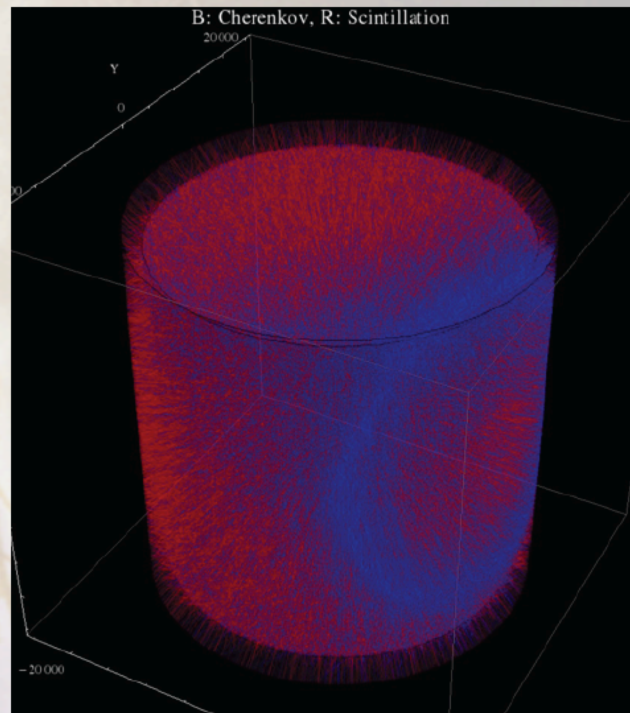
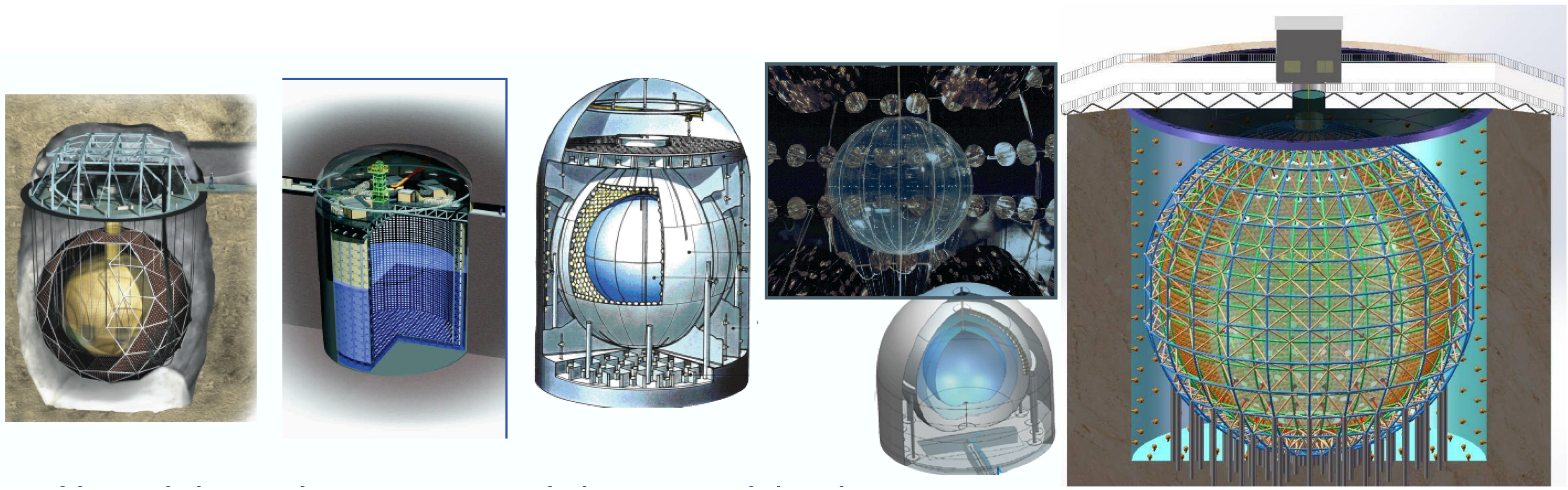
THEIA

An Advanced Liquid Scintillator Detector



Robert Svoboda, NNN, November 4 2016

Our breakthroughs in Neutrino Physics were enabled by the invention of large optical detectors



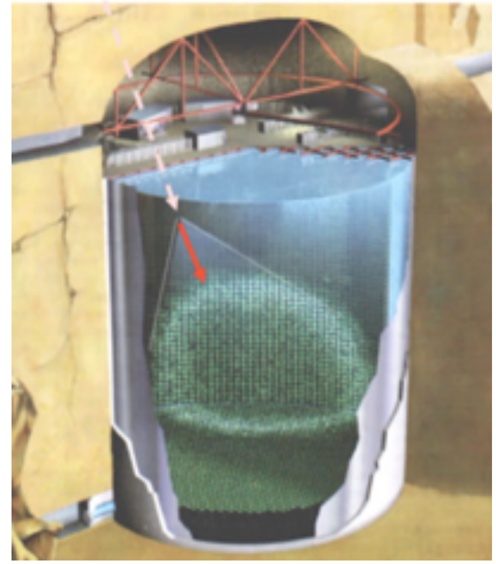
Large size for cost, fast timing for background reduction, low threshold, **reconfigurable as the field progressed**

The New Challenges

- Determination of the mass ordering
- $0\nu\beta\beta$ sensitivity well into NH region
- Resolution of the "new" solar neutrino problem
- Detection of CNO neutrinos from the sun
- Detection of diffuse supernova neutrinos
- Precision measurement of CP violation
- Geo-ν in both oceanic and continental locations
- Explore new ideas on baryon number violation

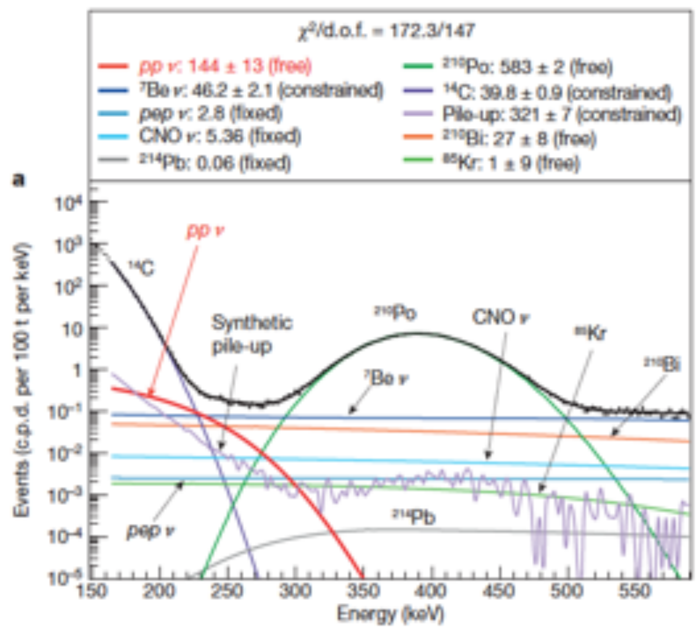
Water Cherenkov

- Excellent Transparency
  - large size
- Directionality
- Particle ID
- Potential for large Isotopic Loading



Liquid Scintillator

- High Light Yield
  - low threshold
  - good energy resolution
- Can be radiologically very clean



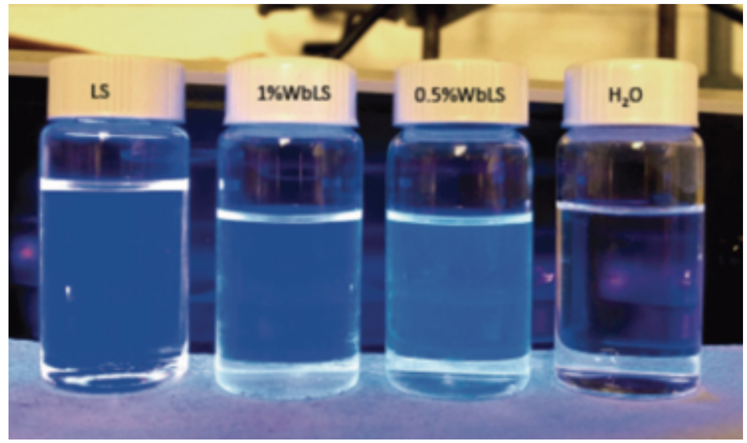
Could we make a Hybrid Detector?

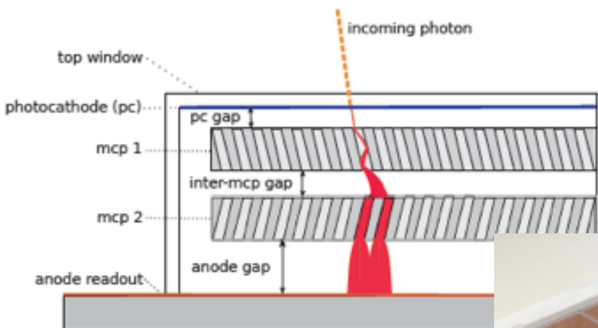
- Use LS mixed with oil or Water-based Liquid Scintillator (WbLS) to adjust light yield and transparency
- Directionality via fast timing to separate Cherenkov and Scintillation light
- Deep location to enable a broad program
- Reconfigurable design: "**follow the physics**"

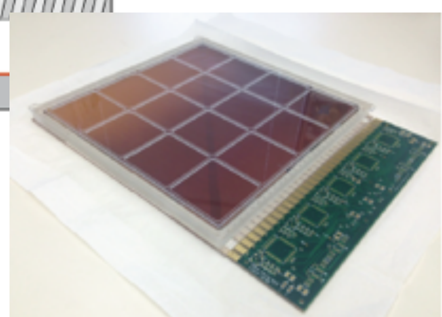
Advanced Scintillation Detector Concept (ASDC)

arXiv:1409.5864

New methods for loading liquid scintillator and for mixing with water

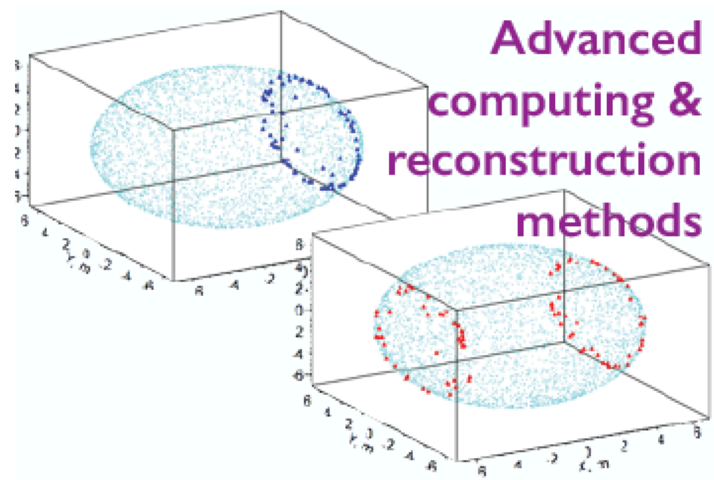






Fast timing and high efficiency photosensors

Advanced computing & reconstruction methods

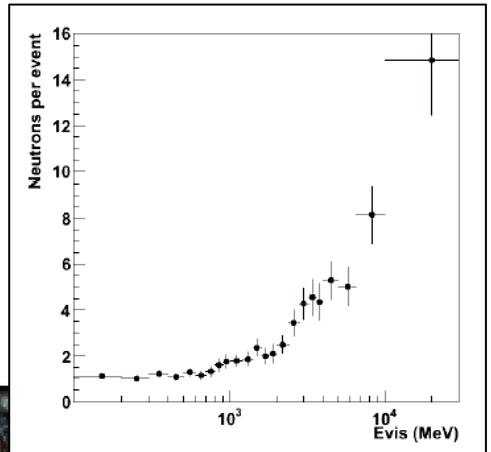


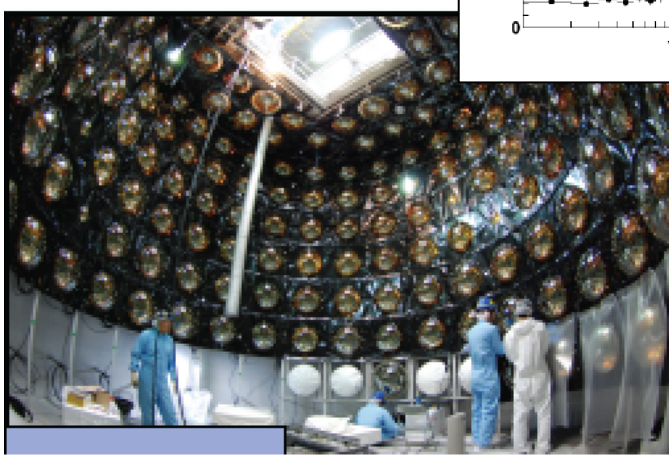
A. Elagin et al., arXiv:1609.09865

Advanced Scintillation Detector Concept (ASDC)

arXiv:1409.5864

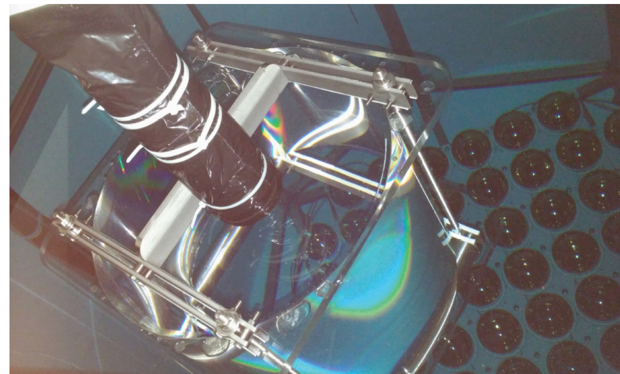
Neutron tagging by gadolinium capture

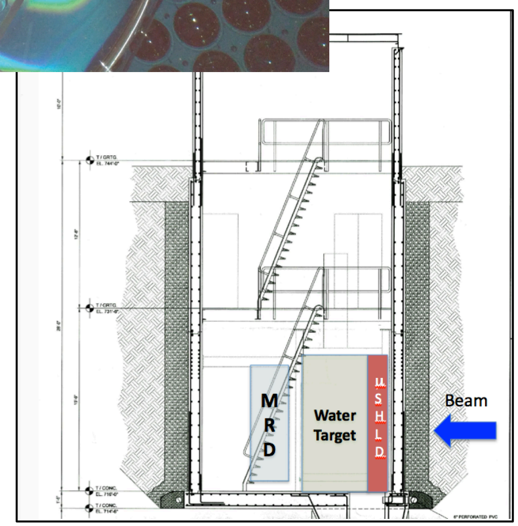




EGADS

Neutrino sign selection via neutron tagging and precision reconstruction



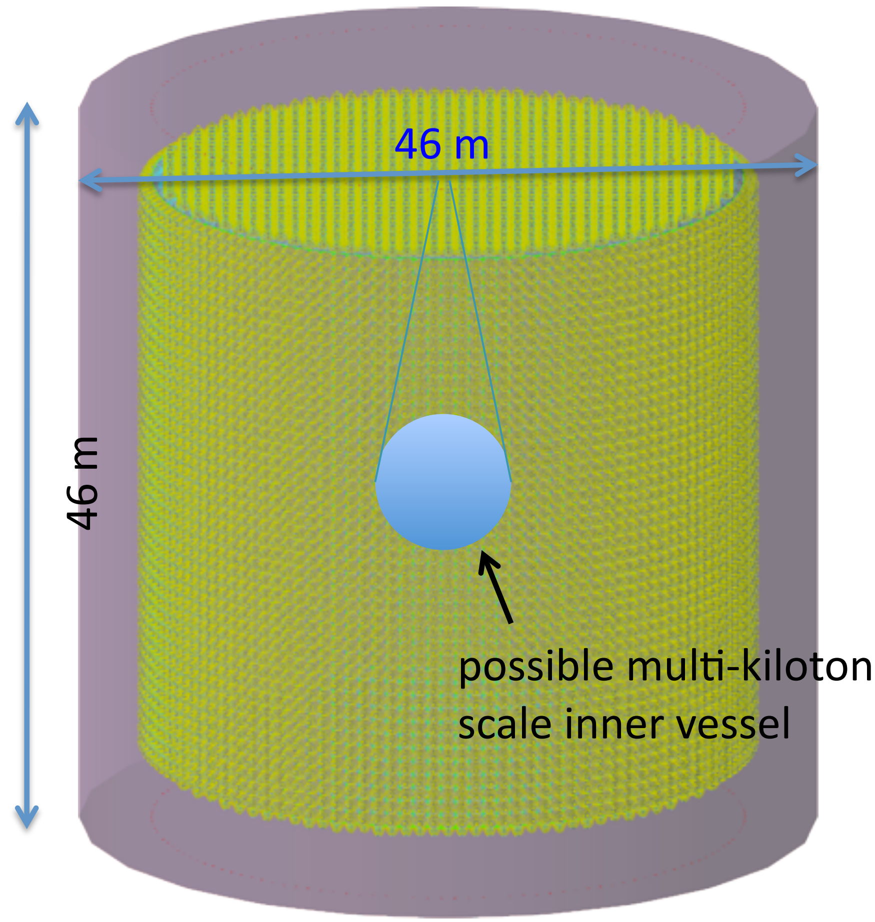


ANNIE

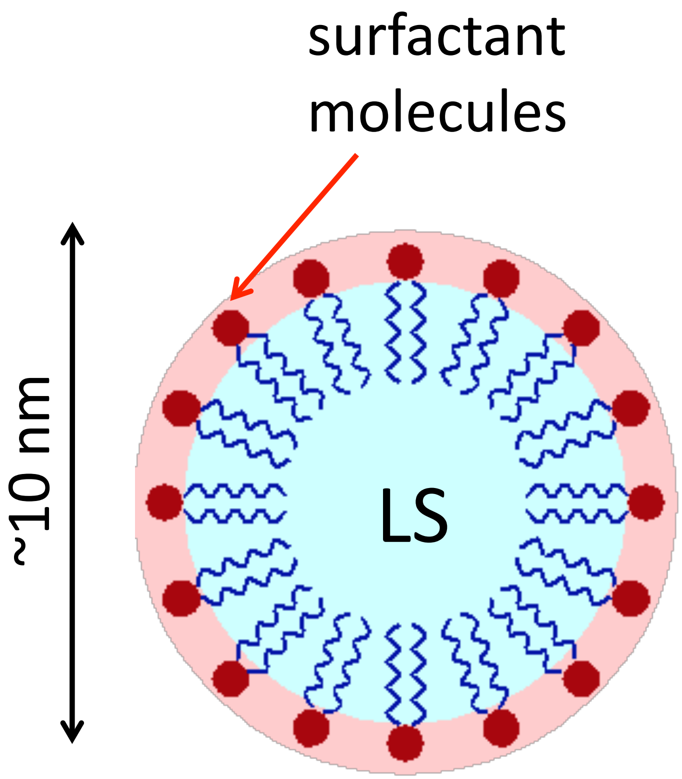
THEIA Concept

arXiv:1409.5864

- **50 kilotons** fiducial
- **Deep depth** (>4000 mwe)
- **Fast timing**, high efficiency photosensors, high coverage
- **Isotopic loading**, possibly with a balloon to avoid "wasting" isotope and to achieve long attenuation lengths
- **Reconfigurable**, capable of economically for long periods to have a broad program



Micelle sequestering of LS in water



Liquid Scintillator (LS) forms 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.

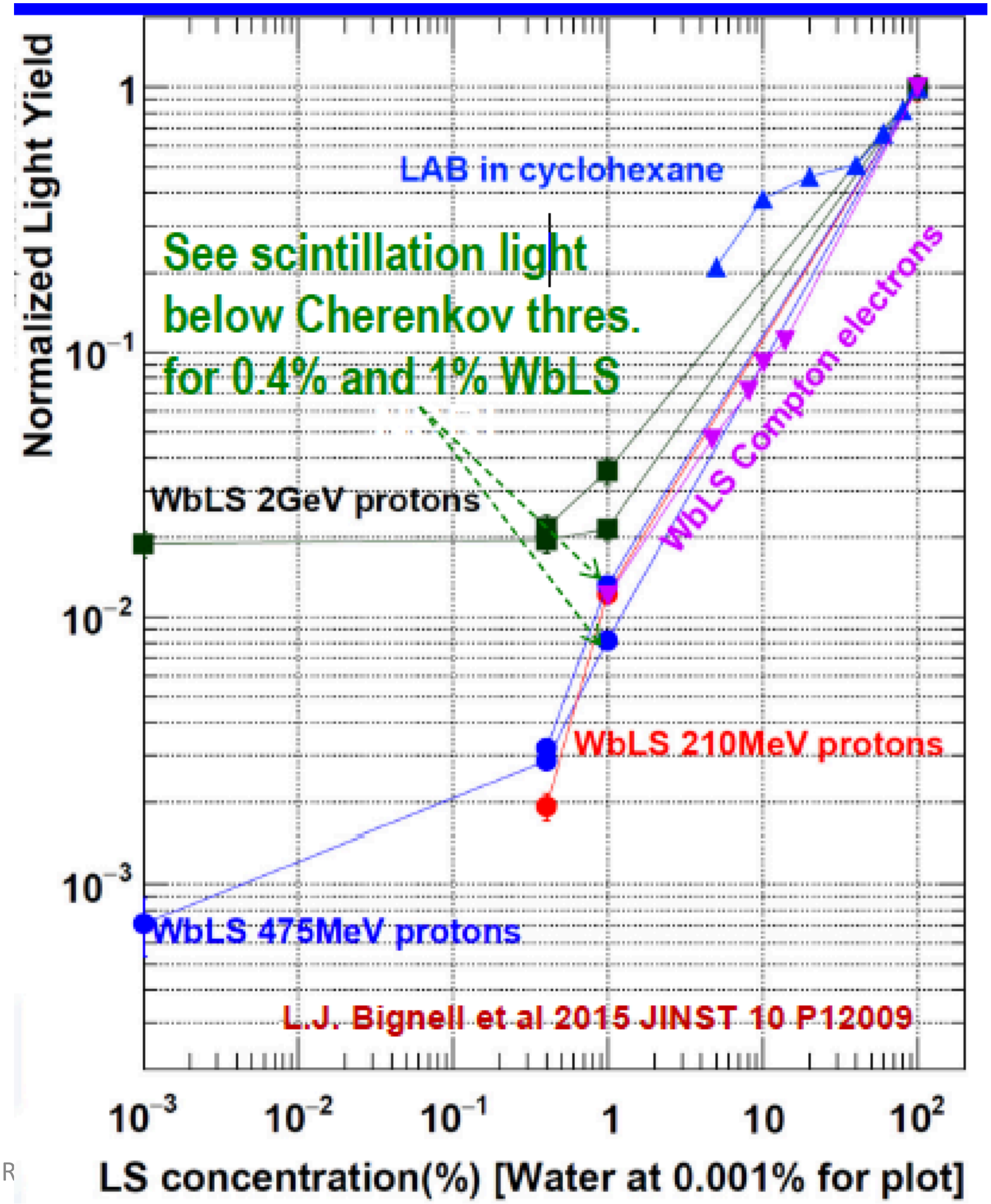
Can adjust scintillation yield by changing micelle concentration.

see M.Yeh talk Parallel 1 session

Dilution of WbLS in water allows for **tuning** light yield to match the physics.

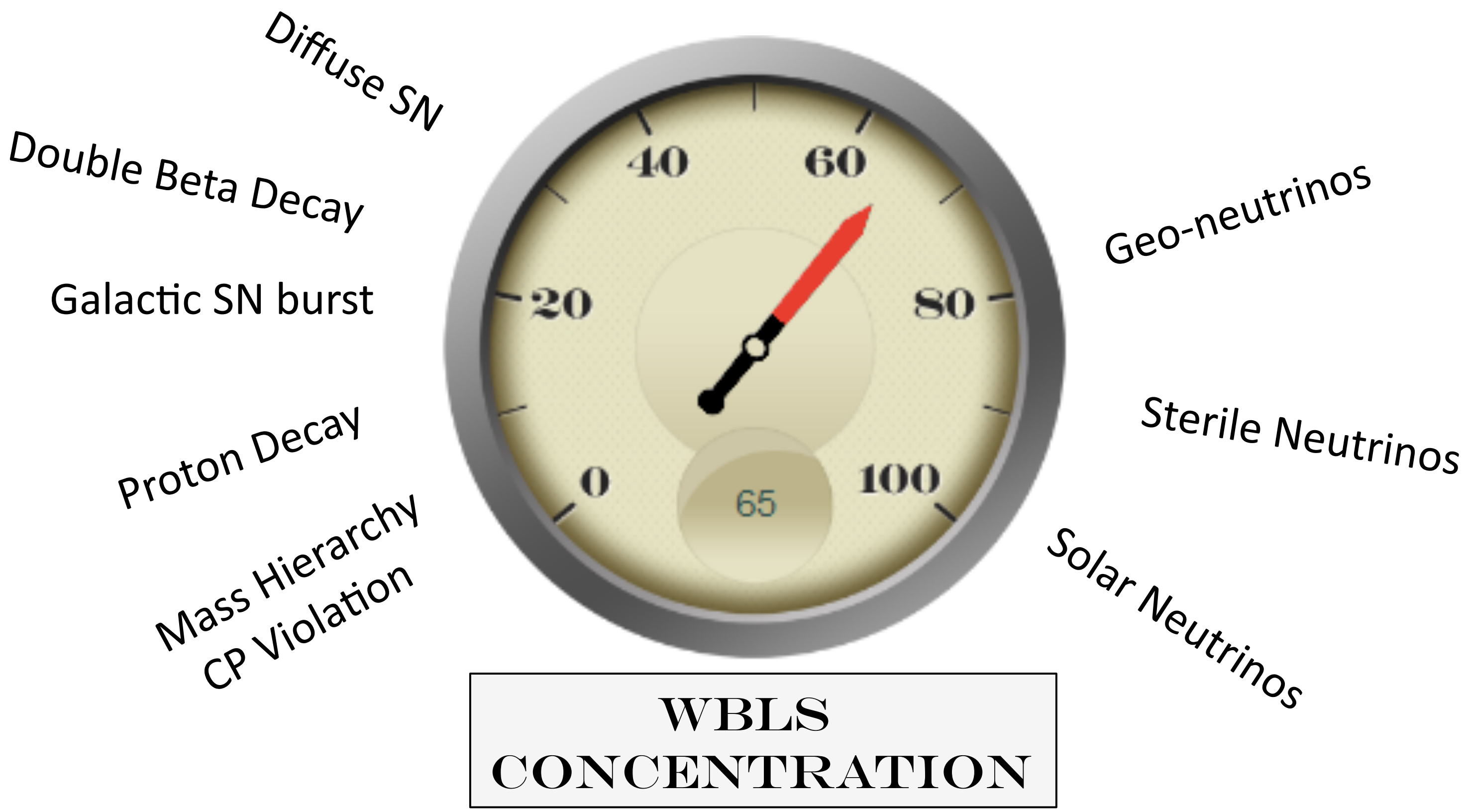
WbLS cocktail in water (violet) and cyclohexane (blue)

(see M.Yeh talk Parallel 1 session)



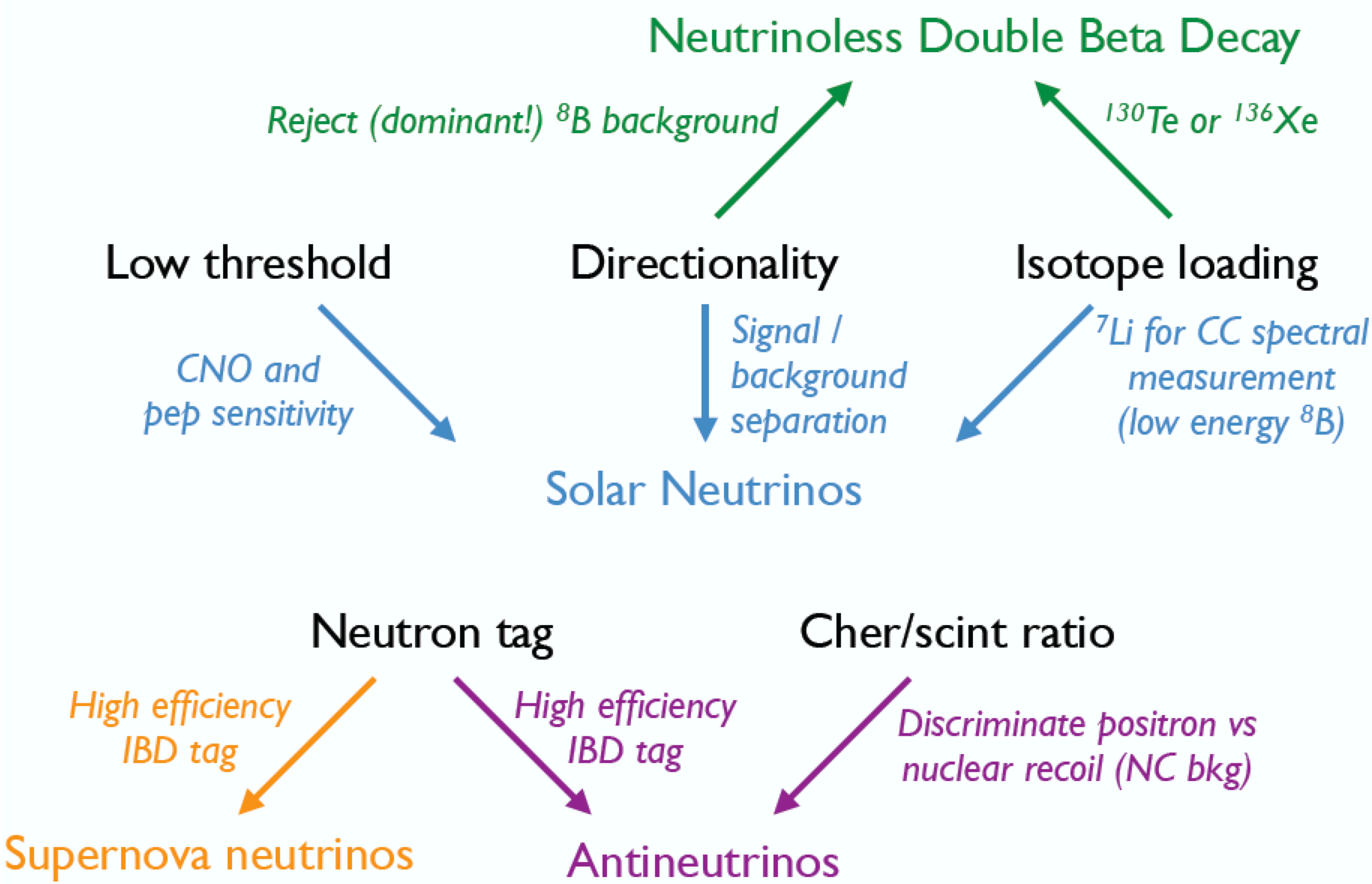
WbLS Concentration Tuned to Physics Needs

A single facility could have a high discovery potential and **a very long useful life** due to *flexibility* and *broad program*

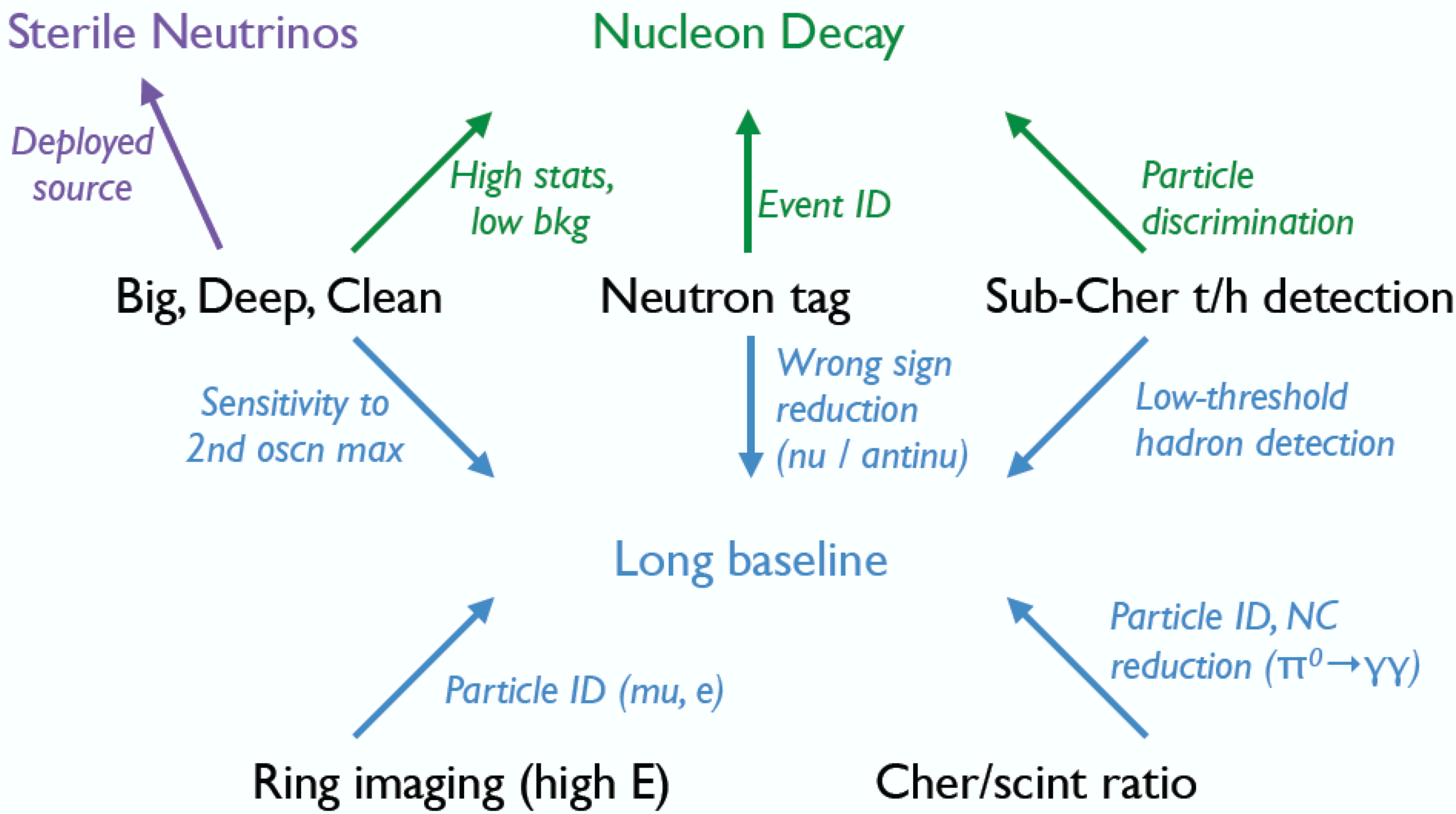


Note: an estimate only!

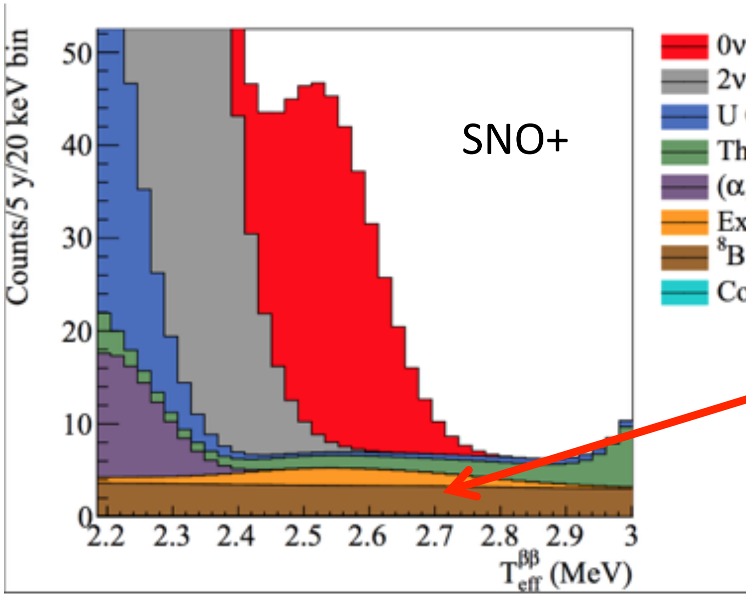
Low-Energy Program



High-Energy Program



0νββ Sensitivity



SNO+ 5 years 0.5% ^{nat}Te

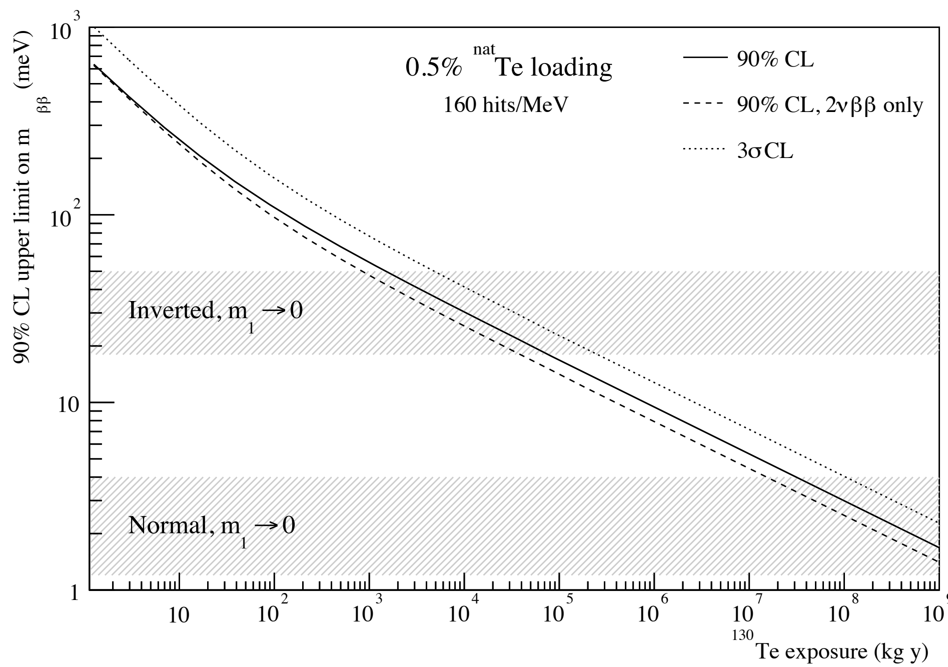
$m_{\beta\beta}$ = 200 meV

Solar neutrinos are expected to be the dominant background

THEIA:

- 3 % ^{nat}Te loading
- 5.5 m FV cut (300 tons ^{130}Te)
- 50% of 8-B solar ν removed by a directional cut

Use of balloon, enrichment, and higher loadings under study



arXiv:1409.5864

Solar Neutrino Sensitivity

1996, W.C. Haxton: isotope loading for CC interaction (water)

"Salty water Cherenkov detectors" W.C. Haxton PRL 76 (1996) 10

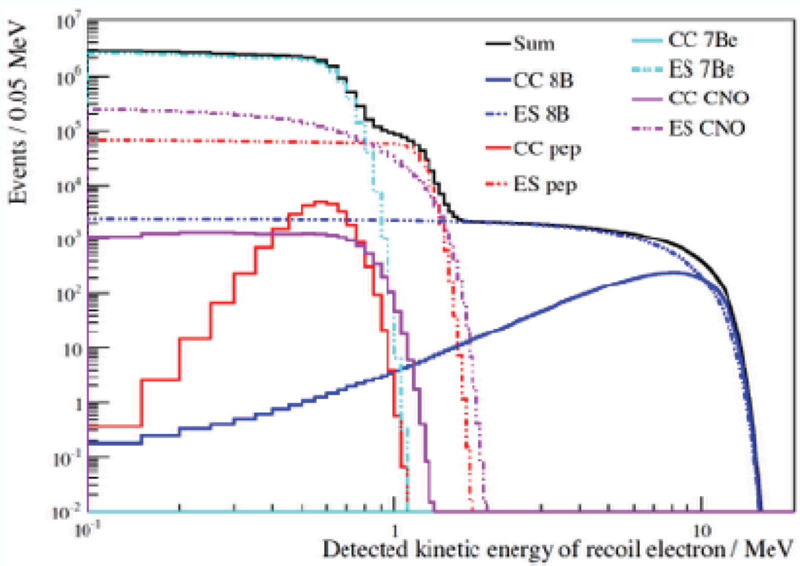
2000s, M. Yeh *et al.*: water-based liquid scintillator

Nucl. Inst. & Meth. A660 51 (2011)

CC detection in WbLS: high-precision spectral measurement to low energy!

⇒ search for new physics, solar metallicity, MSW effect

Unprecedented low-energy statistics (ES)

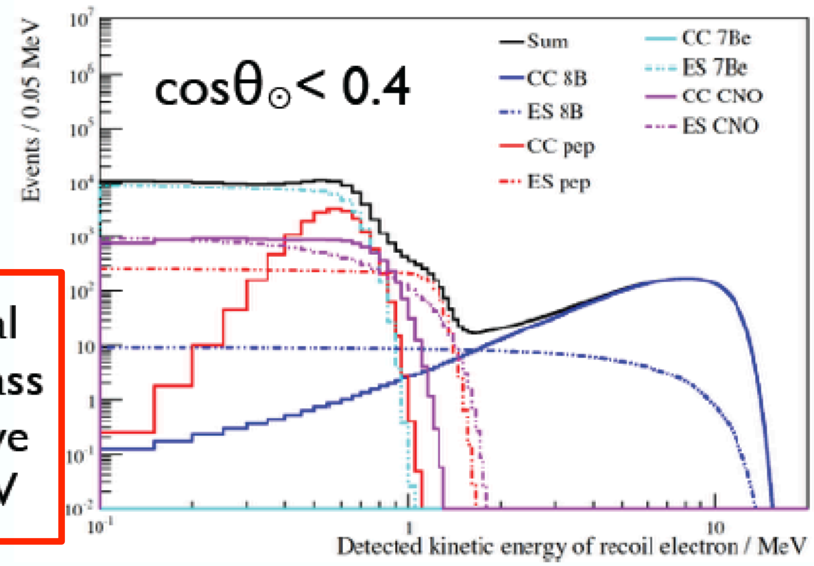


Similar to LENA — Astropart. Phys. 35 (2011) 685-732

+ directionality from Cherenkov

30kt fiducial
1% ^{7}Li by mass
Conservative
100 pe/MeV

Spectral Sensitivity (CC)



Enabled by use of WbLS (^{7}Li, CC)

courtesy G. Orebi Gann

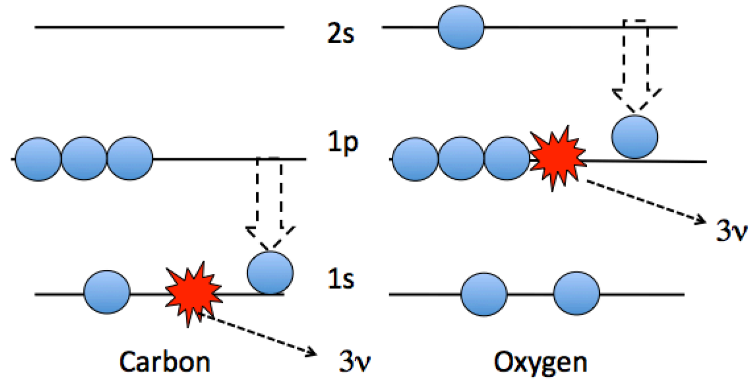
Nucleon Decay: n→3ν

Type of decay associated with Large Extra Dimension (LED) theories. These postulate 100-1000 TeV scale gravity rather than M_{planck}

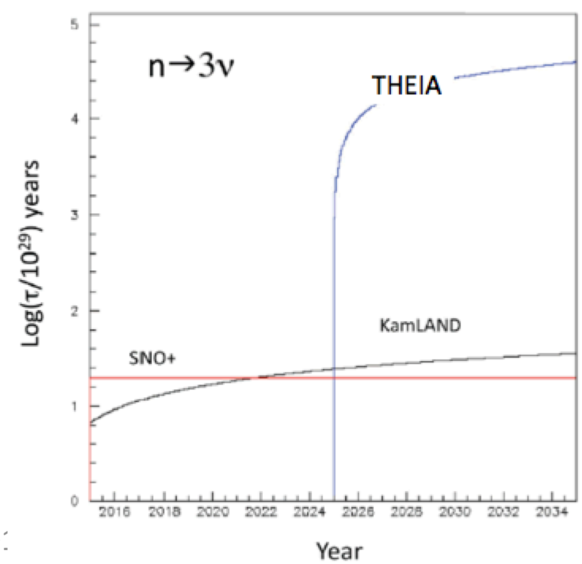
CURRENT:
KamLAND: 5.8×10^{29} years
SNO: 2×10^{29} years

FUTURE:
SNO+: $4\text{-}8 \times 10^{29}$ years

Deep depth and WbLS would allow THEIA to improve these by <u>3 orders of magnitude</u>



^{16}O has 1p decay, ^{12}C does not



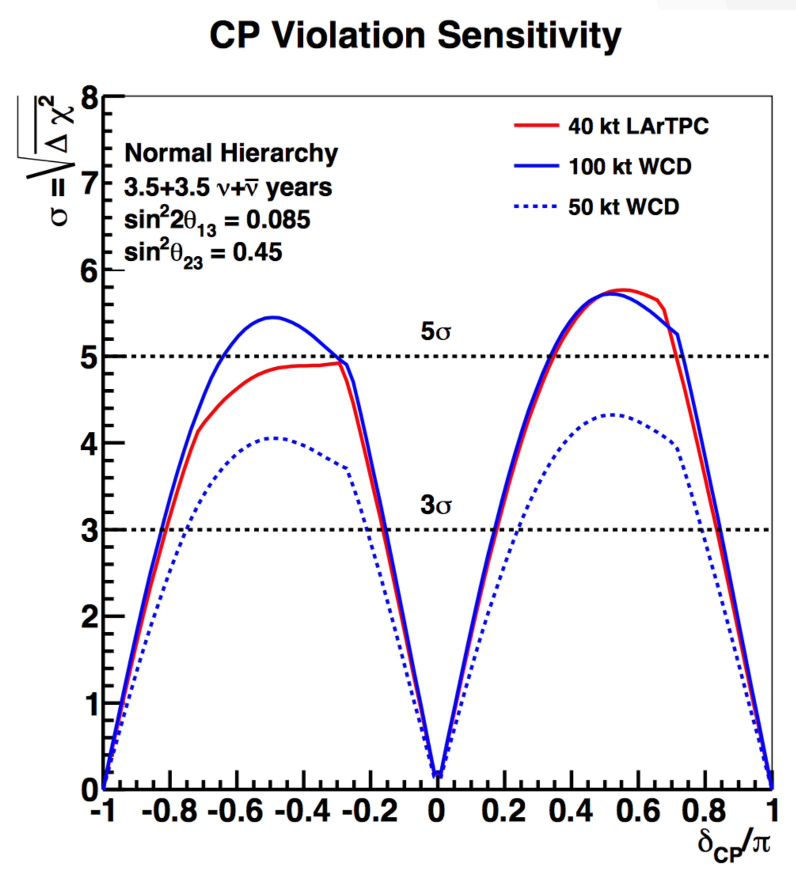
CP Violation

SK has improved their analysis such that the NC background in T2K beam is reduced to 31% of previous value.

LBNF has also made significant progress in making the on-axis beam have higher flux at lower energy.

Assume that with improved timing and light collection NC could be reduced to the 25% level.

E.Worcester, FroST-I, FNAL 2016
M.Wilking, FroST-II, Mainz 2016



In that case 50 kton THEIA gives similar sensitivity to 20 ktons of DUNE

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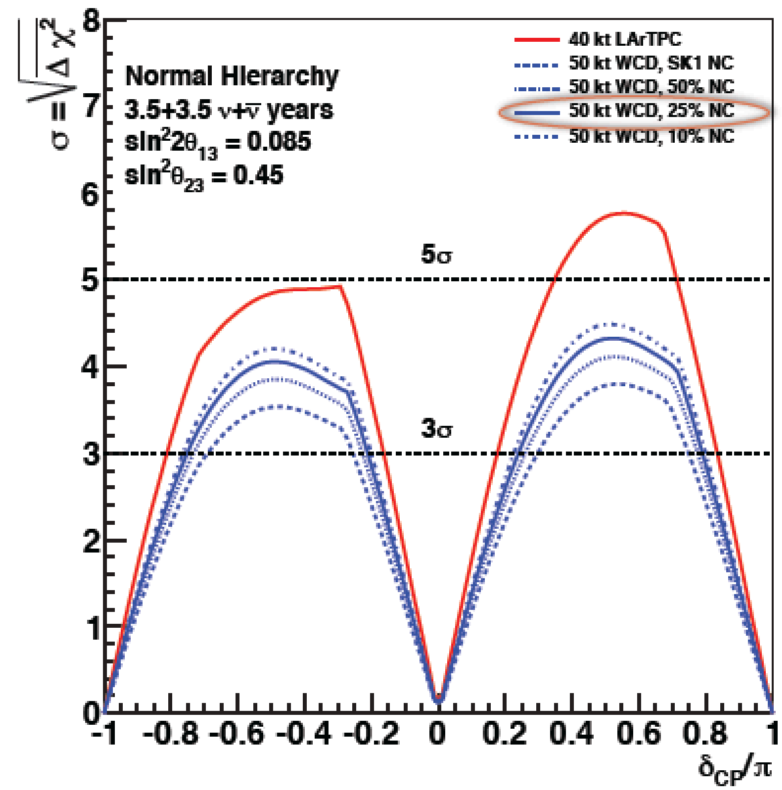
E.Worcester, FroST-I, FNAL 2016
M.Wilking, FroST-II, Mainz 2016

Effects of NC reduction



Need more work to show that WbLS does not diminish NC suppression and also to look at nu/ant-nu tagging

R&D Program - i

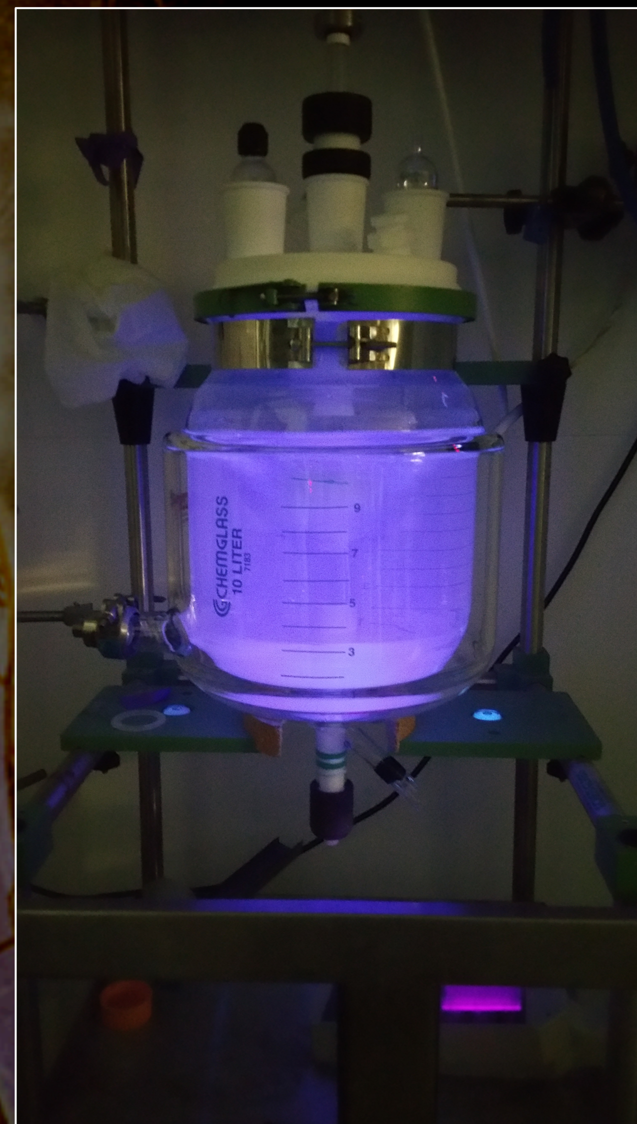
- WbLS cocktail development
  - LS fraction
  - Fluor choice & fraction
  - Isotope loading
- WbLS deployment questions
  - Nanofiltration
  - Purification
  - Recirculation
  - Background levels
  - Materials compatibility
- WbLS cocktail properties
  - Light yield
  - Attenuation
  - Absorption
  - Scattering
  - Quenching
  - Emission spectrum
  - WbLS timing
  - Cherenkov/scintillation separation

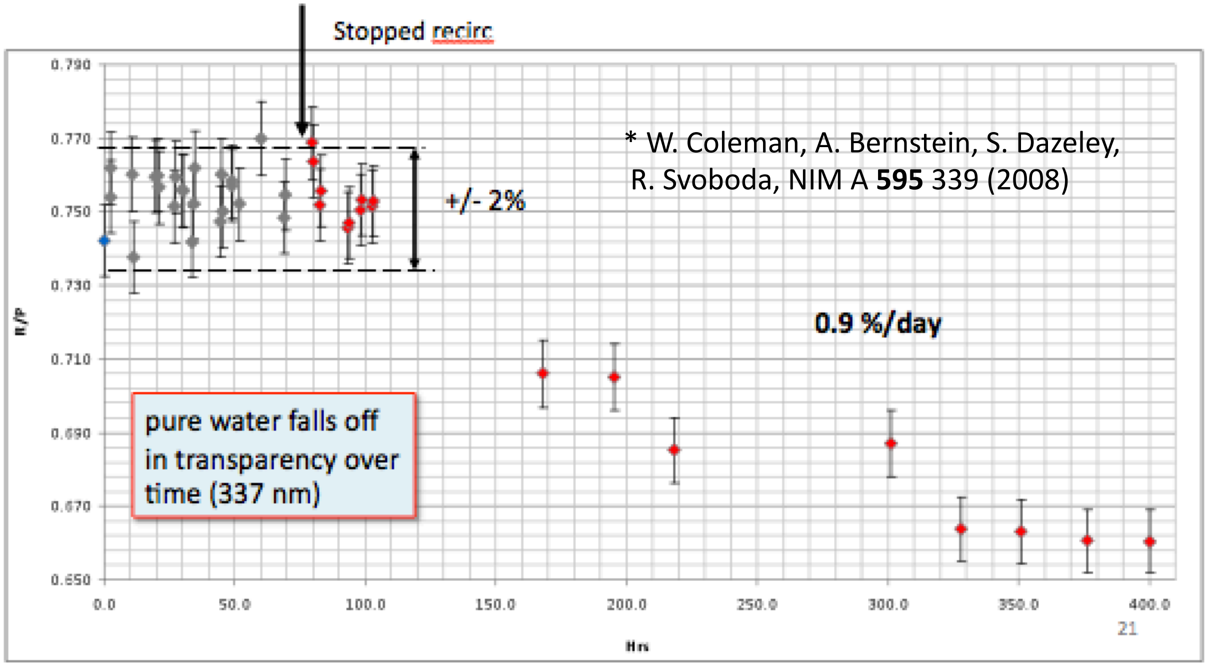
R&D Program - ii

- Photon sensor development
    - Large-area PMTs
    - High efficiency (QE)
    - Ultra-fast detectors
    - Hybrid scheme
    - Characterization
- THEIA physics program
    - Monte Carlo model
    - Detector design
    - Reconstruction techniques
    - Particle ID
    - Background rejection
    - Physics sensitivity studies

Recent Progress

- See parallel session talk on WbLS and LAPPD development
- WbLS purification progress
- Cherenkov/Scintillation light separation
- ANNIE experiment
- Possible site at LBNF





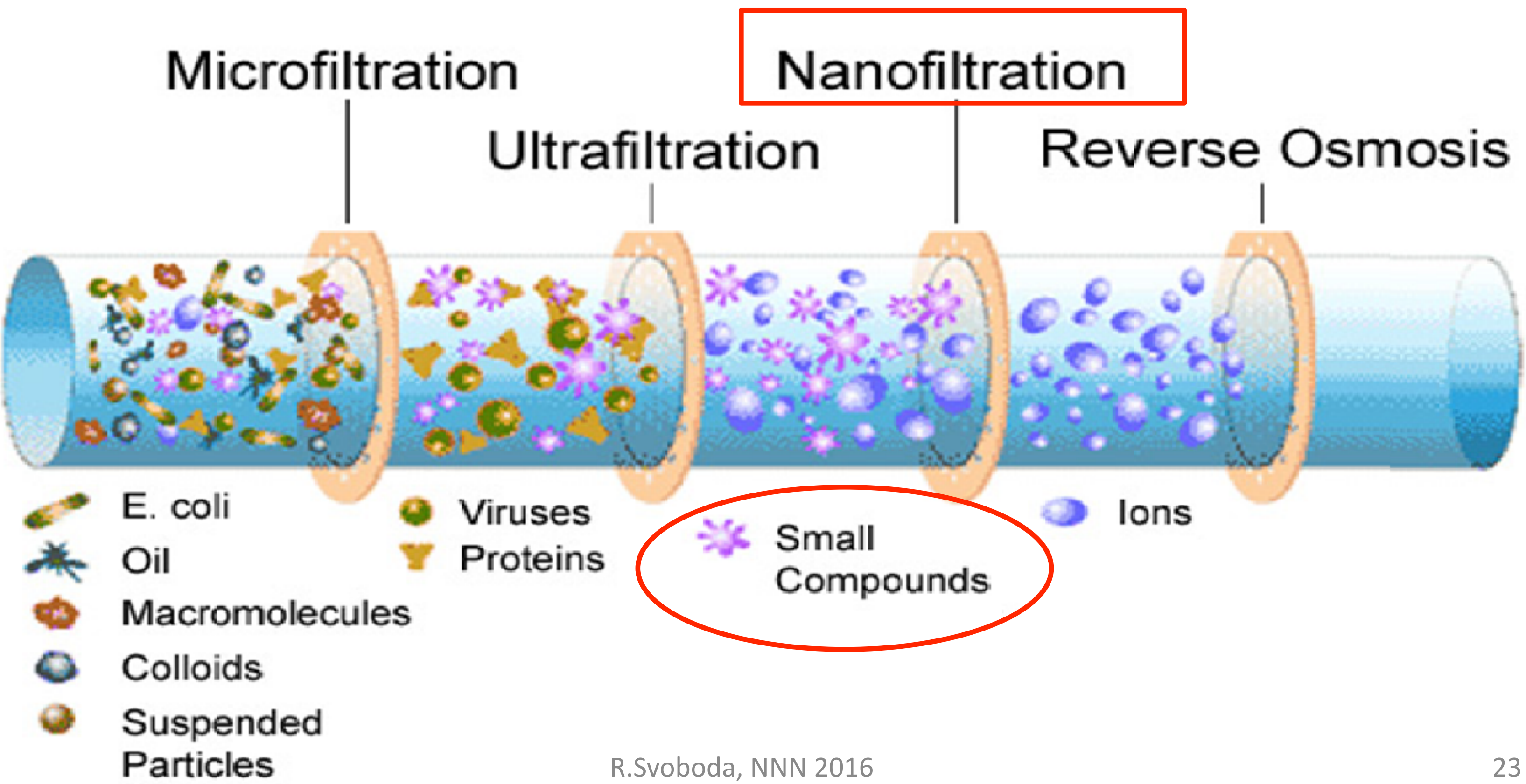
Experience with SK is that water must be recirculated to maintain transparency.

This is likely due to SS tank

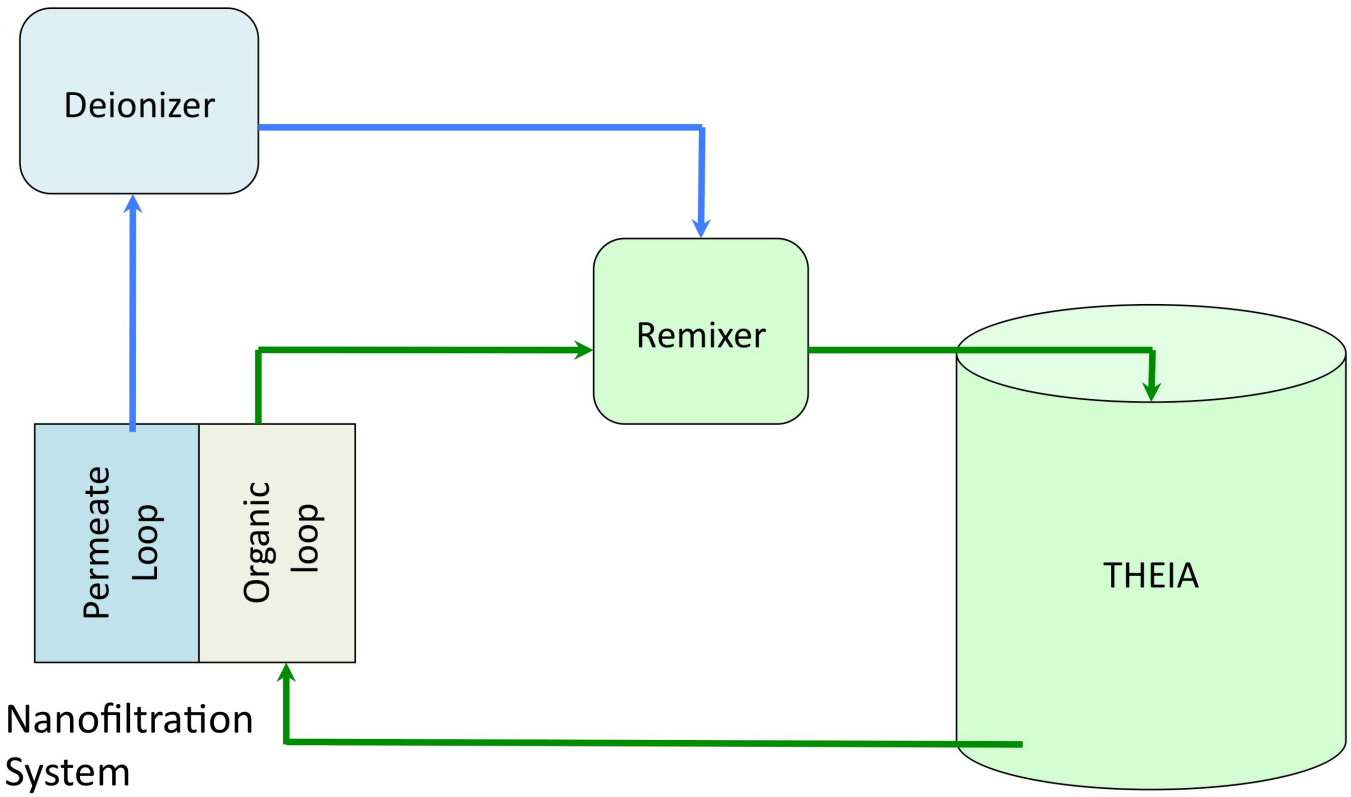
How to recirculate WbLS?

Cannot use EGADS system on WbLS as the molecules of the organic component are non-polar and do not pass through.

Nanofiltration is used by the food industry and by industries concerned with environmental pollution caused by trace amounts of oil in water



Using NF one could try and separate the organic and water stream, purify the water stream, then remix.

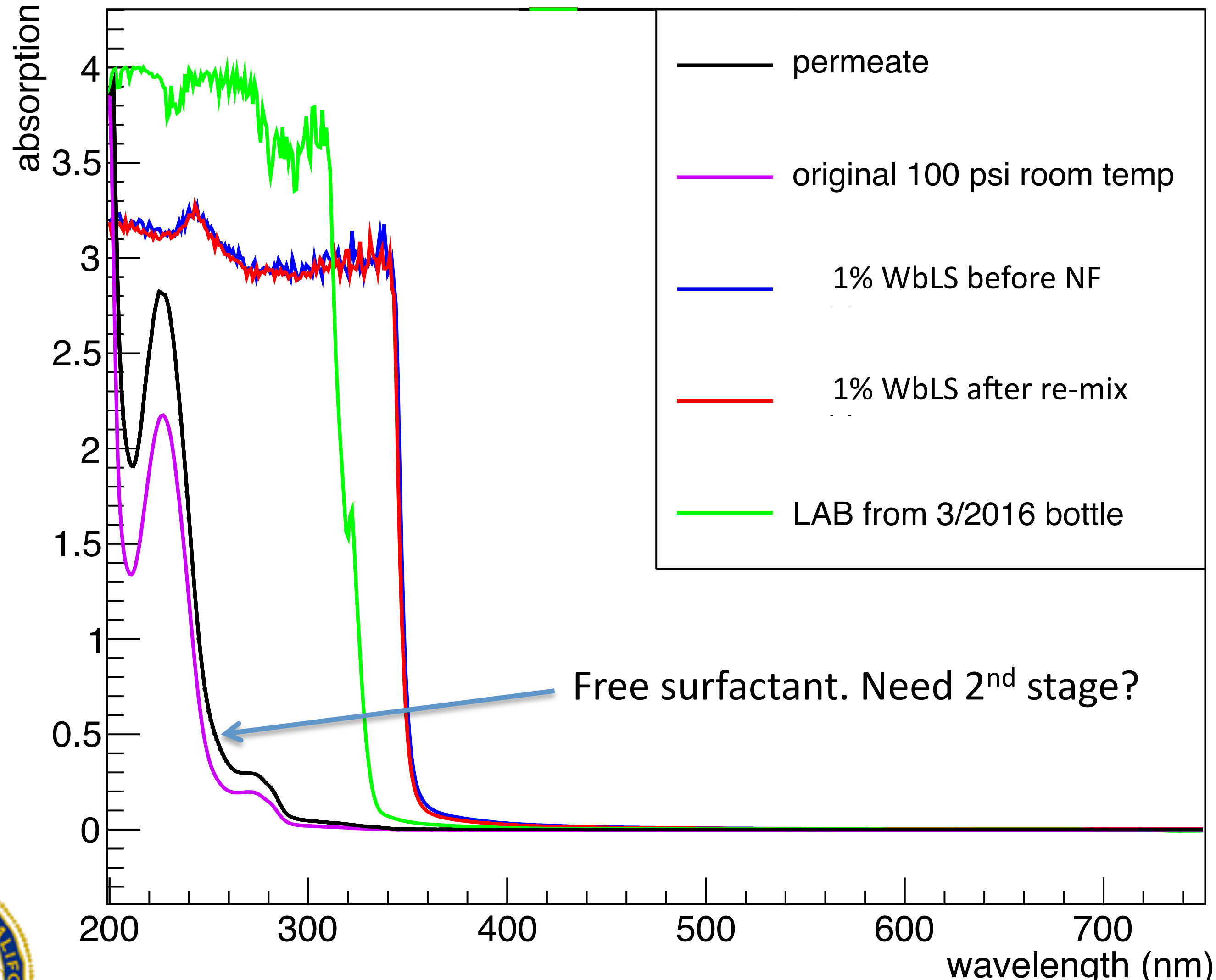


THEIA recirculation concept

There are many considerations

- Identification of appropriate Molecular Weight CutOff (MWCO) hydrophilic materials to use for filters to avoid **surface fouling** and **concentration saturation** effects
- **Optimal temperature and pressure** to yield sufficient flow rate but significant rejection
- **Passage of ionic contaminants** through the system for later removal by deionization
- Micelle formation and **disruption** effects

New! Test Results for Snyder NFW Polymide (300-500 MWCO).



Flow rate sufficient for THEIA using a commercial system.

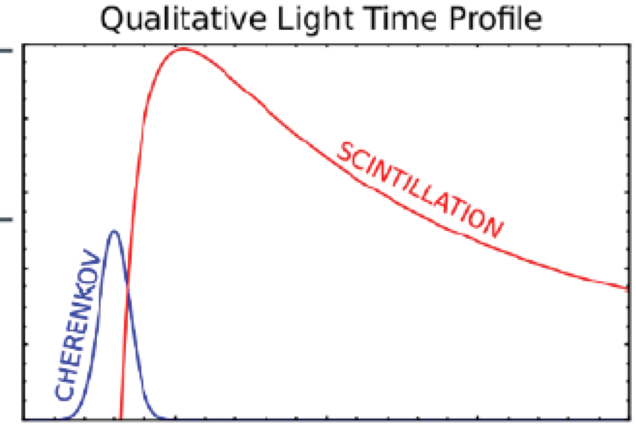
Cherenkov/scintillation separation

Separate signals in:

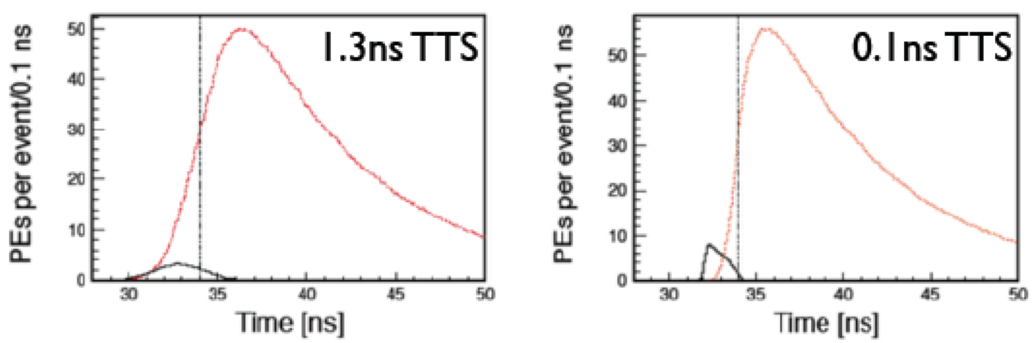
CHESS

- Time
  - Ultra-fast detection (LAPPD?)
  - Delay scint light
- Charge
  - Tune relative light yields
  - Readout sensitivity
- Wavelength
  - LS spectrum (fluor) / readout

Charge: look for Cher ring superimposed on isotropic scint "bkg"

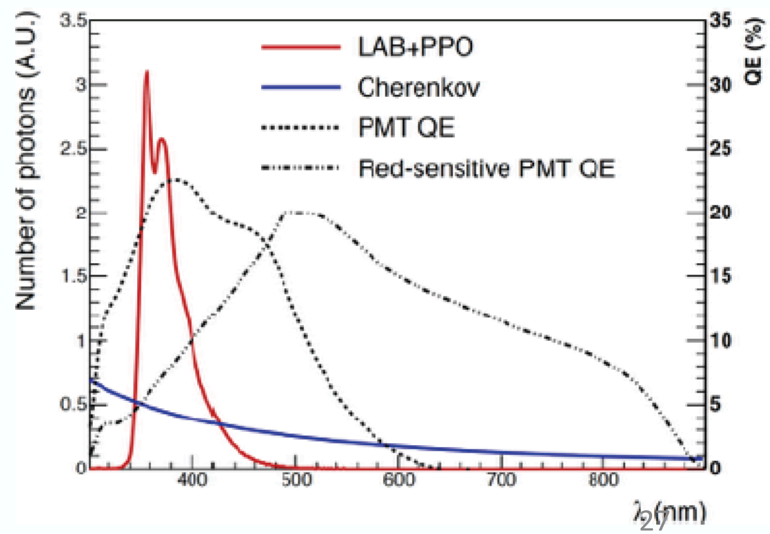


Time: look for prompt Cher peak



Cherenkov (prompt, scarce)
Scintillation (delayed, abundant)

C. Aberle et al, JINST 9 P06012 (2014)



CHESS:
CHErenkov-Scintillation Separation

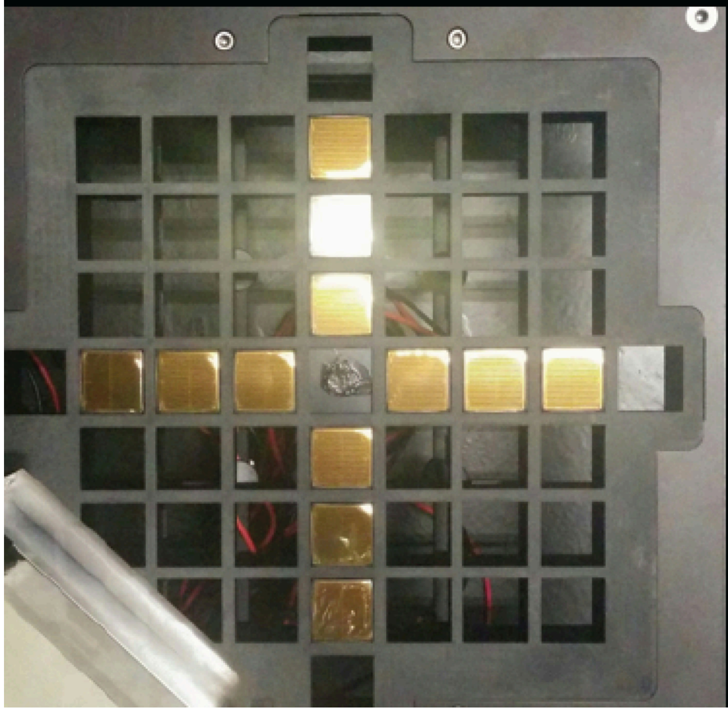
Supported by LBNL LDRD (FY '15-16)

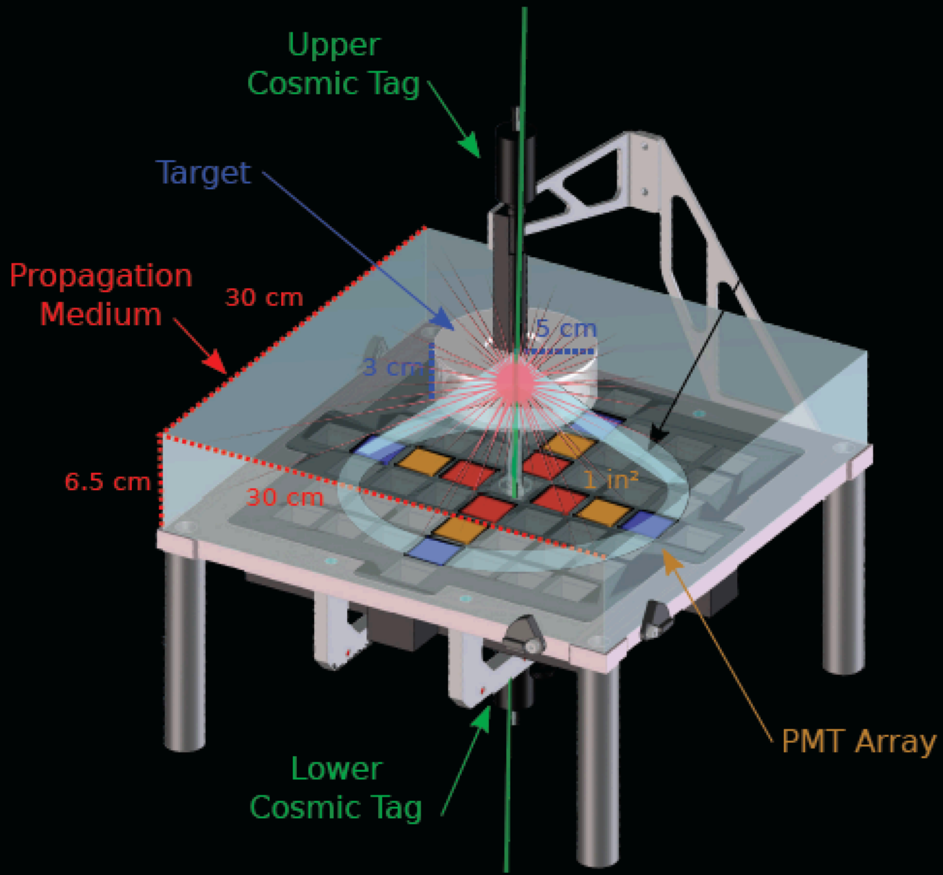
arXiv: 1610.02029

Select vertical cosmic muon events

Image Cherenkov ring in Q and T
on fast-PMT array

Allows charge- and time-based separation



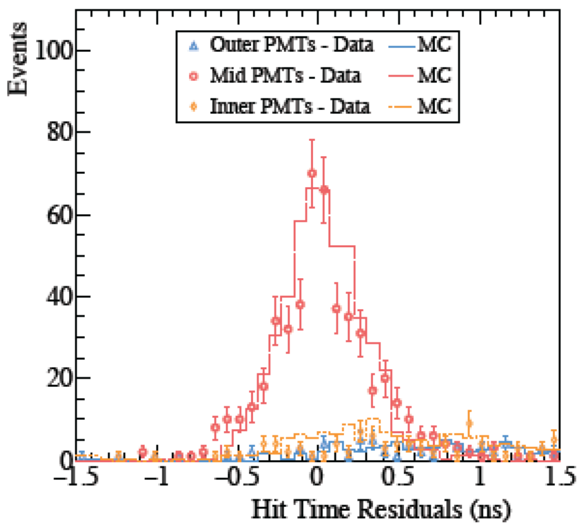


12 1-inch H11934 PMTs (300ps FWHM, 42% QE)
CAEN V1742 (5GHz)
675 samples (135ns window)
CAEN V1730 (500MHz)

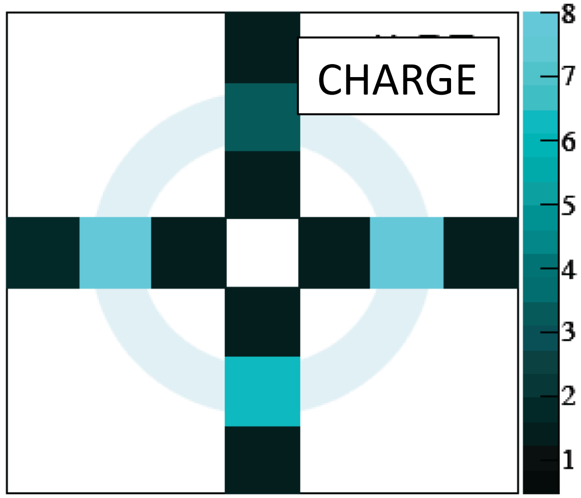
arXiv: 1610.02029

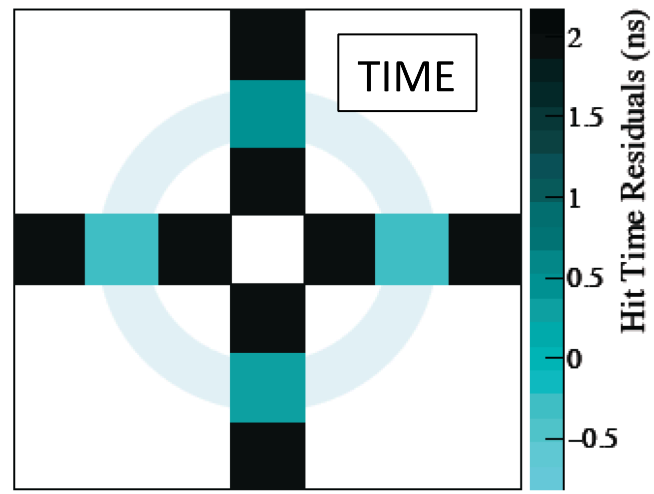
CHESS Water Data

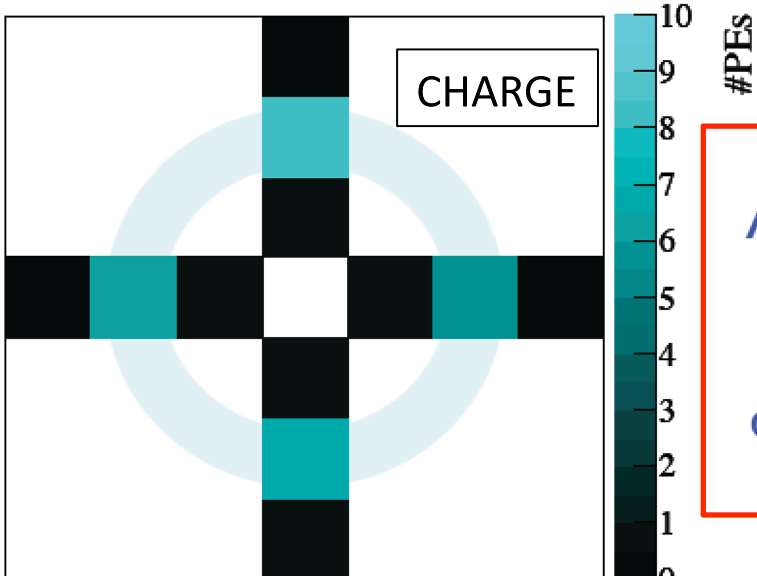
Data well fit
by RAT-PAC MC



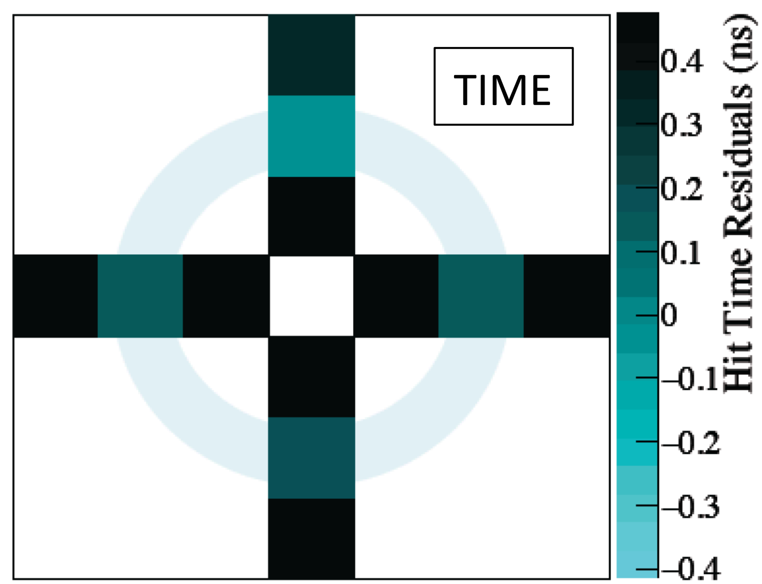
Typical ring candidate event







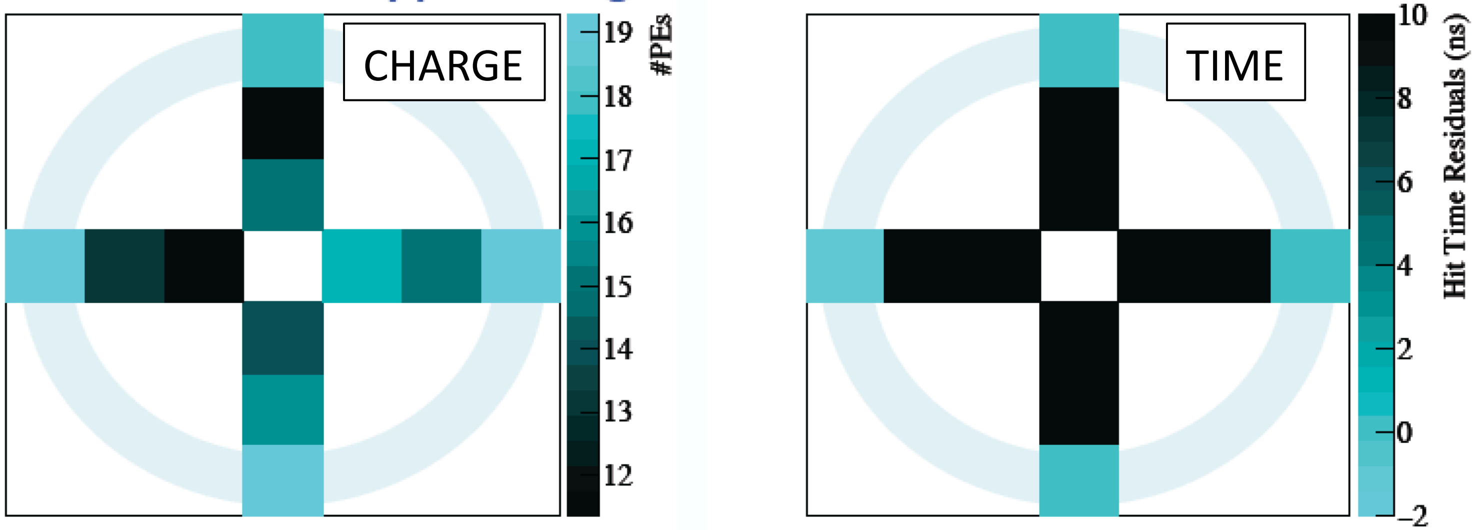
Average across (clean) data set



arXiv: 1610.02011

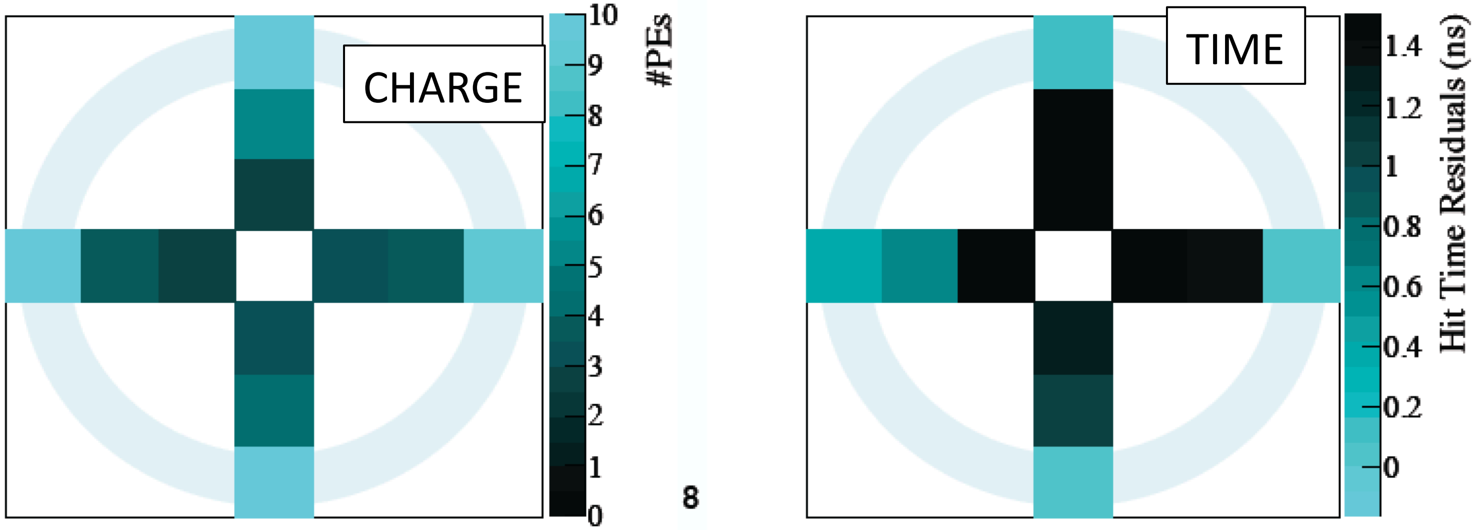
CHESS Results: Pure LAB

Typical ring candidate event



Note the wider ring for LAB as compared to water

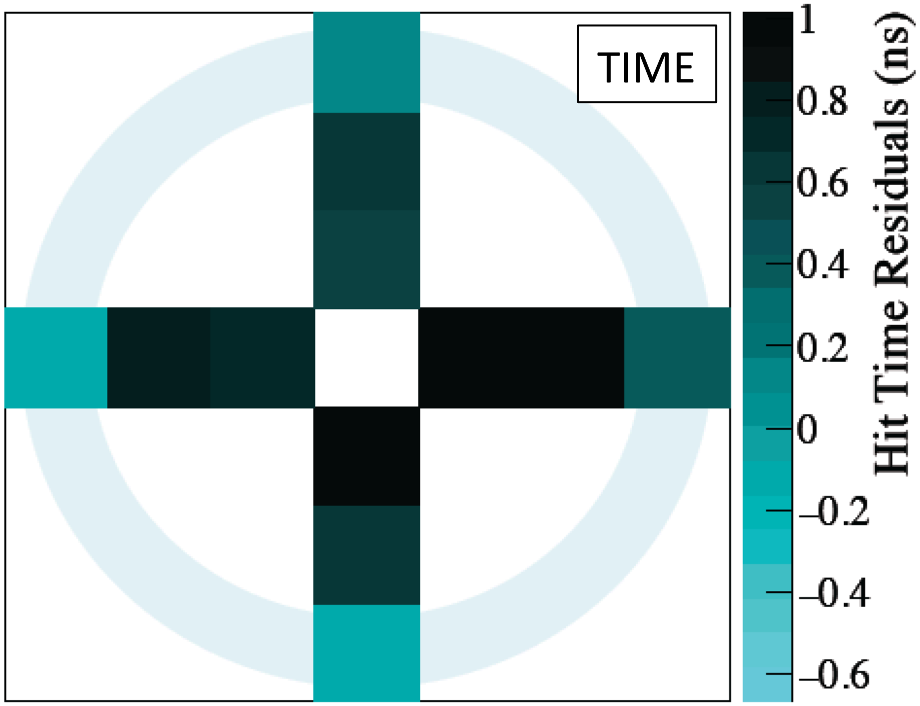
Average over data set (117 events)



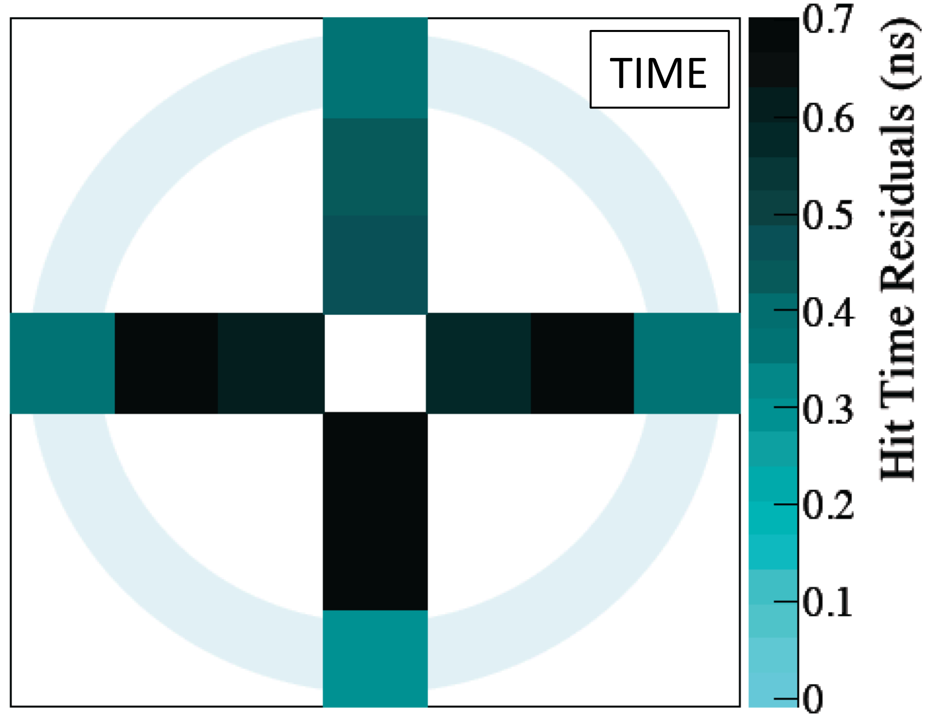
arXiv: 1610.02011

CHESS Results: LAB / PPO

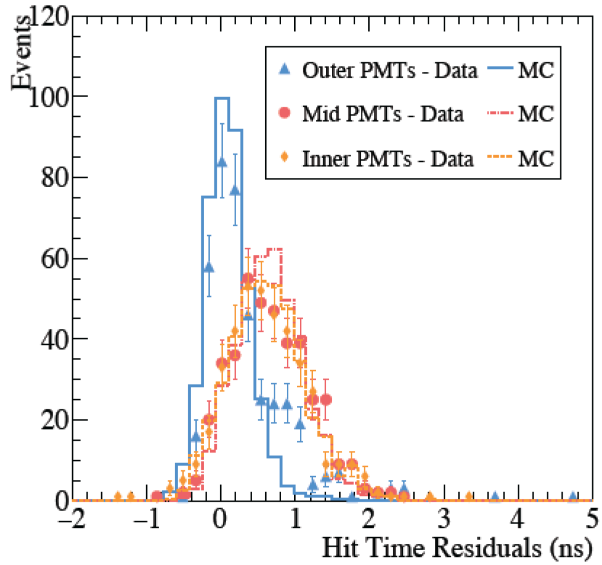
Typical ring candidate event



Average over data set (103 events)

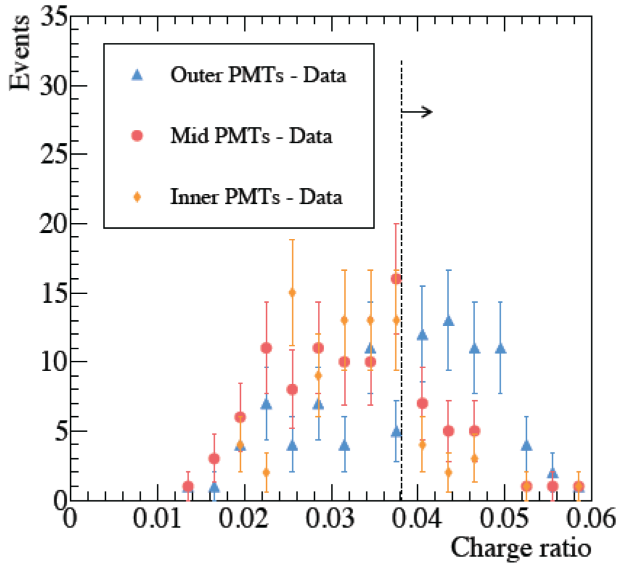


Successful C/LS separation!



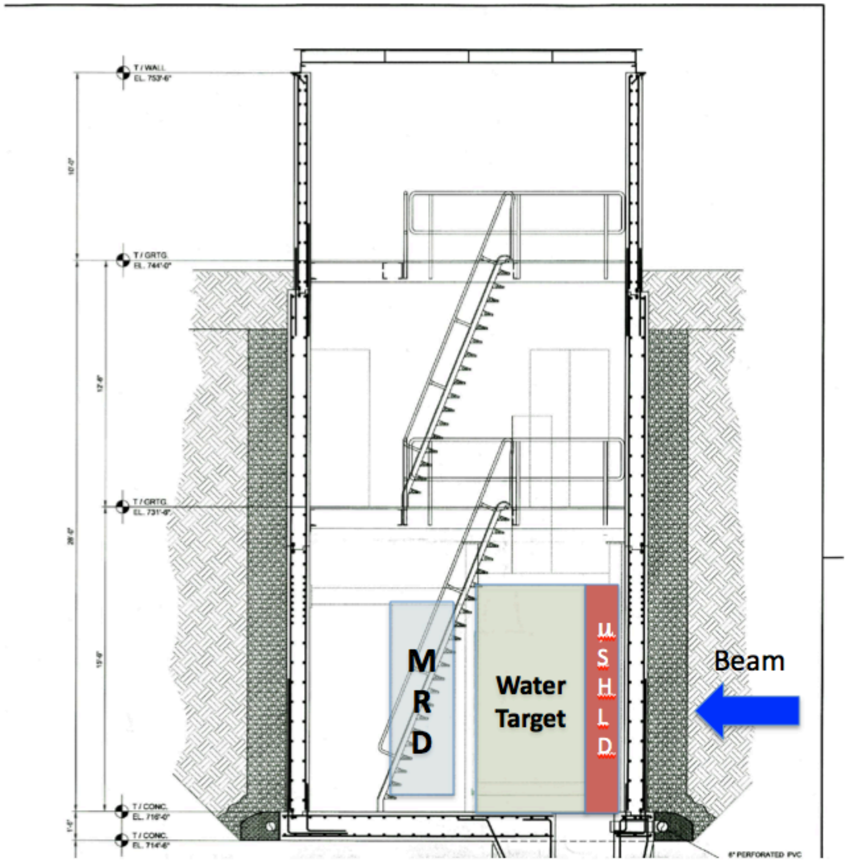
Time at fixed threshold
Corrected by ToF, channel delays

NOTE: Rise time = 0.75 ± 0.25 ns



Ratio of charge in prompt, 5ns window
to charge in total (135ns) window

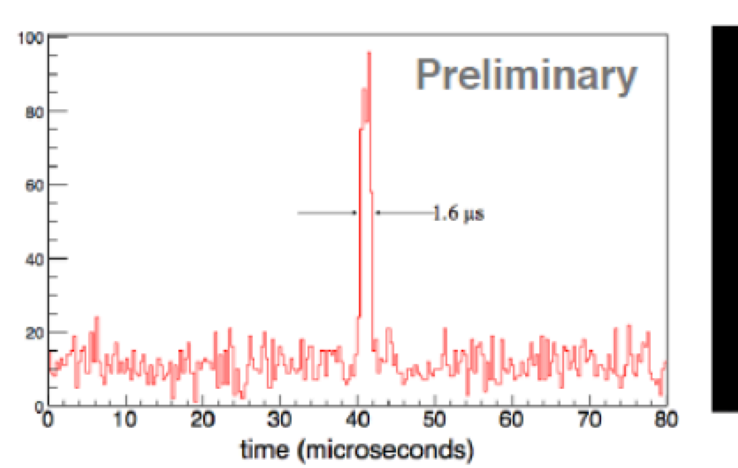
arXiv:1610.02011

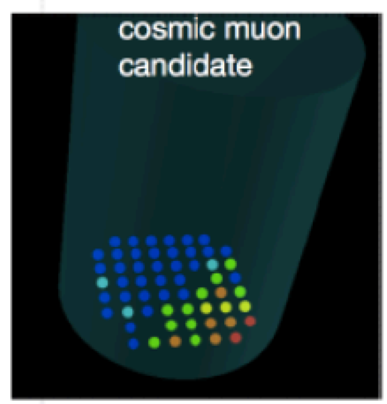


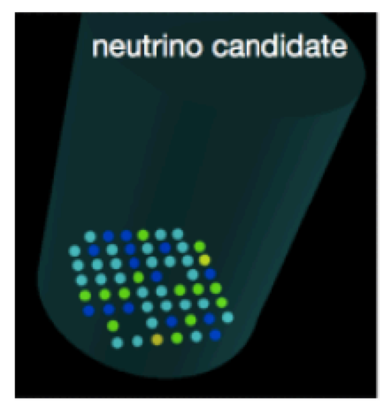
ANNIE

Accelerator Neutrino Neutron Interaction Experiment

- Neutron yield as a function of q^2
- Test of fast timing vertex reconstruction
- Neutrino sign selection? (new idea)





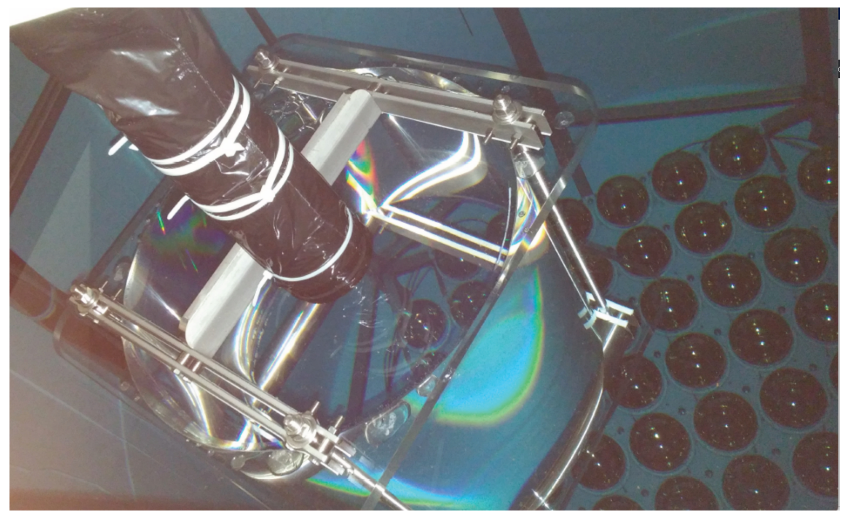


ANNIE Run 1 in progress

ANNIE Phase I: A neutron background measurement using conventional 8" PMTs

ANNIE Status

- Run 1a complete (neutron background)
- **Run 1b starting (fast timing test).**
- Run 2 additional PMT's (in hand), refurbished MRD, ~10 LAPPD



See talks at FroST-II Mainz, October 2016

Sanford Underground Research Facility
FroST - THEIA Detector Workshop

David Vardiman

Project Engineer

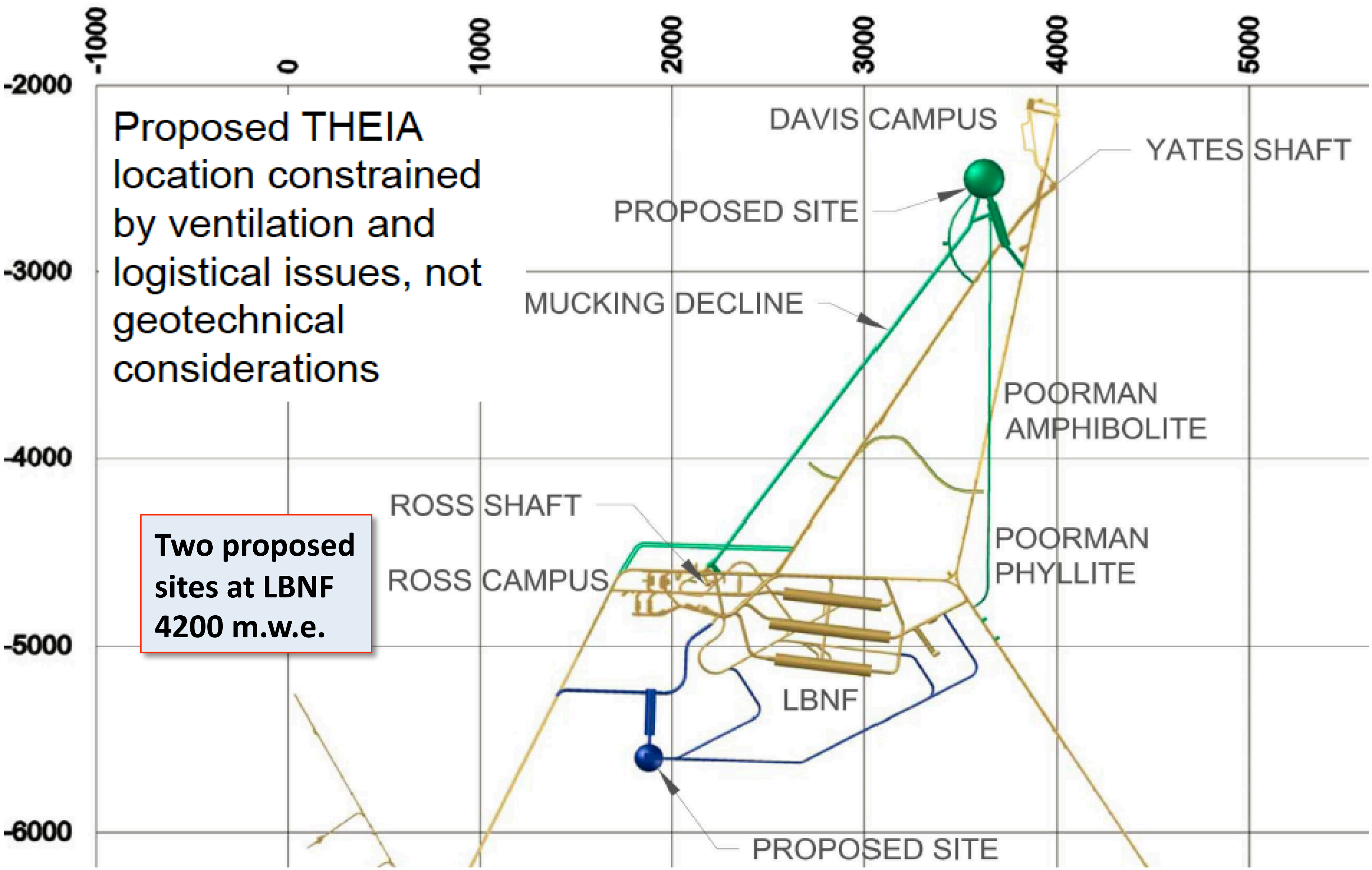
October 22-24, 2016

Sanford
Underground Research Facility
South Dakota Science and Technology Authority

THEIA Project BOE Design

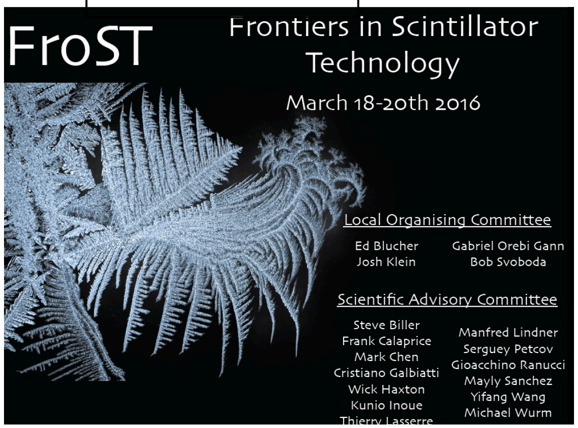
Proposed THEIA location constrained by ventilation and logistical issues, not geotechnical considerations

Two proposed sites at LBNF 4200 m.w.e.



THEIA proto-collaboration

March 2016



THEIA "Interest Group" formed with concept paper:

Advanced Scintillator Detector Concept (ASDC):
A Concept Paper on the Physics Potential of Water-Based Liquid Scintillator

arXiv:1409.5864

J. R. Alonso,[1] N. Barros,[2] M. Bergevin,[3] A. Bernstein,[4] L. Bignell,[5] E. Blucher,[6] F. Calaprice,[7] J. M. Conrad,[1] F. B. Descamps,[8] M. V. Diwan,[5] D. A. Dwyer,[8] S. T. Dye,[9] A. Elagin,[6] P. Feng,[10] C. Grant,[3] S. Grullon,[2] S. Hans,[5] D. E. Jaffe,[5] S. H. Kettell,[5] J. R. Klein,[2] K. Lande,[2] J. G. Learned,[11] K. B. Luk,[8,12] J. Maricic,[11] P. Marleau,[10] A. Mastbaum,[2] W. F. McDonough,[13] L. Oberauer,[14] G. D. Orebi Gann*,[8,12,†] R. Rosero,[5] S. D. Rountree,[15] M. C. Sanchez,[16] M. H. Shaevitz,[17] T. M. Shokair,[18] M. B. Smy,[19] A. Stahl,[20] M. Strait,[6] R. Svoboda,[3] N. Tolich,[21] M. R. Vagins,[19] K. A. van Bibber,[18] B. Viren,[5] R. B. Vogelaar,[15] M. J. Wetstein,[6] L. Winslow,[1] B. Wonsak,[22] E. T. Worcester,[5] M. Wurm,[23] M. Yeh,[5] and C. Zhang[5]

50 authors, 23 institutions, lots of experience: Borexino, DUNE, KamLAND, SNO, Double CHOOZ, SNO+, Daya Bay, LENA, KamLAND-Zen, MiniBOONE, Super-Kamiokande, WATCHMAN, ANNIE, T2K....

October 2016

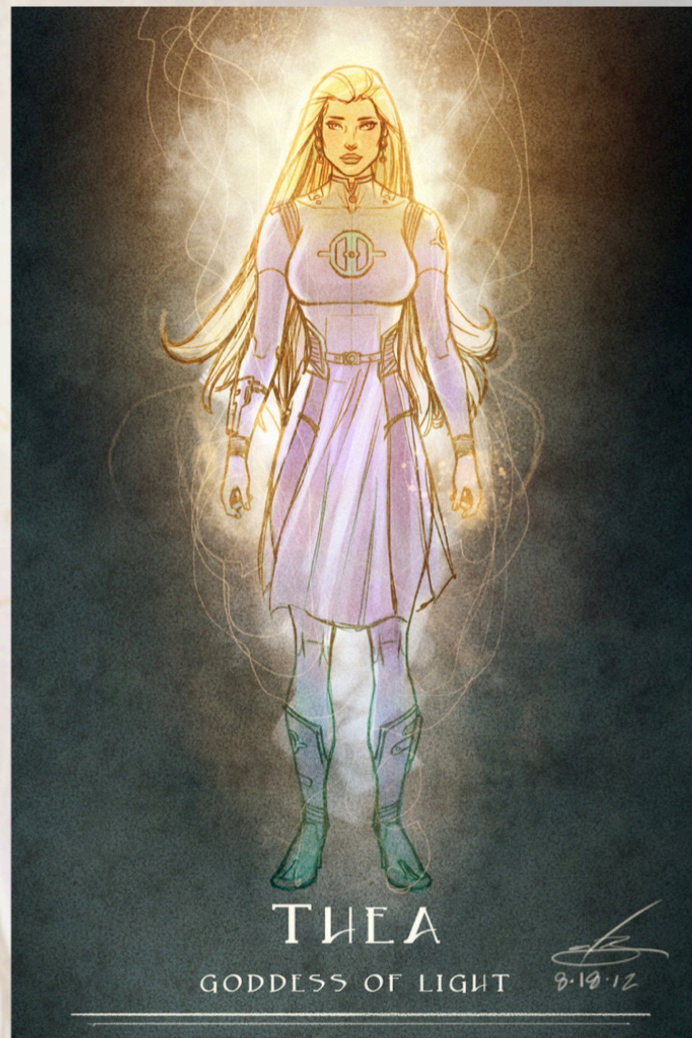
FroST - Topical Workshop for THEIA

Decided to form proto-collaboration to coordinate R&D on international scale: Canada, China, Finland, Germany, Portugal, UK, USA thus far

Next meeting **mid-March 2017** at DESY
All are welcome!

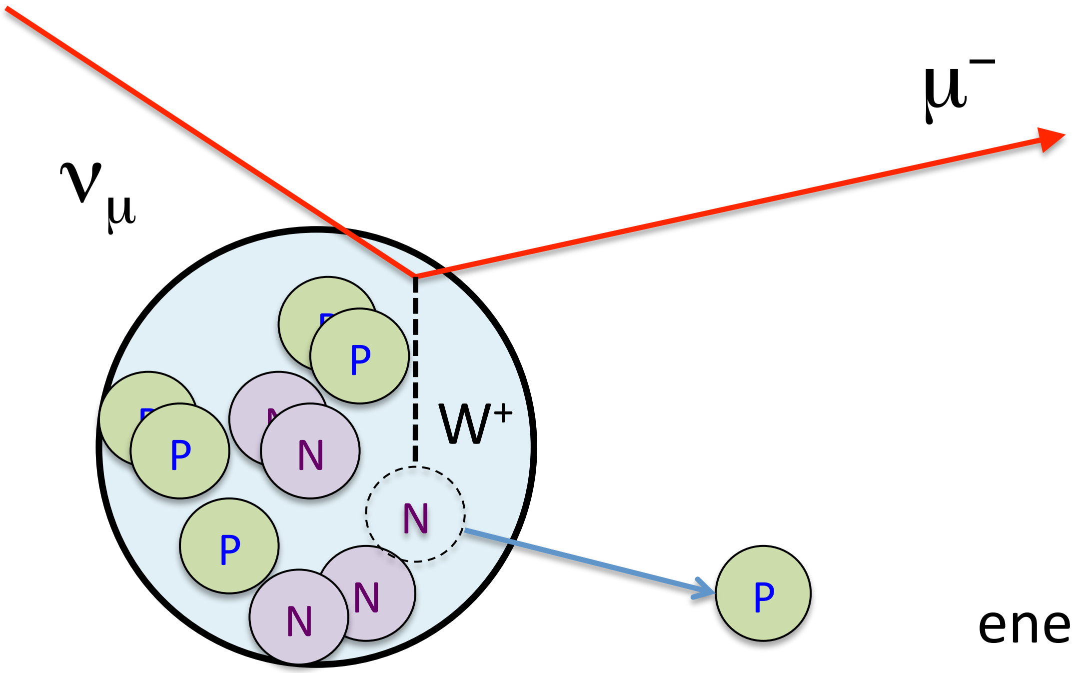
Summary

- Advances in LS technology and photosensors make possible a hybrid WC/LS detector that could be located deep underground at the LBNF, now being built
- Very broad and flexible physics program at deep (4200 mwe) and remote (from reactors) site that will also have a powerful neutrino beam.
- Very active and ambitious R&D program
- International collaboration forming now, new members welcome



Backup

Can one tell neutrinos from anti-neutrinos by looking at neutrons?

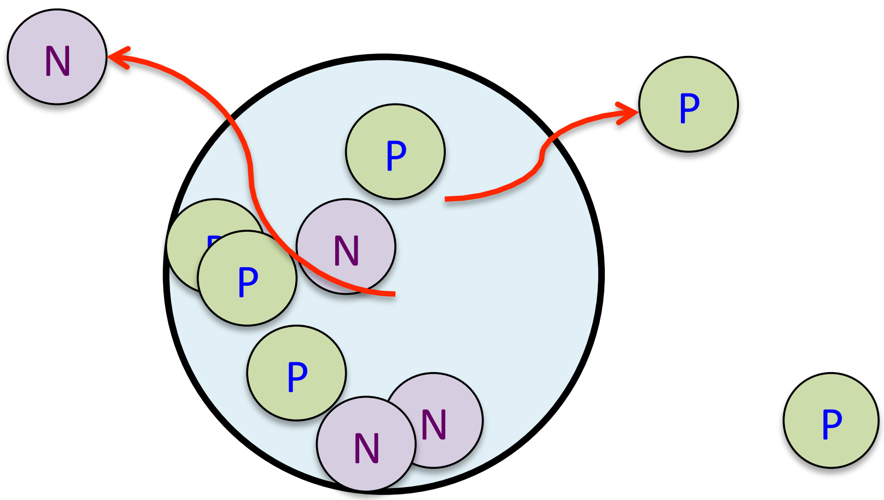


energetic
struck nucleon

NEUTRINO CCQE

Can one tell neutrinos from anti-neutrinos by looking at neutrons?

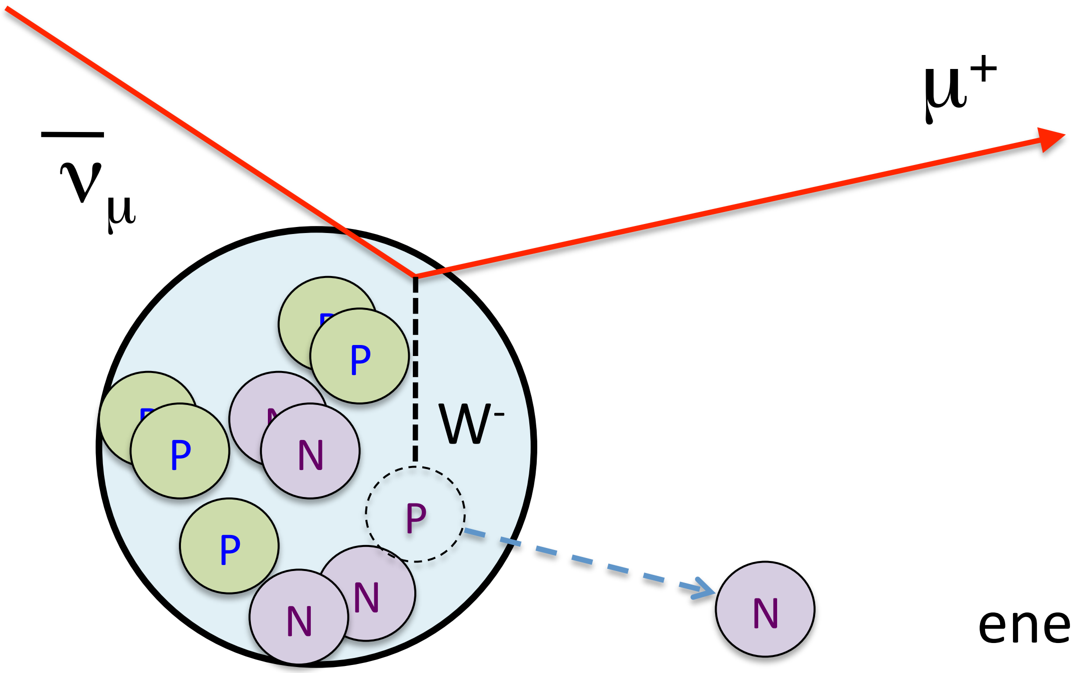
~1 MeV "boil off" nucleons



energetic
struck nucleon

NEUTRINO CCQE

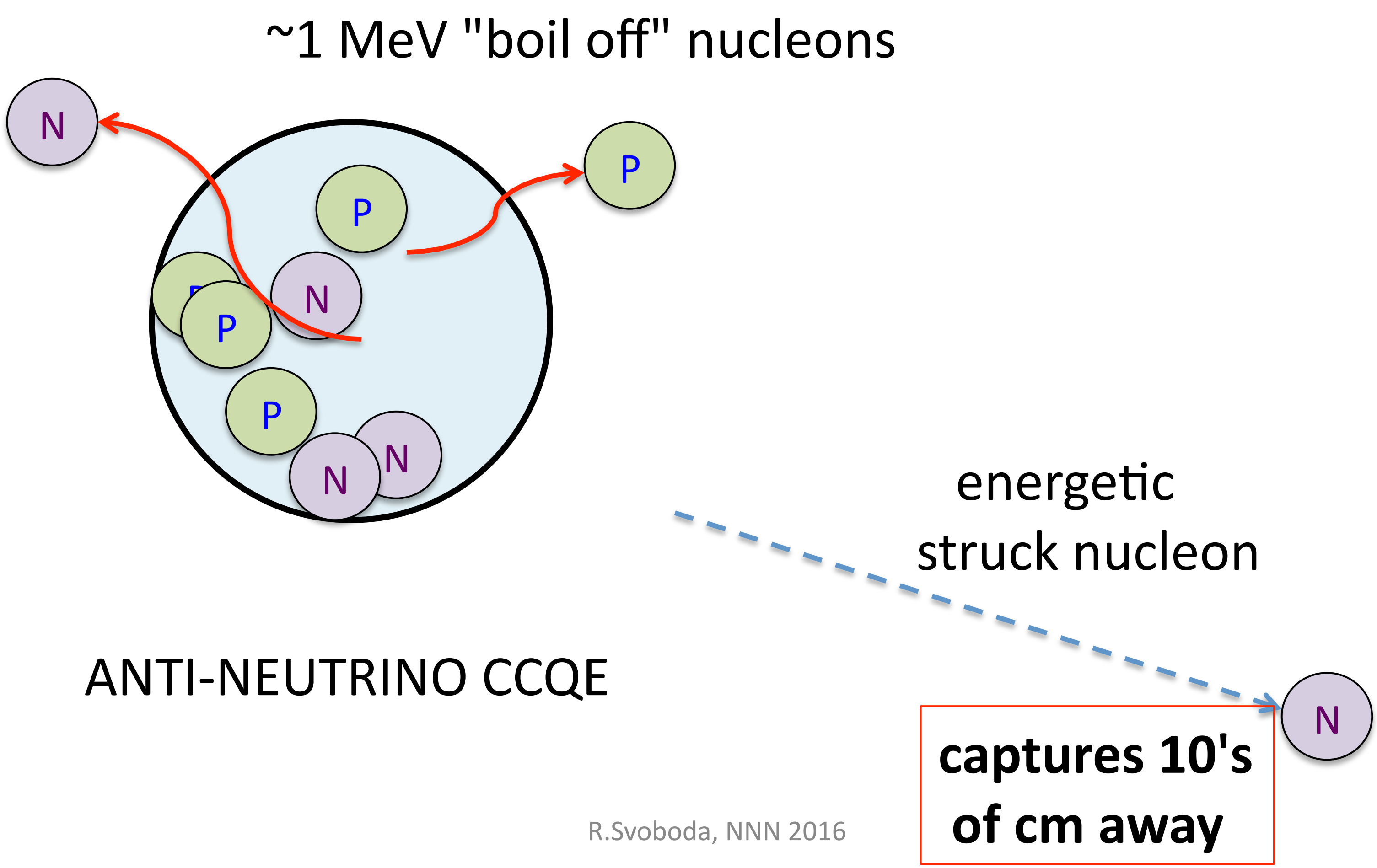
Can one tell neutrinos from anti-neutrinos by looking at neutrons?



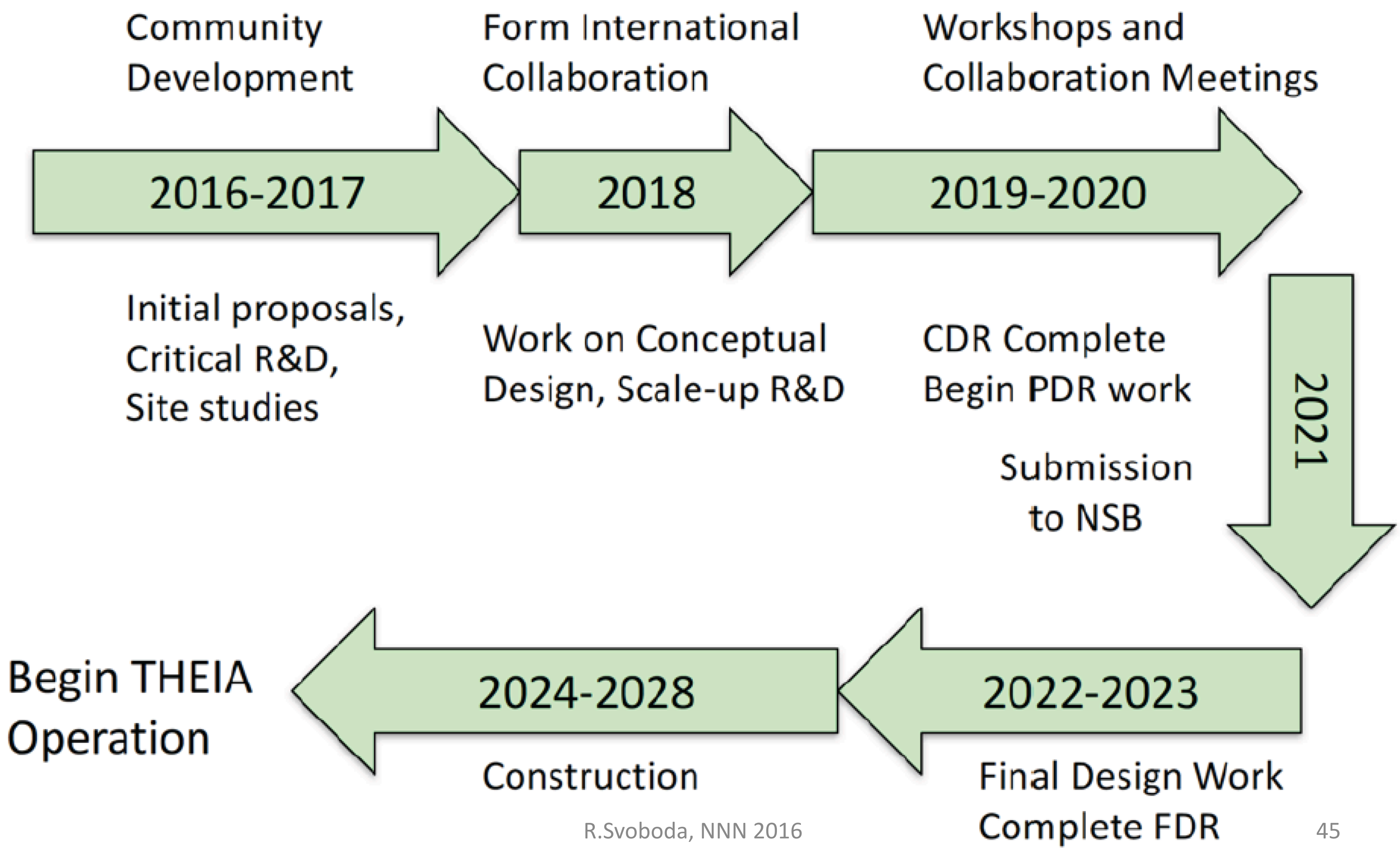
energetic
struck nucleon

ANTI-NEUTRINO CCQE

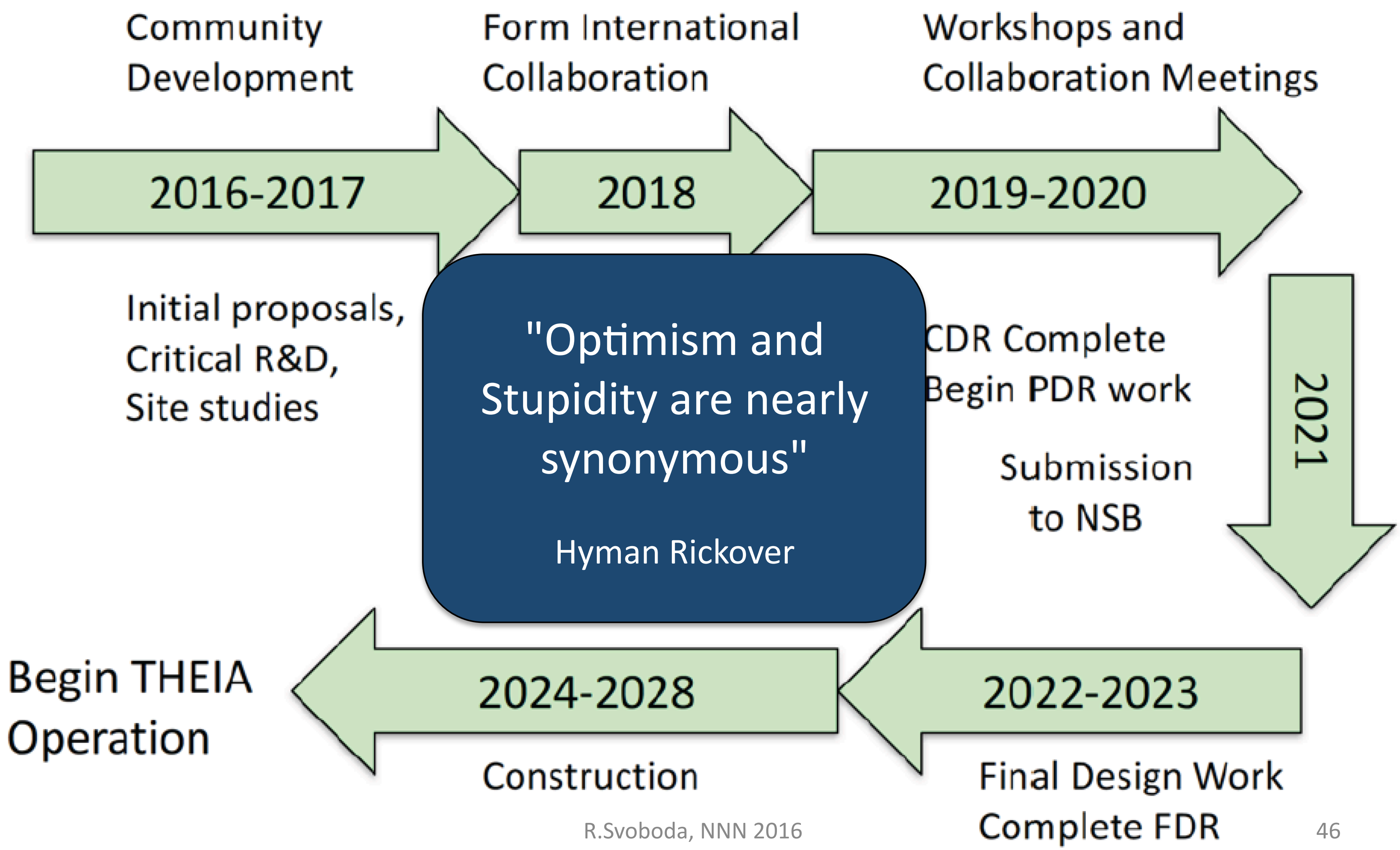
Can one tell neutrinos from anti-neutrinos by looking at neutrons?



THEIA Notional Technically Limited Timeline



THEIA Notional Technically Limited Timeline

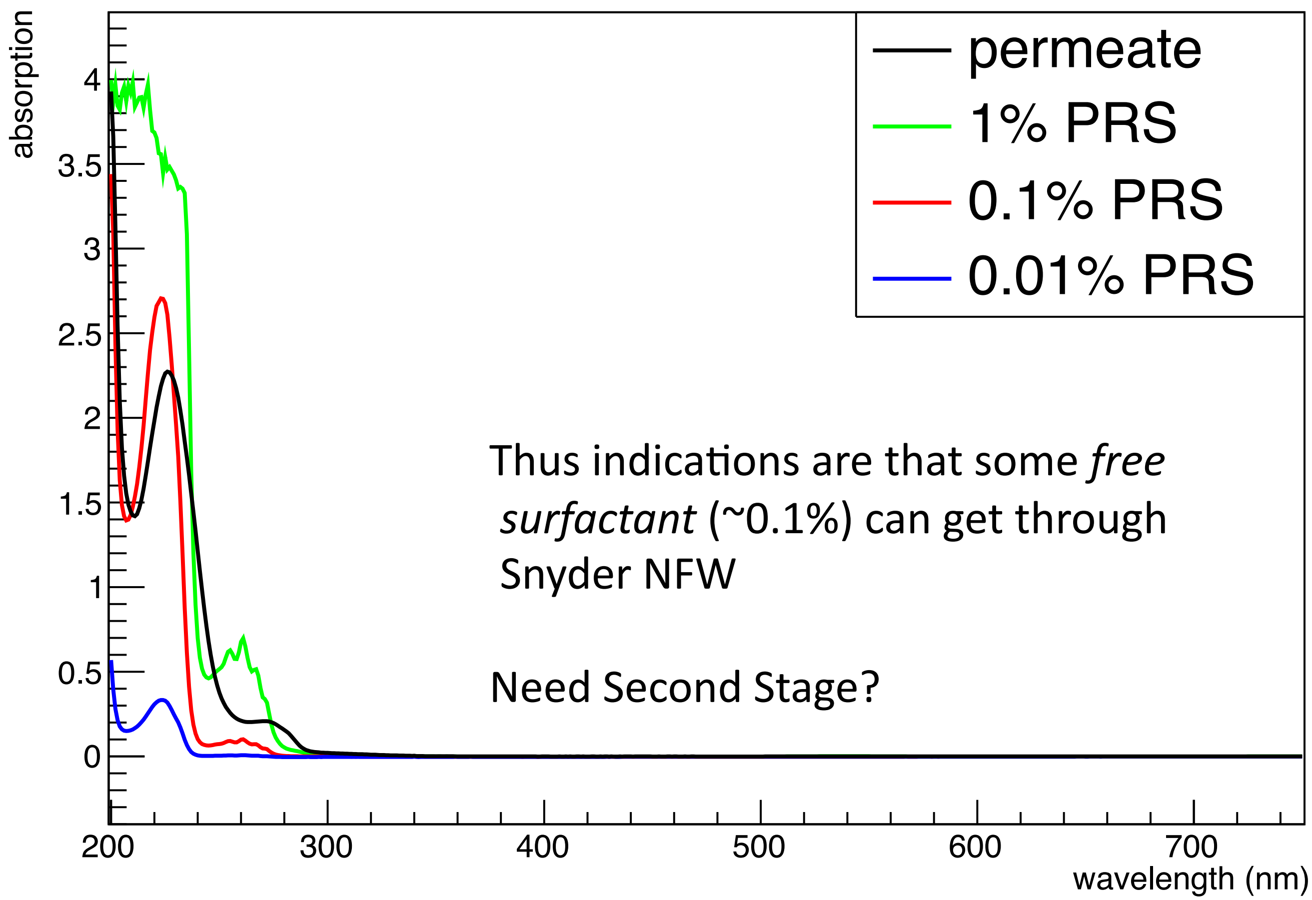


THEIA Project BOE Schedule Estimate

ACTIVITY	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
CD-0 Review	*									
Conceptual Design & BOE										
30% EXC & BSI	*									
75% EXC & BSI	*									
100% EXC & BSI	*									
CD-1 Review		*								
Geotechnical Site Investigation		* * *								
Preliminary Design (CMGC)										
30% EXC & BSI		*								
60% EXC & BSI			*							
90% EXC & BSI			*							
100% EXC & BSI			*							
CD-2 Review			*							
Final Design (CMGC)										
30% EXC & BSI				*						
60% EXC & BSI				*						
90% EXC & BSI				*						
100% EXC & BSI				*						
CD-3 Review					*					
Procurement (CMGC)					* * *					
Construction										
Excavation						* * * *	* * * *			
BSI							* *	* * * *		
Beneficial Occupancy									* * * *	* * * *
CD-4 Review									*	

What is making it through the NF?

PRS calibration =Linear Alkyl Sulfonate



Thus indications are that some *free surfactant* (~0.1%) can get through Snyder NFW

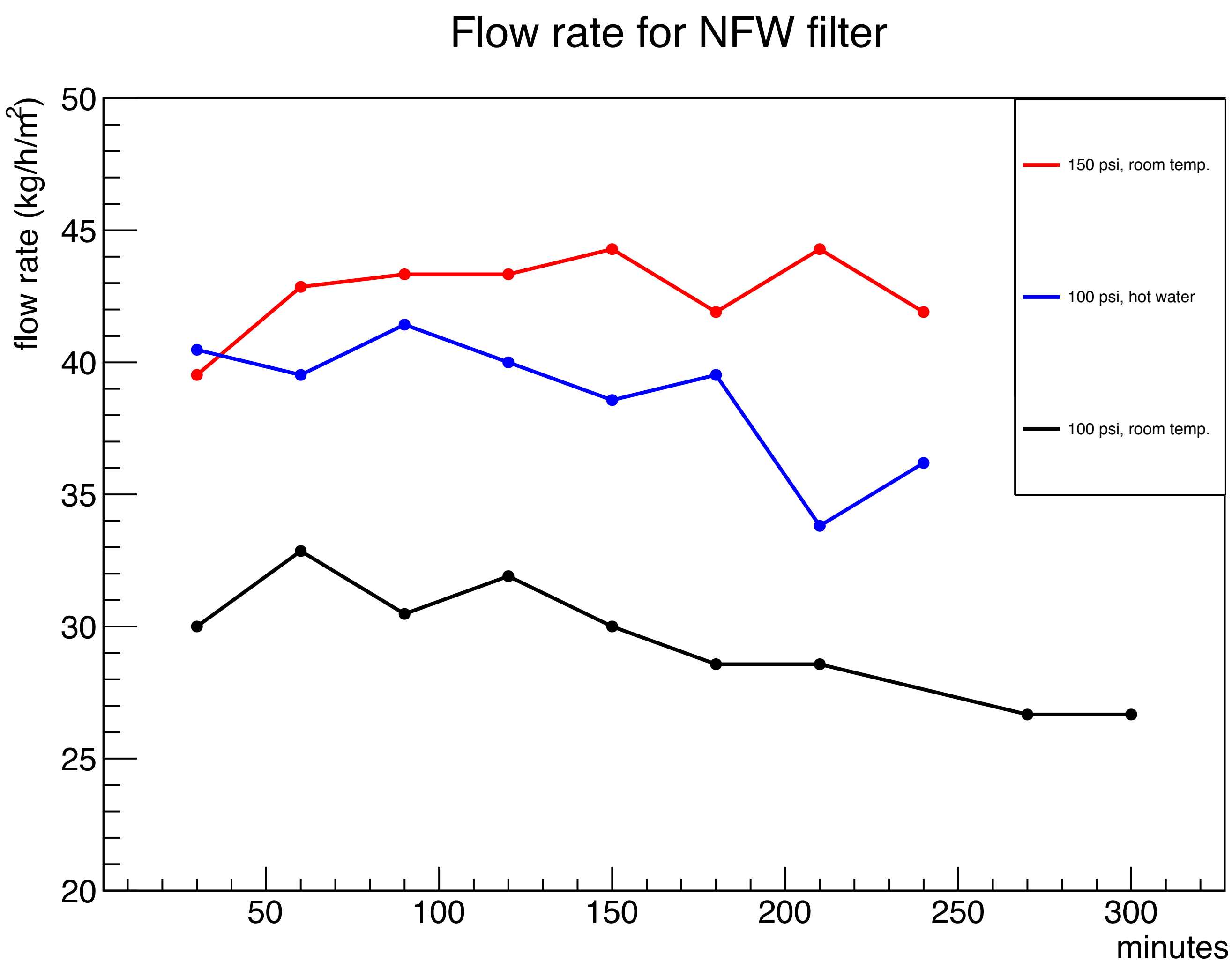
Need Second Stage?

Adding ppb levels of $FeCl_3$ reproduces this effect

Table 4.7: 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

Cannot use EGADS system on WbLS as the molecules of the organic component are non-polar and do not pass through.

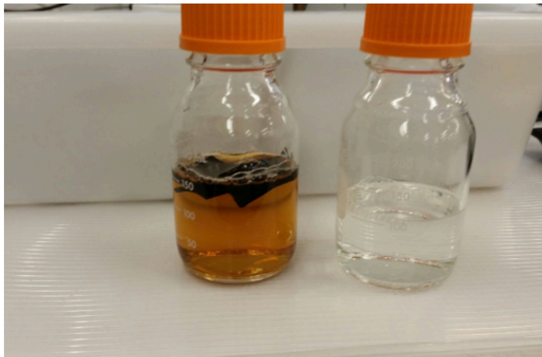


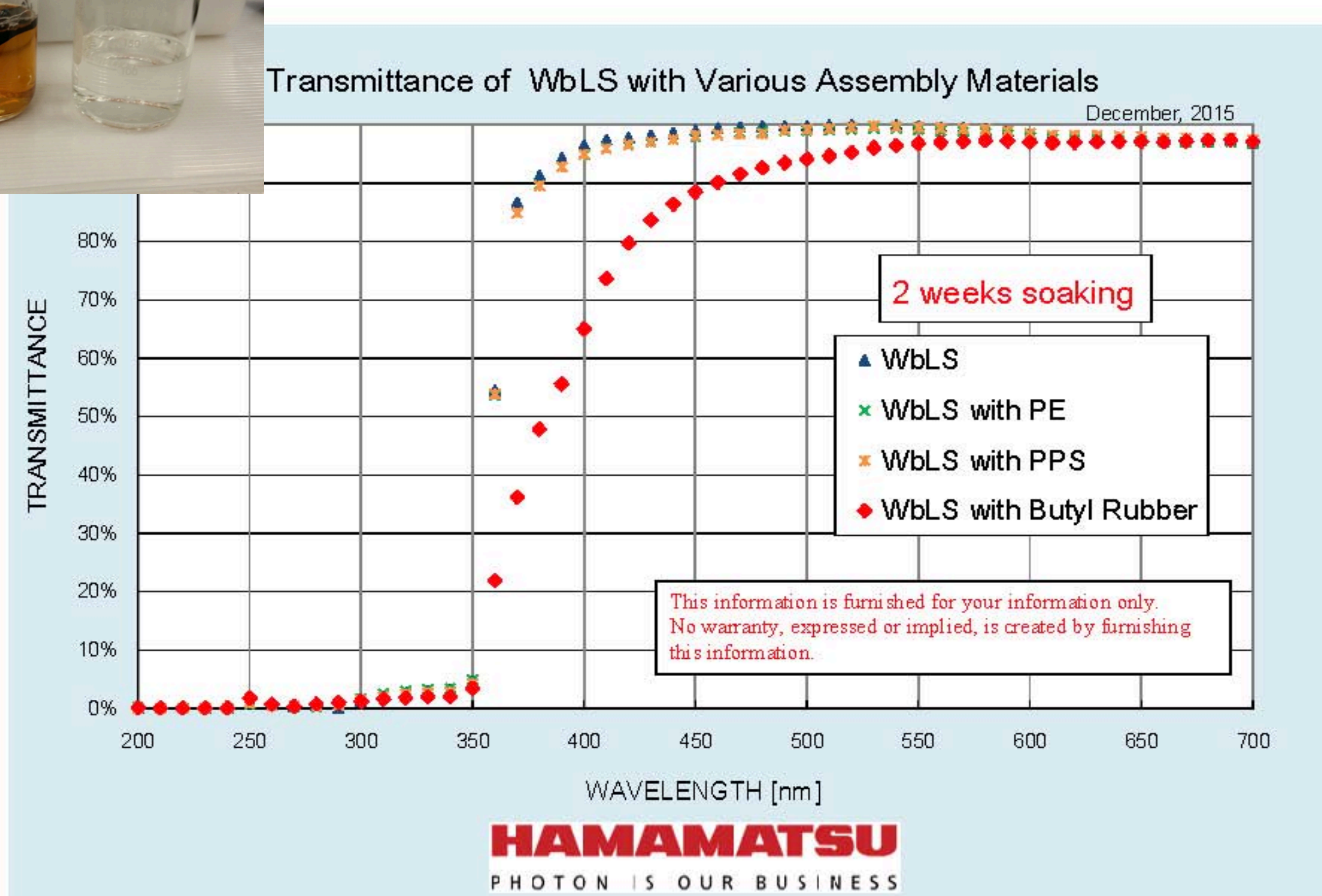
Scale up to commercially available facility would mean about 1 kton per day. **This is feasible for THEIA!**

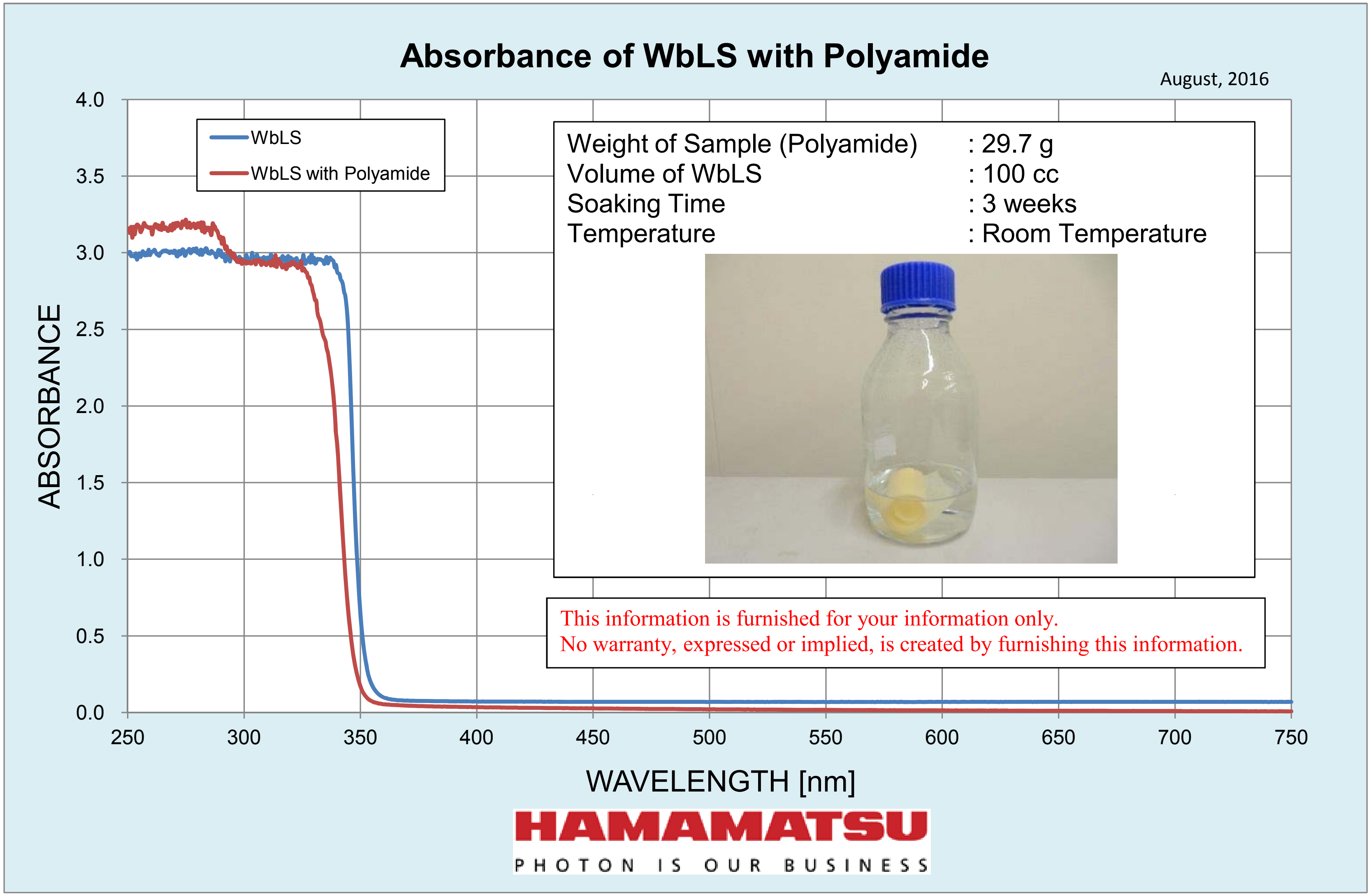
Next Steps

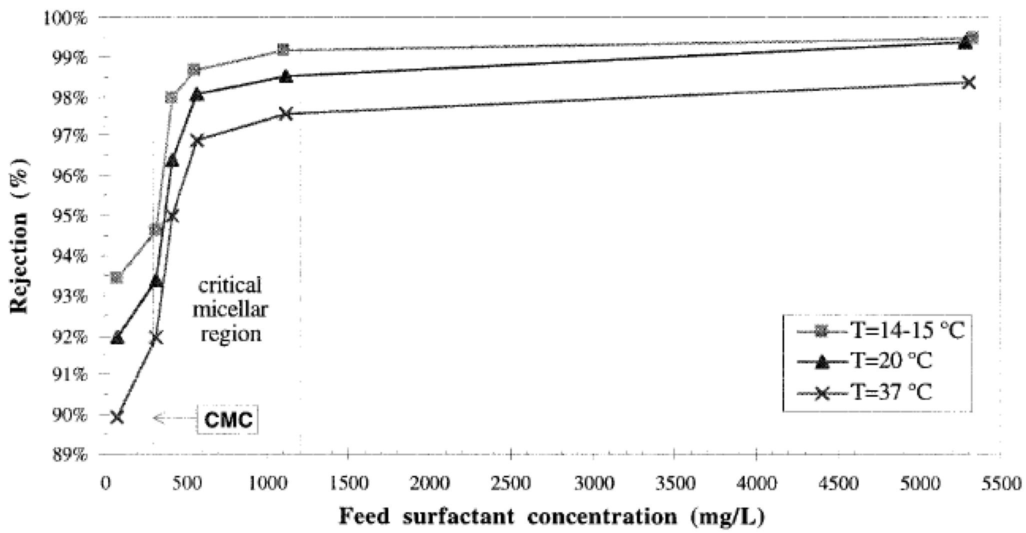
- Try second stage "tight" filter on permeate to remove free surfactant
- Test with ionic contaminants (E.g. iron ions) to see that they make it through both stages
- Test that light yield if not affected by this process
- Temperature and pressure optimization
- Scale up to prototype (ANNIE?)

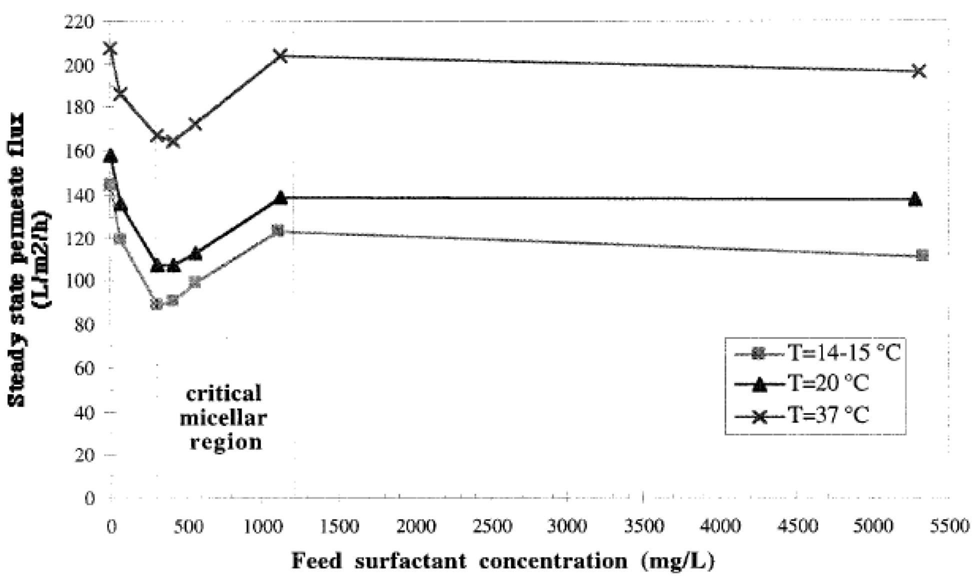
Material Compatibility






Absorbance of WbLS with Polyamide
August, 2016
WbLS
WbLS with Polyamide
Weight of Sample (Polyamide) : 29.7 g
Volume of WbLS : 100 cc
Soaking Time : 3 weeks
Temperature : Room Temperature
This information is furnished for your information only.
No warranty, expressed or implied, is created by furnishing this information.
ABSORBANCE
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
250
300
350
400
450
500
550
600
650
700
750
WAVELENGTH [nm]
HAMAMATSU
PHOTON IS OUR BUSINESS





Feed flow rates and rejection depend on temperature and flow rates. We want high flow rate but also high rejection of organics

Separation of an Anionic Surfactant by Nanofiltration

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RUI A. R. BOAVENTURA[†]

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$$n \to 3\nu$$

This type of decay has been associated with theories with **Large Extra Dimensions** (LED)

Such theories postulate that the fundamental energy scale of gravity is not M_{Planck} but rather is quite small (M_*), and the reason that gravity is so weak is due to propagation in the "folded up" extra dimensions.

A challenge is to suppress proton decay by other than the gauge energy scale – need to invoke other mechanisms to do this and there are many suggestions, some of which lead to this decay mode being important.

An Example...

6D theory in which symmetry in rotations in the "plane" of the 2 extra dimensions give rise to processes that violate baryon number according to $\Delta\Sigma_{45} = 3\Delta B + \Delta L_{SM} - \Delta L_{\nu_s} = 4$ Thus $\Delta B = 1$ processes necessarily involve three quarks and three leptons.

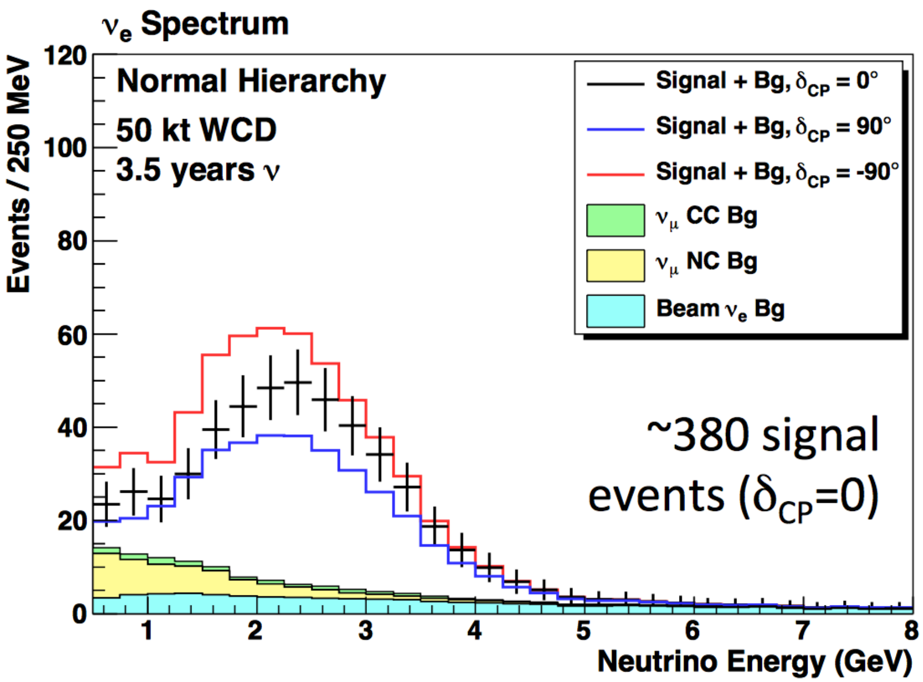
E.g. $n \rightarrow \nu_L \, \overline{\nu}_s \, \overline{\nu}_s$

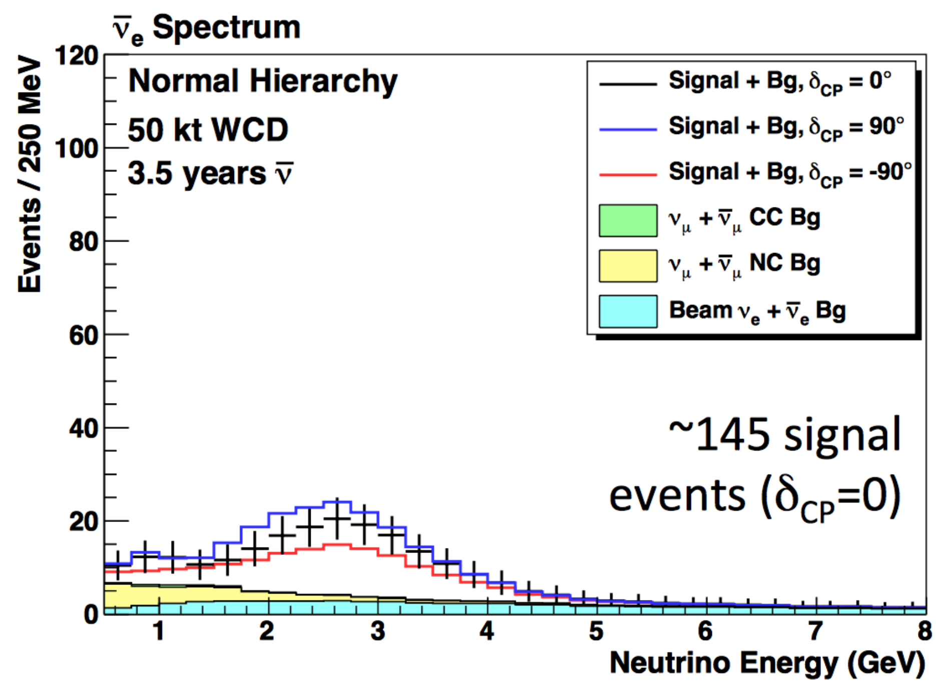
$$\Delta B = 1 - 0 = 1 \quad \Delta L_{SM} = 0 - 1 = -1 \quad \Delta L_{\nu_S} = 0 - (-2) = -2$$

$$\Delta\Sigma_{45} = 3(1) + (-1) - (-2) = 4$$

This would look like an "invisible" nucleon decay inside a nucleus which would leave an excited daughter and nothing else. **How to look for such decays?**

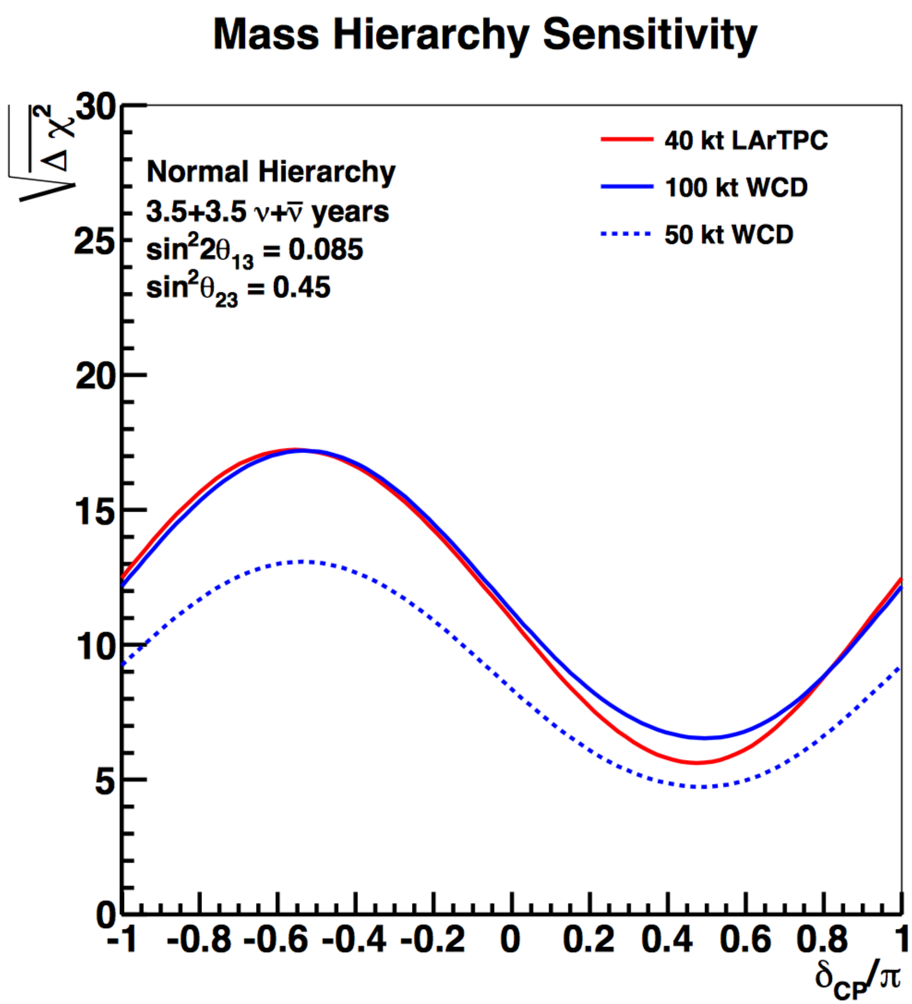
WCD Spectra

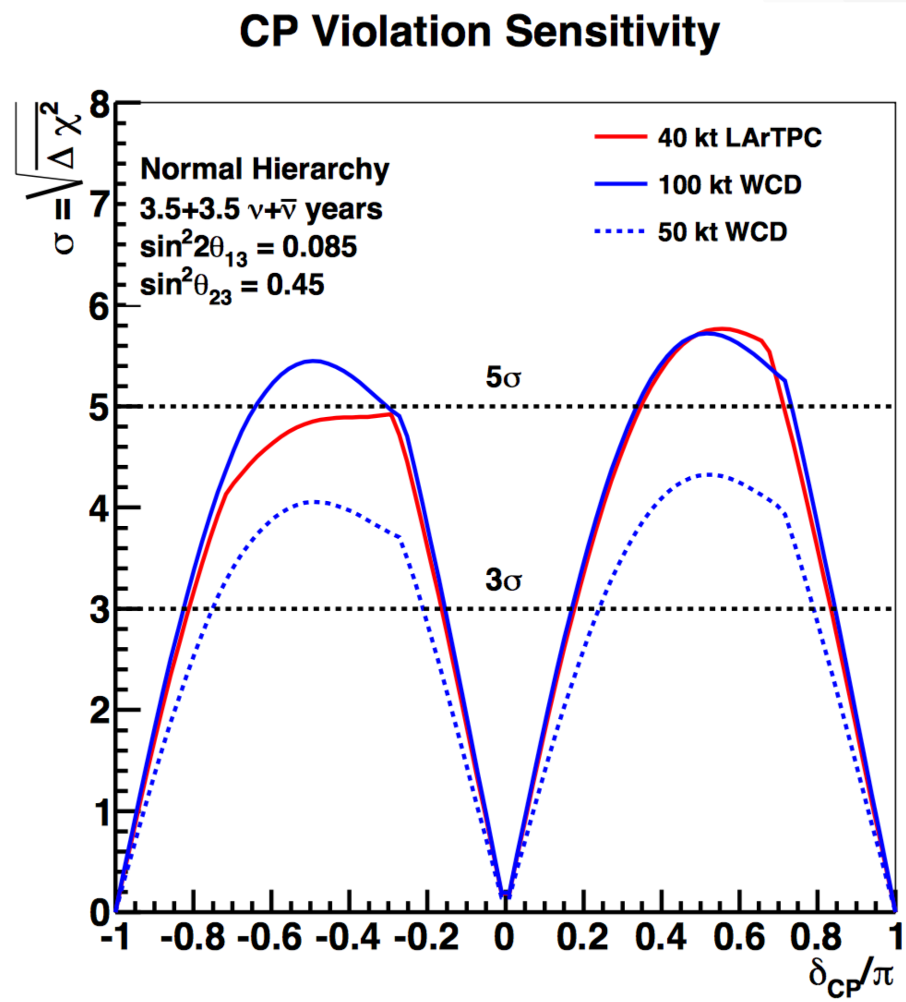




- 50 kT WCD
- Order 500 appearance signal events for $\delta_{CP} = 0$
  - ~½ of DUNE 40-kt LAr TPC
- NC background reduced to 25% of SK1/2 level
  - Possibly still pessimistic

E.Worcester, FroST-I, FNAL 2016





E.Worcester, FroST-I, FNAL 2016

Assumptions

WCD Sensitivity

- DUNE/LBNF beam: 80 GeV, 1.07 MW, 3.5+3.5 ($\nu+\bar{\nu}$) years
- Normalization uncertainty:
  - ν_e uncorrelated: 2% signal, 5% background
- Efficiency and smearing:
  - Efficiency from SuperK1 MC (LL selection)
  - Energy resolution/smearing from SuperK1 MC
    - 10-15%/$\sqrt{E(GeV)}$ ν_e CC QE
    - 20-25%/$\sqrt{E(GeV)}$ ν_e CC nQE
  - Efficiencies out of date – see next slide
- 2-sample fit (ν_e, $\bar{\nu}_e$) – disappearance sample not considered
  - QE-like and nQE-like treated separately in the fit
- Oscillation parameters and uncertainties: NuFit2014