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DARWIN

SENSITIVITY OF THE DARWIN OBSERVATORY TO THE NEUTRINOLESS DOUBLE BETA DECAY

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PHYSICS SEMINAR, LECONTE HALL
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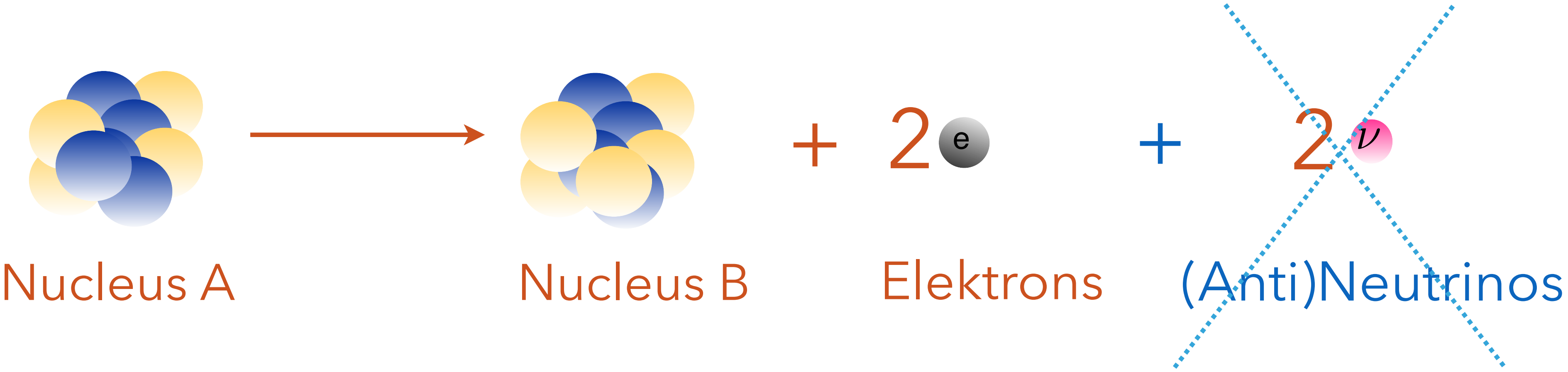
SOME KEY OPEN QUESTIONS IN PARTICLE PHYSICS

- The nature of dark matter
- Baryogenesis
- The strong CP problem
- The fermion mass spectrum and mixing
- The cosmological constant
- …
- Some of these can be addressed with liquid xenon detectors operated deep underground
- Demonstrated excellent sensitivities and scalability to large target masses

SOME OPEN QUESTIONS IN NEUTRINO PHYSICS

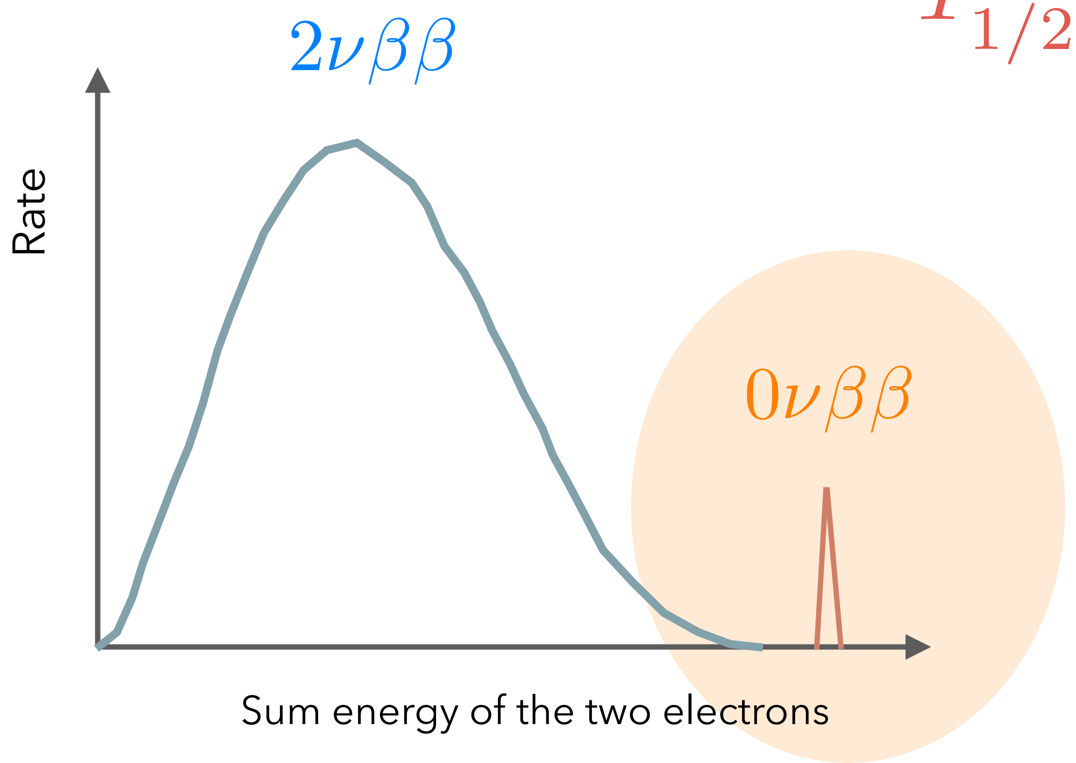
- What is the absolute mass of neutrinos?
- Are neutrinos their own antiparticles?
- These can be addressed with an extremely rare nuclear decay process: *the neutrinoless double beta decay*

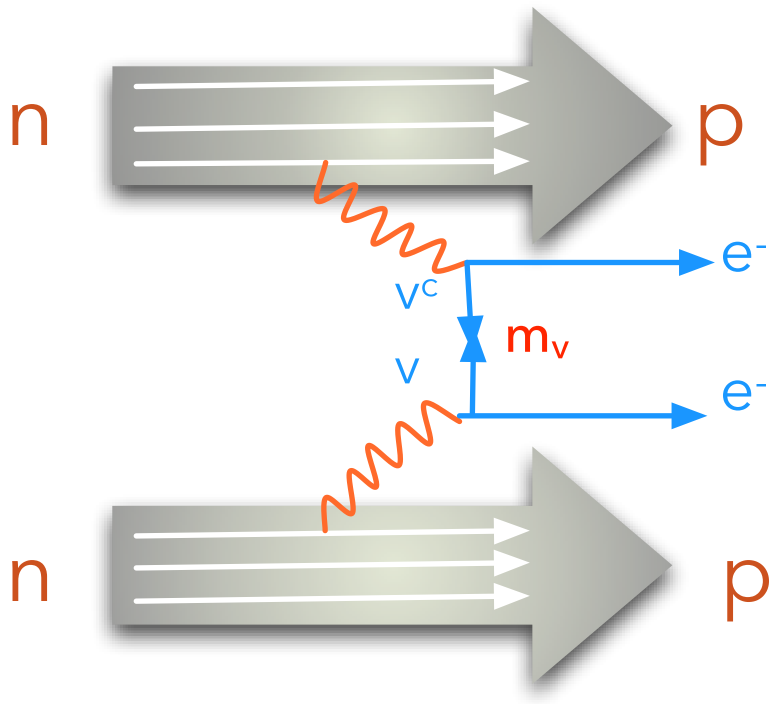


THE NEUTRINOLESS DOUBLE BETA DECAY

- Can only occur if neutrinos have mass and if they are their own anti-particles; $\Delta L = 2$
- Expected signature: sharp peak at the Q-value of the decay

$$T_{1/2}^{0\nu\beta\beta} > 10^{24}\,\mathrm{y}$$





OBSERVABLE DECAY RATE

Leptonic
phase
space

Nuclear
physics
NME

Particle
physics

$$\Gamma^{0\nu} = \frac{\ln 2}{T^{0\nu}_{1/2}} = G^{0\nu}(Q, Z)|M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

Can be
calculated: ~ Q^5

Difficult:
factor 2-3

- With the effective Majorana neutrino mass:

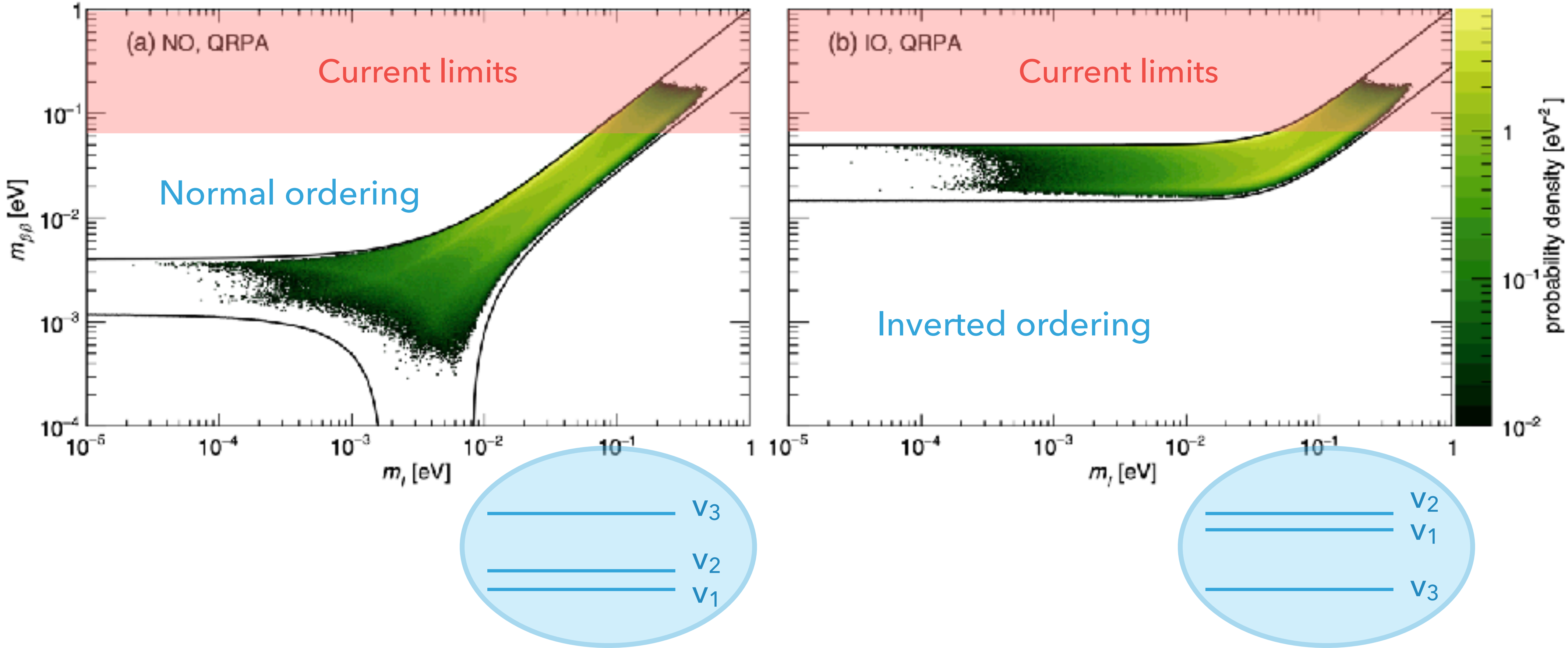
$$|m_{\beta\beta}| = |m_1 U_{e1}^2 + m_2 U_{e2}^2 e^{2\phi_1} + m_3 U_{e3}^2 e^{2i(\phi_2 - \delta)}|$$

- a coherent sum over mass ES, with potentially CP violating phases
  - a mixture of m_1, m_2, m_3, proportional to U^2

NEUTRINO MASS EIGENSTATES AND MIXING MATRIX TERMS

- Probability distribution of $m_{\beta\beta}$ via random sampling from the distributions of mixing angles and Δm^2
- Flat priors for the Majorana phases

Agostini, Benato, Detwiler, PRD 96, 2017



EXPRIMENTAL REQUIREMENTS

- Experiments measure the half-life, with a sensitivity (in the case of non-zero background)

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

$$\langle m_{\beta\beta} \rangle \propto \frac{1}{\sqrt{T^{0\nu}_{1/2}}}$$

Minimal requirements:

large detector masses
high isotopic abundance
ultra-low background noise
good energy resolution

Additional tools to distinguish signal from background:

event topology
pulse shape discrimination
particle identification

EXPERIMENTAL TECHNIQUES*

Heat

CUORE
CUPID

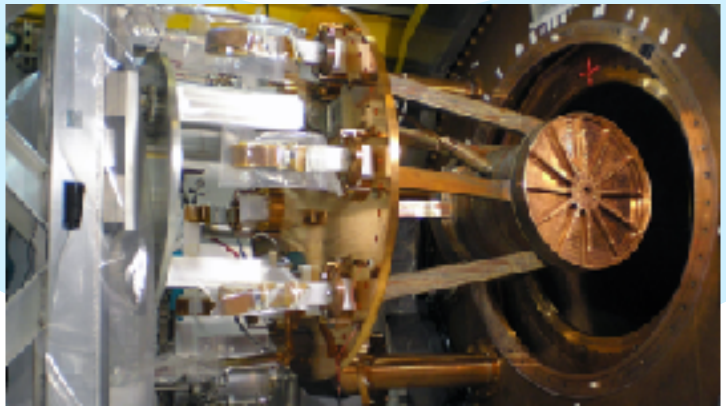
Energy of the
two electrons

Charge

GERDA
MAJORANA
LEGEND
SuperNEMO

Light

KAMLAND-Zen
SNO+

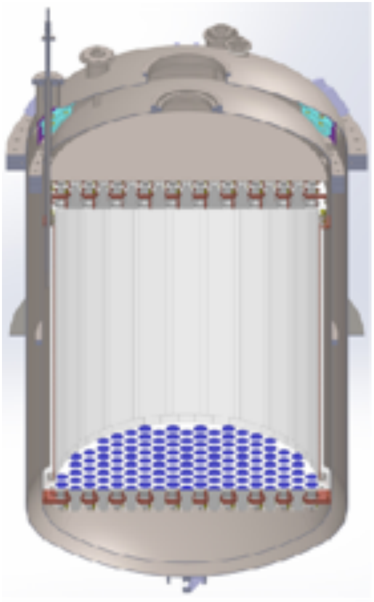


EXO-200
nEXO, NEXT
DARWIN

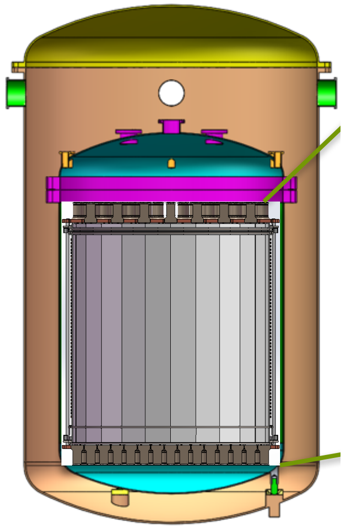
(*not a complete list)

UPCOMING MULTI-TONNE XENON DETECTORS

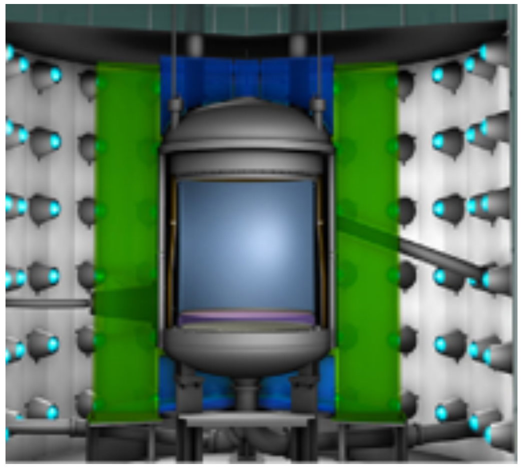
- In construction:
  - LUX-ZEPLIN (10 t LXe), XENONnT (8.4 t LXe), PandaX-4t (4t LXe)
- Planned or design and R&D stage
  - nEXO (5 t ^{enr}Xe), DARWIN (50 t LXe)



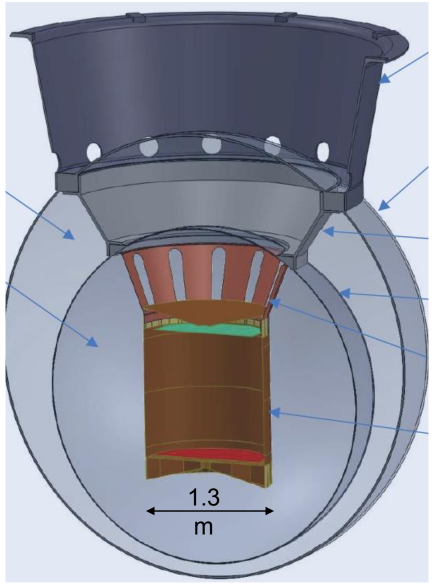
XENONnT
Data taking 2020



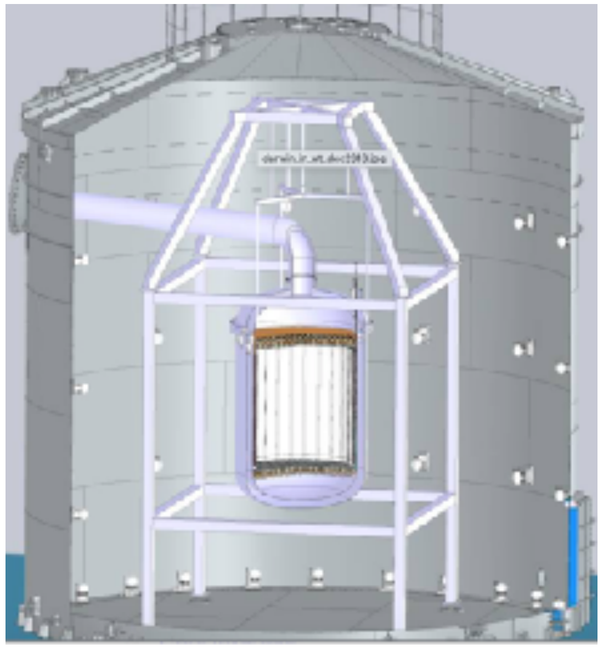
PandaX-4t LXe
Data taking 2020



LUX-ZEPLIN
Data taking 2020



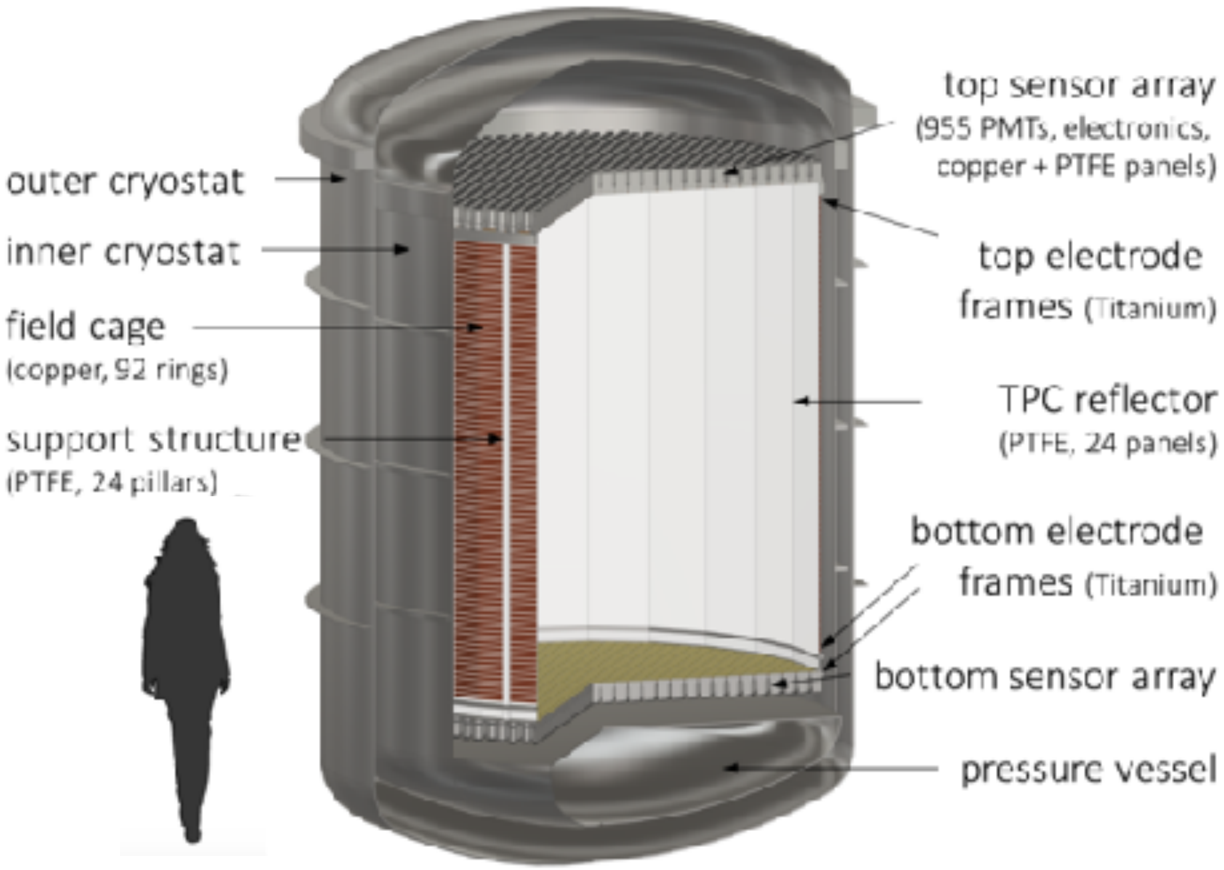
nEXO
Data taking ~202?



DARWIN
Data taking ~2026

DARWIN DESIGN: BASELINE SCENARIO

- Two-phase TPC: 2.6 m ø, 2.6 m height
- 50 t (40 t) LXe in total (in the TPC)
- Two arrays of photosensors (e.g. 1800 3-inch PMTs)
- PTFE reflectors and copper field shaping rings
- Low-background, double-walled titanium cryostat
- Shield: Gd-doped water, for μ and n



DARWIN collaboration, JCAP 1611 (2016) 017

Alternative designs and photosensors
under consideration, will not discuss here

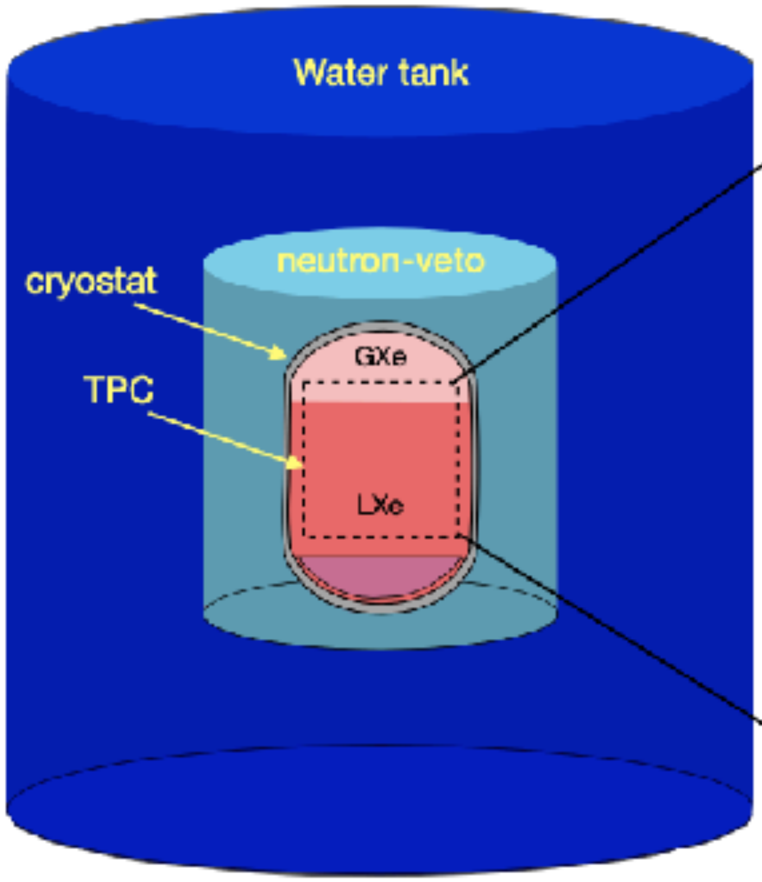
DOUBLE BETA DECAY IN DARWIN: FOR FREE

- ^{136}Xe: excellent candidate
  - abundance in ^{nat}Xe: 8.9%, Q-value: (2457.83±0.37) keV*
- Total amount of ^{136}Xe in DARWIN: ~3.5 tonnes
- Expected (1-σ) energy resolution:
  - ~0.8% at 2.5 MeV, demonstrated by XENON1T
- Ultra-low background environment (^{222}Rn, ^{8}B neutrinos, ^{137}Xe from cosmogenic activation, 2νββ-decays)

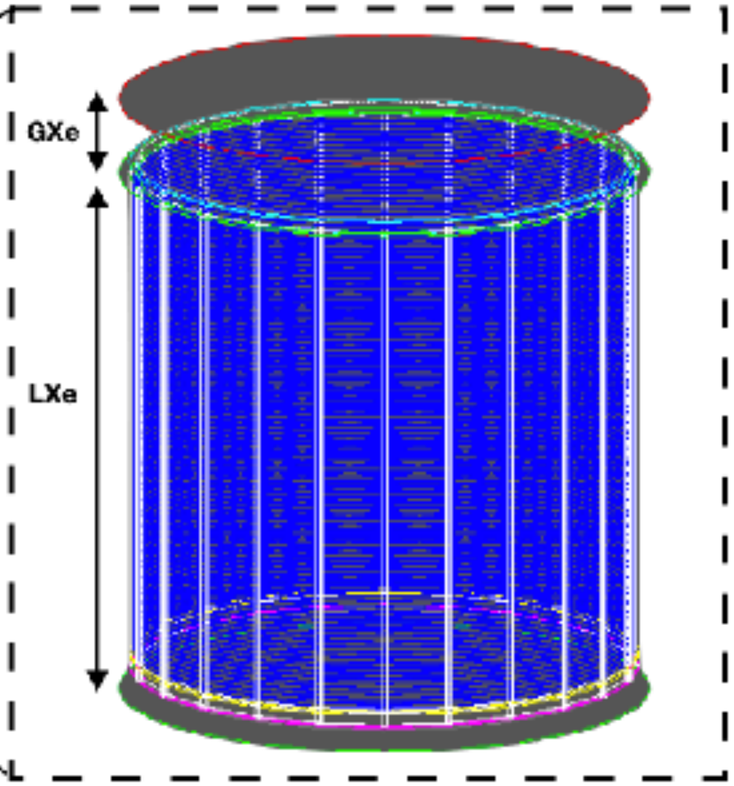
*M. Redshaw et al., PRL 98, 2007: M(136Xe)-M(136Ba) =2457.83(37)

BACKGROUND SIMULATIONS FOR DOUBLE BETA STUDY

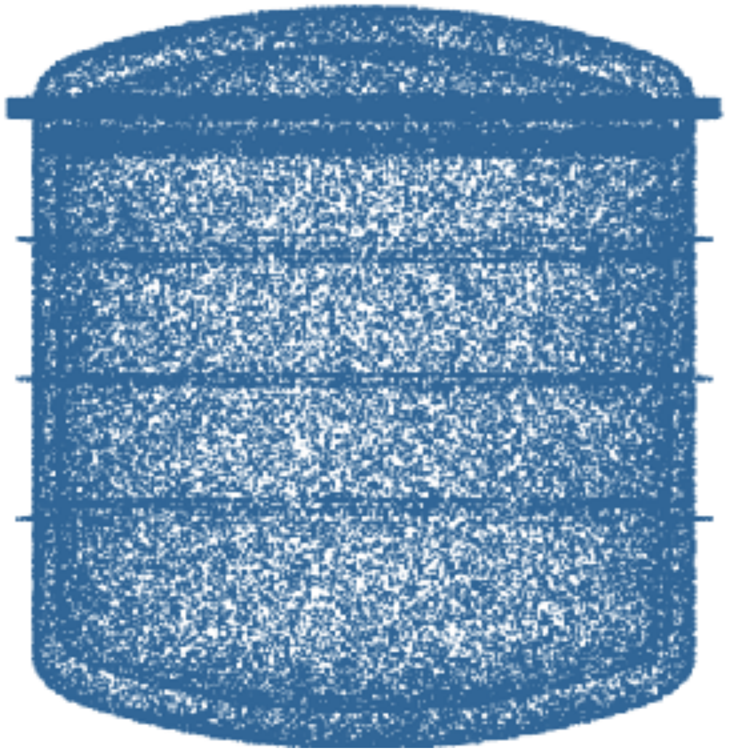
- Detailed detector model in Geant4



sketch of the G4 geometry



detailed G4 TPC geometry



Double-walled Ti cryostat, design by Nikhef

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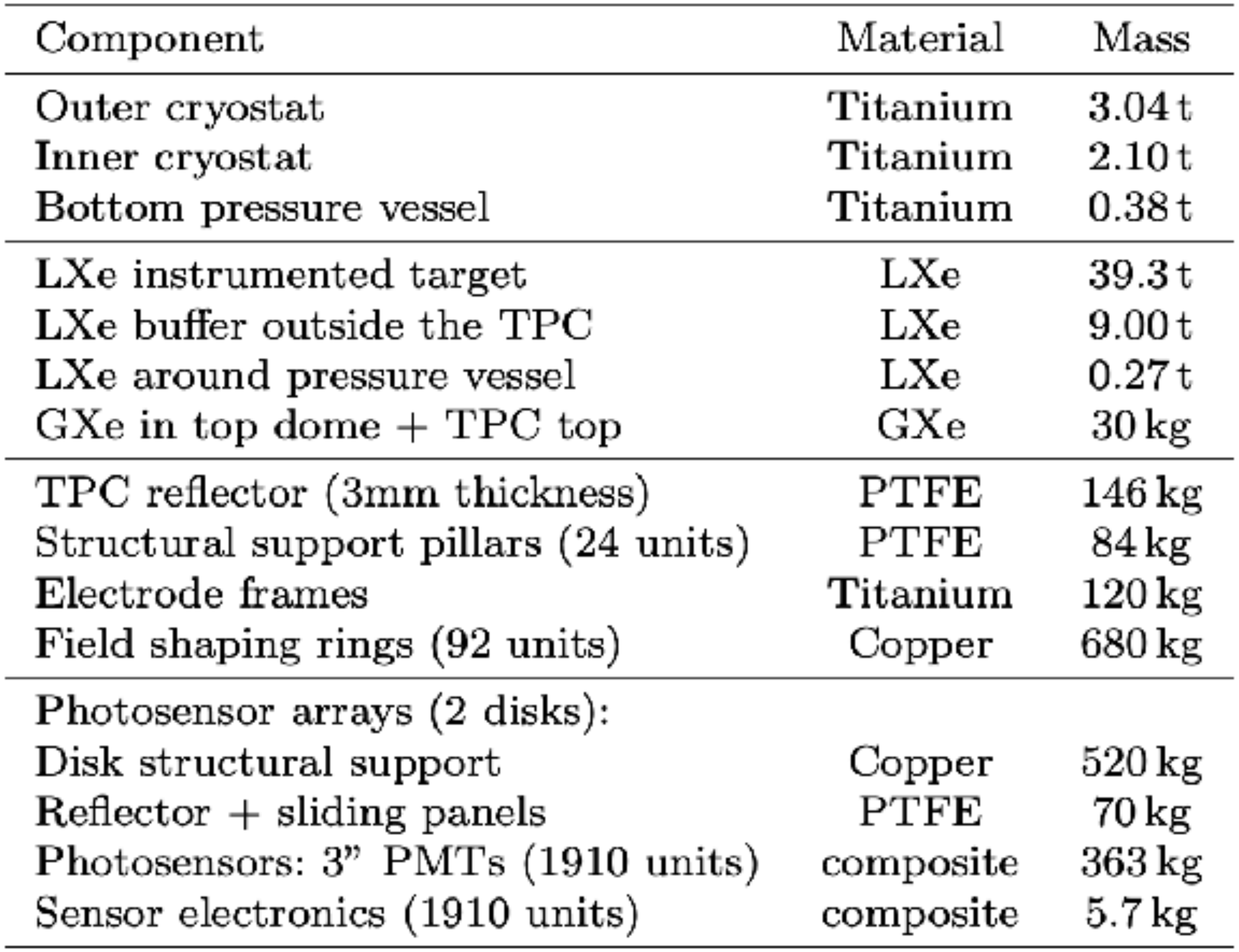


Component	Material	Mass
Outer cryostat	Titanium	3.04 t
Inner cryostat	Titanium	2.10 t
Bottom pressure vessel	Titanium	0.38 t
LXe instrumented target	LXe	39.3 t
LXe buffer outside the TPC	LXe	9.00 t
LXe around pressure vessel	LXe	0.27 t
GXe in top dome + TPC top	GXe	30 kg
TPC reflector (3mm thickness)	PTFE	146 kg
Structural support pillars (24 units)	PTFE	84 kg
Electrode frames	Titanium	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

Cryostat

Xenon

TPC components

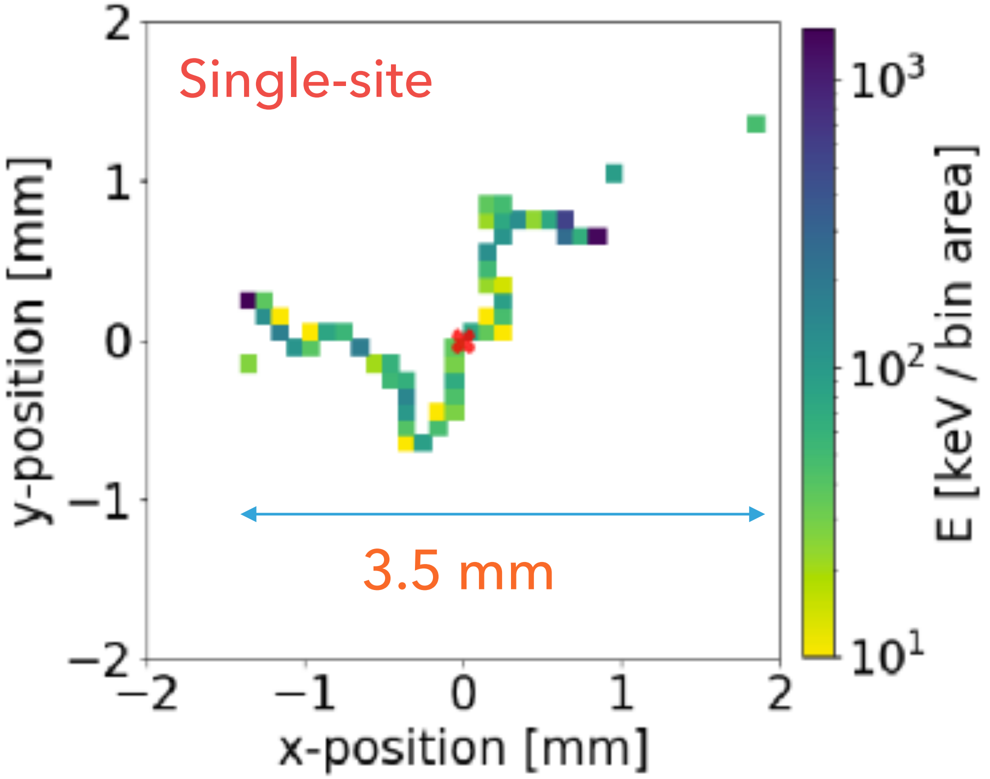
Photosensors and electronics

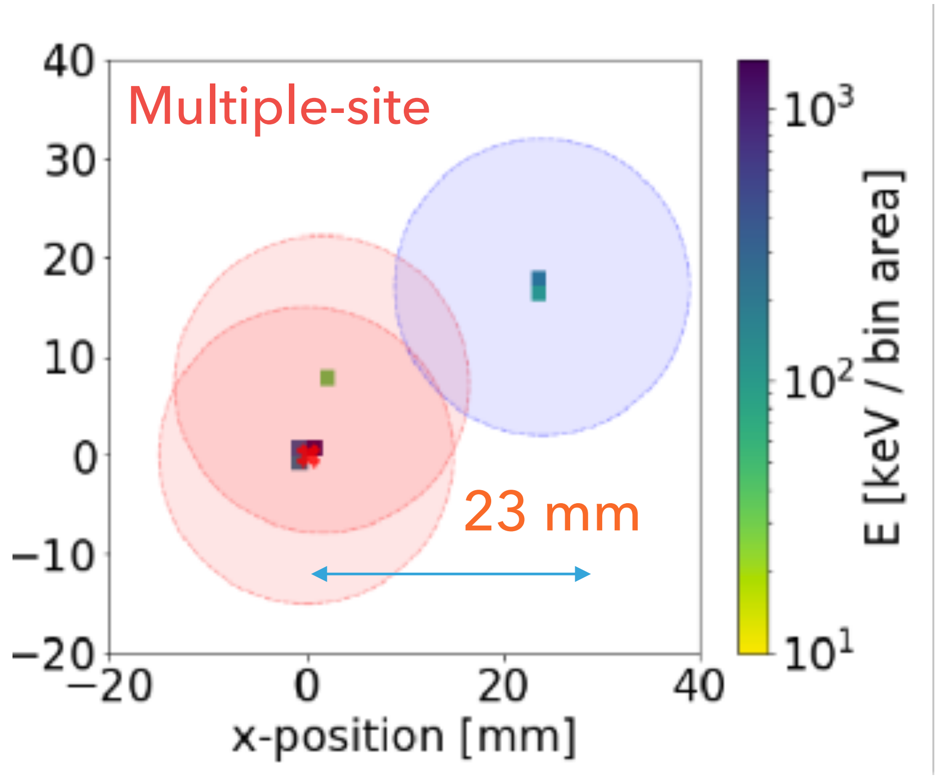
SIGNAL EVENTS IN LIQUID XENON

- Electrons thermalise within O(mm) => single-site topology
- Bremsstrahlung photons: may travel > 15 mm (E>300 keV) => multi-site event
- Energy depositions: spatially grouped using density-based spatial clustering algorithm
    - New cluster, if distance to any previous E_{dep} > ε (separation threshold)

Assumption: ε = 15 mm; 90% efficiency for ββ-events

2 e^- back-to-back



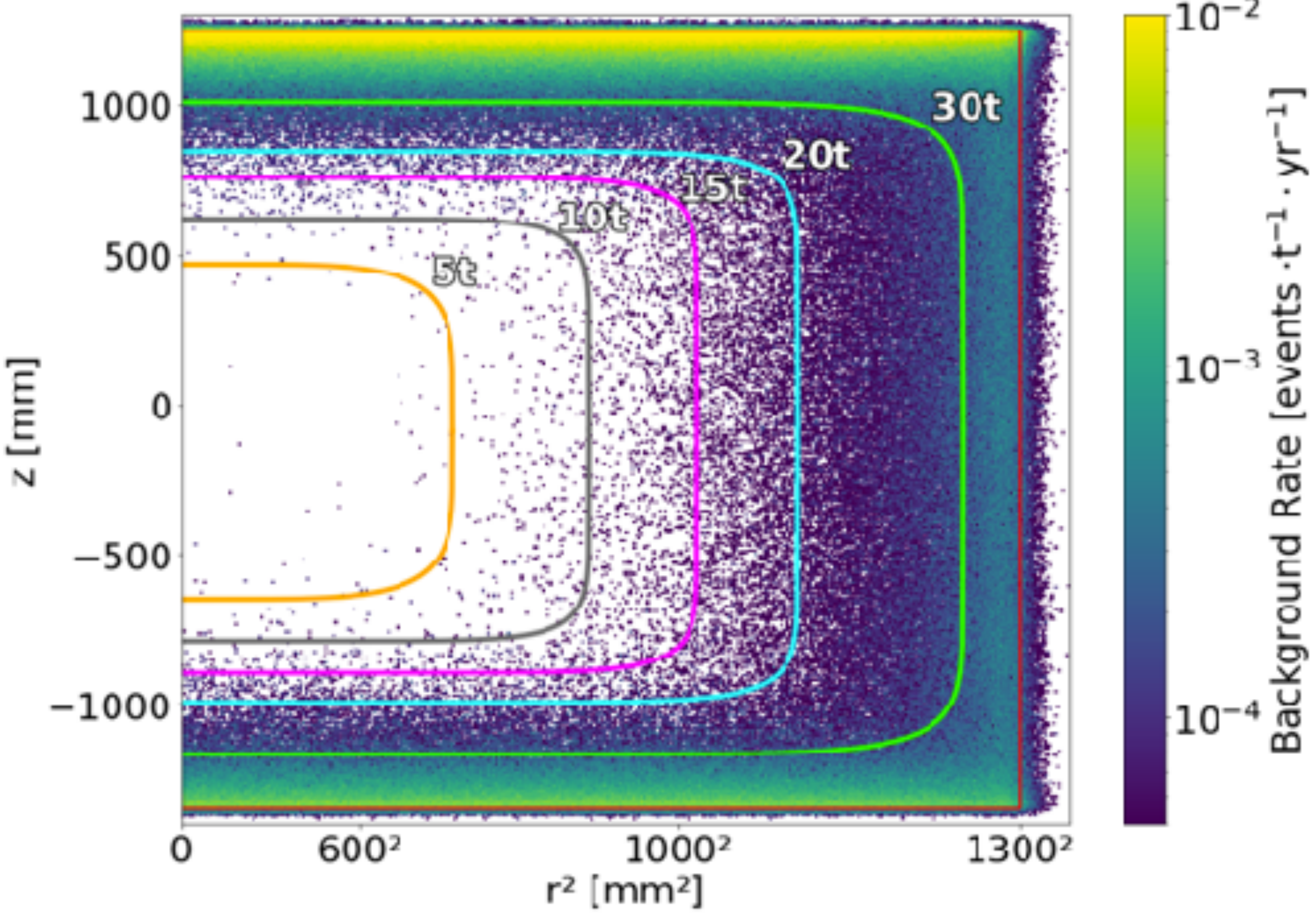


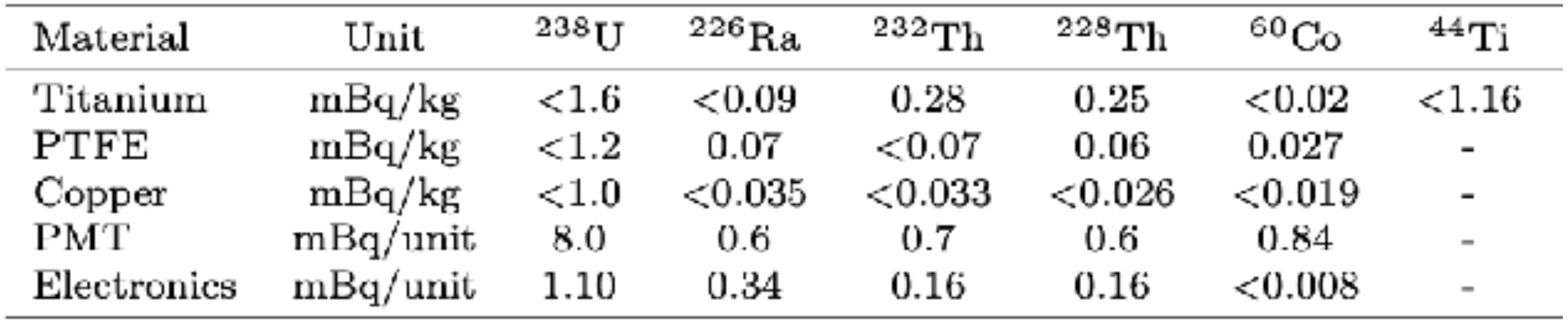
MAIN BACKGROUND COMPONENTS

- Intrinsic:
  - ^{8}B ν's, ^{137}Xe, 2νββ, ^{222}Rn
- Materials:
  - ^{238}U, ^{232}Th, ^{60}Co, ^{44}Ti
- FV cut: super-ellipsoidal

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

100 y of DARWIN run time, event with energy deposits in the ROI [$Q_{\beta\beta}$± FWHM/2]





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

^{44}Ti: $T_{1/2}$ = 59 y, cosmogenic

Ti: LZ, Astrop. Phys., 96 (2017)

Other: XENON, EPJ-C 77 (2017)

ENERGY RESOLUTION

- Anti-correlation between light (S1) and charge (S2)
- Energy scale: based on linear combination of S1 and S2
- Photon gain: g_1 (pe/photon), electron gain: g_2 (pe/electron)

$$\frac{S2}{E} = \frac{g_2}{W} - \frac{g_2}{g_1}\frac{S1}{E}$$

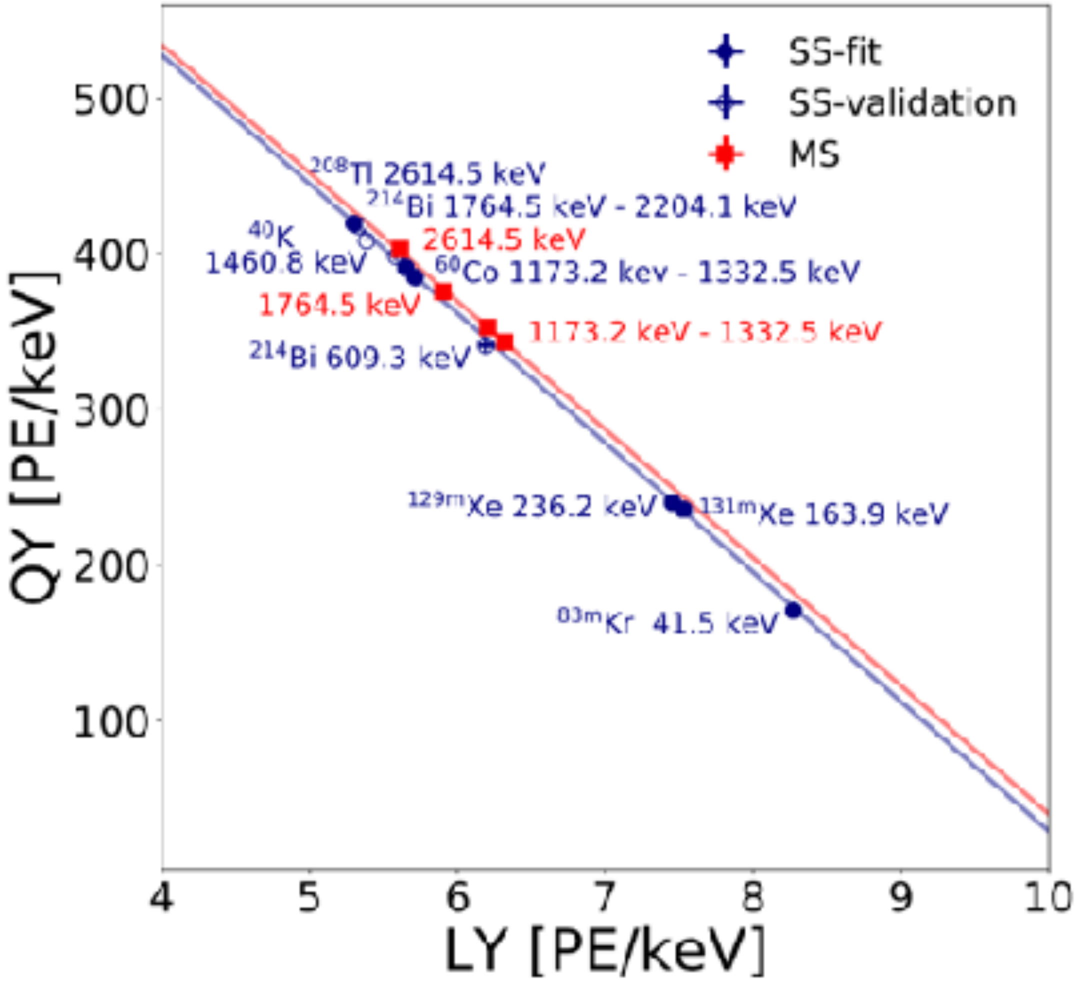
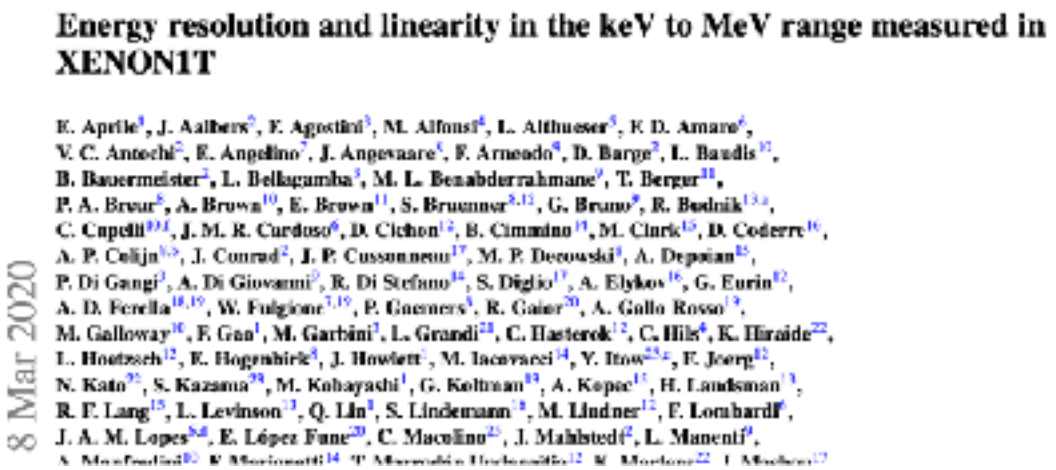


Figure from XENON1T

$$E = (n_{ph} + n_e) \cdot W = \left(\frac{S_1}{g_1} + \frac{S_2}{g_2}\right) \cdot W$$

W-value = (13.7±0.2) eV

ENERGY RESOLUTION

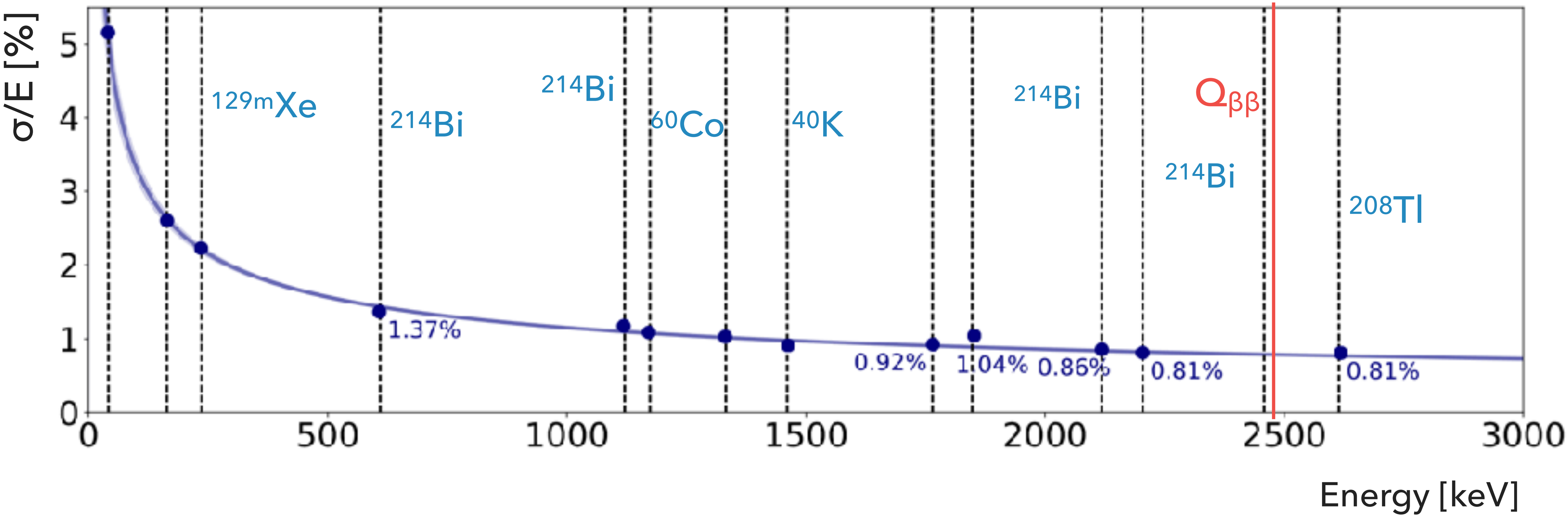


8 Mar 2020

Energy resolution and linearity in the keV to MeV range measured in XENON1T

E. Aprile[1], J. Aalbers[2], F. Agostini[3], M. Alfonsi[4], L. Althueser[5], F. D. Amaro[6],
V. C. Antochi[2], E. Angelino[7], J. Angevaare[8], F. Arneodo[9], D. Barge[2], L. Baudis[10],
B. Bauermeister[2], L. Bellagamba[3], M. L. Benabderrahmane[9], T. Berger[11],
P. A. Breur[8], A. Brown[10], E. Brown[11], S. Bruenner[8,12], G. Bruno[9], R. Budnik[13,a],
C. Capelli[10], J. M. R. Cardoso[6], D. Cichon[12], B. Cimmino[14], M. Clark[15], D. Coderre[16],
A. P. Colijn[8,b], J. Conrad[2], J. P. Cussonneau[17], M. P. Decowski[8], A. Depoian[15],
P. Di Gangi[3], A. Di Giovanni[9], R. Di Stefano[14], S. Diglio[17], A. Elykov[16], G. Eurin[12],
A. D. Ferella[18,19], W. Fulgione[7,19], P. Gaemers[8], R. Gaior[20], A. Gallo Rosso[19],
M. Galloway[10], F. Gao[1], M. Garbini[3], L. Grandi[21], C. Hasterok[12], C. Hils[4], K. Hiraide[22],
L. Hoetzsch[12], E. Hogenbirk[8], J. Howlett[1], M. Iacovacci[14], Y. Itow[23,c], F. Joerg[12],
N. Kato[22], S. Kazama[23], M. Kobayashi[1], G. Koltman[13], A. Kopec[15], H. Landsman[13],
R. F. Lang[15], L. Levinson[13], Q. Lin[1], S. Lindemann[16], M. Lindner[12], F. Lombardi[6],
J. A. M. Lopes[6,d], E. López Fune[20], C. Macolino[25], J. Mahlstedt[2], L. Manenti[9],

- XENON1T
  - 0.8% relative energy resolution (σ/E) around 2.5 MeV



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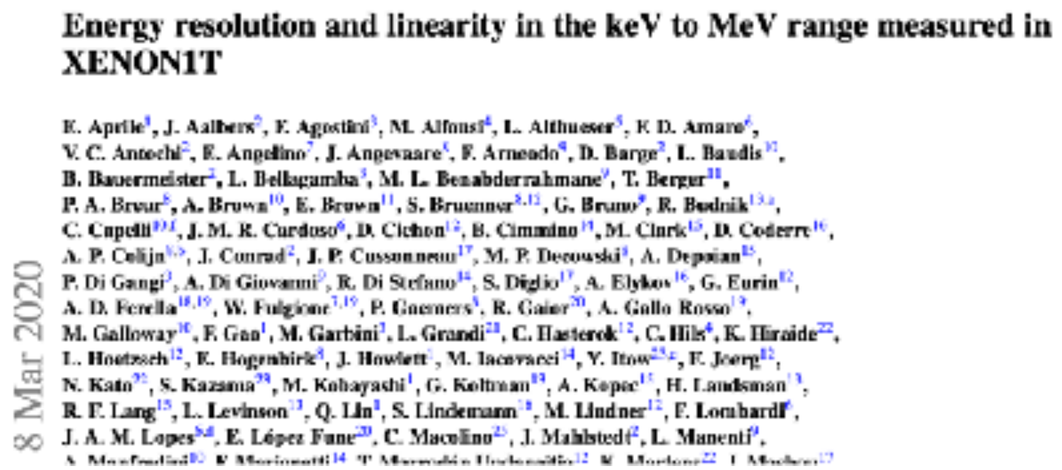

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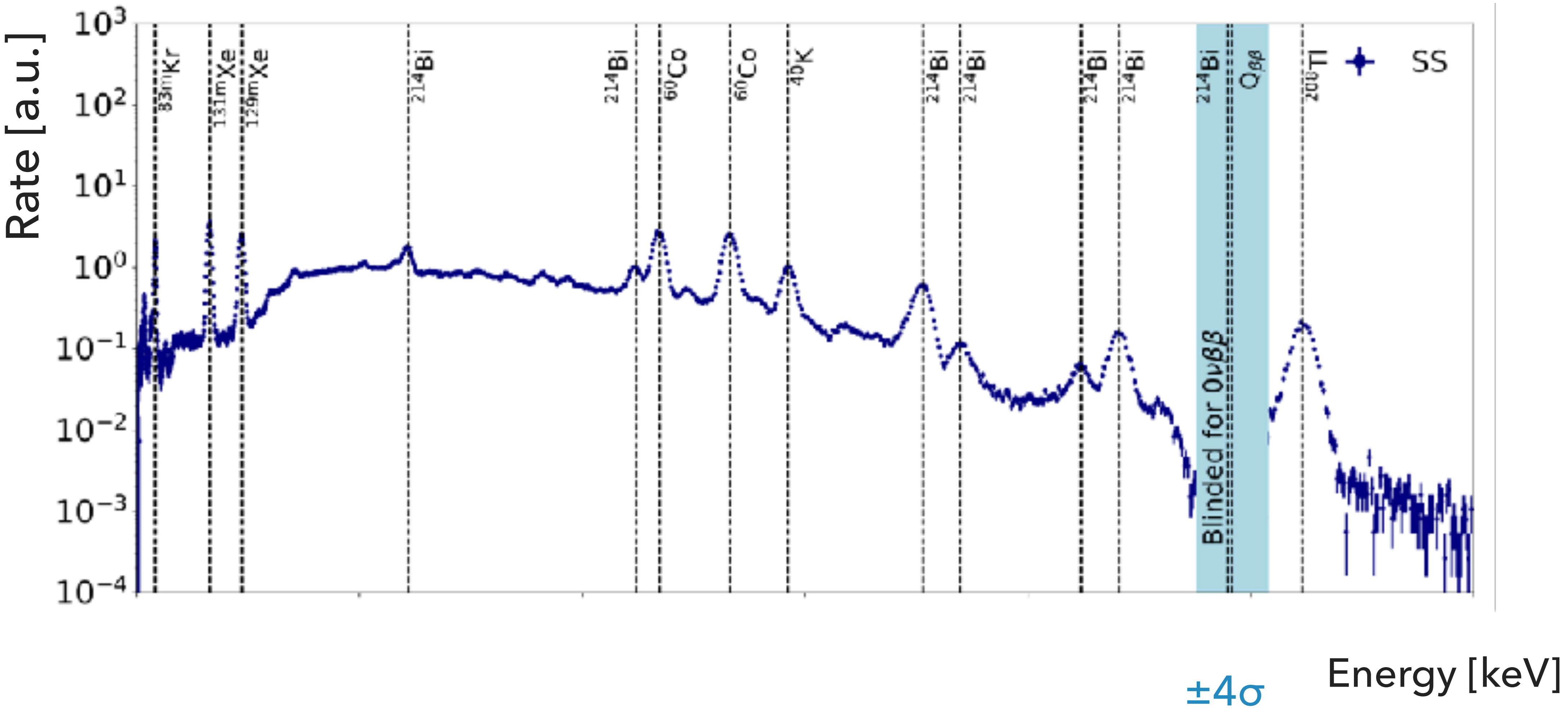
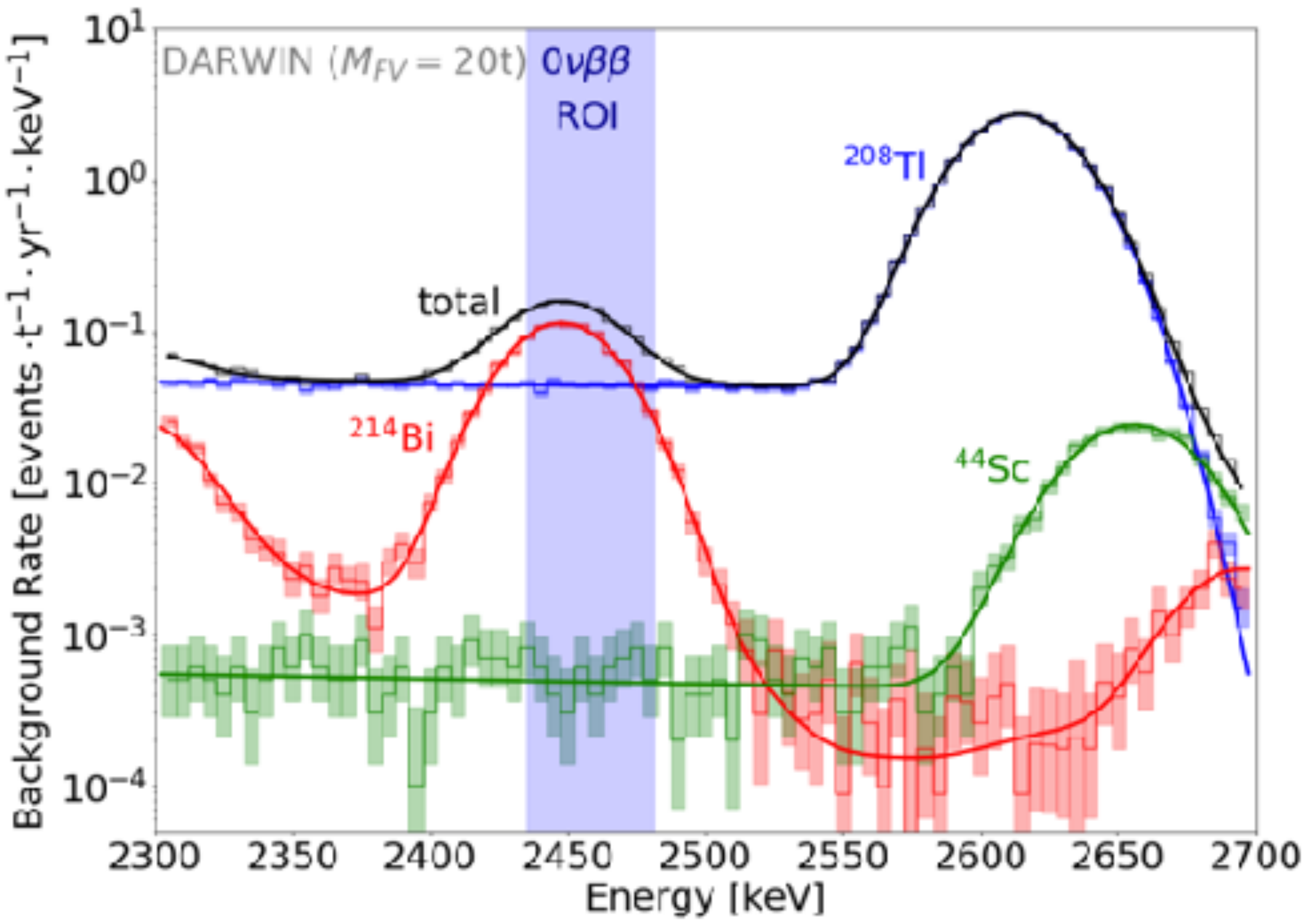
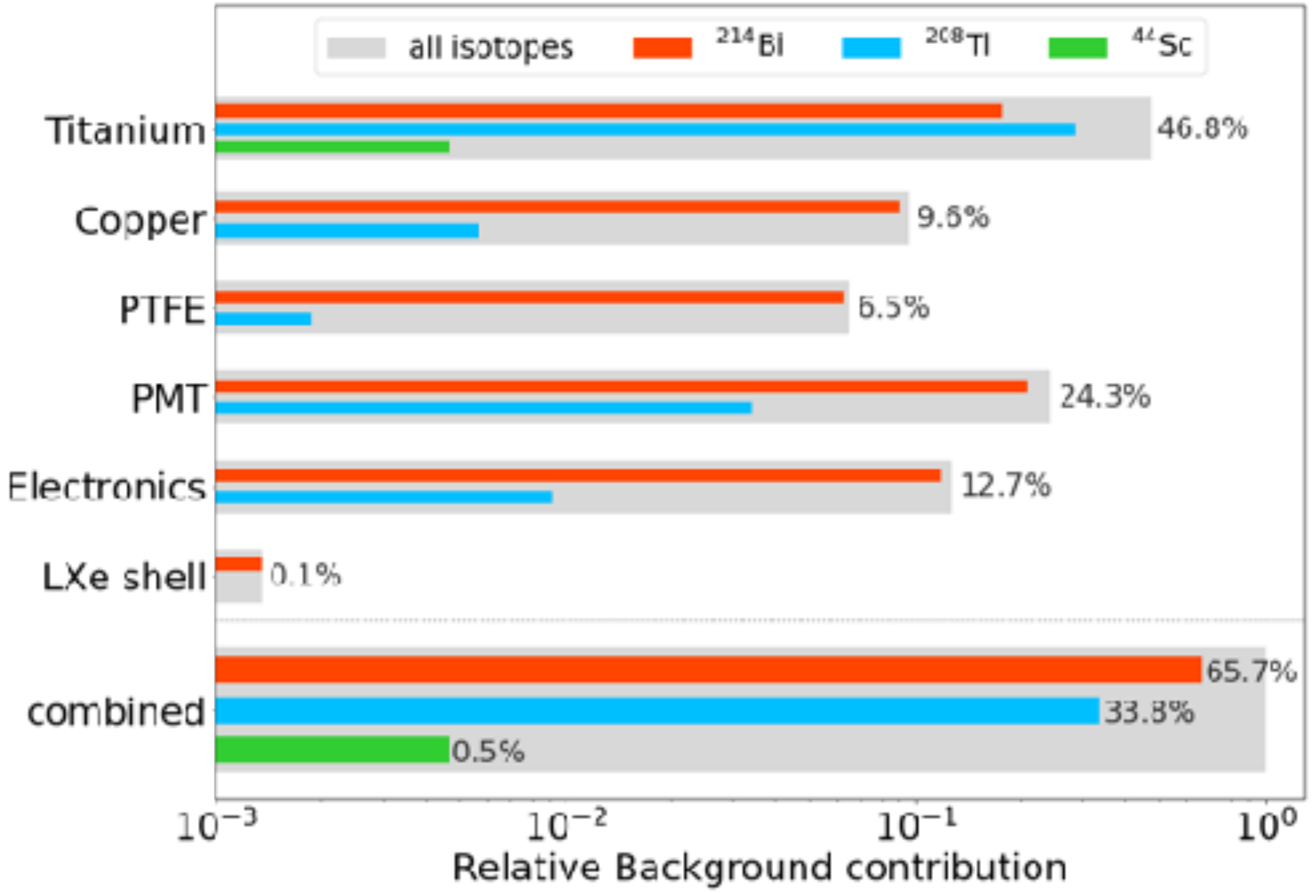


EXTERNAL (MATERIAL) BACKGROUND

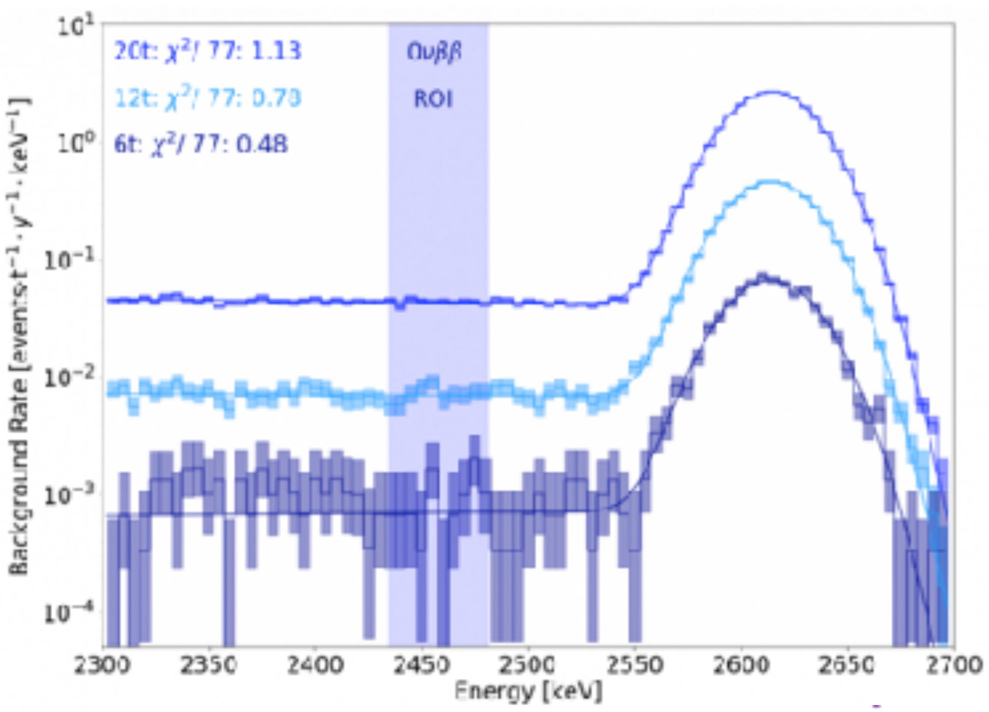
- ROI: [2435-2481] keV = FHWM around $Q_{\beta\beta}$
- ^{214B}Bi: γ at 2.45 MeV, ^{208}Tl, γ at 2.61 MeV; ^{44}Sc, γ at 2.66 MeV



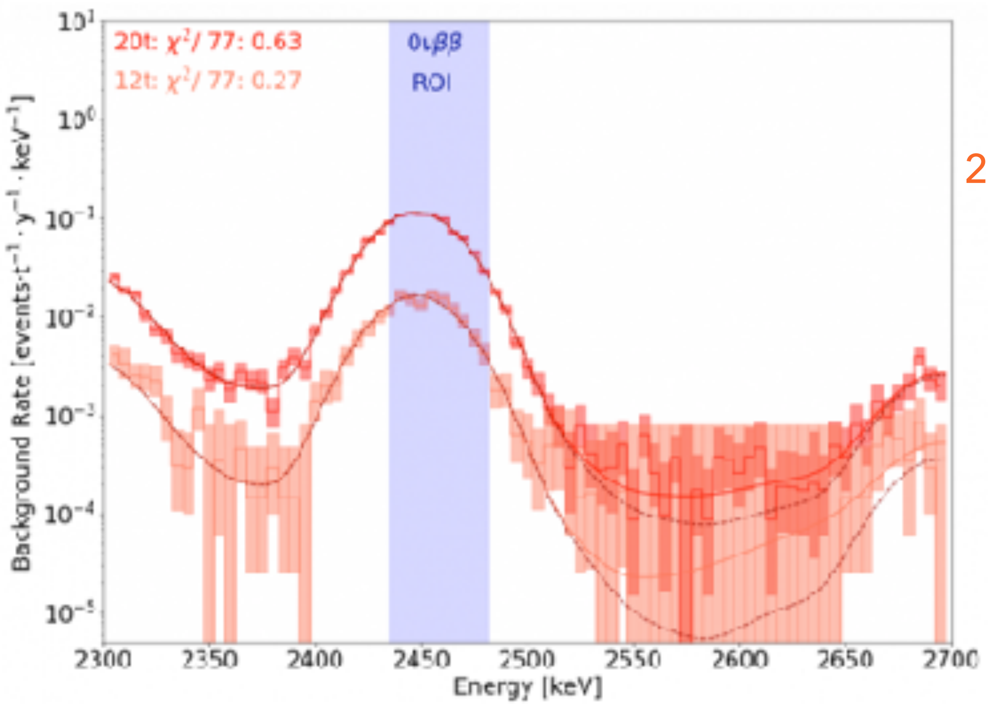


20 tones fiducial volume

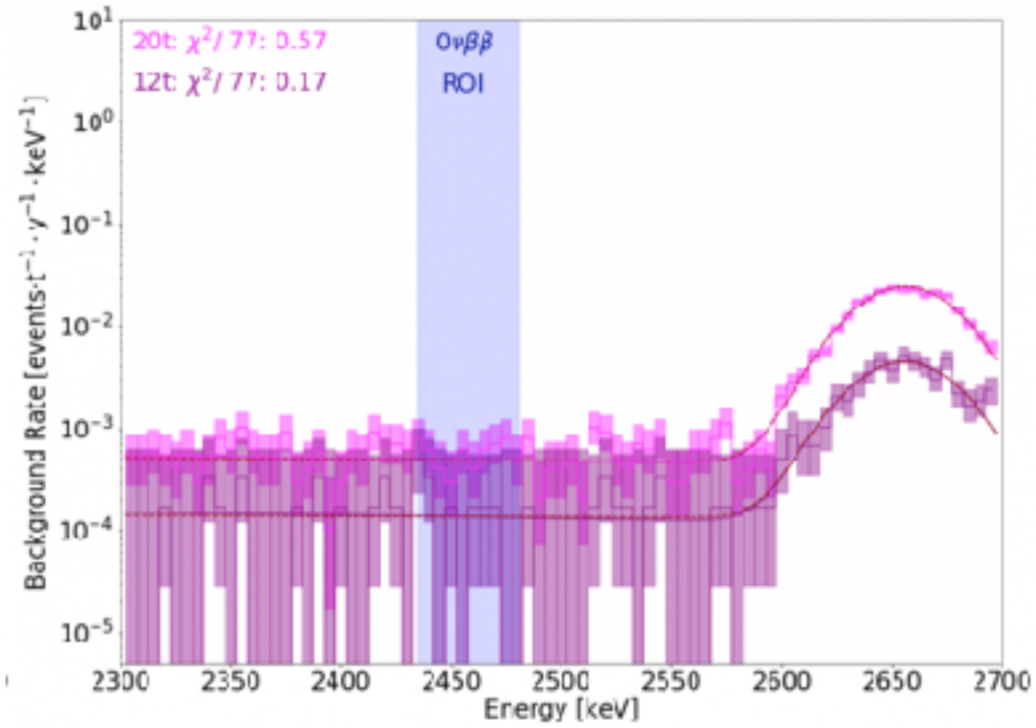
MATERIALS BACKGROUND FOR DIFFERENT FIDUCIAL REGIONS



^{208}Tl (2.61 MeV)



^{214}Bi (2.45MeV)



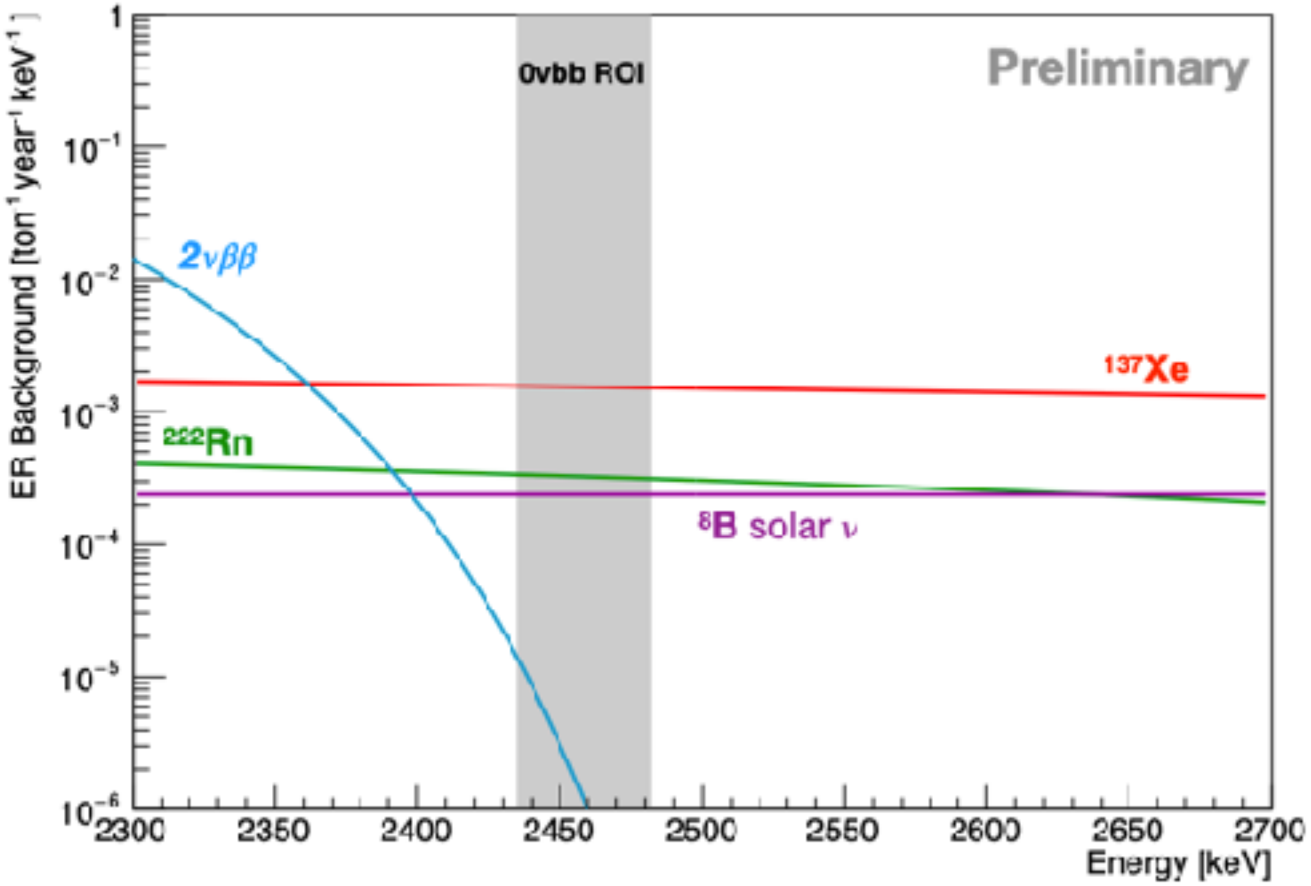
^{44}Sc (2.66 MeV)

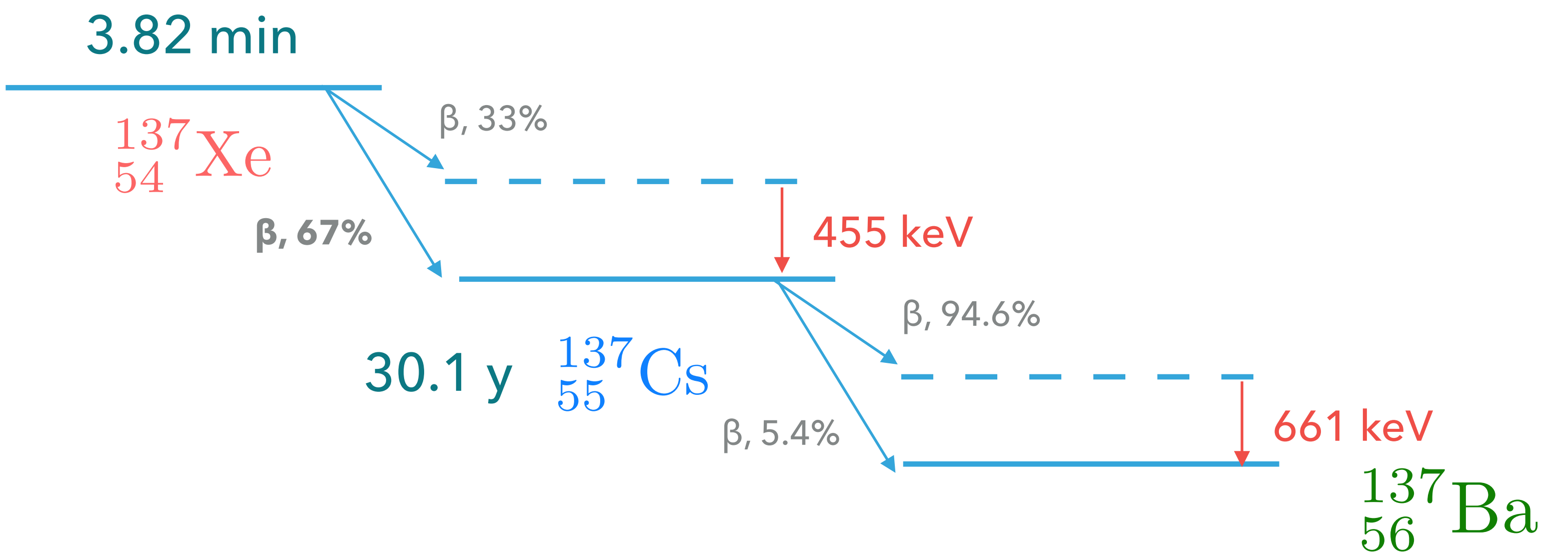
INTERNAL BACKGROUNDS

- ^{222}Rn in LXe:
  - 0.1μBq/kg, 99.8% BiPo tagging
- ^{8}B solar ν
  - $\Phi_{\nu e} = (5.46\pm0.66) \times 10^{6}\ \mathrm{cm^{-2}s^{-1}}$
  - $P_{ee} = 0.50$
- 2νββ-decay: subdominant
- ^{137}Xe: cosmogenic activation underground
  - n + ^{136}Xe -> ^{137}Xe

$T_{1/2}$ = 3.82 min
Q-value: 4173 keV

^{137}Xe: (6.9±0.4) atoms/(t y)




3.82 min

$^{137}_{54}\mathrm{Xe}$

β, 33%

β, 67%

455 keV

30.1 y $^{137}_{55}\mathrm{Cs}$

β, 94.6%

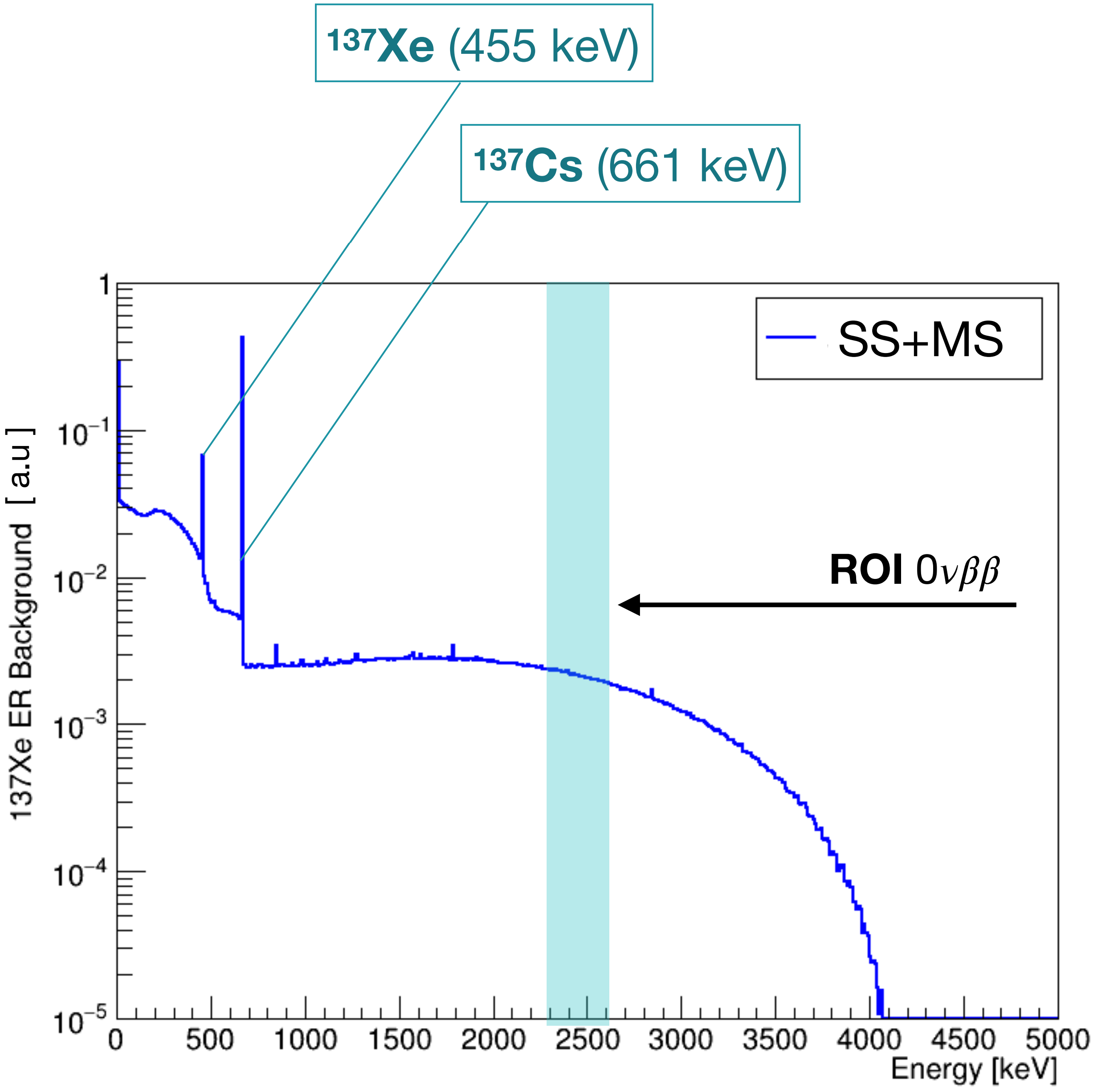
β, 5.4%

661 keV

$^{137}_{56}\mathrm{Ba}$

137-XE BACKGROUND

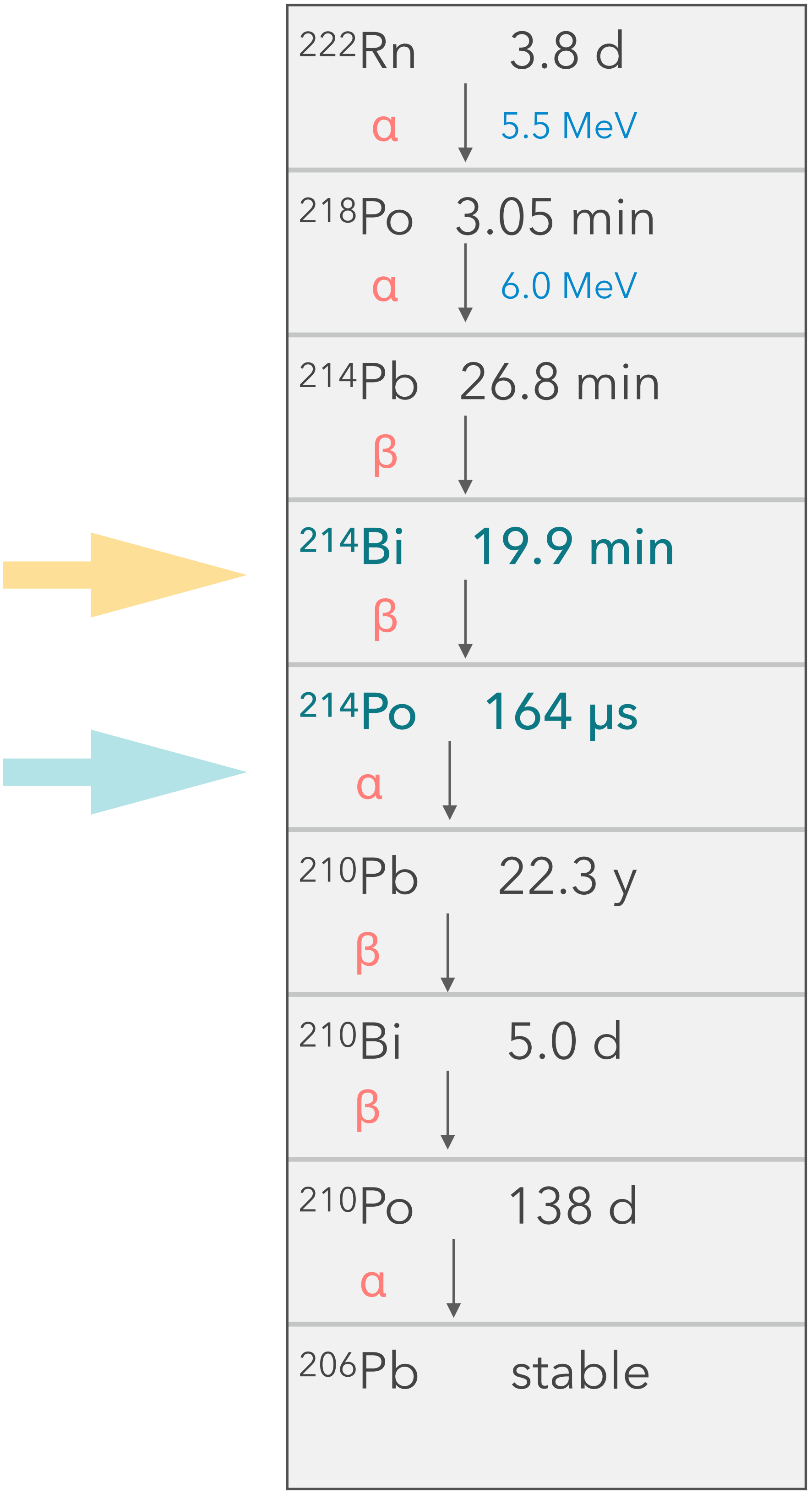
- Simulate ^{137}Xe, production rate by cosmogenic n-capture
  - Rate: 6.9 atoms/(t y)
  - dominated by production on LXe (6.3 atoms/(t y) (at LNGS, 3600 mw.e.)
- nEXO: 2.2 atoms/(t y) at SNOLAB (PRC 97, 2018)
- KamLAND-Zen: 1.42 atoms/(t y) at Kamioka (PRL 117, 2016)



ROI: Q-value ± FWHM/2 = (2435-2481) keV

RADON BACKGROUND

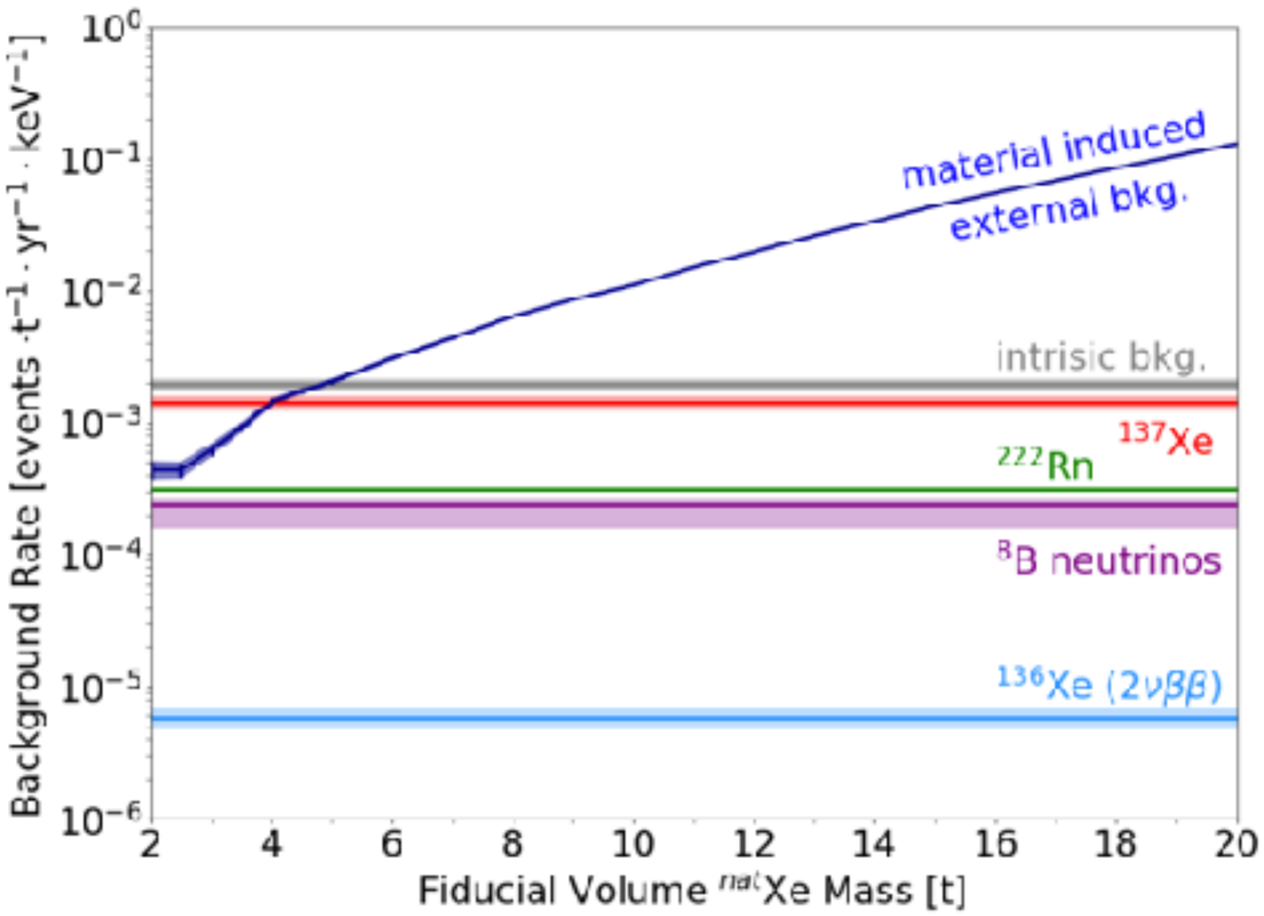
- Assume 0.1 µBq/kg ^{222}Rn (cryogenic distillation + material selection)
- Problematic: ^{214}Bi decay, Q-value = 3.27 MeV, naked β-decay: 19.1% BR
- ^{214}Po: α-decay, $T_{1/2}$ =164.3 µs => active veto for ^{214}Bi-decays
- Assumption: 99.8% tagging efficiency



^{222}Rn 3.8 d
α ↓ 5.5 MeV
^{218}Po 3.05 min
α ↓ 6.0 MeV
^{214}Pb 26.8 min
β ↓
^{214}Bi 19.9 min
β ↓
^{214}Po 164 µs
α ↓
^{210}Pb 22.3 y
β ↓
^{210}Bi 5.0 d
β ↓
^{210}Po 138 d
α ↓
^{206}Pb stable

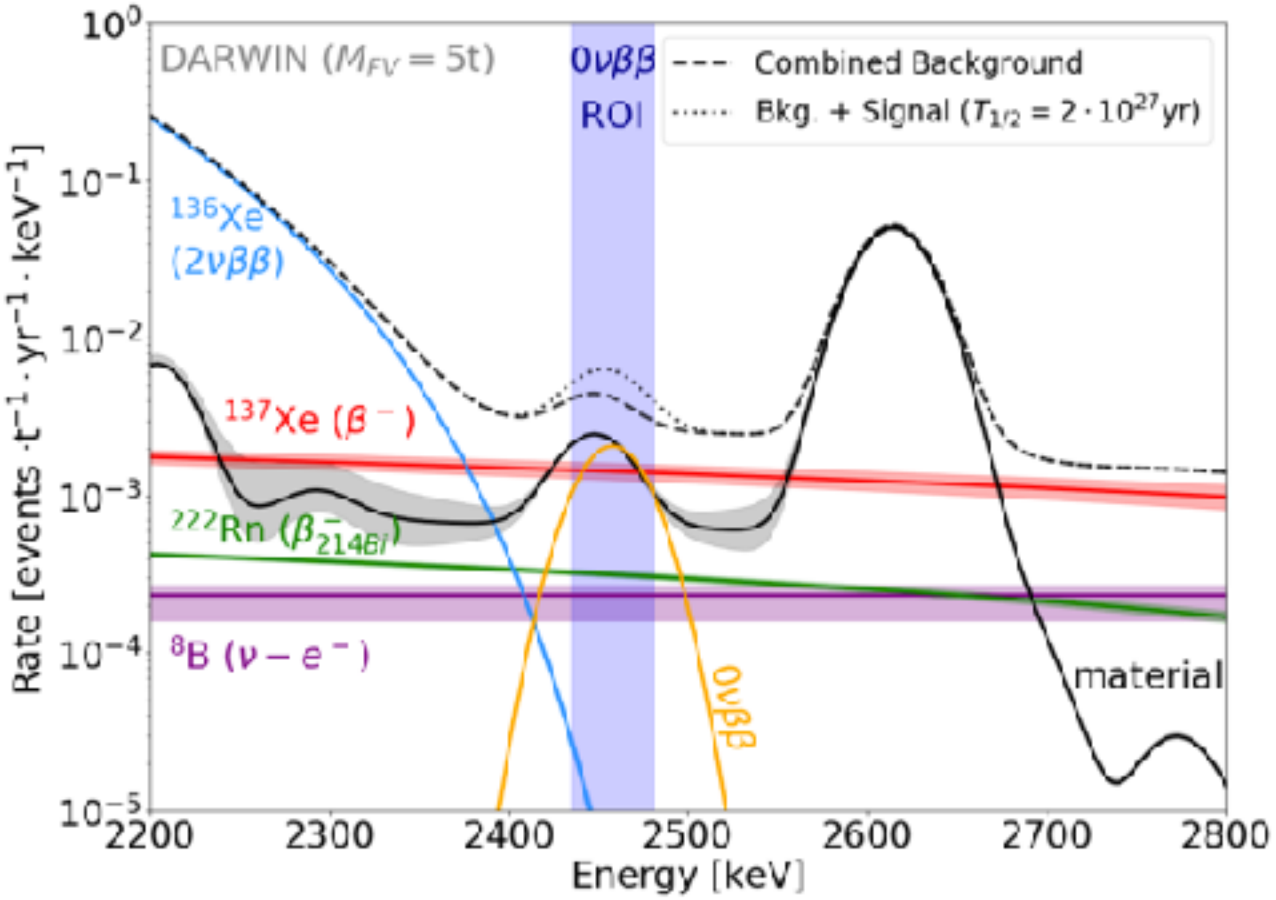
MATERIAL + INTRINSIC BACKGROUND

- ROI: [2435-2481] keV = FHWM around $Q_{\beta\beta}$
- ^{137}Xe: β-decay with Q=4173 keV, $T_{1/2}$=3.82 min (via n-capture on ^{136}Xe)



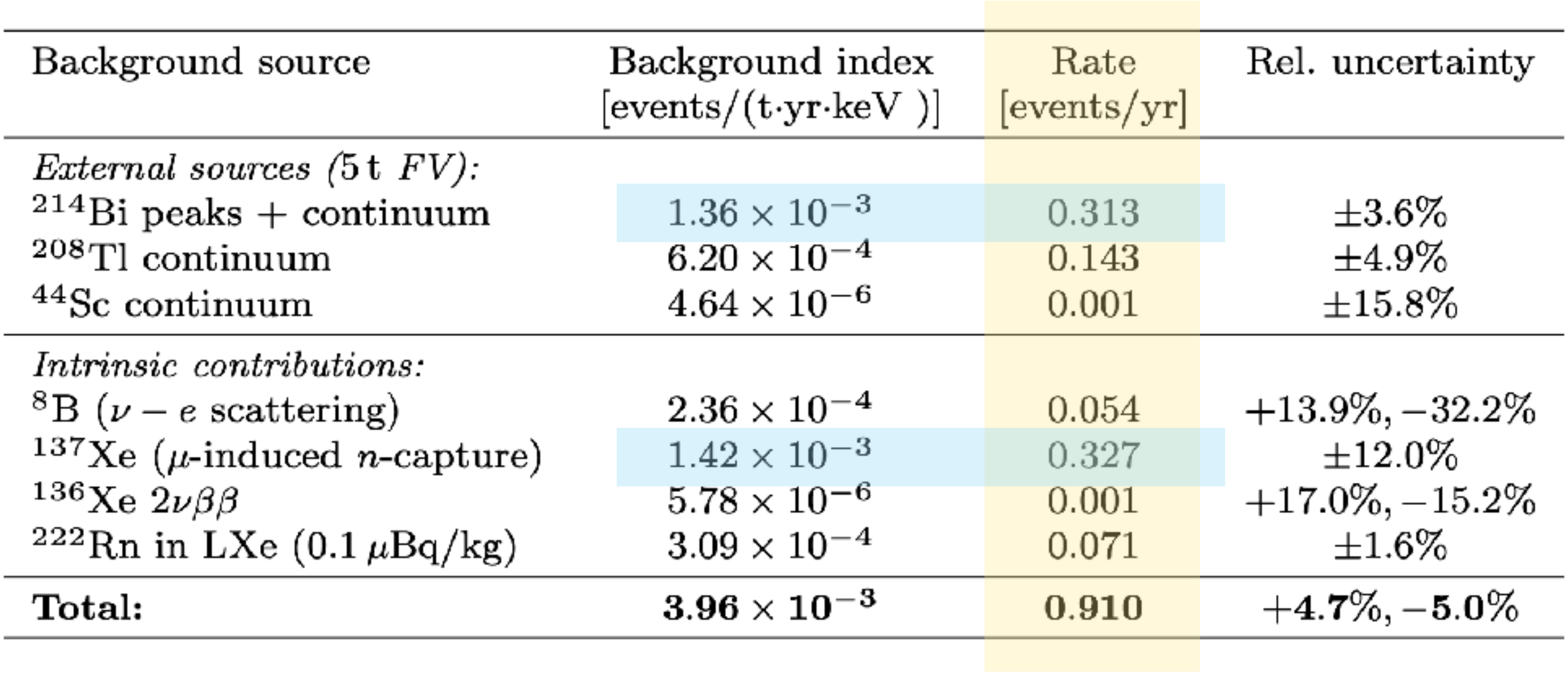
Rate versus fiducial mass

Signal: $T_{1/2}$ = 2 x 10^{27} y



Rate in 5 tonnes fiducial region (0.45 t ^{136}Xe)

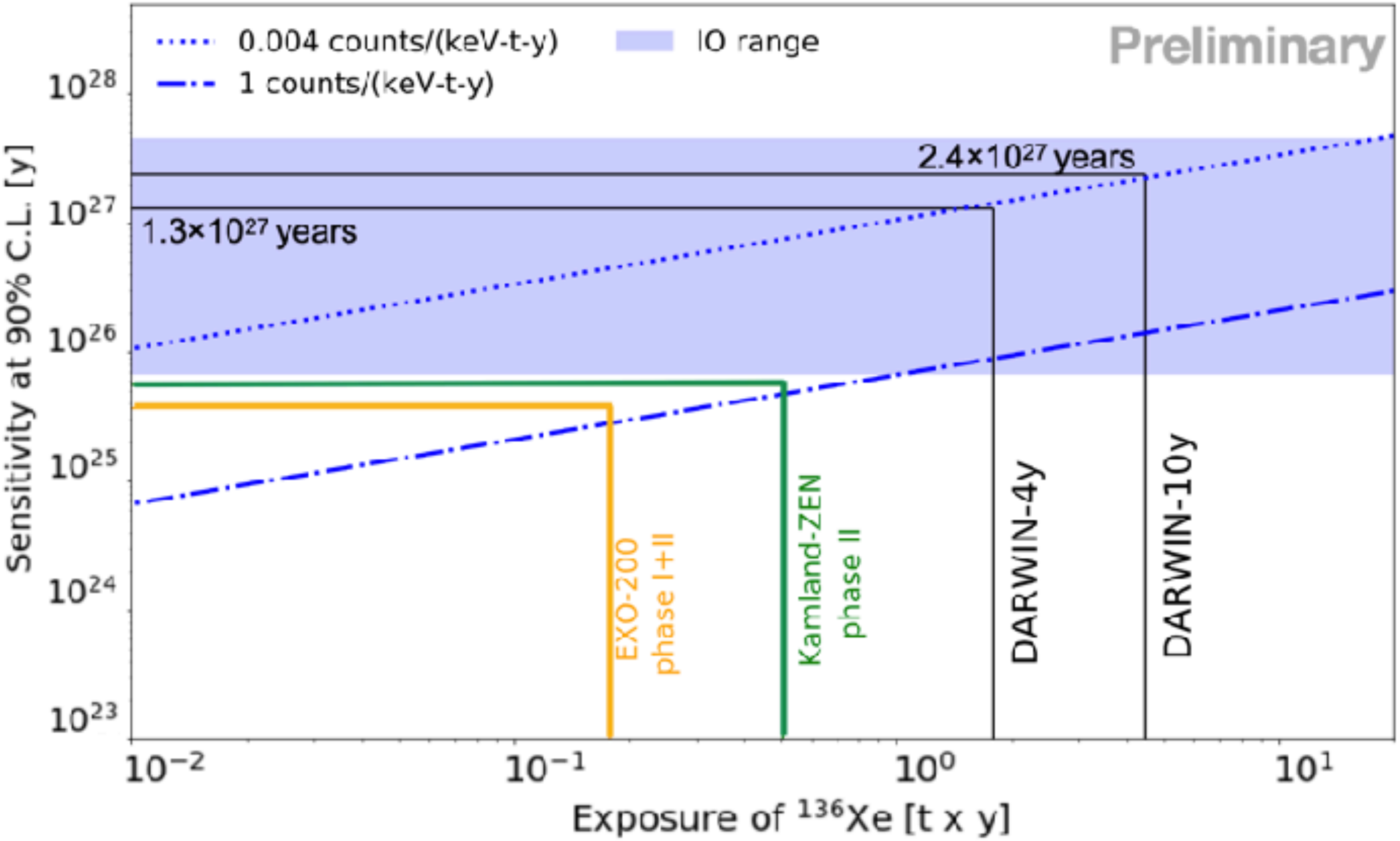
BACKGROUND BUDGET



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**	$+4.7\%, -5.0\%$

DOUBLE BETA DECAY SENSITIVITY

- Profile likelihood analysis, baseline $T_{1/2}$ sensitivity:
- 2.4 x 10^{27} y for 5 t x 10 y exposure (90% CL)

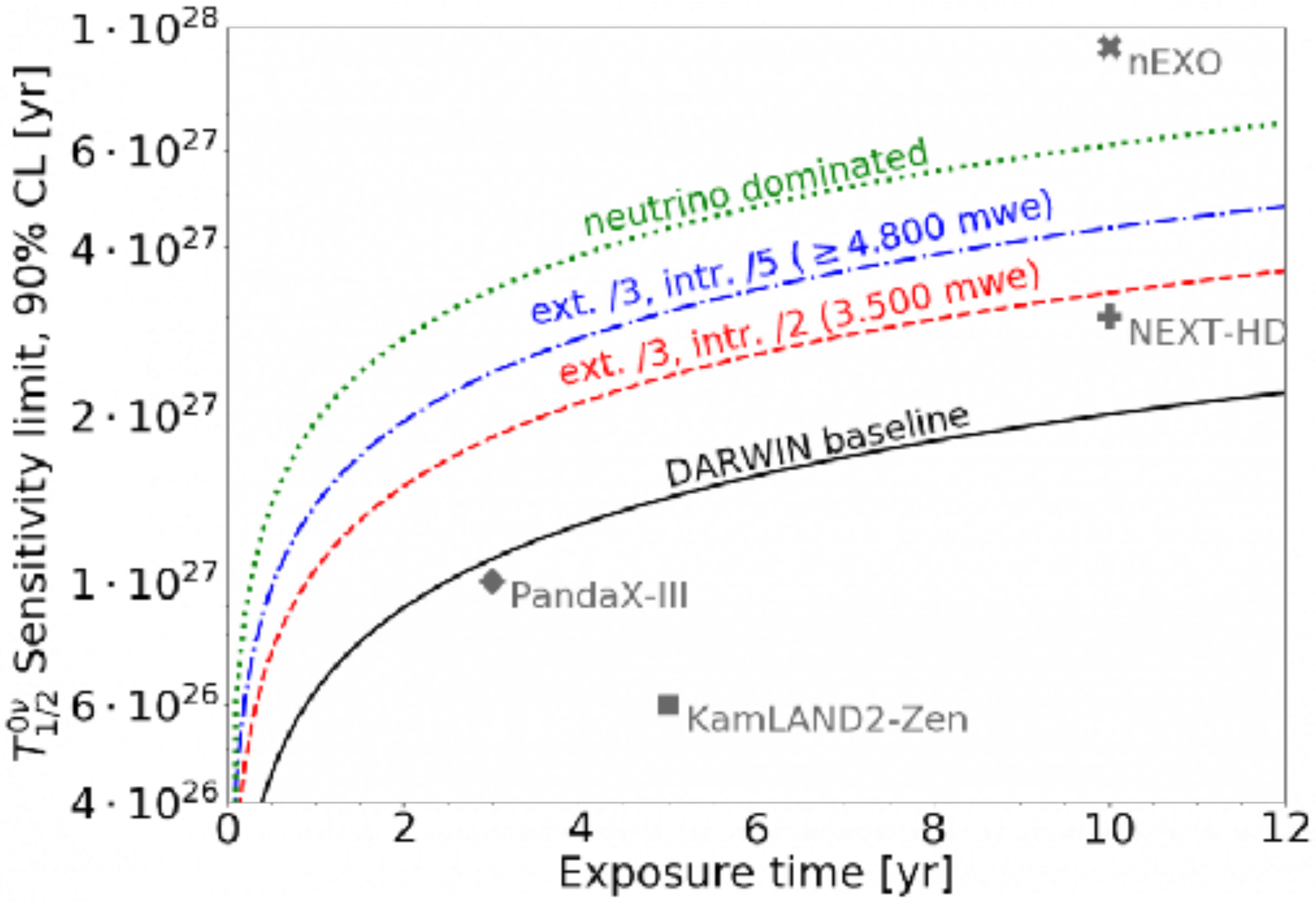


Discovery potential:

1.1 x 10^{27} y at 3-σ

ROOM FOR IMPROVEMENT?

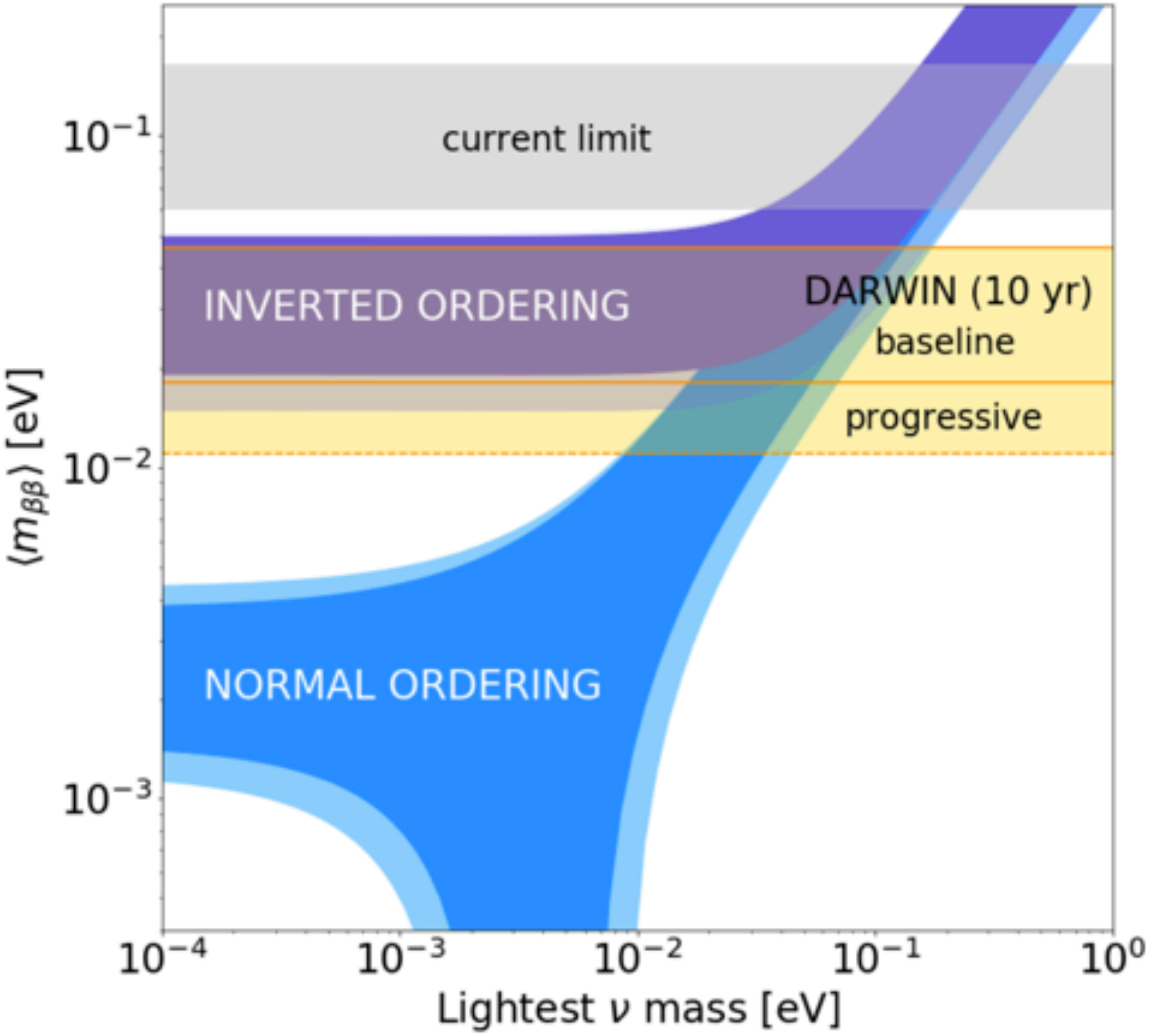
- Reduce external backgrounds
  - SiPMs, cleaner materials & electronics
- Reduce internal background
  - Time veto for ^{137}Xe, deeper lab, BiPo tagging
- Improve signal/background discrimination; resolution…



DARWIN could reach ~6 x 10^{27} y sensitivity

ROOM FOR IMPROVEMENT?

- Reduce external backgrounds
    - SiPMs, cleaner materials & electronics
- Reduce internal background
    - Time veto for ^{137}Xe, deeper lab, BiPo tagging
- Improve signal/background discrimination; resolution…



Baseline: $m_{\beta\beta}$ = (18 – 46) meV

Progressive: $m_{\beta\beta}$= (11– 28) meV

CONCLUSIONS

- DARWIN: dark matter detector, however due to its large mass & ultra-low background: can also look for the $0\nu\beta\beta$-decay of ^{136}Xe
- Expected relative energy resolution (1-σ): ~0.8% at 2.5 MeV
- Studies of the external and intrinsic backgrounds: materials (PMTs, cryostat) & ^{137}Xe are main components
  - room for improvement
- $T_{1/2}$ sensitivity: $(2.4 - 7) \times 10^{27}$ y for baseline - optimistic scenarios

Details in manuscript - on the arXiv in a few days from now

ADDITIONAL SLIDES

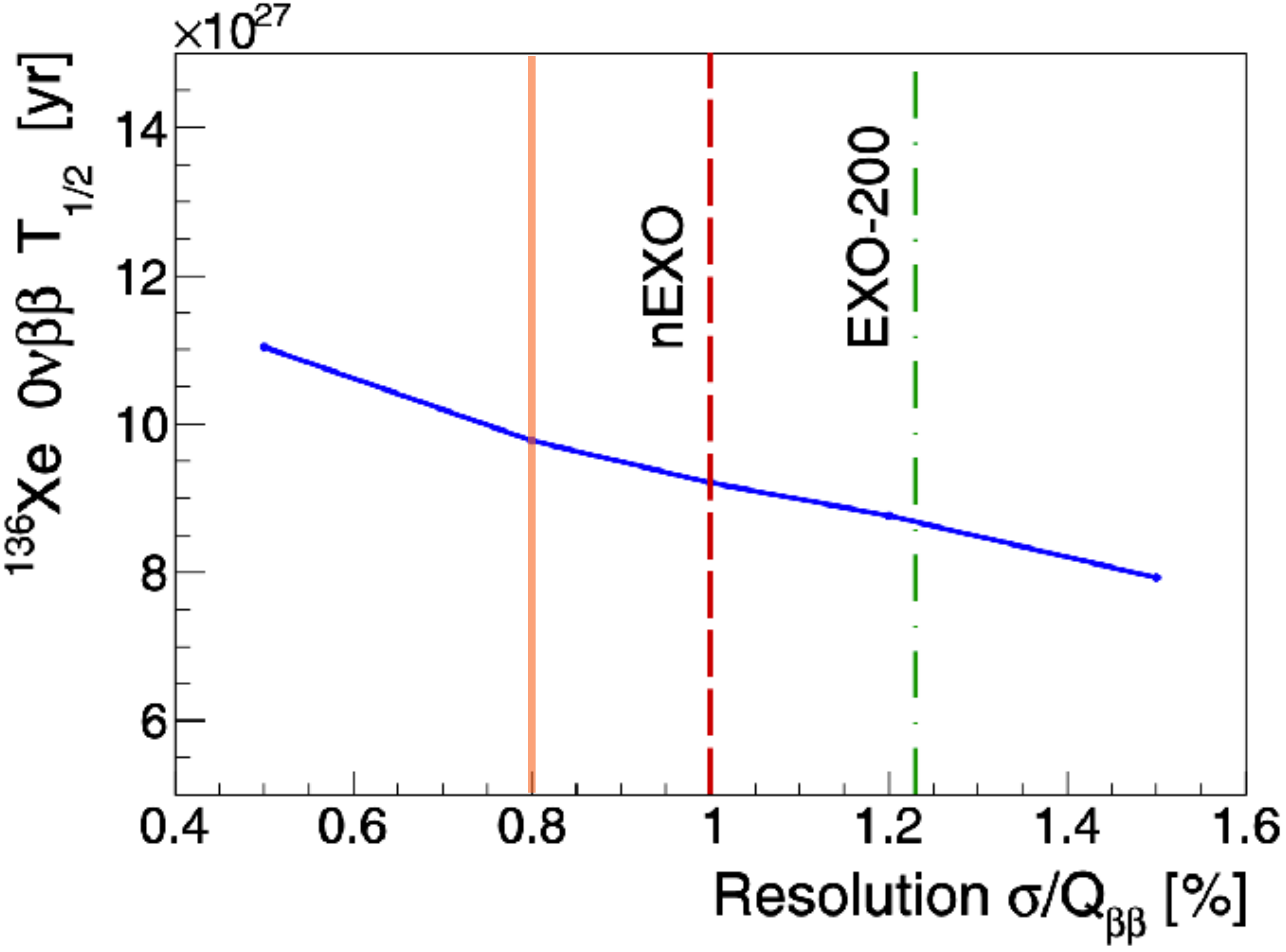
137-XE BACKGROUND

- Simulate ^{137}Xe, production rate by cosmogenic n-capture
- Rate: 6.7 atoms/(t y), dominated by production on LXe (6.3 atoms/(t y) (at LNGS, 3600 mw.e.)
- nEXO: 2.2 atoms/(t y) at SNOLAB (PRC 97, 2018); KamLAND-Zen: 1.42 atoms/(t y) at Kamioka (PRL 117, 2016)

Material	**Muon-induced Neutron Production Rate [n/year]**	**^{137}Xe Production Rate [atoms/kg/year]**
Copper	1.12×10^{4}	7.39×10^{-5}
SS	1.32×10^{5}	2.40×10^{-4}
LXe	1.02×10^{6}	6.34×10^{-3}
Total		6.66×10^{-3}

Experiment	**Location**	**Depth [m.w.e]**	**^{137}Xe Production Rate [atoms/kg/year]**
KamLAND-Zen [2]	Kamioka	2050	1.42×10^{-3}
DARWIN	LNGS	3600	6.66×10^{-3}
nEXO [3]	SNOLAB	6011	2.20×10^{-3}

EFFECT OF ENERGY RESOLUTION ON THE SENSITIVITY

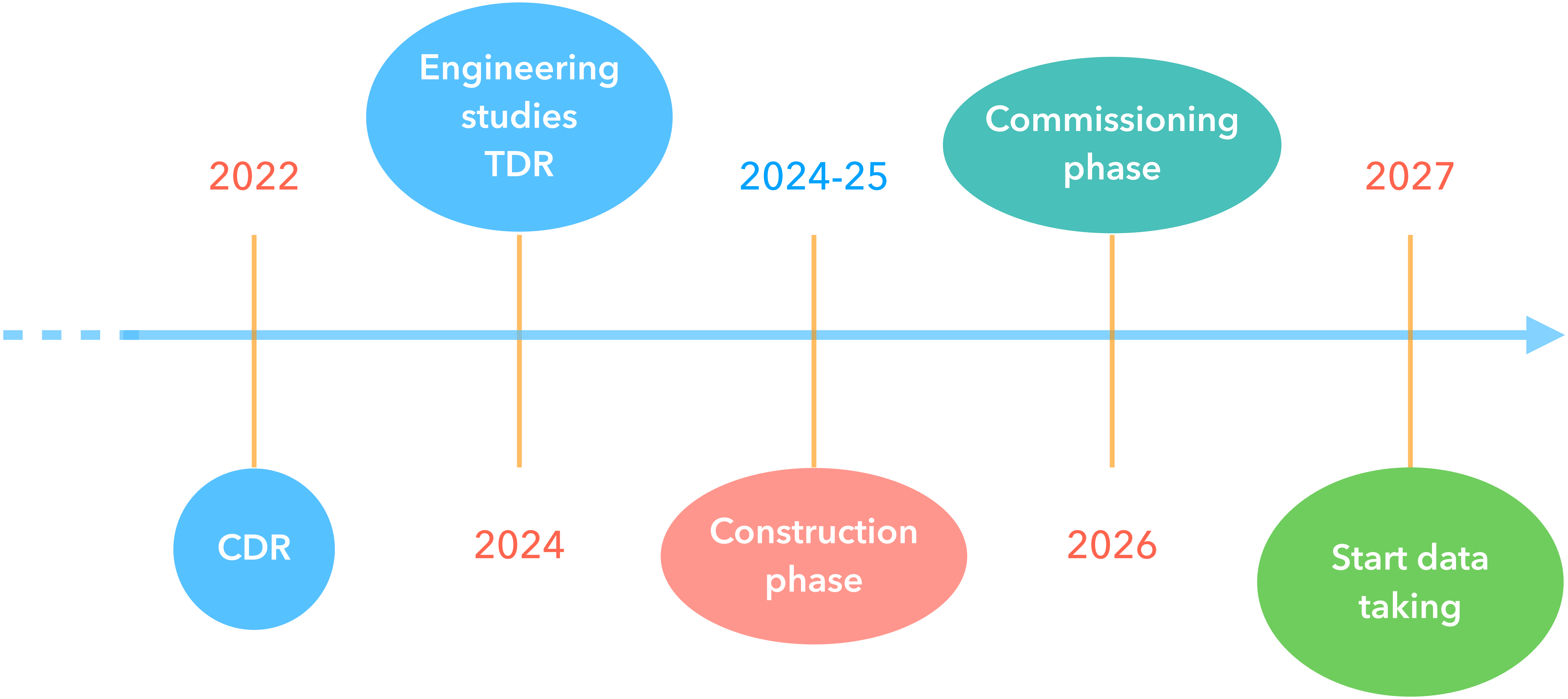


nEXO collaboration Phys.Rev. C97 (2018)

PROJECT OVERVIEW

- 28 groups from 11 countries , working towards CDR and TDR
- R&D and design on several aspects:
  - Detector including cryostat & TPC
  - Light and charge sensors & readout
  - Backgrounds (incl. Rn/Kr removal, materials) & veto
  - LXe procurement, storage, purification & cryogenics
  - Xenon properties and calibration of 50 t detector

DARWIN TIMESCALE



2022

CDR

Engineering studies TDR

2024

2024-25

Construction phase

Commissioning phase

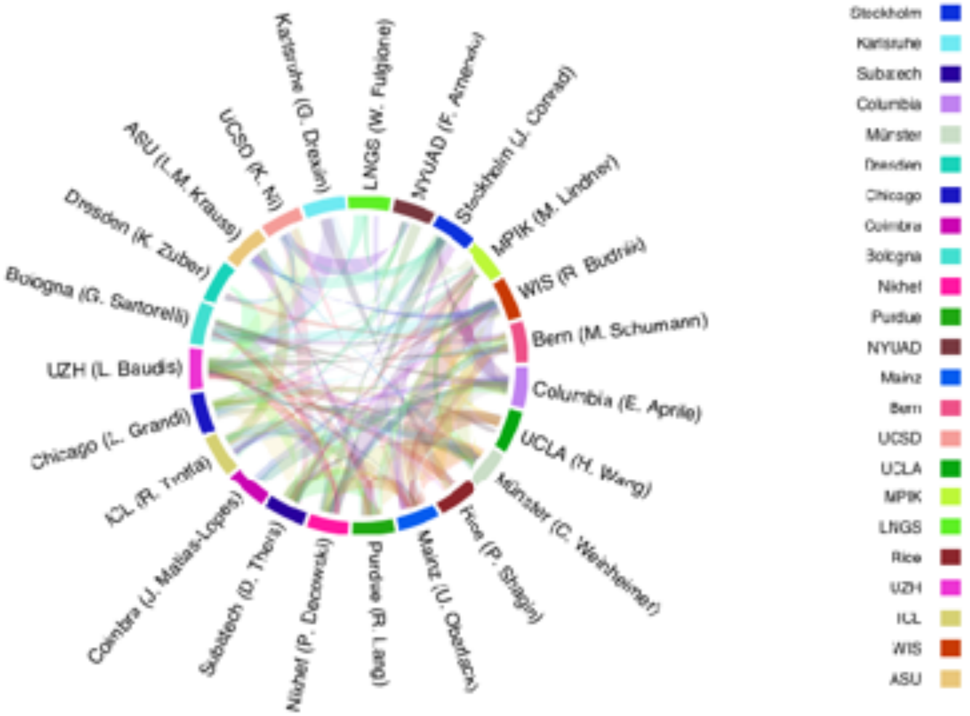
2026

2027

Start data taking

THE DARWIN COLLABORATION

- Consortium in 2010; since 2017 collaboration, MoU signed
- More than 160 members from 26 Institutions



Zurich, December 2018