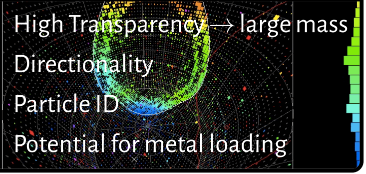
Daniele Guffanti
Johannes Gutenberg–Universität Mainz
on behalf of the **THEIA Collaboration**

Physics potential of THEIA
a hybrid optical neutrino experiment

Neutrino Telescopes 2021 - (Virtually) Venice, 22.02.2021

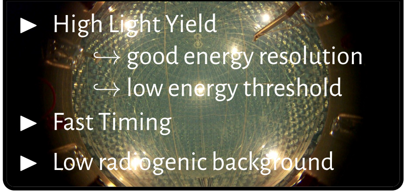
Detector concepts

Čerenkov detectors



- High Transparency $\longrightarrow$ large mass
- Directionality
- Particle ID
- Potential for metal loading

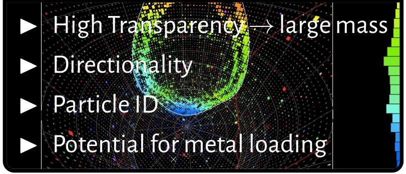
Liquid Scintillator detectors



- High Light Yield
  - $\hookrightarrow$ good energy resolution
  - $\hookrightarrow$ low energy threshold
- Fast Timing
- Low radiogenic background

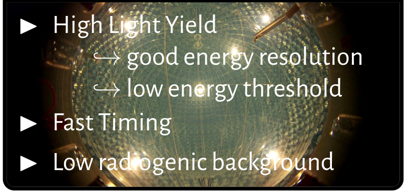
Detector concepts

Čerenkov detectors



- High Transparency $\longrightarrow$ large mass
- Directionality
- Particle ID
- Potential for metal loading

Liquid Scintillator detectors



- High Light Yield
  - $\hookrightarrow$ good energy resolution
  - $\hookrightarrow$ low energy threshold
- Fast Timing
- Low radiogenic background

Innovation

Scintillator

- Water-based Liquid Scintillator
- Slow Scintillators

Photodetector Technologies

- Fast PMTs and PMT modules
- LAPPD
- SiPM arrays
- Dichroic filters

Ev. Reco. Techniques

Detector concepts

Čerenkov detectors

- High Transparency $\rightarrow$ large mass
- Directionality
- Particle ID
- Potential for metal loading

Liquid Scintillator detectors

- High Light Yield
  - $\hookrightarrow$ good energy resolution
  - $\hookrightarrow$ low energy threshold
- Fast Timing
- Low radiogenic background

Innovation

Scintillator

- Water-based Liquid Scintillator
- Slow Scintillators

Photodetector Technologies

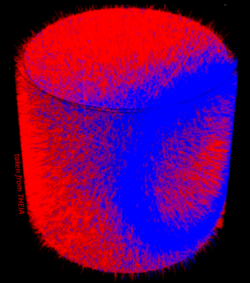
- Fast PMTs and PMT modules
- LAPPD
- SiPM arrays
- Dichroic filters

Ev. Reco. Techniques

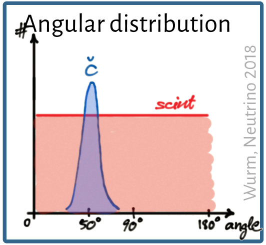
Hybrid Optical Neutrino detectors

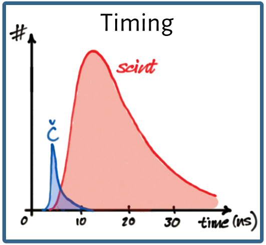
Proven concept,
new technology

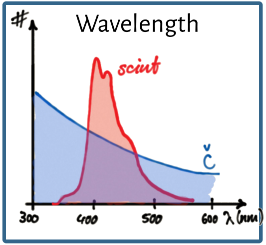
Huge physics potential



Cherenkov/Scintillation discrimination

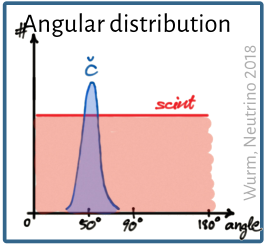


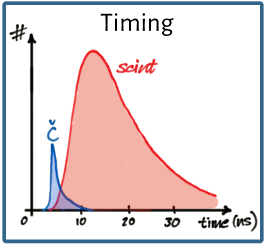


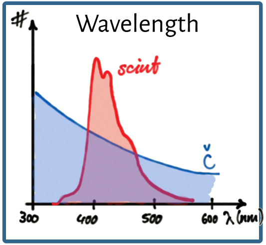


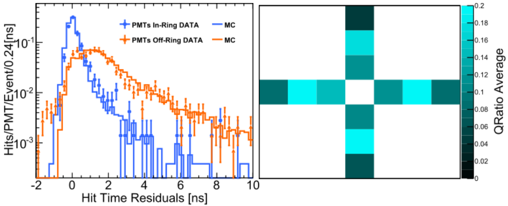
Cherenkov/Scintillation discrimination

See Tanner Kaptanoglu's flash talk on Wednesday February 24, 12:05 - Parallel Session 1



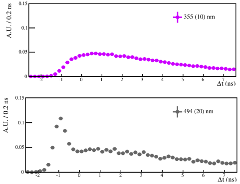






CHESS:
CHErenkov
Scintillation
Separation

Caravaca et al
EPJ C (2020)
EPJ C (2017)
Phys.Rev.C 95 (2017)



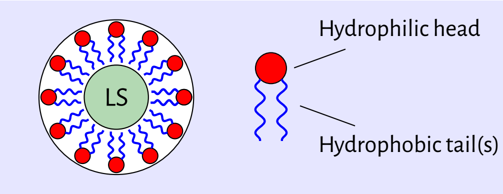
Dichroicon

Kaptanoglu et al,
Phys.Rev.D 101 (2020) 7
JINST 14 (2019) 05

Water-based Liquid Scintillators

Composition

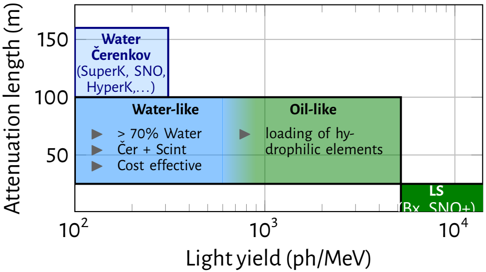
Mix of water and LS made possible by **surfactant** molecules



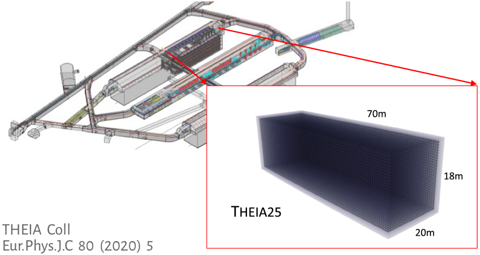
Properties

Depends on relative concentrations

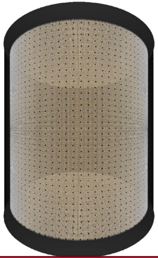
- Reduced light yield (although not linear with LS fraction)
- Increased transparency
- Comparable timing
- Metal loading possibility (Gd, ^{7}Li, ...)



Design options



THEIA Coll
Eur.Phys.J.C 80 (2020) 5



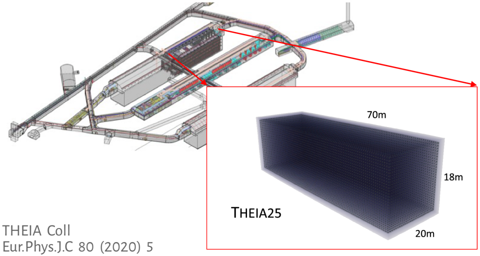
Large scale, multipurpose detector
Two options:

- Baseline: 25 kton (17 kton FV)
- Ideal: 100 kton (70 kton FV)

LS fraction tunable depending on the physics goal

$\hookrightarrow$ **staged approach**

Design options



THEIA Coll
Eur.Phys.J.C 80 (2020) 5

Large scale, multipurpose detector
Two options:

- Baseline: 25 kton (17 kton FV)
- Ideal: 100 kton (70 kton FV)

LS fraction tunable depending on the physics goal

$\hookrightarrow$ **staged approach**

Physics Program

High-energy program

$\approx$ 1% WbLS

- Long baseline neutrino oscillation
- Proton decay search

Low-Energy Program

$\approx$ 5% WbLS

- Solar neutrinos
- Anti-neutrino program
  SN-ν, DSNB, reactor, geo$-\nu$
- Nuetrinoless-$\beta\beta$ decay search
  Sub-volume of LS loaded with 0ν-$\beta\beta$ candidate

Long-baseline neutrino program

- LBNF beam: 1300 km baseline, broad band (1–7 GeV)
- 1490 m overburden (4300 m.w.e.)

DUNE

$(3+)\times$ 17.5 kton LAr TPC
Primary goal: MO, δ_{CP}

THEIA

Strengthen DUNE program
Same beam, different syst.

Long-baseline neutrino program

- LBNF beam: 1300 km baseline, broad band (1–7 GeV)
- 1490 m overburden (4300 m.w.e.)

DUNE

$(3+)\times$ 17.5 kton LAr TPC
Primary goal: MO, δ_{CP}

THEIA

Strengthen DUNE program
Same beam, different syst.

- Significant improvments in the ev. reco. techniques wrt LBNE studies
  - 75% reduction in NC bkg
  - ν_e-CCπ^+ 1 ring, 1 Michel sample accessible
  - High-purity multi-ring ν_e ev. samples
- Liquid Scintillator fraction
  - Measurement of low-energy hadronic products
  - Improved n detection (even w/out Gd loading)

Sensitivity studies

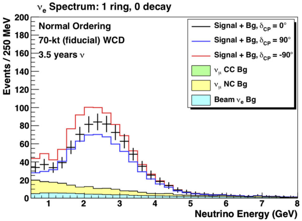
THEIA Coll., Eur.Phys.J.C 80 (2020) 5

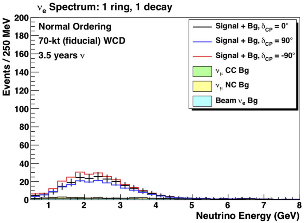
- GLobeS framework, LBNF beam
- Similar systematics budget to DUNE
- Current WČD performance assumed
  (no improvement from WbLS and LAPPD considered)

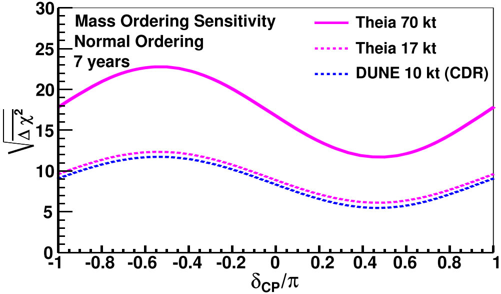
Analysis

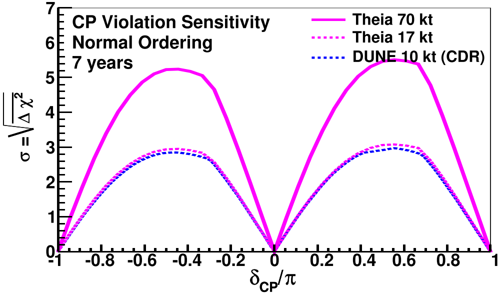
ν_e appearance

9 samples of $\nu_e/\bar{\nu}_e$ with different ev. topologies



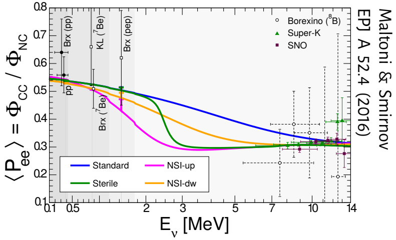




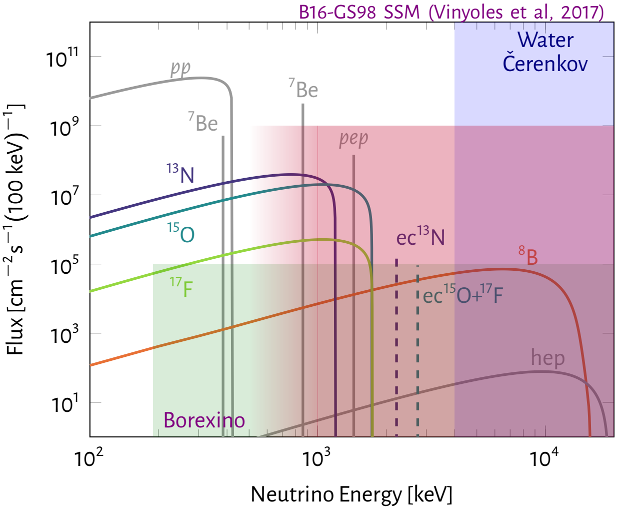


Solar neutrinos in THEIA

- Oscillation probability “upturn”
  Search for new physics with low-energy ^{8}B ν



- Precision measurement of CNO neutrinos
  Important information on solar core composition



Sensitivity to CNO neutrinos

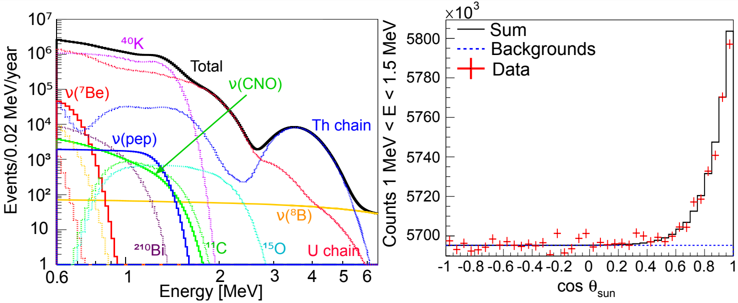
THEIA Coll., Eur.Phys.J.C 80 (2020) 5
Bonventre & Orebi Gann, Eur.Phys.J.C 78 (2018) 6

Large bkg compared to Borexino

Energy spectrum + Reconstructed direction

Effective separation of ν signal

Sensitivity driven by angular resolution, energy threshold and exposure



Sensitivity to CNO neutrinos

THEIA Coll., Eur.Phys.J.C 80 (2020) 5
Bonventre & Orebi Gann, Eur.Phys.J.C 78 (2018) 6

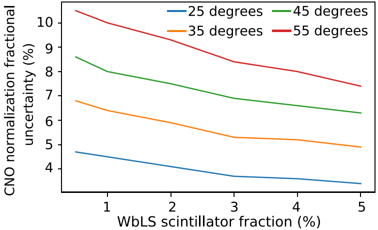
Large bkg compared to Borexino

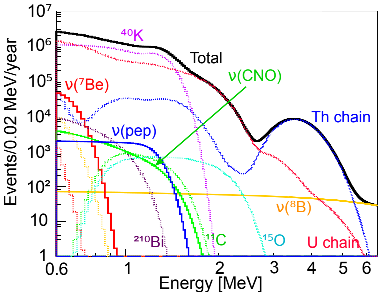
Energy spectrum + Reconstructed direction

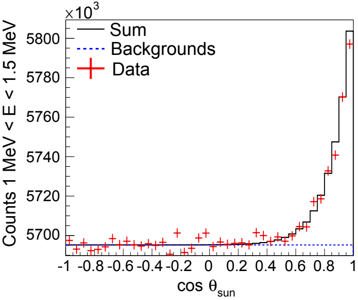
Effective separation of ν signal

Sensitivity driven by angular resolution, energy threshold and exposure

Assuming THEIA-100, 5 yr







Sensitivity to CNO neutrinos

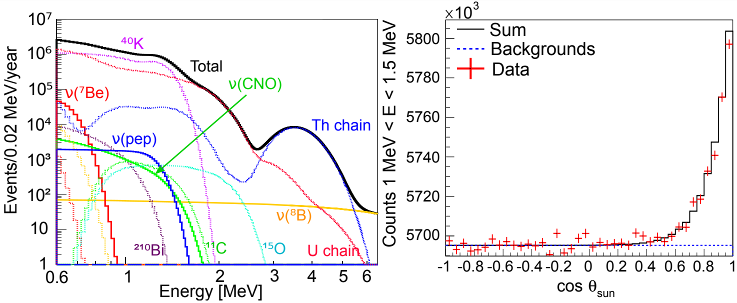
THEIA Coll., Eur.Phys.J.C 80 (2020) 5
Bonventre & Orebi Gann, Eur.Phys.J.C 78 (2018) 6

Large bkg compared to Borexino

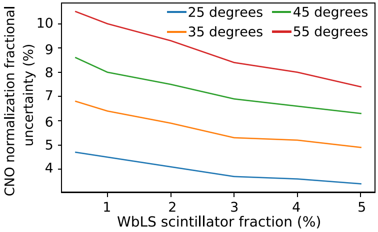
Energy spectrum + Reconstructed direction

Effective separation of ν signal

Sensitivity driven by angular resolution, energy threshold and exposure



Assuming THEIA-100, 5 yr



- High photocoverage crucial to have low-energy threshold and good angular resolution
- Preliminary full ev. reco. shows that these performances can be reached [B.J. Land et al, arXiv:2007.14999]
- A measurement of Φ(CNO) w/ 10% accuracy can be used to infer (C+N) abundance in the Sun core with ≈ photosphere accuracy
  [Serenelli, Peña-Garay & Haxton, Phys.Rev.D 87 (2013) 4, Borexino, Eur.Phys.J.C 80 (2020) 11

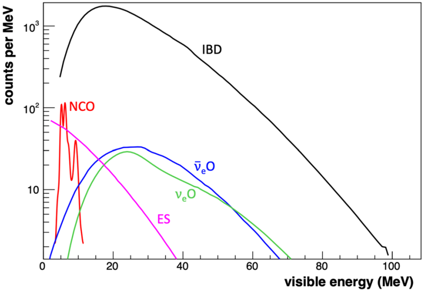
Supernova neutrino burst in THEIA

THEIA Coll., Eur.Phys.J.C 80 (2020) 5

Multiple detection channels → Flavor-resolved spectroscopy

Expectations assuming a SN at 10 kpc
100 kt detector with 10% LS fraction (7% energy resolution)

- Dominant contribution from IBD [exp. 19800 evts.]
  $\bar{\nu}_e + p \to n + e^+ \to$ delayed n capture
- Total flux from NC int. on ^{16}O: [exp. 1100 evts.]
  $\nu + {}^{16}O \to \nu + {}^{16}O^*$
- Good pointing with clean ES on electrons [exp. 960 evts.]
  IBD removed thanks to delayed coincidence e^+-n capture
  $\nu + e^- \to \nu + e^-$
- $\bar{\nu}_e$ & ν_e CC int. on ^{16}O:
  $\bar{\nu}_e + {}^{16}O \to e^+ + {}^{16}N$ (→ delayed tags) [exp. 440 evts.]
  $\nu_e + {}^{16}O \to e^- + {}^{16}F$ (→ delayed tags) [exp. 340 evts.]



Complementary to other experiments

- **@ SURF** Large sample of $\bar{\nu}_e$ completes ν_e collected by DUNE
- Same IBD signal as Juno/SK/HK, but on the other side of the globe

Diffuse Supernova Neutrino Background

THEIA Coll., Eur.Phys.J.C 80 (2020) 5
Sawatzki, Wurm & Kresse, Phys.Rev.D 103 (2021) 2

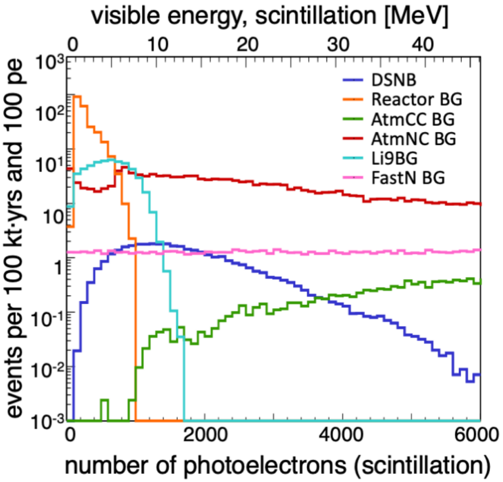
Diffuse, isotropic flux of ν from all SN explosion in the Universe.

- z-dependent core-collapse SN rate
- relative fraction of BH/n-star formation

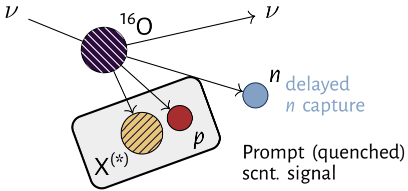
Main int. channel: **IBD** [exp. rate ≈ 1 ev/yr/kton]

Main backgrounds & suppression strategies

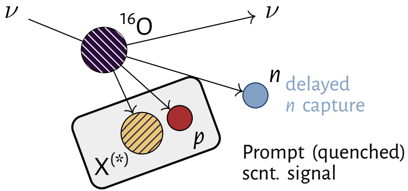
- **Reactor** Irreducible
- **Cosmogenic ^{9}Li** Cosmic muon veto
- **Fast neutron** FV cut, Cher/Scnt ratio
- **Atmospheric νCC bkg** Irreducible
- **Atmospheric νNC bkg**



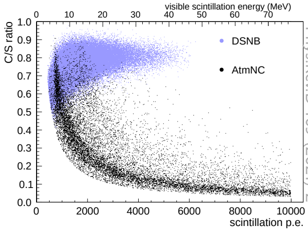
Atmospheric ν NC background



Atmospheric ν NC background

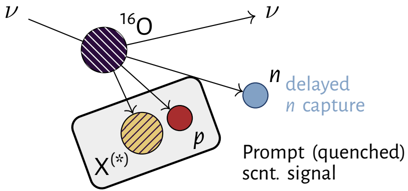


- Cherenkov/Scintillation fraction
  Nuclear fragments typically below Cher thrs.



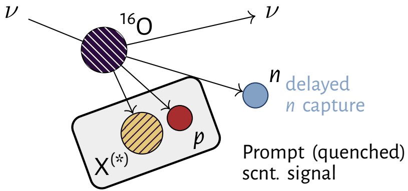
Sawatzki, Wurm & Kresse
Phys.Rev.D 103 (2021) 2

Atmospheric νNC background



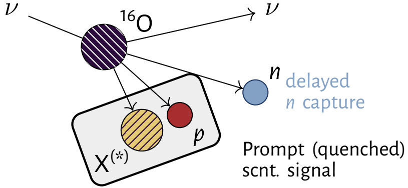
- **Cherenkov/Scintillation fraction**
  Nuclear fragments typically below Cher thrs.
- **Delayed coincidences**
  Exploits ^{15}O (β^+, $t_{1/2} \approx$ 2 min), produced in 50% of atm νNC interactions on ^{16}O

Atmospheric ν NC background

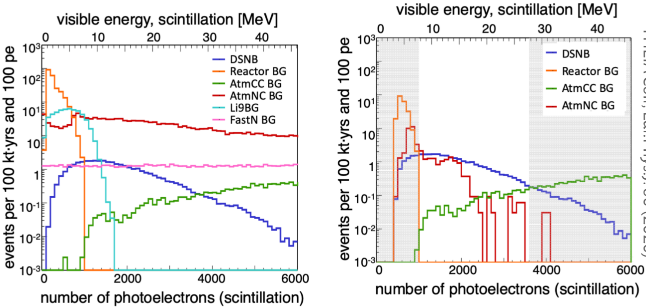


- **Cherenkov/Scintillation fraction**
  Nuclear fragments typically below Cher thrs.
- **Delayed coincidences**
  Exploits ^{15}O (β^+, $t_{1/2} \approx$ 2 min), produced in 50% of atm ν NC interactions on ^{16}O
- **Multi-ring rejection**
  Multiple particles in final states vs single ring for IBD

Atmospheric ν NC background



- Cherenkov/Scintillation fraction
  Nuclear fragments typically below Cher thrs.
- Delayed coincidences
  Exploits ^{15}O (β^+, $t_{1/2} \approx$ 2 min), produced in 50% of atm ν NC interactions on ^{16}O
- Multi-ring rejection
  Multiple particles in final states vs single ring for IBD



THEIA Coll, Eur.Phys.J. 80 (2020)

Expected Sensitivity

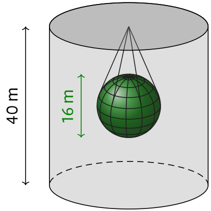
- THEIA-25 5σ evidence in $\approx$ 8 yr
- THEIA-100 5σ evidence in $\approx$ 2 yr
- Significant statistics: first steps towards DSNB spectral analysis, together with SK-Gd and JUNO data

Neutrinoless $\beta\beta$ decay search

THEIA Coll., Eur.Phys.J.C 80 (2020) 5

Detector Configuration

- 50 kton detector
- 90% photocoverage
- Vessel filled with Ultra-pure LAB+PPO ($\sigma_E \simeq 3\%/\sqrt{E}$)
- Loading
  - 5% Te loading (34.1% ^{130}Te)
  - 3% Xe loading (89.5% enriched ^{136}Xe)
    Impractical for current ^{136}Xe production rate

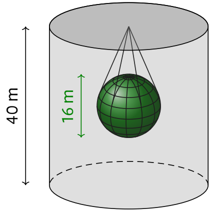


Neutrinoless $\beta\beta$ decay search

THEIA Coll., Eur.Phys.J.C 80 (2020) 5

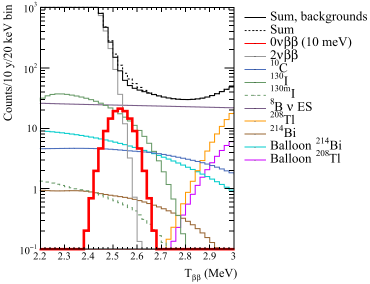
Detector Configuration

- 50 kton detector
- 90% photocoverage
- Vessel filled with Ultra-pure LAB+PPO
  ($\sigma_E \simeq 3\%/\sqrt{E}$)
- Loading
  - 5% Te loading (34.1% ^{130}Te)
  - 3% Xe loading (89.5% enriched ^{136}Xe)
    Impractical for current ^{136}Xe production rate



Background levels

- Double β decay
- Cosmogenics
  92.5% removal of ^{10}C
  with Threefold-coincidence
- Internal contamination
  Target 10^{-17} g/g for U & Th
  + 99.9% removal of ^{214}Bi
- External sources
- Solar neutrinos



^{8}B solar neutrinos are the **dominant background**

↪ **50% reduction** reduction required to cover the IO region

Directional reconstruction in LS [Land et al, arXiv:2007.14999]

Expected sensitivity

Counting in $(-1/2\sigma, 2\sigma)$ around Q-value

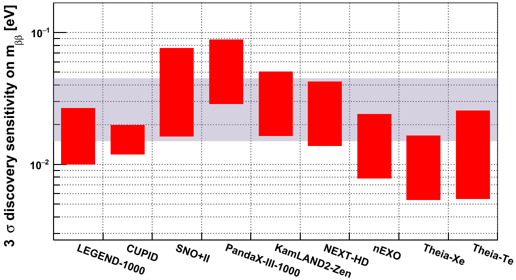
$$\hat{T}^{0\nu\beta\beta}_{1/2}(\alpha) = \frac{N_{\text{target}} \cdot \varepsilon \cdot t \cdot \ln 2}{\text{FC}(n = \text{exp. bkg}; \alpha)}$$

Target mass = 31.4 ton (^{130}Te), 49.5 ton (^{136}Xe)

Livetime $t = 10$ yr

Efficiency $\varepsilon = 66.9\%$

- ^{136}Xe $T^{0\nu\beta\beta}_{1/2} > 2.0 \times 10^{28}$ y, $m_{\beta\beta} < 5.6$ meV
- ^{130}Te $T^{0\nu\beta\beta}_{1/2} > 1.1 \times 10^{28}$ y, $m_{\beta\beta} < 6.3$ meV



Conclusions

- Progress in LS and photodetector technology has opened the way for a **new generation of hybrid optical neutrino experiment**
- **THEIA** plans to combine the advantages of **Water Čerenkov Detectors** and **Liquid Scintillator Experiments** employing **fast photosensors** and novel LS compounds
  - Low Energy threshold
  - Good Energy resolution
  - Directionality
  - Exposure
- **Versatile detector with huge potential for ν physics!**
  - High Energy Program: Neutrino oscillation (complementary to DUNE)
  - Low Energy Program: Solar-ν, SN-ν, DSNB, $0\nu\beta\beta$ search
  - And much more! Nucleon decay, Reactor ν, Geo-ν...