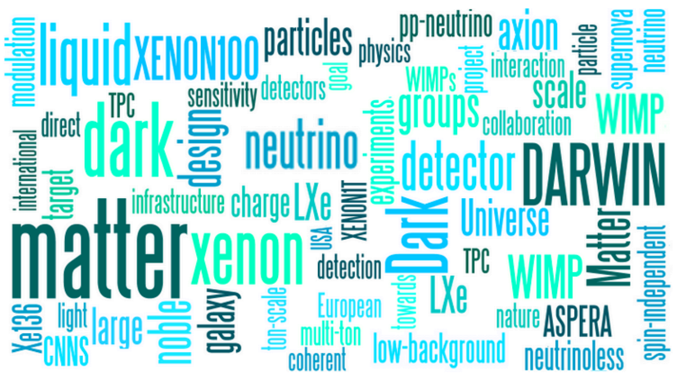
Sensitivity to the neutrinoless double beta decay of the DARWIN Observatory

Patricia Sanchez-Lucas, Universität Zürich

on behalf of the DARWIN Collaboration

www.darwin-observatory.org



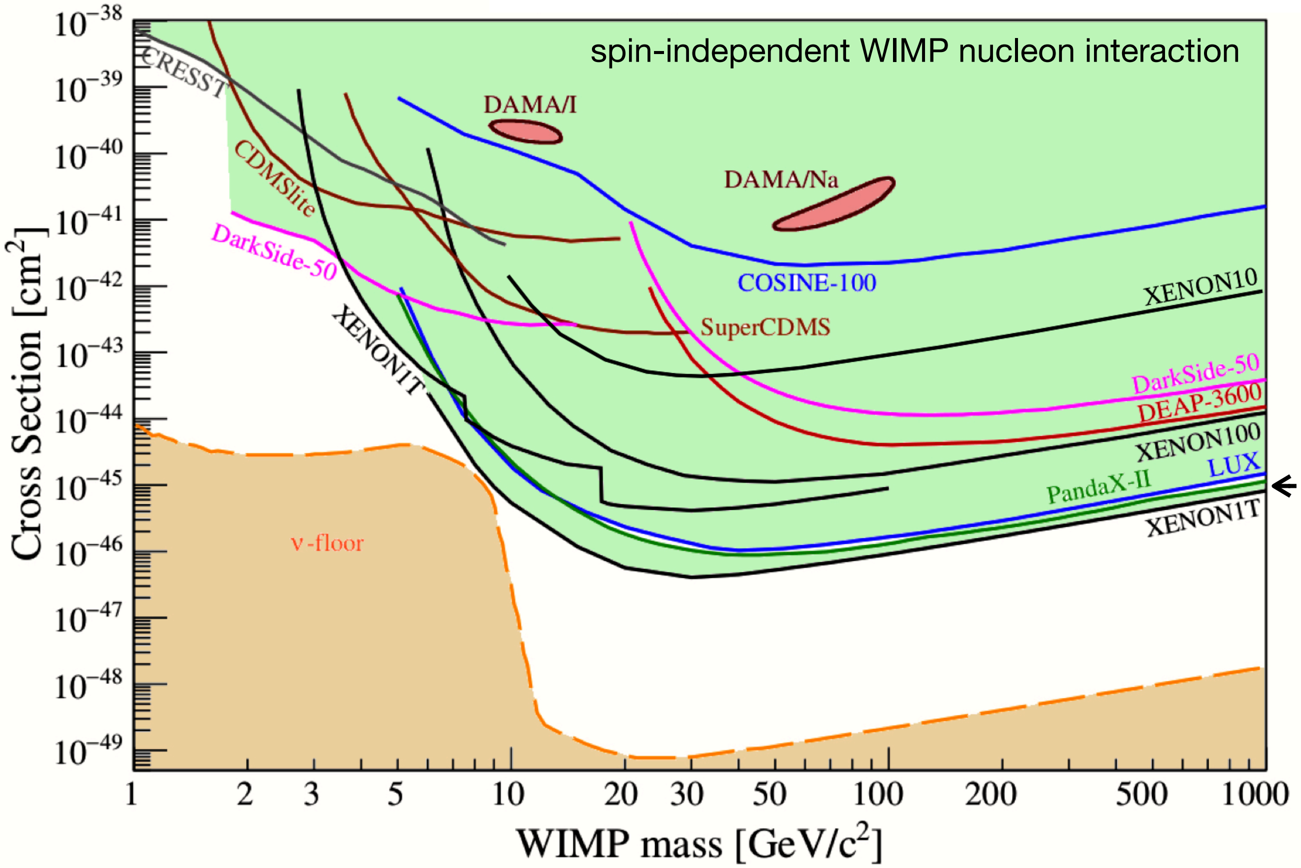
CNNP2020

Cape Town, 24-28 February 2020

WIMP DETECTION LANDSCAPE TODAY

DARWIN

- The highest sensitivity above 2 GeV/c² 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 mass**, plans to increase 100-fold the current sensitivity.



Current Limit (1 t×y)

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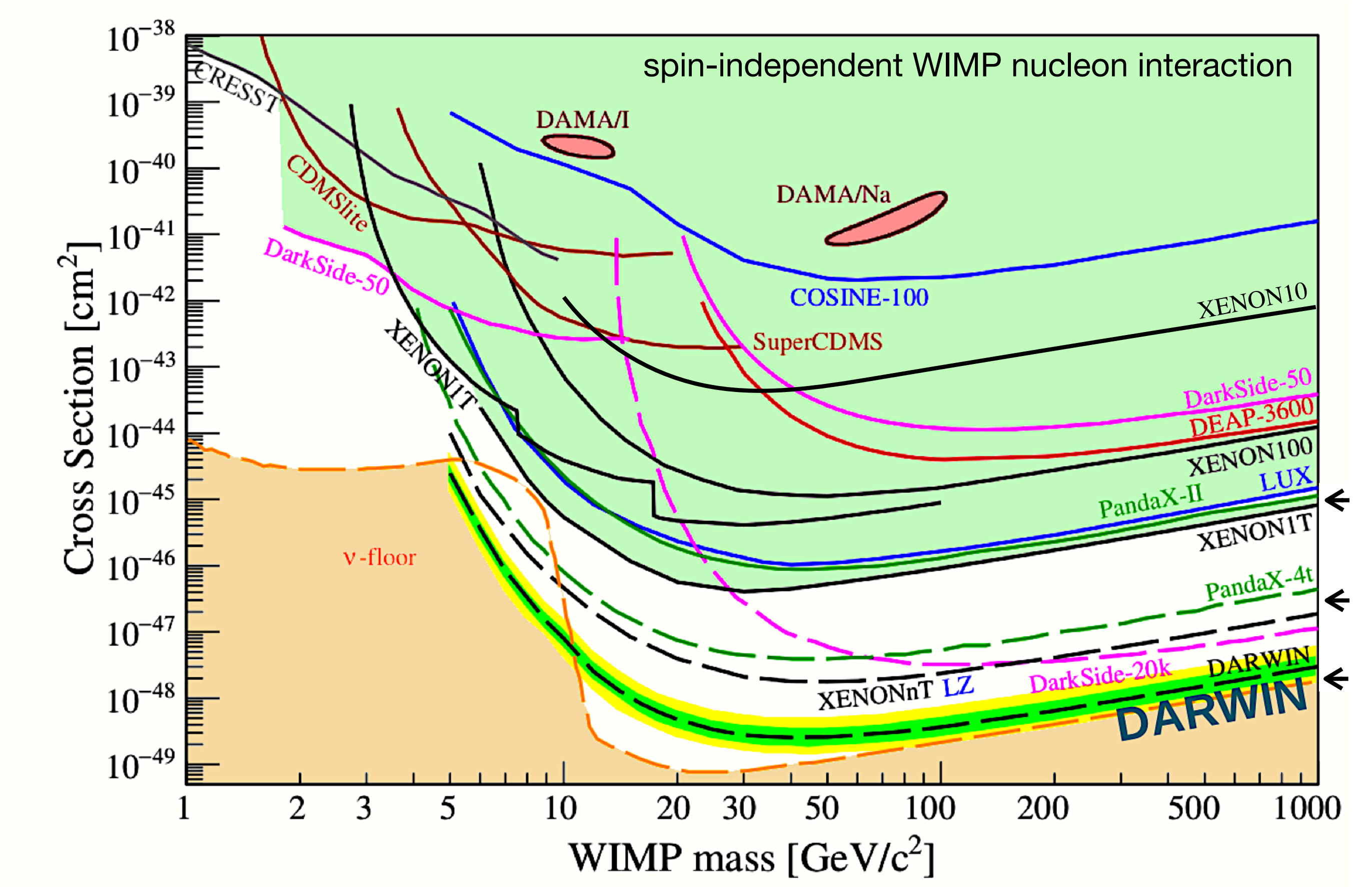


Current Limit (1 t×y)

Near Future Sensitivity

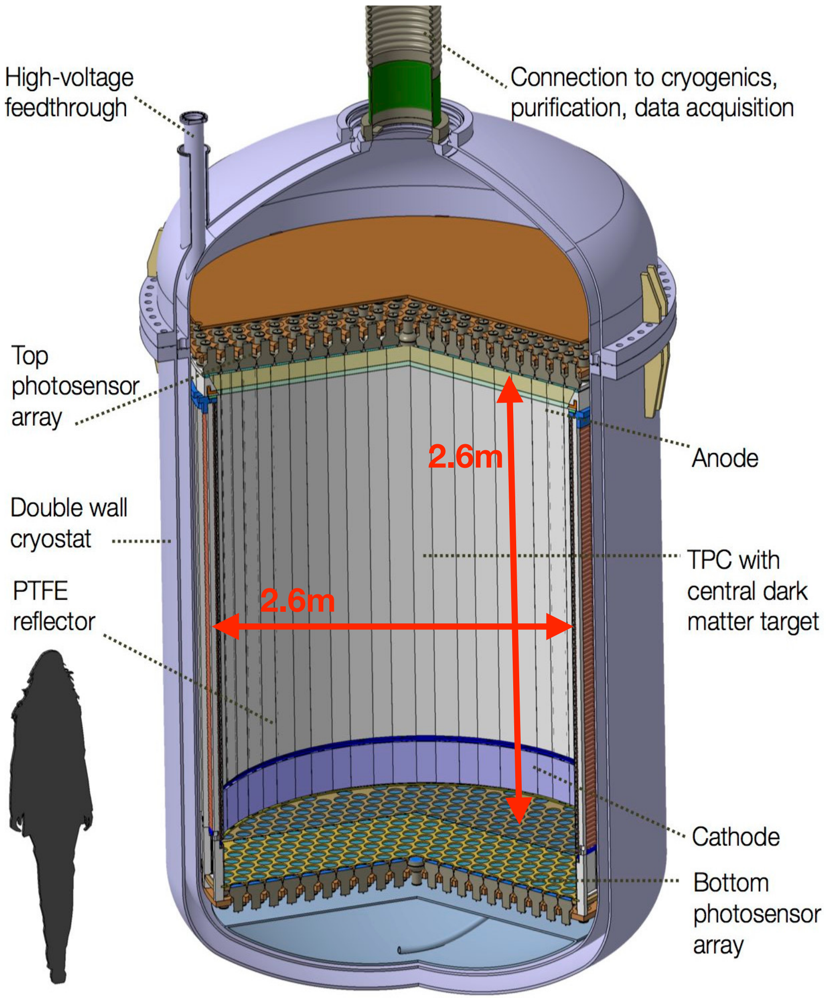
DARWIN

sensitivity limited by he neutrino floor

(200 t×y)

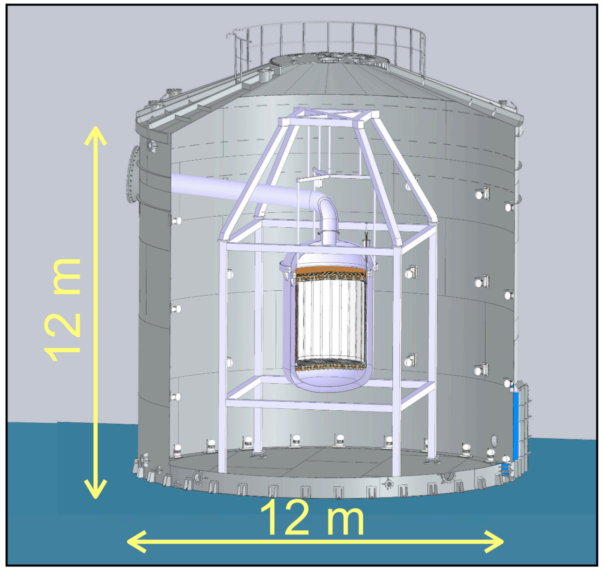
DARWIN BASELINE DESIGN

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



baseline design with PMTs but several alternatives under consideration

- Dual-phase Time Projection Chamber (TPC).
- 50t total (**40t active**) of liquid xenon (LXe).
- Dimensions: **2.6 m diameter and 2.6 m height.**
- Two arrays of photosensors (top and bottom).
- 1910 PMTs of 3" diameter.
- Low-background double-wall cryostat.
- PTFE reflector panels & copper shaping rings.
- Outer shield filled with water (12 m diameter).

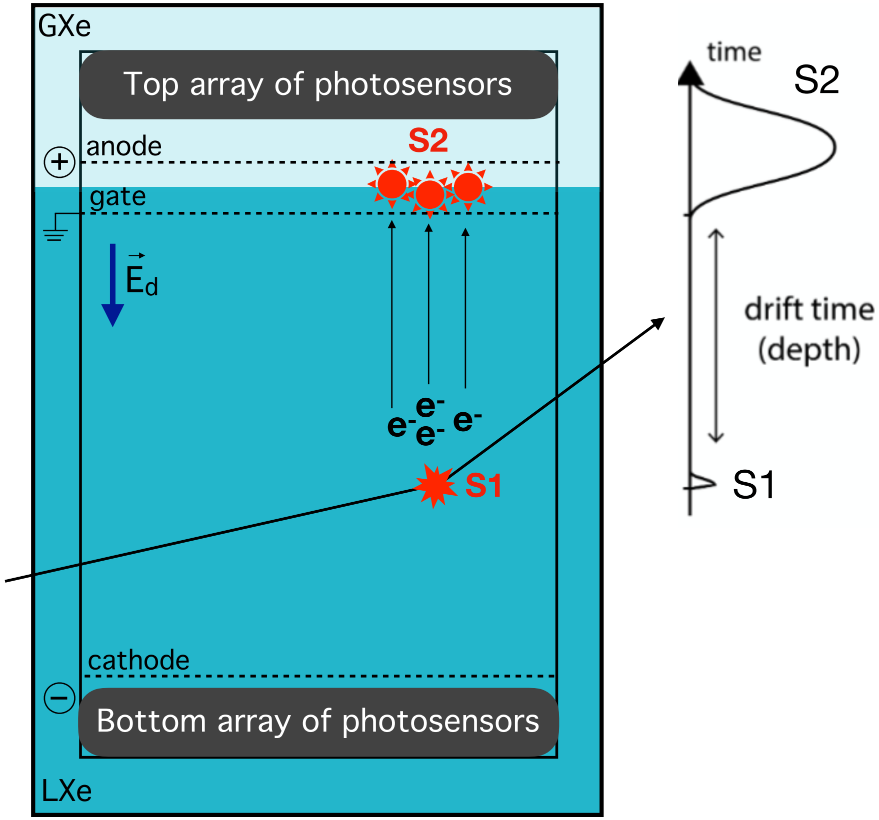


Possible realization of DARWIN inside the water tank

DUAL-PHASE XENON TPC

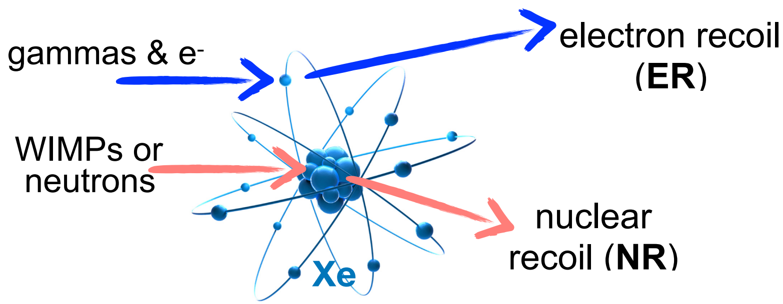
Dual phase TPC working principle

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



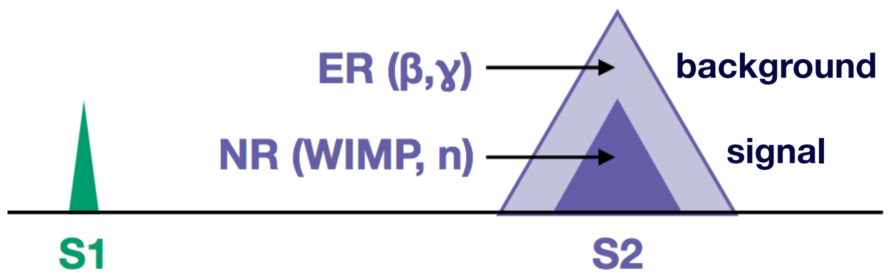
- The dual-phase TPC allows for a 3D position reconstruction.
  x-y from the light sensors, z from the drift time

Particle interactions



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

Particle type discrimination



THE VARIETY OF PHYSICS CHANNELS

DARWIN

Ultra-low Background — Large Target (40t) — 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

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

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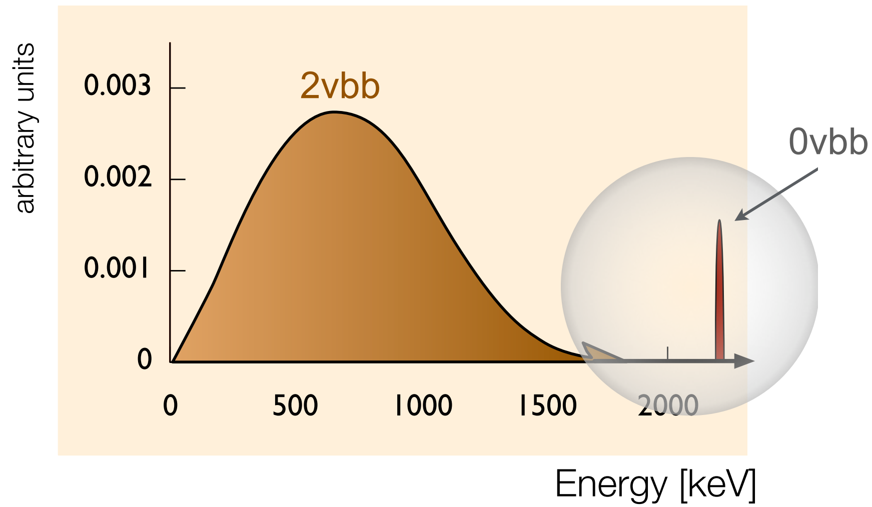
CNNS

WHY LOOK FOR THE $0\nu\beta\beta$ DECAY WITH DARWIN ?

DARWIN

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

- ^{136}Xe excellent candidate:
  - Abundance of **8.9% in natural Xe**.
  - Q-value = 2.458 MeV (above the ROI of WIMPs)
- DARWIN will have more than **3.5 t** of active ^{136}Xe.
- Expected energy resolution < 1% at 2.5 MeV
  - Already demonstrated by XENON1T
    C. Wittweg talk, yesterday
- Ultra-low background environment dominated by intrinsic backgrounds:
  - ^{222}Rn, $2\nu\beta\beta$ decays of ^{136}Xe
  - solar ^{8}B neutrinos
  - ^{137}Xe from cosmogenic activation underground

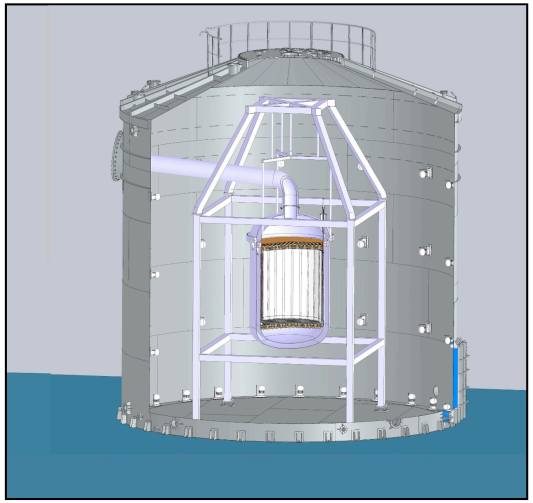


$$T^{0\nu}_{1/2} \propto \frac{\sqrt{Mt}}{\sqrt{B\Delta E}}$$

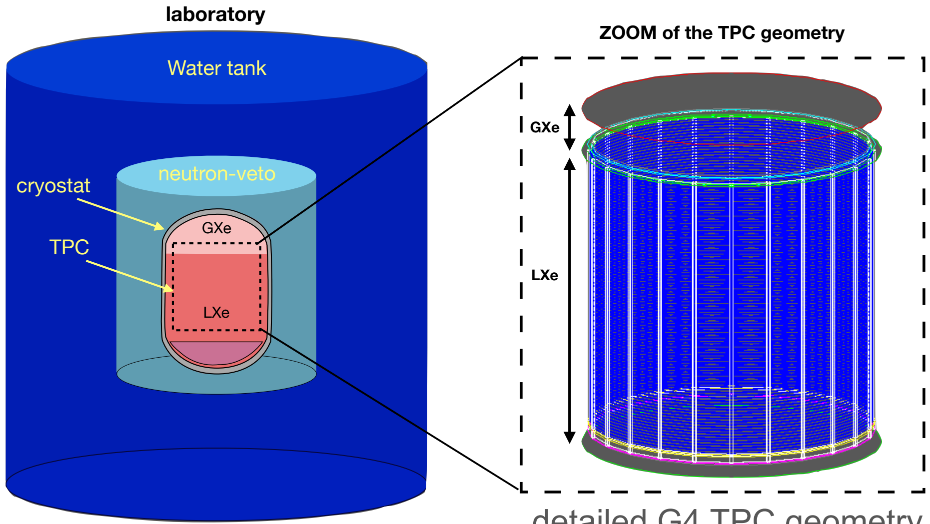
DEDICATED SIMULATIONS: DARWIN GEOMETRY

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

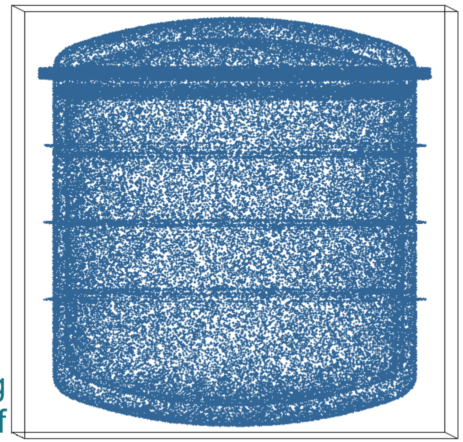
  example: PMTs vs SiPMs

  ➢ disks accounting for the proper amount of material

- Critical components for the BG ➜ Fully simulated in detail

  example: Double wall cryostat

Double Wall Cryostat

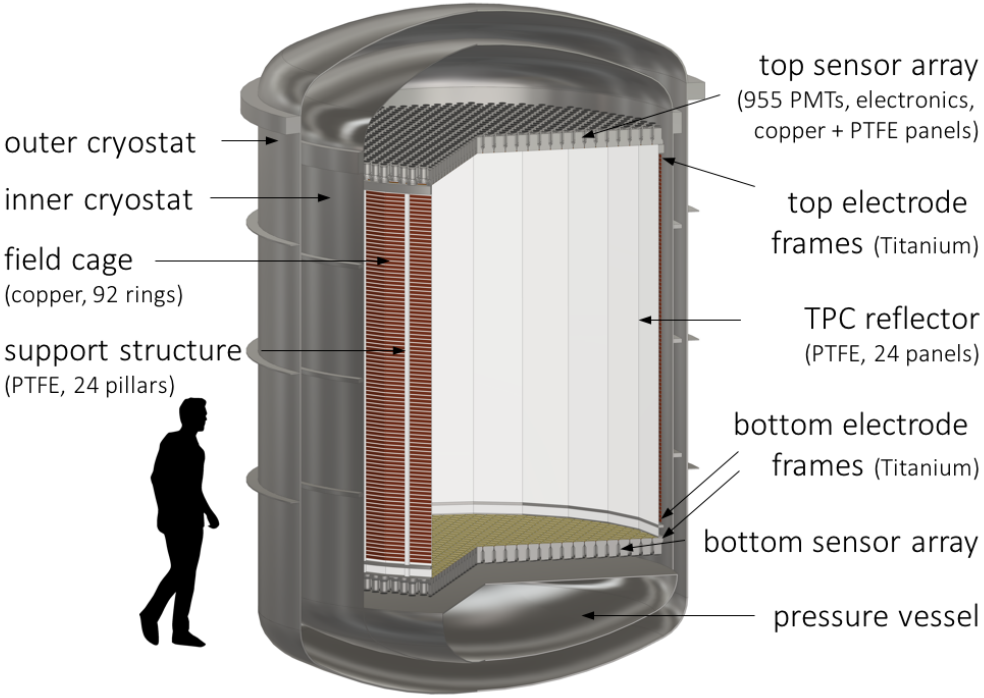


Based on engineering studies at Nikhef

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

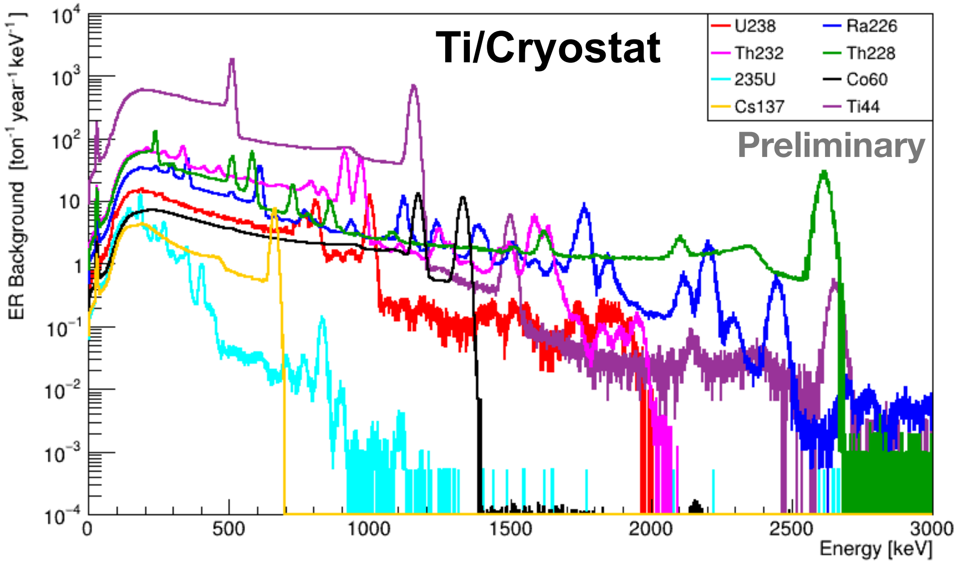
- LZ, *Astropart. Phys.* ***96*** *(2017) 01*
- XENON, *Eur. Phys. J. C* ***77*** *(2017) 12 890*

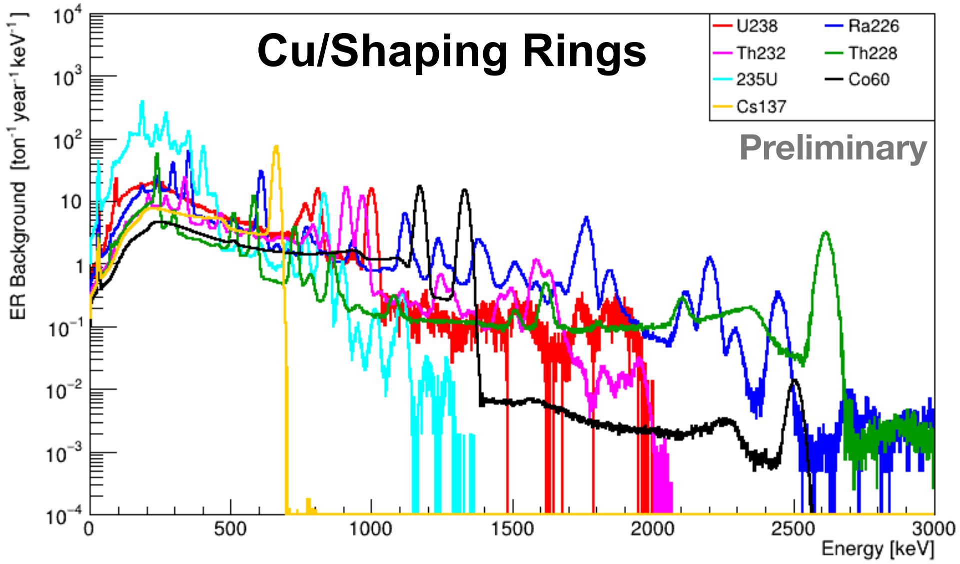
Material	Unit	^{238}U	^{226}Ra	^{232}Th	^{228}Th	^{60}Co	^{44}Ti	Reference
Titanium	mBq/kg	<1.6	<0.09	0.28	0.25	<0.02	<1.16	LZ
PTFE	mBq/kg	<1.2	0.07	<0.07	0.06	0.027	-	XENON
Copper	mBq/kg	<1.0	<0.035	<0.033	<0.026	<0.019	-	XENON
PMT	mBq/unit	8.0	0.6	0.7	0.6	0.84	-	XENON
Electronics	mBq/unit	1.10	0.34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

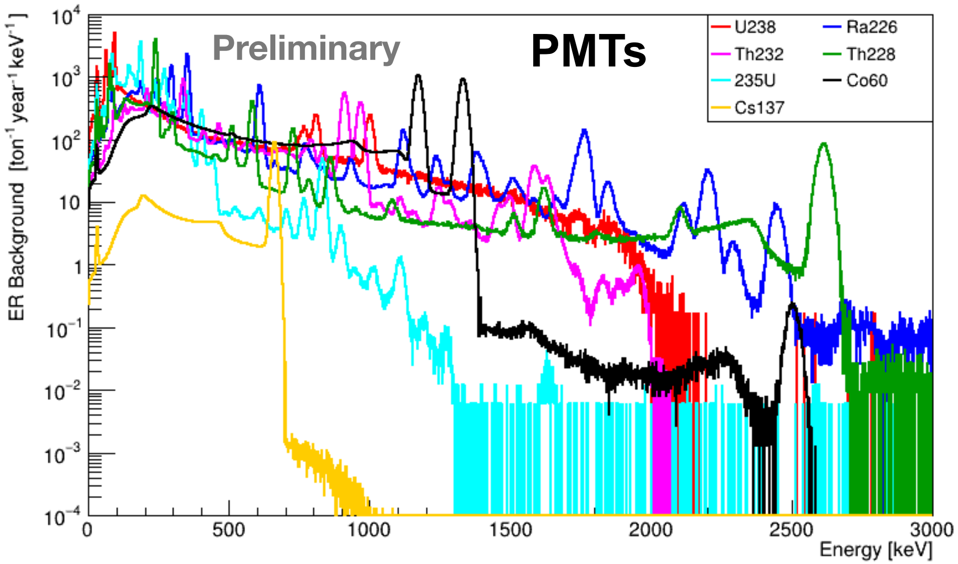
COMPONENTS OF THE MATERIAL BACKGROUNDS

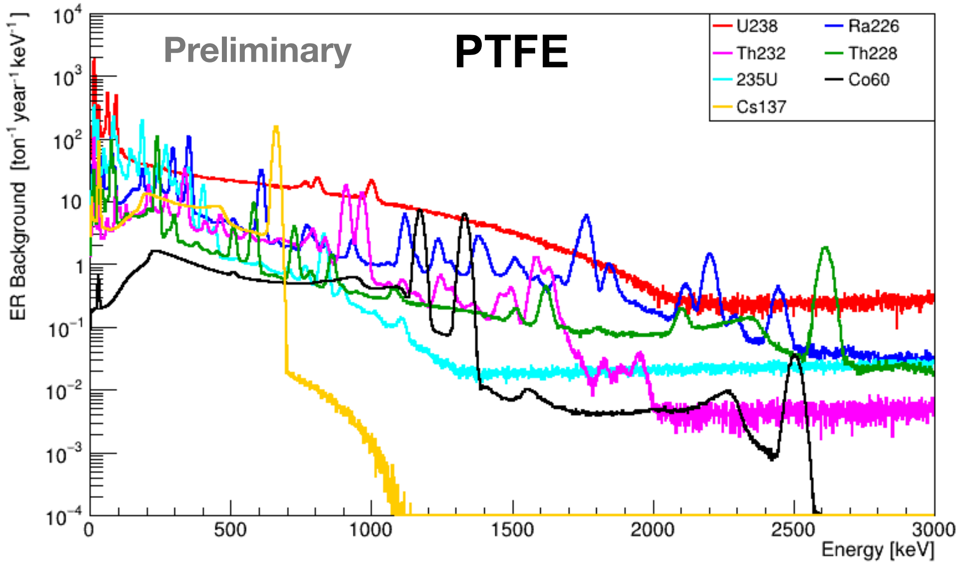
ER background spectra (single site events) for some materials with no fiducialization

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









DEFINITION OF A FIDUCIAL VOLUME

Distribution of the external background events in the detector volume

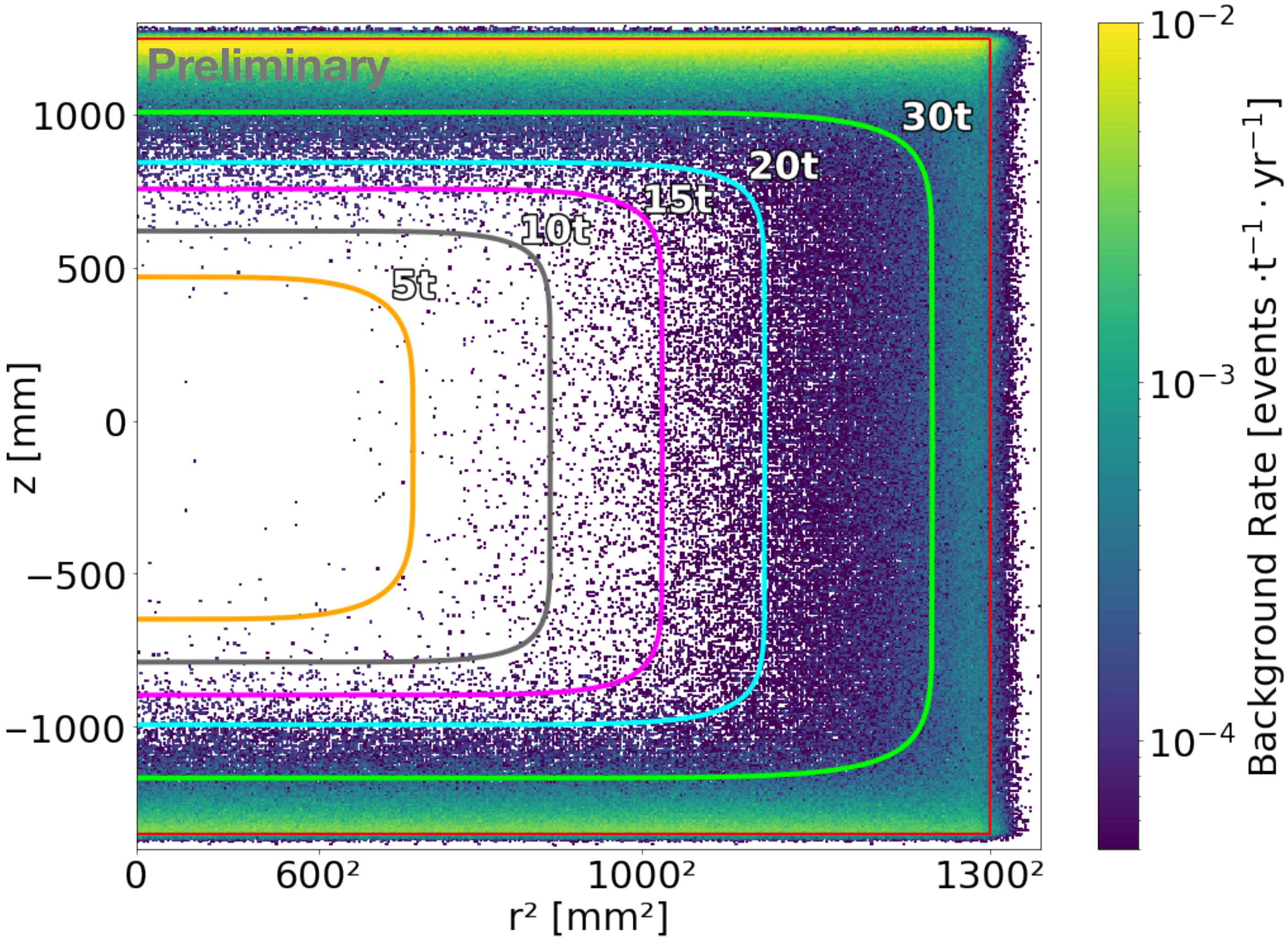
100 years of DARWIN run time, events with energy in the ROI

Super-ellipsoidal cut

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

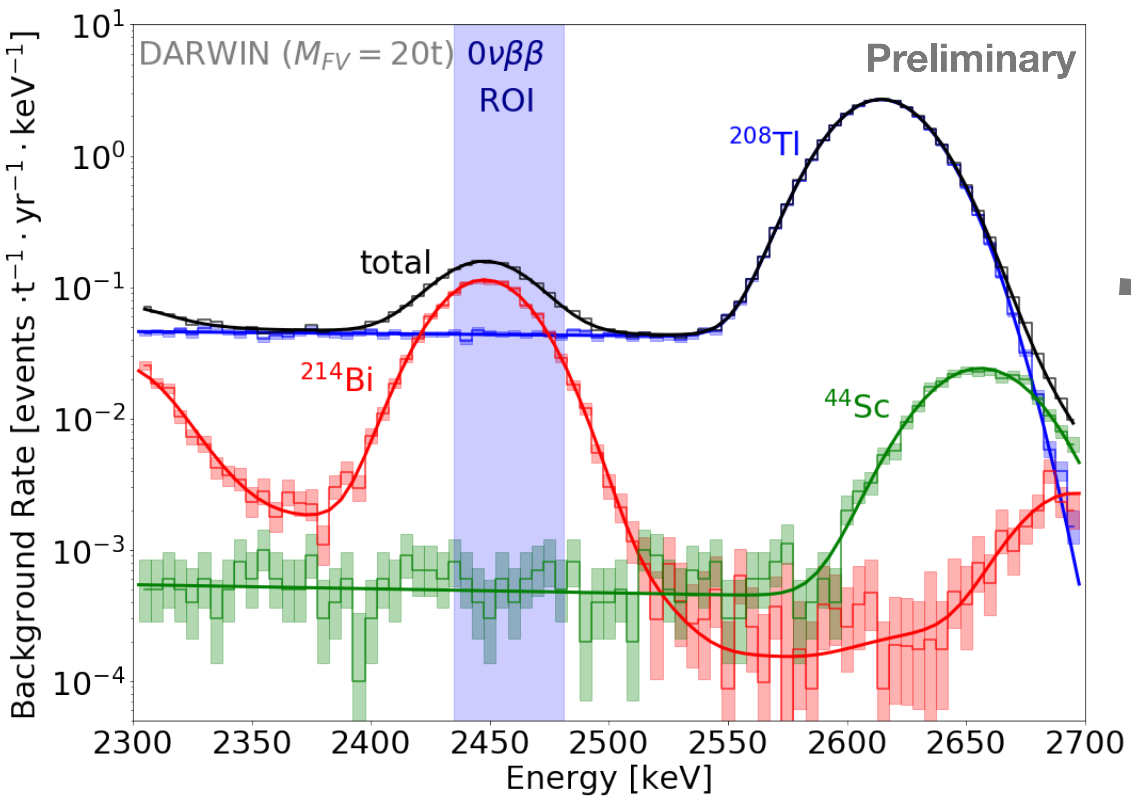
Parameters optimized for each mass

Minimize Background



MATERIAL BACKGROUND: ZOOM AROUND Q-value

Example for 20t (same behaviour for smaller FV)

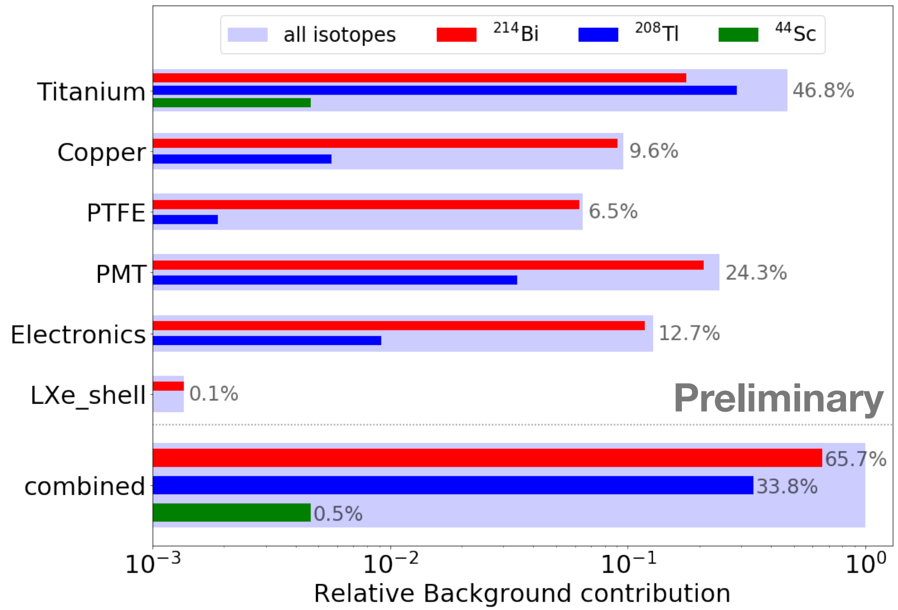


DARWIN ROI for $0\nu\beta\beta$:

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

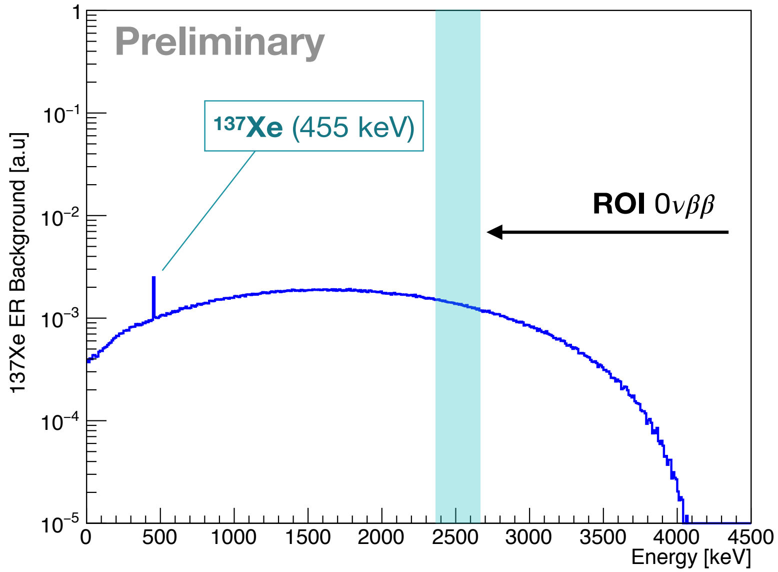
- ^{222}Rn in the LXe:
  - Assumption: 0.1 μBq/kg
  - 10 times lower than XENONnT
  - 99.8 % BiPo tagging efficiency

- Irreducible ^{8}B solar neutrinos (ν-e $\rightarrow \nu$-e):
  - $\phi_{\nu e}$ = 5.46 x 10^{6} cm^{-2} s^{-1}
  - P_e = 0.50

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

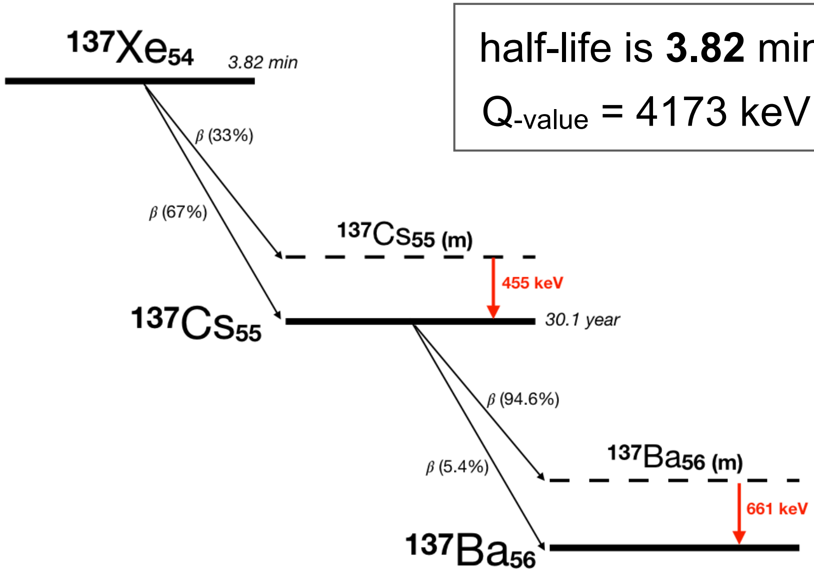
- ^{137}Xe from cosmogenic activation underground:
  - Potential background for a depth of 3500 m.w.e
  - Dedicated simulations of muon-induced neutrons

n + ^{136}Xe —> ^{137}Xe

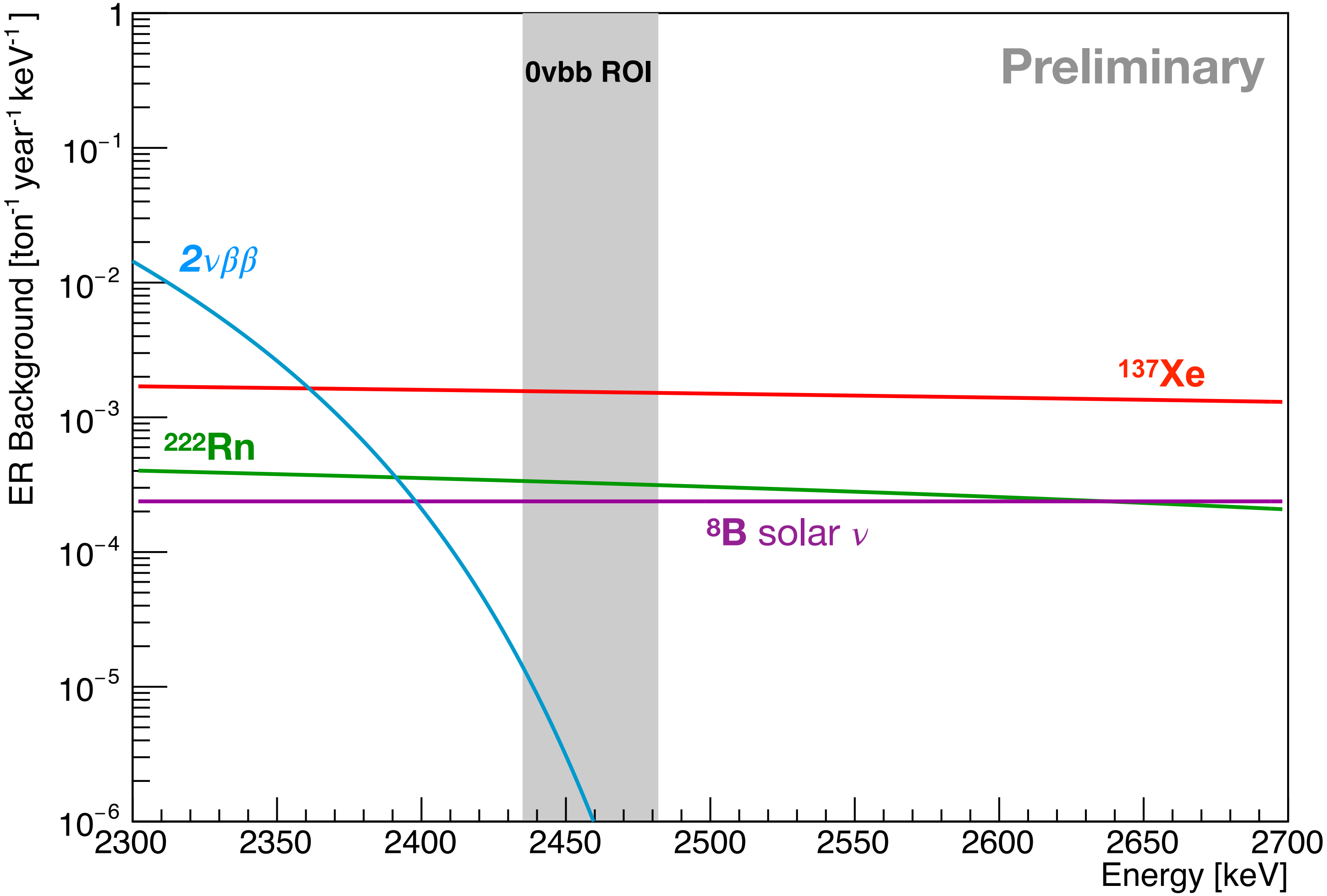


half-life is **3.82** min

Q-value = 4173 keV



INTRINSIC BACKGROUNDS: ZOOM AROUND Q-value



^{137}Xe

production rate from simulations

(6.9 ± 0.4) atoms/(t·yr)

2νββ

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

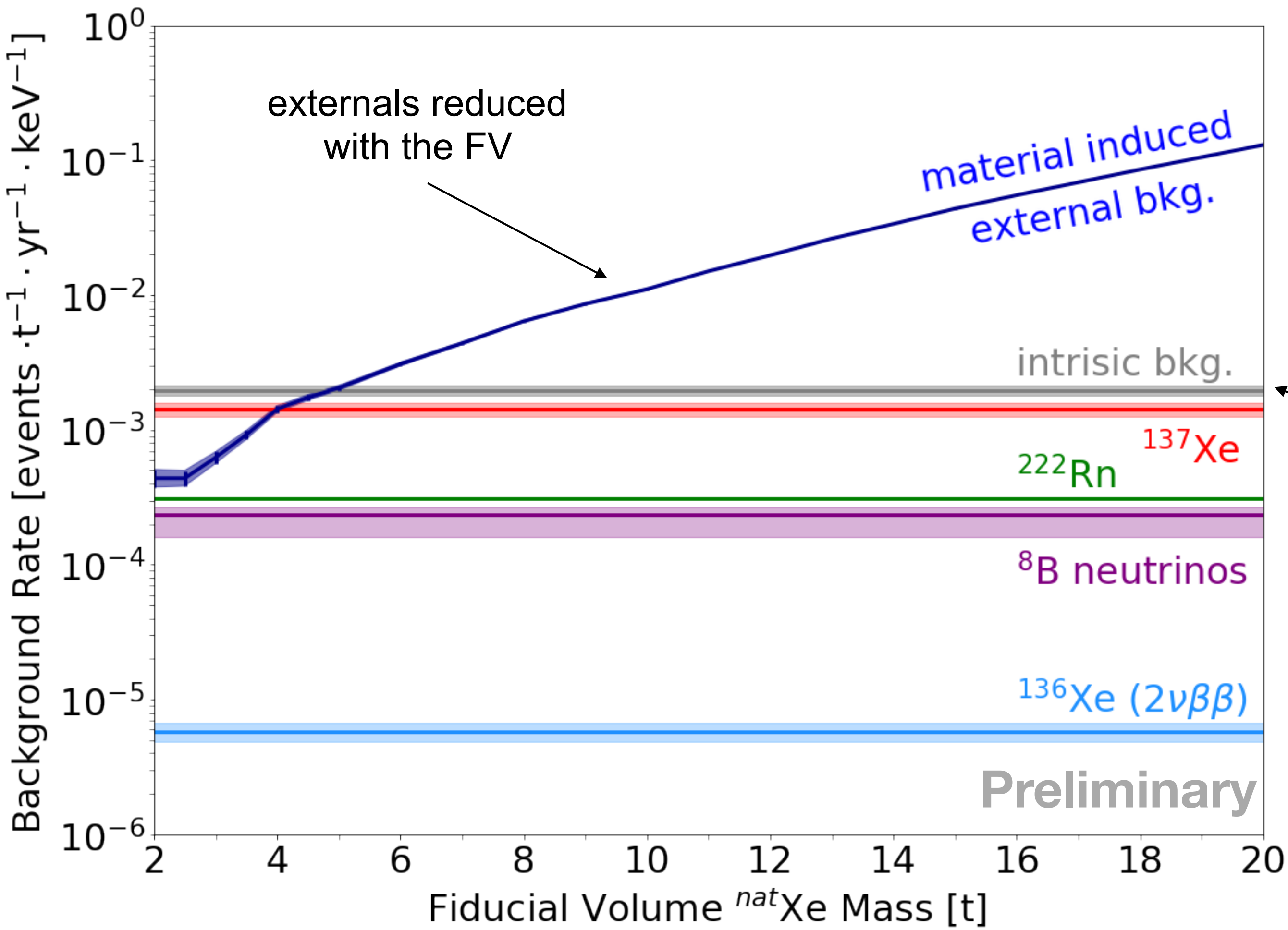
(2.165 ± 0.061)x10^{21} yr

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

Looking for the optimal fiducial mass:



Minimize background without penalizing the exposure

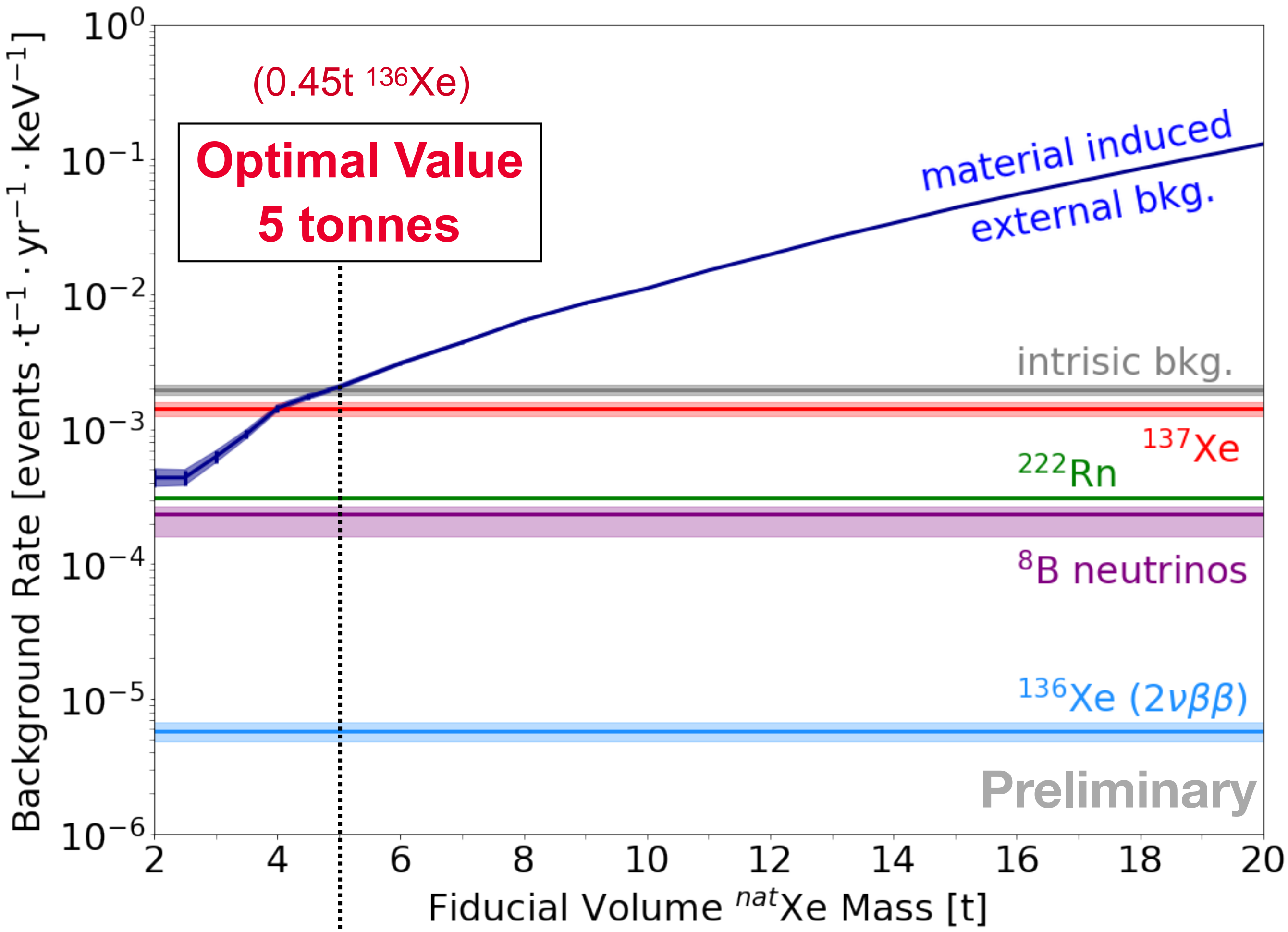
$$T^{0\nu}_{1/2} \propto \frac{\sqrt{Mt}}{\sqrt{B\Delta E}}$$

intrinsics do not change with the fiducialization

TOTAL BACKGROUND: MATERIALS+INTRINSICS

DARWIN

Looking for the optimal fiducial mass:



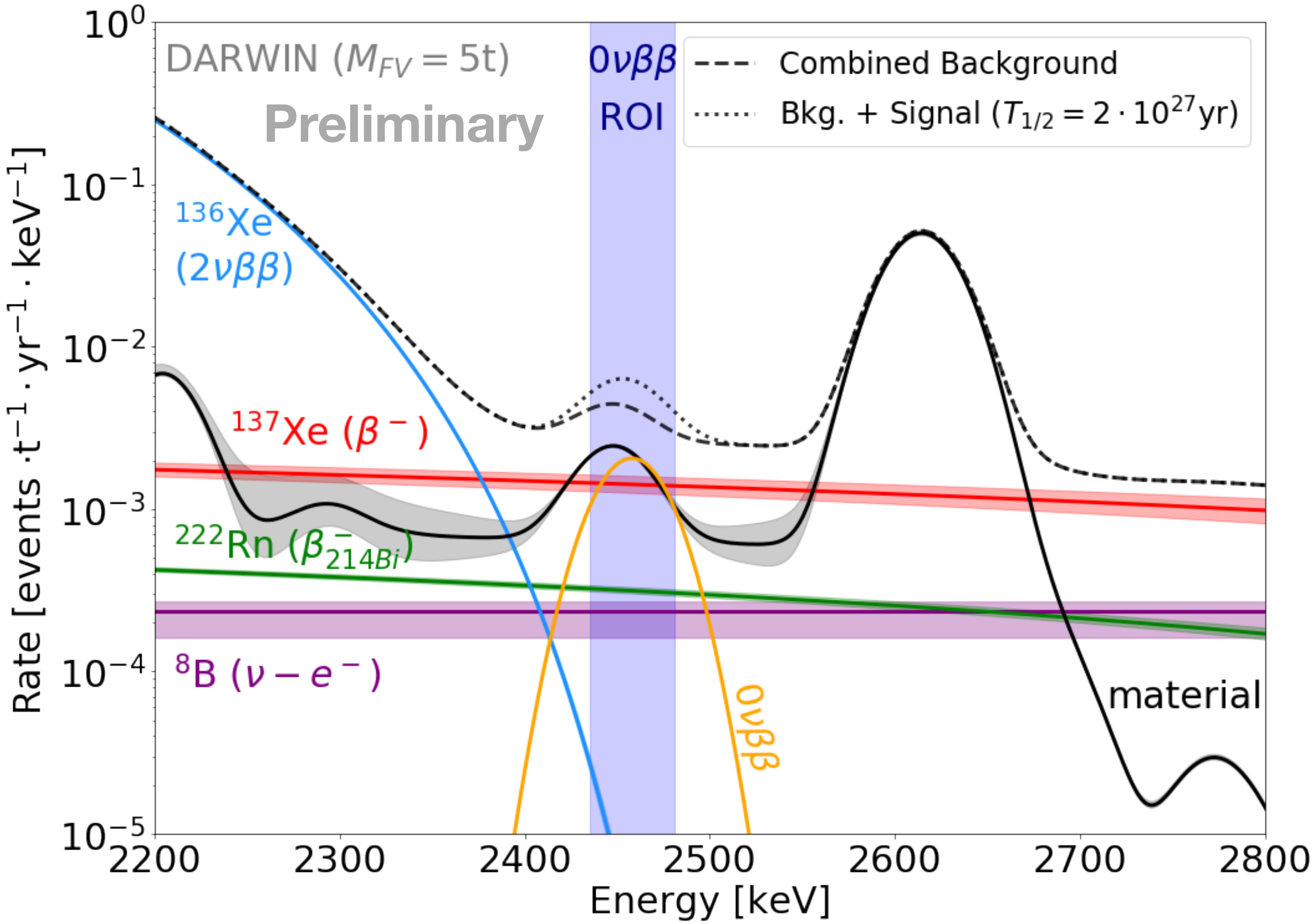
Minimize background without penalizing the exposure

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

This value maximize our sensitivity

TOTAL BACKGROUND FOR 5t FV

DARWIN



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

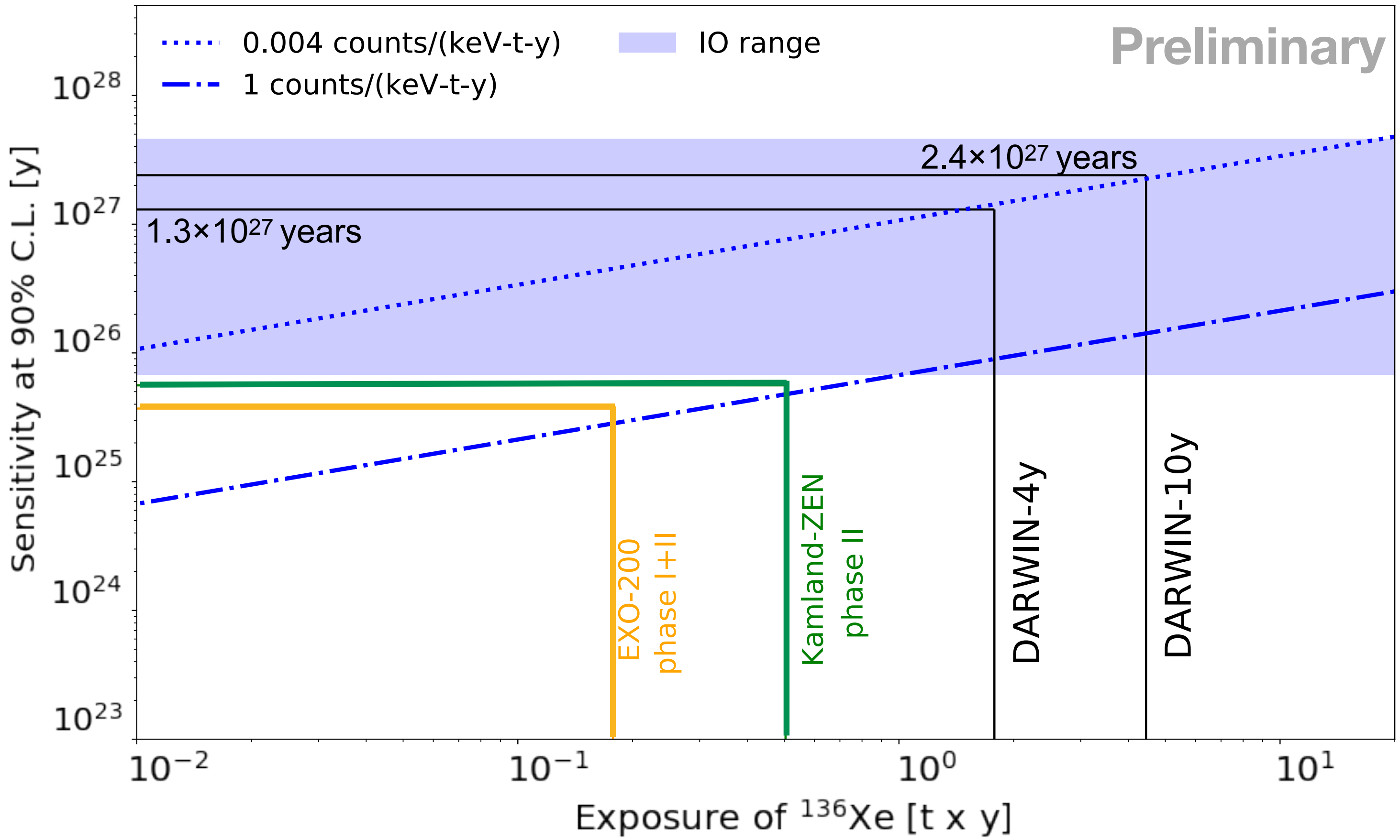
Less than 1 event per year in the ROI !!

The hypothetical $0\nu\beta\beta$ signal in the plot has a strength of 0.5 events/y ($T_{1/2} \approx 2\times10^{27}$ years)

EXPECTED SENSITIVITY FOR THE BASELINE DESIGN

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?

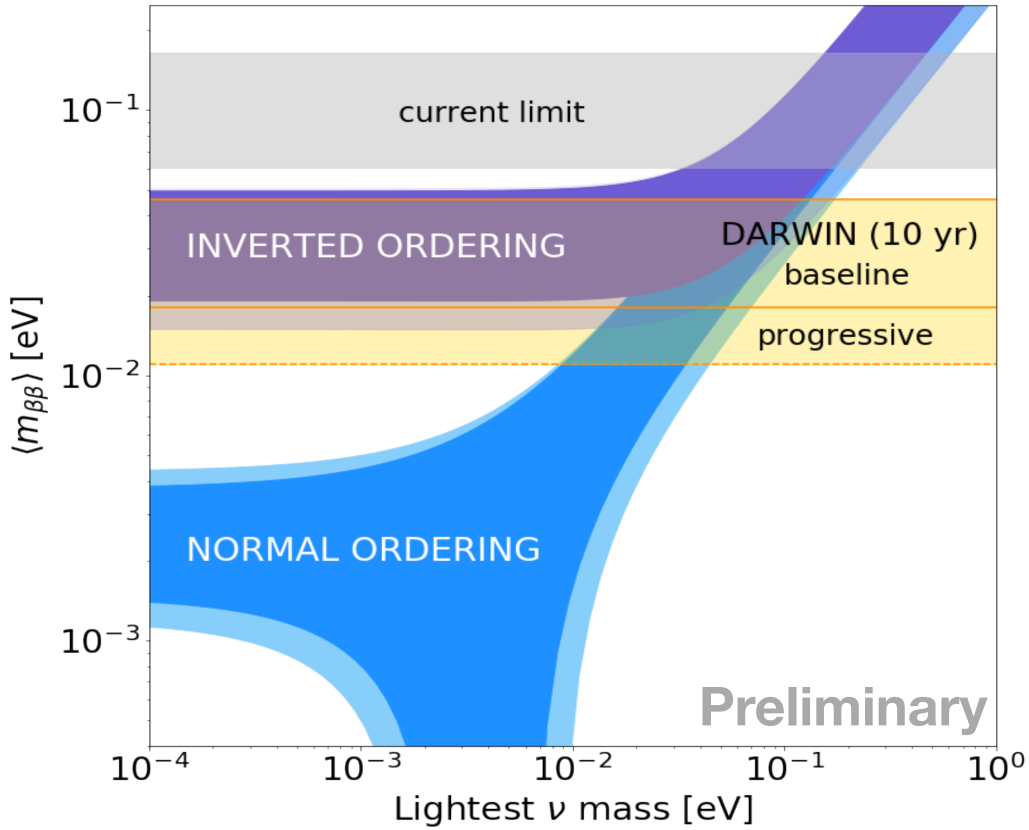
1 Reduce external background

- 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 signal/background discrimination



ROOM FOR IMPROVEMENT !!

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

DARWIN

CONCLUSIONS

- DARWIN will be the ultimate dark matter detector. In addition, its large mass and ultra low background makes it **an excellent detector to look for the 0v$\beta\beta$ decay of ^{136}Xe.**

- Expected energy resolution of ~0.8% at 2.5 MeV

- Dedicated simulations of the **material background:** Contribution at the ROI of the 0vbb dominated by the **PMTs** and the **cryostat**:
  - Other photosensors under investigation,

- Dedicated simulations of the **intrinsic backgrounds: The ^{137}Xe will be the main contribution** for a depth of 3500 m.w.e.

- 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.

- **Still room for improvement:** in a progressive scenario DARWIN can be comparable to dedicated experiments

BACK UP

DARWIN

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
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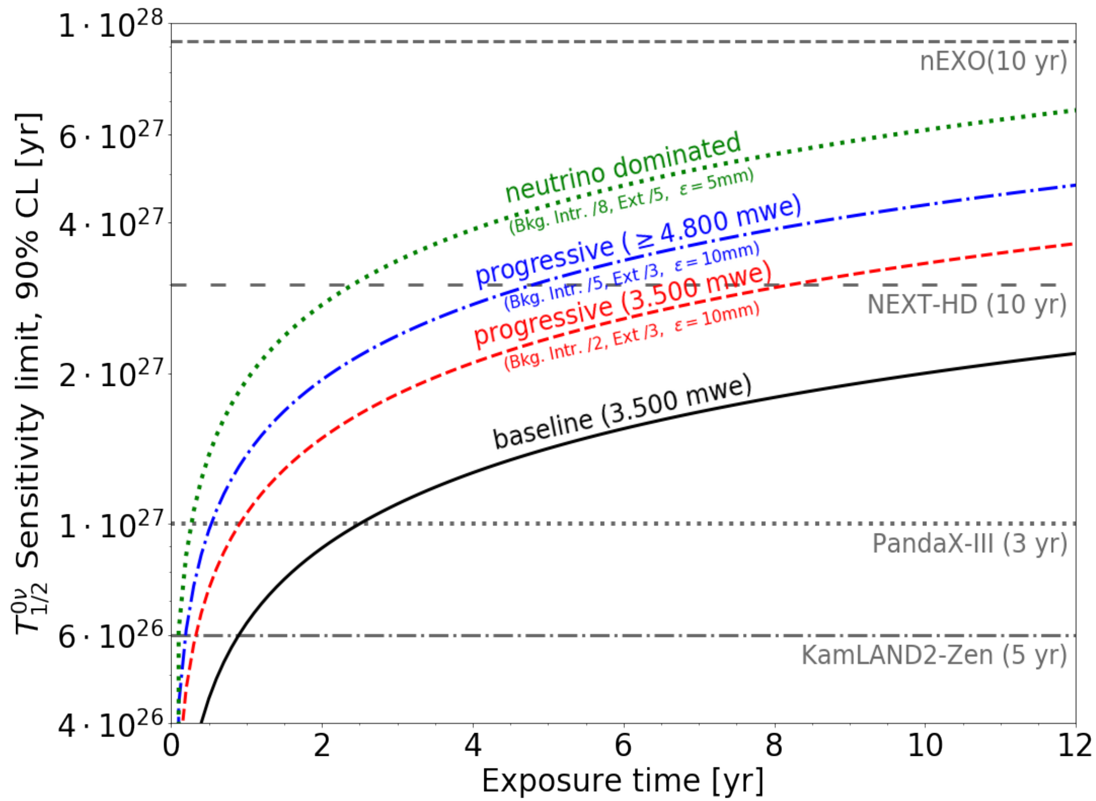
- identify cleaner materials (PTFE, Ti)
- cleaner electronics

② **Reduce internal background**

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

③ **Improve signal/background discrimination**

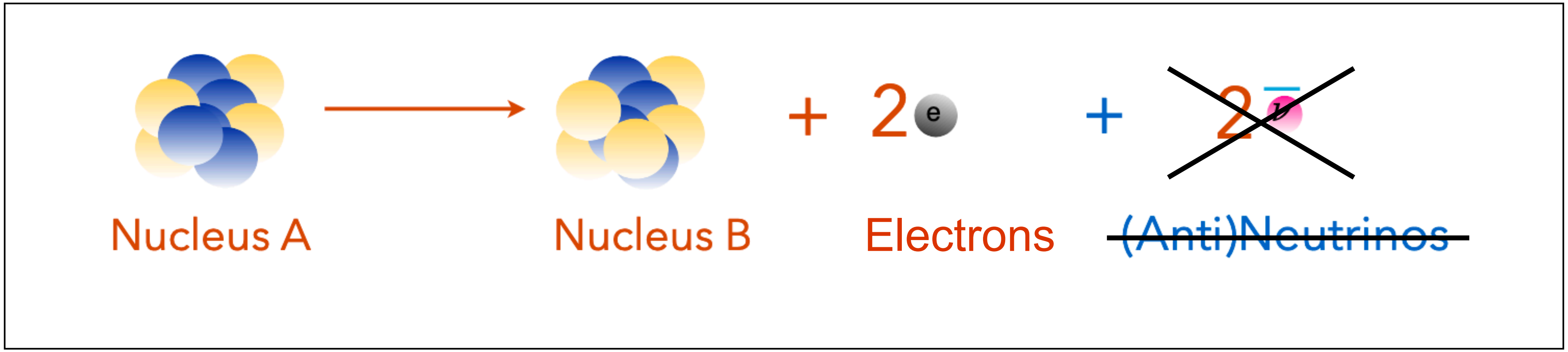


ROOM FOR IMPROVEMENT !!

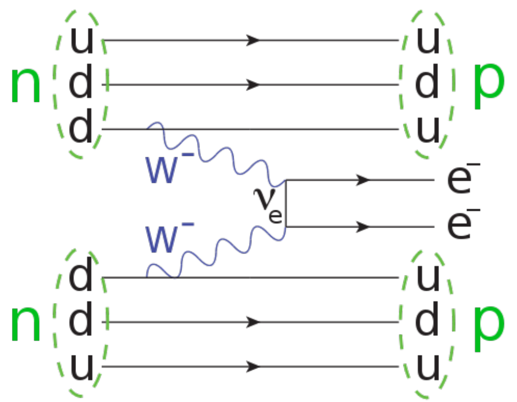
DARWIN could reach a sensitivity of **6×10^{27} years**

DOUBLE BETA DECAY: 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)

DOUBLE BETA DECAY: SOME THEORY

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

Extremely rare nuclear process, NEVER OBSERVED BEFORE

➢ The inverse of the half-life is:

majorana mass

phase space factor

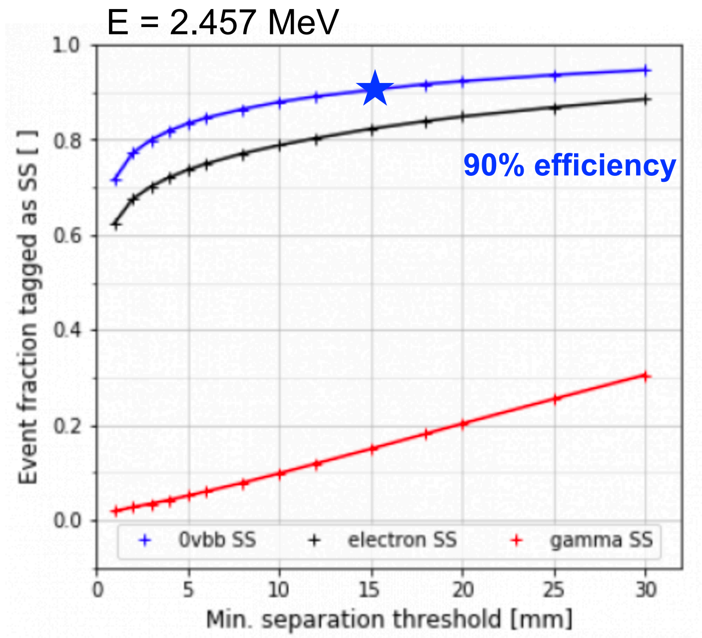
nuclear matrix element

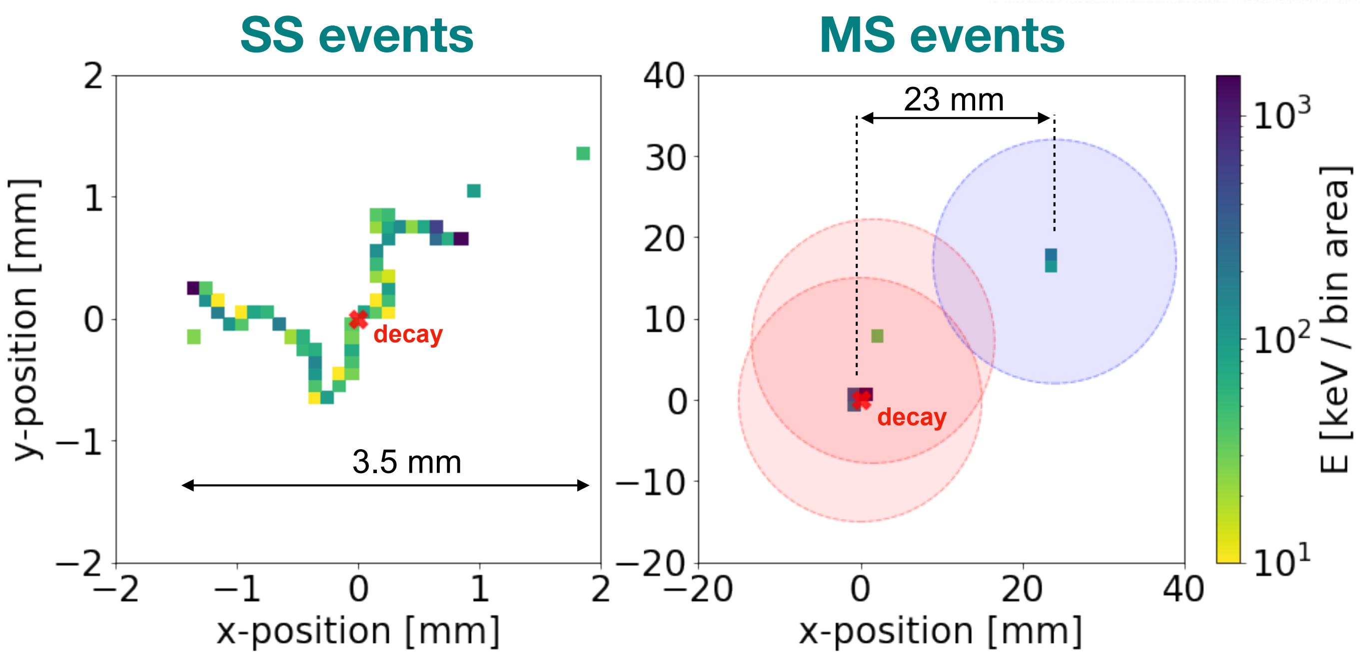
$$\frac{1}{T^{0\nu}_{1/2}} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} |M^{0\nu}|^2$$

electron mass

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)



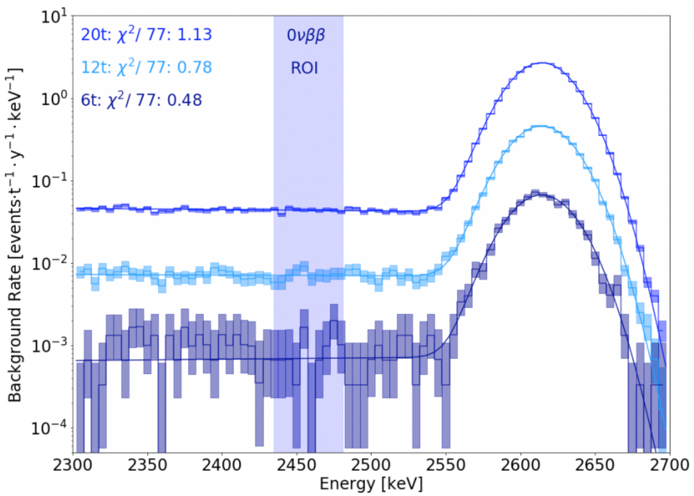


EXTERNAL BACKGROUND: ANALYTIC MODEL

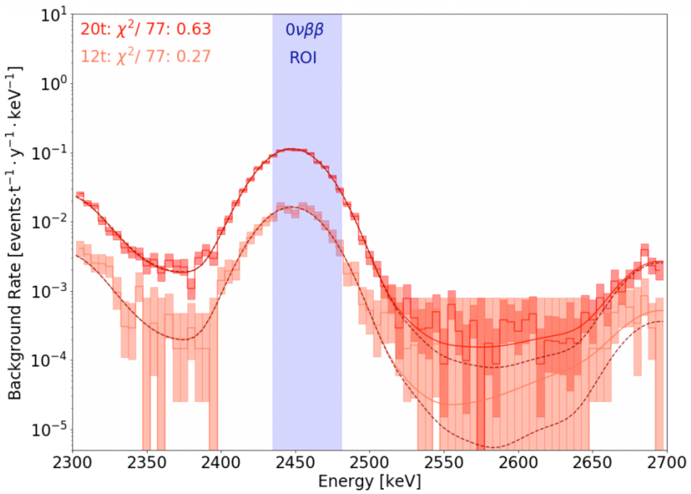
- Understanding of the backgrounds we have in the ROI
- Prediction of the background rate for very smaller fiducial volumes
- Model-derived uncertainty (for 5t FV) is a factor 4 lower than Poissonian errors

Background induced by gammas ➔ contributions in the ROI
from 3 different isotopes

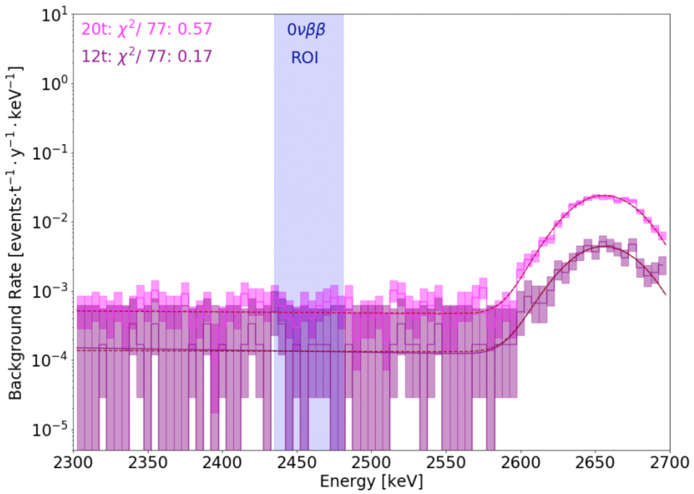
^{208}Tl (2.61 MeV)



^{214}Bi (2.45 MeV + more)



^{44}Sc (2.66 MeV)



Two components per gamma-line:

- ➢ Photo absorption peak (amplitude, E, σ)
- ➢ exponential continuum (intensity at Q-value, exponent/slope)

BACKGROUND INDEX IN THE ROI [2435-2481 keV]

Background source	Background index [events/(t·yr·keV)]	Rate [events/yr]	Rel. uncertainty
External sources (5 t FV):			
^{214}Bi peaks + continuum	1.36×10^{-3}	0.313	$\pm 3.6\%$
^{208}Tl continuum	6.20×10^{-4}	0.143	$\pm 4.9\%$
^{44}Sc continuum	4.64×10^{-6}	0.001	$\pm 15.8\%$
Intrinsic contributions:			
^{8}B ($\nu - e$ scattering)	2.36×10^{-4}	0.054	$+13.9\%, -32.2\%$
^{137}Xe (μ-induced n-capture)	1.42×10^{-3}	0.327	$\pm 12.0\%$
^{136}Xe $2\nu\beta\beta$	5.78×10^{-6}	0.001	$+17.0\%, -15.2\%$
^{222}Rn in LXe (0.1 μBq/kg)	3.09×10^{-4}	0.071	$\pm 1.6\%$
Total:	$\mathbf{3.96 \times 10^{-3}}$	**0.910**	$\mathbf{+4.7\%, -5.0\%}$

Uncertainties from the analytic model

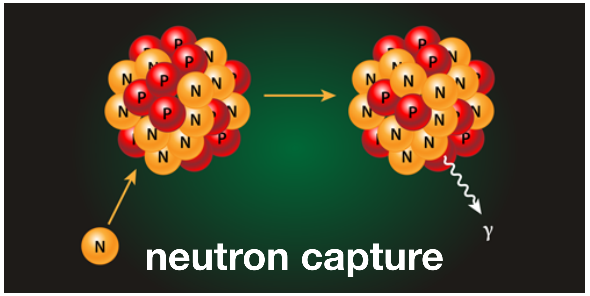
B = 0.91 ± 0.05 events/yr

Less than 1 event per year!!

HOW IS ^{137}Xe PRODUCED?

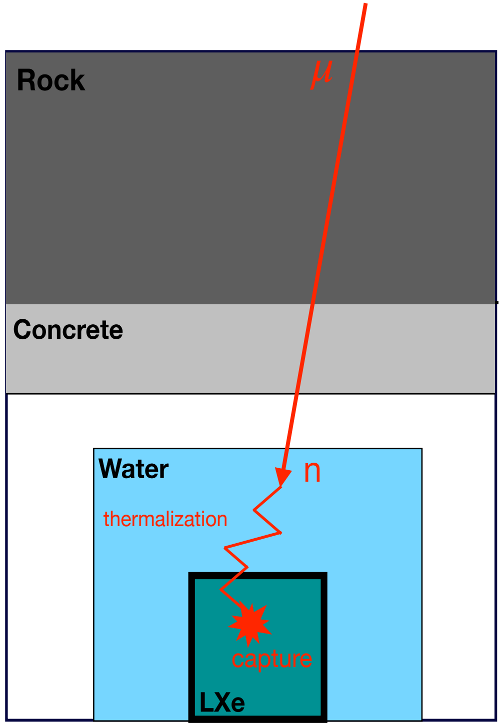
^{137}Xe is mainly produced when **muon-induced neutrons** are captured by ^{136}Xe.

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



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

- 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.

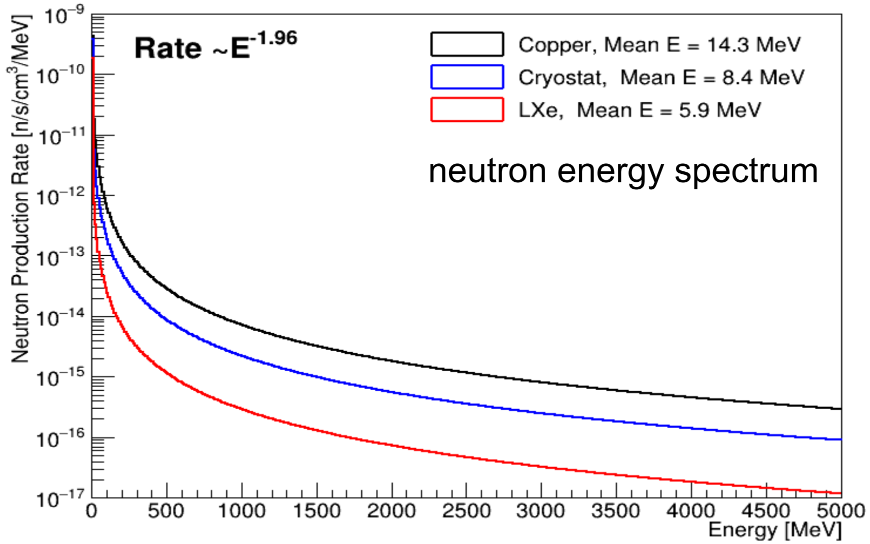


Neutron capture gammas are not a problem because they occur in coincidence with a tag muon

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.



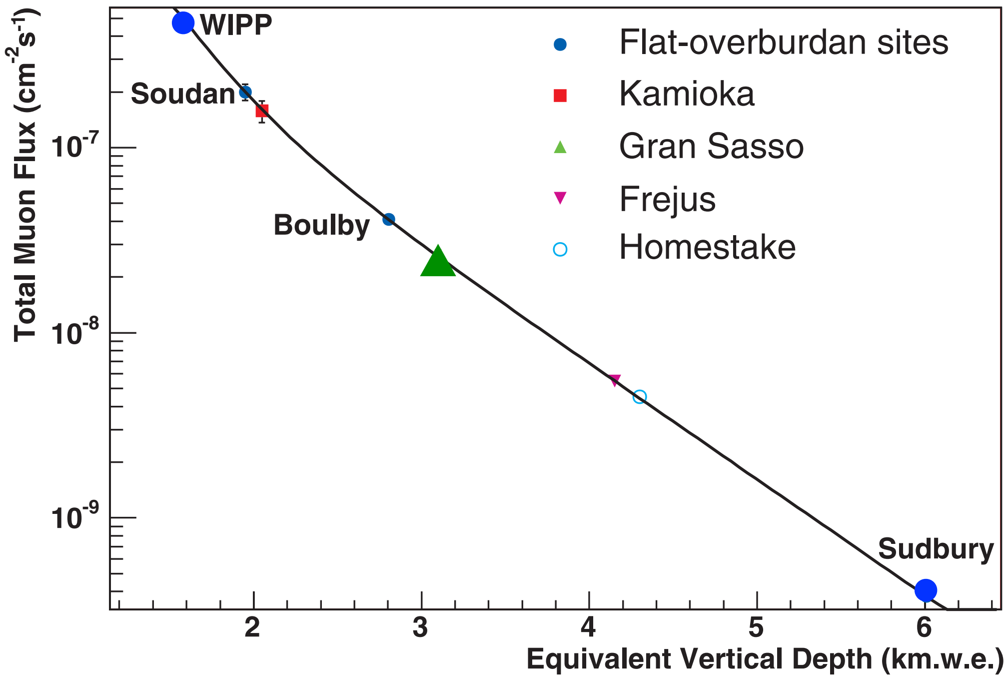
Material	Volume in DARWIN [m^3]	n Production Rate in DARWIN [n/year]	Sim. Events	^{137}Xe isotopes	^{137}Xe Production Rate [atoms/kg/year]
Copper	0.076	1.12×10^4	10^6	234 ± 15	$(6.7 \pm 0.4)\times10^{-5}$
Cryostat	1.076	1.32×10^5	10^6	89 ± 9	$(2.9 \pm 0.3)\times10^{-4}$
LXe	19.976	1.02×10^6	10^6	252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

[2] Y. Wang, PRD 64, 013012 (2001)

^{137}Xe PRODUCTION RATE: COMPARISON

The production rate of ^{137}Xe, dominated by the muon-induced neutrons, depends on the depth our the underground lab

D. Mei, A. Hime,
Phys.Rev.D**73** (2006) 053004



Experiment	Location	Depth [m.w.e]	Muon flux [1/s/cm²]	^{137}Xe Production Rate [atoms/kg/year]
EXO-200[3]	WIPP	1600	$\sim 4\times10^{-7}$	2.95
DARWIN	LNGS	3600	$\sim 2\times10^{-8}$	7.71×10^{-2}
nEXO [4]	SNOLAB	6011	$\sim 4\times10^{-10}$	2.44×10^{-3}

values normalized per kg of ^{136}Xe

- ➢ Our result is consistent with the values given by EXO-200 and nEXO
- ➢ The Xe137 production rate behaves as expected, scaling with the muon flux

[3] EXO-200, JCAP 1604 (2016) 029
[4] nEXO, Phys. Rev. C 97, 065503 (2018)

BACKGROUND PREDICTIONS

Two different backgrounds

Electronic Recoils

- γ-rays from materials
- Intrinsic backgrounds (^{85}Kr, ^{222}Rn, ^{136}Xe)
- Low energy solar neutrinos (pp, ^{7}Be)

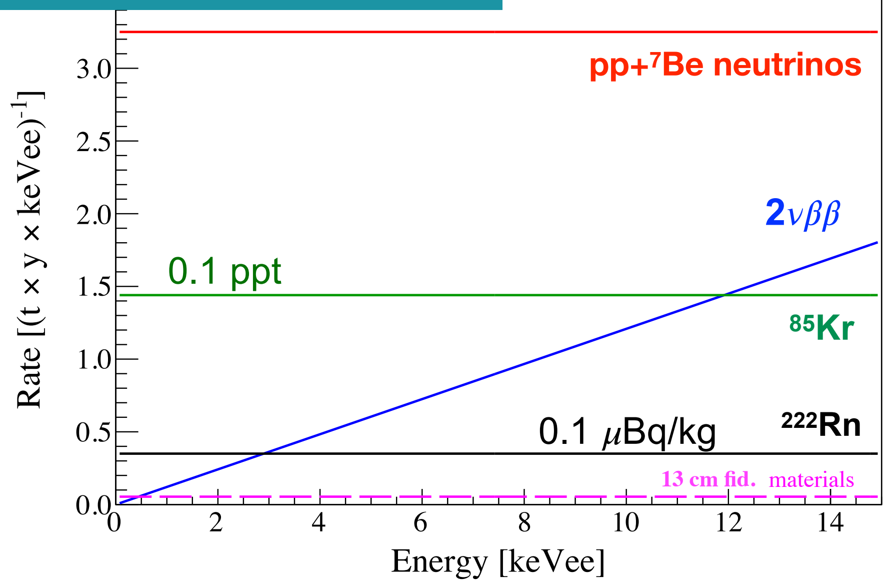
Nuclear Recoils

- Coherent v-N scattering (irreducible)
- Neutrons from the materials
- Cosmogenic and radiogenic (lab) neutrons

(reduced by overburden, veto and fiducialisation)

ER can be rejected based on the S1/S2 ratio

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



DARWIN will require a ER rejection **> 99.98%**

Background contribution before ER discrimination

Source	Rate [events/(t·y·keV)]
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

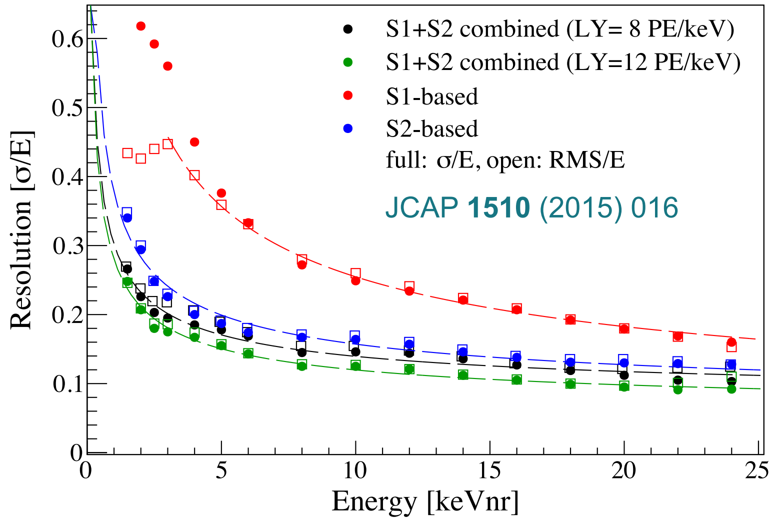
NR

ER = 5.824 events/(t · y · keV$_{ee}$)

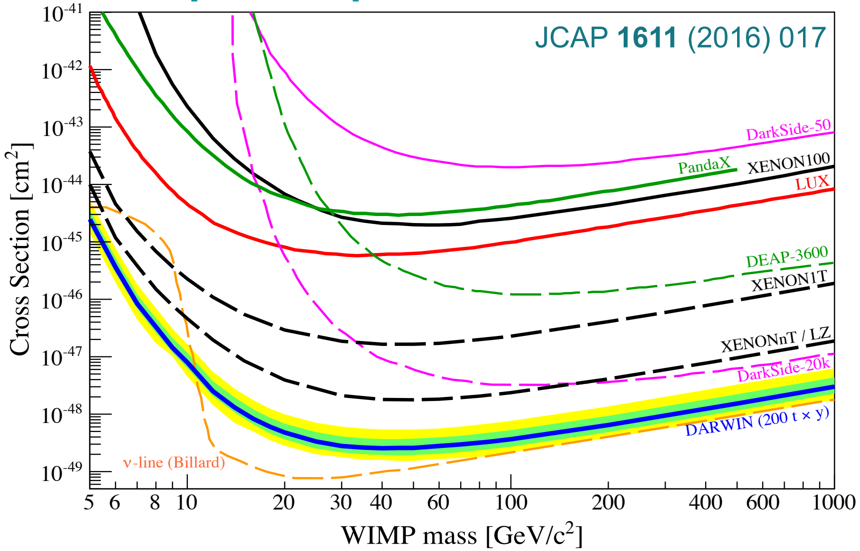
lower than current experiments

SENSITIVITY TO WIMPS

- Considering all mentioned background
- 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

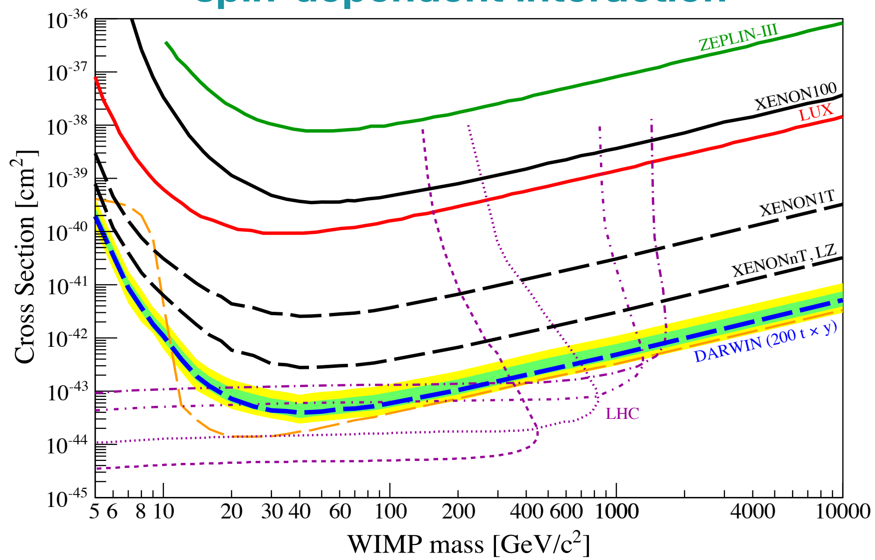


spin-independent interaction



minimum: 2.5×10^{-49} cm^2 at 40 GeV/c^2

spin-dependent interaction



Complementary to LHC searches (14TeV)

SOLAR NEUTRINOS

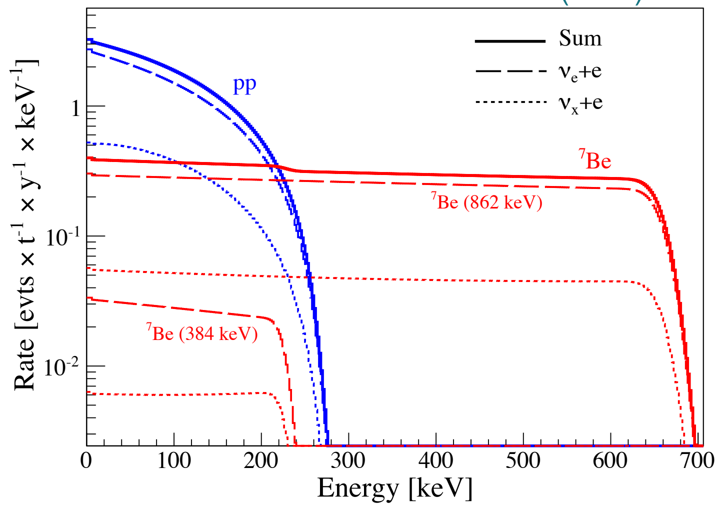
The precise measurement of pp- neutrinos will test the main energy production mechanisms in the Sun

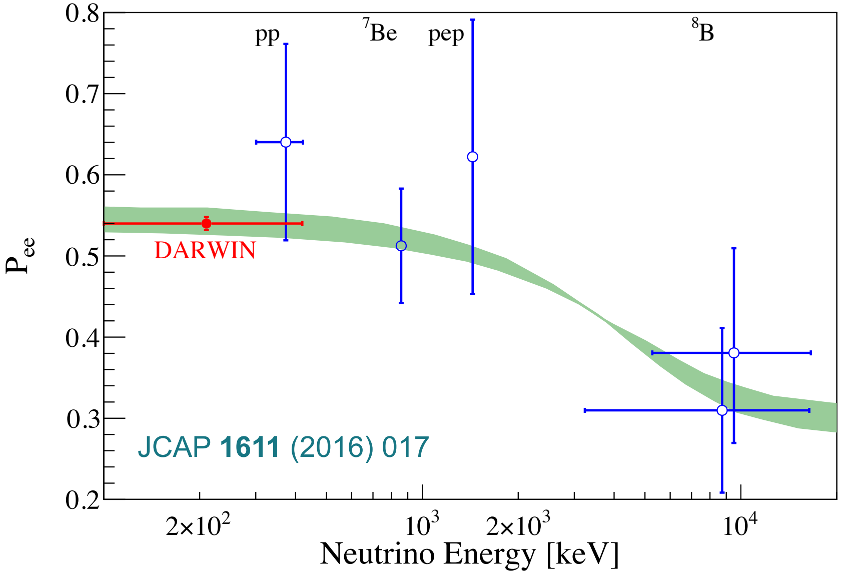
- pp- neutrinos are ~92% of the solar neutrino flux (SSM)
- Detection through neutrino-electron elastic scattering

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

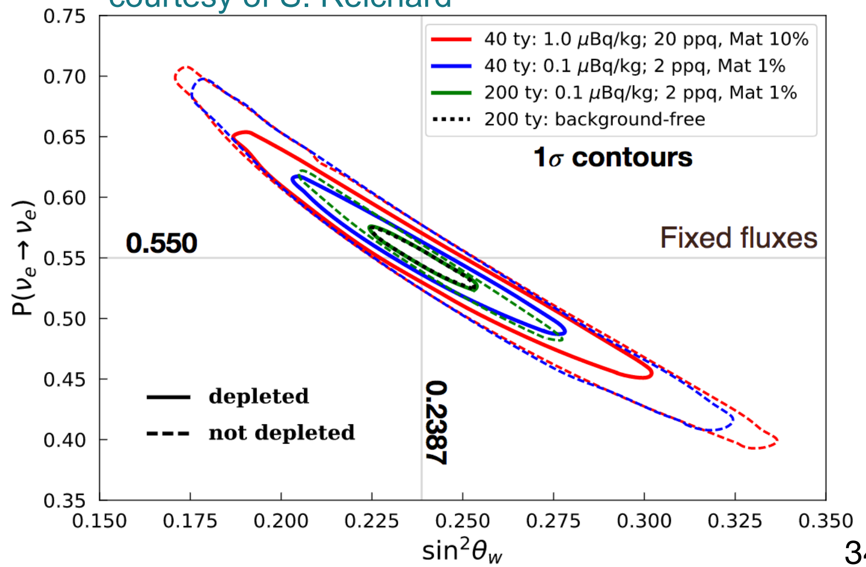
- Real-time measurement of the neutrino flux: **361 events/(t x y)**
  (whole energy range above 2keV$_{ee}$)
- Flux with 2% statistical precision after 1 year
- Measurement of electron neutrino survival probability (P_{ee}) and the neutrino mixing angle below 300 keV.
  (deviation from prediction would indicate new physics)

JCAP **1611** (2016) 017





courtesy of S. Reichard



COHERENT NEUTRINO NUCLEUS SCATTERING (CNNS)

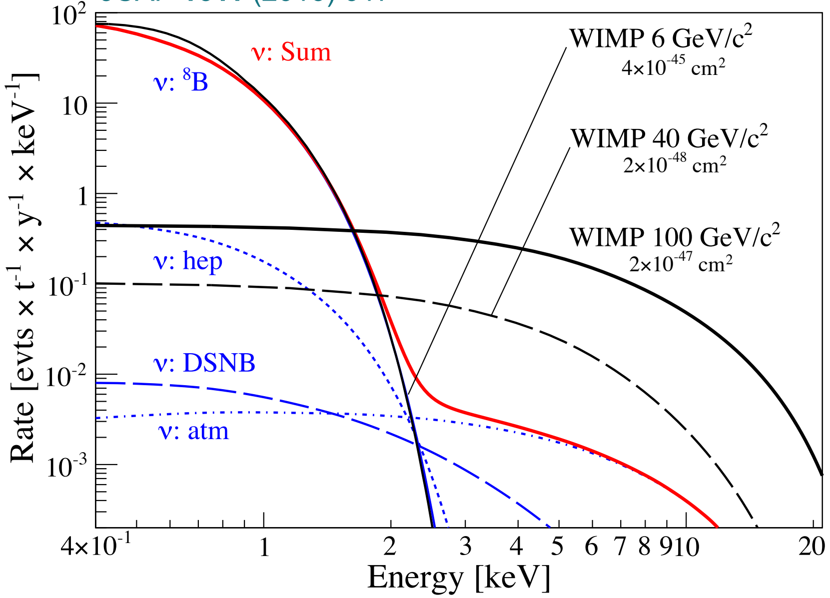
CNNS is a irreducible background for WIMP searches but also one of the scientific goals of DARWIN

$$\nu + A \longrightarrow \nu + A$$

sensitive to all neutrino flavors

^{8}B solar neutrinos

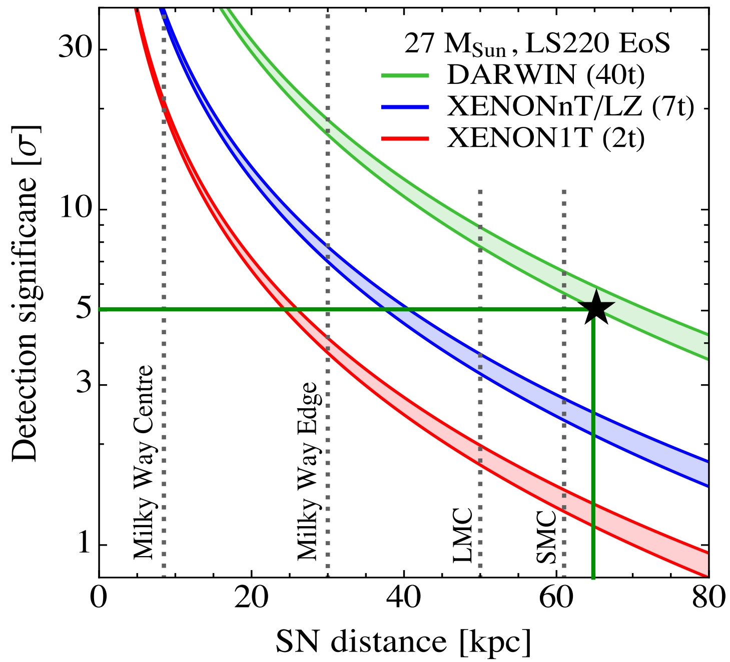
JCAP **1611** (2016) 017



- ^{8}B neutrinos from the Sun:
  E_{th} > 1 keV$_{nr}$ $\longrightarrow$ **90 events/(t × y)**
- Atmospheric neutrinos:
  E_{th} > 1 keV$_{nr}$ $\longrightarrow$ **0.003 events/(t × y)**

Supernova neutrinos

DARWIN will detect SN bursts up to 65 kpc from Earth (5σ), observing **~700 events** from a 27 M$_\odot$ SN progenitor at 10 kpc (window of 7s).

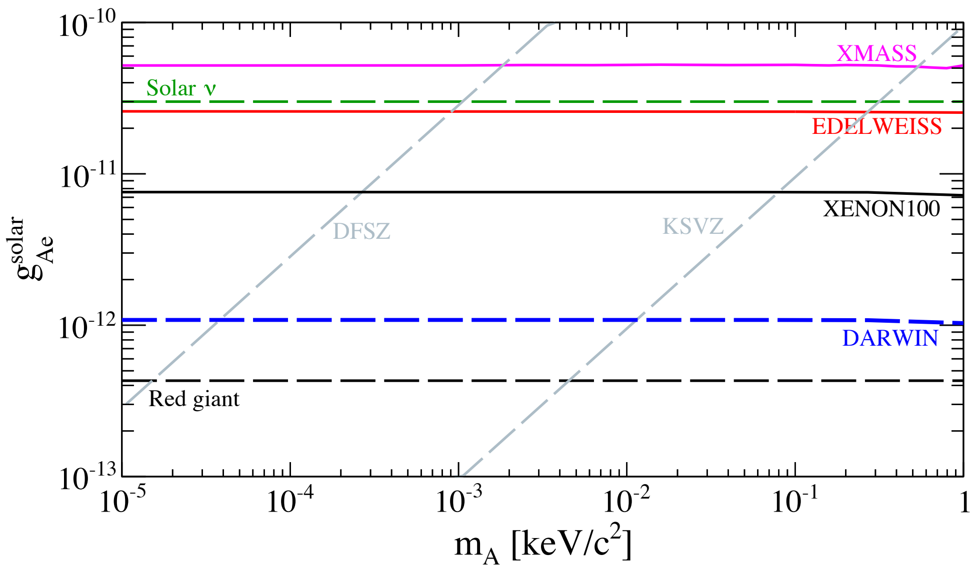


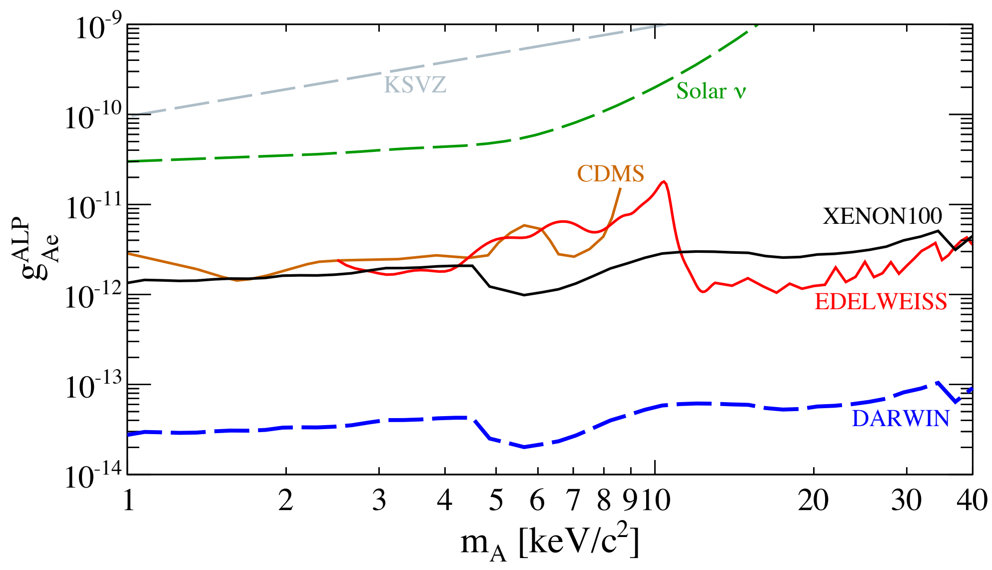
R. F. Lang *et al.*, *Phys. Rev. D* ***94*** *(2016) 103009*

AXION AND AXION-LIKE PARTICLES

Axions and axion-like particles (ALPs) are well motivated dark matter candidates → but **they can be produced in the Sun independently if they are the dark matter candidate or not**

- Measurement via axio-electric effect (ER channel)
- Expected Signal: mono-energetic peak at the particle mass (few keV)
- Dependence of the coupling on the exposure (M×T): $g_{Ae}^{ALP} \propto (MT)^{-1/4}$ $g_{Ae}^{solar} \propto (MT)^{-1/8}$
- Sensitivity to ALPs two orders of magnitude better than current limits (g_{Ae}^{ALP} > 10^{-13} - 10^{-14})
- Modest sensitivity to solar axions (g_{Ae}^{solar} > 10^{-12})
- Main backgrounds: irreducible solar neutrinos & $2\nu\beta\beta$ of ^{136}Xe.





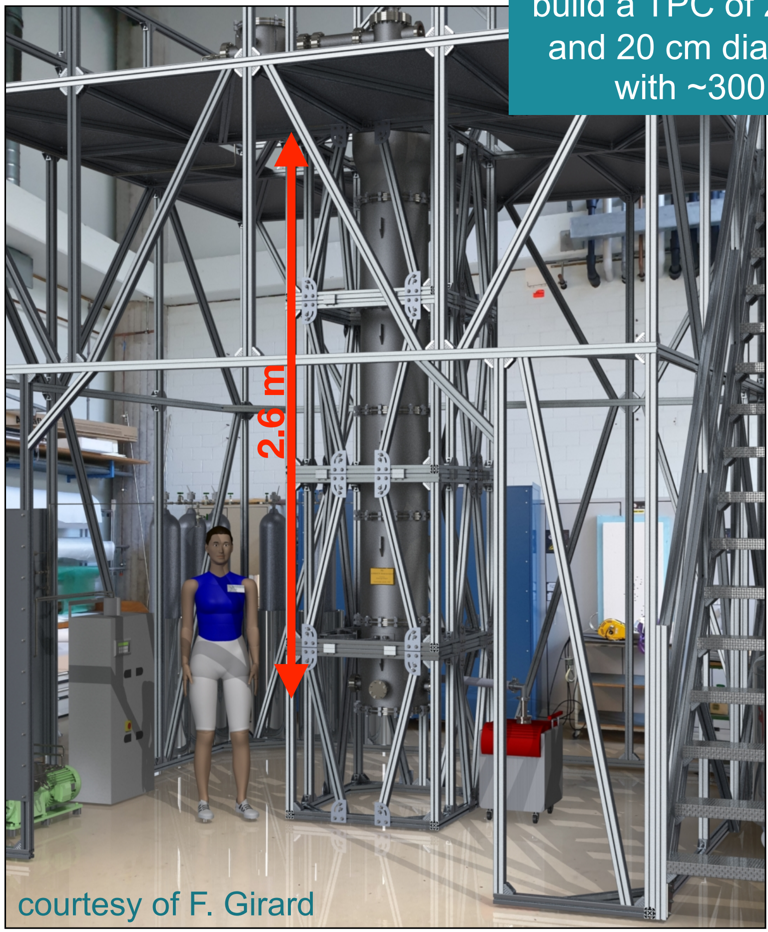
ONGOING R&D: DEMONSTRATORS

DARWIN full-length demonstrator

Universität Zürich[UZH]

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

build a TPC of 2.6 m height and 20 cm diameter filled with ~300kg LXe



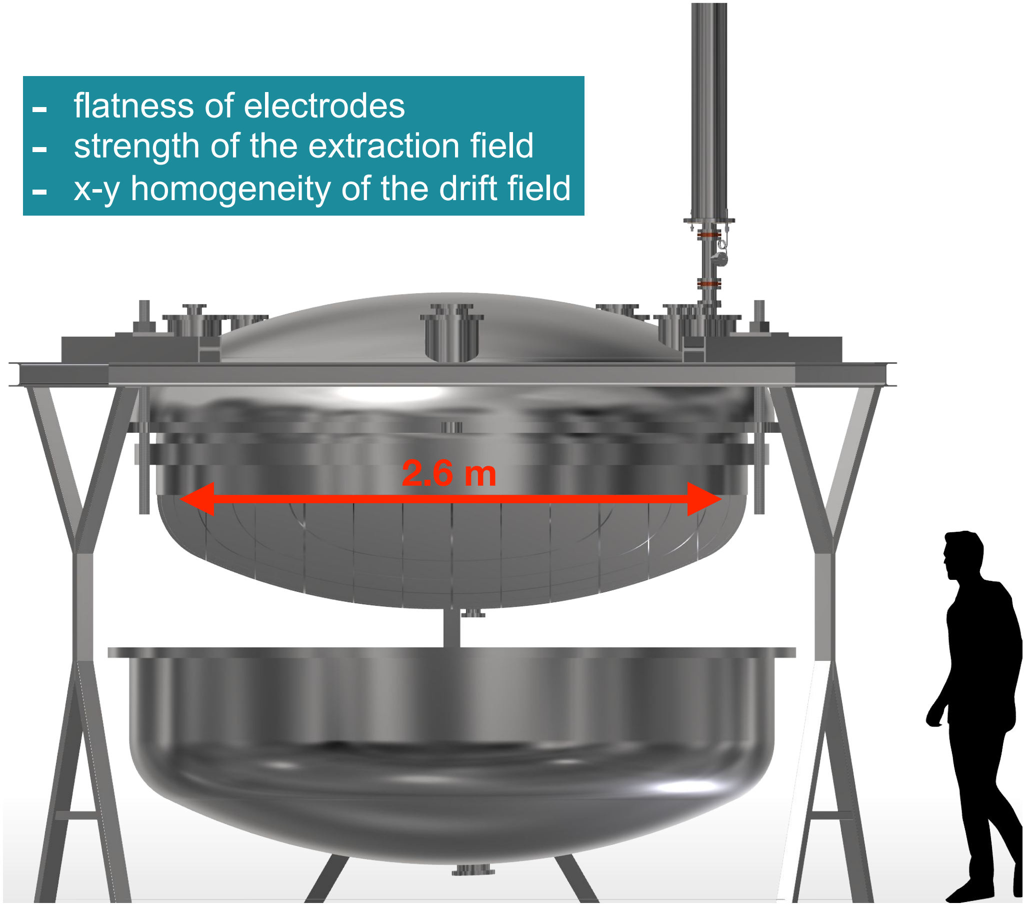
courtesy of F. Girard

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



credit: Florian Tönnies