Sensitivity of the DARWIN observatory to the neutrinoless double beta decay of 136-Xe

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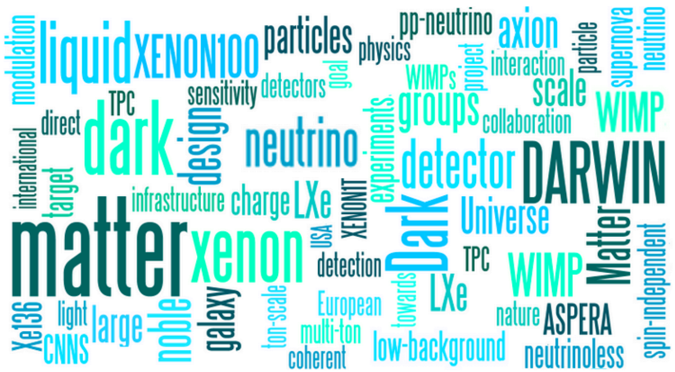
EXPERIMENTAL PARTICLE AND ASTRO-PARTICLE PHYSICS SEMINAR

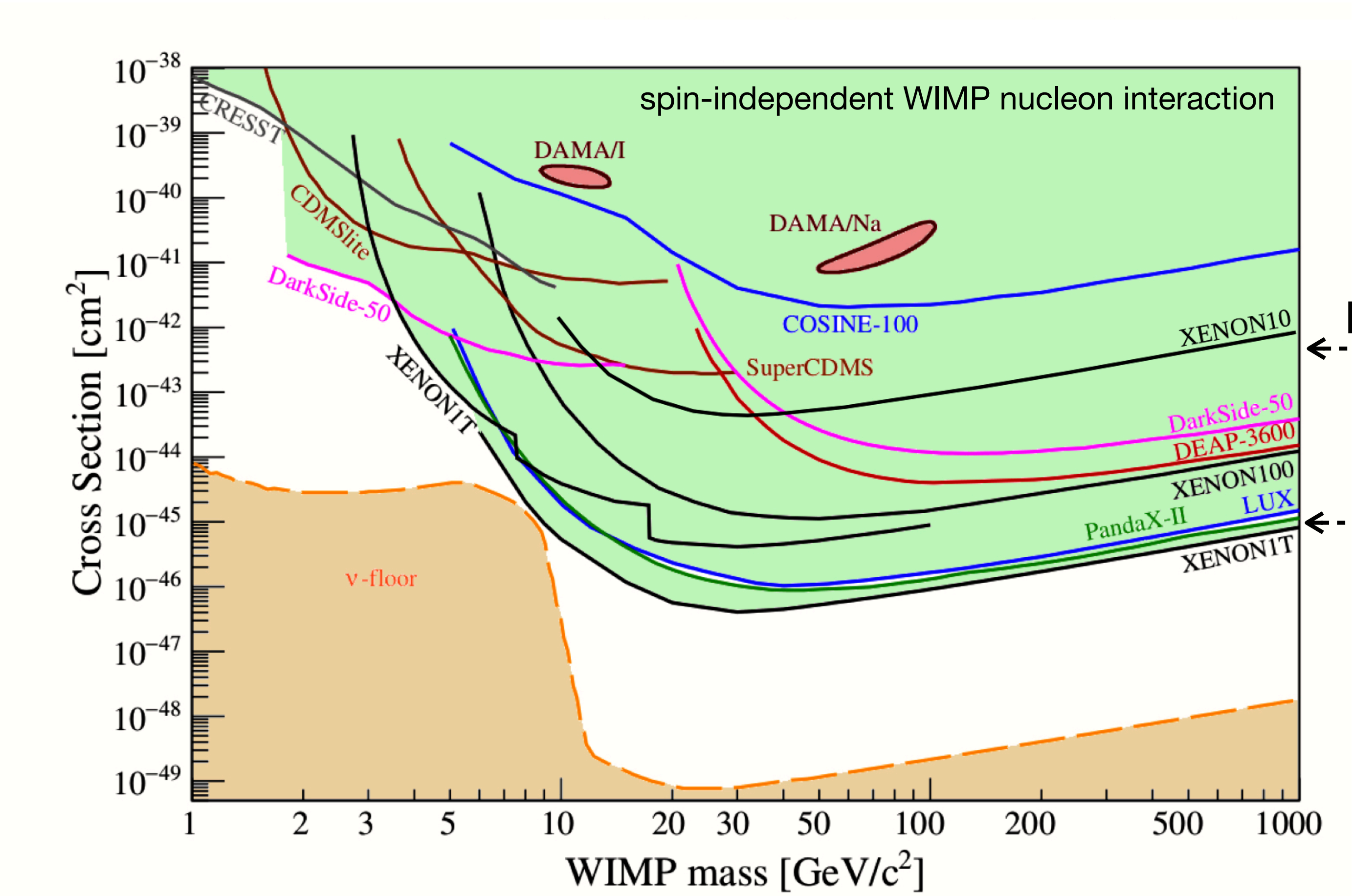
27 April 2020

www.darwin-observatory.org



WIMP DETECTION LANDSCAPE TODAY

- The best sensitivity above 5 GeV/c^2 comes from experiments using liquid noble gases as target (Xe, Ar). (heavy target and easy scalability)
- **DARWIN**, the ultimate LXe WIMP detector, with **50t of total target**, plans to increase 100-fold the current sensitivity.



Past Limits

Current Limits

DARWIN

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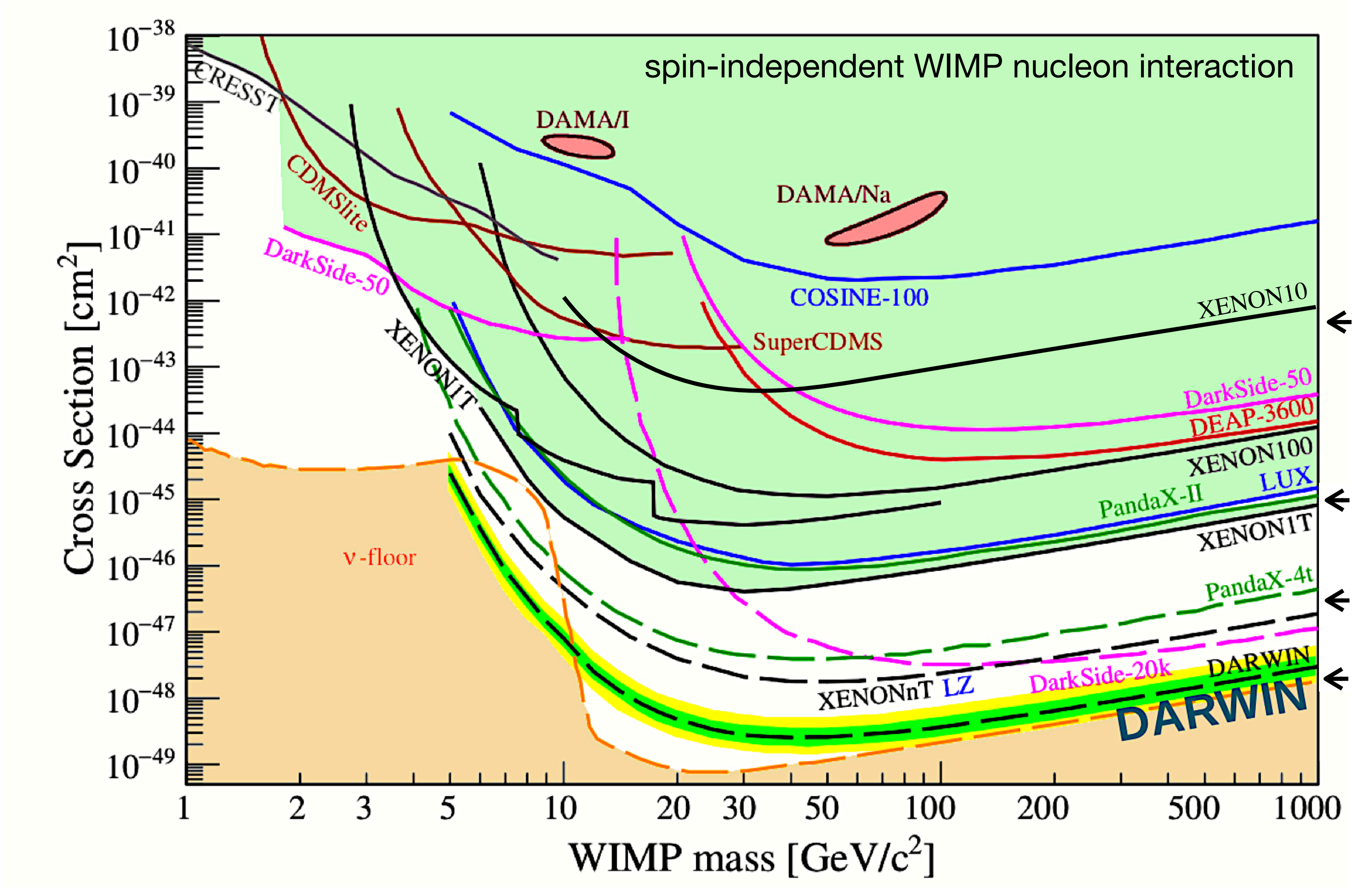


Past Limits

Current Limits

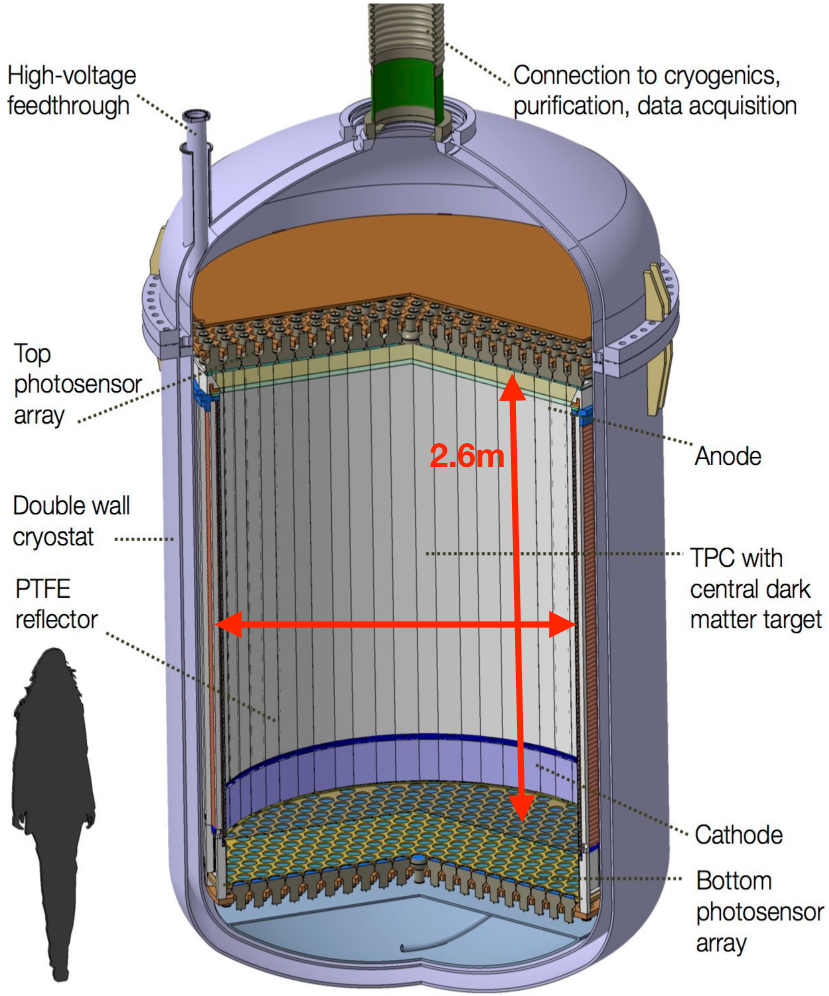
Near Future Sensitivity

DARWIN

sensitivity limited by he neutrino floor

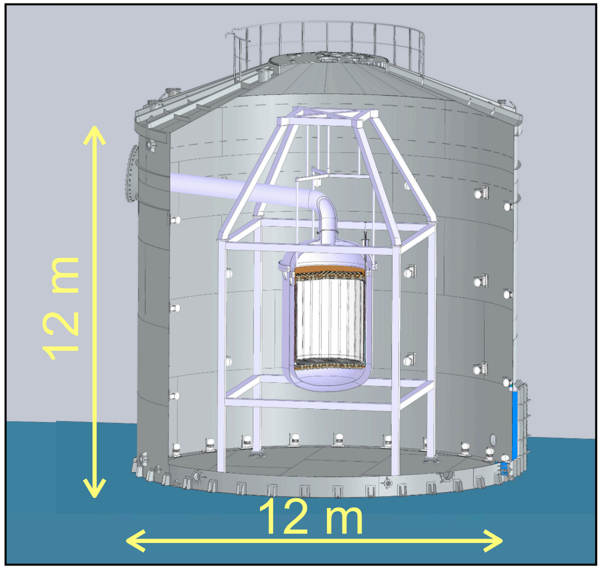
DARWIN BASELINE DESIGN

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 and 2.6 m height.**
- Two arrays of photosensors (top and bottom).
- 1800 PMTs of 3” diameter (~1000 of 4”).
- Low-background double-wall cryostat.
- PTFE reflector panels & copper shaping rings.
- Outer shield filled with water (12 m diameter).



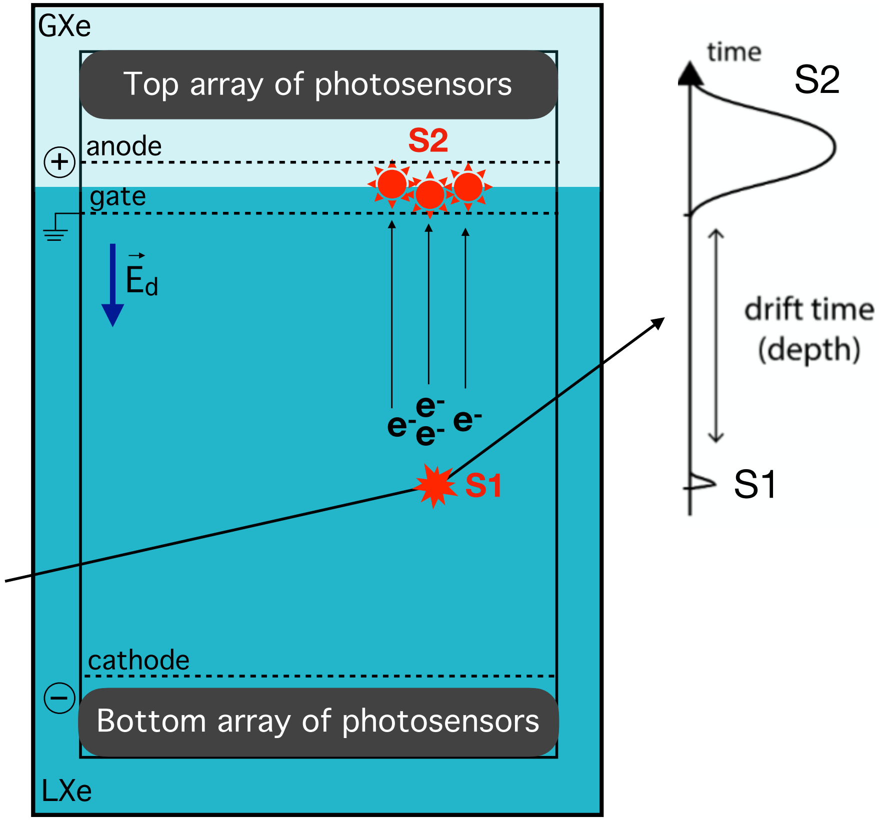
Possible realization of DARWIN inside the water tank

DARWIN

DUAL-PHASE XENON TPC

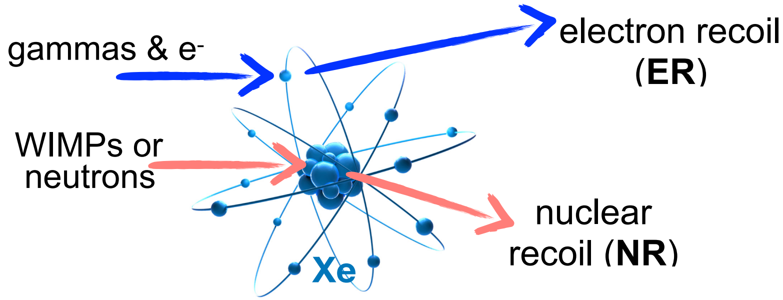
Dual phase TPC working principle

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



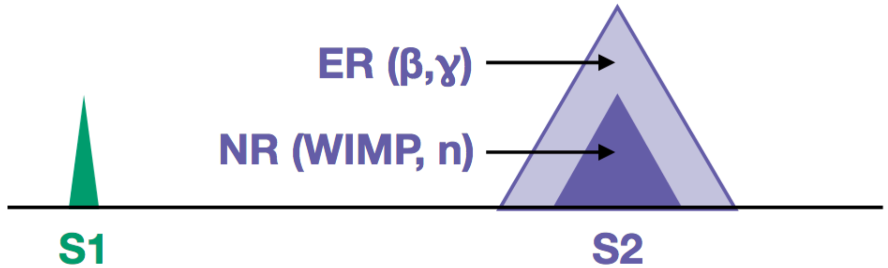
- The dual-phase TPC allows a 3D position reconstruction.
  x-y from the light sensors, z from the drift time

Particle interactions



- The ratio S2/S1 depends on the interacting particle.

Particle type discrimination



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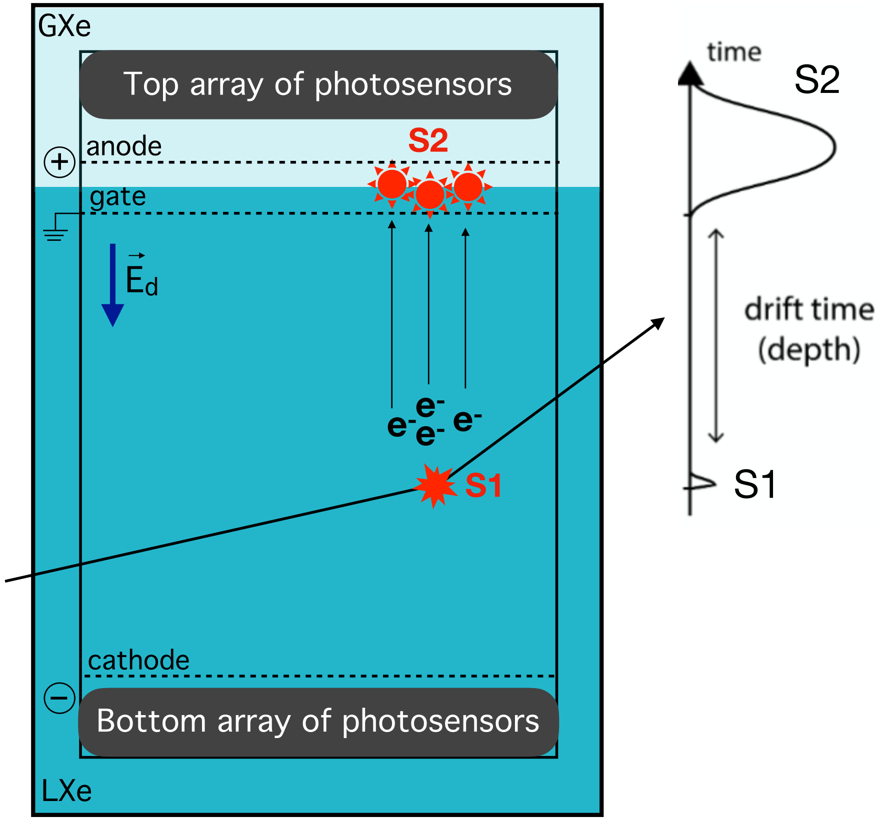

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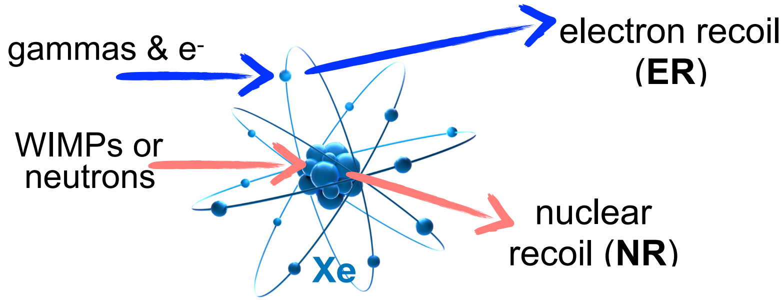

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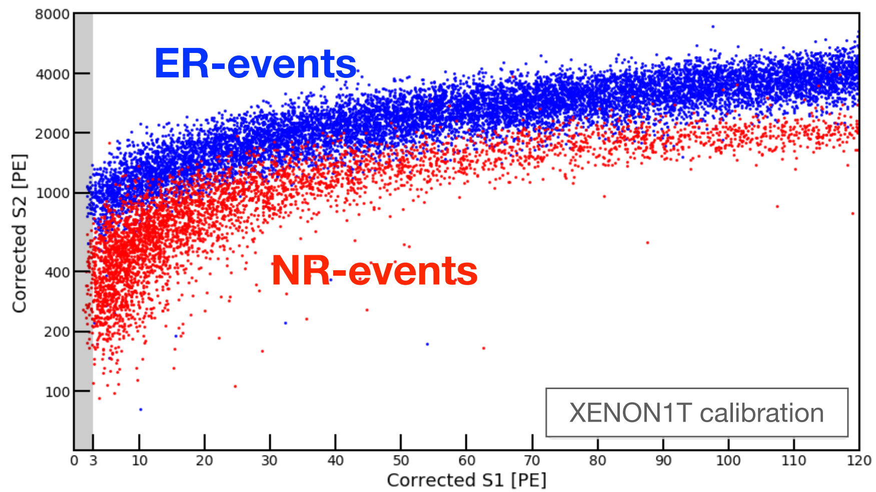
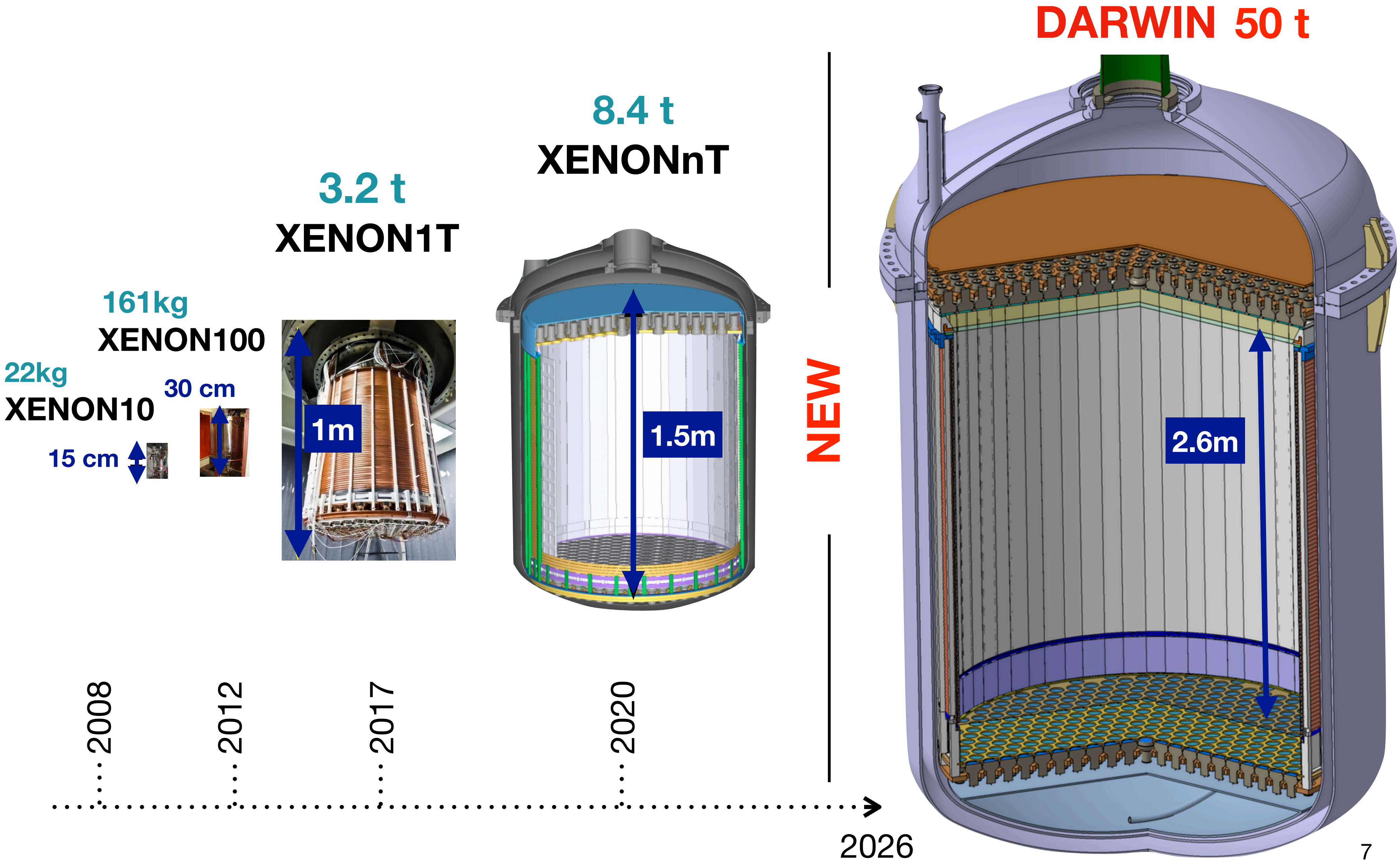


DARWIN IN THE CONTEXT OF THE XENON PROJECT



THE VARIETY OF PHYSICS CHANNELS

DIRECT DETECTION OF DARK MATTER

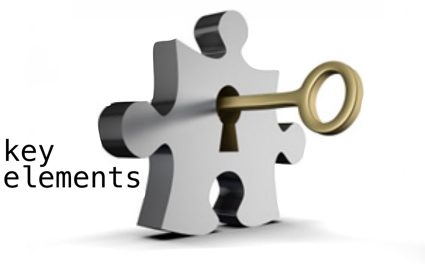
↓

DARWIN

THE VARIETY OF PHYSICS CHANNELS

DARWIN

Ultra-low Background —— **Large Mass (50t)** —— **Low Energy Threshold**



DIRECT DETECTION OF DARK MATTER

DARWIN

THE VARIETY OF PHYSICS CHANNELS

Ultra-low Background —— **Large Mass (50t)** —— **Low Energy Threshold**

DIRECT DETECTION OF DARK MATTER

DARWIN

much more than a dark matter detector

- SOLAR AXIONS
- GALACTIC AXION-LIKE PARTICLES
- BOSONIC SUPERWIMPs
- CNNS
- NEUTRINOLESS DOUBLE-BETA DECAY ^{136}Xe
- LOW-ENERGY SOLAR NEUTRINOS
- GALACTIC SUPERNOVA NEUTRINOS

THE VARIETY OF PHYSICS CHANNELS

DARWIN

Ultra-low Background — **Large Mass (50t)** — **Low Energy Threshold**

key elements

DIRECT DETECTION OF DARK MATTER

↓

DARWIN

much more than a dark matter detector

SOLAR AXIONS

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BOSONIC SUPERWIMPs

CNNS

NEUTRINOLESS DOUBLE-BETA DECAY ^{136}Xe

LOW-ENERGY SOLAR NEUTRINOS

GALACTIC SUPERNOVA NEUTRINOS

DOUBLE BETA DECAYS: SOME THEORY

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

Extremely rare nuclear process, but allowed in the Standard Model

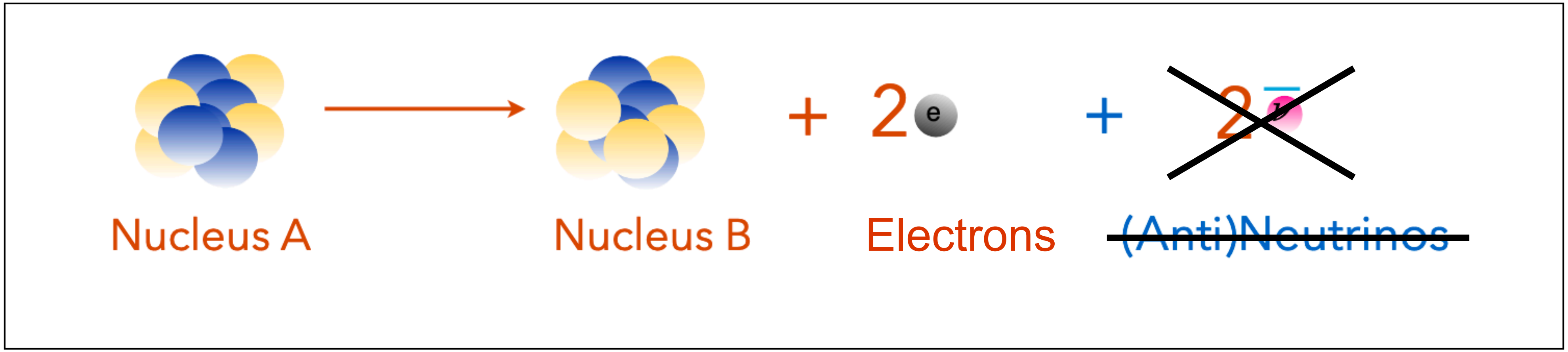
$$\Delta L = 0$$

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

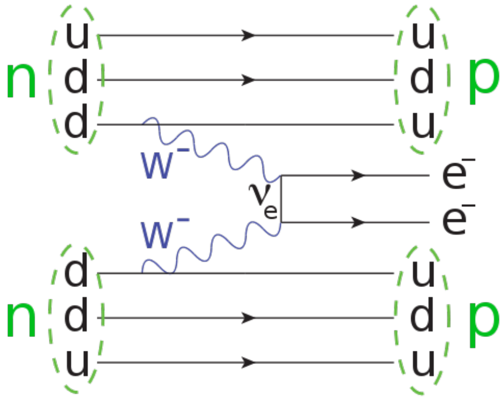
^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U

DOUBLE BETA DECAYS: SOME THEORY

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



Extremely rare nuclear process, NEVER OBSERVED BEFORE



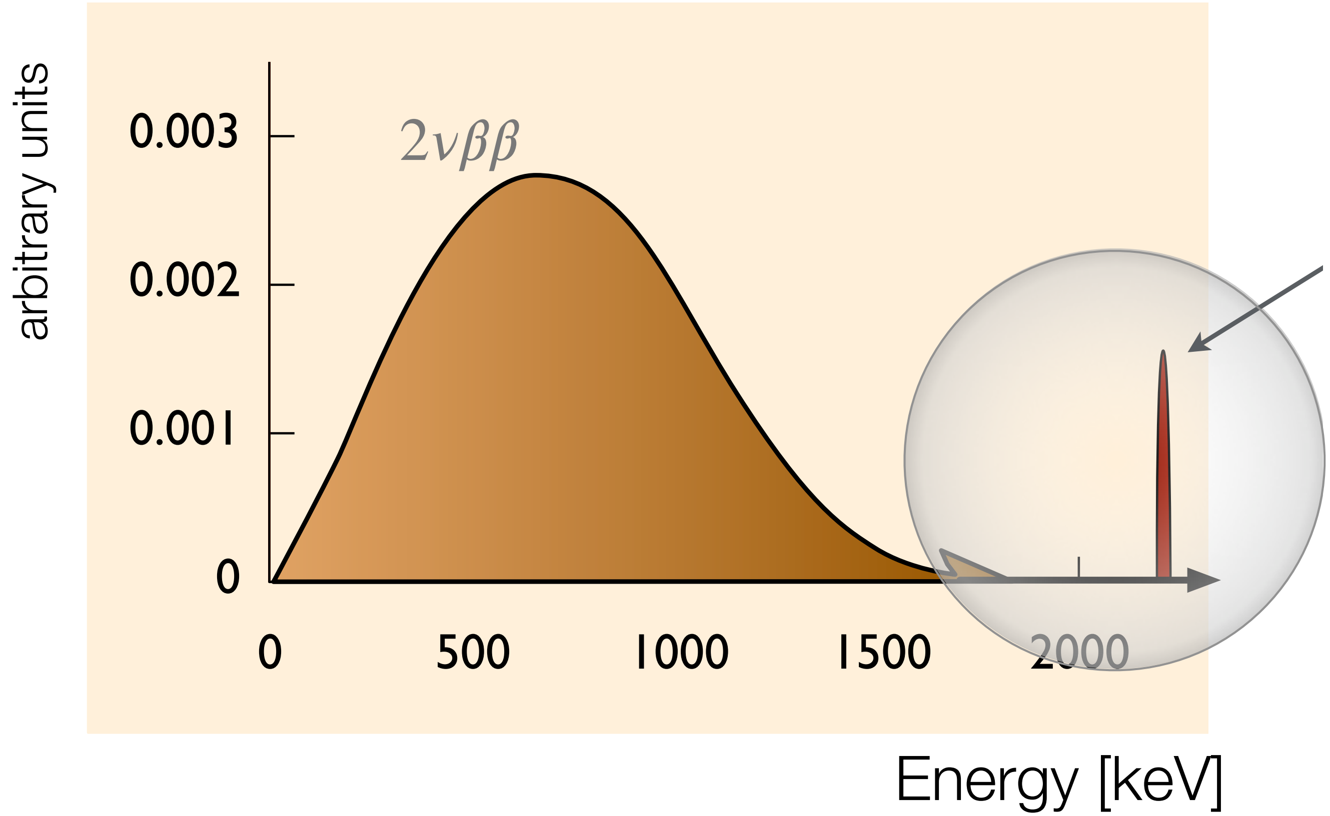
$\Delta L = 2$

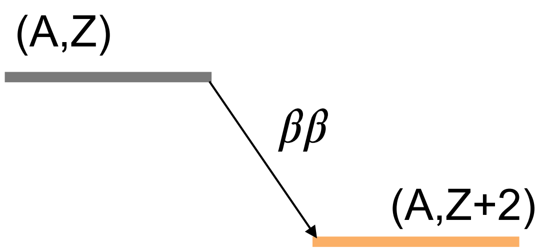
- ➢ Lepton number violation
- ➢ Neutrinos are their own anti-particle (Majorana fermions)

EXPECTED $0\nu\beta\beta$ SIGNAL

DARWIN

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

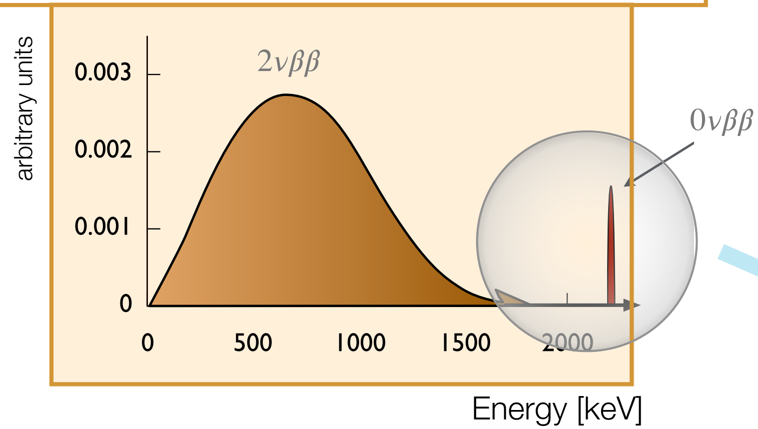




Q-value: mass difference between mother and daughter nucleus

WHAT DO WE NEED TO OBSERVE THIS SIGNAL?

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



① **Large mass of a candidate isotope**

② **Excellent energy resolution**

③ **Ultra-low background**

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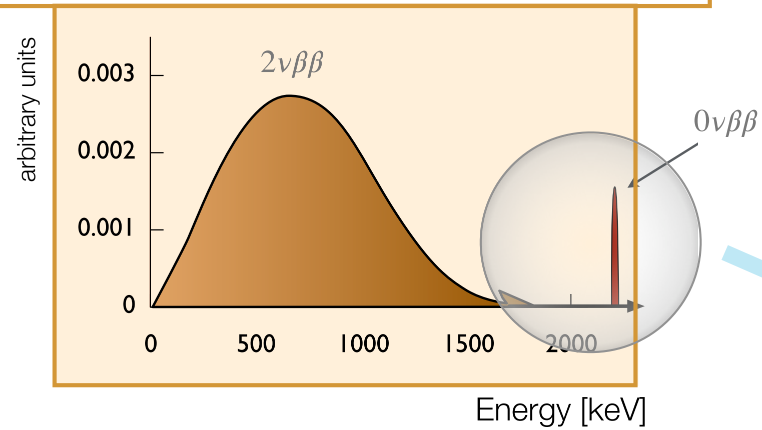

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DARWIN offers the possibility of looking for this process for FREE !!

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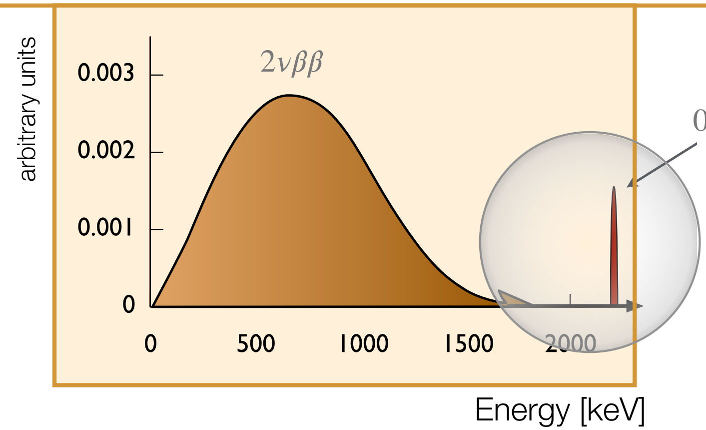

① **Large mass of a candidate isotope**

✓ 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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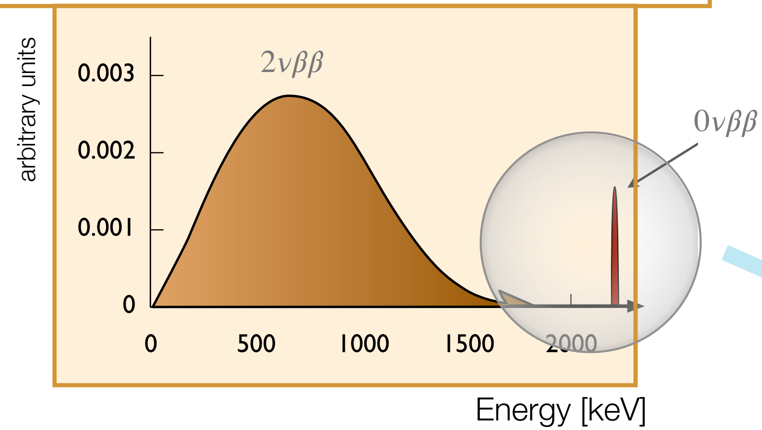

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- As demonstrated by XENON1T [arXiv:2003.03825]

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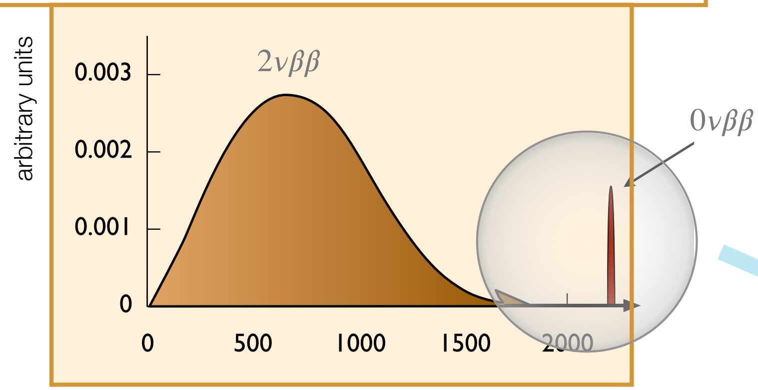

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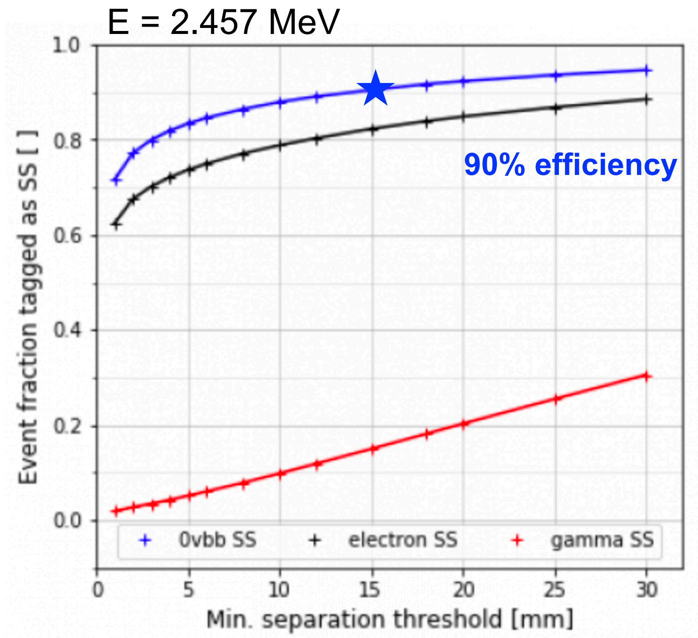
③ **Ultra-low background**

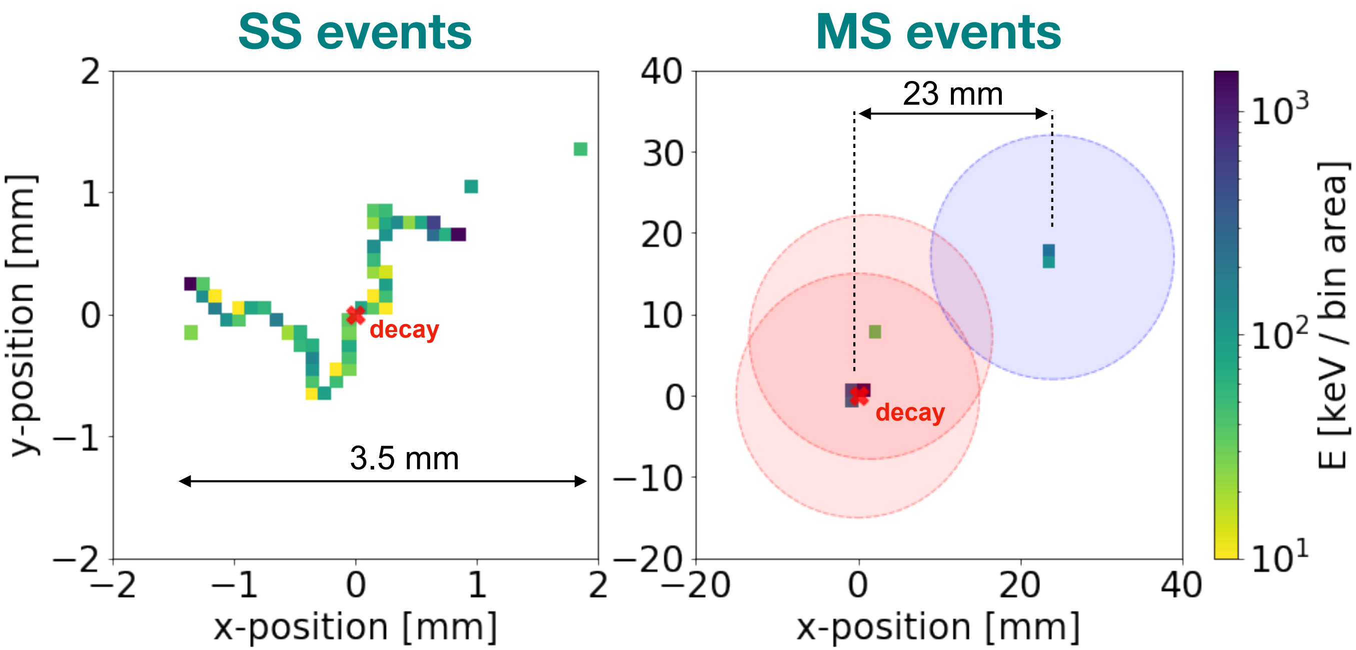
✓ Environment dominated by intrinsic backgrounds

- Material/external backgrounds subdominant
- Irreducible intrinsic background

SIGNAL TOPOLOGY IN LIQUID XENON

- 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)

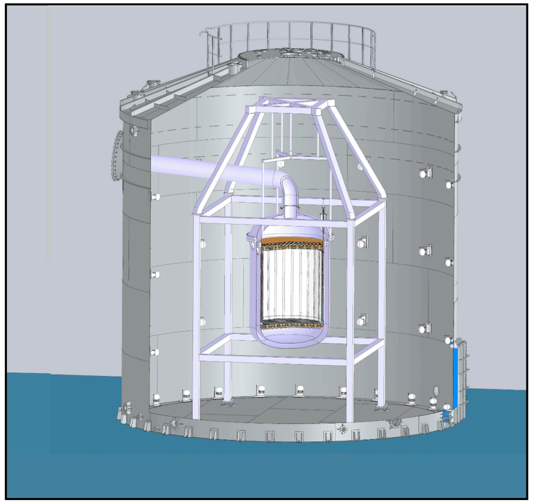




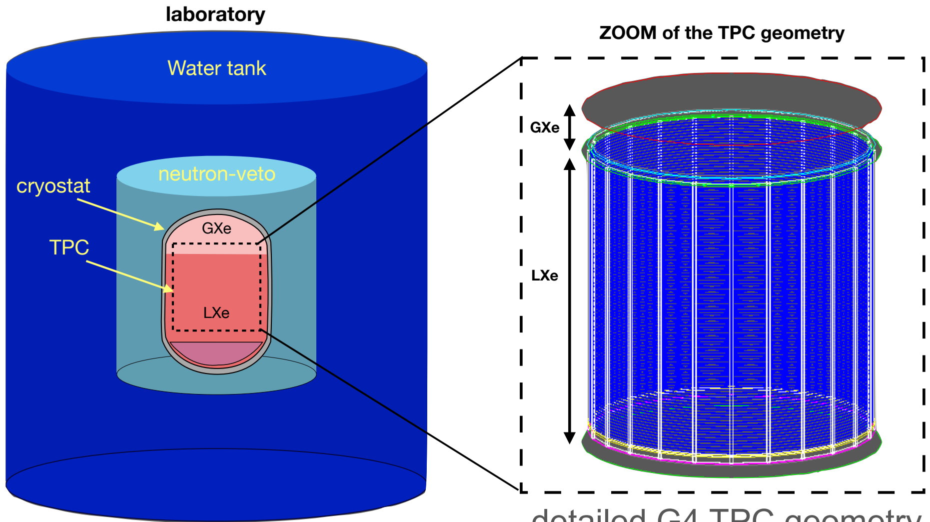
DEDICATED SIMULATIONS: DARWIN GEOMETRY

Detailed detector geometry in Geant4 following the baseline design

all the major components have been included



baseline design



sketch of the G4 geometry

detailed G4 TPC geometry

Simulation criteria

- Elements under considerations ➜ Simplified for modifications

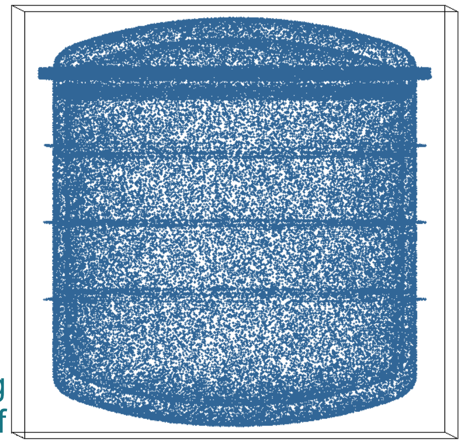
  example: PMTs vs SiPMs

  ➢ disks accounting for the proper amount of material

- Critical components for the BG ➜ Fully simulated in detail

  example: Double wall cryostat

Double Wall Cryostat

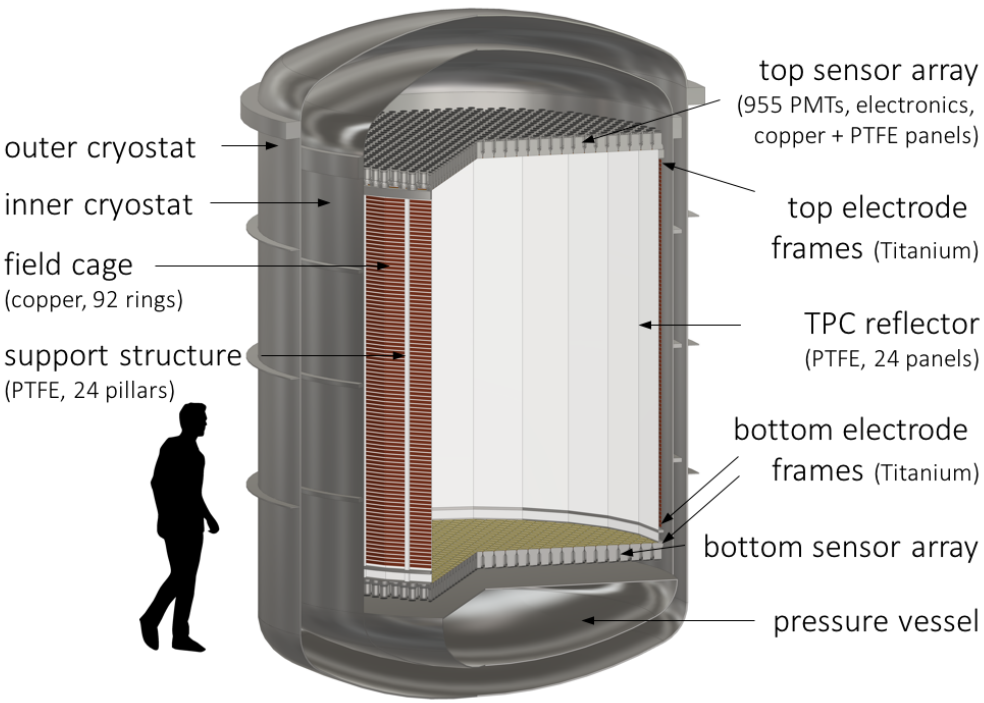


Based on engineering studies at Nikhef

MATERIAL/EXTERNAL BACKGROUNDS:

Detailed detector geometry in Geant4 following the baseline design

all the major components have been included



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

Assumed activity levels ➔ Conservative

upper limits as detection values

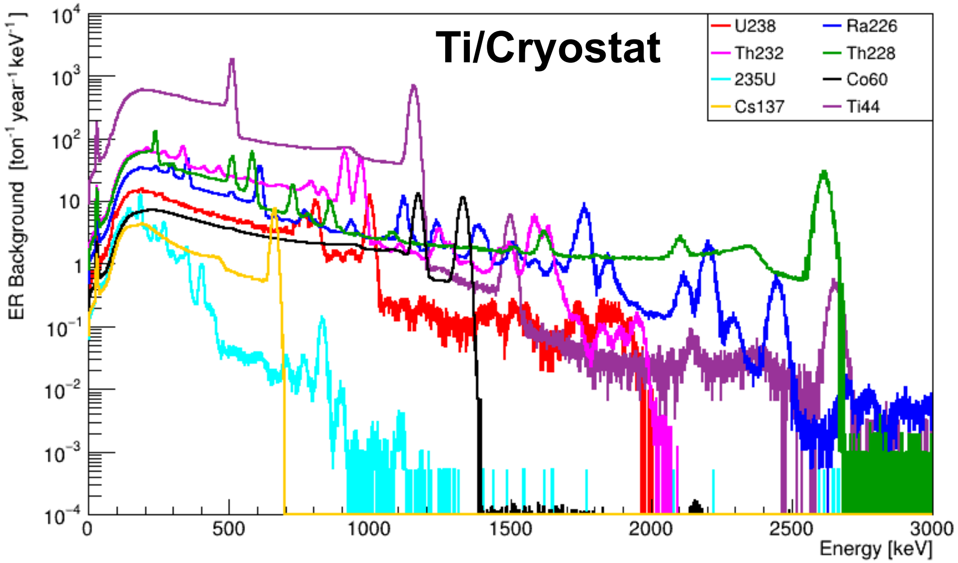
- LZ: *Astropart. Phys.* ***96*** *(2017) 01*
- XENON: *Eur. Phys. J. C* ***77*** *(2017) 12 890*

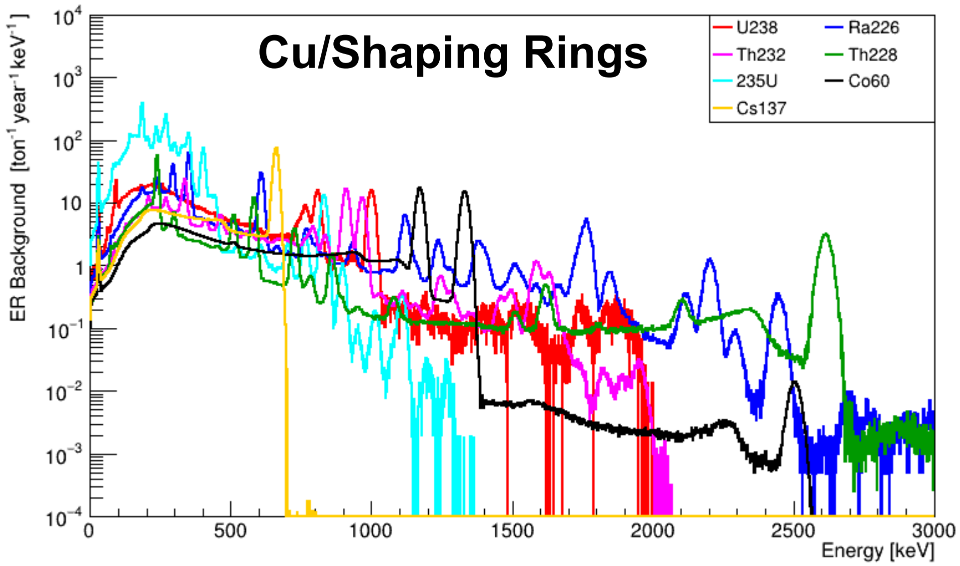
Material	Unit	^{238}U	^{226}Ra	^{232}Th	^{228}Th	^{60}Co	^{44}Ti	Reference
Titanium	mBq/kg	<1.6	<0.09	0.28	0.25	<0.02	<1.16	LZ
PTFE	mBq/kg	<1.2	0.07	<0.07	0.06	0.027	-	XENON
Copper	mBq/kg	<1.0	<0.035	<0.033	<0.026	<0.019	-	XENON
PMT	mBq/unit	8.0	0.6	0.7	0.6	0.84	-	XENON
Electronics	mBq/unit	1.10	0.34	0.16	0.16	<0.008	-	XENON

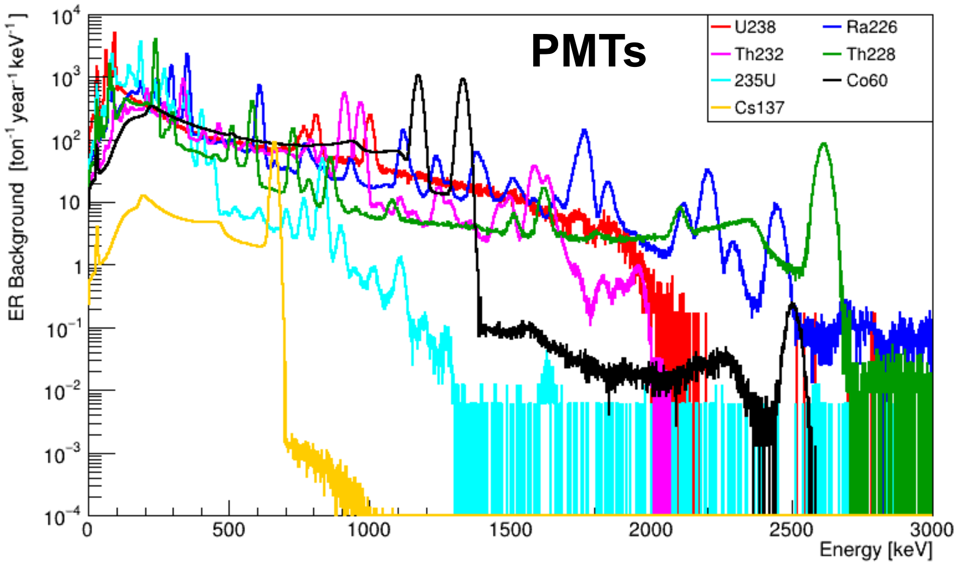
COMPONENTS OF THE MATERIAL BACKGROUNDS

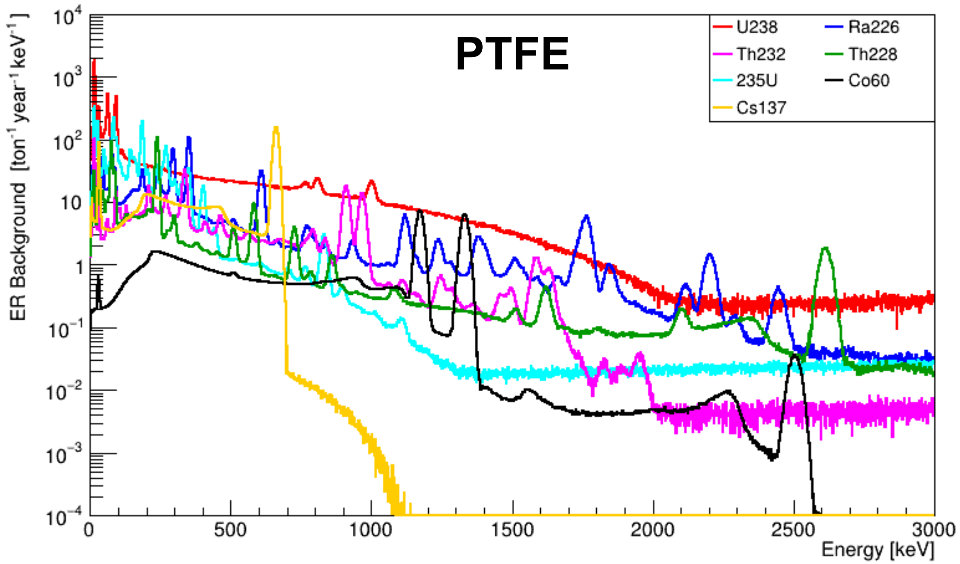
ER background spectra (single site events) for some materials with no fiducialization

➢ long-lived radiogenic nuclei, ^{238}U, ^{232}Th, ^{235}U, ^{60}Co, ^{137}Cs, ^{44}Ti









DEFINITION OF A FIDUCIAL VOLUME

DARWIN

Distribution of the external background events in the detector volume

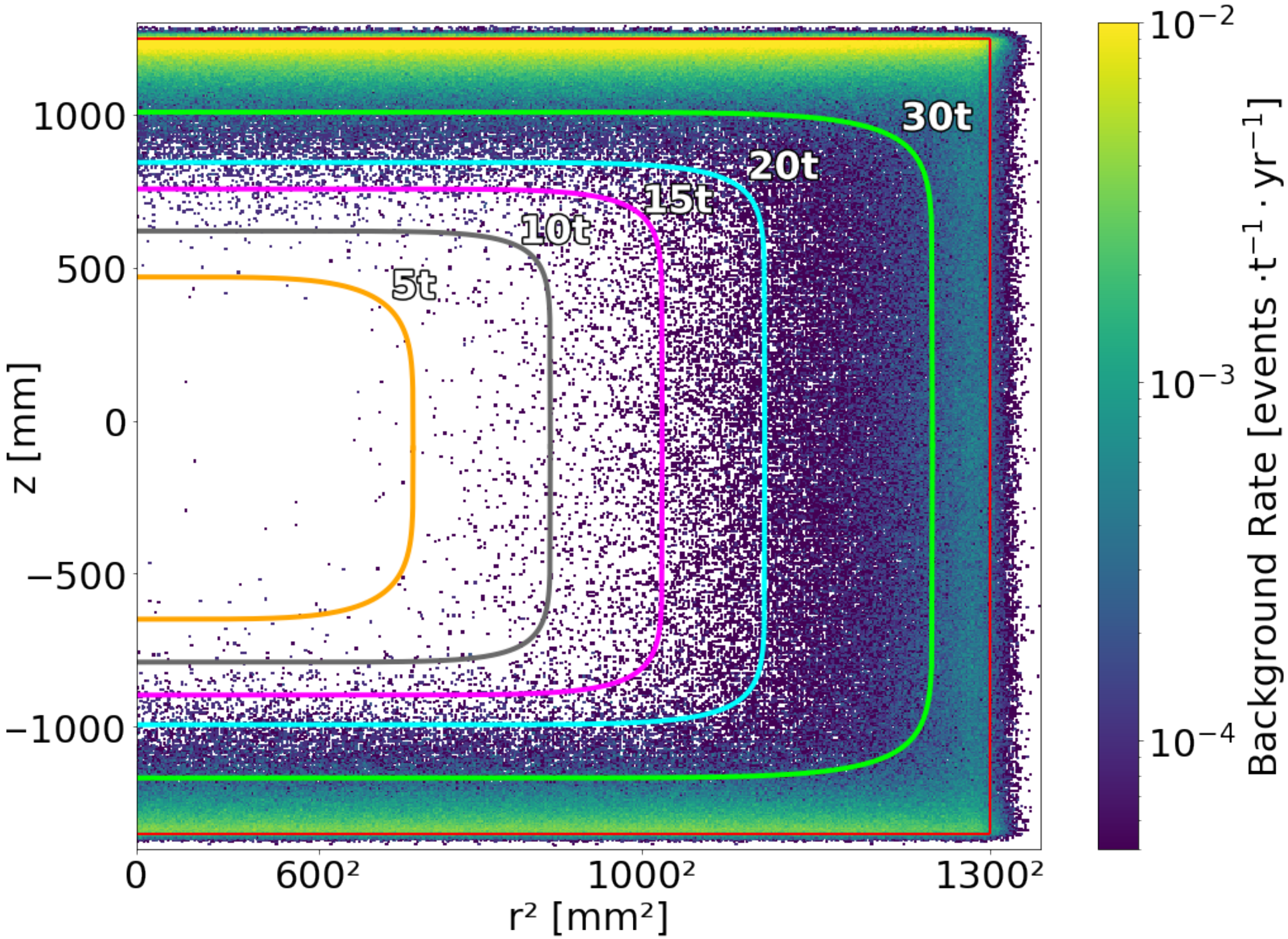
100 years of DARWIN run time, events with energy in the ROI

<u>Super-ellipsoidal cut</u>

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

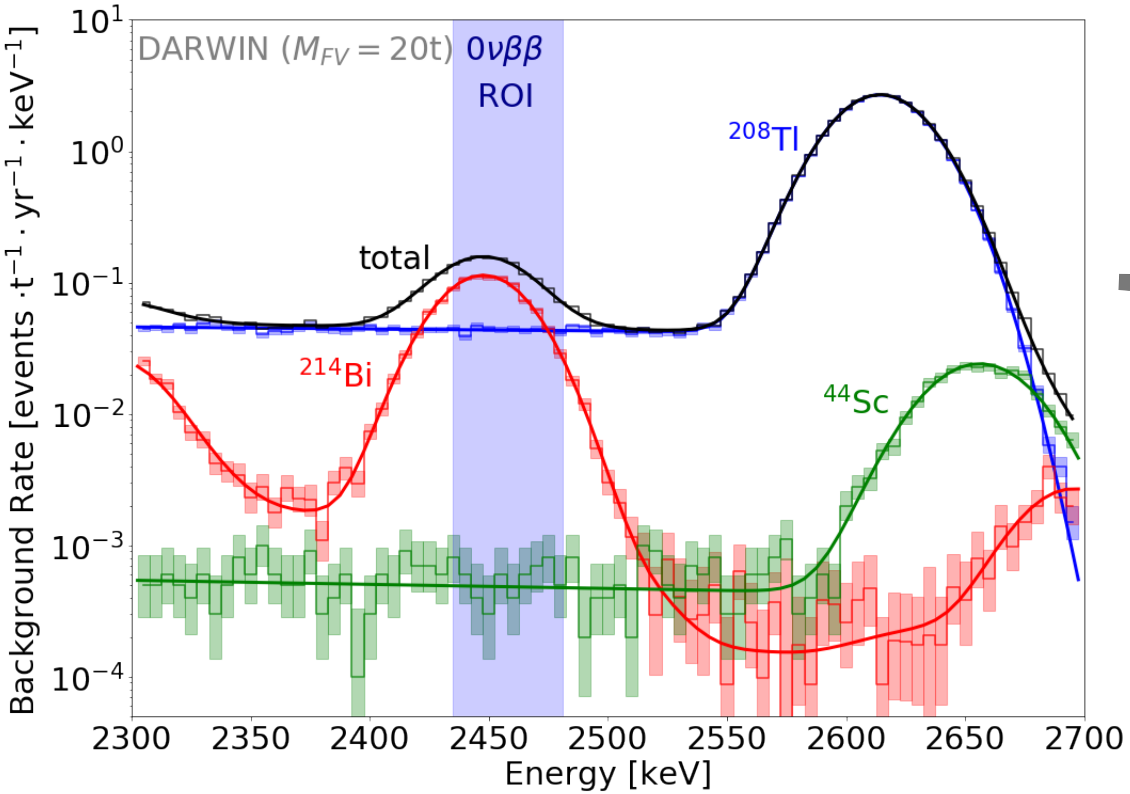
Parameters optimized for each mass

Minimize Background



MATERIAL BACKGROUND: ZOOM AROUND Q-value

Example for 20t (same behaviour for smaller FV)

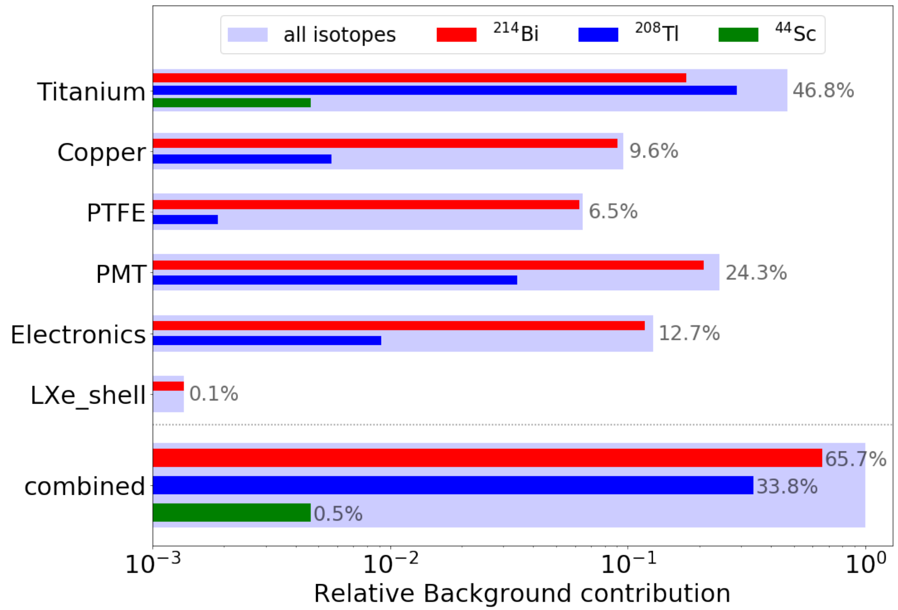


DARWIN ROI for $0\nu\beta\beta$:

Q-value ± FWHM/2

(2435 - 2481 keV)

Mainly from the cryostat and the PMTs



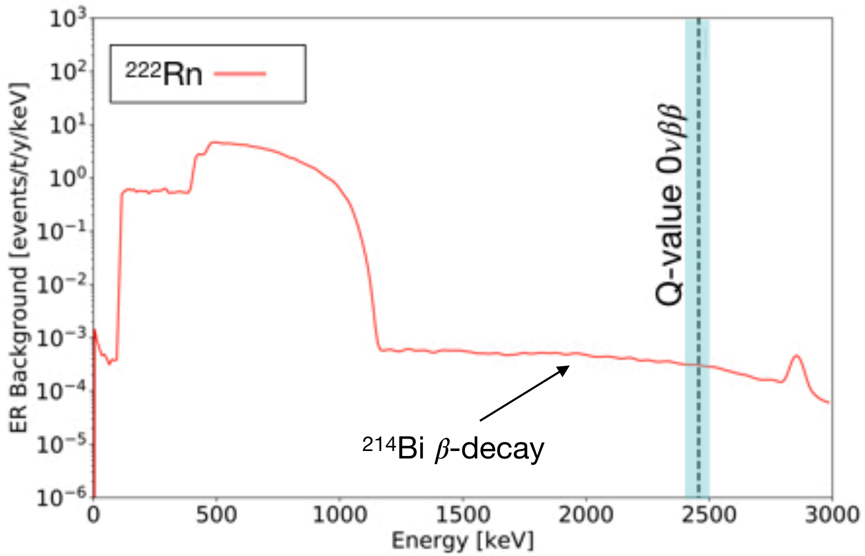
The main external background in the ROI:

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

INTRINSIC BACKGROUNDS:

DARWIN

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



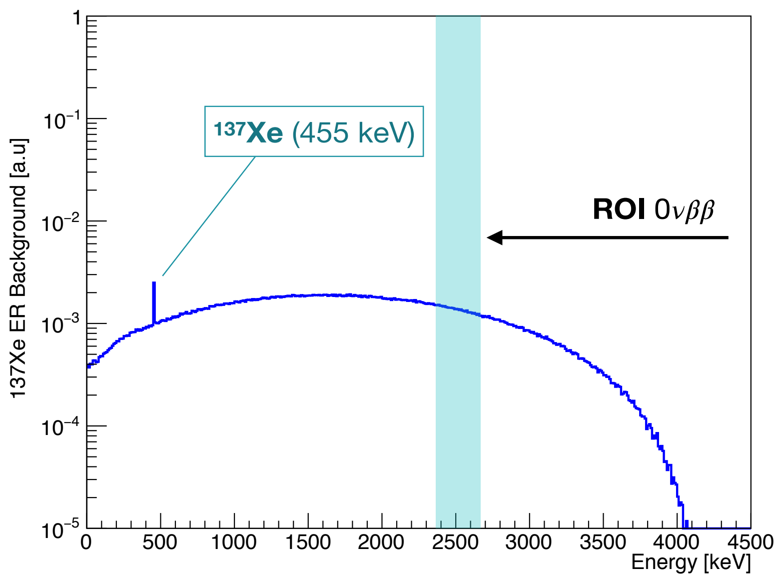
- Irreducible ^{8}B solar neutrinos (ν-e $\rightarrow \nu$-e):

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

- ^{137}Xe from cosmogenic activation underground:

  n + ^{136}Xe —> ^{137}Xe

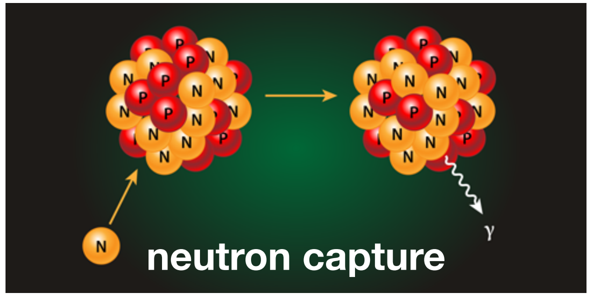
  - Beta decay, $Q_{\text{-value}}$ = 4173 keV
  - Half-life 3.82 min
  - Potential background for a depth of 3500 m.w.e



HOW IS ^{137}Xe PRODUCED?

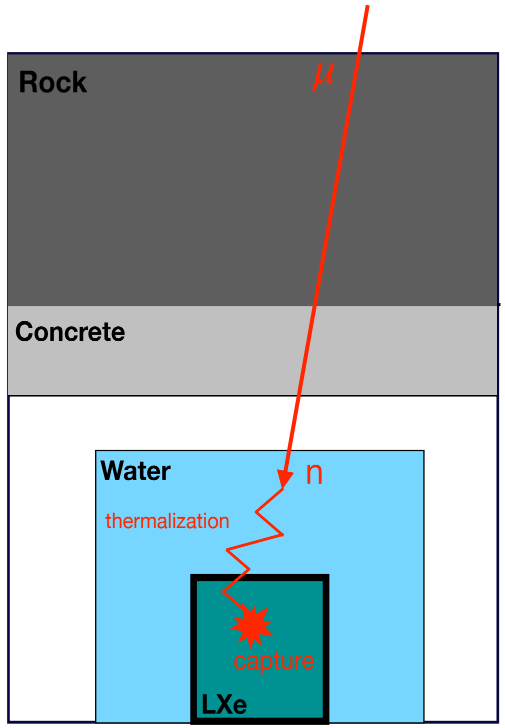
^{137}Xe is mainly produced when **muon-induced neutrons** are captured by ^{136}Xe.

➢ **Radiogenic neutrons can also contribute**
(negligible contribution)



Cosmic Muons ⇒ Fast Neutrons ⇒ Thermalize by collision ⇒ Neutron Capture

- Muon flux reduction underground: 10^6 times (LNGS).
- High energy muons (GeV) can reach the lab.
- Muons produce neutrons when they travel through the **rock, the shields, the cryostat and the detector itself**.
- Once thermalized by collisions, the neutrons are captured in LXe.

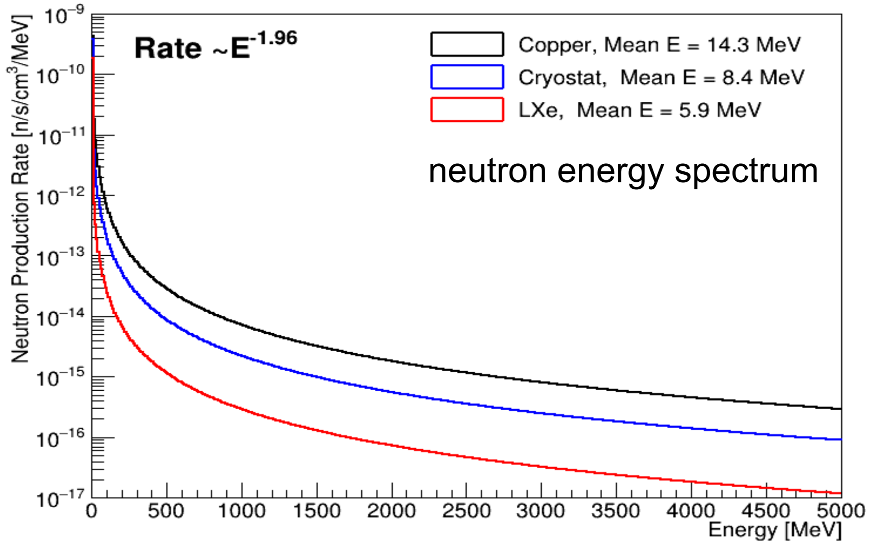


Neutron capture gammas are not a problem because they occur in coincidence with a tag muon

SIMULATION OF THE ^{137}Xe PRODUCTION RATE

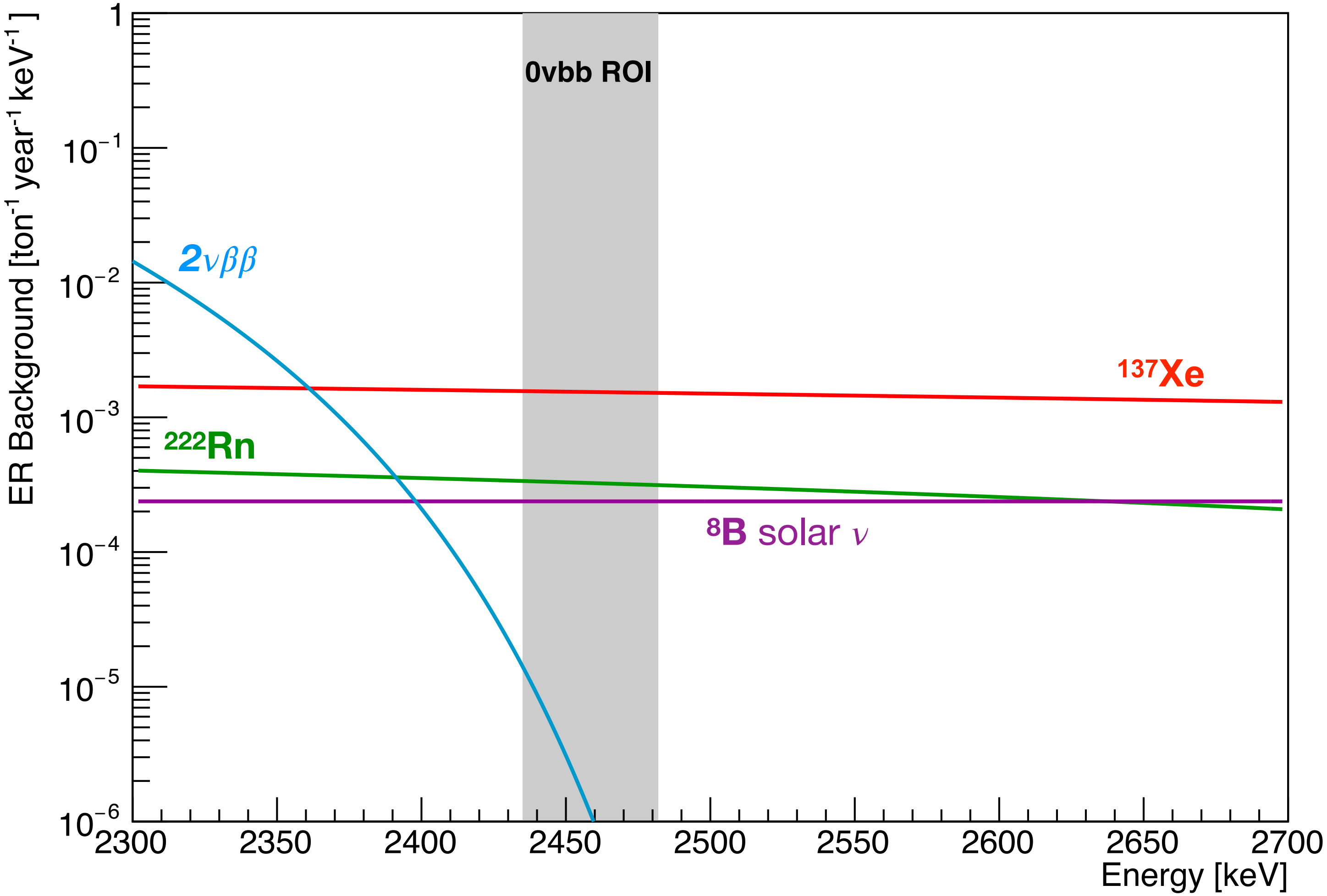
Simulations of the muon-induced neutrons in the DARWIN materials

- Input (1): muon simulations for the LNGS depth
- Input (2): muon-induced neutrons distributions for the different materials
- Neutrons following a power law energy spectrum.
- Simulation of the neutrons and propagate them until the LXe active volume.
- Count number of ^{136}Xe neutron captures.



Material	Volume in DARWIN [m³]	n Production Rate in DARWIN [n/year]	Sim. Events	^{137}Xe isotopes	^{137}Xe Production Rate [atoms/kg/year]
Copper	0.076	1.12×10^{4}	10^{6}	234 ± 15	$(6.7 \pm 0.4)\times10^{-5}$
Cryostat	1.076	1.32×10^{5}	10^{6}	89 ± 9	$(2.9 \pm 0.3)\times10^{-4}$
LXe	19.976	1.02×10^{6}	10^{6}	252 ± 16	$(6.5 \pm 0.4)\times10^{-3}$
Total		1.16×10^{6}			$(6.9 \pm 0.4)\times10^{-3}$

INTRINSIC BACKGROUNDS: ZOOM AROUND Q-value



^{137}Xe

production rate from simulations

(6.9 ± 0.4) atoms/(t·yr)

$2\nu\beta\beta$

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

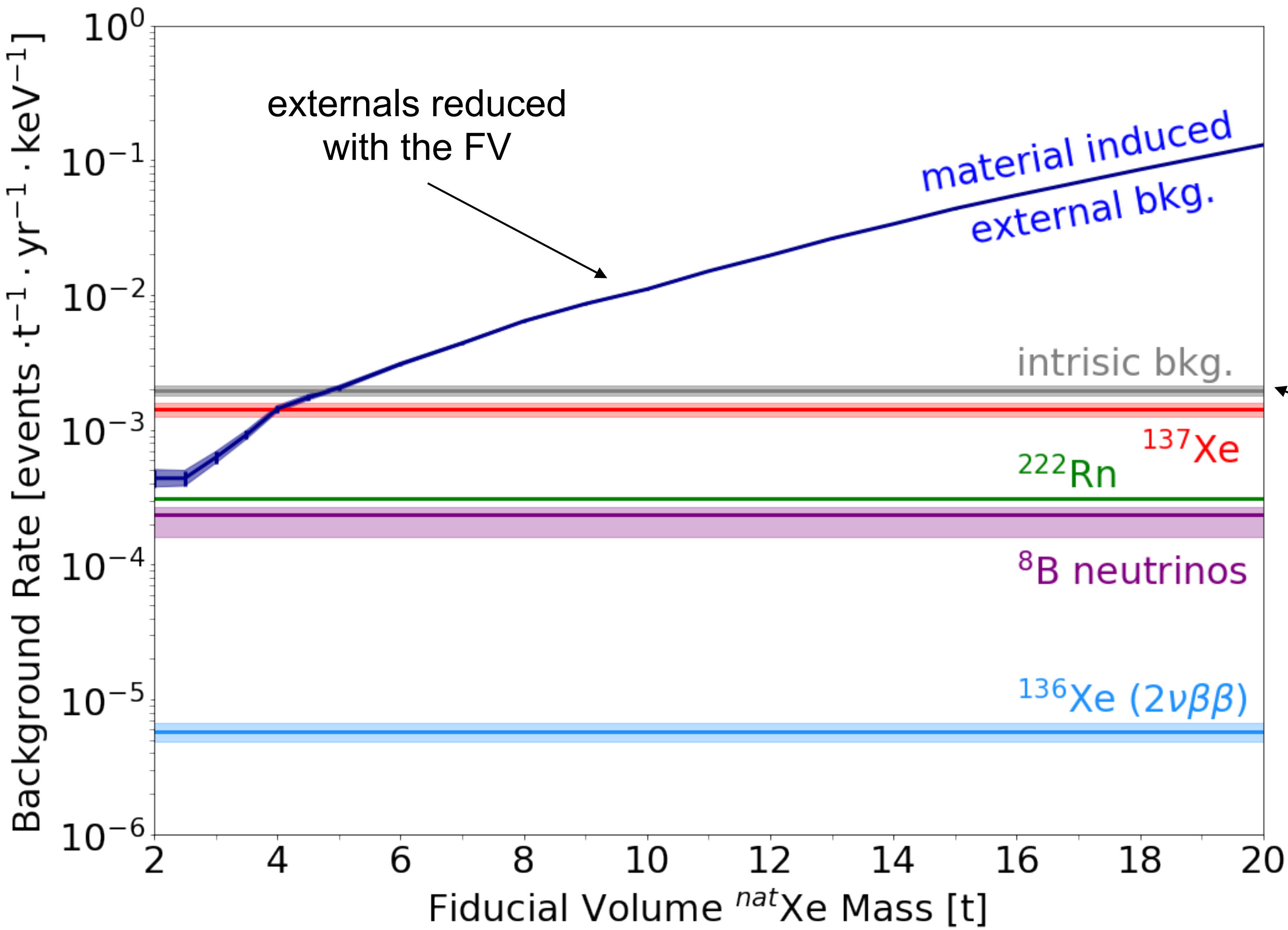
$(2.165 \pm 0.061) \times 10^{21}$ yr

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

Looking for the optimal fiducial mass:



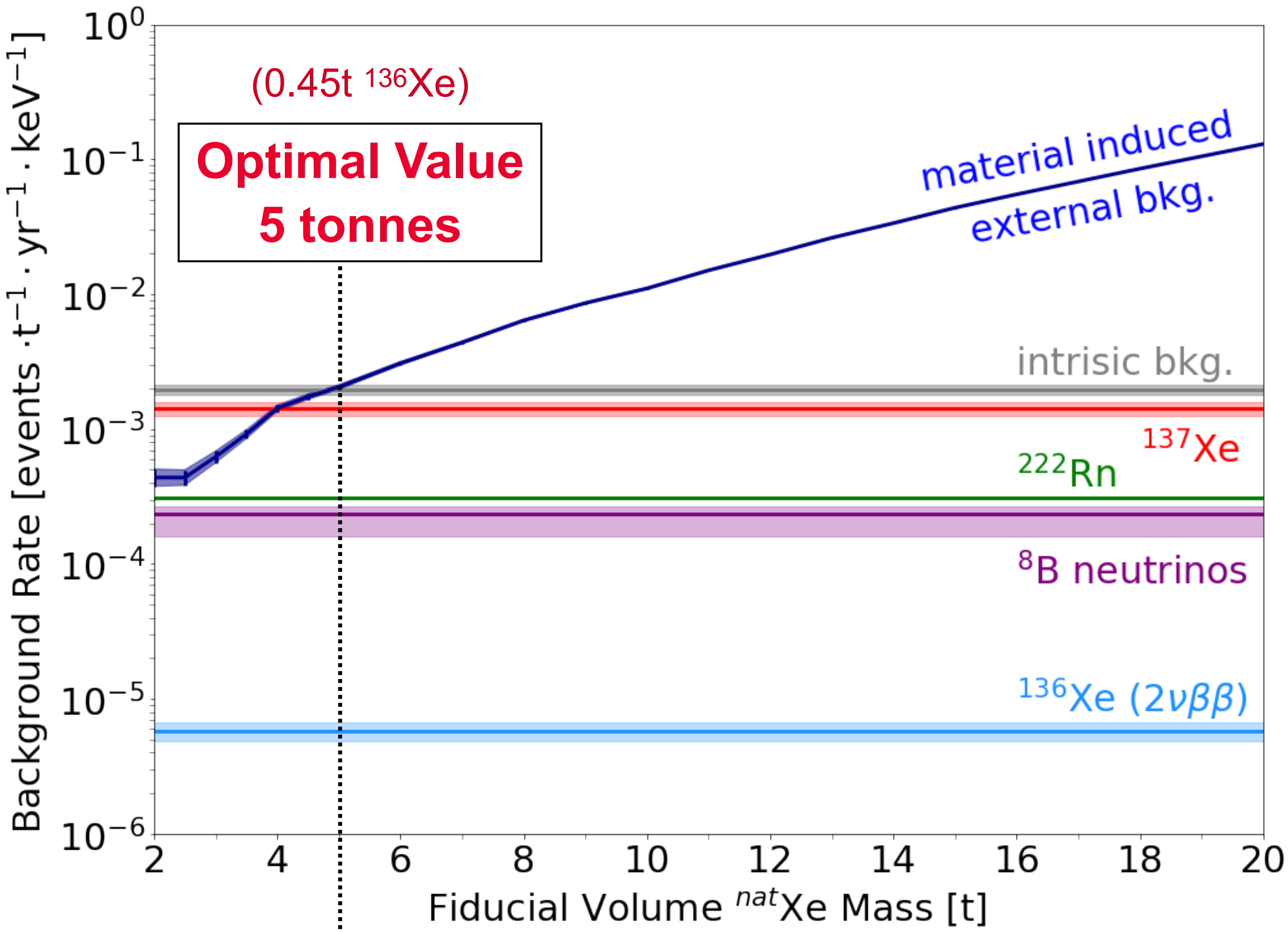
Minimize background without penalizing the exposure

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

TOTAL BACKGROUND: MATERIALS+INTRINSICS

DARWIN

Looking for the optimal fiducial mass:

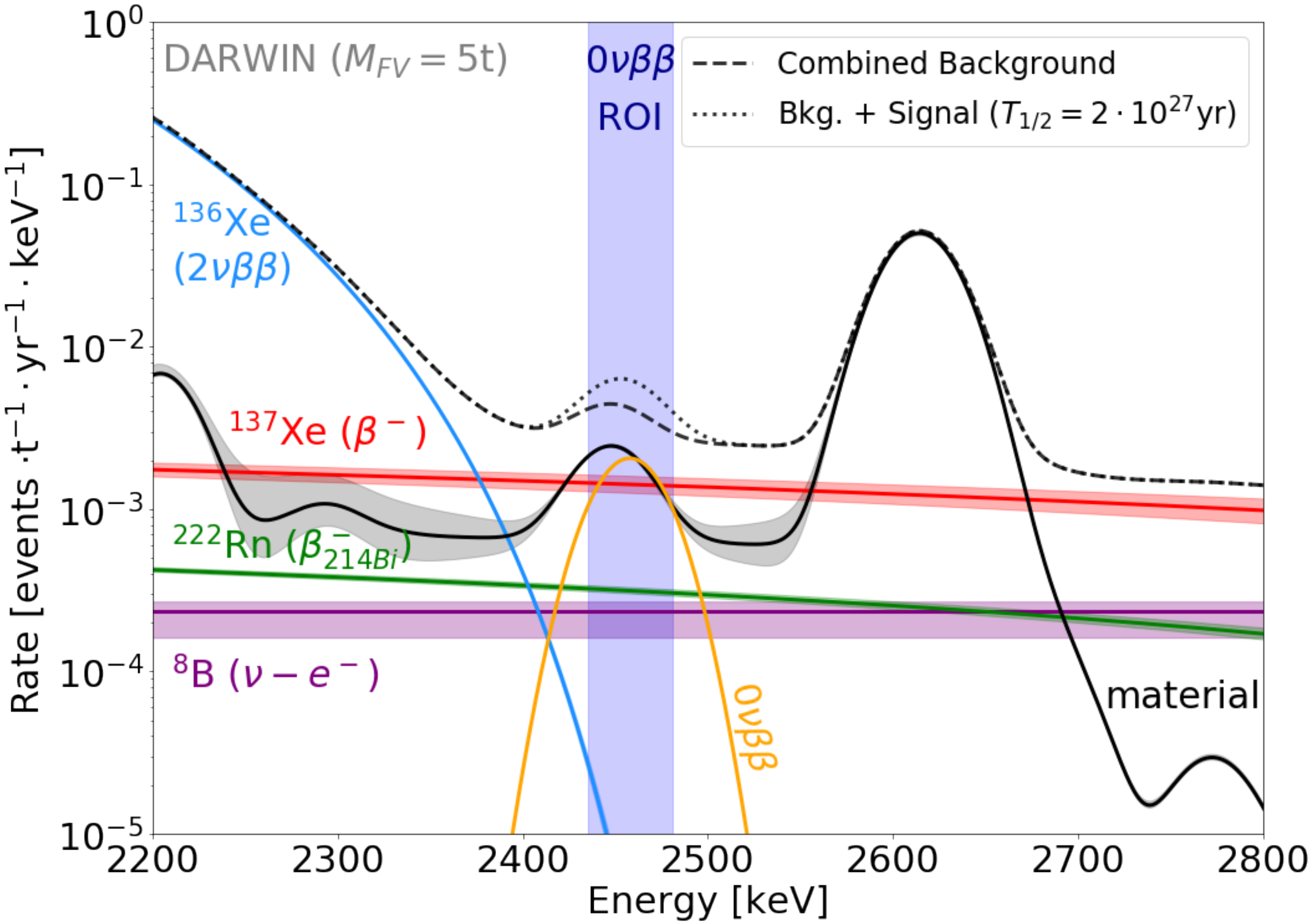


Minimize background without penalizing the exposure

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

This value maximize our sensitivity

TOTAL BACKGROUND FOR 5t FV



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

B = 0.91 events/yr

Less than 1 event per year in the ROI !!

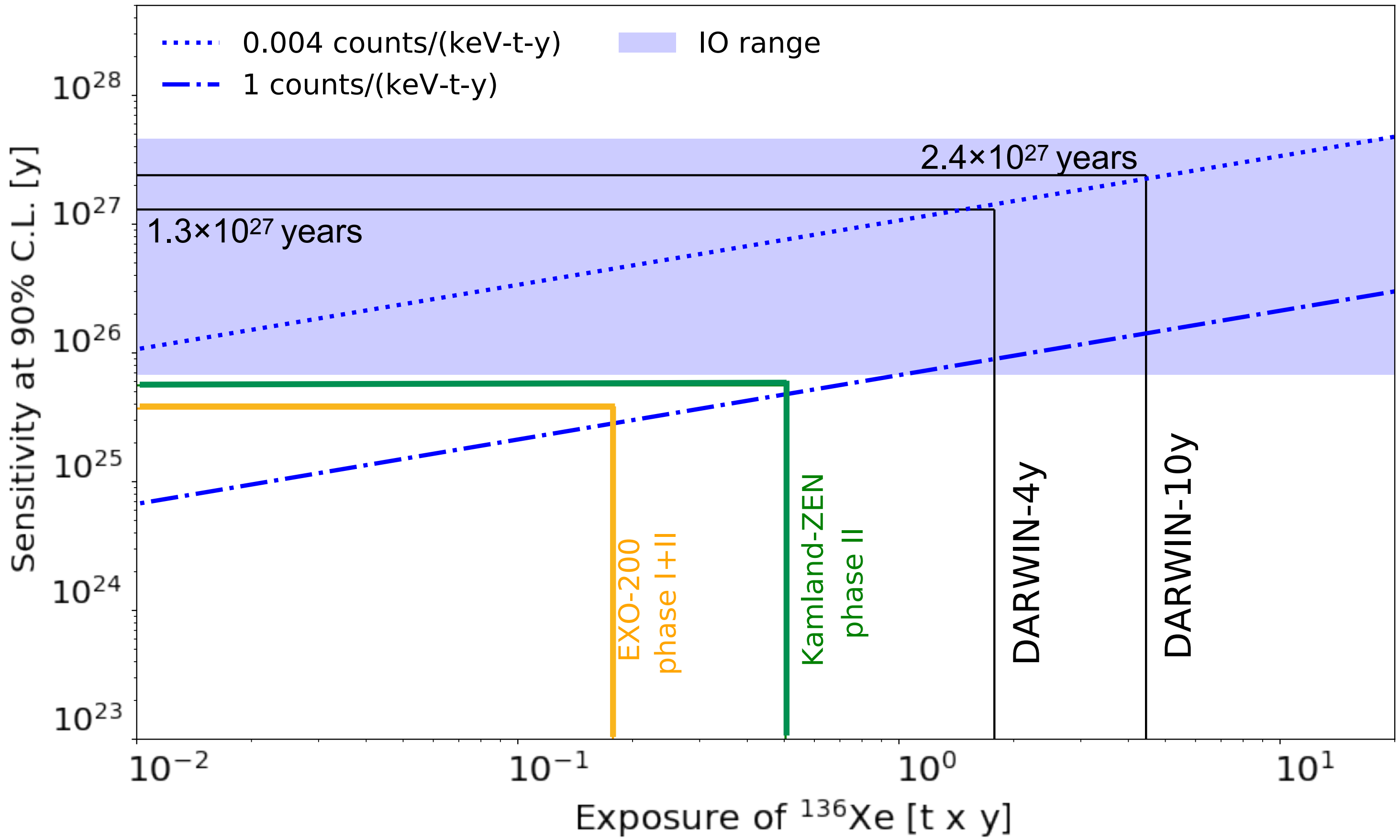
The hypothetical $0\nu\beta\beta$ signal in the plot has a strength of 0.5 events/y ($T_{1/2} \approx 2 \times 10^{27}$ years)

EXPECTED SENSITIVITY FOR THE BASELINE DESIGN

DARWIN

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

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

What could be improved?

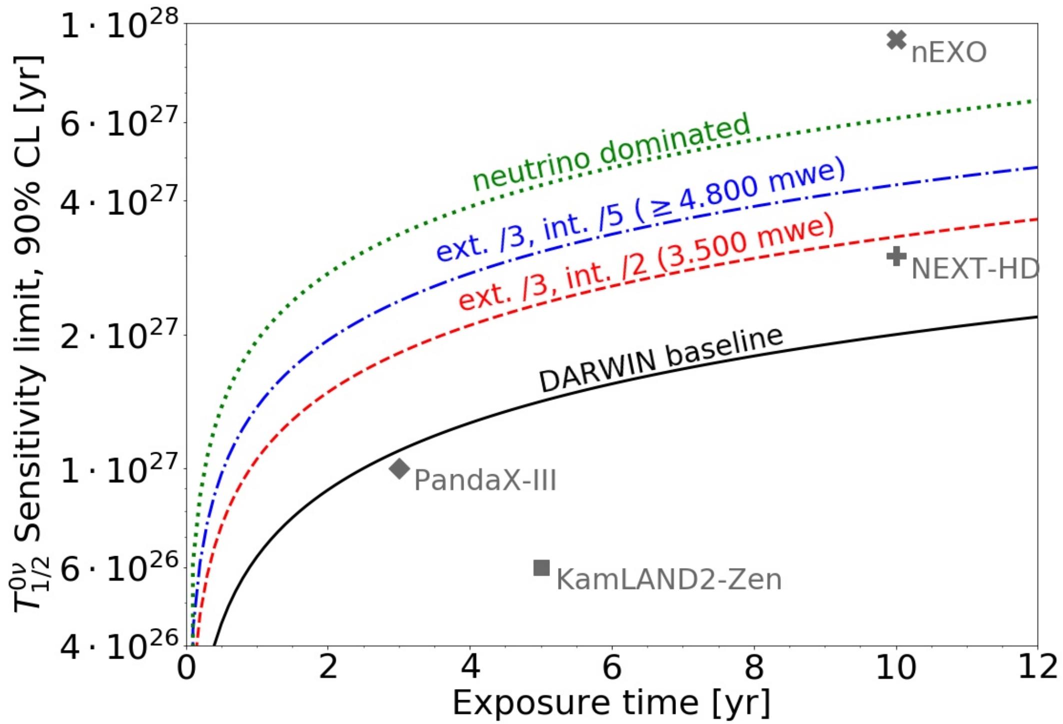
① **Reduce external background**

- 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 **$6{\times}10^{27}$ years**

IMPROVED SCENARIOS

DARWIN

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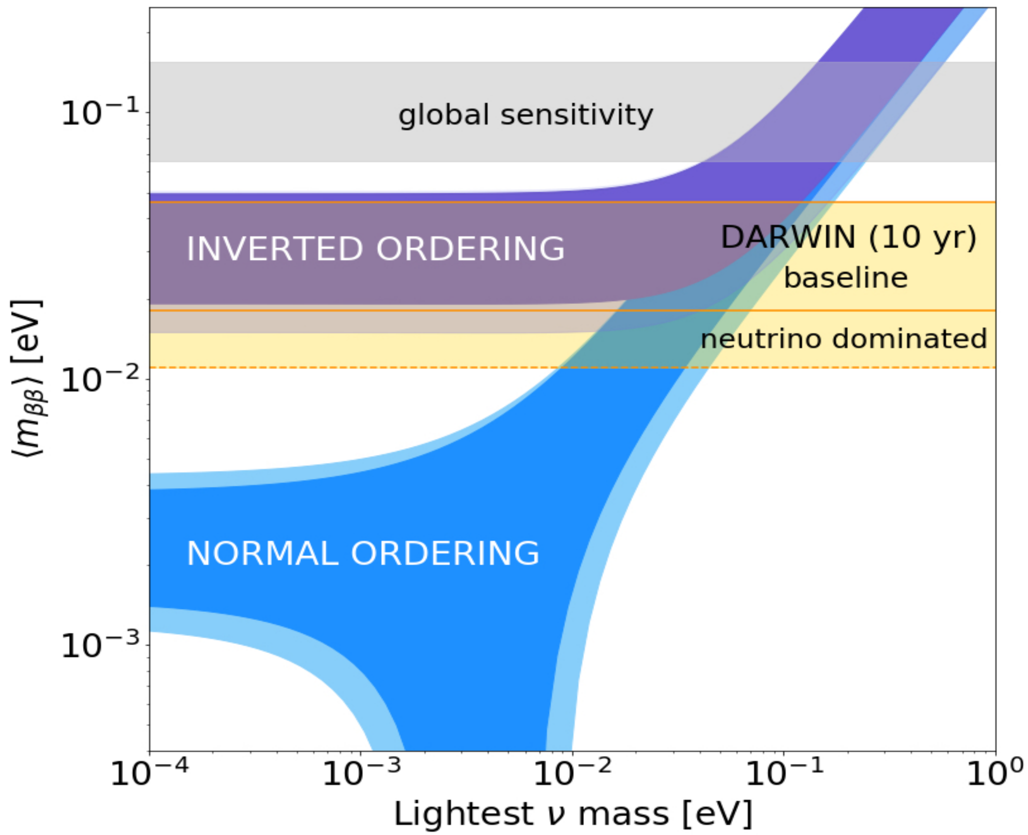

ROOM FOR IMPROVEMENT !!

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

CONCLUSIONS

- DARWIN will be a dark matter detector, but its large mass and low background allow for **an excellent detector to look for the 0ν$\beta\beta$ decay of ^{136}Xe.**
- Expected energy resolution of ~0.8% at 2.5 MeV (already proved by XENON1T)
- Dedicated simulations of the **material and intrinsic background.**
- A statistical analysis provides a sensitivity at 90% C.L of **2.4×10^{27} years** for 5t ×10 year exposure for the baseline design.
- With the baseline scenario DARWIN will be competitive to fully dedicated experiments. **Still room for improvement:** cleaner materials, different photosensors …

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arXiv.org > physics > arXiv:2003.13407

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Physics > Instrumentation and Detectors

[Submitted on 25 Mar 2020]

Sensitivity of the DARWIN observatory to the neutrinoless double beta decay of ^{136}Xe