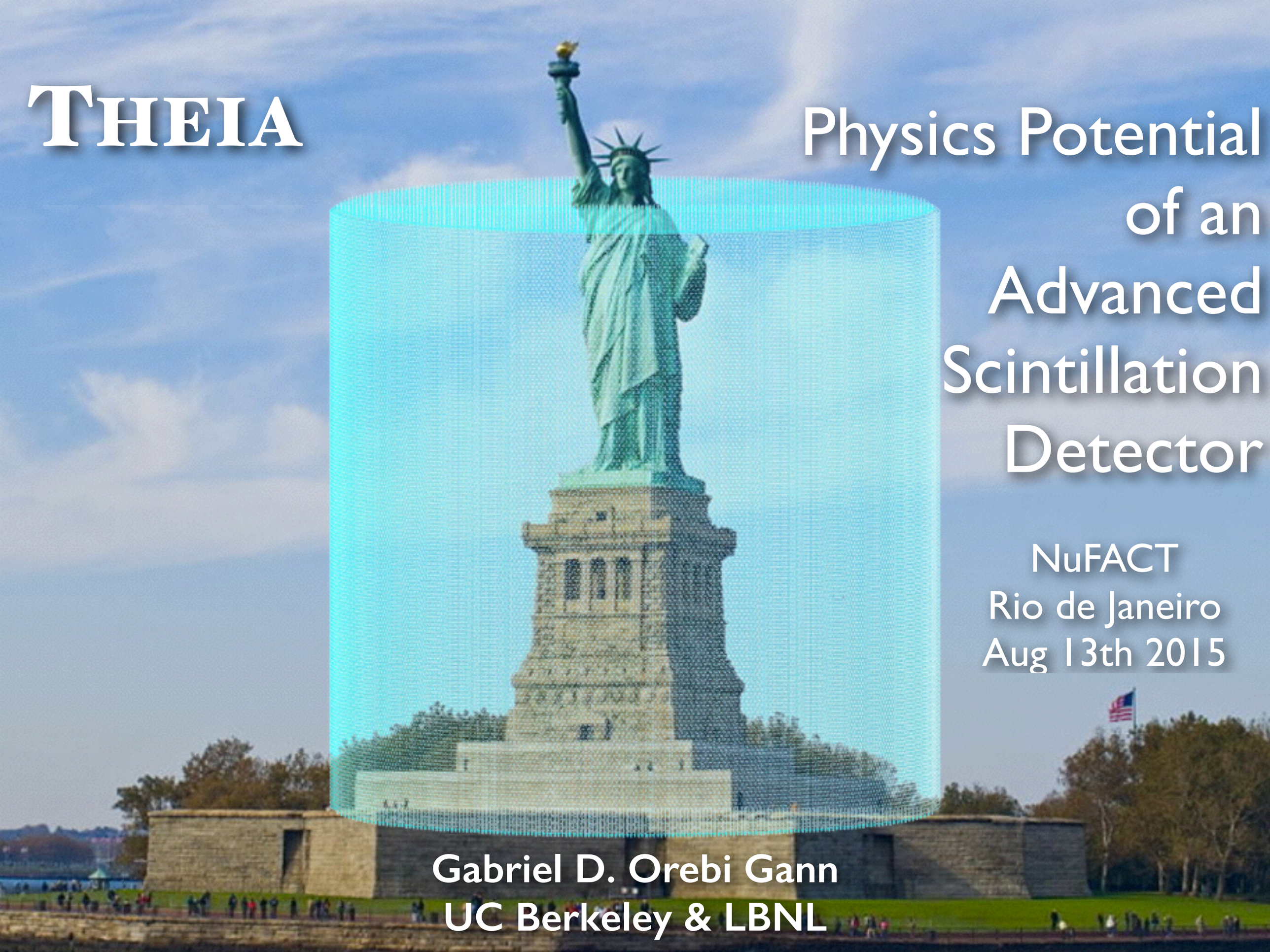
THEIA

Physics Potential of an Advanced Scintillation Detector

NuFACT
Rio de Janeiro
Aug 13th 2015



Gabriel D. Orebi Gann
UC Berkeley & LBNL

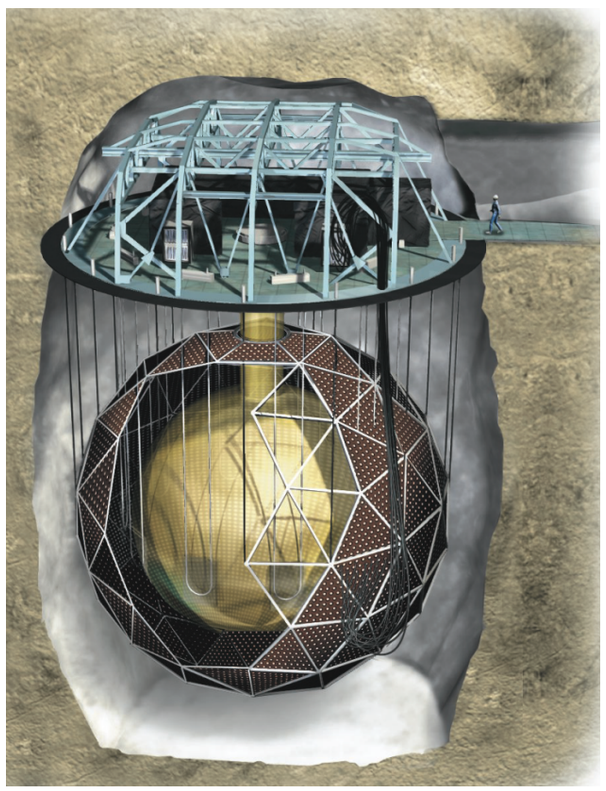
Bird's-Eye View

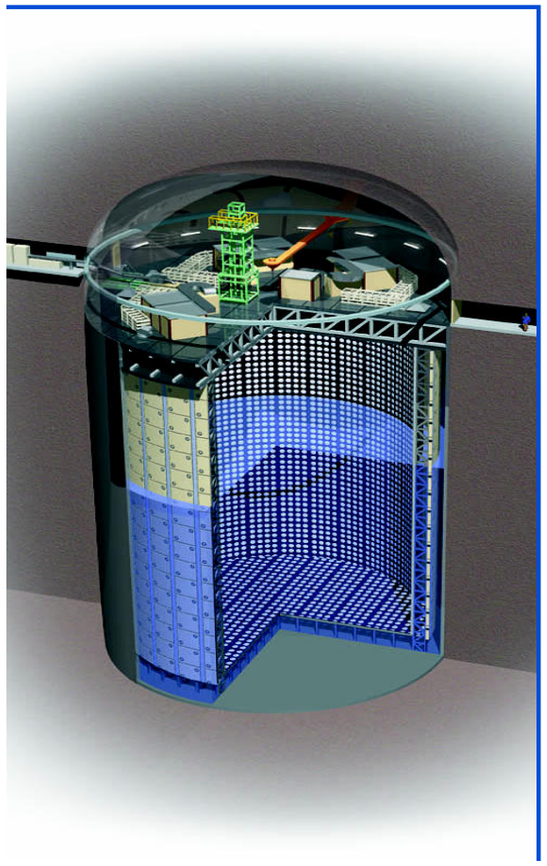
1. The Advanced Scintillation Detector Concept
2. Physics Program
   - Low-energy physics
   - Long-baseline physics
3. Required R&D
   - Planned Demonstrations

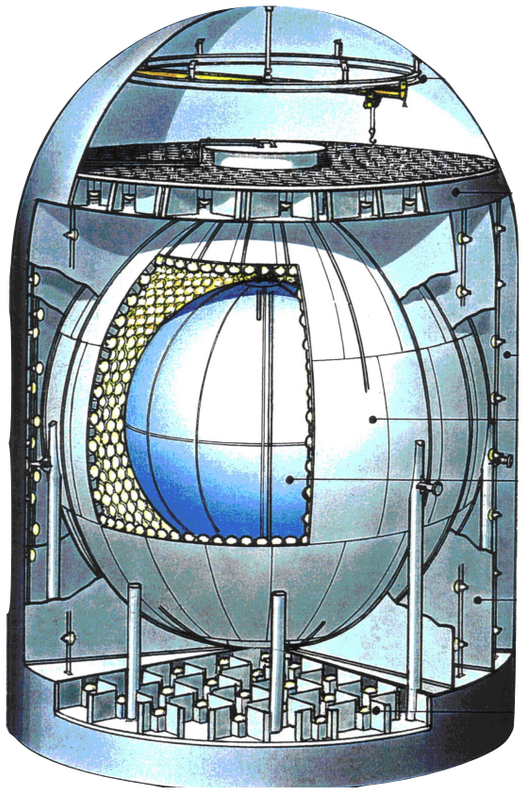
1. Advanced Scintillation Detector Concept

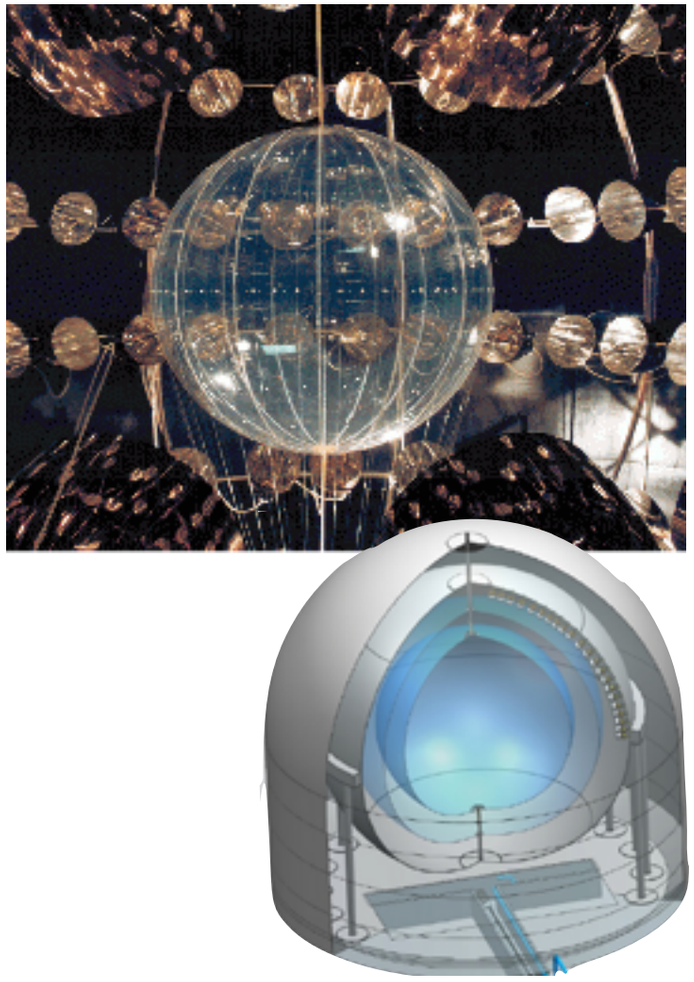
Advanced Scintillation Detector Concept (ASDC)

- **New technology with proven methodology**









House light-producing target inside large monolithic detector

Novel, breakthrough target medium

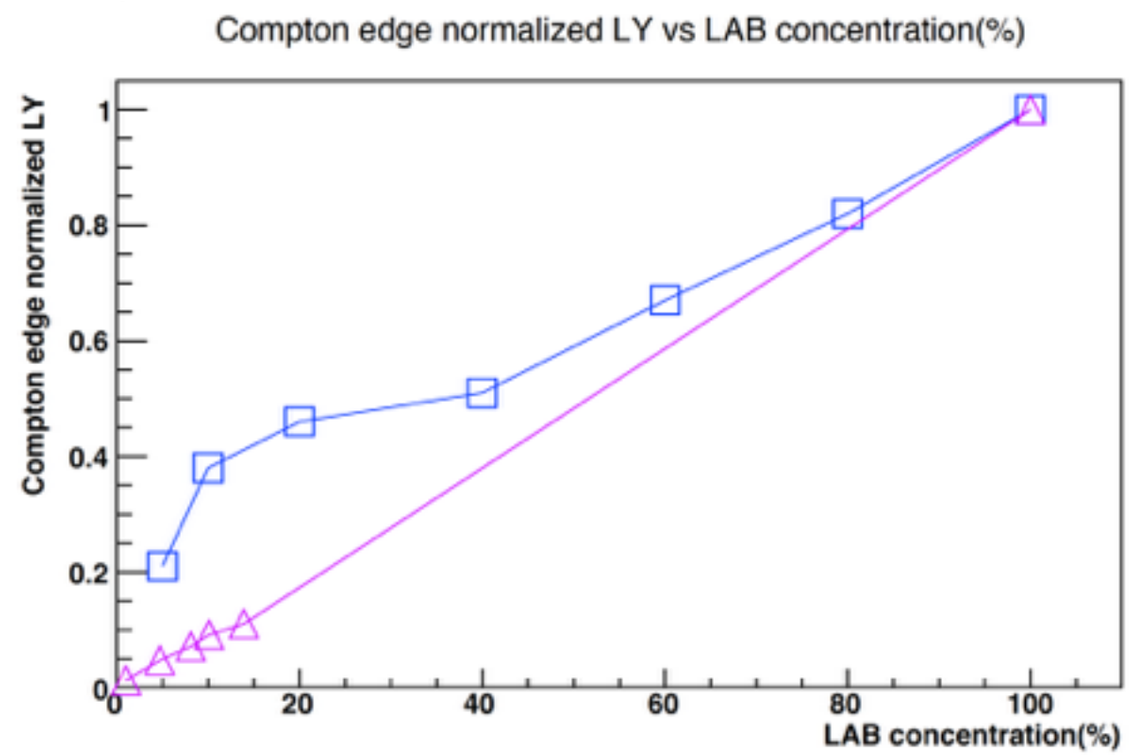
Having our  ... & eating it too!

- Simple mixture of oil and water (!)
  ⇒ **water-based liquid scintillator** (WbLS) -- Minfang Yeh, BNL

1. High light yield of organic scintillator
   a) *Low energy threshold*
   b) *Good energy resolution*

2. Predominantly water
   a) *Low absorption inc. light collection*
   b) *Directional information*

3. Tunable time profile
   ➡ potential for separation of Cherenkov and scintillation signals

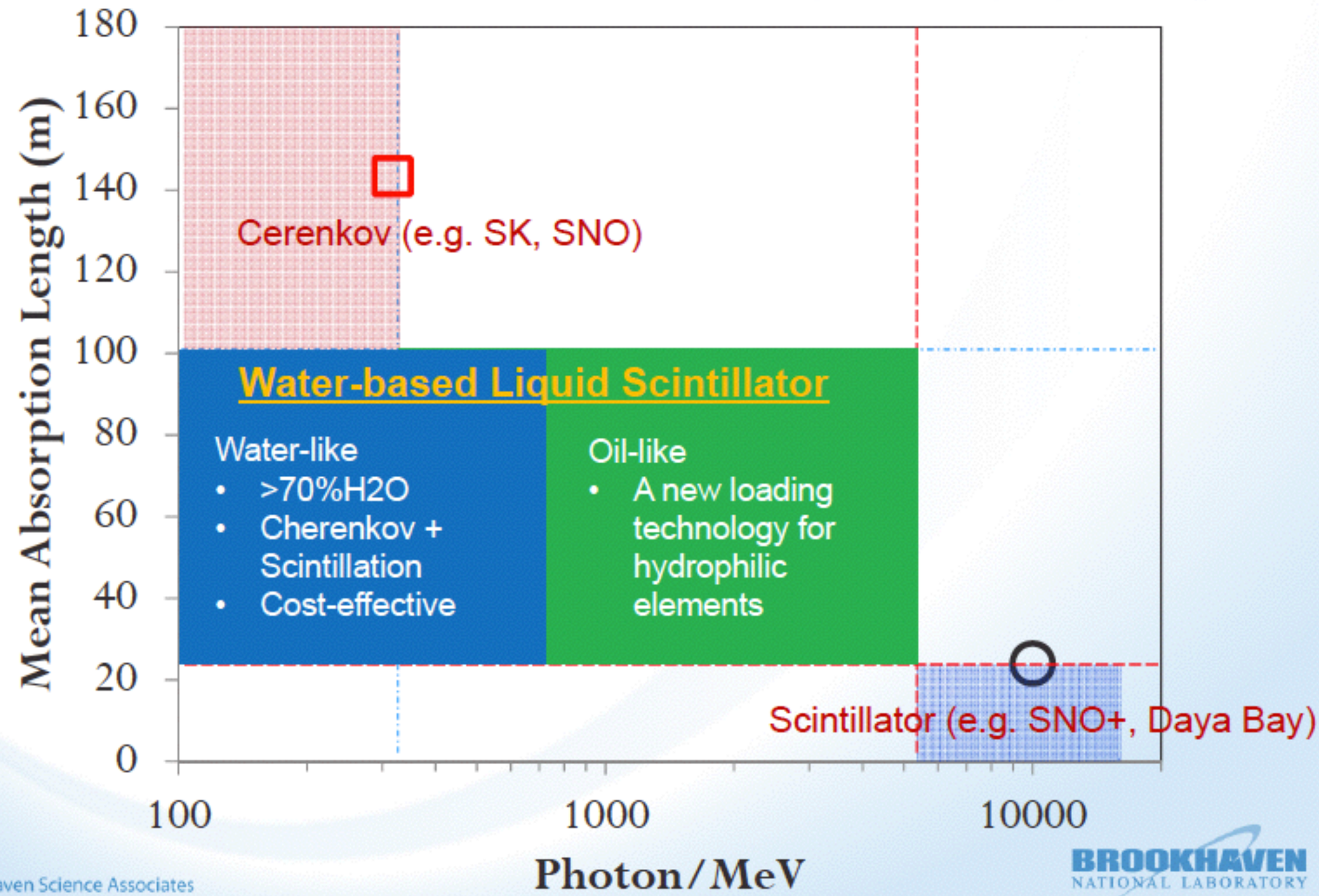


Light yield as a function of LS fraction,
D. Jaffe et al., BNL

4. Loading of metallic ions
   ➡ broad physics applications

Powerful Target Medium

-- Tune to specific physics goals

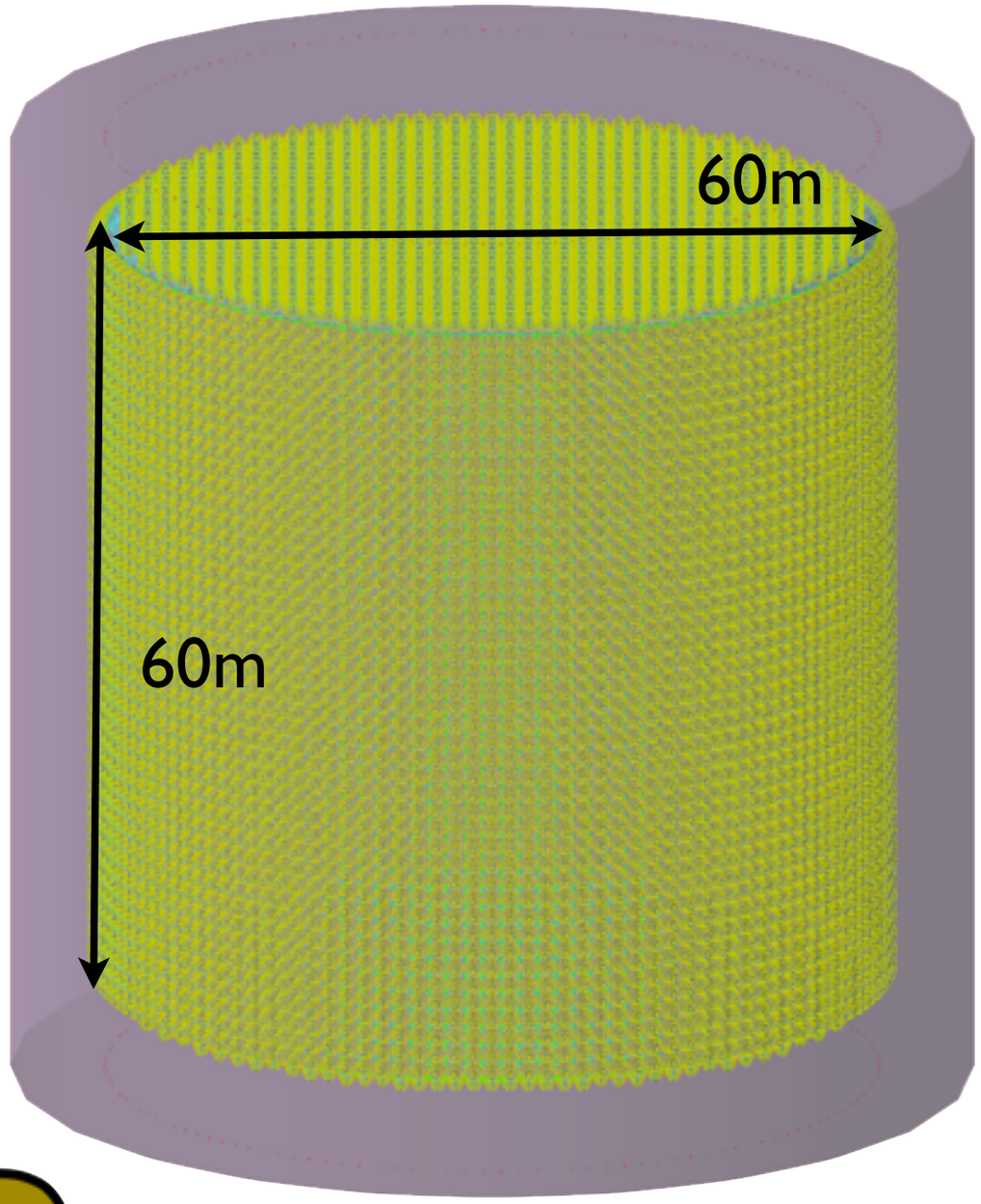


THEIA:

A realisation of the Advanced Scintillation Detector Concept (ASDC)

- Large-scale detector (50-100 kton)
- WbLS target
- Fast, high-efficiency photon detection with high coverage
- Deep u/ground (Pyhäsalmi, Homestake)
- Isotope loading (Gd, Te, Li...)
- *Flexible*! Target, loading, configuration

➡ **Broad physics program!**



Concept paper - arXiv:1409.5864

Detector image product of RAT-PAC

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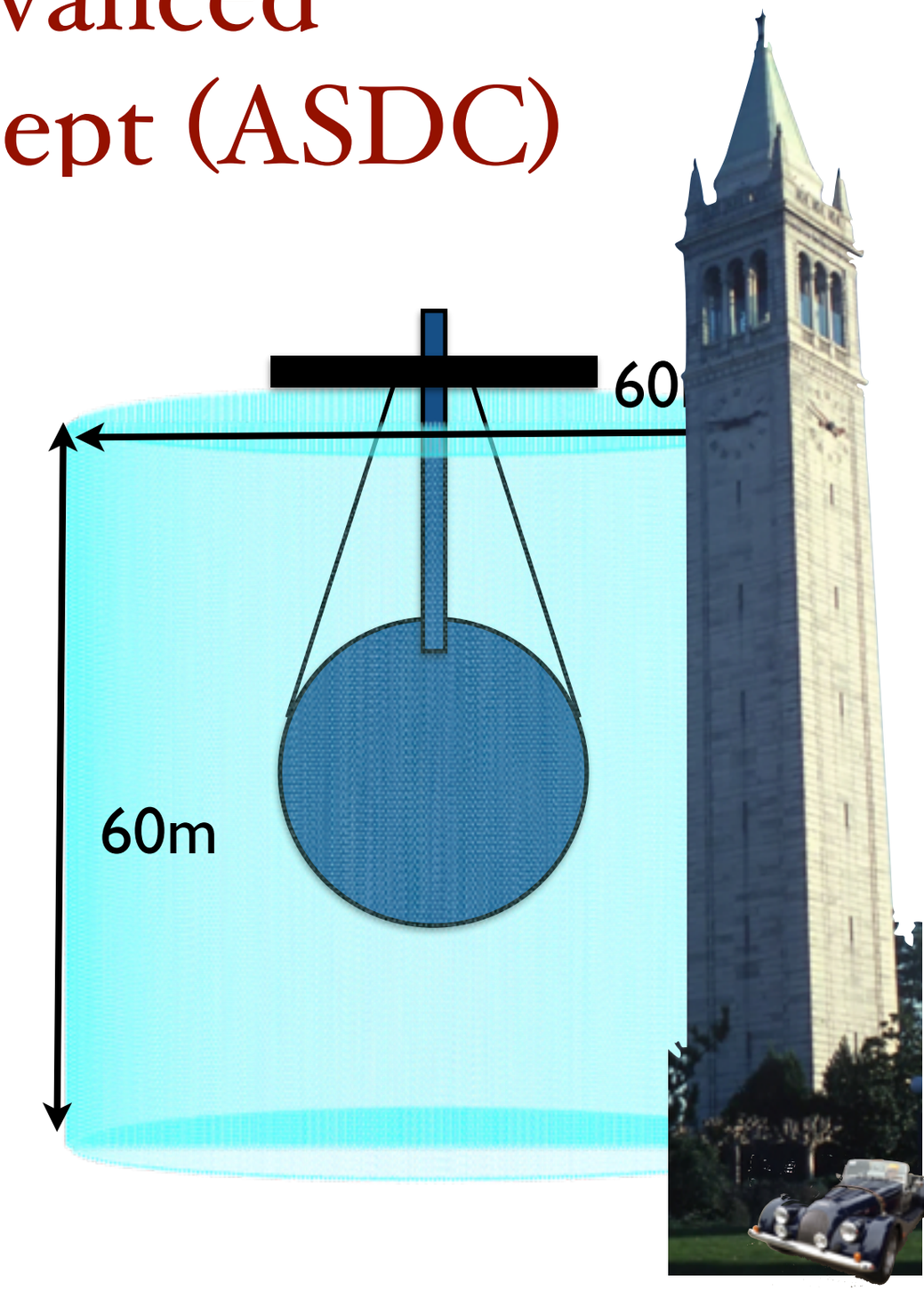

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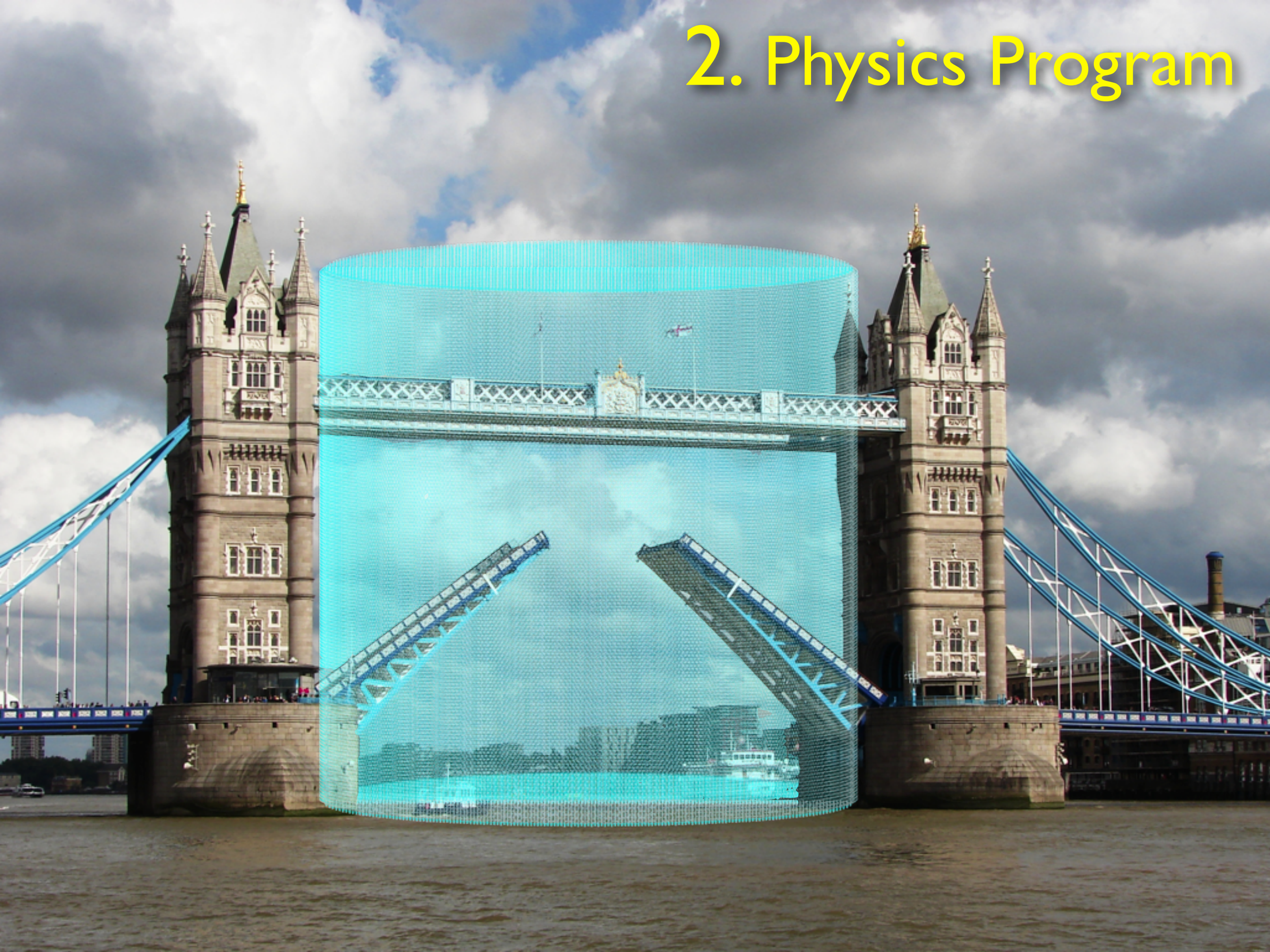
Detector image product of RAT-PAC


Jan Parker 2008


Ian Parker 2006

2. Physics Program



Physics Program

Physics over 5 orders of magnitude

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)

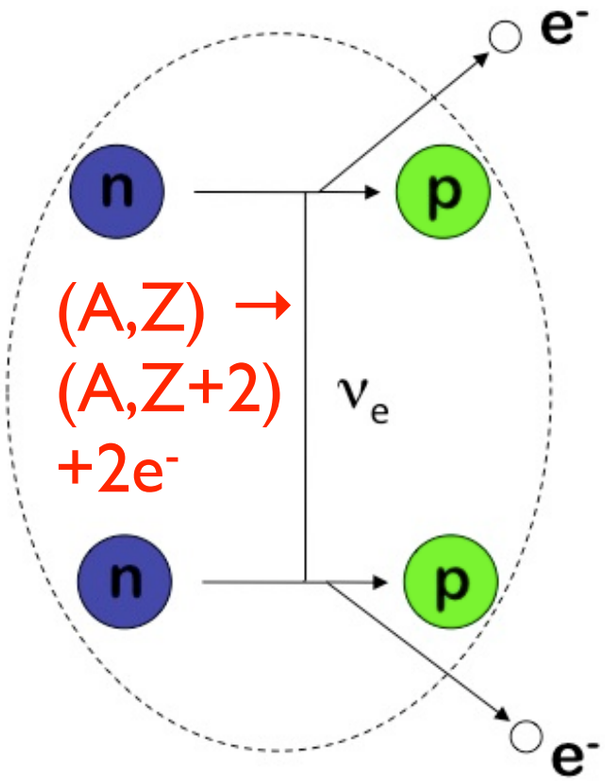
Nuclear Physics

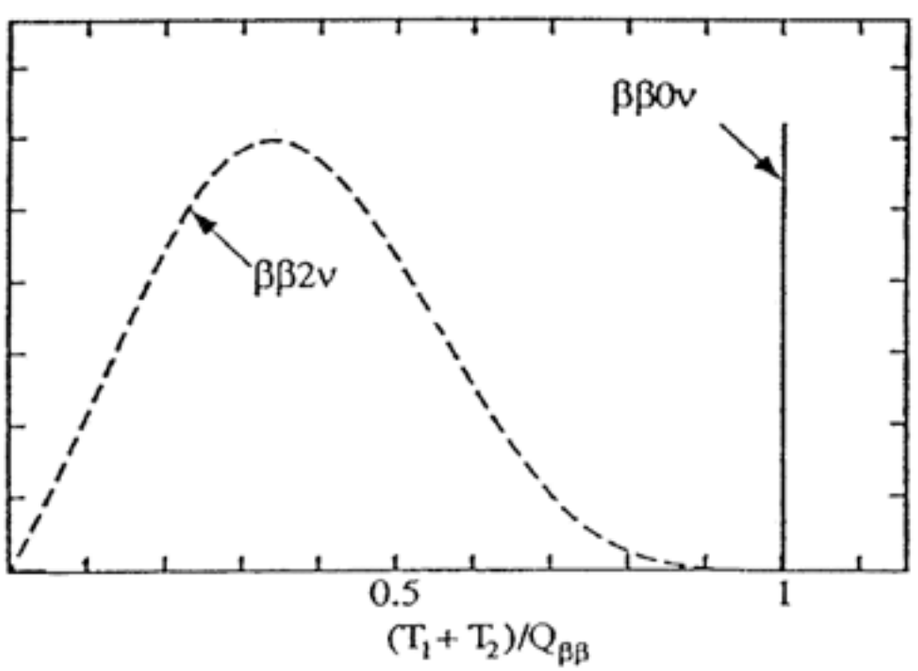
High-Energy Physics

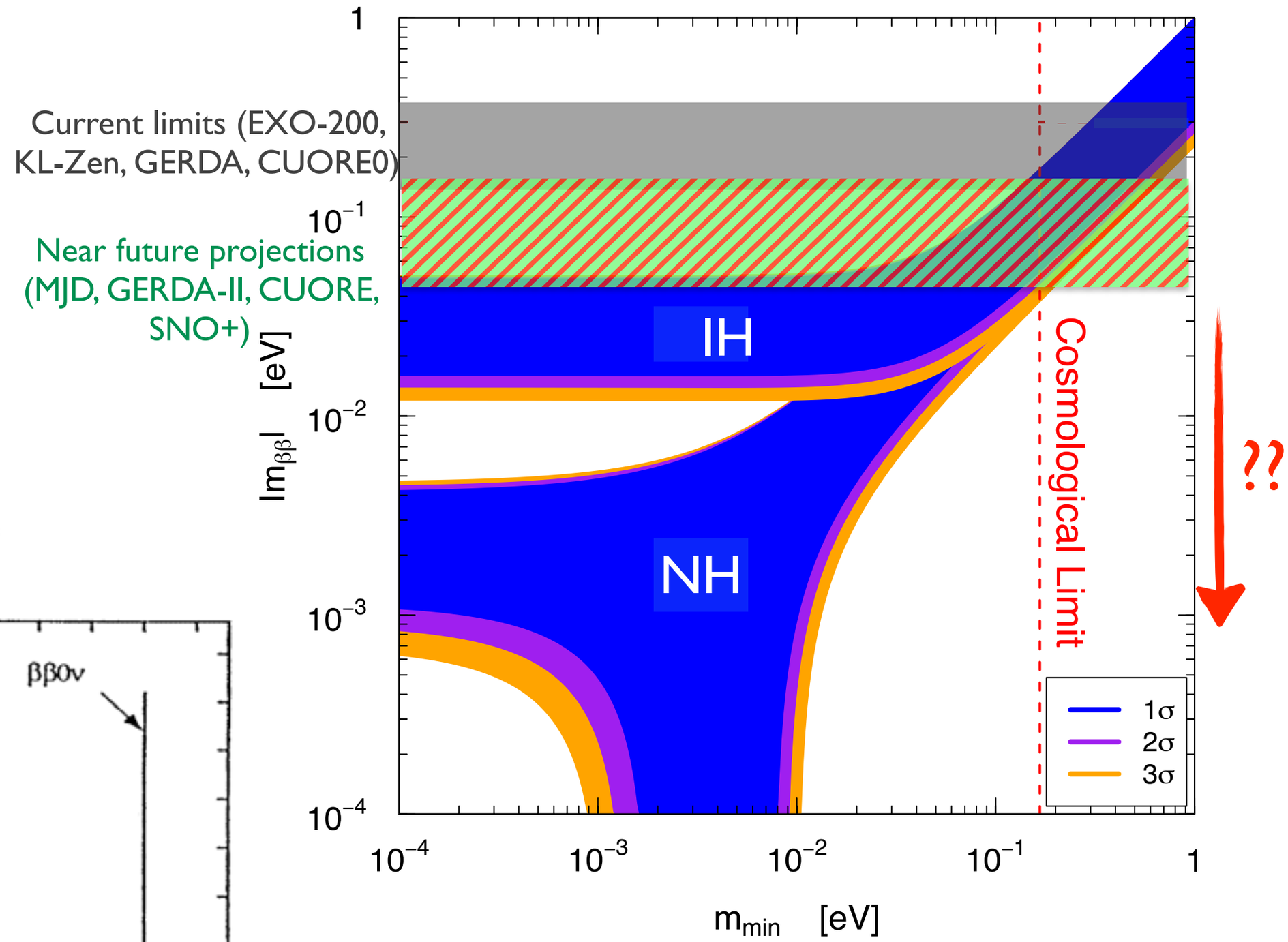
Remarkably, the same detector could show that neutrinos and antineutrinos are the same, ***and*** that "neutrinos" and "antineutrinos" oscillate differently

Leptogenesis

Neutrinoless Double Beta Decay



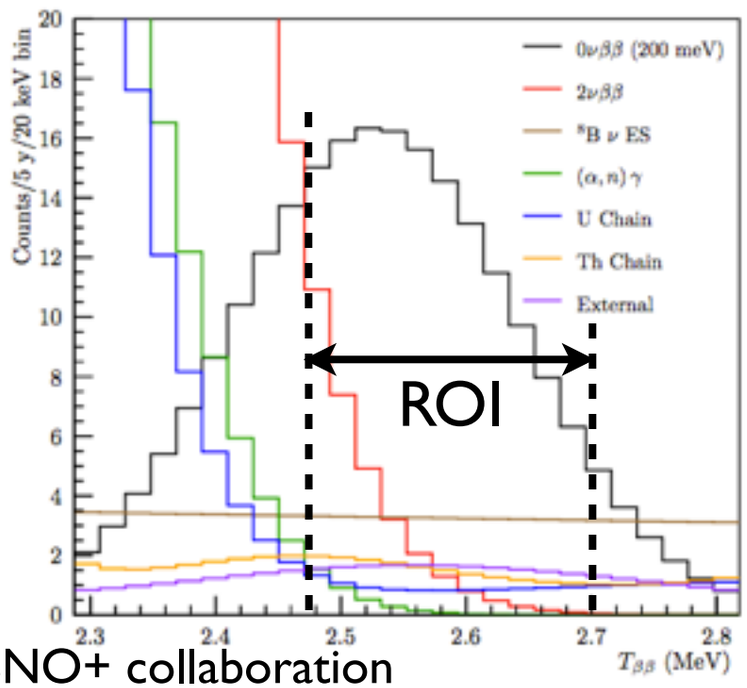




S. M. Bilenky & C. Giunti, Mod. Phys. Lett. A27, 1230015 (2012)

THEIA Sensitivity

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



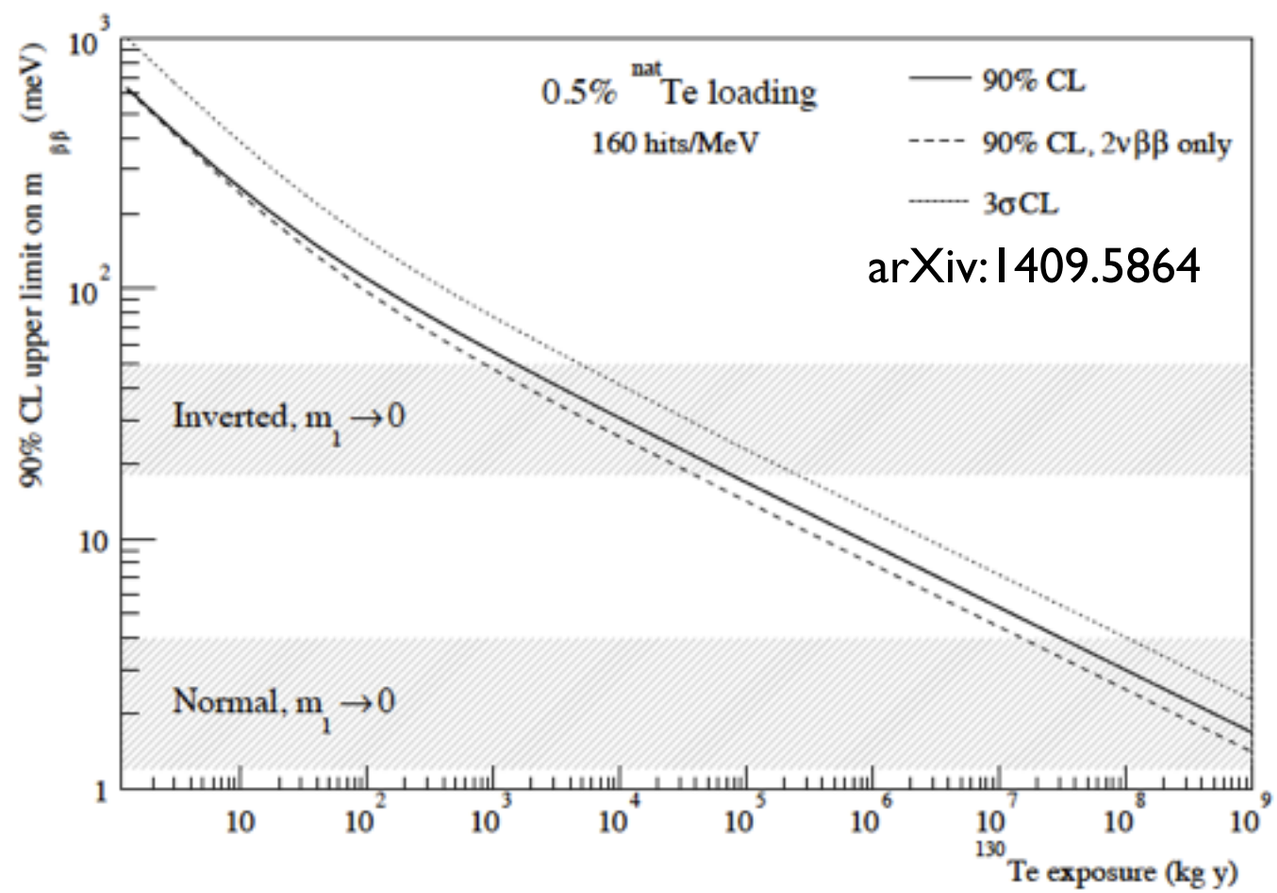
SNO+ collaboration

Builds on critical developments by KLZ & SNO+ collaborations

Ultra-low background, scalable

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

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



50kt detector

50% reduction of ^{8}B

Coincidence tags for int r/a

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

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

⇛ 50t ^{130}Te

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

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

Solar Neutrinos

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

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

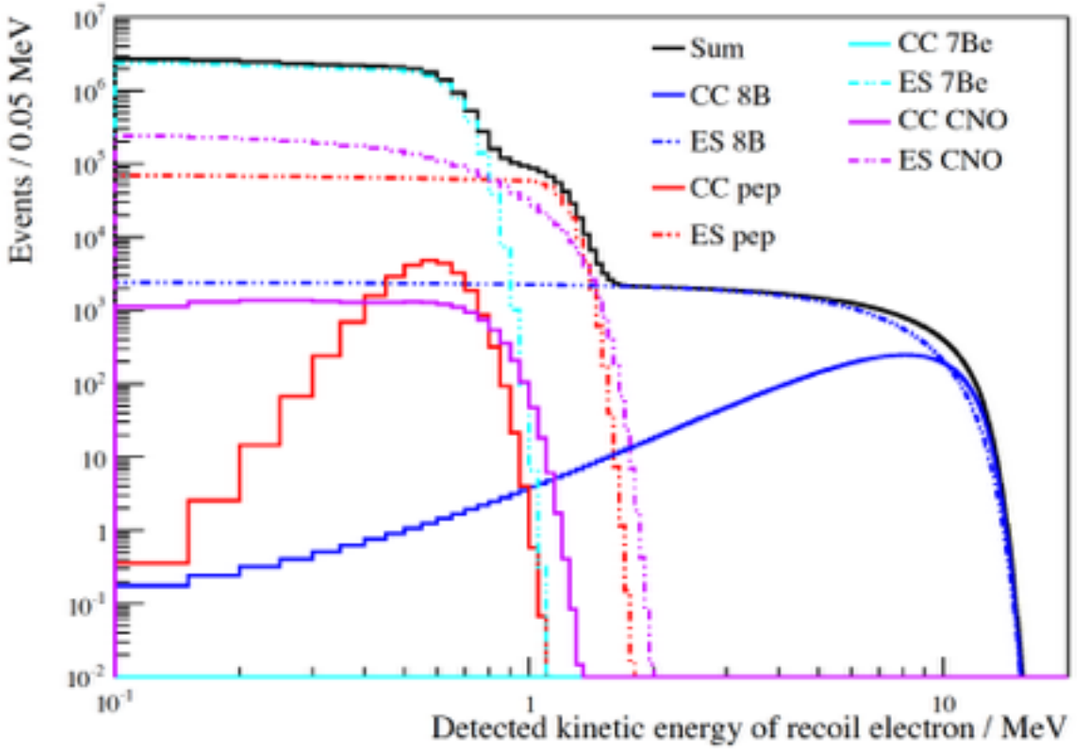
2000s, M. Yeh *et al.*: water-based liquid scintillator

Nucl. Inst. & Meth. A660 51 (2011)

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

⇒ search for new physics, solar metallicity, MSW effect

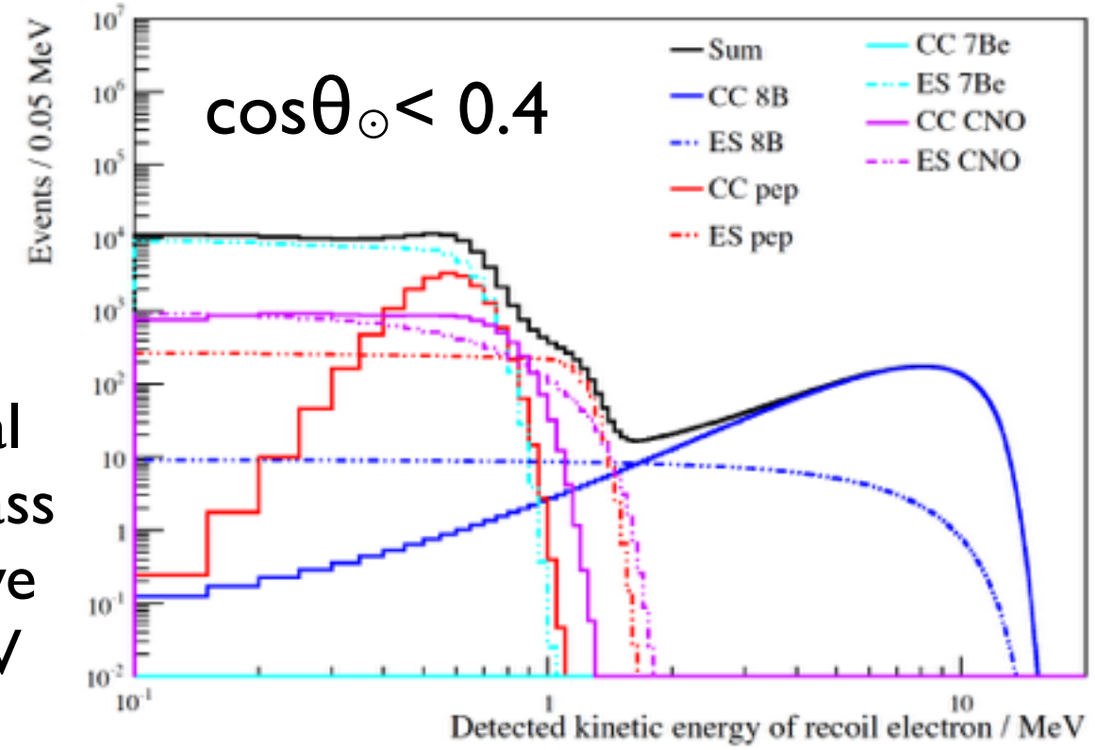
Unprecedented low-energy statistics (ES)



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

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

Spectral Sensitivity (CC)



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

arXiv:1409.5864

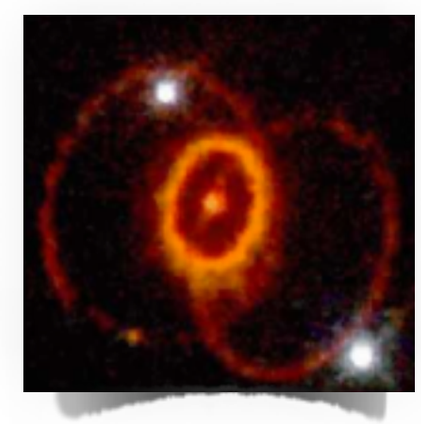
Antineutrino Detection

- 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
- Reduce NC background that limits LS detectors

Geo Neutrinos

- Current total geo-ν exposure: < 10kt-yr (KL + Borexino)
- **THEIA**: large statistics in a complementary geographical location

DSNB



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


Supernova
Neutrinos

Supernova Burst in THEIA

- ~12k events for SN at 10 kpc (50 kt volume)
- ~90% events are IBD

Highly complementary to ν_e-dominated LAr signal

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

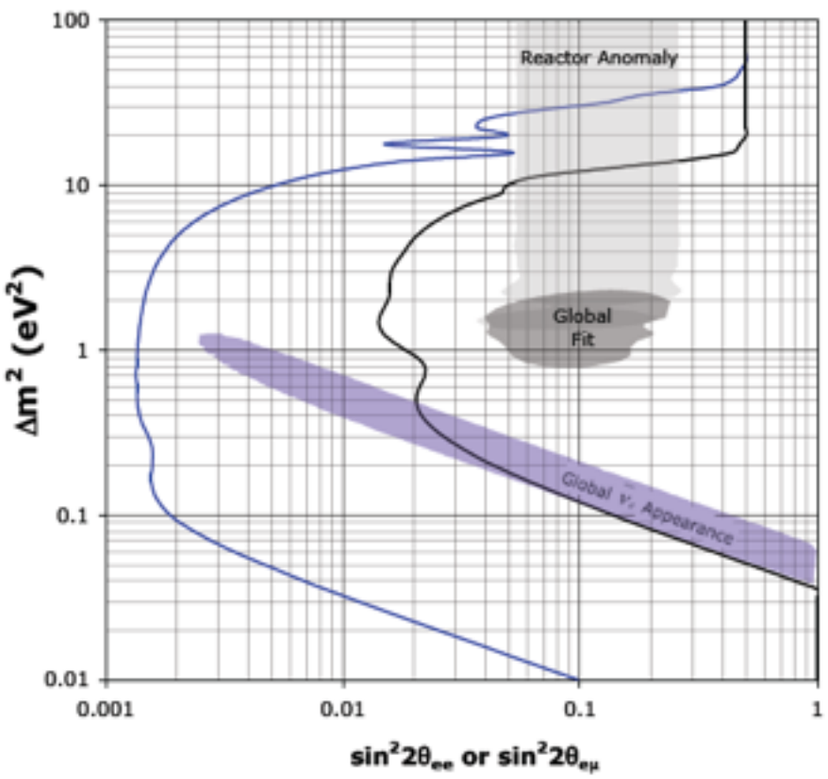
- Enhanced n tag via low threshold scintillation
- Gd reduces n-cap time delay (200μs → 20 μs) ⇒ reduce pile up

Potential for directionality using IBD kinematics arXiv:1504.05466 [astro-ph.IM]

- IBD tag allows extraction of additional signals
- Bkg reduction for ES, doubling pointing accuracy
- ID CC & monoE γ from NC ⇒ sensitive to burst T & subsequent ν mixing

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)

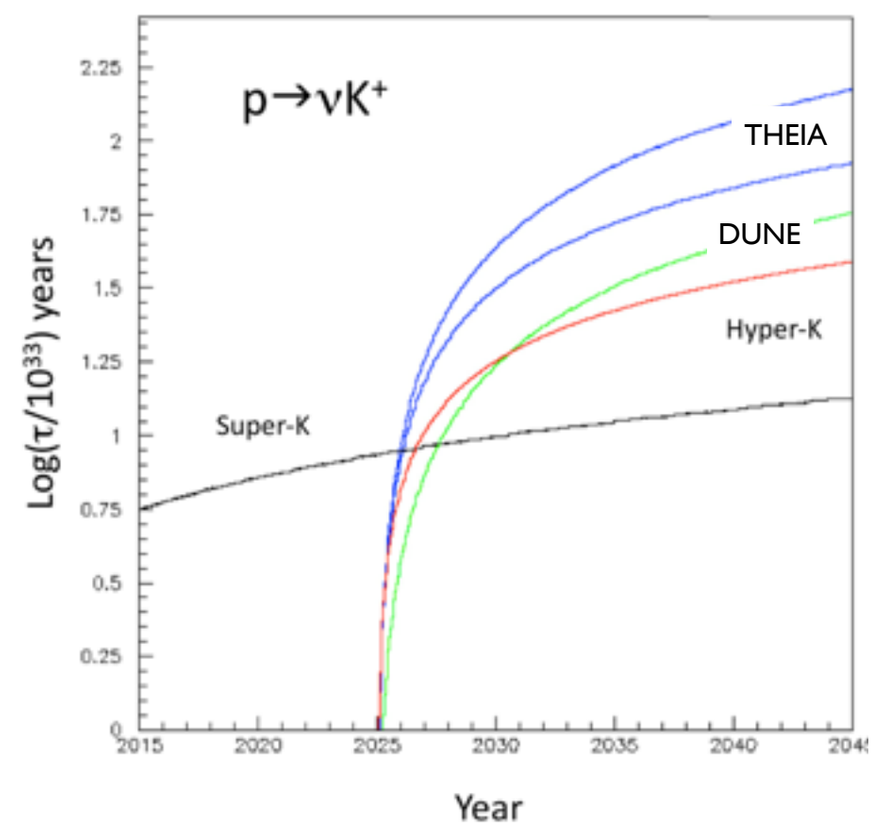


- ν -vs- anti-ν source comparison ⇒ sterile ν + CPT test

arXiv:1505.02550 [hep-ex]

Nucleon Decay

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

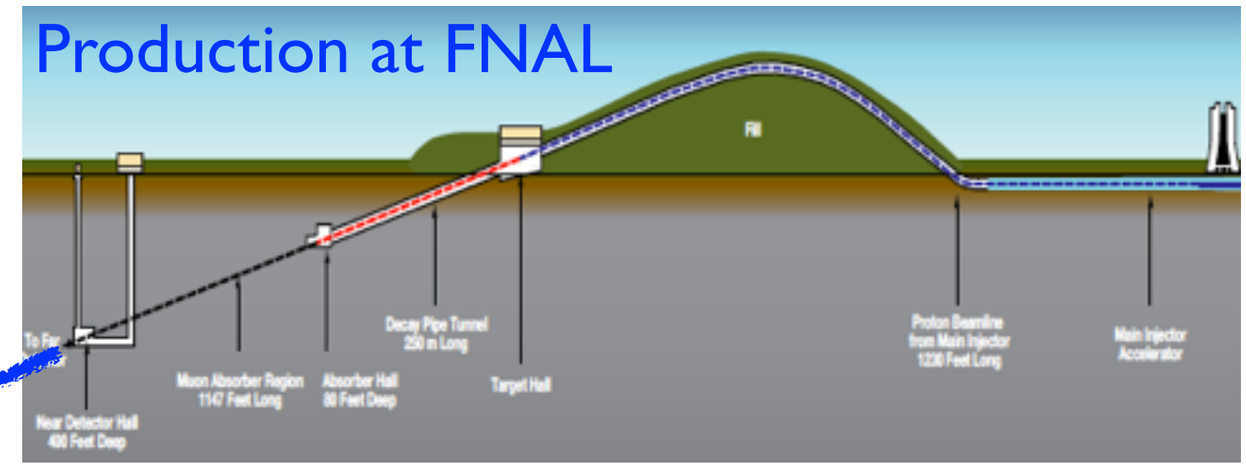


Figs from arXiv: 1409.5864

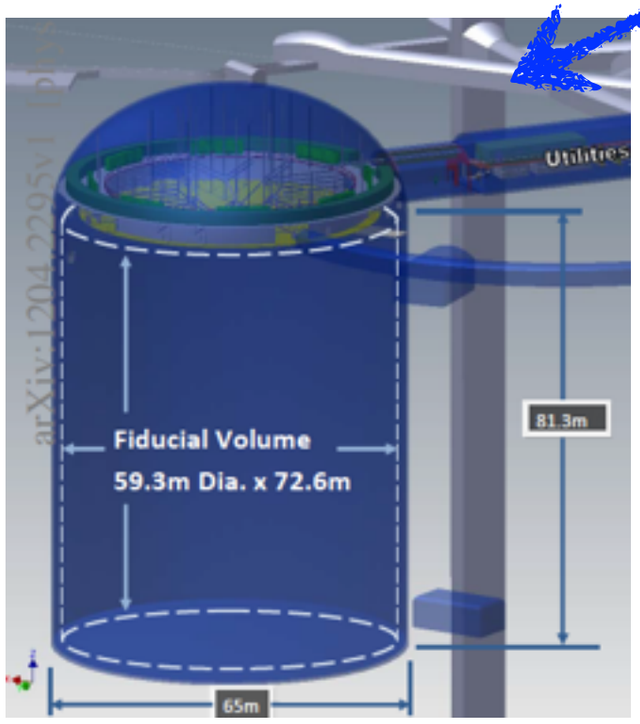
Sub-Chr t/h detection
⇒ Directly visible K^+

Long Baseline Program

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



1300km



Images from arXiv:1204.2295

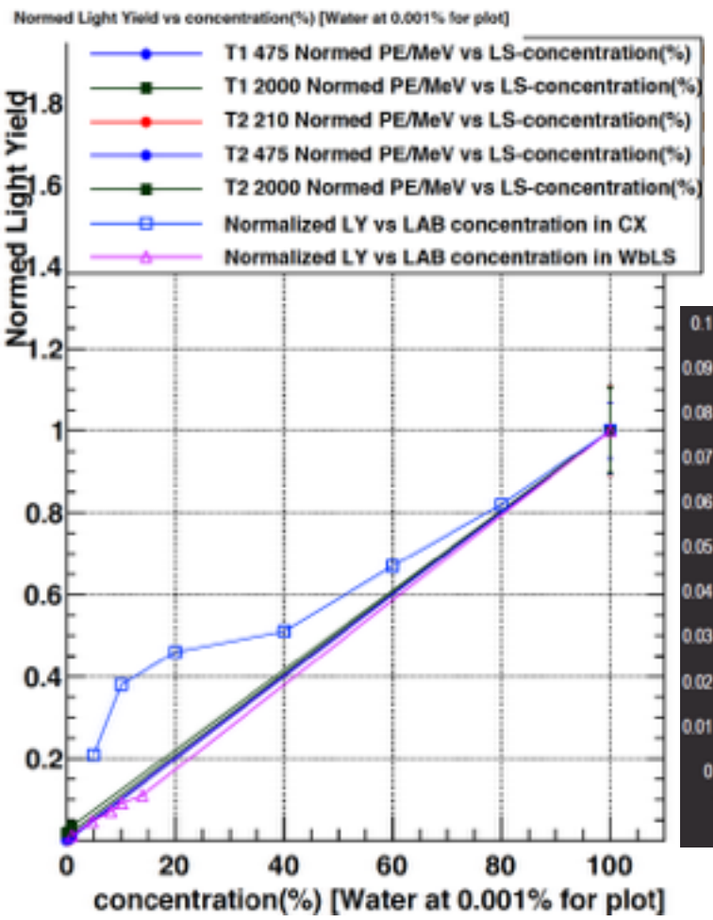
- Ring-imaging of a water Cherenkov detector
- Particle ID from Cher/scint separation
- n and low-E hadron detection (low threshold)
  - reduce wrong-sign component (nu vs anti-nu)
  - reduce NC background by detecting $\pi^0 \rightarrow \gamma\gamma$
- Large size → sensitivity to 2nd oscn max

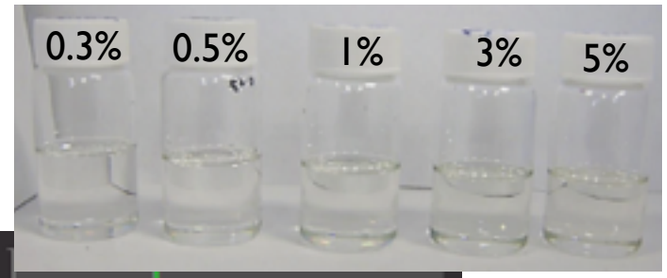
MH sensitivity for 34kT WbLS alone > 4.8 σ

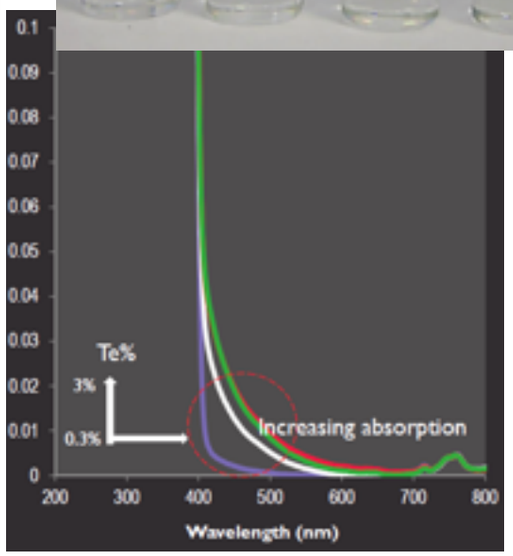
3. Required R&D

(Selection of) Ongoing R&D

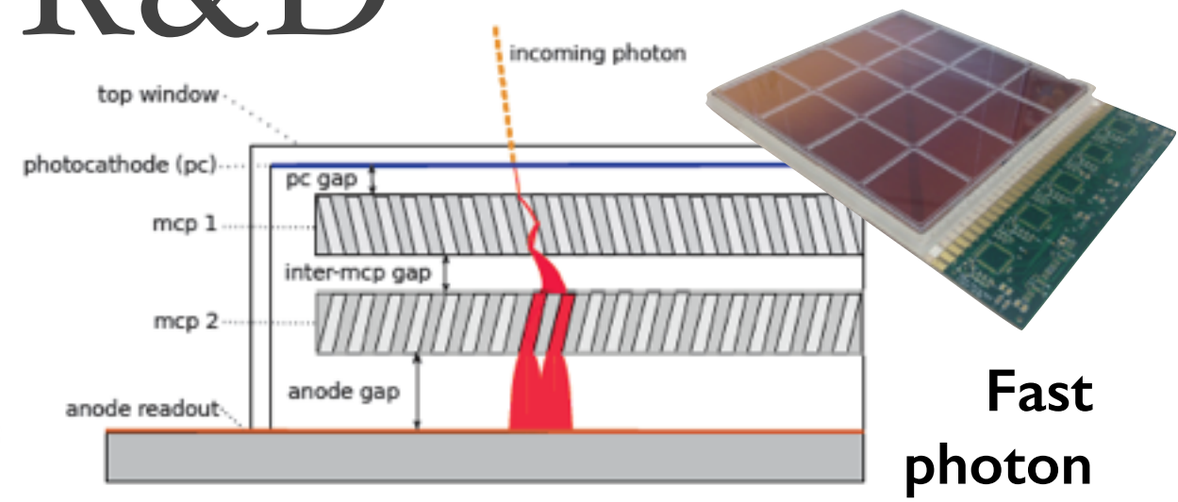
Complete model of light production in WbLS



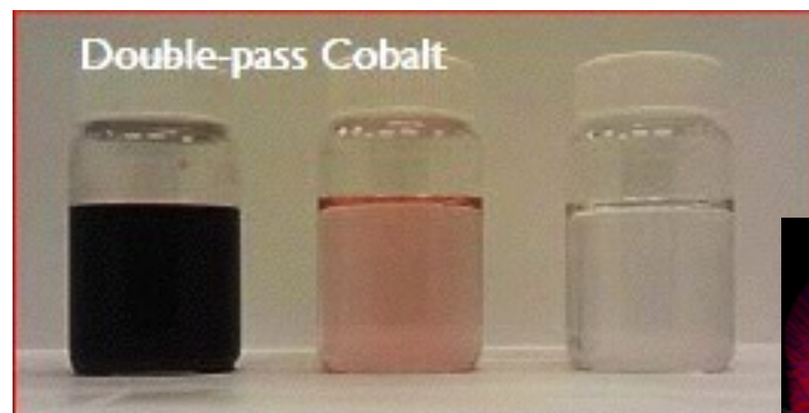




Isotope loading

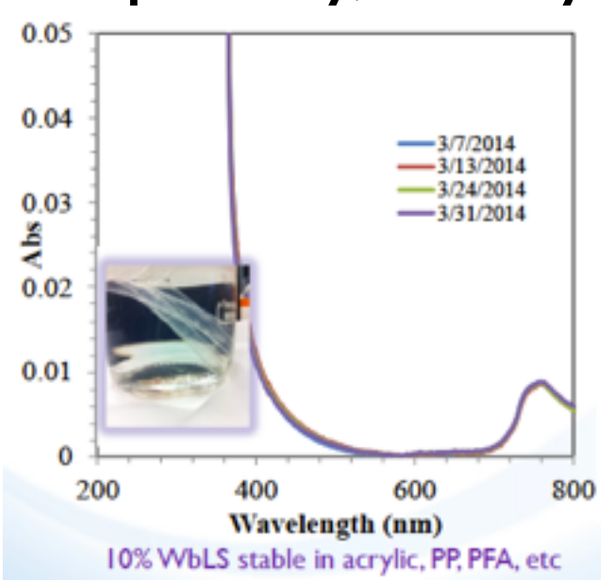


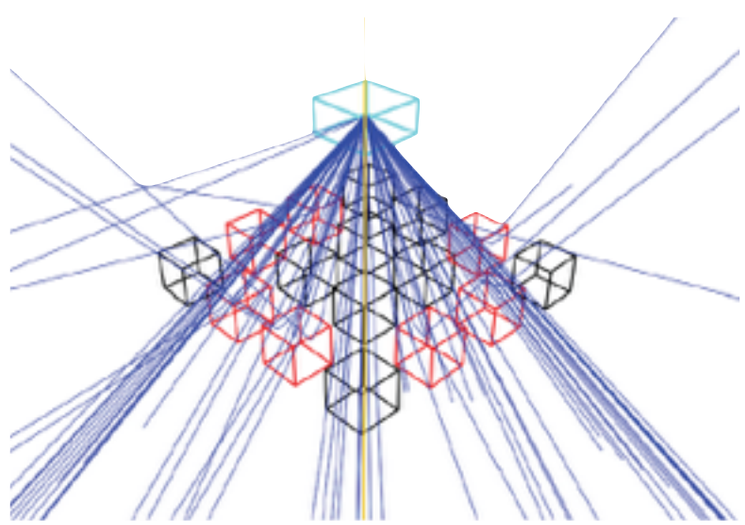
Fast photon detectors (LAPPDs)



Purification

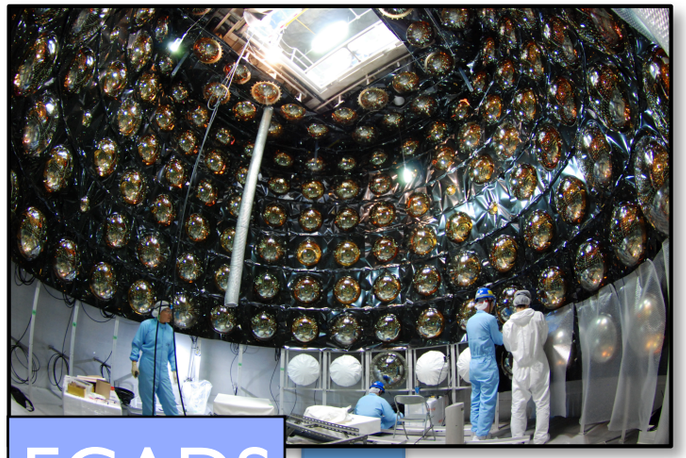
Material compatibility, stability





Ring Imaging

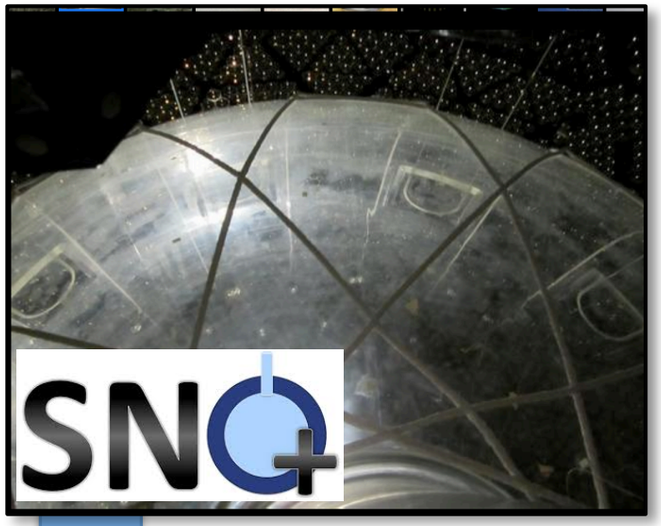
Full Monte Carlo detector model



EGADS

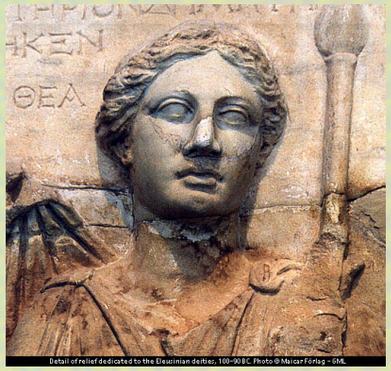
Gd loading and purification

Water-based liquid scintillator



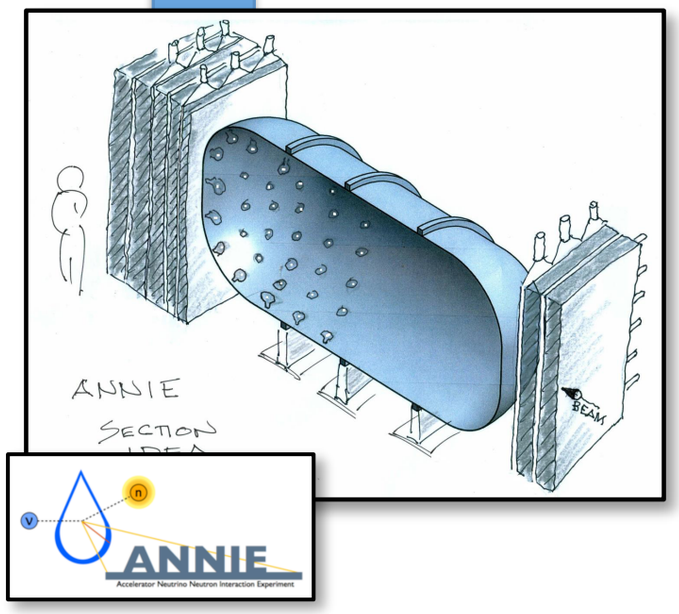
Te loading

THEIA

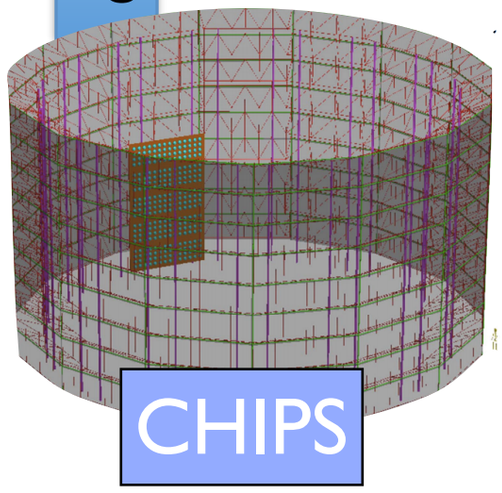


60m

Neutron yield, LAPPD deployment



Infrastructure, underwater integration



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

Concept paper - arXiv:1409.5864

THEIA "Interest Group"

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

Lawrence Livermore National Laboratory
Los Alamos National Laboratory
University of Maryland
MIT
University of Pennsylvania
Princeton University
Sandia National Laboratories
Virginia Polytechnic Inst. & State University
University of Washington

Brunel University London

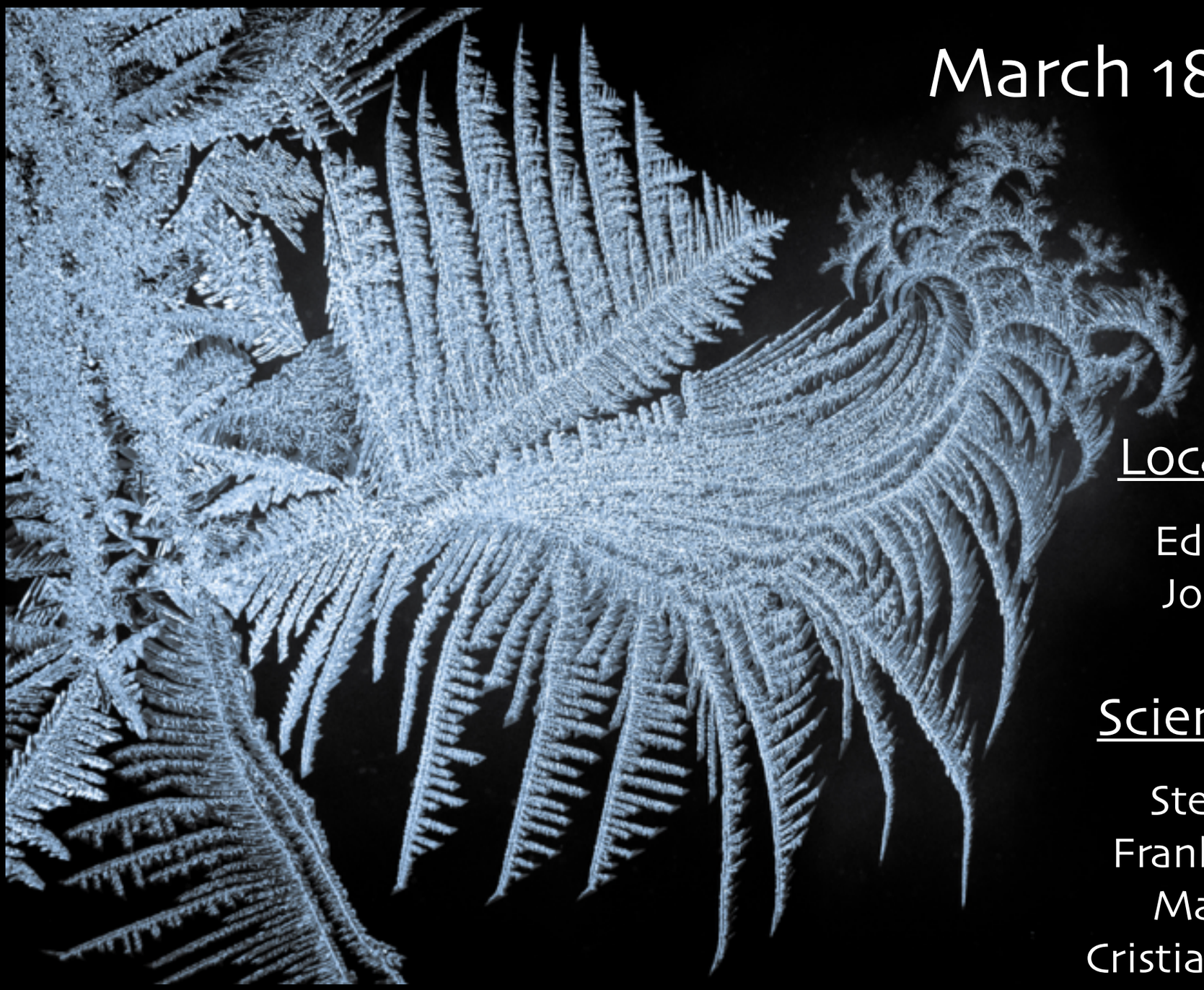
RWTH Aachen University
TUM, Physik-Department
University of Hamburg
Johannes Gutenberg-University Mainz

New participation welcome
contact G. D. Orebi Gann, B. Svoboda, E. Blucher, J. R. Klein

FroST

Frontiers in Scintillator Technology

March 18-20th 2016



Local Organising Committee

Ed Blucher
Josh Klein
Gabriel Orebi Gann
Bob Svoboda

Scientific Advisory Committee

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

THEIA

- Potentially revolutionary technology
- Opportunity to combine conventional neutrino physics with rare-event searches in a single detector
- Unique flexibility to adapt to new directions in the scientific program as the field evolves
- Powerful instrument of discovery

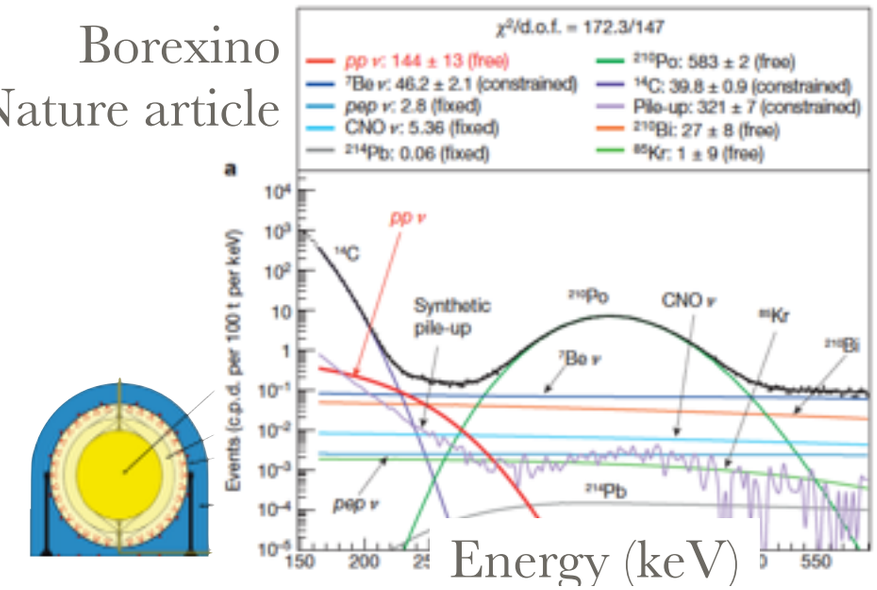
Back up

The Power of a Scintillator Detector

- High light yield: threshold, resolution
- Fast timing at low threshold: coincidence tag
- Particle identification
- Free protons

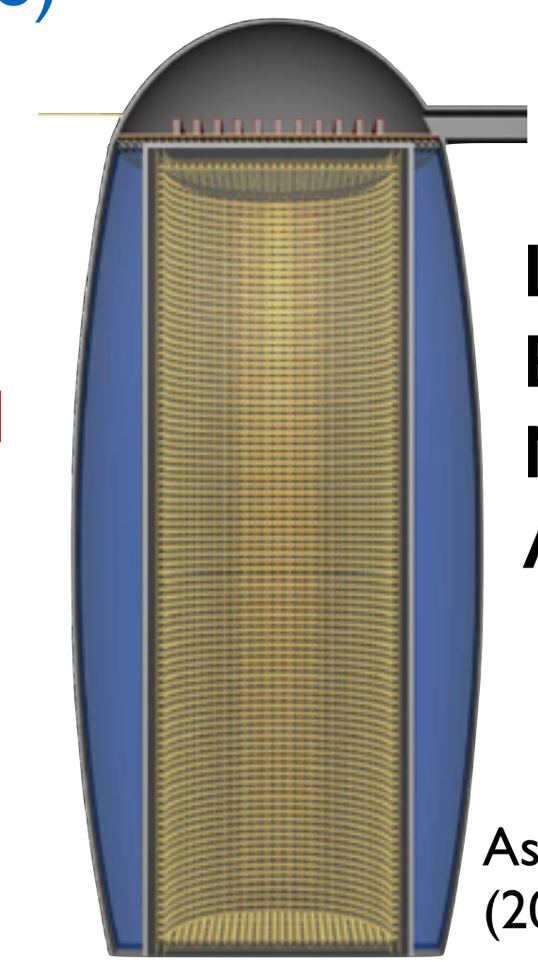
Already demonstrated at kt-scale (KL, Borexino)

Borexino
Nature article



Large-scale detector ⇒ Broad physics program

- Supernova neutrinos
- Diffuse supernova neutrino background
- Solar neutrinos
- Geoneutrinos
- Proton decay
- Atmospheric neutrinos



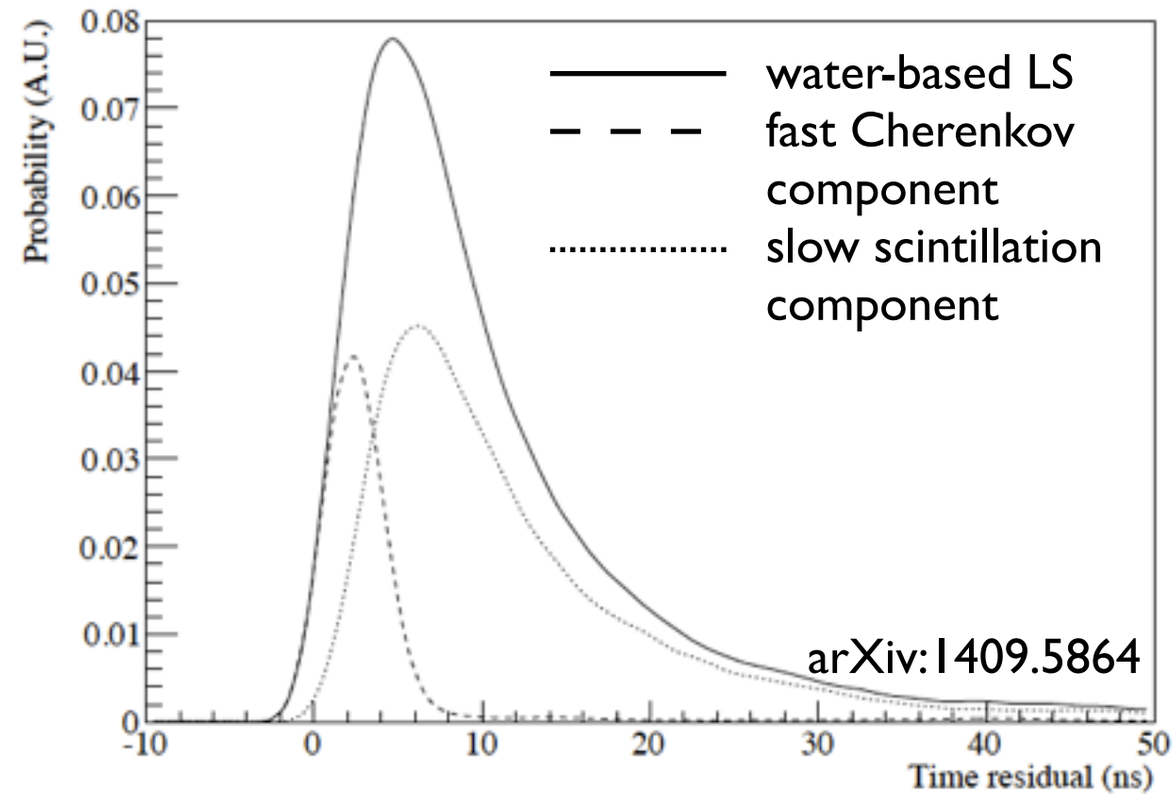
Low
Energy
Neutrino
Astronomy

Astropart. Phys. 35 (2011) 685-732

Cherenkov/scintillation separation

Methods to enhance separation:

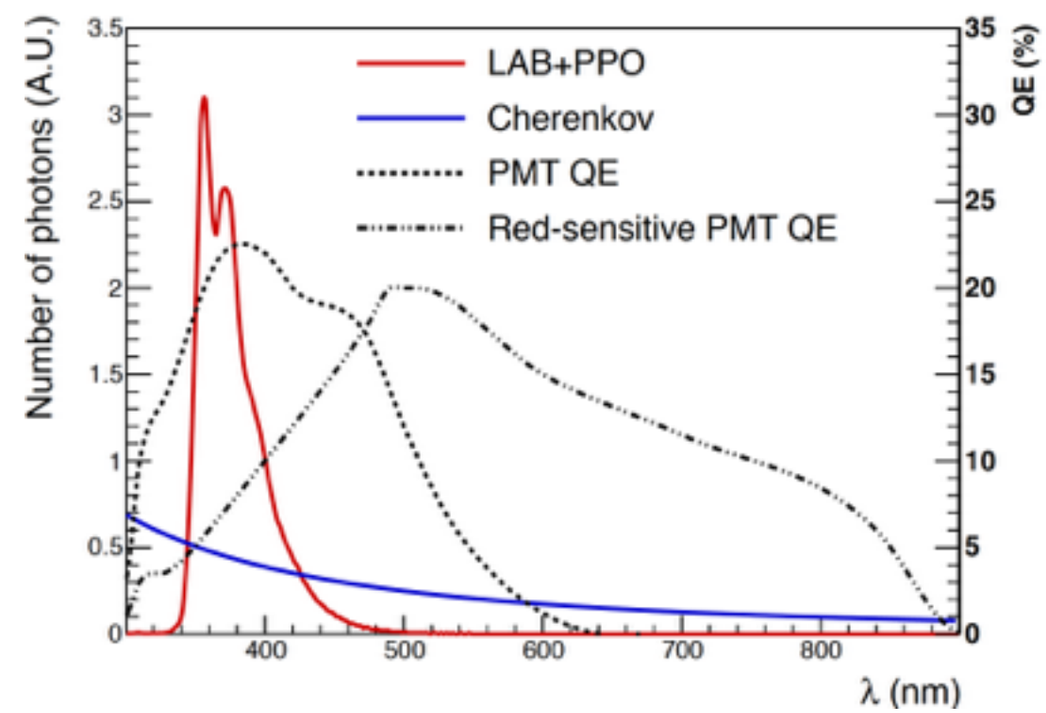
- Ultra-fast photon detection (LAPPDs)
- Delay scintillation light
- Optimize cocktail: scintillation fraction & spectrum (fluor)
- Readout sensitivity



⇒ *Excellent particle ID & background rejection:*

- Sub-Cher-threshold scintillation
- Directionality
- Ring imaging

⇒ *Enables incredibly broad physics program*

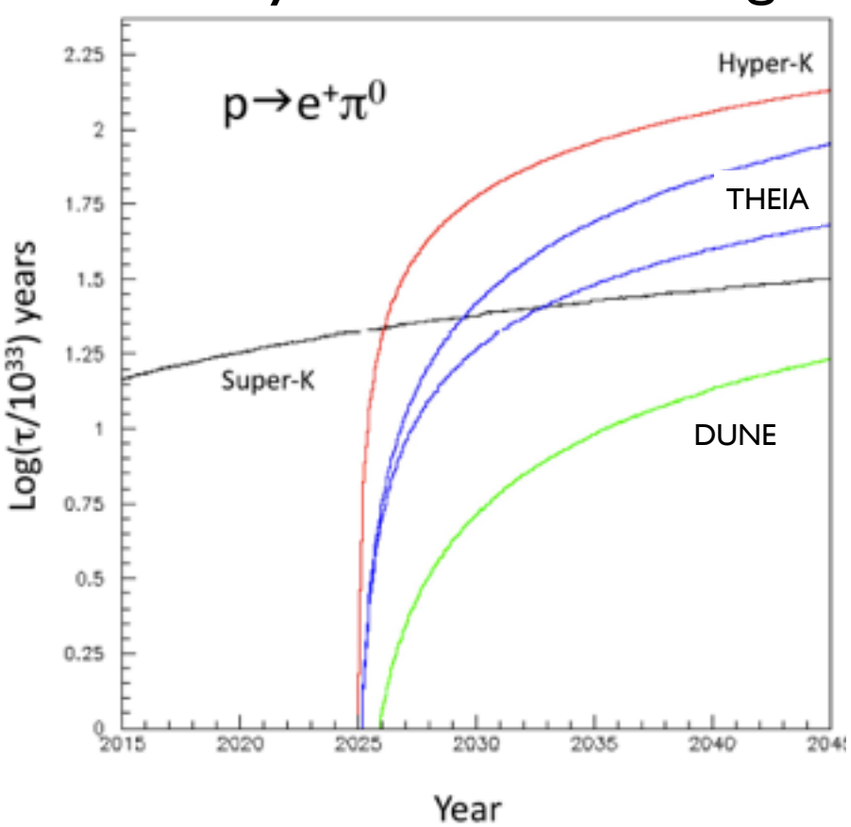


Nucleon Decay

Testing the existence of GUTs with THEIA:

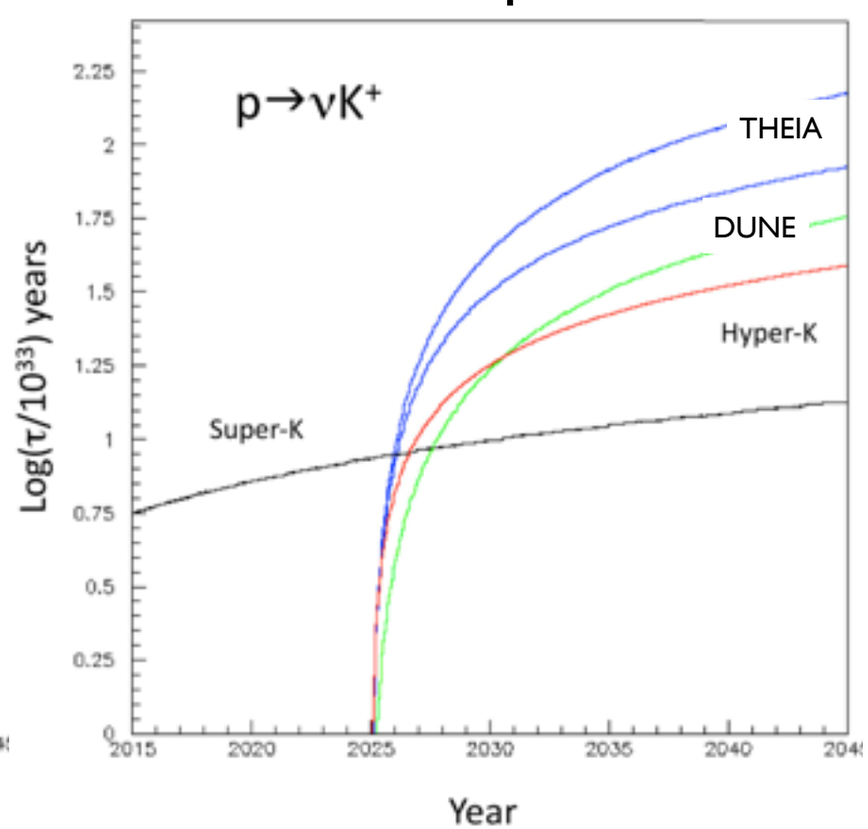
- Large size (statistics), deep location, very clean
- n tagging (low threshold plus potential isotope loading)
- Sub-Cherenkov threshold detection

Heavy X boson exchange



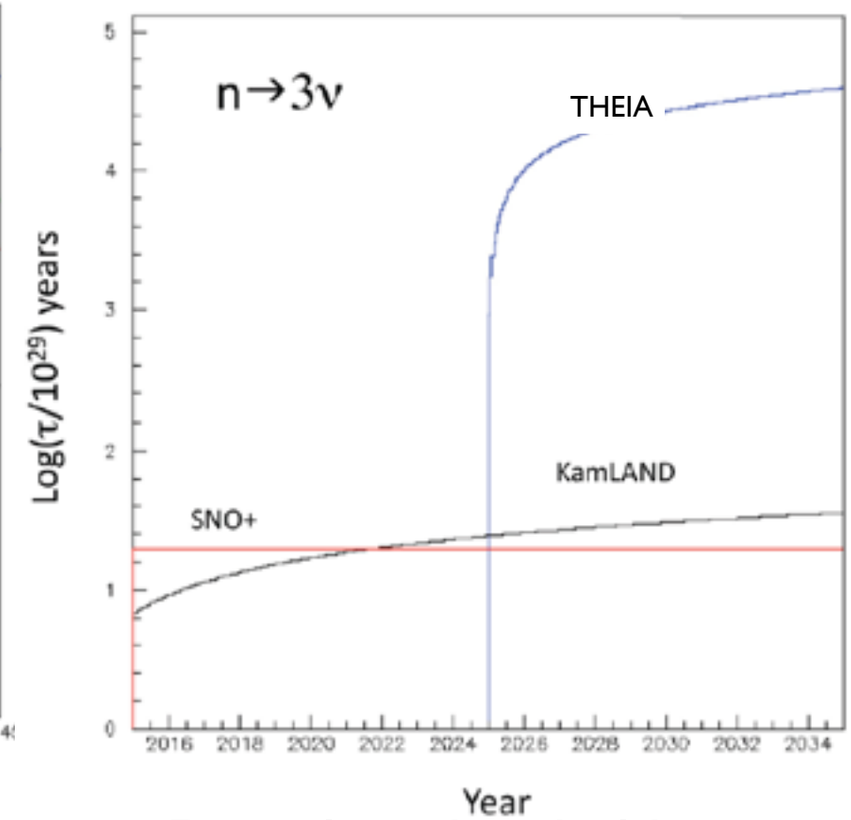
Enhanced n tag
Reduced atmos. ν bkg

2nd order processes



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

Extra dimensions



Deep, low threshold
Directionality + n tag

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

Potential Enhancements @ THEIA

- Separation of scint / Cher light ⇒ particle ID
- Low-threshold scintillation light ⇒ n and low-E hadron detection
- High-precision timing ⇒ improve reconstruction
  - ➡ Reduce "wrong-sign" component by discriminating ν / anti-ν
  - ➡ Reduce NC background by detecting $\pi^0 \rightarrow \gamma\gamma$

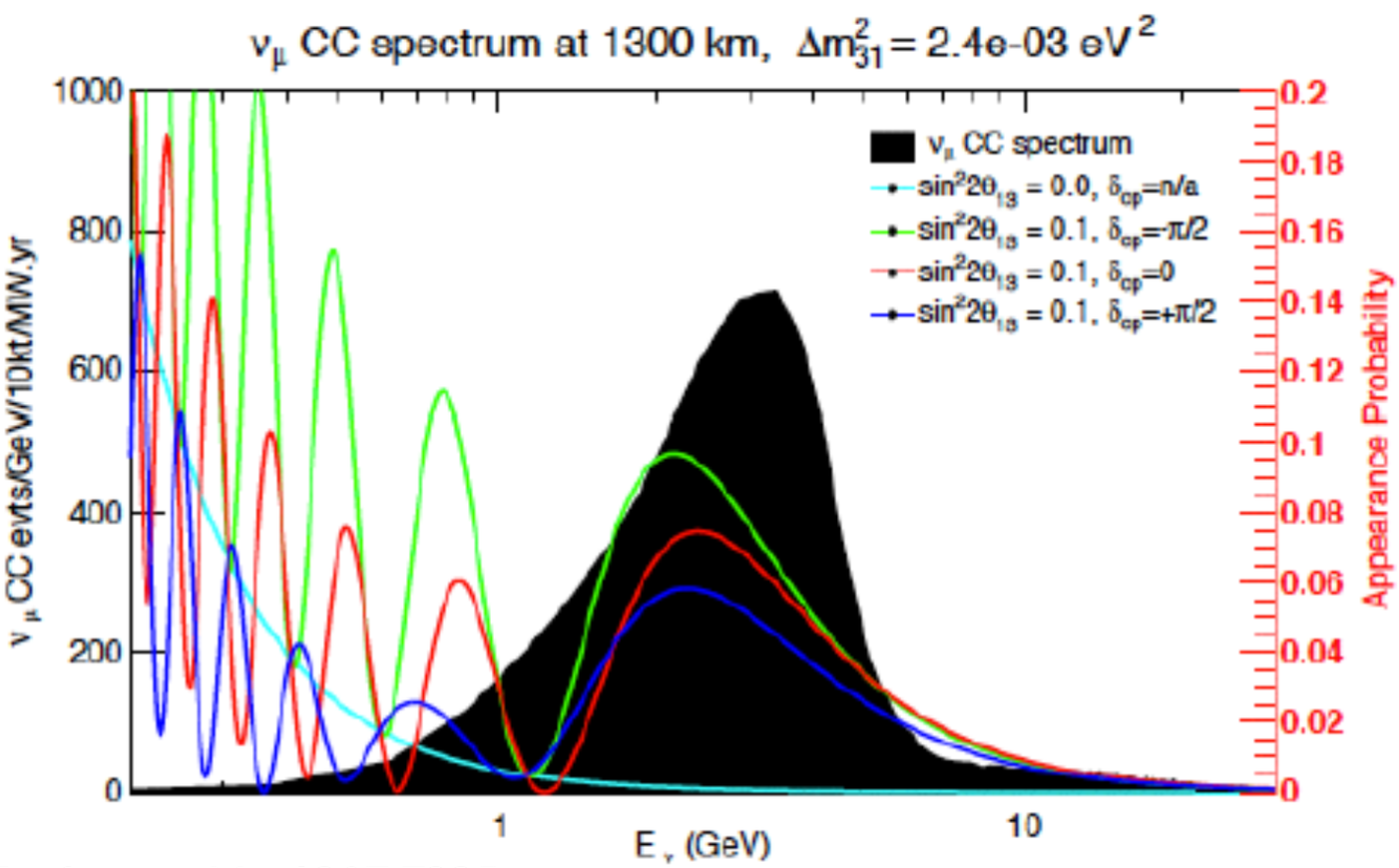
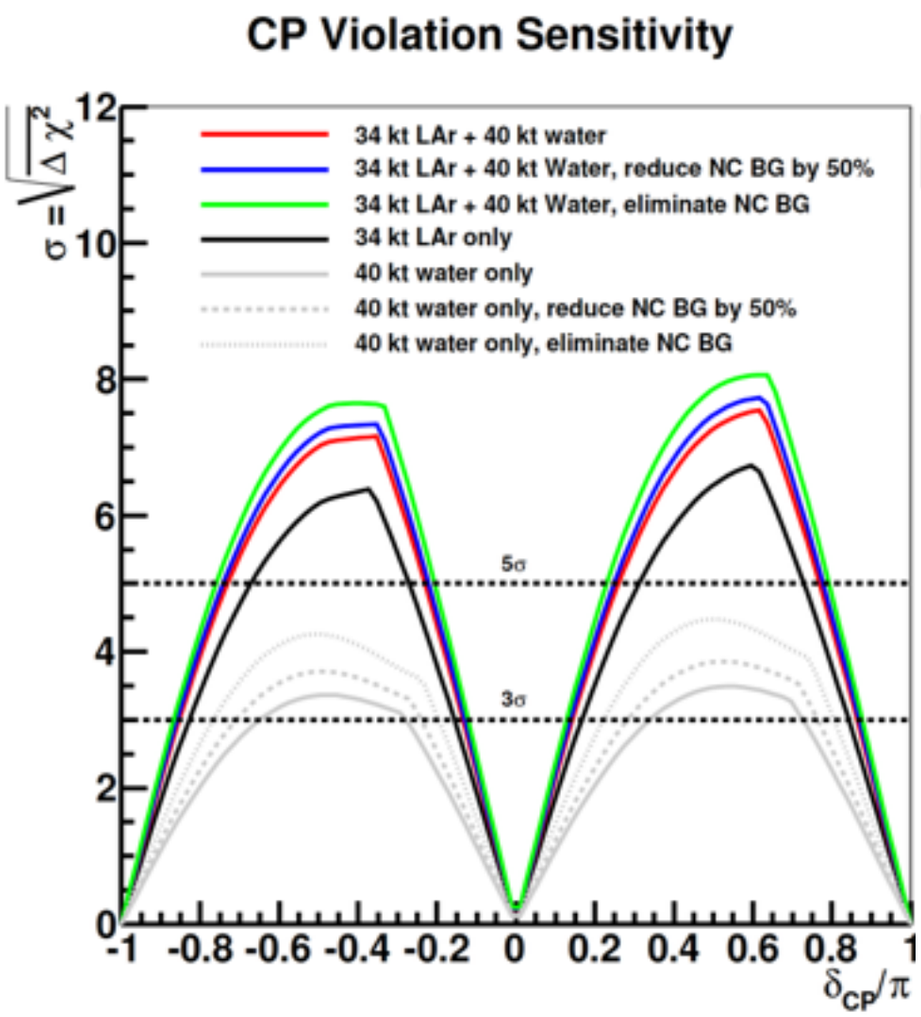


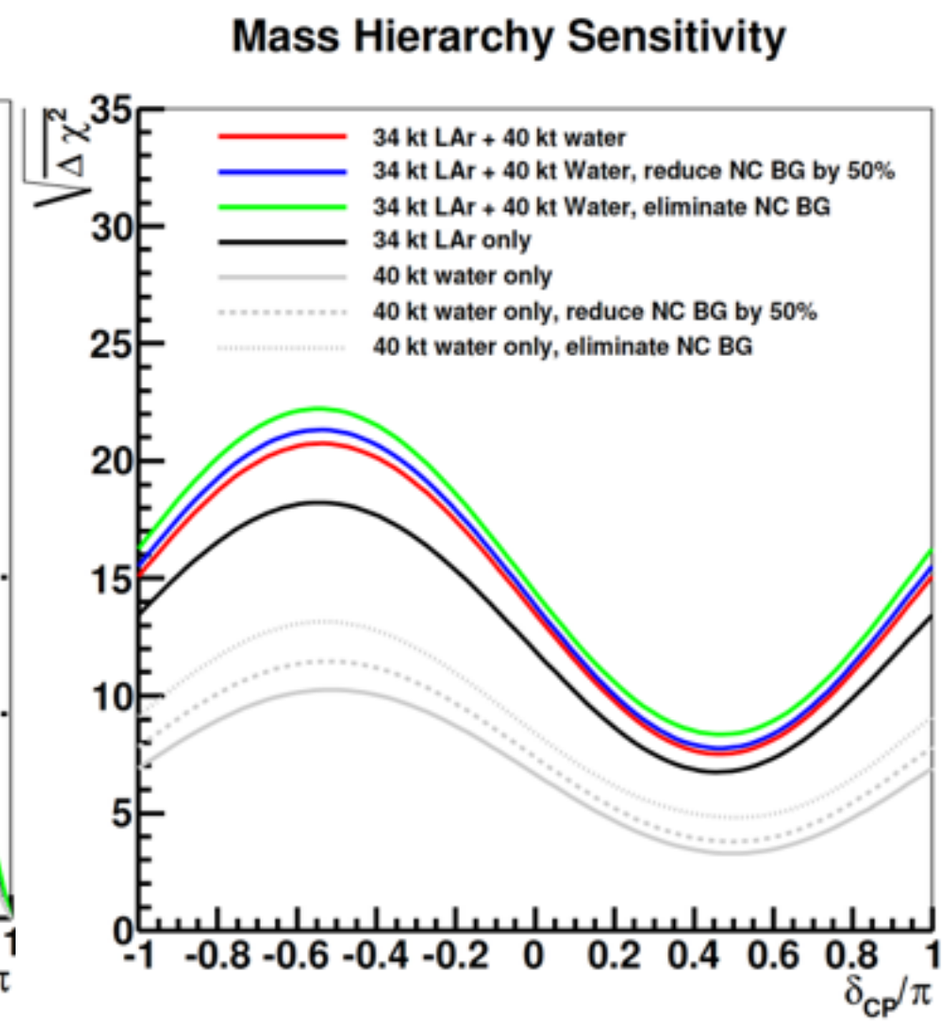
Fig from arXiv:1307.7335

- Large target mass increases sensitivity to second oscillation maximum
- P5 recommended large ~~WCD~~ in scenario C

WbLS would do better!

THEIA Sensitivity





Assumes no improvement over SK-level ring imaging (conservative)

~245 kt-MW-yr exposure

Performance equivalent to or better than 10kt LAr TPC

MH sensitivity for 34kT WbLS alone > 4.8 σ

All figs from arXiv:1409.5864

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