FIPS 2022, CERN

Large Energy Singles as a Probe of Dark Matter

Basudeb Dasgupta (Tata Institute, Mumbai)

with Bhavesh Chauhan, Vivek Datar, and Amol Dighe

based on arXiv:2106.10927 (in JCAP) and arXiv:2111.14586 (in PRD)

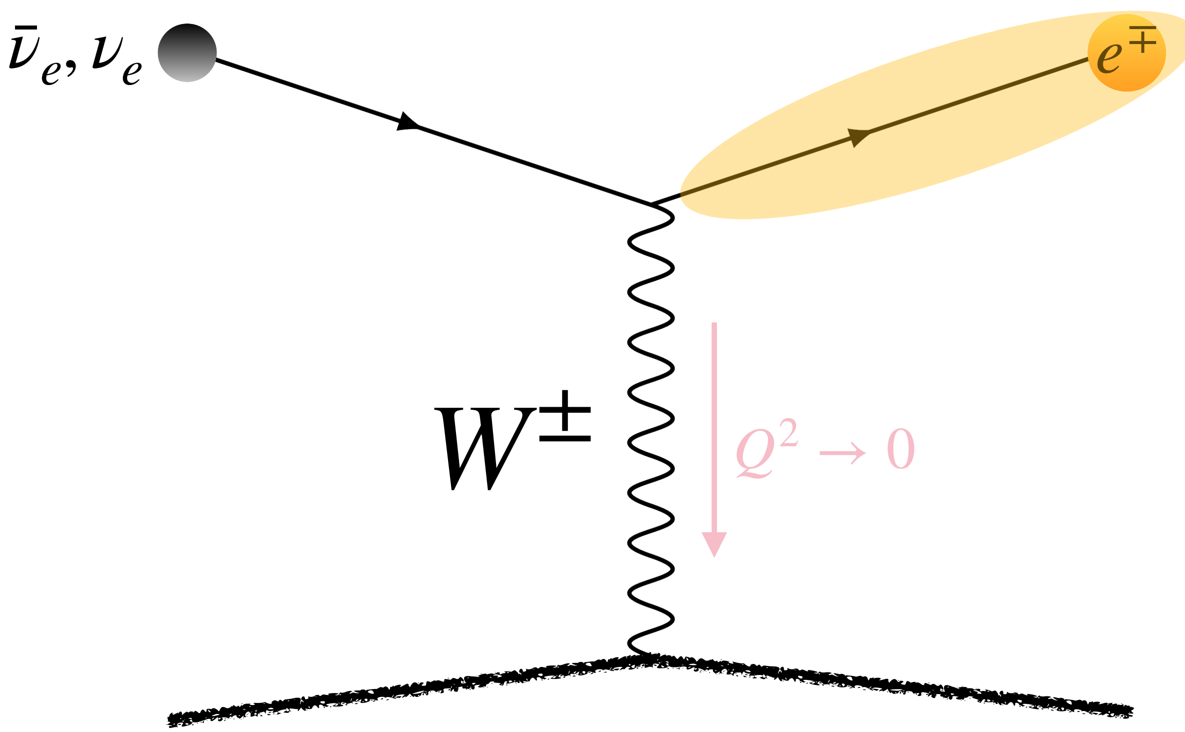
Main Takeaway

- Liquid Scintillator Detectors, such as JUNO, can detect small energy depositions of order MeV
- This allows one to measure the Atmospheric Neutrino Flux in the 100 MeV range (including via Neutral Current)
- In the search for exotic physics, e.g., Boosted DM, the above-said "Large Energy Singles" are the main Standard Model background

If time permits: Add Gadolinium

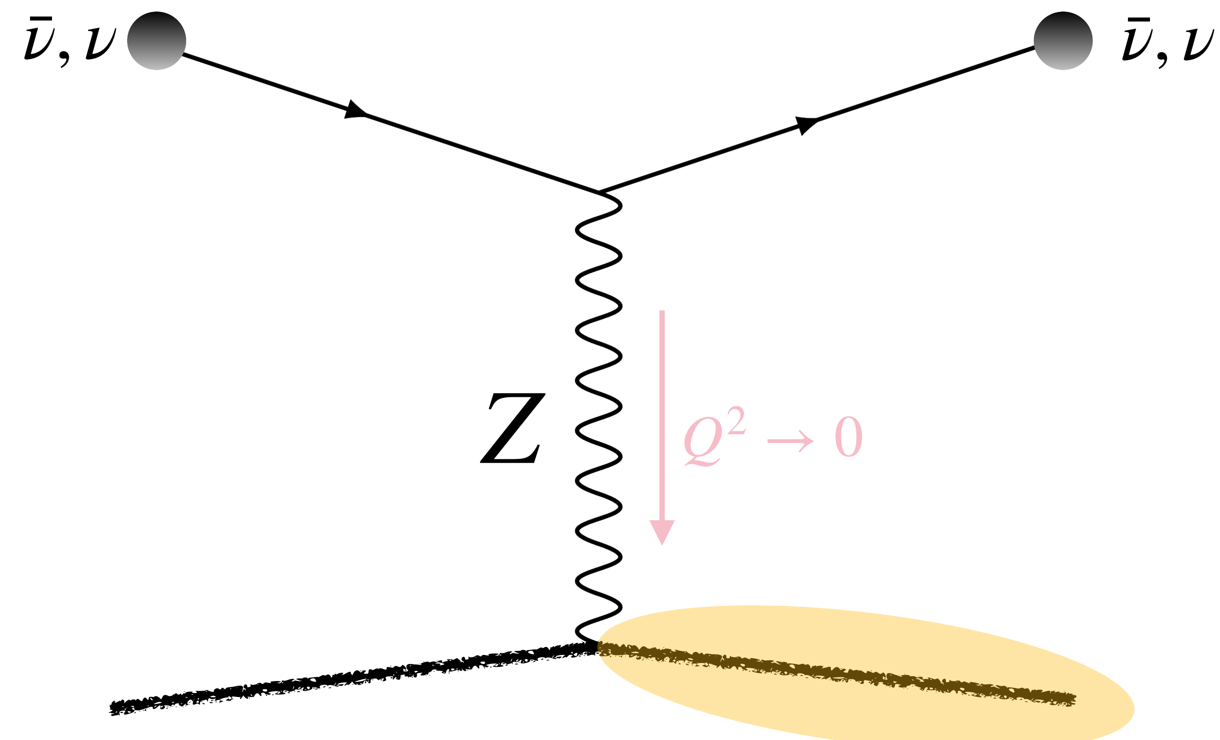
Why detecting NC interaction is difficult?

Charged Current



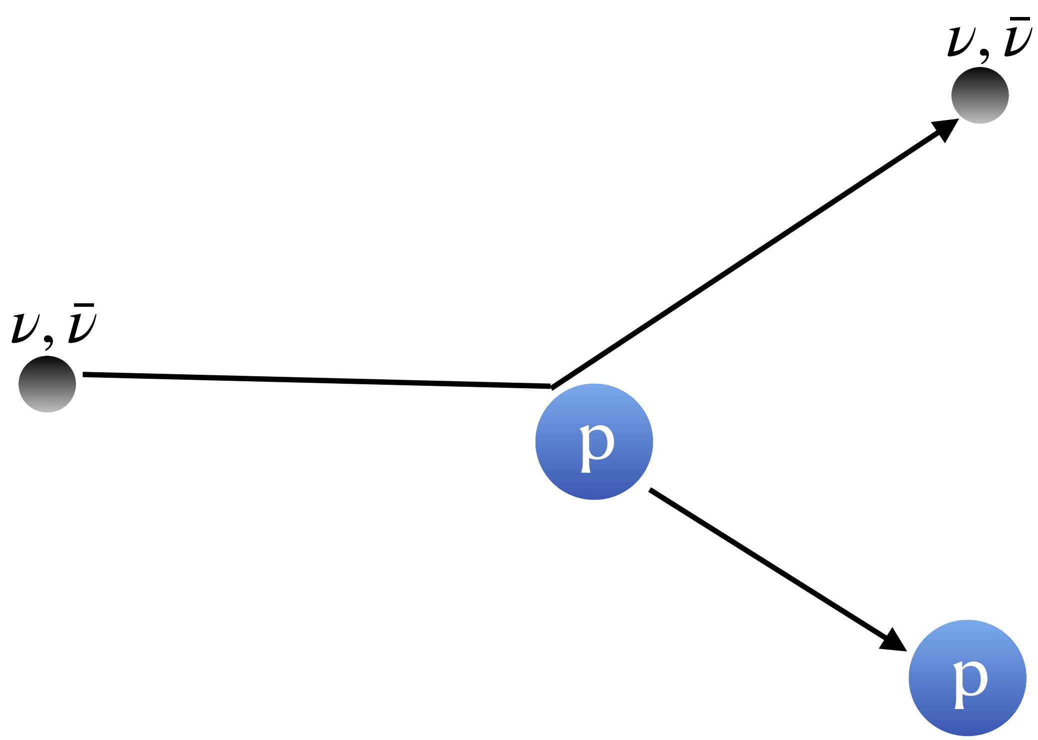
- Larger visible energy
- Reconstructability
- Directionality
- Tagging

Neutral Current



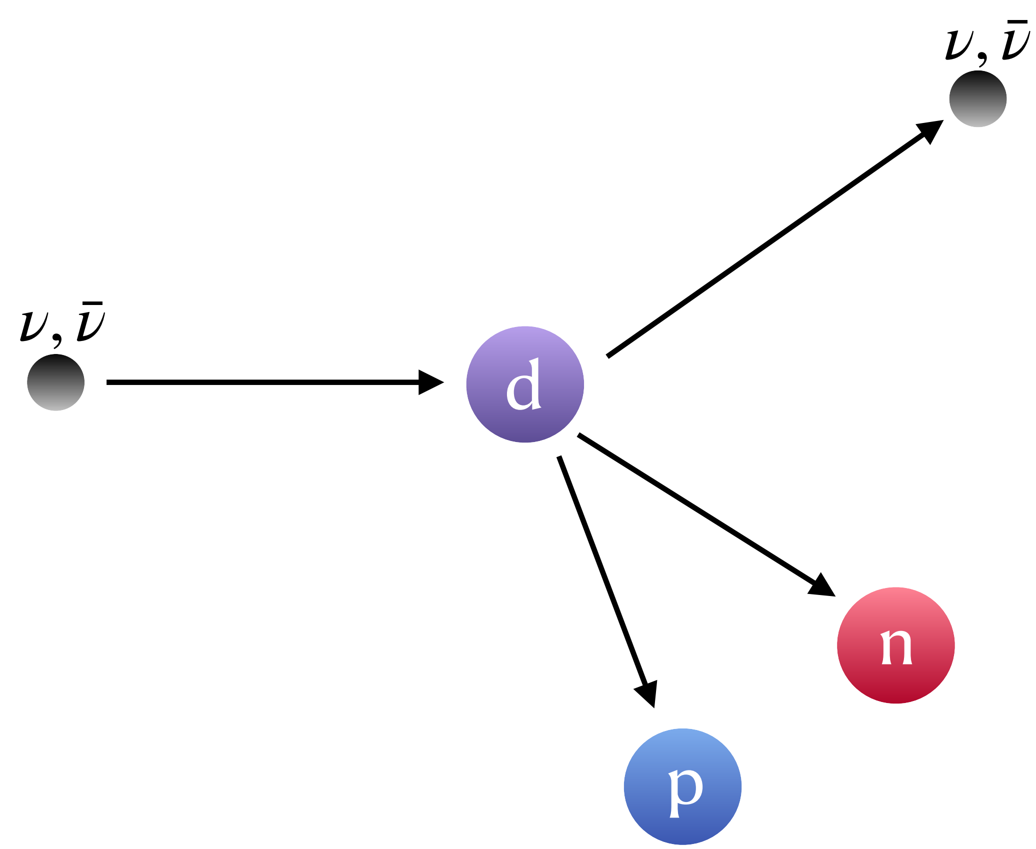
- All neutrino flavors

Two Paths



Elastic Scattering on Proton

Part I : This Talk



Deuteron Dissociation

Part II : Interesting, but not today!

Part I

Neutral-current interactions of neutrinos (or DM) in JUNO

based on arXiv:2111.14586

Basudeb Dasgupta
with Bhavesh Chauhan and Amol Dighe

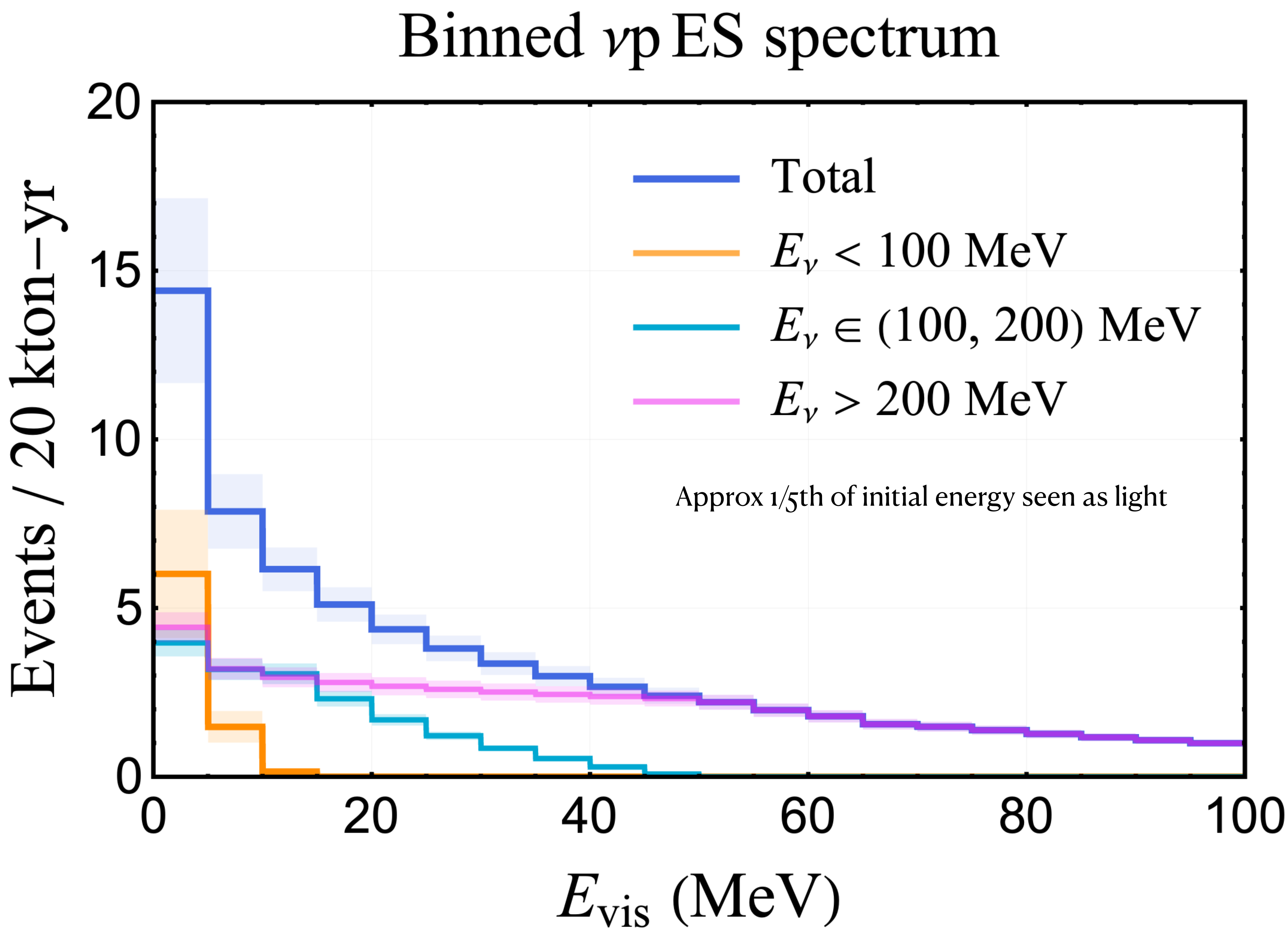
Preamble

- Atmospheric neutrinos are produced in interaction of cosmic rays with Earth's atmosphere.
- Super-Kamiokande has measured the flux of atm. neutrinos from 100 MeV - 10 TeV, using CC interactions.
- How to detect the low-energy atmospheric neutrinos? CC is forbidden due to kinematic threshold, NC due to Cherenkov threshold $\Longrightarrow$ Scintillator Detector!
- JUNO is upcoming large volume (~20 kton) liquid scintillator detector.
- We forecast the signal and backgrounds at JUNO, and propose to maintain a Large Energy Singles (LES) database. The same data can be used to constrain Boosted Dark Matter.

There are two components:

Protons and Carbon

Atmospheric neutrino proton interaction



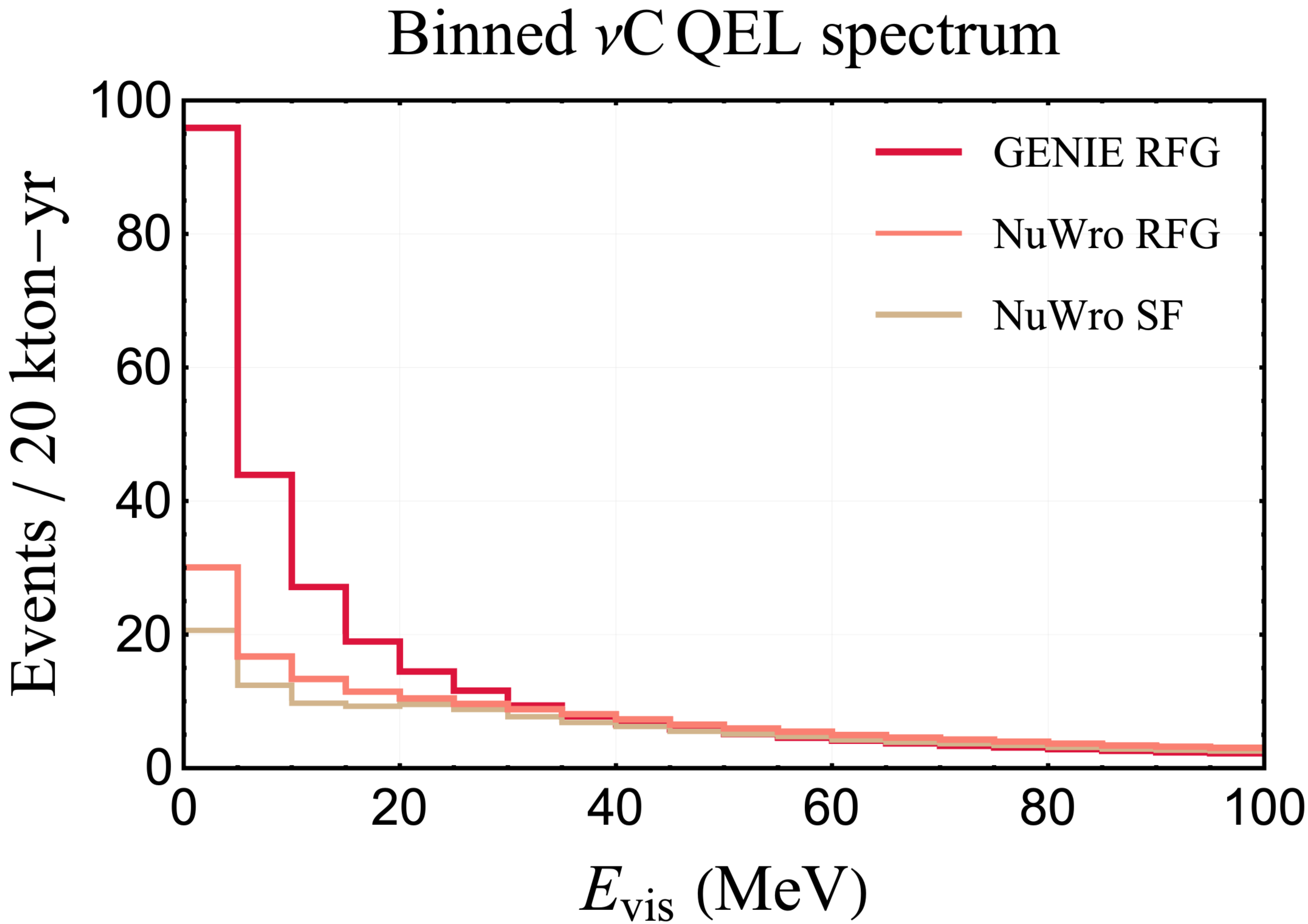
Atmospheric neutrino carbon interaction

- Atmospheric neutrinos can interact with carbon in the detector via the neutral current channel and knockout one or more nucleons.
- The *singles* background arises from proton knockouts (1p, 2p, 3p, ...).

$$
\begin{aligned}
1p: &\quad \nu + {}^{12}\mathrm{C} \to \nu + p + {}^{11}\mathrm{B}^{(*)} \\
2p: &\quad \nu + {}^{12}\mathrm{C} \to \nu + 2p + {}^{10}\mathrm{Be}^{(*)} \\
3p: &\quad \nu + {}^{12}\mathrm{C} \to \nu + 3p + {}^{9}\mathrm{Li}^{(*)}
\end{aligned}
$$

- The cross section for these processes depends on models of nuclear structure (e.g., relativistic fermi gas, spectral function), MC generator (e.g., GENIE, NuWro, NEUT, ...), and some other factors.
- These predictions for JUNO were recently computed by Cheng et. al. (in 2008.04633 and 2009.04085) in the context of DSNB searches.

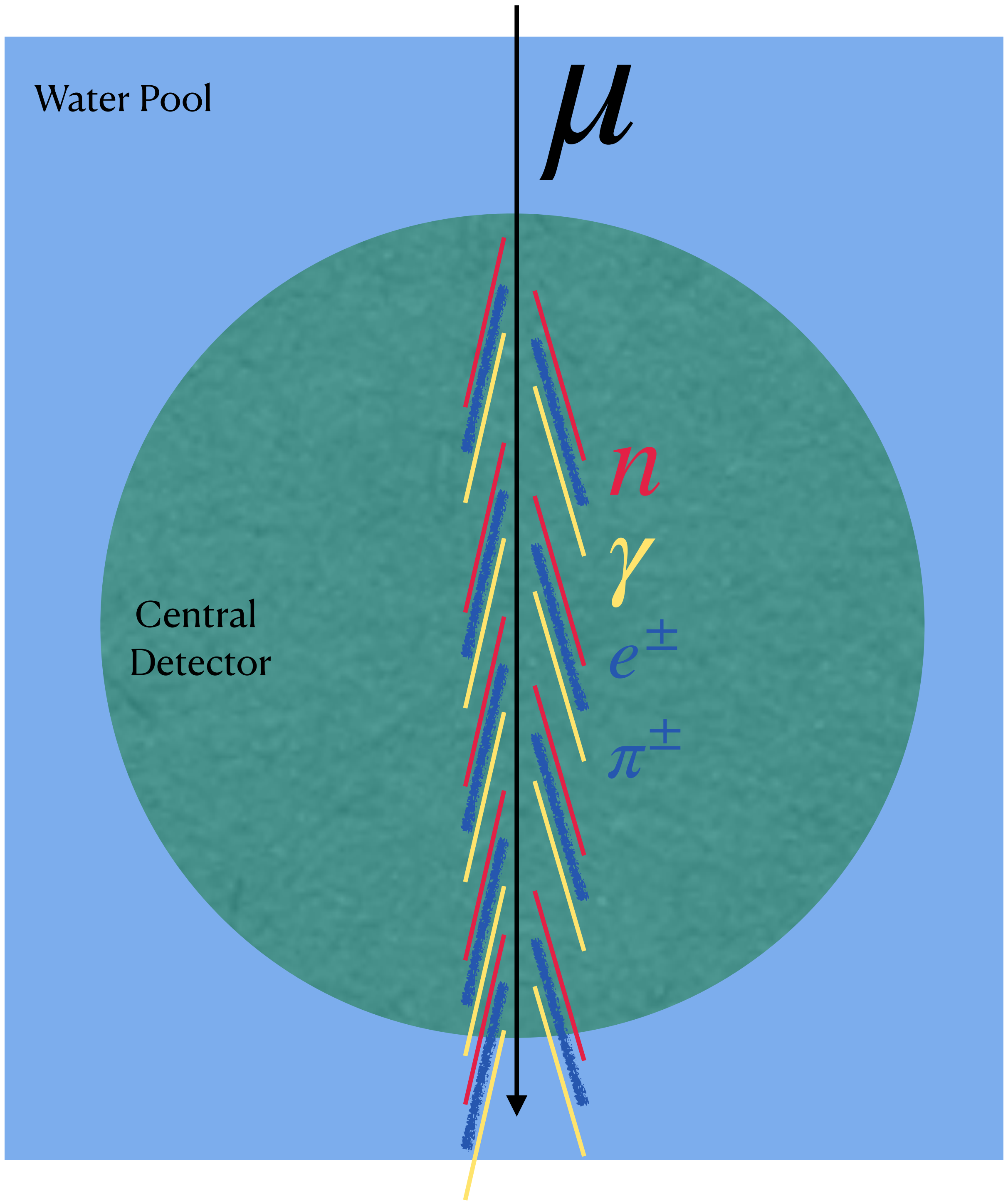
Atmospheric neutrino carbon interaction



Backgrounds?

Muon Spallation Background

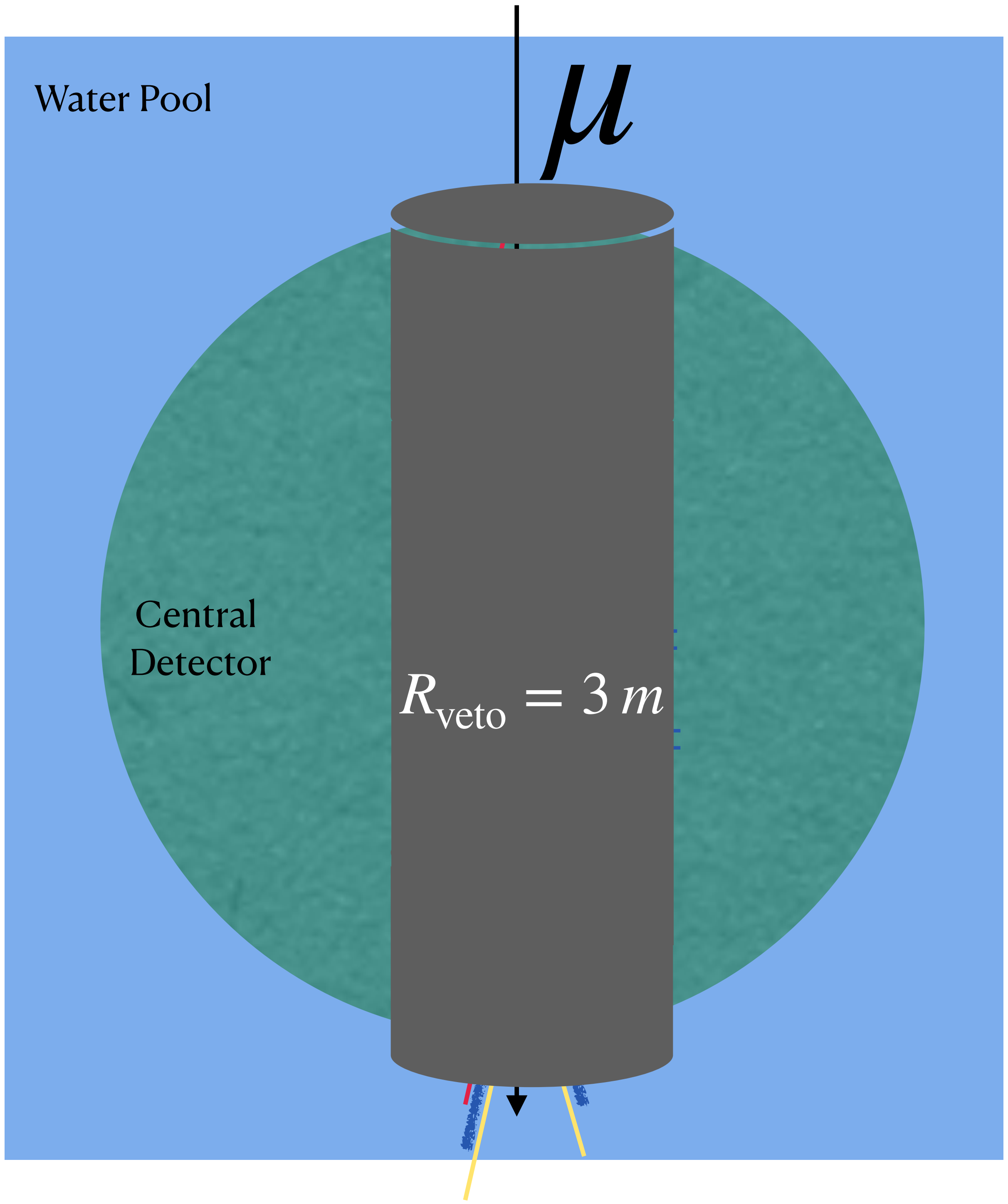
- Cosmic muons that enter the detector, produce a 'shower' of $n, \gamma, e^{\pm}$ which interact with carbon to produce other isotopes through spallation.
- These cosmogenic isotopes decay via $\beta^{\pm}, \beta^{\pm}\gamma, \beta^{\pm}\alpha \ldots$ emission.
- The outer water pool of JUNO can tag these muons, and the expected rate is 3 Hz with $\langle E_{\mu} \rangle \sim 215$ GeV



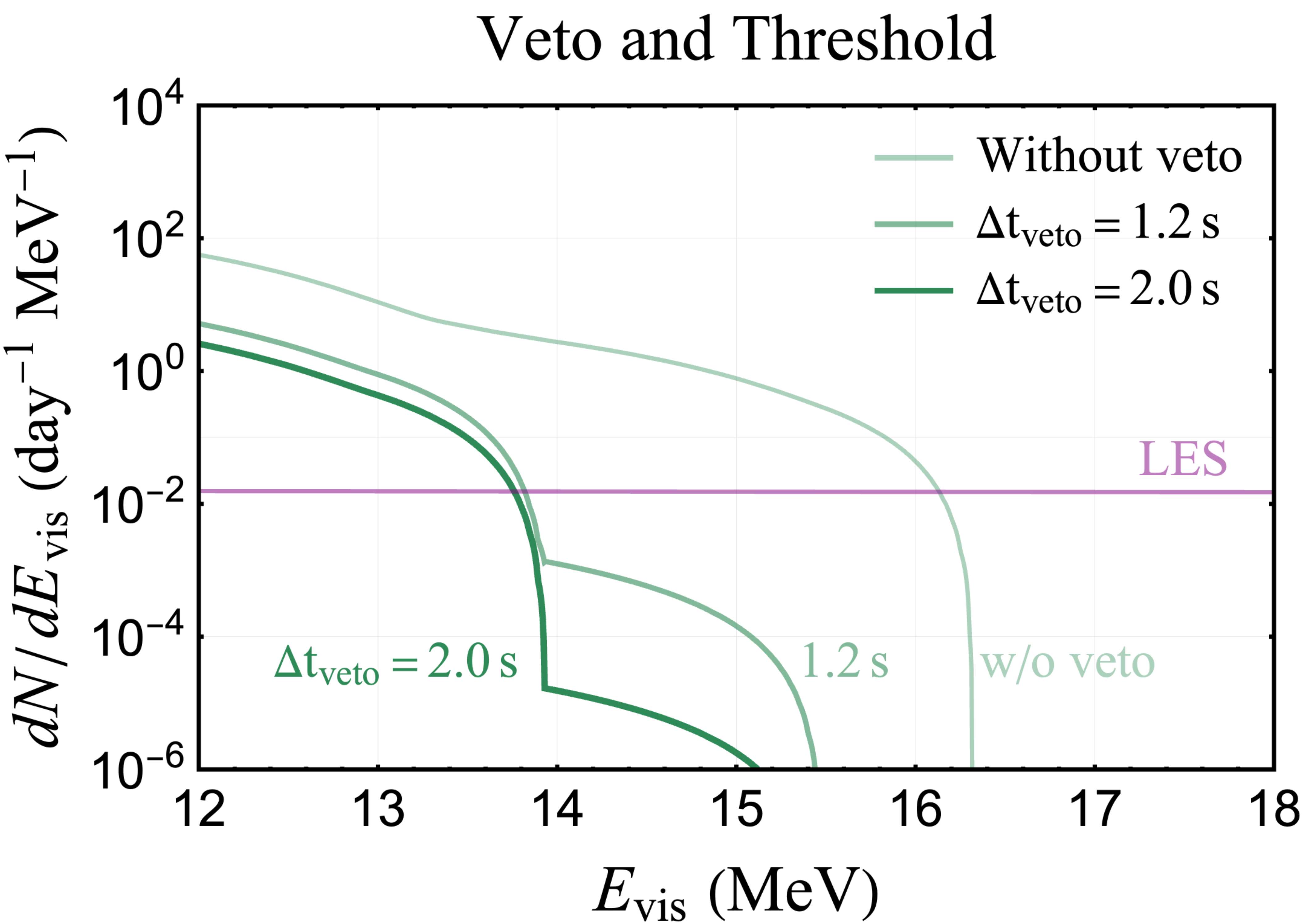
Muon Spallation: Veto

For each tagged muon, blind the region R_{veto} around the track for Δt_{veto}.

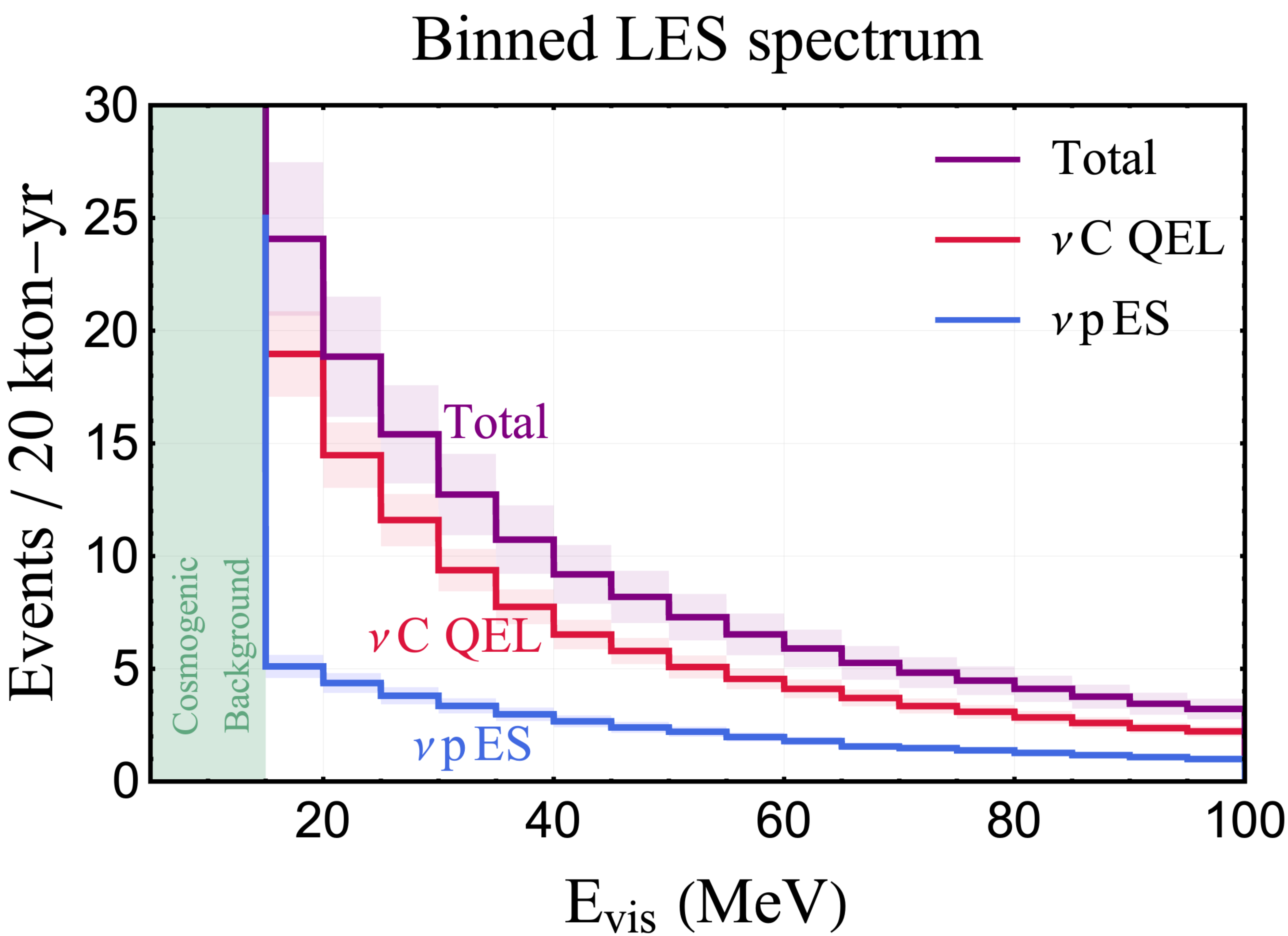
For DSNB search, JUNO uses $R_{\text{veto}} = 3$ m and $\Delta t_{\text{veto}} = 1.2$ s.



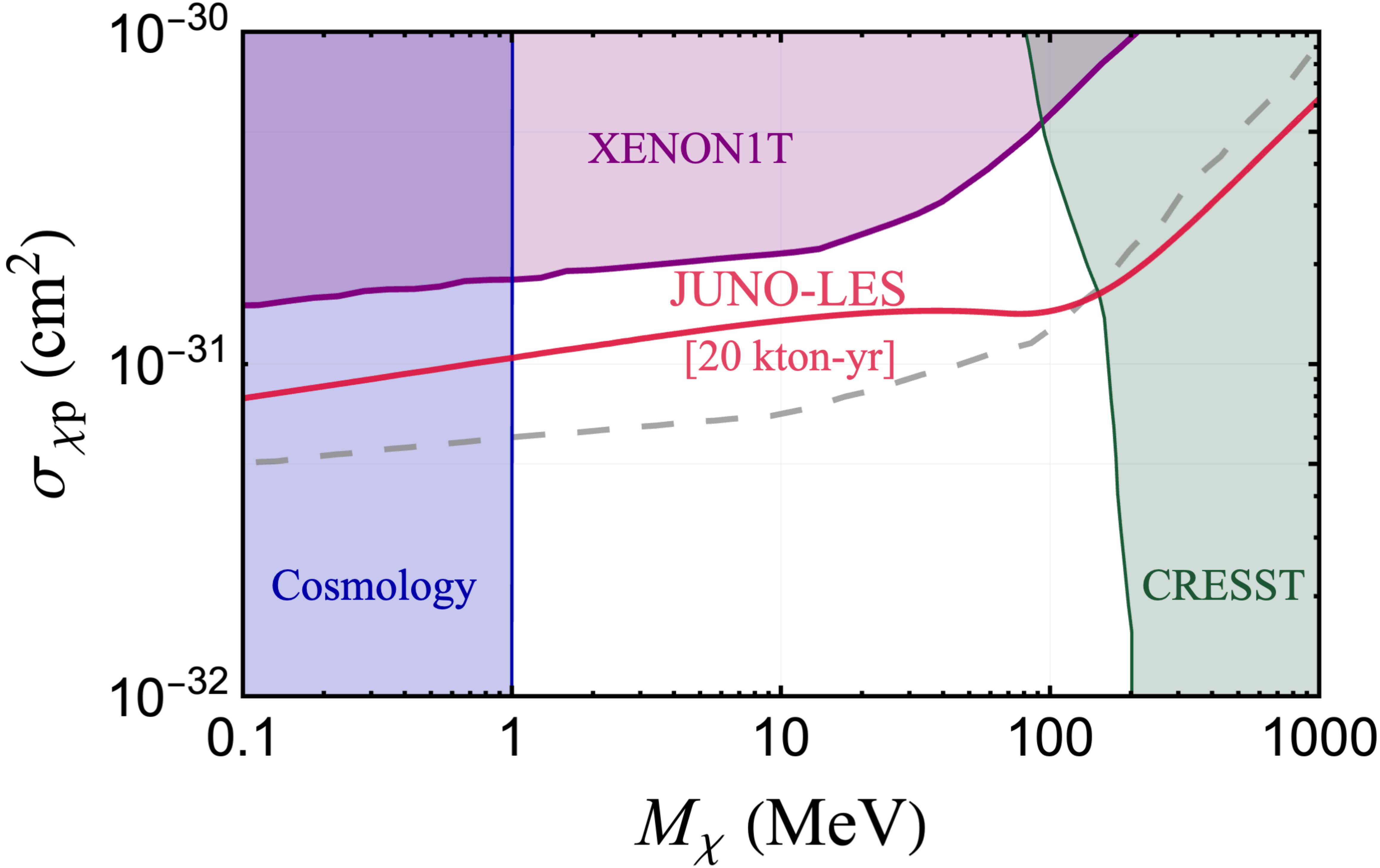
Muon Spallation Background: Threshold



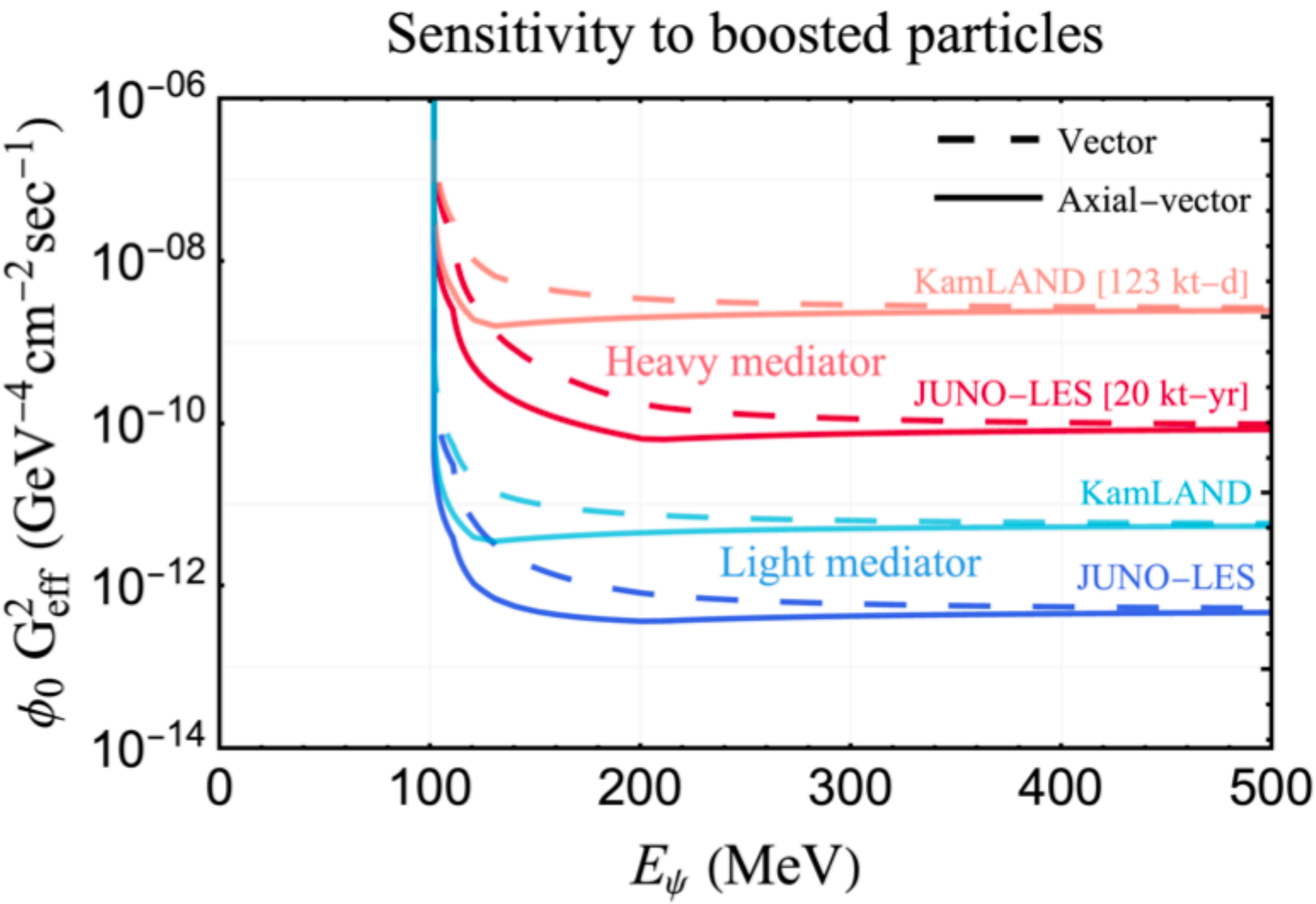
Forecast for JUNO



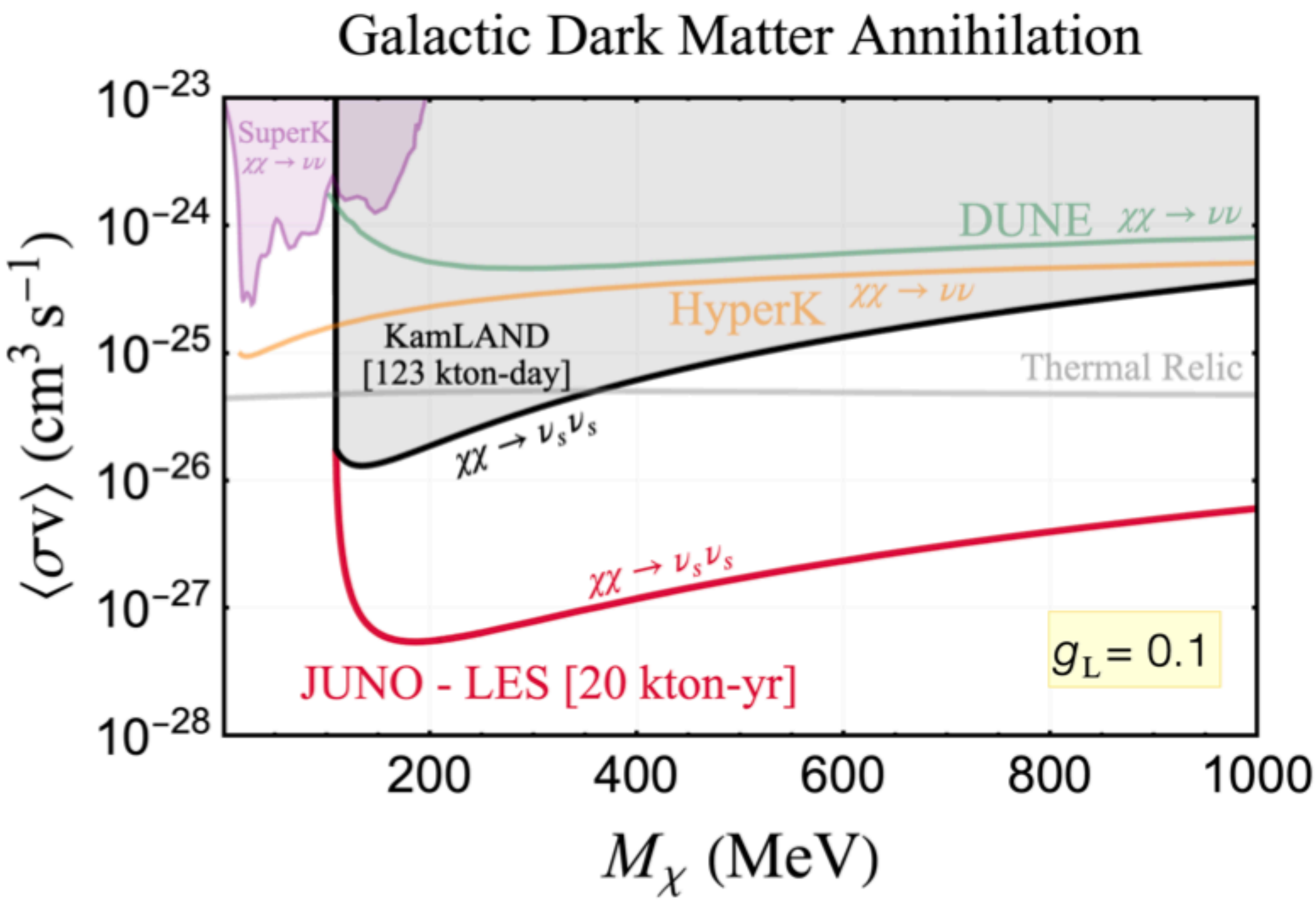
Application: Boosted Dark Matter



Effective Bound on Boosted DM



Bound on Neutrinophilic DM



Summary

- LES arise from low-energy atmospheric neutrinos interactions with protons and carbon in JUNO
- We provide details of the event spectrum as well as backgrounds.
- The lower energy threshold is determined by the decay of cosmogenic isotopes.
- With our preliminary veto, the threshold can be lowered to 15 MeV with only 10% reduction in exposure.
- The νp ES signal is a factor of ~2 smaller than the νC background.
- Comparing total event rates, we estimate that JUNO can identify the signal at 3σ (5σ) with 12 (34) kton-yr of effective exposure.
- This database can also test BSM ideas such as Boosted DM.

Part II

A deuterated liquid scintillator for supernova neutrino detection

based on JCAP 11 (2021) 005 | arXiv:2106.10927

Basudeb Dasgupta
with Bhavesh Chauhan and Vivek Datar

Preamble

- What would the neutrino detectors see if there is a core collapse supernova near our galactic centre?
- Super-Kamiokande would observe several thousand events, Borexino/KamLAND/LVD would observe several hundred events.
- Large fraction of detected events arise from Inverse Beta Decay ($\bar{\nu}_e + p \rightarrow e^+ + n$) which is mediated by Charged Current
- The other flavors (ν_μ, ν_τ, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$) can be detected via:
  - $\nu + e^- \rightarrow \nu + e^-$ (small cross section)
  - $\nu + p \rightarrow \nu + p$ (quenched scintillation) Beacom, Farr, Vogel, hep-ph/0205220
  - $\nu + A \rightarrow \nu + A^*$ (no spectral info.)
- How can we reliably detect the Neutral Current interactions?

Preamble

- The solar neutrino problem was solved when the Sudbury Neutrino Observatory (SNO) measured the Neutral Current interaction by 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
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    https://www.hwb.gov.in/
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    Beacom and Vagins hep-ph/0309300
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Resolved if you have a scintillator!

Preamble

We propose
a kton-scale deuterated liquid scintillator,
with added Gd, and instrumented with PMTs
that can be used to study low energy neutrinos
esp. through the Neutral Current channel.

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Main Purpose of DLS: Solar Neutrinos

This talk: Supernova Neutrinos

Supernova neutrino flux

- The flux of neutrinos from a CCSN is flavor, energy, and time dependent.
- We use a provisional model for fluence

$$F_\alpha^{(0)} = \frac{2.35 \times 10^{13}}{\mathrm{cm}^2\,\mathrm{MeV}} \cdot \left(\frac{\mathscr{E}_\alpha}{10^{52}\,\mathrm{erg}}\right) \cdot \left(\frac{10\,\mathrm{kpc}}{d}\right)^2 \cdot \frac{E_\alpha^3}{\langle E_\alpha\rangle^5} \cdot \exp\left(-\frac{4E_\alpha}{\langle E_\alpha\rangle}\right)$$

≡ Pinching factor : 3

Table : Two fluence models considered

Fluence Model	$\langle E_{\nu_e}\rangle$	$\langle E_{\bar{\nu}_e}\rangle$	$\langle E_{\nu_x,\bar{\nu}_x}\rangle$
High (optimistic)	12	15	18
Low (conservative)	10	12	15

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

Supernova neutrino flux

To include the effects of flavor conversions, we consider two scenarios:

1. Flavor Equilibrium $F_\alpha = \frac{1}{3}\left(F_e^{(0)} + F_\mu^{(0)} + F_\tau^{(0)}\right)$

2. No Oscillation $F_\alpha = F_\alpha^{(0)}$

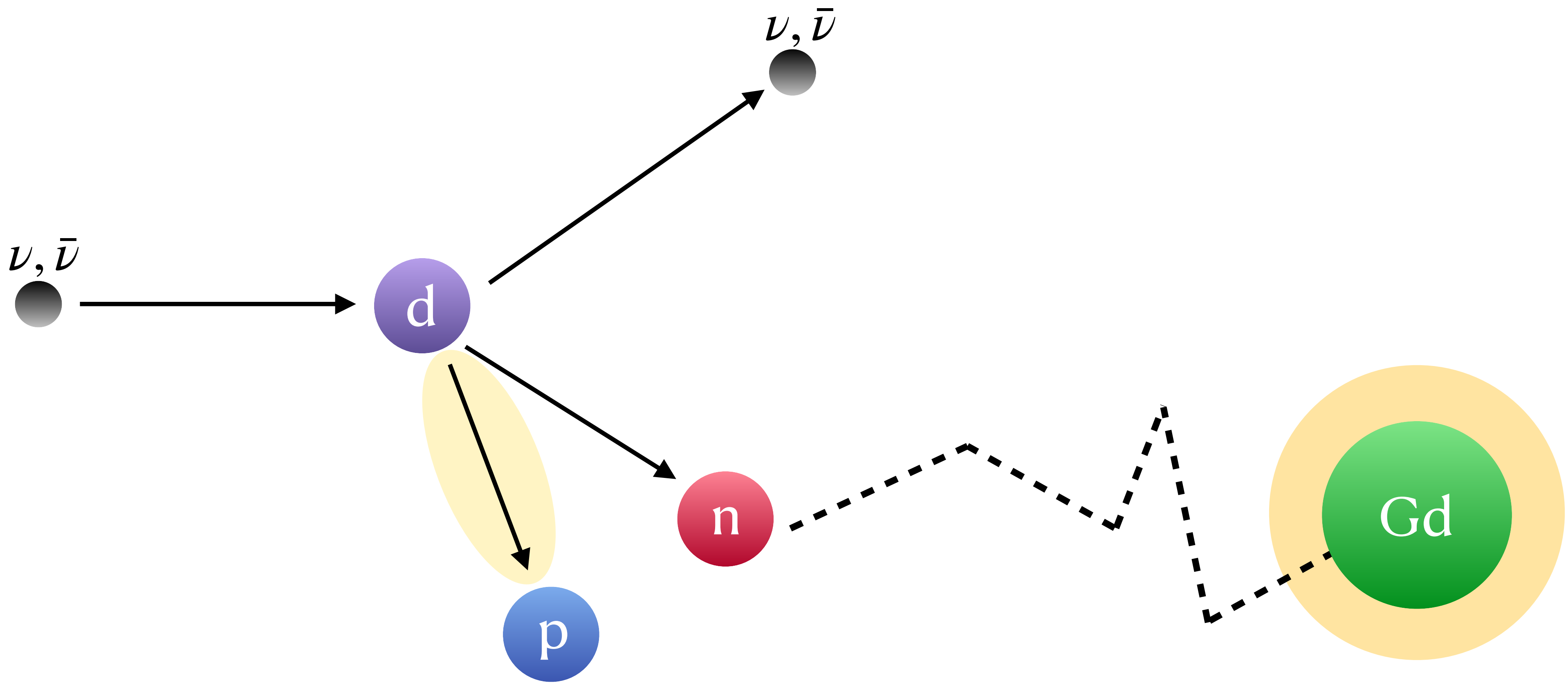
Interactions and detectables

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

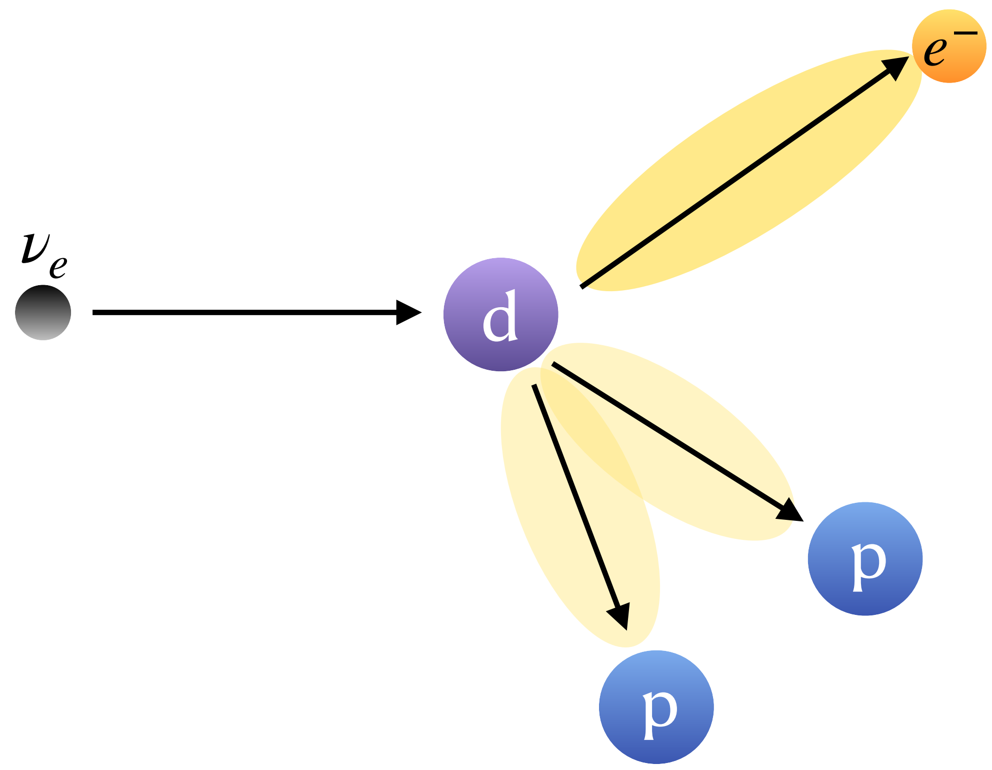
$$\underbrace{\nu,}_{\text{Cannot be detected}} \quad \underbrace{e^{\pm}, \quad p,}_{\text{Scintillation}} \quad \underbrace{n}_{\text{Thermalises and Captured!}}$$

Neutral Current

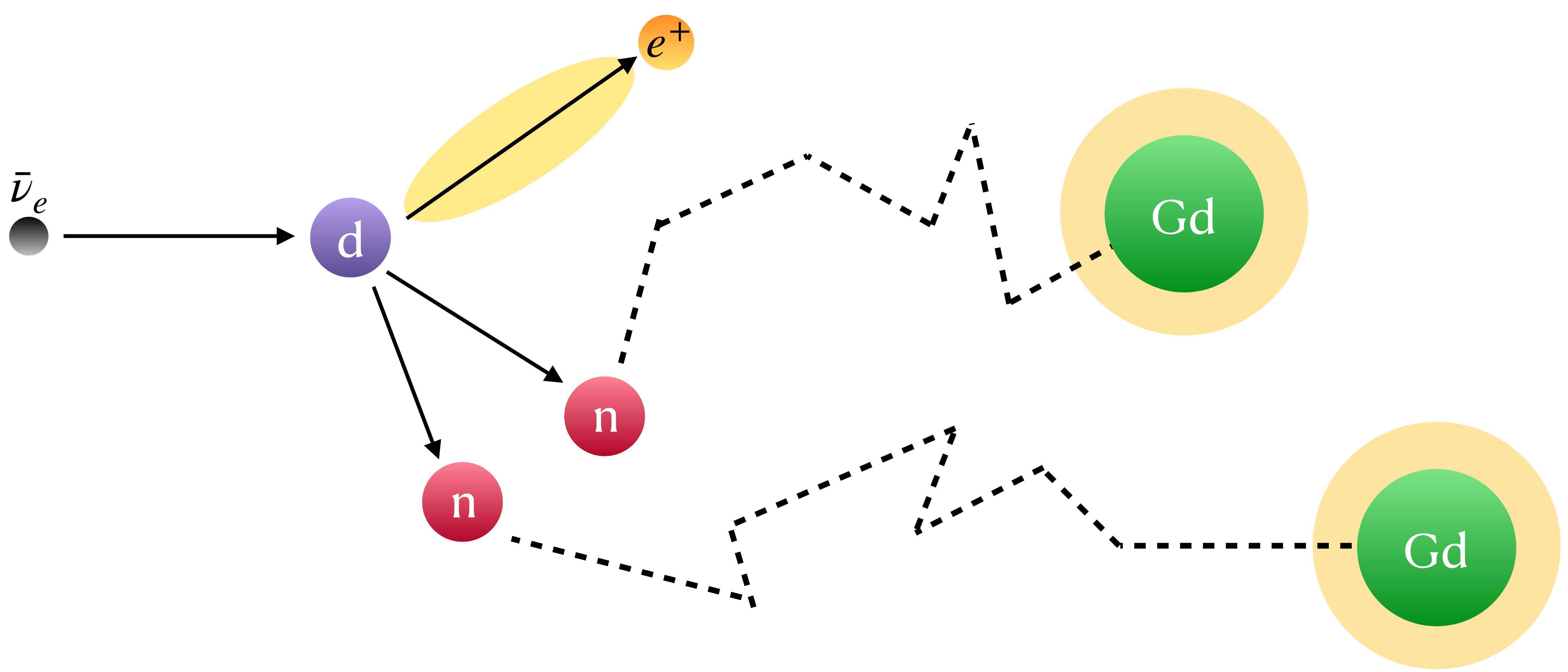


Scenario	Total (rounded off)
High; no oscillation	435
High; flavor equilibrium	435
Low; no oscillation	335
Low; flavor equilibrium	335

Charged Current

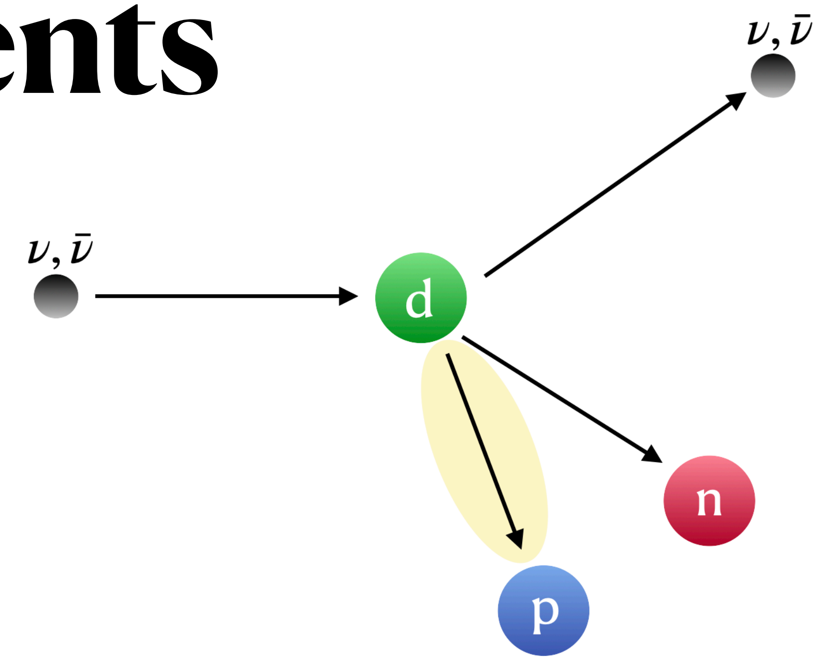


Scenario	ν_e	$\bar{\nu}_e$
High; no oscillation	111	90
High; flavor equilibrium	170	108
Low; no oscillation	84	63
Low; flavor equilibrium	130	81



Spectrum of events

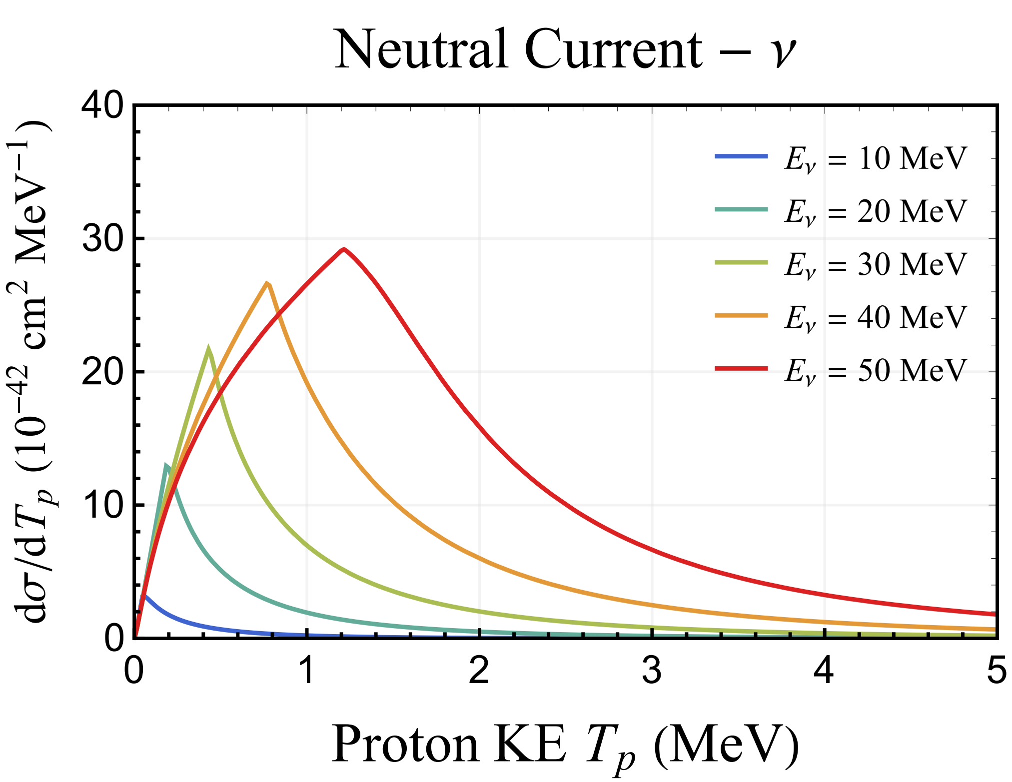
Neutral Current

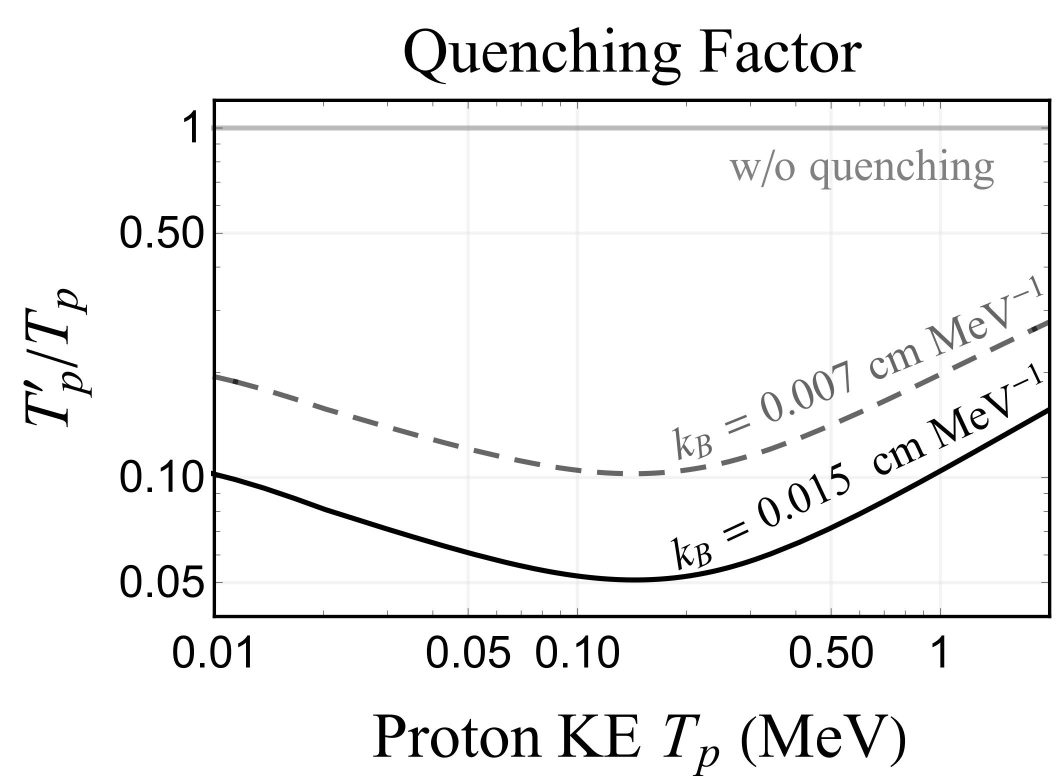


- Detecting scintillation from NC channel has two issues :

1. Small momentum transfer to proton
2. Photosaturation losses / Quenching

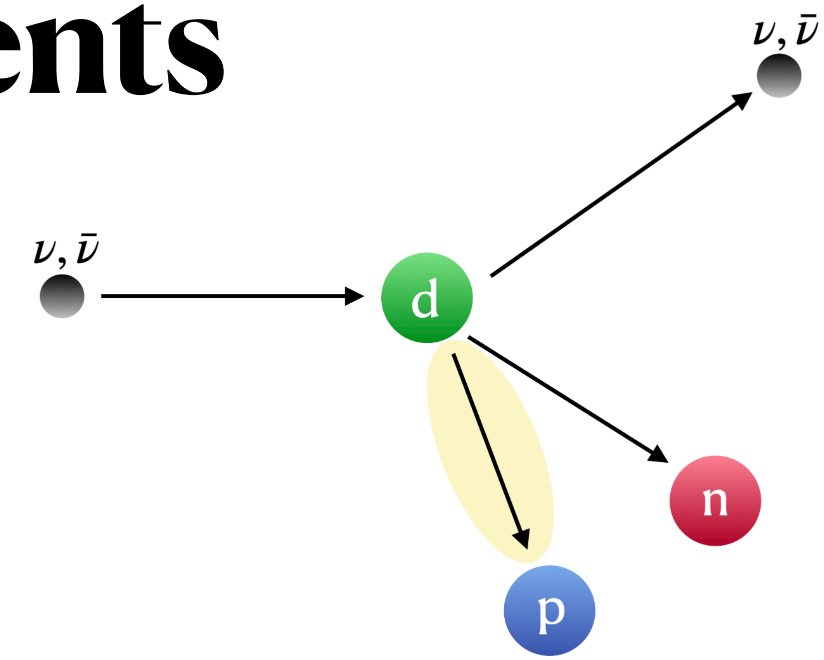
$$E_{vis} = T'_p = Q(T_p) = \int_0^{T_p} \frac{dT}{1 + k_B \langle dT/dx \rangle}$$

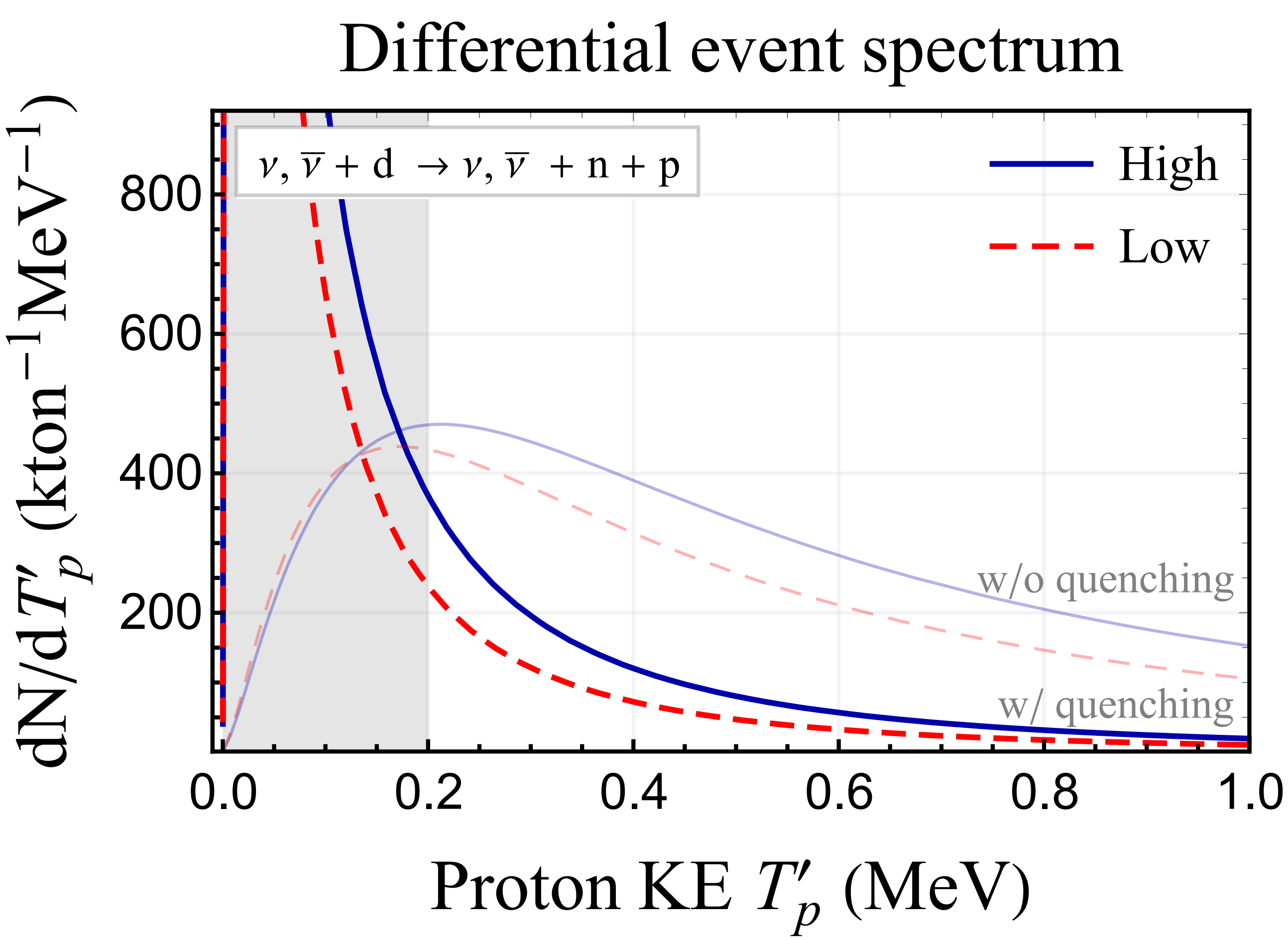


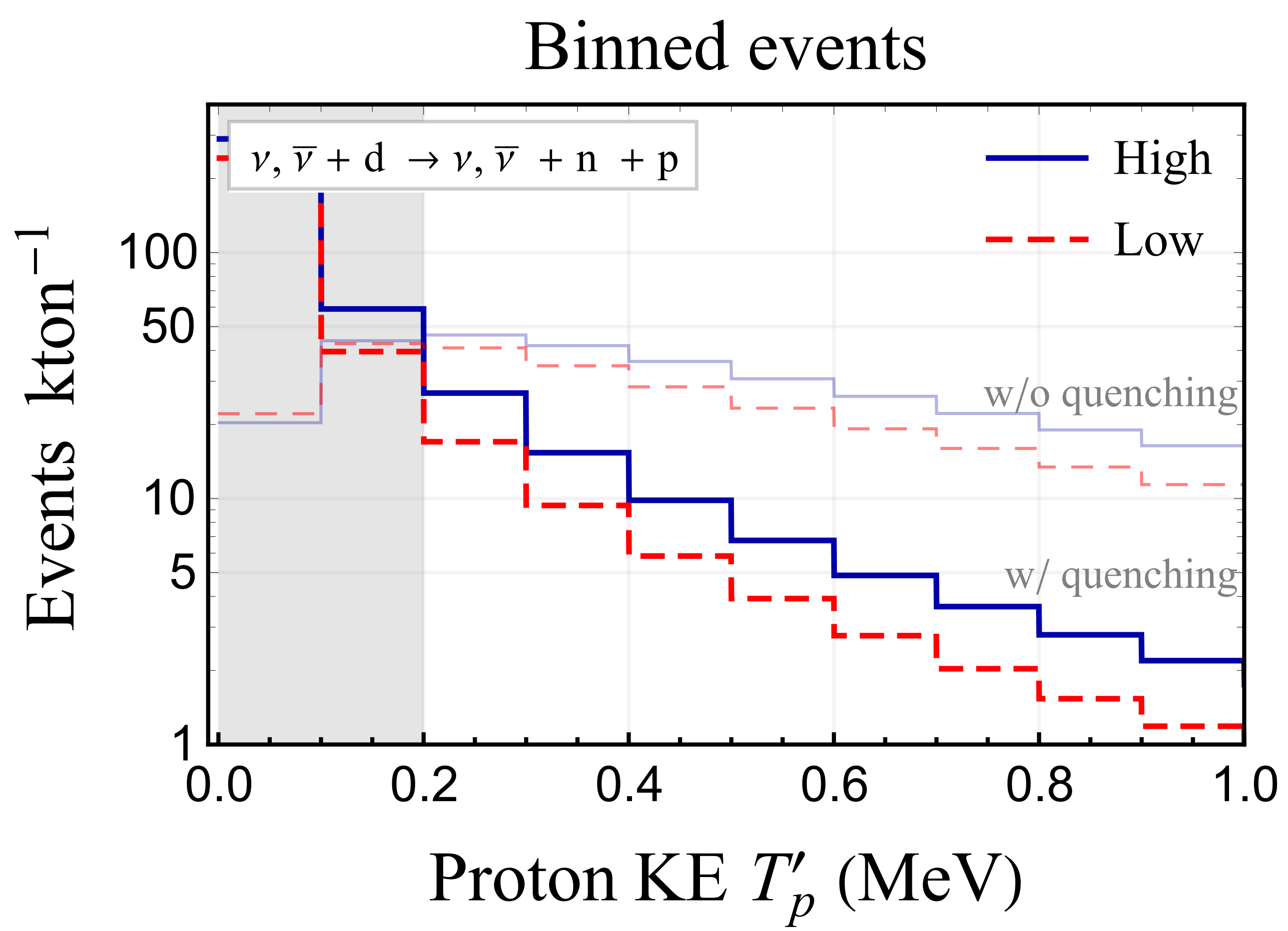


Spectrum of events

Neutral Current





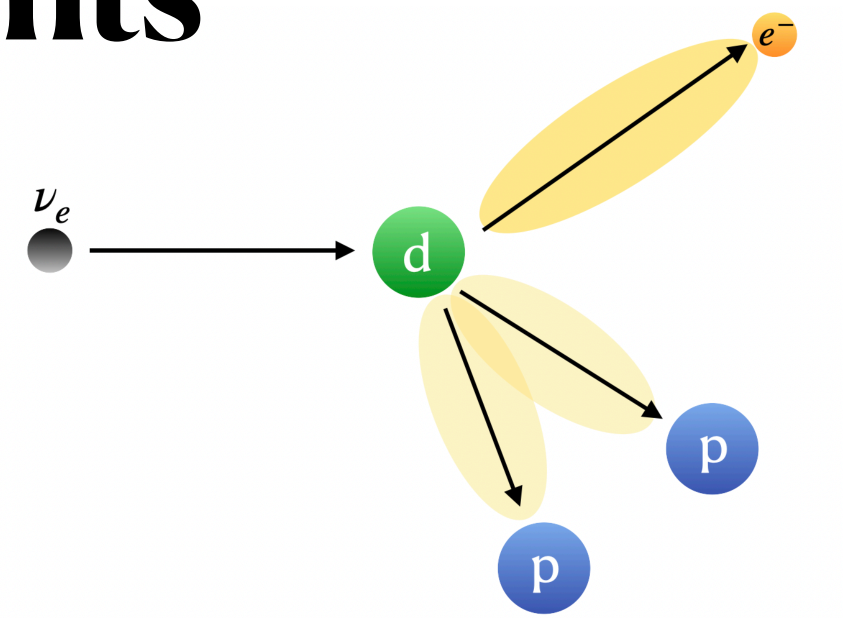


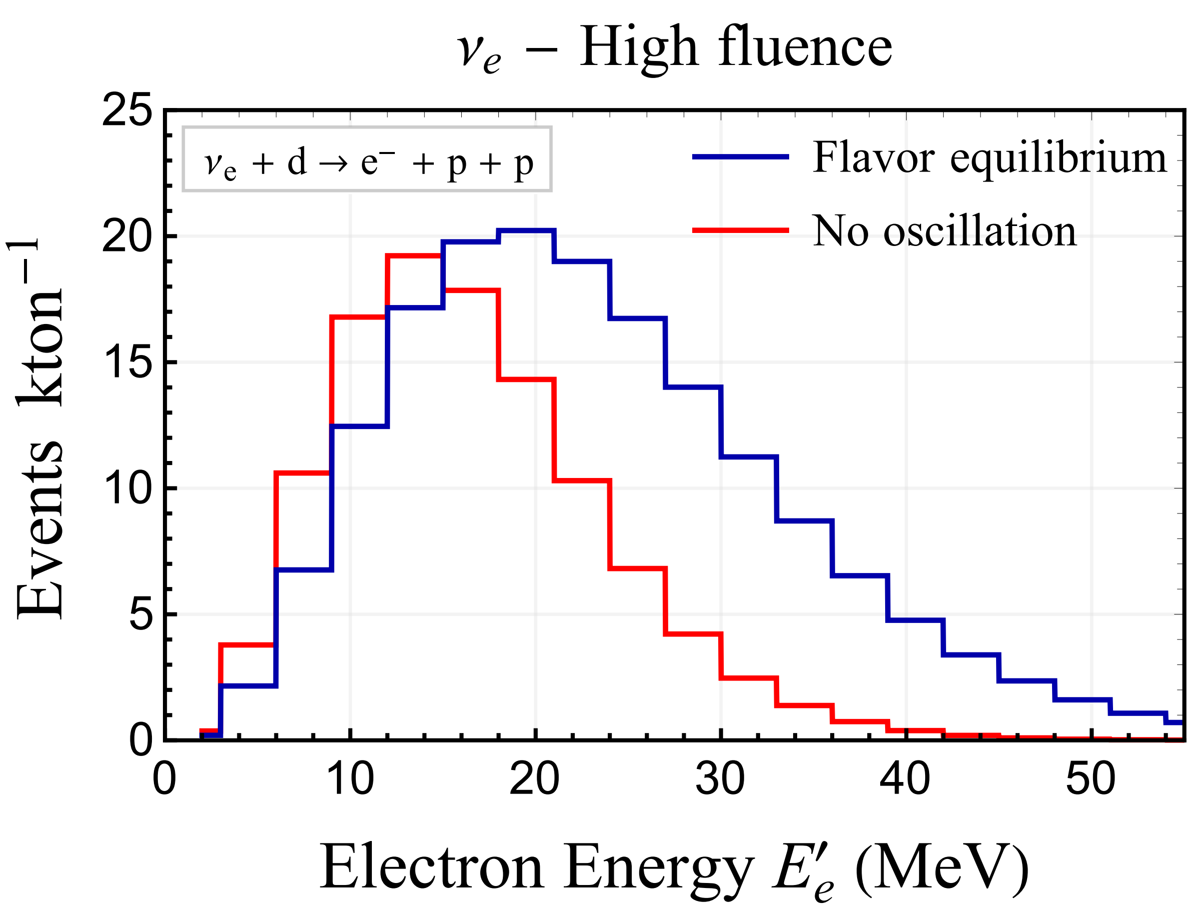
High (Low) Fluence: 84 (50) proton above 200 keV

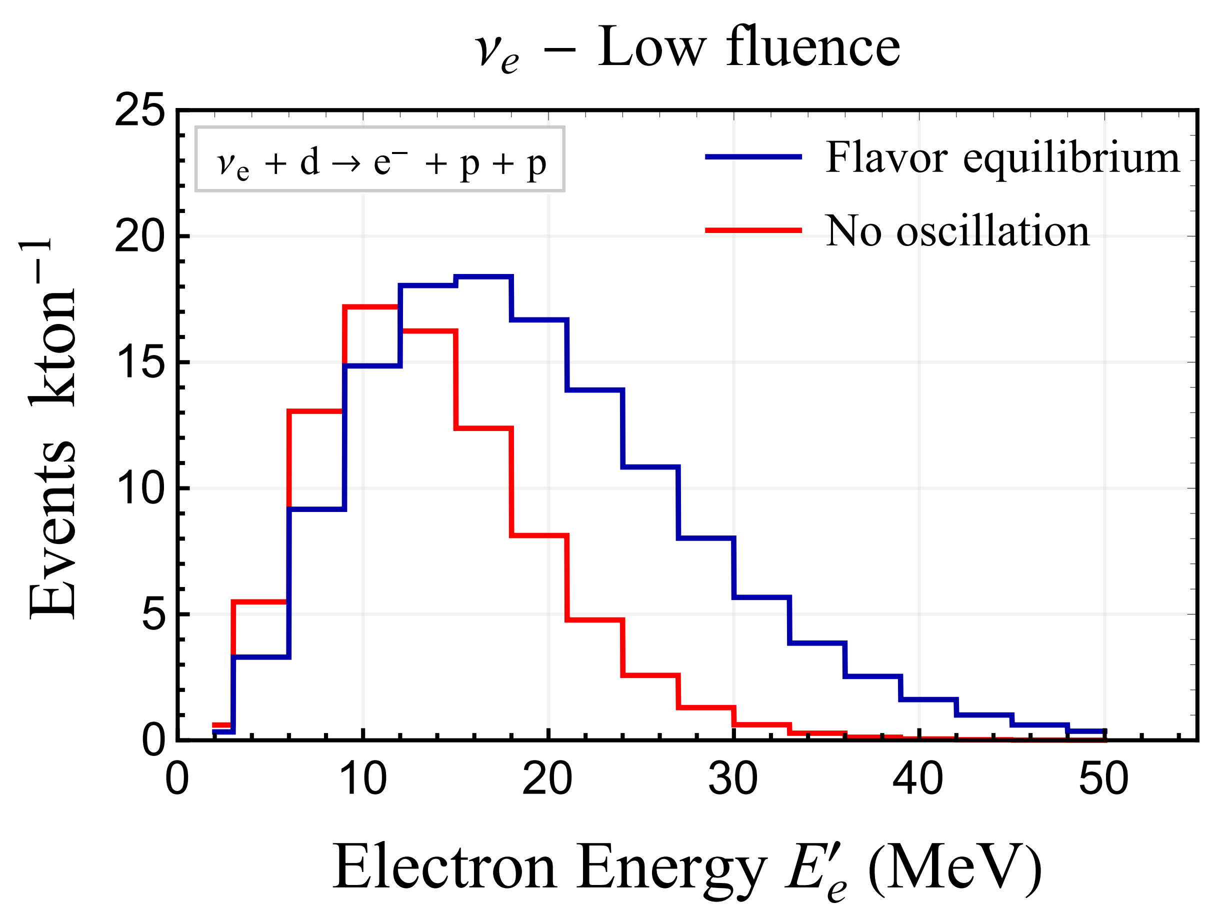
Note: Neutron tag is possible!

Spectrum of events

ν_e - Charged Current





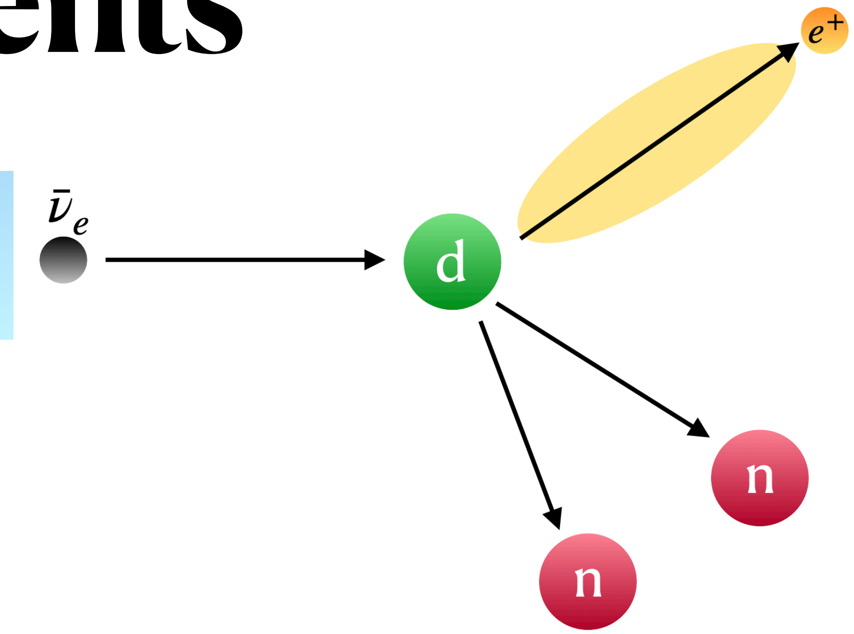


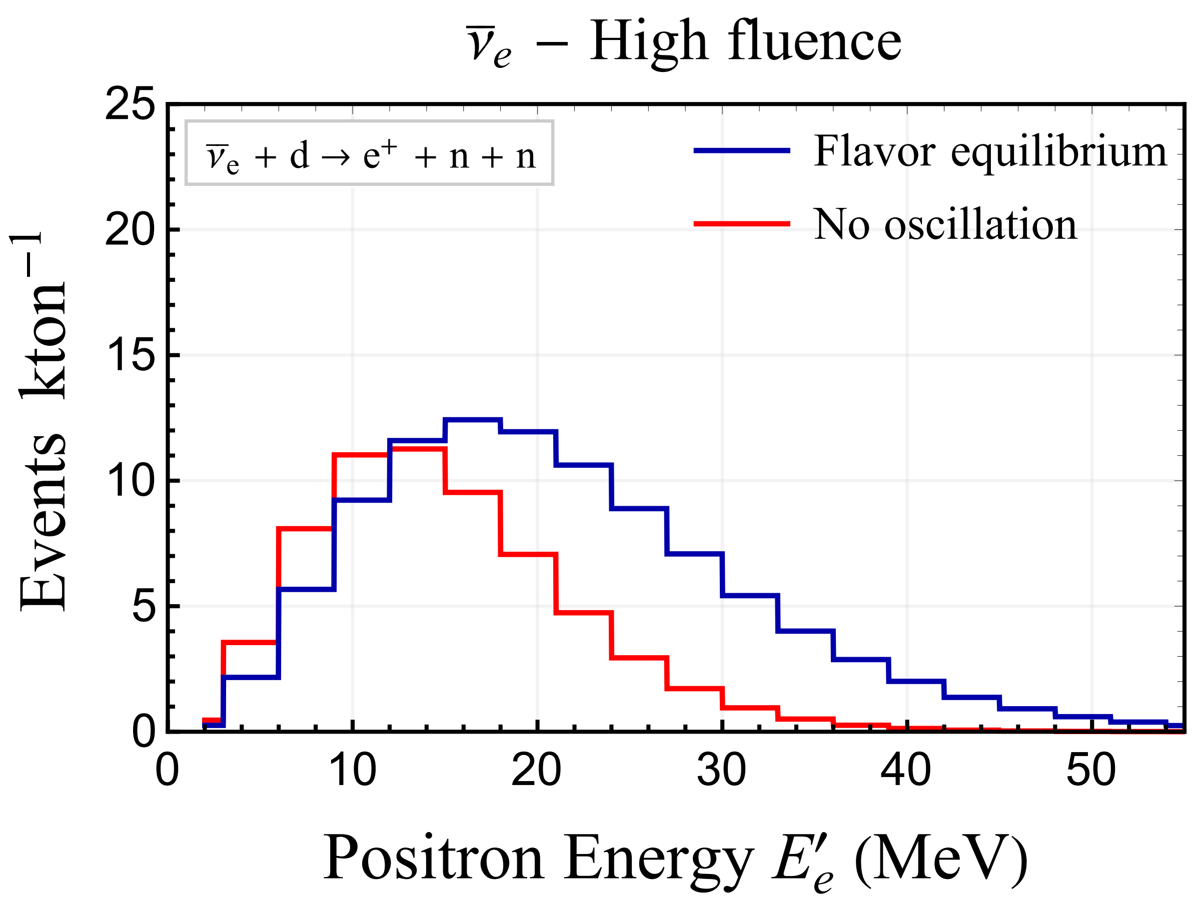
Flavor Eq. : 170 events
No Osc. : 111 events

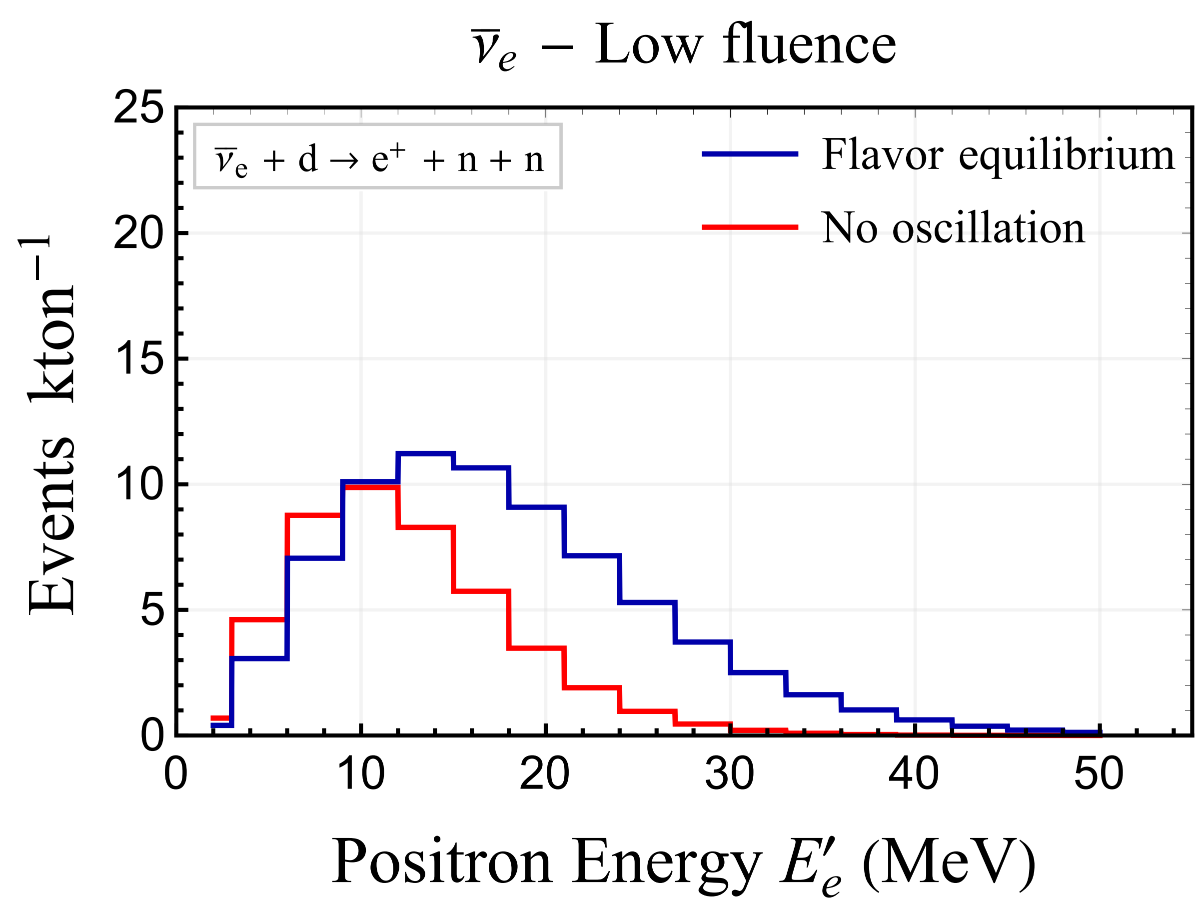
Flavor Eq. : 130 events
No Osc. : 84 events

Spectrum of events

$\bar{\nu}_e$ - Charged Current







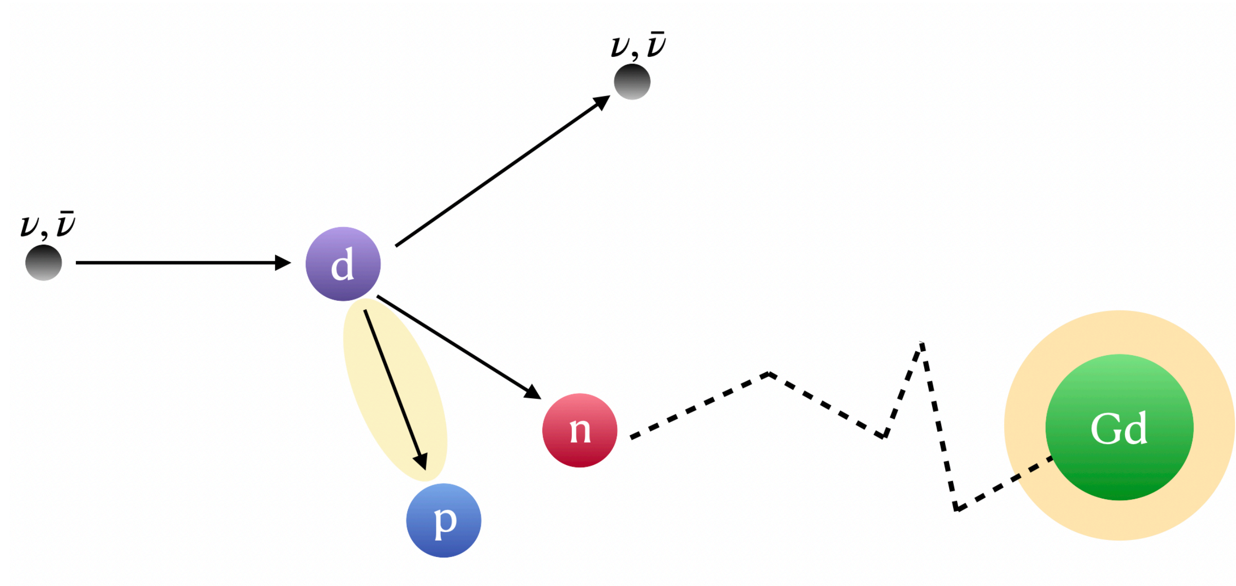
Flavor Eq. : 108 events
No Osc. : 90 events

Flavor Eq. : 81 events
No Osc. : 63 events

A small Detour

For completeness

Secondary Interactions

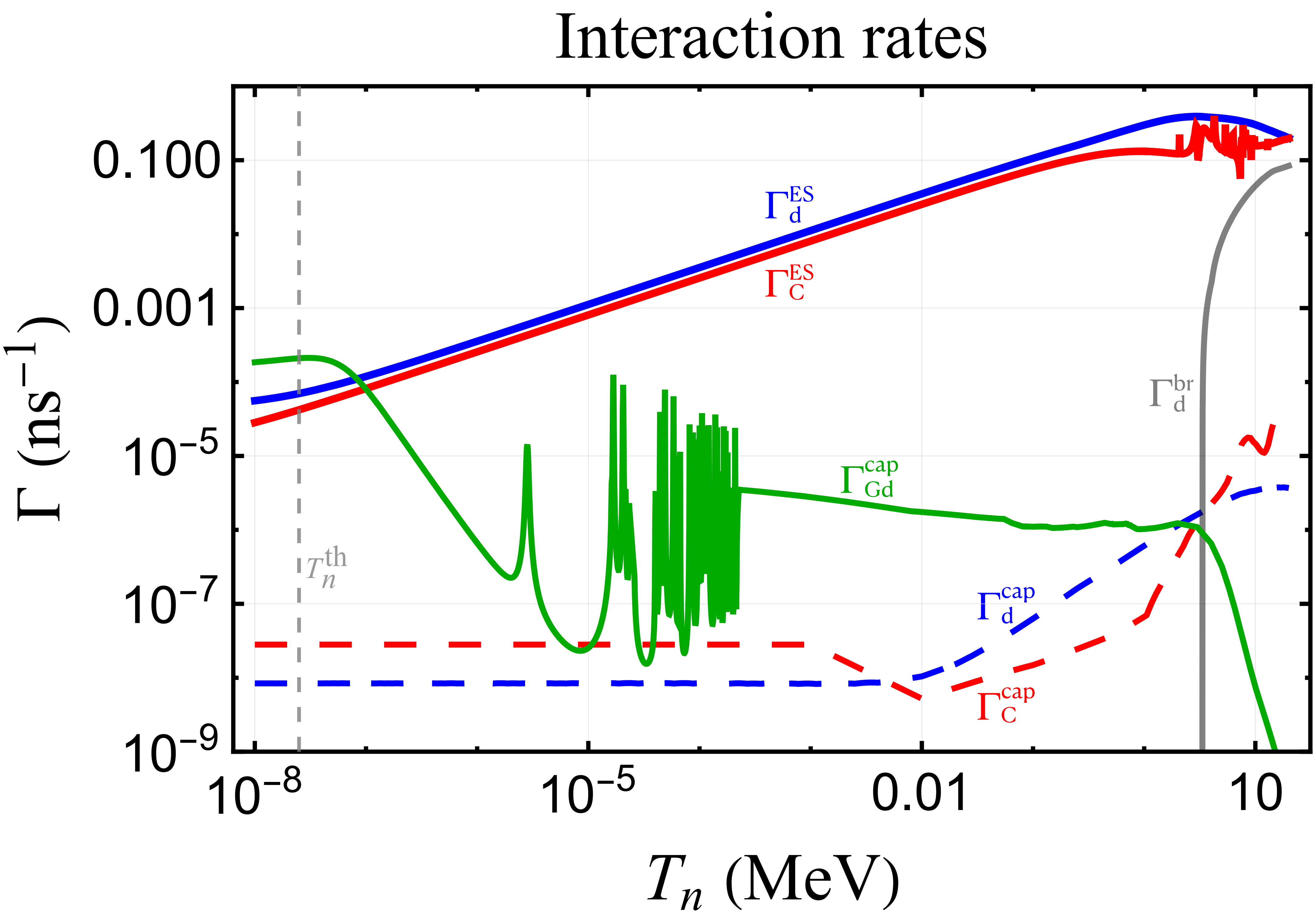


- Final state protons lose energy quickly and travel ~0.1 mm
- The neutrons undergo following secondary interactions:

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

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

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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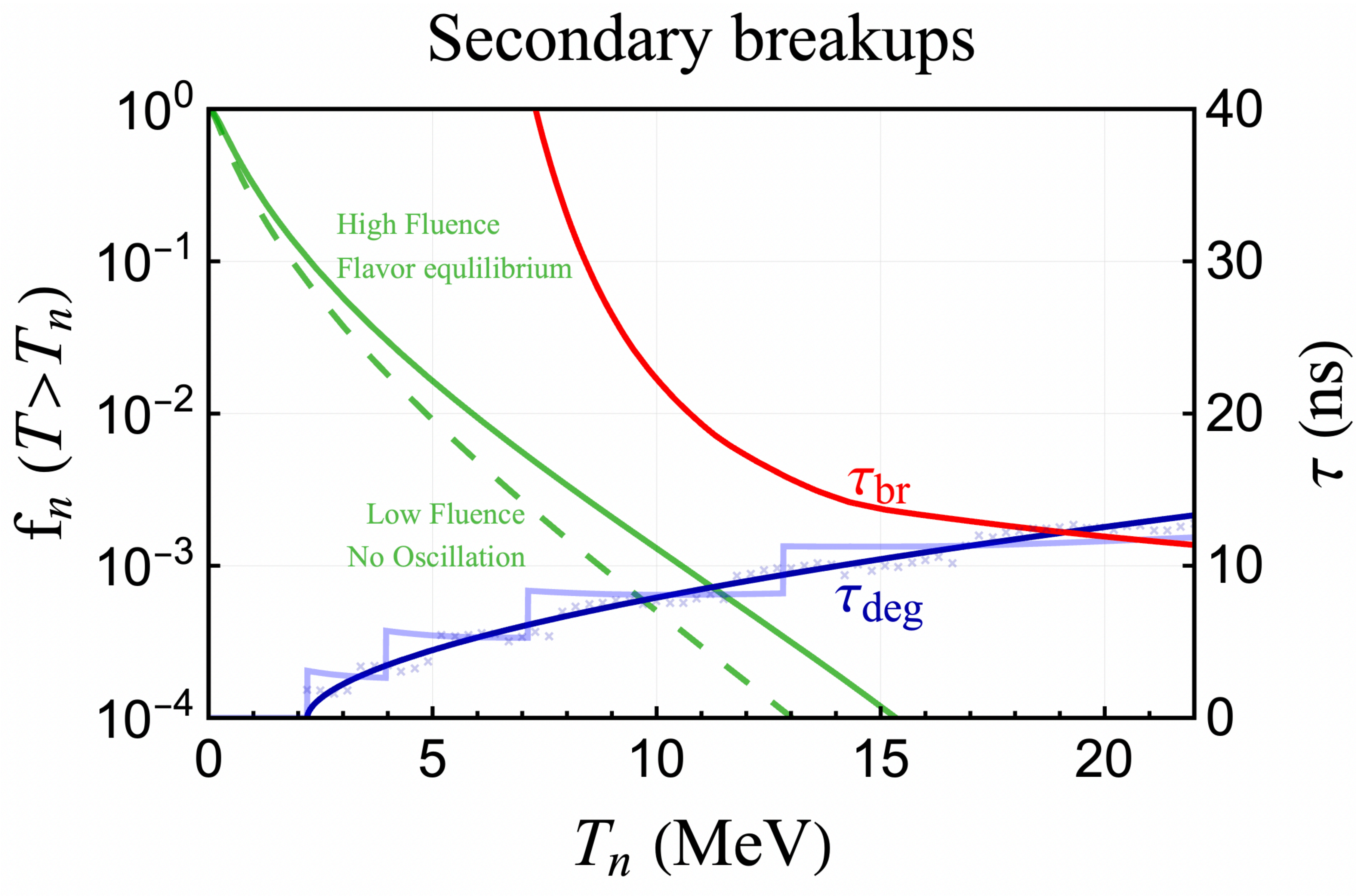
This is the reason why we need Gd.

Secondary Interactions



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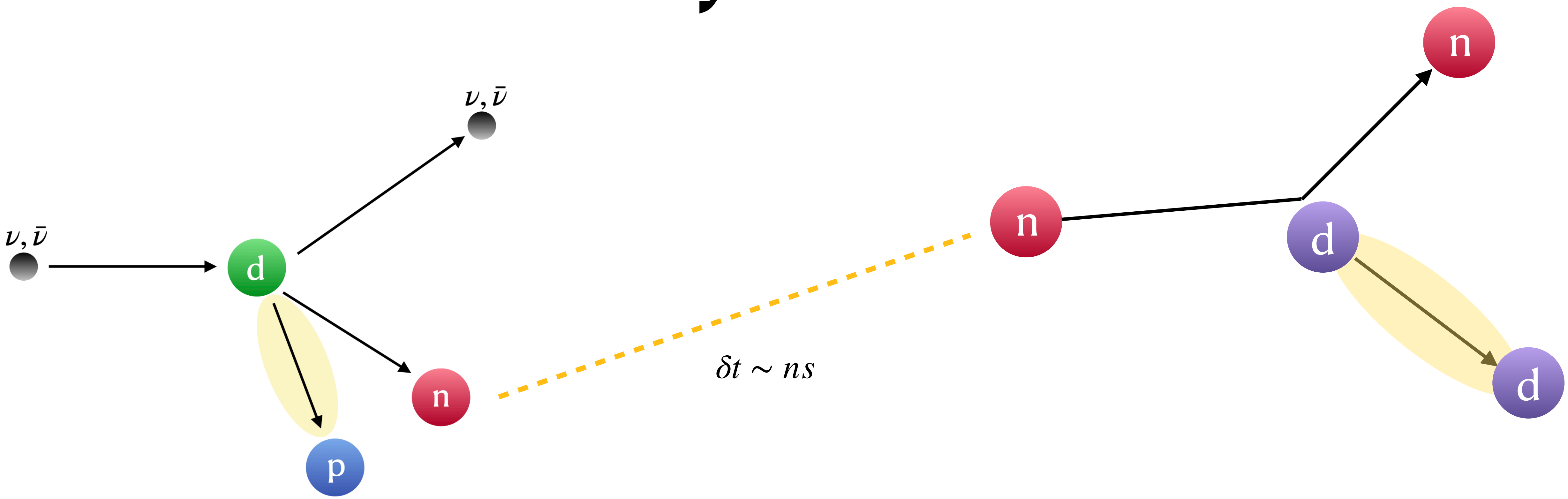
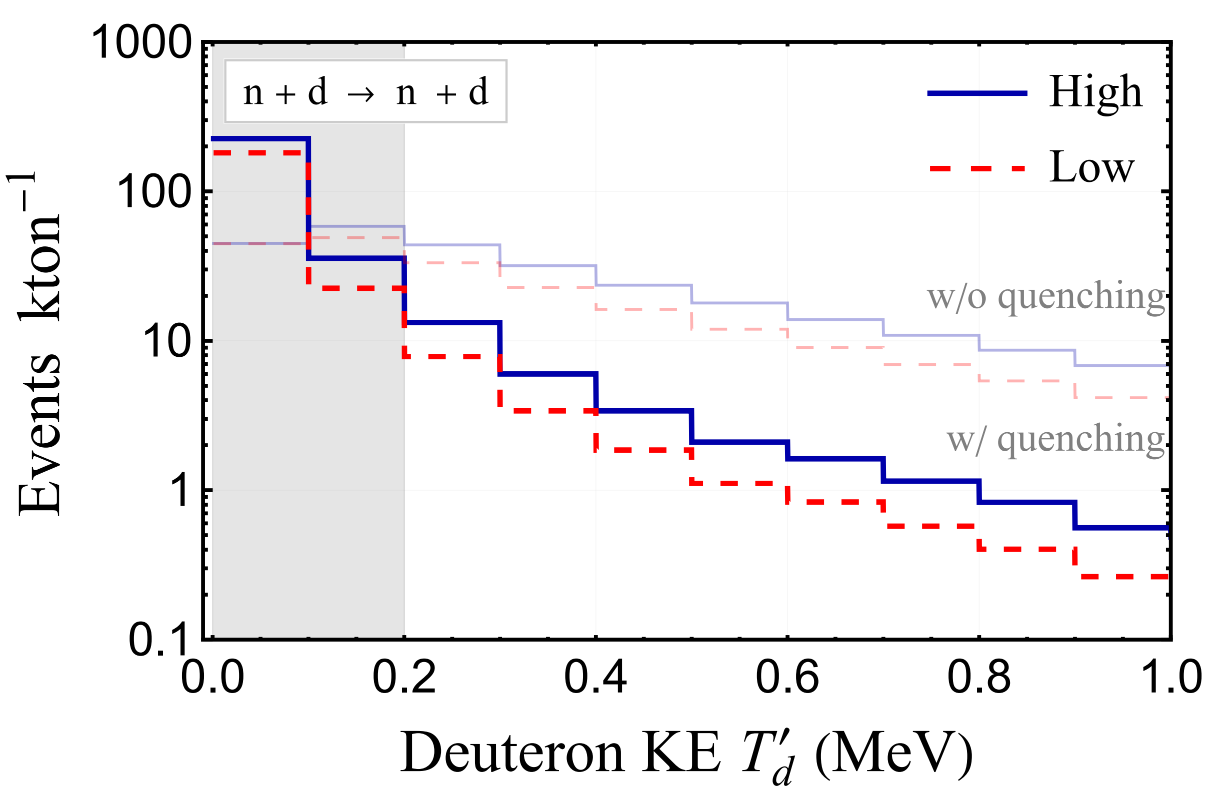
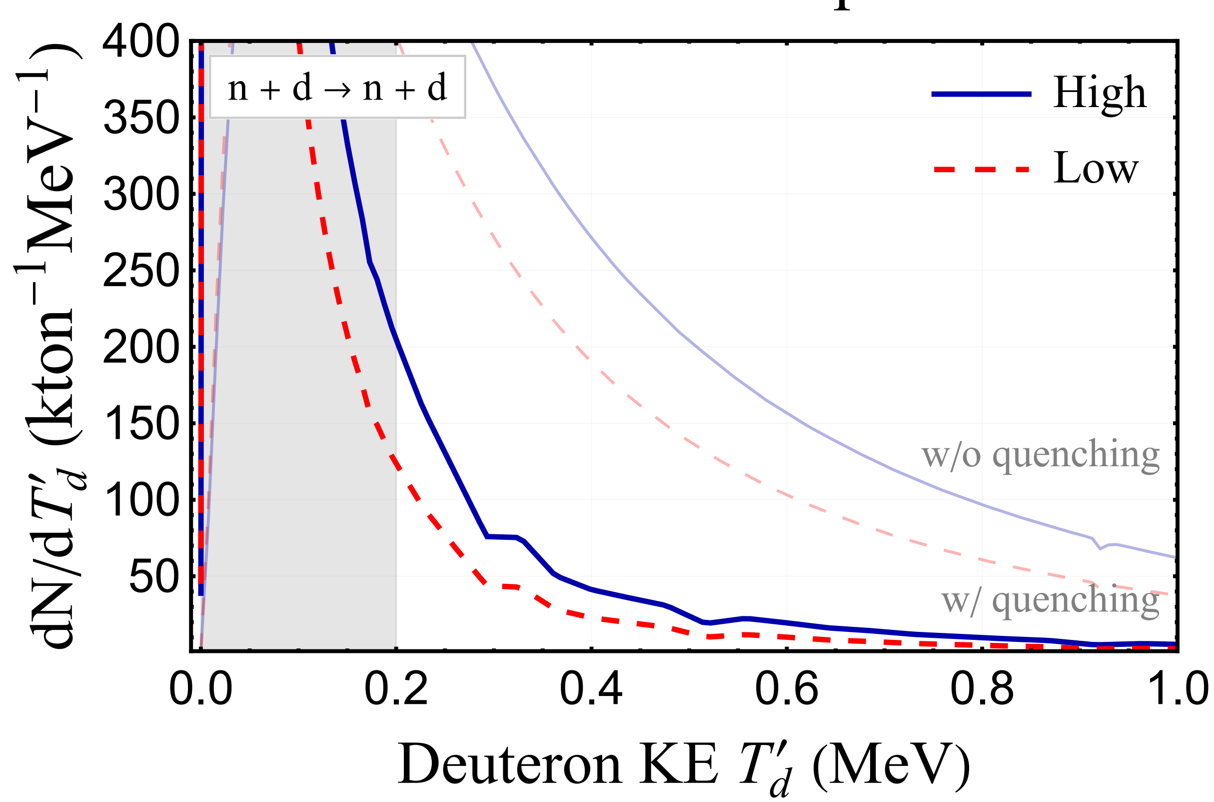


Binned events



Differential event spectrum



An analogy with cricket

Bat. Avg. 52

$+$

Bowl Avg. 33

$\approx$

Bat Avg.: 55 ; Bowl Avg. 33

SNO

- Heavy water D_2O
- Cherenkov
- Sensitivity to NC & CC

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

Borexino

- Pseudocumene C_9H_{12}
- Scintillator
- Low Threshold

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

DLS

- Deuteron Target C_nD_{2n}
- Scintillator
- Sensitivity to NC & CC
- Low Threshold

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

$$\nu_e + d \rightarrow e + p + p$$

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

Summary of Part - II

- A deuterated liquid scintillator is a promising candidate for detecting neutral current interactions of the neutrino.
- The additional final state particle, compared to ordinary scintillator, may help in tagging and mitigating backgrounds.
- For a typical galactic supernova, a kton scale DLS would observe upto 435 NC events along with 170 ν_e CC and 108 $\bar{\nu}_e$ CC events.
- The quenched scintillation of proton can be used to reconstruct the spectrum of non-electron flavor neutrinos.
- Secondary scintillations can be identified with ns timing resolution.
- Measurement of NC interactions will provide overall normalisation of supernova flux, as well as a better understanding of flavour conversion.