Novel VUV Light Detection in Pixelated LArTPCs

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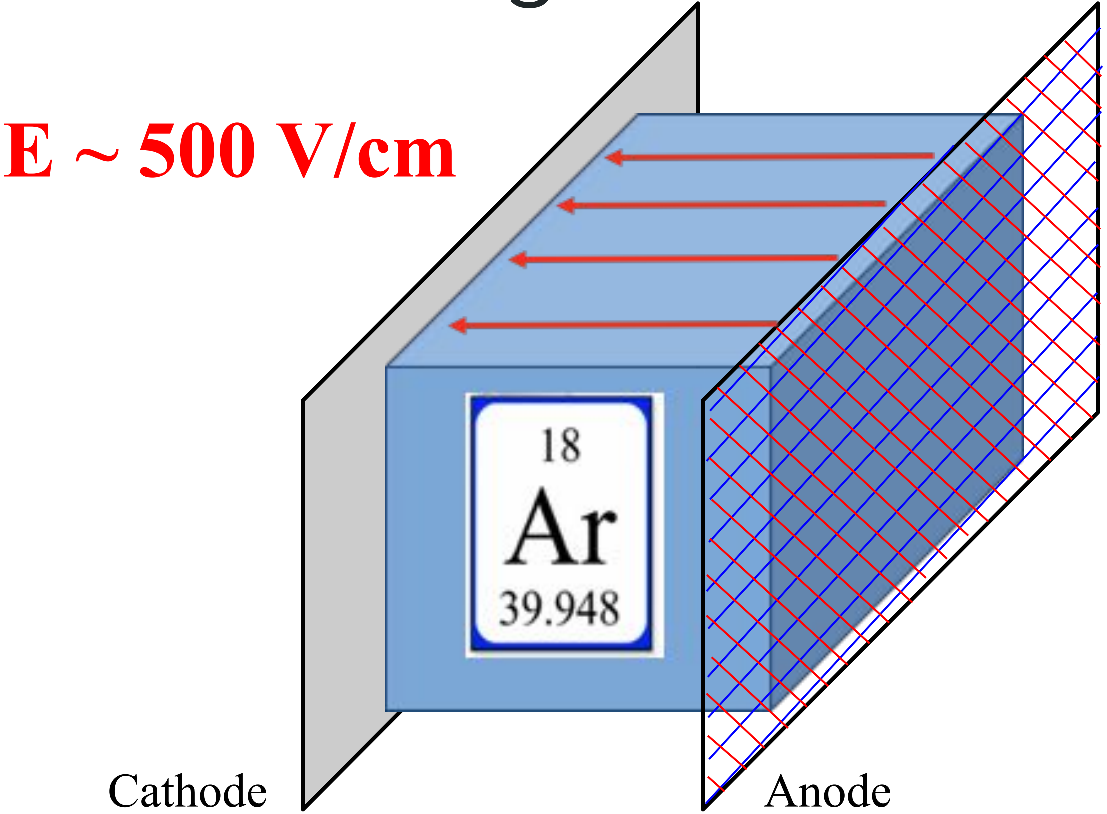
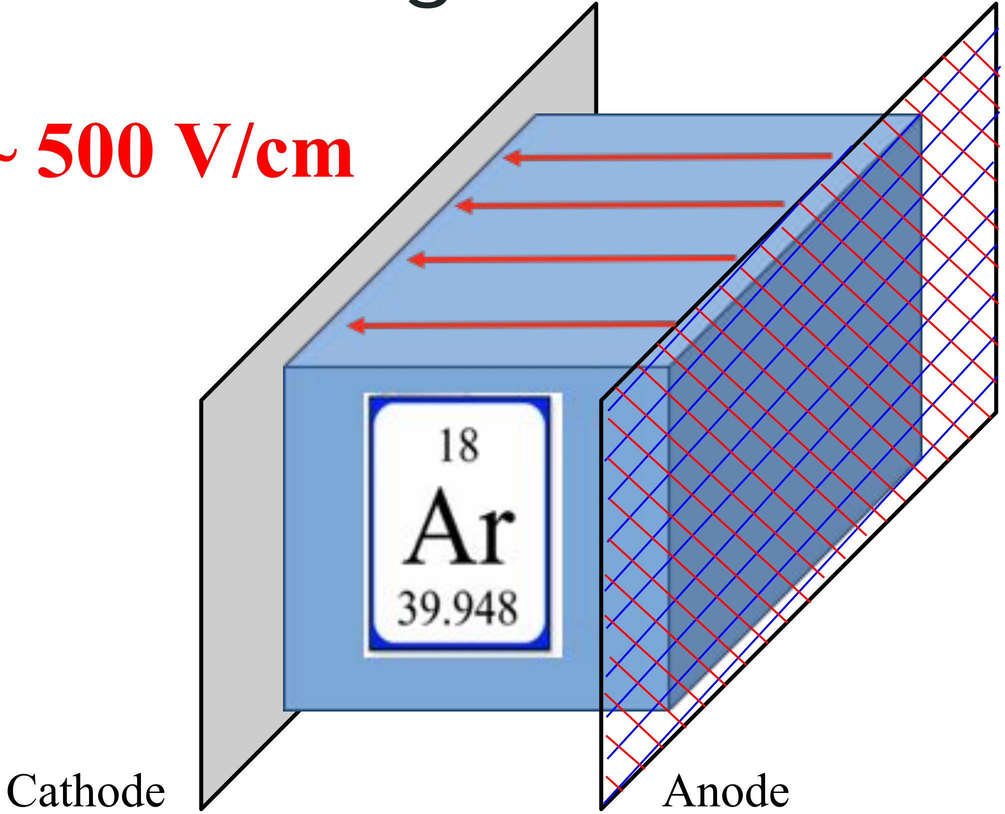
LArTPCs Single Phase w/ wire planes



LArTPCs Single Phase w/ wire planes

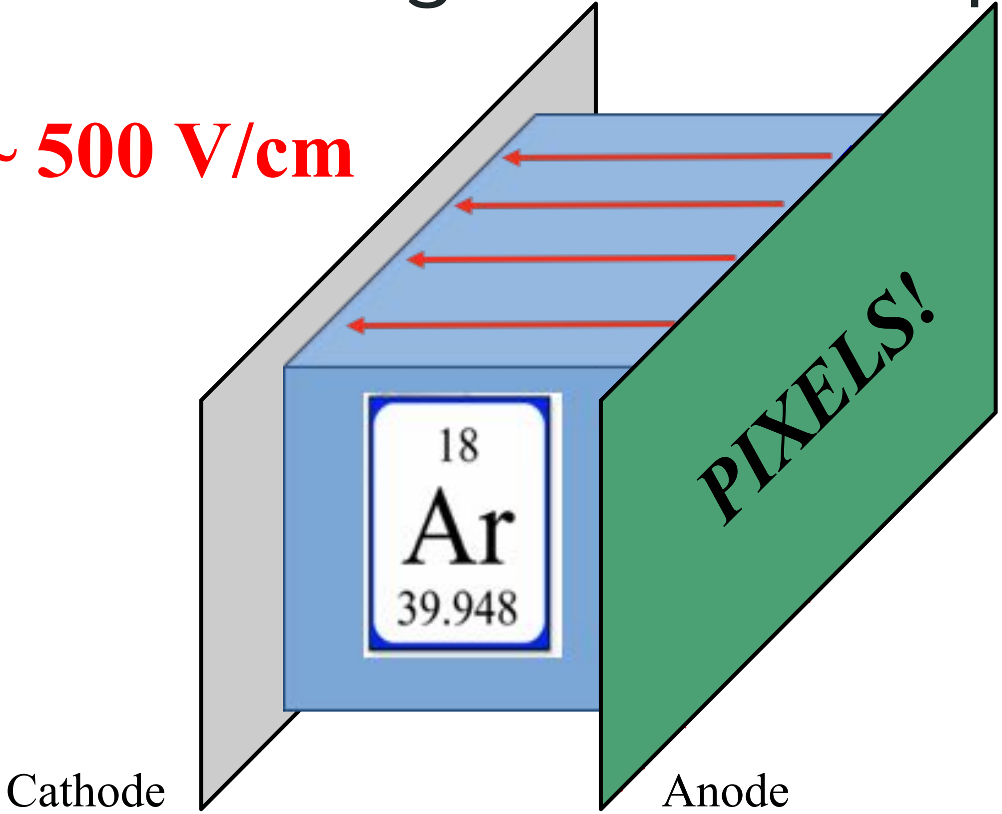
E ~ 500 V/cm



Ar scintillation light
$\lambda = 128$ nm

LArTPCs Single Phase w/ pixels

E ~ 500 V/cm



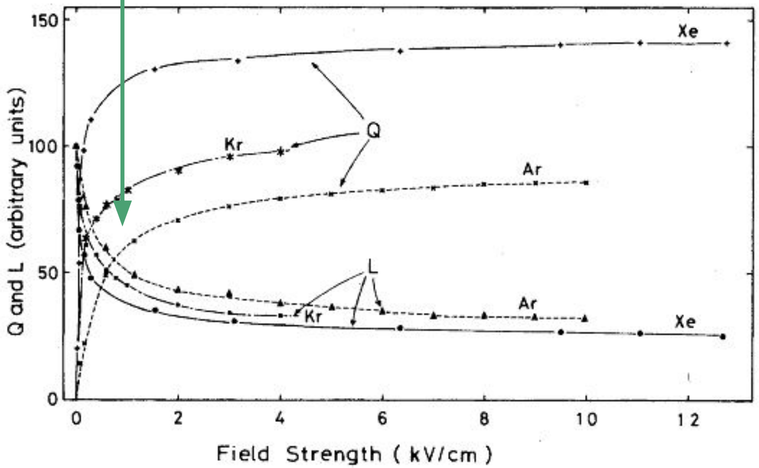
Ar scintillation light
λ = 128 nm
Absorbed by PCB

Why light and charge?

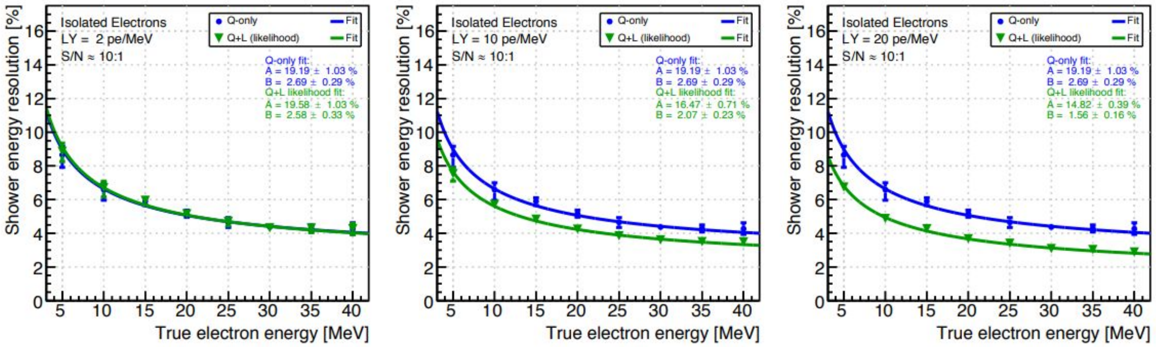
Traditionally used for t_0 and reco in drift direction. At E = 500 V/cm, ½ of half of energy released by charged particle in LAr goes in scintillation light ➡ improvement of energy resolution with light augmented calorimetry.

DUNE LIVES HERE!

Phys. Rev. B, vol. 20, no. 8, p. 3486, 1979



LArIAT arXiv:1909.07920



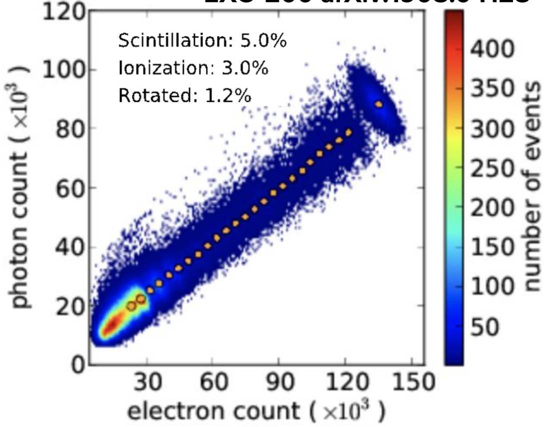
S/N ~ 10

LY = 2 pe/MeV

LY = 10 pe/MeV

LY = 20 pe/MeV

EXO-200 arXiv:1908.04128



What if the whole APA could collect light?

A plane sensitive to UV photons and ionization charge SIMULTANEOUSLY would be a major breakthrough

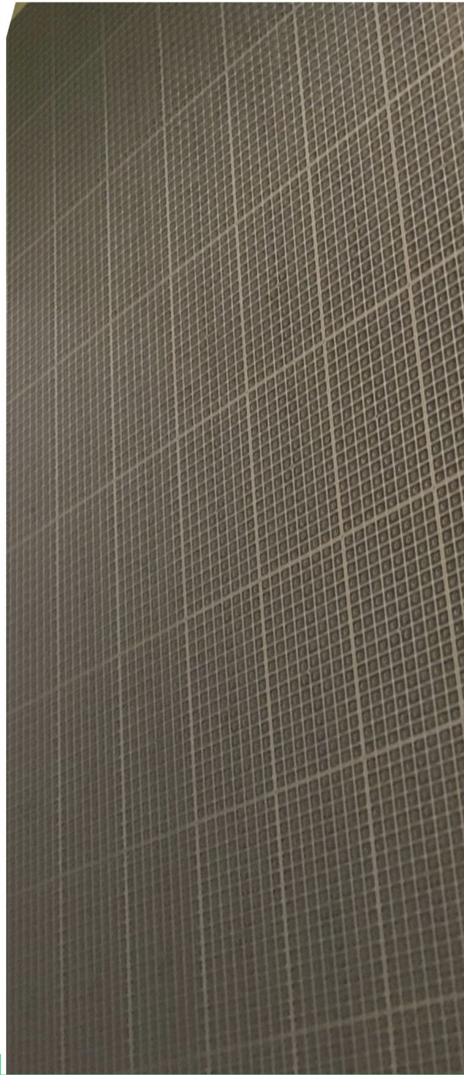
Your effective instrumented area becomes enormous: 100% anode surface

Even if the device has low efficiency you have a huge gain

Quick anode area coverage comparison (geometry alone):

SBND ~50% DUNE ~0.07%

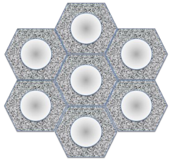
Note: The ideas proposed here have the potential for quite good UV photon efficiency



Unorthodox charge readouts need unorthodox light solutions.

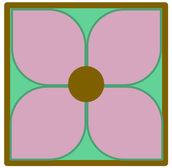
Dual purpose pixels

Nanoplatelets.



Perovskite.

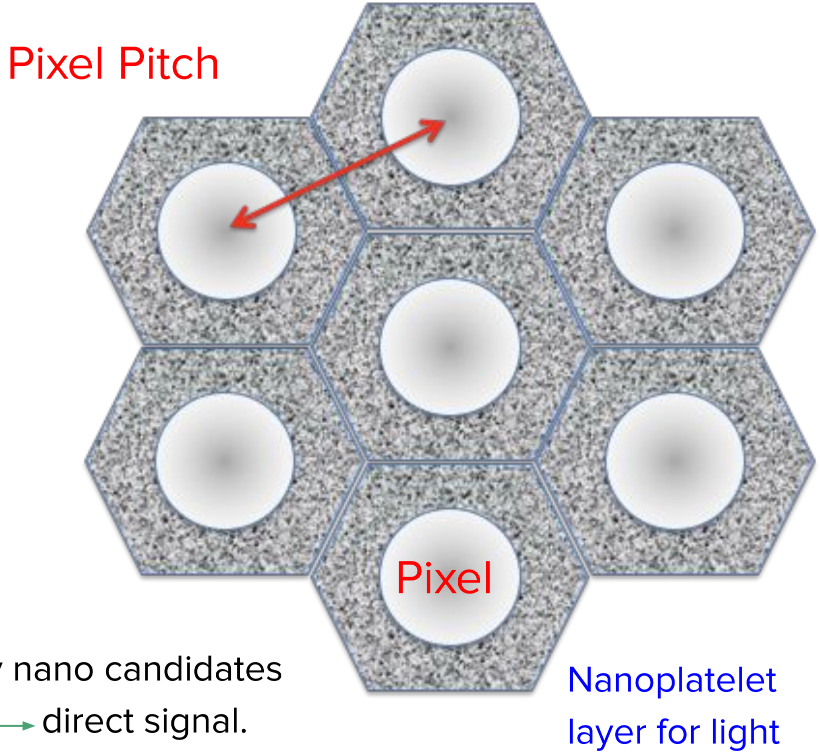
Amorphous Selenium.



Nanoplatelets

The charge collection pixels are isolated using the photon sensors.
The pixel plane is made of a substrate material with nanoplatelets deposited on the substrate,
readout on the back side (outside of TPC)

Nanoplatelets absorb VUV photons, generate electrons: direct conversion of photons to current.



Current SBIR grant with CapeSym, Inc.(8/19–4-20) to identify nano candidates sensitive to 128 nm and 175 nm → form into nanoplatelets → direct signal.

Doping Argon with hundreds of ppm Xenon converts all 128 nm light to 175 nm – may already have suitable candidates to start incorporating into nanoplatelets

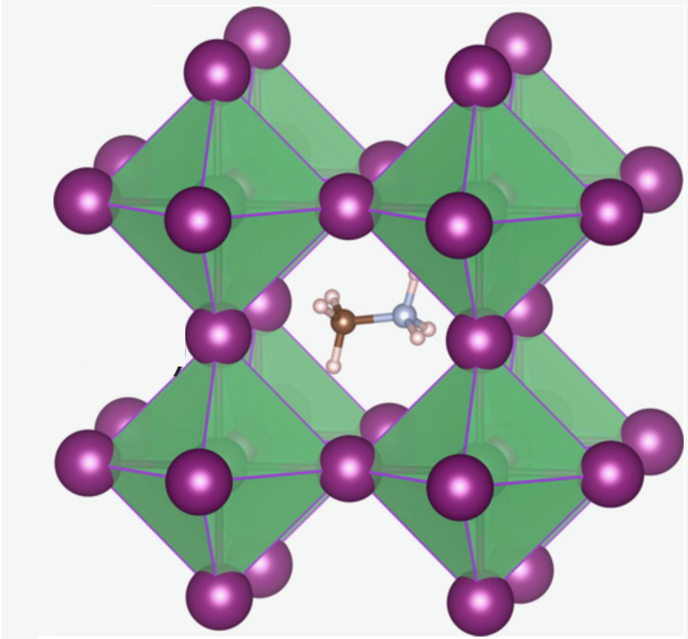
from Steve Magill, ANL.

Perovskites

Perovskites are a potentially very interesting candidate for UV photodetection.
Perovskite: specifically $CaTiO_3$ but used as a generic term for any material with the same crystal structure.

Possible base material for high-efficiency photovoltaics: Methylammonium halides are being studied for their high charge carrier mobility.

Most perovskites have poor UV performance but studies have extended useful range into DUV (200-350nm).



Methylammonium lead triiodide

from Bob Wagner, ANL.

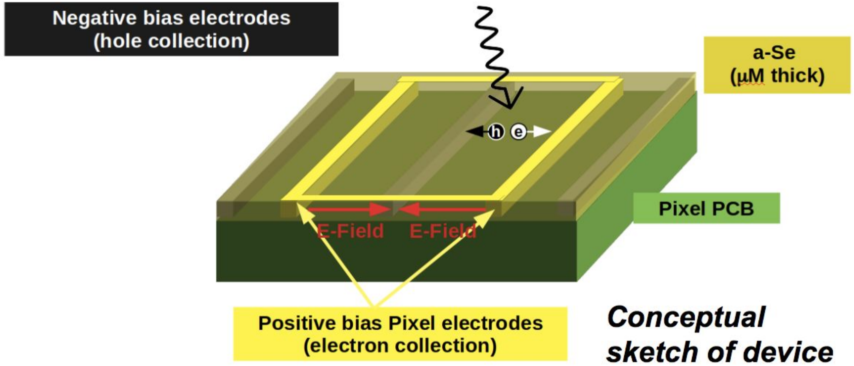
Amorphous Selenium Pixel

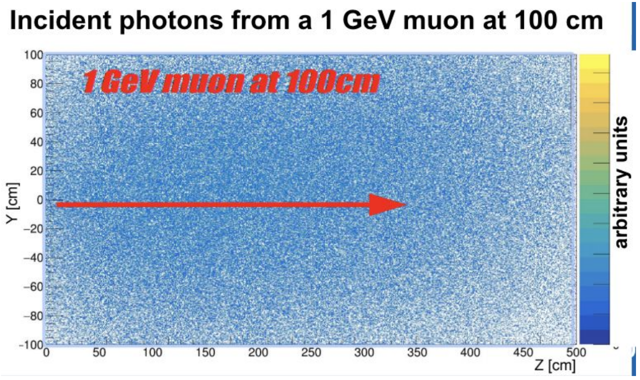
Pixel coating with photo-conducting material: can the pixels collecting ionization charge be used to detect UV photons?

Currently exploring different thin-film photo-conductors which may offer an opportunity

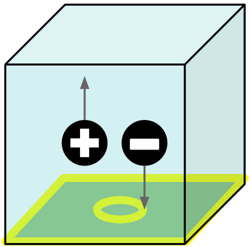
Exploring amorphous Selenium's properties

- Commonly used in X-Ray digital radiography devices



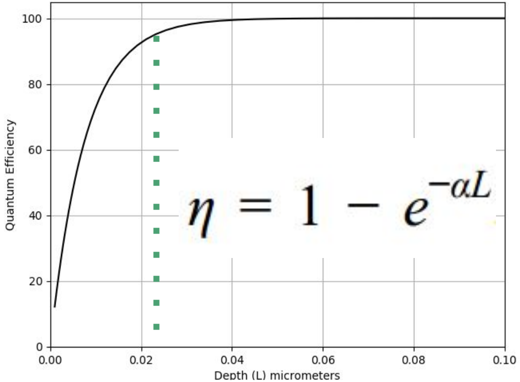


Why is A-Se interesting?



Assume you can apply a uniform electric field on a block of a-Se some micrometers thick where the electron-hole pair is being created.

To figure out the charge produced, you need to know how thick a layer of amorphous selenium will give you a high QE for the single photon of the right energy ➔ Absorption coefficient!



The literature on amorphous selenium reports an attenuation coefficient α ~130 μm^{-1} for photons at 128 nm, resulting in a **QE than 99% for thin coatings (> 1 µm) .**

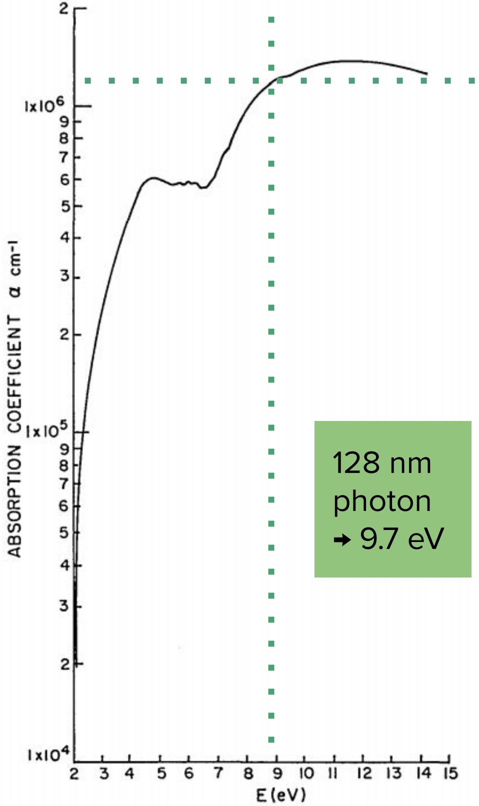


FIG. 6. The spectral dependence of the absorption coefficient, α, of amorphous selenium.

What about the signal? Estimate summary

The amount of charge deposited into the a-Se is given by → $$\Delta Q = q \frac{\Delta E}{W_\pm},$$

where q is the fundamental charge of the electron, and $W_\pm$ is a property of the mobility of A-Se which depends on the electric field and (favorably) on the temperature ($W_\pm$ = 7.07 eV). ΔE is the amount of energy absorbed. In a single 4mm by 4 mm pixel, a reasonable assumption for ΔE is 26.46 eV... You start with ~ 3 photons per pixel at 9.7eV / photon and 0.9 QE.

So, transport in the A-Se ΔQ ~ 26.36/7.07 which means that:
3 photons coming in and 3.7 electrons going out.

At the theoretical breakdown voltage of a-Se (~ 90 Volts/μm)
for 100 μm thick deposition ➜ gain factor up to ~1.5 10^3:
~ 4000 electrons for three 128nm photons on a 4mm pixel pad.

These numbers would be very consistent with the current Q-Pix design choice of being between 0.3 and 1 fC (1800 and 6000 electrons) for a RTD (Reset Time Difference).

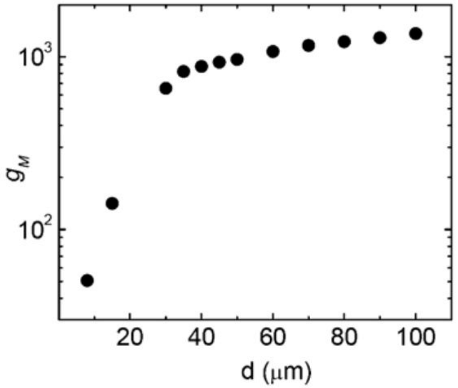


Figure 10 Maximal achievable multiplication gain for different a-Se layer thicknesses.

Modeling of A-Se to understand optical properties w/ VUV light

Professor Muhammad Huda at UTA (condensed matter theorist) has started an A-Se model to better understand and predict the A-Se optical-electronic properties when exposed to 128 nm photons.

The basic approach is Generalized Gradient Approximations in Density Functional Theory, w/ incremental approximations to capture experimentally measured properties via phenomenological models. A promising way to reduce the breakdown voltage is the use of dopands, whose effects can be studied within the constructed model.

A first, crude version of the simulation show a qualitative agreement for the VUV energy region between old data... off to a good start, but... we need more experimental data!

A proposal to build first prototypes that can feedback into this studies has been submitted to FNAL.

LILAr

Potential of Dual Purpose Pixel Solution

The photocathode coverage is close to 100% by construction: by coating or engineering all the anode pixels, the photocathode coverage coincides with the anodic plane coverage.

Absorption of direct VUV light removes any hit in conversion efficiency taken in technology based on wavelength shifting.

If we can achieve gain multiplication in the A-Se, a very high QE is expected (>90%).
Extremely high granularity built in by construction: basic light detection unit 4 by 4 mm.

A study of A-Se absorption in the visible would also be interesting to improve homogeneity in the detection along the drift direction.
A solution including reflective foils at the cathode could be explored.

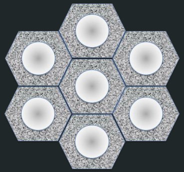
QPix

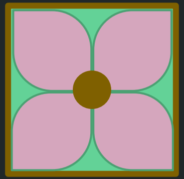
The QPix consortium is exploring pixel based solutions for Kiloton scale LArTPCs:

> a dual purpose pixel sensitive to both light and charge will expand the physics reach of such a detector by means of (at least) light augmented calorimetry.

Exploring “blue sky” ideas for both light and charge ideas to design a discovery machine.

Q-Pix consortium would like the thank the DOE for its support via DE-SC0020065 award





Thank you

ANL UV conversion material research

Ongoing program to develop nanoparticle wavelength shifters tuned to specific absorption wavelength and emission wavelength.

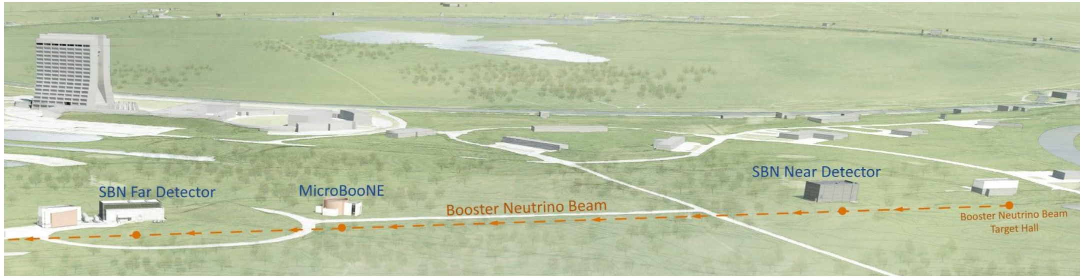
Goal: identify nanoparticle for detection of light at 128 nm and 175 nm (Argon & Xenon) and study applicability to both neutrino and DM experiments.

ANL role: test candidates and characterize in terms of absorption, wavelength-shift size, emission.

Research on materials for direct conversion of UV to electron/(holes) draws on expertise of Argonne Materials Science Division (MSD). Specifically, Alex Martinson (MSD) has experience from solar conversion materials and optoelectronic processes. He is providing 20% of his time researching materials and processes specific for liquid argon UV detection.

Stolen from Bob Wagner, ANL.

SBN(D) as light testbench



The revamping of **ICARUS** included potentiate the light collection system (more PMTs).

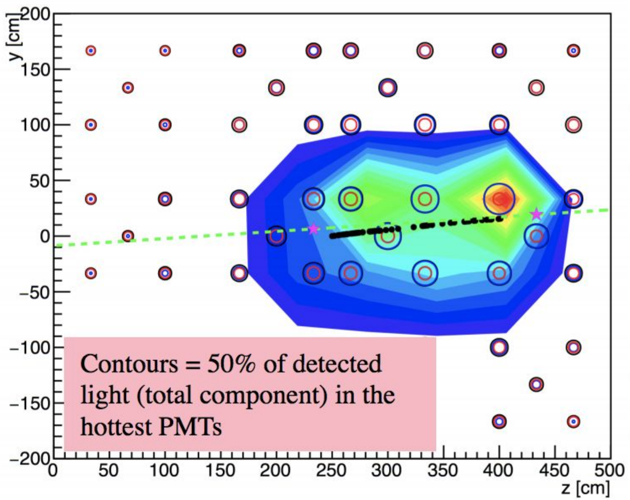
MicroBooNE's PDS original design was focused on triggering on the light… now timing and positional information from the PDS is also used for cosmic discrimination at analysis level.

SBND is going to be the cadillac of PDSs in current large LArTPC generation:

- high granularity: o(100) ARAPUCAs + 120 8'' PMTs
- high coverage (sensitive elements cover ~50%)
- foils for reflected light (position resolution from timing).
- Simulation results: 40 cm position res w/ PMTs alone

Is this the way to light semantic segmentation?

D. Garcia, Lidine 2017

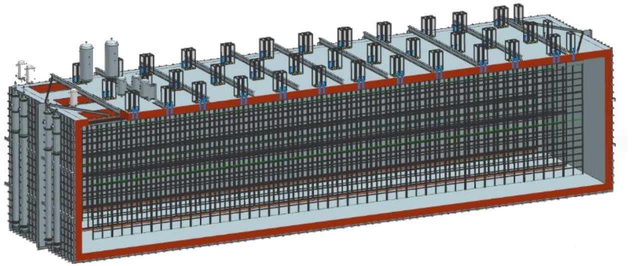


Light Requirements for DUNE

Description	Specification (Goal)	Rationale
Light Yield	> 0.5 PE / MeV (min)	>99% of nucleon decays can be tagged
Time Resolution	< 1μs	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.

Thoughts on current design



Limited real estate for Light Collection System.

How much of the available APA has photon detection capability?

X-Arapuca Design: **130 m^2/10kT**

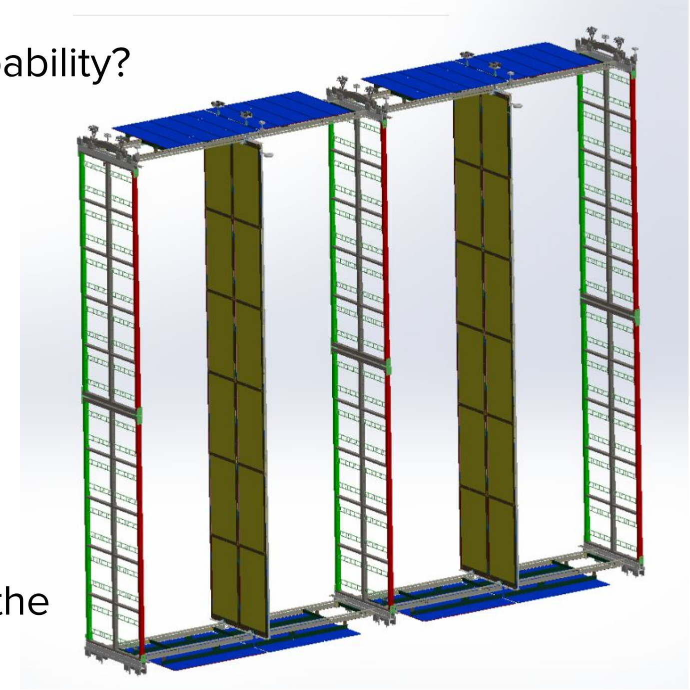
Window area for each supercell (435.24 cm2) x 10 supercells/APA x 152 APA's per 10kT x 2 (Double sided)

APA Active Area: ~200000 m^2/ 10kT

(135,700 cm2) * 152 APAs/10kT

Surface area instrumented is ~ 0.06%

- It is actually effectively less when you take efficiency of the device into account



****** Not meant to disparage the current technology in any way...instead meant to give context to the problem***