University of Zurich[UZH]

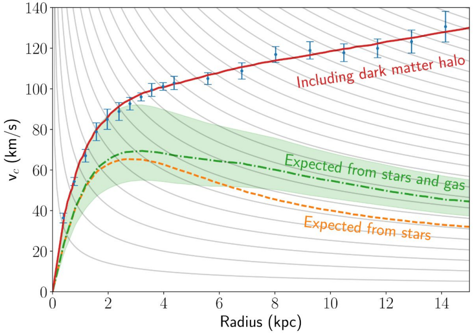
XENONnT status and recent results

Diego Ramírez (UZH) on behalf of the XENON collaboration @ LIDINE2023

September 20th 2023 | Madrid, Spain

Particle dark matter

Galactic scale (rotation curve M33)

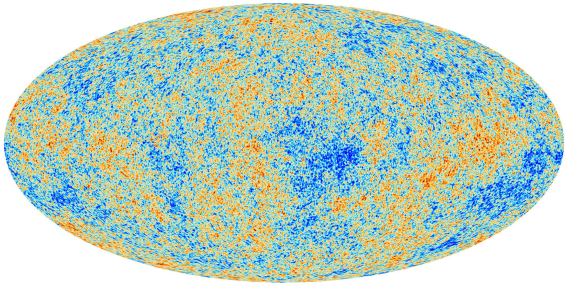


E. Hogenbirk

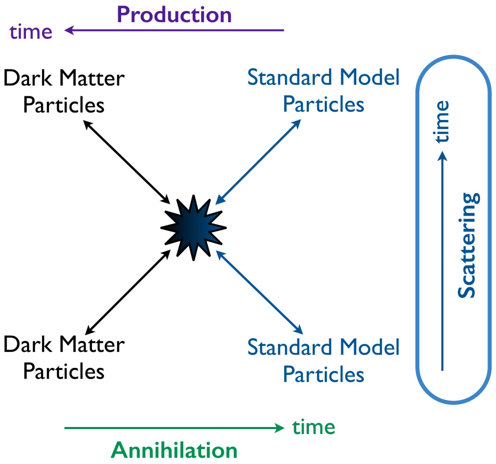
Extragalactic scale (Bullet Cluster)

NASA

Universal scale (CMB)



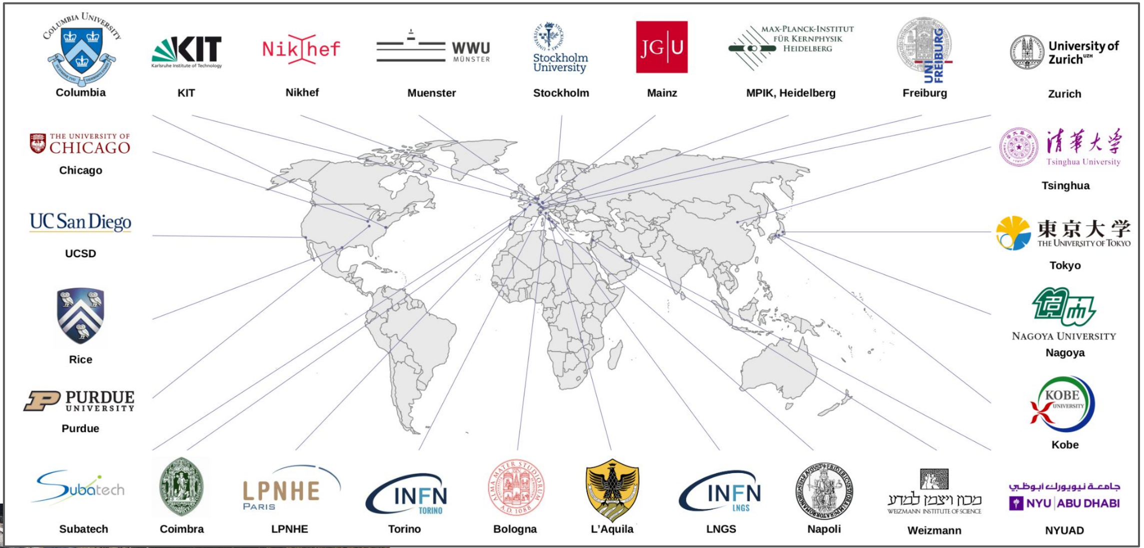
A&A 594 (2016) A1



- Dark matter existence suggested by astrophysical and cosmological observations at all scales
- Weakly interacting massive particle (WIMP) as prime candidate
- The XENON collaboration aims at direct WIMP detection using dual-phase xenon time projection chambers

XENON collaboration

Dark matter direct detection experiment at Laboratori Nazionali del Gran Sasso (LNGS)

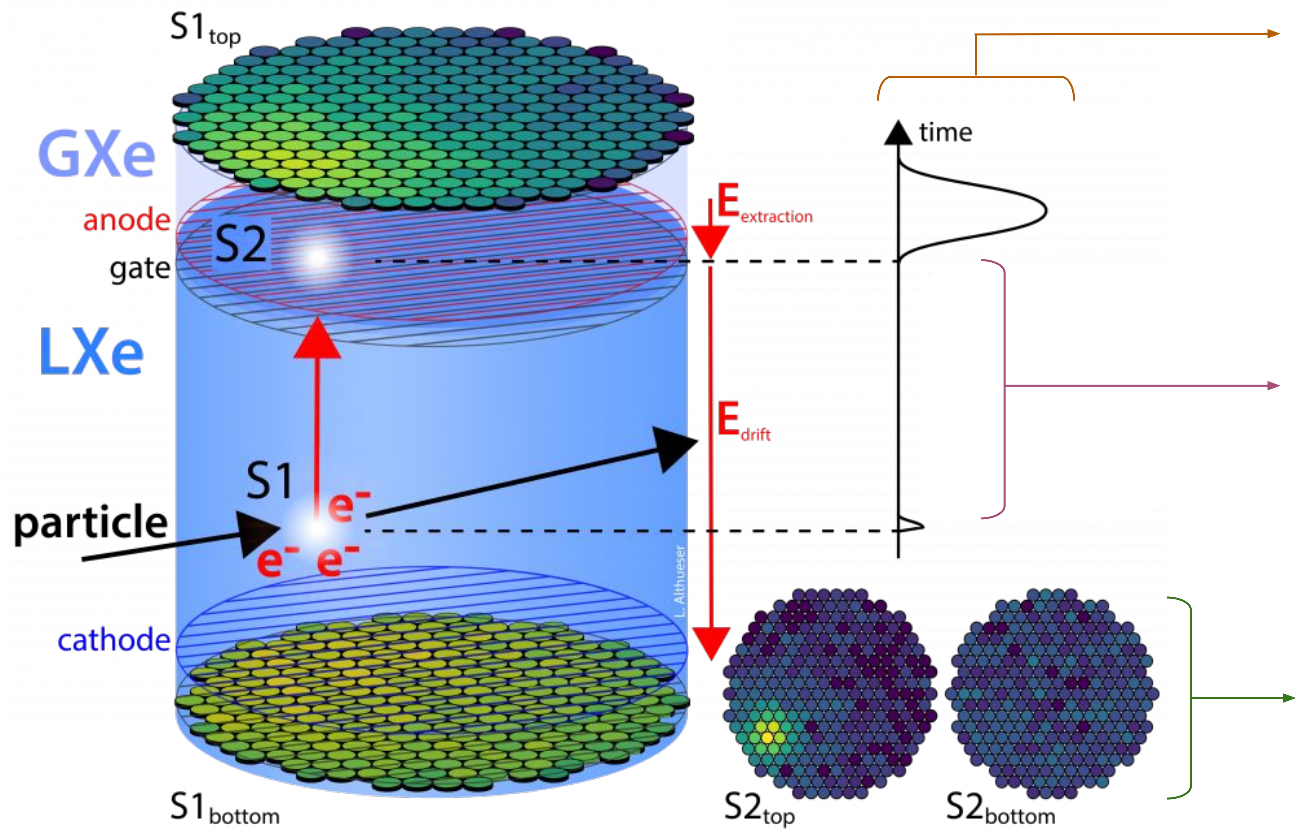


12 countries

28 institutions

~ 170 scientists

Xenon dual-phase time projection chamber

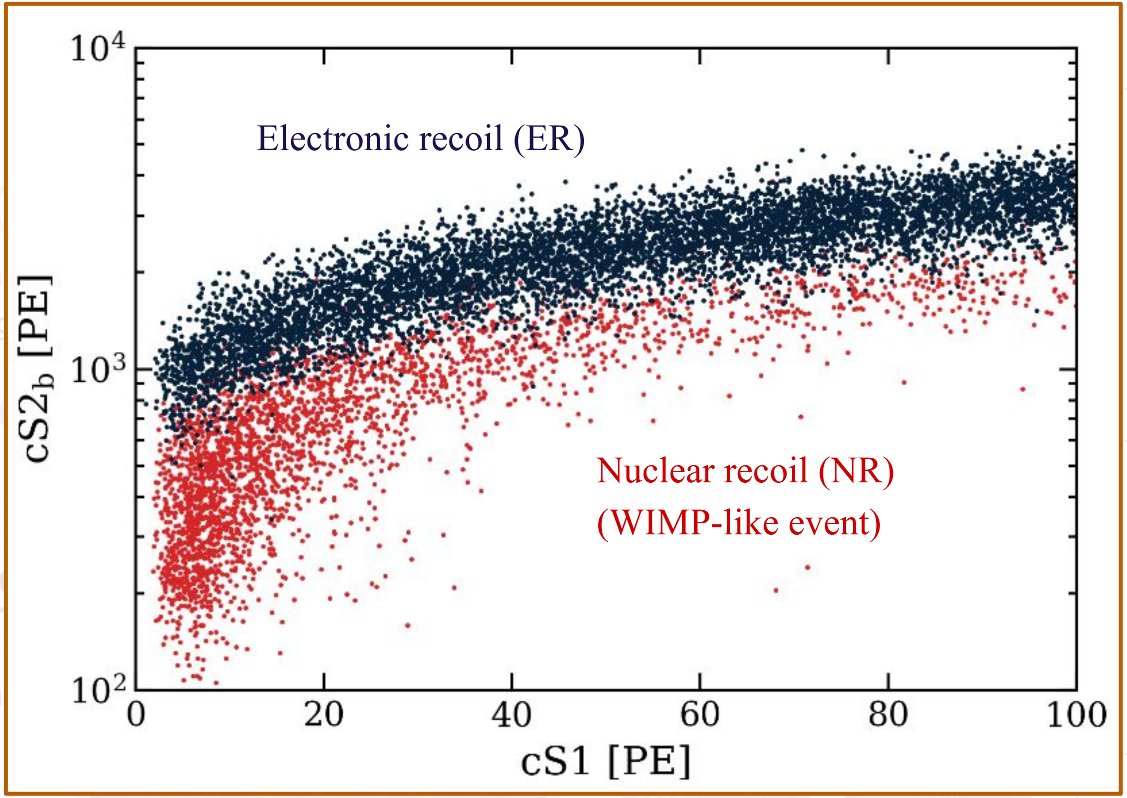


S2/S1 ratio
Signal discrimination

Electron drift time
Z position

S2 hit pattern
XY position

Xenon dual-phase time projection chamber



XENON1T calibration data

S2/S1 ratio

Signal discrimination

Electron drift time

Z position

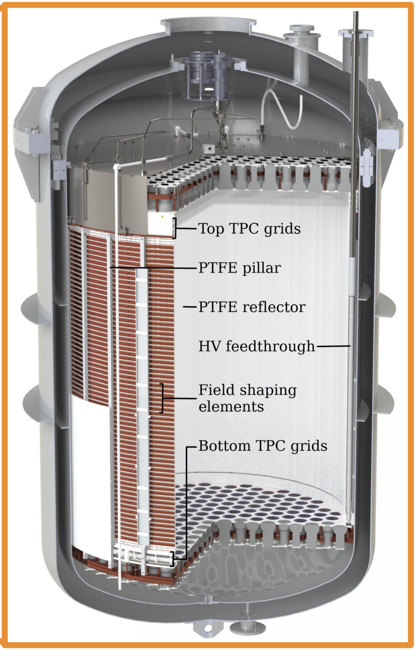
S2 hit pattern

XY position

From XENON**1**T to XENON**n**T

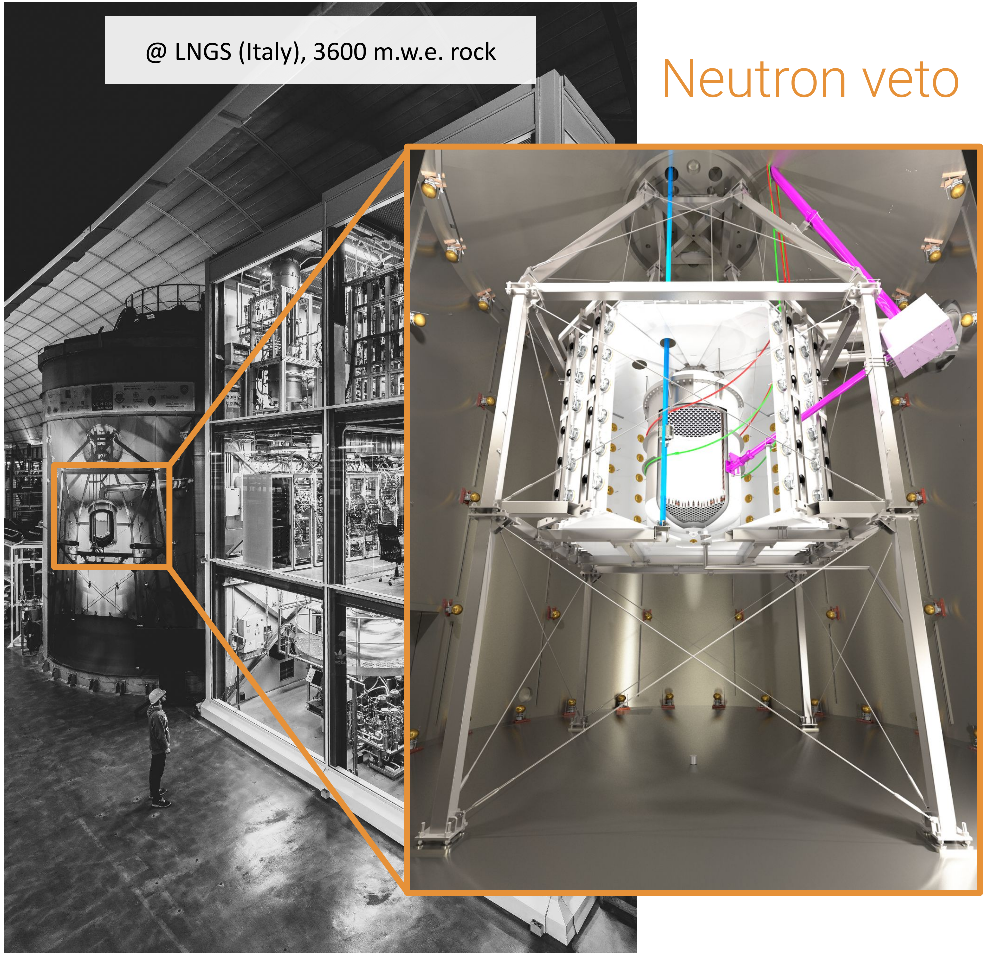
From XENON1T to XENONnT

Time projection chamber (TPC)



- 1.3 m (∅) × 1.5 m
- 8.5 t LXe in cryostat (2.5x XENON1T)
- 5.9 t LXe active (3x XENON1T)
- 494 (3″) PMTs (2x XENON1T)
- Five electrodes made of SS wires
- Two sets of concentric field-shaping rings, top one individually tuneable

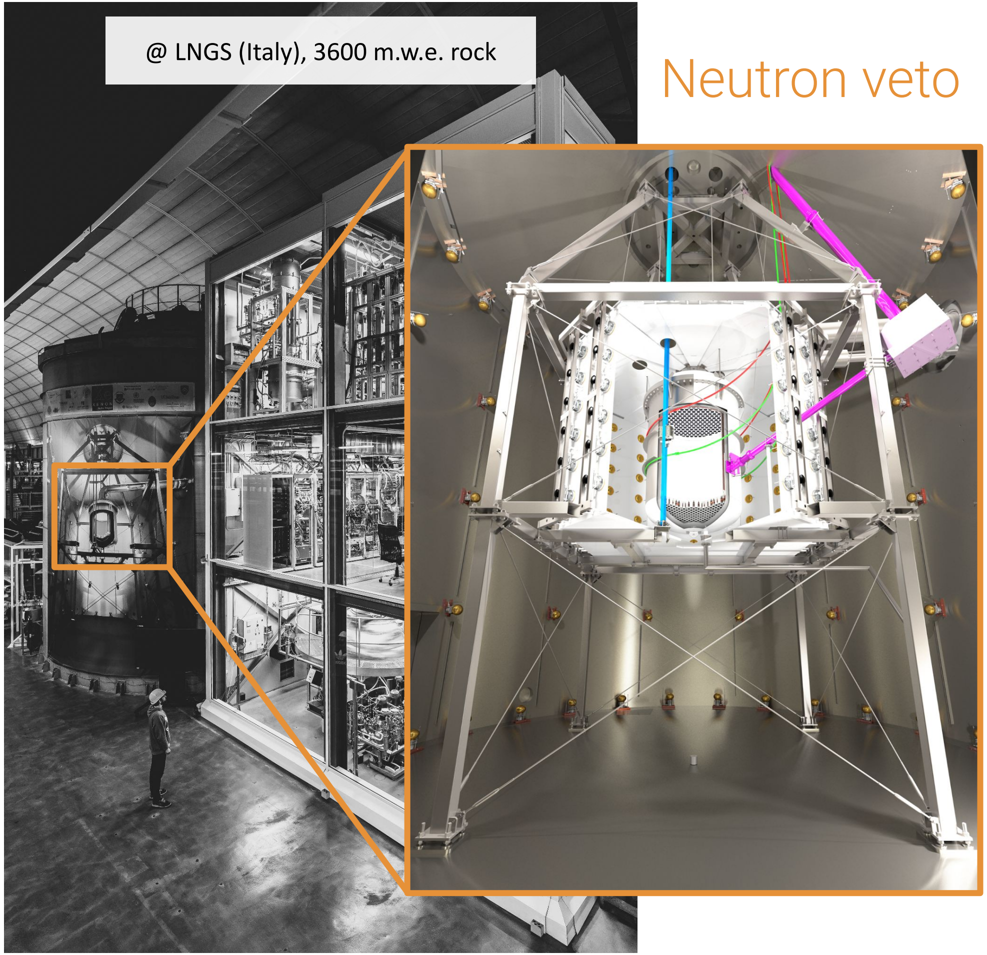
From XENON1T to XENONnT



Neutron veto

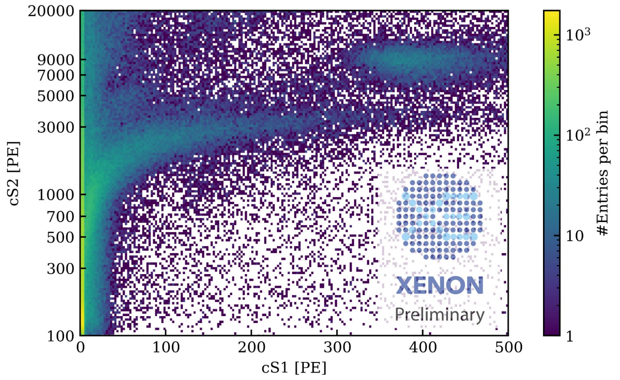
- 120 (8″) PMTs facing the TPC detect Cherenkov light from 2.2 MeV gamma (n-capture on H)
- (53 ± 3) % tagging efficiency (250 μs window, 5-fold PMT coincidence) with 1.6 % lifetime loss
- 0.2 % Gd doping will improve it to ~ 87 % (150 μs, 10-fold) JCAP 11 031 (2020)
- Tagged calibration neutrons to study NR LXe response

From XENON1T to XENONnT

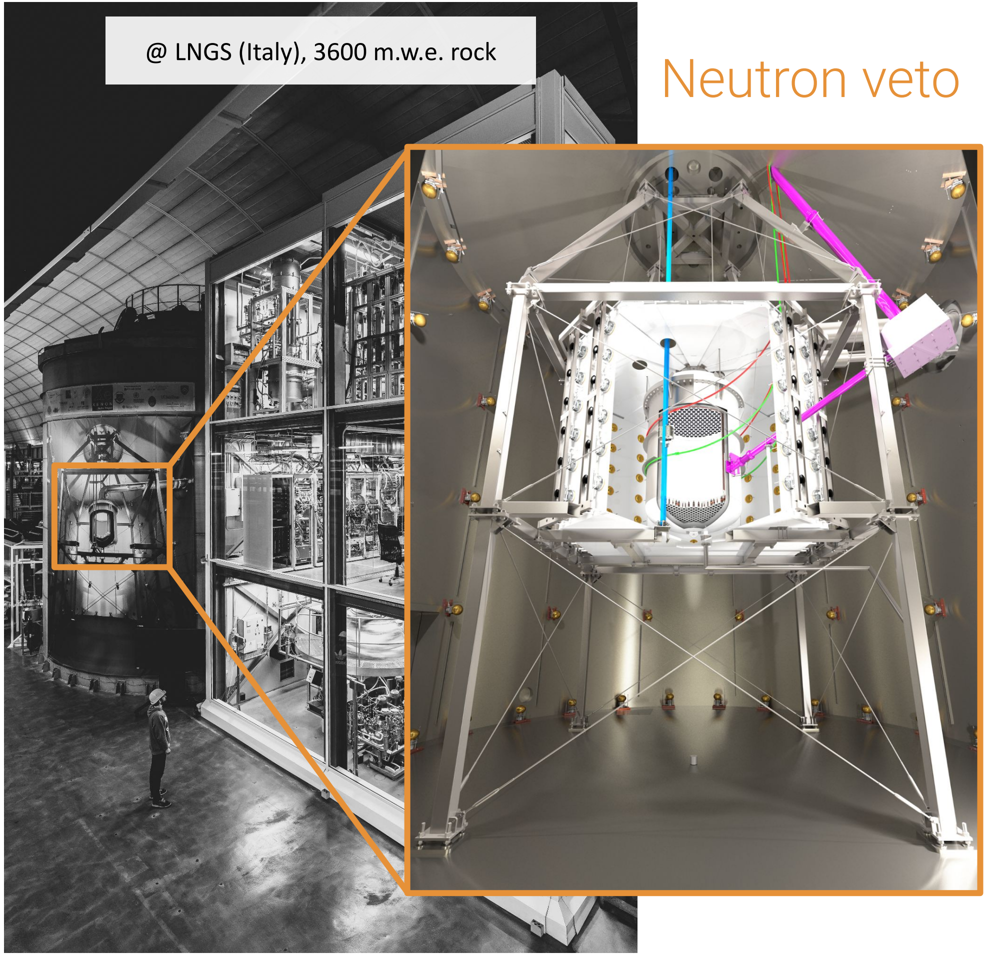


Neutron veto

- 120 (8″) PMTs facing the TPC detect Cherenkov light from 2.2 MeV gamma (n-capture on H)
- (53 ± 3) % tagging efficiency (250 μs window, 5-fold PMT coincidence) with 1.6 % lifetime loss
- 0.2 % Gd doping will improve it to ~ 87 % (150 μs, 10-fold) JCAP 11 031 (2020)
- Tagged calibration neutrons to study NR LXe response

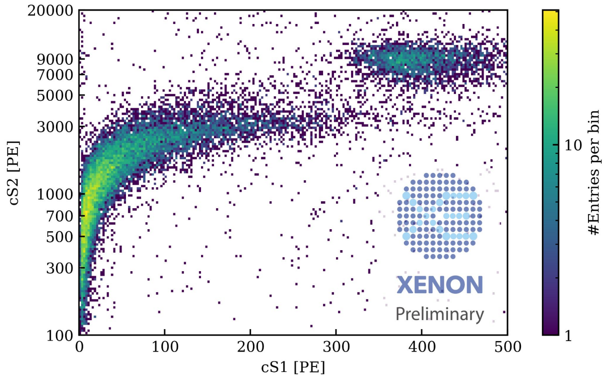


From XENON1T to XENONnT

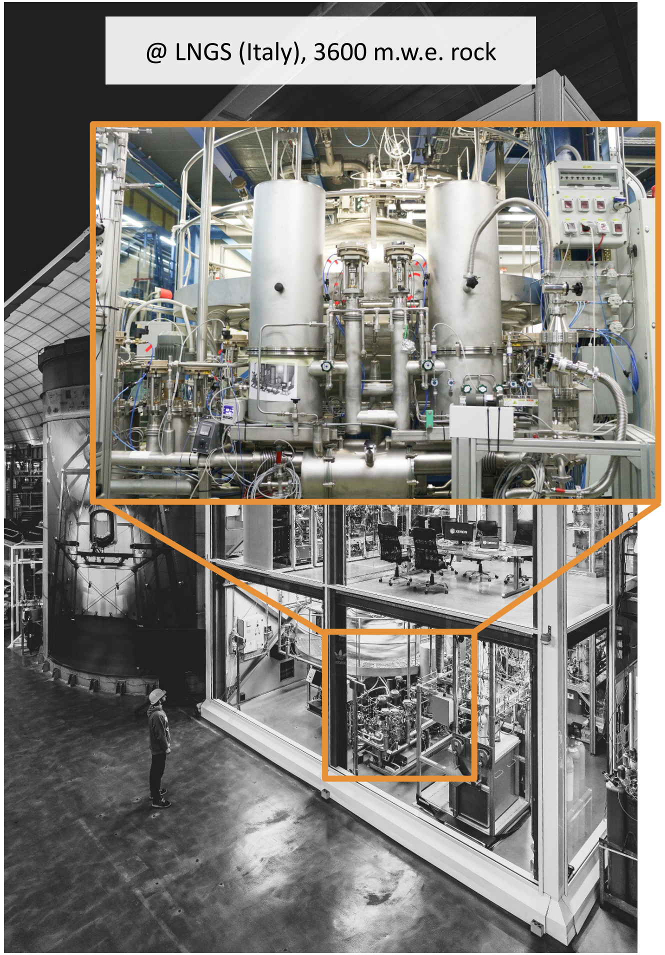


Neutron veto

- 120 (8″) PMTs facing the TPC detect Cherenkov light from 2.2 MeV gamma (n-capture on H)
- (53 ± 3) % tagging efficiency (250 µs window, 5-fold PMT coincidence) with 1.6 % lifetime loss
- 0.2 % Gd doping will improve it to ~ 87 % (150 µs, 10-fold) JCAP 11 031 (2020)
- Tagged calibration neutrons to study NR LXe response



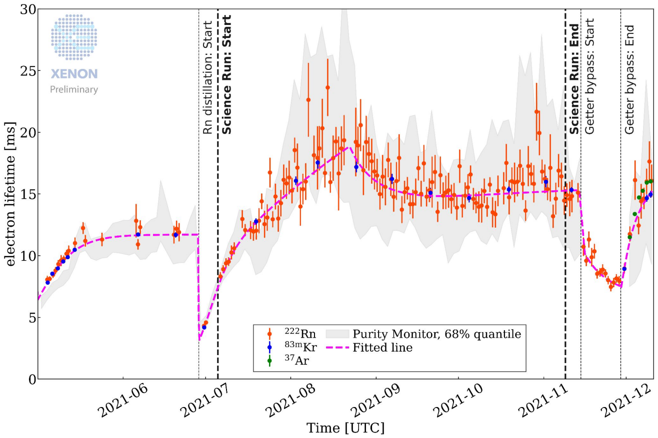
From XENON1T to XENONnT



Liquid xenon purification

Eur. Phys. J. C 82, 860 (2022)

- LXe purity is crucial for electrons to survive until liquid-gas interface
- Novel liquid-phase purification with replaceable filter units, some with extremely low radon emanation (science run mode)
- 2 liters of LXe per minute: 18 h to recirculate entire inventory



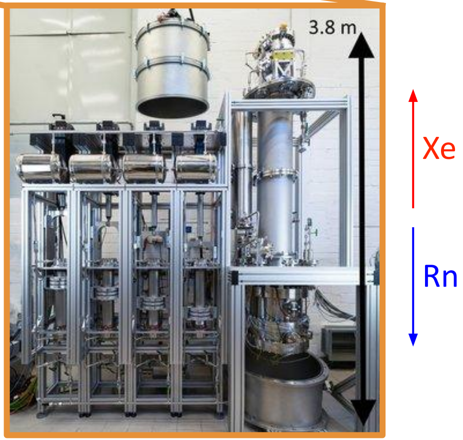
	Max. TPC drift time	Electron lifetime	e^- survival @ max. drift length
1T	0.67 ms	0.65 ms	30%
nT	**2.2 ms**	**> 10 ms**	**> 90%**

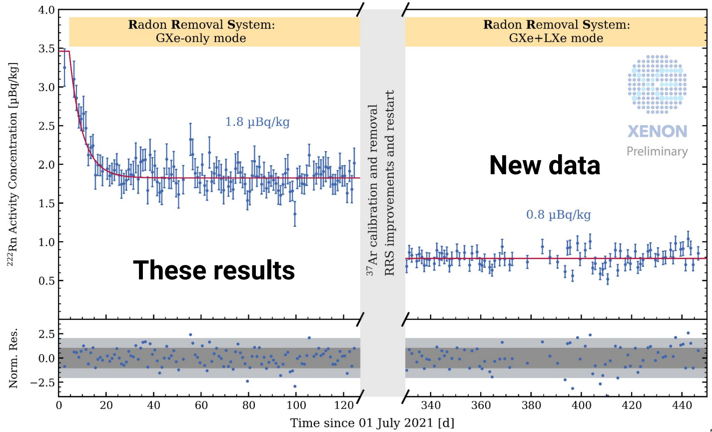
From XENON**1**T to XENON**n**T

Radon distillation column

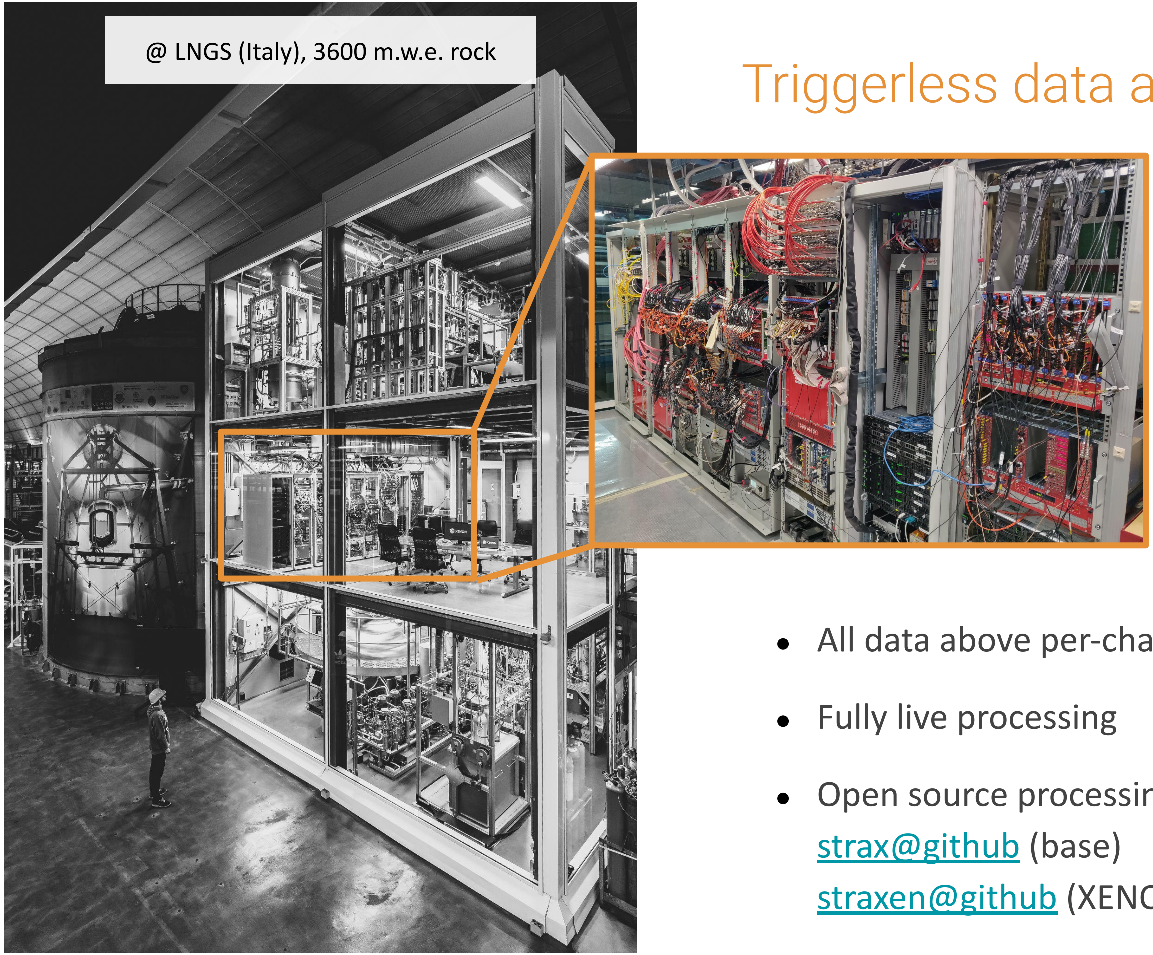
[Eur. Phys. J. C 82, 1104 (2022)]

- “Online” removal of emanating ^{222}Rn ($t_{1/2}$ = 3.8 d) exploiting difference in vapor pressure
- ^{222}Rn Activity concentration equilibrium of 1.77 ± 0.01 μBq/kg with gas extraction only (~ 13 μBq/kg in XENON1T)
- < 1μBq/kg with gas+liquid extraction in current data-taking



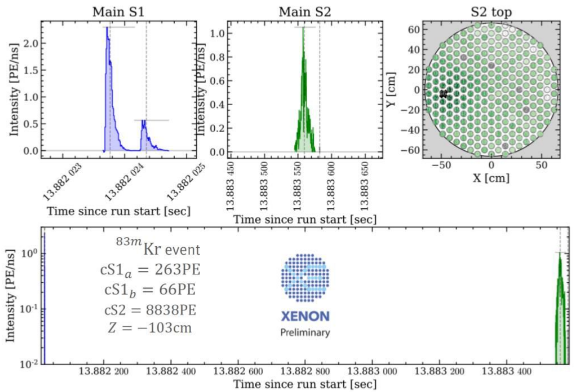


From XENON1T to XENONnT



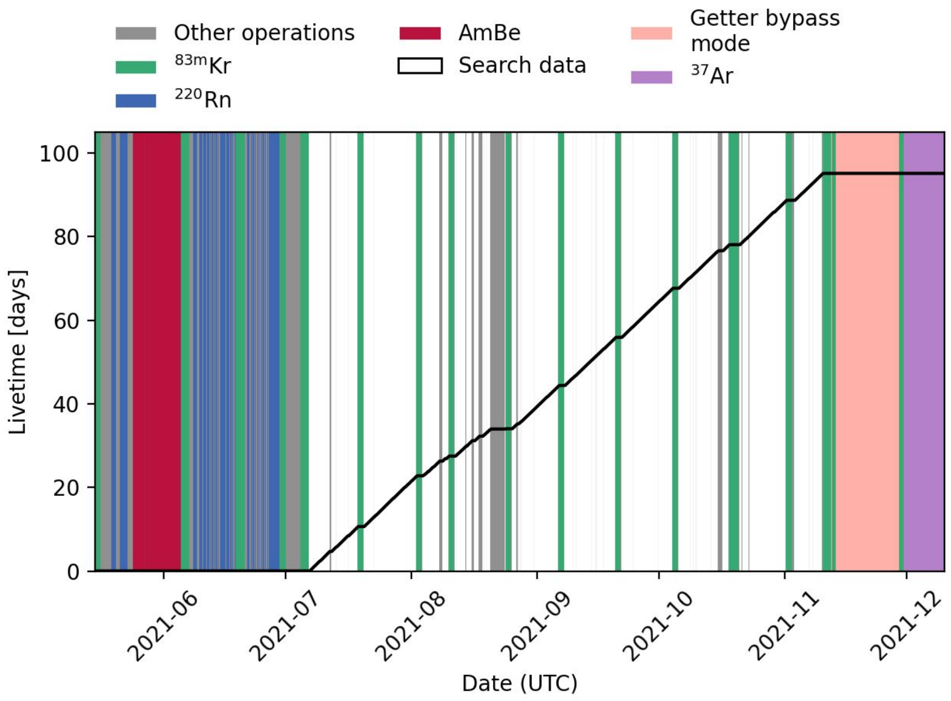
Triggerless data acquisition

JINST 18 P07054 (2023)



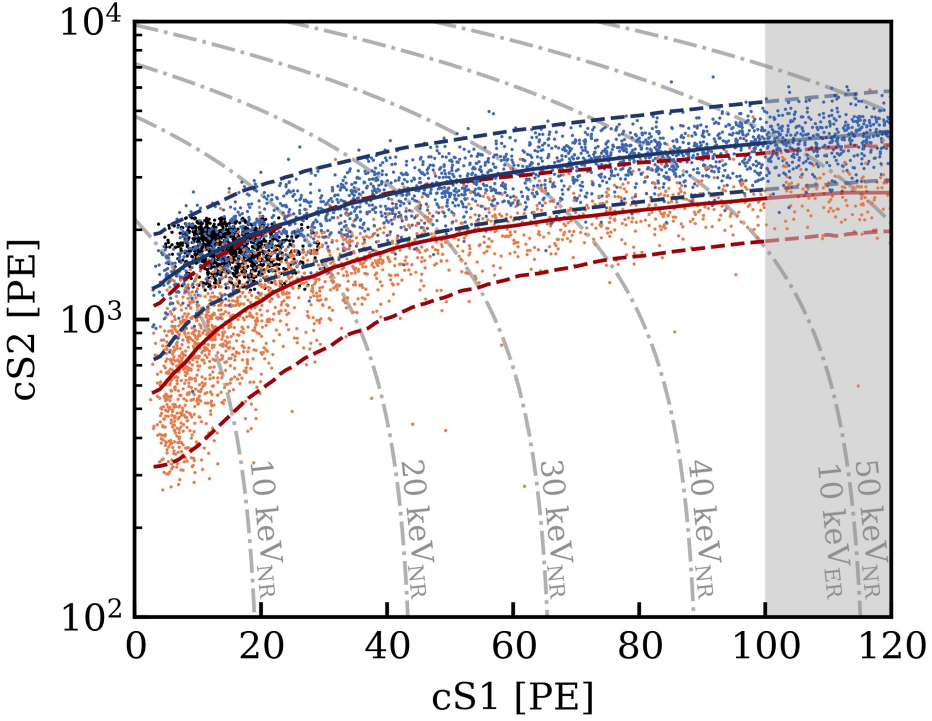
- All data above per-channel threshold stored long term
- Fully live processing
- Open source processing software:
  strax@github (base)
  straxen@github (XENONnT-tailored)

First XENONnT science run (SR0)



- **97.1 days of exposure** from July 6th - Nov 11th 2021 (95.1 days lifetime corrected)
- Radon column operating in gas-only mode
- 477/494 PMTs operative, gain variations below 3% level
- 23 V/cm drift field (cathode limited to –2.75 kV due short-circuit with bottom screen mesh)
- Extraction field in LXe 2.9 kV/cm
- Localized high single-electron emission sporadically, anode ramped down

Detector calibration



ER response model (combined fit)

^{212}**Pb** from ^{220}**Rn** gives a roughly flat β-spectrum, to estimate cut acceptances and energy threshold

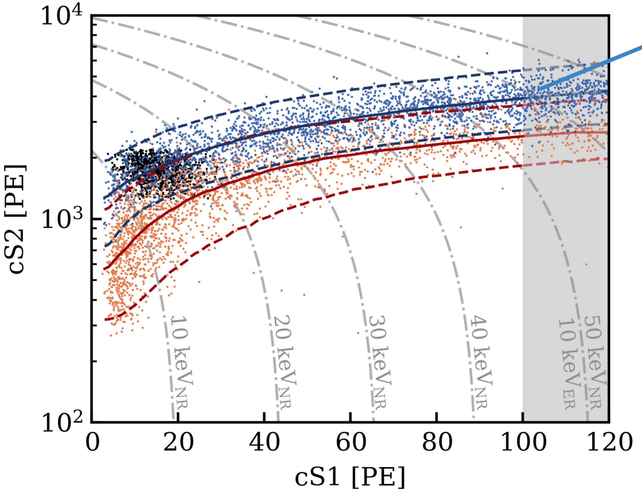
^{37}**Ar** gives a mono-energetic 2.82 keV peak, to model low-energy response and resolution near detector energy threshold

NR response model

^{241}**AmBe** external source emits neutrons which are tagged using the coincident 4.4 MeV γ-ray observed in the neutron veto

New physics searches

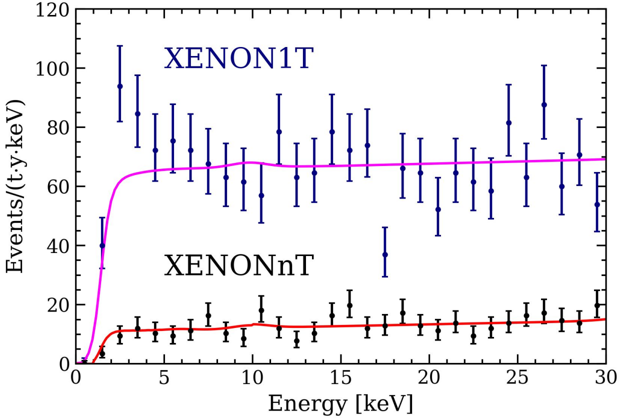
Blinded ER and NR analyses



PRL 129, 161805 (2022)

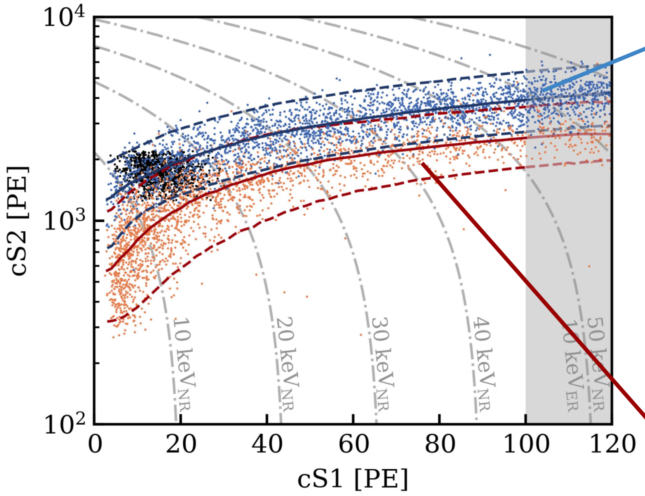
Electronic recoils

- Combine S1 and S2 signals for search in reconstructed energy
- Lowest ever ER background in the field: (15.8 ± 1.3) (t yr keV)$^{-1}$
- No low-energy ER excess found (beyond-SM explanation for XENON1T excess excluded)



New physics searches

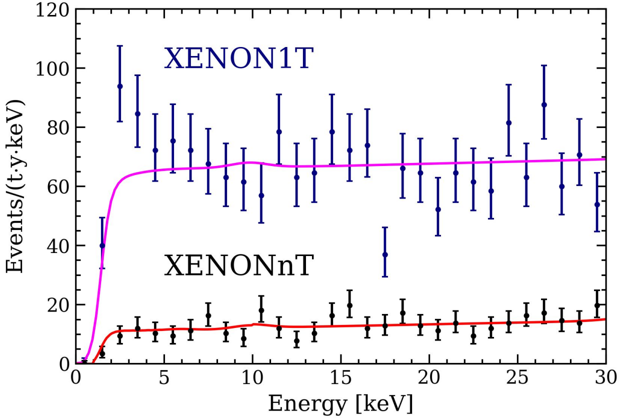
Blinded ER and NR analyses



PRL 129, 161805 (2022)

Electronic recoils

- Combine S1 and S2 signals for search in reconstructed energy
- Lowest ever ER background in the field: (15.8 ± 1.3) (t yr keV)$^{-1}$
- No low-energy ER excess found (beyond-SM explanation for XENON1T excess excluded)



PRL 131, 041003 (2023)

Nuclear recoils (this talk)

- Much lower NR background thanks to ER/NR discrimination
- Search in S1, S2 and radius
- 4.18 t fiducial mass (out of 5.9 t), total exposure of 1.1 t yr

Detection and selection efficiencies

Detection efficiency

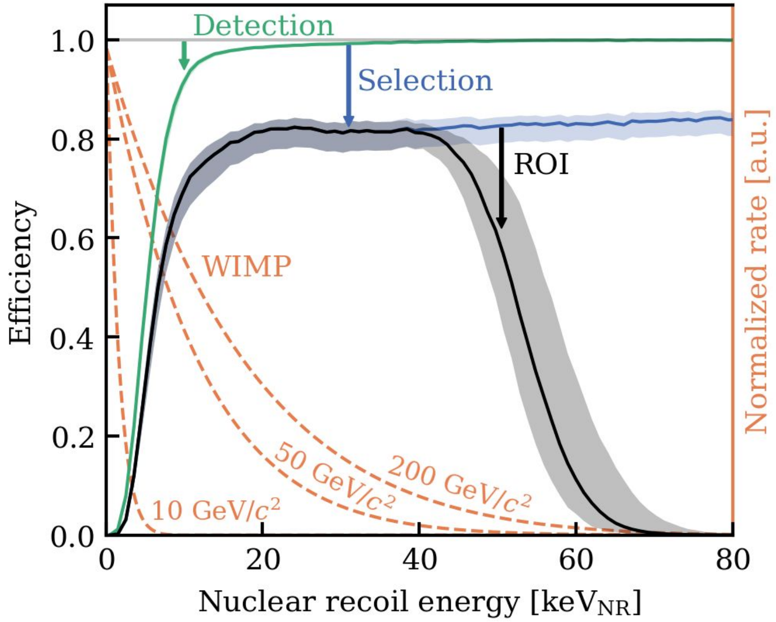
- Driven by 3-fold PMT coincidence requirement to identify an S1
- Data- and simulations-driven, with good agreement

Selection criteria (~ 80 % acceptance)

- S1 and S2 peaks must have PMT patterns, top/bottom area ratios, etc. consistent with real events
- S2 width consistent with the expected diffusion of electrons along drift path
- Single-site (signal-like) events

Region of interest (ROI)

- Constructed to fully contain the WIMP (GeV-scale) recoil spectra
- cS1: 0 - 100 PE | cS2: $10^{2.1}$ - $10^{4.1}$ PE

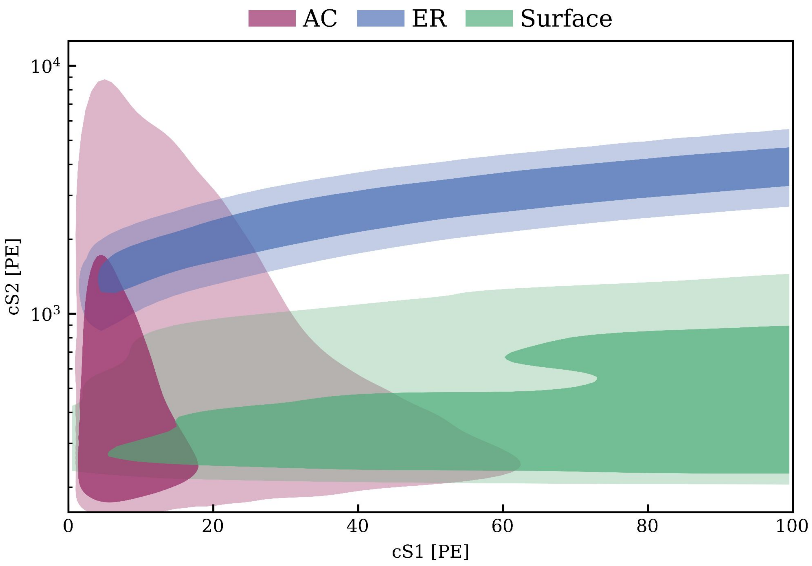


Backgrounds in the WIMP search

Electronic recoil (ER)
Mainly β-decay of ^{214}Pb

Accidental coincidence (AC)
Random pairing of isolated S1 and S2 signals; suppressed by GBDT cut based on S2 shape

Nuclear recoil (NR)
Radiogenic neutrons constrained by neutron veto tagging (~1.1 events), CEvNS less than 0.2 events due to decreased efficiency at low energies



Surface background
^{210}Pb plate-out on TPC walls, leading to ^{210}Po α-decays with electron loss; suppressed by volume fiducialization

Backgrounds in the WIMP search

Electronic recoil (ER)

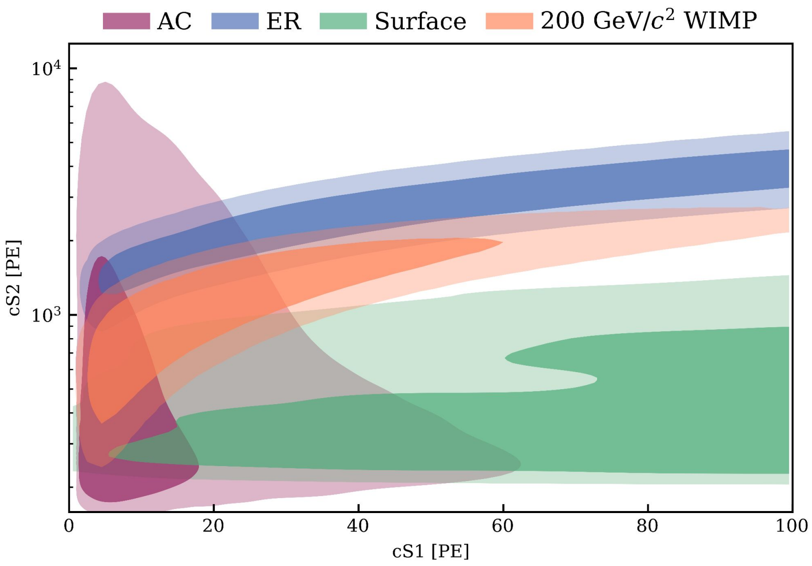
Mainly β-decay of ^{214}Pb

Accidental coincidence (AC)

Random pairing of isolated S1 and S2 signals; suppressed by GBDT cut based on S2 shape

Nuclear recoil (NR)

Radiogenic neutrons constrained by neutron veto tagging (~1.1 events), CEvNS less than 0.2 events due to decreased efficiency at low energies

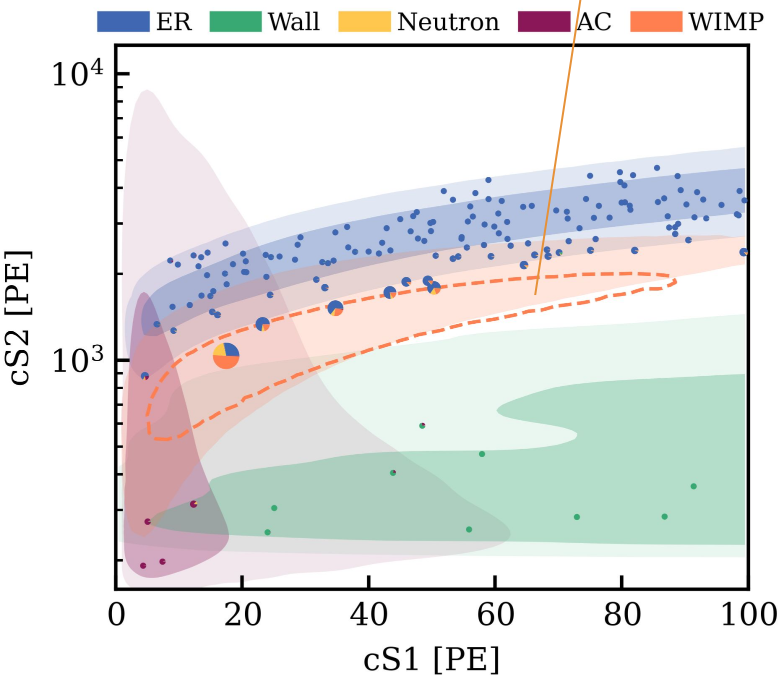


Surface background

^{210}Pb plate-out on TPC walls, leading to ^{210}Po α-decays with electron loss; suppressed by volume fiducialization

WIMP search results

Signal-like region containing 50% of WIMP signal with lowest background



200 GeV/c^2

	Expected	Best fit
ER	134	135 (+12) (−11)
Neutrons	1.1 (+0.6) (−0.5)	1.1 ± 0.4
CEvNS	0.23 ± 0.06	0.23 ± 0.06
AC	4.3 ± 0.2	4.32 ± 0.15
Surface	13 ± 3	12 (+0) (−4)
Tot. background	**154**	**152 ± 12**
WIMP	**-**	**2.6**
Observed	**-**	**152**

No significant excess, 152 events in ROI, 16 in blinded region

WIMP-nucleon cross section limit

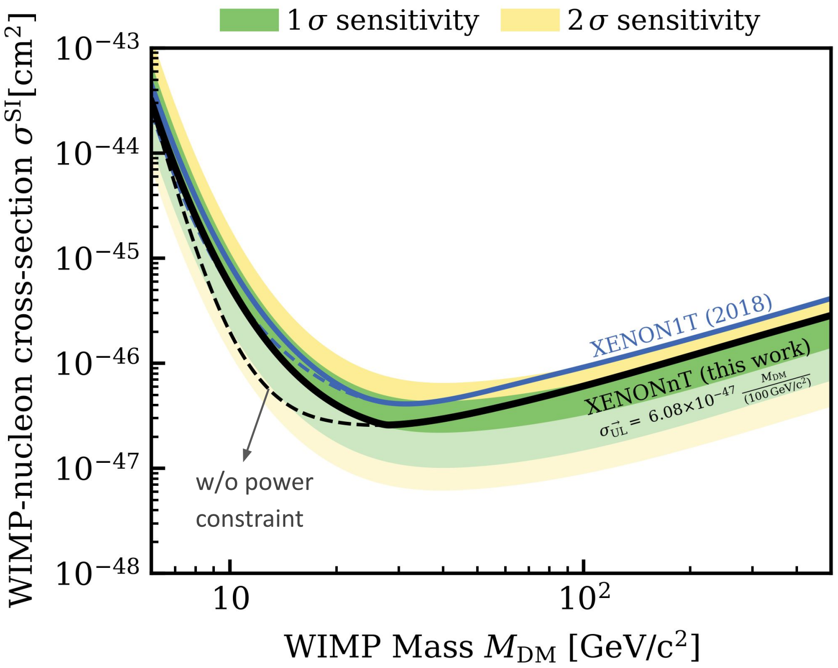
Limit setting

- Unbinned maximum likelihood
- Power-constrained limits (PCL) based on rejection power to avoid spurious exclusion limits
- Conservative choice at median of sensitivity band (pending renewed agreement with community)

Strongest limit: **2.6 · 10^{-47} cm^2** at WIMP mass of **28 GeV/c^2**

Factor 1.6 improvement w.r.t. XENON1T (with considerably shorter lifetime)

Similar improvements in spin-dependent limits



WIMP-nucleon cross section limit

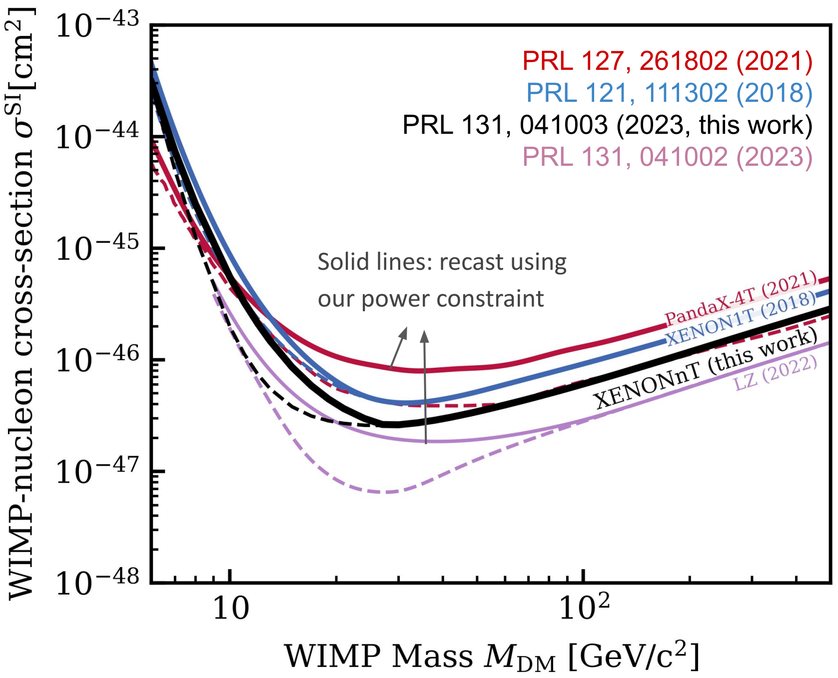
Limit setting

- Unbinned maximum likelihood
- Power-constrained limits (PCL) based on rejection power to avoid spurious exclusion limits
- Conservative choice at median of sensitivity band (pending renewed agreement with community)

Strongest limit: **2.6 · 10^{-47} cm^2** at WIMP mass of **28 GeV/c^2**

Factor 1.6 improvement w.r.t. XENON1T (with considerably shorter lifetime)

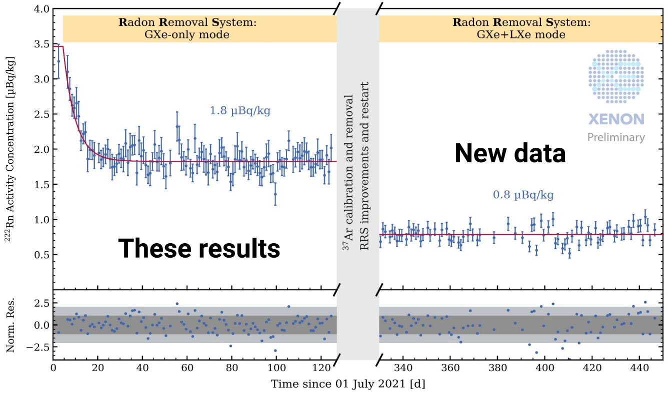
Similar improvements in spin-dependent limits



Summary and outlook

XENONnT SR0:

- Ultrapure target, with an electron lifetime stably above 10 ms
- Lowest ER background in the field: (15.8 ± 1.3) $(t\ yr\ keV)^{-1}$ (~ 5x background reduction w.r.t. XENON1T)
- First blinded searches for electronic and nuclear recoil signals yielded no significant excess over background



Taking more data with:

- 50 % lower ^{222}Rn level by changing flow path
- Planned Gd-loaded neutron veto with ~ 87 % neutron background tagging efficiency

Better WIMP limits, solar neutrinos, double weak decays and more…

Gd plant and mixing of Gd salt in water

xenonexperiment.org

xenon_experiment

xenonexperiment

Summary and outlook

XLZD meeting @ Karlsruhe, June 2022

XLZD consortium

Joining forces towards a next-generation dark matter experiment

(white paper: J. Phys. G 50 (2023) 013001)

XENON

Currently operating with 8.5 tonnes of liquid Xenon at Gran Sasso in Italy

LUX-ZEPLIN

Currently operating with 10 tonnes of liquid Xenon at SURF in South Dakota

DARWIN

Leading many R&D projects designing a future 50 tonnes liquid Xenon detector

xenonexperiment.org

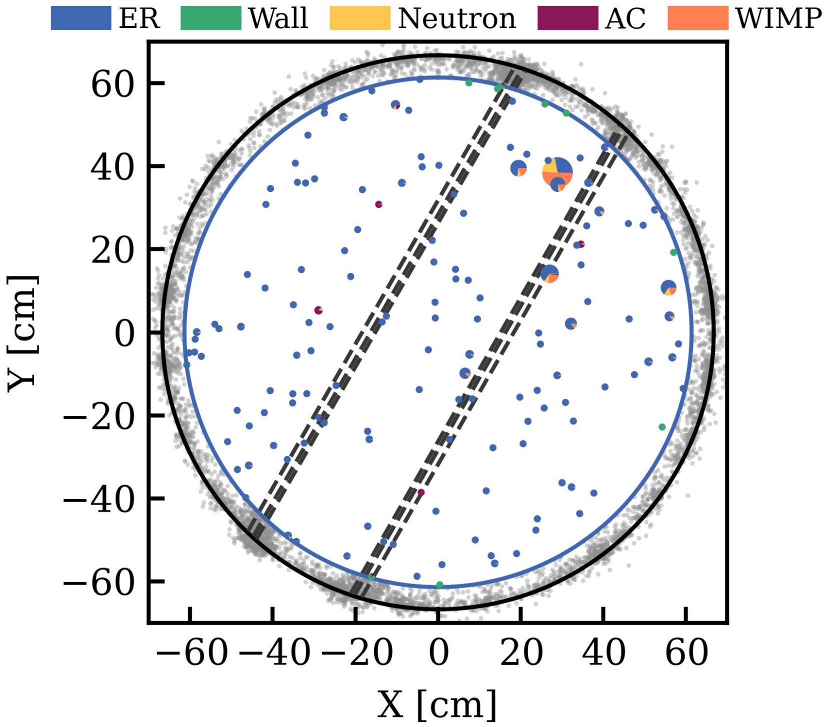
xenon_experiment

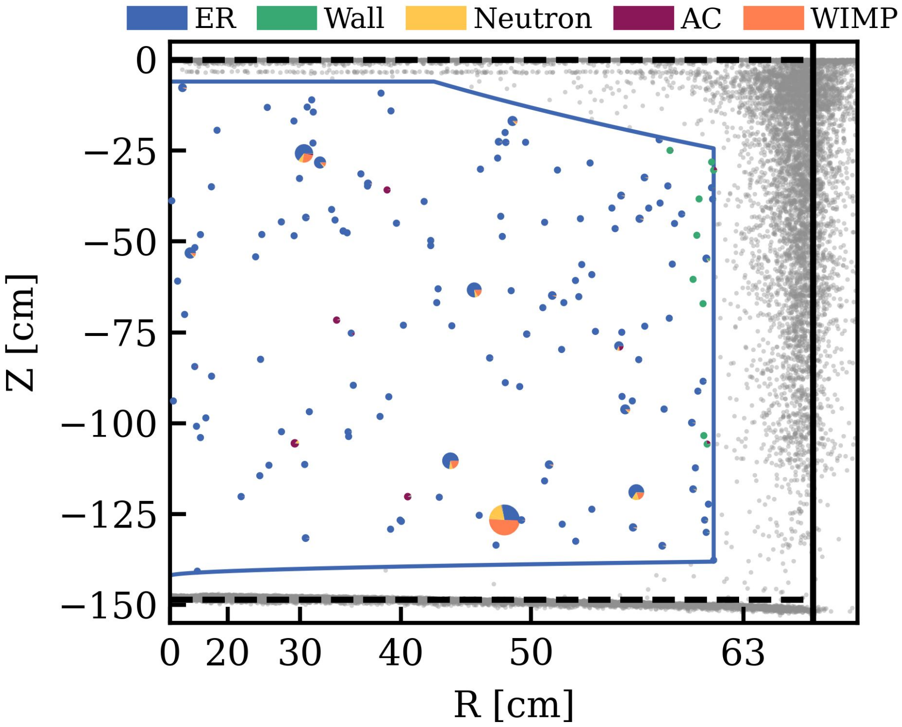
xenonexperiment

xlzd.org

Backup

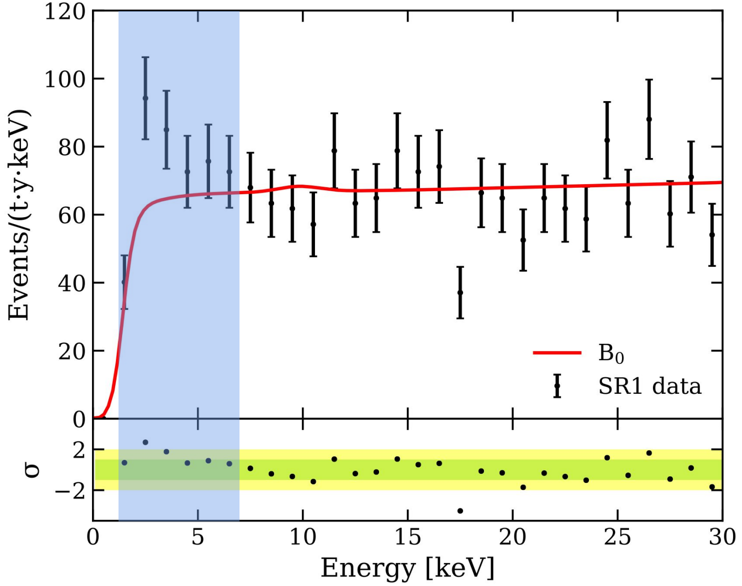
WIMP pie charts





Low-energy ER excess in XENON1T

PRD 102, 072004 (2020)



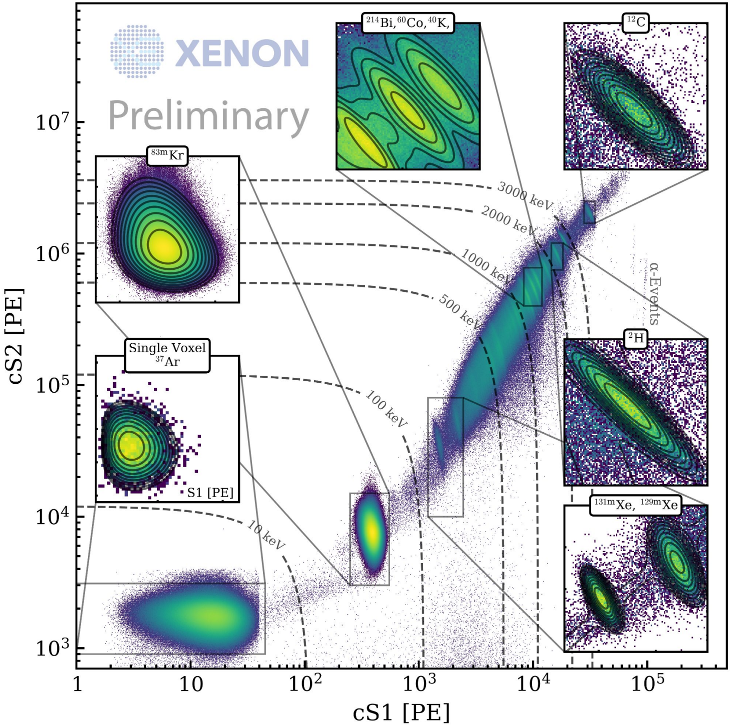
285 events observed vs. 232 ± 15 expected

3.3σ Poissonian fluctuation

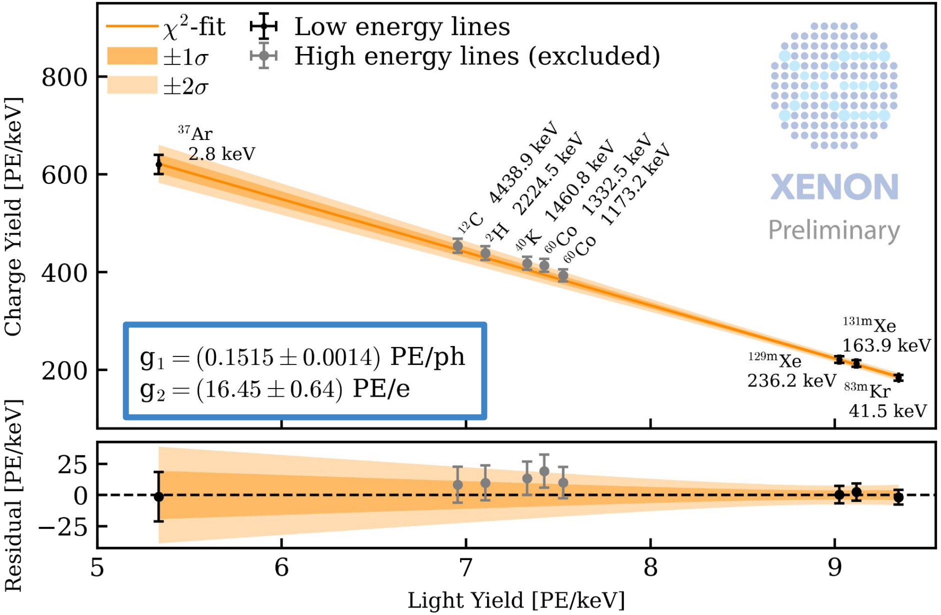
- Compatible with various **beyond-SM** signatures (solar axions, ALPs, dark photons, enhanced neutrino magnetic moment, …)
- Consistent with **potential tritium (^3H) background**, but required contamination conflicts with observed target purity and transparency
- **^{37}Ar removed** by the online Kr distillation. Air leak at 13 l/y could explain excess, but upper limit is 0.9 l/y
- Addressing this question with first XENONnT science data

Energy reconstruction

- Four low-energy calibration points: ^{37}Ar, ^{83m}Kr, ^{129m}Xe and ^{131m}Xe
- Observed 1-2% bias in reconstructed energy used as systematic uncertainty in modeling

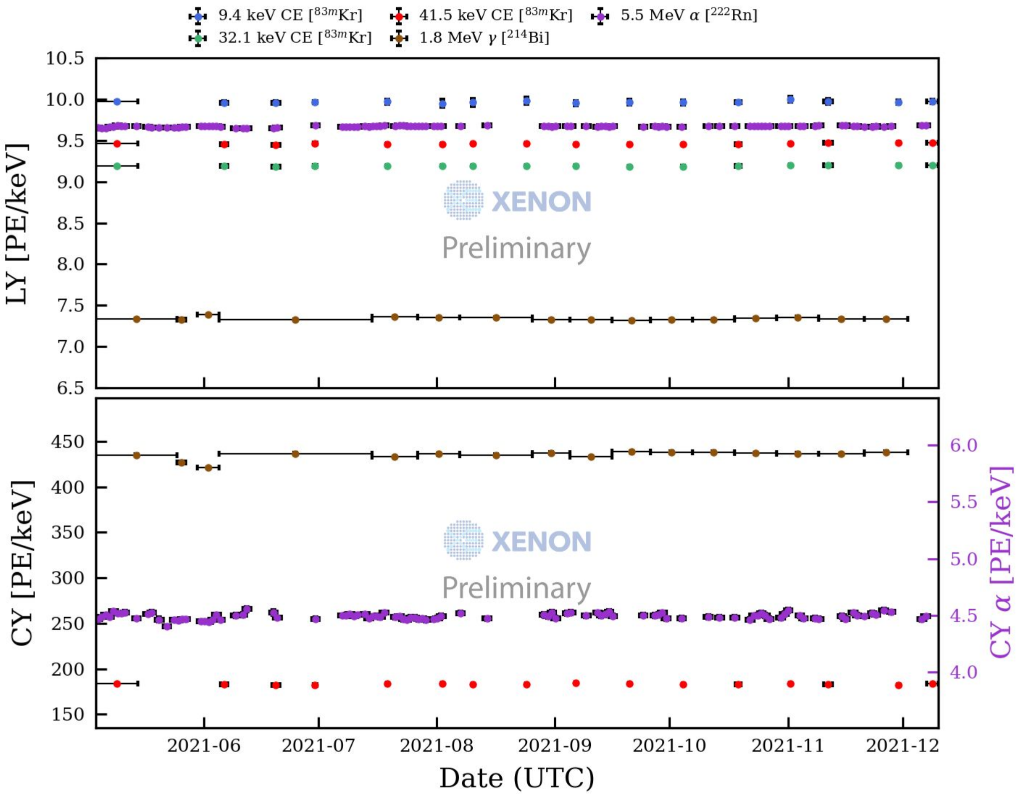


$$E = 13.7\text{eV}\left(\frac{cS1}{g_1} + \frac{cS2}{g_2}\right)$$



Detector response stability

Bi-weekly ^{83m}Kr, α's from ^{222}Rn and γ's from materials background used for monitoring light and charge yields



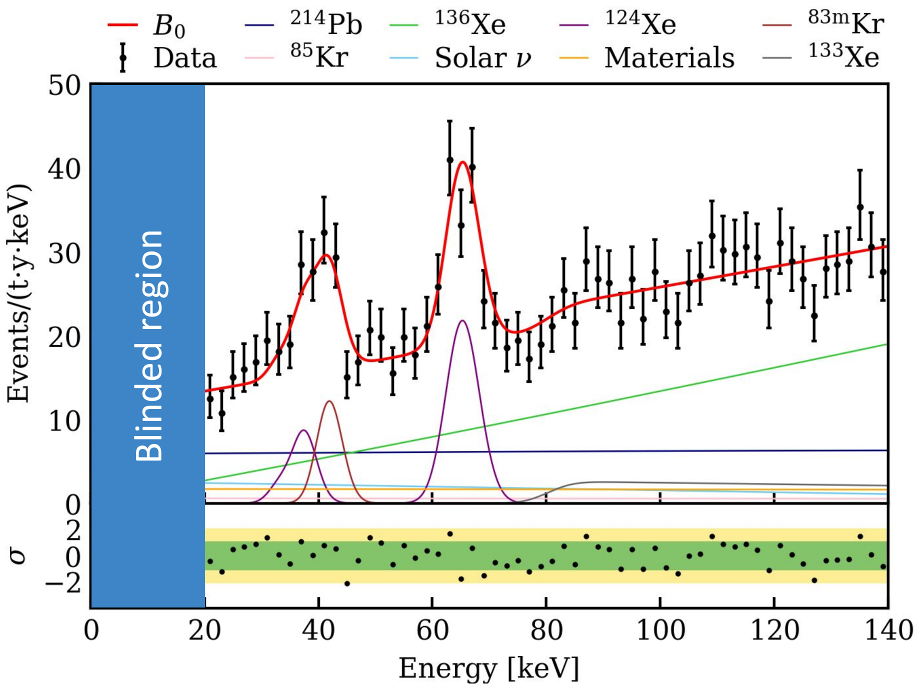
ΔLY = 1%

ΔCY = 1.9%

Electronic recoil background model

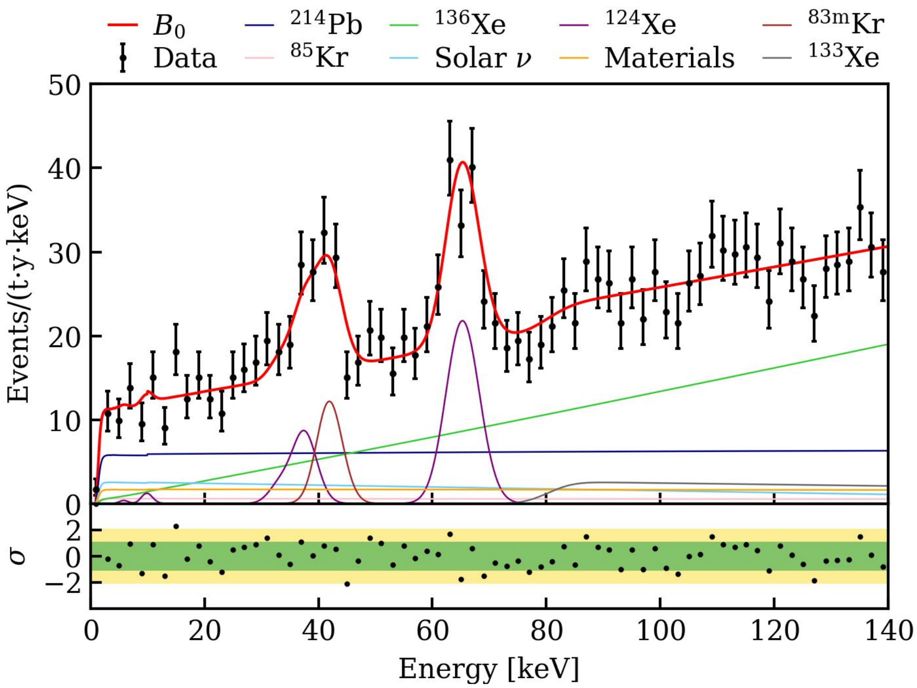
- Energy range (1, 140) keV, exposure 1.16 t y
- NR and ER data below 20 keV blinded
- Background estimates:
  - Constraints by external measurements
  - Data-driven accidental coincidence model
  - Verification in side band before unblinding
  - Double weak processes 2vECEC (^{124}Xe) and 2vββ (^{136}Xe) dominate background
- Various unblinding stages:
  - (10, 20) keV sideband, accidental coincidence, wall sample, full range

PRL 129, 161805 (2022)



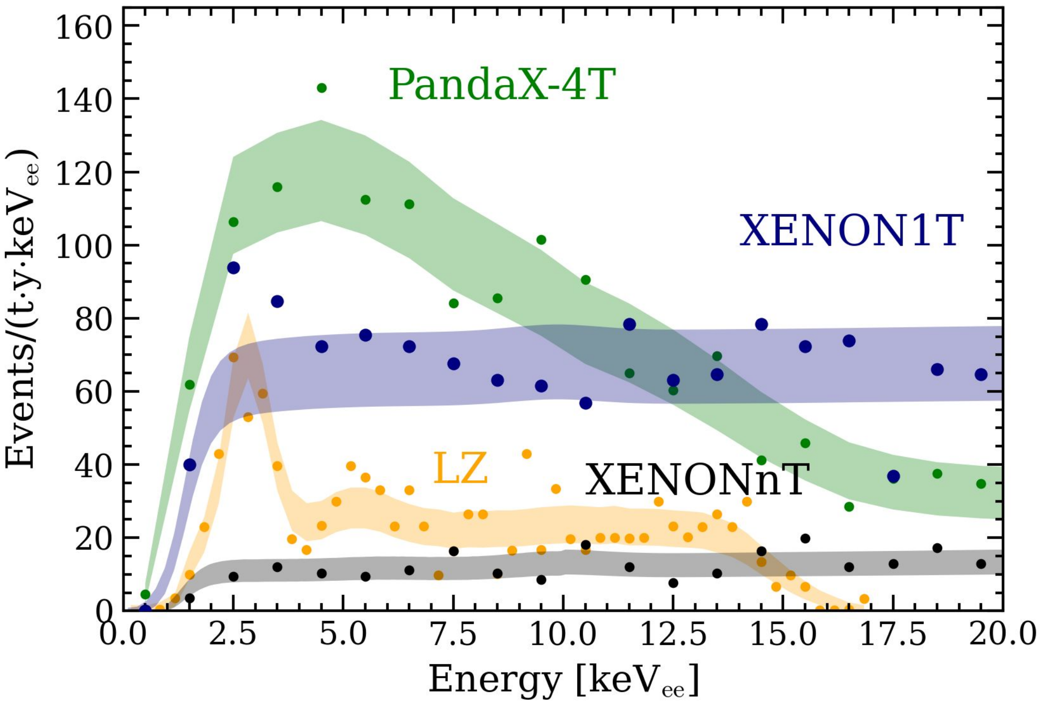
Electronic recoil unblinding

PRL 129, 161805 (2022)



- **No excess observed**
- **A small ^{3}H contamination is the most plausible explanation for the XENON1T excess**. Further time-stability studies in preparation

XENON1T vs. XENONnT



PRL 129, 161804 (2022)
PRD 102, 072004 (2020)
PRL 131, 041002 (2023)
PRL 129, 161805 (2022)

- Factor five background reduction with respect to XENON1T
- No excess below 5 keV found: 8.6σ exclusion on XENON1T excess

Constraints on BSM physics

PRL 129, 161805 (2022)