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Workshop on Cher./Scint. Detection
UPenn
2025/6/5

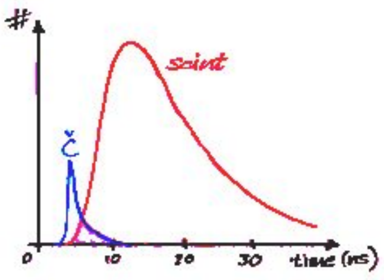
Archers

Cherenkov + Scintillation
in an optical LAr detector

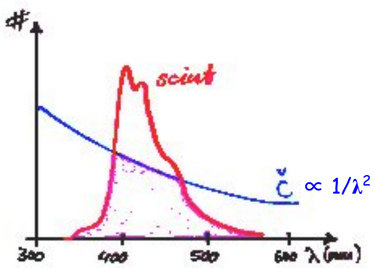
Cherenkov + Scintillation

Cherenkov and scintillation photons are distinguishable via

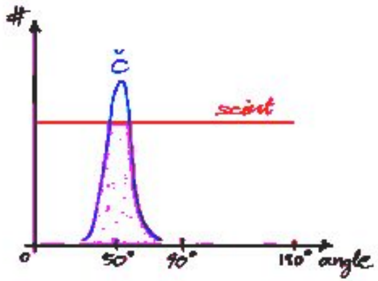
Time



Wavelength



Topology

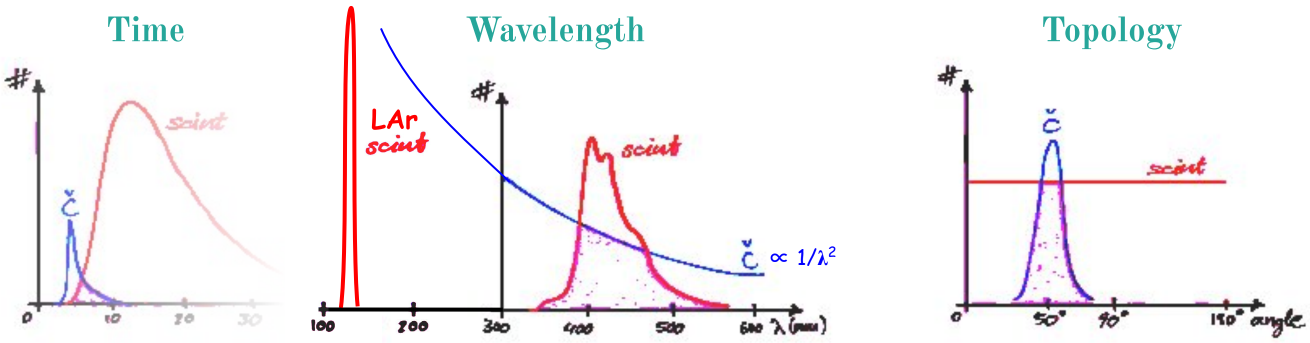


Challenges:

- Timing: Resolving difference between scintillation and Cherenkov.
- Wavelength: Typical photosensors alone do not distinguish wavelengths.
- Yields: Scintillation yields are far greater and attenuation is often significant.

Cherenkov + Scintillation in a LAr detector

In LAr, Cherenkov and scintillation photons are distinguishable via



LAr can addresses some challenges:

- Timing: Fast photon detectors.
- Wavelength: **LAr scintillates narrowly around 128 nm** + spectral sorting/shifting.
- Yields: **LAr has high scint. yield (25k-50k photons/MeV) and favorable absorption.**

Cherenkov + Scintillation Physics in LAr

Similarly expansive program as WbLS detector with basic differences:

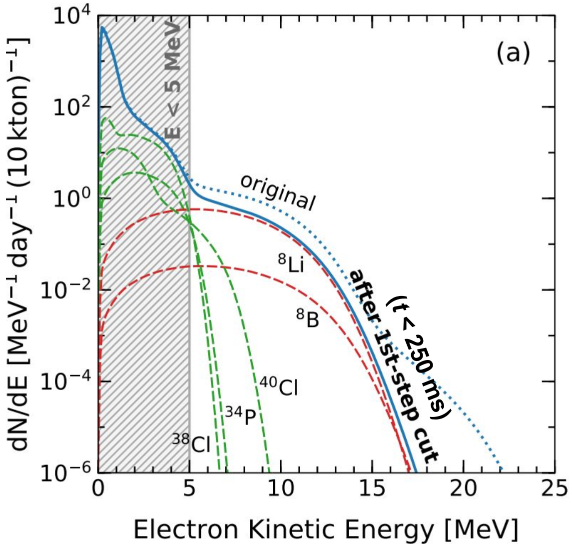
- Finer energy resolution from scintillation.
- Access to lower energies from scintillation.
  - But Ar-specific backgrounds must be suppressed below several MeV - see next slide.
- Without hydrogen.
  - Greater uncertainties in modeling of nuclear interactions.
  - No access to ubiquitous IBD interaction: $\bar{\nu}_e + {}^{1}\mathrm{H} \rightarrow e^{+} + n$,
    but have other unique channels in Ar; e.g., $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^{-} + {}^{40}\mathrm{K}^{*}$ and $\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^{+} + {}^{40}\mathrm{Cl}^{*}$
- Other possibilities, like doping ${}^{136}\mathrm{Xe}$ for a search for neutrinoless double beta decay [inspire 2058896].

Cherenkov + Scintillation Backgrounds in LAr

Sensitivities depend on backgrounds, which LAr has in abundance at low energies.

- Intrinsic radioactivity of atmospheric Ar
  - ^{39}Ar β^- decay (Q = 0.57 MeV) @ 1 Bq/kg.
    ^{42}K β^- decay (Q = 3.5 MeV) @ 0.1 Bq/kg.
  - Underground Ar → ^{39}Ar @ ~0.7 mBq/kg[1].
- Cosmogenic backgrounds
  - Heavier isotopes than in water abundant below several MeV[2]. →
  - ^{41}Ar β^- decay (Q = 2.5 MeV) @ 1600/day/10 kton, $\tau_{1/2} = 6.6\times10^3$ s.
    ^{38}Cl β^- decay (Q = 4.9 MeV) @ 110/day/10 kton, $\tau_{1/2} = 2234$ s.
- Atmospheric neutrino backgrounds

Spallation betas[2]



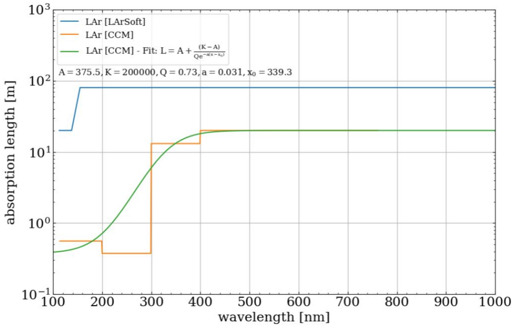
[^{1}DarkSide-50, ^{2}arxiv.org/pdf/1811.07912.pdf]

Cherenkov + Scintillation Optics in LAr

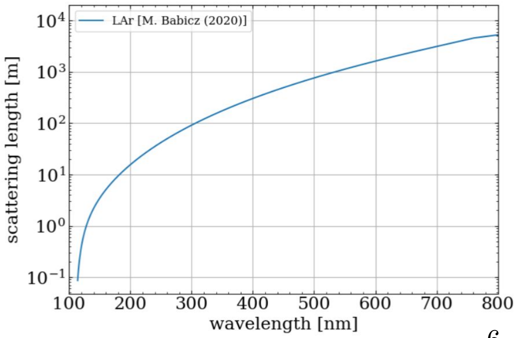
Differences in optics and event interactions:

- Refractive index is lower:
    - 1.24 vs. 1.33 for water ⇒ 80% Cherenkov yield (~61% LS), higher Cherenkov threshold.
    - 1.38 @ 128 nm ⇒ different velocities for Cherenkov and scintillation photons ⇒ greater time separation.
- Z is higher: $Z_{Ar} = 18$. Density is higher: 1.40 vs. 1.00 g/cm^3.
    - Greater scattering, possibly worsening direction resolution.
    - Lower critical energy, impacting reconstructed energy resolution at higher energies.
    - Shorter tracks at lower energies, better containment.
- Favorable attenuation ⇒ low scattering best preserves directional Cherenkov information, but short wavelength scintillation is significantly impacted.

Absorption



Scattering



Archers studies ongoing

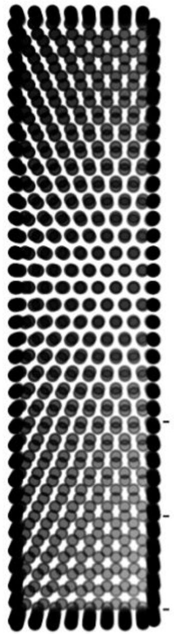
- Collaboration between
  Berkeley/Penn (Logan, Z. Larsen, J. Klein, G. Orebi Gann) & **MIT** (Darcy Newmark, J. Conrad)

- Modeling detector as a DUNE module lined by PMTs.
  - Simulations using ratpac2 and CCM framework.

- PMT coverage 70%
  - 86,000 8” Hamamatsu R5912-02 Mod.
    - QE peaks at 18%.

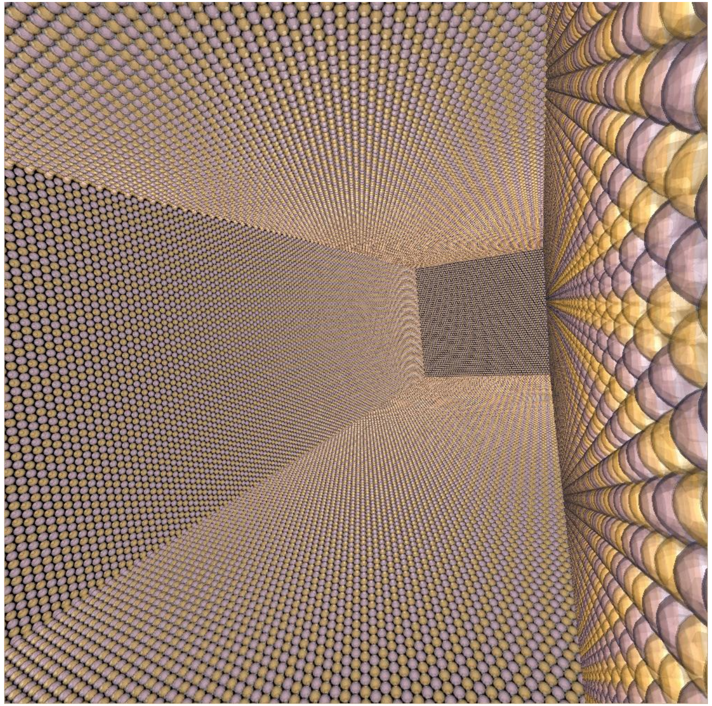
- TPB re-emits visible light isotropically with $\tau \sim 2$ ns.

- Currently comparing low-level quantities and preparing for event recon.



Archers study (OLD)

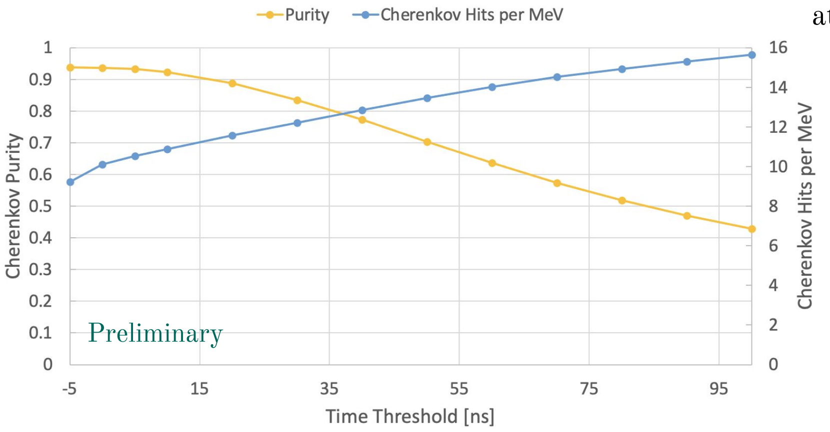
- DUNE-sized and -shaped module covered by PMTs, half coated with wavelength shifter TPB (**light purple**).
  - GPU-accelerated simulations using Chroma[1] to efficiently propagate large numbers of photons in a large detector.
  - Analysis with updated pyrat[2].
- PMTs
  - Coverage: 80% (55,749).
  - 10-inch diameter.
  - Quantum eff.: Hamamatsu R1408 [SNO].
  - TTS $\boldsymbol{\sigma} = 1.0$ ns.
  - Charge resolution $\boldsymbol{\sigma} = 33\%$.
- Assumes no optical absorption in LAr.



[[1]github.com/pennneutrinos/chroma, [2]github.com/llebanowski/pyrat]

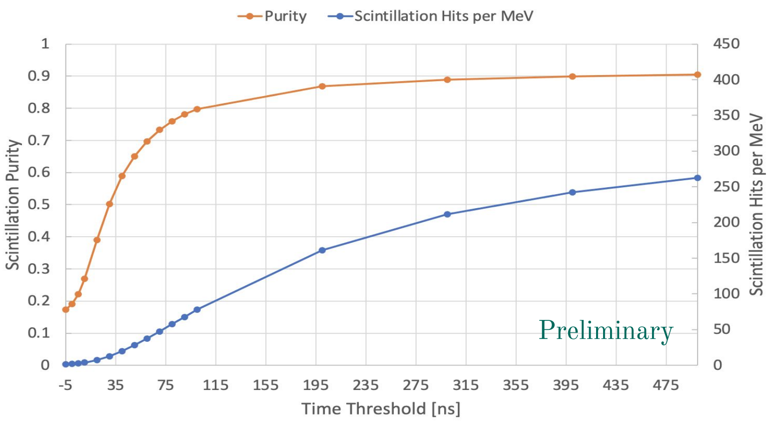
Archers optics (OLD)

Uncoated PMTs with Cherenkov



5-MeV electrons
at the center

Coated PMTs with Scintillation



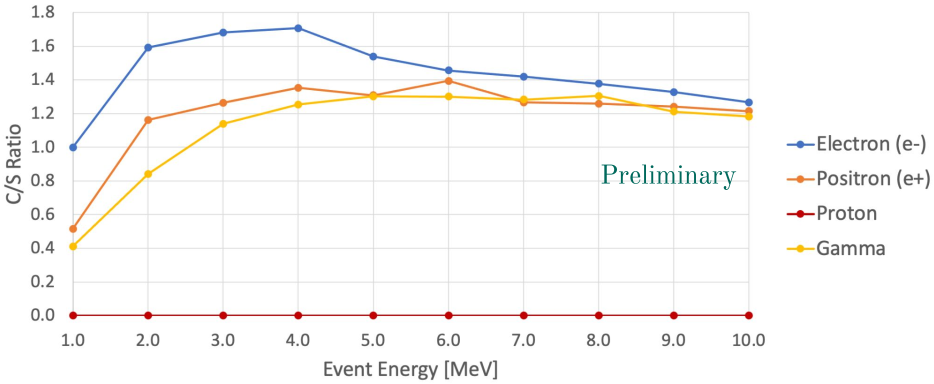
- **Number of uncoated PMTs** that detect Cherenkov photons: **11 per MeV @ 90% purity**, within 20 ns.
  Modern water Cherenkov detectors SNO(+) & Super-K: **~7 per MeV @ 100% purity**.
  Some of the gain may be from TPB absorption of lower-wavelength portion of spectrum and re-emission to neighbor PMTs.

- **Number of coated PMTs** that detect scintillation photons: **~260 per MeV @ 91% purity**, within 500 ns. (~500 p.e./MeV)
  Modern LS detector JUNO: **1100 p.e./MeV @ ≲100% purity**.

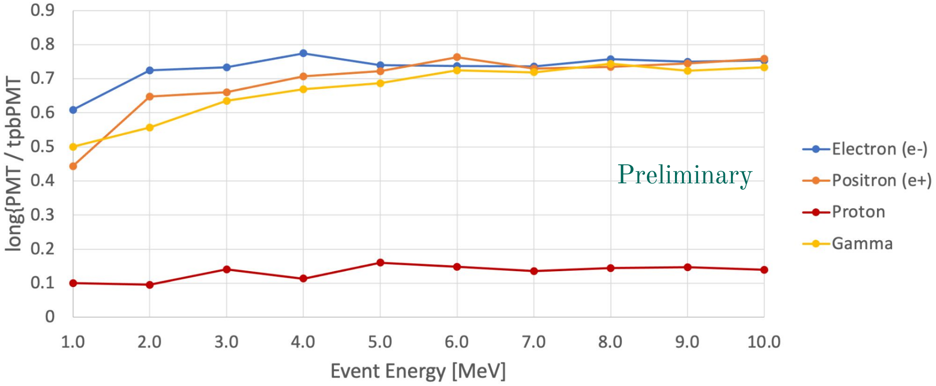
Archers C/s (OLD)

Simplistic particle ID using only the ratio of C/s photons.

Cher. on uncoated PMTs (20 ns) / # scint. on coated PMTs.



Uncoated PMTs (20 ns) / # Coated PMTs.



Good potential for **β/γ** discrimination at low energy (left plot).
The most naive estimator of ratio of PMT types preserves some (right plot) and can certainly be improved.

Archers high energy (OLD)

1-GeV electron

Detected scint:	628k
Detected Cherenkov:	48k
Detected total:	676k

Energy of saturation of PMT output:

55.7k PMTs → ~12 p.e./PMT/GeV.

Some PMTs saturate around 200 p.e./PMT ⇒ 200/12 = 16 GeV saturation energy.

PMT response becomes nonlinear before saturation.

Can consider a high-gain readout like SNO.

Can consider an array of 3” PMTs like JUNO.

Moving forward

Continue developing detector designs using simulations.

- Many degrees of freedom in optimization of photosensors and wavelength shifters/filters.

Improve optical modeling with results from ongoing experiments.

Perform simplistic event analyses aimed at signal-background discrimination and physics sensitivities.

Wavelength shifter could be coated on

- The detector walls
- Coated on/in front of PMTs
- Coated on interstitial panels.

Wavelength shifters other than TPB.

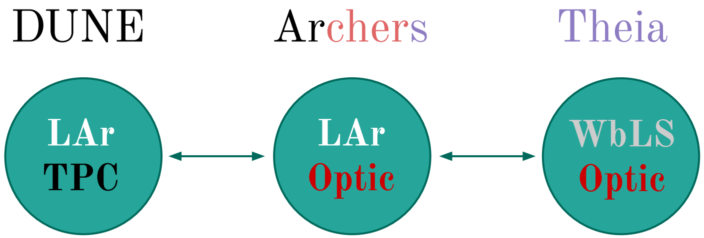
Coating a fraction of PMTs.

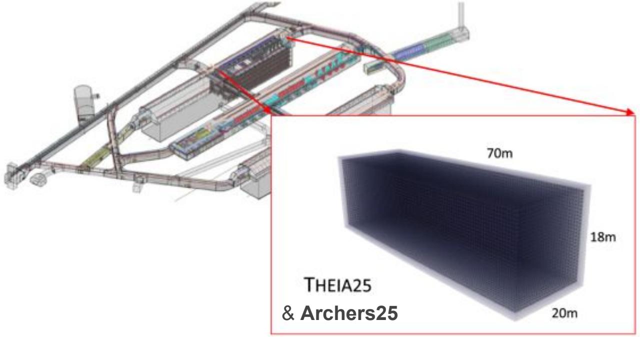
Optimize QE and PMT size.

Conclusion

- Argon is a very interesting and advantageous choice of detector medium.
    - Good energy resolution at low energies.
    - Low energy threshold ...
        - (Very) low energies might be accessible with strong background suppression.
    - Cherenkov counts may be high and reasonably pure, enabling effective PID.

Compelling triumvirate of systematics *and* sensitivities:





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