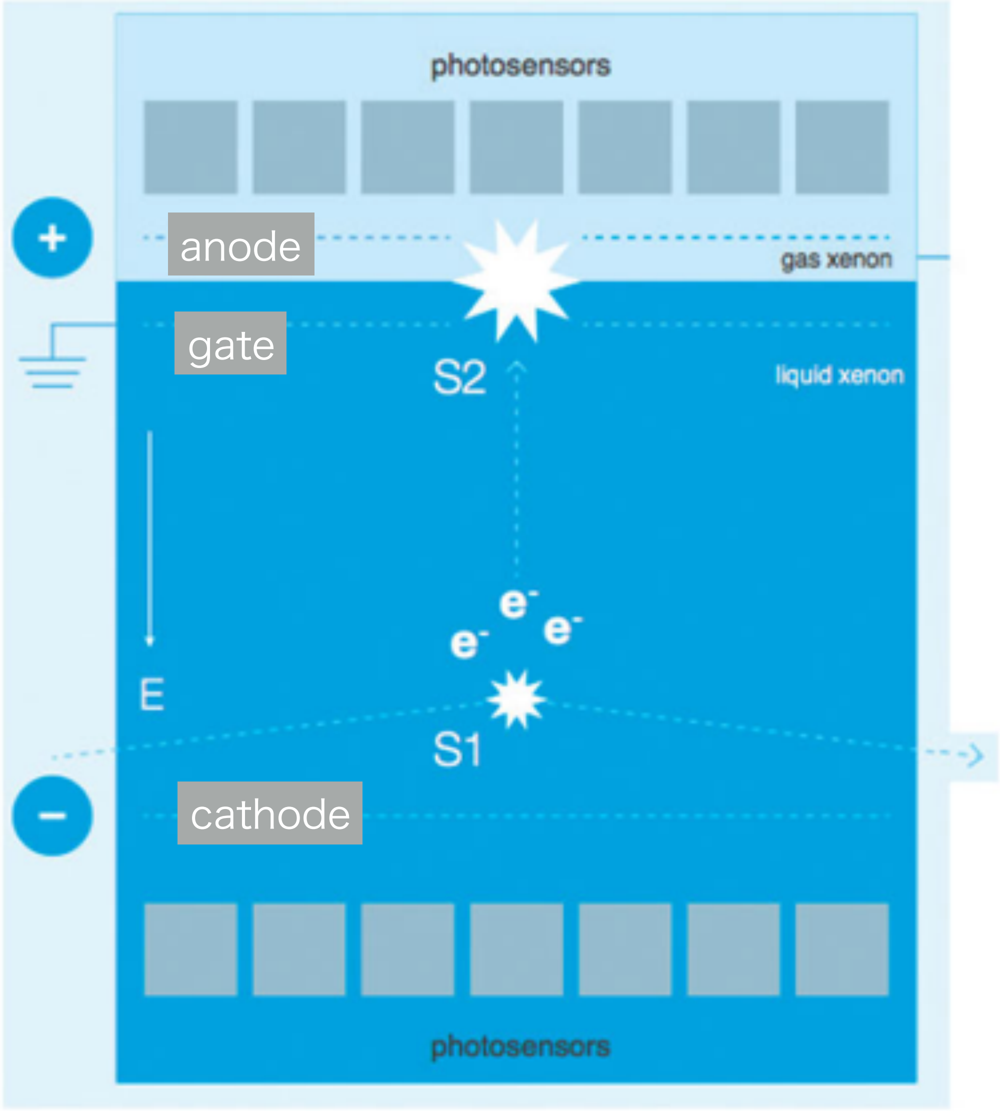
Universität Zürich^UZH

Xe XENON Dark Matter Project

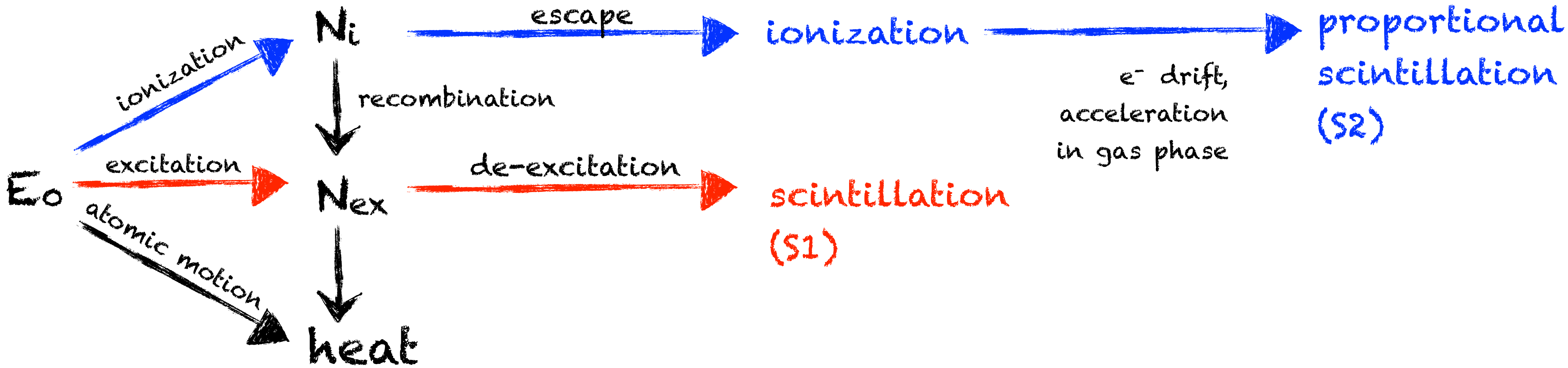
First dark matter search results with XENON1T

Shingo Kazama, University of Zurich, for the XENON Collaboration,
CosPA 2017@Kyoto University, December 13rd 2017

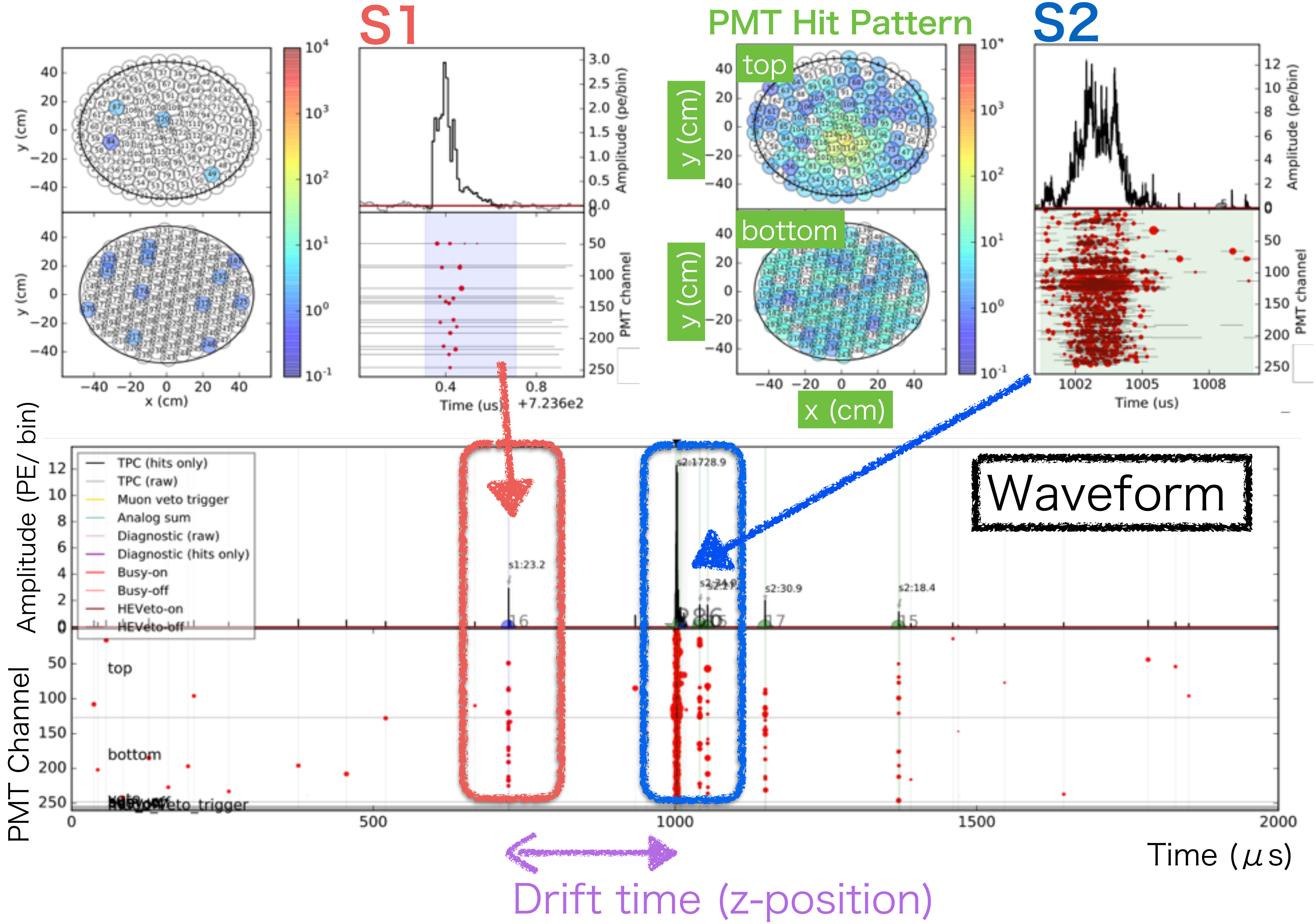
Dark Matter Detection with Liquid Xenon TPC



- 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: $(S2/S1)_{\gamma,e} > (S2/S1)_{\mathrm{WIMP,\ neutron}}$
  - Nuclear recoils have denser tracks, so they have more electron-ion recombination, thus a lower S2/S1



Event Structure



S1

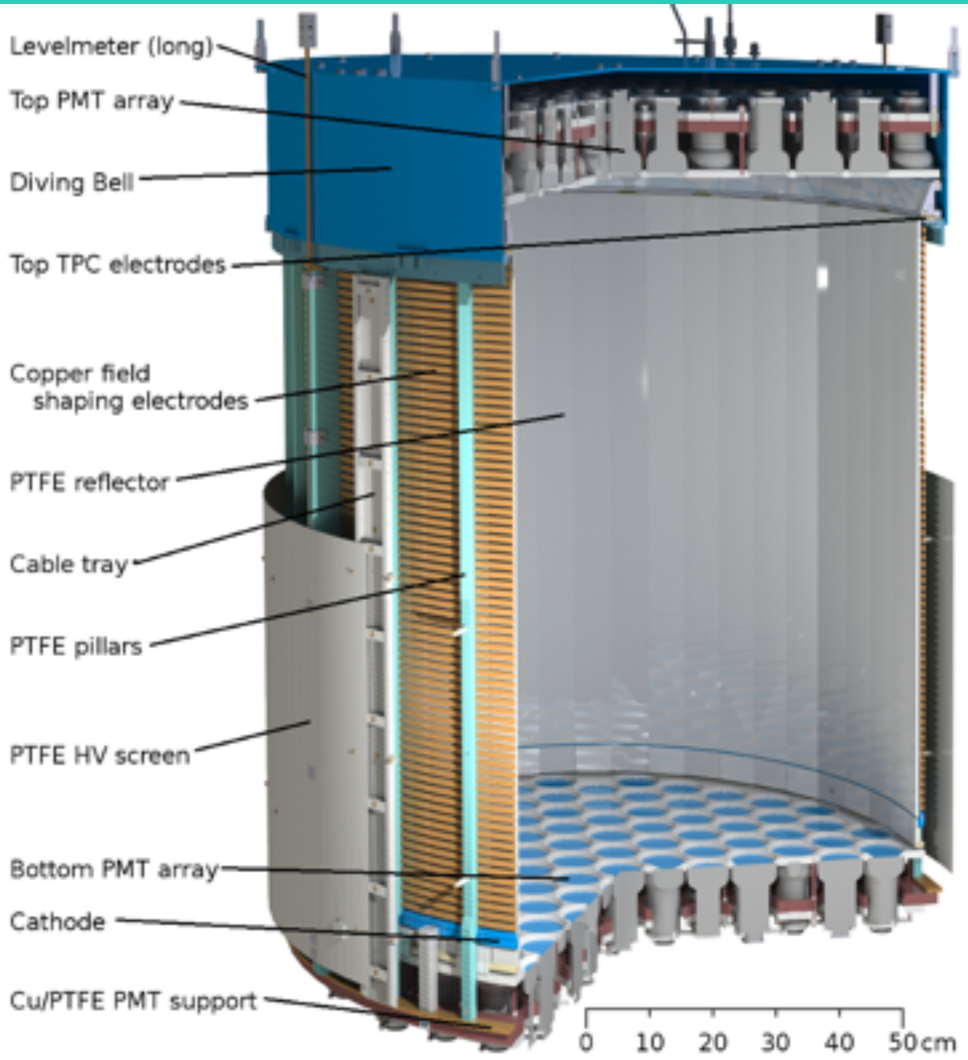
PMT Hit Pattern

S2

Waveform

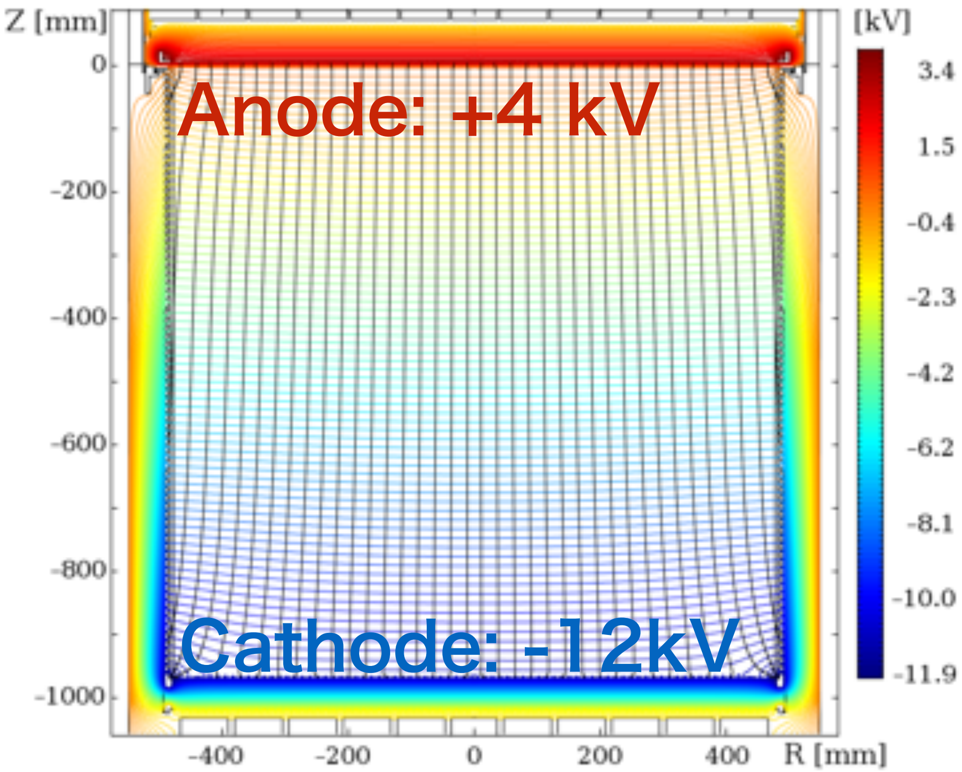
Drift time (z-position)

THE XENON1T TPC

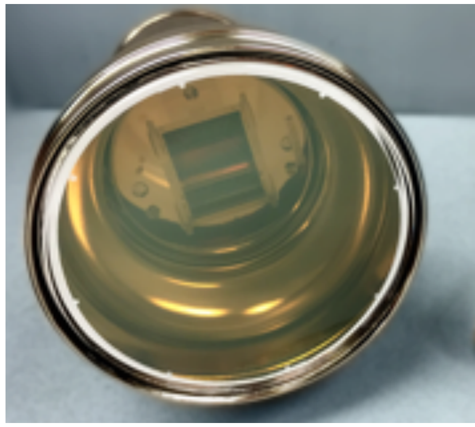


XENON1T TPC

- Located at LNGS, Italy (3600 m.w.e overburden) arxiv:1708.07051
- Double-wall vacuum insulated cryostat, constructed from selected low-activity stainless steel.
- TPC dimensions: 1×1 meters
- LXe mass: 3.2 t (total), 2.0 t (active)
- Active region enclosed by PTFE panels to reflect VUV scintillation light (λ~178nm)
- Highly transparent electrodes (meshes, wires).
- 74 copper field shaping rings and 2 resistor chains
- E_{drift} ~120 V/cm, E_{gas} > 10 kV/cm for the first science run (SR0)

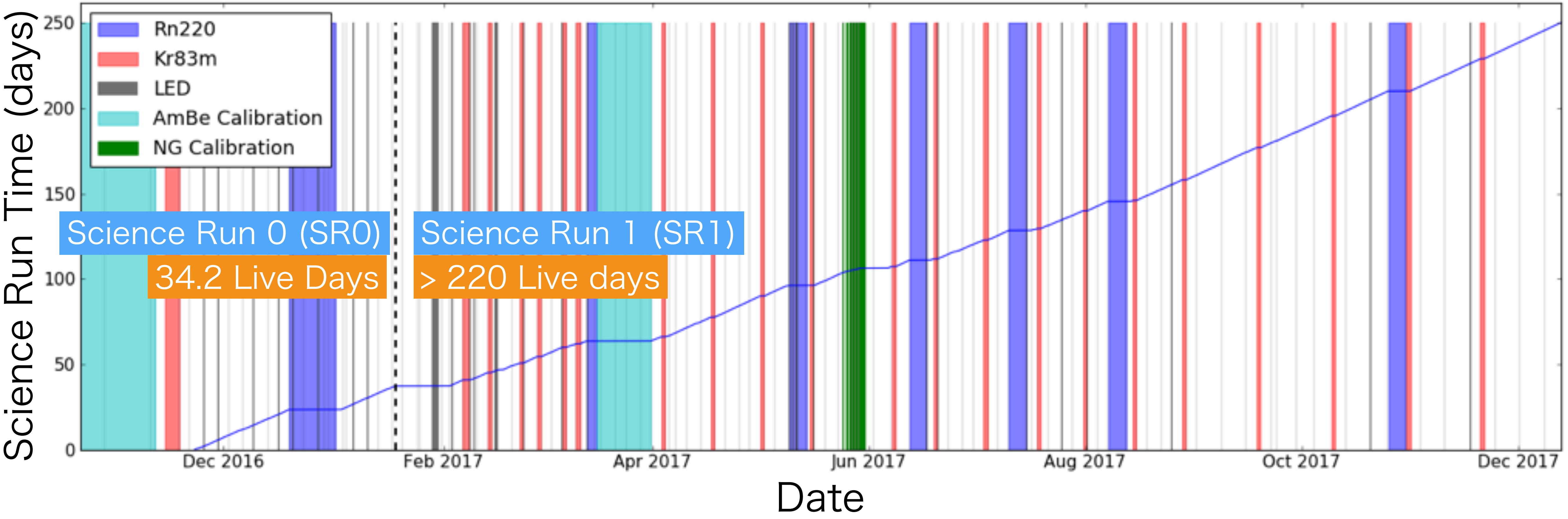


PMTs



- 248 low radioactivity Hamamatsu R11410-21 (3 inch, 127 top, 121 bottom)
- QE ~ 34% @ 178 nm
- Average gain ~ 5×10^6 @ 1.5 kV
- PMT Gain has been stable with 1-2% fluctuation
- Detailed characterisation: JINST 8, P04026 (2013) , JINST 12, P01024 (2017), arXiv:1509.04055

XENON1T Science Runs



Science Run 0 (SR0)
34.2 Live Days

Science Run 1 (SR1)
> 220 Live days

- Earthquake on Jan 18th defined a natural conclusion to SR0
- Quickly resumed data acquisition. Now we have more than 220 days of exposure.
  - Our next target is to achieve 1ton-year exposure.

Science Run 0 data-taking:

- 34.2 live days for dark matter searches
- 3.0 days of ^{220}Rn data (Low-energy ER calibration)
- 3.3 days of ^{83m}Kr data (Spatially dependent signal corrections)
- 16.3 days of ^{241}AmBe data (Low-energy NR calibration)

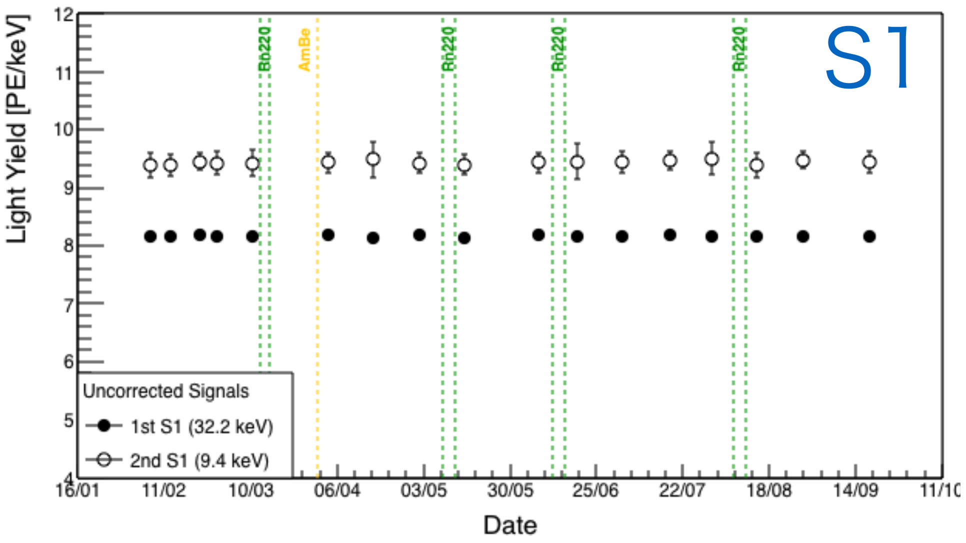
Science Run 1 data-taking:

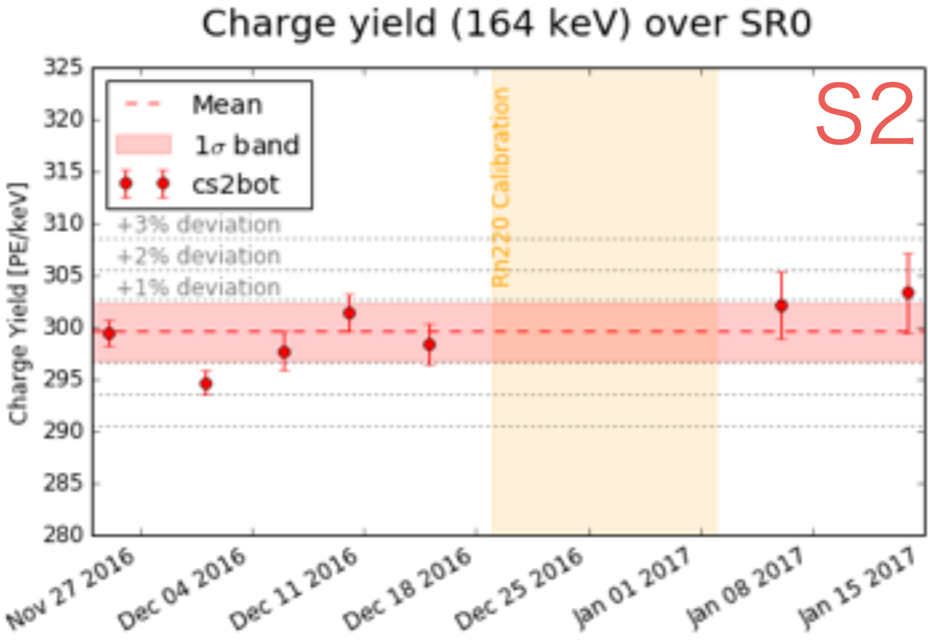
- > 220 live days for dark matter searches
- 25.2 days of ^{220}Rn Data (Low-energy ER calibration)
- 22 days of ^{83m}Kr Data (Spatially dependent signal corrections)
- 14.3 days of ^{241}AmBe and 2.0 days of Neutron-Generator data (Low-energy NR calibration)

Detector Stability

Light/Charge Yield

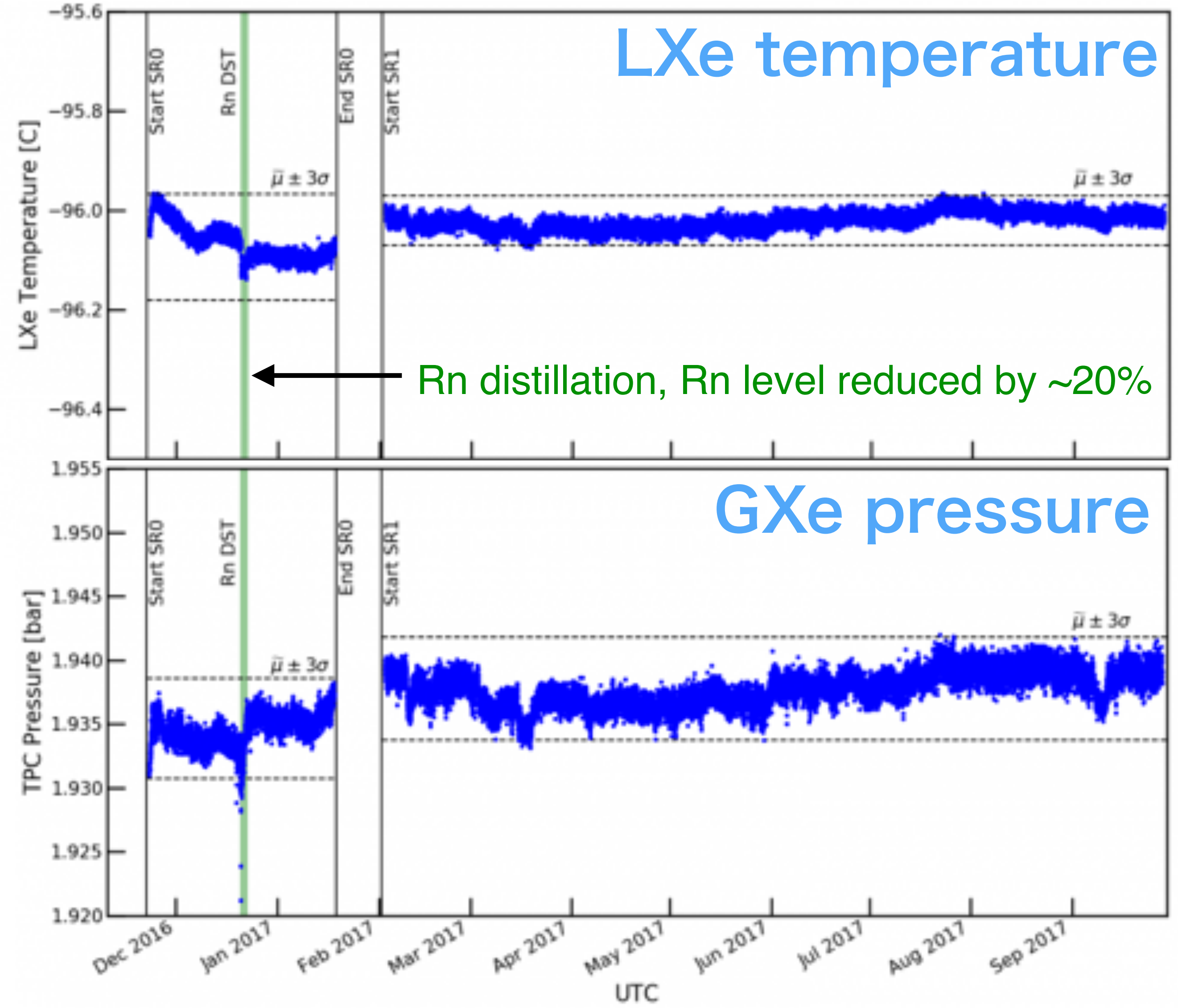
- ^{83m}Kr and ^{131m}Xe used for monitoring
- stable within 1% throughout SR0 and SR1





All parameters are stable throughout SR0

- LXe temperature: (177.08 ± 0.04) K
- GXe pressure: (1.934 ± 0.001) bar
- LXe level: (2.5 ± 0.2) mm

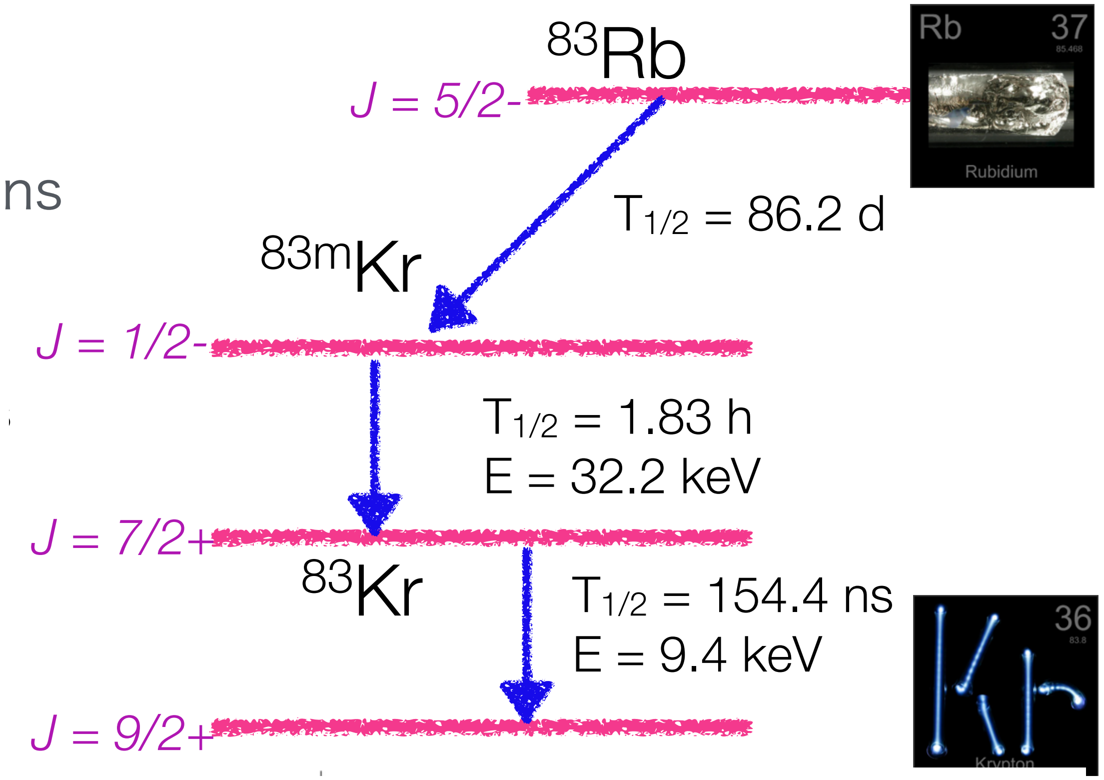


Rn distillation, Rn level reduced by ~20%

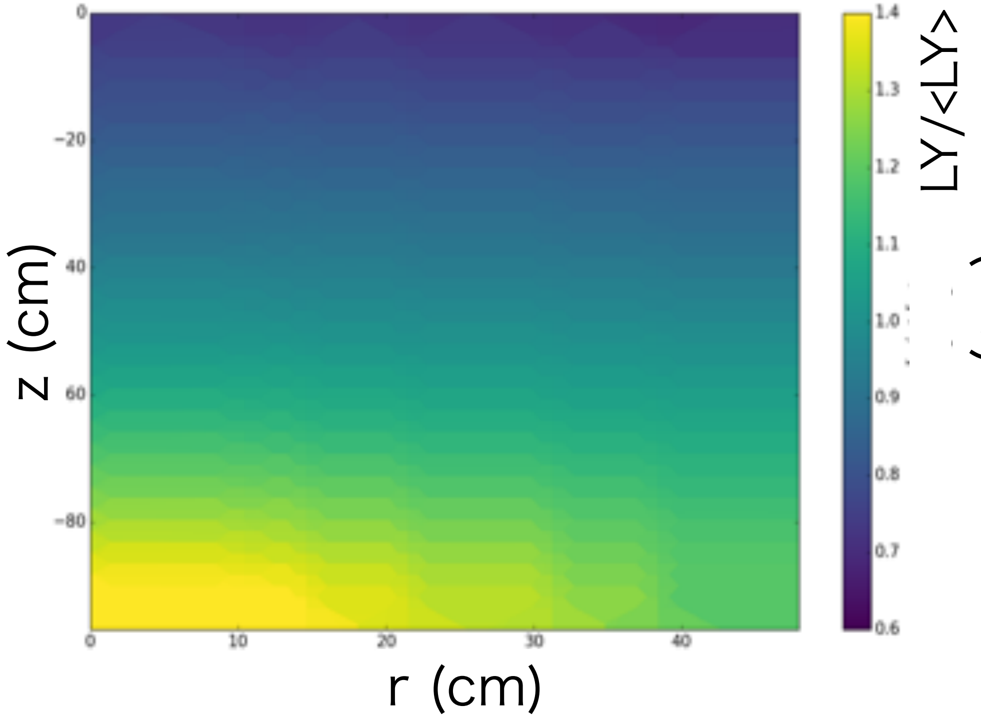
Detector response correction

Spatial signal corrections with ^{83m}Kr source

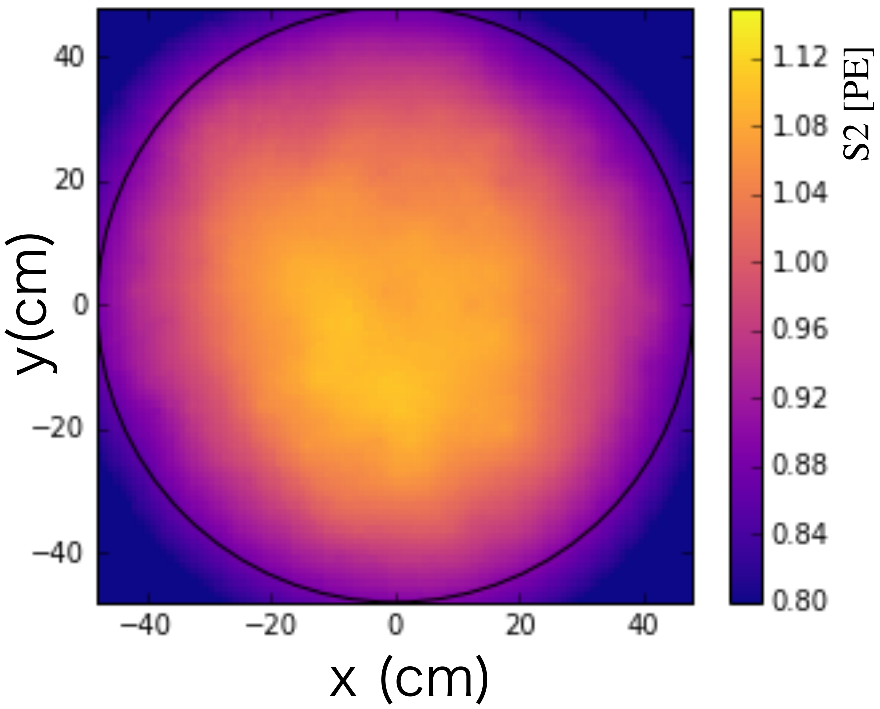
- Internal source (injected into LXe)
- 32.2 keV and 9.4 keV emissions separated by $T_{1/2}$ =154 ns
- Used for several corrections
  - Position dependent light collection efficiency
  - Position dependent S2 amplification
  - Electron lifetime correction
    - increased from 350 μs to 650 μs due to continuous circulation through hot metal getters to remove impurities like water and oxygen



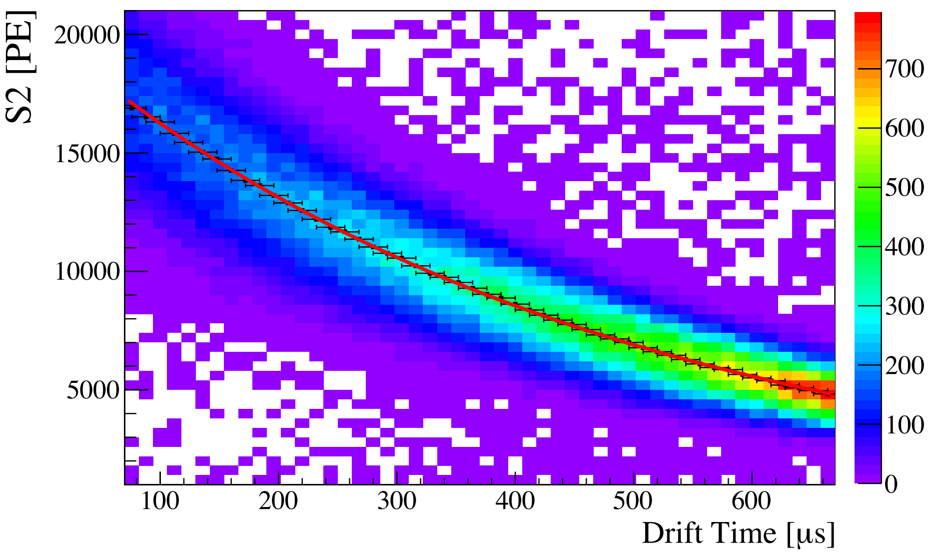
S1 light collection efficiency



S2 gain

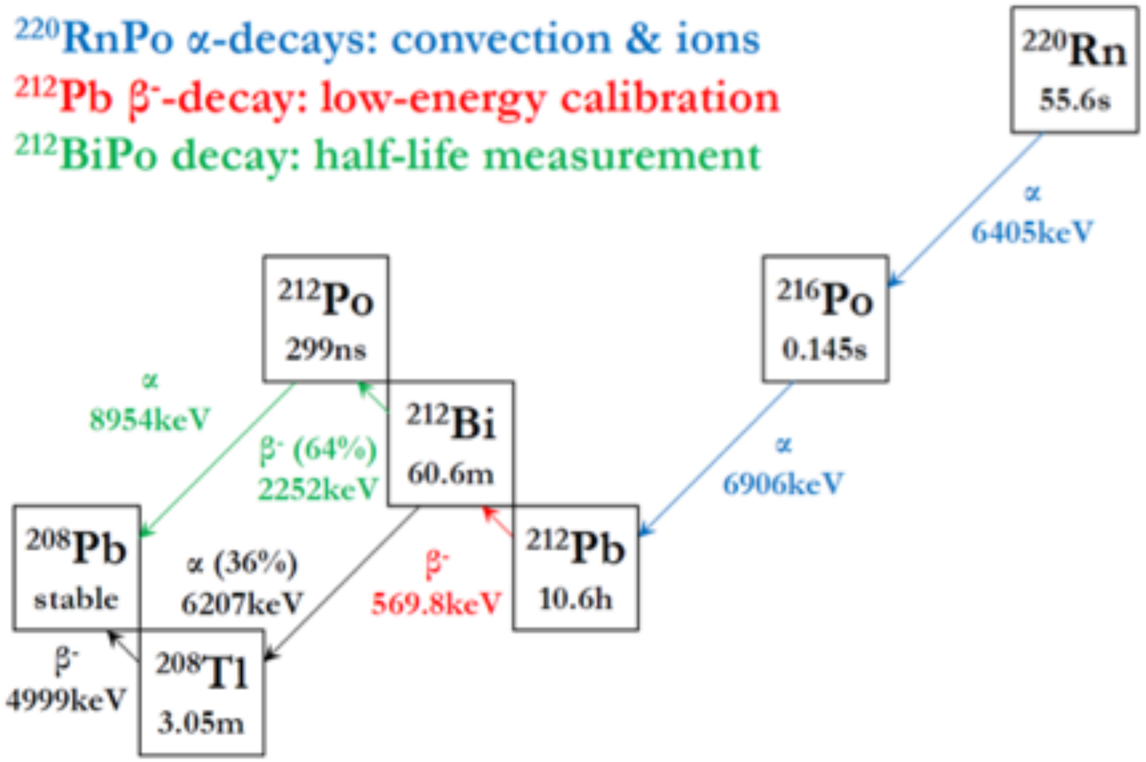


S2 electron lifetime



Electronic/Nuclear Recoil Calibration

Electronic Recoils (ER): ^{220}Rn



- 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

Nuclear Recoils (NR): ^{241}AmBe & Neutron Generator

- External ^{241}AmBe source mounted on a belt is used for SR0

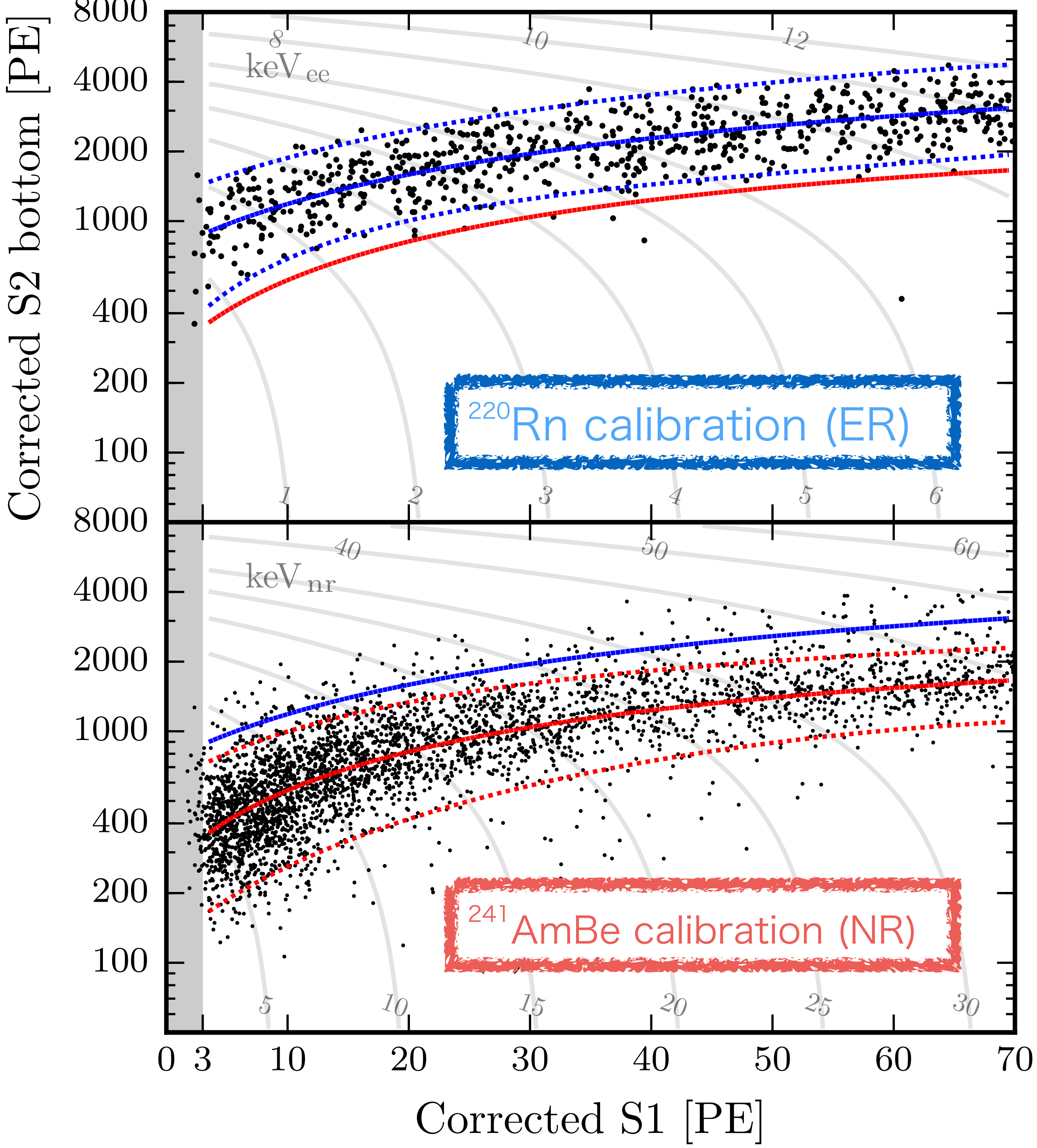
$$^{241}\text{Am} \rightarrow {}^{237}\text{Np} + \alpha + \gamma \ (59.5\ \text{keV})$$

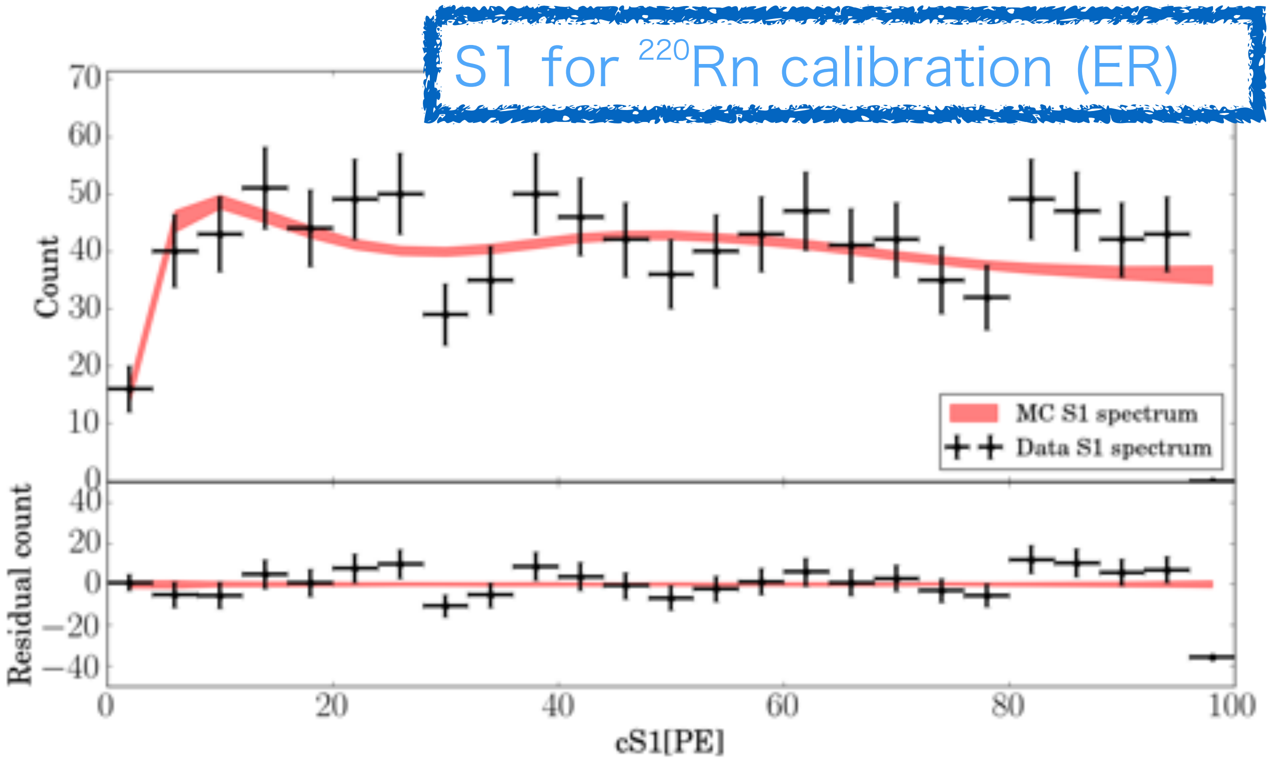
$$^{9}\text{Be} + \alpha \rightarrow {}^{12}\text{C} + \mathbf{n} + \gamma\ (4.4\ \text{MeV})$$

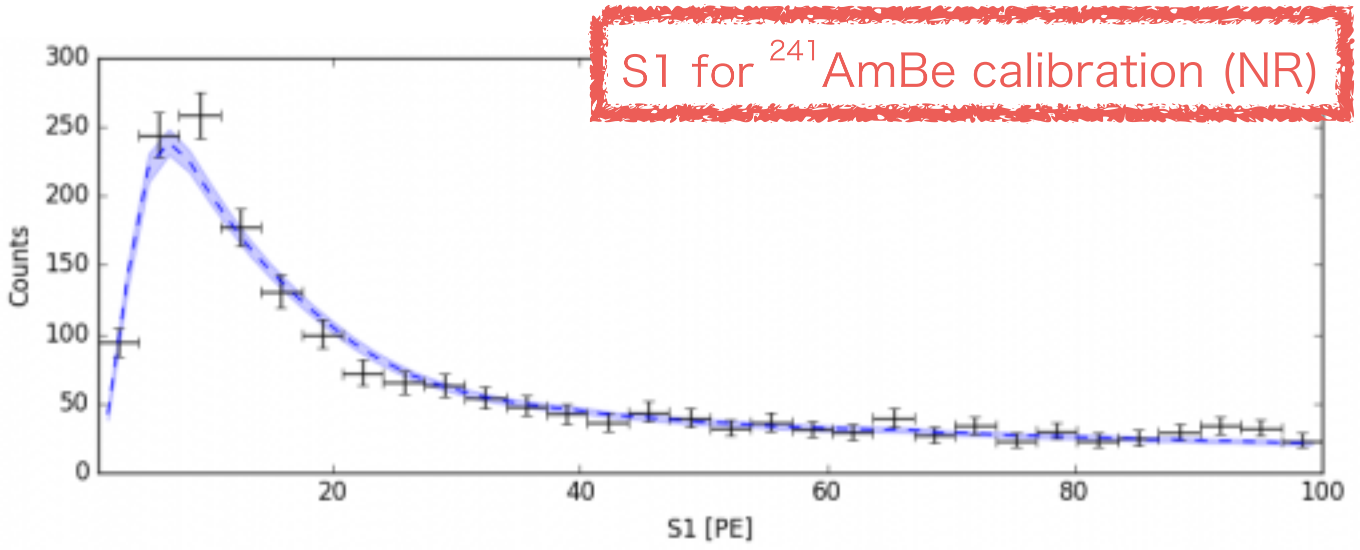
- D-D fusion neutron generator ($\text{D} + \text{D} \rightarrow \text{n} + {}^{3}\text{He}$) has been also commissioned during SR1
  - E_n : peak at 2.45 MeV arxiv:1705.04741
  - Calibration time reduced by an order of magnitude (weeks → days)

Electronic/Nuclear Recoil Calibration

Blue: ER, Red: NR; —: median, ·····: ±2σ







- ER/NR-bands are well separated with each other: ER-leakage fraction below NR mean is ~ 3×10^{-3}
- Simulate LXe microphysics & detector response to fit ^{220}Rn and ^{241}AmBe calibration data
- Background and signal predictions are estimated from tuned models

Electronic Recoil Background

Online Krypton distillation

Eur. Phys. J. C77, 275 (2017)

- ^{85}Kr concentration in LXe (^{nat}Kr/Xe):

  (2.60 ± 0.05)× 10^2ppt @ start of SR0

  ↓

  (0.36 ± 0.06) ppt @ end of SR0
- ER background is now ^{222}Rn dominated

^{222}Rn chain

- Emanation from detector materials
- Extensive screening program and emanation measurements

Eur. Phys. J. C75, 11, 546 (2015) arXiv:1705.01828

- 10 μBq/kg target concentration is reached

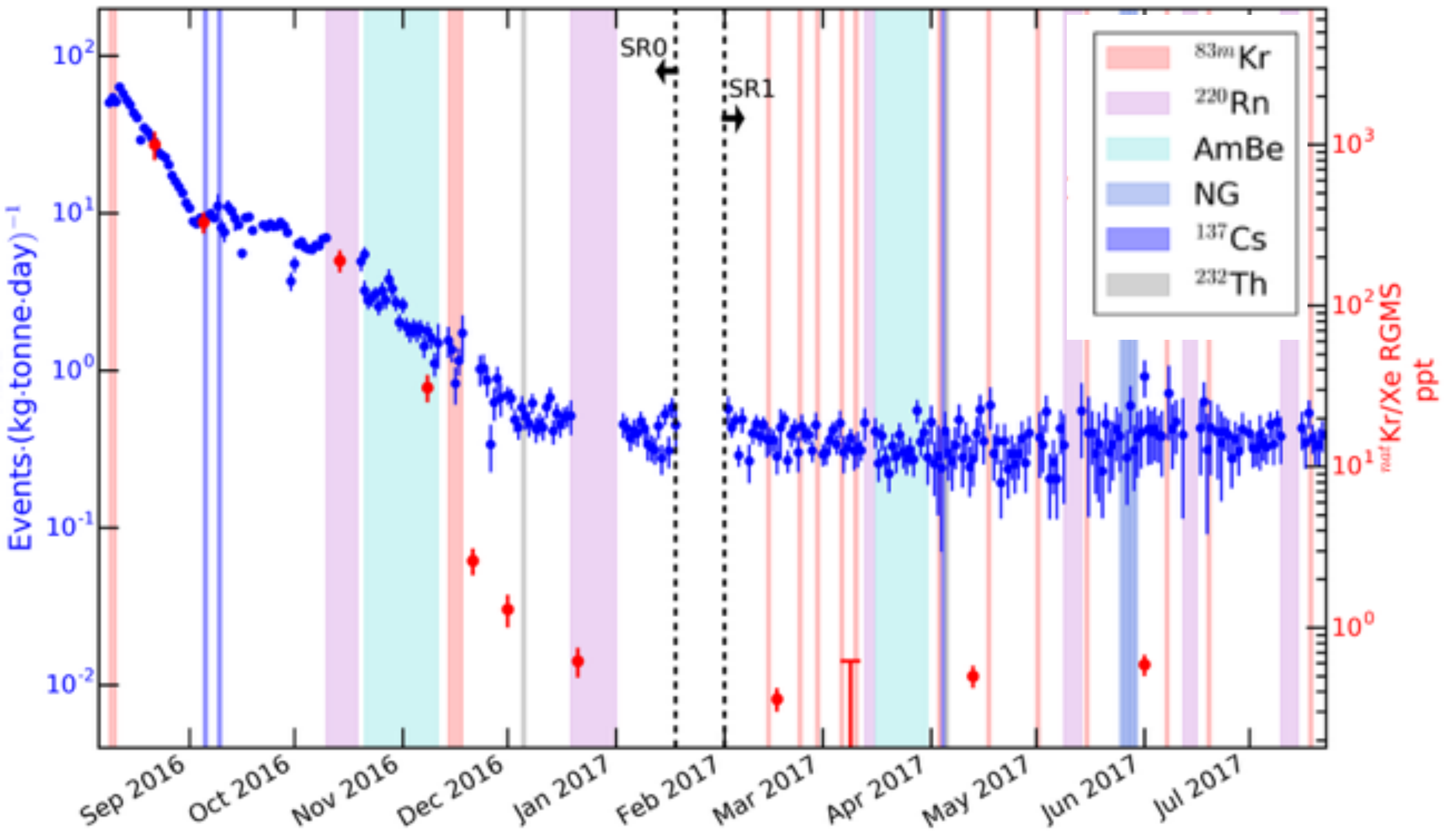
Achieved lowest BG rate in a dark matter experiment

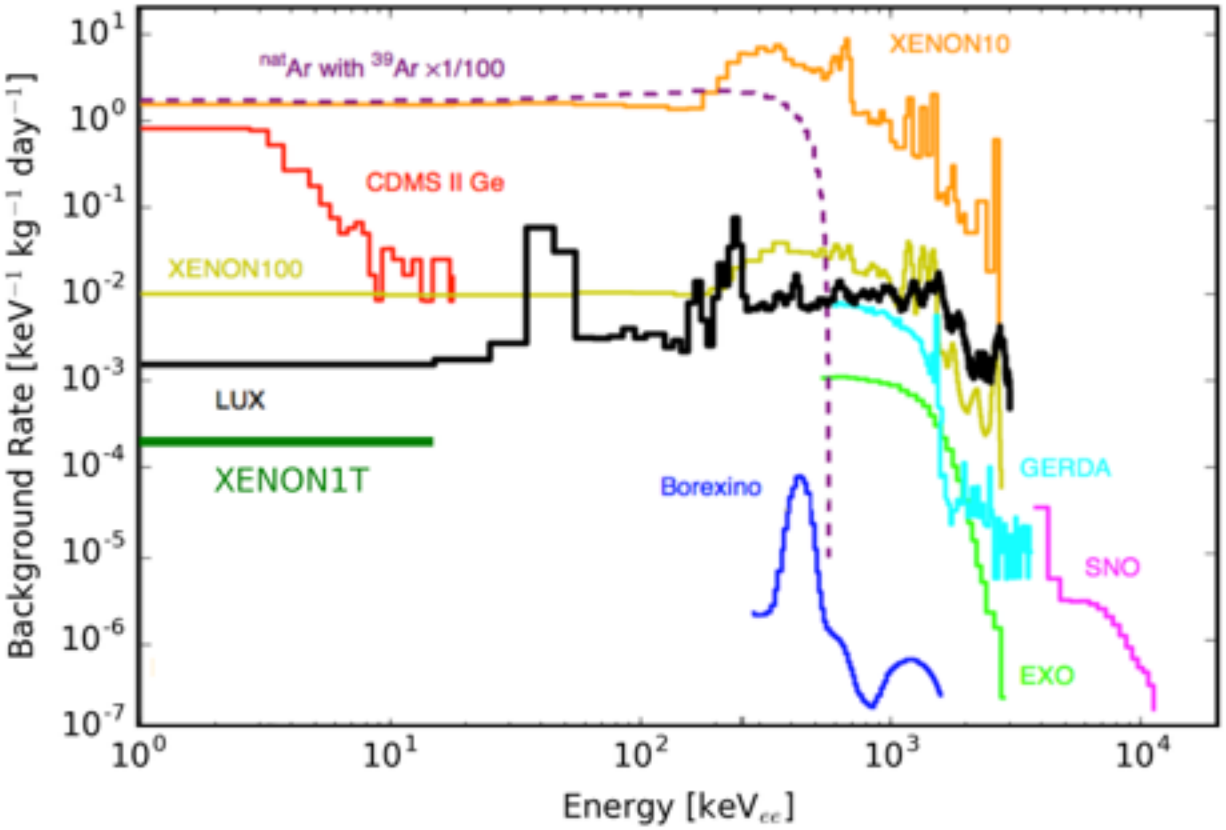
(1.93 ± 0.25)× 10^{-4} events/kg/day/keV$_{ee}$

Further ^{222}Rn reduction possible

- Rn distillation in XENON100: 27 times lower
- First tests in XENON1T promising

Eur. Phys. J. C (2017) 77: 358





Event Selection and Efficiency

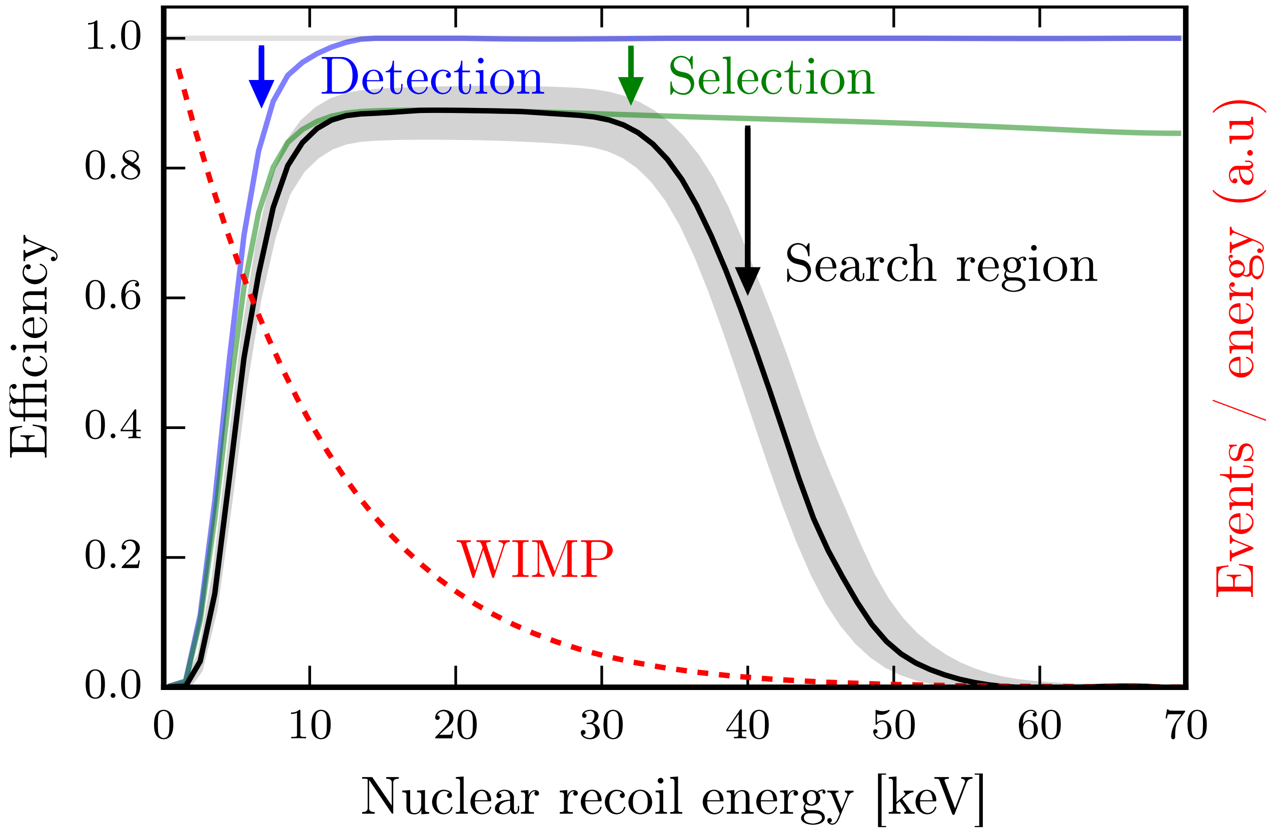
Detection Efficiency estimated from MC:

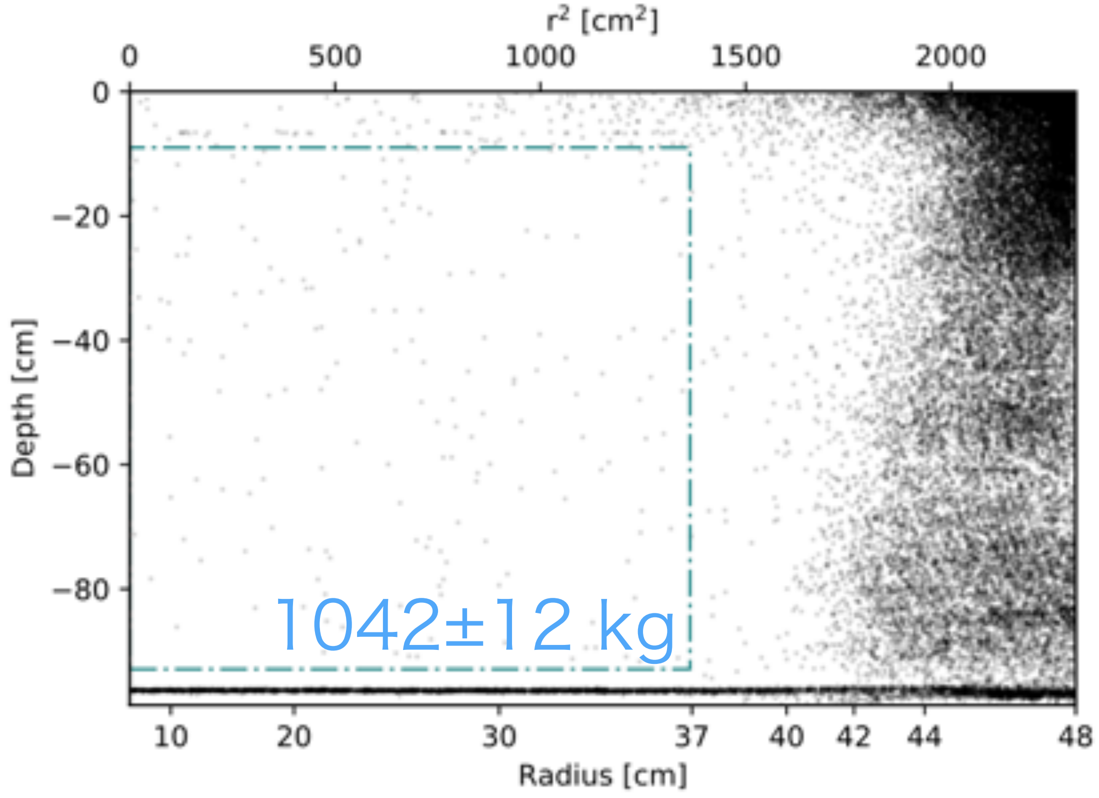
- S1/S2 generation
- Light propagation
- Detector Electronics including electronic noise
- 3-fold PMT coincidence requirement

Event Selection:

- Single scatter
  - only one s2 (> 200 pe) per event
- Event quality
  - events not after a high energy event
  - reject events with noises (uncorrelated signals) before main s2
- Peak quality
  - The S2 signal's time spread must be consistent with the depth of the interaction as inferred from the drift time
  - S1/S2 PMT hit pattern must be consistent with reconstructed position
  - ratio of light seen by top/bottom PMT array must be consistent with an interaction in LXe

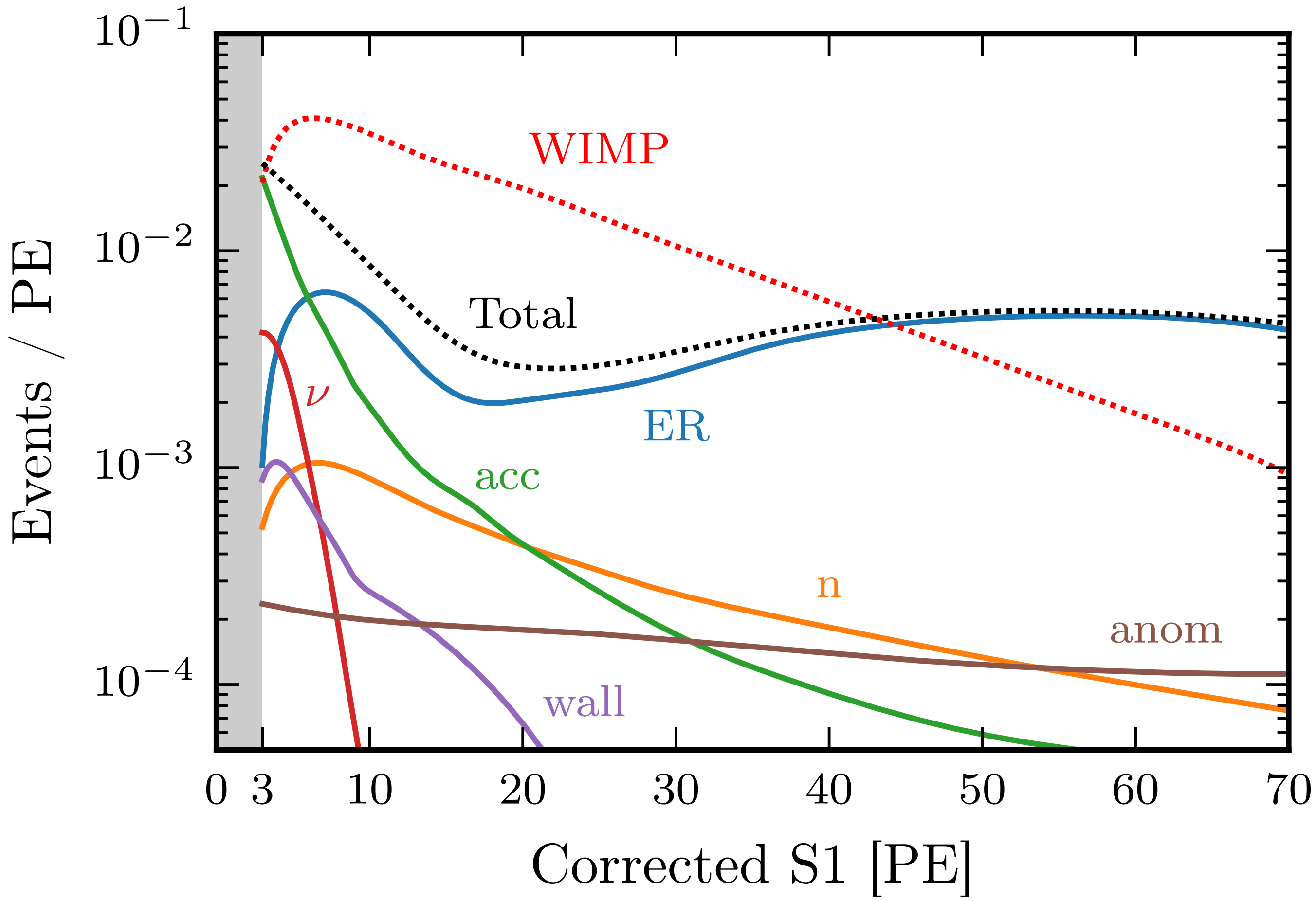
Cut	Events remaining
All Events (cS1 < 200 PE)	128144
Data Quality and Selection	48955
Fiducial Volume	180
S1 Range (3 < cS1 < 70 PE)	63





Background

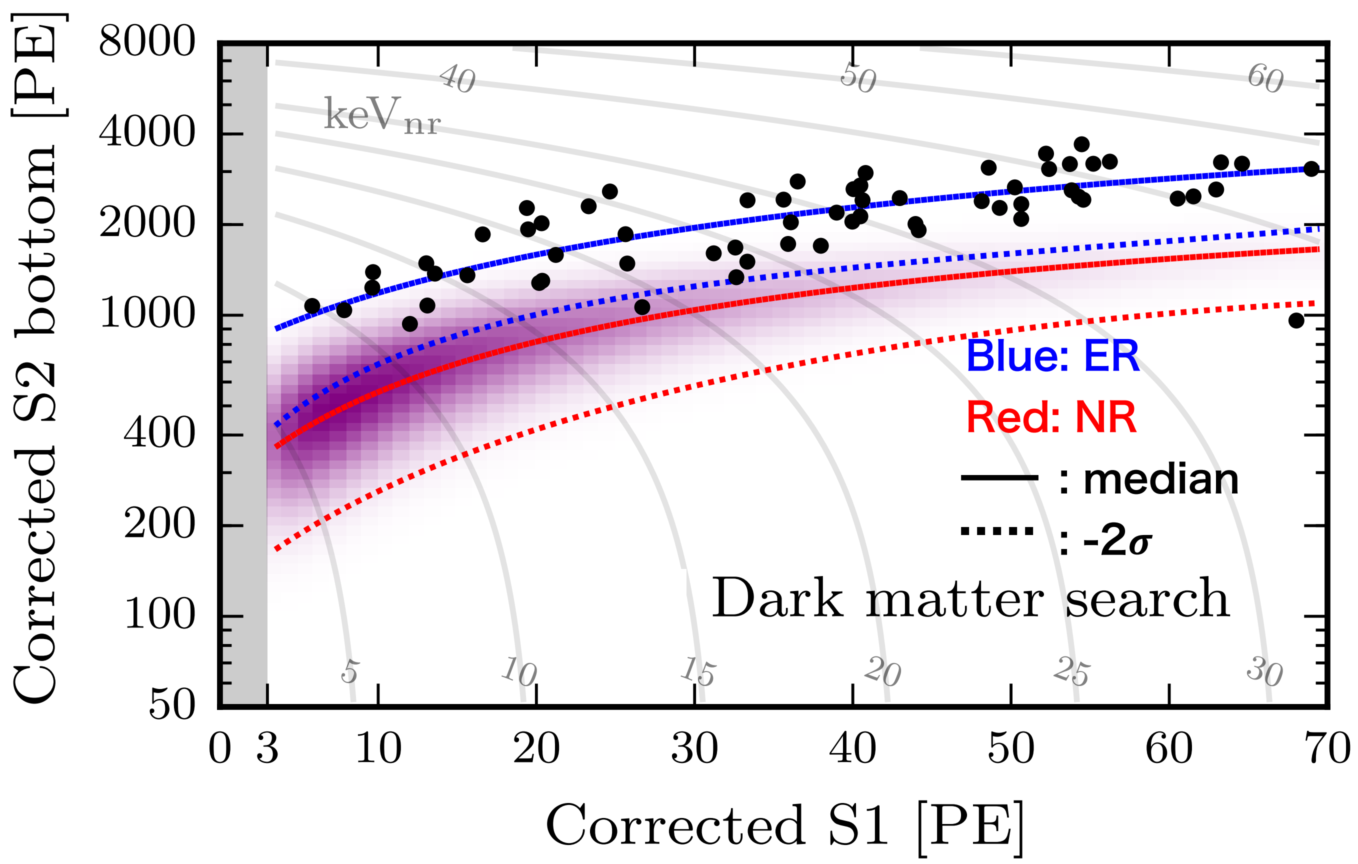
Estimated # of events below NR mean

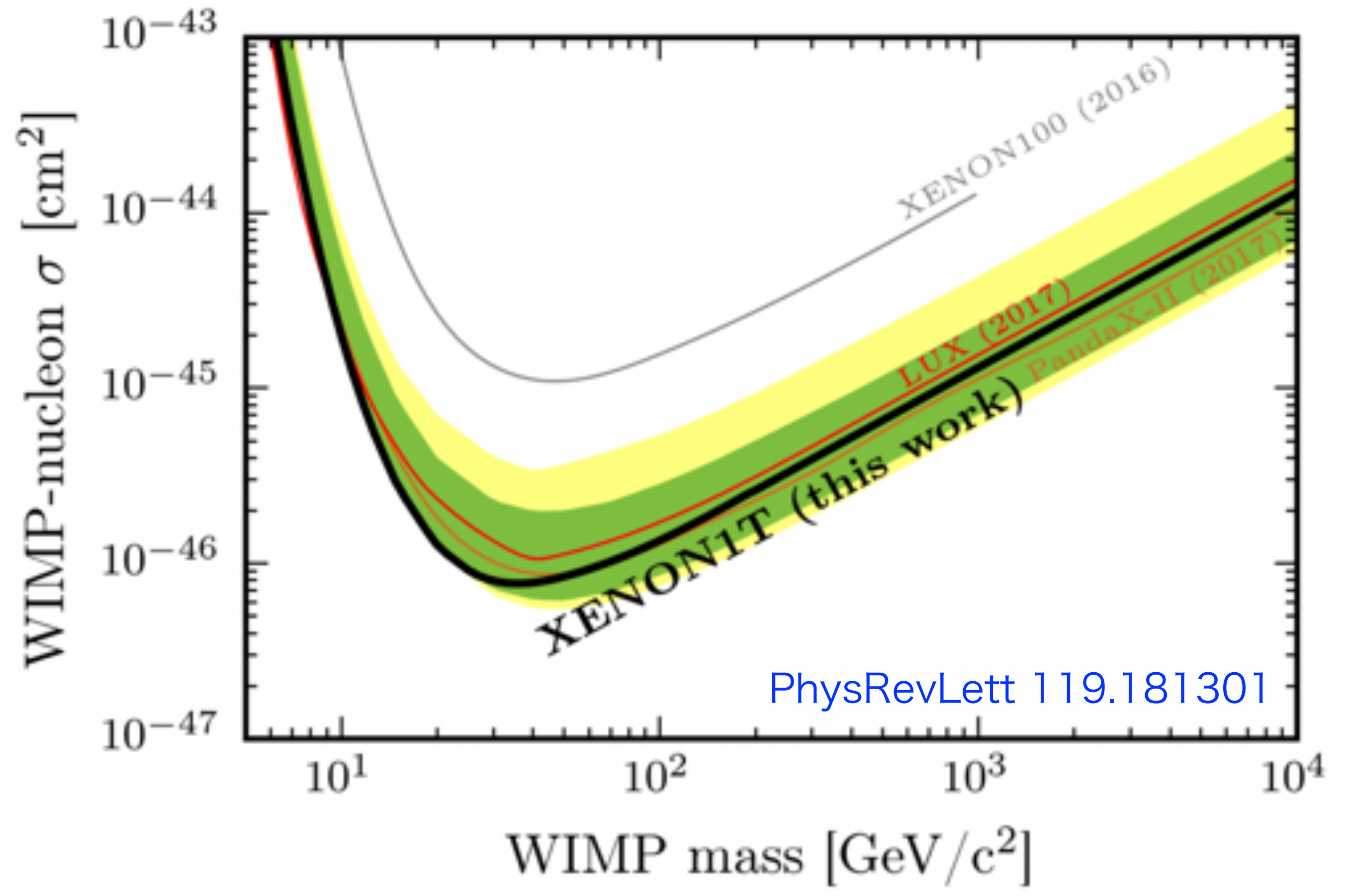


- ER and NR spectral shapes derived from models fitted to calibration data
- Other background expectations are data-driven, derived from control samples.
- Largest BG is Electronic Recoils which leak into the region below NR mean

Background & Signal Rates	Total	Reference: below NR mean
Electronic recoils (ER)	62 ± 8	0.26 (+0.11)(-0.07)
Radiogenic neutrons (n)	0.05 ± 0.01	0.02
CNNS (ν)	0.02	0.01
Accidental coincidences (acc)	0.22 ± 0.01	0.06
Wall leakage (wall)	0.52 ± 0.32	0.01
Anomalous (anom)	0.09 (+0.12)(-0.06)	0.01 ± 0.01
Total background	**63 ± 8**	**0.36 (+0.11)(-0.07)**
50 GeV/c^2, 10^{-46} cm^2 WIMP (NR)	1.66 ± 0.01	0.82 ± 0.06

First Dark Matter Search Results





- Two interesting events are found:
  - 27 pe : at -2.4σ (99.2th percentile) of the ER background.
  - 68 pe: probably anomalous leakage candidate
  - Background-only (no WIMPs) model still best fit at all WIMP masses

- Extended unbinned profile likelihood for statistical interpretation
  - PDF given in cs2-cs1 space
  - ER/NR shape parameters from calibration fits
  - Normalization uncertainties for all BG components

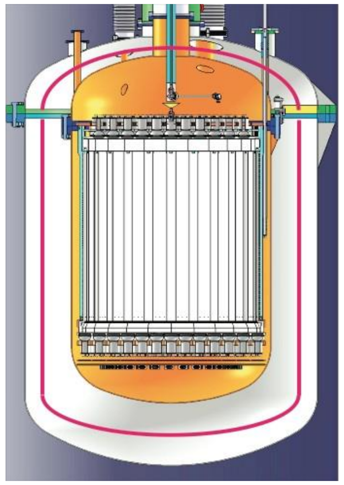
- Strongest exclusion limit: 7.7×10^{-47} cm^2 @ 35 GeV/c^2

Beyond XENON1T

XENON10
Total Xe: 25 kg
Target: 14 kg
Fiducial: 5.4 kg
Limit: ~10^{-43} [cm^2]

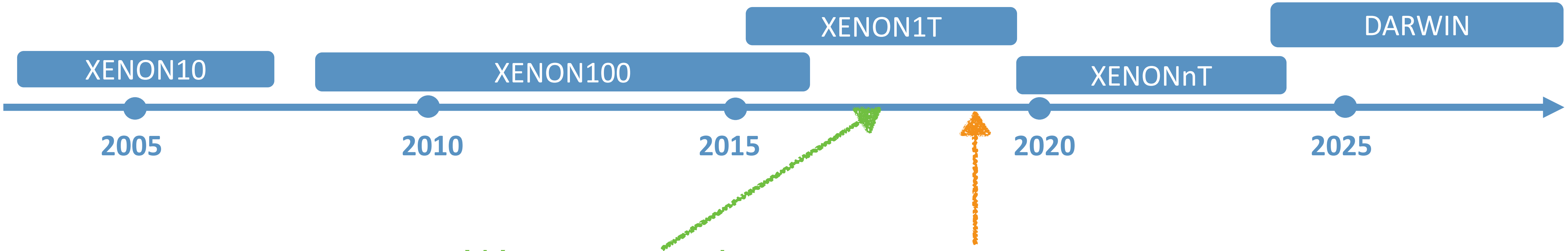
XENON100
Total Xe: 162 kg
Target: 62 kg
Fiducial: 34/48 kg
Limit: ~10^{-45} [cm^2]

XENON1T
Total Xe: 3.2 ton
Target: 2 ton
Fiducial: 1 ton
Limit: ~10^{-47}[cm^2]



XENONnT
Total Xe: ~8 ton
Target: ~6.5 ton
Fiducial: ~5 ton
Limit: ~10^{-48} [cm^2]

DARWIN
Total Xe: 50 ton
Target: 40 ton
Fiducial: 30 ton
Limit: ~10^{-49} [cm^2]



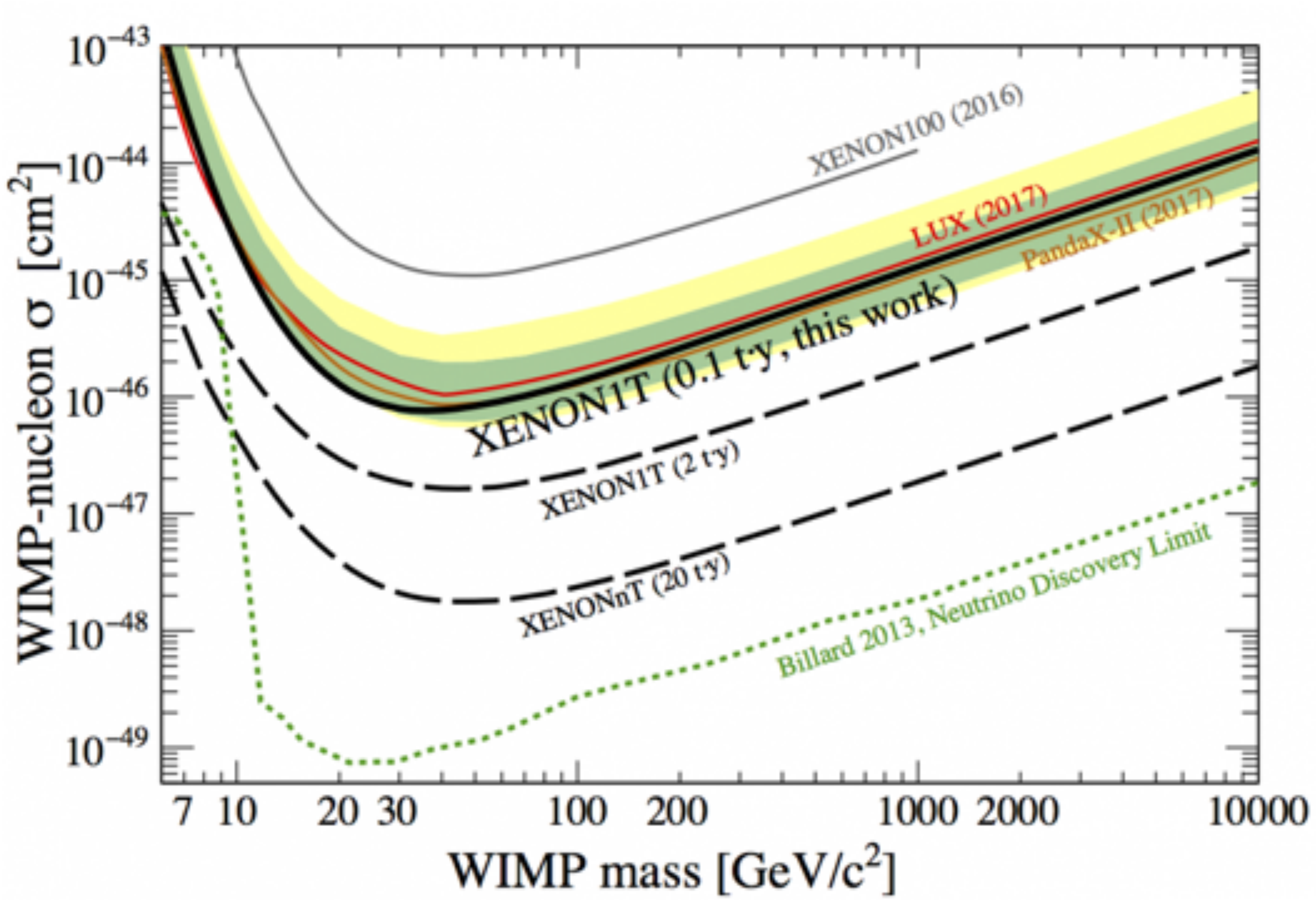
We are now here

Upgrade starting in 2018, operation in 2019

Summary and Outlook

XENON1T is currently leading direct dark matter search

- The XENON1T experiment operates in stable mode and shows very good data taking performance
- First physics results published in PRL, from 34.2 live days of data PhysRevLett 119.181301
- Lowest background in a dark matter detector (~ 0.2 events/(ton d keV))
- More than 220 additional live days of (blinded) science data on disk
  - ~10 times higher sensitivity is expected with 1ton-year exposure.
- New results expected for early next year



XENONnT

= XENON1T facility + larger TPC/cryostat

- fast upgrade with ×10 sensitivity
- ~8t of LXe (~5.9t target, ~5t fiducial)
- # of PMTs: 248 → 494

(PMTs are all ordered and mostly tested in LXe)

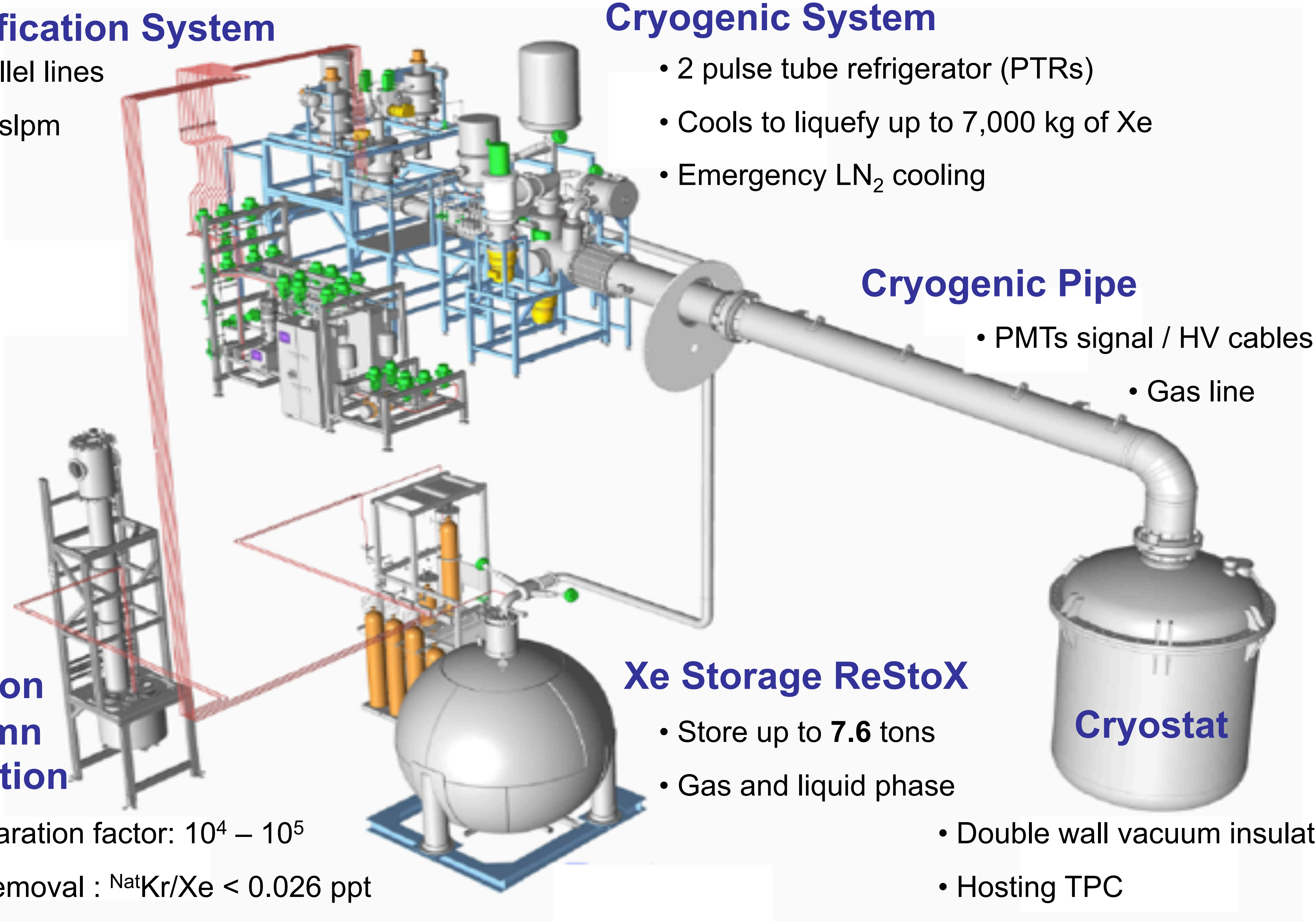
- neutron veto with liquid scintillator

Many subsystems are already in place

- water shield
- cooling, support systems, DAQ, cables
- purification and distillation column
- outer cryostat large enough to accommodate larger detector

BackUp

Xenon1T system



Purification System

- 2 parallel lines
- ~ 100 slpm

Cryogenic System

- 2 pulse tube refrigerator (PTRs)
- Cools to liquefy up to 7,000 kg of Xe
- Emergency LN_2 cooling

Cryogenic Pipe

- PMTs signal / HV cables
- Gas line

Krypton Column Distillation

- Separation factor: $10^4 – 10^5$
- Kr removal : $^{Nat}Kr/Xe < 0.026$ ppt

Xe Storage ReStoX

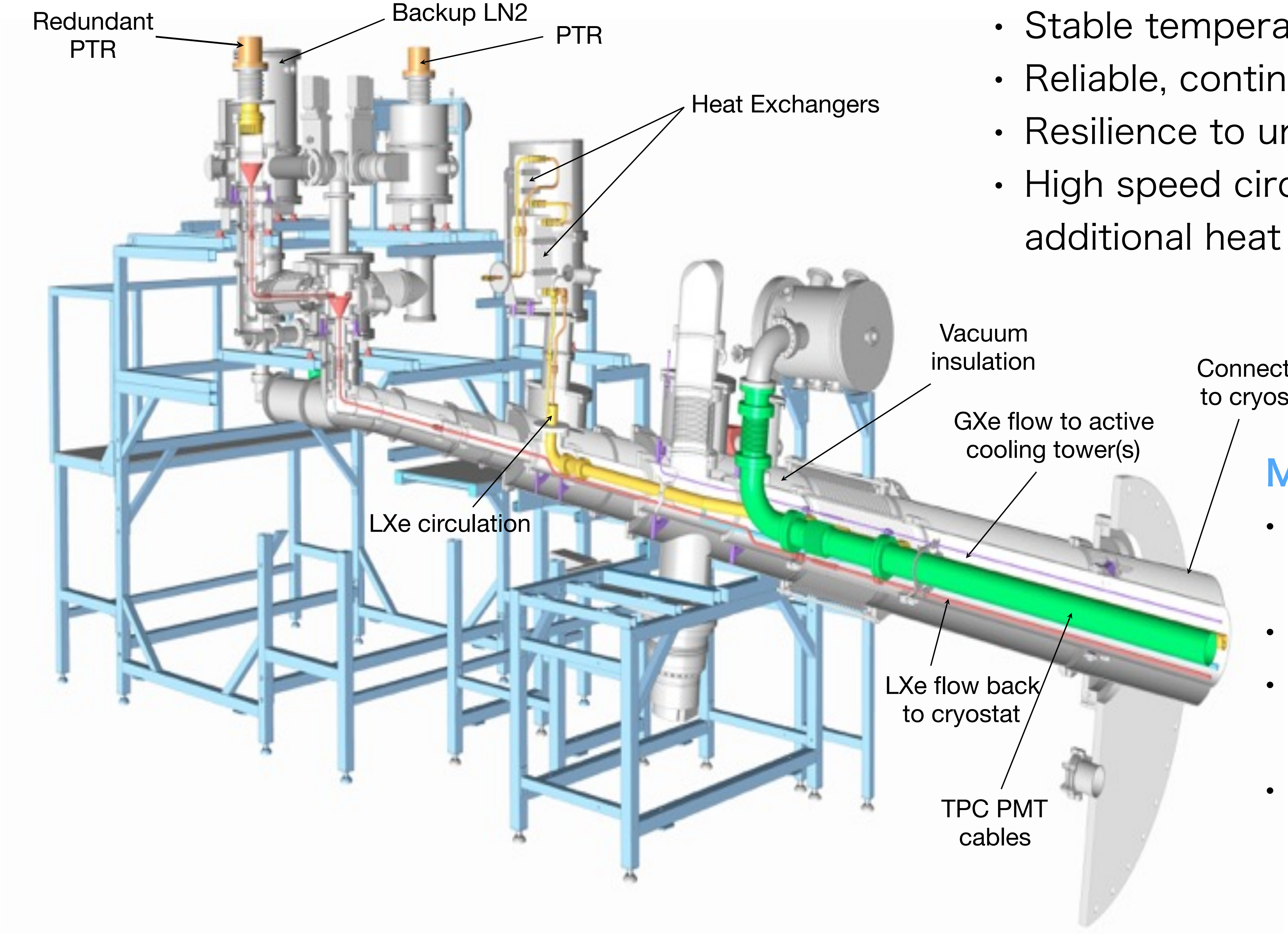
- Store up to **7.6** tons
- Gas and liquid phase

Cryostat

- Double wall vacuum insulated
- Hosting TPC

Cryogenic system

Goal: liquefy 3200 kg of Xe and maintain the xenon in the cryostat in liquid form, at a constant temperature and pressure without interruption.



Design goals:

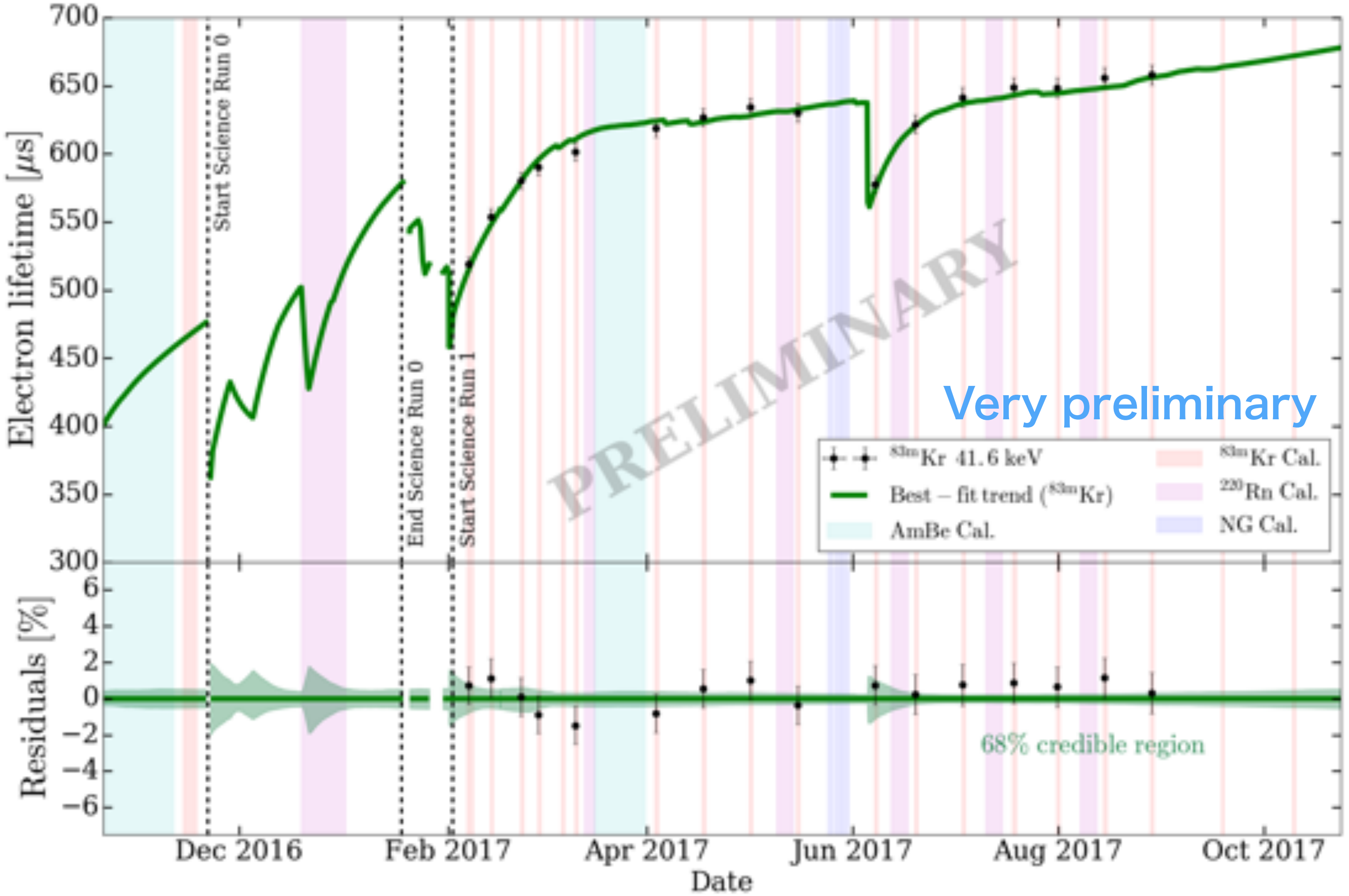
- Stable temperature and pressure control
- Reliable, continuous, long term operation
- Resilience to unexpected failures
- High speed circulation with low additional heat load

Main features:

- Redundant PTR cooling systems
- Backup LN2 cooling tower
- Efficient two-phase heat exchangers
- One PTR can be serviced while the other is in operation

Purification

- Purification system is the heart of the experiment, pumping and distributing high purity xenon to every part of the experiment
- Light absorbing impurities: scintillation light is lost
- Electronegative impurities: electrons are lost during the drift to the gas/liquid boundary.
- Outgassing continuously contaminates Xe
- Continuous recirculation and removing impurities like water and oxygen with hot zirconium oxide getters.
- Total flow rate of 54slpm (design: 100 slpm) driven by up to 4 pumps.
- Gas cleaned to one part per billion (ppb)
- Electron-lifetime is continuously increasing.



Very preliminary

Kr distillation column

- One source of intrinsic contamination of the Xe itself is given by the beta-decay of ^{85}Kr.

- Commercial Xe contains 1 ppm - 10 ppb of Kr, but XENON1T sensitivity demands ~ 0.2 ppt

- In order to reduce the Kr concentration by several orders of magnitude, a cryogenic distillation column has been developed.

- Utilizes different vapor pressure:
  - Kr: 20900 mbar@178K
  - Xe: 2010 mbar@178K

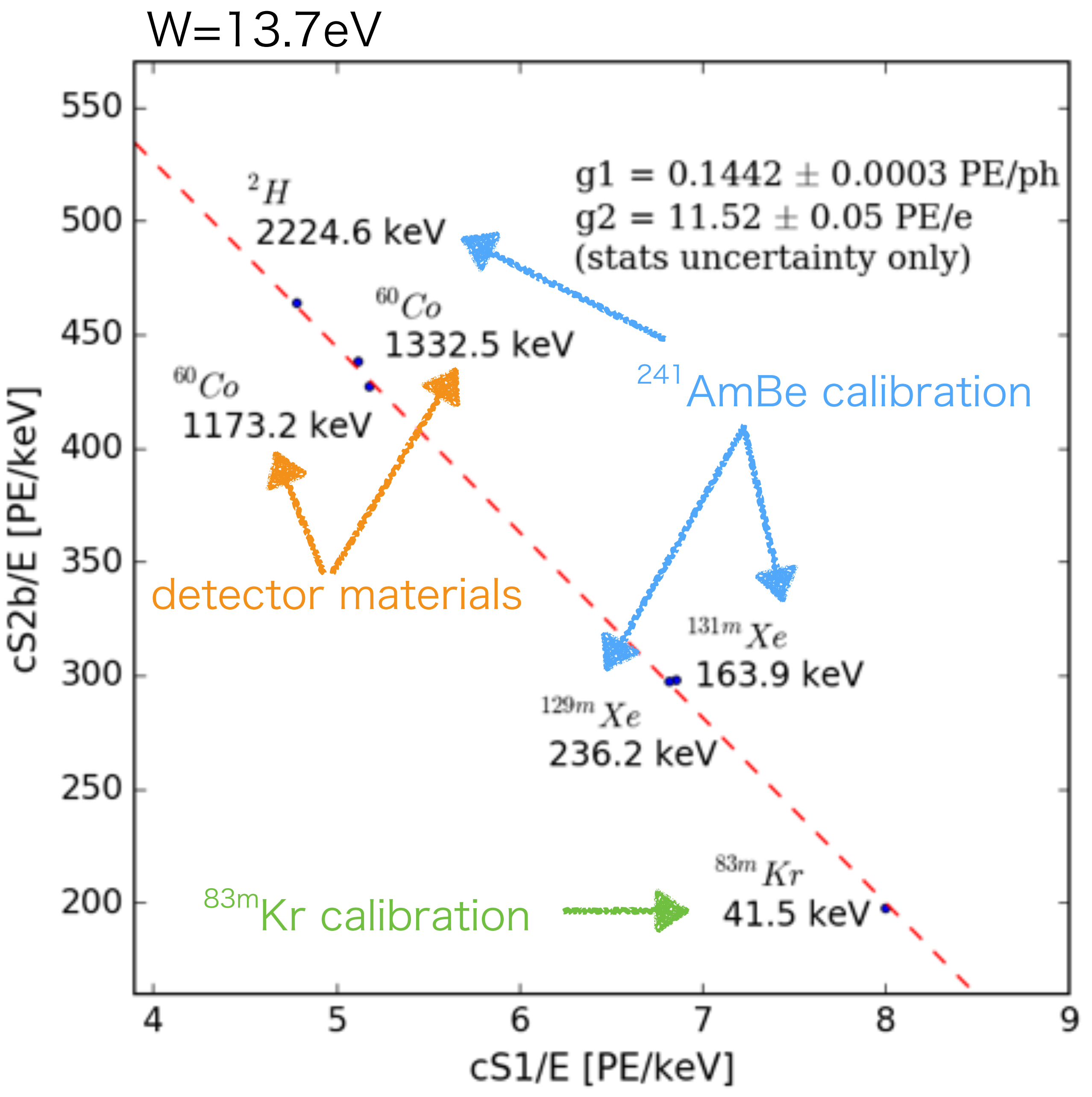
- 5.5 m distillation column

- Processing flow rate: 3kg/h = 8.3 slpm (Thermodynamically stable up to 6.5 kg/hr = 18slpm)

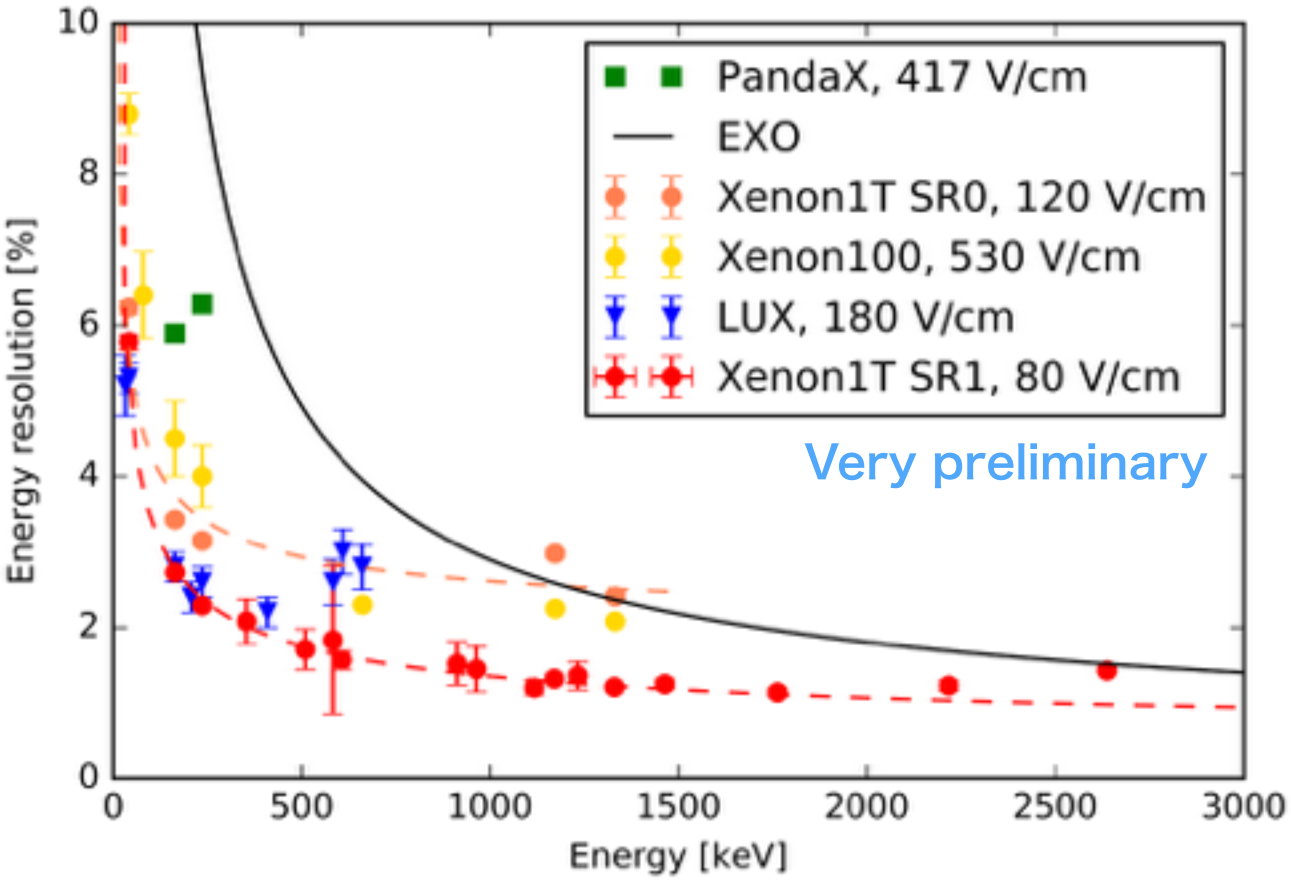
- Separation factor: 10^4- 10^5

Energy response

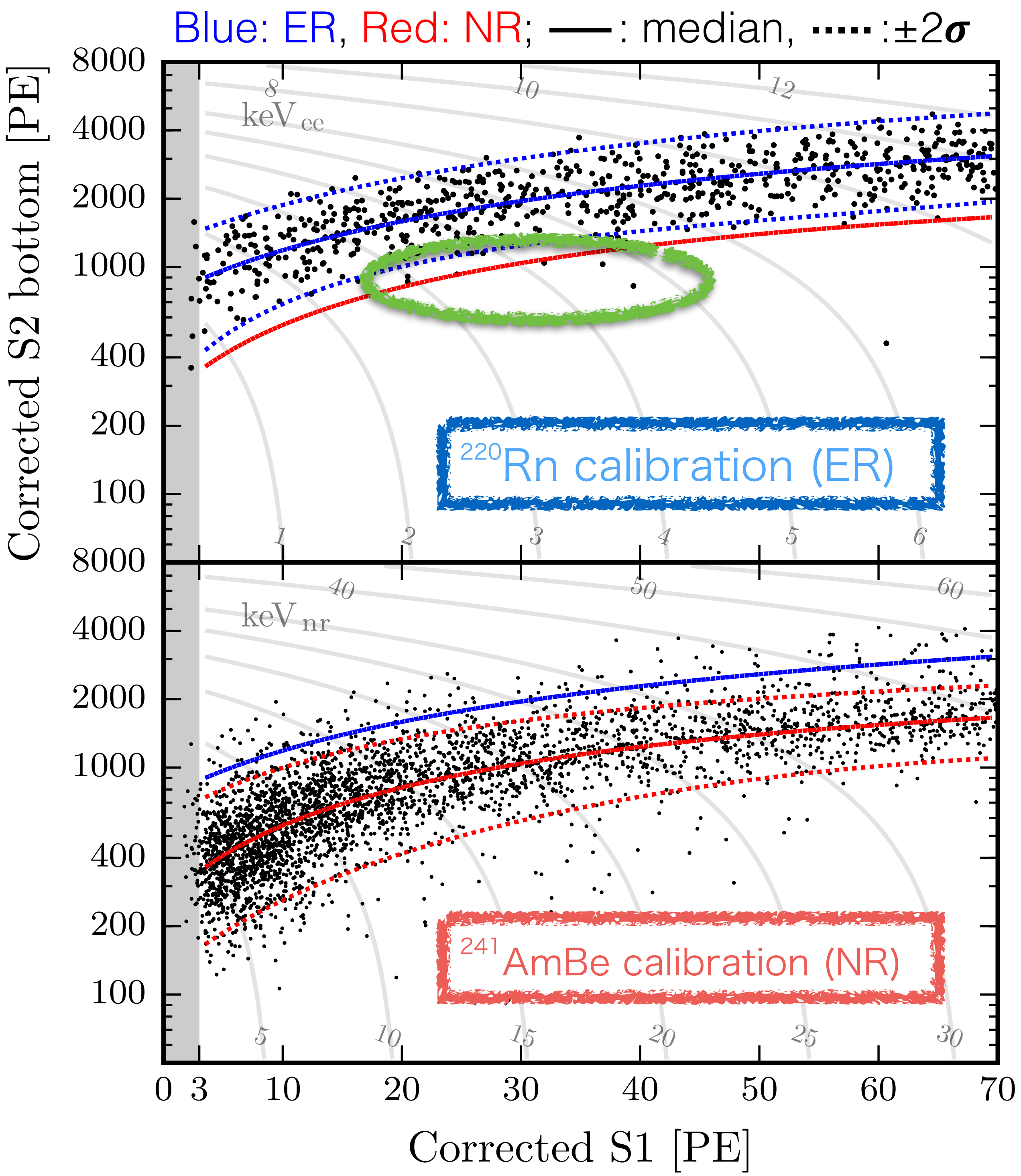
$$E = (n_{ph} + n_e) \cdot W = (\frac{S1}{g1} + \frac{S2}{g2}) \cdot W$$



- Excellent linearity with electronic recoil energy from 40 keV to 2.2 MeV
- g1 = (0.144 ± 0.007) pe/photon corresponds to a light detection efficiency of 12.5 ± 0.6%
- The amplification in gas (g2) corresponds to ~100% extraction of charges from the liquid: g2 = (11.5 ± 0.8) pe/electron
- Energy resolution has been improved from SR0 to SR1.



Background: Electronic Recoil



In principle, ER events can be rejected with s2/s1 information, but finite amount of ER events can leak into NR-region depending on FV size.

^{85}Kr

- ^{85}Kr concentration in LXe (^{nat}Kr/Xe):

  (2.60 ± 0.05) ppt @ start of SR0

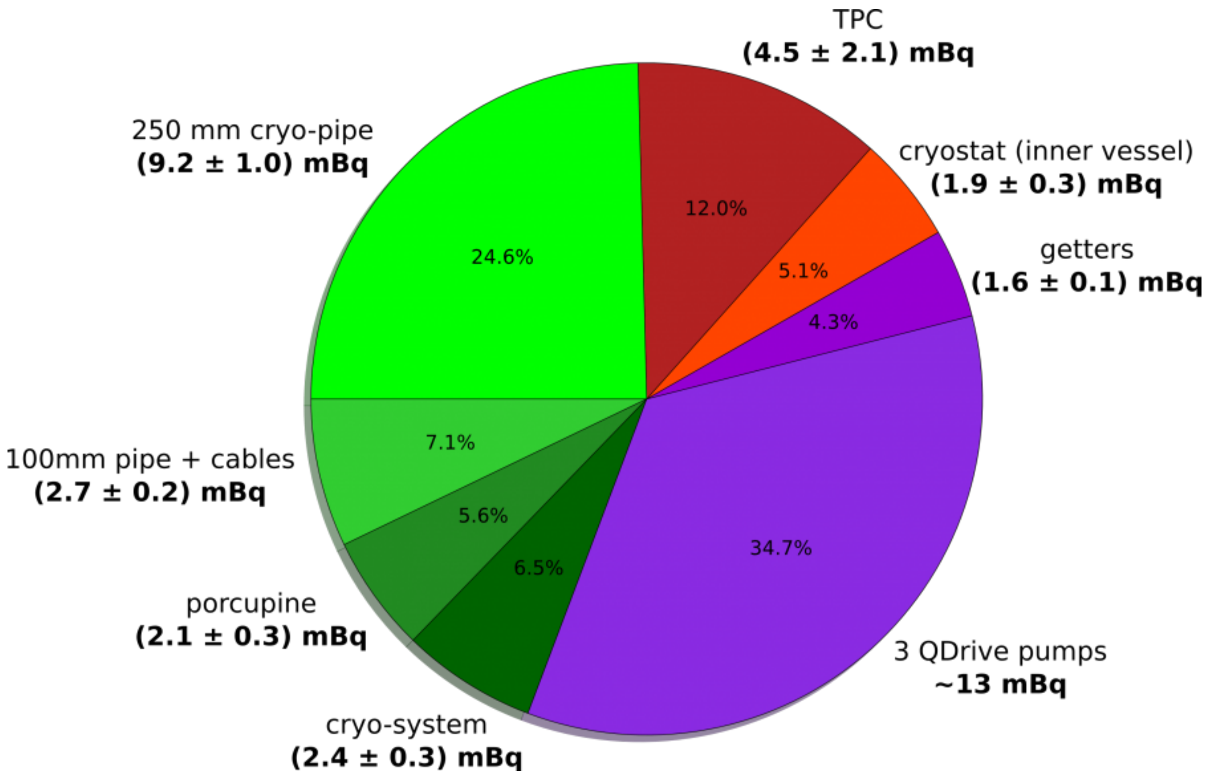
  ↓

  (0.36 ± 0.06) ppt @ end of SR0

- ER background is now ^{222}Rn dominated

^{222}Rn chain (^{214}Pb β-decay)

- Emanation from detector materials
  - Extensive screening program
  - Lowest possible emanation materials chosen
- 10 μBq/kg target concentration is reached

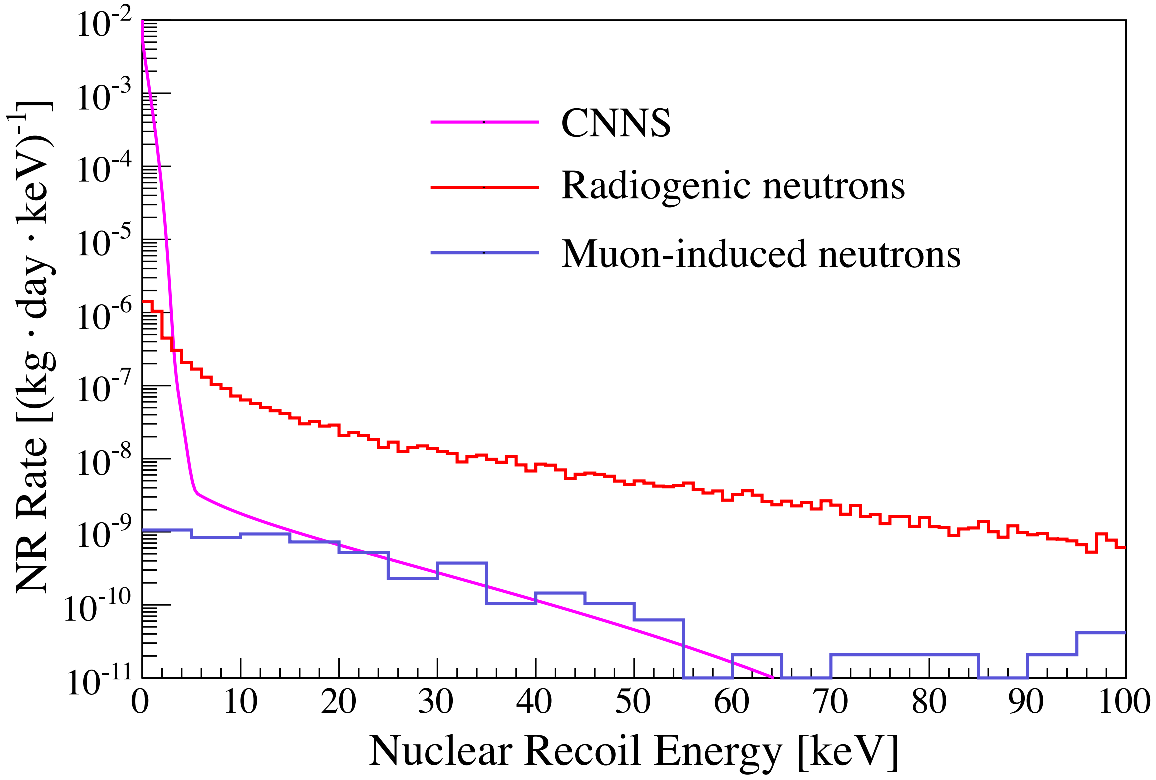


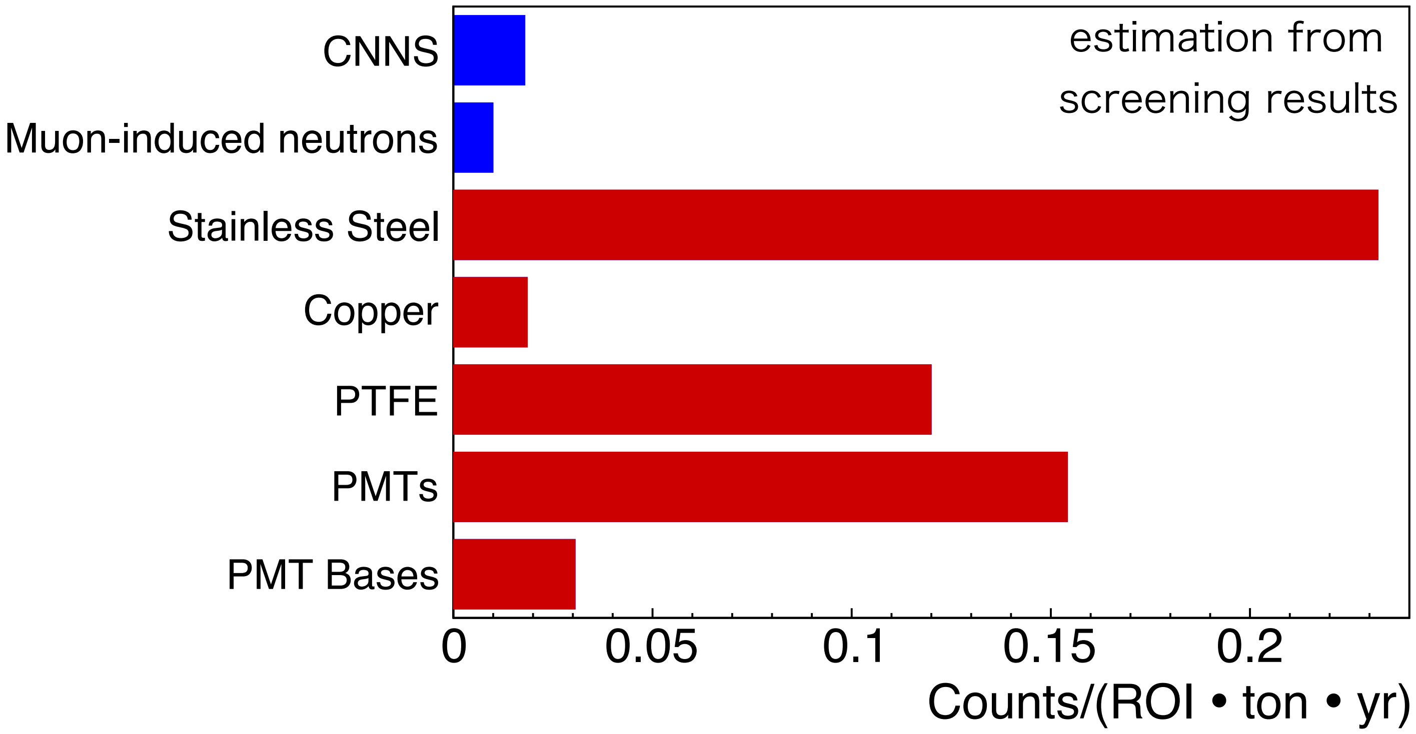
Background: Nuclear Recoil

External neutrons: muon-induced, (α, n), and fission reactions

- Underground location (LNGS, 3600 m.w.e overburden) + active water Cherenkov veto
- Material selection for low ^{238}U, ^{232}Th contaminations

Neutrinos: Coherent neutrino-nucleus scattering (irreducible BG)





- The detector response to NRs is estimated by fitting MC to the ^{241}AmBe calibration data.

- Radiogenic neutrons: (0.6±0.1) $(t·y)^{-1}$ from screening results
- Neutrinos coherent scattering off Xenon nuclei: $(1.8 \pm 0.3) \times 10^{-2}$ $(t·y)^{-1}$
- Muon-induced neutron: < 0.01 $(t·y)^{-1}$

- **NR background is estimated to be negligible for the first science run**

Background: Accidental coincides of S1 & S2

- Isolated S1s may arise from interactions in regions of the detector with poor charge collection, such as below the cathode, suppressing an associated S2 signal.
- Isolated S2s might arise from photoionization at the electrodes, regions with poor light collection, or from delayed extraction.
- Most accidental coincidence events are expected at low S1/S2 regions, which is critical for low mass WIMP searches

$$r_{AC} = r_{\text{lone-s1}} \times \ r_{\text{lone-s2}} \times \ \Delta T\ ,\ \Delta T = \text{maximum drift time } (\sim 650\ \mu\text{s})$$

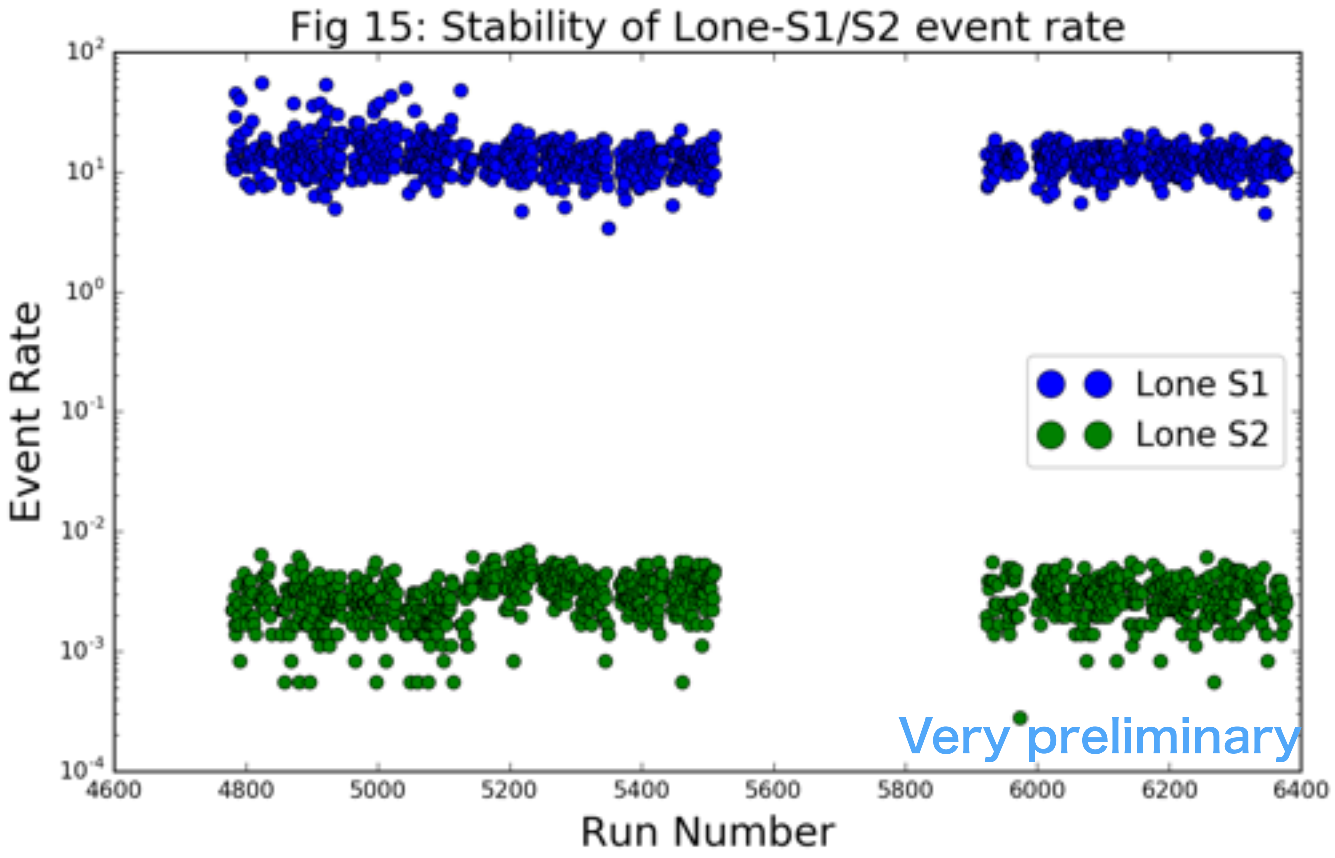
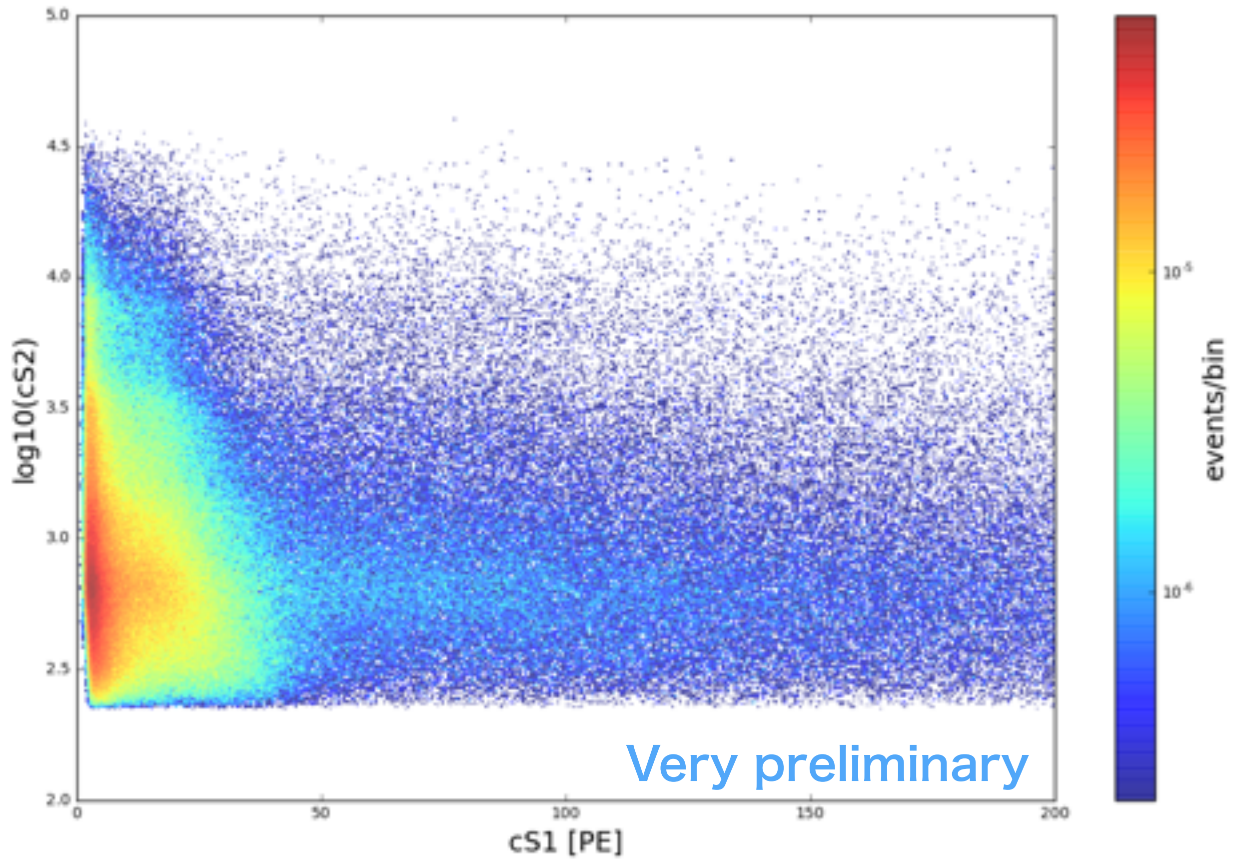


Fig 15: Stability of Lone-S1/S2 event rate

Very preliminary



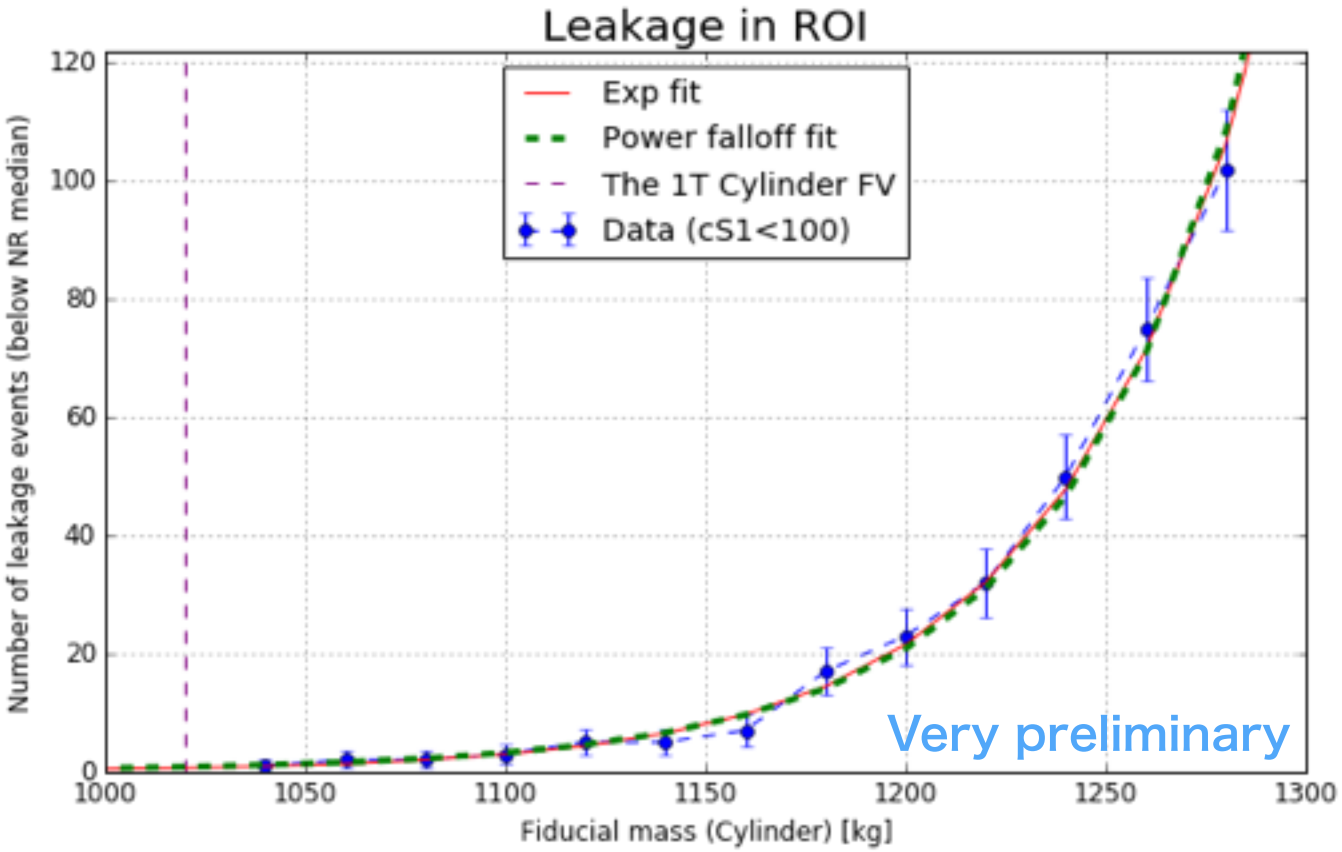
Very preliminary

Background: Wall leakage events

- For events happened near the TPC's PTFE wall, some of charges can be lost on the wall, resulting in unusually small S2 (which can mimic like a WIMP signal)

- Position of these events can be reconstructed inward due to limited position reconstruction resolution because the 5 top PMTs in the outermost ring are unavailable

- BG can be estimated by fitting a function to the number of events in our sideband below the ER band vs the fiducial volume mass.

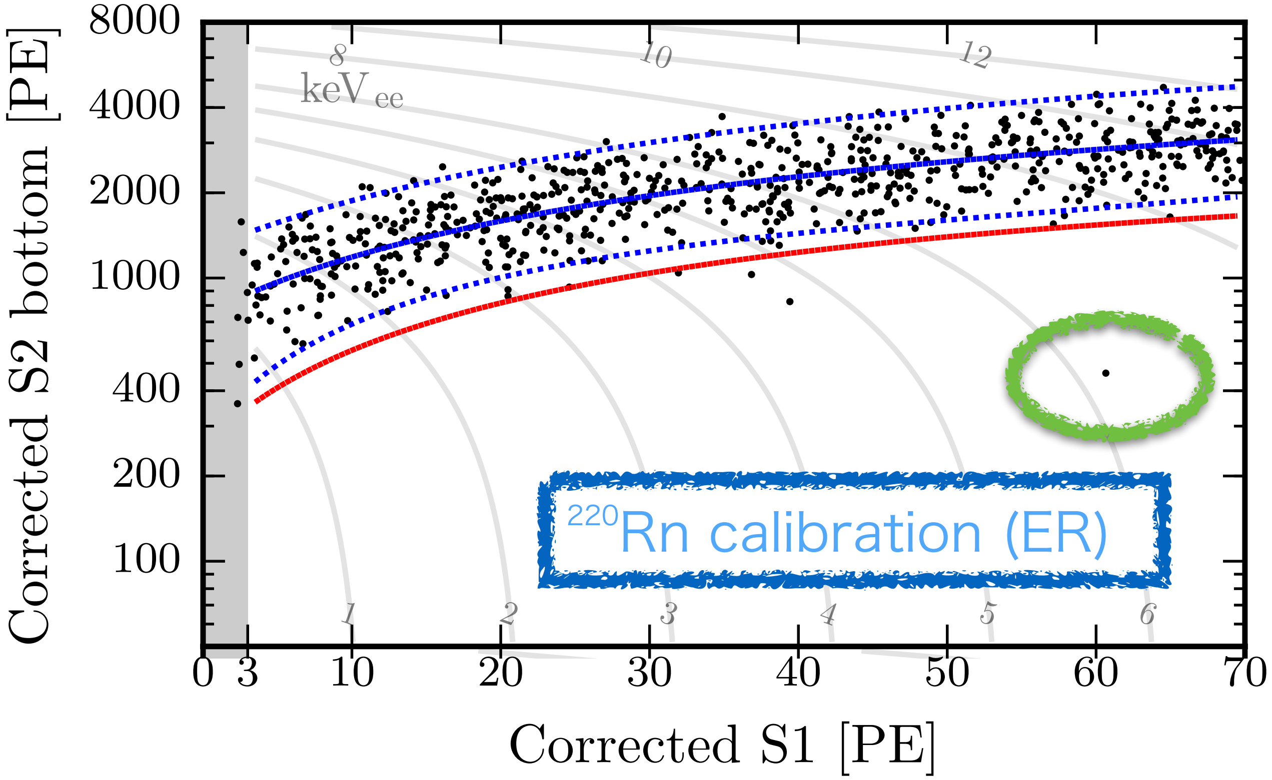


- This BG component is limiting factor for enlarging FV size.

- For SR0, we chose FV size of 1042 kg conservatively.

- Expected to contribute (0.5 ± 0.3) events, with the rate, and (S1, S2) spectrum extrapolated from events outside the fiducial mass.

Background: Anomalous leakage events

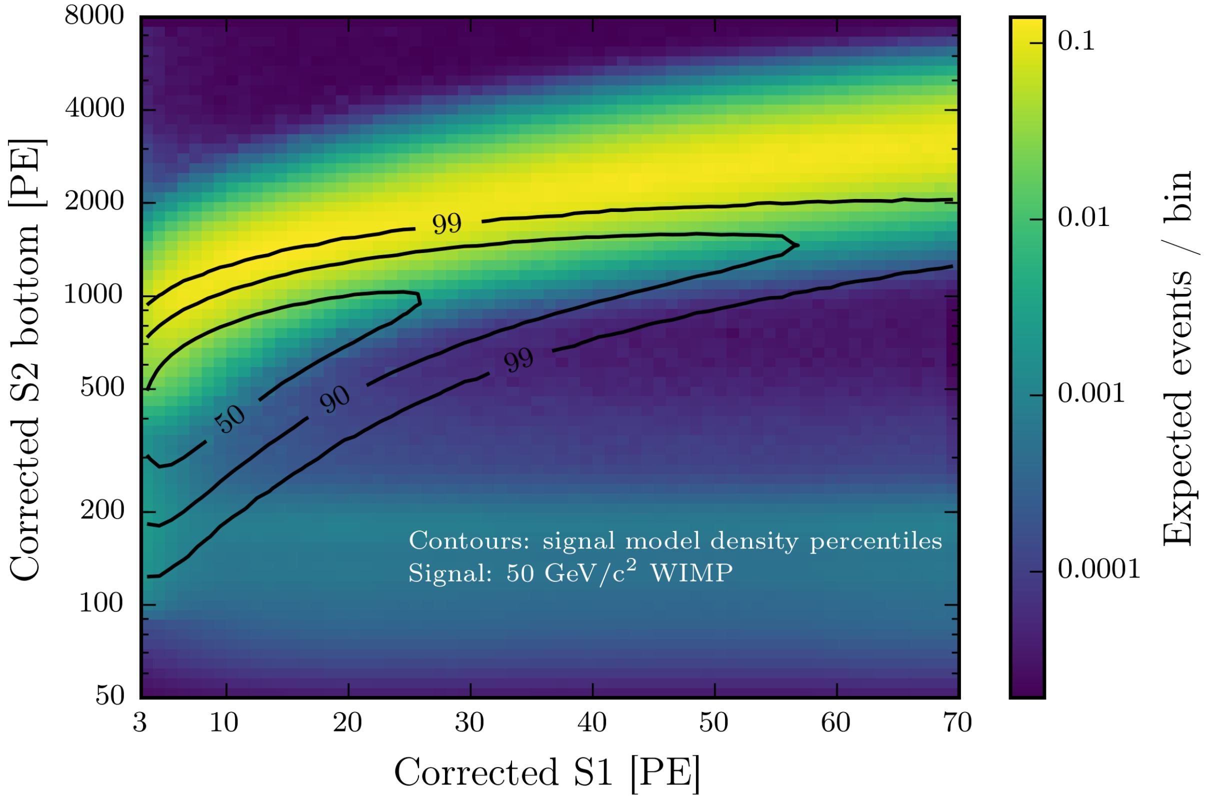


- An event has been found in ^{220}Rn calibration data which has a incredibly small s2,
- This is not consistent with any NR events including WIMP signals.
- We call this BG as anomalous leakage event.
- Origin of this event is still not understood.

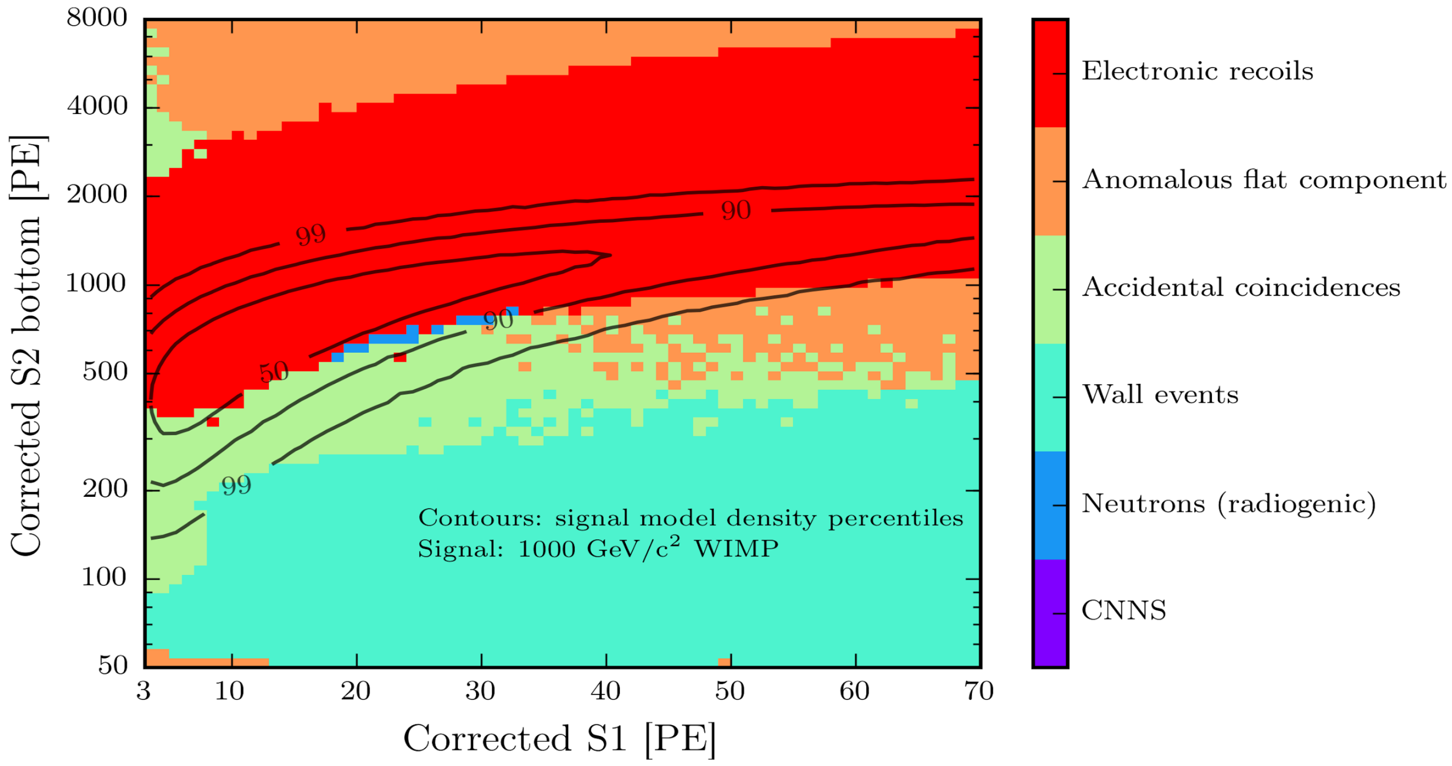
- Hypothesis: S2 reaches the liquid/gas surface and few of the electrons get trapped into the dirt/dust resulting into lower S2 values (energy independent) as found by ZEPLIN collaboration.
- If this hypothesis is true, the number of events should scale with event rate, and its s2 spectrum should be uniformly distributed below their actual s2 size.
- Therefore, we add additional flat pdf component in (s1, s2) space in the profile likelihood.
- Normalization is scaled with the number of events in ER-band

Background: Summary

Total background model



Dominant background component map



Background & Signal Rates	below NR -2σ quantile
Electronic recoils (ER)	0.26 (+0.11)(-0.07)
Radiogenic neutrons (n)	0.02
CNNS (ν)	0.01
Accidental coincidences (acc)	0.06
Wall leakage (wall)	0.01
Anomalous (anom)	0.01 ± 0.01
Total background	**0.36 (+0.11)(-0.07)**
50 GeV/c^2, 10^{-46} cm^2 WIMP (NR)	0.82 ± 0.06

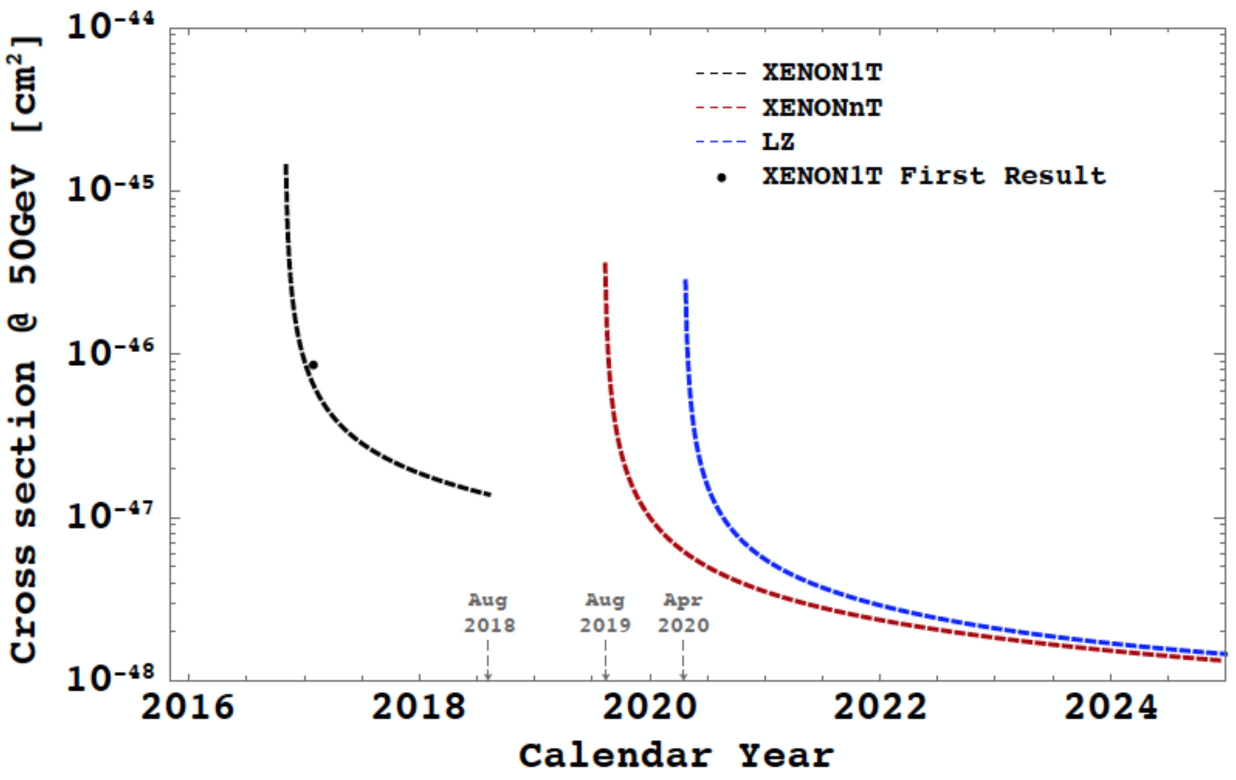
- **ER leakage events:** the most significant background (for > 10 GeV WIMPs)
- **Wall leakage events:** are below the ER band, but too low S2 to hurt much
- **Anomalous leakage events**: contribute extremely small (~ 0.1 events expected)

XENONnT Experiment

- A rapid upgrade to XENON1T, with: 8 t total LXe mass, 6 t active (x3 compared to 1T)
- Most sub-systems can handle a larger detector with up to 10 t of LXe:

	XENON1T	XENONnT
Drift Length (cm)	97	144
Diameter (cm)	96	137
# Top PMTs	127	223
# Bottom PMTs	121	253
Active Mass	2.0	6.0
Total Mass (tonne)	3.2	8.0

- Water tank + muon veto
- Outer cryostat and support structure
- Cryogenics and purification system
- LXe storage system
- Cables installed for XENONnT as well
- New inner cryostat, new TPC, 476 PMTs
- Neutron veto, Rn removal tower, additional LXe storage system
- will start operation ~1-year before LZ experiment



Status of XENONnT Experiment

	XENON1T	status for XENONnT
Muon Veto	operational	ready
Outer cryostat	existing	ready
Cryogenic system	operational	ready
Screening facilities	operational	ready
Distillation column	operational	ready
Calibration system	operational	ready
Slow control	operational	ready
DAQ & electronics	operational	all electronics in hand
Xenon gas	3.2 tonne in use	ready (>8t in hand)
LXe Storage	ReStoX1 operational	ReStoX2 extra safety & storage
PMTs	260 existing	+230 being delivered & tested
TPC & inner cryostat	operational	upgrade design
Purification system	operational	upgrade design
Rn reduction	tested	study on-going
n-veto system	no	study on-going

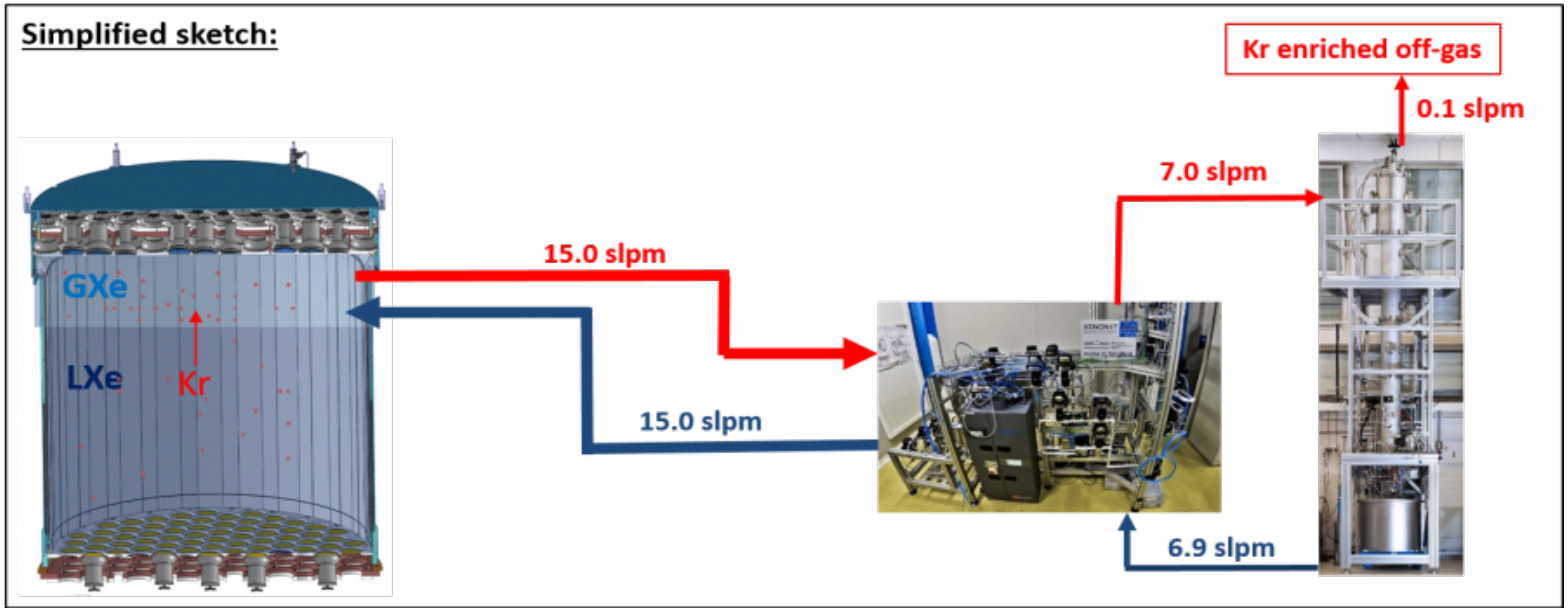
Online Kr distillation

The idea of the online distillation mode is to purify not the whole inventory of the detector, but only the gas-phase on top.

By disturbing the equilibrium between the gas and liquid phase, the Kr is migrating from the liquid to the gas-phase and is removed by that.

At a high cycling speed, the removal process is limited by the migration time of the Kr from the liquid into the gas.

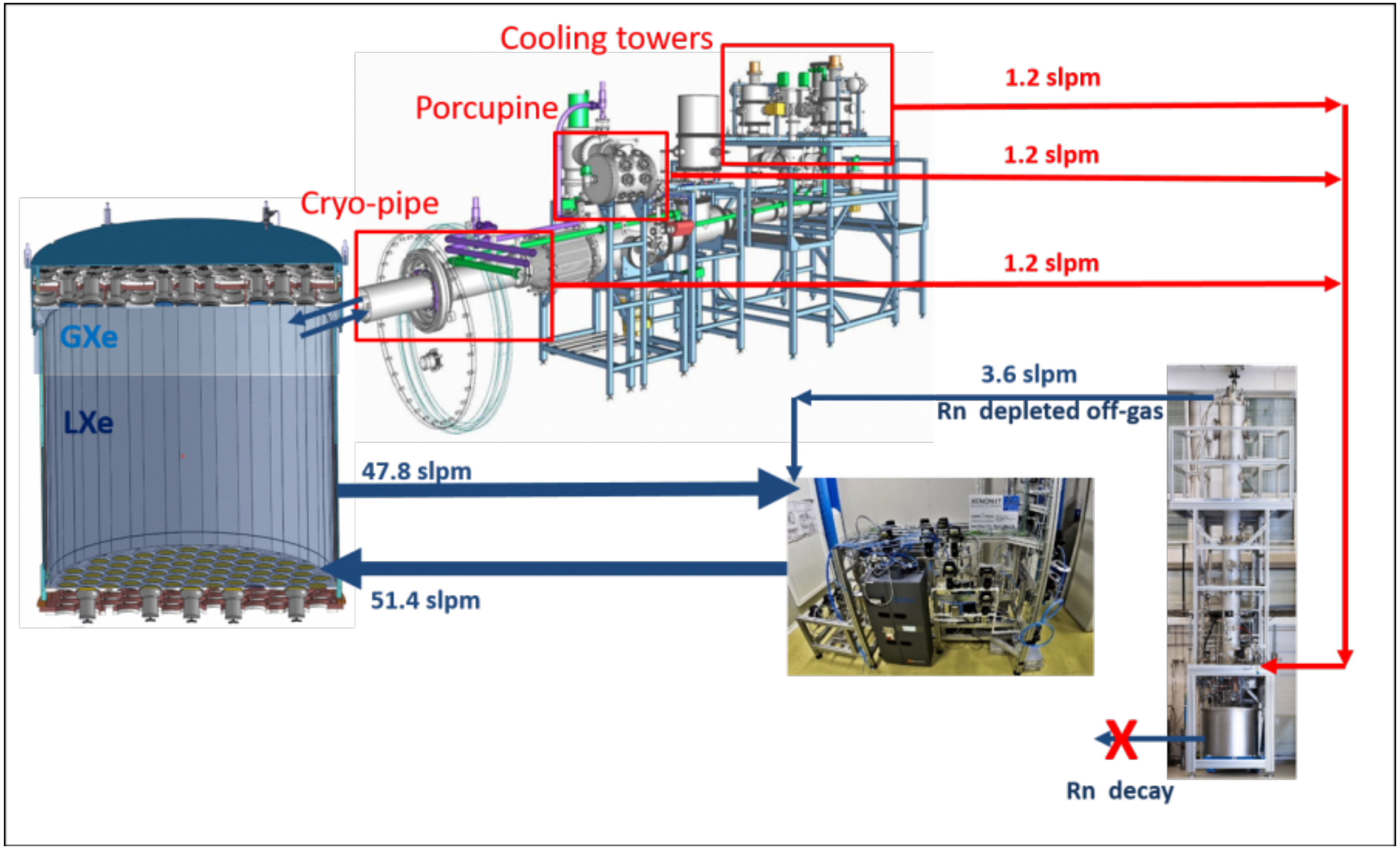
First we remove the bulk of Kr in the gas on short time-scales, like 1-2 days. Afterwards, we stop the distillation and wait to get a Kr equilibrium again. After that is achieved, we remove again the Kr bulk from the gas.



Rn222 reduction

In order to reach the projected sensitivity for XENON1T, a ^{222}Rn concentration of 10µBq/kg is required → Part of ^{222}Rn can be reduced with cryogenic distillation

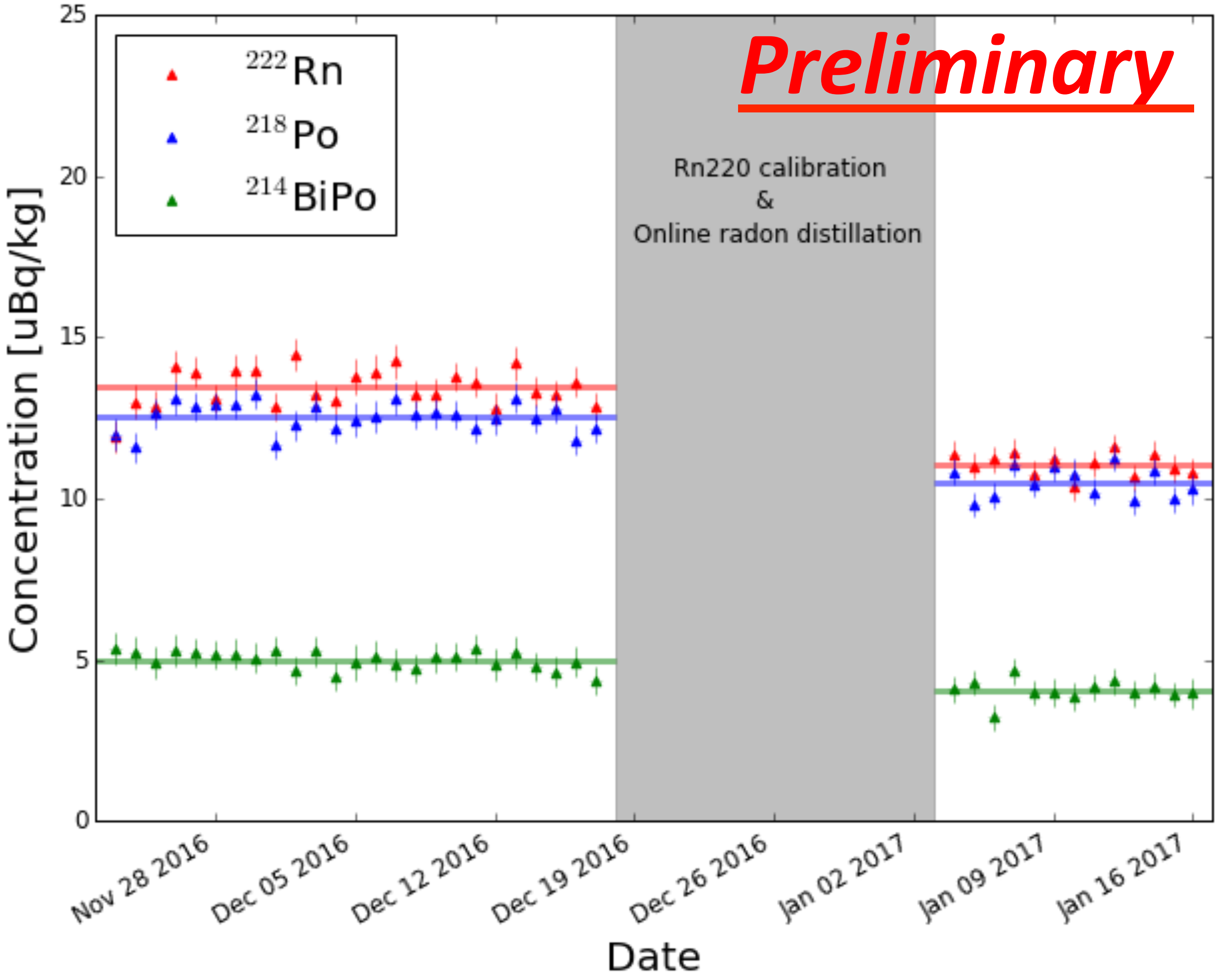
The idea is to extract the radon from the gas-phase before it can enter the liquid-phase of the TPC and guide it to the DST system where it is trapped in the liquid reservoir of the reboiler until desintegration. The radon-depleted off-gas is fed back to purification system.



Rn222 reduction

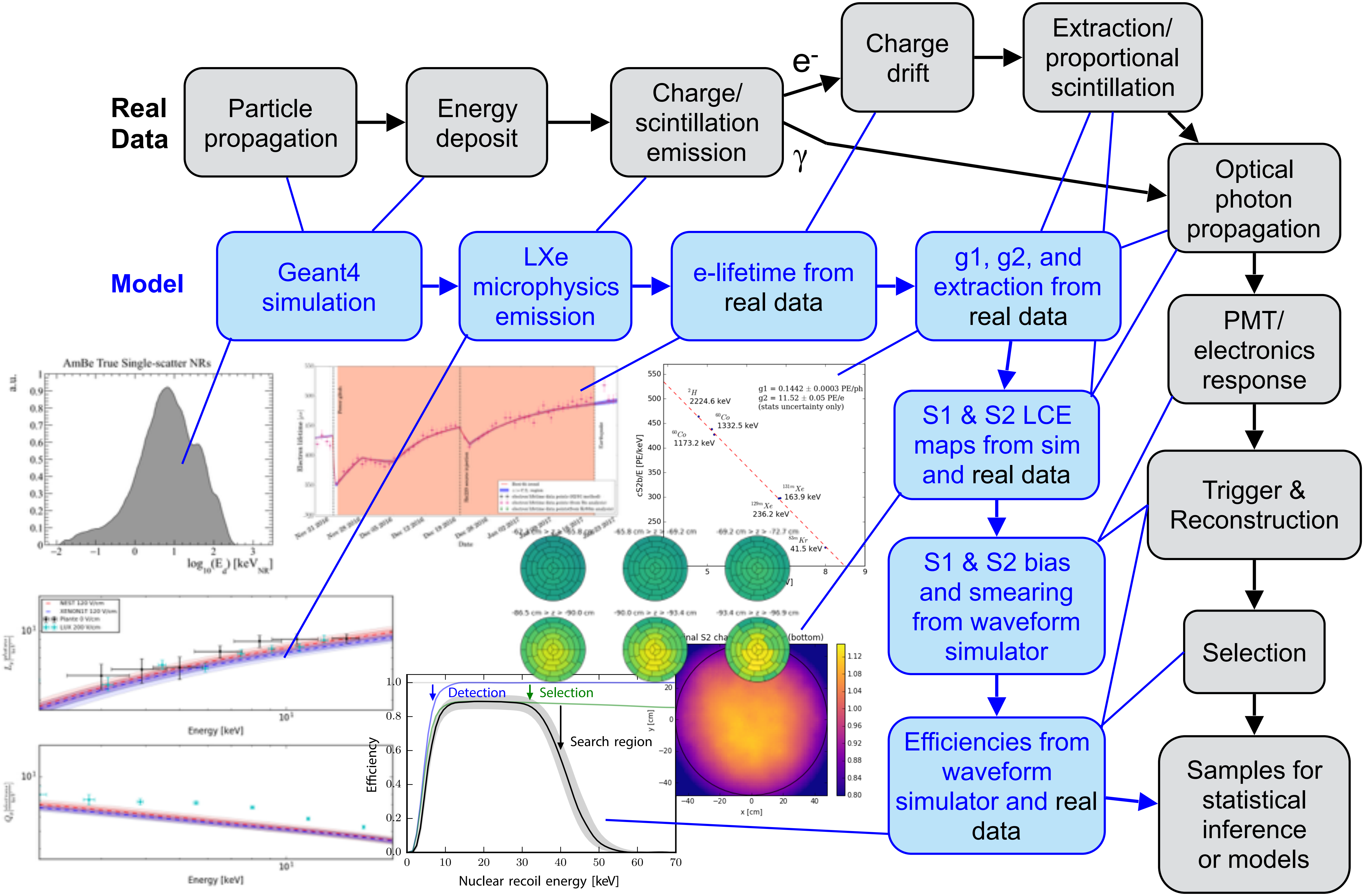
In order to reach the projected sensitivity for XENON1T, a ^{222}Rn concentration of 10µBq/kg is required → Part of ^{222}Rn can be reduced with cryogenic distillation

The idea is to extract the radon from the gas-phase before it can enter the liquid-phase of the TPC and guide it to the DST system where it is trapped in the liquid reservoir of the reboiler until desintegration. The radon-depleted off-gas is fed back to purification system.



- Before the radon distillation an average of 13.4 uBq/kg is found.
- After ~11 days of distillation the average concentration dropped with ~18% to 11.0 uBq/kg.

The ER and NR Models



Real Data

Particle propagation → Energy deposit → Charge/ scintillation emission

Charge/ scintillation emission → e^- → Charge drift → Extraction/ proportional scintillation → Optical photon propagation

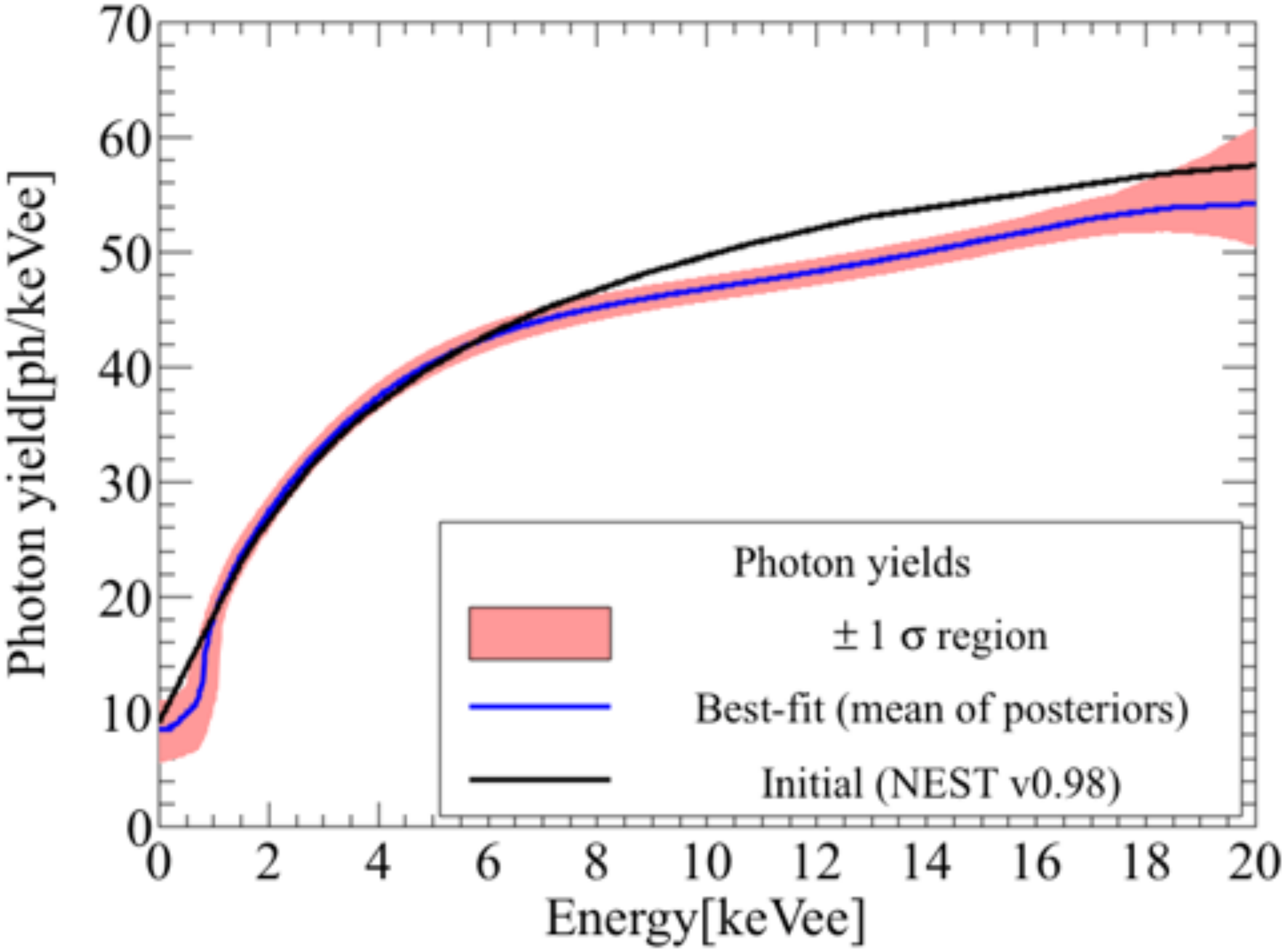
Charge/ scintillation emission → γ → Optical photon propagation

Optical photon propagation → PMT/ electronics response → Trigger & Reconstruction → Selection → Samples for statistical inference or models

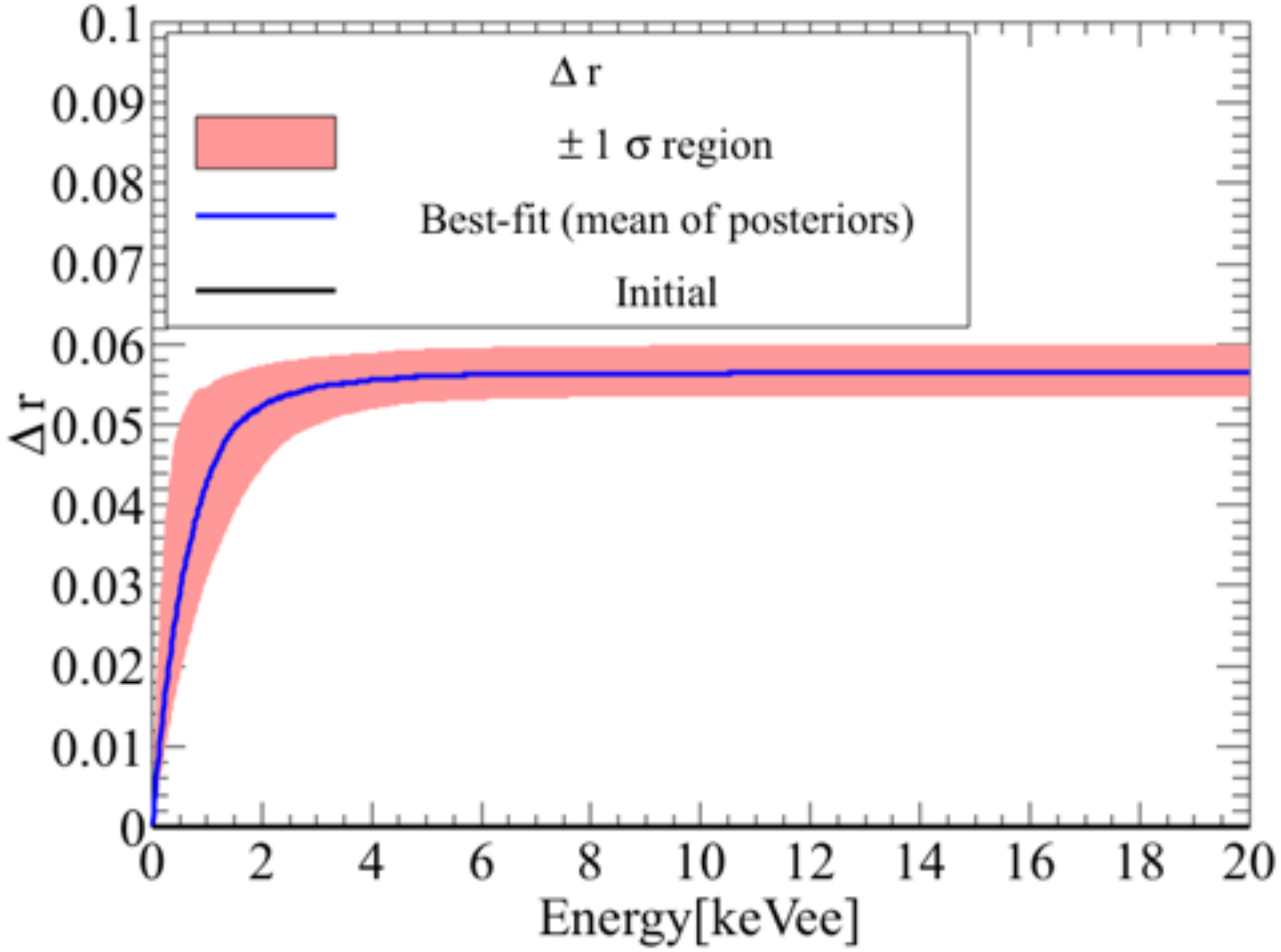
Model

Geant4 simulation → LXe microphysics emission → e-lifetime from real data → g1, g2, and extraction from real data → S1 & S2 LCE maps from sim and real data → S1 & S2 bias and smearing from waveform simulator → Efficiencies from waveform simulator and real data → Samples for statistical inference or models

Rn220 Calibration



Photon Yield



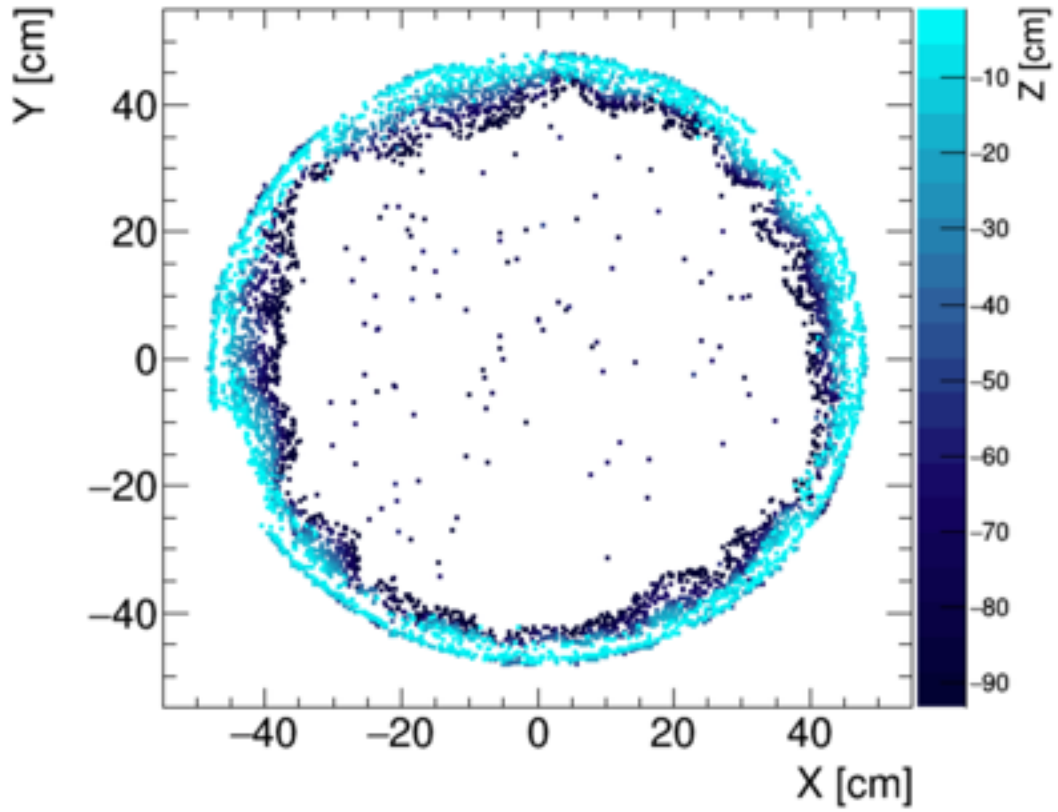
Recombination Fluctuation

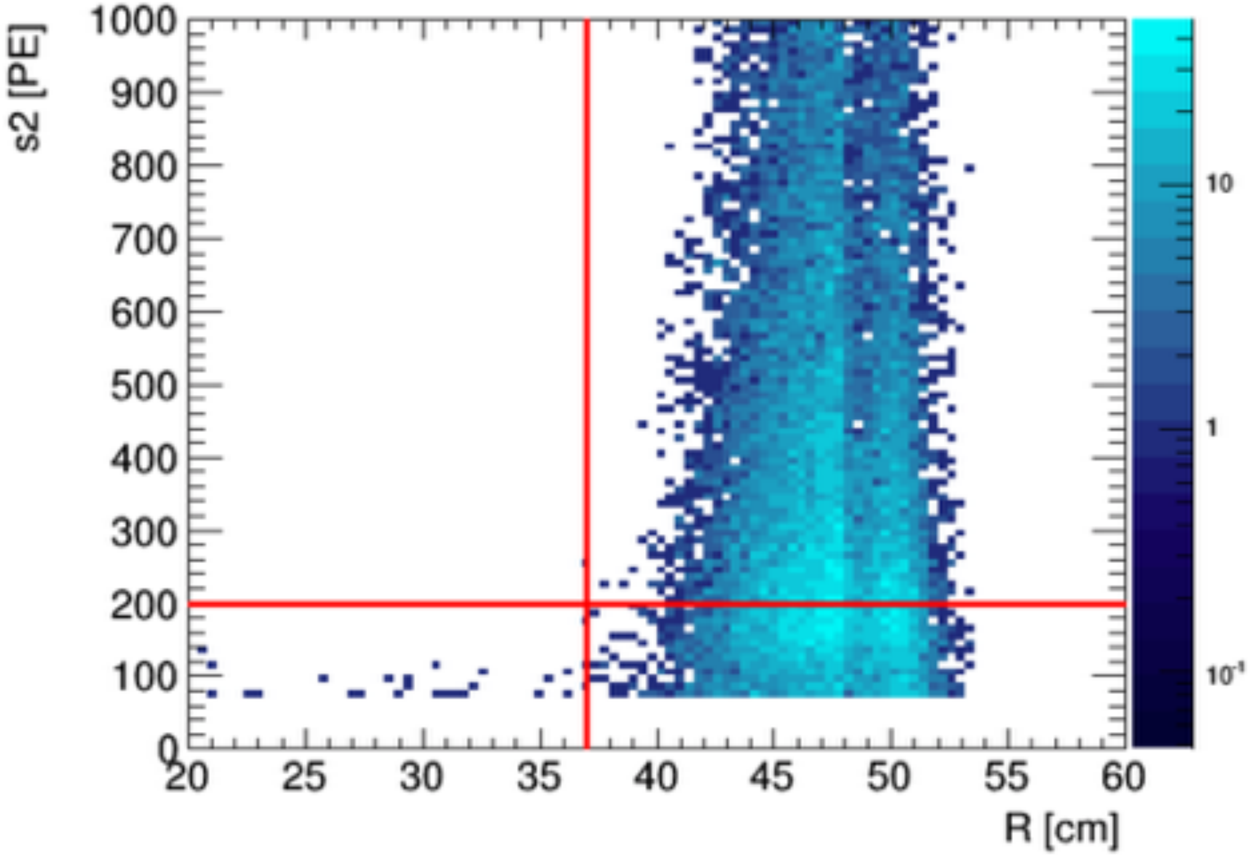
Neutron Activation

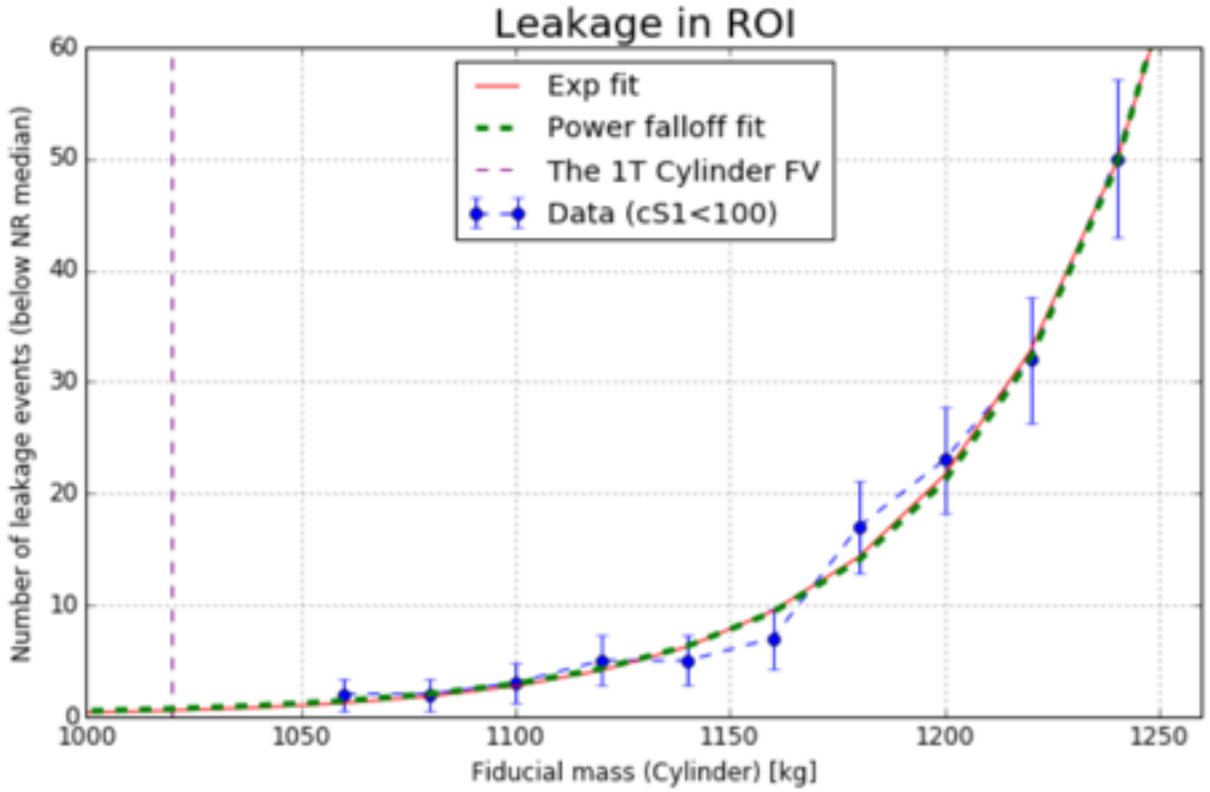
^{A}El	Z	Energy	Half-life
^{131}Xe	54	0.0	Stable
^{131}Xe	54	80.18	0.48 ns
^{131}Xe	54	163.93	11.84 days
^{131}Xe	54	341.14	1.64 ns

^{A}El	Z	Energy	Half-life
^{129}Xe	54	0.0	Stable
^{129}Xe	54	39.578	0.92 ns
^{129}Xe	54	236.14	8.88 days
^{129}Xe	54	274.28	

Wall Leakage





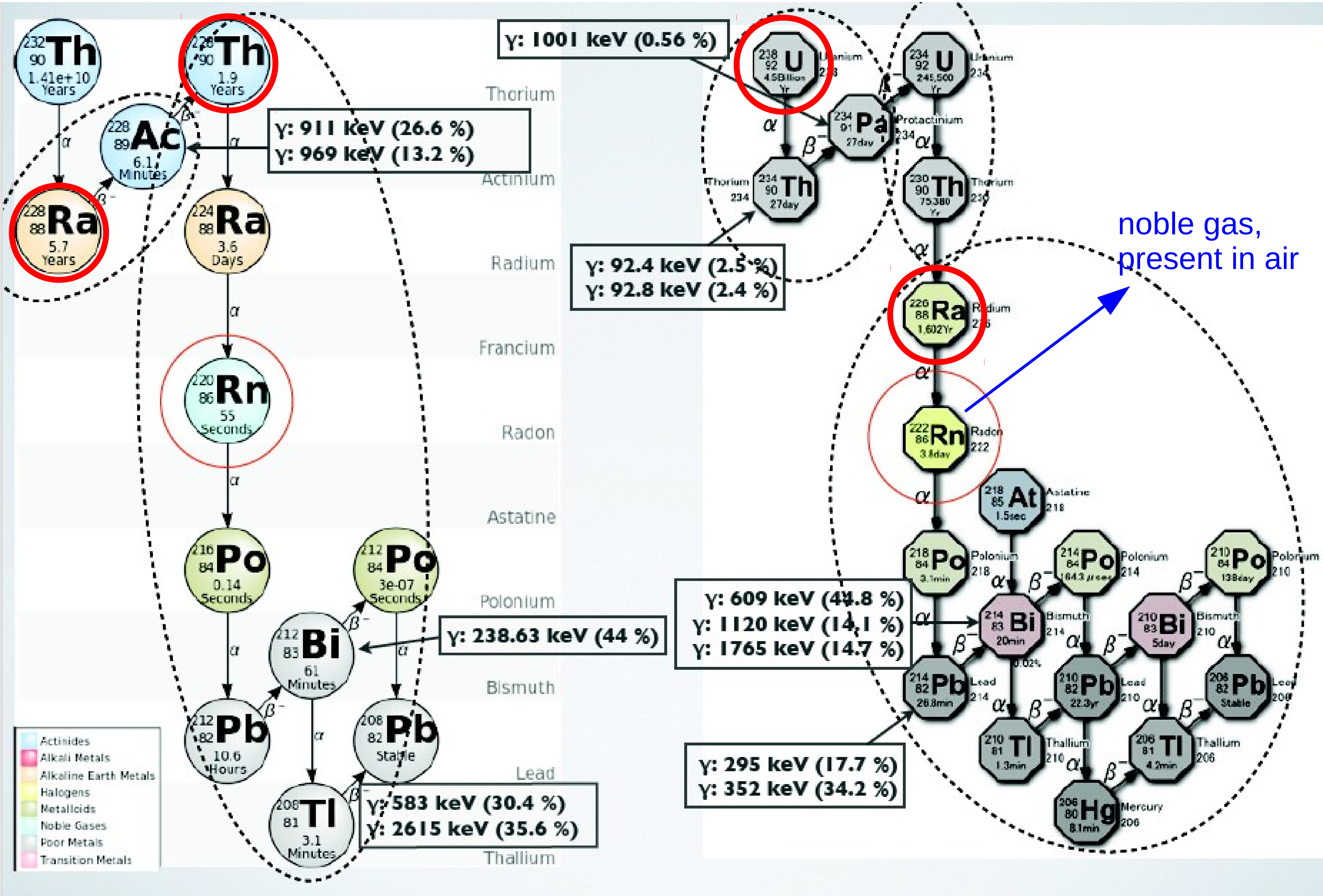


Data driven KDE method to build 2D model

Key methods to reduce wall leakage in SR1:

- Reduce position reconstruction uncertainties
- Improve modelling of top geometry
- Improve field distortion correction
- Full simulation to understand the sources

U and Th Chains



γ: 1001 keV (0.56 %)

γ: 911 keV (26.6 %)
γ: 969 keV (13.2 %)

γ: 92.4 keV (2.5 %)
γ: 92.8 keV (2.4 %)

noble gas, present in air

γ: 238.63 keV (44 %)

γ: 609 keV (44.8 %)
γ: 1120 keV (14.1 %)
γ: 1765 keV (14.7 %)

γ: 295 keV (17.7 %)
γ: 352 keV (34.2 %)

γ: 583 keV (30.4 %)
γ: 2615 keV (35.6 %)