Results of the WIMP search with the XENON1T experiment

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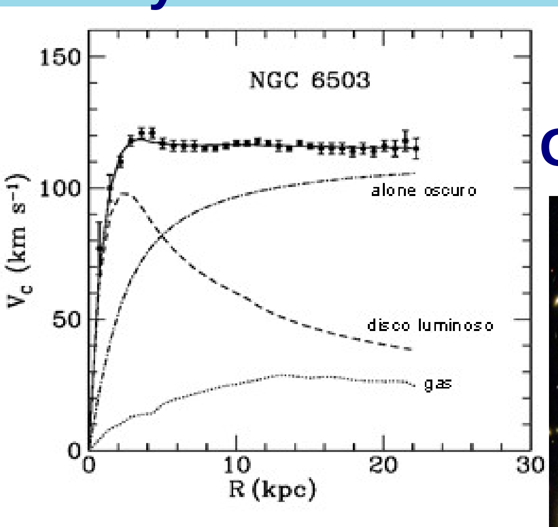
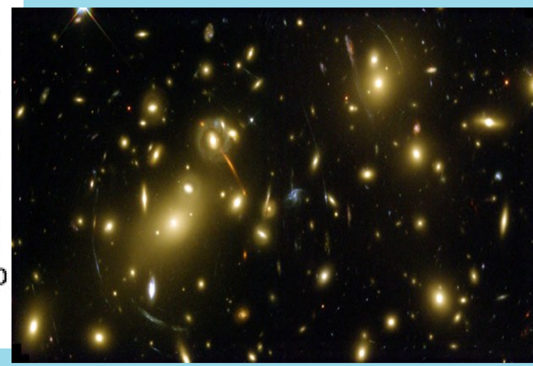
Dark Matter

Evidences for the existence of Dark Matter

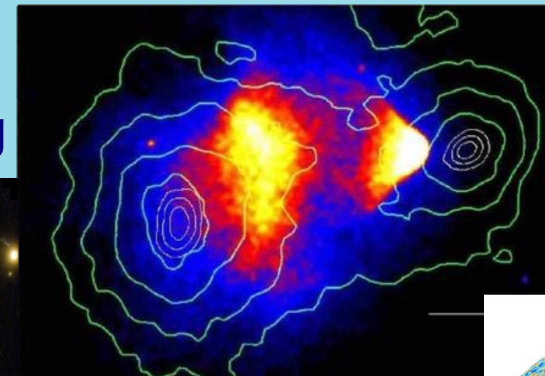
Galaxy rotation curves



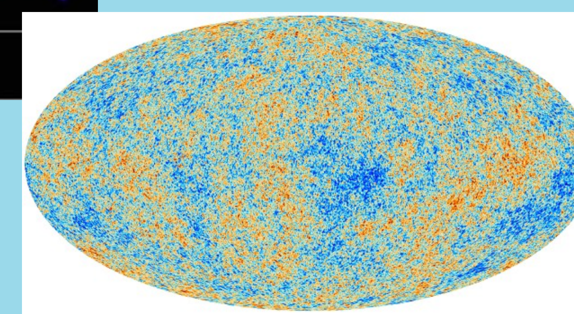
Gravitational lensing



Bullet cluster

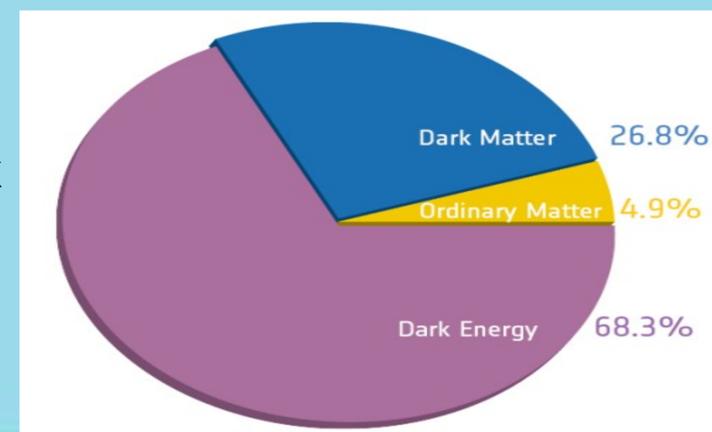


CMB anisotropies

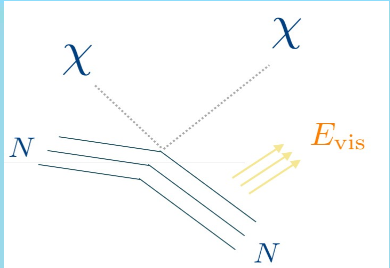


What is DM?

- Massive, neutral and stable particle
- Non-baryonic matter interacting through gravitational and weak forces only
- Constitutes about 27% of the Universe
- Best candidates: Weakly Interacting Massive Particle (*WIMP*)



WIMP direct detection using Xenon

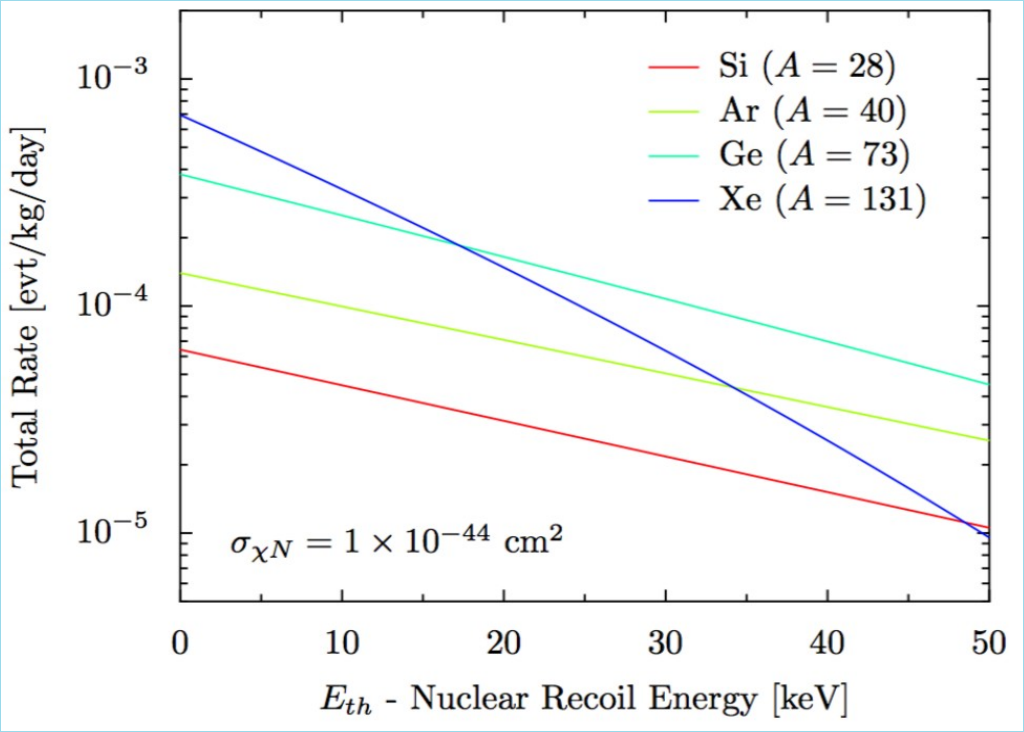


Elastic scattering of WIMPs off target nuclei

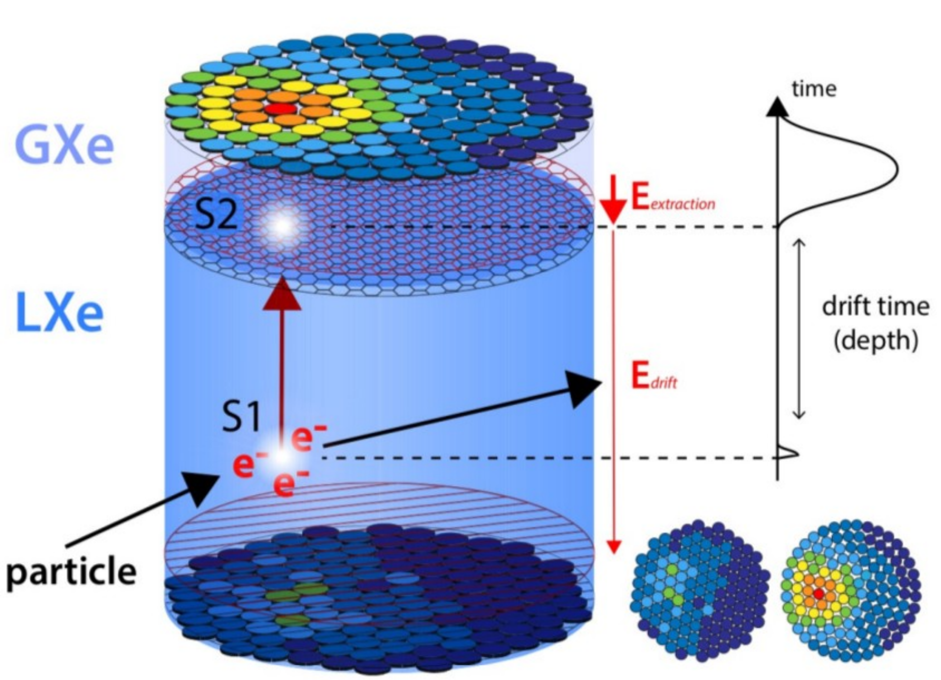
→ measure energy of recoiling nucleus (~ few tens of keV)

Why Xenon?

- Large mass number (A=131)
- High stopping power (Z=54, ρ=2.83 kg/l), i.e. excellent self shielding
- Scalable to large target masses
- 50% of odd-nucleon isotopes (^{129}Xe, ^{131}Xe) for SD interactions
- Efficient scintillator (λ=178 nm)
- No long-lived isotopes (Kr can be reduced to sub-ppt levels and ^{136}Xe negligible in the low energy ROI)
- High light/charge yield
- Xenon is liquid at -95°C: “easy” cryogenics



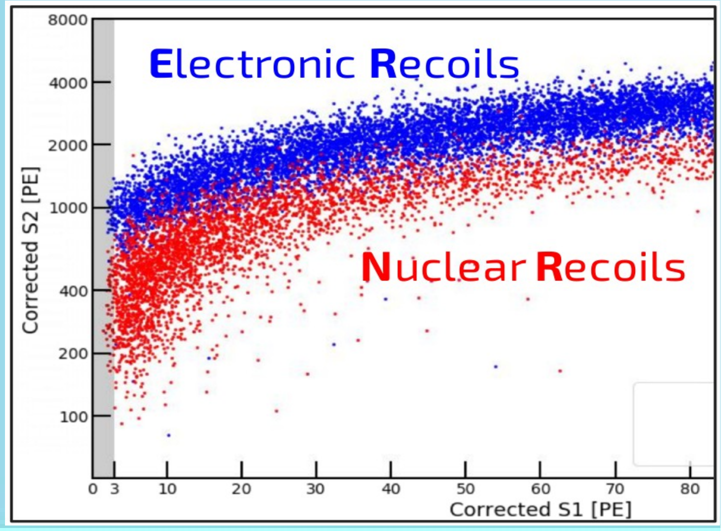
The XENON detection technique



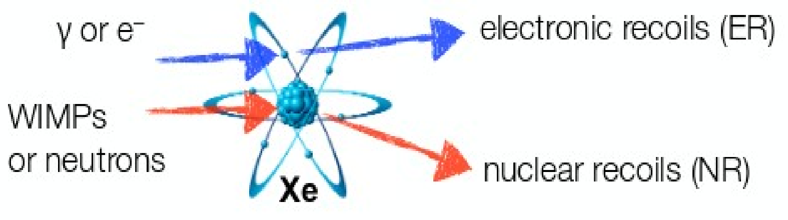
- **S1**: light signal in LXe
  → prompt scintillation photons
- **S2**: charge signal in GXe
  → secondary scintillation from drifted e⁻

Reconstruction of energy using both S1 and S2 (*Combined Energy Scale)*

- 3D position reconstruction:
  x,y from S2 pattern in top PMT array and **z** using drift time



- WIMPs (or n) scattering off Xe nucleus → **NR**
- e⁻, γ backgrounds scattering off Xe electrons → **ER**



Particle-type discrimination from S2/S1 ratio:

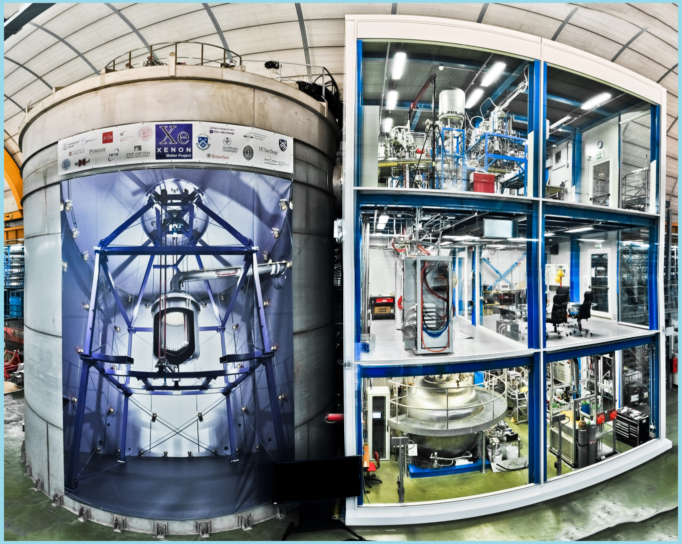
$$S2/S1_{NR} << S2/S1_{ER}$$

The XENON project

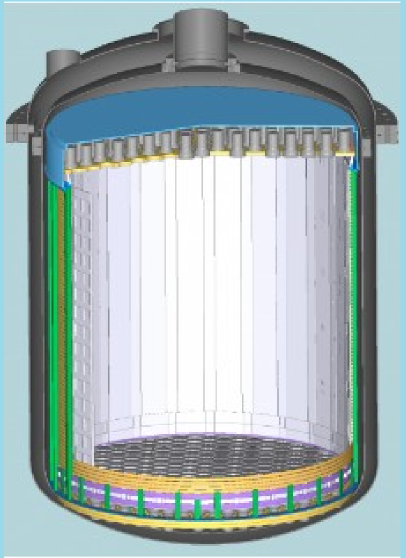
XENON10

XENON100

XENON1T



XENONnT



25 kg	161 kg	3.2 ton	8 ton
15cm drift	30 cm drift	1 m drift	1.5 m drift
$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	$\sim 10^{-47}$ cm^2	$\sim 10^{-48}$ cm^2
BG~1000 (keV t y)$^{-1}$	BG~5 (keV t y)$^{-1}$	BG~0.2 (keV t y)$^{-1}$	BG~0.02 (keV t y)$^{-1}$

The XENON1T Collaboration

165 scientists, 25 institutions, 11 countries

The XENON1T detector

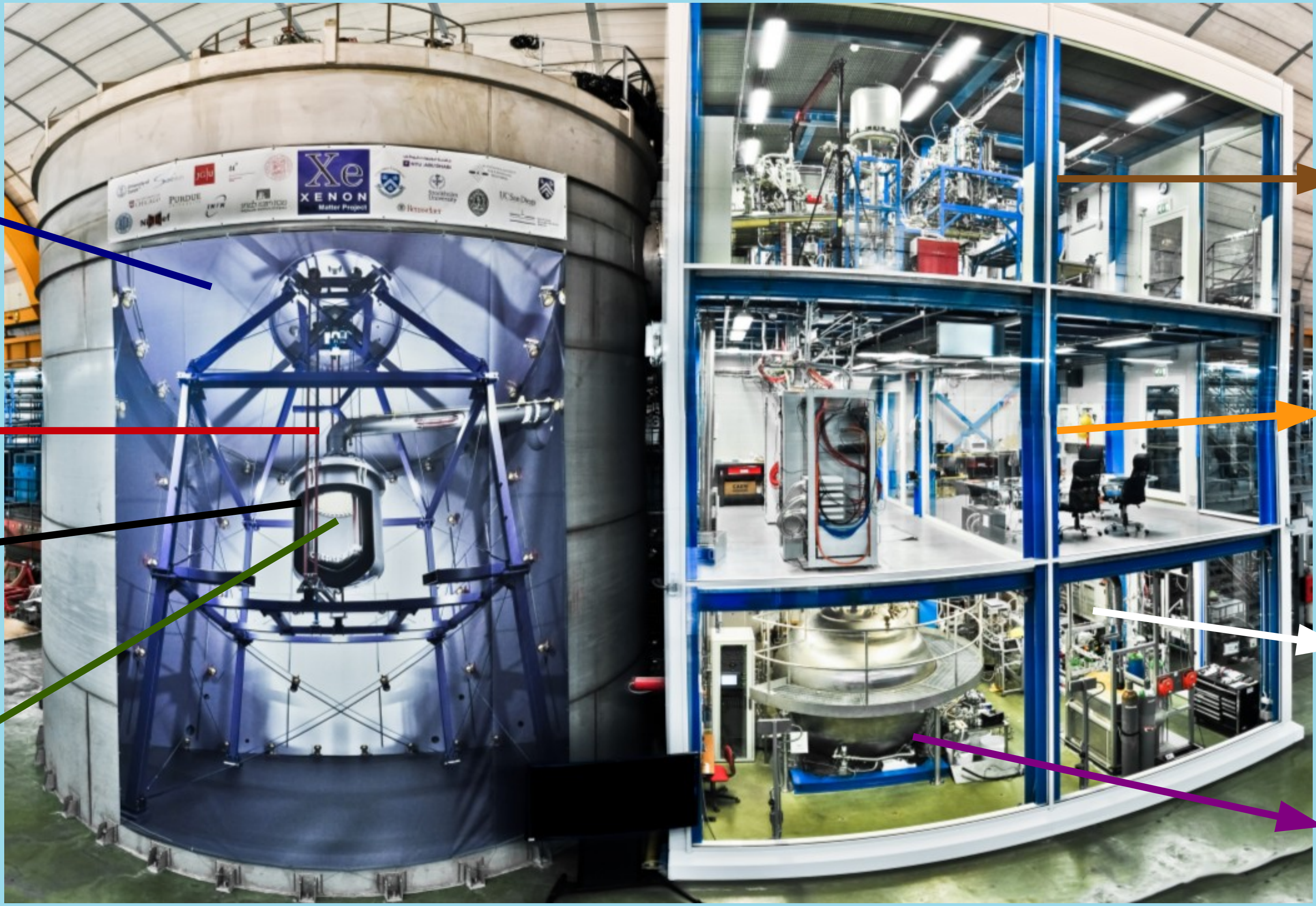
Eur. Phys. J. C. (2017) 77:881

Muon Veto:
- 84 8'' PMTs
- 700 t ultra pure water

External calibrations

Cryostat

TPC:
- 248 3'' PMTs
- 3.2 t LXe



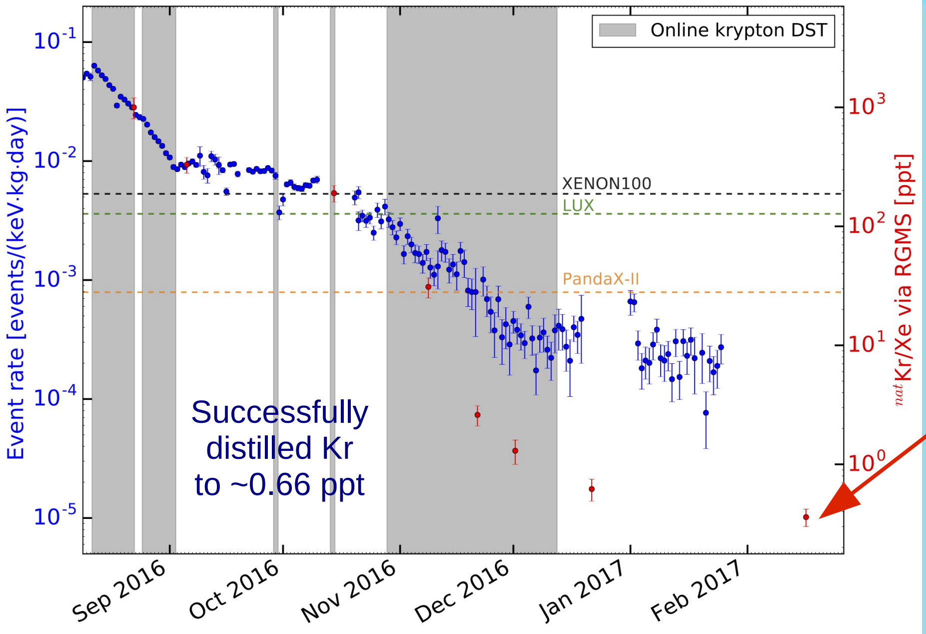
Cryogenics and purificarions

DAQ and Slow Control

Kr distillation column

Xe Storage and Recovery

Electronic recoil backgrounds



- **^{222}Rn: 10 µBq/kg**
  careful surface emanation control and further reduction by online cryogenic distillation
- **^{85}Kr: sub-ppt (Kr/Xe)**
  achieved with online cryogenic distillation
- **Materials radioactivity**
  HPGe gamma screening: subdominant

JCAP 04, 027 (2016)

	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

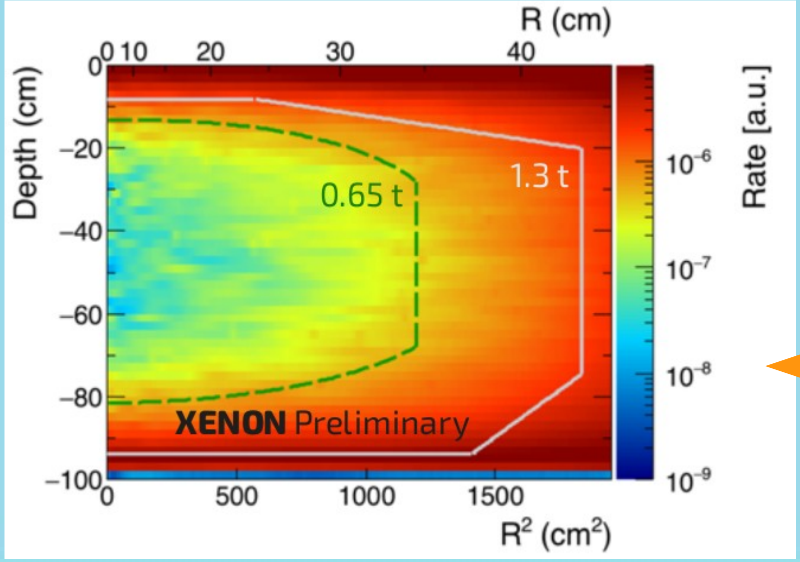
Expectations in 1-12 keV search window, 1t FV, single scatters

- MC simulations:
  75 ± 6 events/(t·y·keV)
- Measured (in 1.3t FV and below 25 keVee):
  82^{+5}_{-3}(sys) ± 2(stat) events/(t·y·keV)

Lowest ER background ever achieved in a DM detector!

Nuclear recoil backgrounds

- **Cosmogenic neutrons**
  Induced by cosmic muons.
  Significantly reduced by rock overburden, water passive shield and active Cherenkov Muon Veto
- **Radiogenic neutrons**
  From (α,n) and spontaneous fission from ^{238}U and ^{232}Th contained in detector's materials.
  Reduced via radiopure material selection, scatter multiplicity and fiducialization
- **Coherent elastic ν-nucleus scattering (CEνNS)**
  Mainly from ^{8}B solar ν.
  Constrained by flux and cross-section measurement, is an irreducible background below 1 keV



JCAP 04, 027 (2016)

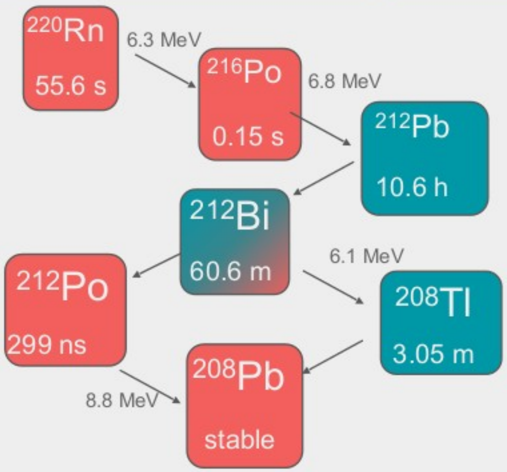
	Rate [$t^{-1} y^{-1}$]	Fraction [%]
Cosmogenic neutrons	<0.01	<2.0
Radiogenic neutrons	**0.6 ± 0.1**	**96.5**
CEνNS	0.012	2.0

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

Calibration sources

Electronic recoil

^{220}Rn: Low Energy ER

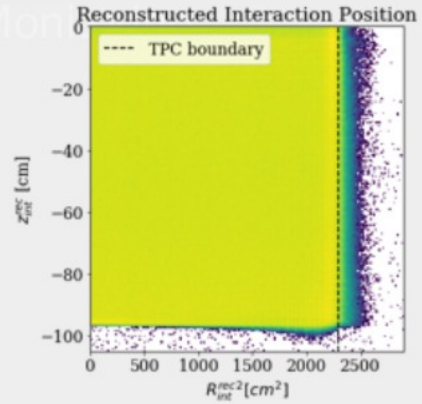


Type: Internal
Freq: 1-2 Months
Length: Few days

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

Spatial

^{83m}Kr: Stability and

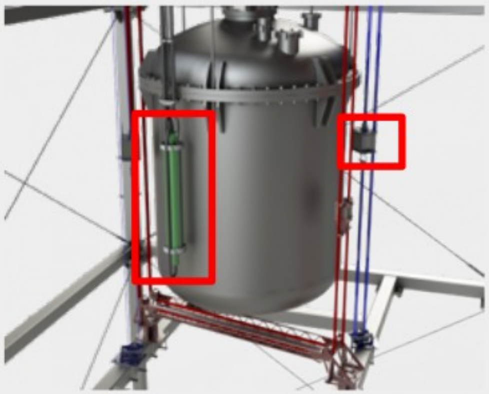


Type: Internal
Freq: 2-3 weeks
Length: 1 day
Half life: 1.83h

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

Nuclear recoil

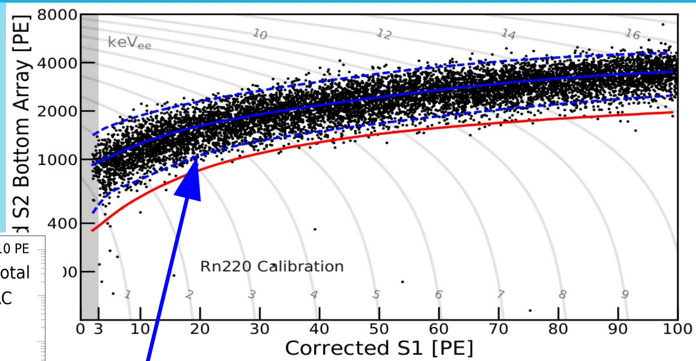
Neutrons: Signal Response

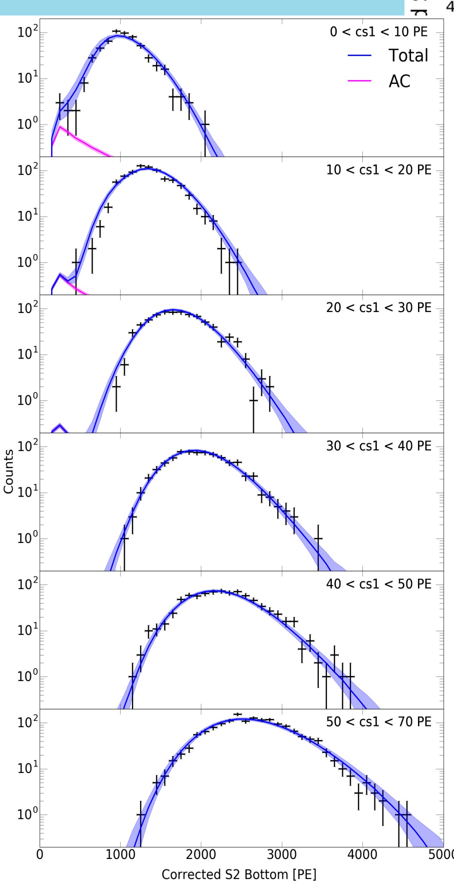


Type: External
Freq: As needed
Length: 6 weeks (AmBe)
2 days (generator)

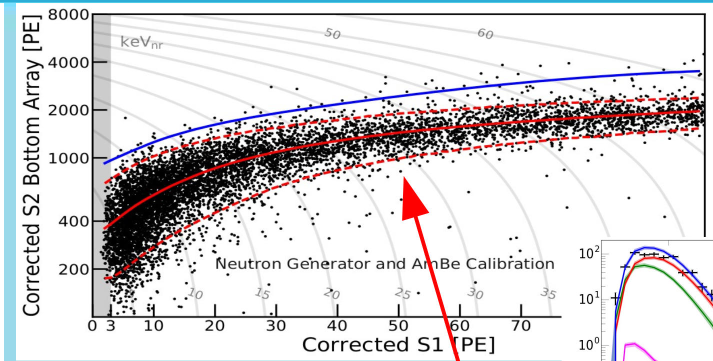
ER and NR calibrations

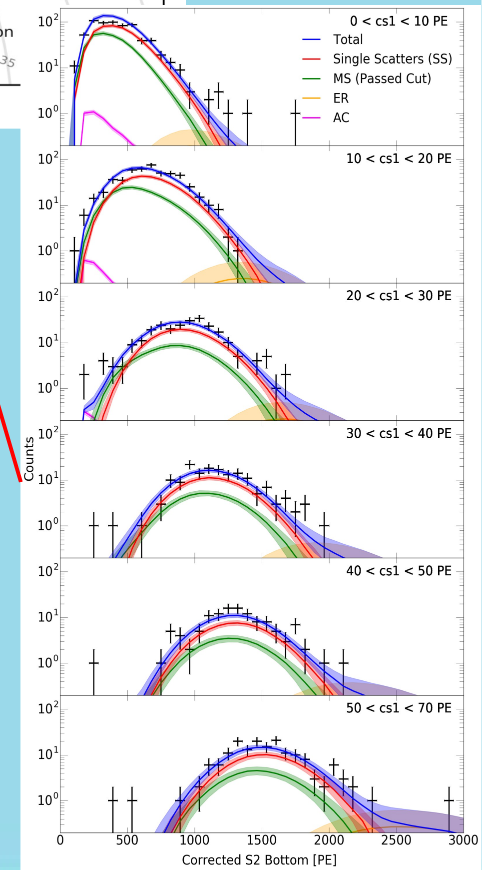
ER (^{220}Rn)





NR (neutron generator)

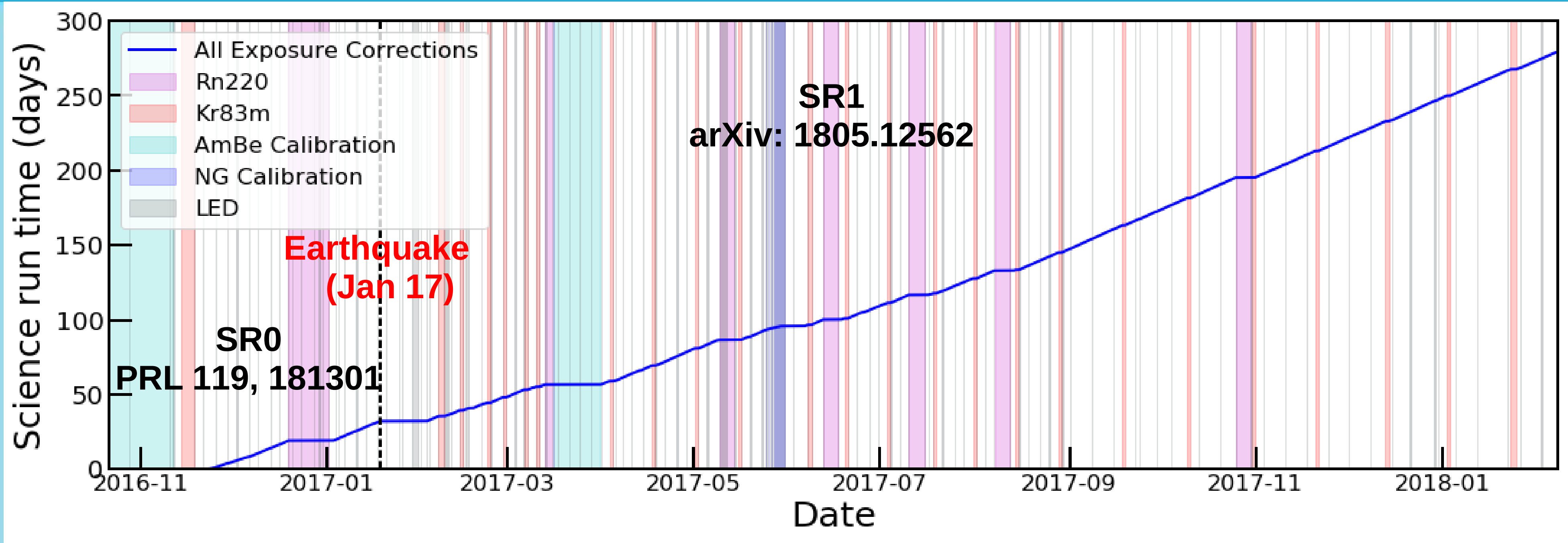




- Detailed MC simulations of LXe microphysics and detector processes
- Parameters tuned and constrained by calibration data

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

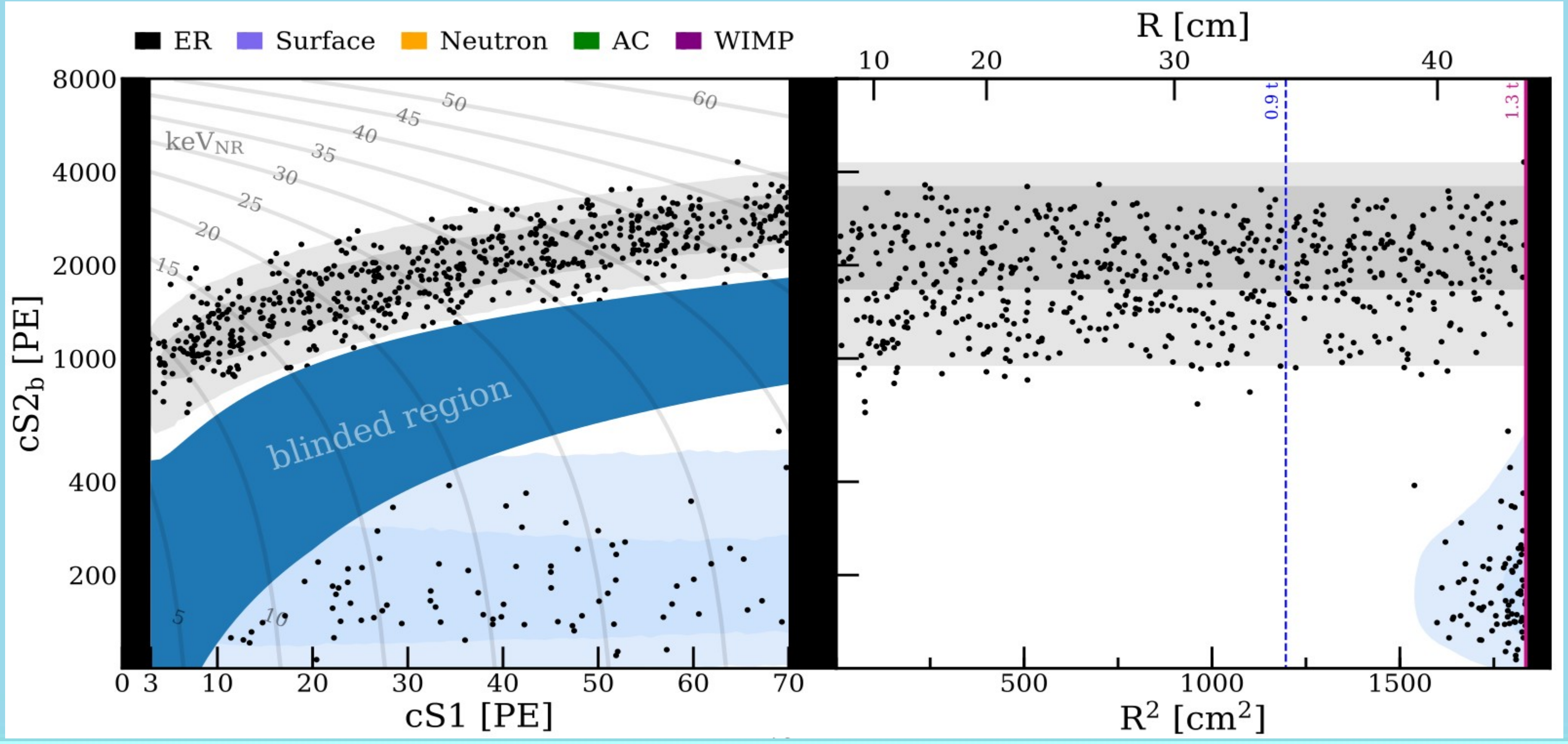
DM and calibration data



- 279 days of DM data taking (including correction for dead time) since Spring 2016
- 32.1 days of SR0, 246.7 days of SR1
- 1 year of data in stable detector conditions (temperature, pressure, level, etc.), within a few %
- The largest exposure reported to-date with this type of detector
- 140 days of calibration data

DM search data: blinded and salted

- Blinding:
  to avoid potential bias in event selection, the signal/background nuclear recoil ROI was blinded
- Salting:
  to protect against post-unblinding tuning of cuts and background models, an undisclosed number and type of event was added to data



Dark matter search with XENON1T:

results

Background prediction and unblinding

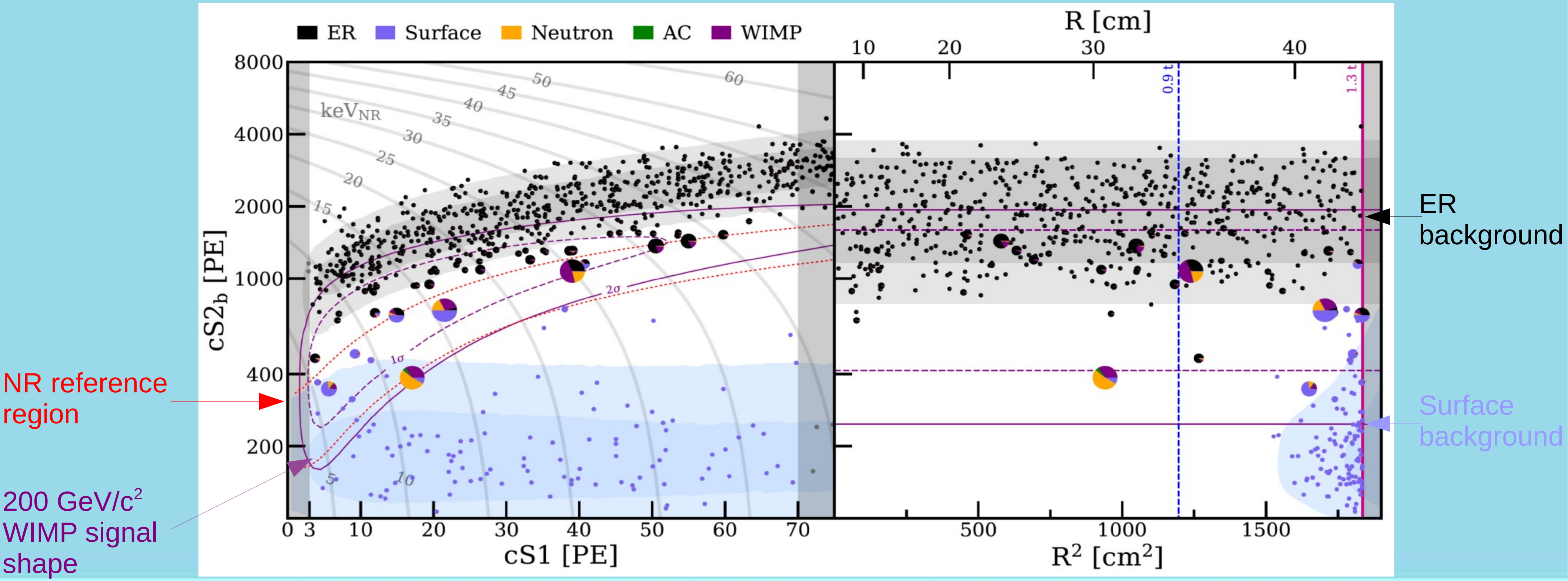
Mass	1.3 t	1.3 t	0.9 t	0.65 t
(cS1, $cS2_b$)	Full	Reference	Reference	Reference
ER	627±18	1.62±0.30	1.12±0.21	0.60±0.13
neutron	1.43±0.66	0.77±0.35	0.41±0.19	0.14±0.07
CEνNS	0.05±0.01	0.03±0.01	0.02	0.01
AC	$0.47^{+0.27}_{-0.00}$	$0.10^{+0.06}_{-0.00}$	$0.06^{+0.03}_{-0.00}$	$0.04^{+0.02}_{-0.00}$
Surface	106±8	4.84±0.40	0.02	0.01
Total BG	735±20	7.36±0.61	1.62±0.28	0.80±0.14
$\text{WIMP}_{\text{best-fit}}$	3.56	1.70	1.16	0.83
Data	739	14	2	2

arXiv:1805.12562

- Reference region is defined within [NR median, NR median-2σ]
- ER is the most significant background and uniformly distributed in the volume
- Surface background contribute most in reference region, but its impact is sub-dominant 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

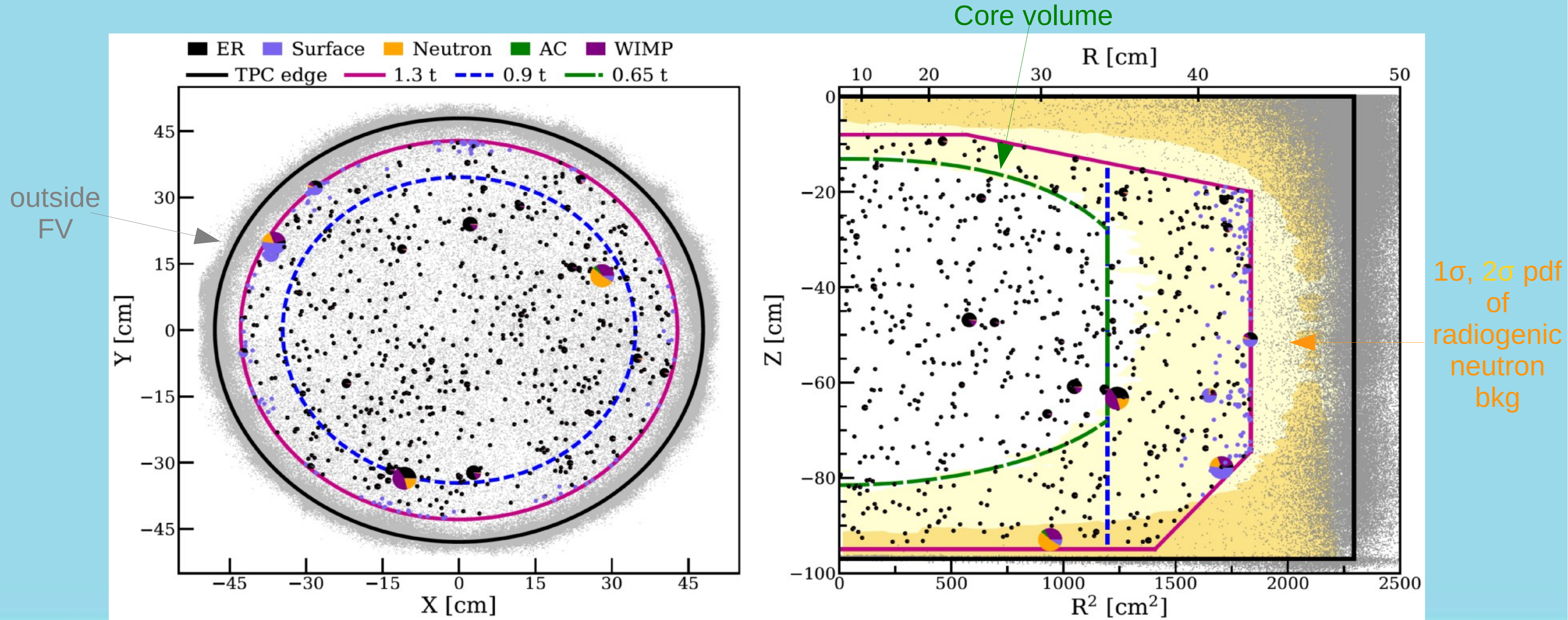
Results: energy space

- Results interpreted with un-binned profile likelihood analysis in cS1, cS2, R, Z space
  - here we show $cS2_b$ *vs* cS1, R^2
- Events passing all selection criteria are shown as pie charts representing the relative PDF from each component for the best-fit model for 200 GeV/c^2 WIMP (σ_{SI}=4.7·$10^{-47}$$cm^2$)
- Larger charts represent events with larger WIMP probability



Results: spatial distribution

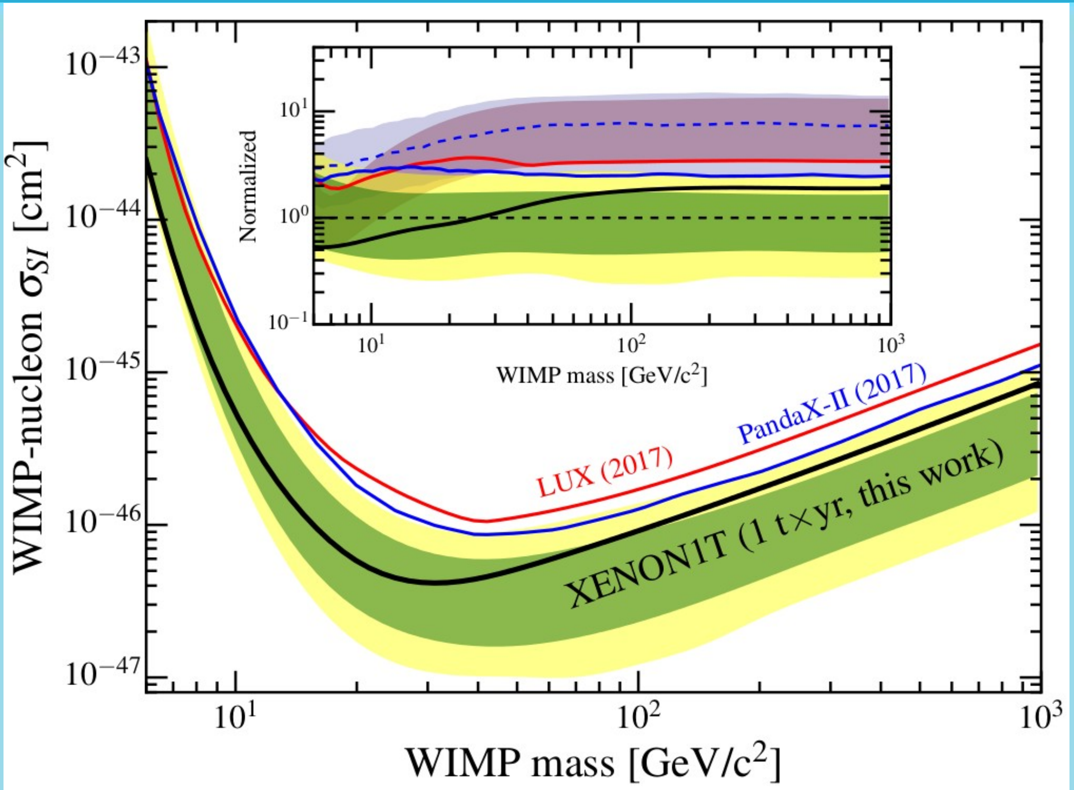
- Results interpreted with un-binned profile likelihood analysis in cS1, cS2, R, Z space
  - here we show Y *vs* X, Z *vs* R^2
- Core volume (0.65 t): modeled in order to have a negligible amount of surface and neutron background. The two bins, in/out core volume, allow to increase the fiducial volume



New constraints of WIMPs

Minimum at
$4.1 \cdot 10^{-47}$cm² for a WIMP of 30 GeV/c²

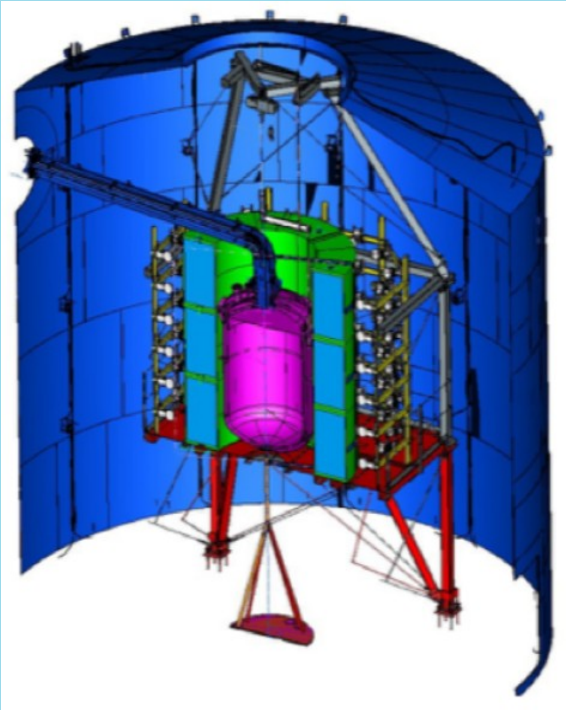
Submitted to PRL
arXiv:1805.12562



- Spin Indipendent WIMP-nucleon cross section: most stringent 90% CL upper limit on WIMPs above 6 GeV/c²
- 7 times better sensitivity compared to previous experiments (LUX, PANDAX-II)
- 1 sigma upper fluctuation at higher WIMP masses. No significant (>3 sigma) excess at any scanned WIMP mass

What next? XENONnT!

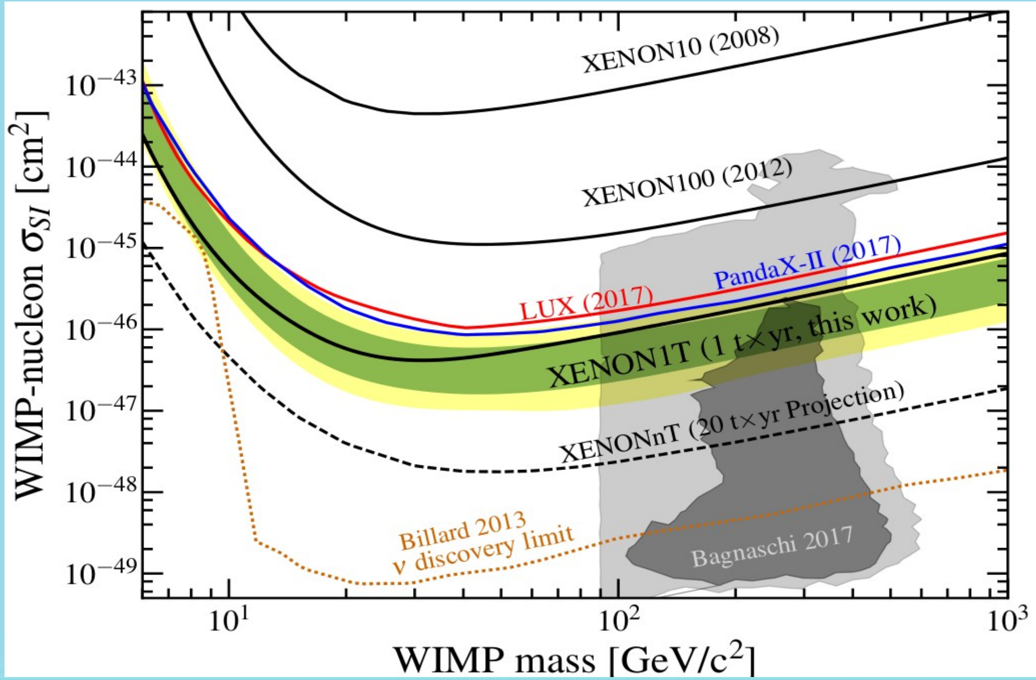
- Most of the XENON1T subsystems have been designed in order to accommodate also a larger dark matter detector: XENONnT
- The upgrades especially involve
  - **TPC**: larger inner cryostat, 476 PMTs
  - **LXe purification**: faster cleaning (5000 SLPM) of large LXe volume
  - **Rn distillation**: online removal of ^{222}Rn emanated inside the detector
  - **Neutron Veto** (new!): tag the neutron-induced background
- The total LXe mass in XENONnT will be 8 t (~4 t fiducial)
- The background will be reduced by a factor ~10
- The installation of XENONnT starts in 2018 and the commissioning in 2019



A feasible option for the Neutron Veto detector of XENONnT

Conclusions

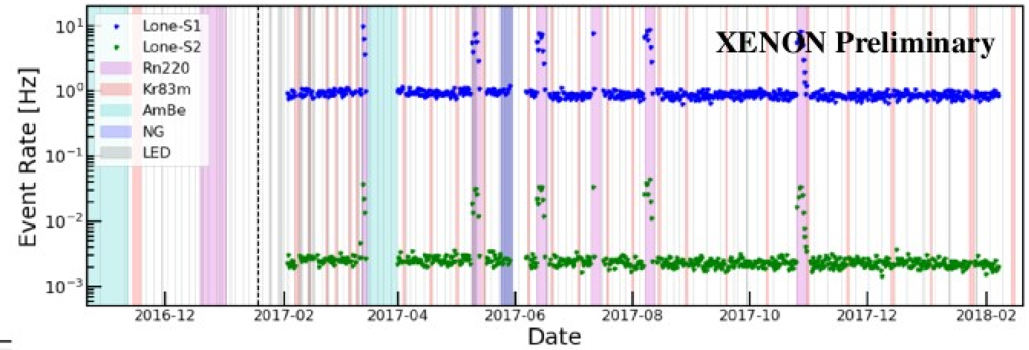
- First multi-ton scale LXe-TPC successfully operated for more than 1 year
- Lowest background ever achieved in any DM detector: 82 events/(t·y·keV)
- Strongest limit on WIMP-nucleon SI cross-section above 6 GeV/c^2: minimum at $4.1\cdot10^{-47}$cm^2 for a WIMP of 30 GeV/c^2
- XENON1T is continuing data taking
- XENONnT will improve the sensitivity by another order of magnitude

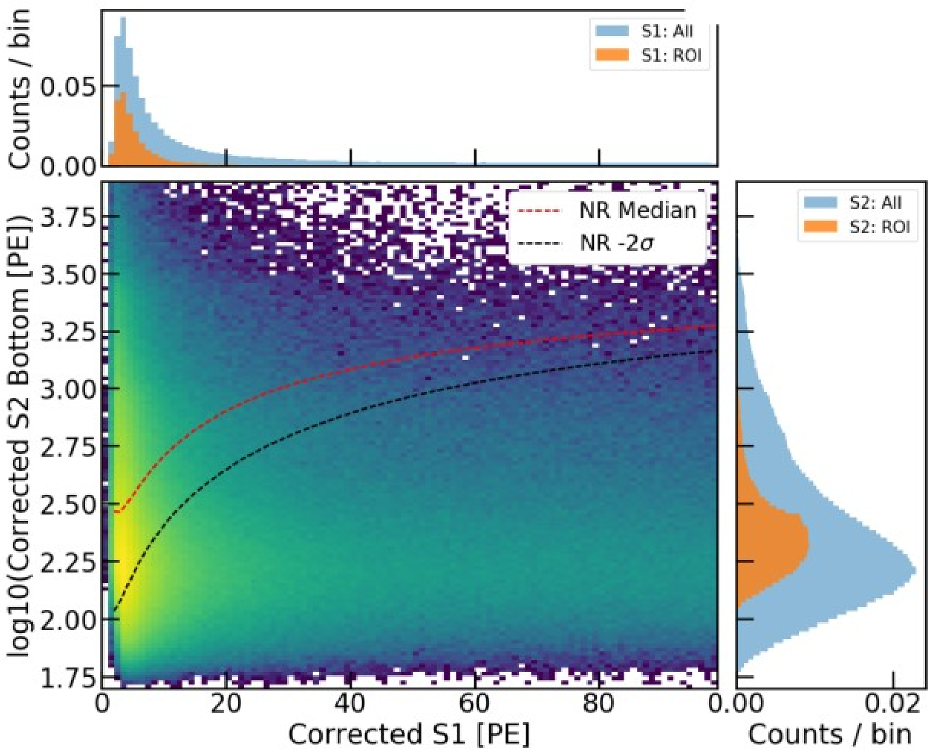


Backup slides

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



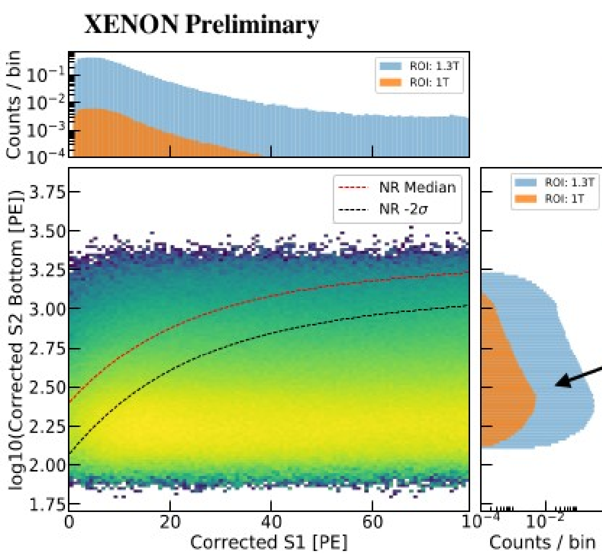


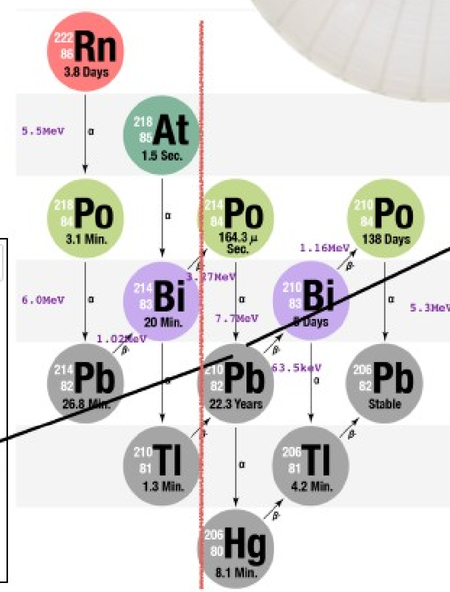
Empirical model shows an overall small rate in the ROI for NRs

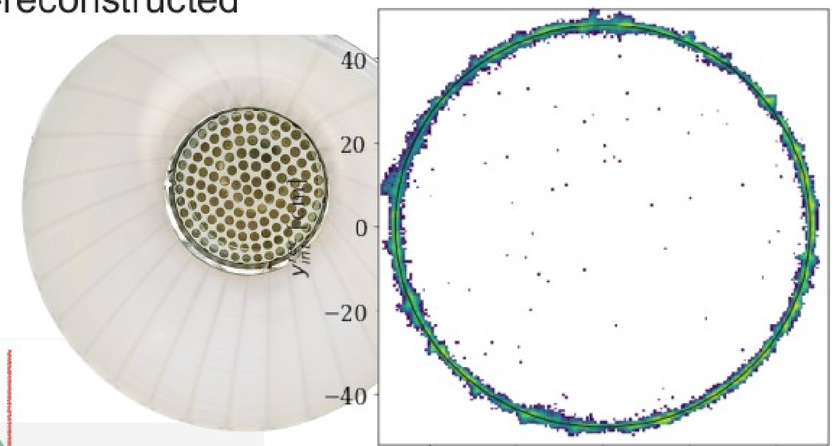
- Select unpaired S1/S2 from data
- Randomly pair to form events
- Apply selection conditions from analysis
- Performance verified with ^{220}Rn data and background sidebands

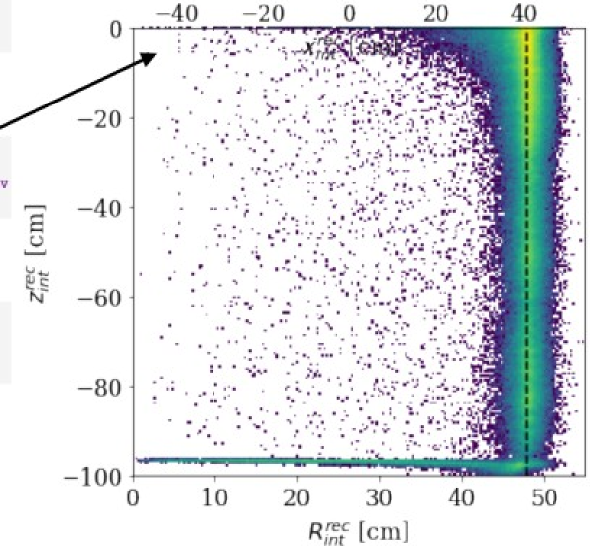
Surface background

- 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

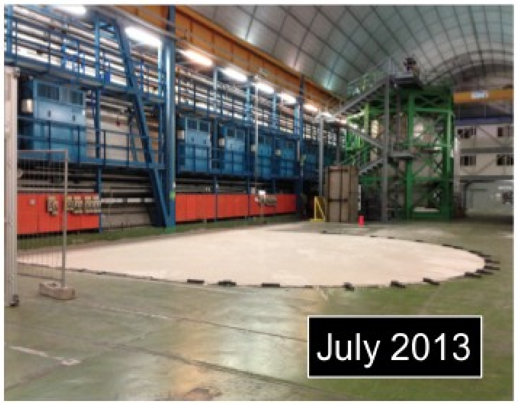


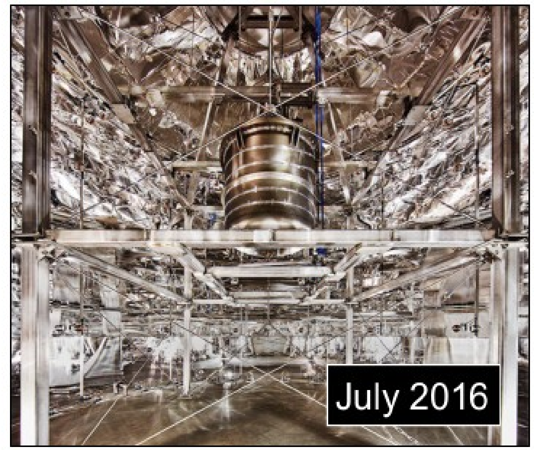






Water Cherenkov Muon Veto



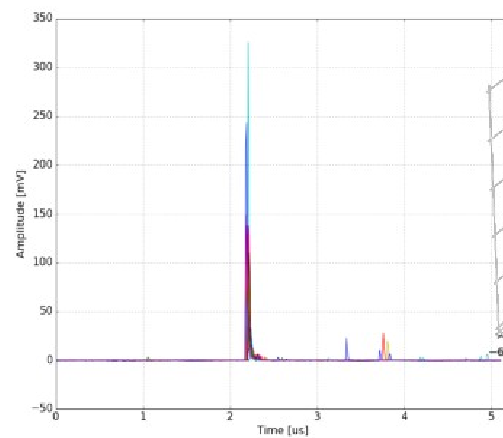


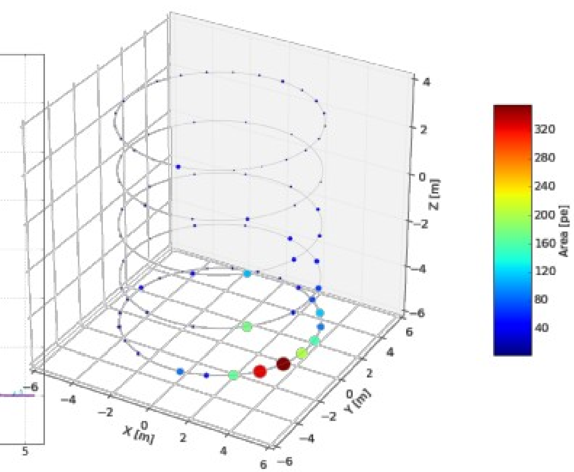
700 ton pure water instrumented with 84 high-QE 8" PMTs

Active shield against muons

Trigger efficiency > 99.5% for muons in water tank

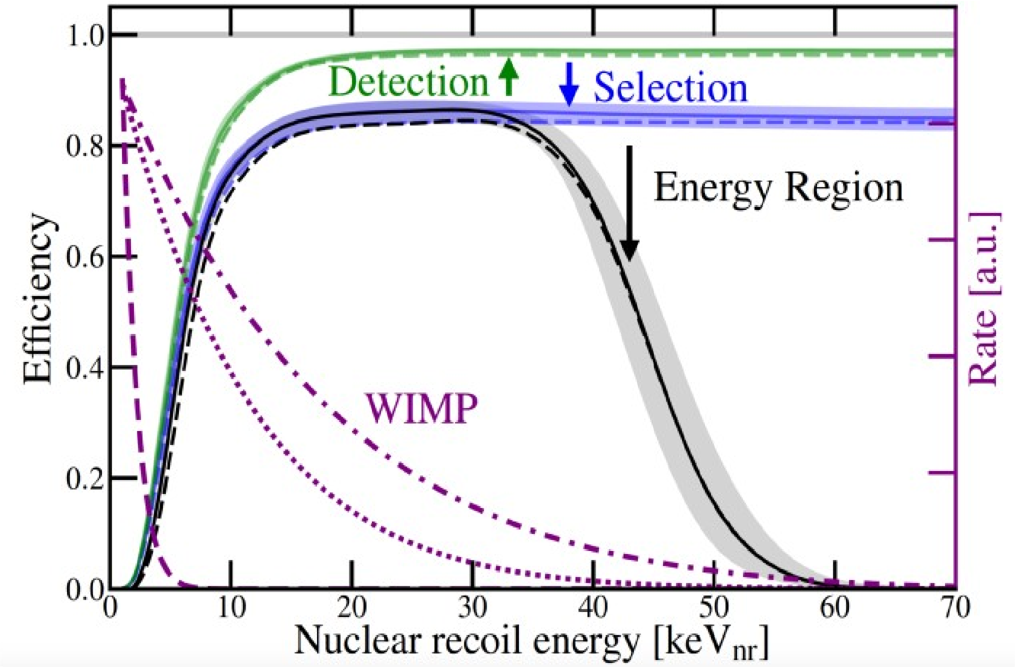
Cosmogenic neutron background suppressed to < 0.01 events/ton/yr





JINST 9, 11007 (2014)

Detection efficiency

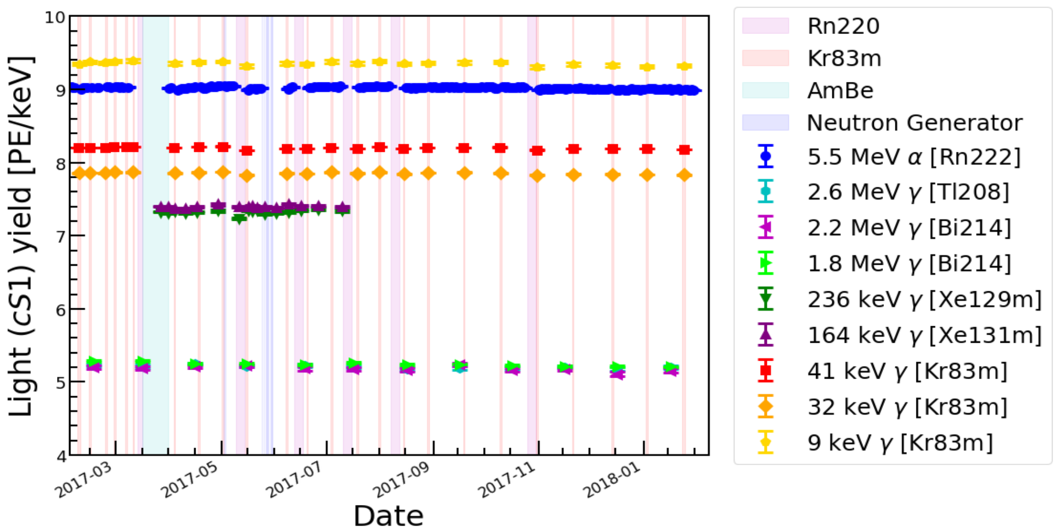


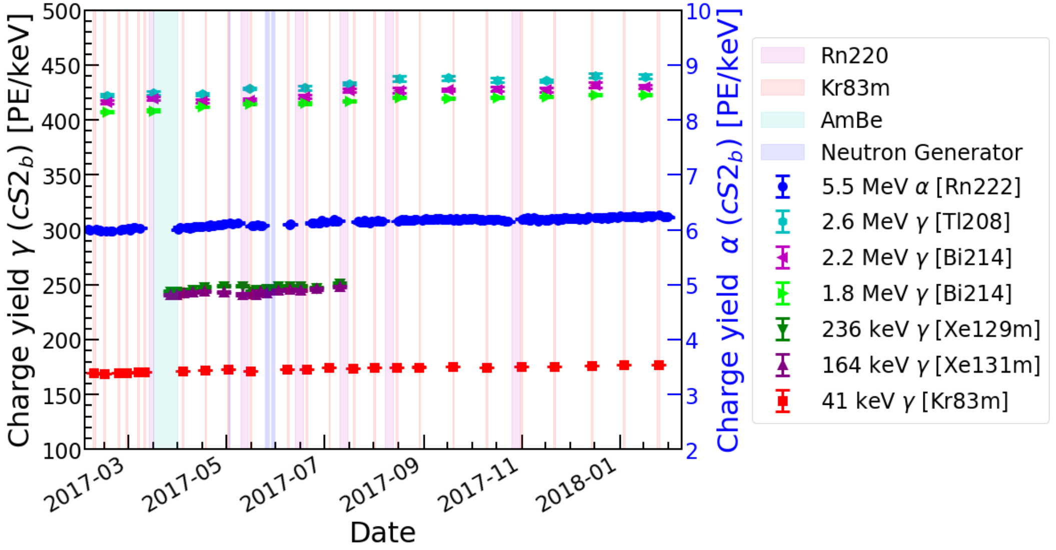
- Detection efficiency dominated by 3-fold coincidence requirement
  - Estimated via novel waveform simulation including systematic uncertainties
- Selection efficiencies estimated from control or MC data samples
- Search region defined within 3-70 PE in cS1
- 10 GeV (dashed), 50 GeV (dotted) and 200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

Light and Charge signals stability

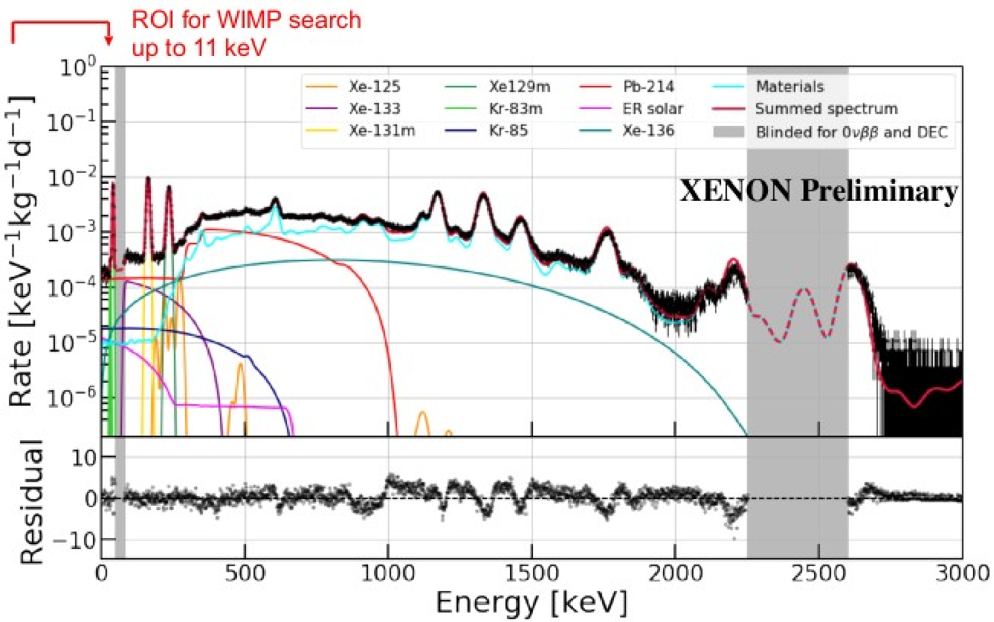
Light and charge yield stability monitored with several sources:

- ^{222}Rn daughters
- Activated Xe isotopes after neutron calibrations
- ^{83m}Kr calibrations
- ^{214}Bi and ^{208}Tl for high energy calibration
- Stability is within 0.2% for light yield and 1.5% for charge yield



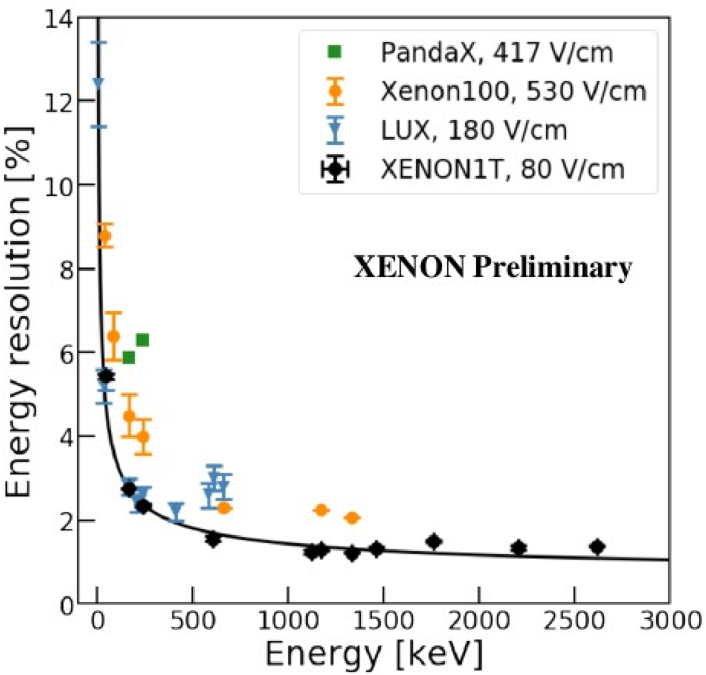


Energy resolution



- 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