Results and news from the XENON project

14th Workshop on Dark Side of the Universe
Annecy-le-Vieux, France

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Weizmann Institute of Science

On behalf of the XENON collaboration

The XENON Collaboration

Columbia **RPI** **Nikhef** **Muenster** **Stockholm** **Mainz** **MPIK, Heidelberg** **Freiburg** **Zurich**

Chicago

UCLA

UCSD

Rice

Tokyo

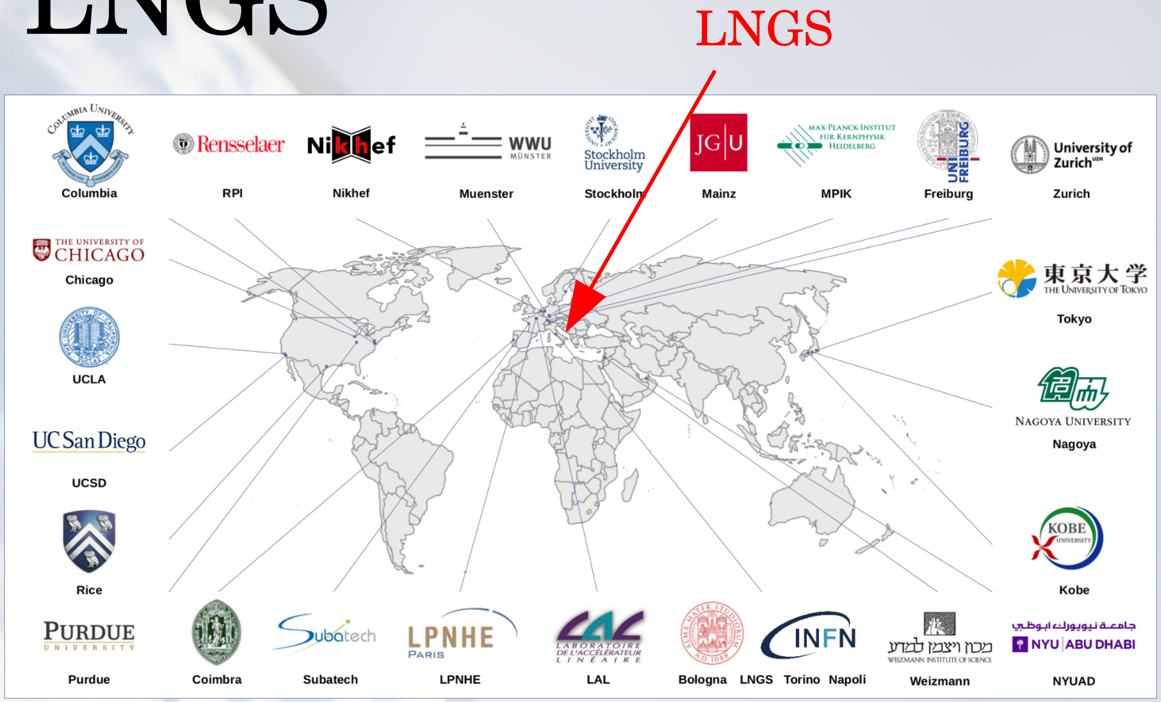
Nagoya

Kobe

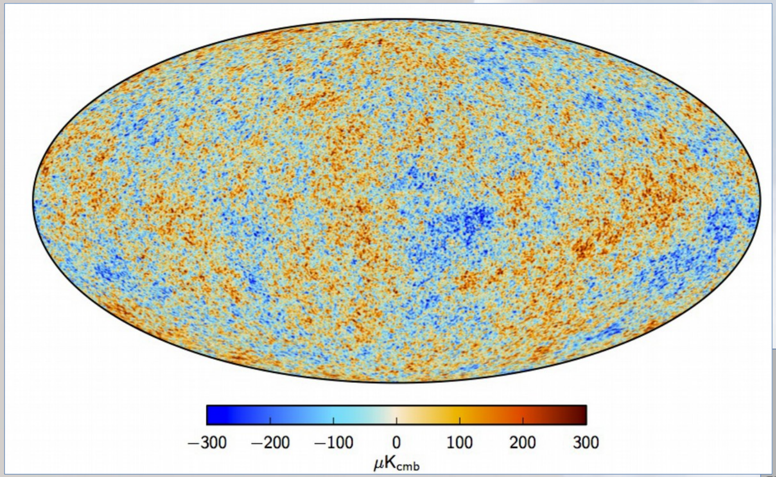
170 Scientists

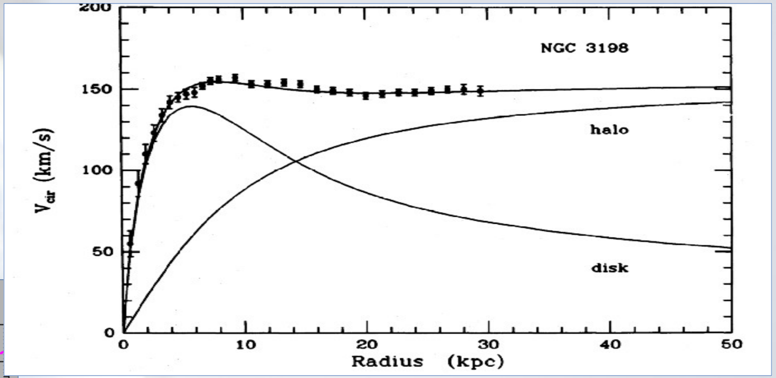
Purdue **Coimbra** **Subatech** **LPNHE** **LAL** **Bologna** **LNGS** **Torino** **Napoli** **Weizmann** **NYUAD**

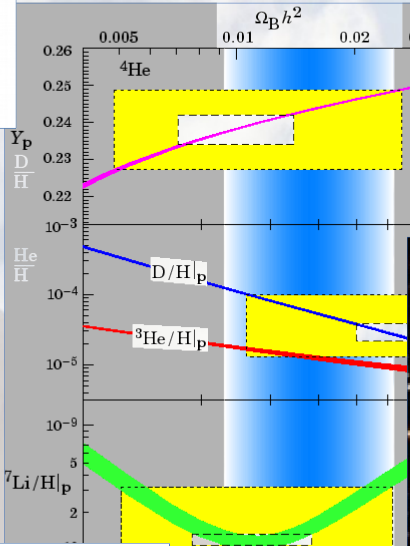
The XENON Collaboration at LNGS

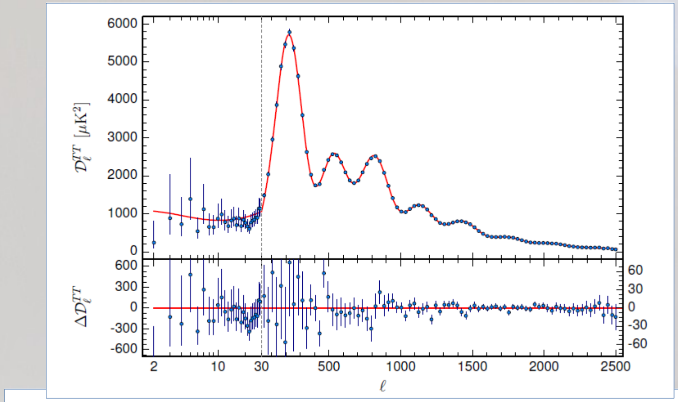


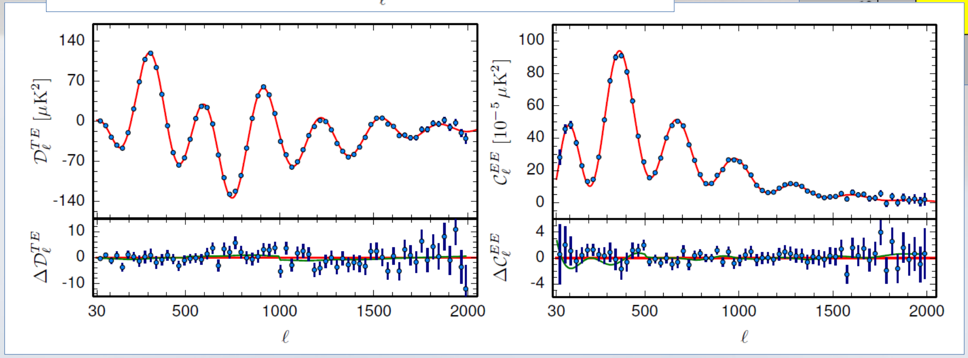
DM evidence on one slide



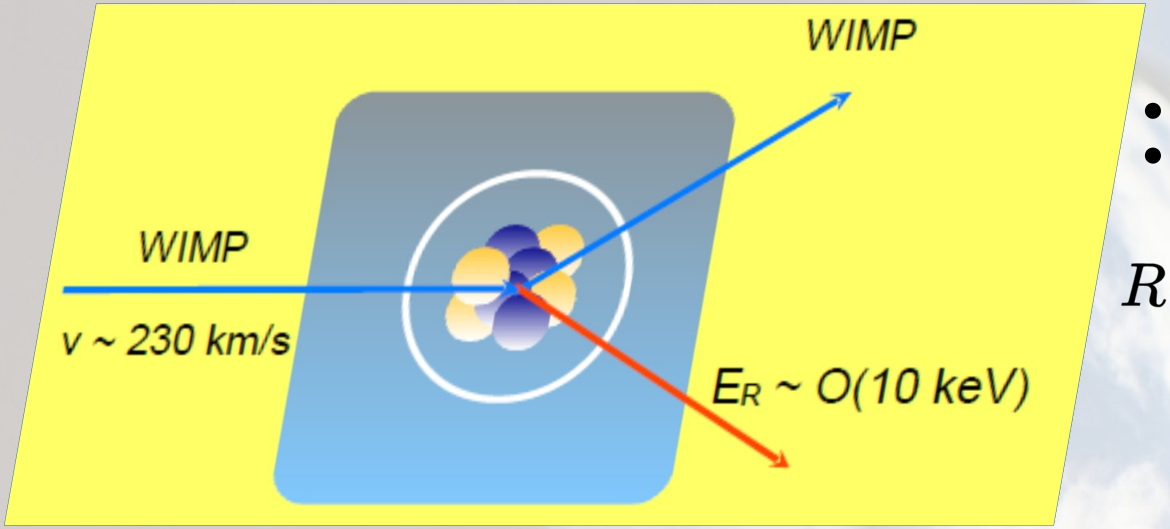








Direct Dark Matter Detection



- DM collision with nucleus
- Induces nuclear recoil
    - ○ Look for low energy NRs

$$R \propto \rho_0 \sigma_{wn} N A^2$$

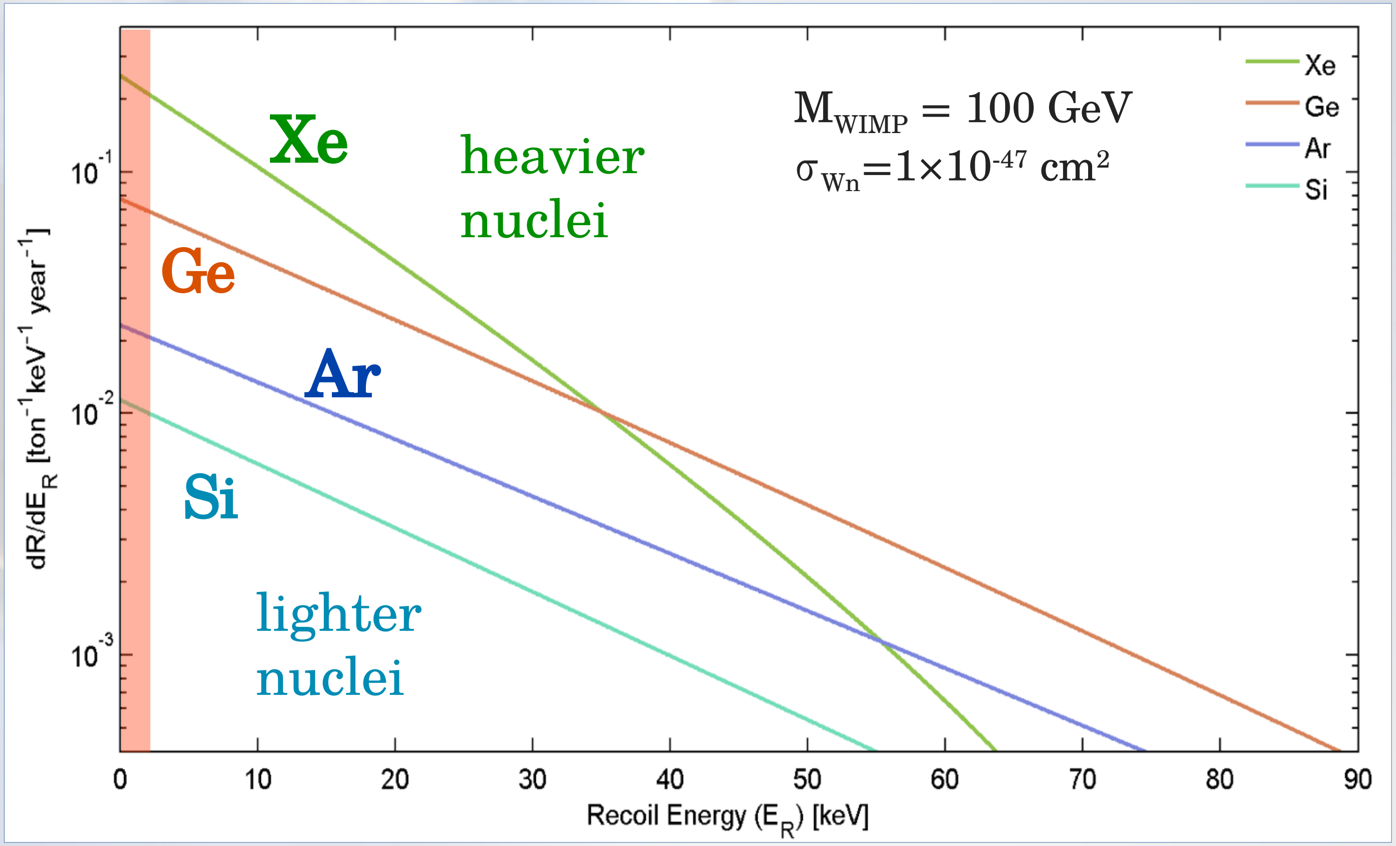
Xenon ~ 130^2

Large detector

Cross section

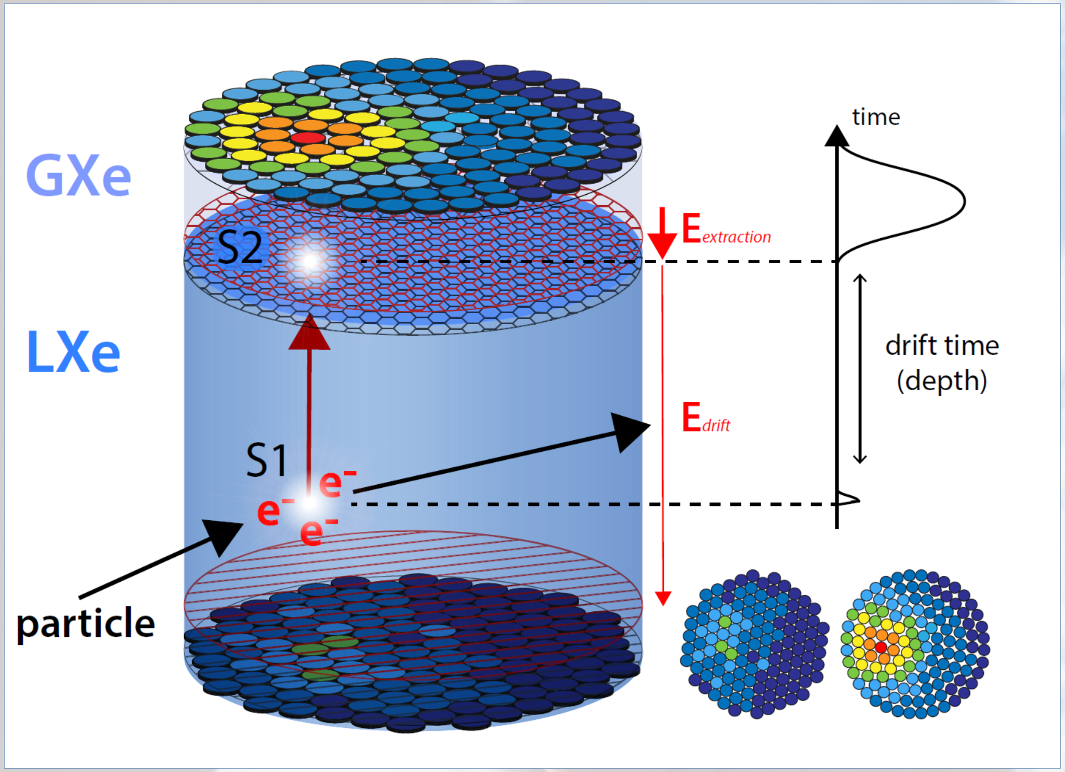
DM Density

- R is total DM scattering rate
- ρ_0 is local DM density
- N is number of nuclei
    - ○ Need many Avogadro's # of atoms
- A is atomic number
    - ○ Points to heavier targets
- σ_{Wn} is WIMP-nucleon cross section

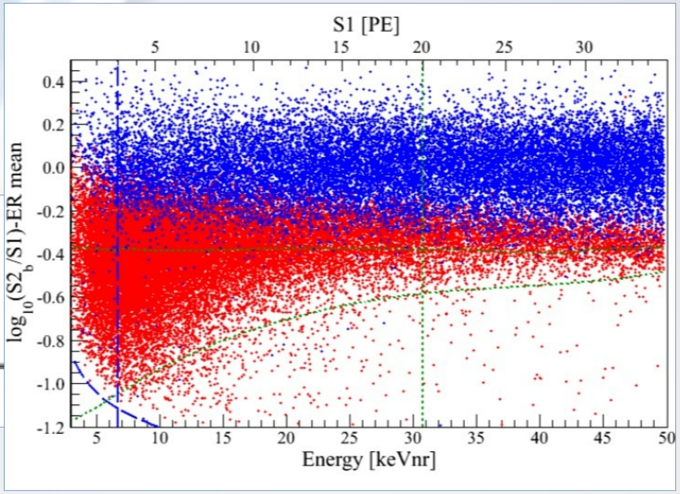


R. Budnik, DSU 2018

Dual Phase TPC – Time Projection Chamber



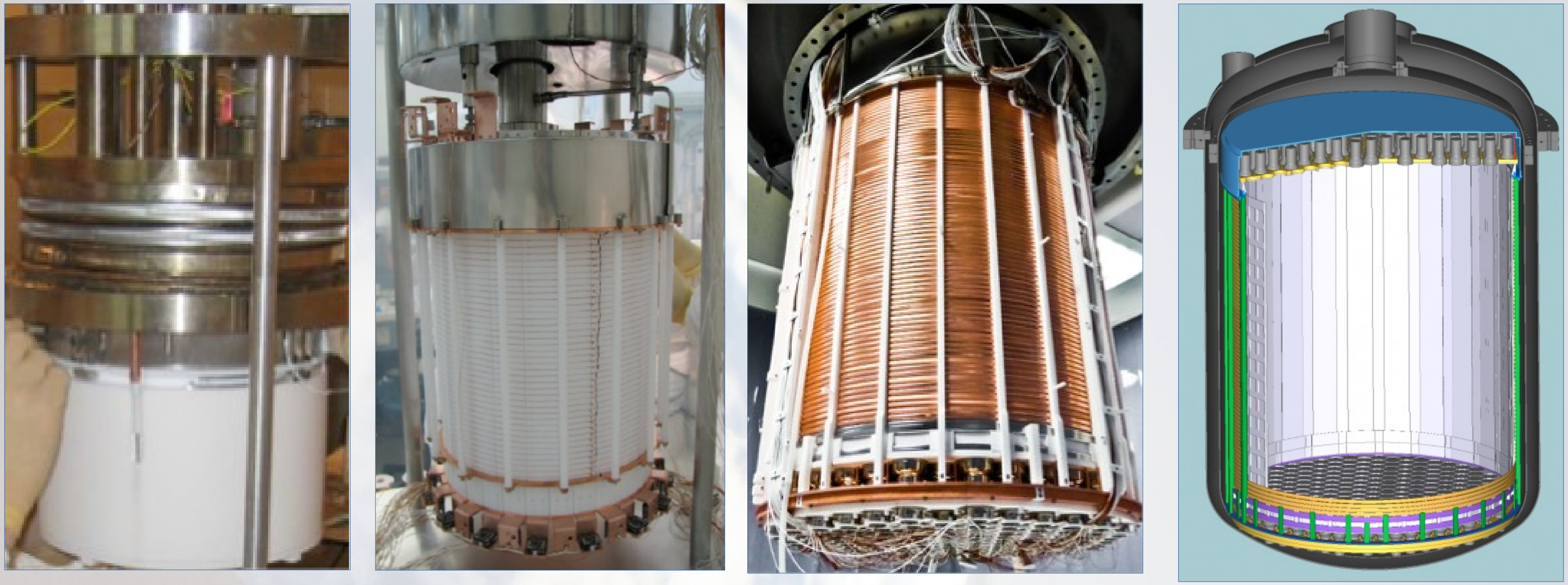
- Prompt scintillation photons give first signal (S1)
- Ionized e- drift up to the anode and amplified, giving S2
- Time difference gives Z position
- S2 Hit pattern on top gives XY position
- Ratio S2/S1 indicates type of interaction



ER

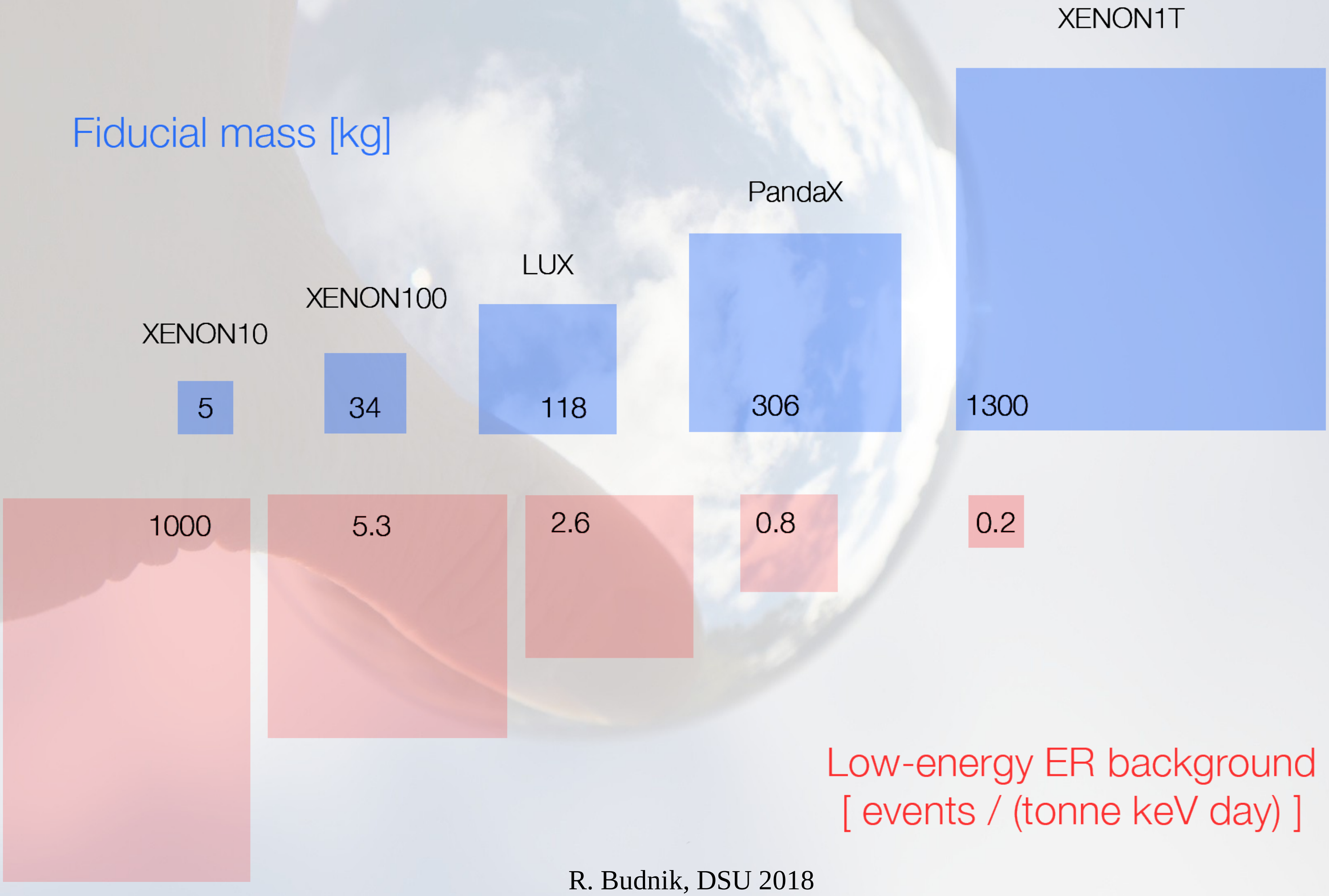
NR

The Phased XENON program

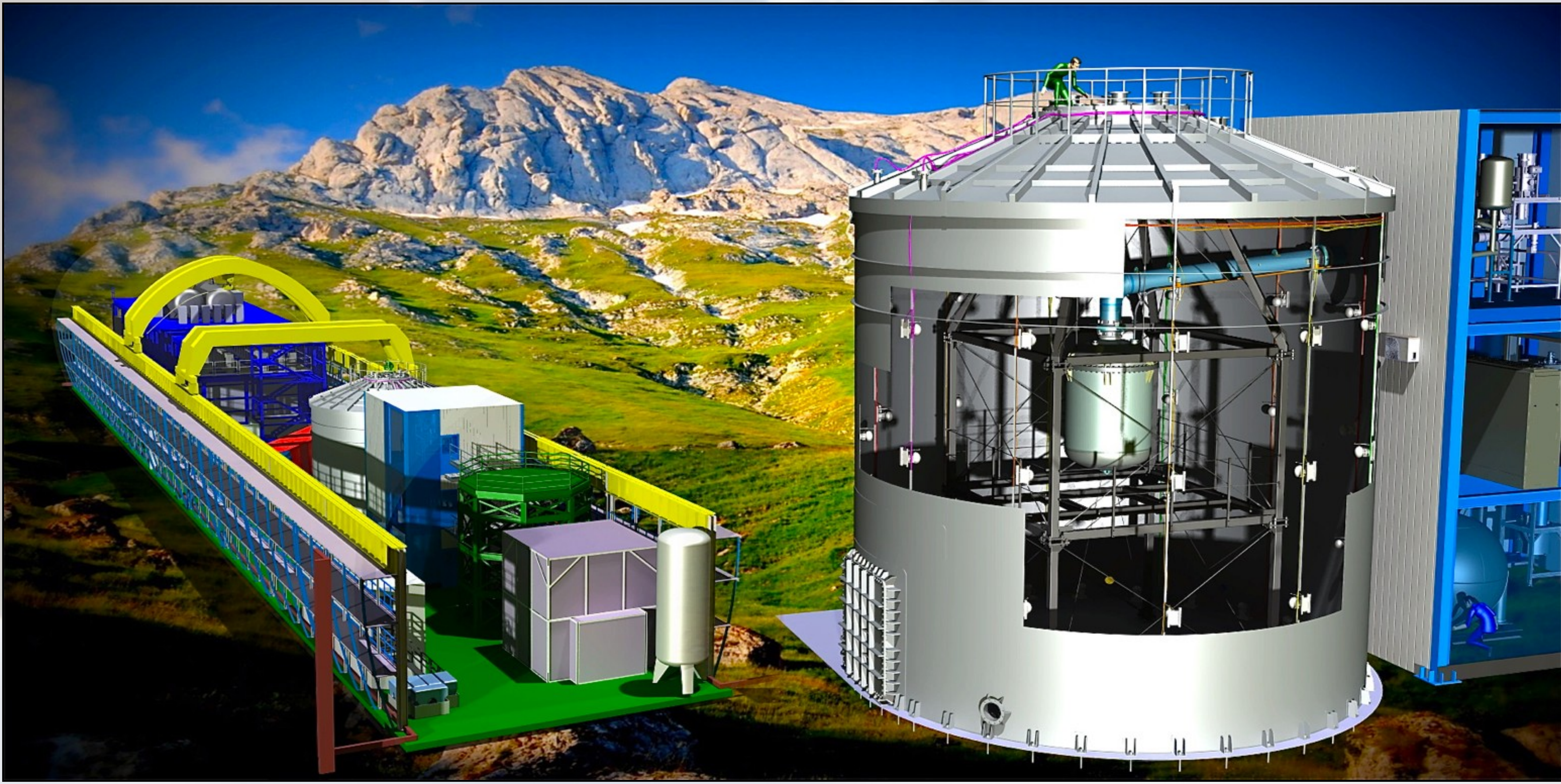


Years	2005-2007	2008-2016	2012-2018	2019-2023
Total mass	25 kg	161 kg	3.2 ton	8 ton
Length	15cm drift	30 cm drift	1 m drift	1.5 m drift
Sensitivity reach	$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	$\sim 10^{-47}$ cm^2	$\sim 10^{-48}$ cm^2

Evolution of LXeTPCs as WIMP detectors



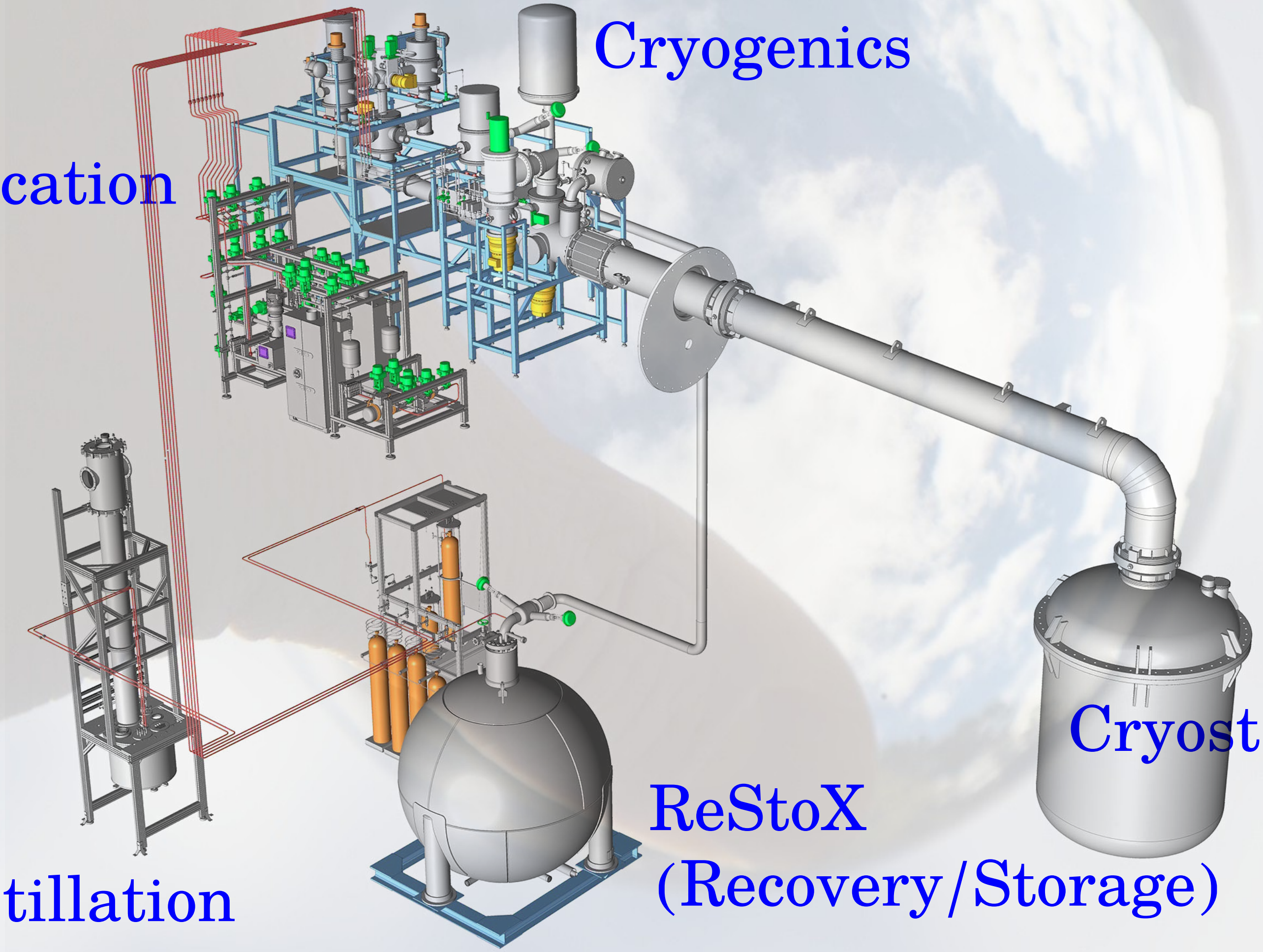
The XENON1T Experiment @ LNGS



XENON1T: All Systems


arXiv:1708.07051

Cryogenic Plants



Slow Control

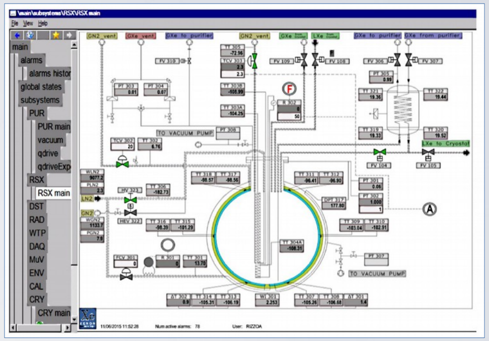
Cryogenics

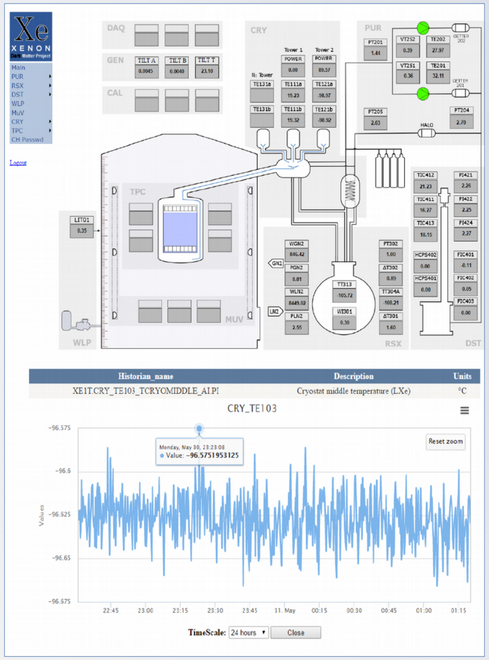
Purification

Distillation

ReStoX
(Recovery/Storage)

Cryostat



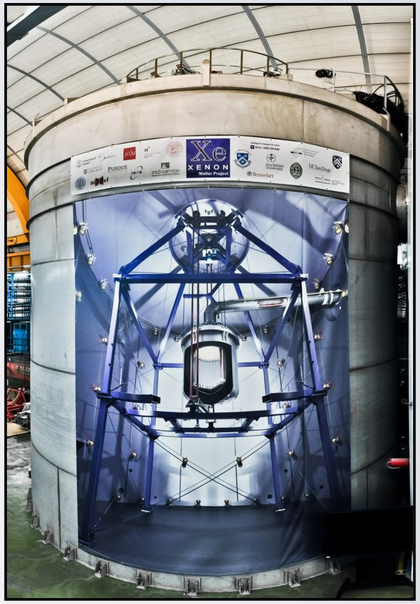


Historian_name	Description	Units
XE1T.CRY_TE103_TCRYOMIDDLE_AI.PI	Cryostat middle temperature (LXe)	°C

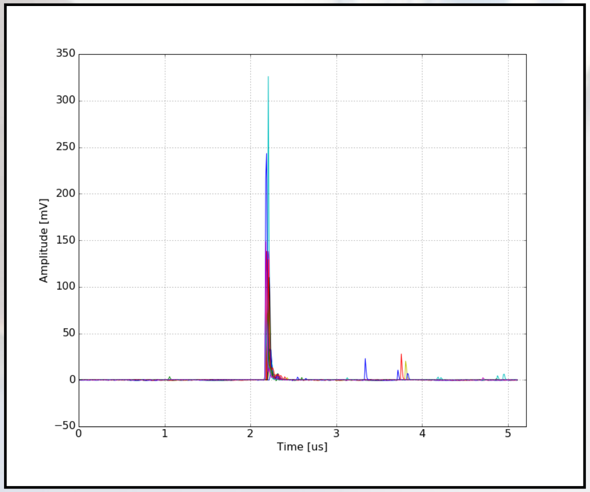
Water Cerenkov μ Veto

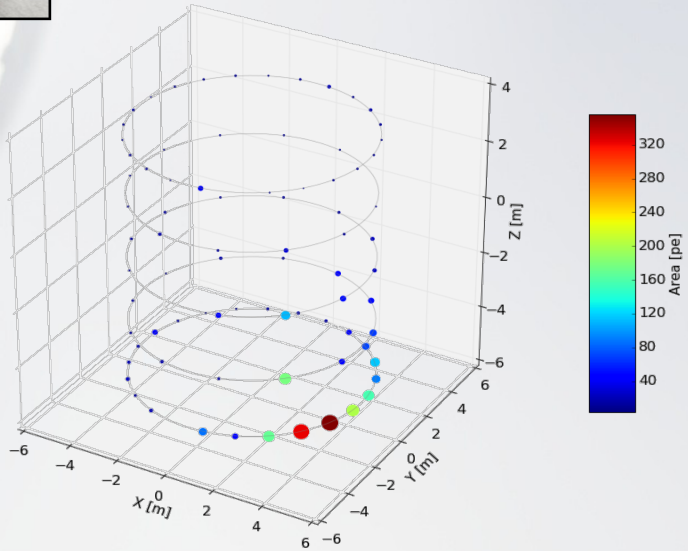
July 2013

July 2016



- 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

3.2 t LXe @180 K

2.0 t active target

viewed by 248 PMTs

~1 meter drift length
~1 meter diameter

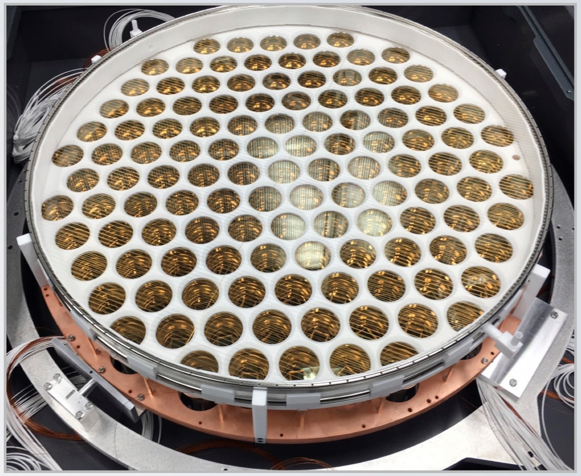
Understanding the Detector

The XENON1T Light Detection System

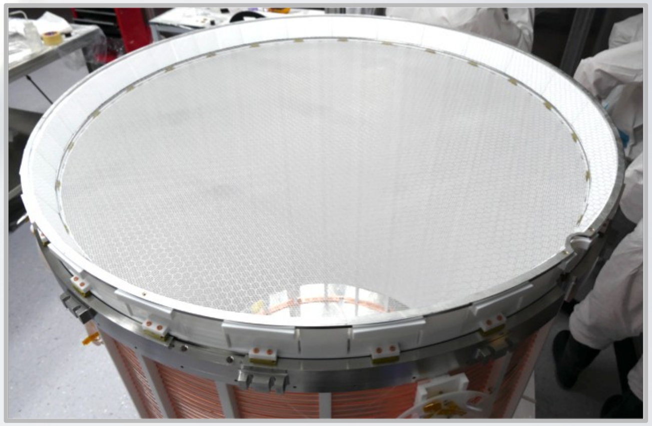
- 248 3-inch low-radioactivity Hamamatsu R11410-21 PMTs arranged in two arrays
- 35% QE @ 178 nm
- each PMT digitized at 100MHz
- operating gain 1-5x10^6 @ 1.5kV stable within 1-2 %
- SPE acceptance ~94%
- High reflectivity PTFE lining of entire inner volume
- Highly-transparent (>90%) grid electrodes

EPJC 75 (2015) 11, 546

127 PMTs in the top array

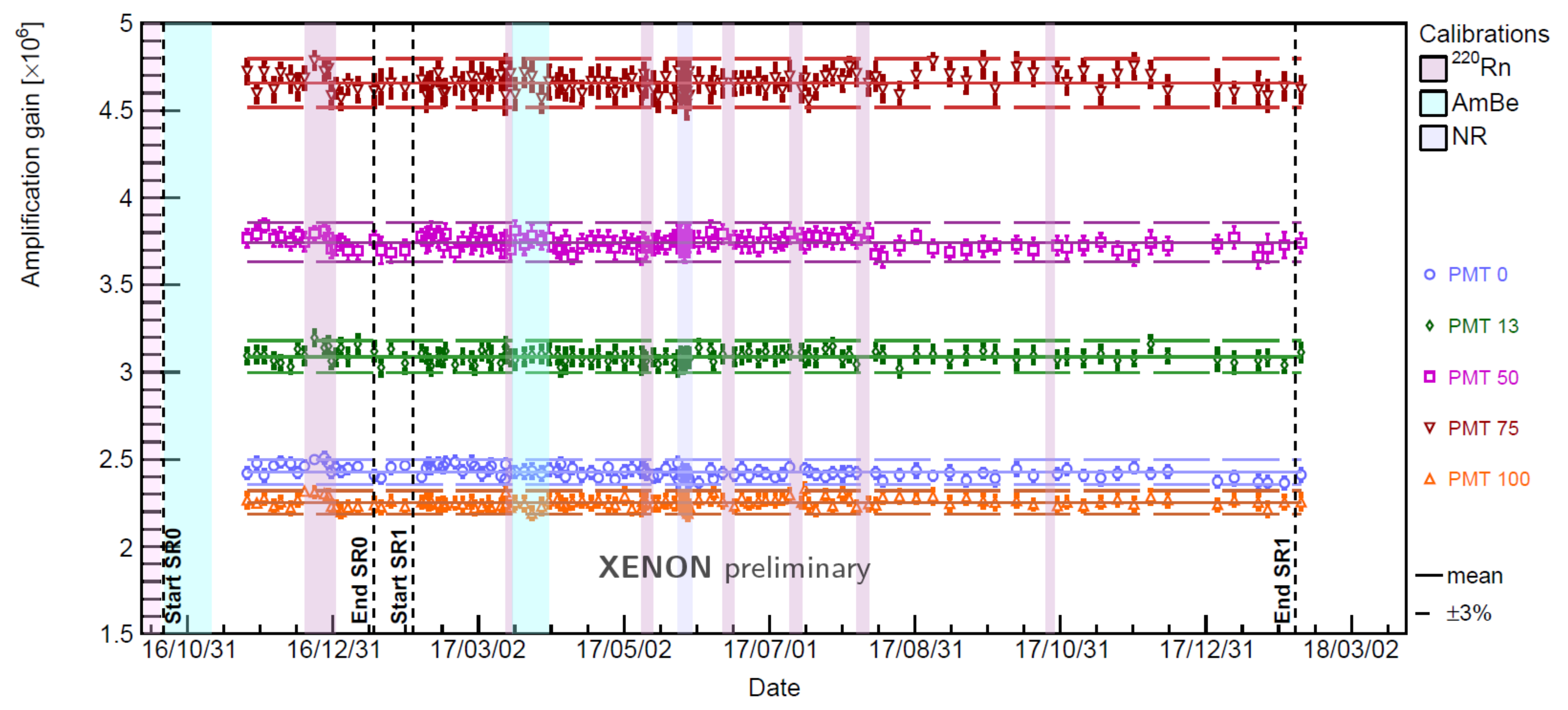


121 PMTs in the bottom array



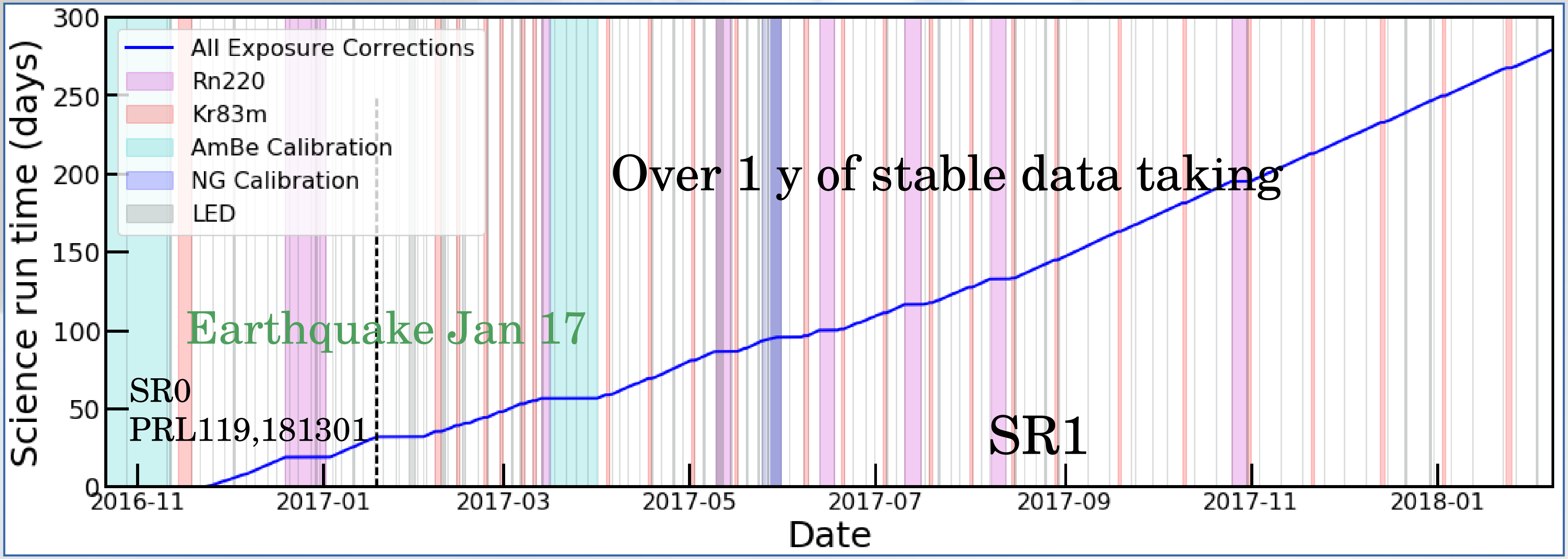
The XENON1T Light Detection System

PMT gain stability



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



Data Analysis: overview

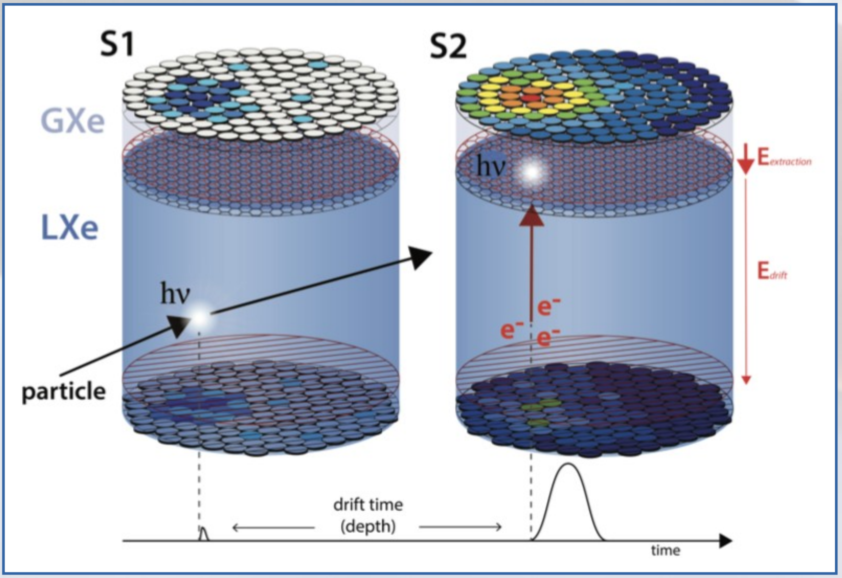
XENON1T (real waveforms)

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**

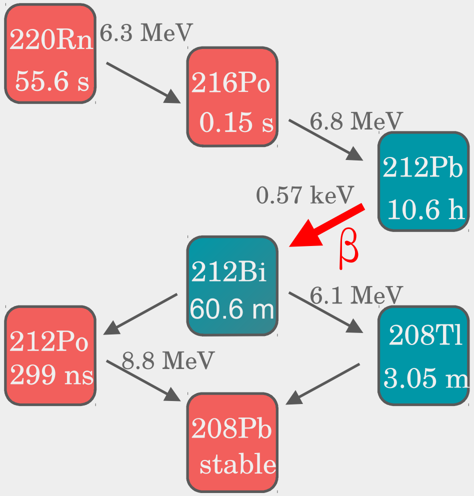


PAX
Processor for Analyzing XENON

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

Calibration Sources

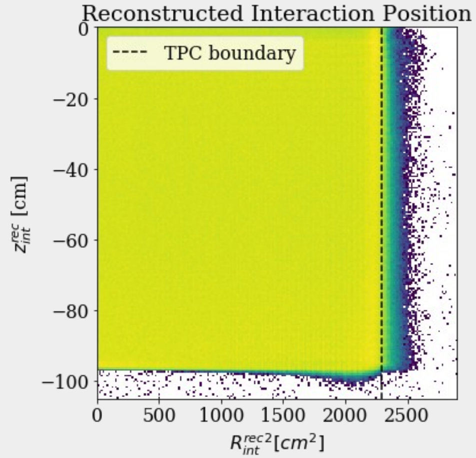
^{220}Rn: Low Energy ER



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

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

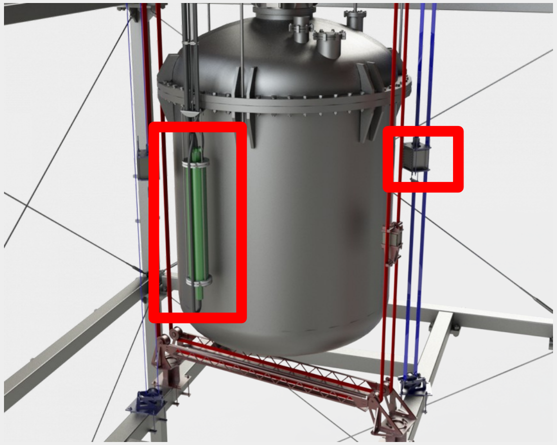
^{83m}Kr: Stability and Monitoring



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

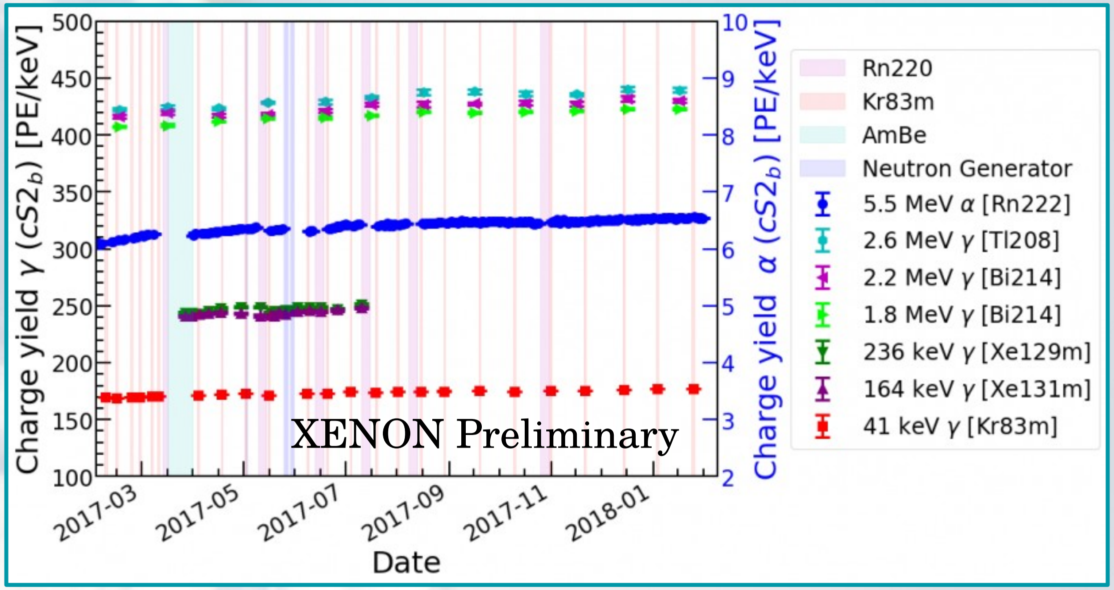
Neutrons: Signal Response

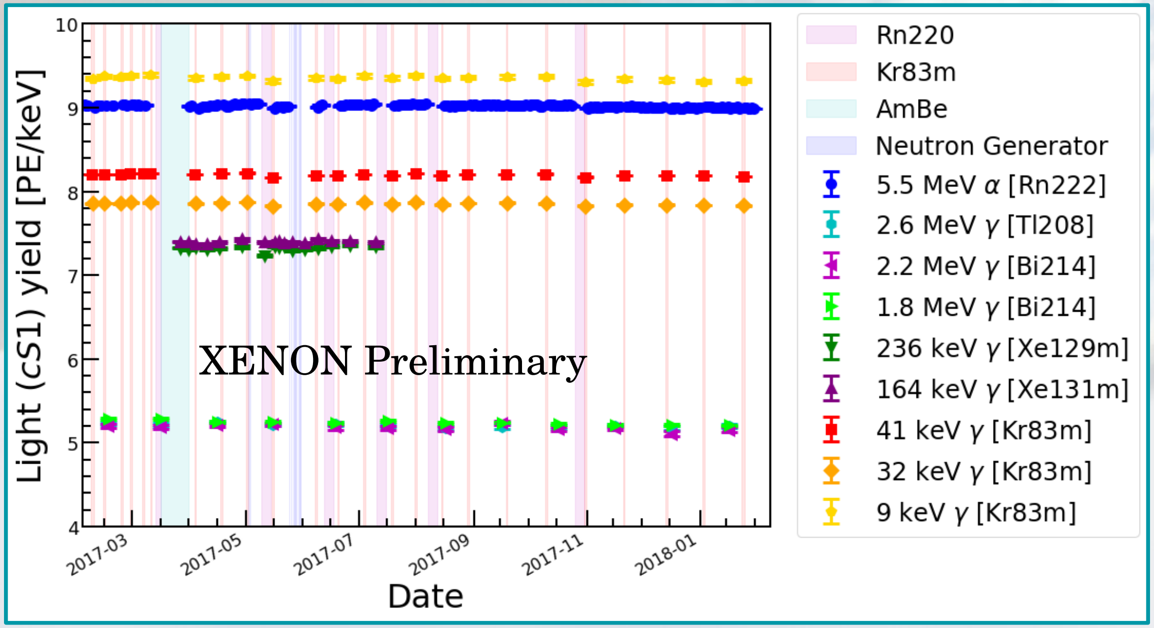


Type: External
Freq: As needed
Length: 6 weeks (AmBe)
2 days (generator)

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 α's.
Excellent agreement with optical Monte Carlo simulations and with model of purity evolution

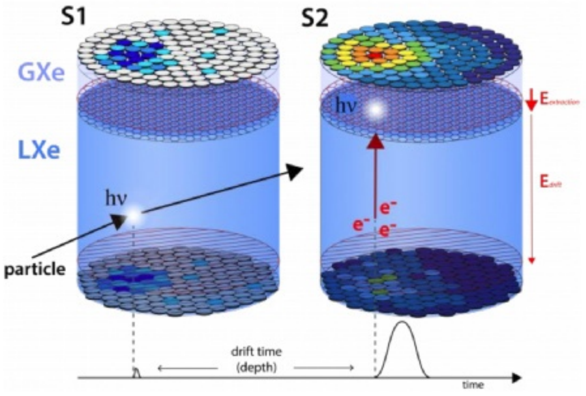




Light and charge yield stability monitored with several sources:

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

Energy Resolution

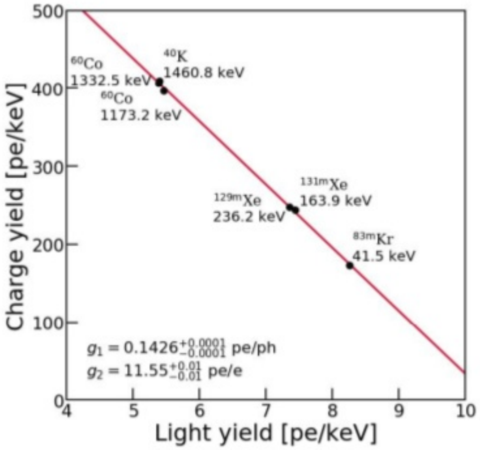


Energy loss to *either* light or charge channel
→ S1/S2 anticorrelation

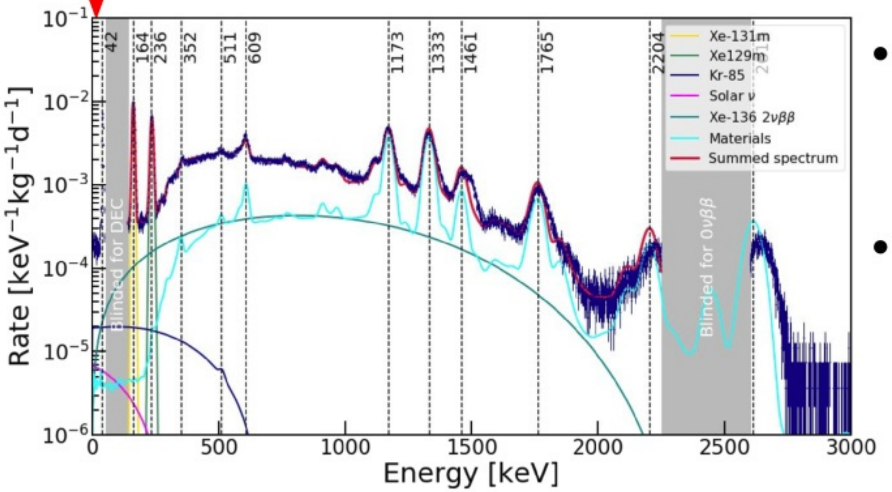
$$\frac{S1}{E} = \frac{n_\gamma}{n_e + n_\gamma} \times \frac{g1}{W}$$

$$\frac{S2}{E} = \frac{n_e}{n_e + n_\gamma} \times \frac{g2}{W}$$

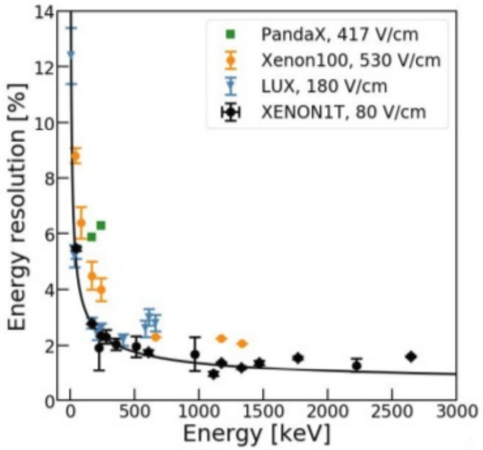
“Doke plot” → linear fit to calibration isotopes



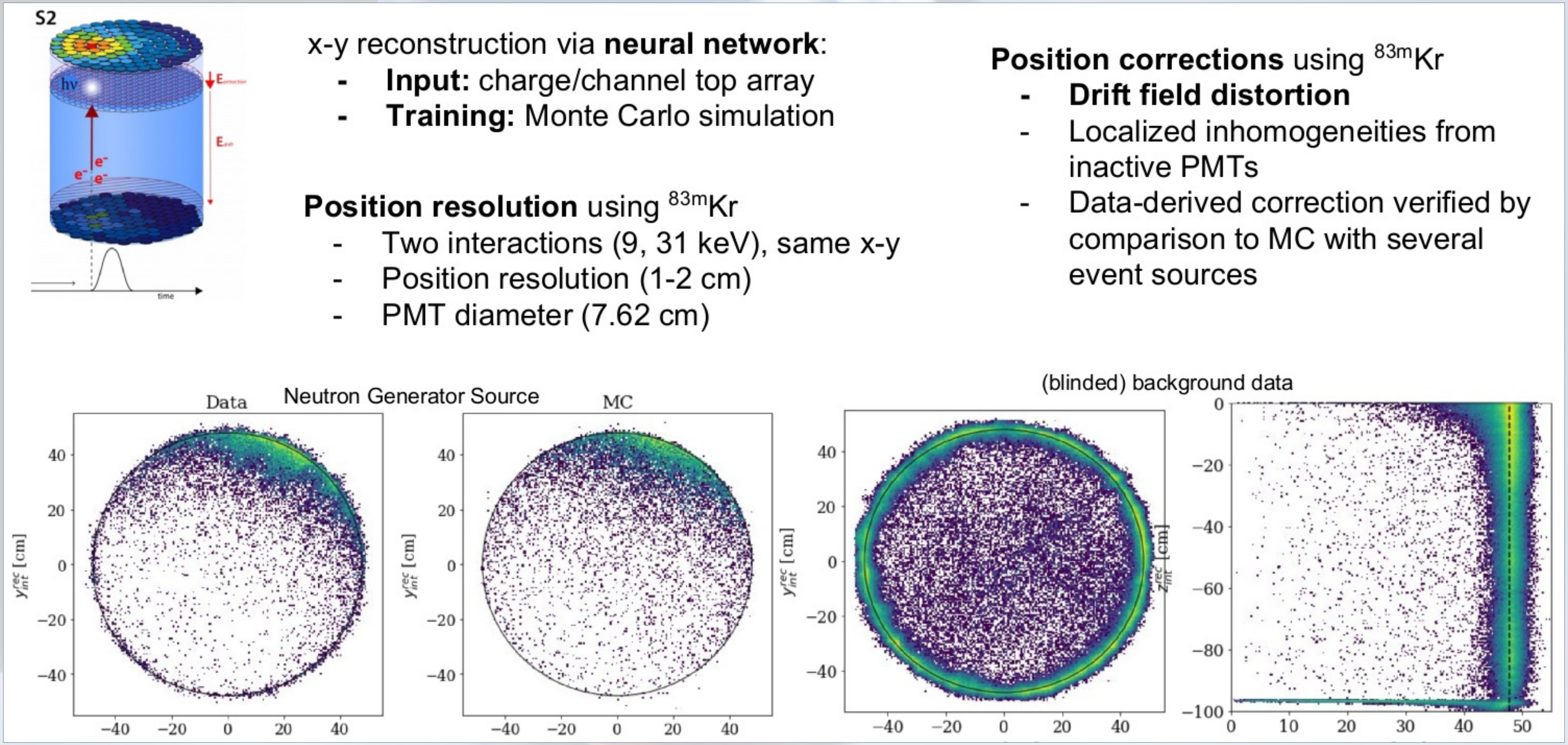
ROI for WIMP search up to ~30 keV



- Solve the above for E for combined energy reconstruction
- Excellent resolution across a broad energy range



Position Reconstruction



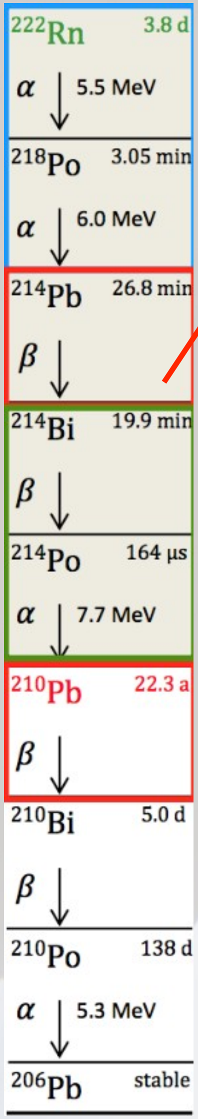
x-y reconstruction via **neural network**:
- **Input:** charge/channel top array
- **Training:** Monte Carlo simulation

Position resolution using ^{83m}Kr
- Two interactions (9, 31 keV), same x-y
- Position resolution (1-2 cm)
- PMT diameter (7.62 cm)

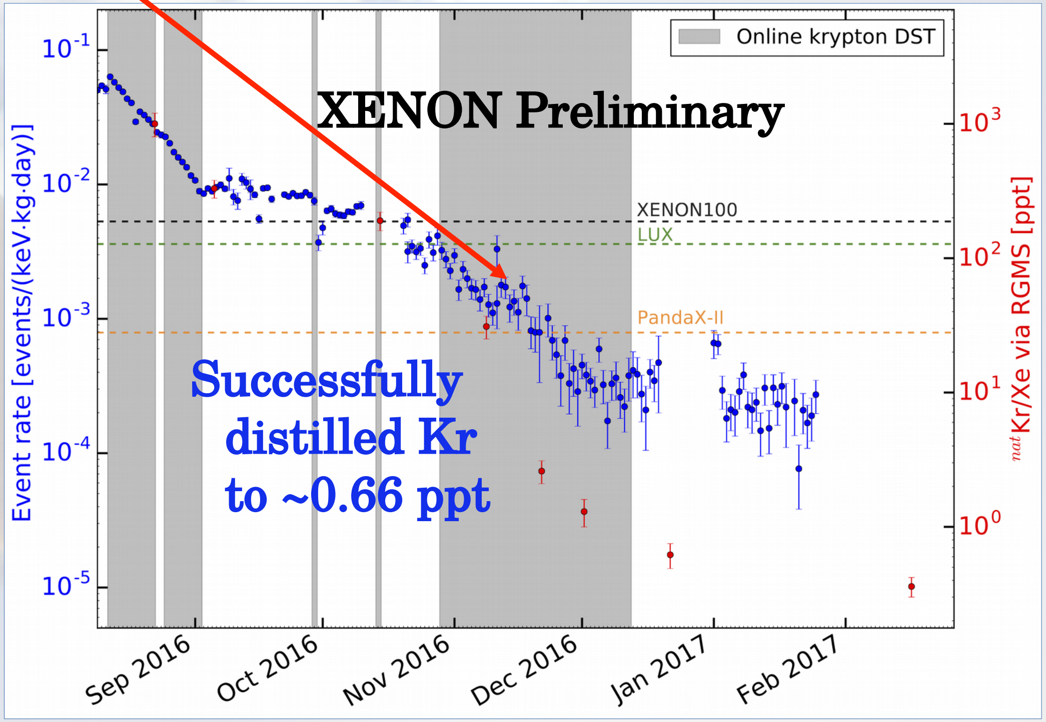
Position corrections using ^{83m}Kr
- **Drift field distortion**
- Localized inhomogeneities from inactive PMTs
- Data-derived correction verified by comparison to MC with several event sources

Understanding the Backgrounds

Electronic Recoil Backgrounds



- Rn222 : 10 μBq/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 γ screening): subdominant



Successfully distilled Kr to ~0.66 ppt

Electronic Recoil Backgrounds

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

JCAP04 (2016) 027

Source	Rate [$t^{-1}\ y^{-1}$]	Fraction [%]
^{222}Rn	620 ± 60	85.4
^{85}Kr	31 ± 6	4.3
Solar ν	36 ± 1	4.9
Materials	30 ± 3	4.1
^{136}Xe	9 ± 1	1.4
Total	720 ± 60	

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

(75 ± 6) events / (t·year·keV)

Measured: in 1300 kg FV and below 25 keVee

(82^{+5}_{-3} (syst)± 2 (stat)) events / (t·year·keV)

Lowest ER background ever achieved in a DM detector!

Nuclear Recoil Backgrounds

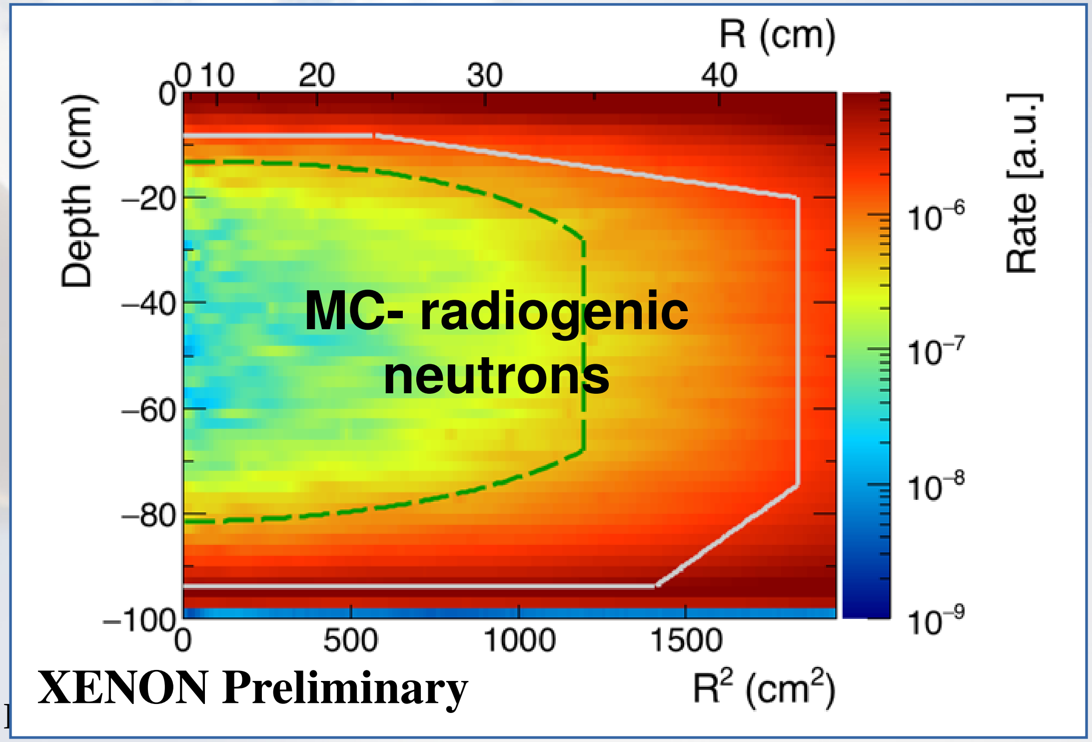
Cosmogenic μ-induced neutrons significantly reduced by rock overburden and muon veto

Coherent elastic ν-nucleus scattering, constrained by ^{8}B neutrino flux and measurements, is an 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)



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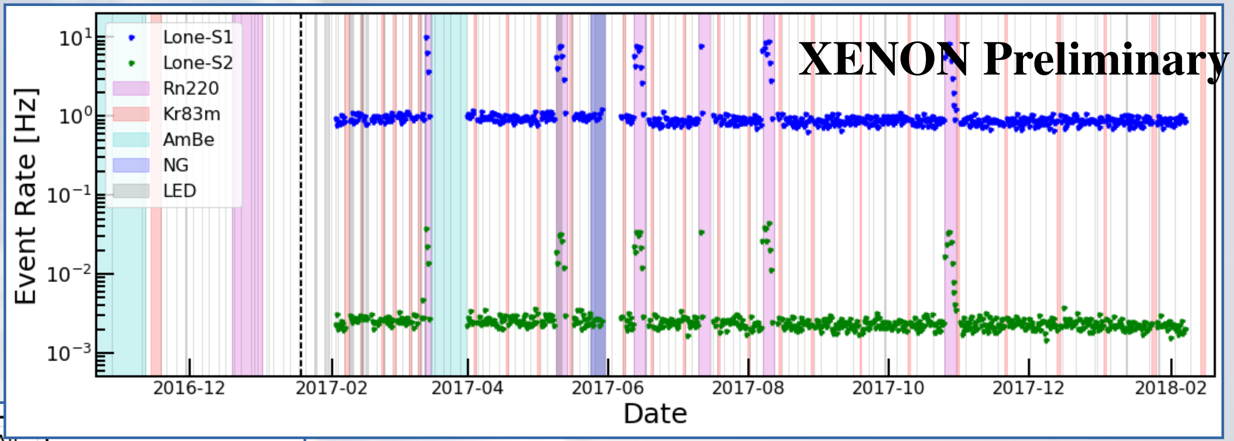
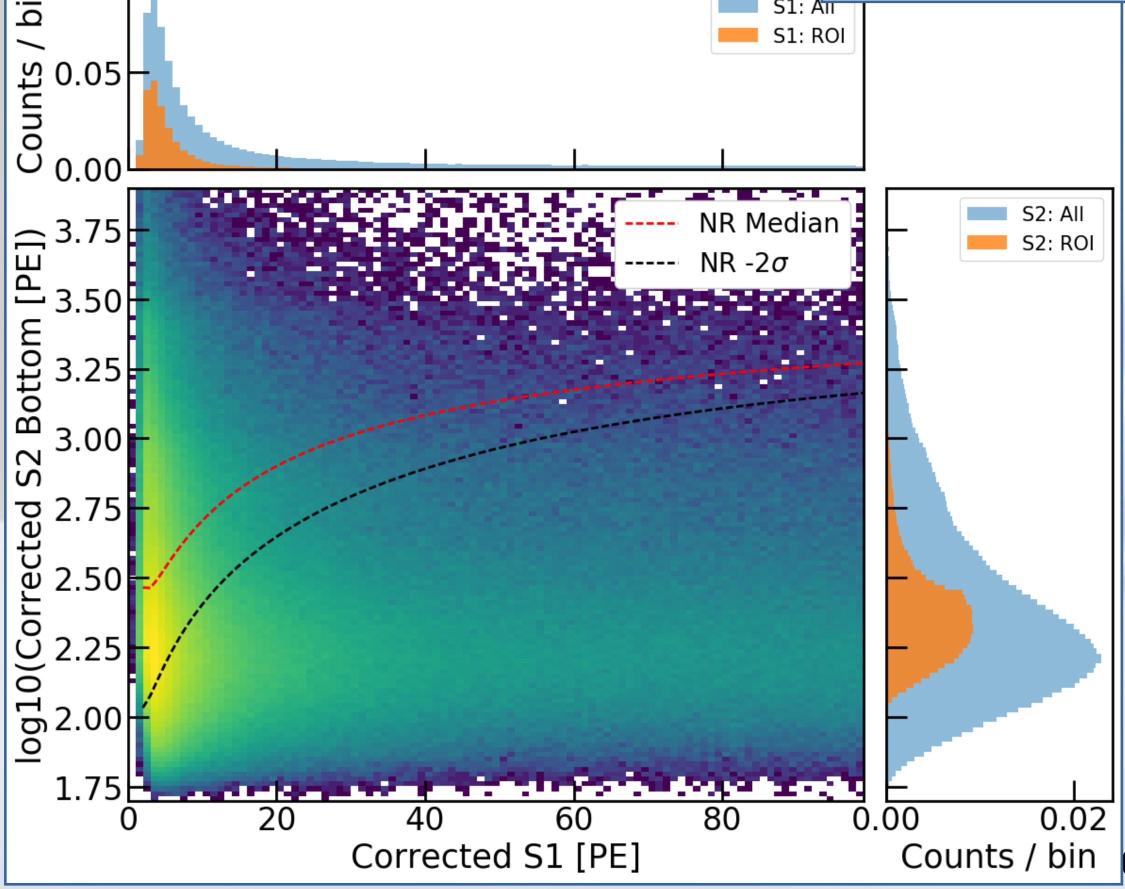
Accidental Coincidence Background

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





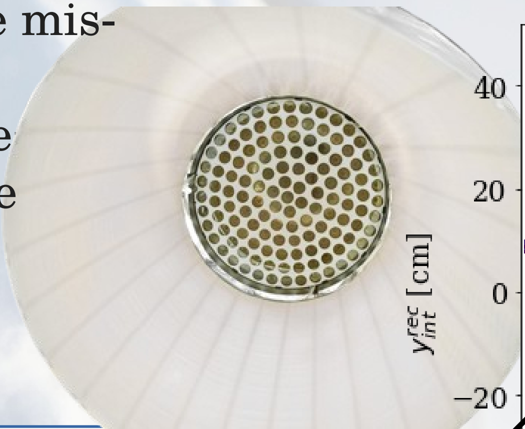
Empirical model shows an overall small rate in the ROI for NRs

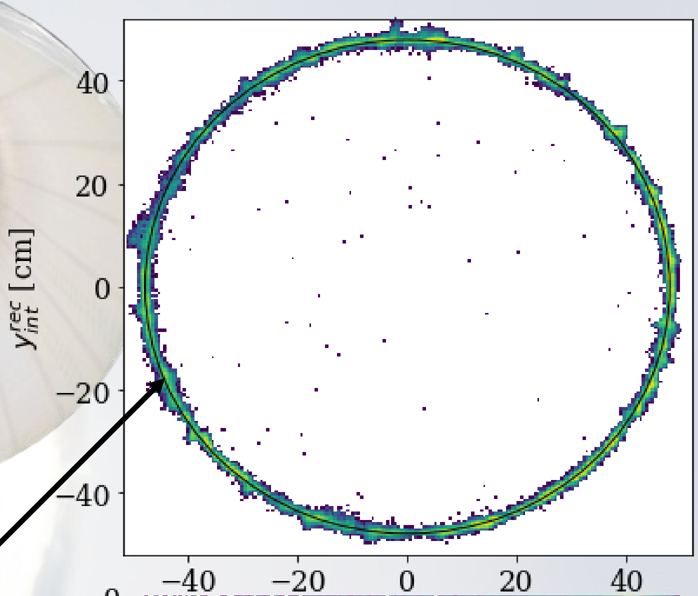
- Select unpaired S1/S2 from data
- Randomly pair to form events
- Apply selection conditions from analysis
- Performance verified with ^{220}Rn data and background sidebands

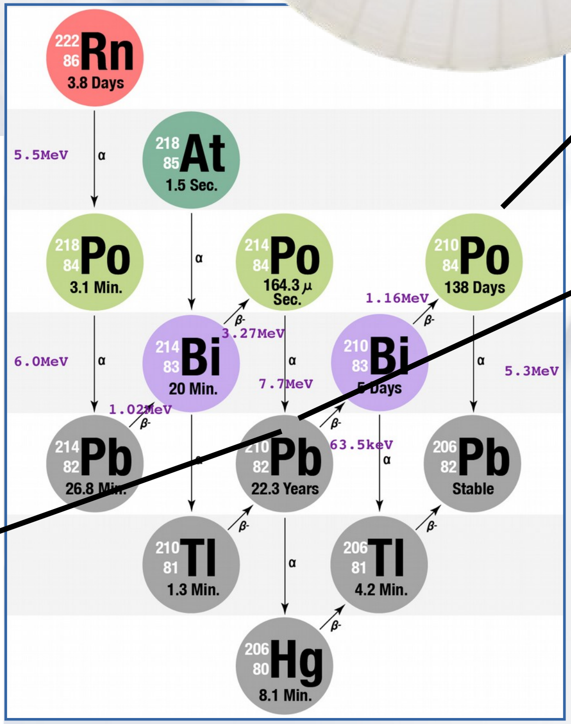
Surface Background

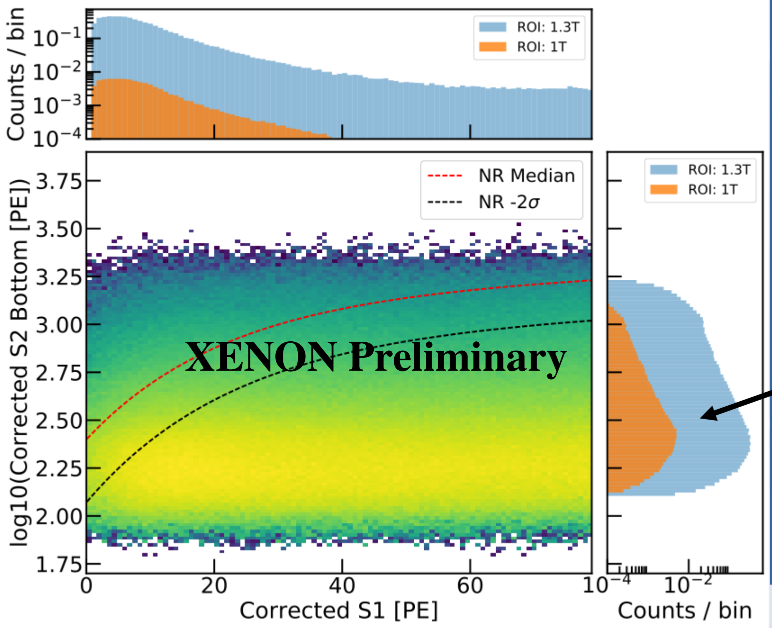
^{210}Pb and ^{210}Po plate-out on PTFE surface produce events with reduced S2 -> can be mis-reconstructed into NR signal region

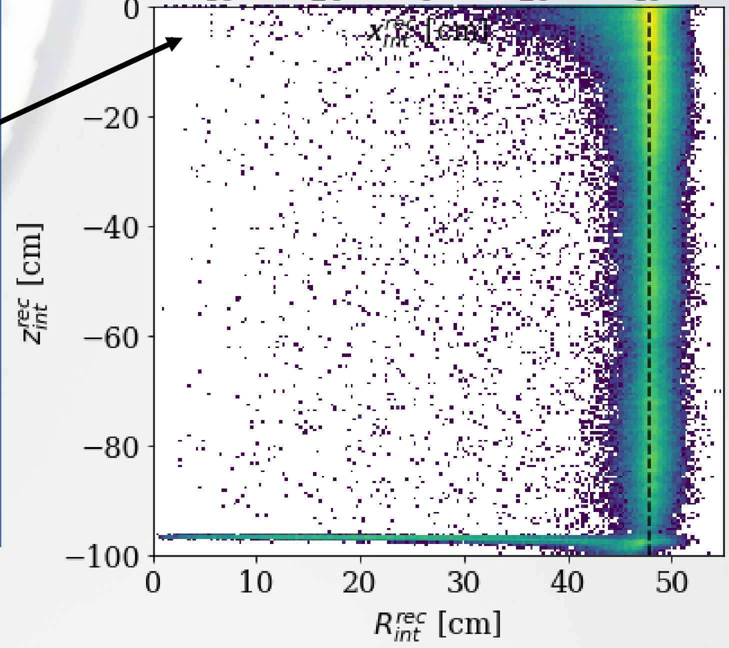
- Suppressed by fiducialization of volume
- Data-driven model derived from surface event control samples





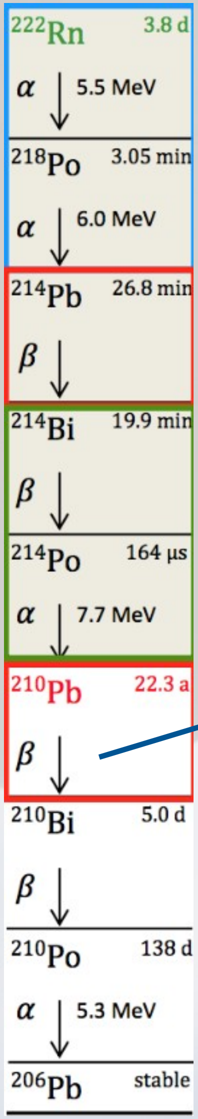


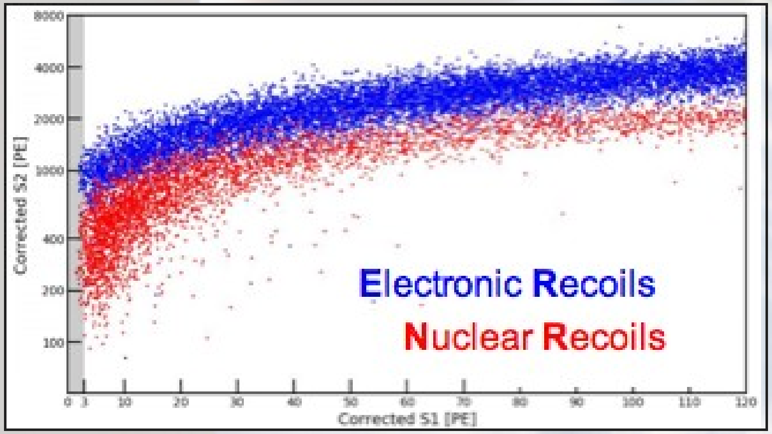


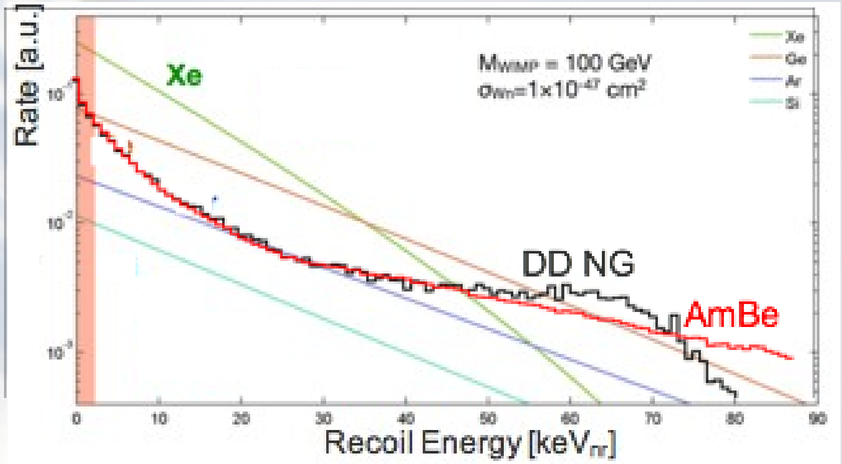


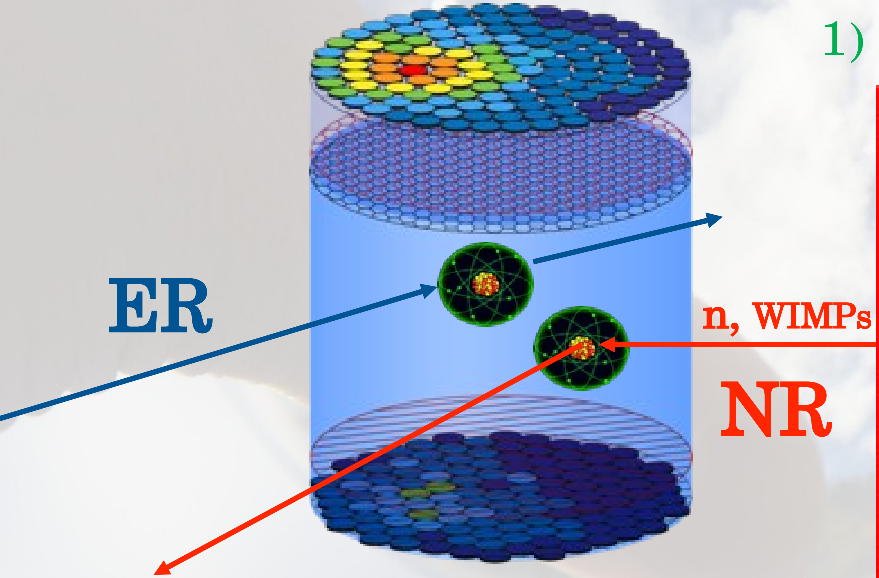
Response to Electronic and Nuclear Recoils

Calibrating ERs and NRs

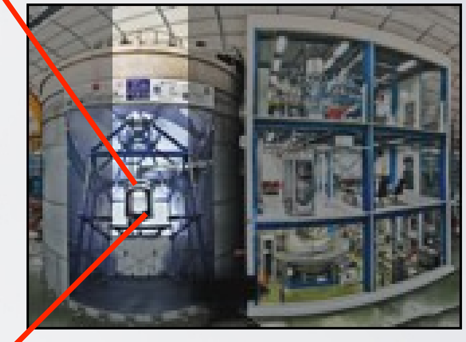






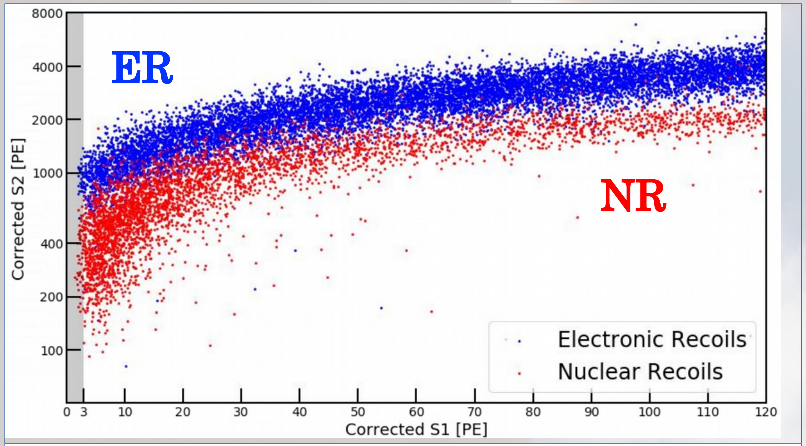


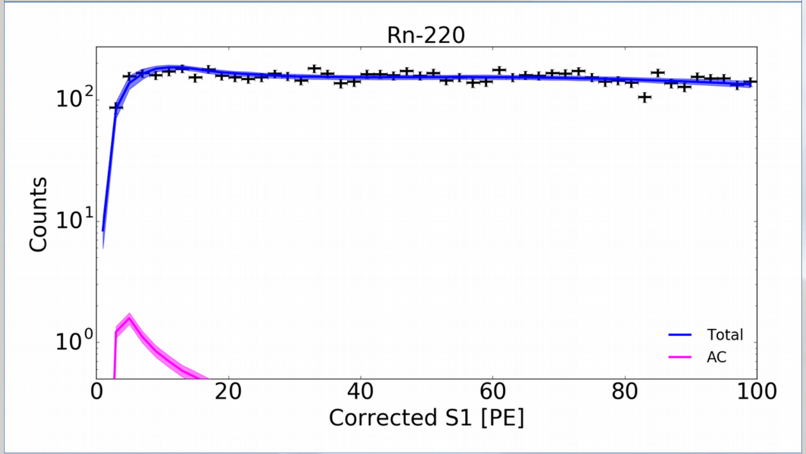
1) DD fusion neutron generator

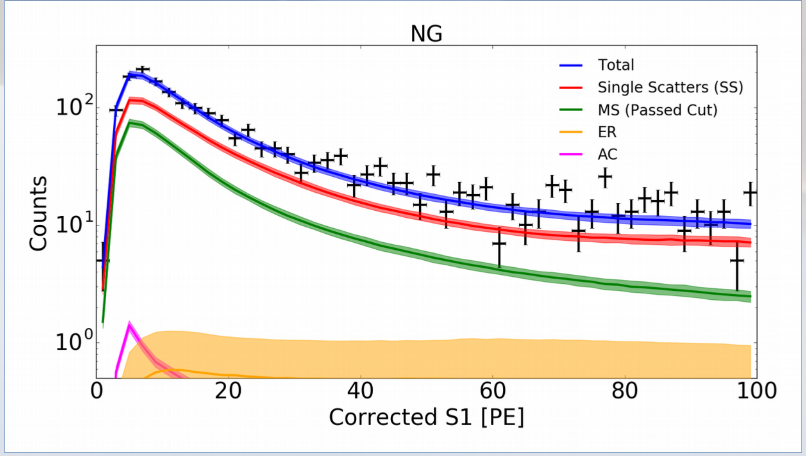


2) AmBe radioactive source

Calibrating ERs and NRs

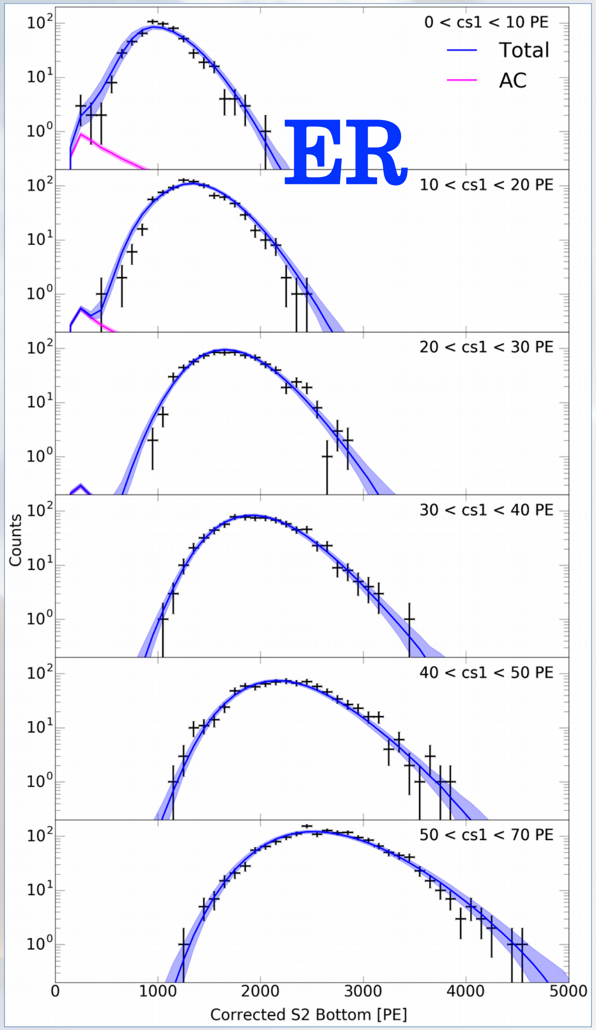


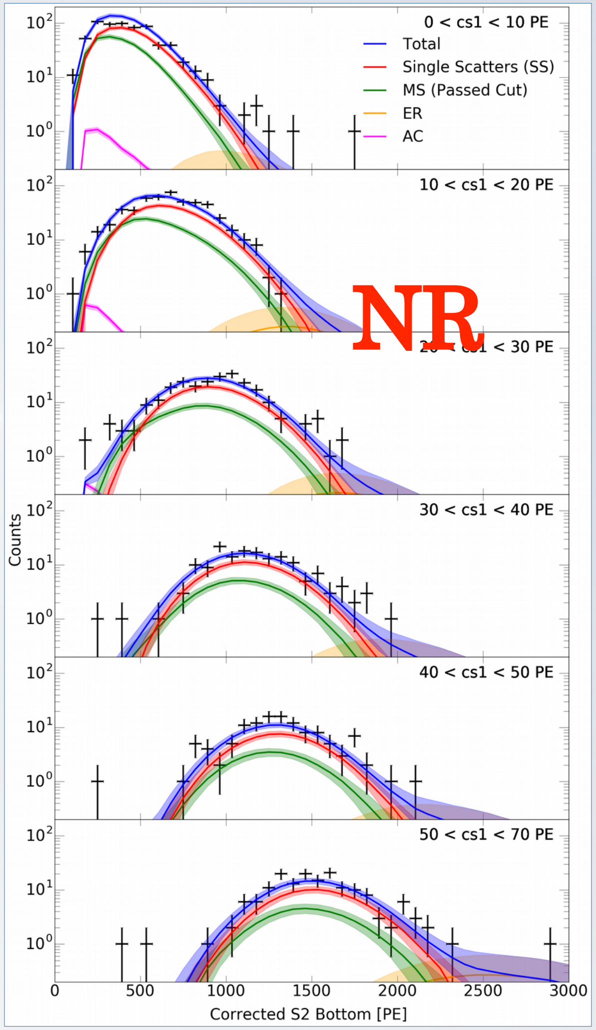




Particle propagation with detailed detector geometry and LXe physics modeled

Parameters tuned and constrained by calibration data



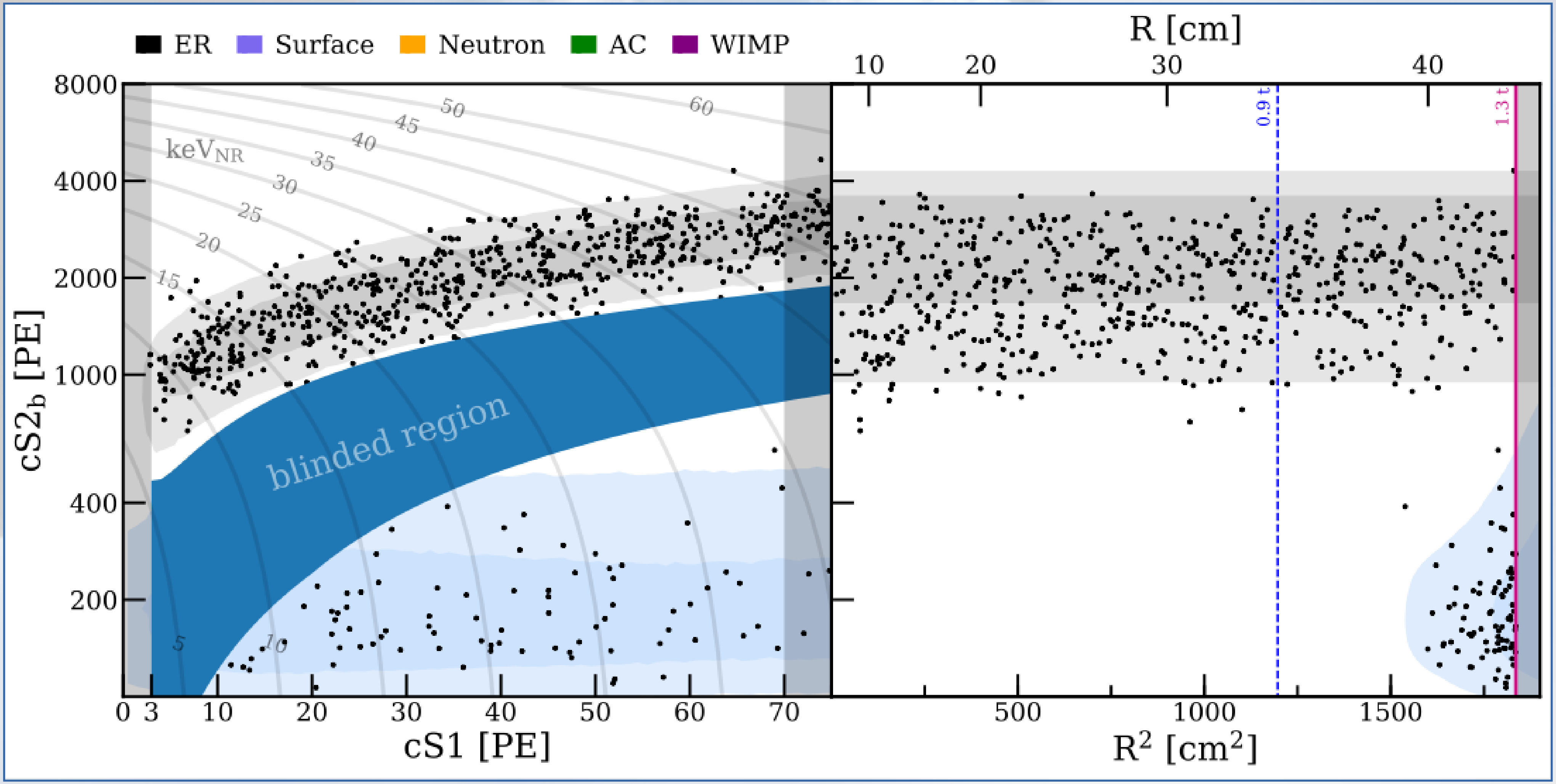


ER rejection: ~99.7% with NR acceptance within [-2σ, median] for both runs.

R. Budnik, DSU 2018

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

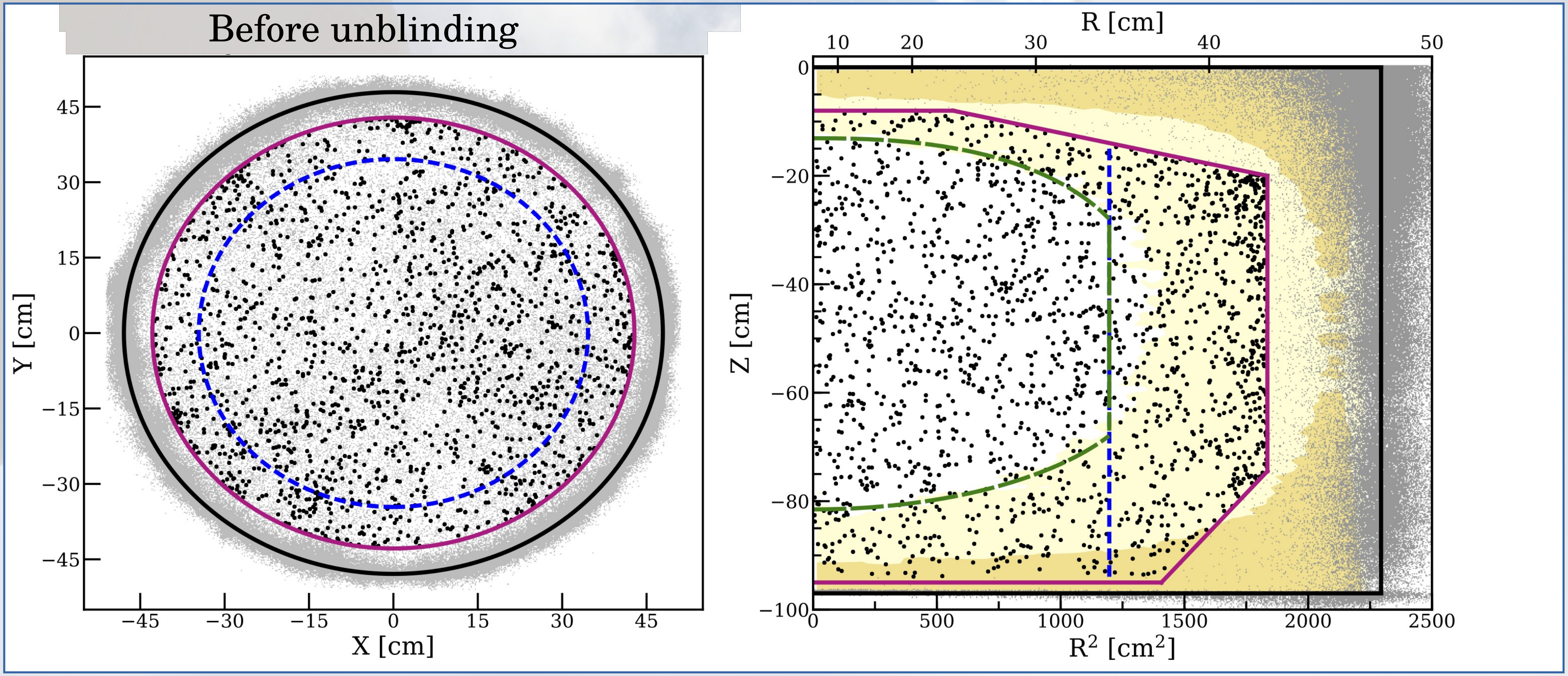


R. Budnik, DSU 2018

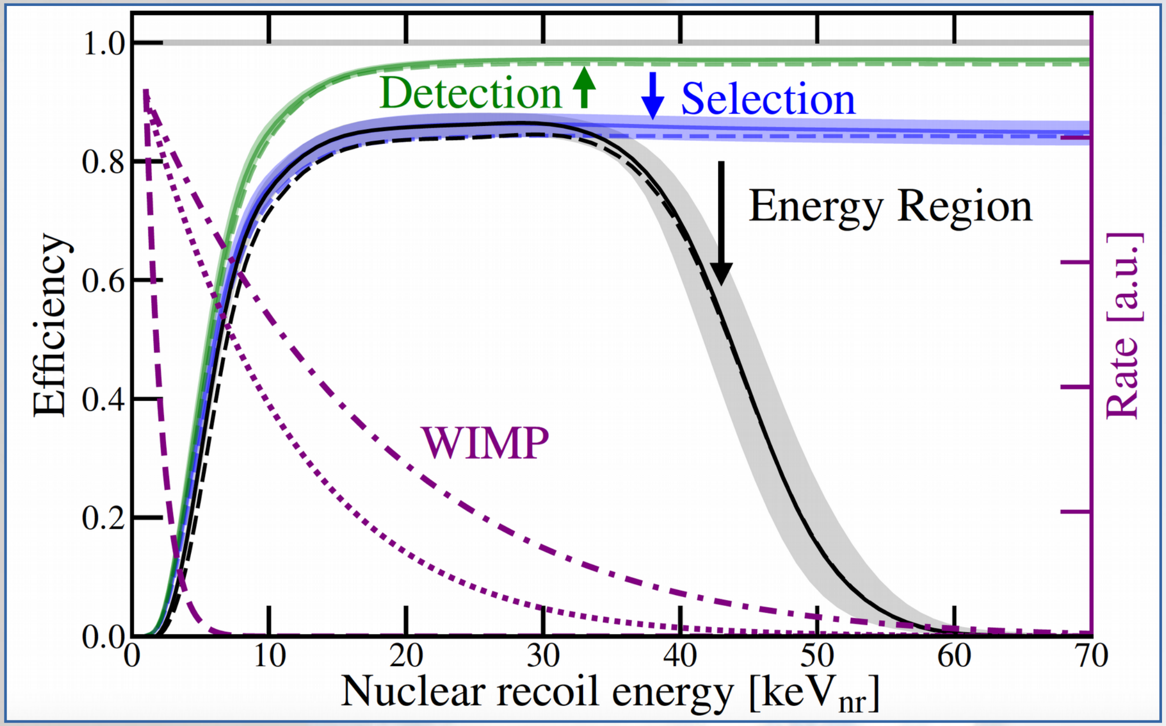
Fiducial Volume Optimization

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


Before unblinding

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

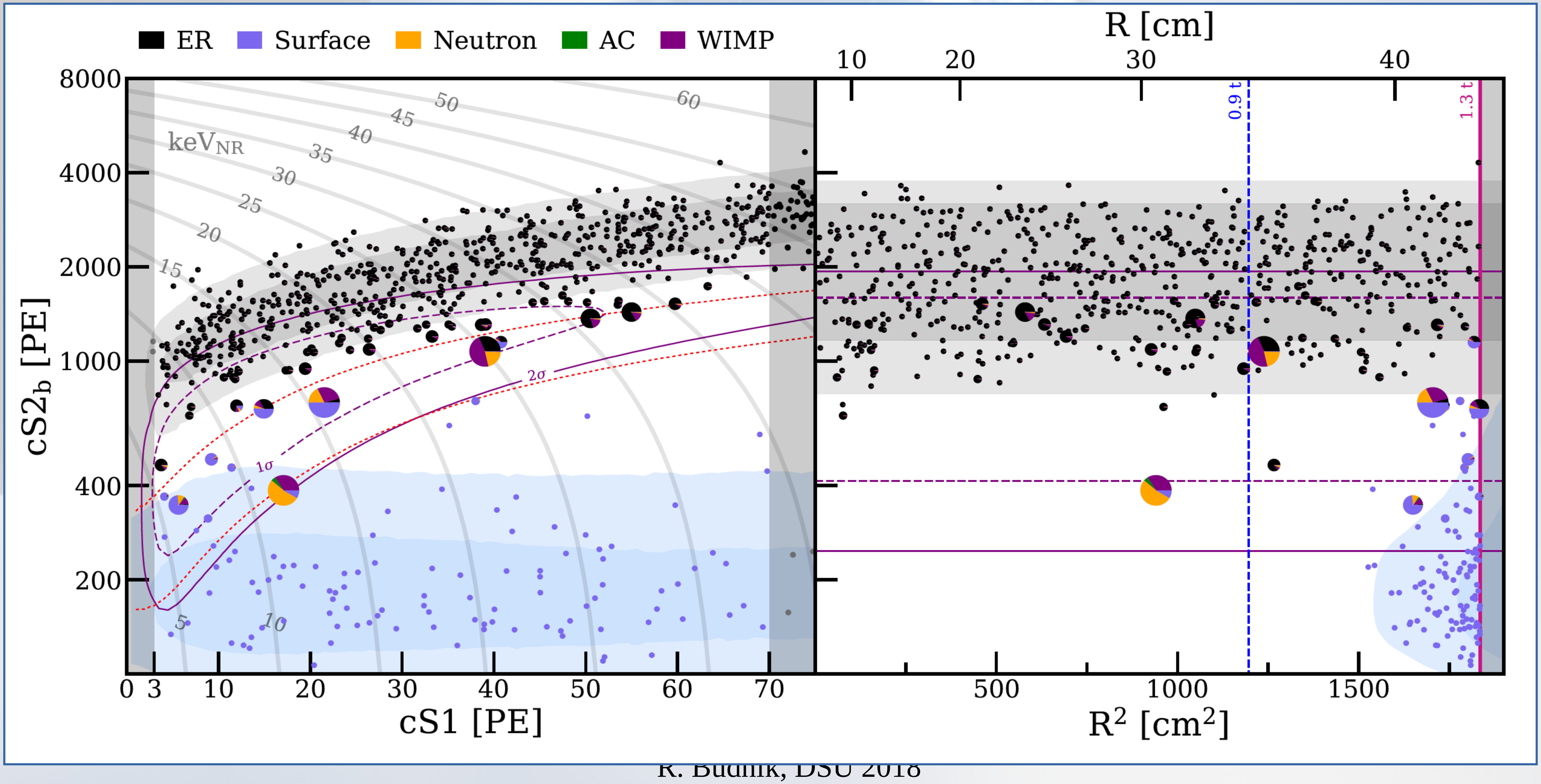
Background prediction and Unblinding

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

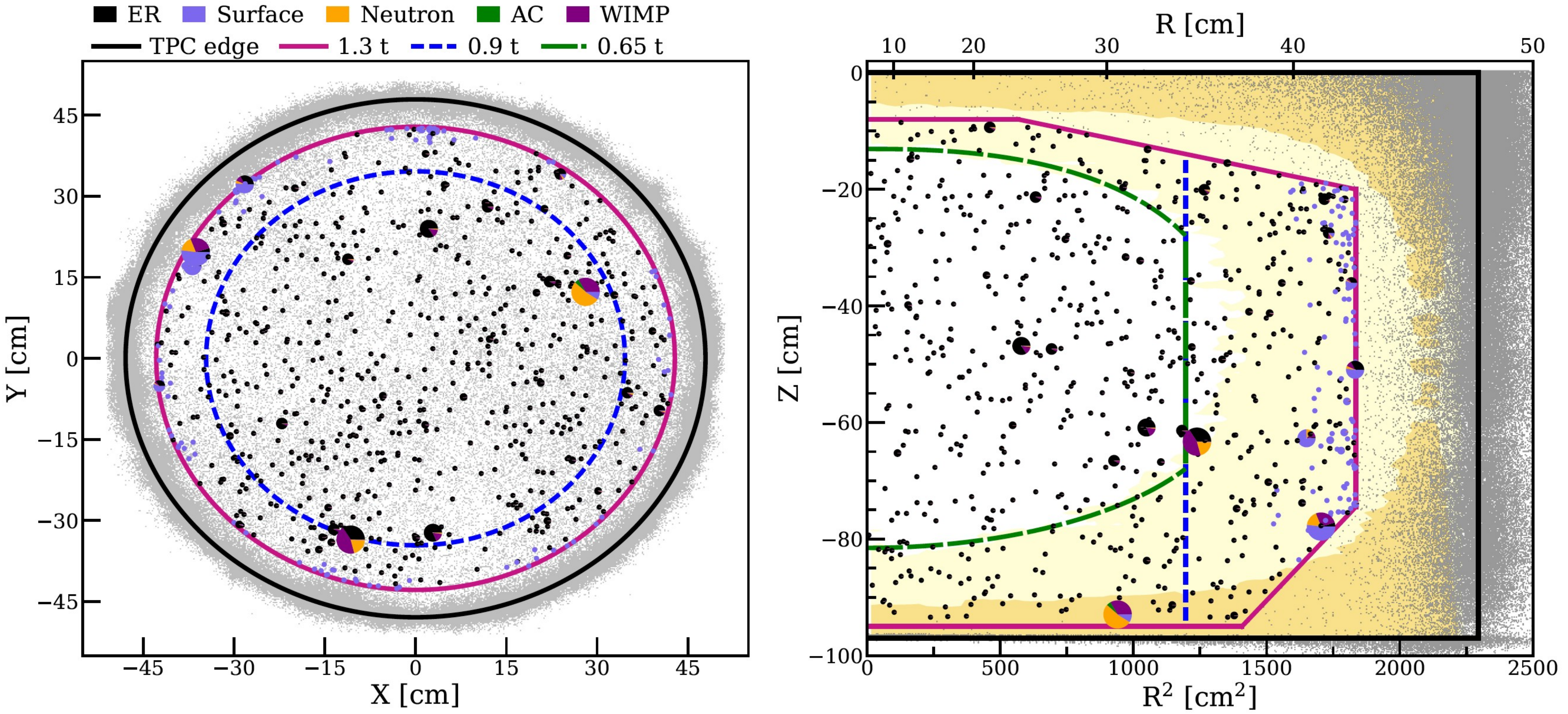
Dark Matter Search Results

- 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 $4.7\text{x}10^{-47}$ cm^2

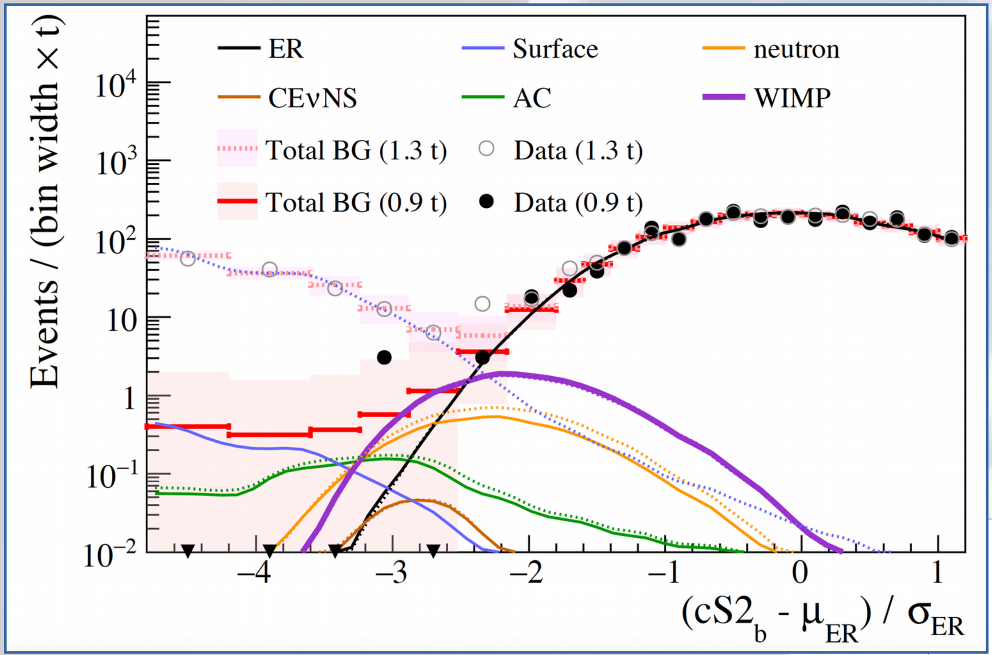


Spatial Distribution of Dark Matter Search Data

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

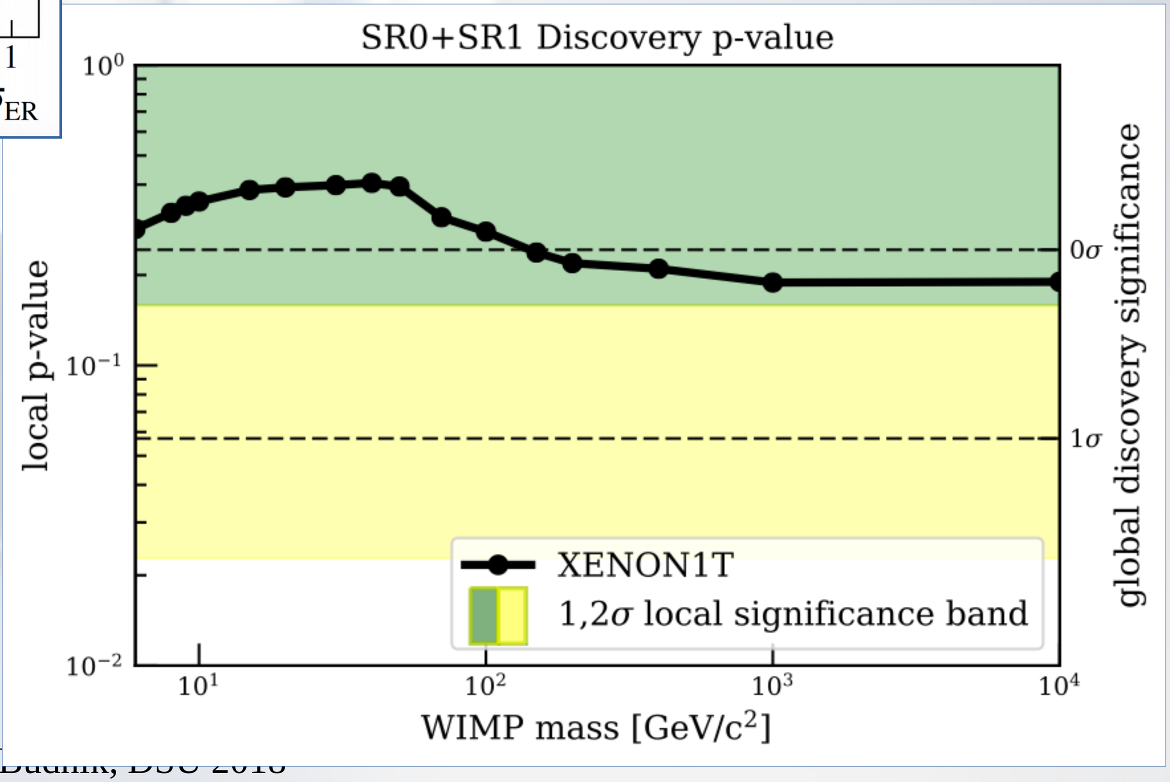


Statistical Interpretation



- 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 ER 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



Safeguard

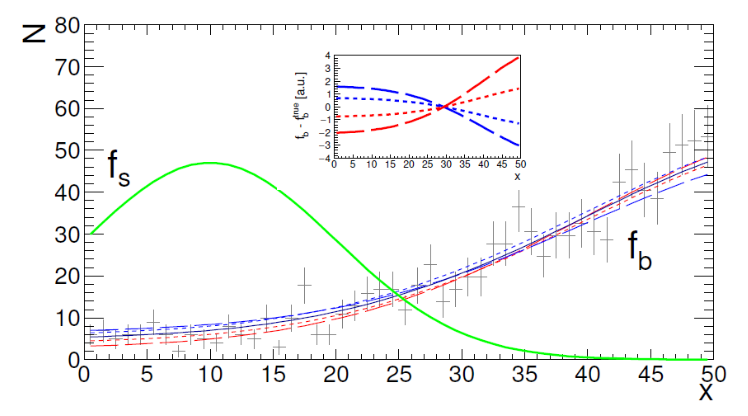
- A term added to the likelihood that incorporates uncertainties in modeling of the background, against calibration
- Accounts for mismodeling of calibrated background
- Gives indication on the quality of modeling
- Prevents ER band leakage mismodeling

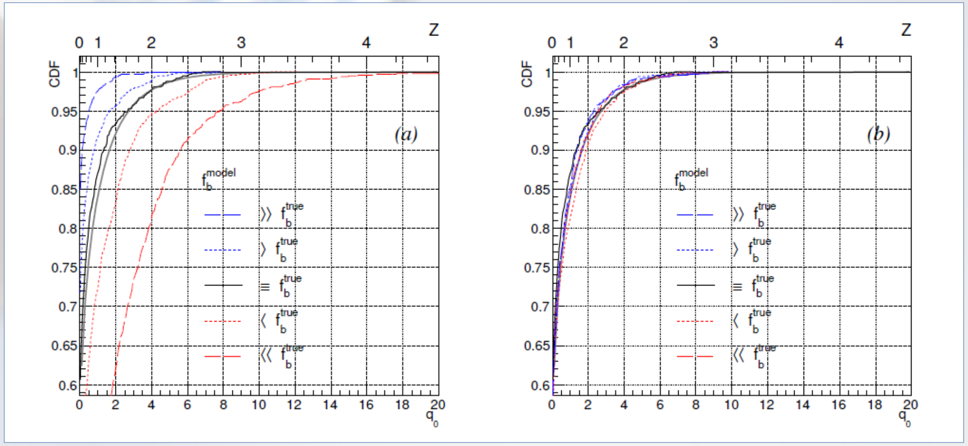
$$\mathcal{L}_{\text{phys}} \times \mathcal{L}_{\text{cal}} = \text{Poiss}(N|N_s + N_b) \prod_{i=1}^{N} \frac{N_s f_s(x_i) + N_b(1-\epsilon) f_b(x_i) + N_b \epsilon f_s(x_i)}{N_s + N_b}$$

Science

$$\times \prod_{i=1}^{N_c} (1-\epsilon) f_b(x_i) + \epsilon f_s(x_i),$$

Calibration





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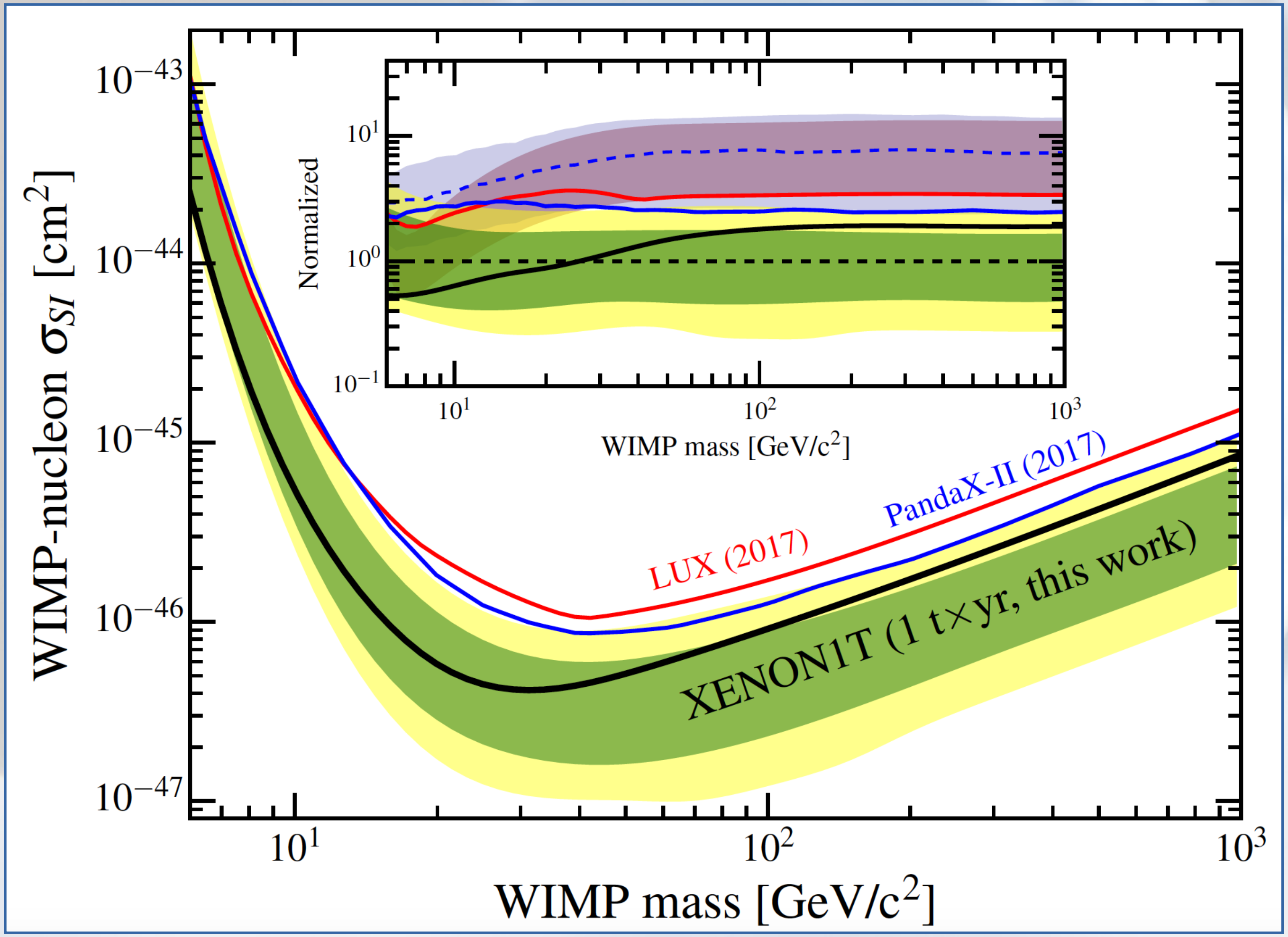
XENON1T Dark Matter Search Results



- 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

More on the plate

- ER low rate and improved energy resolution allow most sensitive searches on many channels (axions, nuclear transitions…)
- EFT, chiral EFT, π-exchange, inelastics and other interpretations of current data
- Extending the range to high E
- Annual modulation
- Low mass searches with alternatice channels (S2-only, Migdal effect…)

XENONnT – Swift upgrade

x4

1/10

MINIMAL UPGRADE

XENON1T infrastructure and sub-systems originally designed for a larger LXe TPC

FIDUCIAL XE TARGET

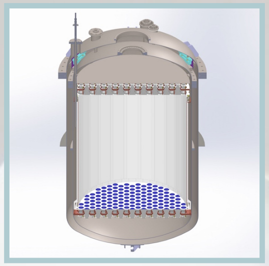
Fiducial mass: ~4 t
Target LXe mass: 5.9 t
Total LXe mass: 8 t

BACKGROUND

Identified strategies to reduce ^{222}Rn backgorund by a factor ~10

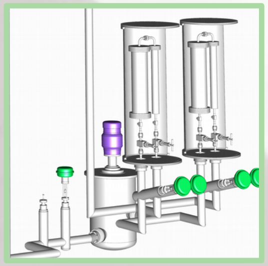
FAST TURNAROUND

Installation starts in 2018
Commissioning in 2019



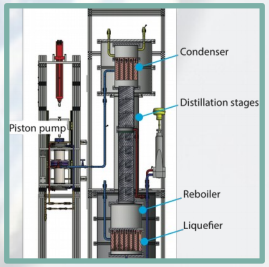
NEW TPC

Larger inner cryostat
476 PMTs



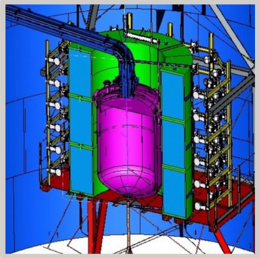
LXe PURIFICATION

Faster cleaning of large LXe volume (5000 SLPM)



RADON DISTILLATION

Online removal of ^{222}Rn emanated inside the detector

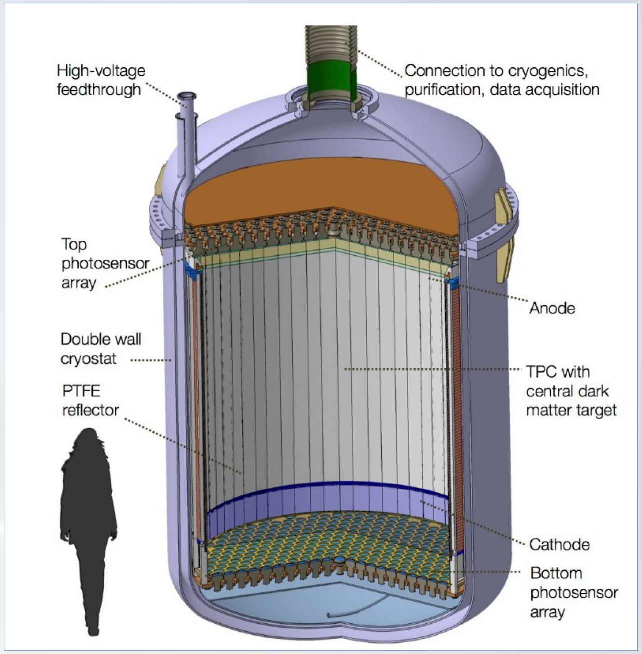


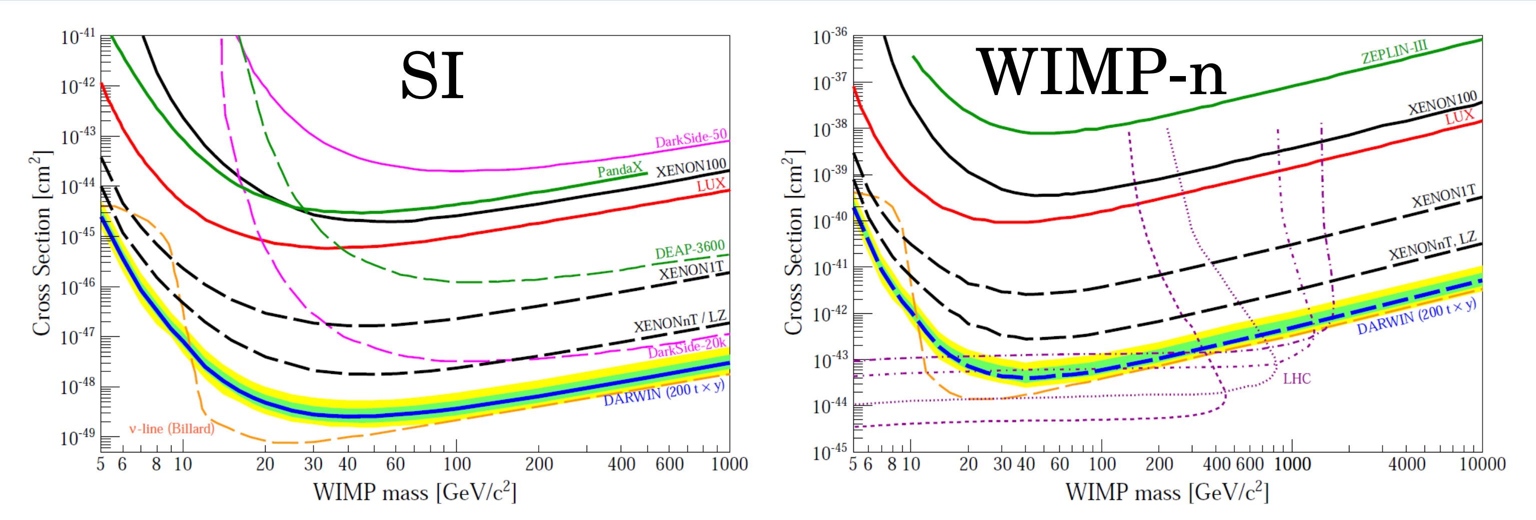
NEUTRON VETO

Tagging and in-situ measurement of neutron-induced background

DARWIN – The ultimate LXe exp

- Can we reach the ν floor?
  - Would require O(50t) Xe
  - **Backgrounds** at unprecedented levels
  - Technology stretching to the end: HV, purity, calibration, stability…
  - Probably means cooperation between long-time competitors





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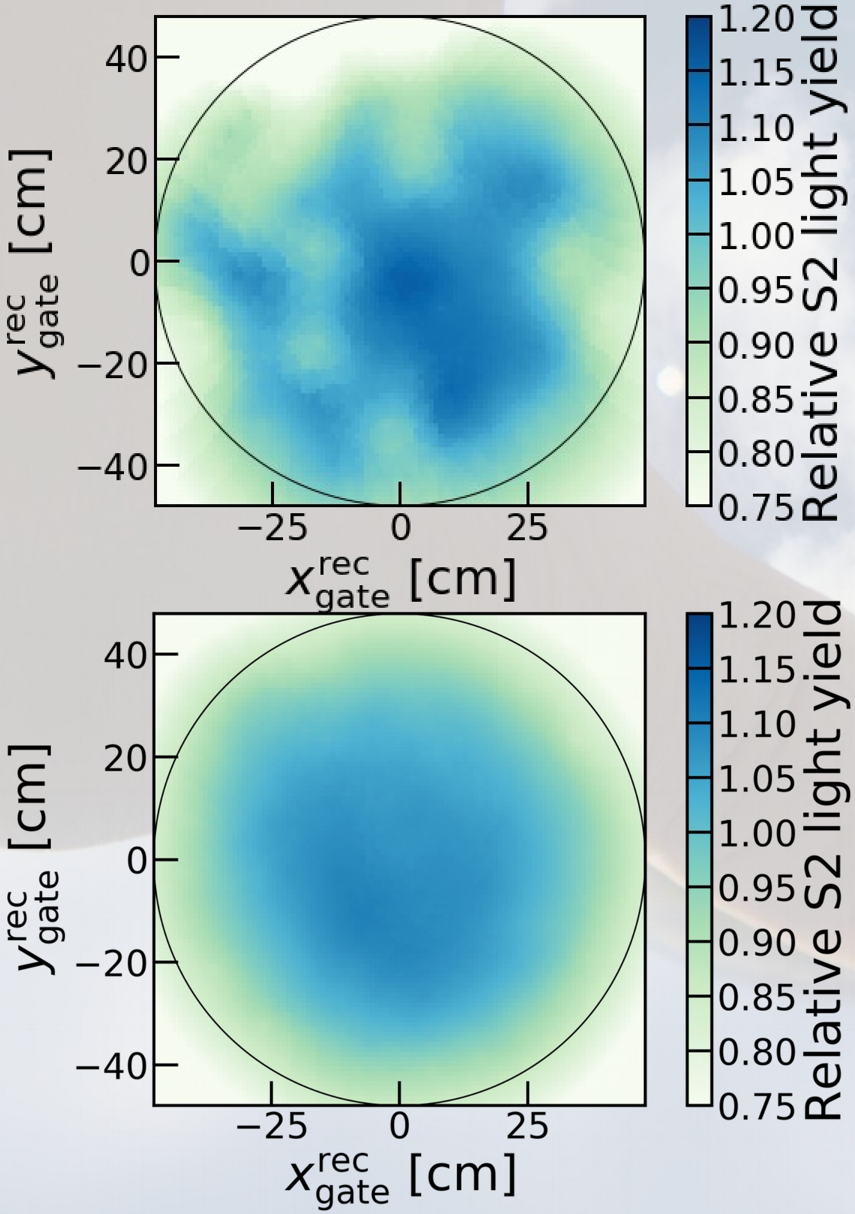
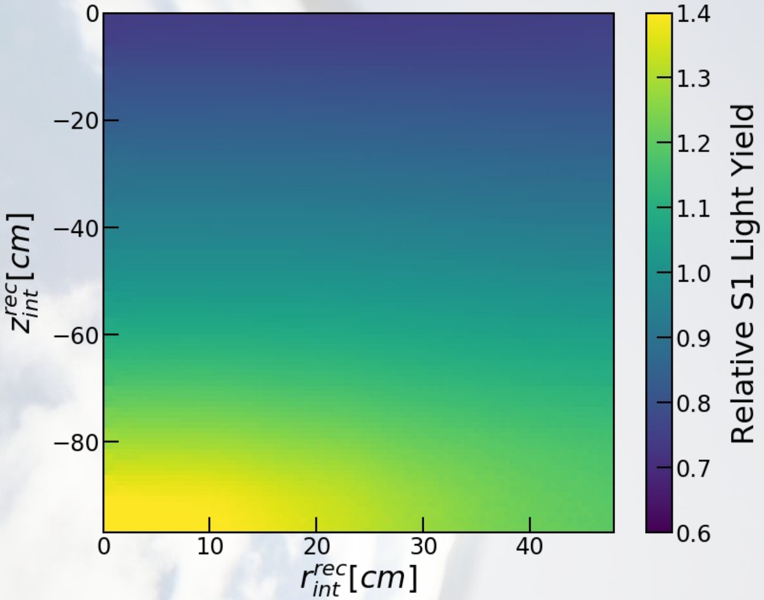
Summary

- The XENON1T took a full tonne X year of DM search data, and has the highest sensitivity for all WIMP masses > 6 GeV by factor ~7
- Strongest limit above 6 GeV on WIMP-nucleon SI cross-section at $4.1\text{x}10^{-47}$ cm^2 for a WIMP of 30 GeV
- No SI WIMP signal was found, albeit a small statistical fluctuation of high E/m_χ
- The (low E) ER and NR backgrounds are the lowest ever recorded
- XENONnT upgrade in full speed – expecting first light in 2019!
- Many more results on the way – ER, axions, DEC, modulation, EFT…

S2 XY corrections



S1 corrections



Position Reconstruction “before”