LATEST RESULTS OF 1 TONNE YEAR DARK MATTER SEARCH WITH XENON1T

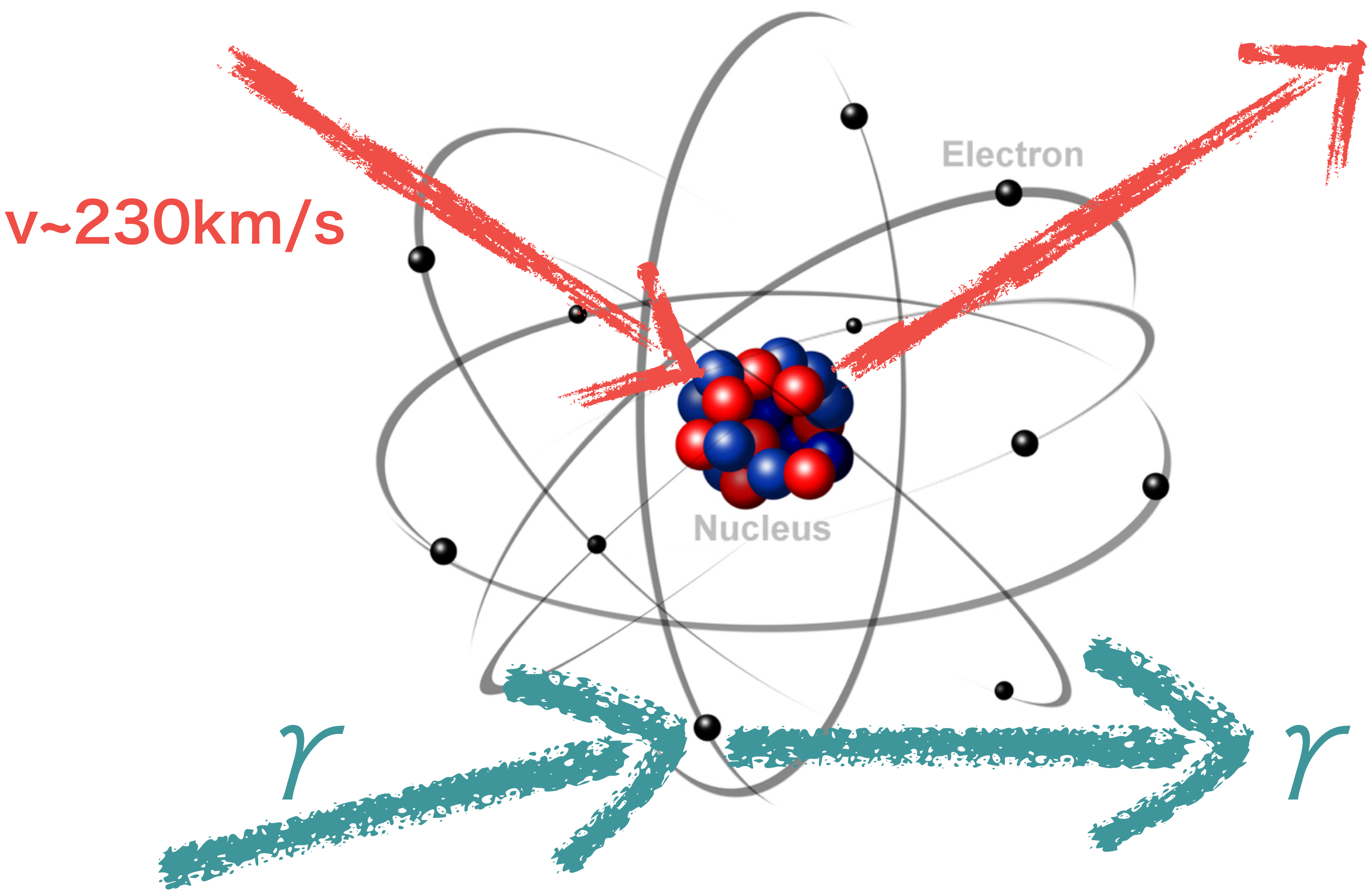
風間慎吾
名古屋大 高等研究院 & KMI

新テラスケール研究会, JULY 27, 2018

DIRECT DARK MATTER DETECTION

- Elastic scattering of dark matter particles off nuclei (Nuclear Recoil, NR)
- Momentum transfer ~ O(10) MeV
- Recoil Energy ~ O(1-10) keV

Signal: $\chi N \rightarrow \chi N$ (NR)



Backgrounds:

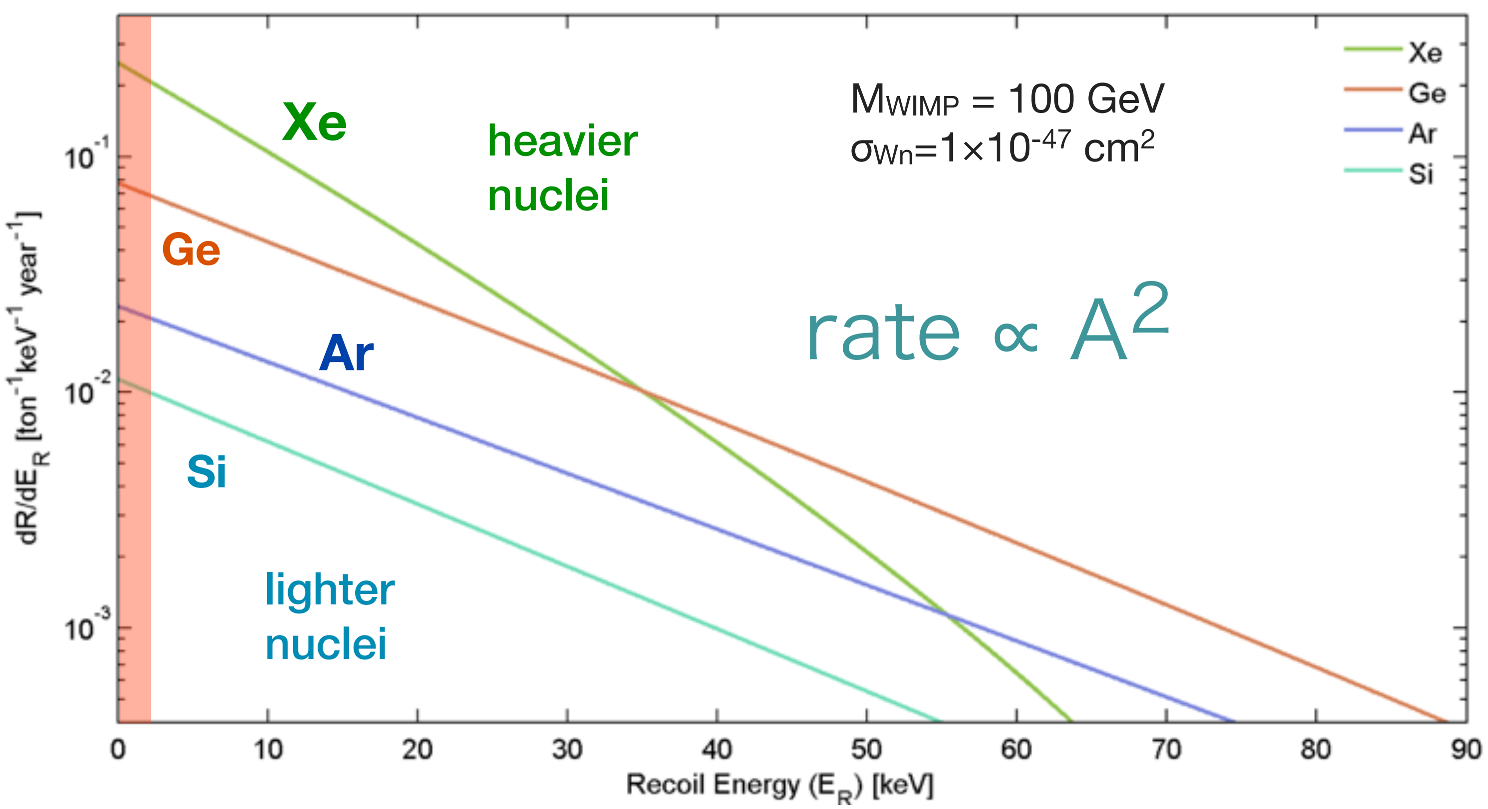
$\gamma e^- \rightarrow \gamma e^-$ (ER)

$nN \rightarrow nN$ (NR)

$\nu N \rightarrow \nu N$ (NR)

DIRECT DARK MATTER DETECTION

- Recoil Energy ~ O(1-10) keV
- Event rate $\propto N \times \rho/m_\chi \times \sigma_{\chi\text{-}N}$ (< O(1) events/ton/year)



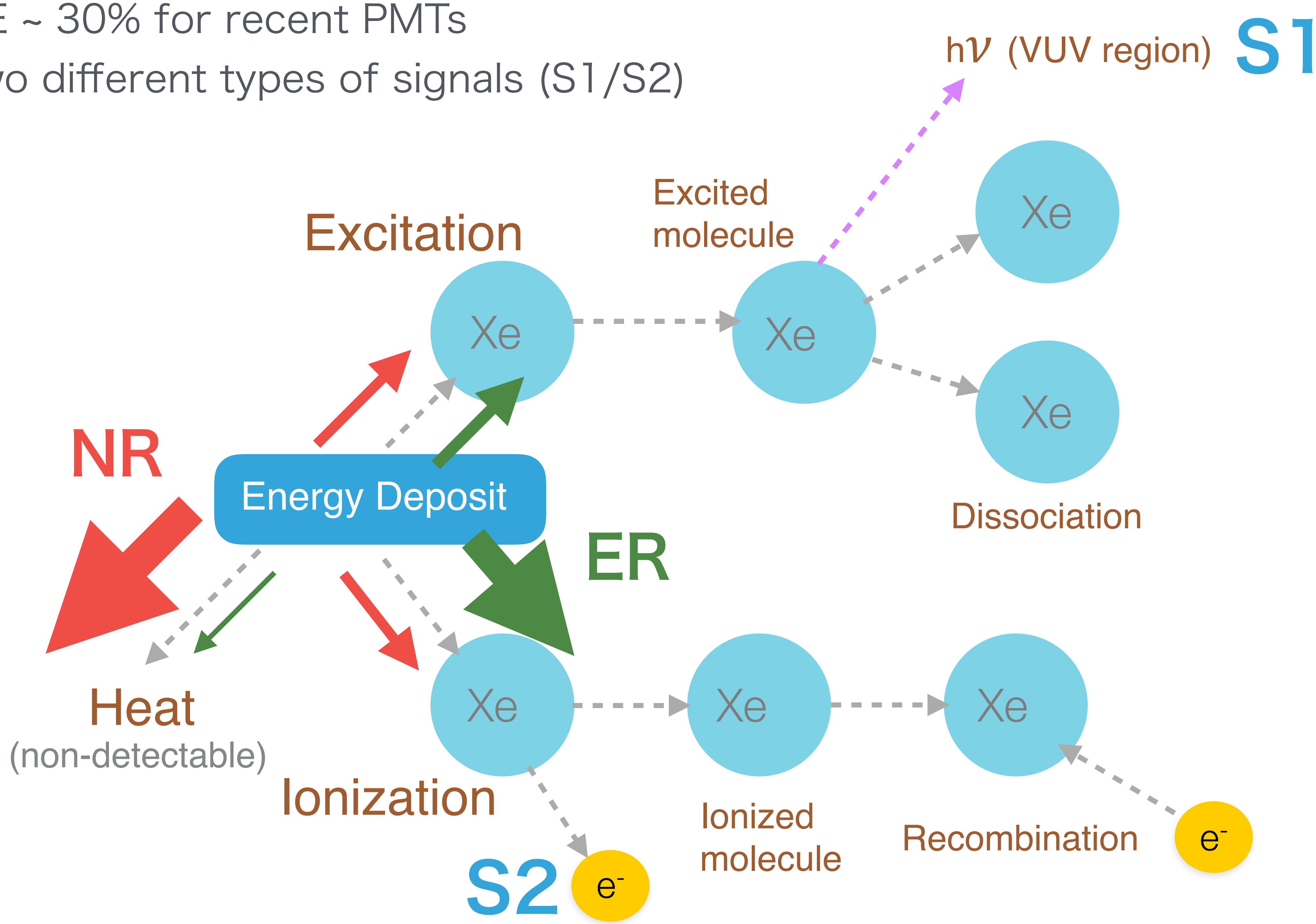
For discovery, we need

- ✓ large total mass
- ✓ high atomic number
- ✓ very low energy threshold
- ✓ ultra low background
- ✓ good Signal/BG discrimination

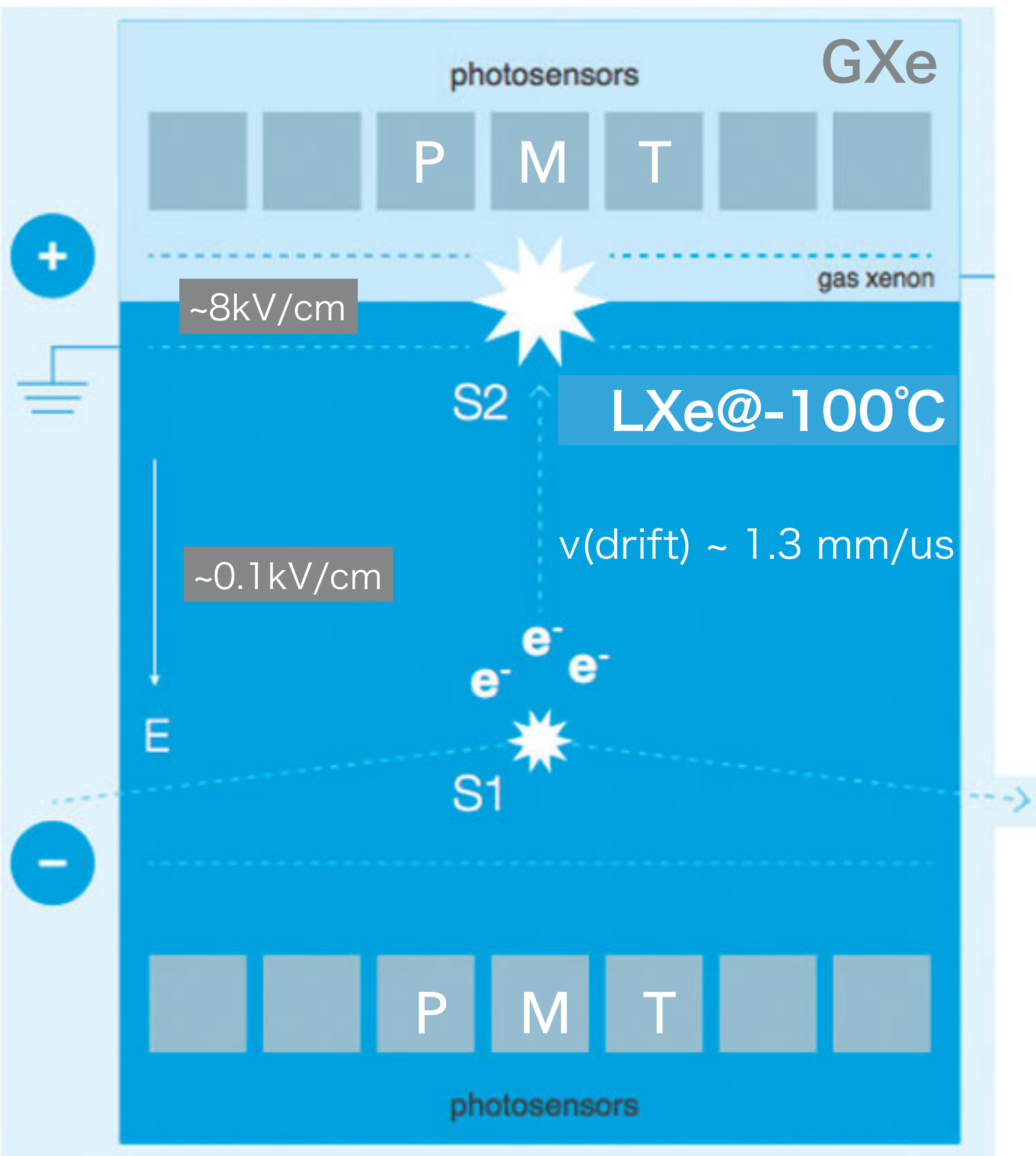
Xe
XENON
Dark Matter Project

XENON AS A DARK MATTER DETECTION MEDIUM

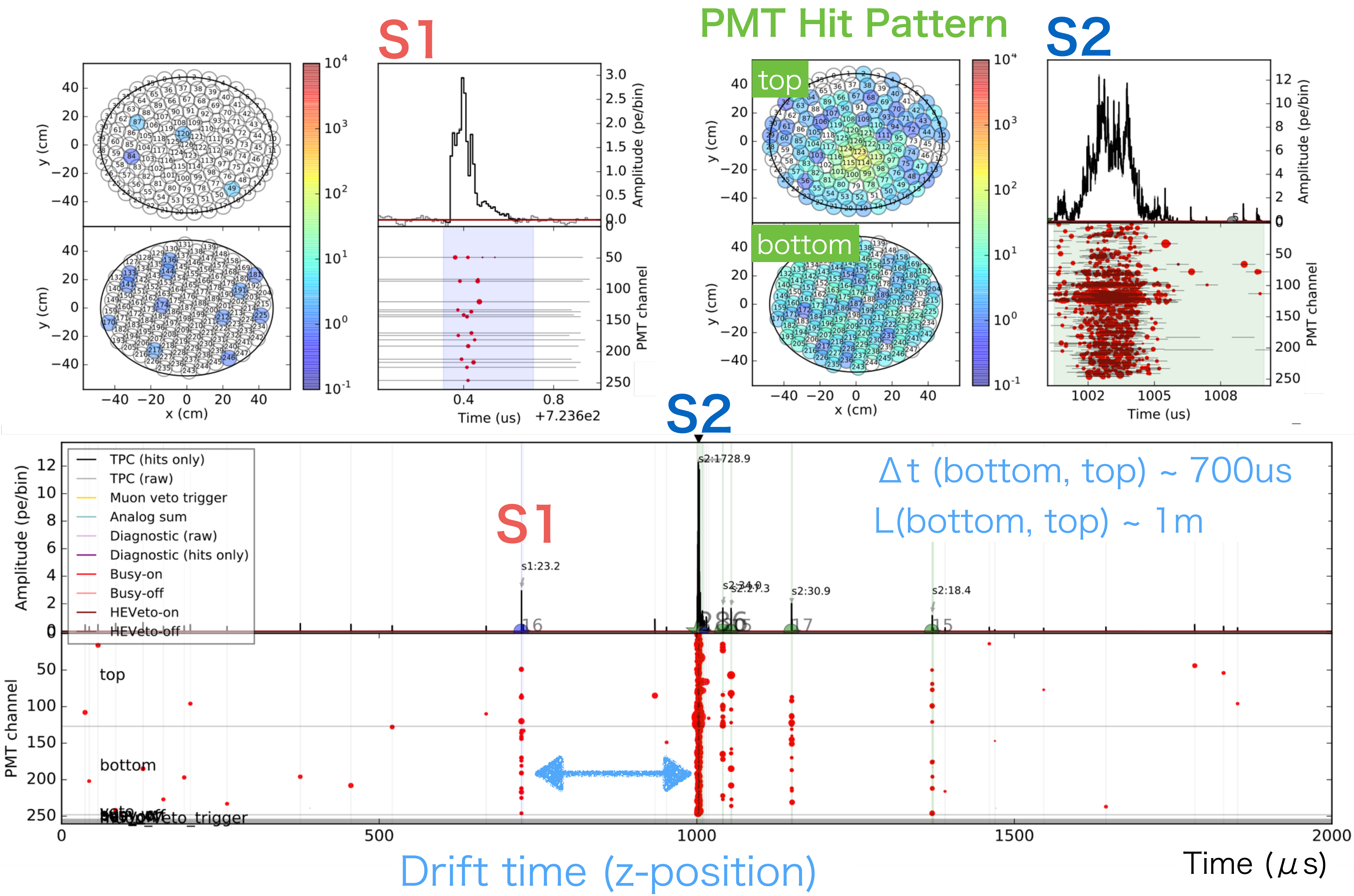
- Efficient scintillator (λ=178 nm, ~7eV)
- QE ~ 30% for recent PMTs
- Two different types of signals (S1/S2)



A LIQUID XENON TIME PROJECTION CHAMBER

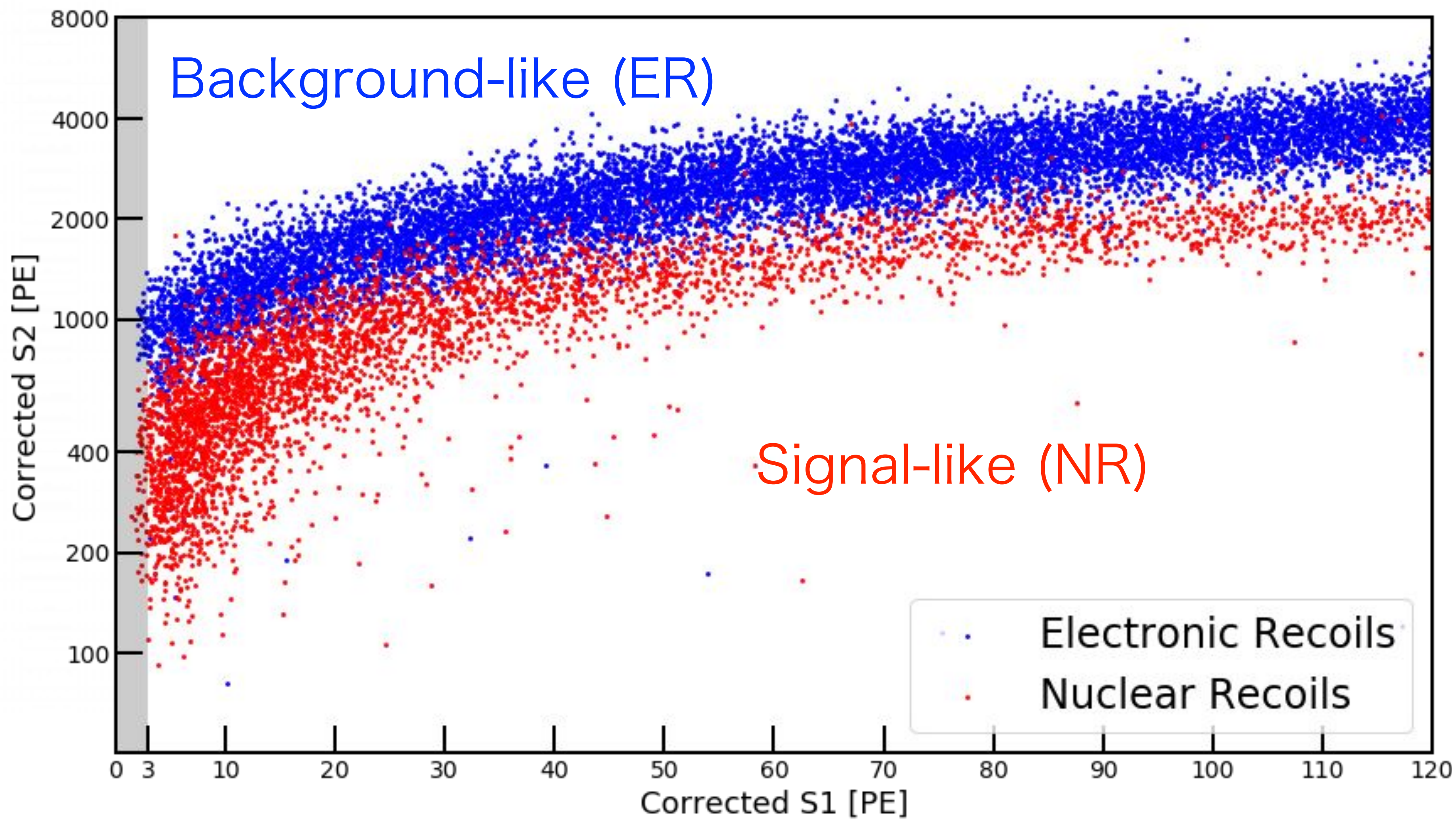


- Primary scintillation light (**S1**) is produced promptly at the interaction site
- Ionization electrons drift up through the LXe in the applied electric field
- Some recombine with ions, releasing more scintillation light (**S1**)
- Others are extracted above the liquid surface into gas phase region, where they form secondary proportional scintillation light (**S2**)
- Event vertex reconstruction in 3D space
  - **X,Y position: S2 hit-pattern in top PMT array**
  - **Z position: electron drift time (Δt (s1, s2))**
- Particle type discrimination:
  - $(S2/S1)_{\gamma,e}$ (ER) > $(S2/S1)_{\text{WIMP, neutron}}$ (NR)


S1
PMT Hit Pattern
S2
top
bottom
y (cm)
x (cm)
Time (us)
+7.236e2
Amplitude (pe/bin)
PMT channel
S2
S1
Δt (bottom, top) ~ 700us
L(bottom, top) ~ 1m
TPC (hits only)
TPC (raw)
Muon veto trigger
Analog sum
Diagnostic (raw)
Diagnostic (hits only)
Busy-on
Busy-off
HEVeto-on
HEVeto-off
s1:23.2
s2:1728.9
s2:30.9
s2:18.4
Drift time (z-position)
Time (μs)

A XENON TIME PROJECTION CHAMBER

S2/S1 comparison between ER and NR



- S2/S1 is an important parameter for signal/BG discrimination: **$(S2/S1)_{ER} > (S2/S1)_{NR}$**
- ER events leaking into NR-band can be a significant BG.
- Does ton-scale detector like XENON1T have a similar discrimination power as for smaller detectors like XENON10, 100, LUX and PandaX?

XENON1T DETECTOR AND PERFORMANCES

XENON1T/NT

170 scientists

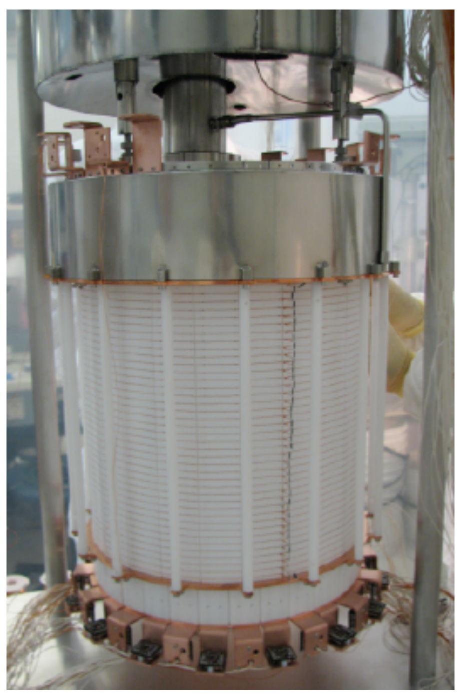
25 institutions

11 countries

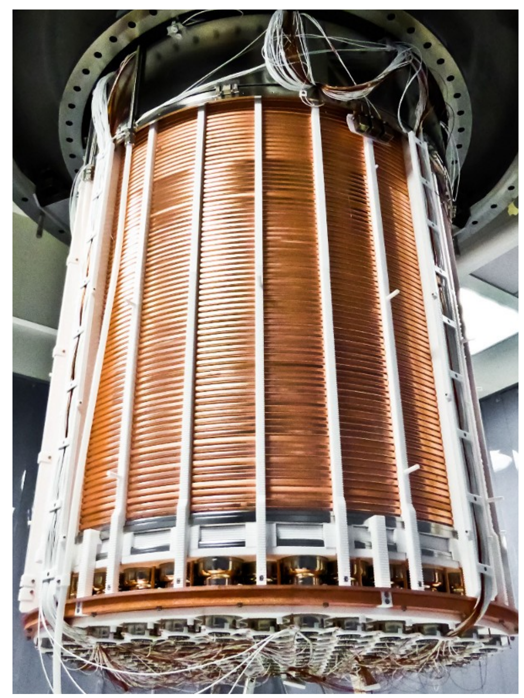
THE XENON (&DARWIN) TIMELINE

XENON10

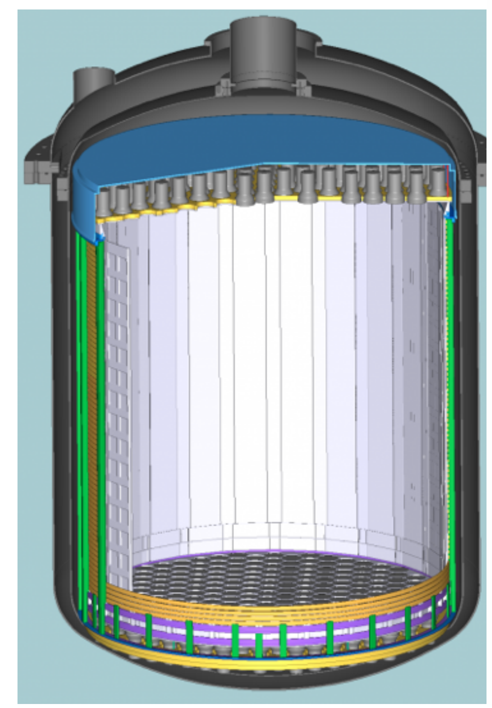
XENON100



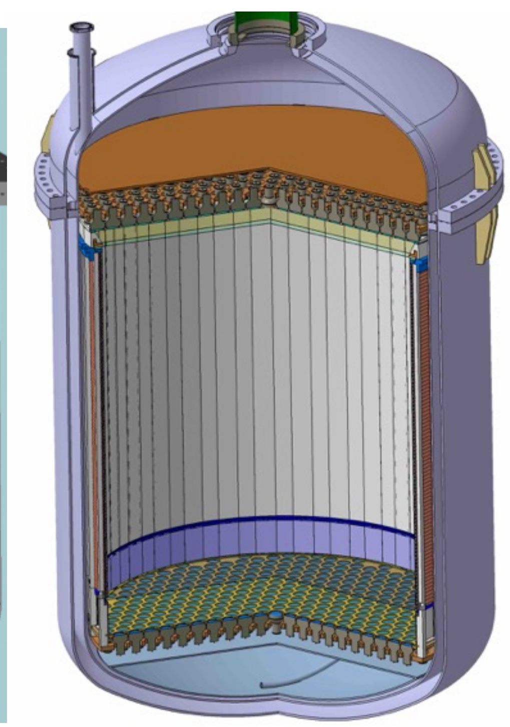
XENON1T



XENONnT

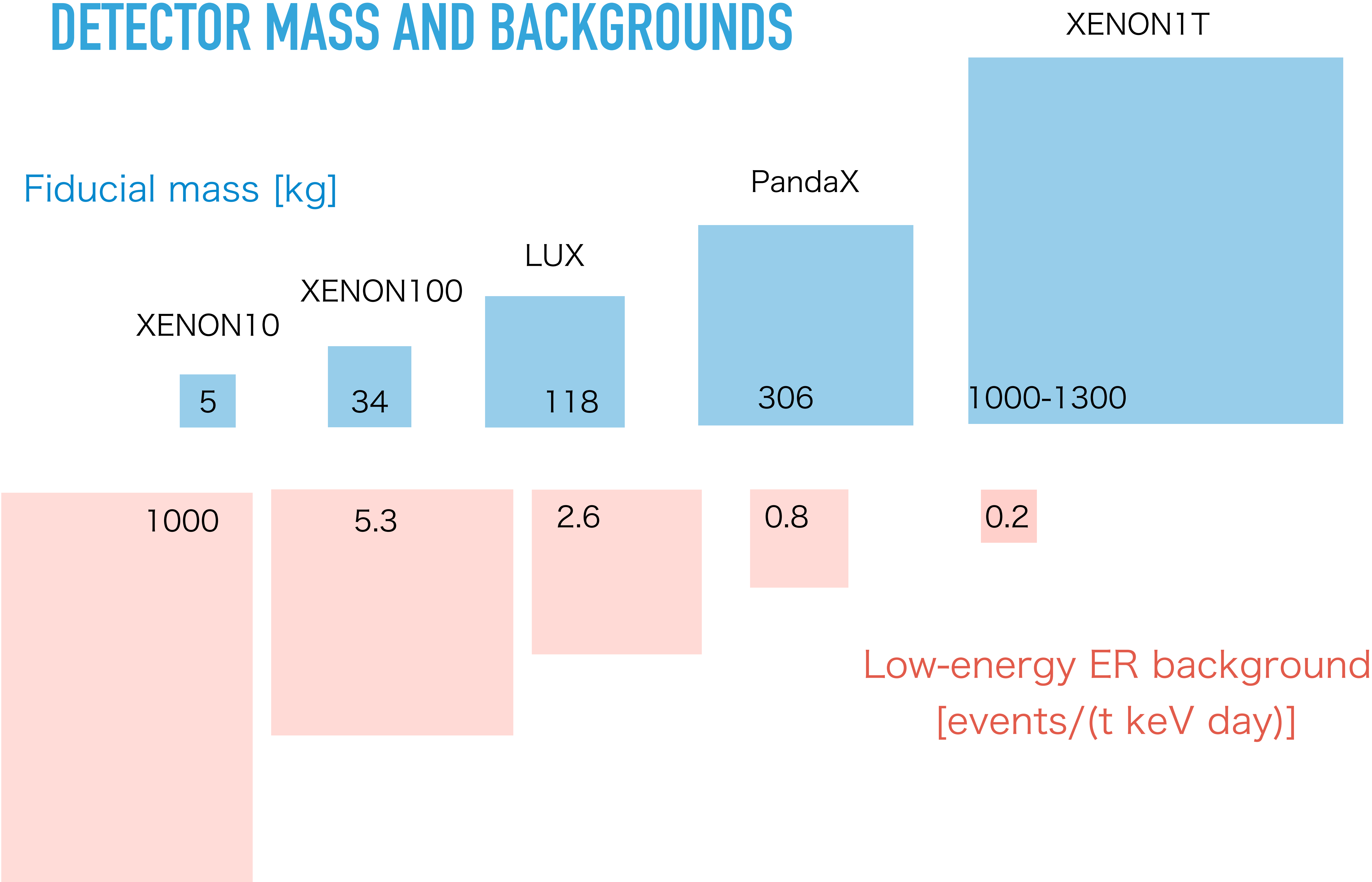


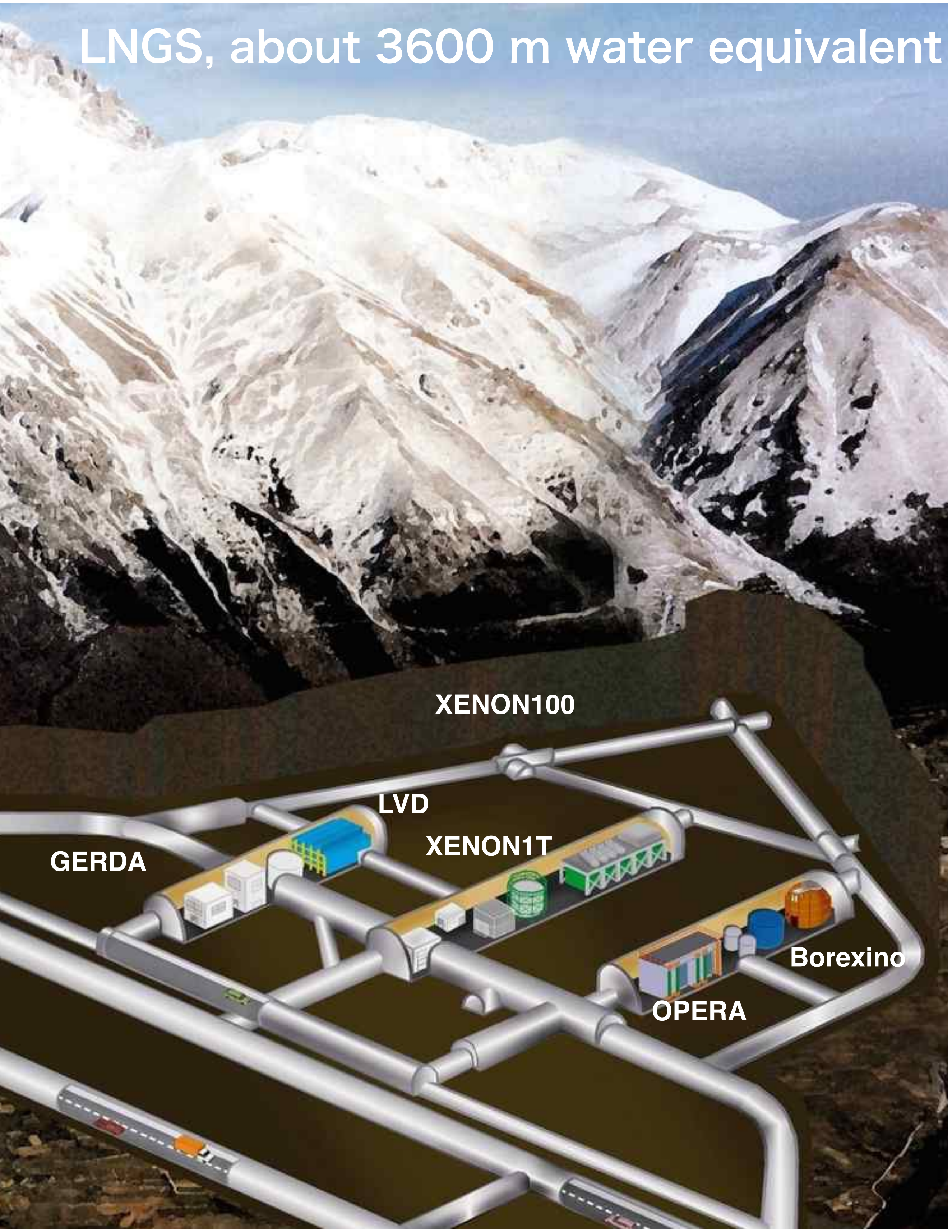
DARWIN



2005-2007	2008-2016	2012-2018	2019-2023	2020+
15 kg	161 kg	3200 kg	8200 kg	50 tonnes
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2	~10^{-49} cm^2

DETECTOR MASS AND BACKGROUNDS




LNGS, about 3600 m water equivalent
XENON100
LVD
XENON1T
GERDA
Borexino
OPERA

XENON1T AT THE GRAN SASSO LABORATORY

Water tank and Cherenkov muon veto

Cryostat and support structure for TPC

Time projection chamber

Cryogenics pipe (cables, xenon)

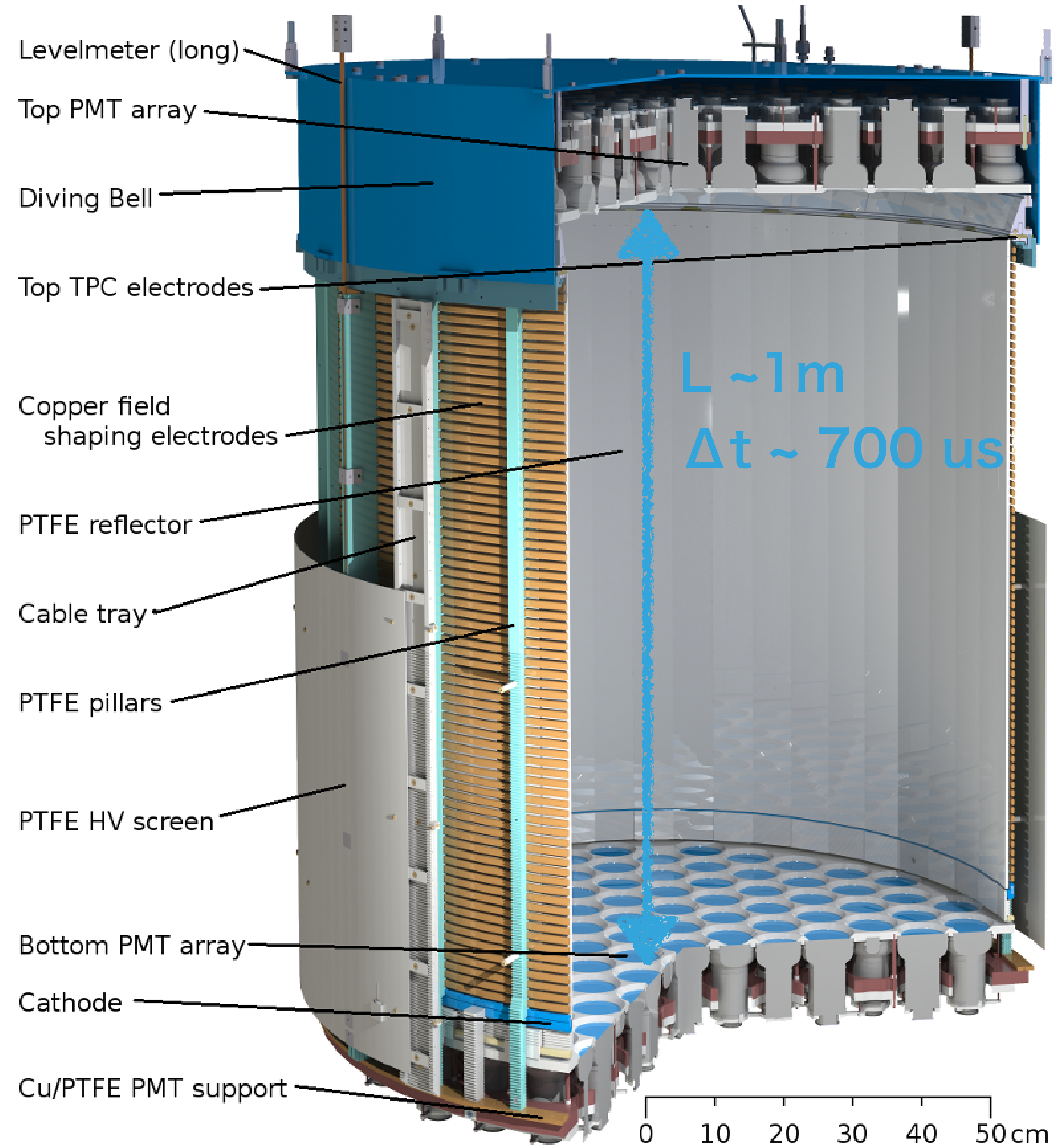
Cryogenics and purification

Data acquisition and slow control

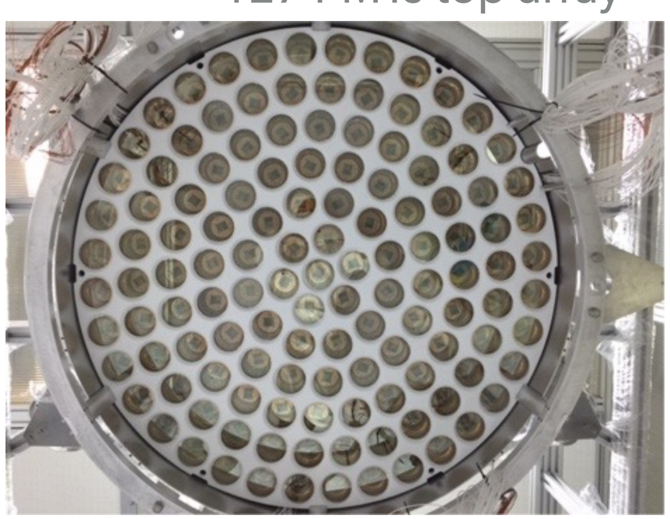
Xenon storage, handling and Kr removal via cryogenic distillation

THE TIME PROJECTION CHAMBER

- 3.2 t LXe in total, 2 t in the TPC
- 97 cm drift, 96 cm diameter
- 248 3-inch PMTs (R11410-21, QE~35%)
- 74 Cu field shaping rings, 5 electrodes, 4 level meters
- Fully covered with high reflectivity PTFE to maximize light collection.
- E-drift = 0.122 kV/cm for SR0, 0.08kV/cm for SR1 (design value is ~ 1kV/cm)
- E-extraction ~ 8kV/cm (d(anode, gate) = 5mm)



127 PMTs top array



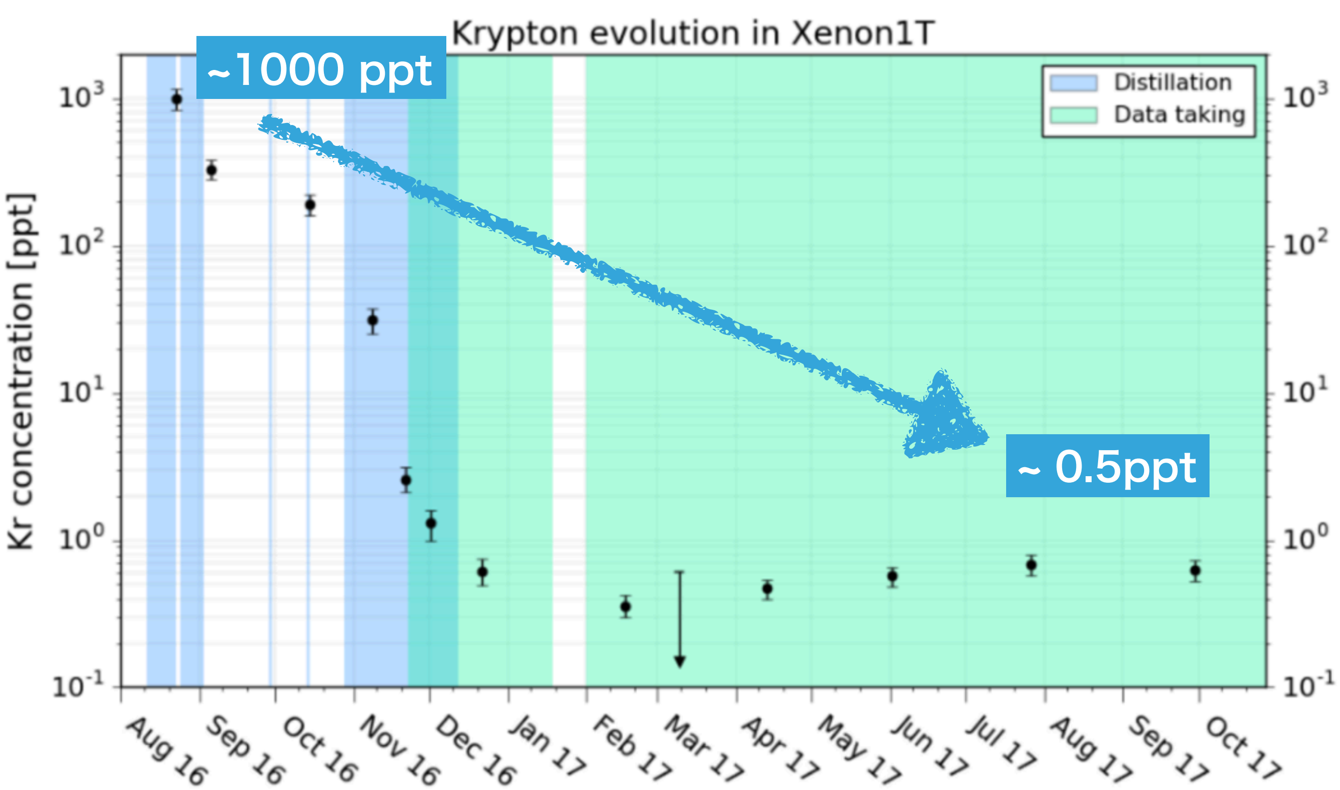
121 PMTs bottom array

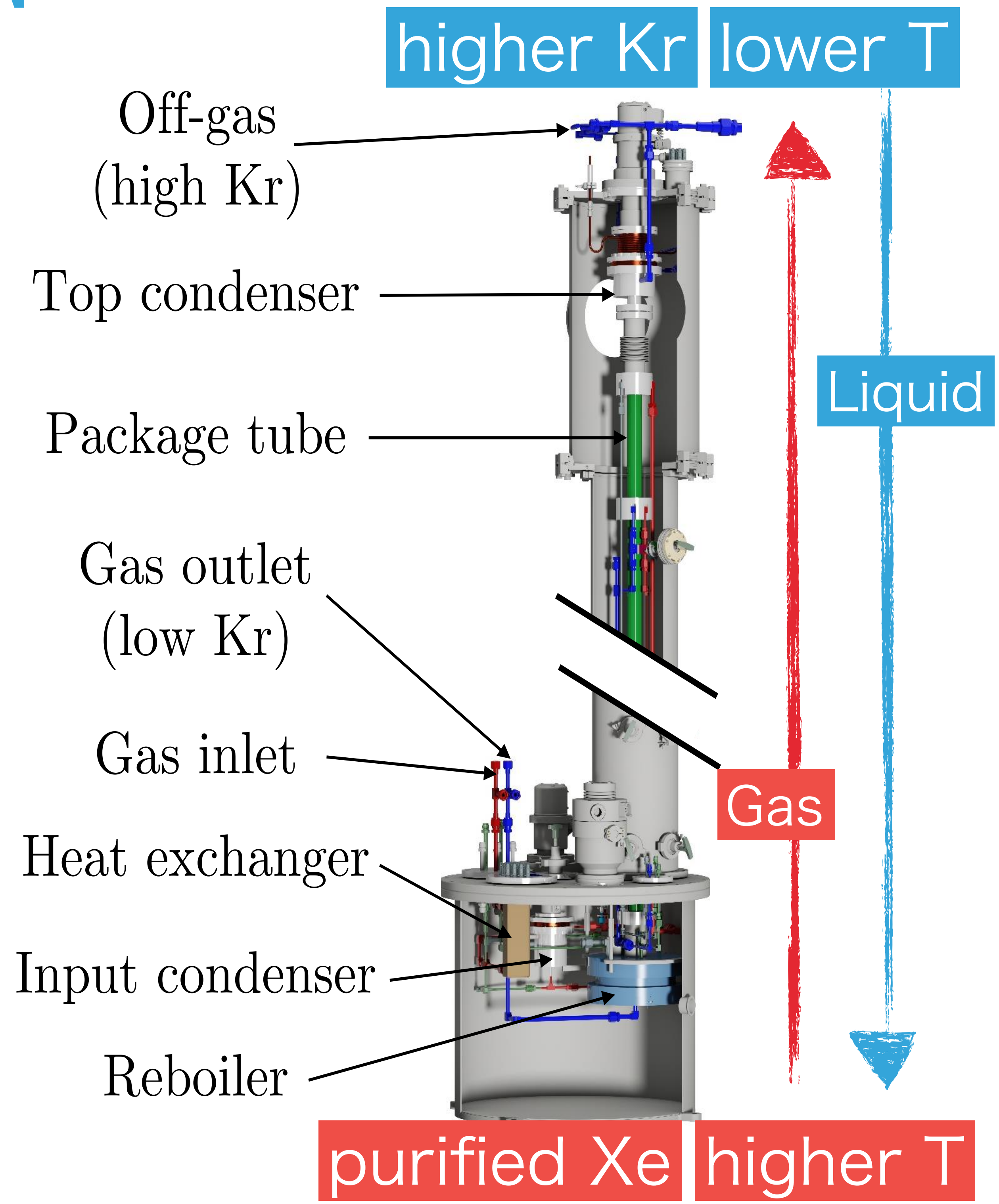
XENON collaboration, EPJ-C 77 (2017) 5

For Rn removal - see XENON collaboration, EPJ-C 77 (2017) 6

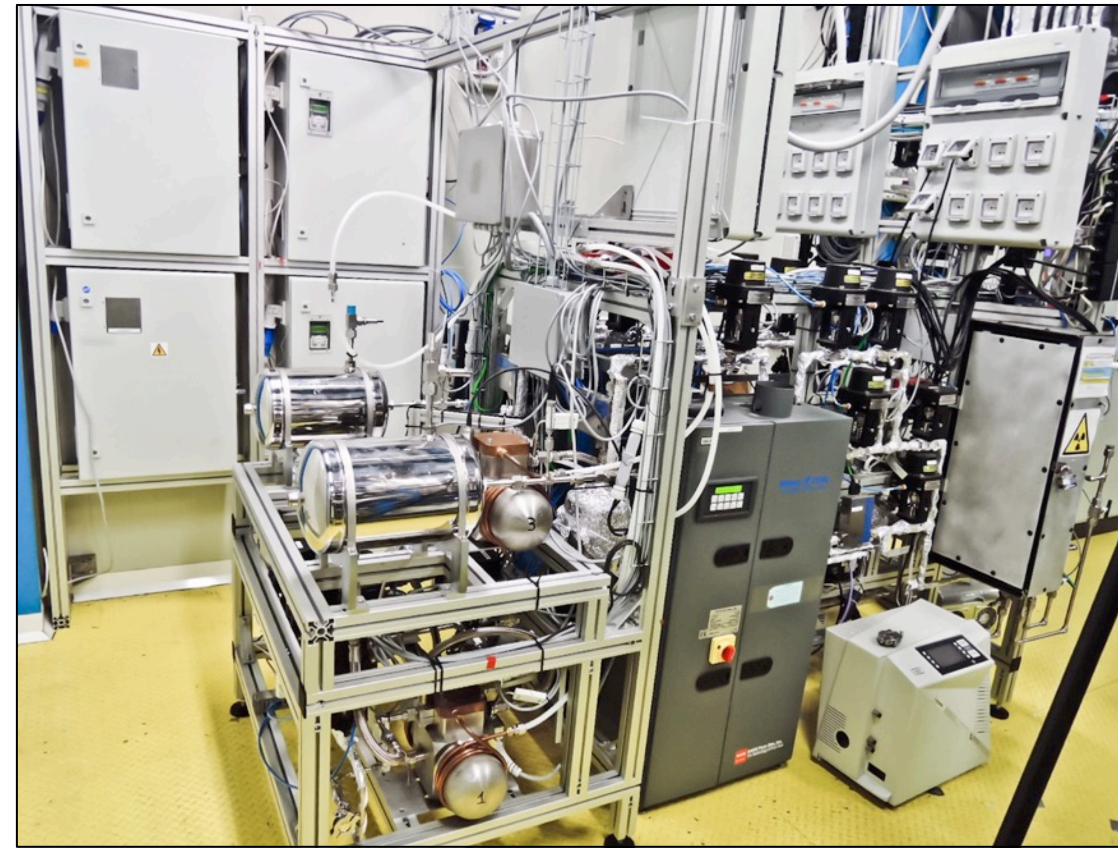
THE KRYPTON DISTILLATION COLUMN

- Commercial Xe: 1 ppm - 10 ppb ^{nat}Kr,
- ^{85}Kr is unstable ($T_{1/2}$ = 10.8 y, Q-value = 687 keV)
- Solution: 5.5 m cryogenic distillation column
- Utilizes different vapor pressure:
  - Kr: 20900 mbar@178K, Xe: 2010 mbar@178K
  - boiling point@2bar Xe:178K, Kr:140-150K
- 6.5 kg/h output > 6.4×10^5 separation, to < 48 ppq

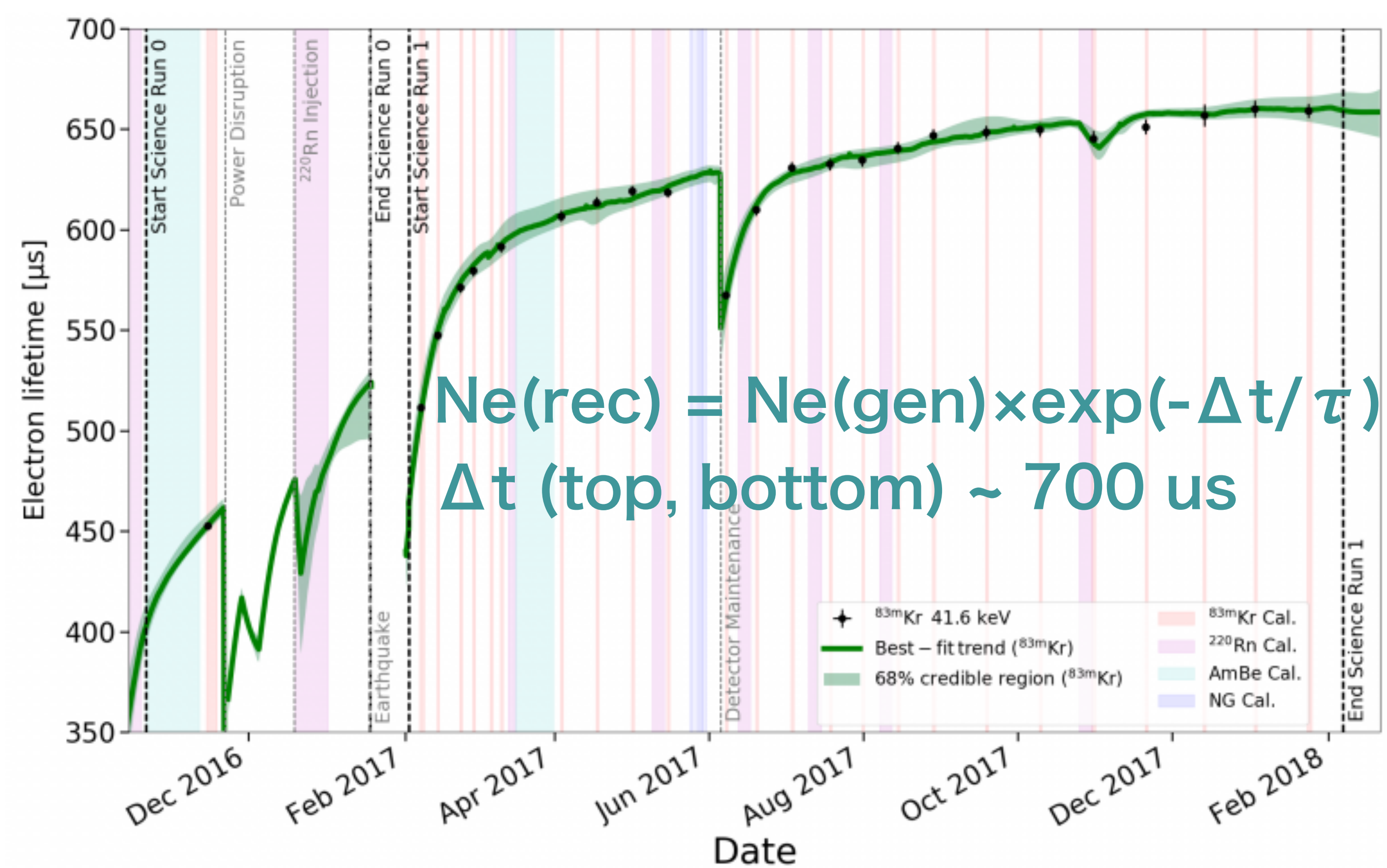




XENON PURIFICATION

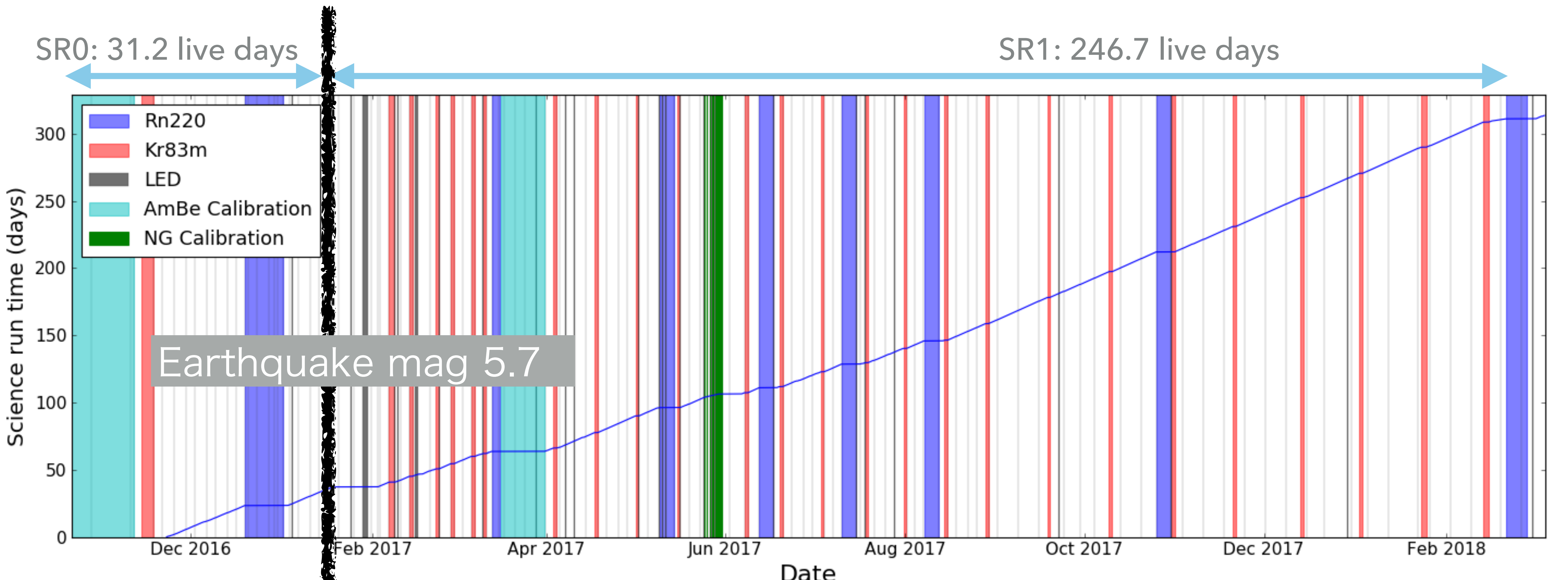


- Electronegative impurities in the Xe gas and from materials outgassing reduce charge (and light) signals.
- To drift electrons over 1 meter requires < 1ppb (O_2 equivalent)
- Solution: continuous gas circulation at high flow through heated getter material
- Total flow rate of 54slpm (design: 100 slpm) driven by up to 4 pumps.
- electron lifetime is monitored regularly with ERs calibration sources.



DATA OVERVIEW

- First science run (SR0): Oct 2016 - Jan 2017 (31.2 live days)
- Second science run (SR1): Feb 2017 - Feb 2018 (246.7 live days)
- 1 tonne x year exposure given 1.3 tonne fiducial volume: the largest reported to-date with this type of detector



E-drift = 0.122 kV/cm

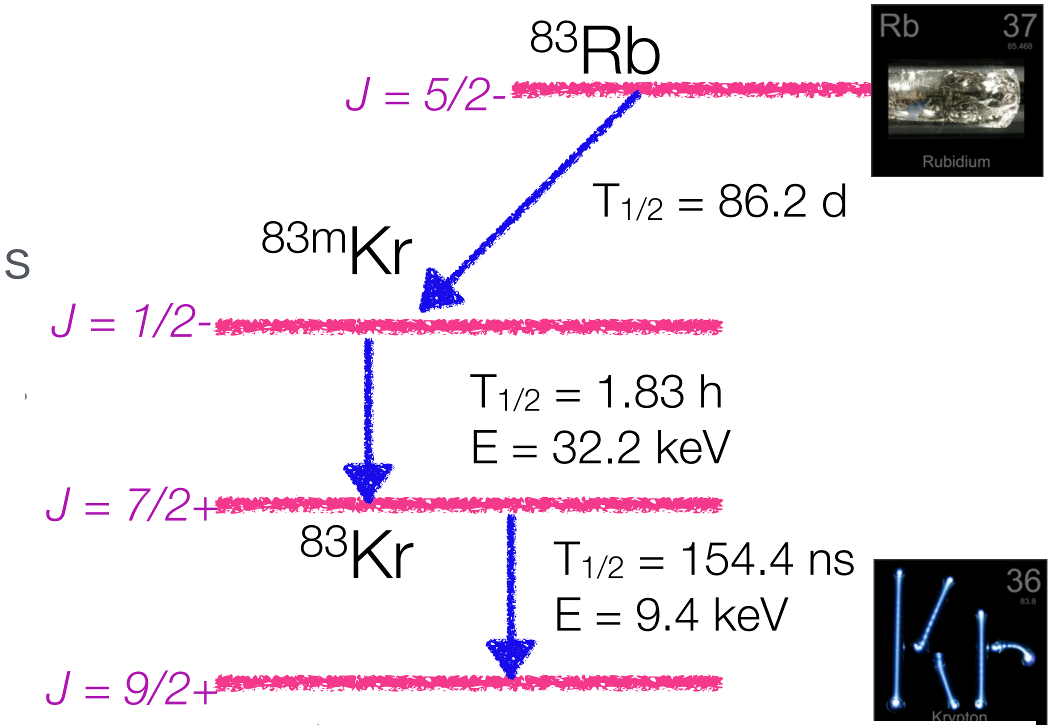
E-drift = 0.08 kV/cm

(E-drift (design) ~ 1 kV/cm)

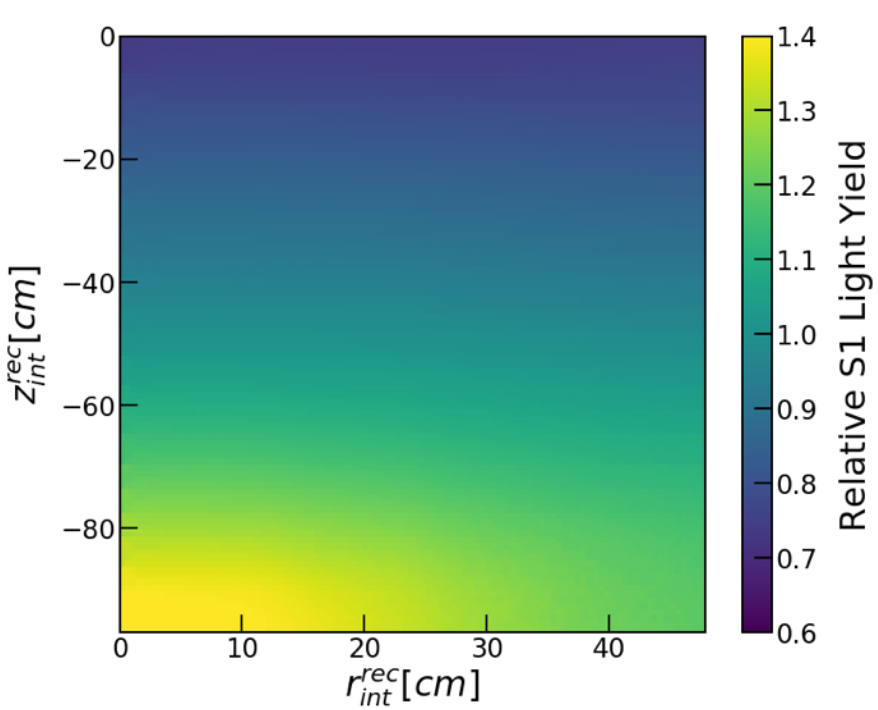
CALIBRATION – DETECTOR RESPONSE CORRECTION –

Spatial signal corrections with ^{83m}Kr source

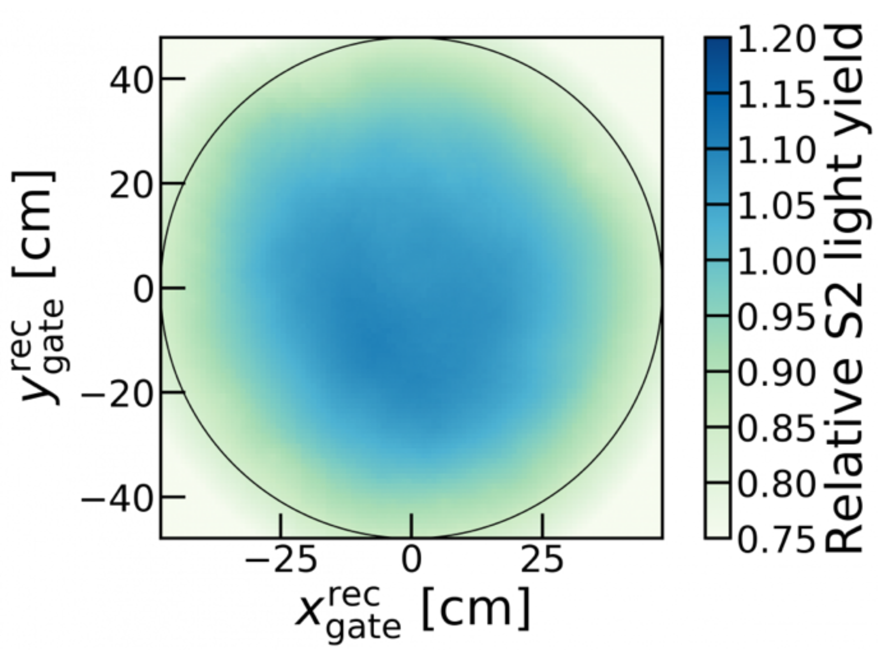
- Internal source (injected directly into LXe)
- 32.2 keV and 9.4 keV emissions separated by $T_{1/2}$ =154 ns
- Used for several corrections
  - Position dependent light collection efficiency
  - Position dependent S2 amplification
  - Electron lifetime correction



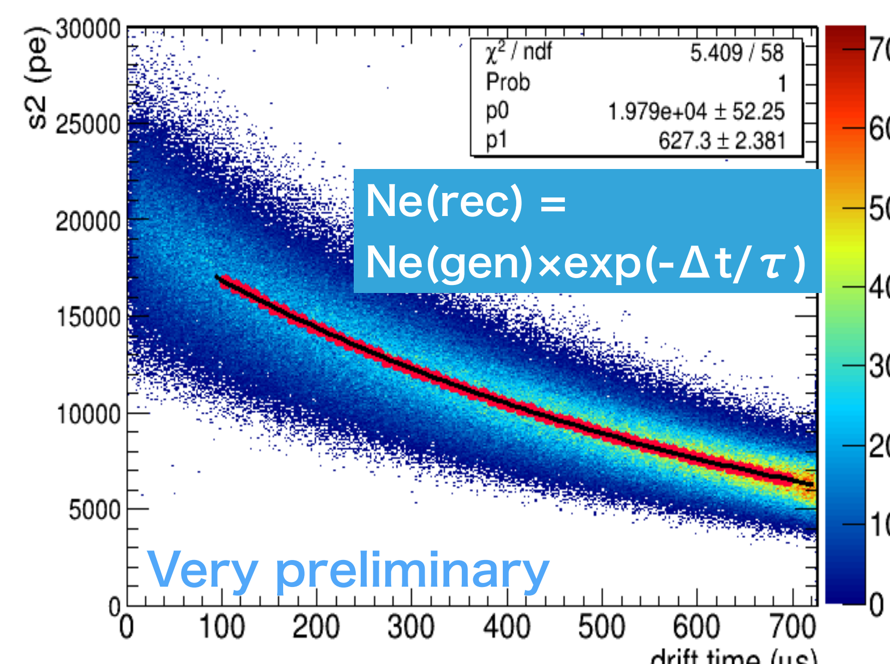
S1 light collection efficiency



S2 gain

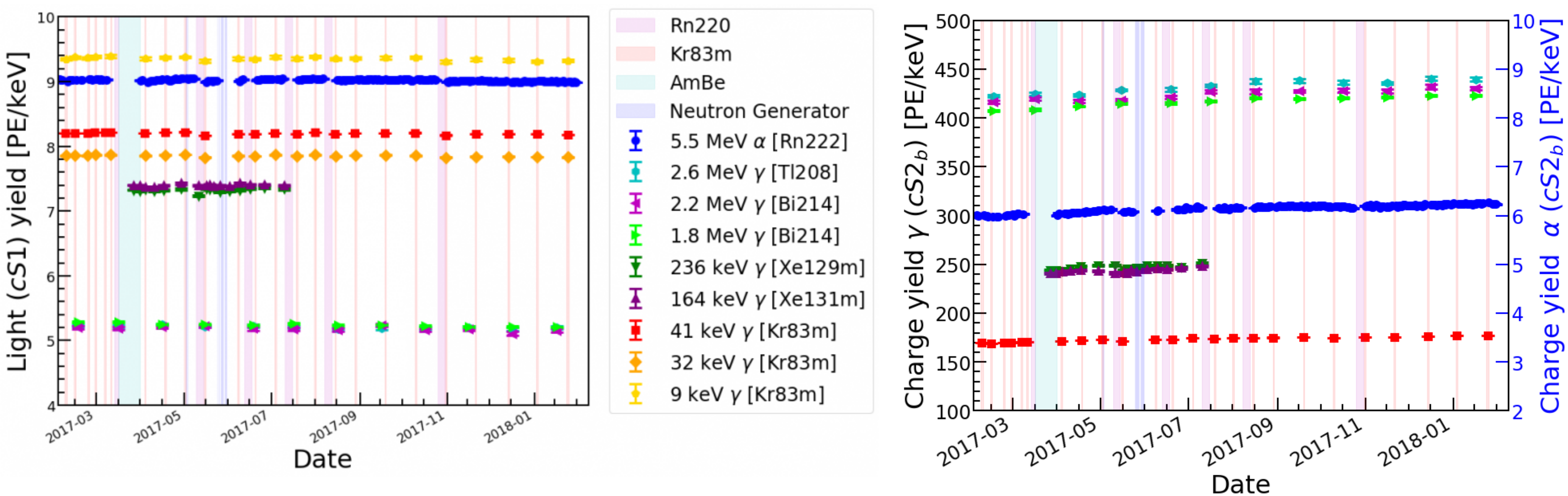


S2 electron lifetime



LIGHT AND CHARGE YIELD VERSUS TIME

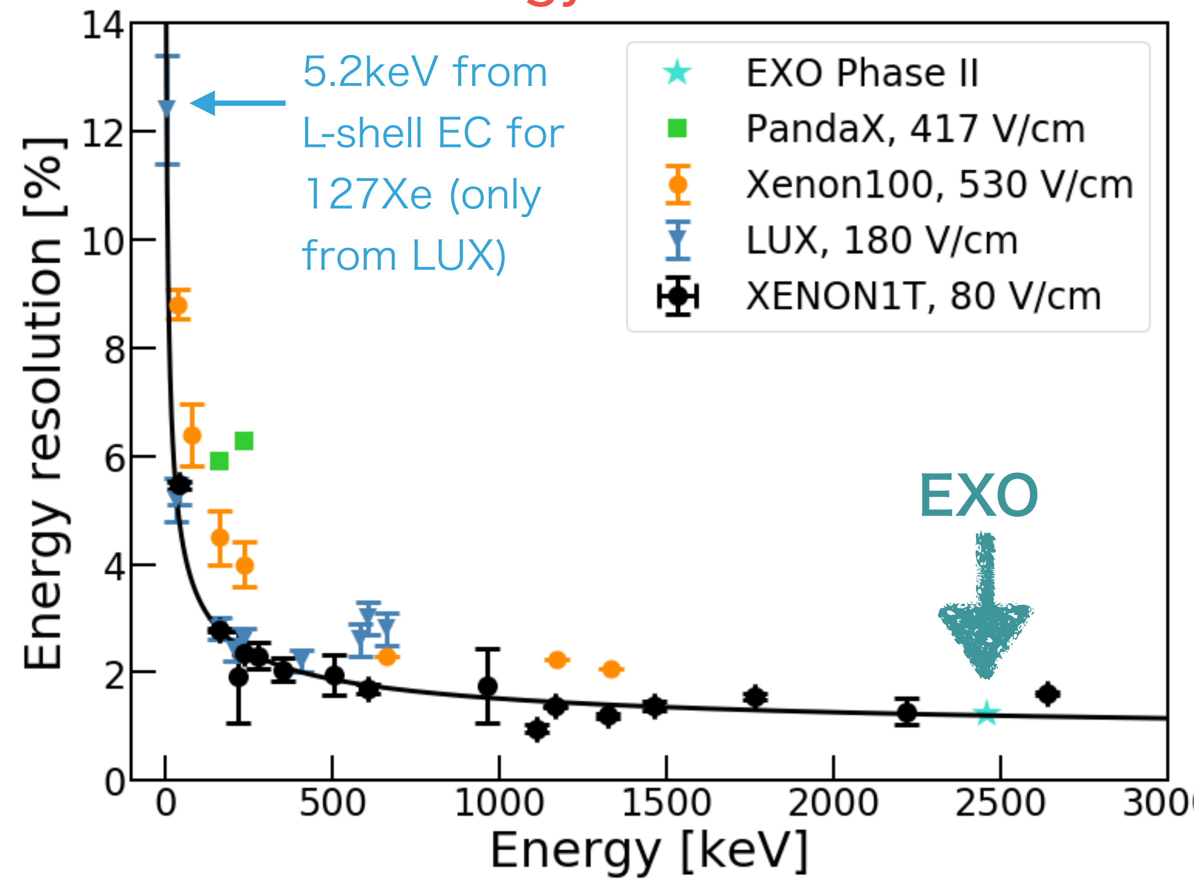
- Light yield: stable within 0.16% (^{83m}Kr) and 0.18% (^{222}Rn alphas)
- Charge yield: slightly increasing for all sources, 1.4% (^{83m}Kr) and 1.2% (^{222}Rn alphas)



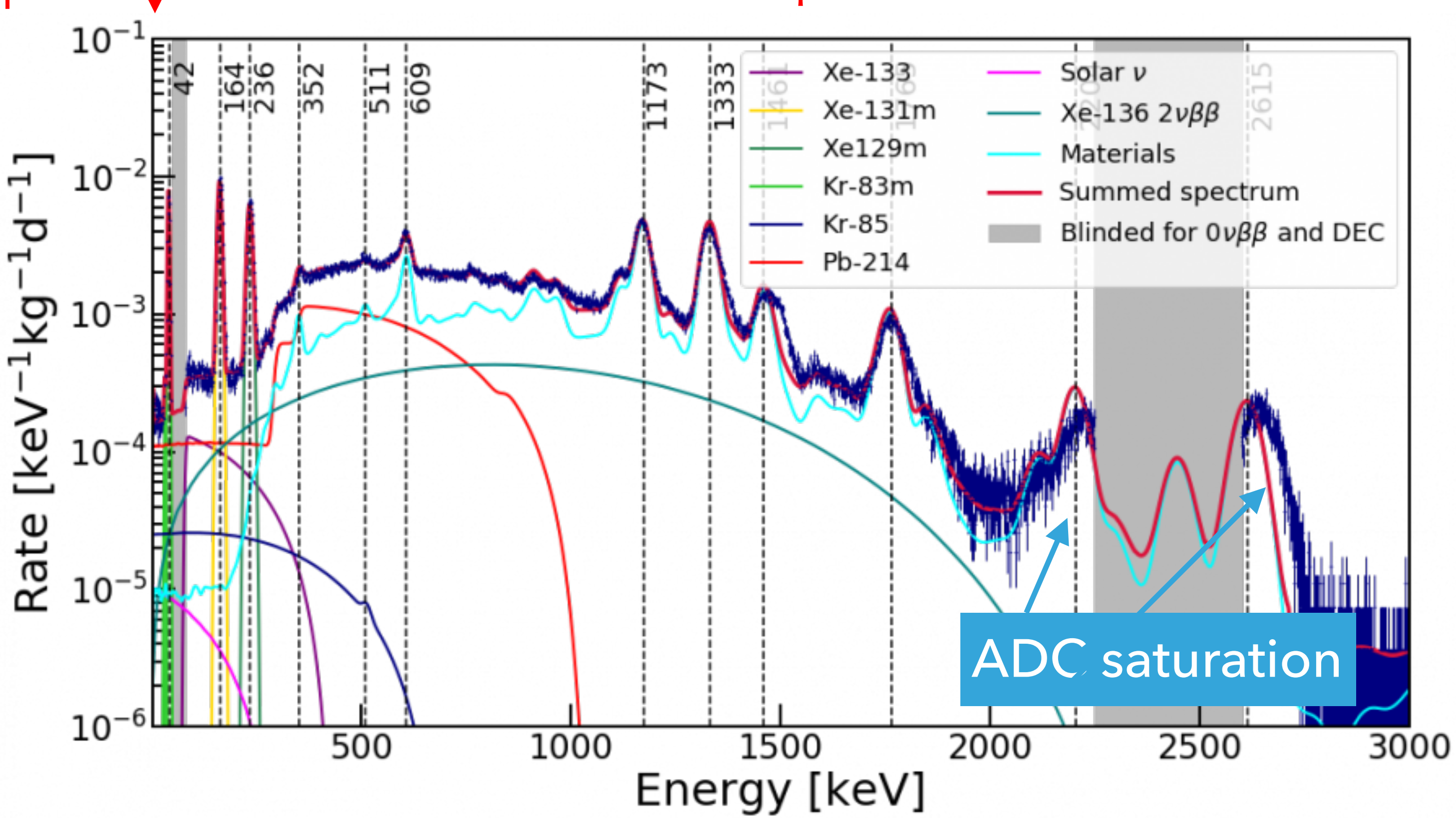
ENERGY RESOLUTION

- One of the best among Xe-TPCs
- Covers large energy range
- Relevant for $0\nu\beta\beta$-analysis (^{136}Xe) & for background understanding

1.5% energy resolution at 2.5 MeV



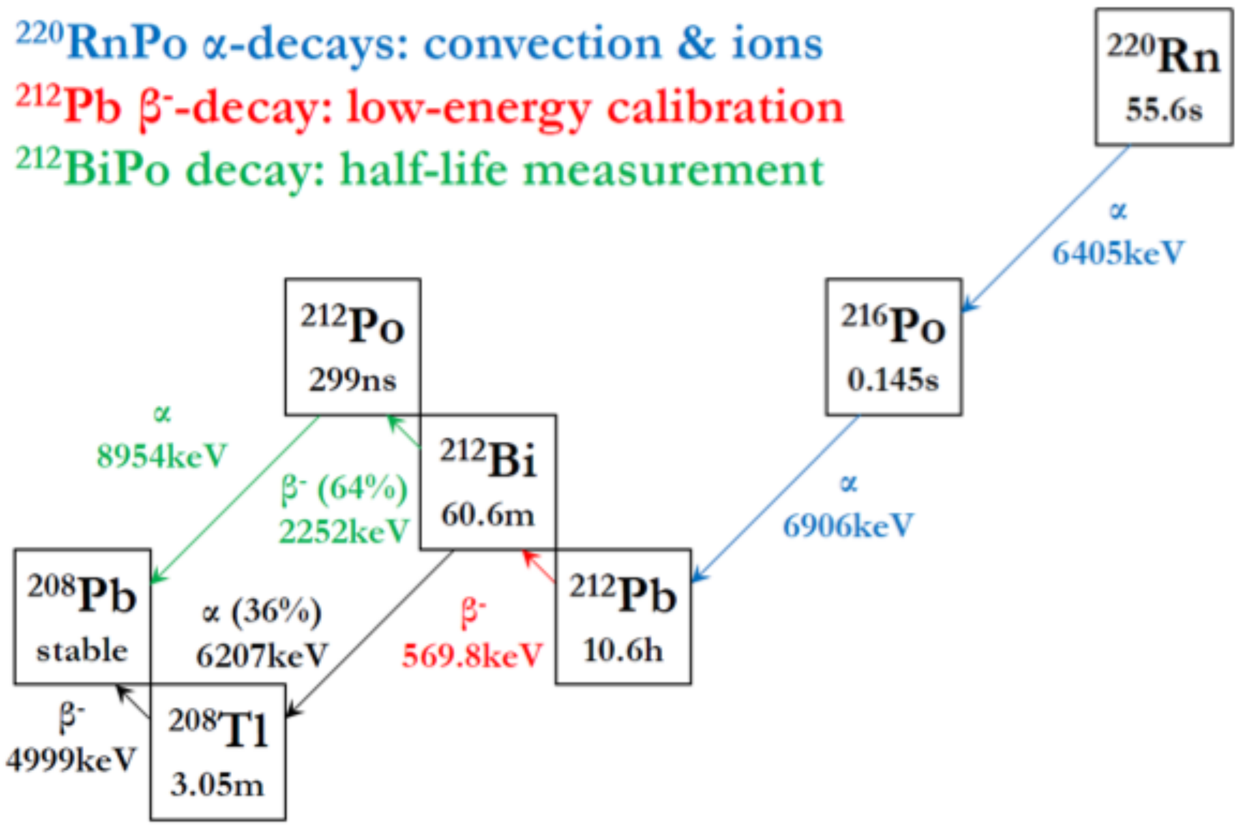
ROI for WIMP search up to 11 keV



- Background spectrum: data versus MC
- Good agreement between predicted and measured background spectrum
- Kr: 0.66 ppt; Pb214: ~ 10 uBq/kg
- Gammas based on screening measurements
- Blinded regions: $0\nu\beta\beta$-search

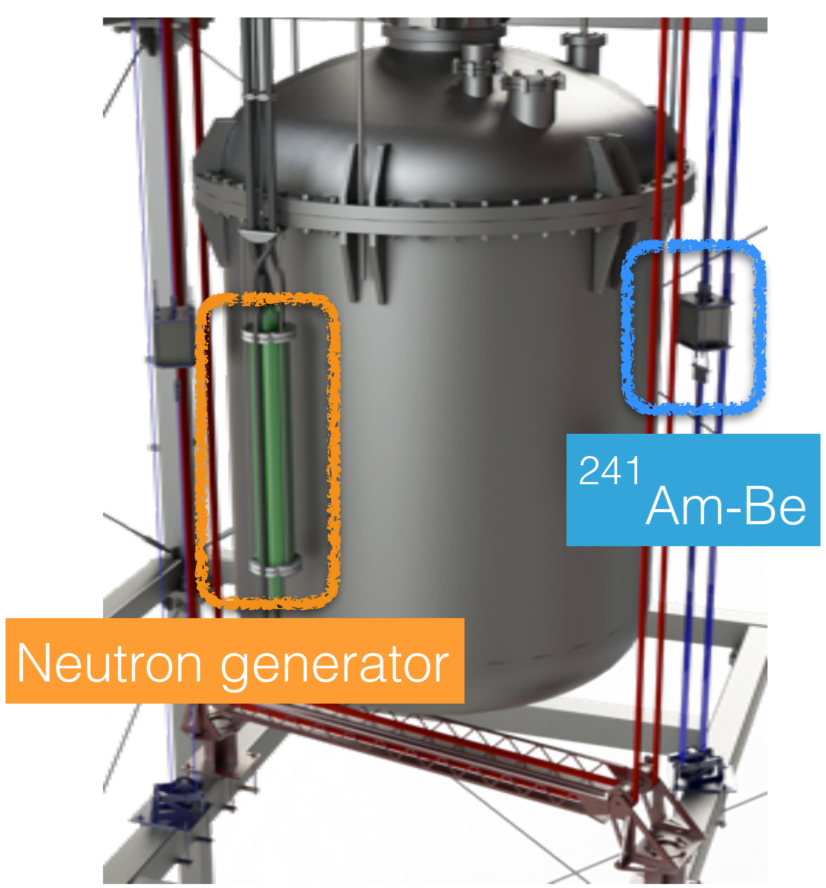
ER/NR CALIBRATION

ER



- Energies of commonly used γ-ray sources are not sufficient to reach fiducial volume
- Inject ^{220}Rn (decay product of ^{228}Th) into xenon
- ^{212}Pb buildup → β^- decay to ^{212}Bi (low energy ER events)
- Decay of activity dominated by ^{212}Pb half-life (10.6h)
  - No long-lived isotopes
  - No purification requirement on LXe

NR



- External source mounted on a belt ((α, n) reaction)

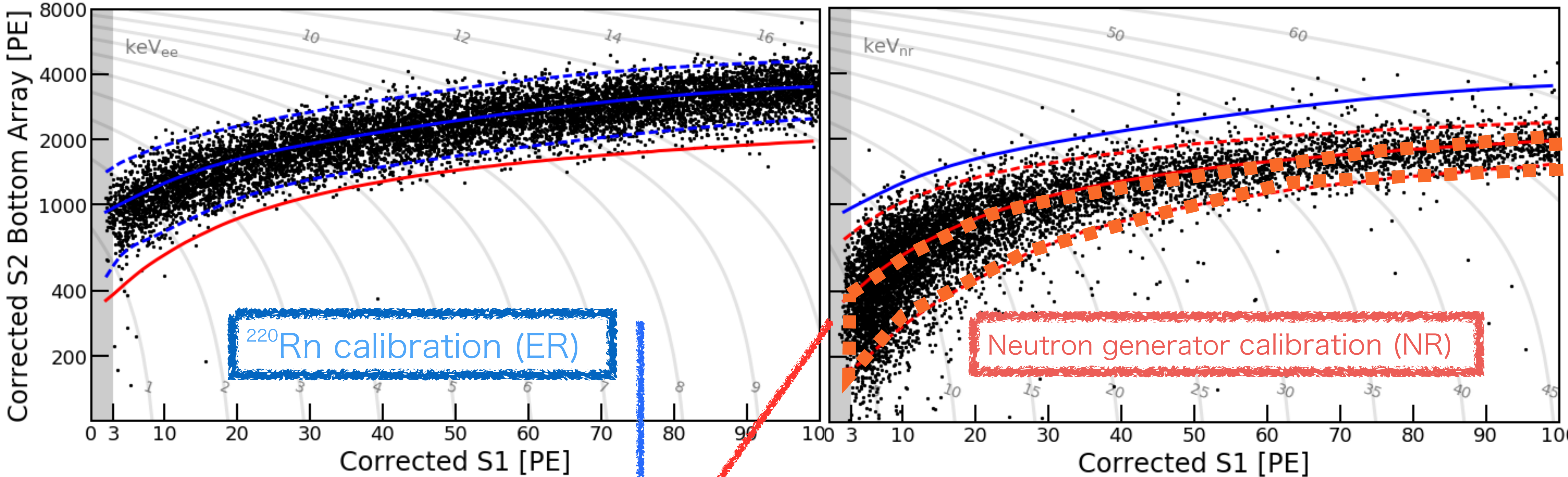
  ^{241}Am → ^{237}Np + α + γ (59.5 keV)

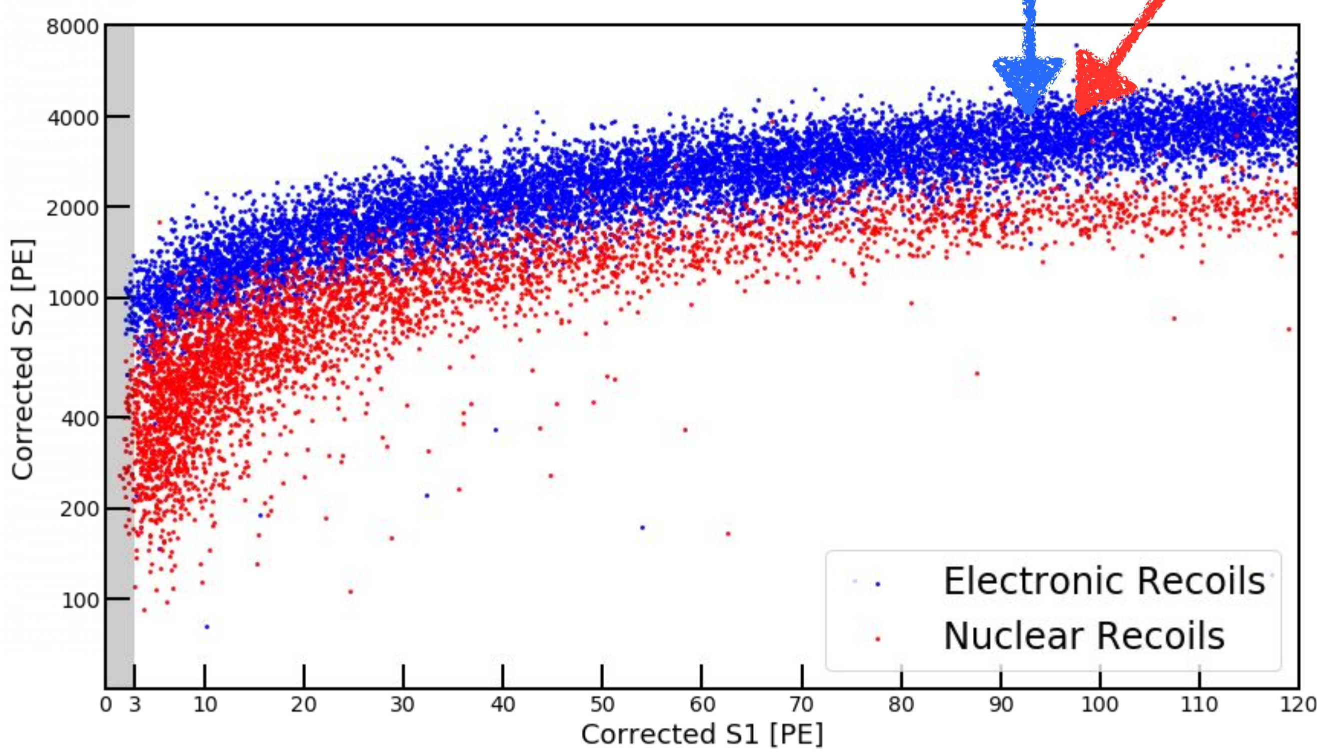
  ^{9}Be + α → ^{12}C + **n (O(1)MeV)** + γ (4.4 MeV)

- D-D fusion neutron generator (D + D → n + ^{3}He) is also commissioned
- E_n : peak at 2.45 MeV
- Calibration time reduced by an order of magnitude (weeks → days)

ER/NR BAND DISTRIBUTIONS

Blue: ER, Red: NR; ——: median, ·····:$\pm 2\sigma$

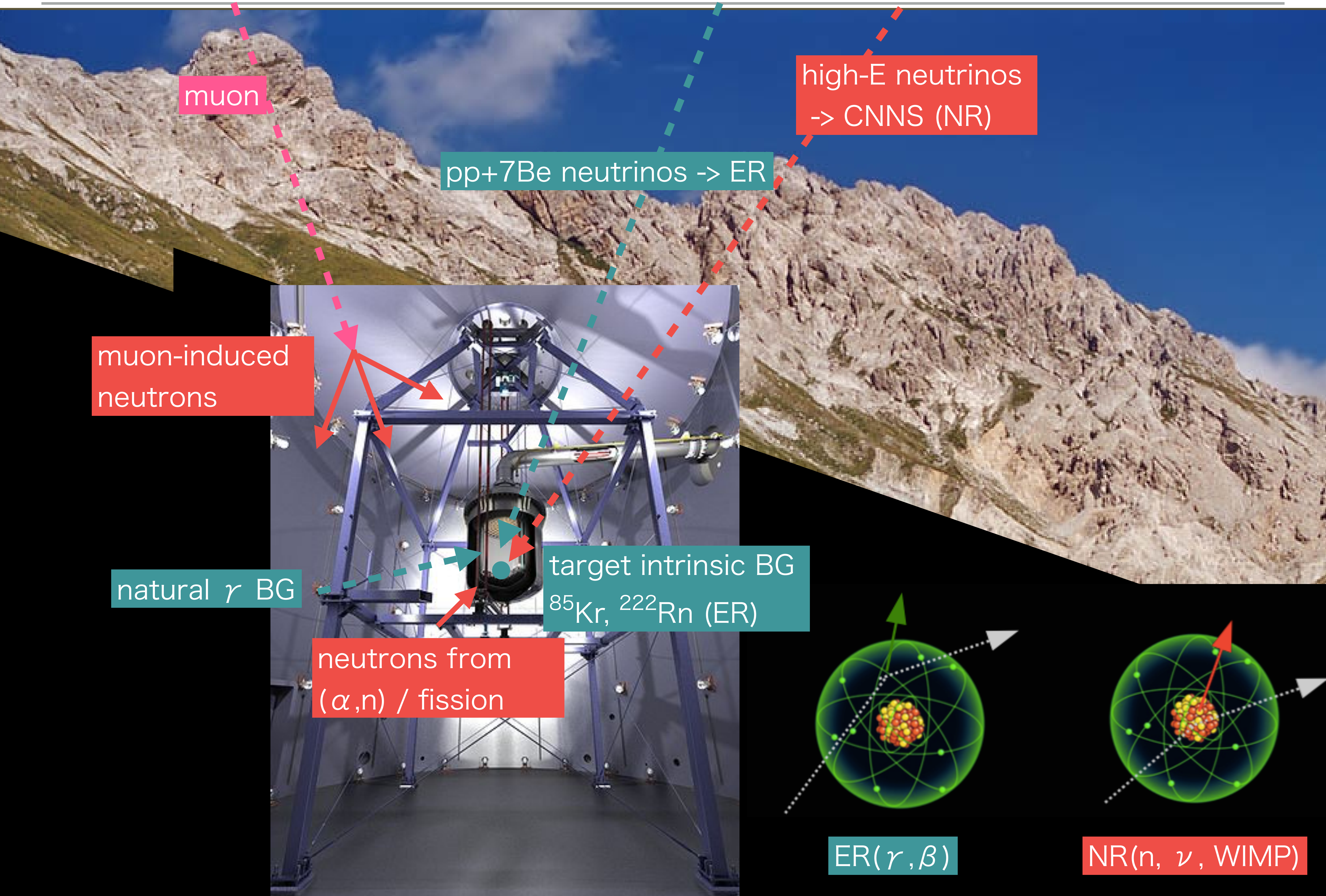




- ER and NR are well separated with each other, but separation is not perfect
- The region below NR-mean and above NR -2σ region was used as signal region in the past.
- Current analysis uses full S1 & S2 shapes in the profile likelihood, but still can be used as a reference
- ER-leakage fraction below NR mean is ~ $(1\text{-}3)\times10^{-3}$, which is similar discrimination power as for XENON100, LUX and Panda-X experiments.

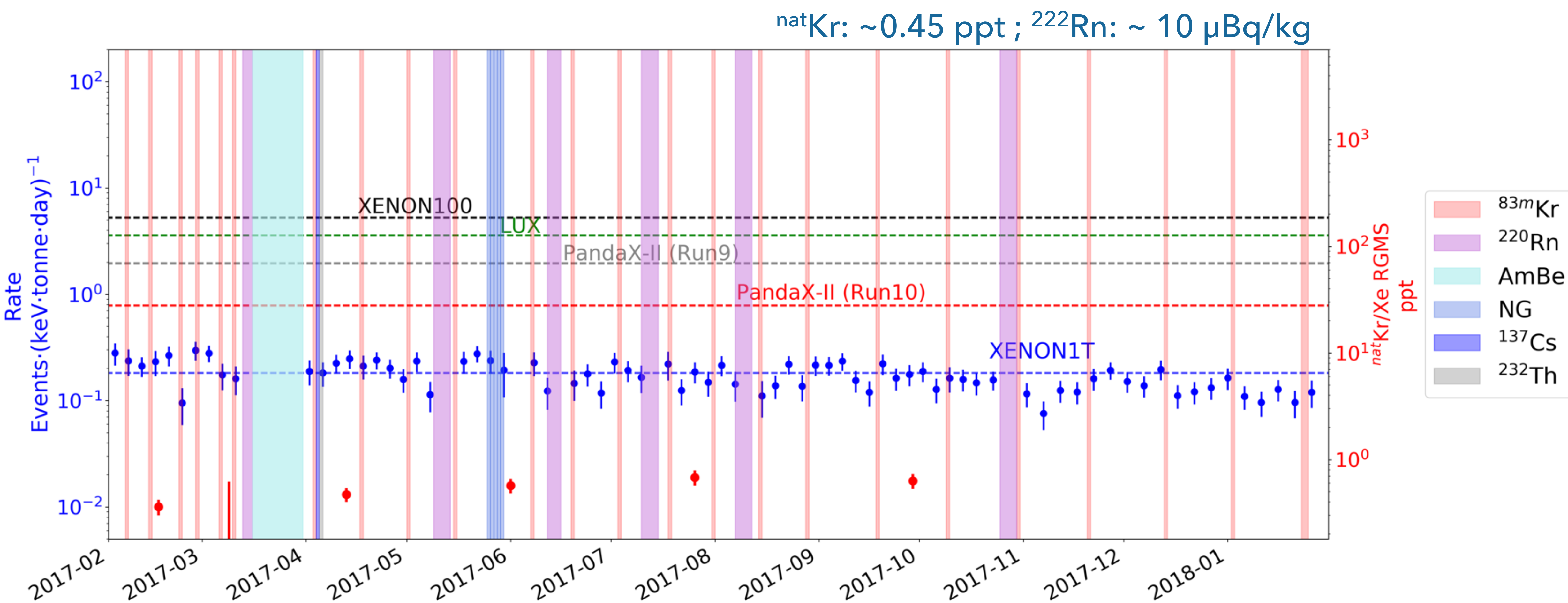
BACKGROUNDS FOR XENON1T ANALYSIS

BACKGROUND SOURCES



ER BACKGROUND PREDICTIONS AND DATA

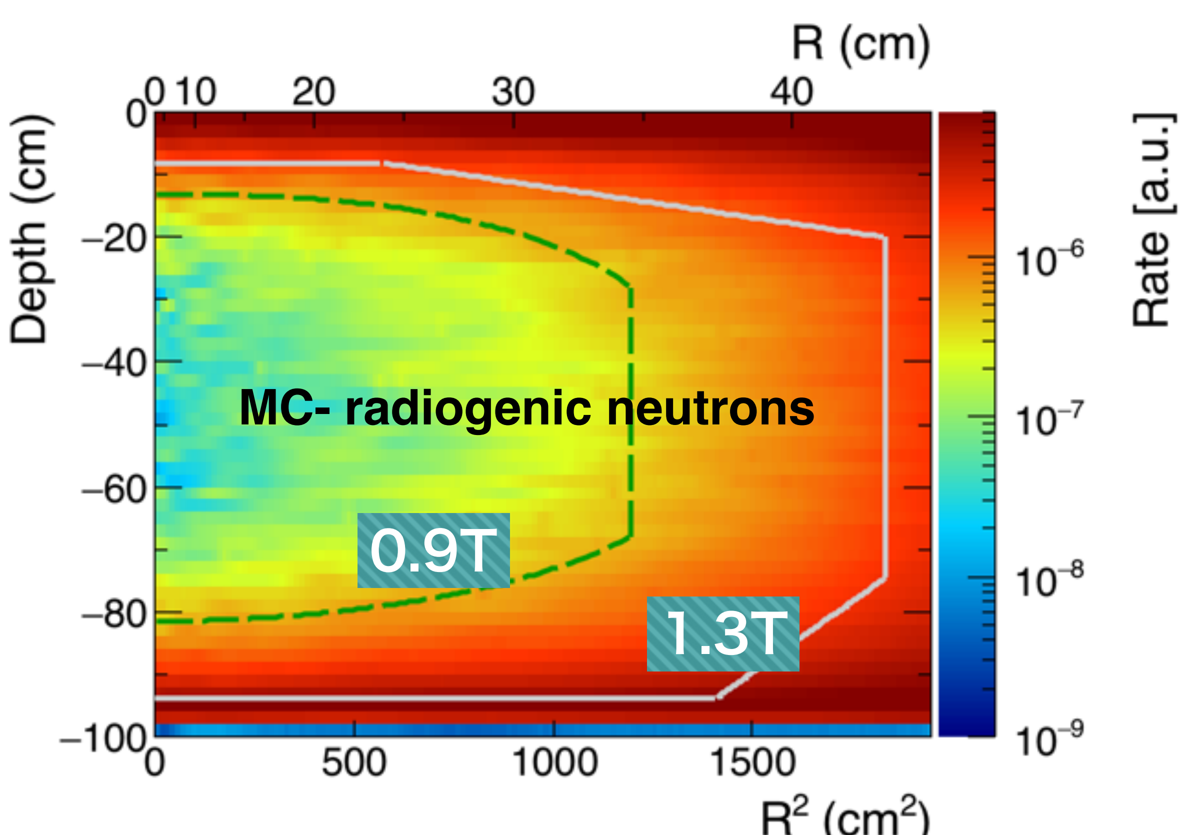
- ER rate: (82±3) events/(keV t y), in 1.3 t and below 25 keV$_{ee}$
  - In the reference region, ~0.2 events/(keV t y)
- Lowest background ever achieved in a dark matter detector



^{222}Rn: 85.4%, ^{85}Kr: 4.3%, solar ν: 4.9%, materials: 4.1%, ^{136}Xe: 1.4%

NUCLEAR RECOIL BACKGROUND

- Muon-induced neutrons: reduced by overburden and veto
- CEνNS from ^{8}B neutrinos: irreducible background < 1 keV
- Radiogenic neutrons from (α,n) and fission from ^{238}U and ^{232}Th: reduced via material selection, multiplicity and fiducialisation

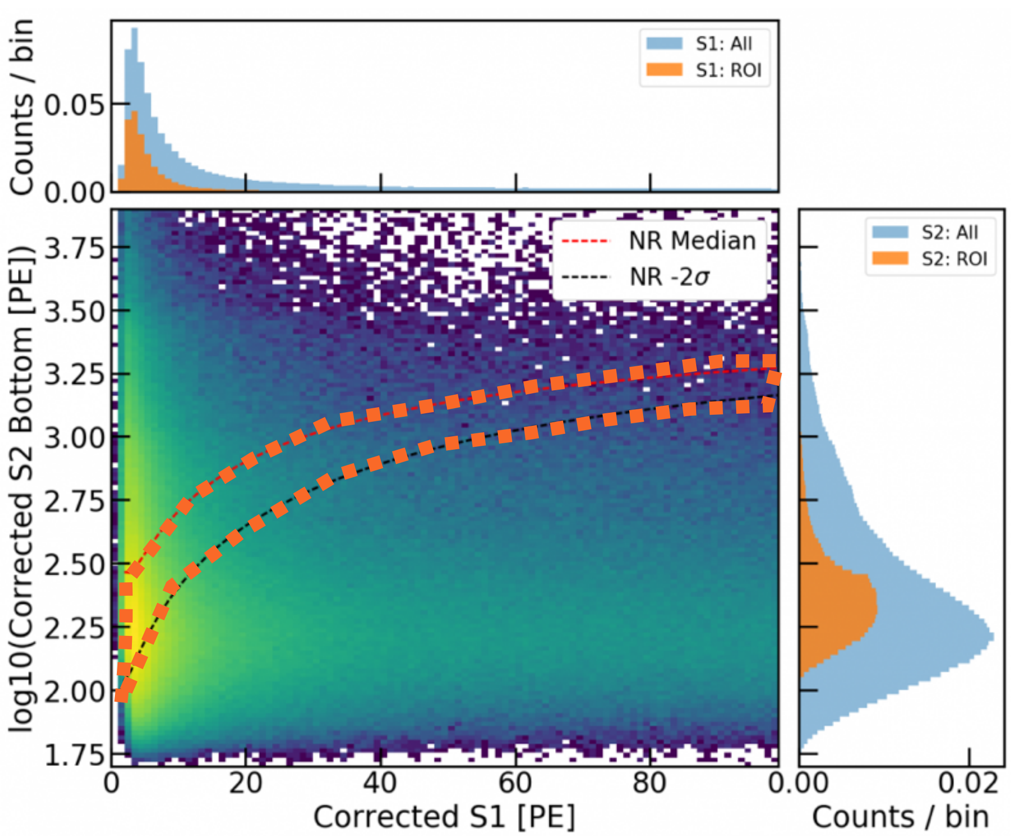


Source	Rate [t^{-1} y^{-1}]	Fraction [%]
Radiogenic	0.6±0.1	96.5
CEνNS	0.012	2.0
Cosmogenic	<0.01	<2.0

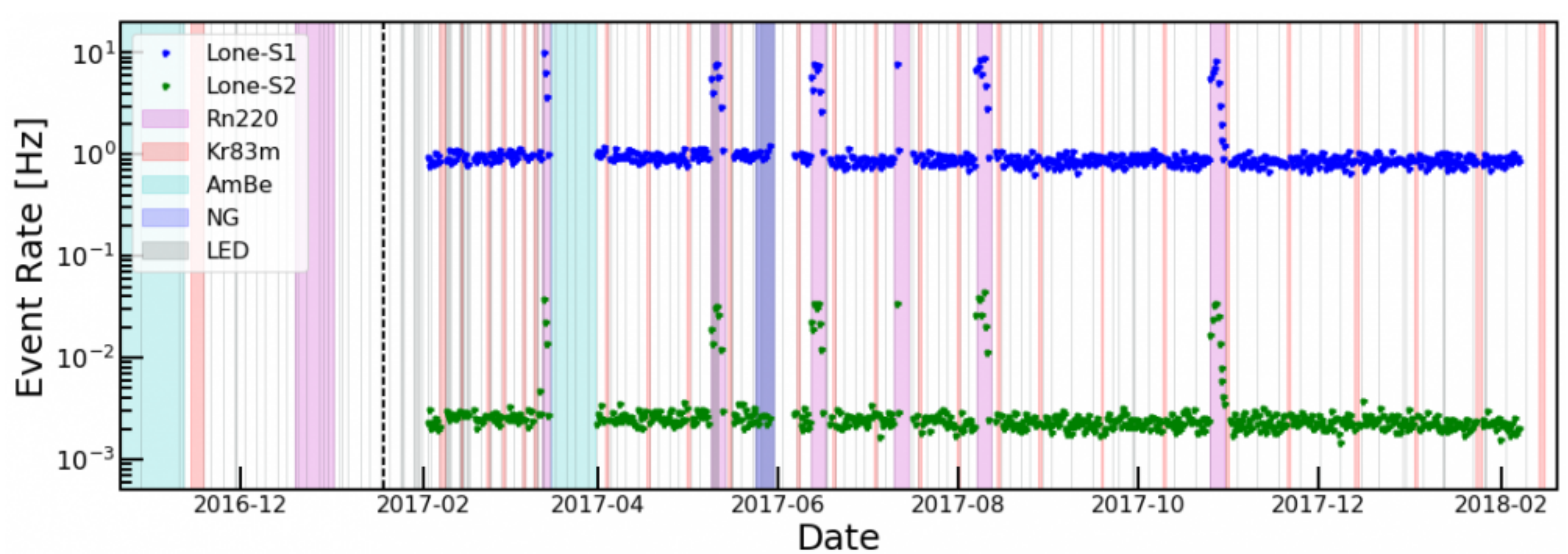
Expectation in 1tonne FV, 4-50 keV$_{nr}$ window

ACCIDENTAL COINCIDENCE BACKGROUND

- “Lone” S1- S2 coincidences: S1 from e.g. events below the cathode, S2 e.g. near field grids - can fake events that populate signal region
- Empirical model: select unpaired S1 and S2 from data, randomly pair to form events; apply analysis selection criteria
- Performance verified using ^{220}Rn data and sidebands background data



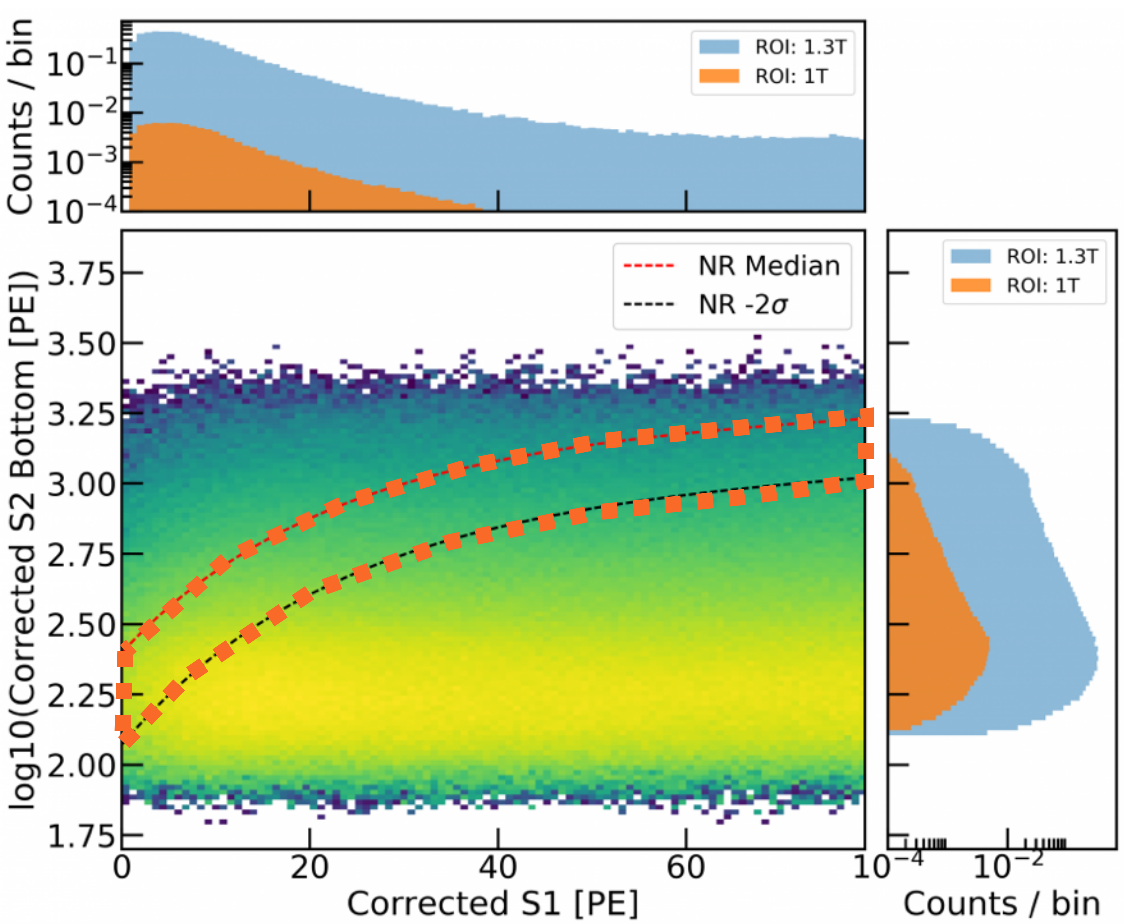
Lone S1 and S2 rates versus time

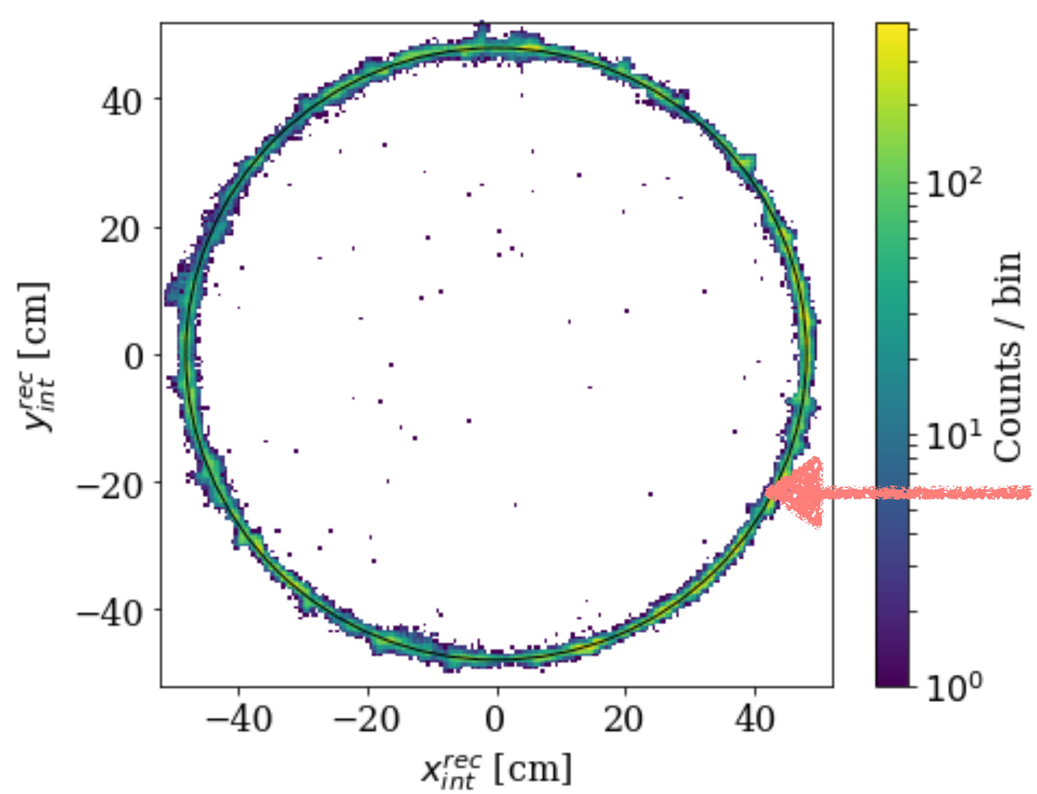


SURFACE BACKGROUND

- During construction, ^{222}Rn progeny plate out on the inner PTFE walls,
- All short-lived isotopes decay away, leaving ^{210}Pb, ^{210}Bi and ^{210}Po on PTFE surface
- S2 for these isotopes becomes smaller due to charge loss on the PTFE walls: event can be reconstructed in the NR region
- can be suppressed by fiducialization of volume
- Data driven model derived from surface-event samples

^{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	7.7 MeV
^{210}Pb	22.3 y	β	
^{210}Bi	5.0 d	β	
^{210}Po	138 d	α	5.3 MeV
^{206}Pb	stable		

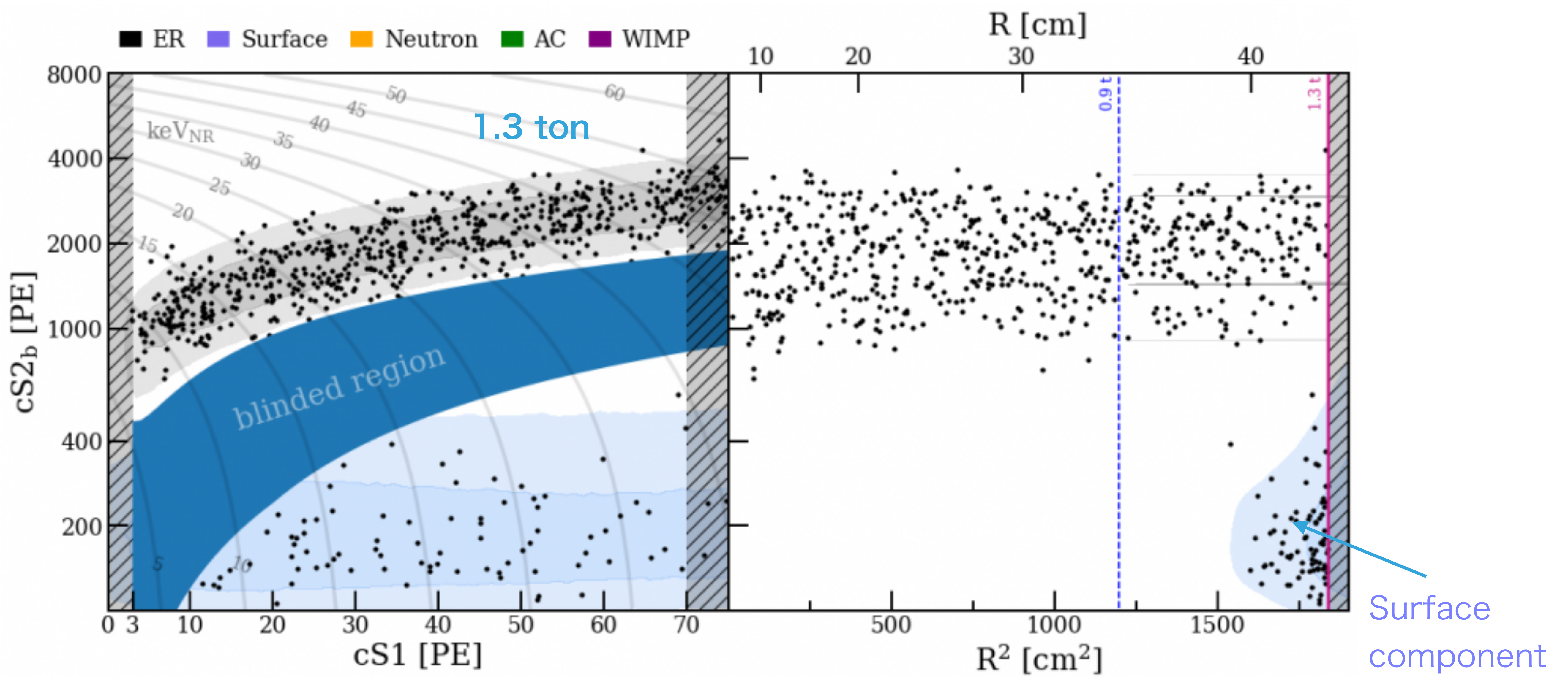




EVENT SELECTION AND RESULTS

DARK MATTER SEARCH DATA

- Blinded: to avoid bias in event selection and signal & BG modelling.
- NR ROI reference region was blinded from the start of SR1 analysis.
- Salted: to protect against post-unblinding tuning of cuts and background models



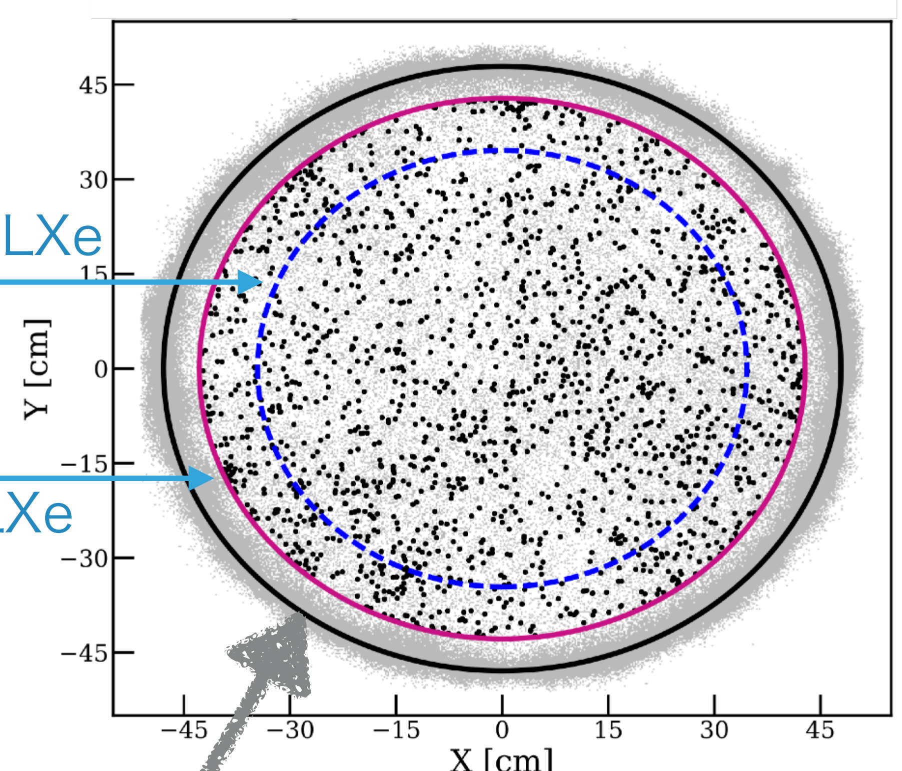
FIDUCIAL VOLUME SELECTION

- Optimised prior to unblinding by taking into account materials and surface background: 1.0 t → **(1.3±0.01) t**

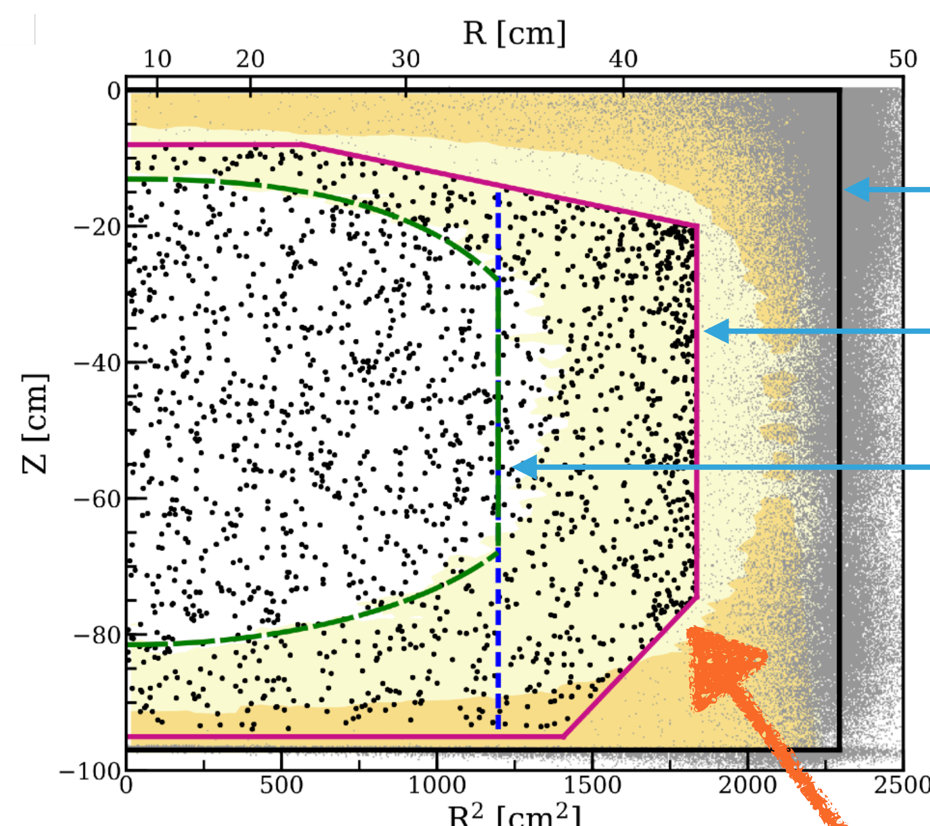
- PDFs for Profile Likelihood
  - **(S1, $S2_b$, r) space + [inner(0.9t) or outer(1.3t)]**

0.9 t LXe

1.3 t LXe



Grey: events outside FV



TPC boundary

1.3 t LXe

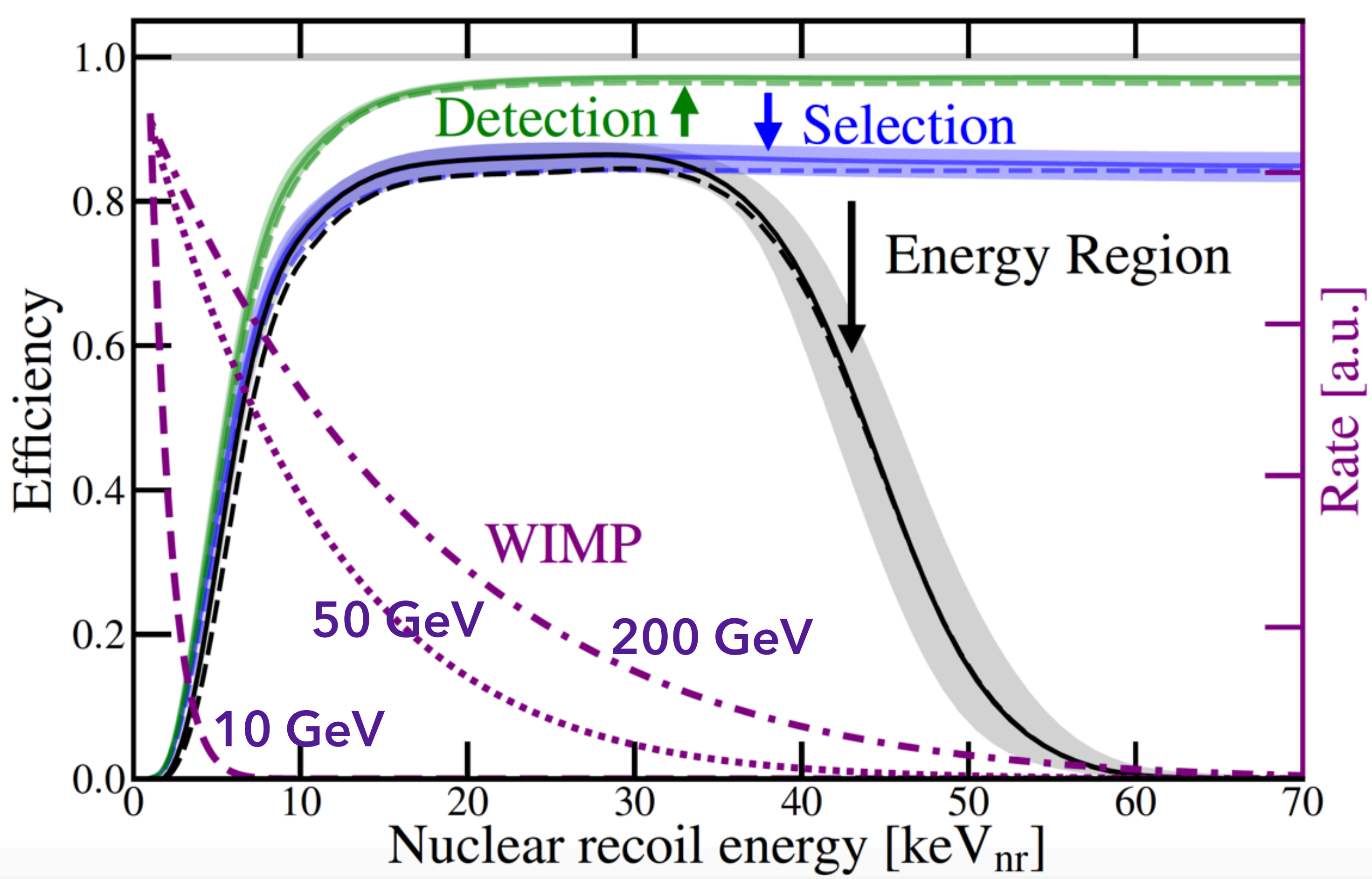
0.9 t LXe

Fiducial volume (1.3 t): 8 cm below liquid level, 2.9 cm above cathode; r_{max} = 42.8 cm

1σ (2σ) probability density percentiles of radiogenic neutrons

EVENT SELECTION AND DETECTION EFFICIENCY

- Detection efficiency: due to 3-fold PMT coincidence requirement
  - Estimated via waveform simulation including systematic uncertainties
- Selection efficiencies: from MC and data control samples
- Dark matter search region: [3-70] PE in S1



Bands: 68% credible regions

ROI: [3 - 70] PE corresponds to

ER: [1.4 - 10.6] keV_{ee}

NR: [4.9 - 40.9] keV_{nr}

BACKGROUND PREDICTION AND UNBLINDING

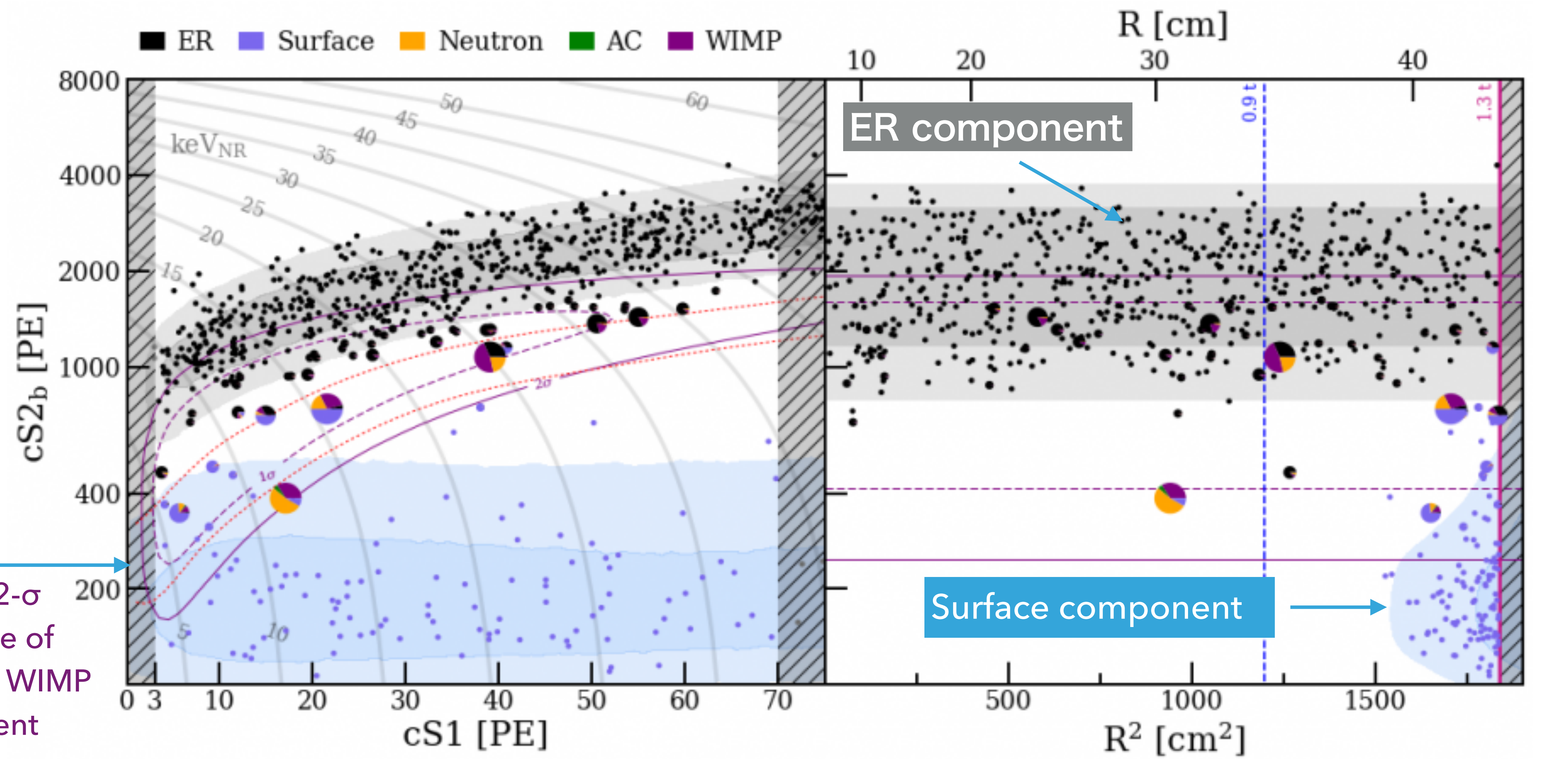
- Reference region: space between NR median and NR-2σ
- Numbers in reference region for illustration only, statistical inferences based on PL analysis in (S1, $S2_b$, r, z) space
- ER(^{222}Rn): most significant background, uniformly distributed
- Surface background: significantly reduced with fiducial volume cut
- Neutron background is less than one event, and impact is further suppressed by position information
- Other background components are completely sub-dominant

Best fit event rates with 278.8 days live-time

Source	1.3 tonnes	0.9 tonnes
(S2, S1)	Full ROI	Reference NR
ER	627±18	1.12±0.21
Radiogenic	1.44±0.66	0.41±0.19
CEvNS	0.05±0.01	0.02±0.00
Accidental	$0.47^{+0.27}_{-0.00}$	$0.06^{+0.03}_{-0.00}$
Surface	106±8	0.02±0.00
Total	**735±20**	**1.62±0.28**
Data	**739**	**2**
$\mathrm{WIMP}_{\text{best-fit}}$ 200 GeV, 4.2e-47 cm^2	3.56	1.16

DARK MATTER SEARCH RESULTS

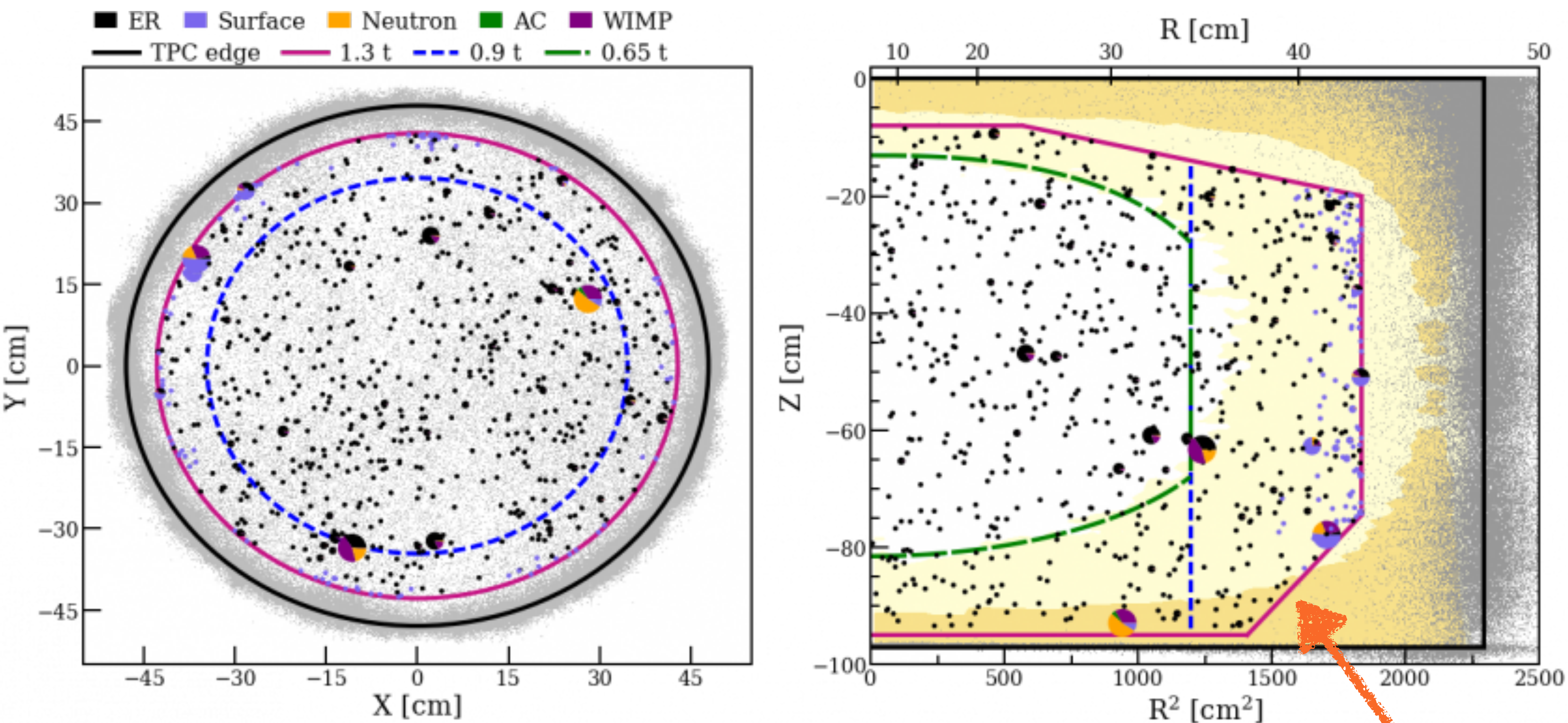
- Results interpreted with unbinned profile likelihood analysis (all model uncertainties included in the likelihood as nuisance parameters)
- Piecharts: relative PDF from the best fit of 200 GeV WIMPs with 4.7×10^{-47} cm^2



1-σ and 2-σ percentile of 200 GeV WIMP component

SPATIAL DISTRIBUTION OF EVENTS

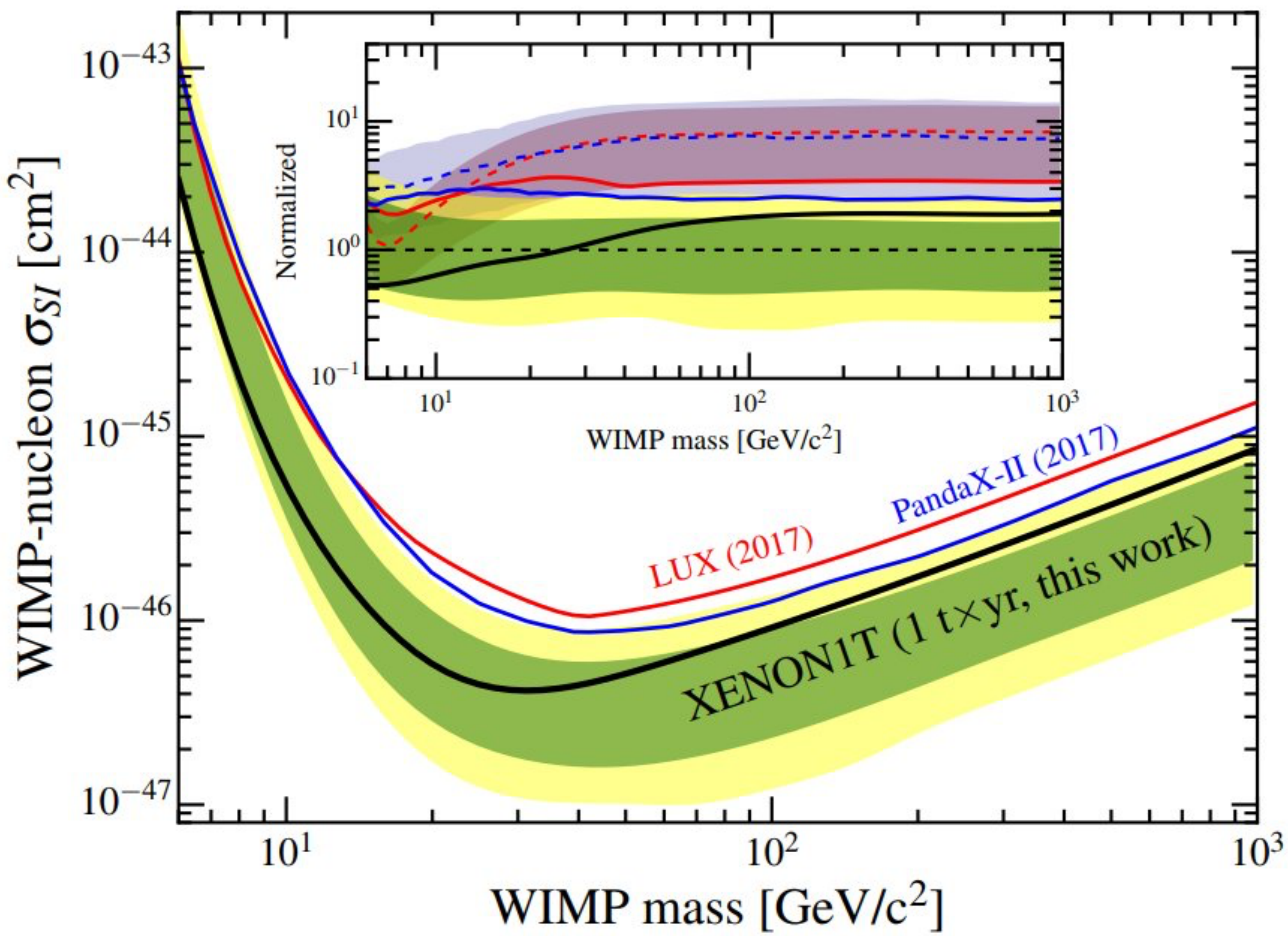
- Results interpreted with unbinned profile likelihood analysis (all model uncertainties included in the likelihood as nuisance parameters)
- Core volume: to distinguish WIMPs over neutron background



1σ (2σ) probability density percentiles of radiogenic neutrons

NEW CONSTRAINTS ON WIMPS

- Strongest upper limit (at 90% CL) on SI WIMP-nucleon cross sections > 6 GeV
- Median sensitivity: factor 7 higher than for previous experiments (LUX, PandaX-II)
- 1-σ fluctuation at higher WIMP masses could be due to background or signal



$$\sigma_{\mathrm{SI}} < 4.1 \times 10^{-47} \mathrm{cm}^2 \text{ at } 30\,\mathrm{GeV}/\mathrm{c}^2$$

FAST UPGRADE TO XENONNT !

XENONNT

Minimal Upgrade

The XENON1T infrastructure and sub-systems were originally designed to **accommodate a larger LXe TPC**.

Fiducial Xe Target

XENONnT TPC features:

total Xe mass = 8 t

target mass = 5.9 t

fiducial mass = ~4 t

Background

Record low-back levels in XENON1T dominated by ^{222}Rn-daughters.

Identified strategies to effectively **reduce ^{222}Rn by ~ a factor 10**.

Fast Turnaround

Use **XENON1T sub-systems,** already tested

Fast pace:

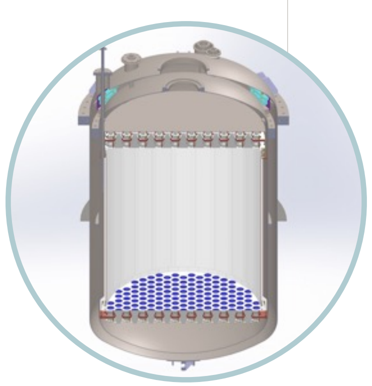
Installation starts in 2018

commissioning in 2019

LZ is expected to start at 2020

XENONNT

Japanese group contribution



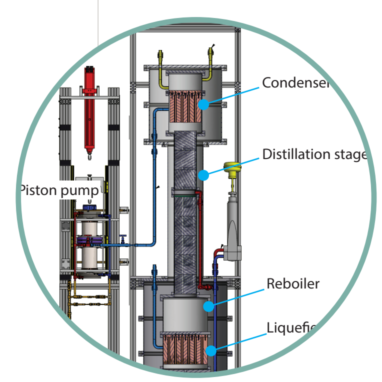
New TPC

5.9-ton Time Projection Chamber

LXe Purification

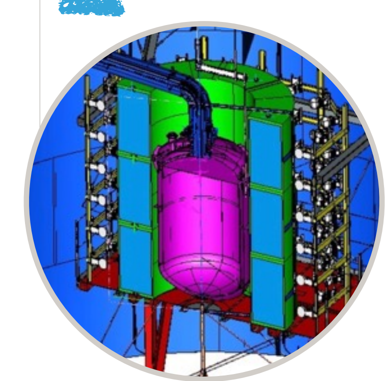
To achieve fast cleaning of the large LXe volume (5L/min LXe, 5000 SLPM GXe)

↕ GXe purification (120 SLPM)



Radon Distillation

To online remove the ^{222}Rn emanated inside the detector



Neutron Veto

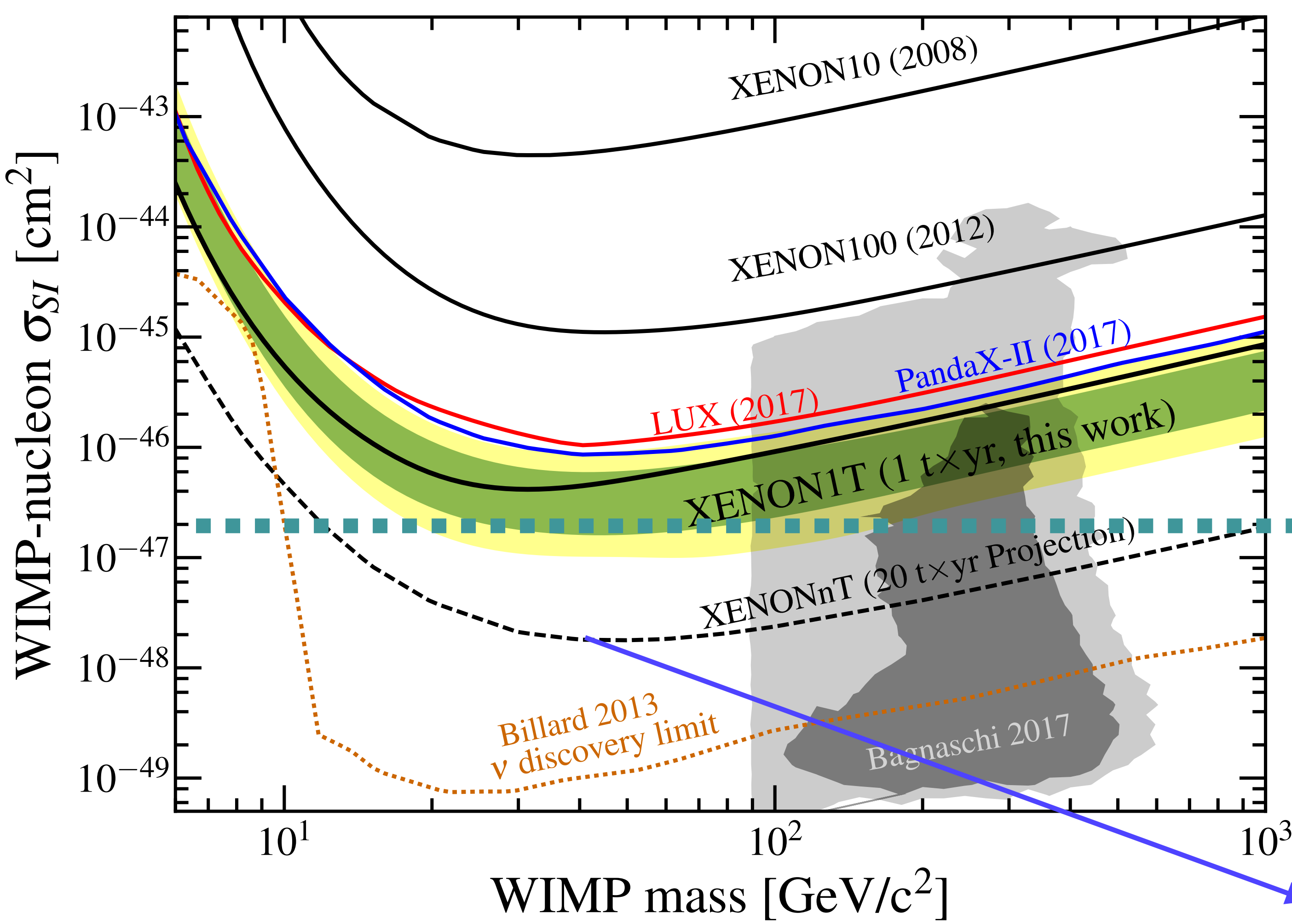
To tag and measure in situ neutron-induced background

1 candidate is already observed in XENON1T

XENONNT VS LZ

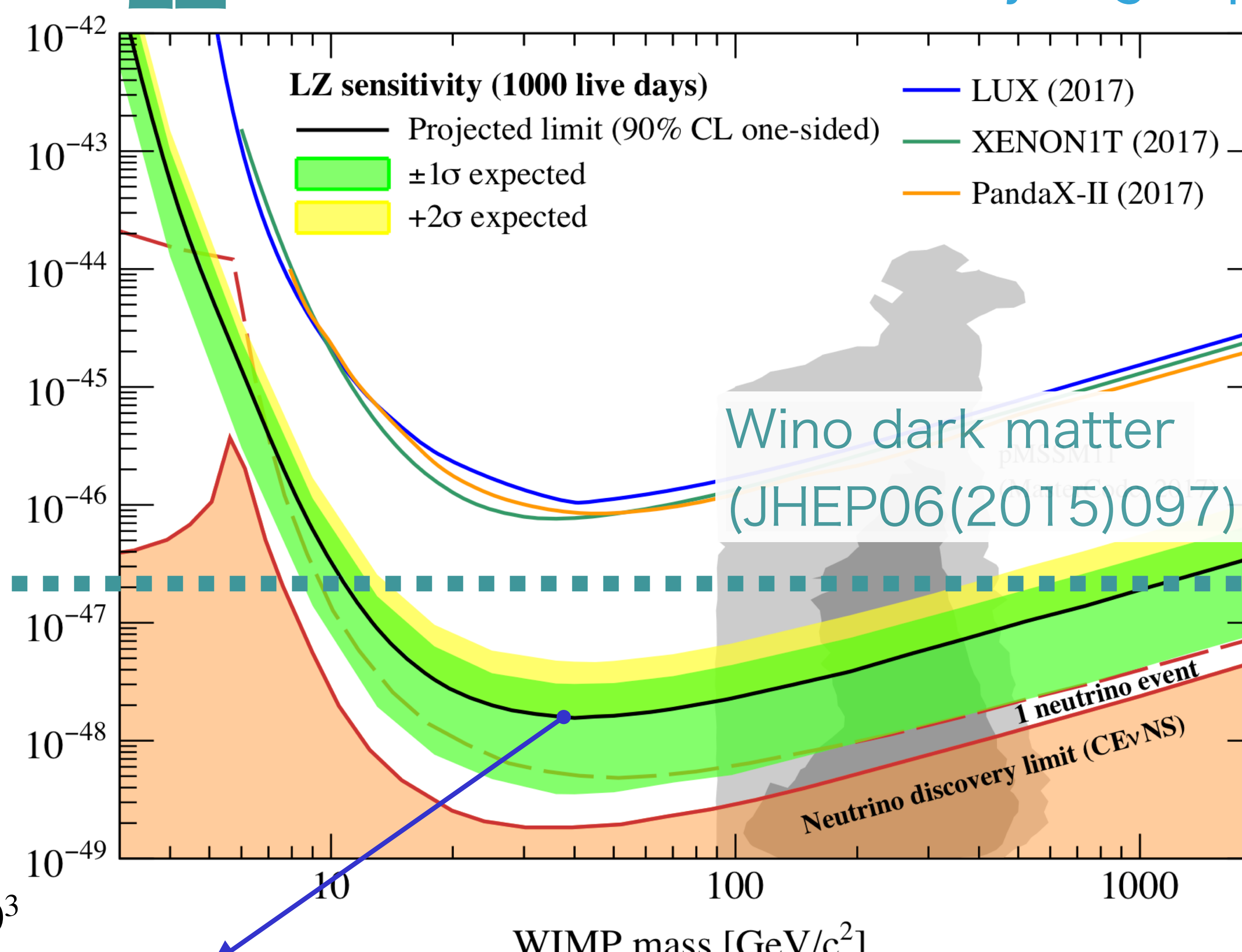
- 10 times higher sensitivity with 20 ton-year (4 ton × 5 year) exposure until ~2024
- LZ also has a similar expected sensitivity with 15 ton-year (5.6 ton × 1000 days)
- can exclude Wino dark matter up to ~1TeV mass

XENONnT



LZ

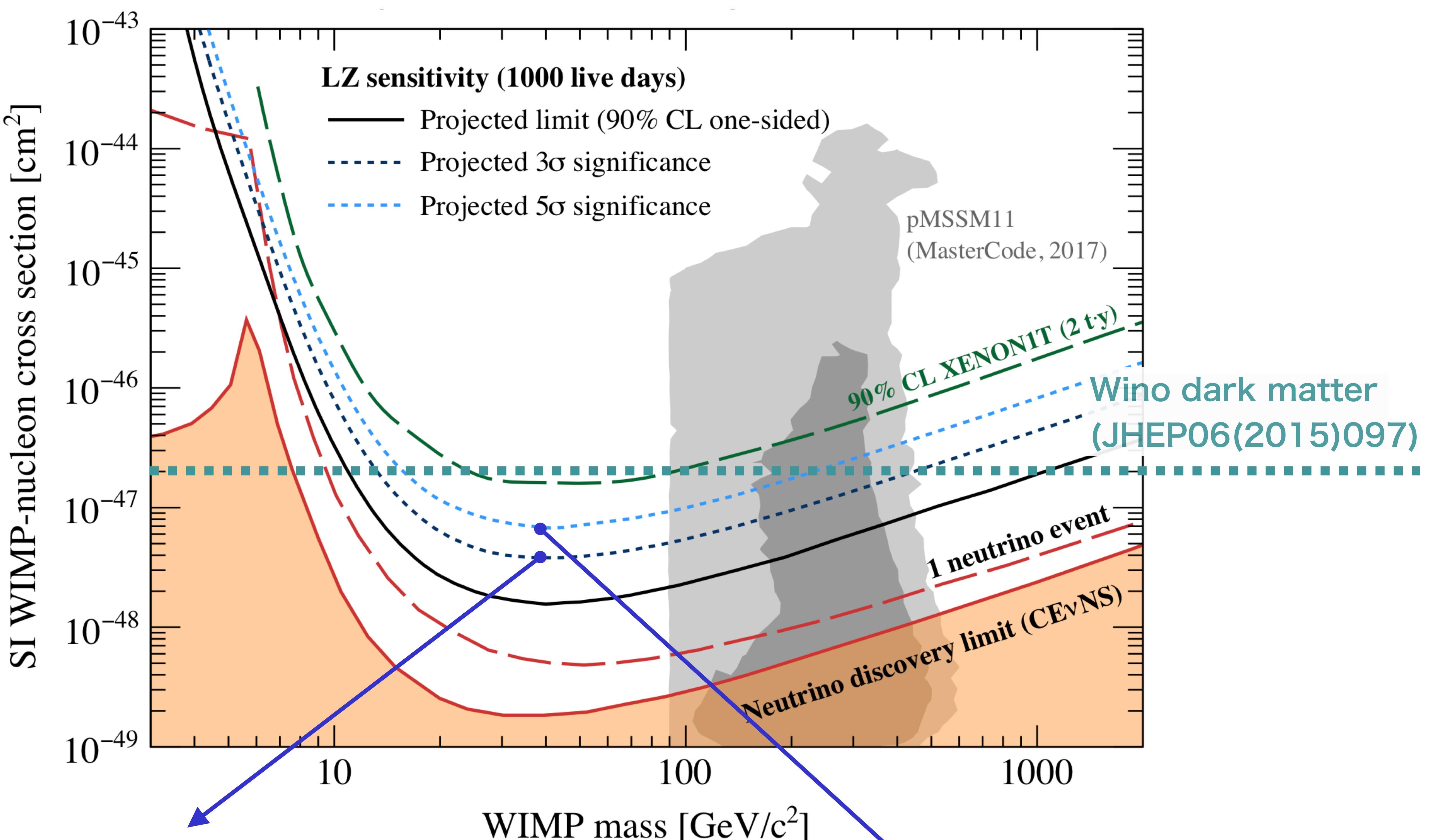
[talk by LZ group]



10^{-48} cm^2 @ 40 GeV/c^2

talk by LZ group

DISCOVERY POTENTIAL?

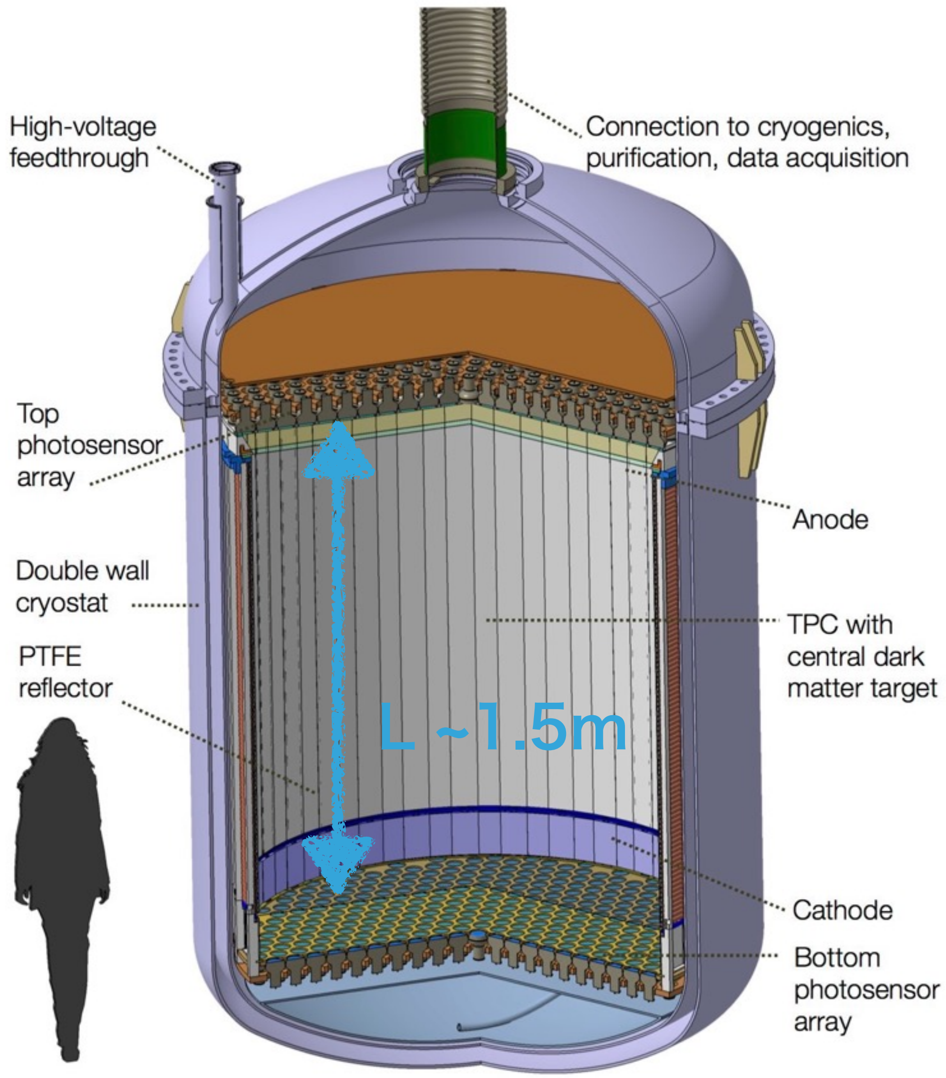


3σ: 3.8 × 10^{-48} cm^2 @ 40 GeV/c^2

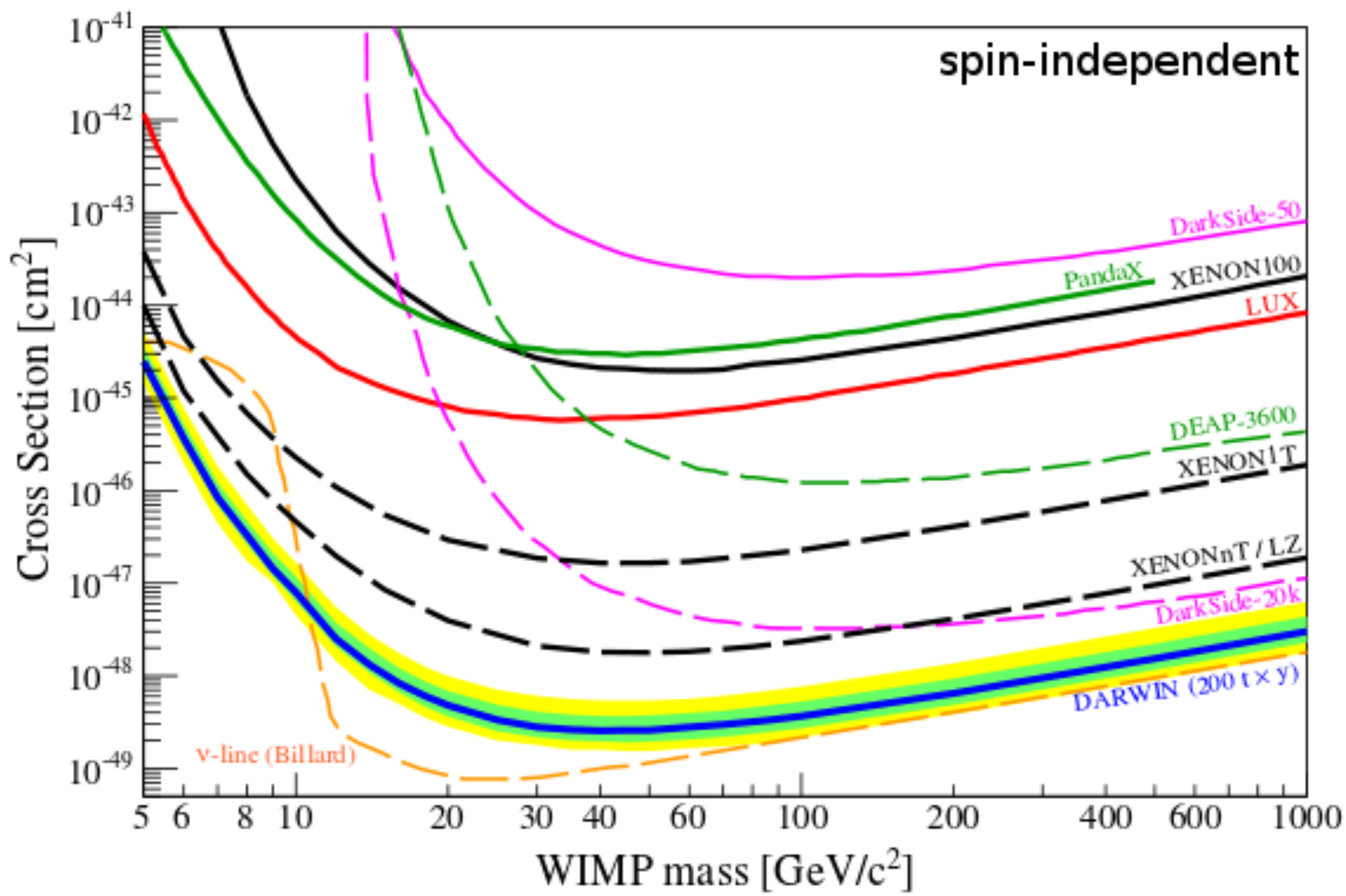
5σ: 6.7 × 10^{-48} cm^2 @ 40 GeV/c^2

DARWIN?

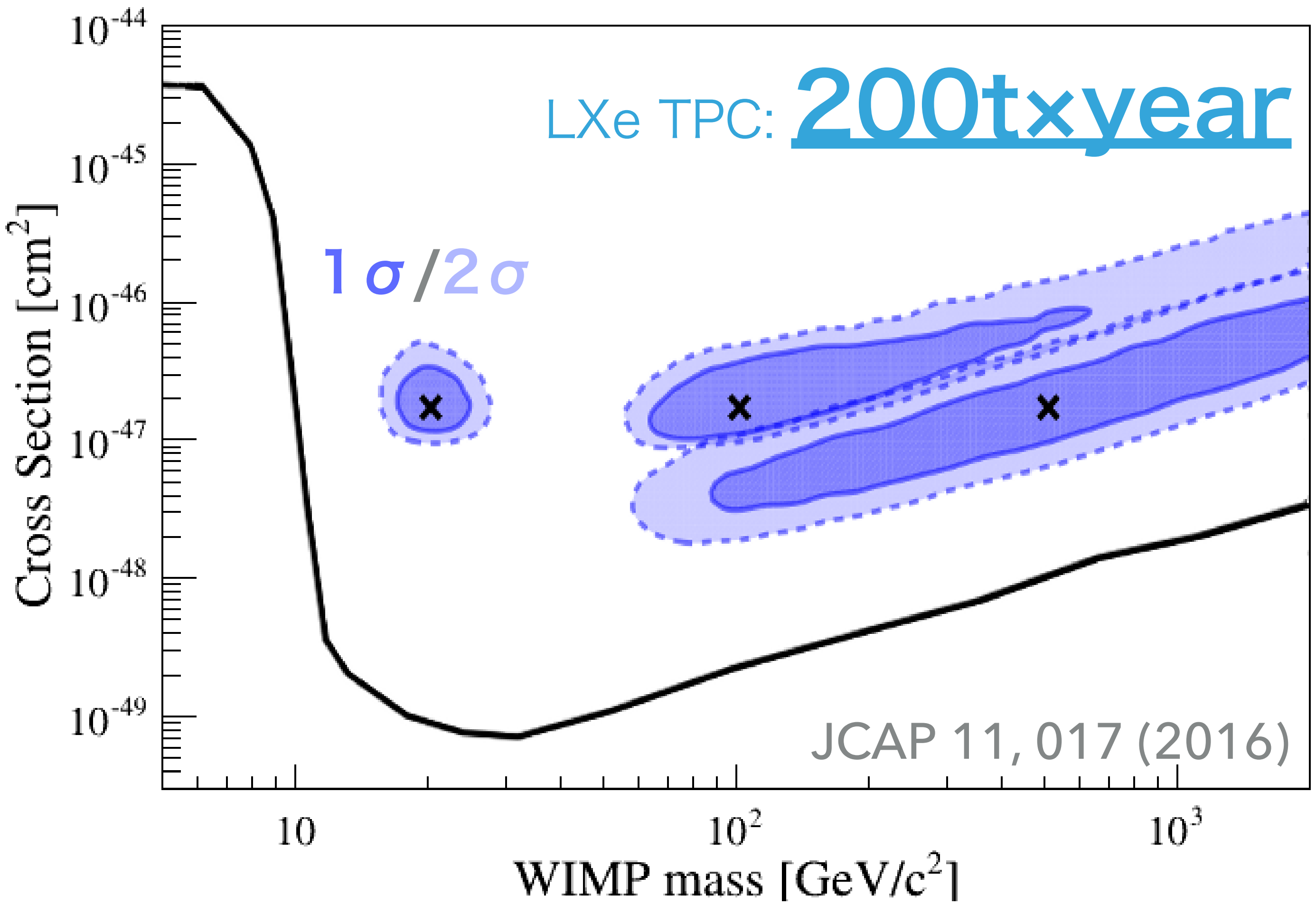
R&D and prototypes supported by two ERC grants: Ultimate (Freiburg) and Xenoscope (Zürich)

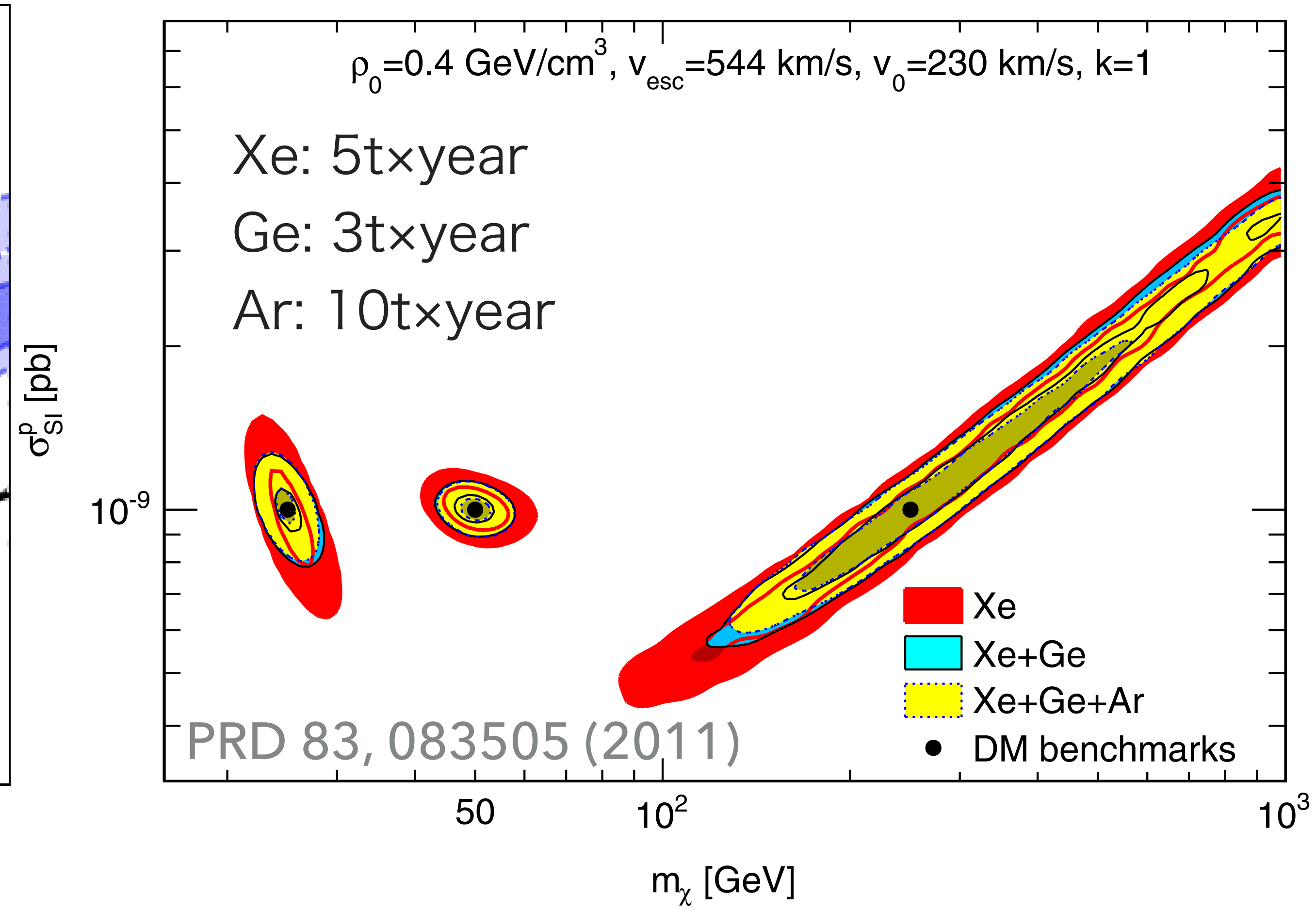


2020+
50 tonnes
~10^{-49} cm^2



CAN WE RECONSTRUCT DARK MATTER MASS?





Capability to reconstruct WIMP parameters

- $m\chi$ = 20, 100, 500 GeV, 10^{-47}cm^2
- Because WIMP spectra are largely degenerated, no target can reconstruct masses > 500 GeV

- $m\chi$ = 25, 50, 250 GeV, 10^{-45}cm^2
- small improvement by combining Xe+Ge+Ar

SUMMARY AND OUTLOOK

- The first multi-ton scale LXe-TPC was operated > 1 y
- Achieved the lowest background in a dark matter detector
- Result from an analysis of 1 tonne year exposure: the strongest upper limit on SI WIMP-nucleon cross sections for masses > 6 GeV, with 4.1×10^{-47} cm^2 at 30 GeV
- XENON1T acquires more data until its upgrade, XENONnT, is ready for installation at LNGS
- Many analyses in the pipeline ($0\nu\beta\beta$-decay, annual modulation, low-mass WIMPs, Migdal effect, bosonic SuperWIMPs, etc)
- XENONnT is designed for a factor 10 increase in sensitivity with 20 ton×year exposure. will start data-taking next year!