Direct Dark Matter Search with the
XENON1T EXPERIMENT

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INFN Bologna

WIN2019 | Bari | 5 June 2019

THE XENON COLLABORATION

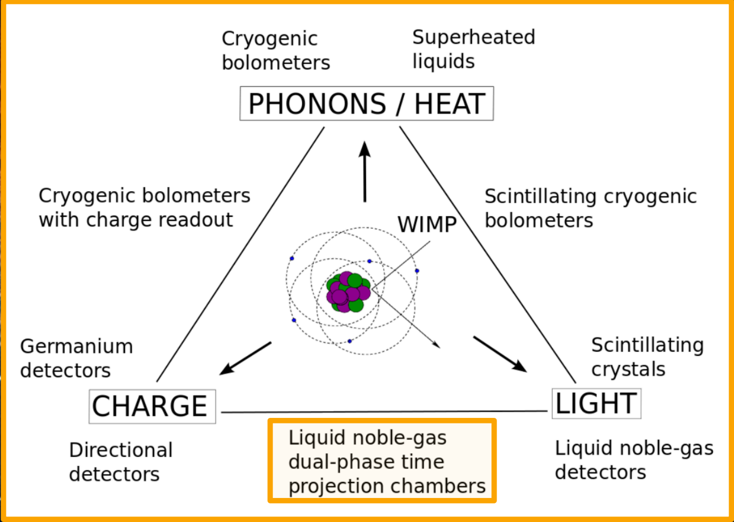
160 SCIENTISTS

27 INSTITUTIONS

11 COUNTRIES

DARK MATTER DETECTION STRATEGY

- **DIRECT DETECTION**
- **INDIRECT DETECTION**
- **PRODUCTION AT COLLIDERS**



XENON TARGET FOR WIMP INTERACTION

HIGH A=131
$\sigma_{WIMP-N} \sim A^2$ → Larger probability of SI WIMP-nucleon interactions

SELF SHIELDING
High Z=54 and high density ρ=2.8 g/cm^3

SCALABILITY
Compact detectors scalable to larger dimensions

HIGH PURITY
^{136}Xe decay rate negligible
^{85}Kr removed to <ppt level

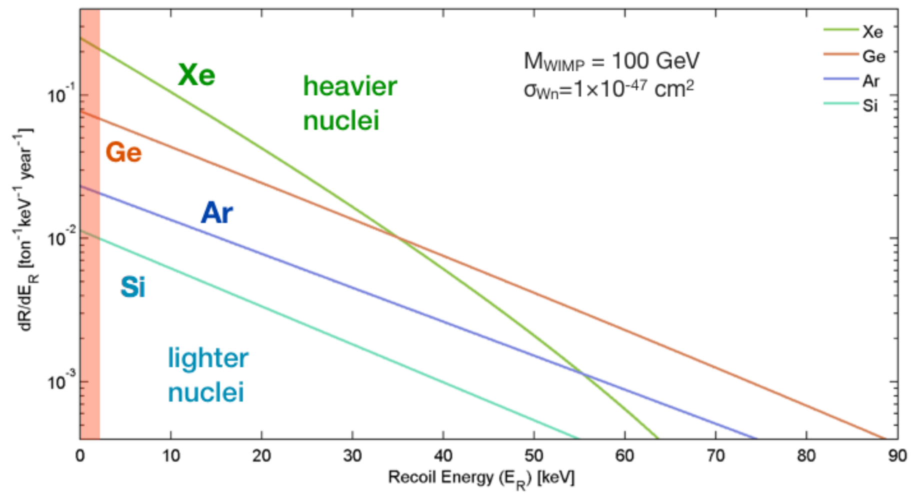
LIGHT AND CHARGE YIELDS
Highest among noble liquids

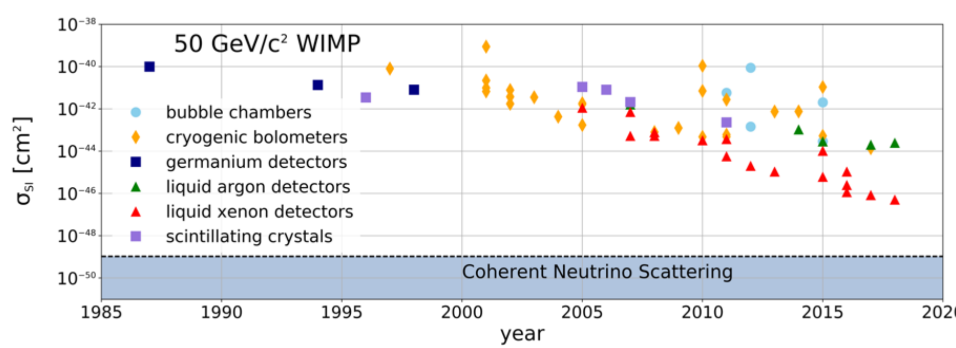
"EASY" CRYOGENICS
Xenon is liquid at -95° C

VUV SCINTILLATION LIGHT
178 nm → no need for wavelength shifters

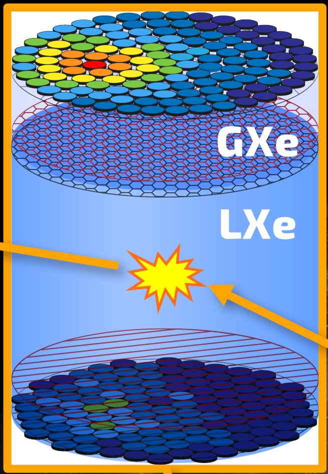
ODD-NUCLEON ISOTOPES
^{131}Xe and ^{129}Xe allow to study also the Spin-Dependent interaction

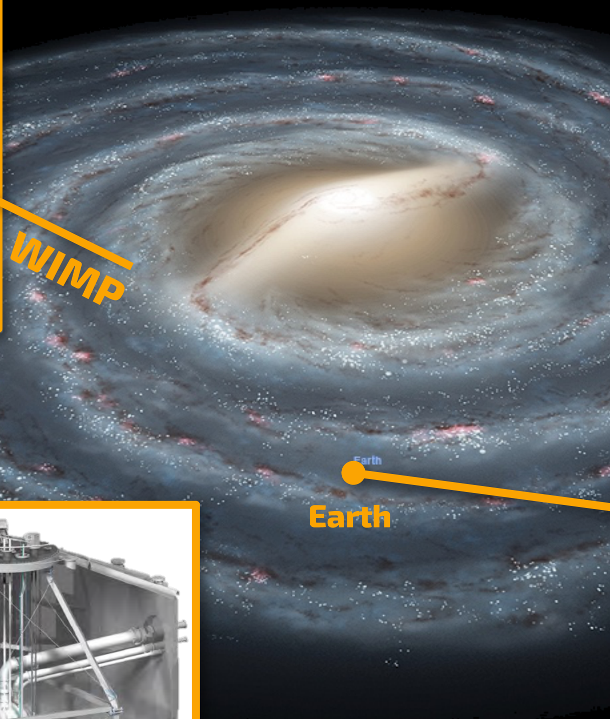
WIMP SIGNATURE
Single elastic scatter on target nucleus
Recoil energy <50 keV





DARK MATTER SEARCH WITH XENON1T





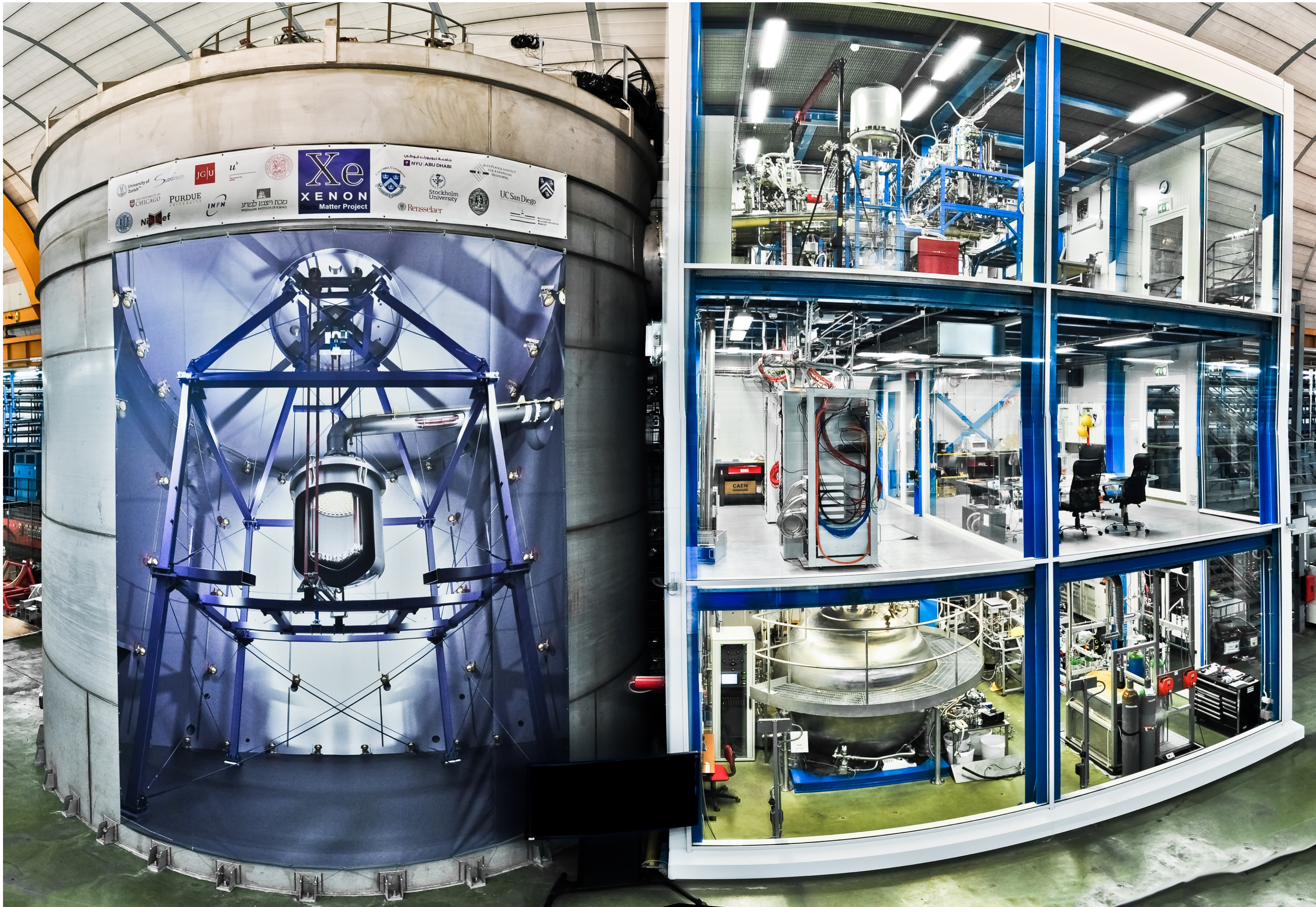
UNDERGROUND LNGS (ITALY)
3600 m.w.e. rock shielding

MUON VETO CHERENKOV DETECTOR
700 tonnes active ultra-pure water shield instrumented with 84 PMTs

THE XENON1T EXPERIMENT

AT LNGS

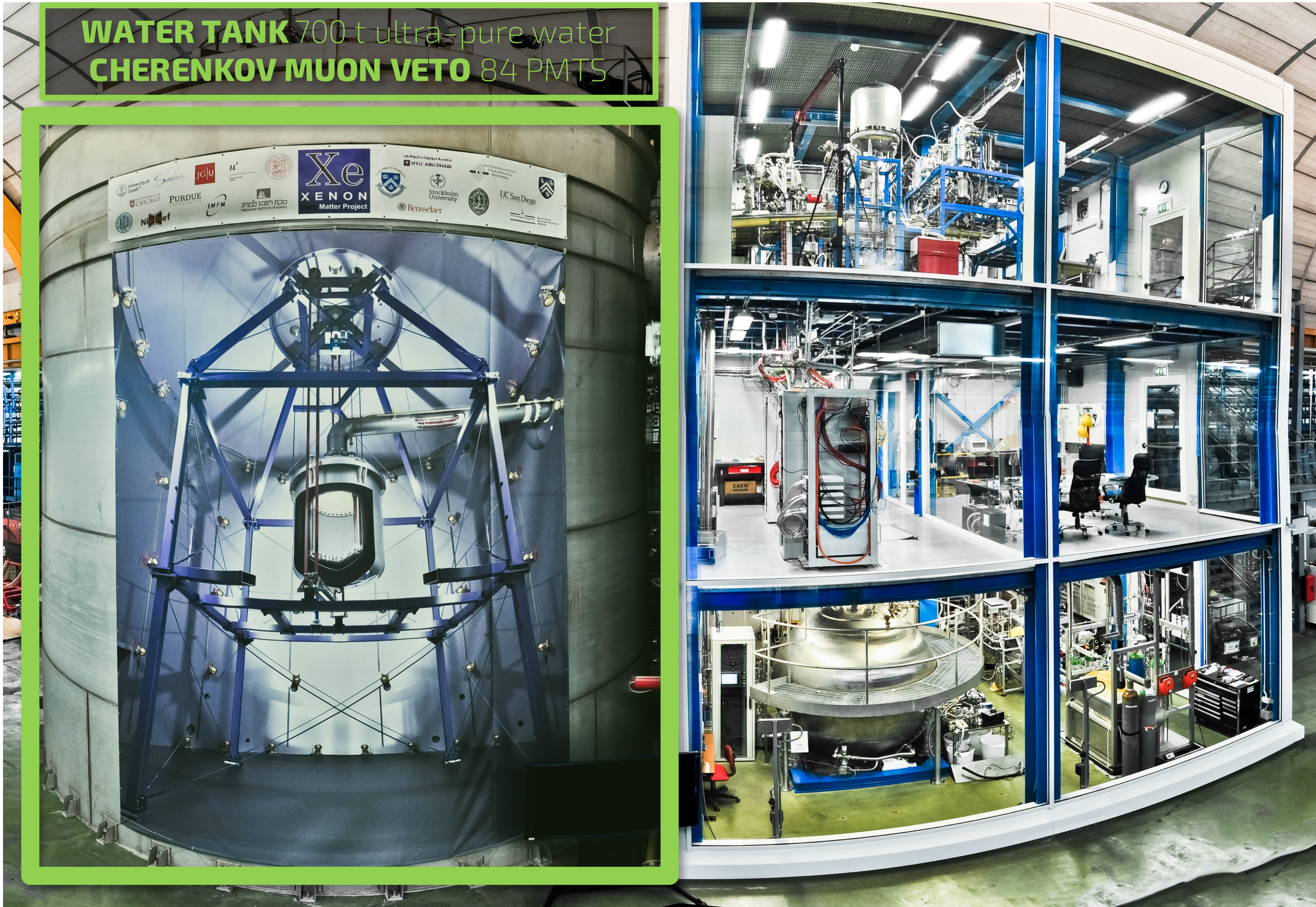
Eur. Phys. J. C. (2017) 77:881



THE XENON1T EXPERIMENT

AT LNGS

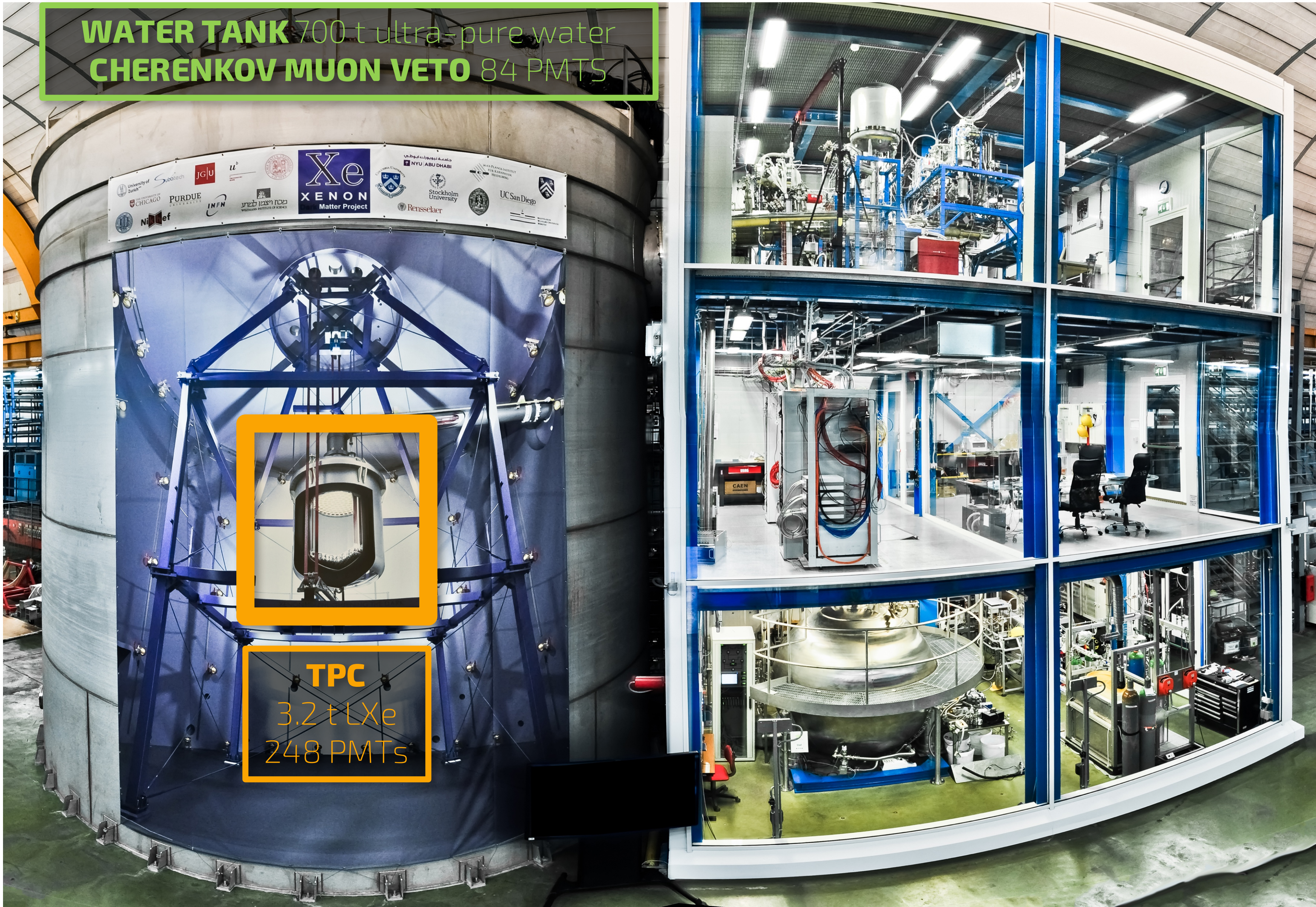
[Eur. Phys. J. C. (2017) 77:881]



THE XENON1T EXPERIMENT

AT LNGS

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



THE XENON1T EXPERIMENT

AT LNGS

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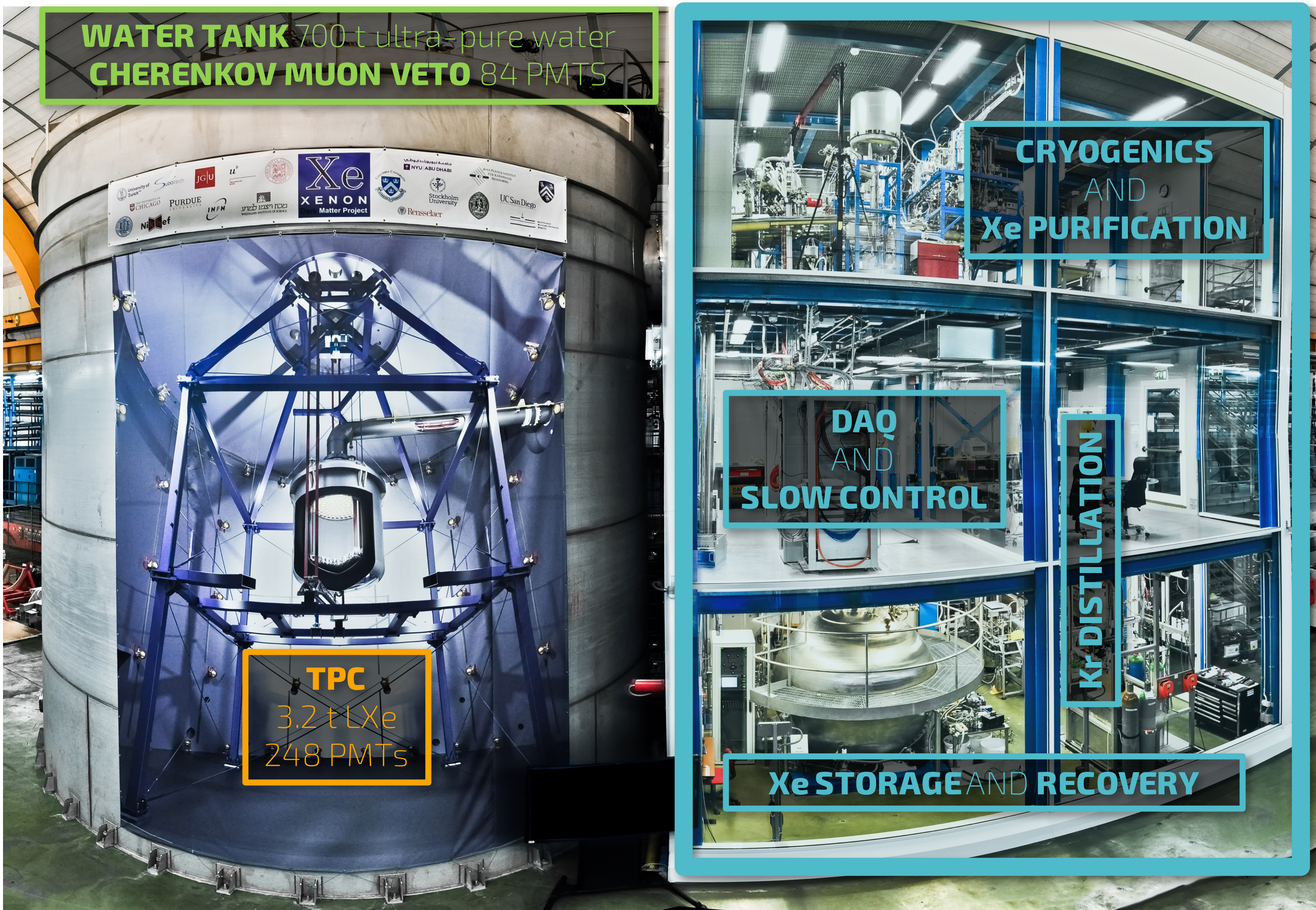


LIQUID XENON-BASED DETECTORS

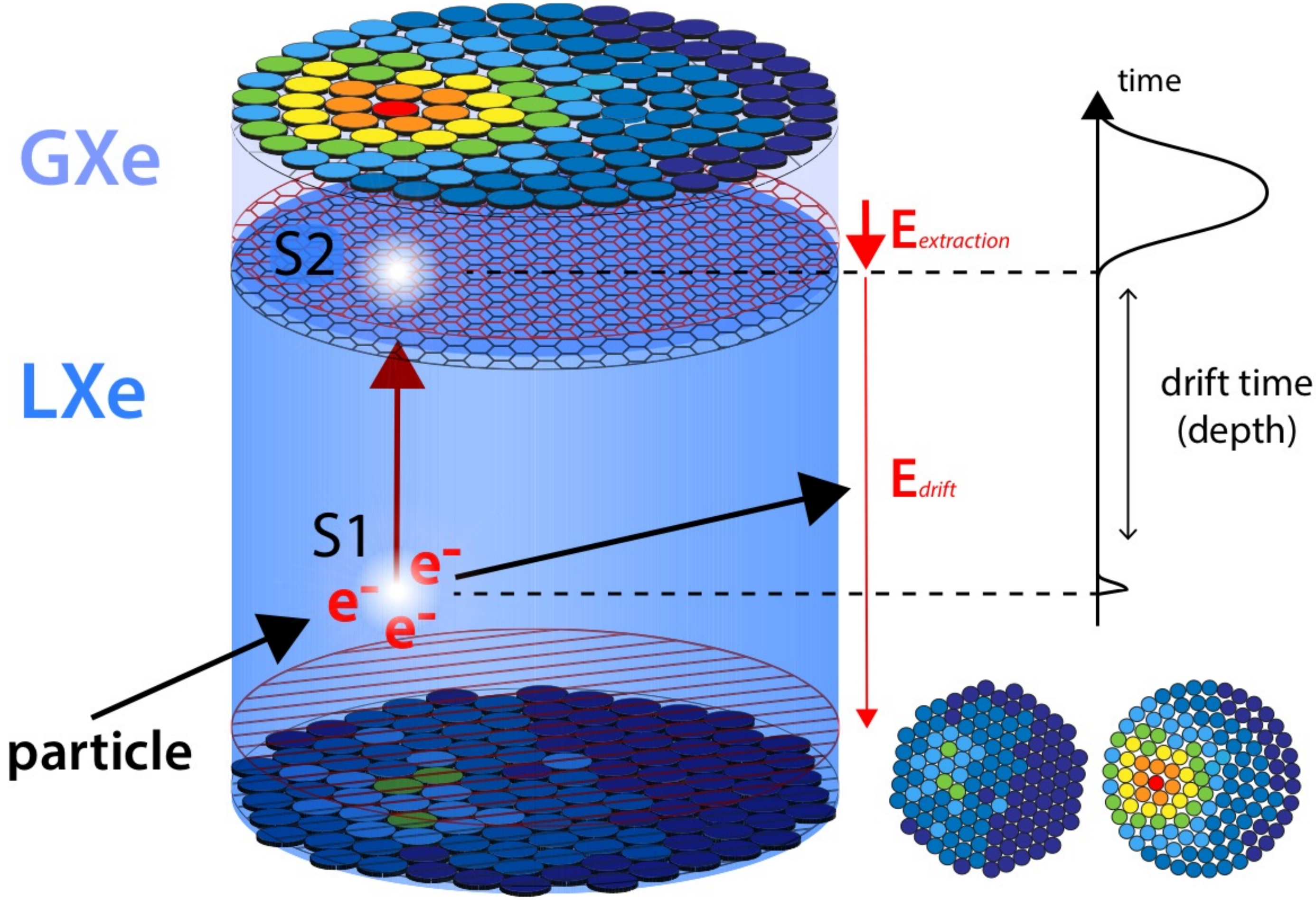
EVOLUTION OF SPECIES

LOADING

TOTAL LXe mass
3.2 tonnes

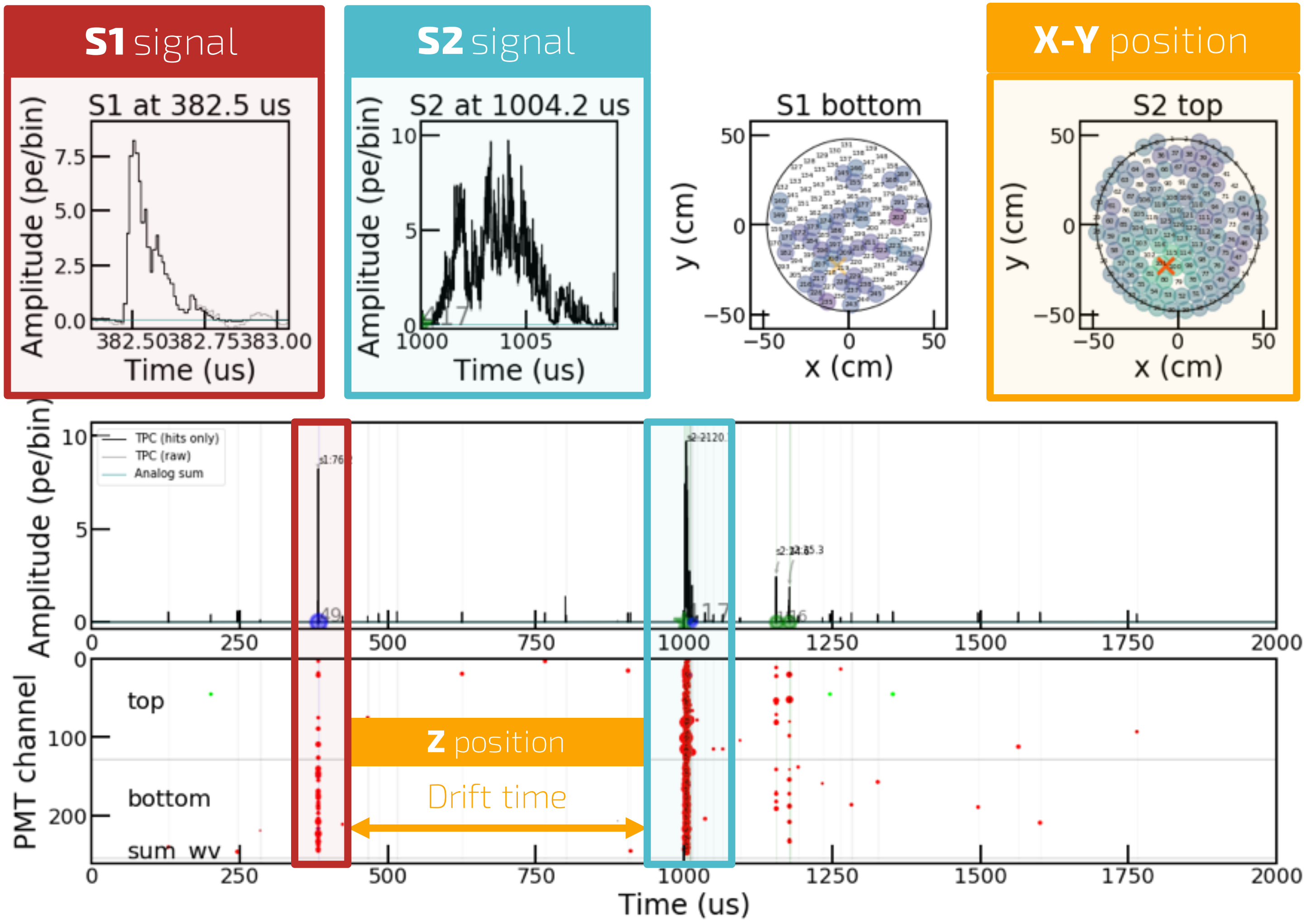
	XENON10	XENON100	LUX	PANDA X-II	**XENON1T**	XENONnT
Year	2005	2008	2013	2016	**2016**	2019
ACTIVE LIQUID XENON TARGET MASS	22 kg	105 kg	250 kg	580 kg	**2000 kg**	6000 kg
LOW ENERGY ER BACKGROUND $[t \cdot d \cdot keV]^{-1}$		5.3	2.6	0.8	**0.2**	0.02 (Goal)

DETECTION PRINCIPLE



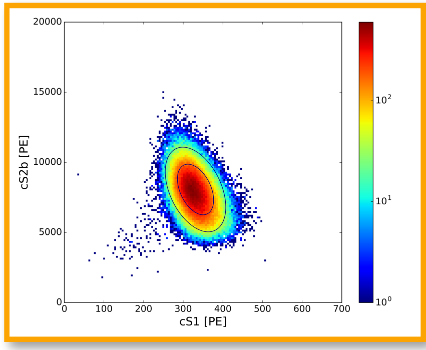
A REAL XENON1T WAVEFORM

PAX
Processor for Analyzing XENON



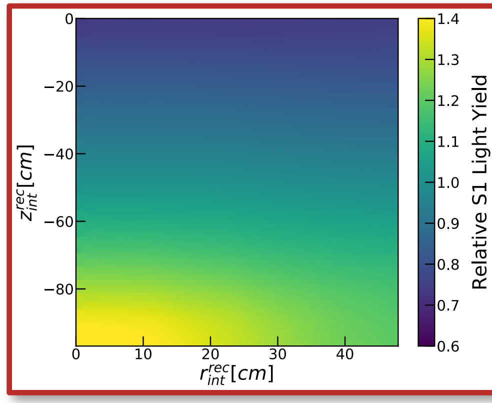
S1 - S2 SIGNAL CORRECTIONS

FOR SPATIAL-DEPENDENT DETECTOR RESPONSE



^{83m}Kr CALIBRATIONS

41.5 KeV line uniformly distributed in the TPC

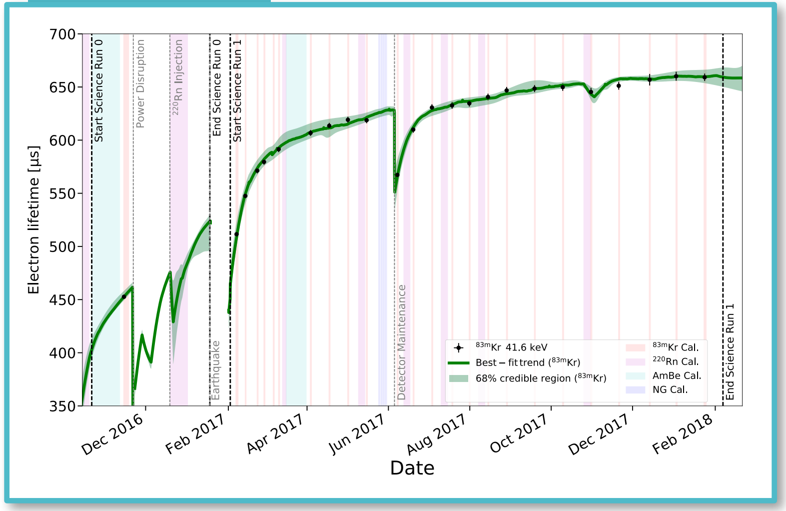


S1 LCE

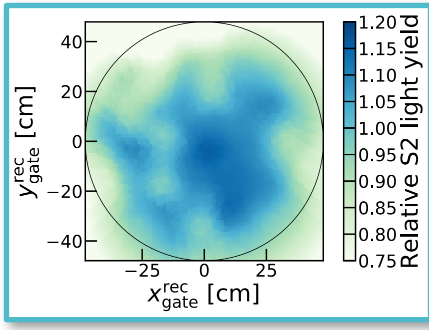
x-y-z-dependent correction

ELECTRON LIFETIME

z-dependent S2 correction



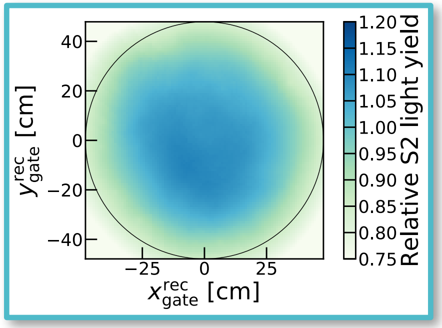
***TOP** PMT ARRAY*



S2 LCE

x-y-dependent correction

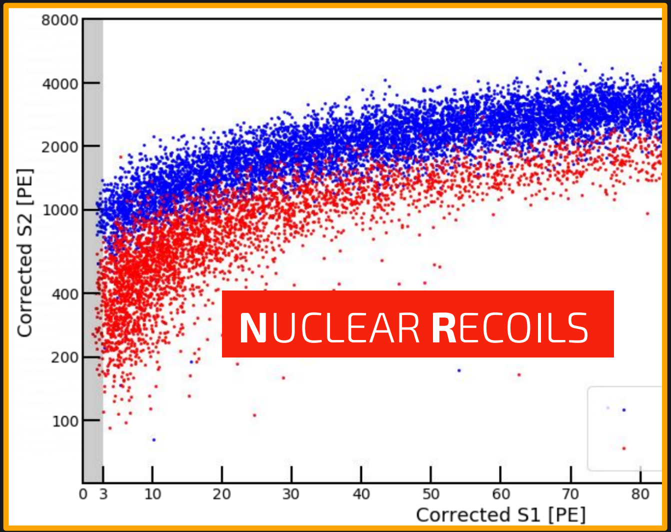
***BOTTOM** PMT ARRAY*

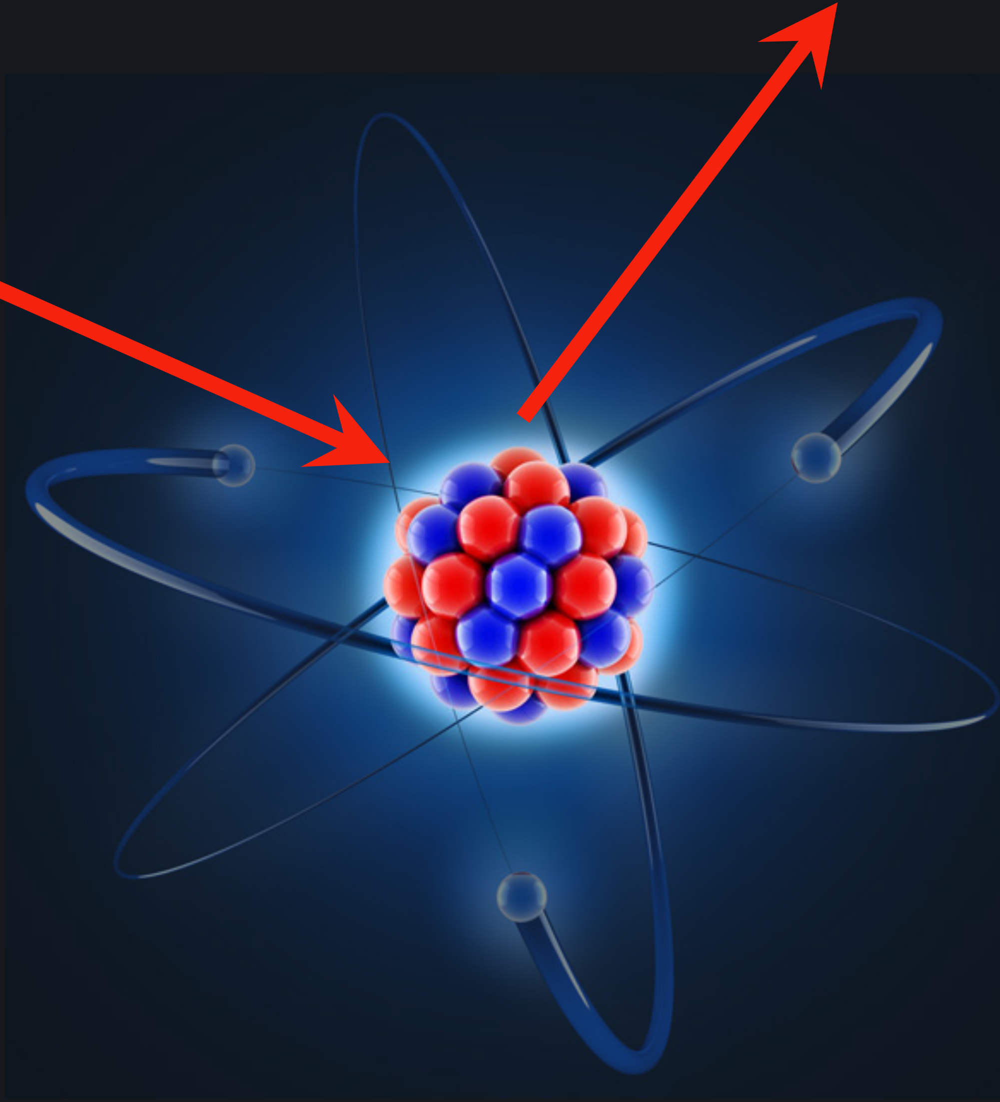


RECOIL TYPE DISCRIMINATION

NUCLEAR RECOILS

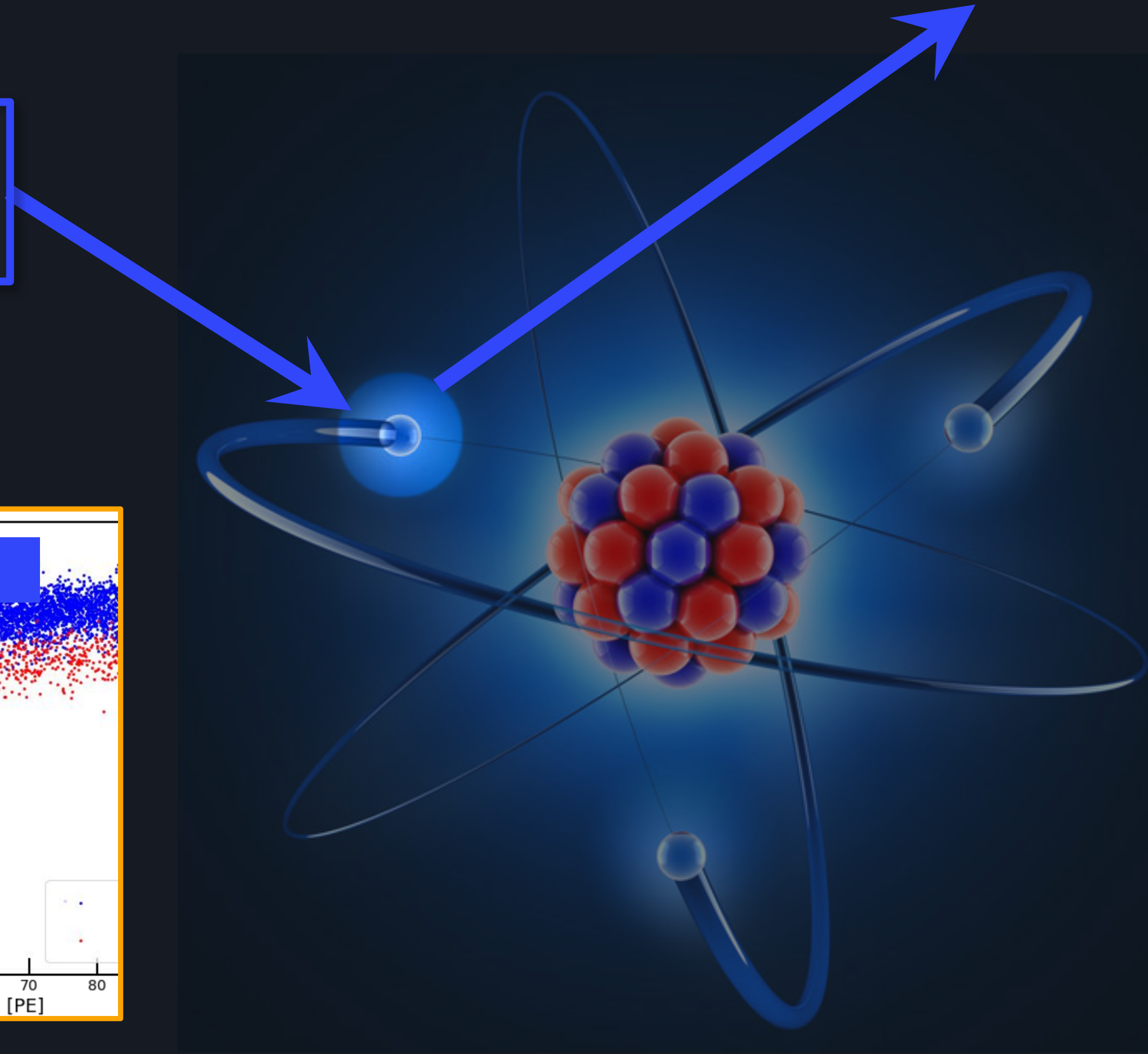
WIMP
Neutron
Neutrino (CNNS)

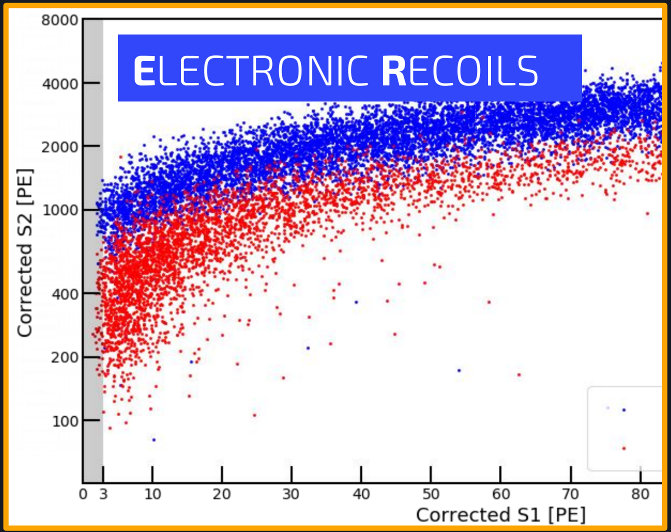




RECOIL TYPE DISCRIMINATION

ELECTRONIC RECOILS





NUCLEAR RECOIL BACKGROUND

COSMOGENIC NEUTRONS

JINST 9, P11006 (2014)

- Induced by cosmic muons
- Reduced to negligible contribution by rock overburden, water passive shield and active Cherenkov Muon Veto

RADIOGENIC NEUTRONS

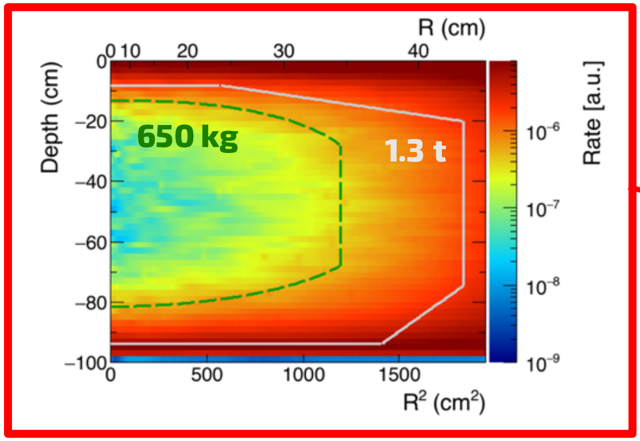
Eur. Phys. J. C. (2017) 77:890

- From (α,n) and spontaneous fission in detector's materials
- Reduced via radiopure material selection, scatter multiplicity and volume fiducialization
- Final prediction constrained by multiple neutron scatters observation

COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING (CNNS)

- Mainly from ^{8}B solar ν
- Irreducible background at very low energy (< 1 keV)
- Constrained by solar ν flux and CNNS cross section measurement

JCAP 04, 027 (2016)



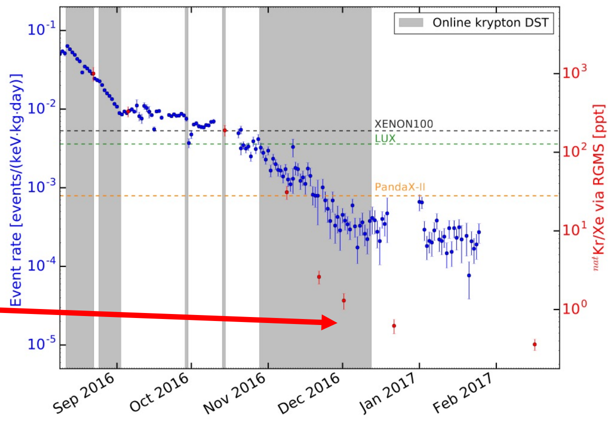
	Rate [t^{-1} y^{-1}]	Fraction [%]
Cosmogenic neutrons	<0.01	<2.0
Radiogenic neutrons	**0.6 ± 0.1**	**96.5**
CNNS	0.012	2.0

Expectations in 1 t FV, in [4,50] keV_{nr}, single scatters

ELECTRONIC RECOIL BACKGROUND

INTRINSIC RADIOACTIVE ISOTOPES

- **^{222}Rn (10 μBq/kg)**
  Most dangerous is β-decay of ^{214}Pb.
  Emanated from inner surfaces in contact with Xenon.
  Extensive screening campaign and careful radiopure material selection.
- **^{85}Kr (0.66 ppt)**
  β-emitter, Xenon contaminant.
  Reduced by a factor >10^3 via cryogenic distillation.
- **^{136}Xe (~9% of ^{nat}Xe)**
  Double-β-emitter.



SOLAR NEUTRINOS

- Well constrained from solar and nuclear physics.
- Subdominant and rreducible background.

RADIOACTIVE ISOTOPES IN DETECTOR MATERIALS

- **γ-rays** from ^{238}U and ^{232}Th decay chains and from ^{60}Co and ^{40}K.
- They can undergo forward Compton scattering before entering the LXe active mass and produce a flat spectrum at low energies.
- Reduced by radiopure material selectrion and volume fiducialization.

	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 t FV, in [1,12] keV_{ee}, single scatters, **before ER/NR discrimination**
JCAP 04, 027 (2016)

XENON1T BACKGROUND LEVEL

THE LOWEST EVER FOR DARK MATTER DETECTORS

GEANT4 SIMULATIONS of all known background components

Convolved with the measured energy resolution

LOW ENERGY BACKGROUND RATE

82^{+5}_{-3} (sys) ± 3 (stat) $(t\ y\ keV)^{-1}$

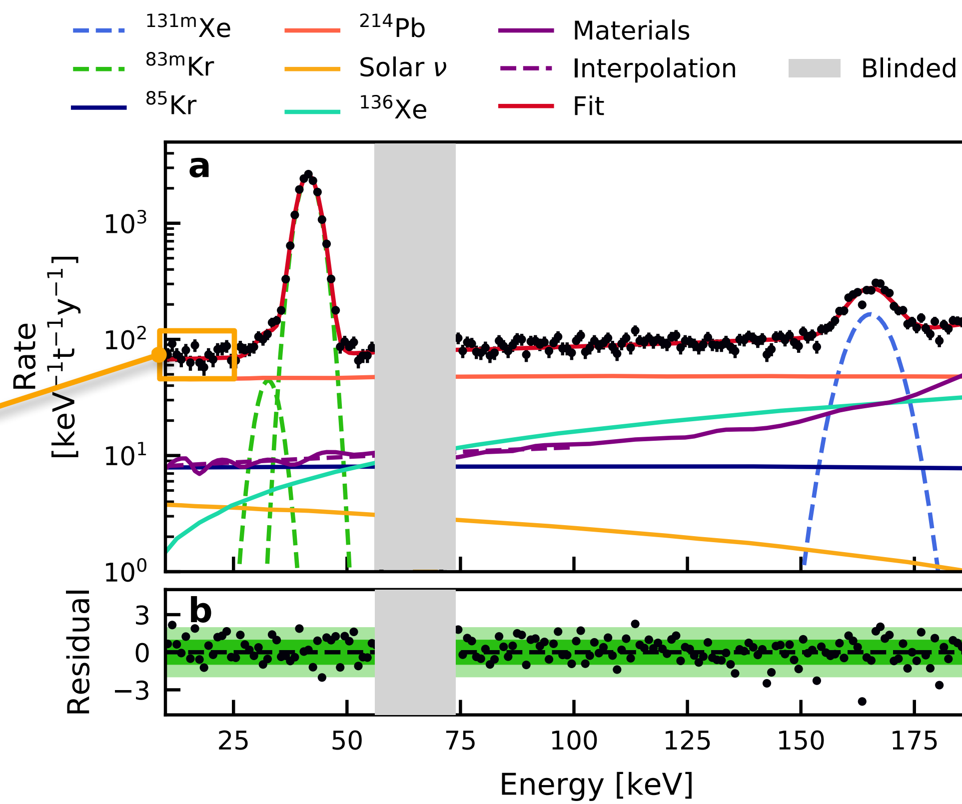
The lowest ever among DM detetctors

ER background in 1300 kg FV and below 25 keV_{ee}

SIMULATION PREDICTION

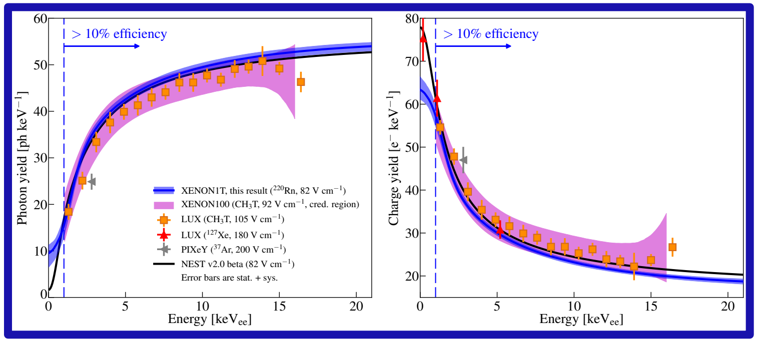
71 ± 7 $(t\ y\ keV)^{-1}$

Very well understanding of background

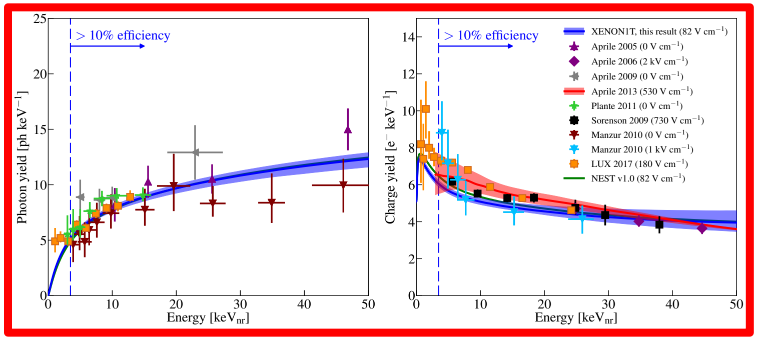


DETECTOR RESPONSE MODEL

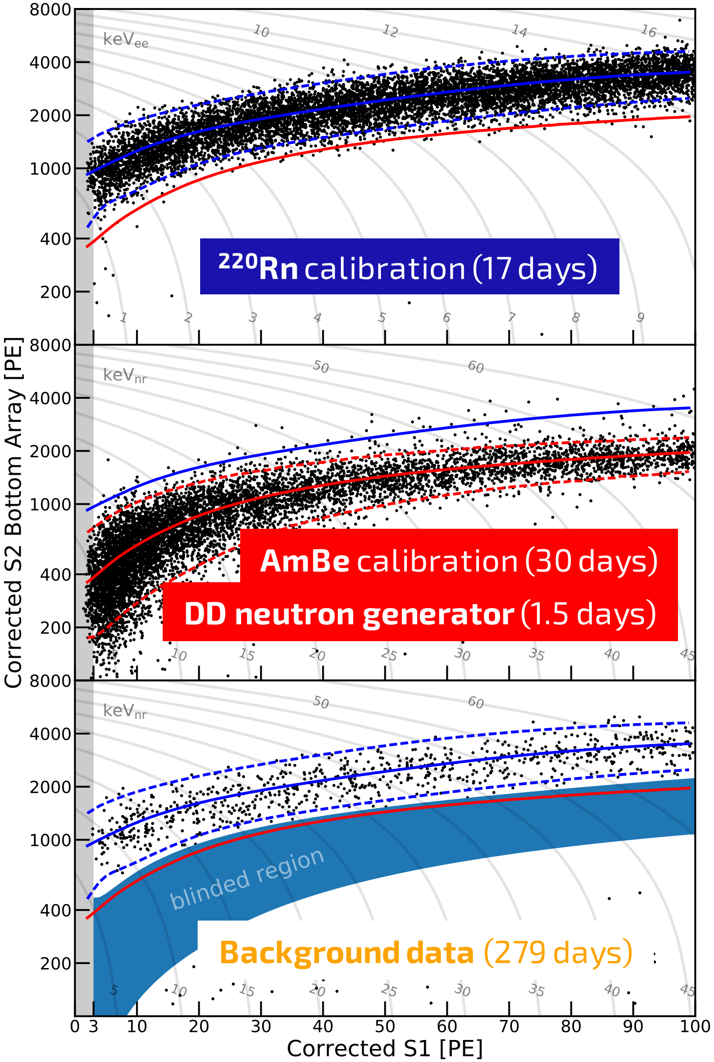
TO LOW ENERGY ERs AND NRs



ER



NR



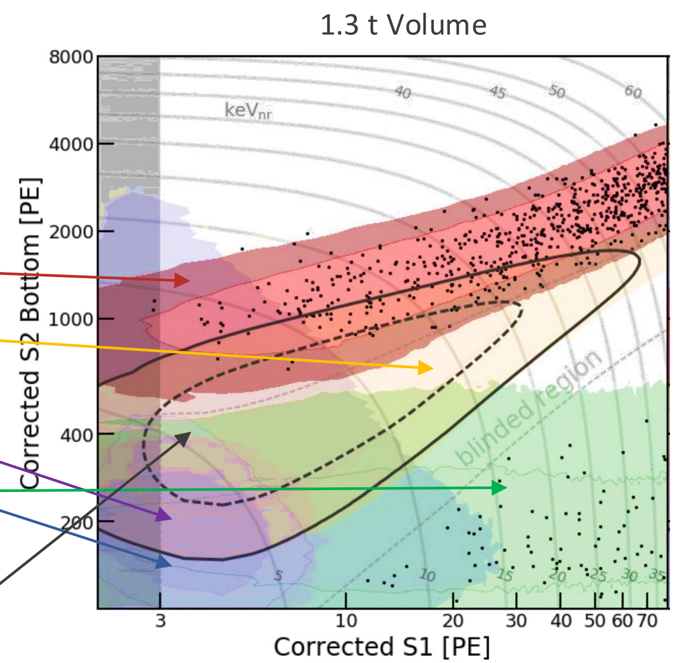
- Combined ER/NR fit
- Detailed MC simulations of LXe microphysics and detector processes
- 99.7% ER rejection
  in NR reference region [NR median,-2σ]

BACKGROUND MODEL FOR WIMP SEARCH

1 TON-YEAR EXPOSURE

278.8 days live-time

	1.3 t	0.65 t	Mass
	Full ROI	NR Reference	(S2,S1) region
ER	627 ± 18	0.60 ± 0.13	
neutron	1.43 ± 0.66	0.14 ± 0.07	
CNNS	0.05 ± 0.01	0.01	
AC	0.47 $^{+0.27}$	0.04 $^{+0.02}$	
Surface	106 ± 8	0.01	
TOTAL BKG	**735 ± 20**	**0.80 ± 0.14**	



BACKGROUND MODELS

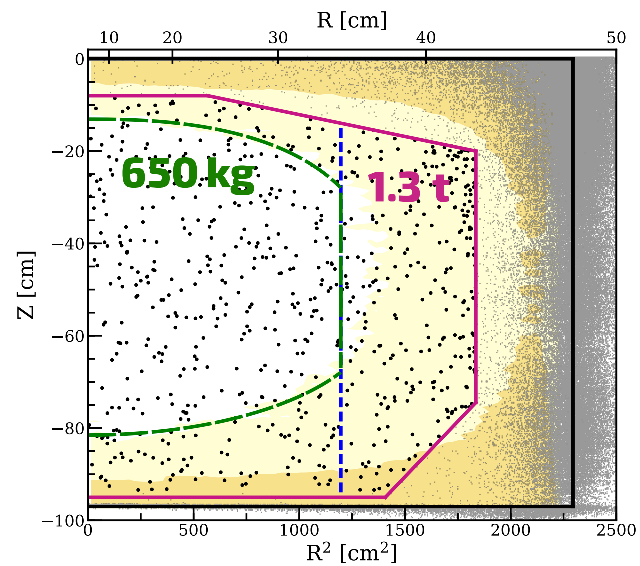
In 4-dimensional space: S1, S2, r, z

STATISTICAL INFERENCE

Done with PLR analysis in 1.3 t fiducial volume and full (S1,S2) space, corresponding to [4.9, 40.9] keV$_{nr}$ and [1.4, 10.6] keV$_{ee}$.

NR REFERENCE REGION

Between NR median and -2σ quantile. Numbers in table are for illustration; final results from complete PLR statistical inference.

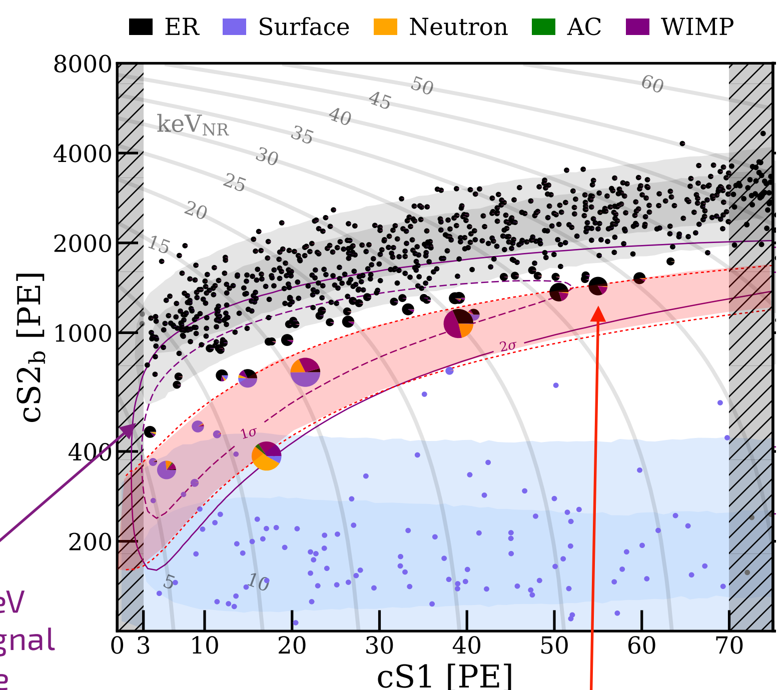


DATA UNBLINDING

BLINDING AND SALTING
Data blinded in the NR signal region and salted with unknown number of fake events

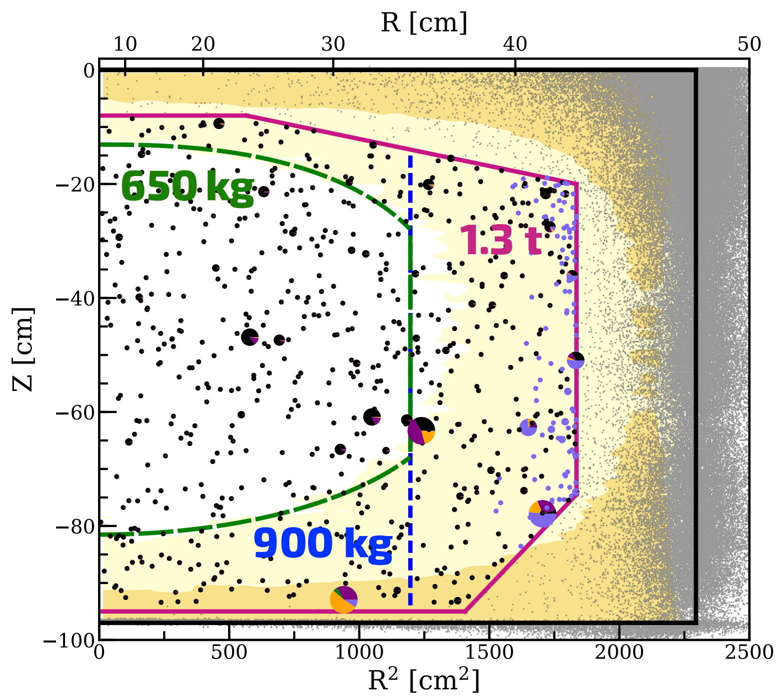
PIE CHARTS
Events passing all selection criteria are shown as pie charts representing the relative PDF from each component for the best-fit model for 200 GeV WIMP (σ_{SI}=4.7•10^{-47} cm^2)

STATISTICAL INTERPRETATION
Unbinned profile likelihood with all model uncertainties included as nuisance parameters.



200 GeV WIMP signal shape 1-2σ contours

--- NR Reference region

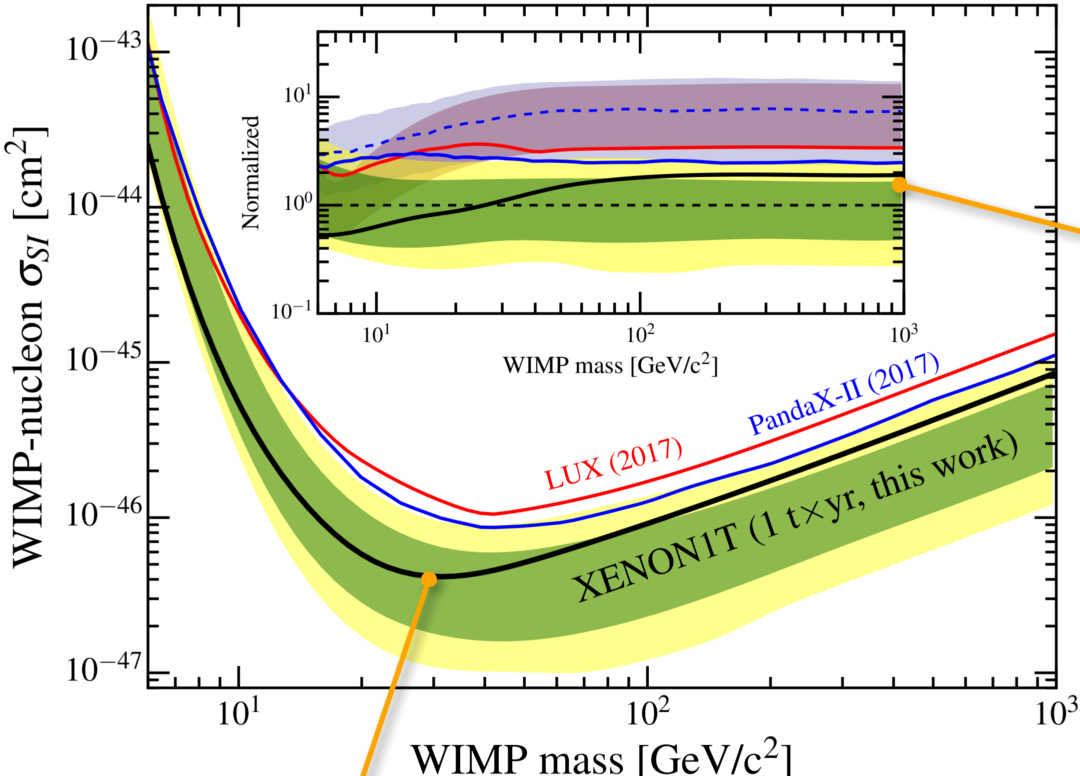


SPIN-INDEPENDENT WIMP INTERACTION

Phys. Rev. Lett. 121, 111302

WORLD BEST CONSTRAINT ON WIMP DARK MATTER

Most stringent exclusion limits (at 90% CL) for WIMPs > 6 GeV/c^2



x7 IMPROVED SENSITIVITY with respect to previous experiments (LUX, PANDAX-II)

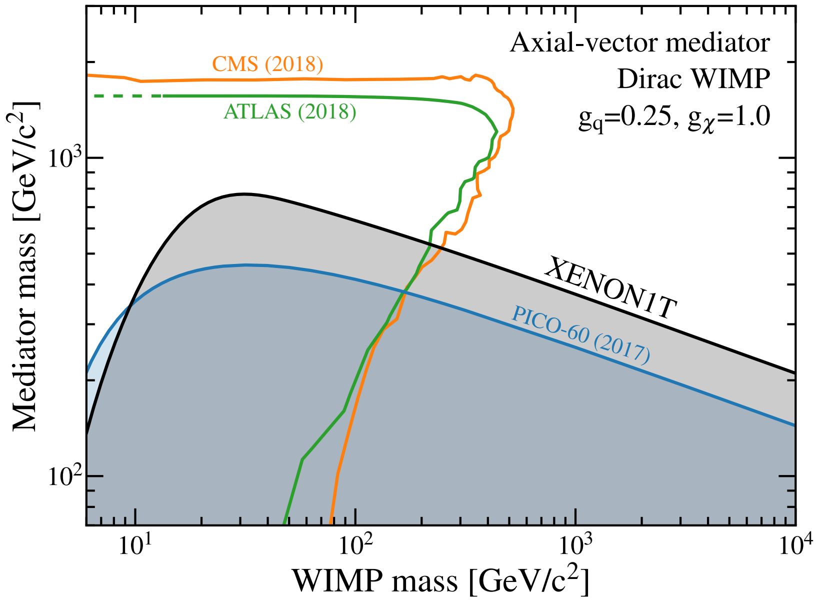
σ_{SI} < 4.1·10^{-47} cm^2 at 30 GeV/c^2

SPIN-DEPENDENT WIMP SEARCH

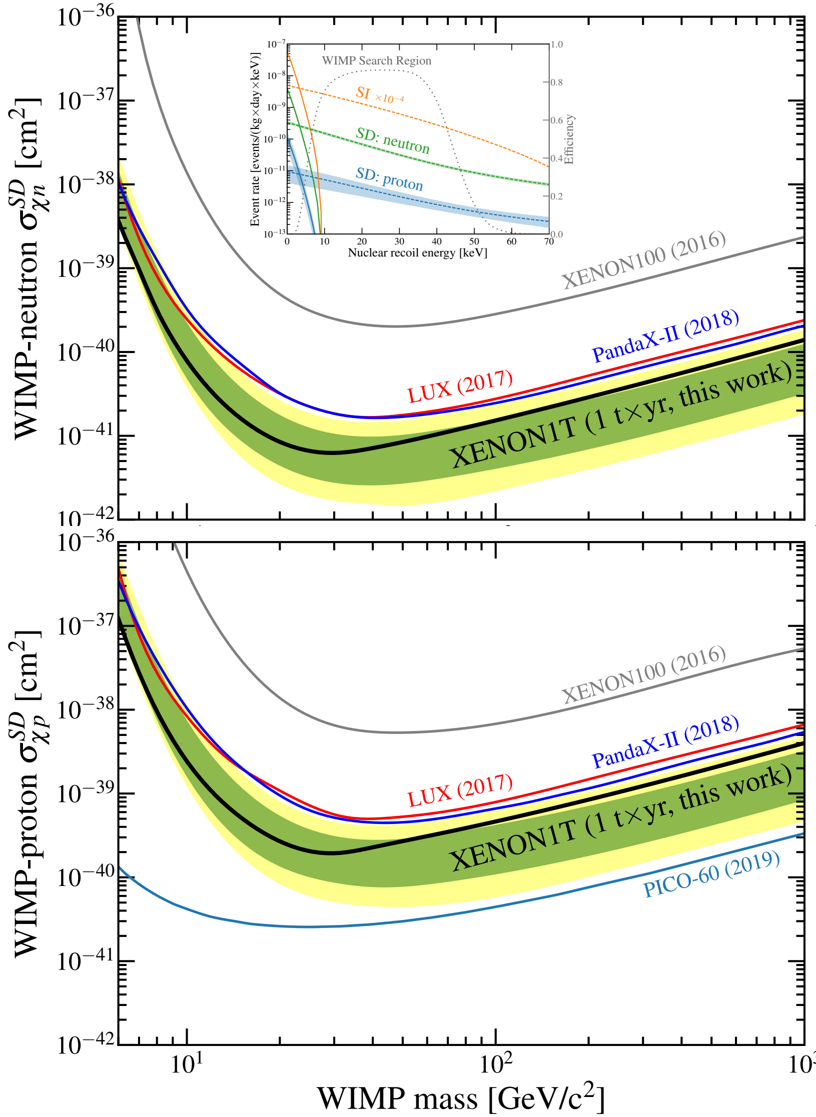
[Phys. Rev. Lett. 122, 141301](#)

- Same data selection
  Different interpretation

- Excluded new parameter space in isoscalar theory with axial-vector mediator (restricted model for comparison with LHC)



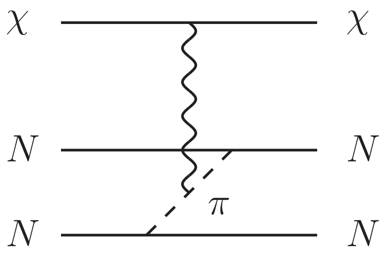
- WIMP interaction on ^{129}Xe and ^{131}Xe



WIMP-PION COUPLING SEARCH

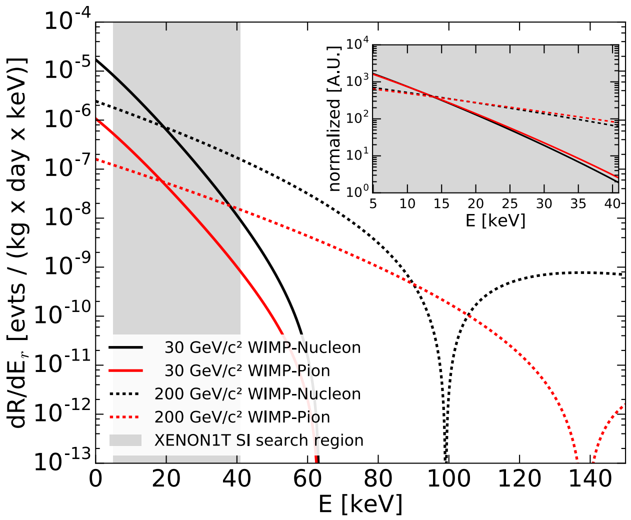
Phys. Rev. Lett. 122, 071301

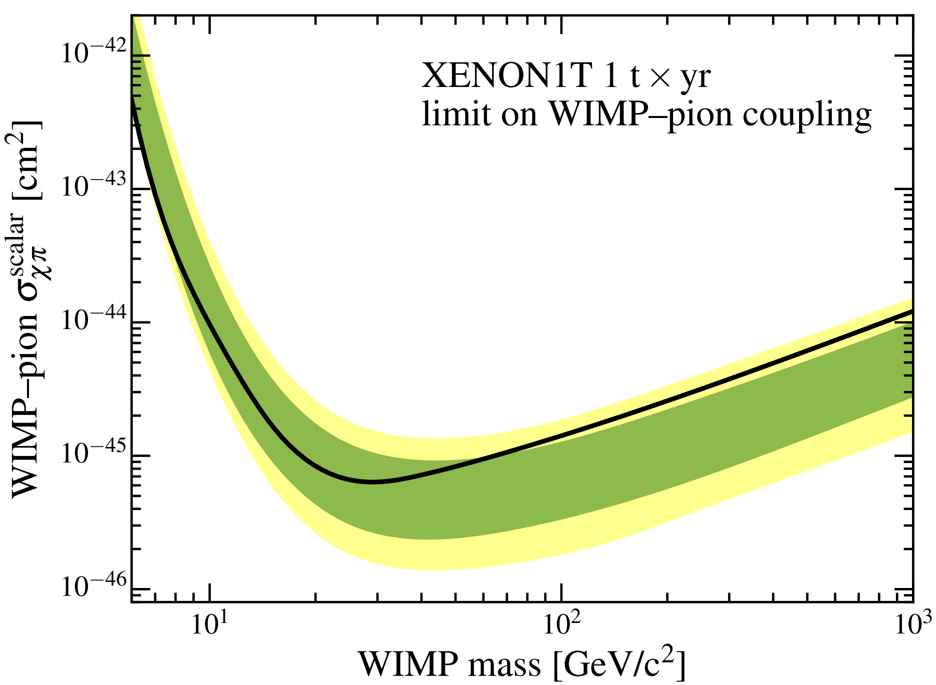
- WIMP coupling to a virtual pion exchanged between nucleons in a nucleus



- Pion-exchange currents can be coherently enhanced by total number of nucleon
- May dominate in scenarios where SI WIMP-nucleon interaction is suppressed

- First ever result on WIMP-pion coupling





- Signal model similar to SI WIMP-nucleon coupling

"A spectacular bonus"

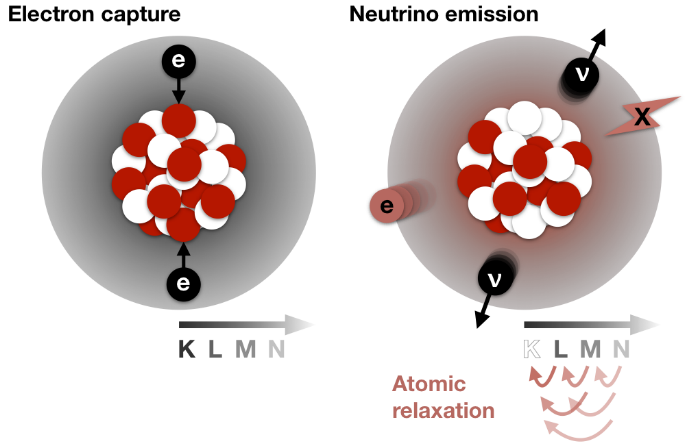
DISCOVERY OF DOUBLE ELECTRON CAPTURE IN ^{124}Xe

- First observation of 2νECEC decay
- Measured half-life
  $(1.8 \pm 0.5_{stat} \pm 0.1_{sys}) \times 10^{22}$ yr
  The longest ever!
- $\sim 10^{12}$ times larger than the age of the Universe

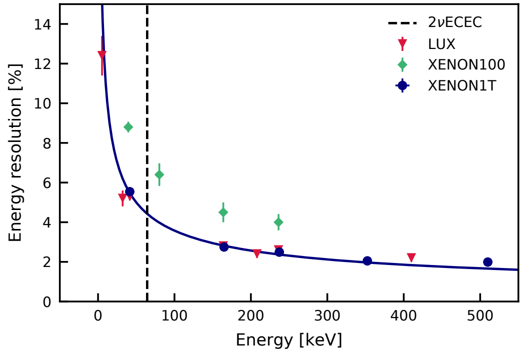
$^{124}Xe\ 2\nu ECEC$ DECAY

$^{124}Xe \longrightarrow {}^{124}Te + \nu_e + \nu_e$

- SIGNATURE: mono-energetic peak at **(64.3 ± 0.6) keV**
  Energy released by X-rays and Auger electrons (atomic relaxation)



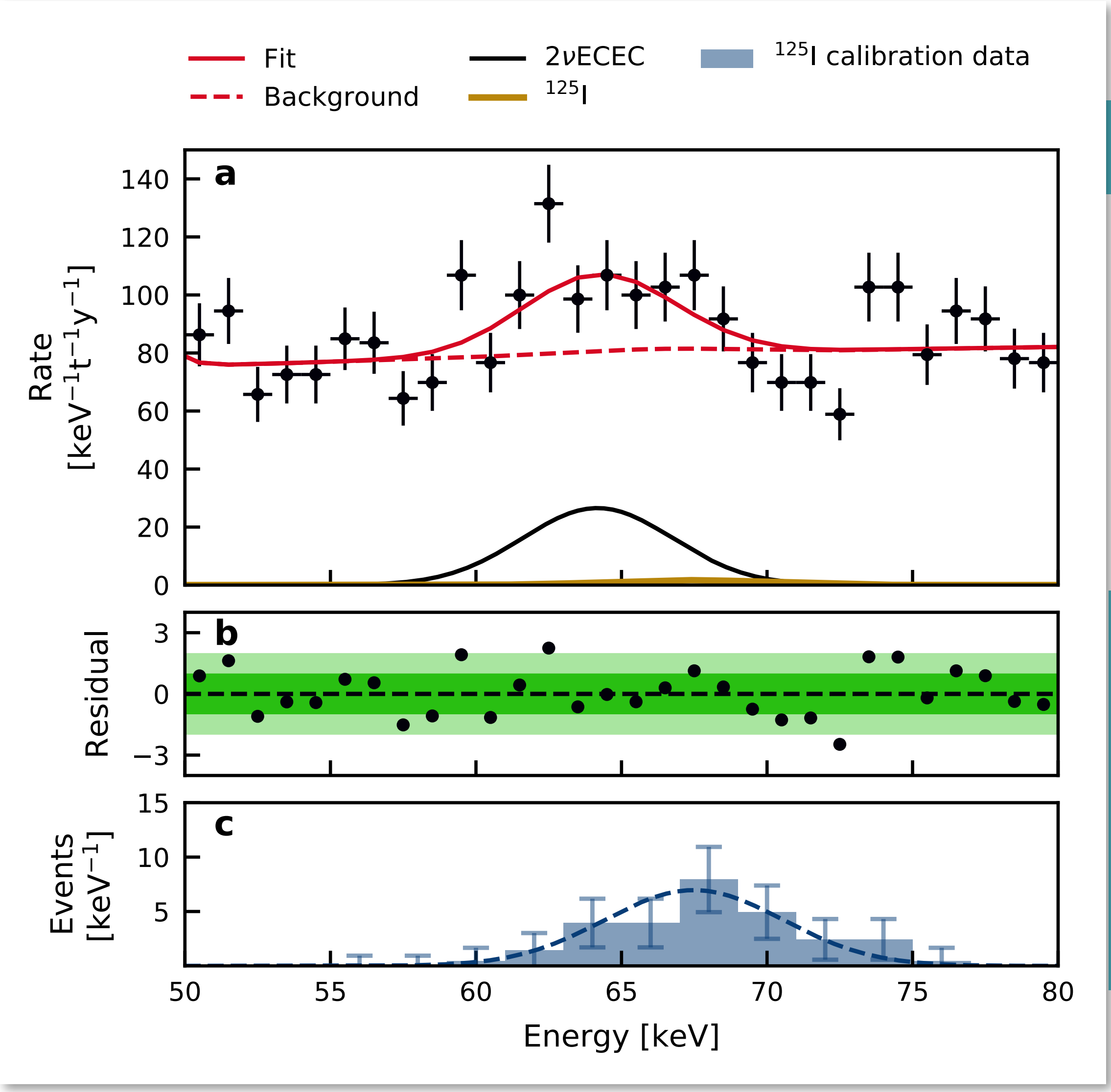
- Blinded search in (56, 72) keV
- Total fiducial mass $(1502 \pm 9_{stat})$ kg
- Dataset livetime 177.7 days
- ^{124}Xe isotopic abundance $(9.94 \pm 0.14_{stat} \pm 0.15_{sys}) \times 10^{-4}$
- Close ^{125}I peak at 67.3 keV
  Expectation derived from ^{125}Xe activation model (during neutron calibrations)
- Energy resolution at $E_{2\nu ECEC}$ (4.1 ± 0.4) %



^{124}Xe 2νECEC DECAY

UNBLINDING RESULTS

[Nature 568, 532-535 (2019)]



FIT RESULTS

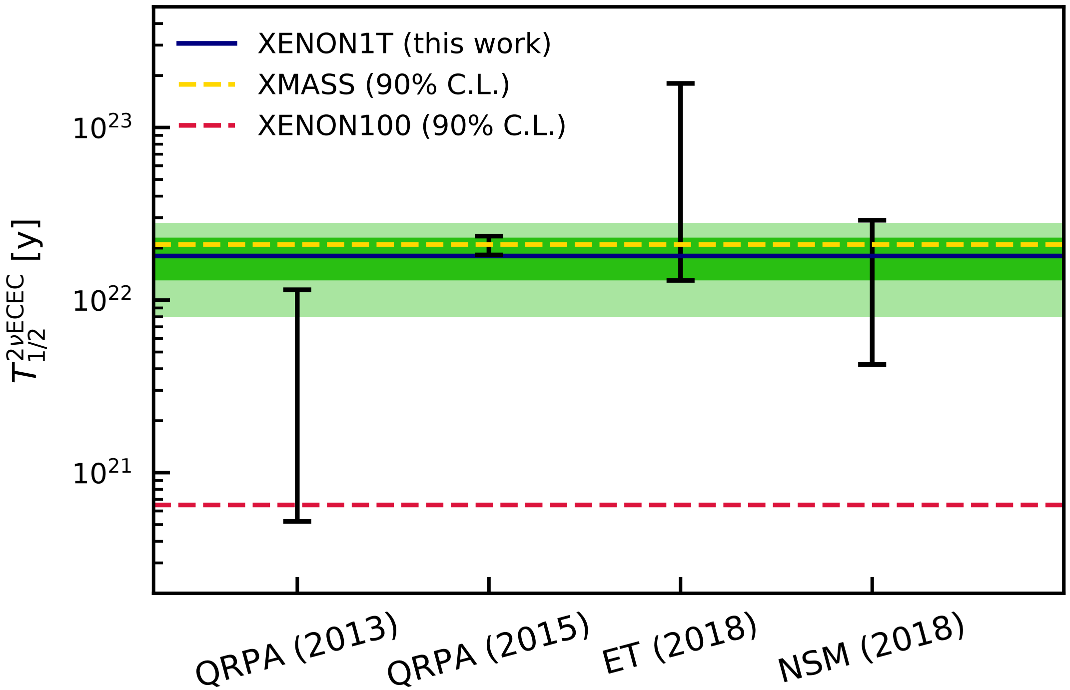
- **2νECEC PEAK**
  $\mu = (64.2 \pm 0.5)$ keV
  $\sigma = (2.6 \pm 0.3)$ keV
- **^{125}I BACKGROUND**
  $N_{I\text{-}125} = 9 \pm 7$
  Expected 10 ± 7
- **2νECEC EVENTS OBSERVED**
  126 ± 29
- **DISCOVERY SIGNIFICANCE**
  4.4 σ

THE RAREST DECAY EVER OBSERVED

$T_{1/2} = (1.8 \pm 0.5_{stat} \pm 0.1_{sys}) \times 10^{22}$ yr

Nature 568, 532-535 (2019)

> This measurements is the first benchmark for nuclear structure models of proton-rich nuclei



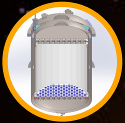
$$T_{1/2}^{2\nu ECEC} = \ln 2 \frac{\epsilon \eta N_A m t}{M_{Xe} N_{2\nu ECEC}}$$

Data selection acceptance
$\varepsilon = 0.967 \pm 0.007_{stat} \pm 0.033_{sys}$
^{124}Xenon isotopic abundance
$\eta = (9.94 \pm 0.14_{stat} \pm 0.15_{sys}) \times 10^{-4}$
Avogadro's number
$N_A = 6.022 \times 10^{22}$ mol^{-1}
Fiducial mass
$m = (1502 \pm 9_{stat})$ kg
Livetime
$t = 177.7$ d
Xenon mean molar mass
$M_{Xe} = 131.293$ g/mol
Number of 2νECEC events
$N_{2\nu ECEC} = 126 \pm 29$

> It sets the stage for 0νECEC searches hunting for the Majorana neutrino

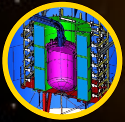
WHAT'S NEXT: XENONnT

x4 **LXe TARGET**
- Fiducial mass 1 t → 4 t



LARGER TPC
- 248 → 494 PMTs

÷10 **ER BACKGROUND**
- Radon distillation
- Improved LXe purification



NR BACKGROUND
- Neutron Veto

FAST UPGRADE
- Installation ongoing

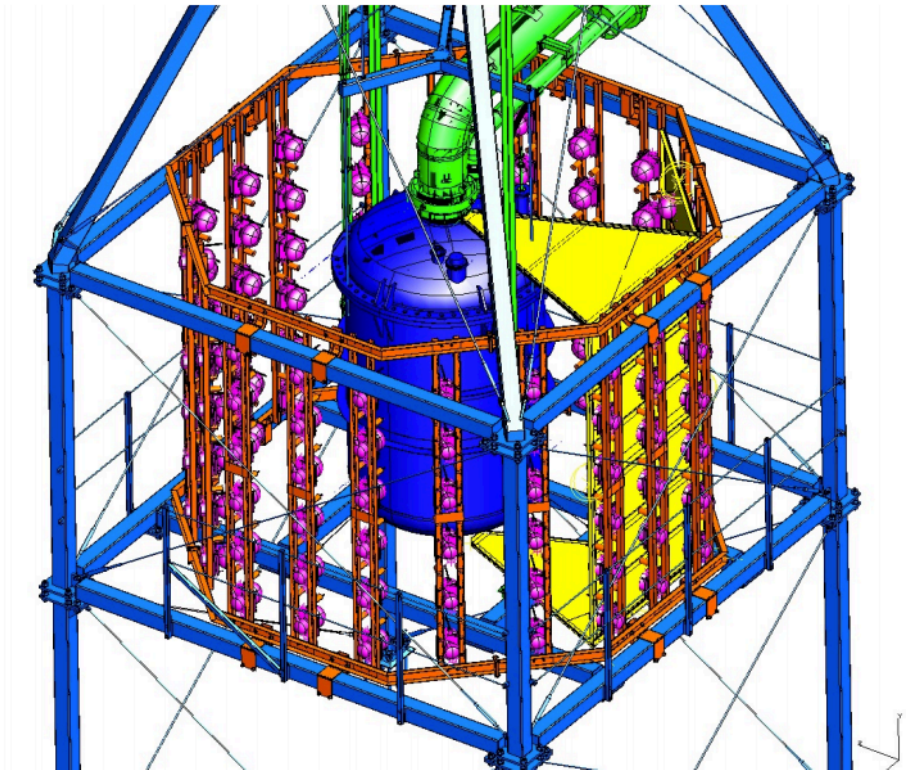
DIRECT DARK MATTER SEARCHES
- Improve XENON1T results on WIMPs by 1 order of magnitude
- Test several DM hypotheses (ALPs, Dark Photons, Annual modulation, ...)

RARE PROCESS SEARCHES
- Neutrinoless double electron capture
- ^{124}Xe decays with positron emission ($2\nu EC\beta^+$, $2\nu\beta^+\beta^+$, $0\nu EC\beta^+$, $0\nu\beta^+\beta^+$)
- Neutrinoless double beta decay
- ...

NEUTRON VETO

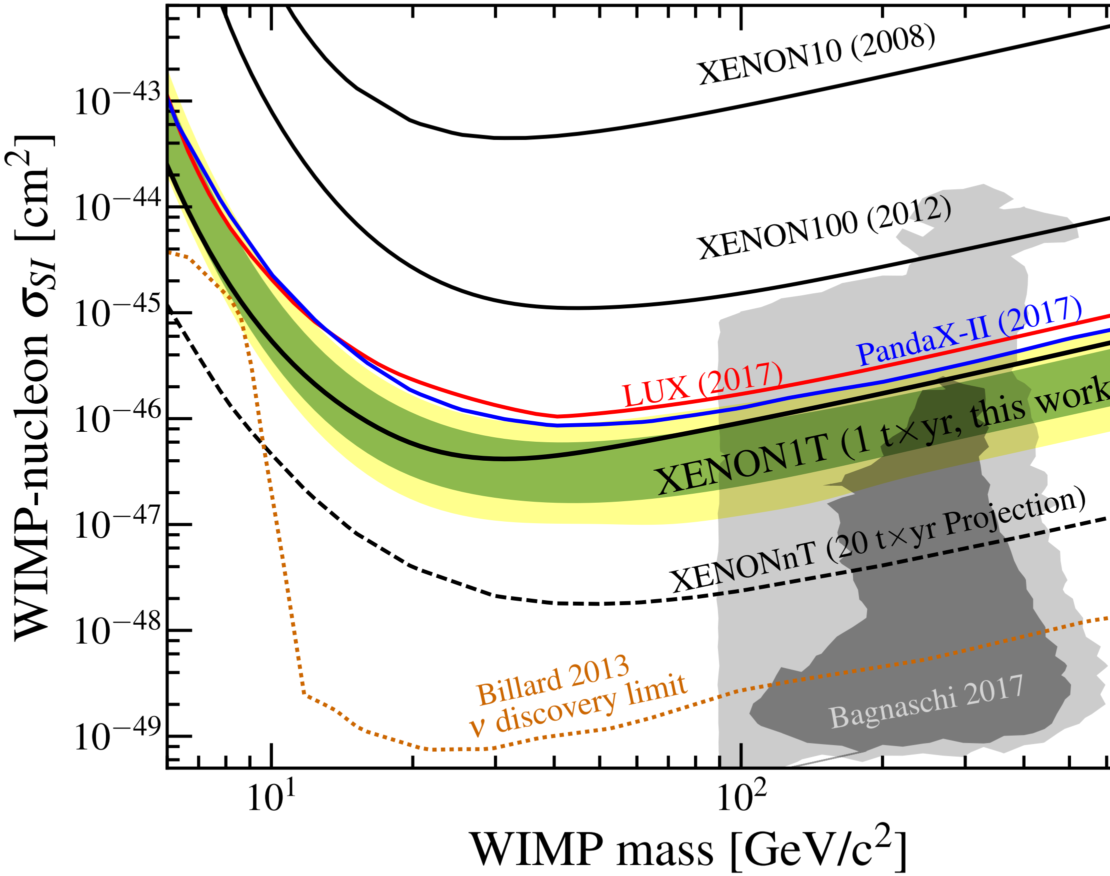
A NEW SUB-DETECTOR FOR XENONnT

- Region outside the cryostat instrumented with additional 120 PMTs
- Doped water with 0.2% concentration of Gadolinium sulphate
- Optically separated from Muon Veto system by ePTFE reflector
- Reduction of neutron background thanks to ~85% neutron tagging efficiency
- Boost in the sensitivity to WIMPs by a factor ~2



SUMMARY AND OUTLOOK

- **FIRST MULTI-TON LXe-TPC**
  Operated > 1 year
- **LOWEST BACKGROUND**
  ever among DM detectors
- **BEST WIMP LIMITS**
  SI > 6 GeV/c^2
- **^{124}Xe 2νECEC DISCOVERY**
  Rarest decay ever observed directly
- **XENON1T ANALYSES**
  Many DM and rare processes searches ongoing
- **XENONnT GOAL: x10 BETTER SENSITIVITY**
  Larger detector, lower background, 5 years data taking



xenon1t.org | twitter.com/xenon1t | digangi@bo.infn.it | www.bo.infn.it/xenon

BACKUP SLIDES

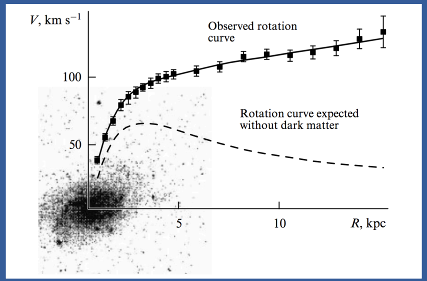
XENON

XENON Dark Matter Project

EVIDENCES OF DARK MATTER

GALAXY AND CLUSTERS SCALE

ROTATION CURVES



M33 Galaxy

BULLET CLUSTER

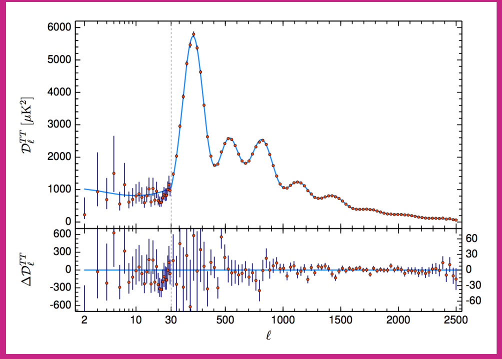
Luminous vs Dark matter

LENSING

SDSS J1038+4849 Clusters

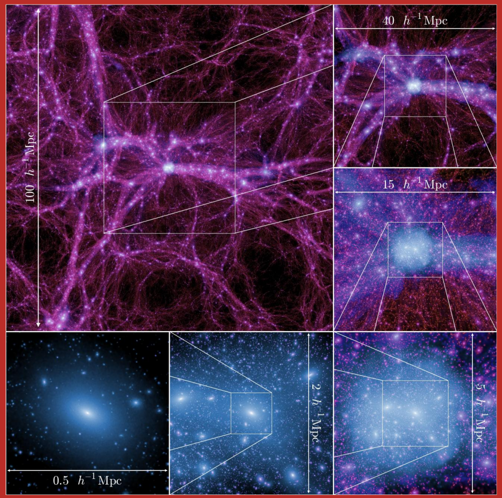
COSMOLOGICAL SCALE

CMB + ΛCDM



PLANCK 2018

STRUCTURE FORMATION

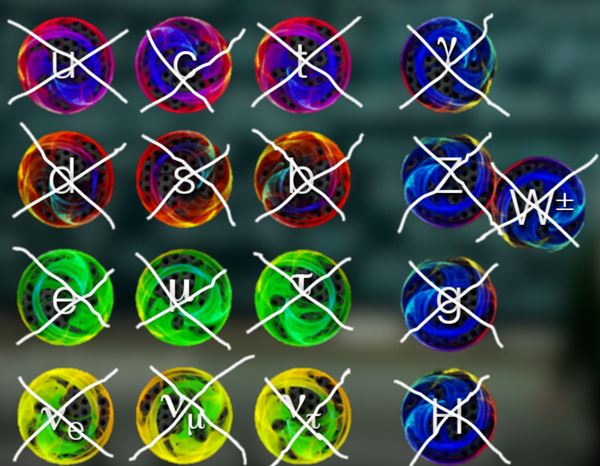


Millennium-II Simulation

PARTICLE DARK MATTER

- **STABLE**
- **NON-RELATIVISTIC**
- **NEUTRAL**
- **NO EM INTERACTION**
- **NO STRONG INTERACTION**
- **NON-BARYONIC**

NO SM CANDIDATE



WIMP "MIRACLE"

The measured dark matter **relic density***

$$\Omega_{DM}h^2 = \frac{3\times10^{-27}\,\mathrm{cm^3 s^{-1}}}{\langle\sigma_{ann}v\rangle} = 0.120 \pm 0.001$$

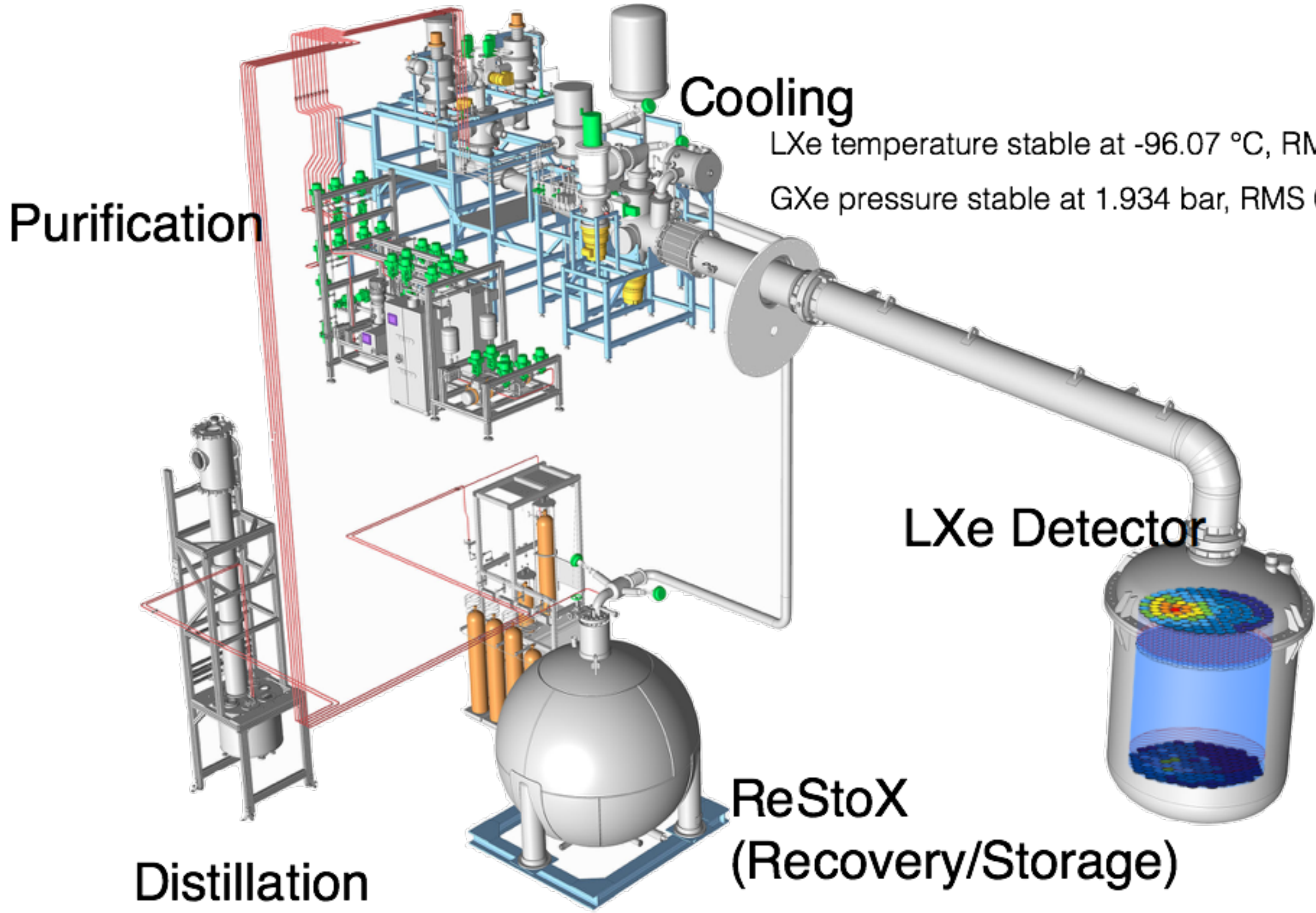
is obtained with **mass** (~100 GeV/c^2) and **annihilation cross section** (~10^{-25} cm^{3}s^{-1}) typical of the **weak scale**

Weakly **I**nteracting **M**assive **P**articles
- Most investigated class of DM candidates
- Naturally arise in SUSY models (e.g. neutralino)

Other candidates
- Axions or ALPs
- Kaluza-Klein
- Wimpzillas
- and many others…

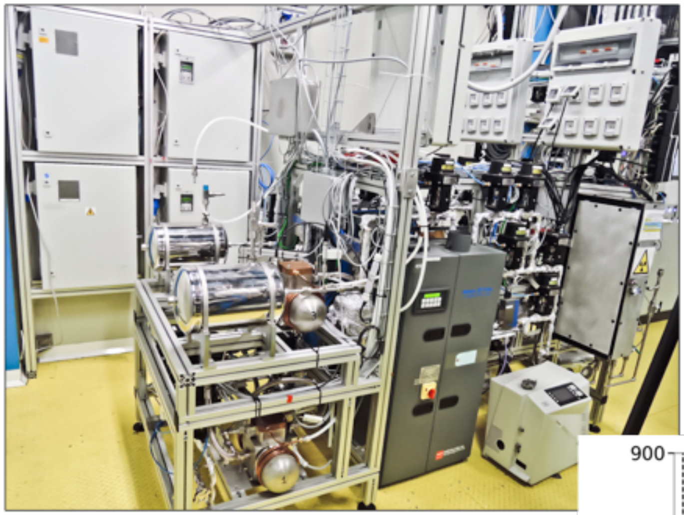
UNIVERSE ENERGY: BARYONIC MATTER **5%** DARK MATTER **26.5%** * DARK ENERGY **68.5%**

XENON SYSTEMS



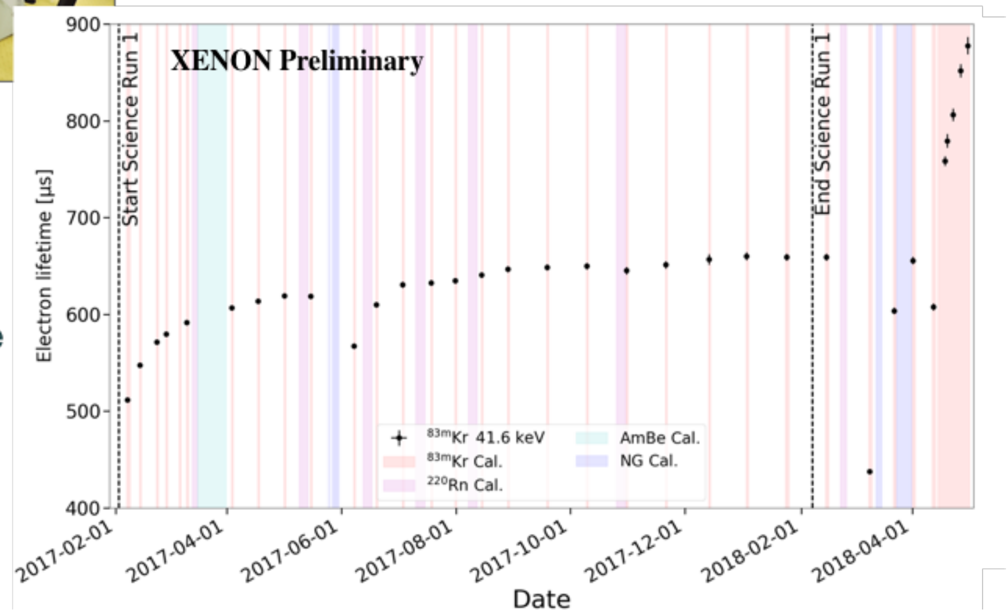
XENON PURIFICATION

ELECTRON LIFETIME



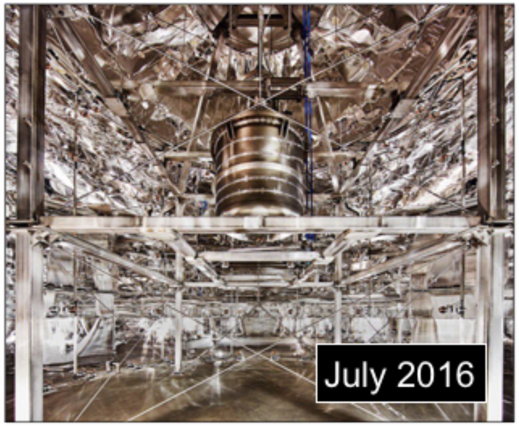
- Electronegative impurities in the Xe gas and from materials outgassing reduce charge (and light) signal.
- To drift electrons over 1 meter requires < 1ppb (O2 equivalent)
- Solution: continuous gas circulation at high flow through heated getter material

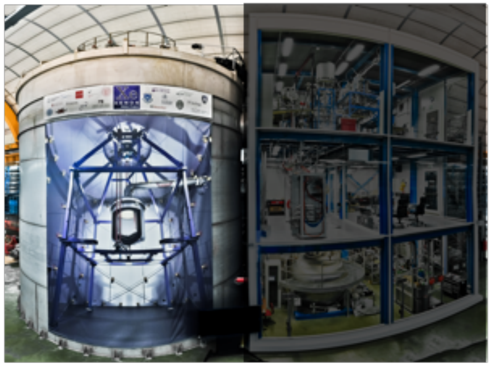
- electron lifetime is monitored regularly with ERs calibration sources.
- Current value, following increase in gas flow, approaches 1 msec



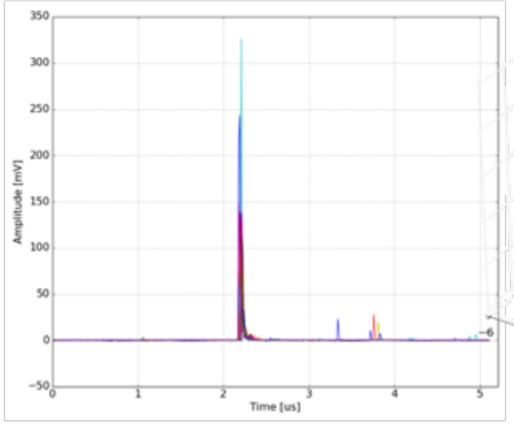
MUON VETO

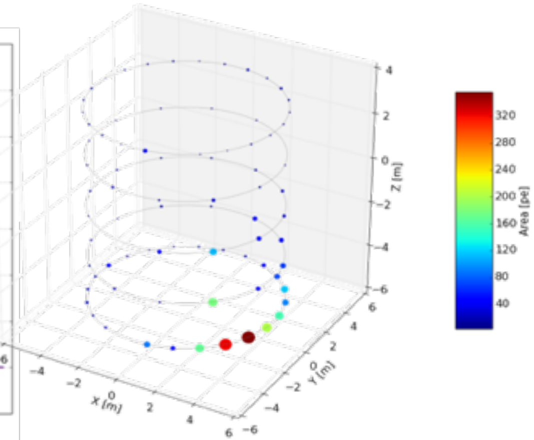
WATER CHERENKOV SUB-DETECTOR





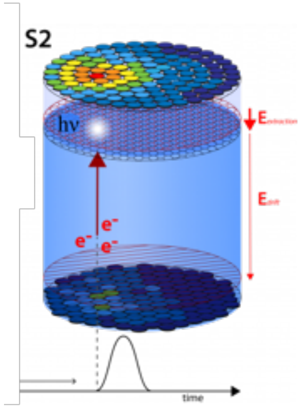
- 700 ton pure water instrumented with 84 high-QE 8" PMTs
- Active shield against muons
- Trigger efficiency > 99.5% for muons in water tank
- Cosmogenic neutron background suppressed to < 0.01 events/ton/yr





JINST 9, 11007 (2014)

POSITION RECONSTRUCTION

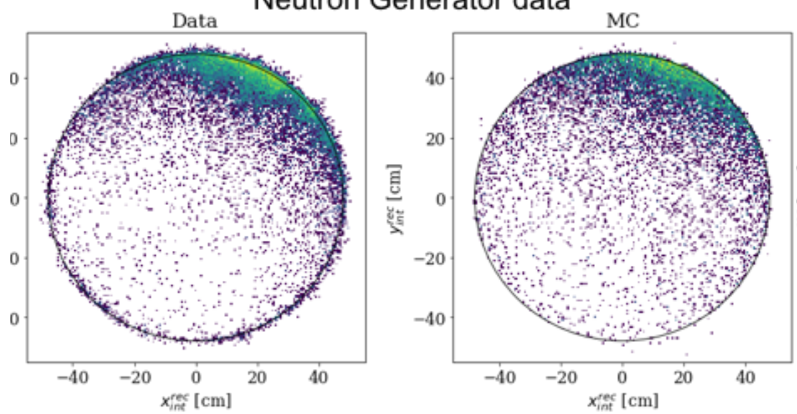


X-Y reconstruction via **neural network**:
- **Input:** charge/channel top array
- **Training:** Monte Carlo simulation

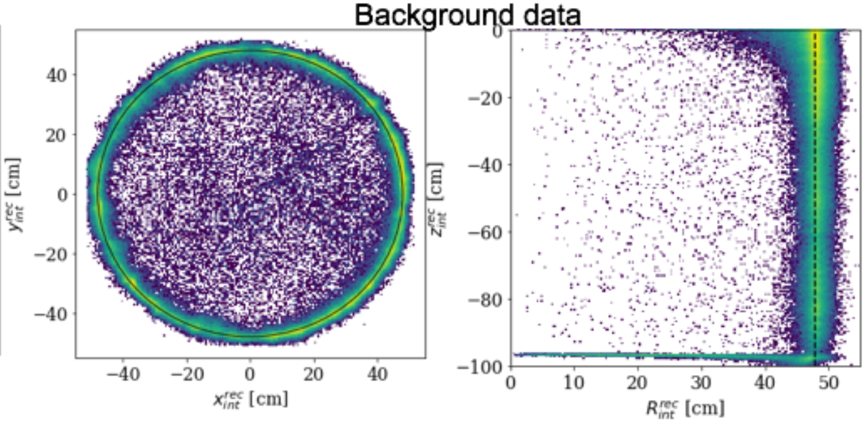
Position resolution using ^{83m}Kr
- Two interactions (9, 31 keV), same x-y
- Position resolution (1-2 cm)
- PMT diameter (7.62 cm)

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

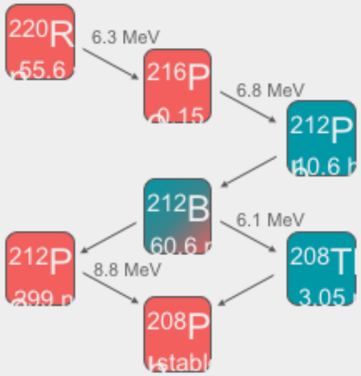


Background data



CALIBRATIONS

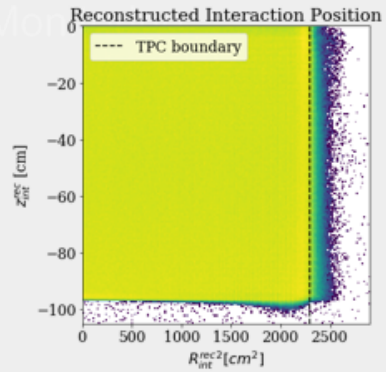
^{220}Rn: Low Energy ER



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

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

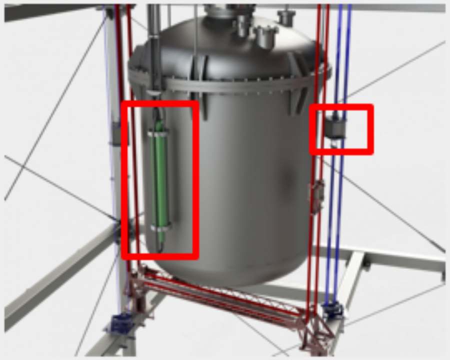
^{83m}Kr: Stability and



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

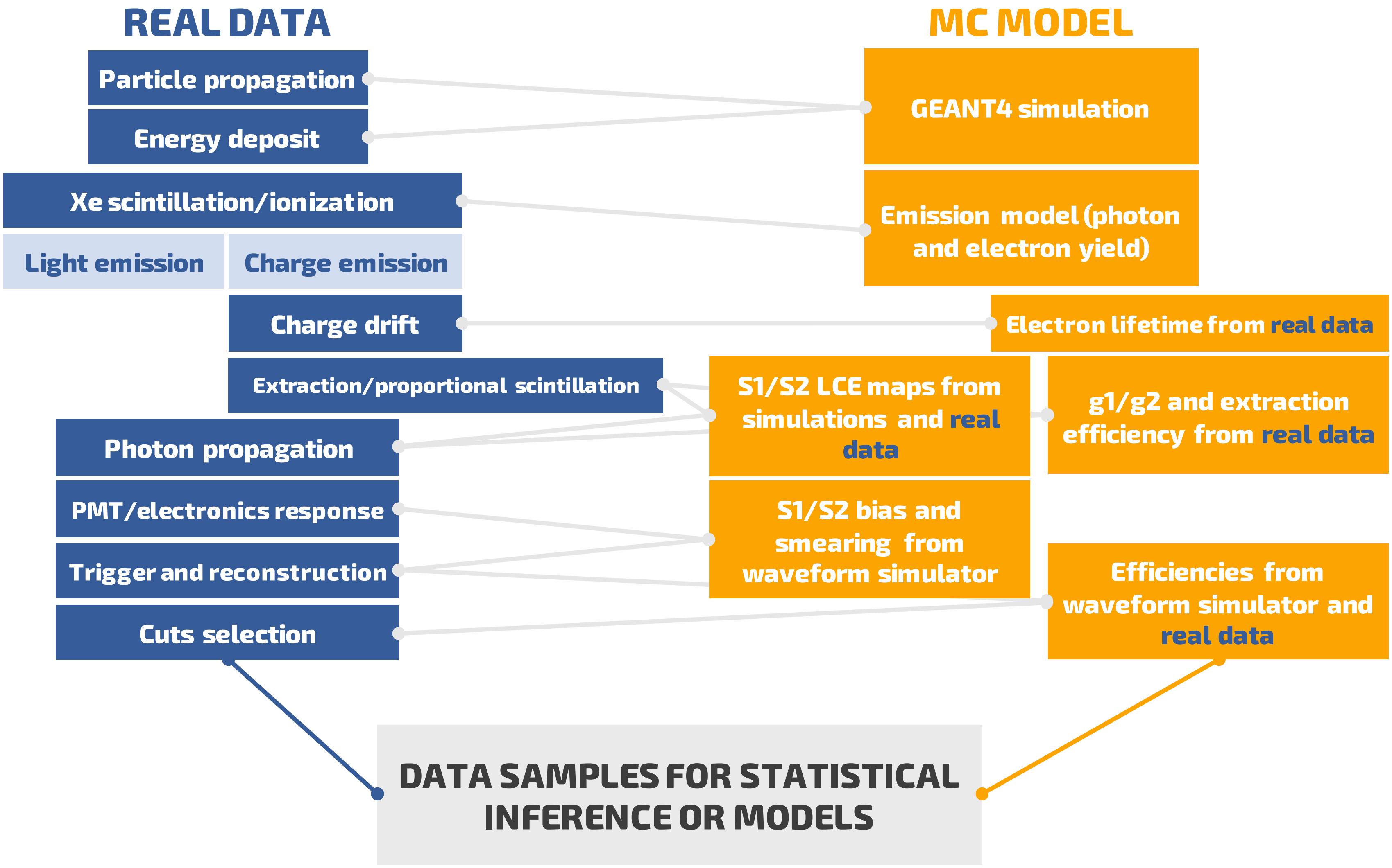
Neutrons: Signal Response



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

ER AND NR MODELING

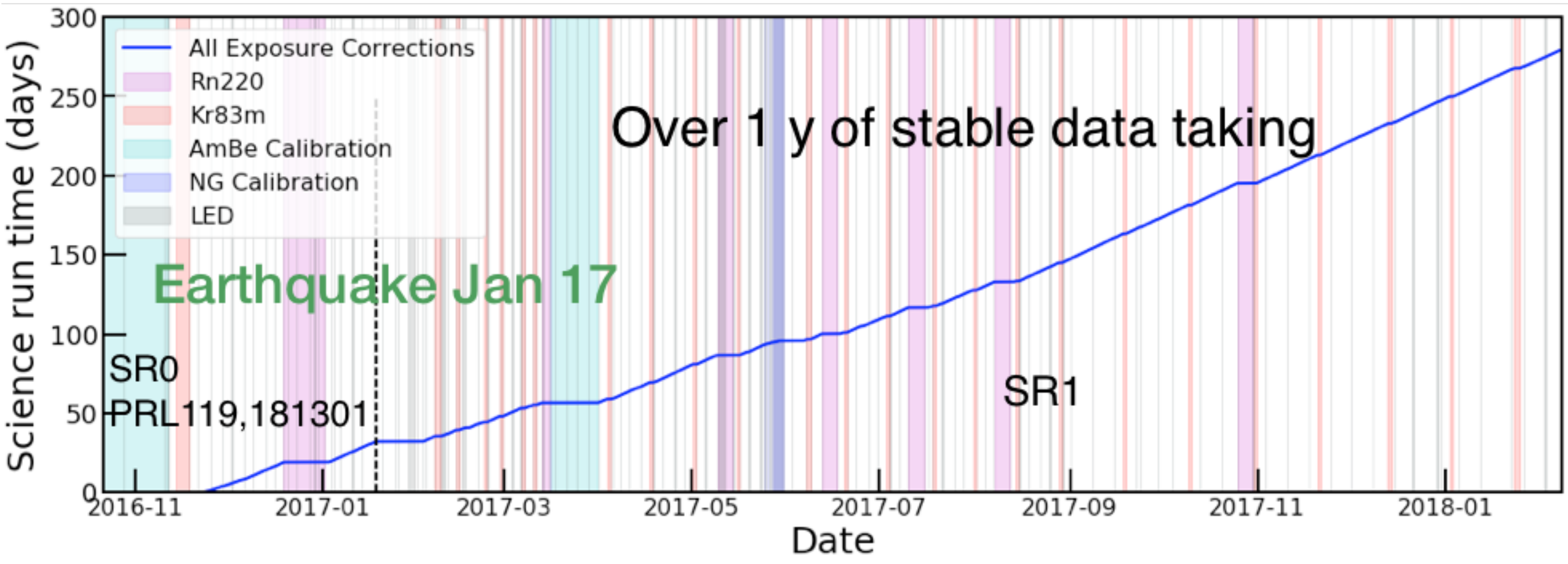
REAL DATA AND MC SIMULATIONS



XENON1T TIMESCALE

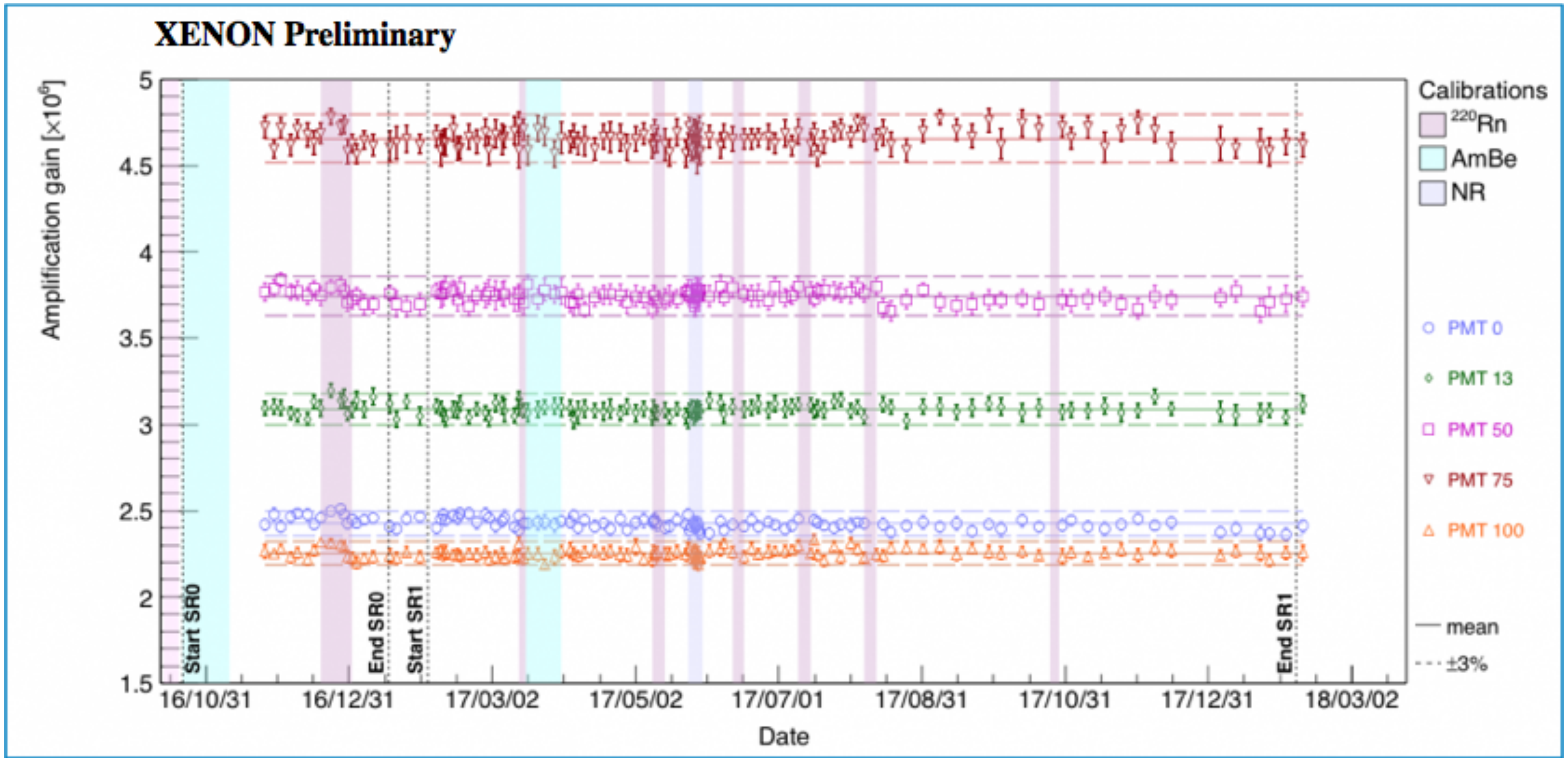
SCIENCE AND CALIBRATION DATA

- 279 days high quality data (livetime-corrected) spanning more than 1 year of stable detector's operation. The LXeTPC has been "cold" since Summer 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



LIGHT DETECTION SYSTEM

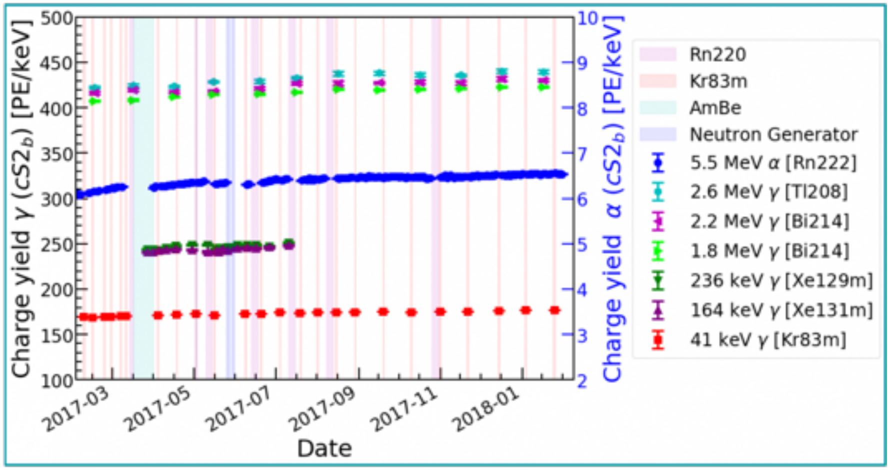
PMT STABILITY

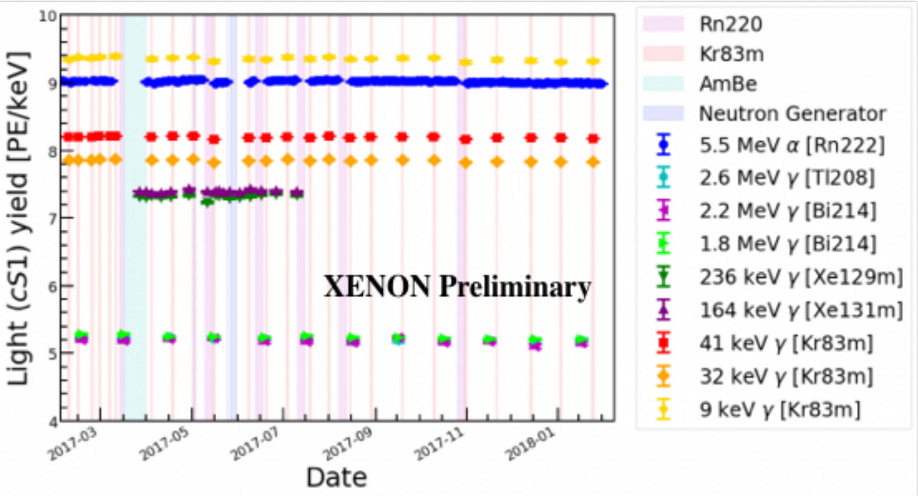


LIGHT AND CHARGE SIGNALS

TIME 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



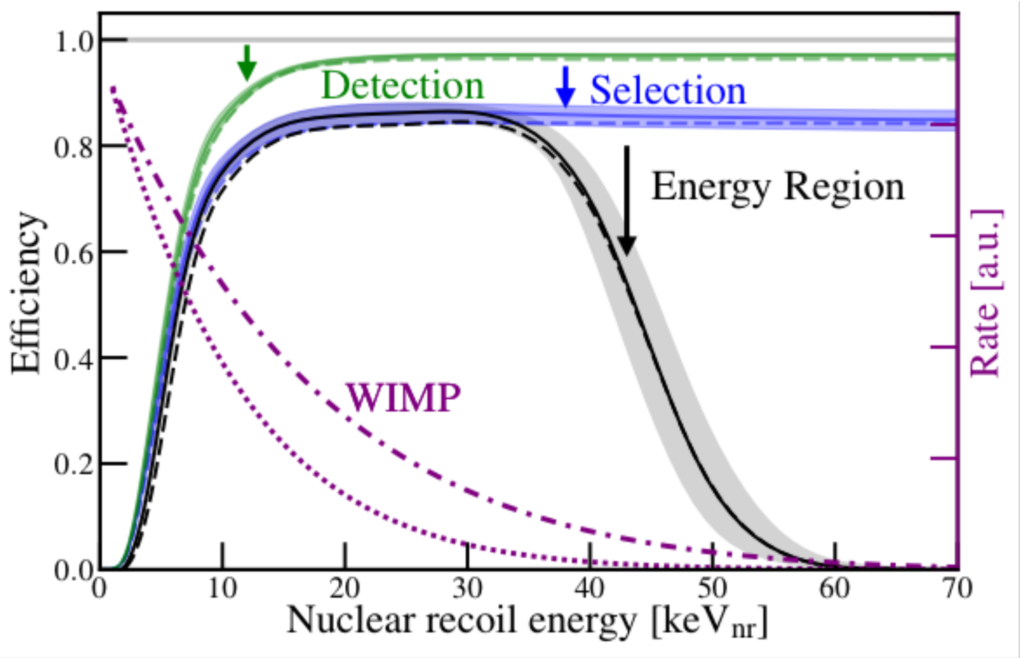


Light and charge yield stability monitored with several sources:

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

WIMP SEARCH

DATA SELECTION AND DETECTION EFFICIENCY

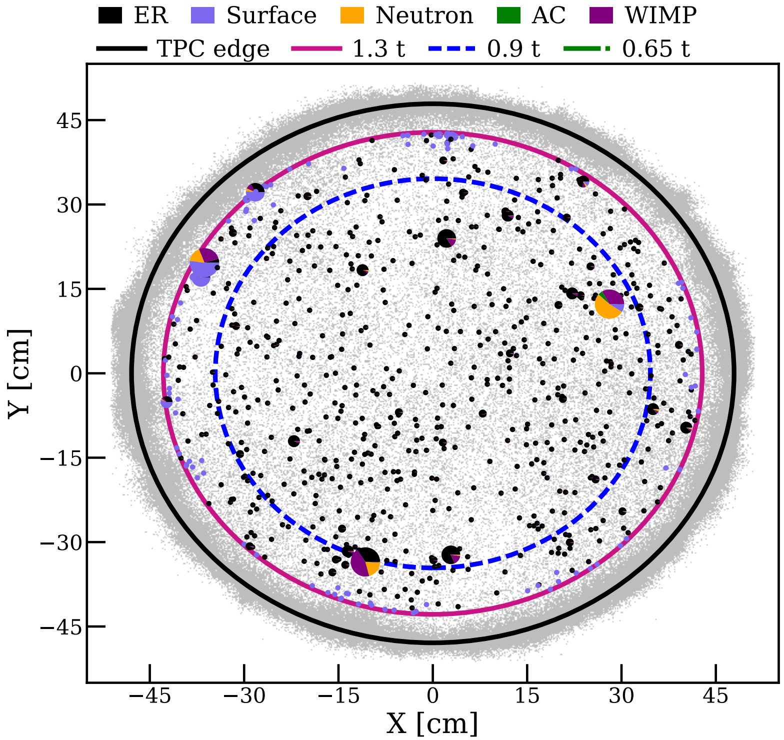


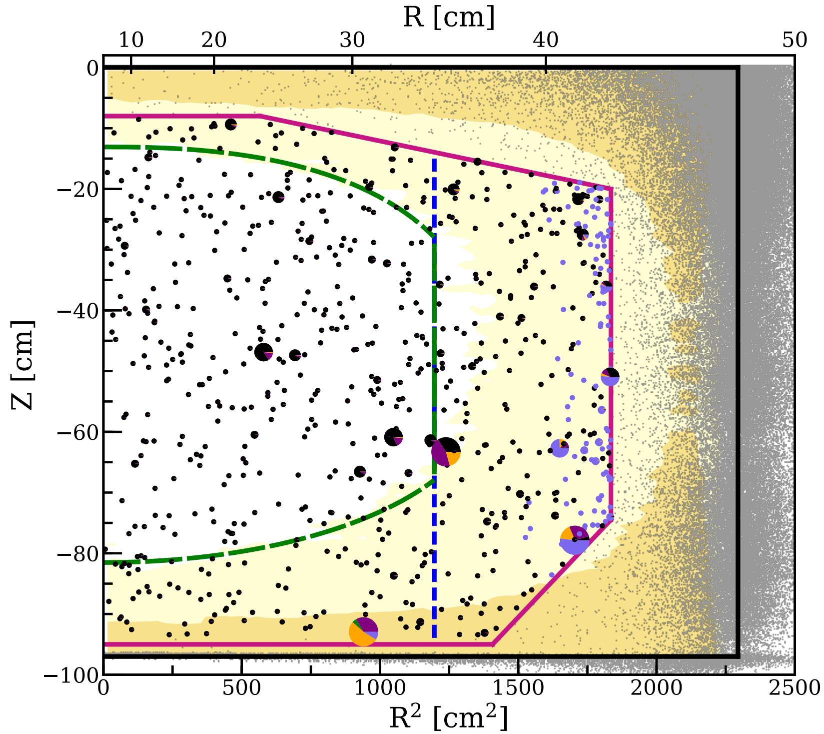
- Detection efficiency dominated by 3-fold coincidence requirement
  - Estimated via novel waveform simulation including systematic uncertainties
- Selection efficiencies estimated from control or MC data samples
- Search region defined within 3-70 PE in cS1
- 50 GeV (dotted) and 200 GeV (dashed and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

SPATIAL DISTRIBUTION

▸ Core volume

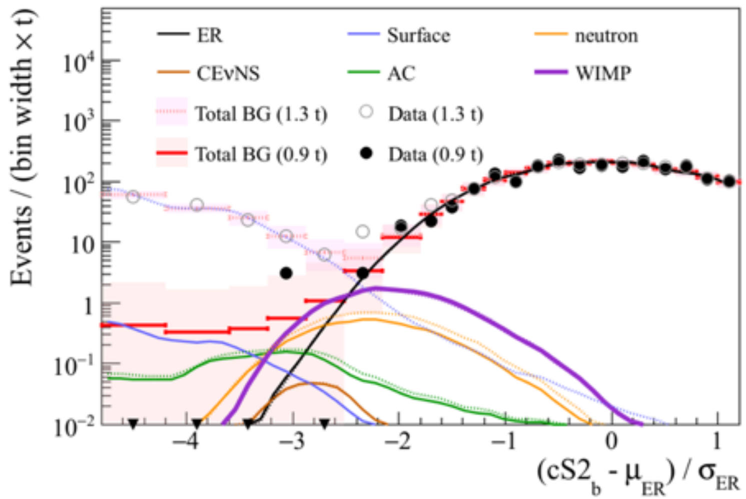
The innermost volume is free of surface and neutron background.
The spatial modeling of backgrounds allows to increase the fiducial volume.





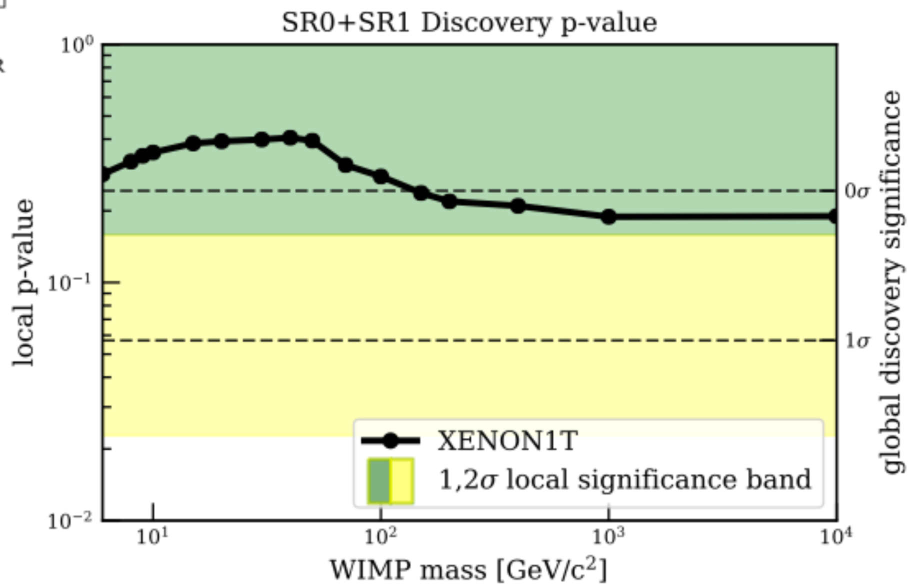
STATISTICAL INTERPRETATION

< 1 SIGMA DISCOVERY SIGNIFICANCE



- Extended unbinned profile likelihood analysis
- Example left: Background and 200 GeV WIMP signal best-fit predictions, assuming 4.2×10^{-47} cm^2, compared to data in 1.3T and 0.9T
- 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



PREDICTED AND OBSERVED DATA

Reference and smaller fiducial masses are illustrative. Data analysis and statistical inference is performed on the full dataset with PLR approach and backgrounds/signal shape accounted.

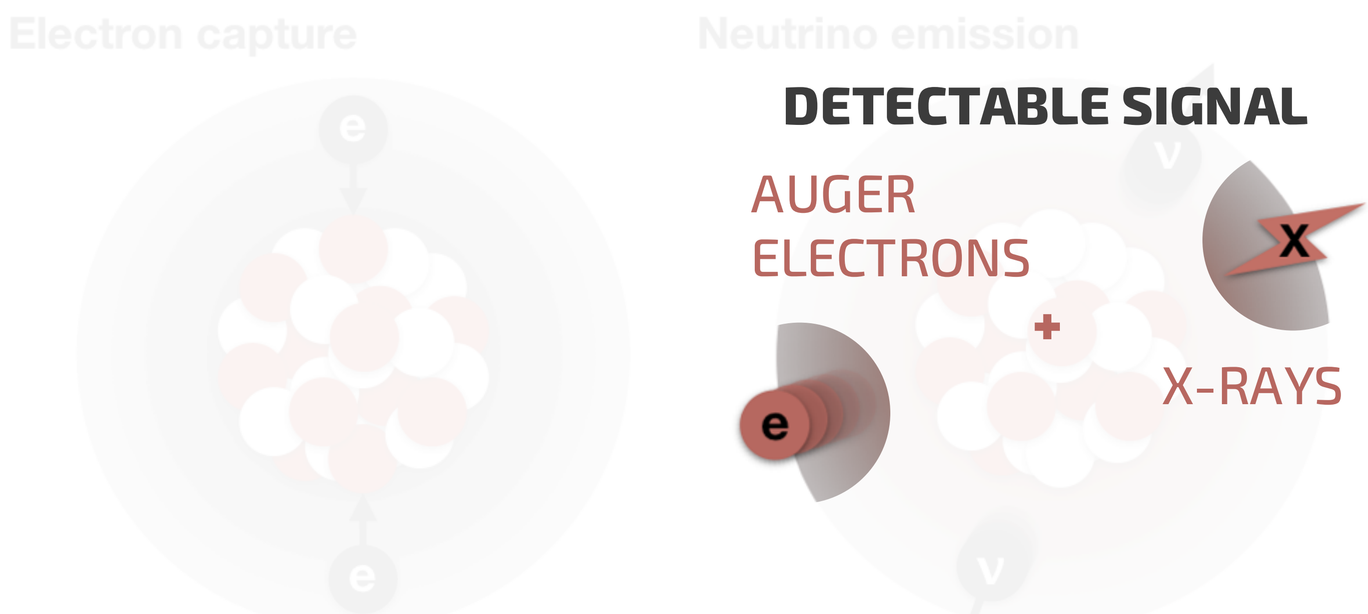
Mass	1.3 t	1.3 t	0.9 t	0.65 t
($cS1$, $cS2_b$)	Full	Reference	Reference	Reference
ER	627 ± 18	1.62 ± 0.30	1.12 ± 0.21	0.60 ± 0.13
neutron	1.43 ± 0.66	0.77 ± 0.35	0.41 ± 0.19	0.14 ± 0.07
CEνNS	0.05 ± 0.01	0.03 ± 0.01	0.02	0.01
AC	$0.47^{+0.27}_{-0.00}$	$0.10^{+0.06}_{-0.00}$	$0.06^{+0.03}_{-0.00}$	$0.04^{+0.02}_{-0.00}$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

WIMP expectation under best-fit model at m=200 GeV (cross-section = 4.7×10^{-47} cm^2)

THE RAREST DECAY EVER OBSERVED

Double Electron Capture (2νECEC)

- Binding energy released: ~ **1 MeV** carried away mostly by neutrinos



- Experimental signature: **$\mathcal{O}$(keV)** cascade of X-rays and Auger electrons

THE RAREST DECAY EVER OBSERVED

Key ingredients for discovery

Very large detector
Huge number of atoms (^{124}Xe) present in the LXe target

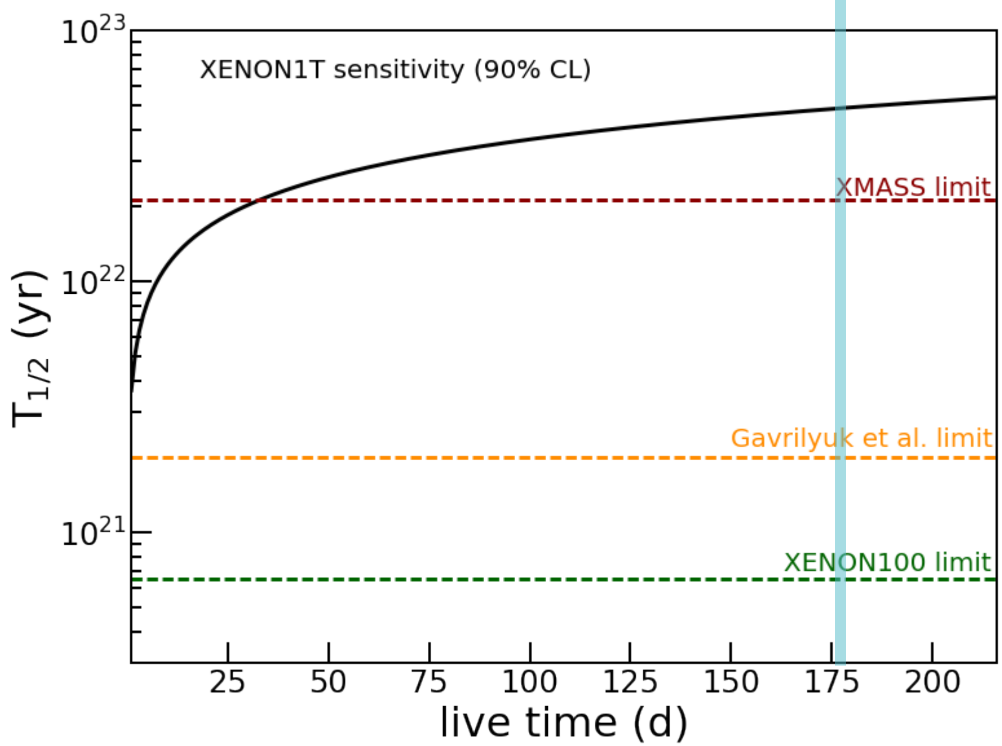
Very silent detector
Extremely low and well characterized background level

HOW ABOUT 2νECEC of ^{124}Xe?

XENON1T SENSITIVITY AND PREVIOUS LIMITS

PREVIOUS SEARCHES OF ^{124}Xe DECAY

- Gas proportional counters using enriched Xenon
- Large Xe-based dark matter detectors



XENON1T DATA FOR 2νECEC SEARCH

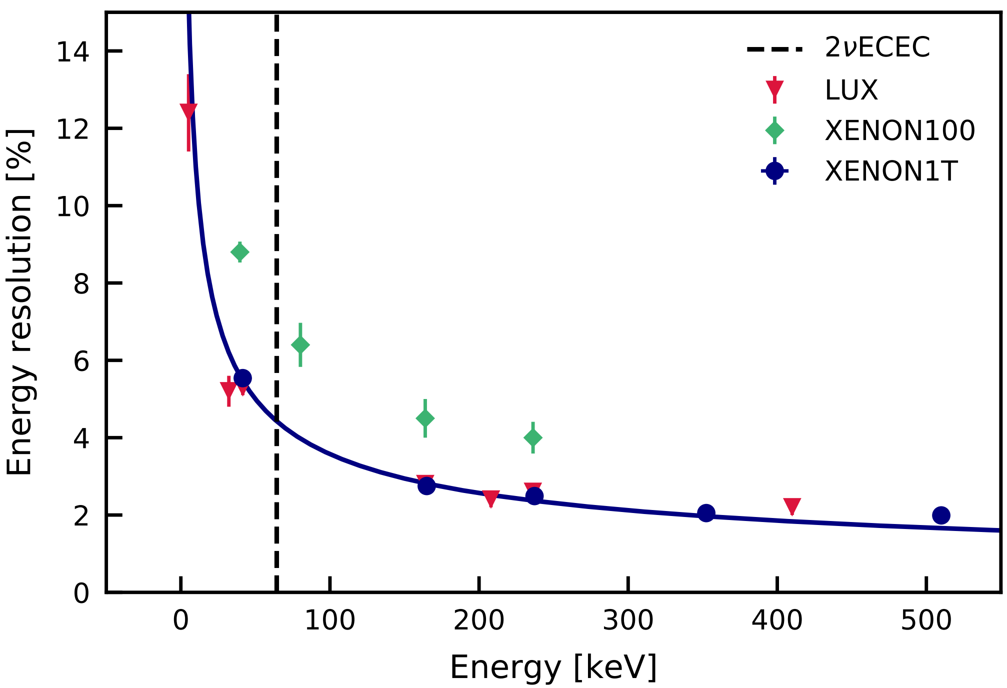
- Data taking period
  2 February 2017 - 8 February 2018
- Final live time
  177.7 days

XENON1T ENERGY SCALE

ENERGY RESOLUTION

Fitting Gaussian functions to mono-energetic peaks

- *^{83m}Kr (41.5 keV)*
  Injected calibration source
- *^{131m}Xe (163.9 keV) and ^{129m}Xe (236.2 keV)*
  Activated metastable isotopes during neutron calibrations
- *^{214}Pb (351.9 keV) and ^{208}Tl (510.8 keV)*
  Radioactive isotopes in the TPC materials



Data points fitted with the phenomenological function:

$$\frac{\sigma_E}{\mu_E} = \frac{a}{\sqrt{E}} + b$$

- Energy resolution at $E_{2\nu ECEC}$ = 64.3 keV **(4.1 ± 0.4) %**

THE ^{125}I BACKGROUND PEAK

ACTIVATION AND REMOVAL MODEL

- Additional background from EC decay of ^{125}I
  Due to neutron activation of ^{125}Xe, especially during neutron calibration runs

$$^{124}\mathrm{Xe} + n \longrightarrow {}^{125}\mathrm{Xe} + \gamma$$

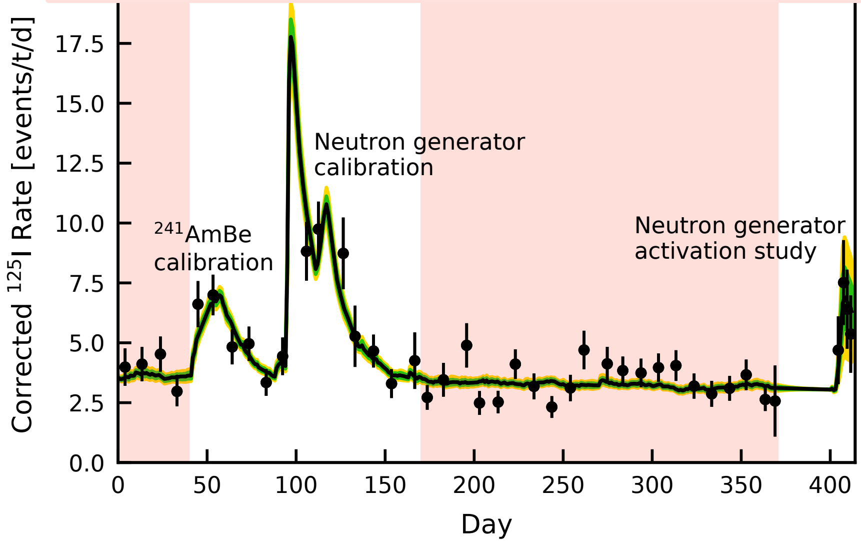
$$^{125}\mathrm{Xe} \xrightarrow[\mathrm{EC}]{16.9\,\mathrm{h}} {}^{125}\mathrm{I}^* + \nu_e$$

$$^{125}\mathrm{I} \xrightarrow[\mathrm{EC}]{59.4\,\mathrm{d}} {}^{125}\mathrm{Te}^* + \nu_e$$

$$^{125}\mathrm{Te}^* \xrightarrow{1.48\,\mathrm{ns}} {}^{125}\mathrm{Te} + \gamma + \mathrm{X}$$

- **^{125}I DECAY**: mono-energetic peak at **67.3 keV** (very close to the 2νECEC peak)

- **LIVETIME SELECTED: 177.7 d**
  Time periods with ^{125}I rate at background level



- **ACTIVATION MODEL**
  Based on ^{125}Xe rate evolution

- **^{125}I REMOVAL TIME CONSTANT**
  (9.1 ± 2.6) d
  Thanks to Xenon purification loop through hot Zirconium getters

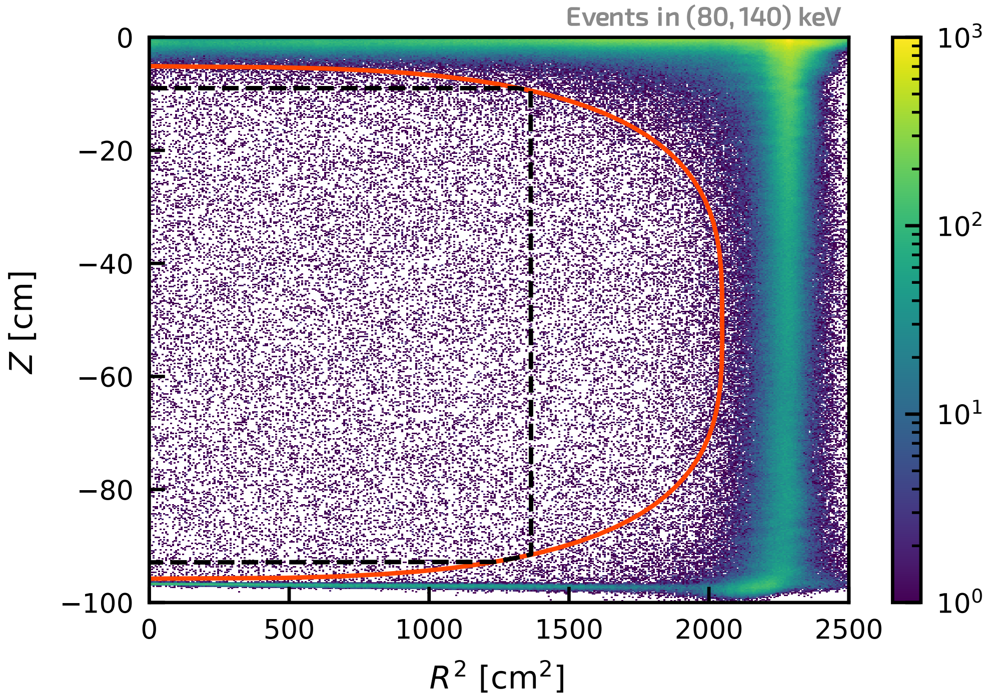
- **^{125}I EXPECTED EVENTS IN 177.7 d**
  N_{I-125} = 10 ± 7

FIDUCIAL MASS

OPTIMIZED ON DISCOVERY SENSITIVITY

Sensitivity ∝ Mass / $\sqrt{N_{background}}$
optimized in (80, 140) keV sideband since signal region was blinded

- Total fiducial volume
  1.502 t superellipsoid

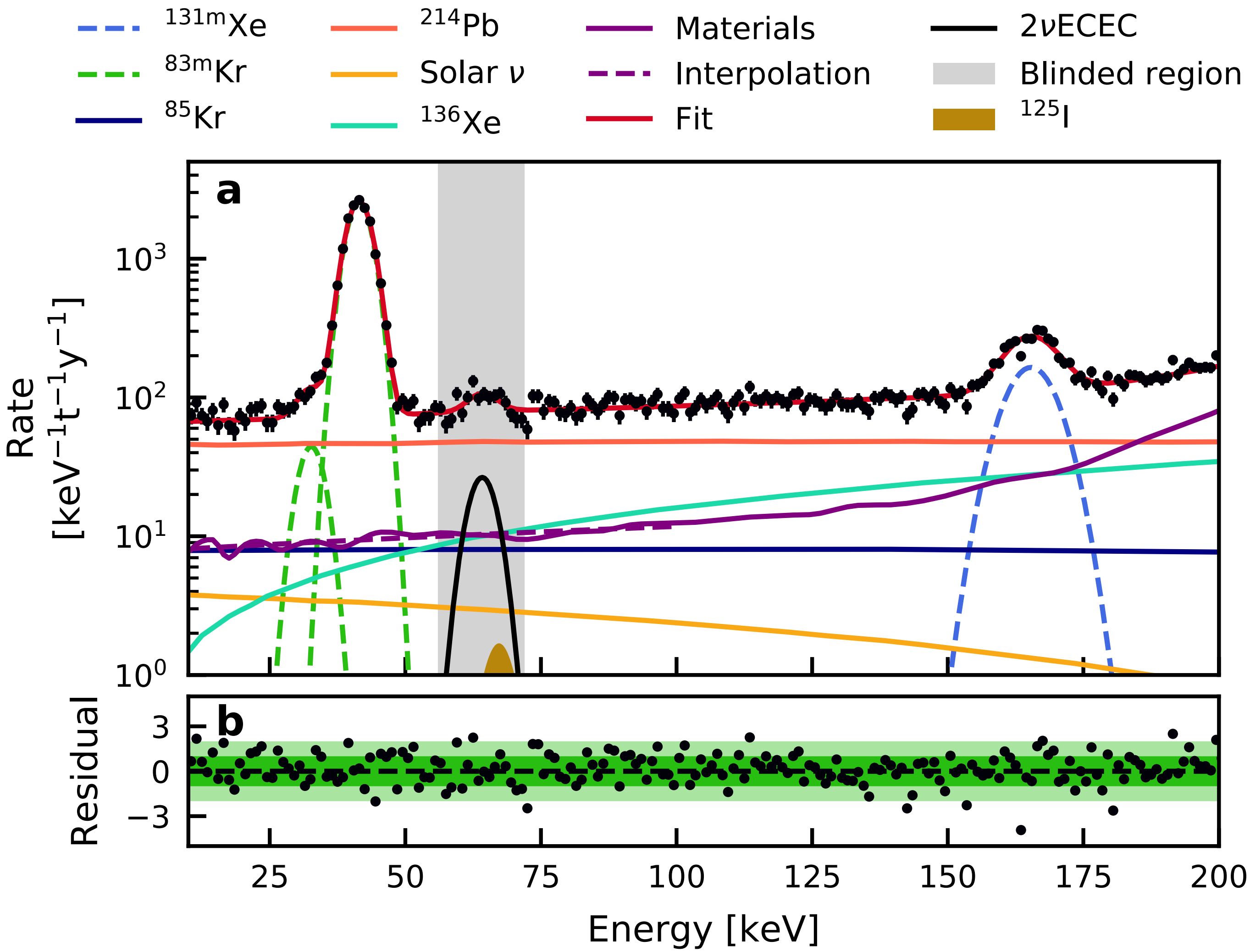


Volume segmented into
- INNER volume (1.0 t)
- OUTER volume (0.5 t)

Intrisic background sources and solar neutrinos are homegeneously distributed.

Background from materials is greatly reduced in the inner volume.

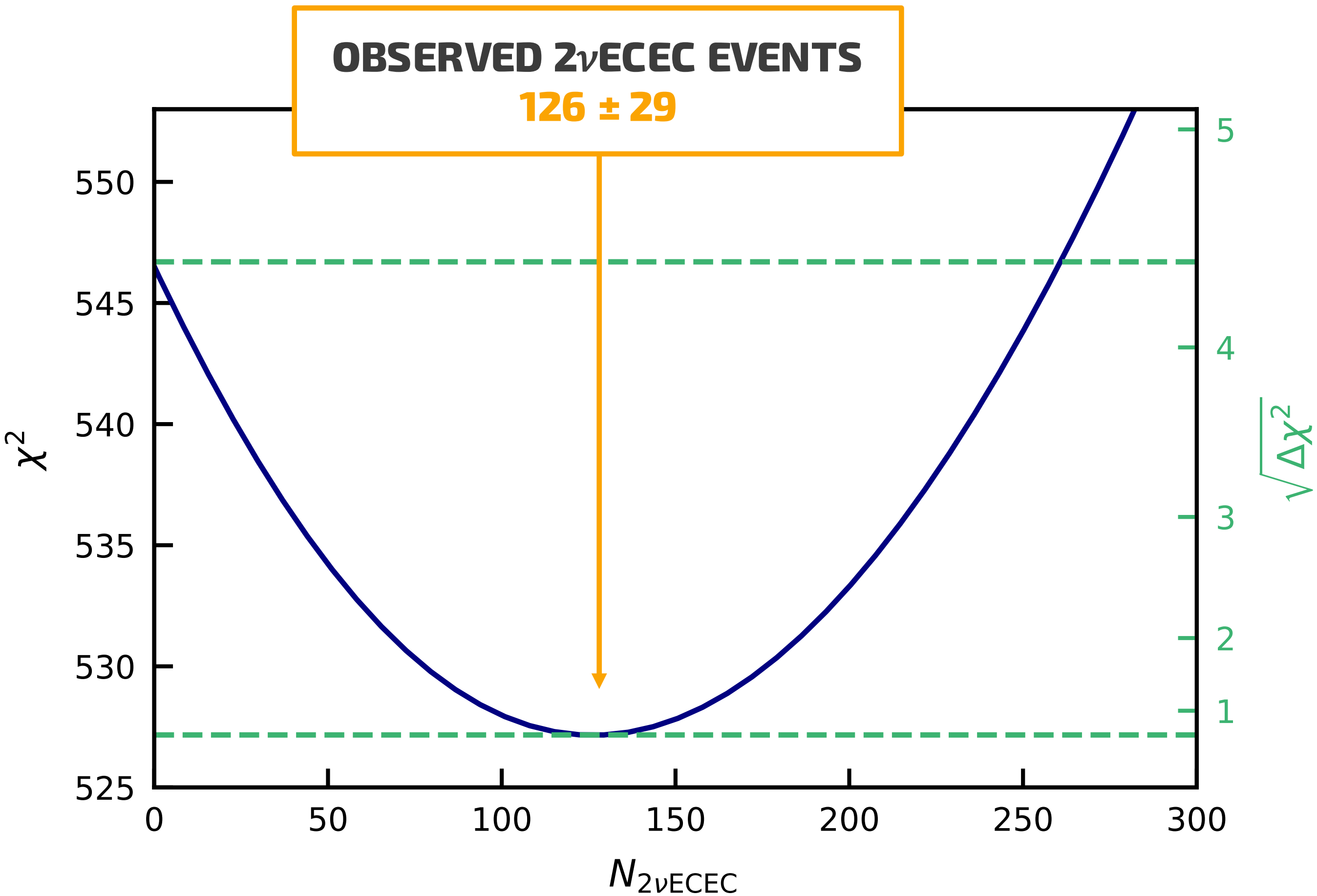
UNBLINDING THE SIGNAL REGION



DISCOVERY SIGNIFICANCE

4.4 σ

Chi-square difference between background and signal hypothesis



CONSISTENCY CHECKS

- ✓ Signal homogeneously distributed in space
- ✓ Signal events accumulated linearly with exposure
- ✓ Fits of inner (1.0 t) and outer (0.5 t) fiducial volumes yield consistent results
- ✓ Linearity of the energy response is ensured by the ^{125}I peak observed at the expected position and separated from the 2νECEC peak by more than the energy resolution
- ✓ Systematic uncertainties on cut acceptance, fiducial mass and number of ^{125}I events included as fit parameters
- ✓ Knowledge from external measurements (material screening, ^{85}Kr concentrations measurements, elemental abundances) are incorporated through constraint terms
- ✓ No constrained fit parameters are pulled significantly ($<1\,\sigma$) away from the expected value

DEC FIT PARAMETERS

b) Constrained fit parameter	Value ± uncertainty	Parameter pull [σ]
ν_{solar} multiplier	1.00 ± 0.20	0.3
^{136}Xe $2\nu\beta\beta$ multiplier	1.00 ± 0.05	-0.2
Volume$_{inner,outer}$ multipliers	1.00 ± 0.01	0.7_{inner}, -0.7_{outer}
High energy acceptance$_{inner,outer}$ multipliers	0.67 ± 0.33	0.1_{inner}, -1.0_{outer}
^{85}Kr concentration	(0.66 ± 0.12) ppt ^{nat}Kr/Xe	0.3
$N_{^{125}I}$	(10 ± 7) events	-0.2
$\mu_{^{125}I}$	(67.3 ± 0.5) keV	-0.1
$\sigma_{^{125}I}$	(2.8 ± 0.5) keV	-0.1
$\mu_{2\nu ECEC}$	(64.3 ± 0.6) keV	-0.3
$\sigma_{2\nu ECEC}$	(2.6 ± 0.3) keV	-0.2
$\mu_{^{83m}Kr,1}$	(32.2 ± 0.6) keV	0.7
$\mu_{^{83m}Kr,2}$	(41.5 ± 0.6) keV	-0.1
$\mu_{^{131m}Xe}$	(163.9 ± 0.6) keV	2.4
$\mu_{^{129m}Xe}$	(236.2 ± 0.6) keV	1.0

UPGRADED Xe PURIFICATION SYSTEM

REDUCING ^{222}Rn CONTAMINATION