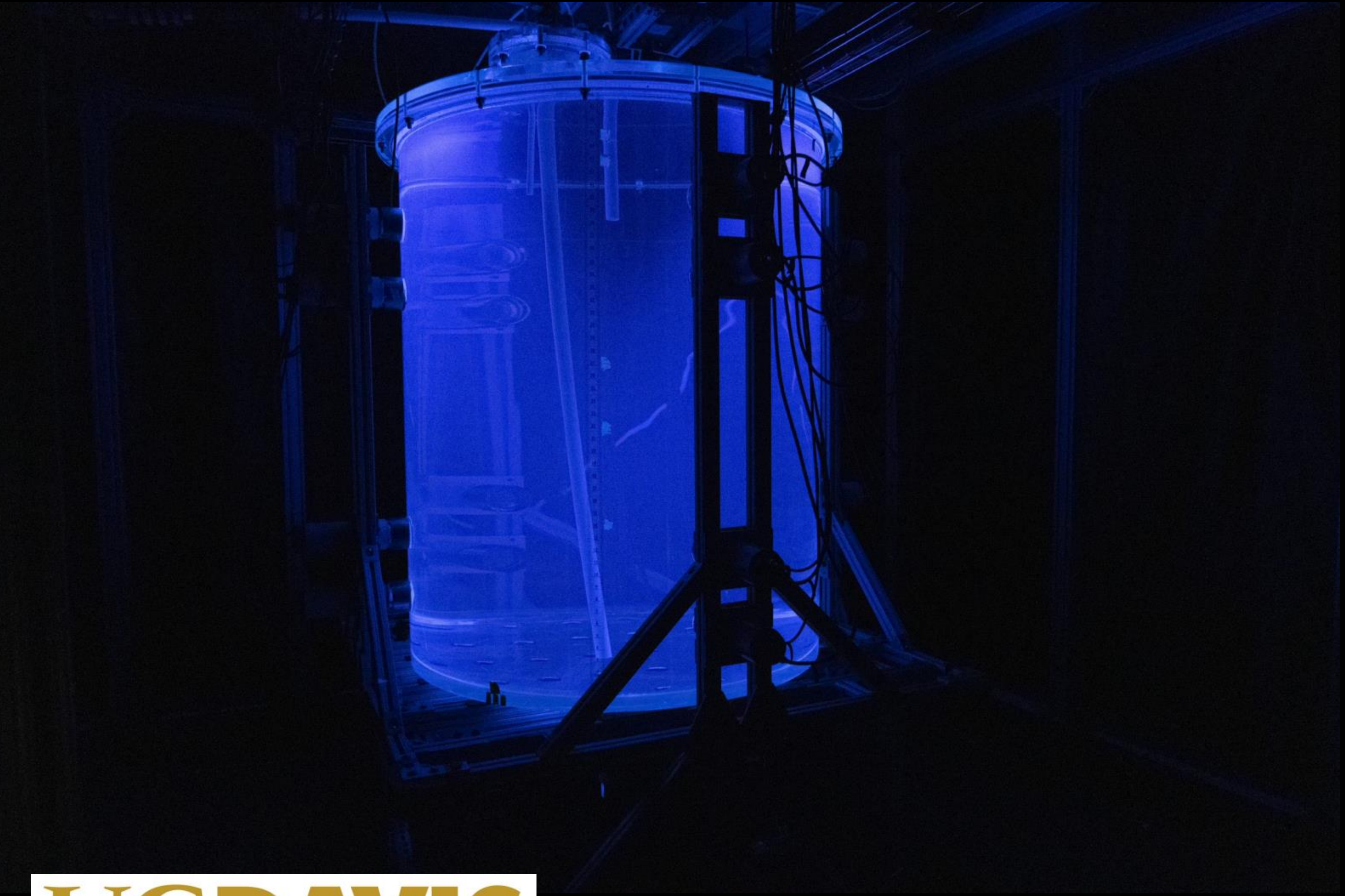
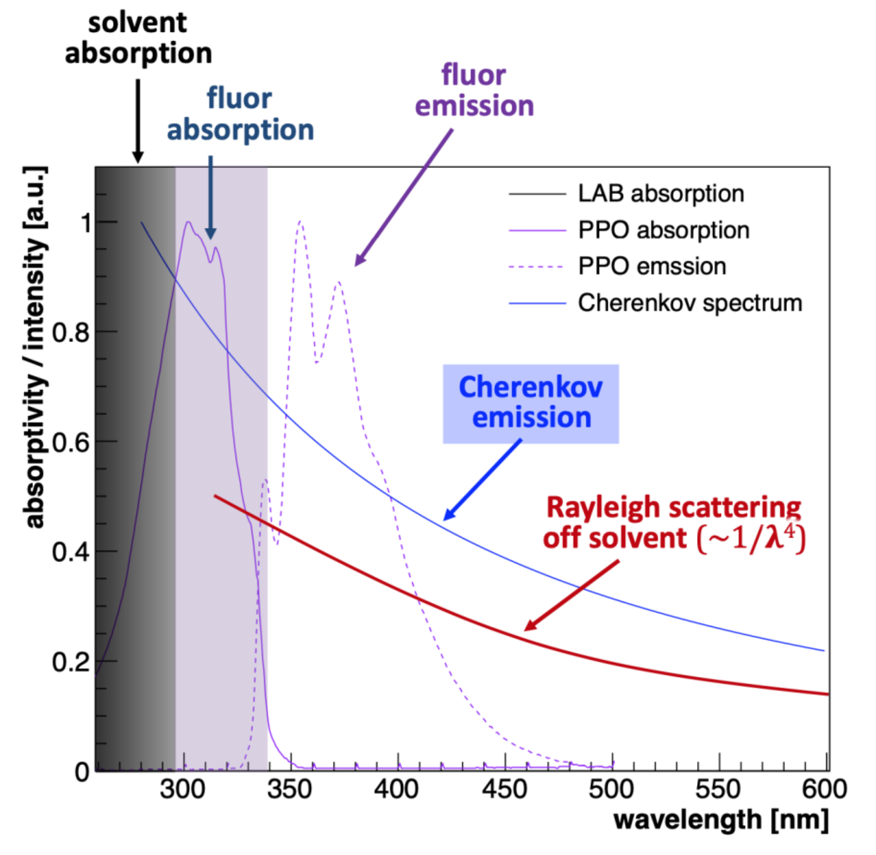
Status of the 30-ton Purification Demonstrator at Brookhaven





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Theia White Paper details the science that could be done by making a *Hybrid Optical Detector* that could *separate Cherenkov and scintillation light using* Water-based Liquid Scintillator

Eur. Phys. J. C (2020) 80:416
https://doi.org/10.1140/epjc/s10052-020-7977-8

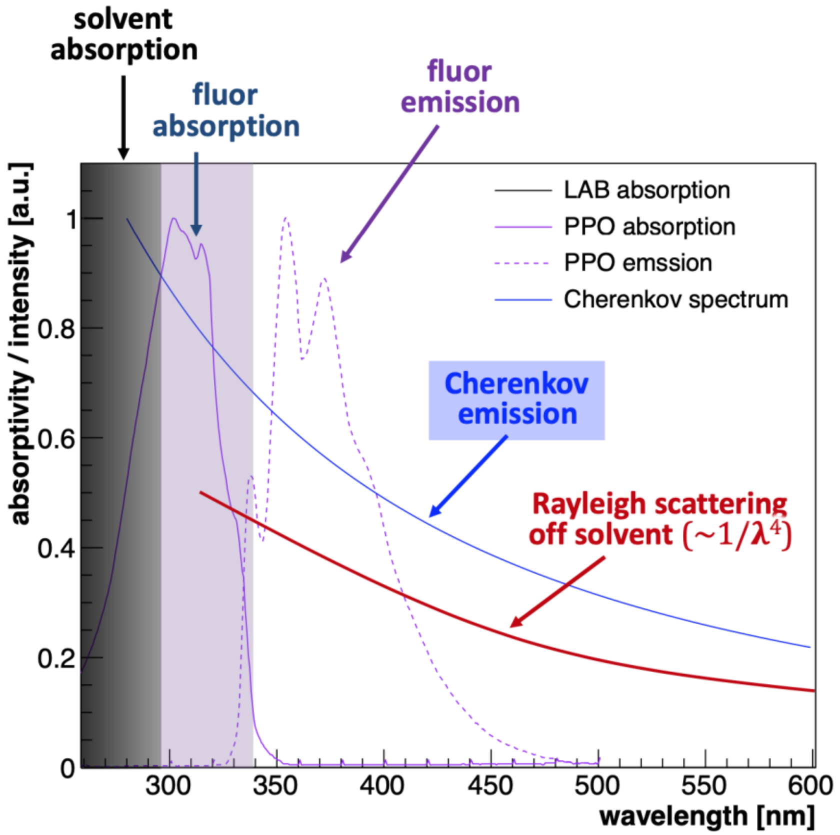
THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

THEIA: an advanced optical neutrino detector

M. Askins[1,2], Z. Bagdasarian[3], N. Barros[4,5,6], E. W. Beier[4], E. Blucher[7], R. Bonventre[2], E. Bourret[2], E. J. Callaghan[1,2], J. Caravaca[1,2], M. Diwan[8], S. T. Dye[9], J. Eisch[10], A. Elagin[7], T. Enqvist[11], V. Fischer[12], K. Frankiewicz[13], C. Grant[13], D. Guffanti[14], C. Hagner[15], A. Hallin[16], C. M. Jackson[17], R. Jiang[7], T. Kaptanoglu[4], J. R. Klein[4], Yu. G. Kolomensky[1,2], C. Kraus[18], F. Krennrich[10], T. Kutter[19], T. Lachenmaier[20], B. Land[1,2,4], K. Lande[4], J. G. Learned[9], V. Lozza[5,6], L. Ludhova[3], M. Malek[21], S. Manecki[18,22,23], J. Maneira[5,6], J. Maricic[9], J. Martyn[14], A. Mastbaum[24], C. Mauger[4], F. Moretti[2], J. Napolitano[25], B. Naranjo[26], M. Nieslony[14], L. Oberauer[27], G. D. Orebi Gann[1,2,a], J. Ouellet[28], T. Pershing[12], S. T. Petcov[29,30], L. Pickard[12], R. Rosero[8], M. C. Sanchez[10], J. Sawatzki[27], S. H. Seo[31], M. Smiley[1,2], M. Smy[32], A. Stahl[33], H. Steiger[27], M. R. Stock[27], H. Sunej[8], R. Svoboda[12], E. Tiras[10], W. H. Trzaska[11], M. Tzanov[19], M. Vagins[32], C. Vilela[34], Z. Wang[35], J. Wang[12], M. Wetstein[10], M. J. Wilking[34], L. Winslow[28], P. Wittich[36], B. Wonsak[15], E. Worcester[8,34], M. Wurm[14], G. Yang[34], M. Yeh[8], E. D. Zimmerman[37], S. Zsoldos[1,2], K. Zuber[38]



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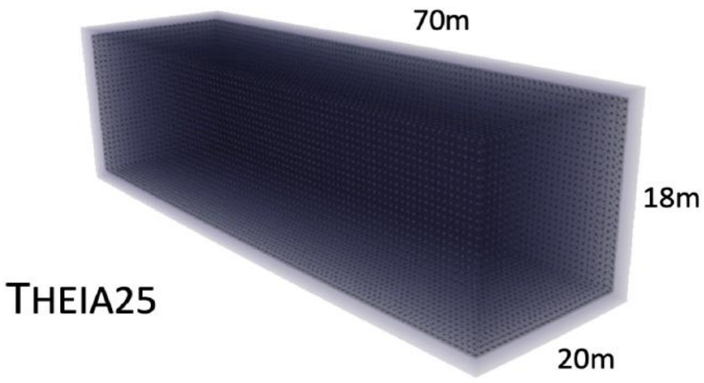
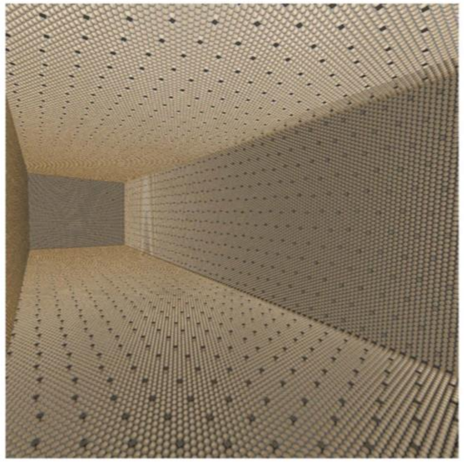
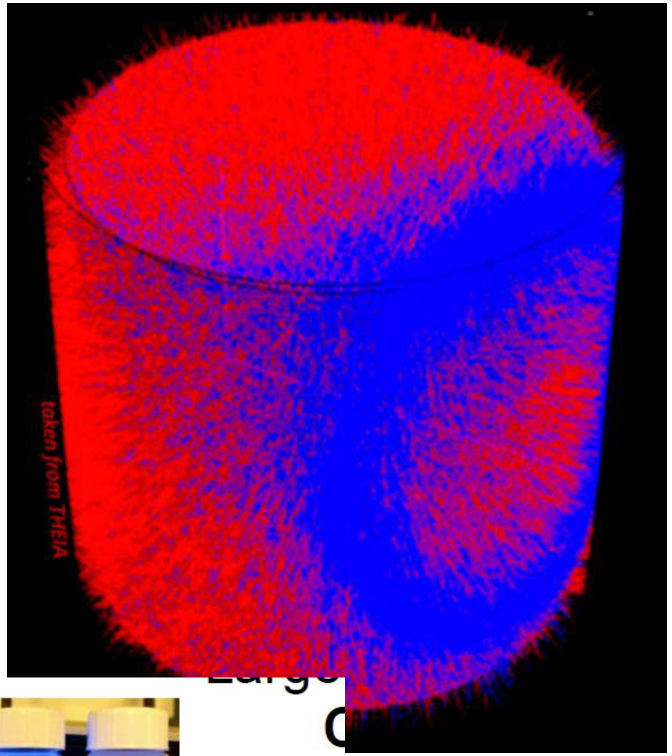
Hybrid Cherenkov/Scintillator Module ("Theia")

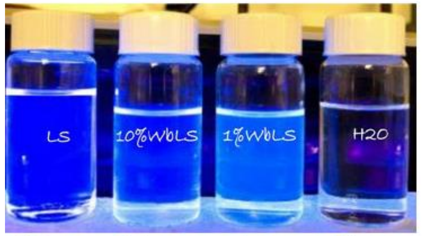




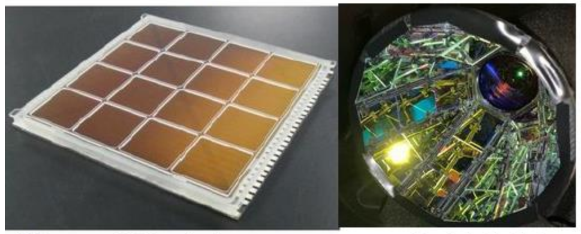


Hybrid signals allow broad physics program:

- CP violation with sensitivity same as 1 DUNE module for Theia25
  - Low-Z target allows cross check with Hyper-K
  - Requires changes to ND suite
- Precision low-energy solar neutrinos (CNO, pep, ^{8}B MSW transition)
- Diffuse supernova background neutrinos
- Literally complementary supernova burst signal: anti-ν_e vs. ν_e
- Eventual $0\nu\beta\beta$ experiment with sensitivity beyond inverted ordering
- Solar and Geo neutrinos



Novel target medium: (Wb)LS

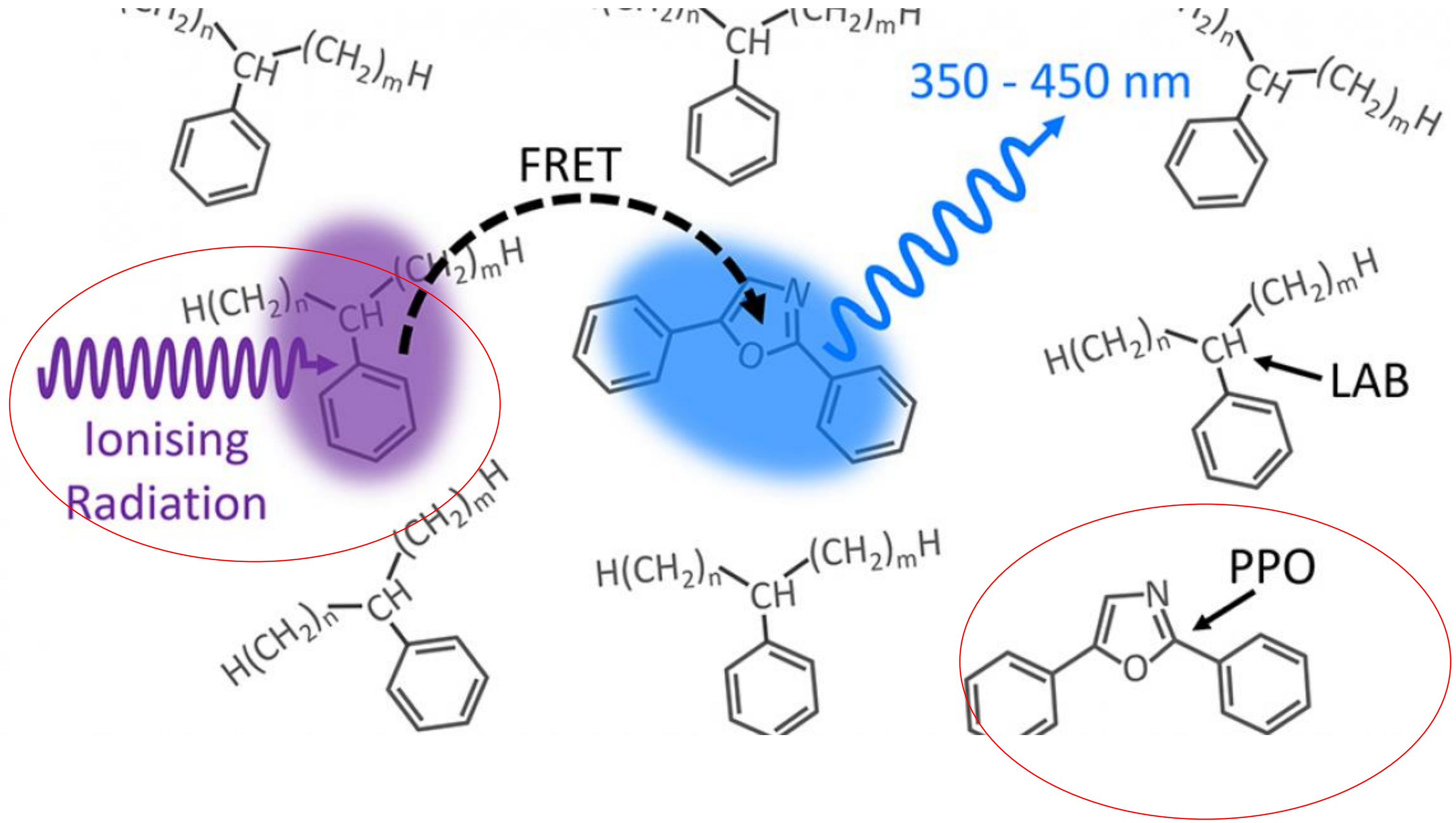


Novel light sensors: LAPPDs, dichroicons

New technologies make this possible

How Does This Work?

Many aromatic organic compounds naturally scintillate due to benzene ring excitation. Addition of a *fluor* (e.g. PPO) is necessary for high light yield



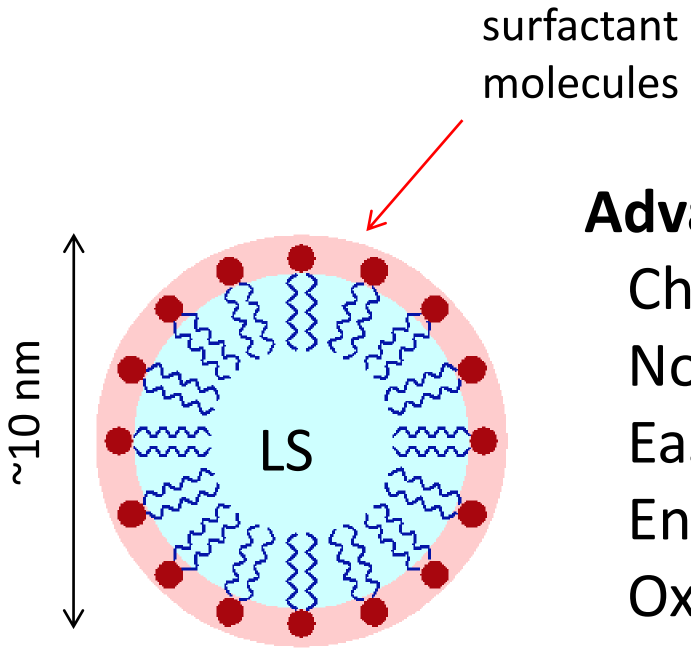
unless a PPO molecule can absorb the energy, it will eventually be lost to heat. Thus, adding PPO increases the light yield in addition to speeding up the process

If one could dissolve aromatic compounds in water in droplets with size larger than the scale size of this molecular process it should still work

The time it takes to transfer energy to the PPO gets shorter as concentration increases.

Water-based Liquid Scintillator

WbLS works by forming small (~10 nm scale) droplets called *micelles* in water that are stabilized by surfactant molecules with a hydrophilic head and hydrophobic tail. Micelles form under controlled chemical conditions and are shown to be stable over year time scales.

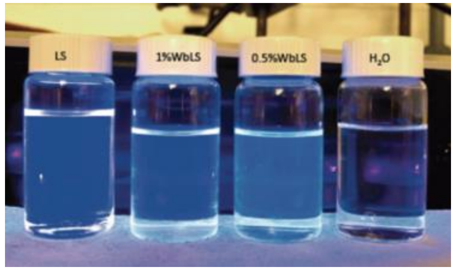


Advantages:

- Cheaper than LS
- Non-combustible
- Ease of loading Li, Te, etc
- Environmentally friendly
- Oxygen nuclei instead of Carbon

Disadvantages

- Radiological cleanliness more difficult
- Lower light yield than pure LS

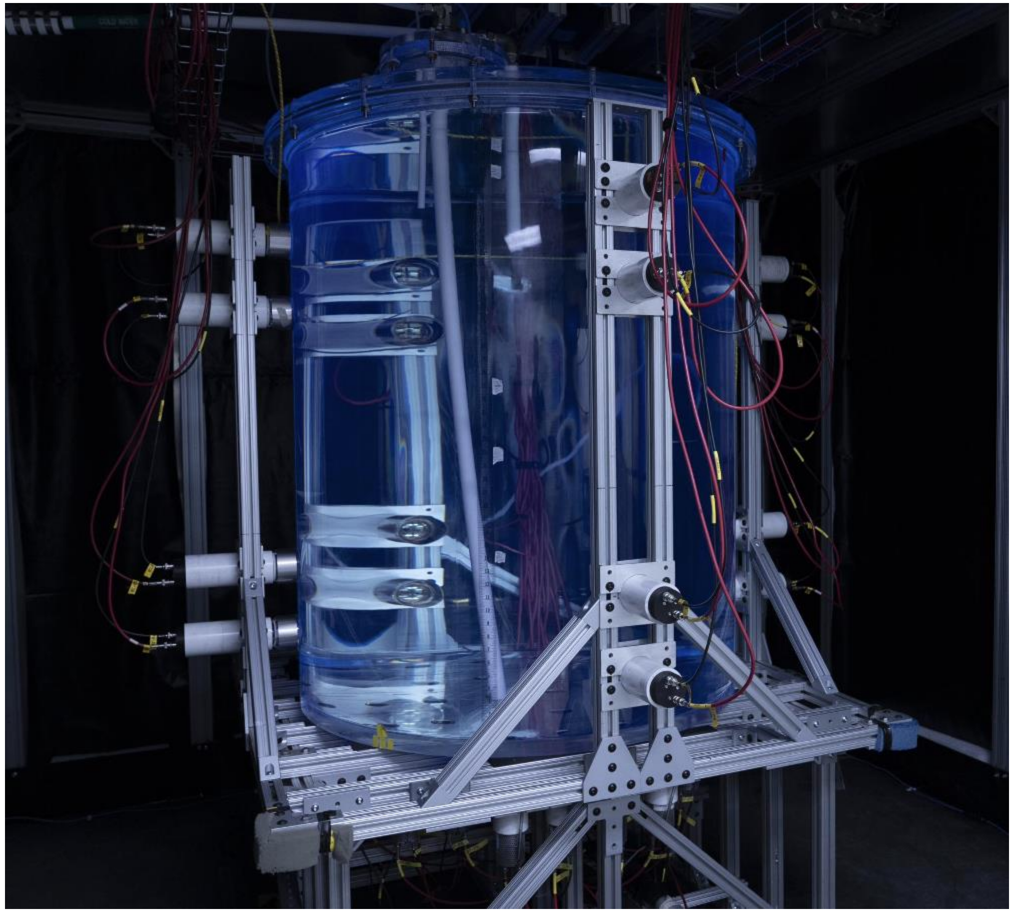


Large scale demonstrators are now under construction

- The development of hybrid optical detectors is now beyond the "R&D stage"

- A coherent program of prototyping is well underway. Expect completion by early 2025

- These prototypes will allow us to complete the final work on most remaining technical options, including:
  - fill media characterization
  - photosensor array composition
  - liquid purification system parameters
  - low energy and high energy event reconstruction



BNL 1-ton demonstrator

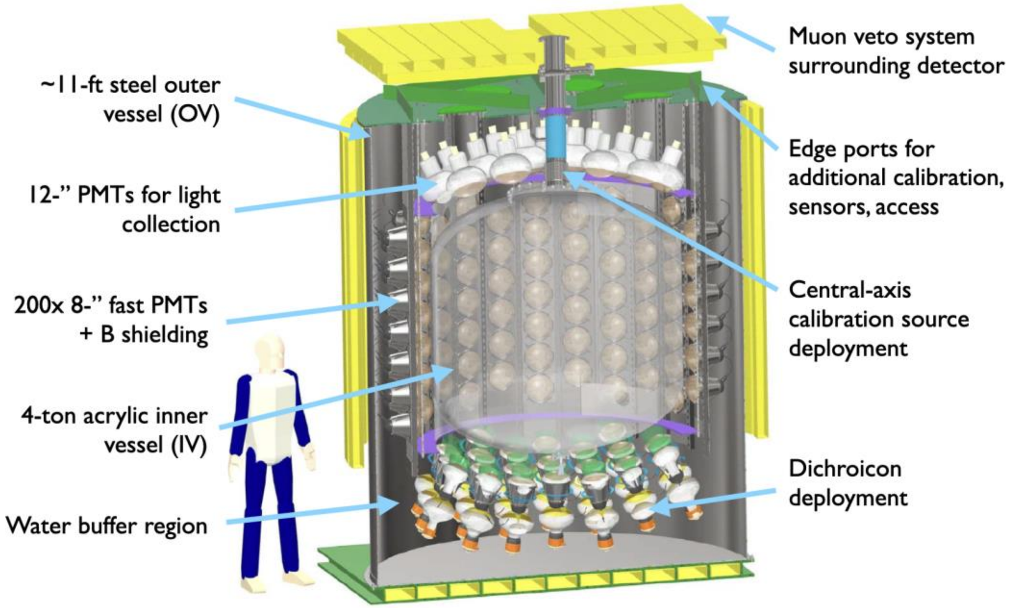
Eos: performance demonstrator

Project goals:

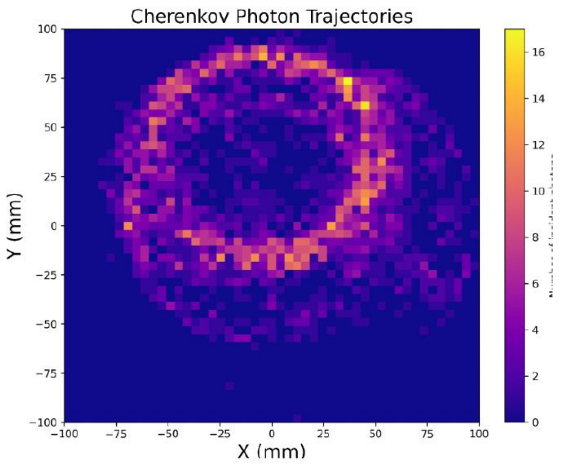
- Demonstrate event reconstruction using hybrid Cherenkov + scintillation signatures
- Validate models to support large-scale detector performance predictions
- Provide a flexible testbed to demonstrate impact of novel technology

Integrated testbed to demonstrate the performance of novel technology:

- 4-ton target mass: *water, WbLS, organic LS*
- 200 8" PMTs: *R14688-100, 900ps FWHM*
- CAEN V1730 readout
- Dichroicon deployment for spectral sorting
- Deployable sources for studies of vertex, energy, direction reconstruction & PID



Eos detector paper published: JINST 18 P02009 (2023),



Germany

JG|U
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PRiSMA+

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TECHNISCHE UNIVERSITÄT MÜNCHEN

Turkey

ERCIYES UNIVERSITY 1978 Research University

Portugal

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1290 UNIVERSIDADE D COIMBRA

Finland

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Canada

SNOLAB

(see H.Steiger talk this conference)

USA

BERKELEY LAB

The University of California Berkeley 1868

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Penn University of Pennsylvania

Lawrence Livermore National Laboratory

BOSTON UNIVERSITY

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STATE

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RUTGERS

IOWA

BARTOSZEK ENGINEERING

South Dakota School of Mines & Technology

University of Colorado Boulder

The University of Chicago 1890

California State University Stanislaus

California State University East Bay 1957

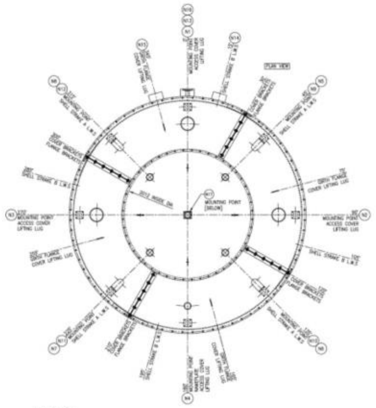
BUTTON

Boulby **U**nderground **T**echnology **T**estbed **O**bserving **N**eutrinos

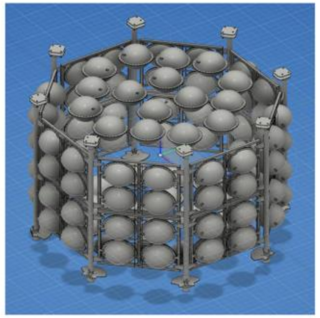
AWE
Lawrence Livermore National Laboratory
Pacific Northwest NATIONAL LABORATORY
UKRI Science and Technology Facilities Council
Boulby Underground Laboratory

THE UNIVERSITY OF WARWICK
University of Sheffield
Penn UNIVERSITY of PENNSYLVANIA
THE UNIVERSITY of EDINBURGH
University of Glasgow
UNIVERSITY OF LIVERPOOL

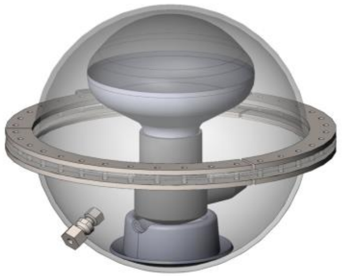
BUTTON low-background testbed for neutrino detector hardware and fill media.



- ~30 tonnes
- ~100 Hamamatsu R7081 10” PMTs



- Modular support structure to facilitate swapping out **advanced photosensor technology**.



- Compatible with **novel fill materials**.

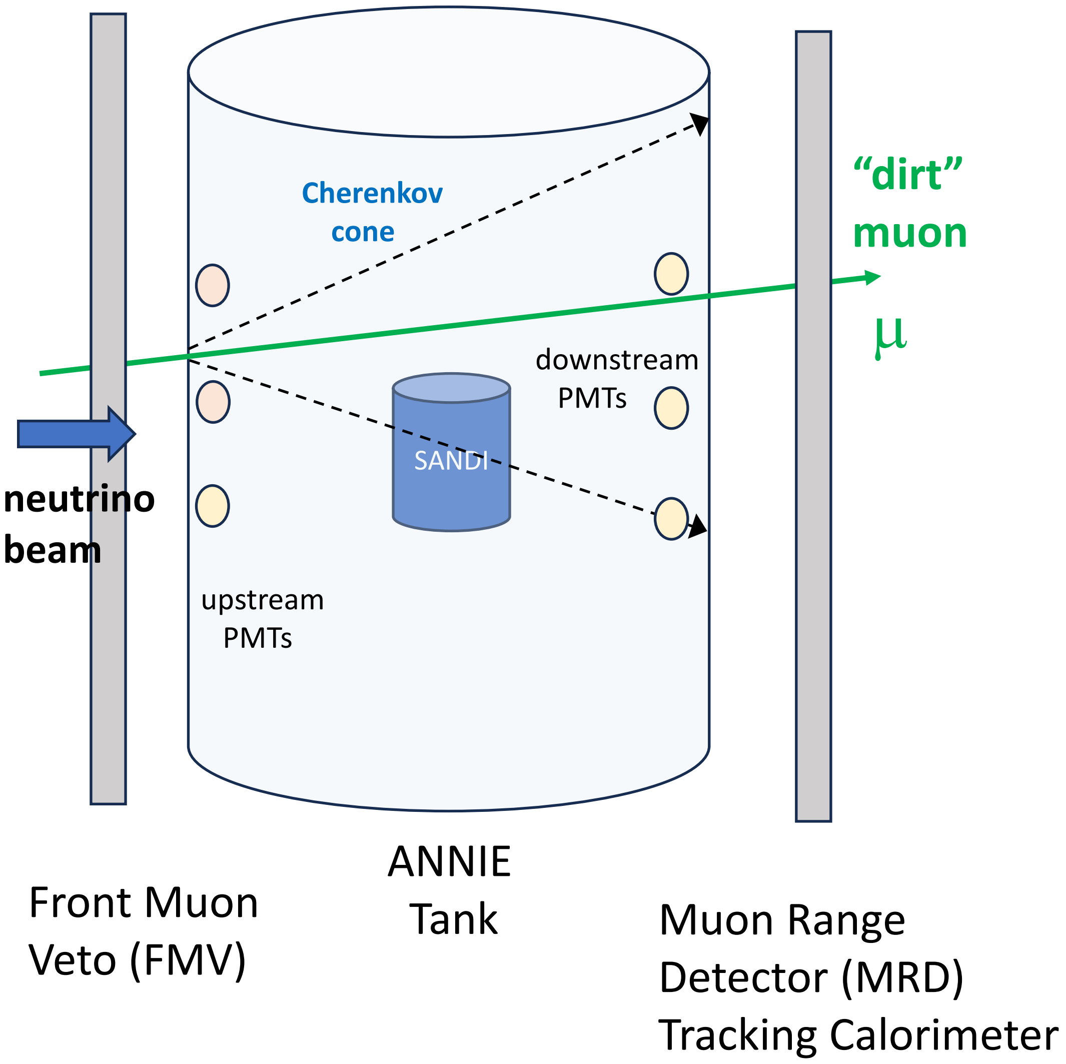
Underground 30-ton demonstrator to test radiological purity and backgrounds relevant to Theia physics program

Construction to be completed in 2024

Larger follow-on larger detector also being planned

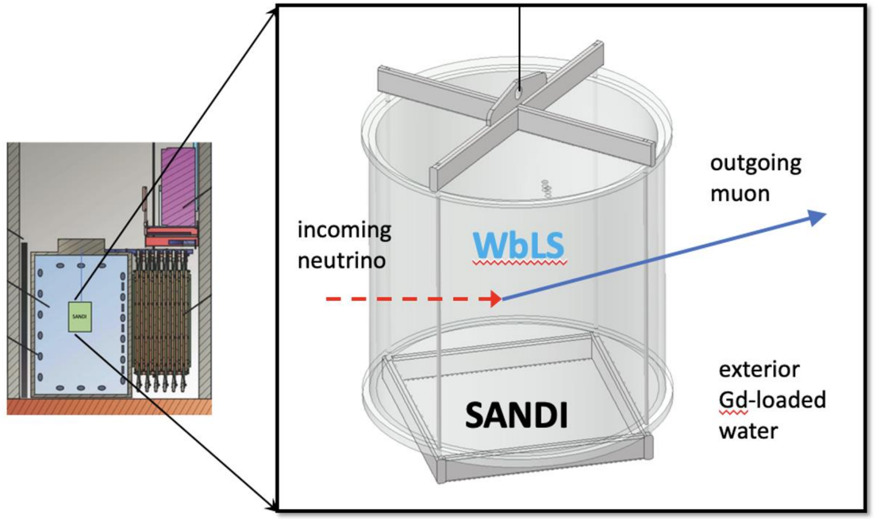
ANNIE High Energy Reconstruction Test

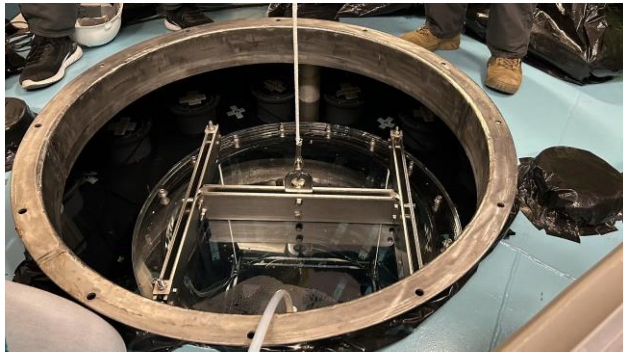
(First deployment last March. See M.Wurm talk this conference)



SANDI

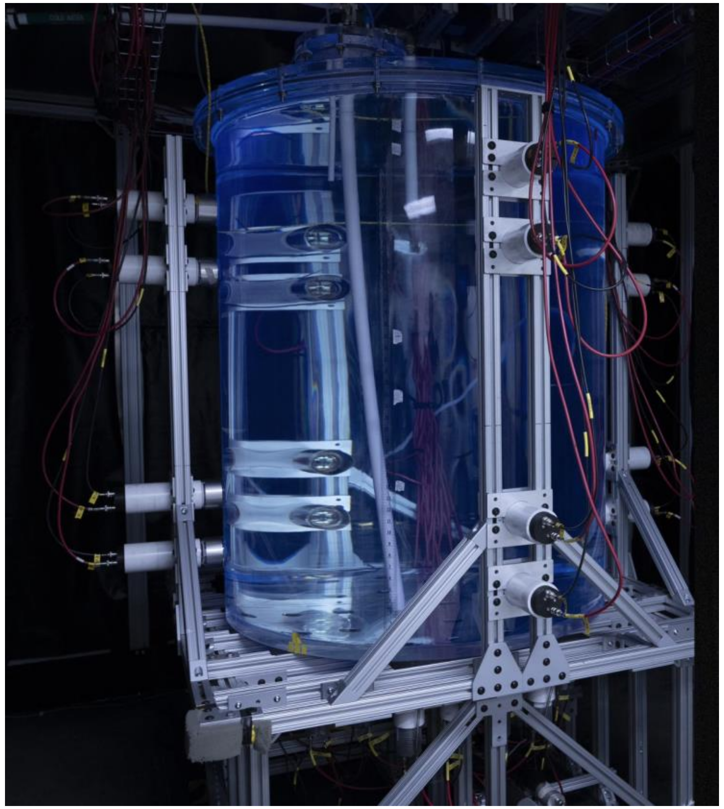
(Scintillator for ANNIE Neutrino Detection Improvement)



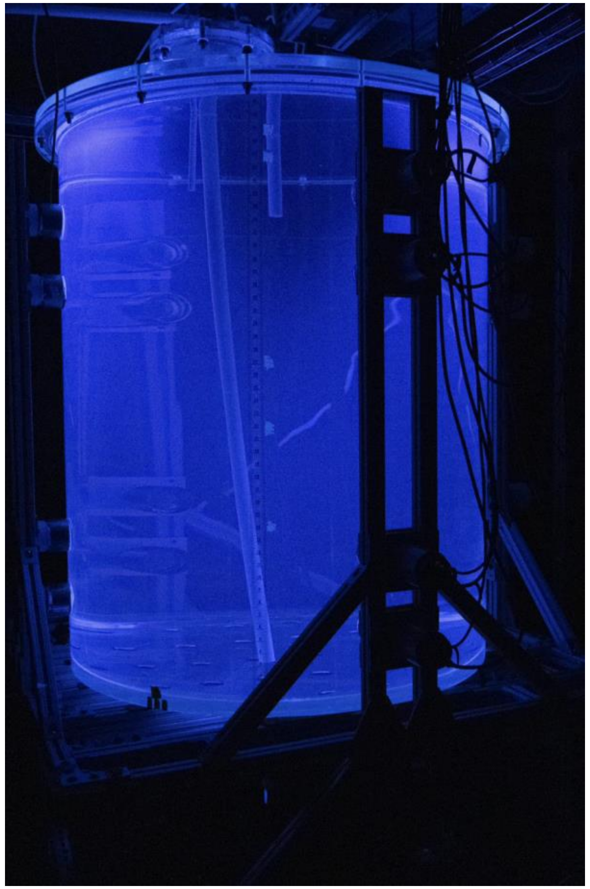


Theia Purification Demonstrators

- Fully-functional recirculation and WbLS purification system.
  - This system can also handle purification even with ion doping of the WbLS
  - Demonstrator has instrumentation to determine effectiveness of recirculation and allow for spike tests of known optical and radiological contaminants (e.g. iron ions)
- This project is a follow-on to the existing 1-ton Demonstrator, **now running** at BNL



1-ton Demonstrator at Brookhaven



filled with WbLS

Why Do We Need This?

- **Leaching products** from detector materials can absorb or scatter light
  - Iron ions, colloids, compounds
  - UV absorbers from plastics
  - other possible ions (e.g. nitrates)
- Can also contain **radioactive contaminants**
  - 238-Uranium → 222-Rn → 214-Bi (among others) → 210-Pb (22 year half life) → 210-Bi (Q=1.2 MeV)
  - 232-Th → 208-Tl (2.6 MeV gamma)
  - 40-K (1.4 MeV gamma)
  - Radon (to a lesser extent)
    - hard to remove from detector in short time scale, but leads to 214-Bi and 210-Pb

All large liquid detectors built to date require some form of *in situ* purification. Theia will need this.

Example: Super-Kamiokande

Quantitative tests using a 19 meter attenuation arm show that even clean stainless steel exposed to ultrapure water will leech impurities into the water that absorb UV light.

It was also shown that this could be due to iron ions going into solution even at ppb levels.

Table 3
The change in ρ resulting from the addition of $FeCl_3$ to pure water

Pure water value	14 ppb $FeCl_3$ in water	28 ppb $FeCl_3$ in water
0.901 ± 0.018	0.355 ± 0.018	0.156 ± 0.008

Contents lists available at ScienceDirect
Nuclear Instruments and Methods in Physics Research A
journal homepage: www.elsevier.com/locate/nima

Transparency of 0.2% $GdCl_3$ doped water in a stainless steel test environment

W. Coleman [a,*], A. Bernstein [b], S. Dazeley [b], R. Svoboda [b,c]

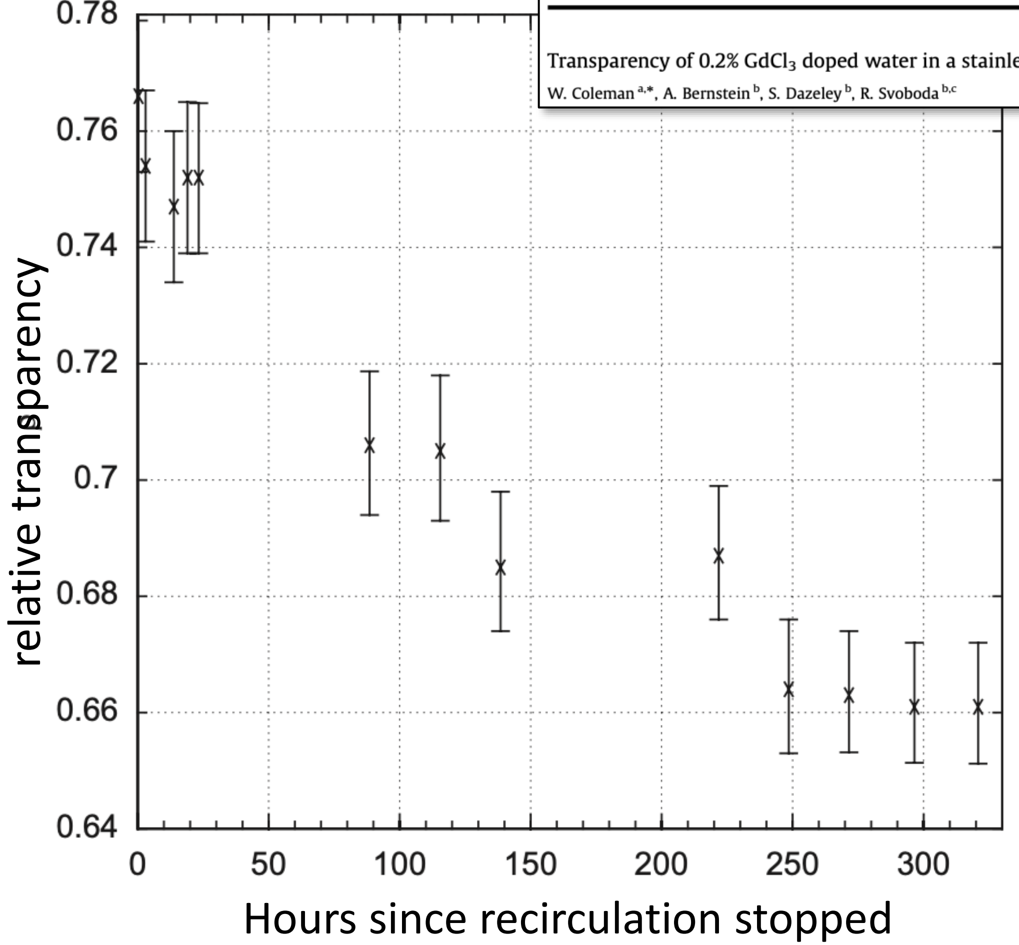


Fig. 5. ρ of pure water measured over approximately 14 days at 337 nm. Recirculation of the water through the system was turned off at $t = 0$. From this point, the water remained undisturbed in the LTA and ρ decreased at the rate of ~1% per day.

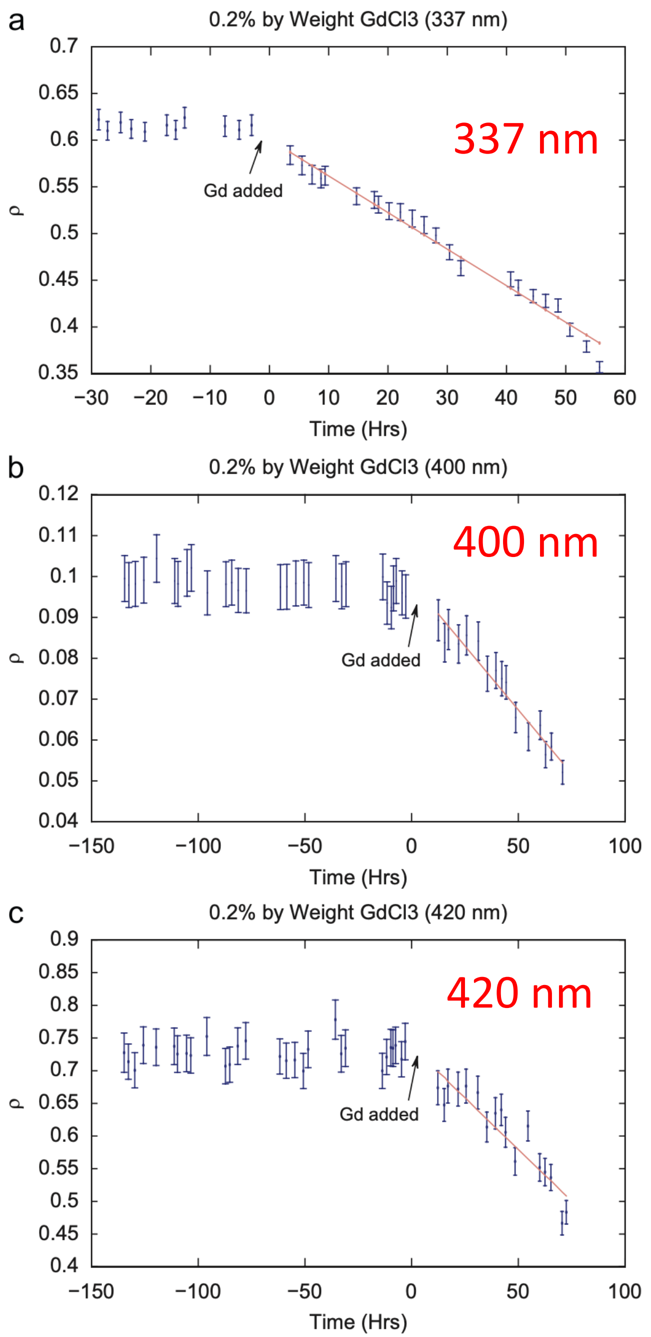
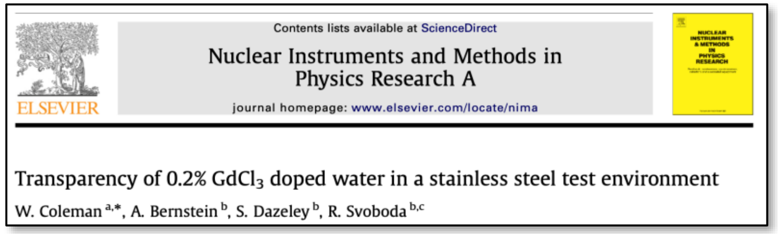


Fig. 7. Decrease in transparency versus time resulting from addition of 0.2% $GdCl_3$ in pure water for 337 nm (a), 400 nm (b) and 420 nm (c). The red line shows the least squares best fit to the data after addition of the $GdCl_3$.

LLNL tests showed that the loss of transparency is broad spectrum, not just Gd absorption lines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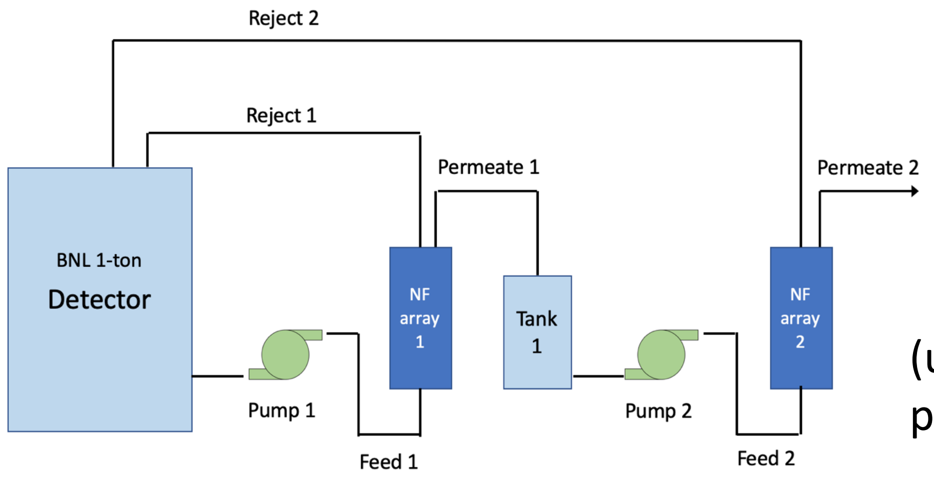
Several of the potential physics topics that could be addressed involve the addition of dissolved ions: Gd, Li, Te

These same tests showed that for Gd the ion itself did not cause a loss of transparency - it was just that fact that the liquid can now conduct charge that accelerated the leeching of steel contaminants

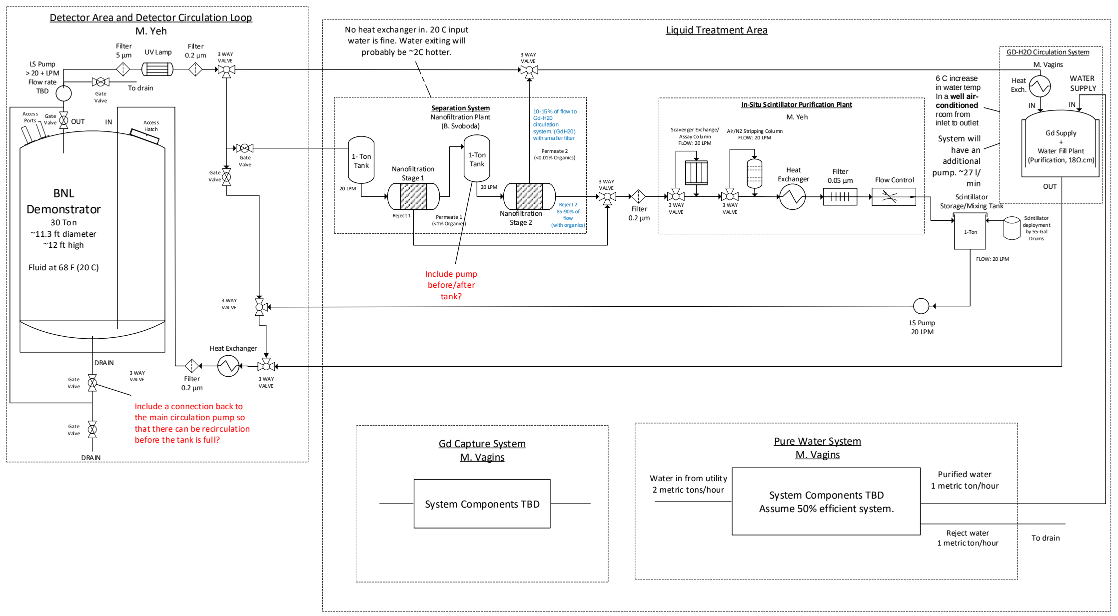
Must solve this problem to make Theia WbLS detector practical!

How to do this?

- Separate the organic components from the water in order to clean the water
- Contaminants must pass through however - this was a challenge now solved!
- Actual tests for contaminants need to be done with spike tests for individual ions, molecules, and iron colloids

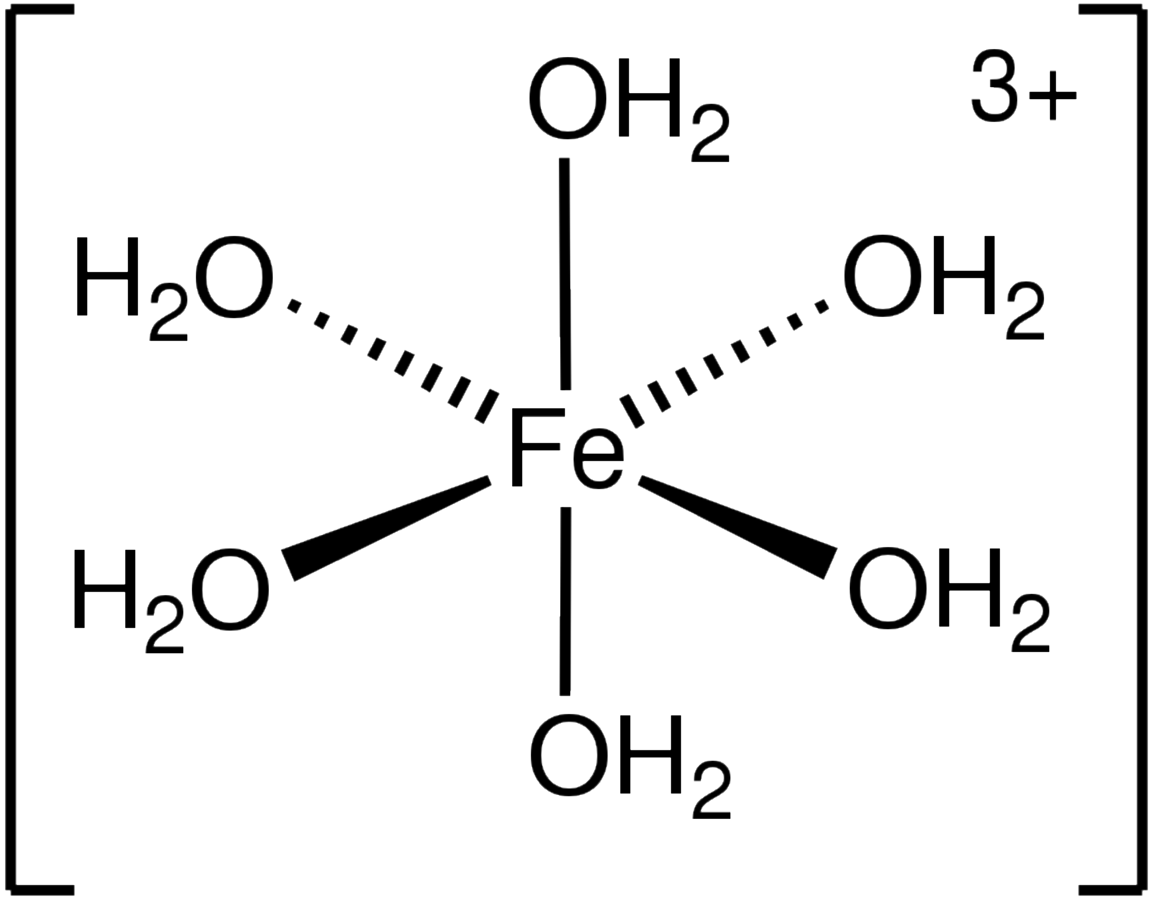


(university physicist)



(BNL engineer)

Iron in solution is not an isolated ion…



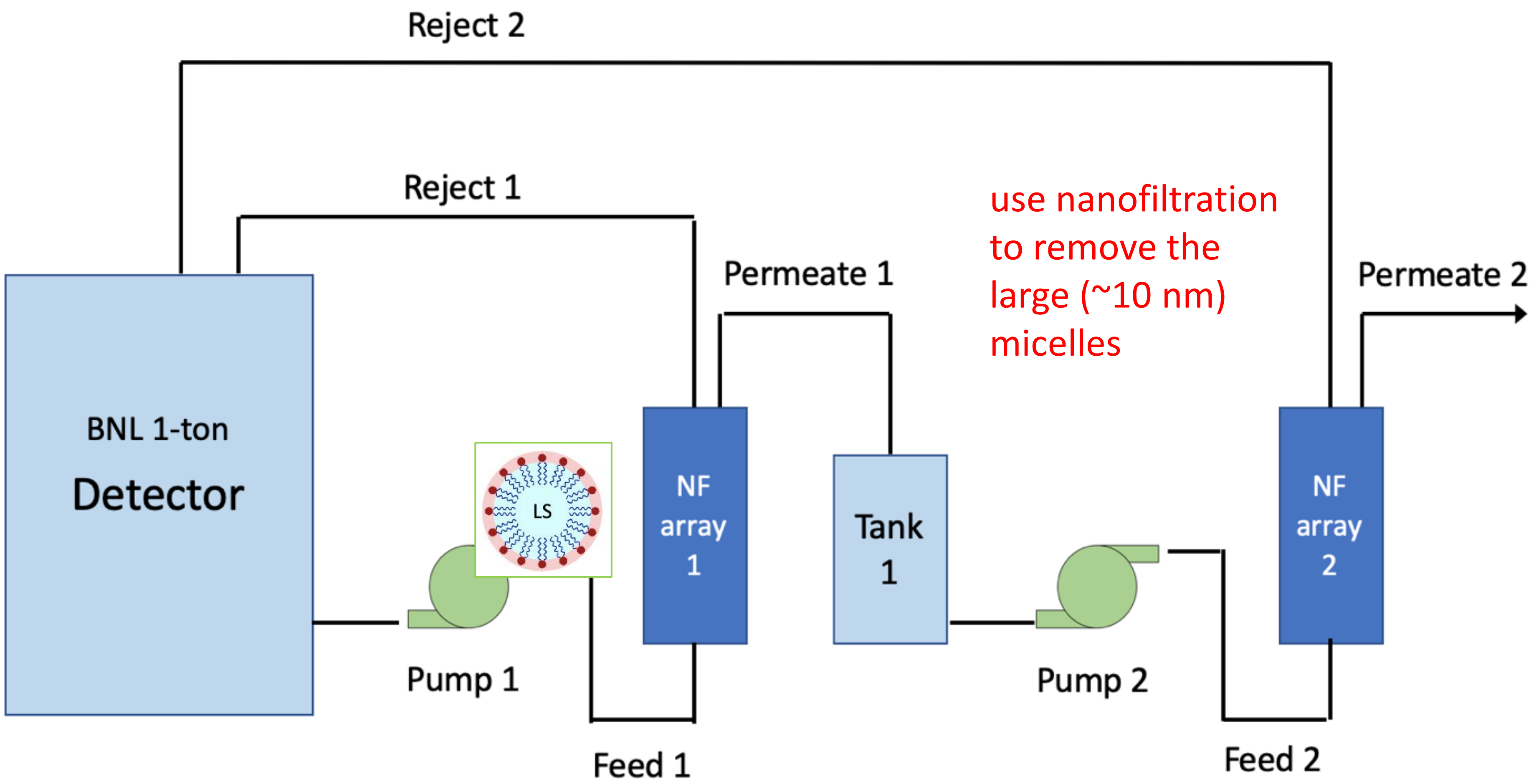
Iron is usually surrounded by 6 OH_2 radicals, giving it an effective molecular weight of 164 Da

The NF shown on the previous slide has a MWCO of 150, so iron tends not to go through much

To be compared with WbLS free surfactants which have MW in the range of 400-600

The basic idea

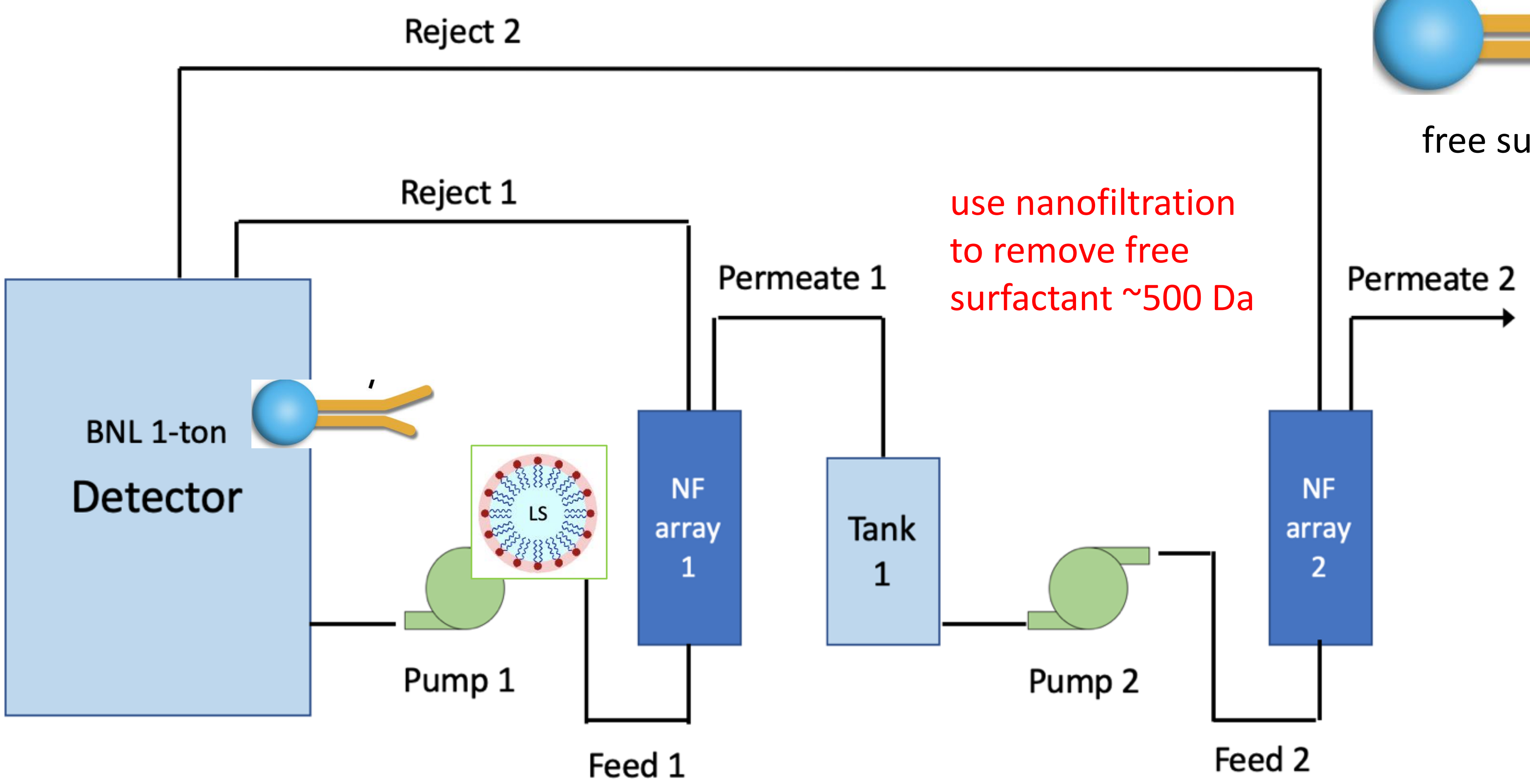
Step 1: remove the micelles from the liquid without disrupting them

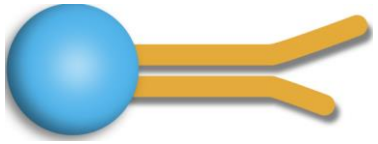


use nanofiltration to remove the large (~10 nm) micelles

The basic idea

Step 2: remove "free" (i.e. non-micellized) surfactant from the permeate of NF array 1

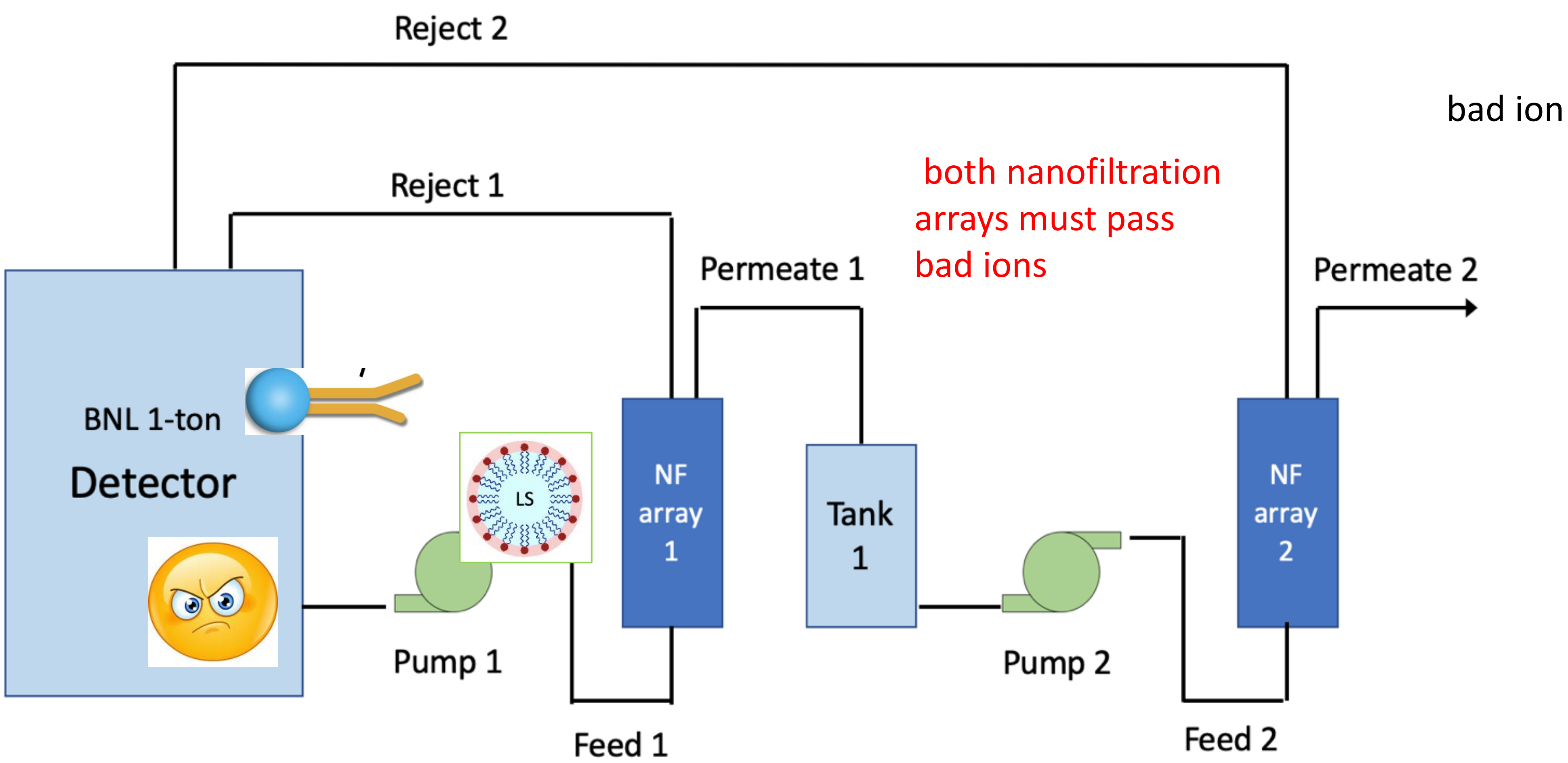




free surfactant

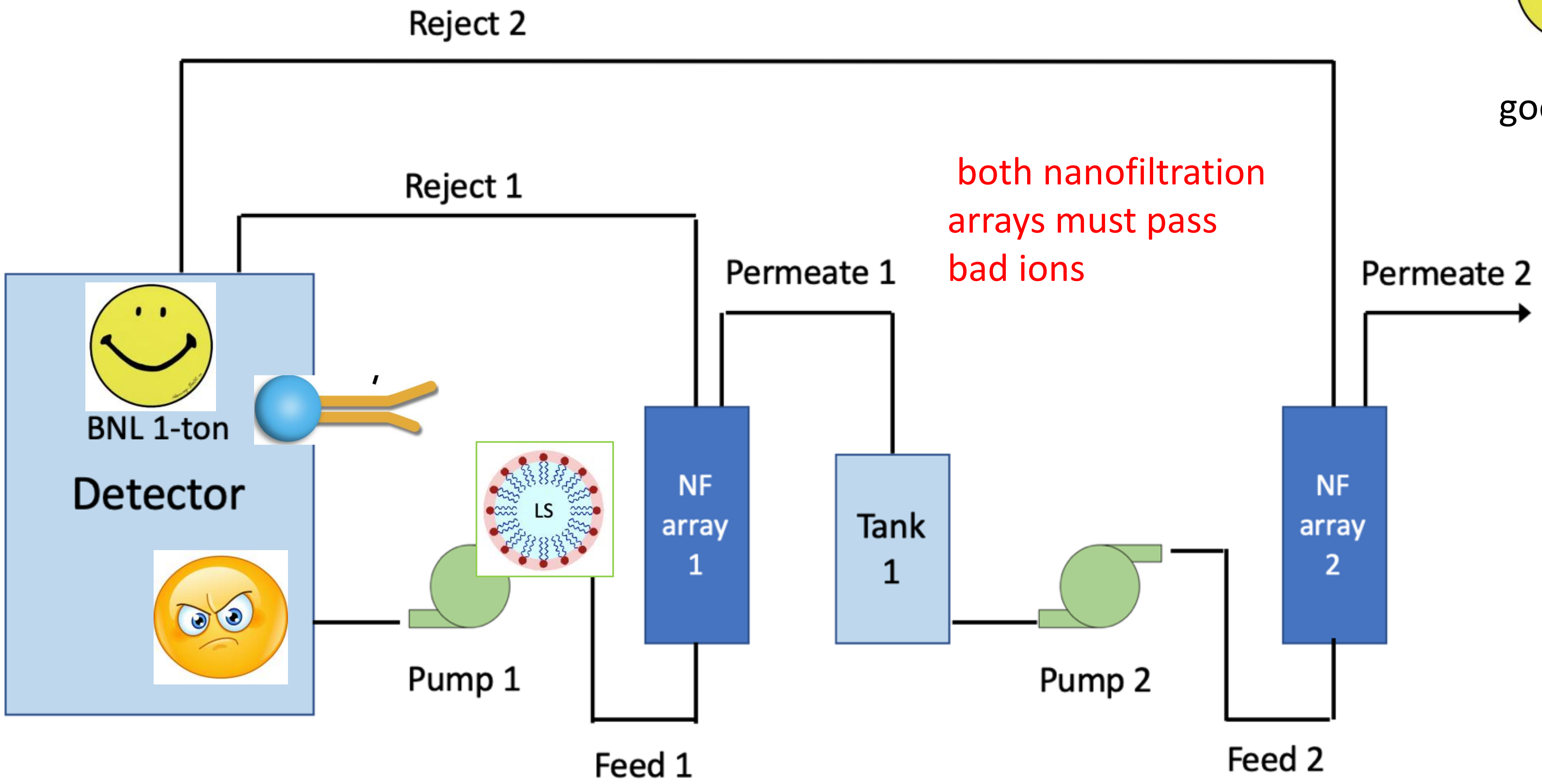
The basic idea

Step 3: pass the "bad" ions to a standard water purification system for removal



The basic idea

Step 4: but keep the good ions!

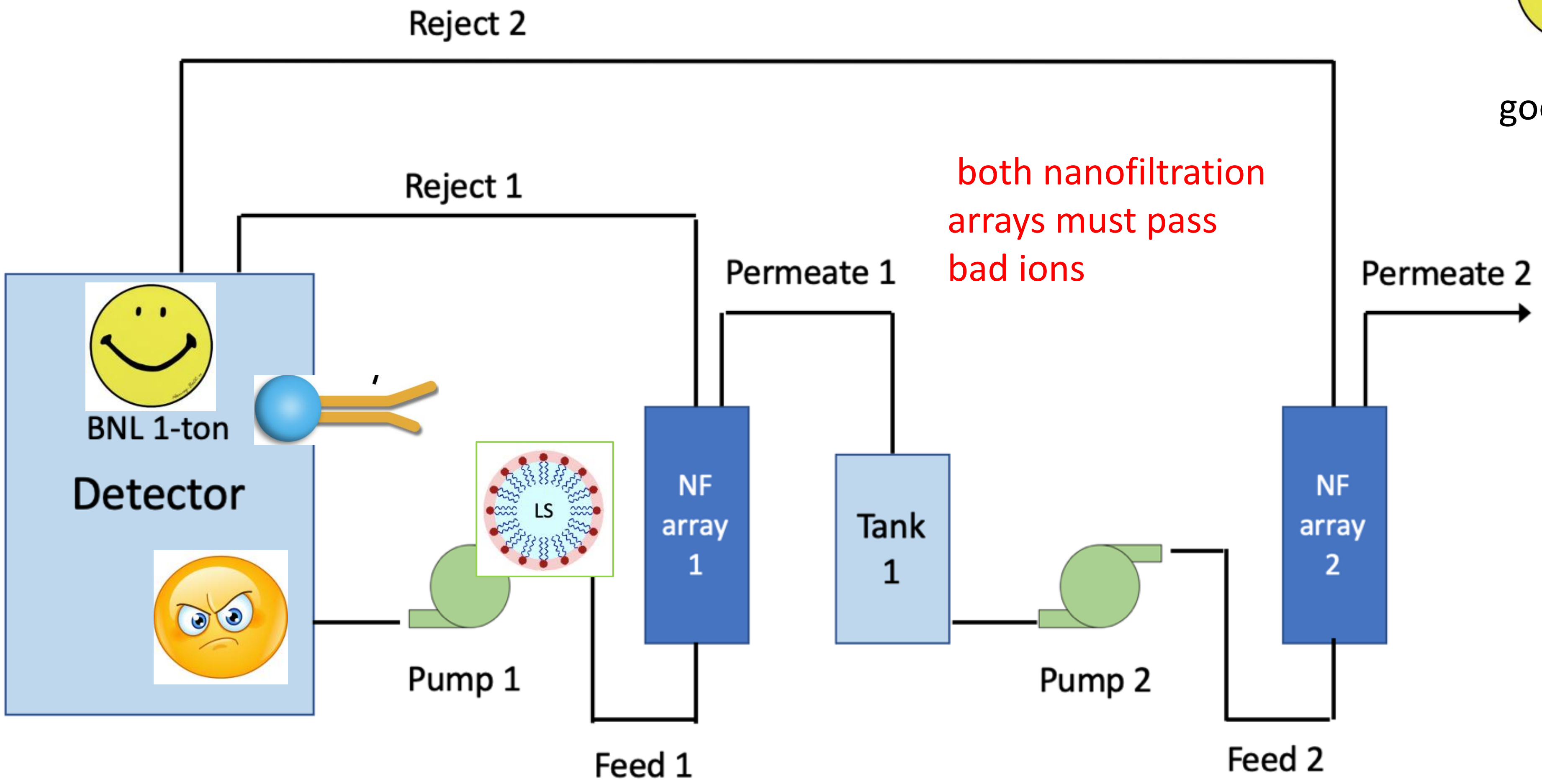


both nanofiltration arrays must pass bad ions

good ion

The basic idea

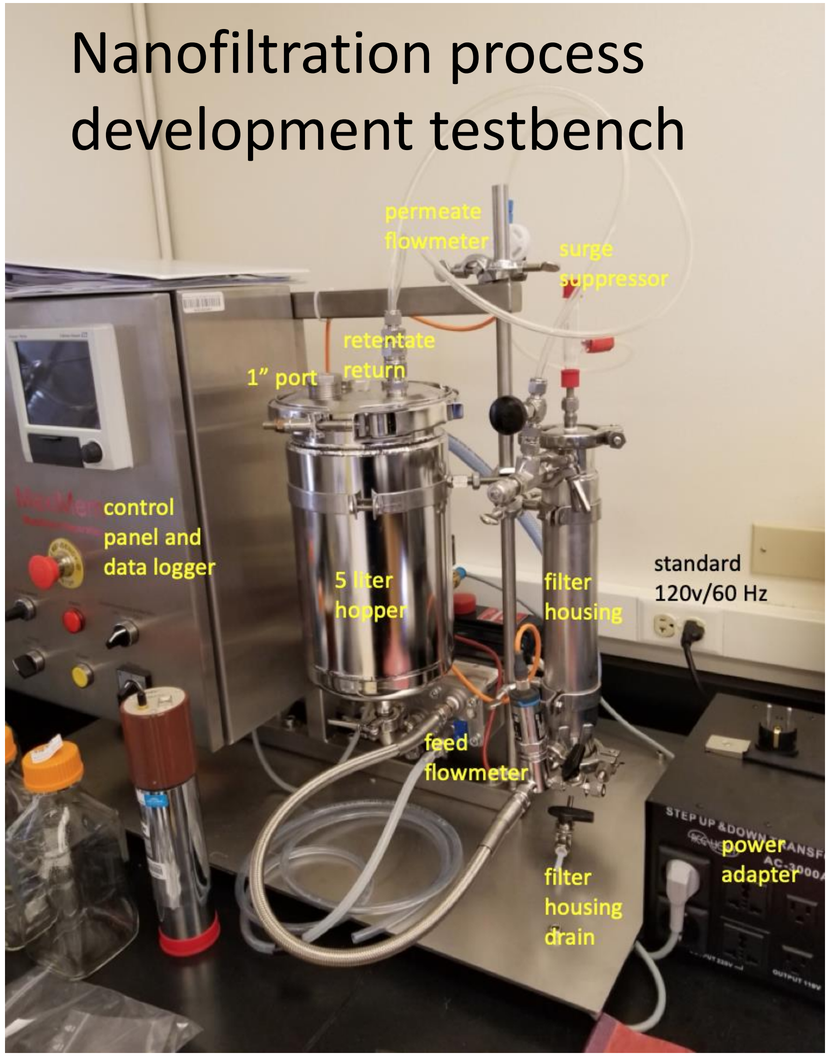
ALL TOGETHER NOW!



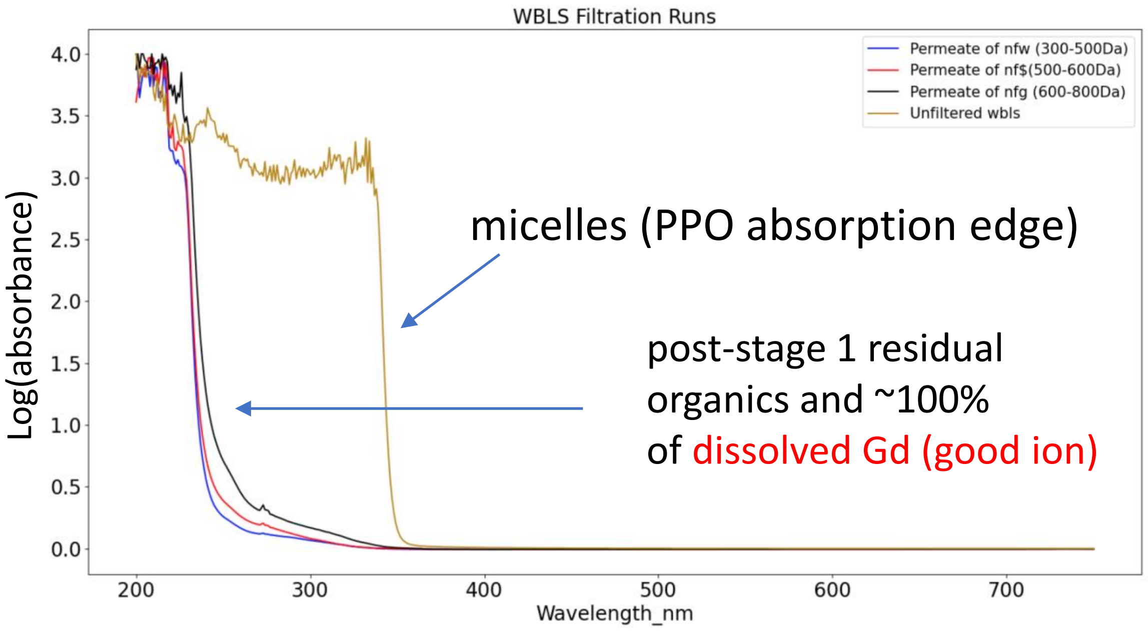
both nanofiltration arrays must pass bad ions

good ion

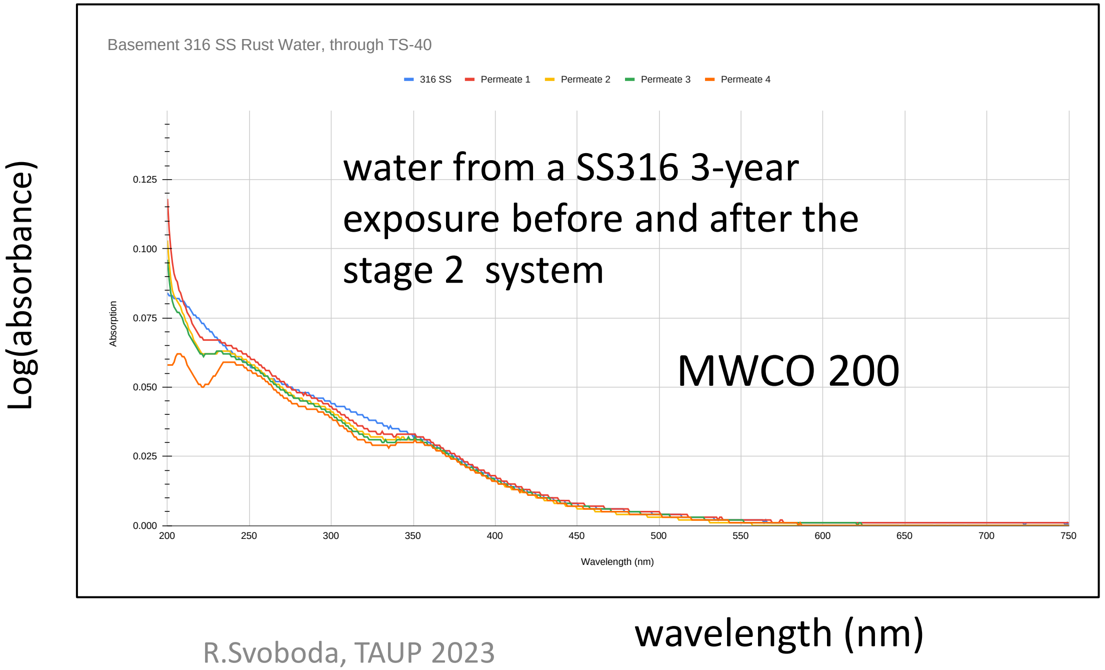
Nanofiltration process development testbench



We are now ready to build a scaled-up version of this!



Array 1: removes (without disruption) the LS-filled micelles. Test show light yield is not affected

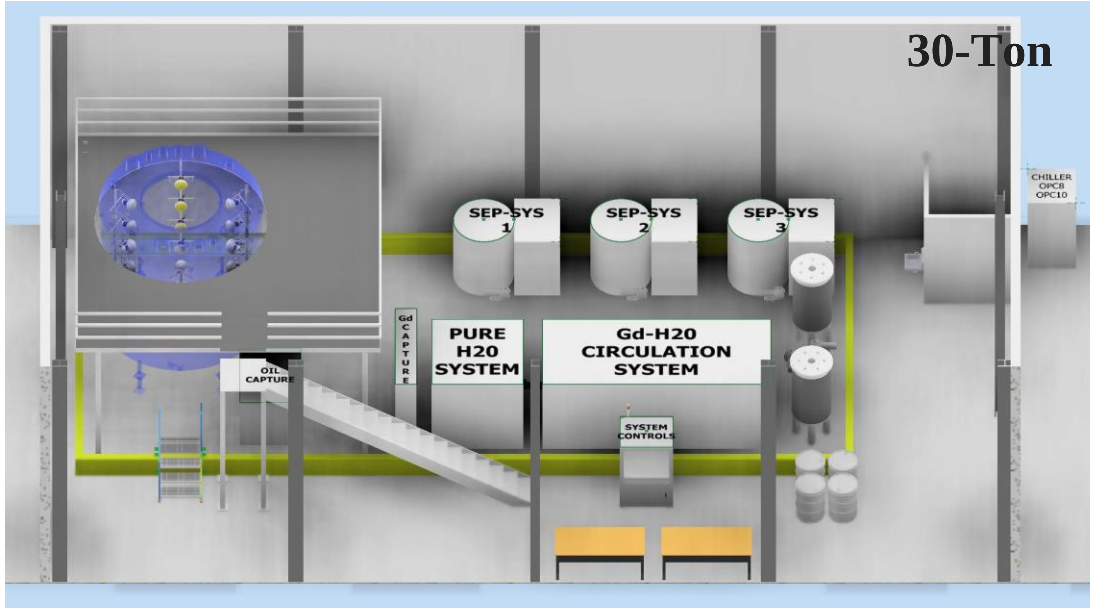


Array 2 passes dissolved iron through to the "standard" water purification system but removes residual organics

30-ton Demonstrator

- **A fully-equipped 30-ton optical detector with in-situ circulation system to demonstrate large-scale WbLS deployment**
- engineering studies of operation parameters, environmental controls and integration with metal purification system (Gd) and nanofiltration system.
- Performance stability, interface, and slow-control
- Capable of adding an Inner Vessel (IV)

National Nuclear Security Administration



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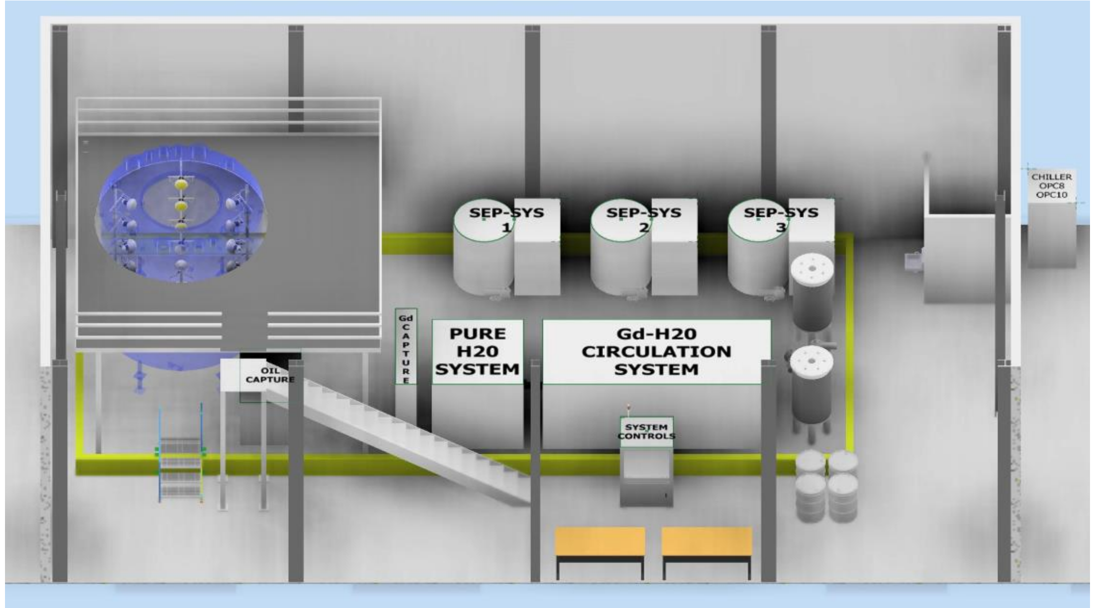
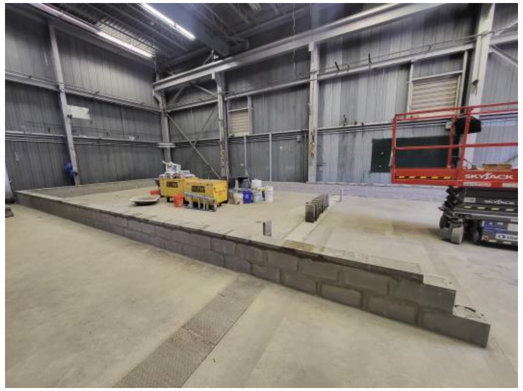


Experimental site at Brookhaven National Lab

power upgrade

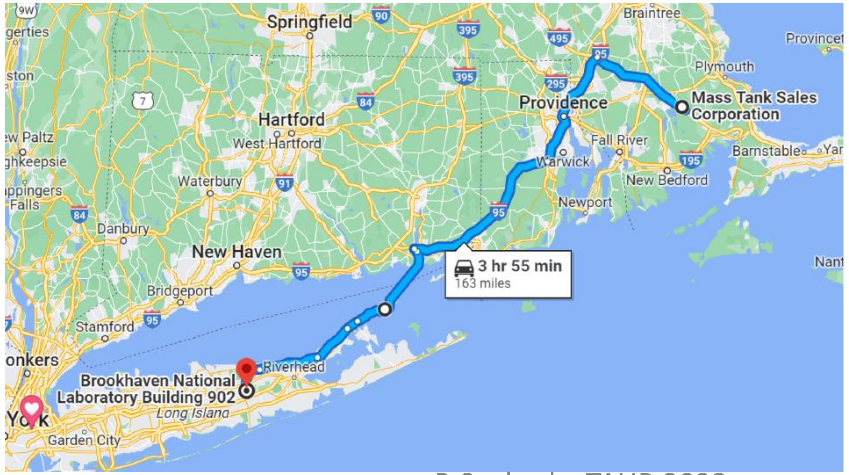
30-Ton Tank will contain PMTs and other instrumentation



secondary containment

National Nuclear Security Administration

30-ton Demonstrator Tank



National Nuclear Security Administration

Summary

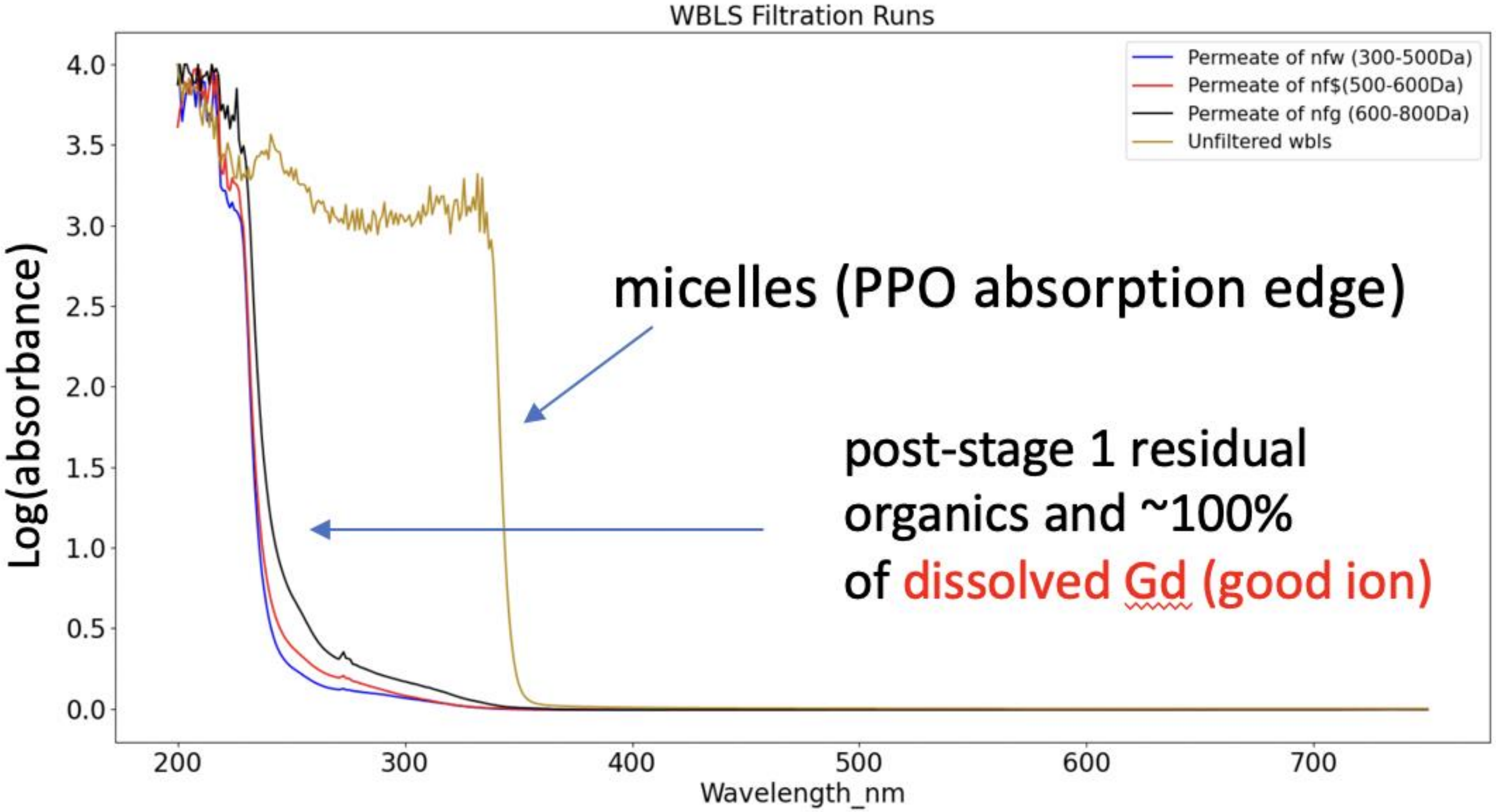
- A major international effort has developed the the needed technology to build the first multi-kiloton scale Optical Hybrid Detector. Such a detector has a wide range of potential scoence opportunities - as discussed in other talks and in the published Theia White Paper.

- A number of large-scale prototypes are now under construction to investigate technical alternatives. These will be completed in the over the next two years, providing date to optimize designs for **unloaded** WbLS in these large detector(s).

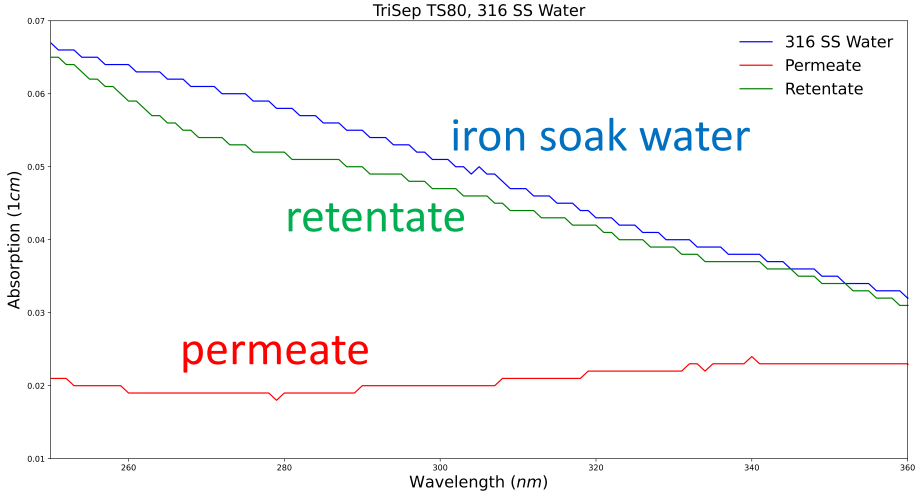
- The R&D to **load and purify WbLS with "good ions"** has now started. A successful Gd-loaded WbLS has already been developed, and the first steps are being taken to load with Te and Li are just getting underway.

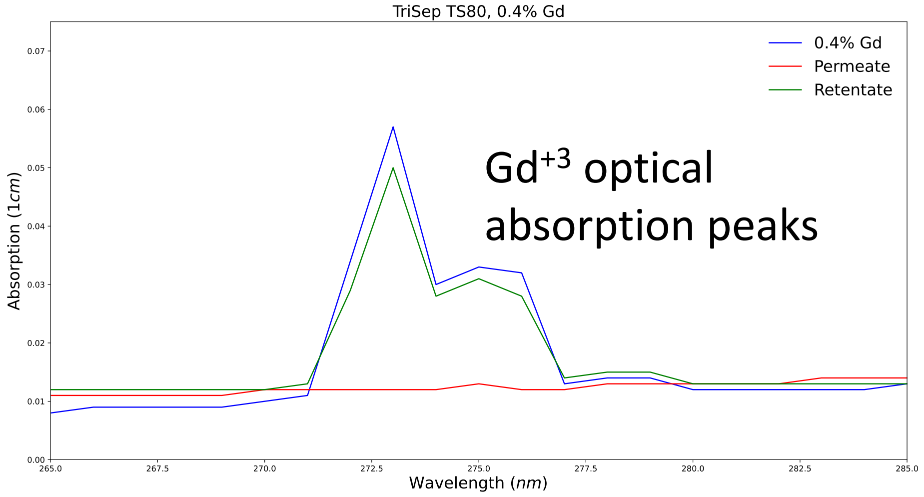
backup slides

Step 1: Separate micelles from the WbLS



Steps 2&3: Pass the bad ions through and keep the good ions



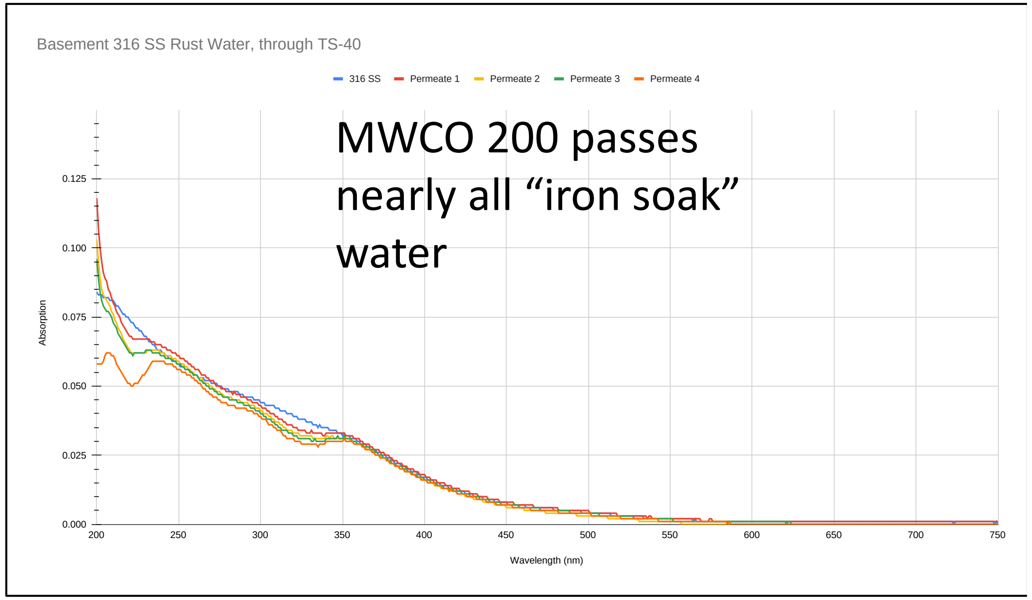


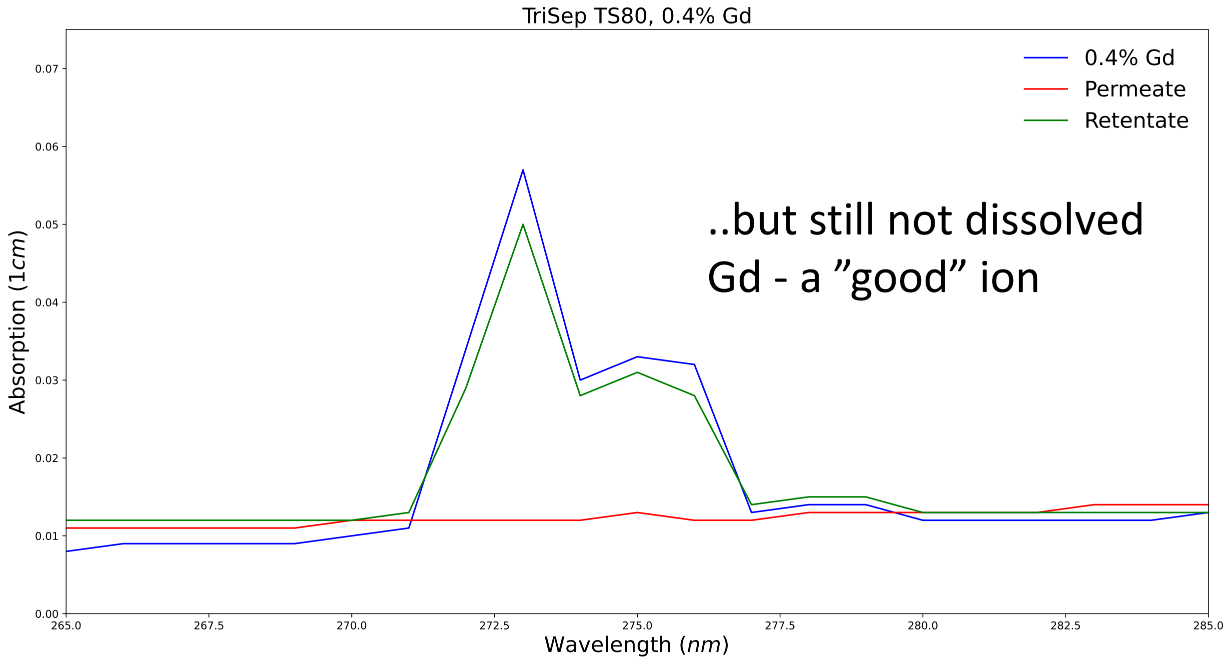
This filter does not pass optical contamination from 316 steel leeching into water - BAD!

Filter does not pass good Gd ions - GOOD!

Not a great candidate…why?

A good candidate for Steps 2&3 has been identified



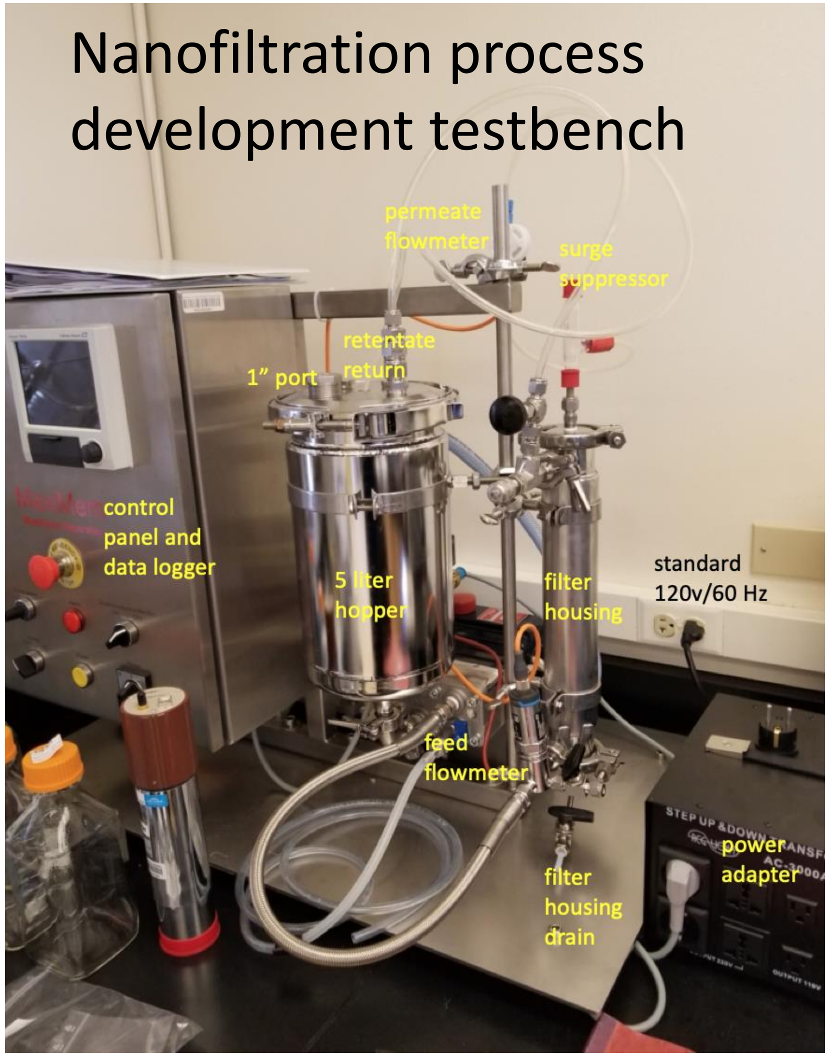


good ion	"bare" MW	coordinated MW
Gd^{+3}	157	301-320
Te^{+3}	128	210-230
Li^{+1}	7	79

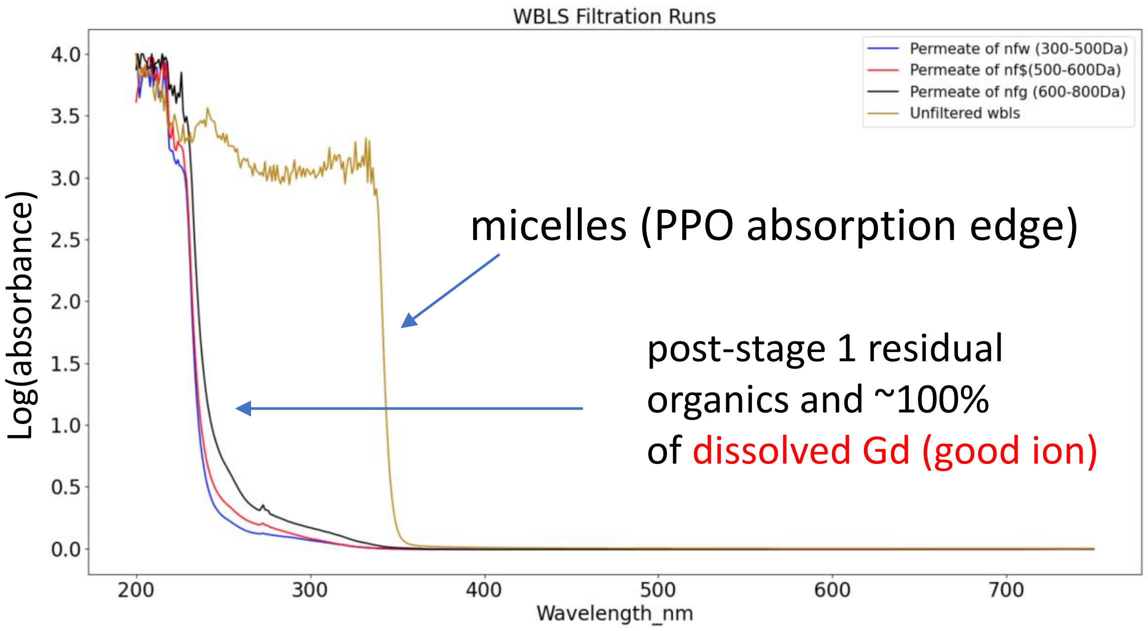
(Fe^{+3} is 164)

Note: MW is not the only consideration. Filter materials also make a difference, as it can interact with the ions.

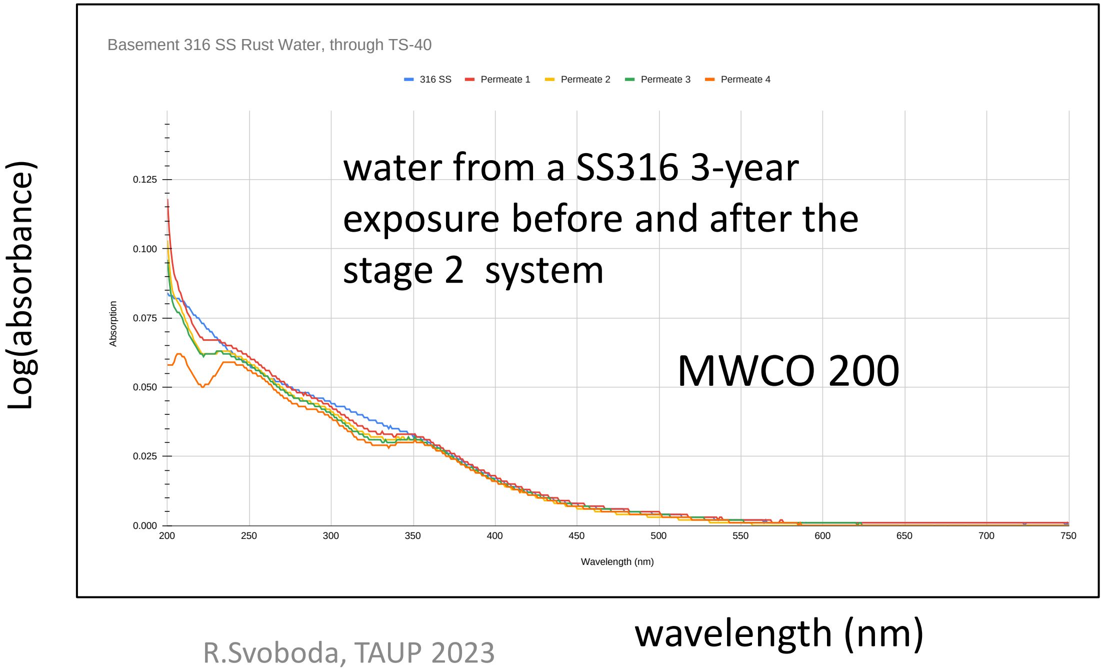
Nanofiltration process development testbench



We are now ready to build a scaled-up version of this!



Array 1: removes (without disruption) the LS-filled micelles. Test show light yield is not affected



Array 2 passes dissolved iron through to the "standard" water purification system but removes residual organics