0νββ and Other Neutrinos

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STFC Ernest Rutherford Fellow @ UCL

PPAP Community Meeting, Nov 20, 2020

Thanks to: H. Araujo, S. Biller, A. Boston, J. Evans, M. Malek,
C. McCabe, C. Patrick, R. Saakyan and A. Vacheret

Neutrino Masses

- First and only **lab observation** of BSM physics
- $\nu = \overline{\nu}$
  - **Majorana** masses, **naturally** small
  - lepton number is not conserved
  - matter/antimatter asymmetry
- right-handed neutrinos
  - **Dirac** mass, fine tuning
  - sterile neutrinos
- neutrino absolute mass value

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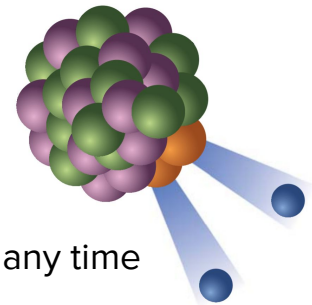
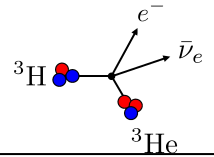
Search for Neutrinoless Double-β Decay (0νββ)

- **matter-generating** nuclear decay
- (A, Z) → (A, Z + 2) + 2e
- ΔL = 2
- $T_{1/2} \sim (m_{\beta\beta})^{-2}$
- **discovery** could come at any time



Search for Short-baseline Neutrino Oscillations

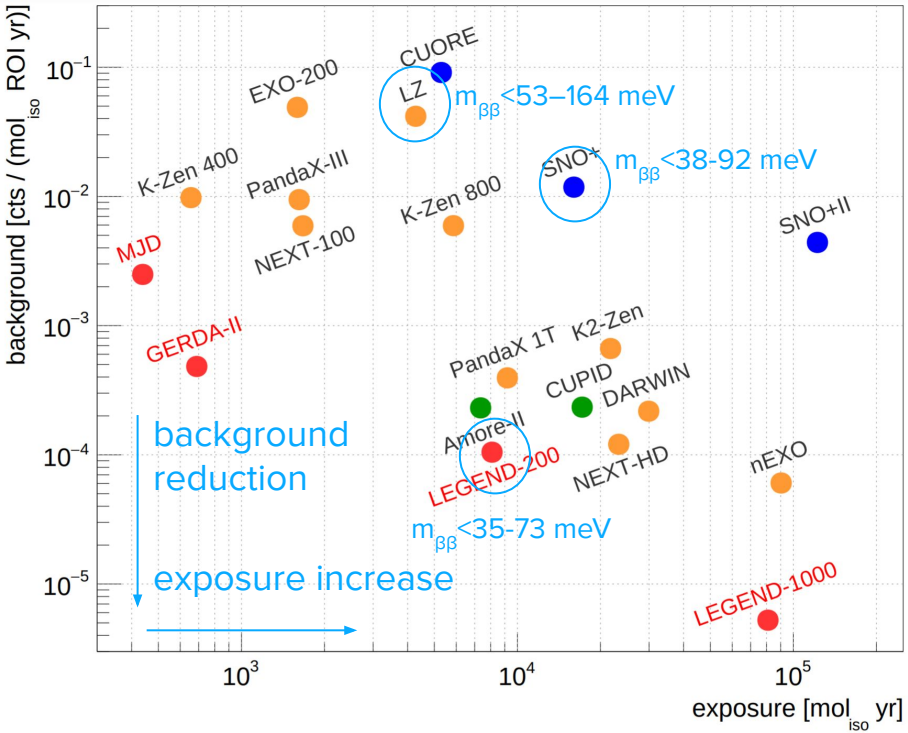
Precision Measurements of Tritium β Decay



UK 0νββ Decay Experiments

Iso	EXPERIMENT	STATUS	TECHNOLOGY
^{76}Ge	LEGEND	in construction (L200)	semiconductor detectors
^{82}Se	SuperNEMO	commissioning	Trackers & Calorimeters
^{100}Mo	NEMO-3	completed	
^{130}Te	SNO+	in construction (Phase I)	Loaded Scintillator
	Watchman	R&D	Loaded Scintillator
^{136}Xe	LZ	commissioning	Time Projection Chamber

Experimental Strategies:
Mass Scalability vs. Background Level
Calorimetry vs. Tracking

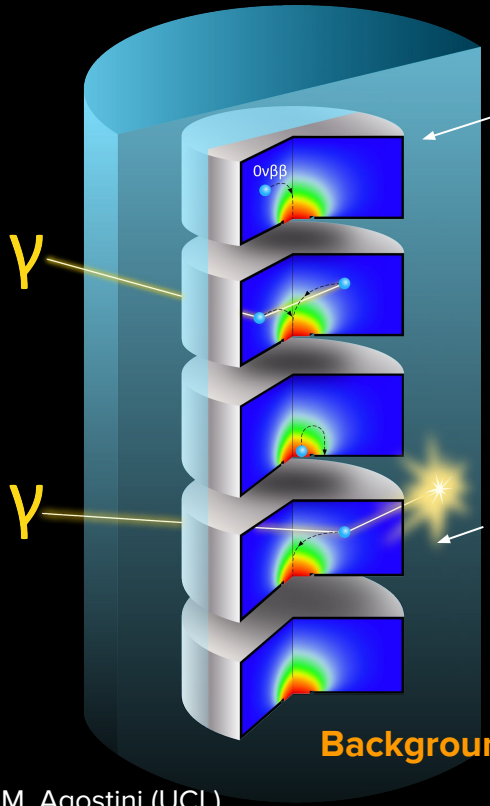


Different background/exposure combinations can lead to similar $m_{\beta\beta}$ sensitivities

LEGEND

240 collaborators
48 institutions
worldwide

Lancaster University
UNIVERSITY OF LIVERPOOL
UCL
THE UNIVERSITY OF WARWICK



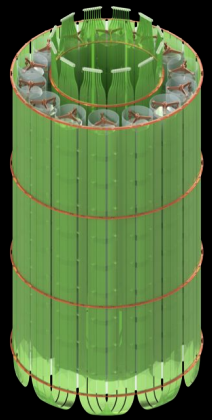
Ge semiconductor detectors
- high efficiency
- <0.1% energy resolution
- event topology

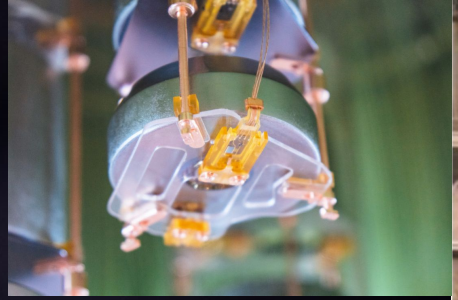
liquid Ar bath
- active shield
- scintillation light

Background-free Discovery Machine

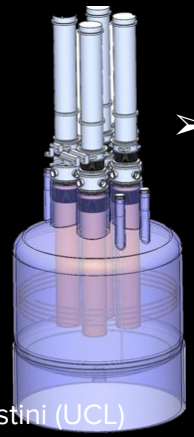
LEGEND in the UK:
- Ge detector R&D
- analysis & sim
- radio-purity assay
- new scintillating materials
- First PhD students!

LEGEND

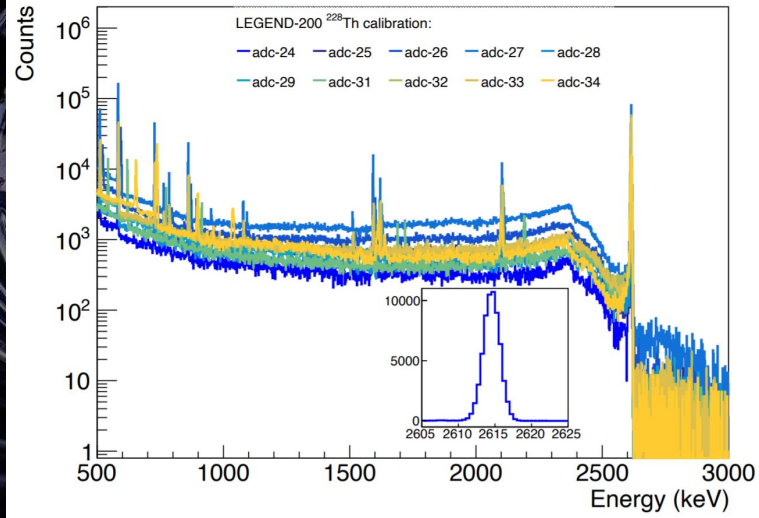




- Ge **background-free** experiment proven by GERDA & MAJORANA
- LEGEND-200 ($T_{1/2} > 10^{27}$ y / $m_{\beta\beta} < 35\text{-}73$ meV)
  - 200 kg of detector mass at LNGS
  - ongoing upgrade of GERDA infrastructure
  - physics data taking in **2021**
- LEGEND-1000 ($T_{1/2} > 10^{28}$ y / $m_{\beta\beta} < 10\text{-}20$ meV)
  - 1 ton of detector mass
  - Conceptual Design Report under preparation for US down-selection



LEGEND-200 integration tests
20 detectors / 4 strings



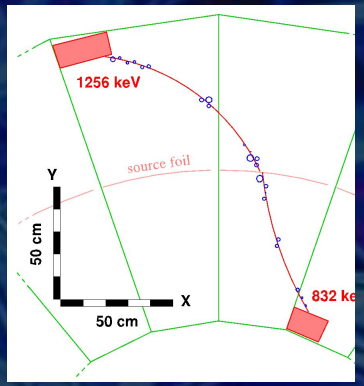
supernemo collaboration

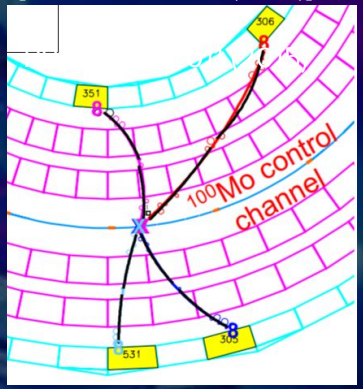
NEMO-3

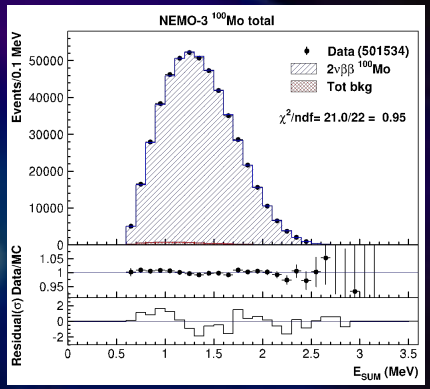
$T_{1/2} > 10^{24}$ y with just 7 kg of ^{100}Mo [PRD 92, 072011 (2015)]

access unique signatures, e.g. 0ν4β [PRL 119, 041801 (2017)]

probes of 0νββ mechanism SSD/HSD [EPJ C79, 440 (2019)]



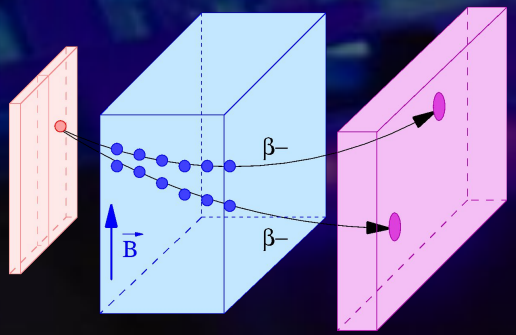


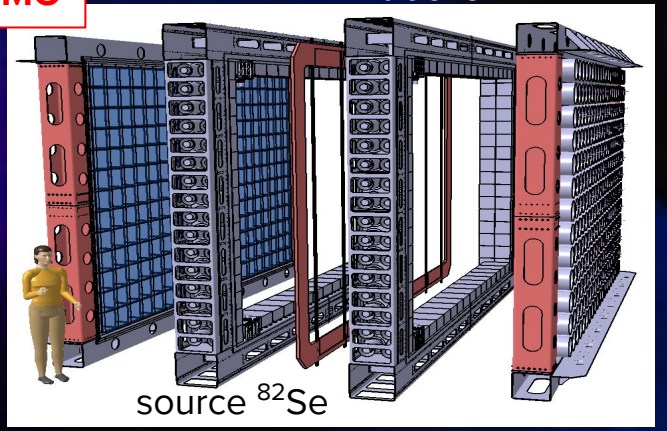


UCL
Imperial
Manchester
Warwick

- Source separated from detector: (almost) any solid isotope can be hosted.
- Full topological event reconstruction including $e^{\pm}$, γ-ray and α-particle identification ➜ strong background control & mechanism probe.
- Successfully exploited by **NEMO-3** experiment: 0νββ limits and 2νββ $T_{1/2}$ for several isotopes.

SuperNEMO

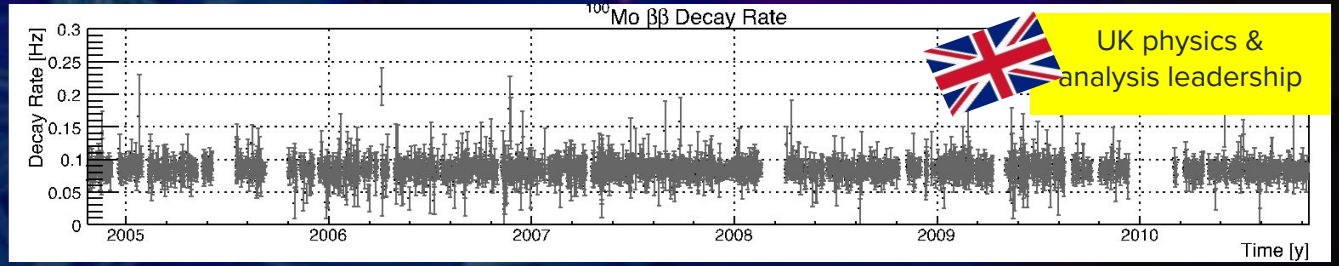




supernemo collaboration

NEMO-3: many analyses still making use of its unique approach

- Search for 2νββ of ^{82}Se to **excited states** of ^{82}Kr (2eNγ final state) which can have exceptionally low background [NPA 996, 121701 (2020)]
- First search for **periodic modulations** in 2νββ decay rate [on arXiv yesterday]



UK physics & analysis leadership

Demonstrator Module (2.5 year run)

17.5 kg × yr initial exposure :

$T^{0\nu}_{1/2} > 6.5 \times 10^{24}$ yr

$\langle m_\nu \rangle < 0.20 - 0.40$ eV

SuperNEMO Demonstrator Module:

final commissioning in progress

- Covid has delayed the turn-on but strong recent progress
- The **Demonstrator Module** will have a unique physics programme: full event reconstruction of 2νββ **gives access** to nuclear physics : e.g. g_A constraints.
- Can the technique be extended to **confirm a signal anywhere in the IH region? R&D and isotope developments** can point the way.

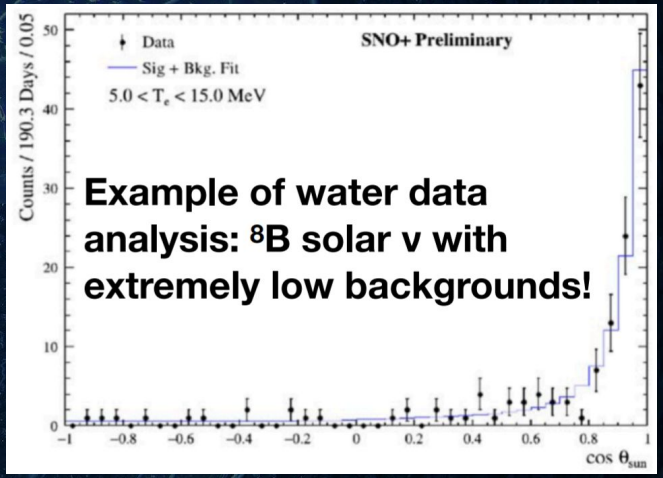
A Highly Scalable, Cost-Effective and Sensitive Approach to 0νββ

(concept developed in UK)

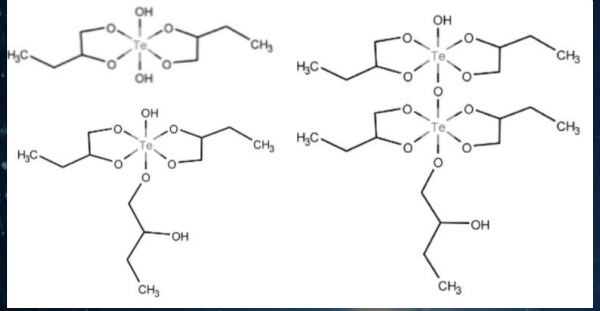
KCL
Lancaster
Liverpool
Oxford
Sussex

Other Physics Includes

- **Solar neutrinos**
- **'Invisible' nucleon decay**
- **Reactor neutrinos**
- **Geo-neutrinos**
- **Supernova neutrinos**



Diol Loading of ^{130}Te in Liquid Scintillator (also developed in UK)



Some recent results from water phase analysis:

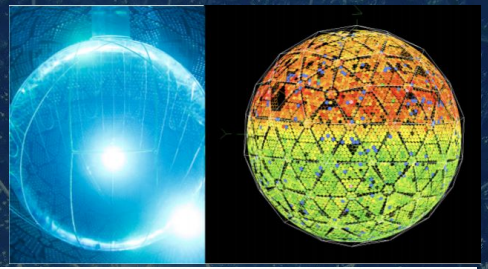
Measurement of neutron-proton capture in the SNO+ water phase, Phys. Rev. C 102 (2020)

Search for invisible modes of nucleon decay in water with the SNO+ detector, Phys. Rev. D 99 (2019)

Measurement of the ^{8}B solar neutrino flux in SNO+ with very low backgrounds, Phys. Rev. D 99 (2019)

One of the very few practical approaches potentially capable of achieving sensitivity to the non-degenerate normal mass hierarchy

SNO+



Transition to scintillator paused halfway due to COVID-19

Now filling again!
(will complete by Spring)

Aim to load Te in 2021
(COVID-dependent etc.)

Tellurium purification and loading systems completed: undergoing commissioning

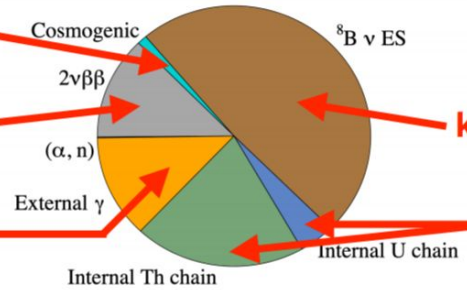
Sensitivity assuming 0.5% Te loading
$T_{1/2} > 2\times10^{26}$ y & $m_{\beta\beta} < 38\text{-}92$ meV

can be verified with multi-site analysis
(NIM 943, 162420, 2019)

known

constrained by water data: target achieved

RoI Targets (9.5 cts/yr)



known

scint data: target achieved, awaiting Te data

Measured unloaded LS light levels at or above expectation

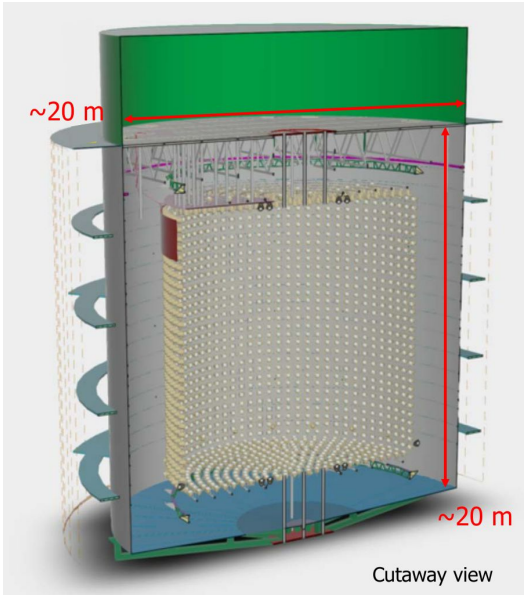
AIT / WATCHMAN

Edinburgh
Glasgow
Liverpool
Sheffield
Warwick

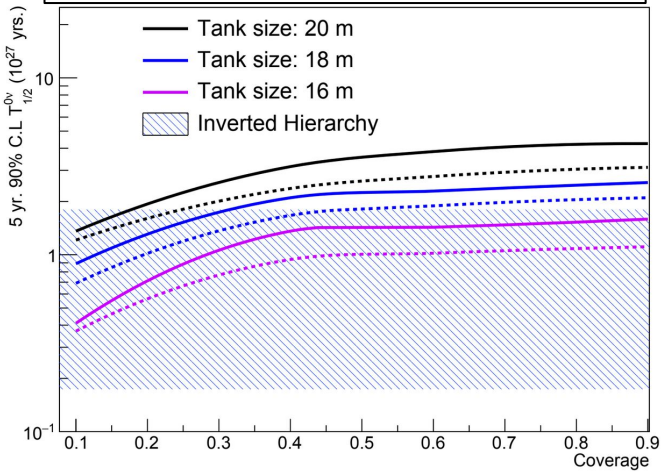
The Advanced Instrumentation Facility (AIT) is a proposed new facility at the STFC Boulby Underground Laboratory.

The nominal detector features:

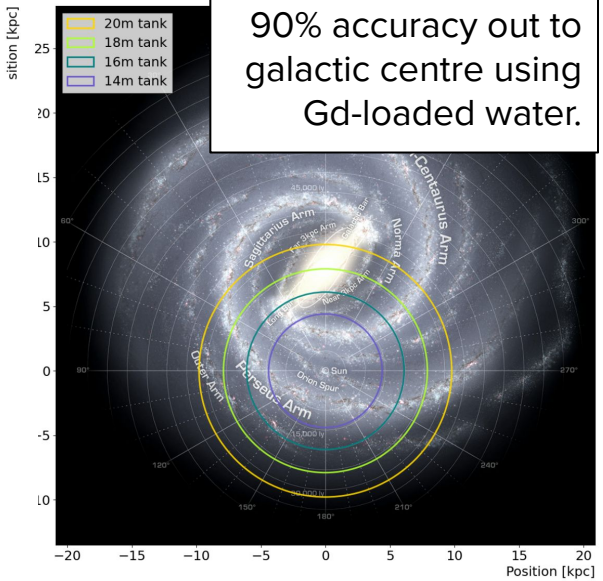
- 6000 tonne
- Initial fill material either Gd-loaded water or water-based liquid scintillator
- Future phases could pioneer new materials



^{130}Te-loaded liquid scintillator **(5%)** and 5 year exposure can cover IO



Supernova model discrimination with 90% accuracy out to galactic centre using Gd-loaded water.

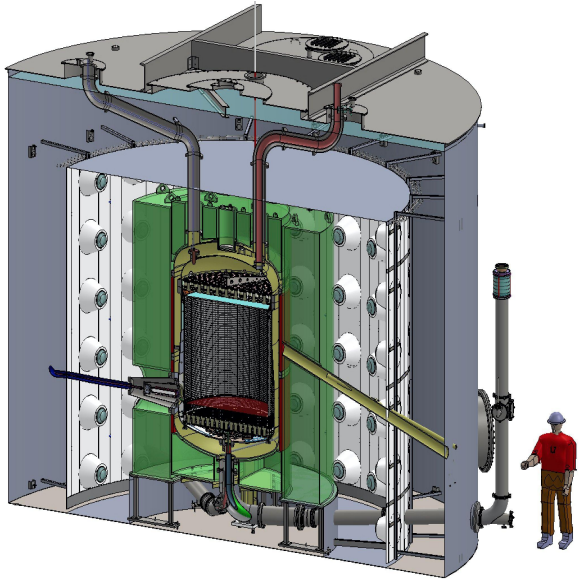


LUX-ZEPLIN (LZ)

Bristol, Edinburgh, Imperial, Liverpool, Oxford, Rutherford Appleton Laboratory, Royal Holloway, UCL, Sheffield

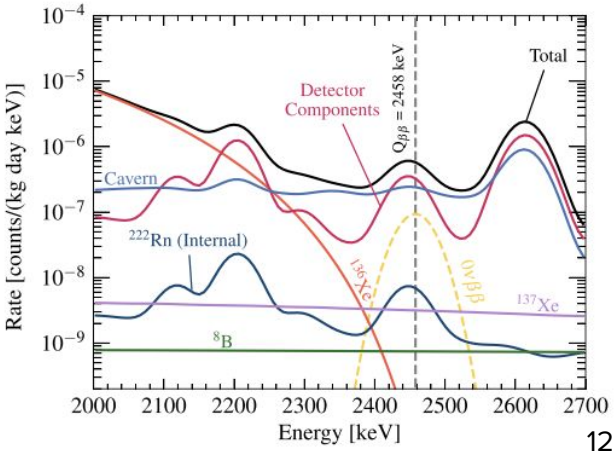
LZ detector:

- 7-T natural Xe-TPC (494 PMTs)
- optimized for DM, not 0νββ decay
- LZ goal: demonstrate potential of this scalable technology at G2 and exploit it fully at G3 scale



- ~1% energy resolution at ^{136}Xe Q-value
- background dominated by gamma-rays and ^{222}Rn
- sensitivity up to $T_{1/2}>10^{26}$ yr

  $m_{\beta\beta}<53–164$ meV



LZ Technical Design Report [1703.09144]
LZ Dark Matter Sensitivity [1802.06039]
LZ 0VBB Decay Sensitivity [1912.04248]

2012 — 2015 (CD1) — 2020 (CD4) — …

DESIGN → CONSTRUCTION → EXPLOITATION

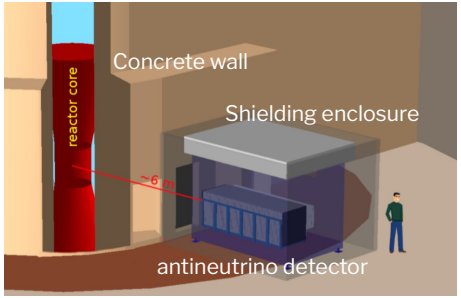
SoLid

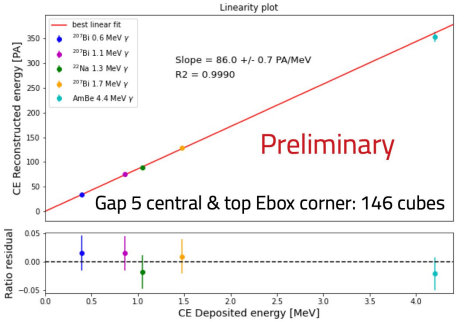
[arXiv:2002.05914]

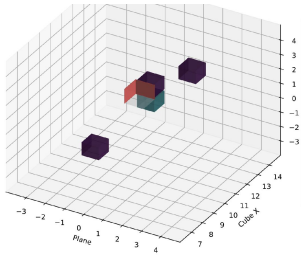
Solid-experiment.org

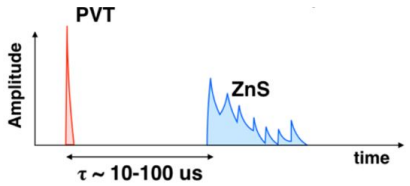
Imperial
Oxford
Bristol
RAL

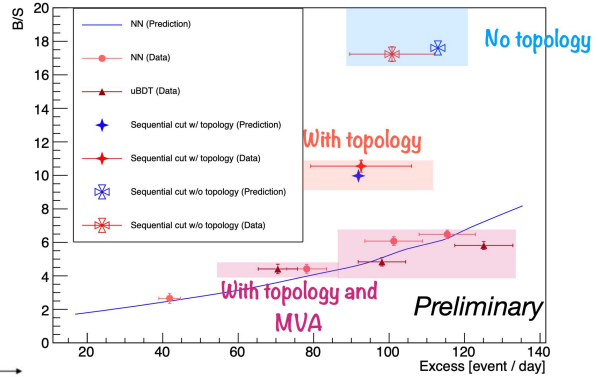
- SoLid has unique features to search for oscillation and measure BR2 pure U-235 antineutrino spectrum
  - Novel detector design - plastic Scint. based with **linear energy response (2% level)**
  - High segmentation to reconstruct **IBD 3D image**
- SoLid experiment **Phase-I completed** (2018-2020)
- **Phase-II** (Now-end of 2021) : Detector “eyes” upgraded successfully in October 2020 with 4th-gen MPPCs (40% increased in light yield confirmed)
- Mature IBD selection using full **topological information & ML techniques** currently achieve S:B 1:5 on track to reach 1:3-1:2 (BiPo 1D-CNN and multi-class BDTs)
- **Sterile search result with Phase-I data in preparation**
- Developing antineutrino direction measurement











Quantum Technologies for Neutrino Mass Consortium

UCL · NPL National Physical Laboratory · Prifysgol Abertawe Swansea University · The University of Warwick · University of Cambridge

A collaboration of particle, atomic and solid state physicists, electronics engineers and quantum sensor experts

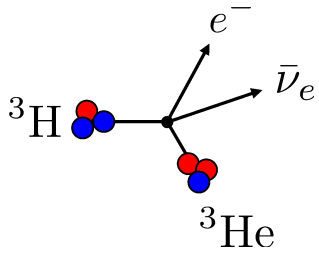
3-yr proposal goal:

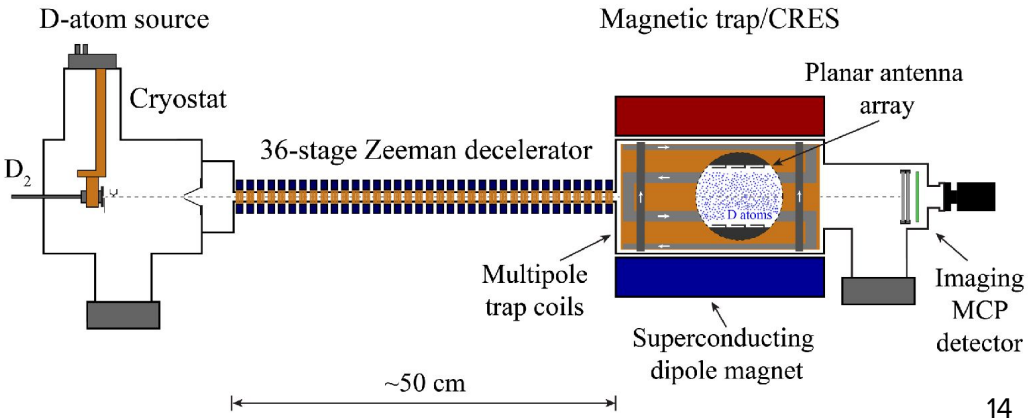
Technology demonstration for neutrino mass determination from ^{3}H β-decay

- Trapping ~10^{20} D/T atoms
- B-field mapping with ≲0.1 ppm precision
- Quantum limited microwave electronics

Ultimate goal:

Neutrino mass measurement at a Tritium facility (e.g. *Culham Centre for Fusion Energy*) with *O*(10 meV) sensitivity





Conclusions

- Neutrino masses offer a unique window to new BSM physics
- **0νββ decay**
  - unique test for **Majorana** neutrinos
  - **discovery** could come at any time
  - LEGEND-200, SuperNEMO, SNO+ Phase I, LZ soon **online**!
  - promising ideas for the **future** (L-1000, SNO+ Phase II, WATCHMAN)
- **Short Baseline Oscillations & β-decay**
  - SOLID: **physics results** from Phase I in preparation, Phase II **ongoing**
  - **quantum tech** could be a **break-through** to measure the absolute mass scale