TAPP

25-27 Sep 2024, IMSc Chennai

The Road to a Deuterium-based Scintillator Detector

based on the DLS Science Case White Paper

+ JCAP 11 (2021) 005 by Bhavesh Chauhan, BD, Vivek Datar

+ ongoing work by the DLS Study Group at TIFR

+ ongoing work by DLS Task Force of DAE

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Remember SNO ?

- The solar neutrino problem was solved largely in part due to the Sudbury Neutrino Observatory (SNO) measurement of the Neutral Current neutrino-dissociation of deuteron:

$$\nu + d \rightarrow \nu + p + n$$

$$n + d \rightarrow {}^{3}\mathrm{H} + \gamma$$

- Challenges for SNO-like detector:
    - Heavy water is expensive and unavailable
    - Low neutron capture efficiency
    - Large Threshold
    - Proton is undetected
    - No spectral information

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India can manufacture!

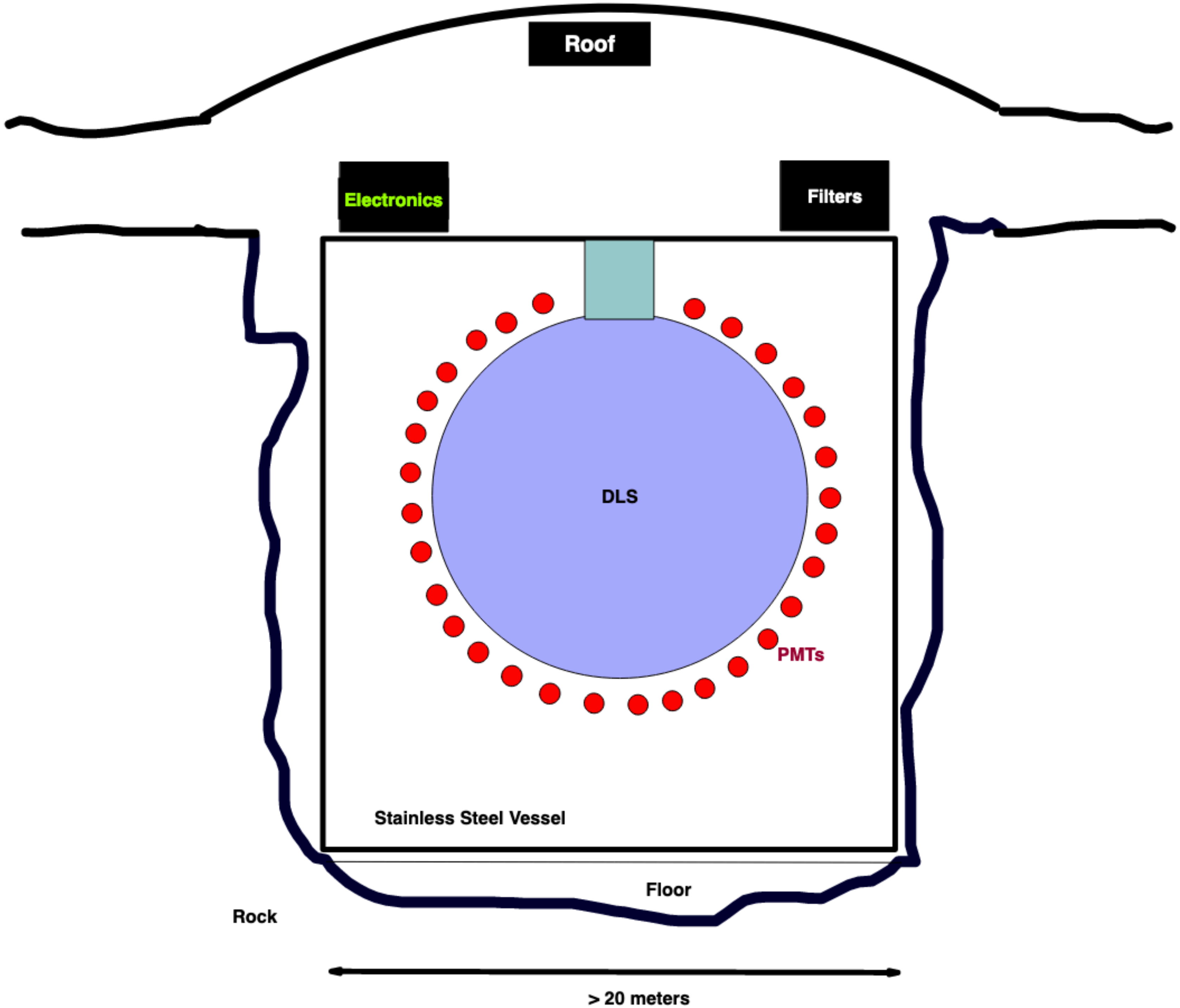
https://www.hwb.gov.in/

Just add Gd

Resolved if you have a scintillator!

50-100 more light compared to Cherenkov light
= lower threshold (<1 MeV)
+ better energy resolution (~3% at 10 MeV)

Concept Drawing



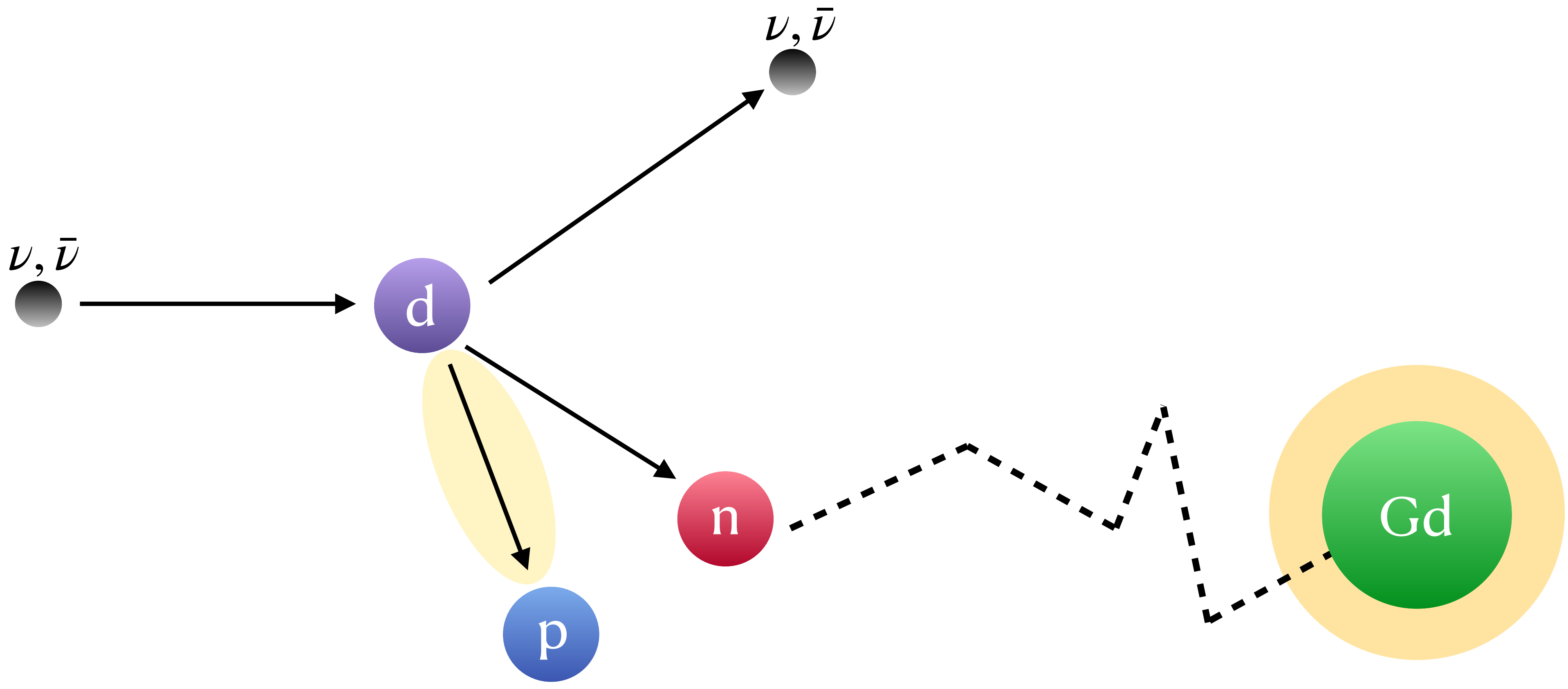
Interactions and Detectables

Table : Neutrino deuteron interactions

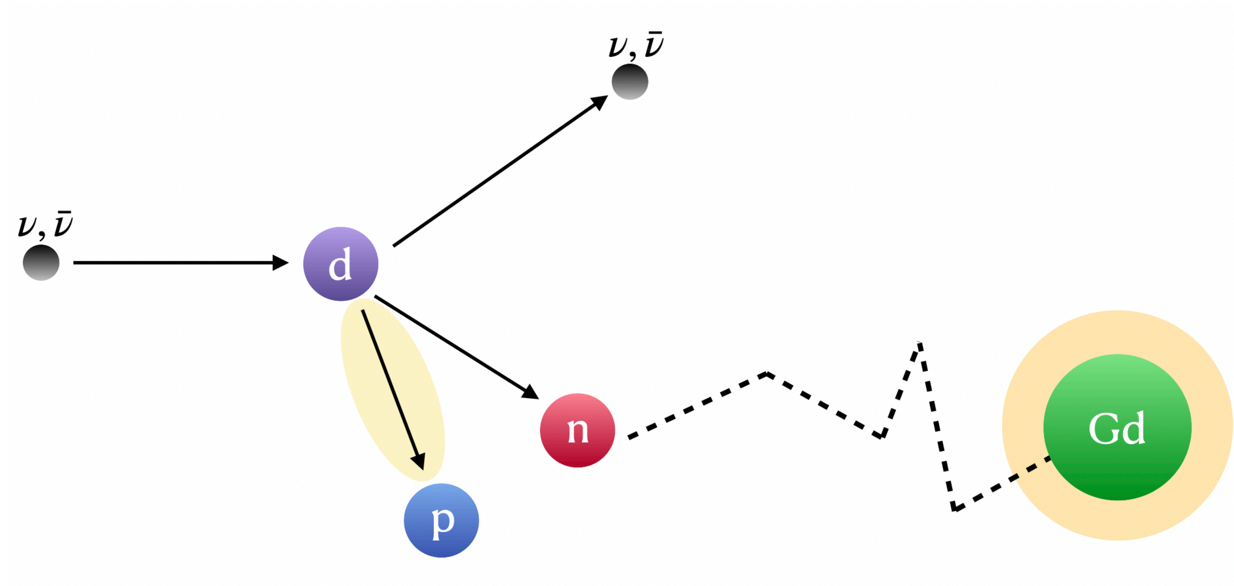
Interaction	Channel	-Q (MeV)
$\nu + d \rightarrow \nu + n + p$	NC	2.224
$\overline{\nu} + d \rightarrow \overline{\nu} + n + p$	NC	2.224
$\nu_e + d \rightarrow e^- + p + p$	CC	1.442
$\overline{\nu}_e + d \rightarrow e^+ + n + n$	CC	4.028

$$\underbrace{\nu,}_{\text{Cannot be detected}} \quad \underbrace{e^{\pm}, \quad p,}_{\text{Scintillator = low threshold}} \quad \underbrace{n}_{\text{Thermalises and Captured! Can be used as a "tag"}}$$

Neutral Current Dissociation



Secondary Interactions

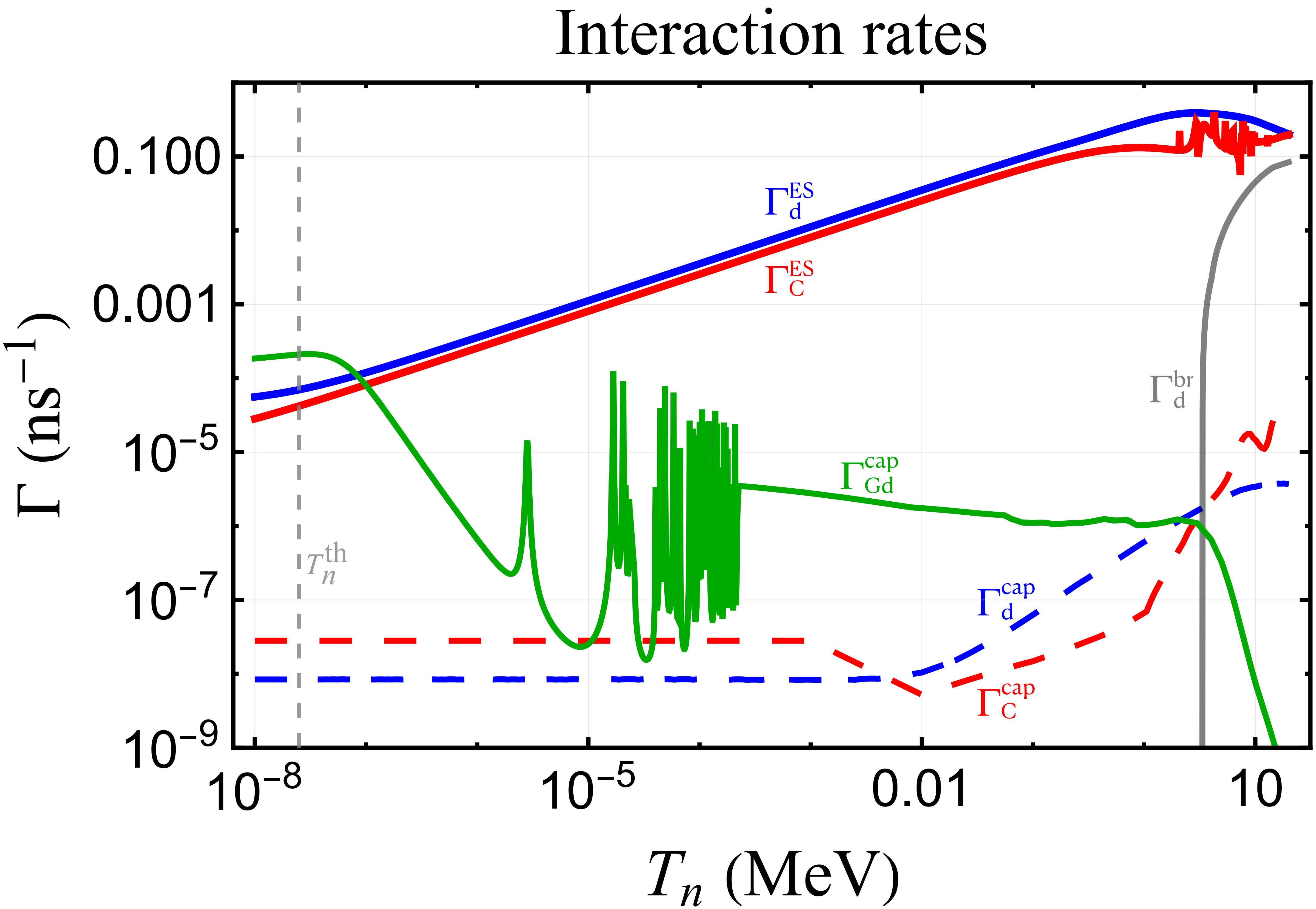


- Final state protons lose energy quickly and travel ~0.1 mm
- The neutrons undergo following secondary interactions:

1. Elastic scattering ($n + A \rightarrow n + A$)
2. Radiative capture ($n + A \rightarrow A' + \gamma$)
3. Deuteron breakup ($n + d \rightarrow n + n + p$)

- We compare the interactions rates ($\Gamma = n\sigma v$) to analytically examine the secondary interactions.

Secondary Interactions



Secondary Interactions

One can estimate the following:

1. $N_{\text{ES}} = \dfrac{1}{\log\left(5/9\right)} \log\left(\dfrac{T_n^{\text{th}}}{T_n}\right) \approx 4\ \log_{10}\left(\dfrac{T_n}{T_n^{\text{th}}}\right) \approx 30 - 35$

2. $N_{\text{cap}}^{\text{no Gd}} = \dfrac{\Gamma^{\text{ES}}(T_n^{\text{th}})}{\Gamma^{\text{cap}}(T_n^{\text{th}})} \approx 3000$

3. Without Gd, $\tau_{\text{cap}} \sim 20\,\text{ms}$

4. With Gd, $\tau_{\text{cap}} \sim 50\,\mu\text{s}$

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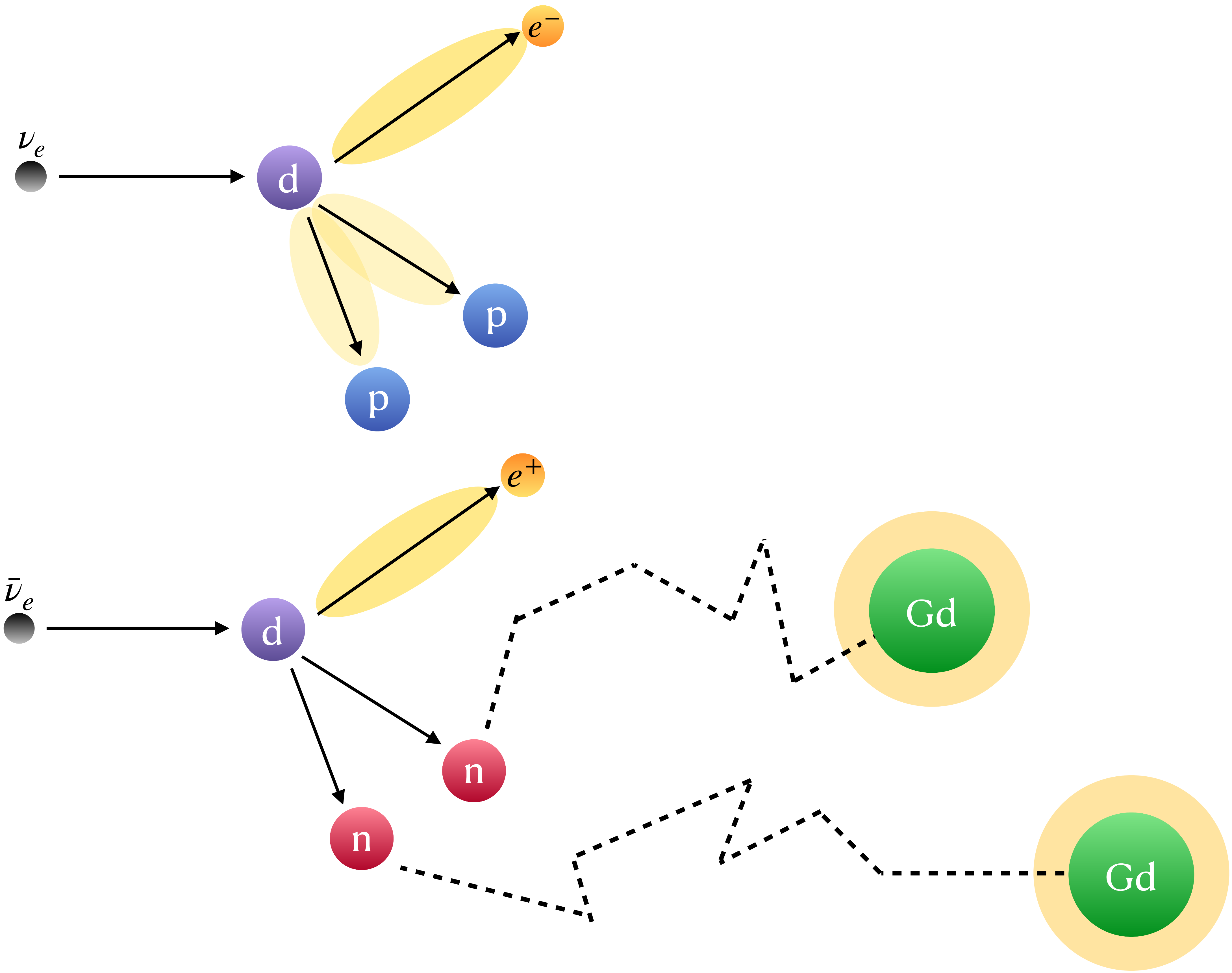
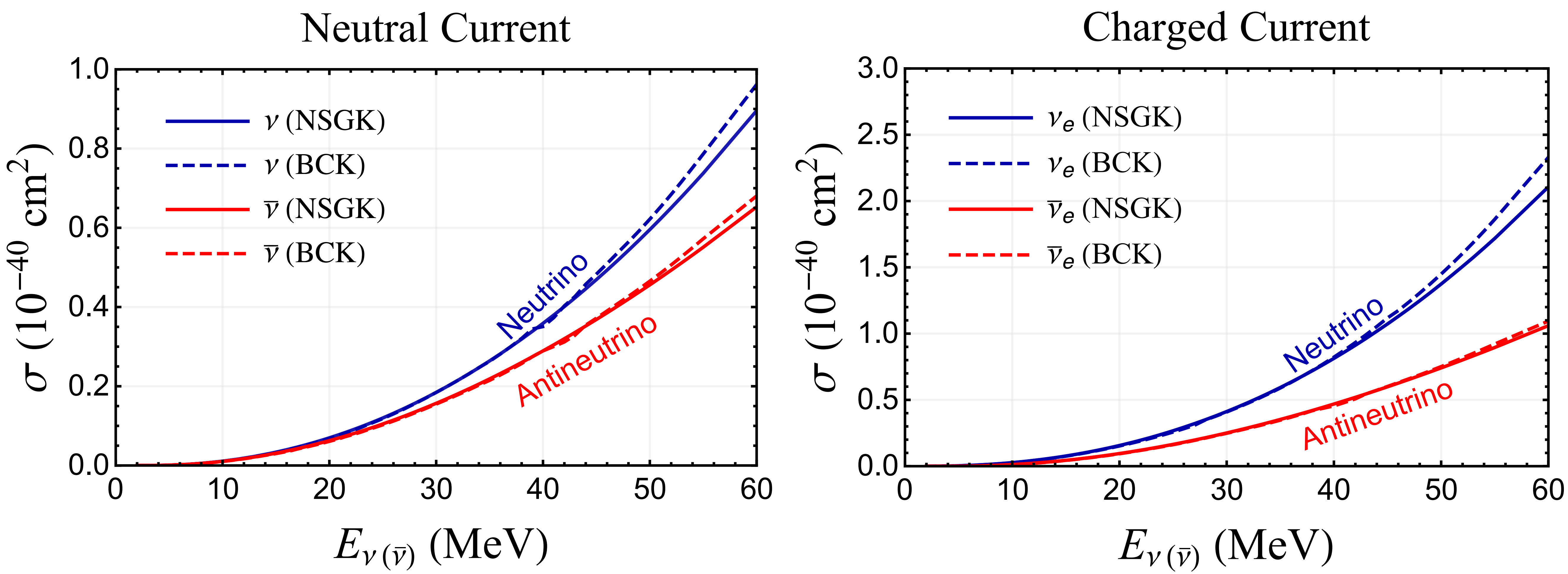
This is the reason why we need Gd.

Charged Current



Cross Sections



Cross sections and differential cross sections obtained using Pionless EFT [nucl-th/0008032] are available at:
https://github.com/bhvzchhn/NeutrinoDeuteron

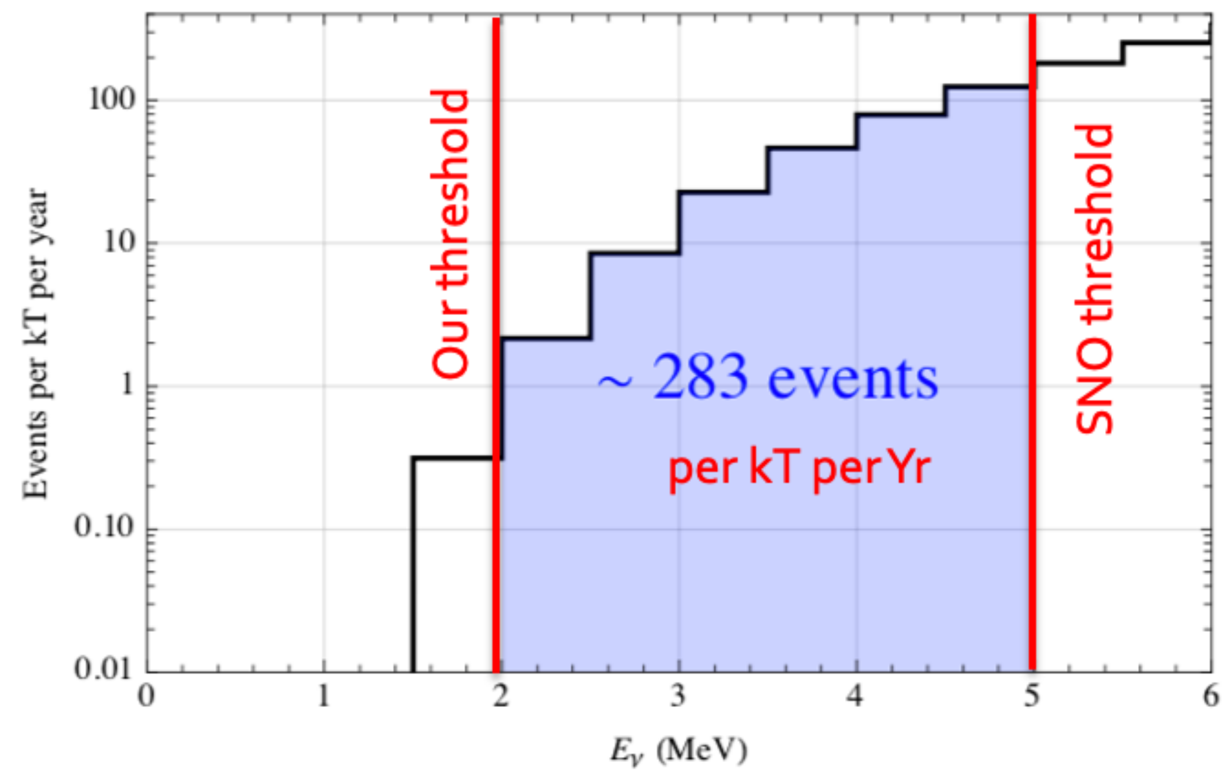
Potential Science Case

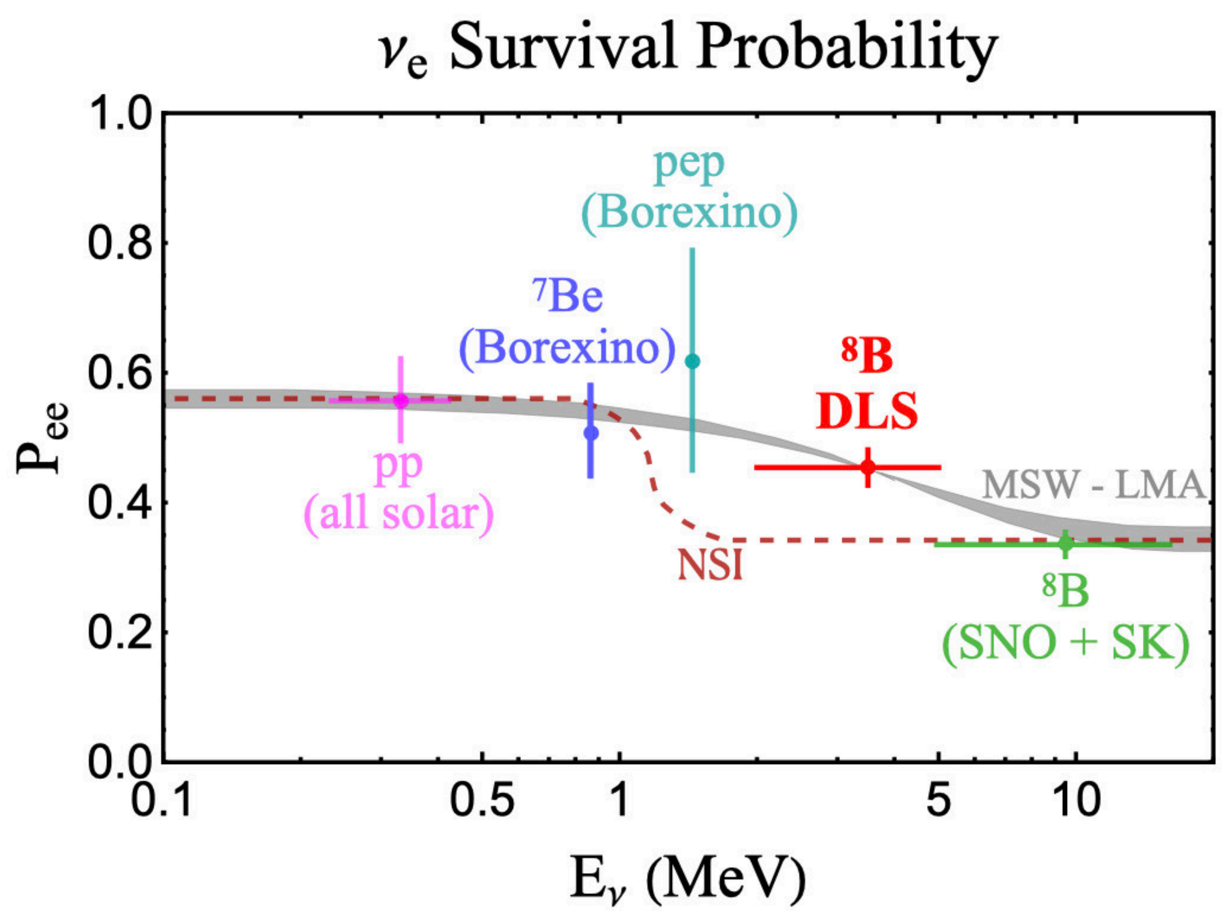
- Solar Neutrinos in the 2-5 MeV range
- Day-Night Asymmetry of Solar Neutrinos
- Unique Opportunities with Supernova Neutrinos
- Other things that other scintillator detectors do …
- New Ideas ???

AIM 1: Solar Neutrinos at DLS

- DLS will detect electron neutrinos (+ all other flavors)
- Approximately 6% precision in survival probability with 1 kton-yr
- Can be a stringent test of the LMA-MSW solution
- May be a way to discover non-standard interactions and other exotic effects

Unique opportunity

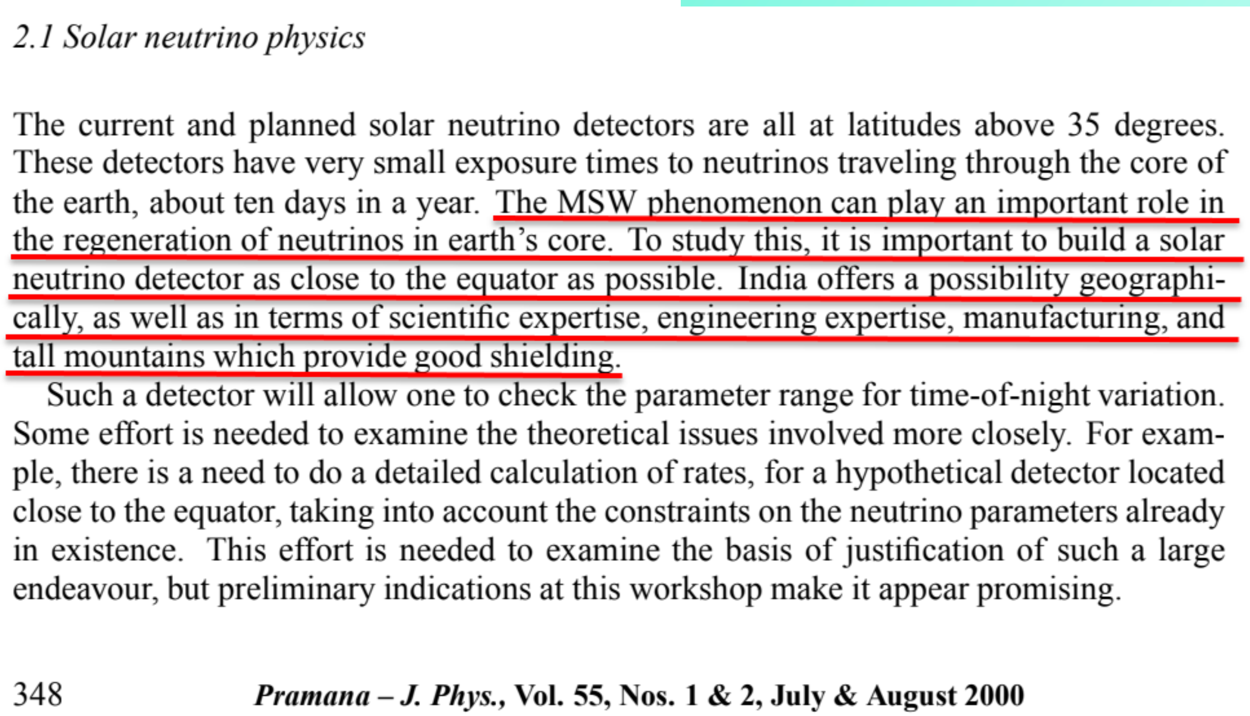




AIM 2: Day-Night Asymmetry

- At night neutrinos can cross the core
- Many Indian locations see substantial day-night effect
- The effect reverses sign at lower energies

We have geographical advantage + low threshold



2.1 Solar neutrino physics

The current and planned solar neutrino detectors are all at latitudes above 35 degrees. These detectors have very small exposure times to neutrinos traveling through the core of the earth, about ten days in a year. The MSW phenomenon can play an important role in the regeneration of neutrinos in earth's core. To study this, it is important to build a solar neutrino detector as close to the equator as possible. India offers a possibility geographically, as well as in terms of scientific expertise, engineering expertise, manufacturing, and tall mountains which provide good shielding.

Such a detector will allow one to check the parameter range for time-of-night variation. Some effort is needed to examine the theoretical issues involved more closely. For example, there is a need to do a detailed calculation of rates, for a hypothetical detector located close to the equator, taking into account the constraints on the neutrino parameters already in existence. This effort is needed to examine the basis of justification of such a large endeavour, but preliminary indications at this workshop make it appear promising.

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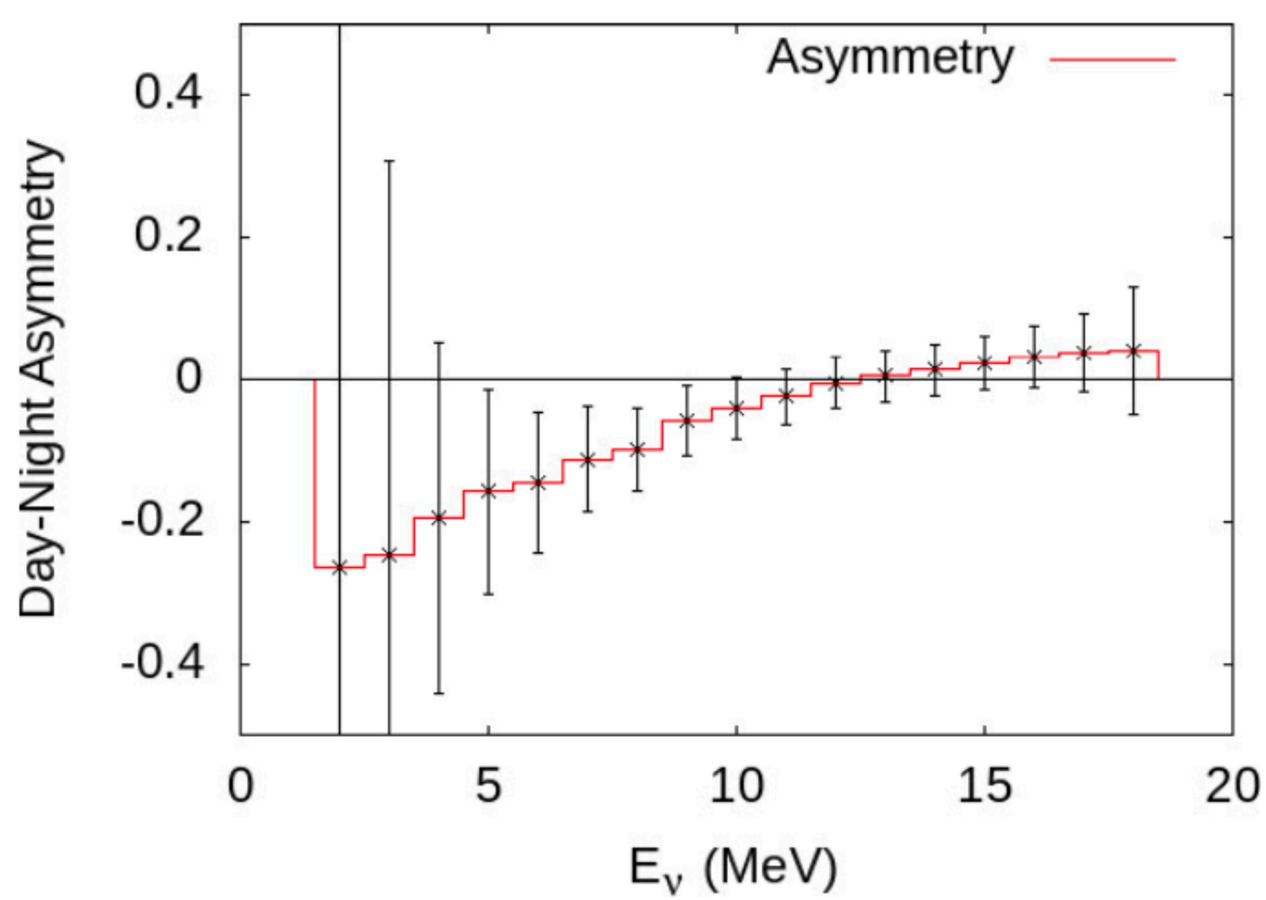
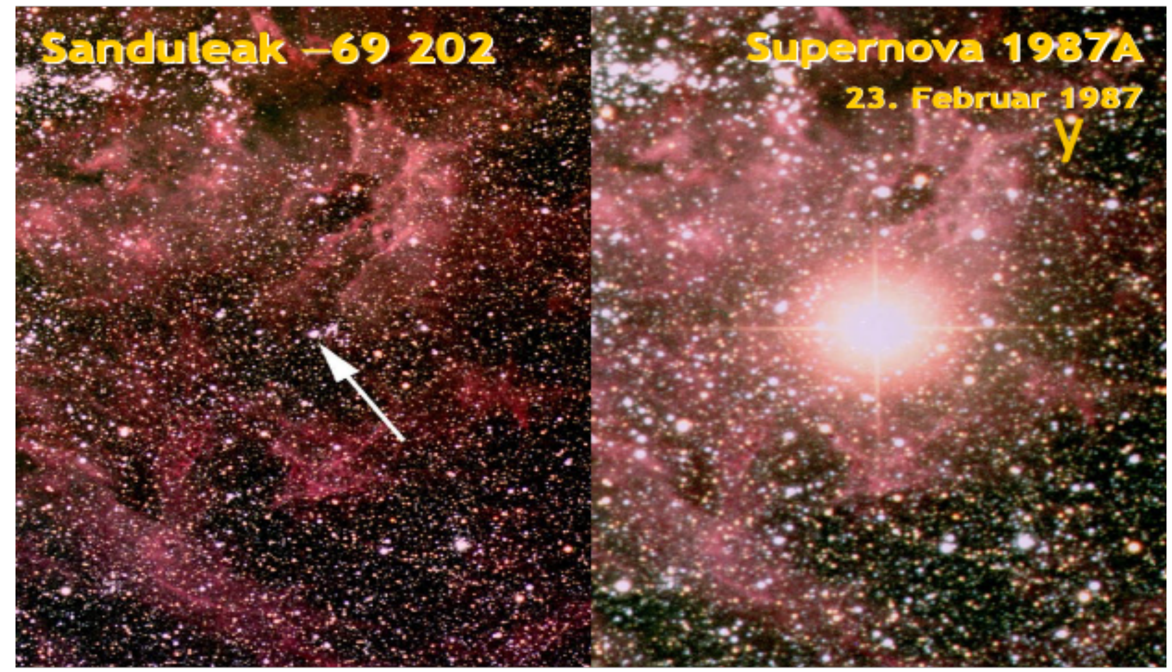
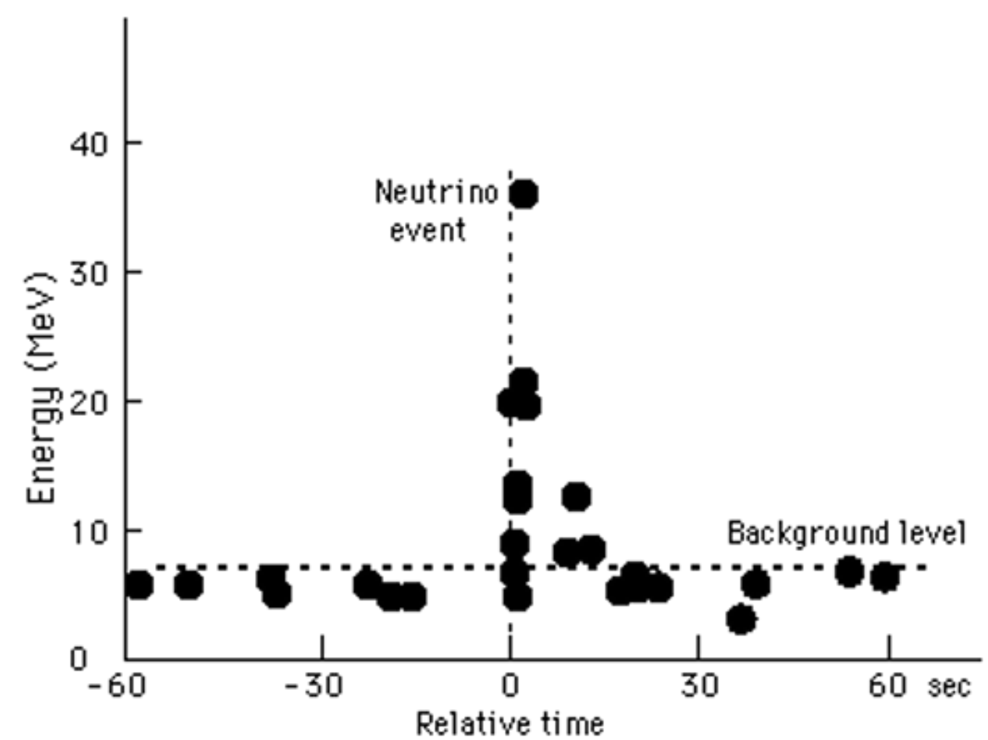


Supernova Neutrinos

- Stars with mass > 8-10 x Sun explode as a supernova
- ~99% of the energy released is through neutrinos in ~ 10secs
- In our galaxy 1-3 / 100 yr. The last one was ~ 1900 (G1.9+0.3) but not seen due to dust. In 1987 a SN seen optically in nearby galaxy and also through neutrinos.

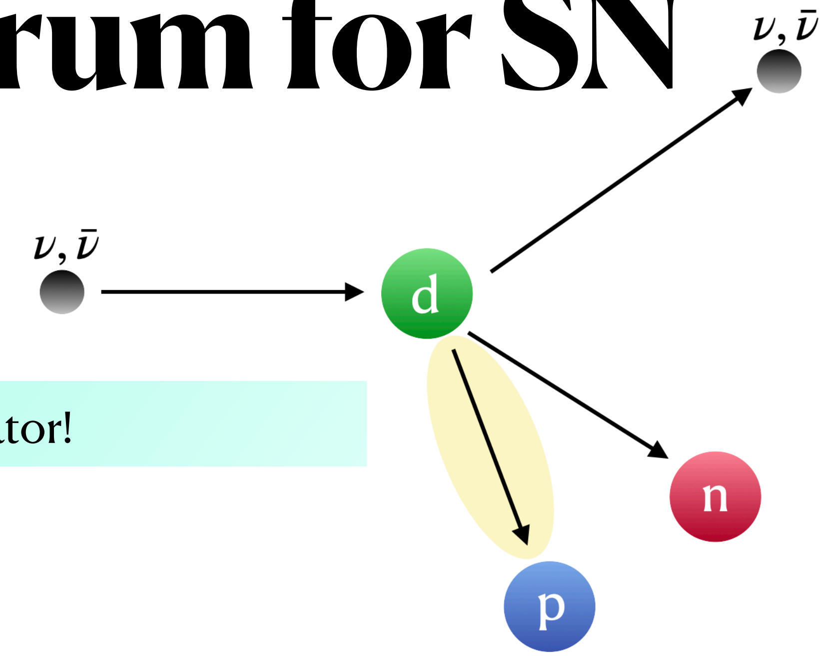




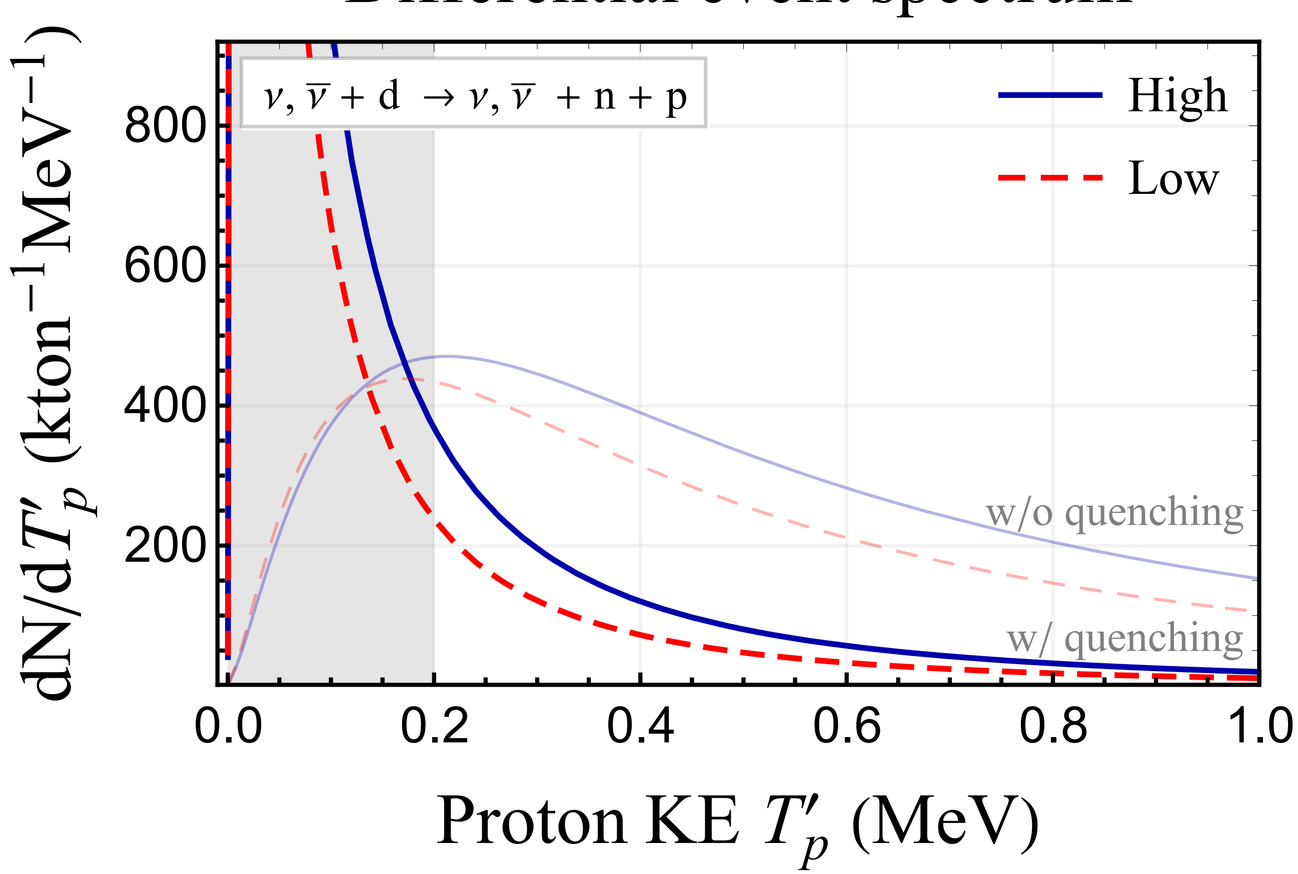
AIM 3: All Flavor Spectrum for SN

Neutral Current

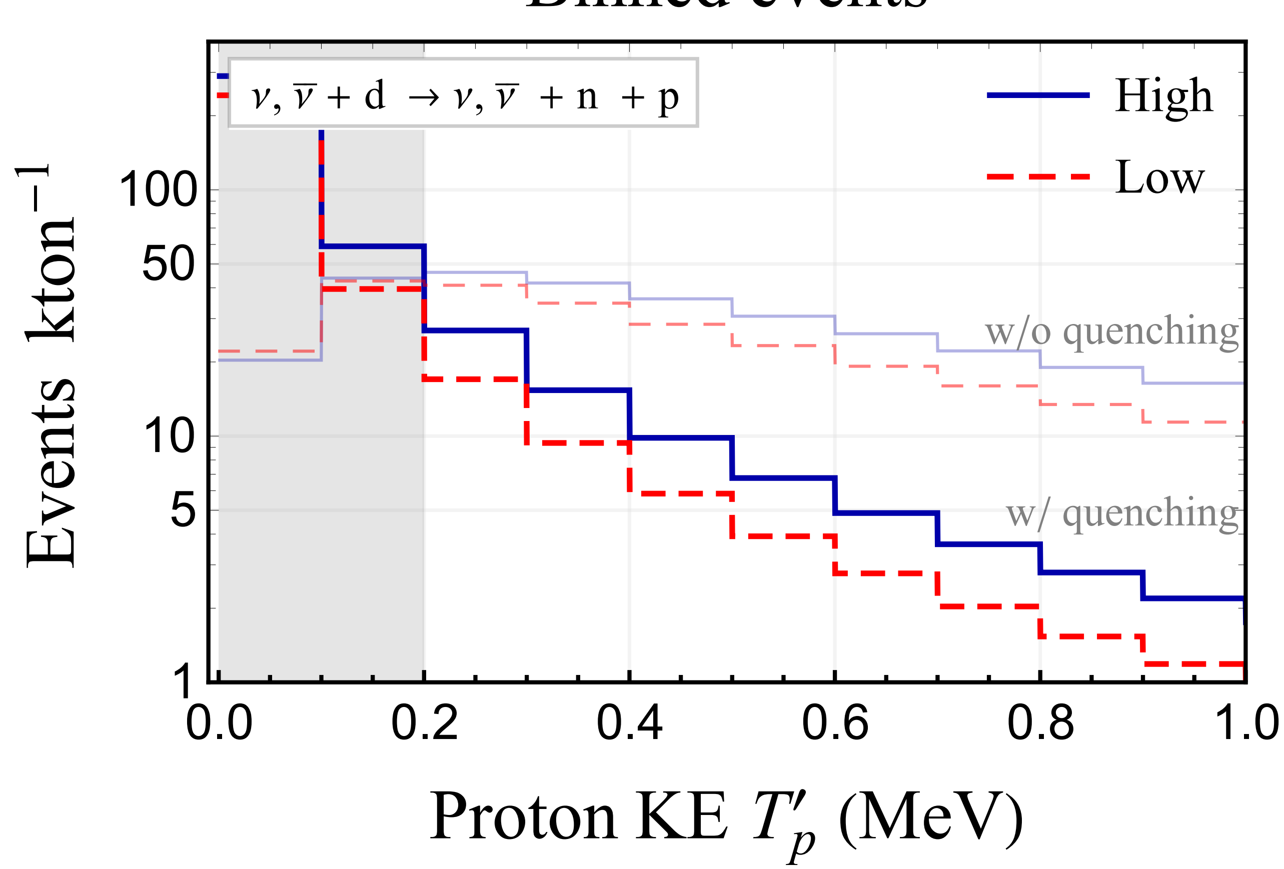
Neutron tag is possible unlike in usual scintillator!



Differential event spectrum



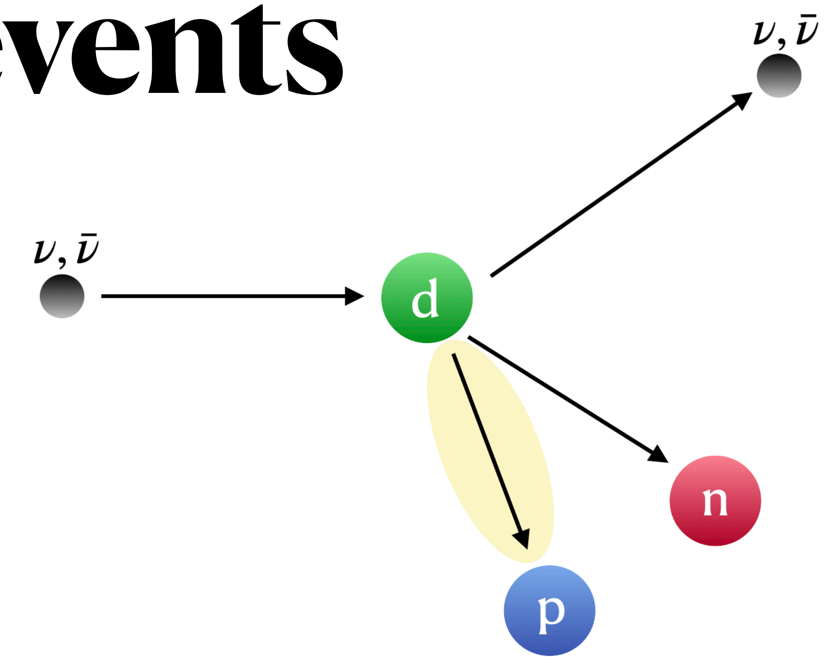
Binned events



High (Low) Fluence: 84 (50) proton above 200 keV

Spectrum of NC events

Neutral Current

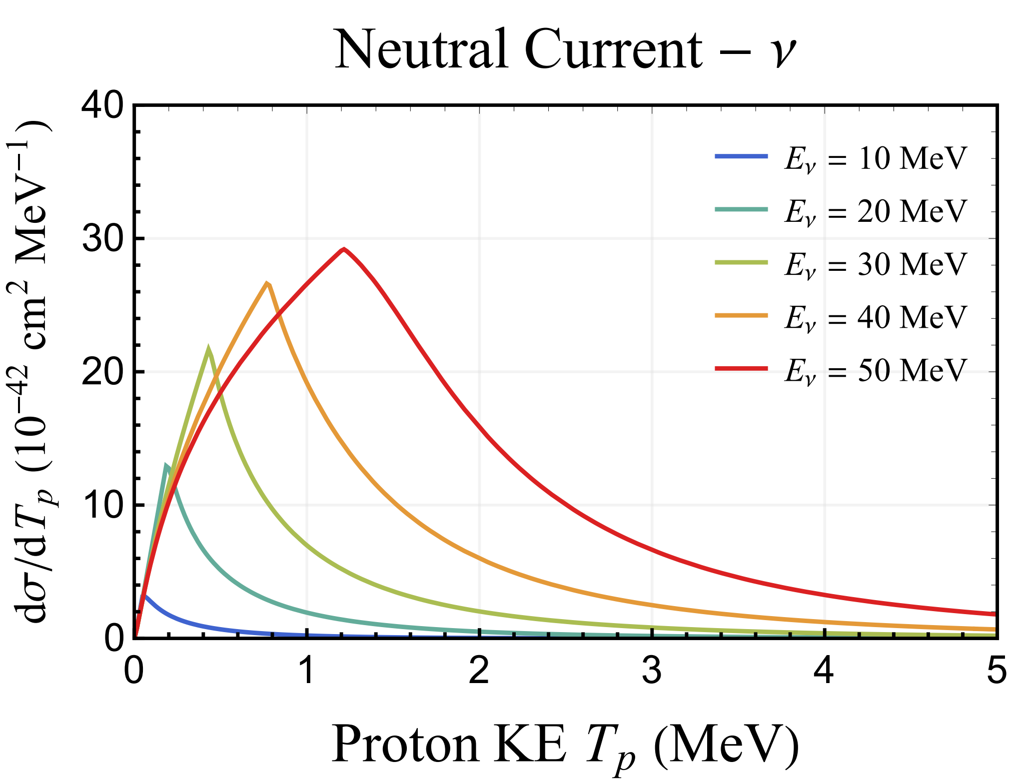


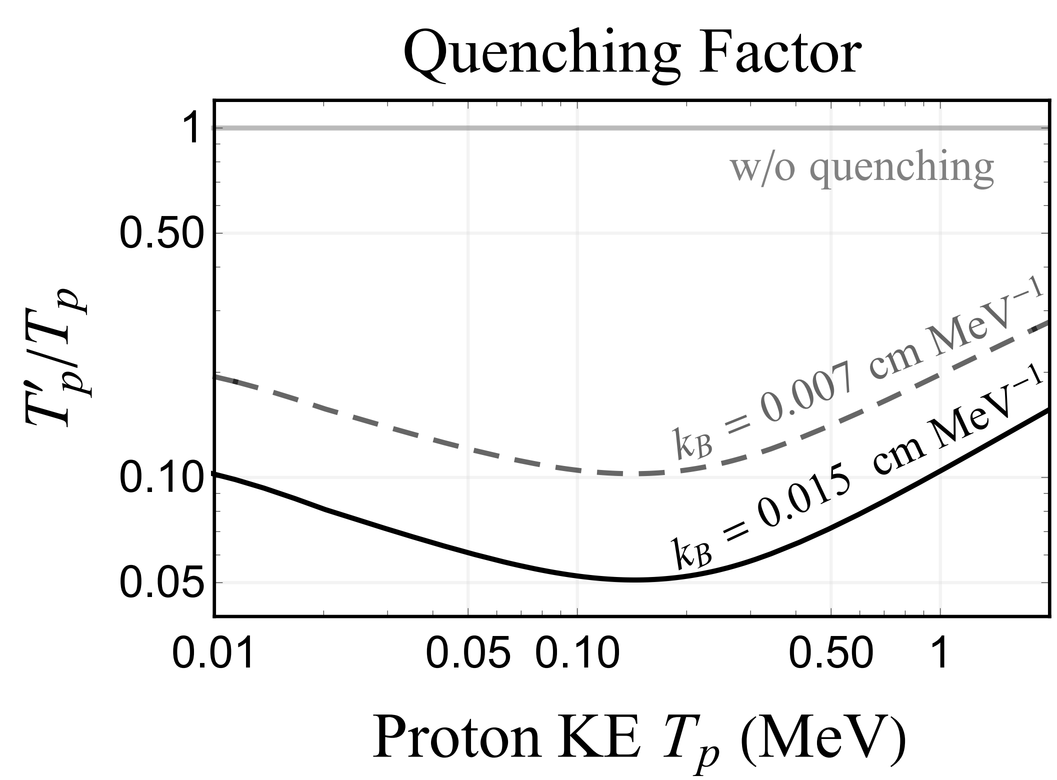
Detecting scintillation from NC channel has two issues :

1. Small momentum transfer to proton

2. Photosaturation losses / Quenching

$$E_{vis} = T_p' = Q(T_p) = \int_0^{T_p} \frac{dT}{1 + k_B \langle dT/dx \rangle}$$





Technical Capabilities Needed

The needed technical capabilities can be divided in five broad classes: development of the chemical process for pure DLS, optical properties of the DLS, detector design and associated materials, development of an underground laboratory, and development of software for optical characterization, detector and physics simulations and analysis. Some key issues are highlighted below.

1. Demonstration of DLS feasibility on scale of 1 ton: This would a crucial first R&D step towards a larger scale-up. This could include examination of other possibilities such as a scintillator based on D_2O with additional of organic scintillator in the same manner as development of a water based liquid scintillator. A pure, bright deuterium based organic scintillator is obviously preferred.

2. Closed loop purification system: A system of purification of the DLS will need to be demonstrated. This purification has two goals: optical transparency, and low radioactivity. To avoid the loss of deuterium, the system needs to be closed with carefully controlled pressure and temperatures and with minimal contact with the atmosphere.

3. Safety issues involving possible loss of inflammable LS and expensive $\mathrm{D_2O}$: The chemistry of DLS will need to chosen for high flash point, and multiple redundant containment and capability to minimize loss of deuterium in case of leaks of accidents.

Technical Capabilities Needed

4. Structural engineering of possibly nested tanks – design and assembly: The most efficient use of DLS which maximizes the sensitive mass will require nested tank design with an inner vessel that is used for containing DLS.

5. Material testing and availability with acceptably low radioactive impurities (which would need a low background HPGe based setup, possibly underground)

6. Sourcing of high QE and low radioactivity PMTs

7. Electronics using signal digitizers and Data Acquisition system

8. Modern software systems for simulations, analysis, and data management.

How does DLS stack up against other detectors?

Neutral Current

Flavor	Ordinary Detector		Deuterated Detector	
	Channel	Detector	Channel	Detector
$\overset{(-)}{\nu}$	$\overset{(-)}{\nu}\, p \to \overset{(-)}{\nu}\, p$	JUNO, THEIA *Spectrum* ✓ *Tagging* ✗	$\overset{(-)}{\nu}\, d \to \overset{(-)}{\nu}\; p\; n$	SNO *Spectrum* ✗ *Tagging* ✗
	$\overset{(-)}{\nu}\ \mathrm{Pb} \to \overset{(-)}{\nu}\ \mathrm{Pb}^*$	HALO *Spectrum* ✗ *Tagging* ✗	$\overset{(-)}{\nu}\, d \to \overset{(-)}{\nu}\; p\; n$	DLS *Spectrum* ✓ *Tagging* ✓

Spectrum ~ "Can reconstruct incident neutrino spectrum"

Tagging ~ "Multiple detectable particles in the final state"

How does DLS stack up against other detectors?

Charged Current

Flavor	Ordinary Detector: Channel	Ordinary Detector: Detector	Deuterated Detector: Channel	Deuterated Detector: Detector
ν_e	$\nu_e\ \mathrm{Ar} \to e^- \mathrm{K}^*$	DUNE *Spectrum* ✓ *Tagging* ✗	$\nu_e\ d \to e^-\ p\ p$	SNO *Spectrum* ✓ *Tagging* ✗
	$\nu_e\ \mathrm{Pb} \to \nu_e\ \mathrm{Bi}^*$	HALO *Spectrum* ✗ *Tagging* ✗	$\nu_e\ d \to e^-\ p\ p$	DLS *Spectrum* ✓ *Tagging* ✓
$\bar{\nu}_e$	$\bar{\nu}_e\ p \to e^+\ n$	SuperK+Gd *Spectrum* ✓ *Tagging* ✓	$\bar{\nu}_e d \to e^+\ n\ n$	SNO *Spectrum* ✓ *Tagging* ✓
	$\bar{\nu}_e\ p \to e^+\ n$	LVD, JUNO *Spectrum* ✓ *Tagging* ✗	$\bar{\nu}_e d \to e^+\ n\ n$	DLS *Spectrum* ✓ *Tagging* ✓

Summary

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