University of Zurich[UZH]

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DARWIN

DARWIN - A NEXT-GENERATION OBSERVATORY FOR DARK MATTER AND NEUTRINO PHYSICS

LAURA BAUDIS
UNIVERSITÄT ZÜRICH
ON BEHALF OF THE DARWIN COLLABORATION

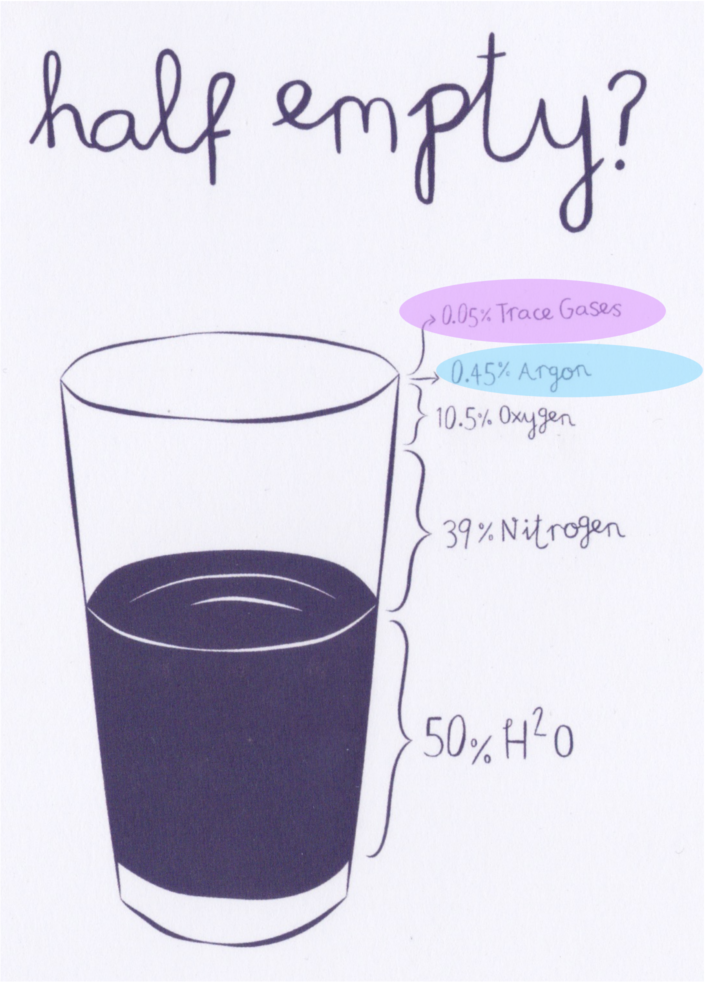
SEMINAR AT BOREXINO COLLABORATION MEETING
DECEMBER 11, 2020

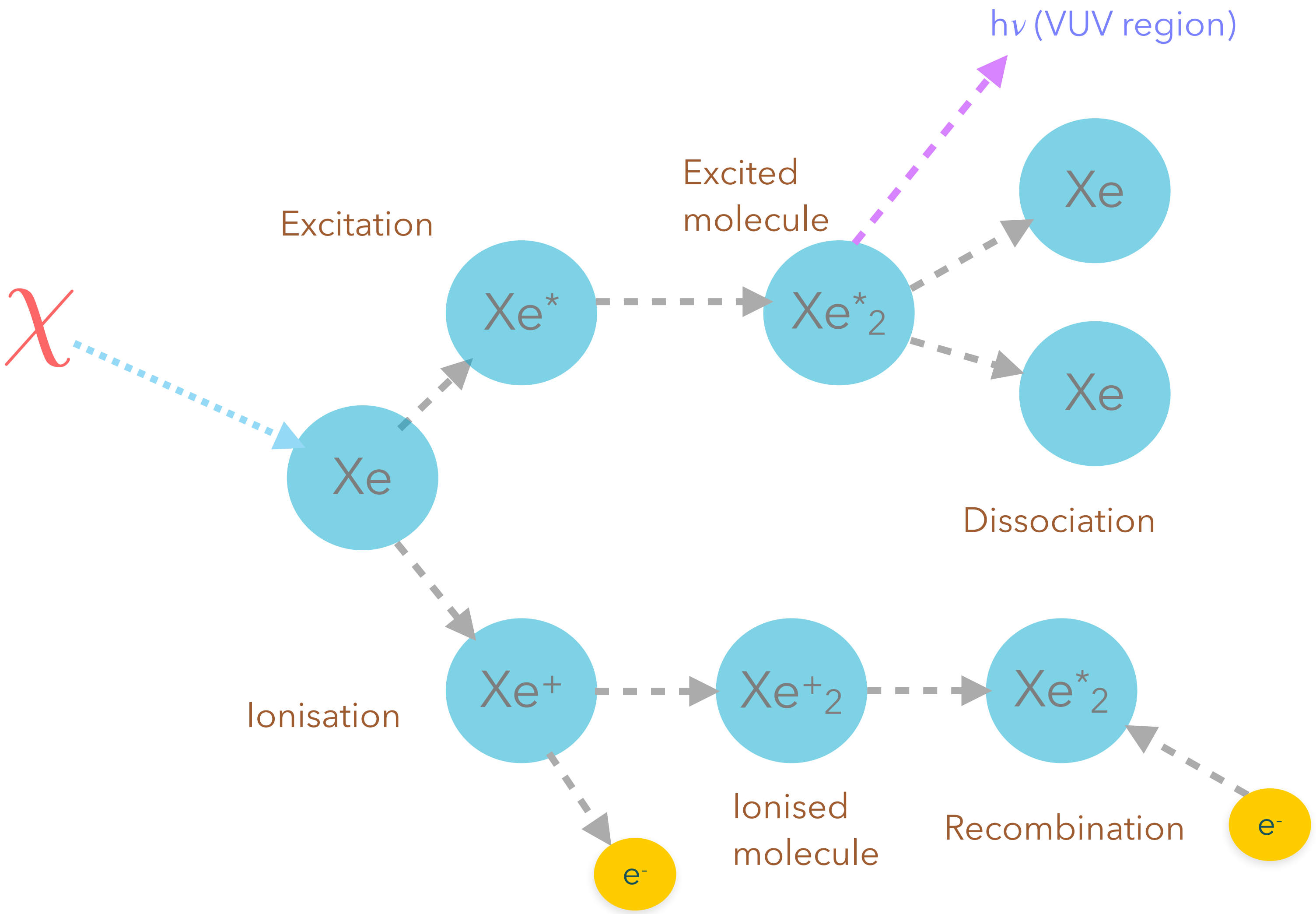
SOME KEY OPEN QUESTIONS IN PARTICLE PHYSICS

- 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

THE DARWIN EXPERIMENT

- Will use a large amount of clean liquid xenon target & detect ionisation and excitation from particle interactions
- Xenon: "the strange one", concentration in the atmosphere: 87 ppb* (by volume)

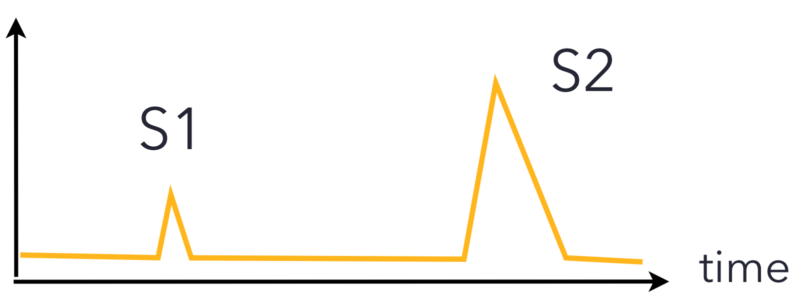


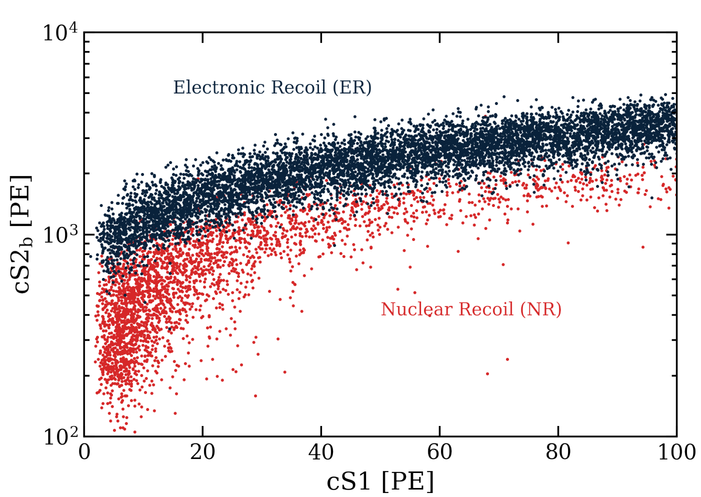


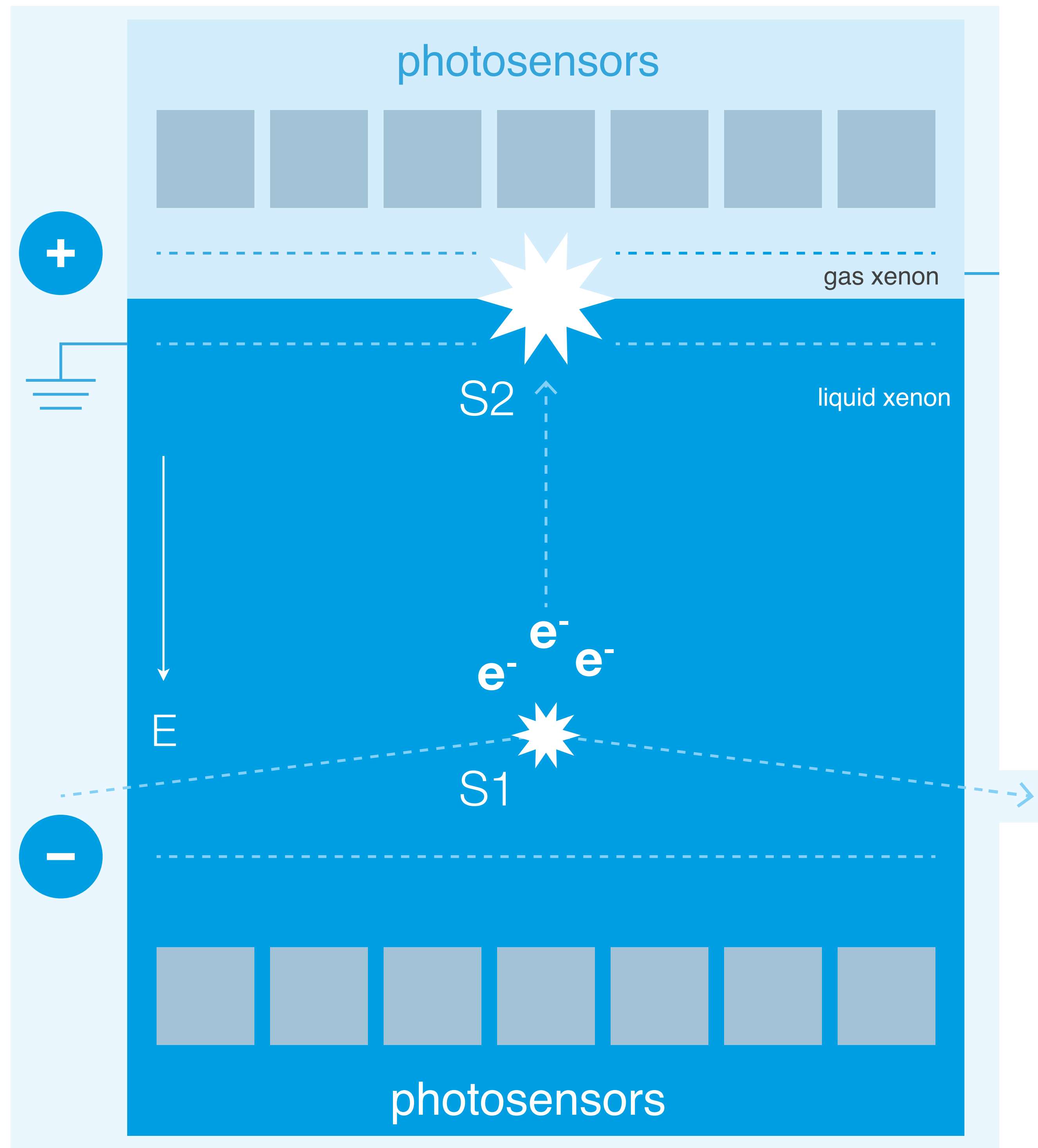
*https://doi.org/10.1007/978-3-319-39312-4_202

DETECTION PRINCIPLE: A TWO-PHASE TPC

- 3D position resolution via light (S1) and charge (S2) signals
- S2/S1 depends on particle ID
- Fiducialisation
- Single versus multiple interactions
- Energy reconstruction (linear combination of S1, S2)

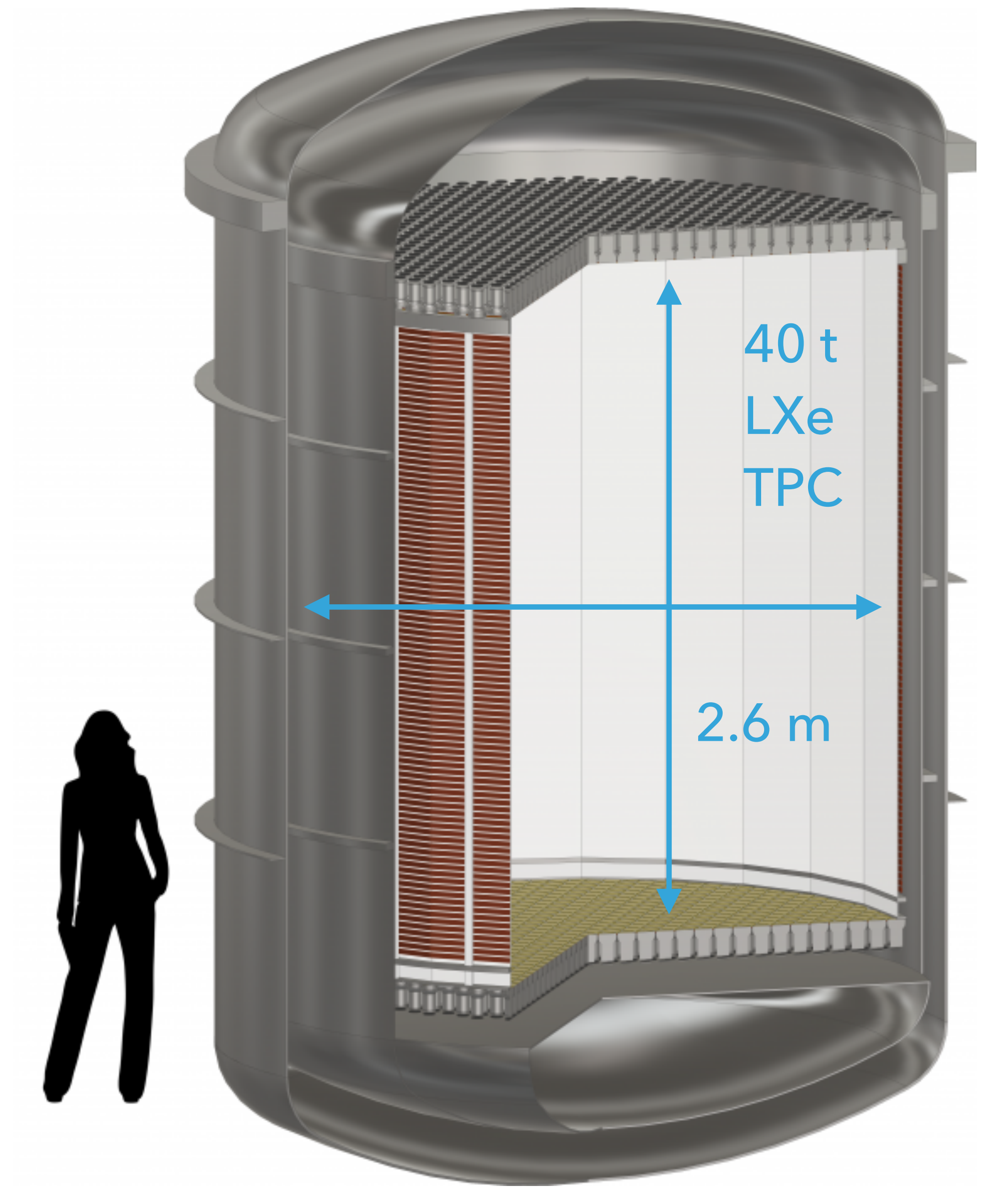






DARWIN DESIGN: BASELINE SCENARIO

- 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



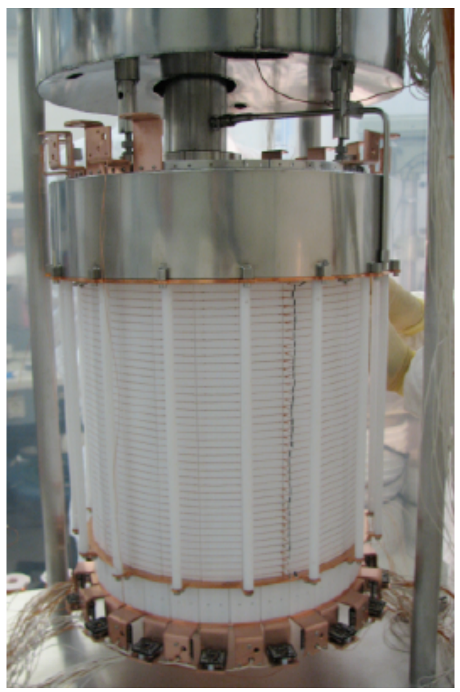
DARWIN collaboration, JCAP 1611 (2016) 017

Alternative designs and photosensors under consideration

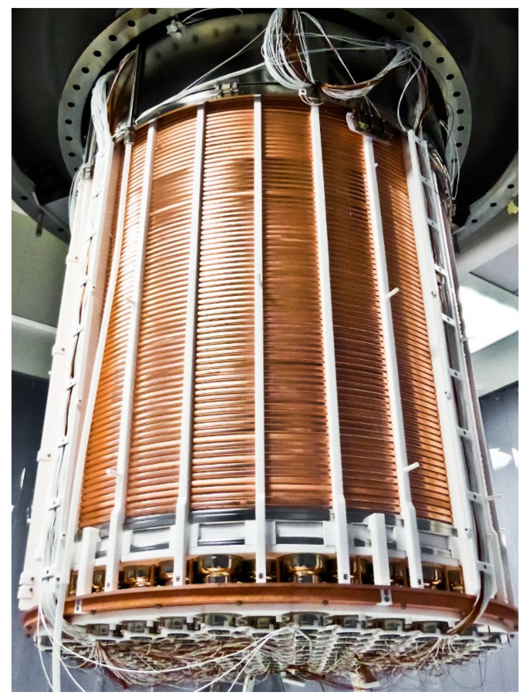
BENCHMARK: THE XENON LEGACY AT LNGS

XENON10

XENON100

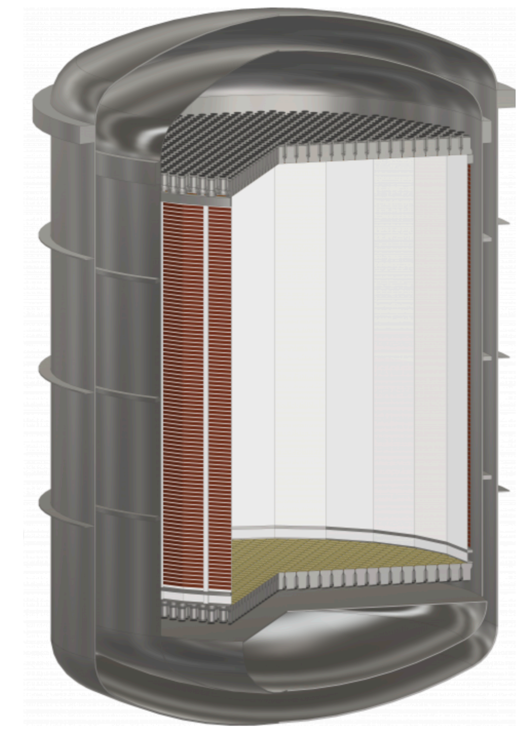


XENON1T



XENONnT

DARWIN



XENON10	XENON100	XENON1T	XENONnT	DARWIN
2005-2007	2008-2016	2012-2018	2020-2025	2027–
15 kg	161 kg	3200 kg	8400 kg	50 tonnes
15 cm	30 cm	96 cm	150 cm	260 cm
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2	~10^{-49} cm^2

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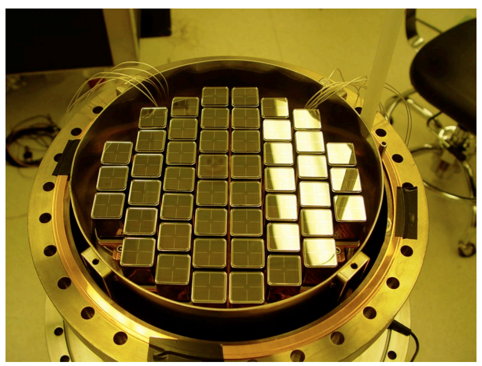
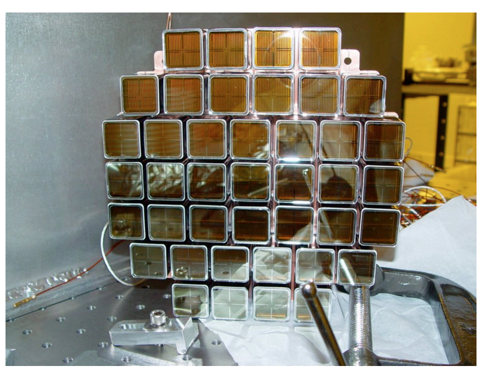
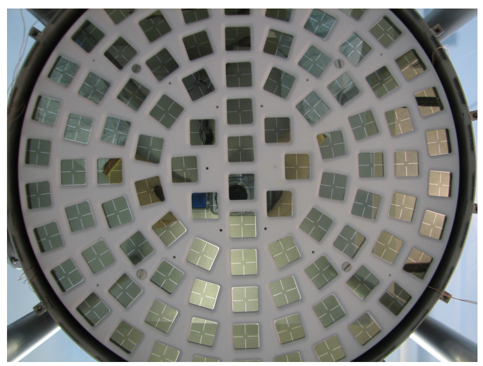
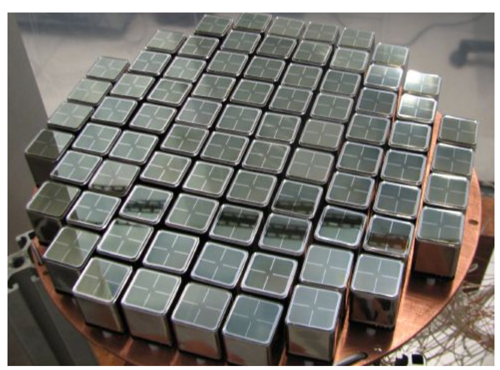
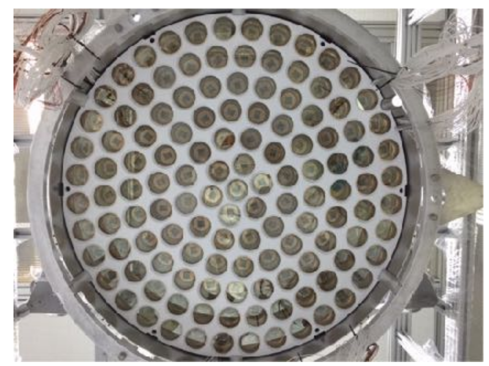
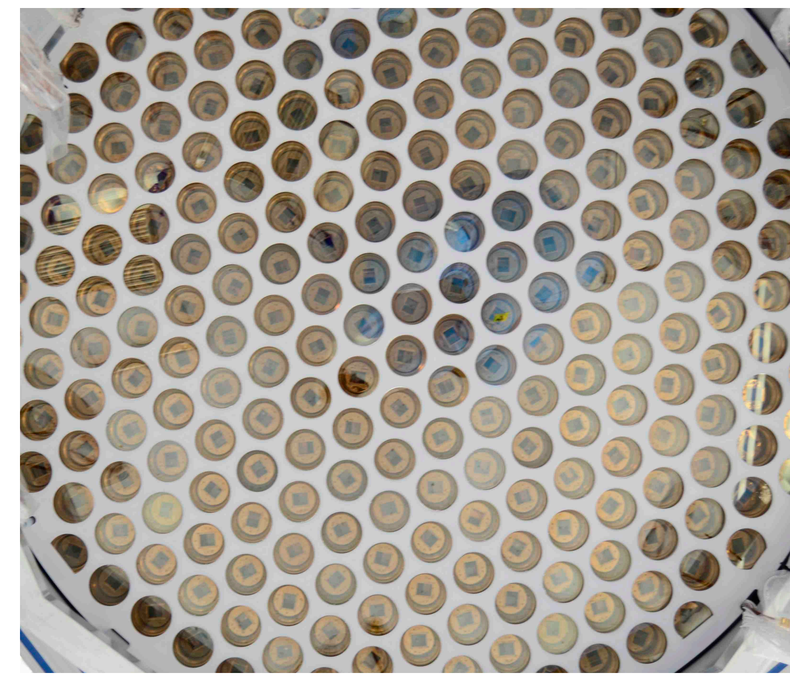
XENON10 XENON100 XENON1T XENONnT



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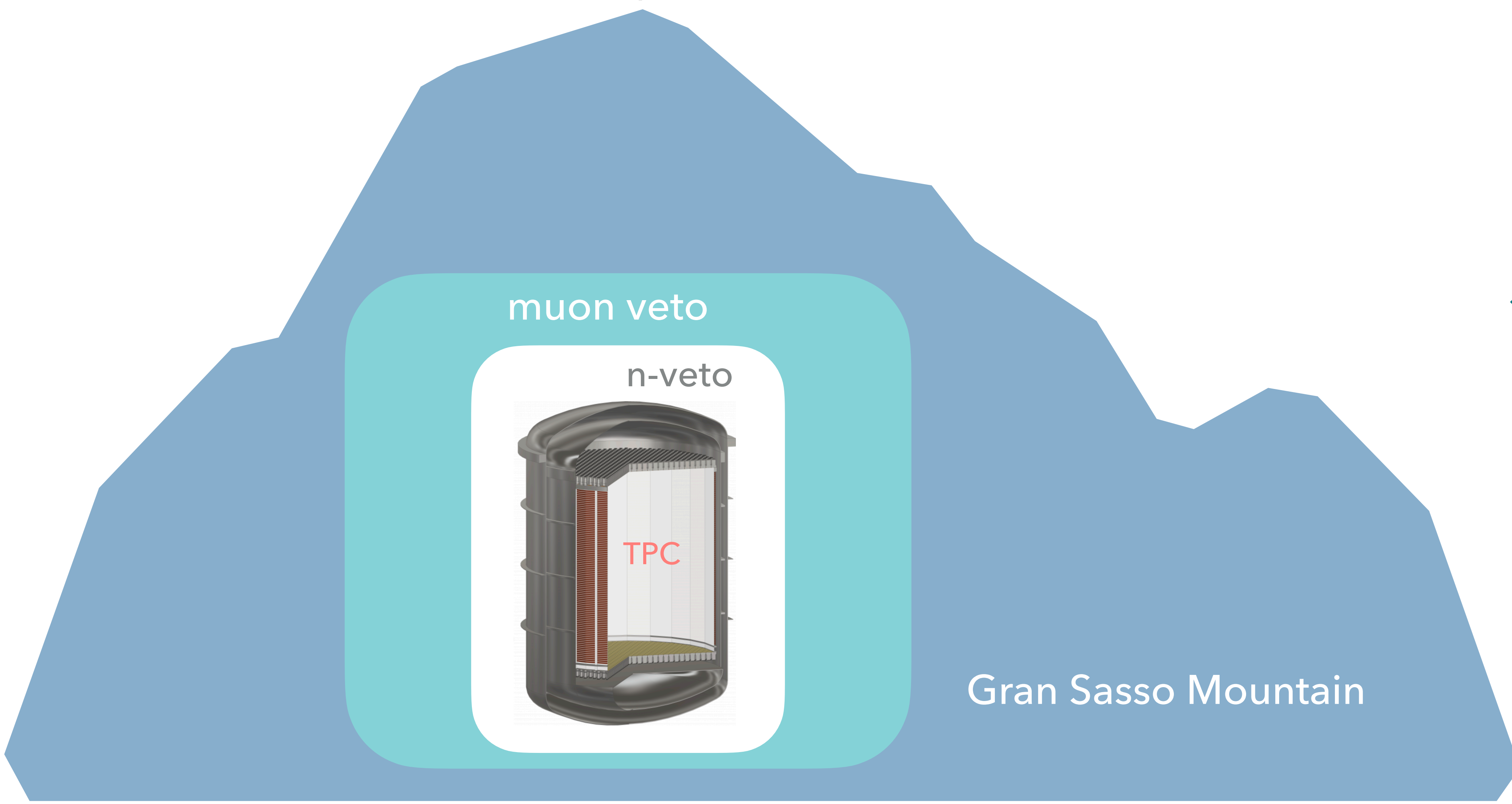
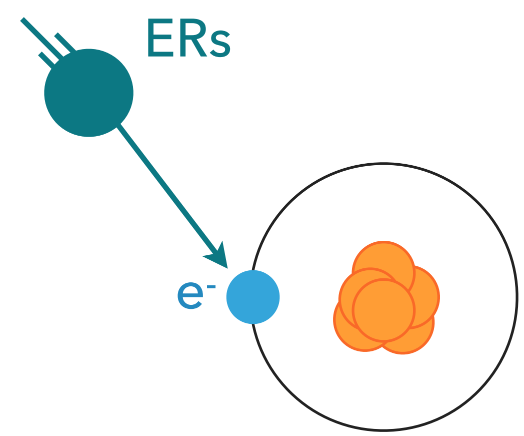
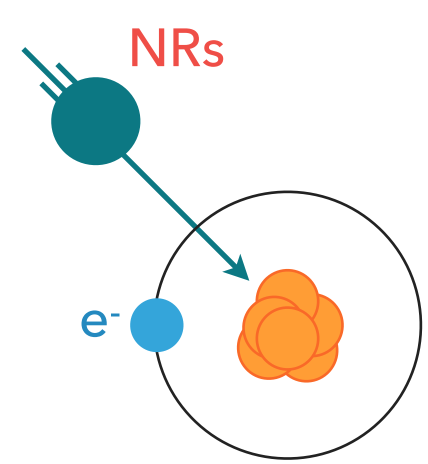
DARWIN BACKGROUNDS: OVERVIEW

- Cosmogenic (muon-induced) neutrons: NRs
- Detector materials (n, γ, α, e^-): NRs and ERs
- Xe-intrinsic isotopes (^{85}Kr, ^{222}Rn, ^{136}Xe, ^{124}Xe, etc): ERs
- Neutrinos (solar, atmospheric): NRs and ERs

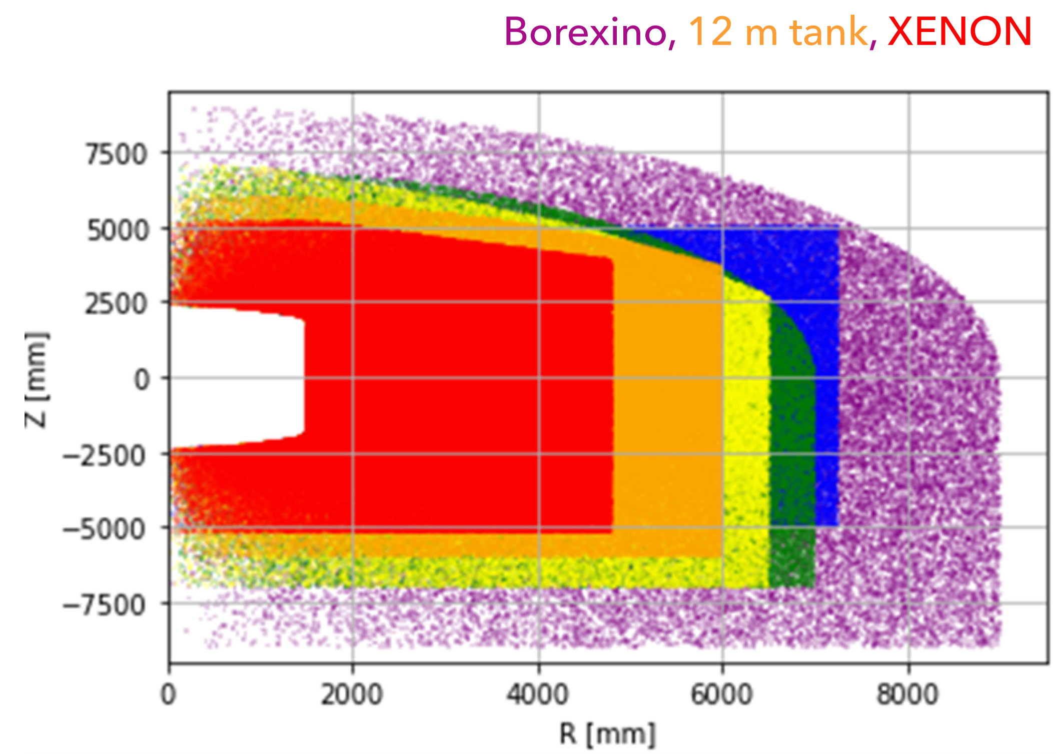




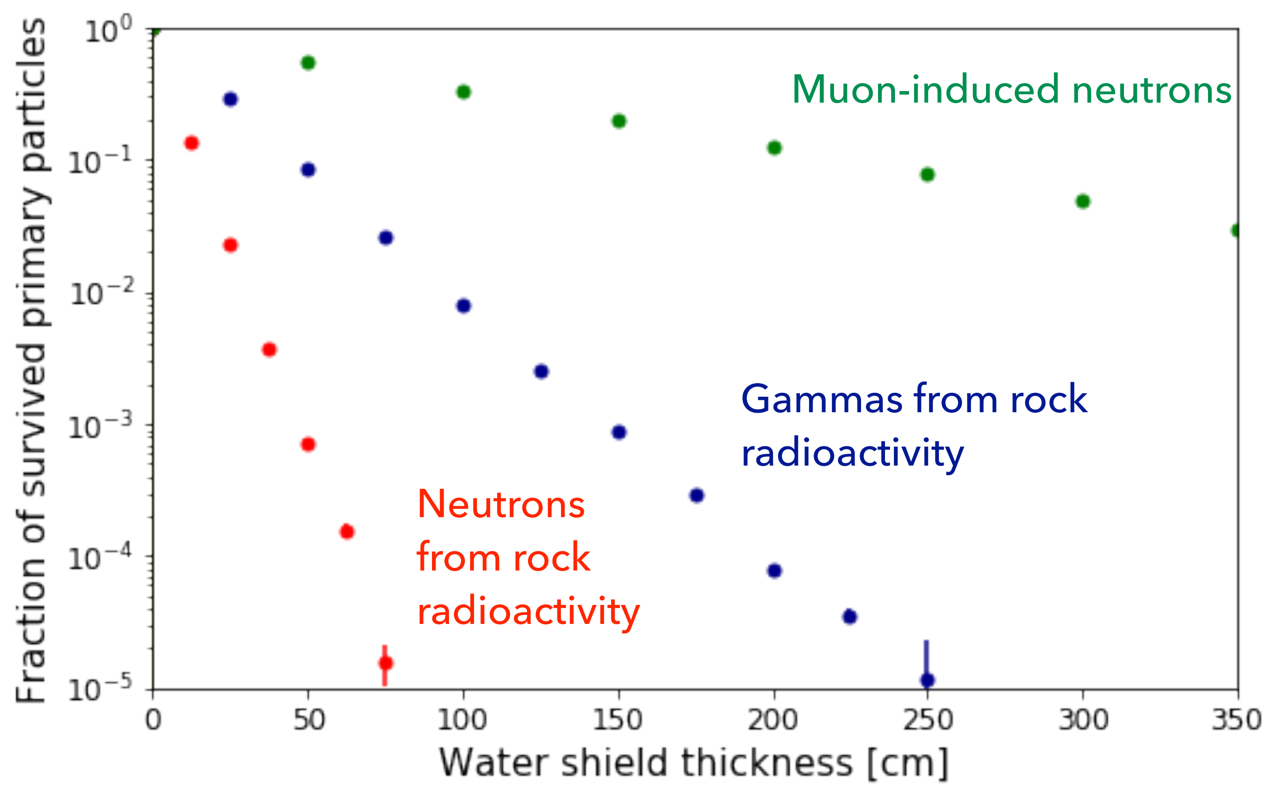


WATER SHIELD AT LNGS

- Full MC simulation for 3600 mwe
- External γ,n background negligible after > 2.5 m
- Muon-induced n at HE:
  - ~0.4 events/(200 t x y) for 12 m ø tank
  - <0.05 events/(200 t x y) for Borexino tank



Simulations of the external background



WATER SHIELD AT LNGS

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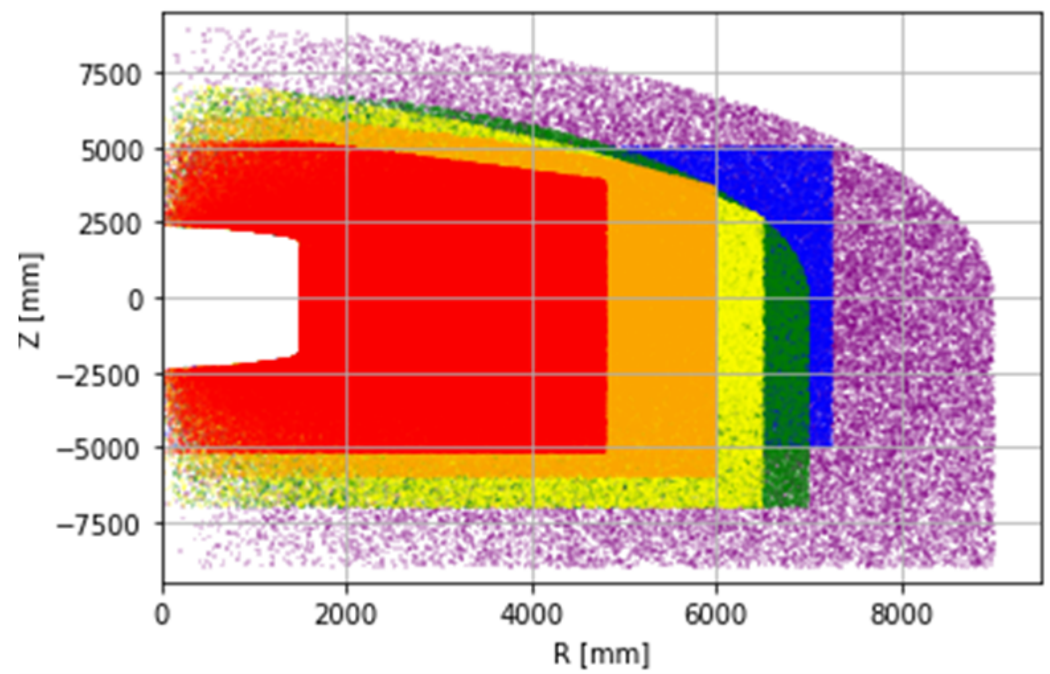
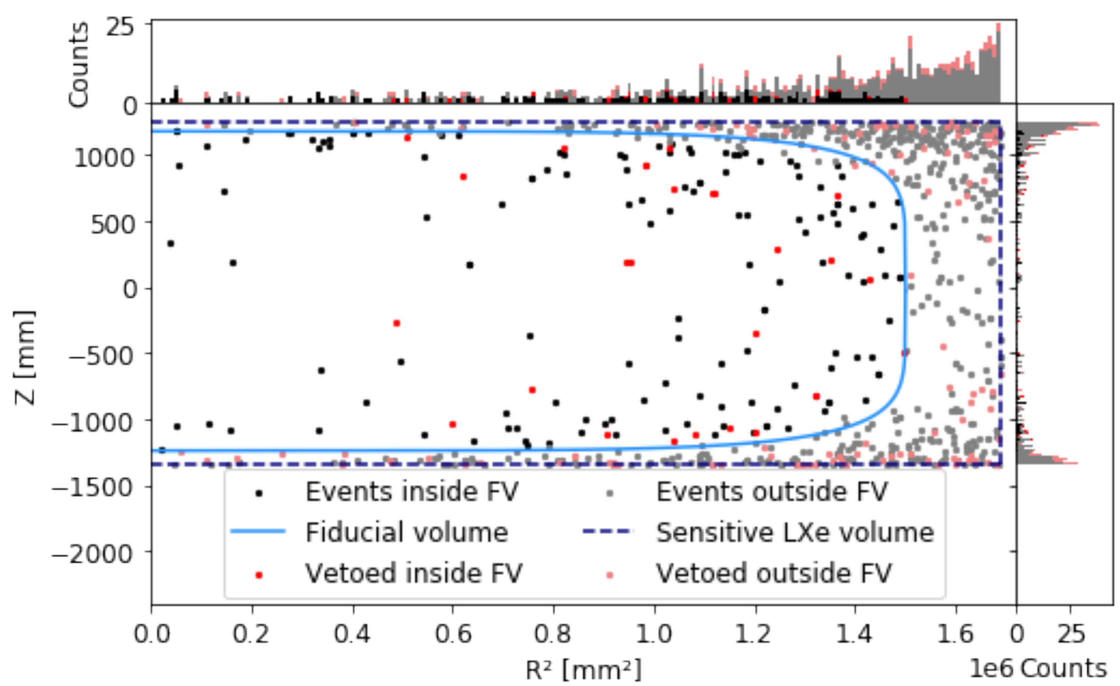
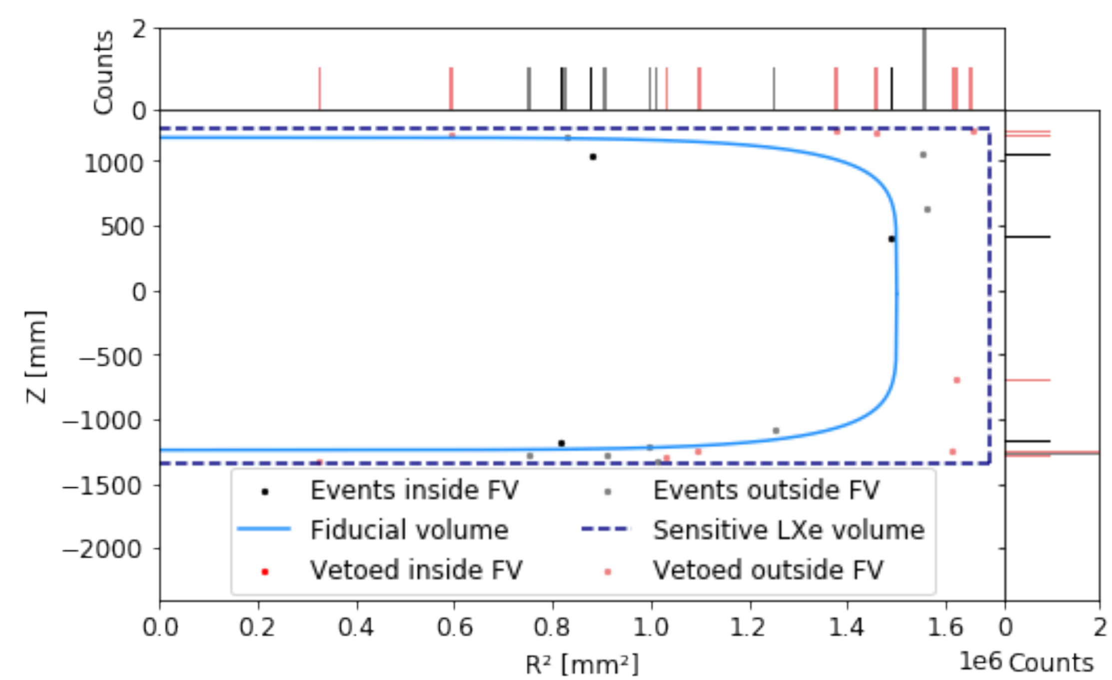
Borexino, 12 m tank, XENON



XENON



Borexino



Single-scatters nuclear recoils; simulated 700 y of DARWIN lifetime

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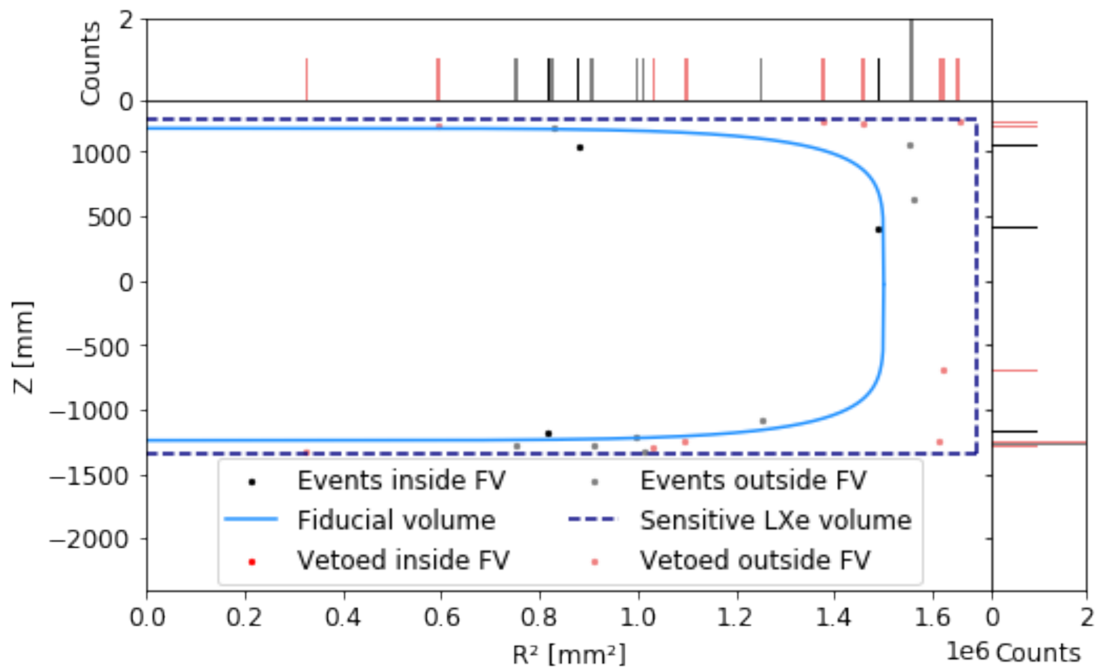
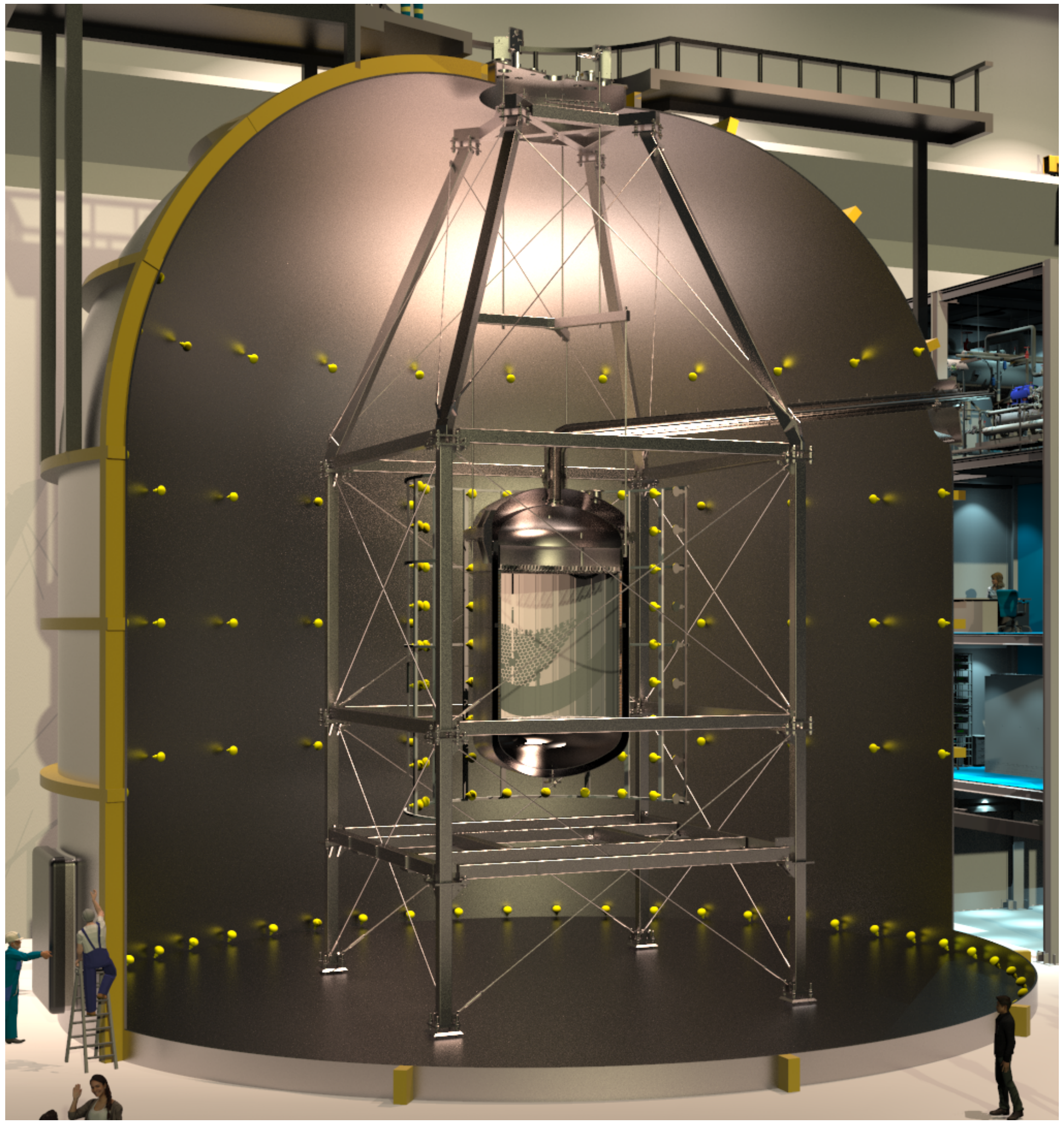
Borexino



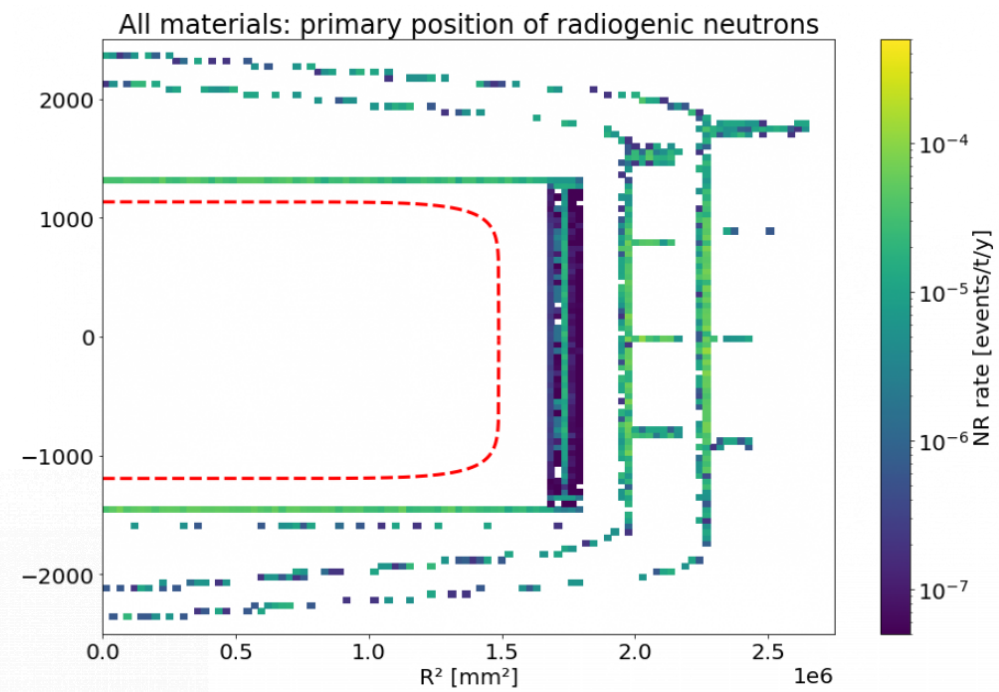
Visualisation of DARWIN in Borexino WT

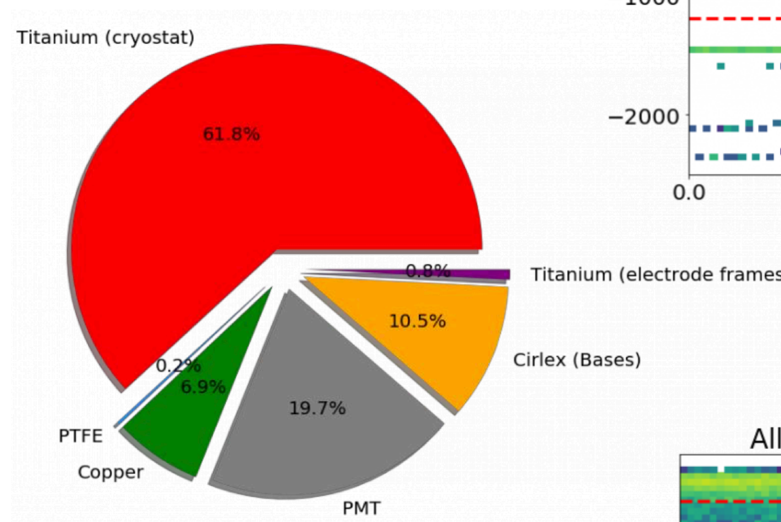


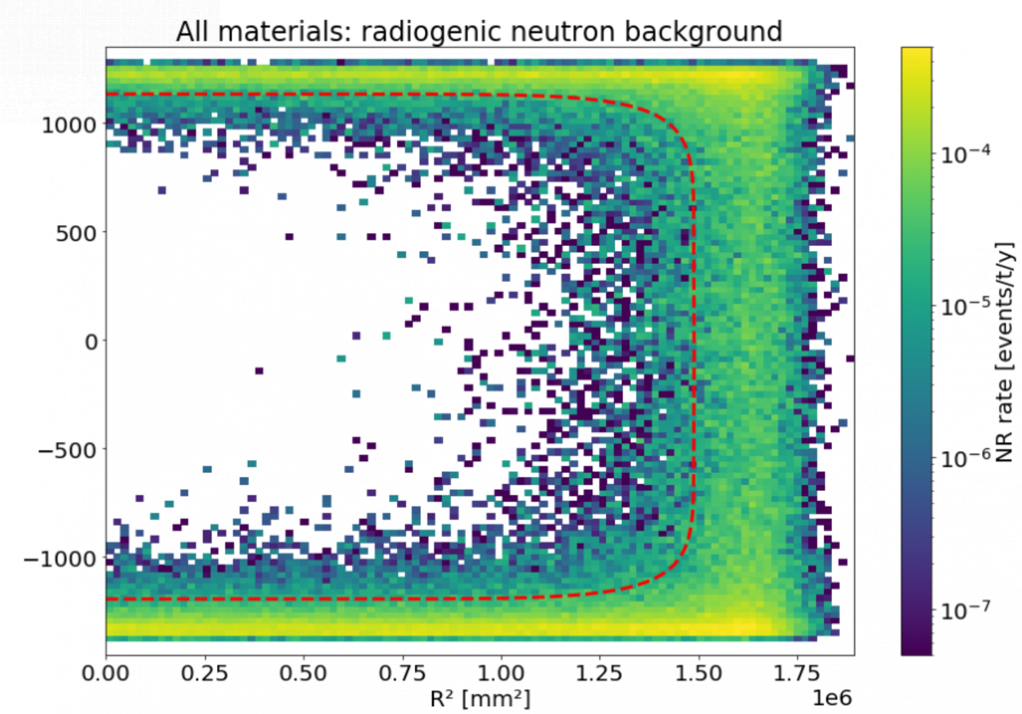
Single-scatters nuclear recoils; simulated 700 y of DARWIN lifetime

NEUTRONS FROM MATERIALS

- MC simulation: define materials and requirements
- Start with achieved specific activities
- Determine required improvements
    - ~2.7 events/(200 t x y)
    - (5,40) keV NR region



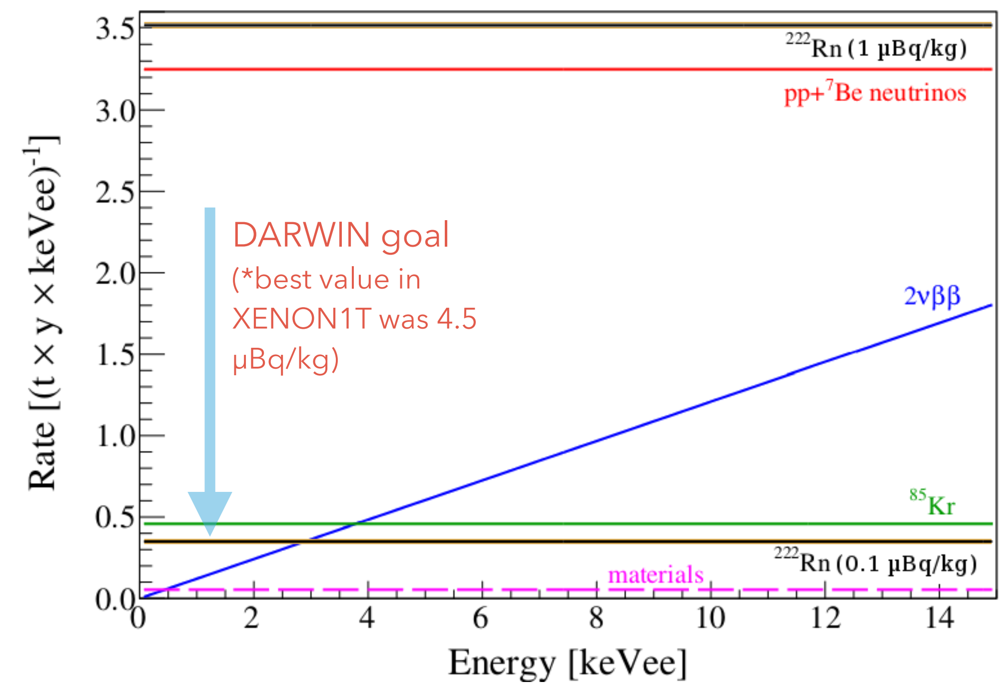


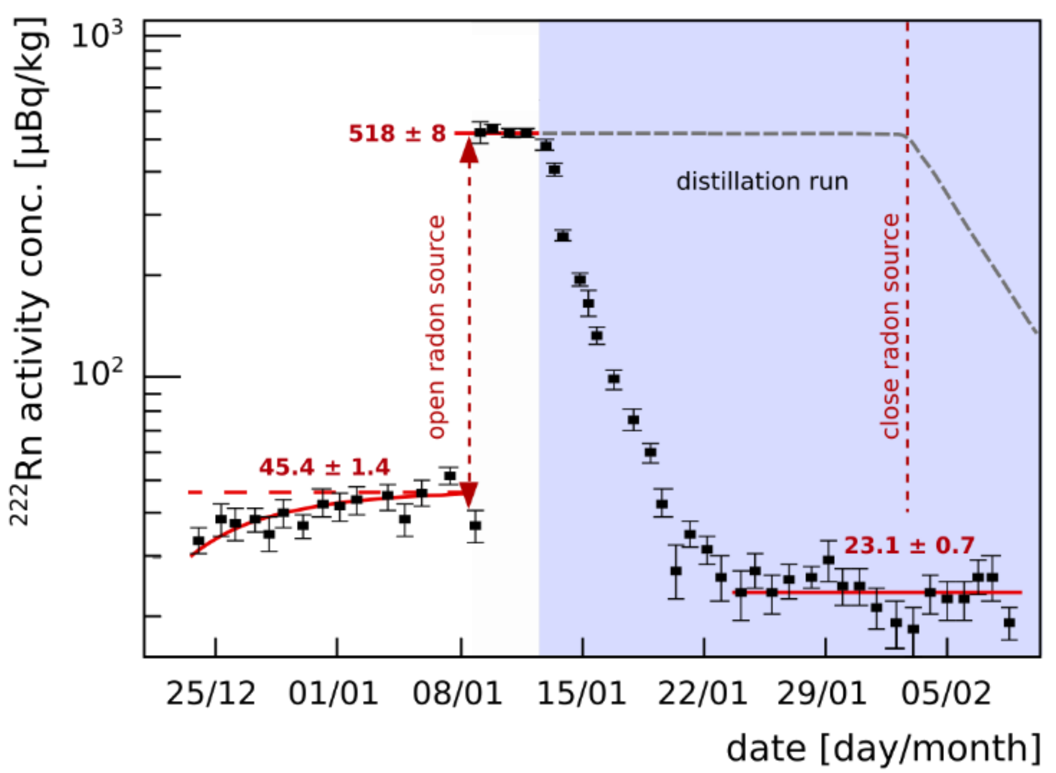


		Activity					
Material	Unit	^{238}U	^{226}Ra	^{235}U	^{232}Th	^{228}Th	Ref.
Titanium	mBq/kg	< 1.6	< 0.09	< 0.02	0.28	0.23	LZ
PTFE	mBq/kg	< 5e-3	< 5e-3	< 2e-4	<1.4e-3	<1.4e-3	EXO
Copper	mBq/kg	< 1	< 0.035	< 0.18	< 0.033	< 0.026	XENON
PMT	mBq/unit	8	0.6	0.37	0.7	0.6	XENON
PMT bases	mBq/unit	0.82	0.32	0.071	0.20	0.15	XENON

LIQUID XENON: RADON BACKGROUND

- DARWIN goal: ER background dominated by solar neutrinos
- ^{222}Rn concentration goal: 45 × below XENON1T best level*
- ^{222}Rn atoms in target: 2.25 × below XENON1T
  - avoid Rn emanation (material selection, surface treatment, detector design)
  - active Rn removal via cryogenic distillation





Example: XENON1T distillation column installed for XENON100

factor > 27 (at 95% CL) reduction factor demonstrated

- dedicated column developed and installed underground for XENONnT

See: XENON collaboration, EPJ-C 77 (2017) 6

LIQUID XENON: RADON BACKGROUND

- DARWIN goal: ER background dominated by solar neutrinos
- ^{222}Rn concentration goal: 45 × below XENON1T
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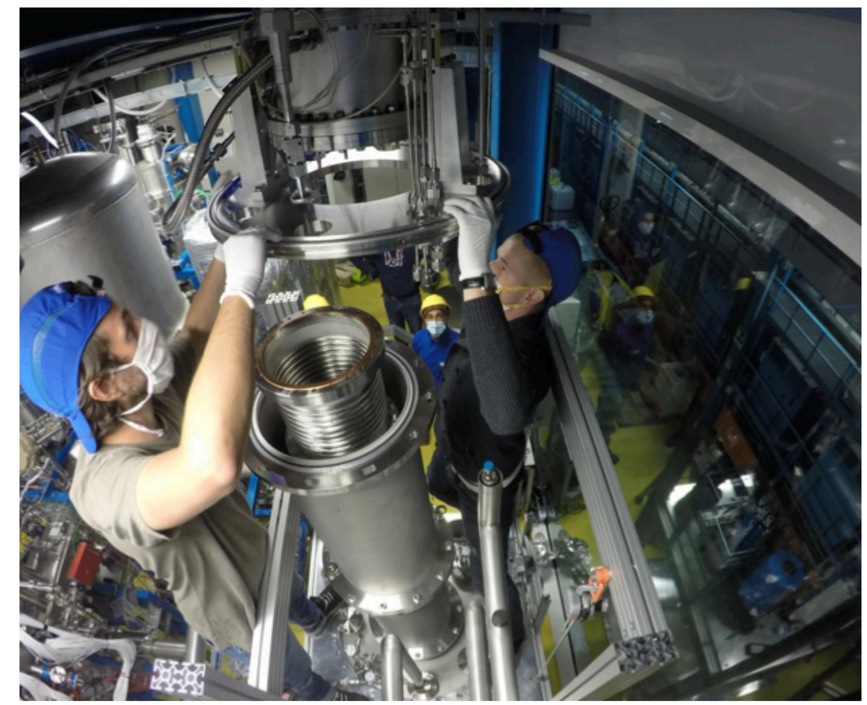
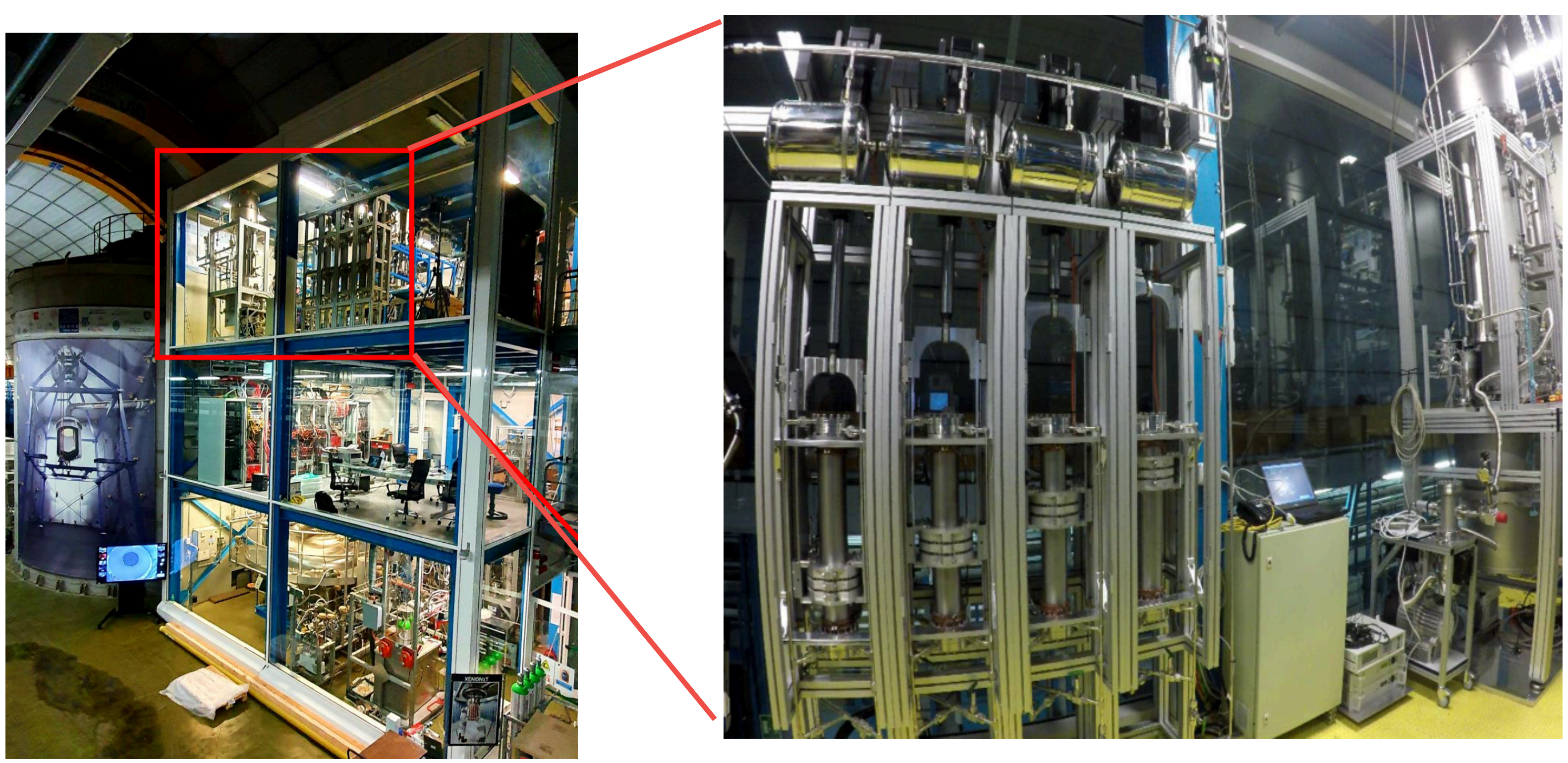


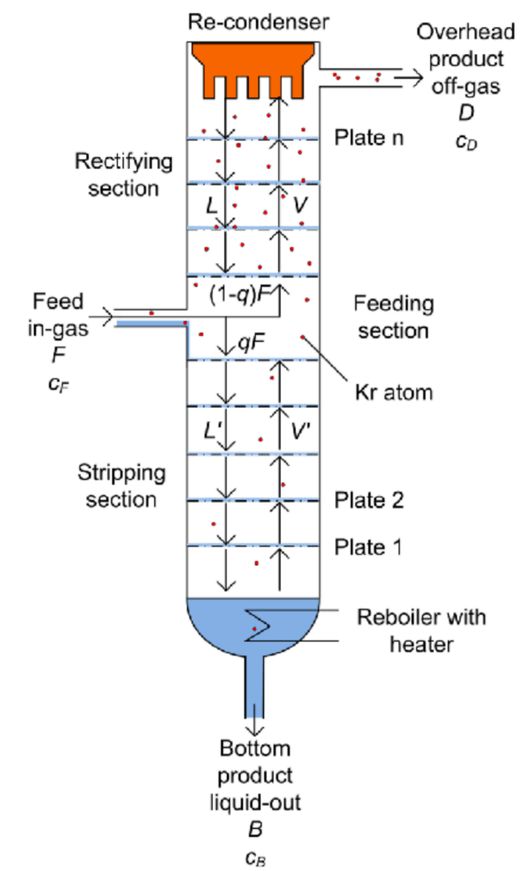


- dedicated column developed and installed underground for XENONnT, 63 kg/h (175 slpm)

LIQUID XENON: KRYPTON BACKGROUND

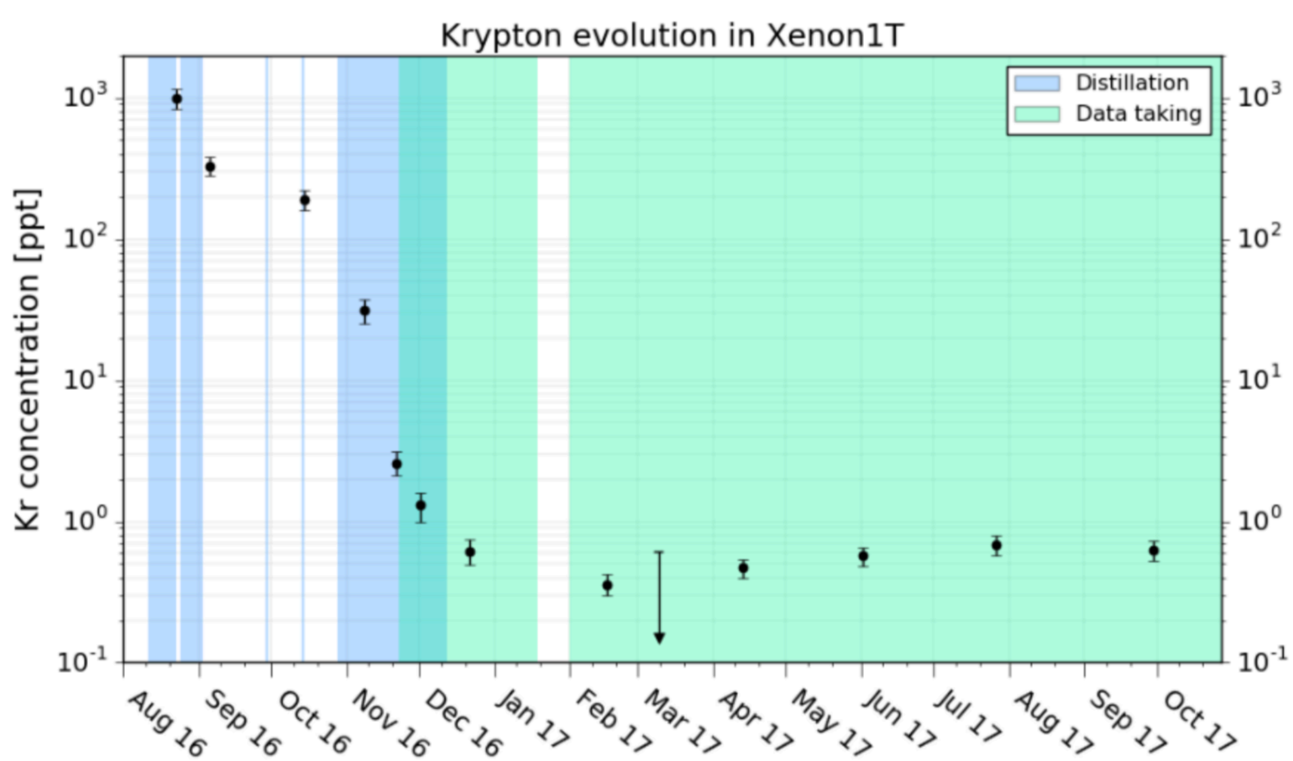
XENON collaboration, EPJ-C 77 (2017) 5

- DARWIN goal: 0.03 ppt ^{nat}Kr (~ 0.1 x pp-v background)
- ^{85}Kr $T_{1/2}$ = 10.8 y, Q-value = 687 keV; $^{85}Kr/^{nat}Kr$ 2 x10^{-11} mol/mol
- 5.5 m distillation column, 6.5 kg/h output; factor > 6.4. x 10^5 separation down to < 48 ppq (= 10^{-15} mol/mol)



As measured by RGMS + Gas Chromatography with 8 ppq detection limit

(EPJ-C 74, 2014)



Evolution of Kr/Xe [ppt, mol/mol] level during online distillation

XENON1T distillation column $^{nat}Kr/Xe$: (0.6±0.1) ppt

XENON1T column has produced gas sample < 0.026 ppt = 2.6 x 10^{-14} (at 90% CL)

- **DARWIN goal achieved**

DARWIN SCIENCE PROGRAMME

DARWIN

- DIRECT DARK MATTER DETECTION
- SOLAR AXIONS
- NEUTRINOLESS DOUBLE BETA DECAY ^{136}XE

DARWIN Collaboration
Eur. Phys. J. C 80, 9 (2020)

- GALACTIC ALPS, DARK PHOTONS
- LOW-ENERGY SOLAR NEUTRINOS

DARWIN Collaboration,
Eur. Phys. J. C 80, 12 (2020)

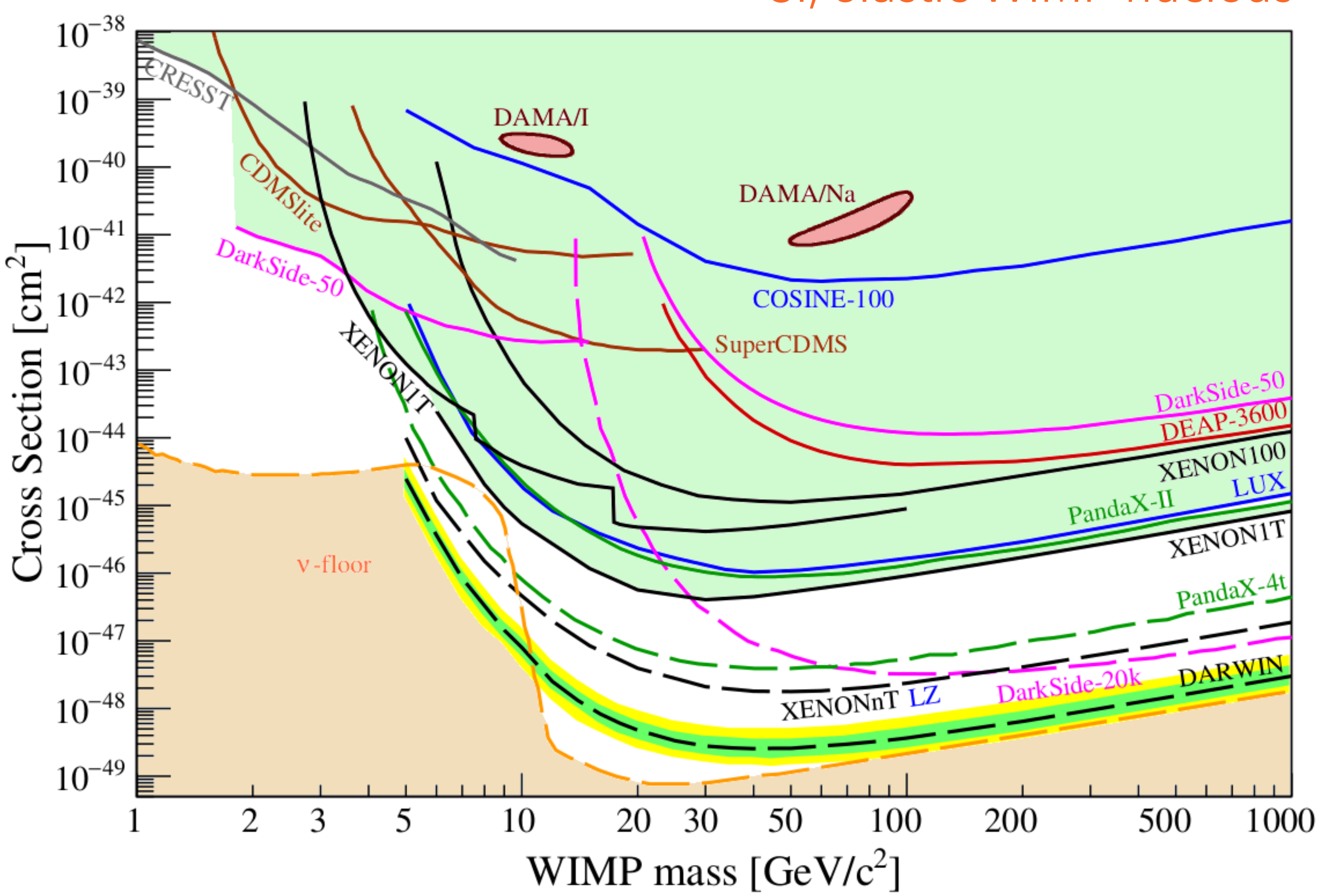
- COHERENT NEUTRINO NUCLEUS SCATTERS
- SUPERNOVA NEUTRINOS

DIRECT DARK MATTER DETECTION: WIMPS

- Probe SI elastic scattering: ^{124}Xe, ^{126}Xe, ^{128}Xe, ^{129}Xe, ^{130}Xe, ^{131}Xe, ^{132}Xe (26.9%), ^{134}Xe (10.4%), ^{136}Xe (8.9%)
- SD elastic + inelastic DM-nucleus scattering: ^{129}Xe (26.4%), ^{131}Xe (21.2%)

DARWIN study: JCAP 10, 016 (2015)

SI, elastic WIMP-nucleus



Exposure

1 t y

20 t y

200 t y

Assumptions for DARWIN:

30 t LXe in FV

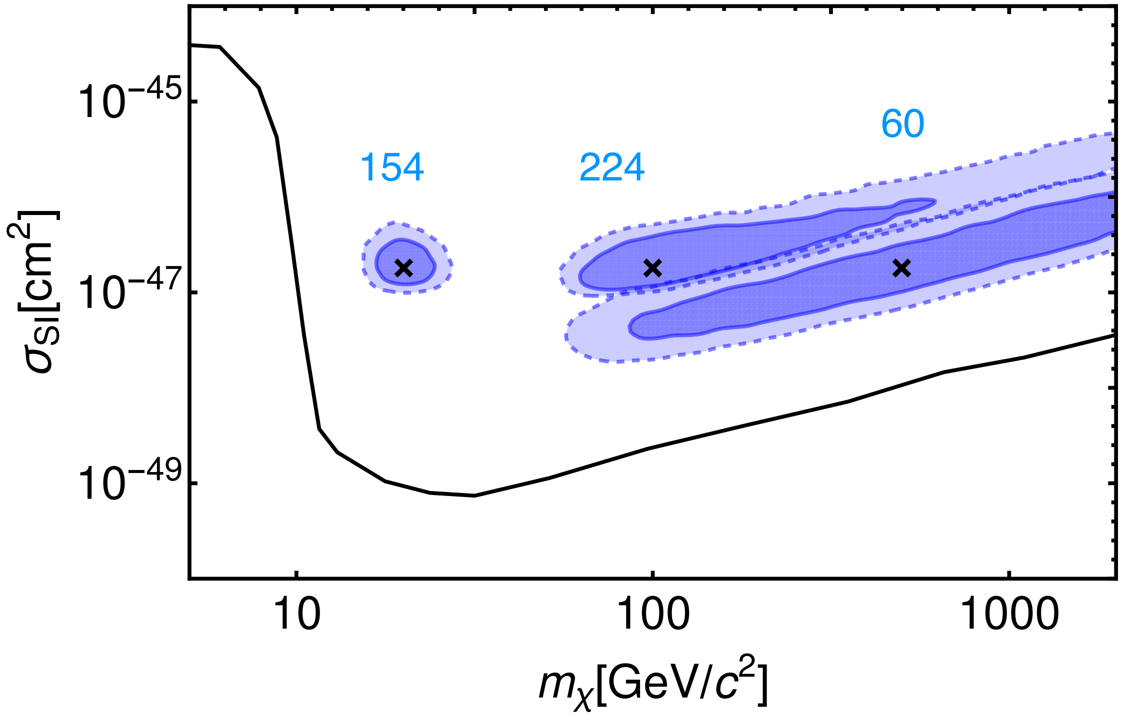
99.98% ER rejection

(at 30% NR acceptance)

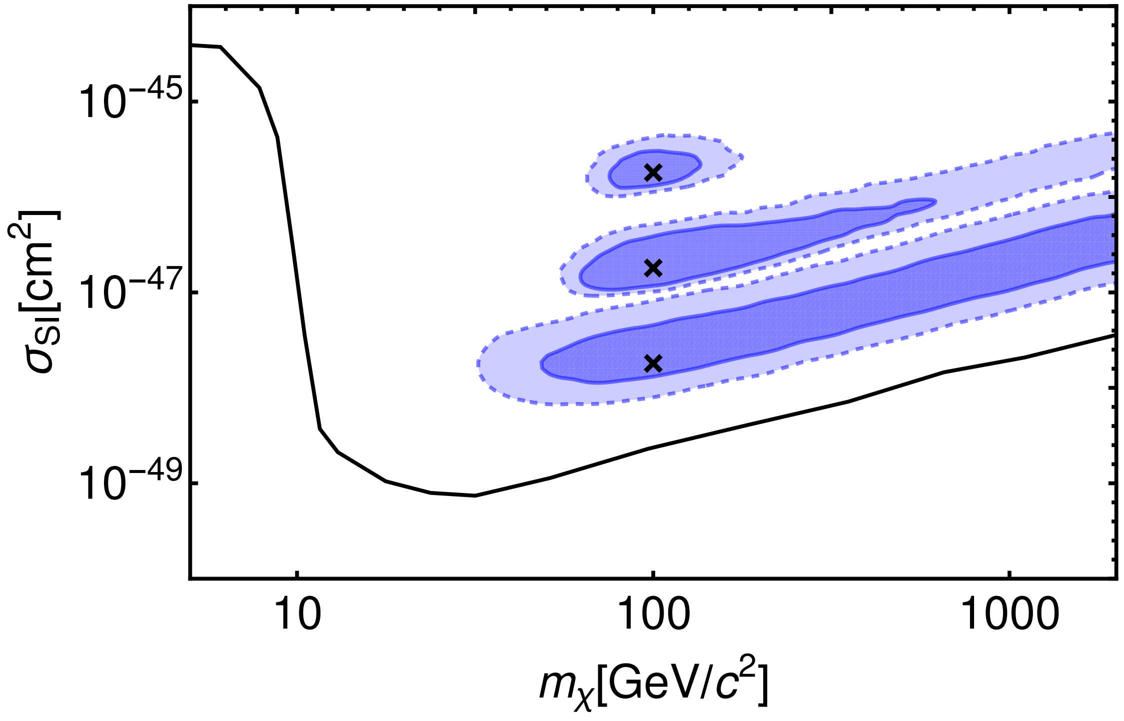
DIRECT DARK MATTER DETECTION: WIMP SPECTROSCOPY

- Capability to reconstruct the WIMP mass and cross section for various masses - here 20, 100, 500 GeV/c² - and cross sections

Exposure: 200 t y



Exposure: 200 t y



1 and 2 sigma credible regions after marginalising the posterior probability distribution over:

$$v_{esc} = 544 \pm 40\,\mathrm{km/s}$$

$$v_0 = 220 \pm 20\,\mathrm{km/s}$$

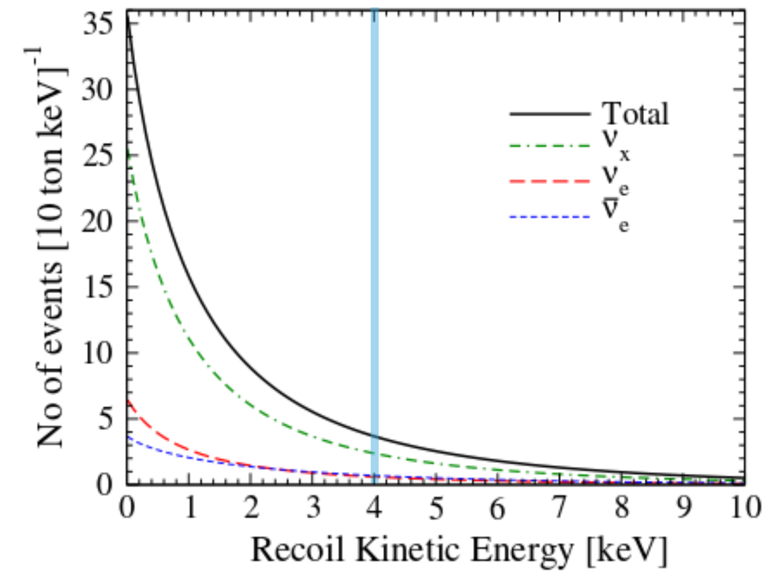
$$\rho_\chi = 0.3 \pm 0.1\,\mathrm{GeV/cm^3}$$

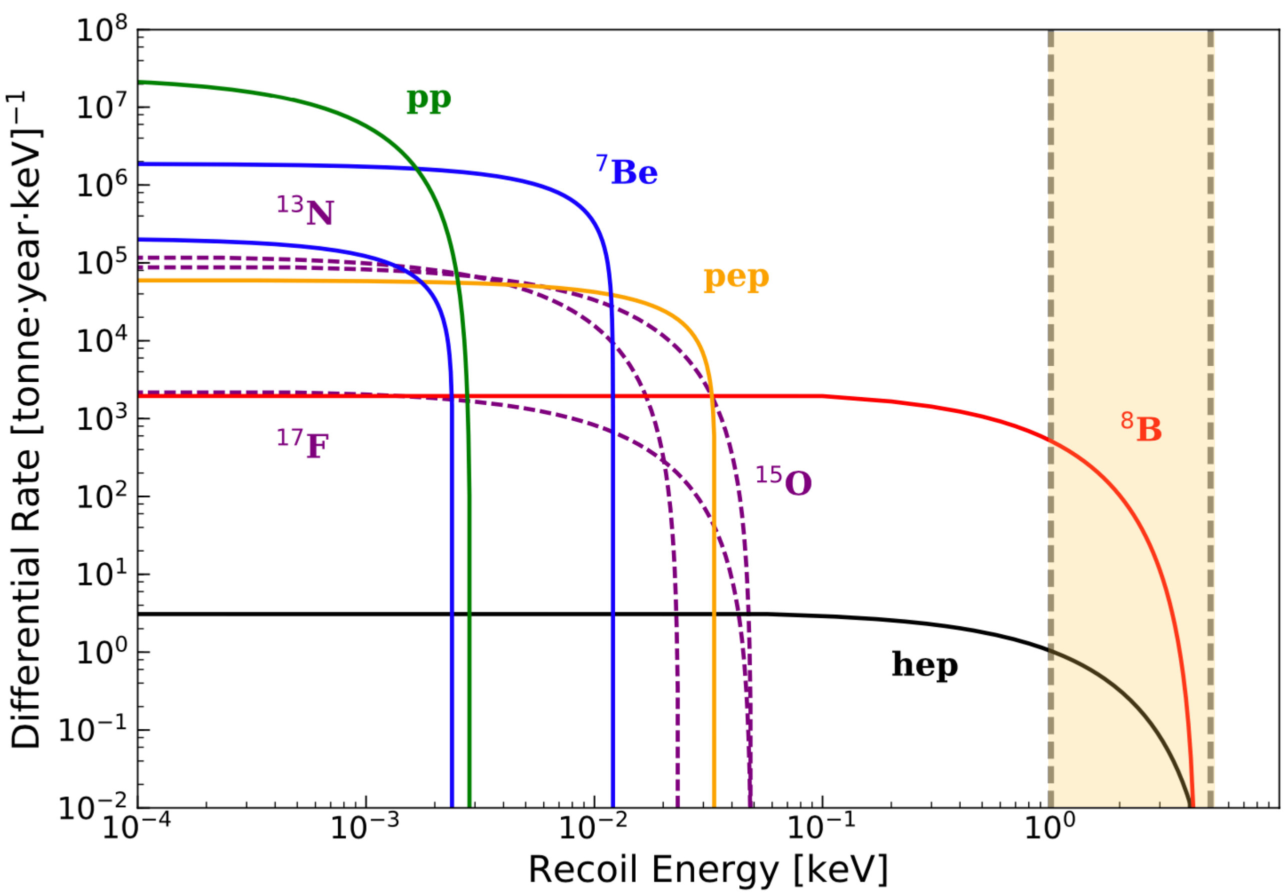
Newstead et al., PRD D 88, 076011 (2013)

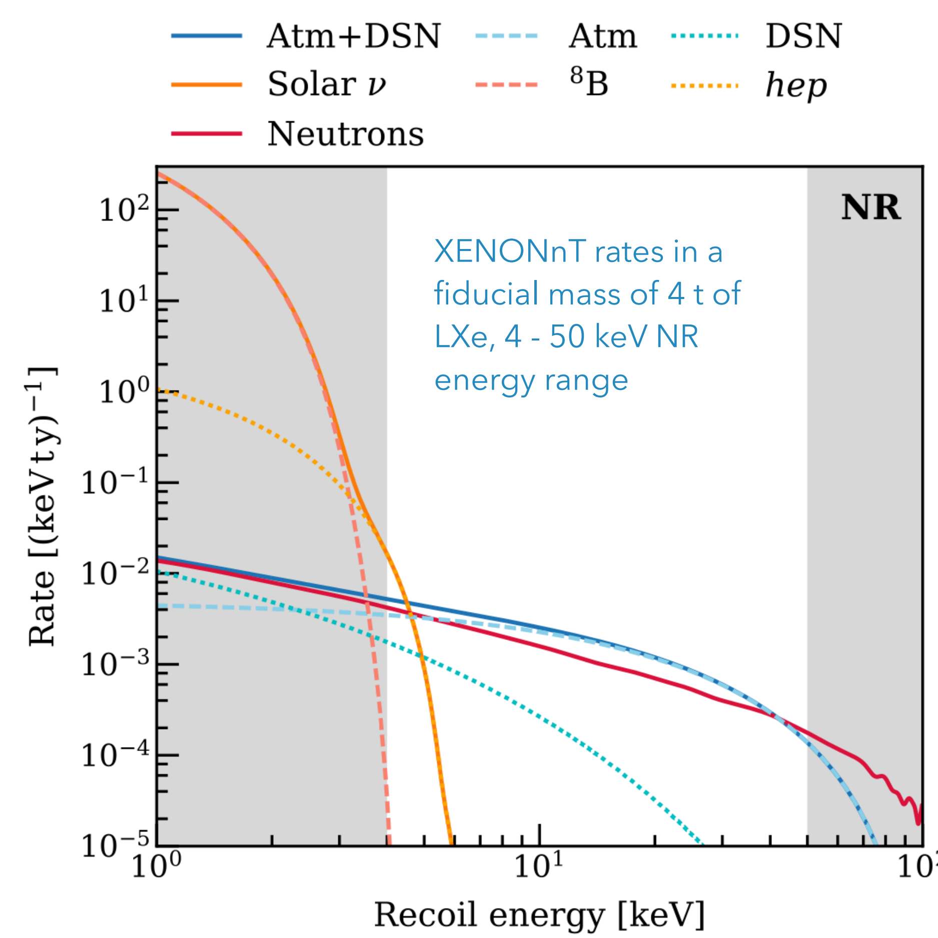
COHERENT NEUTRINO NUCLEUS SCATTERS

- Detect solar ^{8}B ν: 90 events for E_{th} > 1 keV_{nr} (~negligible > 4 keV_{nr})
- Detect supernova ν, sensitive to all neutrino flavours:
  - ~ 700 events from SN with 27 M_{solar} @ 10 kpc
- Planned participation in SNEWS network

PRD D 89, 013011 (2014)







XENON collaboration, JCAP11(2020)031

COHERENT NEUTRINO NUCLEUS SCATTERS

- Detect solar ^{8}B ν: 90 events for E_{th} > 1 keV_{nr} (~negligible > 4 keV_{nr})
- **Detect supernova ν, sensitive to all neutrino flavours:**
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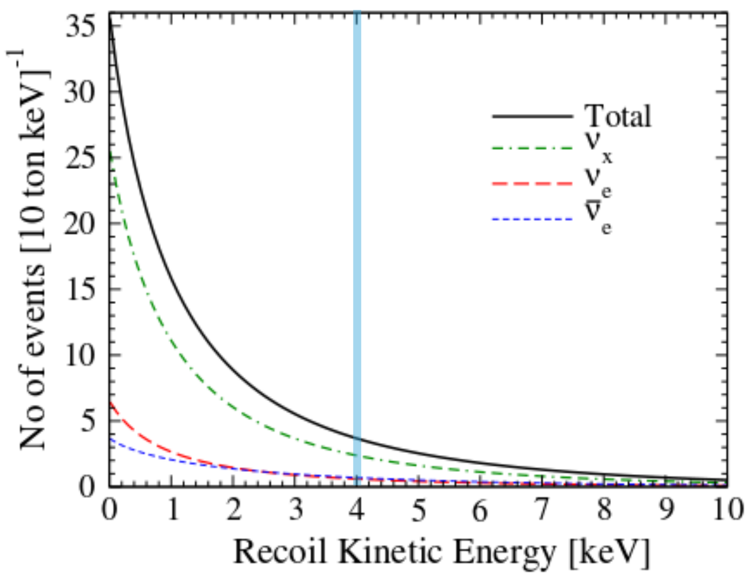
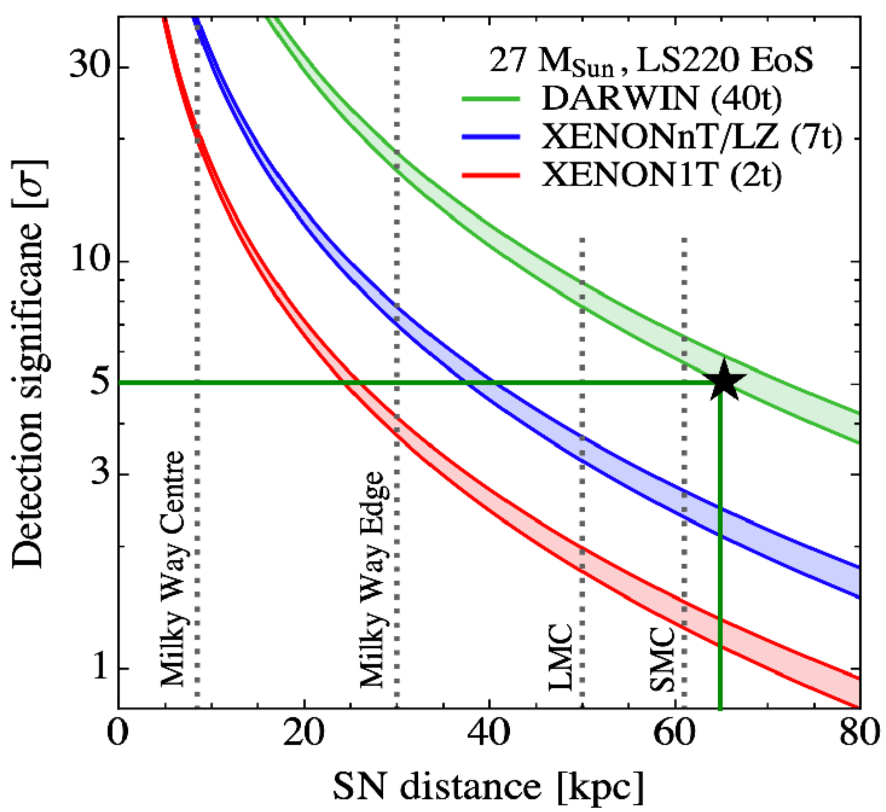
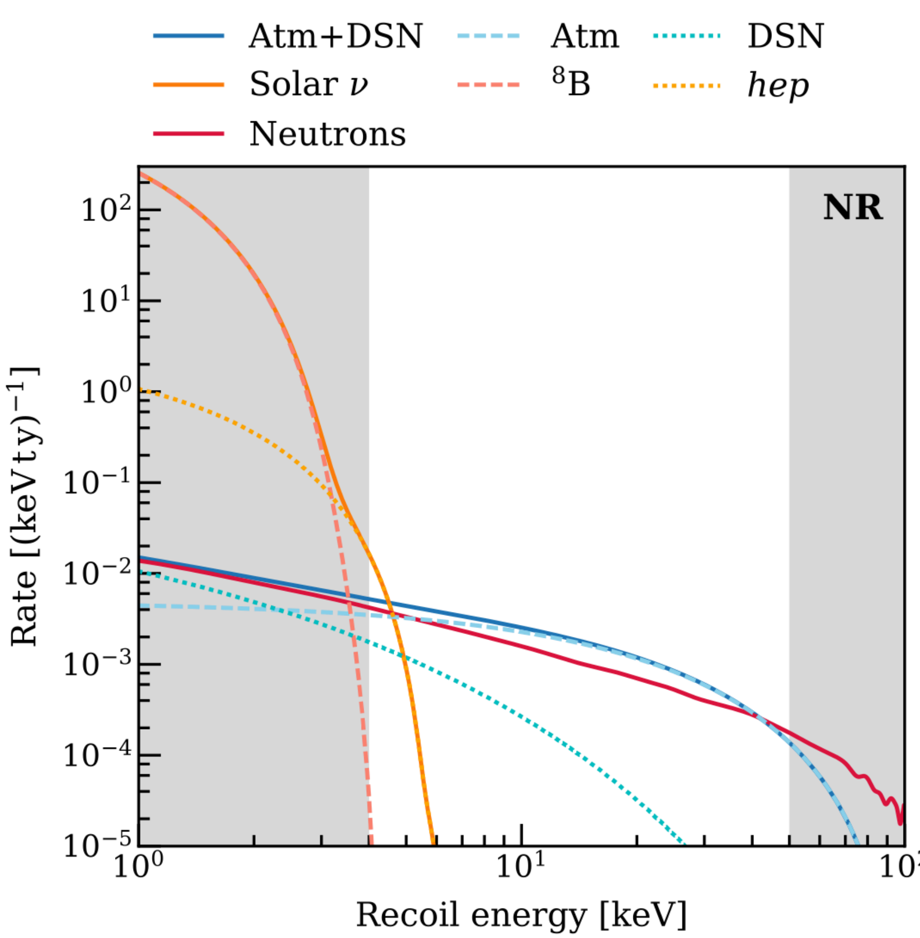
PRD D 89, 013011 (2014)



Signal integrated from [0, 7] s



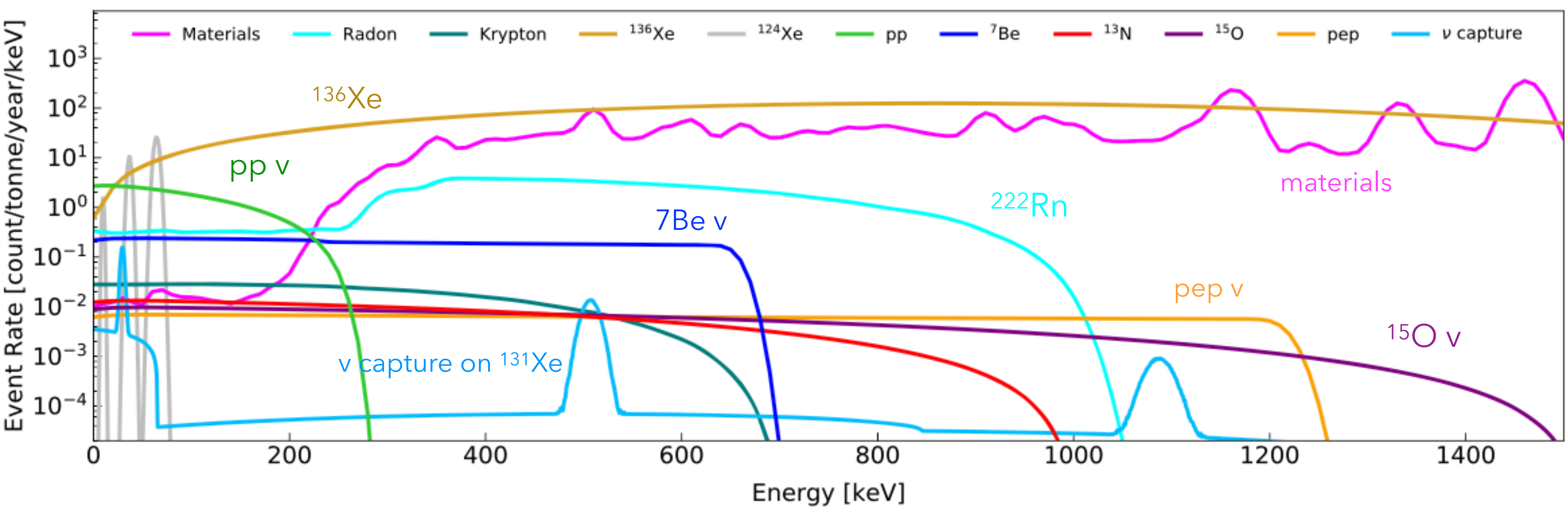
R. Lang et al., PRD 94, 103009



XENON collaboration, JCAP11(2020)031

SOLAR NEUTRINOS

- Real-time measurement, elastic ν-electron interaction $\nu + e^- \rightarrow \nu + e^-$
- Consider signals from 5 solar ν components + ν capture on ^{131}Xe (Q-value = 0.355 MeV), and 5 backgrounds up to 3 MeV; assume an energy threshold for ERs of 1 keV
- Multivariate spectra fit of all 11 components

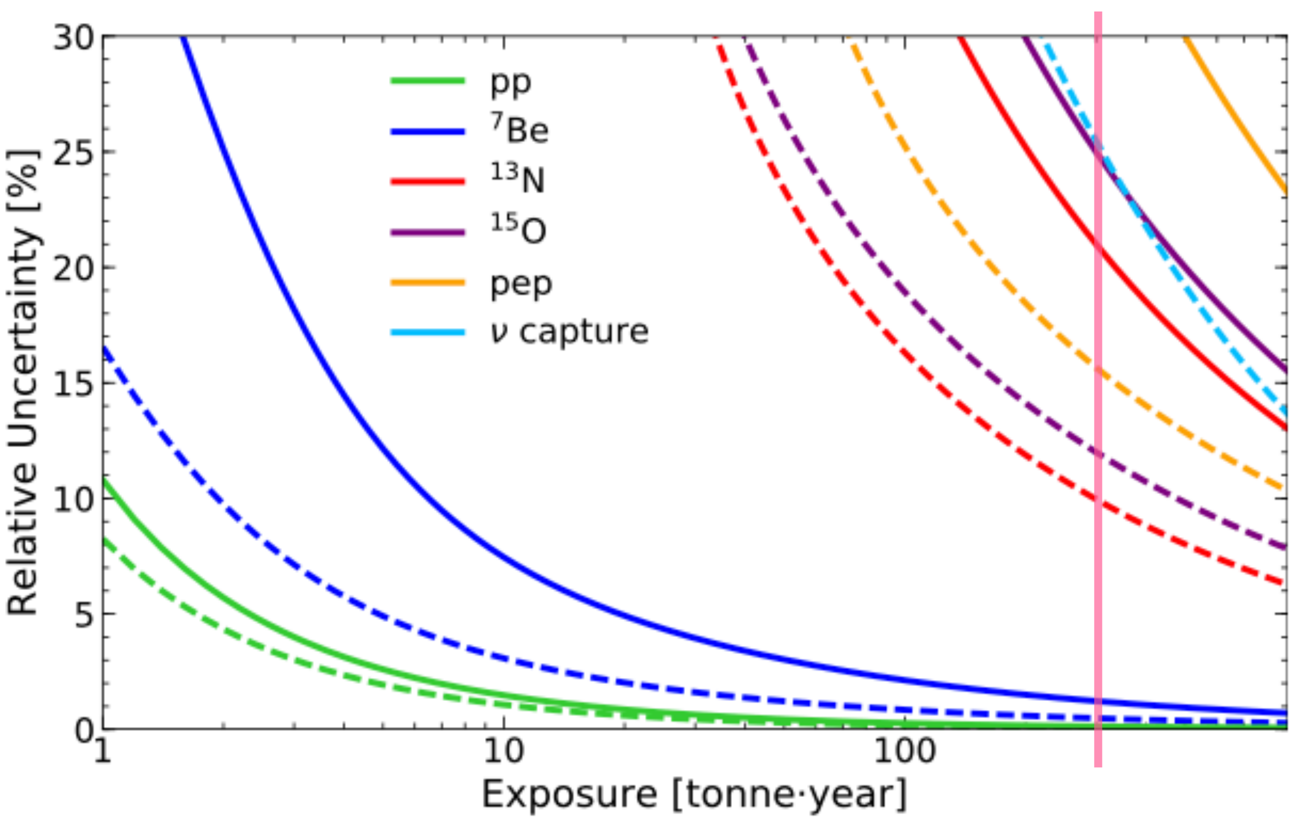


SOLAR NEUTRINOS

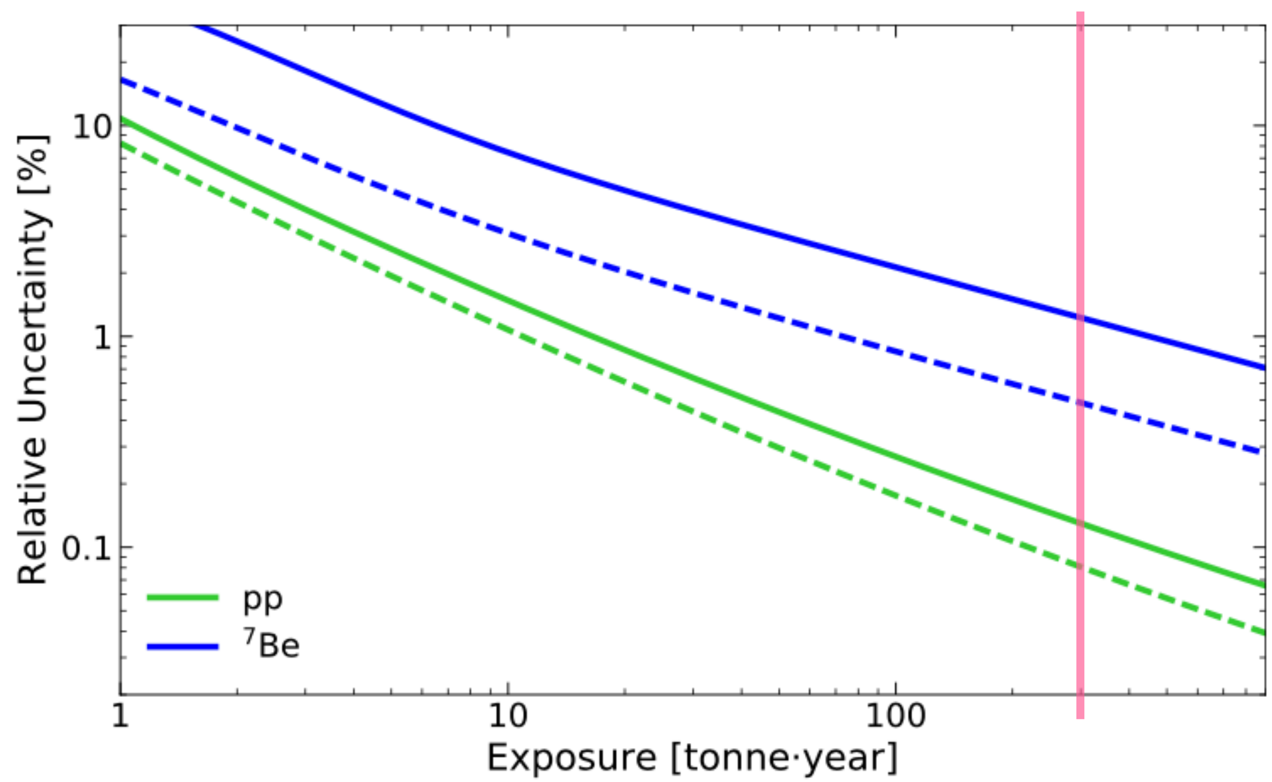
- Determined relative uncertainty of each solar ν component vs exposure
- Solid: natural xenon target; dashed: target depleted in ^{136}Xe

2% precision in 7Be flux with 100 ty

10% precision in pp flux with 1 ty; 0.15 % with 300 ty



300 t y



300 t y

SOLAR NEUTRINOS

Open Access

Regular Article - Experimental Physics

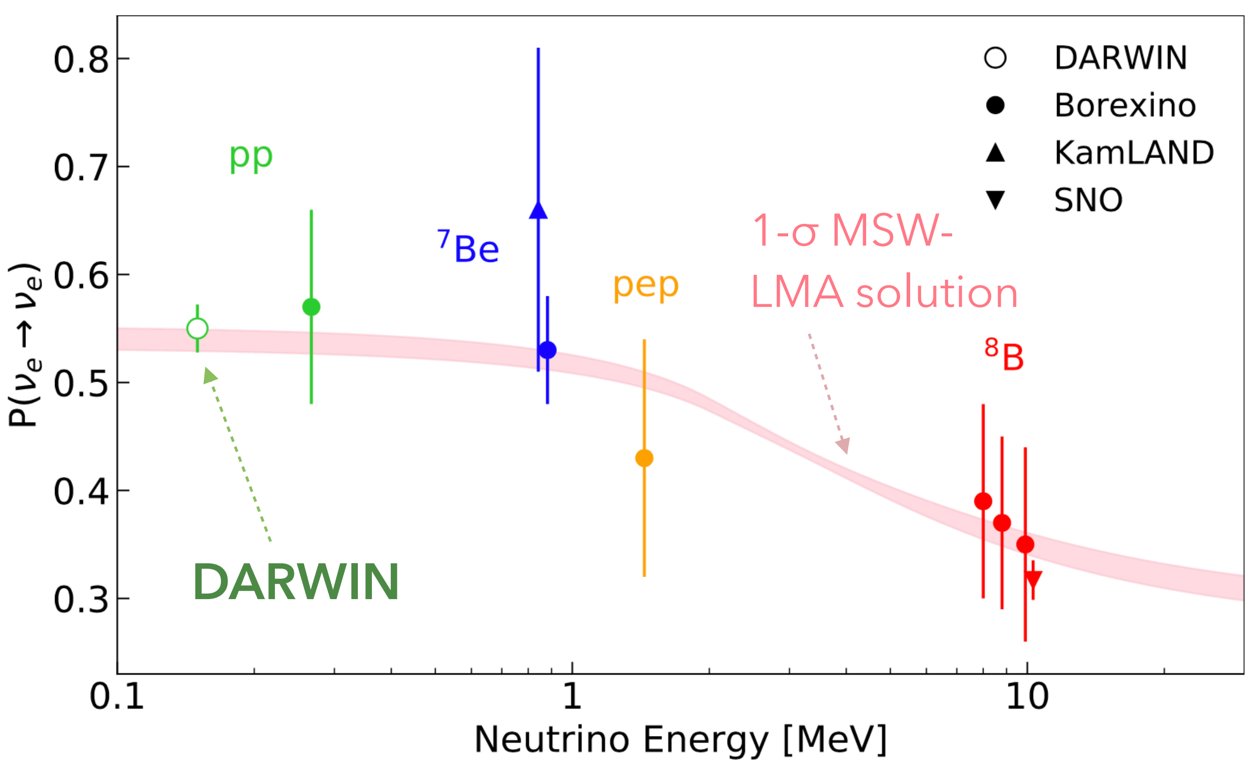
Solar neutrino detection sensitivity in DARWIN via electron scattering

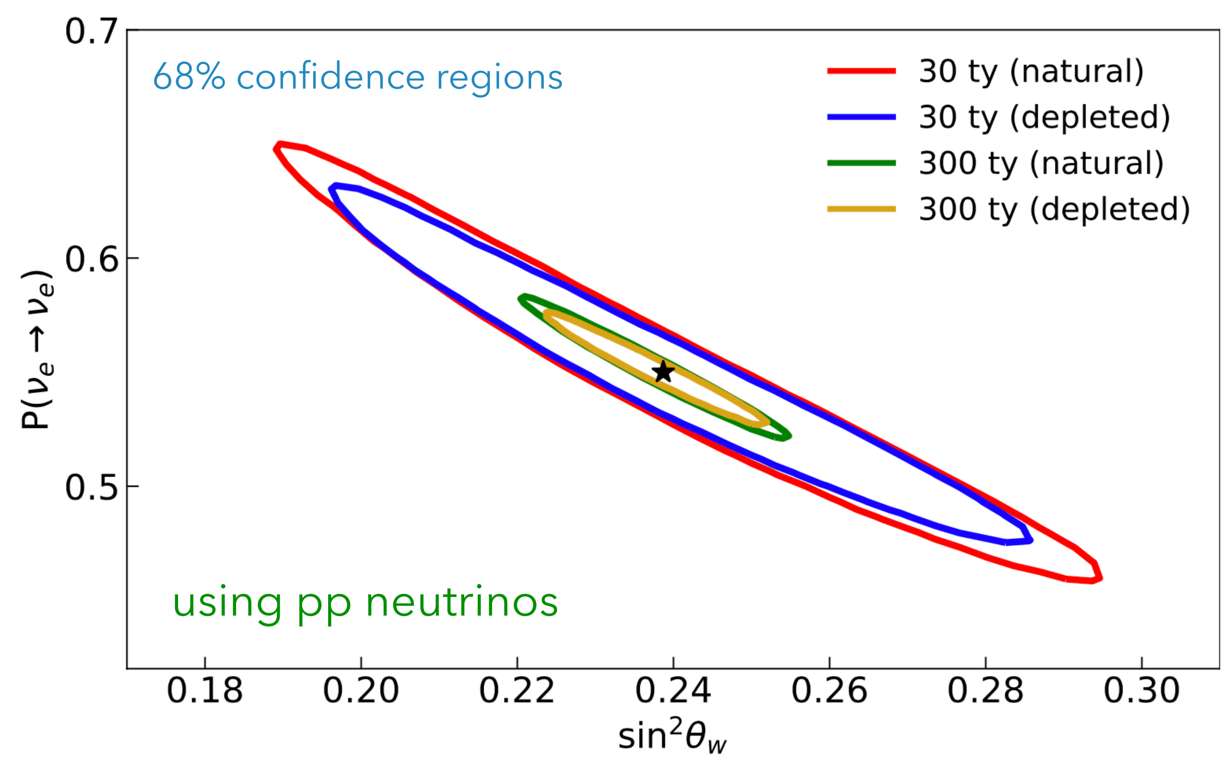
DARWIN Collaboration, J. Aalbers, F. Agostini, S. E. M. Ahmed Maouloud, M. Alfonsi, L. Althueser, F. D. Amaro, J. Angevaare, V. C. Antochi, B. Antunovic et al. (157 more)

Eur. Phys. J. C, 80 12 (2020) 1133
Published online: 10 December 2020, DOI: 10.1140/epjc/s10052-020-08602-7

Abstract | PDF (604.0 KB)

- Main rates: 365 events/(t y) from pp ν and 140 events/(t y) from ^{7}Be ν; ^{13}N: 6.5/(t y), ^{15}O: 7.1/(t y)
- pp-flux measurement: 0.15% statistical precision with 300 t y exposure (sub-percent after 10 t y)
- Measurement of ν_e survival probability & weak mixing angle < 300 keV
  - P_{ee}: 4% relative uncertainty, $\sin^2\theta_W$: 5% relative uncertainty





DOUBLE BETA DECAY IN DARWIN

- ^{136}Xe: excellent candidate
  - abundance in ^{nat}Xe: 8.9%, Q-value: (2457.83±0.37) keV*
- Amount of ^{136}Xe in DARWIN: ~3.6 tonnes (~ 4.5 t in total)
- Expected (1-σ) energy resolution:
  - ~0.8% at 2.5 MeV, demonstrated by XENON1T
- Ultra-low background environment
- Main potential backgrounds: ^{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

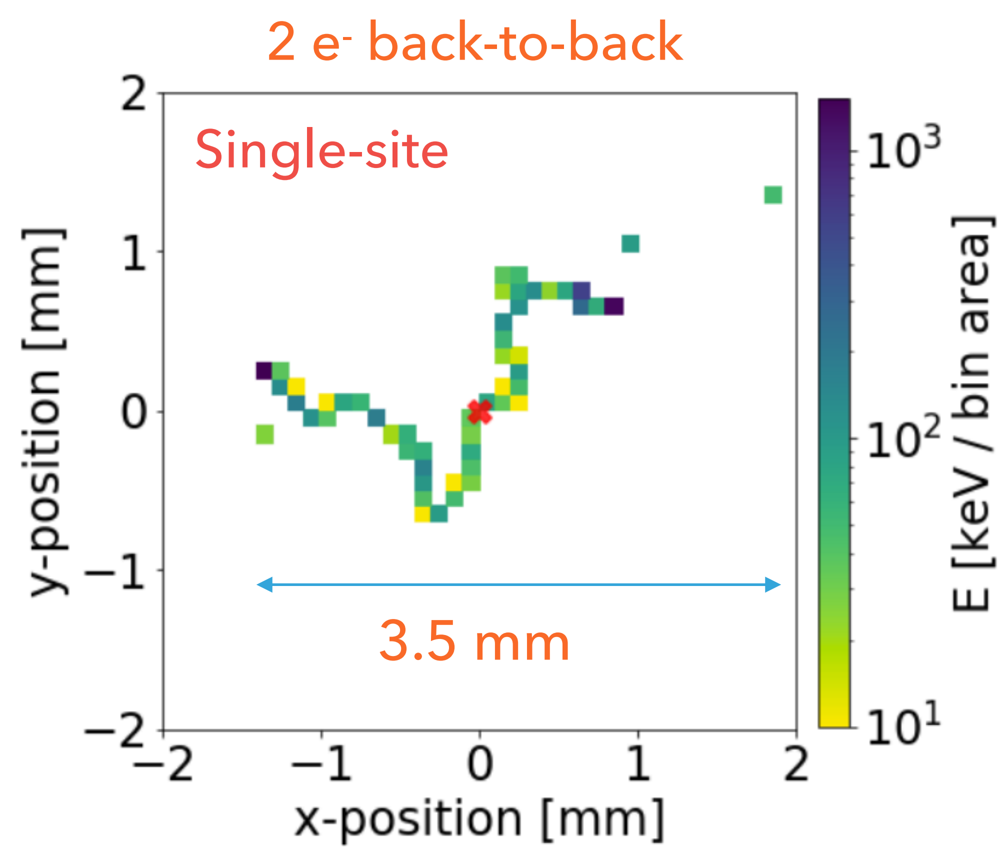
- Detailed detector model in Geant4

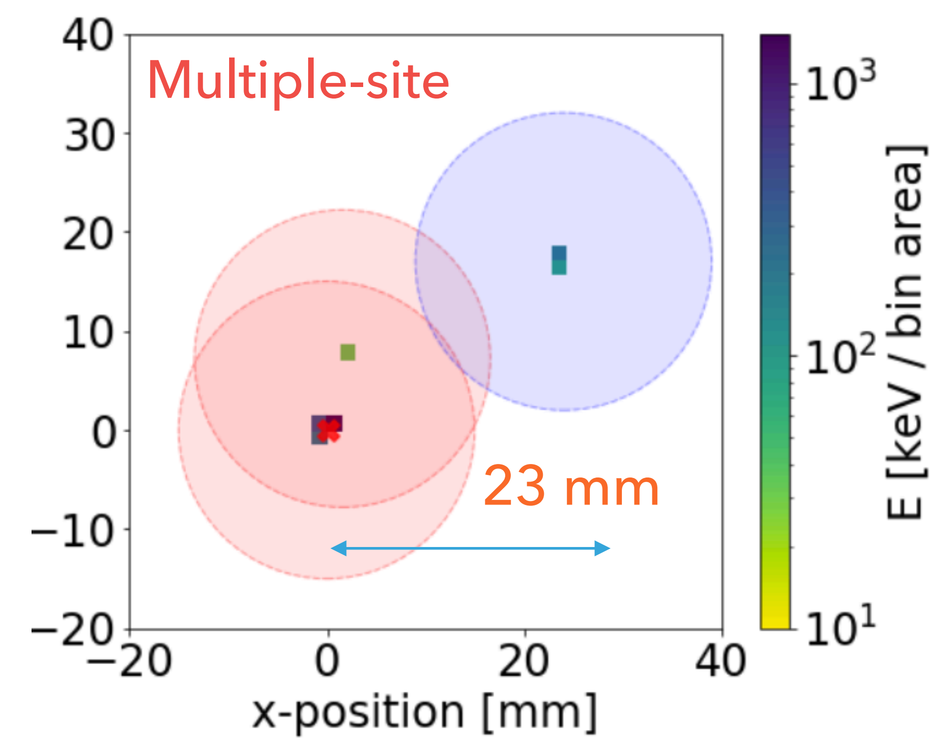
Component	Material	Mass	
Outer cryostat	Titanium	3.04 t	Cryostat
Inner cryostat	Titanium	2.10 t	
Bottom pressure vessel	Titanium	0.38 t	
LXe instrumented target	LXe	39.3 t	Xenon
LXe buffer outside the TPC	LXe	9.00 t	
LXe around pressure vessel	LXe	0.27 t	
GXe in top dome + TPC top	GXe	30 kg	
TPC reflector (3mm thickness)	PTFE	146 kg	TPC components
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):			Photosensors and electronics
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	

SIGNAL EVENTS IN LIQUID XENON

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

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





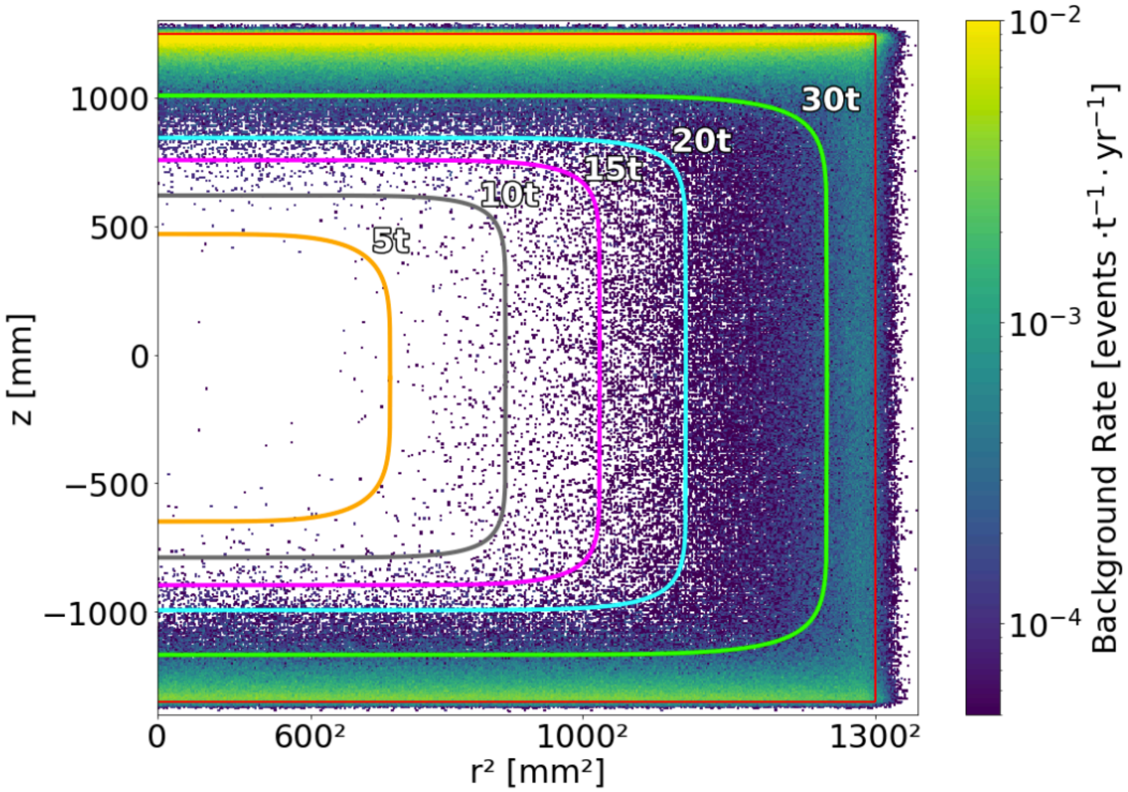
MAIN BACKGROUND COMPONENTS

- 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

External background events with energy deposits in the ROI [$Q_{\beta\beta}$± FWHM/2] = [2435 - 2481] keV



Already achieved specific activities (or upper limits) of detector materials:

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)

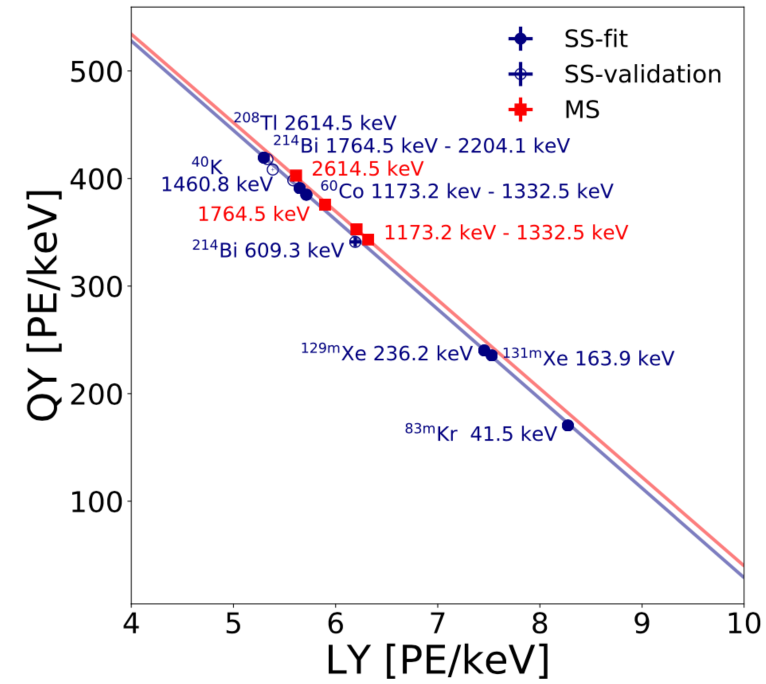
Other: XENON, EPJ-C 77 (2017)

ENERGY RESOLUTION

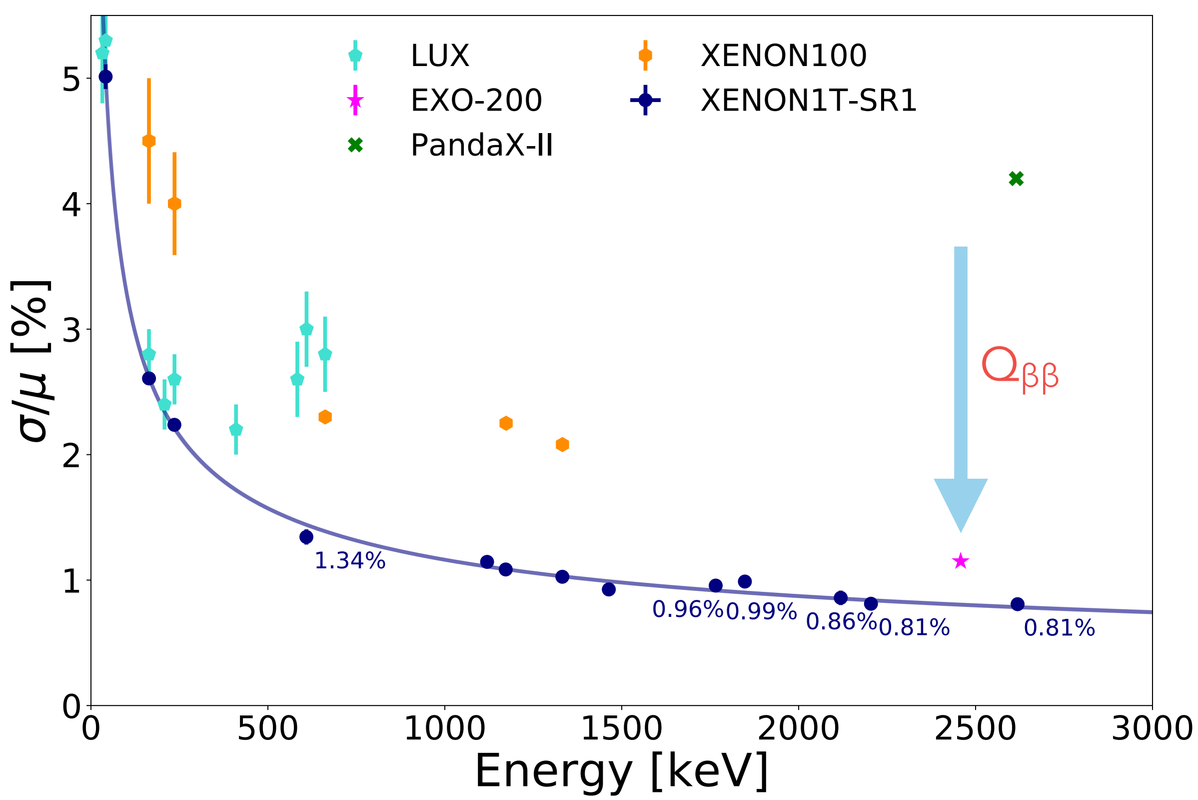
- Anti-correlation between light (S1) and charge (S2)
- Energy scale uses linear combination of S1 and S2
- Photon gain: g_1 (pe/photon), electron gain: g_2 (pe/electron)

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

W-value = 13.7 eV



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



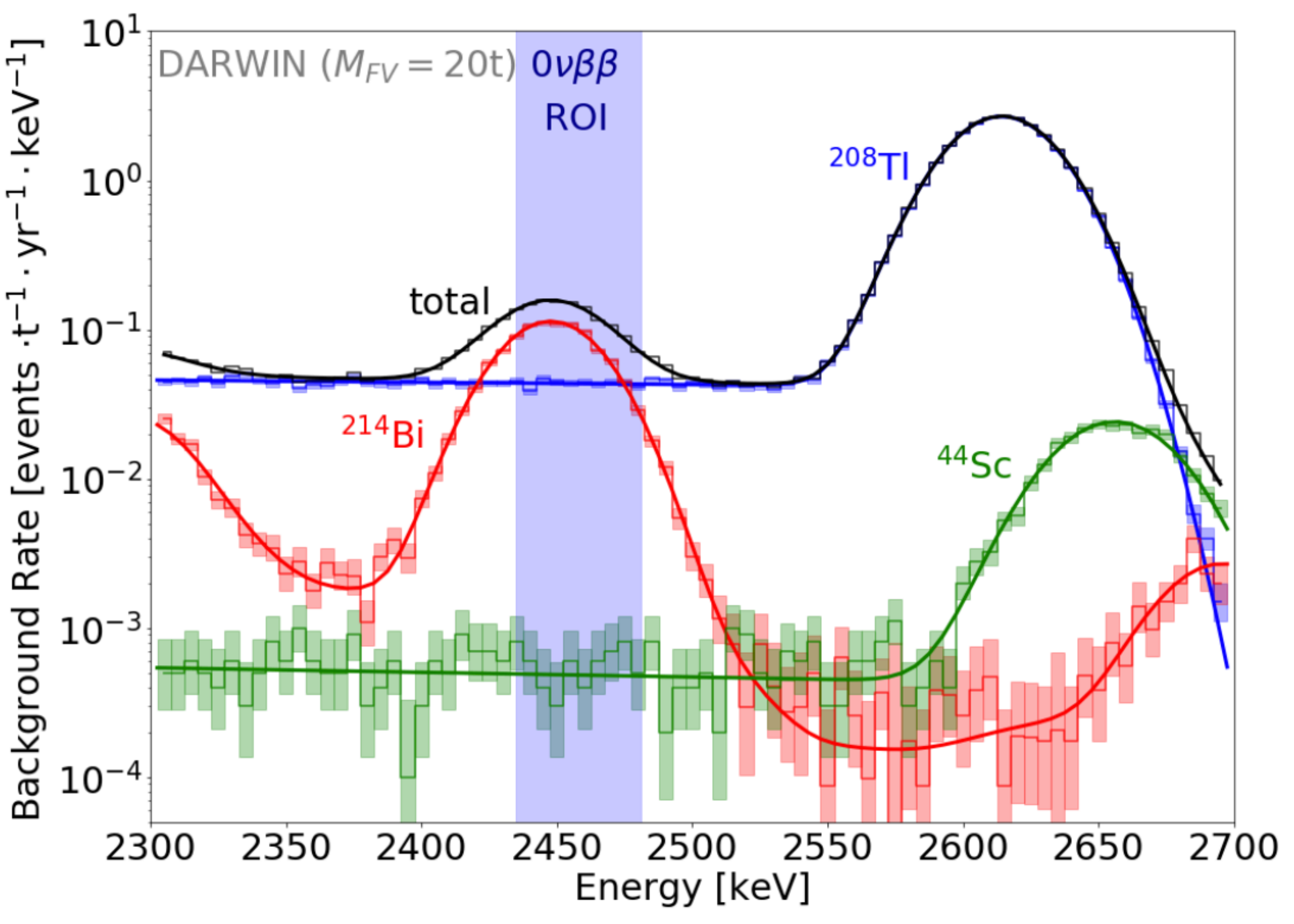
Example for XENON1T:

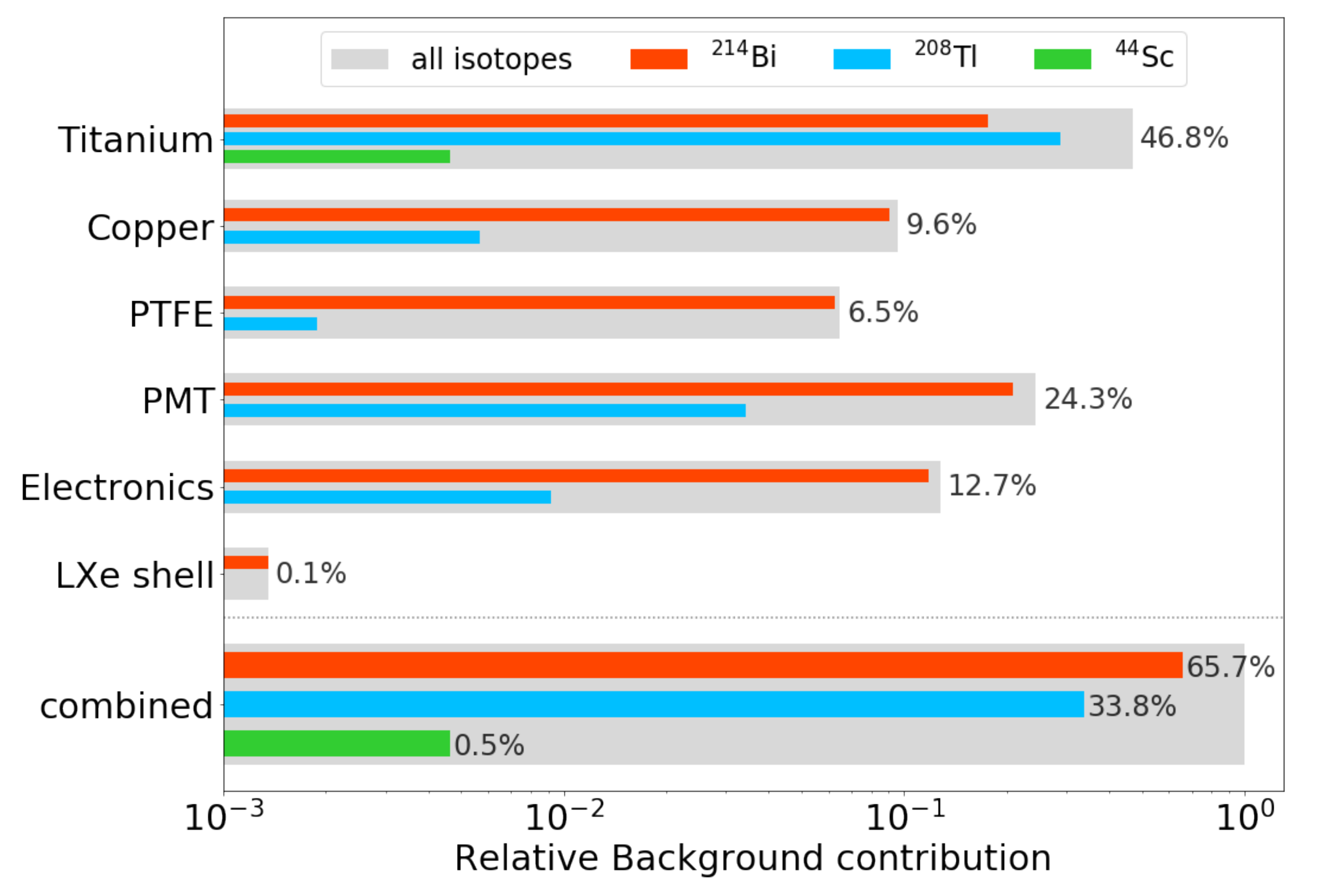
σ/E ≈ 0.8% at $Q_{\beta\beta}$

XENON collaboration,
Eur. Phys. J. C 80 (2020) 9

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



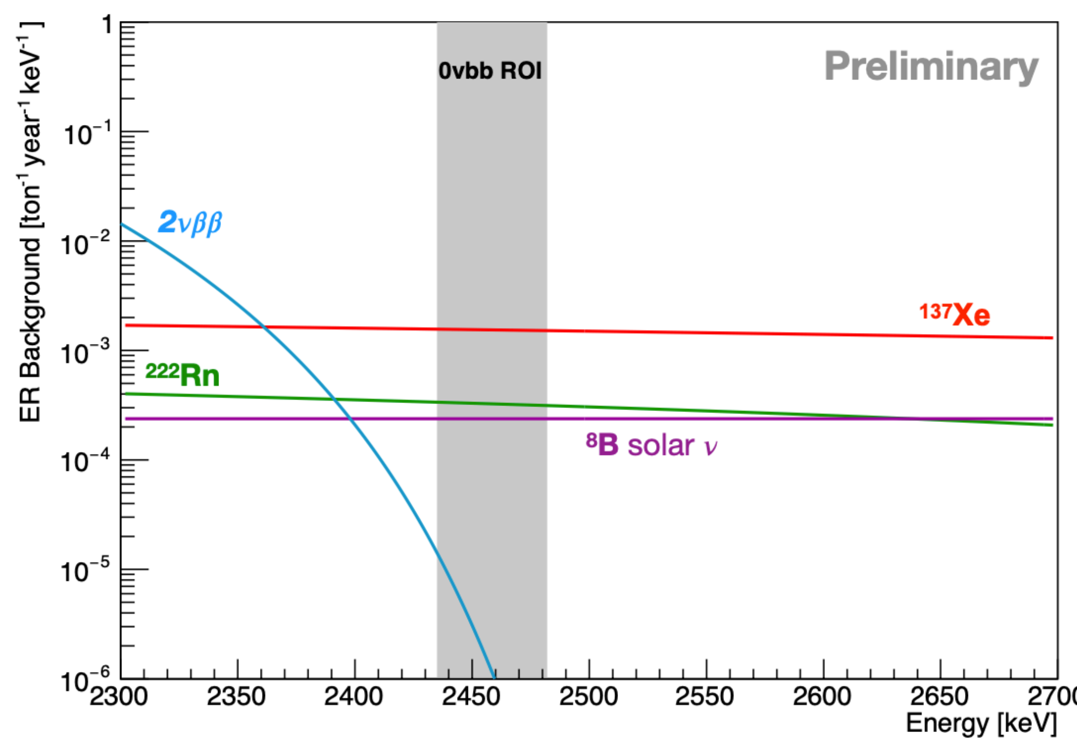


Example for 20 tonnes of LXe in fiducial volume (not the final FV for the study)

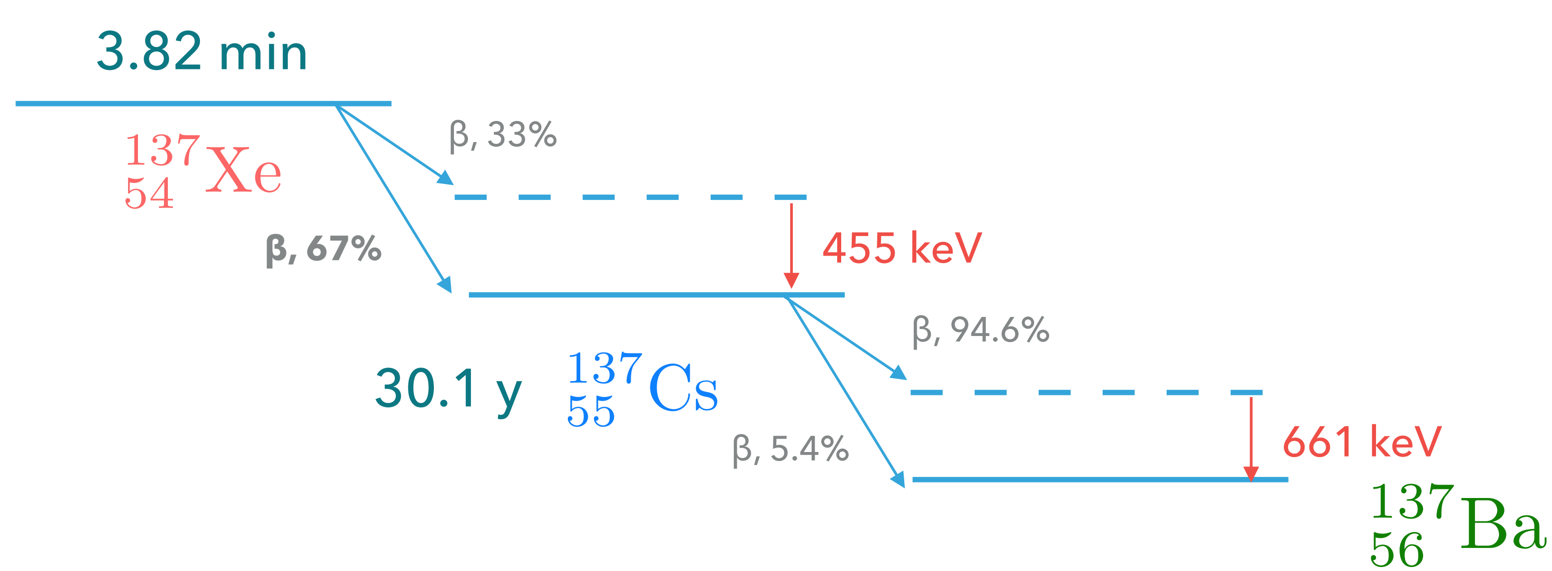
INTERNAL BACKGROUNDS

- ^{222}Rn in LXe:
  - 0.1μBq/kg, 99.8% BiPo tagging
- ^{8}B solar neutrinos
  - $\Phi_{ve} = (5.46 \pm 0.66) \times 10^6\ cm^{-2}s^{-1}$
  - $P_{ee} = 0.50$
- 2vββ-decay: subdominant
- ^{137}Xe: cosmogenic activation underground
  - $n + {}^{136}Xe \rightarrow {}^{137}Xe$

^{137}Xe: (6.9±0.4) atoms/(t y)



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



RADON BACKGROUND

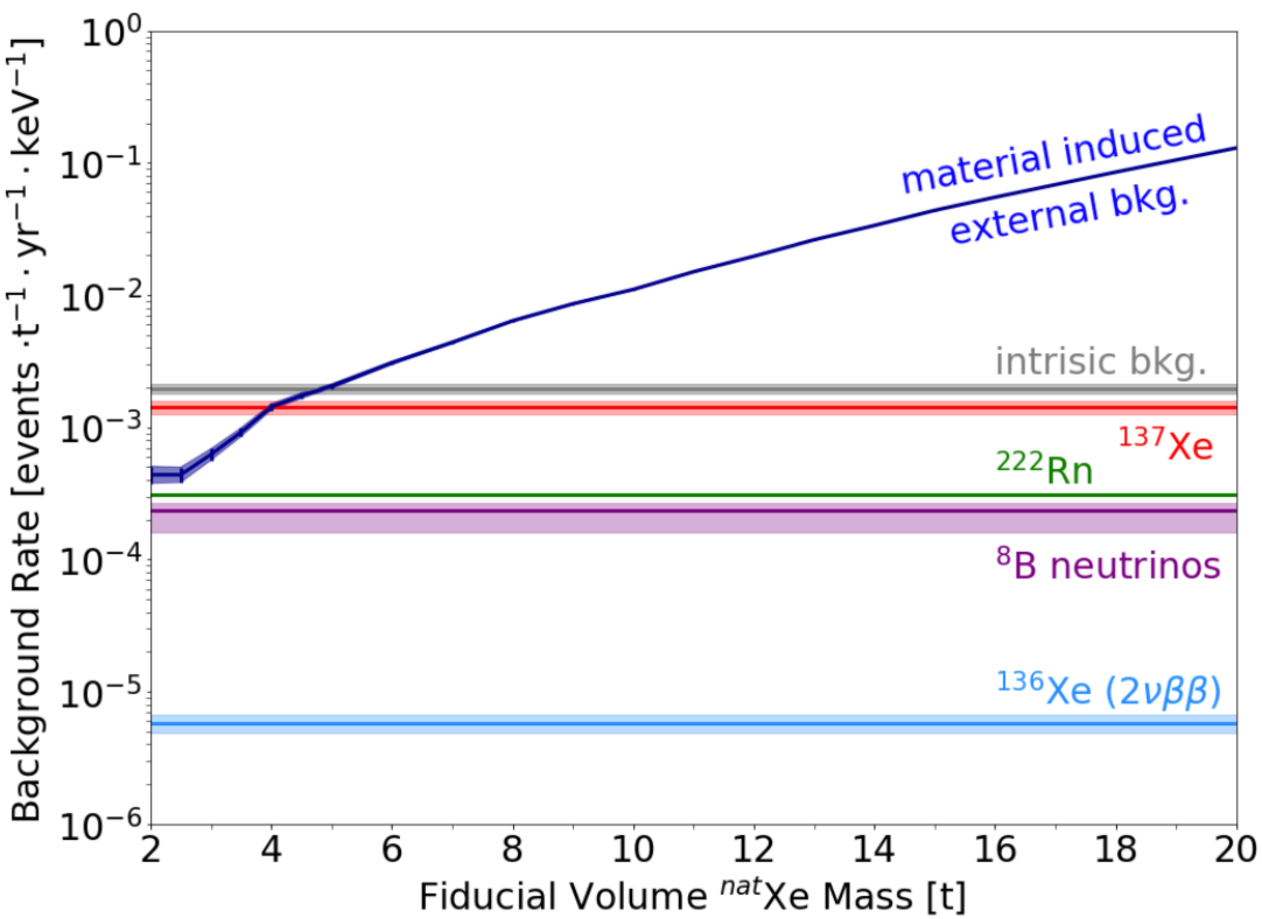
- Assumption:
  - 0.1 μBq/kg ^{222}Rn (cryogenic distillation + material selection)
- Problematic:
  - ^{214}Bi decay, Q-value = 3.27 MeV, "naked" β-decay without γ emission: 19.1% BR
- ^{214}Po:
  - α-decay with short half-life, $T_{1/2}$ =164.3 μs => active veto for ^{214}Bi-decays
- Assumption:
  - 99.8% BiPo 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		

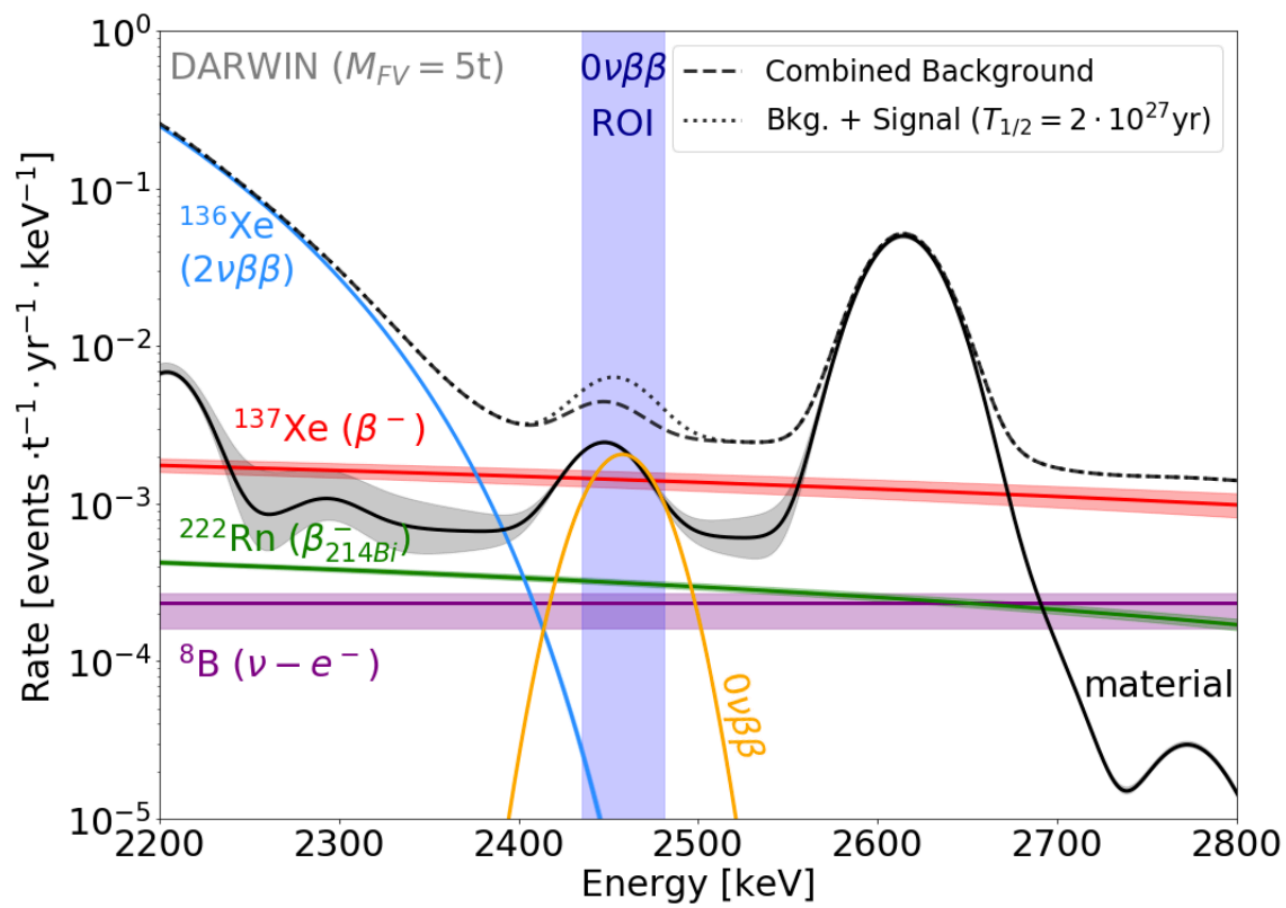
MATERIAL + INTRINSIC BACKGROUND

- 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)

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



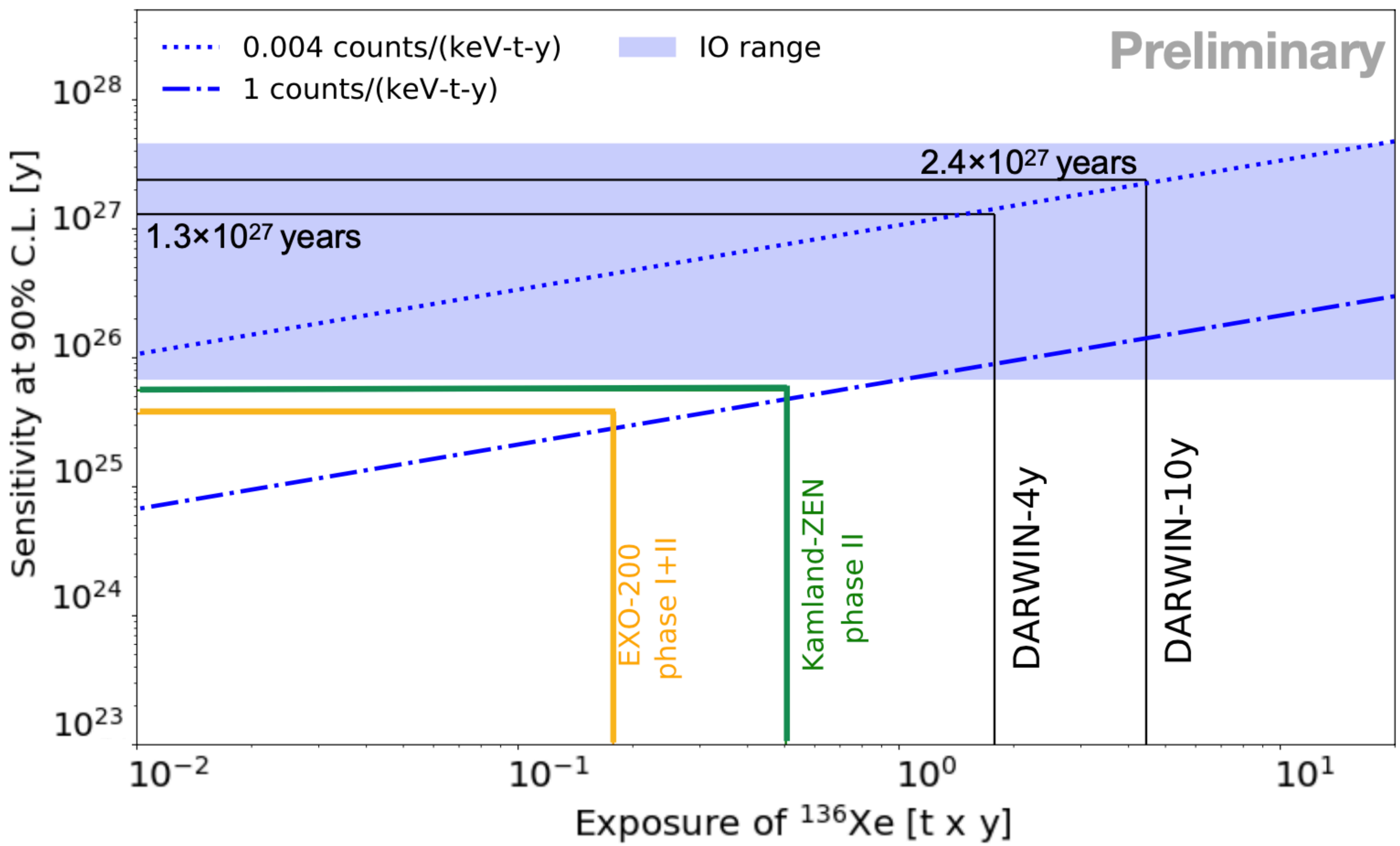
Rate versus fiducial mass



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

DOUBLE BETA DECAY SENSITIVITY

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

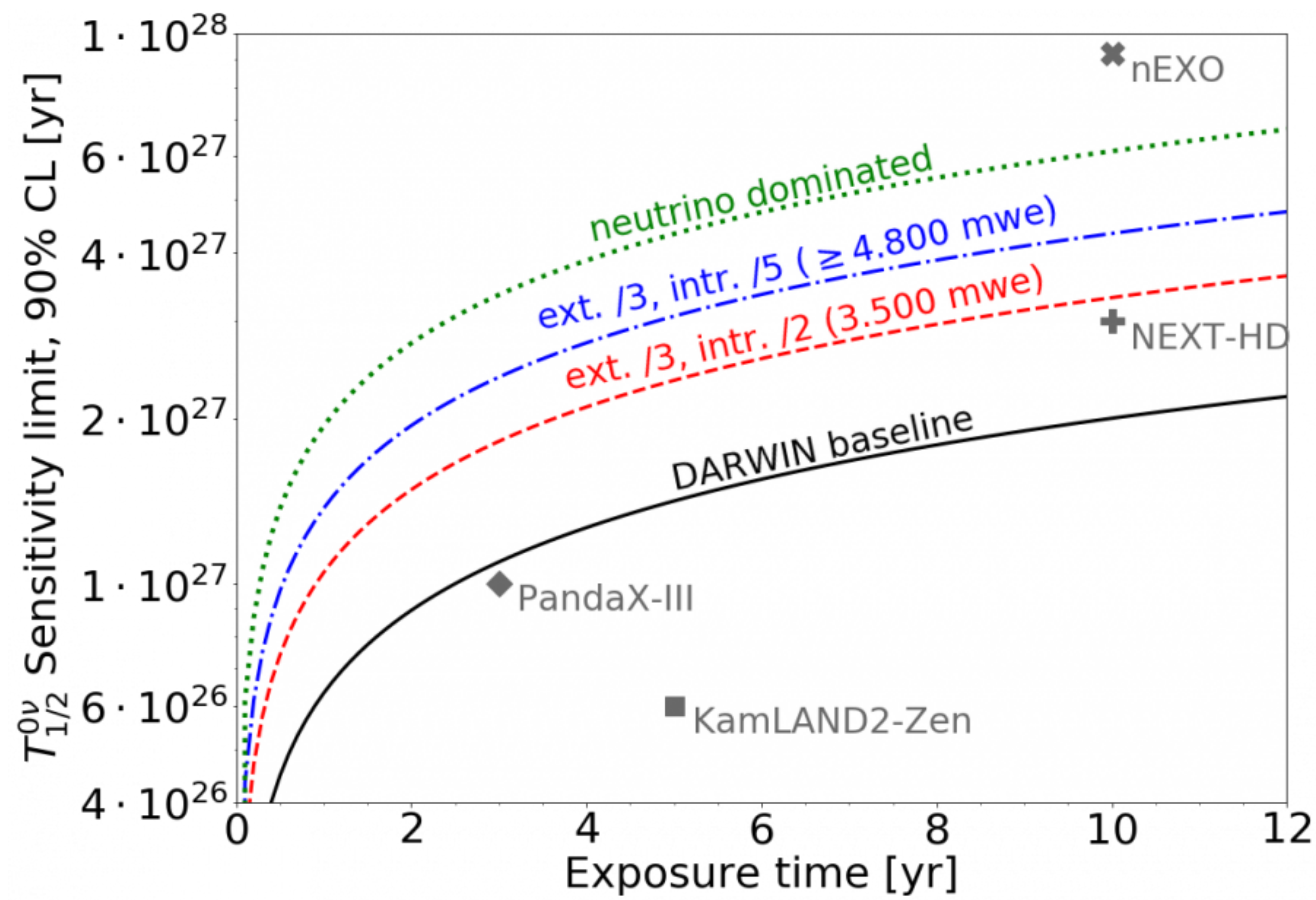


Discovery potential:

1.1 x 10^{27} y at 3-σ

ROOM FOR IMPROVEMENT?

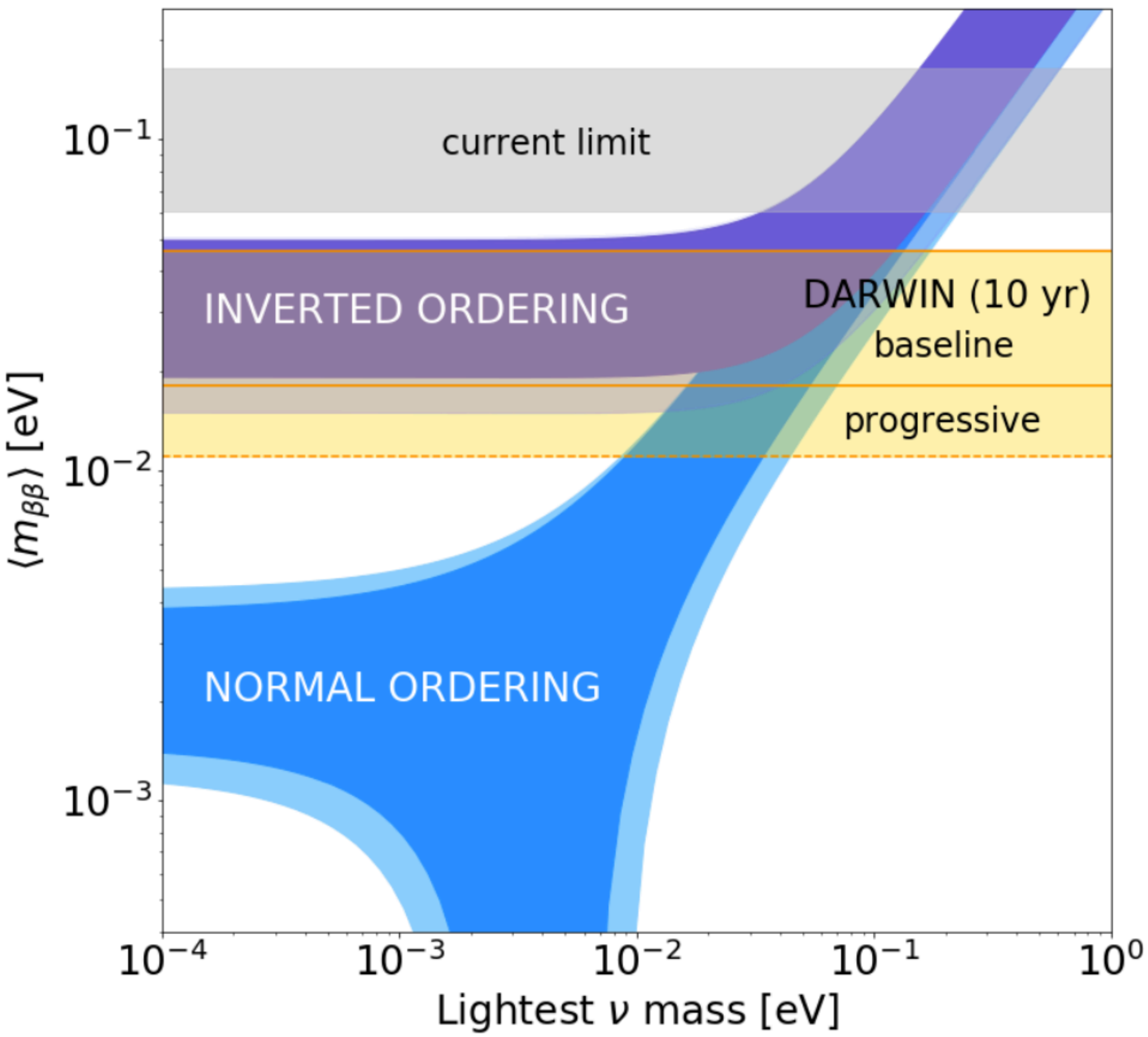
- Reduce external backgrounds
  - SiPMs, cleaner materials & electronics
- Reduce internal background
  - Time veto for ^{137}Xe, deeper lab, BiPo tagging
- Improve signal/background discrimination; resolution…



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

DOUBLE BETA DECAY: COMPARISON WITH OTHER PROJECTS

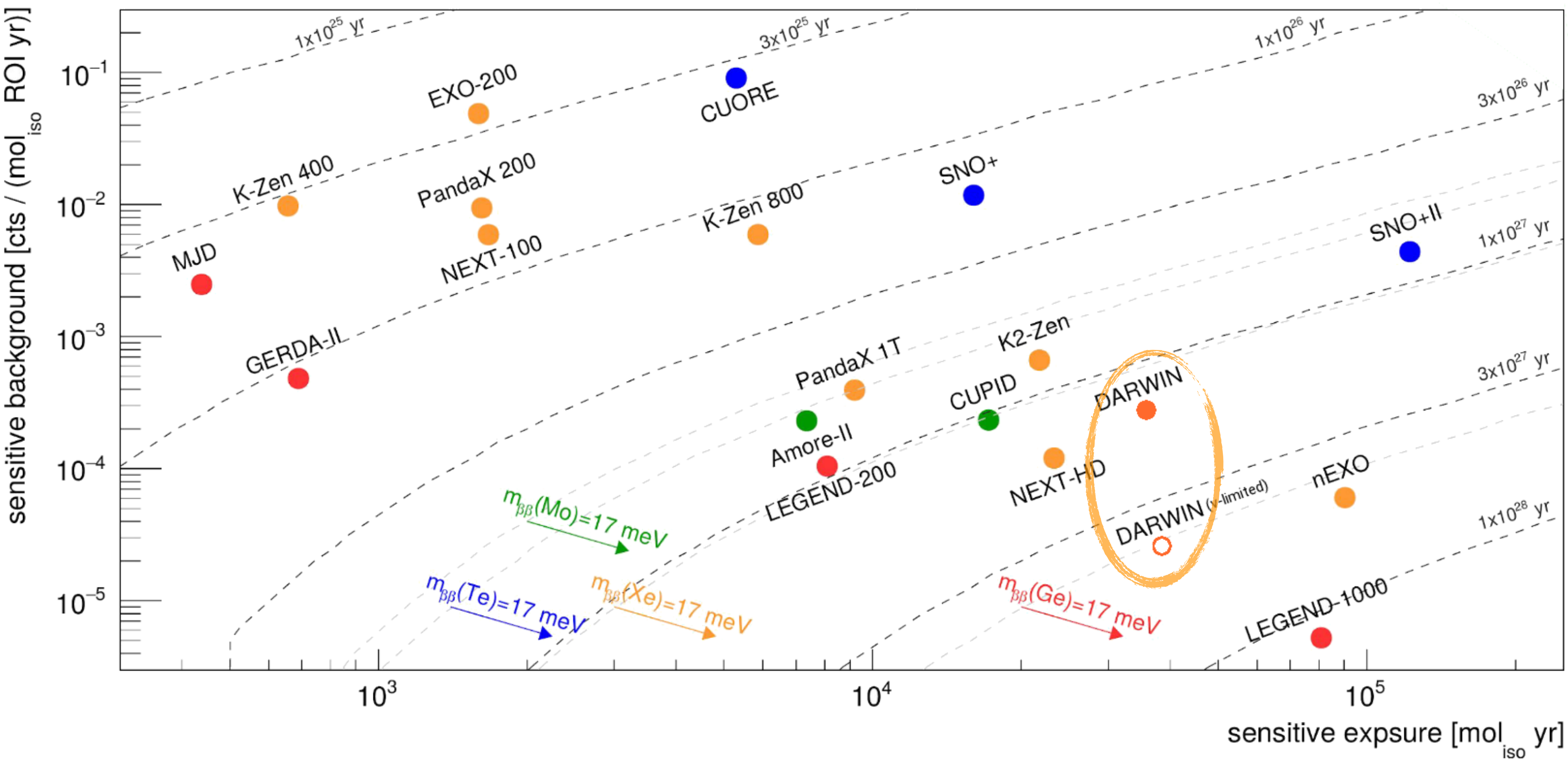


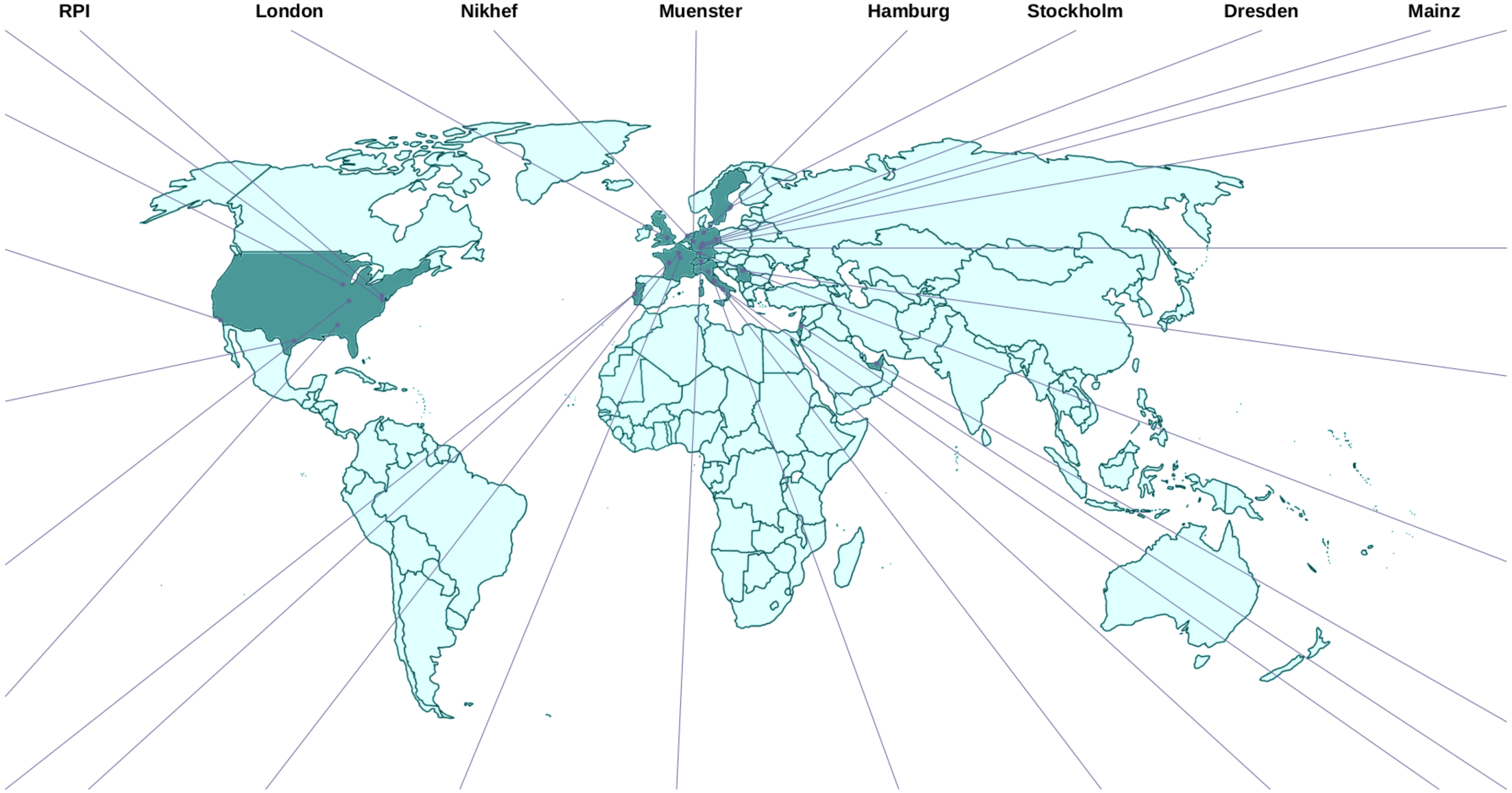
Figure adapted after M. Agostini

PROJECT OVERVIEW

- 33 groups from 12 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

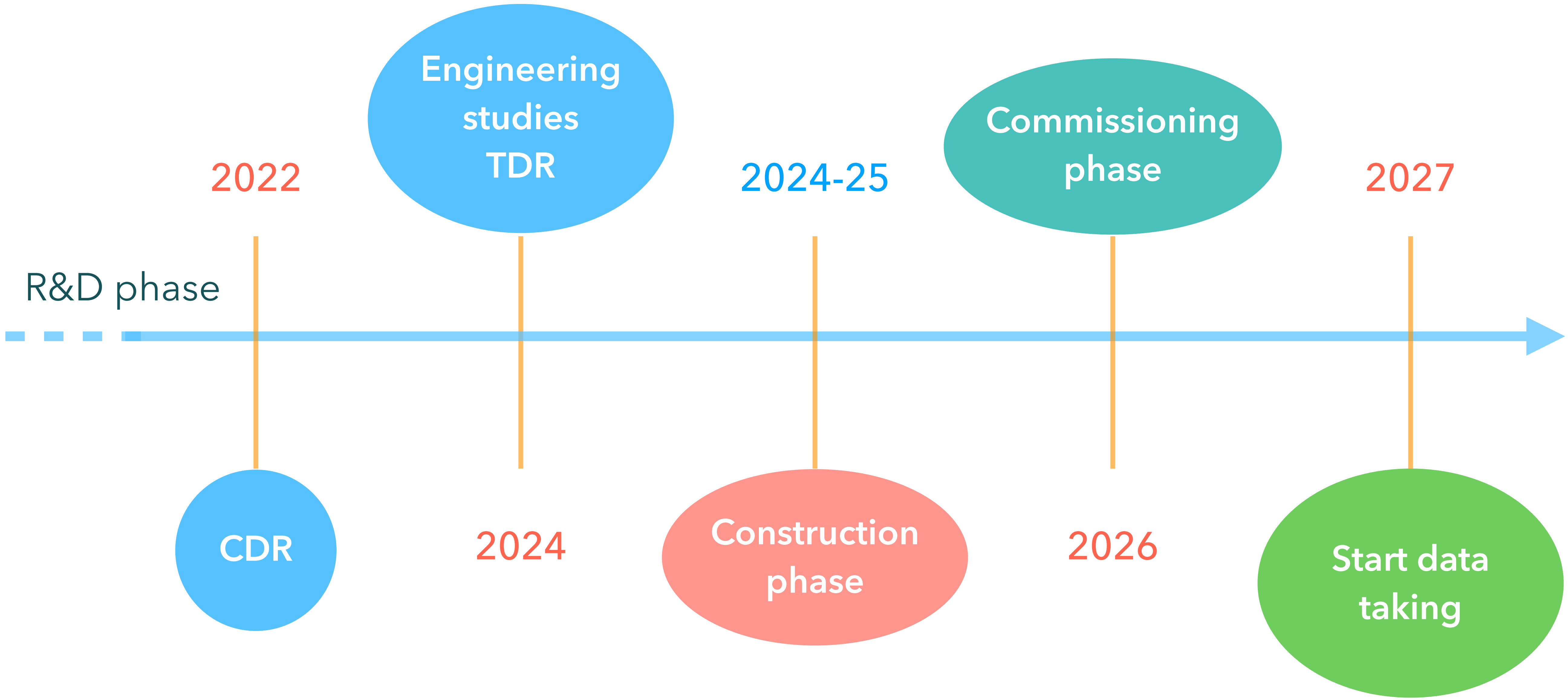
THE DARWIN COLLABORATION

- About 170 members from 33 institutions in Europe, USA and Asia



Columbia
RPI
London
Nikhef
Muenster
Hamburg
Stockholm
Dresden
Mainz
MPIK, Heidelberg
Chicago
UCSD
Rice
Purdue
Alabama
Heidelberg
KIT
Belgrade
Freiburg
NYUAD
Coimbra
Subatech
LPNHE
IJCLab
Zurich
LNGS
L'Aquila
Bologna
Napoli
Weizmann

DARWIN TIMESCALE



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

DETECTOR PROTOTYPES

- Two large-scale demonstrators & test platforms for the entire collaboration
- Smaller R&D projects at various institutions

Test e- drift over 2.6 m (purification, high-voltage)

Test electrodes and homogeneity of extraction field

DETECTOR PROTOTYPES

- Test platform in Freiburg: 2.7 m inner diameter, up to 15 cm in height (5 cm LXe), 400 kg Xe gas
- Test horizontal components, real-scale electrodes, etc

DFG
Deutsche Forschungsgemeinschaft
UNI FREIBURG
erc
European Research Council
Established by the European Commission

DETECTOR PROTOTYPES

- Test platform in Zurich
- 16 cm inner diameter
- up to 2.6 m LXe height
- 400 kg Xe gas
- Test vertical components
- e^- drift
- HV feedthroughs, etc

Universität Zürich[UZH]

European Research Council
Established by the European Commission

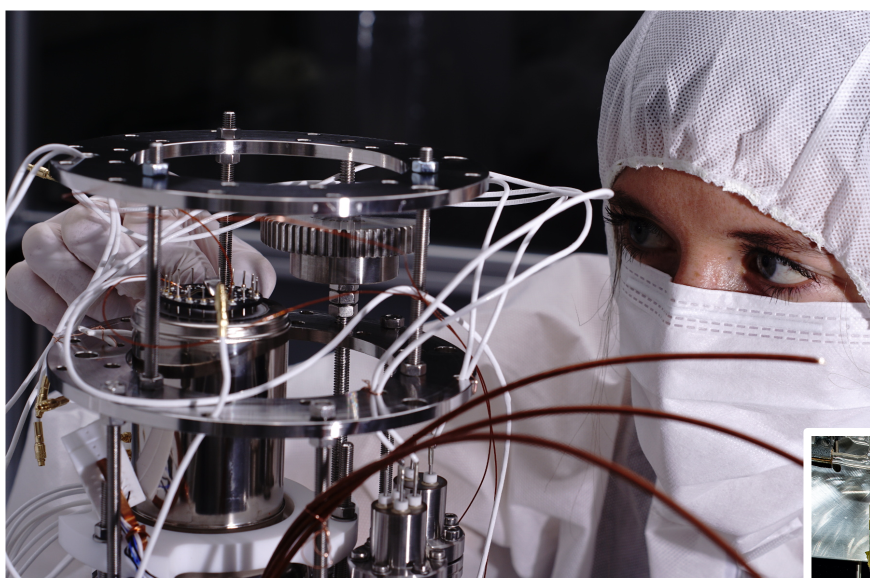
DETECTOR PROTOTYPES: XENOSCOPE

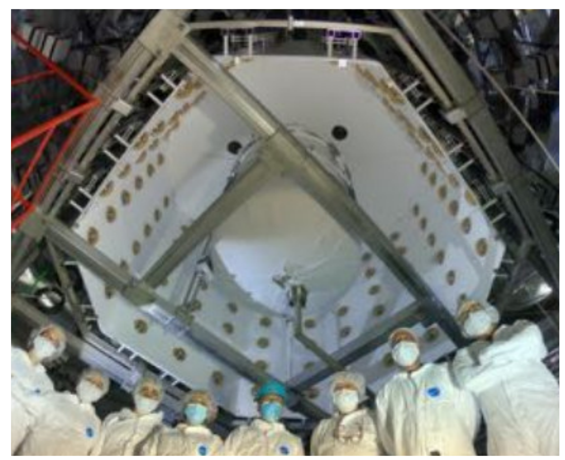
European Research Council
Established by the European Commission

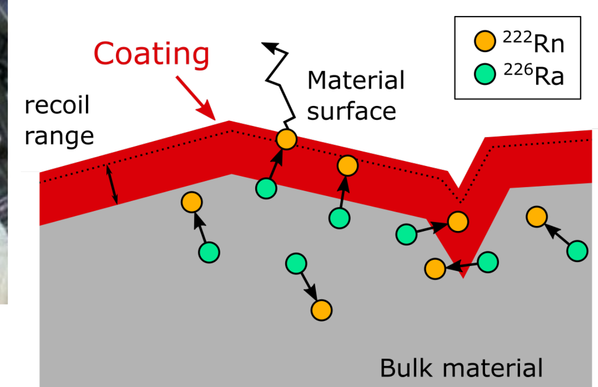
- Under construction at UZH, first commissioning in early 2021
- Support structure, gas system, cryostat, cooling tower, electrical system, etc completed
- HV feed-through, TPC and purity monitor under design/construction
- Goals: test 200 V/cm drift field, 100 slpm purification speed, measure e^- cloud diffusion, etc

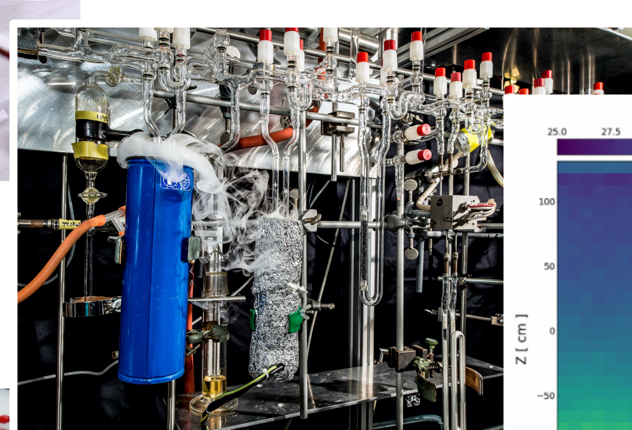
DARWIN R&D EXAMPLES

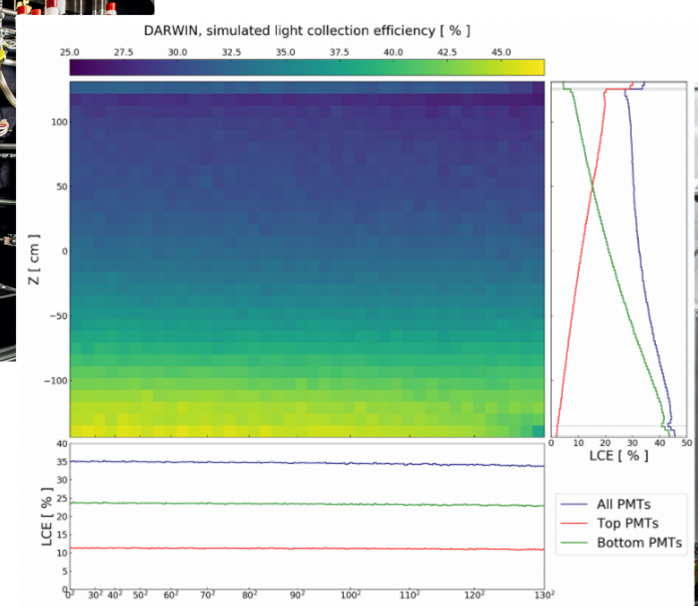
- New detector concepts, analytics and screening, radon reduction, new photosensors, etc

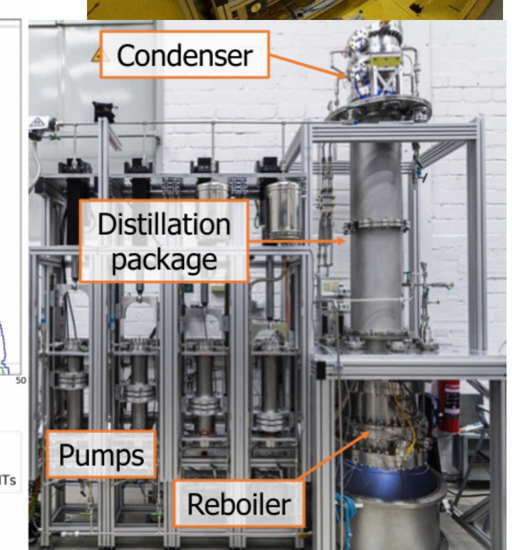


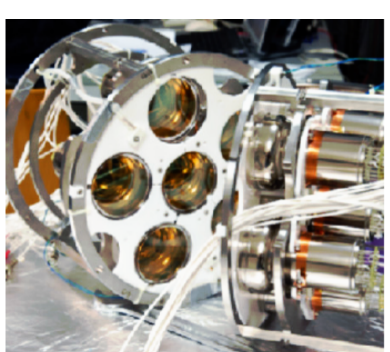


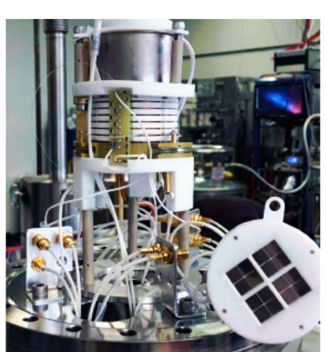












SUMMARY

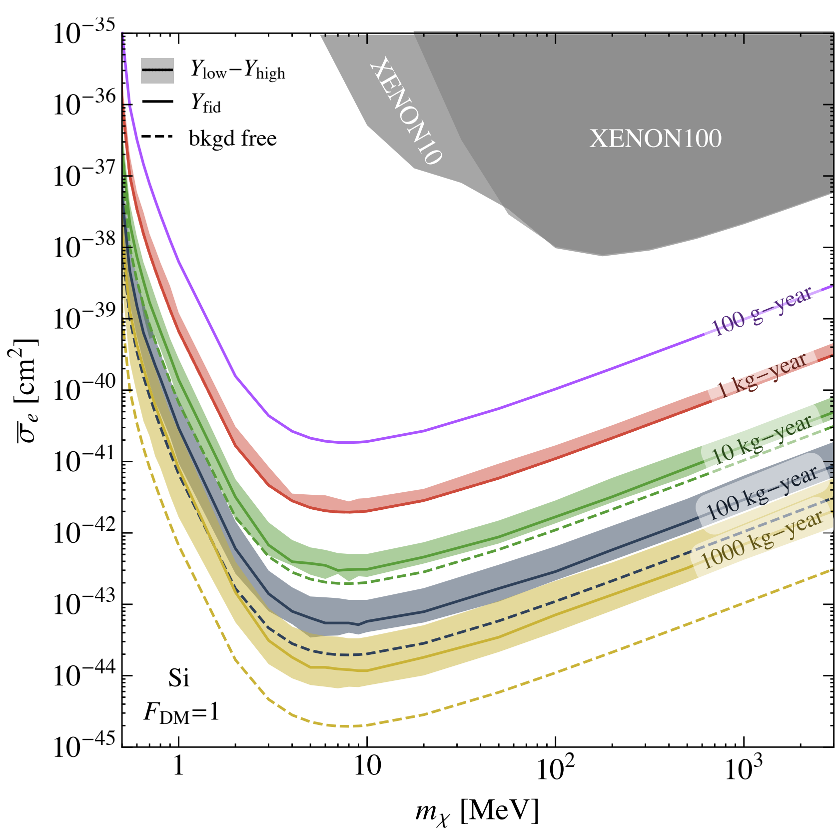
- DARWIN observatory: excellent sensitivity in particle/astroparticle physics
- Due to very low expected event rates, we need:
    - a large detector mass and ultra-low backgrounds (material radio-assay & Rn reduction remain crucial)
    - a very good energy resolution and a low energy threshold
- In general: DM detectors are optimised at keV energy scales, $0\nu\beta\beta$ detectors at MeV-scale energies, solar ν detectors are much larger, monolithic and have ultra-low backgrounds
    - Ideally, DARWIN will have sensitivity to search for a variety of signals in particles physics: neutrinos, $0\nu\beta\beta$, solar axions, dark matter ALPs & dark photons, WIMPs, etc
- Eventually limited by neutrino interactions (but also new physics opportunities!)
- Remember that yesterday's background might be today's signal ;-)

BACKUP SLIDES

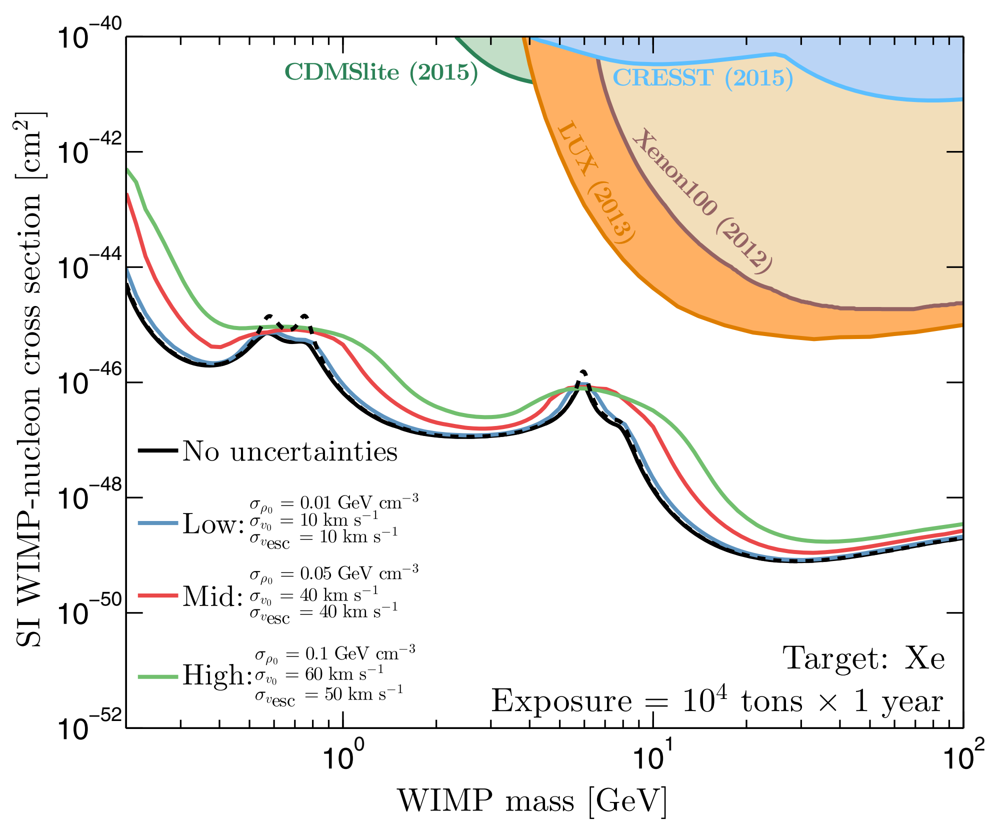
NEUTRINO BACKGROUNDS FOR DM SEARCHES

- Low mass region: limit at ~ 0.1- 10 kg year (target dependent)
- High mass region: limit at ~ 10 ktonne year
- But: annual modulation, directionality, momentum dependance, inelastic DM-nucleus scatters, etc

Discovery limits (2-σ) for various ionisation efficiencies Y, solar ν background only



DM-electron scatters (R. Essig et al, PRD97, 2018)

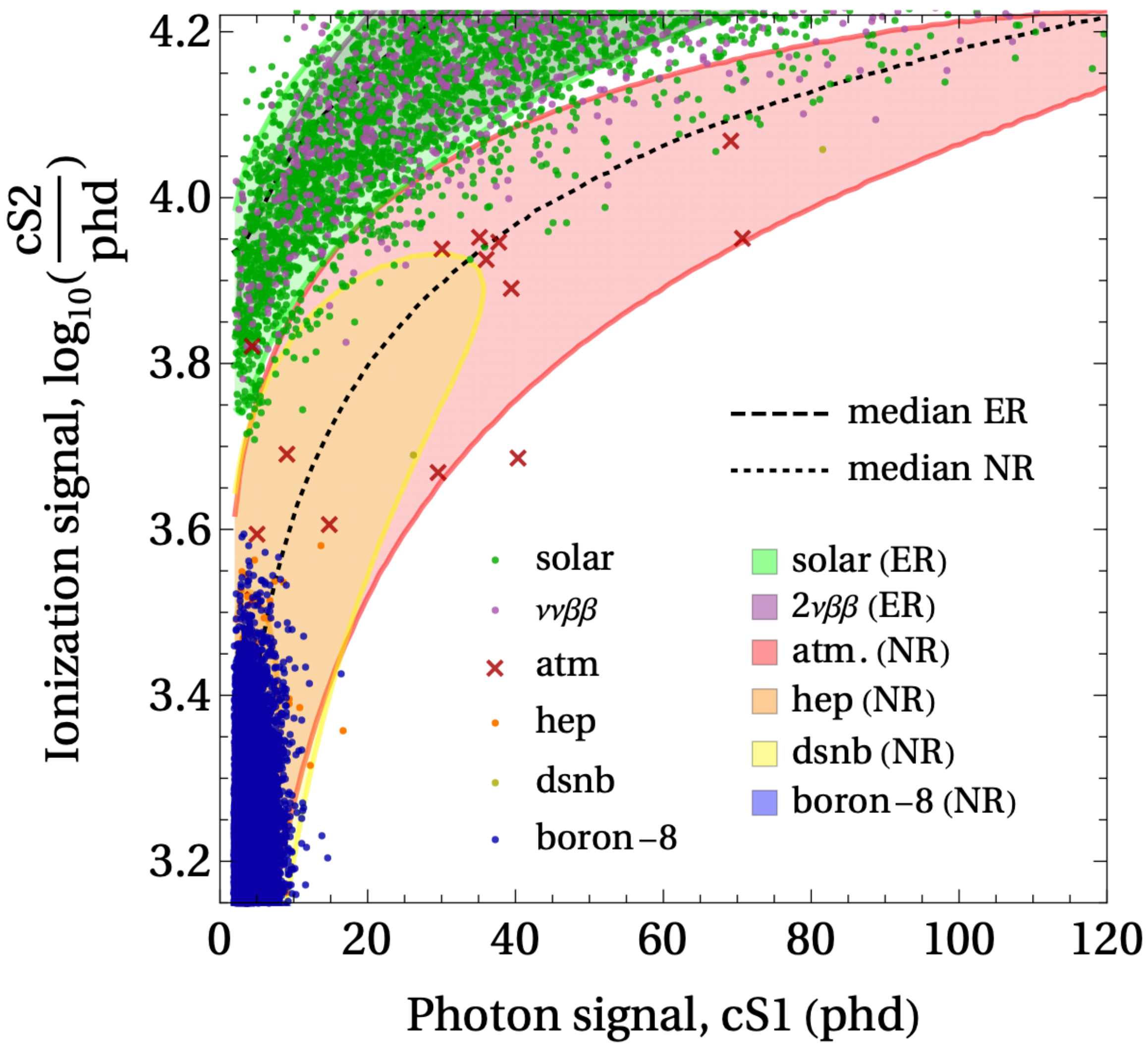


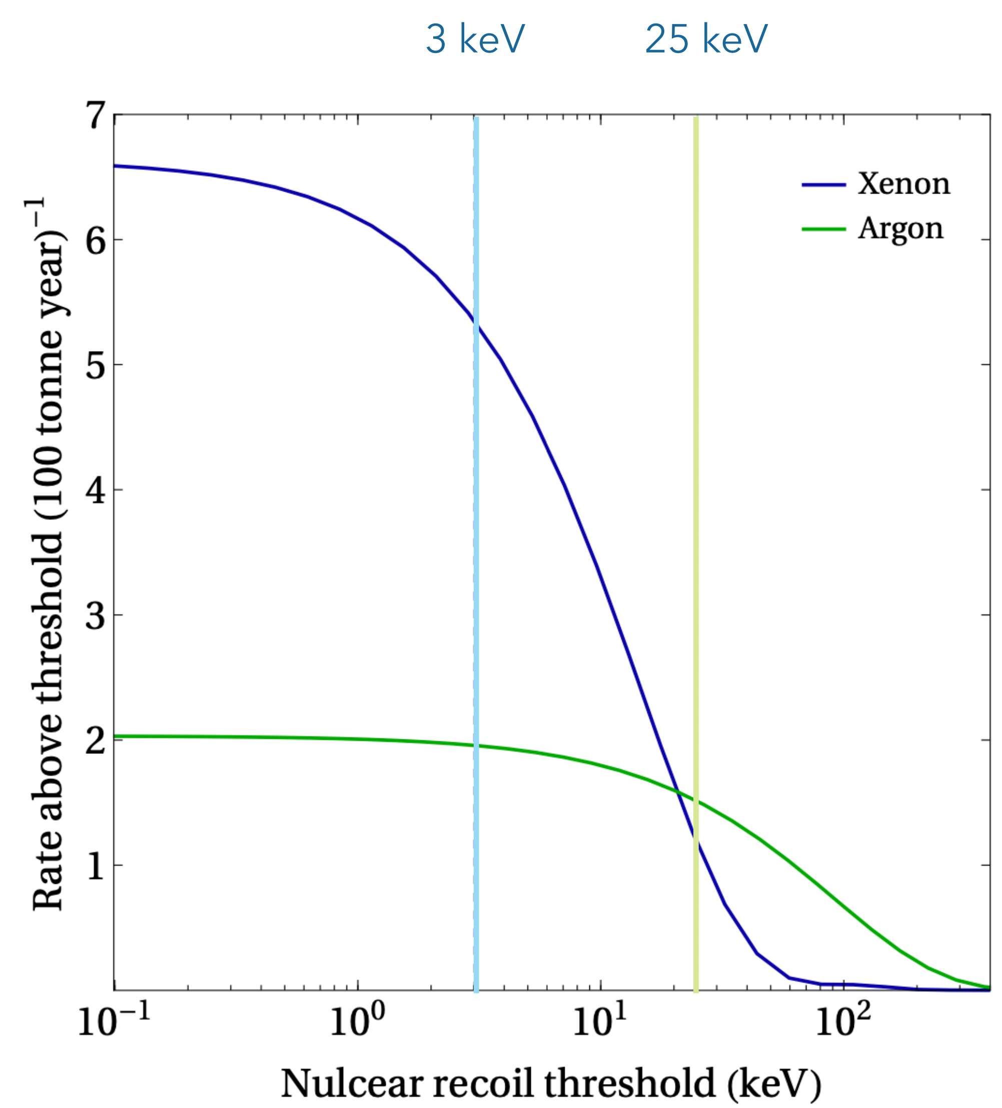
DM-nucleus scatters (C.A.J. O'Hare, PRD94, 2016)

NEUTRINOS IN A DARWIN-LIKE DETECTOR

- Study of sensitivity to atmospheric neutrinos (using NEST to model the signals)
- Below: exposure of 200 t y; need 700 t y to obtain a 5-σ detection of atmospheric neutrinos

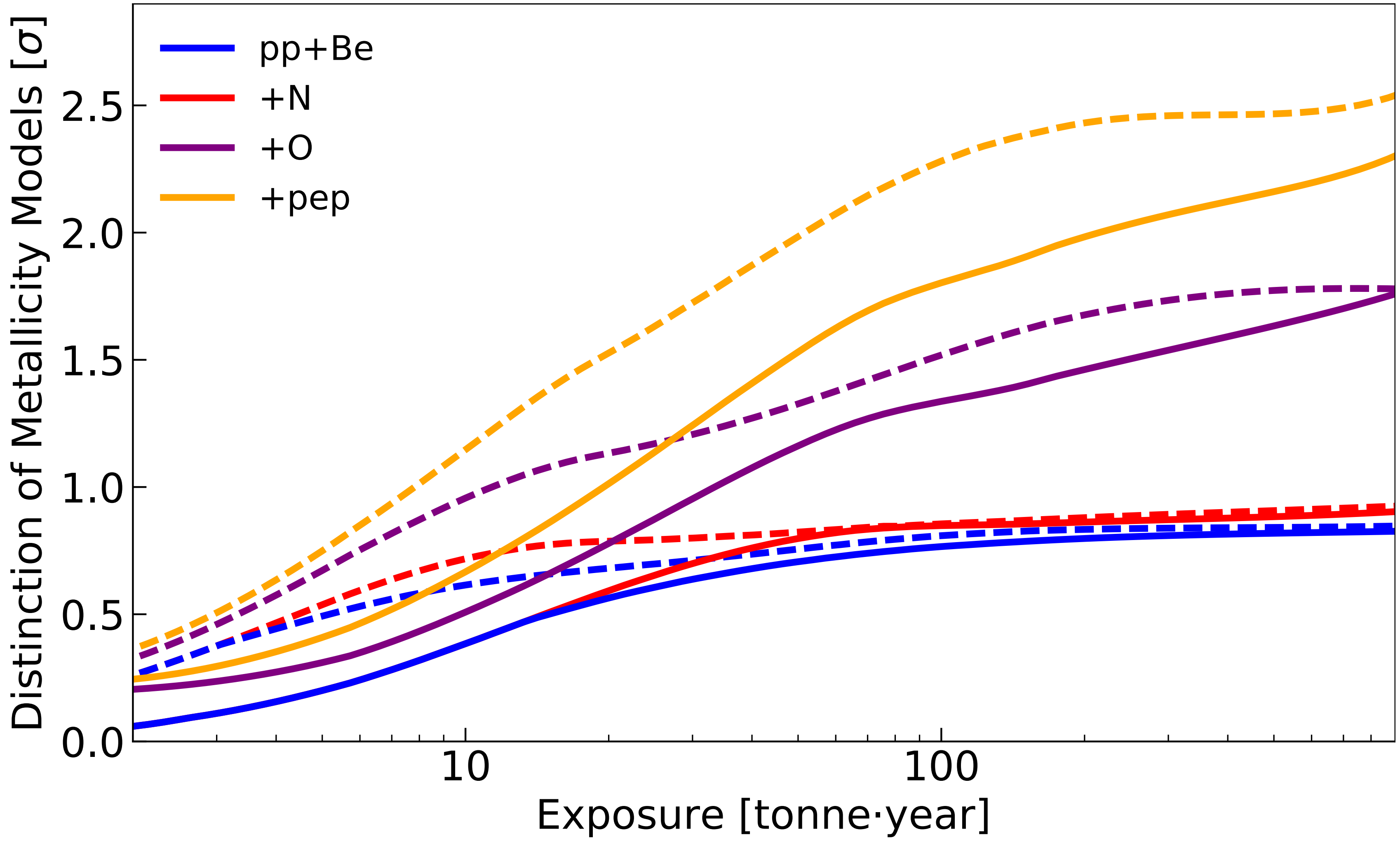
Newstead, Lang, Strigari, arXiv: 2002.08566





SOLAR NEUTRINOS

- Use a combination of neutrino flux measurements to probe the solar metallicity



Significance:
2.0-2.5 σ at 300 t y

Dashed: depleted Xe

Solid: natural Xe

SOLAR NEUTRINOS

- Neutrino capture on ^{131}Xe

$$\nu_e + {}^{131}\mathrm{Xe} \rightarrow {}^{131}\mathrm{Cs}^+ + \underline{\mathrm{e}^-} \rightarrow {}^{131}\mathrm{Xe} + \nu_e + \underline{\gamma + \mathrm{e}^-}$$

Prompt Signature **Delayed Signature**

A	% > Q	R [SNU]	R_{PS} [ty^{-1}]	R_{DS} [ty^{-1}]
pp	17.2	9.7	0.16	0.16
Be	100	17.8	0.30	0.30
N	90.8	1.6	0.03	0.03
O	96.2	1.8	0.03	0.03
pep	100	1.6	0.03	0.03
B	99.98	12.7	0.01*	0.12
			0.56	**0.67**

Georgadze et al.
https://www.sciencedirect.com/science/article/pii/S0927650597000170

* only 11.4% in [0,3] MeV

21.2% abundance

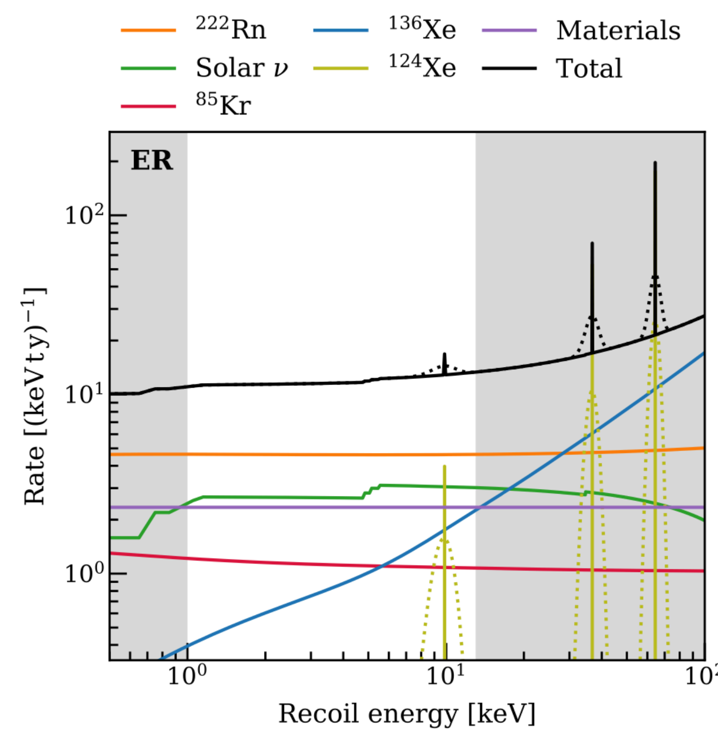
$$Q = 355 \text{ keV}$$

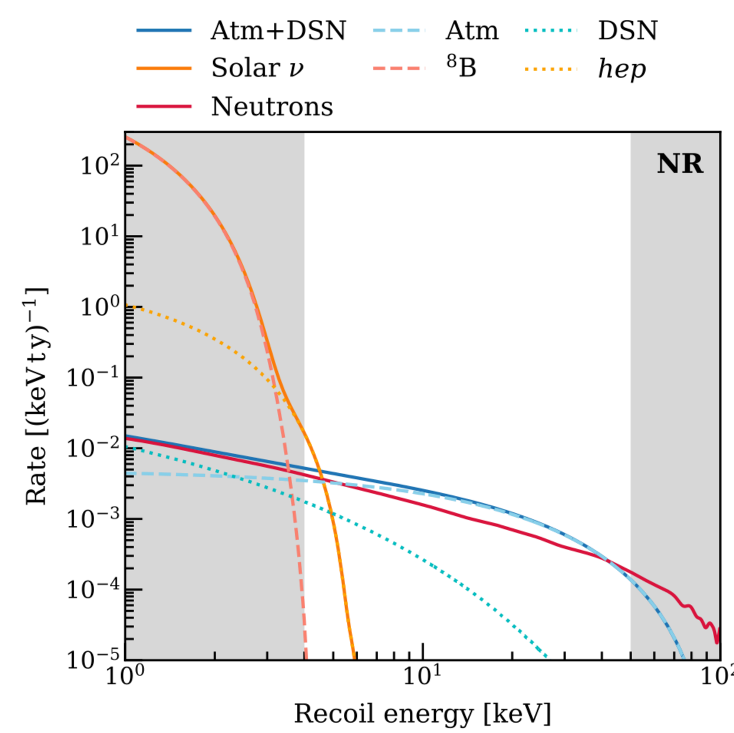
$$E_\nu = 325.5 \text{ keV}$$

$$E_{NC} = 29.5 \text{ keV}$$

XENON-NT: BACKGROUND PREDICTIONS

Source	Rate $[(\mathrm{t\,y})^{-1}]$
ER background	
Detector radioactivity	25 ± 3
^{222}Rn	55 ± 6
^{85}Kr	13 ± 1
^{136}Xe	16 ± 2
^{124}Xe	4 ± 1
Solar neutrinos	34 ± 1
Total	148 ± 7
NR background	
Neutrons	$(4.1 \pm 2.1) \times 10^{-2}$
CEνNS (Solar ν)	$(6.3 \pm 0.3) \times 10^{-3}$
CEνNS (Atm+DSN)	$(5.4 \pm 1.1) \times 10^{-2}$
Total	$(1.0 \pm 0.2) \times 10^{-1}$



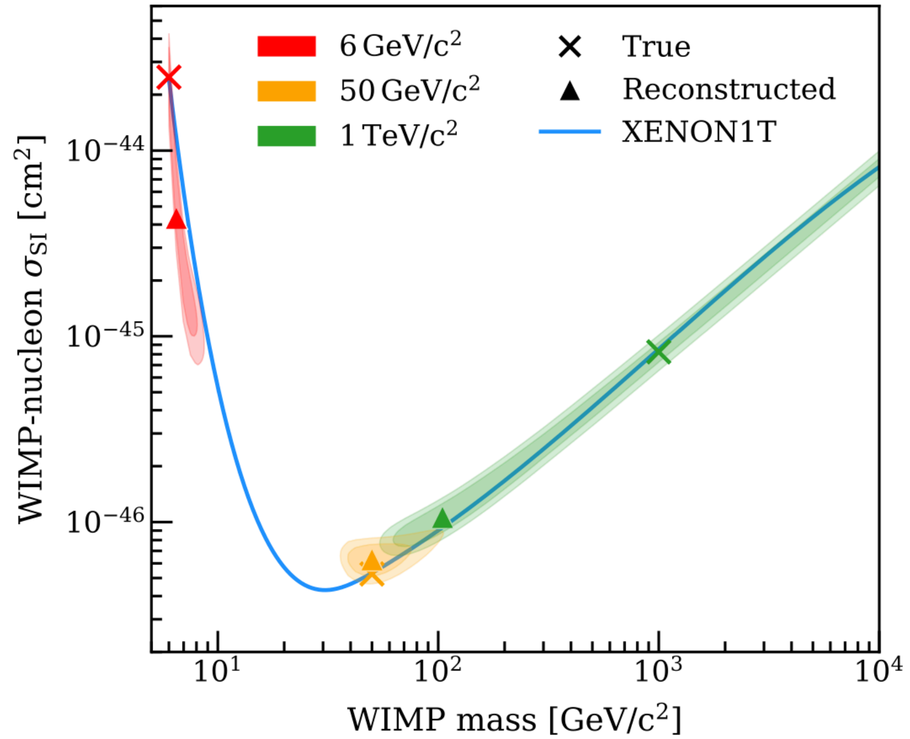


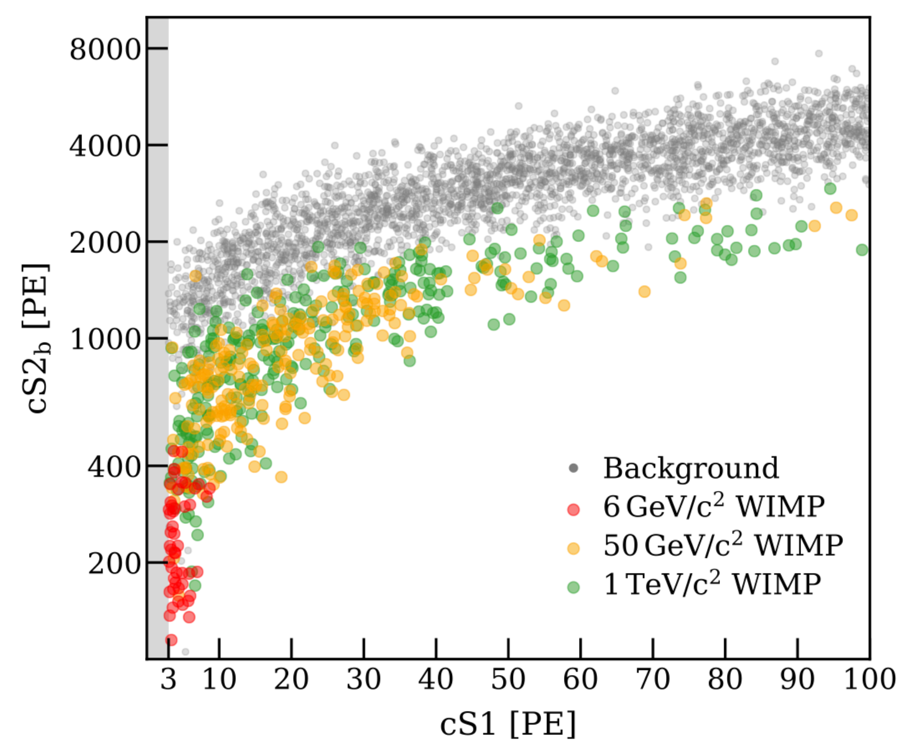
rates in a fiducial mass of 4 t of LXe, 1-13 keV ER, 4 - 50 keV NR energy range

XENON-NT: BACKGROUND PREDICTIONS

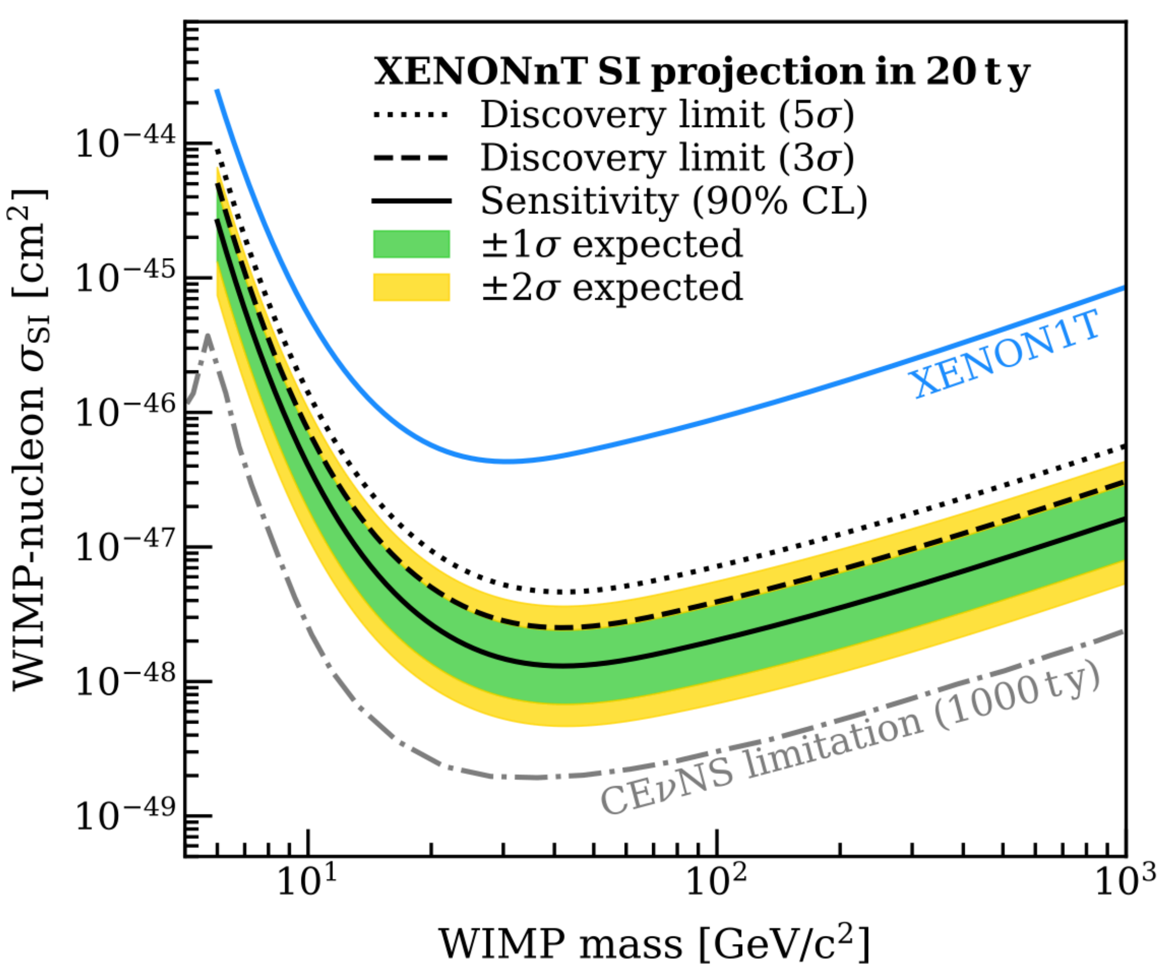
Model component	Expectation value (μ) in 20 t y		Rate uncertainty
	Observable ROI	Reference signal region	(ξ)
Background			
ER	2440	1.56	
Neutrons	0.29	0.15	50%
CEνNS (Solar ν)	7.61	5.41	4%
CEνNS (Atm+DSN)	0.82	0.36	20%
WIMP signal			
6 GeV/c^2 ($\sigma_{\mathrm{DM}} = 3 \times 10^{-44}$ cm^2)	25	19	
50 GeV/c^2 ($\sigma_{\mathrm{DM}} = 5 \times 10^{-47}$ cm^2)	186	88	
1 TeV/c^2 ($\sigma_{\mathrm{DM}} = 8 \times 10^{-46}$ cm^2)	286	118	

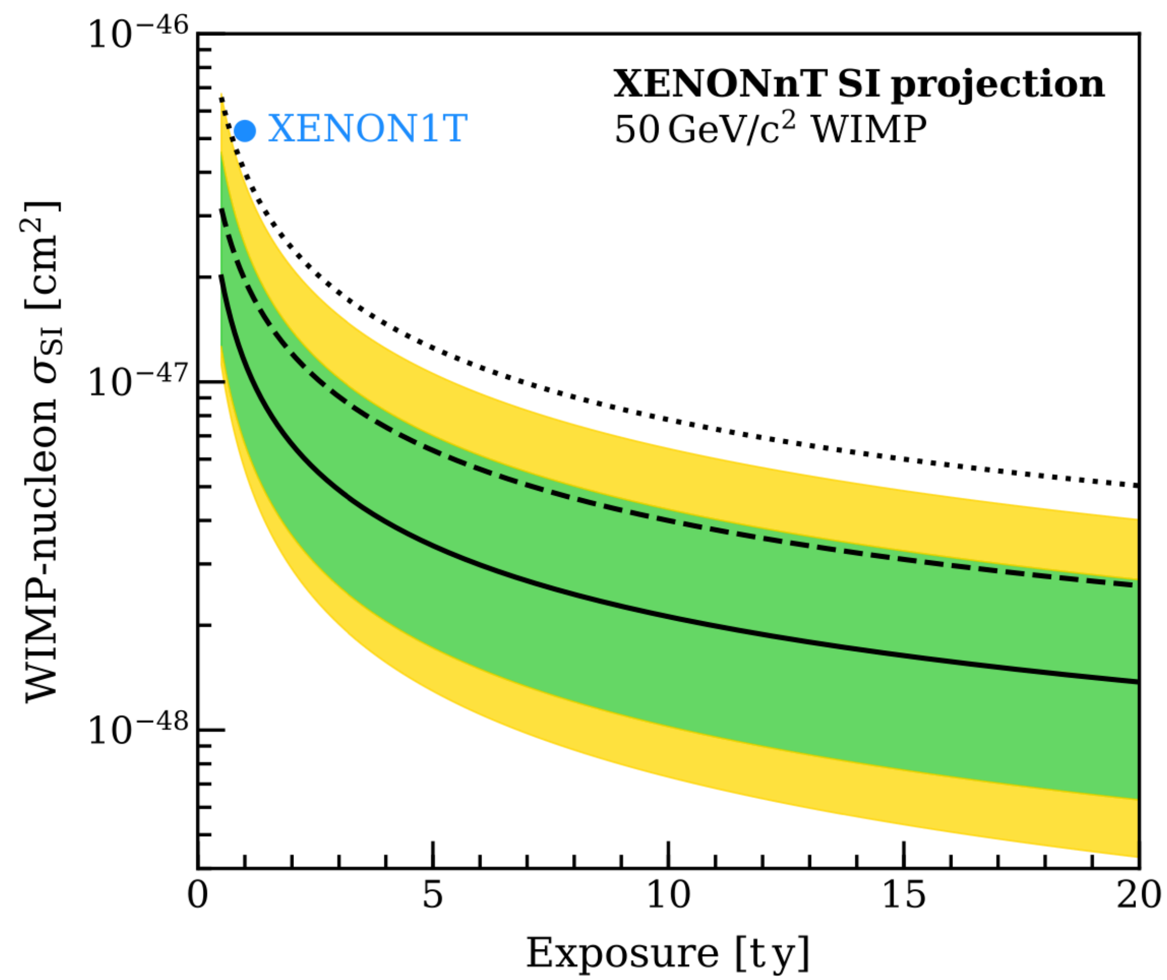
Number of events in the ROI and in a reference WIMP signal region for an exposure of 20 t years



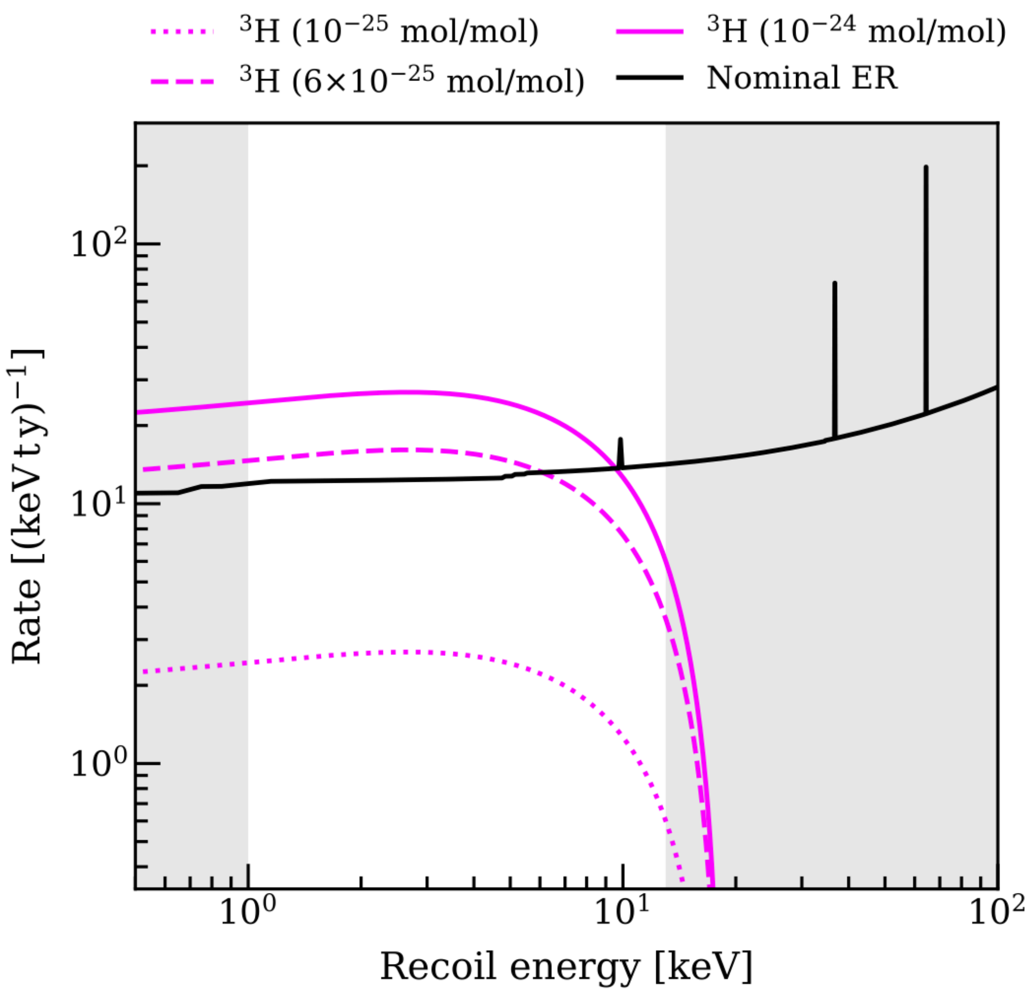


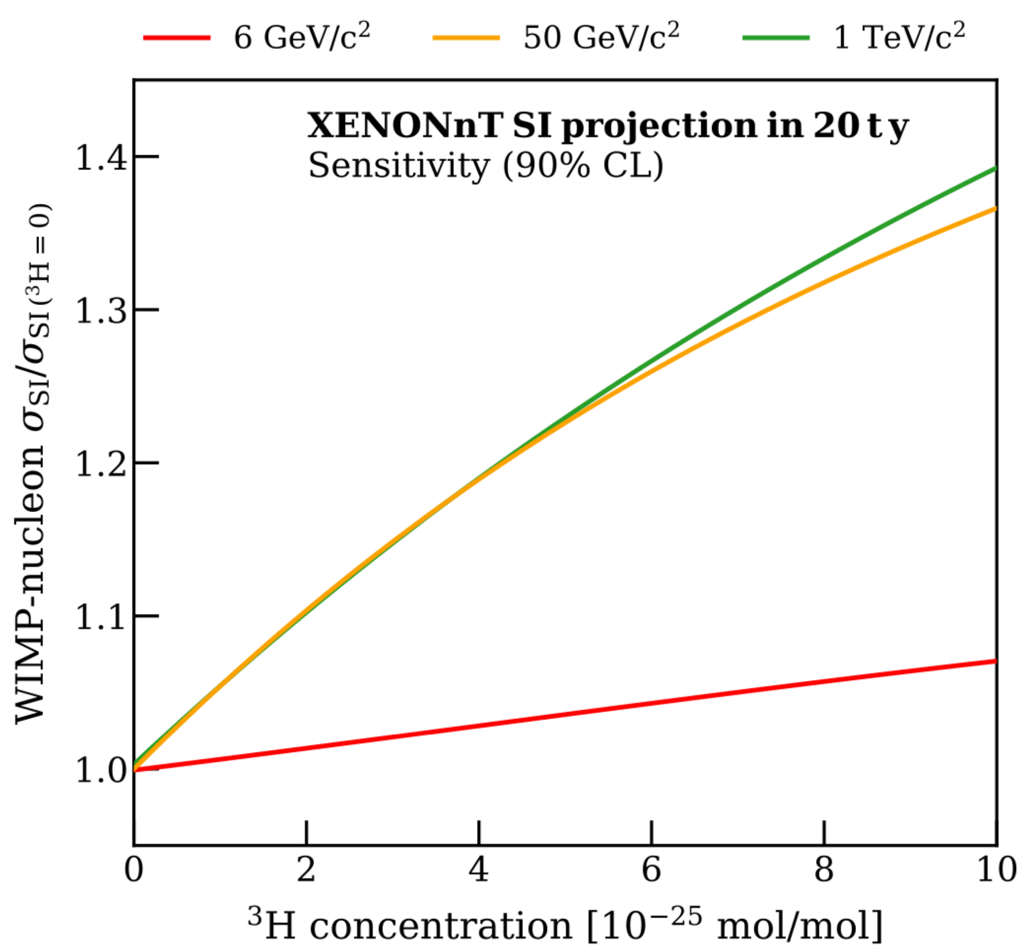
XENON-NT: SCIENCE REACH





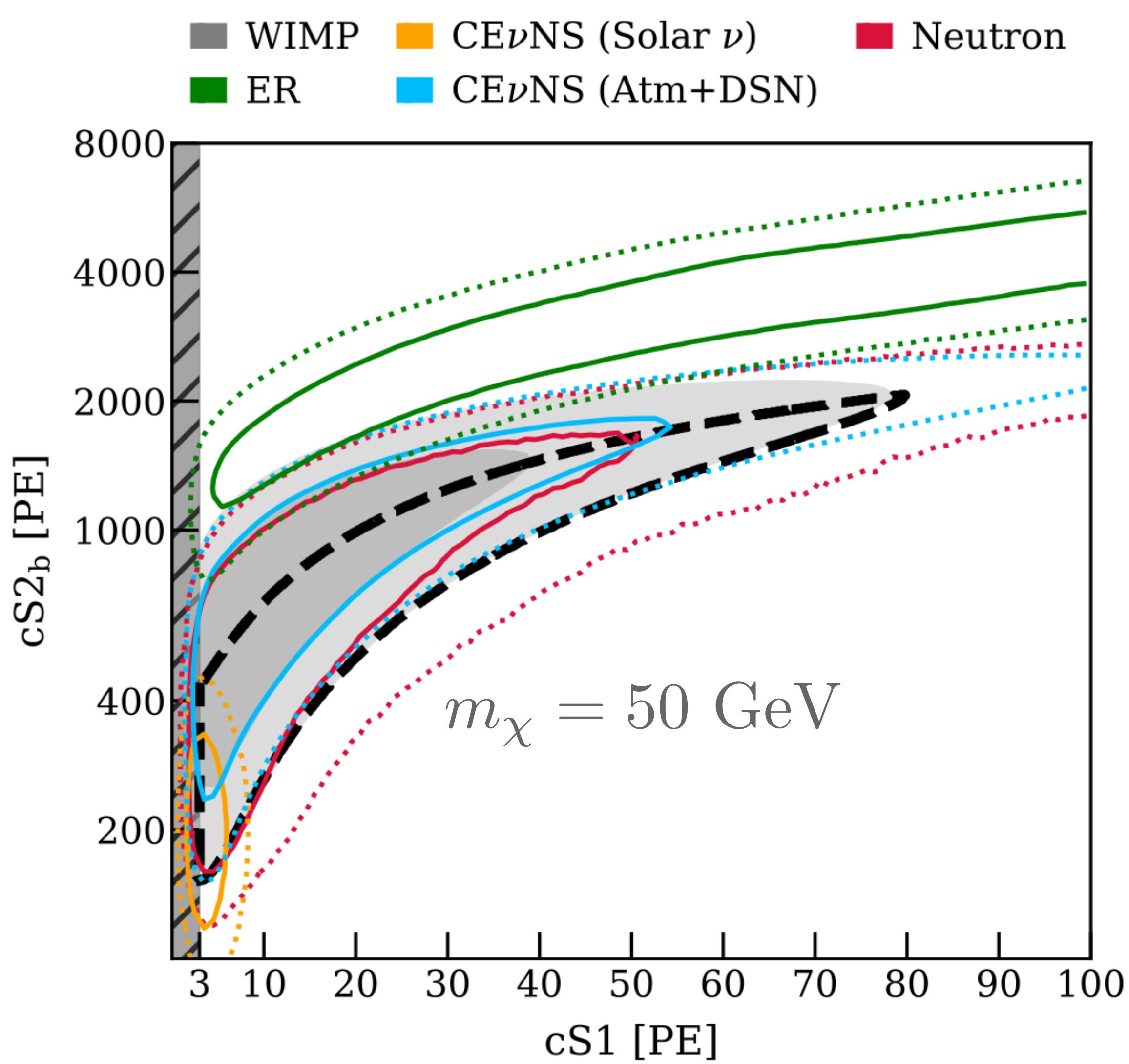
XENON-NT: IMPACT OF (POTENTIAL) TRITIUM



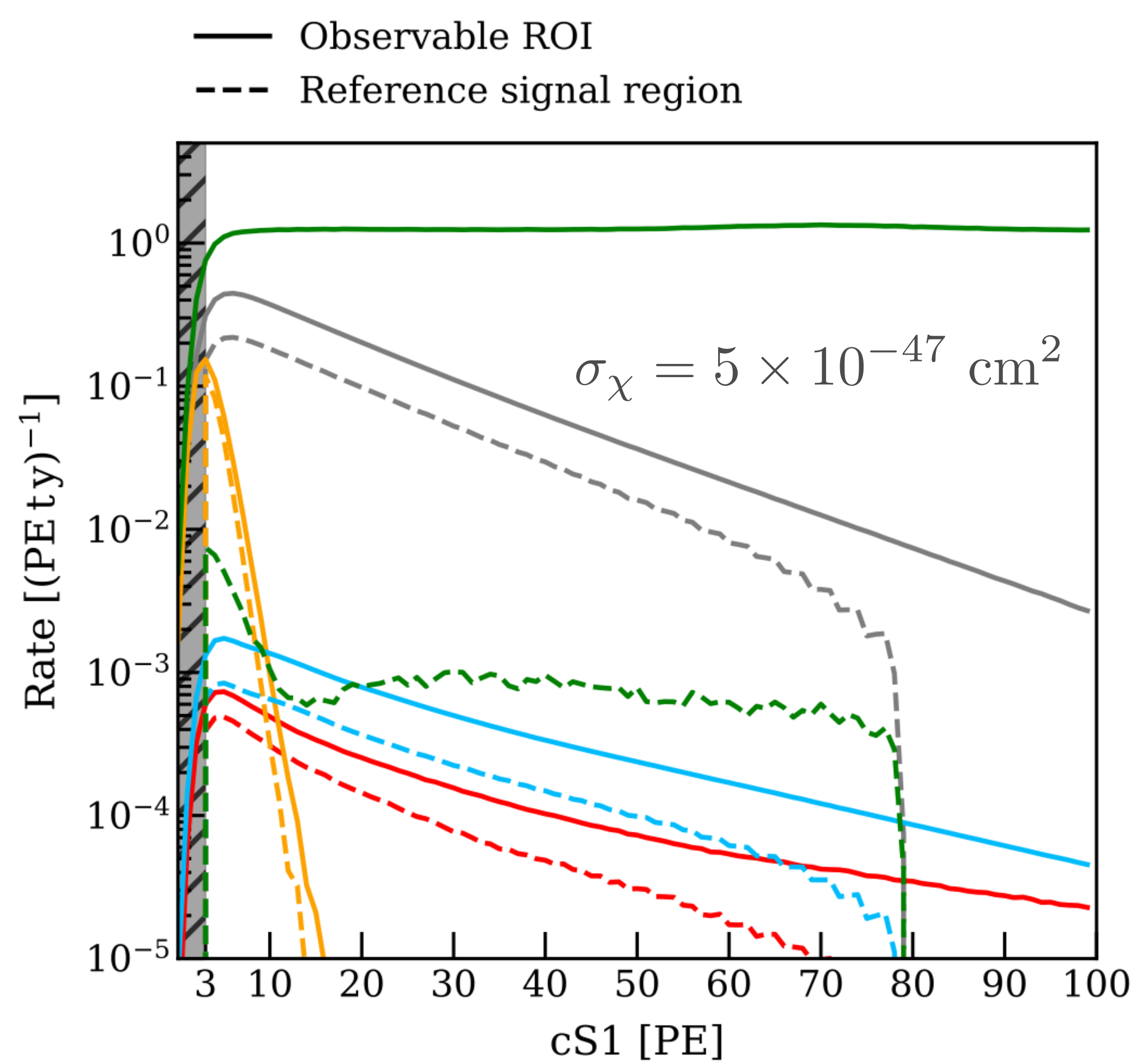


Sensitivity as a function of ^{3}H concentration, relative to the sensitivity with no 3H contribution

XENON-NT: SCIENCE REACH



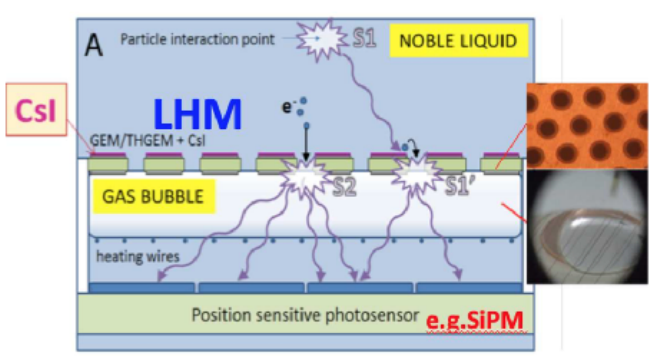
Background and signal PDFs



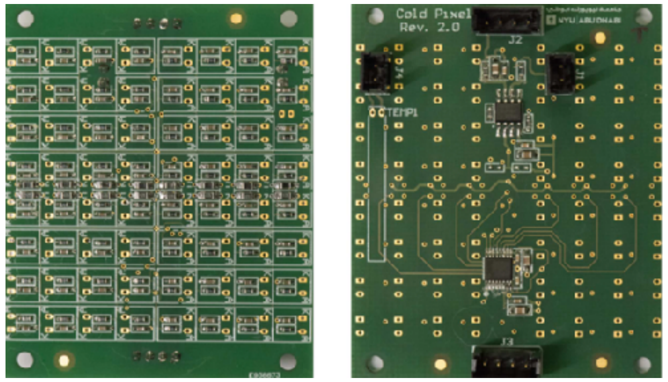
Background and signal PDFs projected on S1 space

LIGHT AND CHARGE SENSORS AND READOUT

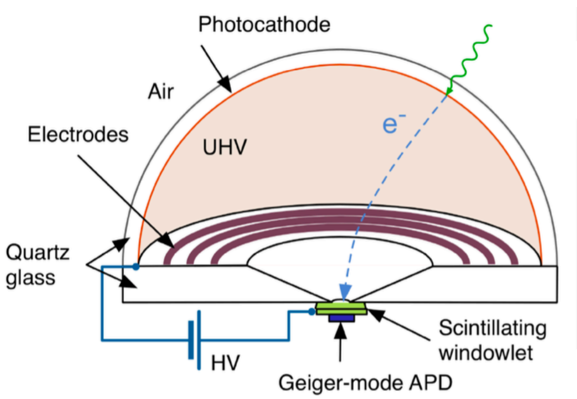
- Test alternative to PMTs: e.g., ABALONE (hybrid photosensor), VUV-SiPMs (FBK, Hamamatsu)
- Develop cryogenic electronics for SiPMs; develop cryogenic digital SiPMs
- Bubble-assisted Liquid Hole Multipliers: local vapour bubble underneath GEM-like perforated electrode in LXe



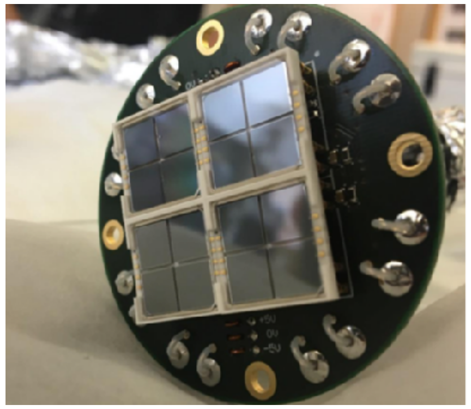
Liquid hole multipliers
E. Erdal, 2018 JINST 13, 2018



Cryogenic preamp for SiPMs, F. Arneodo et al., NIM 936, 2019



ABALONE, D. Ferenc et al., NIM 954, 2020

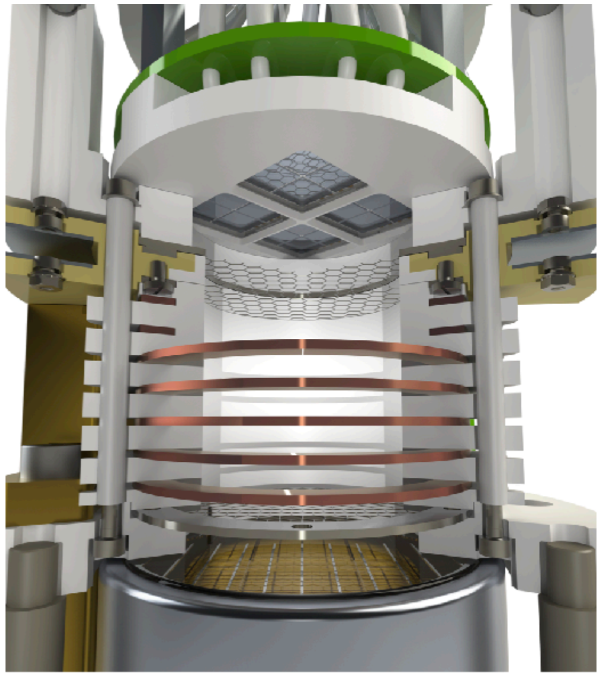


Hamamatsu SiPM arrays in two-phase TPC, LB et al., EPJ-C 80, 2020

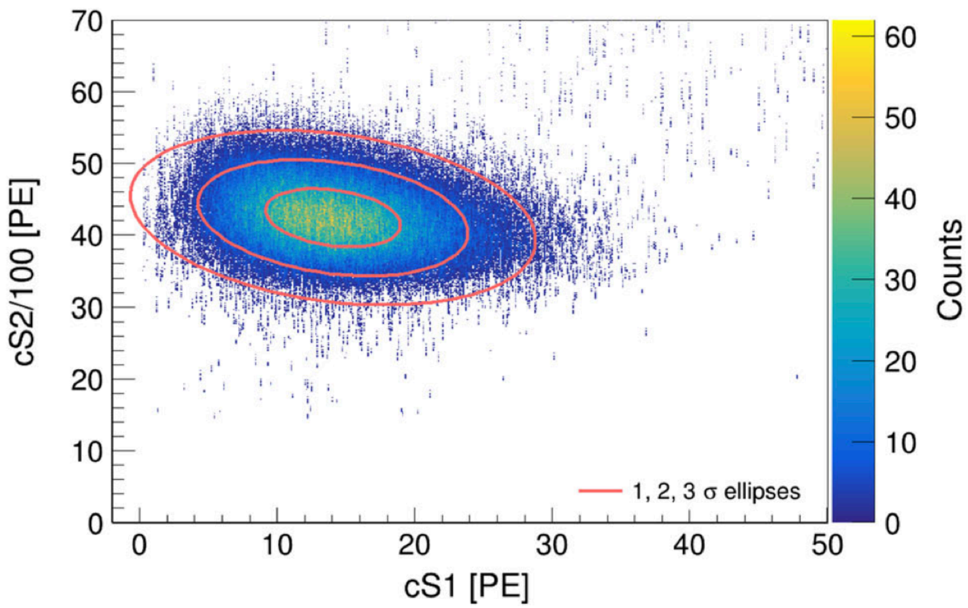
LIGHT AND CHARGE SENSORS AND READOUT

- Test VUV-sensitive SiPMs as potential replacement for PMTs
- First Xe-TPC with SiPM in top array at UZH
- Characterisation with ^{37}Ar and ^{83m}Kr sources

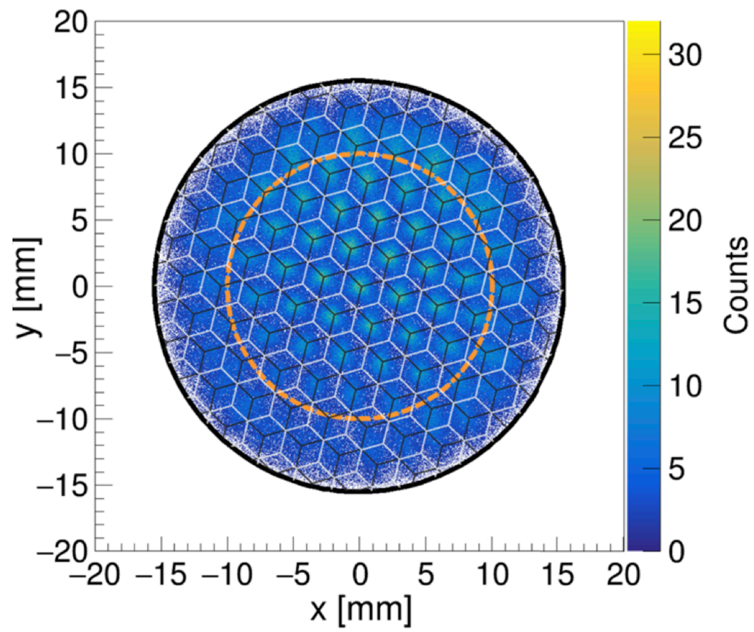
Characterisation with ^{37}Ar source



Upgrade of Xurich-II (LB et al., EPJ-C 80, 2020 and EPJ- C 78, 2018)



S2 versus S1 for the 2.82 keV ^{37}Ar line (K-shell, 90.2% BR)



x-y position reconstruction ~ 1.5 mm resolution

BACKGROUND BUDGET IN DOUBLE BETA REGION

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

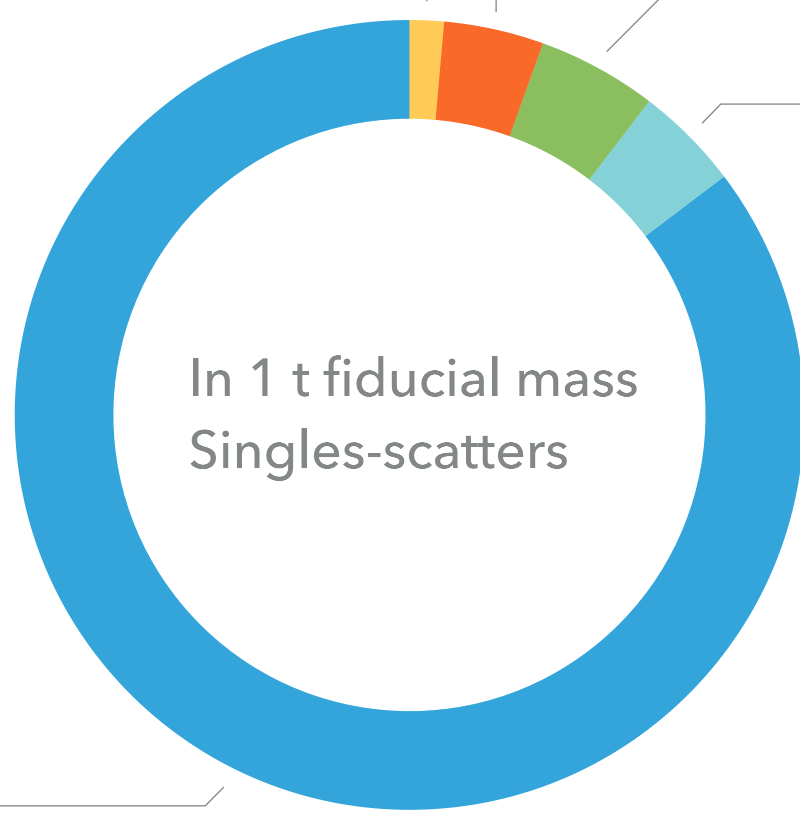
- ER rate: (82±5) events/(keV t y), in 1.3 t and below 25 keV_{ee}
- Lowest background in a dark matter detector

1.4% ^{136}Xe 2νββ-decays

4.1% Materials

4.9% Solar neutrinos

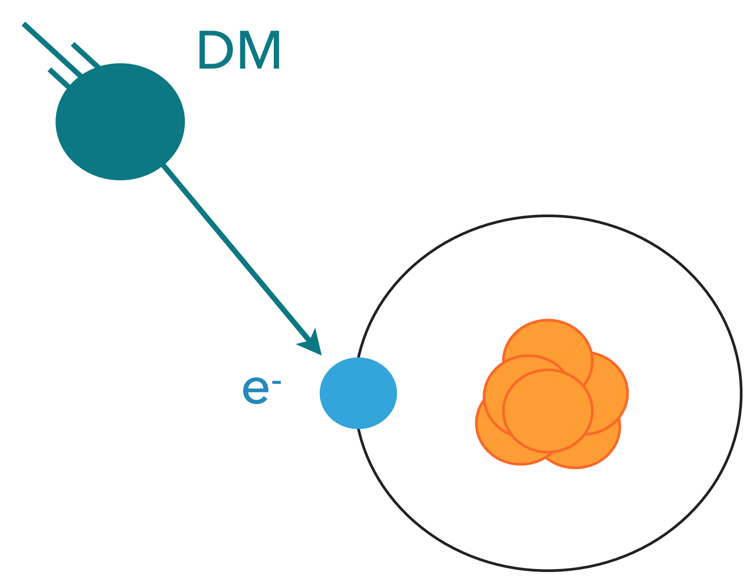
4.3% ^{85}Kr (^{nat}Kr: 0.66 ppt)

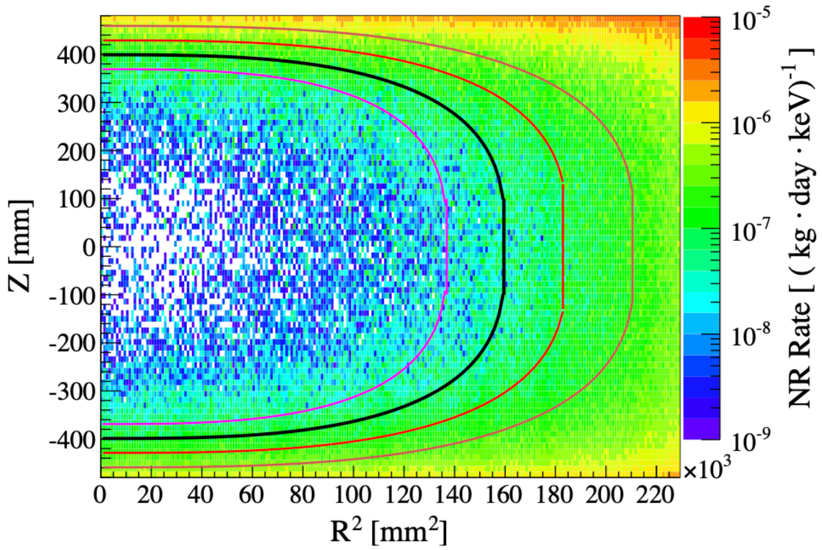


85.3%

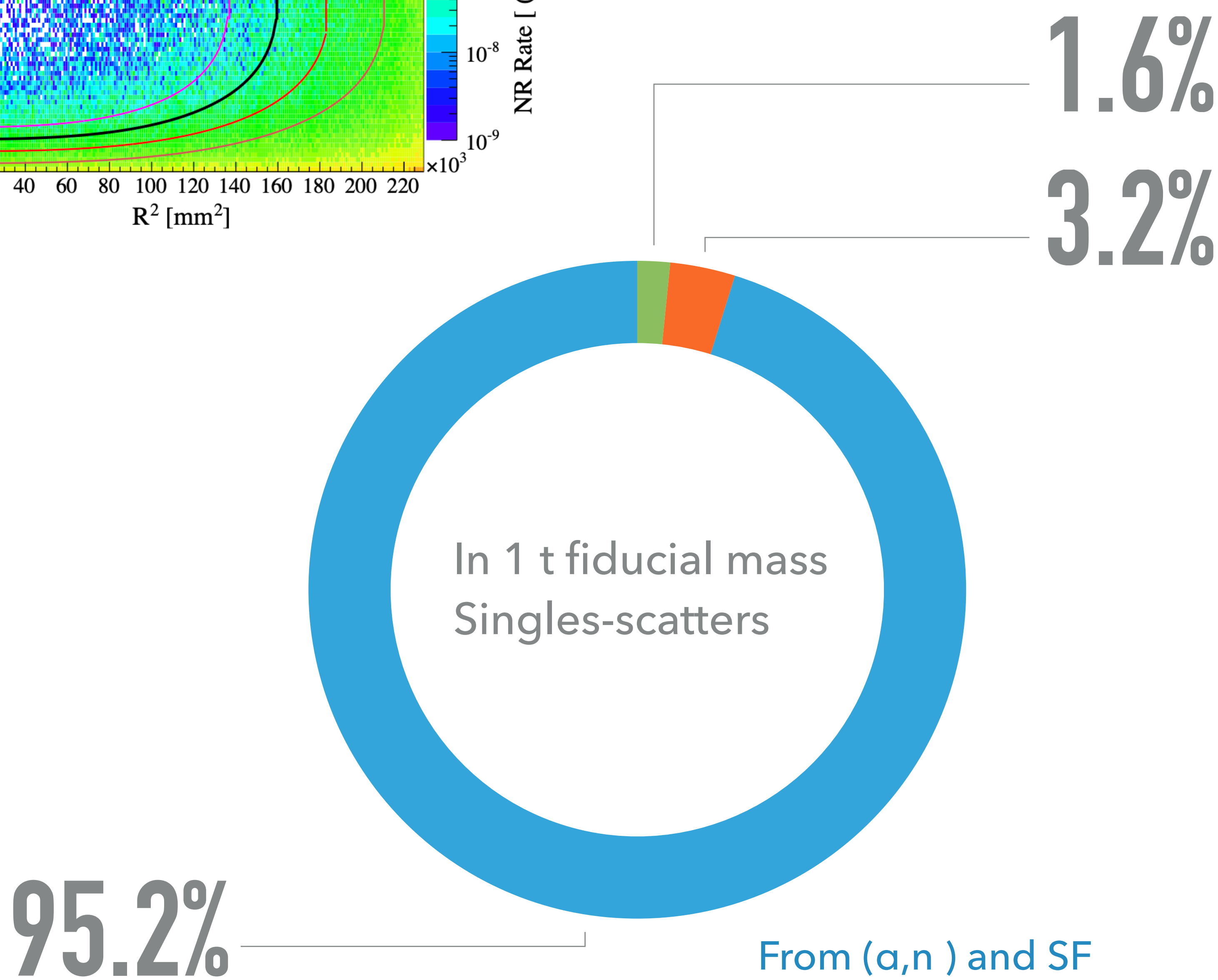
^{222}Rn (10 μBq/kg)

Control surface emanation
Reduce by online distillation

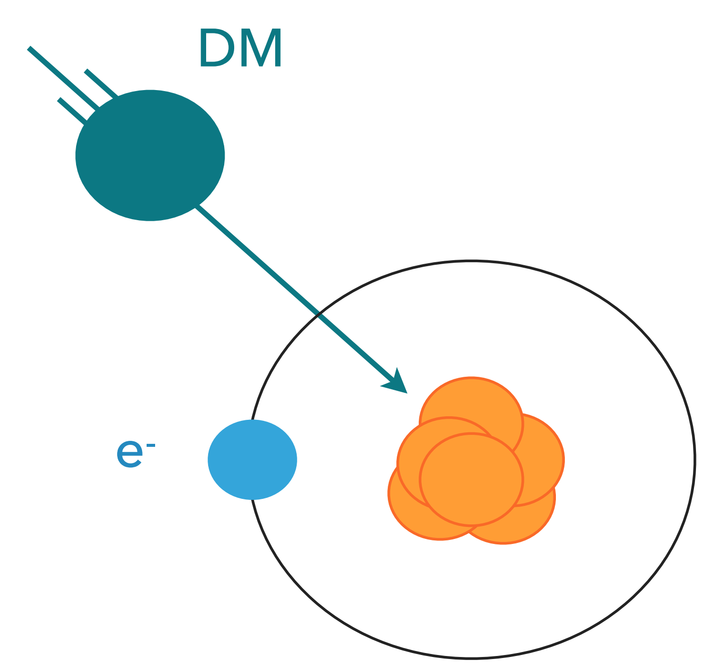




Cosmogenic neutrons (muon induced neutrons); rock overburden, water Cherenkov shield (here upper limit)



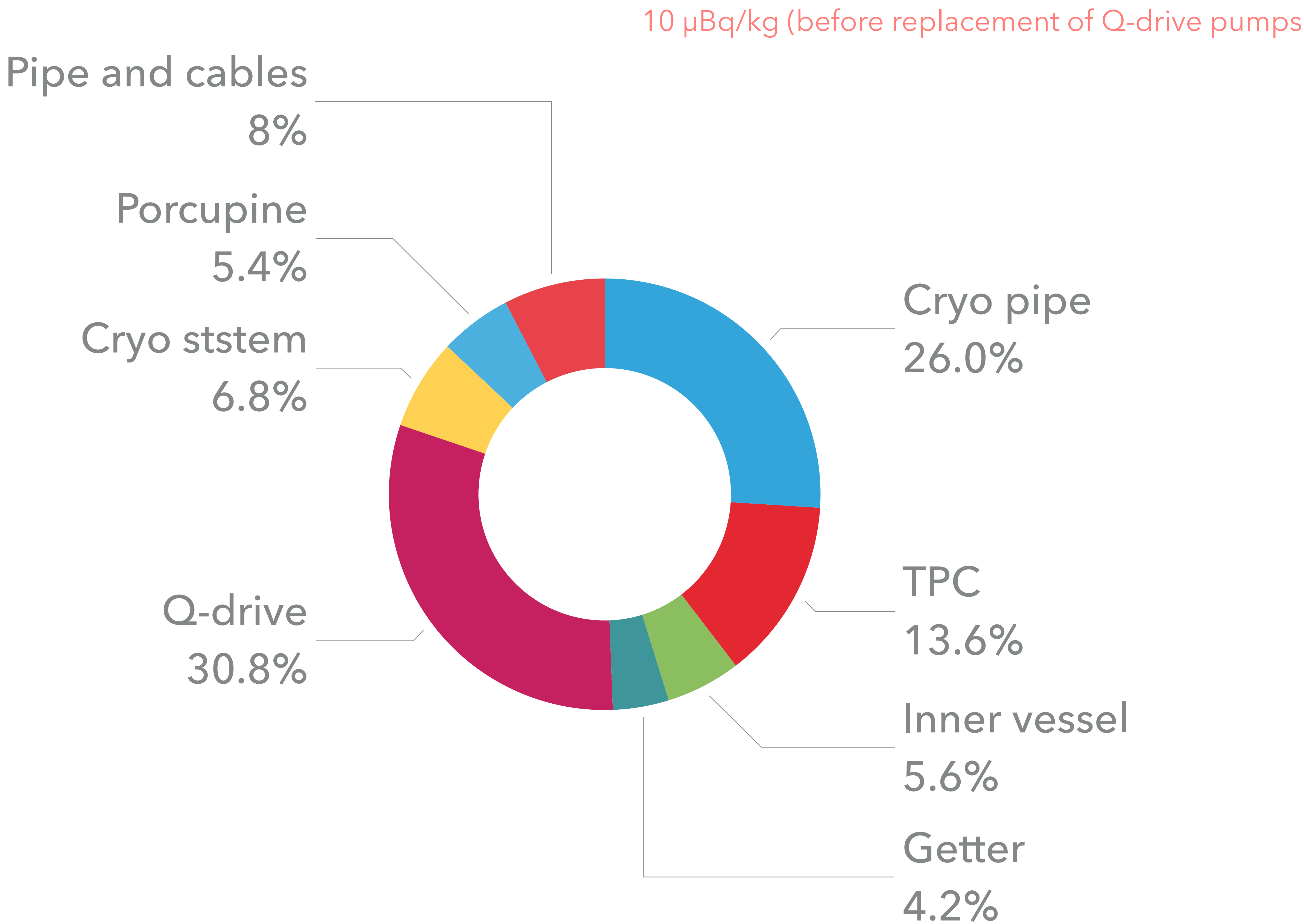
Coherent neutrino-nucleus scattering from ^{8}B neutrinos; irreducible, but relevant at low (<1 keV) energies



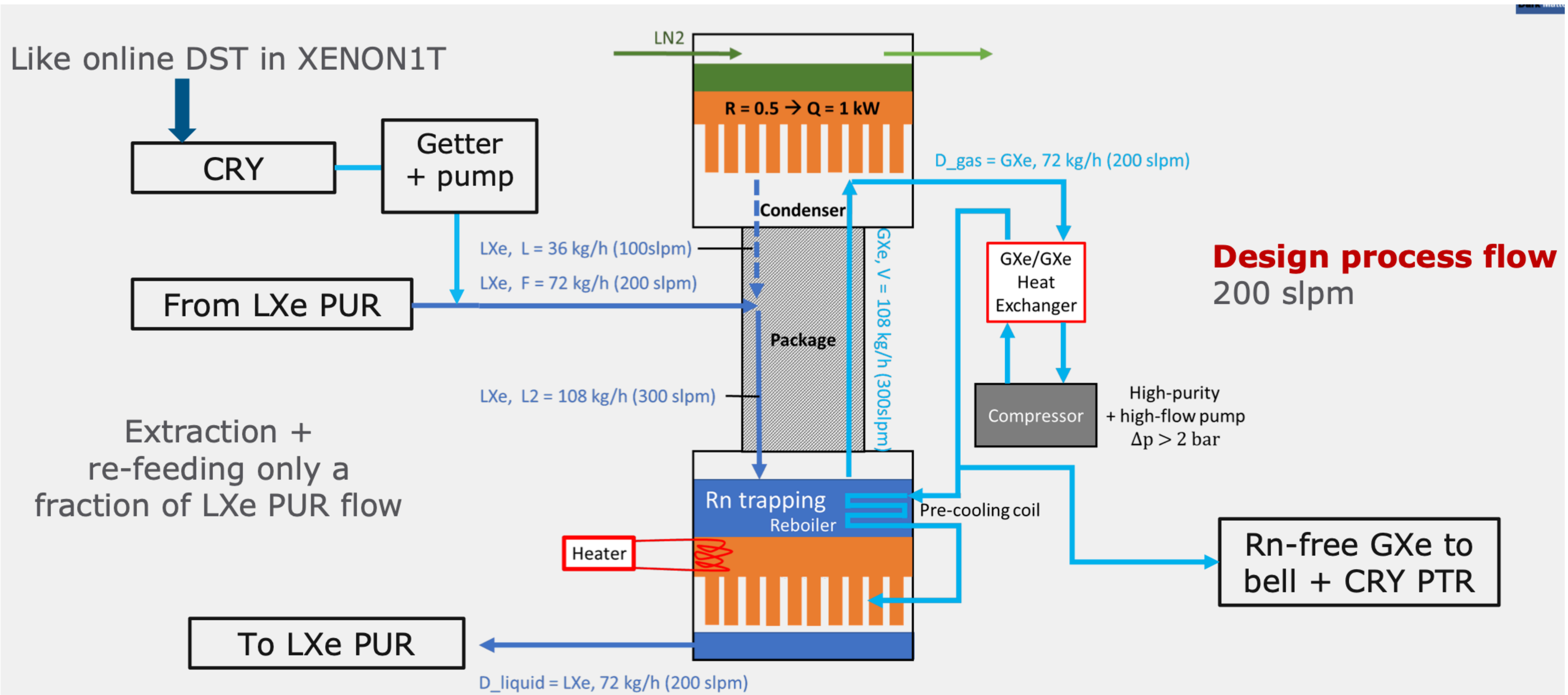
Radiogenic neutrons

From (α,n) and SF reactions; material selection; single versus multiple-scatters

RADON BUDGET IN XENON1T

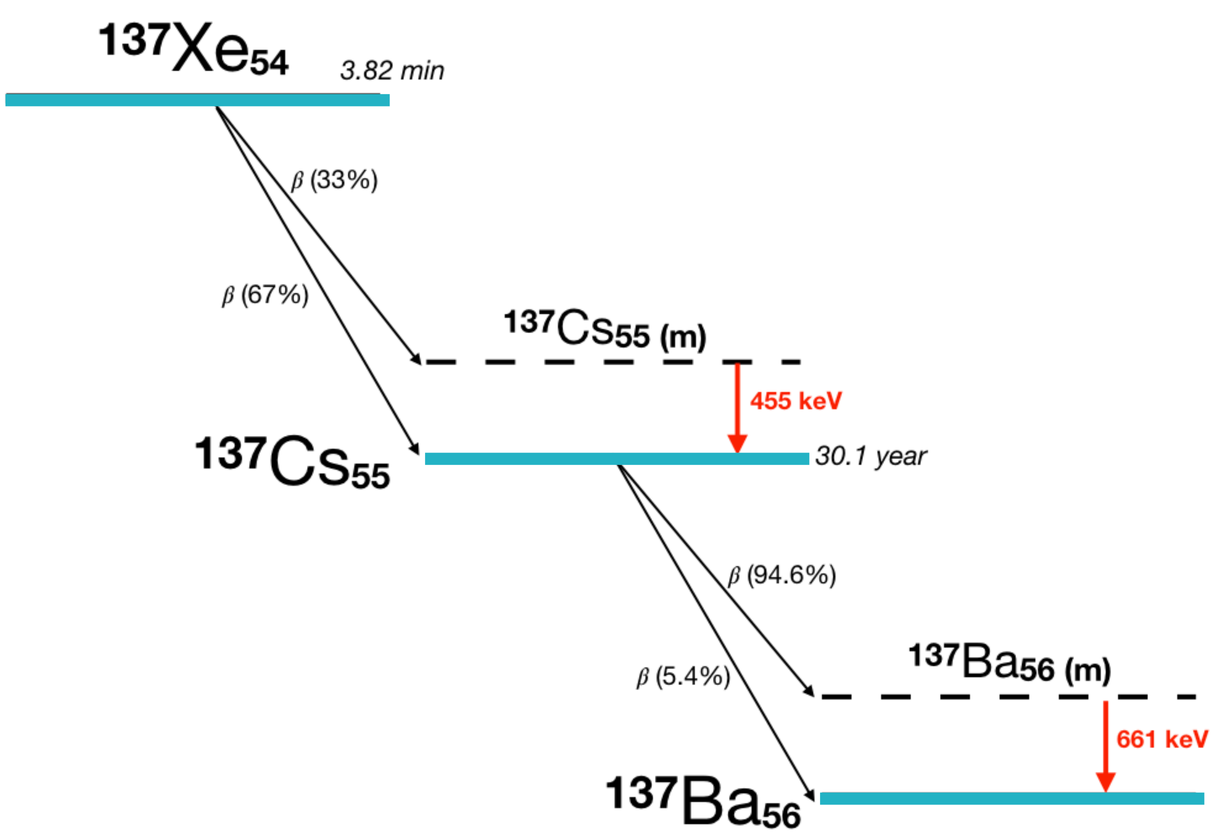


XENON RADON DISTILLATION COLUMN

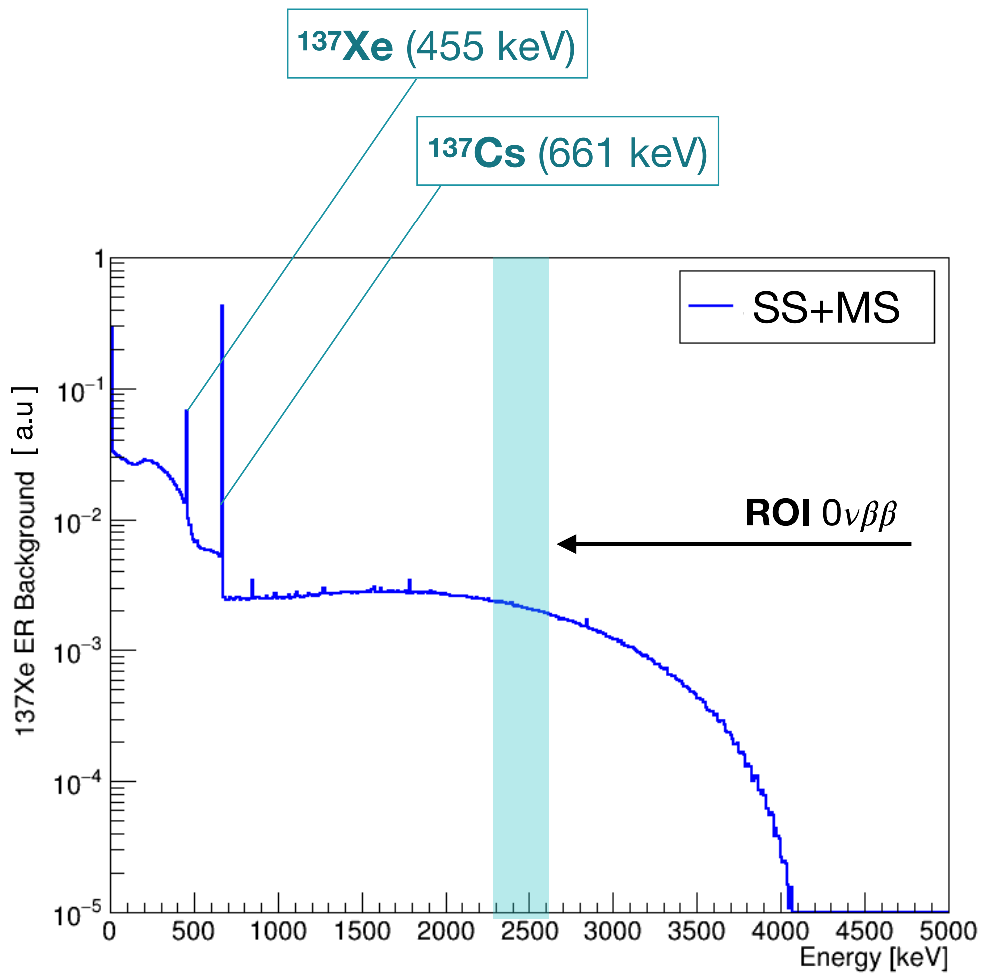


137-XE BACKGROUND

- 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)



Rate in ROI: $(1.40\pm0.06) \times 10^{-3}$ events/(t y keV)



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

137-XE BACKGROUND

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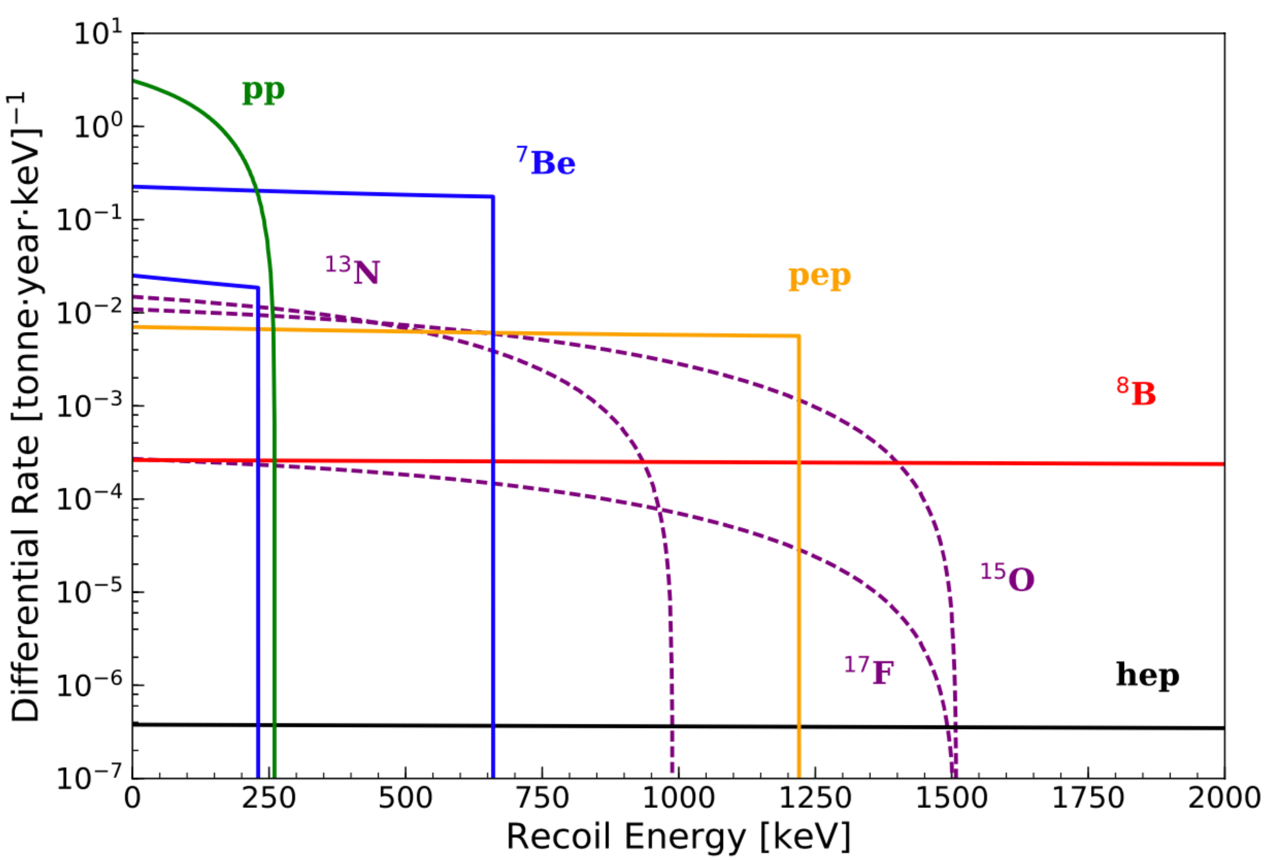
- nEXO: 2.2 atoms/(t y) at SNOLAB (PRC 97, 2018); KamLAND-Zen: 1.42 atoms/(t y) at Kamioka (PRL 117, 2016)

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}

SOLAR NEUTRINOS

- Real-time measurement, elastic ν-electron interaction $\nu + e^- \rightarrow \nu + e^-$



$$\frac{dN_i}{dT} = \Phi_i N_e \sum_j \int P_{ej} \frac{dN}{dE_\nu} \frac{d\sigma_j}{dT} dE_\nu$$

Number of target electrons

Neutrino survival probability

Depends on weak mixing angle

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}[(g_v + g_a)^2 + (g_v - g_a)^2(1 - \frac{T}{E_\nu})^2 + (g_a^2 - g_v^2)\frac{m_e T}{E_\nu^2}]$$

$$g_v = 2\sin^2\theta_w - \frac{1}{2}$$

$$g_a = -\frac{1}{2}$$

For electron neutrinos…

$$g_{v,a} \rightarrow g_{v,a} + 1$$