Large-Scale WbLS Detector R&D

Applied Antineutrino Physics Workshop
11th October, 2018

Gabriel D. Orebi Gann
UC Berkeley & LBNL

THEIA

Overview

- Theia detector concept
- Physics program
- Development of detector capabilities

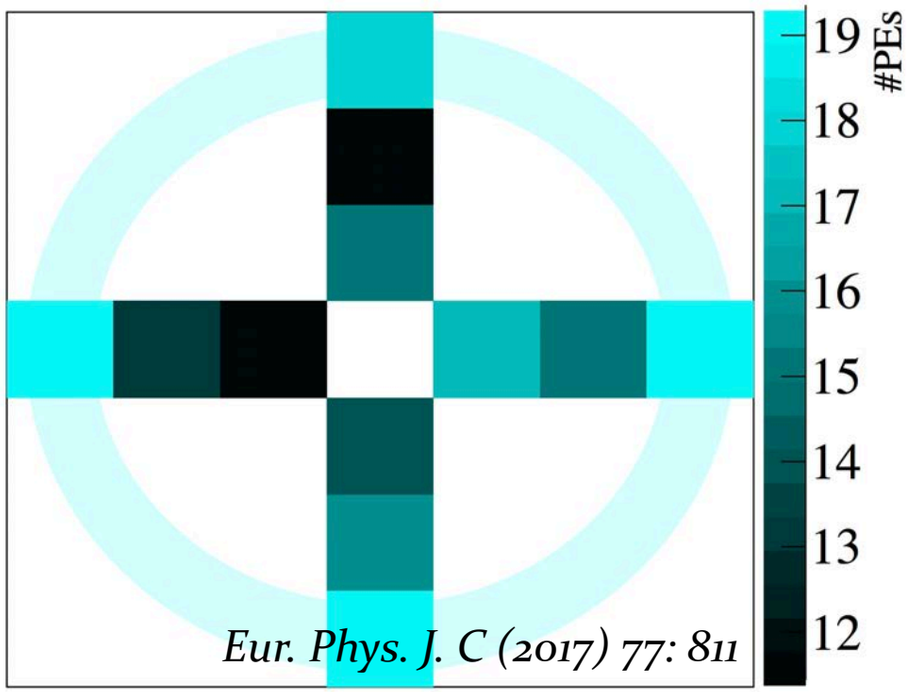
Theia Detector Concept

Cherenkov / Scintillation Separation

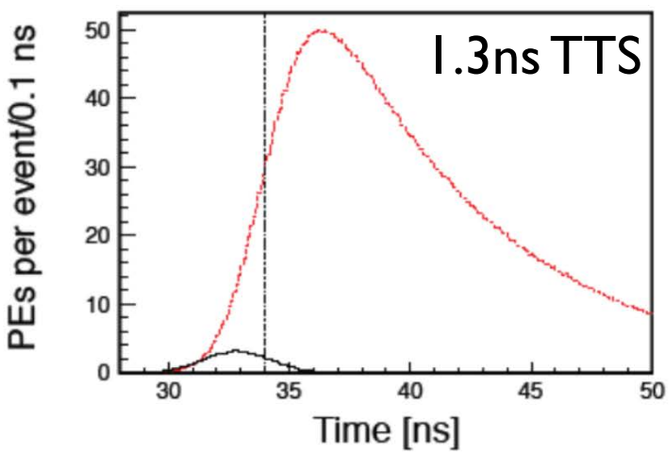
Separation in charge, time, wavelength

Methods to enhance separation:

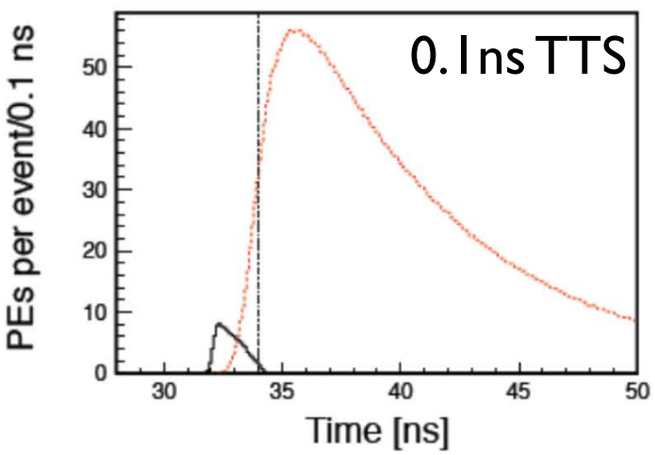
- Ultra-fast photon detection (LAPPDs)
- Delay scintillation light
- Optimize cocktail: scintillation fraction & spectrum (fluor)
- Readout sensitivity



Cherenkov ring observed as photon excess on top of isotropic scintillation "background"

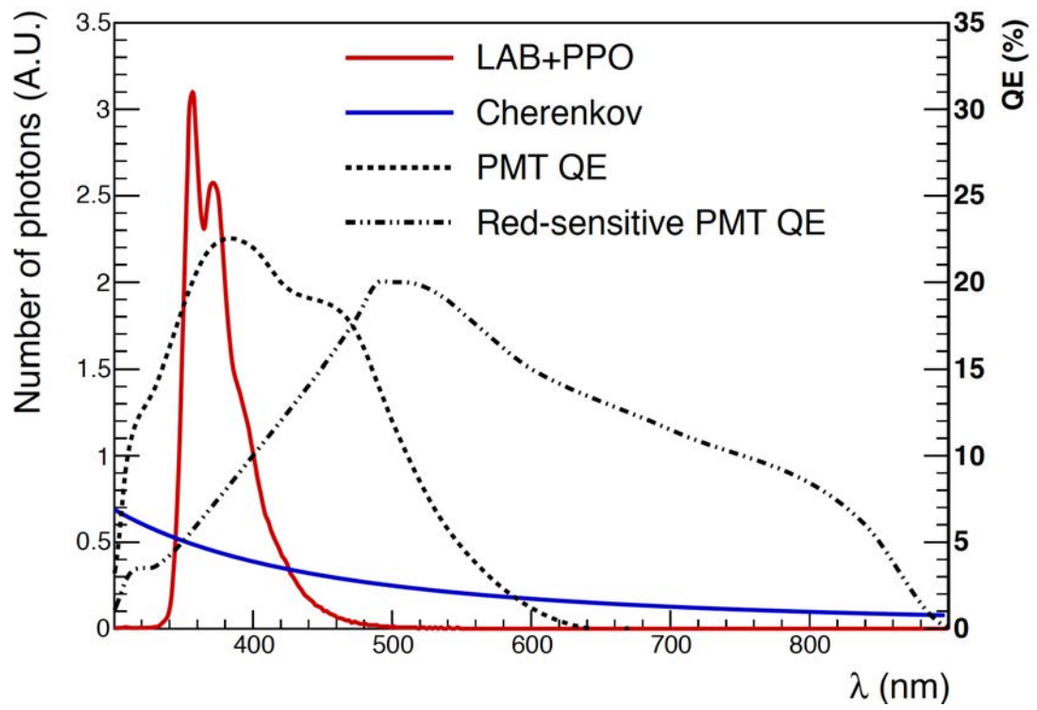


C. Aberle et al, JINST 9 P06012 (2014)



Cherenkov (prompt, scarce)

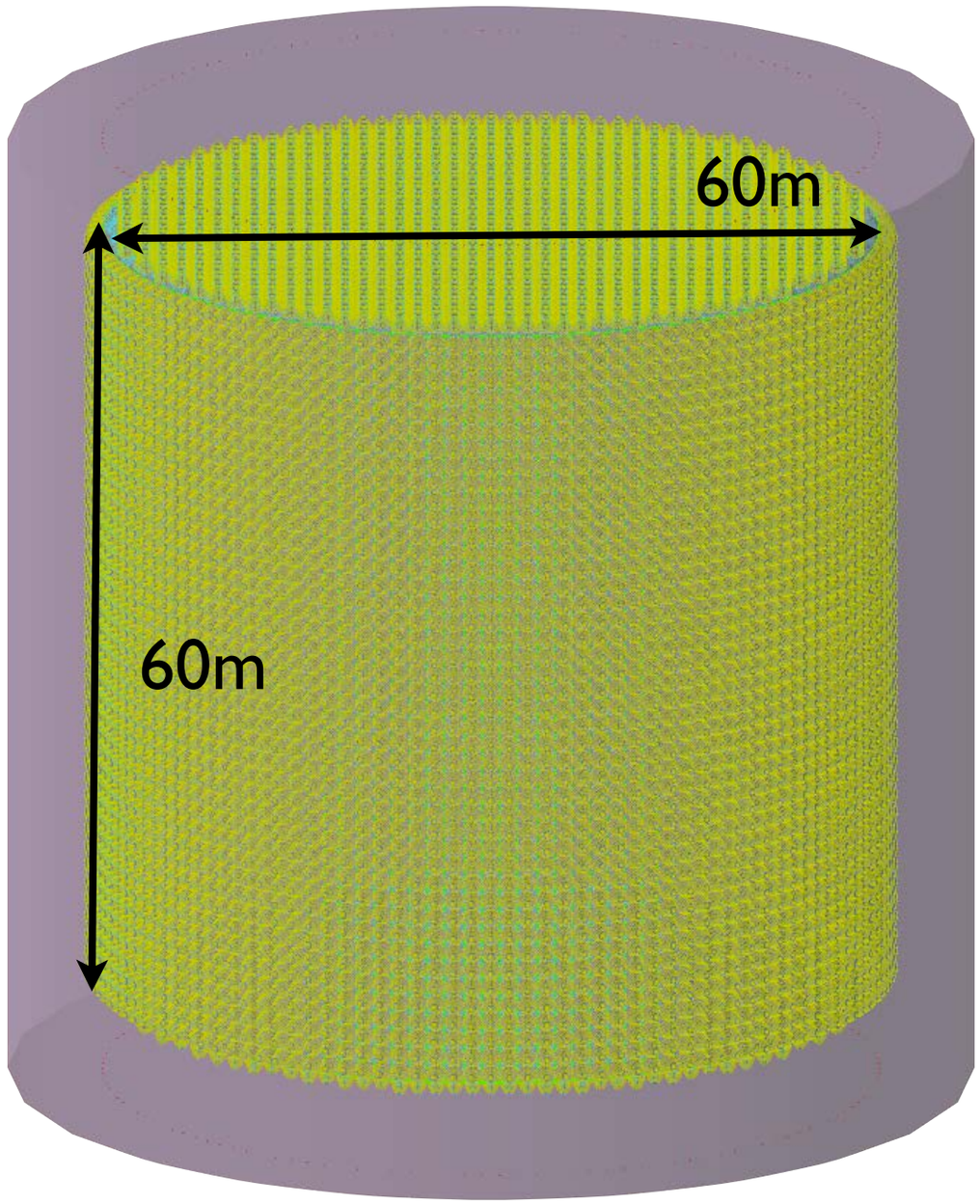
Scintillation (delayed, abundant)



Theia

- Large-scale detector (50-100 kton)
- Water-based LS target
- Fast, high-efficiency photon detection with high coverage
- Deep underground (e.g. Homestake)
- Isotope loading (Gd, Te, Li…)
- ***Flexible***! Target, loading, configuration

➡ **Broad physics program!**



Concept paper - arXiv:1409.5864

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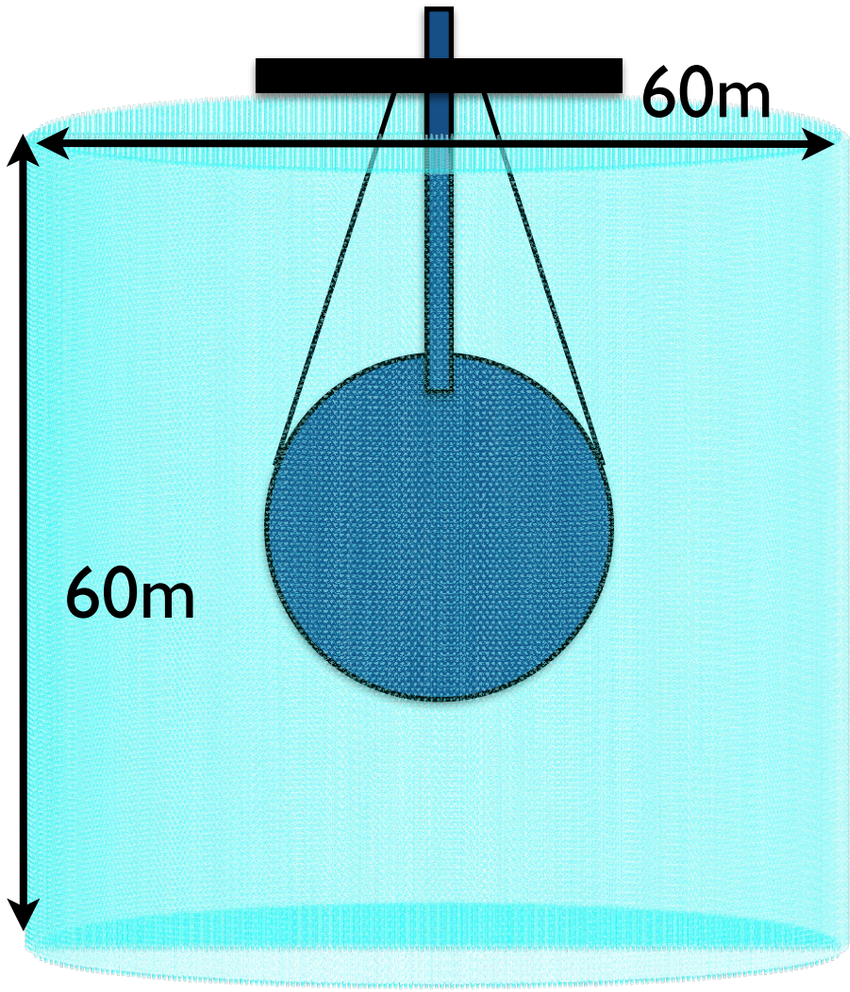

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Theia Physics Program

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

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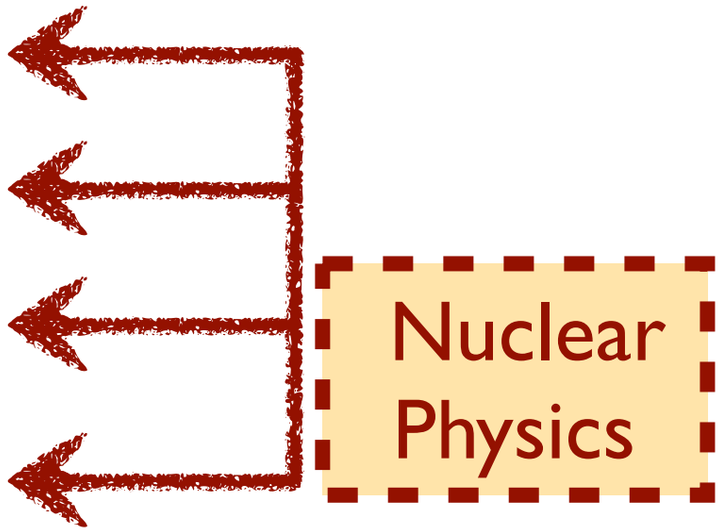

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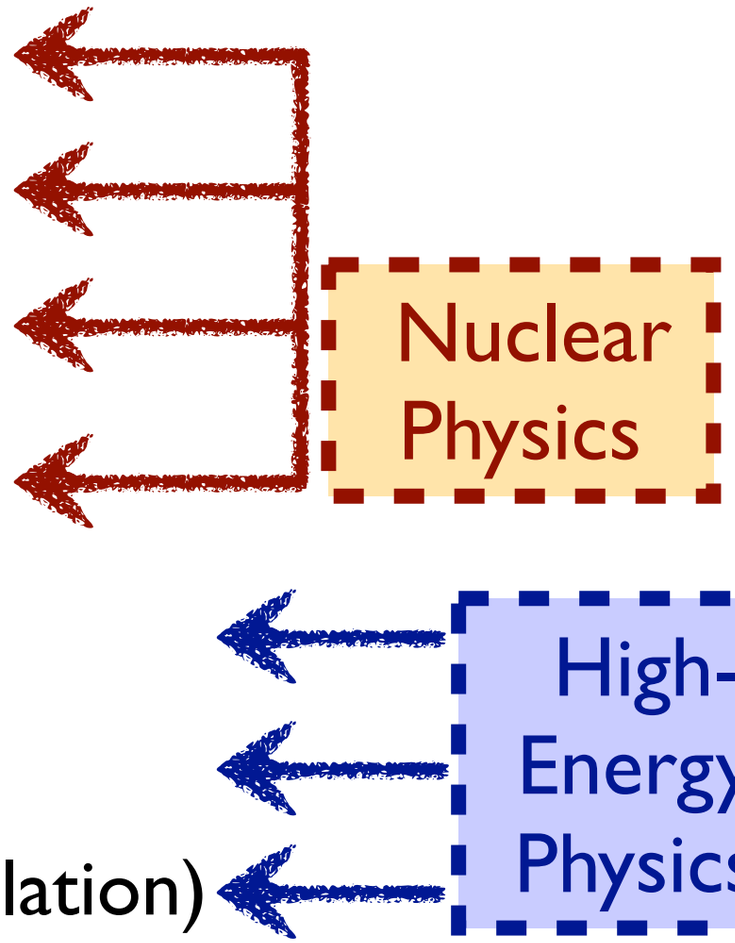

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Physics over 5 orders of magnitude

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

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Leptogenesis

Antineutrino Detection

- Detect via IBD
- High light yield allows enhanced n tag : 2.2 MeV γ from ^{1}H
  - Suppress single-event background that limits water Cherenkov
- Higher detection efficiency than Gd-H_2O due to high scint. yield
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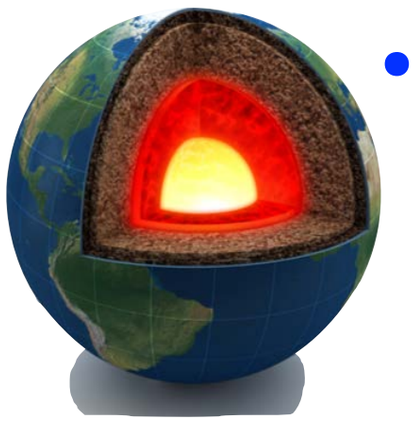

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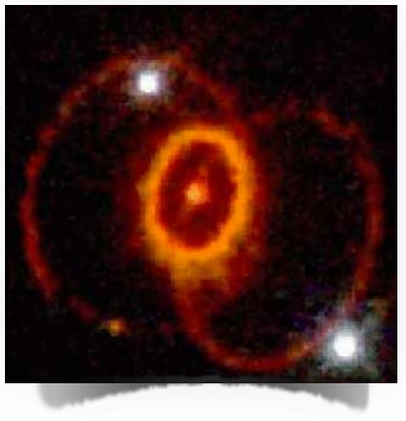

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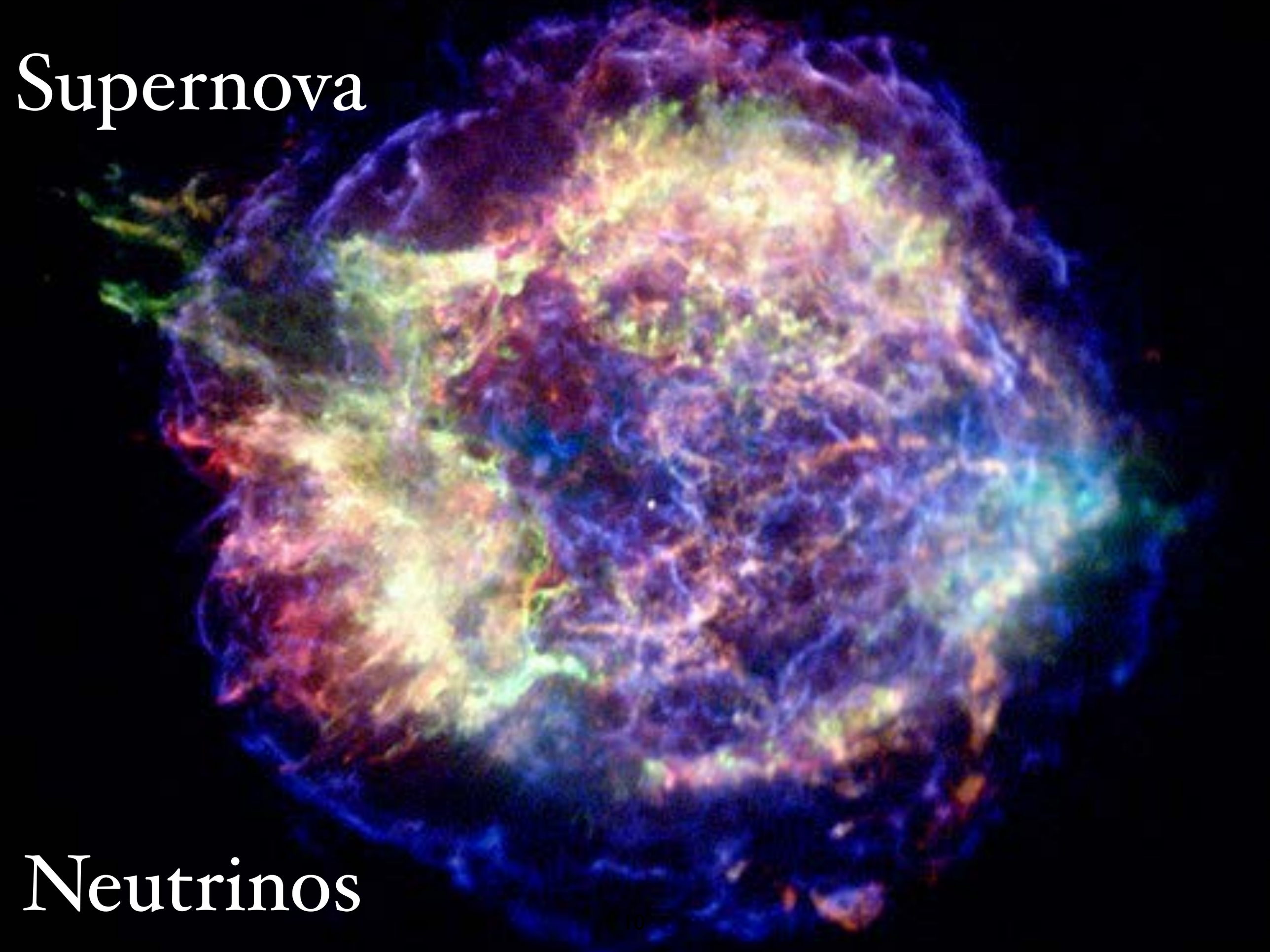
DSNB

- Enhanced n tag
- Reduced NC background
- Most sensitive search to-date
- Plus NaCl for ν signal

Supernova



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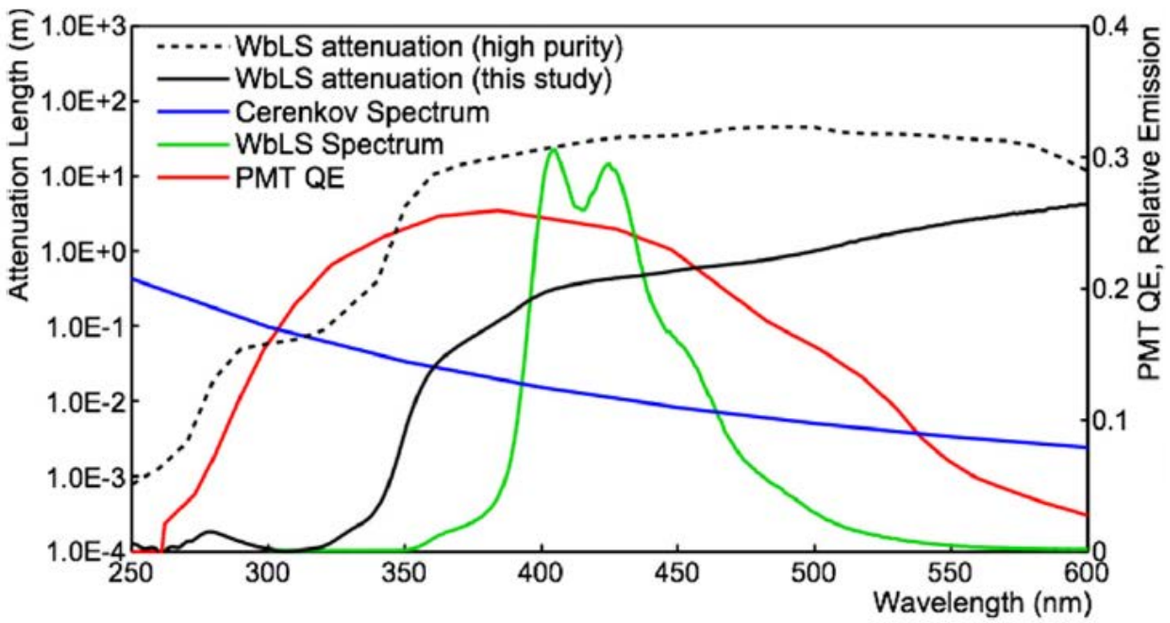
Early warning (PR value)

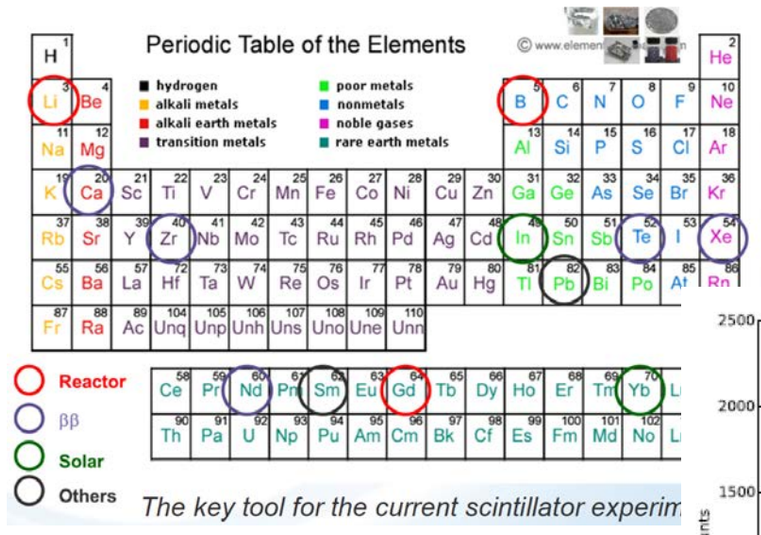
Ongoing R&D

WbLS Development

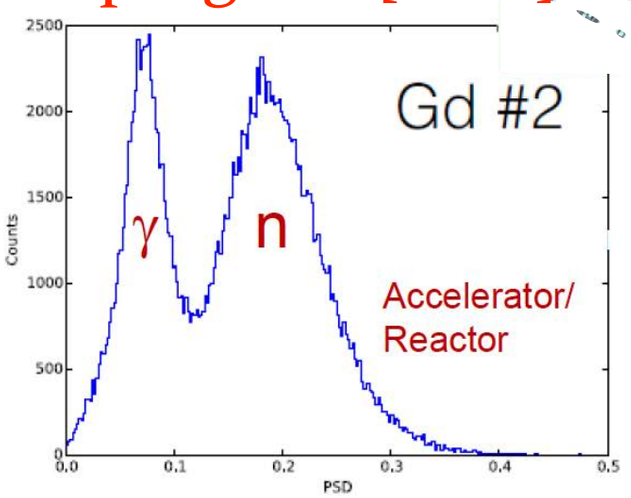
Emission and attenuation [BNL]



Metal loading for broad program [BNL]

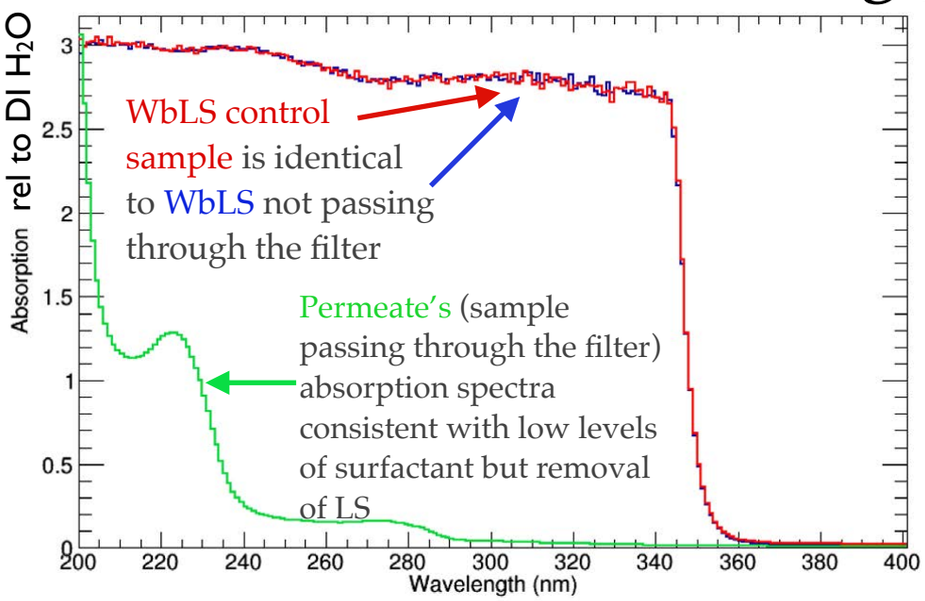


e.g. n/γ separation in Gd-LS



Ton-scale demonstrator & production [BNL]

Nanofiltration & materials testing [UC Davis]



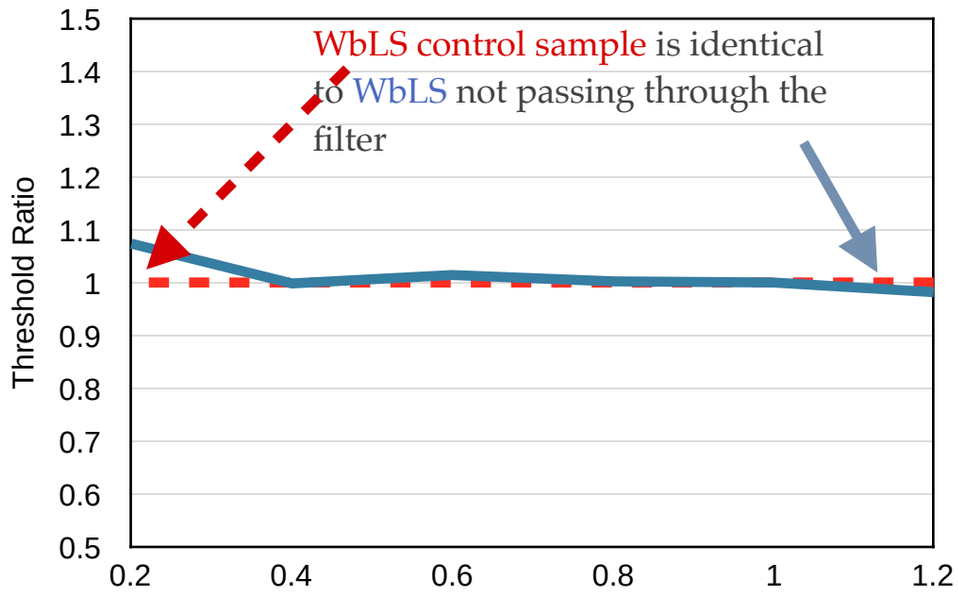
Nanofiltration [UCD]

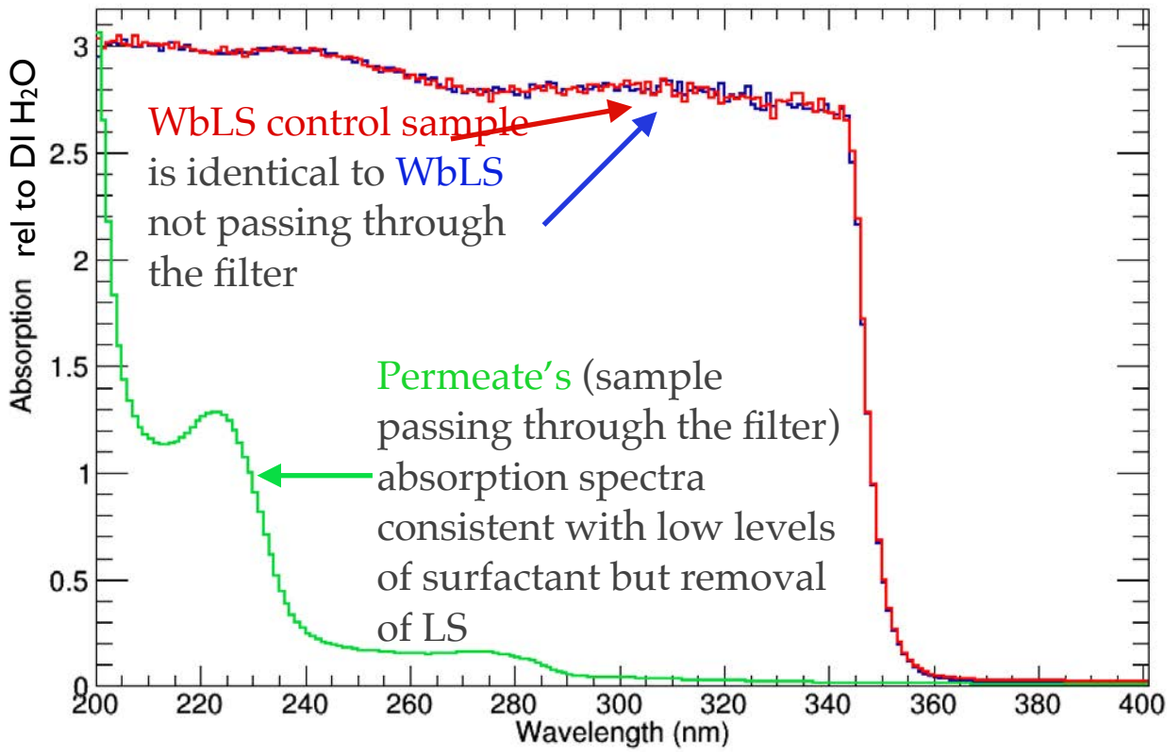
A membrane filtration process

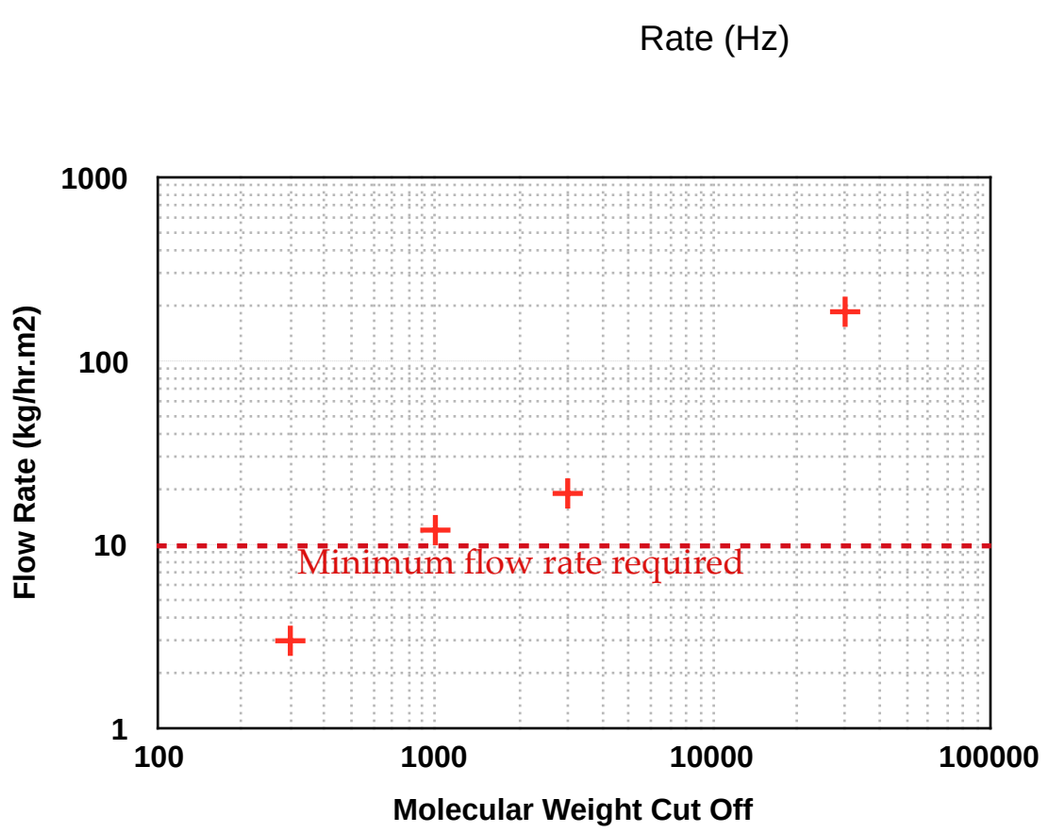
Deionization critical for optical transparency
For WbLS: separate water/LS, filter, recombine

Requirements:

1. Separate water/ions from LS
2. Scalable to large volume (high flow rate)
3. No impact on LS light yield

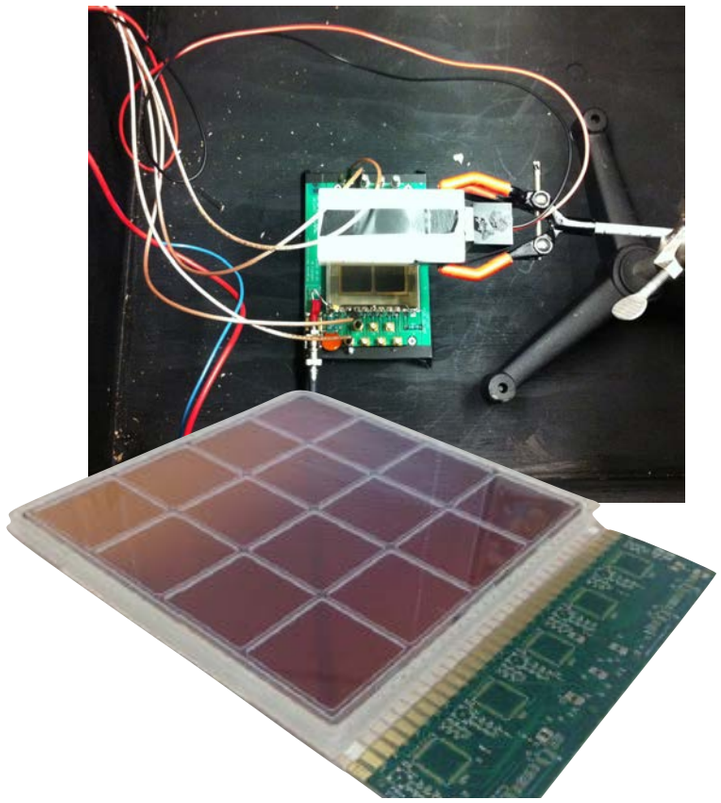




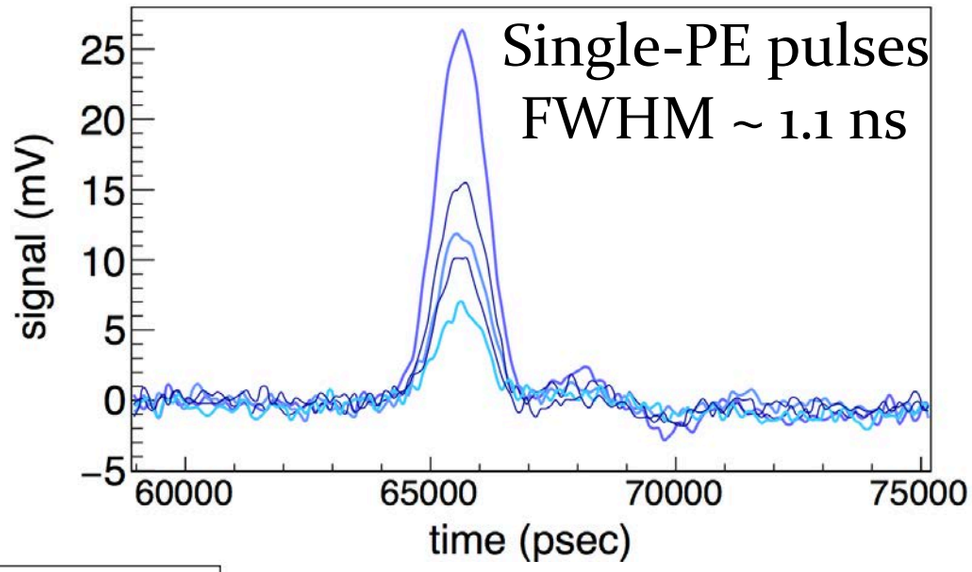


Photon Sensor Development

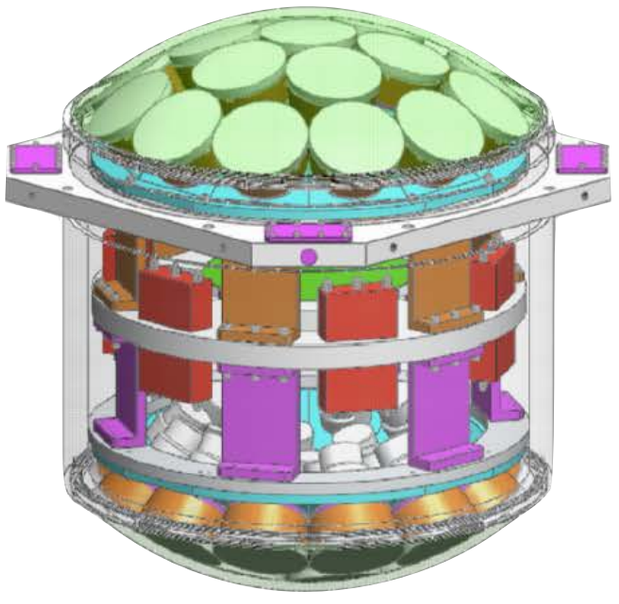
"Standard" PMTs

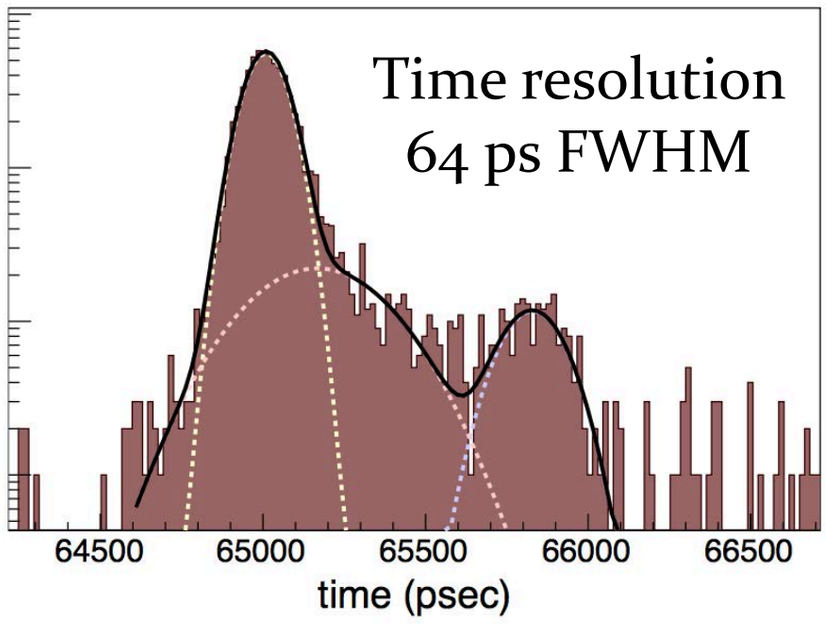


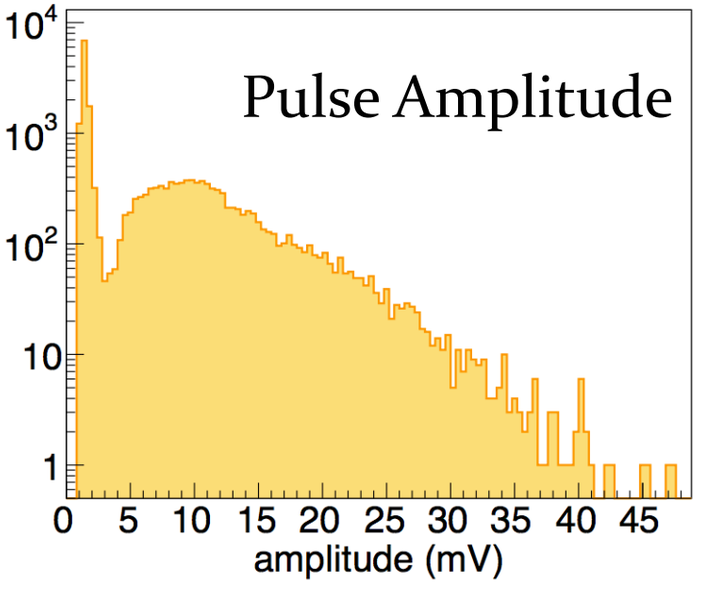
MCP-based photosensors



Modular PMTs







Nucl. Inst. Meth. Phys. Res. A. Volume 814, 19-32, (April 2016); Nucl. Inst. Meth. Phys. Res. A. (Oct. 2016)

CHESS: CHErenkov-Scintillation Separation

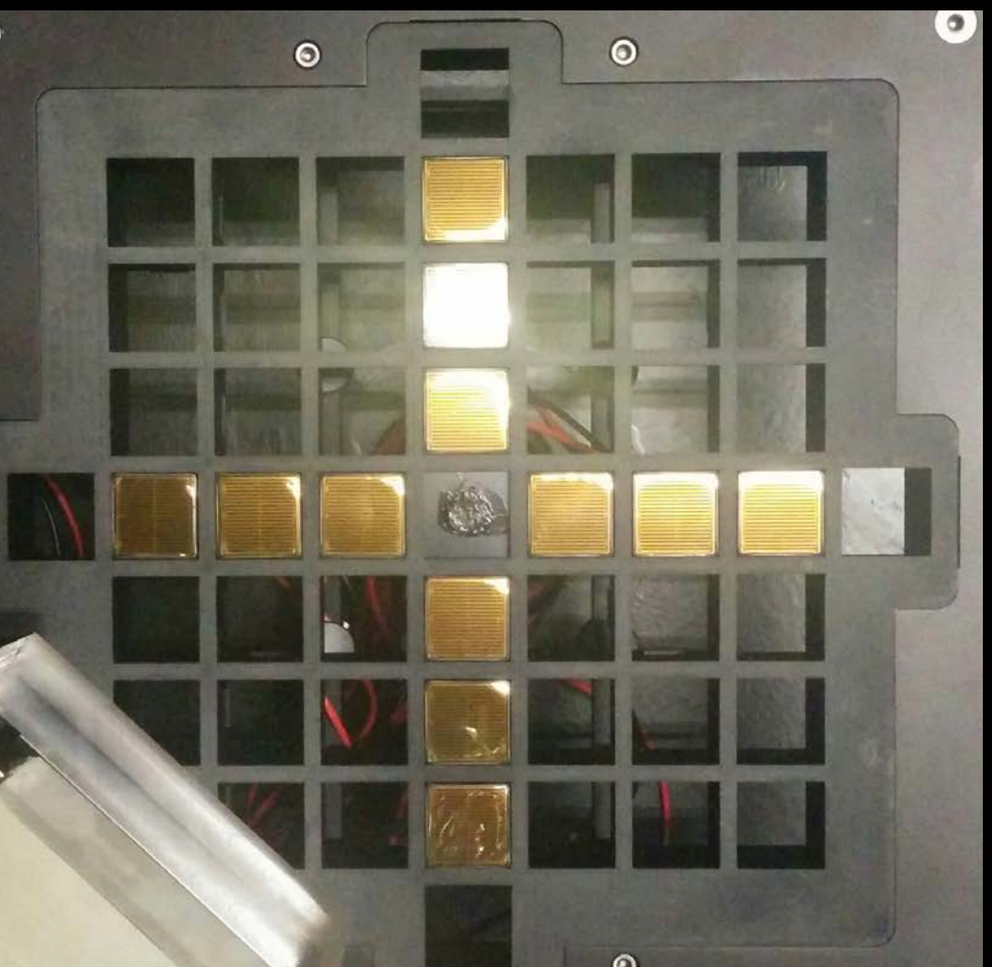
PRC 95 055801 (2017)

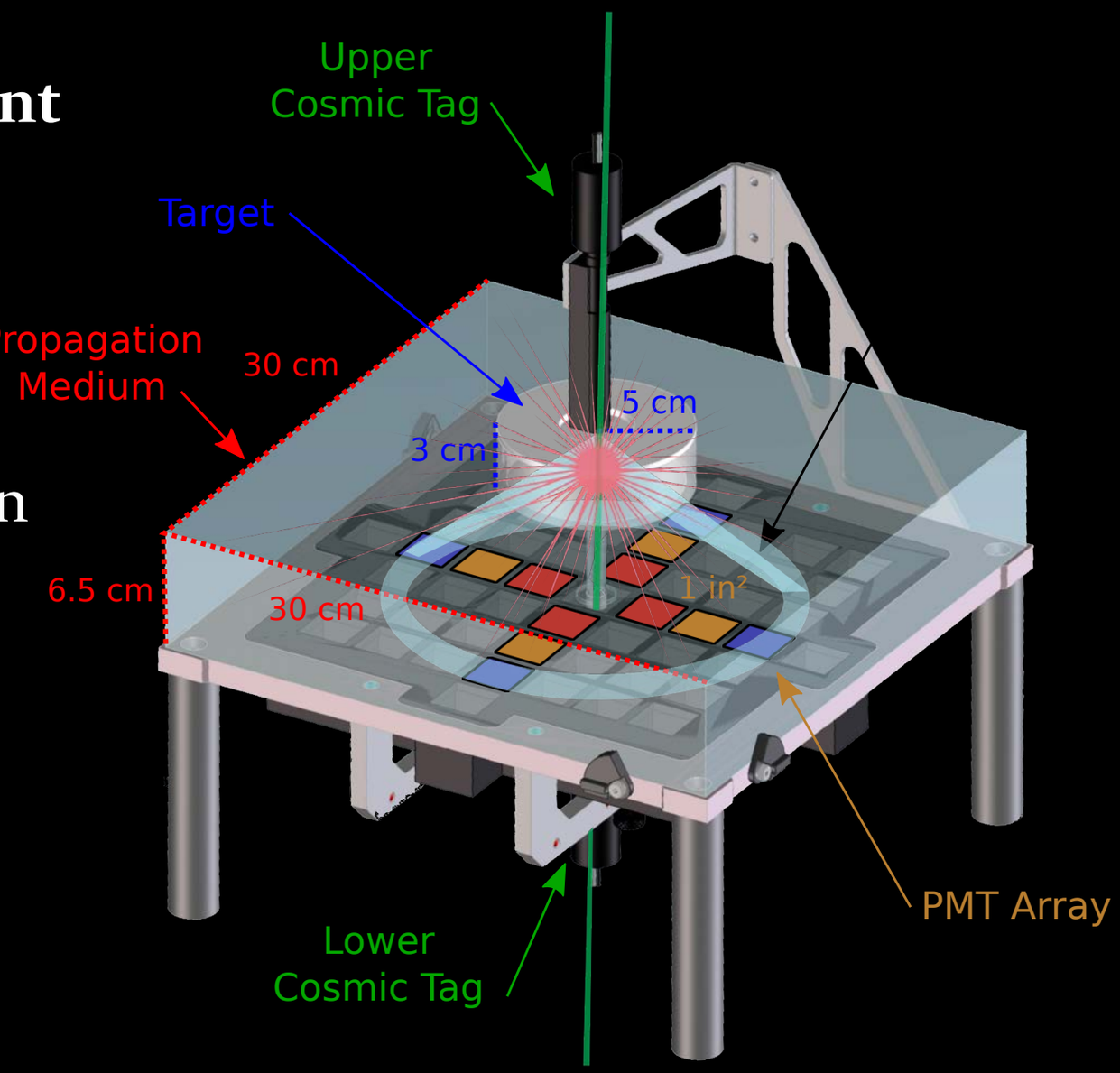
Cosmic muon ring-imaging experiment

Select vertical cosmic muon events

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

Allows charge- and time-based separation





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CAEN V1742 (5GHz)
675 samples (135ns window)
CAEN V1730 (500MHz)

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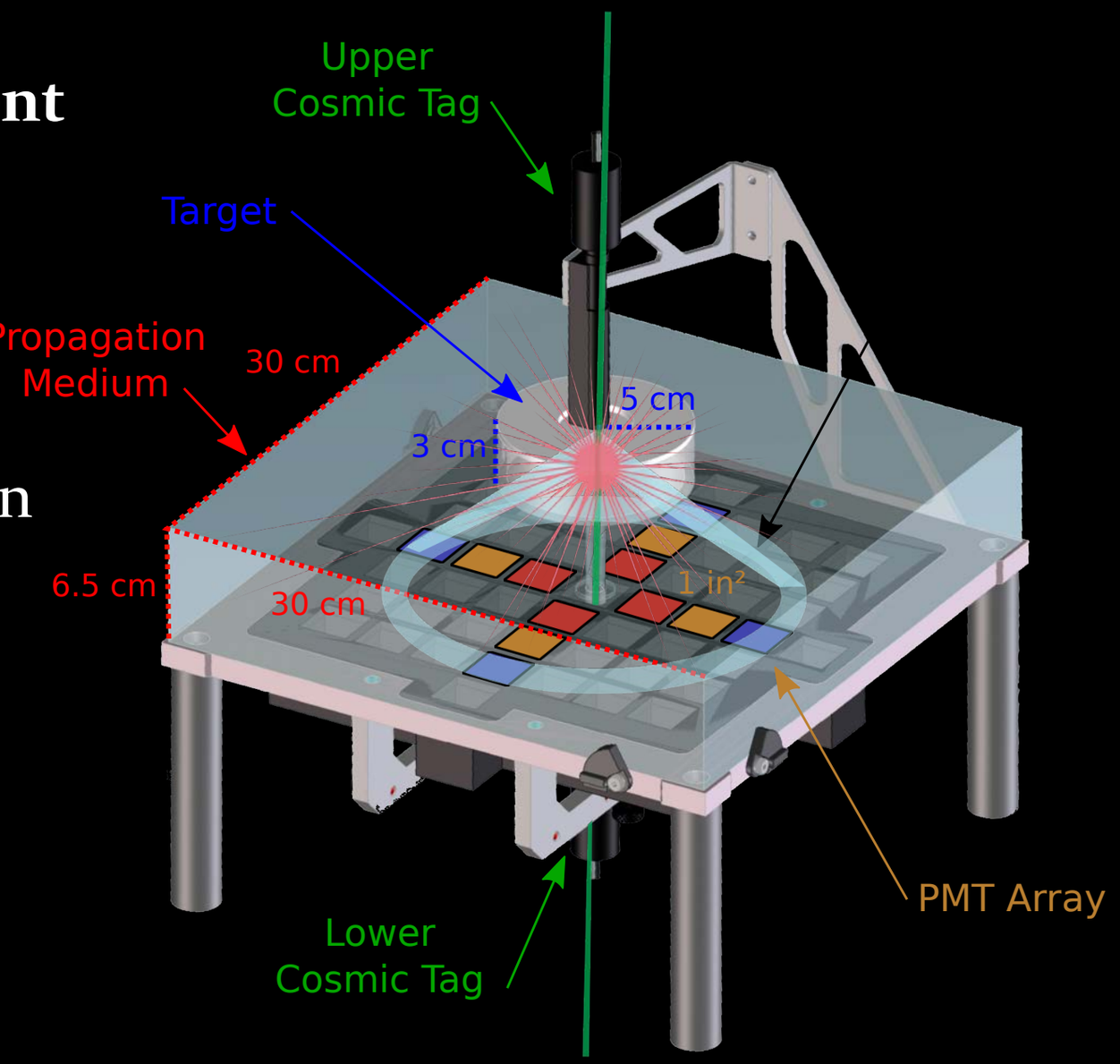

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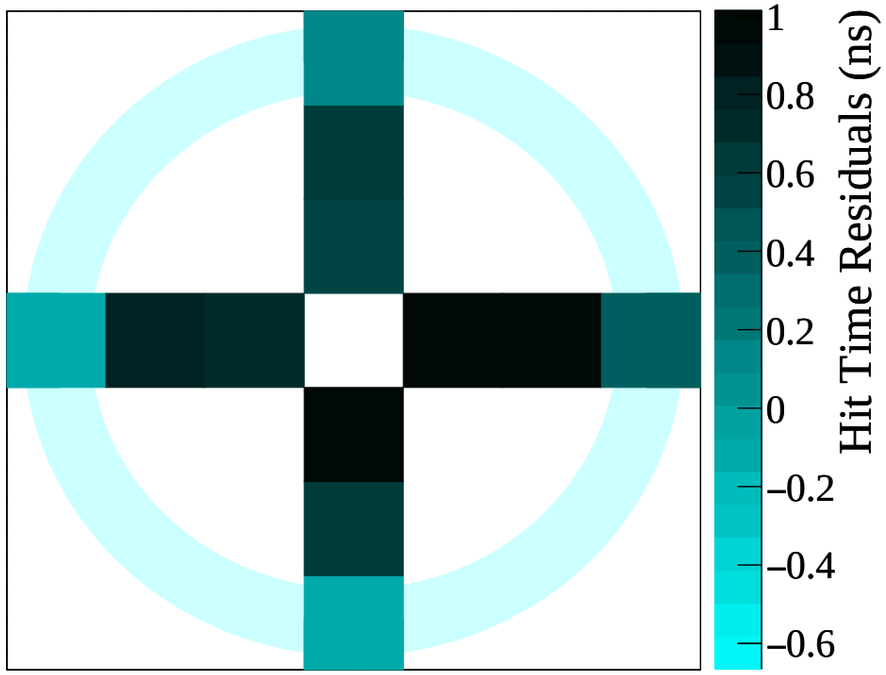
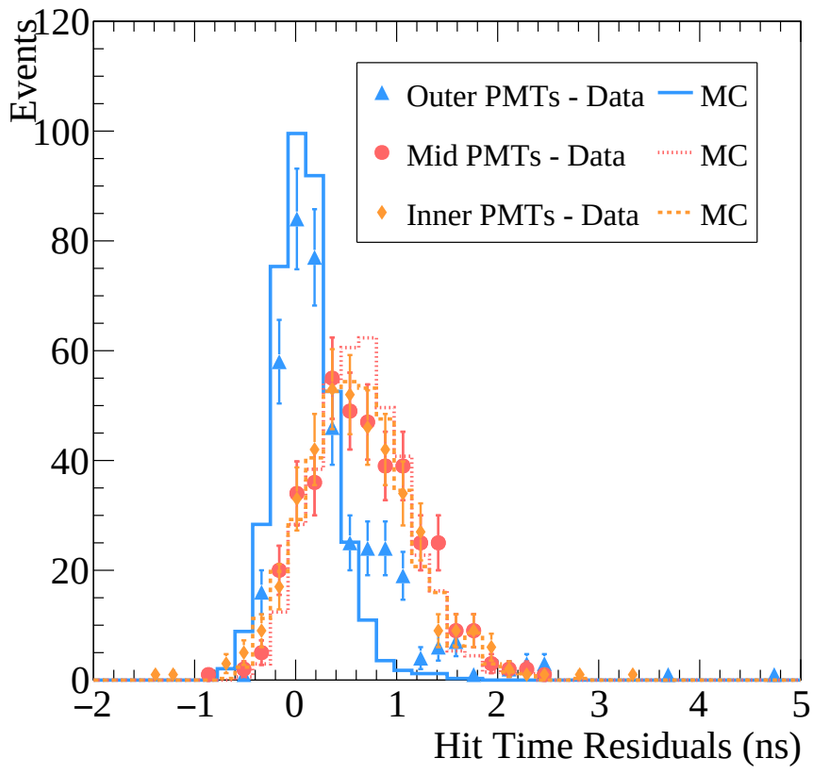
Eur. Phys. J. C (2017) 77: 811

CHESS Results: LAB/PPO

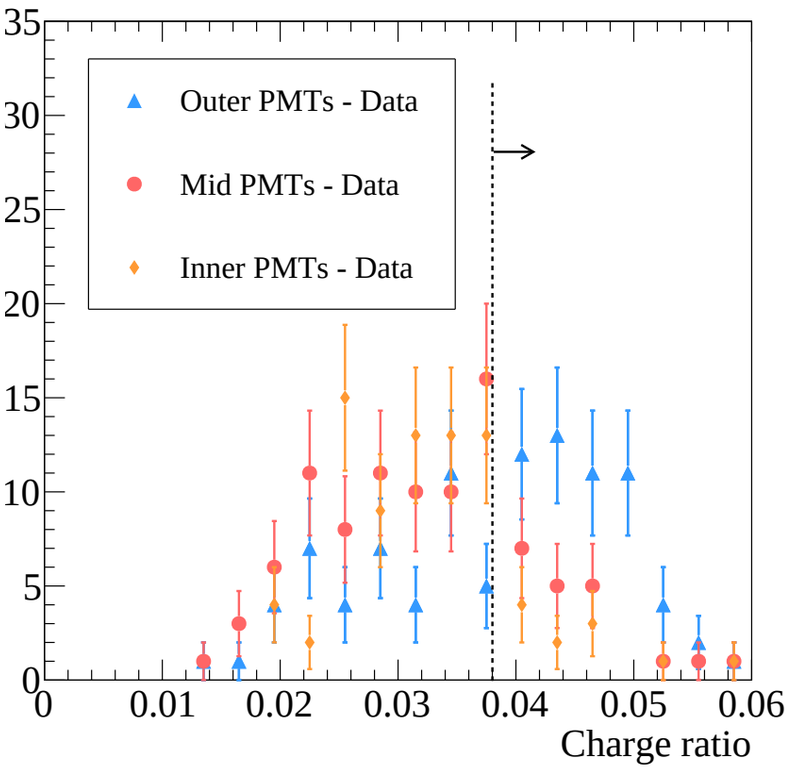


Typical ring candidate event

NOTE: Rise time = 0.75 ± 0.25 ns



Time at fixed threshold
Corrected by ToF, channel delays

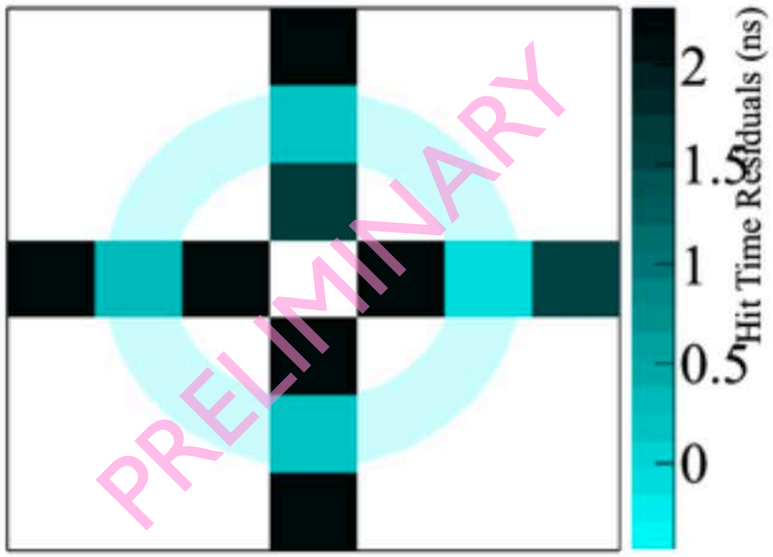


Ratio of charge in prompt, 5ns window to charge in total (135ns) window

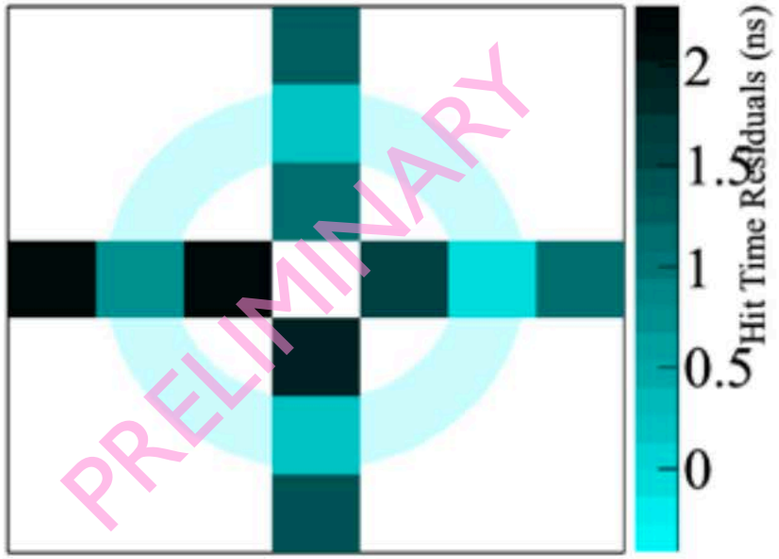
	LAB (time)	LAB (charge)	LAB/PPO (time)	LAB/PPO (charge)
Cherenkov detection efficiency	83 ± 3 %	96 ± 2 %	70 ± 3 %	63 ± 8 %
Scintillation contamination	11 ± 1 %	6 ± 3 %	36 ± 5 %	38 ± 4 %

CHESS Results: WbLS

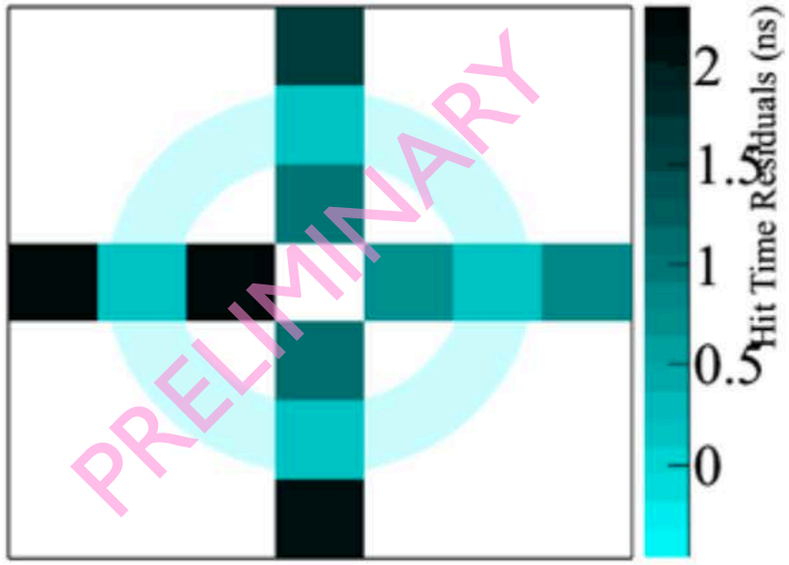
WbLS 1%



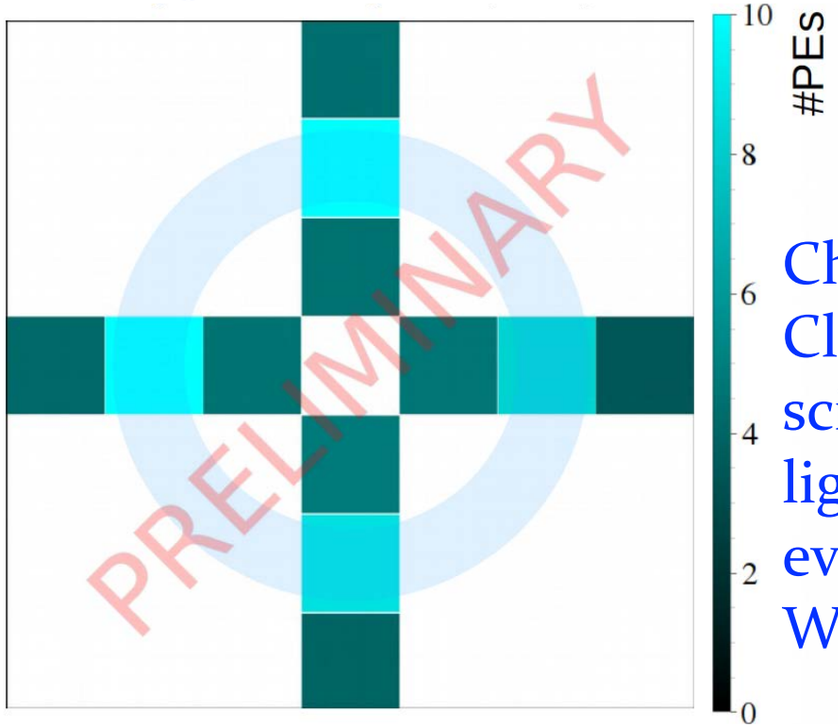
WbLS 5%



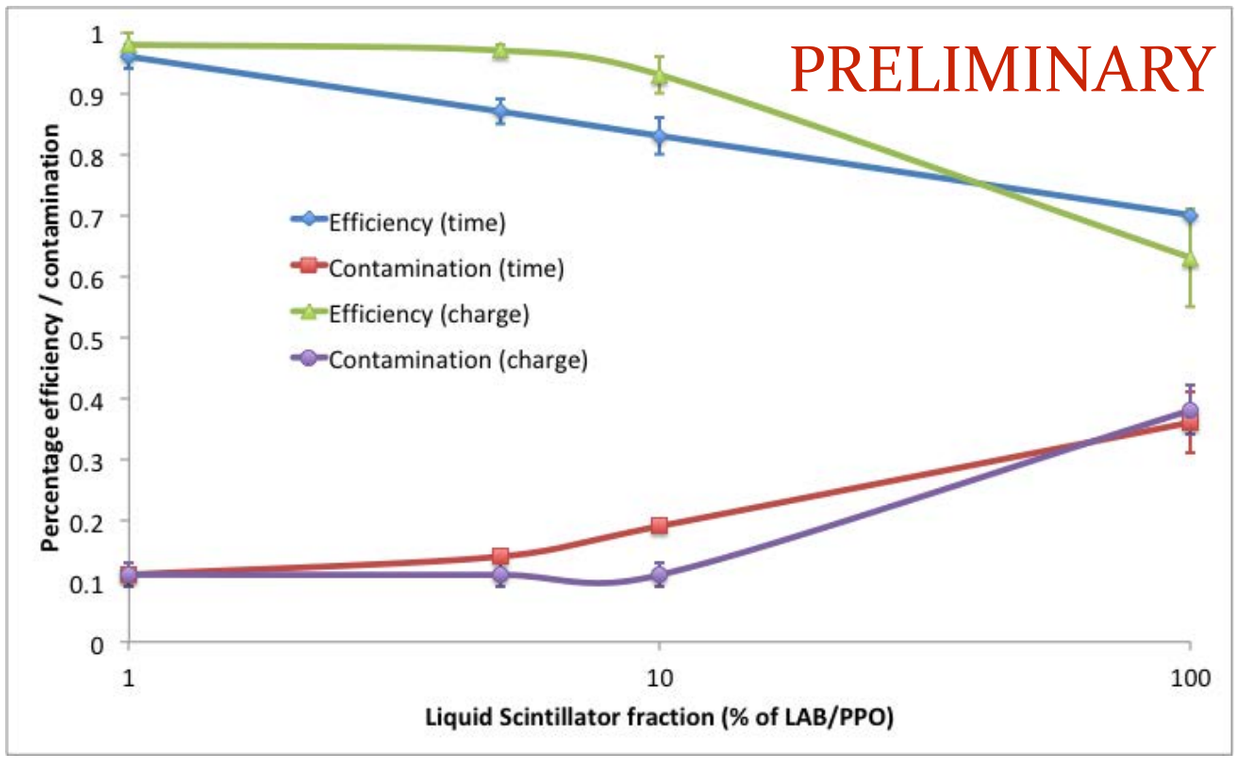
WbLS 10%



Average of WbLS data set

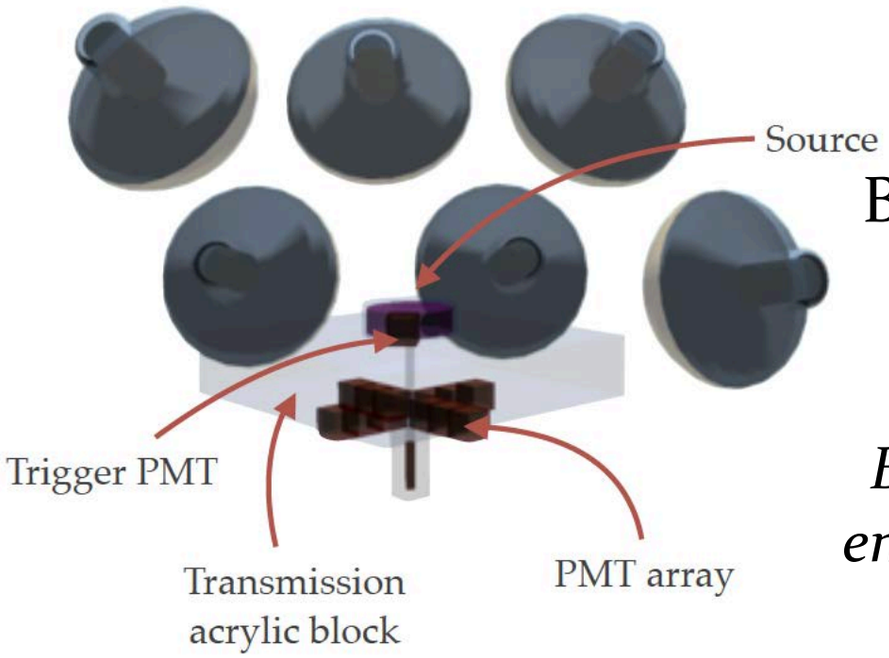


Charge rings: Clearly seeing scintillation light even in 1% WbLS



WbLS Modelling in CHESS

Extract microphysical parameters by fitting using complete MC model



Detailed geometry

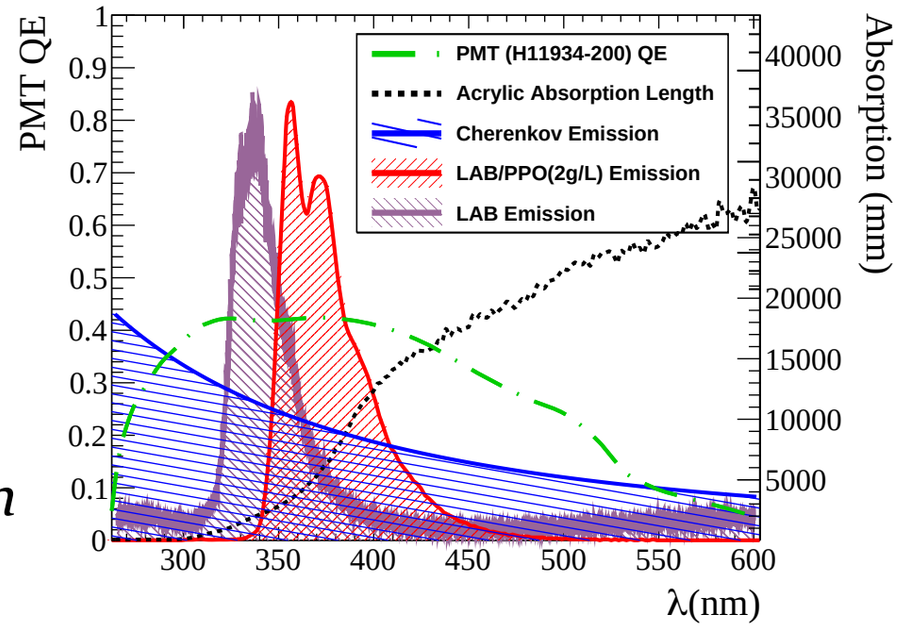
Beta decay generator (90Sr source)

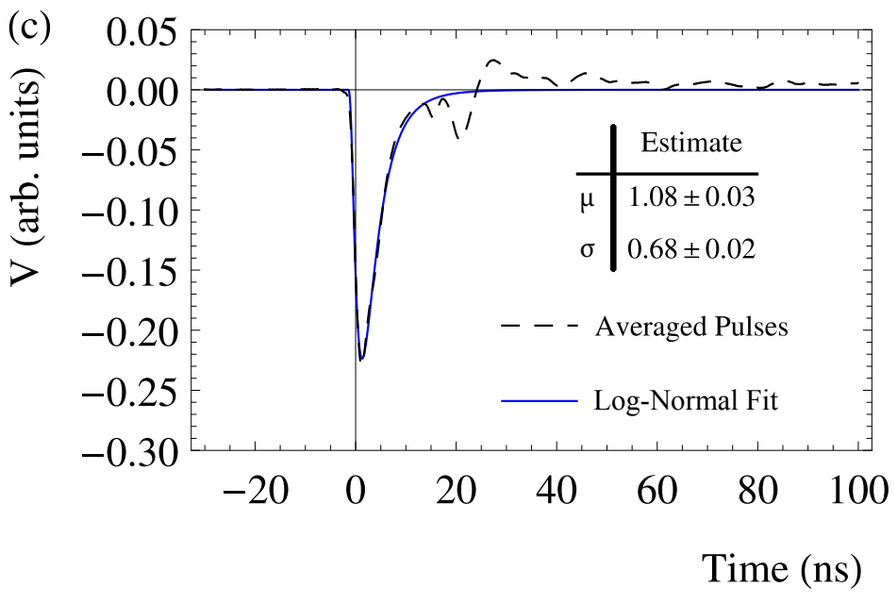
Microphys. simulation: *Birk's constant [1], LAB/PPO emission spectrum, absorption [2], reemission, T profile*

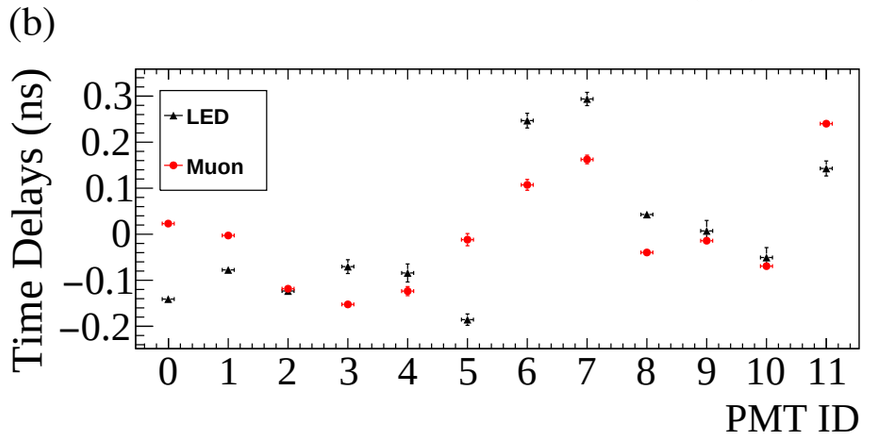
Full photon tracking & optics model

Full PMT geometry: *glass, dynode, casing track photons to dynode*

Full calibrated DAQ model: *waveform, gain, TTS*







[1] B. von Krosigk, et al., Eur. Phys. J. C 73, 2390 (2013).
[2] SNO+ measurements.

PRELIMINARY

Time Profile

Calibrate method using well-understood LAB/PPO target

Time profile model: 3 exp. decay + rise time

$$\rho(t) \propto (1 - e^{-t/\tau_r}) \times \sum_i^3 A_i e^{-t/\tau_i}$$

$\tau_r = 0.7$ ns

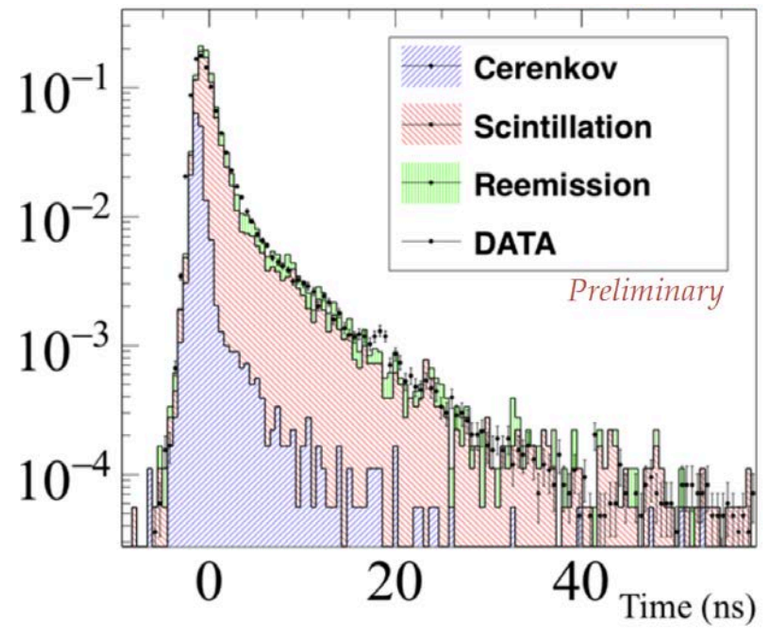
$\tau_1 = 4.3$ ns

$\tau_2 = 16$ ns

$\tau_3 = 166$ ns

H. M. O'Keeffe et al. Nucl. Instum. Methods A640, 119 (2011)

Good agreement between data and model



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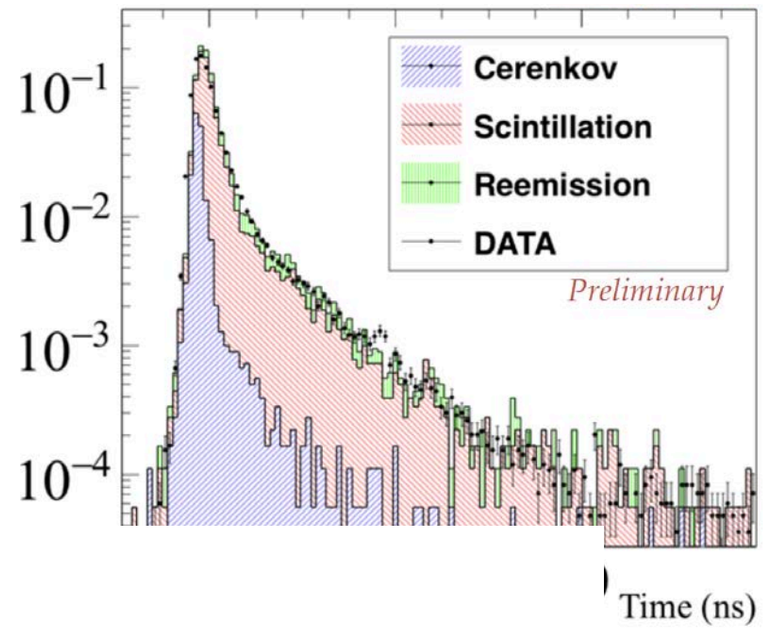
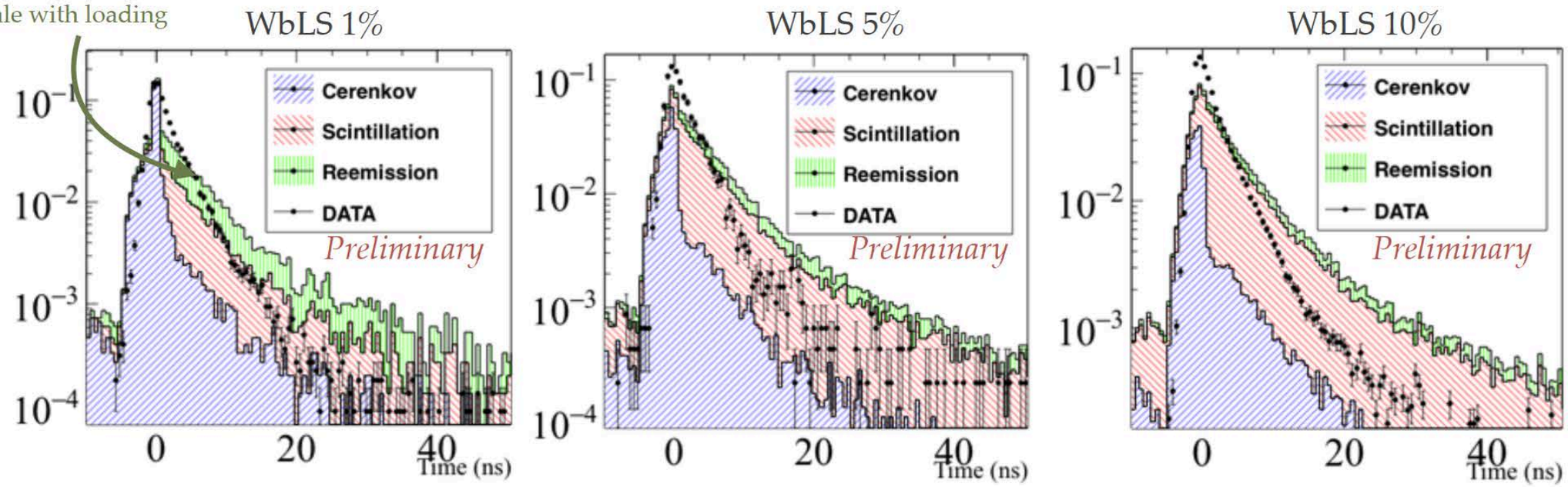


Good agreement between data and model

WbLS time profile does not agree!

Most of reemission component is Cherenkov reemission → Does not scale with loading



Faster than LAB/PPO?

Time Profile Measurement

PRELIMINARY

Modify (parameter values in) underlying timing model in simulation

Fit for WbLS time profile

Time profile model: 3 exp. decay + rise time

$$\rho(t) \propto (1 - e^{-t/\tau_r}) \times \sum_i^3 A_i e^{-t/\tau_i}$$

$\tau_r = 0.7$ ns

$\tau_1 = 4.3$ ns

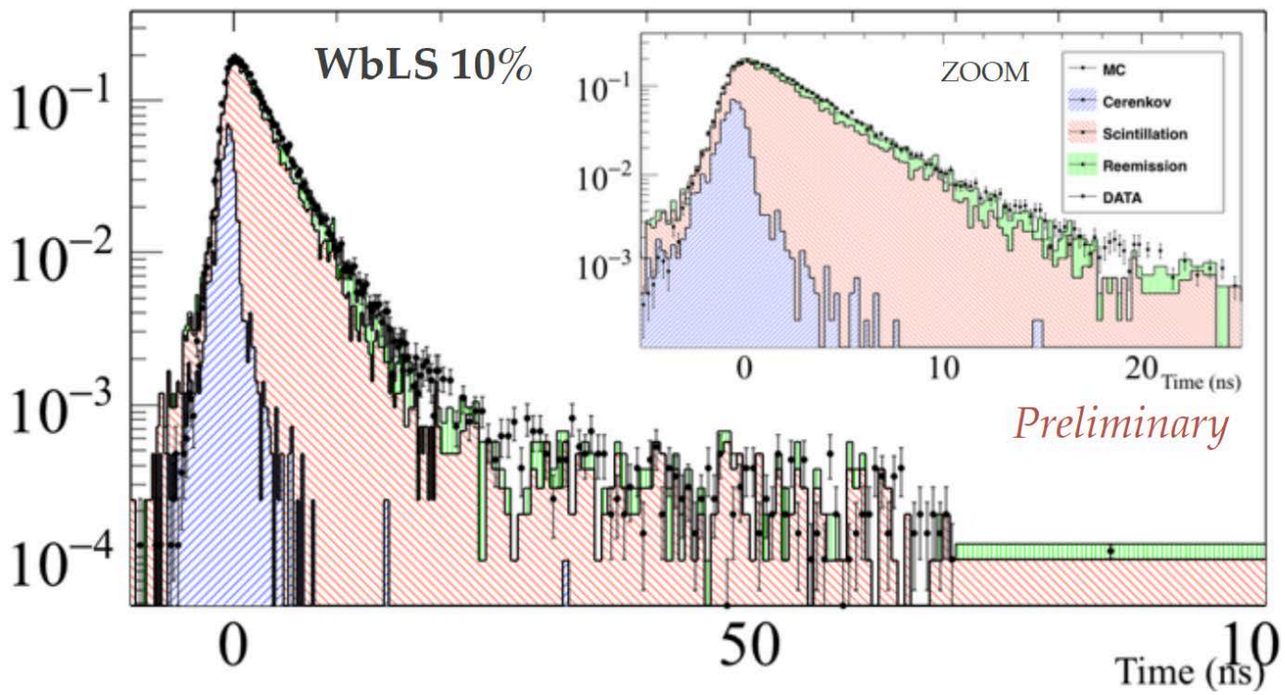
$\tau_2 = 16$ ns

$\tau_3 = 166$ ns

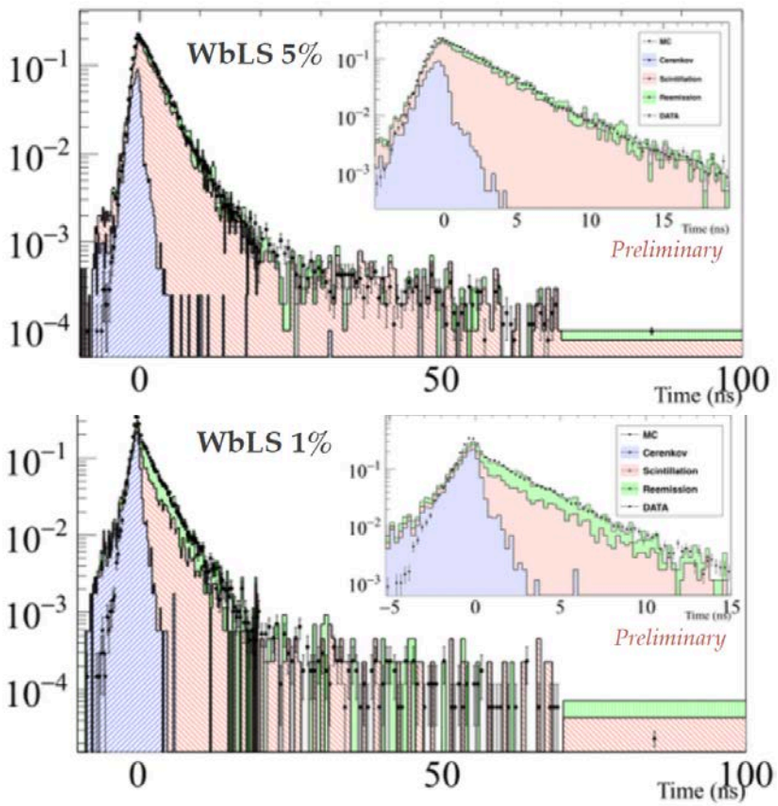
H. M. O'Keeffe et al. Nucl. Instum. Methods A640, 119 (2011)

Fit results:
- τ_r = 0.39
- τ_1 = 2.77
- τ_2 = 21.40
- R_1 = 0.94

Result of fit (10% WbLS)



Cross-check against other samples



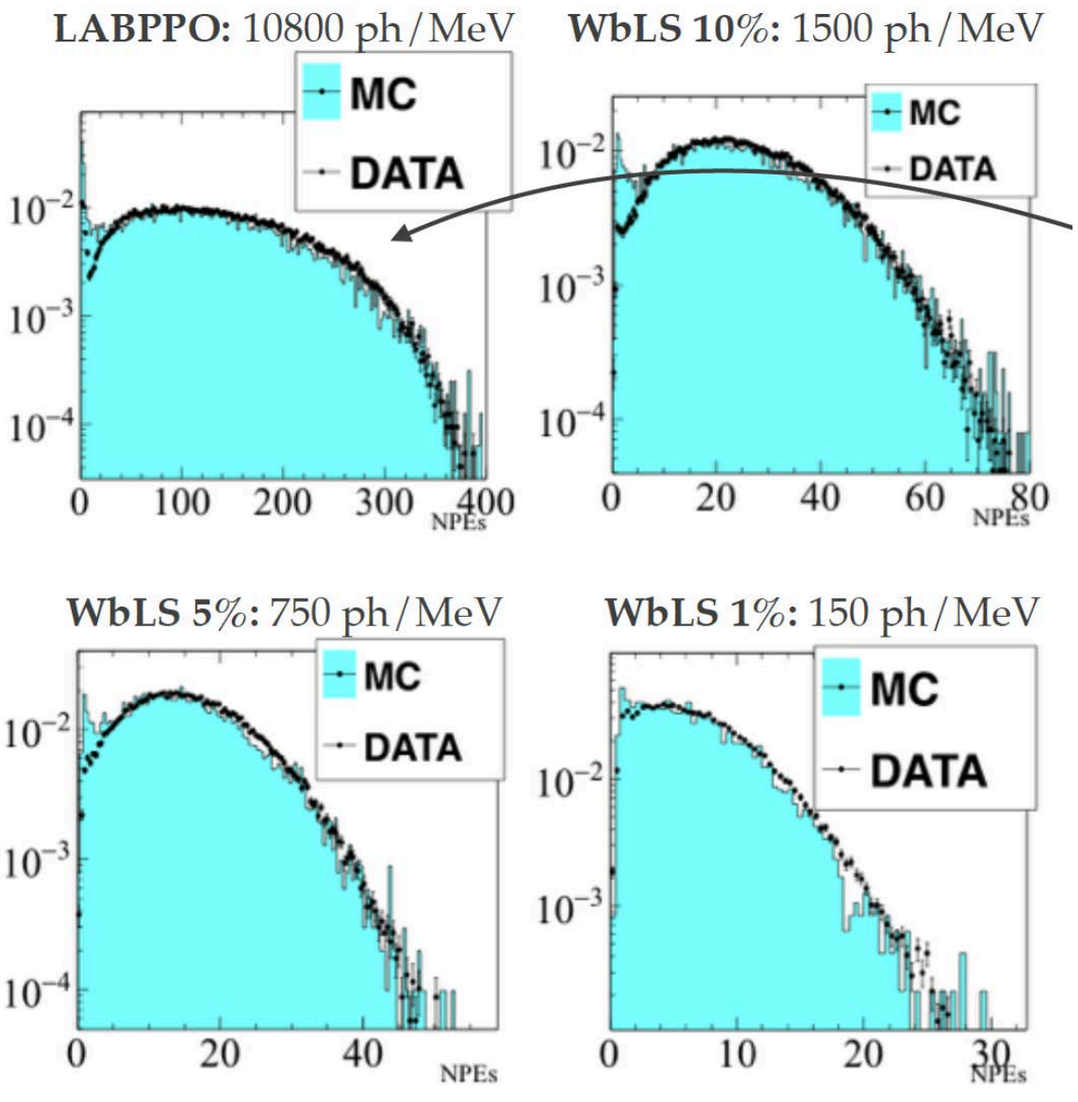
1%, 5% WbLS seem consistent with time profile of 10% cocktail

Preliminary light yield

PRELIMINARY

Note: assumes LAB/PPO wvl emission profile

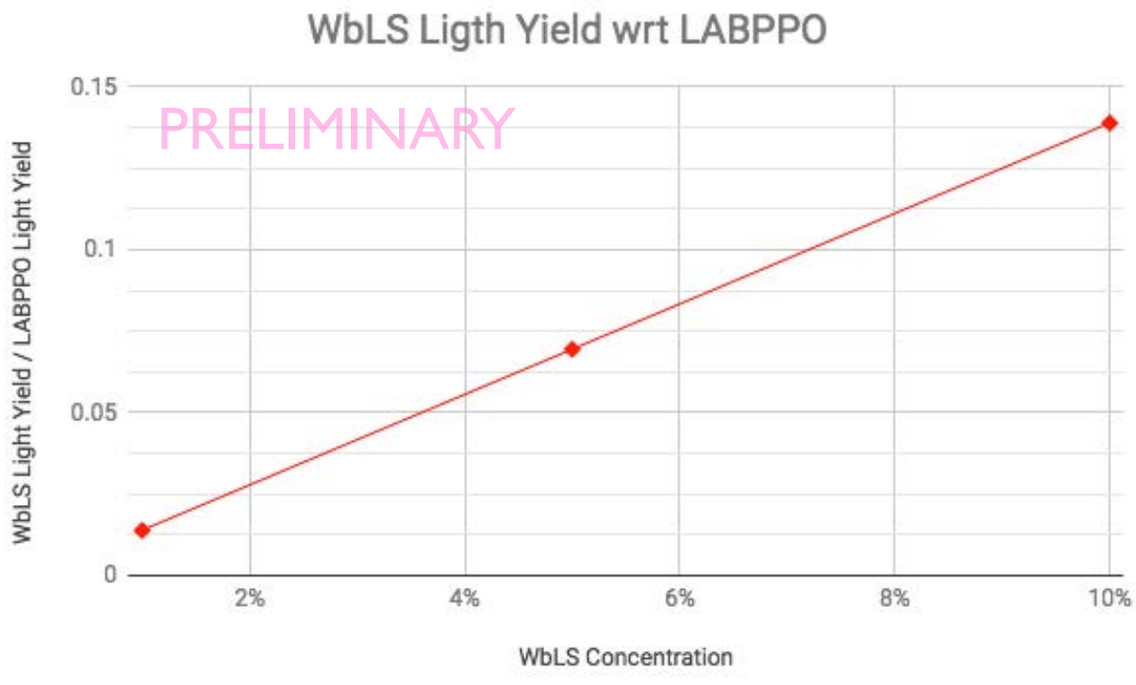
Fit for WbLS time profile



Method: define LAB/PPO LY

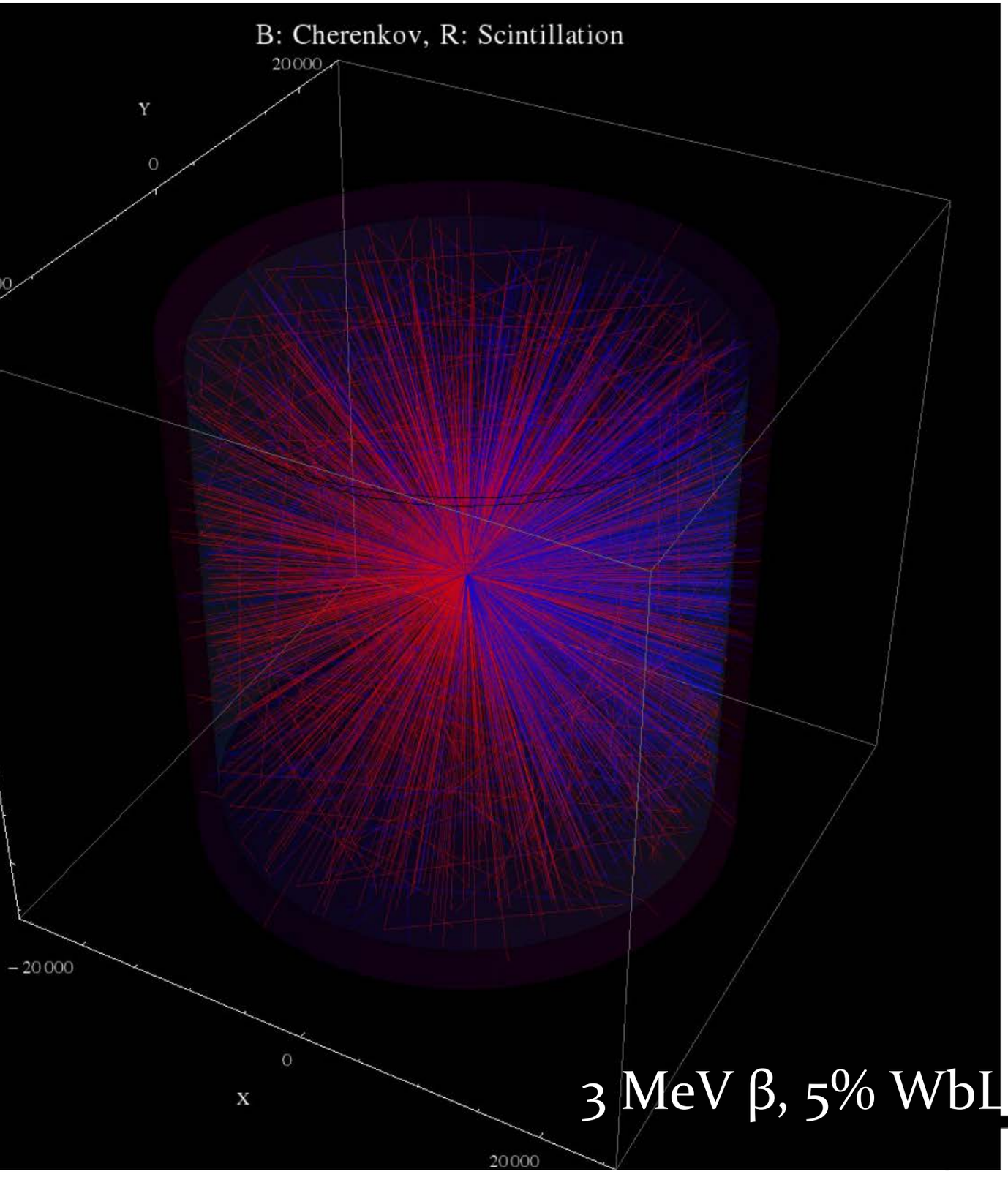
Calibrate setup to LAB/PPO charge collection

Determine LY per WbLS cocktail by data/MC fit



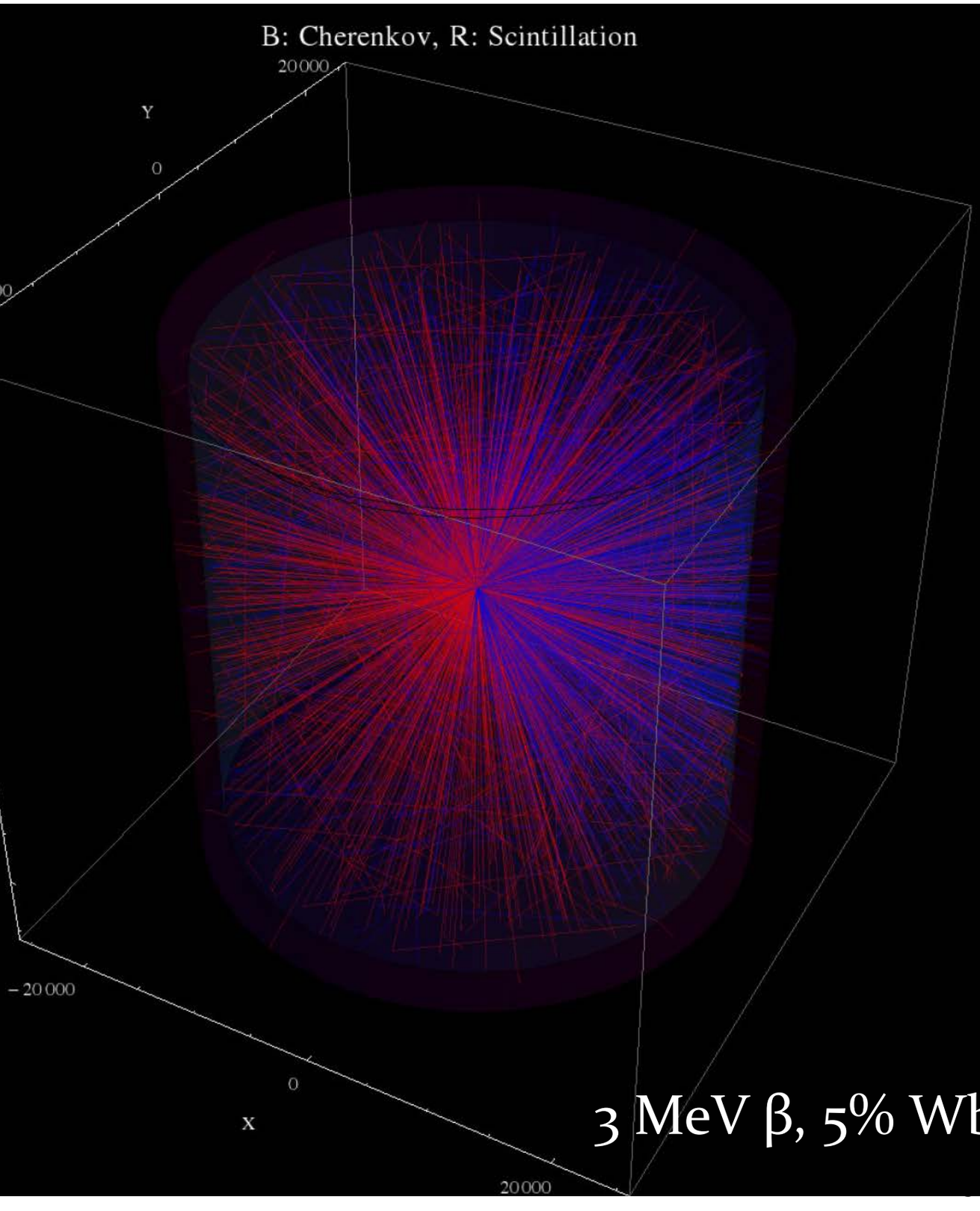
Signal Separation in Theia

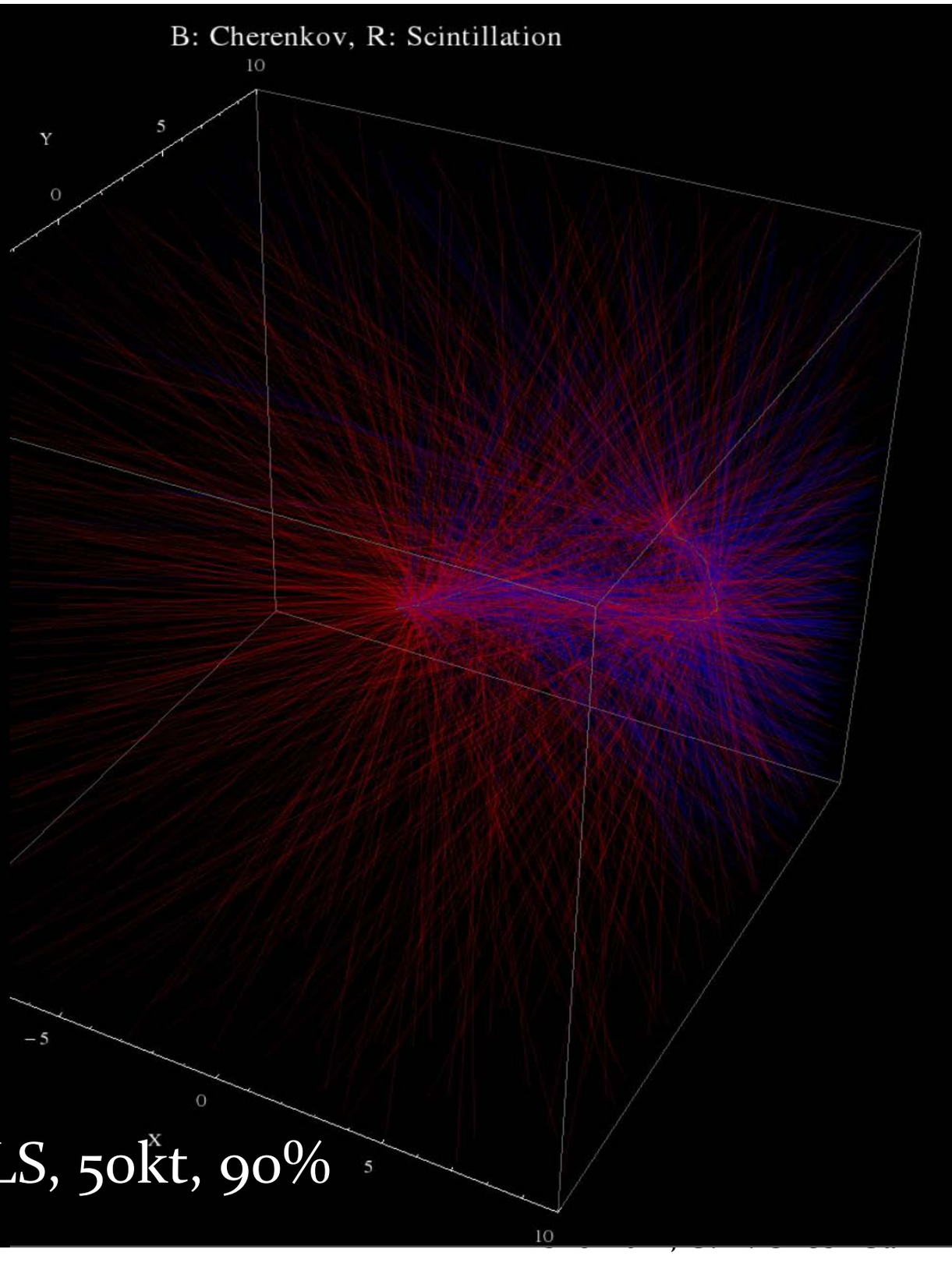
Signal Separation in Theia



3 MeV β, 5% WbL

Signal Separation in Theia

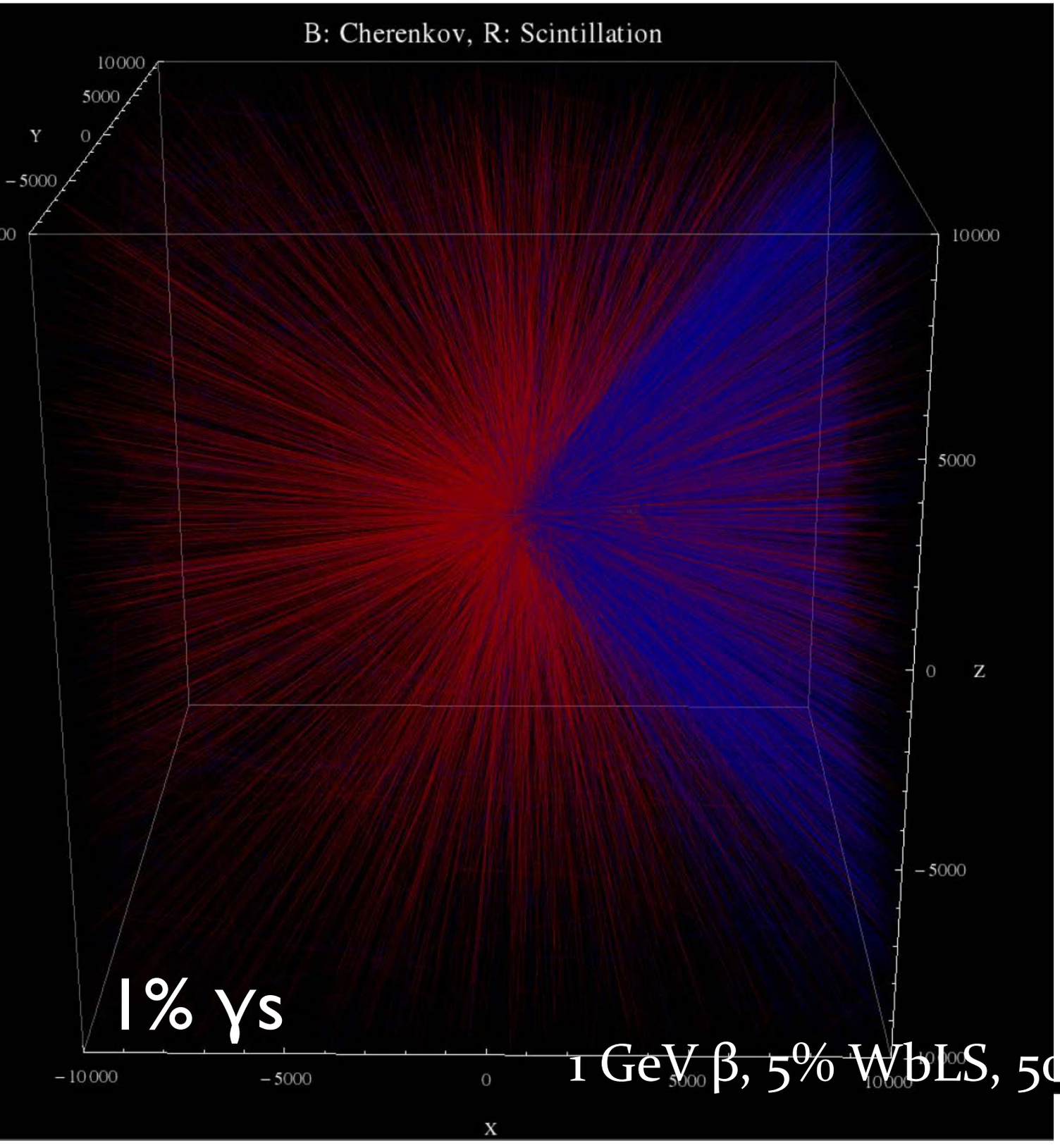




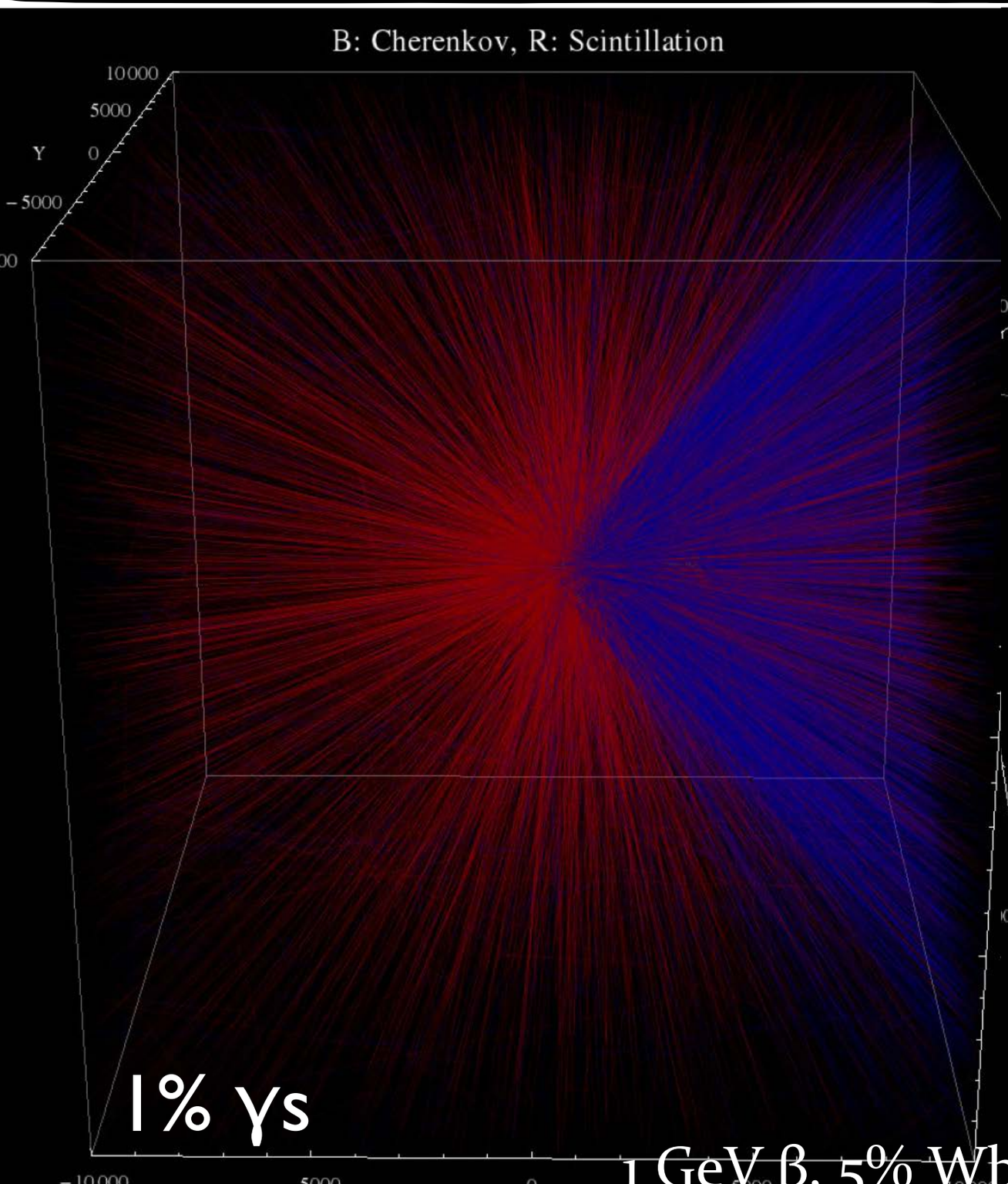
3 MeV β, 5% WbLS, 50kt, 90%

Ring Imaging

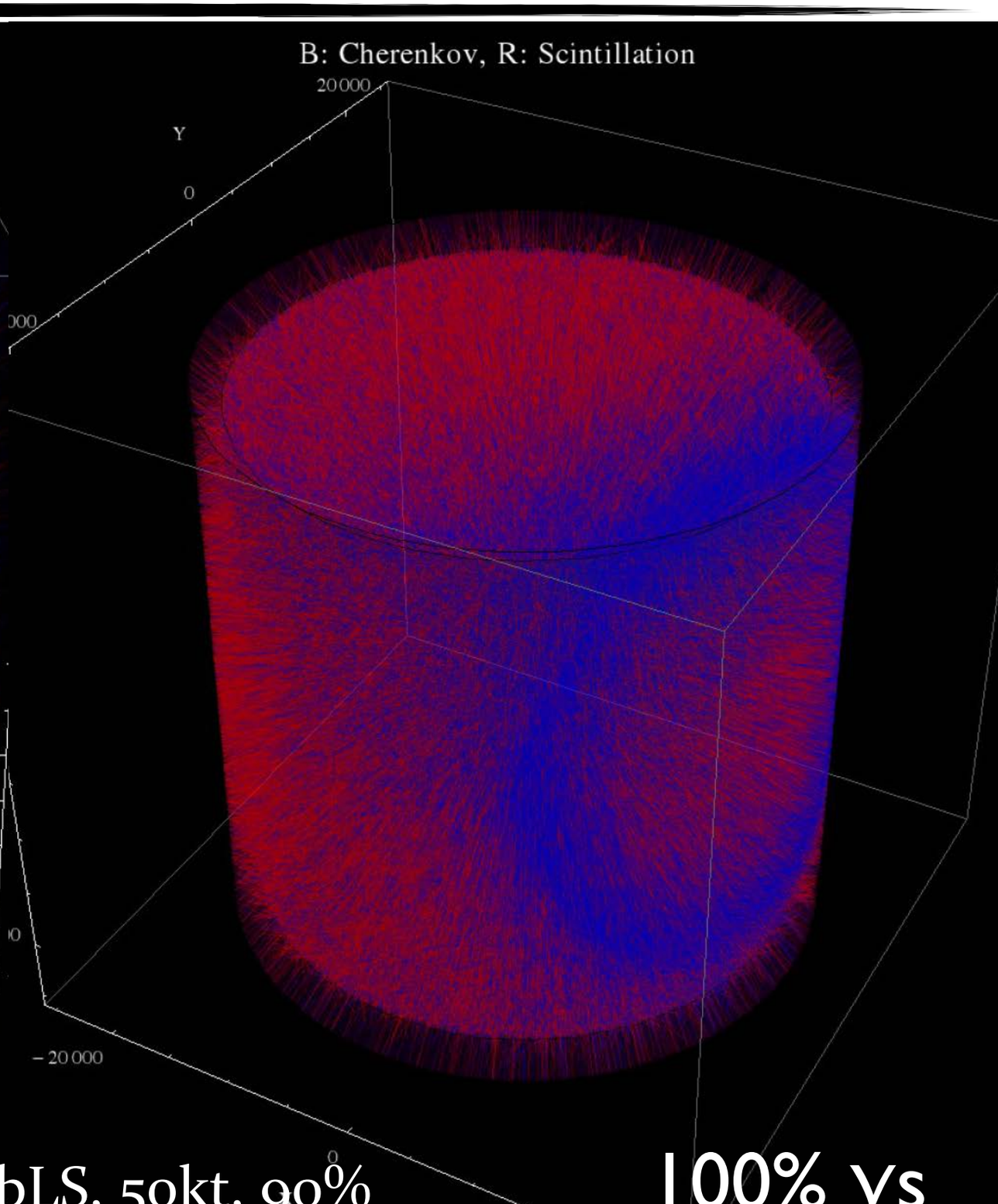
Ring Imaging



Ring Imaging



1% γs

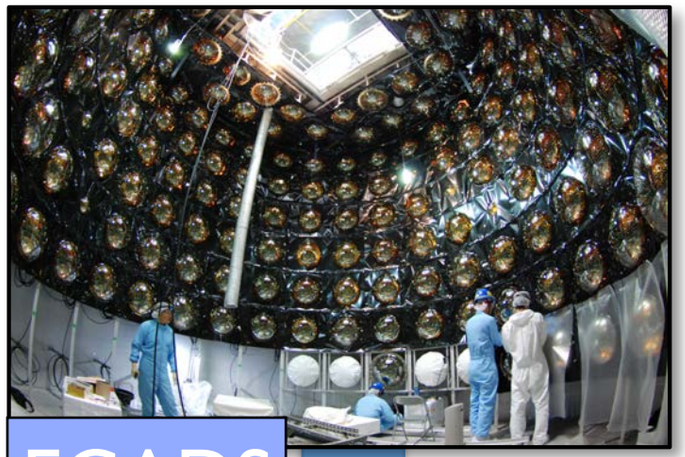


100% γs

1 GeV β, 5% WbLS, 50kt, 90%

Community Interest

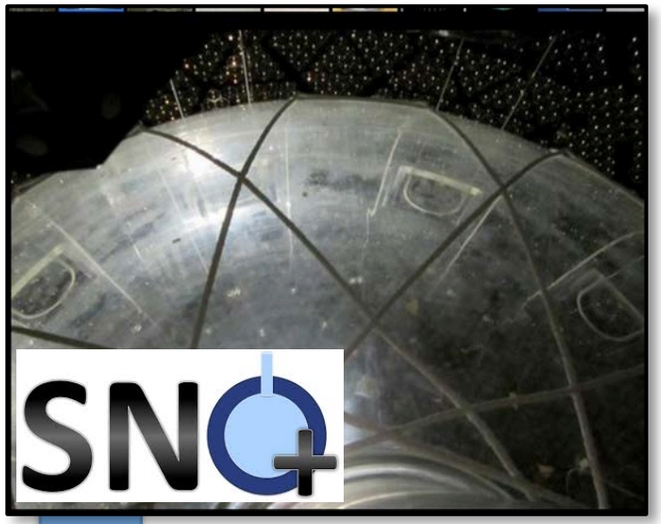
Site	Scale	Target	Measurements	Timescale
UChicago	bench top	H2O	fast photodetectors	Exists
CHIPS	10 kton		electronics, readout, mechanical infrastructure	2019
EGADS	200 ton	H2O+Gd	isotope loading, fast photodetectors	Exists
ANNIE	30 ton			Exists
WATCHMAN	1 kton			2020
NuDot	1 ton	LS	directionality	2018
Penn	30 L	(Wb)LS	light yield, timing, loading	Exists
SNO+	780 ton			2018
CHESS (LBNL)	bench top	WbLS	signal separation, tracking, reconstruction / light yield, loading, attenuation	Exists
BNL	1 ton			Exists



EGADS

Gd loading and purification

Water-based liquid scintillator

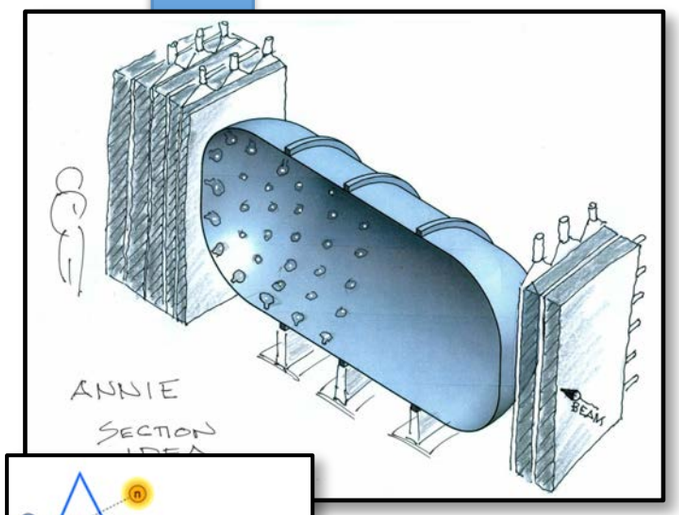


Te loading

THEIA

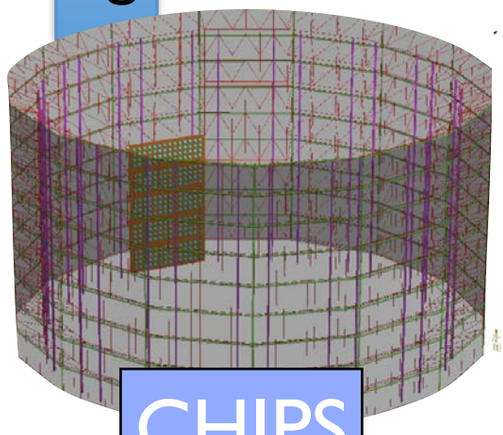
60m

Neutron yield, LAPPD deployment



ANNIE
Accelerator Neutrino Neutron Interaction Experiment

Infrastructure, underwater integration



CHIPS

WbLS, Gd, LAPPD, HQE PMT, full integration prototype

WATCHMAN

Note: not an exhaustive list!

THEIA Collaboration

Concept paper - arXiv:1409.5864

Canada
Alberta
Laurentian
Queens
Toronto

China
Tsinghua

Finland
Jyvaskyla
Oulu

Germany
Aachen
Dresden
Juelich
Mainz
TU Munich
U. Hamburg

Portugal
LIP

UK
Sheffield

US
Brookhaven NL
Boston U.
U. Chicago
Colorado U.
Cornell U.
U. Hawaii
Iowa State
Lawrence Berkeley NL
LSU
MIT
U. Penn
Stony Brook
SURF
Temple
UC Berkeley
UC Davis

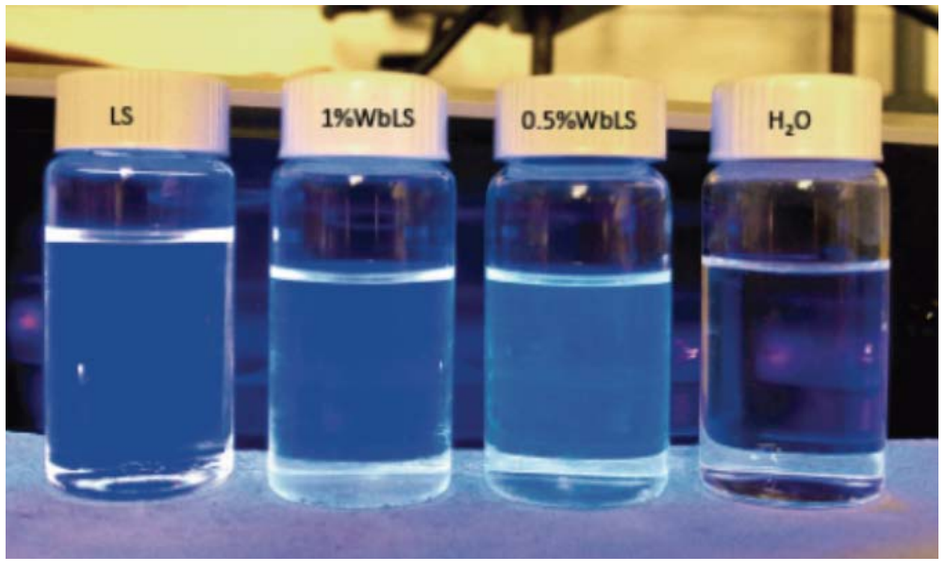
Summary

- **THEIA: broad program of compelling science**
- **Enhanced capabilities for anti-neutrino detection**
- **Flexibility to adapt to new directions in the scientific program as the field evolves**
- **Powerful instrument of discovery**
- **Rich, exciting program of ongoing R&D**

Backup

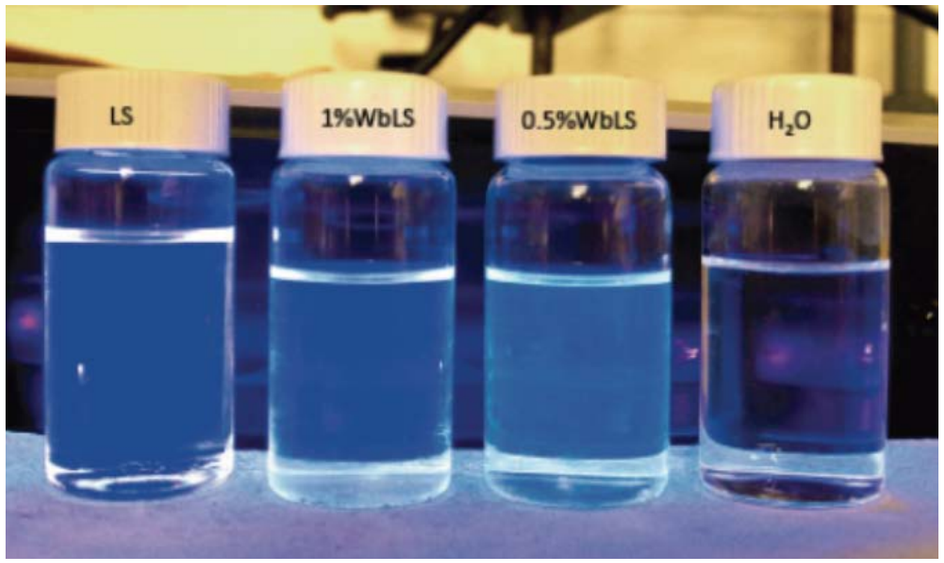
Transformational Opportunity

Transformational Opportunity



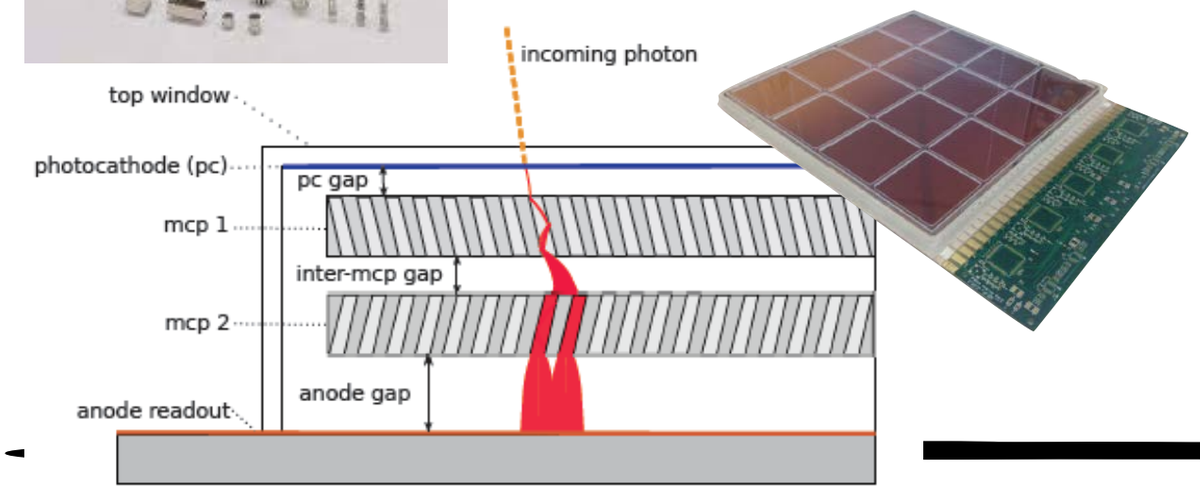
Development of new scintillators e.g. WbLS

Transformational Opportunity

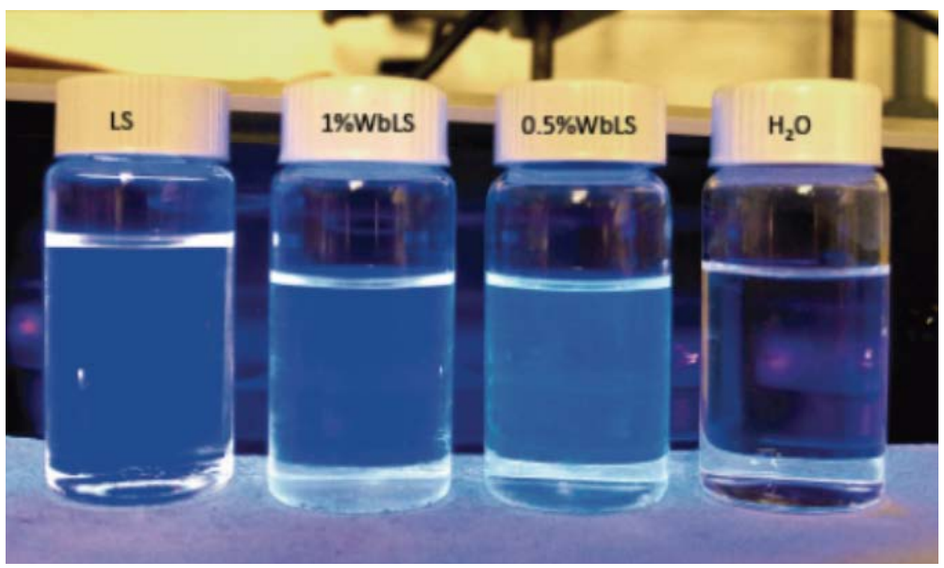


Development of new scintillators e.g. WbLS

Fast, efficient photodetectors



Transformational Opportunity



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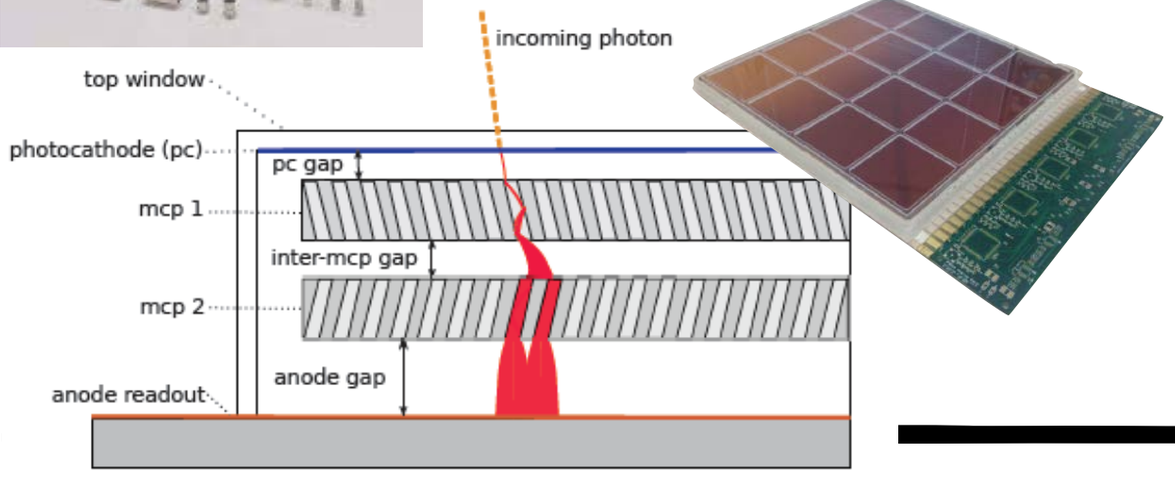
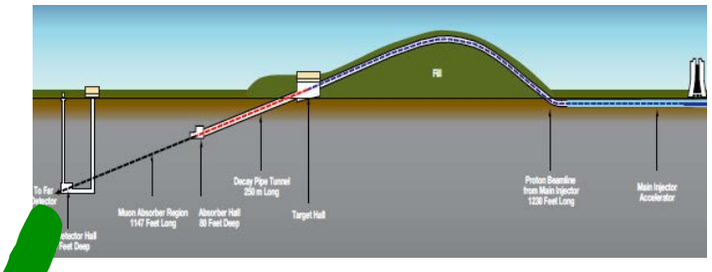
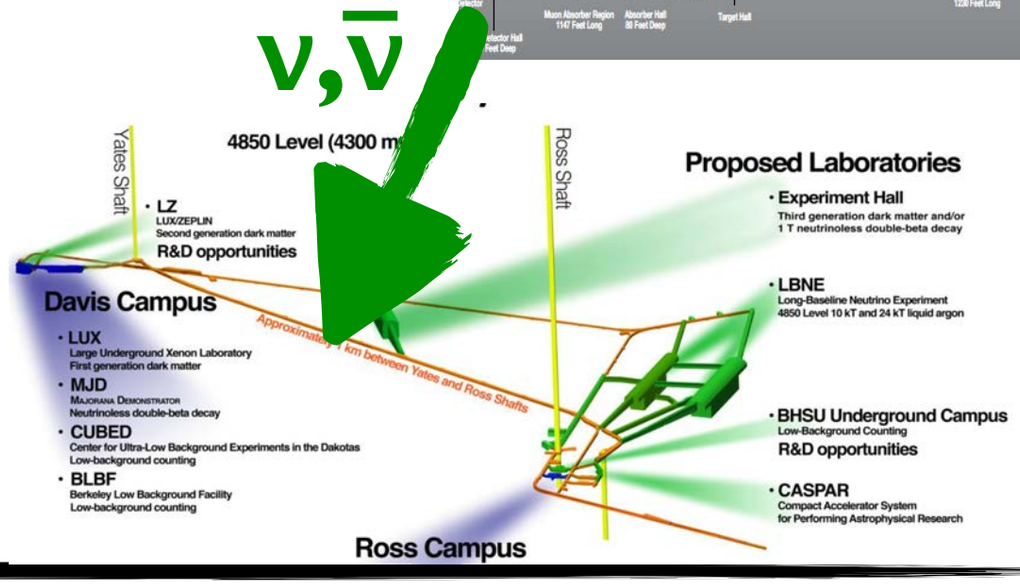


Fully-equipped, deep underground labs (+ beam)





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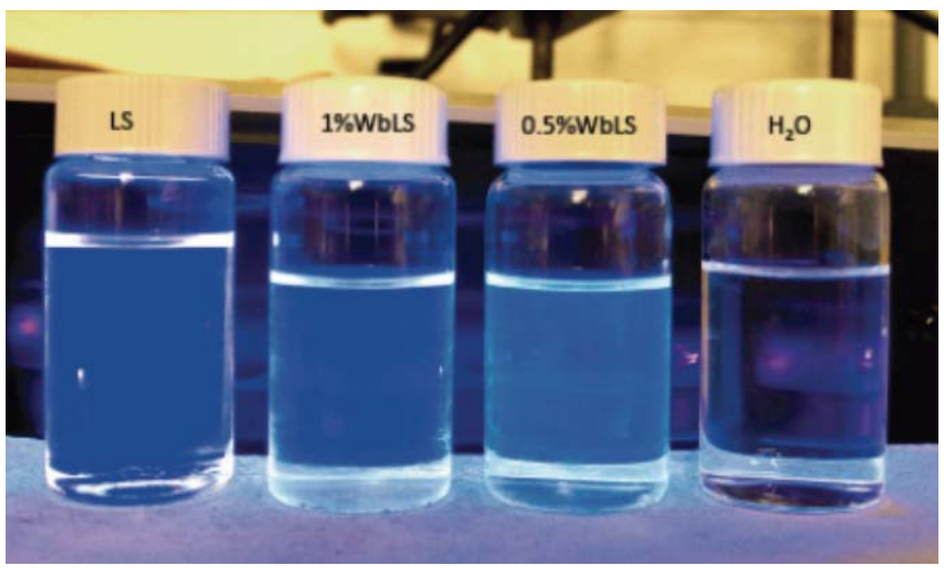

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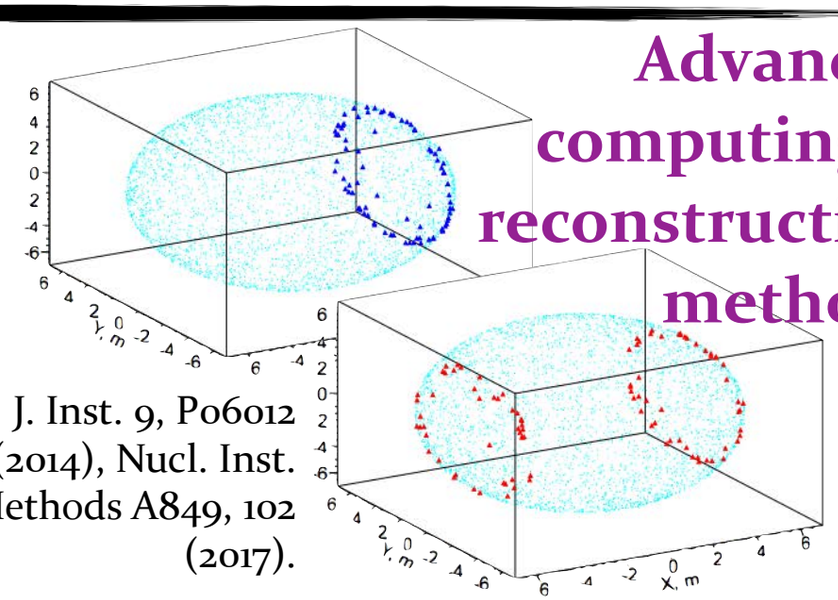
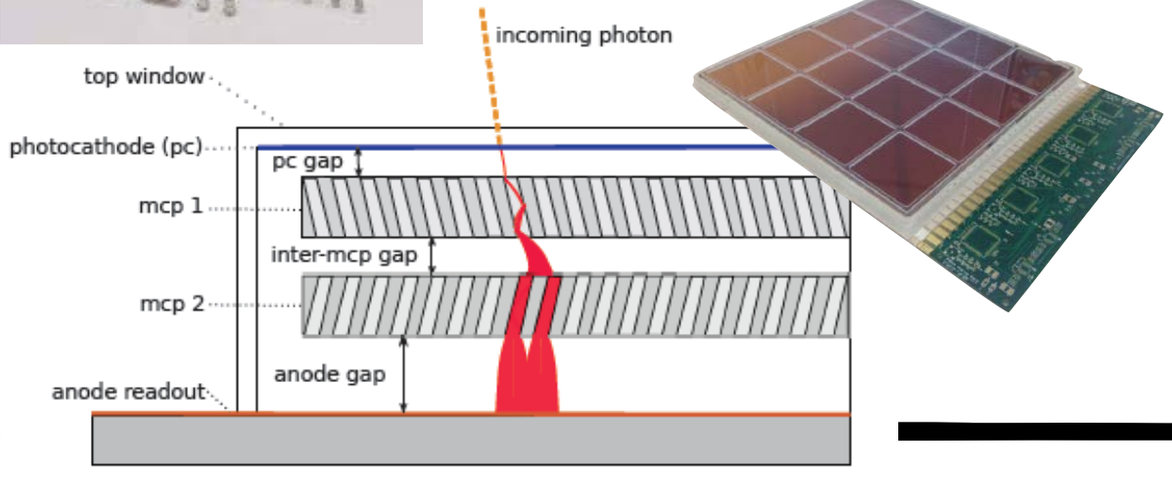


Advanced computing & reconstruction methods

J. Inst. 9, P06012 (2014), Nucl. Inst. Methods A849, 102 (2017).

Fast, efficient photodetectors



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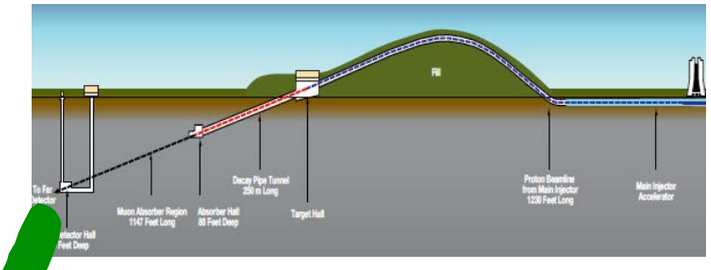
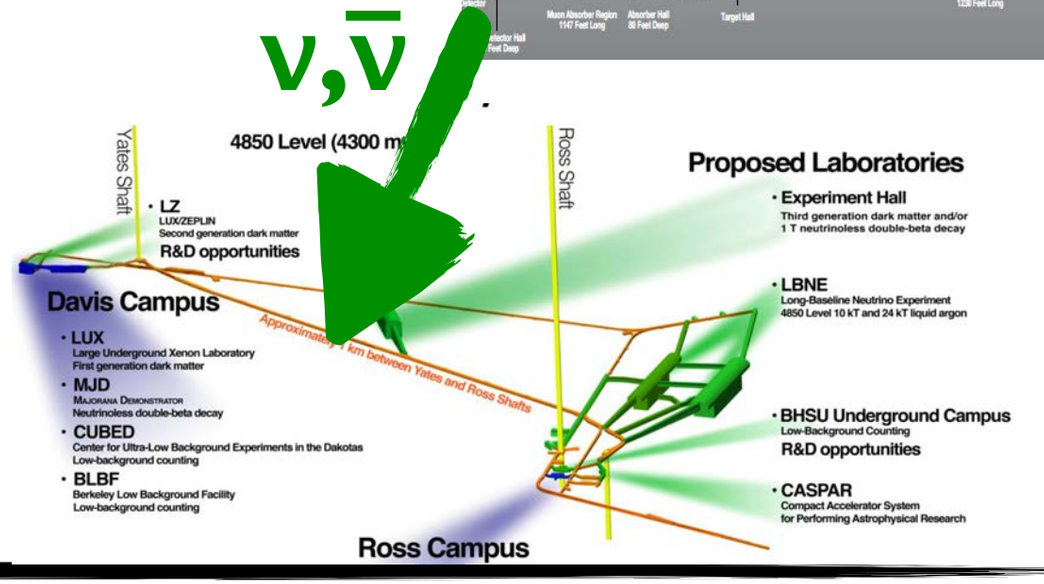
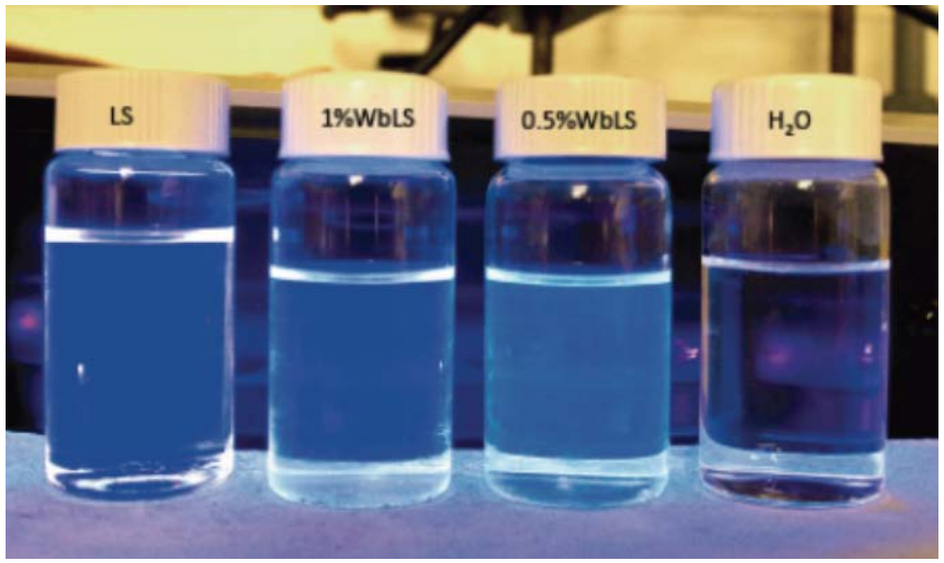


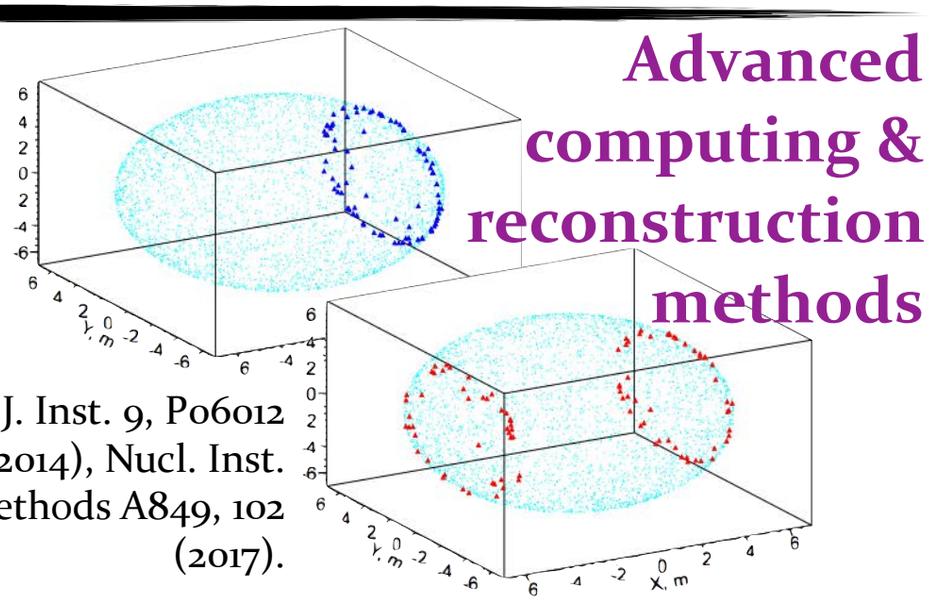


Transformational Opportunity



Development of new scintillators e.g. WbLS

New-generation of large-scale, low-threshold, directional detectors



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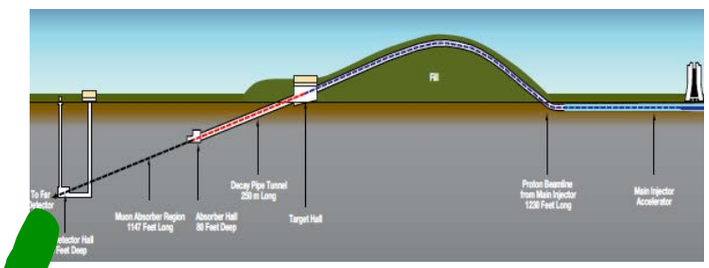
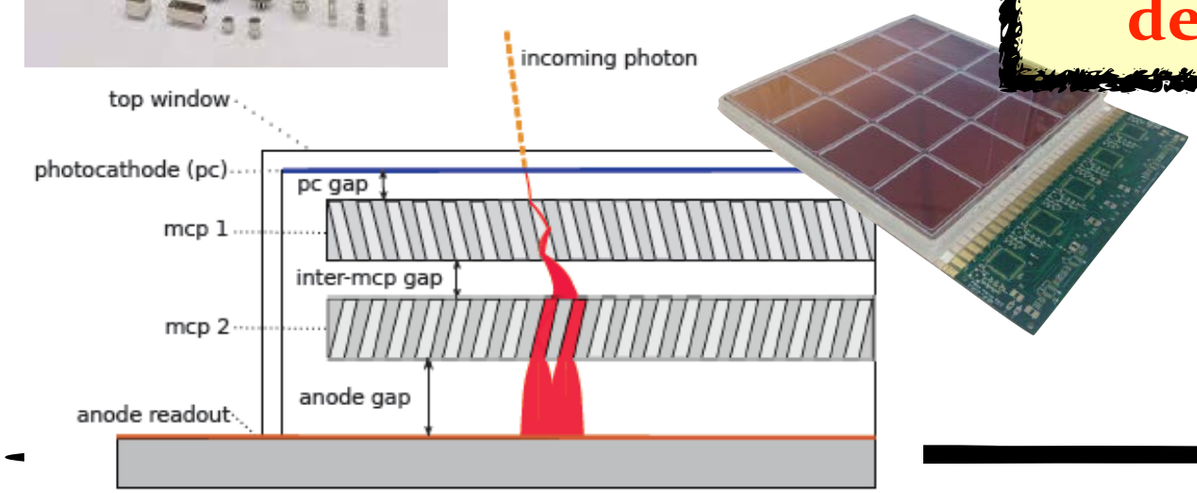
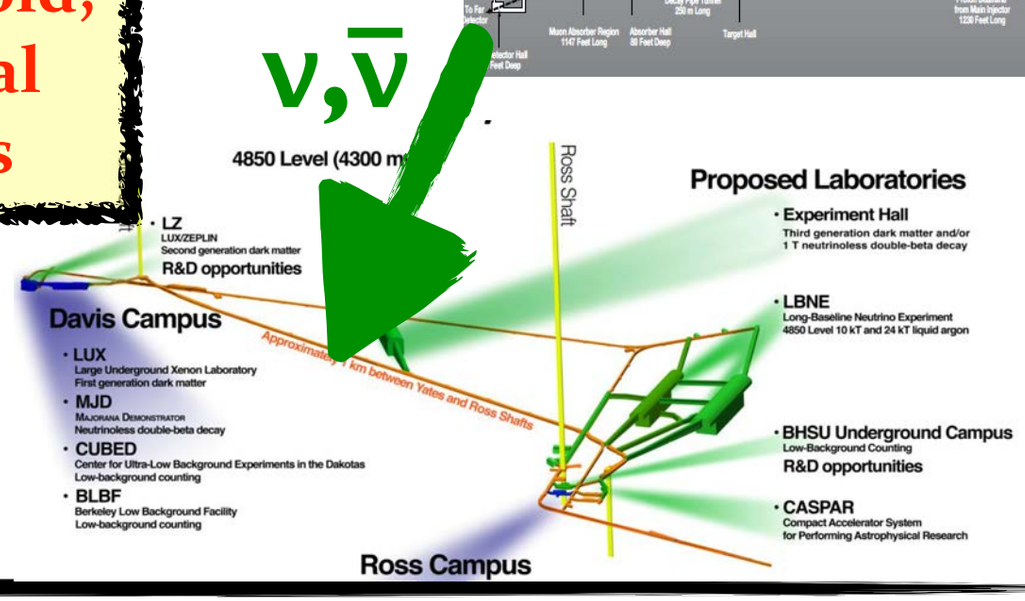
J. Inst. 9, P06012 (2014), Nucl. Inst. Methods A849, 102 (2017).

Fully-equipped, deep underground labs (+ beam)



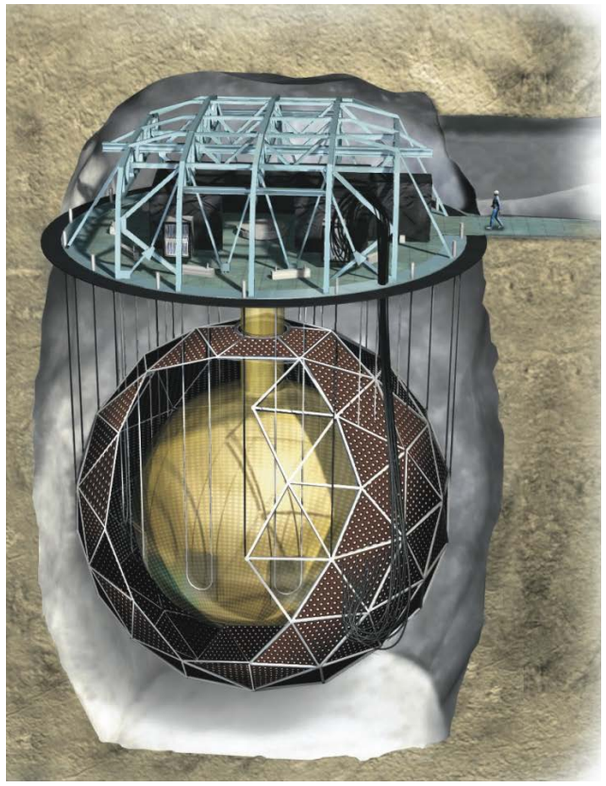
Fast, efficient photodetectors

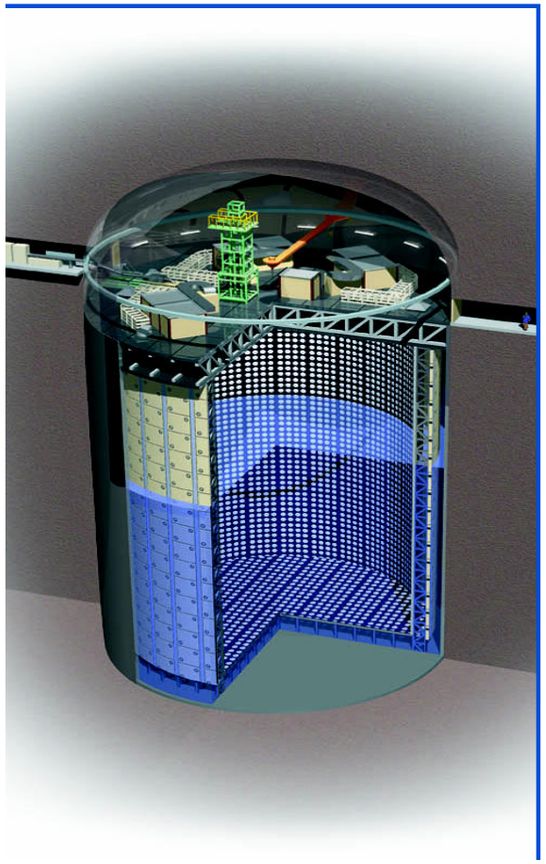


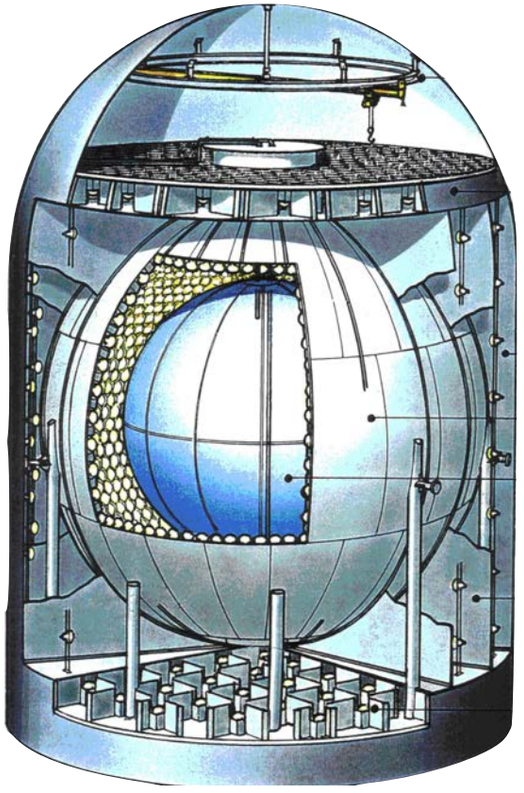


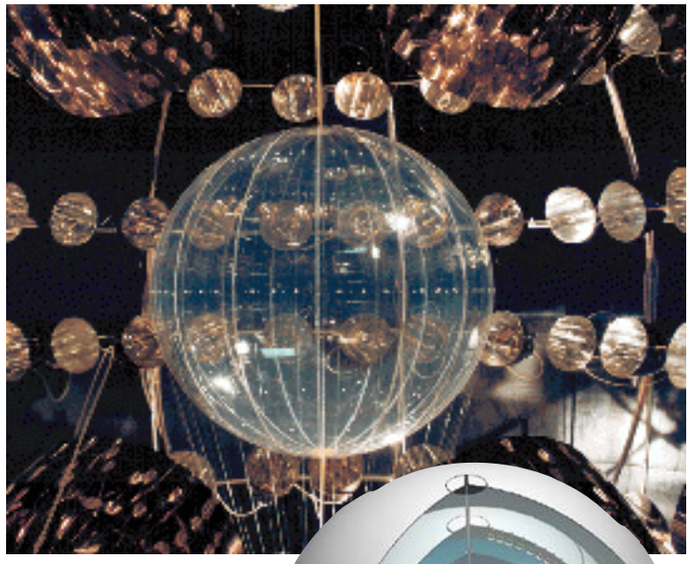
Detector Concept

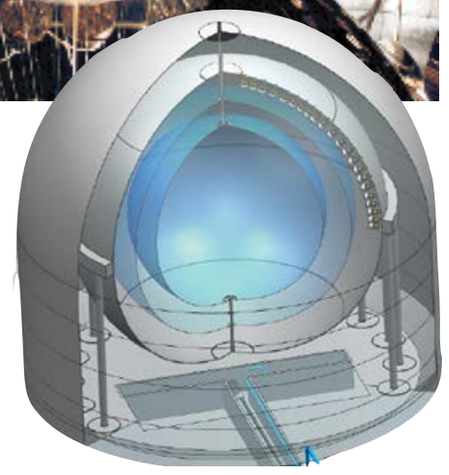
- **New technology with proven methodology**











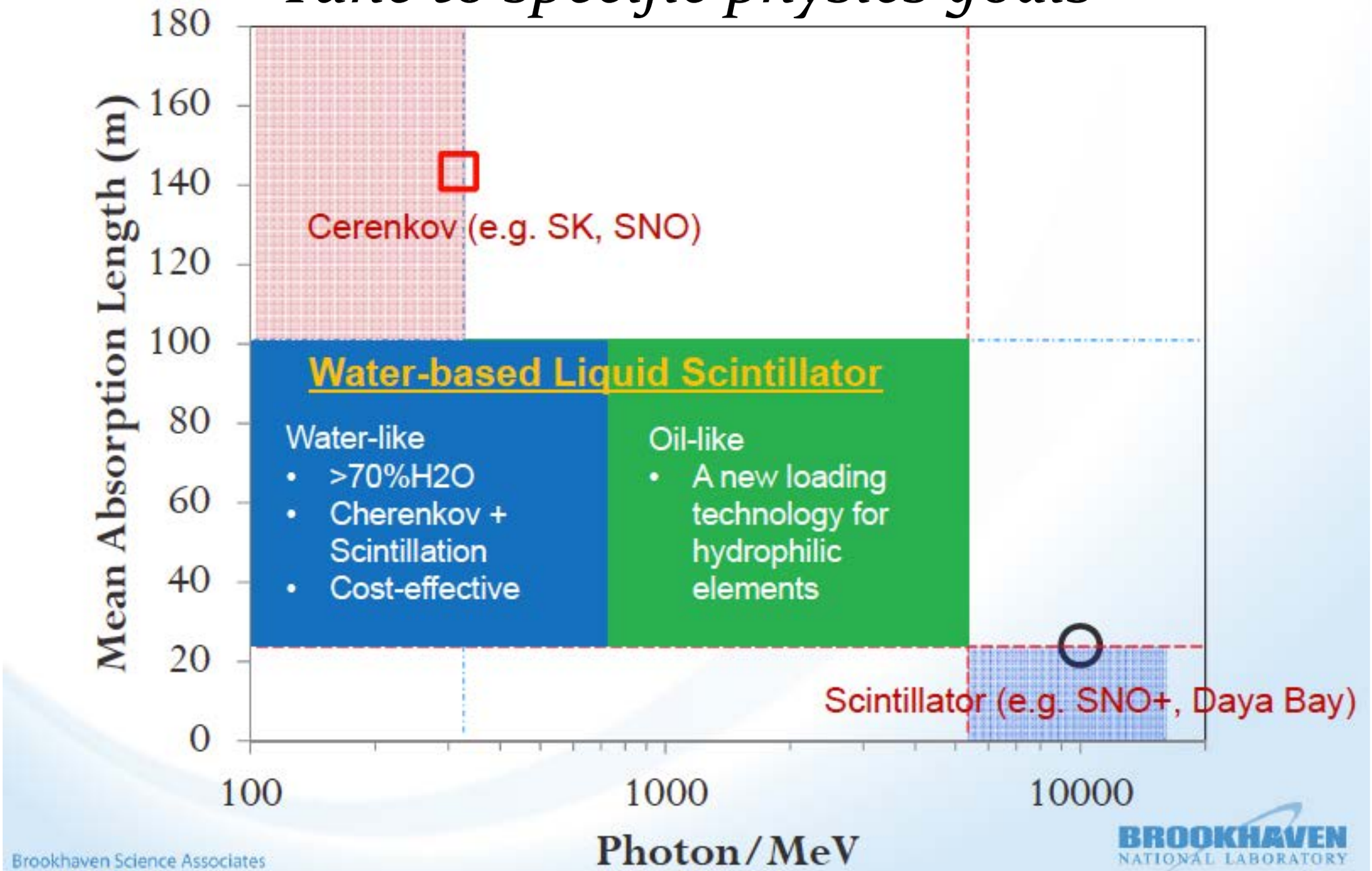
House light-producing target inside large monolithic detector

Novel, breakthrough target medium

Powerful Target Medium

Minfang Yeh et al., BNL

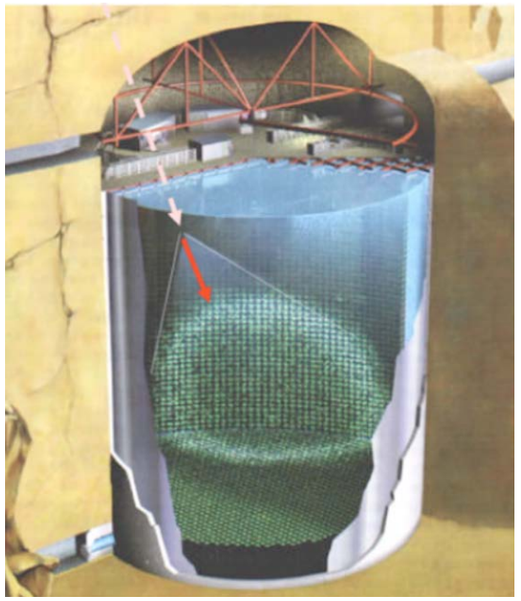
Tune to specific physics goals

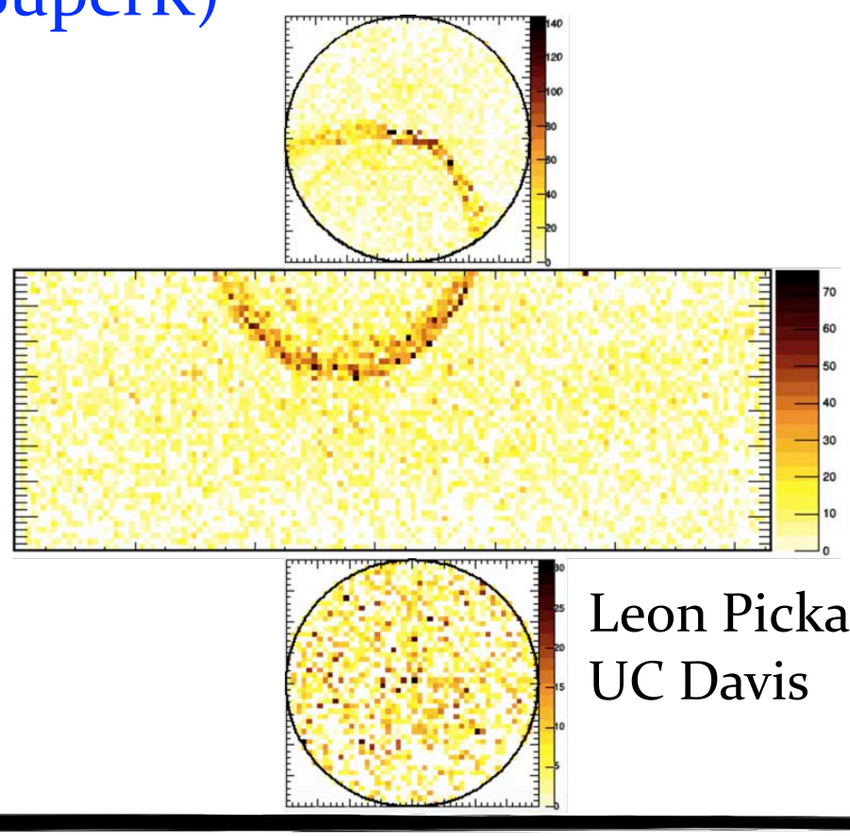


Precision of a Cherenkov Detector

- High transparency: good light collection
- Topological information
  - Particle identification (ring imaging)
  - Directionality
- Metal loading potential

Demonstrated at 1–50 kt-scale (SNO, SuperK)





Leon Pickard,
UC Davis

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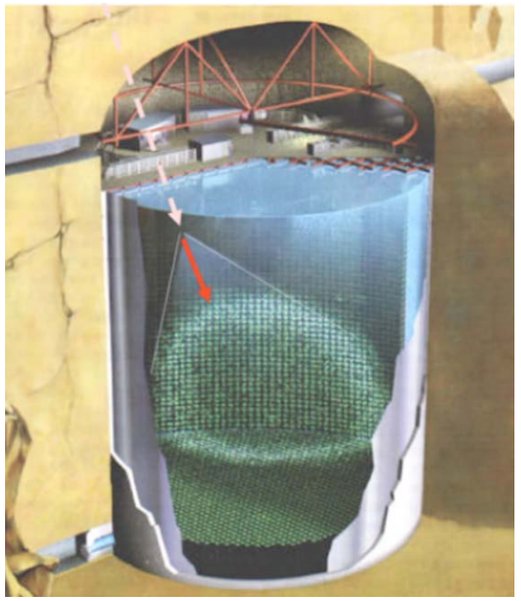
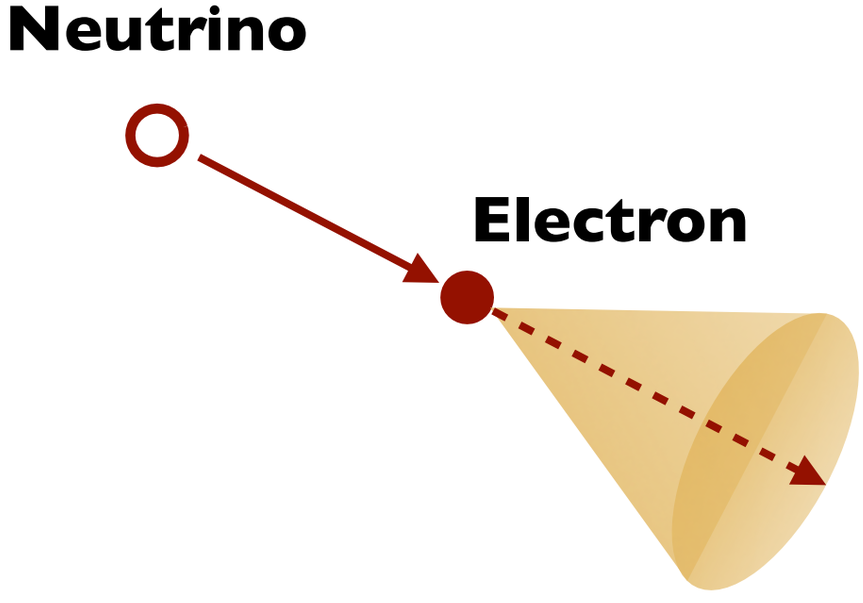
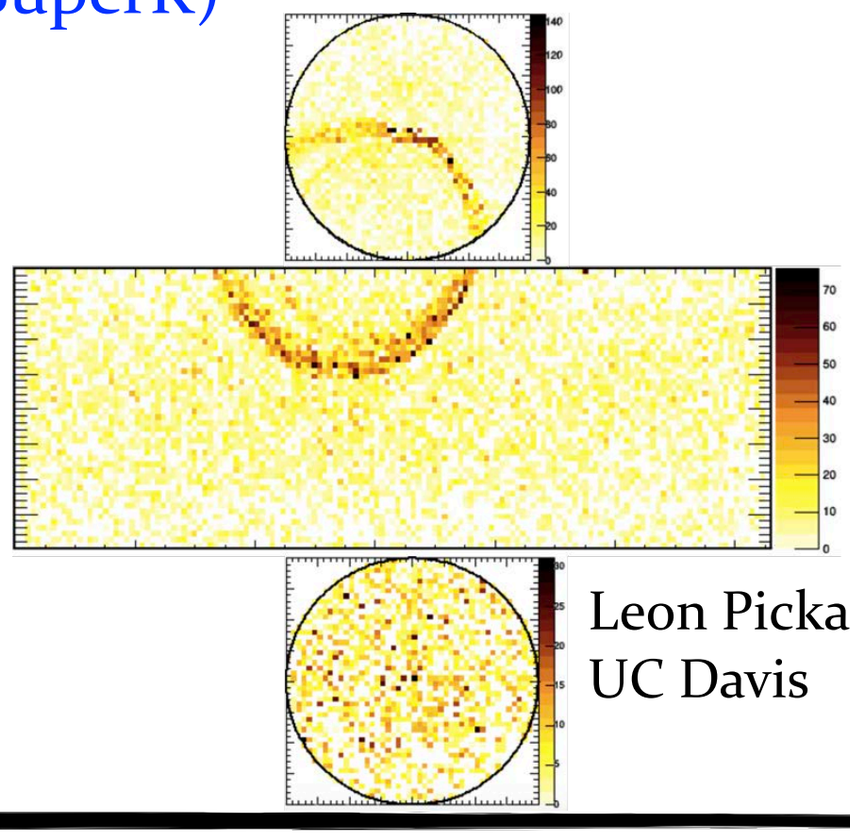






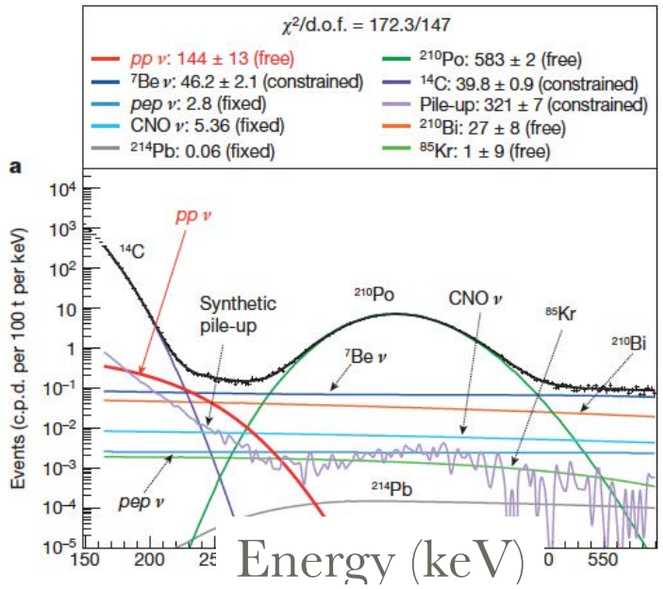
Leon Pickard,
UC Davis

Power of a Scintillation Detector

- High light yield
  - Low threshold, sub-Cherenkov-t/h detection
  - Good energy & vertex resolution
- "Fast" timing at low threshold: coincidence tag
- Particle identification
- Can be made ultra clean

Demonstrated at kt-scale (KL, Borexino)

Borexino Nature article



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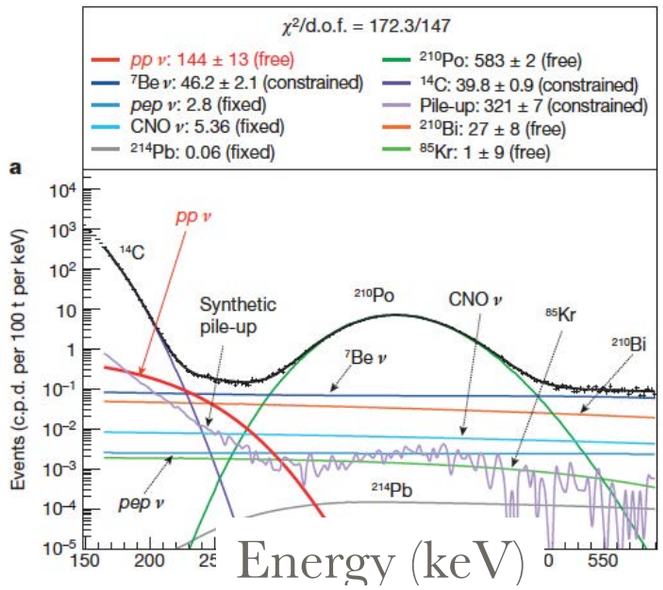

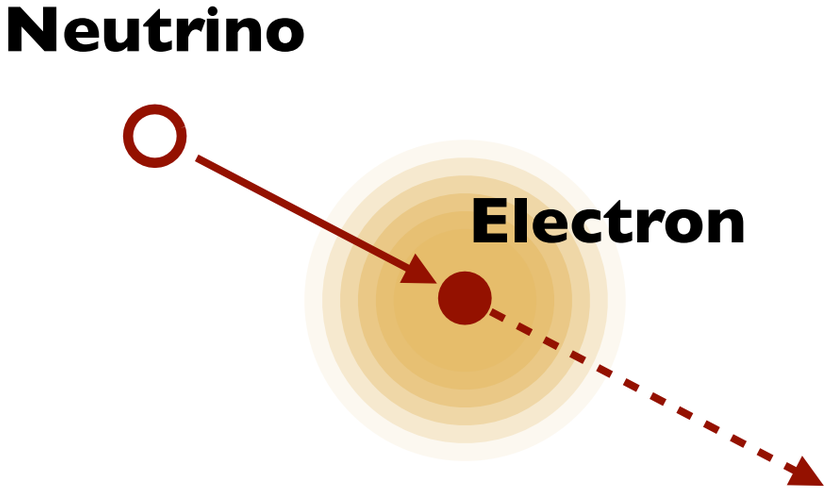

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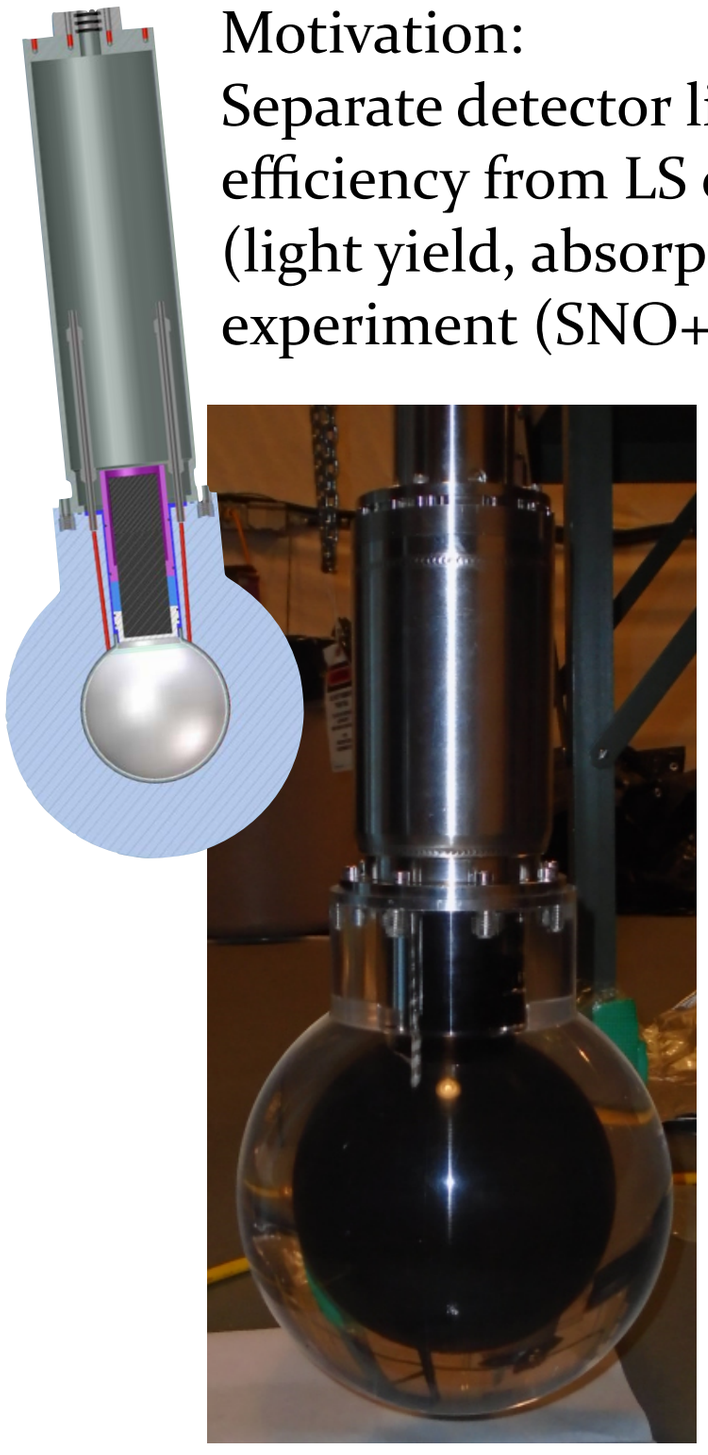
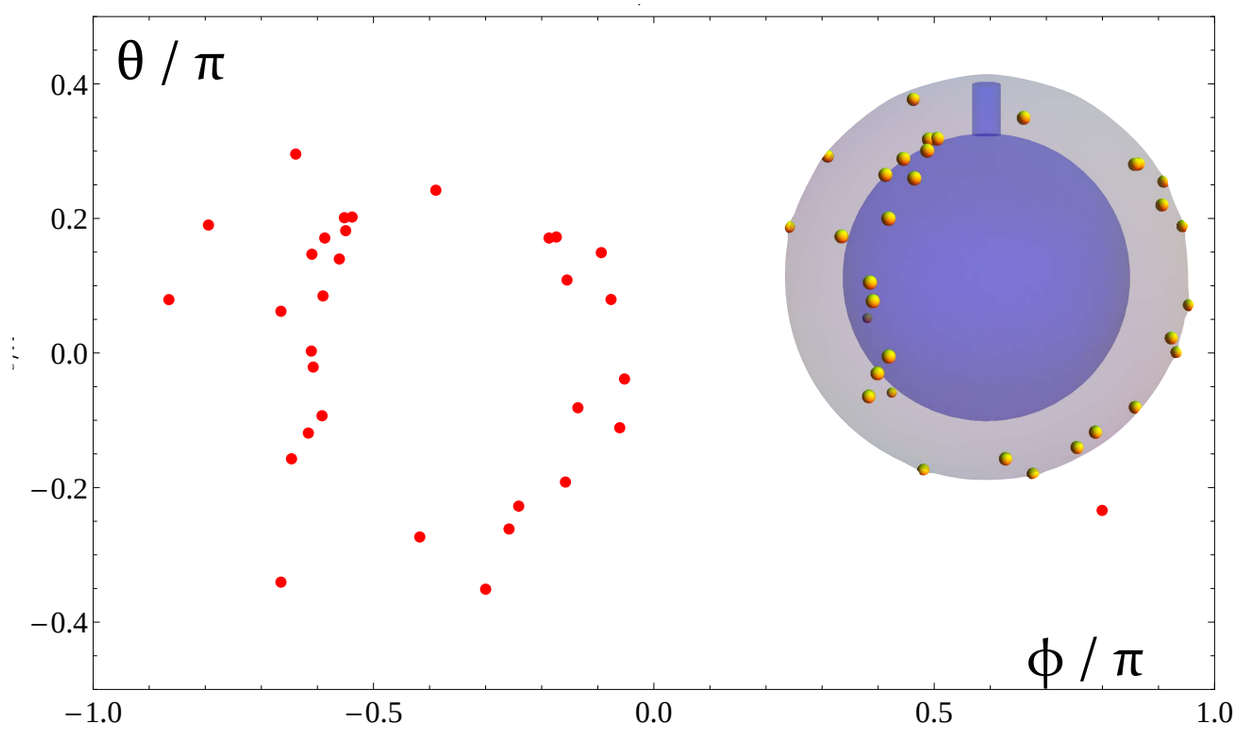
Cherenkov Calibration

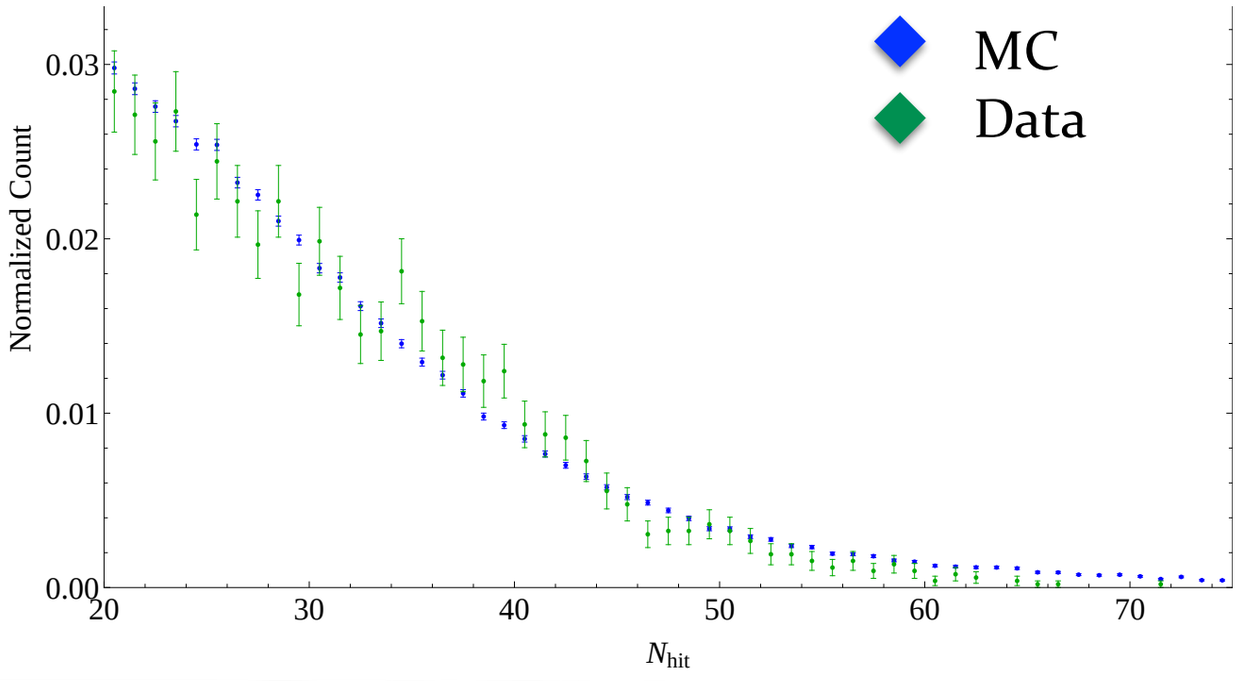


Motivation:
Separate detector light collection efficiency from LS optical properties (light yield, absorption) in a pure LS experiment (SNO+)

Bonus:
Demonstrate transmission of Cherenkov spectrum through LS target

PMT hit pattern in water

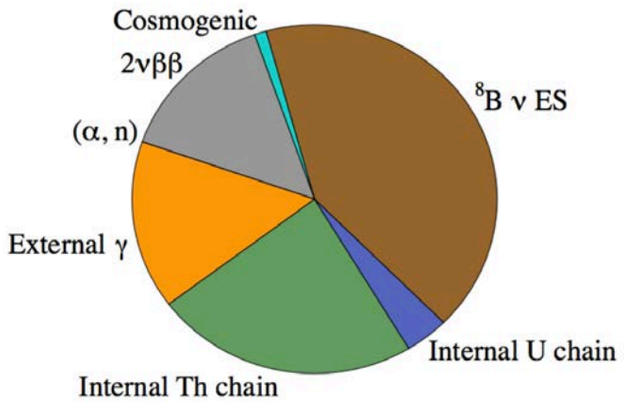




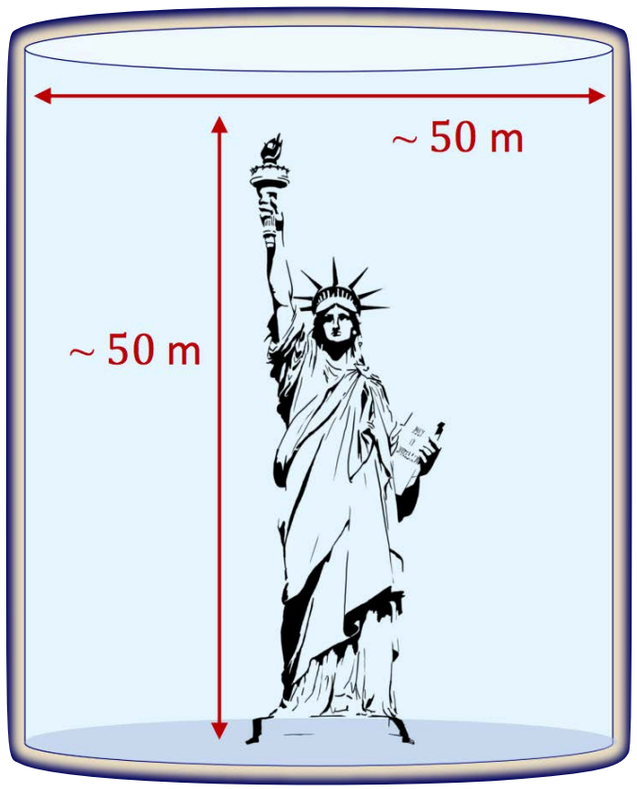
NLDBD with Theia

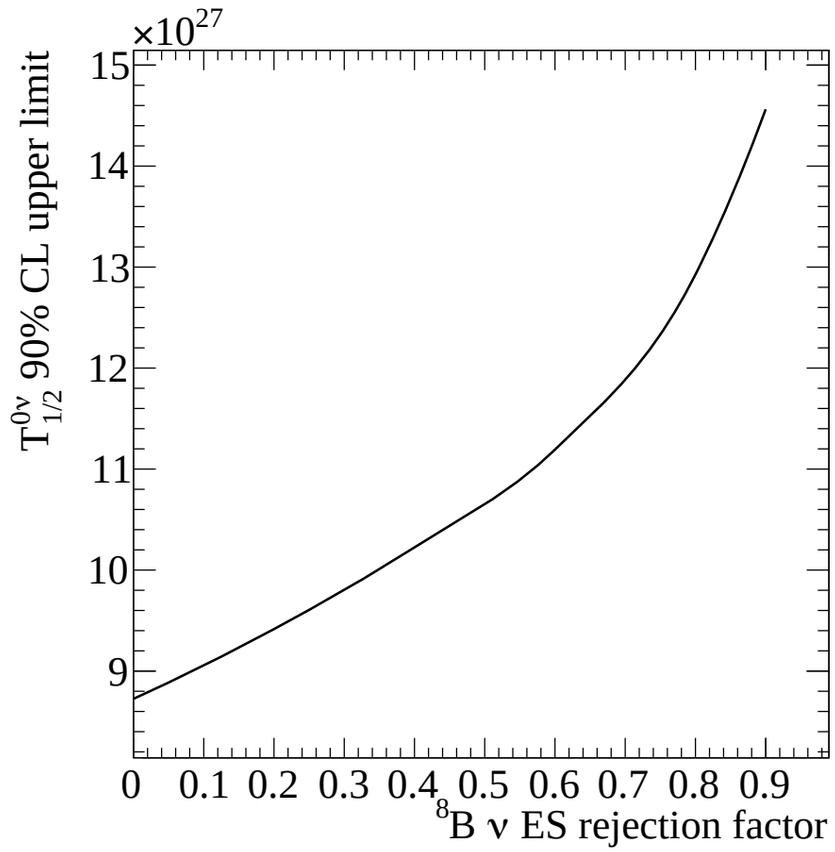
Builds on critical developments by KLZ & SNO+ collaborations

50 kton water-based liquid scintillator detector
High coverage with fast photon detectors
Deep underground
8-m radius balloon with high-LY LS and isotope
7-m fiducial, 3% ^{nat}Te, 10 years



SNO+ Collaboration



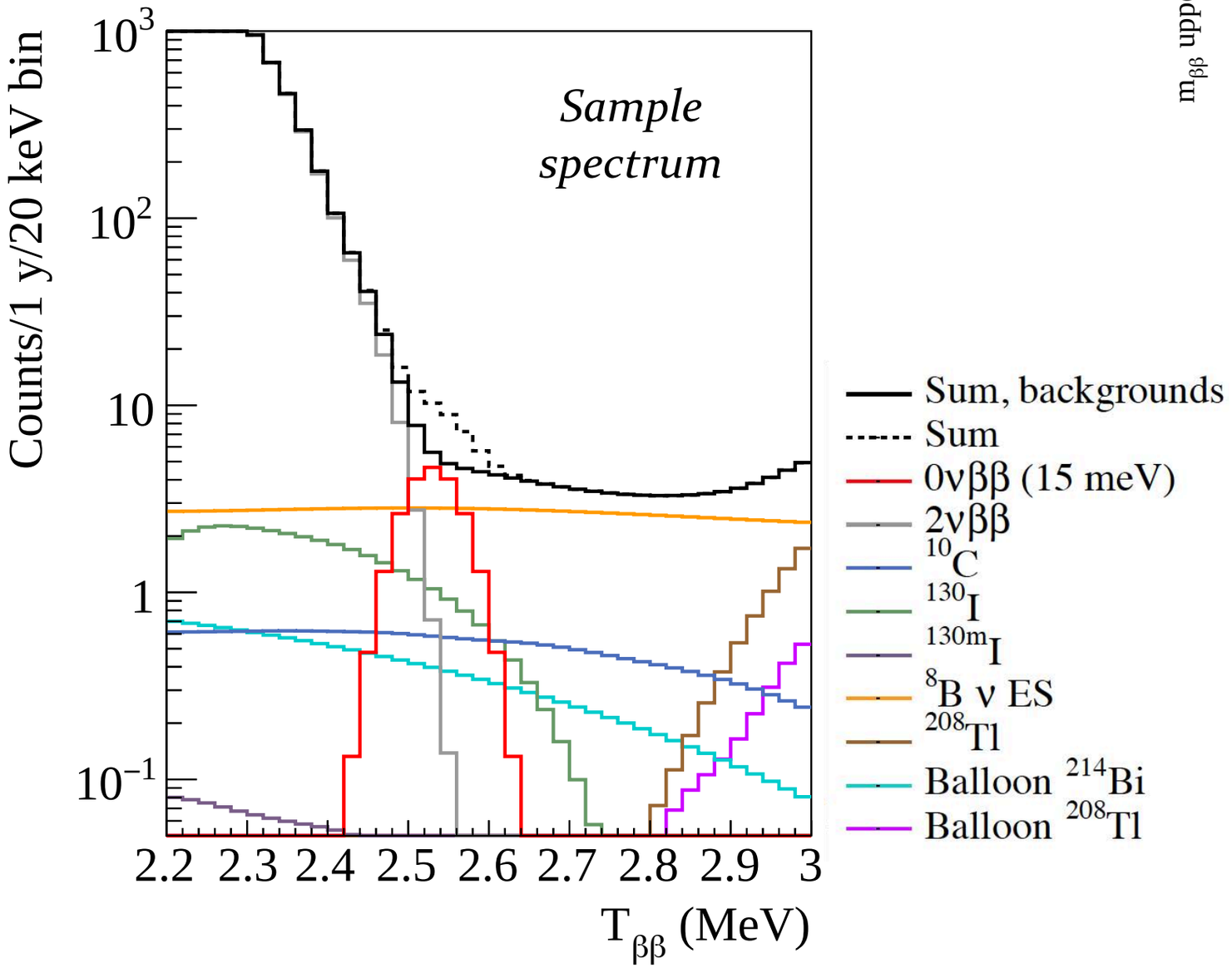


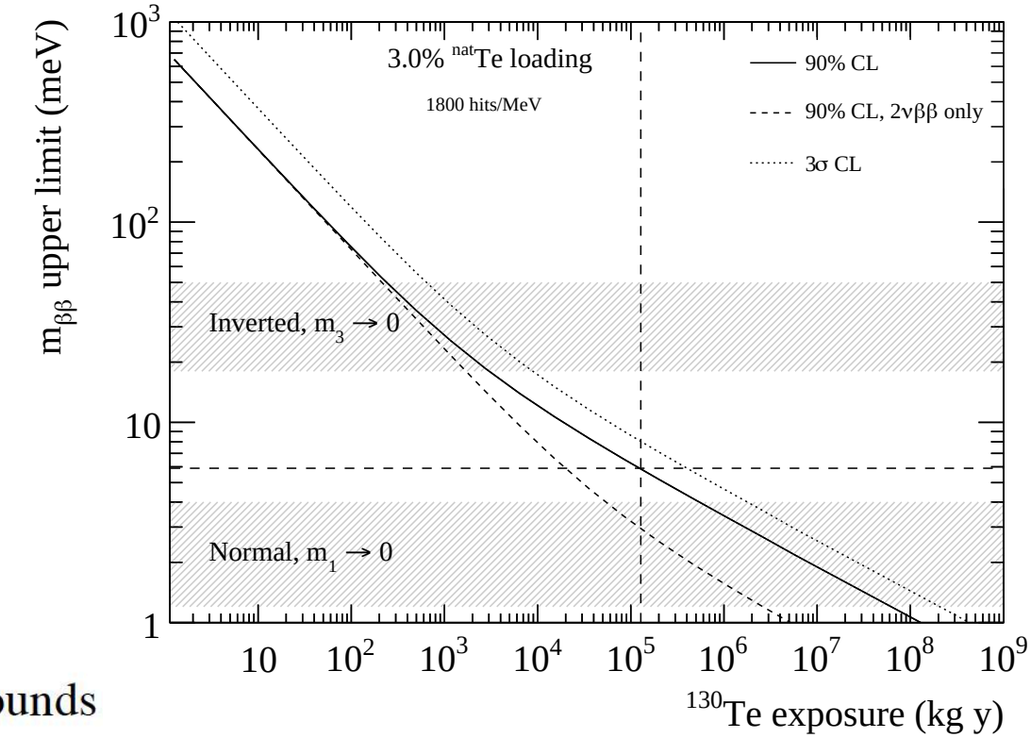
Signal	Events
$0\nu\beta\beta$ (15 meV)	147.3
$0\nu\beta\beta$ (10 meV)	65.6
$2\nu\beta\beta$	11.9
^{8}B Solar ES	132.9
^{10}C	27.0
^{130}I	41.3
^{130m}I	1.5
^{208}Tl	0.007
Balloon ^{214}Bi	17.7
Balloon ^{208}Tl	0.63
Total	232.9

Phys.Rev.Lett.110 : 062502 (2013);Adv.High Energy Phys. 2016 (2016) 6194250; Phys. Rev. D 87 no. 7 : 071301 (2013)

NLDBD with Theia

7-m fiducial, 3% ^{nat}Te, 10 years



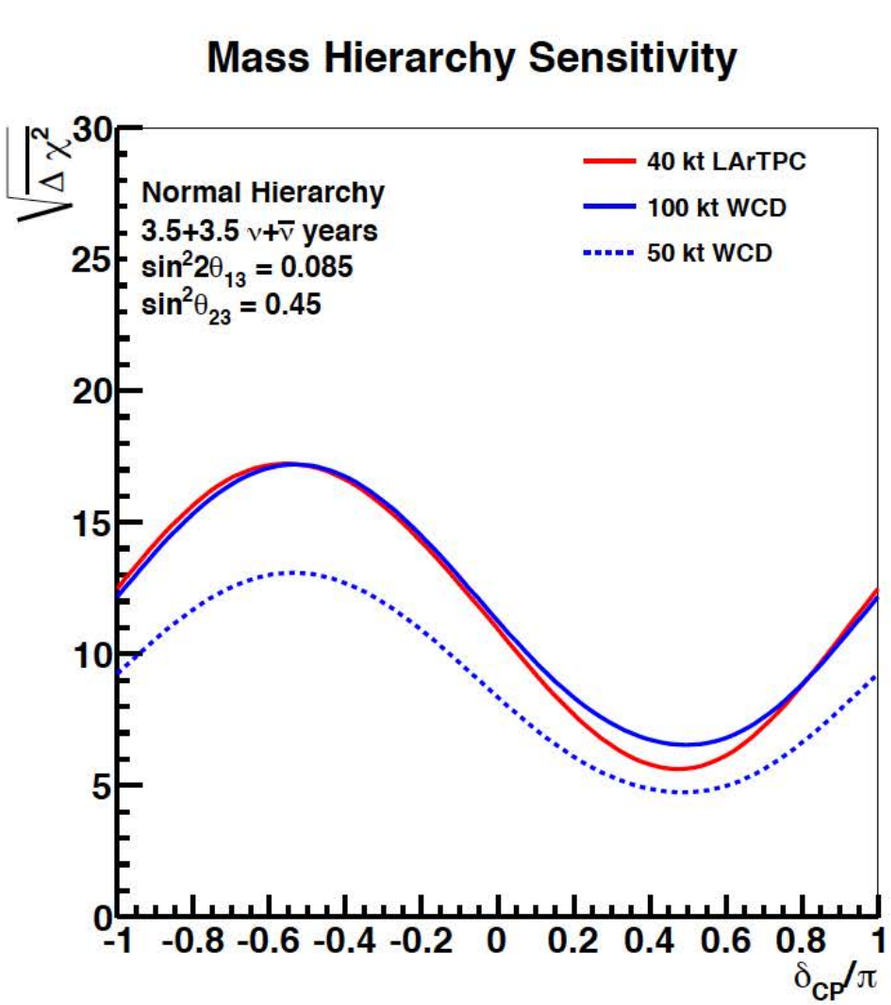


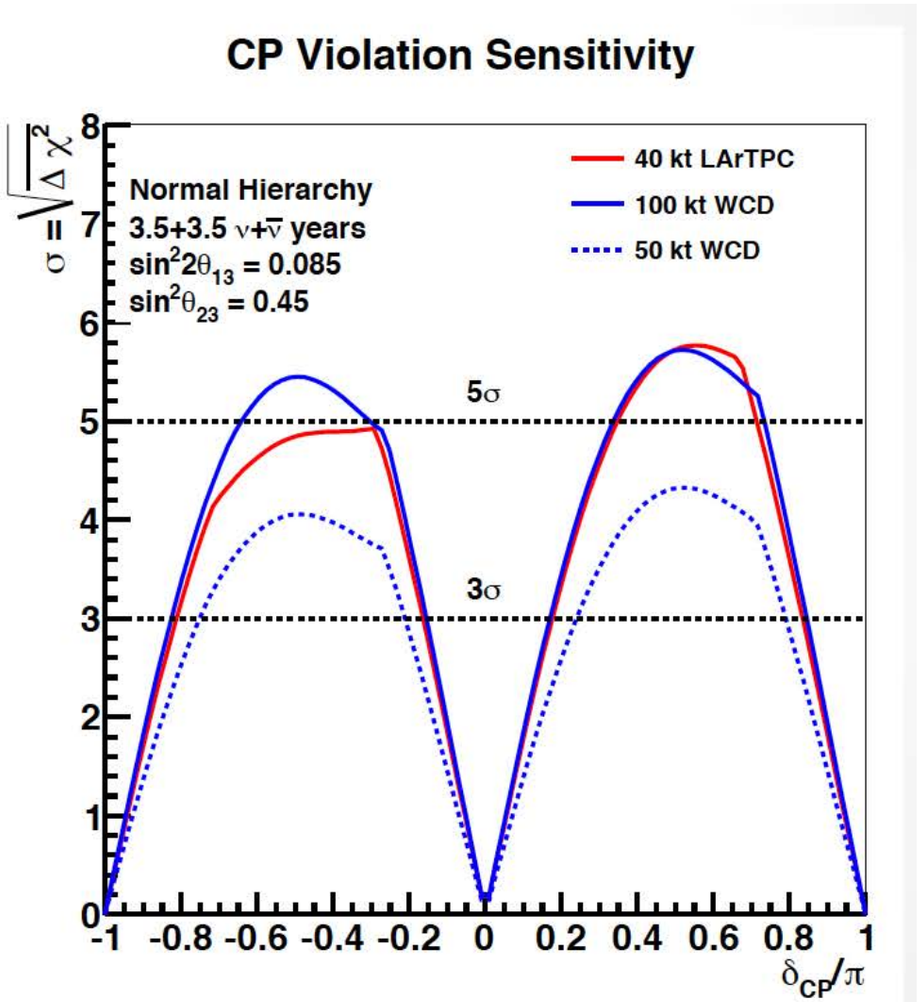
$T_{1/2} > 1.1 \times 10^{28}$ yrs (90% CL)

$m_{\beta\beta} < 6.3$ meV (IBM-2 NME)

Long-Baseline Program

- Large-scale detector at Homestake, in the LBNF beam
- Complementary program to LArTPC (DUNE)
- Build on WCD studies (arXiv:1204.2295)
- Plus advantages from low-threshold scintillation





MH sensitivity for 50kt WbLS alone > 5σ

Study by E. T. Worcester using same GLOBES package used for ELBNF

Open Questions in Solar ν

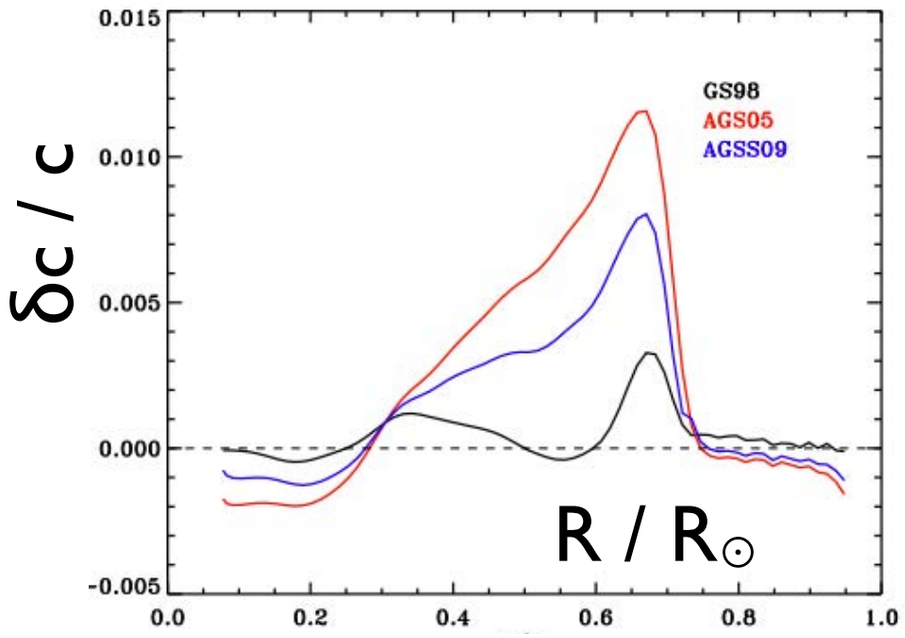
- Detect CNO neutrinos:

Determine solar metallicity

Test understanding of heavier main-sequence stars

Test postulate of homog. T=0 Sun

Text extent of CN-cycle eqm



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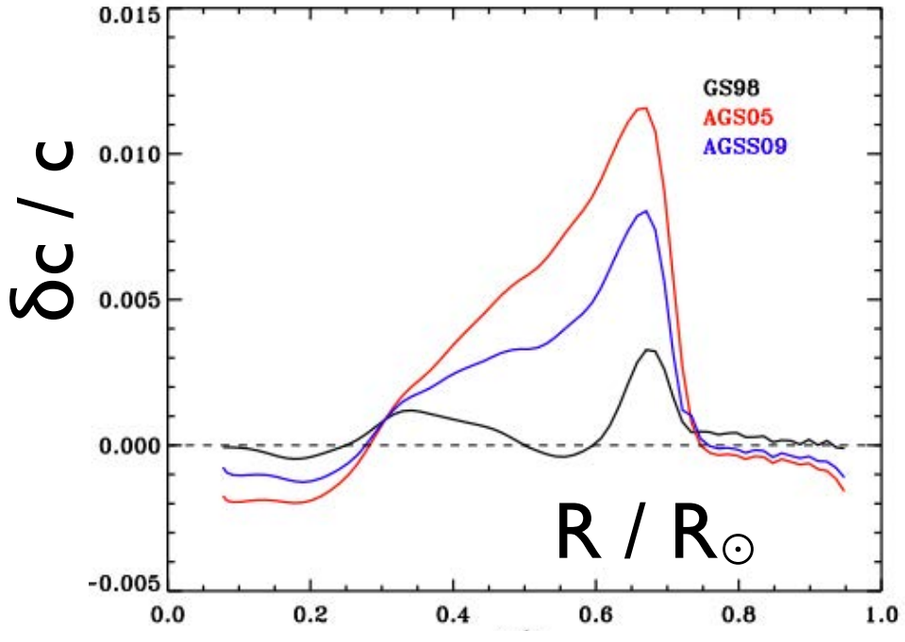
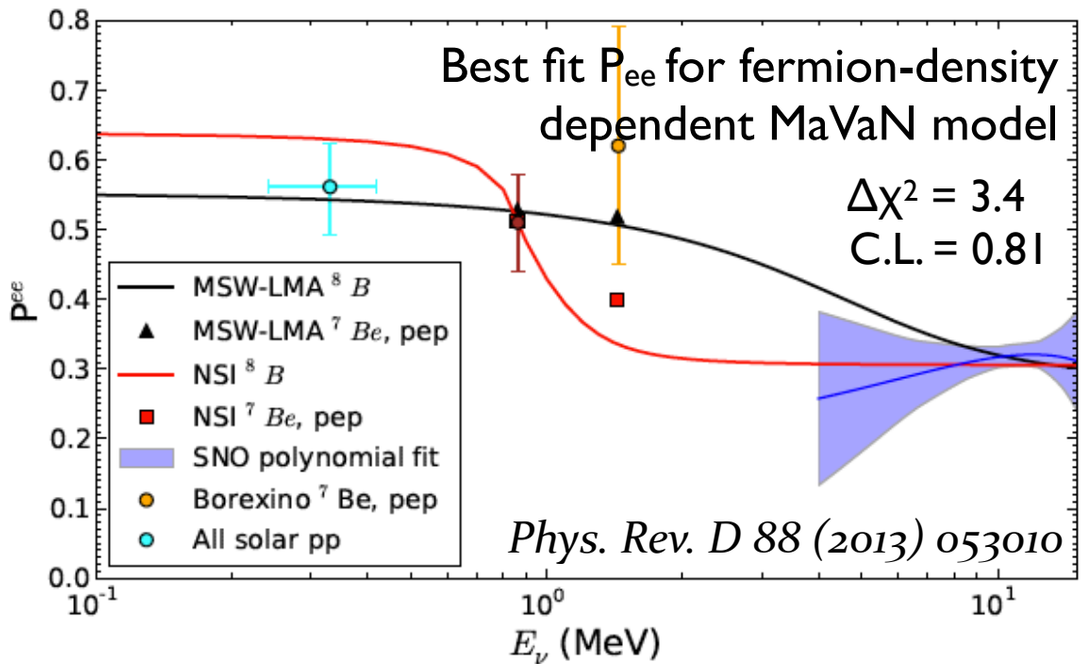


- Probe vacuum-matter transition via low-energy ^{8}B spectrum:

Confirm MSW

Sensitive search for new physics



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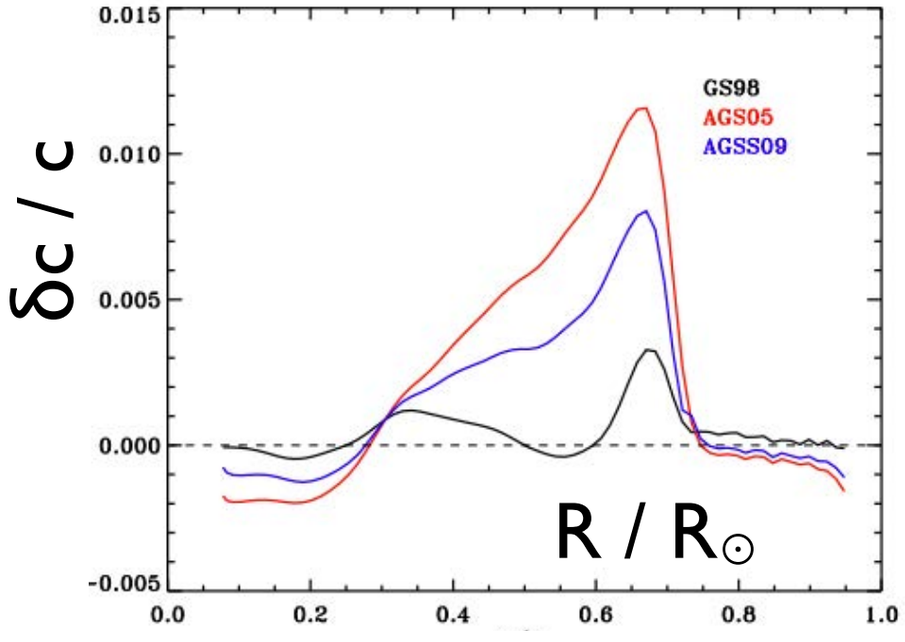

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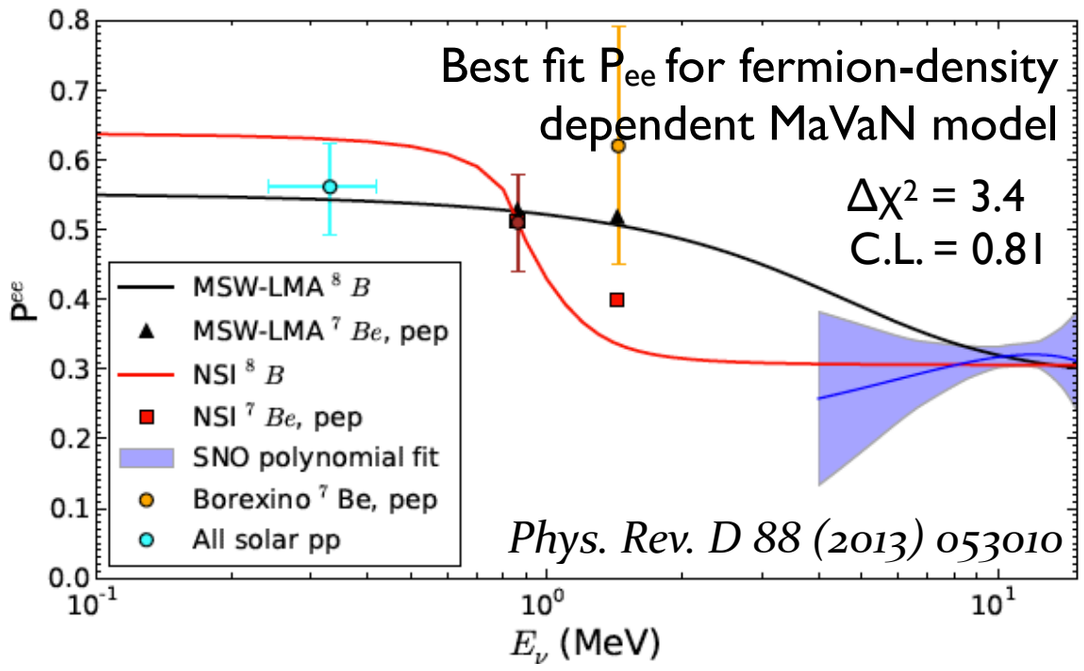


- High-precision pep flux — luminosity
- High-precision ^{7}Be flux — solar T, Δm^2_{21} to 0.1%, geo-tomography

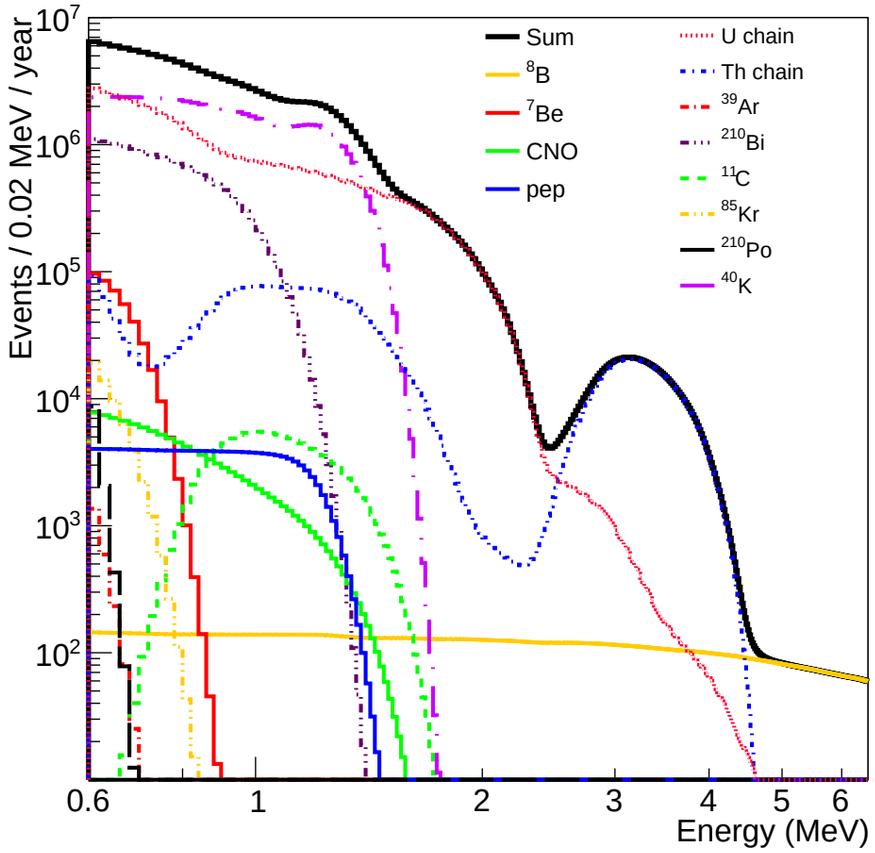
PRD92 013014 (2015)

- Separation of CNO components

Solar Neutrinos with Theia

Solar Neutrinos with Theia

- Dominant background to CNO ν measurement: ^{210}Bi



Solar Neutrinos with Theia

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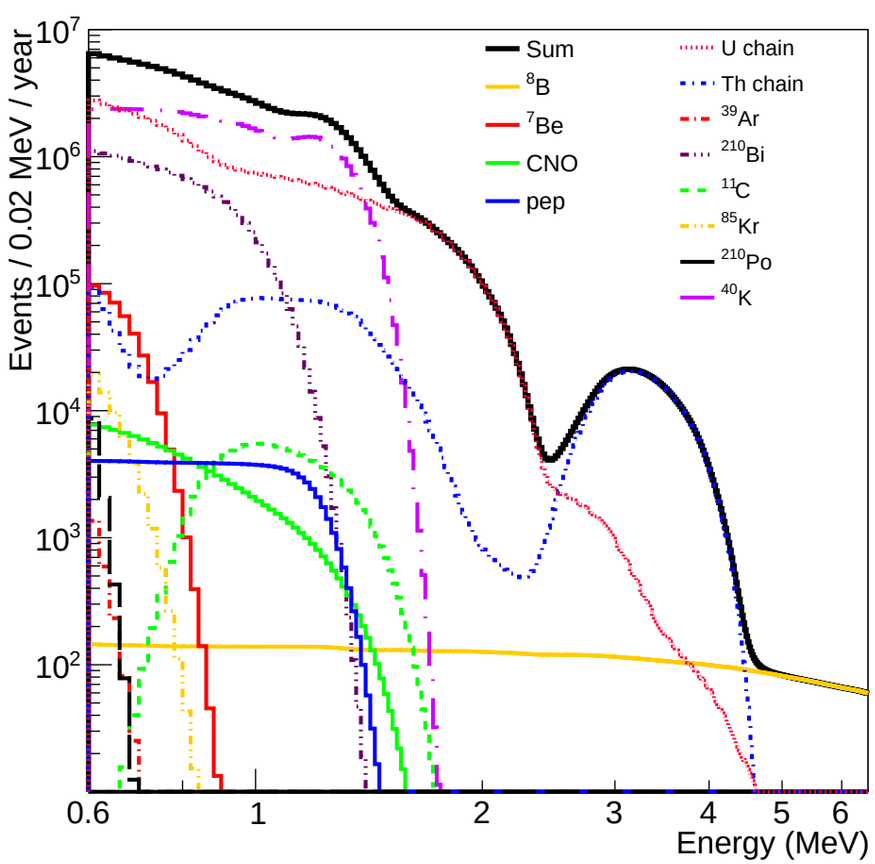
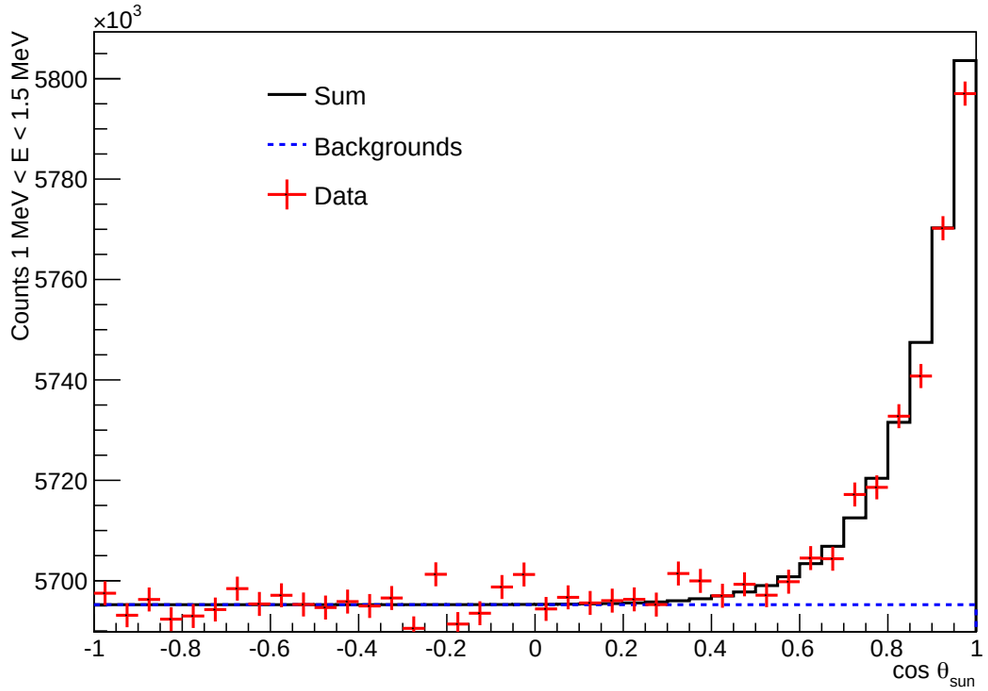




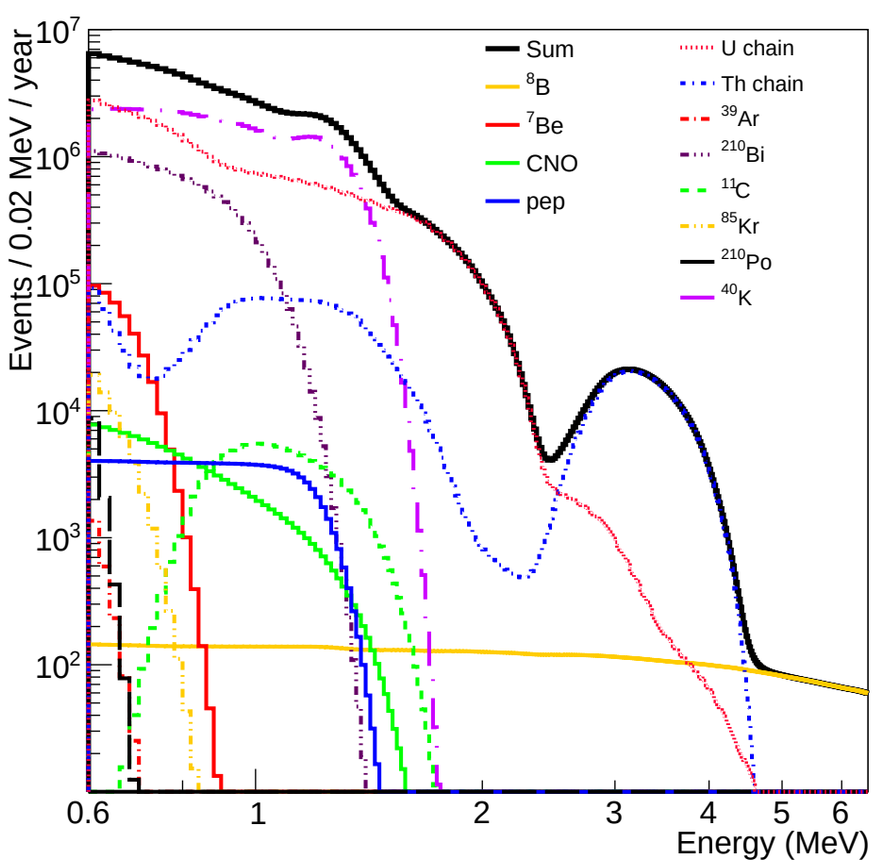
2D fit in energy and cos(θ_{sun})

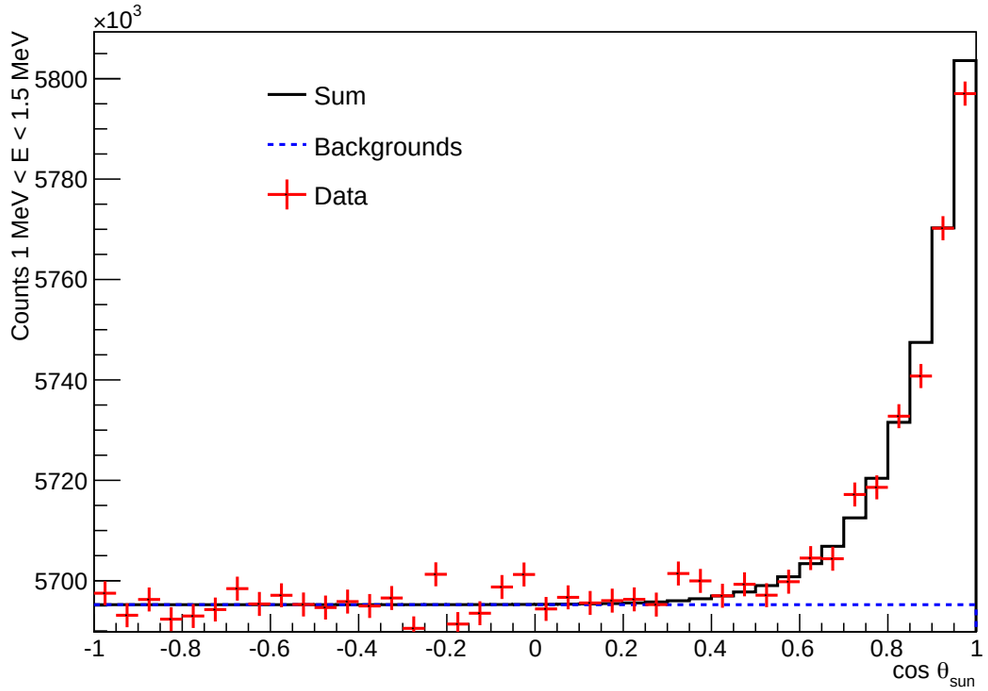
Eur. Phys. J. C (2018) 78: 435

Solar Neutrinos with Theia

- Dominant background to CNO ν measurement: ^{210}Bi
- Theia offers unique low-threshold, directional detection
- Ability to separate Cherenkov and scintillation signals demonstrated in pure LS (LAB + 2 g/L PPO)

PRC 95 055801 (2017)
Eur. Phys. J. C (2017) 77: 811





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Eur. Phys. J. C (2018) 78: 435

Theia Detector Parameters

Baseline detector:

5 years

50-kton (x 50% fiducial)

5% WbLS

90% coverage

25^{o} resn

SNO bkg levels in H_2O

0.1x Borex value for ^{40}K

Borexino-I bkg levels in LS

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Variables considered:

Mass	*25 -- 50-kton*
Target	*0.5 -- 5% WbLS*
Coverage	*60 -- 90%*
Angular resn	*25^{o} - 55^{o}*
Bkg levels in H_2O	*x10-10,000*
BiPo & α rejection	*0 -- 95%*

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	H_2O level (g/gH_2O)	LS Level (g/gLAB)
^{238}U chain	6.63e−15 [37]	1.6e−17 [35]
^{232}Th chain	8.8e−16 [37]	6.8e−18 [35]
^{40}K	6.1e−16[a]	1.3e−18 [36]
^{85}Kr	2.4e−25[b]	2.4e−25 [36]
^{39}Ar	2.75e−24[b]	2.75e−24 [36]
^{210}Bi	3.78e−28[b]	3.78e−28 [36]
^{11}C	0	1.0e5 (ev/kT/year) [4]

[a]The ^{40}K level in water is taken to be 0.1× the Borexino measurement [34]

[b]The ^{85}Kr, ^{39}Ar, and ^{210}Bi levels in water are taken to be the Borexino measured level in scintillator [36], although levels increased by several orders of magnitude are explored

Eur. Phys. J. C (2018) 78: 435

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Angular resolution:

Expected photon hits in Theia:
SNO saw ~36 hits at 5MeV, ~26.7º [31]
SuperK ~ 41 hits at 6MeV ~ 35º [32]

	All Cherenkov photons	
	0.6 MeV	1.0 MeV
25 kT	12.5	37.6
50 kT	11.5	34.7

Eur. Phys. J. C (2018) 78: 435

Theia Flux Sensitivity

Baseline detector:

50-kton target volume (x 50% fiducial)
5% WbLS target material
90% photocathode coverage
25° angular resolution

5 years data taking
H_2O background levels from SNO
exc. 0.1x Borexino value for ^{40}K
LS background levels from Borexino-I

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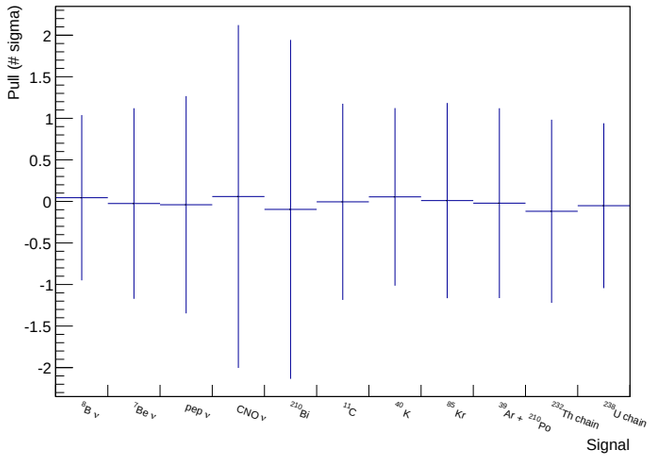
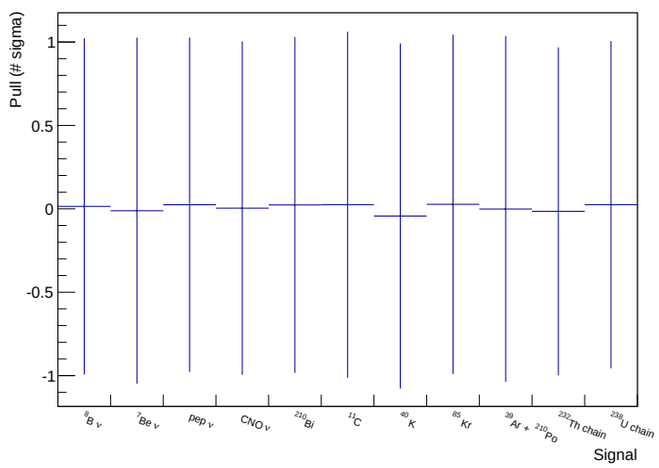


CNO & ^{210}Bi signals highly correlated (-0.84) in pure LS fit, errors not accurate

Pull distribution shows unbiased fit for WbLS Theia detector (mean pull ~0, RMS ~1)



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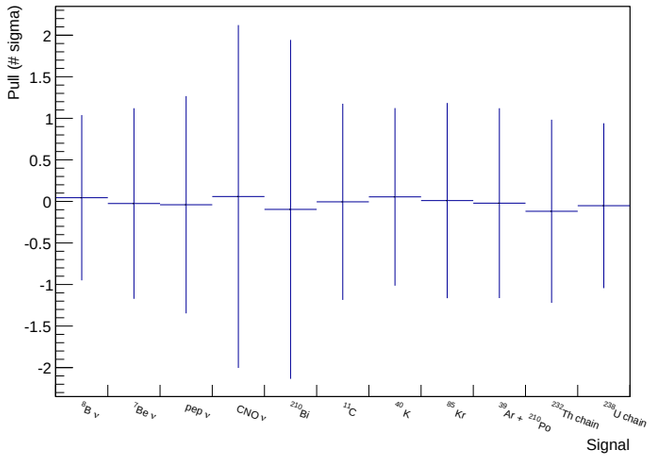
Theia Flux Sensitivity

Baseline detector:

50-kton target volume (x 50% fiducial)
5% WbLS target material
90% photocathode coverage
25° angular resolution

5 years data taking
H_2O background levels from SNO
exc. 0.1x Borexino value for ^{40}K
LS background levels from Borexino-I



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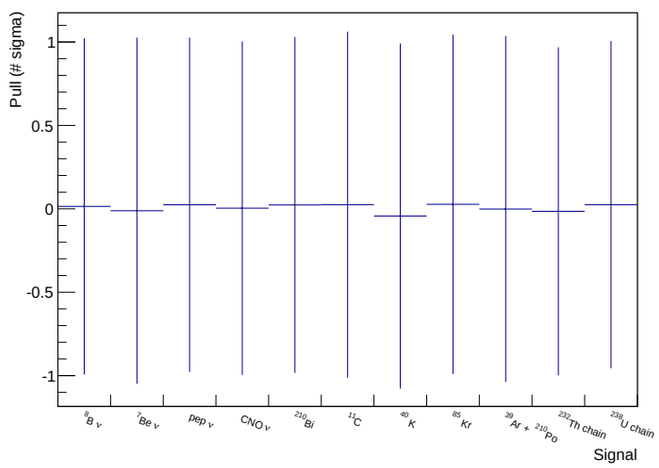

Signal	Normalization sensitivity (%)
^{8}B ν	0.4
^{7}Be ν	0.4
pep ν	3.8
CNO ν	5.3
^{210}Bi	0.1
^{11}C	11.5
^{85}Kr	10.5
^{40}K	0.04
$^{39}Ar/^{210}Po$	21.9
^{238}U chain	0.02
^{232}Th chain	0.05

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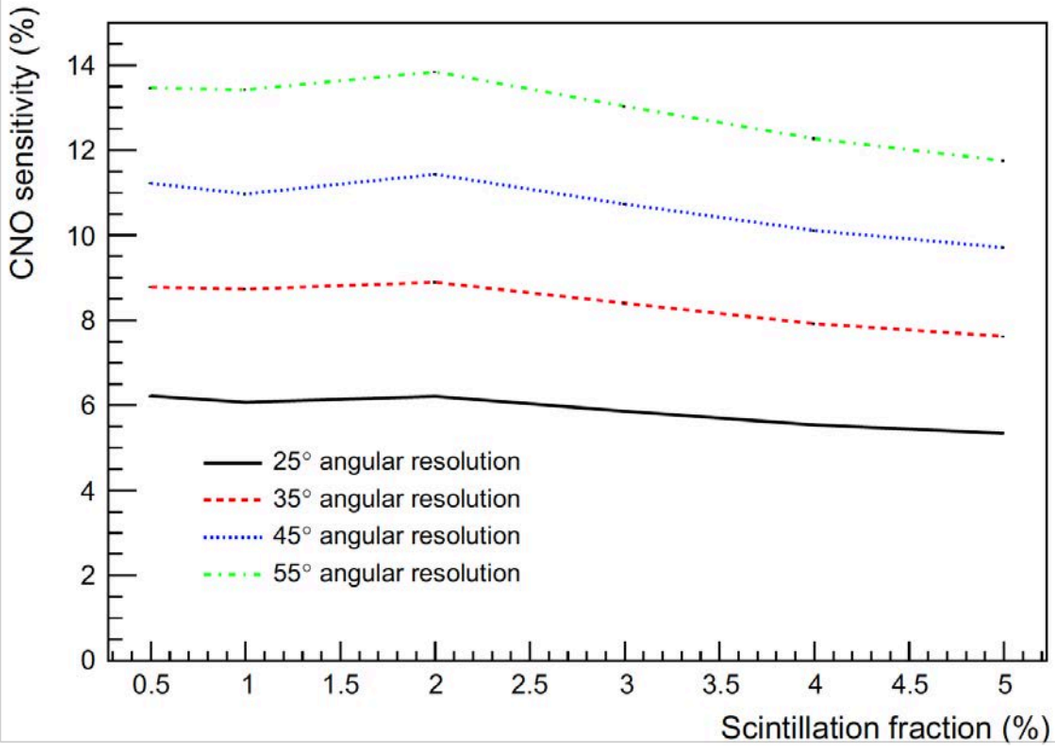
Detector Parameters

Impact of detector design parameters



Target mass	WbLS	Angular resolution			
		25°	35°	45°	55°
50 kT	0.5%	6.2	8.8	11.2	13.5
50 kT	1%	6.1	8.7	11.0	13.4
50 kT	2%	6.2	8.9	11.4	13.8
50 kT	3%	5.9	8.4	10.7	13.0
50 kT	4%	5.5	7.9	10.1	12.3
50 kT	5%	5.3	7.6	9.7	11.8
25 kT	0.5%	8.5	12.2	15.6	18.7
25 kT	1%	8.5	12.1	15.0	18.4
25 kT	2%	8.5	12.1	15.5	18.7
25 kT	3%	8.0	11.5	14.6	17.7
25 kT	4%	7.6	10.9	13.9	16.8
25 kT	5%	7.3	10.5	13.3	16.2

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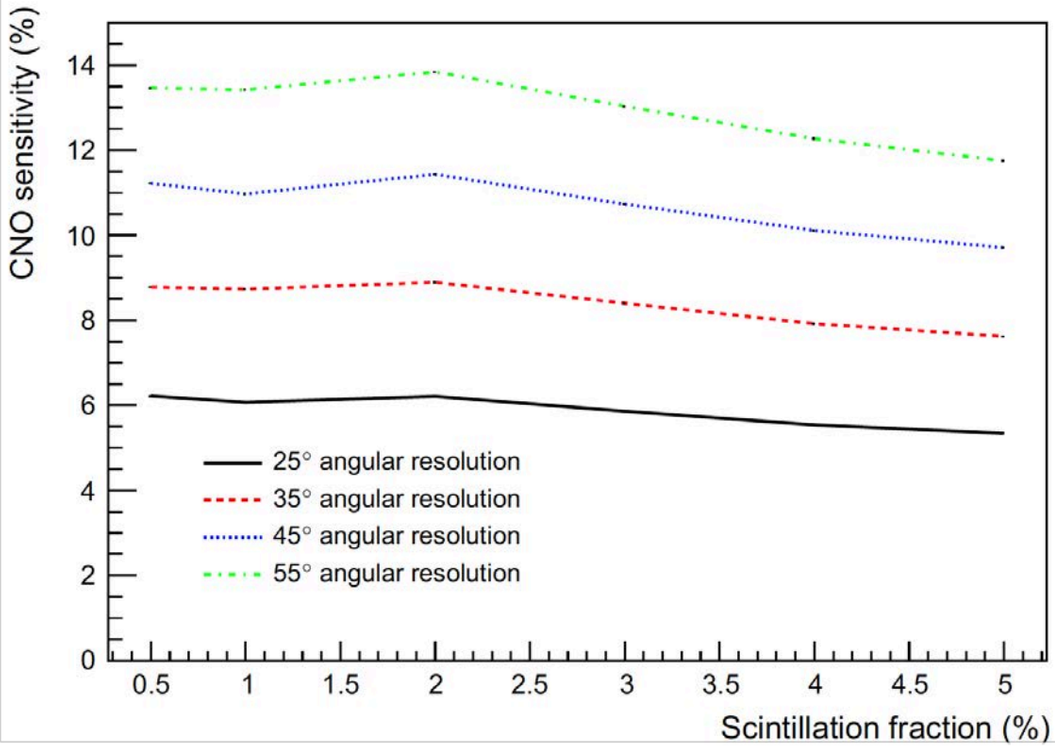

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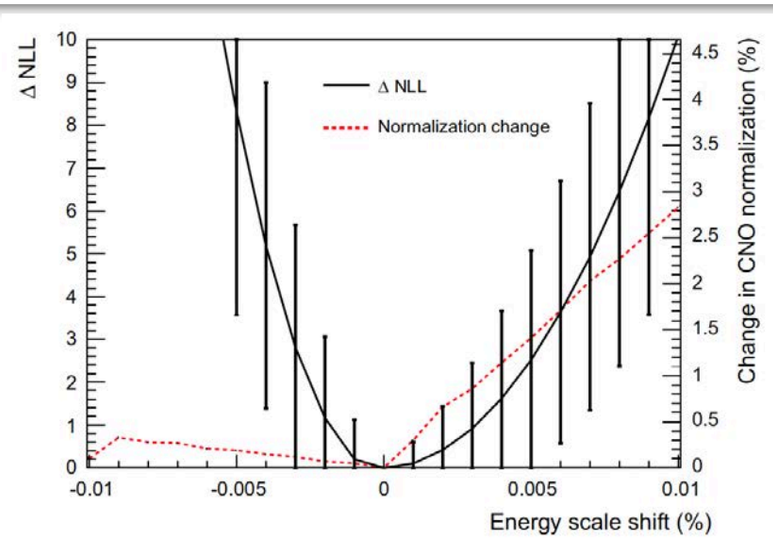

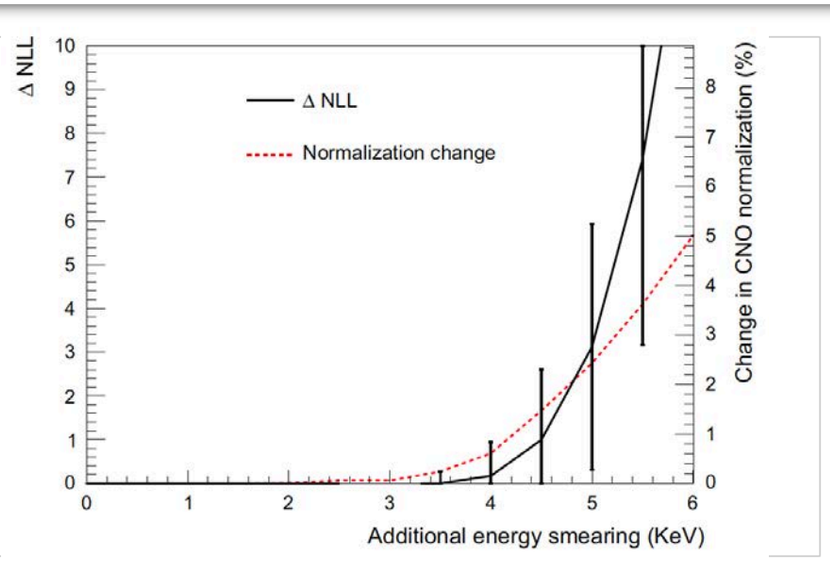

Impact of detector response (energy systematics)

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Backgrounds

Directional sensitivity means the fit is very robust to variations in intrinsic background levels

Sensitivity to ^{40}K level

	Baseline ^{40}K	*x10 ^{40}K*
Signal	Normalization sensitivity (%)	Normalization sensitivity (%)
^{8}B ν	0.4	0.4
^{7}Be ν	0.4	0.9
pep ν	3.8	8.6
CNO ν	5.3	11

Sensitivity to background levels

Fraction of nominal contamination	Isotope ^{11}C	^{210}Bi	^{85}Kr	^{39}Ar
0.1x	5.3	–	–	–
1x	5.3	5.3	5.3	5.3
10x	5.4	5.4	5.3	5.3
100x	5.5	6.0	5.4	5.4
1000x	–	9.4	5.6	5.4
10000x	–	–	5.9	5.5

Sensitivity to background rejection

	CNO sensitivity (%)
Nominal	5.3
No α rejection	5.4
No BiPo in-window rejection	5.4
No α, no BiPo in-window rejection	5.4
No α, no BiPo rejection	6.4

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Theia Spectral Sensitivity

arXiv:1409.5864

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

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

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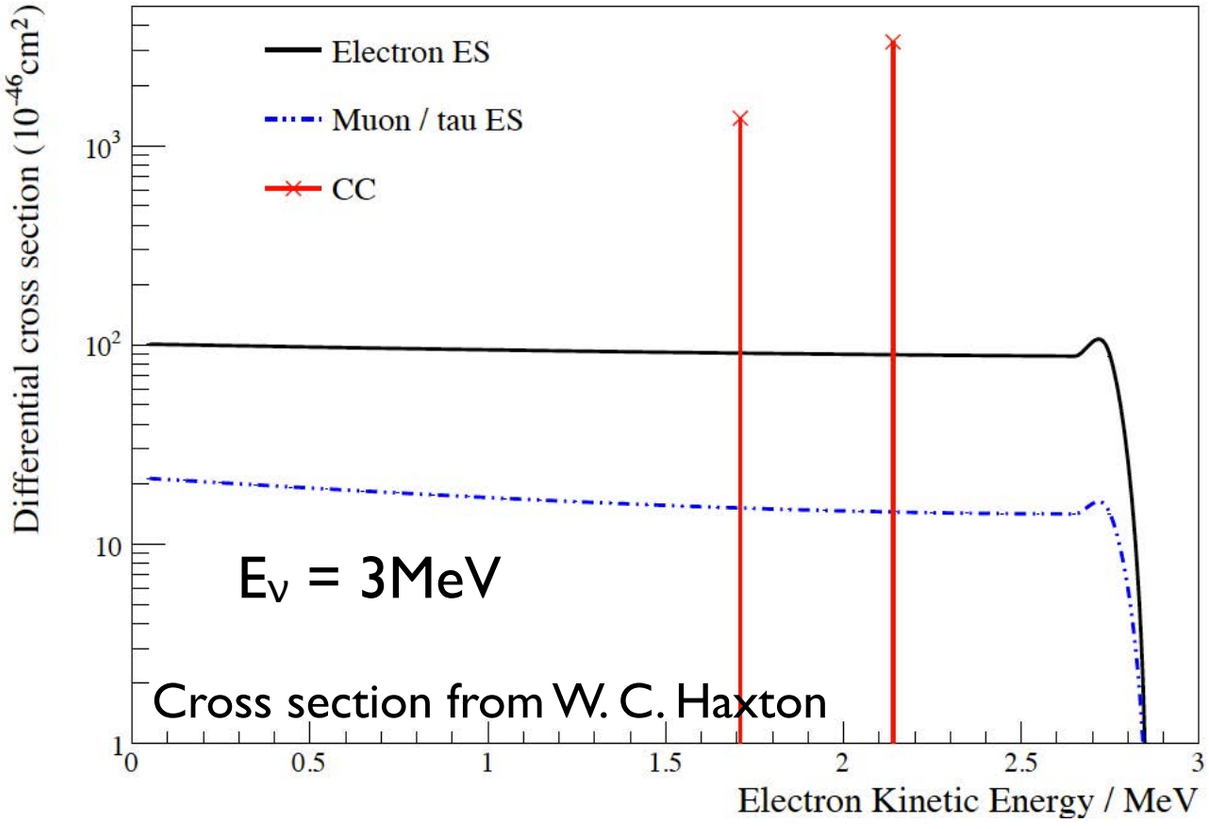

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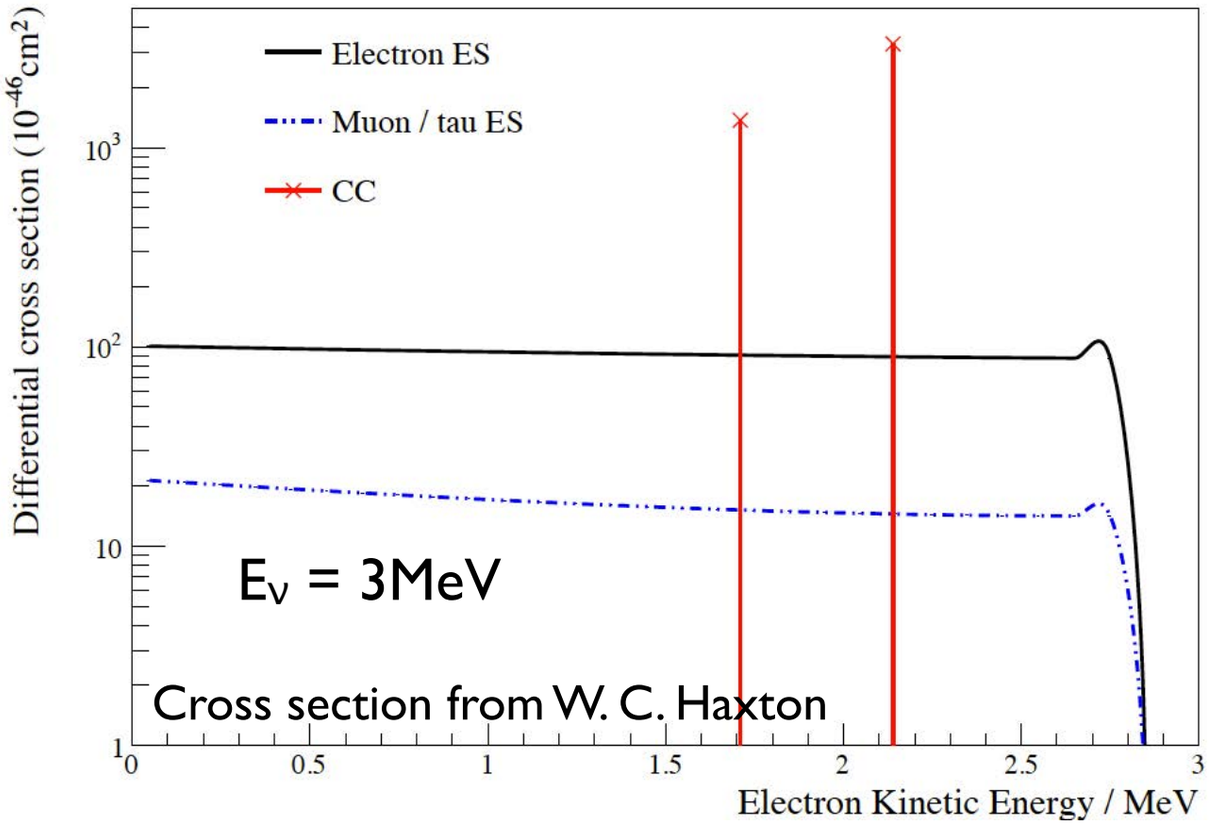

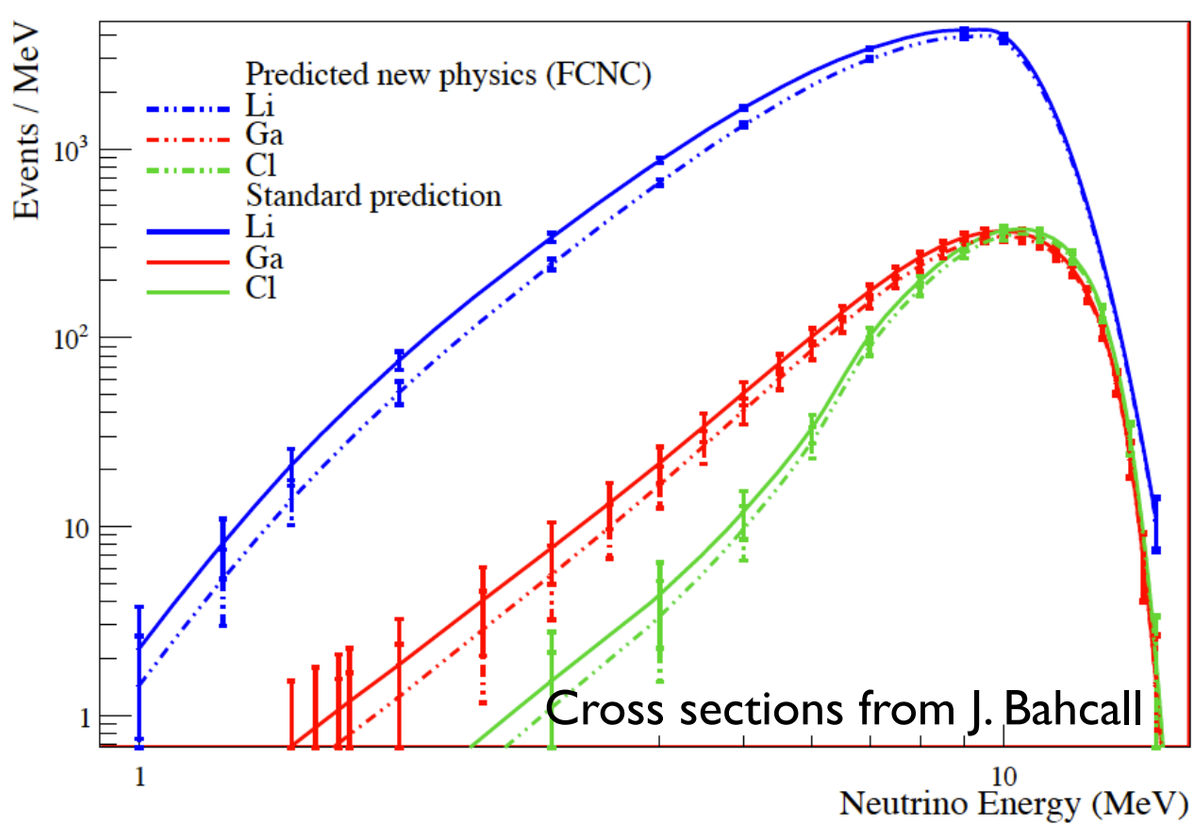

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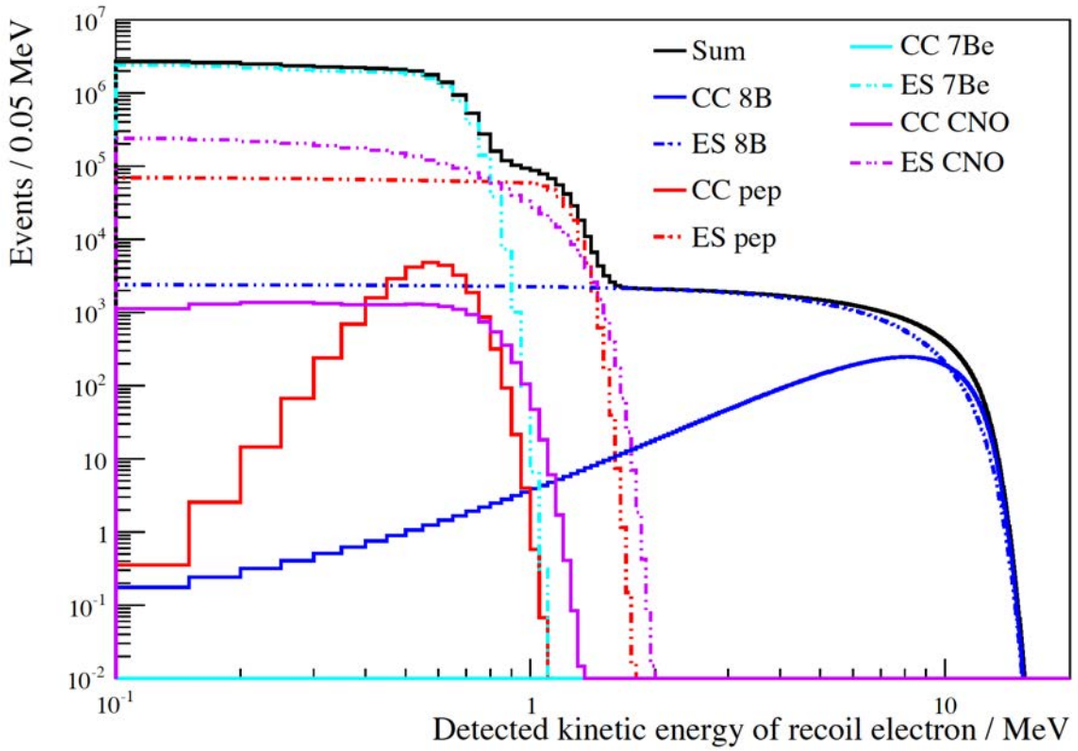
Theia Spectral Sensitivity

Unprecedented low-energy statistics (ES)



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

Similar to LENA — Astropart. Phys. 35 (2011) 685-732
+ directionality from Cherenkov

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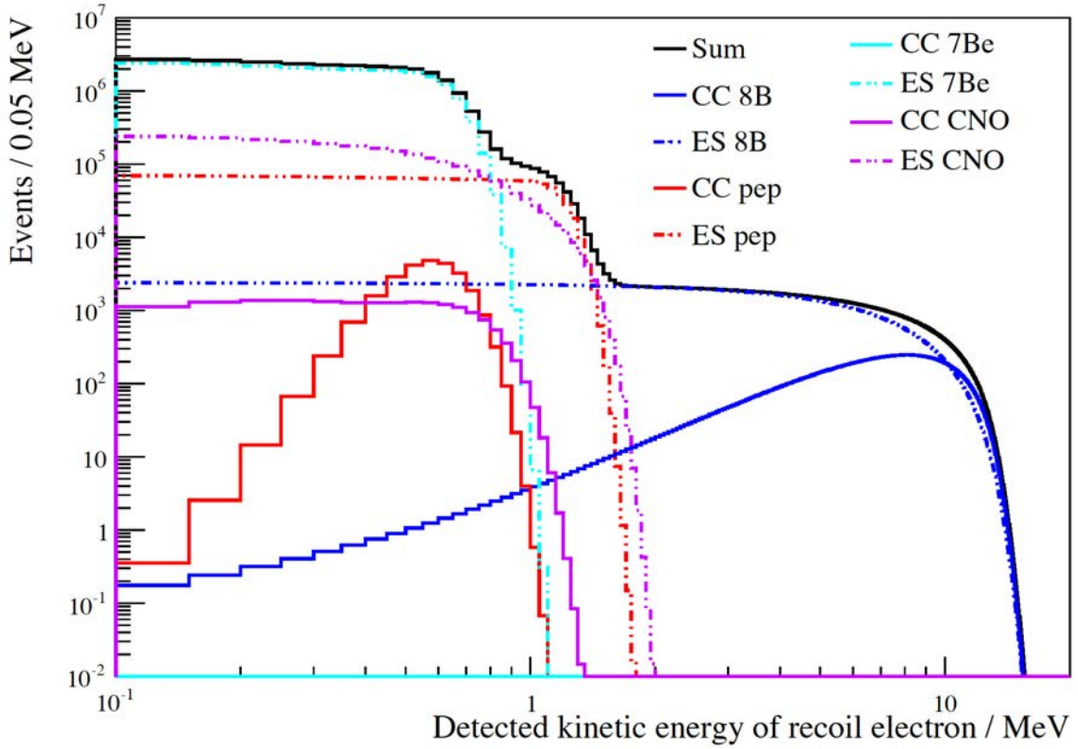

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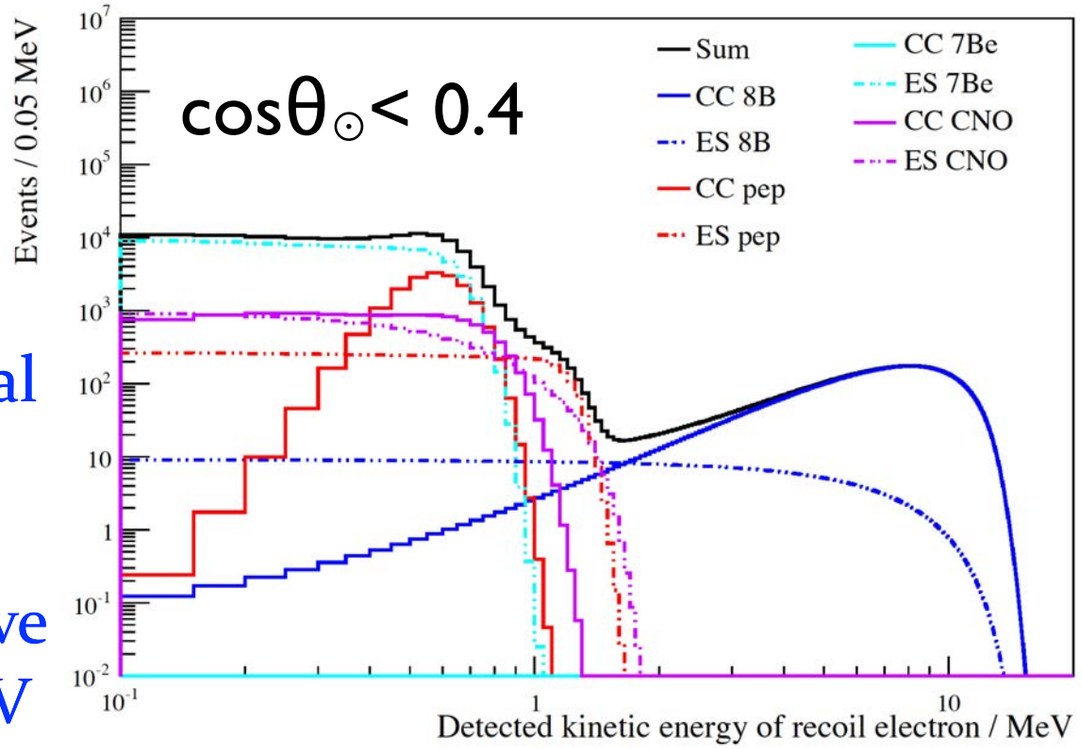

Enabled by use of WbLS (^{7}Li, CC)

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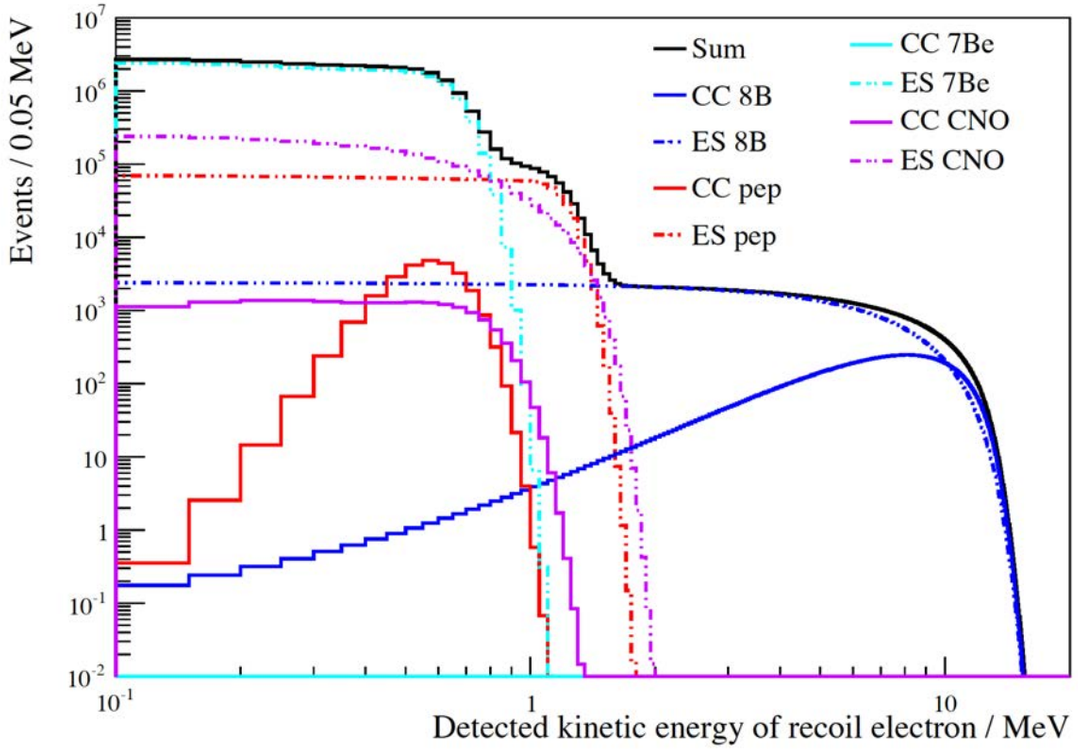

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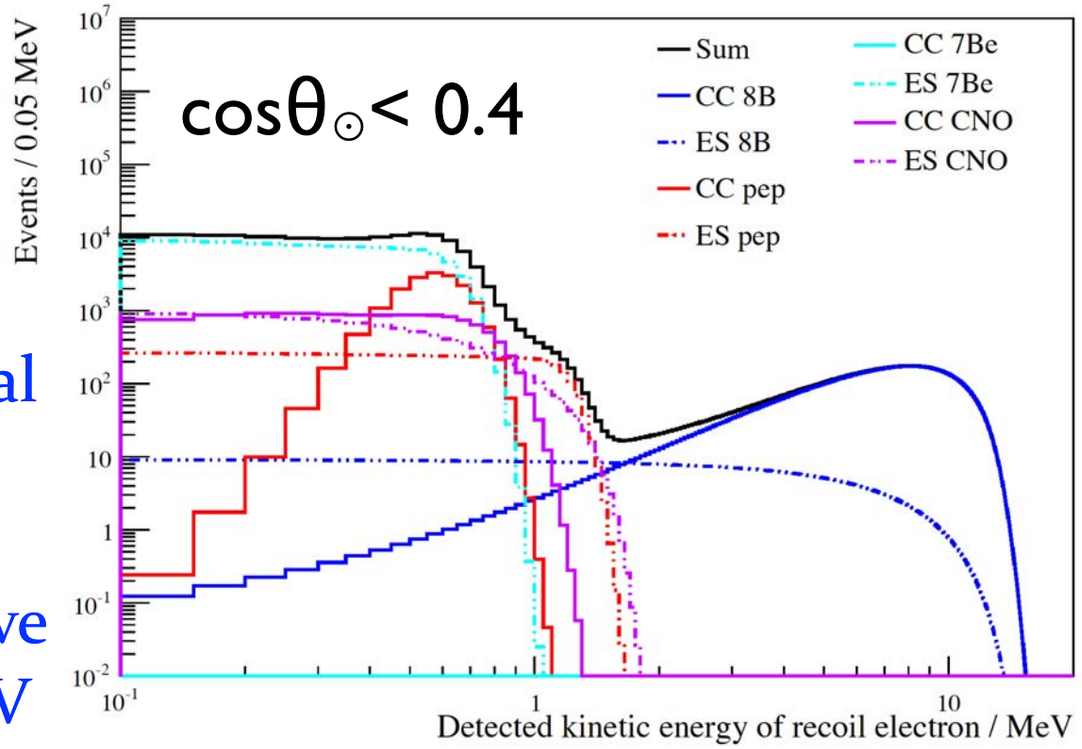

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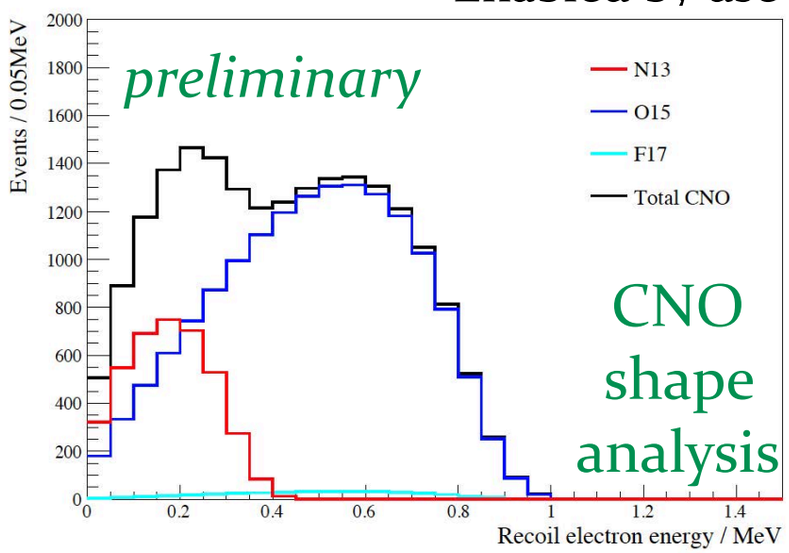
+ directionality from Cherenkov

Enabled by use of WbLS (7Li, CC)

Spectral information could allow separation of constituent CNO components

And potentially detect ecCNO ν

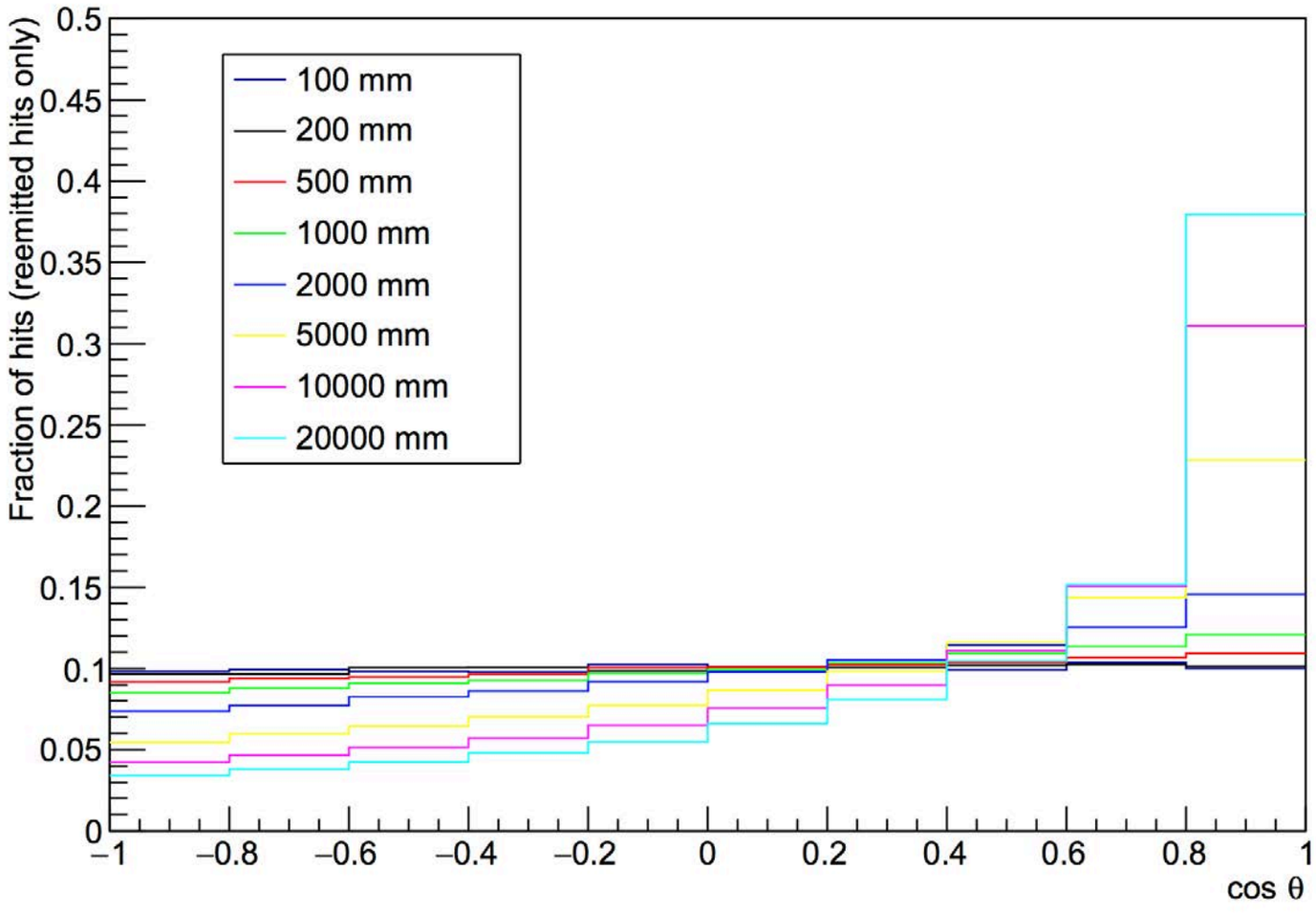


CNO shape analysis

arXiv:1409.5864

Directionality

- Toy MC (uniform and isotropic) as function of absn length (PPO fraction)
- Angle between initial photon direction and PMT hit direction (only plotting photons that are absorbed and reemitted)



^{7}Li Loading

$$^{7}Li + \nu_e \rightarrow {}^{7}Be + e^{-} \quad (\mathrm{Q} = 862\ \mathrm{keV})$$

- Two significant transitions
  - Mixed Fermi / GT transition to GS, threshold = 0.862 MeV
  - Super-allowed GT to 1st ES (~ 430 keV), τ ~ 200 fs
- Potential to differentiate e^- from (e^- + γ) using isotropy of PMT hits
- Contribution of the two known precisely from theory
- Precisely known angular distributions - additional discriminant
- NC on 7Li excites 1st ES of 7Li (478 keV), τ ~ 105 fs

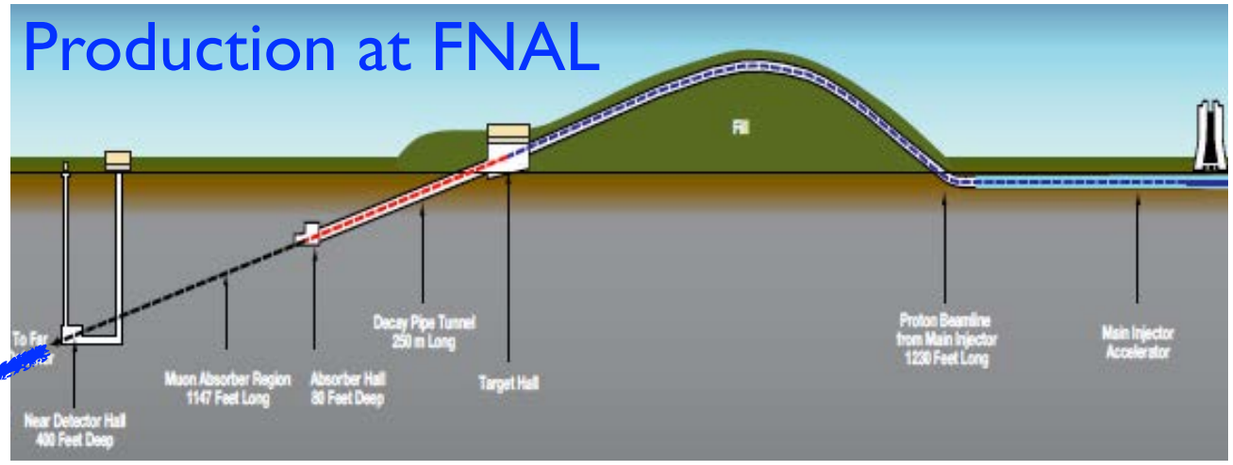
Credit: W. Haxton

Requirements

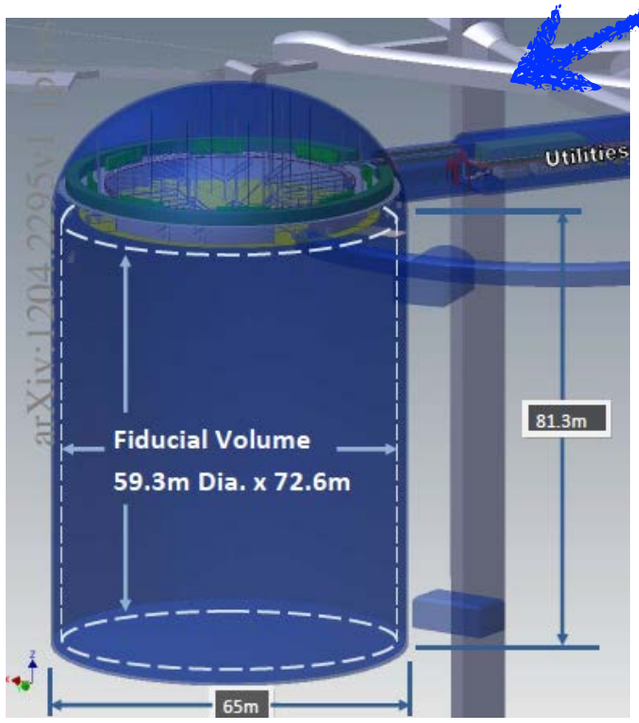
Physics	Size	Cherenkov Priority	Scintillation Priority	Cleanliness Priority
$0\nu\beta\beta$	~few ktonne	Medium	Very high	Very High
Low E Solar νs (< 1MeV)	~10 ktonne	High	Very high	Very High
High E Solar νs (> 1 MeV)	>50 ktonne	High	Low	High
Geo/reactor anti-νs	~10 ktonne	Low	High	Medium
DSNB anti-ns	>50 ktonne	Low	High	Medium
Long-baseline νs	> 50 ktonne	Very high	Low	Low
Nucleon decay (K+ anti-ν)	> 100 ktonne	High	High	Low

Long-Baseline Program

- Large-scale detector at Homestake, in the LBNF beam
- Complementary program to LArTPC (DUNE)
- Build on WCD studies (arXiv:1204.2295)



1300km



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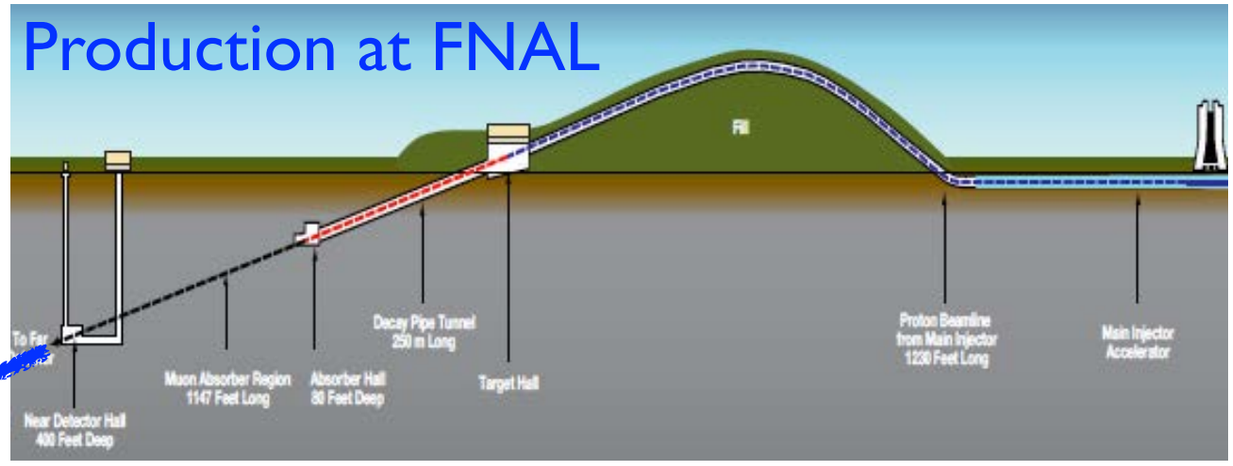

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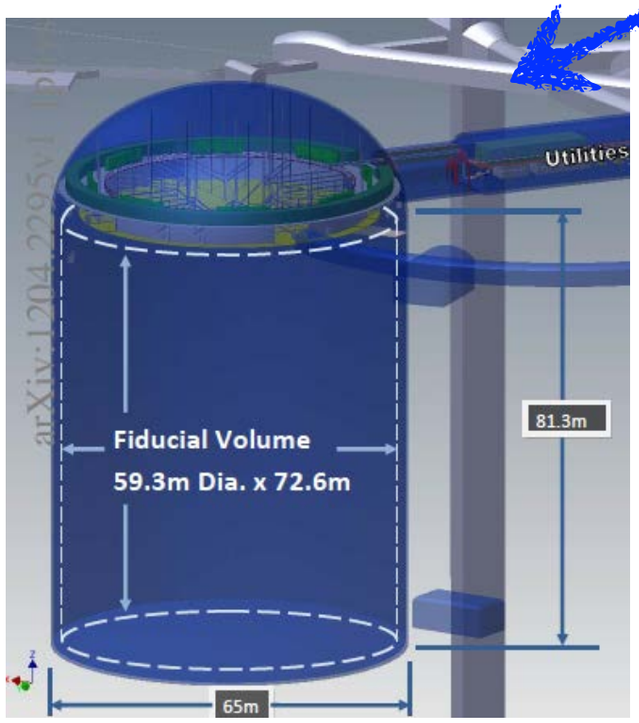
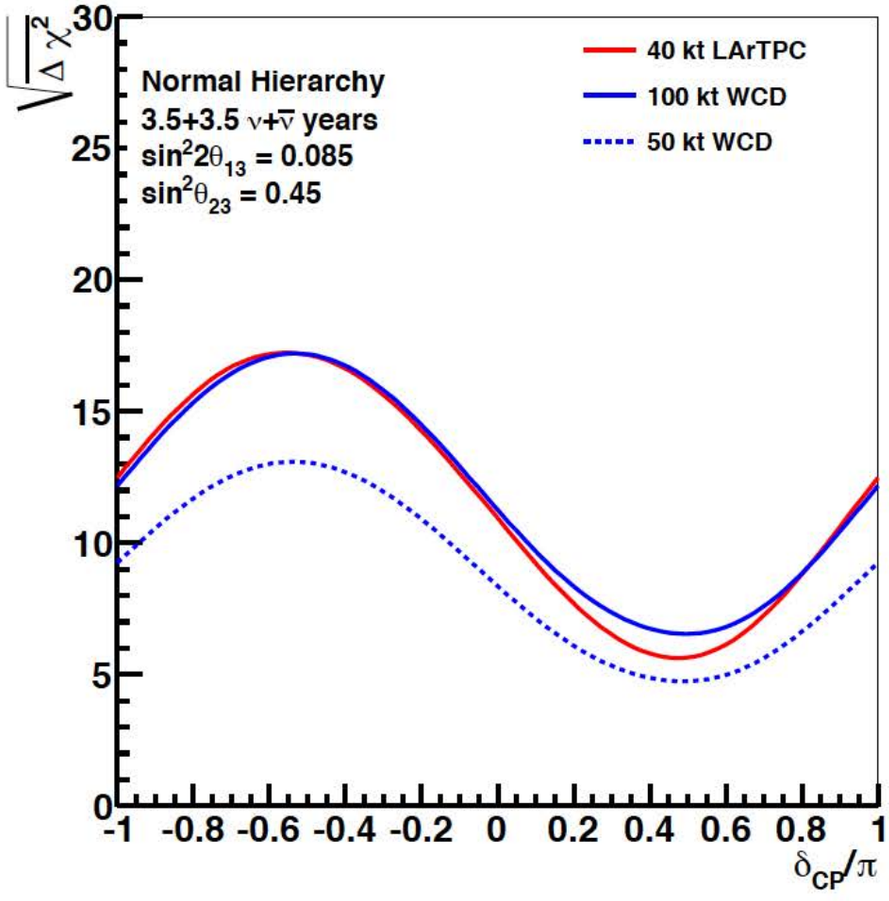


Images from arXiv:1204.2295

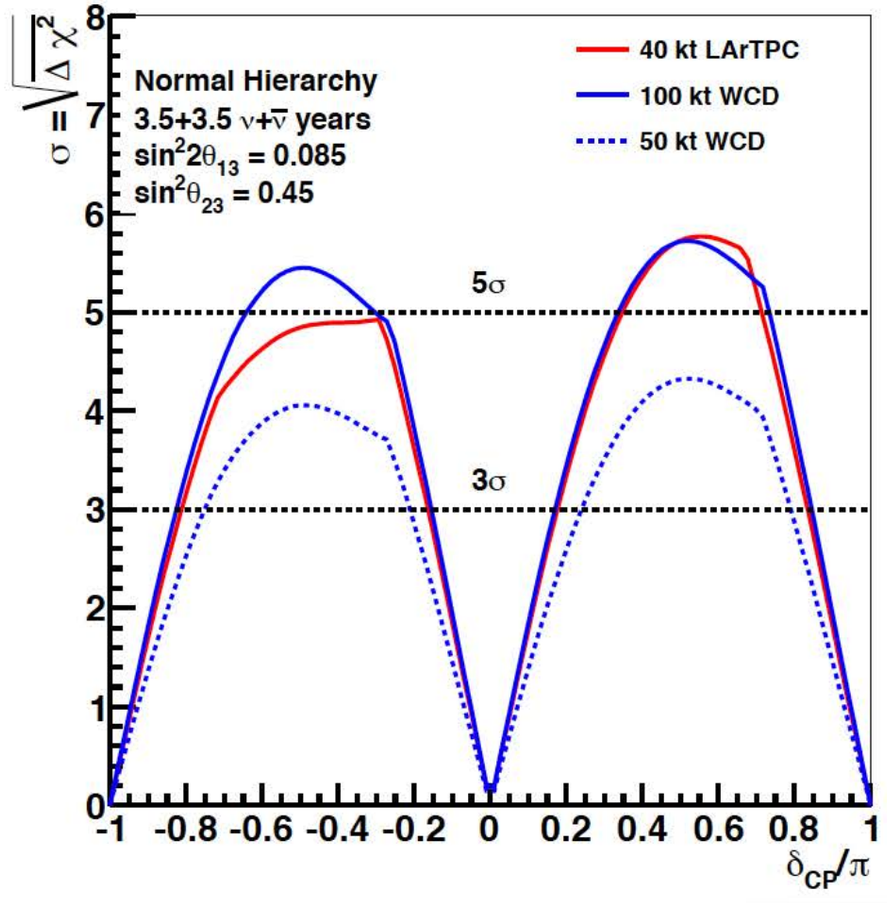
- Ring-imaging of a water Cherenkov detector
- Particle ID from Cher/scint separation
- n and low-E hadron detection (low threshold)
  - reduce wrong-sign component (nu vs anti-nu)
  - reduce NC background by detecting $\pi^0 \rightarrow \gamma\gamma$
- Large size → sensitivity to 2nd oscn max

Long-Baseline Sensitivity

Mass Hierarchy Sensitivity



CP Violation Sensitivity



Synergy with LAr TPC

Independent systematics

High-energy events

~300 kt-MW-yr exposure (40kt LAr)

Performance competitive with 40kt LAr TPC !!

Study by E. T. Worcester using same GLOBES package used for ELBNF

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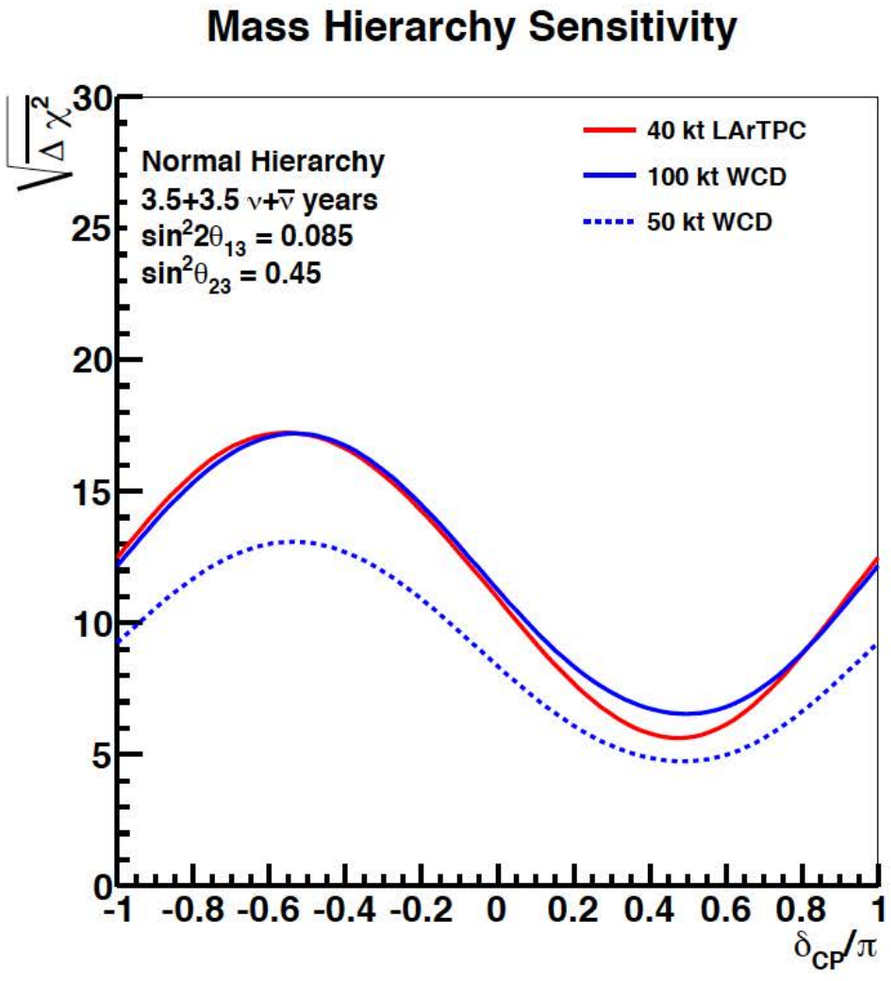

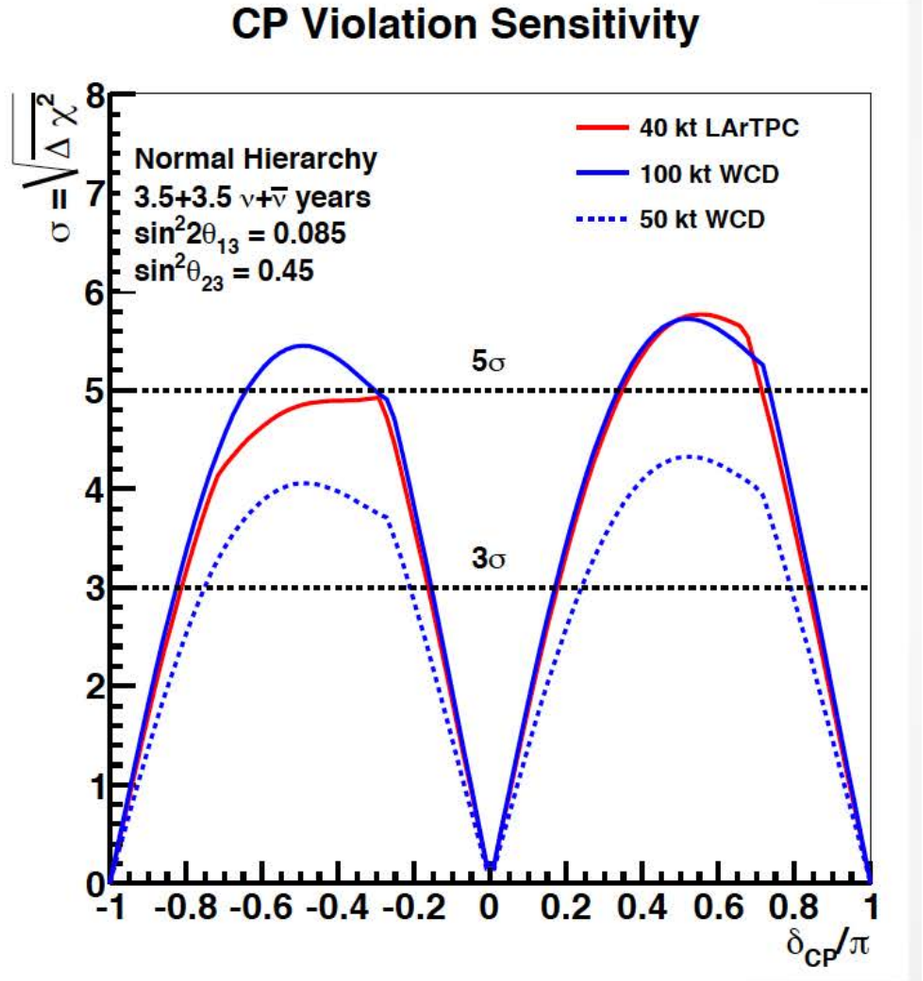

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Performance competitive with 40kt LAr TPC !!

MH sensitivity for 50kt WbLS alone > 5σ

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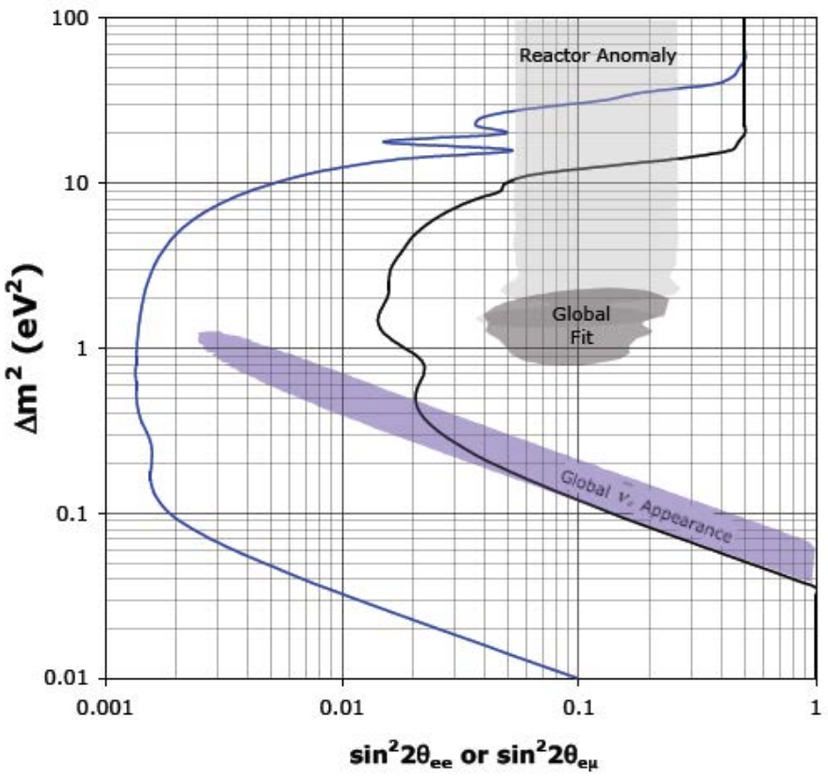
Sterile Neutrinos

Figs from arXiv:1409.5864

Sterile Neutrinos

- Deploy ^{8}Li decay-at-rest (IsoDAR)
  - 13MeV endpoint (above r/a)
  - Required detector response:
    15% (E) & 50cm (R)
  - 5 yrs, 1kt (black) / 20kT fid. (blue)



- Heavy-water based LS: 2n tag
  (reduce bkg in IBD searches)

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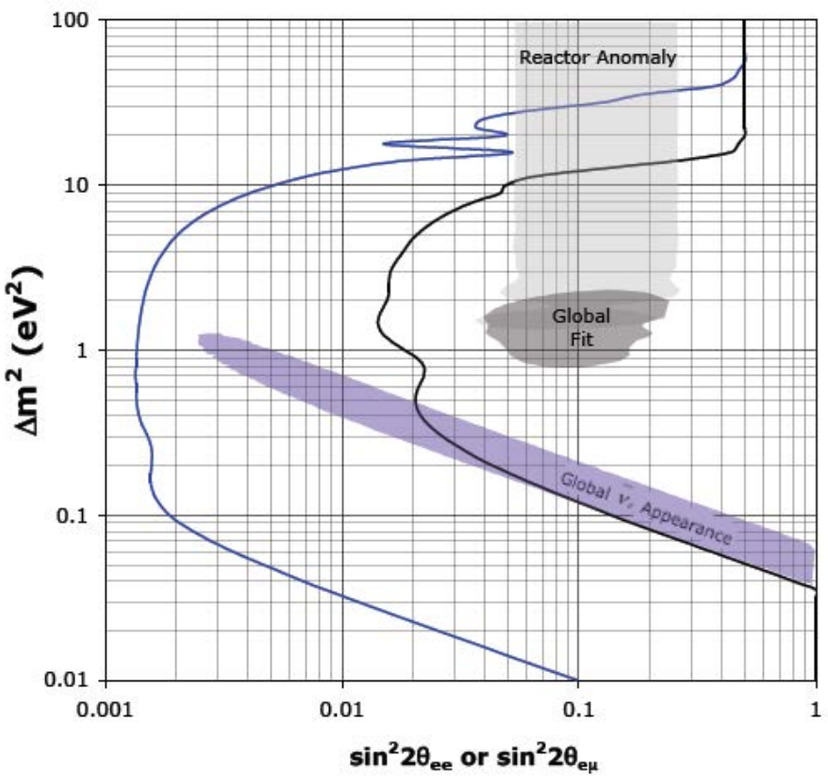

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- Large, deep, very clean
- Enhanced n tag
- Sub-Cherenkov threshold detection
- Sensitive to several modes

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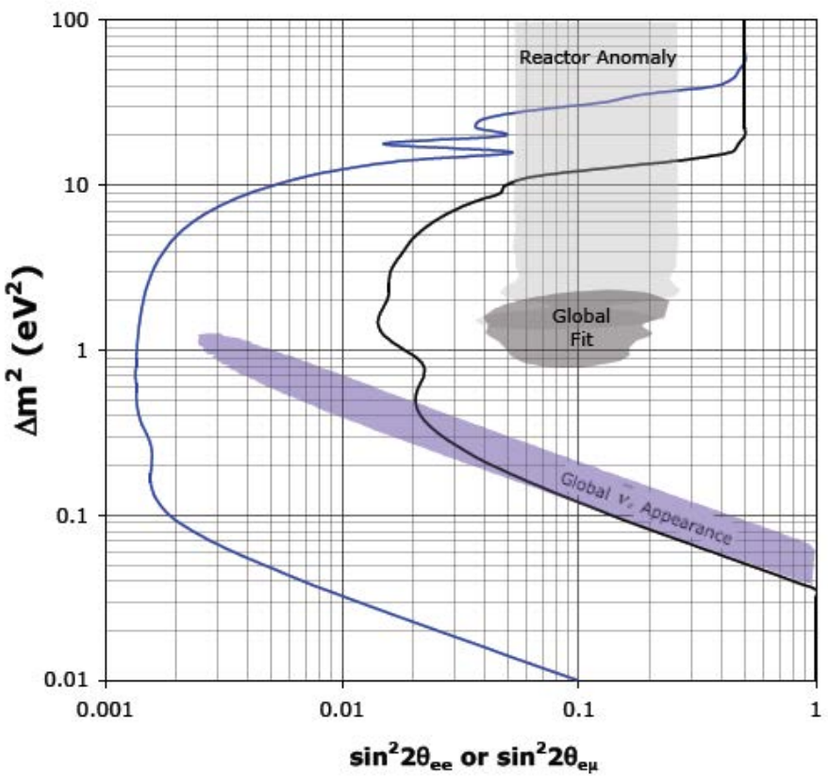

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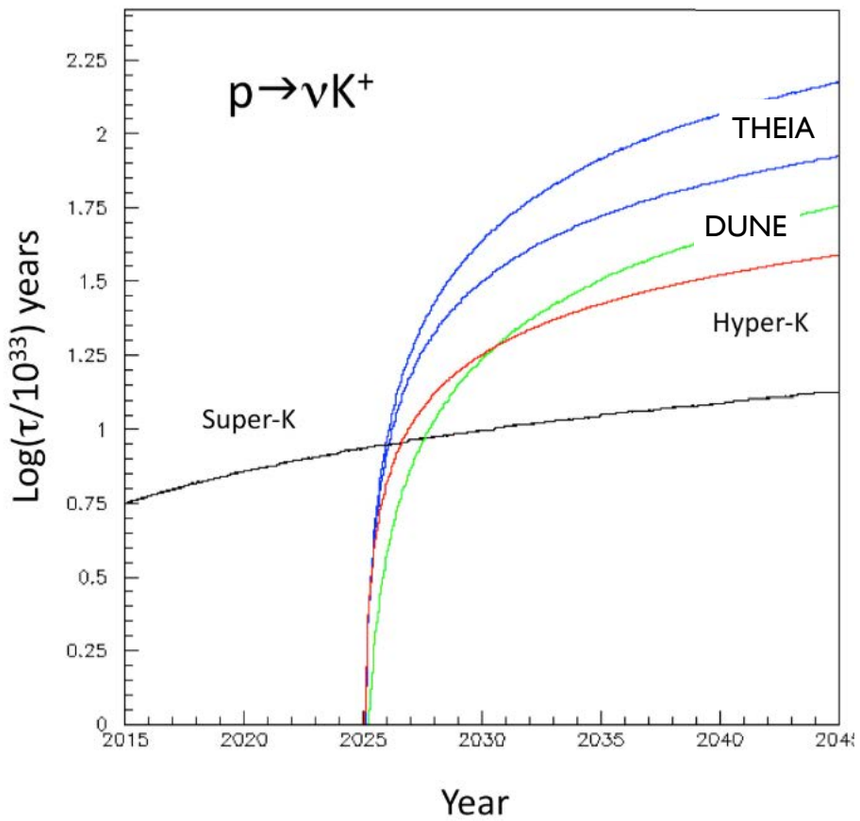
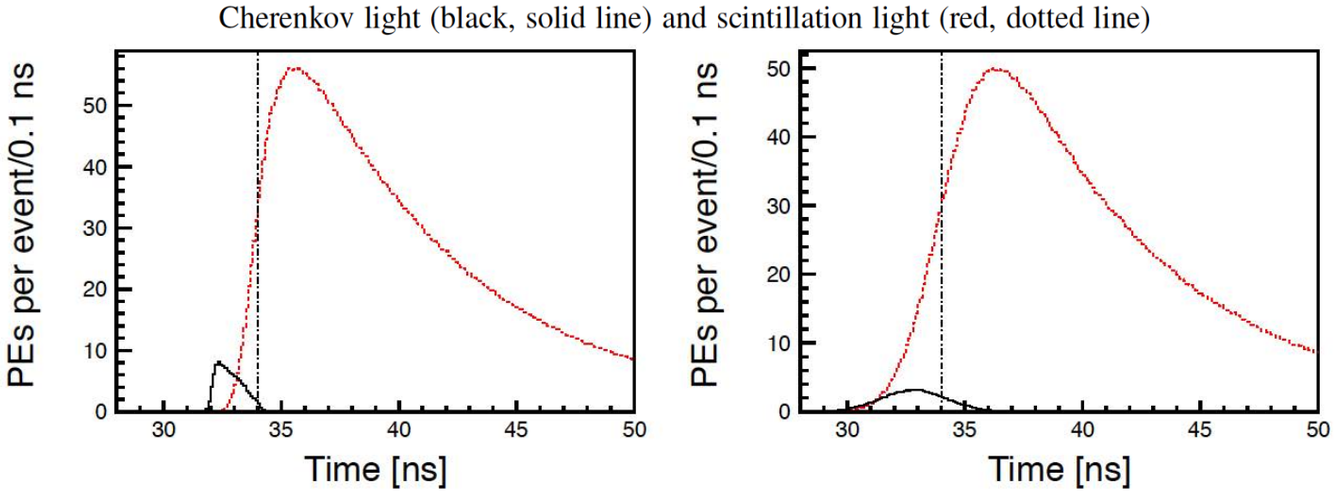


Sub-Chr t/h detection
⇒ Directly visible K^+

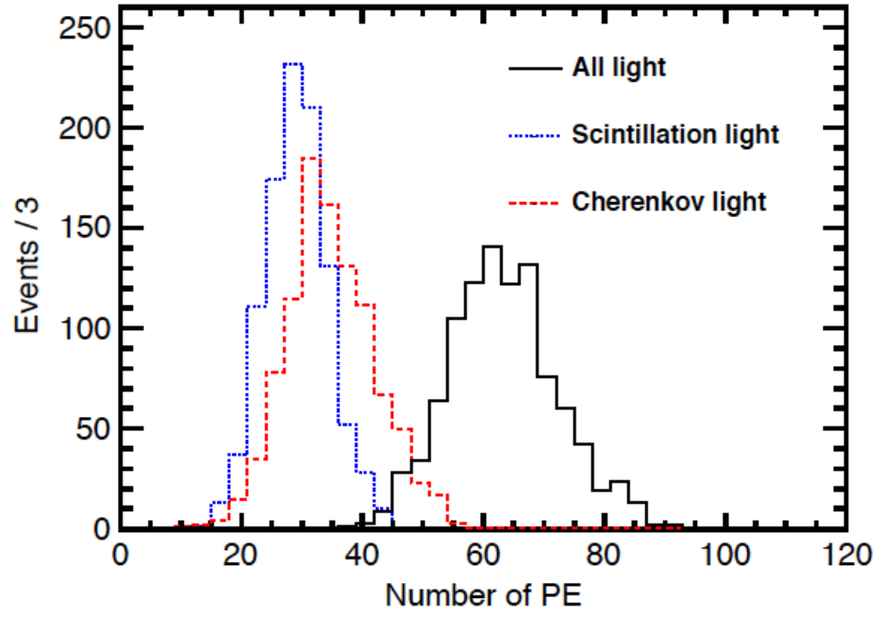
Figs from arXiv:1409.5864

Application of Signal Separation



(a) Default simulation. (b) Increased TTS (1.28 ns).

Photon arrival times in kton-scale LS detector



Composition of early-time sample

J. Instrum. 9, P08012 (2014), Nucl. Instrum. Methods A849, 102 (2017).

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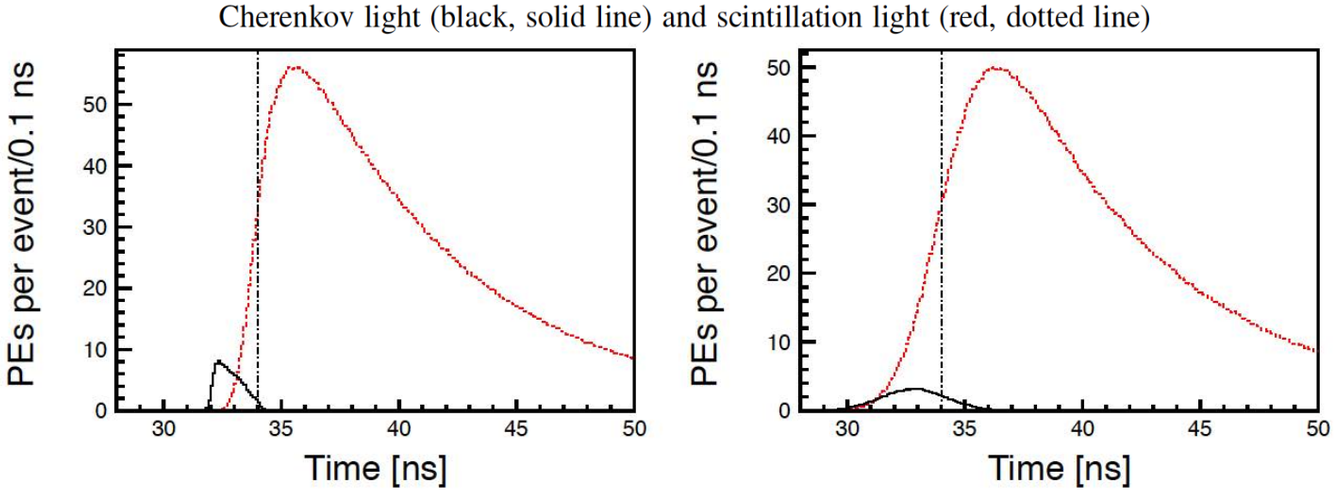

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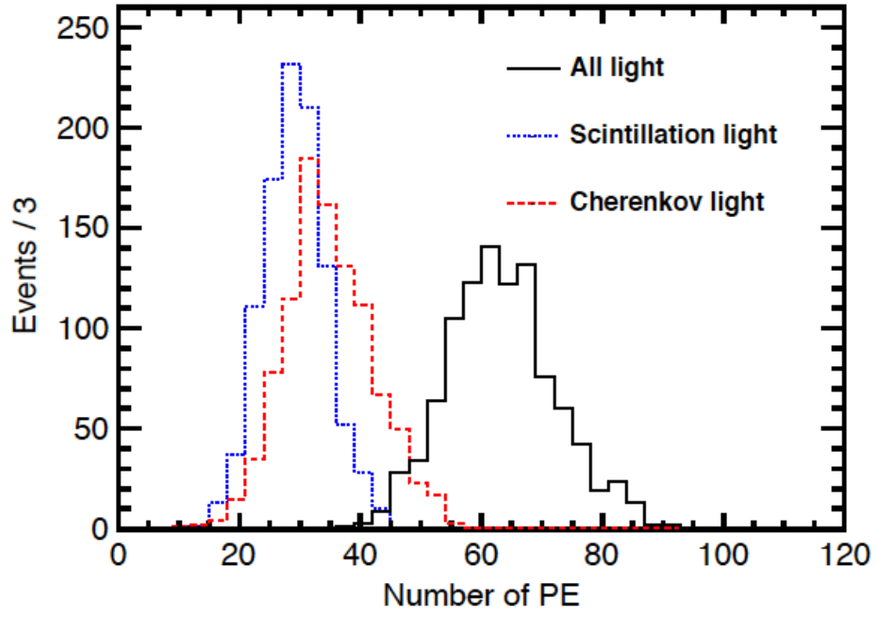
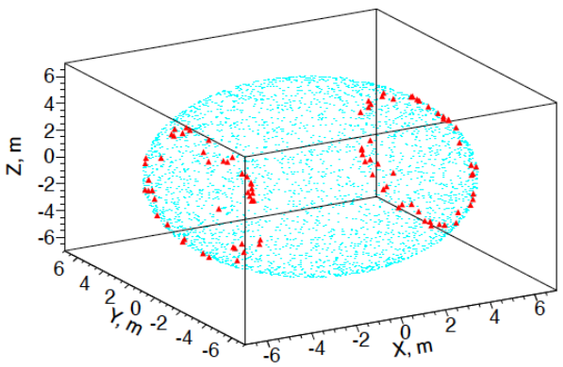
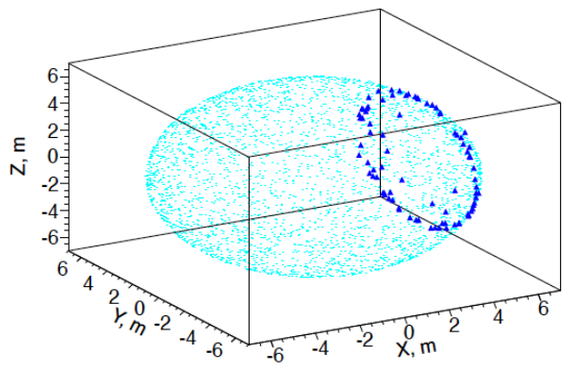


Photon arrival times in kton-scale LS detector

Composition of early-time sample



NLDBD

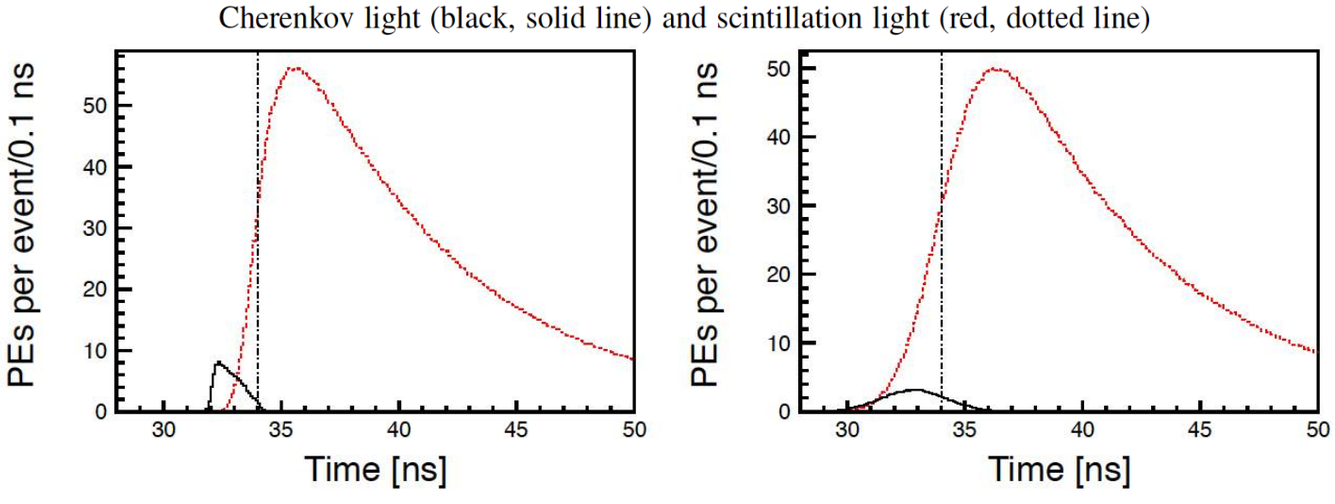


8B solar nu

Spherical harmonics analysis of "idealised" events

J. Instrum. 9, P08012 (2014), Nucl. Instrum. Methods A849, 102 (2017).

Application of Signal Separation



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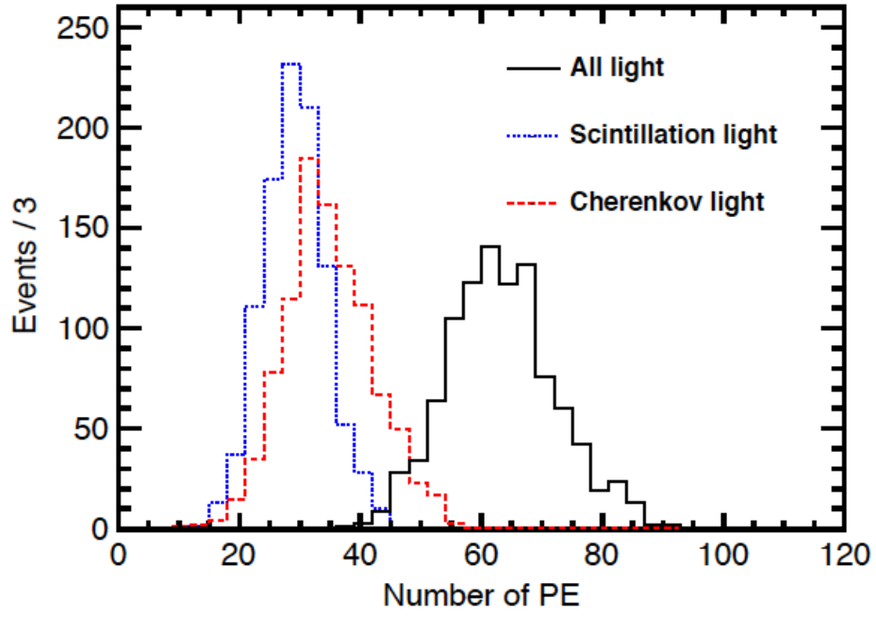
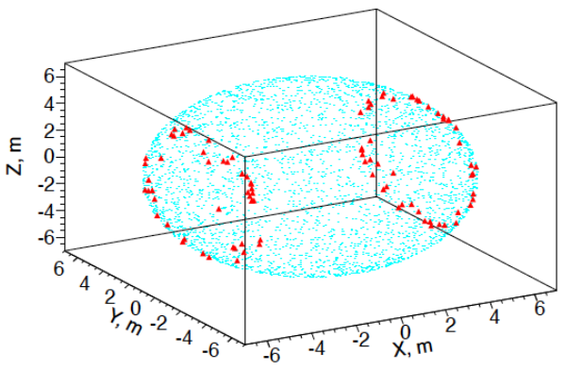
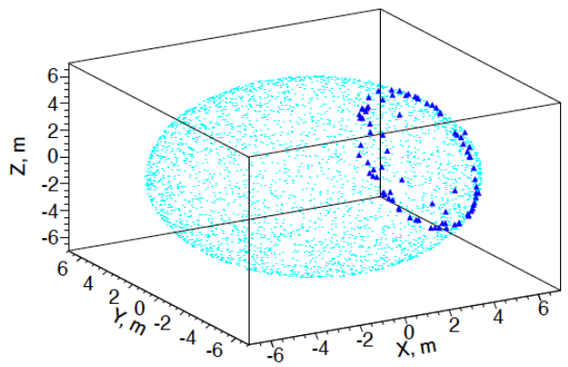


Photon arrival times in kton-scale LS detector



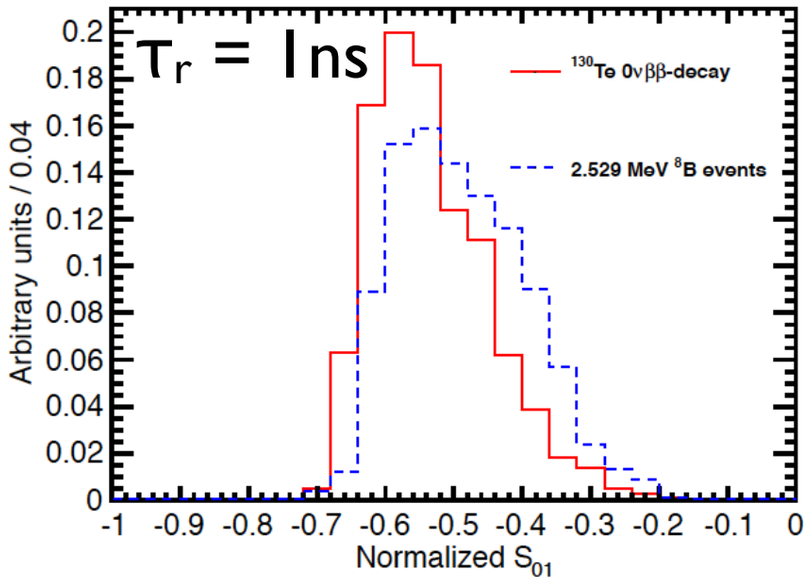
NLDBD



8B solar nu

Spherical harmonics analysis of "idealised" events

Composition of early-time sample

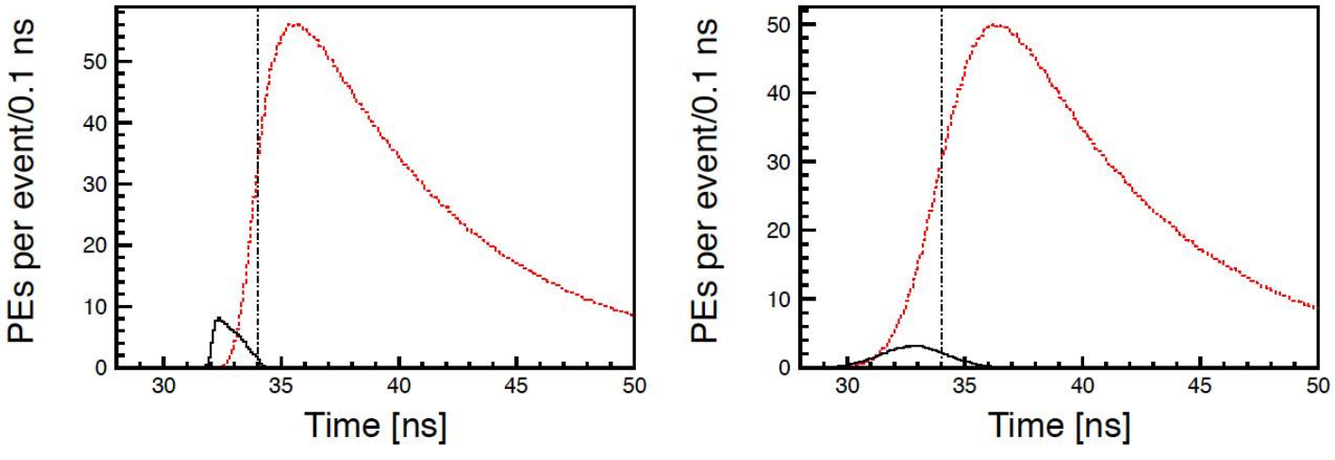


Signal/background discrimination

J. Instrum. 9, P08012 (2014), Nucl. Instrum. Methods A849, 102 (2017).

Application of Signal Separation

Cherenkov light (black, solid line) and scintillation light (red, dotted line)



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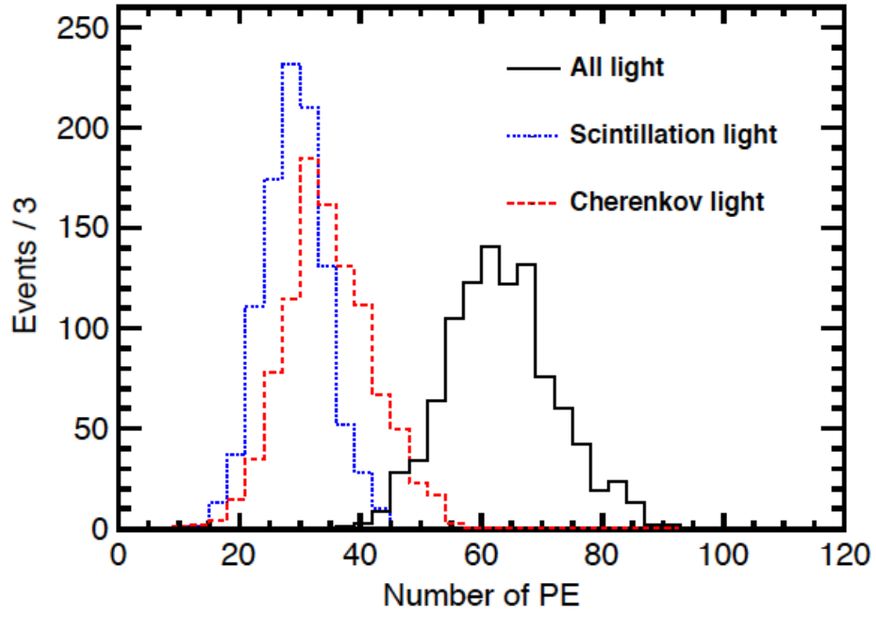
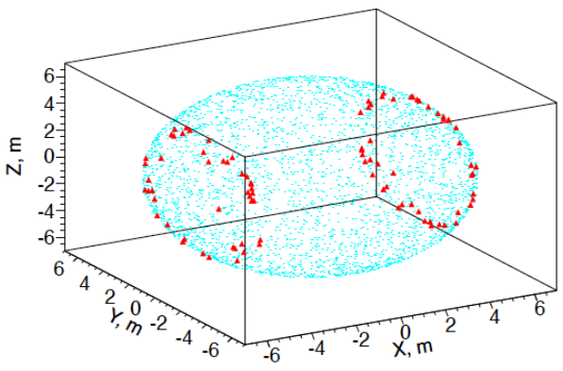
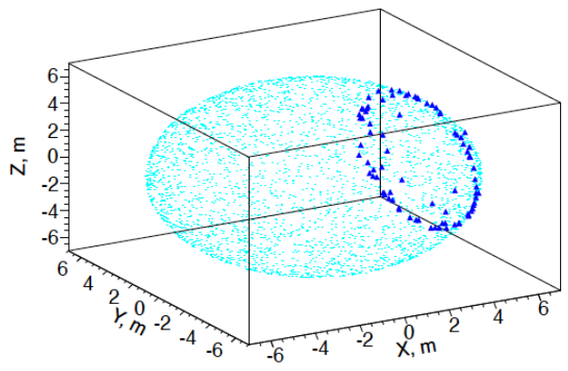


Photon arrival times in kton-scale LS detector



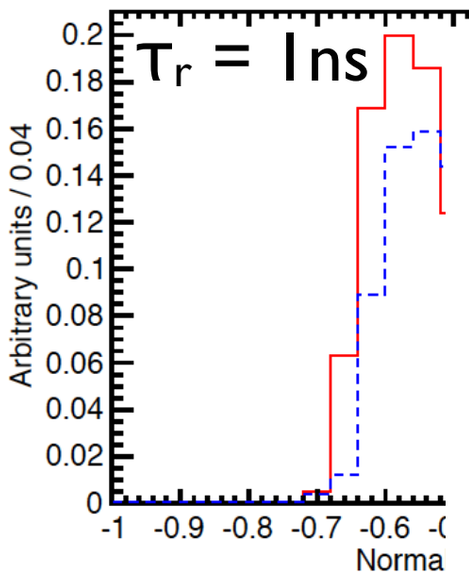
NLDBD

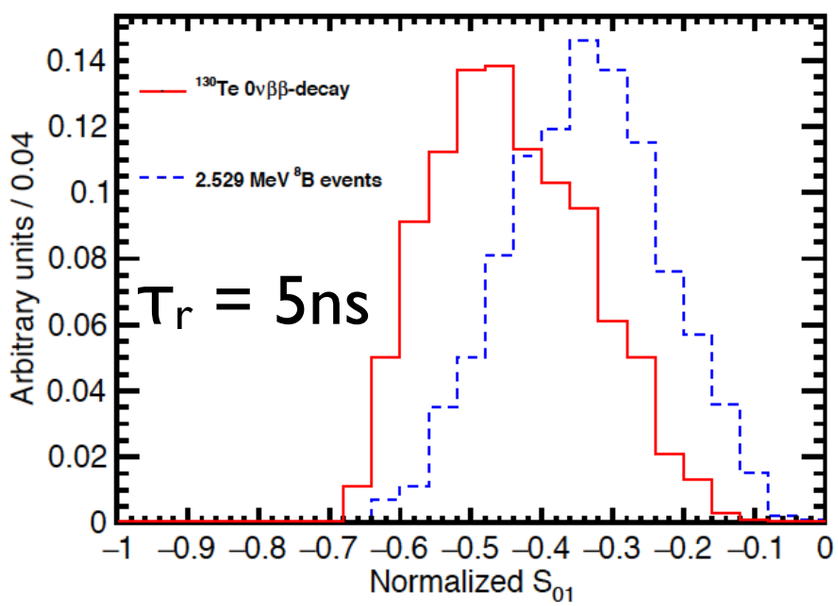


8B solar nu

Spherical harmonics analysis of "idealised" events

Composition of early-time sample

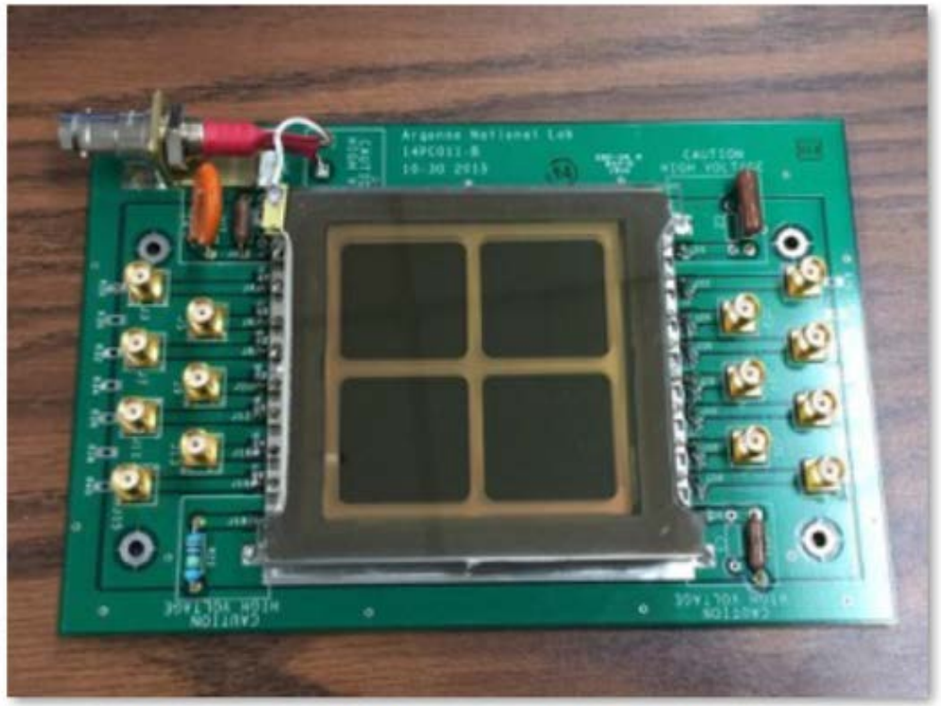




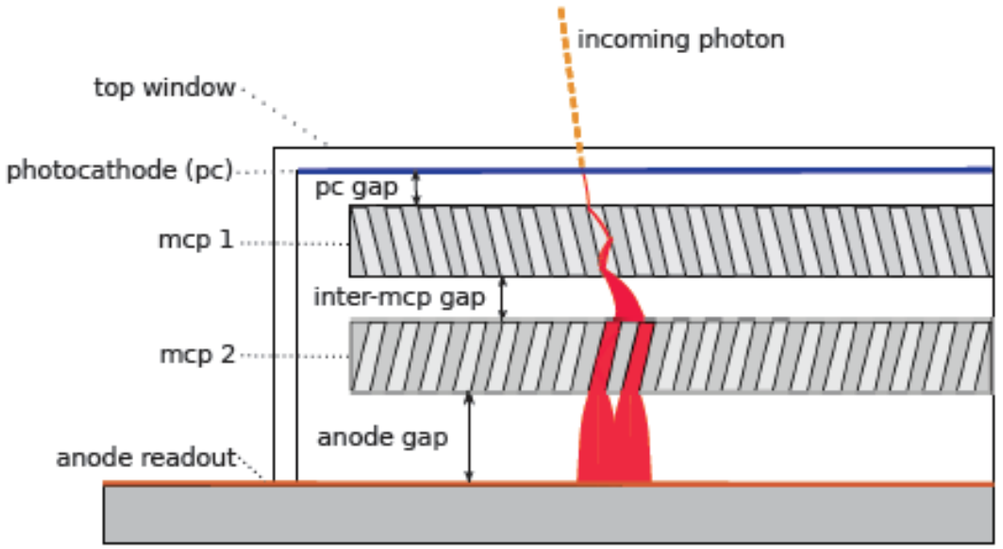
Signal/backgrou discrimination

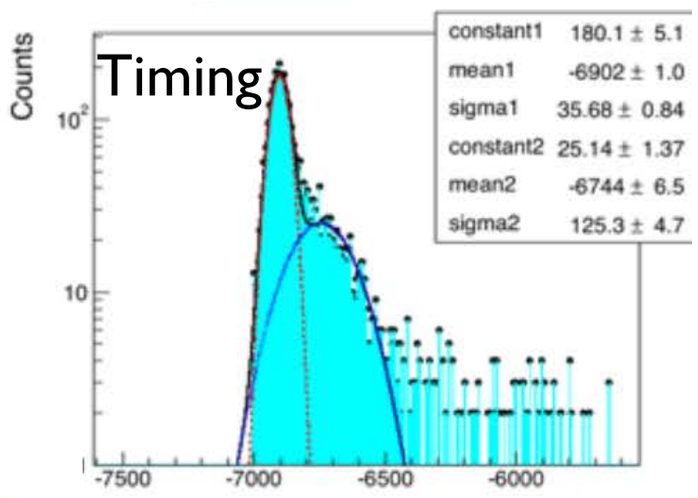
J. Instrum. 9, P08012 (2014), Nucl. Instrum. Methods A849, 102 (2017).

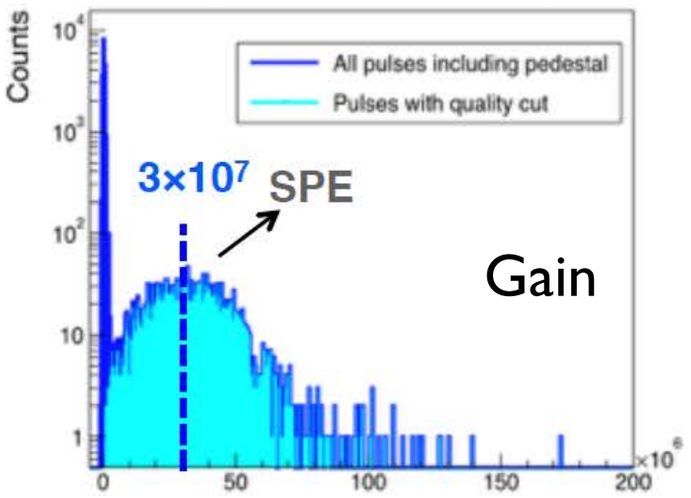
MCP Development [ANL]

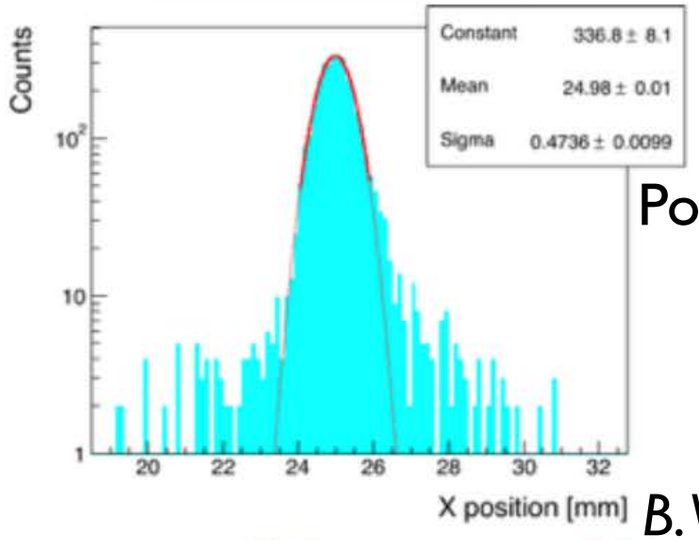


Argonne 6X6 cm MCP-PMT on custom readout board









Position resolution

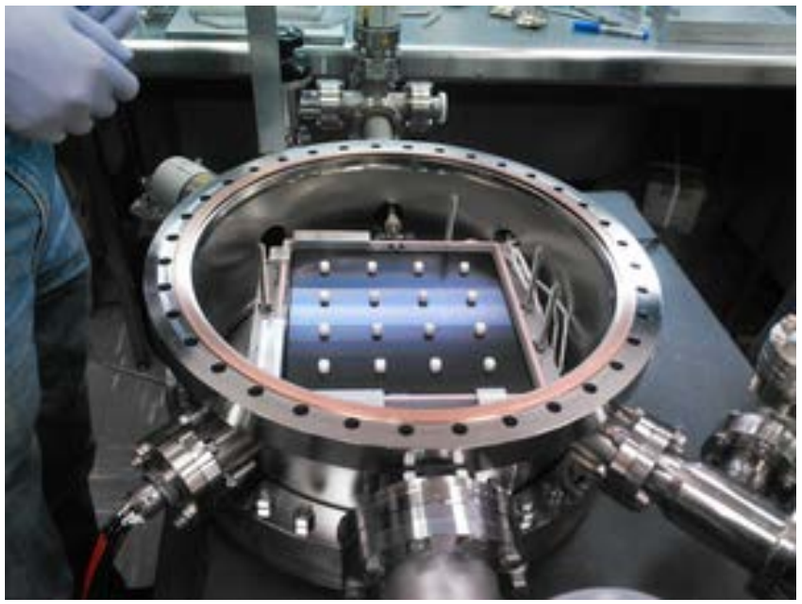
- Argonne routinely producing 6X6 cm² functional detectors with K_2CsSb photocathode
- New IBD-1 design allows HV optimization, as biasing individual components possible
- In addition to assembly of photo-detectors, laser testing facility available and photocathode research ongoing.
- Performance:
  - Gain > 10^7
  - Quantum efficiency ~ 15%
  - Time resolution including the laser jitter: σ ~ 35 ps
  - Position resolution along anode strip: < 1 mm
  - Rate capability > 1 MHz/cm² for single photoelectrons

B. Wagner et al., Argonne NL

LAPPD Development [Chicago]

1. 2nd-gen Optical TPC design e.g. for NLDBD
2. 2nd-gen control card; multi-buffered PSEC4 ASIC
3. Photodetector development, working with INCOM

    1. *Top seal (glass complete, ceramic underway)*
    2. *High resolution pad anodes for LHC (NIM)*
    3. *Monolithic high-bandwidth ceramic body*
    4. *PMT-style batch production (w. INCOM)*
    5. *High-QE photocathode in-situ synthesis*



Gen-II Margherita Dual-Vacuum facility

A. Elagin & master glassblower Joe Gregar

Ceramic base tiles from 4 vendors

H. Frisch et al., Chicago

Nucl. Inst. Meth. Phys. Res. A. Volume 814, 19-32, (April 2016); Nucl. Inst. Meth. Phys. Res. A. (Oct. 2016)