MoO for DUNE!!

A partial report from Module of Opportunity for DUNE workshop

Mark Convery *Gianluca Petrillo* Yun-Tse Tsai

SLAC National Accelerator Laboratory, U.S.A.

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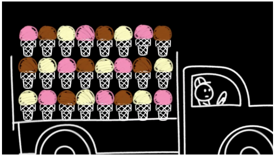
SLAC NATIONAL ACCELERATOR LABORATORY

Outline

1. Introduction to DUNE and the MoOD workshop
2. LArTPC: charge detection and readout
3. LArTPC: light detection and readout
4. LArTPC: doing more with more
5. Alternative detector technologies

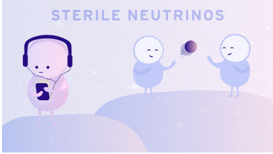
The shortest DUNE introduction ever

The DUNE neutrino observatory has a rich set of physics goals, including...



Three flavour long baseline neutrino oscillation: neutrino mass ordering, CP symmetry violation, octant of oscillation parameter θ_{23}.

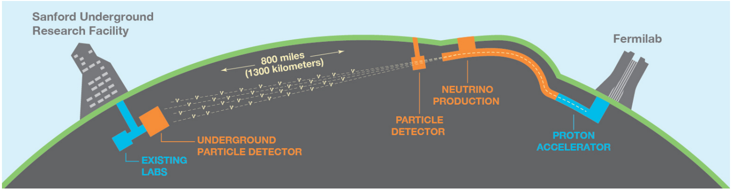
Supernova burst neutrinos: flavour content, spectra, time evolution; and early detection for multi-messenger astronomy.



Detection of baryon number violation, sterile neutrinos, dark matter and a load of other phenomena beyond the Standard Model.

... all within the reach of the current design.

A short introduction to DUNE



The *baseline* design of the detectors to get there includes:

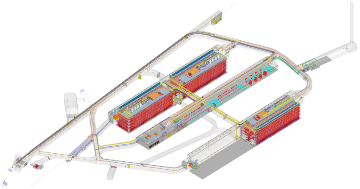
- a high-intensity, wide band neutrino and antineutrino accelerator at Fermilab at GeV range
- a massive "far" detector (FD) 1300 km away buried in a mine in South Dakota, including four 10 kton (fiducial volume) liquid argon TPC's
- a "near" detector (ND) 575 m away from the source to characterise it, made of three components: a vagrant liquid argon TPC, a vagrant magnetised high pressure argon TPC and a settled solid scintillator detector

DUNE schedule

An outline of the current installation start timeline:

→ guideline: install each detector as soon as its cavern is available

1. module 1 (single phase): August 2024
2. module 2 (dual phase): August 2025 (end: May 2026)
3. module 3: just after module 2 is installed
4. module 4: middle 2027?



While the technology for the first modules are mostly identified, the fourth module is further ahead, opening the opportunity to consider more advanced technologies still being developed or defined today.

Assuming a "lead time" of 3 years for ordering the cryostat, the decision on that module should be taken by middle 2024.

The workshop

The Module of Opportunity for DUNE workshop took place on November 12 and 13, 2019, at Brookhaven National Laboratory.

It was open to physicists within and without the DUNE collaboration ("the broader community").

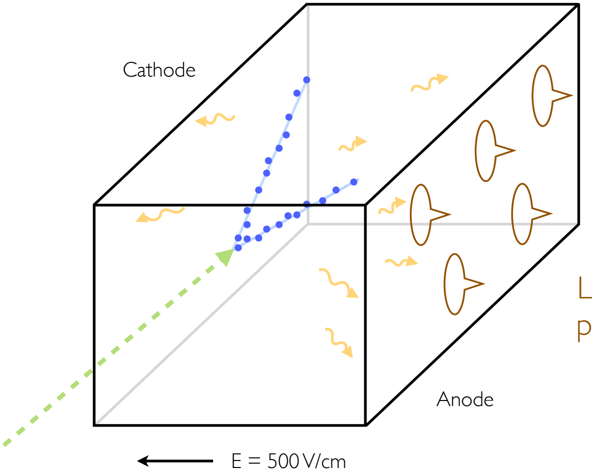
Its agenda included more than 30 contributions, ranging from technical improvements to established technologies for a detector component to completely new full detector designs.

Mandate of the workshop

- the fourth module should support the primary physics program, e.g.
  - help pinning down relevant systematic uncertainties
  - improve energy resolution or detection thresholds
  - complement with additional information (e.g. particle charge)
  - help reduce or discriminate backgrounds
  - enable roads to discovery beyond the current experiment portfolio
- corollary: it must not perform any worse than the others for the main DUNE physics program
- the technology of choice will have to demonstrate a level of readiness at the level of the one ProtoDUNE showed for the first module
- bonus points if it comes with funding...

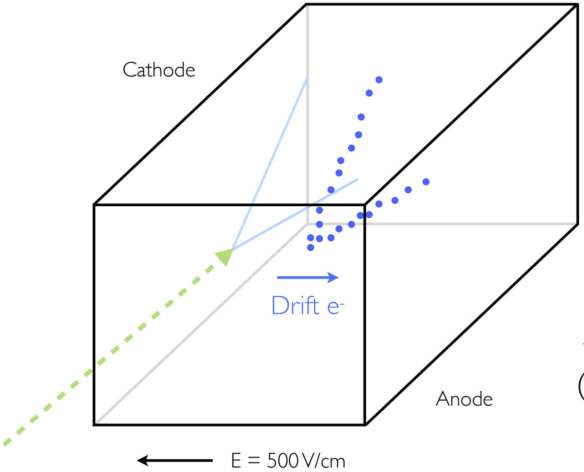
As the first one on the subject, this workshop was open to any idea at any stage of completeness. The second workshop should happen this year (2020) with a "concept paper" backing each proposal to drive and focus the following discussions.

Outline



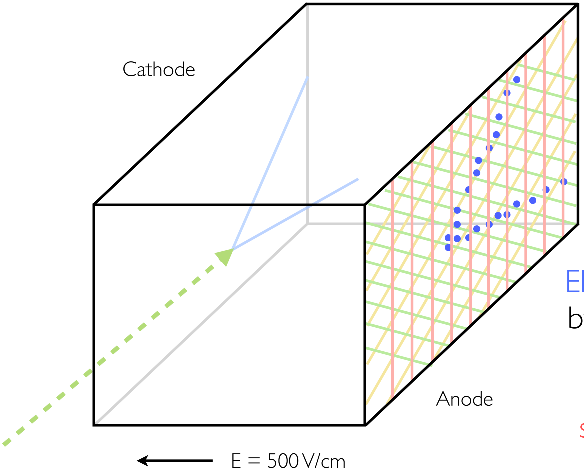
Light collected by photon detectors (10-100ns), determining event time t_0

LArTPC data acquisition



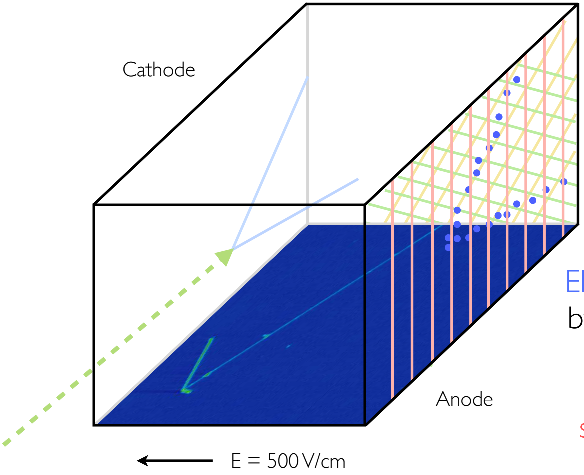
Electrons drift towards anode (drift time at ms scale)

LArTPC data acquisition



Electrons detected by the wire planes at anode, providing the spatial, kinematic information.

LArTPC data acquisition



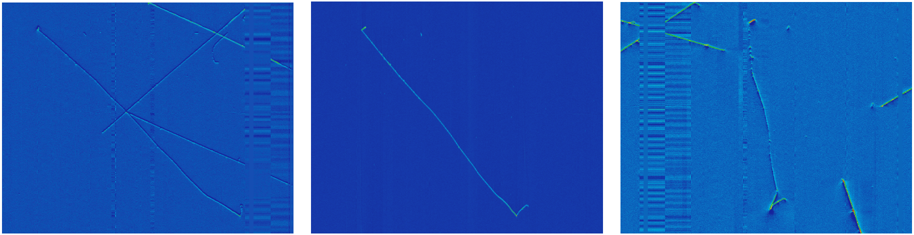
Electrons detected by the wire planes at anode, providing the spatial, kinematic information.

Projections and ambiguities

Features on three views need to be matched to represent the 3D topology of the interaction, and then with the optical detector to pin down the absolute position.

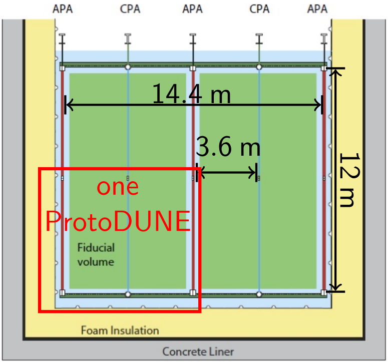
- see an event from MicroBooNE, three views 60° apart
- ordinate describes drift coordinate/drift time, on a common scale
- abscissa describes a coordinate on the plane, all in 3 mm steps

What is happening in this event? where does the five-prong vertex from the first plane show in the other two?



DUNE far detector charge readout: "single phase" (SP)

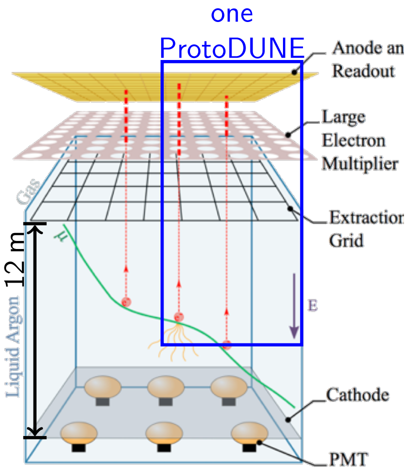
- choice for module 1
- fully demonstrated by ProtoDUNE prototype (6 out of 240 modules)
- Anode ("APA"): three wire planes, wire pitch ≈ 4.5 mm;
- Cathode ("CPA") shared
- modular, drift direction is sandwich APA-CPA-APA-CPA-APA
- anode readout only from top and bottom: TPC may share channels



Liabilities:

- anode planes bulky and fragile
- TPC's share channels
- needs buffer space around cathodes, wasting active volume

DUNE far detector charge readout: “dual phase” (DP)



not in scale

- choice for module 2
- not yet demonstrated to final scale
- charge multiplication in gas (LEM)
- secondary light (“S2”) *not* collected
- two views (strip readout)

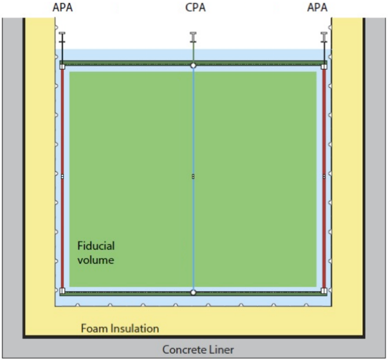
Liabilities:

- only two views
- looong drift distance

Drift distance: longer vs. shorter

One recurrent theme of the workshop was to deal with long drift volumes:

- two TPC's, cathode in the middle
- \+ simpler mechanics
- \+ cheaper (fewer elements)
- \+ no two-sided anode opens options
- \+ can be ProtoDUNE'd
- – attenuation of charge and light (ProtoDUNE: purity saves charge)
- – light is less localised
- – larger bias voltage ($\mathcal{O}(300\,\mathrm{kV})$)
- – harder to achieve $\vec{E}$ uniformity
- dual phase detector *must* live with it



Drift distance becomes 6 – 7 m.

Some of the proposals expressed in the workshop *require* a long drift.

Strip anode plane

Idea: replace wires with *strips*.

- inspired by Dual Phase readout
- wire APA are large ($6 \times 2.4\,\mathrm{m}^2$) and bulky
- nobody likes floating broken wires

⇒ strips deposited on a solid PCB are sturdy

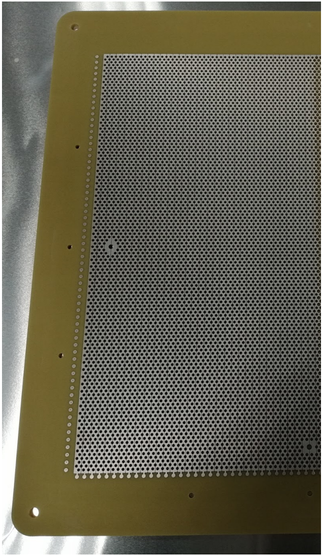
⇒ easy to modularise: smaller modules make installation easier

⇒ shorter strips, more channels: smaller capacitance, reducing noise, well suited for SLAC Cryo ASIC

⇒ probably cheaper too

– with CERN production facilities, no larger than $(1 \times 0.6)\,\mathrm{m}^2$

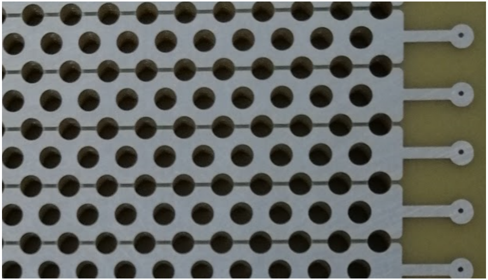
– opaque: needs new optical detector

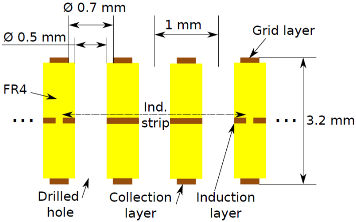


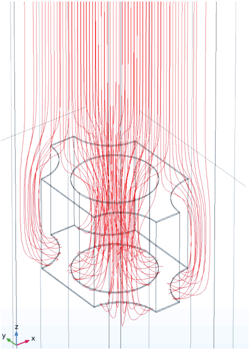
Presented by Bo Yu (BNL)

Strip anode: prototype

- first prototype: *two orthogonal views*
- one induction view, one collection view (top layer is not instrumented)
- no multiplication (i.e. it's not a GEM — it's in liquid anyway)



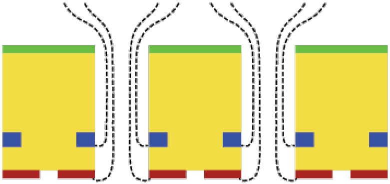


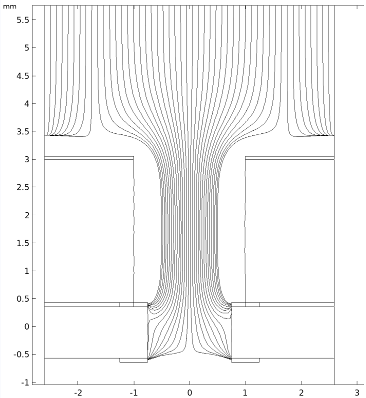


Strip anode: three views

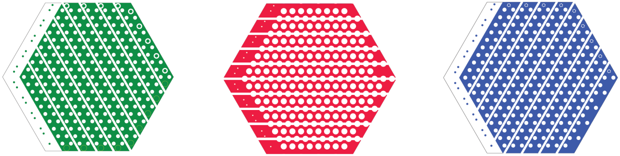
Extending the design to three views (i.e. three planes) is complicate. One example:

- two collection planes sharing charge
- hexagonal shape to avoid short strips





Arrangement of strips and holes in three-layer configuration:



Pixel readout

Idea: replace three “1D” wire planes with one 2D *pixelated* plane

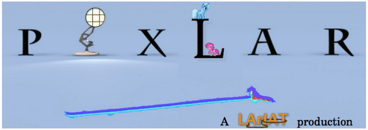
- avoid the reconstruction ambiguity from matching different views (more critical for busy environments like the near detector)
- no special angles with reduced reconstruction efficiency
- should help reconstruct small energy deposits
- still needs to match to optical system for location
- requires less space behind the anode

But:

- more channels, more data
- avoid boiling
- need to be “cost-effective”

Two competitors: LArPix and QPix

- respectively from ND and for FD
- different people
- different readout approach



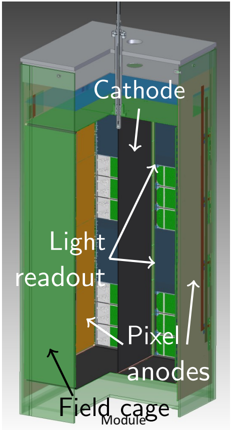
Logo of the first pixel readout prototype tested inside LArIAT.

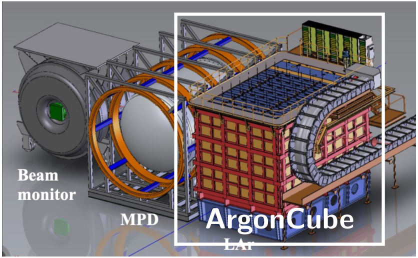
DUNE near detector LArTPC: ArgonCube

ArgonCube collaboration delivers the reference design of the liquid argon component of DUNE ND.

- modular (modules can be replaced)
- designed for crowded environment
- resistive field cage
- 400k pixel demonstrator under construction
- longevity of elements needs to be assessed

ArgonCube

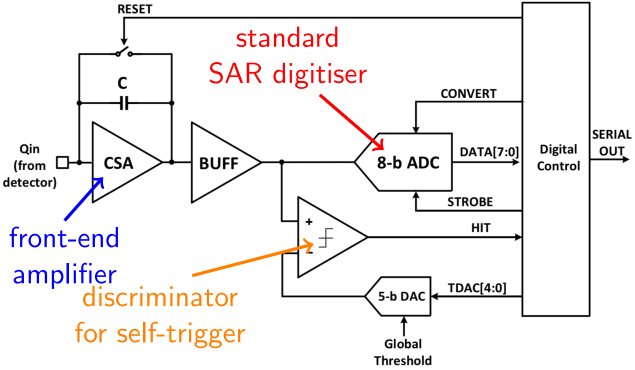


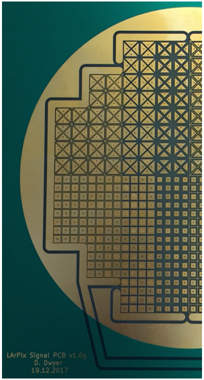


ArgonCube is the brand name of DUNE ND LArTPC component

ArgonCube readout

- self-triggering above a threshold to keep data rate at bay, 8-bit ADC
- data rate expected at DUNE ND: 0.01 Hz/pixel, 2 MB/s (8M pixels)
- under control both power (62 µW) and noise ($<$ 300 electrons)
- prototype pixels have 3 mm pitch

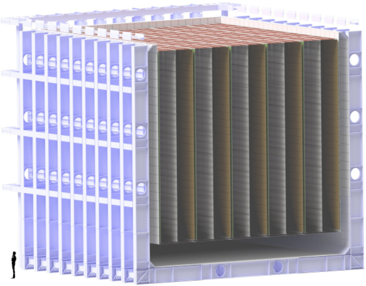




ArgonCube for far detector

In James Sinclair's words, with the translation into Far Detector:

- drift length divided into 10 TPCs (5 cathodes in the middle)
- cathodes divided into 20 sections along the beam
- 200 individual TPCs are contained within an opaque G10 structure
- detector volume $61.8 \times 13.6 \times 14.9\ \mathrm{m}^3$
- active volume 21% larger than DUNE SP



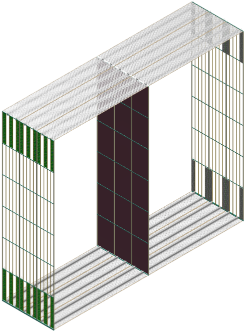
In my words:

- abandoned the idea of replacing modules (maybe the anodes?)
- modules will be taller ($6 \rightarrow 12\ \mathrm{m}$); still less bulky than wire APA
- containment of light will be beneficial
- ... after we find a good way to read it

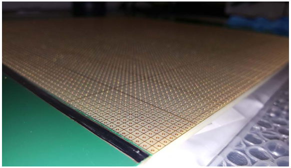
QPix

The design from the QPix Consortium:

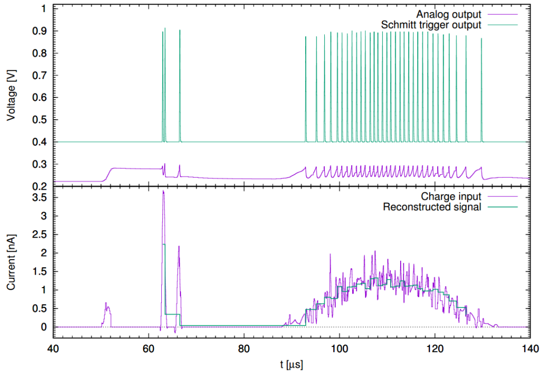
- native to and designed for DUNE Far Detector
- sticks to the 3.4 m drift length design
- 4 side readout planes, 2880 m^2 of pixels
- power consumption under control (51 μW, projected 26 μW)
- simulations suggest noise < 100 electrons
- intrinsically self-triggering channels
- designed for quiet environment
- data rate expected at ND: < 100 MB/s



↑*Half transversal section of DUNE FD with QPix solution*



QPix readout



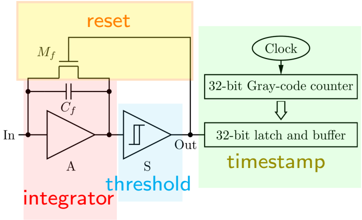
QPix readout electronics:

- integrates charge
- on reaching threshold…

… sends a timestamp

… and resets the charge

⇒ QPix reads a *frequency*



A readout test:

- *(purple, bottom): injected charge*
- *(purple, top): charge integrated by electronics*
- *(cyan, top): pulse when threshold is reached*
- *(cyan, bottom): waveform rebuilt in time domain*

Pixel technology comparison stub

<table>
<tr><th>ArgonCube</th><th>QPix</th></tr>
<tr><td>originally designed for ND</td><td>native to FD</td></tr>
<tr><td colspan="2">millimeter-size pixels</td></tr>
<tr><td colspan="2">low power consumption</td></tr>
<tr><td colspan="2">low noise</td></tr>
<tr><td colspan="2">opaque anode needs alternative light detection</td></tr>
<tr><td>relies on short drift distance</td><td>relies on low occupancy</td></tr>
<tr><td>$8/4.5 \cdot 10^8$ pixels ($3/4$ mm)</td><td>$2.4/1.8 \cdot 10^8$ pixels ($3/4$ mm)</td></tr>
<tr><td>samples collected charge vs. time</td><td>samples time vs. collected charge</td></tr>
<tr><td>cool logo</td><td>no cool logo yet</td></tr>
</table>

Outline

Light Requirements for DUNE

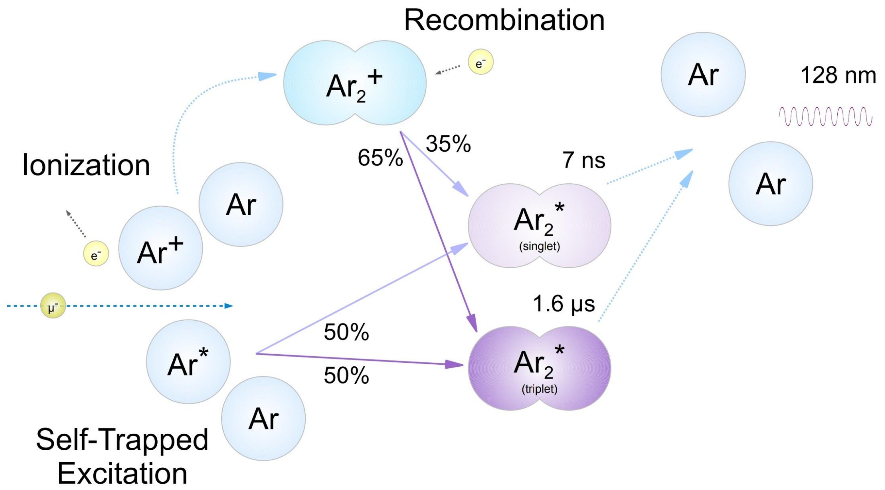
Description	Specification (Goal)	Rationale
Light Yield	> 0.5 PE / MeV (min)	>99% of nucleon decays can be tagged
Time Resolution	$< 1\mu$s	1mm position resolution for 10 MeV supernova ν
Spatial localization in y-z plane	< 2.5 meters	Enables "accurate" TPC to PDS match

From the DUNE TDR Appendix:
Physics deliverable: the PD system should be able to provide a calorimetric energy measurement for high-energy events complementary to the TPC energy measurement. Neutrino energy is an observable critical to the success of the oscillation physics program, and a second independent measurement can provide a cross-check that reduces systematic uncertainties or directly improves resolution for some types of events. 6

("y-z" is the plane where the anodes and cathodes lie, $12 \times 60\ \mathrm{m}^2$*)*

(courtesy of Elena Gremellini)

How



(courtesy of Denver Whittington)

Where

Different locations *may* be available for the photon detection system (PDS):

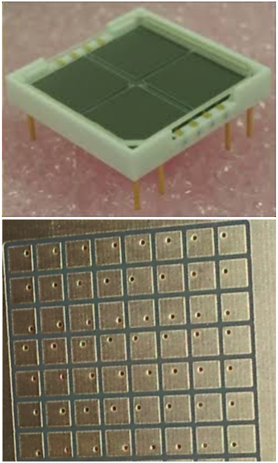
- behind/inside the anode
  → good for wire-based anodes: the “standard” choice
- behind the field cage (which shadows)
  → not available e.g. in ArgonCube resistive cage
- in front of the field cage
  → must not affect the field *and cage*
- in front of the anode
  → must not shadow it
- on the cathode
  → living at 300 kV

Pretty much all these options have been covered by at least one proposal.

Photodetection on the anode: among pixels

Idea: replace a few pixels with photodetectors.

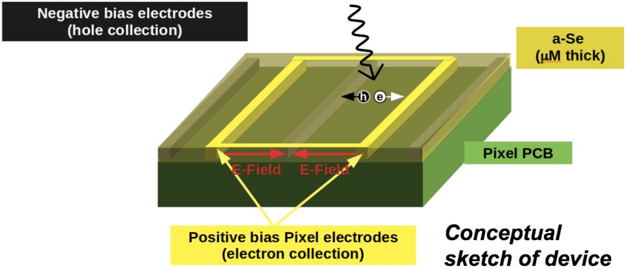
- study carried by the LArPix group
- consider the Efficiency for Detecting the Photons (PDE) which hit the anode surfacel
- have, say, 2% of the anode surface replaced
- use Multi Pixel Photon Counters (MPPC)
  - sensitive to visible, coated with TPB: conversion efficiency 40% $\rightarrow$ PDE 1%
  - sensitive to VUV: conversion efficiency 12% $\rightarrow$ PDE 0.3%
- considering to have LArPix electronics double as MPPC readout (not so for QPix)
- if fast enough (future revision), can be used for light-based self trigger
- tile-wide integration can overcome dark counts



On the pixel readout anode

Idea: install a photodetector *on top* of the pixel.

- idea proposed by the QPix group
- deposit an amorphous selenium thin layer ($\mathcal{O}(100\,\mu\text{m})$)
- also make an electric field happen
- with some back-of-envelop calculation, hope for a few thousand e^- (quantum efficiency $\approx 100\%$, $3\,\gamma$ for $16\,\text{mm}^2$ pixel, gain 10^3)
- not very different from what QPix is used to deal with

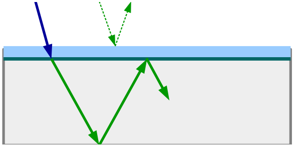


Arapuca

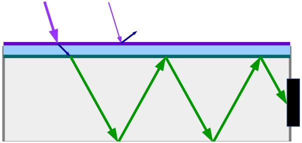
Idea: trap scintillation light for higher photodetection efficiency.

Arapucas are boxes trapping scintillation photons inside:

- paired to a photodetector, they effectively increase its surface
- based on dichroic filters combined with wavelength shifters (WLS)



The principle: dichroic filters are **transparent** *to some wave lengths (say,* 350 nm*), while* **reflecting** *longer wave lengths (say,* 430 nm*).*
After a 350 nm *goes through the dichroic filter, a wavelength shifter turns it into* 430 nm*, and now the dichroic filter is a closed door which bounces it back. As the other faces of the box are also reflective, the photon is now going to bounce in the box "forever".*

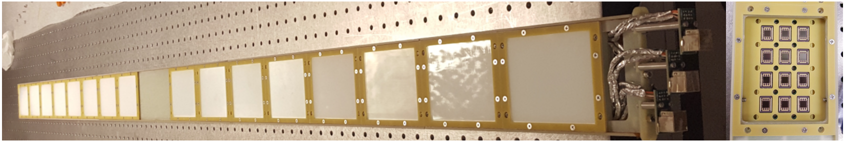


The practice: Ar scintillation light has not the right color, so we make it, by another wave length shifter. We put a photodetector *in the box, and wait for the photon to meet its fate.*

Arapuca in ProtoDUNE

The current implementation of arapuca:

- arapuca inner surface reflection factor is $\mathcal{O}(95\%)$, i.e. most photons are absorbed before the 14^{th} reflection
- boxes are $\mathcal{O}\left(10 \times 10\,\text{cm}^2\right)$
- coupled with Silicon PhotoMultipliers (SiPM)
- succesfully tested in ProtoDUNE:
  - each arapuca has 12 (or 6) SiPM
  - they go in groups of 4 (compromise area with number of channels)
  - a bar accommodates 4 of these groups
- they are the official PDS of the first module of DUNE FD



4×4 arapuca bars used in ProtoDUNE, and the 12 SiPM in one of them.

Arapuca developments

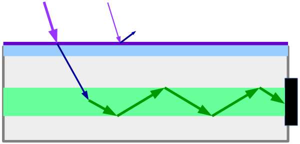
Arapucas technology is still being improved:

- "X-arapuca": second wavelength shifter embedded in a internal light guide
- once photons hit it, they are converted and trapped in the box
- if they are reemitted with high angle, they are trapped *in the guide* and the number of reflections is less

→ either an augmented wavelength shifting guide, or an augmented arapuca

- efficiency: measured $> 3\%$

The "X" in X-arapuca:



In addition to the mechanisms above, if the converted photon is emitted parallel enough to the guide to undergo total internal reflection, it will reflect within and efficiently reach the sensor.
Note that conversion now happens in the bar rather than at the filter.

Arapuca on cathode

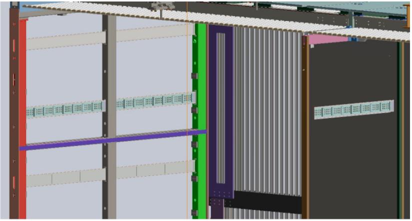
Studying how to mount arapuca photon detectors on DUNE cathode too:

- improves coverage uniformity
- improves absolute coverage

→ how to power? maybe from the first step of field cage

→ how to send signal? maybe convert back to optical and ship it via fiber

→ is the field affected?

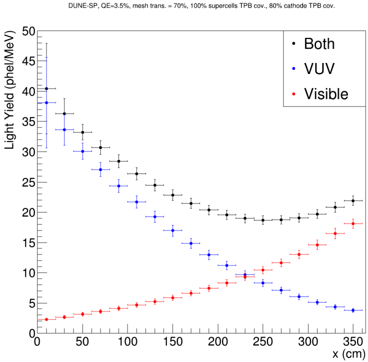


Photon detectors on DUNE cathode: artist impression (a.k.a. GIMP cut&paste).

Reflecting foils

Idea: recover light hitting the cathode bouncing it back to the anode.

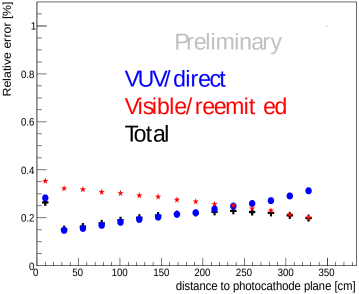
- detection of light far from the PDS (anode) is poor
- covering cathode and/or field cage with reflective foils recovers some
- wavelength shifting to visible is a ticket on a non-stop train to the anode
- tetraphenyl butadiene (TPB), study polyethylene naphthalate (PEN)
- SBND choice: wrap *cathode only*
- ProtoDUNE DP choice: wrap *upper half of field cage* (farther from PDS)

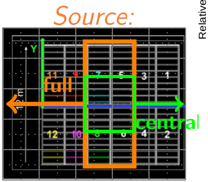


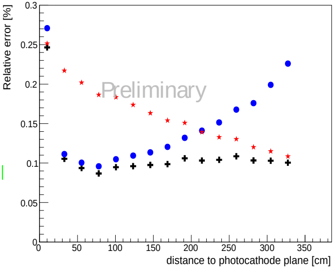
Simulation: photoelectrons detected per MeV vs. the distance of scintillation source from DUNE FD anode.
"VUV" is light reaching the sensors directly, "visible" after reemitted by the cathode (foil coverage: 80%).

Reflecting foils and energy resolution

The additional light can improve energy resolution for soft particles.
Simulation of the fluctuations in the amount of collected light from a point-like 10 MeV source and arapuca PDS (1% efficiency):







uncertainty: ≈ 20%

uncertainty: ≈ 10%

The study (**very preliminary**) shows an improved uncertainty and uniformity.

(study by Diego García-Gámez presented by Andrzej Szelc)

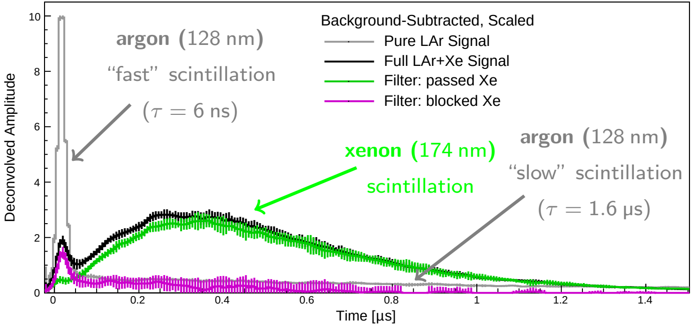
Xenon doping: scintillation mechanism

Xenon doping of LAr introduces a new scintillation energy level:

1. $Ar_2^* + Xe \rightarrow ArXe^* + Ar$
2. $ArXe^* + Xe \rightarrow Xe_2^* + Ar$
3. $Xe_2^* \rightarrow 2Xe + \gamma(174\,\text{nm})$

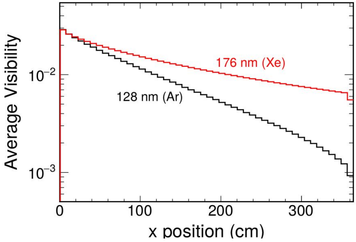
This process happens faster than Ar_2^* triplet decay (1.6 μs). The effects:

- trades "slow" 128 nm photons for "fast" 174 nm light
- kills the fast signal ($\times 0.2$ at 7 ppm):



Xenon doping

- signals from from different sources overlap less
- less Rayleigh scattering ($\lambda_{\mathrm{Xe}} \approx 6\lambda_{\mathrm{Ar}}$) increases visibility at cathode
- Xe^* competes (and wins) with N (impurity that would quench light)



On detection side:

+ photodetector efficiency is better at 174 nm than at 128 nm
− ... but we need two classes of detectors for the two wavelenghts
+ the net effect *is* an increases amount of light collected
  - 100 ppm × 17 kton = 1.7 ton of xenon... (20k\$/ppm)
  - effect on charge needs to be tested
  - it does not freeze... right?

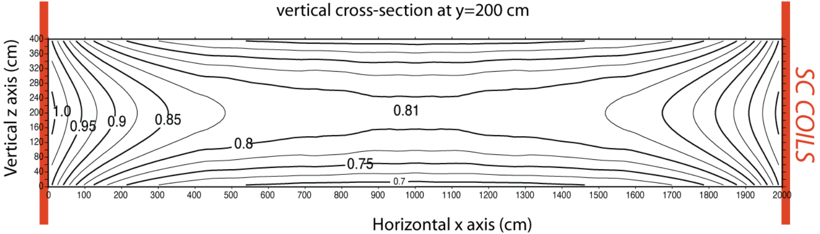
So, Idea: pour 1 ton of xenon into LAr to increase the light collection yield and uniformity.

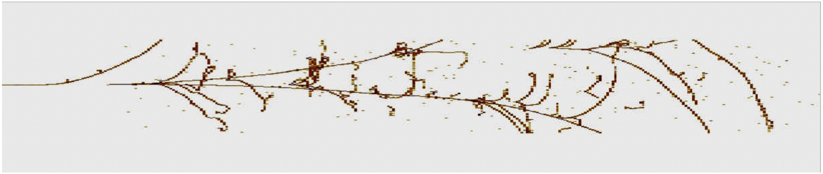
Outline

Magnetisation of DUNE far detector

Idea: use a magnetic field to identify the charge of particles.

- estimate 16 mx16 m 10 kA Helmotz magnets with 80 coils for 1 T field
- uniformity should be better than 20%
- simulations made some time ago with ICARUS detector (below)
- "warm" superconductors (77 K, LN_2) expensive ($\gg 10k$/kA/m)



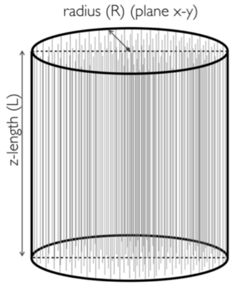


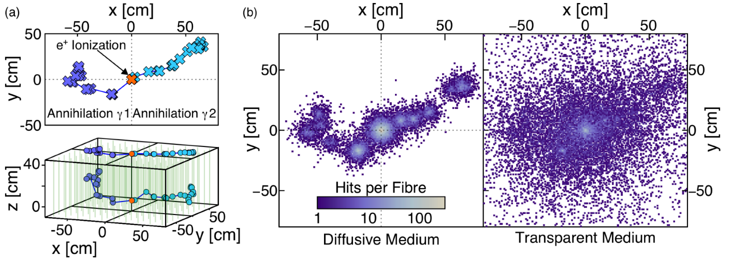
Outline

Opaque liquid scintillator (à la LiquidO)

Idea: imaging via scintillation in opaque medium

- collect scintillation light close to where produced
- opaque scintillation (stocastically) contains the light
- fibers provide 2D imaging (like pixels)
- multiple views (fiber inclinations) and/or two-end readout for the third coordinate

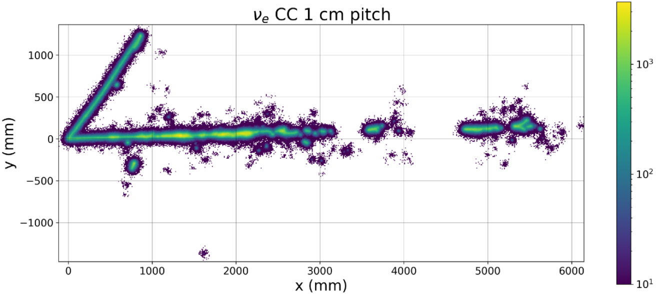


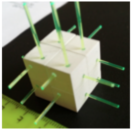


1 MeV e^+ *annihilation (vertical fibres with* 1 cm *pitch; scattering length is* 5 mm*).*

Opaque liquid scintillator: comments

- can measure low energy particles
- two views for 3D: fibers across the 12 m and 14 m directions? (NOνA?)
- for large detectors, it sounds like a mechanical nightmare
- for large detectors, it sounds like a readout nightmare
- DUNE ND solid scintillation detector ("3DST") uses similar principles





An element of DUNE ND 3DST

Water strikes back

Idea: add a complementary detector into DUNE.

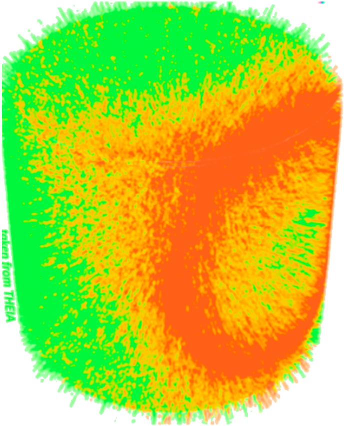


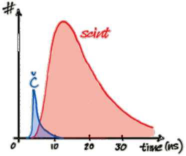
Illustration: scintillation and Cerenkov light in the same event.

- water-based liquid scintillator
- different target, different uncertainties
- complement for supernova neutrino detection ($p\bar{\nu}_e \to ne^+$, "IBD")
- in case of discoveries, compare to HyperK on an equal footing

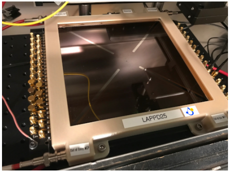
It was called THEIA; DUNE's is THEIA25.

Separate Cherenkov and scintillation light by:

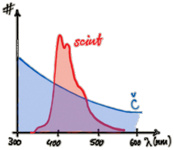
- timing



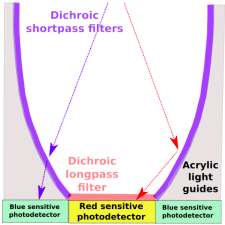
"LAPPD" have sub-ns resolution and large area (tested in ANNIE)



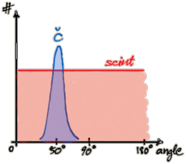
- spectrum



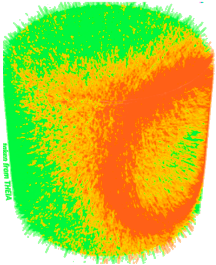
"dichroicons" separate and sample two wavelength bands:



- direction



at reconstruction time



Theia: summary

- proposed $< 20\%$ scintillator
- can accommodate 25 kton of liquid in DUNE cavern (17 kton fiducial)
- coverage:
  - 25% with PMT (10" $\times > 20k$)
  - 3% with Large Area Picosecond PhotoDetectors (LAPPD) ($(20\,\text{cm})^2$ detectors $\times 700$)
- geometry not ideal for beam interactions
- could it arbitrate between DUNE 30 kton and HyperKamiokande divergent results?
- is the solid scintillator in DUNE ND ("3DST") enough for interaction systematics reduction?

Other topics

Other topics included:

- using resistive plate multiplication (S. Bressler)
- reading the light with CCD cameras (A. Nomerotski)
- composite optical detectors to read both visible and UV light (T. Kaptanoglu)
- forecasts for future data acquisition (A. Thea)

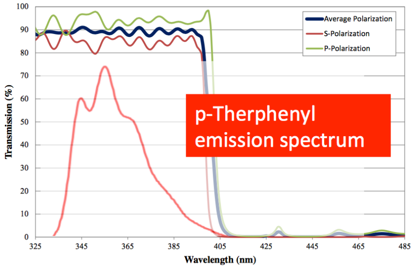
Summary

- the technology choice for the last of the four modules of DUNE far detector is still open
- many proponents, many proposals... which can leverage on each other
- possibly the final design will draw *some* elements from several of them
- funding them will be a relevant aspect of the decisions
- its design needs to be finalised by 2024
- DUNE is set in motion to get the best possible options

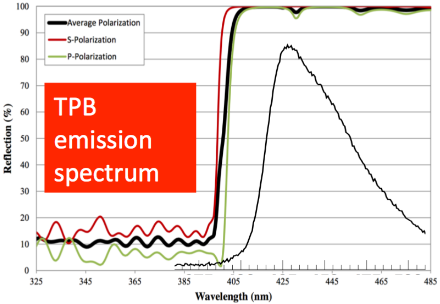
Additional material

Dichroic filter spectra

These are the spectra of dichroic filter and wavelength shifters used in the first incarnation of arapuca (used in ProtoDUNE):



Transmission spectrum of dichroic filter: 90% for $\lambda < 400$ nm; overlapped is the emission spectrum of the outer wavelength shifter (peak: ≈ 360 nm).



Reflection spectrum of dichroic filter: 100% for $\lambda > 410$ nm; overlapped is the emission spectrum of the inner wavelength shifter (peak: ≈ 425 nm).