Theia

International Workshop on Next-Generation Nucleon Decay and Neutrino Detectors

3rd November, 2018

Gabriel D. Orebi Gann
UC Berkeley & LBNL

Transformational Opportunity

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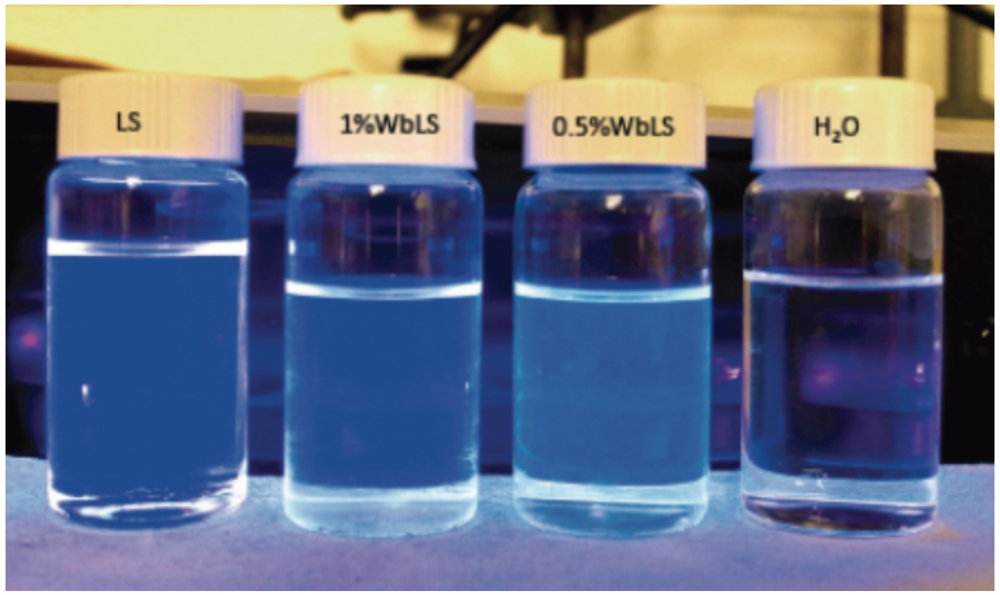

Development of new scintillators e.g. WbLS

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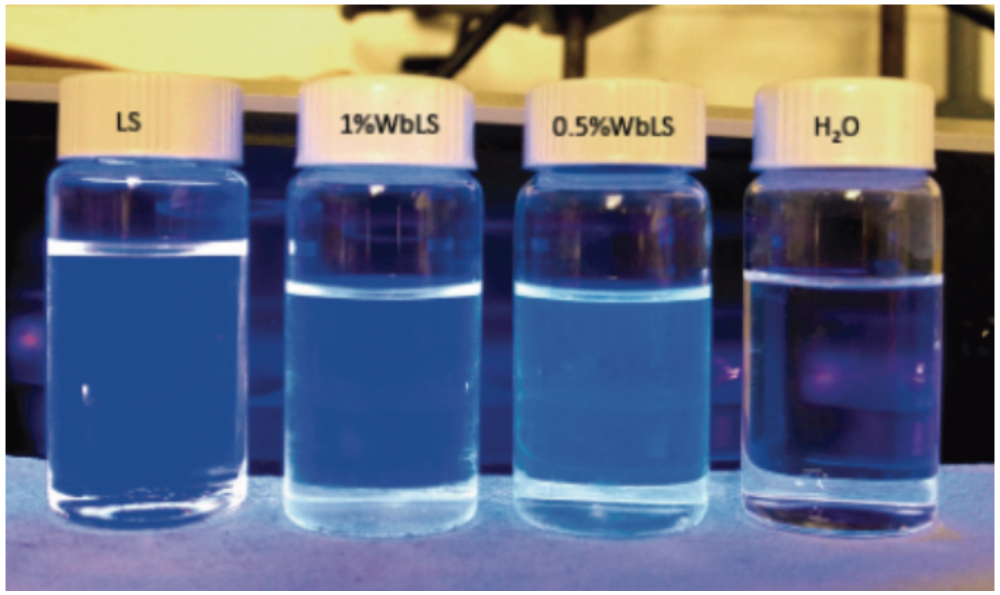

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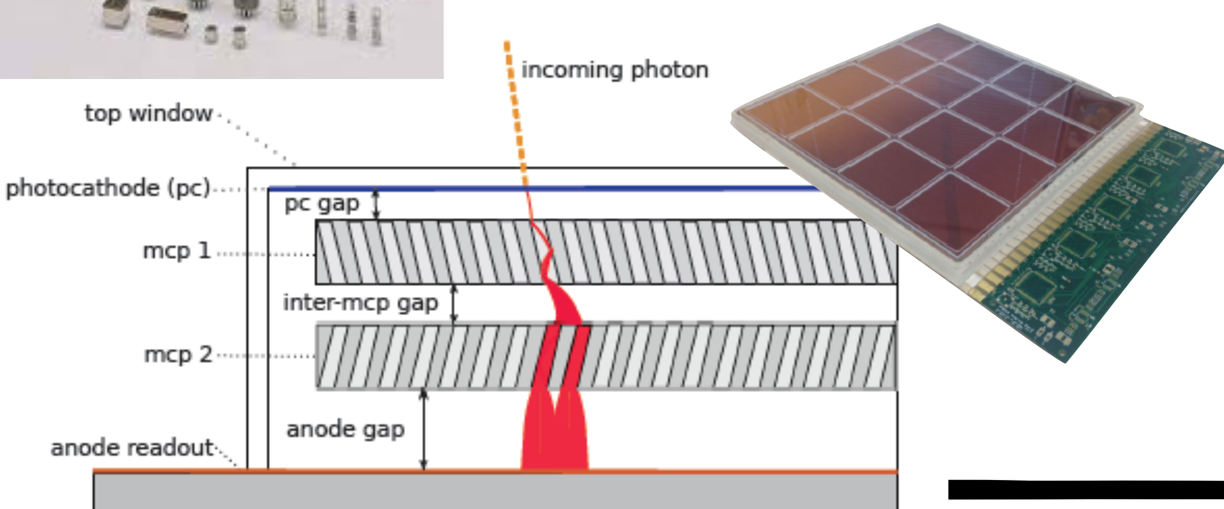

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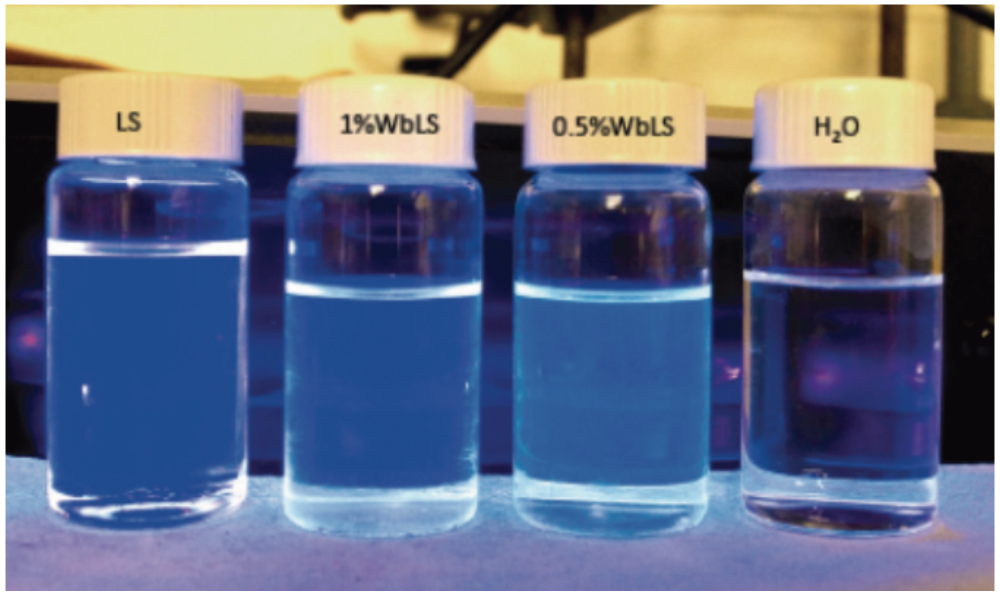

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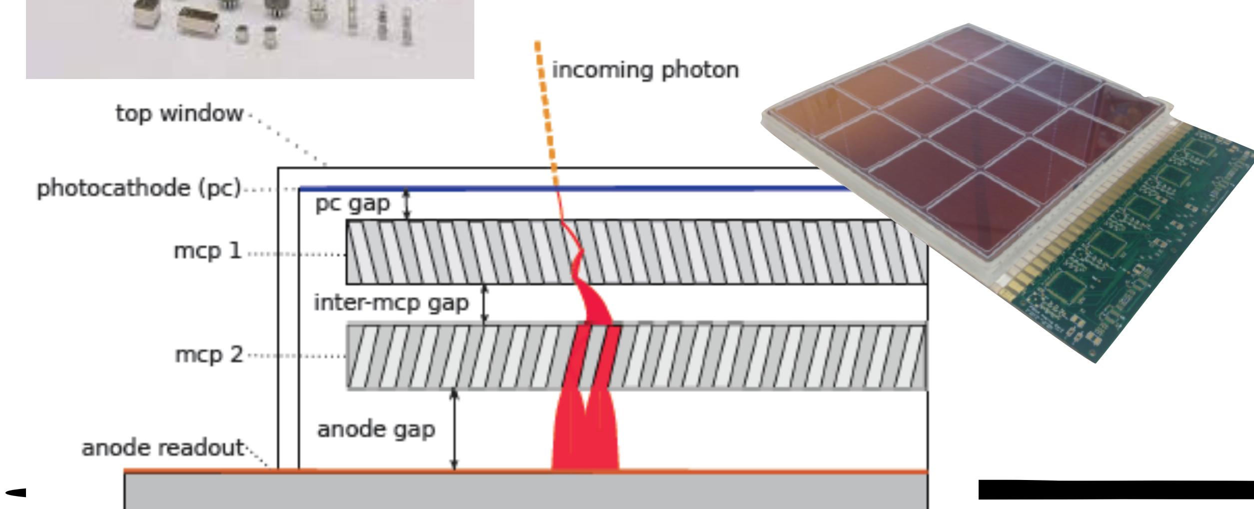
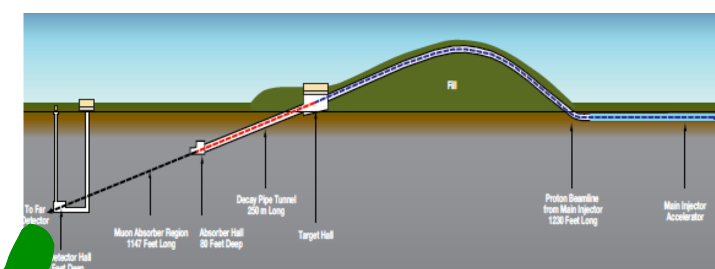
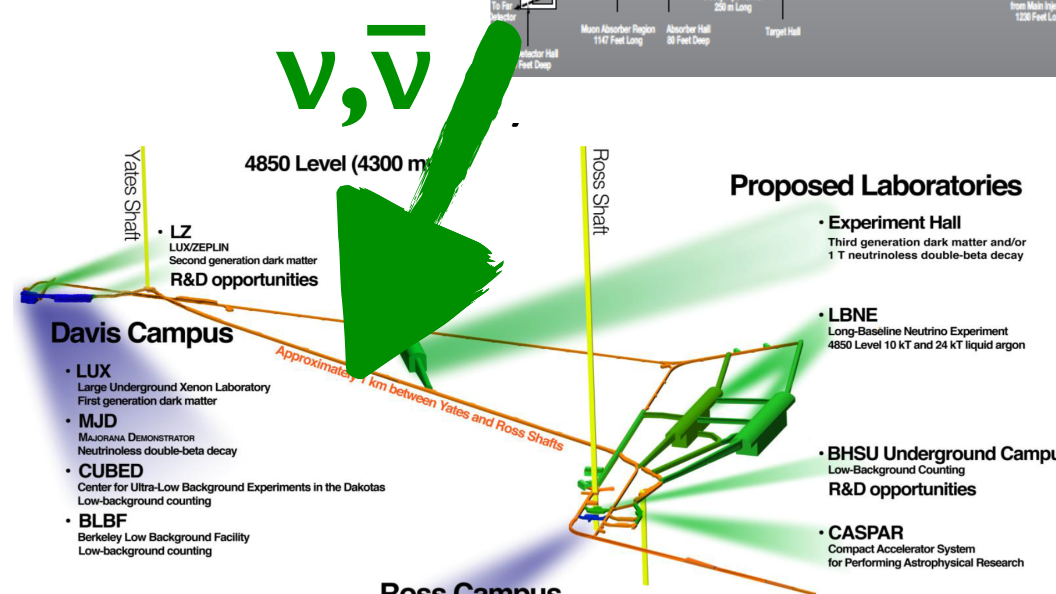


Fully-equipped, deep underground labs (+ beam)





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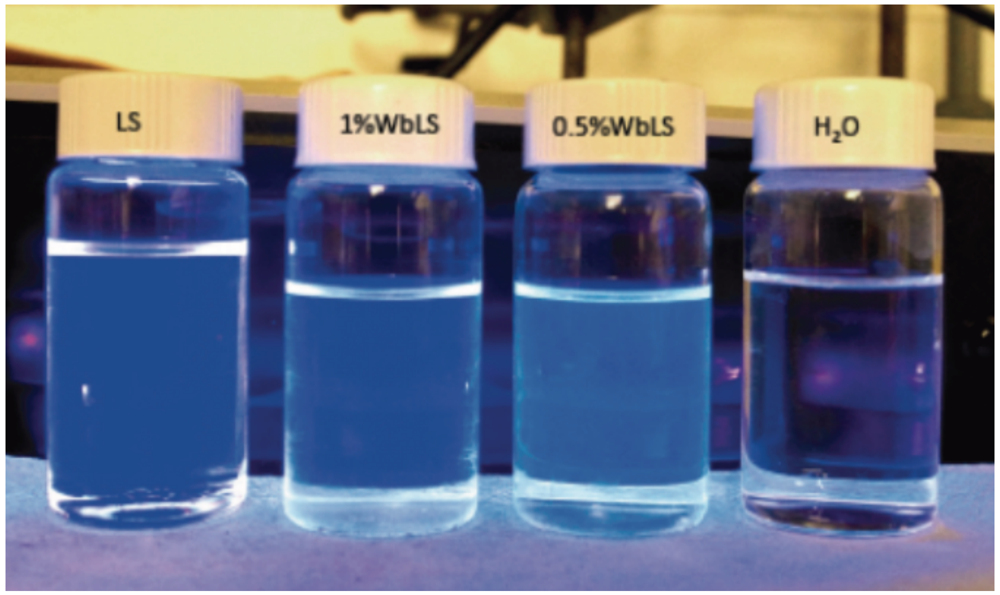

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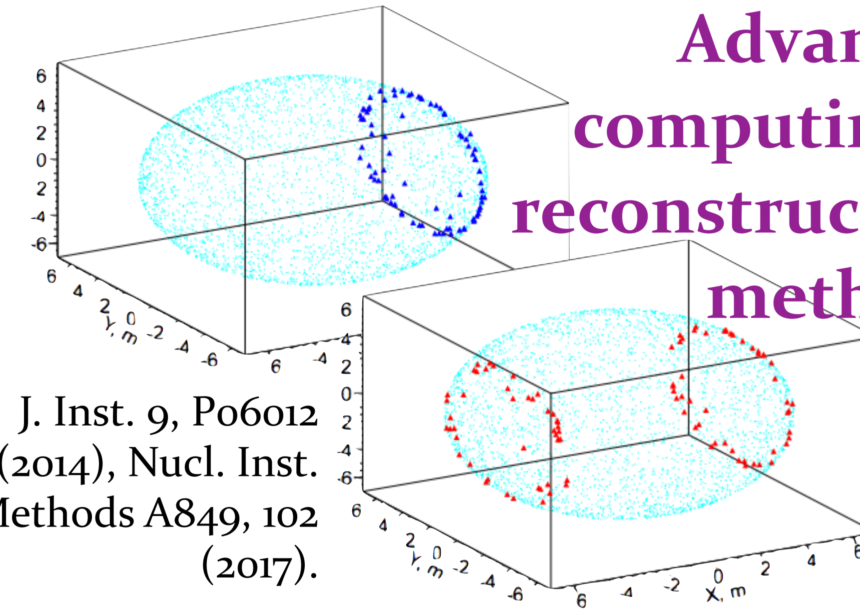

J. Inst. 9, P06012 (2014), Nucl. Inst. Methods A849, 102 (2017).

Advanced computing & reconstruction methods

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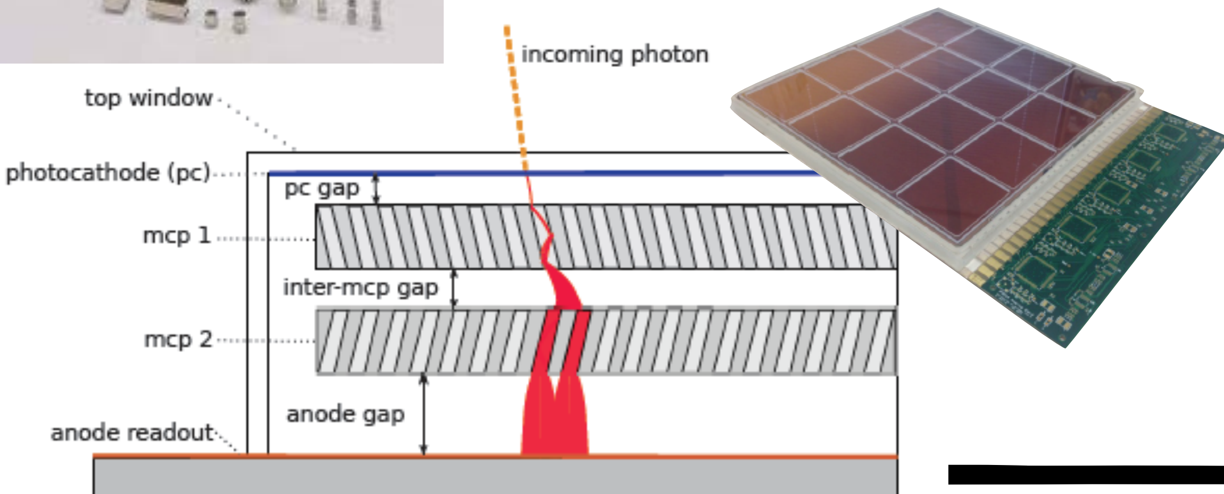

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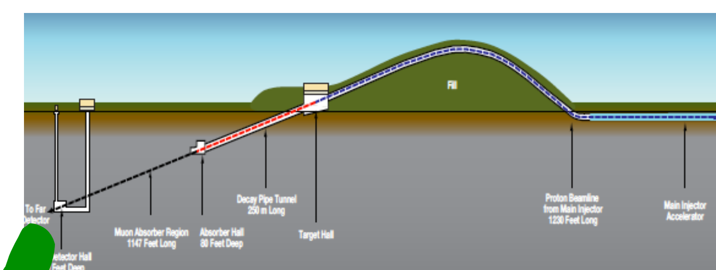

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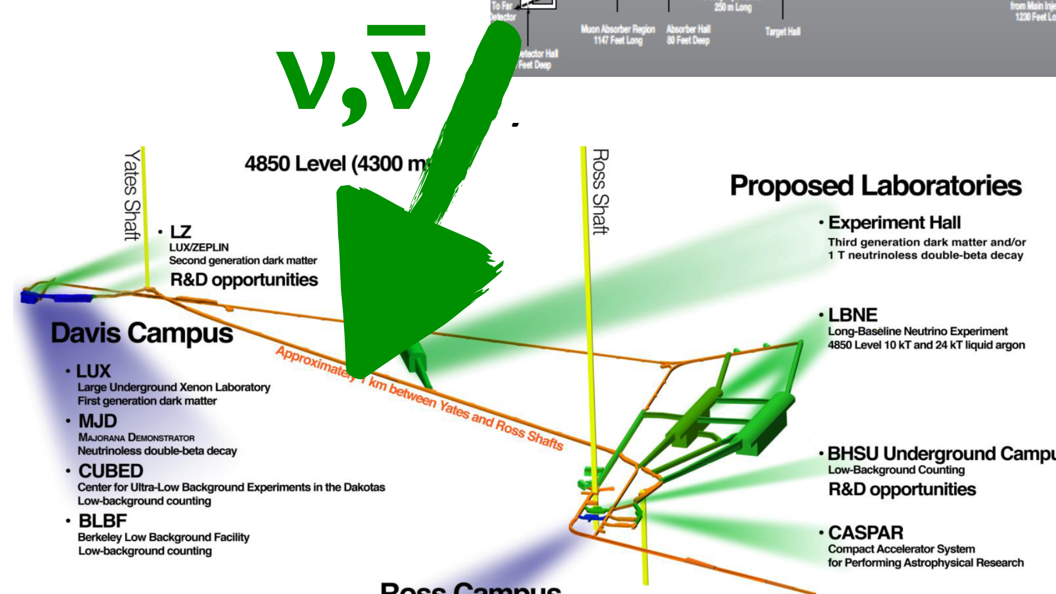

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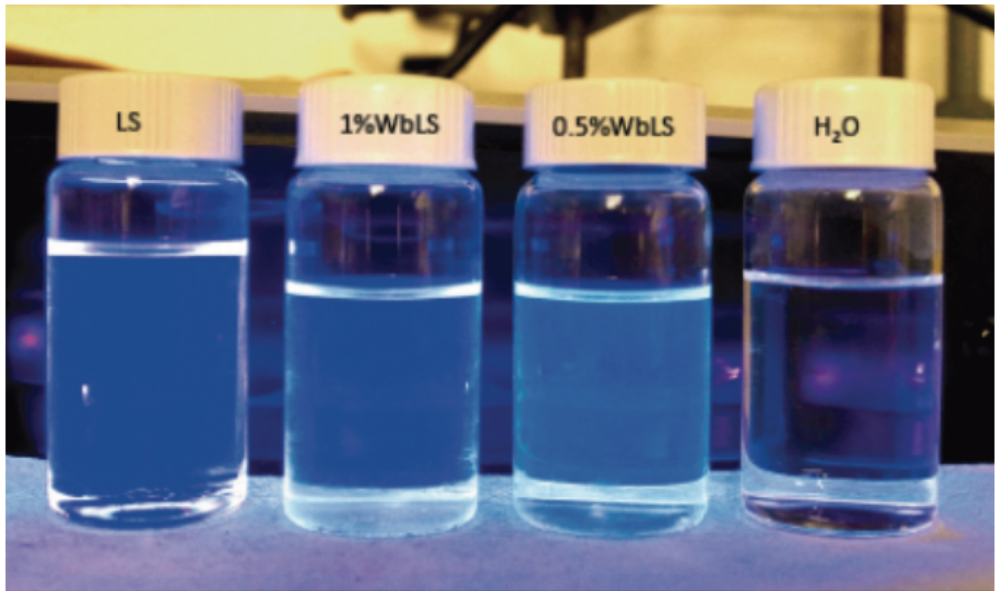
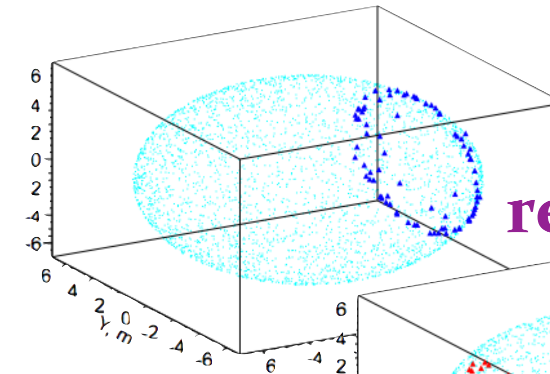


Development of new scintillators e.g. WbLS

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



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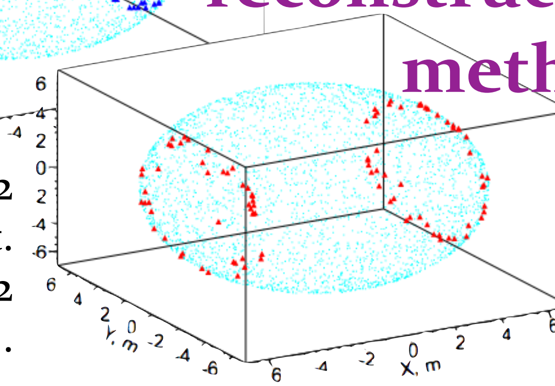

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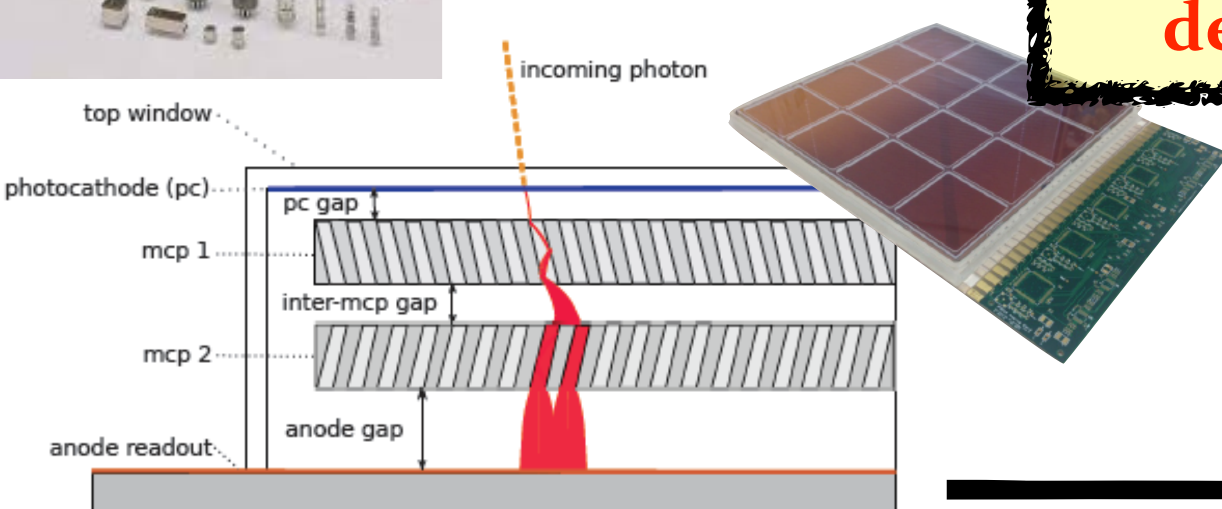

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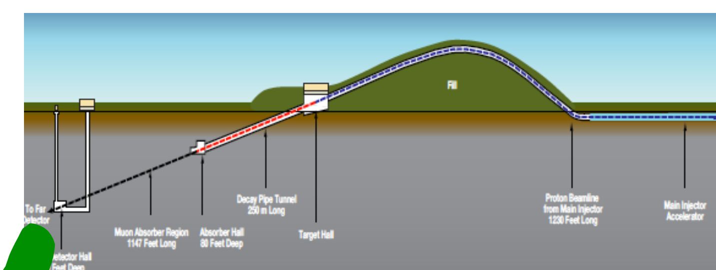
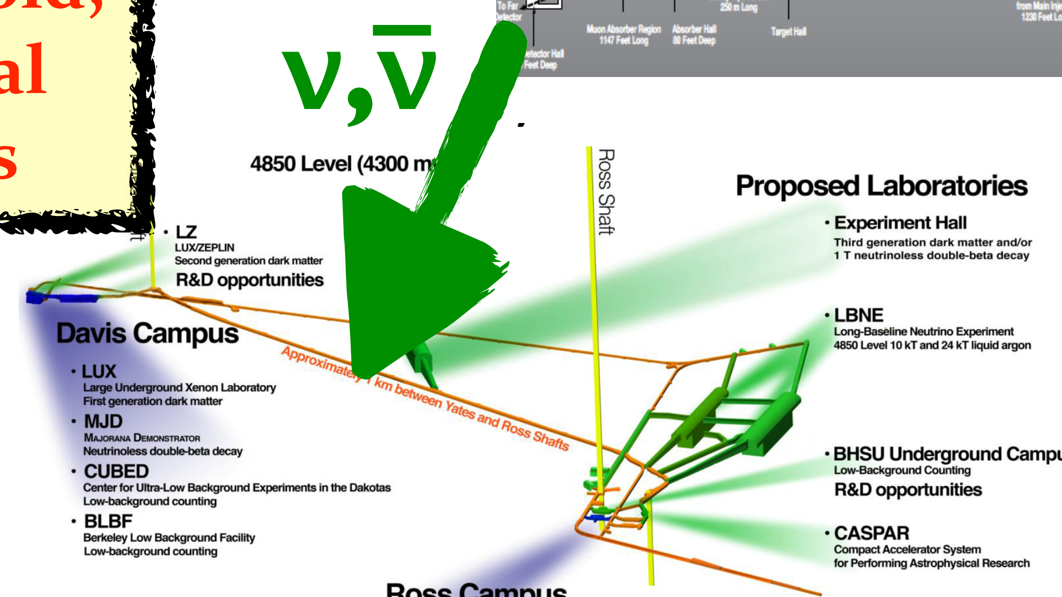
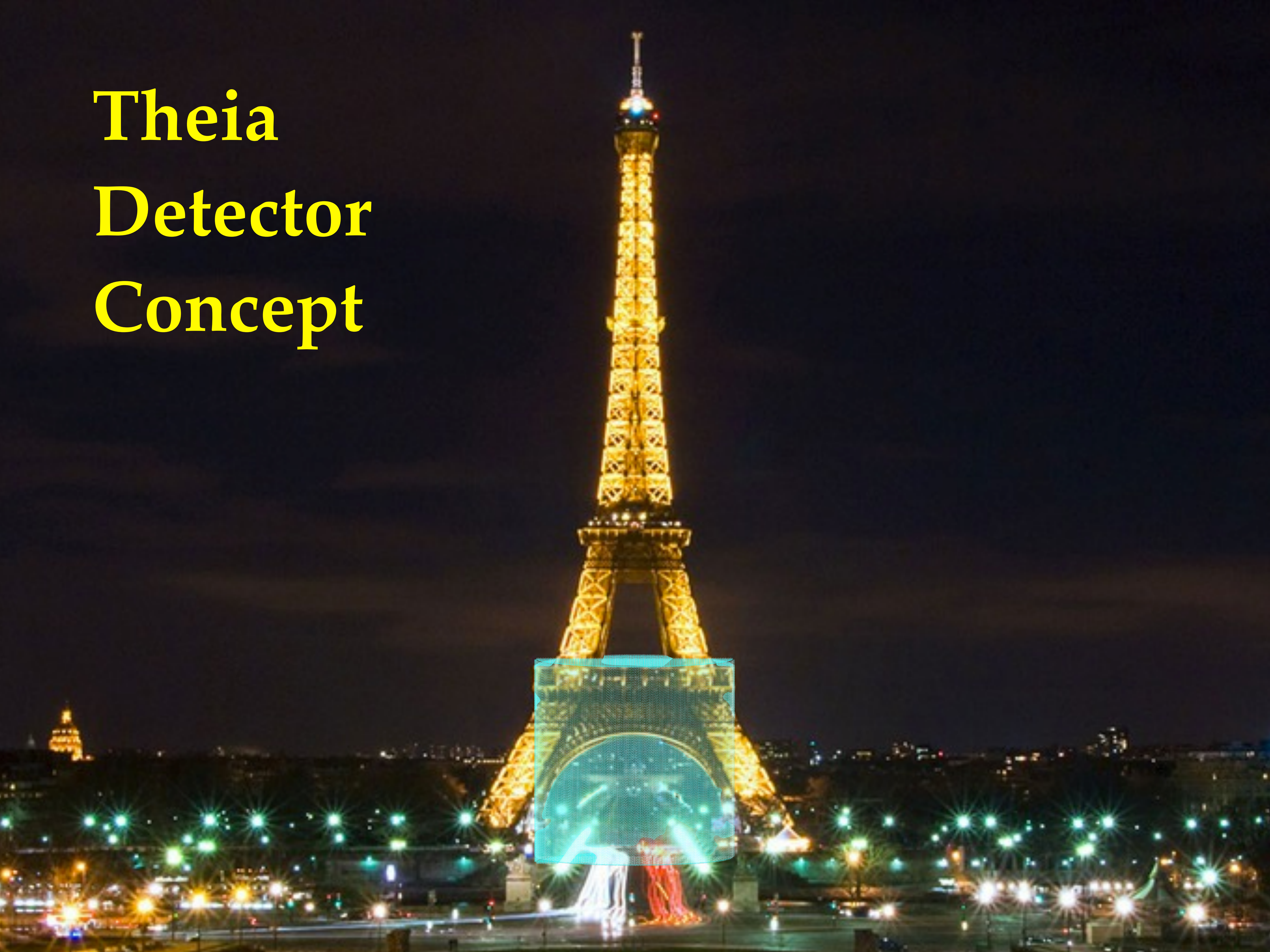




Overview

- Detector concept
- Physics Program
- Development of Detector Capabilities

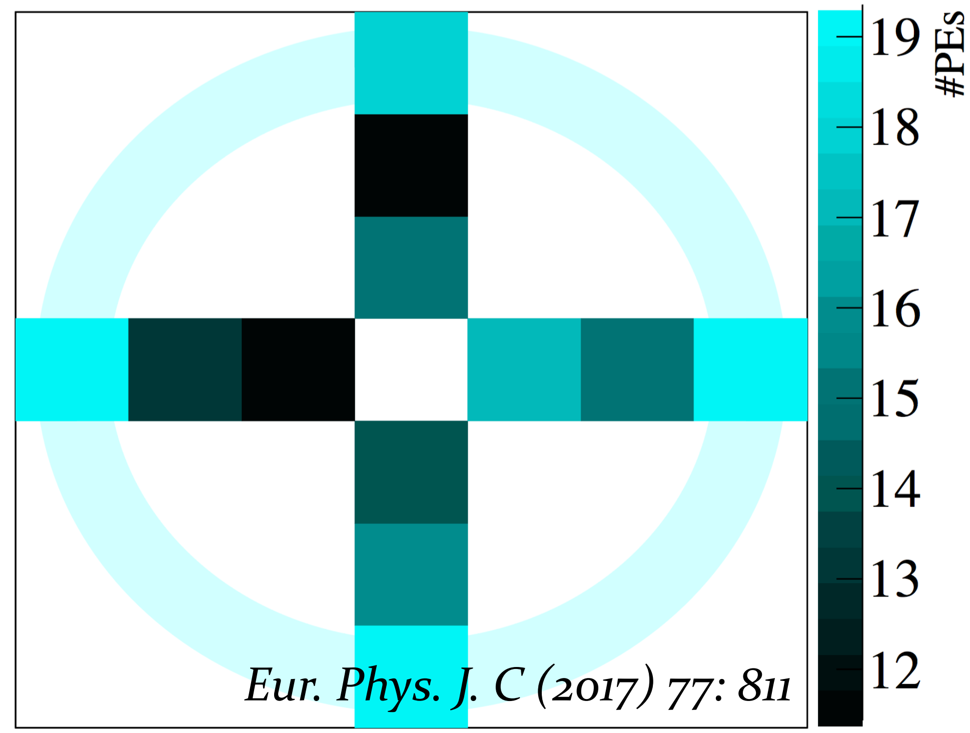

Theia
Detector
Concept

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"

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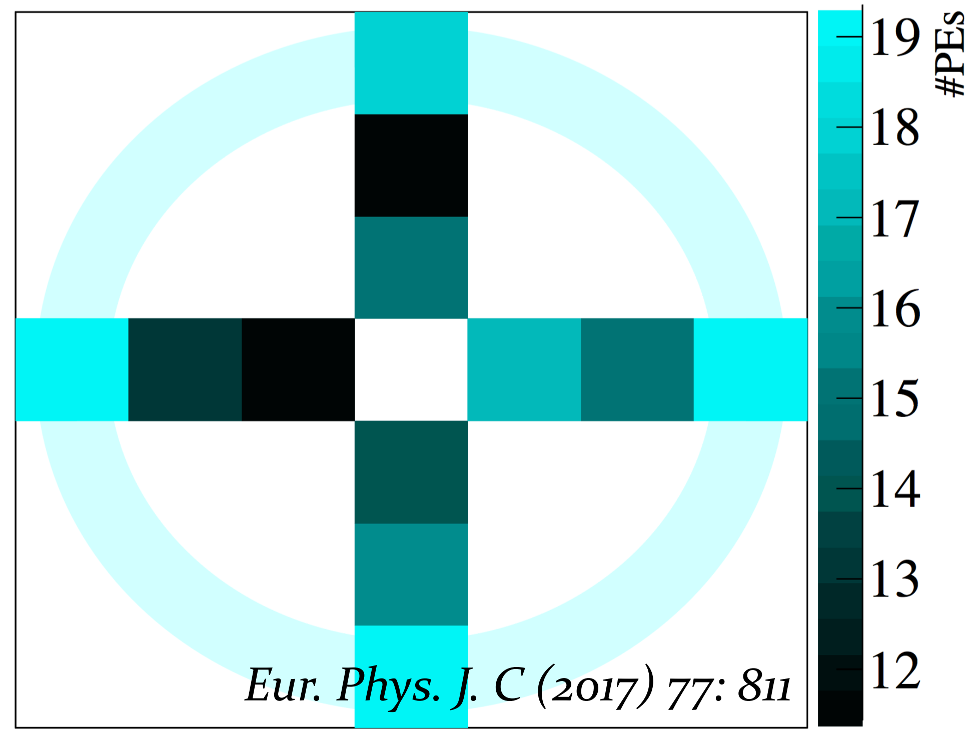

Eur. Phys. J. C (2017) 77: 811

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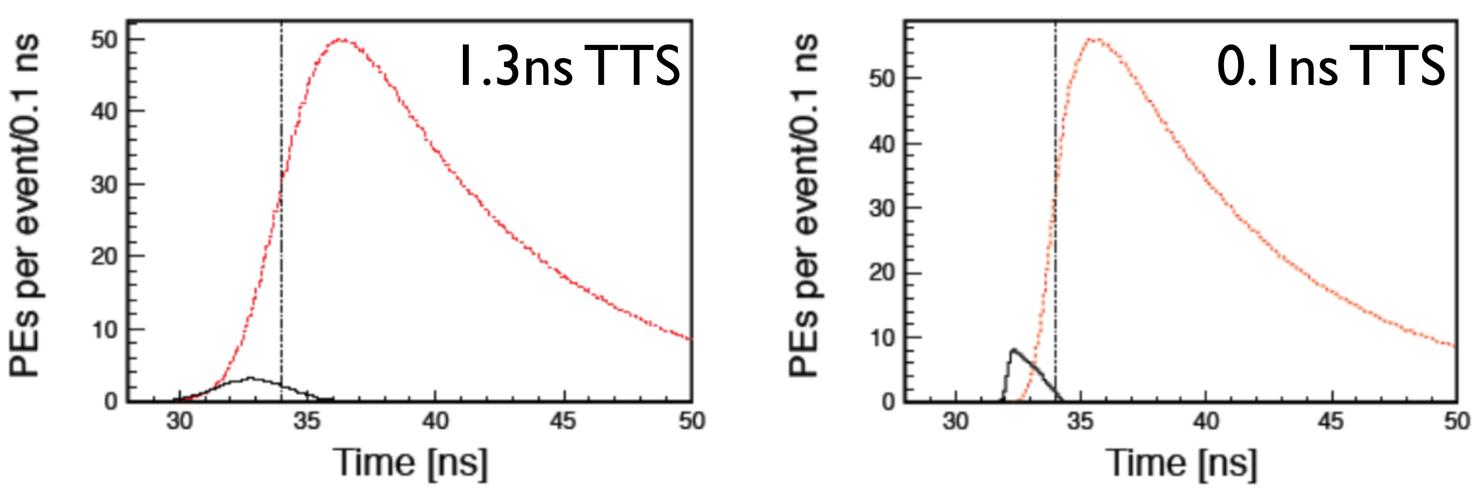

C. Aberle et al, JINST 9 P06012 (2014)

Cherenkov (prompt, scarce)

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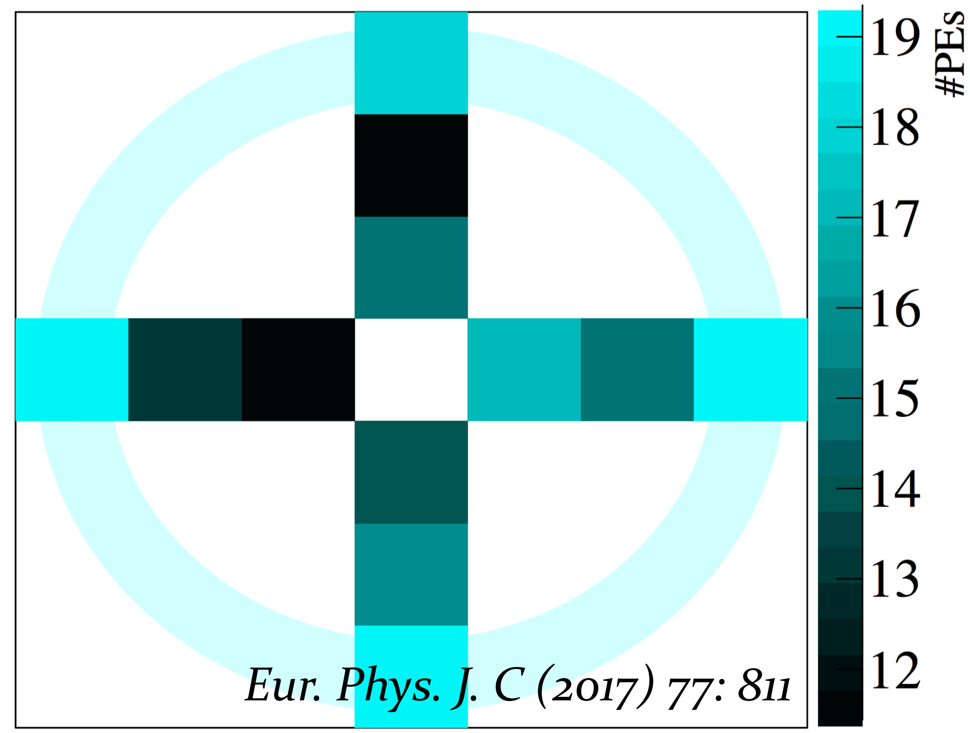

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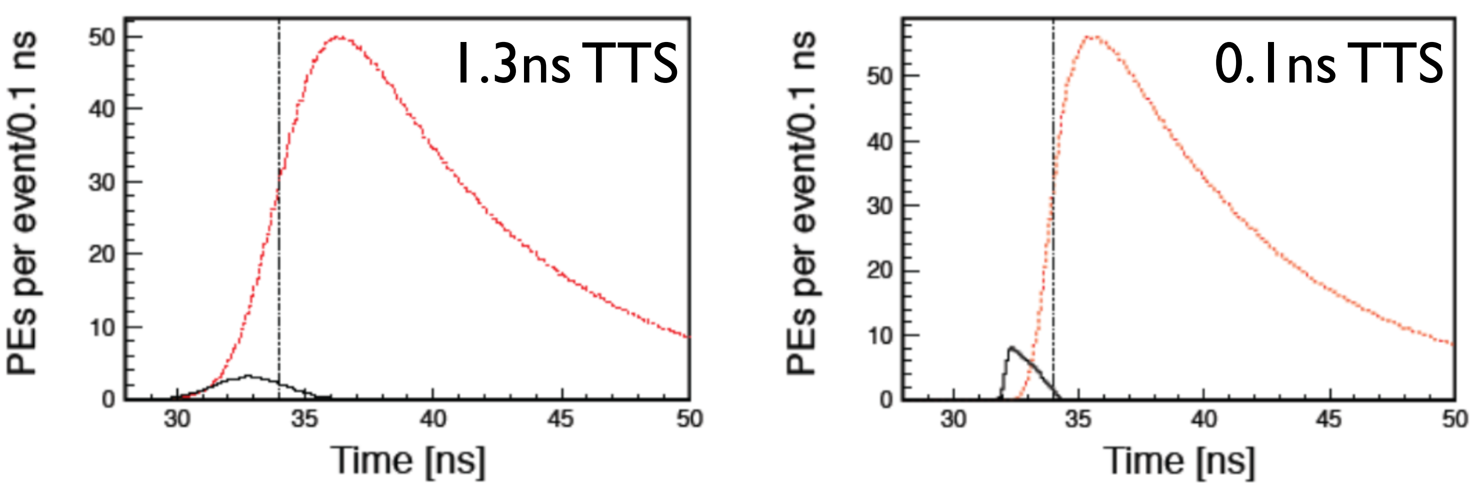

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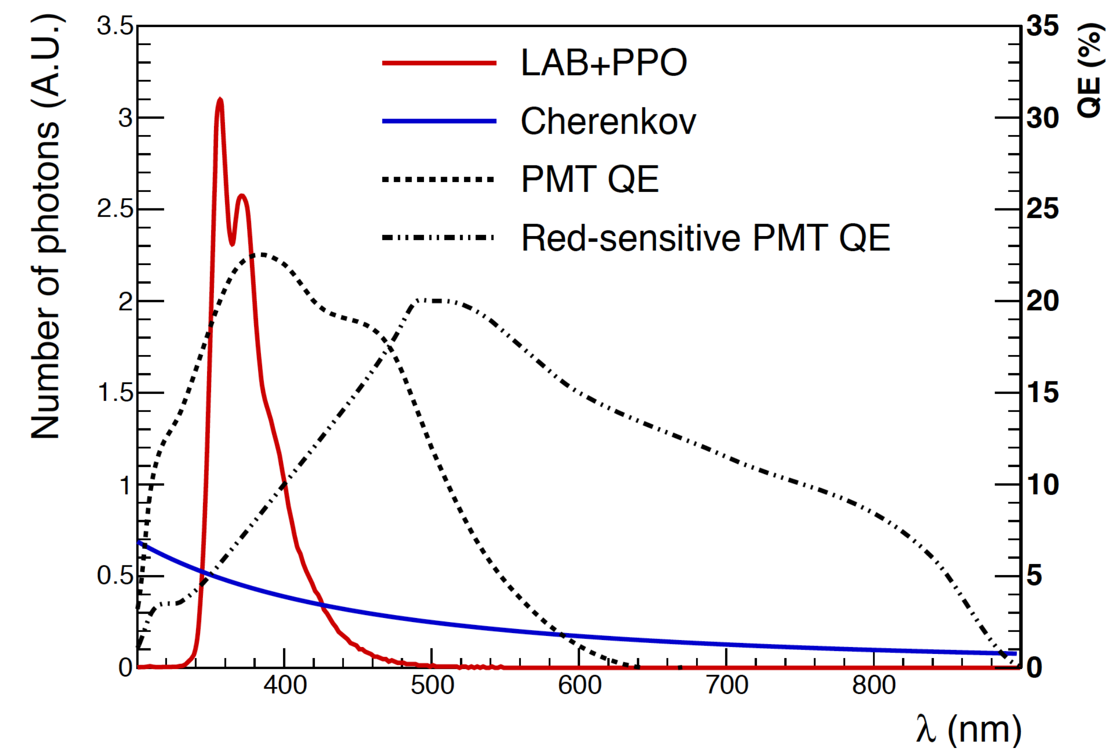
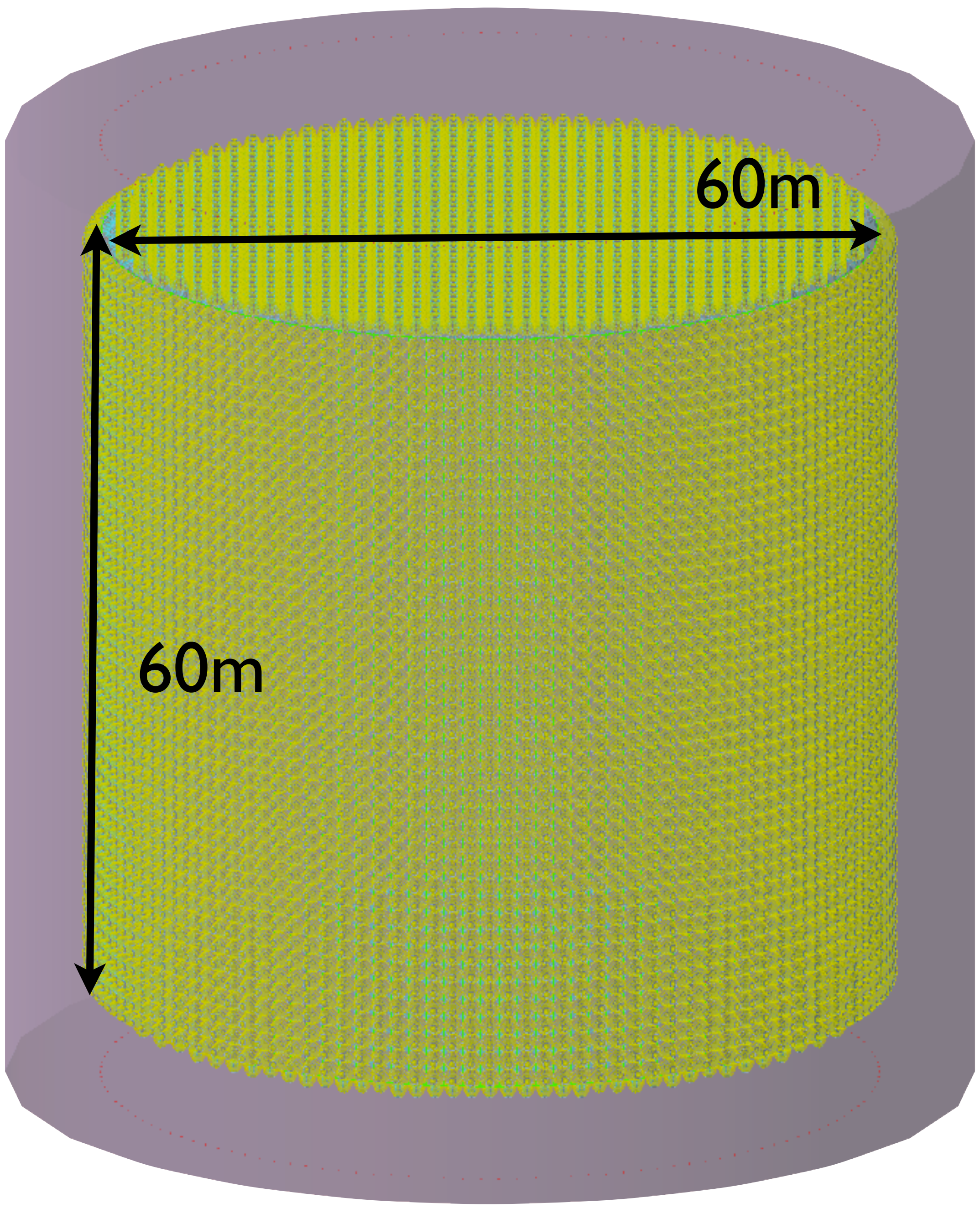
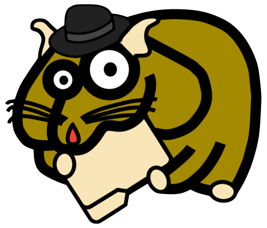


Theia

- 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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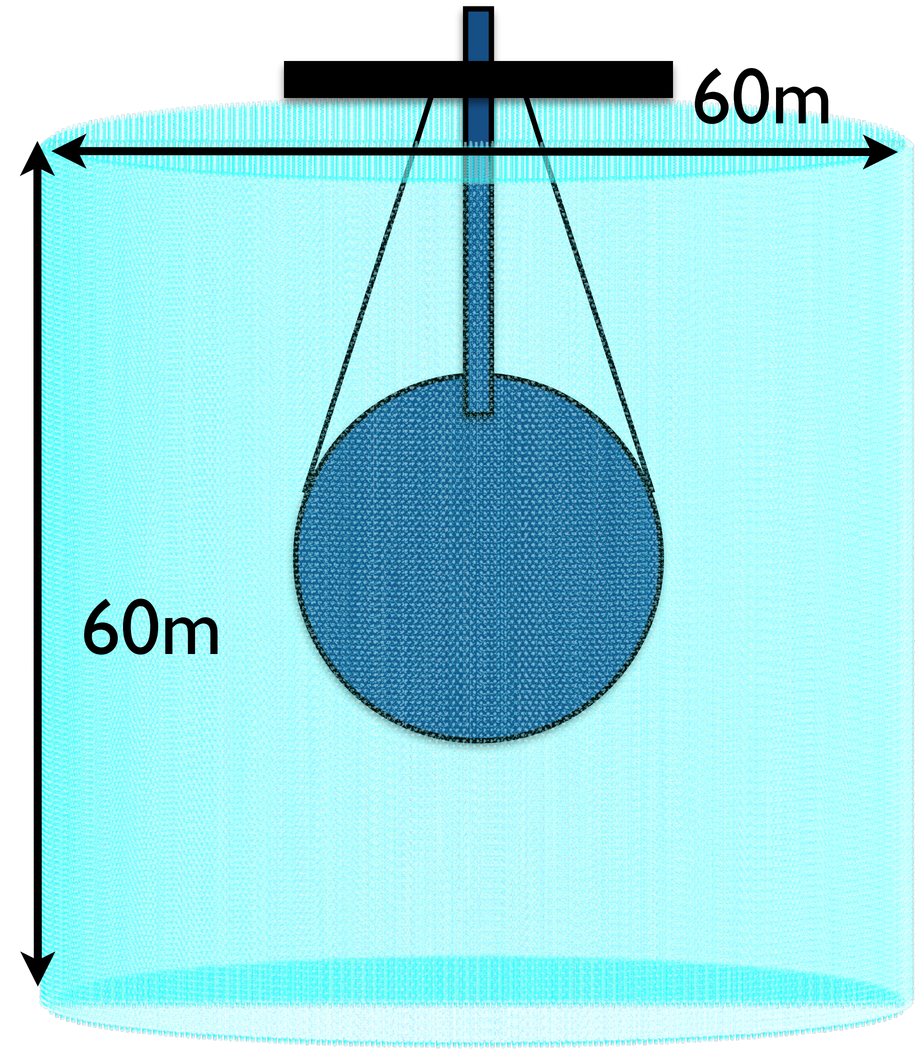

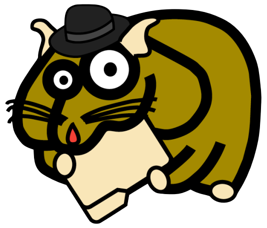

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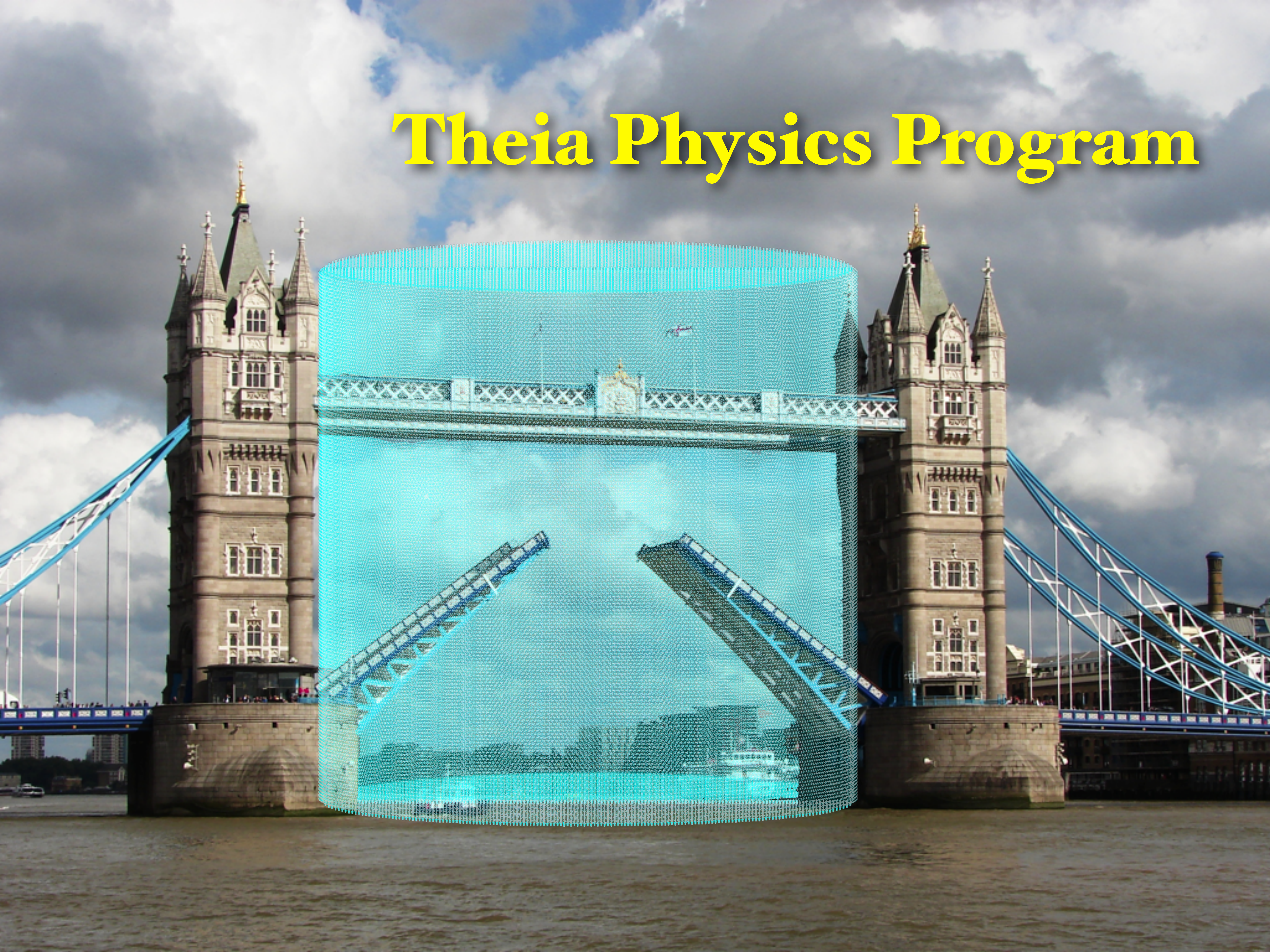
Theia Physics Program



Physics Program

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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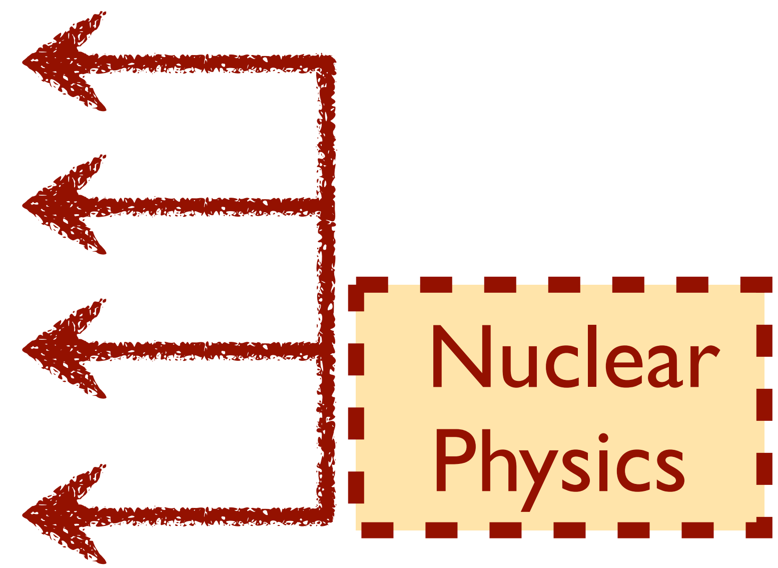

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Nuclear Physics (items 1–4)

High-Energy Physics (items 5–7)

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Physics over 5 orders of magnitude

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Nuclear Physics (1–4)

High-Energy Physics (5–7)

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

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Nuclear Physics

High-Energy Physics

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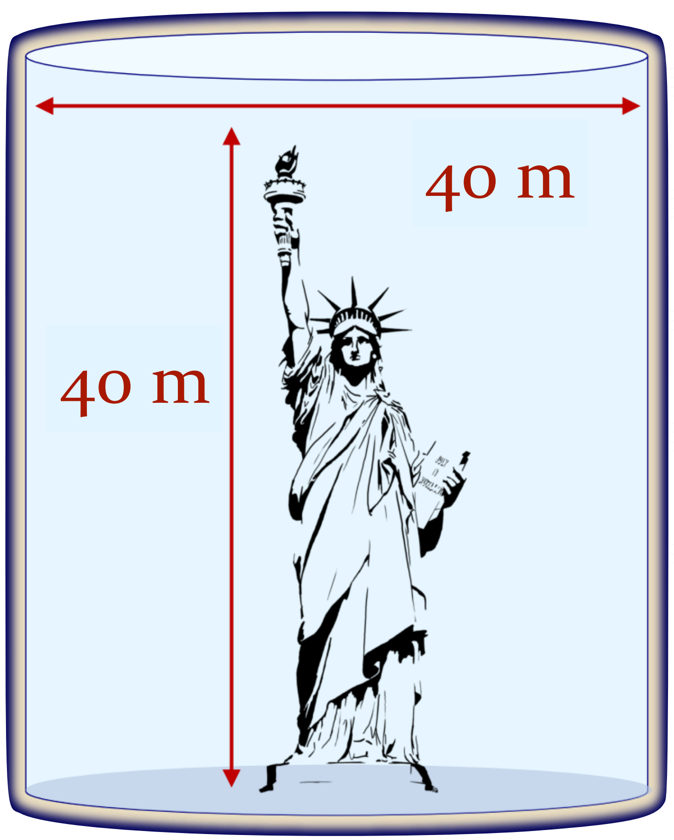
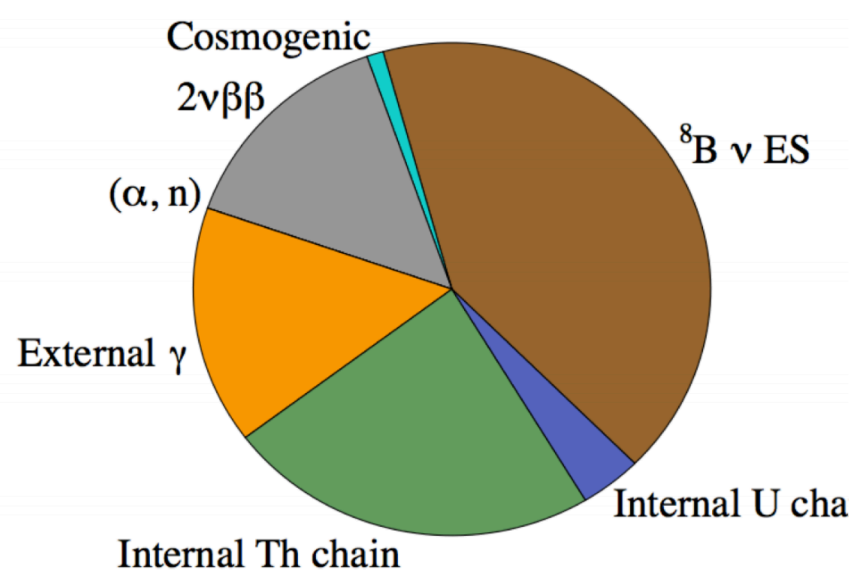
Leptogenesis

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 or ^{enr}Xe, 10 years



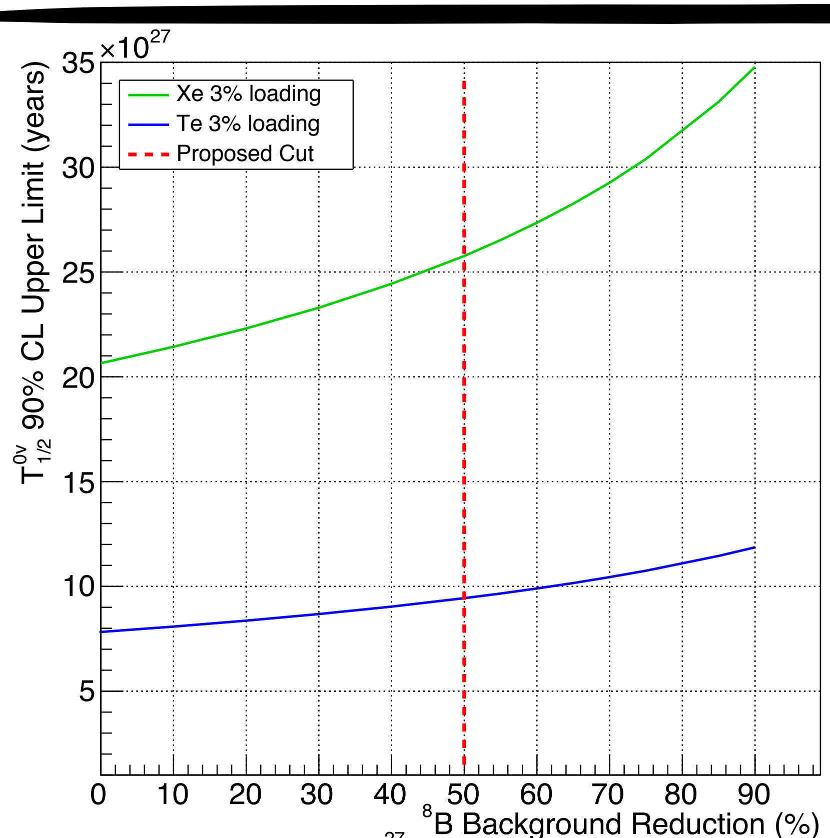


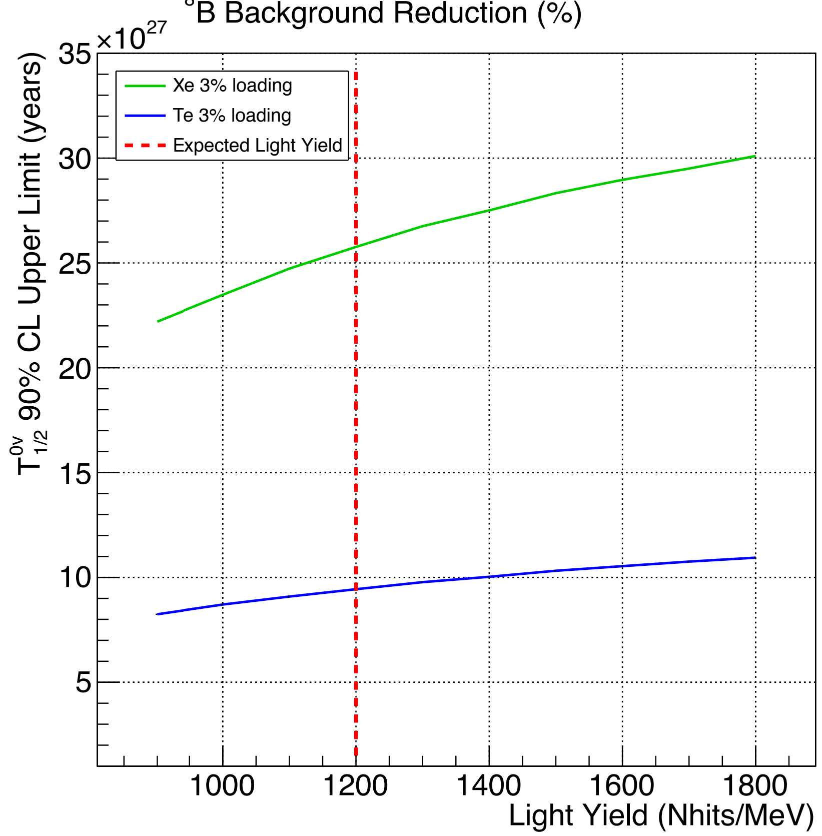
SNO+ Collaboration

Signal	Events/ROI·y Te Loading	Events/ROI·y ^{enr}Xe Loading
$0\nu\beta\beta$ (10 meV)	65.4	116.4
$2\nu\beta\beta$	48.0	38.2
^{8}B Solar ES (50%)	138.5	138.4
^{10}C (92.5%)	24.6	25.4
^{130}I	48.3	—
^{130m}I	1.7	—
^{136}Cs	—	0.57
^{208}Tl	0.02	0.002
^{214}Bi (99.9%)	4.0	4.4
Balloon ^{214}Bi (50%)	24.0	27.4
Balloon ^{208}Tl (50%)	0.25	0.14
Total	289.5	234.5

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

NLDBD with Theia





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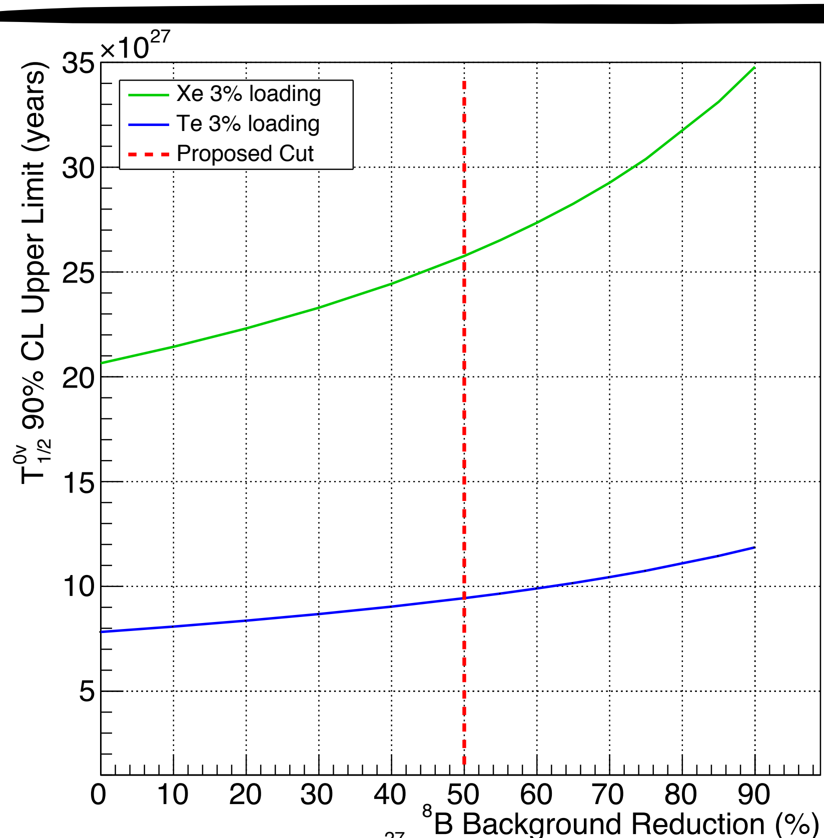

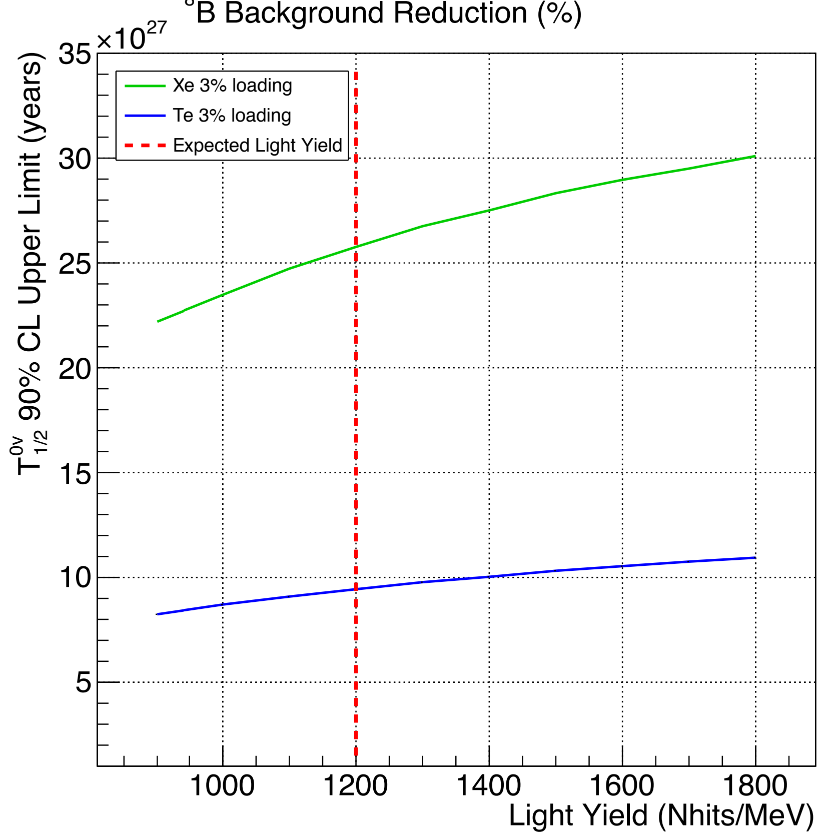

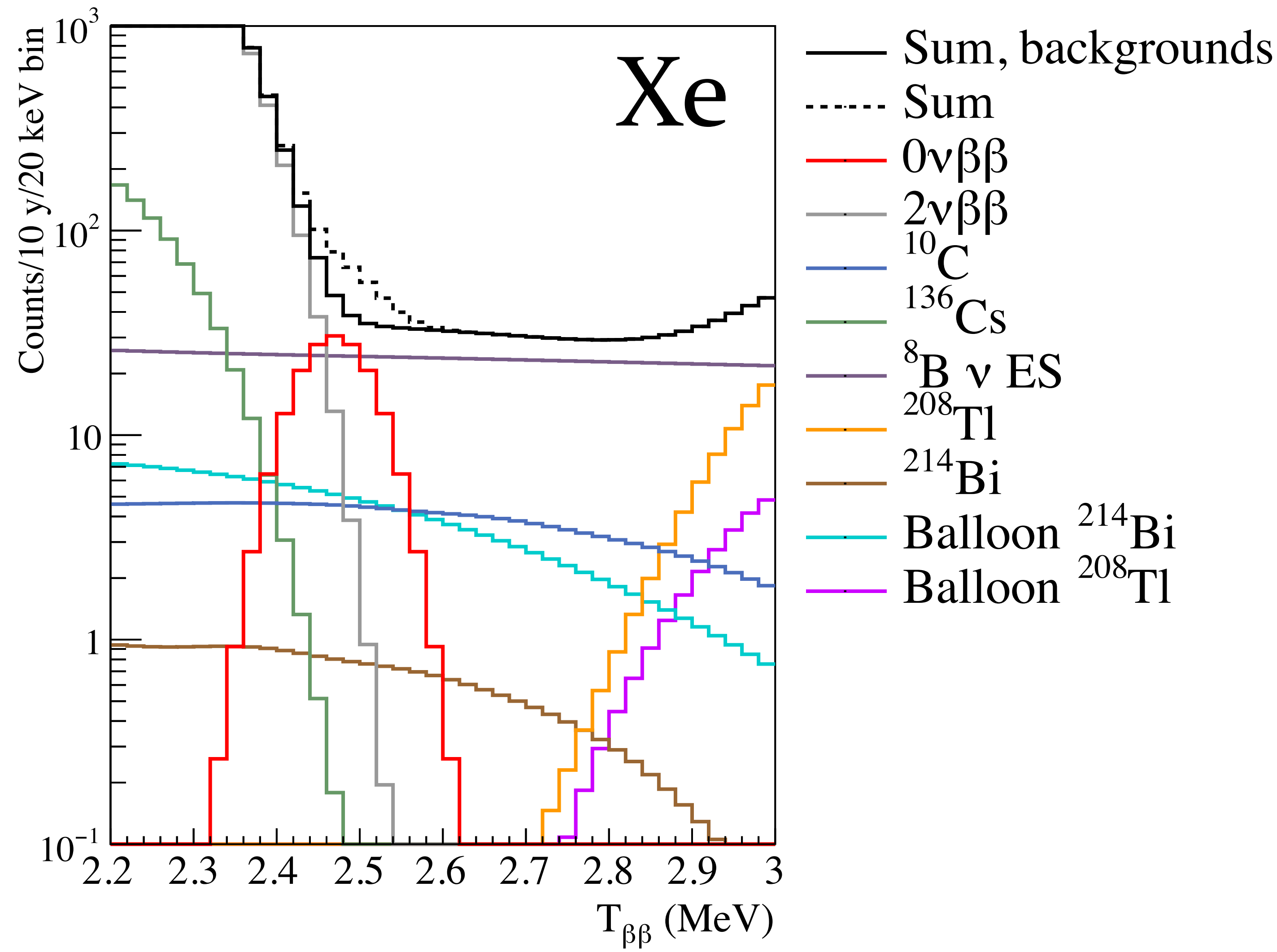

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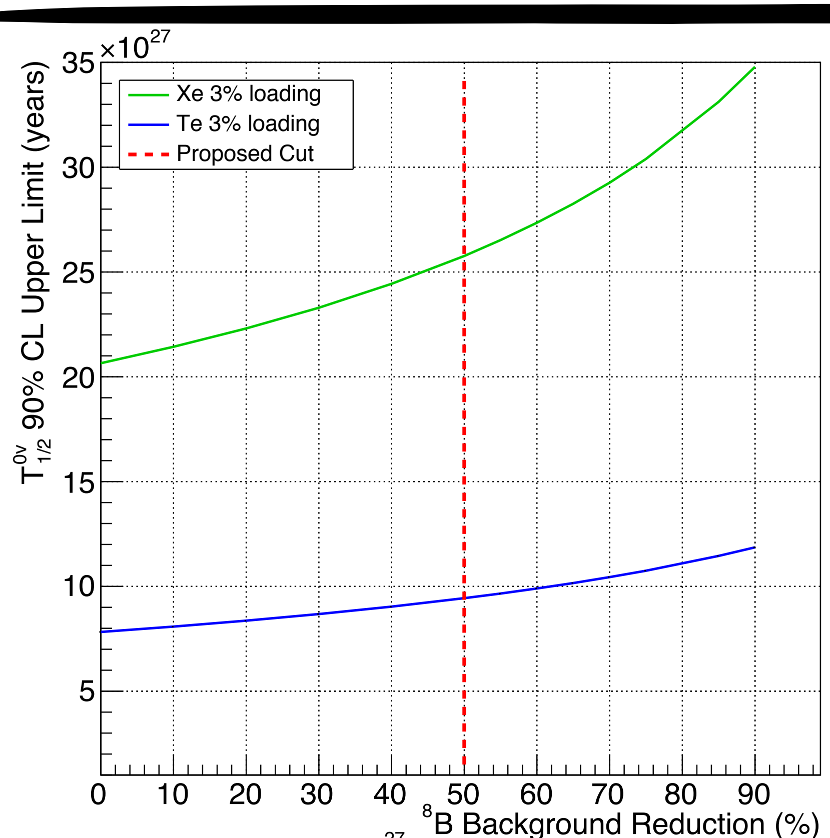
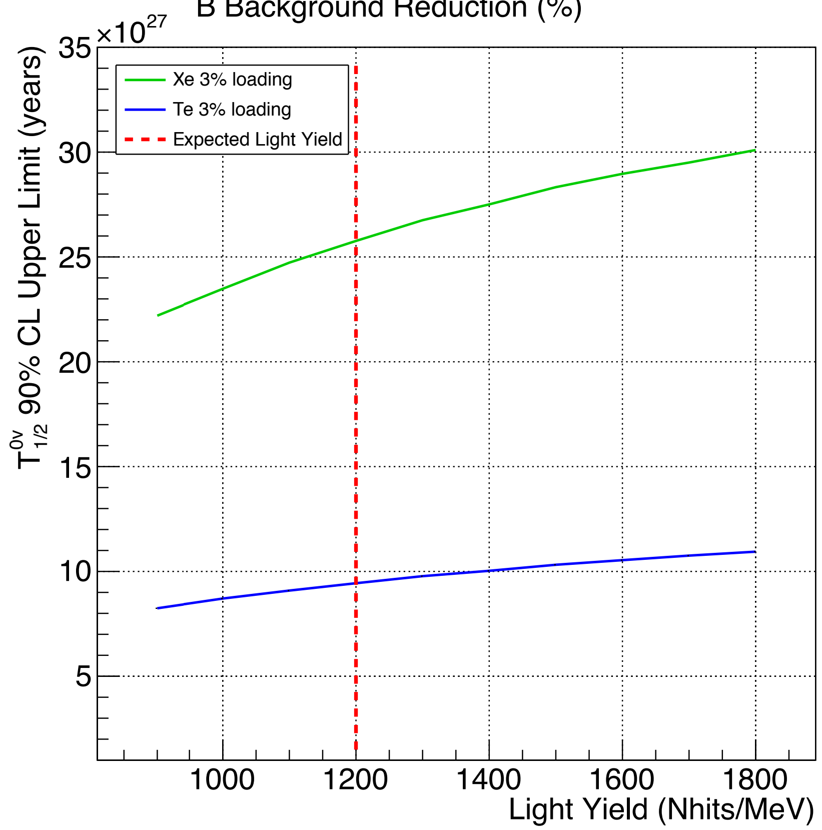
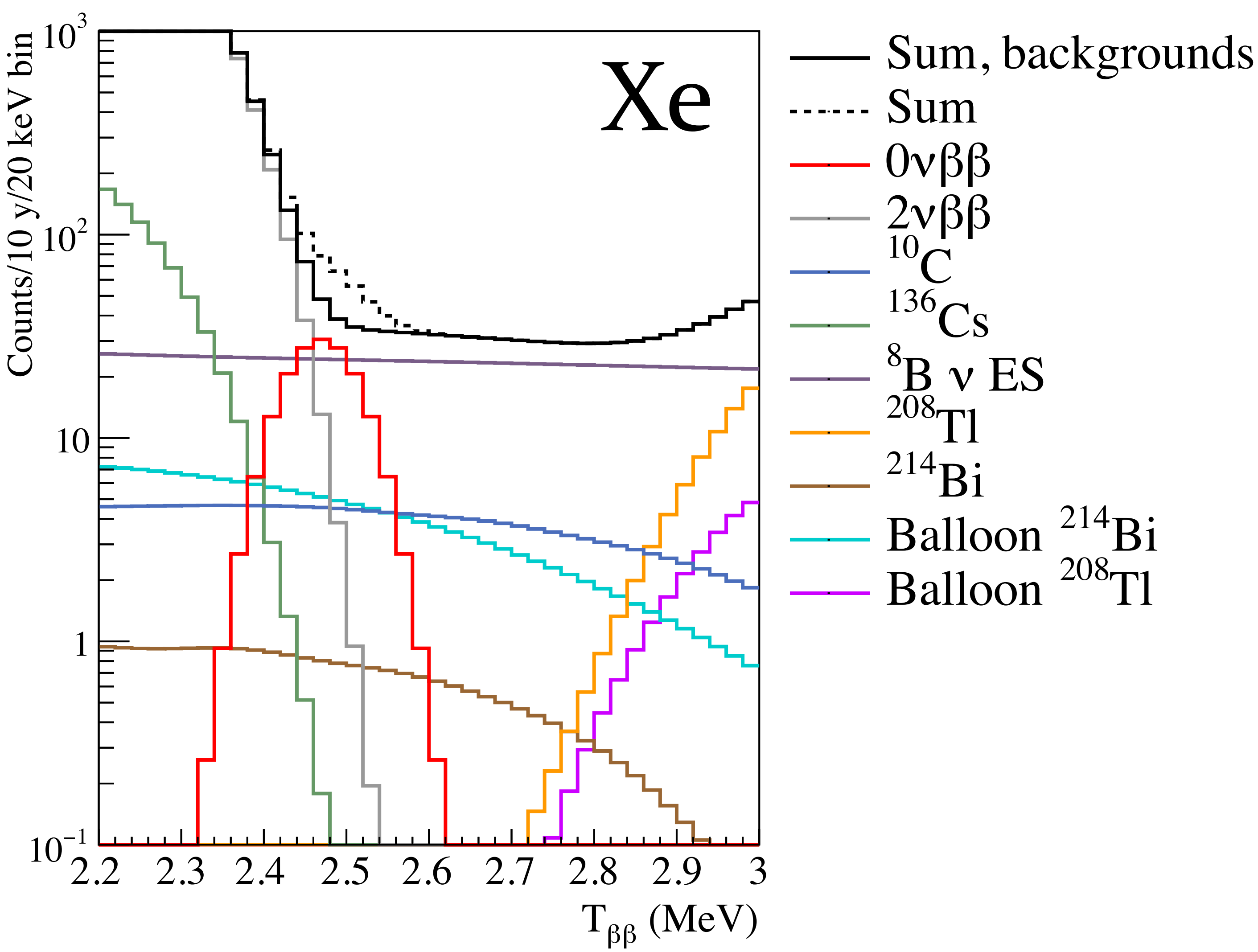




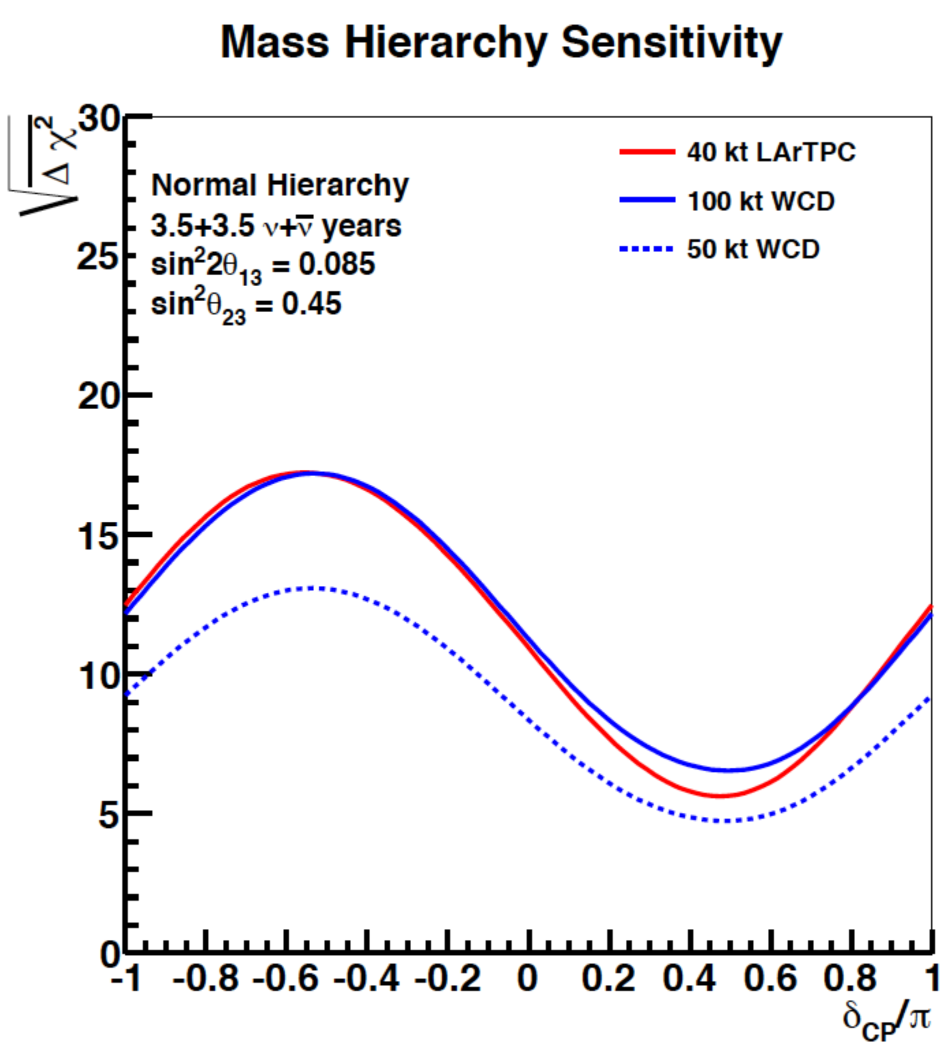


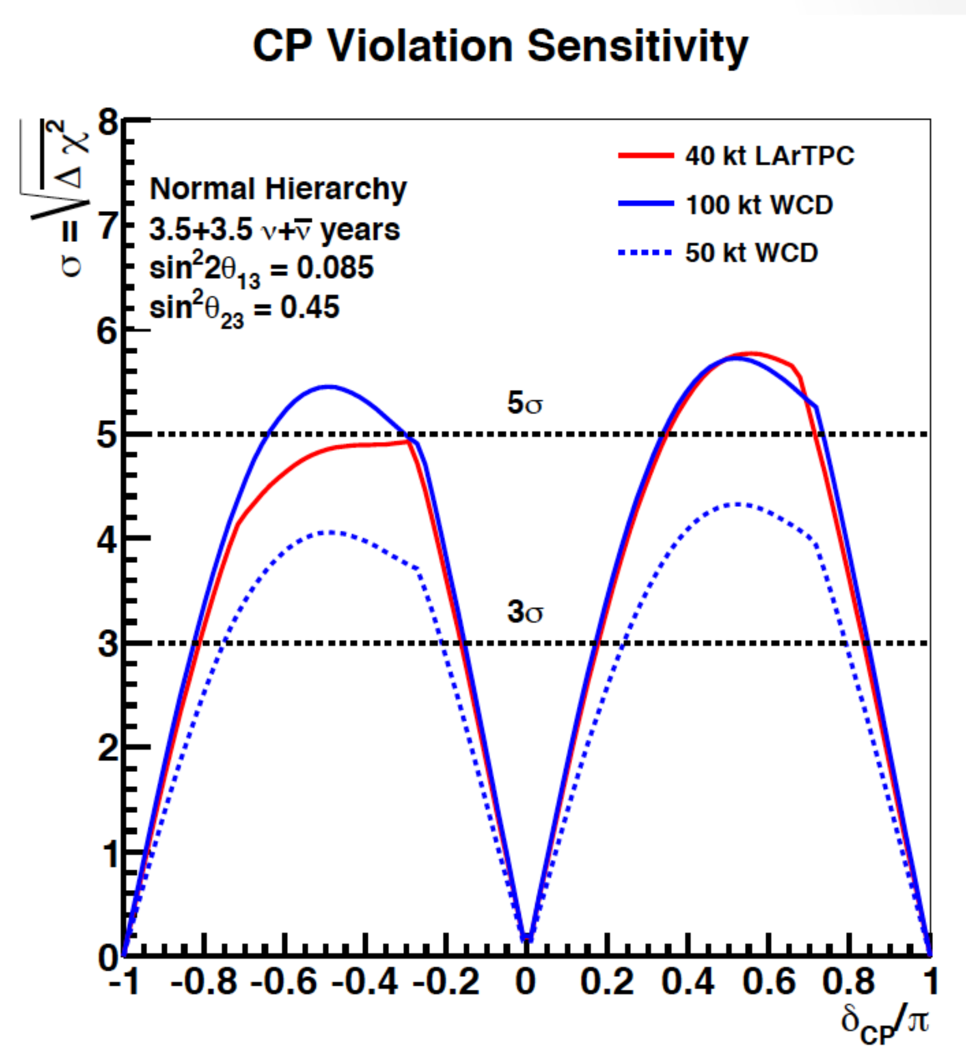
$T_{1/2} > 2.6\ (0.97) \times 10^{28}$ yrs
90% CL for Xe (Te)
$m_{\beta\beta} < 4.9\ (6.7)$ meV

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

- *Assumes 75% reduction in NC background relative to SK-I*
- *Uses only single-ring samples*





MH sensitivity for 50kt WbLS alone > 5σ

More sophisticated analysis nearly complete with modern SK-style analysis and reconstruction tools + multi-ring samples

Nucleon Decay

Testing the existence of GUTs with THEIA:

- Large size (statistics), deep location, very clean
- n tagging (low threshold plus potential isotope loading)
- Sub-Cherenkov threshold detection

Nucleon Decay

Testing the existence of GUTs with THEIA:

Figs from arXiv:1409.5864, assume 100t FV; studies based on Phys. Rev. D 72 , 075014 (2005); LAr from JHEP 0704:041,2007

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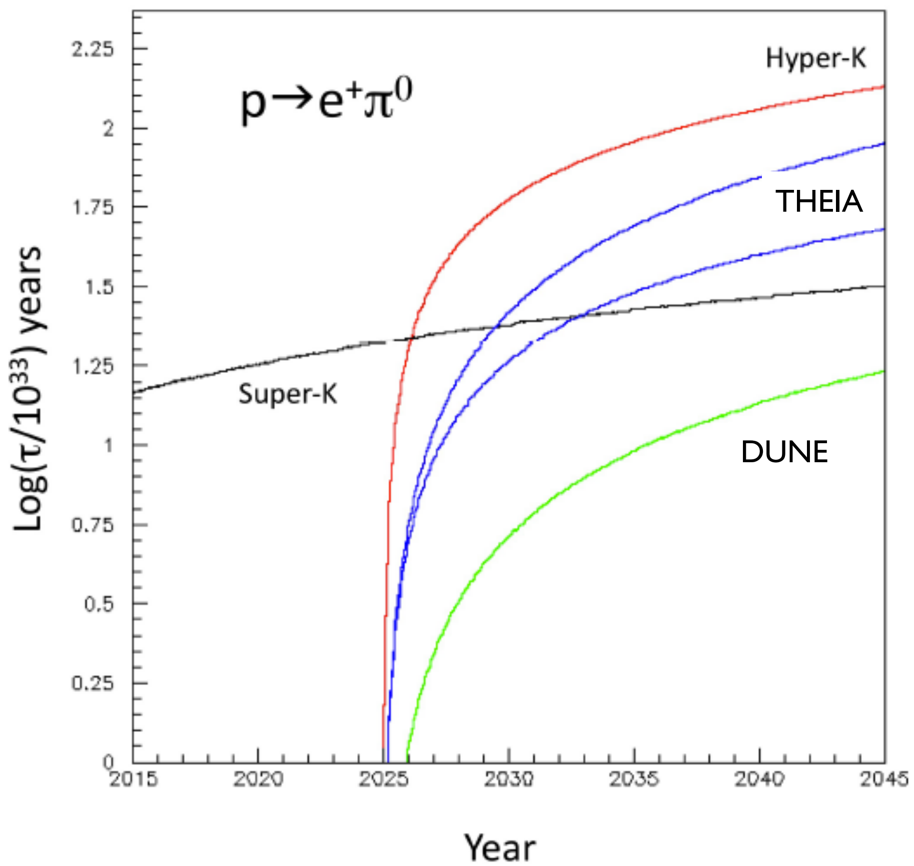
Heavy X boson exchange



Enhanced n tag

Reduced atmos. ν bkg

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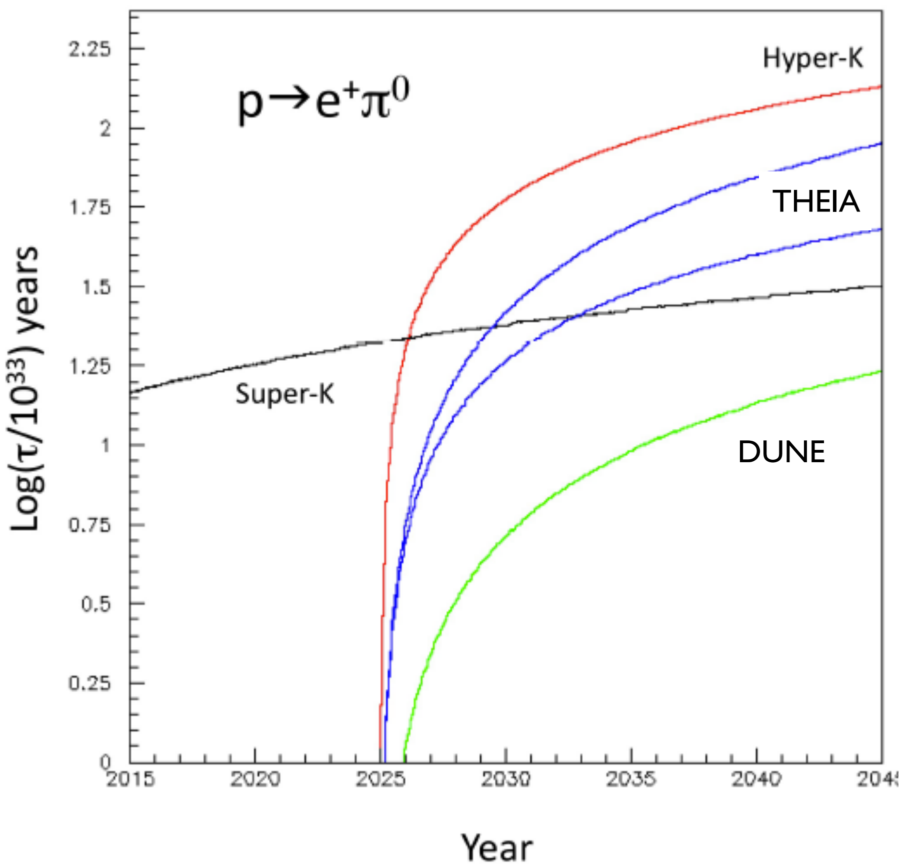

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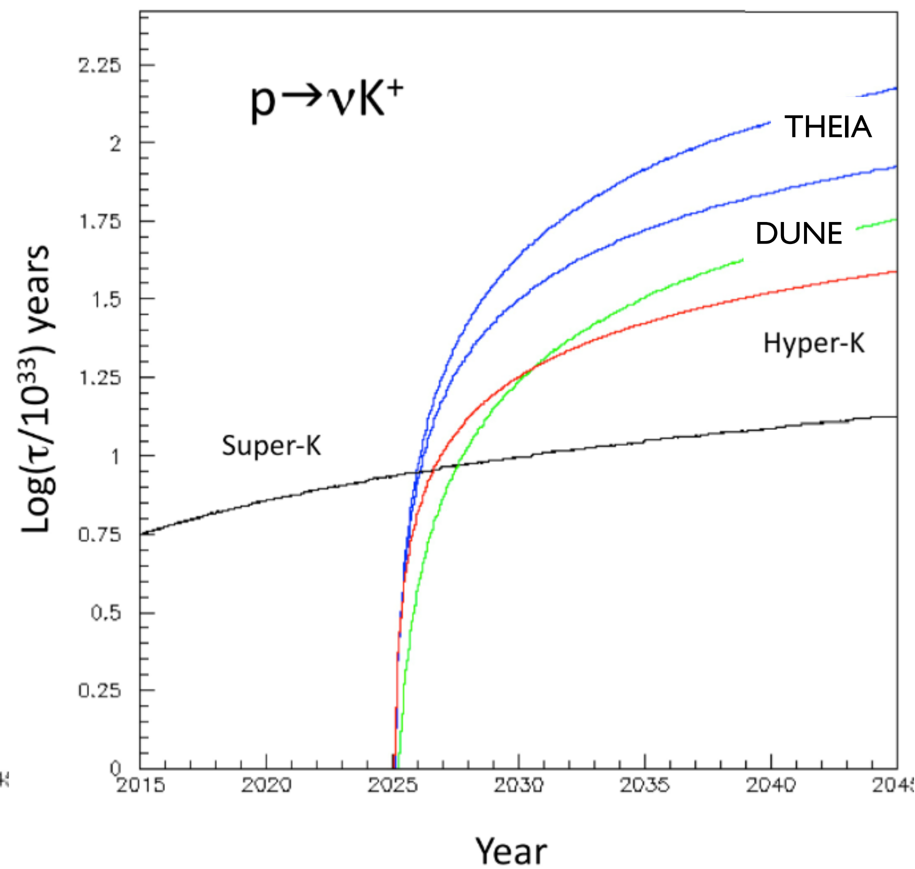
2nd order processes



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

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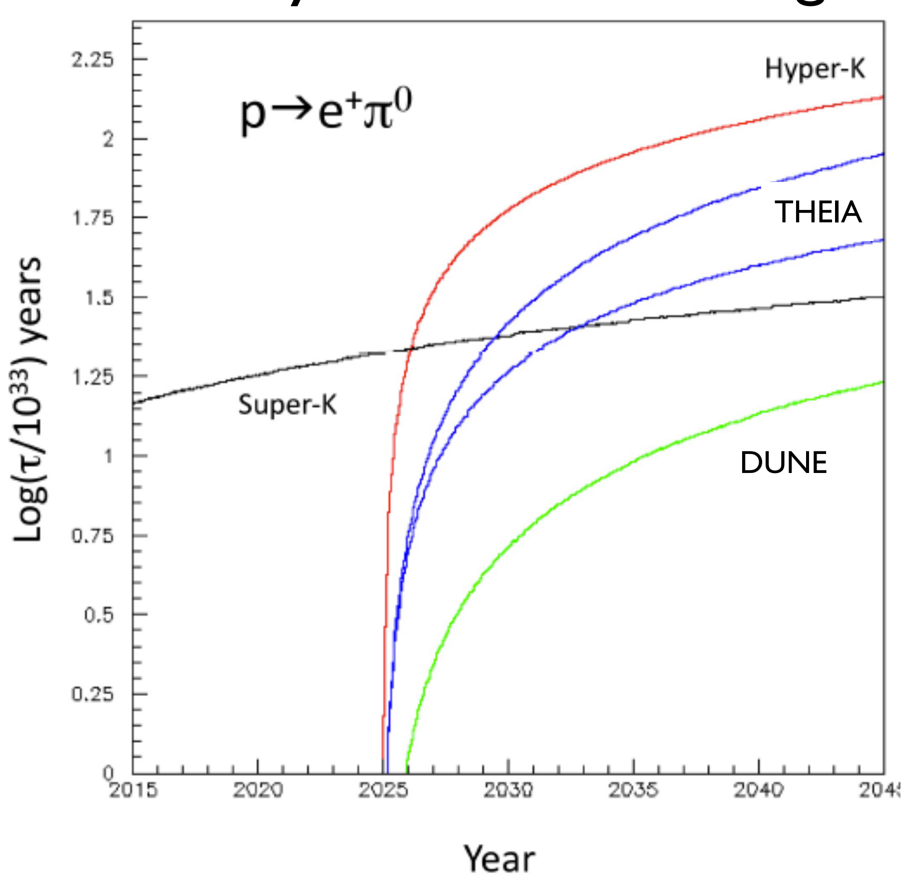

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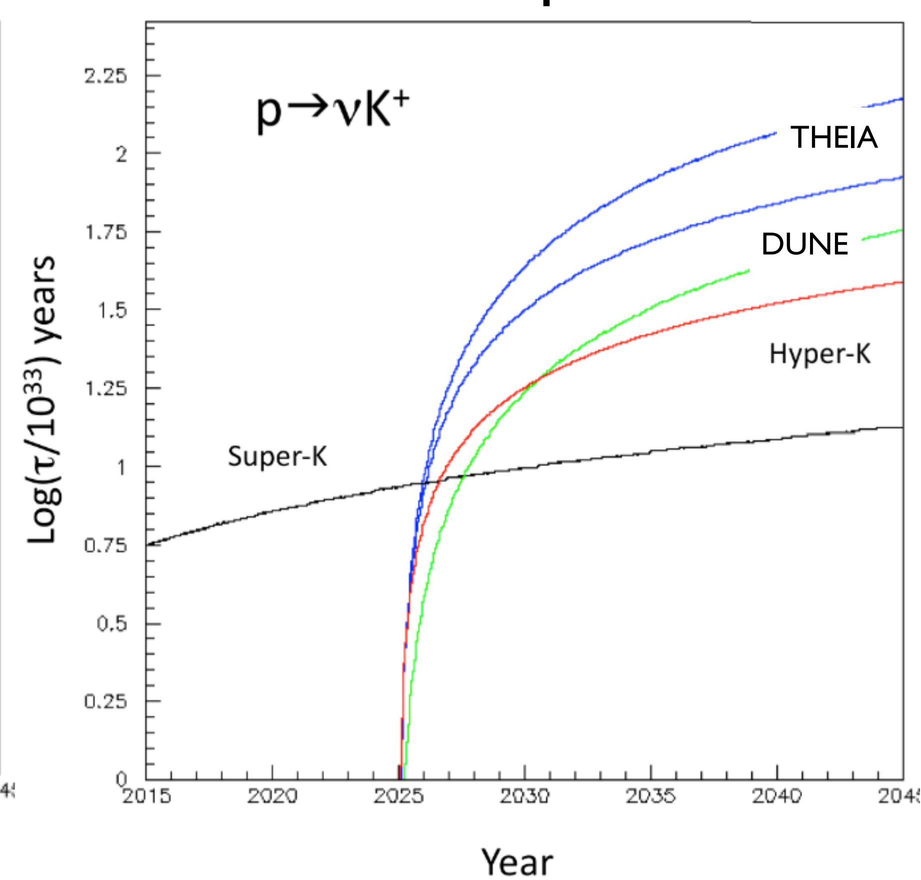

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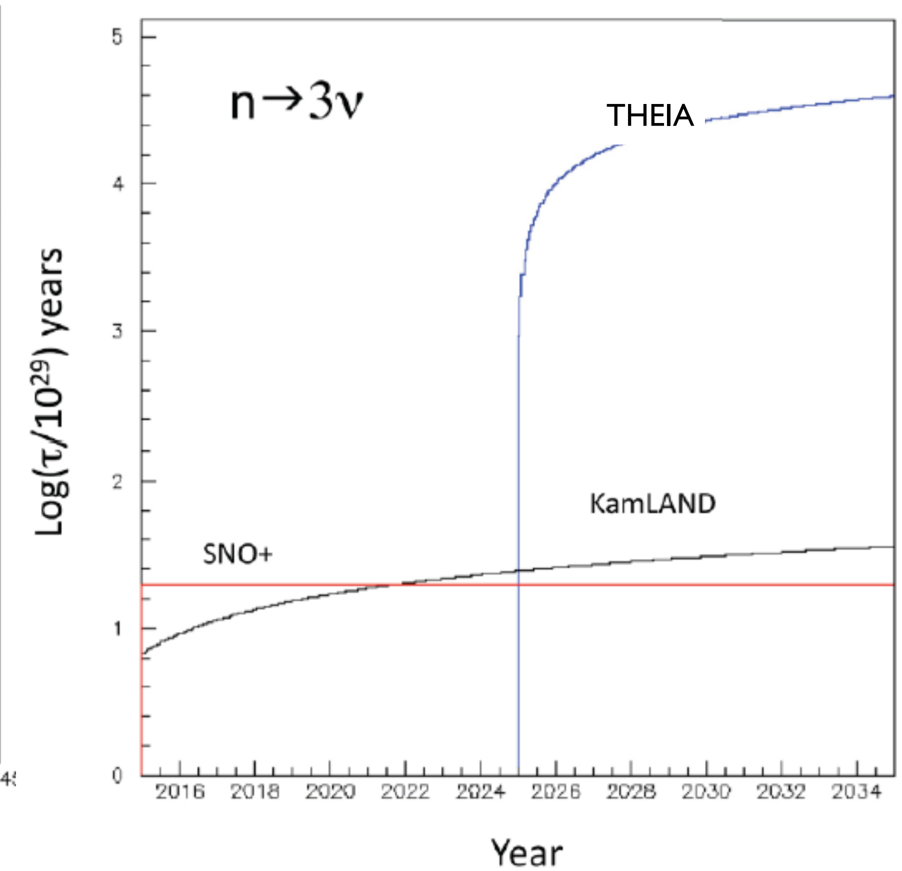
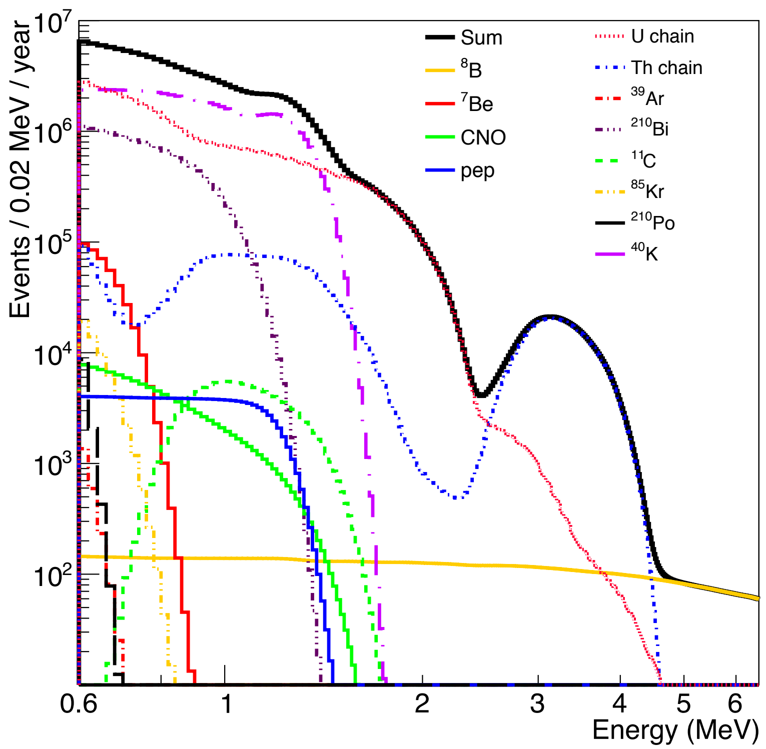
Extra dimensions

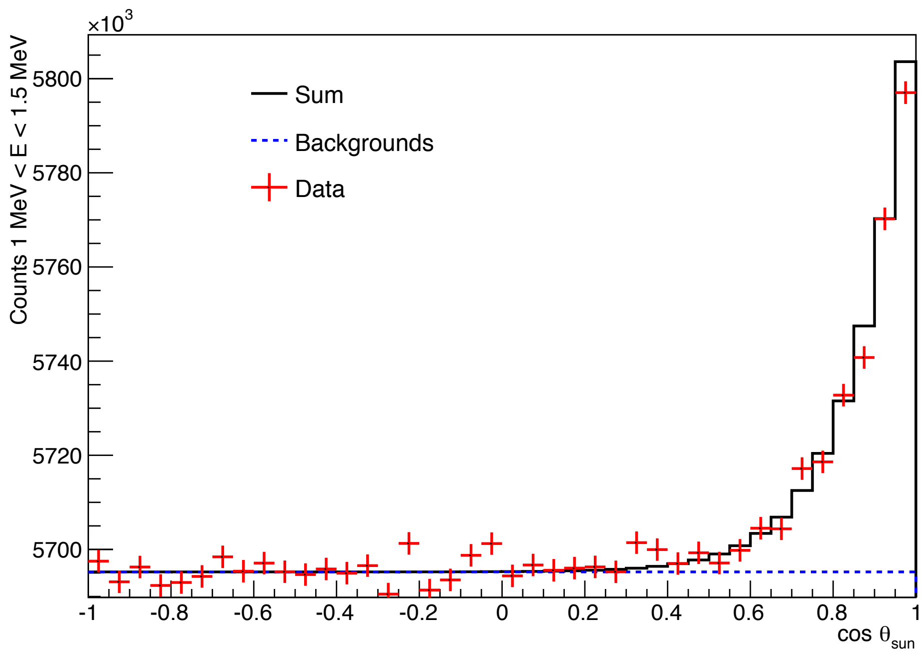


Deep, low threshold

Directionality + n tag

Solar Neutrinos with Theia

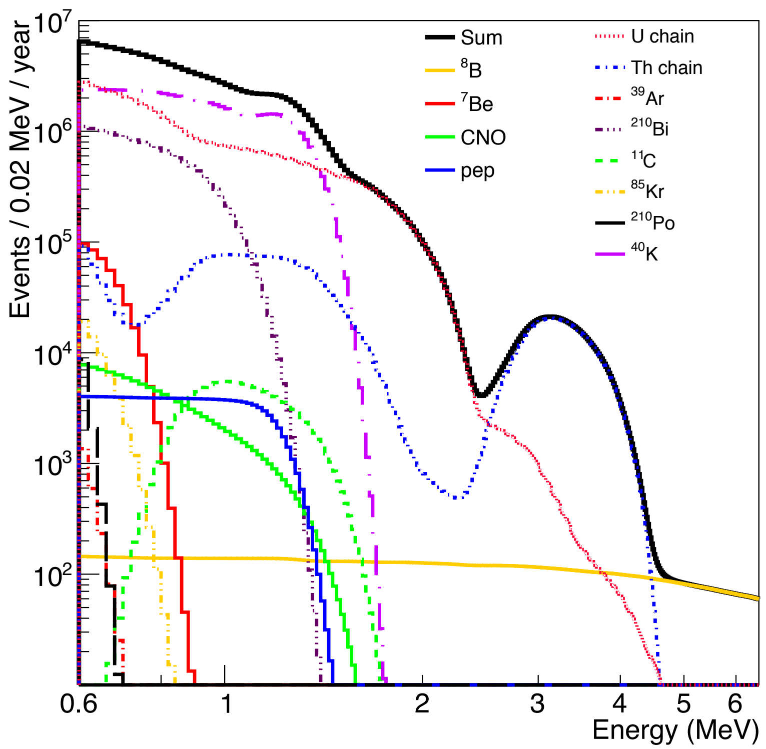


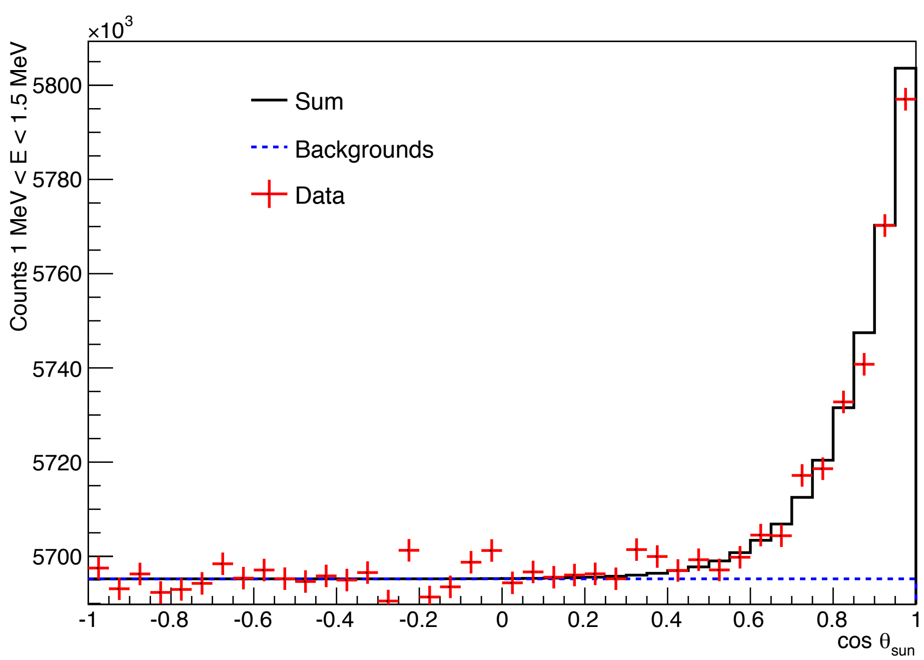


2D fit in energy and cos(θ_{sun})

- Dominant background to CNO ν measurement: ^{210}Bi
- Theia offers unique low-threshold, directional detection

Solar Neutrinos with Theia





2D fit in energy and cos(θ_{sun})

- Dominant background to CNO ν measurement: ^{210}Bi
- Theia offers unique low-threshold, directional detection

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

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

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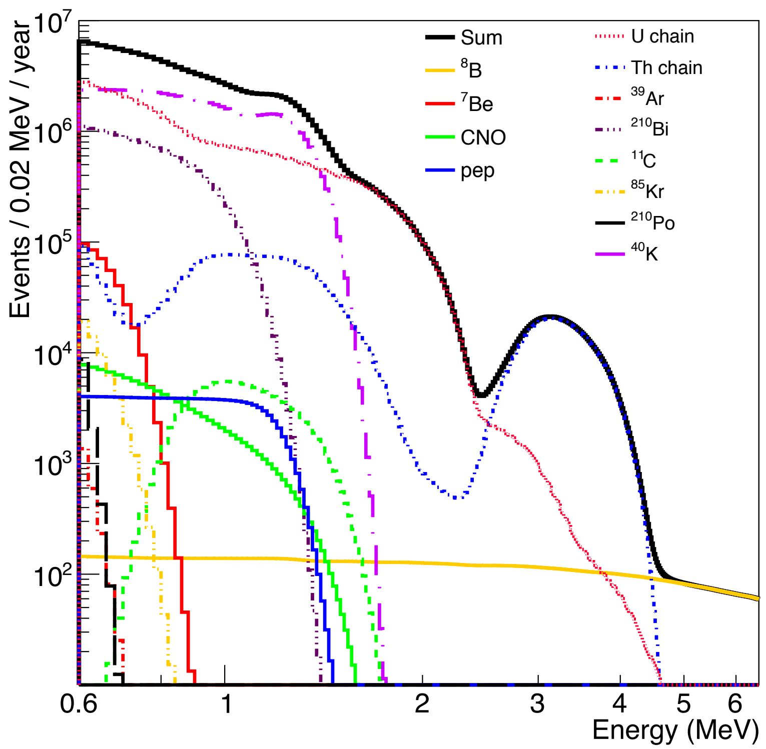

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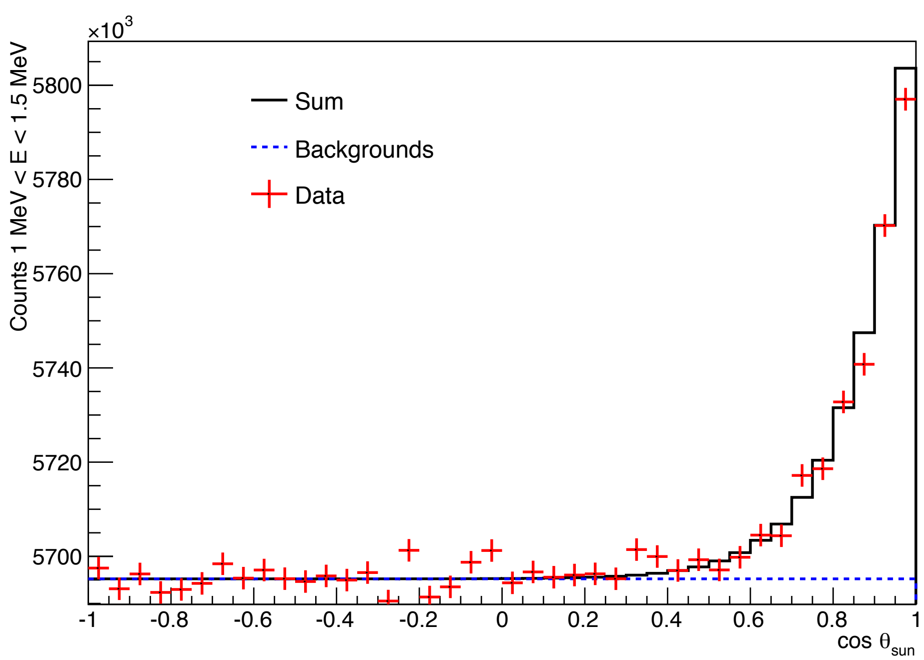

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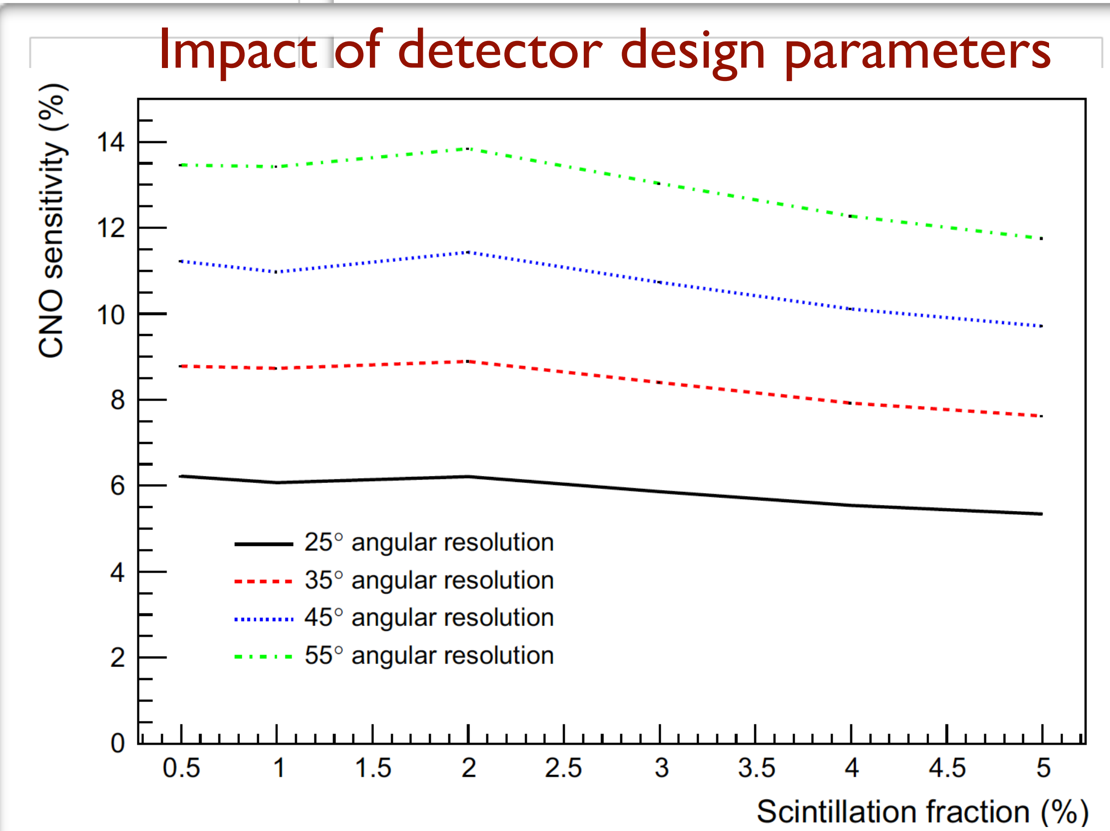


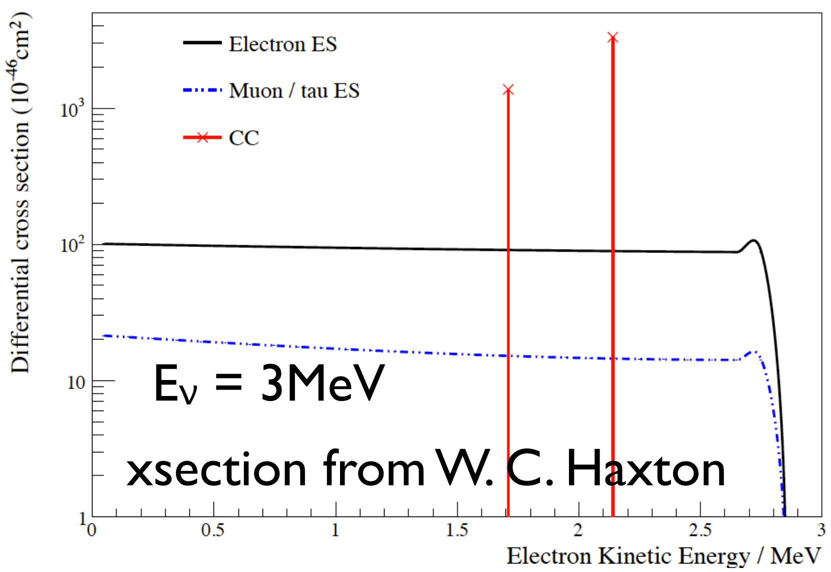
Theia Spectral Sensitivity

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

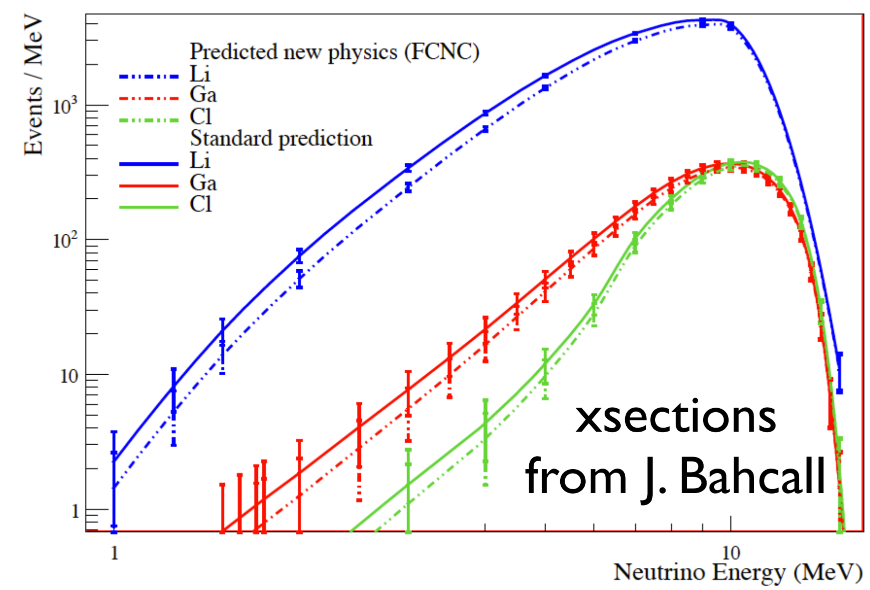
"Salty water Cherenkov detectors" W.C. Haxton PRL 76 (1996) 10

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

⇒ search for new physics, solar metallicity, MSW effect



Detector:
30kt fiducial
1% 7Li by mass
Conservative 100 pe/MeV



arXiv:1409.5864

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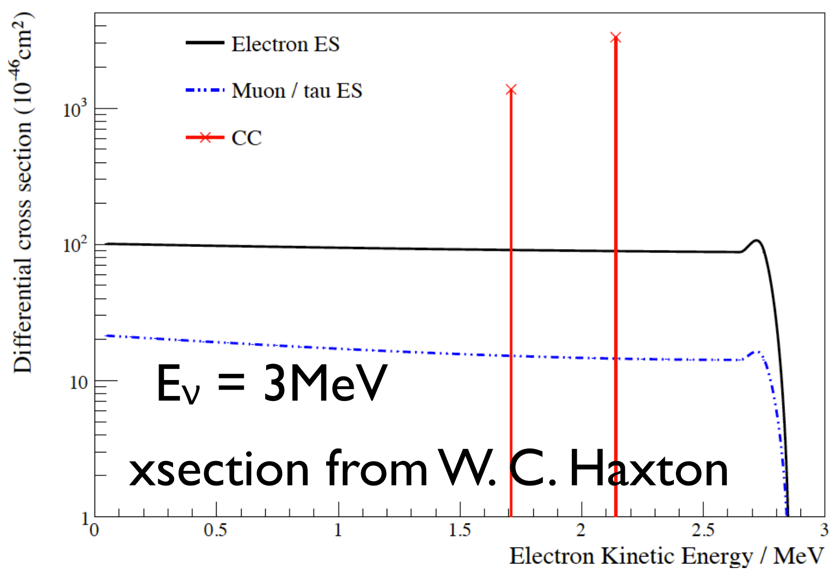

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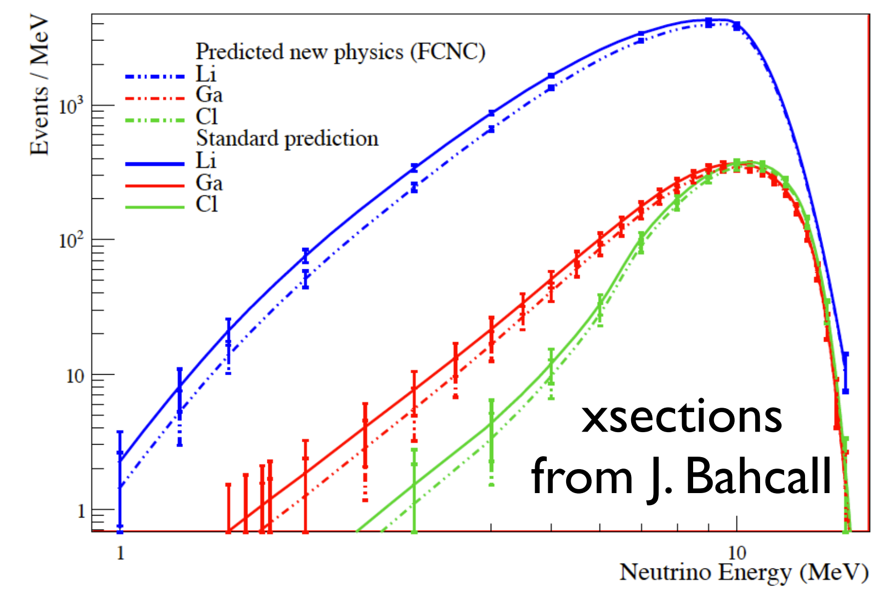
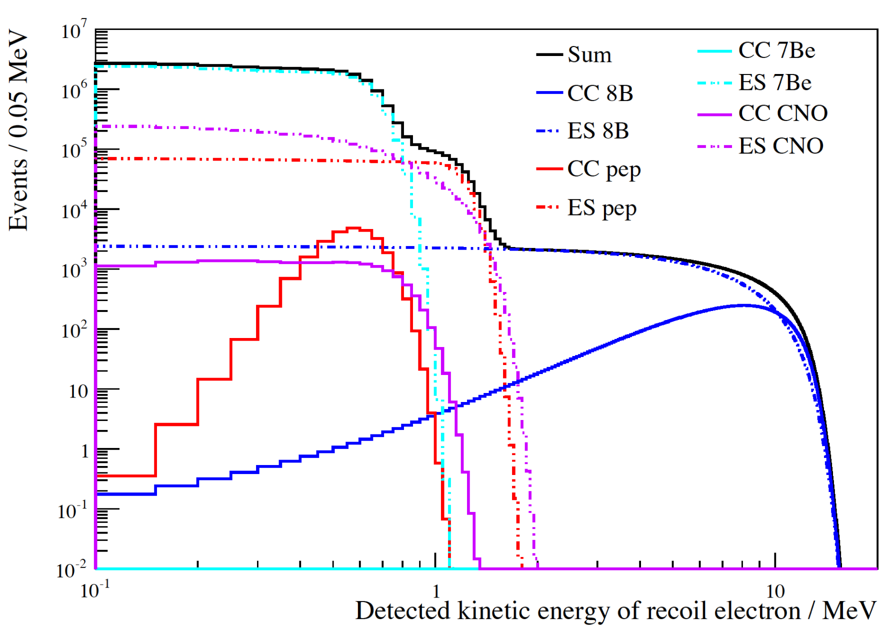




Unprecedented low-energy statistics (ES)

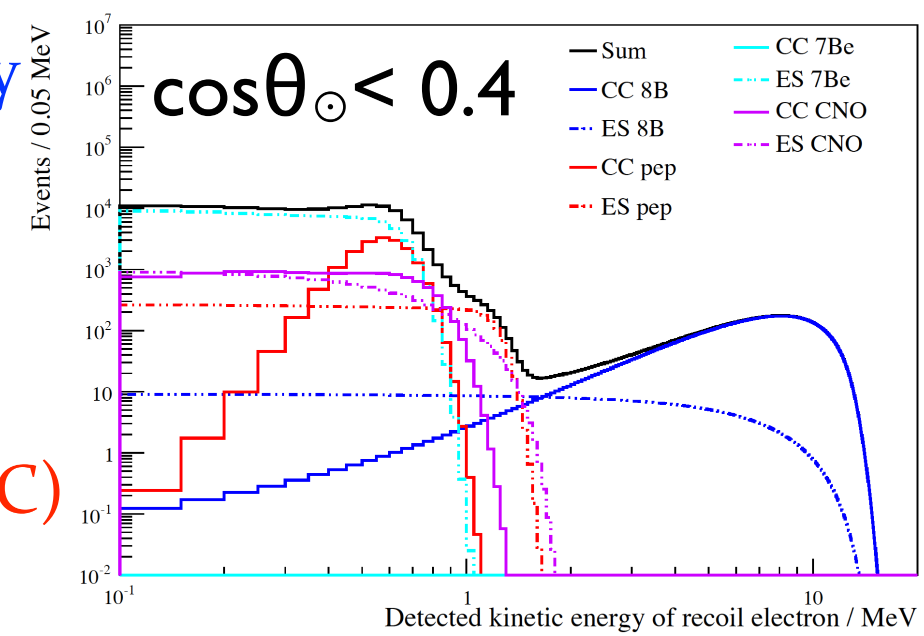
Similar to LENA —

Astropart. Phys. 35 (2011) 685-732

+ directionality from Cherenkov

Plus Spectral Sensitivity (CC)

arXiv:1409.5864



Antineutrino Detection

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

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- Current total geo-ν exposure: < 10kt-yr (KL + Borexino)
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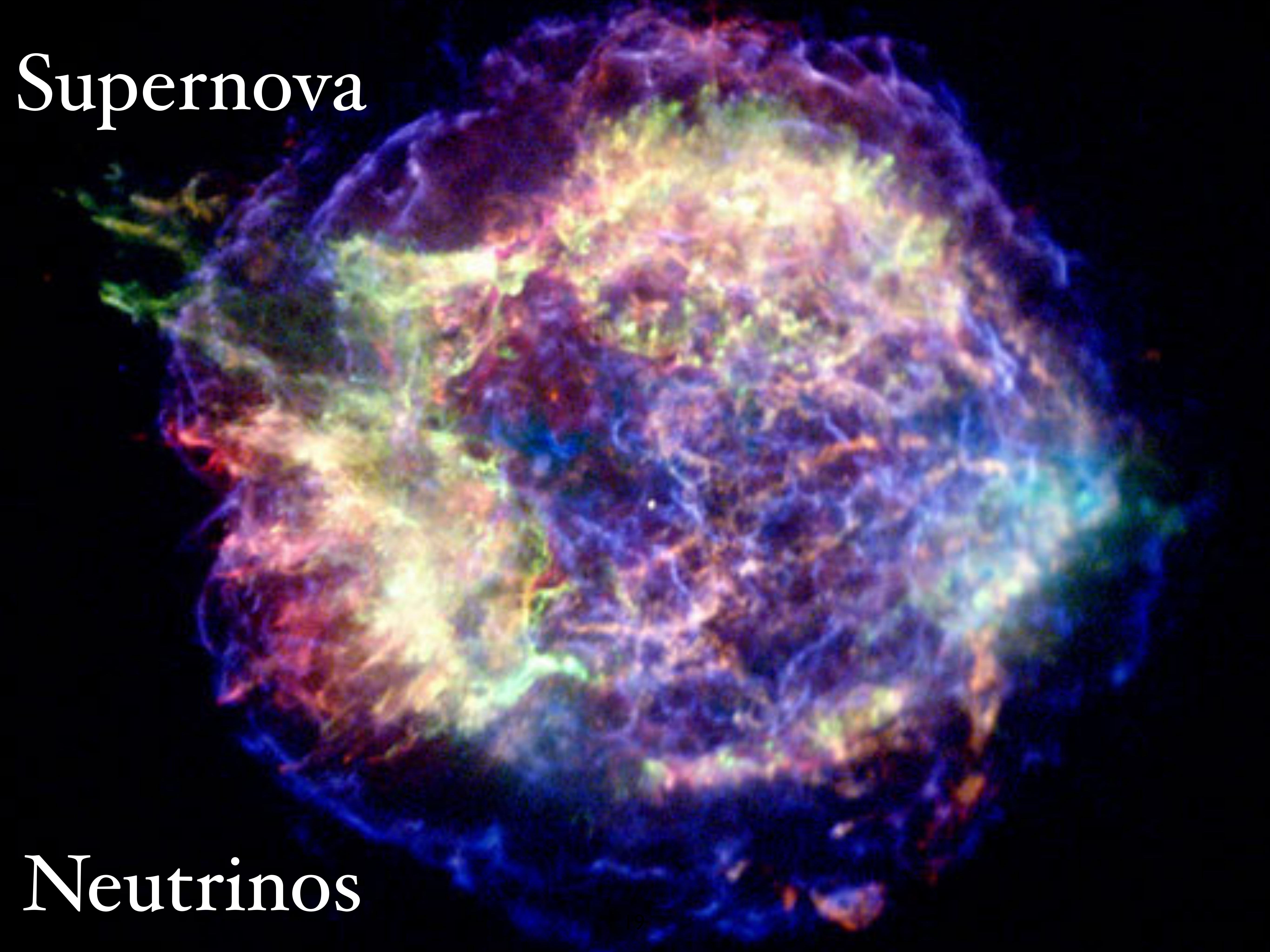
DSNB

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


Supernova
Neutrinos

Supernova Detection

Neutrino Reaction	Percentage of Total Events	Type of Interaction
$\overline{\nu}_e + p \rightarrow n + e^+$	88%	Inverse Beta
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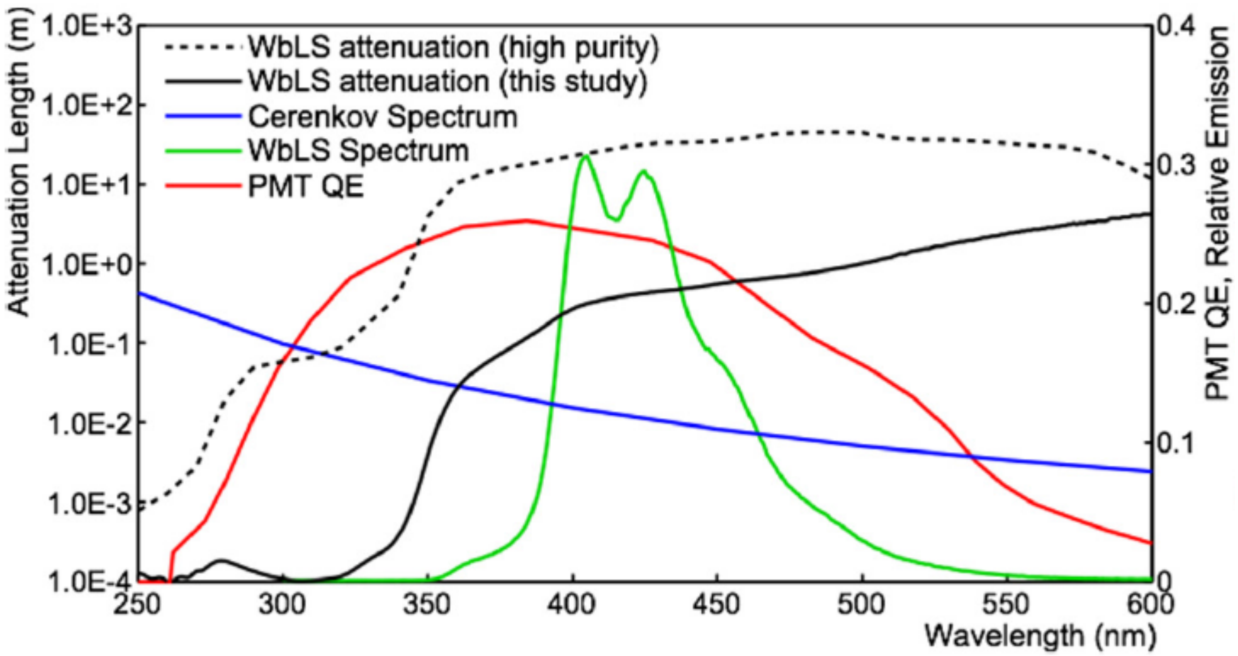
Early warning (PR value)


Ongoing R&D

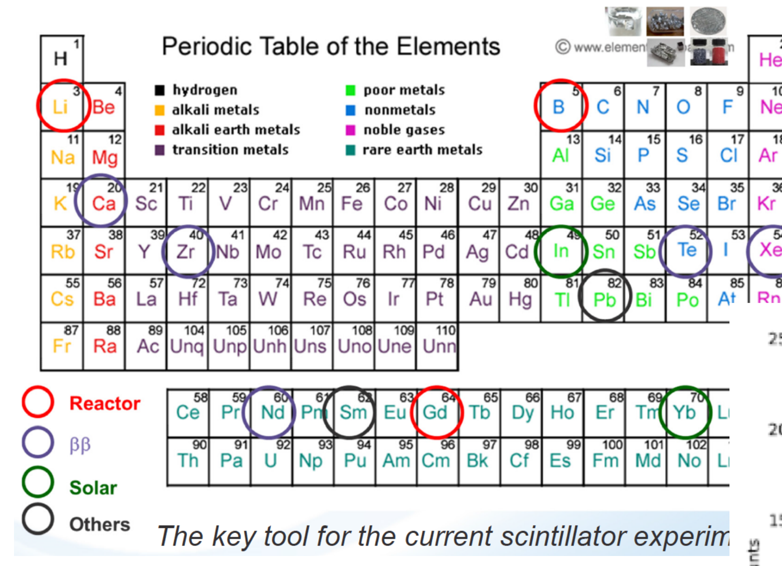
WbLS Development

Talk by M.Yeh [Thurs pm]
Poster by V. Fishcer

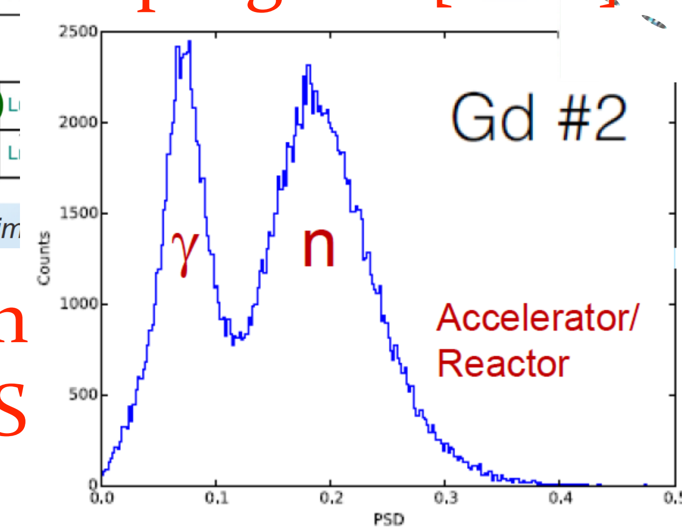
Emission and attenuation [BNL]



Metal loading for broad program [BNL]

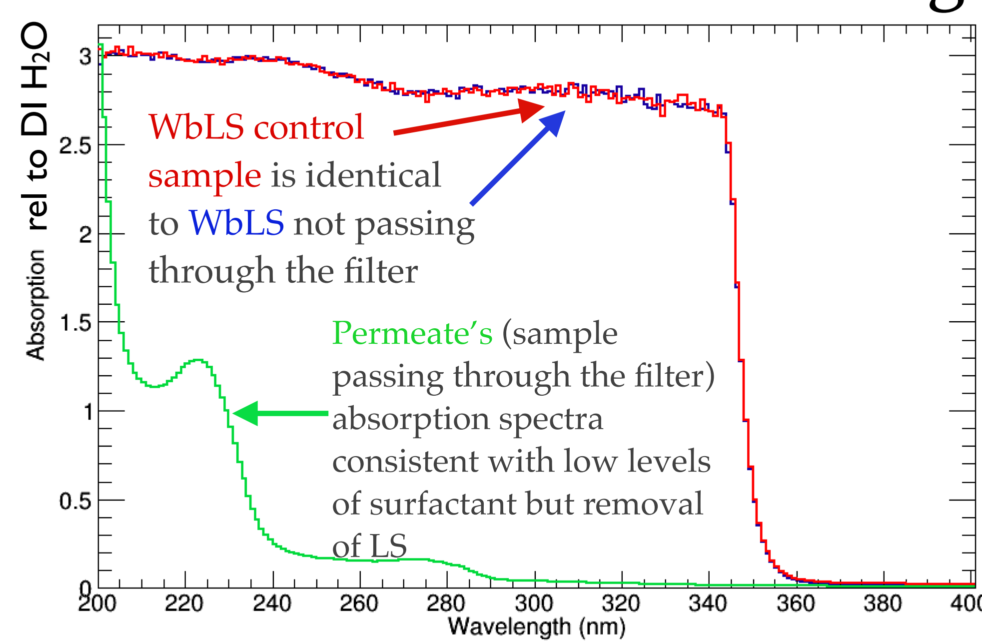


e.g. n/γ separation in Gd-LS



Ton-scale demonstrator & production [BNL]

Nanofiltration & materials testing [UC Davis]

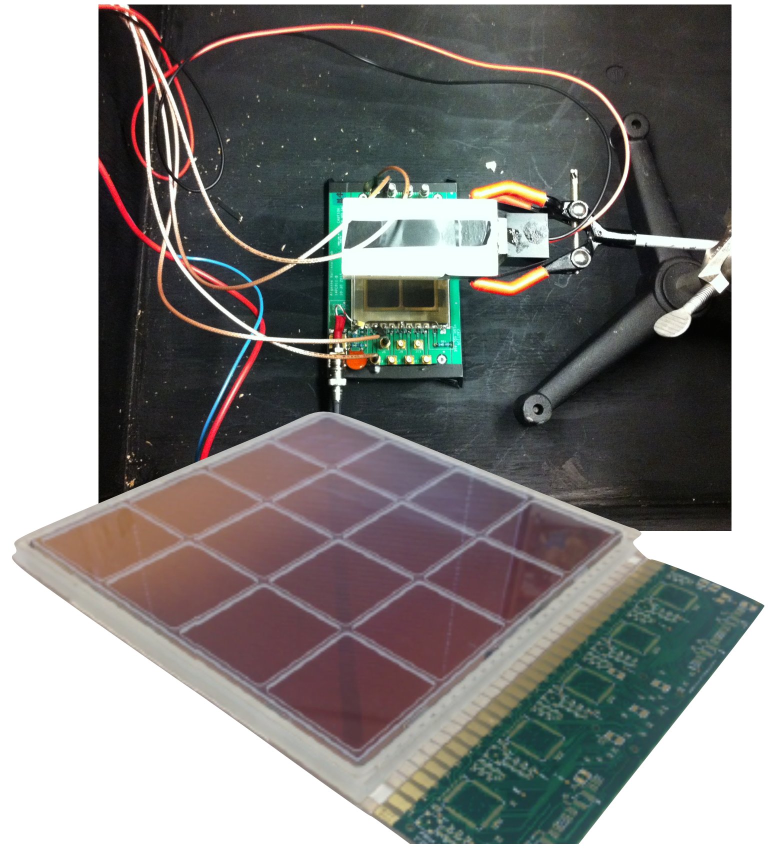


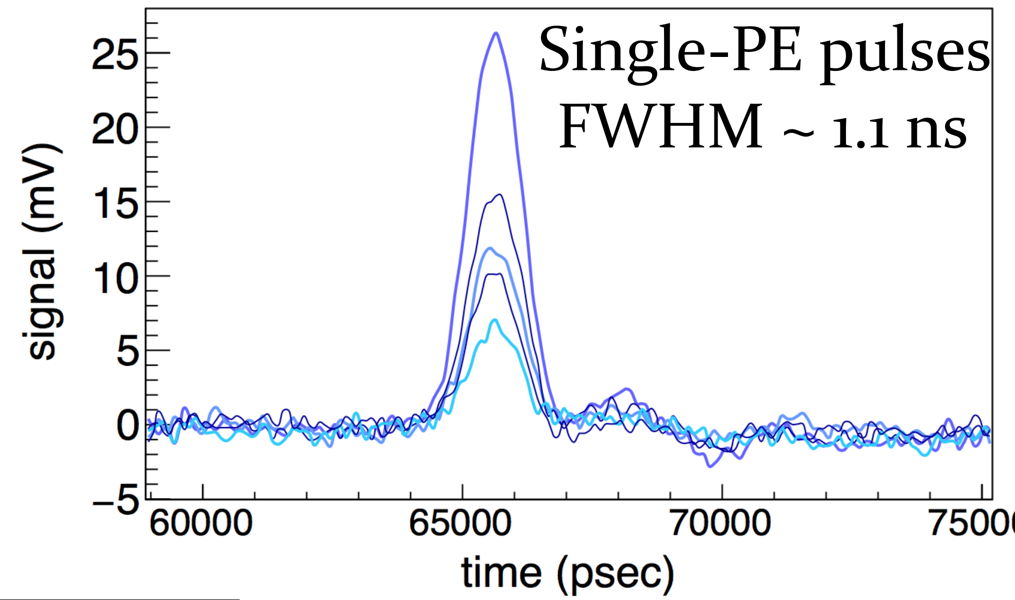
Talks by V. Fischer, S. Qian, L. Wen, A. Lyashenko, J. Kameda, T. Lindner

Photon Sensor Development

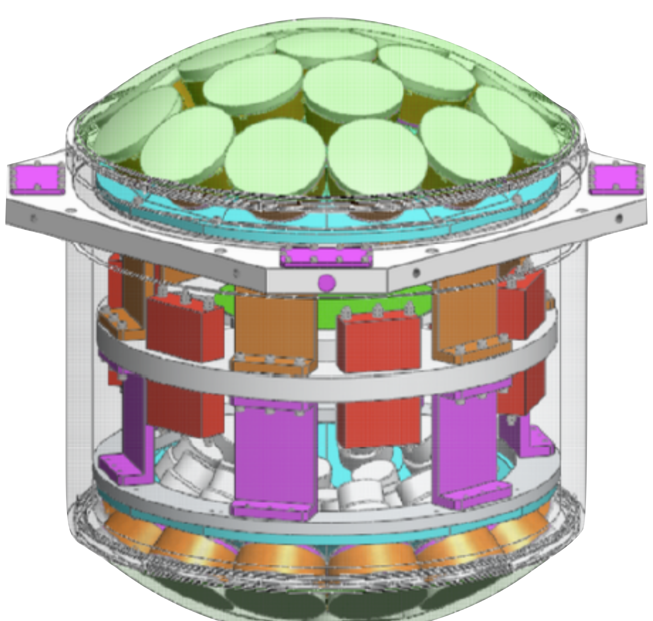
“Standard” PMTs

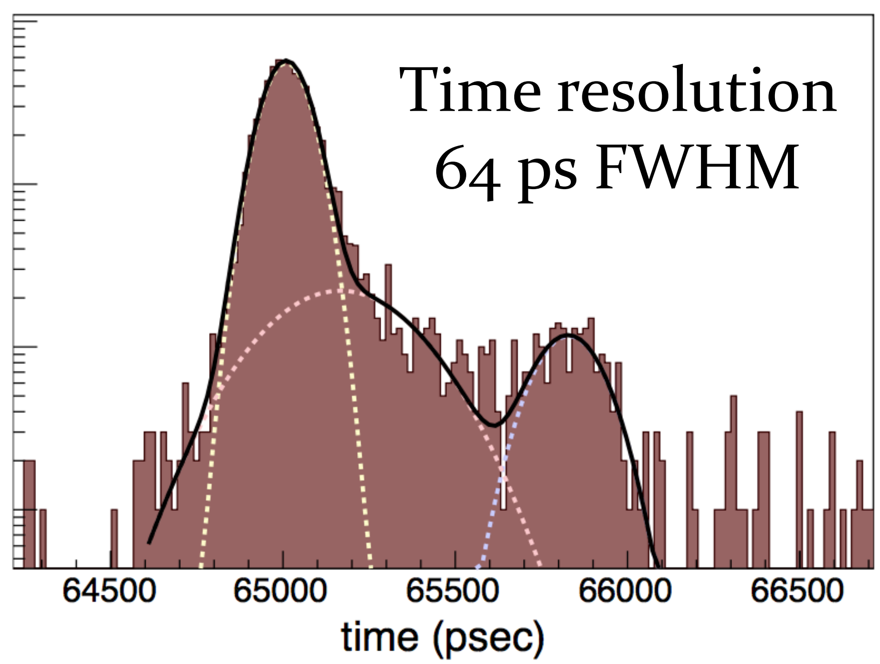
MCP-based photosensors [ANL, Chicago, INCOM]

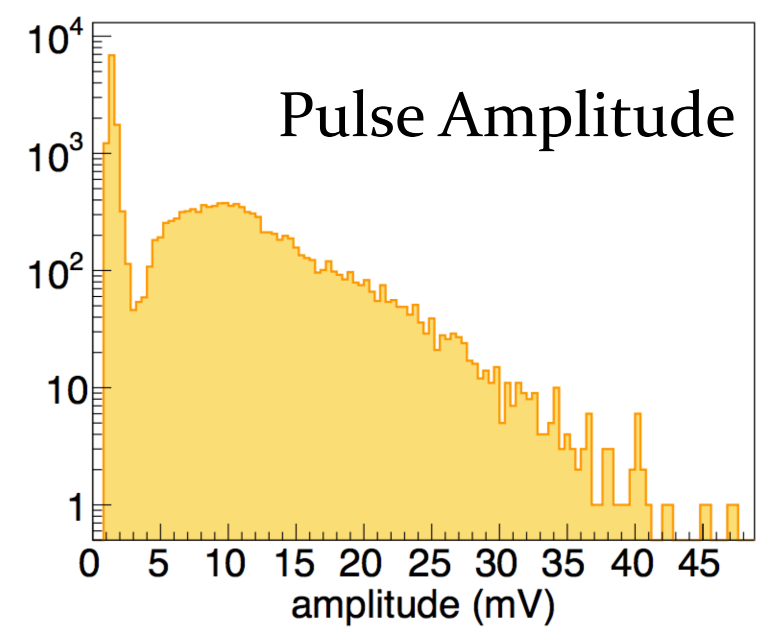




Modular PMTs





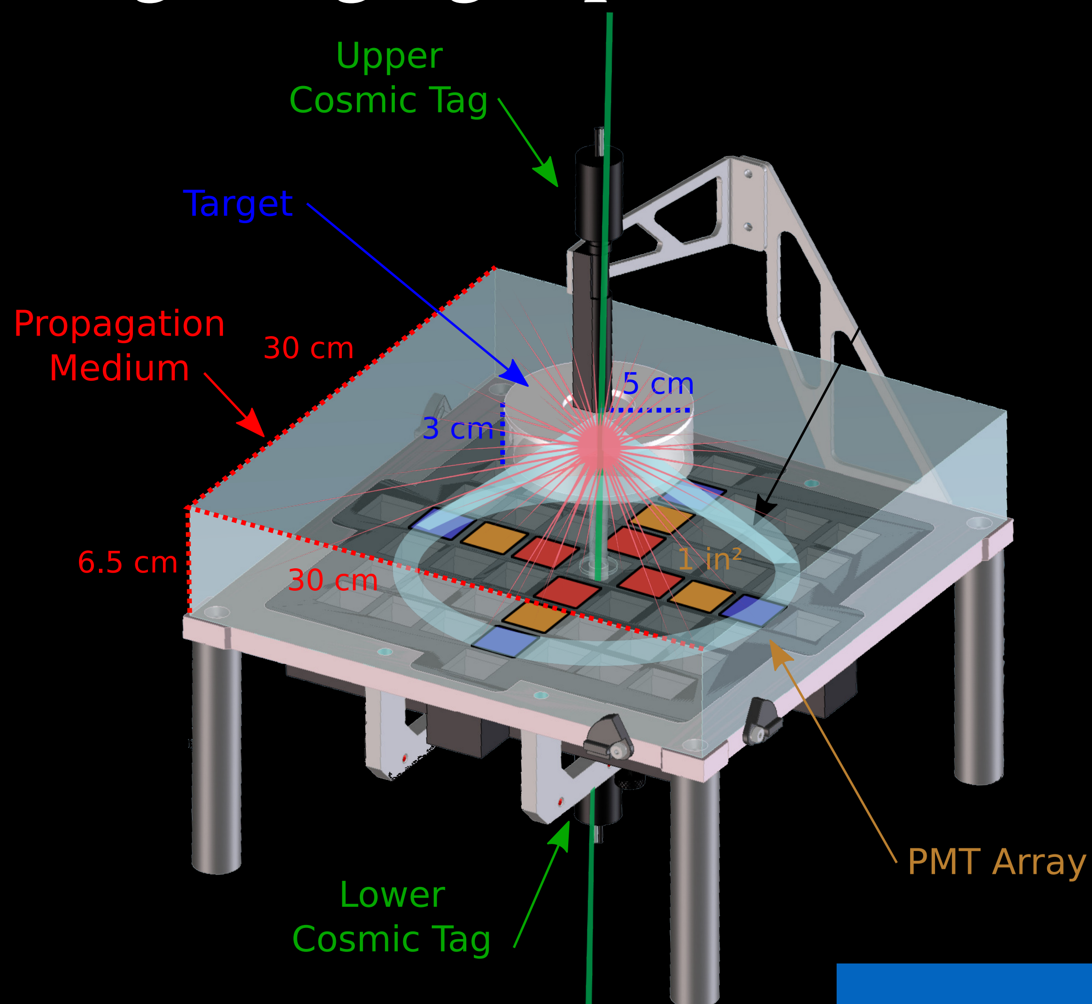


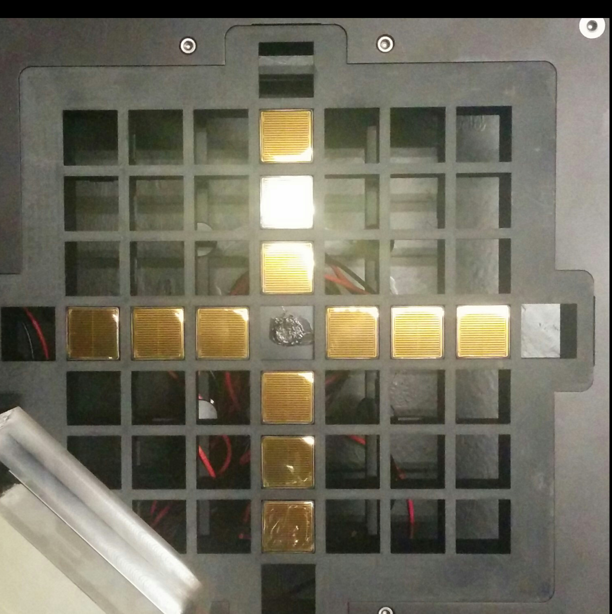
Nucl. Inst. Meth. Phys. Res. A. Volume 814, 19-32, (April 2016); Nucl. Inst. Meth. Phys. Res. A. (Oct. 2016)

CHESS:
CHErenkov-Scintillation Separation

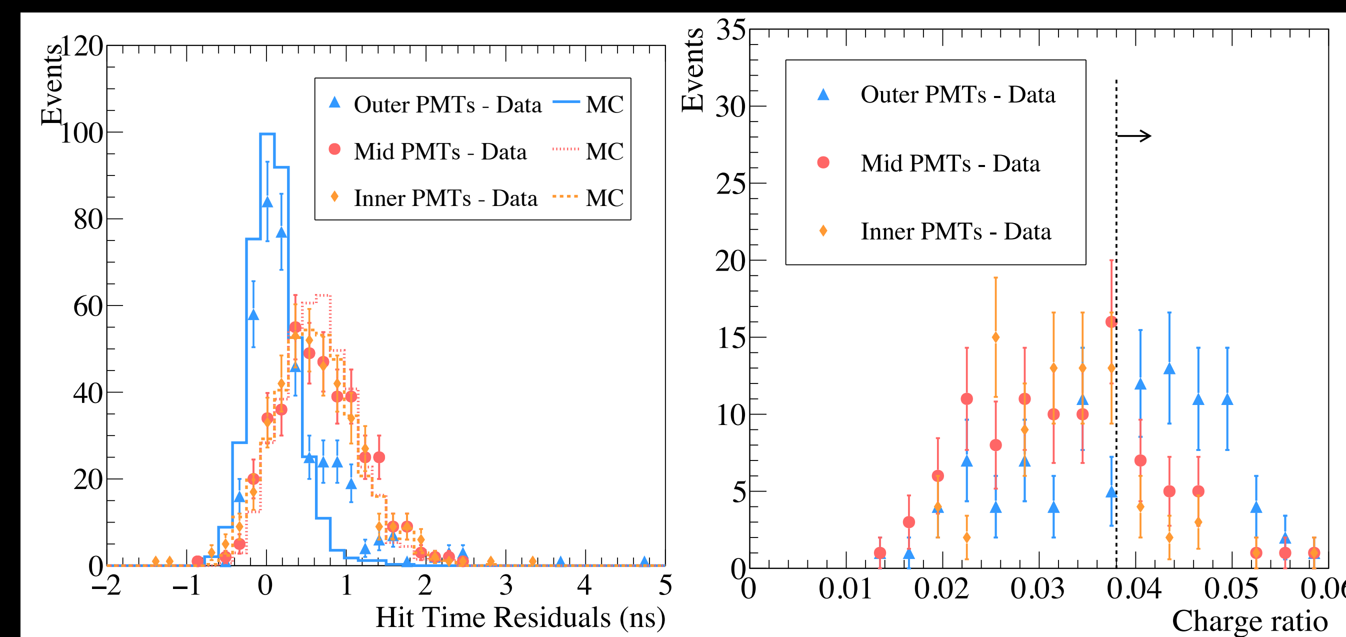
PRC 95 055801 (2017)

Ring-imaging experiment





Time- and charge-based separation in LAB/PPO



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

	LAB (time)	LAB (charge)	LAB/PPO (time)	LAB/PPO (charge)
Cherenkov detection efficiency	83 ± 3 %	96 ± 2 %	70 ± 3 %	63 ± 8 %
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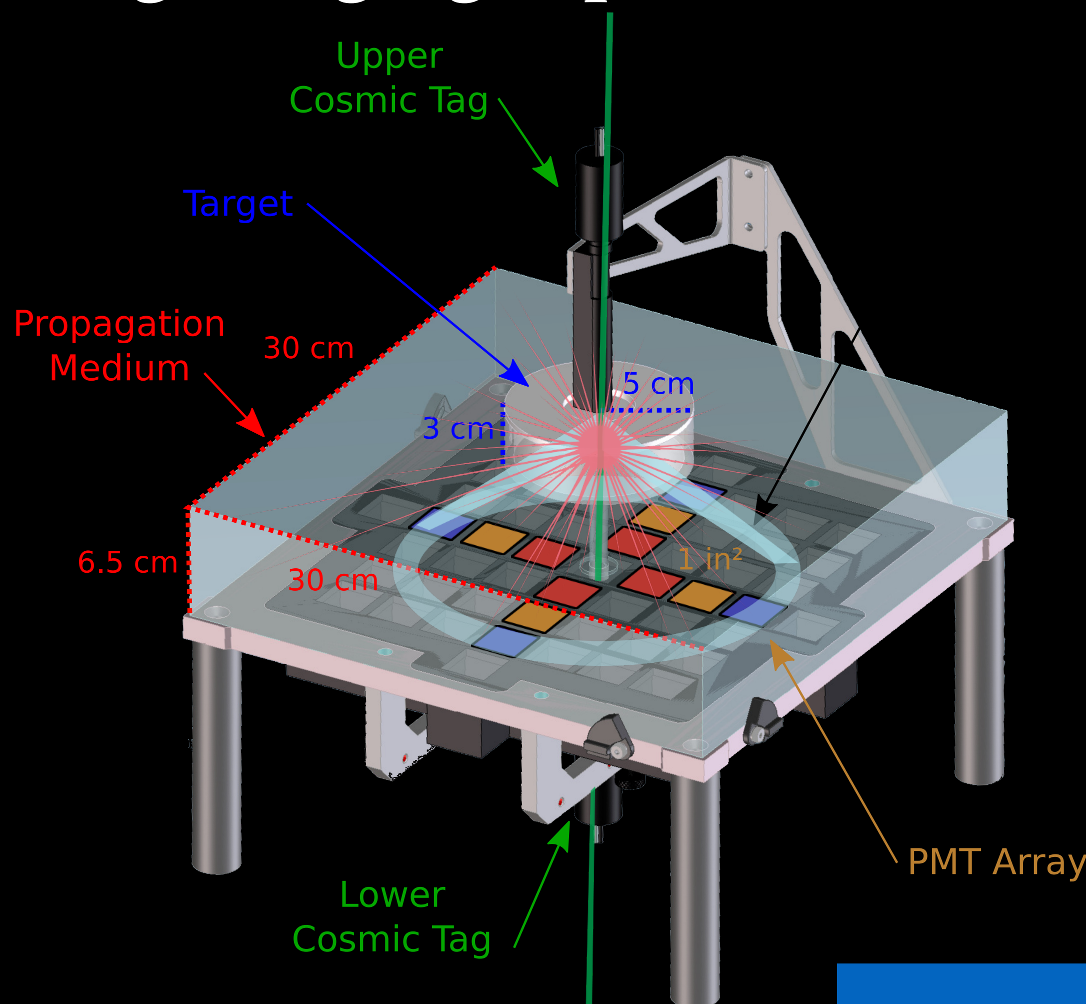

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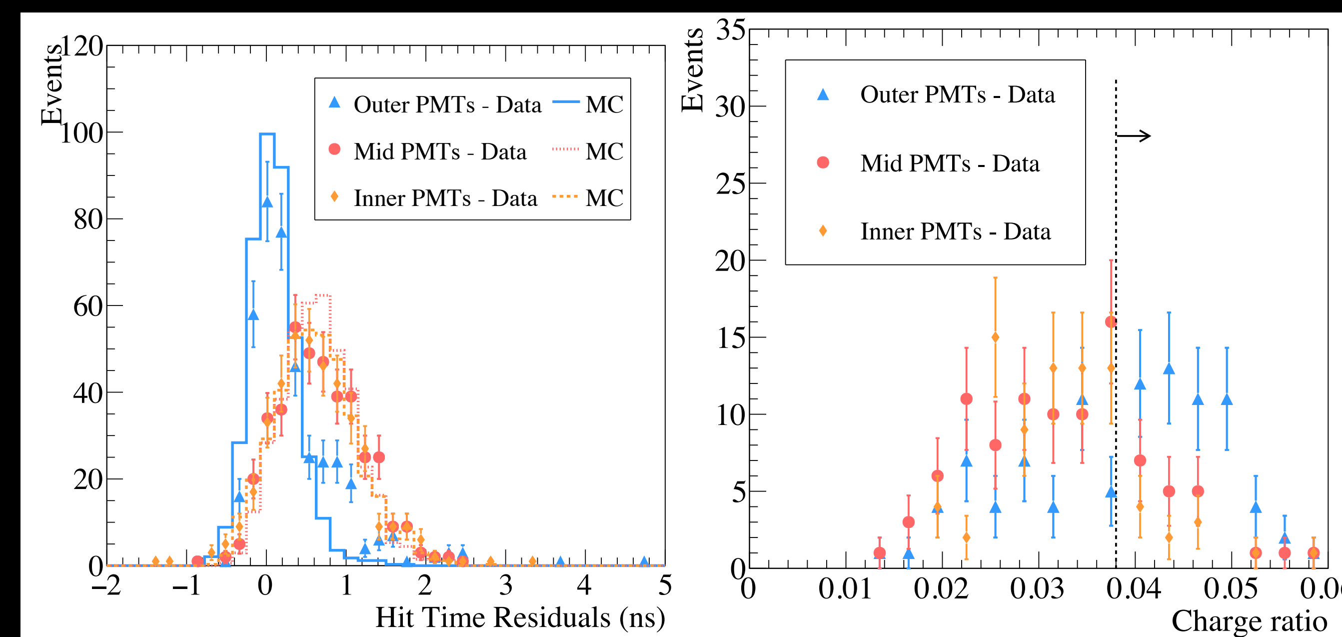

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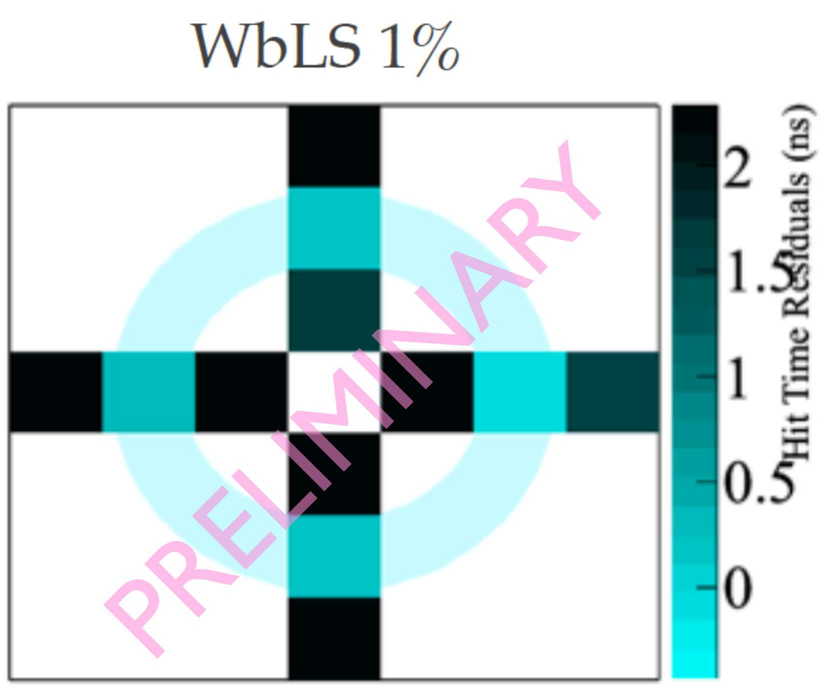
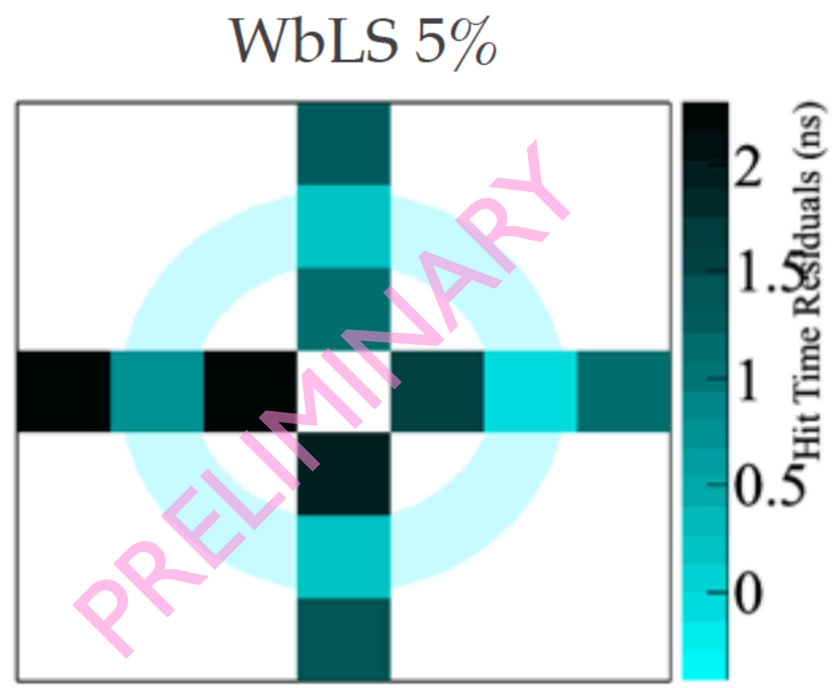
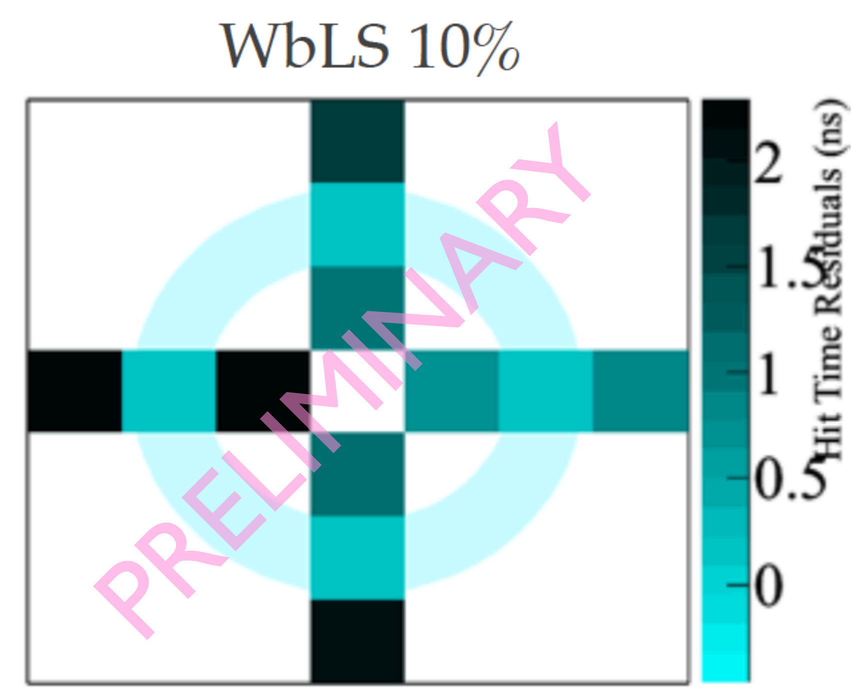
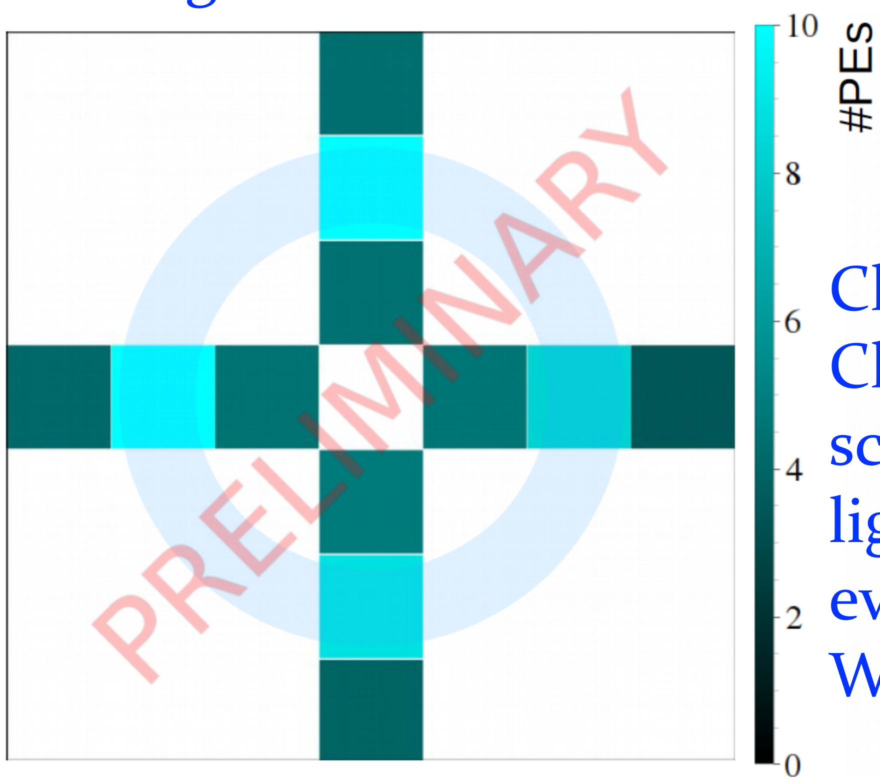
CHESS Results: WbLS



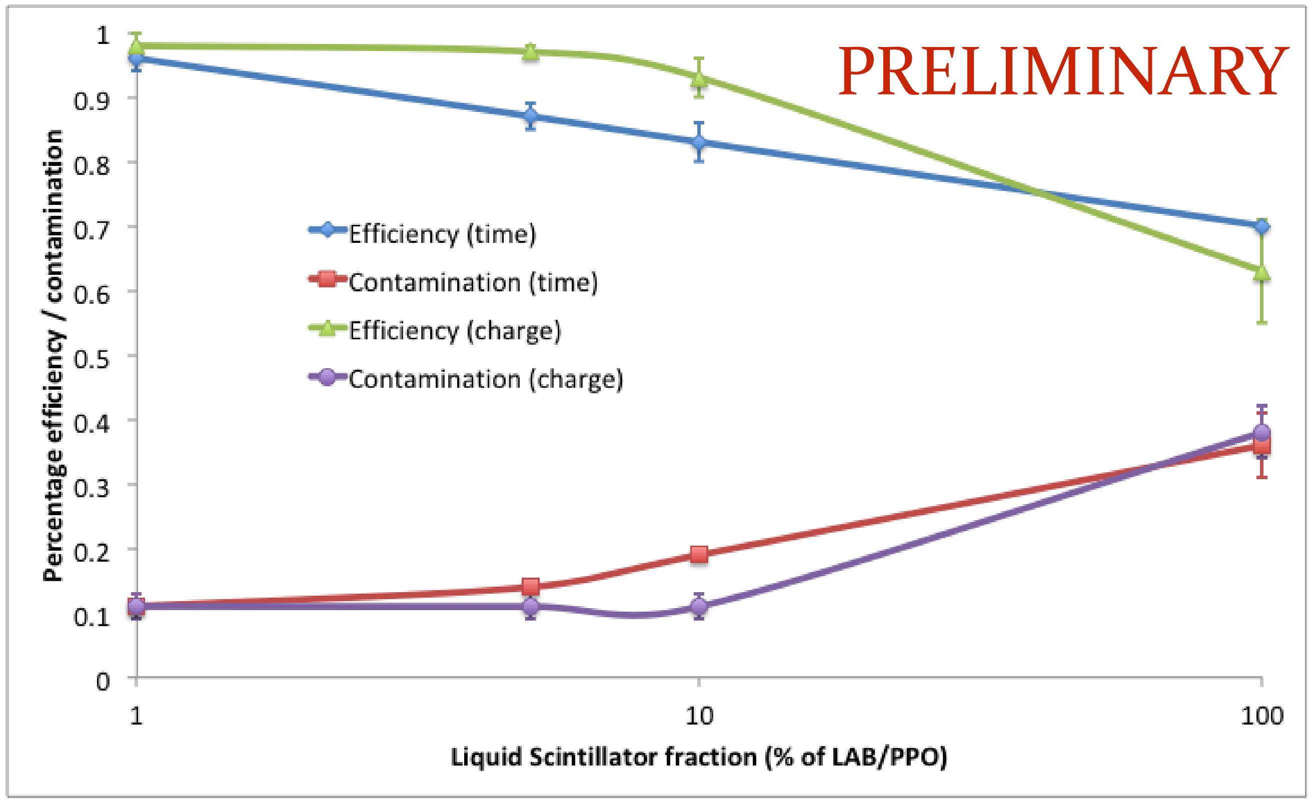




Average of WbLS data set



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



Time Profile

PRELIMINARY

Extract microphysical parameters by fitting to MC model

90Sr source, single pe regime, detailed MC

Calibrate method using well-understood LAB/PPO target

Time profile model: 3 exp. decay + rise time

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

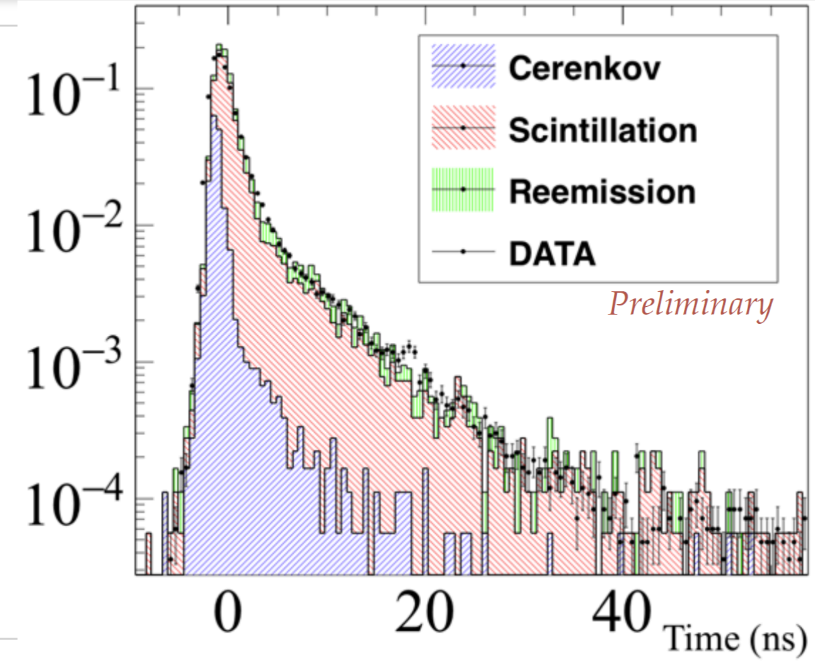
$\tau_r = 0.7$ ns

$\tau_1 = 4.3$ ns

$\tau_2 = 16$ ns

$\tau_3 = 166$ ns

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



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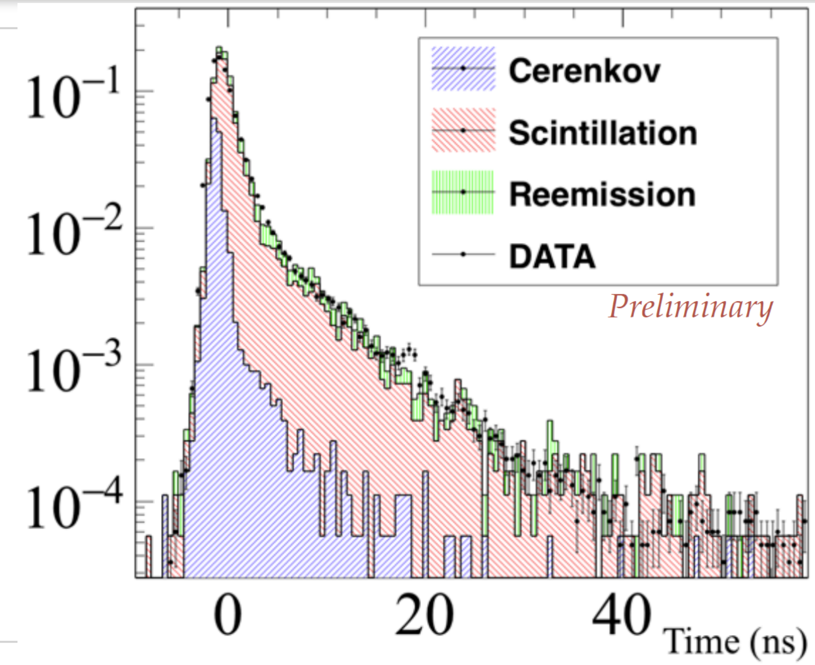

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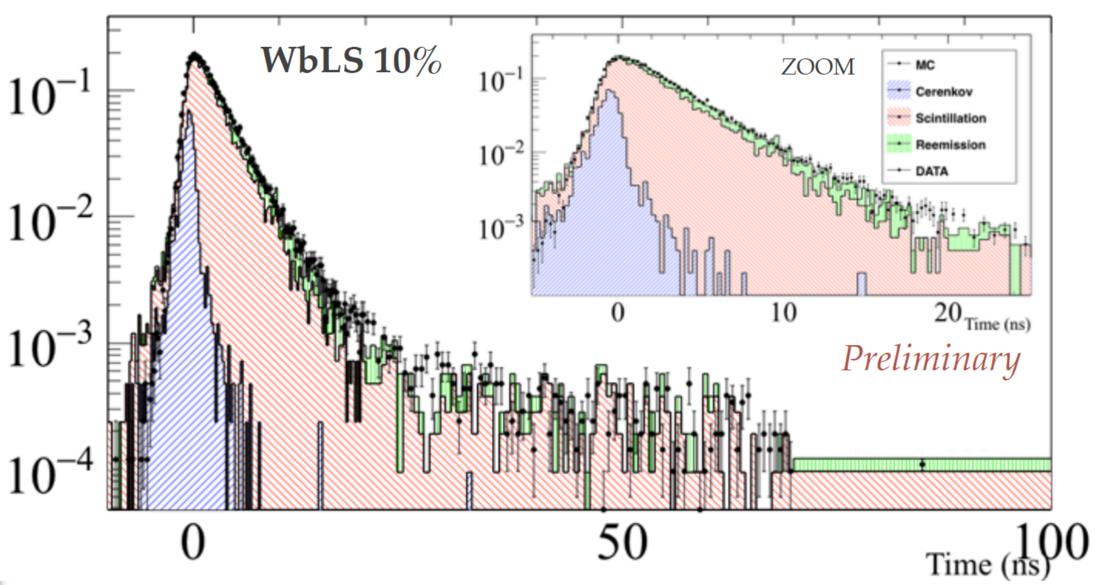
Fit for scintillation time profile of WbLS

Result of fit (10% WbLS)



Fit results:
- $\tau_r = 0.39$
- $\tau_1 = -2.77$
- $\tau_2 = -21.40$
- $R_1 = 0.94$

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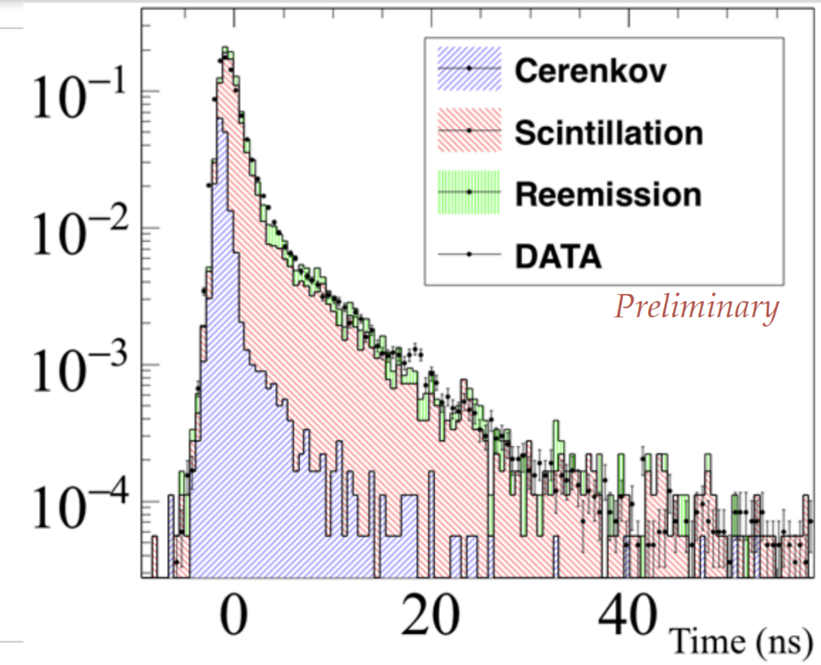
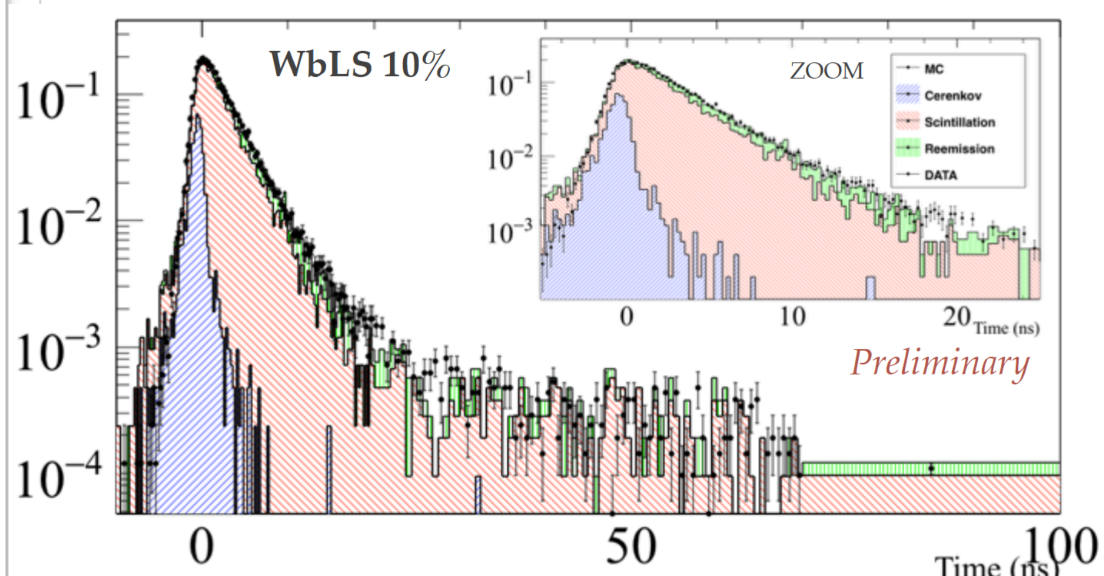
H. M. O'Keeffe et al. Nucl. Instum. Methods A640, 119 (2011)

Good agreement between data and model "out of the box"



Fit for scintillation time profile of WbLS

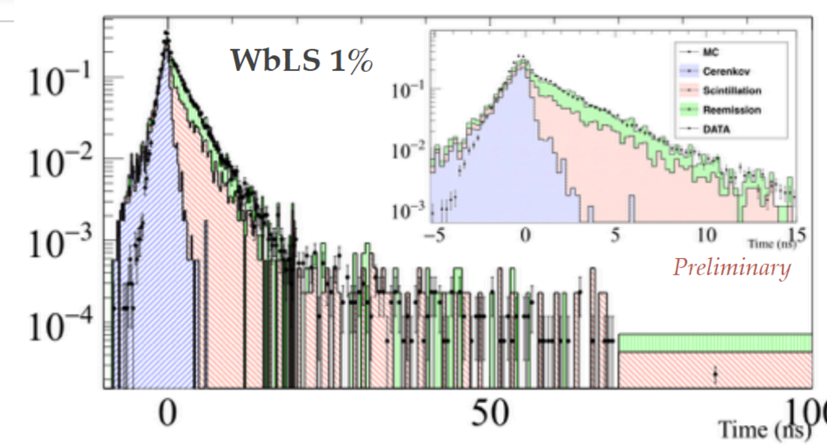
Result of fit (10% WbLS)

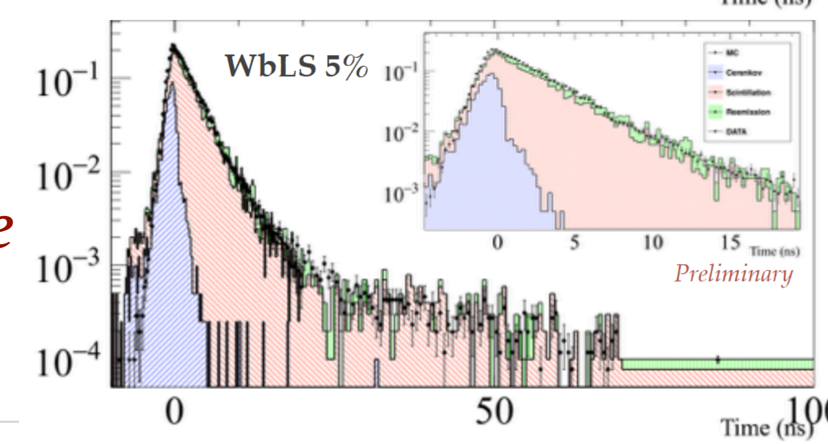


Fit results:

- $\tau_r = 0.39$
- $\tau_1 = -2.77$
- $\tau_2 = -21.40$
- $R_1 = 0.94$

1%, 5% WbLS seem consistent with time profile



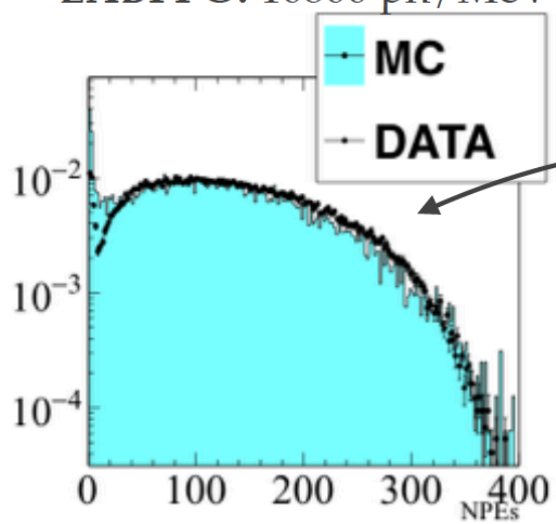


Preliminary light yield

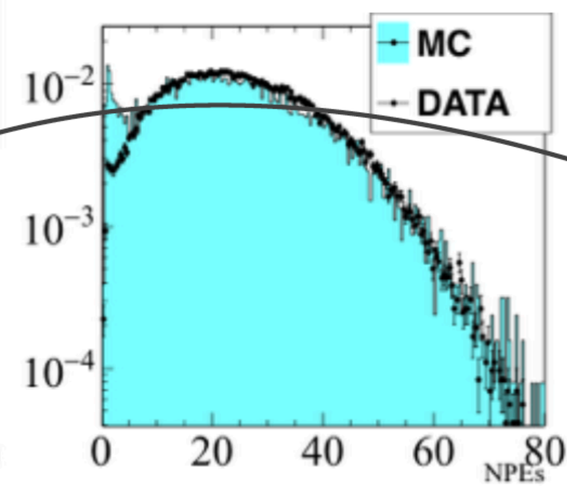
Note: assumes LAB/PPO wvl emission profile

Fit for WbLS time profile

LABPPO: 10800 ph/MeV



WbLS 10%: 1500 ph/MeV

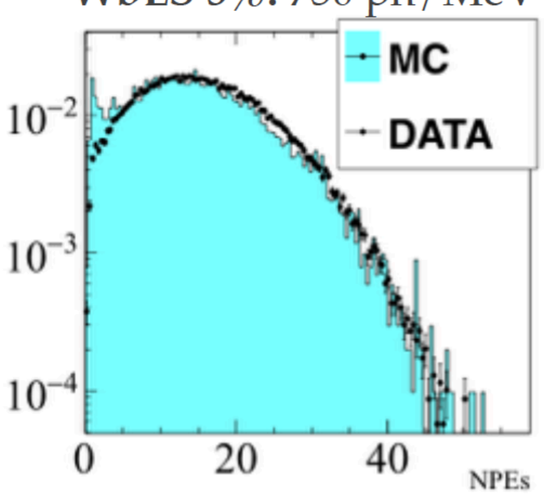


Method: define LAB/PPO LY

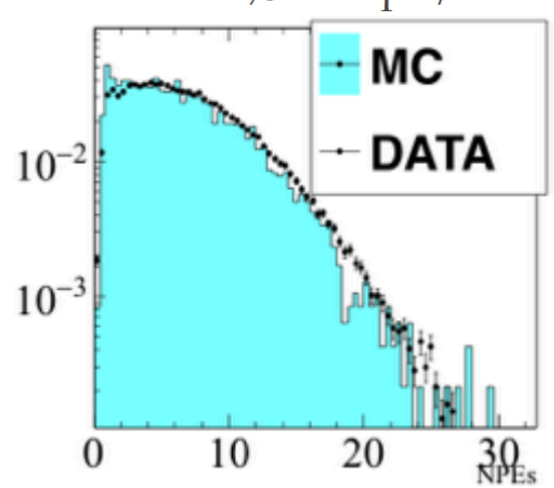
Calibrate setup to LAB/PPO charge collection

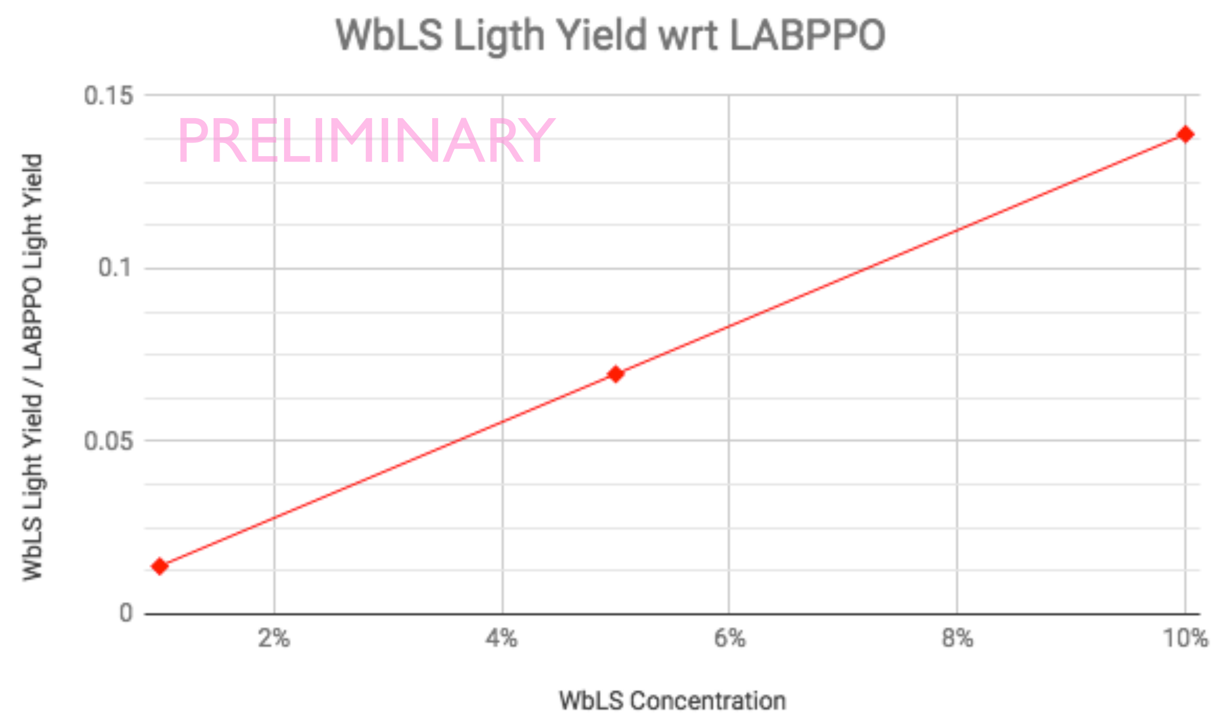
Determine LY of WbLS cocktail (data/MC fit)

WbLS 5%: 750 ph/MeV



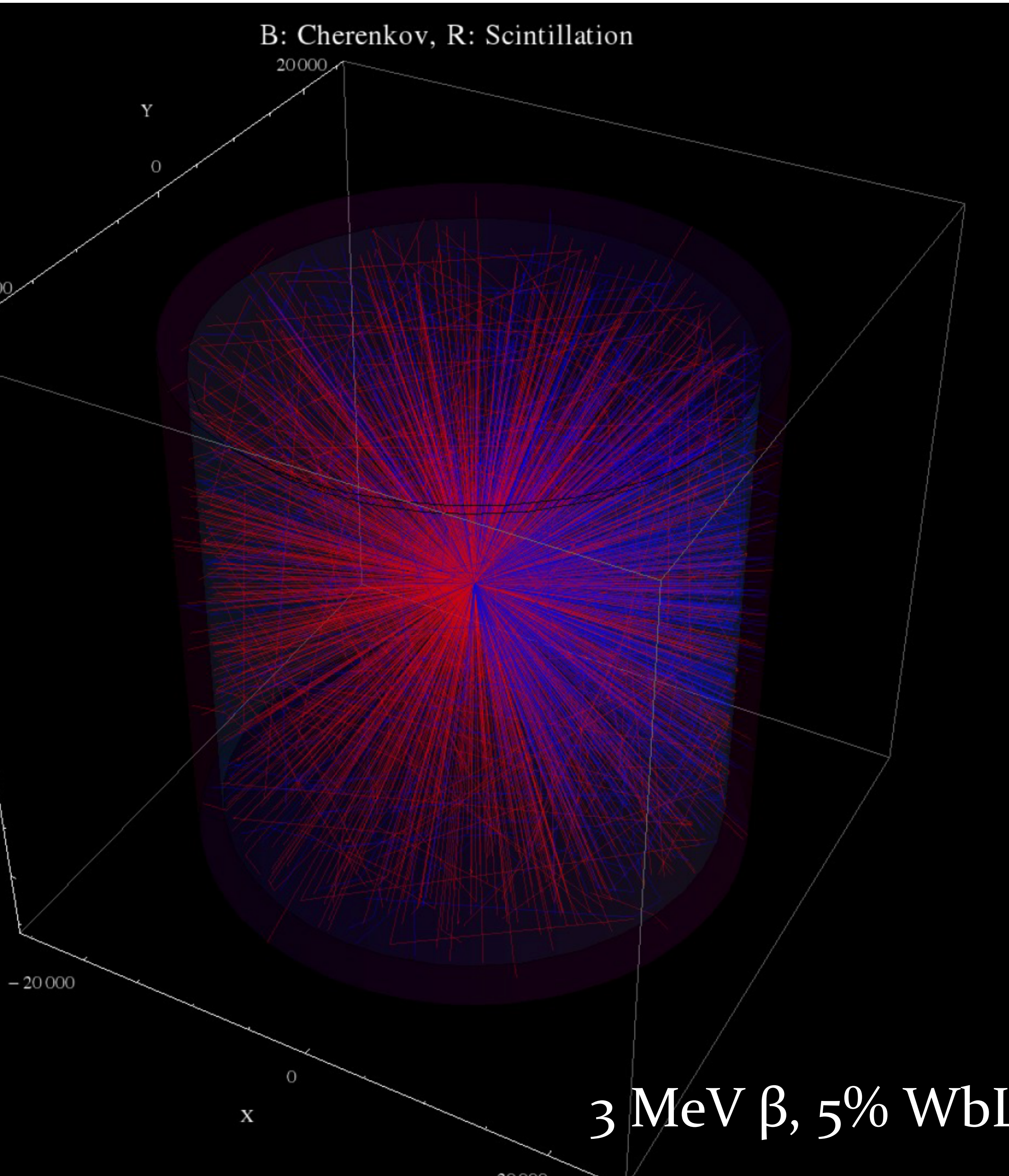
WbLS 1%: 150 ph/MeV





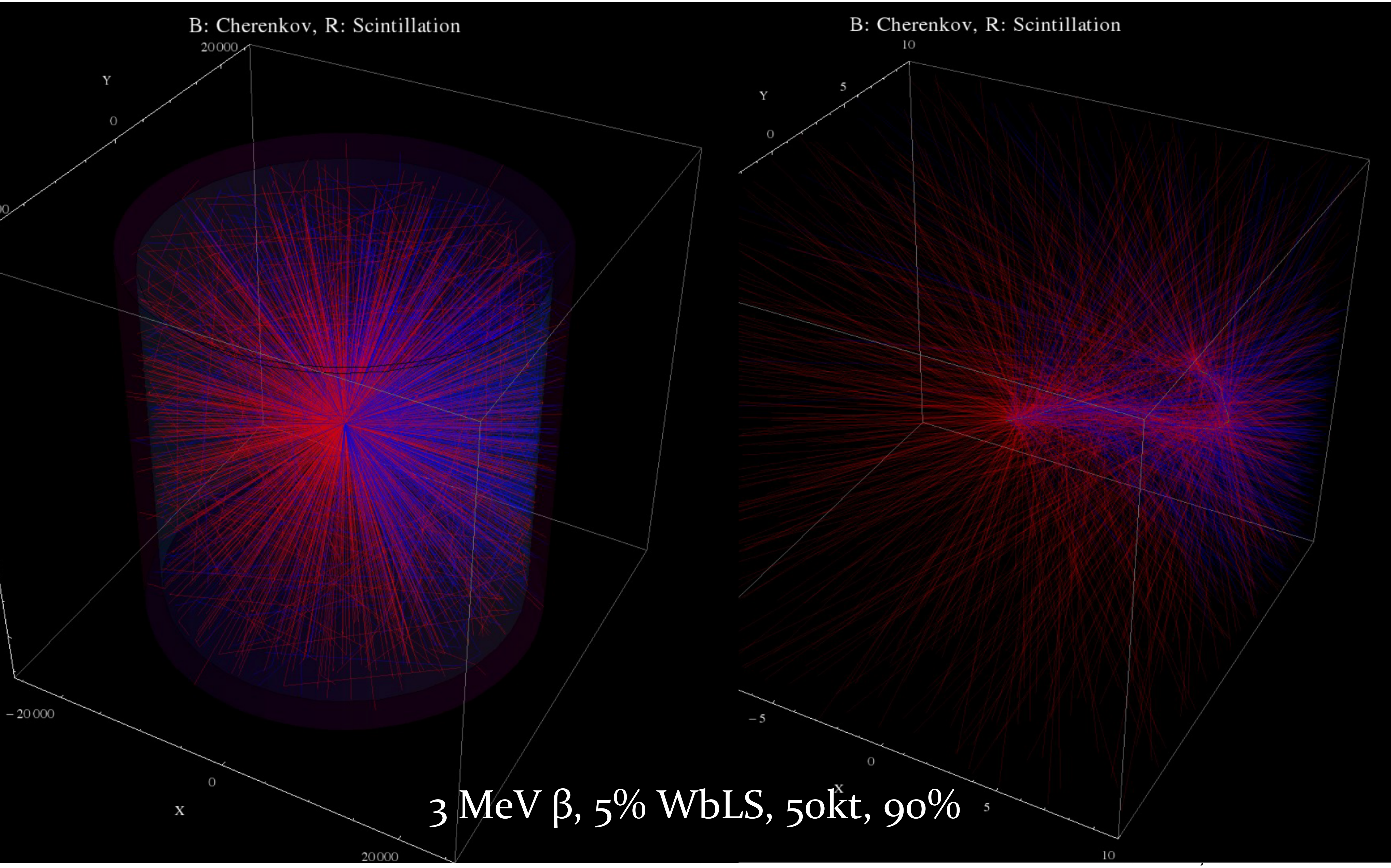
Signal Separation in Theia

Signal Separation in Theia



3 MeV β, 5% WbL

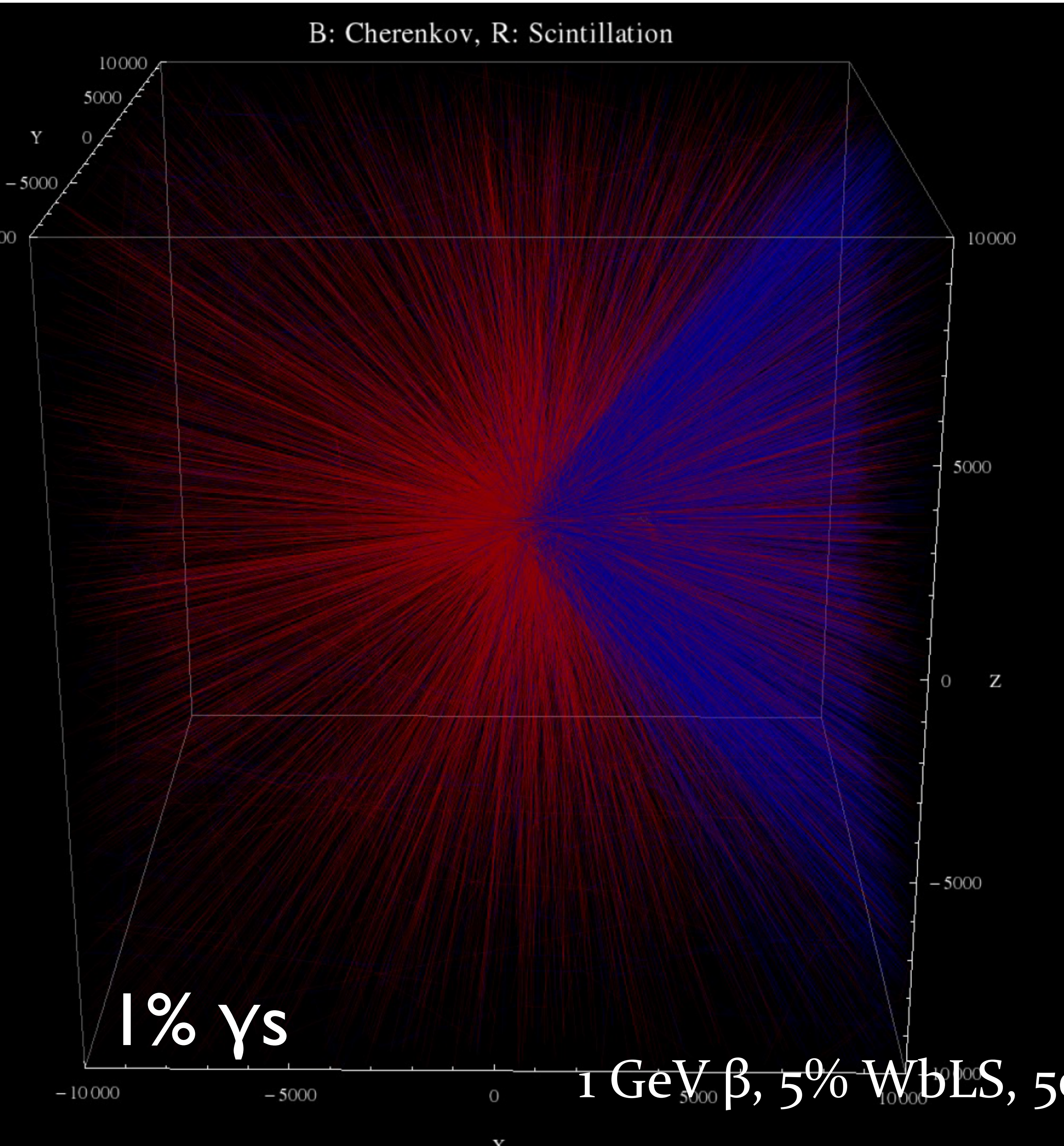
Signal Separation in Theia



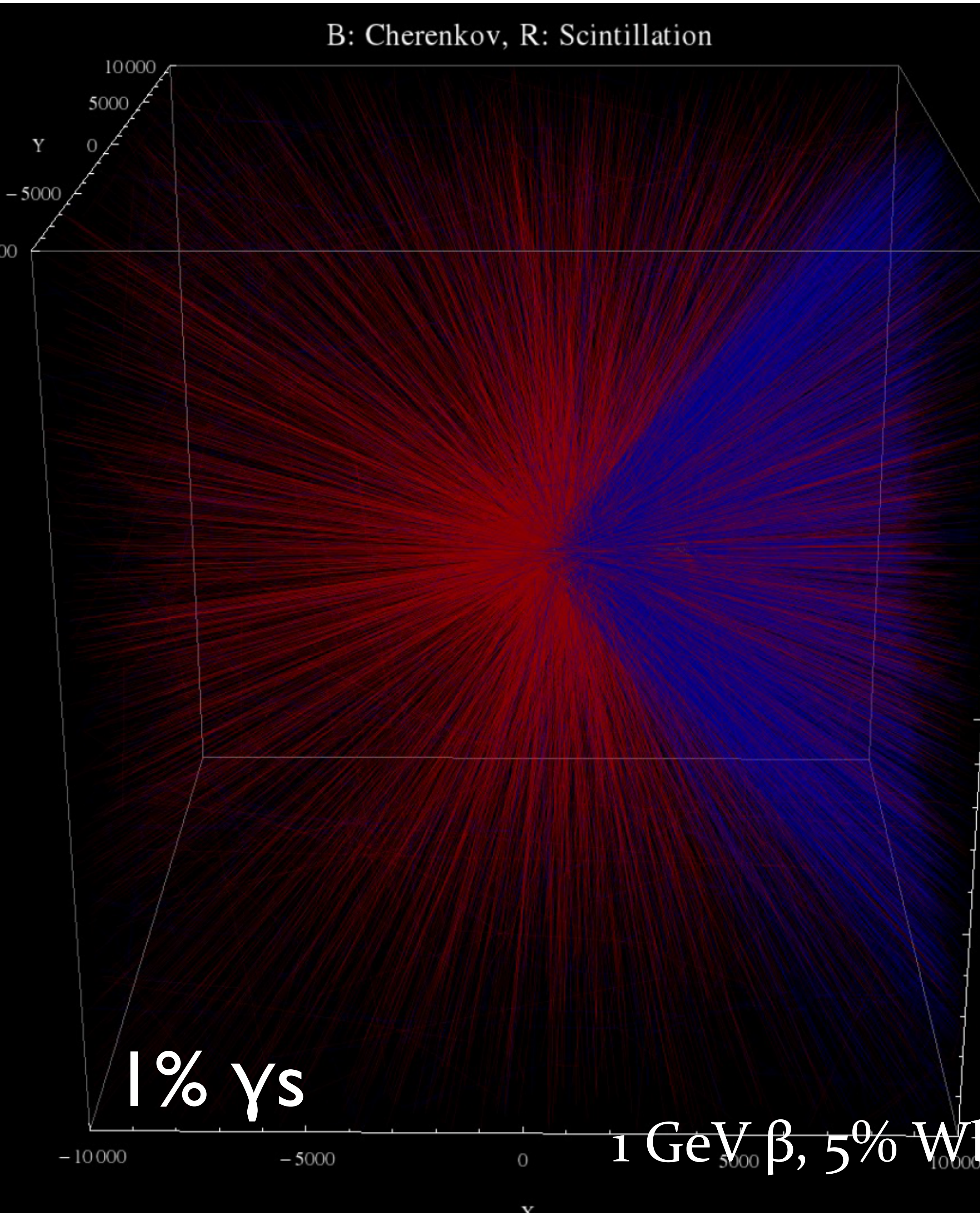
3 MeV β, 5% WbLS, 50kt, 90%

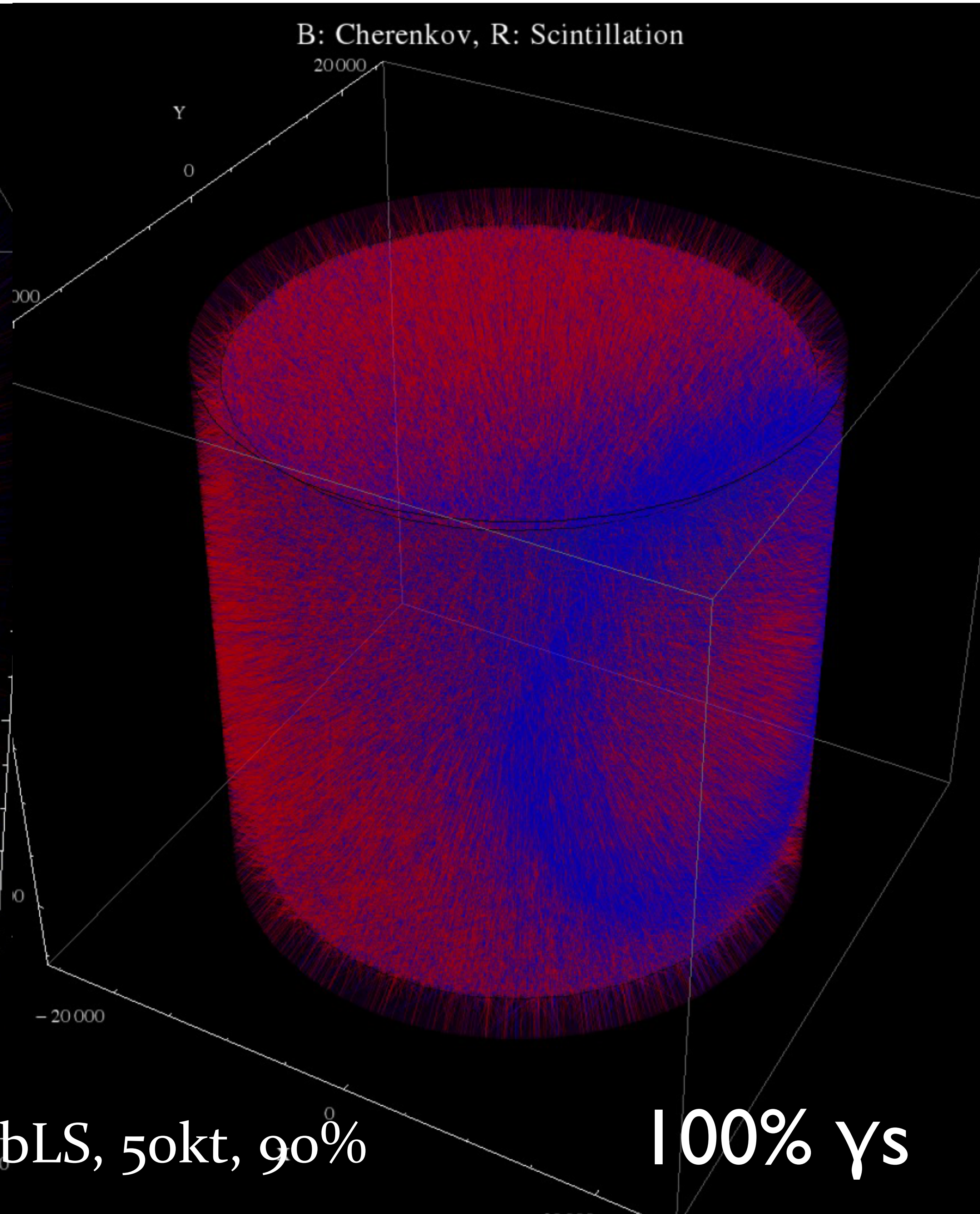
Ring Imaging

Ring Imaging



Ring Imaging



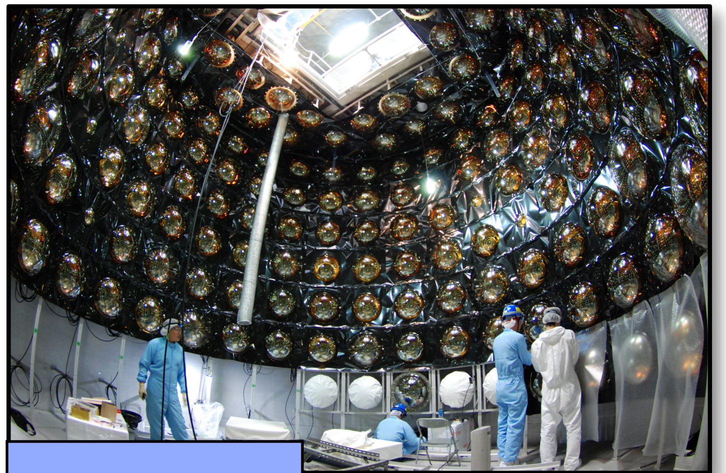


1 GeV β, 5% WbLS, 50kt, 90%

Talks by M. Askins, V. Fishcer, C. Mauger

Community Interest

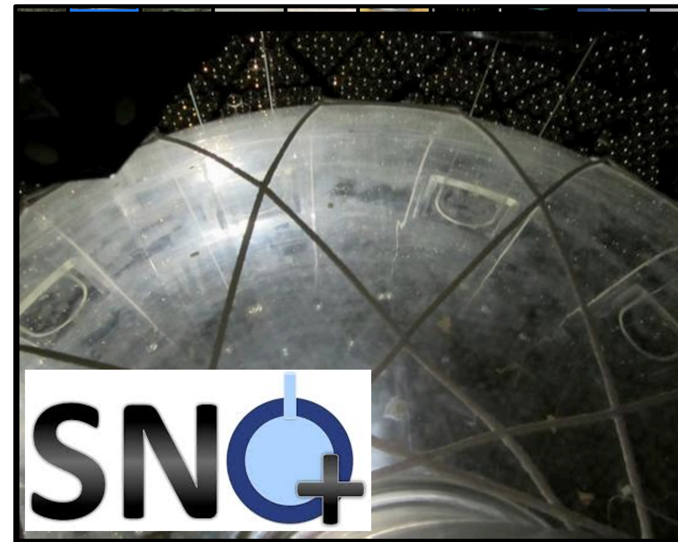
Site	Scale	Target	Measurements	Timescale
UChicago	bench top	H2O	fast photodetectors	Exists
CHIPS	10 kton		electronics, readout, mechanical infrastructure	2019
EGADS	200 ton	H2O+Gd	isotope loading, fast photodetectors	Exists
ANNIE	30 ton			Exists
WATCHMAN	1 kton			2020
NuDot	1 ton	LS	directionality	2018
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

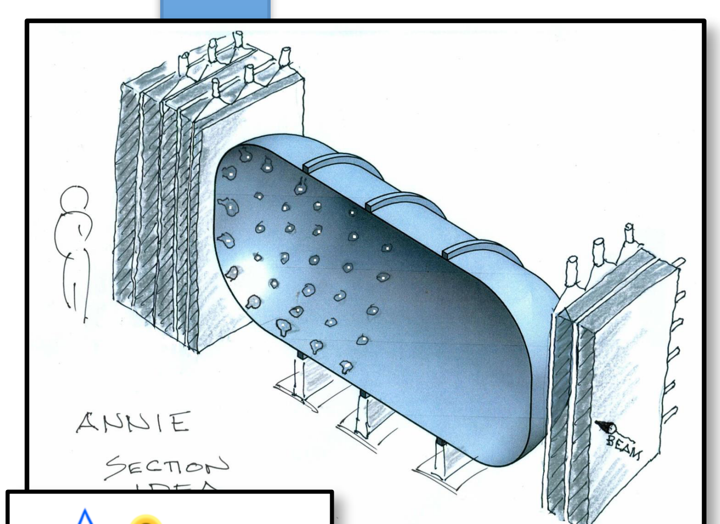


Te loading

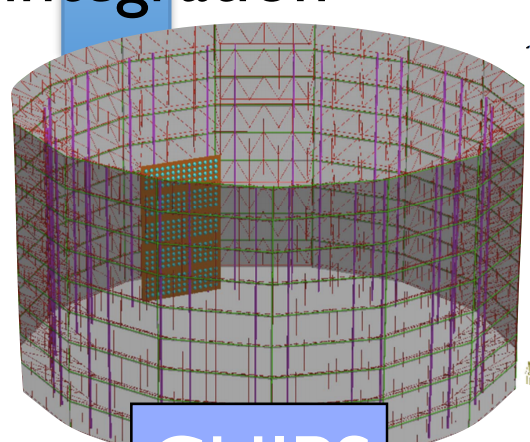
Neutron yield, LAPPD deployment

Infrastructure, underwater integration

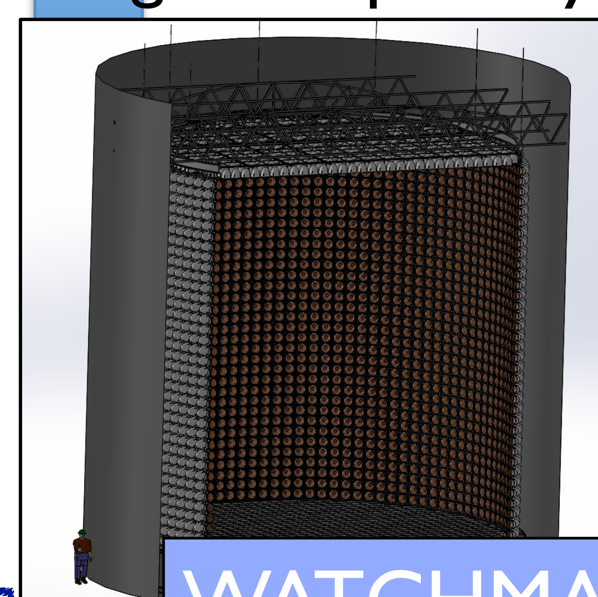
WbLS, Gd, LAPPD, HQE PMT, full integration prototype



ANNIE



CHIPS



WATCHMAN

Note: not an exhaustive list!

Theia Collaboration

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
- 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