Sterile neutrino searches with a Deuterated Liquid Scintillator

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DAE BRNS HEP SYMPOSIUM 2022, IISER Mohali

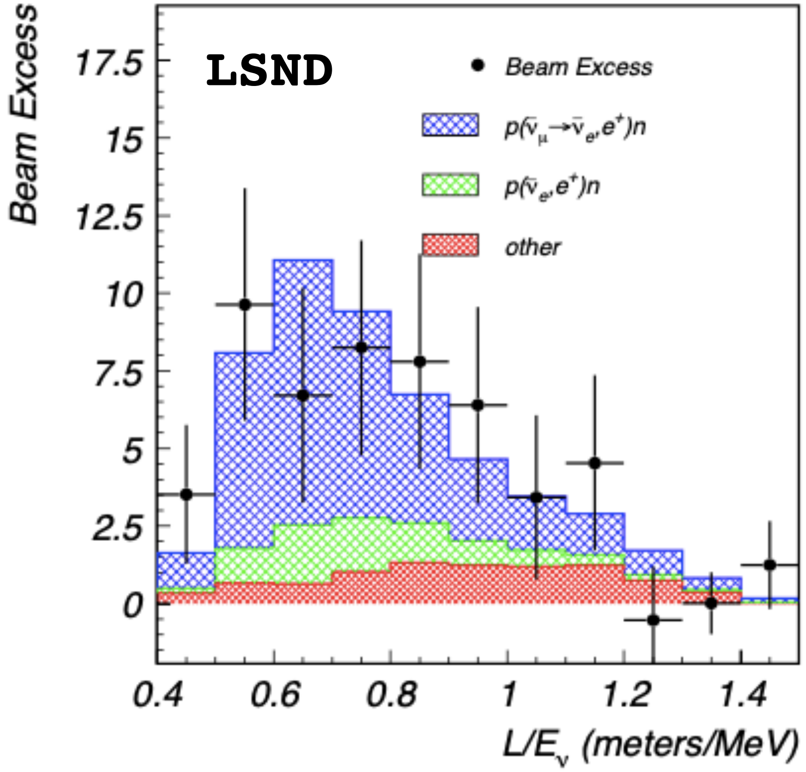
Outline

- Short baselines anomalies and sterile neutrinos
- Two flavor neutrino oscillation probabilities
- Deuterated liquid scintillator
- Sterile neutrino searches
- Challenges with background events

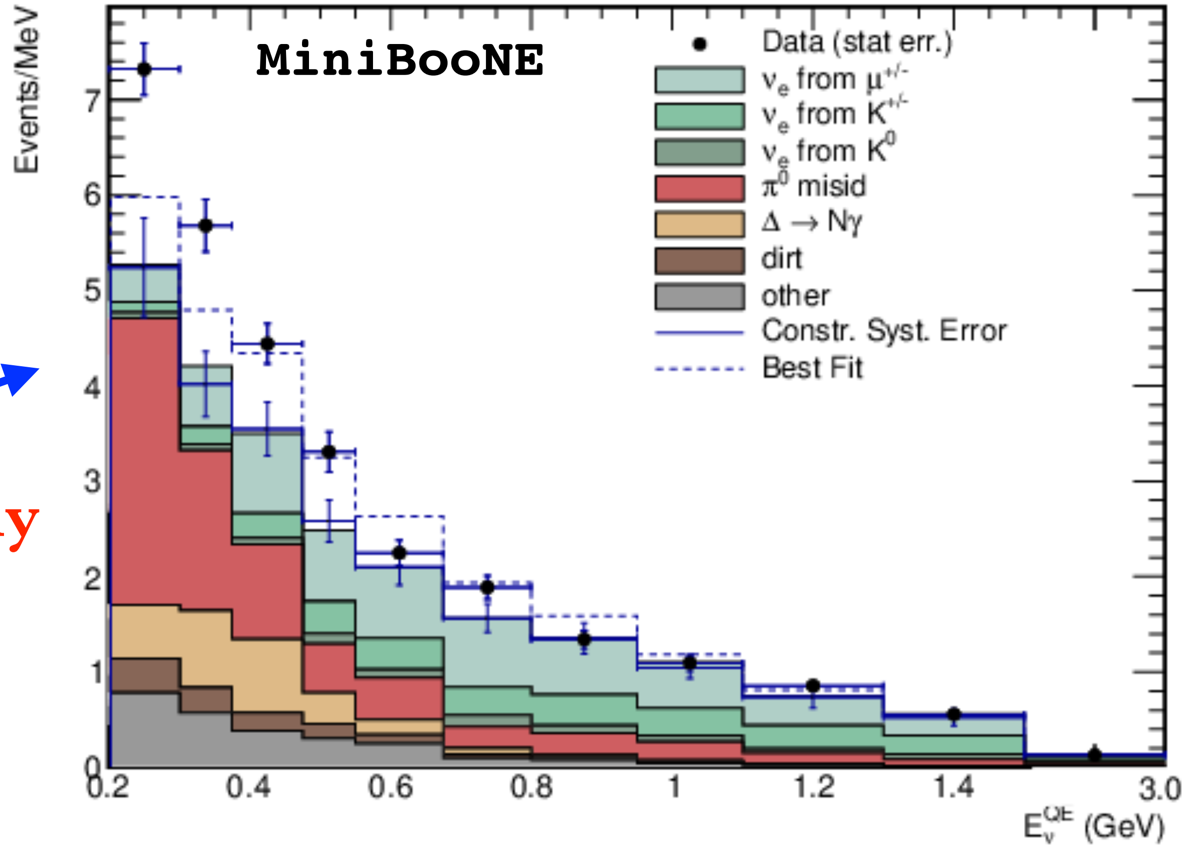
Short-baseline anomalies

A bunch of unaccounted flavor transitions when neutrino travel short distances !

Phys.Rev.D 64 (2001) 112007



Phys. Rev. D 103, 052002 (2021)

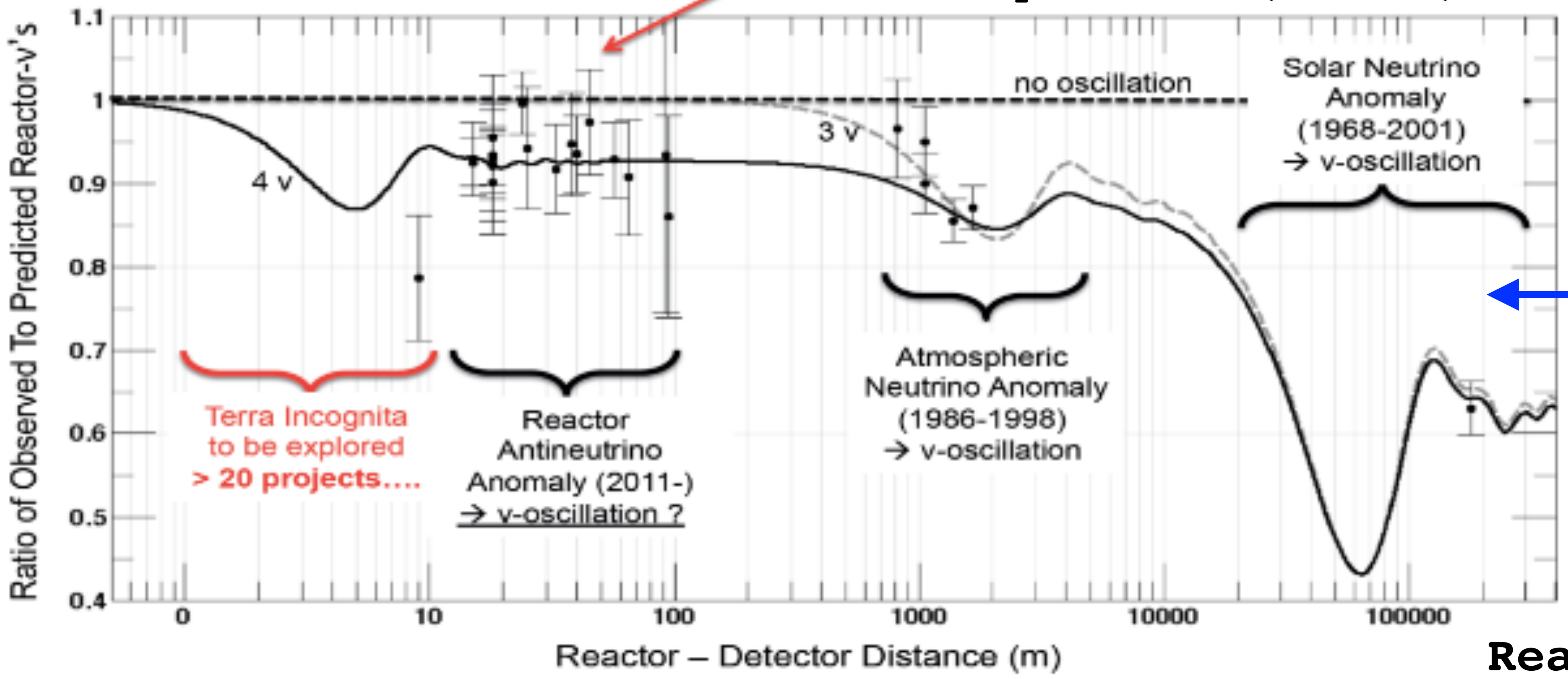


Appearance anomaly

Surplus of $\overset{(-)}{\nu}_e$

- **Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)**

Phys.Rev.D83,073006,2011



Disappearance anomaly

Deficit of $\bar{\nu}_e$

Reactor antineutrino anomaly

Sterile neutrino

- For the baselines and neutrino energies of the short-baseline experiments, the data cannot be explained by oscillations due to the solar or atmospheric mass-squared differences.

- The measurement of the invisible decay width of the Z boson limits the number of light SM active neutrinos to $N_\nu = 2.9840 \pm 0.0082$.

- The simplest way to explain the SBL anomalies is to assume the existence of new light neutrinos which are similar to active neutrinos in masses, mixings except that they do not undergo weak interactions.

- Conventionally, these new neutrinos have been called “Sterile”. Sterile neutrinos are SM singlets.

- SBL anomalies can be explained if Active and Sterile neutrinos are mixed. In the simplest case of the 3+1 model, a sterile neutrino of mass $\sim$ 1eV is needed along with the 3 active neutrinos.

Probabilities in two flavors

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(\vec{x}, t)\rangle|^2$$

`Assumption 1`: All energy eigenstates are produced with the same 3-momentum i.e. $p_1 = p_2 = p$

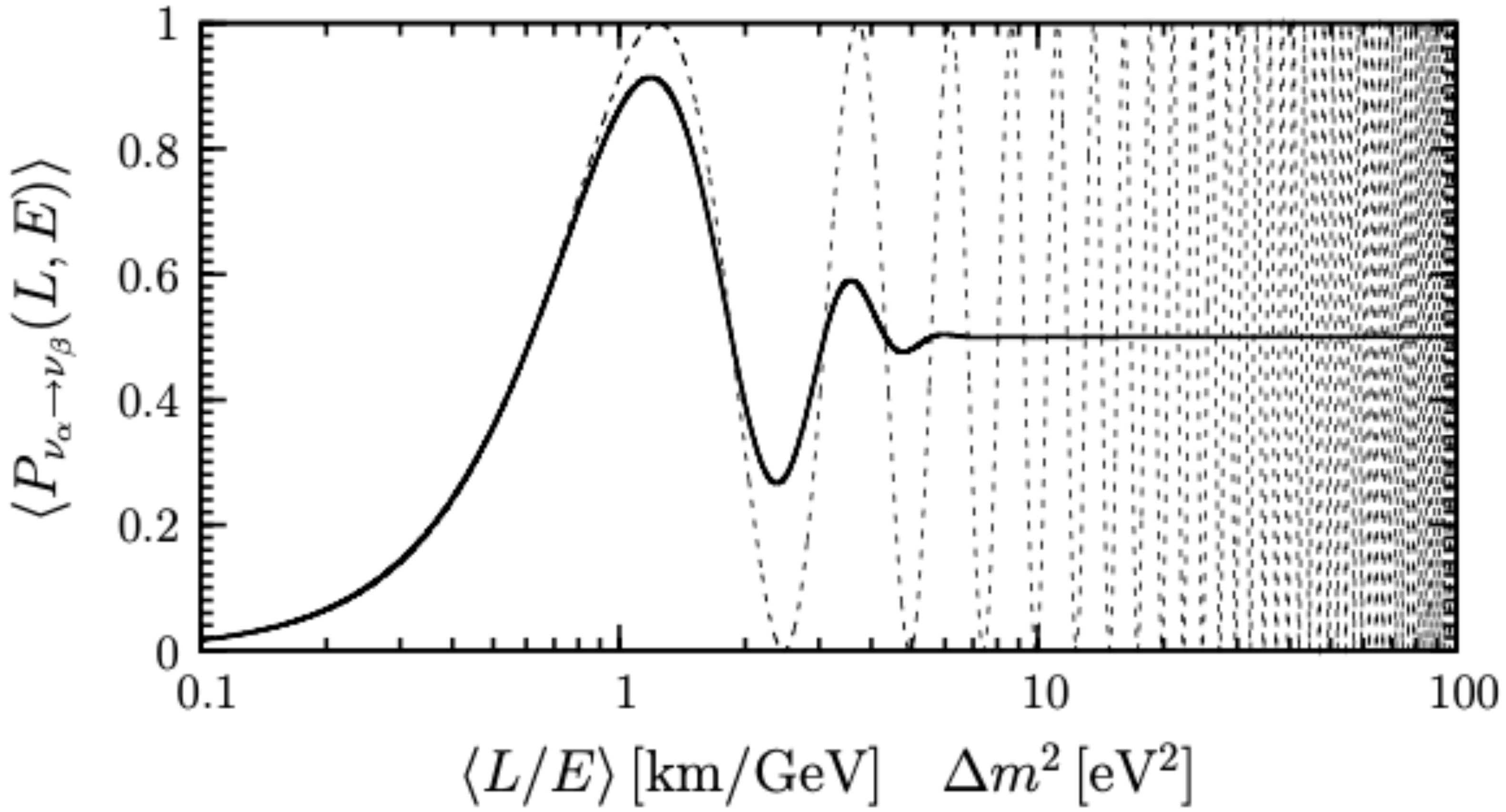
`Assumption 2`: Neutrinos are relativistic i.e.
(1) $t = T = L$
(2) $E_i = p + m_i^2/2p$

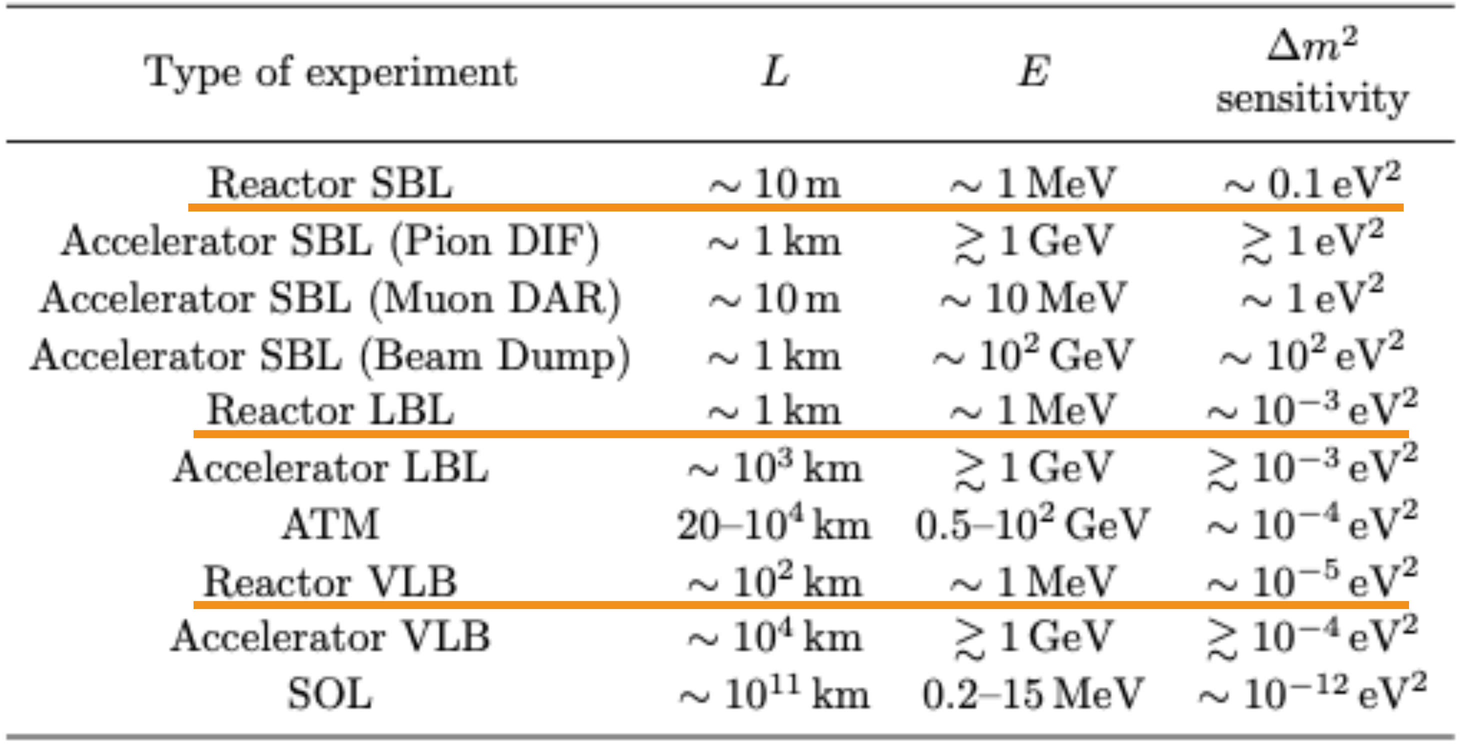
$$P\left(\nu_e \to \nu_e\right) = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

Disappearance Channel

$$P\left(\nu_e \to \nu_x\right) = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

Appearance Channel





Type of experiment	L	E	Δm^2 sensitivity
Reactor SBL	$\sim 10\,\mathrm{m}$	$\sim 1\,\mathrm{MeV}$	$\sim 0.1\,\mathrm{eV}^2$
Accelerator SBL (Pion DIF)	$\sim 1\,\mathrm{km}$	$\gtrsim 1\,\mathrm{GeV}$	$\gtrsim 1\,\mathrm{eV}^2$
Accelerator SBL (Muon DAR)	$\sim 10\,\mathrm{m}$	$\sim 10\,\mathrm{MeV}$	$\sim 1\,\mathrm{eV}^2$
Accelerator SBL (Beam Dump)	$\sim 1\,\mathrm{km}$	$\sim 10^2\,\mathrm{GeV}$	$\sim 10^2\,\mathrm{eV}^2$
Reactor LBL	$\sim 1\,\mathrm{km}$	$\sim 1\,\mathrm{MeV}$	$\sim 10^{-3}\,\mathrm{eV}^2$
Accelerator LBL	$\sim 10^3\,\mathrm{km}$	$\gtrsim 1\,\mathrm{GeV}$	$\gtrsim 10^{-3}\,\mathrm{eV}^2$
ATM	20–$10^4\,\mathrm{km}$	0.5–$10^2\,\mathrm{GeV}$	$\sim 10^{-4}\,\mathrm{eV}^2$
Reactor VLB	$\sim 10^2\,\mathrm{km}$	$\sim 1\,\mathrm{MeV}$	$\sim 10^{-5}\,\mathrm{eV}^2$
Accelerator VLB	$\sim 10^4\,\mathrm{km}$	$\gtrsim 1\,\mathrm{GeV}$	$\gtrsim 10^{-4}\,\mathrm{eV}^2$
SOL	$\sim 10^{11}\,\mathrm{km}$	0.2–$15\,\mathrm{MeV}$	$\sim 10^{-12}\,\mathrm{eV}^2$

`(from Neutrino Phys. and Astrophys., Giunti and Kim)`

Reactor antineutrino fluxes

As an example: Kudankulam Nuclear Power Plant

- ✴ Tirunelveli, Tamil Nadu
- ✴ Pressurized light-water reactors
- ✴ Total 6 units commissioned - 2 operational and 4 more to be built by 2027
- ✴ Power of each unit: 3 GWth

$$\begin{aligned}\phi(E_\nu) = \; & f_{^{235}U} \exp\left(0.870 - 0.160E_\nu - 0.091E_\nu^2\right) \\ & + f_{^{239}Pu} \exp\left(0.896 - 0.239E_\nu - 0.0981E_\nu^2\right) \\ & + f_{^{238}U} \exp\left(0.976 - 0.162E_\nu - 0.0790E_\nu^2\right) \\ & + f_{^{241}Pu} \exp\left(0.793 - 0.080E_\nu - 0.1085E_\nu^2\right)\end{aligned}$$

`Phys. Rev. D 39 (1989) 3378`

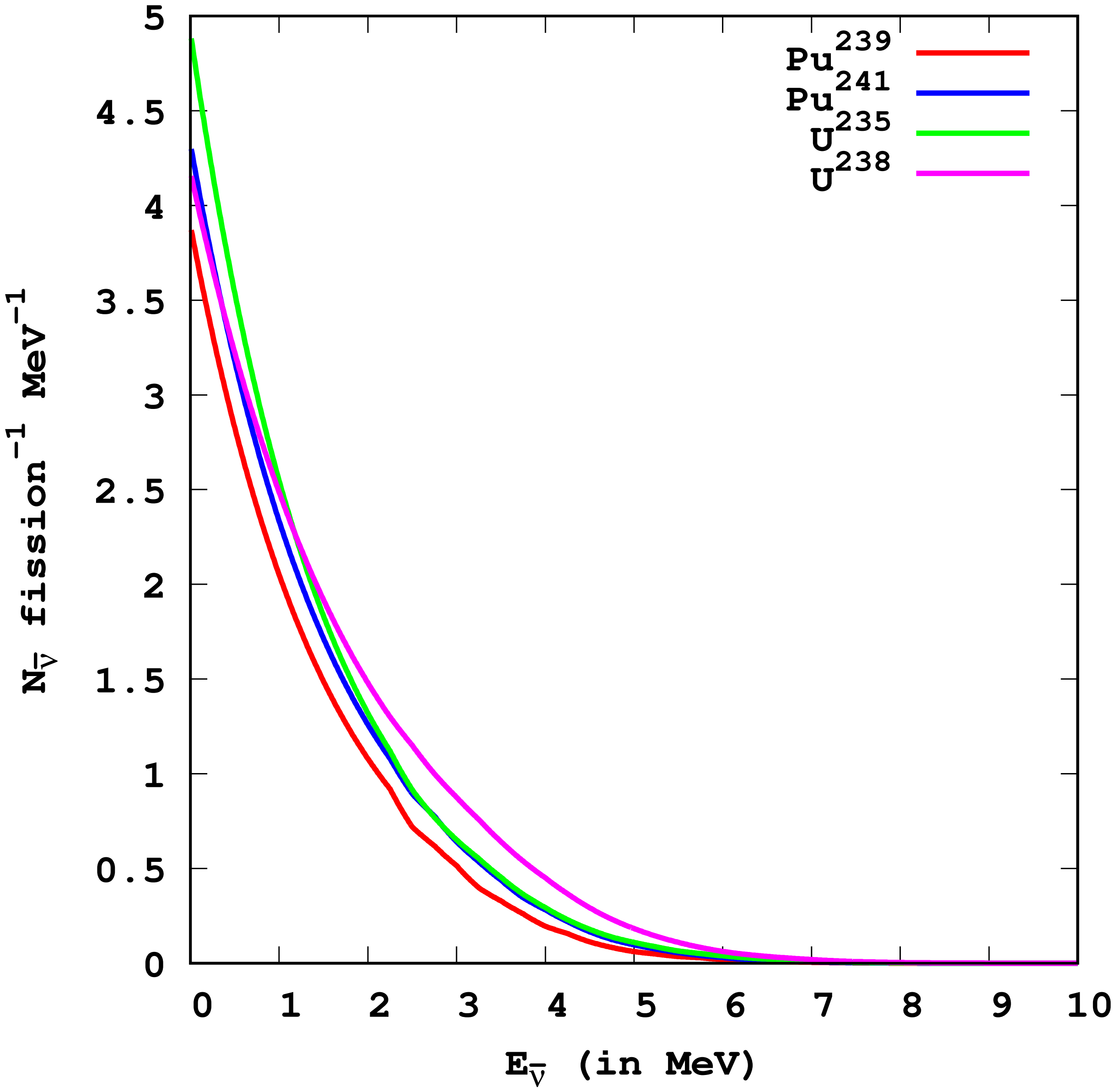
For a PWR type reactor:

$$f_{235_U} = 0.58,\ f_{239_{Pu}} = 0.30,\ f_{238_U} = 0.07,\ f_{241_{Pu}} = 0.05$$

`(changes with time)`

Huber-Mueller Fluxes

`Phys. Rev. C 83 (2011) 054615`
`Phys. Rev. C 84 (2011) 024617`



Deuterated Liquid Scintillator

- We consider a liquid scintillator which is 100% deuterated such as C_nD_{2n}
- A deuterated liquid scintillator (DLS) will be sensitive to all neutrino flavors. Therefore, it can see both CC and NC events.
- SNO experiments could conclusively establish neutrino oscillations by observing both CC and NC events. However, it could only do a counting experiment.
- As India is one of largest producer of heavy water, availability of deuterium is not a problem.
- DLS can detect neutrinos mainly via. dissociation of the deuteron.
- Observing NC events in addition to CC events cannot provide crucial information regarding non-unitarity of the 3x3 PMNS matrix - especially in new physics scenarios with sterile neutrinos.
- DLS may be able to provide spectral information of the NC events in addition to total rates.
- However, it comes with its own set of challenges - especially with respect to background suppression and observation of scintillation signal at very low energies.

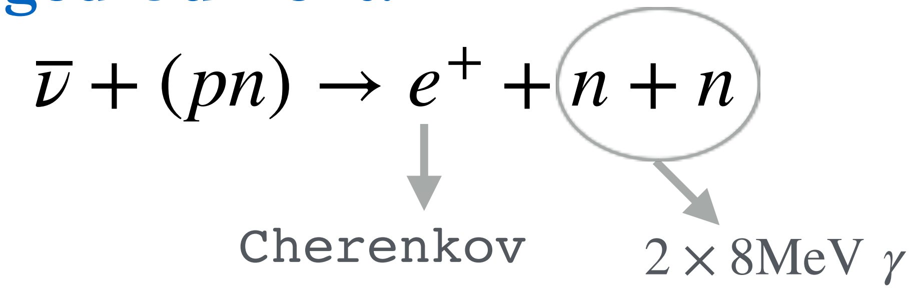
for a study with supernova neutrinos, see JCAP 11 (2021) 005

Cross Sections on Deuterium

JCAP 11 (2021) 005

https://github.com/bhvzchhn/NeutrinoDeuteron

Charged Current:

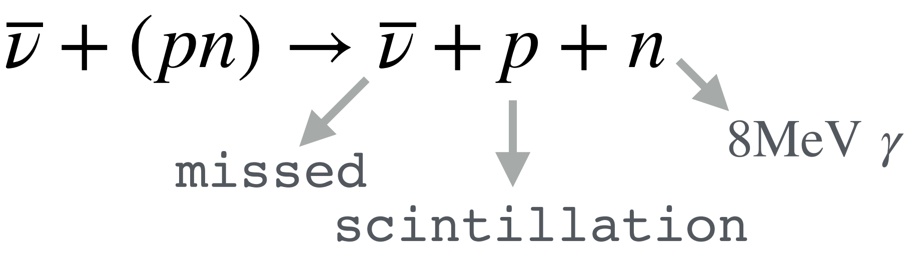


$$\bar{\nu} + (pn) \rightarrow e^{+} + n + n$$

Cherenkov

$2 \times 8\text{MeV}\ \gamma$

Neutral Current:

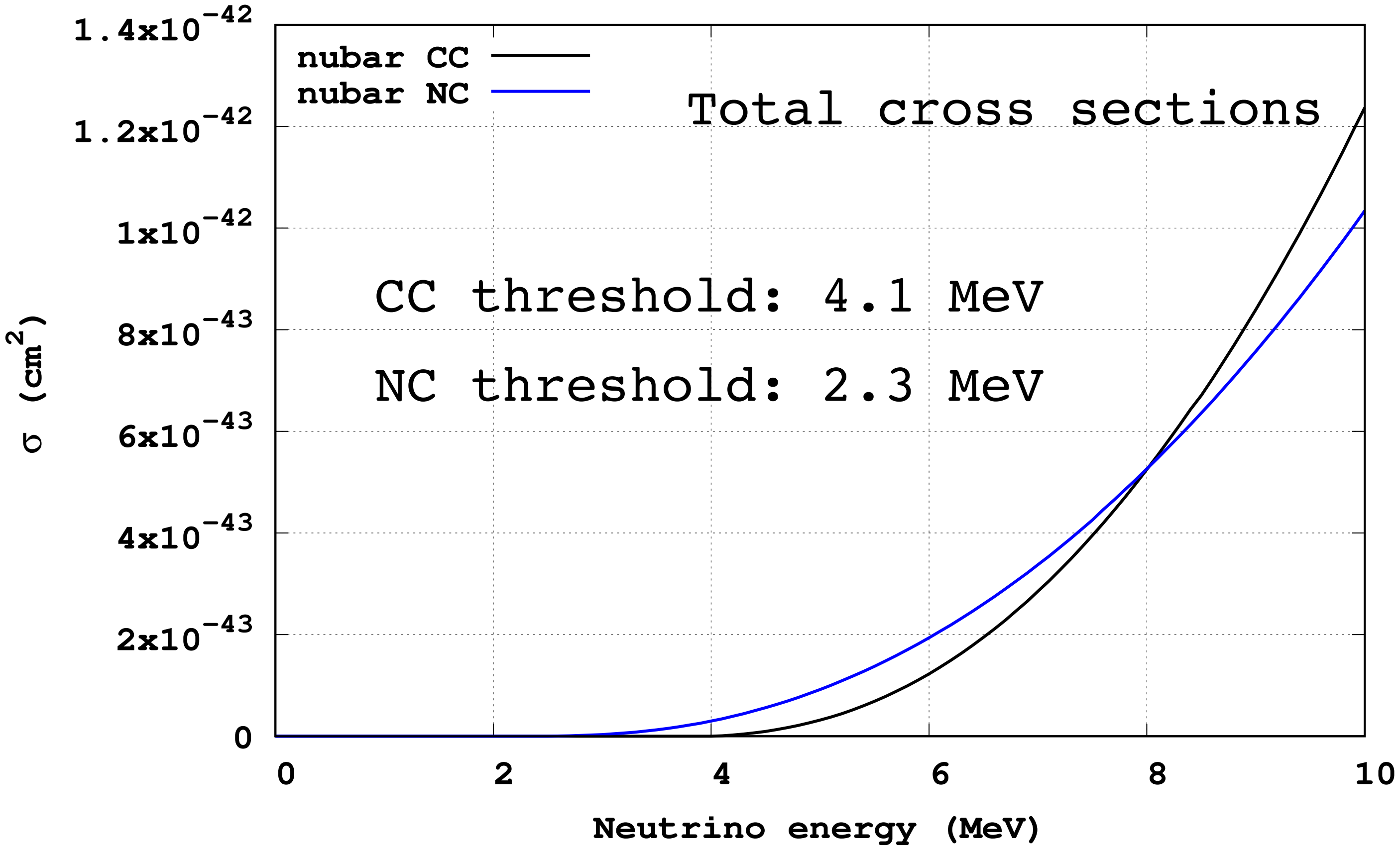


$$\bar{\nu} + (pn) \rightarrow \bar{\nu} + p + n$$

missed

scintillation

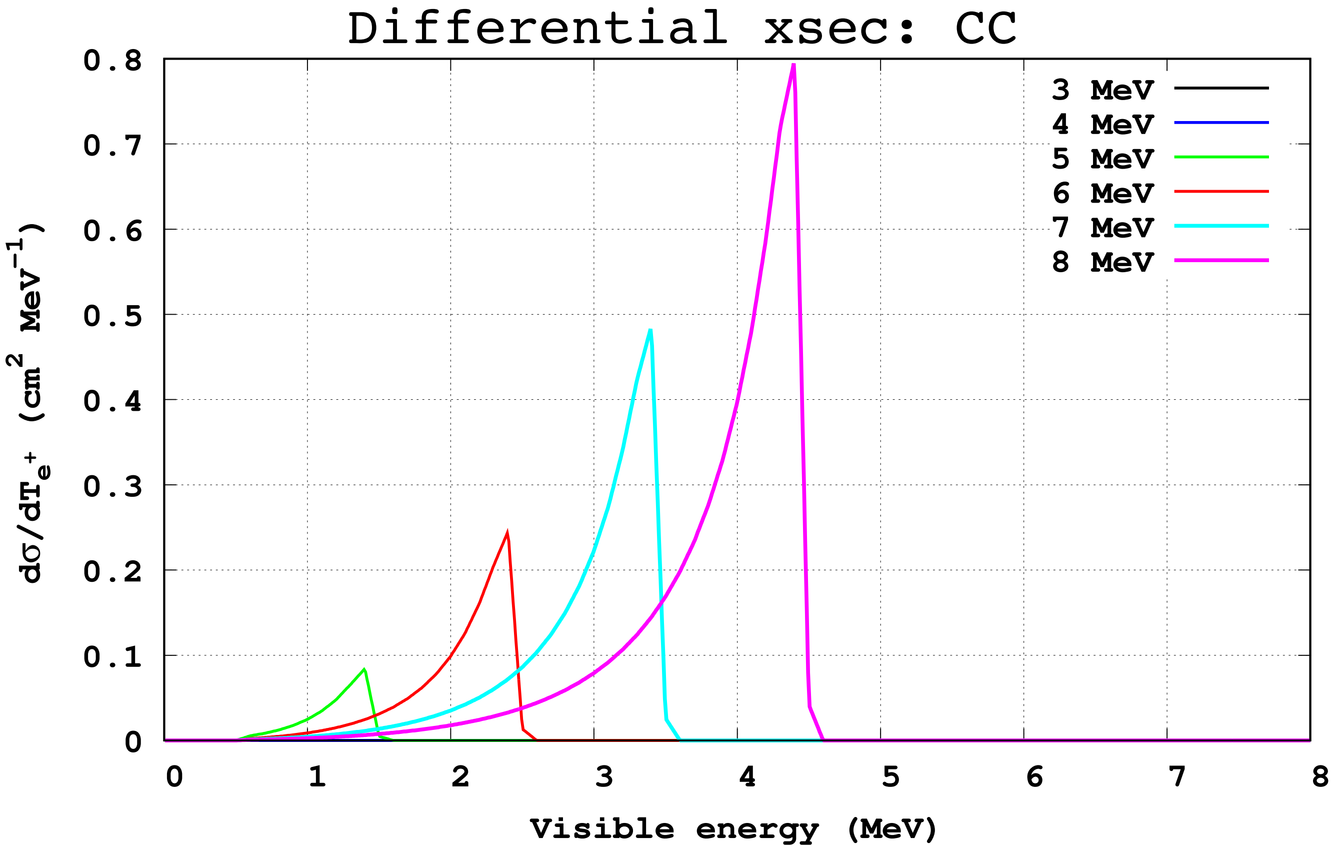
$8\text{MeV}\ \gamma$



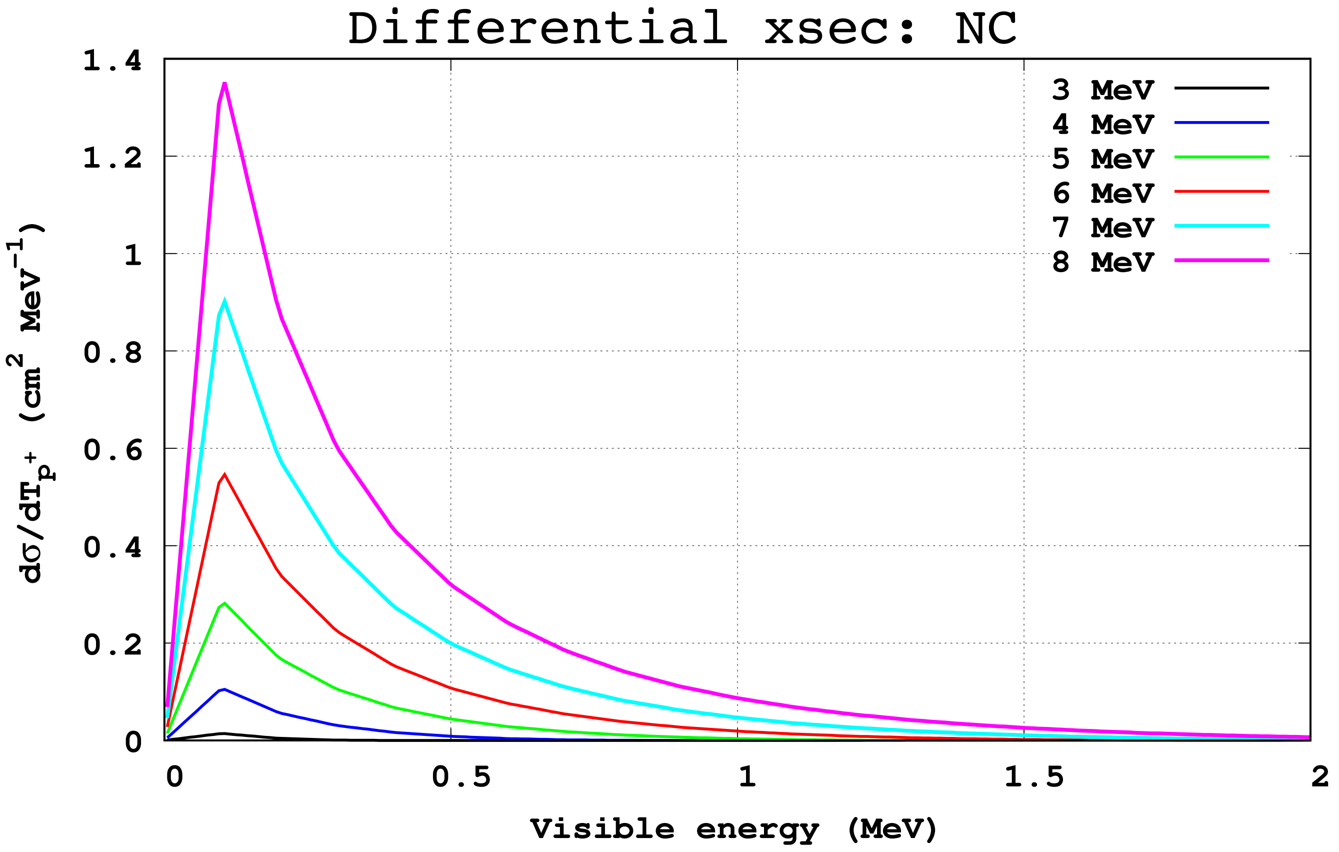
Total cross sections

CC threshold: 4.1 MeV

NC threshold: 2.3 MeV

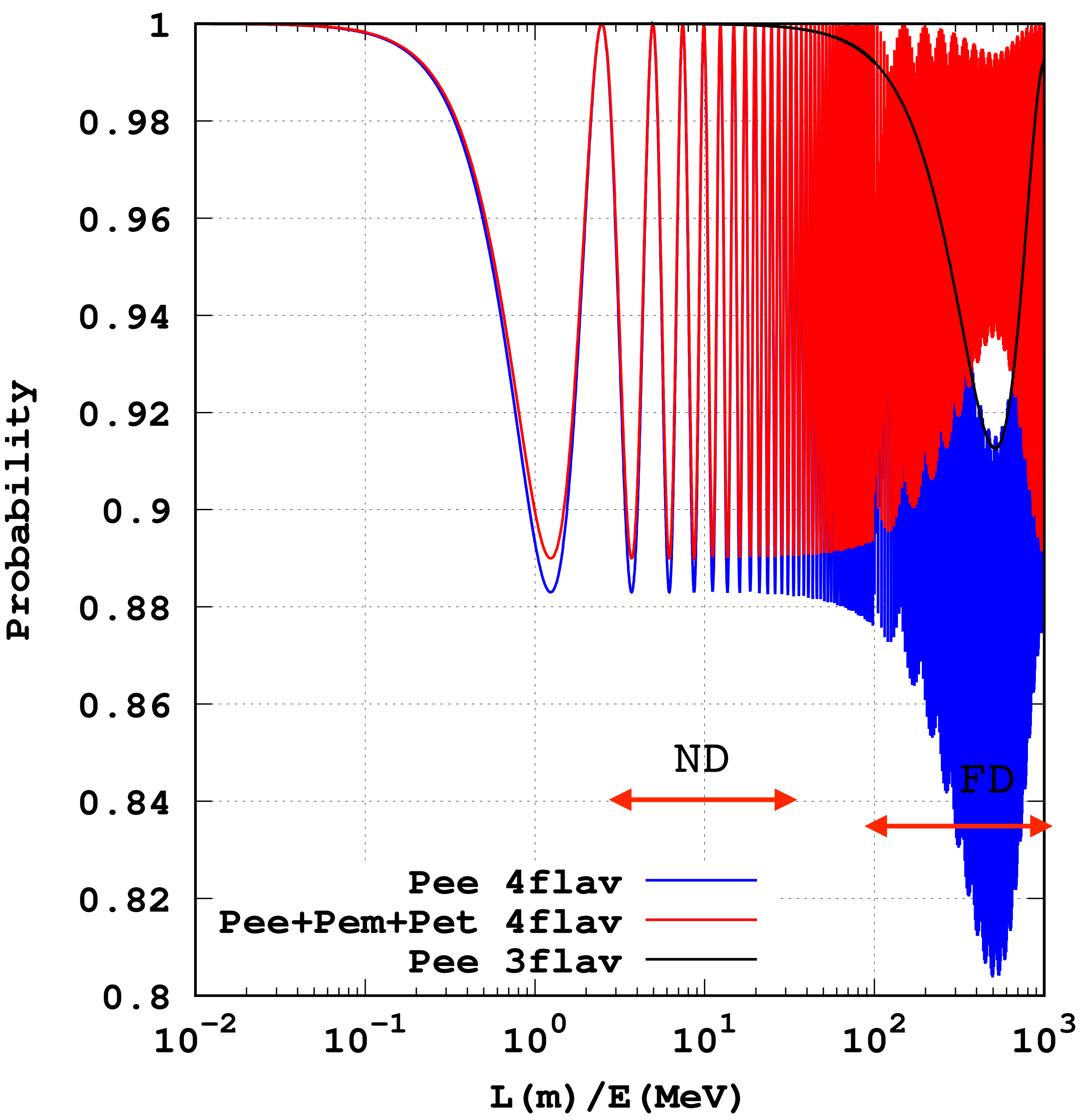


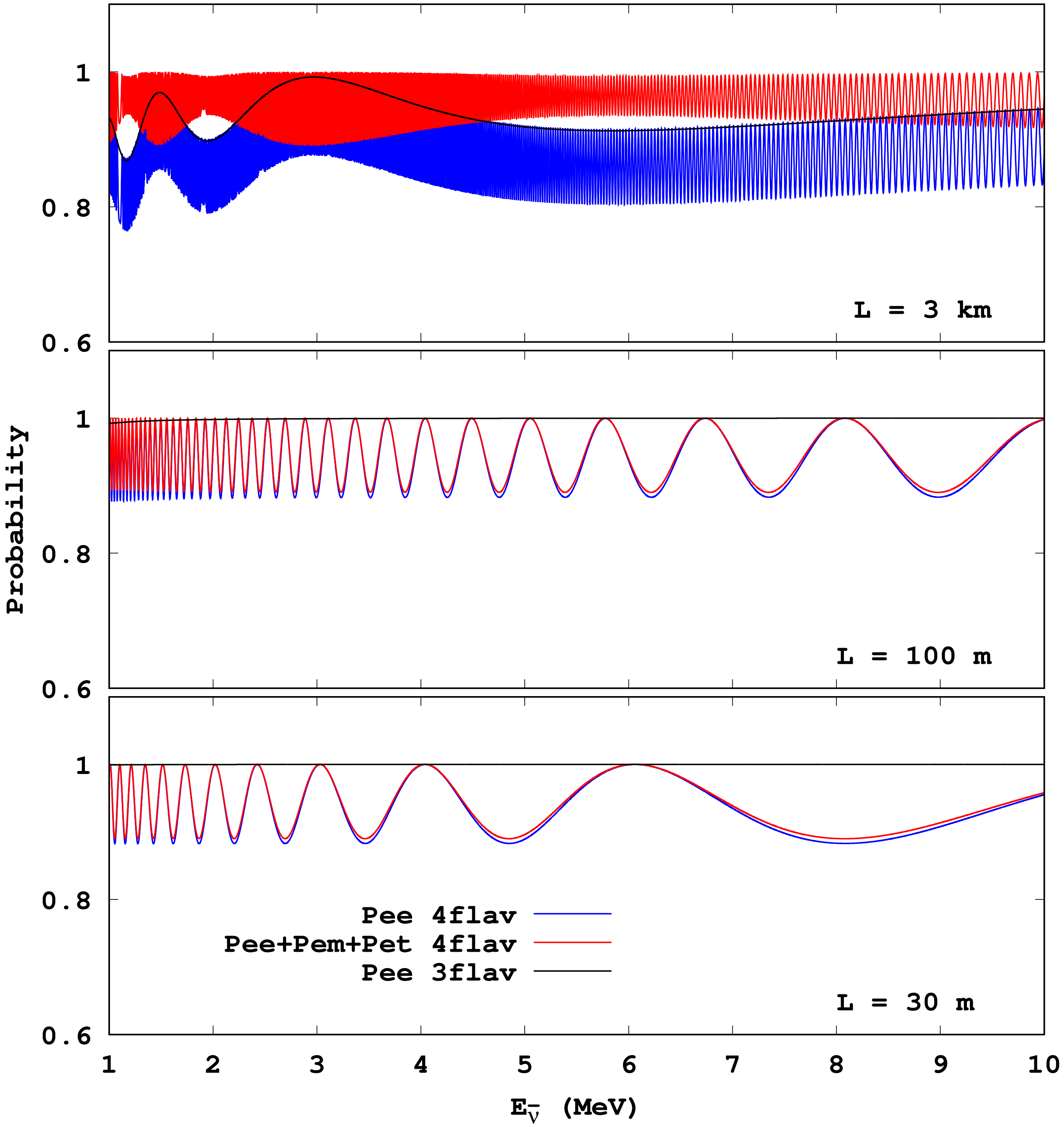
Differential xsec: CC



Differential xsec: NC

Probability plots





At near detector distances: $P_{ee} \approx P_{ee} + P_{e\mu} + P_{e\tau} \approx 1 - P_{es} \implies$ 2-neutrino oscillation: θ_{14} and Δm^2_{41}

Insensitive to Earth matter, mass ordering, octant or CP violation

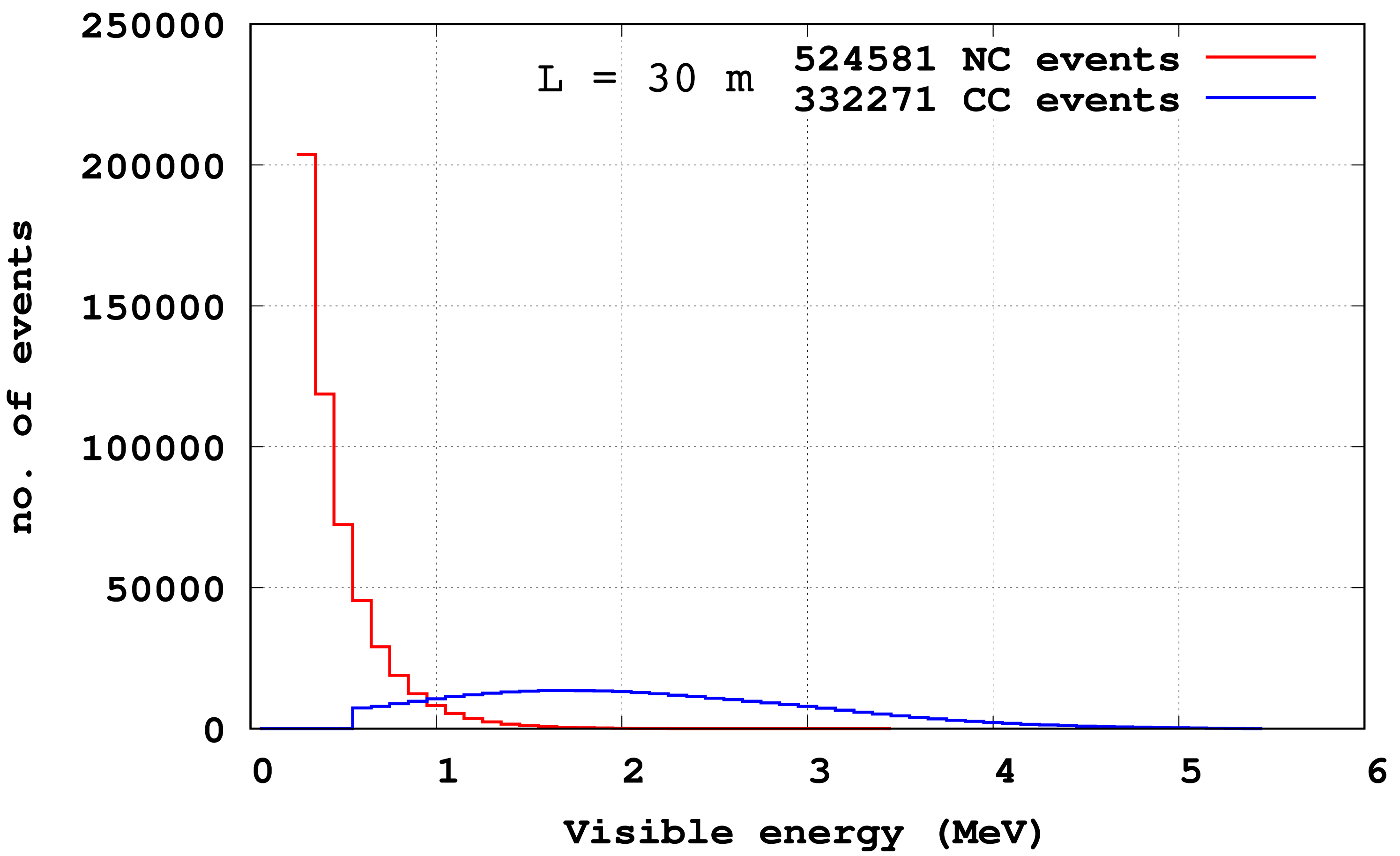
Full 4-flavor effects only at far detector: sensitivity to additional oscillation parameters

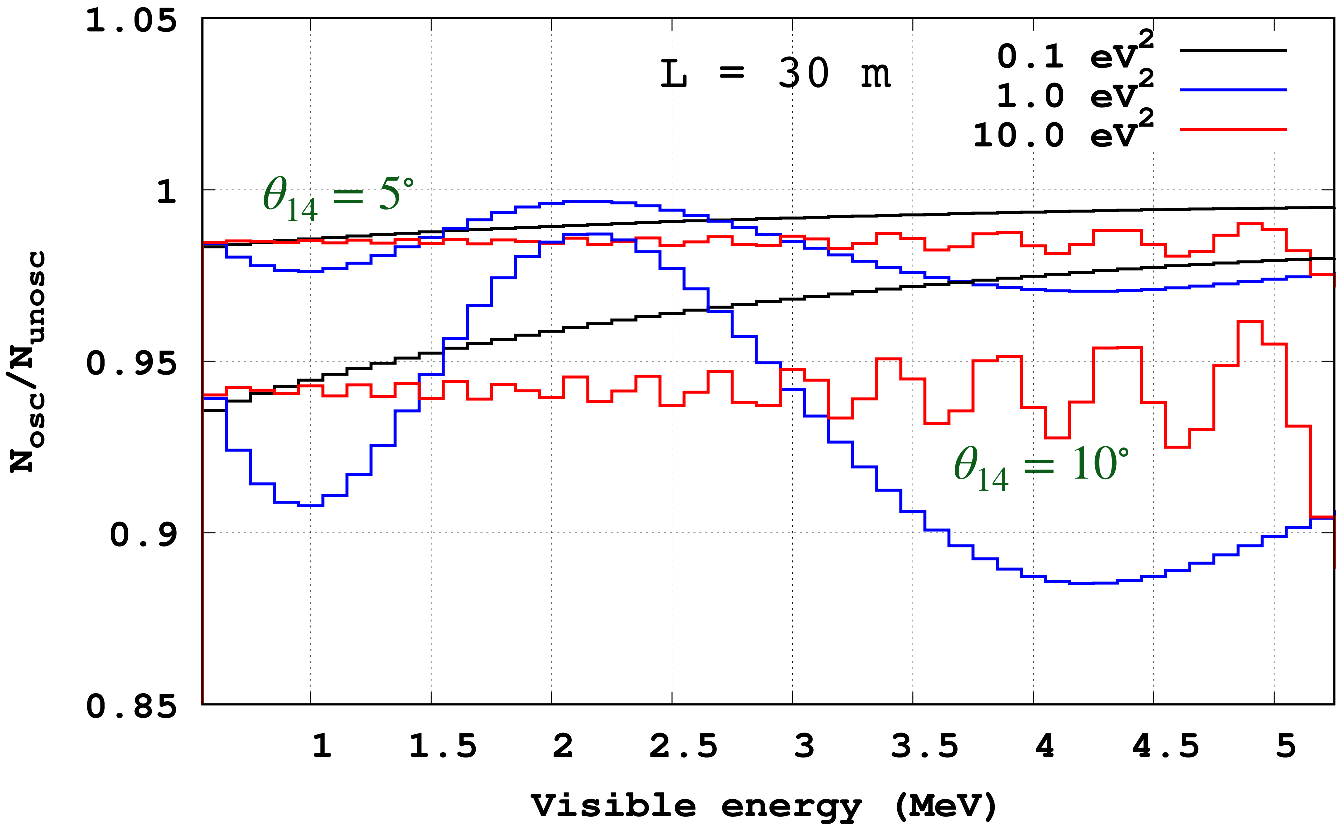
Events plots

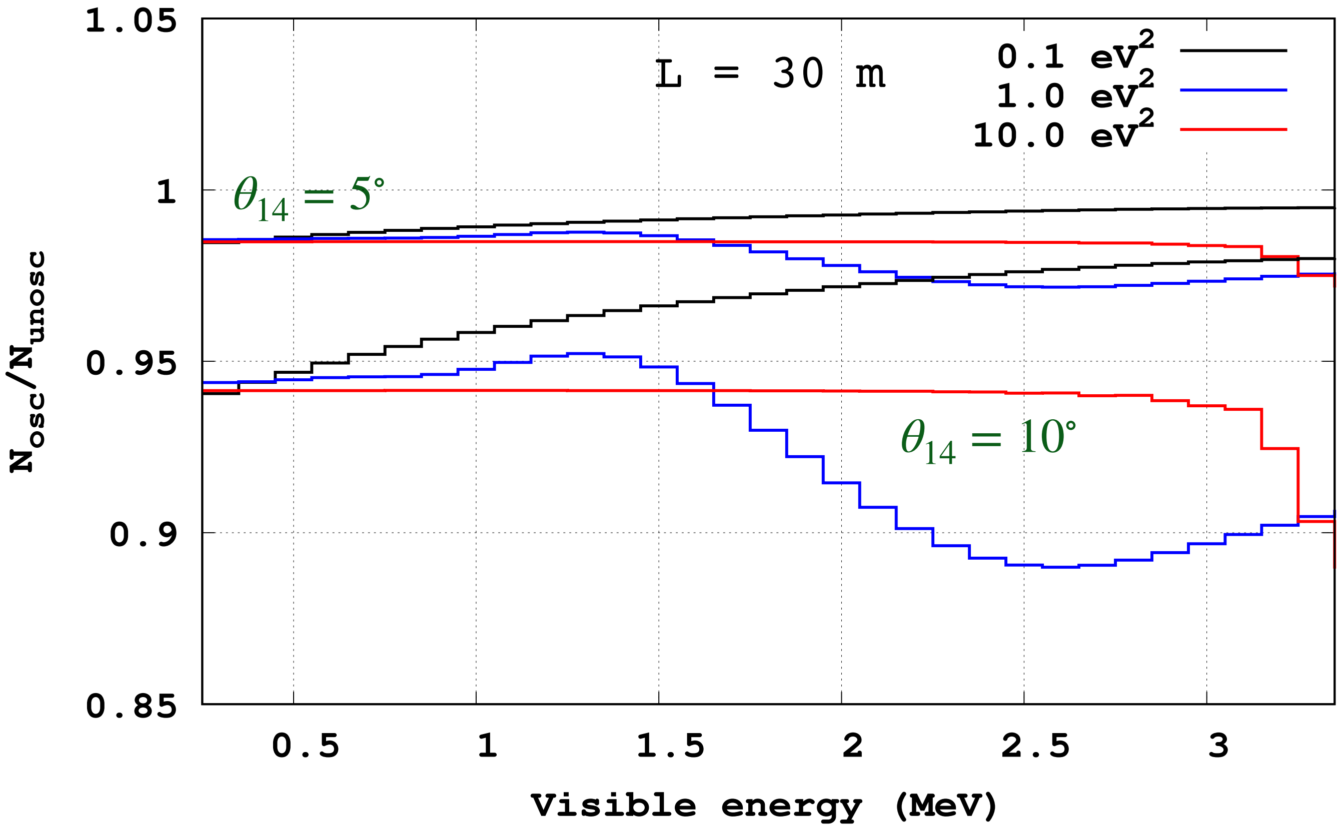
Visible Energy:
For CC: e^+
ForNC: p

NC events pile up between 0.0 - 3.5 MeV

Δm^2 and $\sin^2 2\theta$ - driven features in both NC and CC spectra



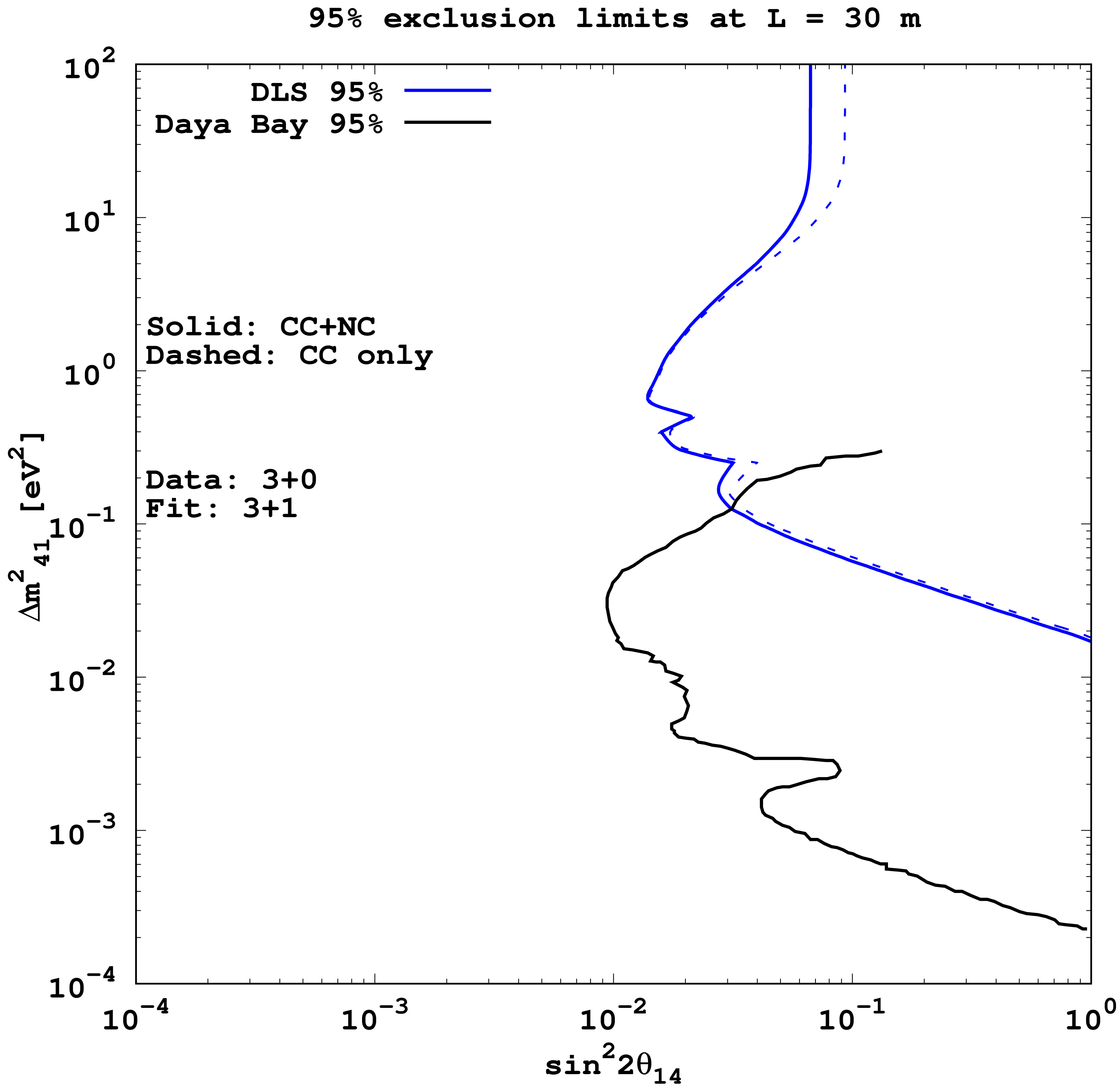




Sterile neutrino exclusion sensitivity

Results comparable with Daya Bay
(with much less stats)

Complementarity in sensitivity



5% normalization & 5% tilt error

Challenges with background events

- Below 200 KeV, the scintillation from radioactive C inundate the detector
- Other radioactive impurities of heavier elements can also produce photons that can dissociate the deuterium - problem for NC events
- Main problem in case of neutron tagging is cosmic muon induced backgrounds.
- Possible to mitigate via:
  - a) muon veto detector
  - b) timing information of the muon events via. plastic scintillators
  - c) going underground
  - d) statistical subtraction using reactor downtime
- Millisecond window between prompt event neutron capture

Concluding remarks

Several worldwide efforts for sterile neutrino searches

Here we explore the possibility of a DLS detector

DLS can in-principle see both CC and NC events

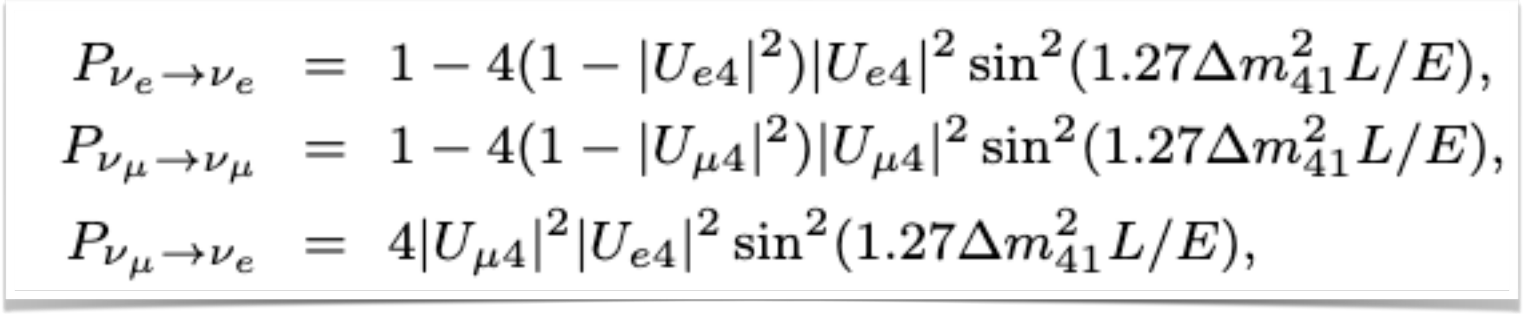
Sterile oscillation exclusion sensitivity in electron channel comparable to present global constraints

Main challenges in the analysis comes from cosmic muon induced background - more work going on!

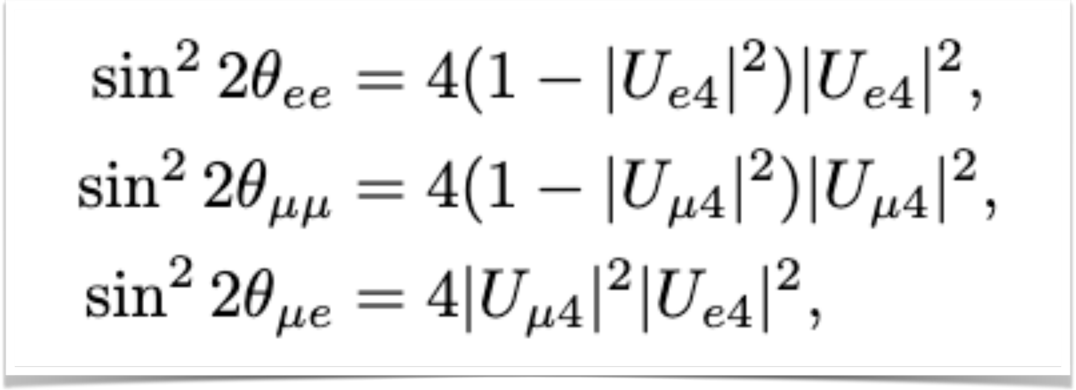
Supernova neutrinos, Geoneutrinos,
Solar neutrinos, low energy atmospheric neutrinos,
neutrino tomography

THANK YOU FOR YOUR ATTENTION!

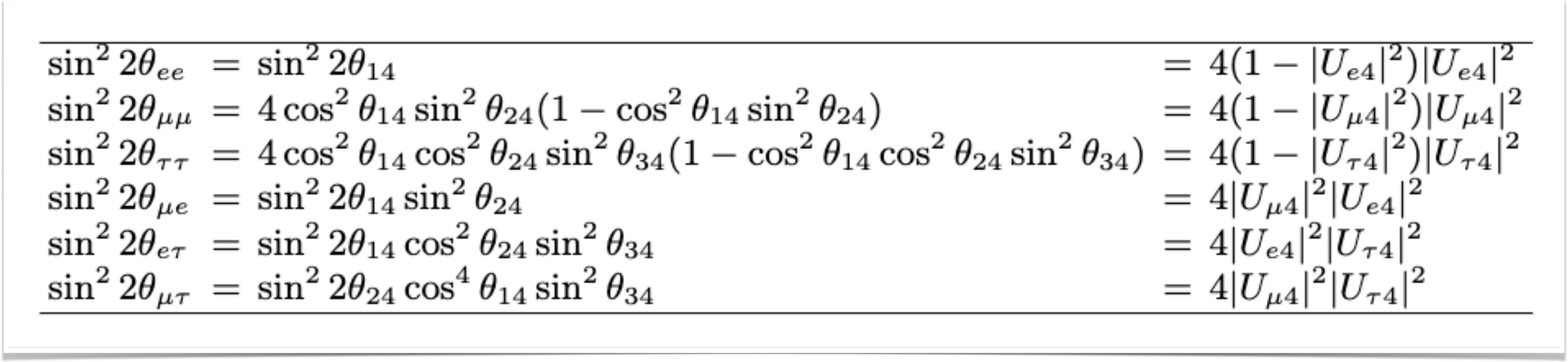
Back up slides



$$\begin{aligned}
P_{\nu_e\to\nu_e} &= 1-4(1-|U_{e4}|^2)|U_{e4}|^2\sin^2(1.27\Delta m^2_{41}L/E),\\
P_{\nu_\mu\to\nu_\mu} &= 1-4(1-|U_{\mu4}|^2)|U_{\mu4}|^2\sin^2(1.27\Delta m^2_{41}L/E),\\
P_{\nu_\mu\to\nu_e} &= 4|U_{\mu4}|^2|U_{e4}|^2\sin^2(1.27\Delta m^2_{41}L/E),
\end{aligned}$$



$$\begin{aligned}
\sin^2 2\theta_{ee} &= 4(1-|U_{e4}|^2)|U_{e4}|^2,\\
\sin^2 2\theta_{\mu\mu} &= 4(1-|U_{\mu4}|^2)|U_{\mu4}|^2,\\
\sin^2 2\theta_{\mu e} &= 4|U_{\mu4}|^2|U_{e4}|^2,
\end{aligned}$$



$$\begin{aligned}
\sin^2 2\theta_{ee} &= \sin^2 2\theta_{14} &&= 4(1-|U_{e4}|^2)|U_{e4}|^2\\
\sin^2 2\theta_{\mu\mu} &= 4\cos^2\theta_{14}\sin^2\theta_{24}(1-\cos^2\theta_{14}\sin^2\theta_{24}) &&= 4(1-|U_{\mu4}|^2)|U_{\mu4}|^2\\
\sin^2 2\theta_{\tau\tau} &= 4\cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}(1-\cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}) &&= 4(1-|U_{\tau4}|^2)|U_{\tau4}|^2\\
\sin^2 2\theta_{\mu e} &= \sin^2 2\theta_{14}\sin^2\theta_{24} &&= 4|U_{\mu4}|^2|U_{e4}|^2\\
\sin^2 2\theta_{e\tau} &= \sin^2 2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34} &&= 4|U_{e4}|^2|U_{\tau4}|^2\\
\sin^2 2\theta_{\mu\tau} &= \sin^2 2\theta_{24}\cos^4\theta_{14}\sin^2\theta_{34} &&= 4|U_{\mu4}|^2|U_{\tau4}|^2
\end{aligned}$$