ECFA

European Committee for Future Accelerators

UNIVERSITY OF LIVERPOOL

Noble Liquids Properties

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ECFA Roadmap Process Liquid Detectors, April 9th 2021

Outline

- LAr and LXe Properties
- LAr VUV scintillation light
- Xe doping to increase and wavelength shift S1
- LAr NIR
- Superradience LXe
- High Voltage -in particular for dual phase
- Radiopurity
- Underground calibration

Working with LAr and LXe

- Liquefied noble gases intrinsic properties are ideal for neutrino and Dark Matter detectors.
- The combination of their scintillation properties, the high ionisation yield and the fact that the ionisation electrons released remain free to drift across long distances favourably distinguishes these liquids from other dense detector media.
- Another notable property of the ‘noble liquids’ is the possibility of extracting electrons to the gas phase, where the ionization signal can be amplified through secondary scintillation or avalanche mechanisms.

Working with LAr and LXe

https://lar.bnl.gov/properties/

Property	Argon	Xenon
Atomic No. (Z)	18	54
Max recoil energy (% of incident n energy)	9.5	3.0
Boiling point	87.3	165
Density (g/cc)	1.4	3.0
Electron mobility (cm2/v*s)	400	2200
Ion drift velocity at 1kV/cm (mm/µs)	2.2	2.4
Energy resolution (FWHM@ 662 keV) scint. only (%)	8%	8%
Scintillation wavelength (nm)	128 (WLS /doping) also NIR	175 (UV quartz PMT window)
Scintillation yield (photons/MeV)	40000	42000
Fast decay time (ns)	7 (25% light)	4.3
Slow decay time (ns)	1500 (75% light)	22 (100% in ≤ 22 nm)

Working with LAr and LXe

https://lar.bnl.gov/properties/

Property	Argon	Xenon
Superradience	to be discovered	to be discovered
Dielectric constant ε	1.505	1.85
Break down voltage (kV/cm)	40 -100 (depends on purity, stressed electrode area, pressure)	40-100 (depends on purity, stressed electrode area, pressure)
W value for ionization (eV/pair)	23.6	15.6
Rayleigh scattering length (cm)	54	36
Radiopurity	^{39}Ar 1Bq/kg (need depleted for DM)	^{136}Xe < 10uBq/kg
Cost ($/kg)	≈ 2.0	≈ 1500
Availability	Abundant (1 % in atmosphere)	limited

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Working with Cryogenics at the large scale

- Accurate liquid leveling in particular for dual phase detectors
- Large cryostats and stable cryogenic operation
- Purification and recirculation system to achieve <1 ppb electronegative impurities

See Christian's talk

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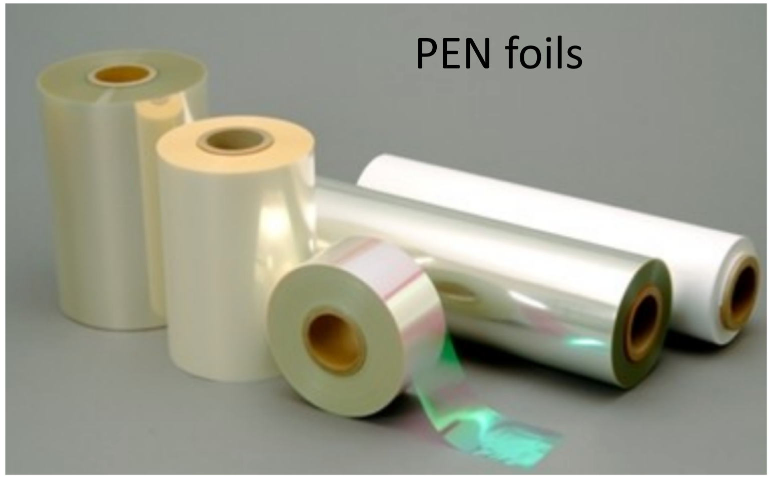
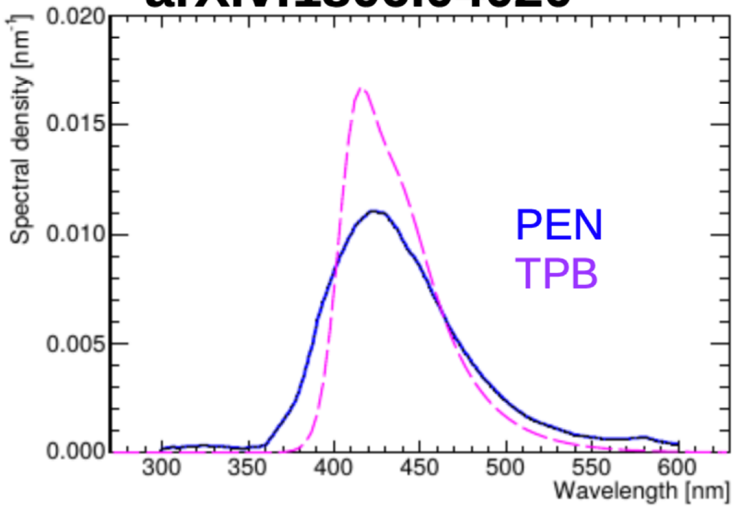
VUV scintillation and WLS

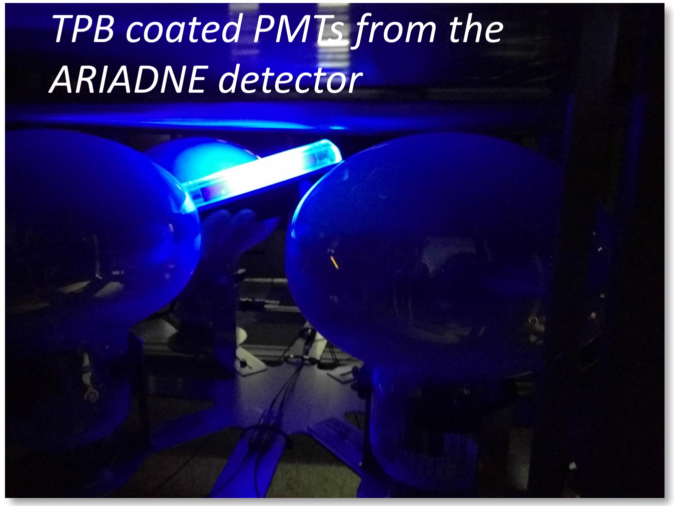
- LAr very efficient Pulse Shape Discrimination (PSD) due to the significant difference in relative intensities of the fast and slow components
- Disadvantage comes from the wavelength of scintillation lies in the VUV range
- A common and convenient solution of this problem is to use wavelength shifters (WLS) and more recently PEN foils

(See also Giuliana's talk)



arXiv:1806.04020





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VUV scintillation and Xe doping

- WLS is convenient but it has some issues as well:
  - Low geometrical efficiency
  - Sensitivity to mechanical stress
  - Scattering and re-absorption of the re-emitted light inside the WLS layer
  - Dependence of the WLS efficiency on the coating method

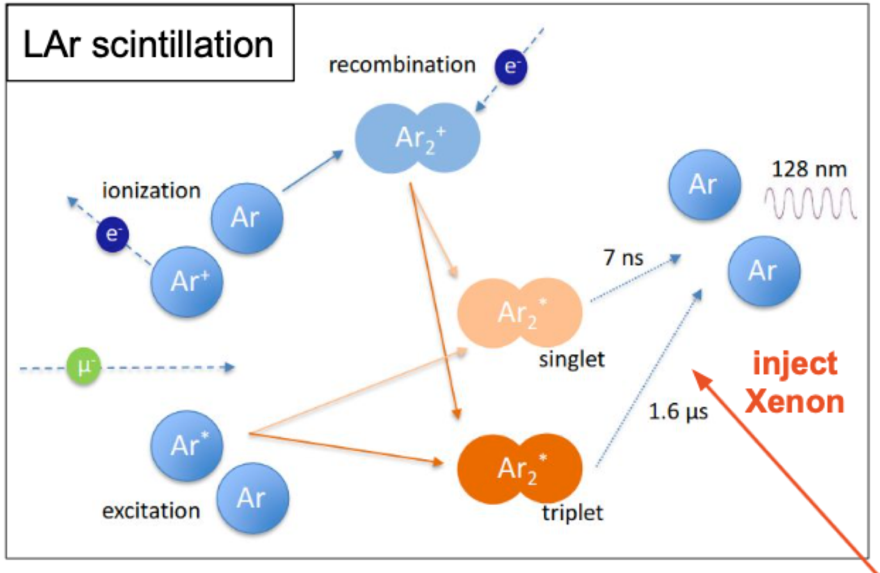
(PEN foils perhaps solves this)

Xenon doping

Shift 128 nm wavelength to 175 nm

- More uniform light distribution
- Increase light yield and detection efficiency
- Possible mitigation for N_2 contamination

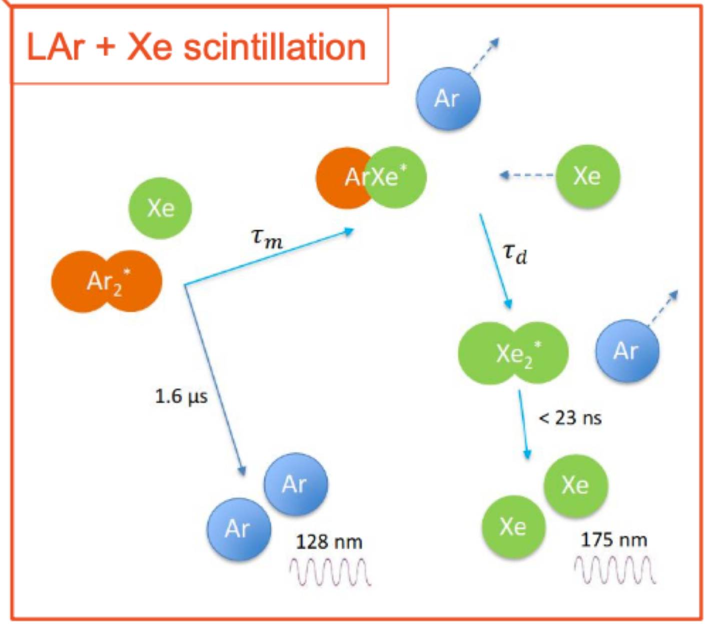
VUV scintillation and Xe doping



- The excited atoms often bond with ground state atoms to form metastable molecules known as excimers that then decay, emitting scintillation at 128 nm
- The ions can recombine with electrons to form excited atoms, in turn producing excimers and then scintillation light at 128 nm

With the presence of Xenon

- The excited Ar dimer may interact with Xe and forms excited ArXe* molecule
- The time scale of ArXe* creation τ_m depends on Xenon concentration
- The excited ArXe* dimer can interact with Xenon creating a Xe_2^*. Time scale for this process τ_d depends on Xenon concentration as well
- Eventually, Xe_2^* de-excites and creates 175 nm light



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VUV scintillation and Xe doping

ProtoDUNE-SP had successful Xe-injection

- In total 13.5 kg of Xe, 18.8 ppm in mass, injected into the cryostat
- The effects of N_2 contamination has been recovered with a small amount of Xe
- At ~10 ppm level, LAr slow component has been fully converted into Xe light
- 1.7 - 2 times increase in the total collected light has been observed

- What further steps need to be done to decide on Xe doping as a baseline for LAr neutrino detectors?
- How is the PSD effected with Xe doping ?

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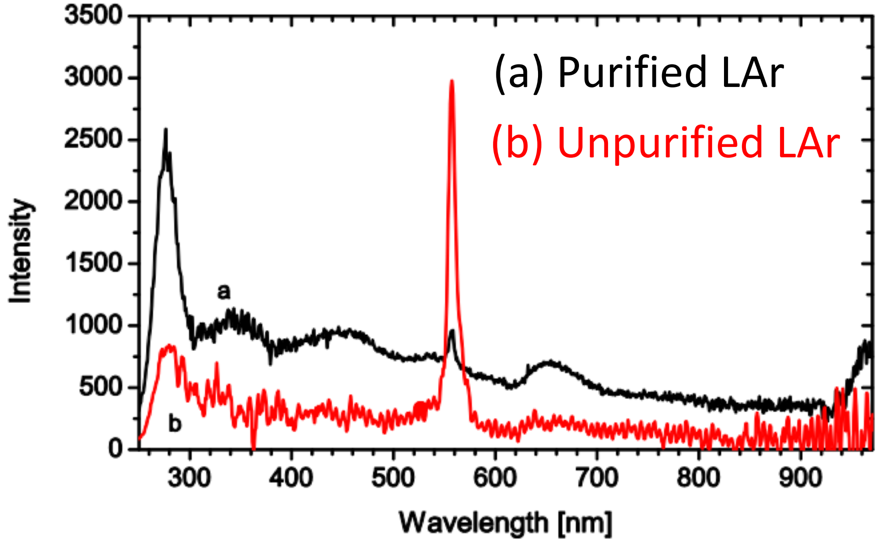
LAr NIR light

- NIR light could also potentially provide an alternative to the challenges faced by VUV
- Need further accurate determination of NIR Light yield (current results indicate 500 photons/MeV)
- Discrimination ability?

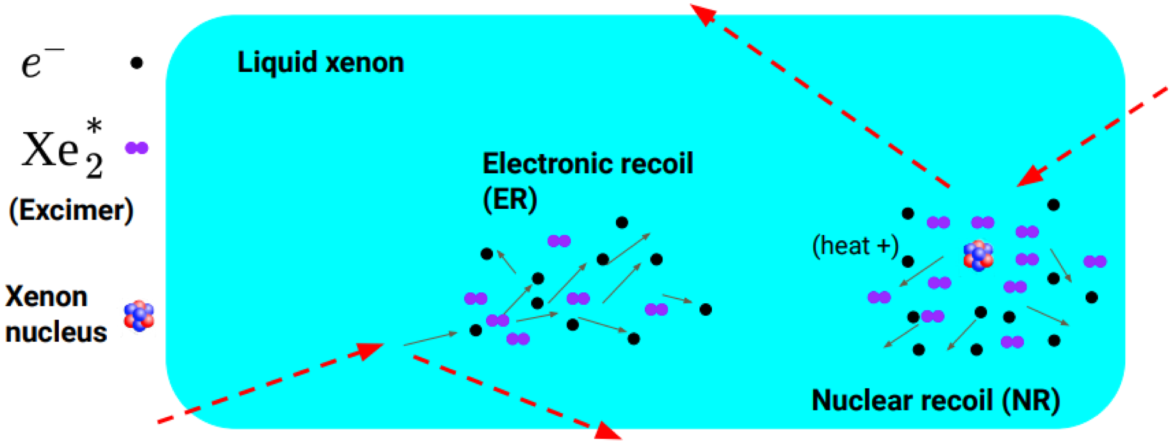
C. Escobar *et. al*
https://arxiv.org/abs/1803.01886

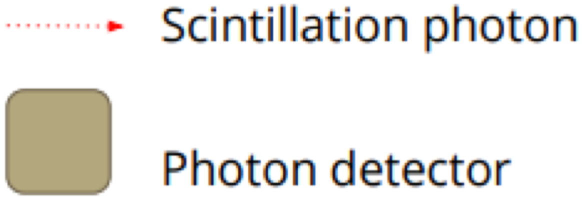
A. Bondar *et. al*
https://arxiv.org/pdf/1204.0180.pdf

T. Heindl *et al*
https://arxiv.org/pdf/1511.07720.pdf

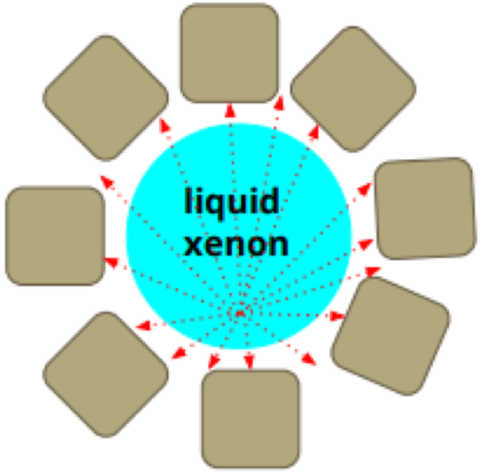


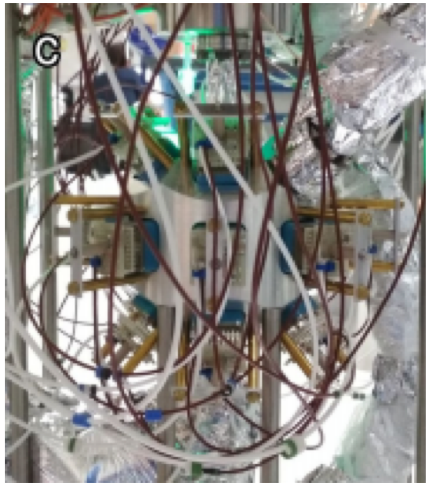
Directional and temporal pattern of scintillation from LXe



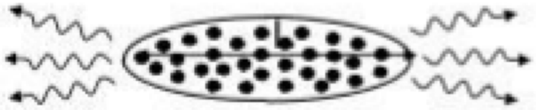


DireXeno





- **Objective**: studying the temporal and directional scintillation pattern from liquid xenon.
- **Method:** Estimate each photon's time of emission and its direction.
- **Goal:** Produce an accurate scintillation model.
- **Discover:** hypothetical Superradiant emission where there is a directional correlation between the photons on a sub ns scale.



Superradiance, T<1ns.

https://indico.cern.ch/event/981296/contributions/4140628/attachments/2166071/3655840/DireXeno.pdf

https://arxiv.org/abs/1909.08197

Property	Argon	Xenon
Dielectric constant ε	1.505	1.85
Break down voltage (kV/cm)	40 -100 (depends on purity, stressed electrode area, pressure)	40-100 (depends on purity, stressed electrode area, pressure)

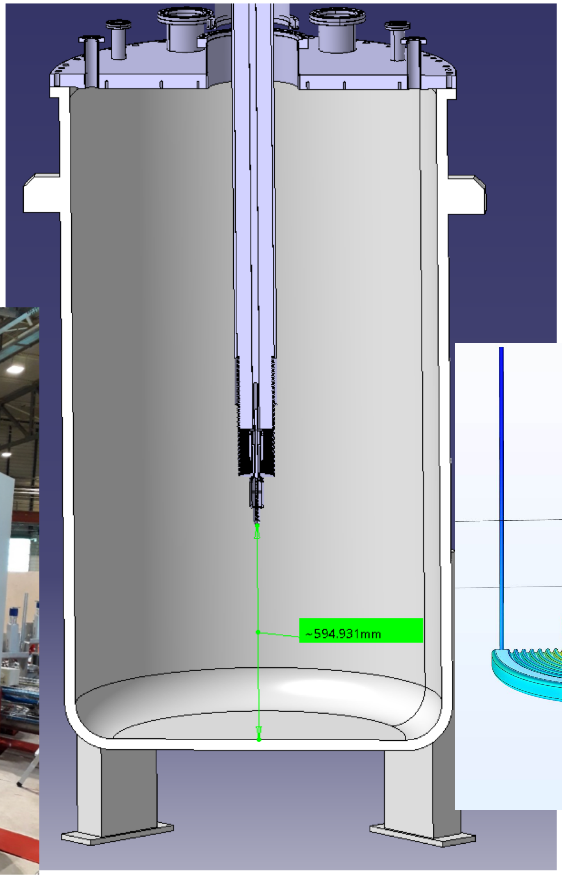
https://arxiv.org/pdf/1908.06888.pdf

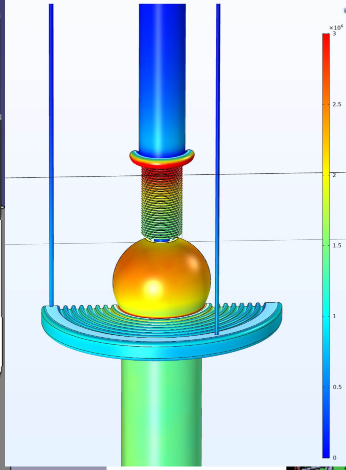
High Voltage

- In order to drift at 0.5kV/cm over 12 m you will need 600kV at the cathode!
- Need to develop new HV FTs
  (For DM an extra challenge is radiopurity)
- Power supplies currently limited to ~350 kV

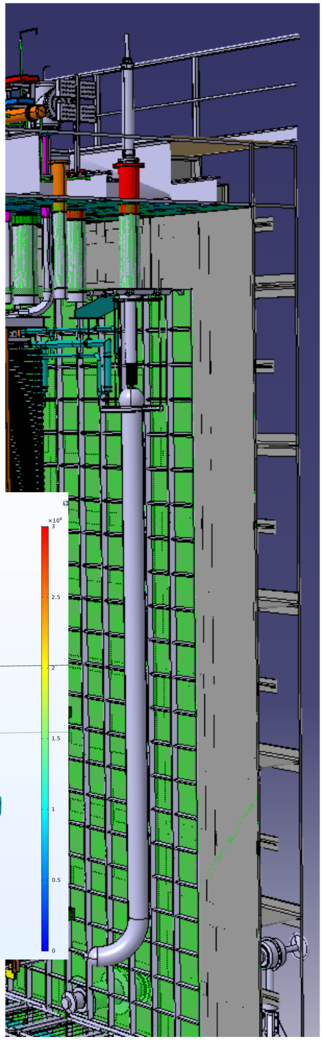
- Is it an intrinsic show stopper for 600kV?
  (If achieved you gain a lot of detector volume)
- How Xe doping influences break down voltage?

Planned HV tests @CERN NP





ProtoDUNE



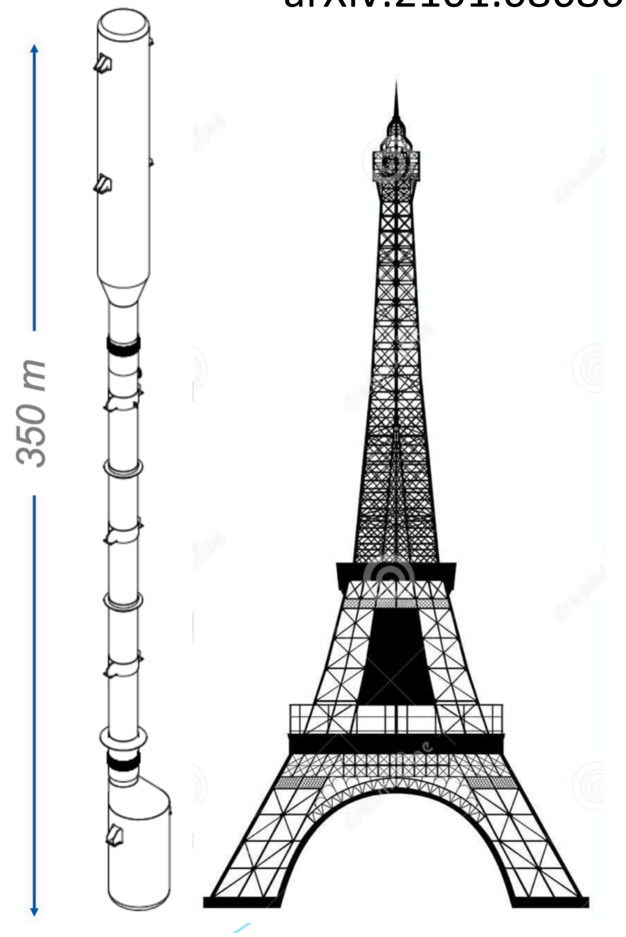
Property	Argon	Xenon
Radiopurity	^{39}Ar 1Bq/kg (need depleted for DM)	^{136}Xe < 10uBq/kg

arXiv:2101.08686

Radio-Purity

See Christian's talk

- Underground Argon -UAr
- ARIA project (Darkside Collab.), production of depleted argon, below the UAr levels
- ^{39}Ar is background for dark matter but may be useful for energy calibration for LAr neutrino detectors



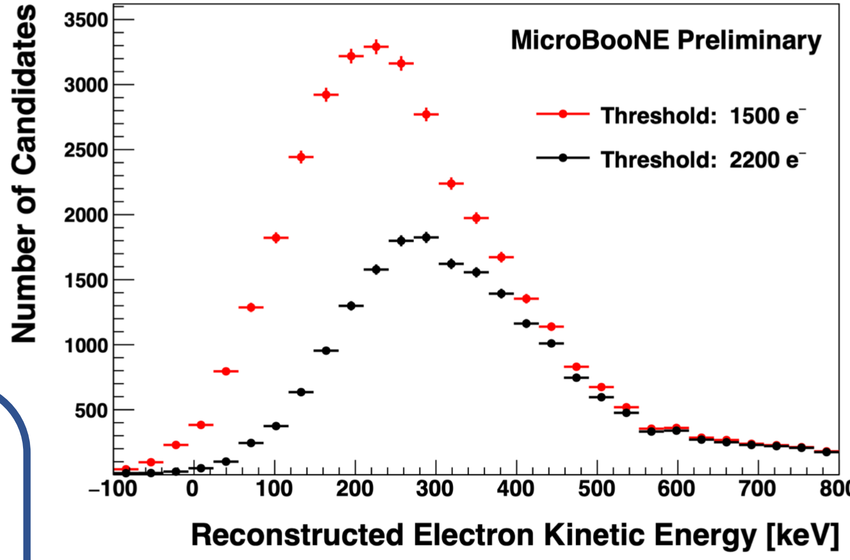
ARIA -distillation column

Property	Argon	Xenon
Radiopurity	^{39}Ar 1Bq/kg	^{136}Xe < 10uBq/kg
W value for ionization (eV/pair)	23.6	15.6

Calibrating Large detectors Underground

Very few cosmics need alternatives!

MICROBOONE-NOTE-1050-PUB



^{39}Ar

- β-decay with Q = 565 keV
- well defined spectrum = "standard candle"

Pros:

- High statistics
- Uniform
- Sensitive to:
  - e^- lifetime
  - Recombination

Cons

- Low energy only
- Unknown position in drift direction
- Triggering/DAQ

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W value for ionization (eV/pair)	23.6	15.6

Calibrating Large detectors Underground

Very few cosmics need alternatives!

- Neutron anti-resonance at 57 keV → LAr nearly transparent → travel far
- Neutron capture: n + ^{40}Ar → ^{41}Ar + 6.1-MeV γ's

(dedicated measurements at Los Alamos ARTIE)

DD pulse neutron generator

Pros:

- Triggered
- High statistics

- Neutron capture
- γ energy scale + resolution
- *e* lifetime (to be investigated)

Cons

- Non-uniform coverage

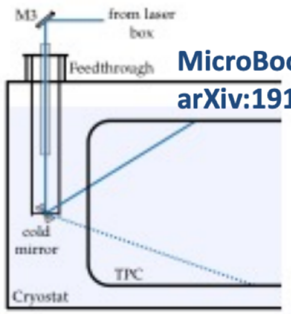
Property	Argon	Xenon
W value for ionization (eV/pair)	23.6	15.6

Calibrating Large detectors Underground

Very few cosmics need alternatives!

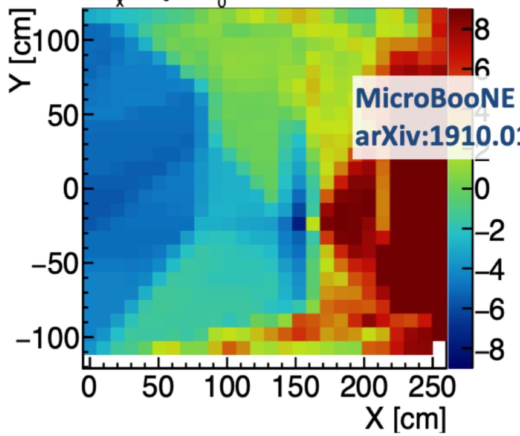
LASER (Multiphoton Ionisation)

Tested with MicroBooNE and planed for the ProtoDUNE Run2

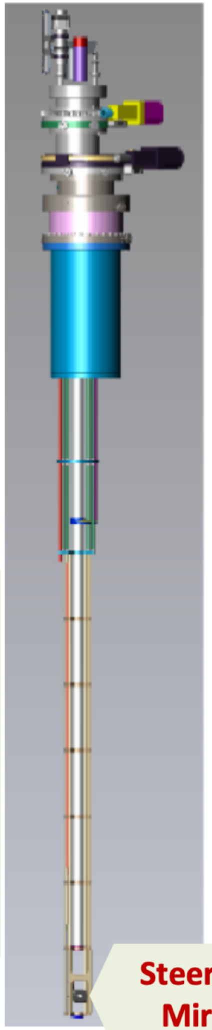


MicroBooNE arXiv:1910.01430

E-field distortions



MicroBooNE arXiv:1910.01430



Precision rotation and translation + laser interface

Retractable periscope

Steerable Mirror

Pros:

- High statistics
- Well defined tracks
  - E-field
  - Alignment
  - e^- lifetime

Cons:

- Need many periscopes to get full coverage
- Design difficulty

Moving forwards –Provocative questions

- What further steps need to be done to decide on Xe doping as a baseline for LAr neutrino detectors?
  - Do we understand if the Pulse shape Discrimination will be compromised?

- Do we fully understand the exact conditions/environment for the breakdown voltage of LAr?
  - How will Xe doping influence break down voltage?

- Is 600kV power supply and FT an intrinsic show stopper for LArTPCs?
  - Do we need better engagement with industry to achieve this?
  - Can we live with 300kV and 0.25kV/cm e^- drift field?