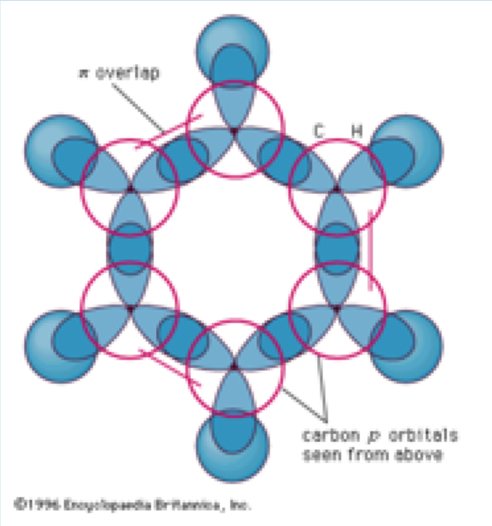
Water-base Liquid Scintillator

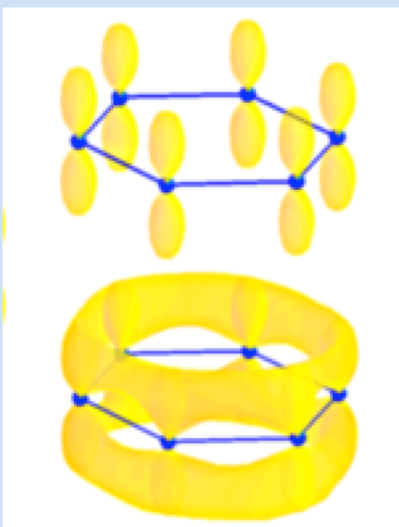
- Description
- Physics Potential
- Status of Development
- Future Plans

Robert Svoboda, J-PARC, August 2015

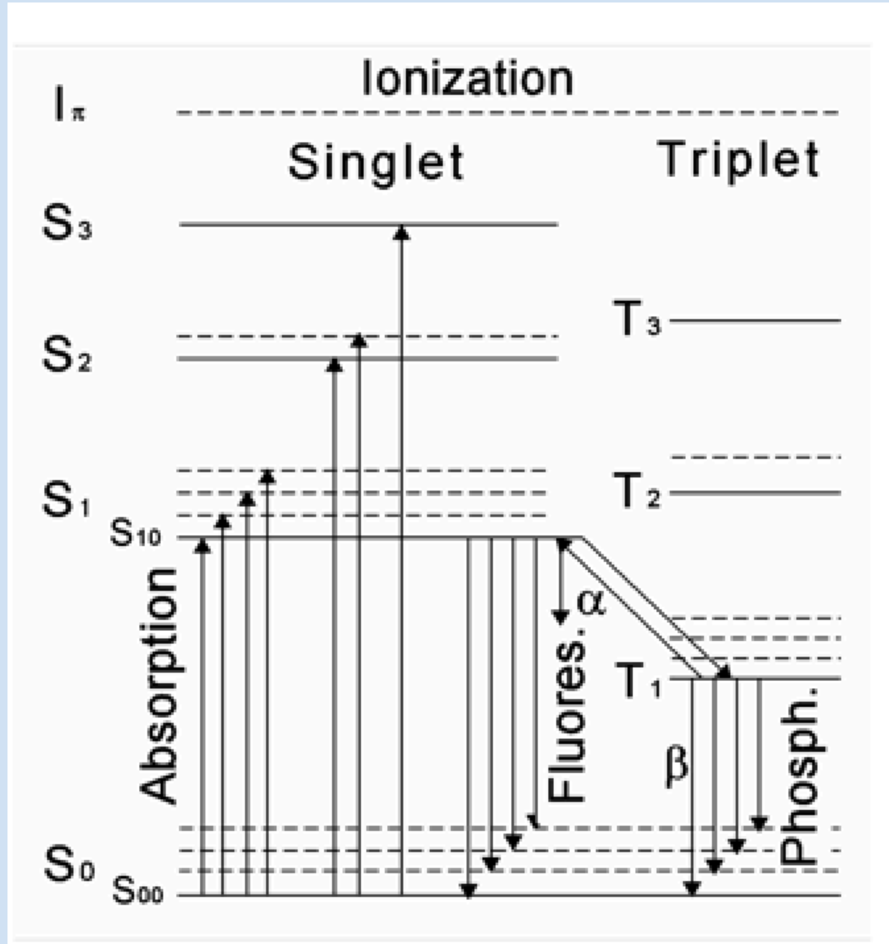
How Does it Work?



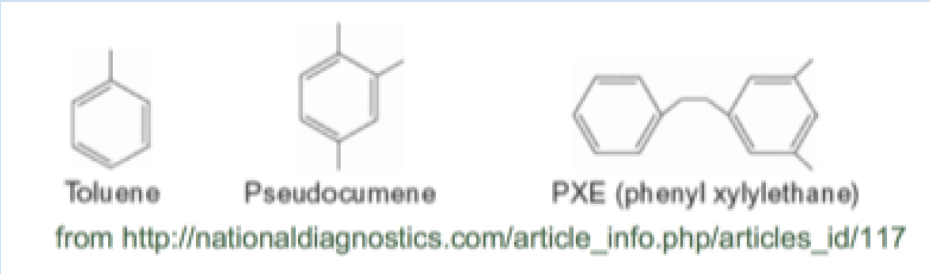
planer σ orbitals of
a benzene ring

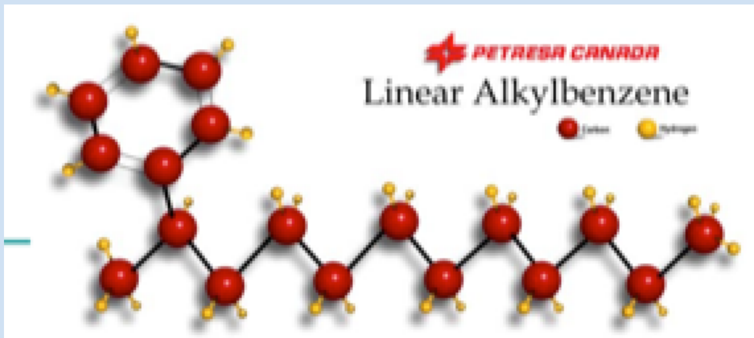


π orbitals merge above
and below ring



Singlet and triplet states of the quantum
current ring, with vibrational sub-levels. Add
a fluor and Stokes Shift and you have a scintillator.





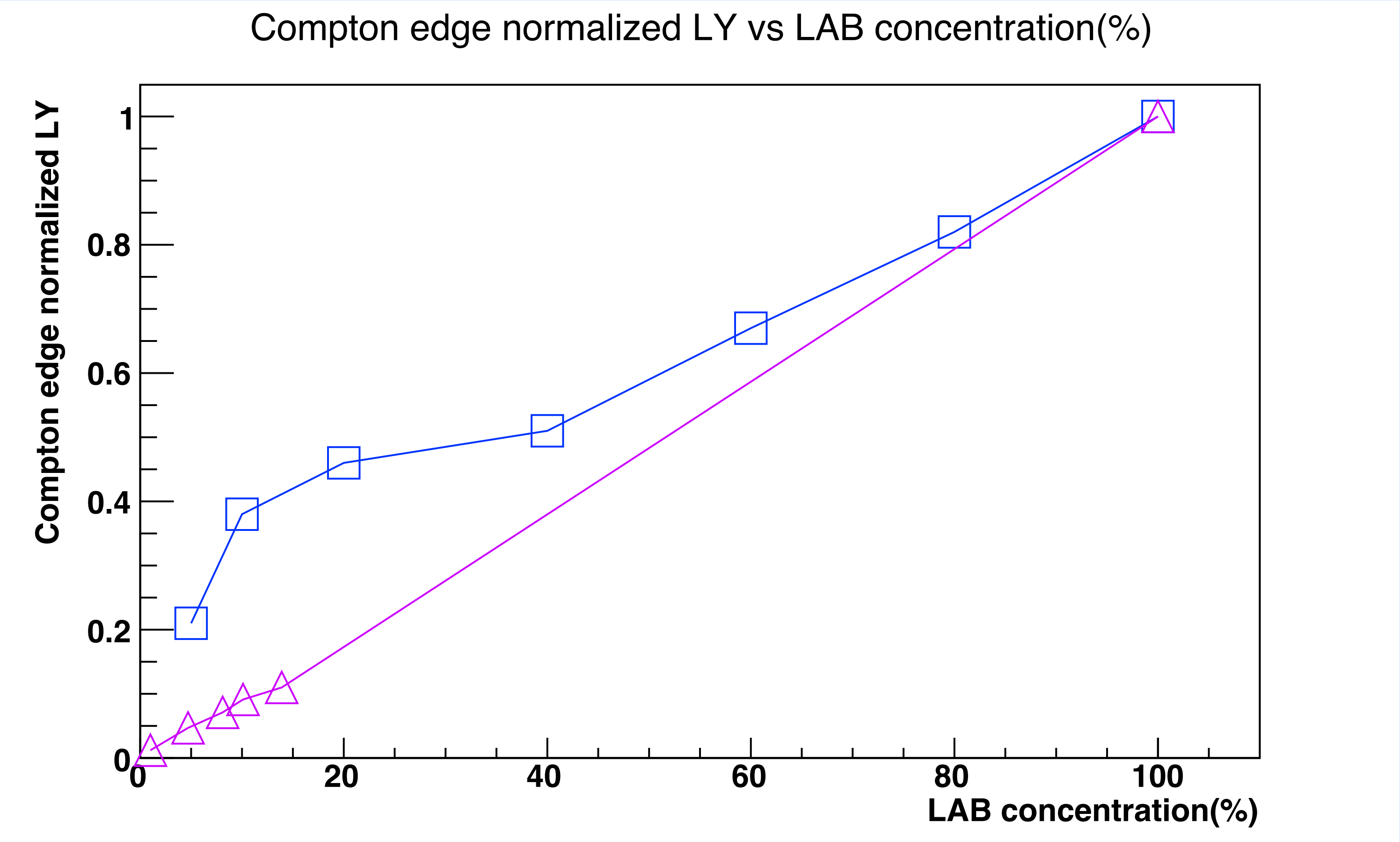
That's why organic scintillators always are made with solvents that have a benzene ring.

Unlike cryogenic electron drift detectors, there is no fundamental reason that they won't work in water.

Main challenges are then how to dissolve organic liquids in water, and how to keep the solution stable. Sort of like dissolving oil into water...

BNL has solved these basic issues with a proprietary mixture that is tunable for the light output.

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



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

What can you do with this?

Advanced Scintillator Detector Concept (ASDC):

A Concept Paper on the Physics Potential of Water-Based Liquid Scintillator

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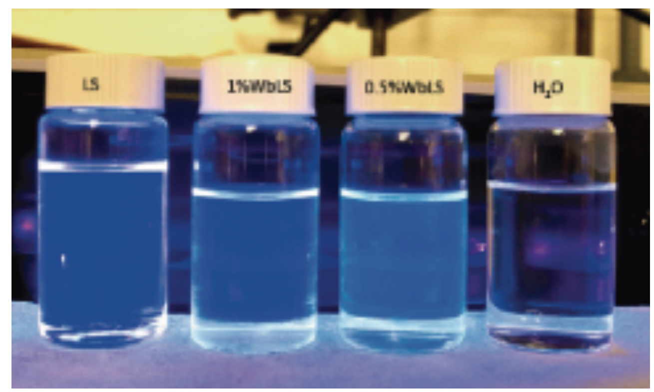
arXiv:1409.5864

Advanced Scintillator Detector Concept (ASDC) concept paper posted on archive.



1% gives ~100 optical photons/MeV

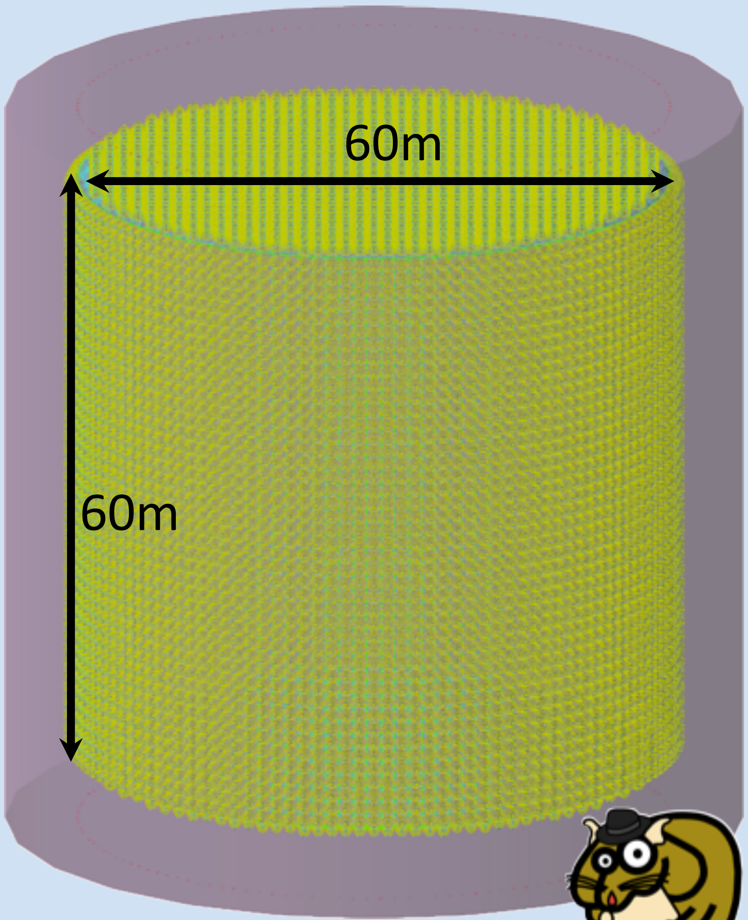
4% WbLS gives approximately four times the light yield of pure water

THEIA: A realisation of the Advanced Scintillation Detector Concept (ASDC)

Concept paper - arXiv:1409.5864

- 50-100 kton WbLS target
- High coverage with ultra-fast, high efficiency photon sensors
- 4800 m.w.e. underground (Homestake).
- Is Kamioka a possibilty?
- Comprehensive low-energy program: solar neutrinos, supernova, DSNB, proton decay, geo-neutrinos, DBD
- In the LBNF beam: long-baseline program complementary to proposed LAr detector

➡**Broad physics program!**



Detector image product of RAT-PAC

THEIA "Interest Group"

Brookhaven National Laboratory
University of California, Berkeley
University of California, Davis
University of California, Irvine
University of Chicago
Columbia University
University of Hawaii at Manoa
Hawaii Pacific University
Iowa State University
Lawrence Berkeley National Laboratory
Lawrence Livermore National

Laboratory
RWTH Aachen University
TUM, Physik-Department
University of Hamburg
Johannes Gutenberg-University Mainz

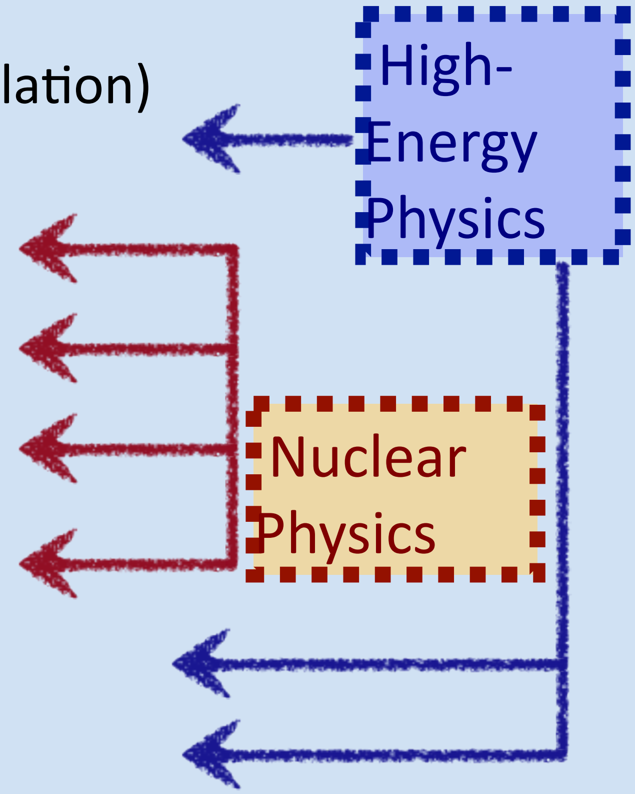
Los Alamos National Laboratory
University of Maryland
MIT
University of Pennsylvania

Brunel University

Princeton University
Sandia National Laboratories
Virginia Polytechnic Inst. & State University
University of Washington

Potential Physics Program

1. Long-baseline physics (mass hierarchy, CP violation)
2. Neutrinoless double beta decay
3. Solar neutrinos (solar metallicity, luminosity)
4. Supernova burst neutrinos & DSNB
5. Geo-neutrinos
6. Nucleon decay
7. Source-based sterile searches



Remarkably, the same detector could show that neutrinos and antineutrinos are the same, ***and*** that "neutrinos" and "antineutrinos" oscillate differently

Supernova Burst ν in Theia

- ~90% events are IBD
- Enhanced neutron tag via low threshold scintillation. Even better if Gd added. Current SK efficiency ~18%. With Gd will be ~60%-70%.
- Enhanced energy resolution of prompt IBD. For 4% loading this would be a factor of two.

Neutrino Reaction	Percentage of Total Events	Type of Interaction
$\overline{\nu}_e + p \to n + e^+$	88%	Inverse Beta
$\nu_e + e^- \to \nu_e + e^-$	1.5%	Elastic Scattering
$\overline{\nu}_e + e^- \to \overline{\nu}_e + e^-$	<1%	Elastic Scattering
$\nu_x + e^- \to \nu_x + e^-$	1%	Elastic Scattering
$\nu_e +^{16} O \to e^- +^{16} F$	2.5%	Charged Current
$\overline{\nu}_e +^{16} O \to e^+ +^{16} N$	1.5%	Charged Current
$\nu_x +^{16} O \to \nu_x + O^*/N^* + \gamma$	5%	Neutral Current

- Better separation of NC mono-energetic 5-10 MeV gammas from background
- Better efficiency for low energy electrons from the 15 MeV threshold CC interactions. Potential for detection of nuclear breakup.

Diffuse Supernova ν in Theia

- Muon induced spallation is a major background. Current SK threshold is 13.3 MeV. Scintillation light has the potential to enhance identification of (n,p) events and proton nuclear de-excitation final states.
- A 90% neutron detection efficiency would also reject multiple neutron events (2 of 13 DSNB backgrounds in SK are "double" even with 18% efficiency).

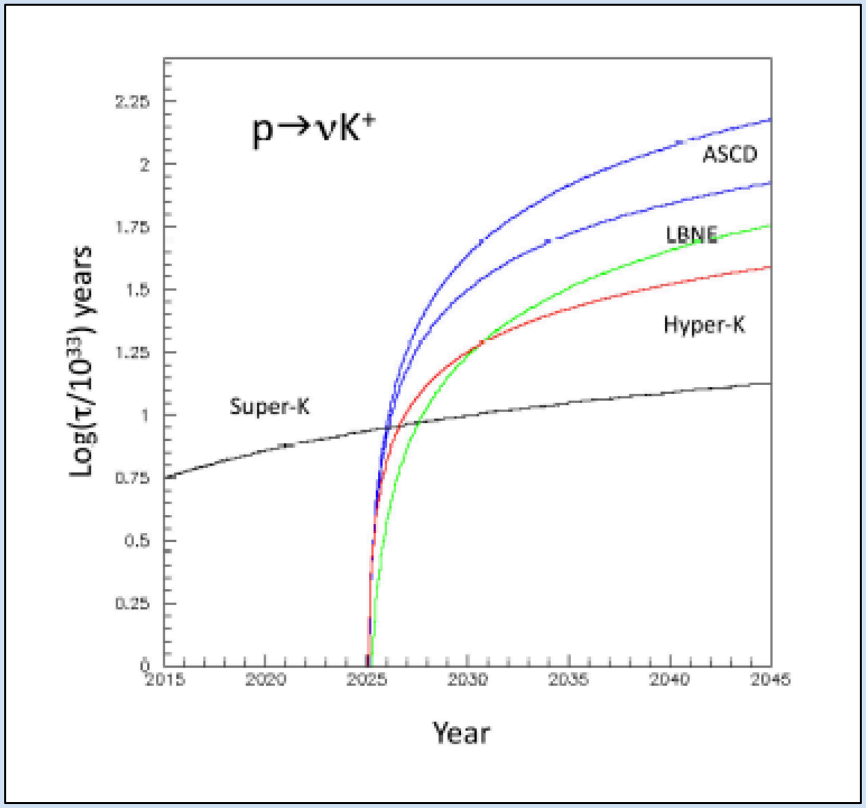
Table 3: Total flux for each SRN model (F_M), predicted number of SRN events in 22.5 kton·year with a neutrino energy range of 13.3~31.3 MeV (N_P), predicted number of SRN events in 22.5 kton·year with a neutrino energy range of 13.3~31.3 MeV (T_P) after IBD efficiency correction and flux upper limit at 90% C.L. (F_{90})($cm^{-2}s^{-1}$).

SRN model	F_M	N_P	T_P	F_{90}
Constant SN [1]	52.3	10.8	1.4	147.5
HBD 6 MeV [10]	21.8	4.4	0.6	150.9
Chemical evolution [4]	8.5	1.5	0.2	172.6
Heavy metal [5, 6]	31.3	4.7	0.6	201.8
LMA [7]	28.8	4.2	0.5	208.8
Failed SN [9]	12.0	1.7	0.2	214.9
Cosmic gas [3]	5.3	0.7	0.1	230.6
Star formation rate [8]	18.7	1.8	0.2	316.3
Population synthesis [2]	42.1	1.3	0.2	986.1

- Low energy "stealth" muon events can be clearly identified. No longer a problem.
- Enhanced energy resolution for signal and background rejection

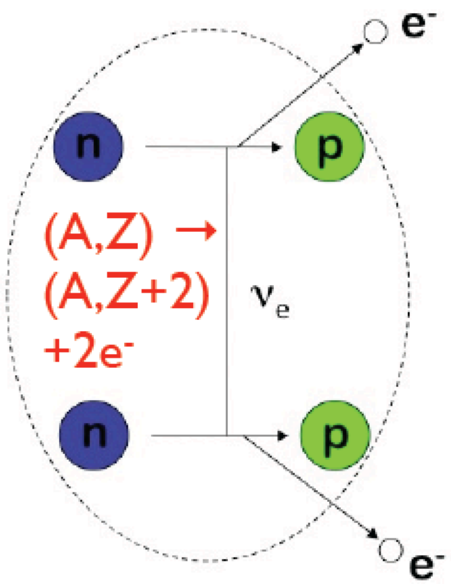
$p \rightarrow \nu K^+$ Proton Decay in Theia

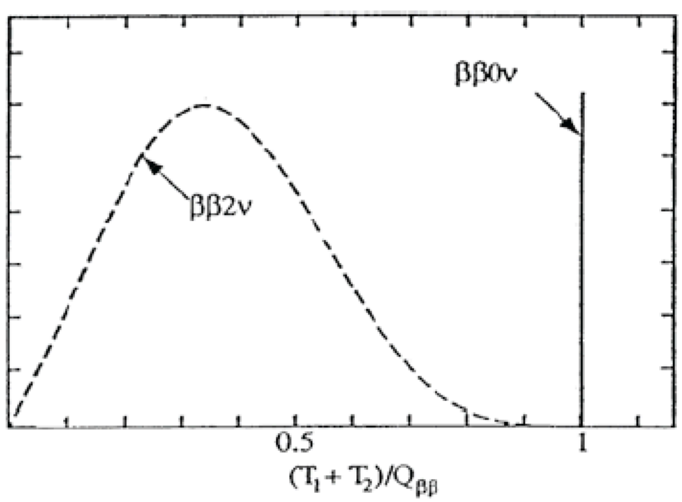
- SK limited due to the fact that the K^+ is below Cherenkov threshold.
- With WbLS this is no longer the case. Kaons identified via time structure.
- Studies by LENA and ASDC group show that expected efficiency is about 70% in detailed MC studies.
- Background depends on effectiveness of n-tagging
- JUNO should do well here

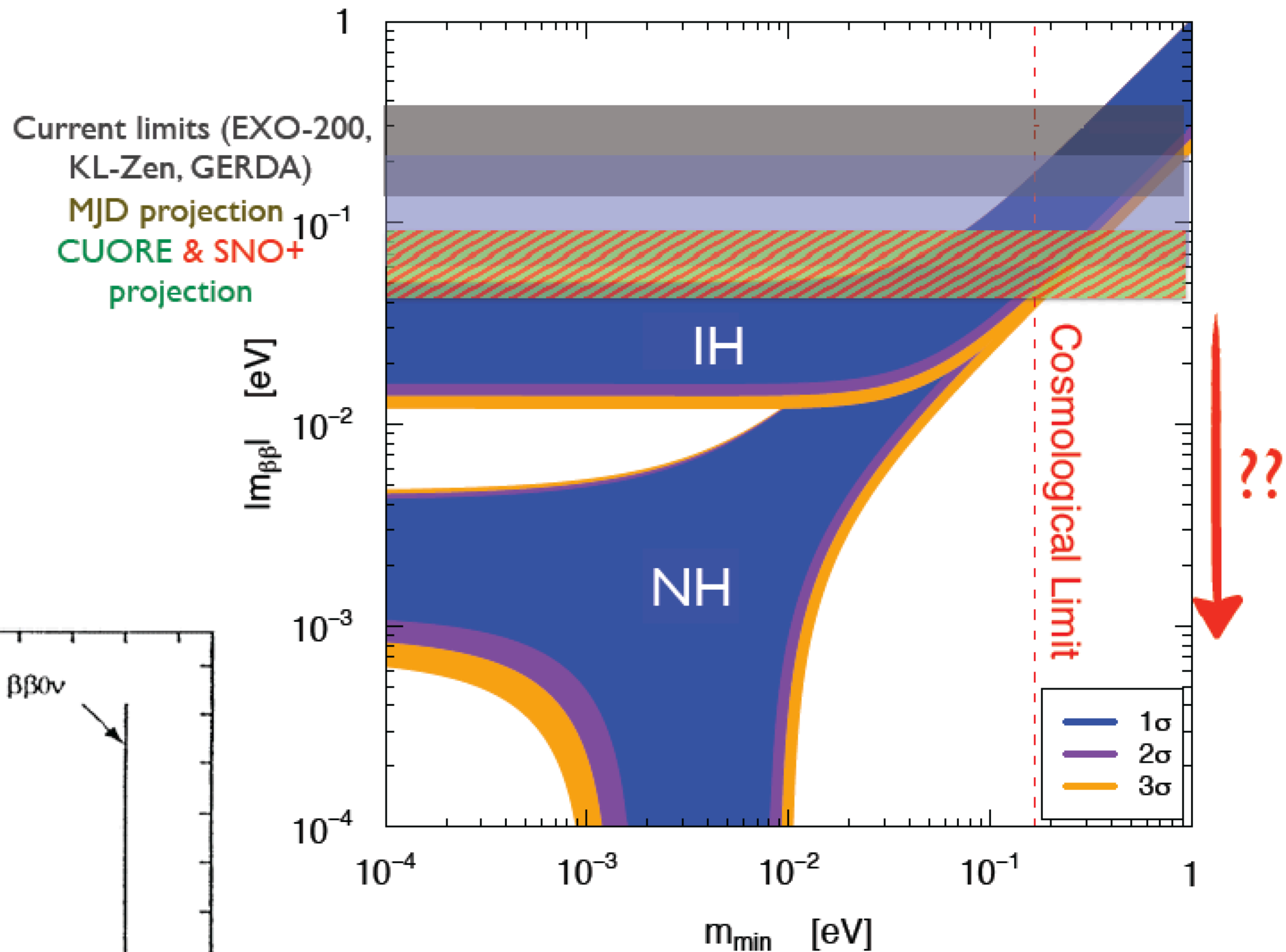


SK: current + 19% efficiency for future
HK: SKII + 3.5% = 16.5%
LBNE: 34 kT Bueno et al. efficiencies
ASDC: LENA efficiencies and pessimistic (0%) and optimistic (90%) n-tagging

Neutrinoless Double Beta Decay





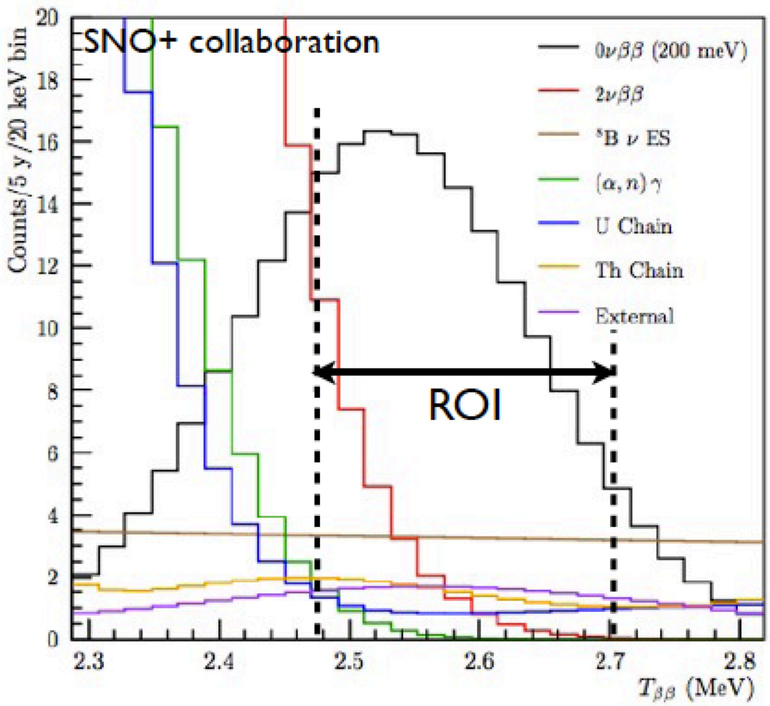


S. M. Bilenky & C. Giunti, Mod. Phys. Lett. A27, 1230015 (2012)

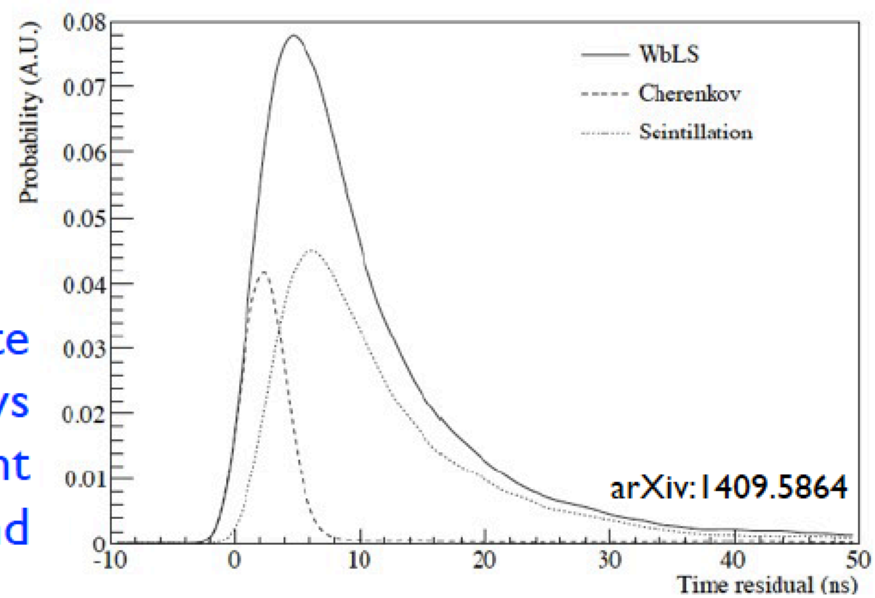
Slide courtesy of G.D. Orebi Gann

Liquid Scintillator Approach

Projected spectrum in SNO+: 5 years, 0.3% ^{nat}Te



Asymmetric ROI (-0.5 - 1.5 σ):
2.1 0νββ events / yr
7.3 8B solar ν events / yr

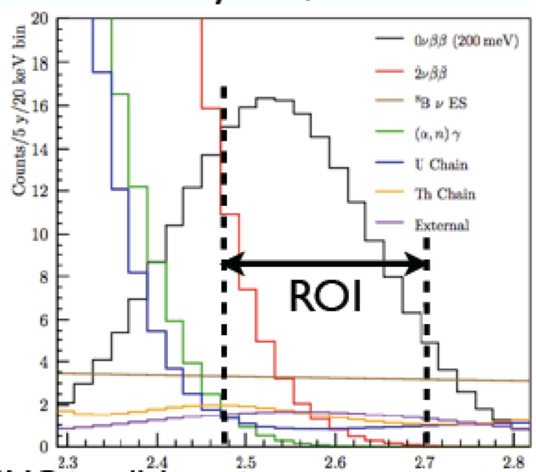


Use of precision timing to separate Chr / scint components allows directional cut to reject dominant ^{8}B solar ν background

Slide courtesy of G.D. Orebi Gann

THEIA Sensitivity

Projected spectrum in SNO+: 5 years, 0.3% ^{nat}Te



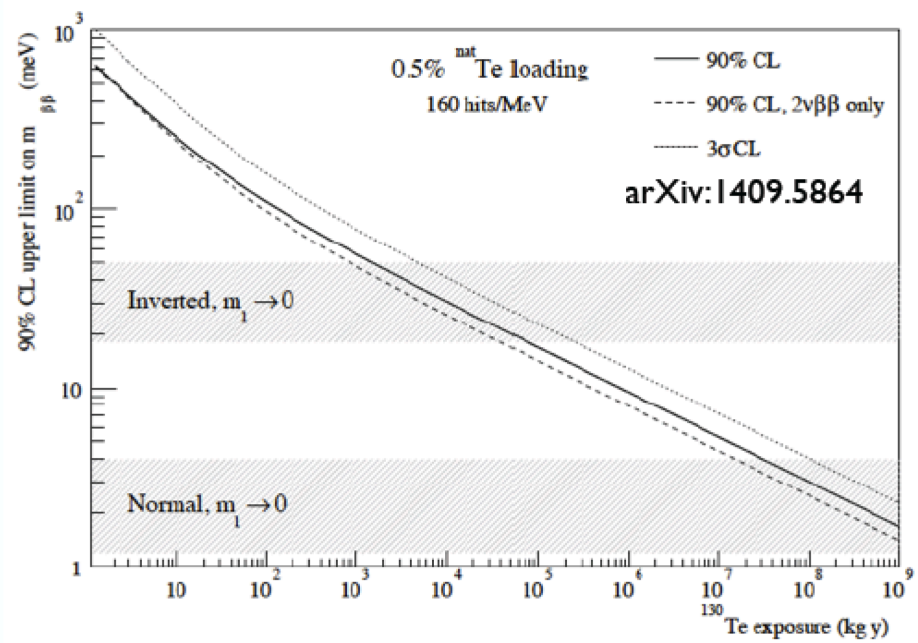
SNO+ collaboration

Builds on critical developments by KLZ & SNO+ collaborations

Ultra-low background, scalable

Asymmetric ROI (-0.5-1.5 σ): 2.1 2νββ & 7.3 ^{8}B ν events / yr

Cher / scint separation allows directional cut to reject dominant ^{8}B solar ν background



50kt detector

50% reduction of ^{8}B

Coincidence tags for int r/a

R_{fit} > 5.5m from PMTs (30kt fid)

0.5% loading (^{nat}Te) in 50kt

⇛ 50t ^{130}Te

Phys.Rev.Lett.110 : 062502 (2013);
SNO+ white paper under development;
Phys. Rev. D 87 no. 7 : 071301 (2013)

⇛ 3σ discovery for $m_{\beta\beta}$=15meV in 10 yrs

Slide courtesy of G.D. Orebi Gann

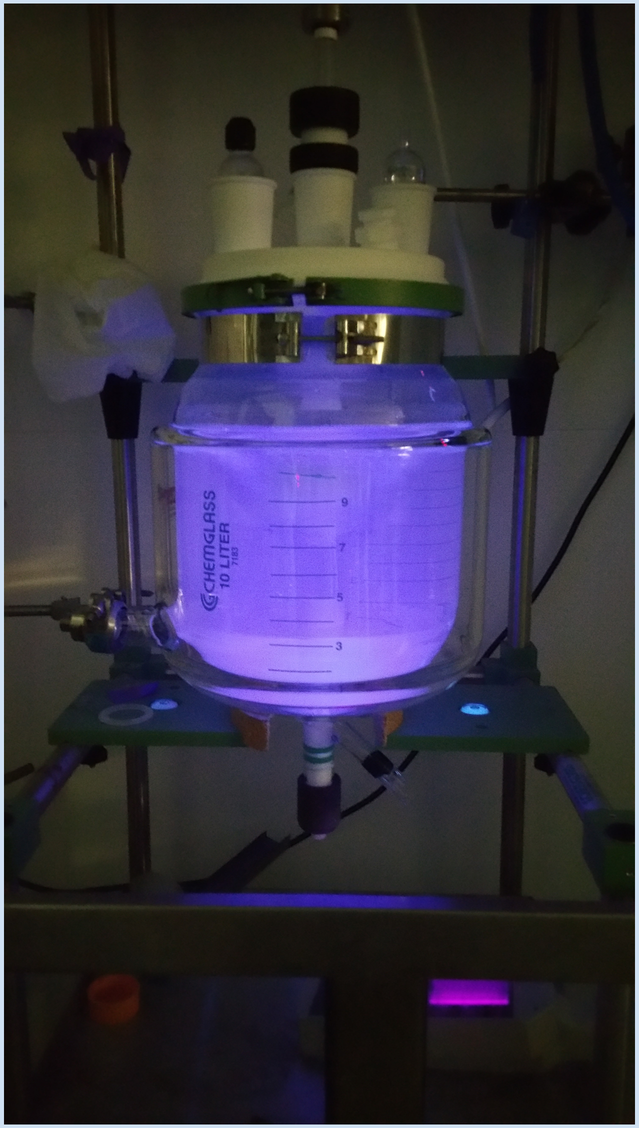
Other Physics (see archive paper)

- Long Baseline Neutrinos: Enhanced NC rejection discussion for Homestake site
- Solar neutrinos: possible addition of 7-Li and enhanced efficiency at low energy
- Geo-neutrinos: neutron tagging

WbLS Development Status

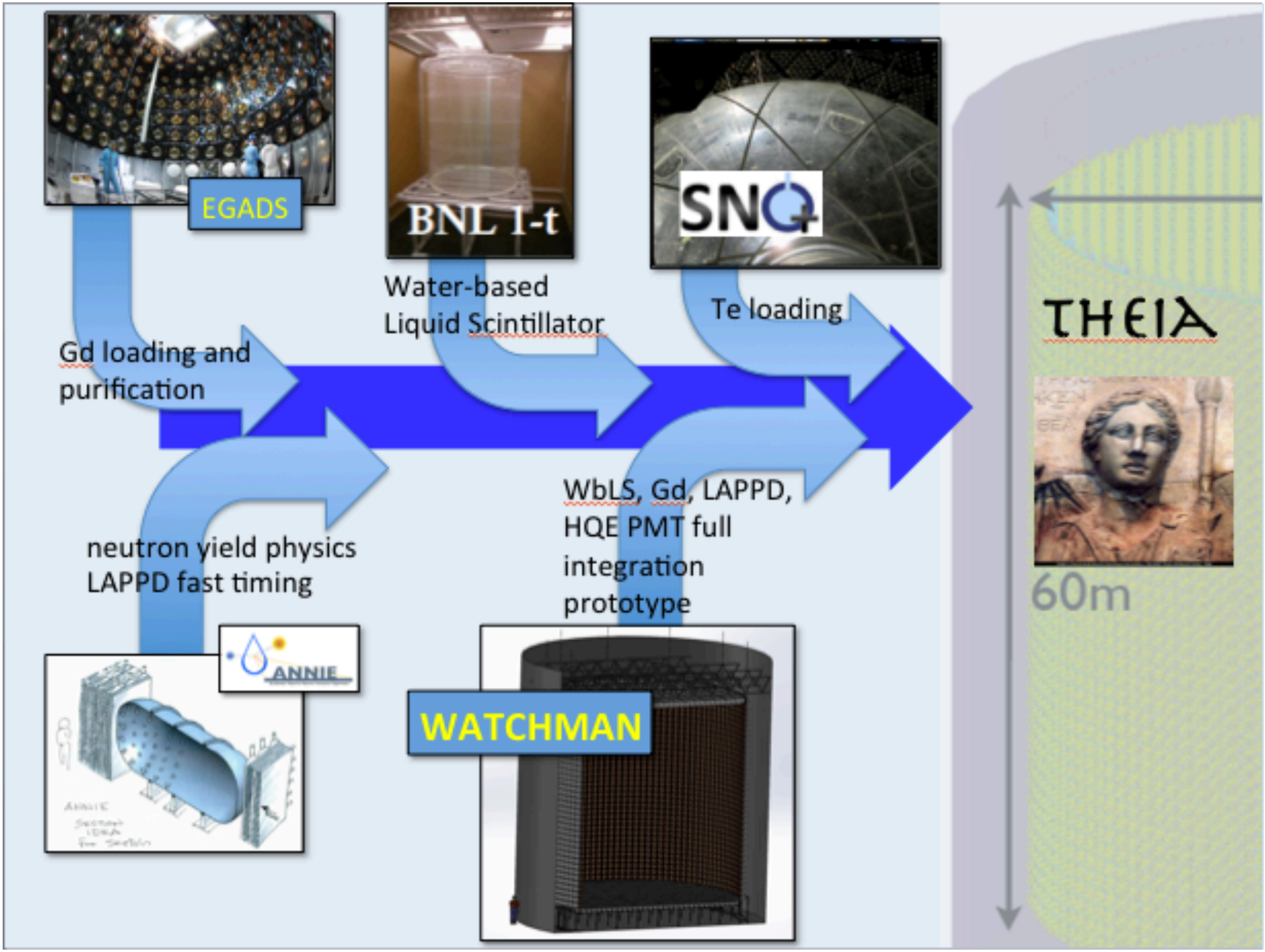
- Light yield studies at BNL and soon at LBNL
- Stability and material compatibility studies at BNL (uncovered one problem so far – butyl rubber adhesive).
- Purification studies at UC Davis using NanoFiltration (NF) to separate organic components from water.
- Scaled up production: 10 liters produced in June with BNL 5 liter reactor. Used for NF and Material studies.
- 100 liter batch under production. Will be used for attenuation length studies (currently have on 1-meter arm). Will use UCI and/or LLNL facility.
- 1-ton BNL prototype approved and under construction.

BNL WbLS production



Planned Demonstrations

Site	Scale	Target	Measurements	Timescale
UChicago	bench top	H2O	fast photodetectors	Exists
CHIPS	10 kton	H2O	electronics, readout, mechanical infrastructure	2019
EGADS	200 ton	H2O+Gd	isotope loading, fast photodetectors	Exists
ANNIE	30 ton			2016
WATCHMAN	1 kton			2019
UCLA/MIT	1 ton	LS	fast photodetectors	2015
Penn	30 L	(Wb)LS	light yield, timing, loading	Exists
SNO+	780 ton			2016
LBNL	bench top	WbLS	light yield, timing, cocktail optimization, loading, attenuation, reconstruction	Early 2015
BNL	1 ton			Summer 2015
WATCHMAN-II	1 kton			2020


EGADS
BNL 1-t
SNO+
Water-based
Liquid Scintillator
Te loading
Gd loading and
purification
THEIA
60m
neutron yield physics
LAPPD fast timing
WbLS, Gd, LAPPD,
HQE PMT full
integration
prototype
ANNIE
WATCHMAN

Bad News/Good News

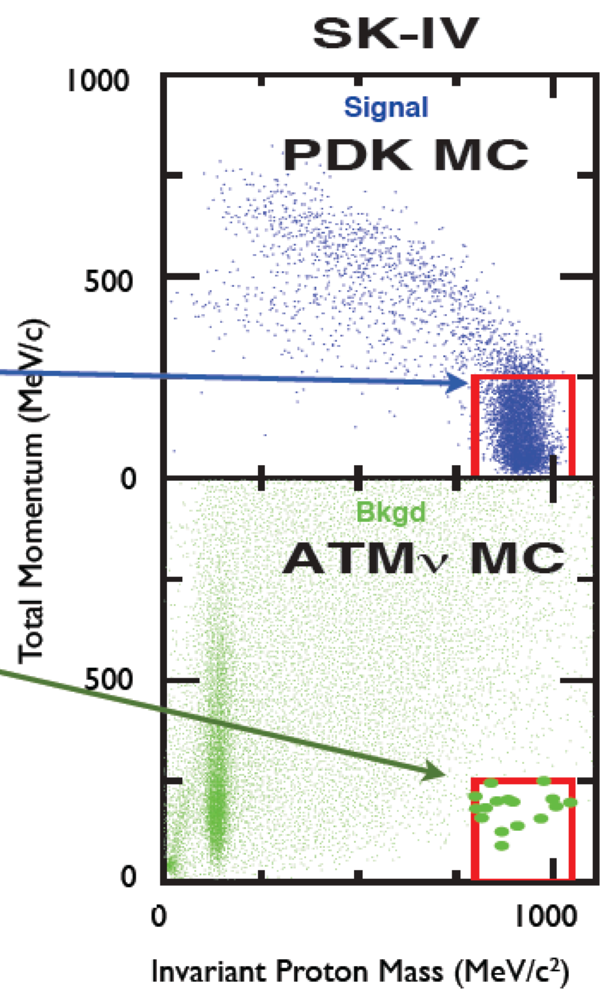
- **Bad News**: 1-kton WATCHMAN proposal rejected by DOE ("too expensive for R&D").
- We were **encouraged** to submit smaller scale R&D proposals. LOI to DOE/HEP last week, proposal due September. Also, discussion with DOE/DNN last week for FY16 went well.
- **Good News:** ANNIE received Stage One approval from Fermilab and is going ahead with a background run starting **THIS YEAR!**

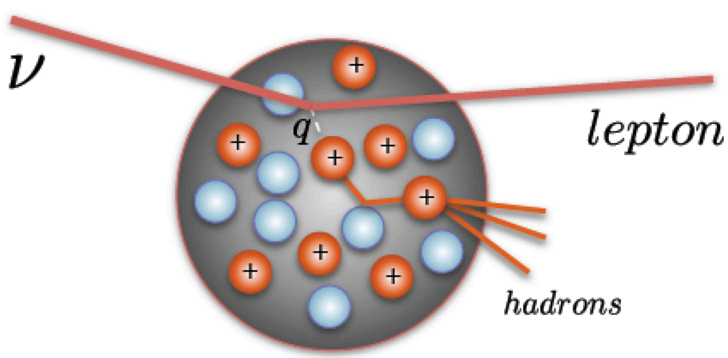
Motivation

Backgrounds come almost exclusively from atmospheric neutrino interactions

Proton decay events are expected to only rarely produce neutrons in the final state.

High energy neutrino interactions typically produce neutrons in the final state





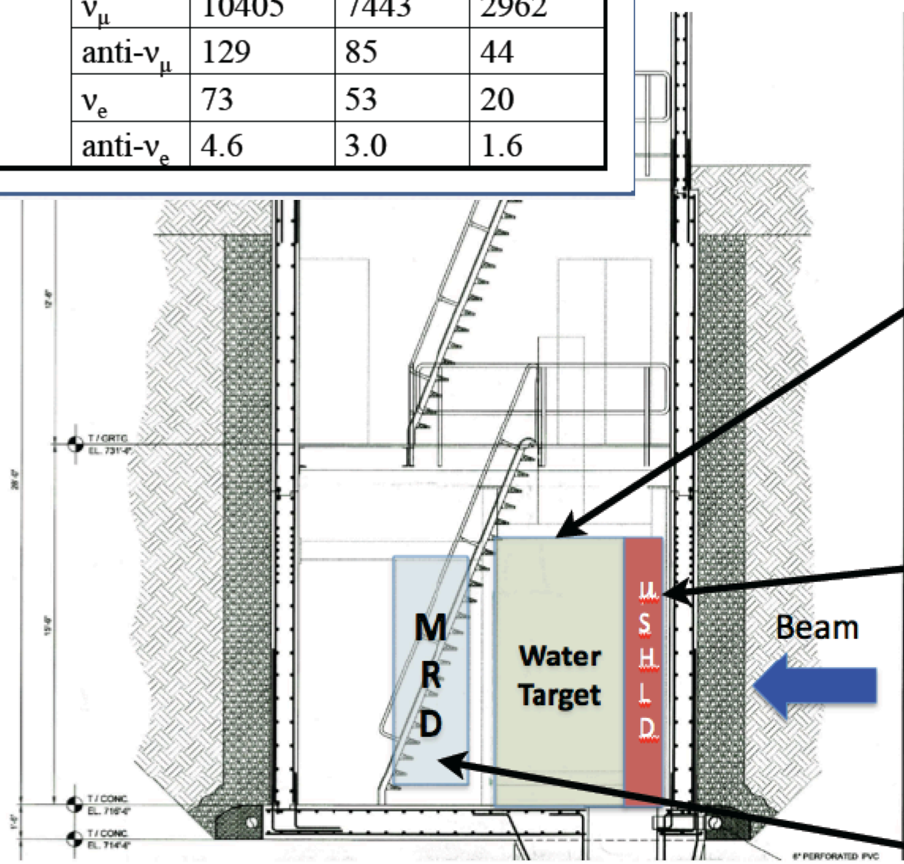
I. Anghel[1,4], G. Davies[4], F. Di Lodovico[11], A. Elagin[9], H. Frisch[9], R. Hill[9], G. Jocher[5], T. Katori[11], J. Learned[11], R. Northrop[9], C. Pilcher[9], E. Ramberg[3], M.C. Sanchez[1,4], M. Smy[7], H. Sobel[7], R. Svoboda[6], S. Usman[5], M. Vagins[7], G. Varner[10], R. Wagner[1], M. Wetstein[9], L. Winslow[8], and M. Yeh[2]

[1]Argonne National Laboratory [2]Brookhaven National Laboratory [3]Fermi National Accelerator Laboratory [4]Iowa State University [5]National Geospatial-Intelligence Agency [6]University of California at Davis [7]University of California at Irvine [8]University of California at Los Angeles [9]University of Chicago [10]University of Hawaii [11]Queen Mary University of London

Rates Expected with 1x10[20] POT exposure at SciBooNE pit

Djurcic

	Total Events [1/1ton/10^{20}POT]	ν-type	Total (per ν-type)	Charged Current	Neutral Current
Booster Beam (ν-mode, Target = CH_2)	10419	ν_μ	10210	7265	2945
		anti-ν_μ	133	88	45
		ν_e	72	52	20
		anti-ν_e	4.4	3	1.4
Booster Beam (ν-mode, Target = H_2O)	10612	ν_μ	10405	7443	2962
		anti-ν_μ	129	85	44
		ν_e	73	53	20
		anti-ν_e	4.6	3.0	1.6



3m x 3m x 3m tank of Gd enhanced water instrumented with photosensors.

Existing veto on muons produced upstream of the detector (FACC)

Existing Muon Range Detector (MRD)

“ANNIE Hall”

(formerly the SciBooNE pit)

Fermilab

Nigel S. Lockyer
Director's Office
630.840.3211 - office
630.338-6584 - cell
Lockyer@fnal.gov

February 5, 2015

Matthew Wetstein
HEP Division
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

Dear Matt,

Thank you very much for your presentation of the LOI update "*P-1063: ANNIE*" at the January meeting of the Fermilab Physics Advisory Committee (PAC). The committee explicitly mentioned its appreciation of the carefully prepared presentations for this meeting.

The future neutrino program hosted by Fermilab was a major topic at the meeting. Excerpts from the PAC report on ANNIE are attached. As you can see, the committee was "*impressed by the progress being made by the ANNIE collaboration*" and recommended "*that the ANNIE collaboration be granted Stage 1 approval and be supported to proceed with Phase I of their proposed work.*" The committee would also like an update on LAPPD progress at their next meeting, and in addition would like to know how the collaboration would achieve the proposed physics goals in a timely fashion if the development of the LAPPD detectors suffers significant delays.

I accept the PAC recommendation, and grant P-1063 Stage 1 approval for the first phase of the ANNIE work. I look forward to hearing of progress on ANNIE in the future.

Sincerely,

Nigel

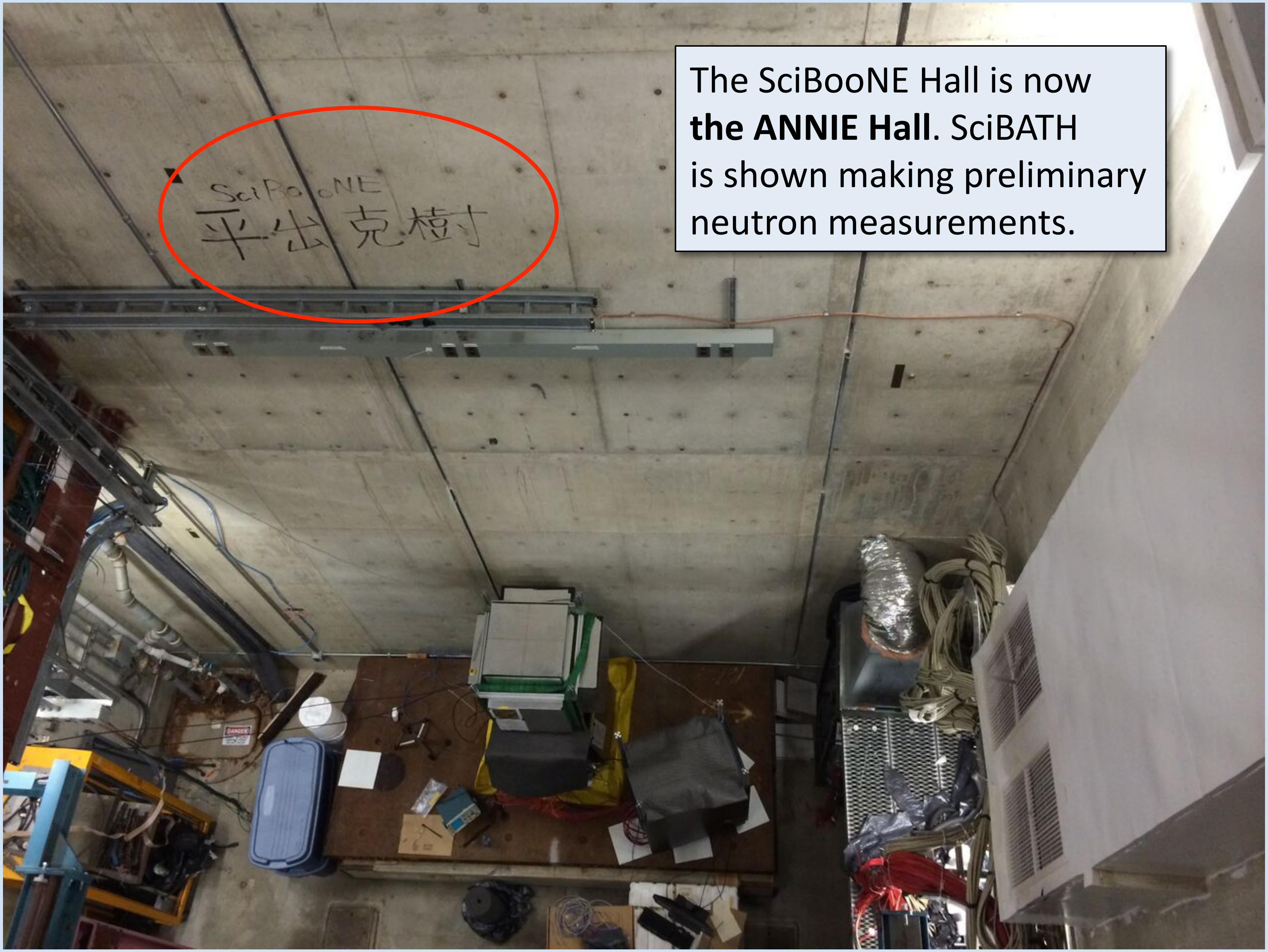
Nigel S. Lockyer
Director of Fermilab

See ANNIE presentation at January 2015 FNAL PAC meeting for details.

First Phase will be neutron background measurement with SciBATH followed by 20 ton water tank with LS (perhaps WbLS) moveable target.

Second Phase will be neutron yield experiment using Booster Neutrino Beam (BNB) and LAPPD fast light sensors

May include internal WbLS target – under discussion



The SciBooNE Hall is now **the ANNIE Hall**. SciBATH is shown making preliminary neutron measurements.

2015-2016 Run

- **Seeking more collaborators**, especially those interested in proton decay, DSNB physics and WbLS/LAPPD R&D.
- ***Seeking* readout electronics** for Muon Range Detector for Phase 0 (400 channels) and CDF paddle vetos (50 channels) and a group to make it work. ***SK electronics?***
- Would also like ***more PMT's*** if possible to enhance capture gamma detection.

FroST

Frontiers in Scintillator Technology

March 18-20th 2016

Local Organising Committee

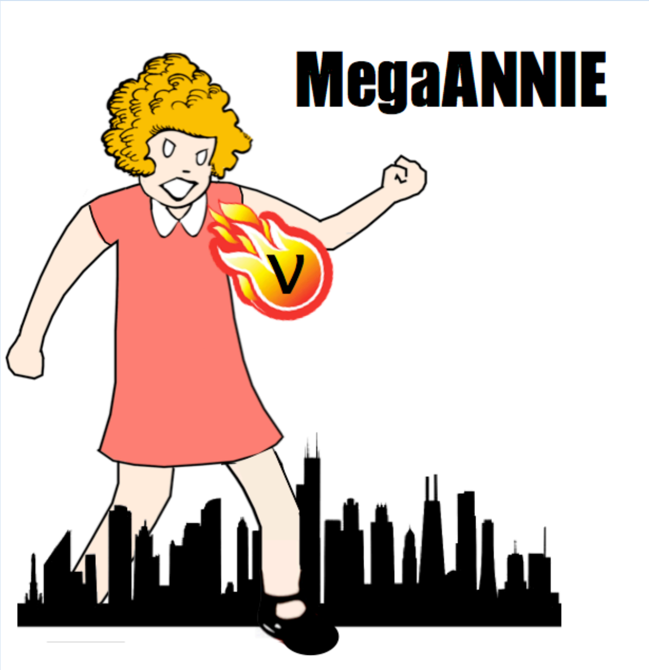
Ed Blucher
Josh Klein
Gabriel Orebi Gann
Bob Svoboda

Scientific Advisory Committee

Steve Biller
Frank Calaprice
Mark Chen
Cristiano Galbiatti
Wick Haxton
Kunio Inoue
Thierry Lasserre
Manfred Lindner
Serguey Petcov
Gioacchino Ranucci
Mayly Sanchez
Yifang Wang
Michael Wurm

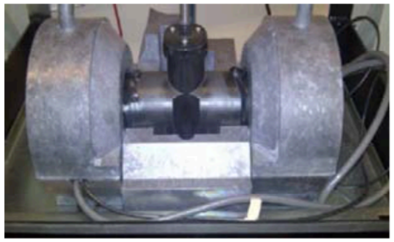
Thanks!

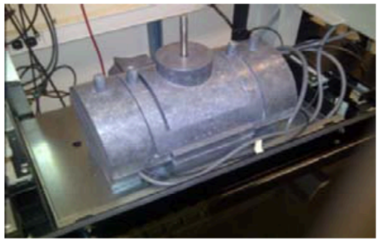
Nanofiltration Lab

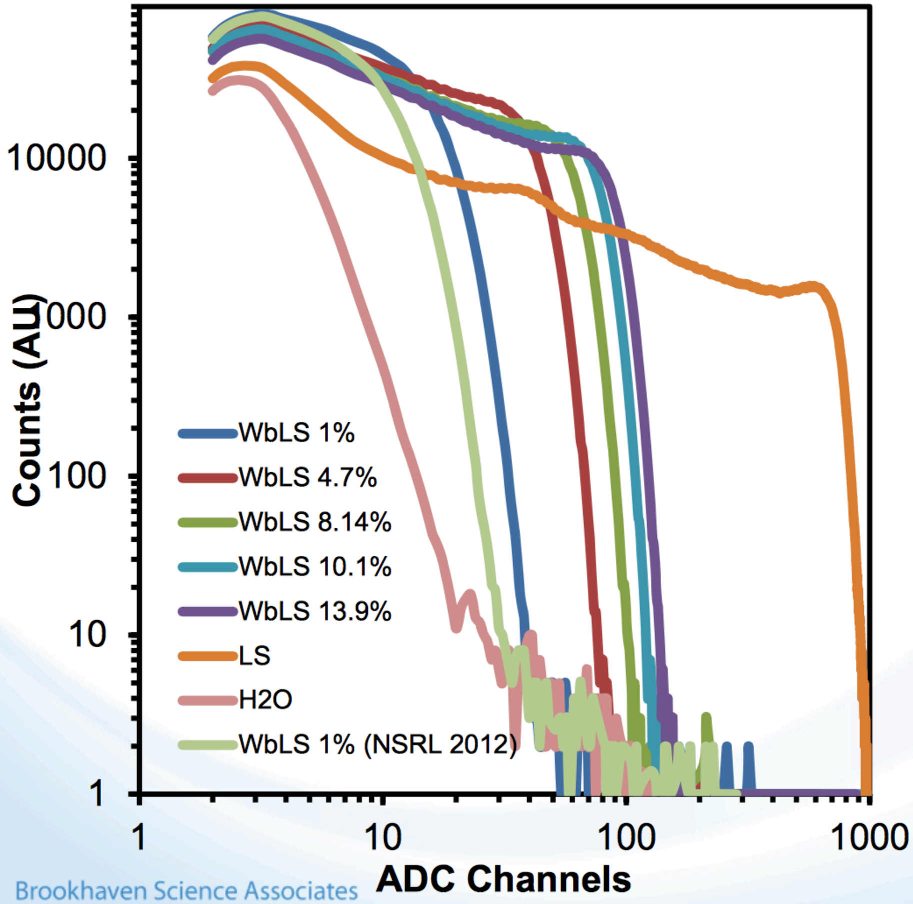


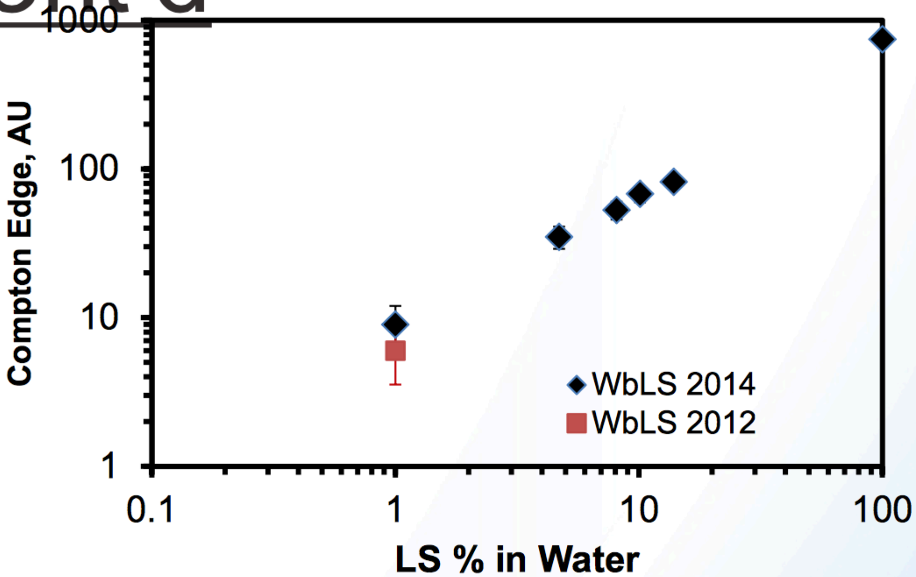
Future?

1% WbLS-2014 cont'd









- WbLS light-yield as a function of LS% loading
  - Higher light-yield at the cost of optical transmission
- Linear correlation between light-yield and LS% (up to ~15%)
  - Different behavior with that of pure scintillator
- WbLS-2014 has ~25% more light-yield than WbLS-2012