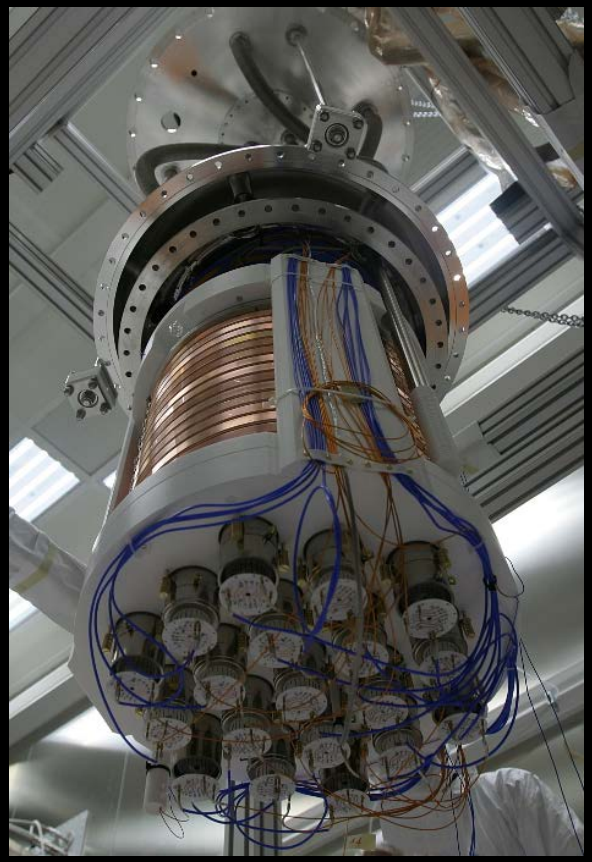
Searching for Dark Matter WIMPs
With
Liquid Argon & Sodium Iodide Detectors

Frank Calaprice
Princeton University

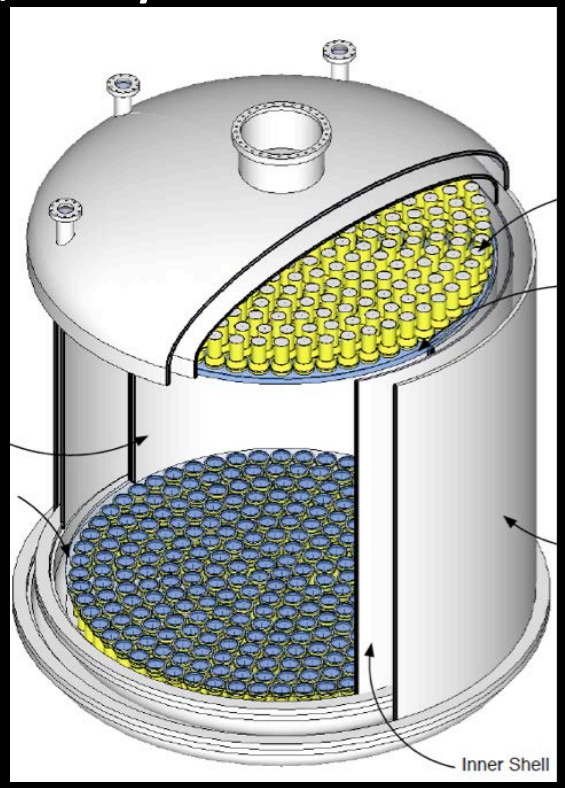
Nygren Fest LBNL May 2-3 2014

The DarkSide Program at Gran Sasso Lab, Italy

DarkSide-10
prototype
10 kg active
200 days Princeton
500 days LNGS



DarkSide-50
50/33 kg active/fiducial
Sensitivity~10^{-45} cm^2
in 3-year run



DarkSide-G2
3.3/2.8 T active/fiducial
Sensitivity~10^{-47} cm^2
in 5-year run

WIMP Signals & Backgrounds.

- WIMP Signal
  - Low energy nuclear recoil (10-100 keVr) produced by WIMP-nucleus scattering.
  - Choose detector with different nuclear and electron recoil signals.
  - Expected rates are small: < 1 cpy/ton, need multi-ton detector.

- Background Signals:
  - Neutrons, betas/gammas, surface $^{210}Po \rightarrow {}^{206}Pb + {}^{4}He$
  - Design for "background free" results.
    - Neutron veto
    - Pulse shape analysis to separate nuclear from electron recoils.
    - TPC defined fiducial volume without surface background.

Why use LAr for Dark Matter?

LAr Pluses

- Powerful PSD in scintillation signal.
  - Excellent separation of electron/nuclear recoils.
- Proven scalability to multi-ton masses
  - ICARUS.
- Bright scintillator with low energy threshold.
  - 40 photons/keVee; 8-10 pe/keVee
- Ionization detector for 2-phase TPC
  - Well defined fiducial volume reduces surface backgrounds.
  - S2/S1 helpful for discrimination.
- Liquid nobles can be radio-pure.

LAr Minuses

- ~~Cosmogenic radioactive ^{39}Ar in Atmospheric argon (AAr).~~
  - Underground argon (UAr) found.
  - ^{39}Ar. < 0.65% of Aar.
- ~~Detecting 128 nm photon is difficult.~~
  - Wevelength shifters, reflectors, special PMTs developed.
  - High Light yield: 8-10 pe/keV !
- AAr is cheap. UAr is not.
  - But still affordable @ ~$1M/ton.

Toward Background-Free

1. Underground argon with low ^{39}Ar (<0.65% atmospheric)
2. Pulse Shape Discrimination
   - Rejection factor for electron recoils > 10^8
3. Two-phase LAr TPC
   - Scintillation/ ionization detection (S2/S1)
   - 3D position fiducial volume without surface background
4. Neutron Veto for TPC
   - Boron-loaded liquid scintillator veto (>99%)
   - Active Rejection & Measurement of Background Neutrons
5. External Active Water Shield (Cerenkov detector)
   - Identify and reject cosmogenic muon events.
   - Suppresses radiogenic and cosmogenic neutrons/gammas.

Argon Scintillation Pulse Shape Analysis

- 1983: A. Hitachi, et. al. measure scintillator pulse shapes for ionizing particles in argon.
- 2005: Boulay and Hime suggest pulse shape discrimination to suppress ^{39}Ar beta radioactivity with huge rate of ~1 Bq/kg.
- So powerful it can suppress ~10^8 electron recoils to detect 1 nuclear recoil.
- Argon without ^{39}Ar it could be the ideal dark matter detector!!

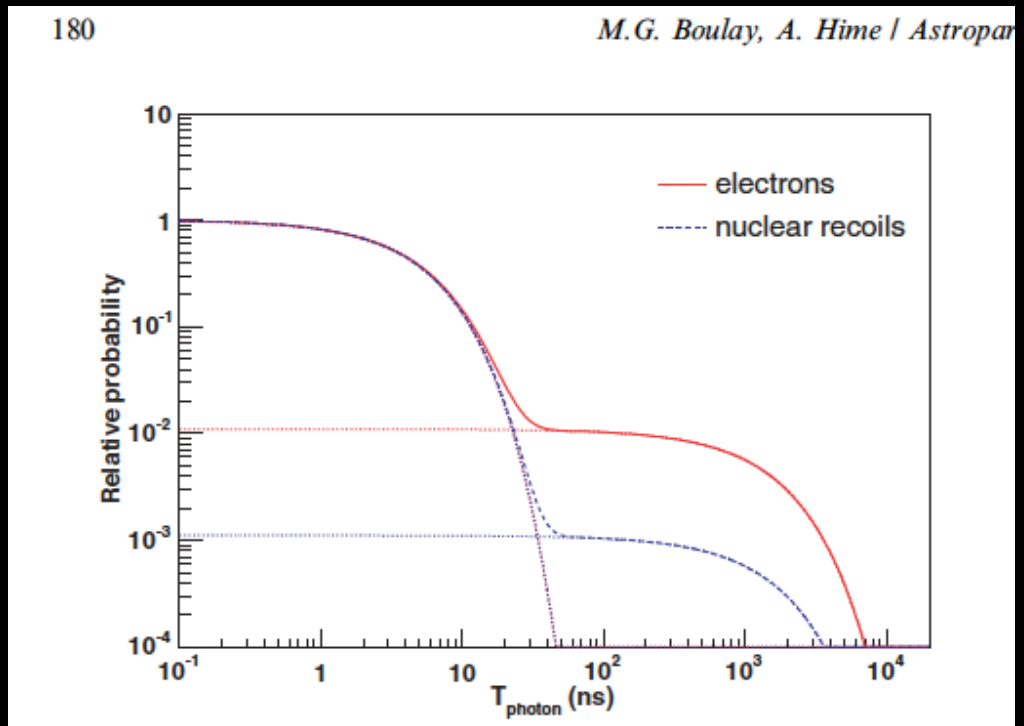
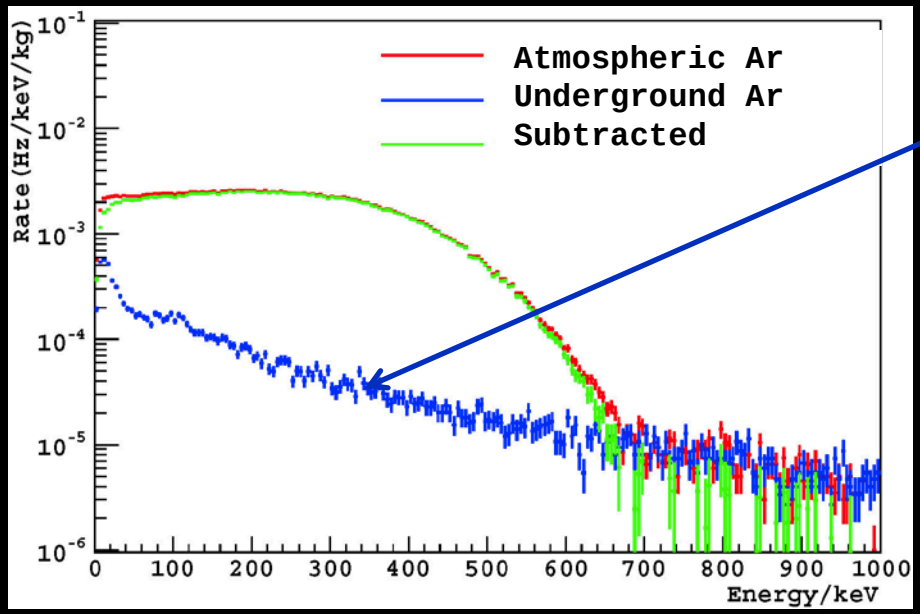


Fig. 1. Scintillation time distribution for electrons and nuclear recoils in liquid argon from Ref. [8]. The dotted lines show the contributions from the singlet (prompt) and triplet (late) components separately.

Underground Argon

- Cosmogenic ^{39}Ar β-decay (260 yr), in atmospheric argon at 1 Bq/kg is the main electron recoil background in normal argon.
- Underground argon (^{40}K) will have low ^{39}Ar, except for U, Th pro.
- Geologist Mukapadjay (Harvard) said to me in 2006:
  - Earth's mantle has low U and Th, so argon from mantle gas should have low ^{39}Ar
  - CO_2 from wells in U.S. Southwest comes mainly from mantle. Go there!



- Our measurements give an **upper limit** of 6.5 mBq/kg, a factor of >150 reduction.
- At this limit, ^{39}Ar still the dominant β/γ background, but not by much.

Jingke Xu Ph.D. thesis, 2013

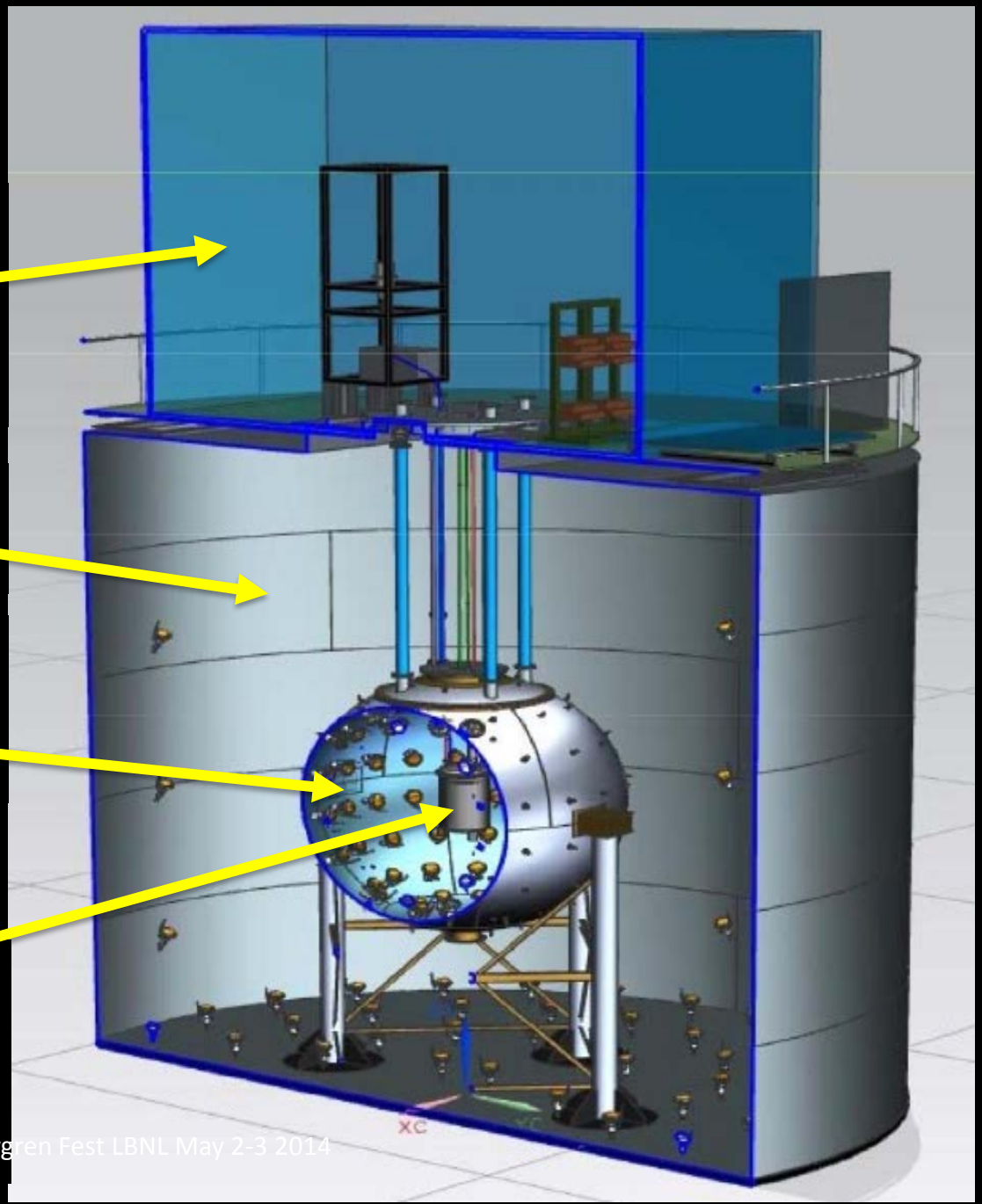
DS-50 @ LNGS

Rn-free clean room
(10-15 mBq/m^3 in 110 m^3)
Used for assembling TPC
and deployment

Water Cherenkov muon veto: 10^3
m^3 H_2O with 76/80 8" PMTs

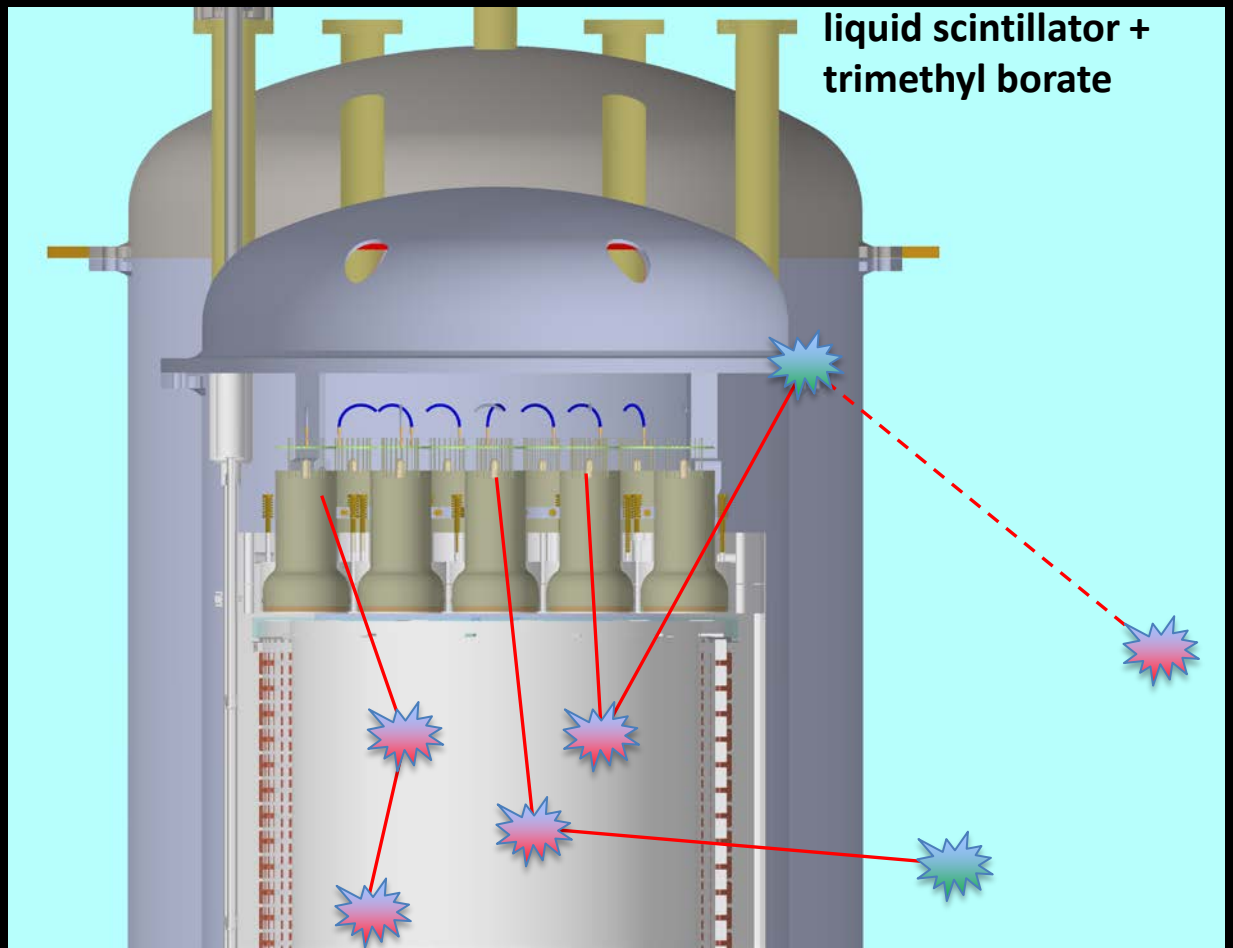
Boron-loaded liquid scintillator
(50% TMB + 50% PC) as
neutron veto with 108/110 8"
PMTs

150kg LAr TPC with 2 x 19
3" PMTs
AAr at present with 1Bq/kg ^{39}Ar
UAr with < 6.5 mBq/kg ^{39}Ar



Reducing neutron-induced **nuclear recoil background.**

- Radiogenic (α,n) from detector components dominates
- Screen and select materials for extremely high radiopurity
- PMTs largest source, then cryostat steel
- Highly efficient neutron veto rejection ≥100
- Position reconstruction/multiple interactions



neutron

gamma

interaction giving nuclear or *e* recoil

neutron capture

Water Cherenkov

TPC hanging in LSV

Nygren Fest LBNL May 2-3 2014

PMTs + Cold-Amps in LAr

R11065 PMTs
(R11065-20 problems)

PMT Gain = 3×10^5

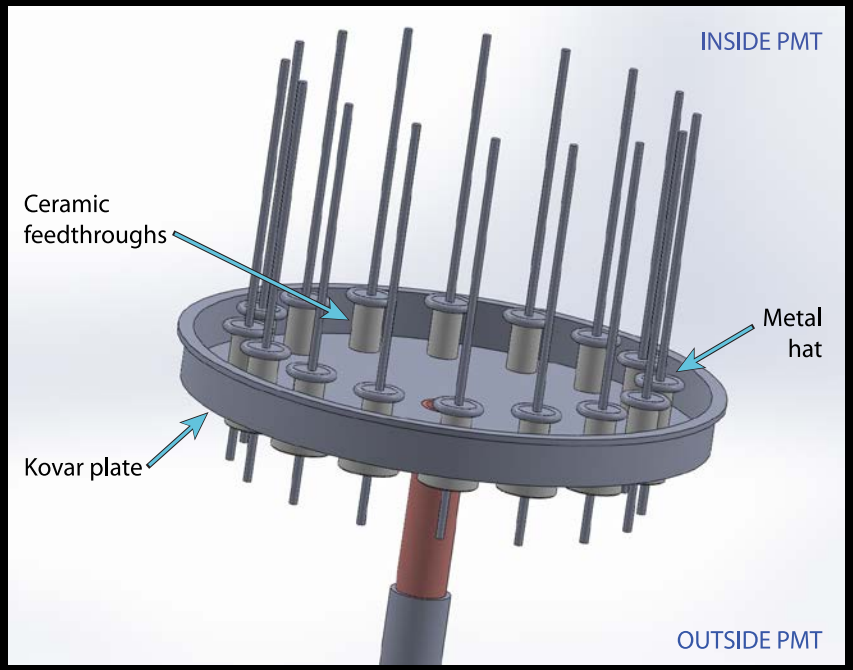
PMT HV ~ 1200 V

Noise 3 mV on 200 MHz

Borosilicate glass feedthrough for pins. Glass is main souce of neutron background.

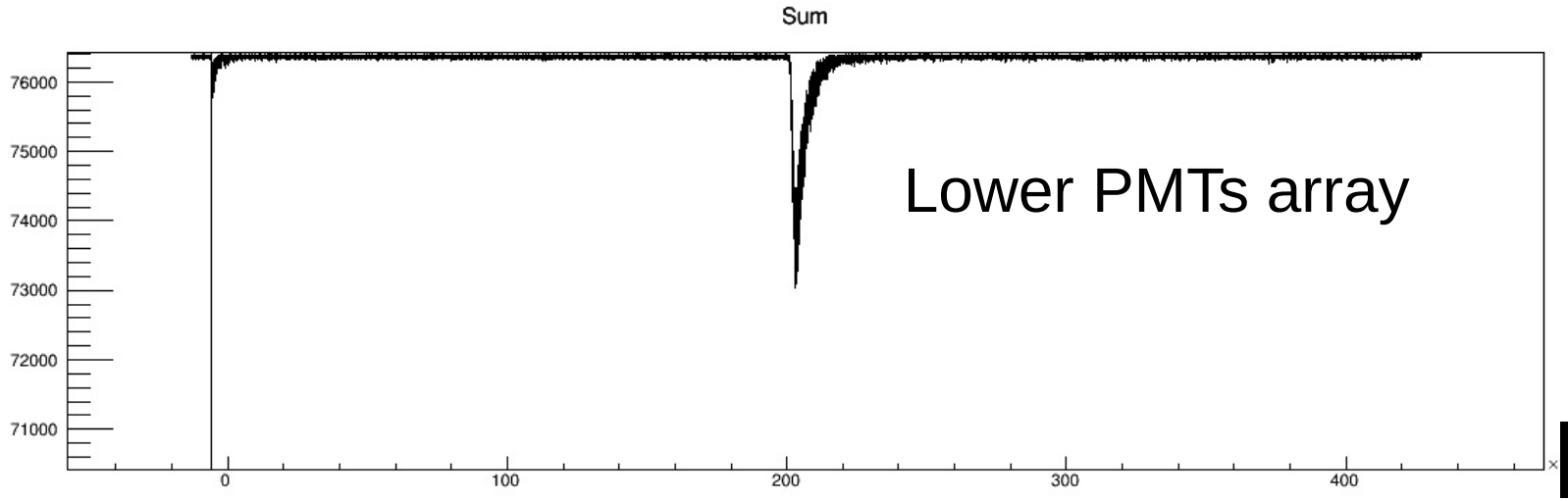
Reducing PMT Radioactivity

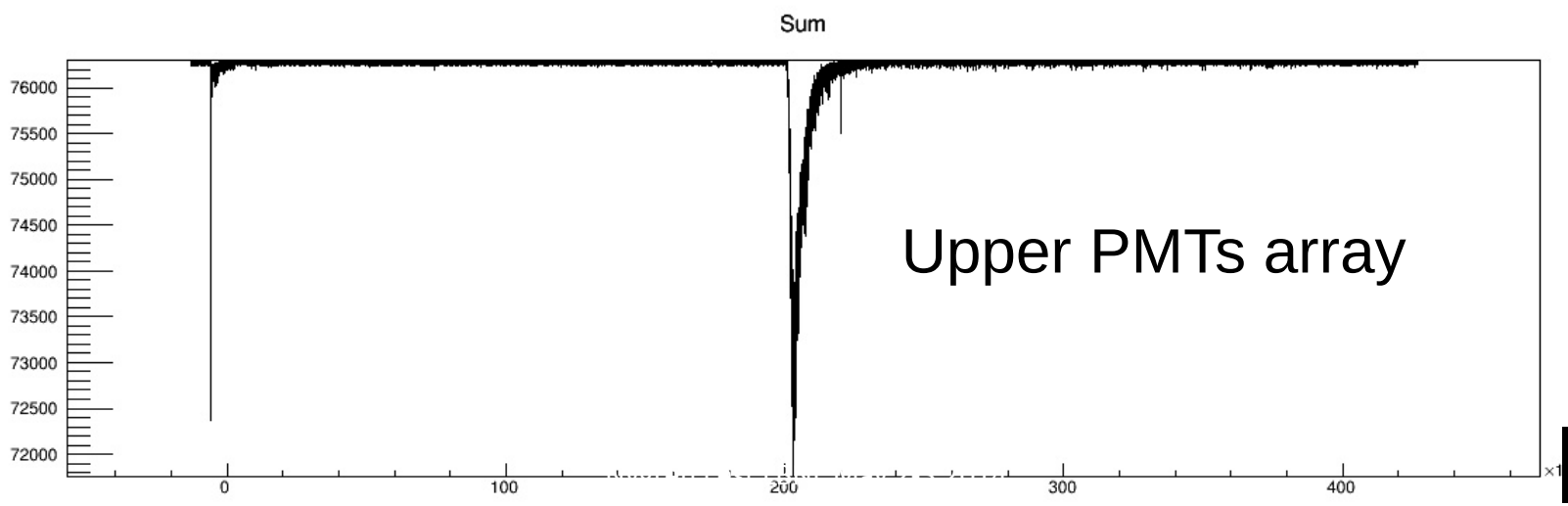
Synthetic Alumina Ceramic Feedthrough



Main background in R11065-20 is due to ceramic pin feed-through plate. Radio-pure synthetic ceramic has been developed by Princeton and OxiMaTec for PMT feedthroughs.

S1 and S2 signals





Pulse Shape Discrimination

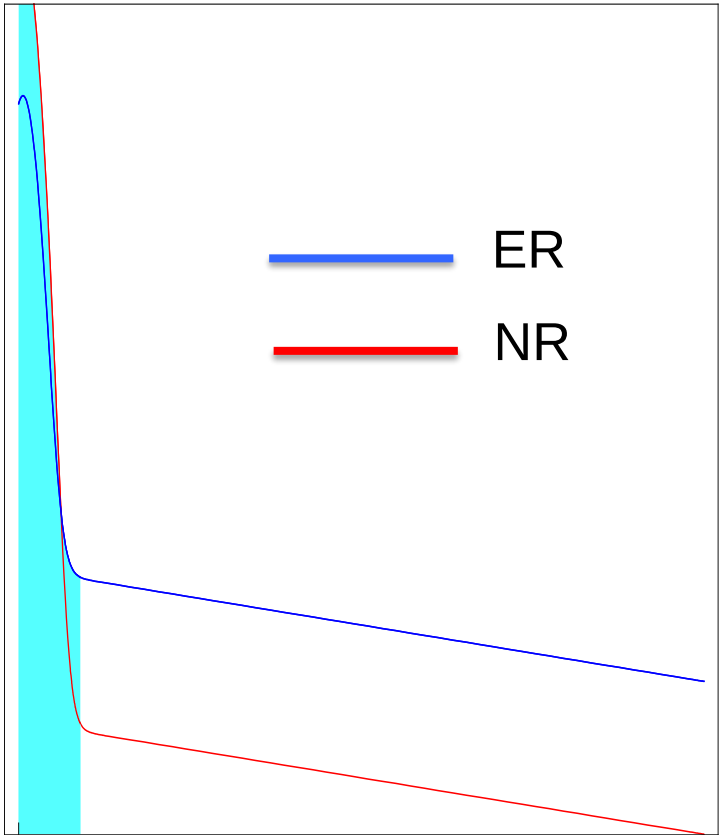
$$f(t) = \left(\frac{q}{\tau_F} e^{-t/\tau_F} + \frac{1-q}{\tau_S} e^{-t/\tau_S} \right)$$

$$\tau_F = 6ns$$

$$\tau_S = 1600ns$$

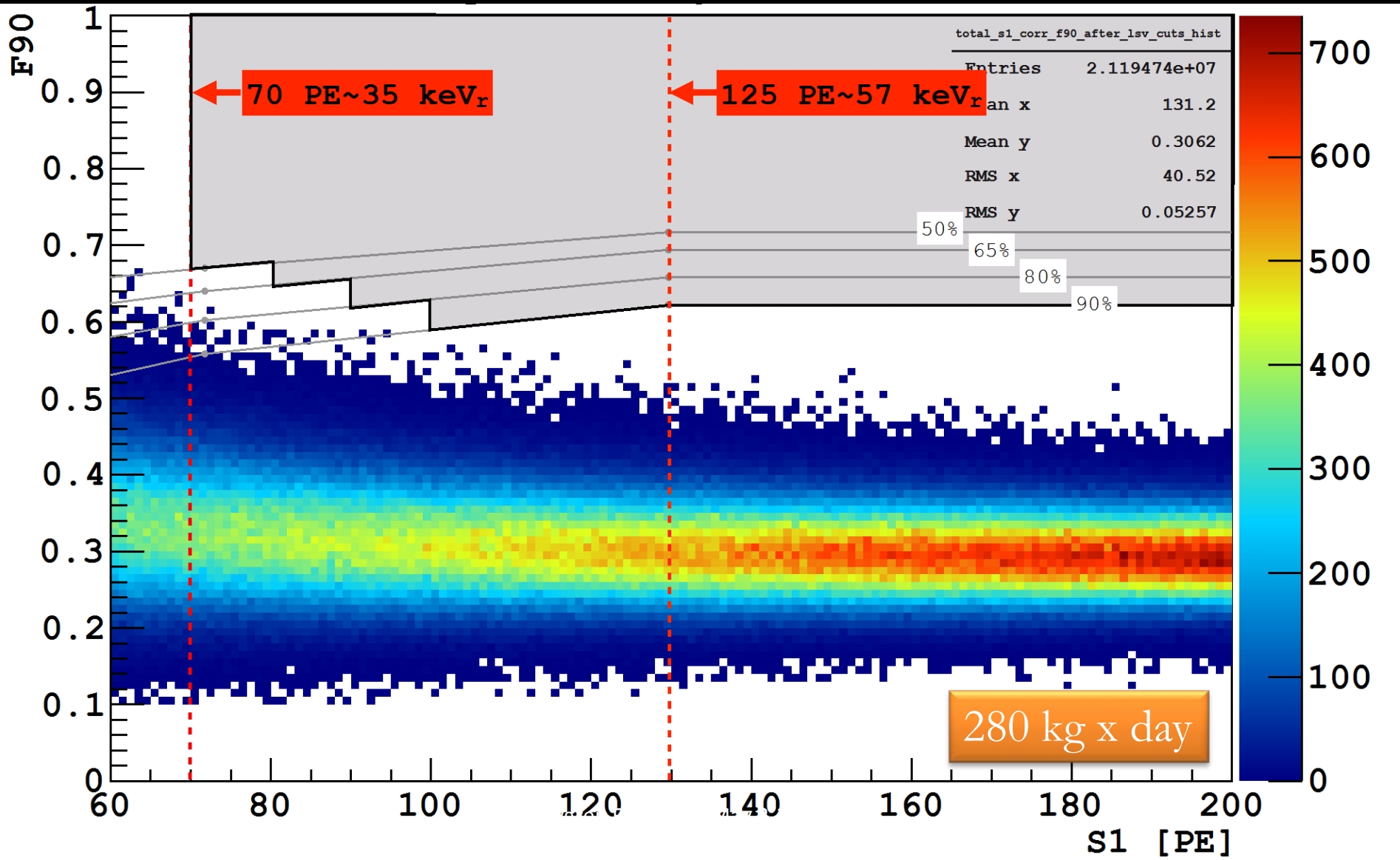
$$q = \begin{cases} 0.3 \text{ ER} \\ 0.7 \text{ NR} \end{cases}$$

$$F_{90} = \frac{\int_0^{90ns} dt\, f(t)}{\int_0^{\infty} dt\, f(t)} = \begin{cases} 0.3 \text{ ER} \\ 0.7 \text{ NR} \end{cases}$$



[ ]

Pulse Shape F_{90}



Neutron veto

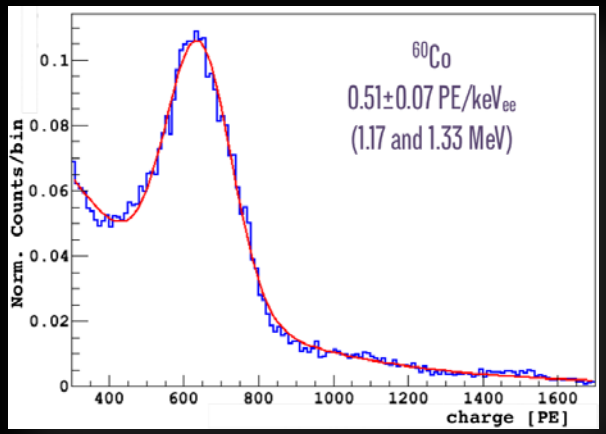
- 30 tons of boron-loaded liquid scintillator
  - 50% TMB [$B(OCH_3)_3$] + 50% PC + 3 g/l PPO

$$
\begin{aligned}
{}^{10}B(19.9\%)+n \rightarrow \quad & {}^{7}Li(\text{g.s.})+\alpha,\ 6.4\% \\
\rightarrow \quad & {}^{7}Li^{*}+\alpha,\ {}^{7}Li^{*} \rightarrow {}^{7}Li+\gamma(478\text{keV}),\ 93.7\%
\end{aligned}
$$

- 108 8" PMTs
- High reflectivity of inner surface of containment vessel
- n-veto expected performance: < 1 event in 3 years after n-veto rejection and TPC cuts

Neutron Veto works but ^{14}C is High

- High light yield measured using ^{14}C spectrum and ^{60}Co contamination in cryostat.
- High ^{14}C contamination found in TMB.
  - $^{14}C/^{12}C \sim 10^{-13}$, not 10^{-18} as in Borexino.
  - Contamination traced to change in TMB production.
    - DOW U.S. used mineral sources.
    - DOW Europe used biogenic sources

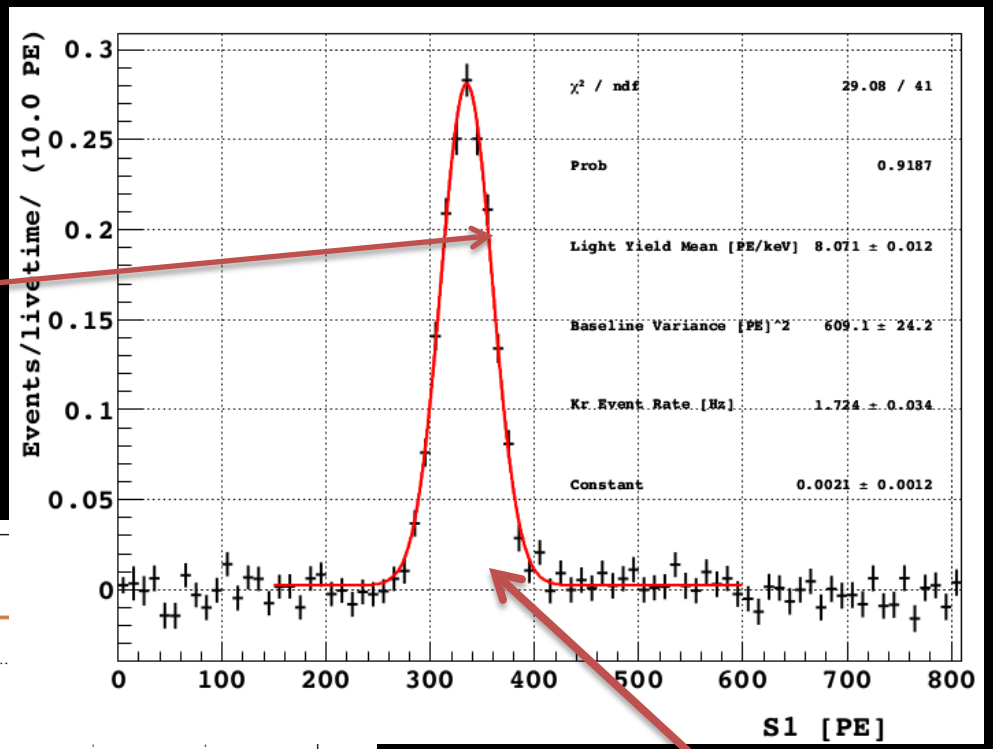


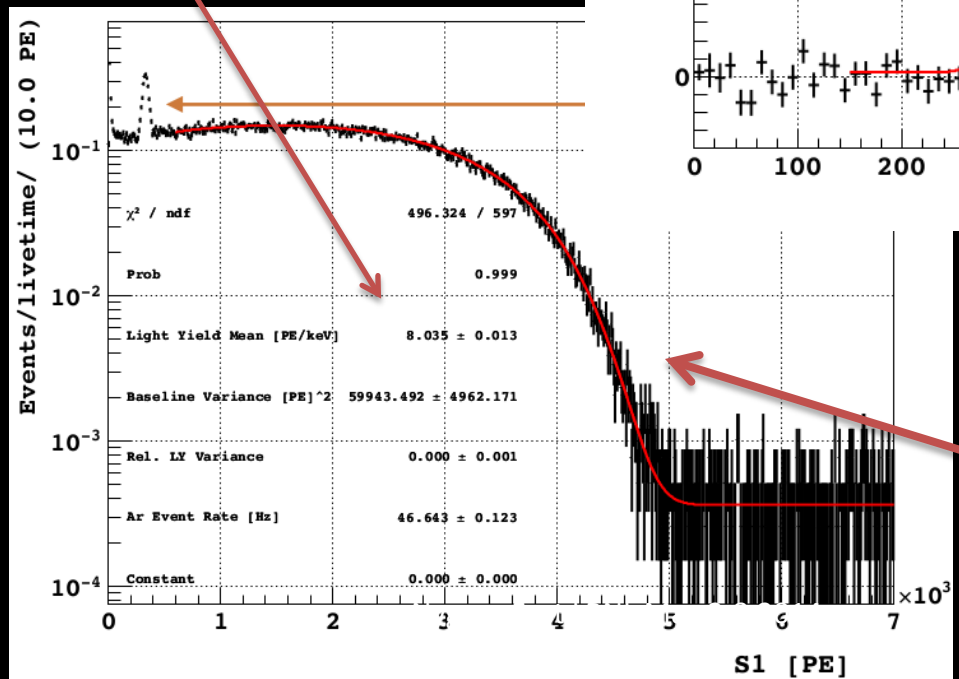
TPC

- In operation S1/S2 mode with 50 kg AAr
- Expected 1-2 neutron/month (mainly from measured activity of PMTs) w/o veto cut (with R11065 PMTs). Veto rejection factor = 100: <u>need a n-veto</u>
- In operation with 38 3" R11065 PMTs. (-20 PMTs failed)
  - Gain stability 1-2%
  - HV: E_{drift} = 200 V/cm, $E_{extraction}$ = 2.8 kV/cm
  - Light yield ~ 8 p.e./keVee
  - Electron lifetime ~5ms
    - To compare with max drift time of ~ 400 μs
  - ^{83m}Kr internal calibration (two times) 41.5 keVee sum line

Light yield @ null field

Light Yield ~ 8 pe/keV$_{ee}$
at **null field**





^{83m}Kr peak
41.5 keV, $T_{1/2}$=1.83h

^{39}Ar spectrum
565 keV

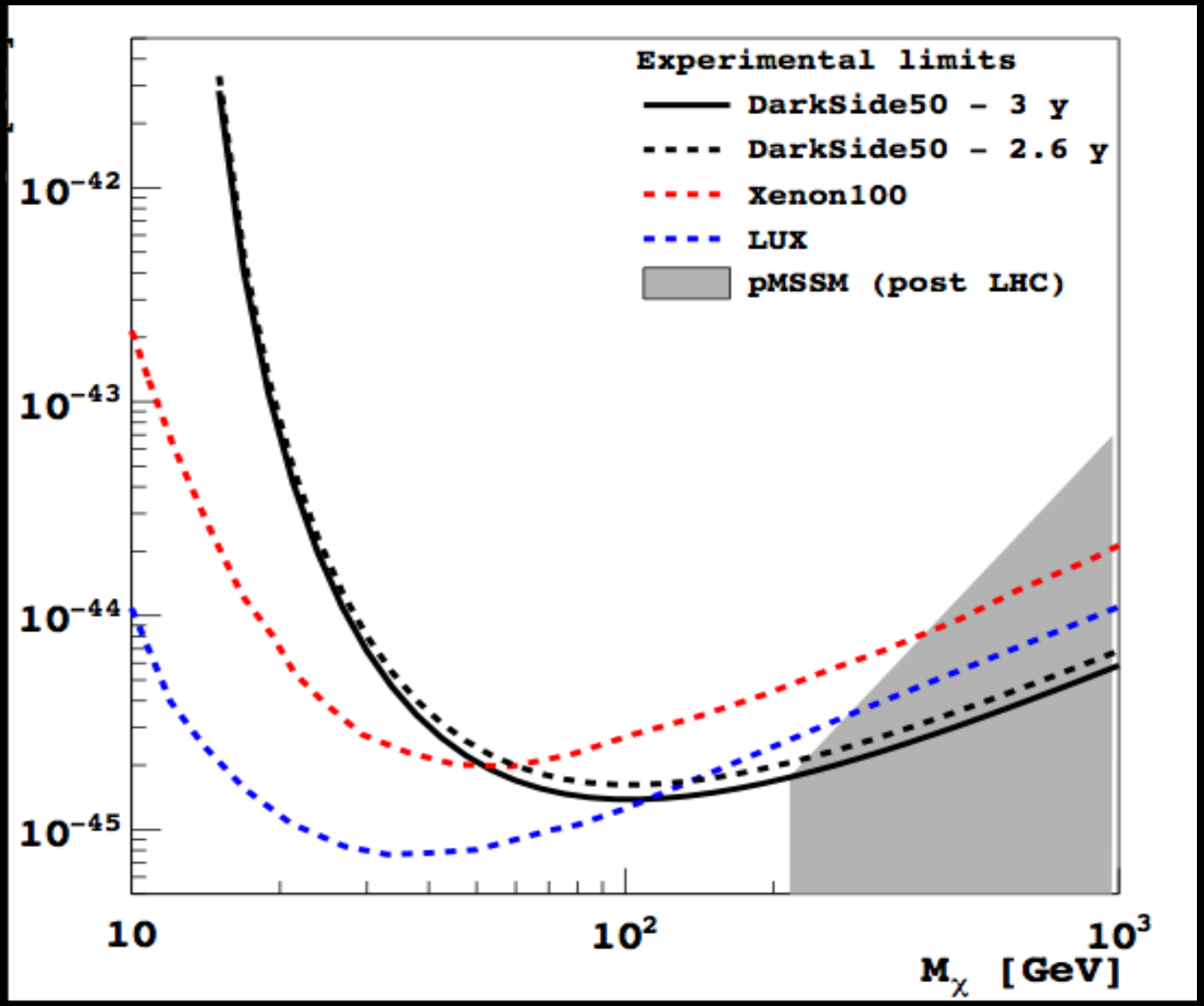
Summary of 1st DS-50 data

- In operation with AAr since Oct 2013
- TPC (AAr), neutron veto and muon veto commissioned
  - Analyzed 280 kg x day (~ 1 week exposure)
  - S2/S1 and x-y cut still under development
  - neutron veto light yield ~ 0.5 p.e./keVee
  - neutron veto scintillator acquired with TPC trigger
  - neutron veto scintillator with high ^{14}C contamination
- No background in PSD in upper 50% NR acceptance region in $3x10^7$ events
- LY @ null field ~ 8 p.e./keV_{ee}
- Rn contamination from Bi-Po < 0.85 mBq/kg_Ar
- Already collected data more data for further studies (50kg LAr)

Near Future Goals

- More data with AAr
  - ^{39}Ar spike test
  - neutron calibration: deployment system in preparation
  - improve fiducialization
- Replace PC+TMB with PC soon
  - ✓ 600l of PC+TMB distilled to separate components
  - ✓ plan: dispose TMB and re-use PC
- Using new TMB (samples from companies measured)
- Replace AAr with UAr: Aug-Sep
  - reduce ^{39}Ar background by a factor > 150

DS-50 expected sensitivity with UAr



Main Goal of Darkside-50

A Dark Matter "Background Free Demonstrator"

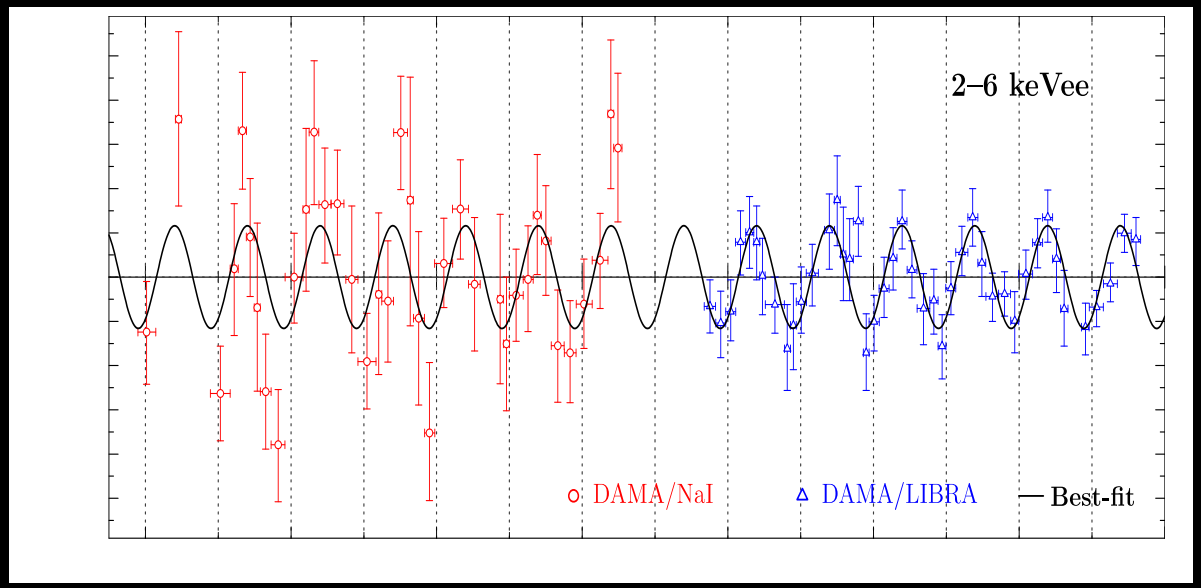
- Size of the 50-kg Darkside was determined by current production capacity of underground argon.
- Main goal of DS-50 is to test novel features for "background-free" results for large multi-ton detectors.
- Darkside-50 operating since Oct-Nov. 2013
  - First data for G2 Proposal made public.
  - Still commissioning detector.
  - No release of new data yet - new release in 2014?

The DAMA/LIBRA Modulation

Systematic effect or evidence for Dark Matter?

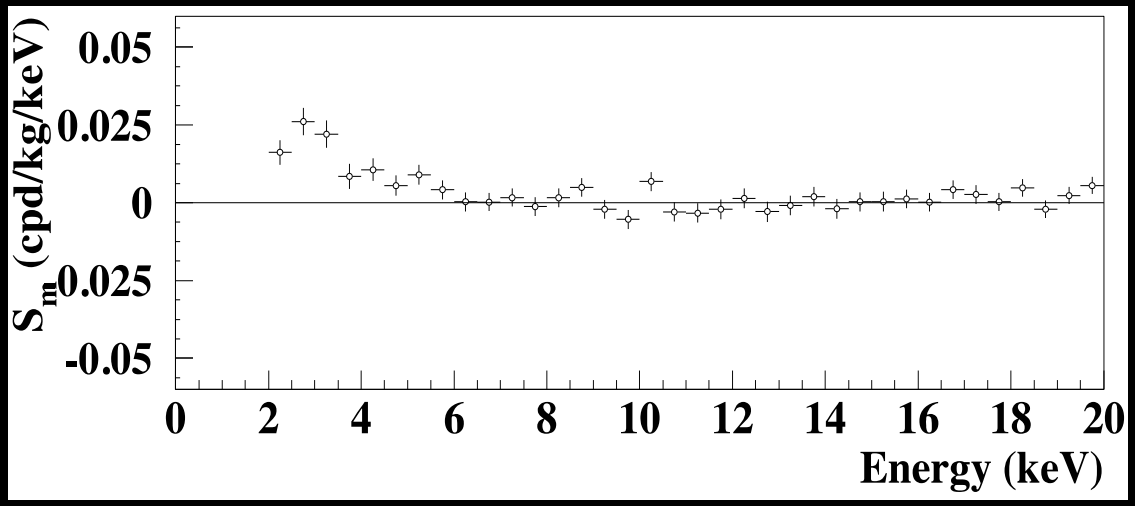
Modulation:

- 1 year period
- Peak in May (WIMP phase)
- ~9σ significance



Amplitude:

- 2-6 keV_{ee}
- Most prominent at ~3 keV_{ee}

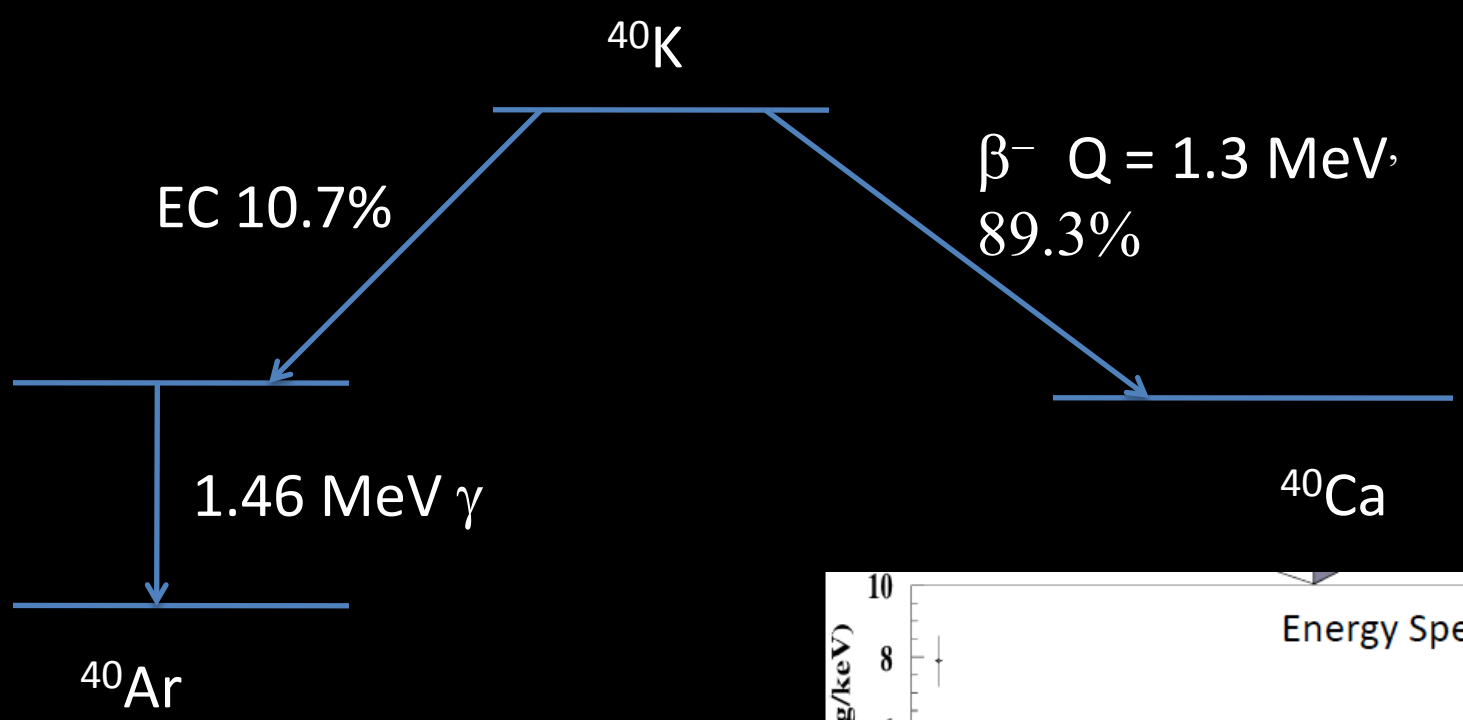


SABRE

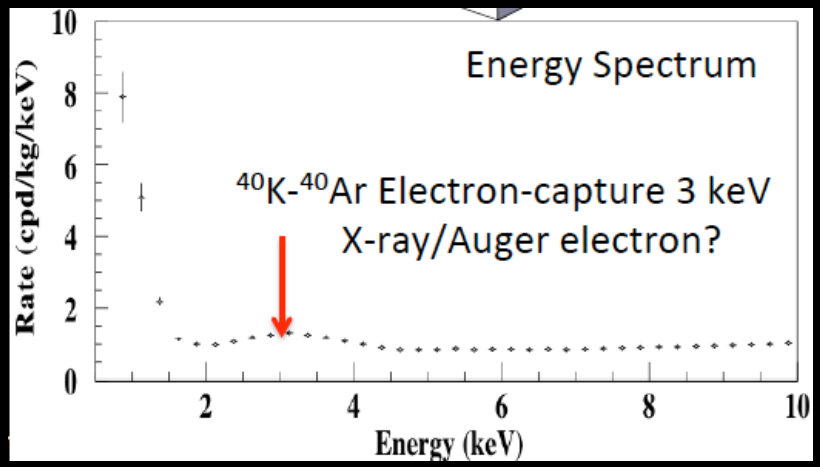
(Sodium iodide with Active Background REjection)

- DAMA/LIBRA signal conflicts with LUX and other experiments. Is this systematic effect or something new?
  - An independent check with NaI(Tl) detector is lacking.
- SABRE will address this need with a new NaI(Tl) detector with better control of backgrounds.
  - Liquid scintillator veto to reject internal ^{40}K and other radiogenic and cosmogenic backgrounds.
  - NaI(Tl) crystals based on higher radio- purity NaI powder.
  - New photo-detectors with lower background.
  - Low-background electroformed Cu enclosure.

Decay Scheme of ^{40}K

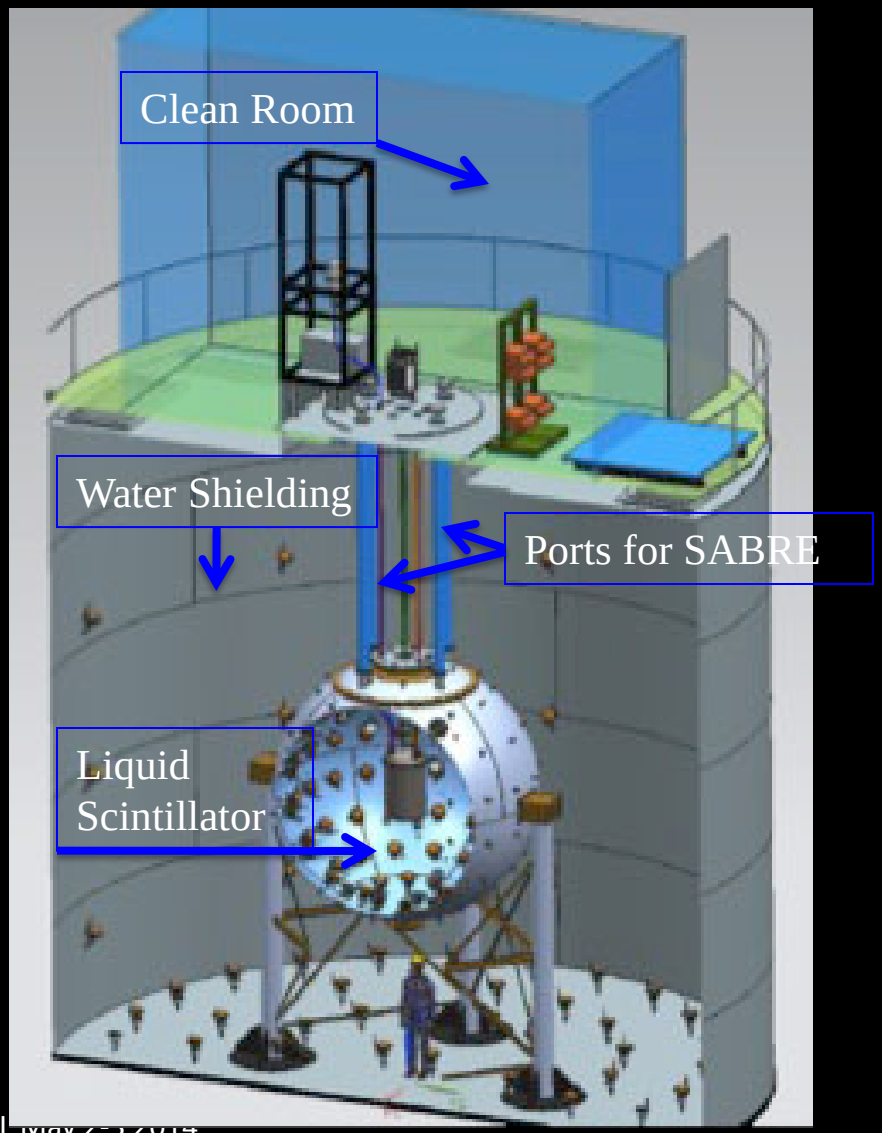


EC decay produces 1.46 MeV γ and hole in ^{40}Ar K-shell, which then fills giving 3 keV X-ray/Auger electron.



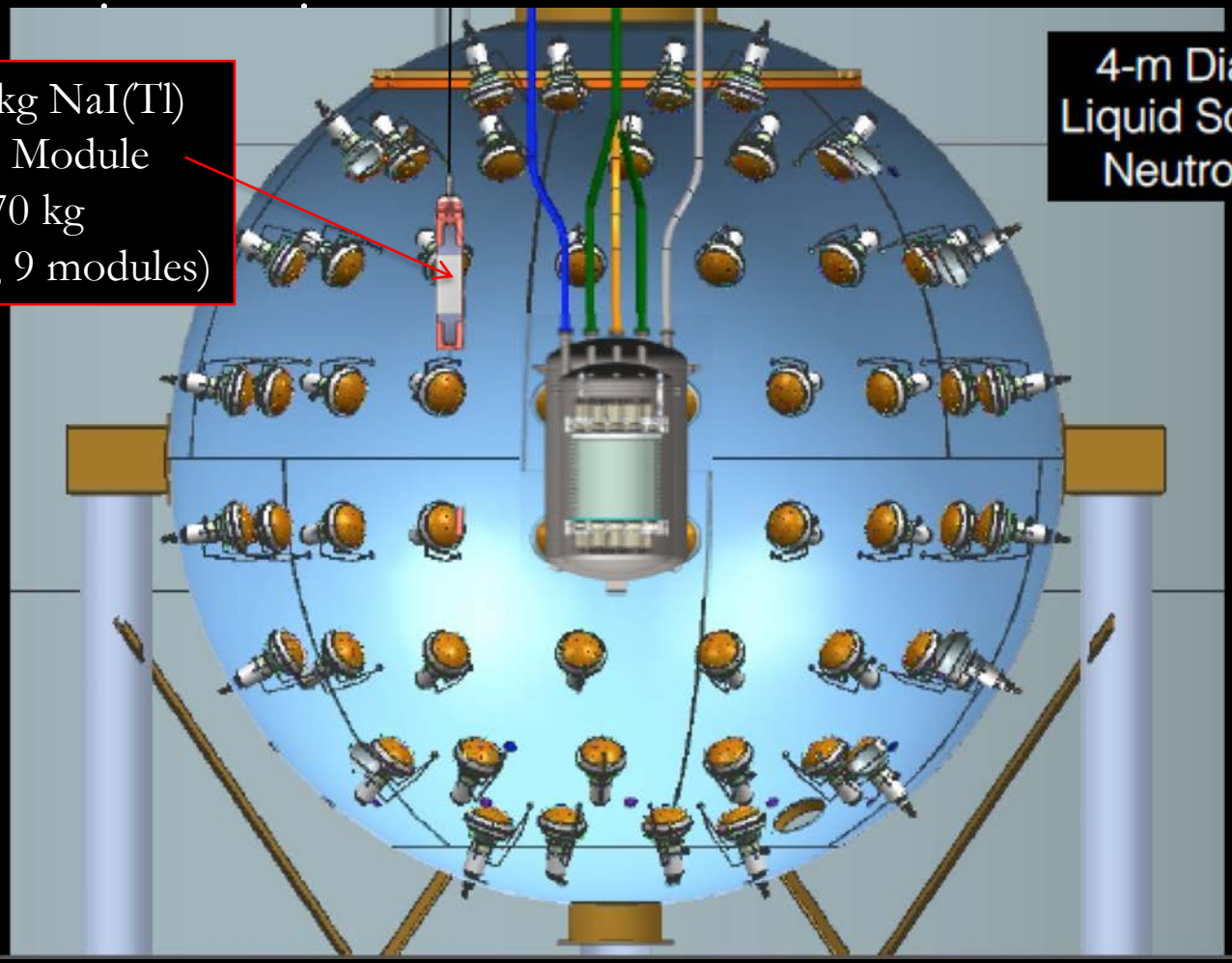
DarkSide Liquid Scintillator Neutron Veto

- Darkside L.S. Veto is Operating.
- 4-m diameter Liq. Scinillator
- Shielded by >3-4 m of water
- There are four 6-inch ID ports for inserting detectors, or calbration sources.
- The plan is to insert NaI(Tl) detector modules inside the scintillator.
- First step, is 1-kg modules for radio-purity tests st 2014.
- Using 3 ports we can accommodate 70 kg of SABRE modules.

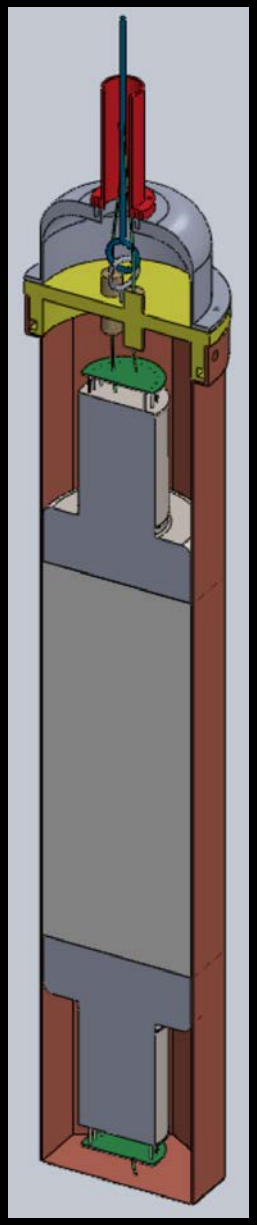


DarkSide Liquid Scintillator Neutron Veto

Initially to test NaI(Tl) radiactivity: Later for 70-kg SABRE?



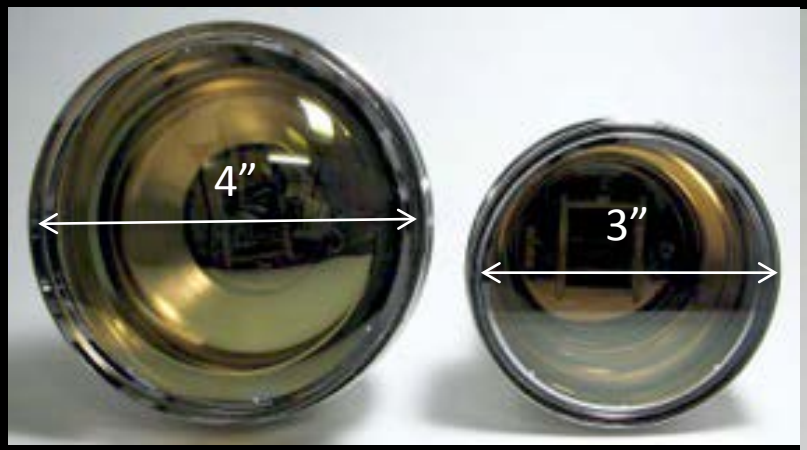
NaI(Tl) Detector Module



- Hamamatsu R11065-series Low Radioactivity PMT
  - ~30-35% Q.E.
  - ~1 mBq U and Th (lower chain activity)
  - ~1 mBq Co, ~10 mBq K
- New 4-inch Hamamatsu PMT available soon.
  - Lower background with synthetic ceramic feedthrough plate.
- Negligible background due to low radioactivity & veto.
  - High light collection efficiency without light guide used in DL.
- LNGS pre-amp (A. Razeto) to reduce PMT dark rate.
  - Feasibility of lower threshold energy in test phase. (< 1 keV).
- PNNL electroformed copper for enclosure
  - U, Th radioactivity: ~μBq/kg
  - Same as used in the Majorana $0\nu\beta\beta$ decay experiment

Large Low-background PMT R&D

Hamamatsu 4” Version of 3” R110065 Metal Bulb Series



Light yield of large NaI crystals
to be used in Darkside and SABRE
will increase
with larger PMTs matched to crystals.

A 4” version of the low background R11065 PMT is well matched to crystals and is in development.

Development of NaI Powder

Element	Seastar-MV Lab (ppb)	Sigma-Aldrich (ppb)	DAMA Powder (ppb)	DAMA Crystal (ppb)
[K]	12	3.5 (18)*	100	~13
[Rb]	14	0.2	n.a.	<0.35
[U]	<0.2 (0.003.5)**	<1.7 (<0.001)**	~0.020	0.0005-0.0075
[Th]	<0.1 (<0.001)**	<0.5 (<0.001)**	~0.020	0.0007-0.010

Chemical purification research started 2004 at Princeton in collaboration with commercial companies.
J. Benziger, F. Calaprice, A. Wright

Notes:
All values provided by companies are based on their measurements.
Seastar- MV Lab values by ICPMS were validated by gamma ray counting at [K] ~35 ppb.
DAMA/LIBRA valaues are published.

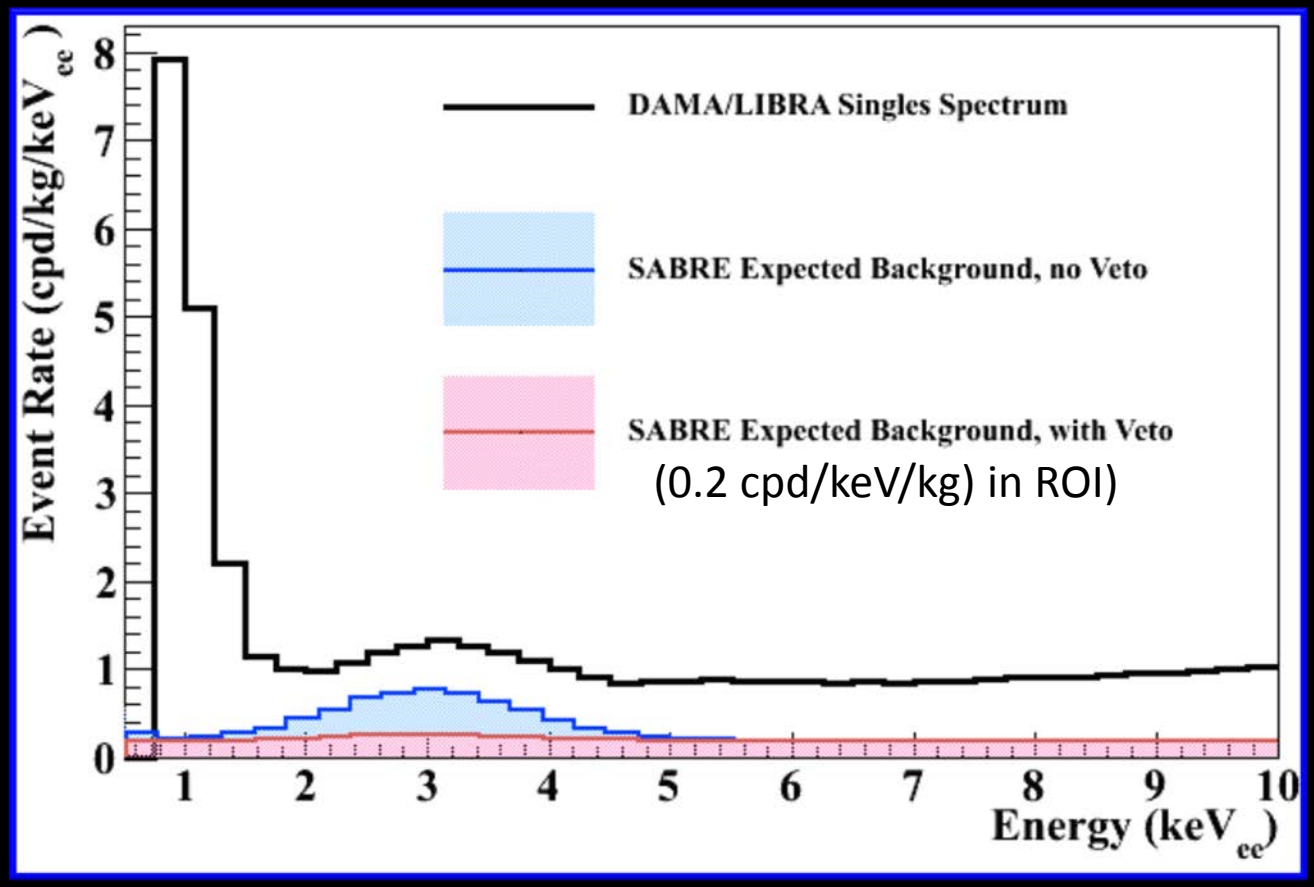
* Denotes measurement by Seastar.
** Denotes measurement at PNNL by E. Hoppe and company.

Development of Crystal Growth

- Crystal growth at Radiation Monitoring Devices
  - Vertical Bridgeman
  - Kyropoulos
- Crystal growing tests show [K] reduced by x4.
  - Zone refining also effective.
  - More tests underway to reduce backgrounds.

SABRE Background Simulation

Based on radio-purity of NaI powder

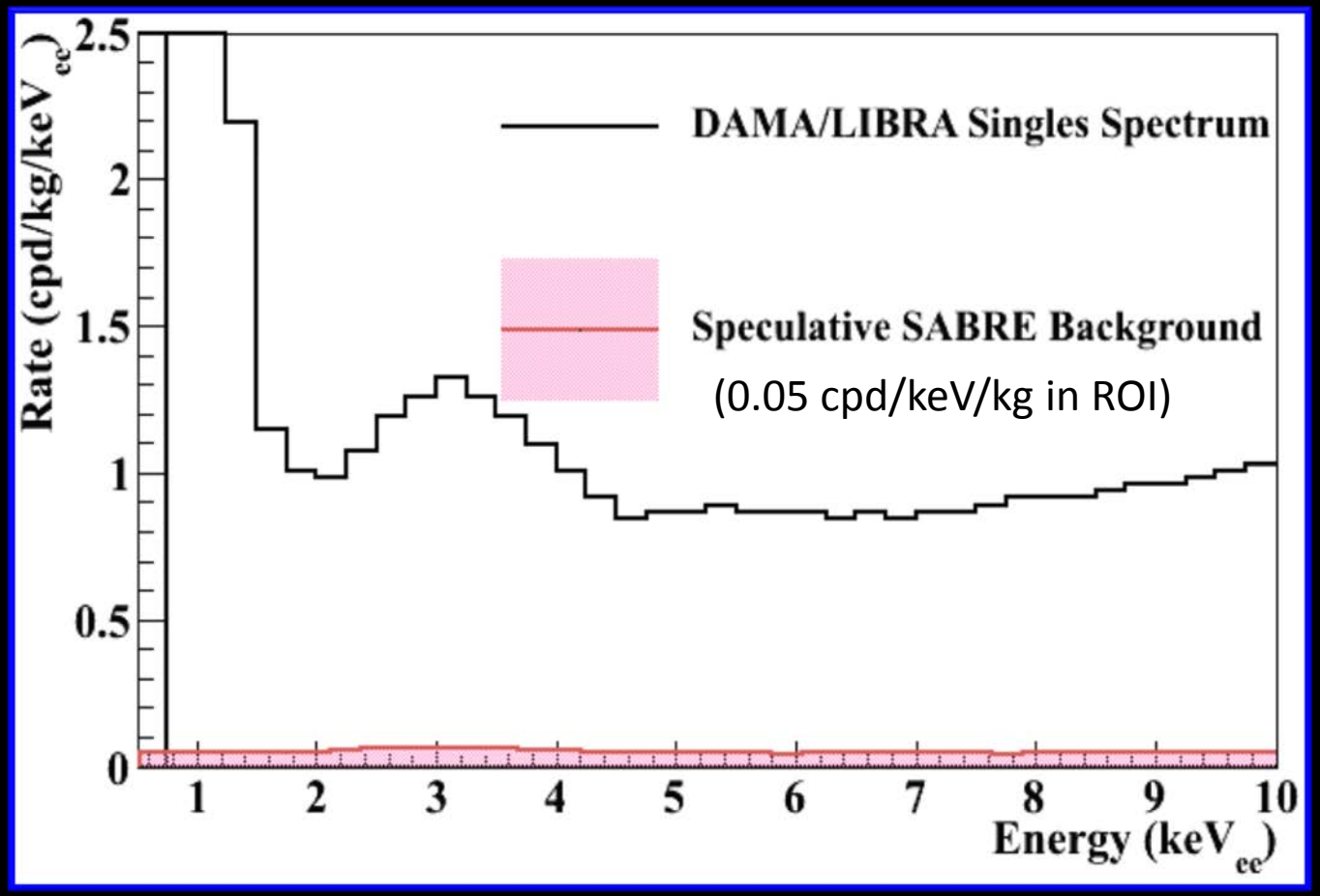


* This spectrum is based on measured radioactivity in NaI powder.

* External background is estimated to be relatively small compared to internal.

Speculative SABRE Background

Based on reduction of U, Th, K, Rb by x4 during crystal growth.



Reduction of [K] by x4 was observed in test of standard NaI.

Summary

- SABRE is developing low-background NaI(Tl) detector modules to check DAMA-LIBRA effect.
- Good progress has been made.
- Production of NaI crystals is underway.
- Confirmation of low background NaI(Tl) modules by direct counting in Darkside veto, late 2014.

Dave Nygren on DAMA/LIBRA

Feb 4 2011

A testable conventional hypothesis for the DAMA-LIBRA annual modulation

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email: *drnygren@lbl.gov*

Abstract: The annual modulation signal observed by the DAMA-LIBRA Collaboration may plausibly be explained as a consequence of energy deposited in the NaI(Tl) crystals by cosmic ray muons penetrating the detector. Delayed pulses in the approximate energy range of interest have been observed as a sequel to energy deposited by UV irradiation. The same behavior may be reasonably expected to occur for energy deposited by any source of ionization or excitation. D-L can test this hypothesis by searching in current data for time correlations between muon events and pulses in the modulation energy range, or by renewed operation of the array at a sufficiently low temperature that freezes out the phenomenon.

assumptions about WIMP winds. The annual modulation signal observed by D-L is the result of a carefully executed ultra-low background experiment and is not generally challenged. Subsequent data taken in 2009 with detector updates is consistent with [1], and

Happy Retirement Dave!

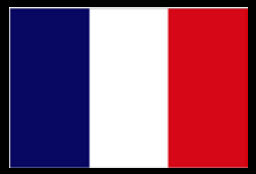
Thanks for sharing some fascinating ideas during my short sabbatical stay here.

May you enjoy many more years of half-baked ideas.

Spares

The DarkSide Collaboration

IHEP



APC, Université Paris Diderot

IPHC, Université de Strasbourg

INFN LNGS

Università degli Studi Genova

Università degli Studi Milano

Università degli Studi Federico II Napoli

Università degli Studi Perugia

Università degli Studi Roma Tre

Jagiellonian University

KINR, NAS Ukraine

Joint Institute for Nuclear Research – Dubna

Lomonosov Moscow State University

Kurchatov Institute – Moscow

Saint Petersburg Nuclear Physics Institute

Augustana Black Hills State Fermilab

Princeton SLAC Temple University

University of Arkansas UCLA University of Chicago

University of Hawaii University of Houston

University of Massachusetts Virginia Tech

SABRE Collaboration
(growing)

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E. Shields, S. Westerdale, A. Nelson

University of Houston:

E. Hungerford, S. Davini, G. Korga

LNGS:

Aldo Ianni, Alessandro Razeto

Milan:

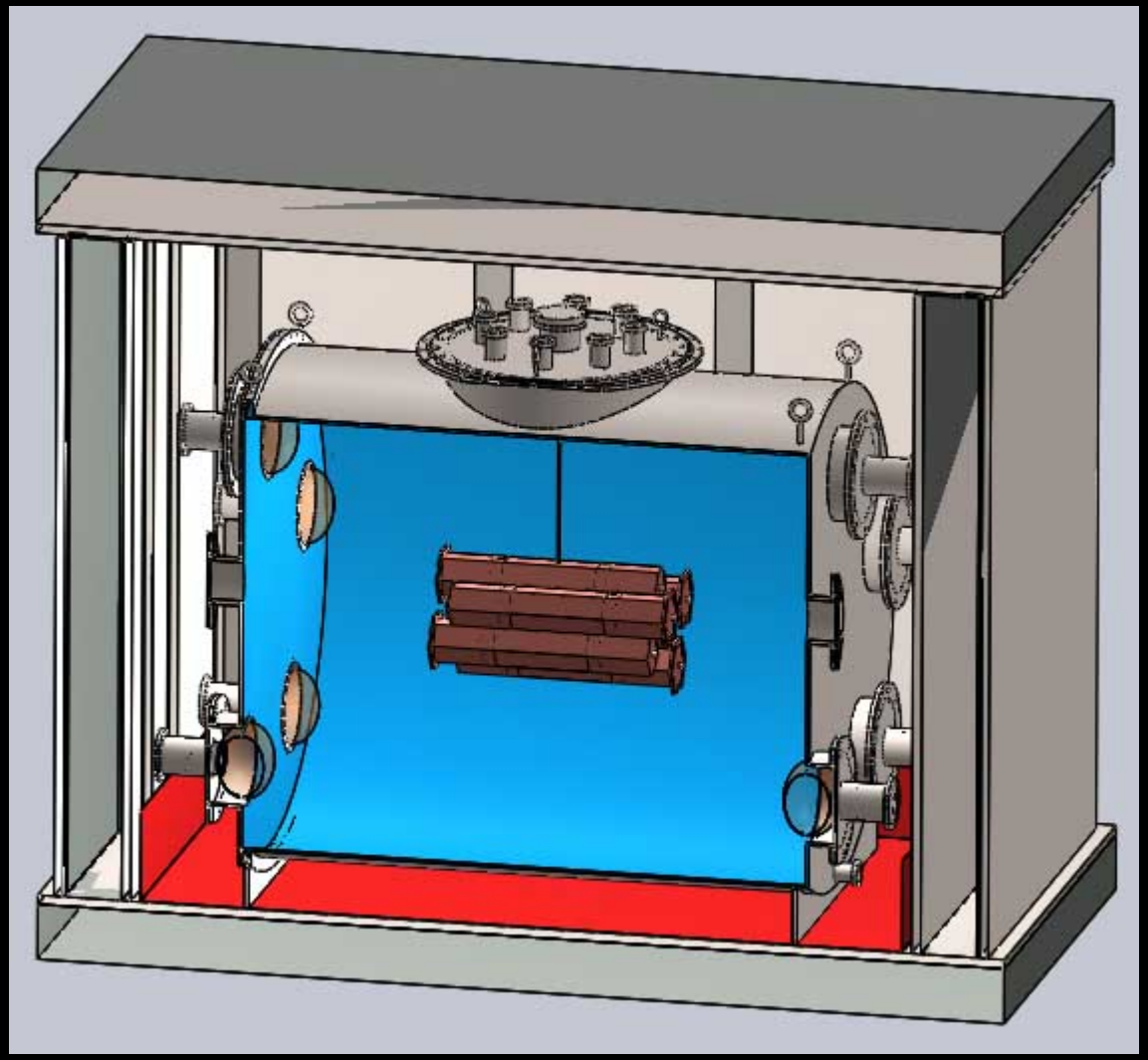
Davide D'Angelo

PNNL:

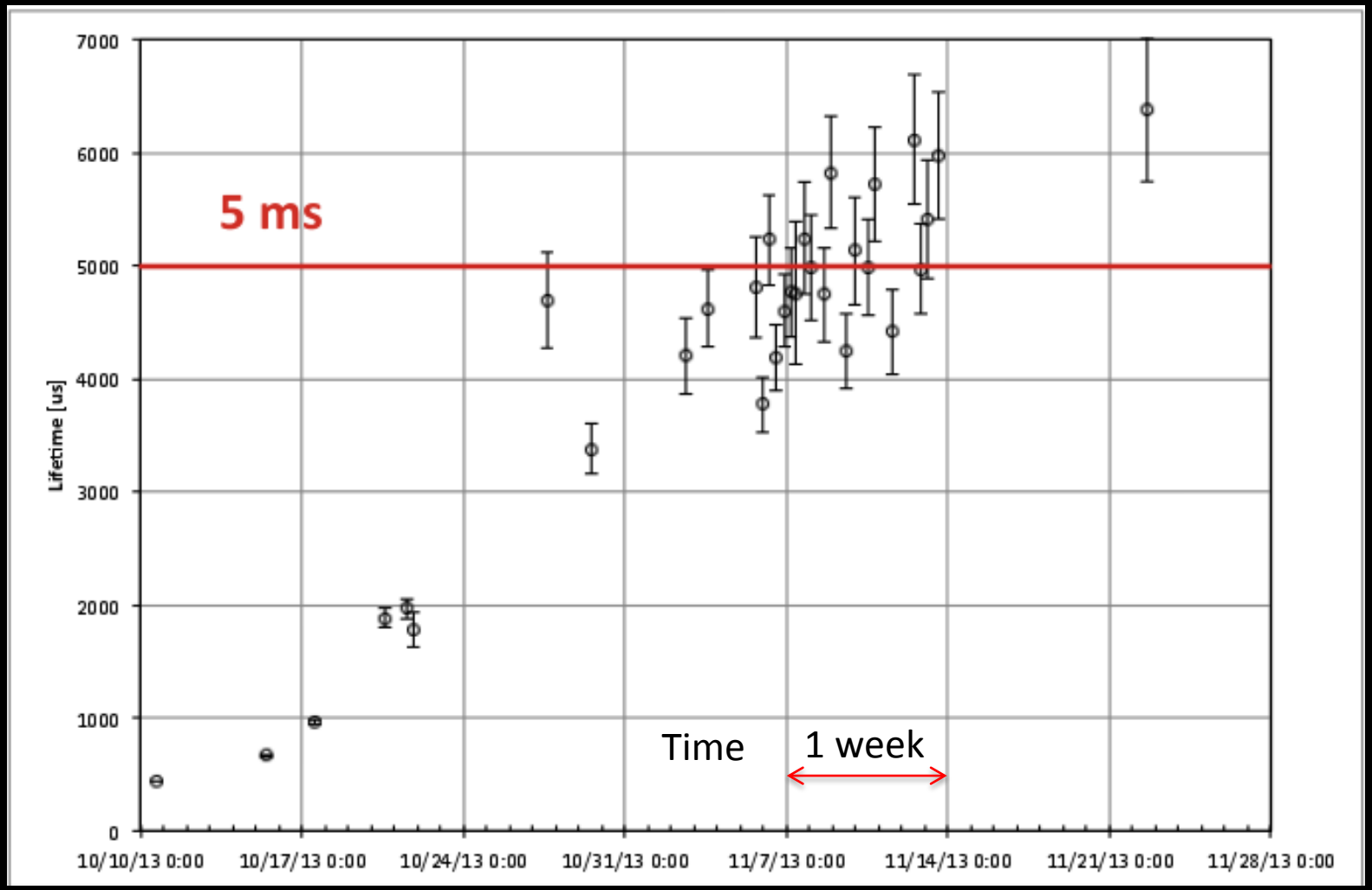
E. Hoppe, J. Orrell, C. Overman

SABRE Veto Detector for 50-60 kg NaI(Tl)

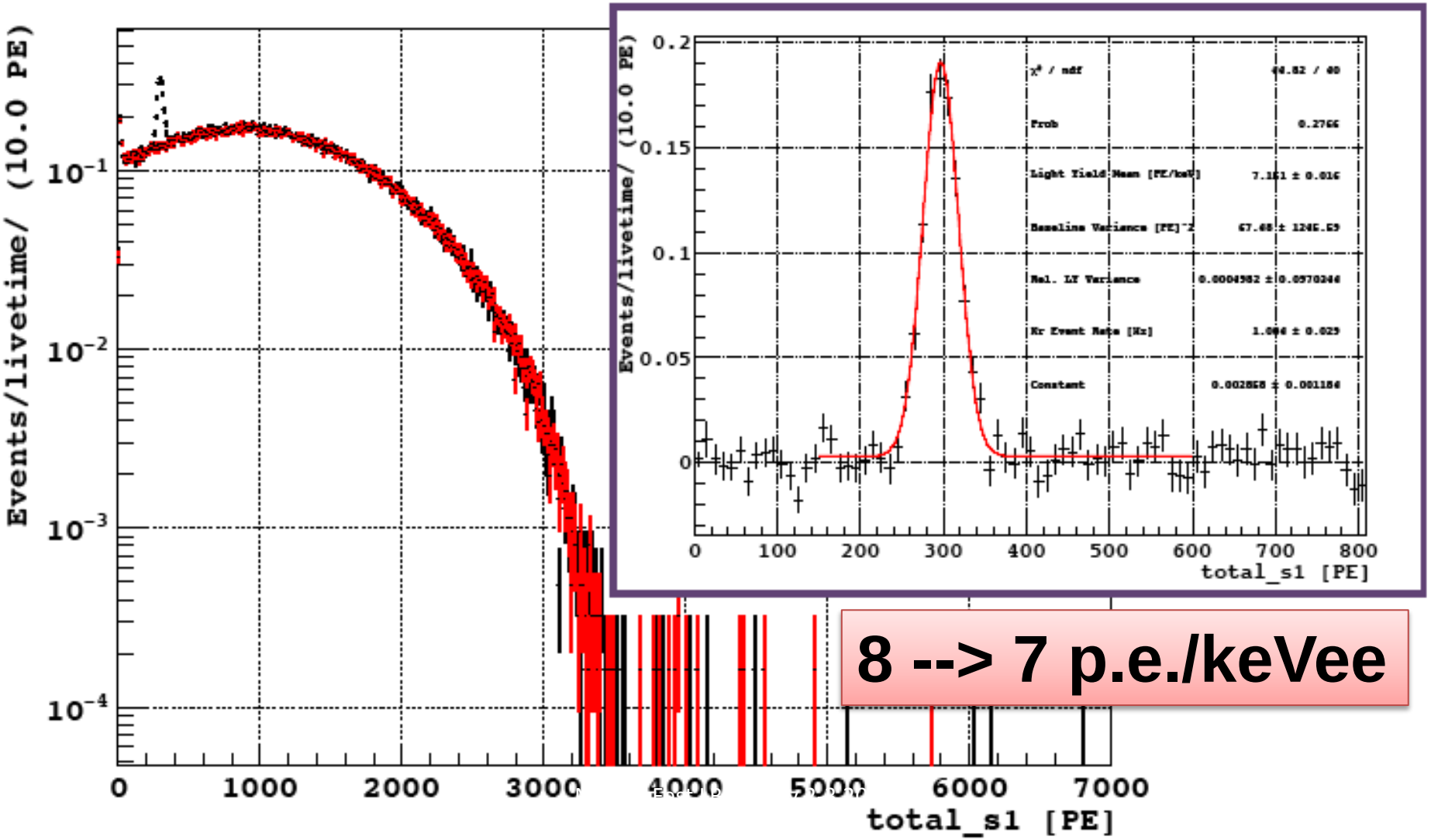
- Sufficient NaI(Tl) mass
  - Bkgnd < 0.4 cpd/kg/keV
- Cylinder: 1.5 m x 1.5 m
- LAB scintillator: 2 tons
- PMTs: Ten 8-inch Ham.
- Reflector: Lumirror
- L.Y.: 0.22 p.e./keV
- Shielding: 25cm steel.
  - Small footprint.
- Portable: LNGS, SNOLab, Australia?
- Funded by NSF.
  - In construction.



e^- lifetime


7000
6000
5000
4000
3000
2000
1000
0
Lifetime [us]
5 ms
Time
1 week
10/10/13 0:00
10/17/13 0:00
10/24/13 0:00
10/31/13 0:00
11/7/13 0:00
11/14/13 0:00
11/21/13 0:00
11/28/13 0:00

Light Yield @ 200V/cm



8 --> 7 p.e./keVee