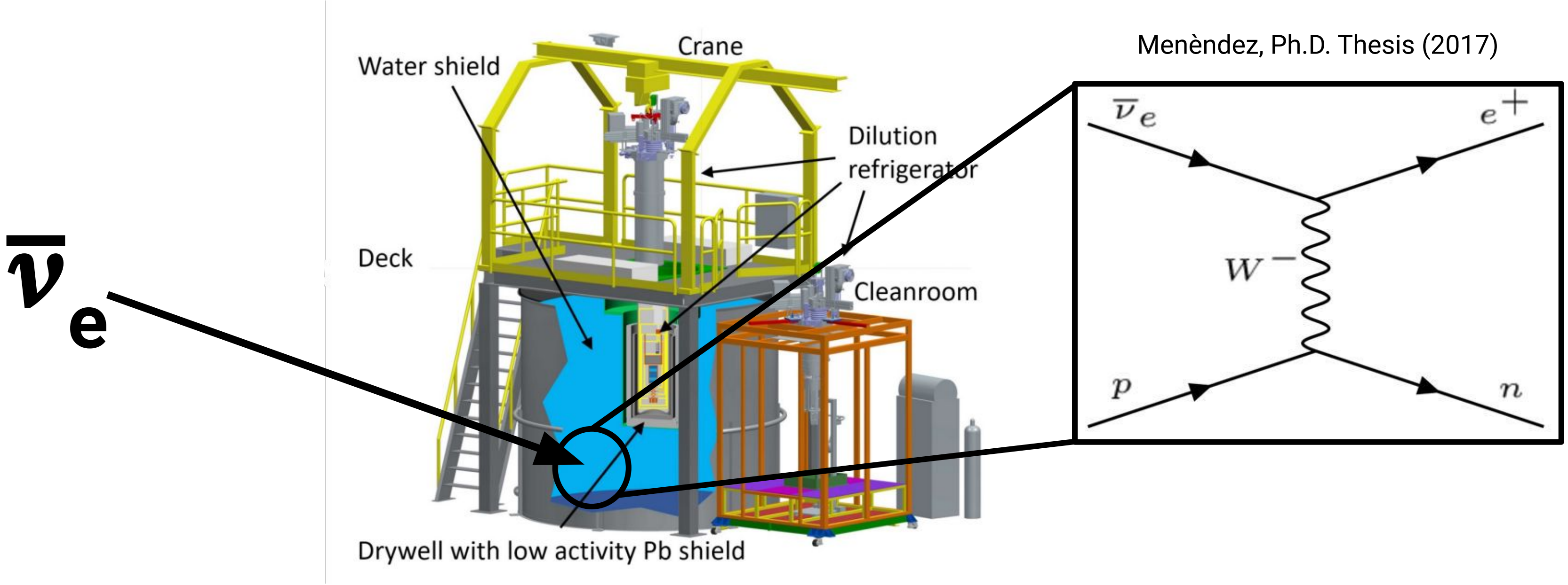
Outline

- **Describe the Problem**
- **Neutrino Interactions: Inverse Beta Decay (IBD)**
- **Information We Need**
  - Neutrino-Proton Cross Section
  - CUTE Fridge as a Target
  - Galactic Core-Collapse Supernovae (CCSN) Flux Models
- **Interactions as a Function of Distance**
- **EDI Component**

Determine the number of neutrino interactions there would be in the CUTE water tank as a function of distance to the next galactic core-collapse supernova.



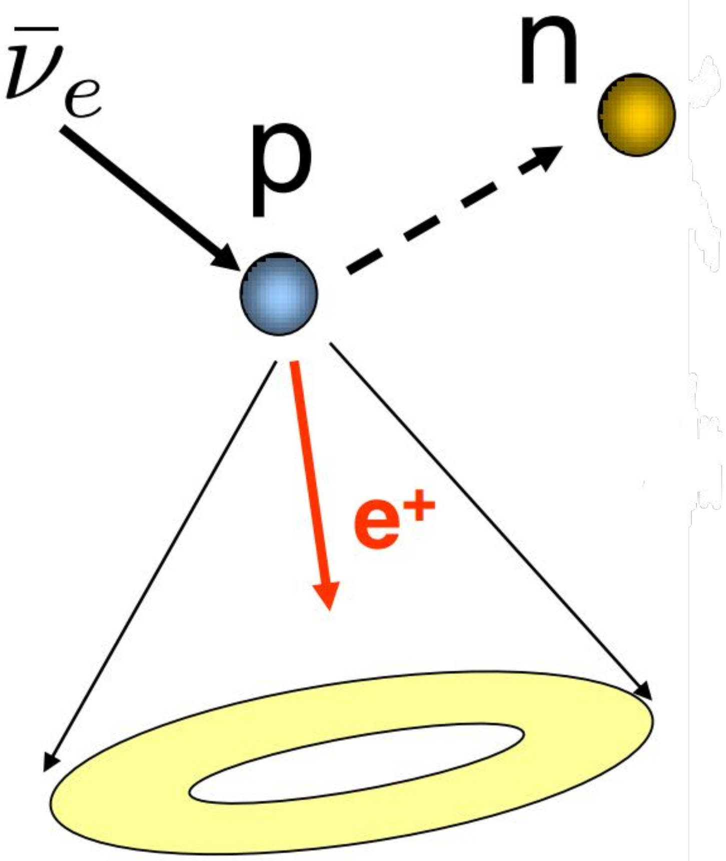
Andy Kubik, RISQ 2024

Neutrino Interactions

➢ Only weakly interact with the nuclei in a water tank

➢ Assume that cross-section for inverse beta decay (IBD) is overwhelmingly dominant ($\sim 92.6\%$ of interactions)*

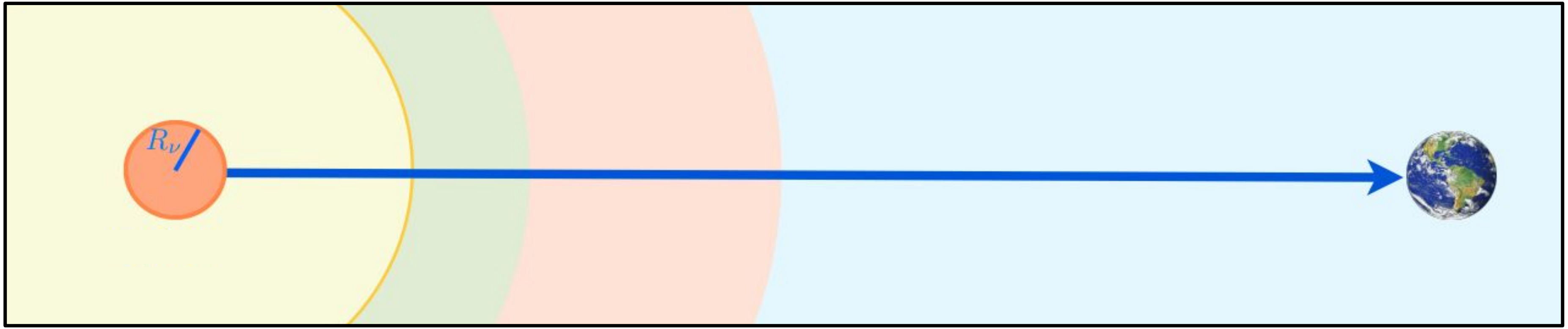
➢ For simplicity, we will find the cross-section for IBD interactions and scale by a factor of $1/0.926$ to estimate the total number of interactions from all processes



Irene Tamborra, International Neutrino Summer School 2021

*K. Scholberg, 2011

Information We Need for the Calculation



Irene Tamborra, International Neutrino Summer School 2021

$$N_{\bar{\nu}_e \text{ interactions}} = N_{\text{targets}} \int_{E_\nu} \left[\int_t \Phi(E_\nu) dt \right] \cdot \sigma(E_\nu) dE_\nu$$

 # protons in CUTE fridge

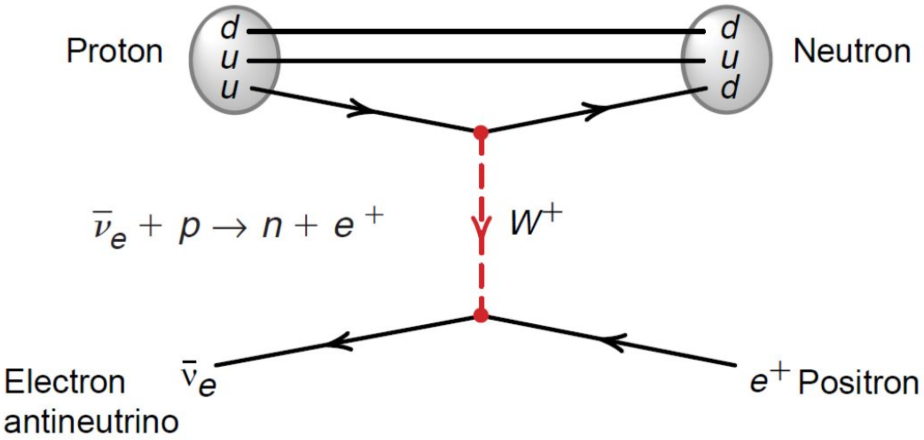
Time-integrated flux in units [count] / [energy x area]

Cross section as a function of energy

Kate Scholberg, Supernova Hack Days IV

Neutrino-Proton Cross Section

$$\overline{\nu}_e(p_\nu) + p(p_p) \rightarrow e^+(p_e) + n(p_n)$$



$$\frac{d\sigma}{dt} = \frac{G_F^2 \cos^2\theta_C}{2\pi(s - m_p^2)^2}|\mathcal{M}|^2$$

$$\mathcal{M} \propto J_\mu^{lepton} J^\mu_{hadron}$$

Mandelstam variables:

$$s = (p_\nu + p_p)^2, t = (p_\nu - p_e)^2, u = (p_\nu - p_n)^2$$

arXiv:astro-ph/0302055

Neutrino-Proton Cross Section

$$\overline{\nu}_e(p_\nu) + p(p_p) \to e^+(p_e) + n(p_n)$$

$$J_\mu^{lepton} = \overline{v}_{\nu_e}\gamma_\mu(1-\gamma_5)v_e$$

$$J^\mu_{hardon} = \overline{u}_n\left(f_1\gamma^\mu + g_1\gamma^\mu\gamma_5 + i f_2\sigma^{\mu\nu}\frac{q_\nu}{2M} + g_2\frac{q^\mu}{M}\gamma_5\right)u_p$$

$$|\mathcal{M}|^2 = A(t) - (s-u)B(t) + (s-u)^2C(t)$$

$$|\mathcal{M}|^2 \propto L^{\mu\nu}(p_l, q)H_{\mu\nu}(p_h, q) \qquad p_l \cdot p_h = s - u$$

Mandelstam variables:

$$s = (p_\nu + p_p)^2, t = (p_\nu - p_e)^2, u = (p_\nu - p_n)^2$$

arXiv:astro-ph/0302055

Neutrino-Proton Cross Section

$$|\mathcal{M}|^2 = A(t) - (s-u)B(t) + (s-u)^2 C(t)$$

$$16\,A = (t - m_e^2)\Big[4|f_1^2|(4M^2 + t + m_e^2) + 4|g_1^2|(-4M^2 + t + m_e^2) + |f_2^2|(t^2/M^2 + 4t + 4m_e^2) + 4m_e^2 t|g_2^2|/M^2 + 8\mathrm{Re}[f_1^* f_2](2t + m_e^2) + 16m_e^2\mathrm{Re}[g_1^* g_2]\Big]$$
$$-\Delta^2\Big[(4|f_1^2| + t|f_2^2|/M^2)(4M^2 + t - m_e^2) + 4|g_1^2|(4M^2 - t + m_e^2) + 4m_e^2|g_2^2|(t - m_e^2)/M^2 + 8\mathrm{Re}[f_1^* f_2](2t - m_e^2) + 16m_e^2\mathrm{Re}[g_1^* g_2]\Big] - 32m_e^2 M\Delta\mathrm{Re}[g_1^*(f_1 + f_2)]$$
$$16\,B = 16t\mathrm{Re}[g_1^*(f_1 + f_2)] + 4m_e^2\Delta\left(|f_2^2| + \mathrm{Re}[f_1^* f_2 + 2g_1^* g_2]\right)/M$$
$$16\,C = 4(|f_1^2| + |g_1^2|) - t|f_2^2|/M^2.$$

$$\{f_1, f_2\} = \frac{\{1 - (1+\xi)t/4M^2, \xi\}}{(1 - t/4M^2)(1 - t/M_V^2)^2}, \quad g_1 = \frac{g_1(0)}{(1 - t/M_A^2)^2}, \quad g_2 = \frac{2M^2 g_1}{m_\pi^2 - t}$$

arXiv:astro-ph/0302055

Neutrino-Proton Cross Section

Rest frame of proton

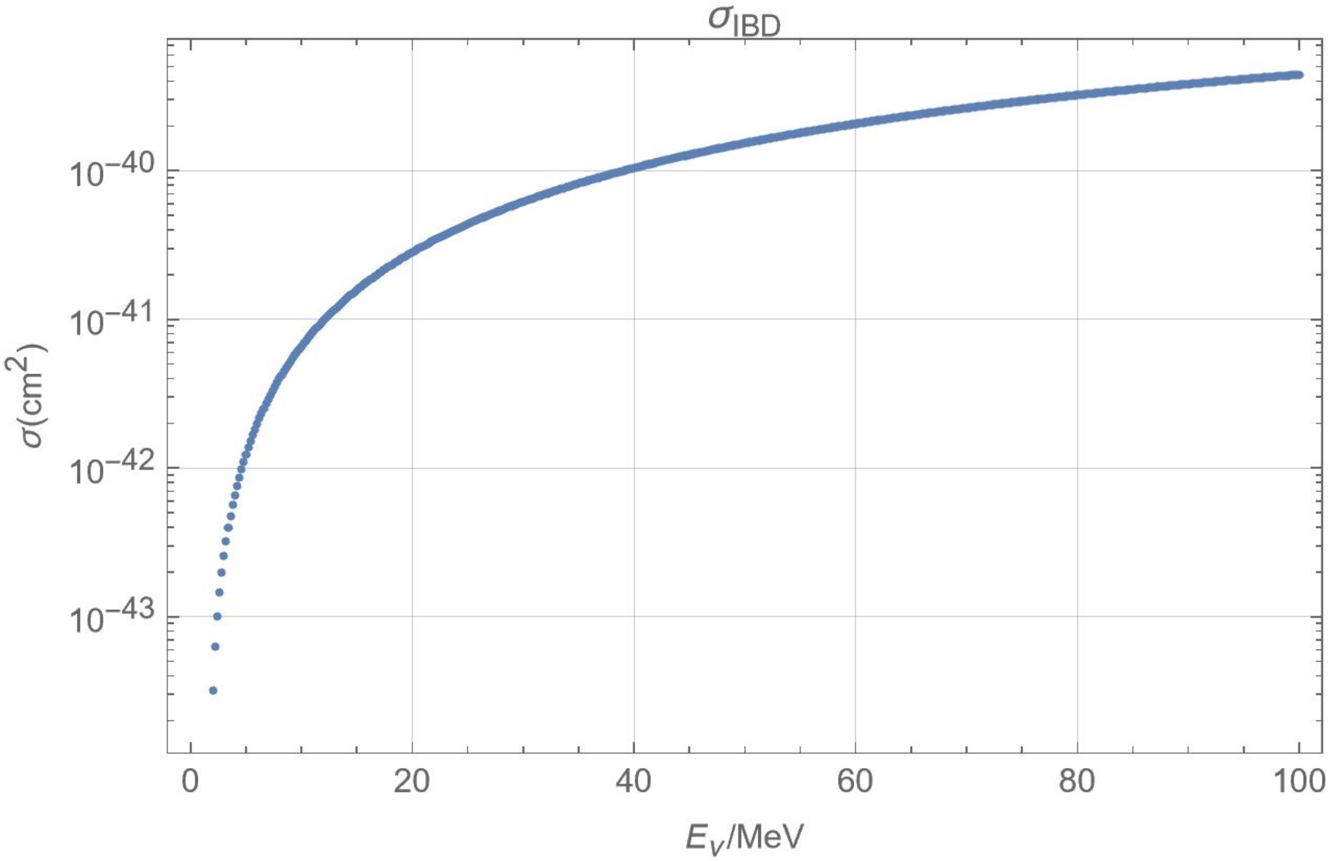
$$s - m_p^2 = 2m_p E_\nu, \qquad s - u = 2m_p(E_\nu + E_e) - m_e^2, \qquad t = m_n^2 - m_p^2 - 2m_p(E_\nu - E_e)$$

$$\frac{d\sigma}{dE_e}(E_\nu, E_e) = 2m_p \frac{d\sigma}{dt} \qquad \sigma(E_\nu) = \int_{E_1}^{E_2} \frac{d\sigma}{dE_e}(E_\nu, E_e)\, dE_e$$

$$E_{1,2} = E_\nu - \delta - \frac{1}{m_p} E_\nu^{\rm CM}(E_e^{\rm CM} \pm p_e^{\rm CM}), \qquad \delta \equiv \frac{m_n^2 - m_p^2 - m_e^2}{2m_p}$$

$$E_\nu^{\rm CM} = \frac{s - m_p^2}{2\sqrt{s}}, \qquad E_e^{\rm CM} = \frac{s - m_n^2 + m_e^2}{2\sqrt{s}}, \qquad p_e^{\rm CM} = \frac{\sqrt{[s - (m_n - m_e)^2][s - (m_n + m_e)^2]}}{2\sqrt{s}}$$

Neutrino-Proton Cross Section



CUTE Fridge Geometry

Fridge:

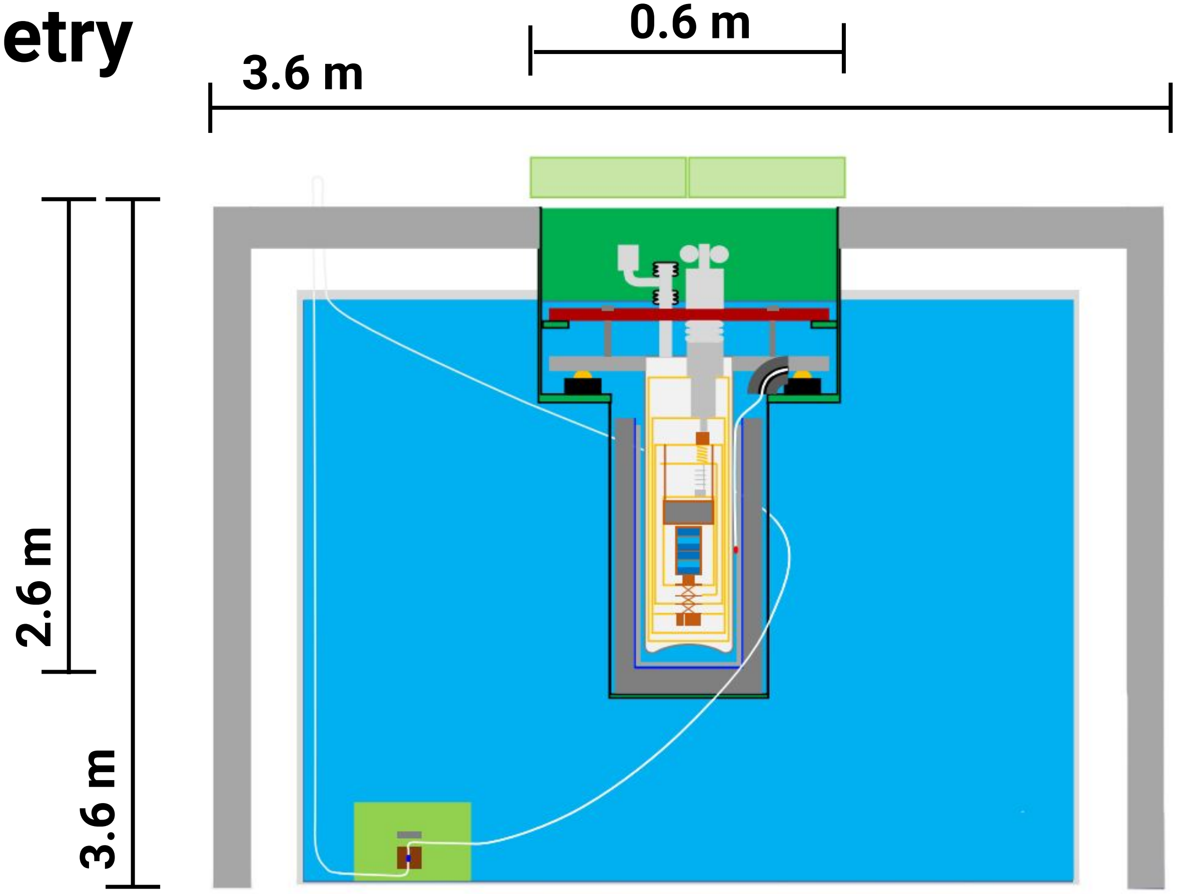
3.6 m in height
3.6 m in diameter

Drywell:

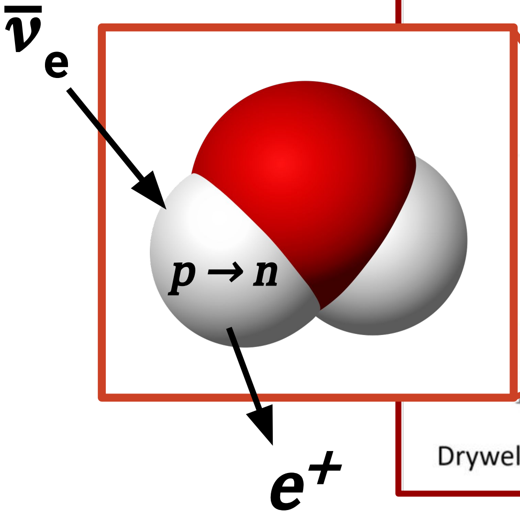
2.6 m in height
0.6 m in diameter

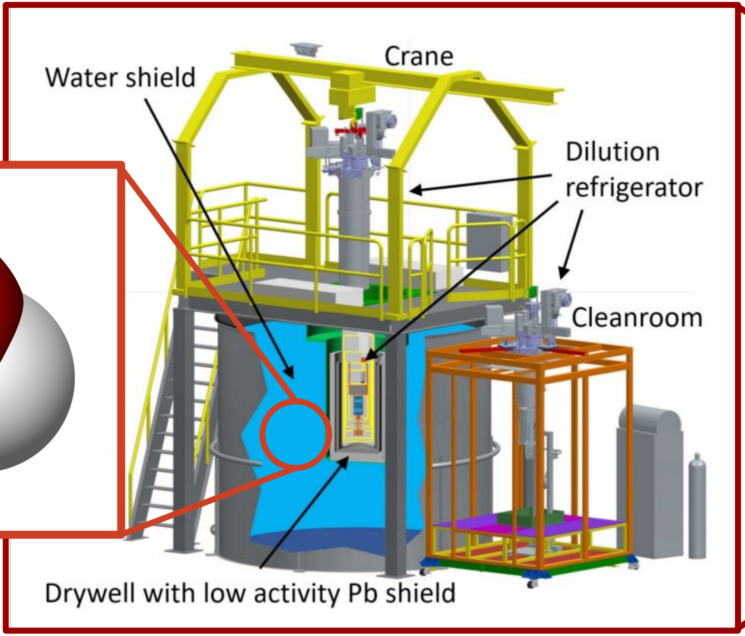
Water Tank:

≈ 35.9 m^3 volume

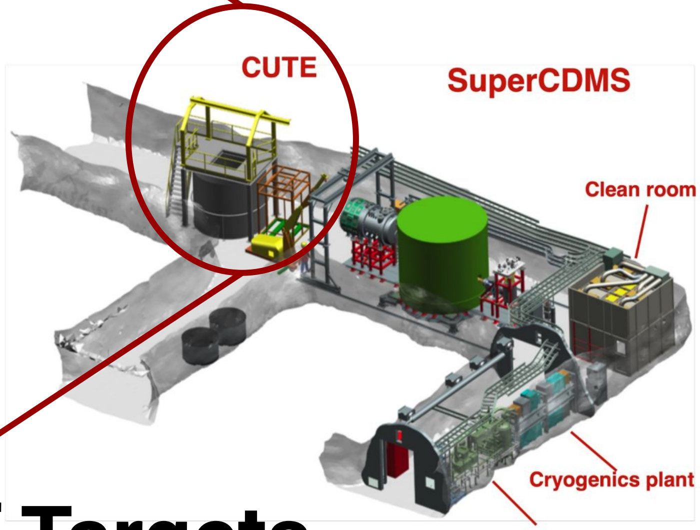


Miriam Diamond, TRISEP 2024





[Andy Kubik, RISQ 2024]



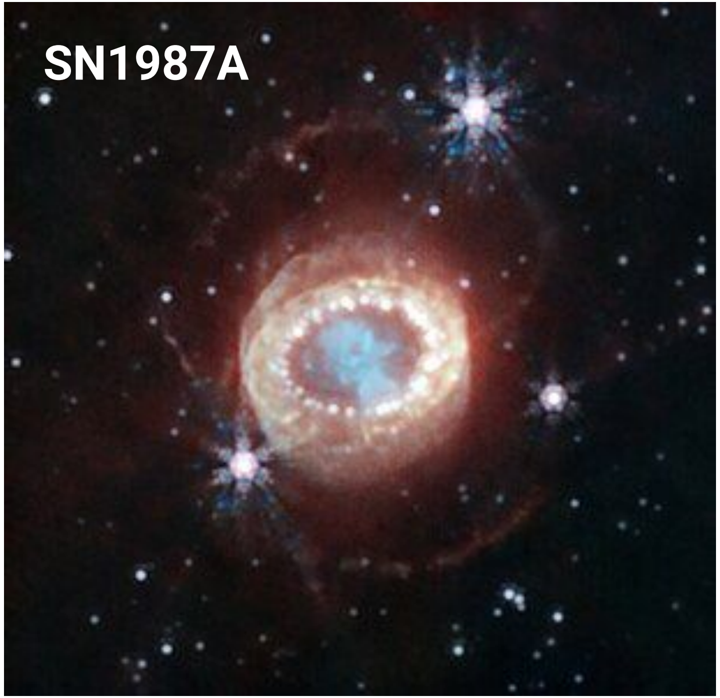
Finding Number of Targets

volume · **density** · **molar weight** · **Avogadro's number** · **molecular makeup**

$$N_p = (35.9\,\mathrm{m}^3)\left(\frac{10^6\,\mathrm{g}}{1\,\mathrm{m}^3}\right)\left(\frac{1\,\mathrm{mol}}{18\,\mathrm{g}}\right)\left(\frac{6\times10^{23}\,\mathrm{molecules}}{1\,\mathrm{mol}}\right)\left(\frac{2\,\mathrm{free\ protons}}{1\,\mathrm{molecule}}\right) \approx 2.4\times10^{30}\,\mathrm{free\ protons}$$

Galactic Core Collapse Supernova (CCSN)

- Expected to occur in our galaxy around three times per century.
- Occur when the iron core of a massive star exceeds the Chandrasekhar limit and collapses into a compact object, emitting ~99% of its gravitational binding energy in the form of 10^{58} neutrinos of ~10s of MeV each
- Neutrinos can freely escape the extremely dense material of the supernova while the light is scattered, meaning the neutrino signal will reach an observer before any light
- The most likely distance for the next galactic CCSN is around 12-15kpc from Earth



NASA/ESA/CSA James Webb Telescope image of the supernova remnant

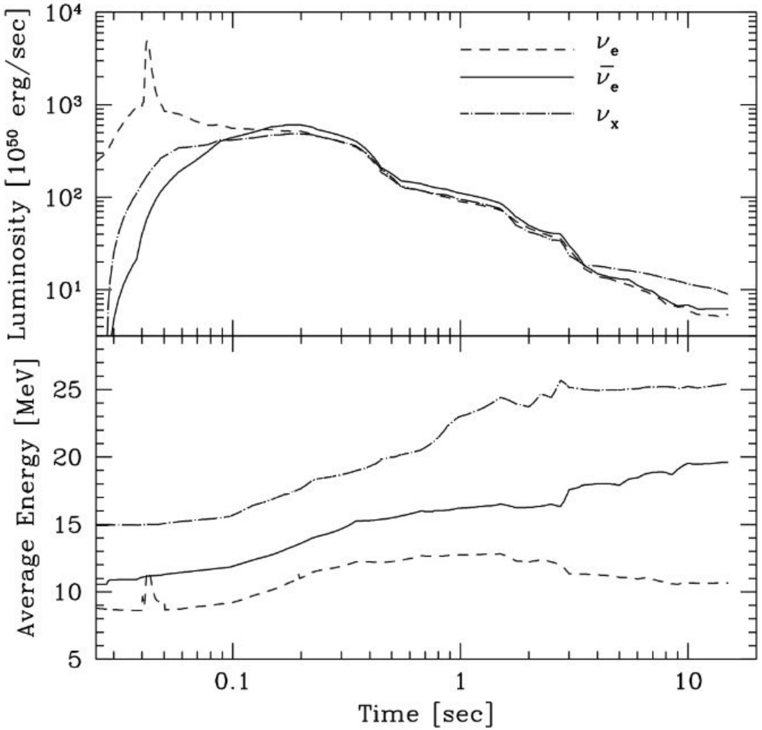
K. Scholberg, 2012

Livermore Model

- Numerical model based on data from **SN1987A**

- Realistic Monte Carlo simulations for neutrino detection based on the Super-Kamiokande detector

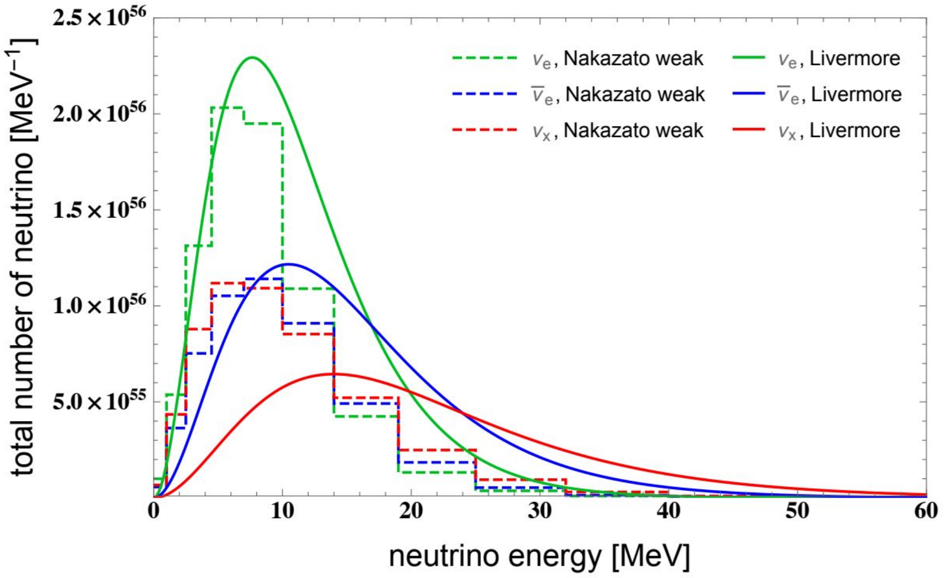
- **Assumption: 20 $M_\odot$** progenitor

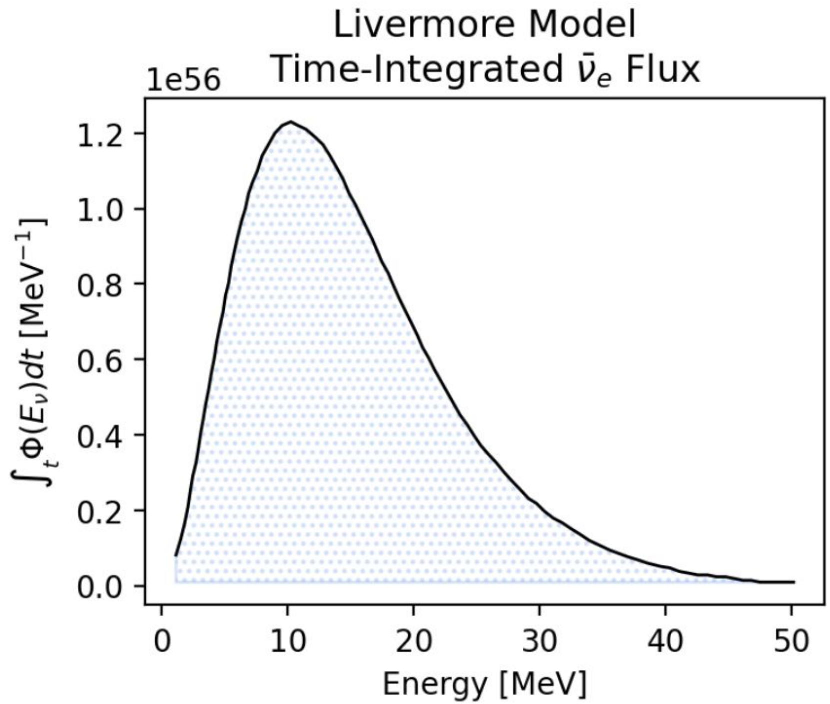


T. Totani et al., 1998

Time-Integrated Neutrino Flux Model

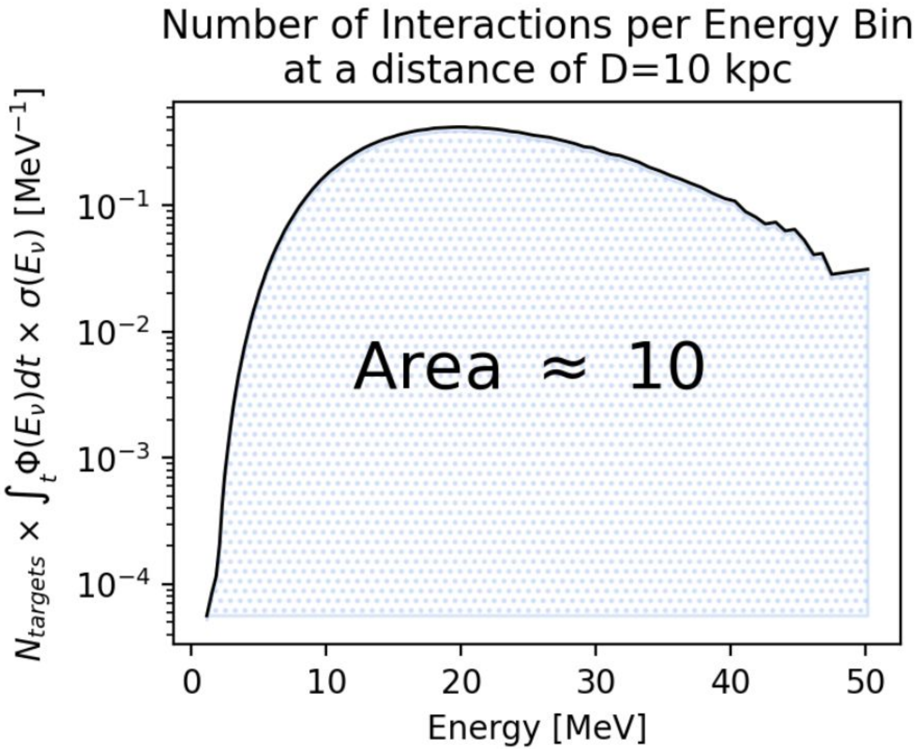
A. L. Foguel, 2020





Digitized a $\bar{\nu}_e$, **Livermore** flux spectrum plot into data points using *https://plotdigitizer.com/app*

Example Calculation at D=10 kpc

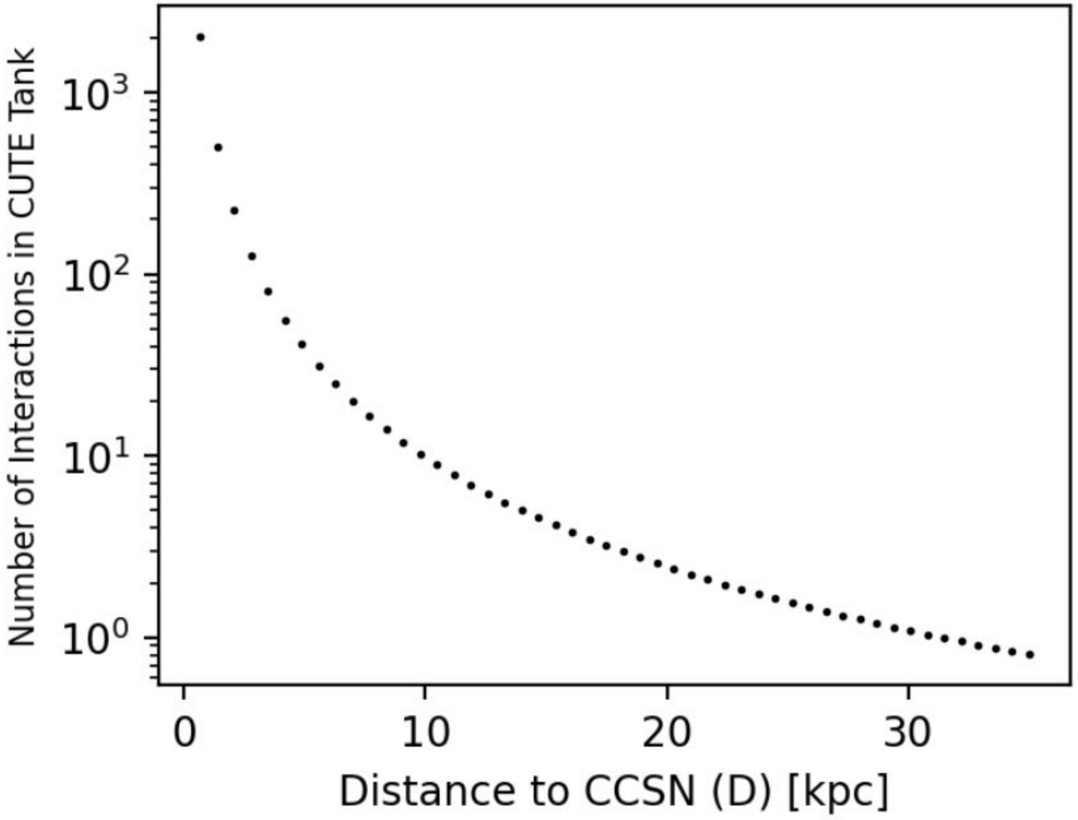


interactions / energy bin = $N_{targets}$ **x** $\int \Phi dt$ **x** σ

Integrate over all energies to find the total number of neutrino interactions

If a CCSN occurs at **D=10 kpc** , **≈10 neutrinos** interact with the CUTE water tank

Total Number of Interactions as a Function of Distance



Follow the same procedure as before, but evaluate time-integrated flux as a function of arbitrary distance between CCSN and Earth

$$\mathbf{N_{interactions} = 986.8 / D^2}$$

EDI Component

You are in a collaboration with about **50 people** from **4 different countries** and **8 different institutions**. You have recently had interest from **2 new institutions** to join the collaboration.

Both institutions have **international students** and for some of them **travel restrictions apply**, such as long wait times for a VISA.

What can/should your collaboration do to understand how to best support these new collaborators. This includes how you would work to fully understand their needs and how to mitigate barriers.

EDI Proposal

- ➢ Provide mentorship / guidance for advisors of international students for how to best support and adapt to the challenges they may face
- ➢ Offer letters of referral for VISA / study permit applications
- ➢ Provide relocation funding assistance
- ➢ Schedule collaboration meetings well in advance and in locations that are considerate of members' travel restrictions
- ➢ Provide anonymous feedback surveys on international student / travelling experience in the collaboration
- ➢ Collaboration Ombudsperson available for confidential support and guidance to international students