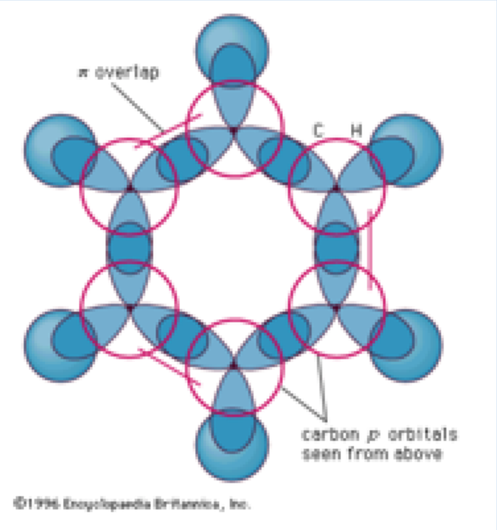
Water-base Liquid Scintillator

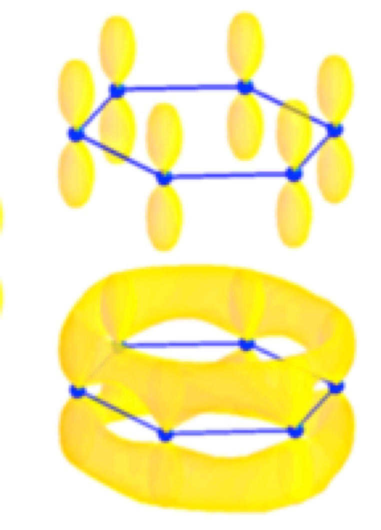
- Description
- Physics Potential
- Status of Development
- Future Plans

Robert Svoboda, SNOLAB, August 2015

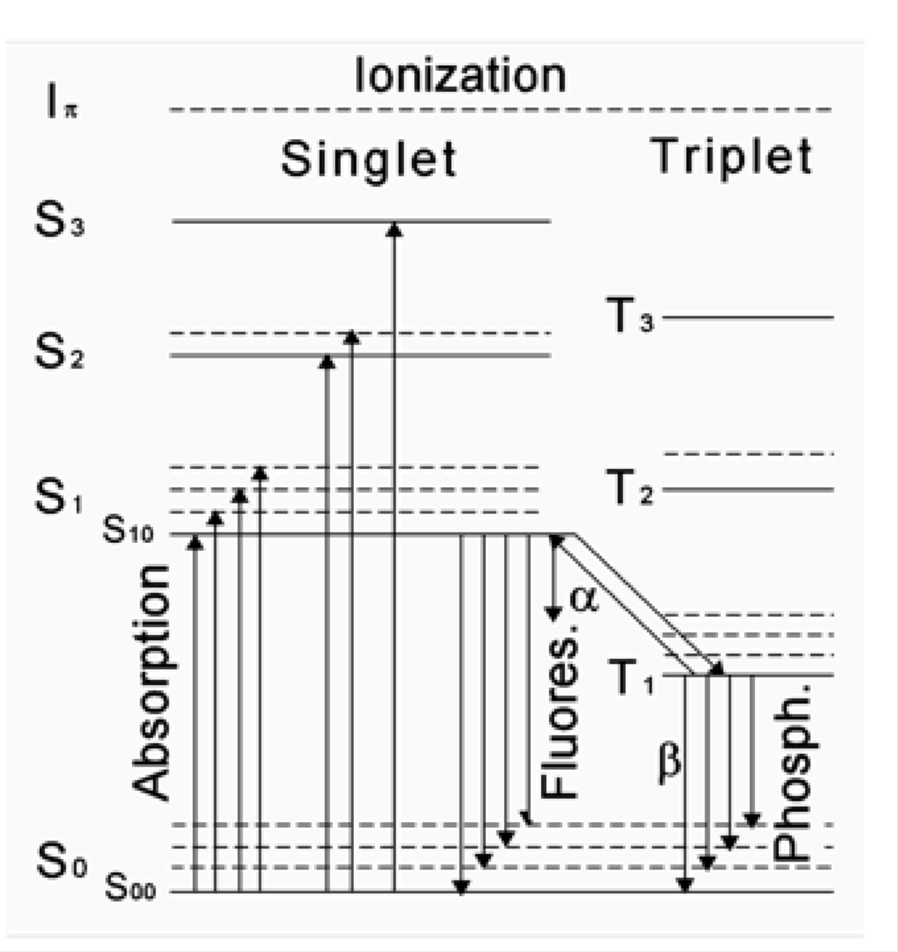
How Does it Work?



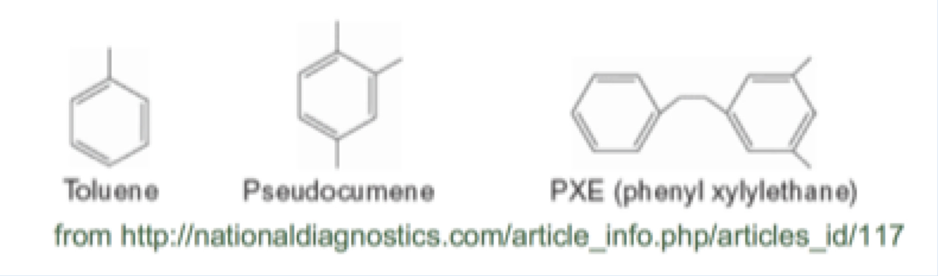
planer σ orbitals of
a benzene ring



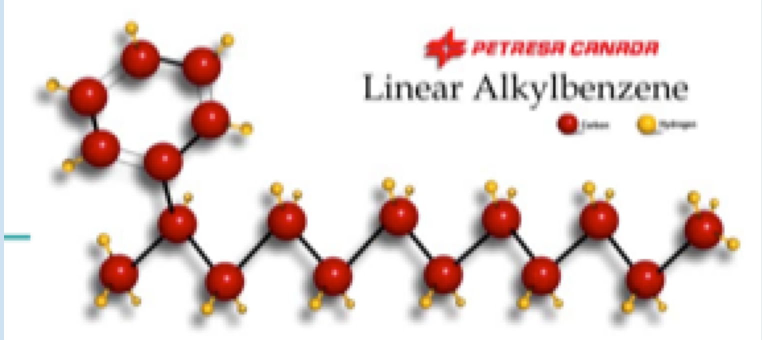
π orbitals merge above
and below ring



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



from http://nationaldiagnostics.com/article_info.php/articles_id/117



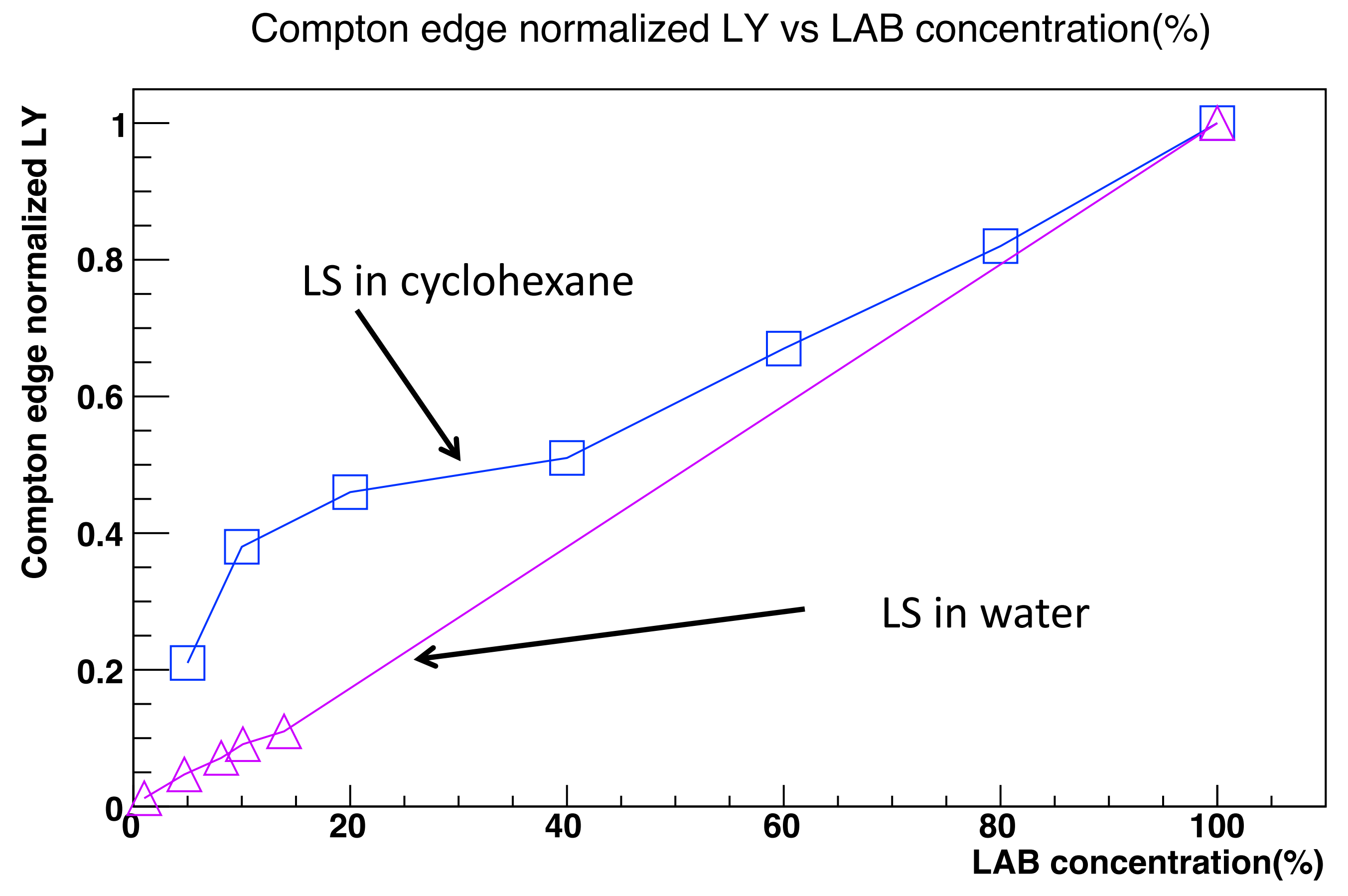
That's why organic scintillators always are made with solvents that have a benzene ring.

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...

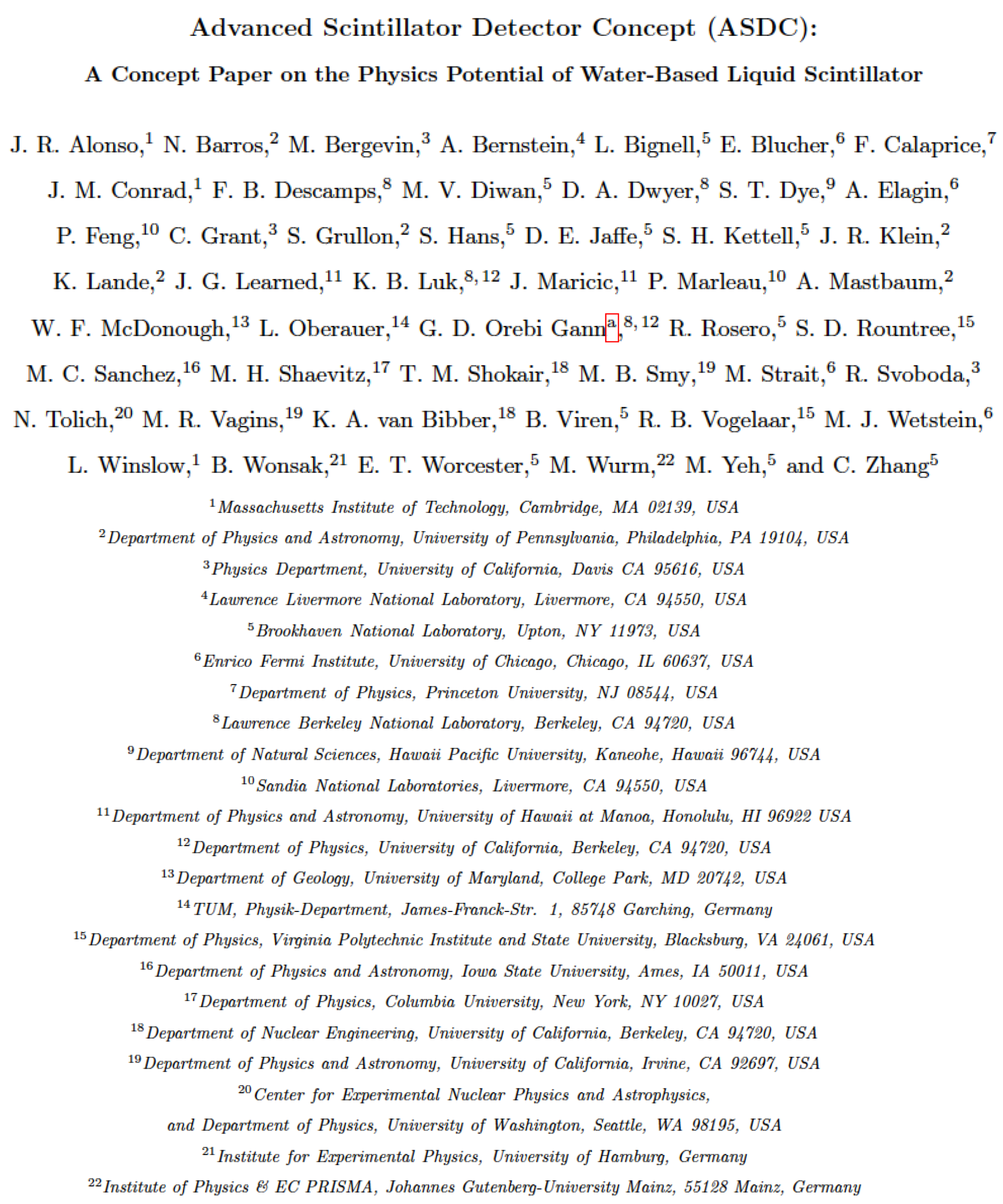
BNL has solved these basic issues with a proprietary mixture that is tunable for the light output.

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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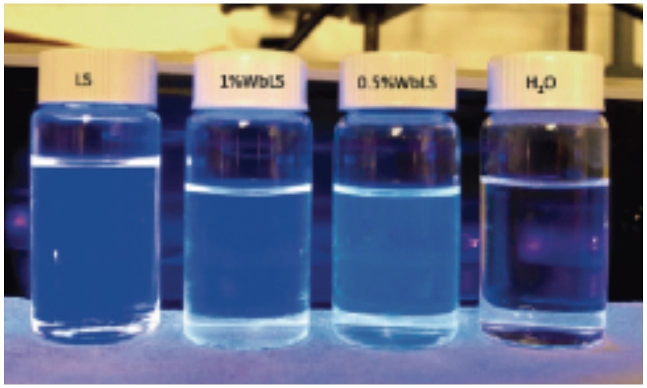
arXiv:1409.5864

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



1% gives ~100 optical photons/MeV

4% WbLS gives approximately 3-4 times the light yield of pure water

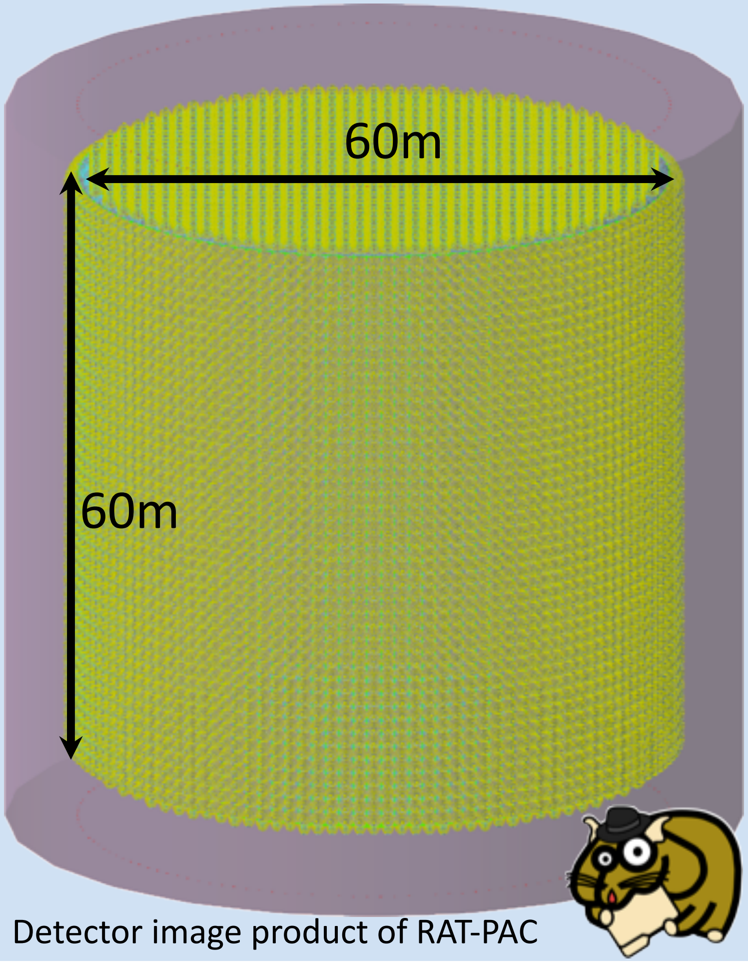
THEIA:

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"

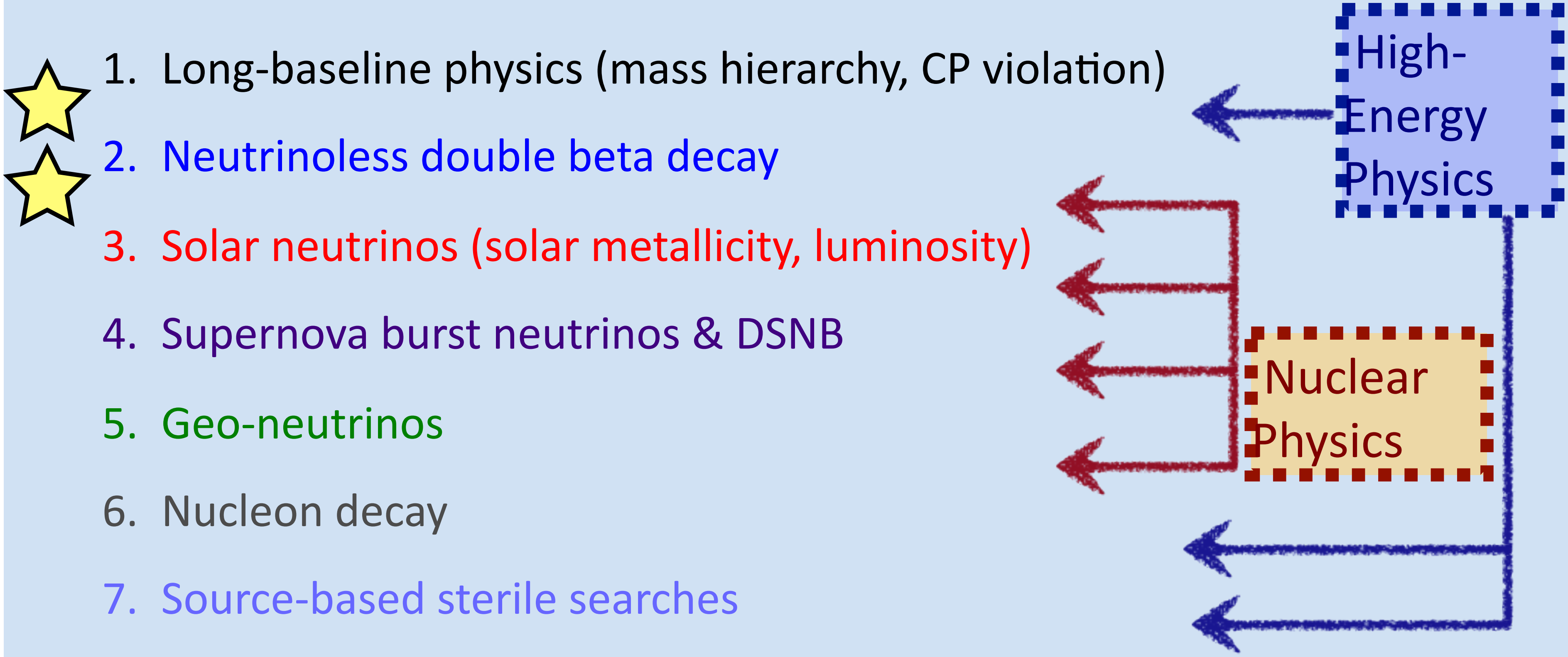
Brookhaven National Laboratory
University of California, Berkeley
University of California, Davis
University of California, Irvine
University of Chicago
Columbia University
University of Hawaii at Manoa
Hawaii Pacific University
Iowa State University
Lawrence Berkeley National Laboratory
Lawrence Livermore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

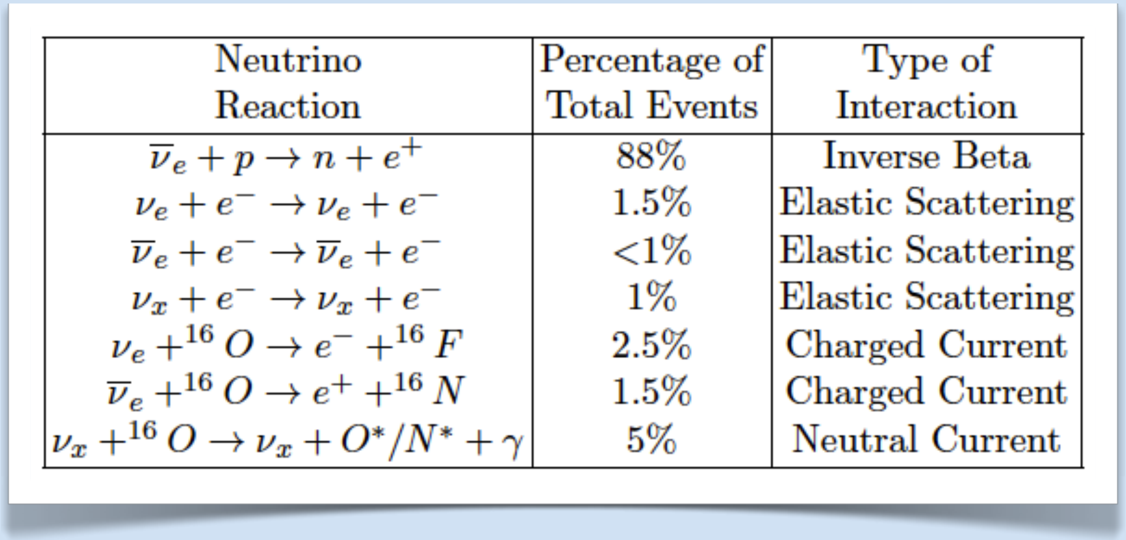
High-Energy Physics

Nuclear Physics

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 ~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
$\overline{\nu}_e + p \rightarrow n + e^+$	88%	Inverse Beta
$\nu_e + e^- \rightarrow \nu_e + e^-$	1.5%	Elastic Scattering
$\overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^-$	<1%	Elastic Scattering
$\nu_x + e^- \rightarrow \nu_x + e^-$	1%	Elastic Scattering
$\nu_e +^{16} O \rightarrow e^- +^{16} F$	2.5%	Charged Current
$\overline{\nu}_e +^{16} O \rightarrow e^+ +^{16} N$	1.5%	Charged Current
$\nu_x +^{16} O \rightarrow \nu_x + O^*/N^* + \gamma$	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).

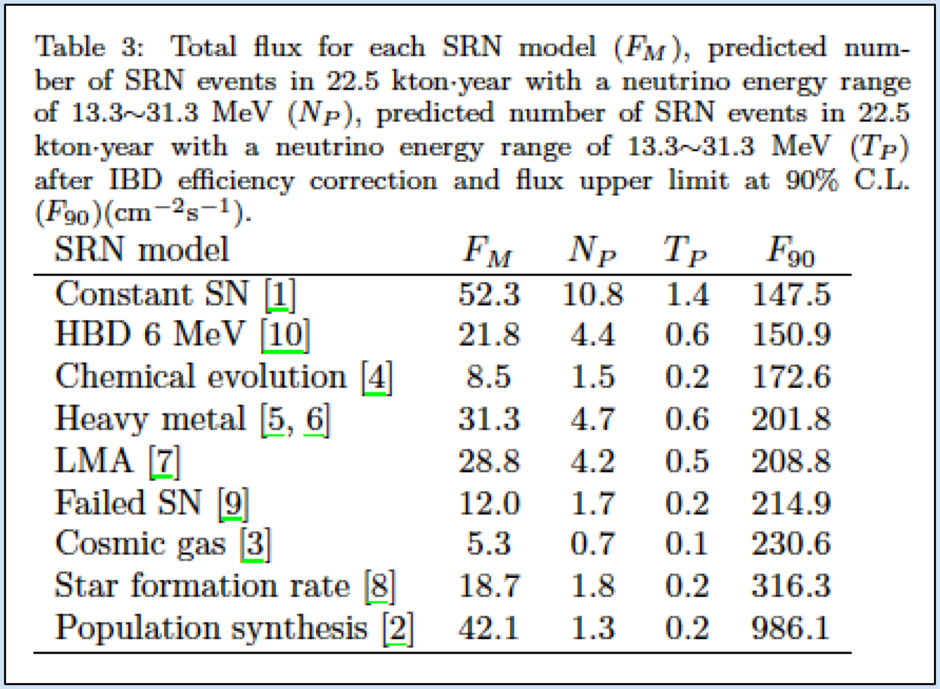


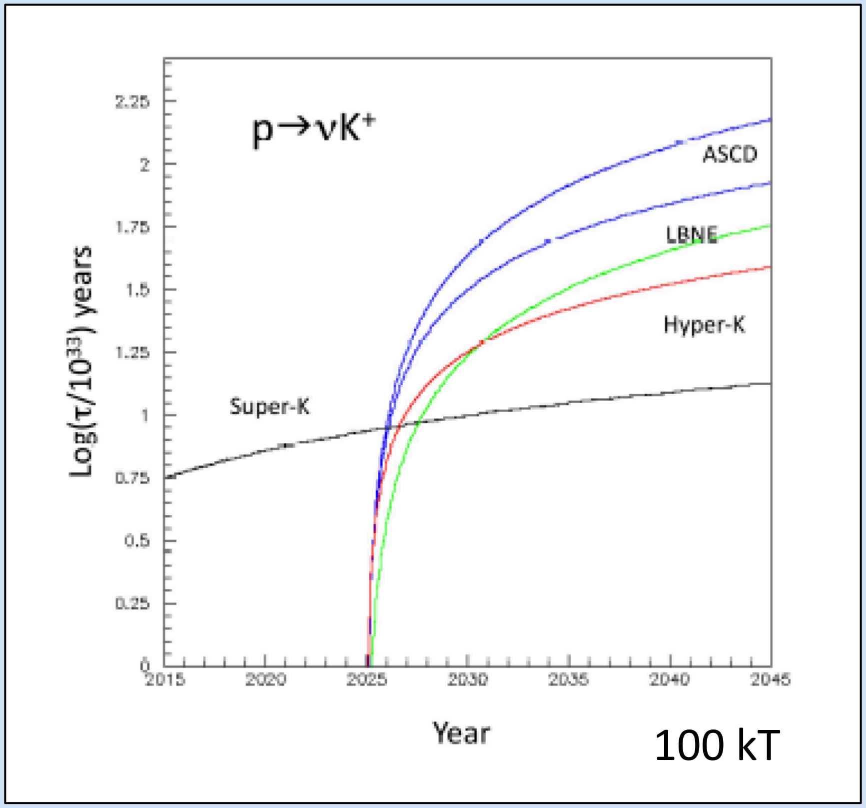
Table 3: Total flux for each SRN model (F_M), predicted number of SRN events in 22.5 kton·year with a neutrino energy range of 13.3∼31.3 MeV (N_P), predicted number of SRN events in 22.5 kton·year with a neutrino energy range of 13.3∼31.3 MeV (T_P) after IBD efficiency correction and flux upper limit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

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

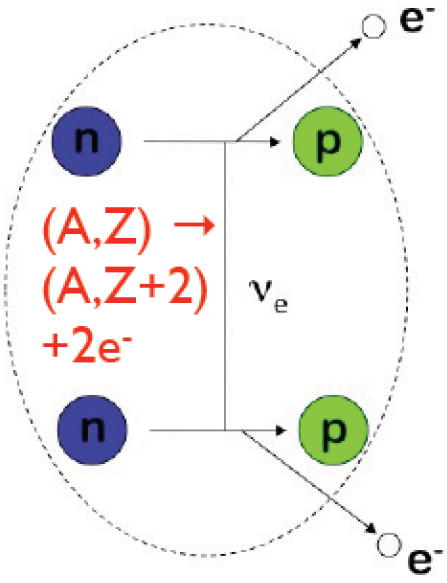
$p \rightarrow \nu K^+$ Proton Decay in Theia

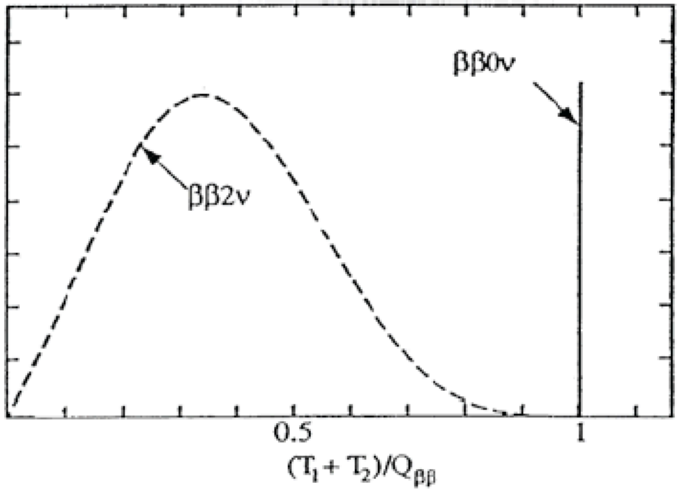
- SK limited due to the fact that the K^+ is below Cherenkov threshold.
- With WbLS this is no longer the case. Kaons identified via time structure.
- Studies by LENA and ASDC group show that expected efficiency is about 70% in detailed MC studies.
- Background depends on effectiveness of n-tagging
- Other modes such as $n \rightarrow 3\nu$ also greatly enhanced sensitivity

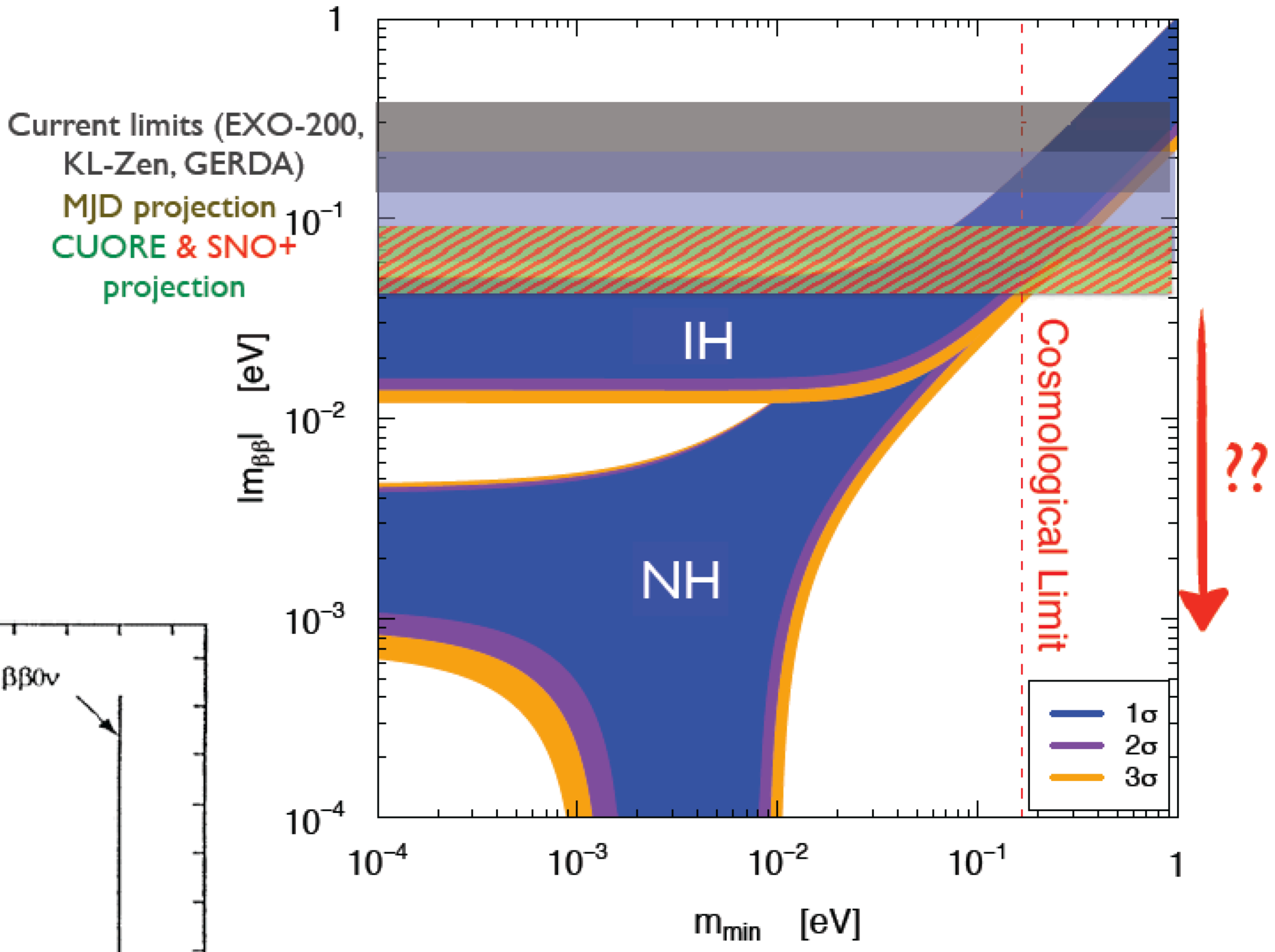


SK: current + 19% efficiency for future
HK: SKII + 3.5% = 16.5%
LBNE: 34 kT Bueno et al. efficiencies
ASDC: LENA efficiencies and pessimistic (0%) and optimistic (90%) n-tagging

Neutrinoless Double Beta Decay





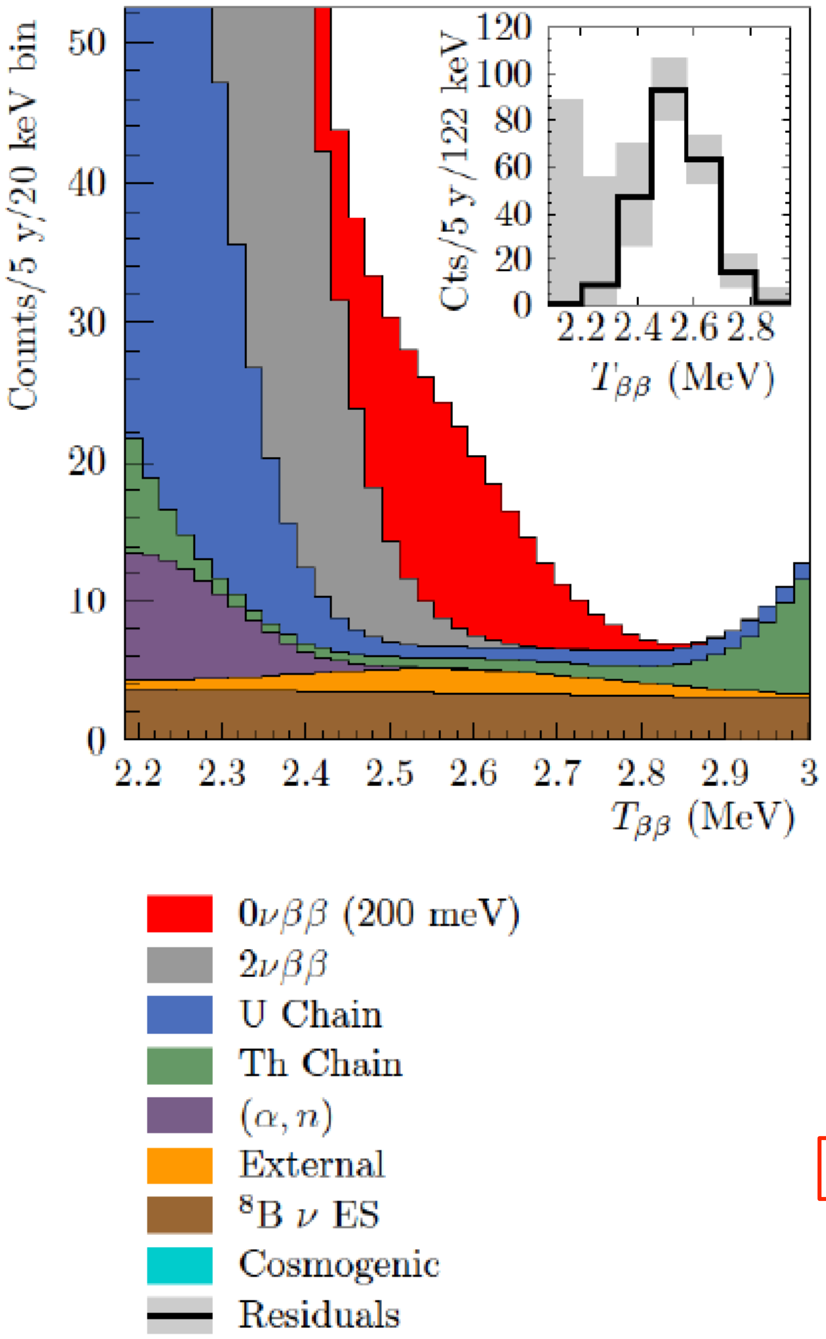

Current limits (EXO-200, KL-Zen, GERDA)

MJD projection

CUORE & SNO+ projection

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

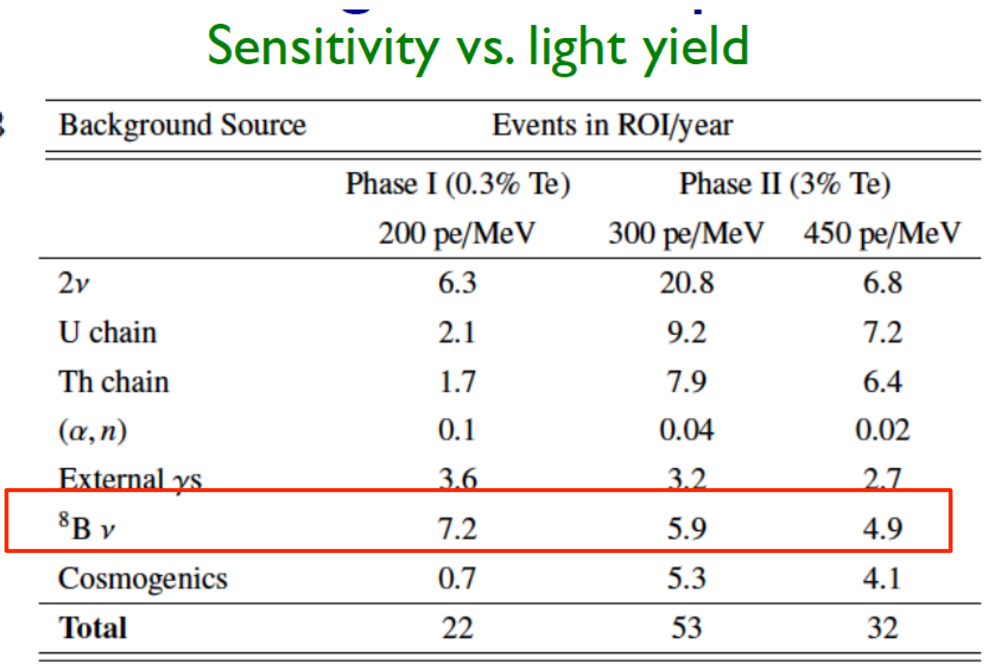
Slide courtesy of G.D. Orebi Gann



LS Approach: SNO+

Asymmetric ROI -0.5σ to $+1.5\sigma$

Photocoverage is critical to sensitivity
Ultimate limit due to solar neutrinos
Can we cut these events while still maintaining energy resolution?



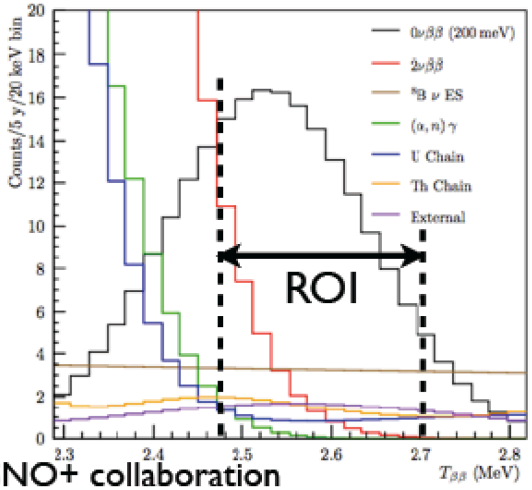
Sensitivity vs. light yield

Background Source	Events in ROI/year		
	Phase I (0.3% Te)	Phase II (3% Te)	
	200 pe/MeV	300 pe/MeV	450 pe/MeV
2ν	6.3	20.8	6.8
U chain	2.1	9.2	7.2
Th chain	1.7	7.9	6.4
(α, n)	0.1	0.04	0.02
External γs	3.6	3.2	2.7
^{8}B ν	7.2	5.9	4.9
Cosmogenics	0.7	5.3	4.1
Total	22	53	32

THEIA Sensitivity

Builds on critical developments by KLZ & SNO+ collaborations

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

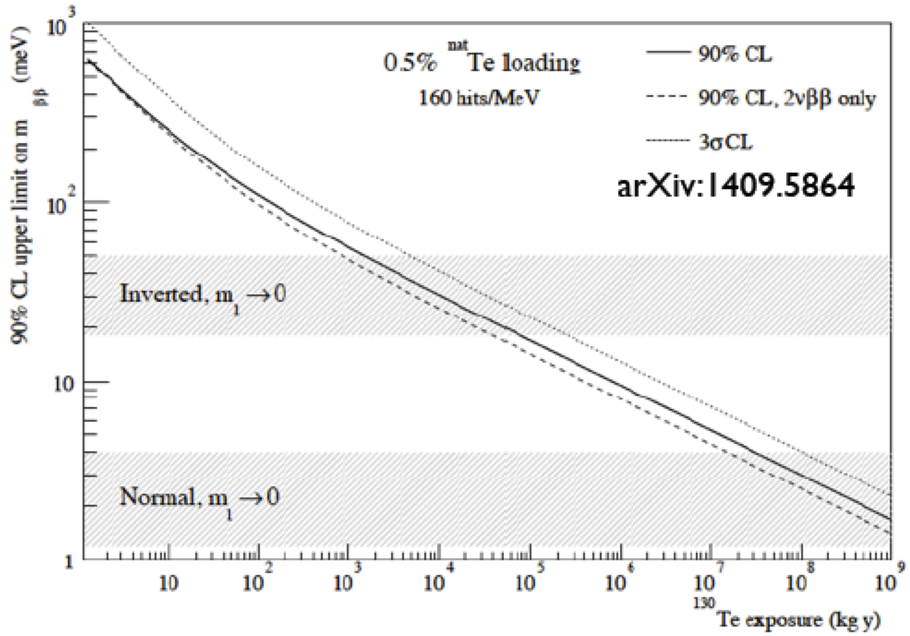


SNO+ collaboration

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)

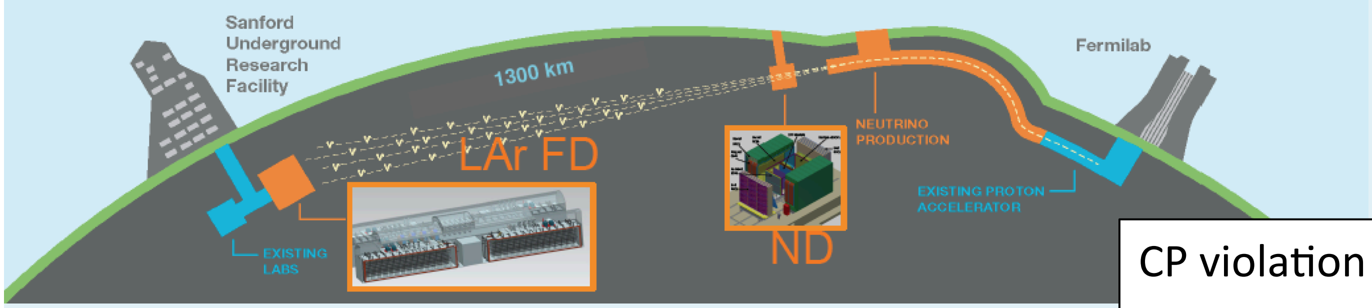
0.5% loading (^{nat}Te) in 50kt

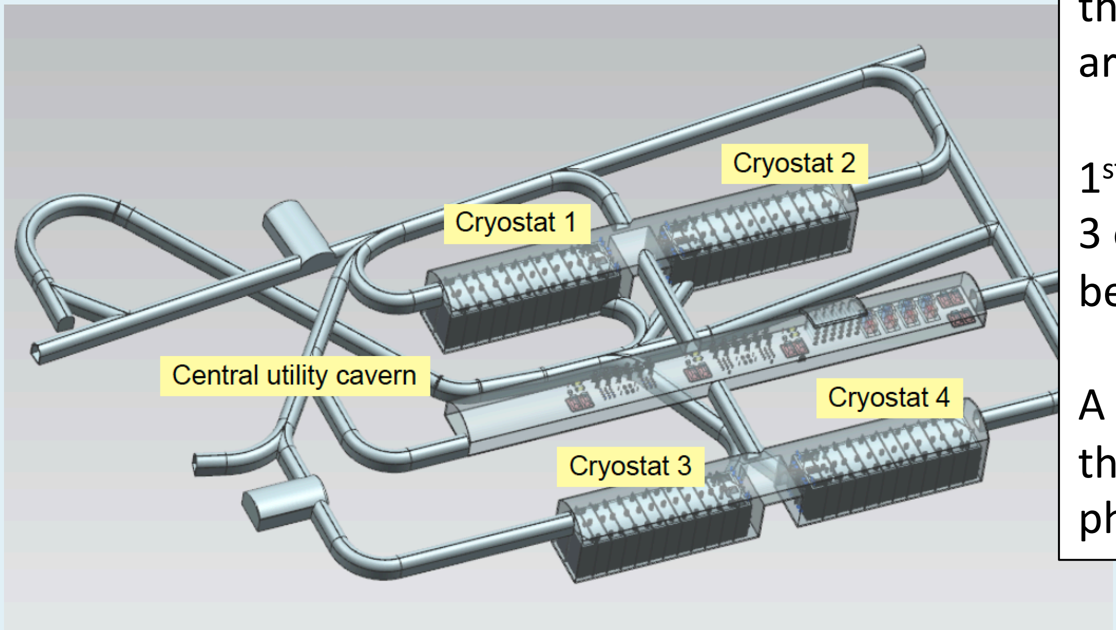
⇛ 50t ^{130}Te

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





CP violation and Mass Ordering

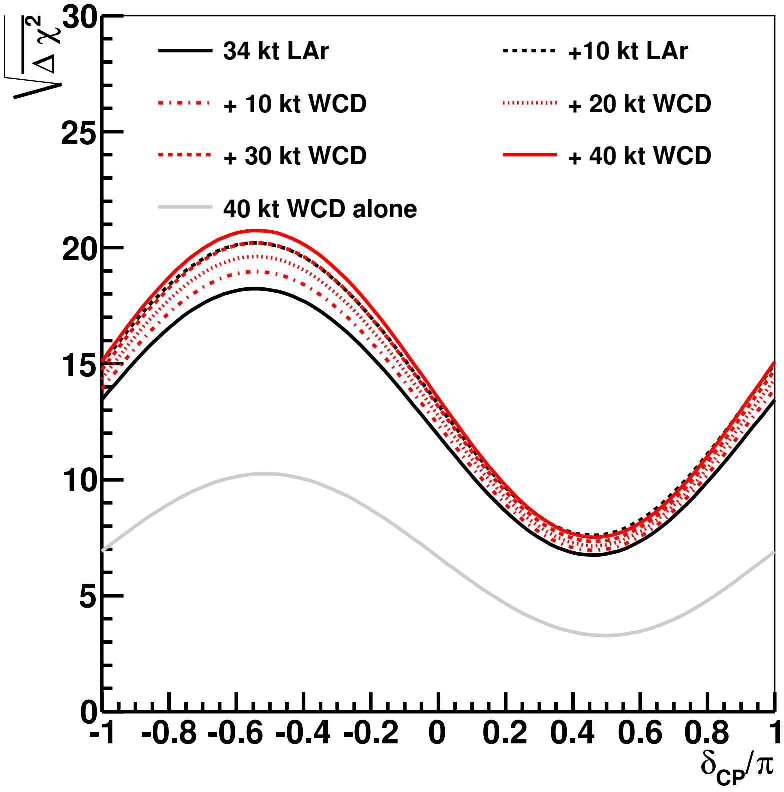
Due to financial considerations
the current plan is four liquid
argon detectors built in series

1st is single phase TPC
3 others not settled yet (two-phase
being considered)

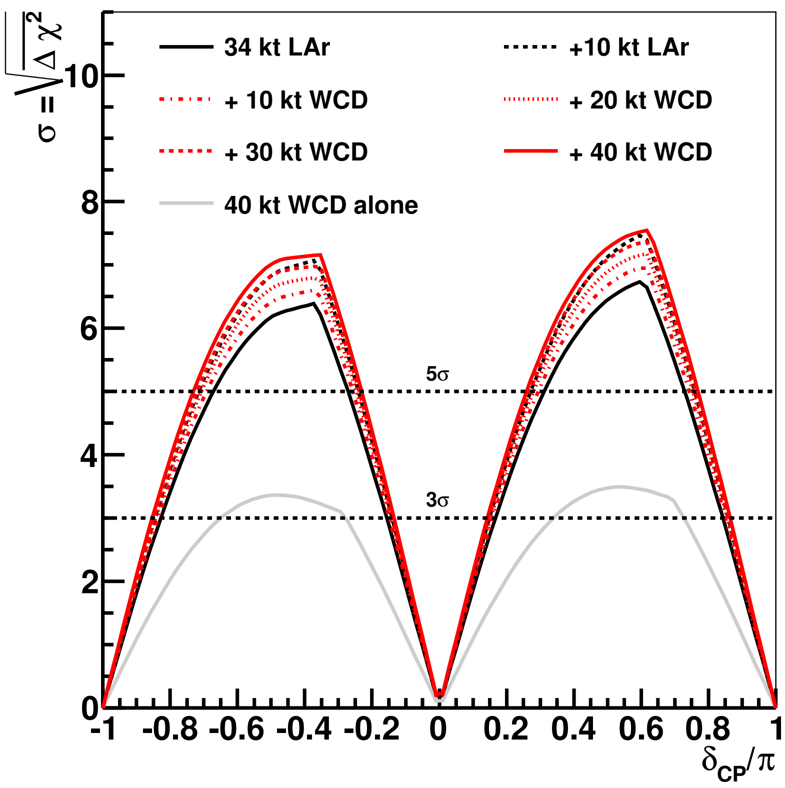
A different kind of detector for one of
these three would add greatly to the
physics program – WbLS?

Effect of adding a 40 kton SK detector instead of last 10 kT LAr

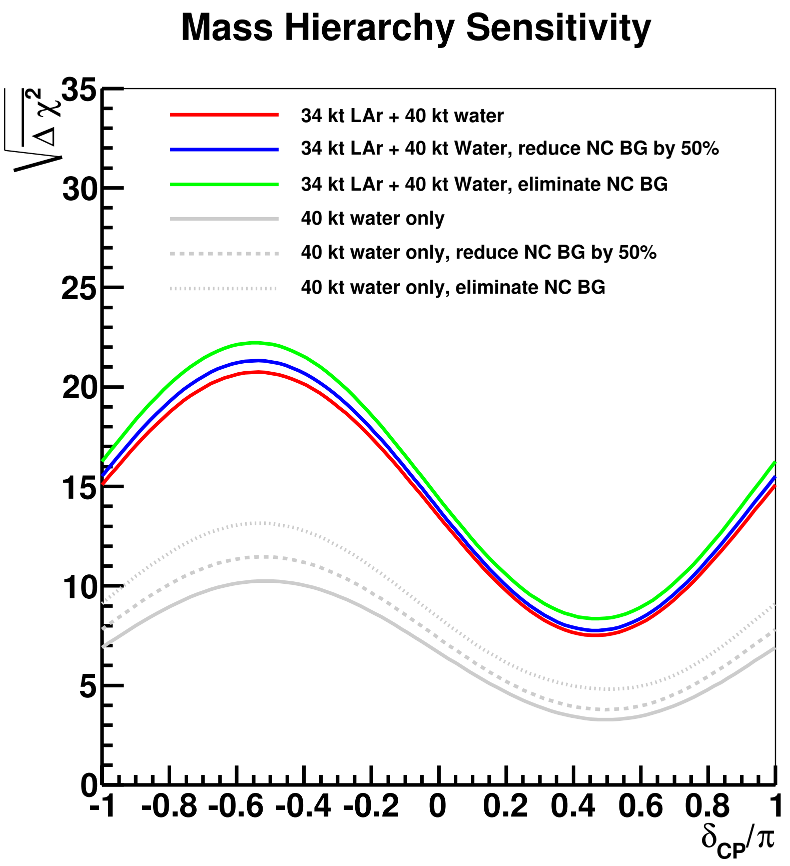
Mass Hierarchy Sensitivity

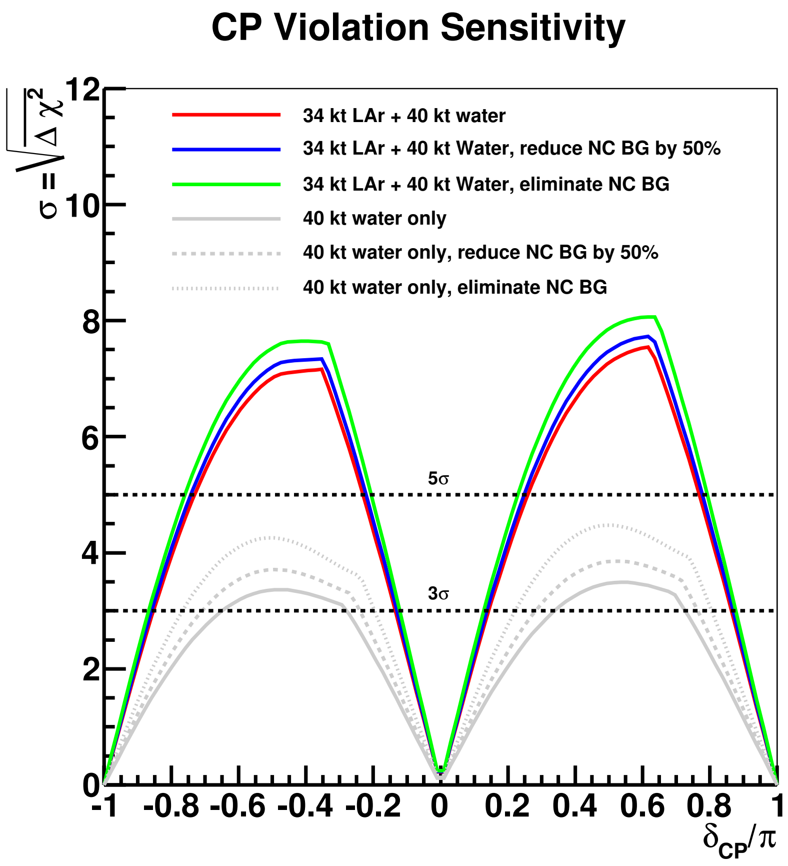


CP Violation Sensitivity



Potential of Improved NC rejection using fast timing and WbLS





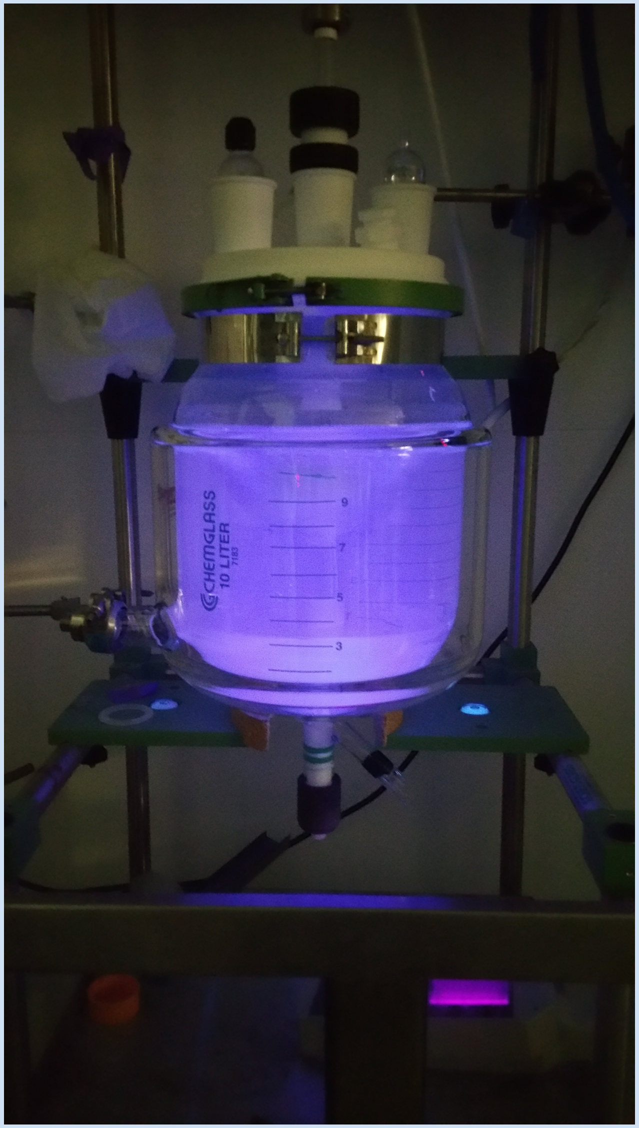
Other Physics (see archive paper)

- Solar neutrinos: possible addition of 7-Li and enhanced efficiency at low energy
- Geo-neutrinos: neutron tagging
- These require maximal LS loading
- **The advantage of a Theia-like detector is that it is fairly easy to adapt the science program by varying target loading**

WbLS Development Status

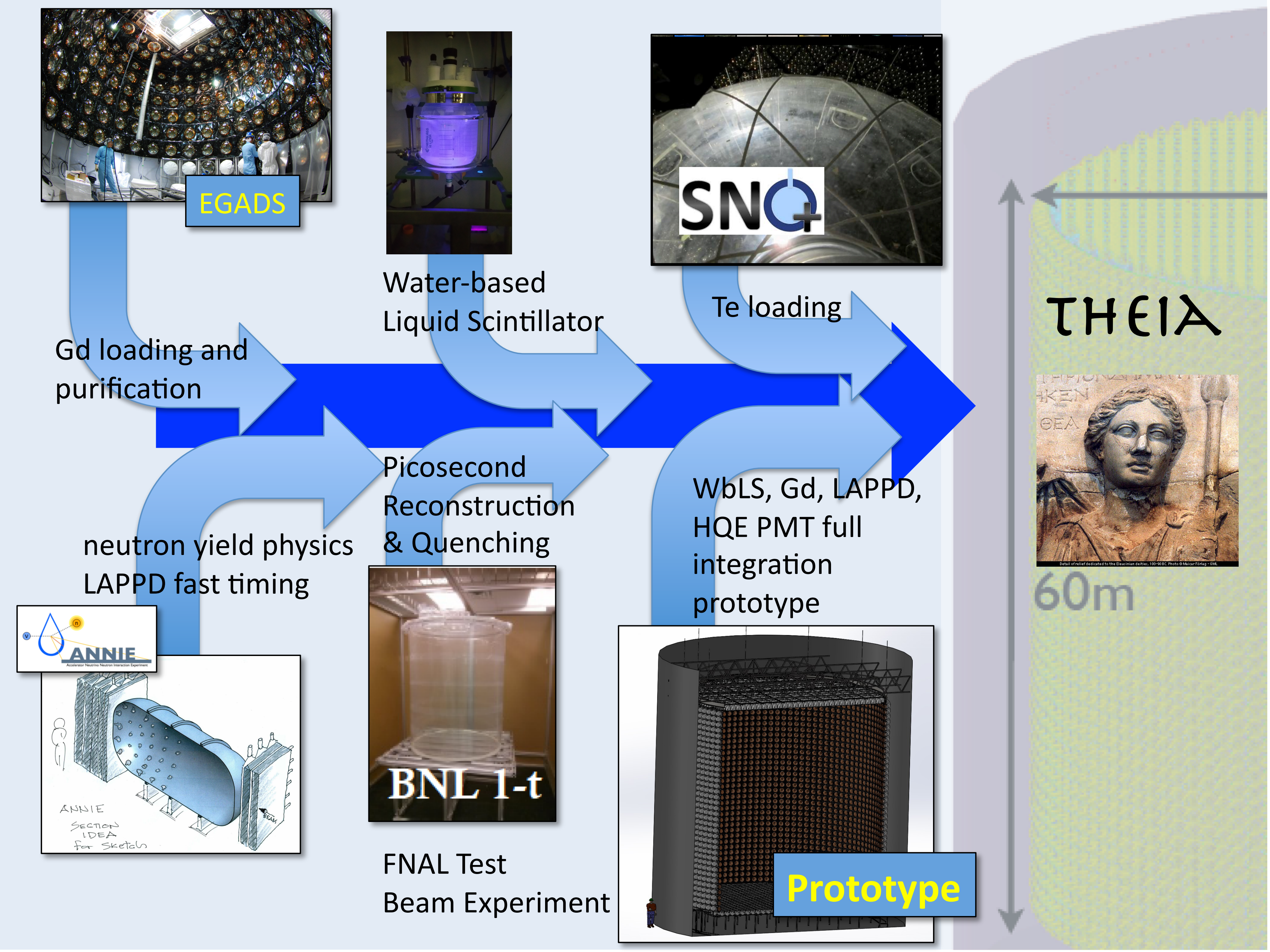
- Light yield studies at BNL and soon at LBNL
- Stability and material compatibility studies at BNL (uncovered one problem so far – butyl rubber adhesive).
- Purification studies at UC Davis using NanoFiltration (NF) to separate organic components from water.
- Scaled up production: 10 liters produced 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



Current and 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 (ANNIE)	Exists
ANNIE	30 ton			2015
Gadzooks!	22 kton			202x
FNAL Beam Test	1 ton	(Wb)LS	Event Reconstruction	2016
Penn	30 L	(Wb)LS	light yield, timing, loading	Exists
SNO+	780 ton			2017
LBNL	bench top	WbLS	light yield, timing, cocktail optimization, loading, attenuation, reconstruction	2015
BNL	1 ton			2015
Future?	~1 kton			202X



Gd loading and purification

Water-based Liquid Scintillator

Te loading

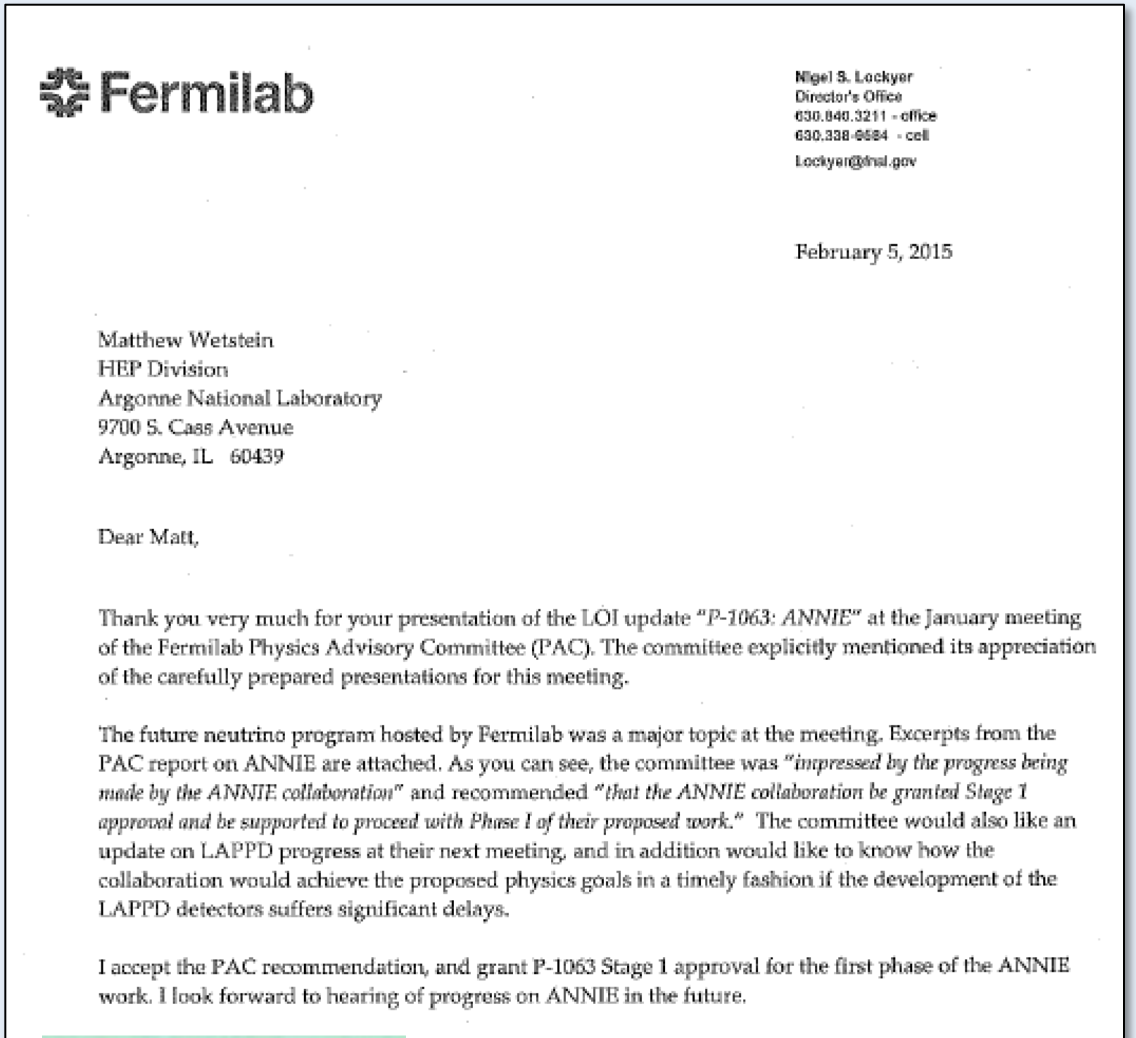
neutron yield physics
LAPPD fast timing

Picosecond Reconstruction & Quenching

WbLS, Gd, LAPPD, HQE PMT full integration prototype

FNAL Test Beam Experiment

Detail of relief dedicated to the Eleusinian deities, 100–90 BC. Photo © Maicar Förlag – GML



Fermilab

Nigel S. Lockyer
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February 5, 2015

Matthew Wetstein
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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.

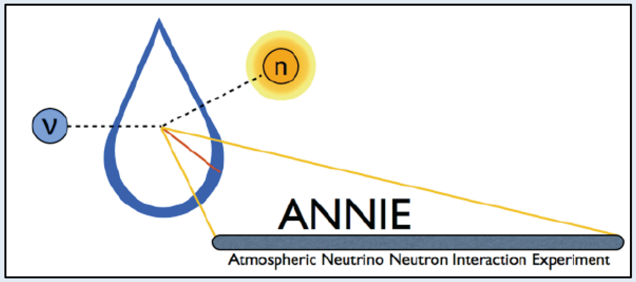
The future neutrino program hosted by Fermilab was a major topic at the meeting. Excerpts from the PAC report on ANNIE are attached. As you can see, the committee was "*impressed by the progress being made by the ANNIE collaboration*" and recommended "*that the ANNIE collaboration be granted Stage 1 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

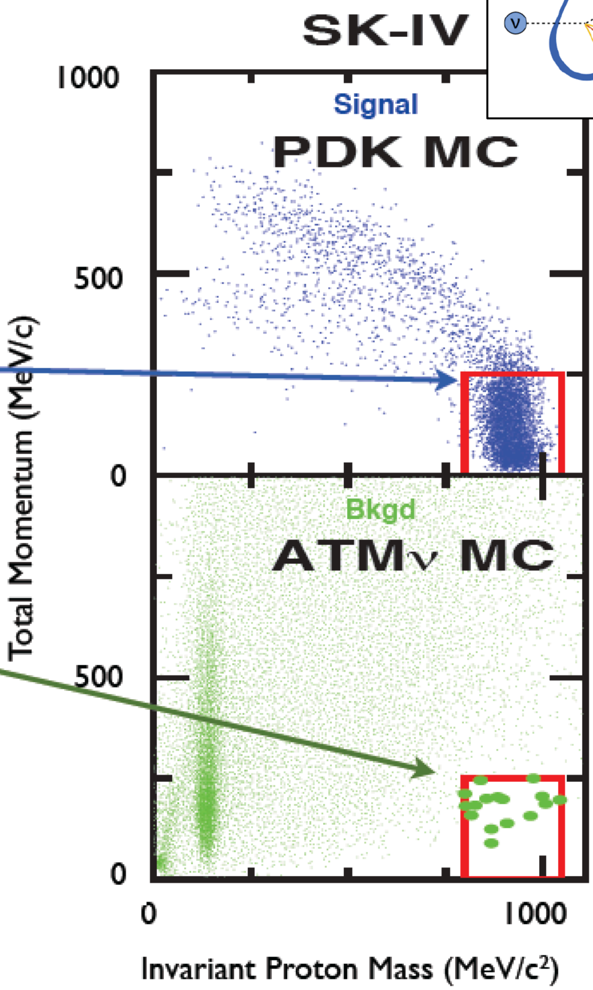
May include internal WbLS target – under discussion

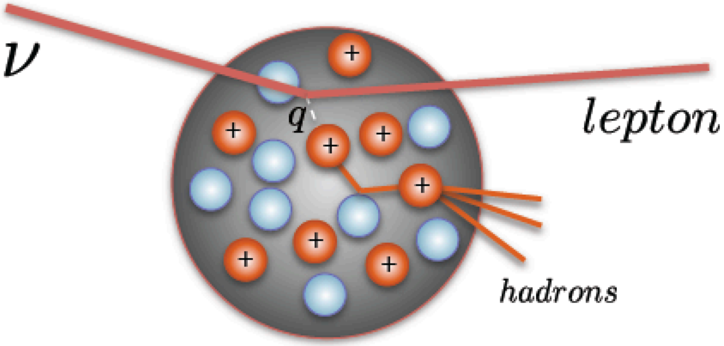
Motivation

Backgrounds come almost exclusively from atmospheric neutrino interactions

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

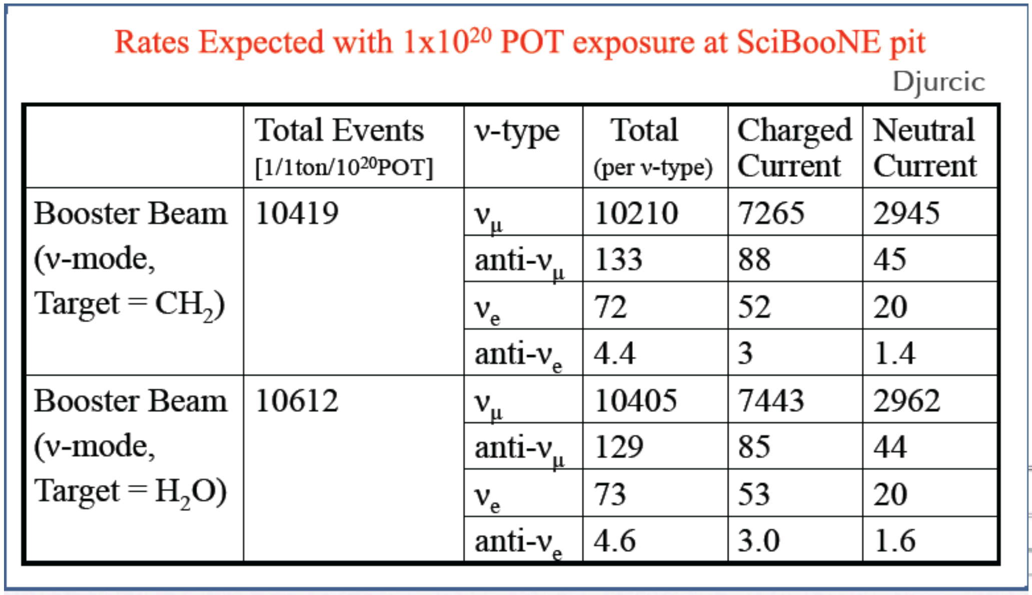
High energy neutrino interactions typically produce neutrons in the final state





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



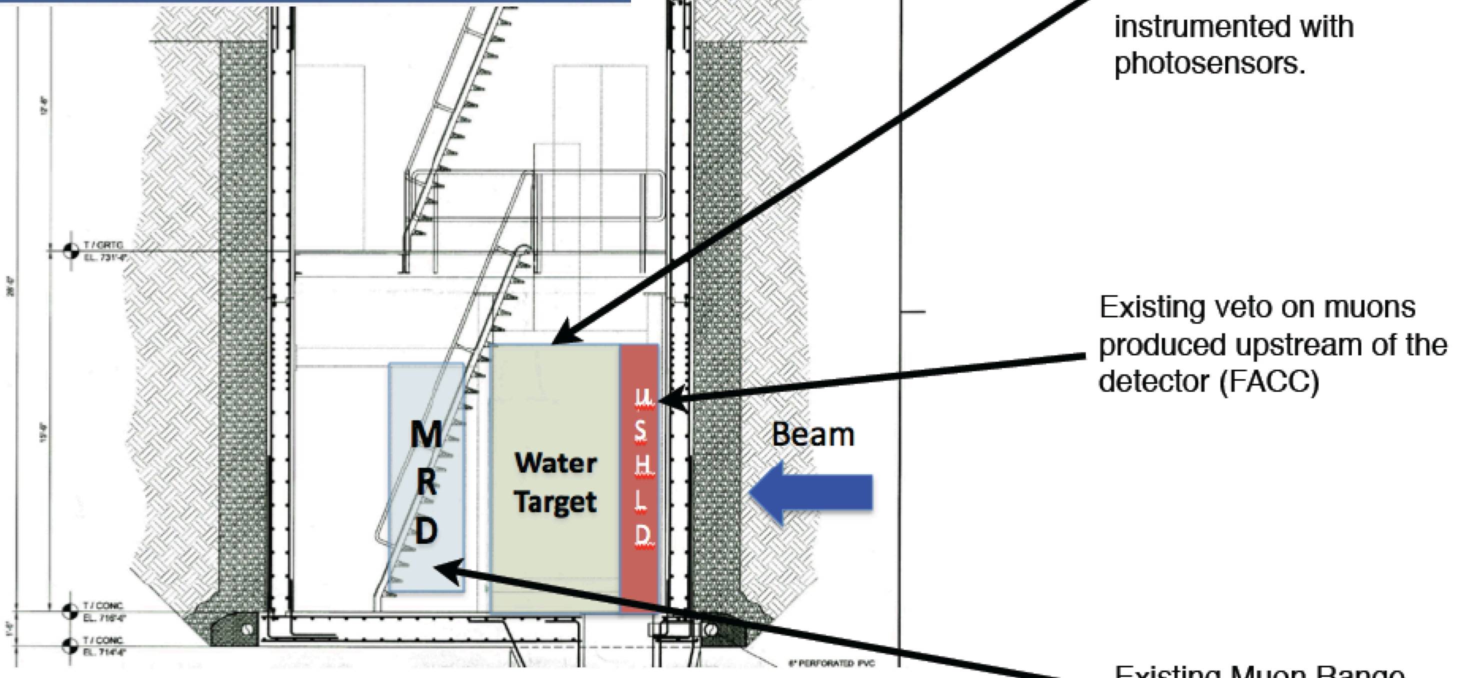
Rates Expected with 1x10^{20} POT exposure at SciBooNE pit

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

ANNIE

Atmospheric Neutrino Neutron Interaction Experiment



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

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

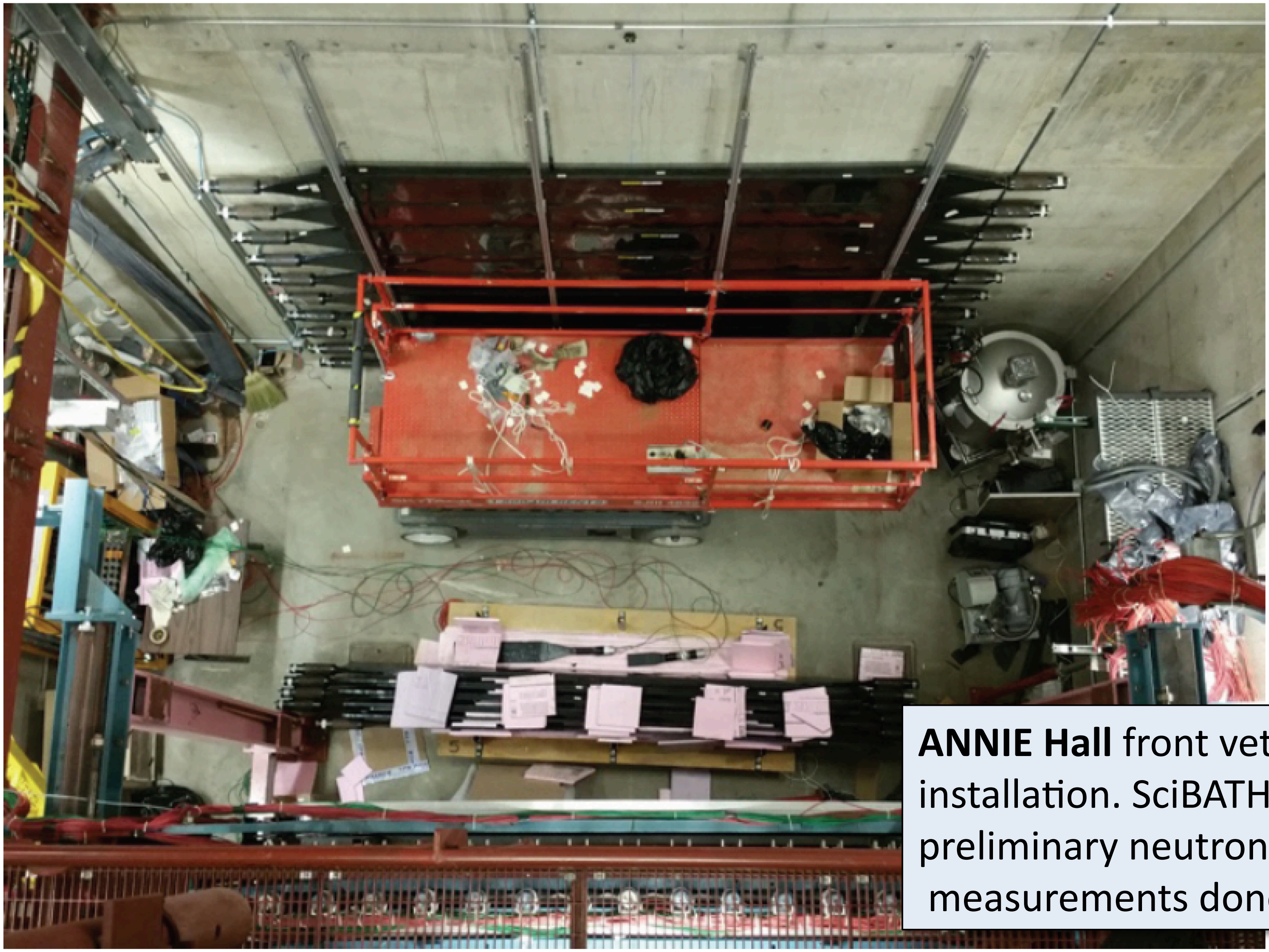
Existing Muon Range Detector (MRD)

"ANNIE Hall"

(formerly the SciBooNE pit)

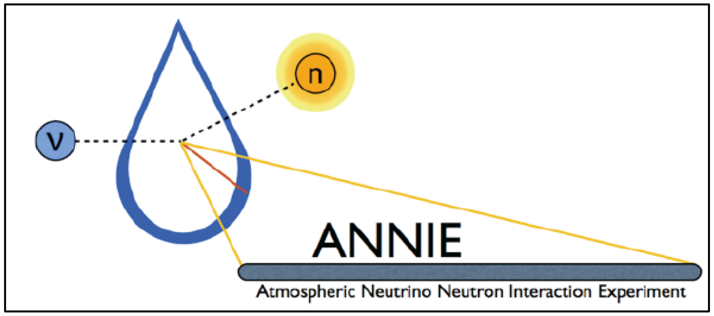
For documentation and animation of the wall construction, go to:

https://cdcvs.fnal.gov/redmine/projects/annie_experiment/wiki/Veto_design



ANNIE Hall front veto installation. SciBATH preliminary neutron measurements done.

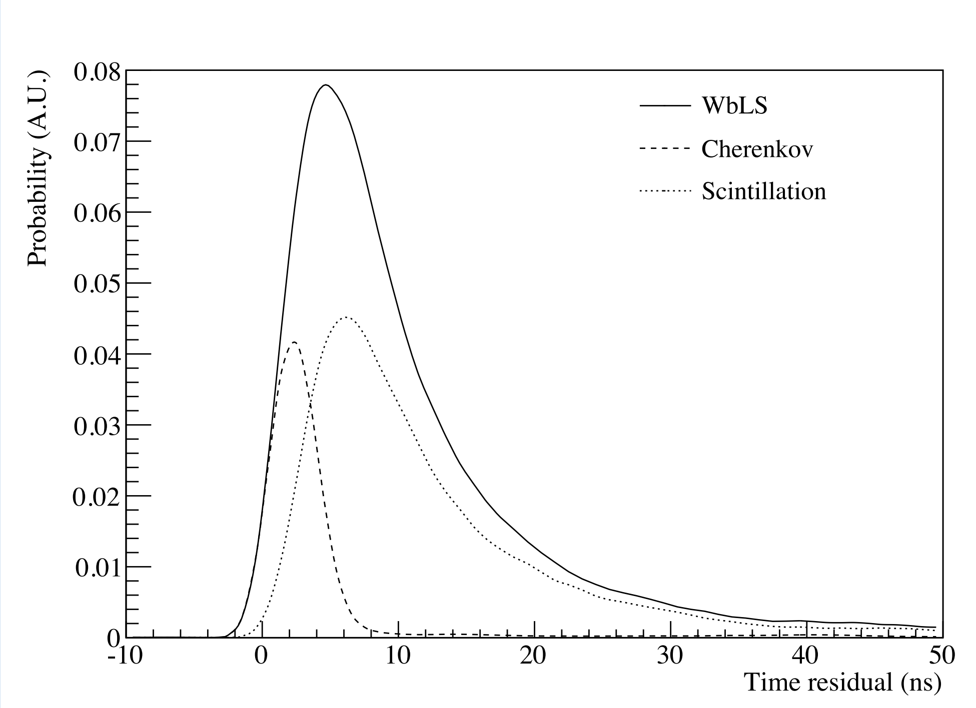
2015-2016 Run



- Goal is to measure "skyshine" neutron backgrounds as a function of position in the tank using a scintillator target.
- Proposal for full ANNIE program 2017-2021 being prepared
- 40 LAPPD (+ fast 1-inch PMT's), 60 8-inch PMT, 20 11-inch PMT, 50 *NEW* 10" PMT

Proton Beam Test (Proposed)

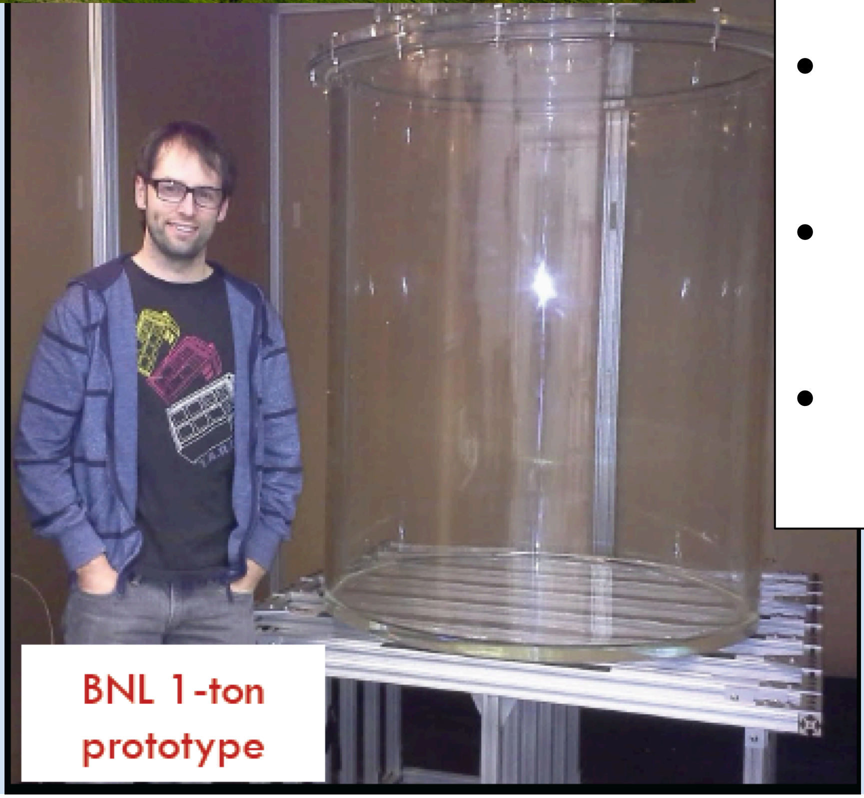
- Reconstruction of tracks in WbLS and particle ID require separation of scintillation and Cherenkov light via timing and pattern.



Arrival time difference between scintillator and Chernkov light in a 50 kT detector with 1% WbLS

FNAL test Beam Facility

- Use existing 1-ton BNL WbLS prototype in proton beam 300-2000 GeV
- Cherenkov threshold 470 MeV
- Small fast PMT array
- Demonstrate Cherenkov / Scintillation Light separation
- Measure proton quenching as a function of energy
- Proposed at FNAL Test Beam for 2017-2018



BNL 1-ton prototype

FroST

Frontiers in Scintillator Technology

March 18-20th 2016

Local Organising Committee

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Josh Klein
Gabriel Orebi Gann
Bob Svoboda

Scientific Advisory Committee

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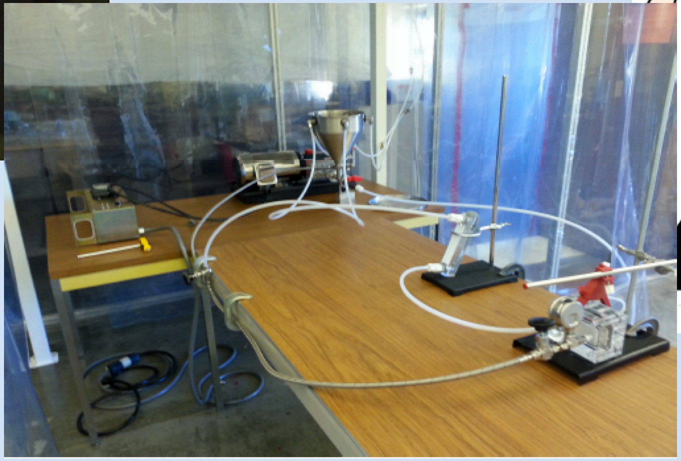
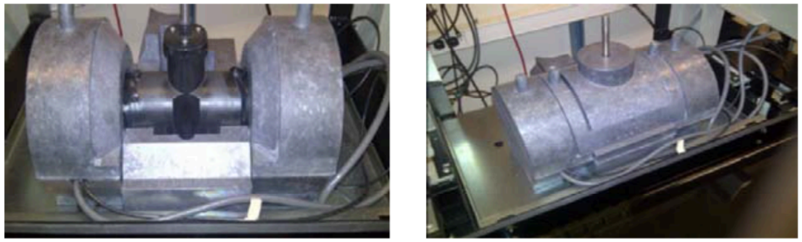
Michael Wurm

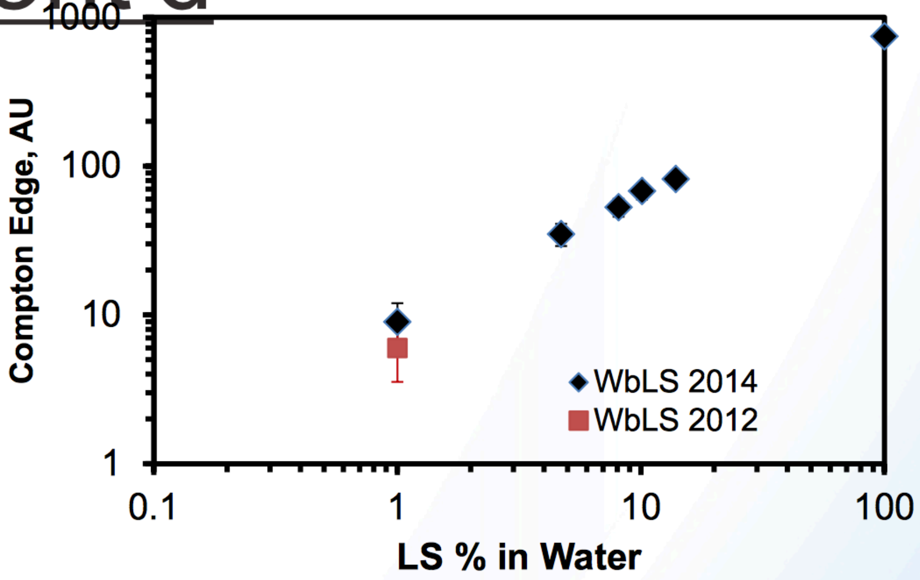
Thanks!

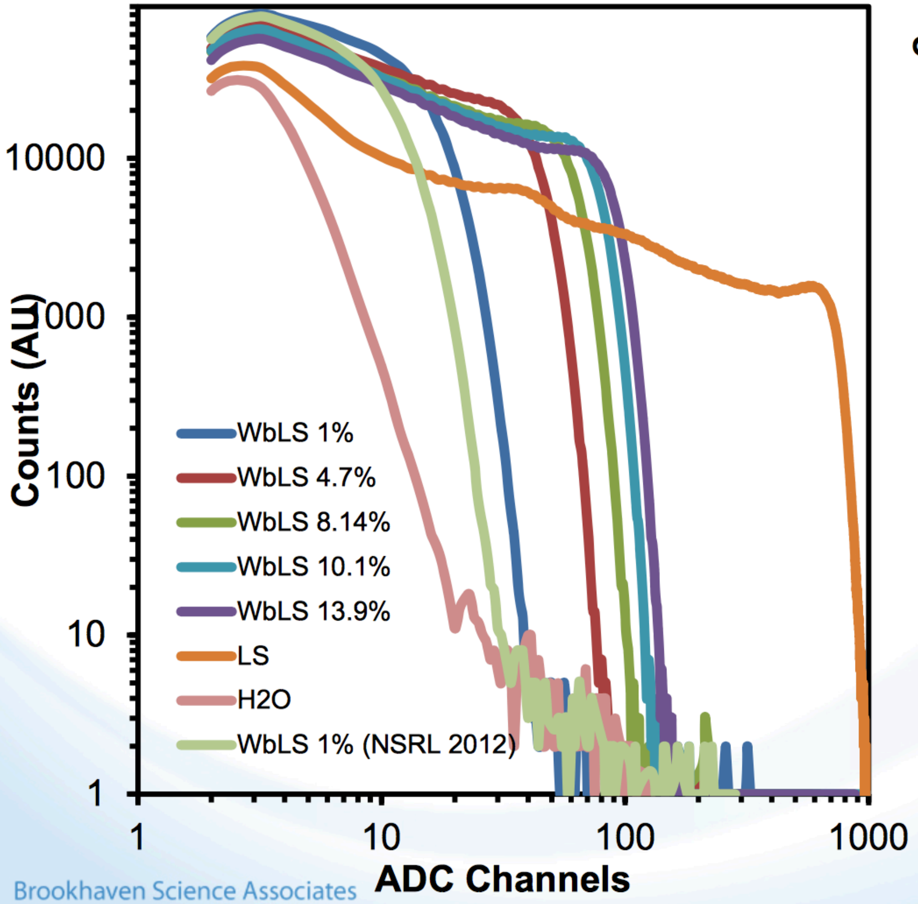
Detail of relief dedicated to the Eleusinian deities, 100-90 BC. Photo © Maicar Förlag - GML



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