Results from the 1 tonne x year Dark Matter Search with XENON1T

Elena Aprile
Columbia University

LNGS
May 28, 2018

The XENON Collaboration: ~165 scientists

Columbia RPI Nikhef Muenster Stockholm Mainz MPIK Freiburg Zurich

Chicago

UCLA

UCSD

Rice

Tokyo

Nagoya

Kobe

PURDUE UNIVERSITY

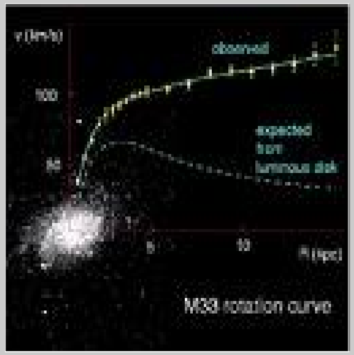
Subatech

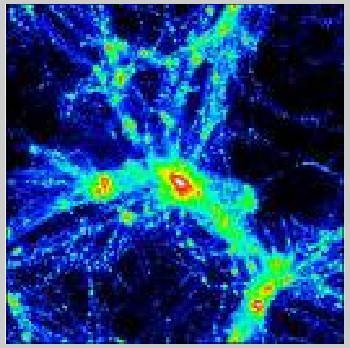
LPNHE PARIS

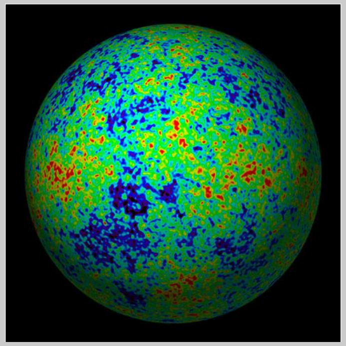
INFN

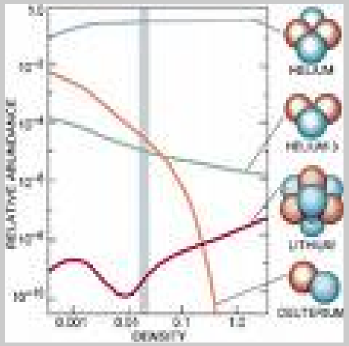
NYU ABU DHABI

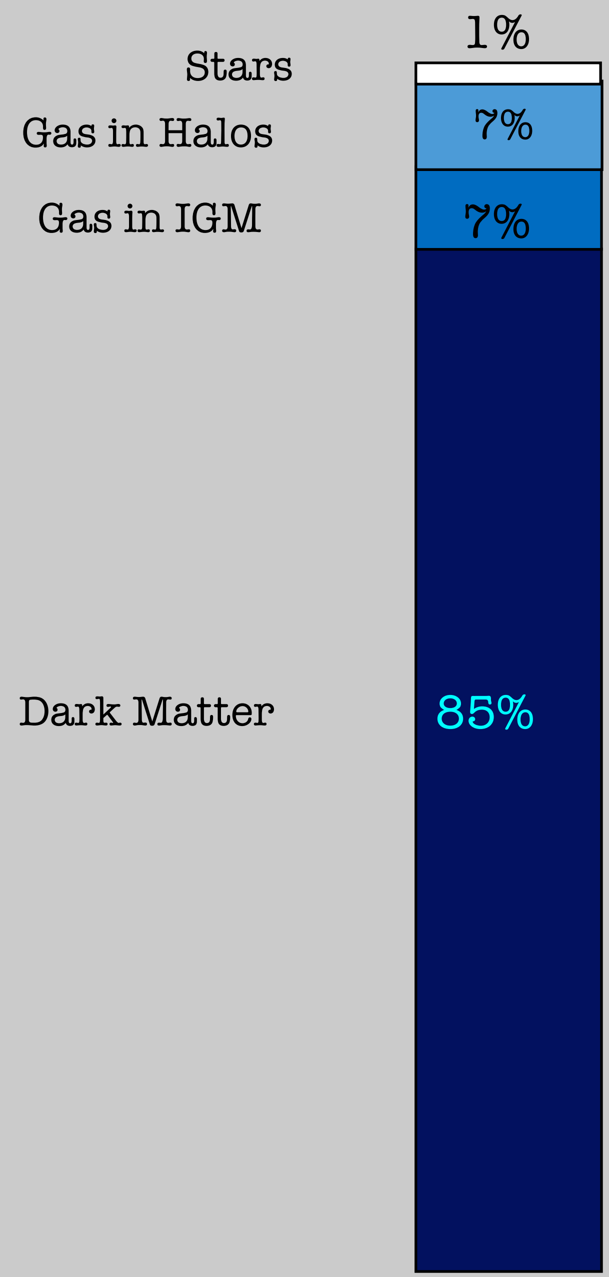
The Matter in the Universe: 85% invisible

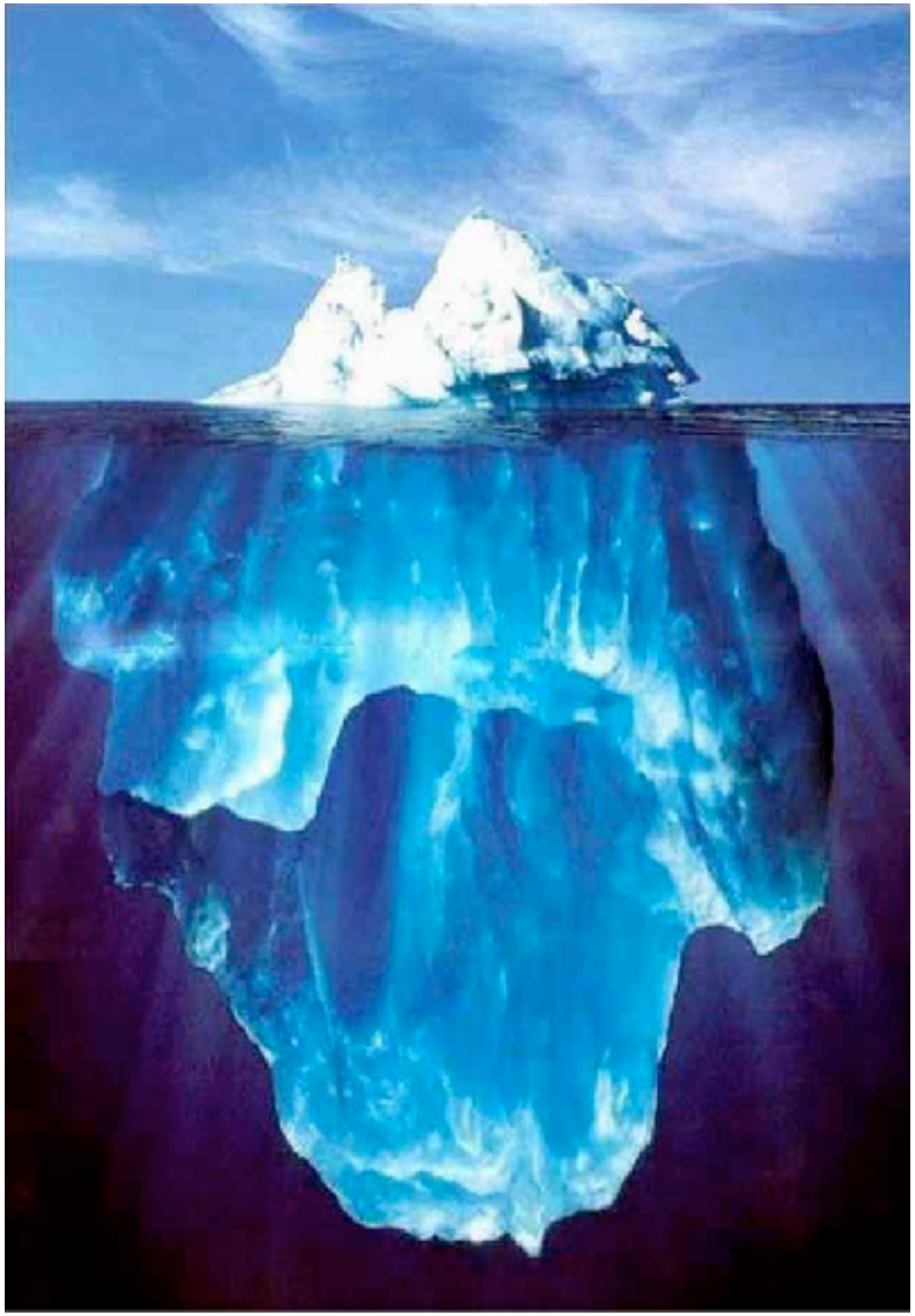






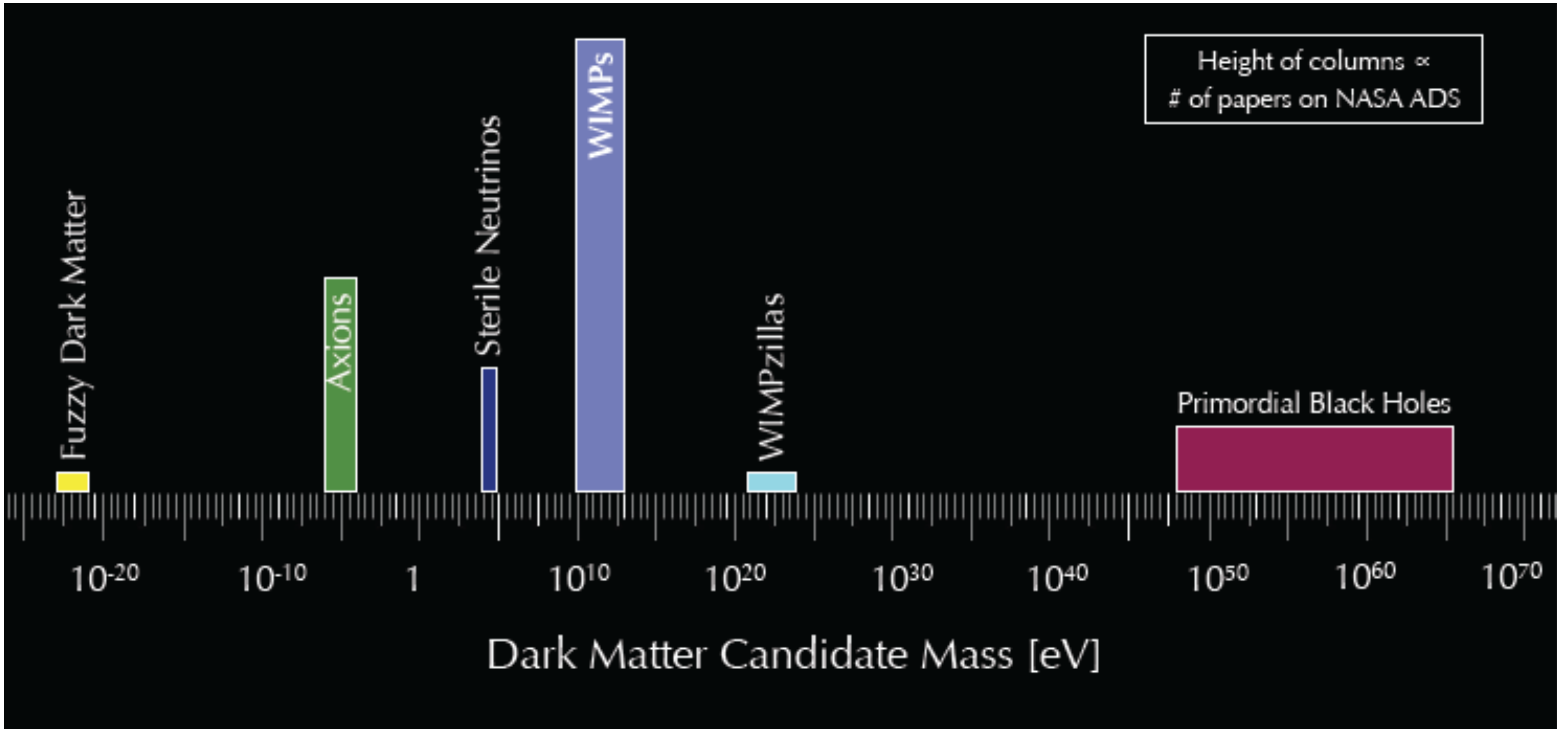






What is Dark Matter?

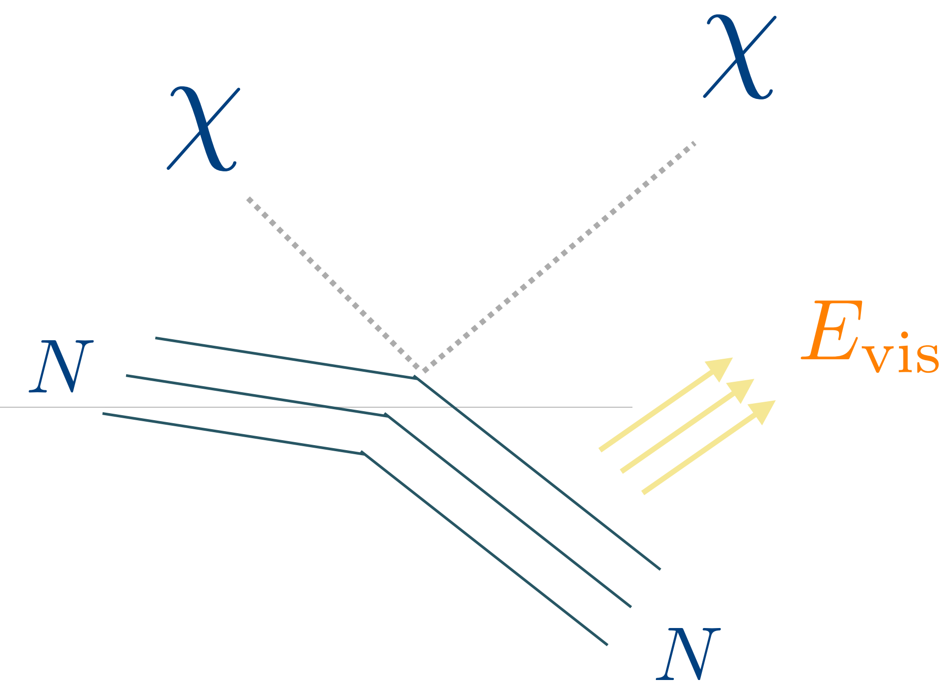
- *tens of DM models, each with its own phenomenology*
- *models span 90 orders of magnitude in DM candidate mass*
- *WIMPs by far the most studied class of DM candidates*

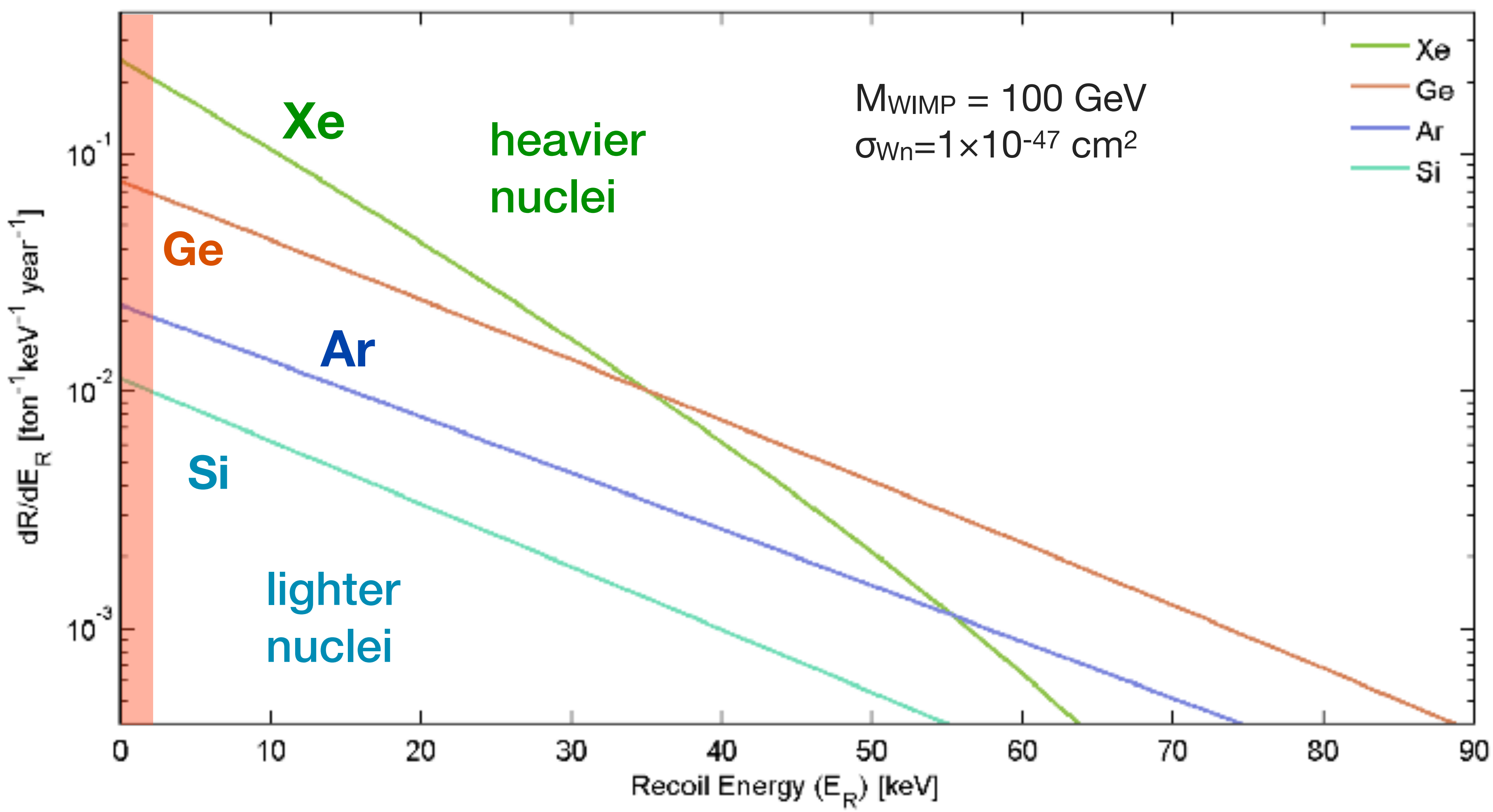


WIMPs direct detection

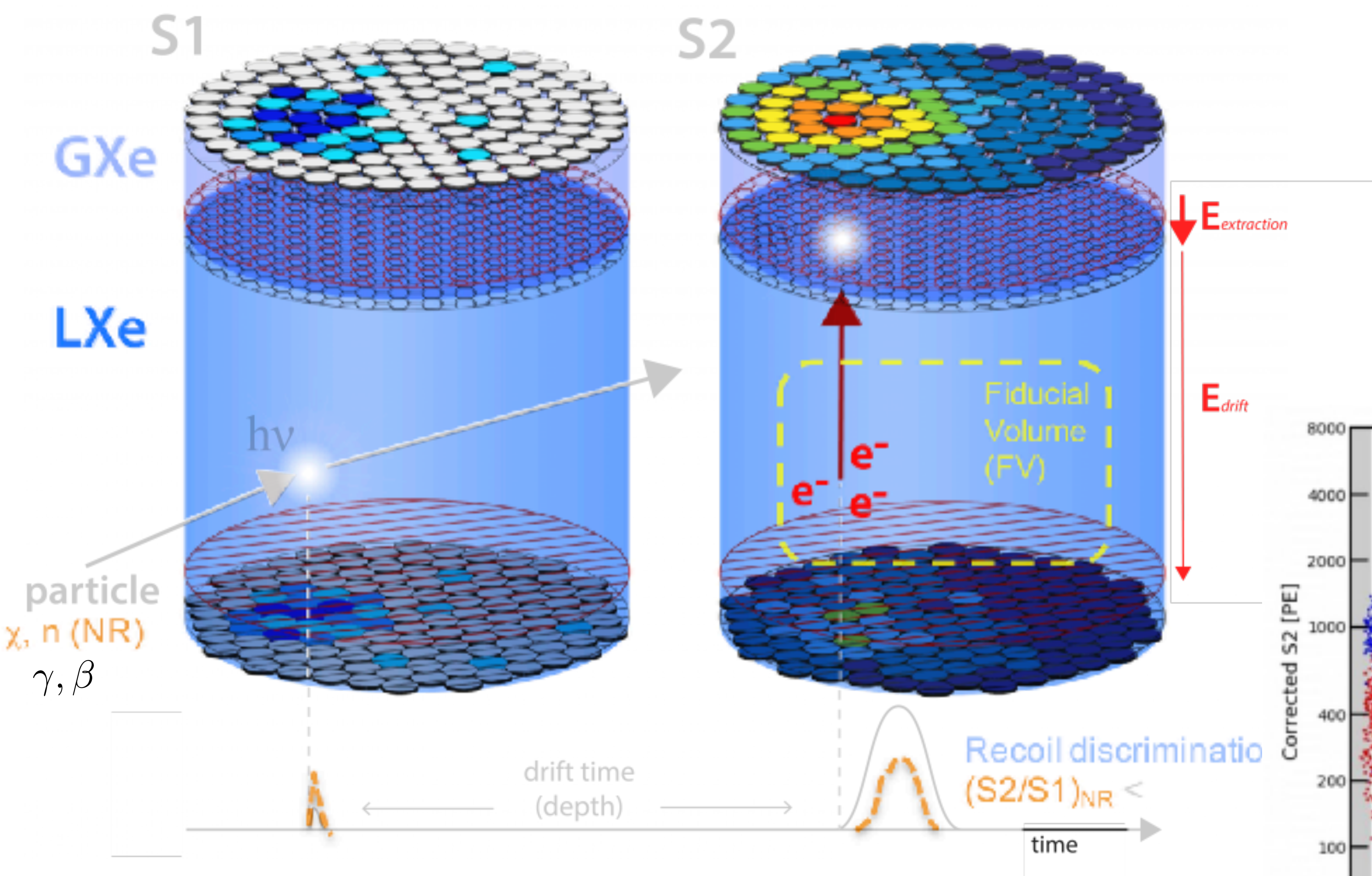
Collisions of WIMPs with atomic nuclei

=> Measure energy of recoiling nucleus

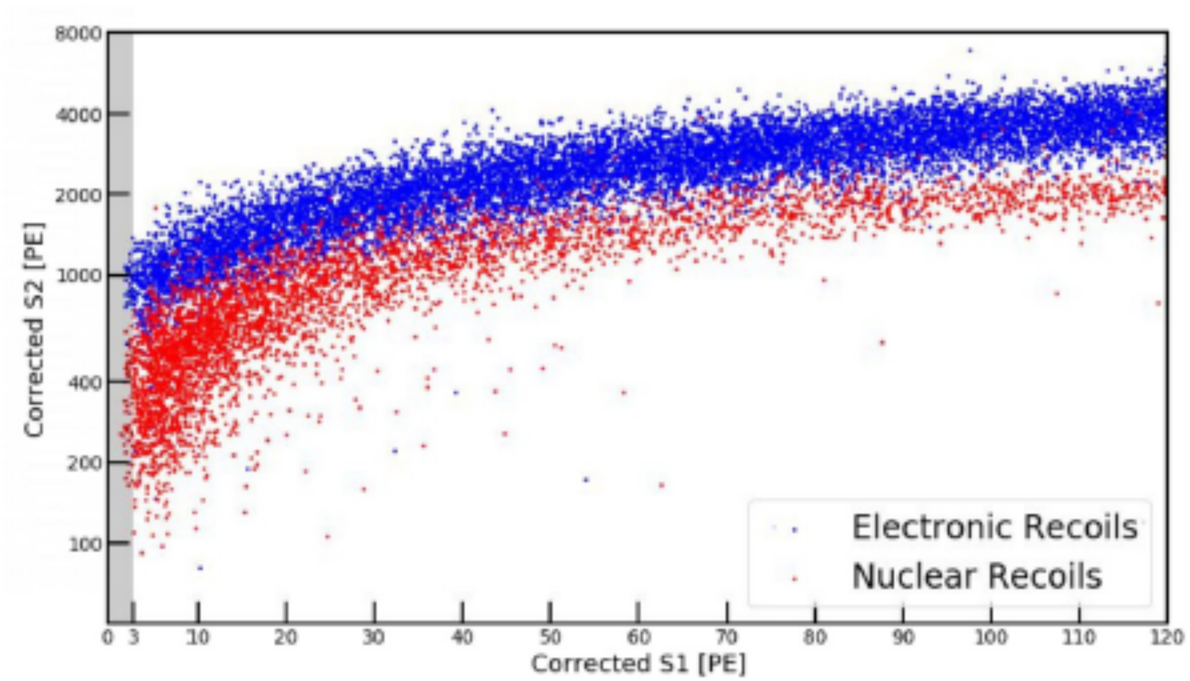




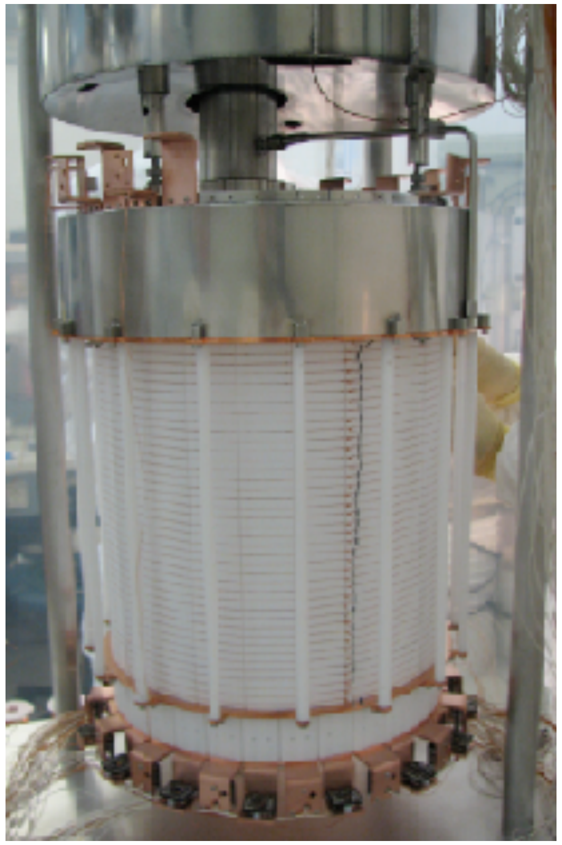
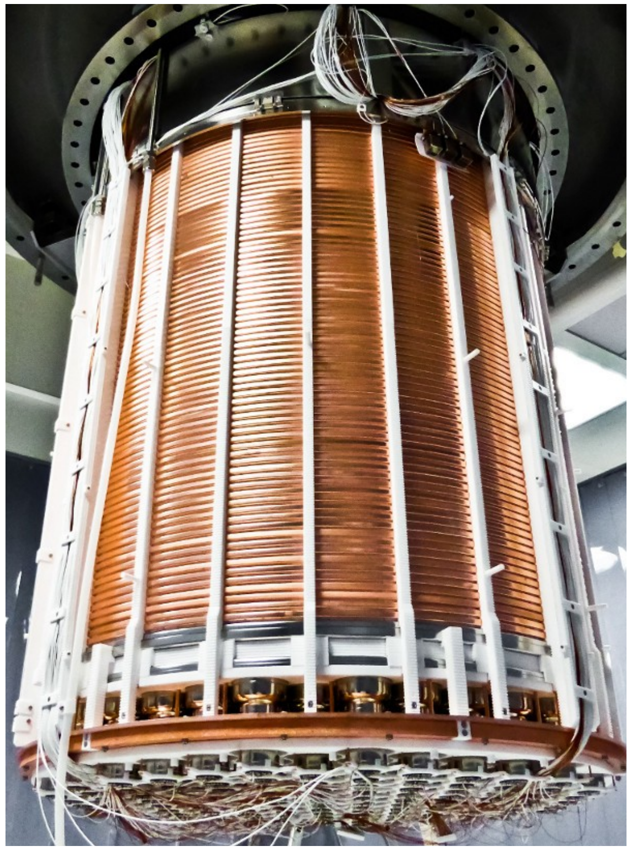
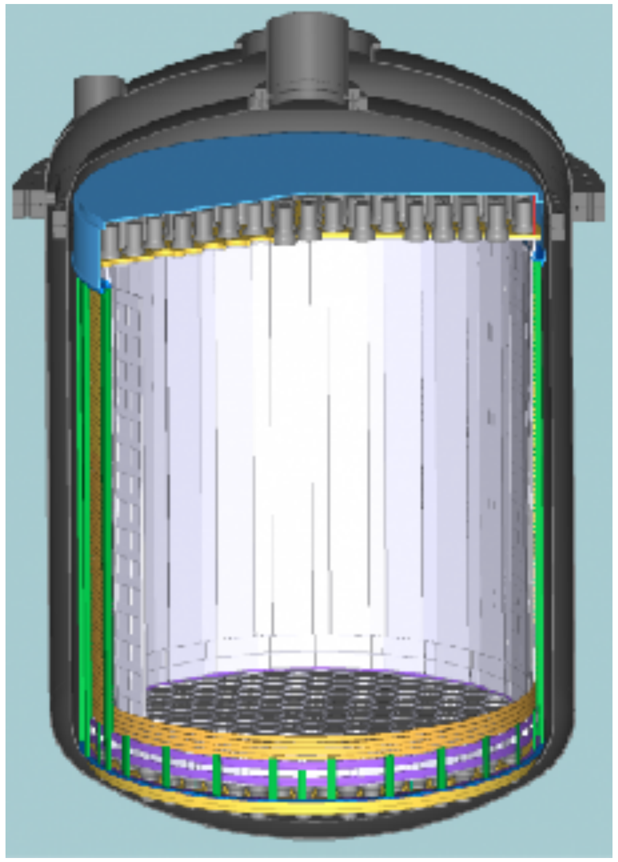
Two-phase Xe Time Projection Chamber as WIMP detector



- *two signals for each event:*
  - *Energy from S1 and S2 area*
  - *3D event imaging: x-y (S2) and z (drift time)*
  - *self-shielding, surface event rejection, single vs multiple scatter events*
- *Recoil type discrimination form ratio of charge (S2) to light (S1)*

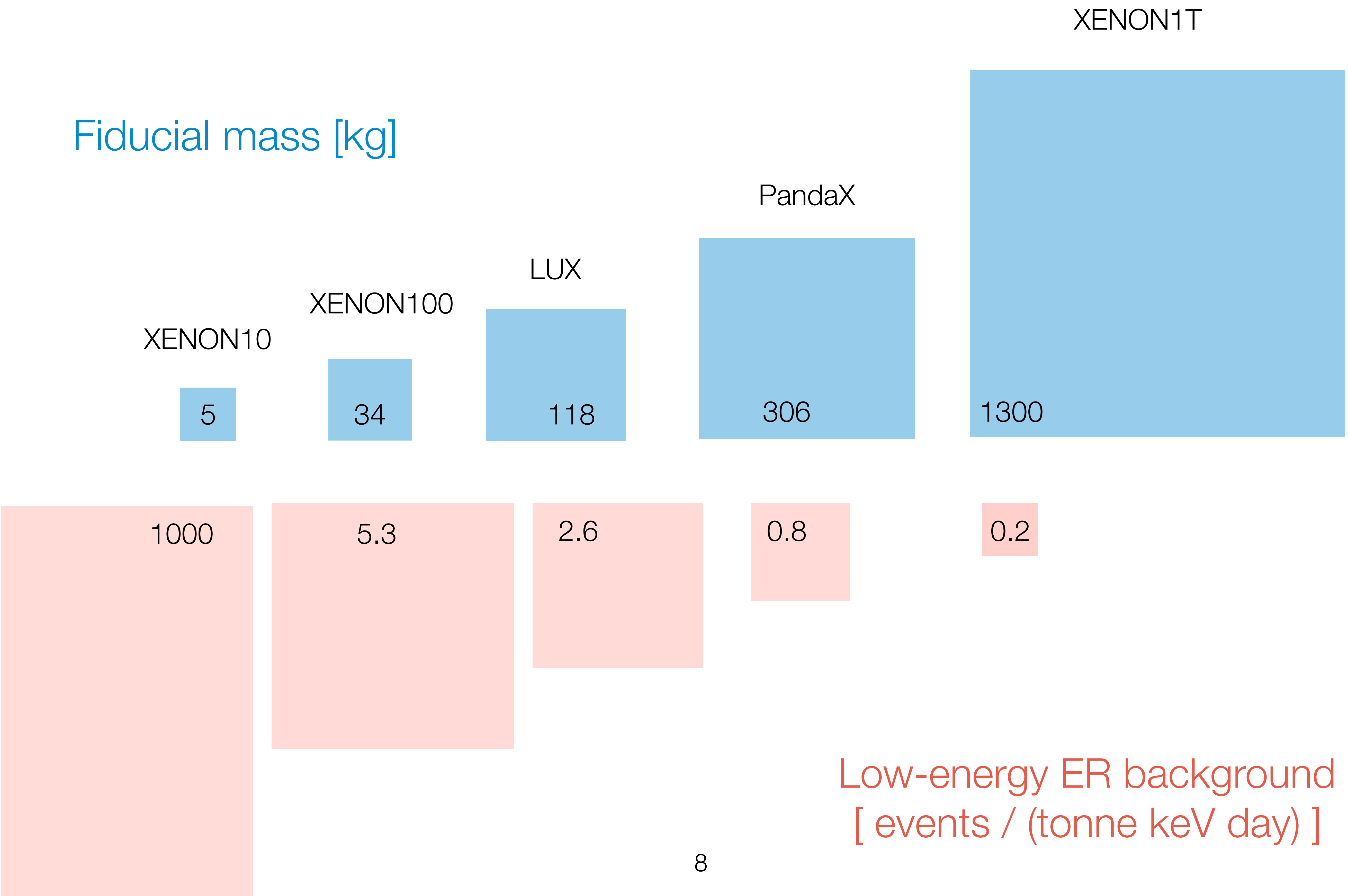


The phases of XENON

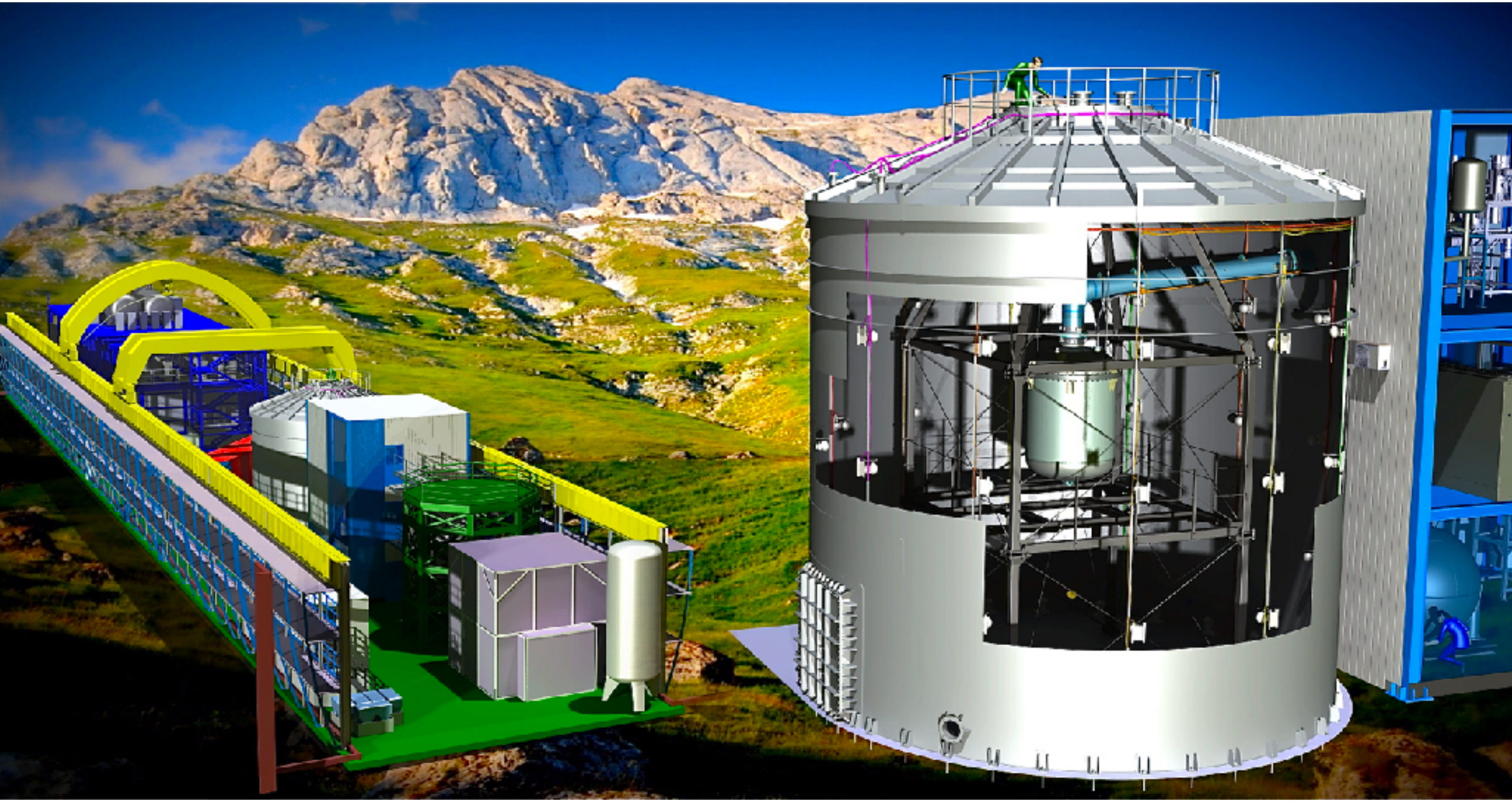
XENON10	XENON100	XENON1T	XENONnT
			

2005-2007	2008-2016	2012-2018	2019-2023
25 kg - 15cm drift	161 kg - 30 cm drift	3.2 ton - 1 m drift	8 ton - 1.5 m drift
$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	$\sim 10^{-47}$ cm^2	$\sim 10^{-48}$ cm^2

Impressive evolution of LXeTPCs as WIMP detectors



The XENON1T Experiment @ LNGS



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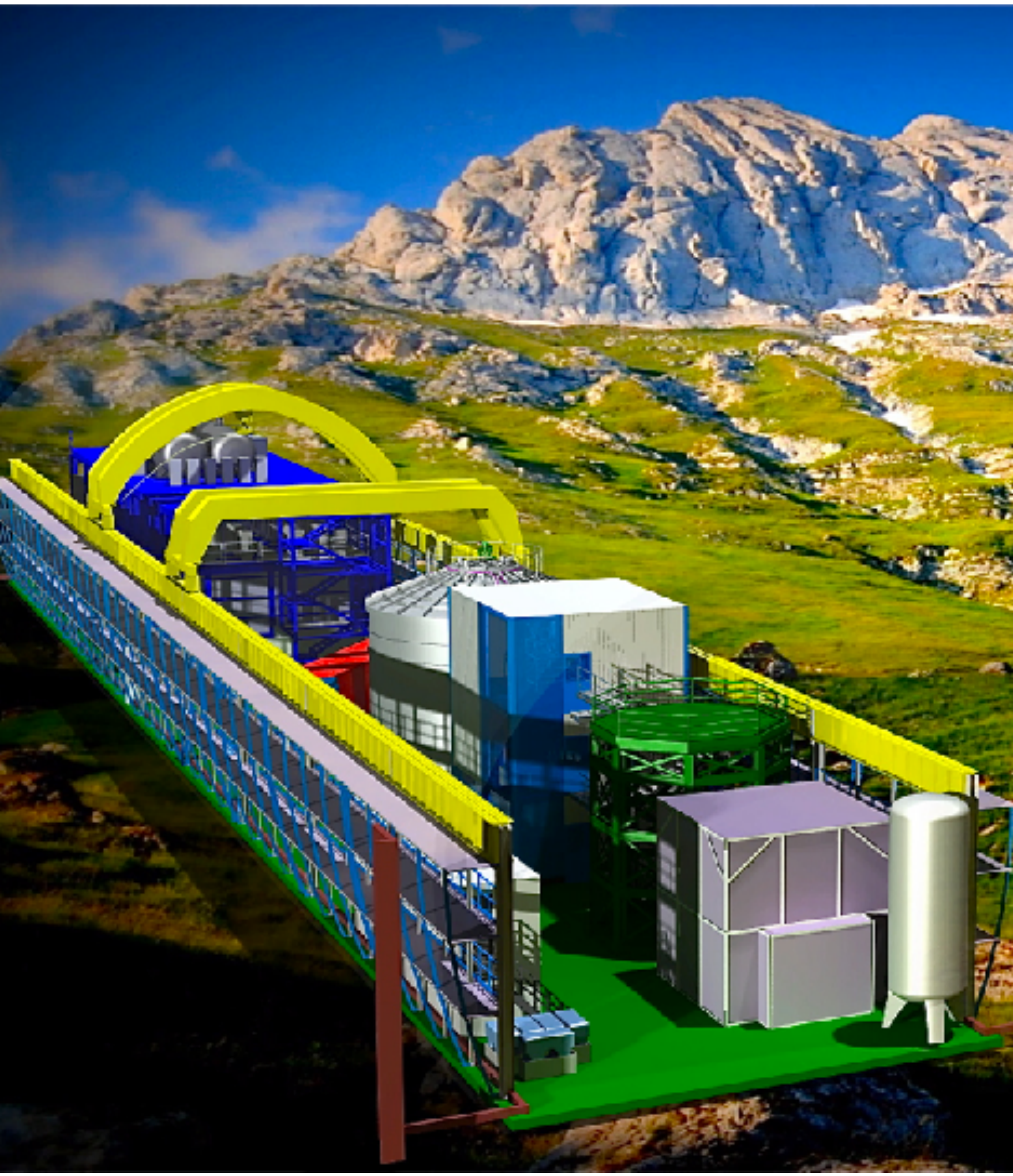
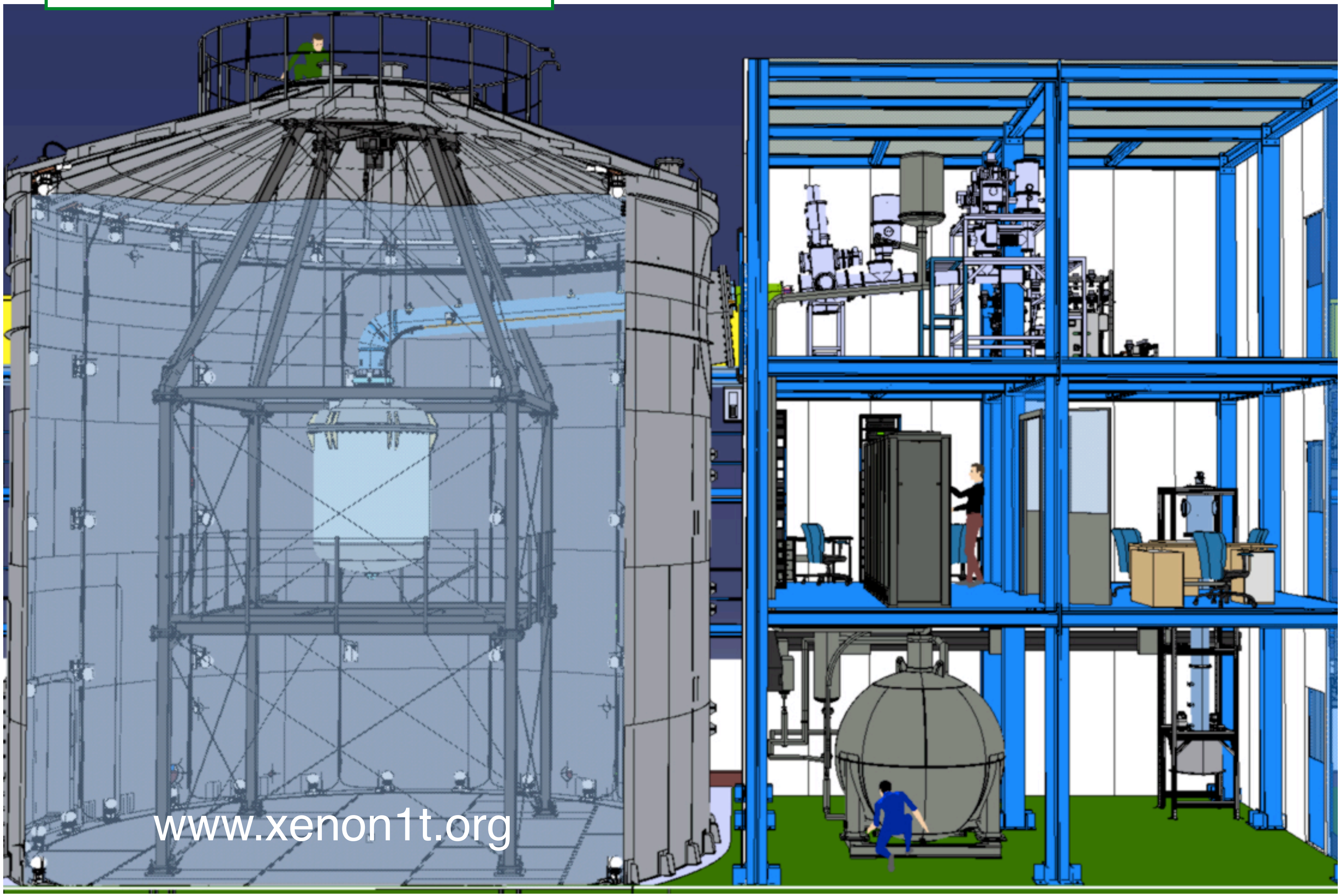


XENON1T: All Systems

E. Aprile et al.,
"The XENON1T Dark Matter Experiment",
EPJ C 77, 881 (2017).



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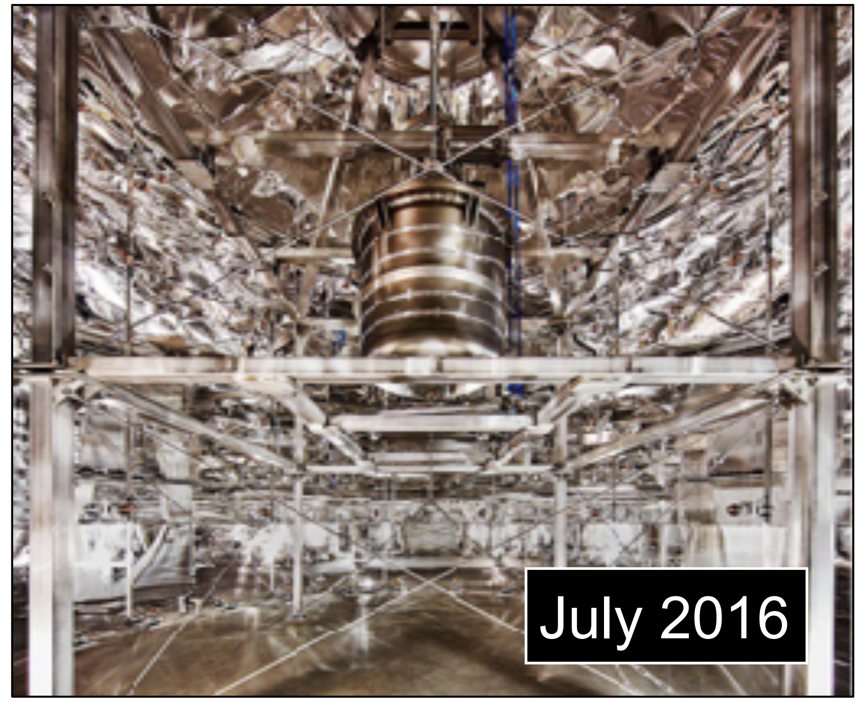
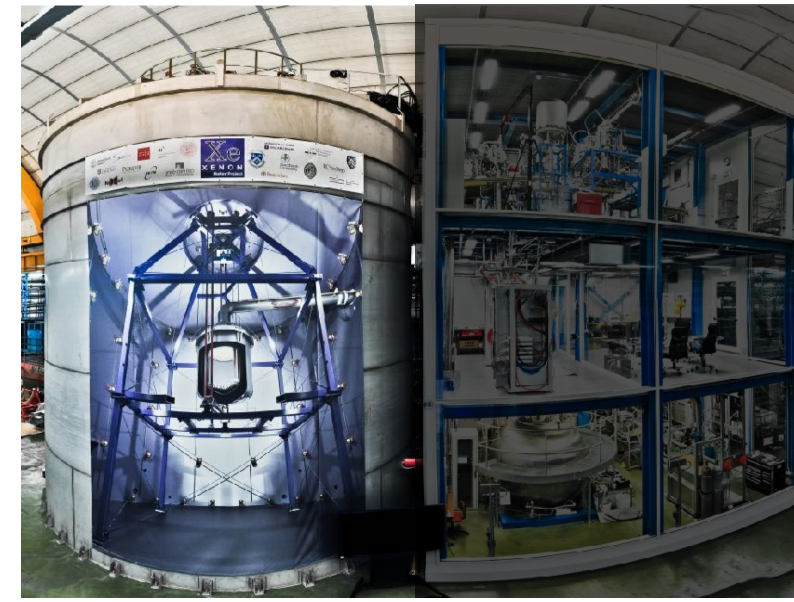
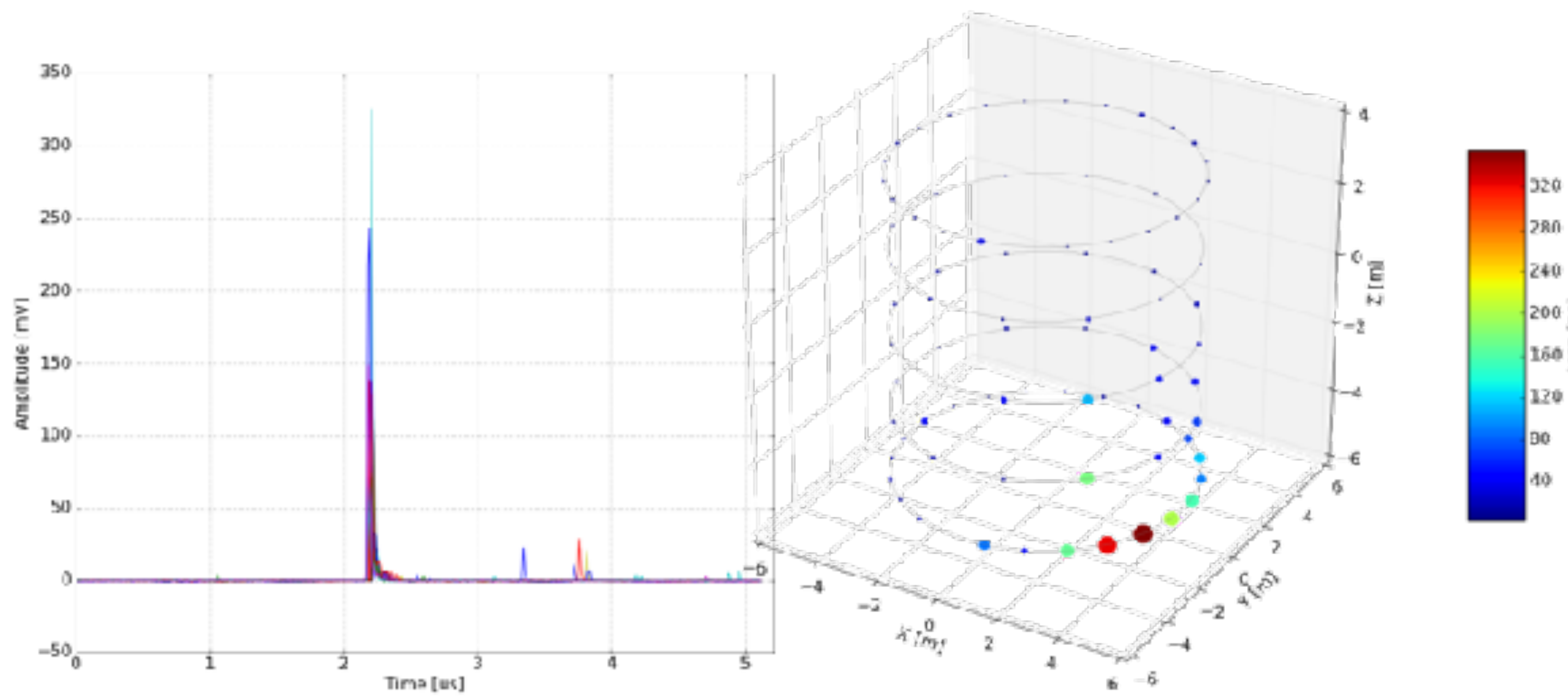
Water Cherenkov Muon Veto





- 700 ton pure water instrumented with 84 high-QE 8" PMTs
- Active shield against muons
- Trigger efficiency > 99.5% for muons in water tank
- Cosmogenic neutron background suppressed to < 0.01 events/ton/yr



JINST 9, 11007 (2014)

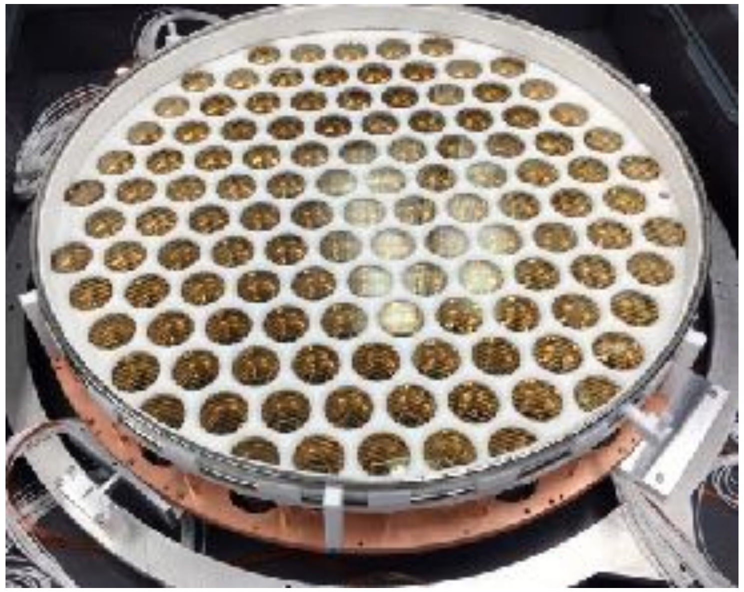
The XENON1T Time Projection Chamber

Understanding the Detector

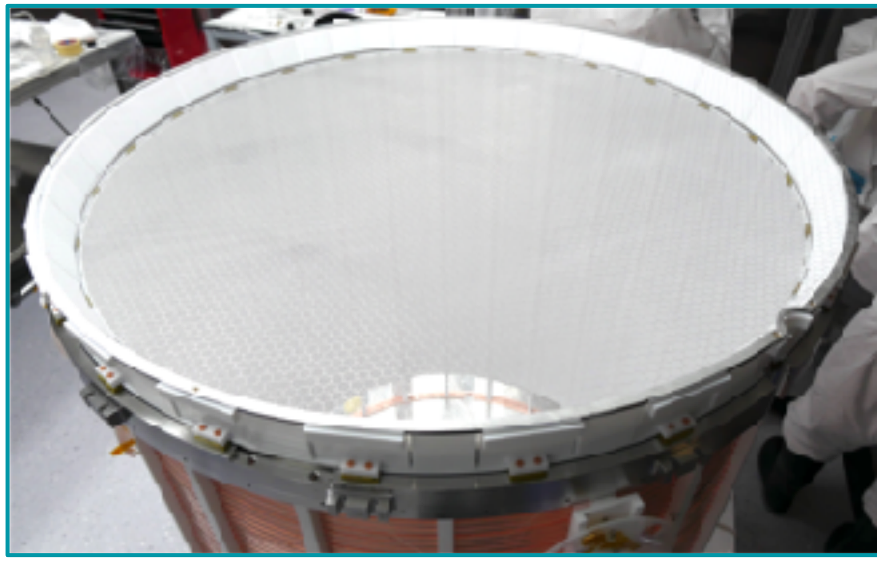
The XENON1T Light Detection System

- 248 3-inch low-radioactivity Hamamatsu R11410-21 PMTs arranged in two arrays.
- 35% QE @ 178 nm
- each PMT digitized at 100MHz
- operating gain 1-5x10^6 @ 1.5kV stable within 1-2 %
- SPE acceptance ~94%
- High reflectivity PTFE lining of entire inner volume
- Highly-transparent (>90%) grid electrodes

127 PMTs in the top array



121 PMTs in the bottom array



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- ope 1.5k
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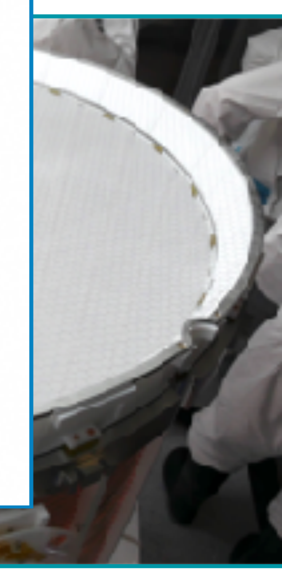
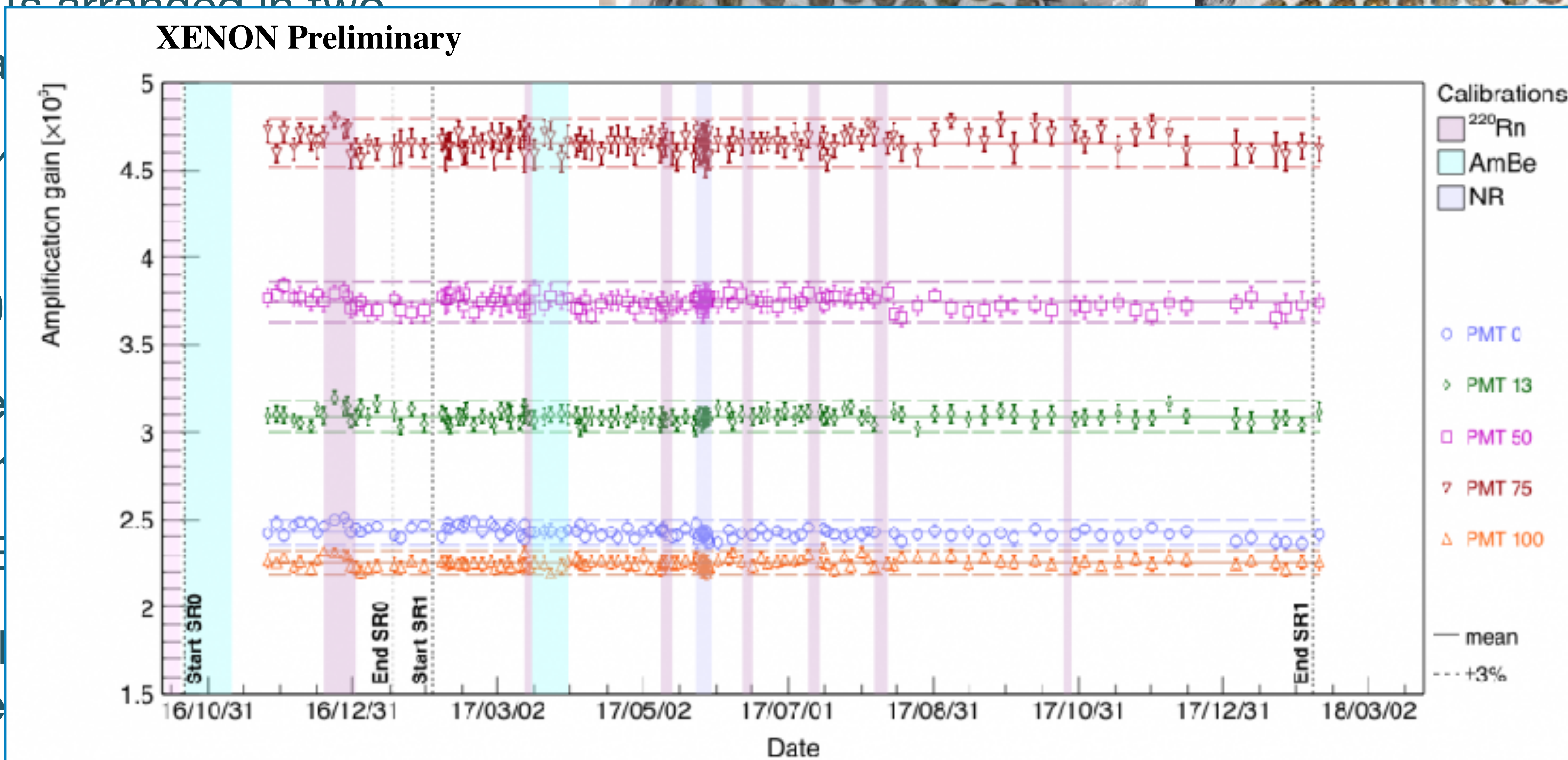
EPJC 75 (2015) 11, 546

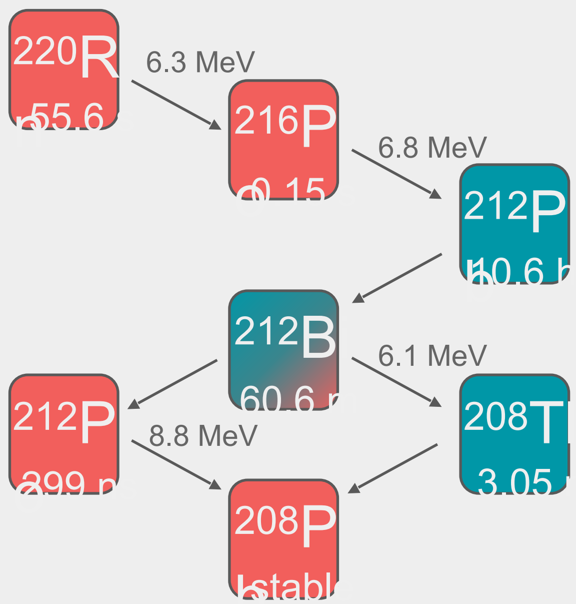
m array





Calibration Sources

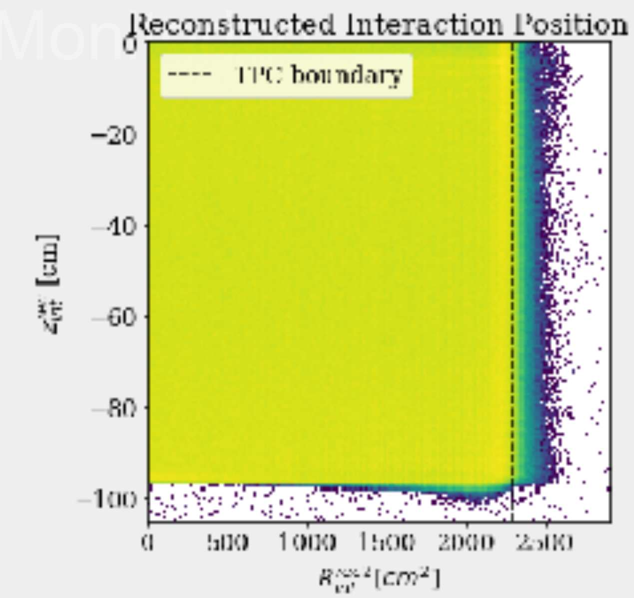
^{220}Rn: Low Energy ER



Type: Internal
Freq: 1-2 Months
Length: Few days

Stable background conditions after a couple days (10.6h longest $T_{1/2}$)

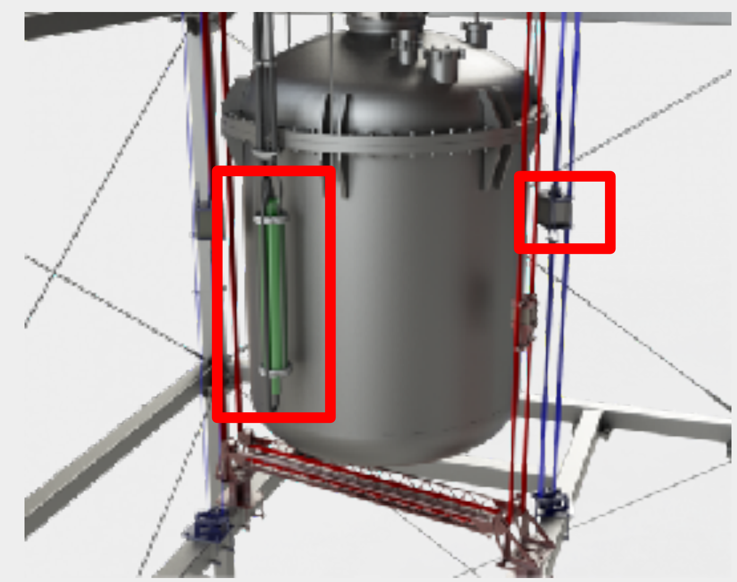
^{83m}Kr: Stability and



Type: Internal
Freq: 2-3 weeks
Length: 1 day
Half life: 1.83h

9.4 keV and 32.1 keV lines (~150 ns delay) homogeneous in volume

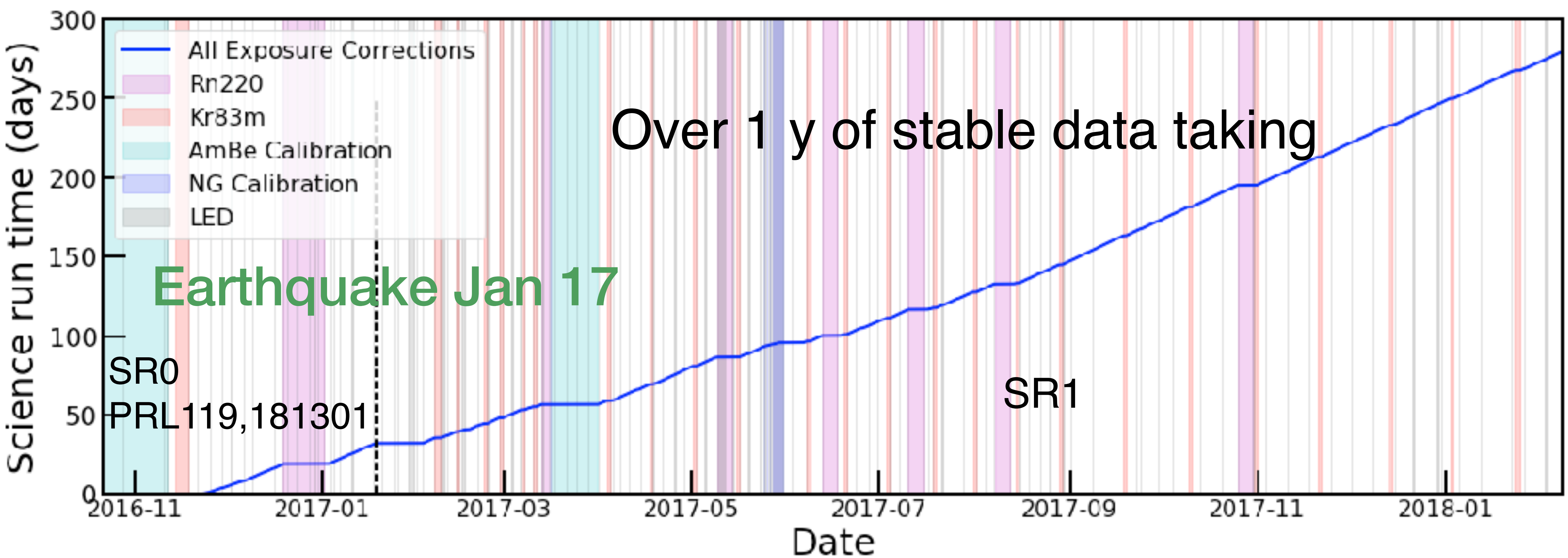
Neutrons: Signal



Type: External
Freq: As needed
Length: 6 weeks (AmBe)
2 days (generator)

XENON1T: science and calibration data

- 279 days high quality data (livetime-corrected) spanning more than 1 year of stable detector's operation. The LXeTPC has been "cold" since Spring 2016
- 1 tonne x year exposure given 1.3 tonne fiducial volume: the largest reported to-date with this type of detector
- Experiment still running smoothly and collecting more data



Data Analysis: overview

XENON1T (real waveforms)

Geant4 + waveform simulation

Raw data Processor (PAX)

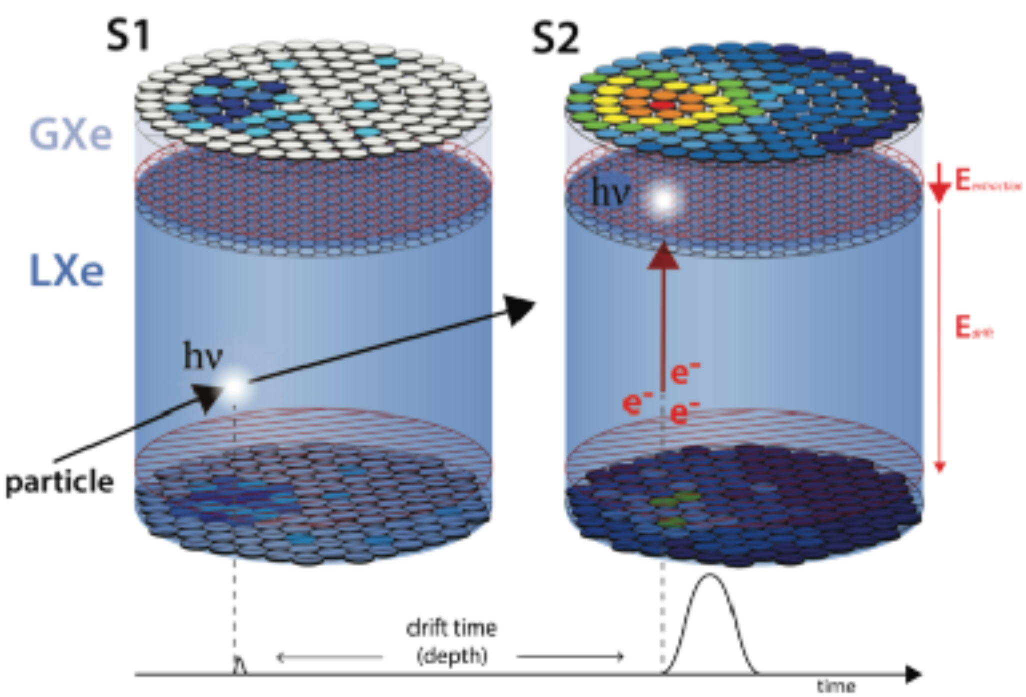
- peak-finding
- S1, S2 identification
- Interactions Reconstruction
  - position
  - energy
  - interaction type
  - …

Detector Calibration

Background Modeling

Statistical Interpretation

Physics Results



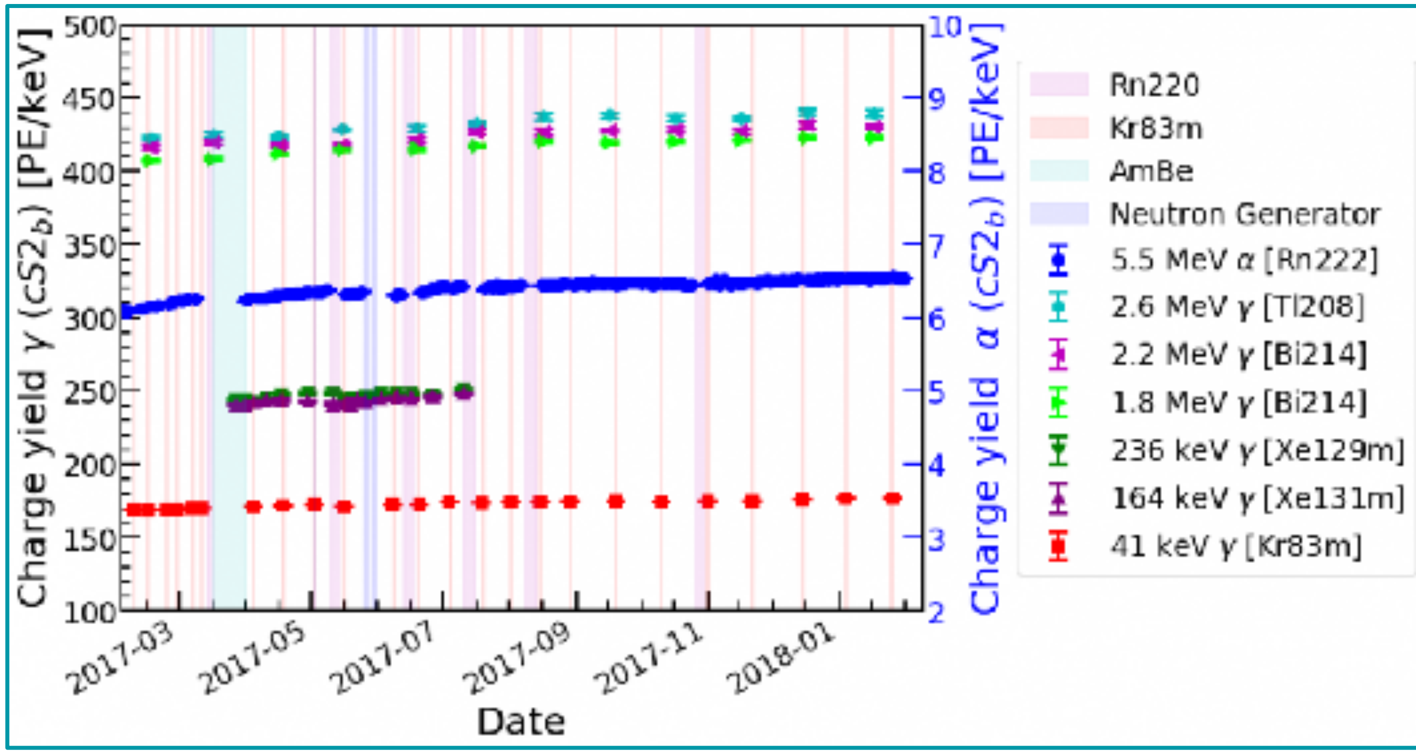
PAX

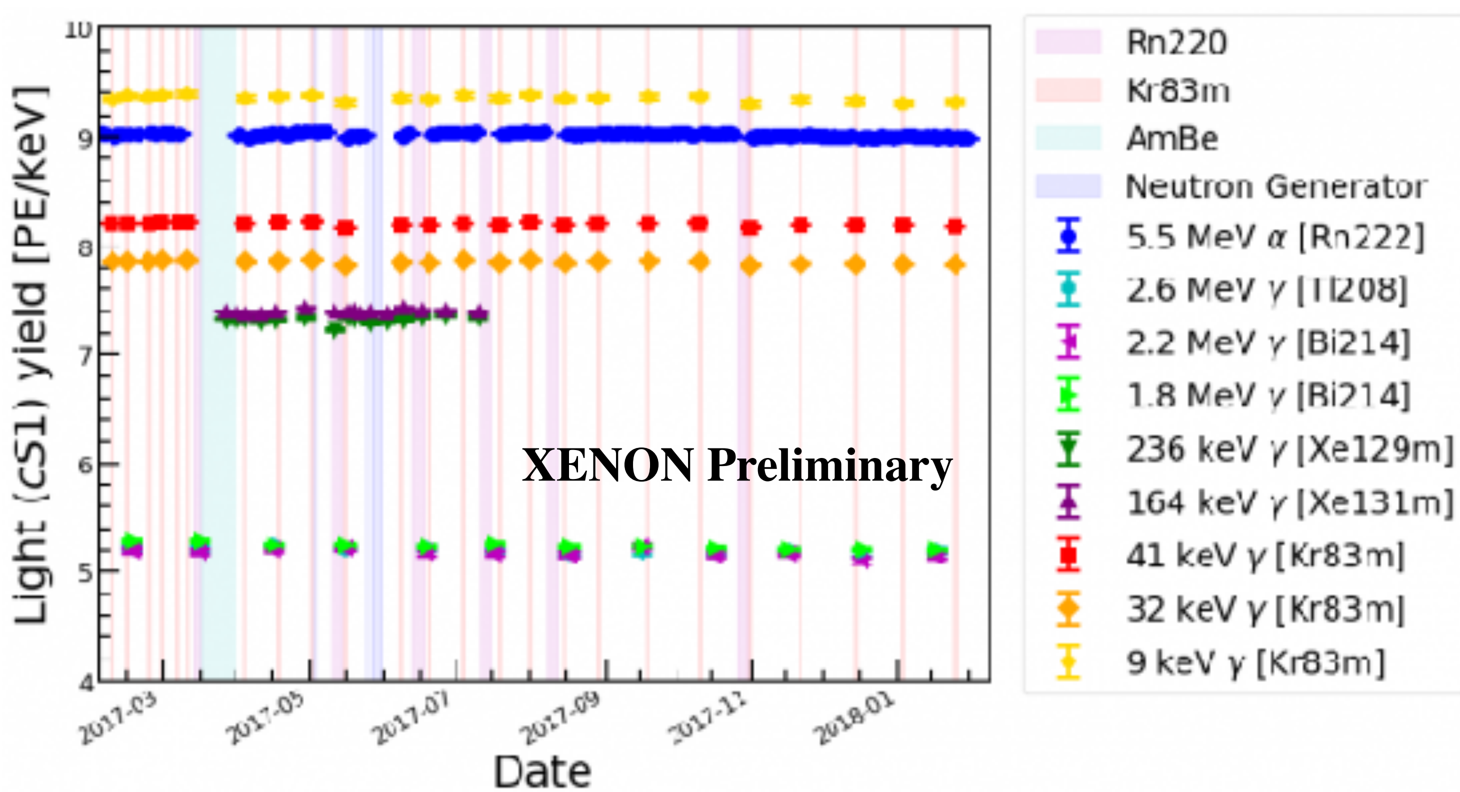
Processor for Analyzing XENON

Developed by the XENON collaboration Publicly available to the community
https://github.com/XENON1T/pax

Light and Charge Signals Stability

Position dependence of light (solid angle) and charge (attenuation length) signals very well understood through measurement with ^{83m}Kr, ^{222}Rn alphas. Excellent agreement with optical Monte Carlo simulations and with model of purity evolution

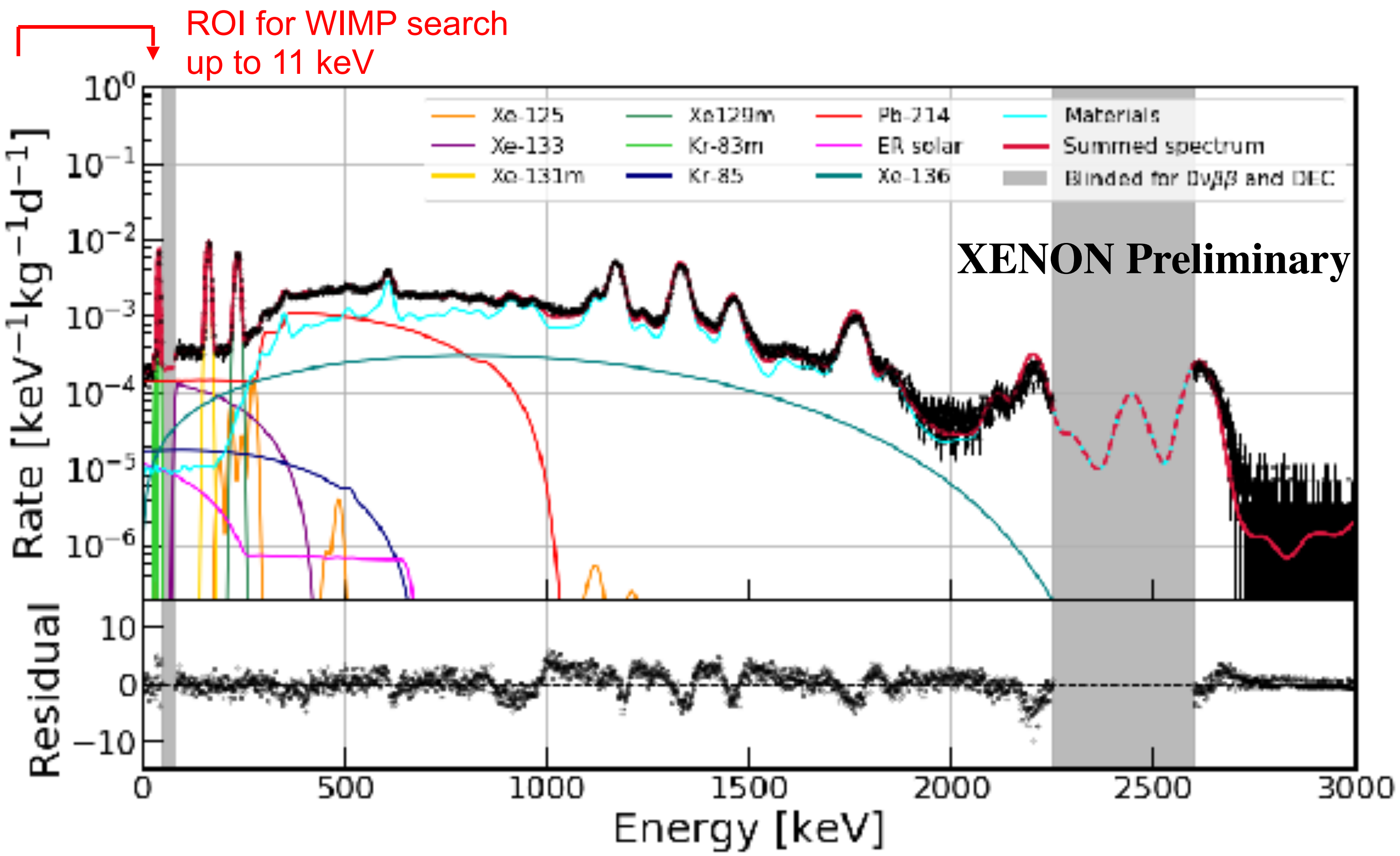




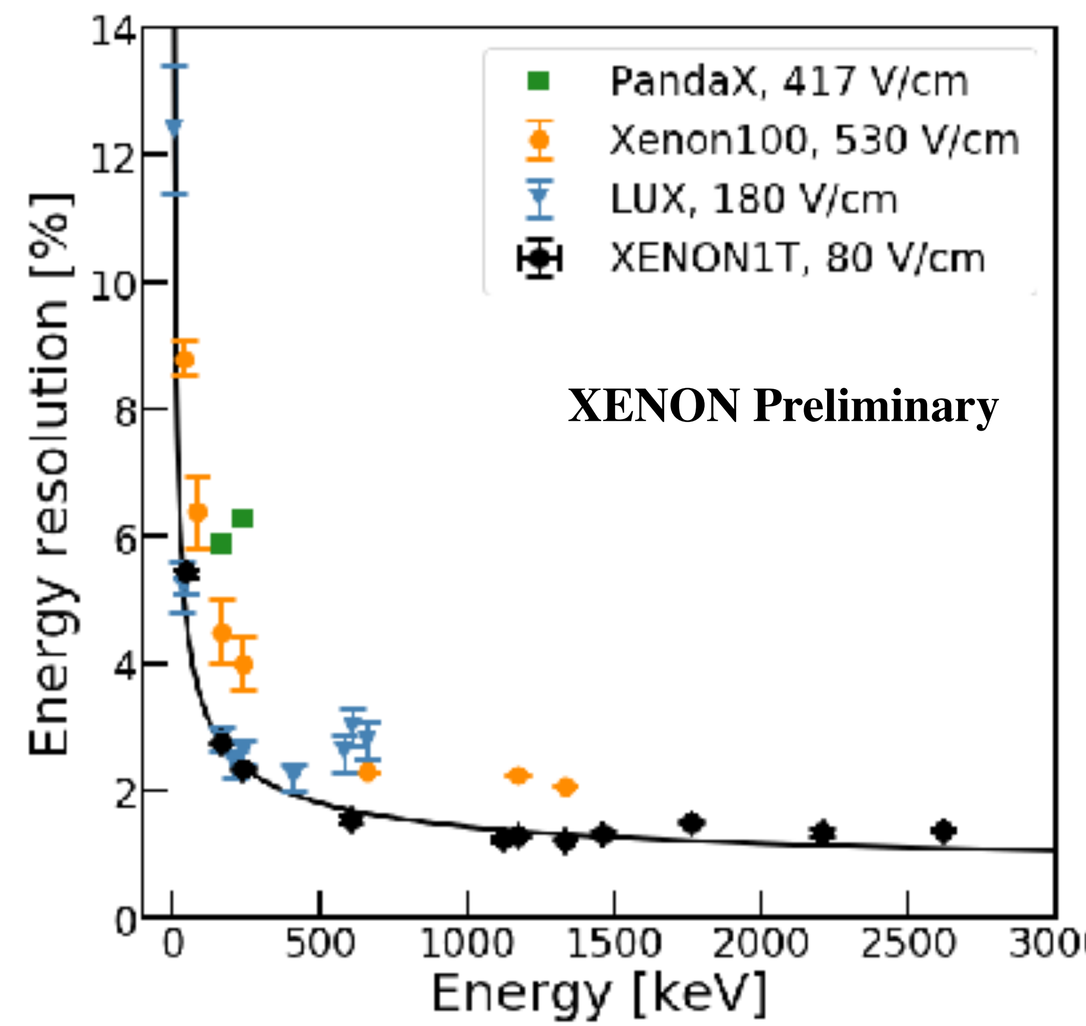
Light and charge yield stability monitored with several sources:

- ^{222}Rn daughters
- Activated Xe after neutron calibrations
- ^{83m}Kr calibrations
- Stability is within a few %

Energy Resolution

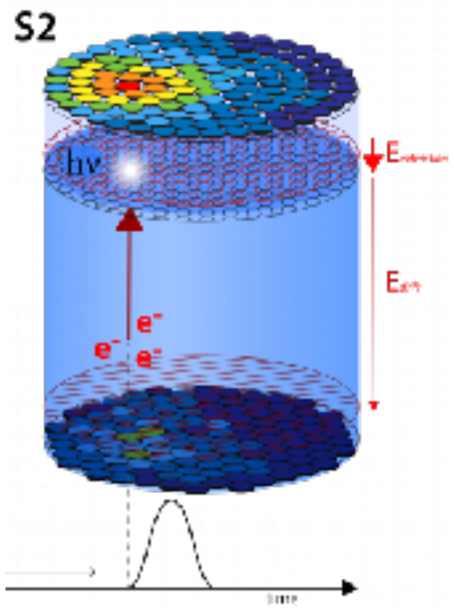


- Energy reconstructed from anti correlated S1 and S2. Excellent linearity from keV to MeV
- Best energy resolution measured with this large LXeTPC ~1.6% resolution (sigma) at 2.5 MeV



- Good agreement between predicted and measured background spectrum
- Kr: 0.66 ppt; Pb214: ~ 10 uBq/kg
- Gammas based on screening measurements

Position Reconstruction



X-Y reconstruction via **neural network**:

- **Input:** charge/channel top array
- **Training:** Monte Carlo simulation

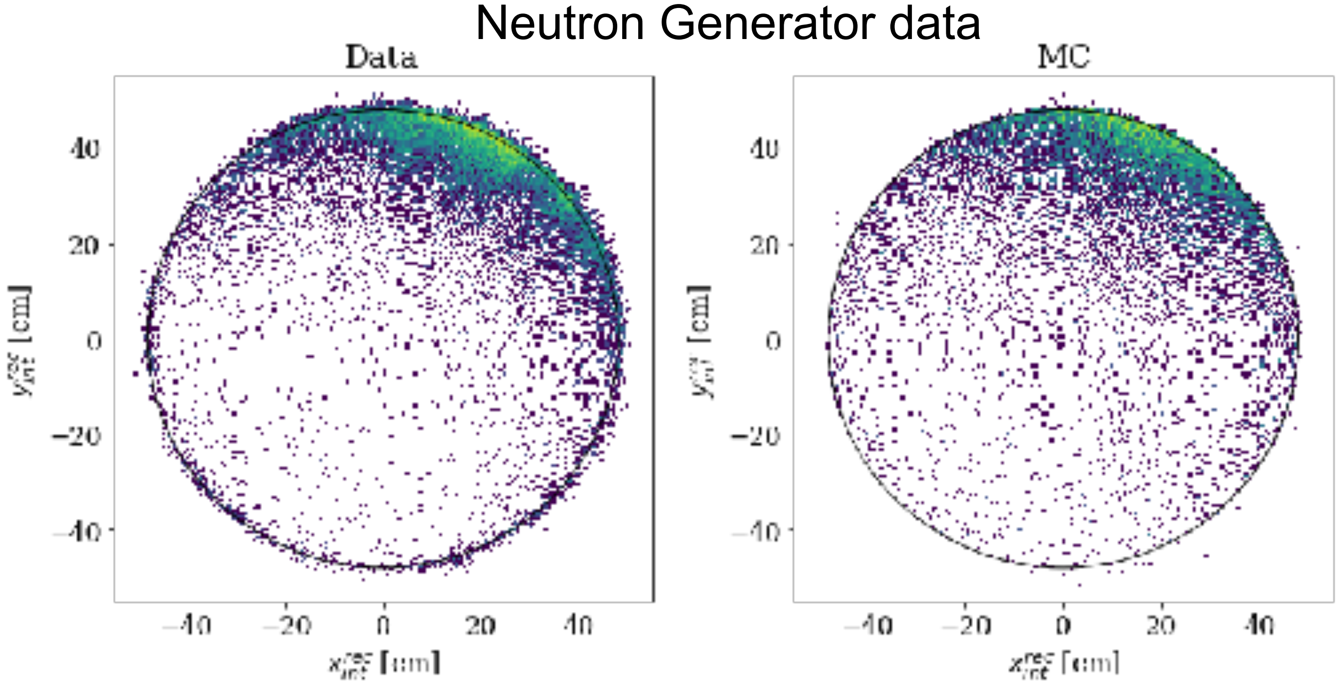
Position resolution using ^{83m}Kr

- Two interactions (9, 31 keV), same x-y
- Position resolution (1-2 cm)
- PMT diameter (7.62 cm)

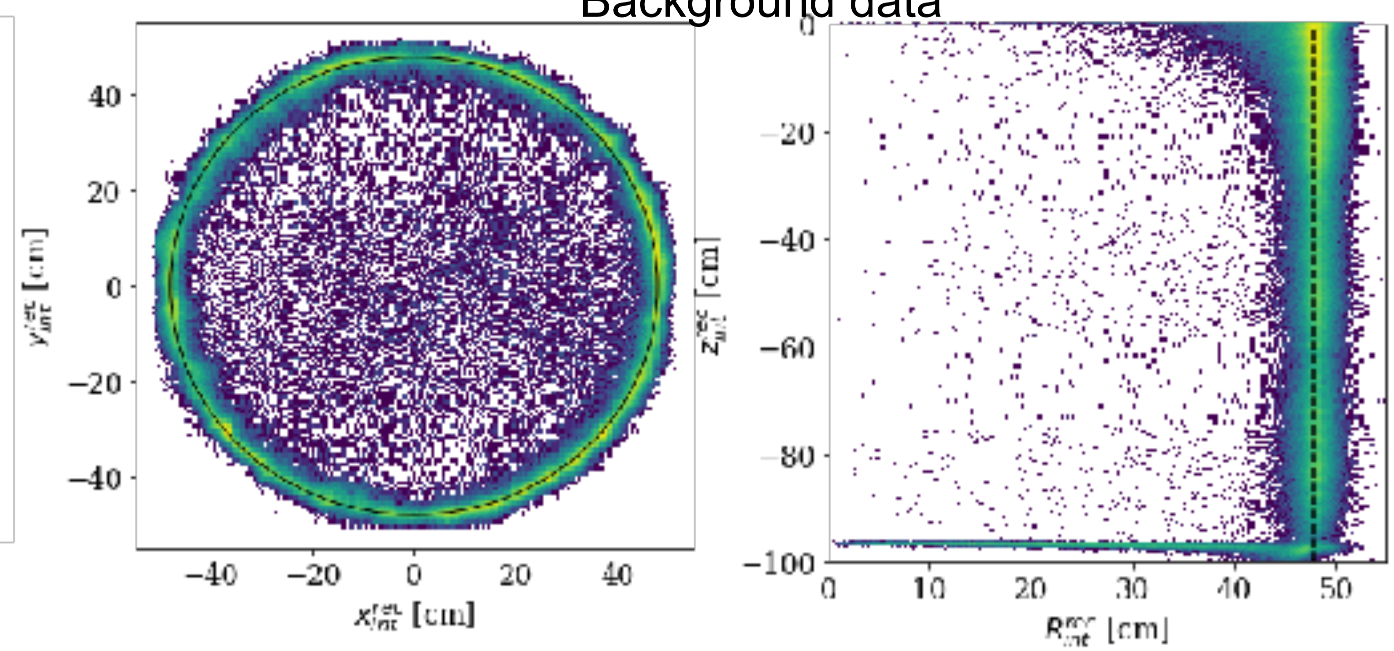
Position corrections using ^{83m}Kr

- **Drift field distortion**
- Localized inhomogeneities from inactive PMTs
- Data-derived correction verified by comparison to MC with several event sources

Neutron Generator data

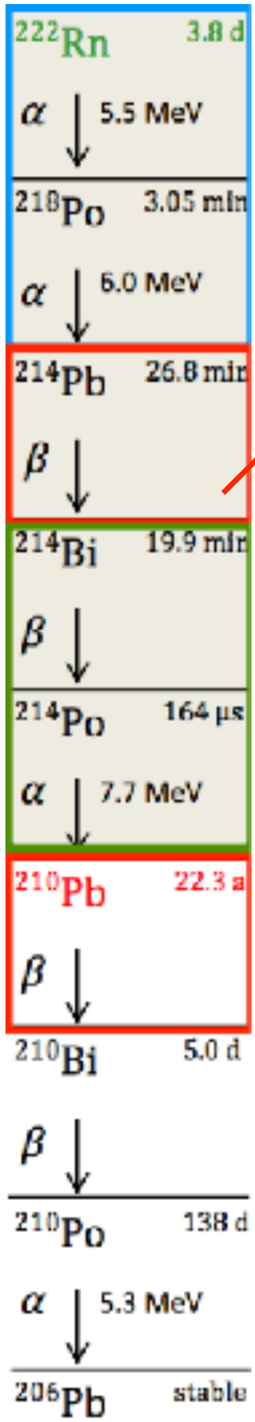


Background data

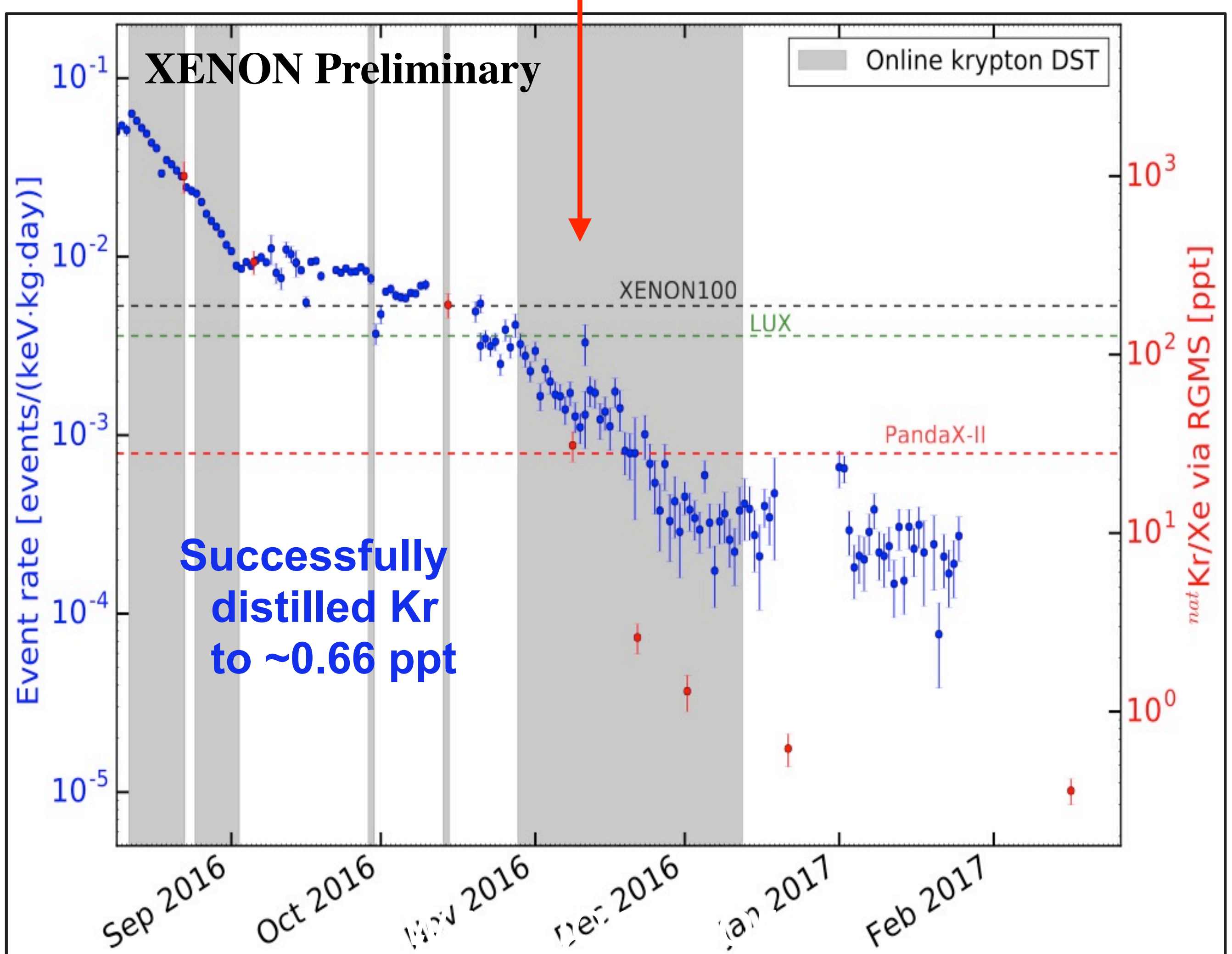


Understanding the Backgrounds

Electronic Recoil Backgrounds



- **Rn222 : 10 uBq/kg**
  - **Achieved with careful surface emanation control and measurements**
  - **Further reduction with online cryogenic distillation**
- **Kr85 : sub-ppt Kr/Xe**
  - **Achieved with online cryogenic distillation**
- **Materials radioactivity (HPGe gamma screening): subdominant**



Source	Rate [t-1 y-1]	Fraction [%]
222Rn	620 ± 60	85,4
85Kr	31 ± 6	4,3
Solar ν	36 ± 1	4,9
Materials	30 ± 3	4,1
136Xe	9 ± 1	1,4
Total	720 ± 60	

(Expectations in 1-12 keV search window, 1t FV, single scatters, *before ER/NR discrimination*)

JCAP04 (2016) 027

ER Background Evolution

Predicted: (considering 10 uBq/kg of ^{214}Pb, and on average 0.66 ppt of Kr):

(76 ± 8) events / (ton·year·keV)

Measured:

($82\ ^{+5}_{-3}$ (syst.) ± 3 (stat)) events / (ton·year·keV)

Lowest ER background ever achieved in a DM detector !

Nuclear Recoil Backgrounds

Cosmogenic μ-induced neutrons significantly reduced by rock overburden and muon veto

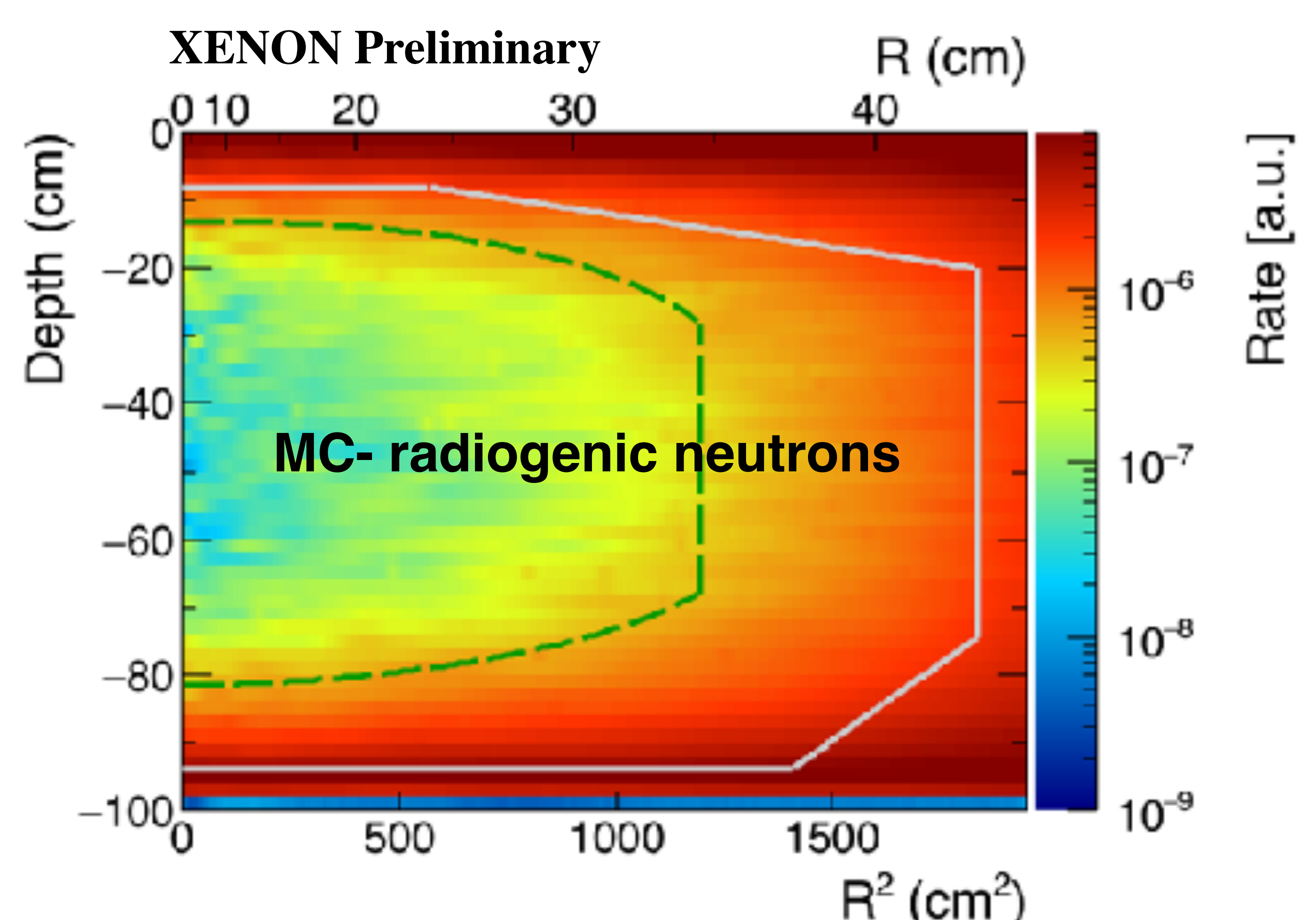
Coherent elastic ν-nucleus scattering, constrained by ^{8}**B** neutrino flux and measurements, is an an irreducible background at very low energy (1 keV)

Radiogenic neutrons from (α, n) reactions and fission from ^{238}U and ^{232}Th: reduced via careful materials selection, event multiplicity and fiducialization

Source	Rate [t^{-1} y^{-1}]	Fraction [%]
Radiogenic n	0.6 ± 0.1	96,5
CEνNS	0,012	2,0
Cosmogenic n	< 0.01	< 2.0

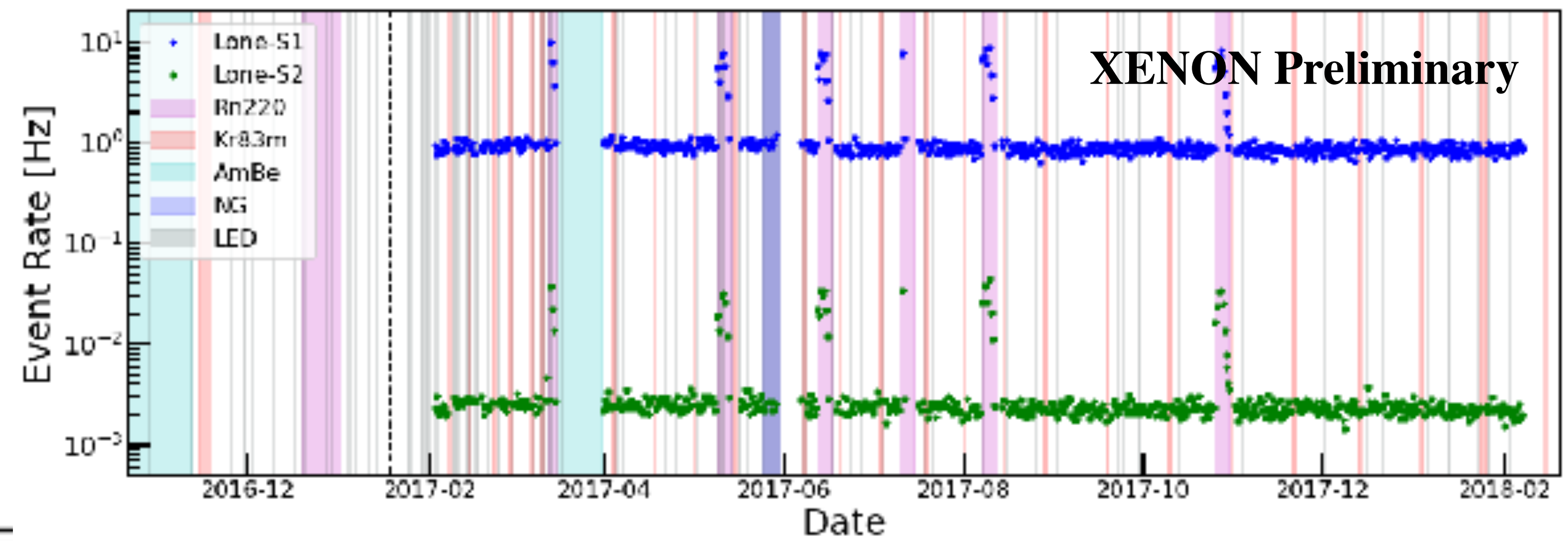
(Expectations in 4-50 keV search window, 1t FV, single scatters)

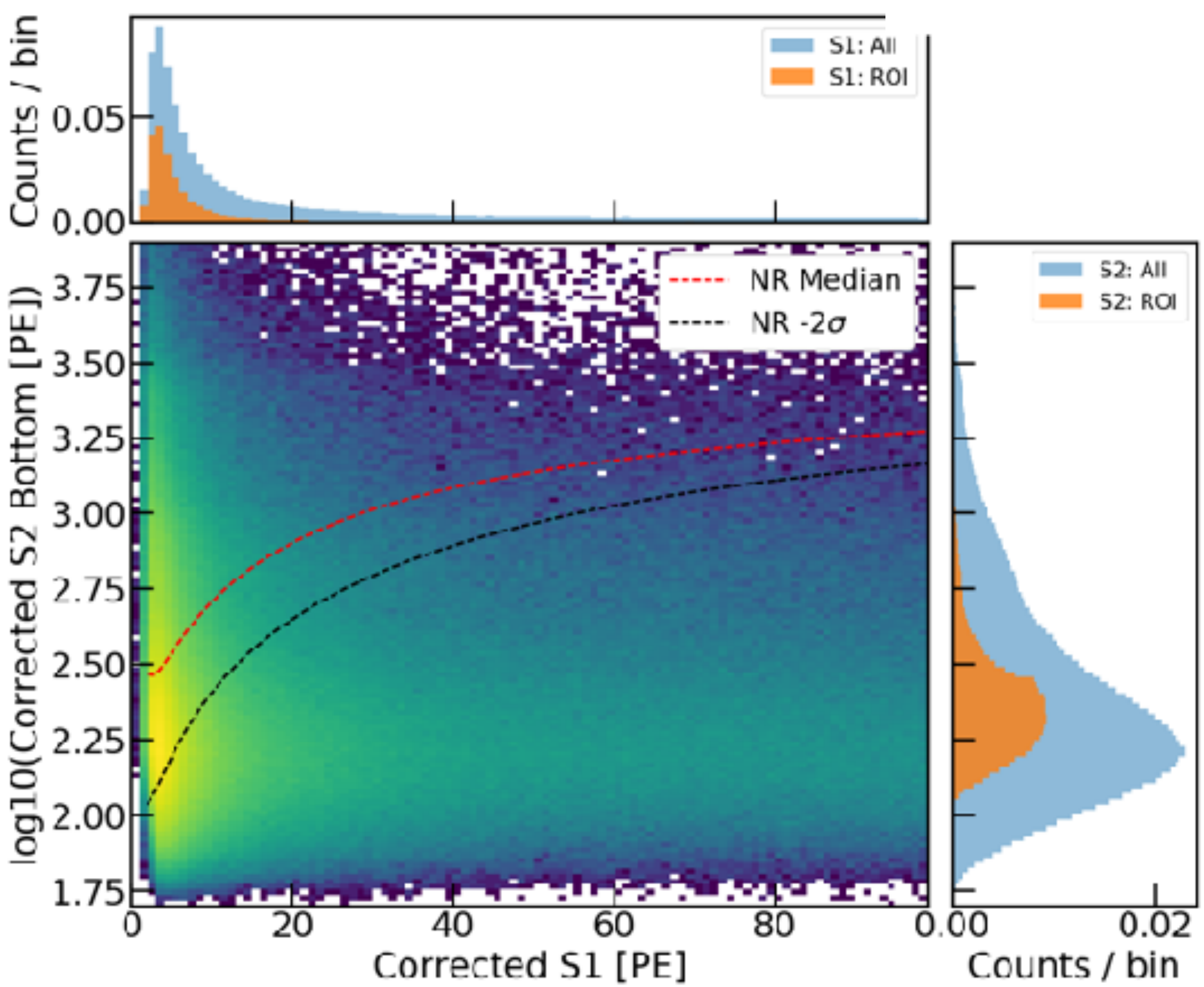
JCAP04 (2016) 027



Accidental Coincidence Background

A "lone" S1 or S2 signal produced in light and charge insensitive regions of the TPC may be accidentally combined to produce fake events in signal region





Empirical model shows an overall small rate in the ROI for NRs

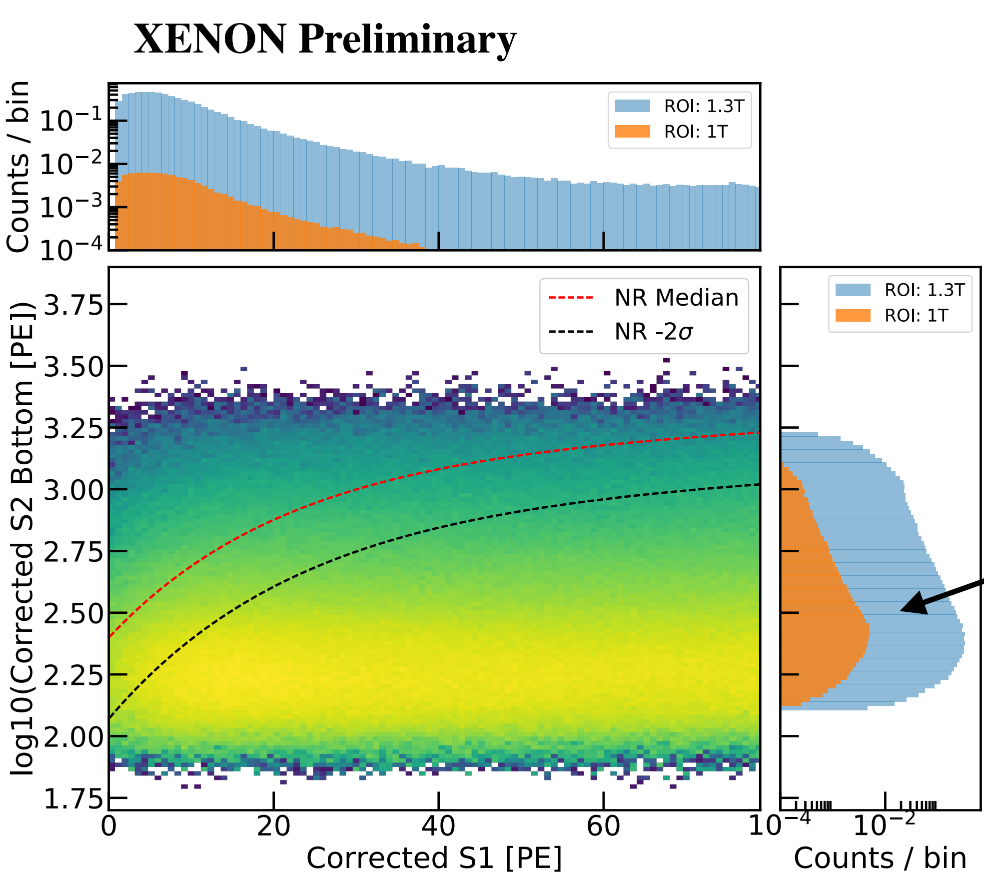
- Select unpaired S1/S2 from data
- Randomly pair to form events
- Apply selection conditions from analysis
- Performance verified with ^{220}Rn data and background sidebands

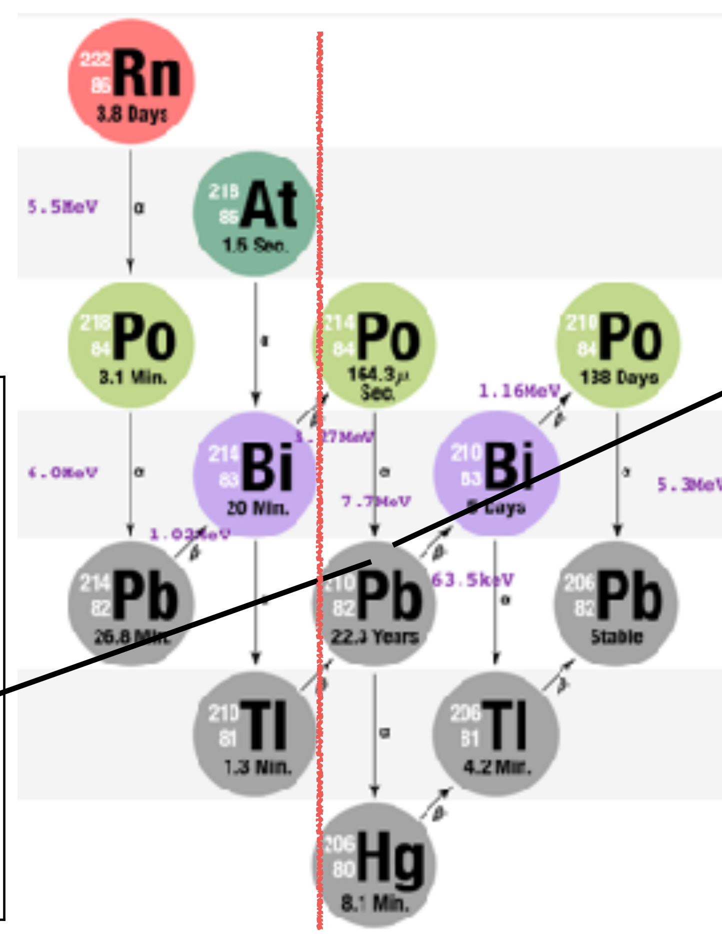
Surface Background

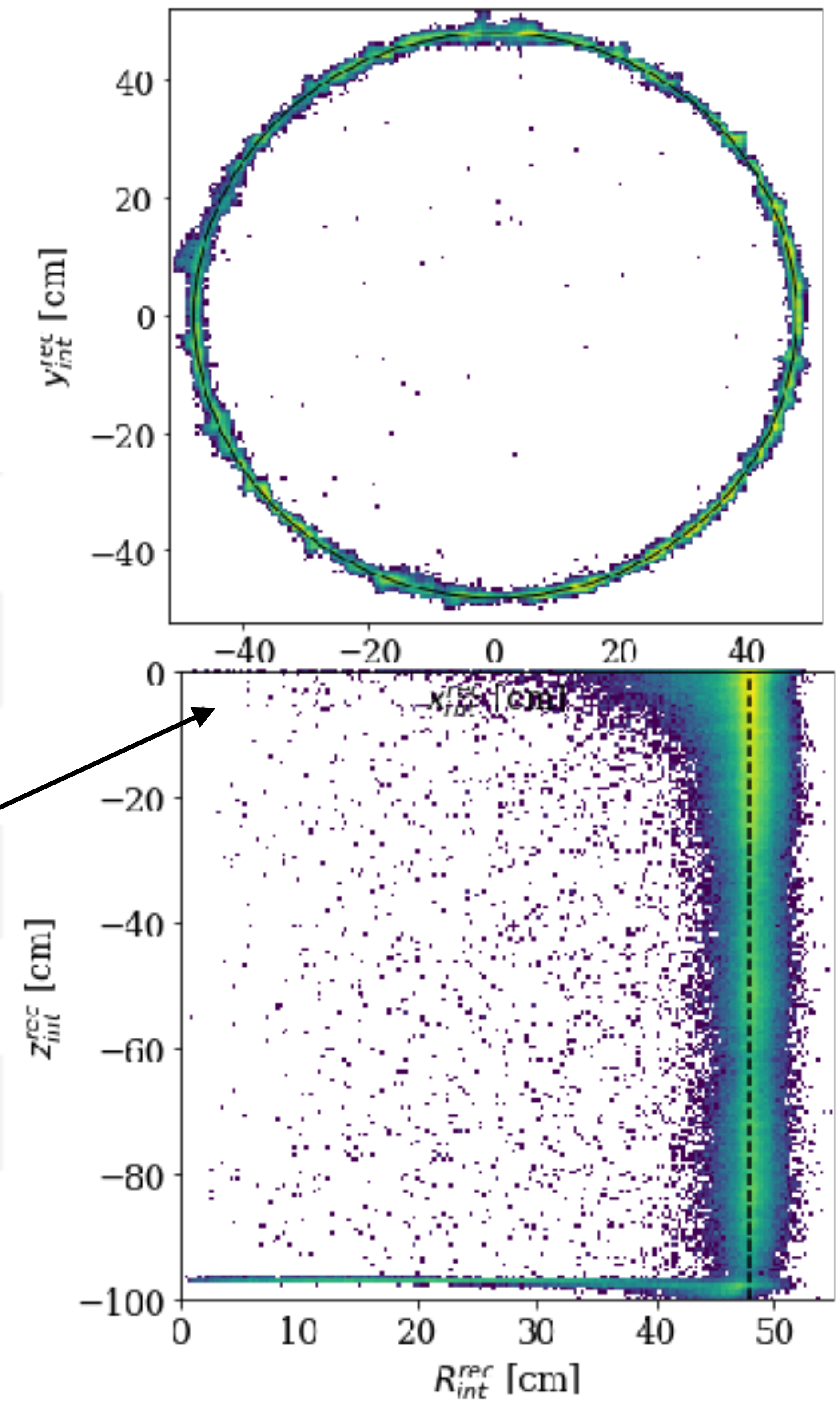
- Pb210 and Po210 plate-out on PTFE surface produce events with reduced S2 -> can be mis-reconstructed into NR signal region

- Suppressed by fiducialization of volume

- Data-driven model derived from surface event control samples







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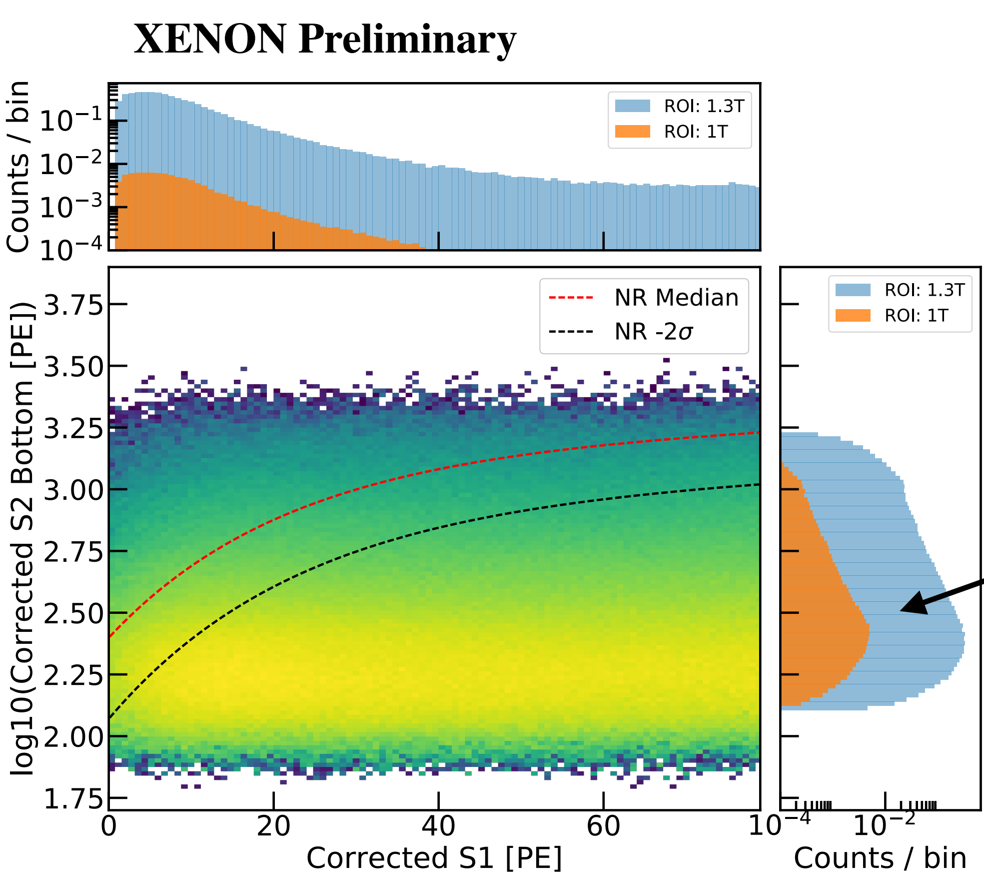

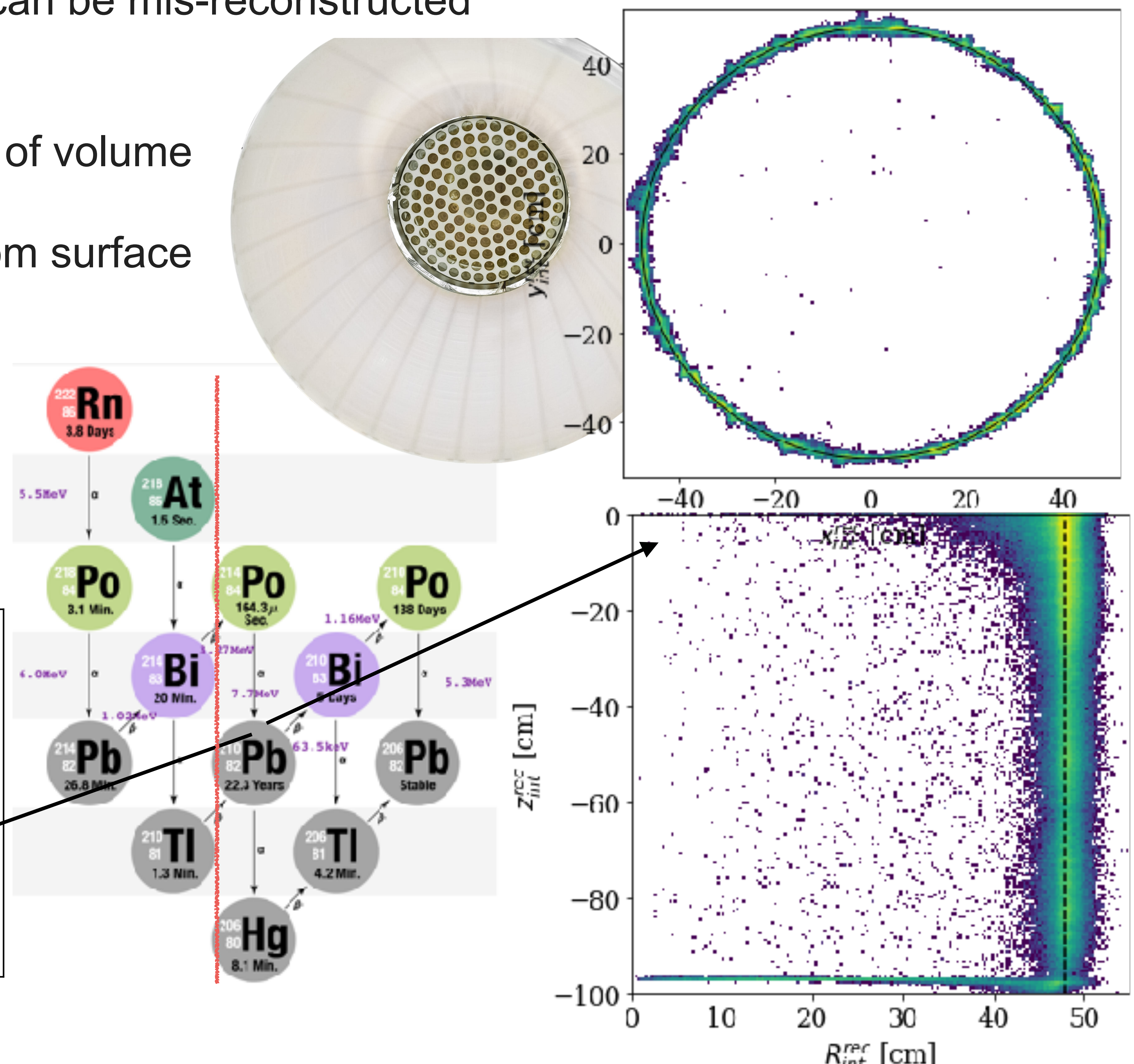

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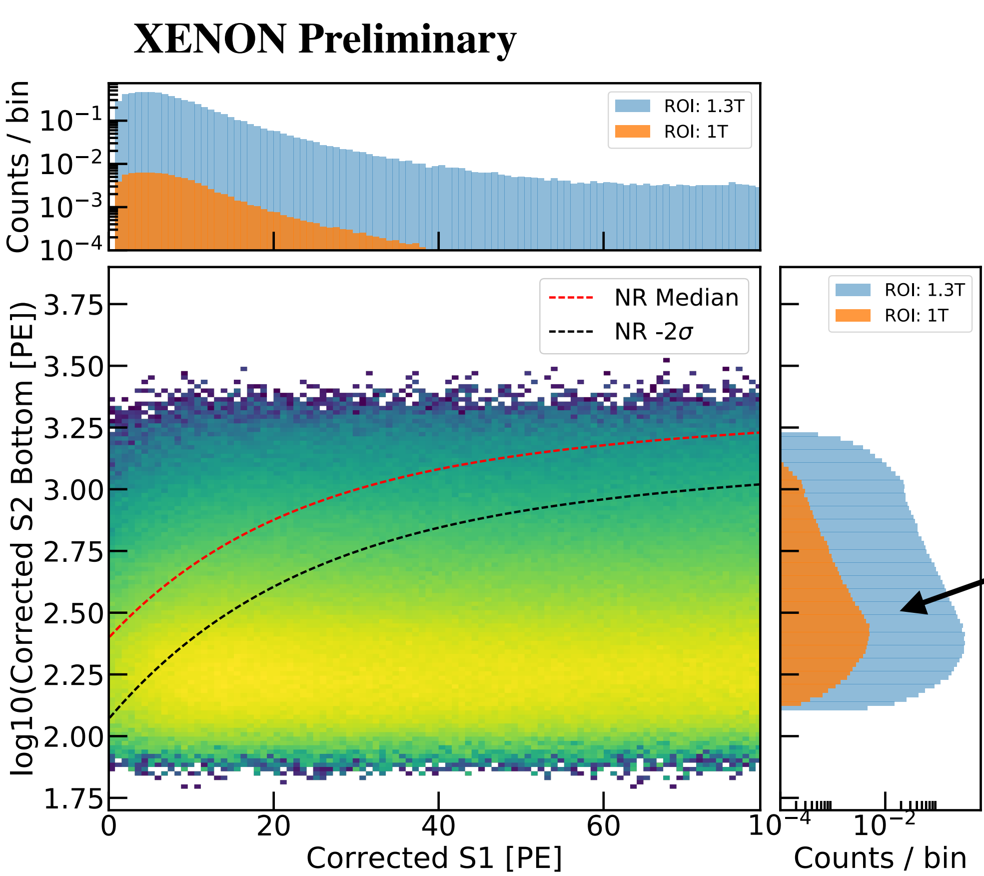
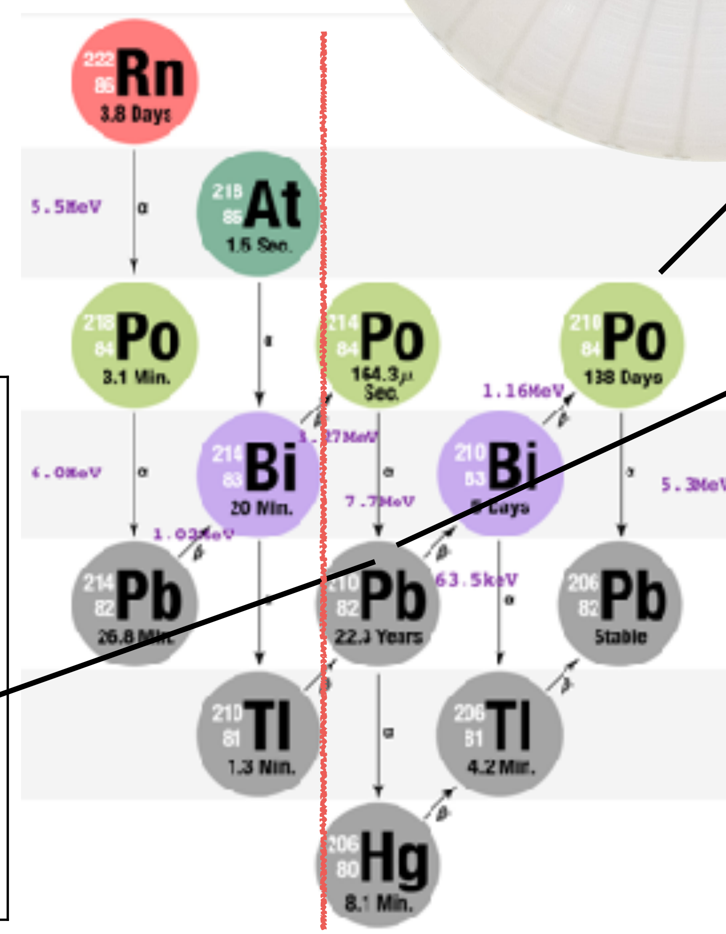
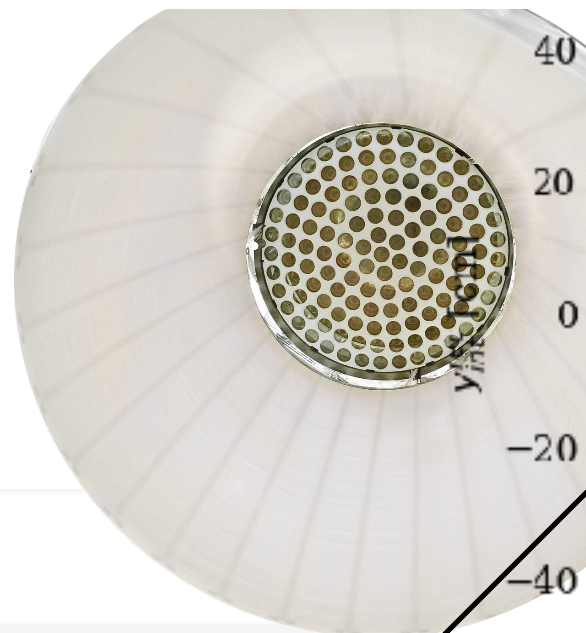
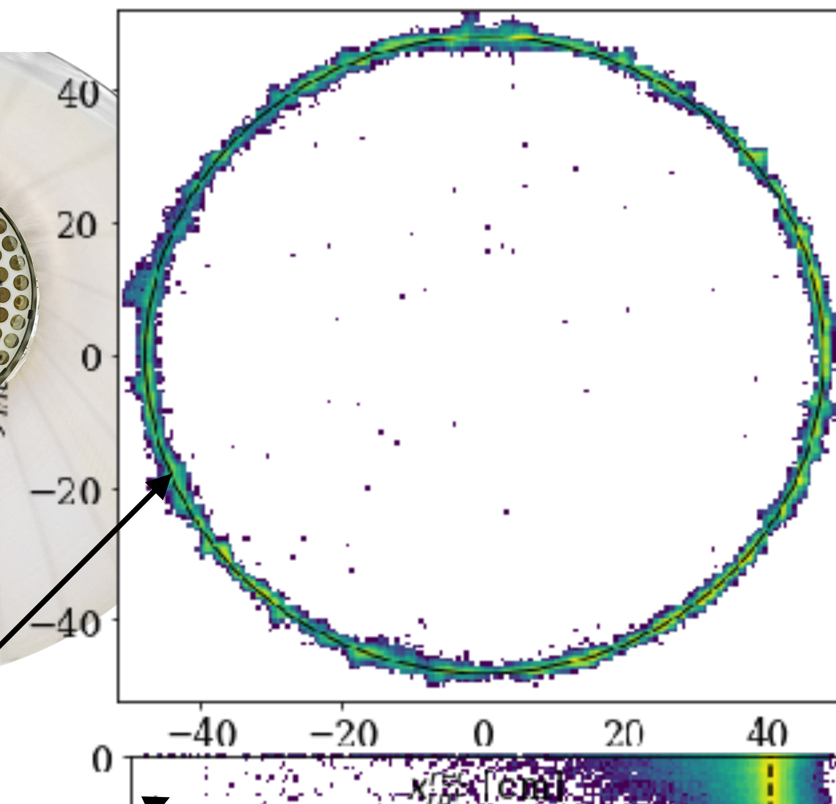
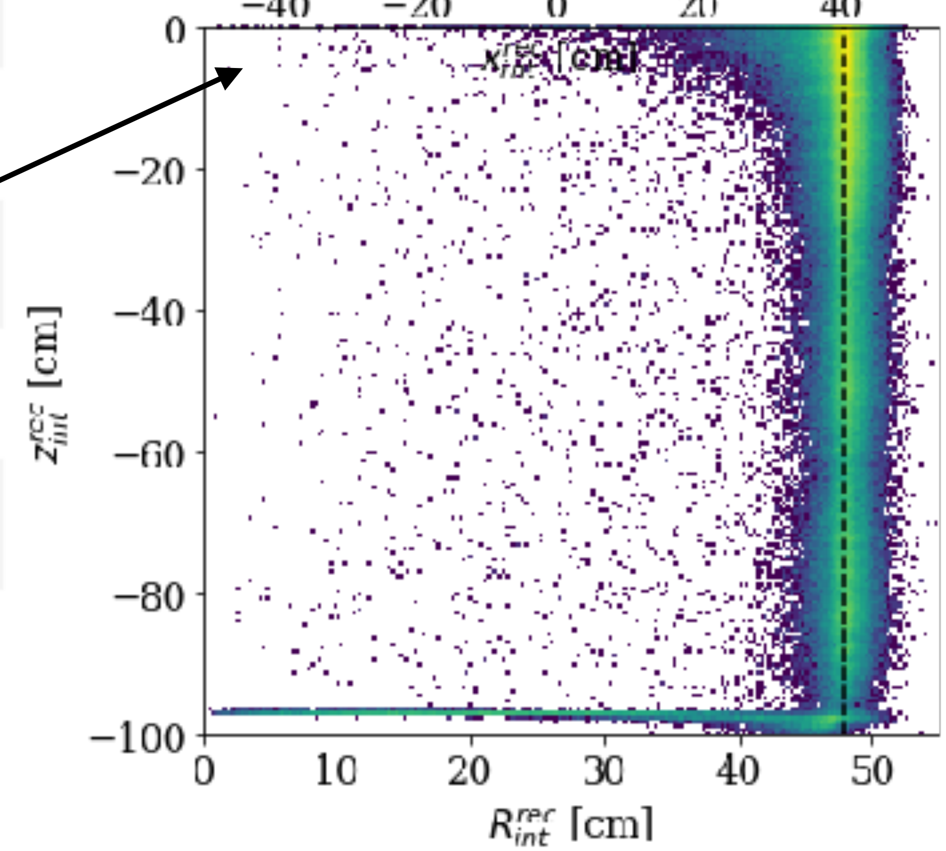




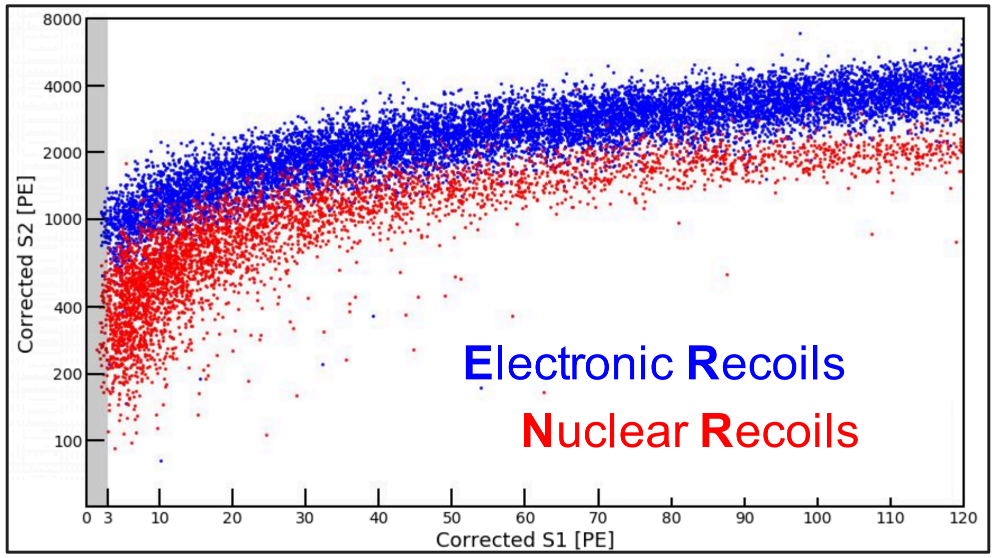


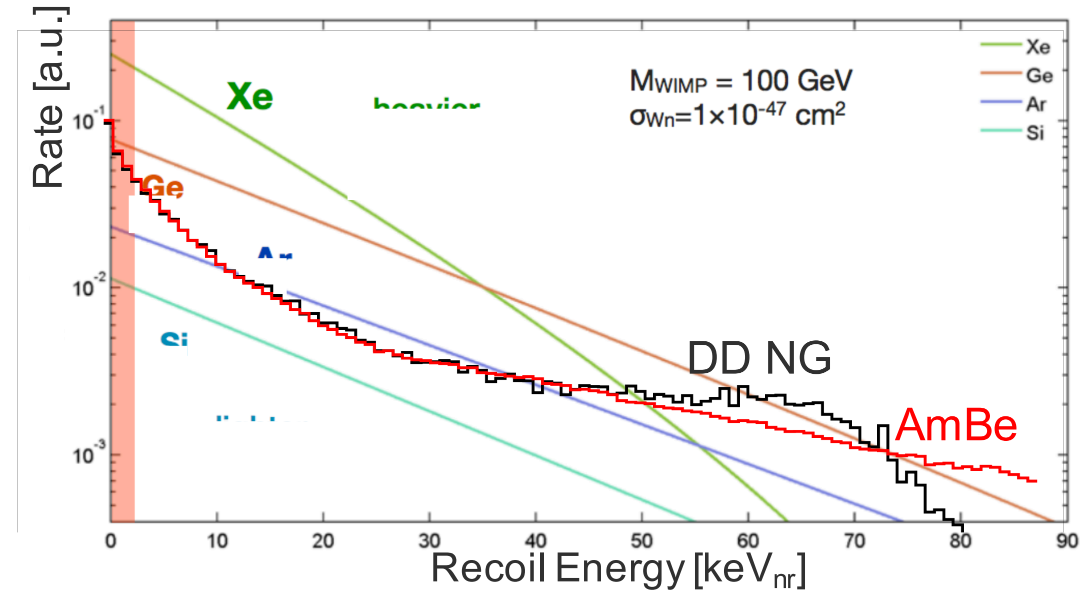


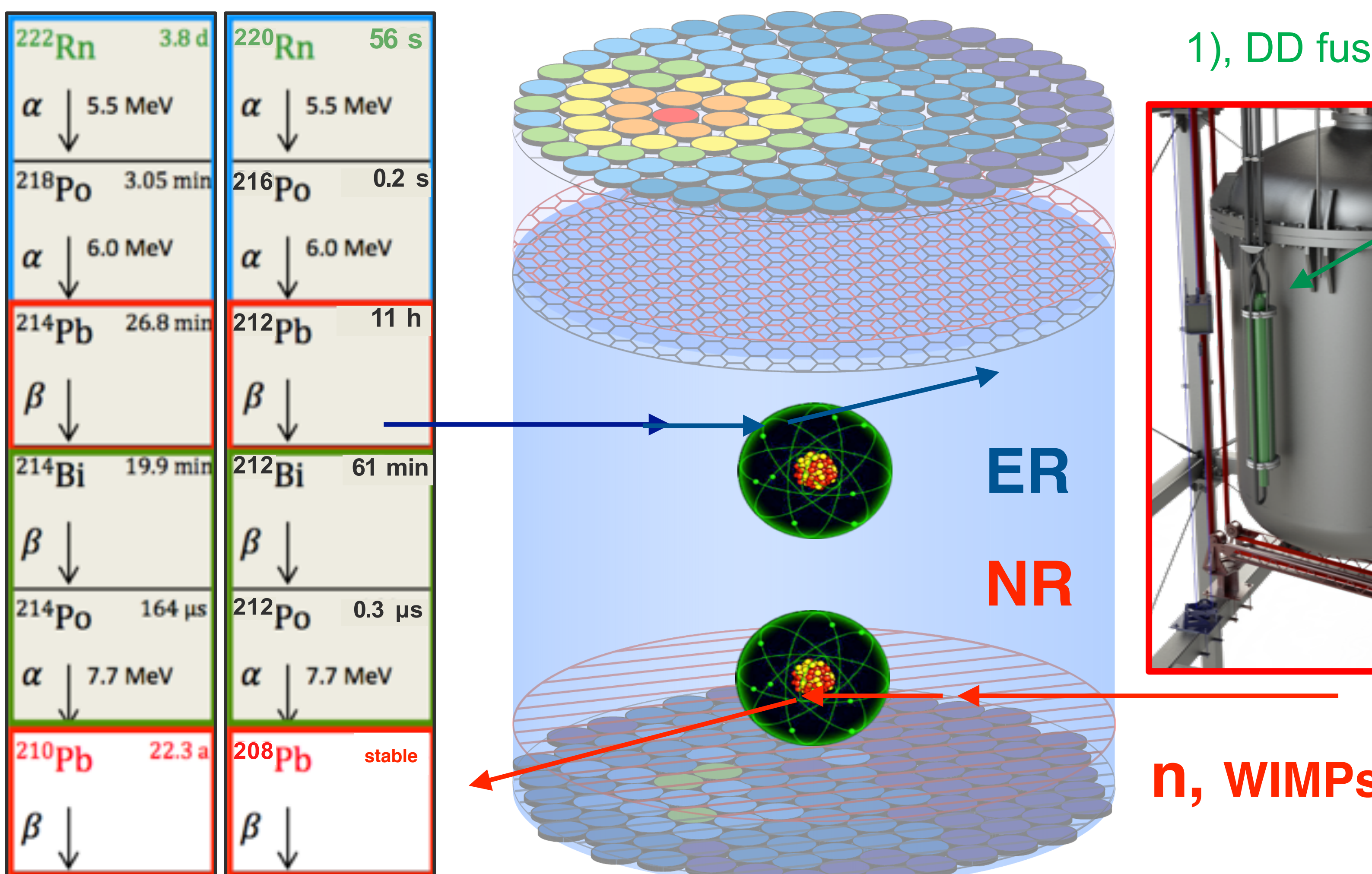


Response to Electronic and Nuclear Recoils

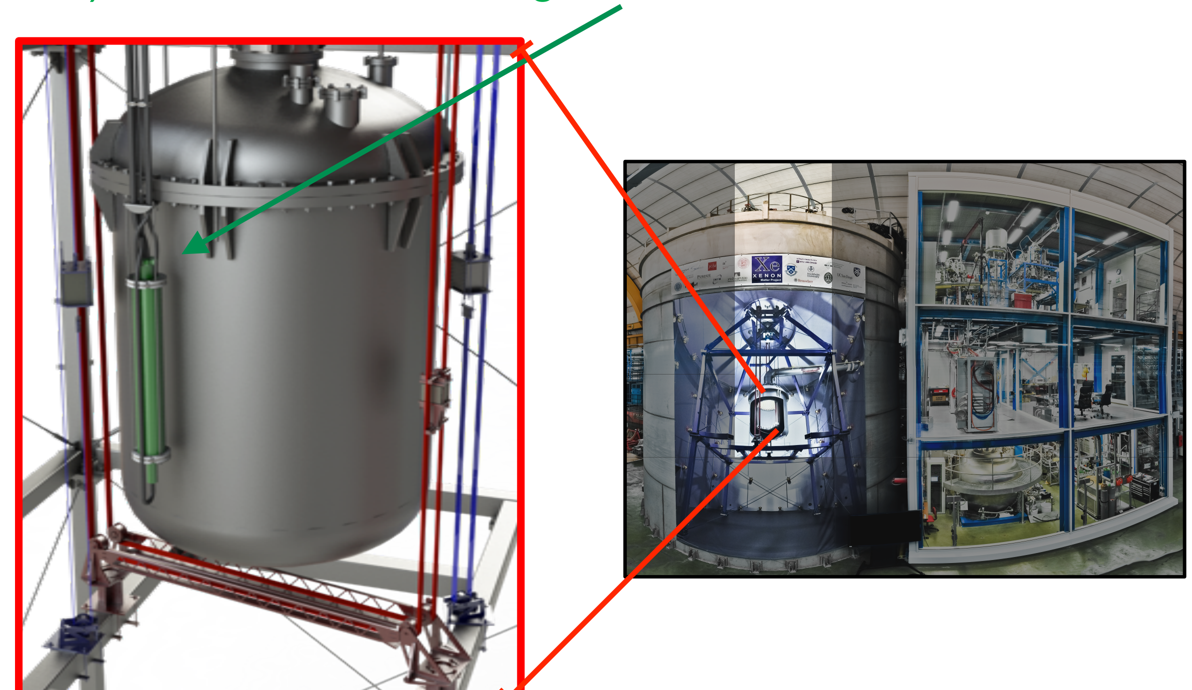
Calibrating ERs and NRs





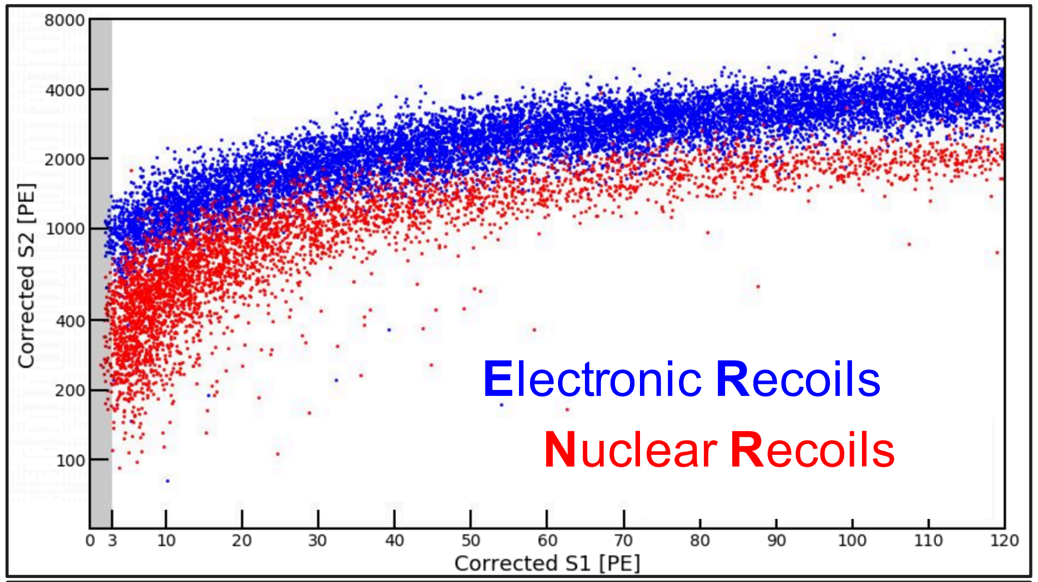


1), DD fusion neutron generator

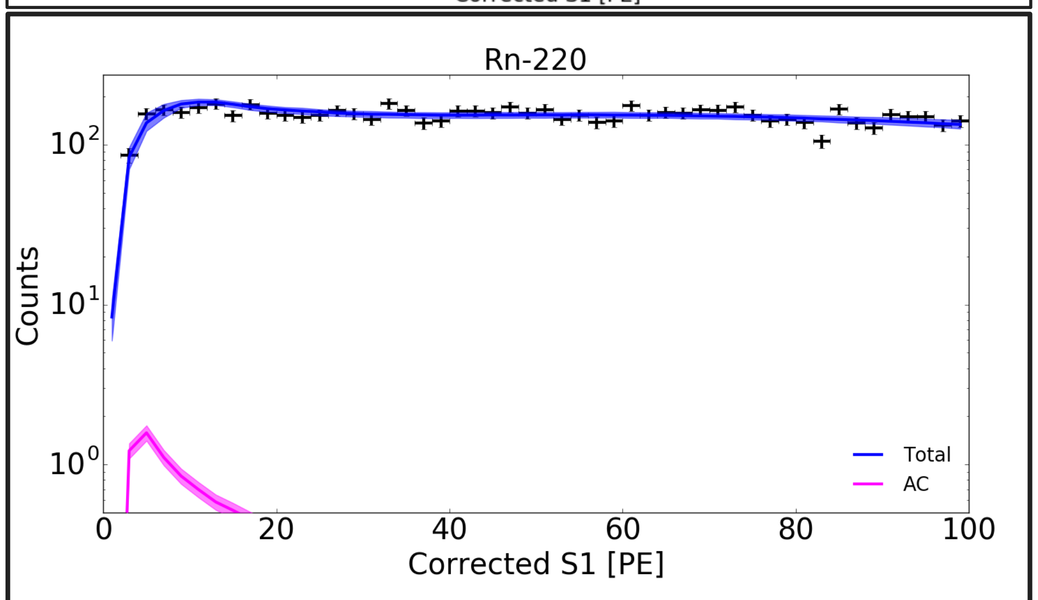


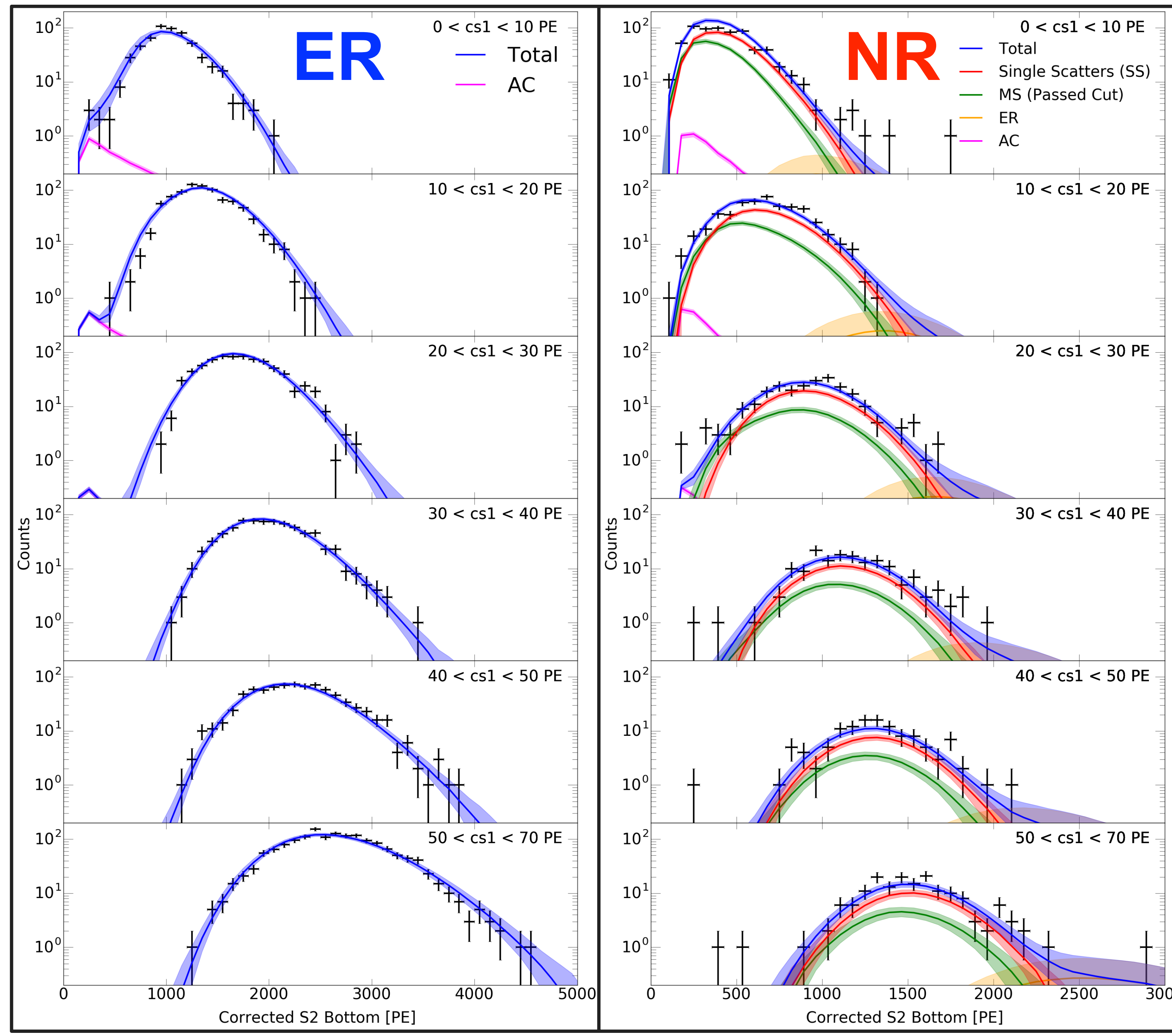
2), AmBe radioactive source

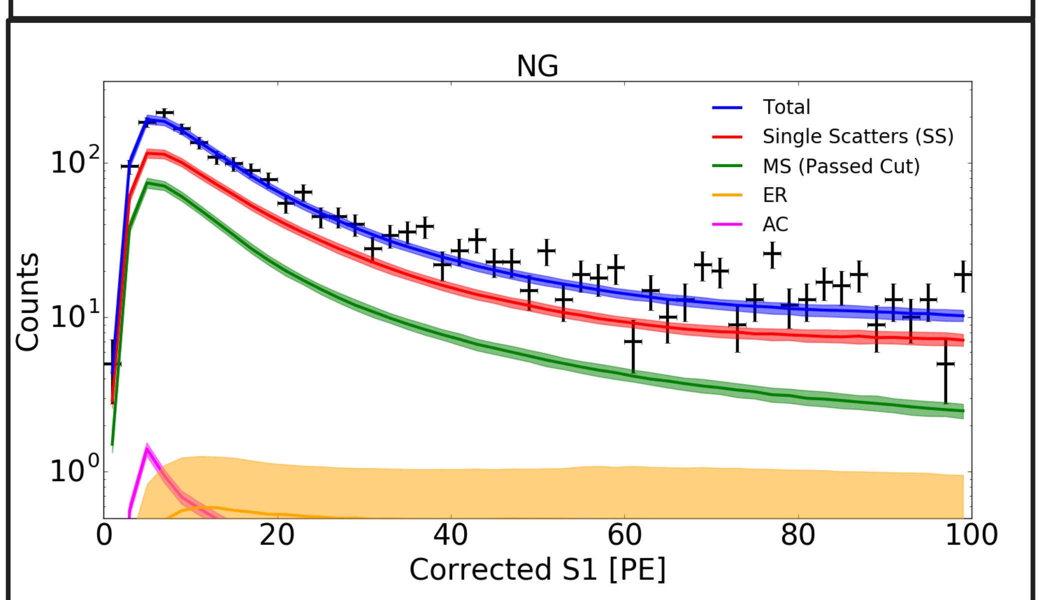
Calibrating ERs and NRs



Particle propagation with detailed detector geometry and LXe physics modeled
Parameters tuned and constrained by calibration data



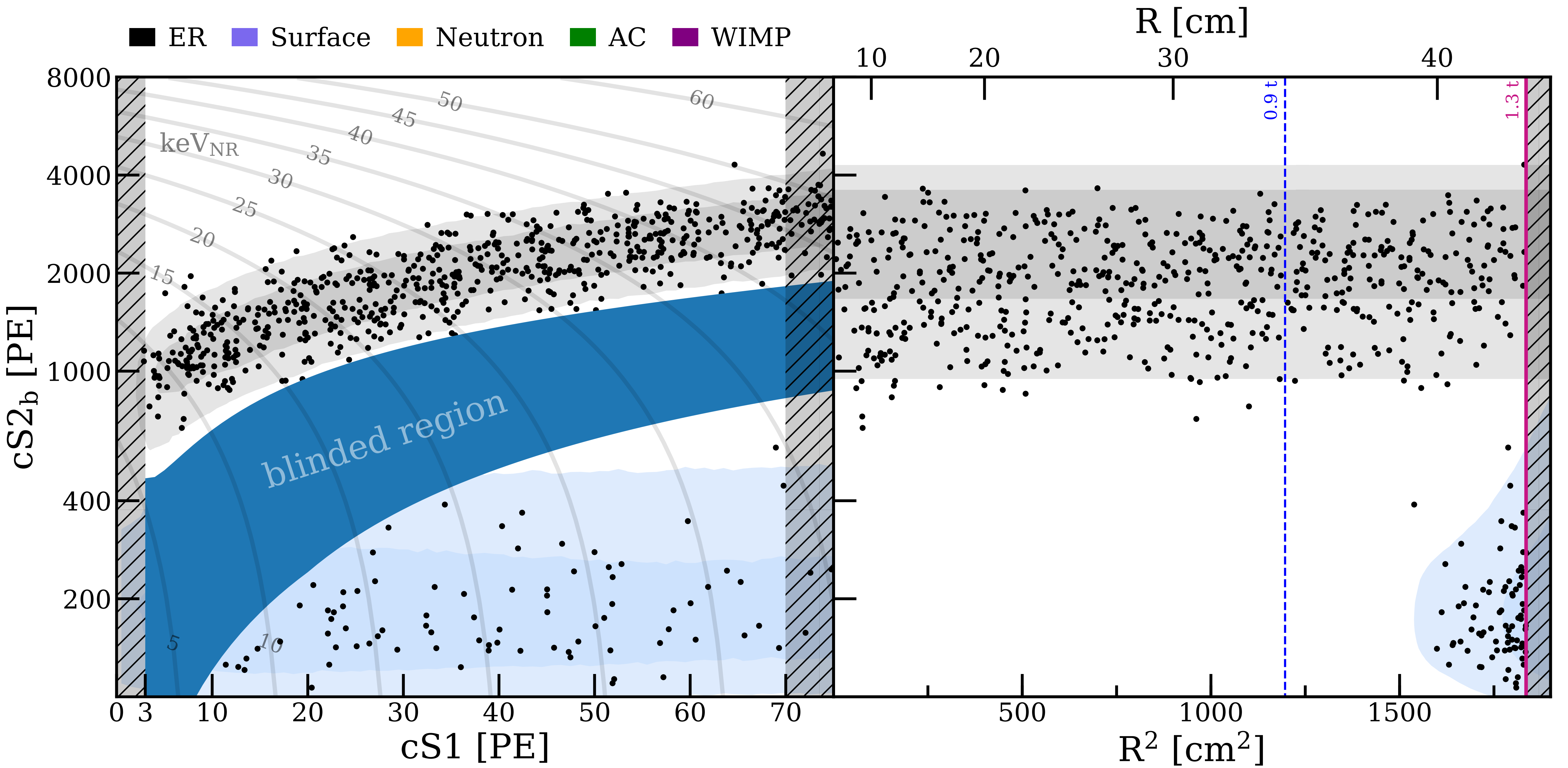




ER rejection: ~99.7% with NR acceptance within [-2σ, median] for both runs.

Dark Matter Search Data: Blinded and salted

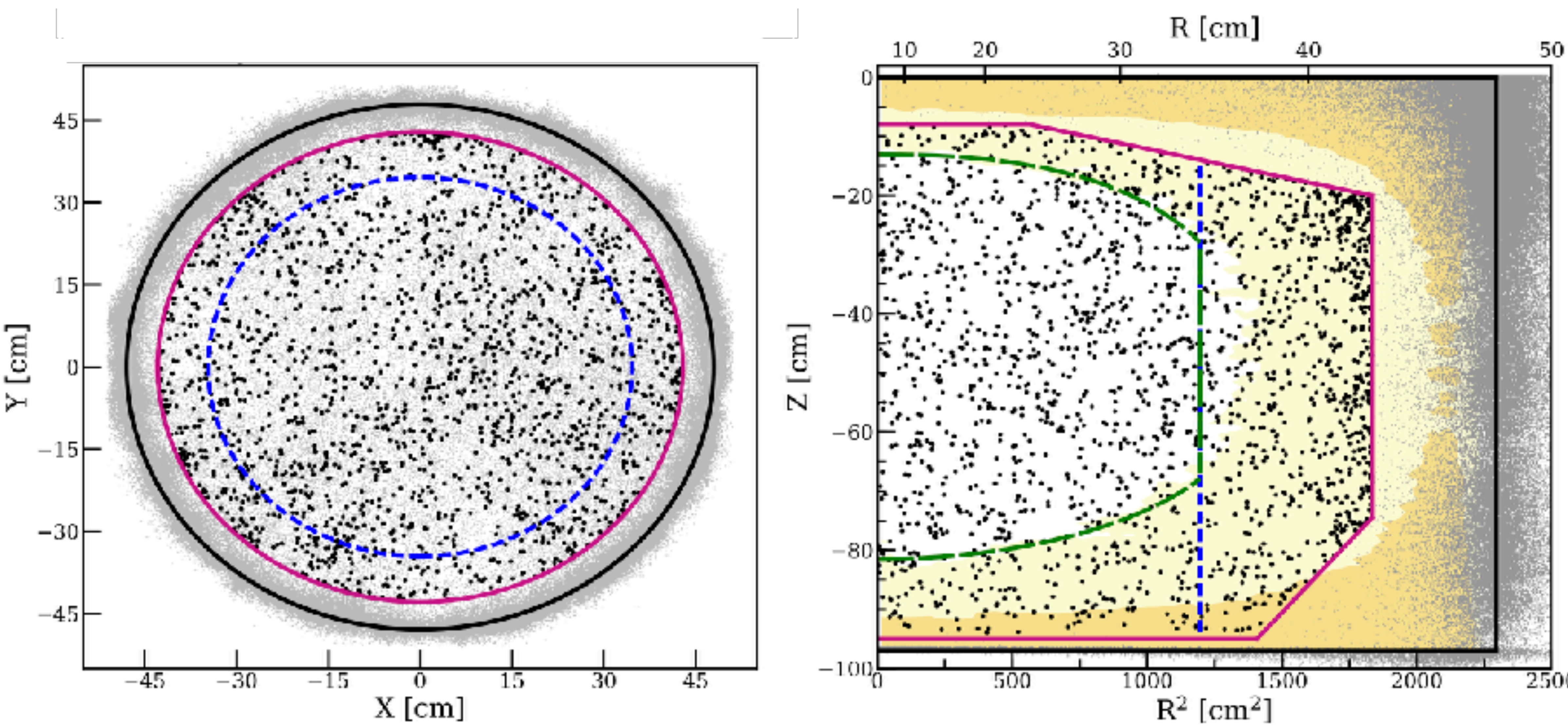
- Blinding: to avoid potential bias in event selection and the signal/background modeling the nuclear recoil ROI (S2 vs S1 only) was blinded from the start of SR1 analysis (and SR0 re-analysis).
- Salting: to protect against post-unblinding tuning of cuts and background models, an undisclosed number and type of event was added to data



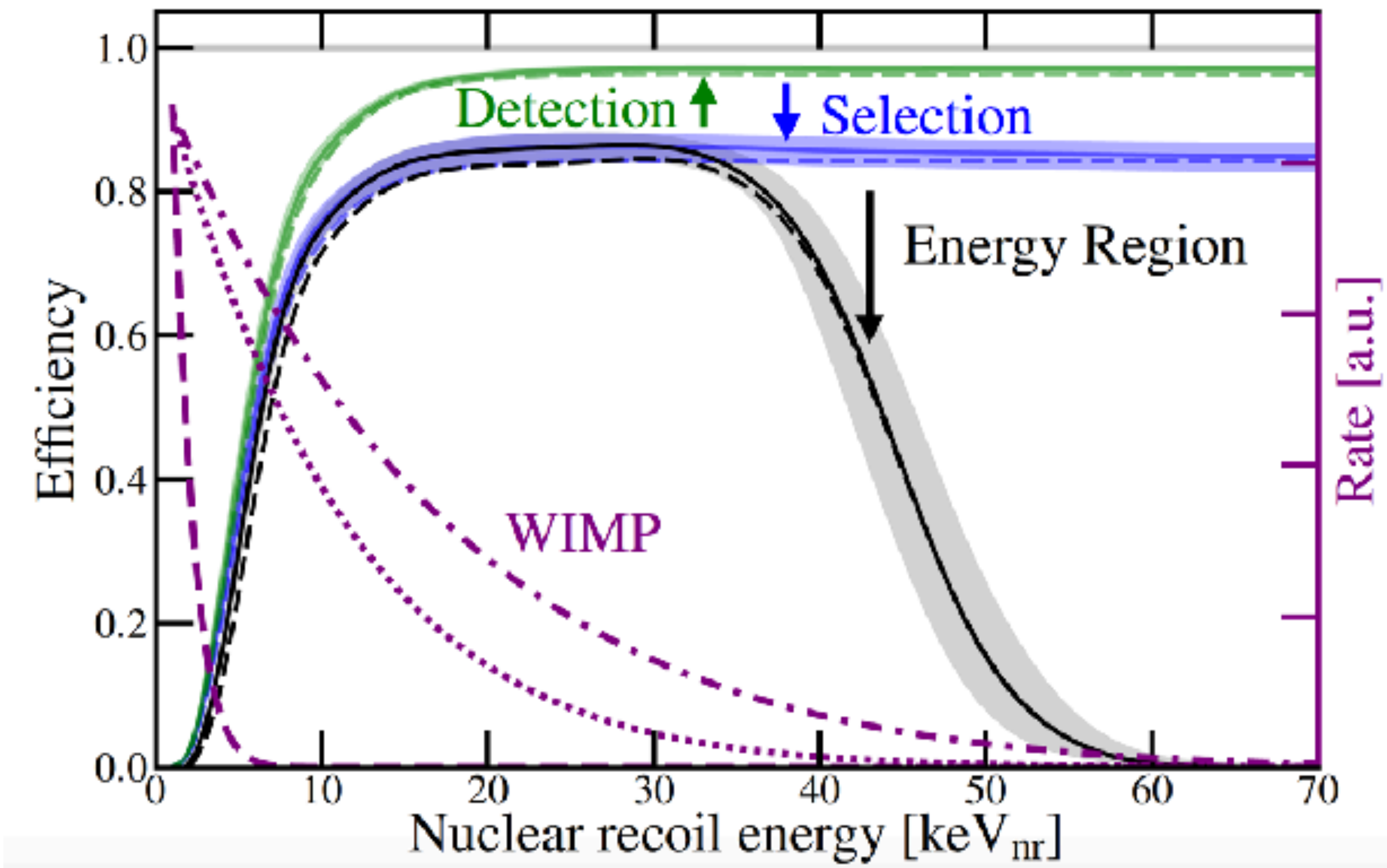
Fiducial Volume Optimization

Optimize FV prior to unblinding to reduce materials and surface background

- FV volume increased from 1 tonne (in SR0 First Result) to 1.3 tonne thanks to improvements in position reconstruction, including PTFE charge-up and field corrections
- new surface background model allowed inclusion of radius, R, in statistical inference to maximize useful volume. Analysis space became cS1, cS2b, R and Z



Event Selection & Detection Efficiency



- Detection efficiency dominated by 3-fold coincidence requirement
  - Estimated via novel waveform simulation including systematic uncertainties
- Selection efficiencies estimated from control or MC data samples
- Search region defined within 3-70 PE in cS1
- 10 GeV (dashed), 50 GeV (dotted) and 200 GeV (dashed-dotted) WIMP spectra shown

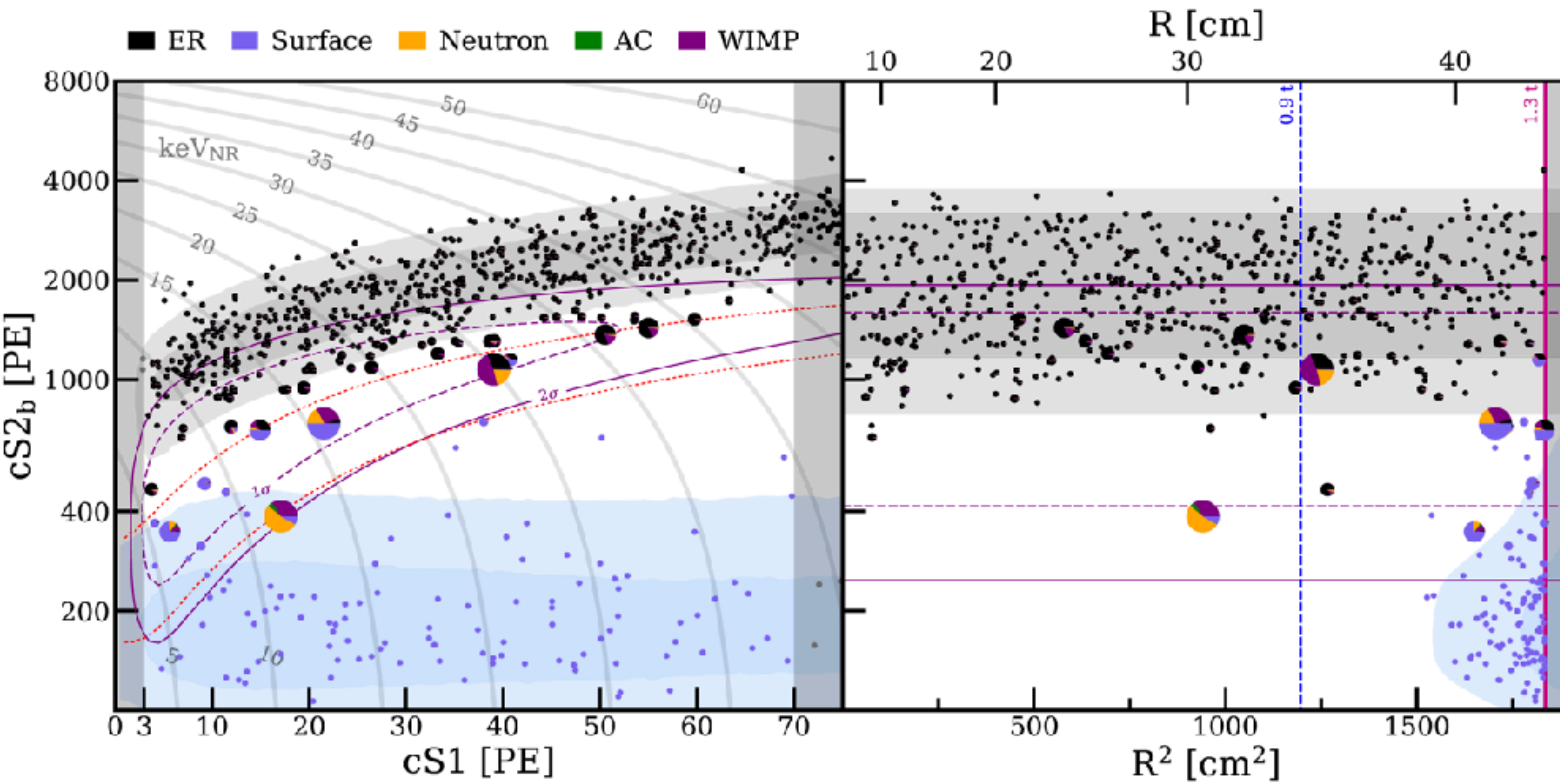
Background prediction and Unblinding

Mass	1.3t	1.3t
(S2, S1)	Full	Reference
ER	627±18	1.62±0.30
Neutron	1.43±0.66	0.77±0.35
CENNS	0.05±0.01	0.03±0.01
AC	0.47±0.27	0.10±0.06
Surface	106±8	4.84±0.40
BG	735±20	7.36±0.61
Data	**739**	**14**
WIMPs best-fit for m=200 GeV: 4.7 10^{-47} cm^2	3.56	1.70

- Reference region is defined as between NR median and NR - 2sigma
- ER is the most significant background and uniformly distributed in the volume
- Surface background contributes most in reference region, but its impact is subdominant in inner R
- Neutron background is less than one event, and impact is further suppressed by position information
- Other background components are completely sub-dominant
- Numbers in the table are just for illustration, statistical interpretation is done based on profile likelihood analysis

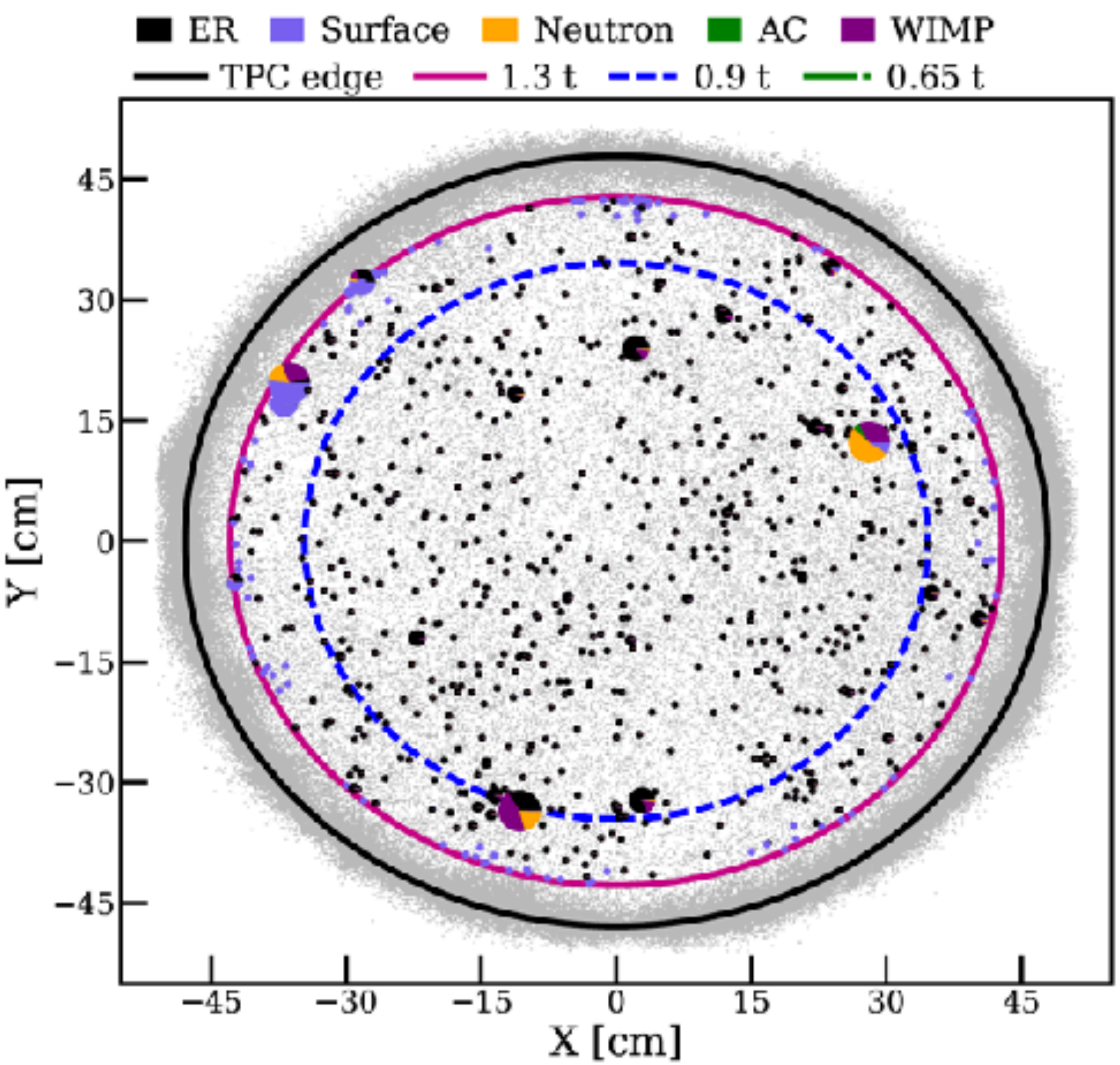
Dark Matter Search Results

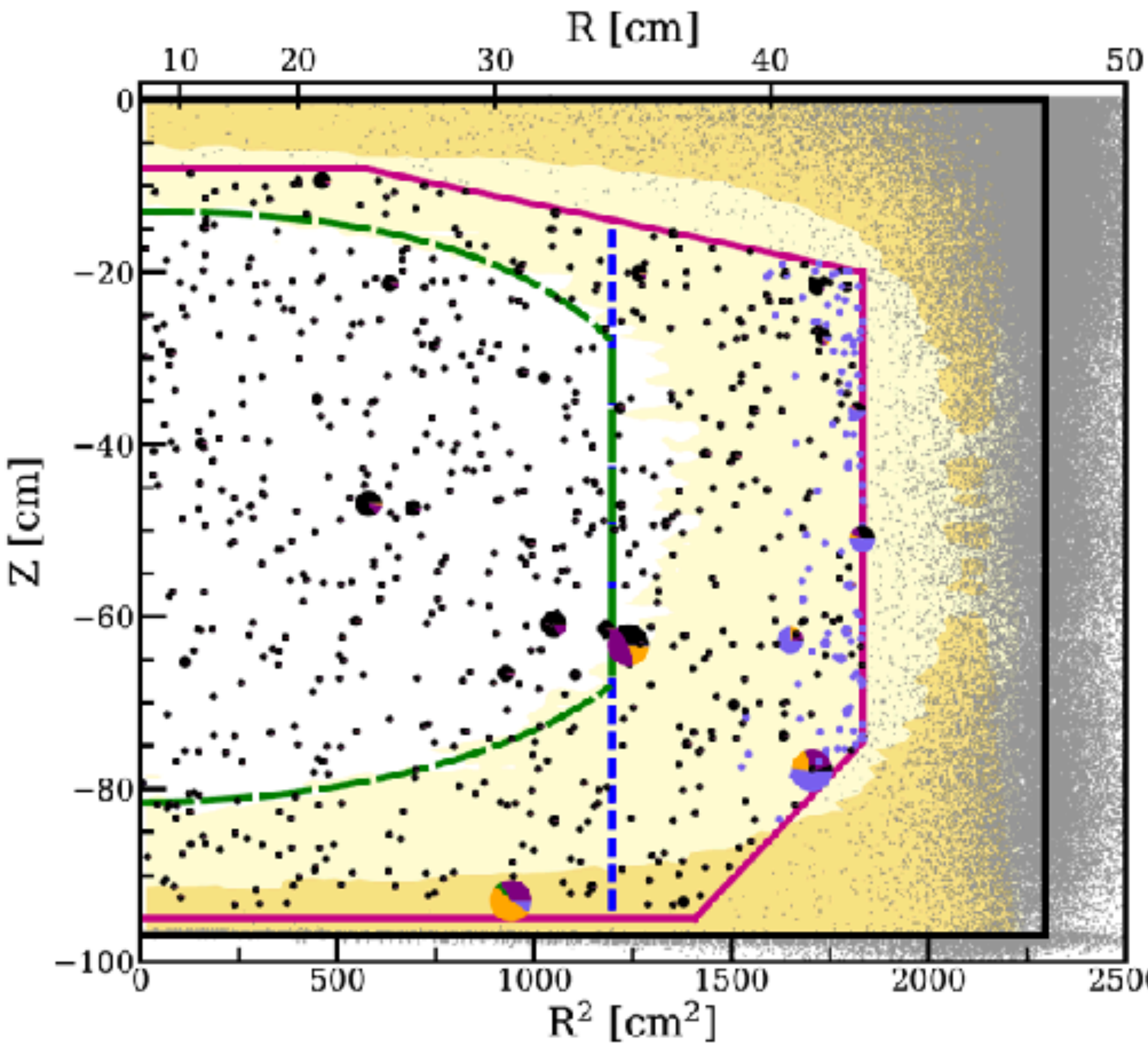
- Results interpreted with unbinned profile likelihood analysis in cs1, cs2, r space
- piechart indicate the relative PDF from the best fit of 200 GeV/c^2 WIMPs with a cross-section of 4.7×10^{-47} cm^2



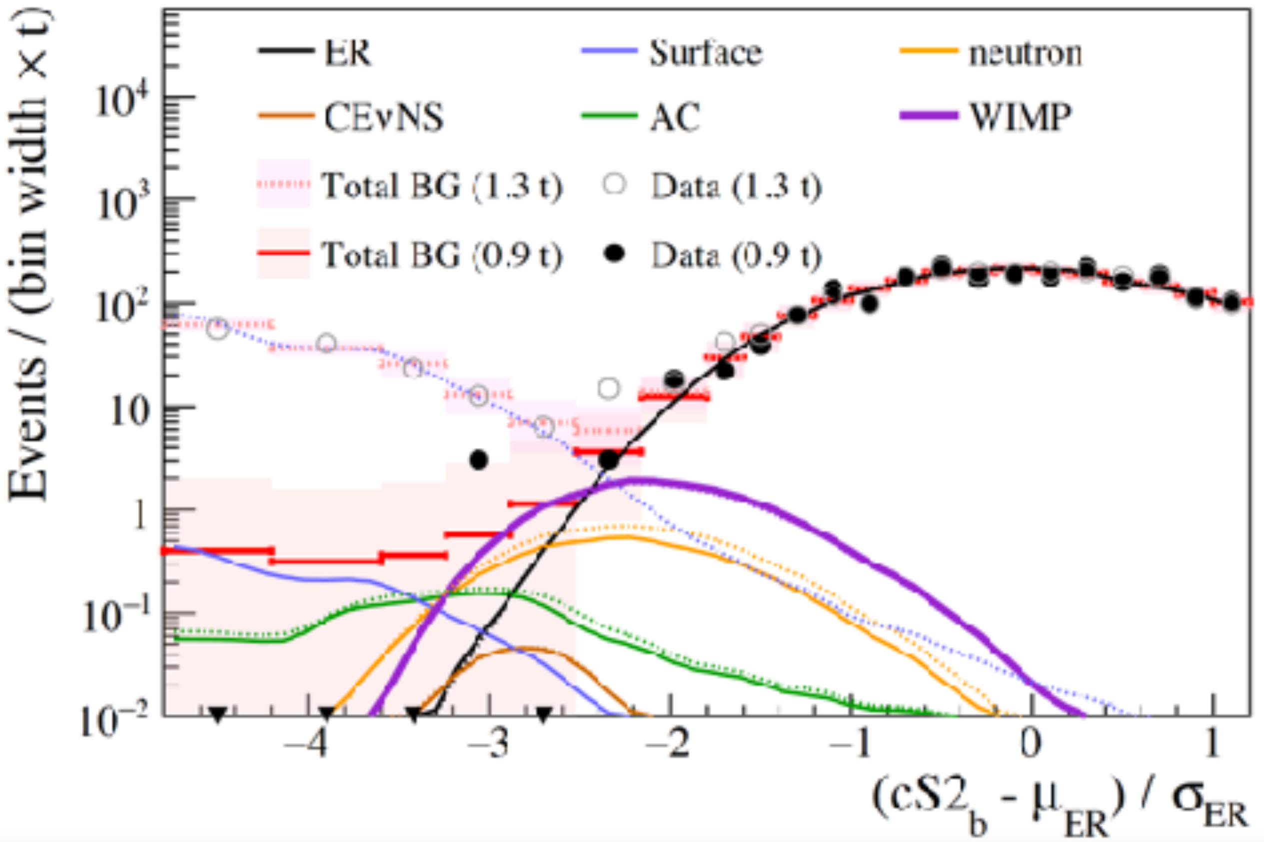
Spatial Distribution of Dark Matter Search Data

- Results interpreted with unbinned profile likelihood analysis in cS1, cS2, r space
- **Core volume** to distinguish WIMPs over neutron background



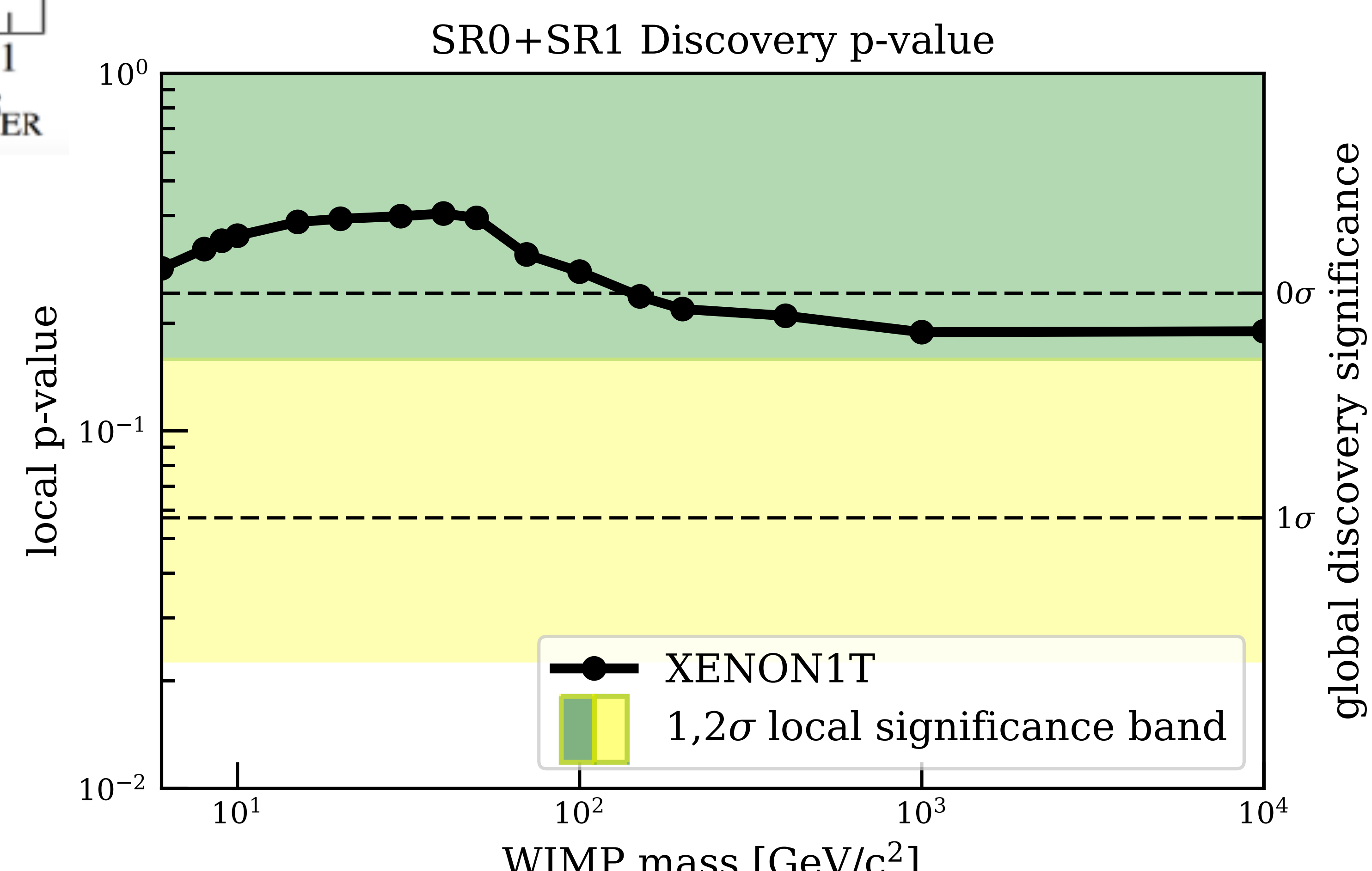


Statistical Interpretation

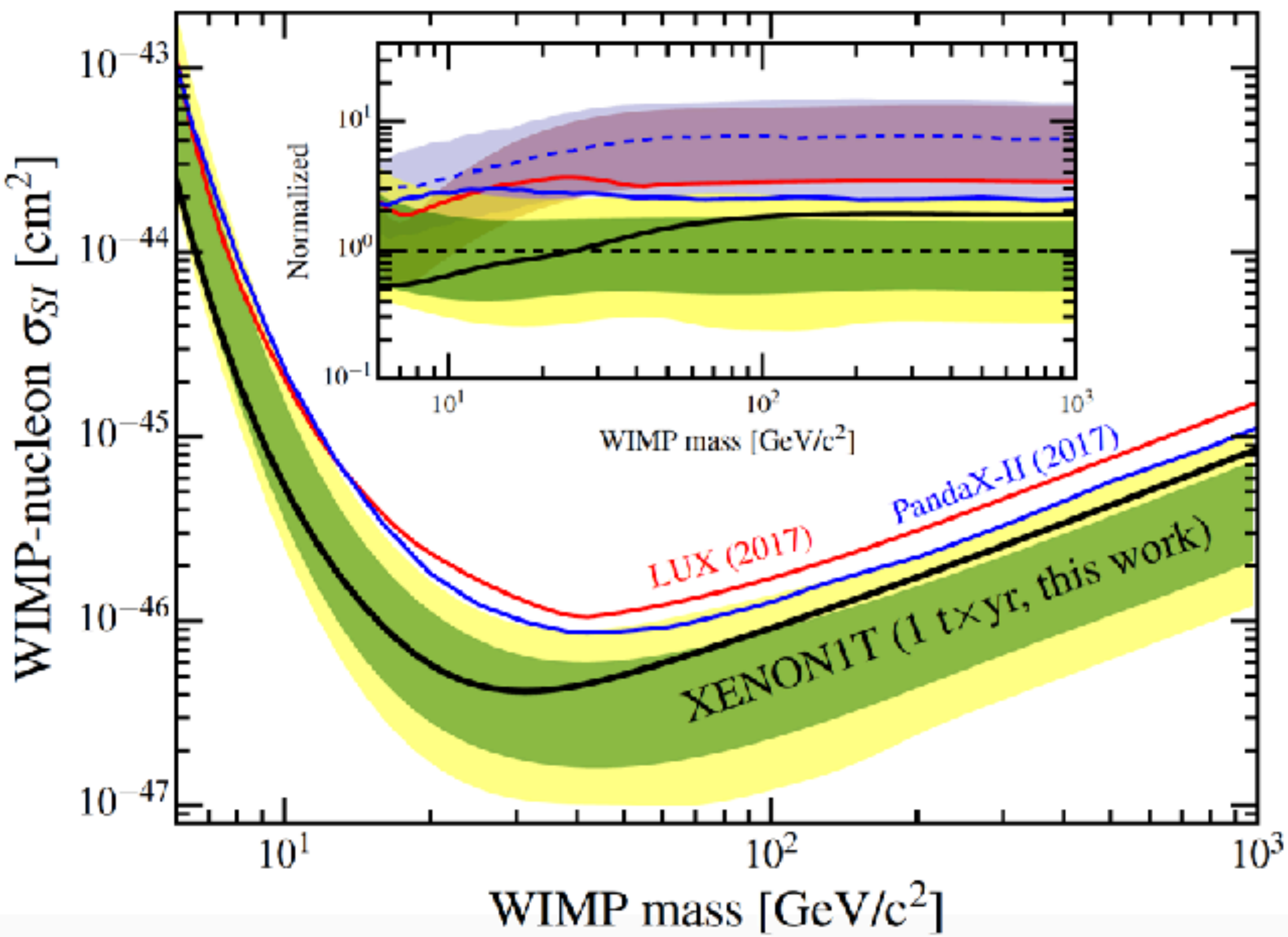


- Extended unbinned profile likelihood analysis
- Example left: Background and 200 GeV WIMP signal best-fit predictions, assuming 4.7 x 10^{-47} cm^2, compared to data in 1.3 t and 0.9 t
- Most significant ER & Surface backgrounds shape parameters included
- Safeguard to protect against spurious mis-modeling of background

- No significant (>3 sigma) excess at any scanned WIMP mass
- Background only hypothesis is accepted although the p-value of ~0.2 at high mass (200 GeV and above) does not disfavor a signal hypothesis either



XENON1T Dark Matter Search Results



- Most stringent 90% CL upper limit on WIMP-nucleon cross section at all masses above 6 GeV
- Factor of 7 more sensitivity compared to previous experiments (LUX, PandaX-II)
- ~ 1sigma upper fluctuation at high WIMP masses, could be due to background or signal

Minimum at 4.1x10^{-47} cm^2 for a WIMP of 30 GeV/c^2

The next step: XENONnT

Aprile et al., Eur. Phys. J. C (2017) 77: 881. *XENON1T sub-systems*

Aprile et al., JCAP 77 (2016), 358. *online Rn-removal*

Aprile et al., Eur. Phys. J. C (2017) 77: 275. *online Kr-removal*

Aprile et al., JCAP 4 (2016), 27. *sensitivity*

Minimal Upgrade

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

x4

Fiducial Xe Target

XENONnT TPC features:

total Xe mass = 8 t

target mass = 5.9 t

fiducial mass = ~4 t

1/10

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

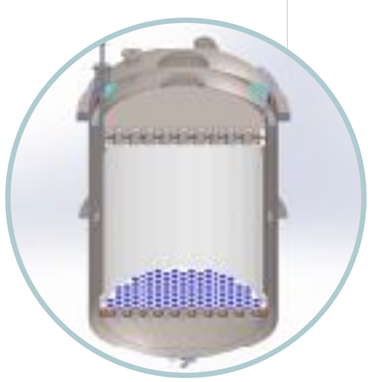
Fast pace:

Installation starts in 2018

commissioning in 2019

XENON1T Infrastructure and sub-Systems (already operative)

Aprile et al., Eur. Phys. J. C (2017) 77: 881

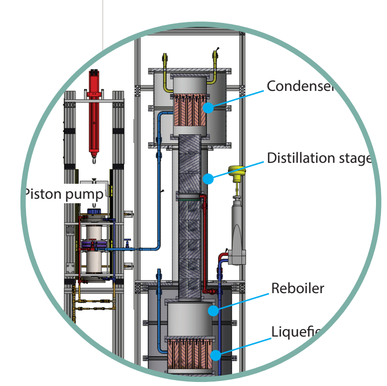


New TPC

5.9-ton Time Projection Chamber

LXe Purification

To achieve fast cleaning of the large LXe volume (5000 SLPM)



Radon Distillation

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

Neutron Veto

To tag and measure in situ neutron-induced background

Summary

- Successfully operated the first multi-ton scale LXeTPC for > 1 year
- Achieved lowest background in any DM detector: 0.2 events / (t keV d)
- With XENON1T we have surpassed the sensitivity projections of the proposed XENON program and yet have found no sign of WIMPs
- The result from a blind analysis of 1 tonne x year data places strongest limit above 6 GeV/c² on WIMP-nucleon SI cross-section at 4.1×10^{-47} cm² for a WIMP of 30 GeV/c²
- the search with XENON1T continues until its upgrade with a larger and better detector, XENONnT, to enable another boost in sensitivity