WbLS in ND-GAr:

An *Even-More* Multipurpose ND for DUNE Phase 2?

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ND-GAr Meeting

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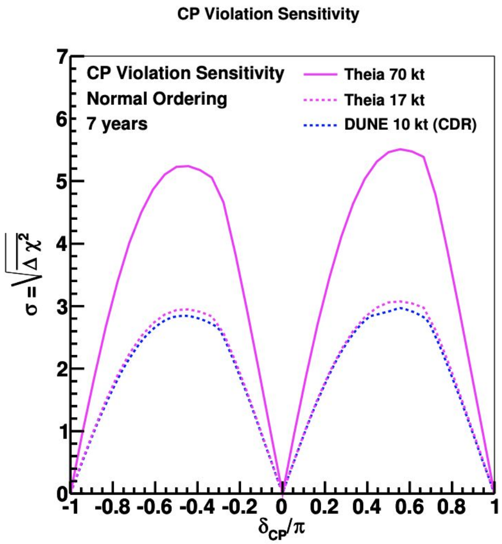
FD Module of Opportunity

- DUNE Phase 1 will create 4 far detector caverns, but only 2 far detectors
- DUNE Phase 2 goal is to produce 2 new FDs, upgrade the beam, and upgrade the ND
  - Ongoing US P5 process may end up weighing in on these elements with regard to US funding
- Additional funding sources / new collaborators can substantially improve the odds of completing DUNE Phase 2
  - e.g. a WbLS detector (Theia) would grow the collaboration and substantially broaden the physics program (DSNB, SN burst, solar CNO, 0νββ, …) and provide a different target nucleus for the LBL program
  - Other options are also being explored (e.g. LiquidO)
- New FD detector technologies require new ND capabilities
- Expanding the capabilities of ND-GAr (e.g. to include WbLS targets) can grow the number of ND-GAr stakeholders and funding opportunities

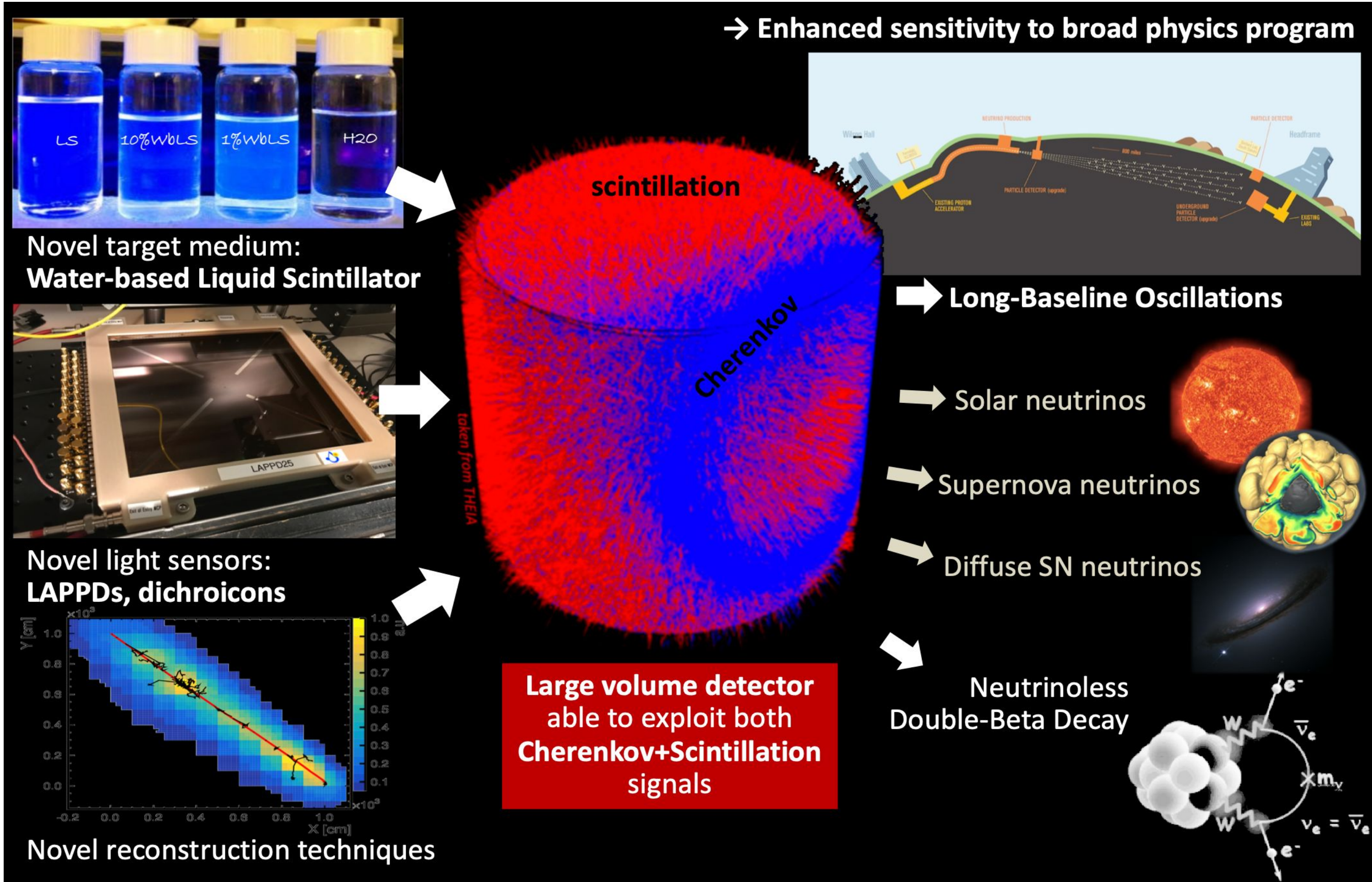


Brief Introduction to Theia

The European Physical Journal C 80 no. 5, (May, 2020)

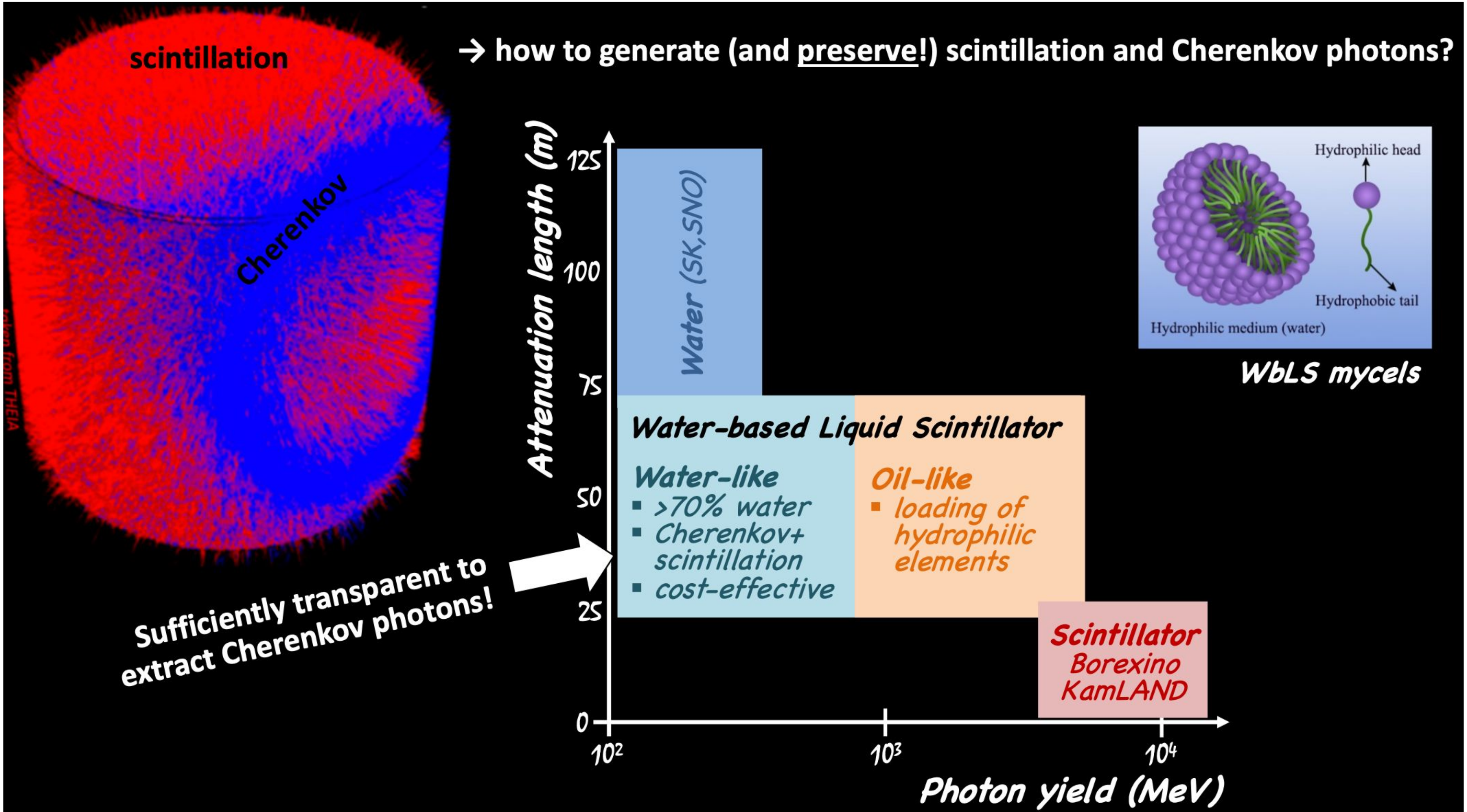
(slide from M. Wurm)

- Observe both Cherenkov and scinitllation light for each event
- At High-E, operates much like Super-K
  - with additional information about below-Cherenkov-threshold hadrons
- Low-E threshold is lowered
  - More photons near and below Cherenkov threshold



WbLS Concentrations

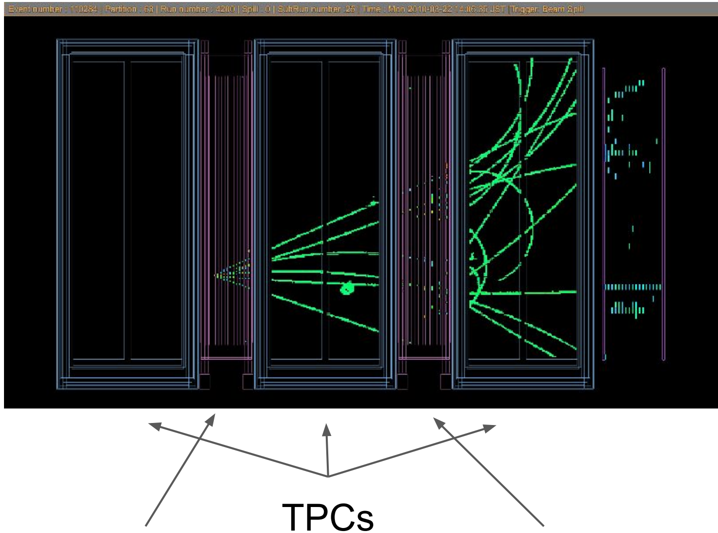
(slide from M. Wurm)



WbLS Near Detector Considerations

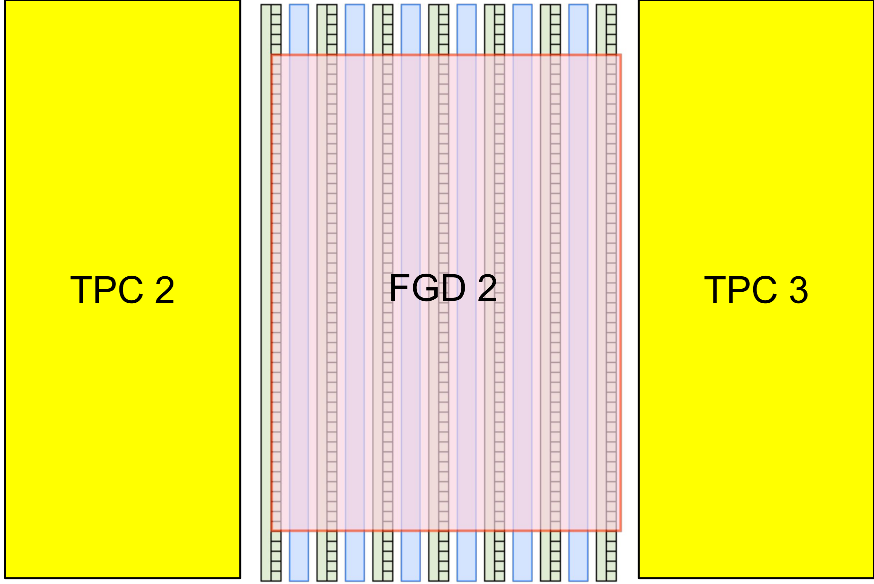
- A key component of LAr detectors is hadron calorimetry
  - Neutrino energy is the sum of the reconstructed lepton energy and the (corrected) deposited hadronic energy
- For water Cherenkov detectors, E_ν reconstruction is performed with above-Cherenkov particles
  - The Theia LBL sensitivity studies were performed without utilizing scintillation light
- The primary requirement for a Theia near detector is to measure above-Cherenkov-threshold particles
  - This is the approach used for the primary T2K / Hyper-K near detector
  - Additional external measurements of Cherenkov/scintillation ratio may be needed
    - Large R&D program with several WbLS detectors is currently underway

T2K Near Detector (ND280)

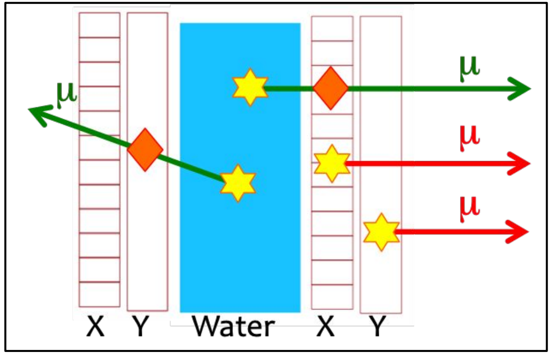


T2K Fine-Grained Detector (FGD2)

- T2K already employs water targets embedded within X & Y layers of scintillator bars
  - This reduced T2K's neutrino interaction uncertainties on water by ~30%
- One of the most important detector uncertainties is disentangling events occurring within water to events occurring in adjacent scintillator layers
- The key difference using WbLS is the water layers themselves can be instrumented
  - Surrounding scintillator layers are not longer a strict requirement
  - Must ensure a sufficient llight yield to record MIPs



7 xy + 6 water modules
192x2 bars/layer



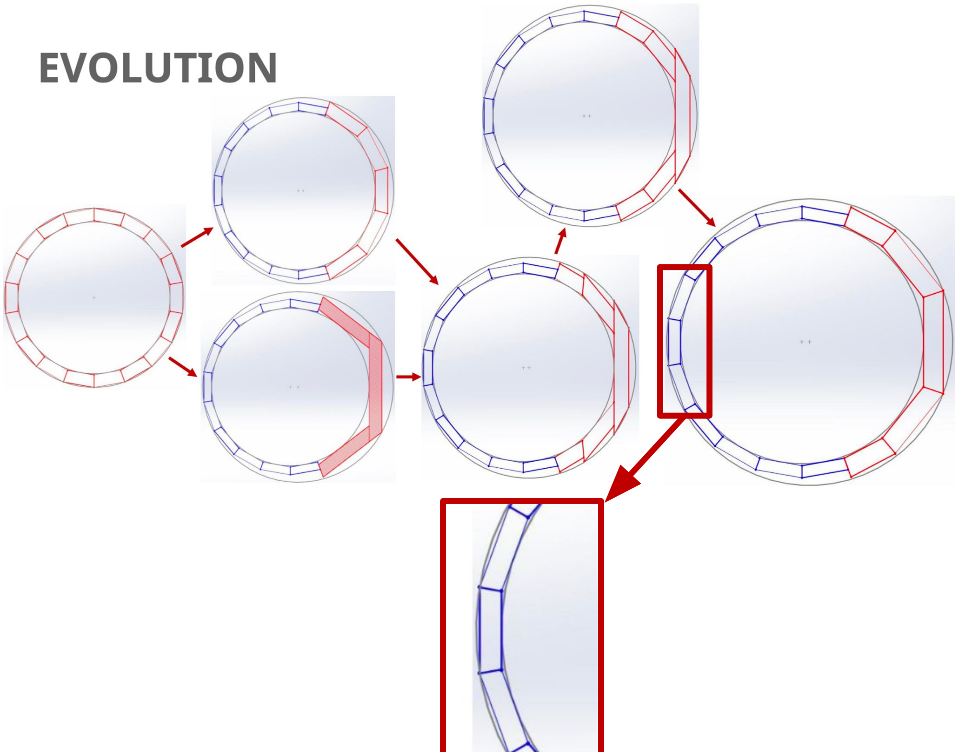
Phys. Rev. D 101, 11 (2020) pp.112004

ND-GAr “Thin” Upstream ECAL

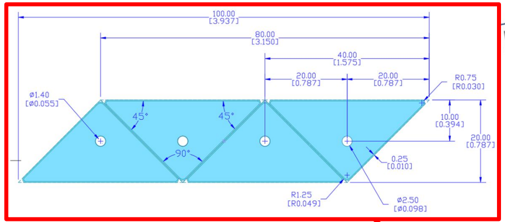
- The ND-GAr ECAL is most needed in the downstream direction
- The upstream portion has been redesigned to be “thin”
- Questions for ND-GAr ECAL experts:
  - How does the thickness requirement vary as a function of angular position? Can the most upstream portions be thinner?
  - Could the downstream-most layers of the upstream ECAL be composed of WbLS? What would be the light yield requirements in this case?
    - Some additional effort may be available to perform relevant studies

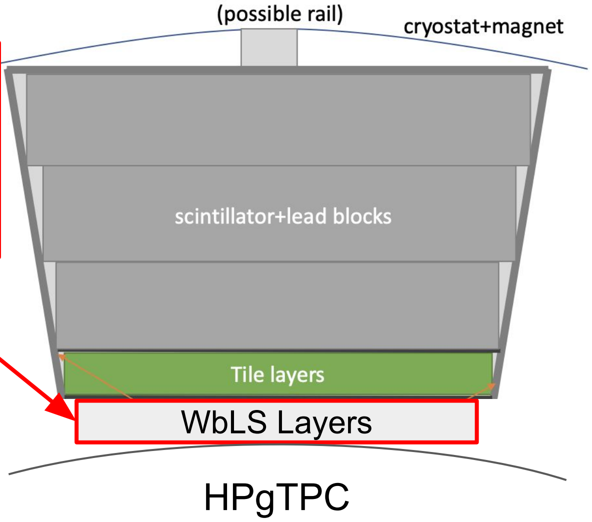
ND-GAr ECAL Design Evolution

https://indico.fnal.gov/event/50217/contributions/241513/attachments/155287/202160/220517_DUNE_CM_Talk_ECAL_Concepts.pdf

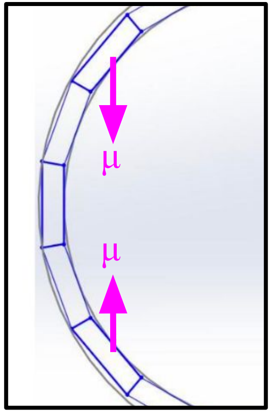


WbLS Inside ND-GAr ECAL



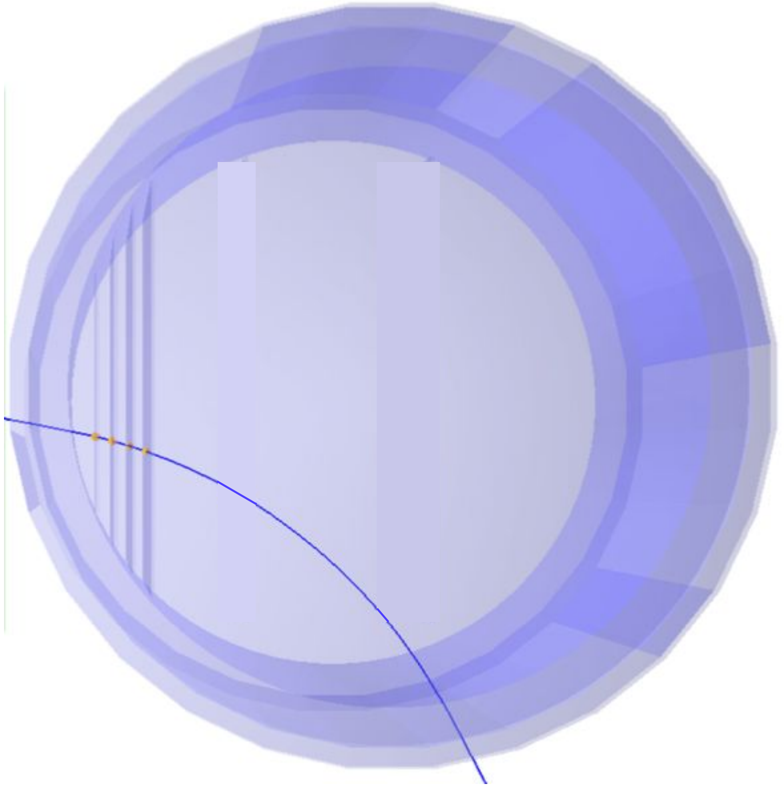


- WbLS layers would need to track X & Y positions
  - Optically segmented X & Y bars or 3D cubes
  - Or perhaps a non-segmented LiquidO detector with X & Y fibers
- Order of magnitude size estimate:
  5 m long TPC * ~4 m total layer width * 5 cm thickness
  ≈ 1 ton WbLS detector mass
  - Similar to the target mass for the GAr TPC
- Additional benefit: variation in detector configurations allows for sampling all of the muon angle phase space
  - The lack of muon acceptance near 90° was an important limitation of the T2K FGD+TPC configuration



WbLS + GAr TPC?

Figure adapted from
ND-GAr-Lite proposal



- A more invasive approach: integrate WbLS layers into the GAr TPC
  - Lower threshold particle detection
  - Precision tracking upstream + downstream of each layer
- Important to not harm ND-GAr physics
  - Minimize reduction of GAr-TPC fiducial volume
  - Minimize loss of performance in upstream ECAL (these layers would effectively form the first ECAL layers, but would consist of <1 radiation length)
- Many technical issues to consider
  - Additional penetrations and support structure in the pressure vessel
  - Field shaping on the surfaces of the WbLS layers
  - Potential liquid leaks
    - The T2K FGD2 water layers were held at lower pressure so that small leaks would produce gas ingress rather than water outflow

Summary and Next Steps

- Purpose of today's talk is to begin a discussion with ND-GAr experts on potential synergies between the ND-GAr and WbLS communities for DUNE Phase 2
  - Many potential benefits to such a collaboration (both politically and to enhance DUNE physics)
  - Additional potential person-power exists to study the options discussed today
- Multiple options for integrating WbLS into ND-GAr could be considered
  - Minimally invasive: place targets in downstream most layers of upstream ECAL
  - More invasive: integrate WbLS layers into GAr-TPC
- Based on the discussion here and any subsequent feedback from ND-GAr experts, I'll present a slightly more detailed concept at the DUNE Phase 2 ND workshop at Imperial College June
  - More discussion is also welcome at the upcoming DUNE collaboration meeting