Water-based Liquid Scintillator in WCTE

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Stony Brook University
WCTE Workshop
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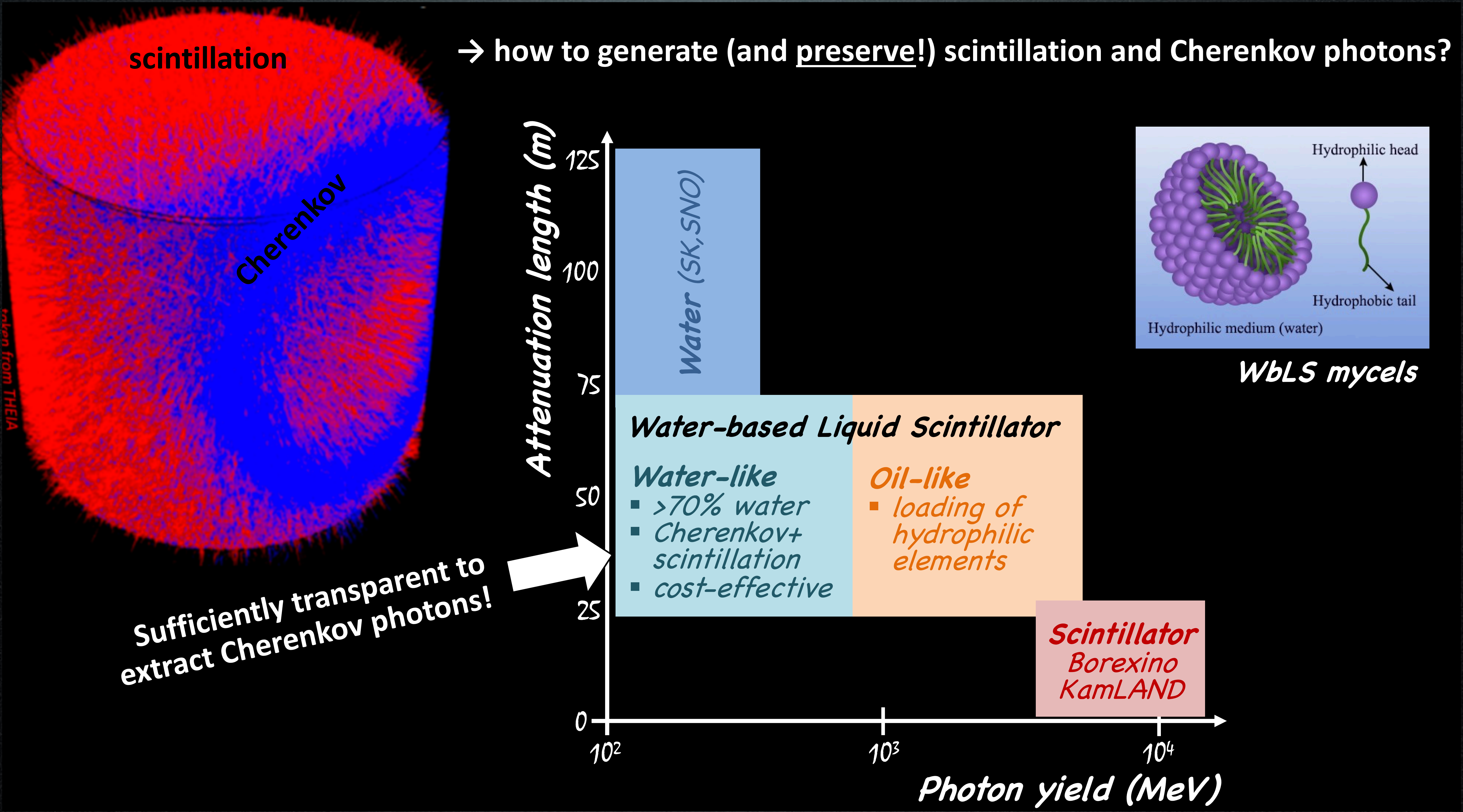
Water-based Liquid Scintillator (WbLS)



- Target medium can be adjusted to physics goals
  - Different physics accessible in different phases of the experiment

Cherenkov / Scintillation Separation

- Several tools are available to separate Cherenkov and scintillation photons:

Timing

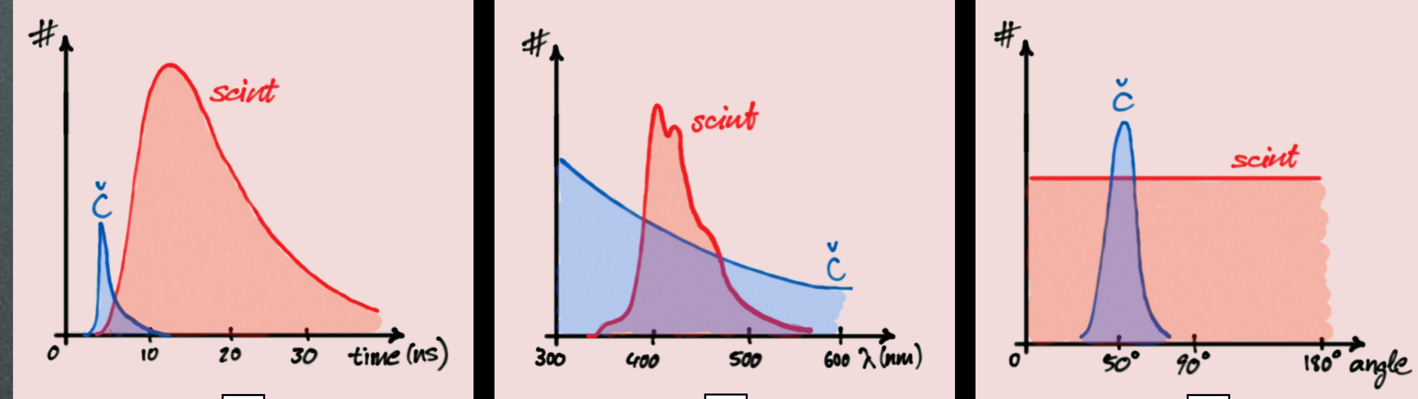
"instantaneous chertons" vs. delayed "scintons"
→ ns resolution or better

Spectrum

UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity

Angular distribution

increased PMT hit density under Cherenkov angle
→ sufficient granularity



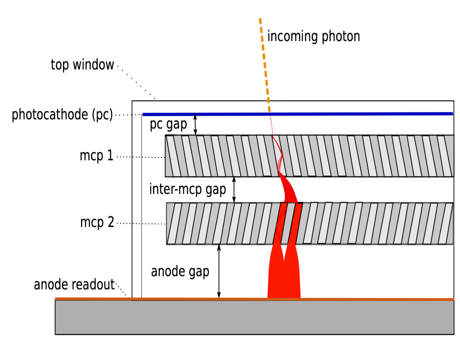
LAPPDs: ~60ps timing

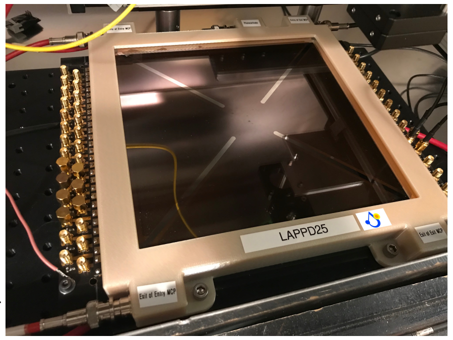
Dichroic filters

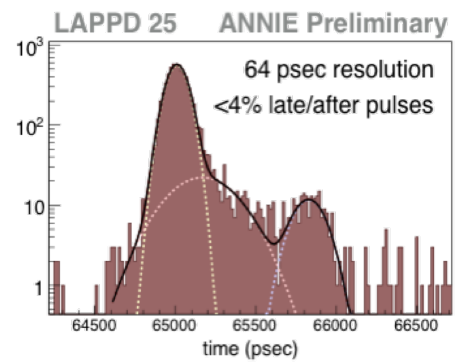
Standard PMTs

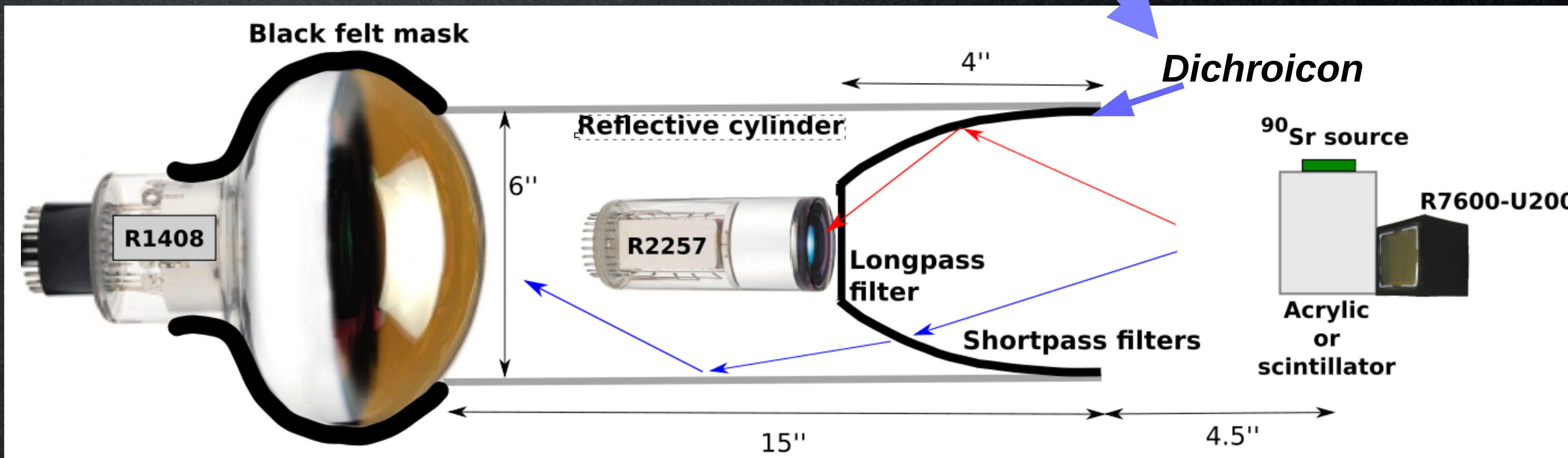
Large Area Picosecond Photon Detectors

- Area: 20-by-20 cm^2
- Amplification of p.e. by two MCP layers
- Flat geometry: ultrafast timing ~65ps
- Strip readout: spatial resolution ~1cm
- Commercial production by Incom, Ltd.

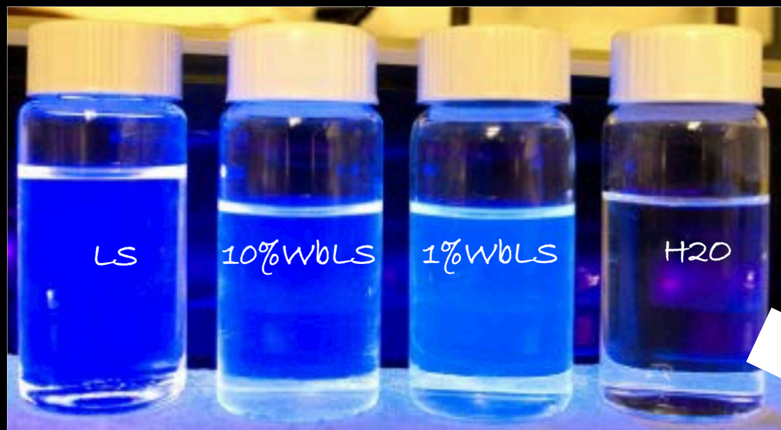




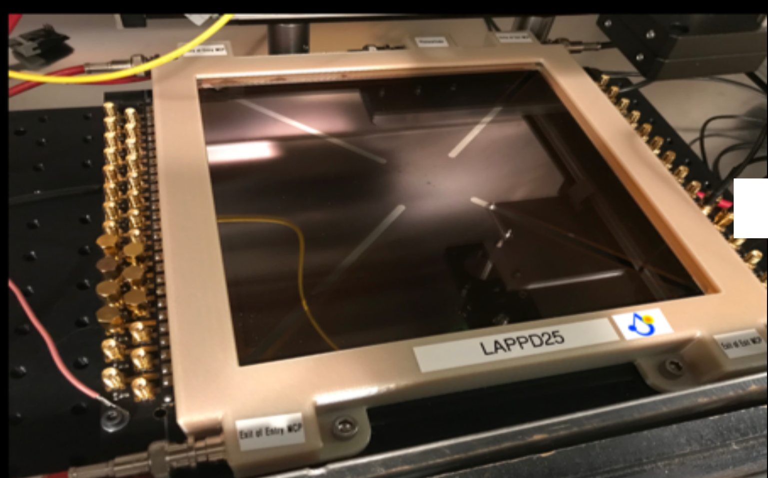




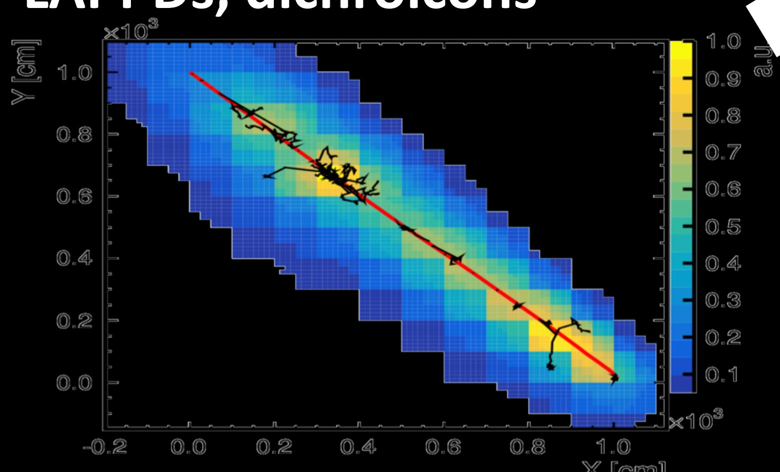
Proposed Theia Experiment



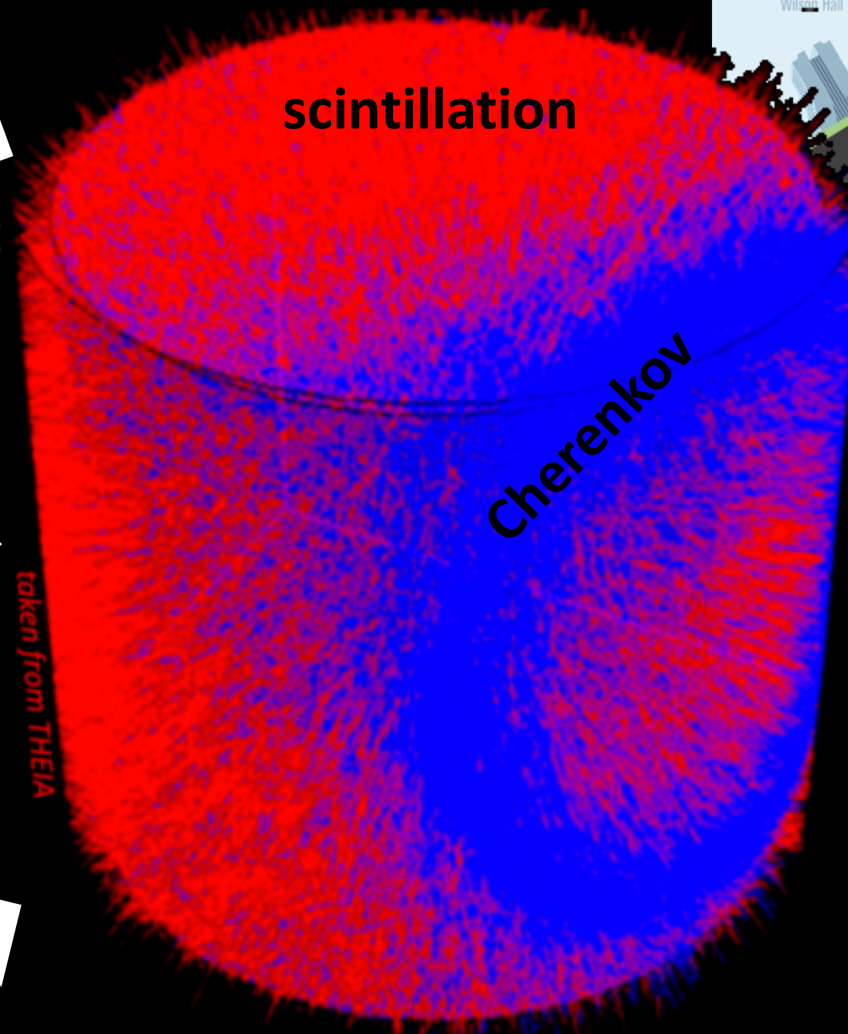
Novel target medium:
Water-based Liquid Scintillator



Novel light sensors:
LAPPDs, dichroicons



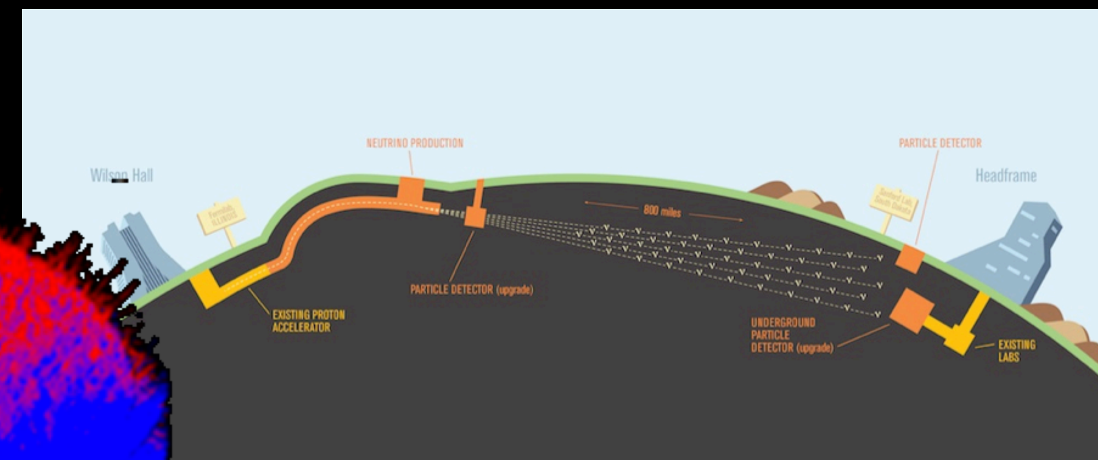
Novel reconstruction techniques



Large volume detector able to exploit both **Cherenkov+Scintillation** signals

Theia white paper: M. Askins, et al., European Physics Journal C 80 416 (2020)

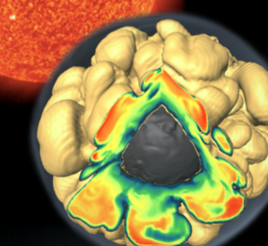
→ **Enhanced sensitivity to broad physics program**



Long-Baseline Oscillations

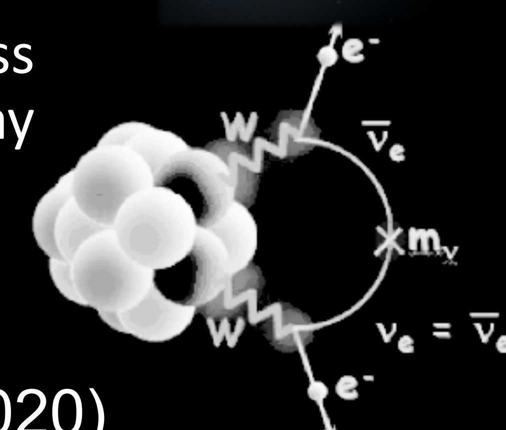
Solar neutrinos

Supernova neutrinos



Diffuse SN neutrinos

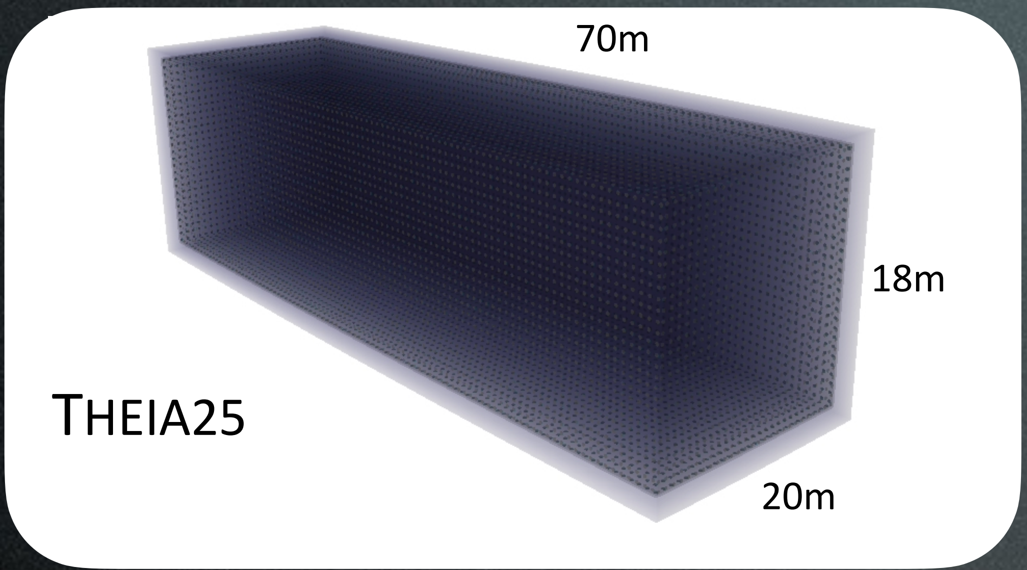
Neutrinoless Double-Beta Decay

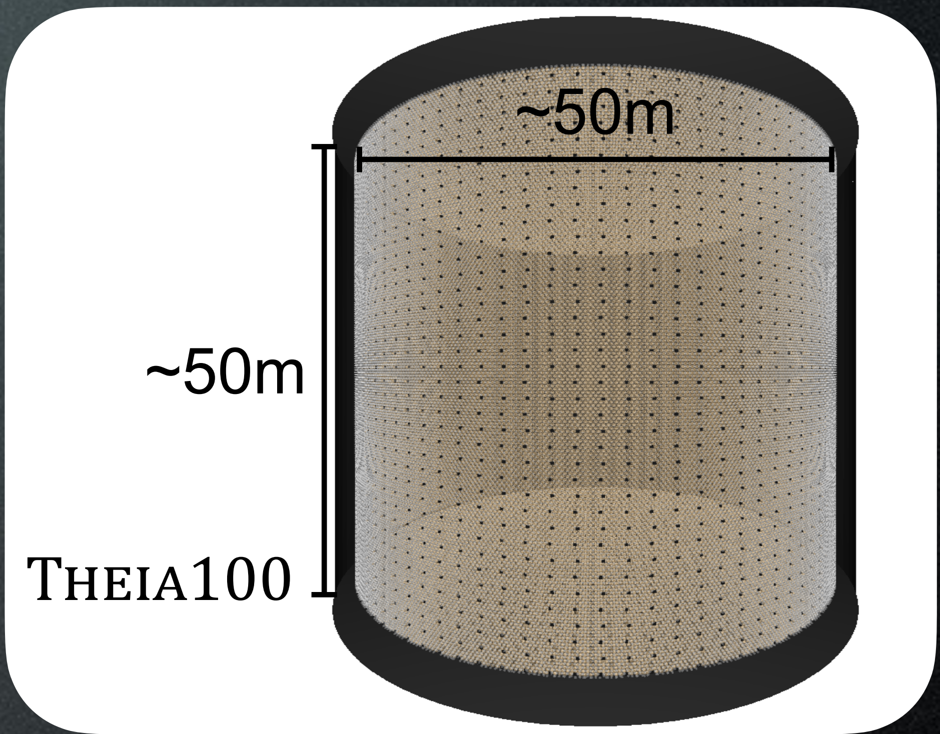


Detector and Staging

- The Theia white paper considers 2 potential detector configurations:

Either detector would exploit the huge investment in LBNF made by the US physics community





Designed to fit in the 4th DUNE cavern (i.e. the “Module of Opportunity”)

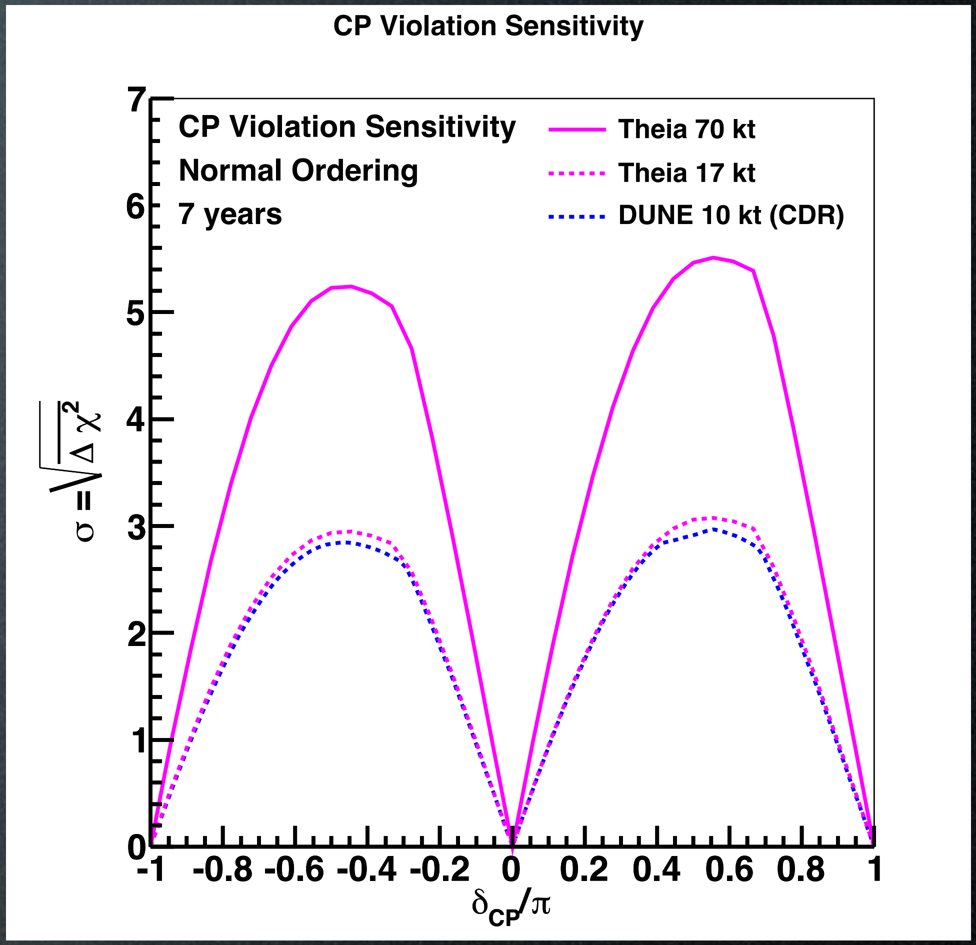
- The detector is envisioned to run in 3 phases:
  - **Phase 1**: Long-baseline neutrinos (LBNF)
    1-10% WbLS
  - **Phase 2**: Low-energy neutrinos
    Increased WbLS and photocoverage
  - **Phase 3**: Multi-ton $0\nu\beta\beta$
    Several kton balloon of isotope+LAB+PPO

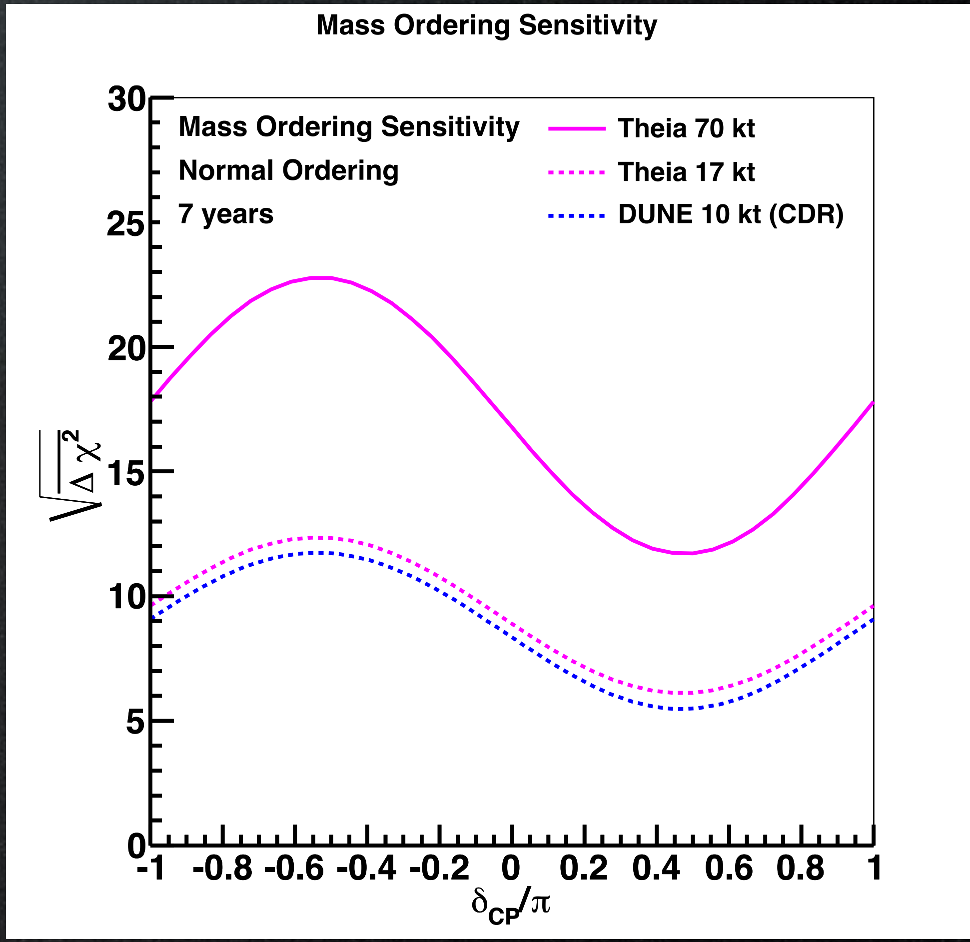
Physics Goals

- Long-baseline: δ_{CP}, θ_{23}, Δm_{32}^2
- Proton decay ($K^{+}\nu$, 3ν)
- Supernova (SN) neutrinos
- Diffuse SN background
- Solar neutrinos
- Geoneutrinos
- $0\nu\beta\beta$ search

Sensitivity

- Sensitivities produced with the same GLoBES framework used for the DUNE CDR analysis
  - Systematic assumptions are also consistent with the CDR (2% signal, 5% background, uncorrelated among all samples)
  - Theia disappearance samples are not included here (impact is minimal)
- Both the CP and mass hierarchy sensitivity are similar for a 10 kt LAr module, and a 17 kt Theia module





Challenges for WbLS in WCTE

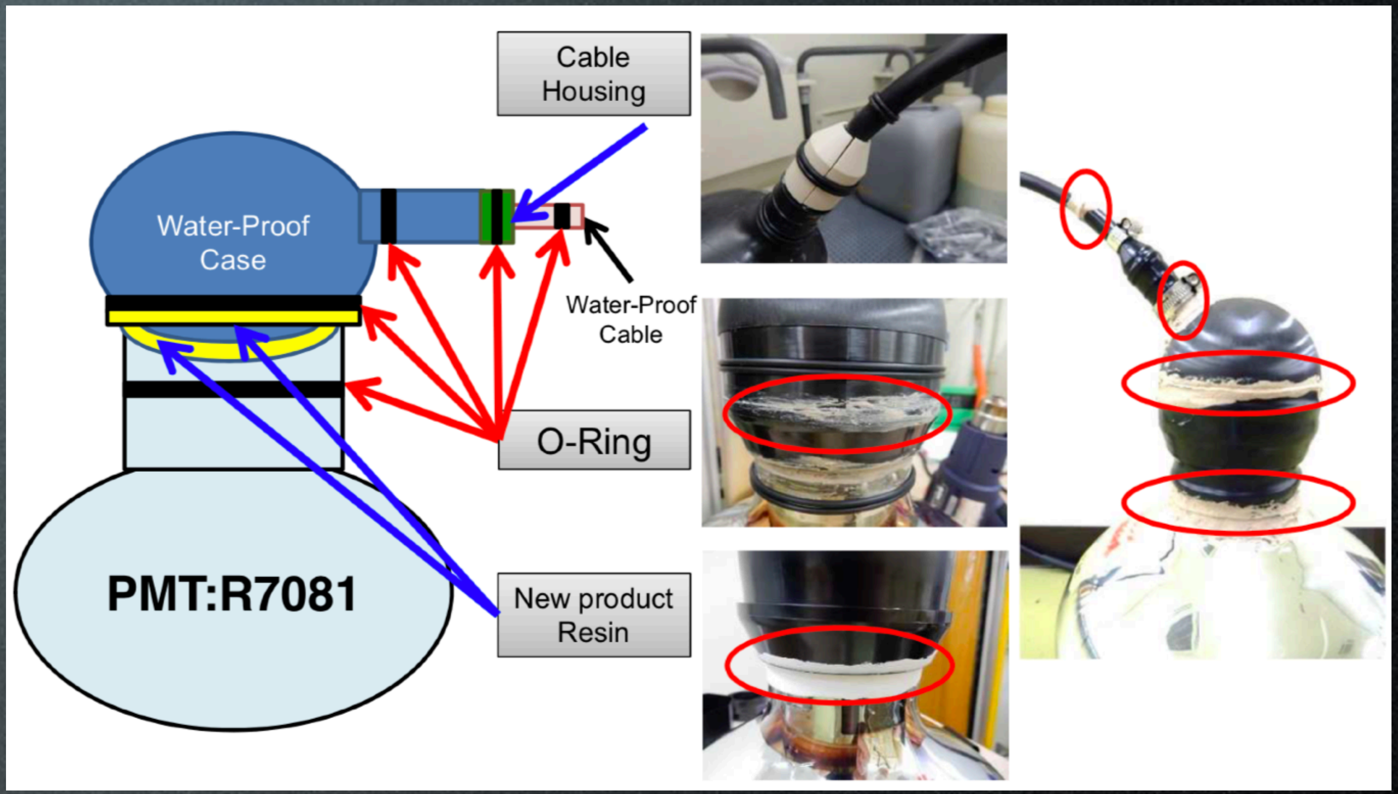
- **Materials compatibility**
  - Some materials used in Water Cherenkov detectors interact poorly with WbLS
  - Careful selection of materials is needed for anything that will come in contact with WbLS (potentially: mPMTs, cables, support structure, calibration systems, ...)
- **Water system**
  - A complete WbLS filtration and circulation system does not yet exist
    - Water system R&D is ongoing at a few locations
  - We are currently exploring whether a partial system could be sufficient at the 25 ton scale

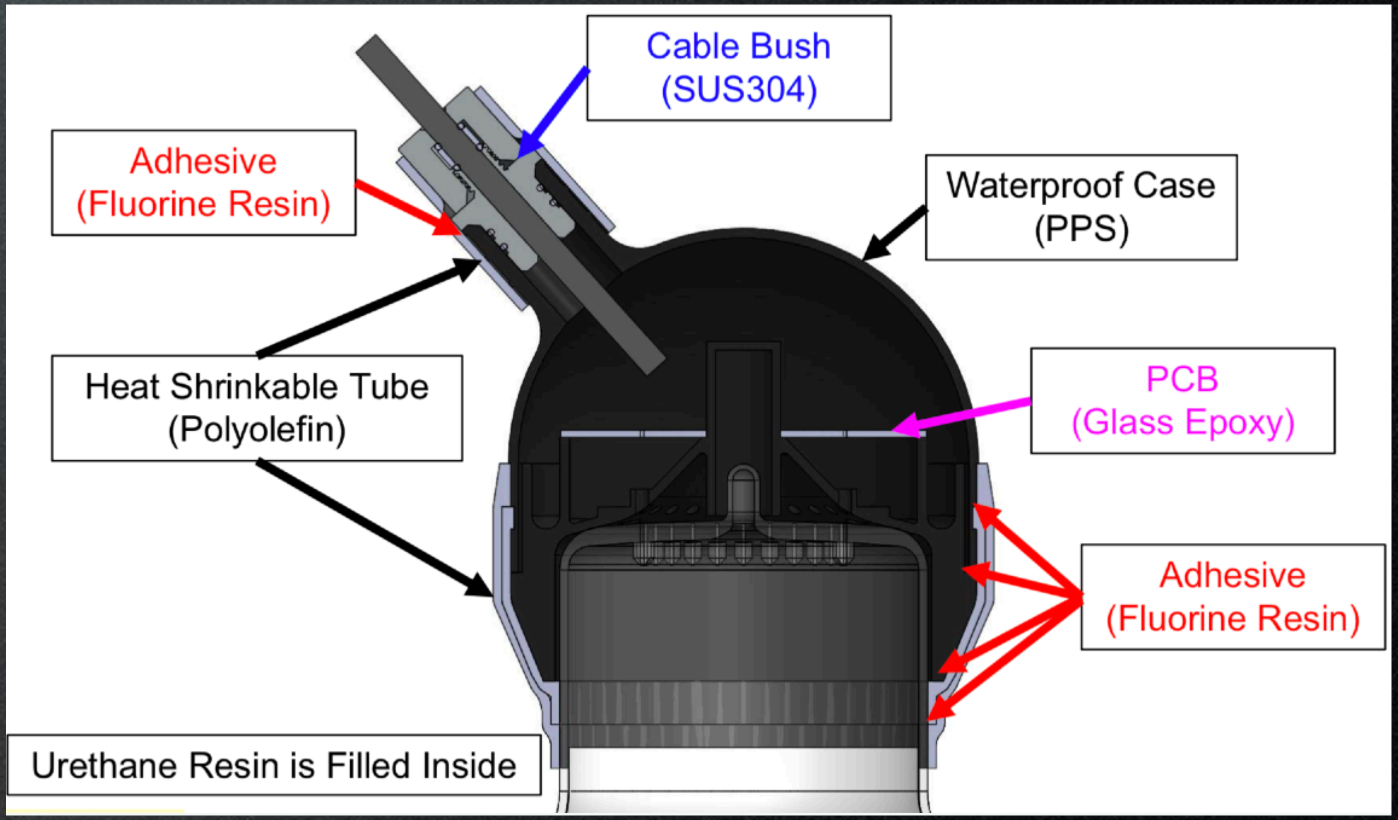
WbLS Materials

- Several materials are known to work well with WbLS
  - Stainless steel (e.g. alloys 316, 304)
  - PTFE (teflon; polytetrafluoroethylene)
  - PFA: Perfluoroalkoxy alkane
  - FEP: Fluorinated ethylene propylene
  - Arkema's Kynar PVDF (polyvinylidene fluoride)
  - PP: polypropylene
  - Acrylic
  - PE: Polyethylene (but only without UV-protection additives, which cause leaching)
- Additional materials compatibility testing capacity is available at BNL (and perhaps UC Davis)

Hamamatsu WbLS PMT

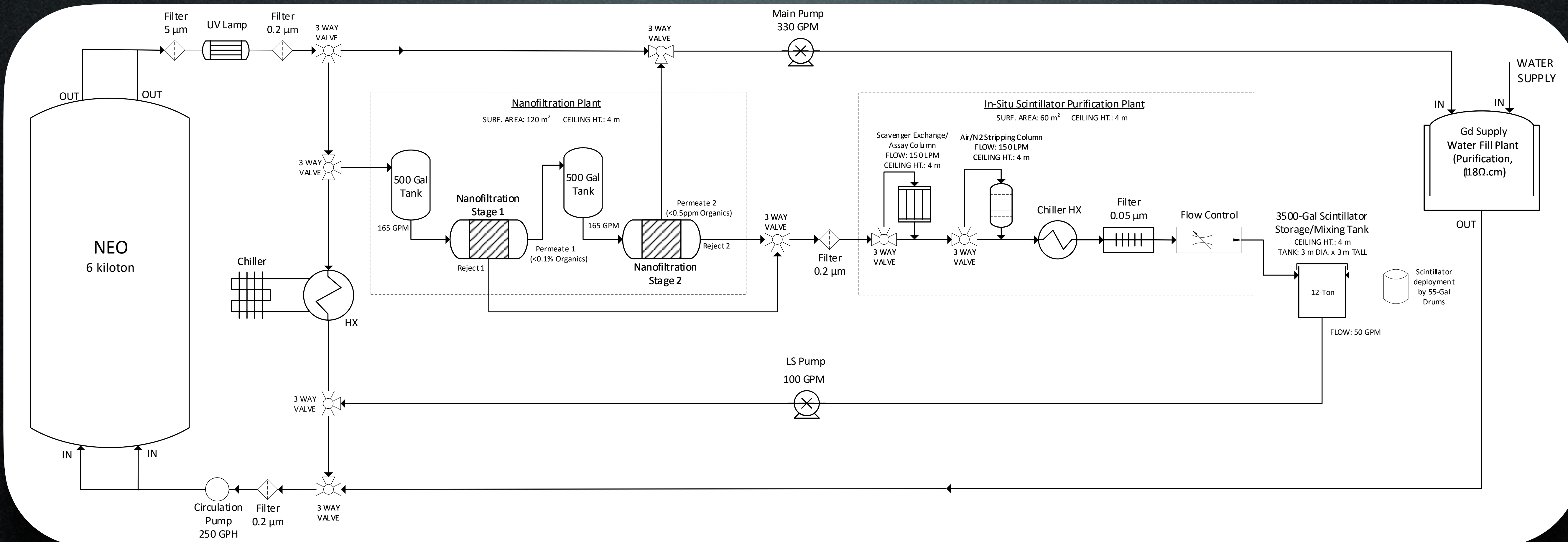
- Butyl rubber adhesive dissolves in WbLS
- Several “fluorine resins” were tested
  - F113 showed no signs of transmittance degradation in a 1 month WbLS soak test
- No resin failures after a variety of soak tests, temperature variations (55°C to -20°C), and pressure tests up to 0.6 MPa gauge pressure
- A new iteration is under development (Hamamatsu claims 2-3 months from now)





L. Pickard, https://indico.bnl.gov/event/6963/contributions/32648/attachments/31549/49833/WbLS_Compatibility_THEIA.pdf

“Complete” Water System



- Water system under development for NEO
  - Nanofiltration stage (known technology; small scale systems exist)
  - Scintillator purification stage (still at R&D stage)
- Based on existing prototype systems, need to determine which components would be necessary for a many-week run in WCTE

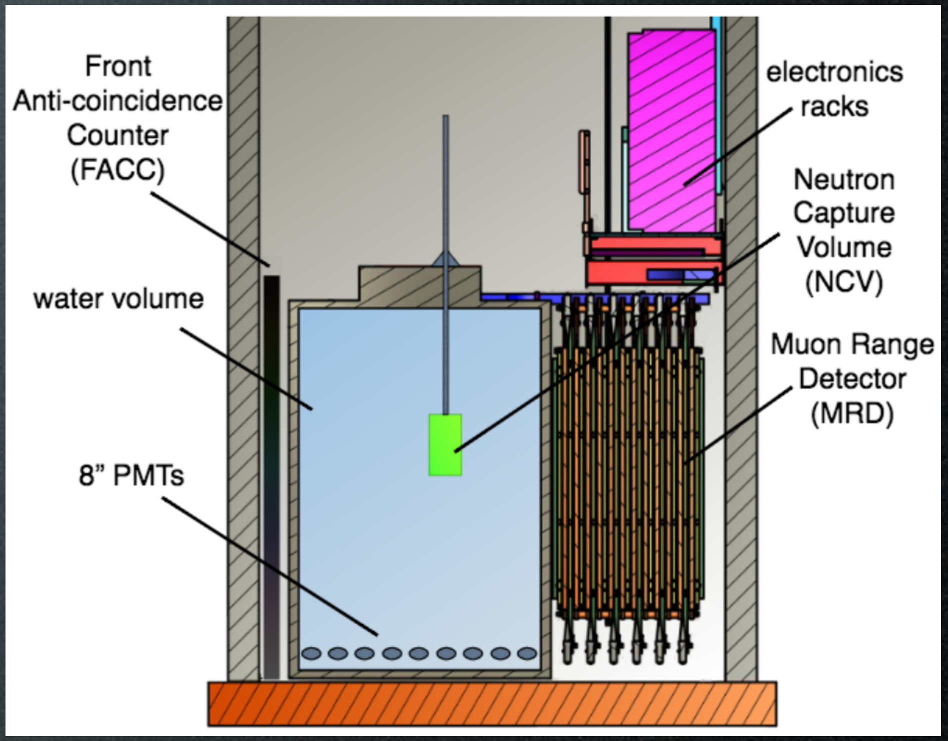
BNL 1 Ton

- Water fill/recirculation system: RO, DI, and degassing at 1 L/minute
- These were bypassed during WbLS introduction
  - (a special degassed for WbLS was used, but not used; 12% reduction in WbLS light yield in bench test)
- After WbLS was introduced, recirculation system was stopped, and monitoring PMTs indicated stable optical properties for ~1 month
  - Future plans for improved monitoring of WbLS mixing and recirculation rate studies

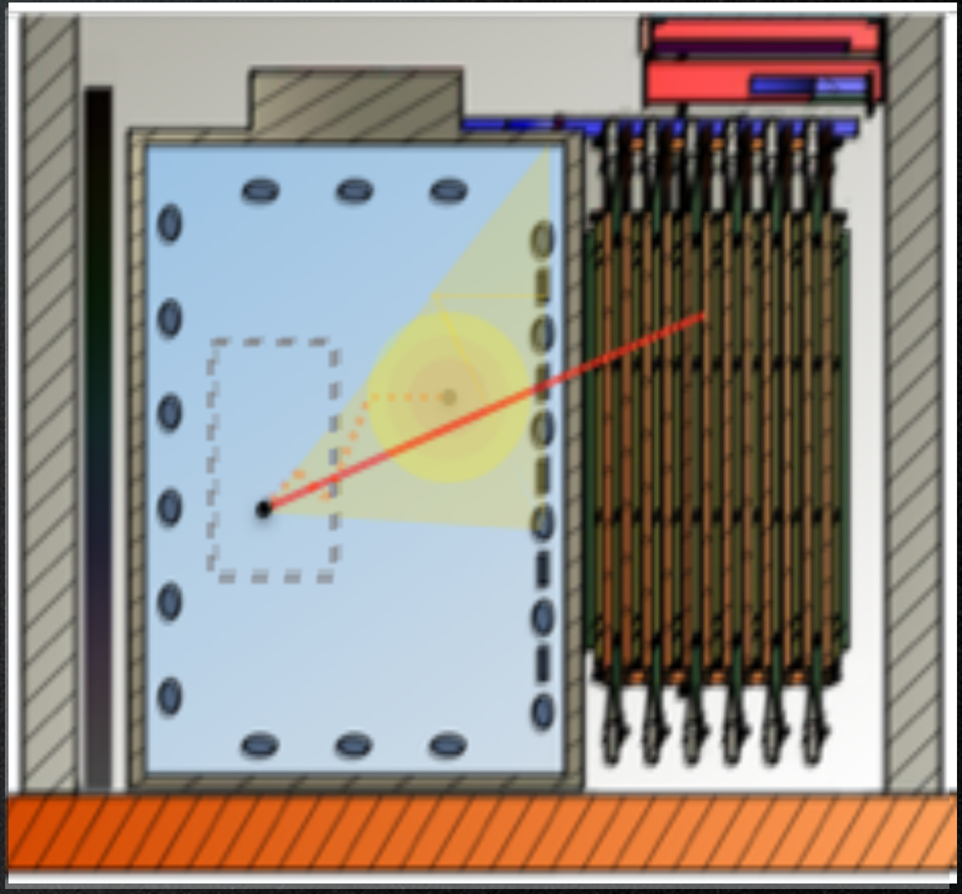
ANNIE

- Phase I (2016-2017): deployed a 50 cm x 50 cm Gd-doped LS volume to measure neutron backgrounds at several locations
- Phase II (2019-??): Gd-doped water with LAPPDs
- Phase III (future): WbLS phase with more LAPPDs

Phase I: Small GdLS Volume

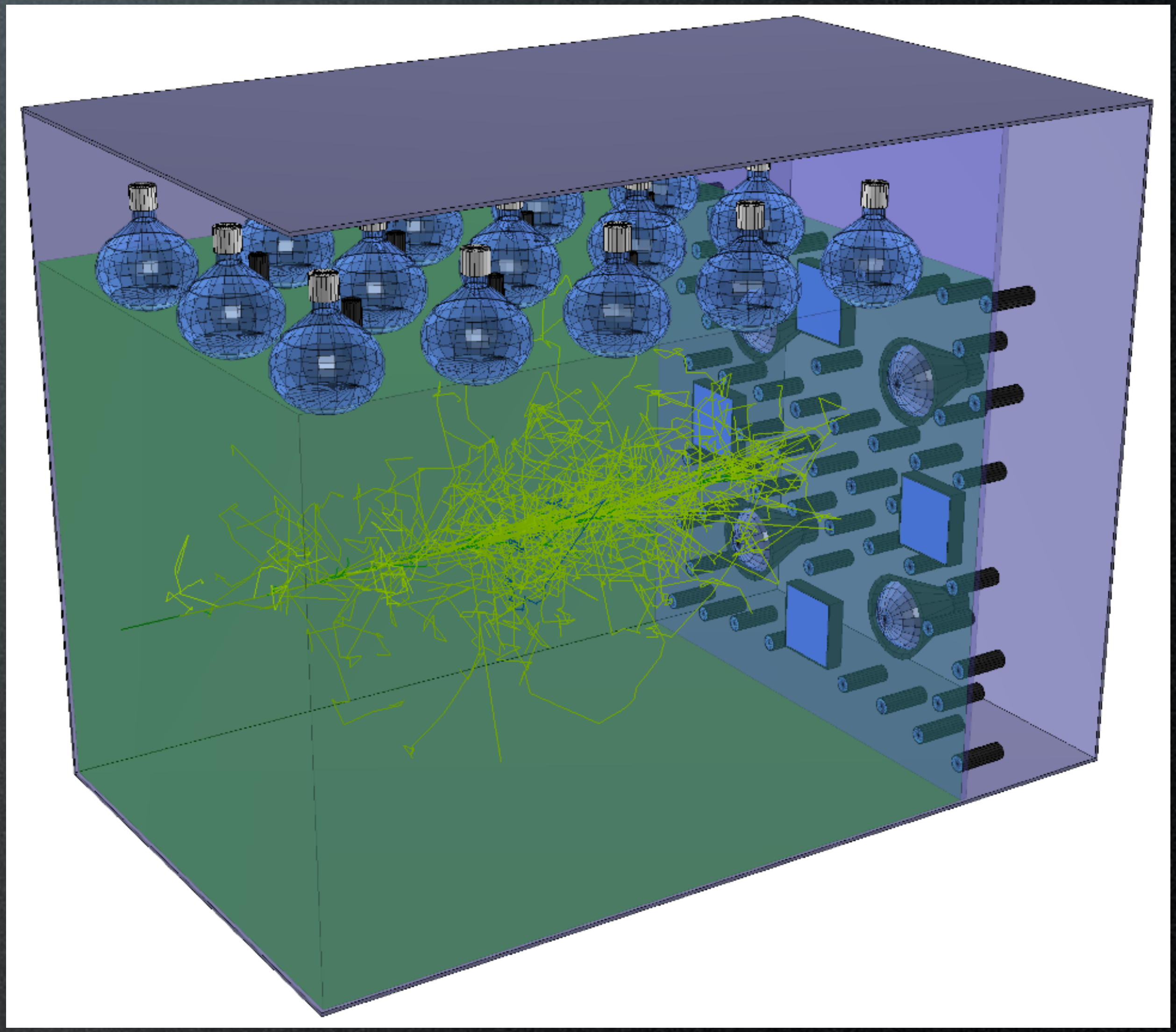


Phase II: Full Gd Loading



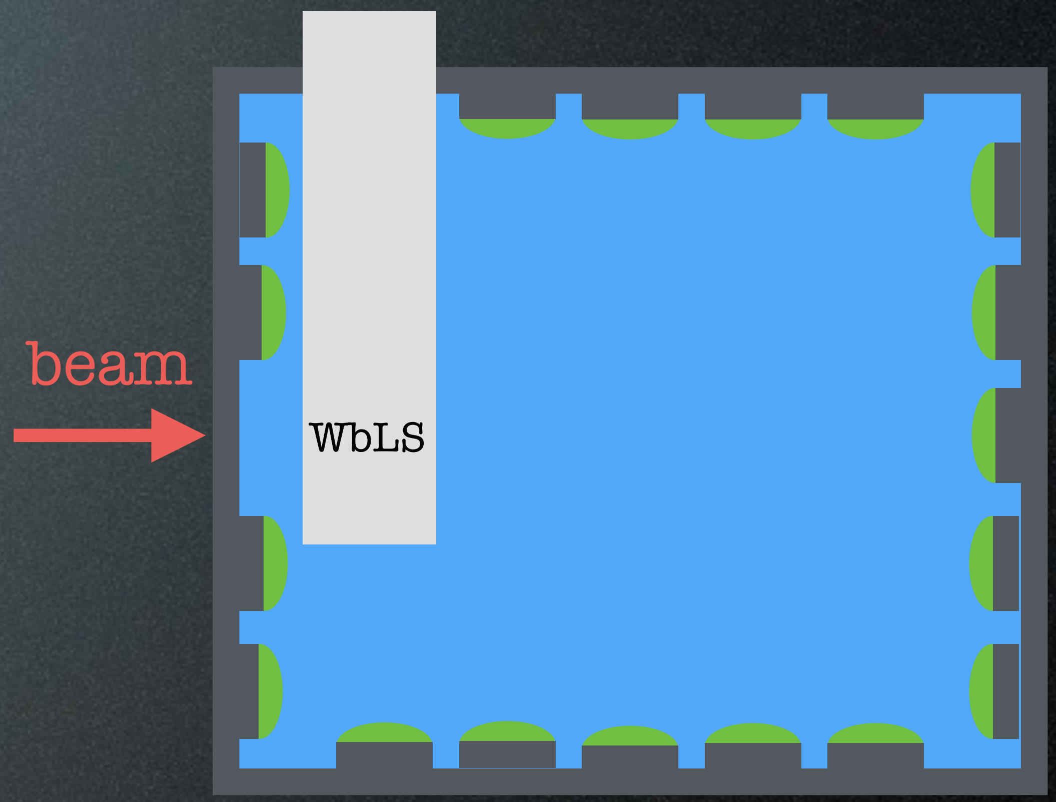
Possible Collaborative Efforts

- Several German groups are seeking funds for a smaller-scale WbLS test in a CERN test beam (Dresden, Hamburg, Jülich, Mainz, Tübingen)
- 1.5 x 1.5 x 2 m^3 box
- Acrylic wall separating WbLS from photosensors
  - LAPPDs, dichroicons, 2” PMTs
  - 8” Borexino PMTs (~1.2 ns) dipped in WbLS from above
- Planning for 0.3 to 3 GeV/c
- Significant potential for collaboration (results needed by mid-2024)

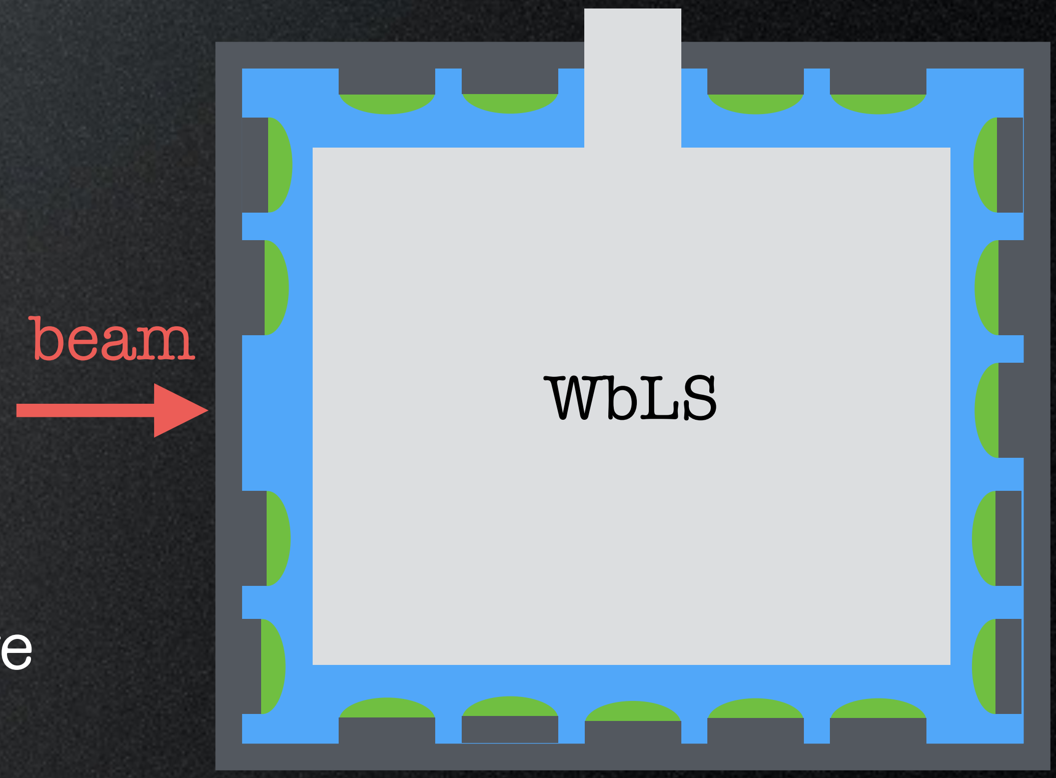


WCTE Containment Vessel Options

- If materials compatibility is too difficult, a separate volume of WbLS could be deployed
- A smaller volume of known thickness in the upstream portion of the tank
  - Can study Cher/scint separation, scint production, & reconstruction performance
  - Less invasive; water system requirements reduced



- A tube along the beam line
  - Allows for more detailed study of light produced by stopping particles
- A larger volume (cylindrical or spherical) which fills the bulk of the tank
  - More wholistic study of particle scatters and late time activity (e.g. Michels)
  - More extensive modifications; more expensive



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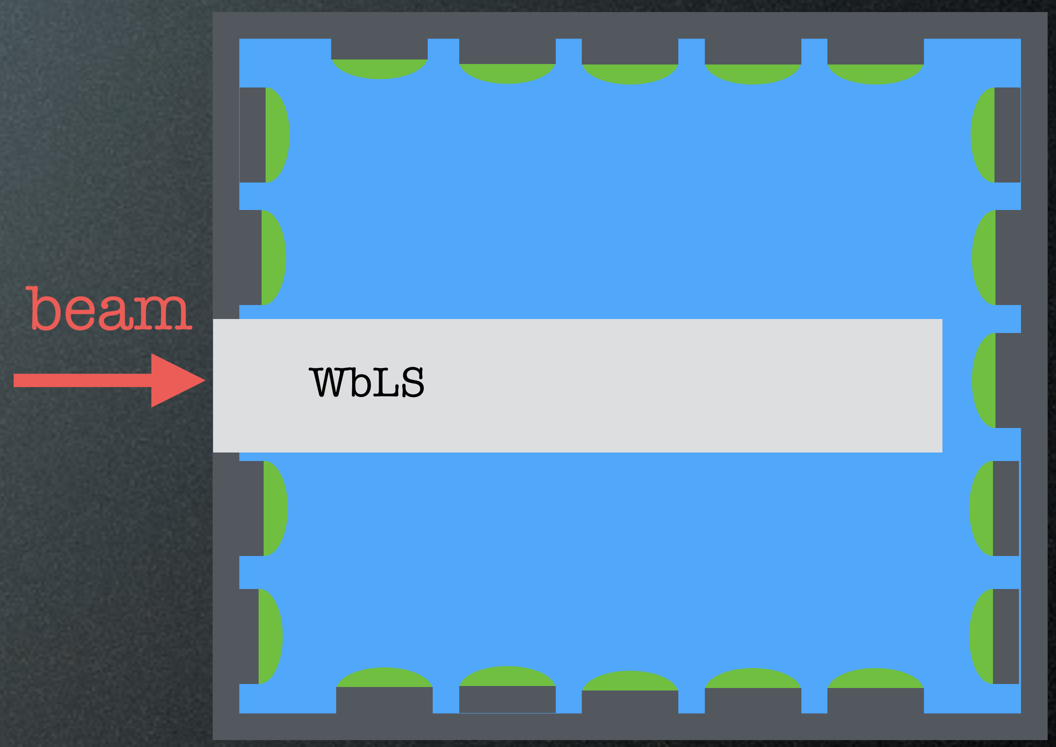

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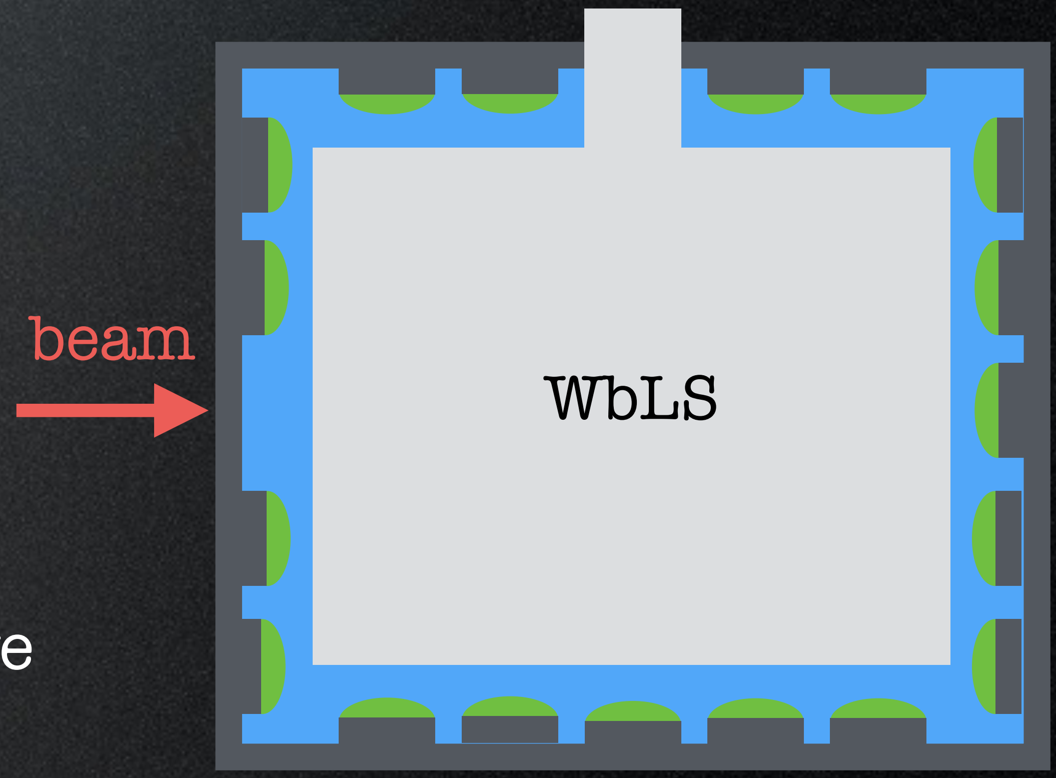
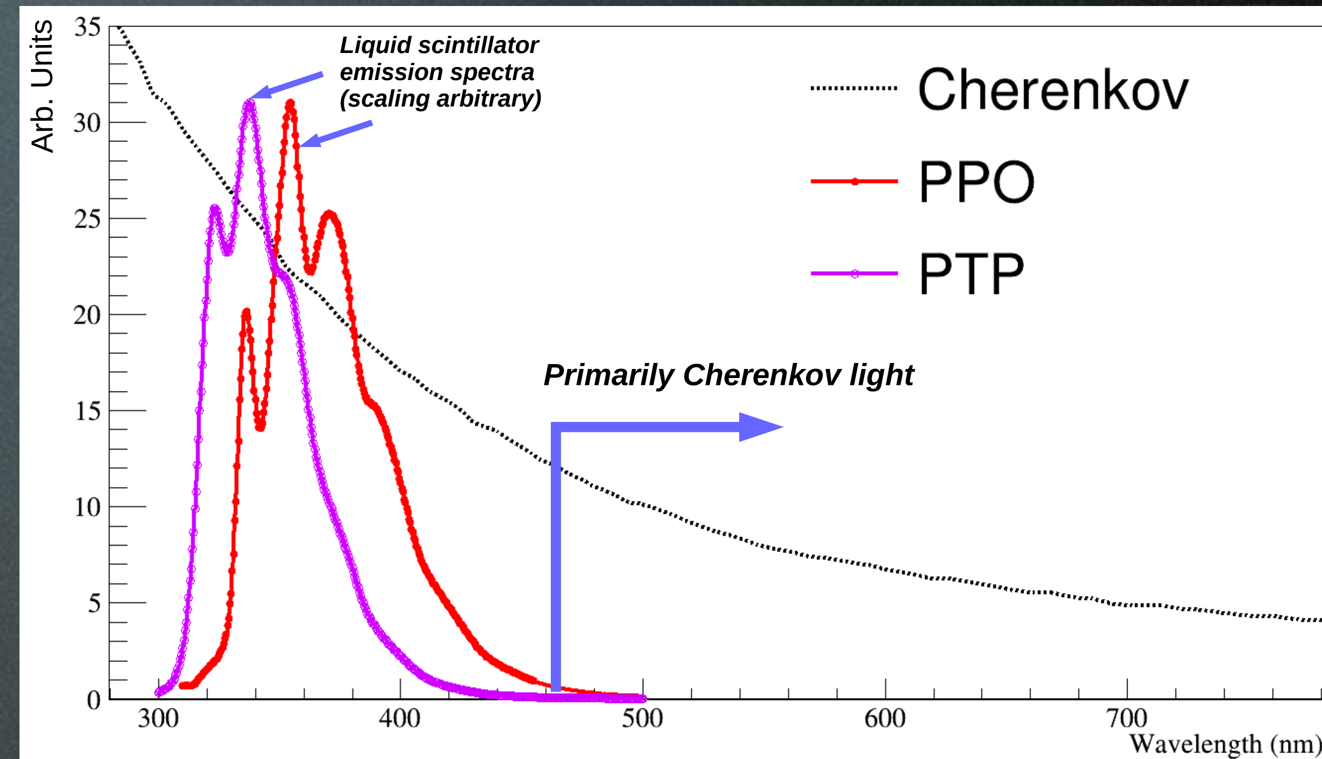
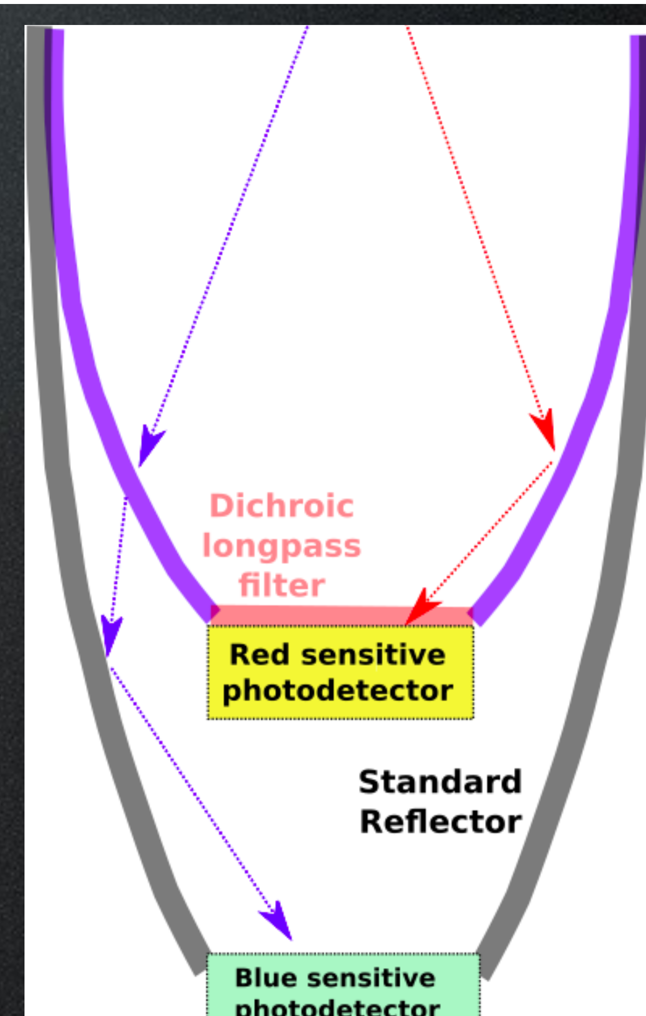


Dichroicon: Cher/Scint Separation

- Goal: separately detect light below and above ~500 nm
  - < 500 nm: Scint + Cher light (charge measurement)
  - > 500 nm Cher-only light (direction measurement)

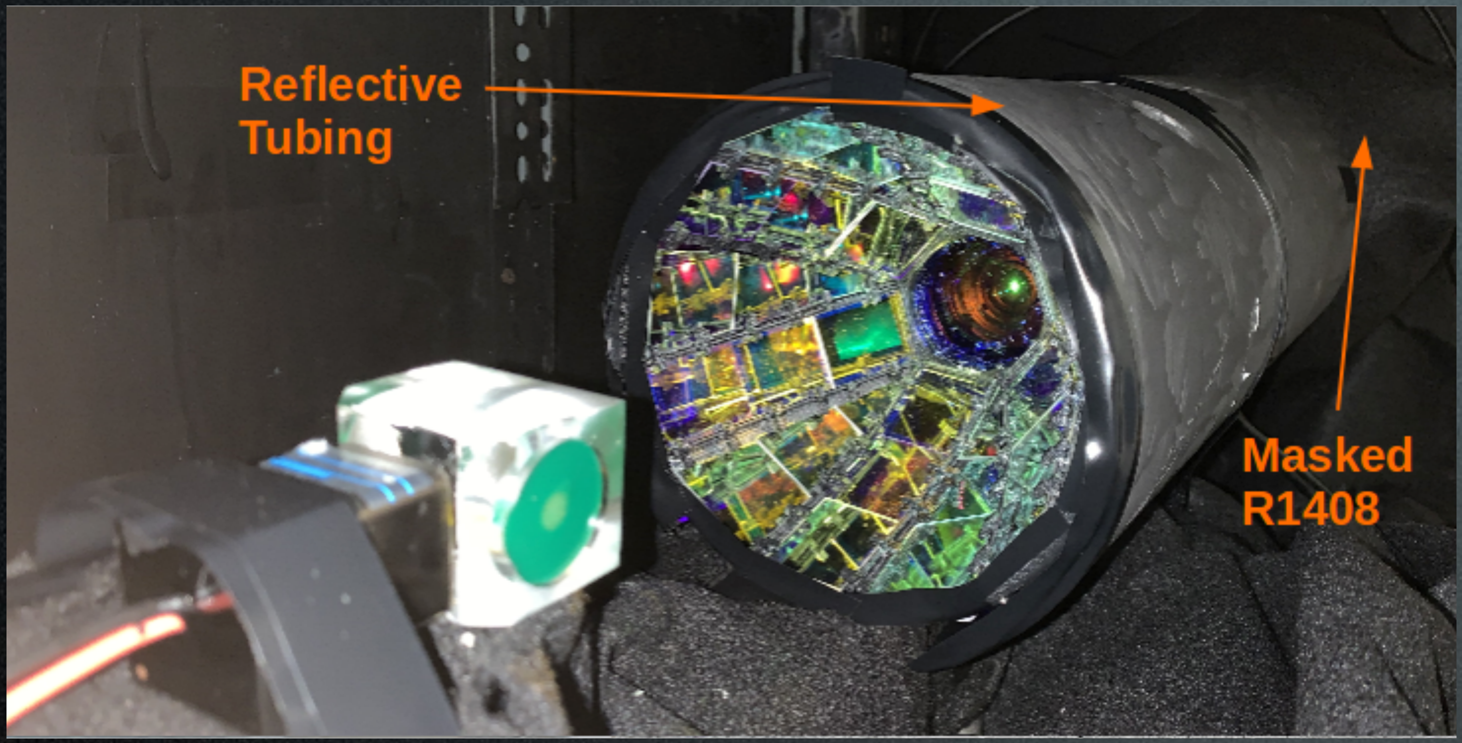


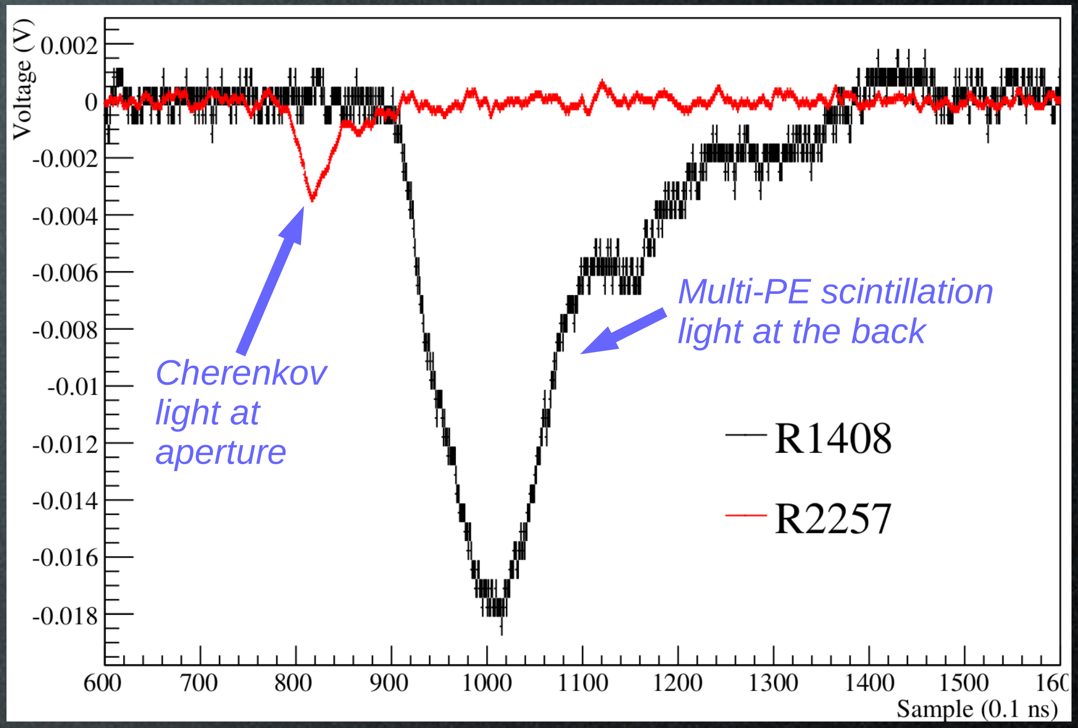
- A Winston cone made of a dichroic filter reflects only red light to red-filtered photosensor
  - Side benefit: red light is faster, with less scattering and dispersion
- Blue light passes through the cone to a standard reflector and is measured by a separate photodetector



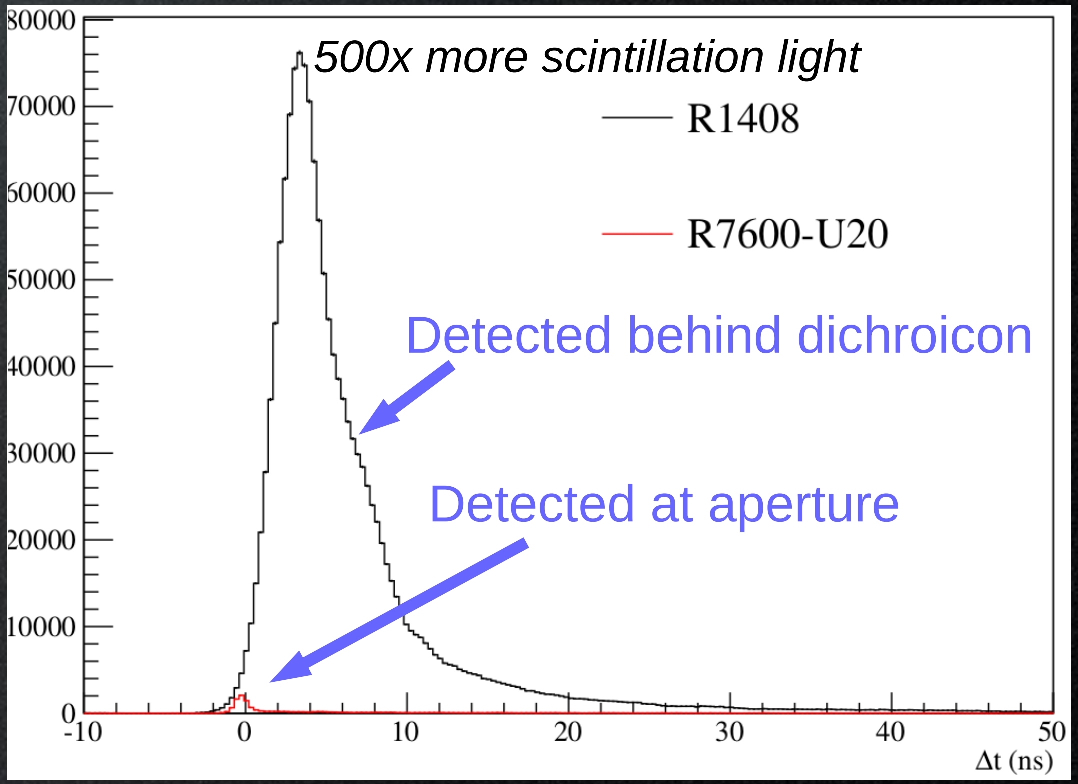
T. Kaptanoglu; https://indico.bnl.gov/event/6963/contributions/32650/attachments/25488/38204/theia_dichroicon_talk.pdf

Dichroicon Performance





- Pure Cherenkov and (mostly) scintillation signals can be detected separately
- Cherenkov signal can still be seen in the presence of a very large scintillation signal



Summary

- WbLS technology is still at an early stage, and effort is ongoing to understand large-scale applications
  - WbLS filtration/recirculation system R&D is ongoing
  - Various scaled-down options are being explored for WCTE based on initial results from test setups at UC Davis and BNL
- If WbLS is to be a possibility for WCTE, we need to consider capability of materials in mPMTs, cables, support structure, etc.
  - Otherwise, a separate contained volume of WbLS would be required
- UPenn has interest in deploying some dichroicons for Cherenkov/scintillation separation studies
- German groups are applying for funding for WbLS studies in a CERN test beam, and collaboration may be possible