DARWIN: A NEXT-GENERATION MULTI-TON XENON OBSERVATORY

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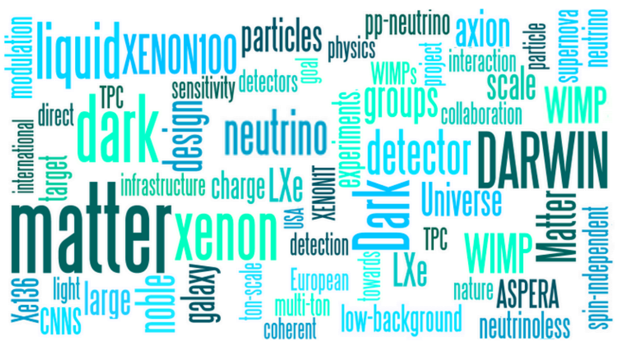
DARWIN COLLABORATION

www.darwin-observatory.org



IFIC ONLINE SEMINAR

23 MARCH 2021

NEED OF A MULTI-TON XENON OBSERVATORY

Still Many Unknows in Particle Physics

Dark Matter

fundamental nature?

WIMPs?

mass range?

type/strength of interaction ?

⋮

Neutrinos

absolute mass scale?

Dirac vs Majorana nature?

magnetic dipole moment?

⋮

Solar Axions

are they produced?

strong CP problem?

axion couplings?

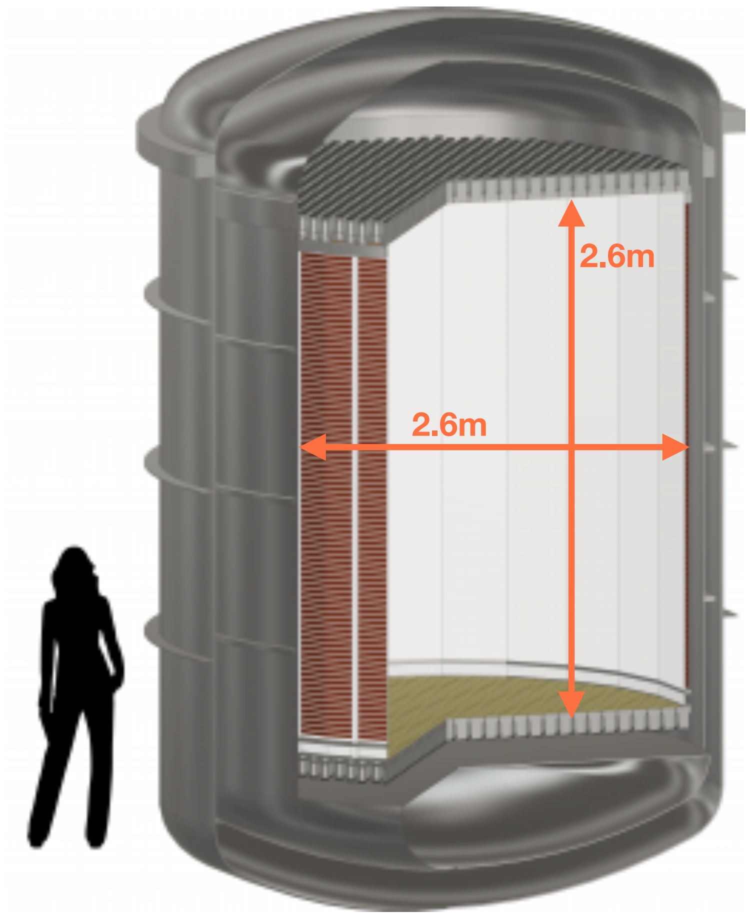
⋮

Many of these questions can be answered by a large liquid xenon detector located deep underground like …

DARWIN

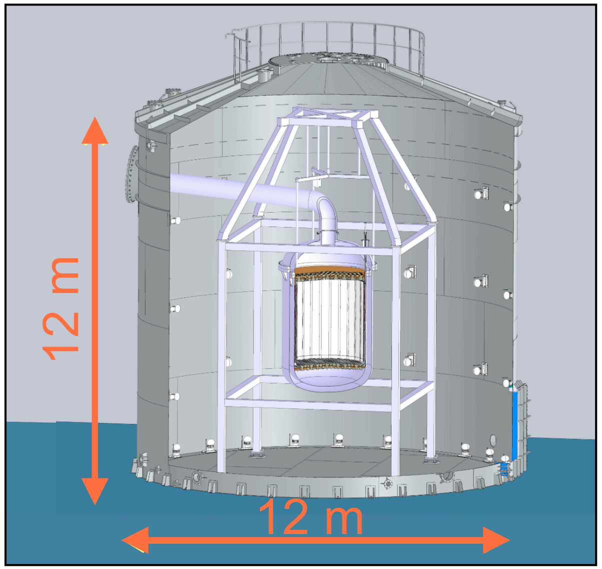
DARWIN BASELINE DESIGN

DARWIN Collaboration,
JCAP **1611** (2016) 017



baseline design with PMTs but several alternatives under consideration

- Dual-phase Time Projection Chamber (TPC)
- 50t total (**40 t active**) of liquid xenon (LXe)
- Dimensions: **2.6 m diameter x 2.6 m height**
- Two arrays of photosensors (1800 PMTs of 3”)
- Low-background double-wall Ti cryostat
- PTFE reflector panels & copper shaping rings
- Outer shield with Gd doped water (veto μ & n)



Possible realisation of the water tank

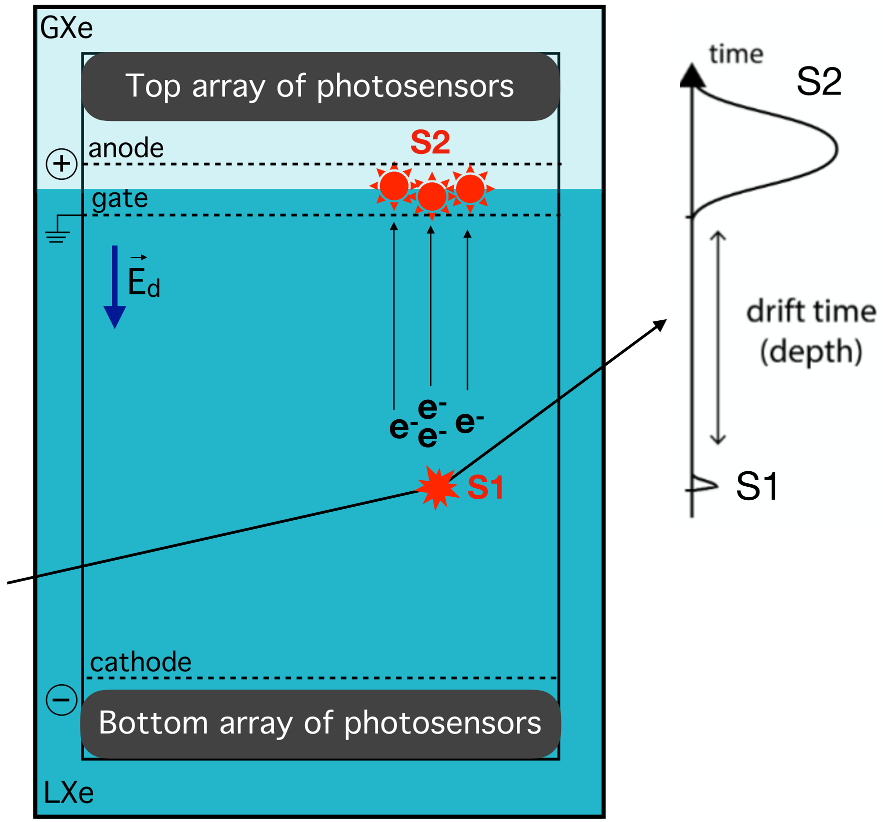
DUAL-PHASE XENON TPC

Dual phase TPC working principle

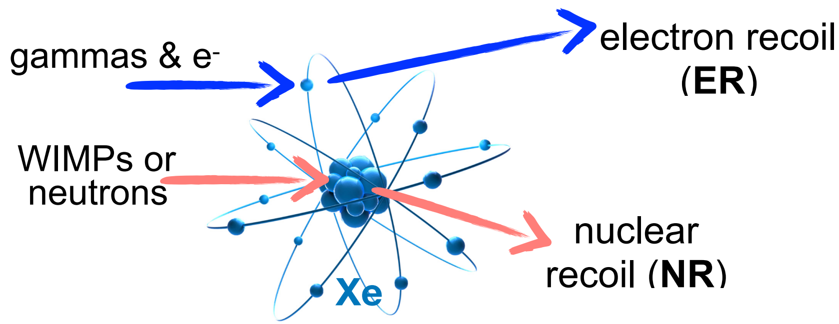
Detection of the scintillation **light** (**S1**) and the delayed scintillation light proportional to the **charge** (**S2**)

3D Position and Energy reconstruction:

- (x-y) from S2 pattern, z from drift time
- Energy from S1 and S2

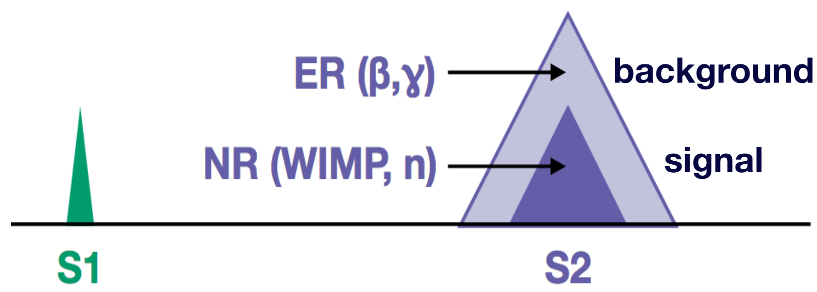


Particle interactions



S2/S1 depends on the particle ID

- Allows for particle type discrimination



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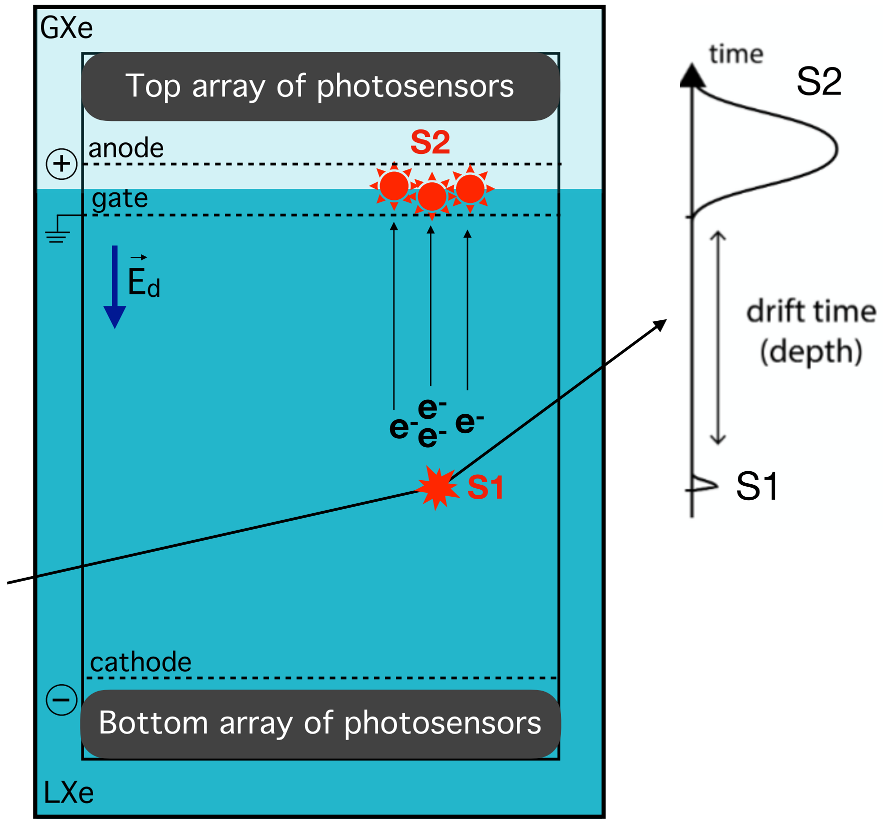

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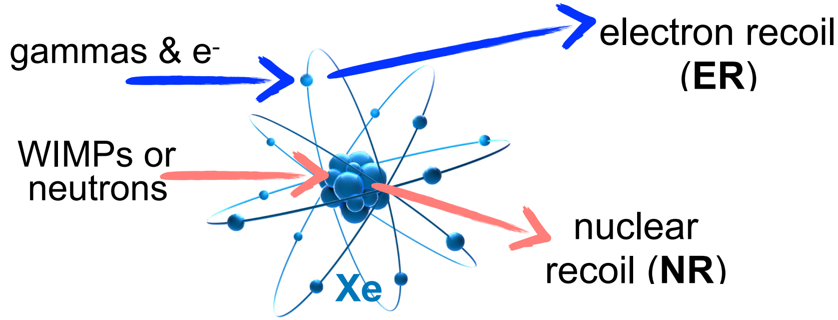

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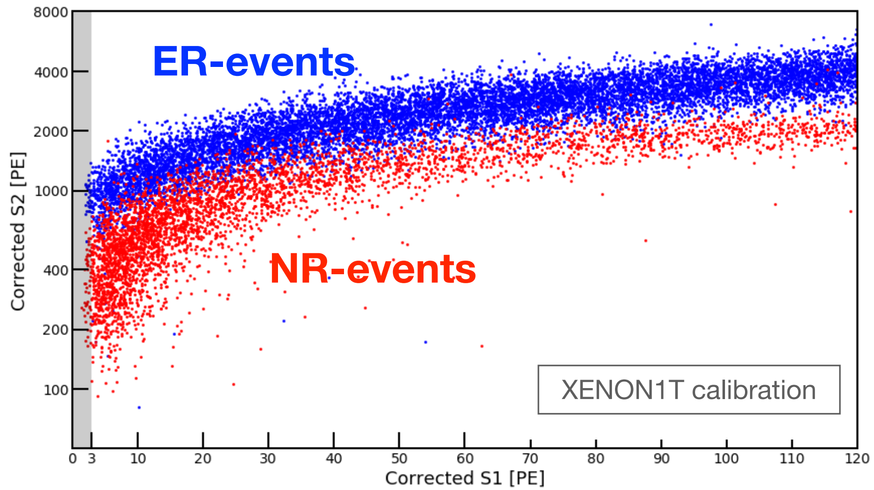
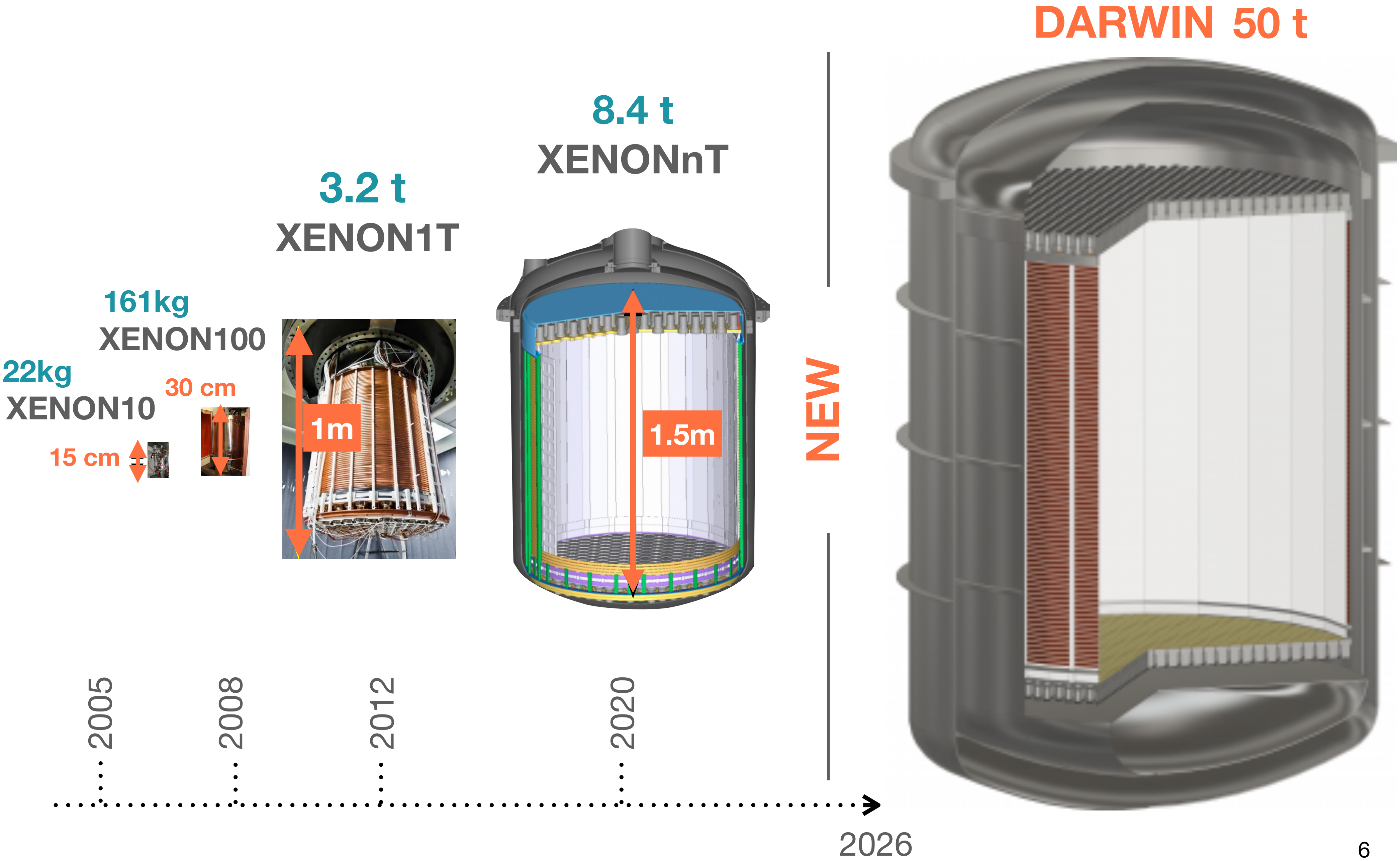


DARWIN IN THE CONTEXT OF THE XENON PROJECT



DARWIN SCIENCE PROGRAMME

Ultra-low Background —— **Large Mass** —— **Low Energy Threshold**

DIRECT DETECTION OF DARK MATTER

↓

DARWIN

DARWIN SCIENCE PROGRAMME

DARWIN

Ultra-low Background — **Large Mass** — **Low Energy Threshold**

DIRECT DETECTION OF DARK MATTER

SOLAR AXIONS

NEUTRINOLESS DOUBLE-BETA DECAY ^{136}Xe

DARWIN Collaboration, EPJ C80, 808 (2020)

GALACTIC AXION-LIKE PARTICLES

DARWIN

much more than a dark matter detector

LOW-ENERGY SOLAR NEUTRINOS

DARWIN Collaboration, EPJ C80, 1133 (2020)

BOSONIC SUPERWIMPs

GALACTIC SUPERNOVA NEUTRINOS

COHERENT SOLAR NEUTRINO-NUCLEUS SCATTERS

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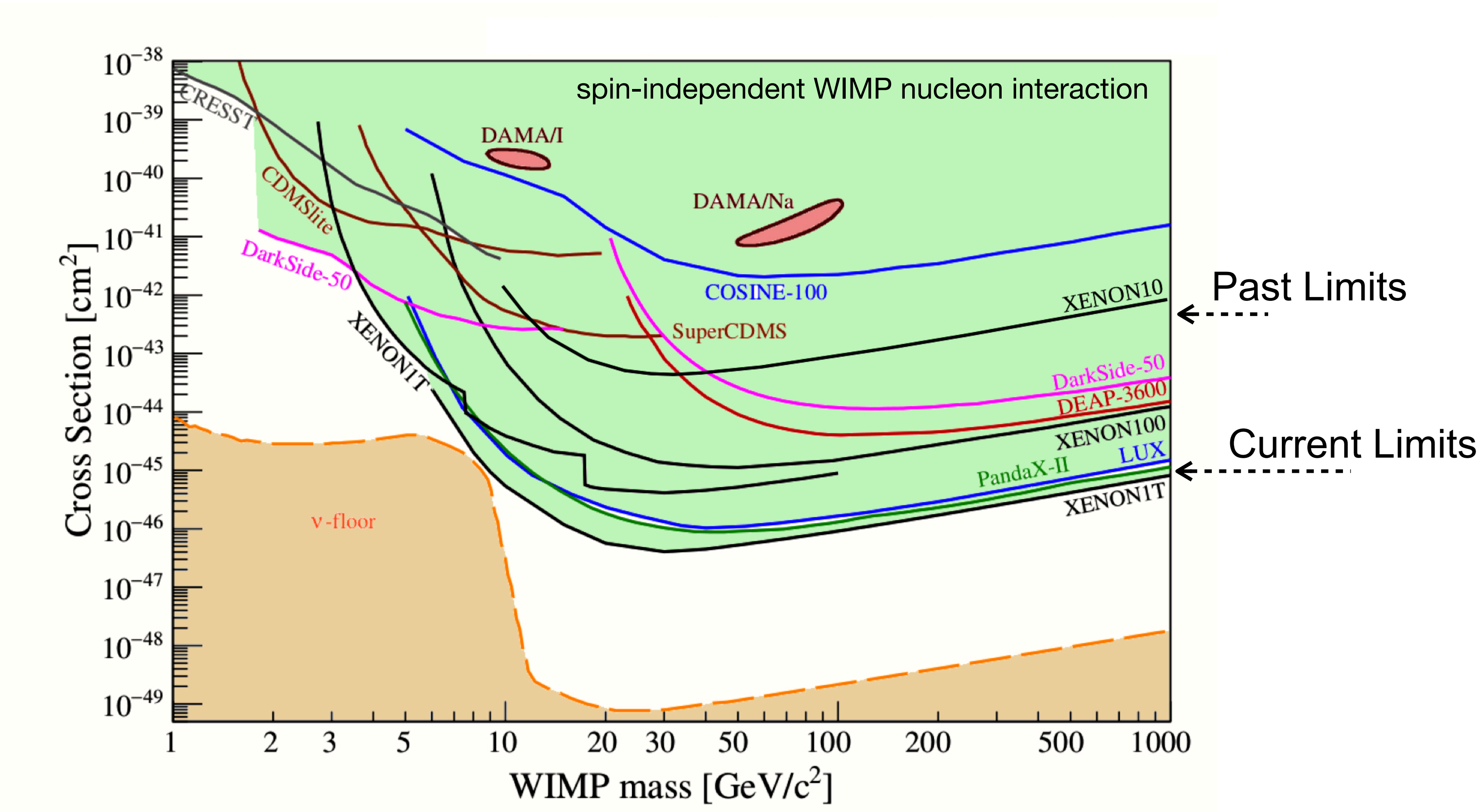
WIMP DIRECT DETECTION OVERVIEW

- The best sensitivity above 5 GeV/c² comes from experiments using liquid noble gases as target (Xe, Ar). (heavy target and easy scalability)
- **DARWIN**, with its **50t of total target**, plans to increase 100-fold the current sensitivity.



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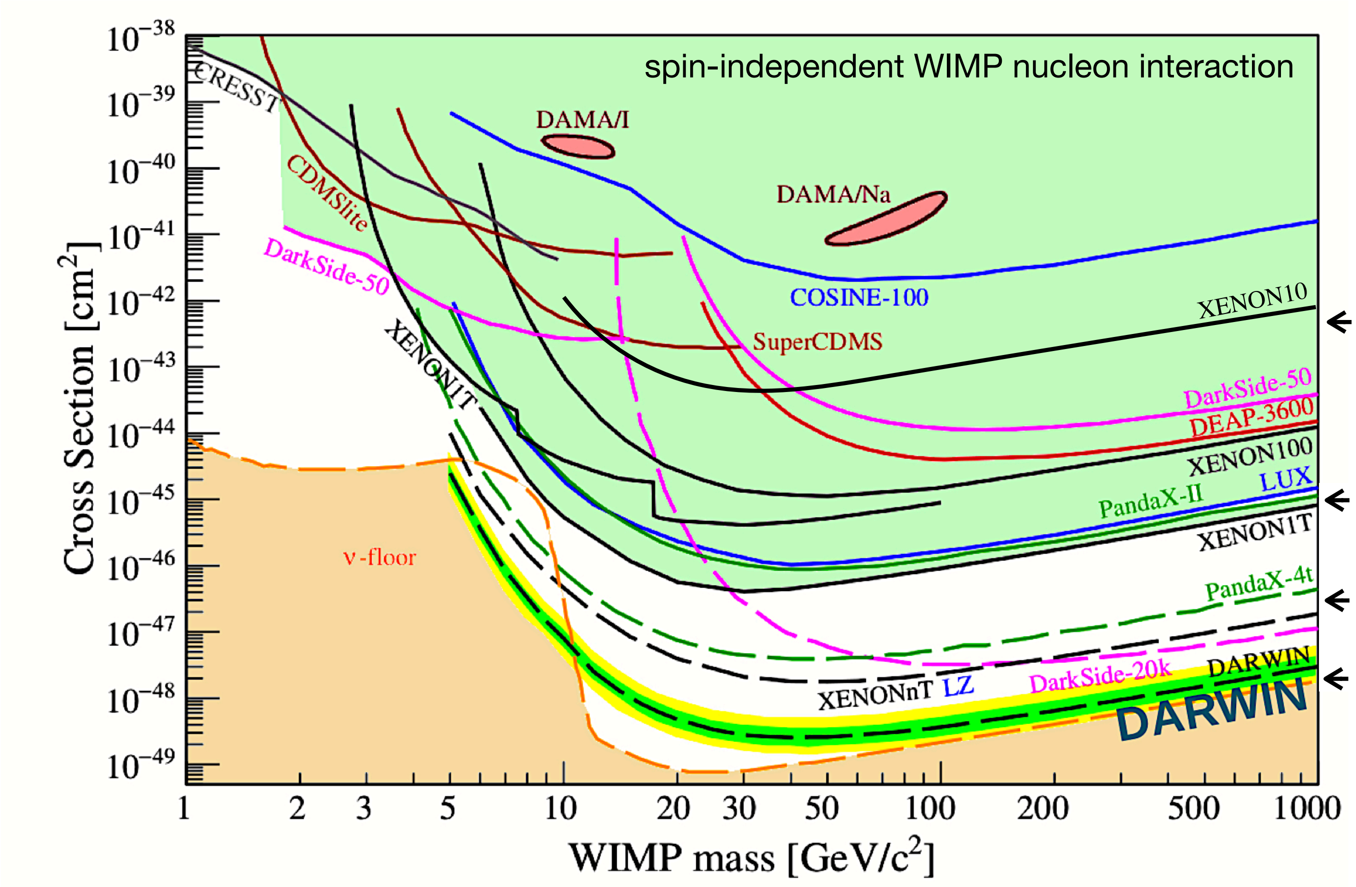


Past Limits

Current Limits

Near Future Sensitivity

DARWIN

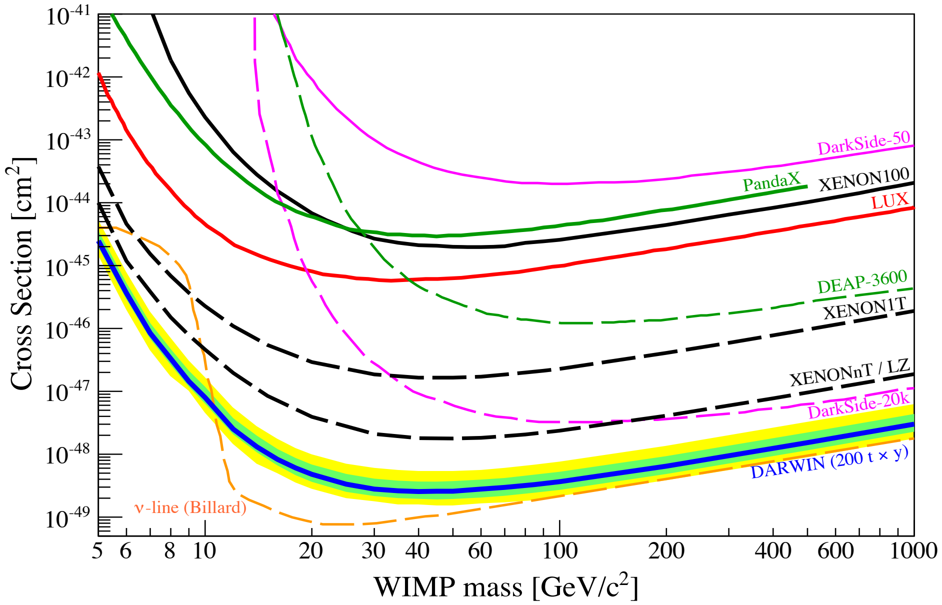
sensitivity limited by he neutrino floor

SENSITIVITY TO WIMPS

Schumann et al.,
JCAP **1510** (2015) 016

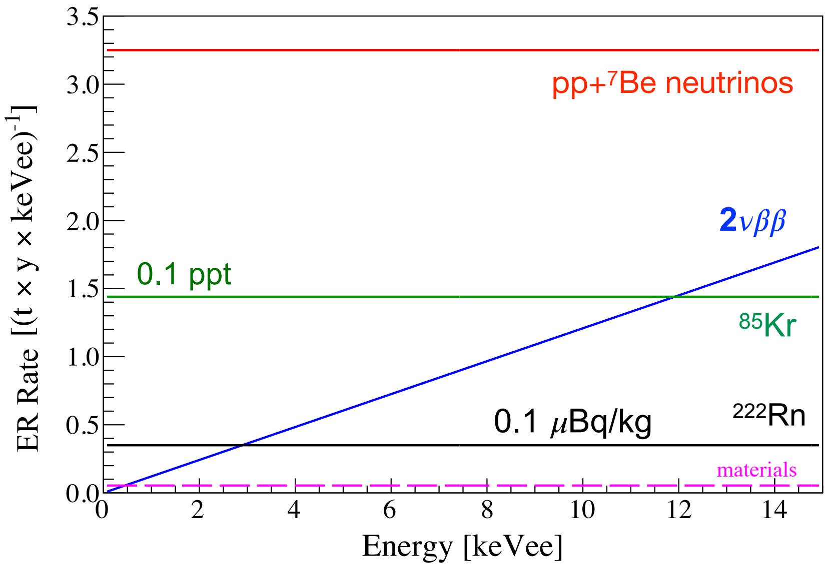
- Assumed an exposure 200 t x y (30t FV)
- 99.98% ER rejection (30% NR acceptance)
- Combined (S1+S2) energy scale
- Energy window 5-35 keV_{NR}
- Light yield 8PE/keV

spin-independent interaction



minimum: 2.5×10^{-49} cm² at 40 GeV/c²

Background Assumptions



before ER discrimination

Source	Rate [events/(t·y·keVxx)]
γ-rays materials	0.054
neutrons*	3.8×10^{-5}
intrinsic ^{85}Kr	1.44
intrinsic ^{222}Rn	0.35
$2\nu\beta\beta$ of ^{136}Xe	0.73
pp- and ^{7}Be ν	3.25
CNNS*	0.0022

NR

ER = 5.824 events/(t · y · keV_{ee})

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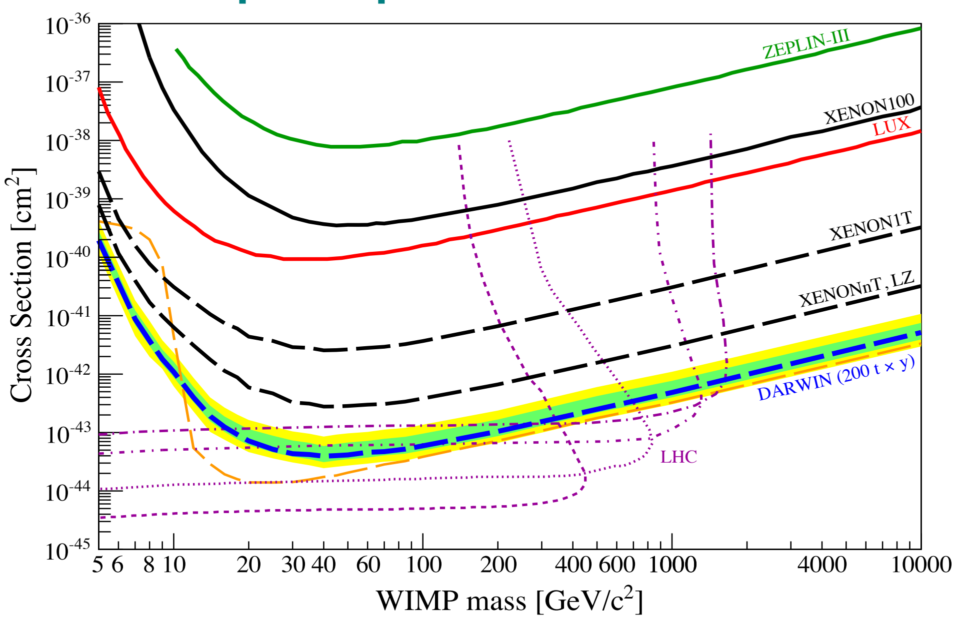
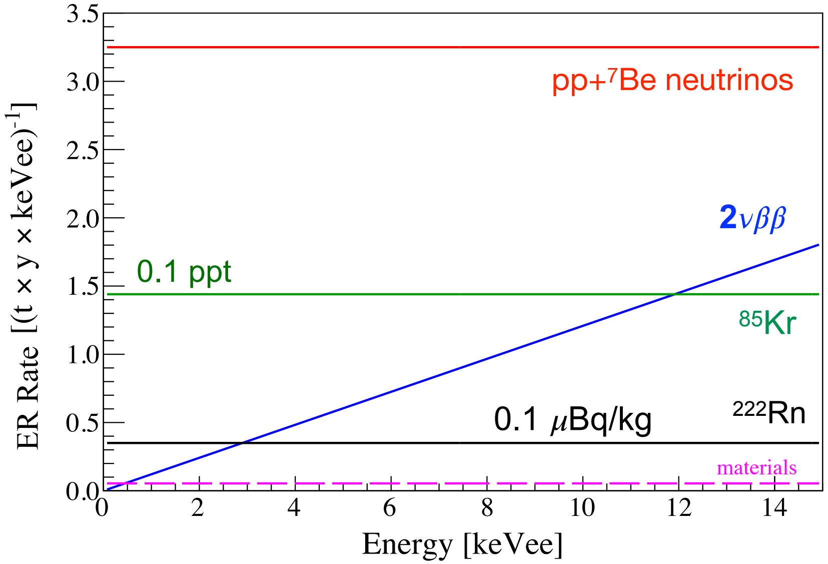


Complementary to LHC searches (14TeV)

Background Assumptions



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SOLAR NEUTRINO DETECTION

DARWIN

DARWIN Collaboration, Eur. Phys. J. C 80, 1133 (2020)

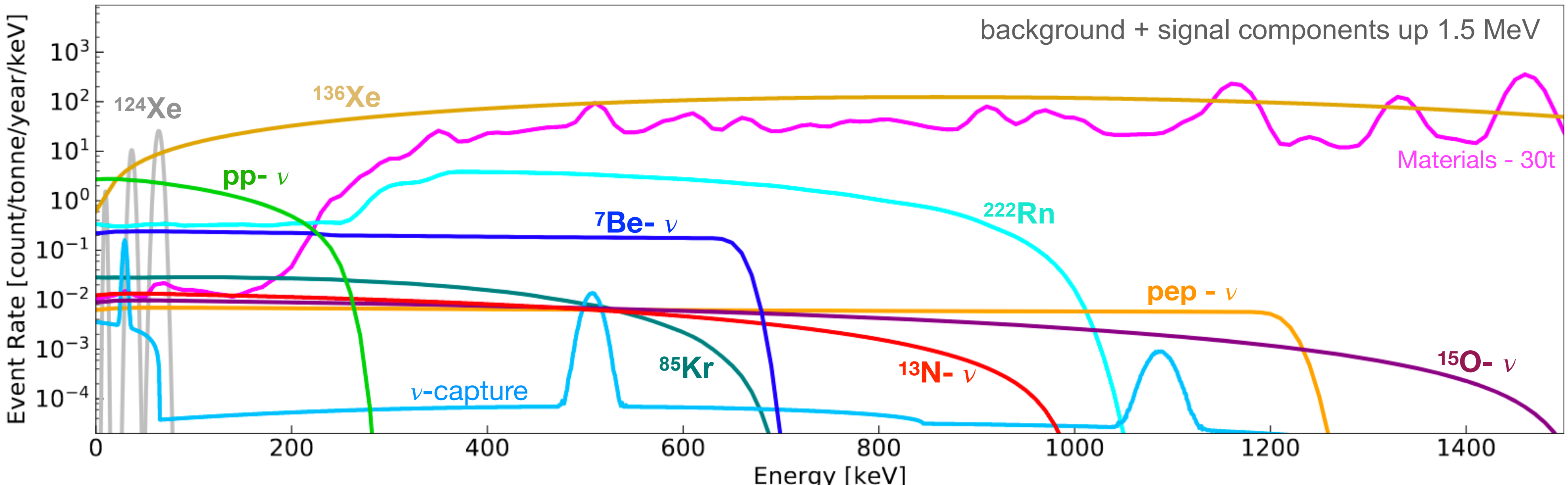
- pp- neutrinos are ~92% of the solar neutrino flux (SSM)
- Detection through neutrino-electron elastic scattering (ER)

$$\nu_x + e \longrightarrow \nu_x + e$$

- Multivariate spectral fit of 11 components up to 3 MeV
  - 5 background components
    (γ-materias, ^{222}Rn, ^{85}Kr, 2v2b-^{136}Xe, 2v2EC-^{124}Xe)
  - 5 neutrino components + neutrino capture ^{131}Xe
    (pp, ^{7}Be, ^{13}N, ^{15}O, pep, nu-capture)

neutrino fluxes high-Z SSM

component	$\Phi[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	P_{ee}
pp	$5.98\cdot10^{10}$	0.55
^{7}Be	$4.93\cdot10^{9}$	0.52
^{13}N	$2.78\cdot10^{8}$	0.52
^{15}O	$2.05\cdot10^{8}$	0.50
pep	$1.44\cdot10^{8}$	0.50



SOLAR NEUTRINO DETECTION

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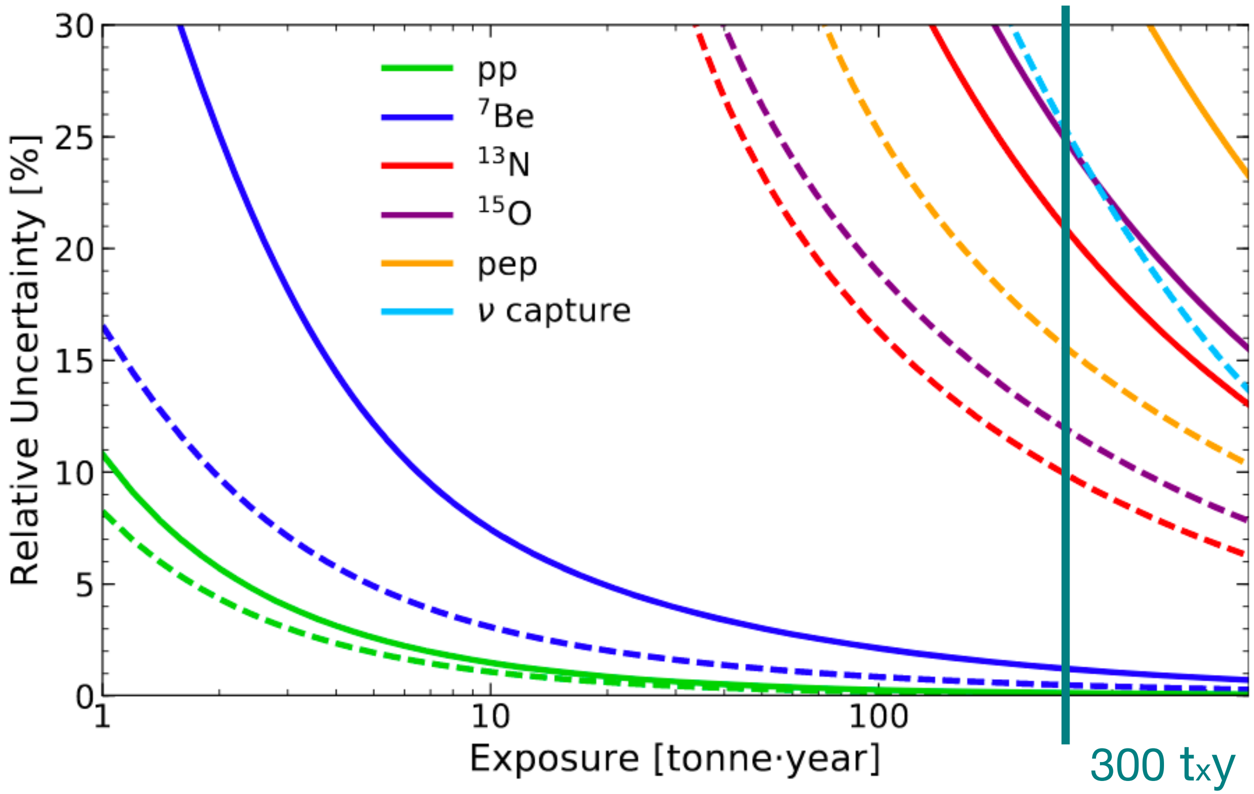
DARWIN Collaboration, Eur. Phys. J. C 80, 1133 (2020)

- Assuming high-Z SSM model
- Measured relative uncertainty for each neutrino component
- Two scenarios: natural xenon vs depleted xenon (no ^{136}Xe)

  (^{136}Xe abundance of 8.9% in natural xenon - main background)

300 txy is 10 years of data taking for 30t FV!!



pp-,^{7}Be-,^{13}N- and ^{15}O-components can be observed with a precision lower than 25% after 300 txy for natural xenon

(All of them for depleted xenon)

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DARWIN Collaboration, Eur. Phys. J. C 80, 1133 (2020)

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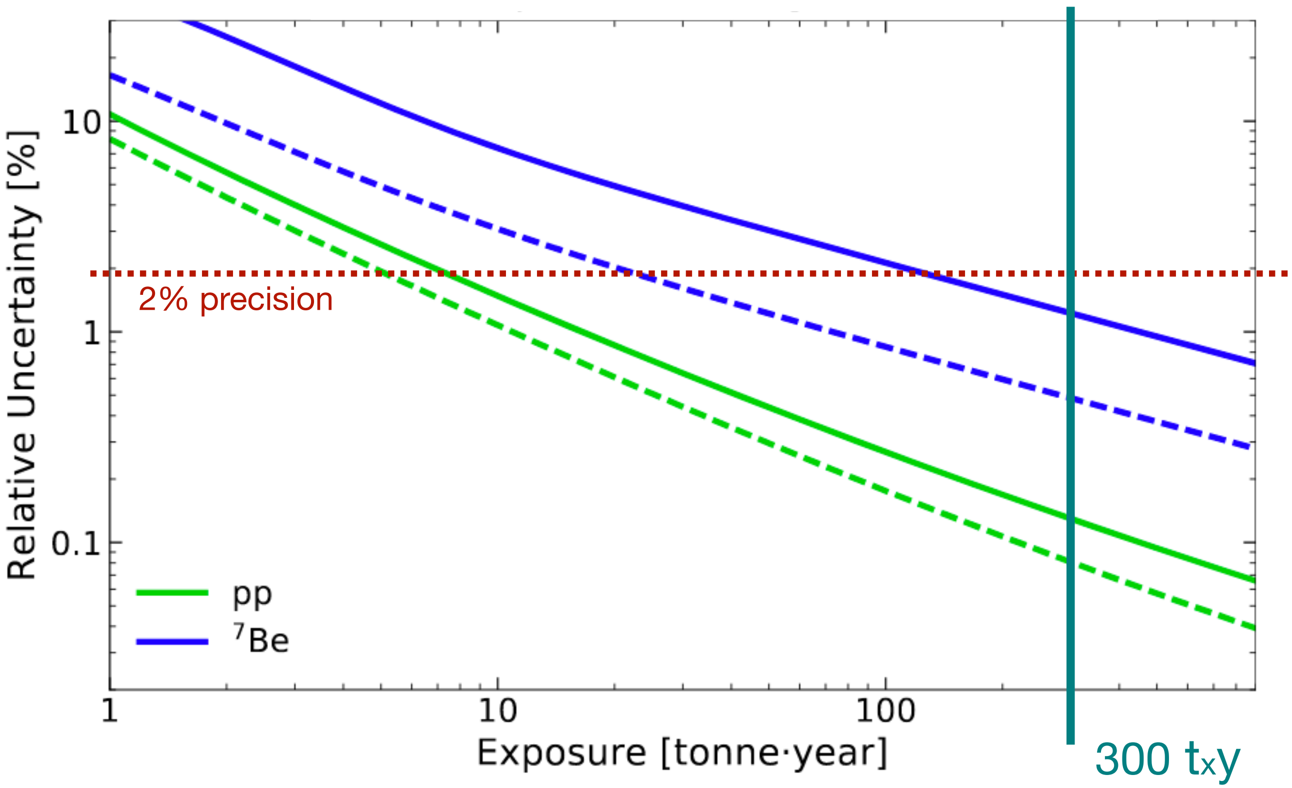


pp- and ^{7}Be-components with a precision lower than 2% after 300 txy for natural xenon

(10% precision in pp flux after only 1 txy)

SOLAR NEUTRINO DETECTION

DARWIN Collaboration, Eur. Phys. J. C 80, 1133 (2020)

- Real-time measurement of the neutrino flux:

  pp-ν —— 365 events/(t x y) (whole energy range above 1 keV_{ee})

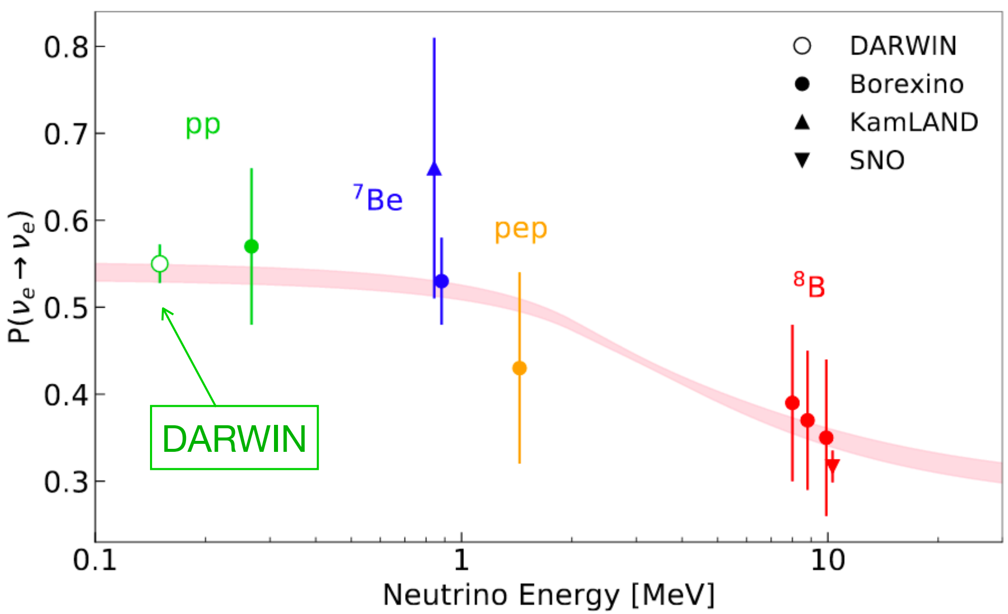
  ^{7}Be-ν —— 140 events/(t x y)

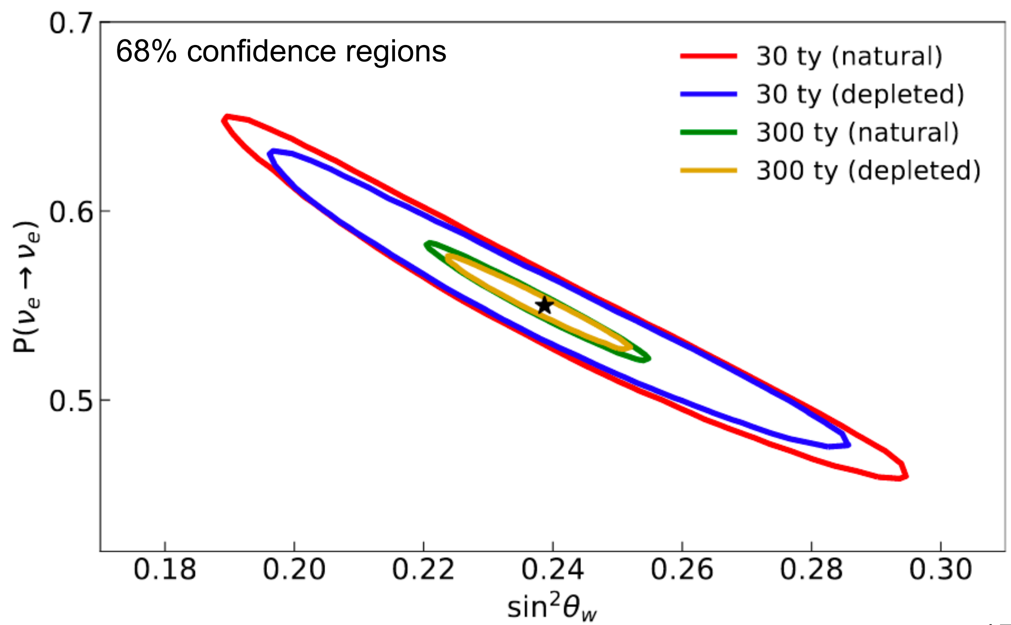
  ^{13}N-ν —— 6.5 events/(t x y)

  ^{15}O-ν —— 7.1 events/(t x y)

- Measurement of electron neutrino survival probability (P_{ee}) and the neutrino mixing angle below 300 keV.

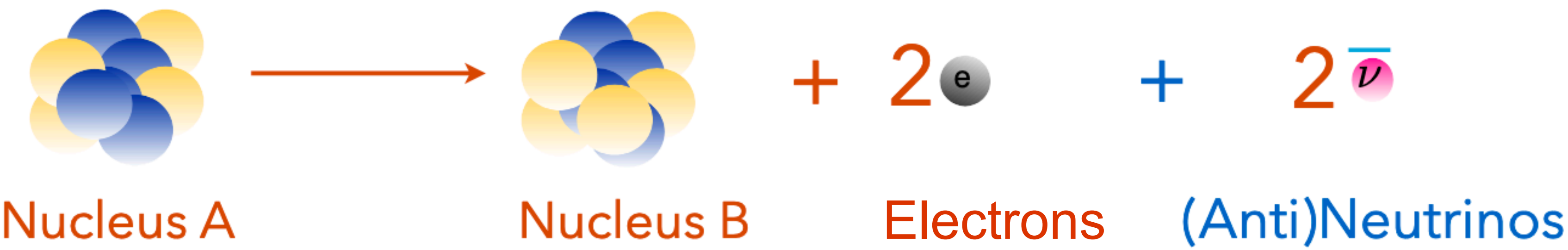
  (deviation from prediction would indicate new physics)





DOUBLE BETA DECAYS: INTRODUCTION

Two-Neutrinos double beta decay $(2\nu\beta\beta)$



Extremely rare nuclear process, but allowed in the Standard Model

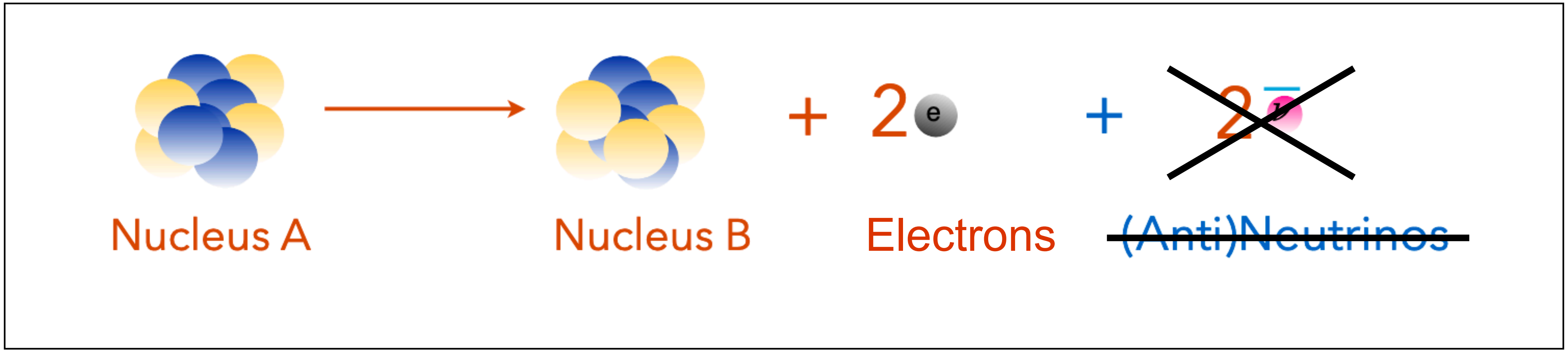
$$\Delta L = 0$$

Observed in more that 10 nuclei: ⟶ $T_{1/2} > 10^{18}$ years

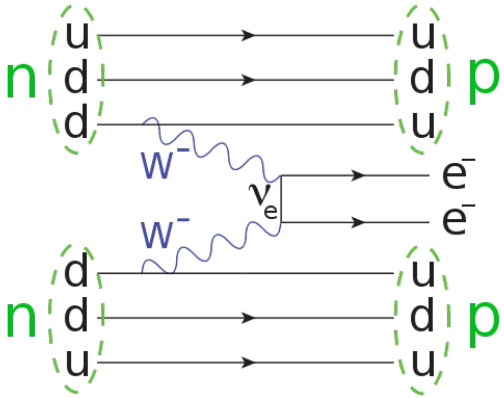
^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U

DOUBLE BETA DECAYS: INTRODUCTION

Neutrinoless double beta decay $(0\nu\beta\beta)$



Extremely rare nuclear process, NEVER OBSERVED BEFORE

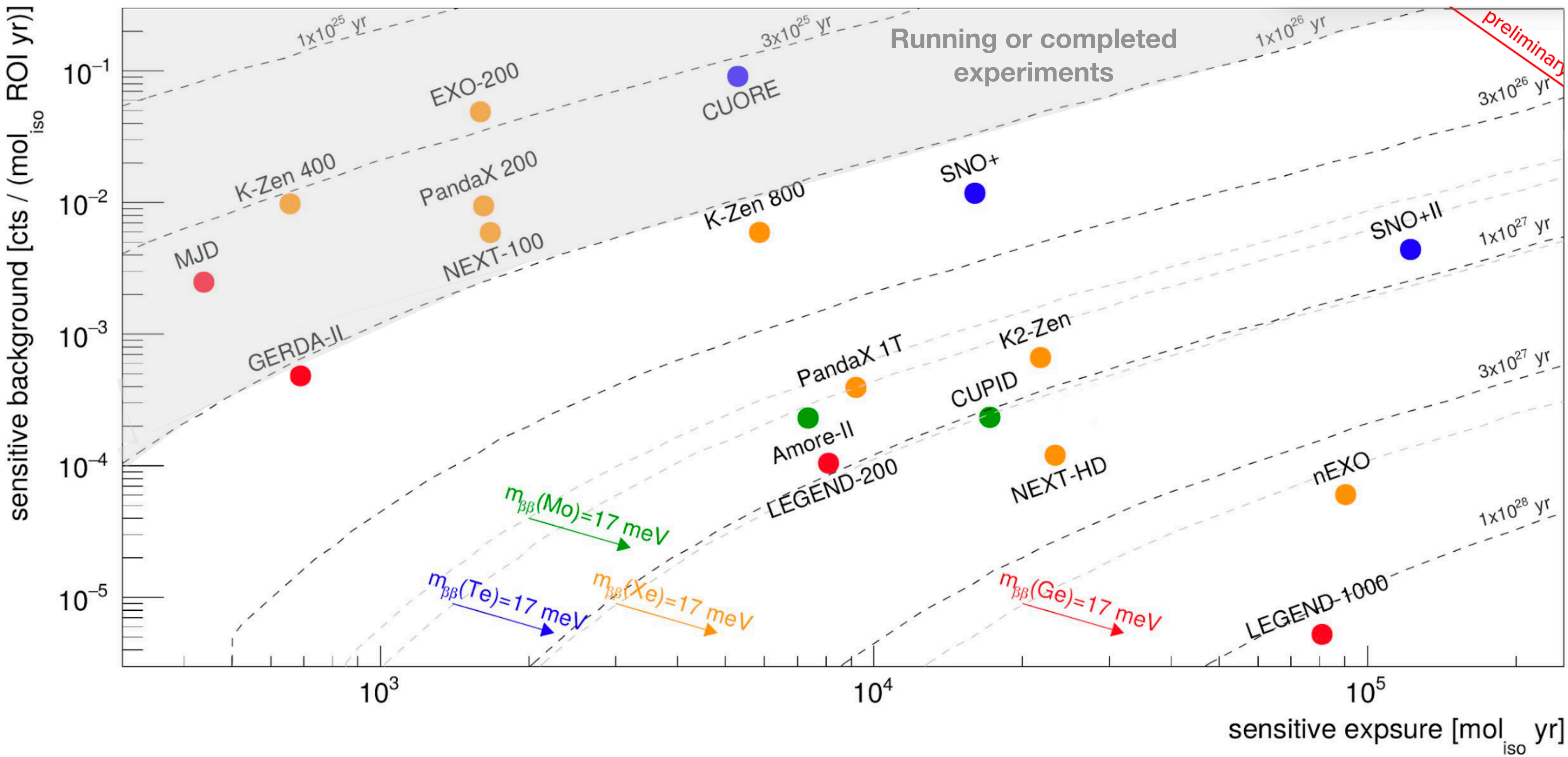


$\Delta L = 2$

- ➢ Lepton number violation
- ➢ Neutrinos are their own anti-particle (Majorana fermions)

$0\nu\beta\beta$ EXPERIMENTS OVERVIEW

Different experiments with different isotopes



Nowadays a very active, exciting and promising field

Figure adapted from M. Agostini in TAUP2019

$0\nu\beta\beta$ EXPERIMENTS OVERVIEW

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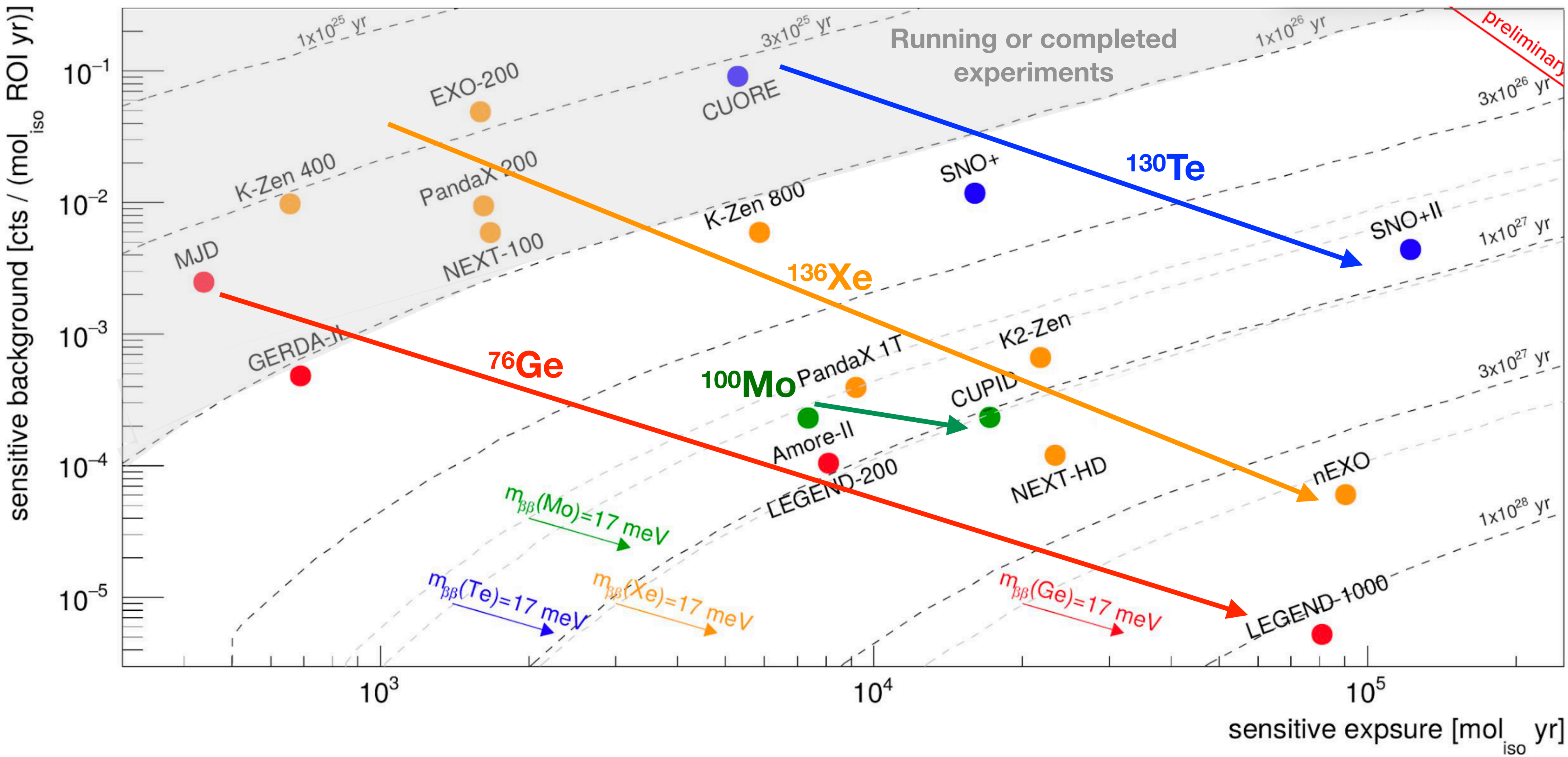

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DARWIN

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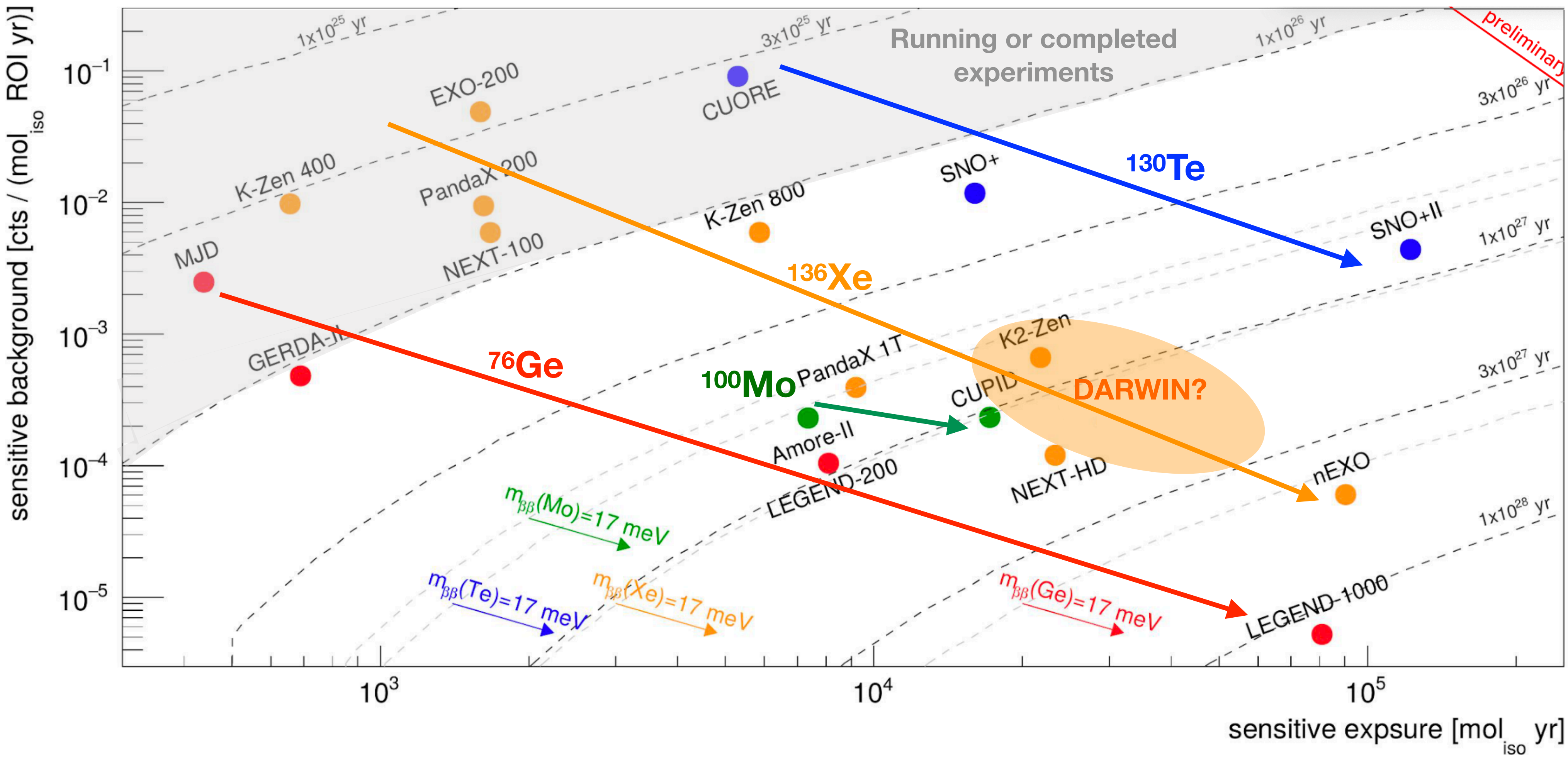

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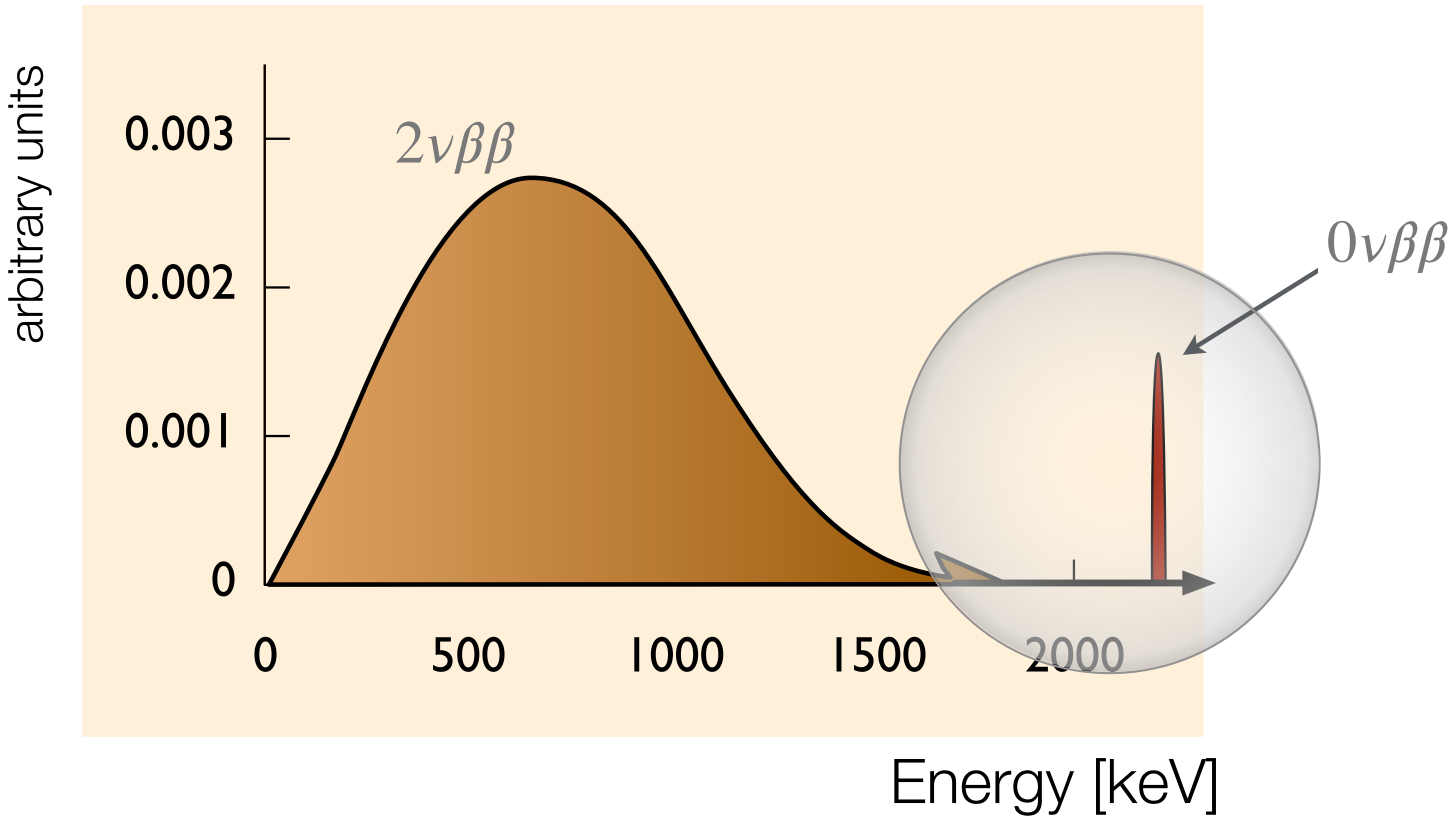
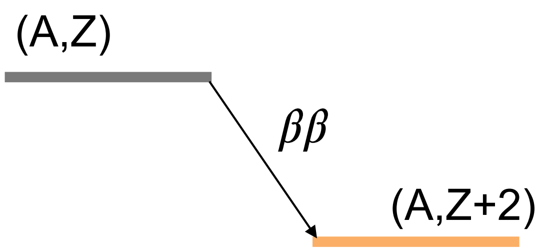
EXPECTED $0\nu\beta\beta$ SIGNAL

DARWIN

Sharp peak at the end of the $2\nu\beta\beta$ energy spectrum, Q-value

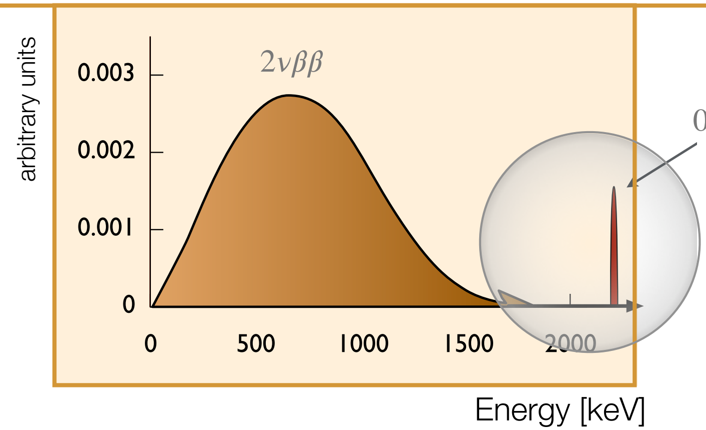




Q-value: mass difference between mother and daughter nucleus

WHAT DO WE NEED TO OBSERVE THIS SIGNAL?

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



1. Large mass of a candidate isotope
2. Excellent energy resolution
3. Ultra-low background

WHAT DO WE NEED TO OBSERVE THIS SIGNAL?

DARWIN

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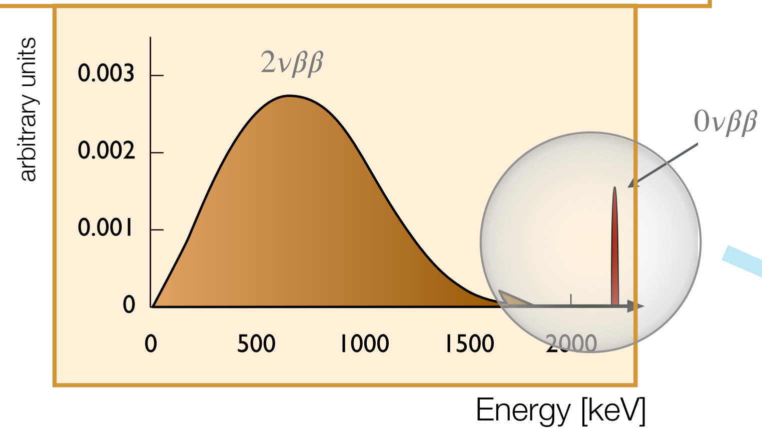

① **Large mass of a candidate isotope**

② **Excellent energy resolution**

③ **Ultra-low background**

DARWIN offers the possibility of looking for this process for FREE !!

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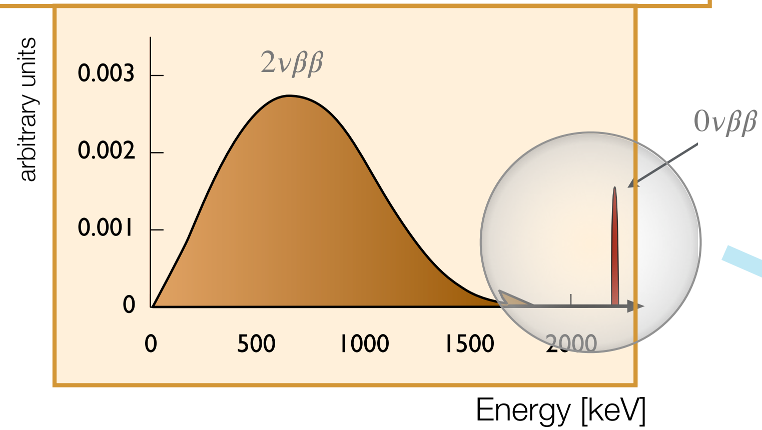

① **Large mass of a candidate isotope**

✓ more than 3.5 t of active ^{136}Xe.

- No enrichment (8.9% in natural Xe)
- Q-value = 2.458 MeV

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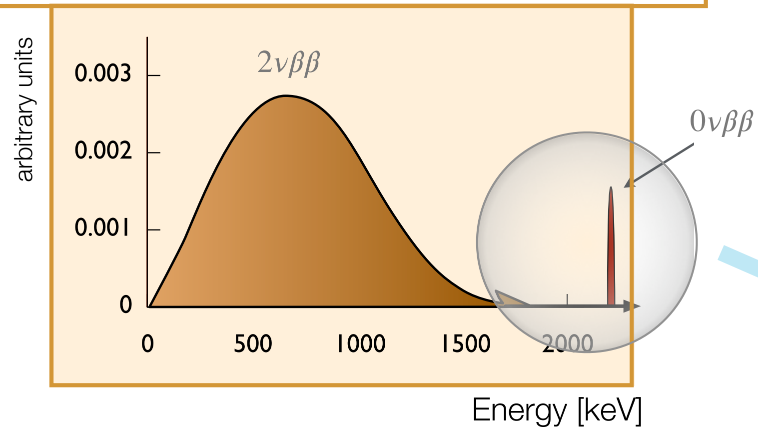

1

Large mass of a candidate isotope

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2

Excellent energy resolution

✓ resolution of ~0.8% at 2.5 MeV

- As demonstrated by XENON1T

Eur. Phys. J. C 80, 785 (2020)

3

Ultra-low background

WHAT DO WE NEED TO OBSERVE THIS SIGNAL?

DARWIN

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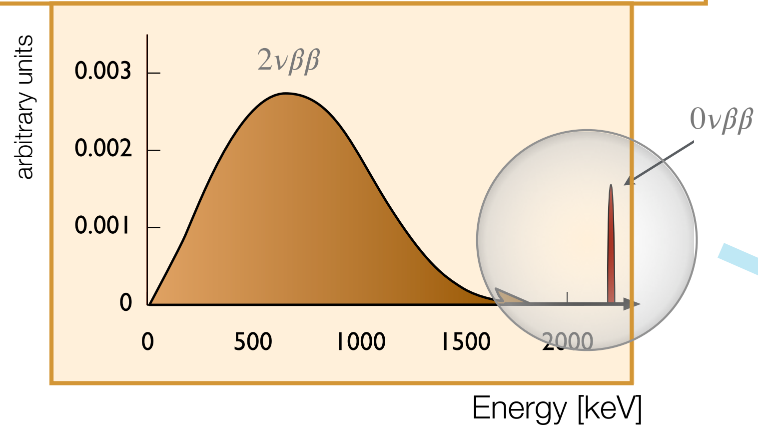

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Eur. Phys. J. C 80, 785 (2020)

3

Ultra-low background

✓ Environment dominated by intrinsic backgrounds

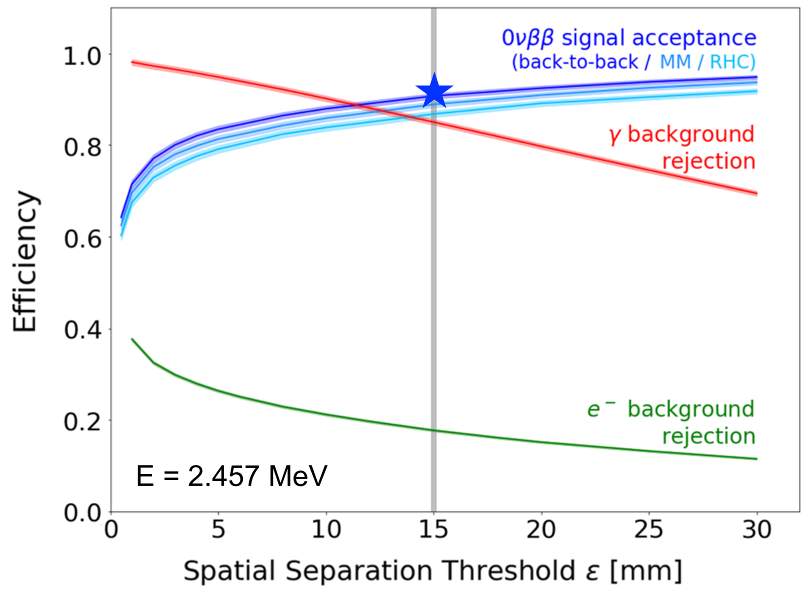
- Material/external backgrounds subdominant
- Irreducible intrinsic background

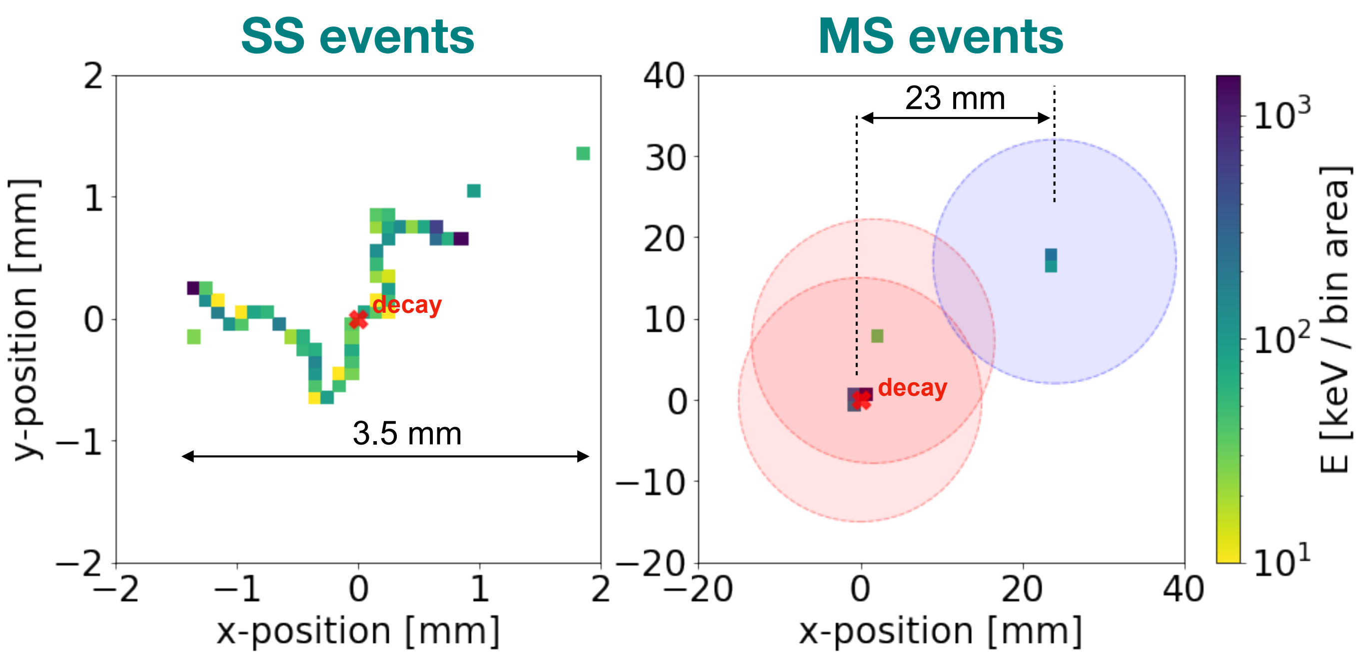
SIGNAL TOPOLOGY IN DARWIN

DARWIN Collaboration, Eur. Phys. J. C 80, 808 (2020)

- Treat the 0vbb signal as a single-site (SS) events
  - Not always true if e- emits Bremsstrahlung photons that travel some distance
  - Events misidentified as MS and rejected
- We use ε **= 15mm** for SS/MS identification

90% efficiency for 0vbb events (equal share)



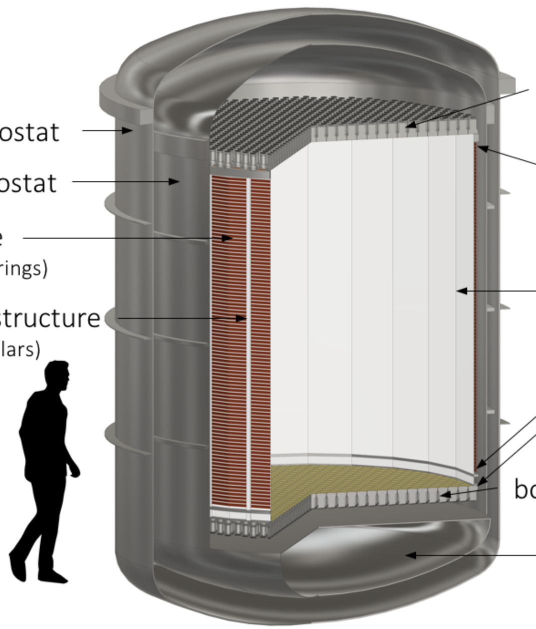


MATERIAL BACKGROUND SIMULATIONS

DARWIN

DARWIN Collaboration, Eur. Phys. J. C 80, 808 (2020)

Detailed detector geometry in Geant4 following the baseline design



Element	Material	Mass
Outer cryostat	Ti	3.04 t
Inner cryostat	Ti	2.10 t
Bottom pressure vessel	Ti	0.38 t
LXe instrumented target	LXe	39.3 t
LXe buffer outside the TPC	LXe	9.00 t
LXe around pressure vessel	LXe	0.27 t
GXe in top dome + TPC top	GXe	30 kg
TPC reflector (3mm thickness)	PTFE	146 kg
Structural support pillars (24 units)	PTFE	84 kg
Electrode frames	Ti	120 kg
Field shaping rings (92 units)	Copper	680 kg
Photosensor arrays (2 disks):		
Disk structural support	Copper	520 kg
Reflector + sliding panels	PTFE	70 kg
Photosensors: 3”PMTs (1910 Units)	composite	363 kg
Sensor electronics (1910 Units)	composite	5.7 kg

Simulation criteria

- Elements under considerations ➜ Simplified for modifications
  example: PMTs vs SiPMs
  - disks accounting for the proper amount of material
- Critical components for the BG ➜ Fully simulated in detail
  example: Double wall cryostat
- Conservative Activity Levels ➜ Already achieved by XENON and LZ

DEFINITION OF A FIDUCIAL VOLUME

DARWIN Collaboration, Eur. Phys. J. C 80, 808 (2020)

Distribution of the external background events in the detector volume

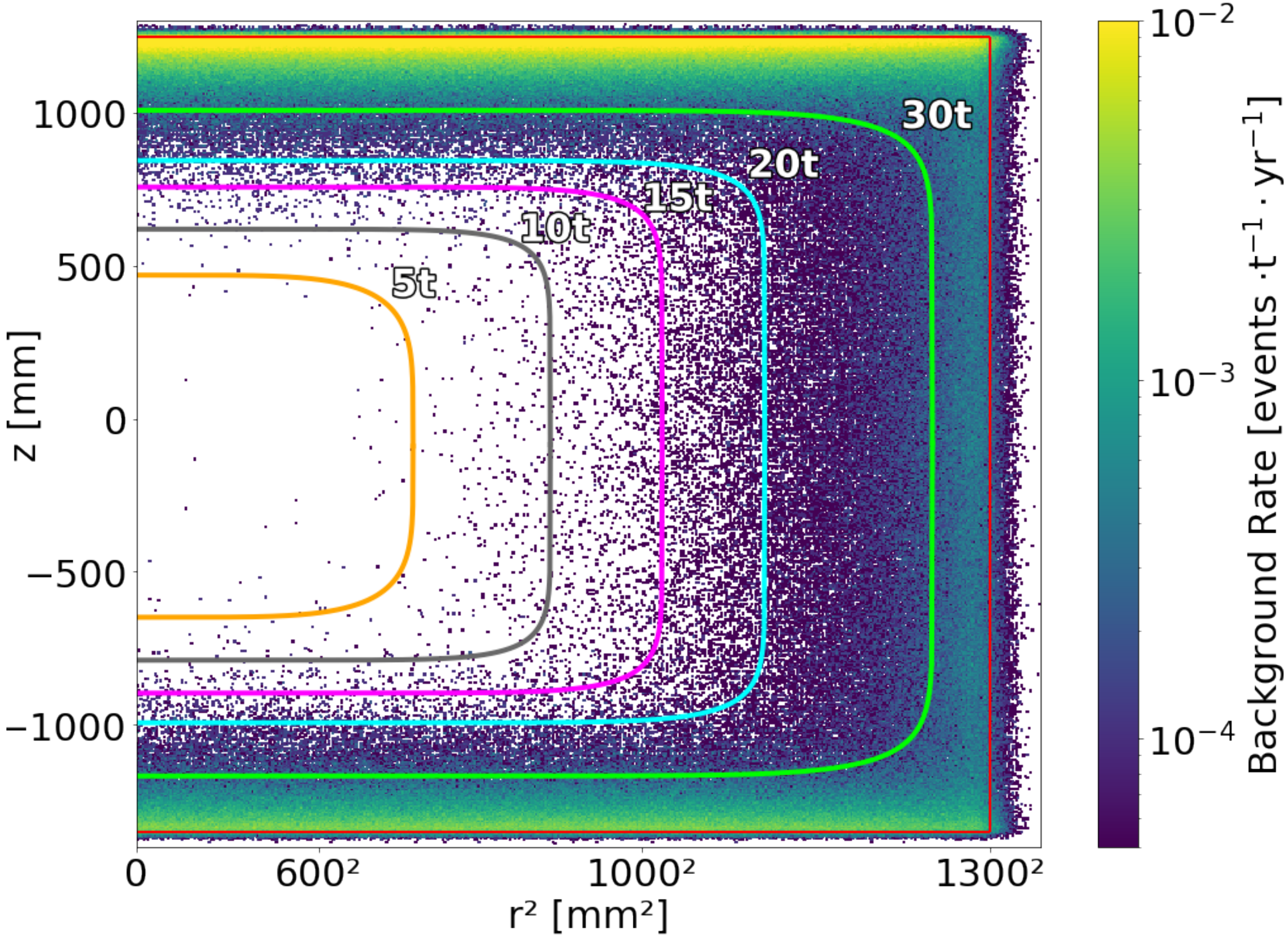
100 years of DARWIN run time, events with energy in the ROI

<u>Super-ellipsoidal cut</u>

$$\left(\frac{z+z_0}{Z_{max}}\right)^t + \left(\frac{r}{R_{max}}\right)^t < 1$$

Parameters optimised for each mass

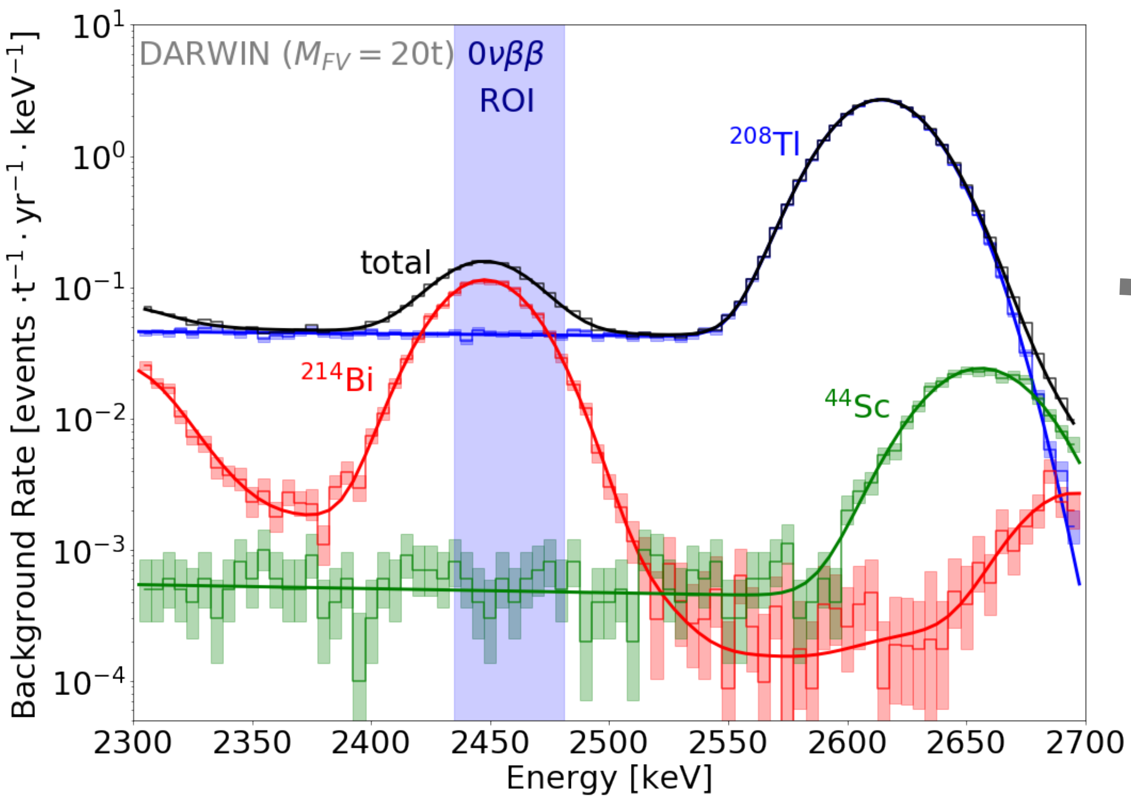
Minimise Background



MATERIAL BACKGROUND: ZOOM AROUND Q-value

DARWIN Collaboration, Eur. Phys. J. C 80, 808 (2020)

Example for 20t (same behaviour for smaller FV)

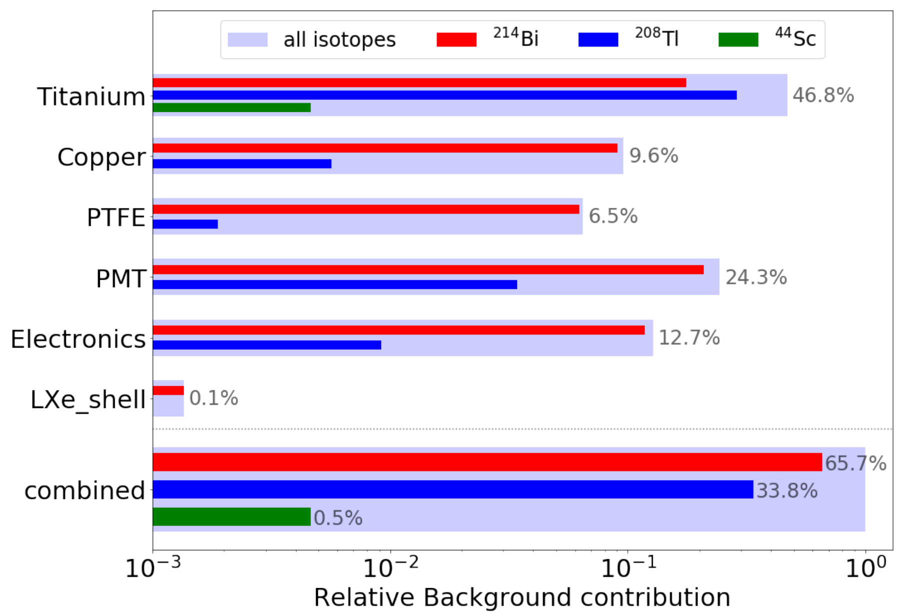


DARWIN ROI for $0\nu\beta\beta$:

Q-value ± FWHM/2

(2435 - 2481 keV)

Mainly from the cryostat and the PMTs



The main external background in the ROI:

- ^{214}Bi absorption peak (2.45 MeV)
- Compton scattered photons from ^{208}Tl

INTRINSIC BACKGROUNDS

DARWIN Collaboration, Eur. Phys. J. C 80, 808 (2020)

- ^{222}Rn in the LXe:
  - Assumption: 0.1 μBq/kg
  - 10 times lower than XENONnT
  - 99.8 % BiPo tagging efficiency

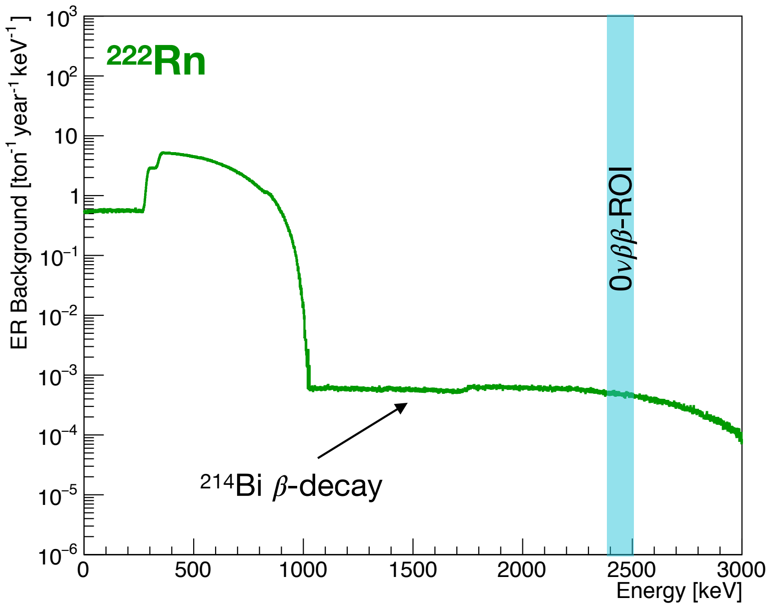
- Irreducible ^{8}B solar neutrinos (ν-e $\rightarrow \nu$-e):

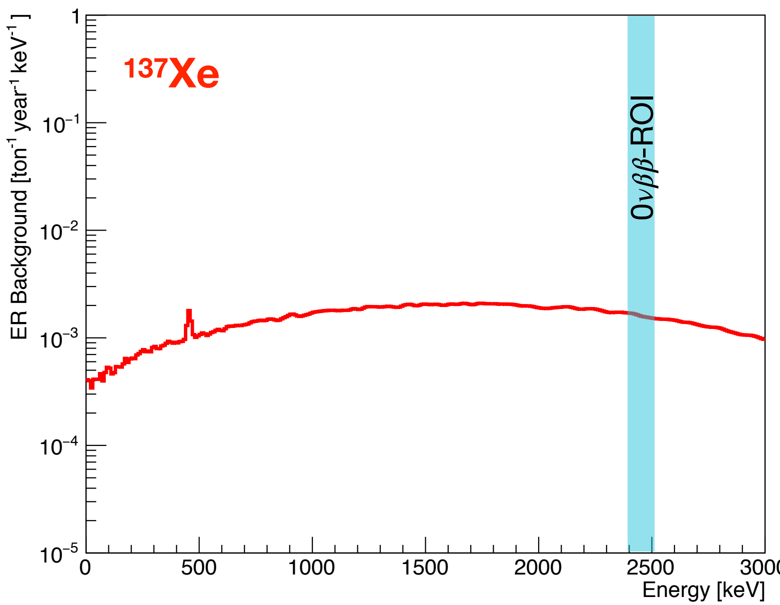
- 2νbb decay of ^{136}Xe.
  - Subdominant due to the energy resolution

- ^{137}Xe from cosmogenic activation underground:

n + ^{136}Xe —> ^{137}Xe

  - Beta decay, $Q_{\text{-value}}$ = 4173 keV
  - Half-life 3.82 min
  - Potential background for a depth of 3500 m.w.e

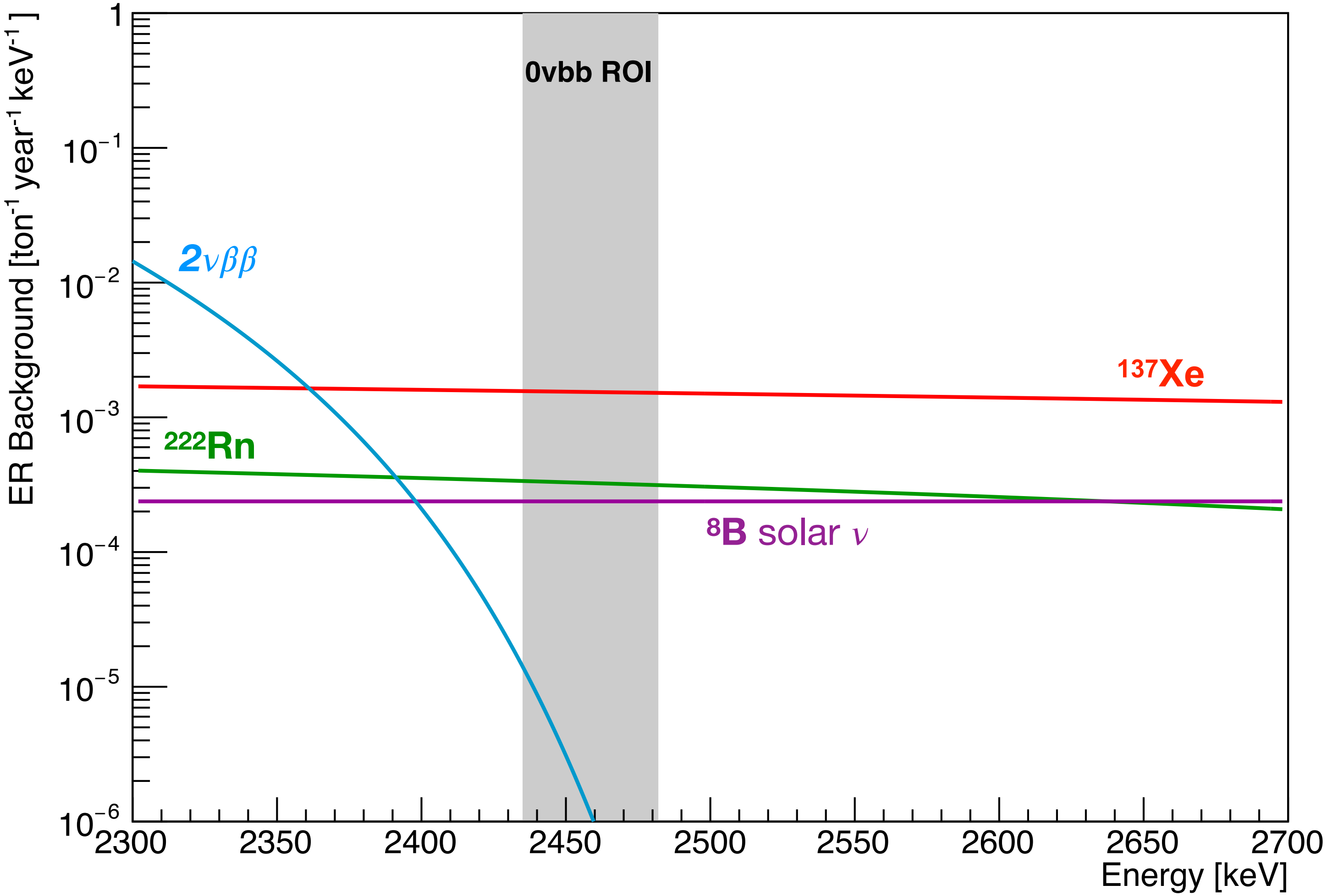




INTRINSIC BACKGROUNDS: ZOOM AROUND Q-value

DARWIN

DARWIN Collaboration, Eur. Phys. J. C 80, 808 (2020)



^{137}Xe

production rate from simulations (for LNGS depth)

(6.9 ± 0.4) atoms/(t·yr)

$2\nu\beta\beta$

assuming a measured half-life, $T_{1/2}$

(2.165 ± 0.061)x10^{21} yr

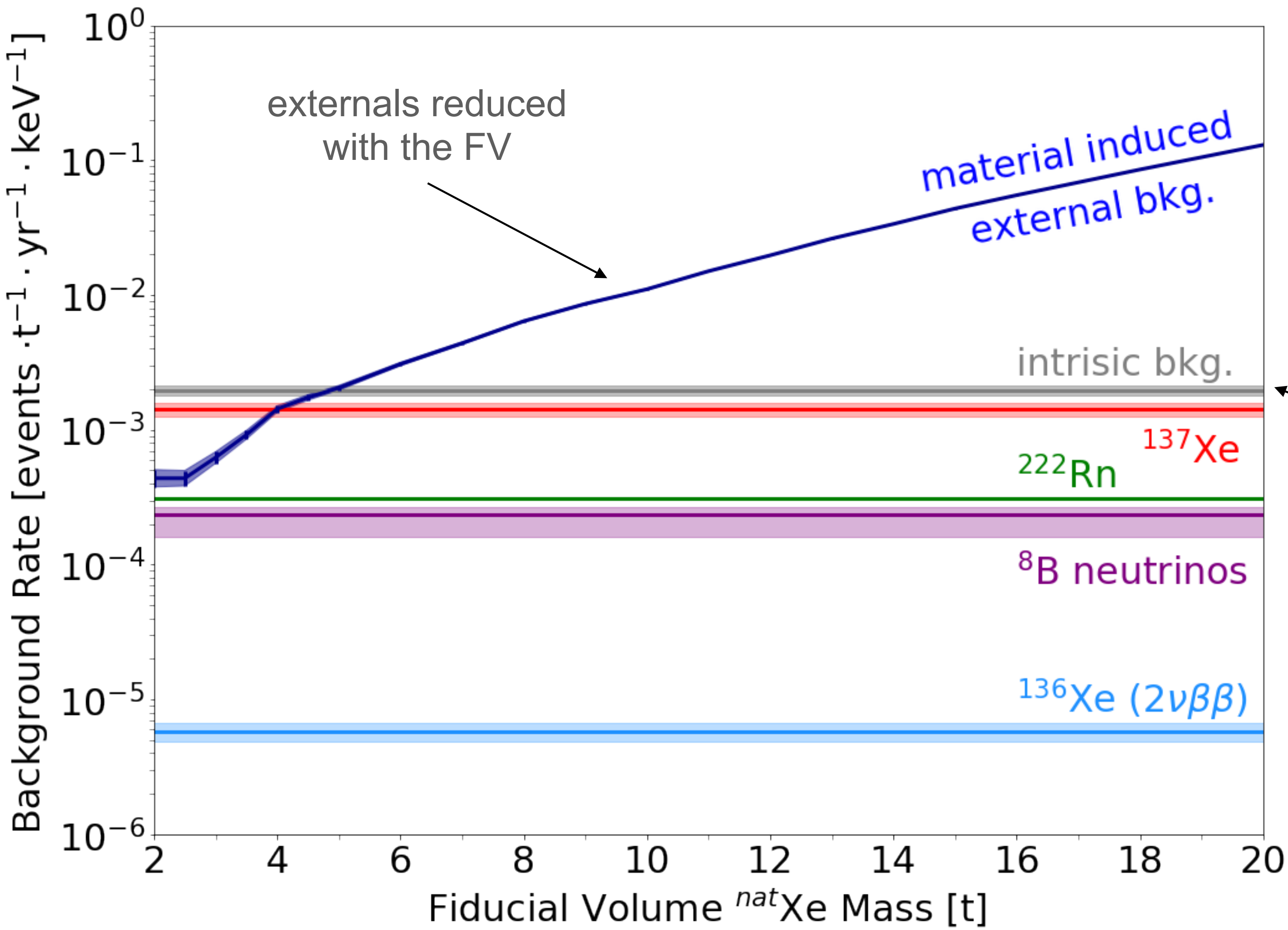
EXO-200 Collaboration, Phys. Rev. C89 (2014) 015502

Sitting DARWIN at LNGS, the intrinsic backgrounds will be dominated by the ^{137}Xe

TOTAL BACKGROUND: MATERIALS + INTRINSICS

DARWIN Collaboration, Eur. Phys. J. C 80, 808 (2020)

Looking for the optimal fiducial mass:



Minimize background without penalizing the exposure

$$T^{0\nu}_{1/2} \propto \frac{\sqrt{Mt}}{\sqrt{B \Delta E}}$$

intrinsics do not change with the fiducialization

TOTAL BACKGROUND: MATERIALS + INTRINSICS

DARWIN

DARWIN Collaboration, Eur. Phys. J. C 80, 808 (2020)

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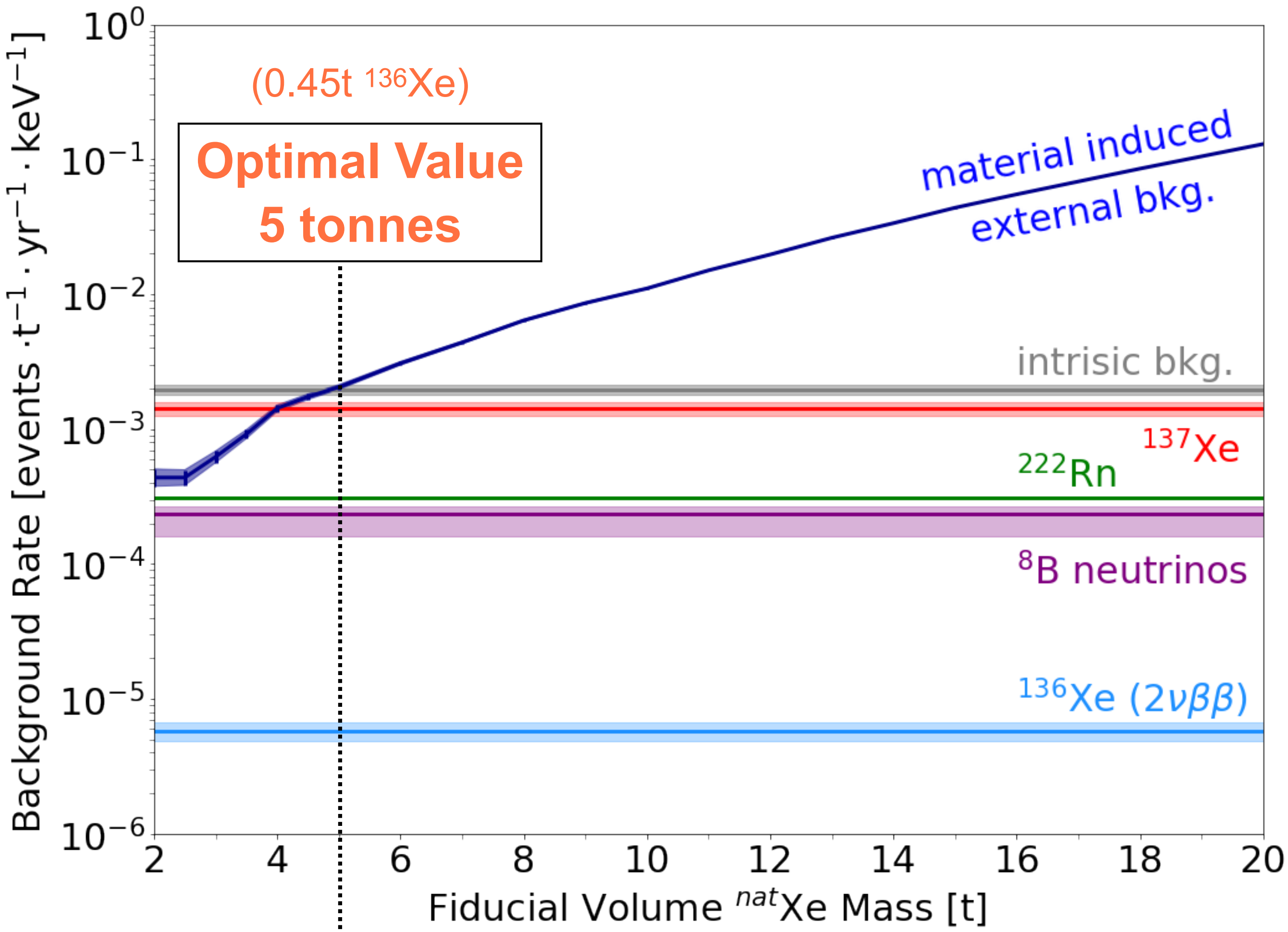


Minimize background without penalizing the exposure

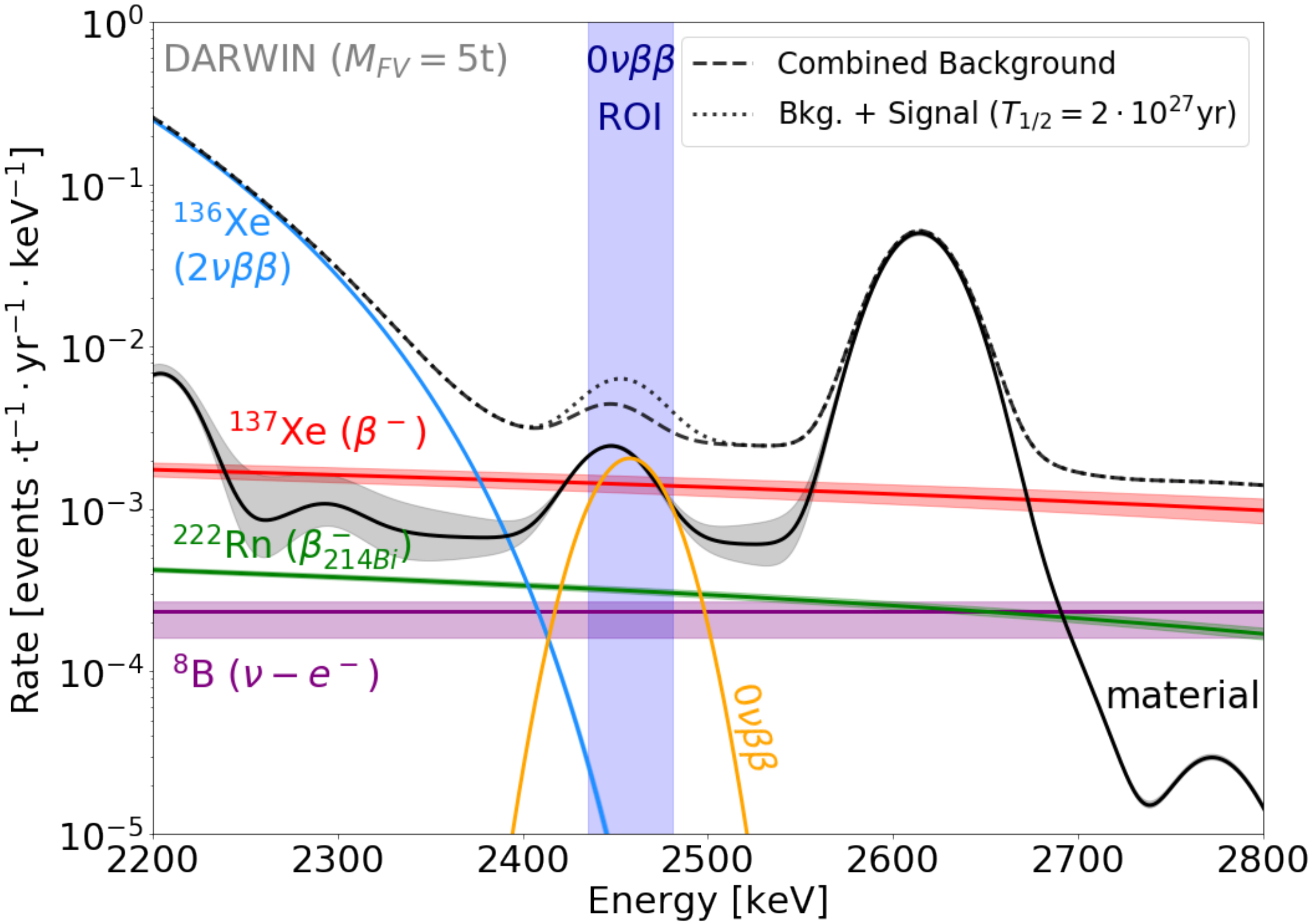
$$T^{0\nu}_{1/2} \propto \frac{\sqrt{Mt}}{\sqrt{B\Delta E}}$$

This value maximize our sensitivity

TOTAL BACKGROUND FOR 5t FV

DARWIN

DARWIN Collaboration, Eur. Phys. J. C 80, 808 (2020)



Background source	FV scenario: 5 t Events in ROI/(t·y·keV)
Detector Material	2.0×10^{-3}
^{137}Xe	1.4×10^{-3}
^{222}Rn in LXe	3.1×10^{-4}
^{8}B neutrinos	2.4×10^{-4}
^{136}Xe $2\nu\beta\beta$	5.8×10^{-6}
TOTAL	**3.96×10^{-3}**

B = 0.91 events/yr

Less than 1 event per year in the ROI !!

The hypothetical $0\nu\beta\beta$ signal in the plot has a strength of 0.5 events/y ($T_{1/2} \approx 2 \times 10^{27}$ years)

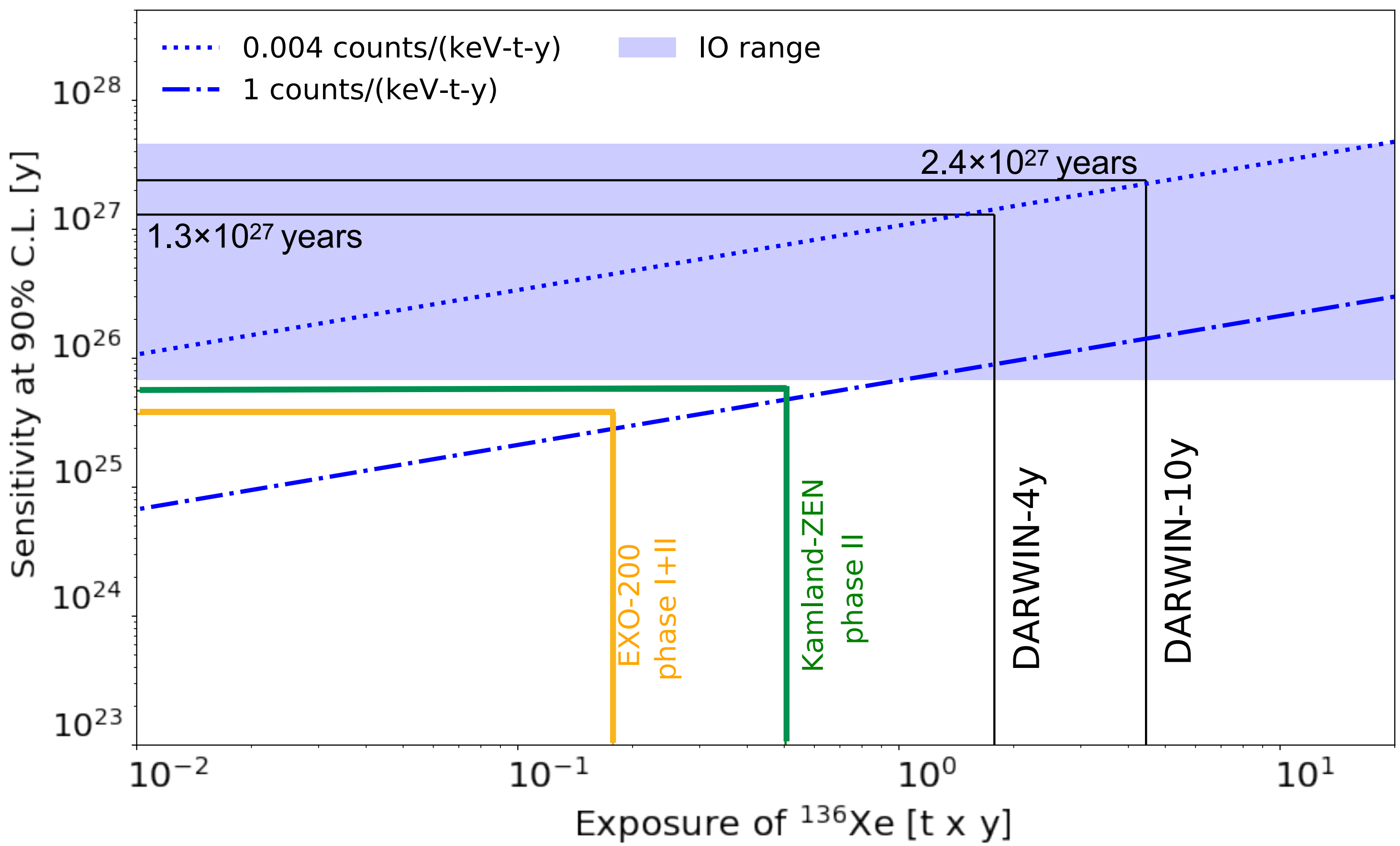
EXPECTED SENSITIVITY FOR THE BASELINE DESIGN

DARWIN

DARWIN Collaboration, Eur. Phys. J. C 80, 808 (2020)

Profile likelihood analysis for the sensitivity:

DARWIN will reach a sensitivity at 90% C.L of **2.4×10^{27} years**
for a 5t × 10 year exposure



In case of signal

Discovery potential at 3σ after 10 years of data:

1.1×10^{27} years

- EXO-200 Collaboration, Phys. Rev. Lett. **120**, 072701 (2018)
- KamLAND-Zen Collaboration, Phys. Rev. Lett. **117**, 082503 (2016)

IMPROVED SCENARIOS

DARWIN Collaboration, Eur. Phys. J. C 80, 808 (2020)

- Baseline scenario not optimised for 0vbb
- Pre-achieved radio-purity of materials

What could be improved?

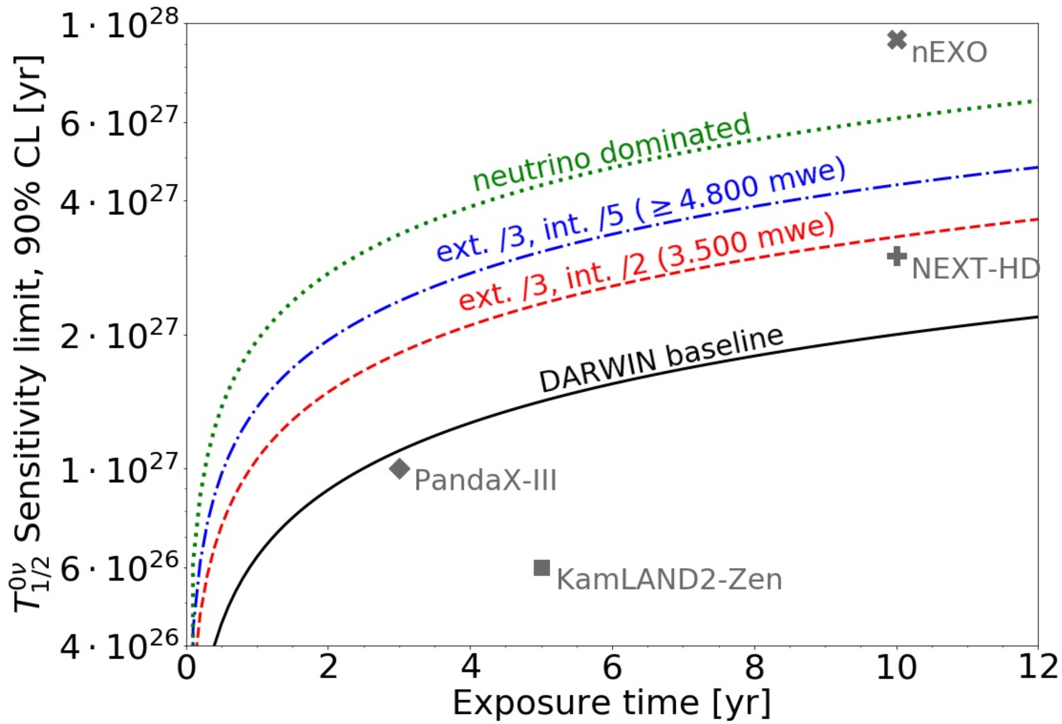
(1) **Reduce external background**

- top array of SiPMs
- bottom array of cleaner PMTs
- identify cleaner materials (PTFE, Ti)
- cleaner electronics

(2) **Reduce internal background**

- time veto for the ^{137}Xe
- deeper lab
- better BiPo tagging technics

(3) **Improve SS/MS discrimination**



ROOM FOR IMPROVEMENT !!

DARWIN could reach a sensitivity of **6×10^{27} years**

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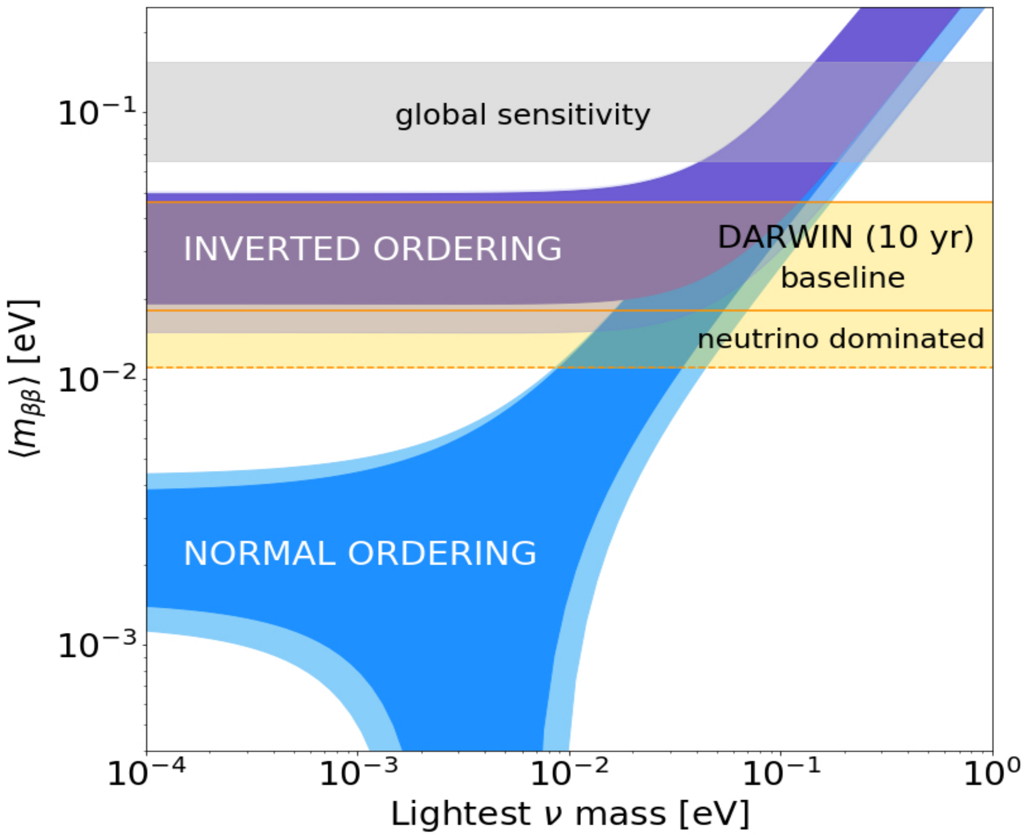

ROOM FOR IMPROVEMENT !!

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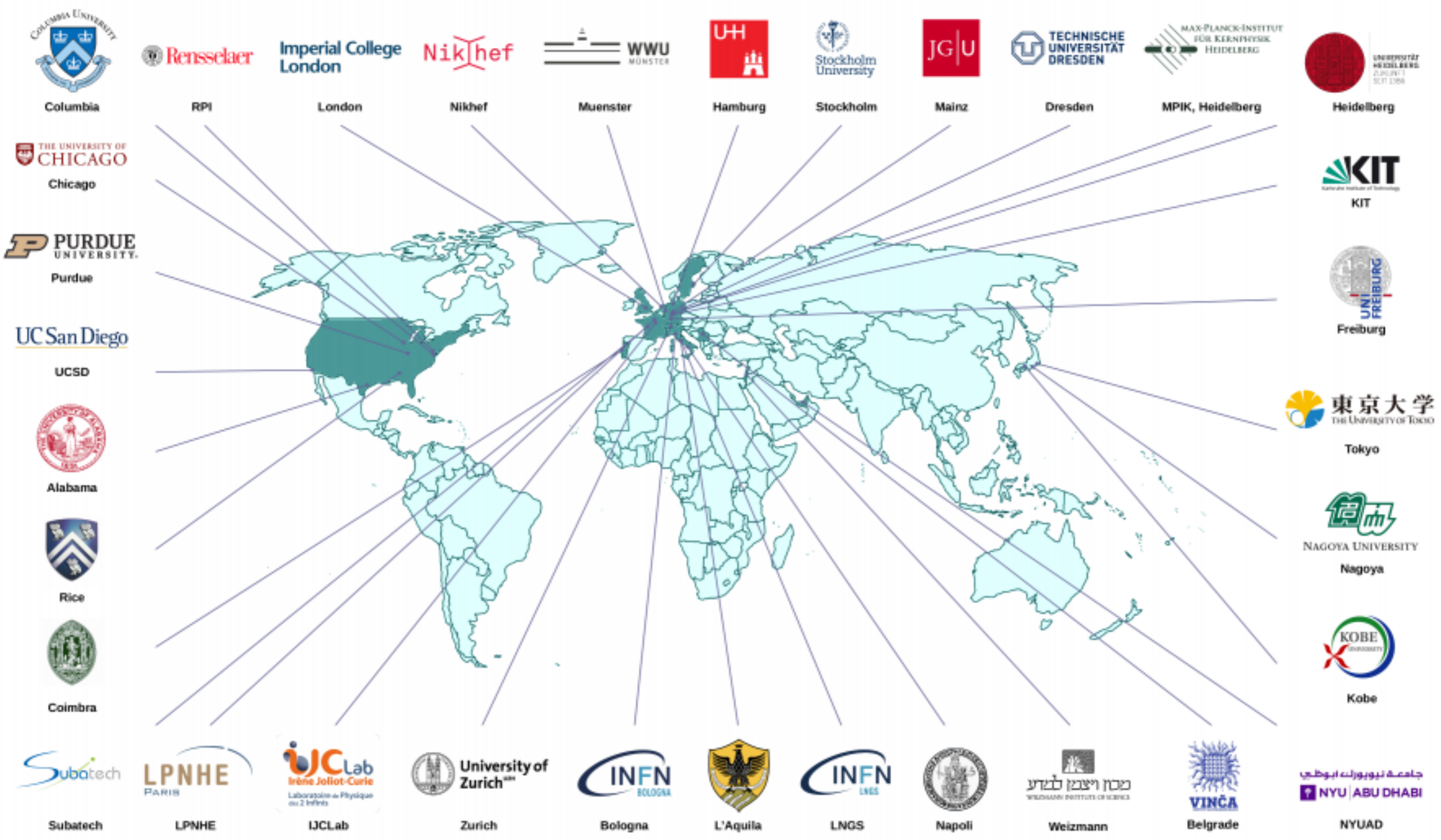
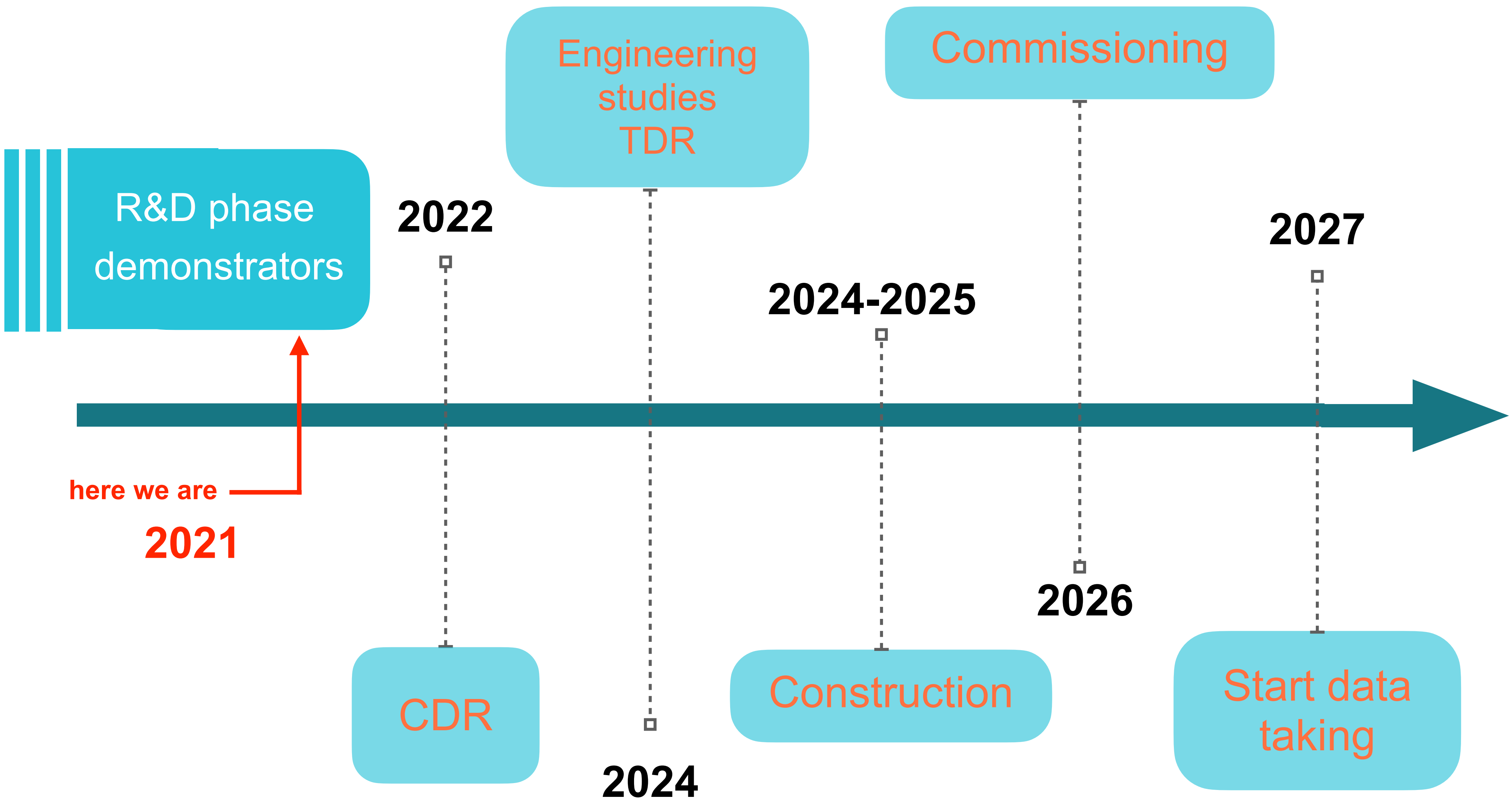
OVERVIEW OF THE DARWIN COLLABORATION

- More than 170 members from 33 institutions in 11 countries and growing…



www.darwin-observatory.org

DARWIN TIME SCALE



★ 2019: LoI submission to LNGS, invited to submit a CDR

ONGOING R&D: DEMONSTRATORS

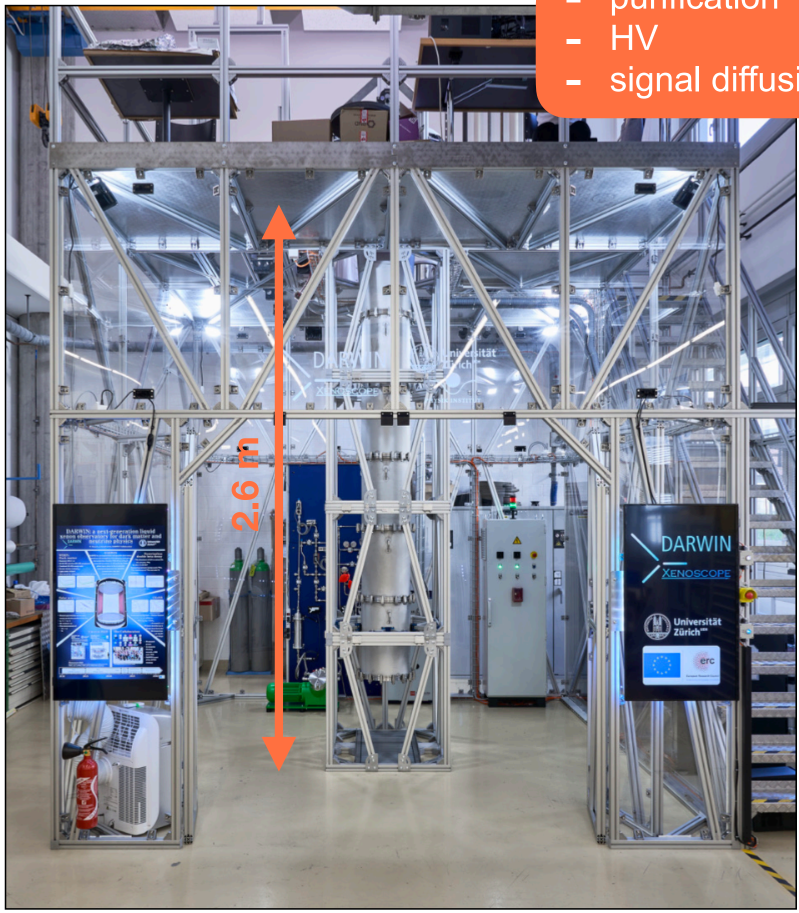
DARWIN

DARWIN full-length demonstrator

Universität Zürich[UZH]

The main goal is the demonstration of the electron drift over the full height of DARWIN

- purification
- HV
- signal diffusion



DARWIN full-(x,y) scale demonstrator

UNI FREIBURG

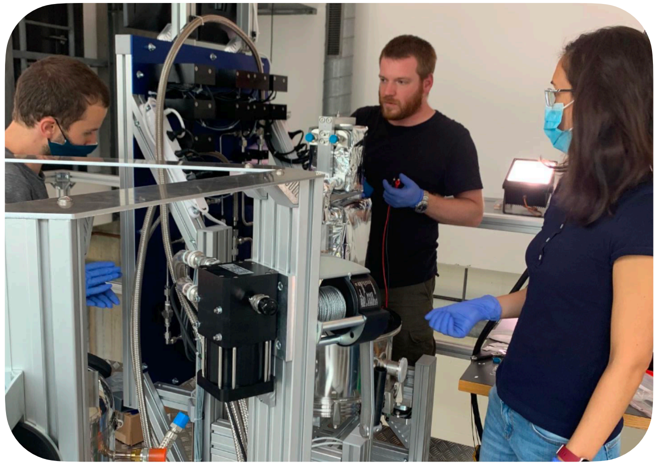
The main goal is to test components at real diameter under real conditions

- flatness of electrodes
- strength of the extraction field
- x-y homogeneity of the drift field

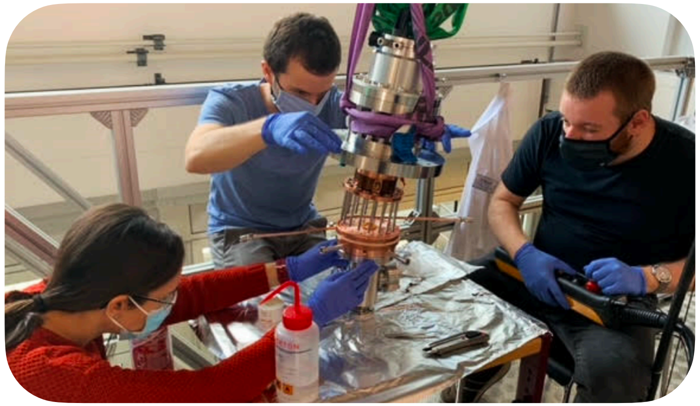
COMMISSIONING OF THE ZURICH DEMONSTRATOR

Commissioning started at the beginning of 2021

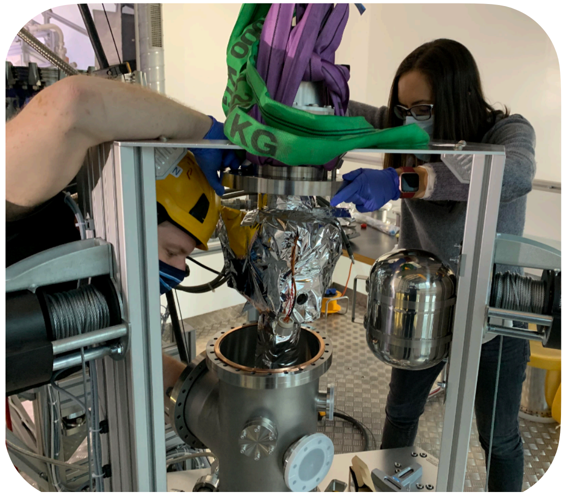
Installation Heat Exchanger



Installation Cold Head Cryo-Tower



Assembly Cryo-Tower

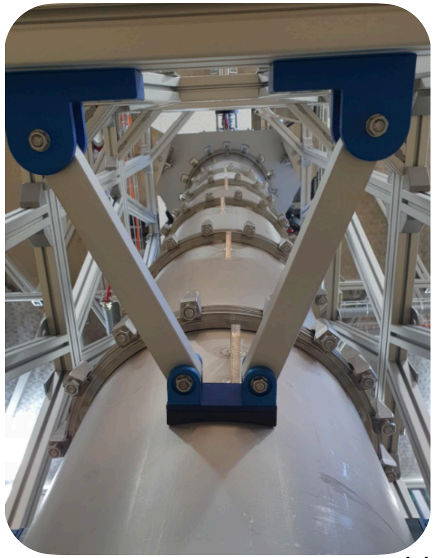


Assembly Storage Array

Assembly Inner Vessel

Mylar Installation

Assembly Outer Vessel



Universität Zürich[UZH]

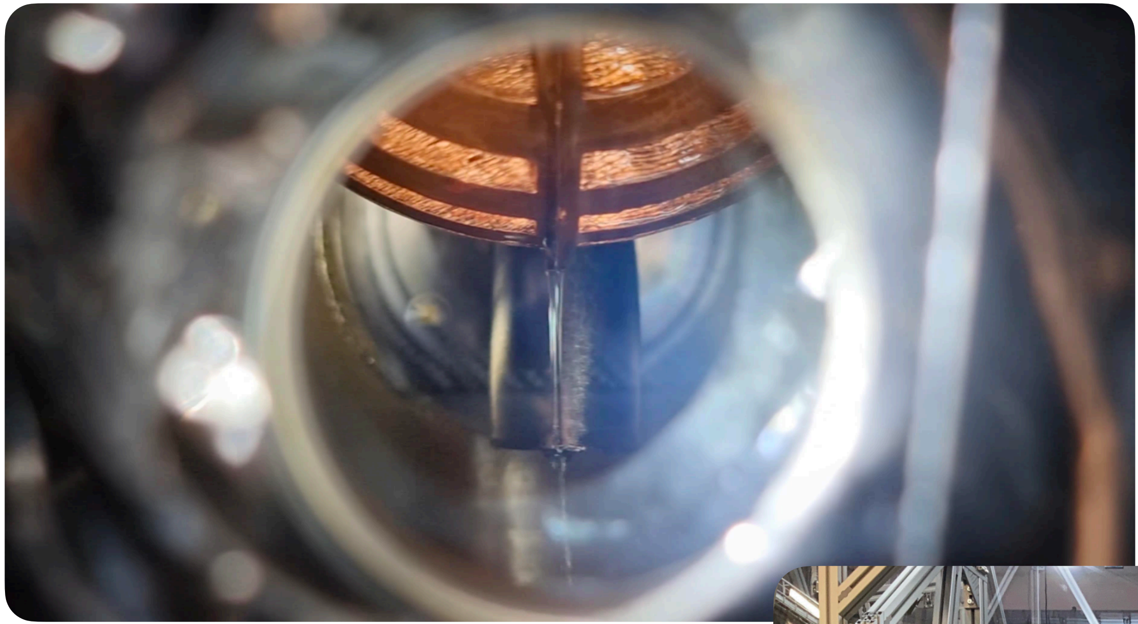
erc European Research Council Established by the European Commission

MARCH 2021: FIRST LXe FILL

DARWIN

Universität Zürich[UZH]

erc European Research Council
Established by the European Commission



LXe flow from the view port

First LXe fill successfully achieved in the DARWIN vertical demonstrator

- Facility if fully operational
- Commissioning run underway
- The best is yet to come…

Part of the Xenoscope team

SUMMARY

- DARWIN observatory: excellent sensitivity for dark matter and neutrino physics
- The large mass (50t), low-energy threshold and ultra-low background, offer the possibility of **a broad physics programme:**
  - WIMP dark matter (sensitivity down to the neutrino floor)
  - Low energy solar neutrinos (1% precision in pp flux after 1 year of data)
  - Neutrinoless double-beta decay (half-life sensitivity of 2.4×10^{27} years)
  - and much more …
- DARWIN is a growing collaboration, currently **33 institutions from 13 countries**.
- R&D and prototypes in their way
  - CDR for the end of 2022

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Thank you for your attention!!