The Photo Detection System in DUNE

Journées de Rencontre Jeunes Chercheurs
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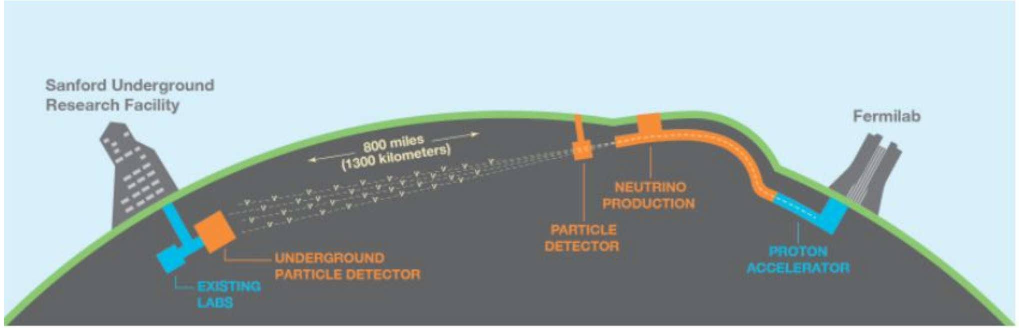
27/10/2023

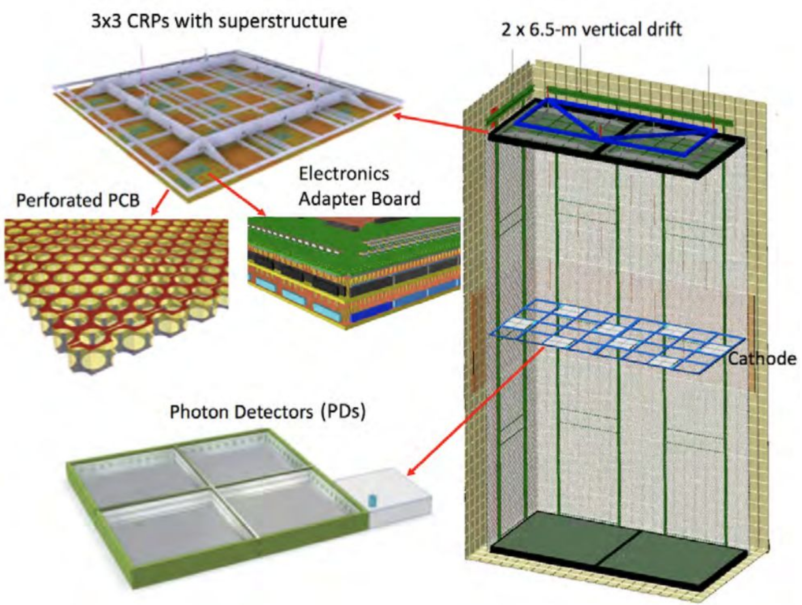
The DUNE experiment



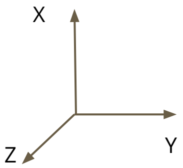
1. The Far Detector of the DUNE experiment will consist of four gigantic, 17-kiloton Liquid Argon modules.
2. The first module is a **Single Phase, Horizontal Drift** LArTPC
   → ProtoDUNE-SP: first operation of LArTPC at the kiloton scale.
3. The **Vertical Drift** concept is proposed for the second module.
4. There are 3 key science objectives:
   a. Study of neutrino oscillations: mass hierarchy, CP violation and mixing angles
   b. Supernova neutrino bursts study
   c. Beyond standard model physics signatures

LArTPC: Vertical Drift (VD) module

- Charge-readout planes (CRP) (anode) on top and bottom.
- Cathode in the center at -300 kV
- 6,5 m drift distance
- Fiducial mass ~14.7 kt
- PDS on the cathode and walls



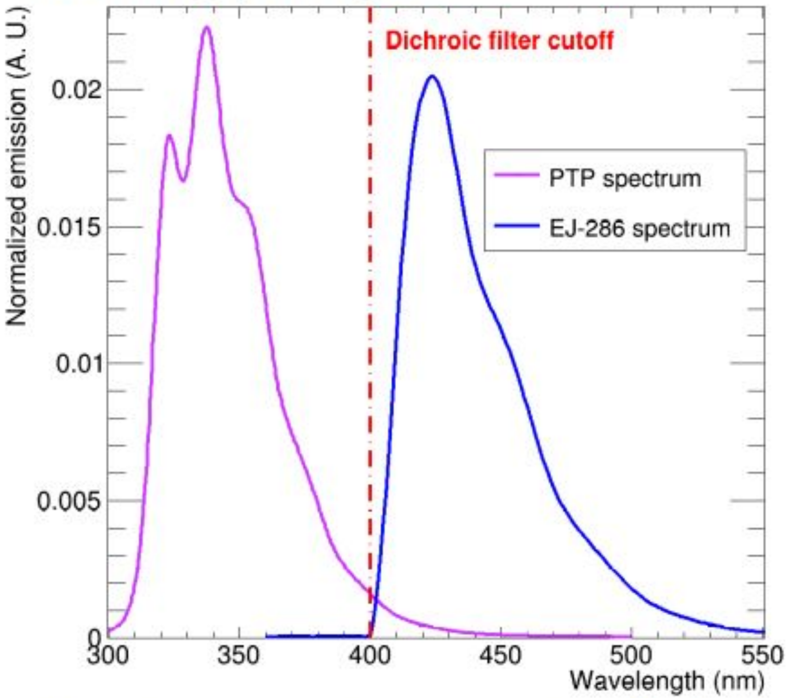
- Cryostat dimension:
  62 m x 15.1 m x 14 m

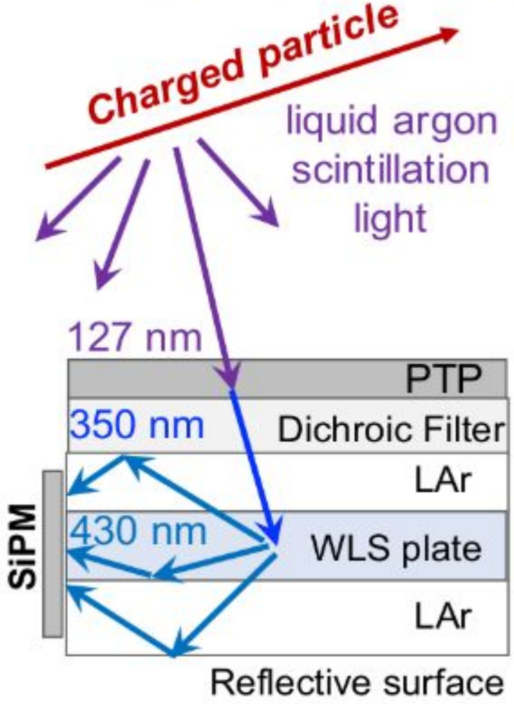


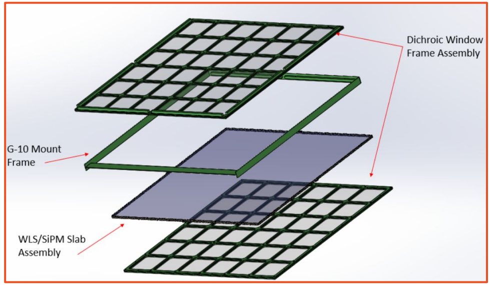
X-Arapuca

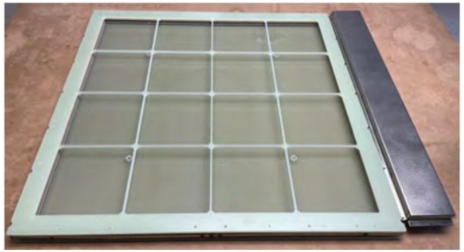
- Working principle

PTP → p-Terphenyl
SiPM → Silicon photomultiplier







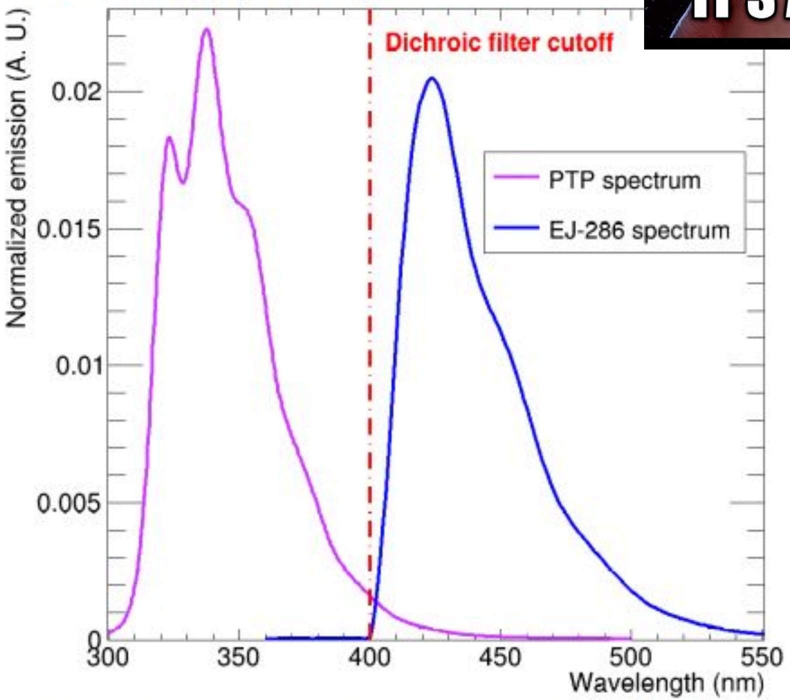


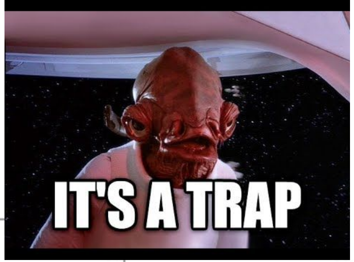
Arapuca module

The device makes use of a **dichroic filter** in combination with two **wavelength shifters (WLS)**

X-Arapuca

- **Working principle**





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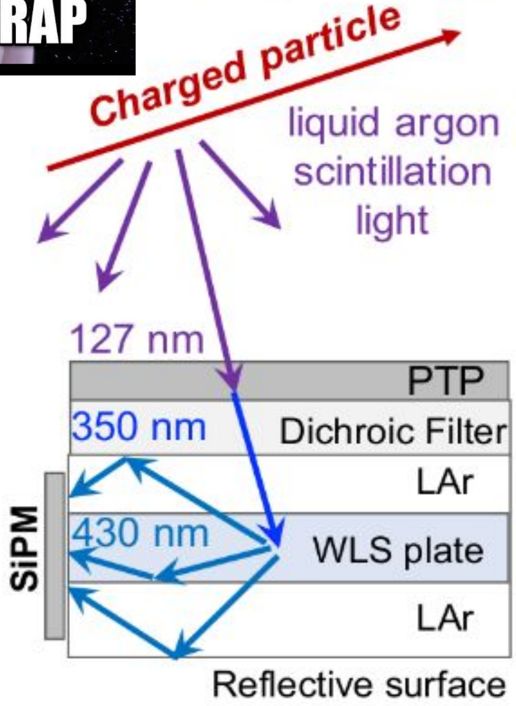
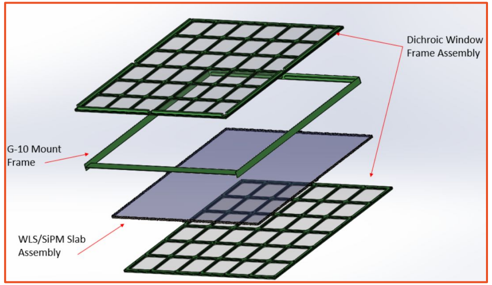
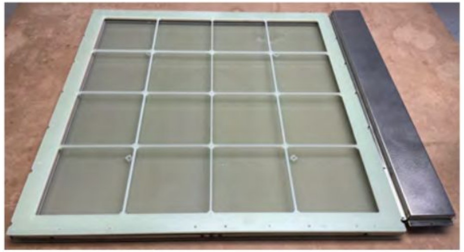






Arapuca module

The device makes use of a **dichroic filter** in combination with two **wavelength shifters (WLS)**

Supernova (SN)

Supernova explosion:

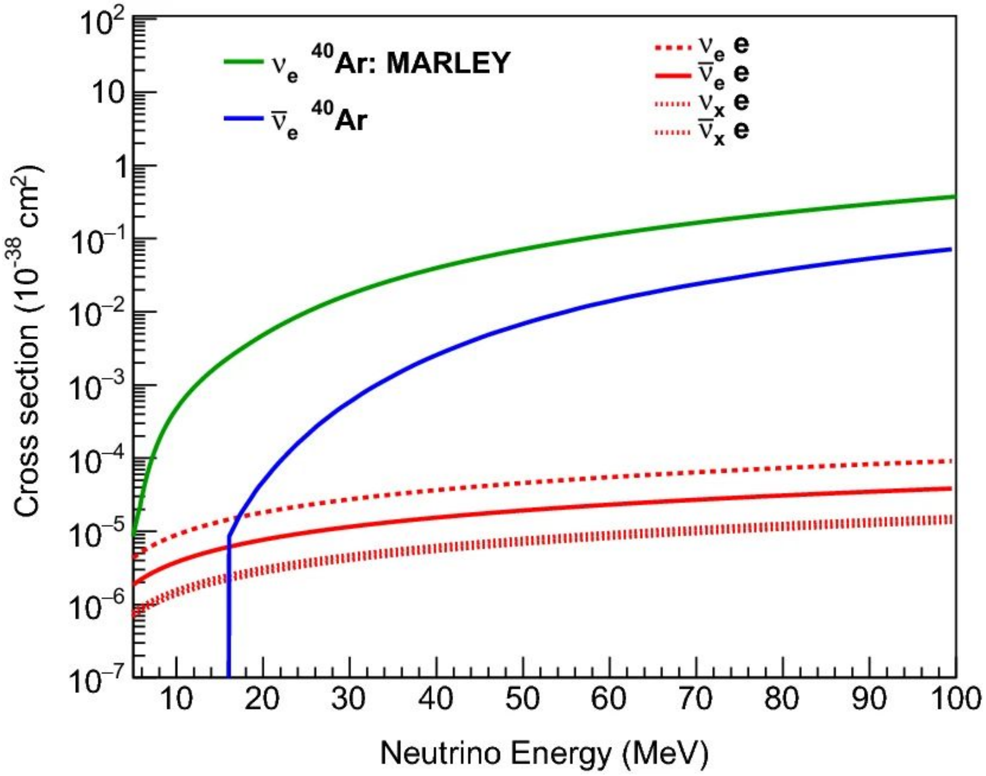
→ Low energy neutrinos of all flavors are emitted

DUNE → sensitivity of 10 - few tens of MeV →CC interactions produce short electron tracks in LAr

$$\nu_e +^{40} Ar \rightarrow e^- +^{40} K^*$$

Also, deexcitation gammas product of K* allow for a unique way of tagging interactions

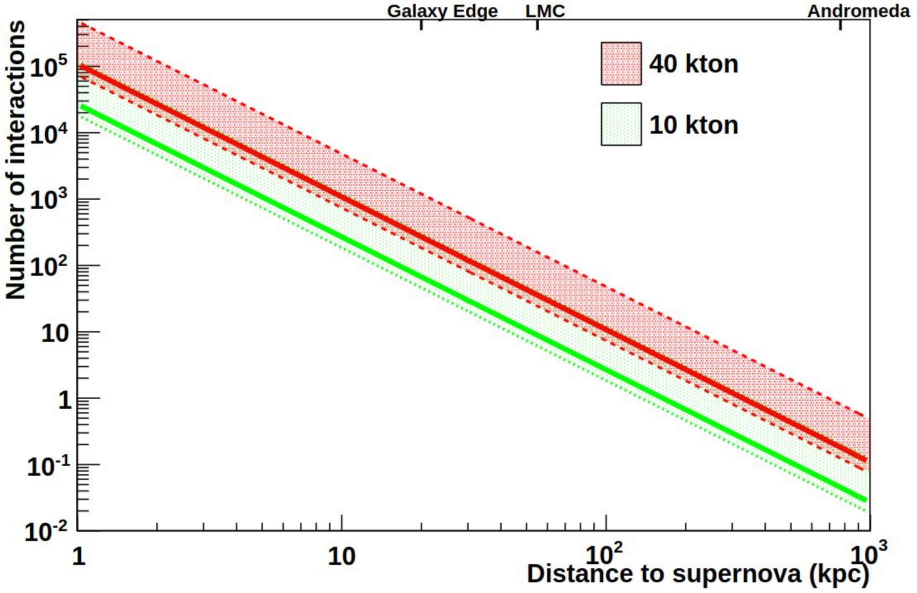
SN cross sections



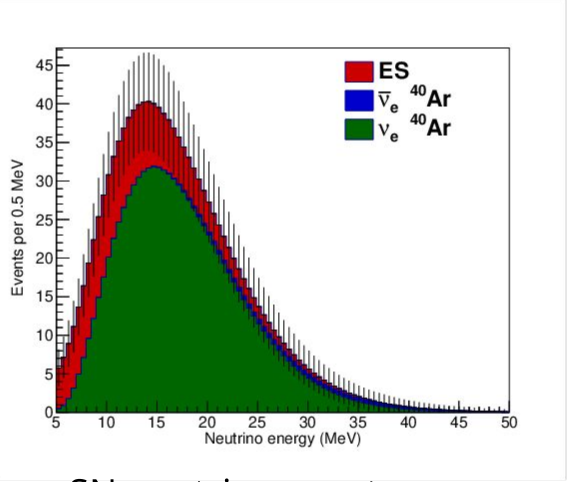
The nue + 40Ar channel has the highest cross section

Directionality

- **Main objective**: SN localization
- Neutrinos arrive before light signal
- Gives astronomers a chance to see the complete SN light curve!



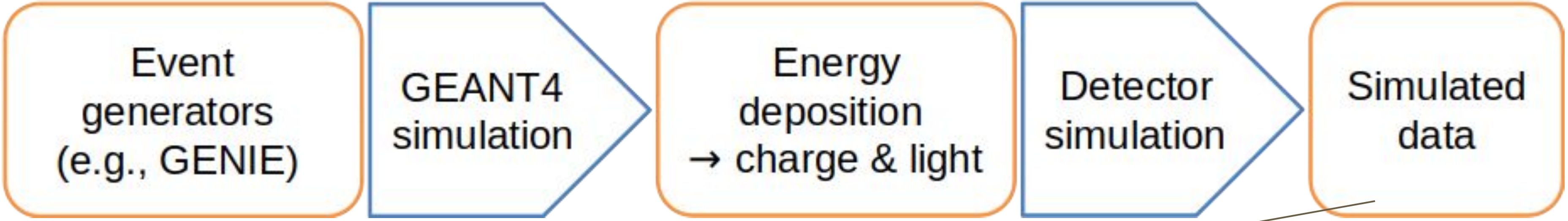
Number of expected interactions as a function of SN distance



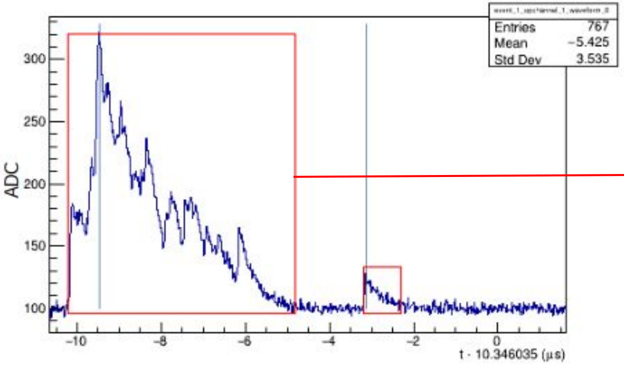
SN neutrino spectrum

Simulation and reconstruction

Scintillation light simulation



Example of an optical waveform

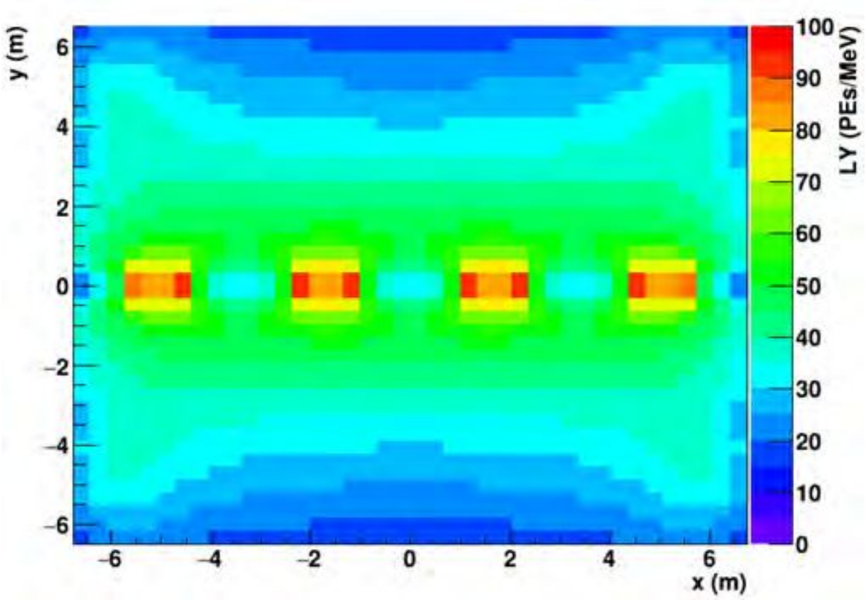


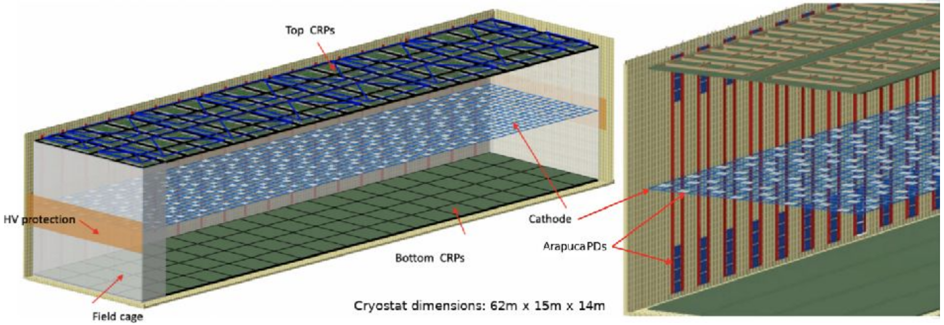
hit finding:
searches for peaks on individual waveforms channel-by-channel, identifying the time and the total amount of PEs

Light yield

The **light yield (LY)** is defined as the amount of PEs obtained per unit of energy (usually MeV) → LY = PE/MeV

<LY> expected for DUNE > 20 PEs/MeV



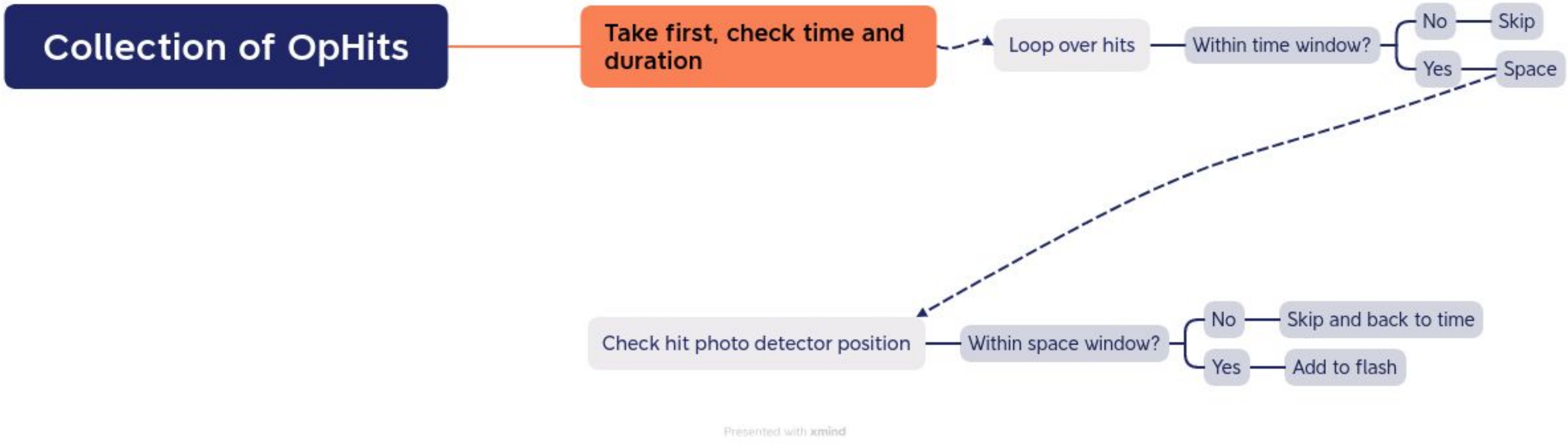


Xe doped (10 ppm) LAr LY → <LY> ~ 39 PEs/MeV

Clustering for position reconstruction

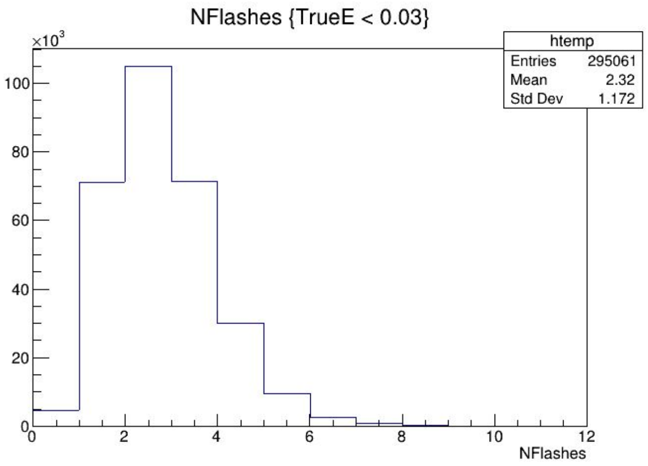
- Objective: generate *flashes* → clusterings of optical hits related in time and space
- With these flashes, we can perform a position reconstruction for the true event
- PDS reconstruction + TPC reconstruction →great imaging capabilities

Creating flashes: how does it work?



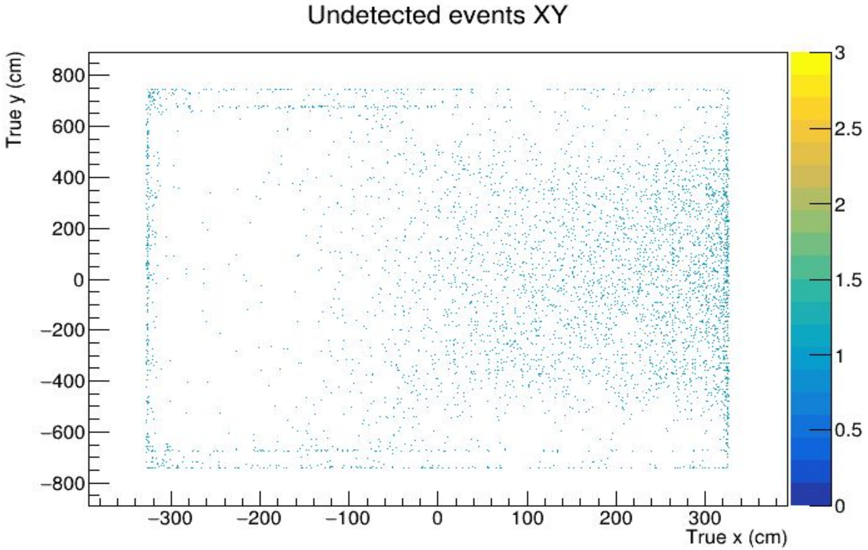
#Flashes

- 4-30 MeV SN nues with a flat spectrum
- <LY> ~ 30 PEs/MeV



- The mean #flashes is ~2.32. Since all the hits come from a single signal event, ideally this value would be ~ 1
- Amount of 0 flashes is ~ 1.6 %

Undetected points

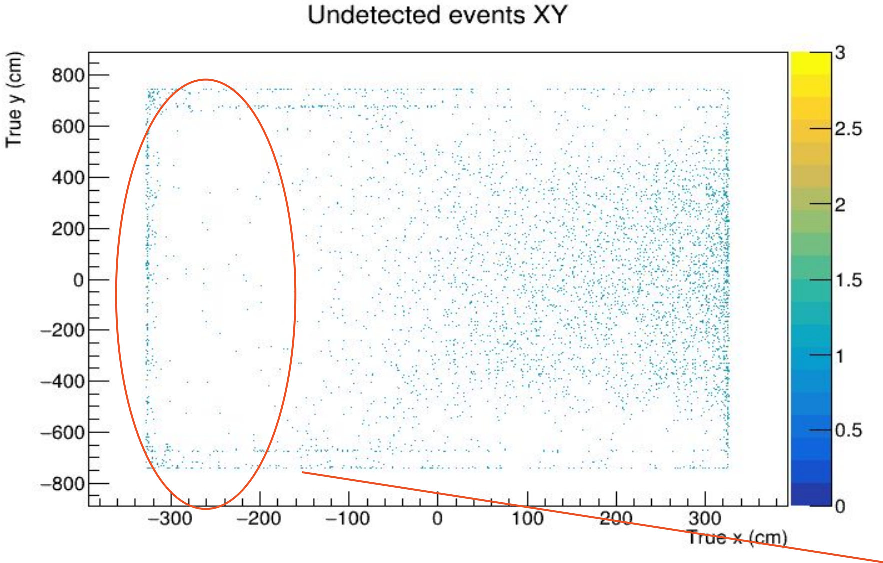


Top volume simulated

x →drift axis
y →walls axis

1. Amount of 0 flashes ~1.6%
2. Most of the undetected point occur further away from the cathode and the walls

Undetected points



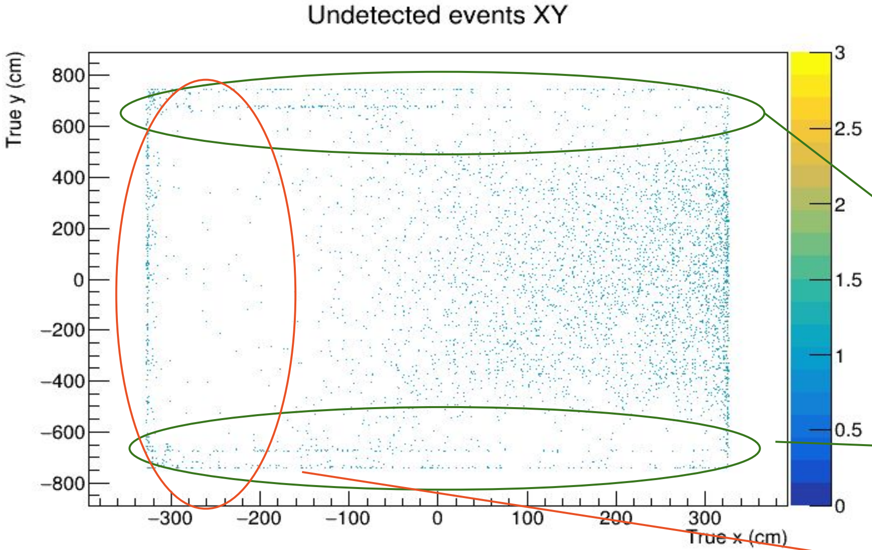
x →drift axis
y →walls axis

Top volume simulated

Cathode

1. Amount of 0 flashes ~1.6%
2. Most of the undetected point occur further away from the cathode and the walls

Undetected points



x →drift axis
y →walls axis

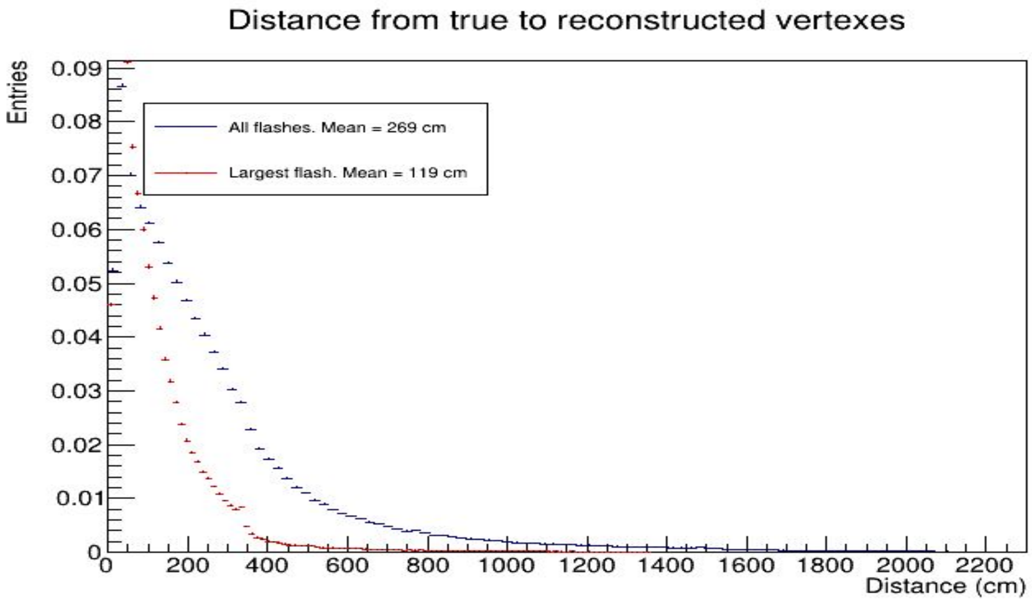
Walls

Top volume simulated

Cathode

1. Amount of 0 flashes ~1.6%
2. Most of the undetected point occur further away from the cathode and the walls

Spatial resolution



- Resolution for *all* flashes (blue), and the *largest* flash (red).
- Flashes with lower amount of PEs have a worse reconstruction

Signal + background

Background model

Component	Activity (mBq/cm^3)
^{39}Ar in LAr	1.41
^{42}Ar and ^{42}K in LAr	0.128×10^{-3}
^{85}Kr in LAr	0.16
^{222}Rn chain in LAr	1.395×10^{-3}
^{40}K in cathode	9.1
^{238}U chain in cathode	0.113
^{60}Co in anode	0.361
^{238}U chain in anode	95
^{222}Rn chain in PDS	0.021
External neutrons (rocks, concrete walls, etc)	7.6×10^{-3}
Cavern gammas	64

The two bigger points of interest are:

1. Low energy, lots of events: mainly Ar39/Ar42 (Ar 39 is generated at a rate of 1/Ls, which with 17 kt of LAr would produce ~ 10^{10} particles of 2 MeV each.
2. High energy, fewer events: mainly neutrons, which capture producing a ~6.1 MeV gamma shower.

Signal + background simulation

Signal

- SN nue
- 5-30 MeV energy spectrum
- Entire simulation extends through +- 4 ms (determined by the electron drift time), with the signal is located at **T=0**.

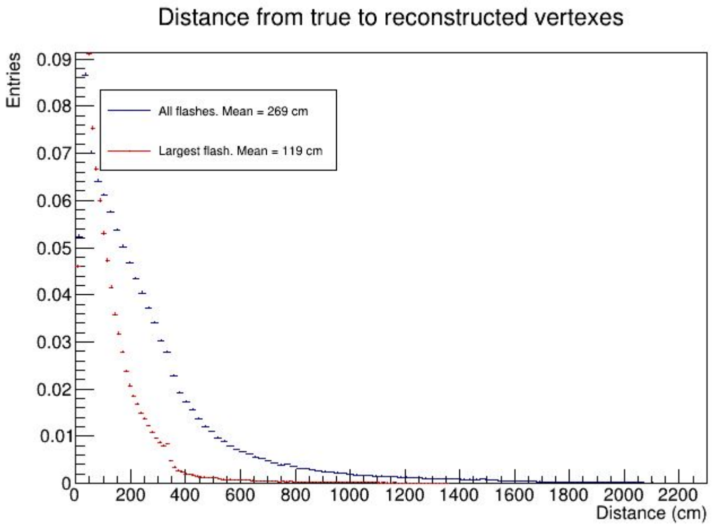
Background

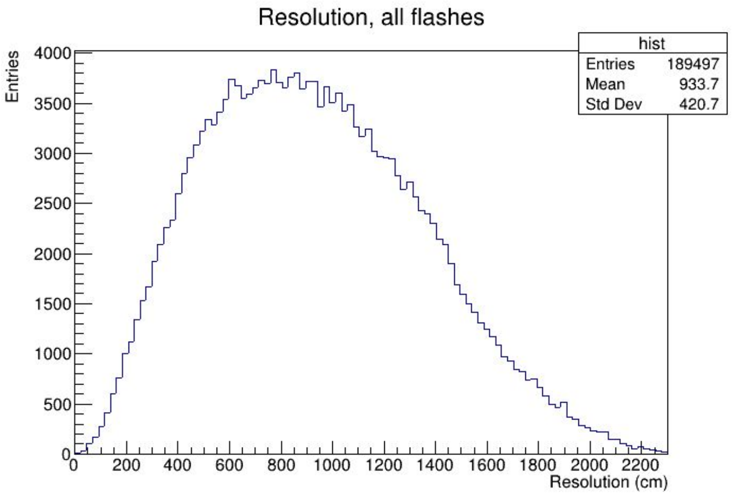
- Background extends throughout the *entire* detector, and also throughout the *entire* time window **T = +- 4 ms.**

Resolution comparison

Background →more light across the detector and throughout the entire time window (+- 4 ms considering TPC drift) →more flashes

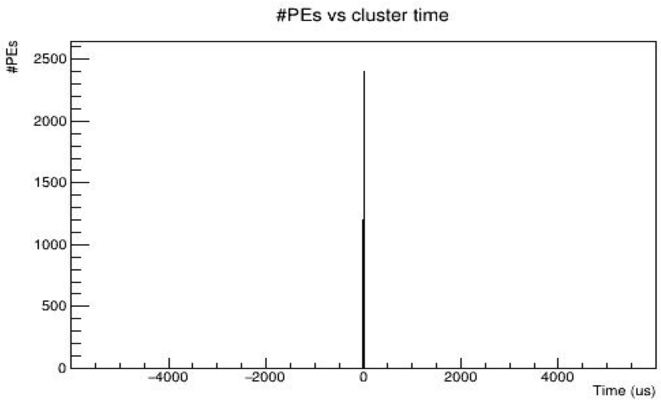
For example, looking at the spatial resolution:



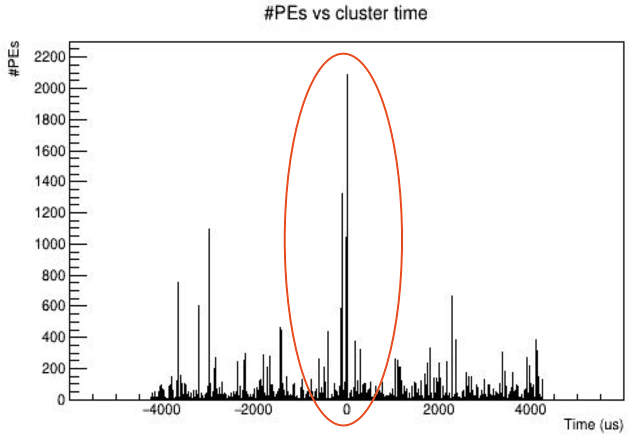


#PEs vs time, near X-Arapuca

30 MeV nue signal only



30 MeV nue signal plus background

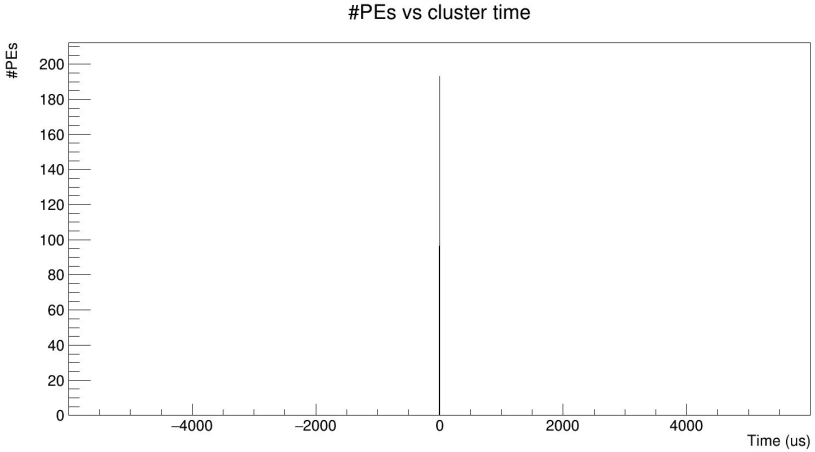


Neutrino signal is higher than background when close to an X-Arapuca

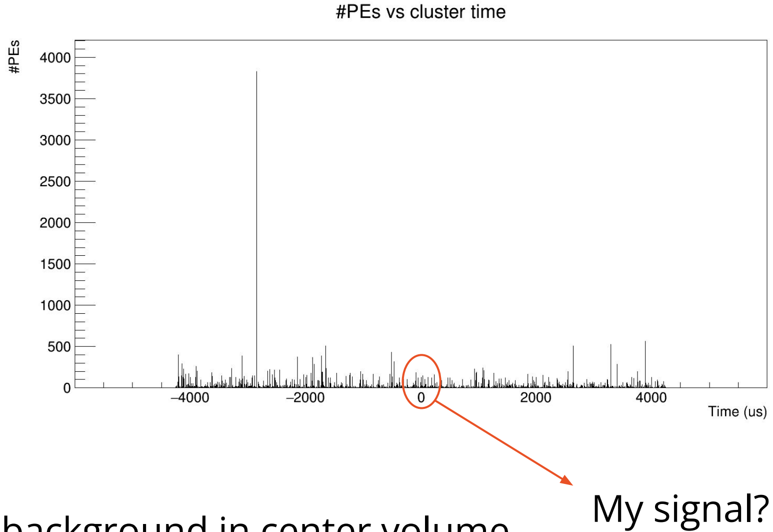
My signal

#PEs vs time, center volume

30 MeV nue signal only

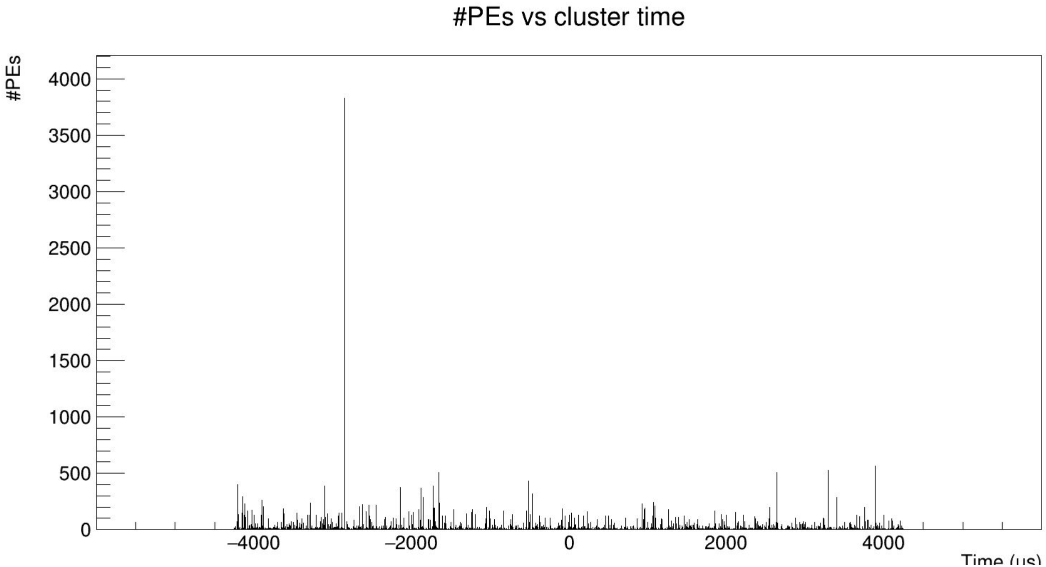


30 MeV nue signal plus background



The neutrino signal strength is comparable to the background in center volume

What is the plan?



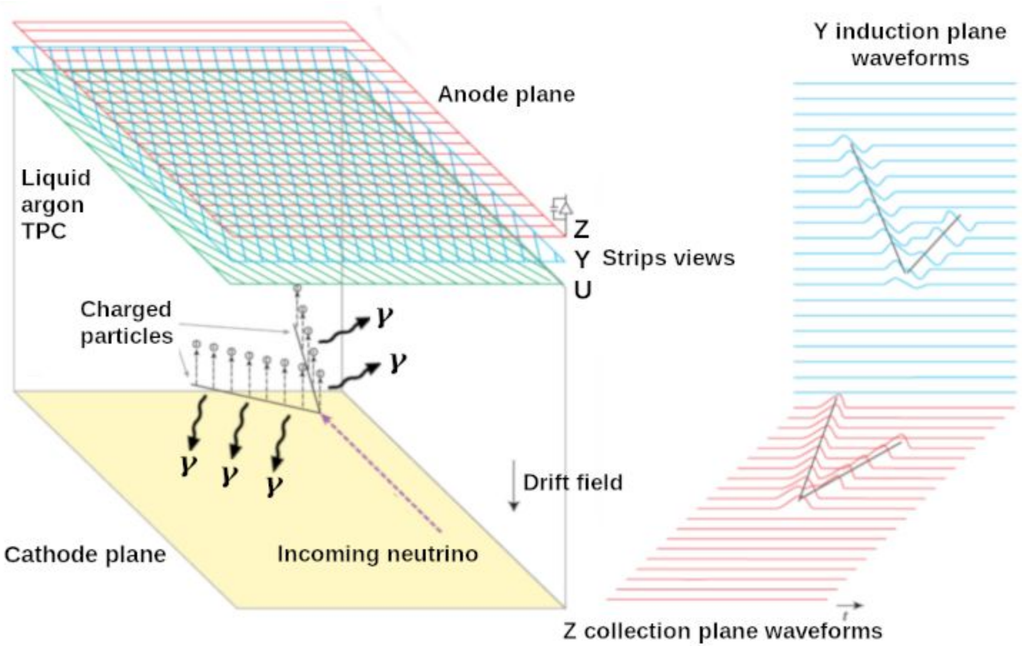
- Objective: explore clustering to maximise number of photons from the neutrino signal
- Explore discrimination capability as a function of spatial position

Conclusions

- Clustering algorithm shows good performance for a signal only simulation, with a spatial resolution of ~1.2m when considering the largest flash
- Background induces some significant alteration in the clustering process due to the high amount of extra PEs generated
- Obtain a set of parameters for signal identification and background discrimination
- El sadness

Backup slides

Time Projection Chamber (TPC)



ν + LAr →charged particles

↓

LAr Ionization and scintillation

↓

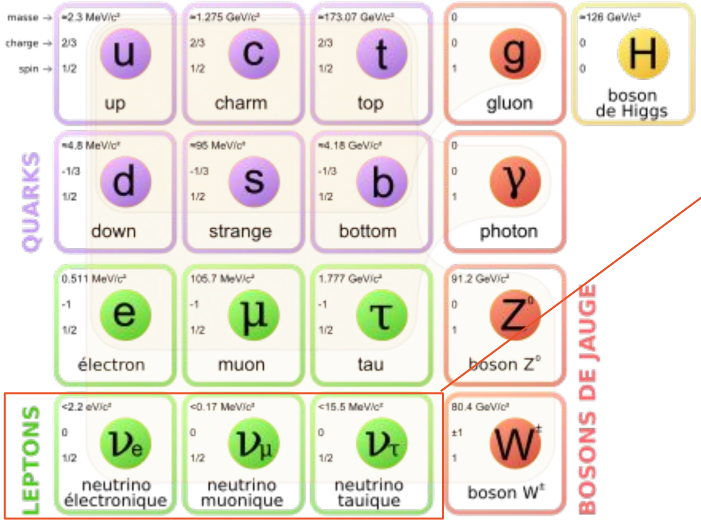
e- drift towards anode, γ detected with Photo-detection system (PDS)

↓

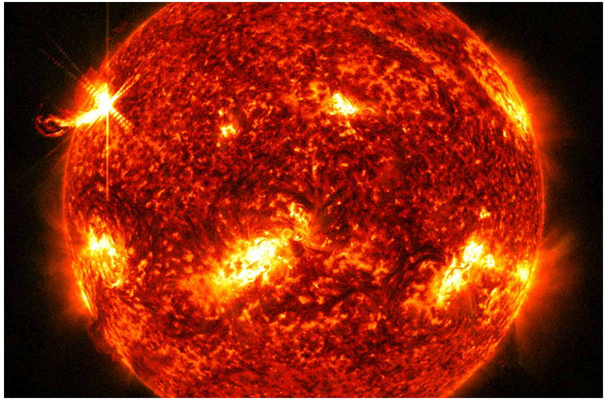
Trace reconstruction due to excellent imaging capabilities

Neutrinos

Neutrinos →elementary particles in the standard model



- Leptons →weak interaction
- Three flavors: *electronic (e), muonic (*μ*) and tauonic (*τ*)*
- Very small cross section
- Mass?



Neutrino oscillations

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix} \cdot \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

Weak interaction eigenstates

PMNS matrix

Mass eigenstates

Neutrino oscillations

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \cdot \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

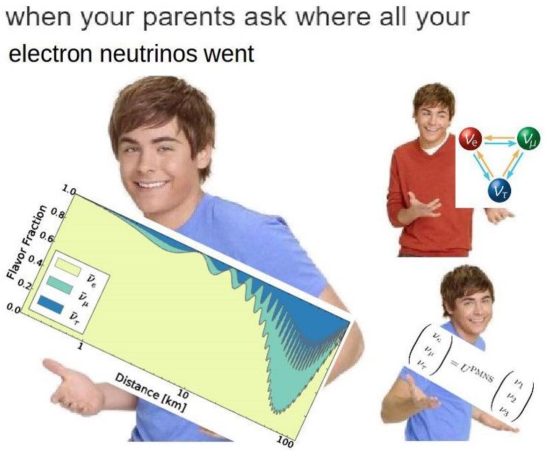
$$P(\nu_\alpha \to \nu_\beta; L) = \delta_{\alpha\beta} - 4 \sum_{j>k} \mathrm{Re}(U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k}) \sin^2\left(\frac{\Delta m^2_{jk} L}{4E}\right)$$

$$\pm 2 \sum_{j>k} \mathrm{Im}(U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k}) \sin^2\left(\frac{\Delta m^2_{jk} L}{2E}\right)$$

with L the baseline, and E the neutrino energy

Neutrino oscillations

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \cdot \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$



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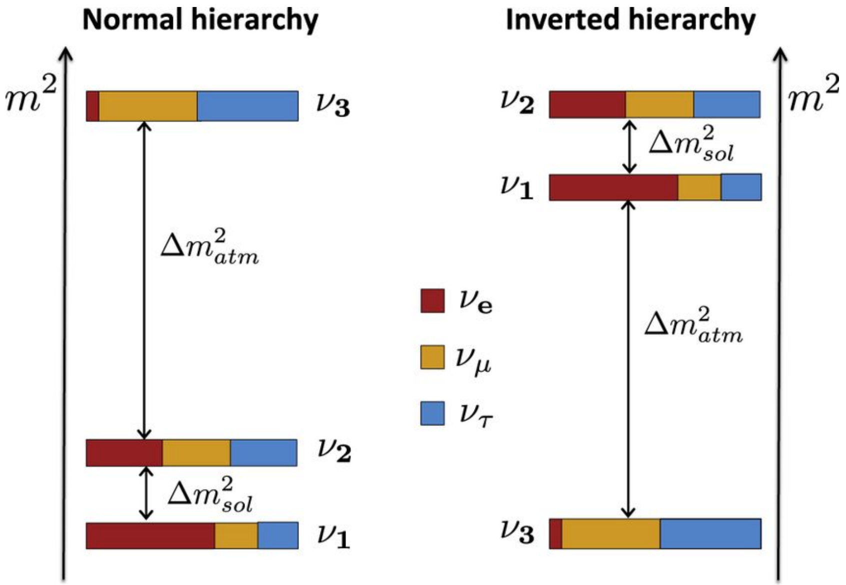
Mass term

CP violation term

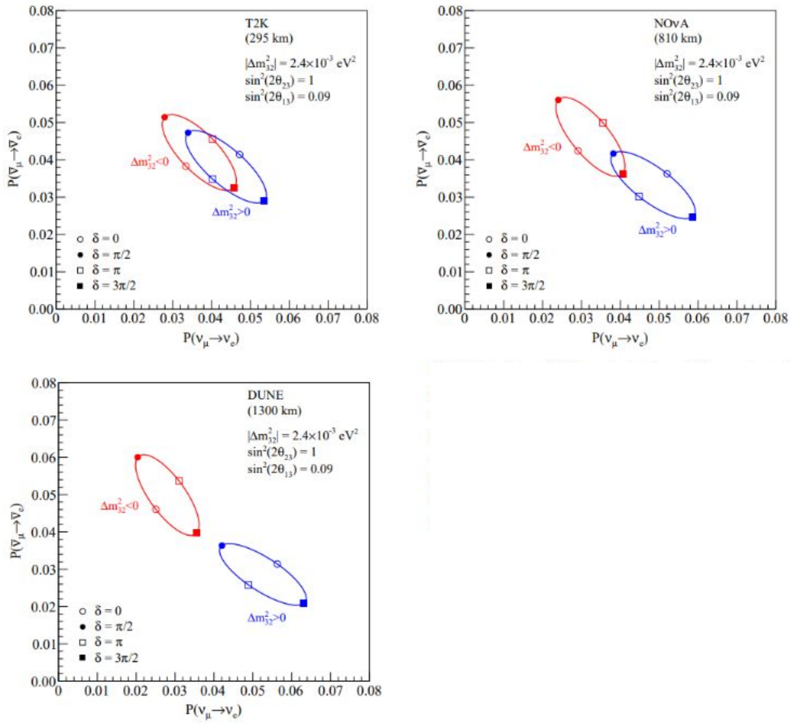
with L the baseline, and E the neutrino energy

Mass hierarchy



- m1 < m2 < m3 → *normal* mass hierarchy
- m3 < m1 < m2 → *inverted* mass hierarchy

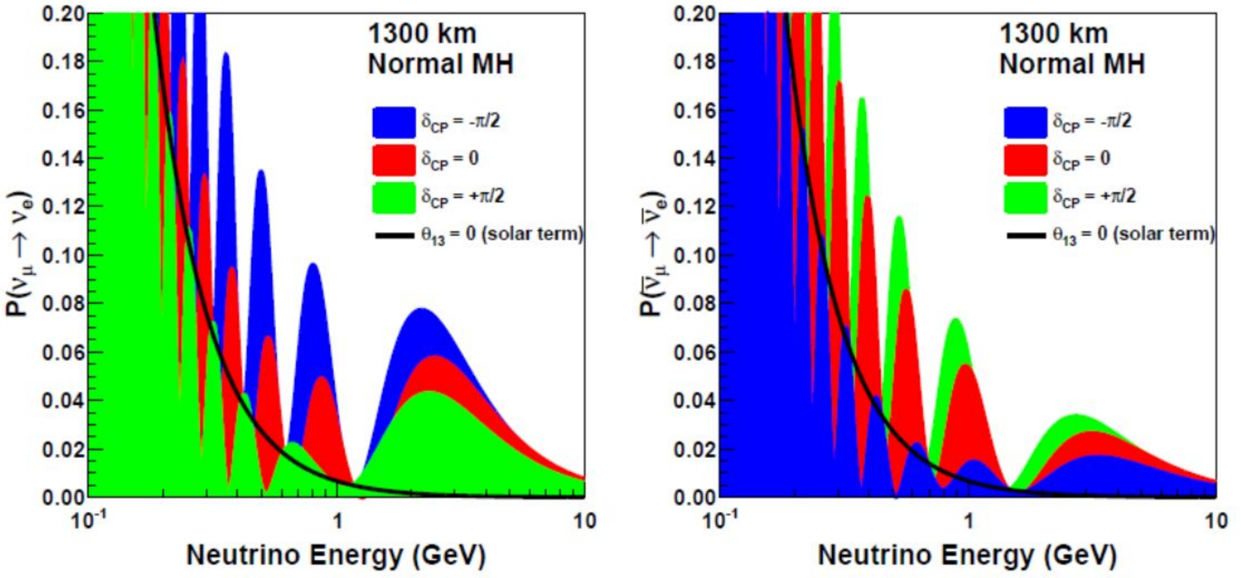
Matter effects



→

The longer the baseline L, the greater the difference for the normal and inverted hierarchy, for all values of δcp

Beam energy



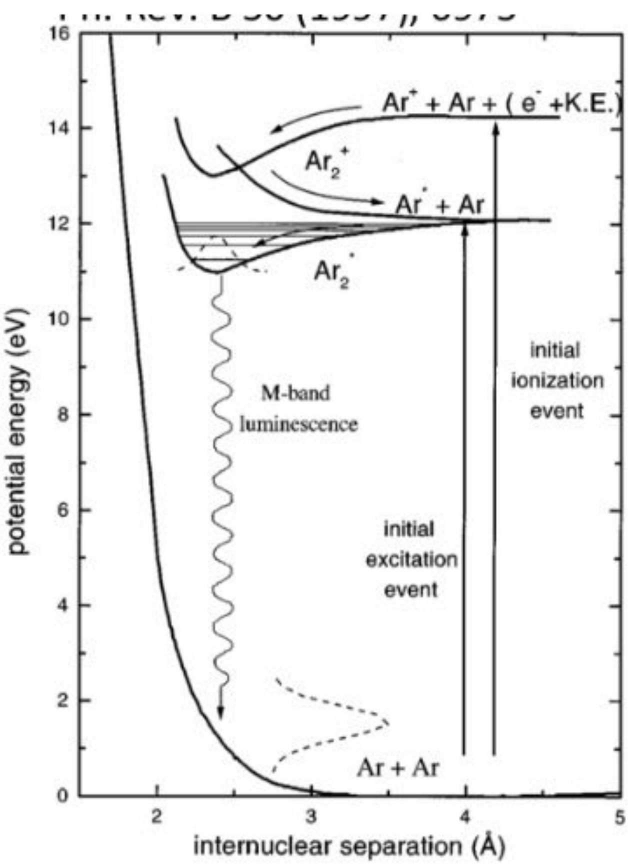
DUNE → wide-band beam (0.5-8 GeV), as opposed to T2K and No**v**a, which peak at 0.6 and 1.9 GeV respectively.

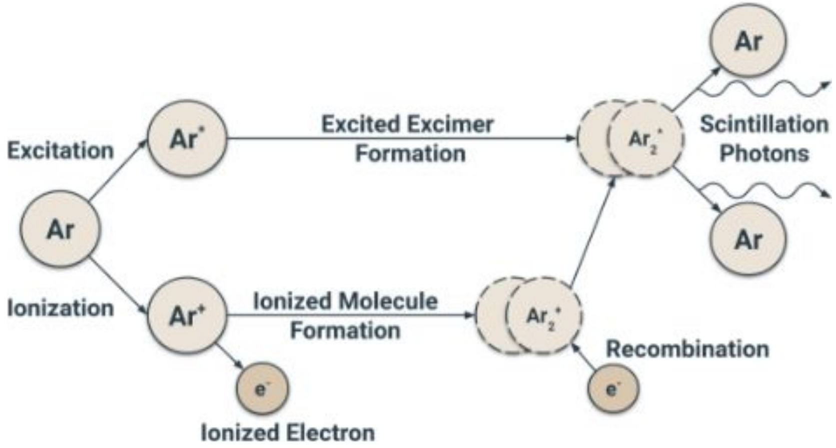
Longer baseline and wider-band beam →measurement of the first peak at higher energies, and second peak, which is more sensitive to δcp

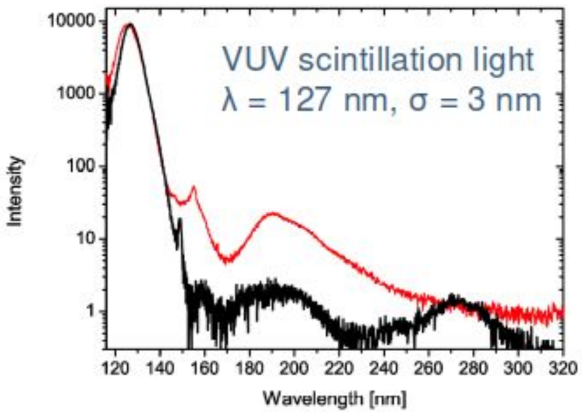
Position reconstruction analyzer module

- Position reconstruction → OpFlashFinder algorithm (LarSoft)
- Objective: generate *flashes*, which are clusterings of optical hits related in time and space, aiming towards matching together points that have the same event origin
    - Time window: 2 us
    - Space window: 15m

LArTPC - Scintillation



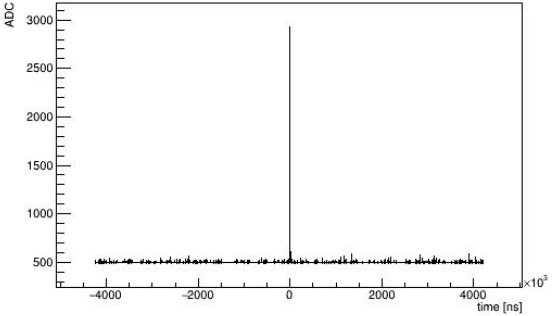




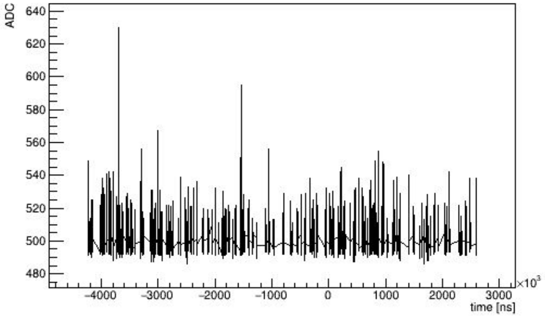
preguntar

Waveforms

Nue close to a X-arapuca



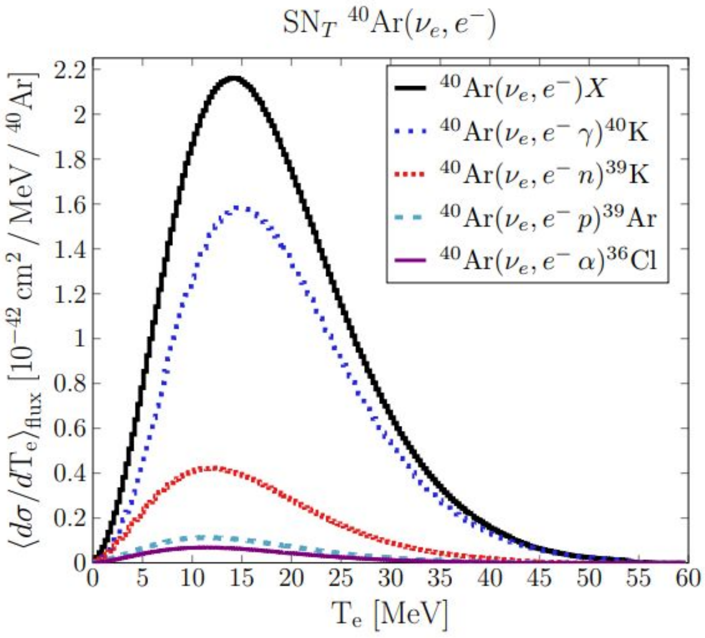
Nue in central volume



Left: spb signal for a nue close to an optical channel. Nue →(-310, -630, 1950) m, Opch → (-326, -627, 1973) m
Right: spb signal for a nue in the center of the detector. Nue → (0, 0, 1000) m, Opch →(-326, -44, 1011) m

- 10 ADC →1 SPE
- 500 ADC baseline → account for potential undershoot.
- Waveforms are generated within a 5us acquisition window

Neutron events



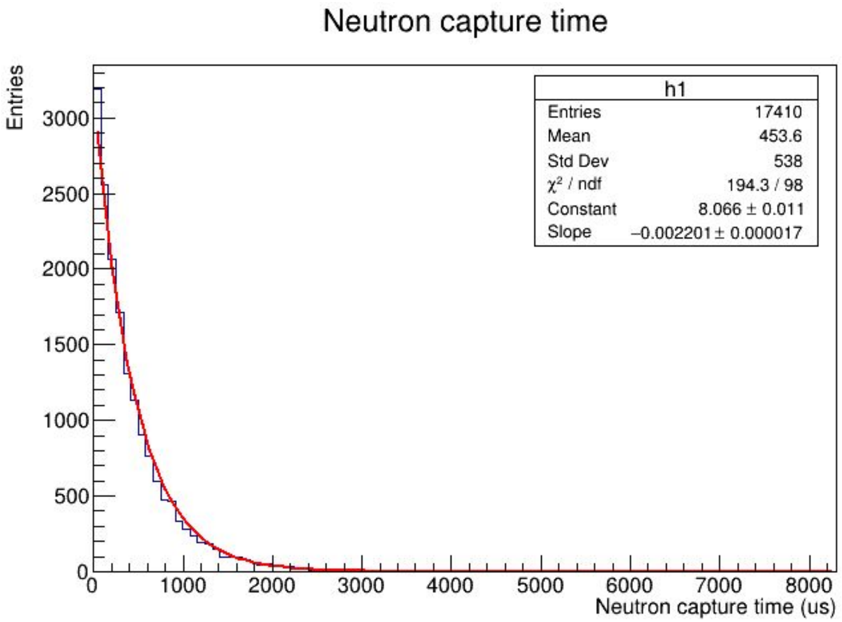
Flux-averaged differential cross section

Neutron generation has a peak at ~12 MeV nue energy → well within our energy range

Neutrons can then be captured and produce a ~6.1 MeV gamma showers

$$n^0 + ^{40}Ar \rightarrow ^{41}Ar + \gamma_{6.1MeV}$$

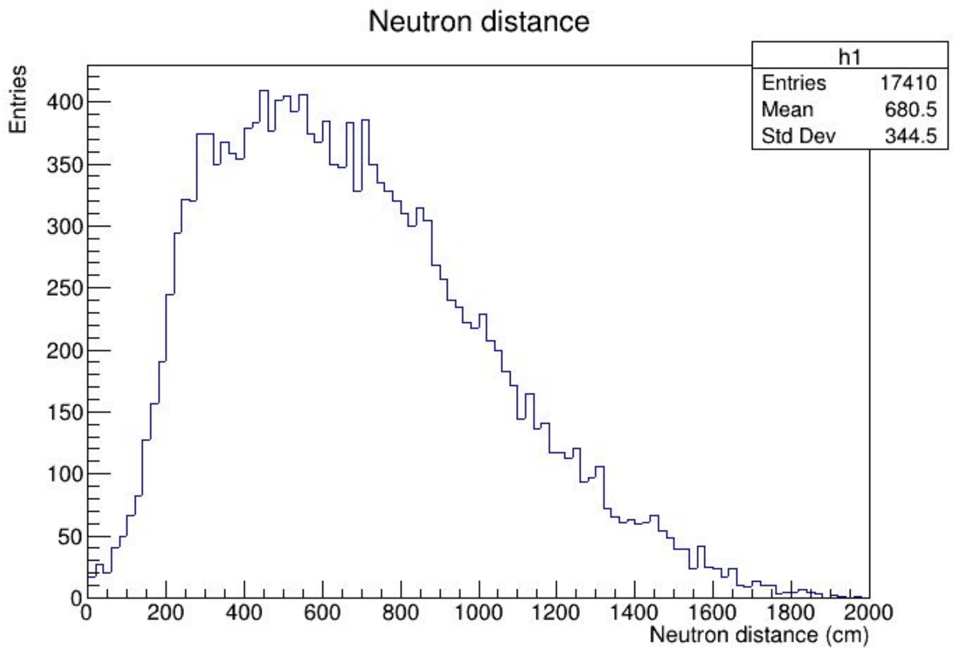
Neutron capture time



Neutron capture time → ~454 us

Photons generated via this capture would have a distinct detection time compared to the once generated via nue + LAr interactions

Neutron capture distance



Neutron capture distance → 680 cm (6.8m)

↓

If neutron produces gammas due to capture far away from the neutrino source, the algorithm could potentially generate clusters associated to this capture