Exploring neutrinoless double beta decay with the DARWIN observatory

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on behalf of the DARWIN collaboration

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Experimental overview

Which nuclei can decay via $0\nu\beta\beta$?

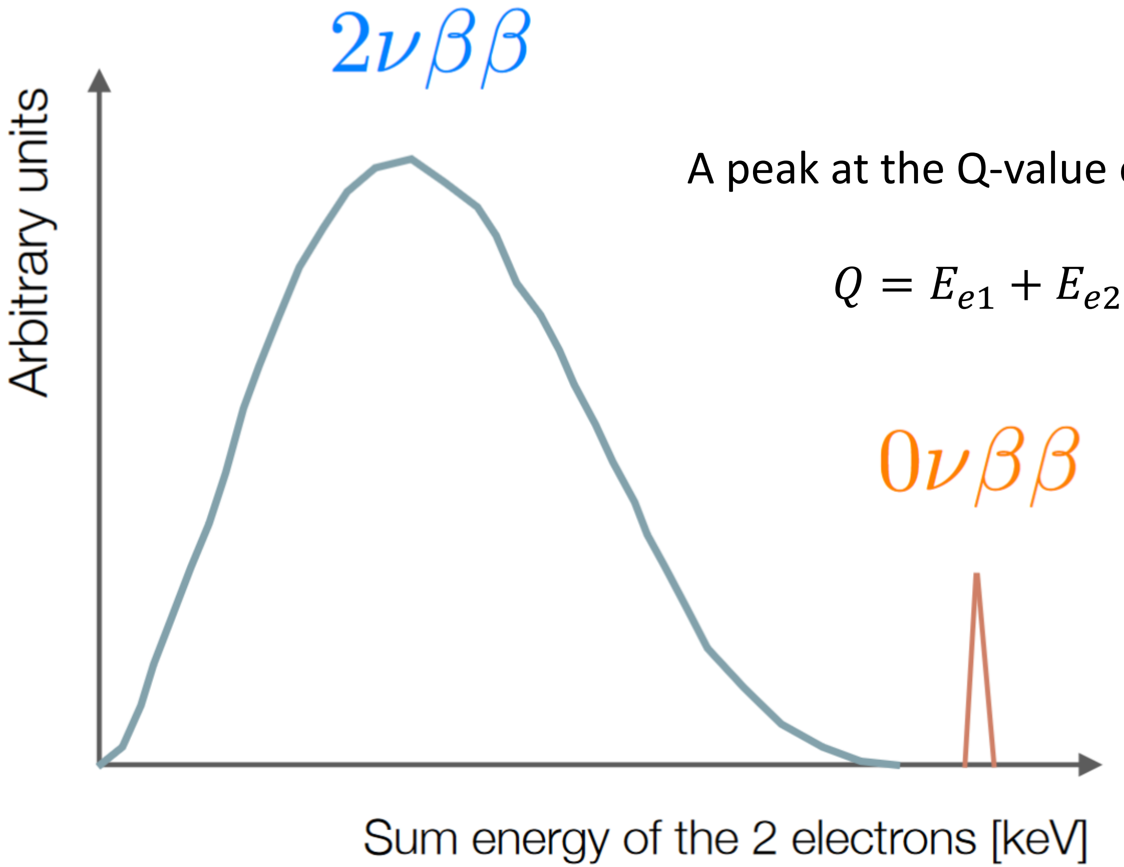
- Number of events around the Q-value region:

$$N \propto \frac{N_A}{W} \cdot \frac{a \cdot \epsilon \cdot M \cdot t}{T_{1/2}}$$

- N_A: Avogadro number
- W: molar mass
- a: isotopic abundance
- ϵ: detection efficiency
- M: total active mass
- t: measuring time
- $T_{1/2}$: half-life of the isotope

Candidate	Q [MeV]	Abund [%]
^{48}Ca -> ^{48}Ti	4.271	0.187
^{76}Ge -> ^{76}Se	2.039	7.8
^{82}Se -> ^{82}Kr	2.995	9.2
^{96}Zr -> ^{96}Mo	3.350	2.8
^{100}Mo -> ^{100}Ru	3.034	9.6
^{110}Pd -> ^{110}Cd	2.013	11.8
^{116}Cd -> ^{116}Sn	2.802	7.5
^{124}Sn -> ^{124}Te	2.228	5.64
^{130}Te -> ^{130}Xe	2.530	**34.5**
^{136}Xe -> ^{136}Ba	2.479	8.9
^{150}Nd -> ^{150}Sm	3.367	5.6

What do we expect to see?



A peak at the Q-value of the decay

$$Q = E_{e1} + E_{e2} - 2m_e$$

So far, no observation of this decay.

Best limits on $T_{1/2}^{0\nu}$

- ^{136}Xe: $3.8 \cdot 10^{26}$ yr (KamLAND-Zen)
- ^{130}Te: $2.2 \cdot 10^{25}$ yr (CUORE)
- ^{76}Ge: $1.8 \cdot 10^{26}$ yr (GERDA)

Experimental requirements

$$T_{1/2}^{0\nu} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

Energy resolution (↑ ΔE)

Background index (↑ B)

In summary, to improve sensitivity, we require:

1. Large active masses of the detectors
2. Low background
3. High isotopic abundance (or an isotope that can be enriched)
4. Good energy resolution

How do we try to detect this?

TPCs

XENON, NEXT, nEXO, DARWIN

Charge

GERDA, Majorana, LEGEND, SuperNEMO, COBRA

Light

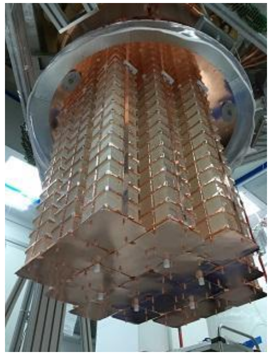
KamLAND-Zen, SNO+

Scintillation bolometers

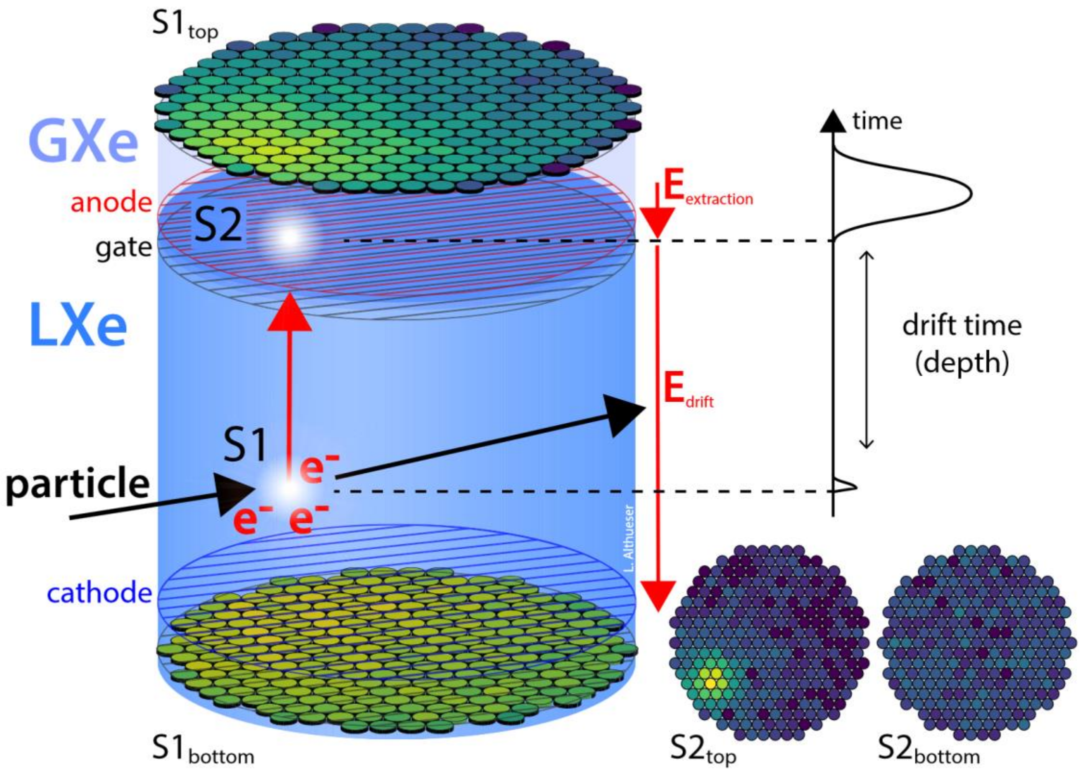
CUPID

Heat

CUORE

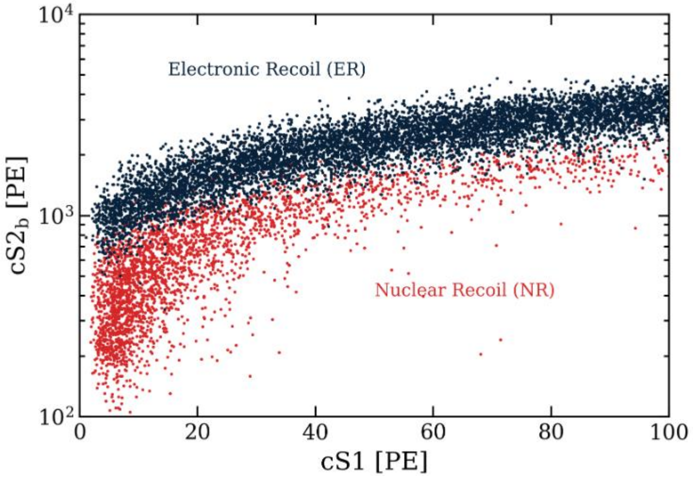


Why xenon TPCs?



(Credit: XENON collaboration)

- High light (S1) and charge (via proportional scintillation, S2) yield
- Good energy reconstruction (linear combination of S1 & S2)
- 3D position resolution:
    - Single versus multiple scatters
    - Fiducialisation
- Particle ID via S2/S1



Already operating xenon TPCs

XENON (LNGS)

World leading experiments in dark matter searches

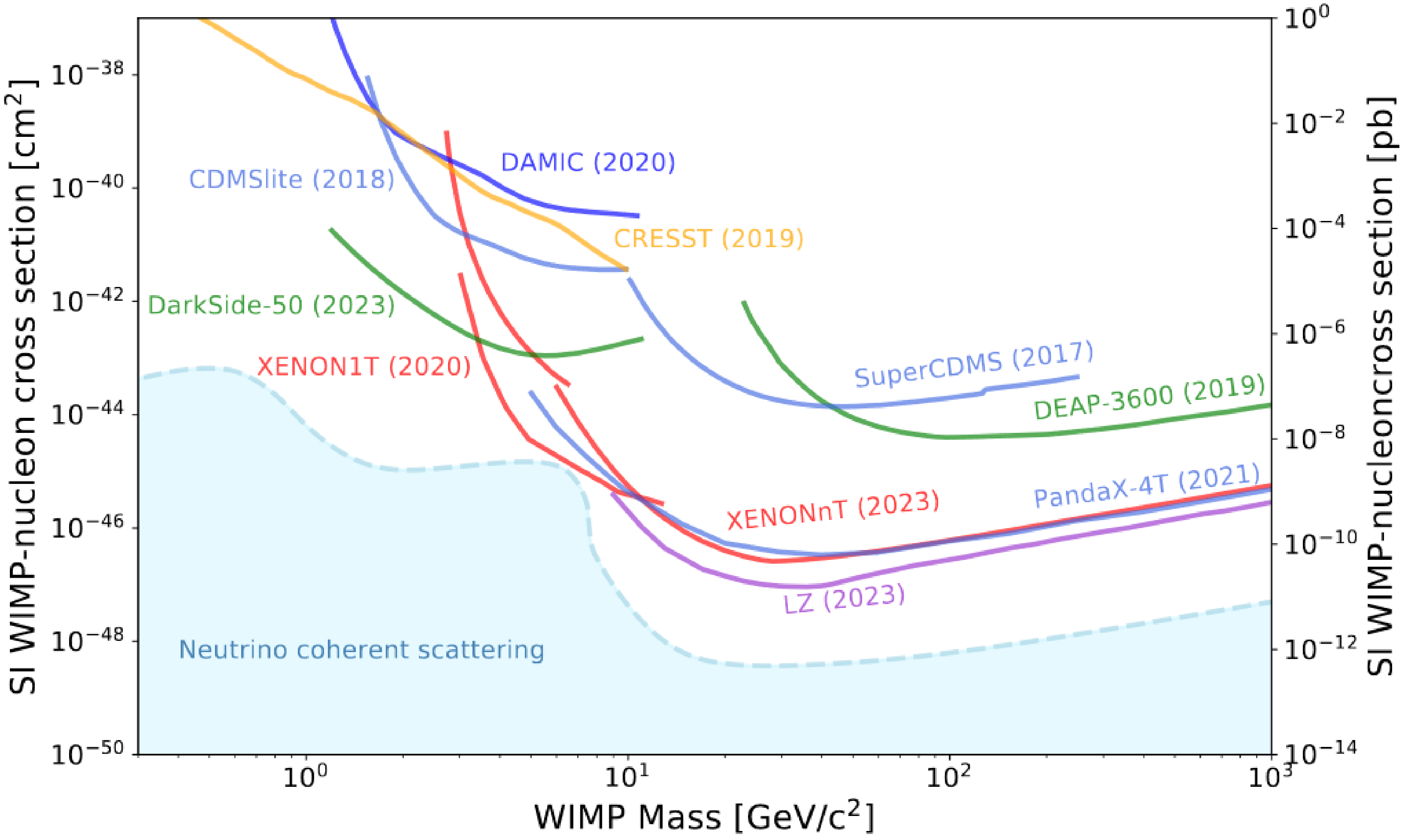
Very similar detectors:

- They operate < 10 t of xenon
- Same detection principle

PandaX (CJPL)

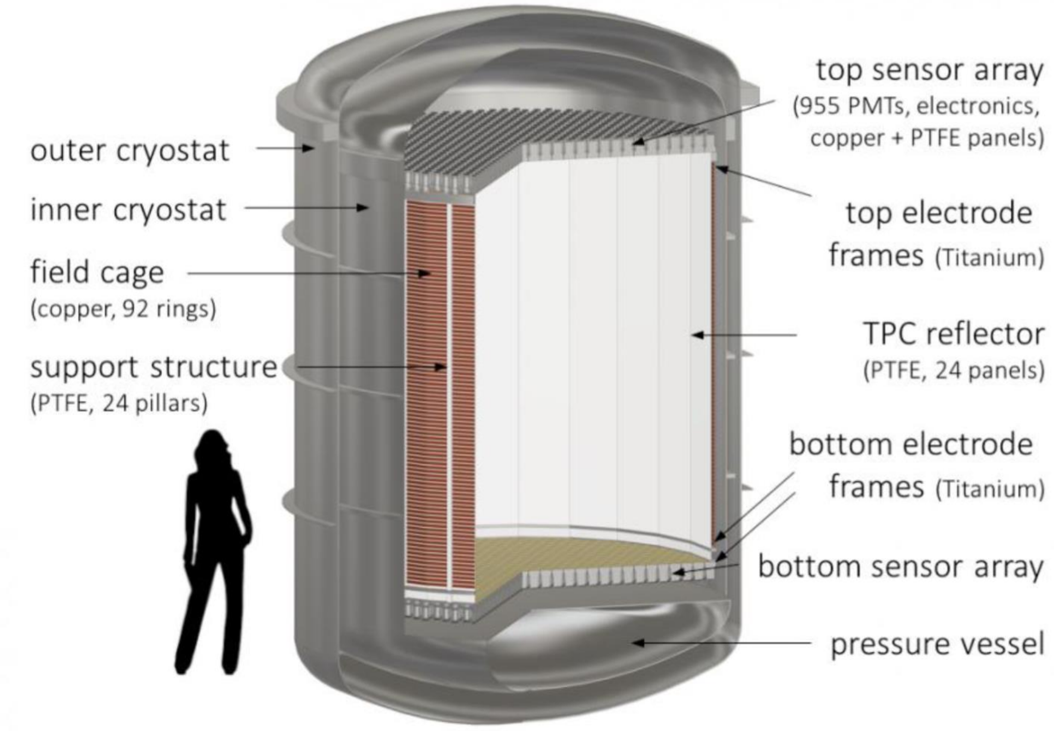
LZ (SURF)

WIMP detection sensitivity



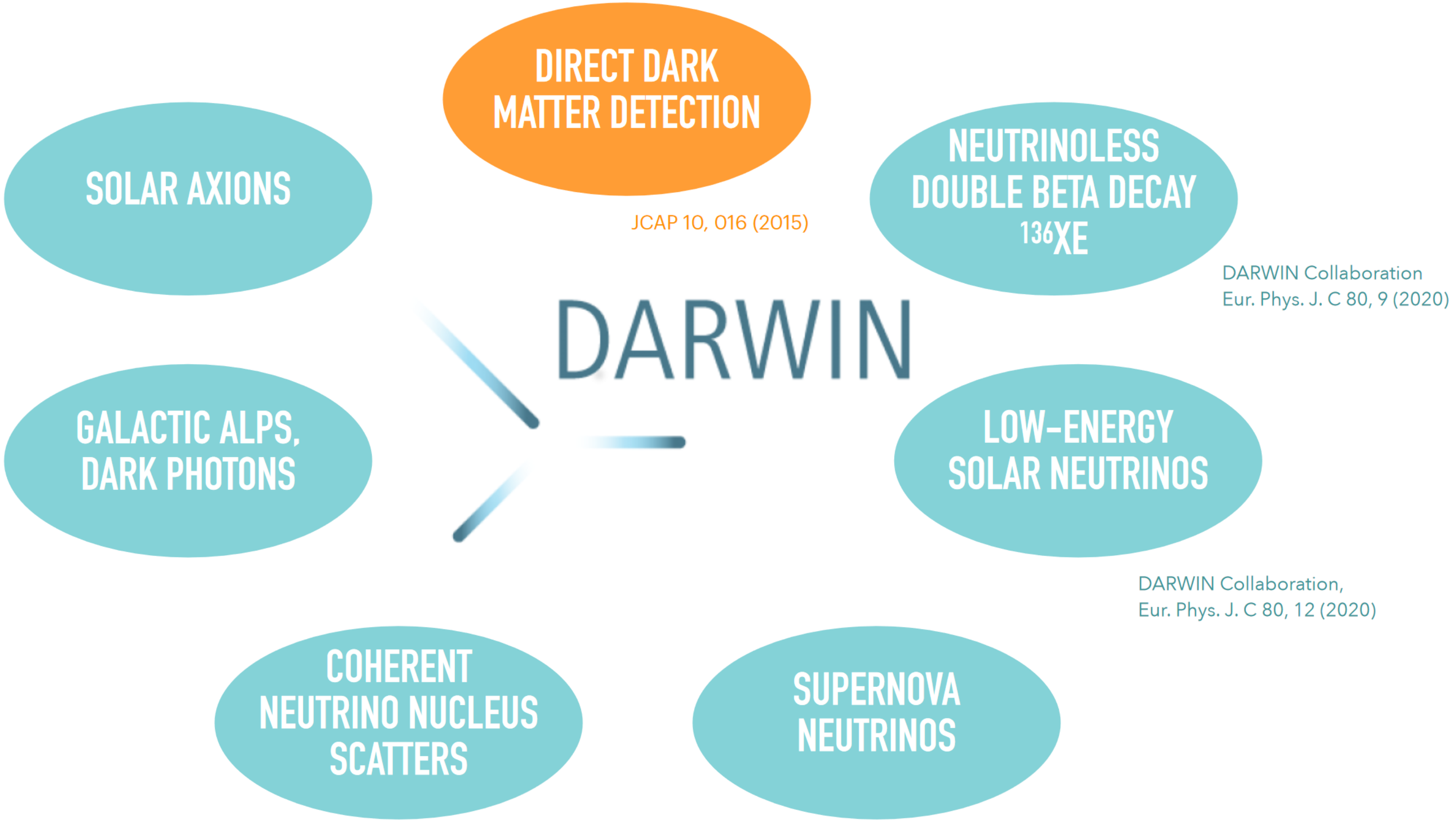
The DARWIN observatory

- Proposed next-generation xenon experiment
- It consists of a dual-phase time projection chamber (TPC) filled with 50 t of xenon
- 2.6 m in diameter and 2.6 m height
- Low background, double-walled titanium cryostat
- Two arrays of photosensors



DARWIN science goals

University of Zurich[UZH]

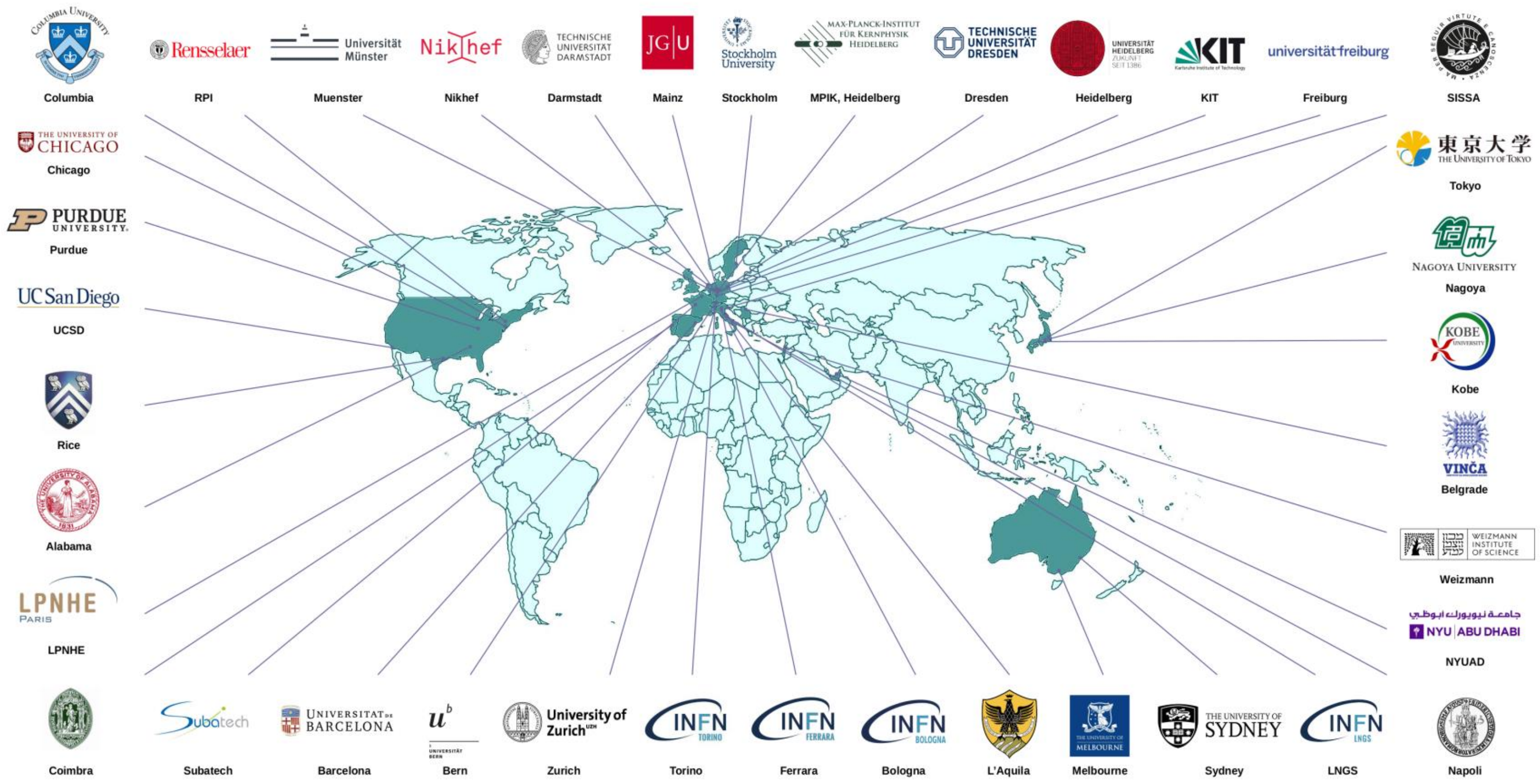


DARWIN, with its large mass, low-energy threshold and ultra-low background, will open a large variety of physics channels

➡ In particular, $0\nu\beta\beta$ of ^{136}Xe

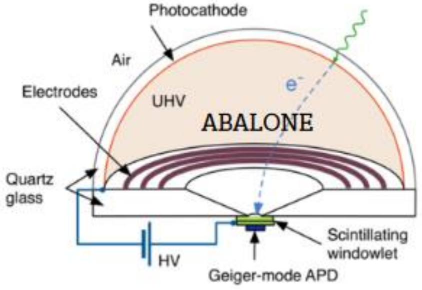
University of Zurich[UZH]

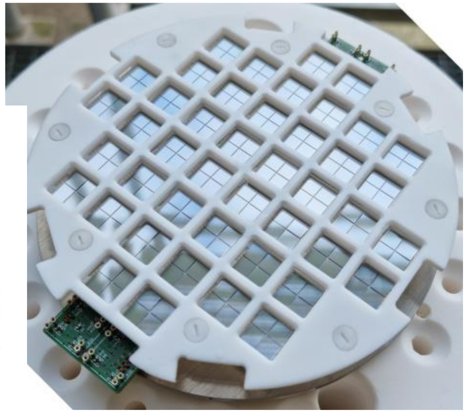
DARWIN collaboration

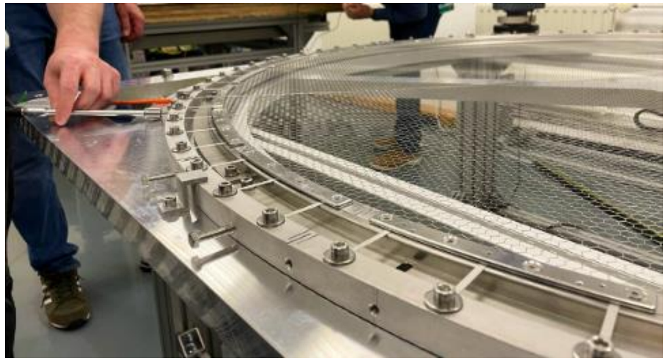


200 members from 35 institutions
in Europe, USA, Asia, Australia

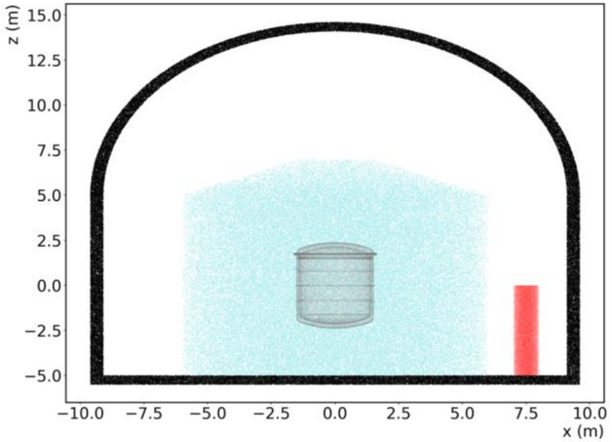
DARWIN R&D


Photocathode
Air
Electrodes
UHV
ABALONE
Quartz glass
HV
Geiger-mode APD
Scintillating windowlet






3.8 m


z (m)
x (m)

Why is DARWIN a good $0\nu\beta\beta$ detector?

- It contains a lot of natural xenon:
  - 9% is ^{136}Xe
  - Q value of ^{136}Xe $0\nu\beta\beta$ far from other backgrounds
  - It can be enriched

- It can achieve a good energy resolution:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} + b \approx 0.8\% \text{ at Q} \quad \text{(Demonstrated by XENON1T)}$$

- It can reach a low background rate

Backgrounds in DARWIN

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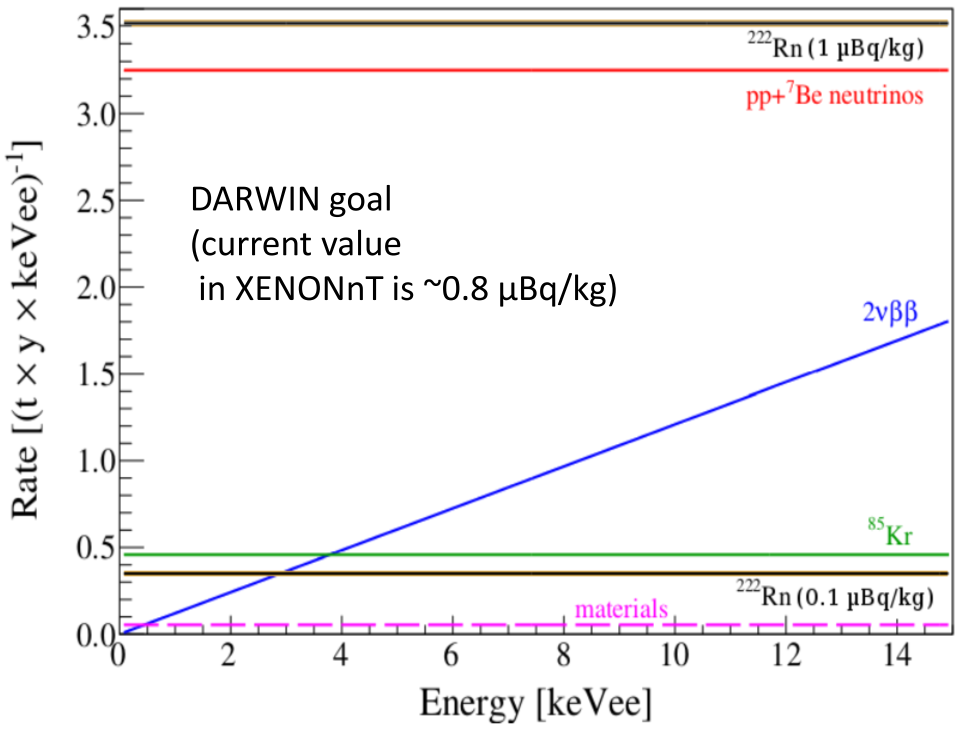
- Nuclear recoils
  - **Muon-induced neutrons** → water tank to stop neutrons from rock-concrete (6 m radius cylinder)
  - **Radiogenic neutrons** → improve material selection

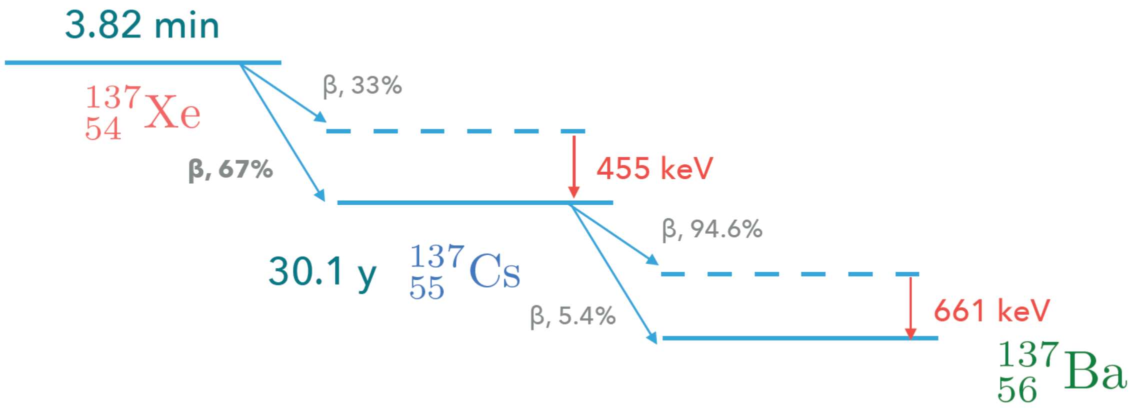
- Electronic recoils
  - **Intrinsic**: ^{222}Rn, ^{85}Kr, ^{136}Xe, ^{124}Xe
  - **Materials**: Traces of U and Th decay chains
  - **Neutrinos**: neutrino-electron scattering from solar neutrinos, ^{7}Be neutrinos

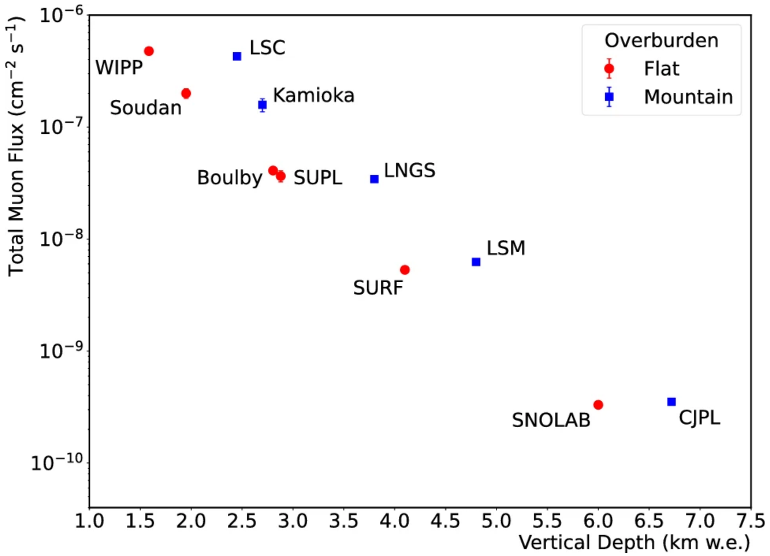
We have performed detailed Geant4 simulations to estimate the impact of specific backgrounds (materials and cosmogenic)



Cosmogenic activation: ^{137}Xe

In addition to these backgrounds, the ^{137}Xe beta decay can mimic a 0νββ signal





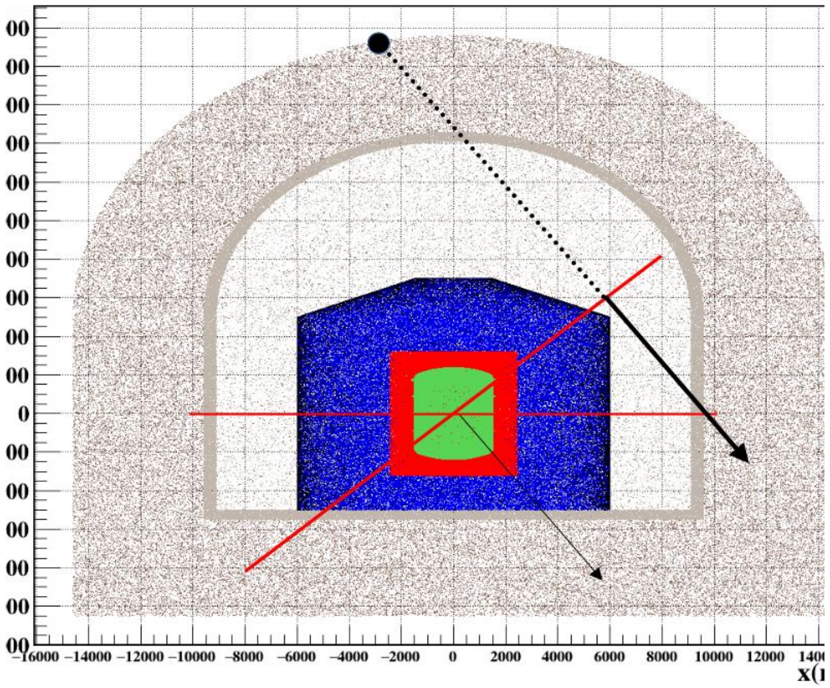
- Muons induce neutron cascades when they pass through the detector
- ^{137}Xe is produced after a neutron is captured by ^{136}Xe

➡ It depends on the underground location

Cosmogenic simulations for several locations: DARWIN collaboration, Eur. Phys. J. C (2024) 84

The simulations

- Realistic simulation of the geometry of the TPC
- Shielding materials (rock, concrete)
- Several physics lists tested
- Realistic muon generator (based on MUSIC)



We obtain production rates of ^{137}Xe, muon-induced neutrons, isotopes produced by spallation…

Sensitivity of DARWIN to the ^{136}Xe $0\nu\beta\beta$

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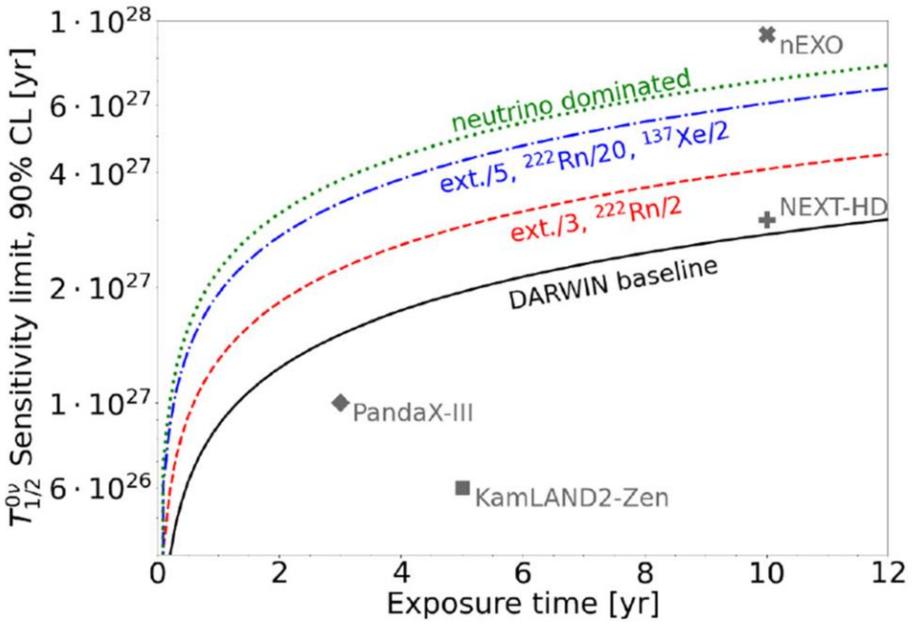
- Although the final location of the experiment is not yet decided, we have taken the Gran Sasso (LNGS) laboratory as a reference for our calculations
- Region Of Interest: 2435 – 2481 keV (Q ± FWHM/2)
- Exposure: 10 yr
- Fiducial mass: 5 t
- Energy resolution: 0.8% at Q = 2457.83 ± 0.37 keV

Sensitivity at 90% CL:

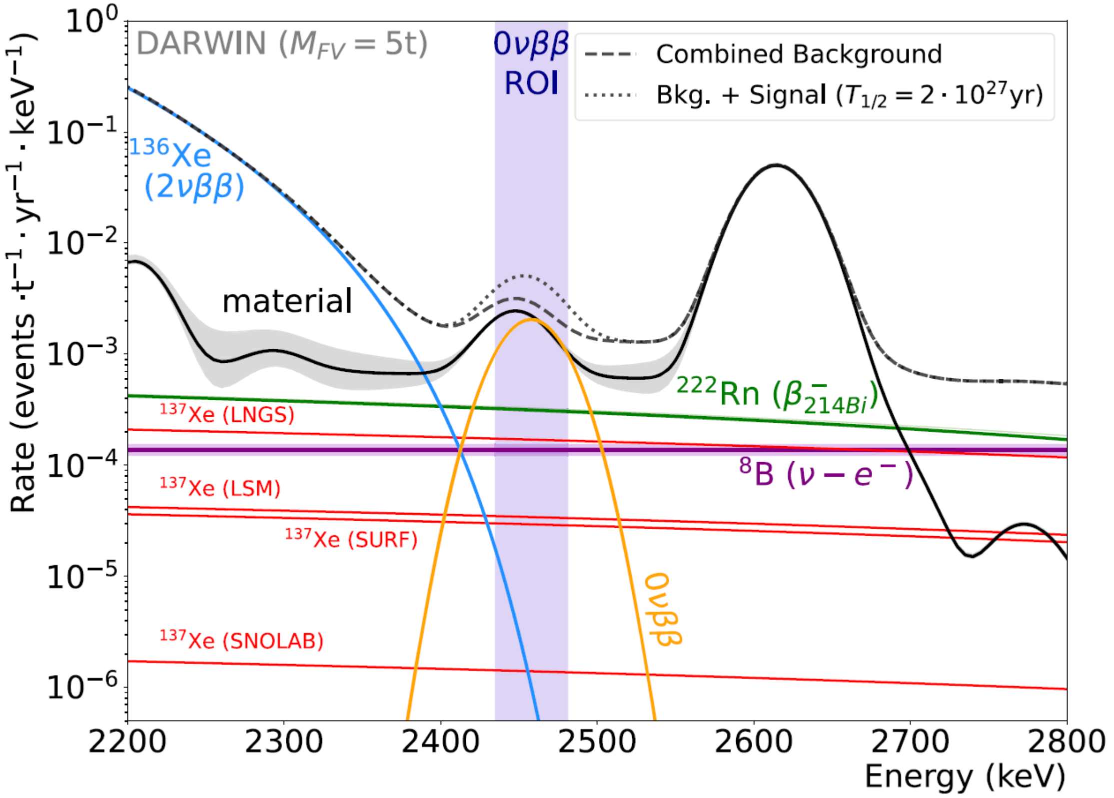
$$T^{0\nu}_{1/2} = \ln 2 \cdot \frac{\epsilon \cdot f_{ROI} \cdot a \cdot N_A}{1.64\, M_{Xe}} \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \approx 2.7 \cdot 10^{27}\, yr$$



DARWIN collaboration, Eur. Phys. J. C (2023) 83

Background and signal of ^{136}Xe 0νββ

Signal: $2 \cdot 10^{27}$ yr



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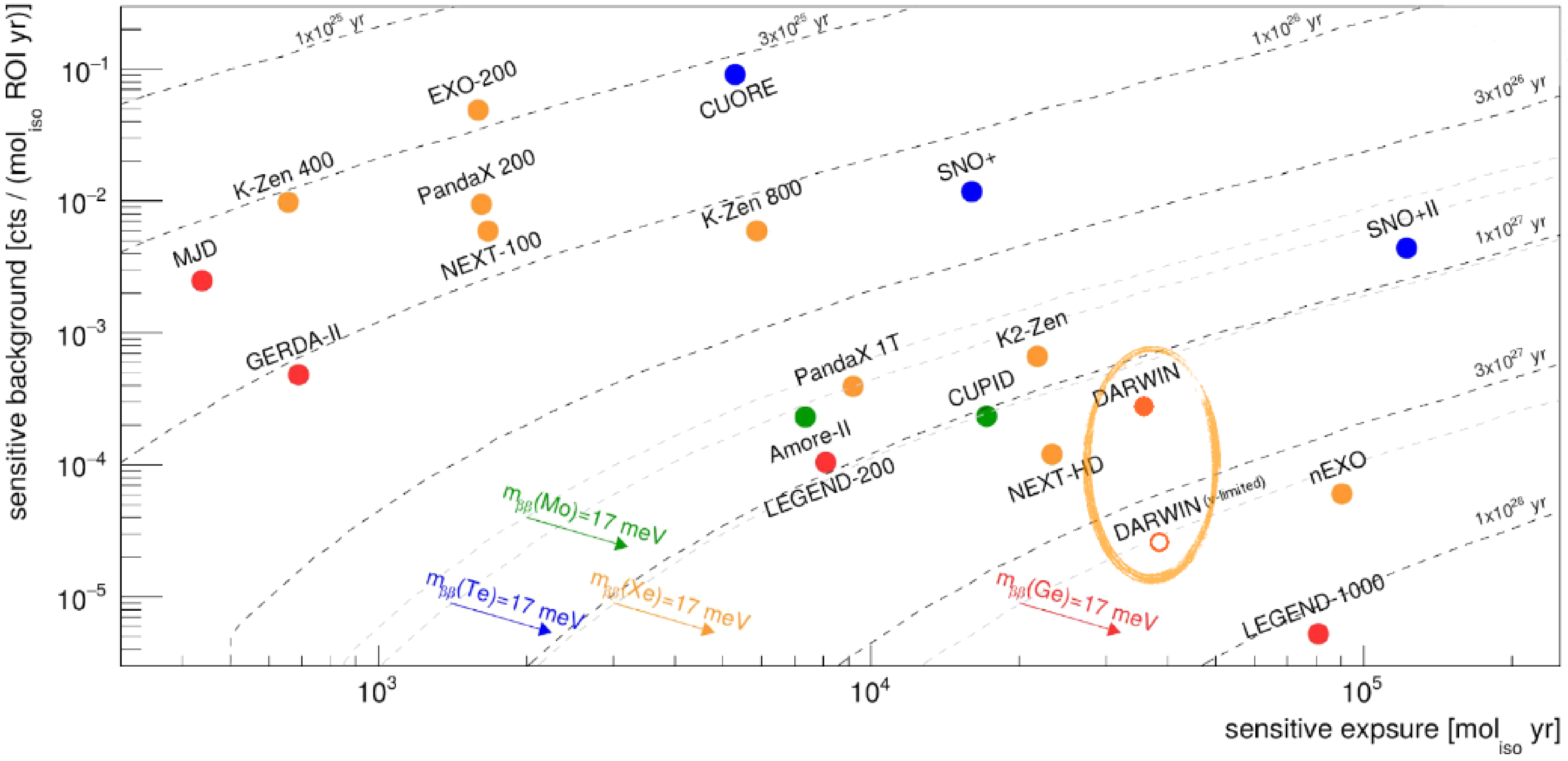
Type	Background index	Rate	Rel. uncertainty
External (5 t FV)			
^{214}Bi peaks + continuum	$1.36 \cdot 10^{-3}$	0.313	±3.6%
^{208}Tl continuum	$6.20 \cdot 10^{-4}$	0.143	±4.9%
^{44}Sc continuum	$4.64 \cdot 10^{-6}$	0.001	±15.8%
Intrinsic contributions			
^{8}B ($\nu - e$ scattering)	$1.51 \cdot 10^{-4}$	0.035	±13.5%
^{137}Xe	$1.69 \cdot 10^{-4}$	0.039	±10.2%
^{136}Xe (2νββ)	$5.78 \cdot 10^{-6}$	0.001	±17.0%
^{222}Rn in LXe (0.1 μBq kg^{-1})	$3.09 \cdot 10^{-4}$	0.071	±1.6%
Total	$2.62 \cdot 10^{-3}$	0.603	±2.4%

Events/(t yr keV)

Events/yr

Comparison with other experiments



The future: XLZD

- Merger of DARWIN,XENON and LUX-ZEPLIN collaborations to build and operate next-generation liquid xenon detector
- New, stronger international collaboration with demonstrated experience in xenon time projection chambers

RAL (2024)

KIT (2022)

Collaboration has been established (September 2024)

https://xlzd.org/

Evolution timeline

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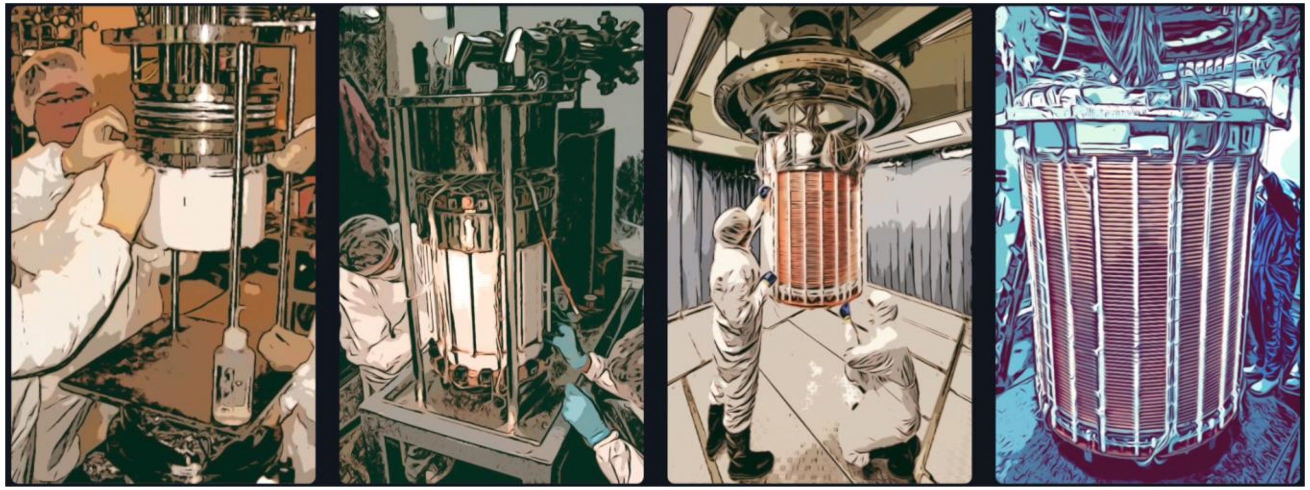


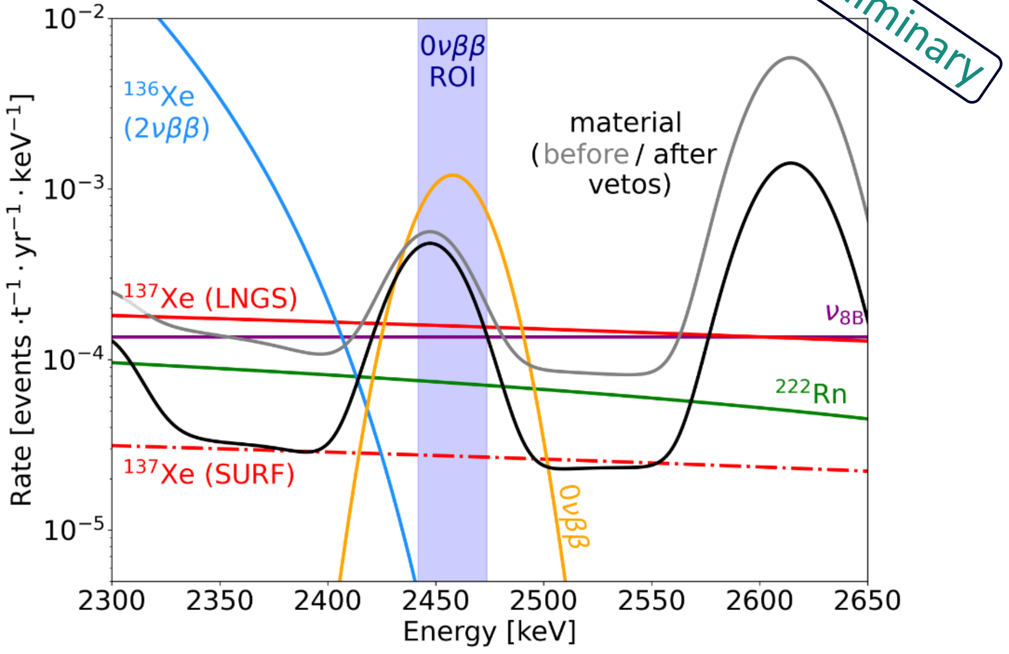
XENON10	XENON100	XENON1T	XENONnT	XLZD
25 kg LXe	160 kg LXe	3200 kg LXe	8500 kg LXe	**60 t LXe**
600 $[\mathrm{t\ d\ keV}]^{-1}$	5.3 $[\mathrm{t\ d\ keV}]^{-1}$	0.2 $[\mathrm{t\ d\ keV}]^{-1}$	0.04 $[\mathrm{t\ d\ keV}]^{-1}$	Reduce background down to pp level
Started in 2006	2008	2015	2020	

Sensitivity with XLDZ

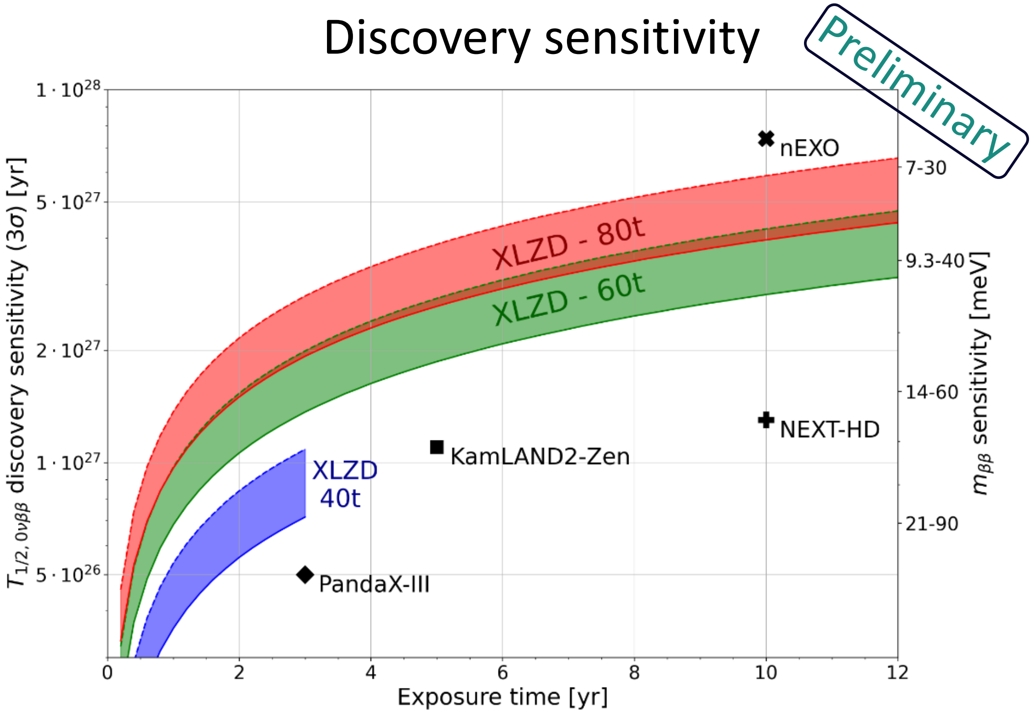
Assumptions:

0.1 µBq/kg ^{222}Rn materials radiopurity already identified

Signal: $5 \cdot 10^{27}$ yr



Discovery sensitivity



Summary

- The neutrinoless double beta decay ($0\nu\beta\beta$) would prove the Majorana nature of the neutrino
- Despite being a dark matter experiment, DARWIN is sensitive to other physics channels of interest
- In its baseline design it contains 50 t of natural xenon (9% ^{136}Xe)
- Simulations yield an expected sensitivity limit for DARWIN of $T^{0\nu}_{1/2} = 3 \cdot 10^{27}$ yr for a 10 year exposure with 5 t fiducial mass
- The XLZD experiment will operate ~60 t of xenon in ultra-low background conditions
- Its sensitivity to the $0\nu\beta\beta$ would be competitive with other experiments dedicated to the study of this process

Nice pictures of Xenoscope TPC