DARK MATTER SEARCH WITH THE XENON1T EXPERIMENT

Background Predictions, Data Analysis and Final Results

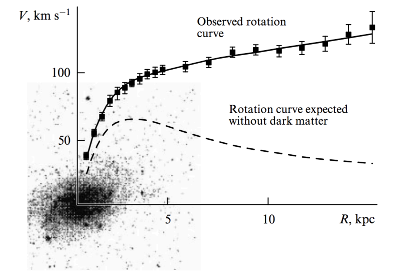
PIETRO DI GANGI

Esame Finale Dottorato | 18 Marzo 2019

EVIDENCES OF DARK MATTER

GALAXY AND CLUSTERS SCALE

ROTATION CURVES



M33 Galaxy

BULLET CLUSTER

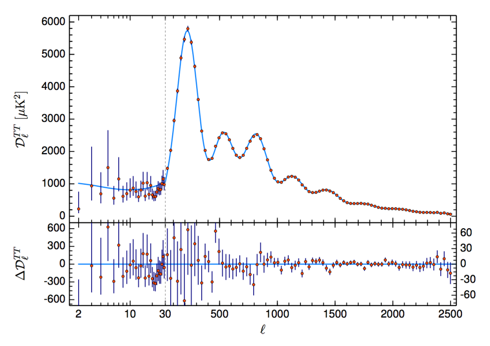
Luminous vs Dark matter

LENSING

SDSS J1038+4849 Clusters

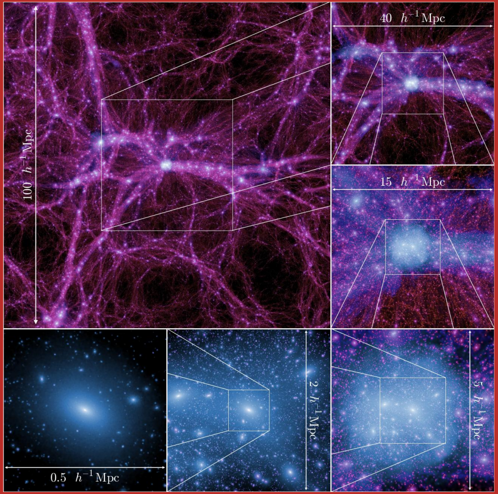
COSMOLOGICAL SCALE

CMB + ΛCDM



PLANCK 2018

STRUCTURE FORMATION

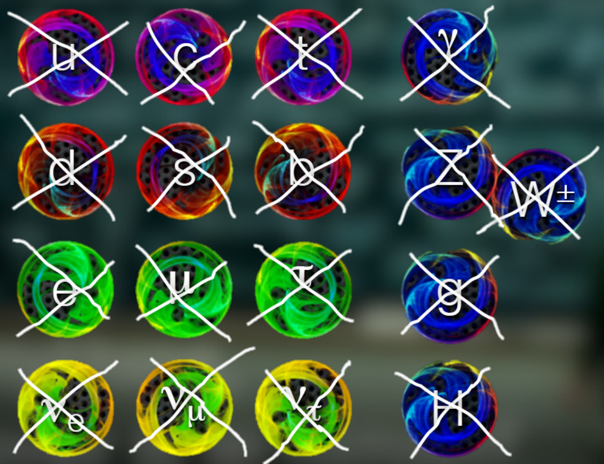


Millennium-II Simulation

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)

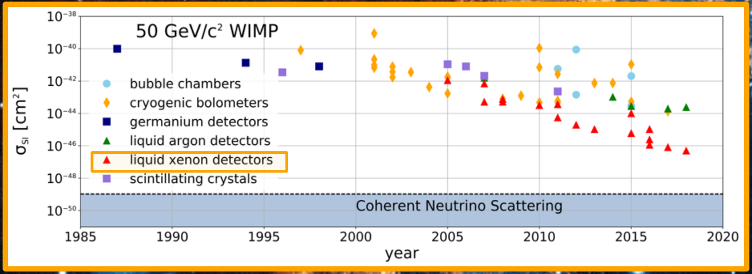
Other candidates

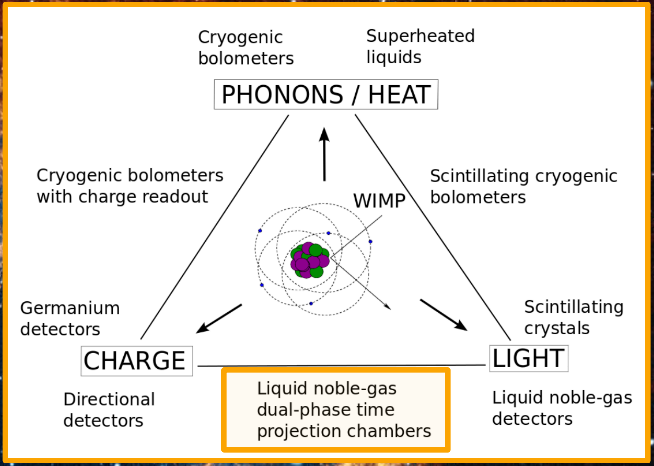
- Axions or ALPs
- Kaluza-Klein
- Wimpzillas
- and many others…

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

DARK MATTER DETECTION STRATEGY

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




Cryogenic bolometers

Superheated liquids

PHONONS / HEAT

Cryogenic bolometers with charge readout

WIMP

Scintillating cryogenic bolometers

Germanium detectors

Scintillating crystals

CHARGE

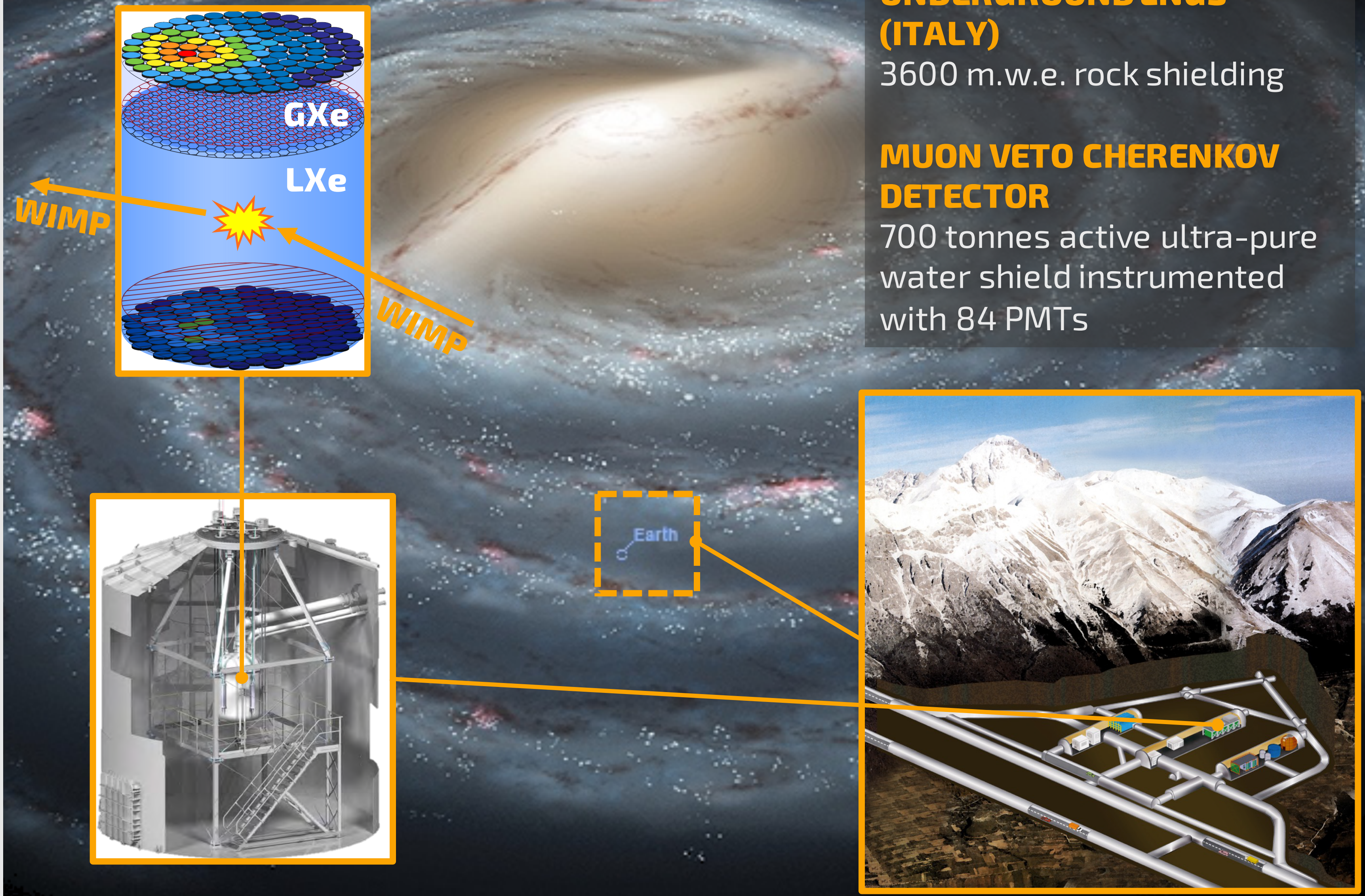
LIGHT

Directional detectors

Liquid noble-gas dual-phase time projection chambers

Liquid noble-gas detectors

WIMP SEARCH WITH XENON1T

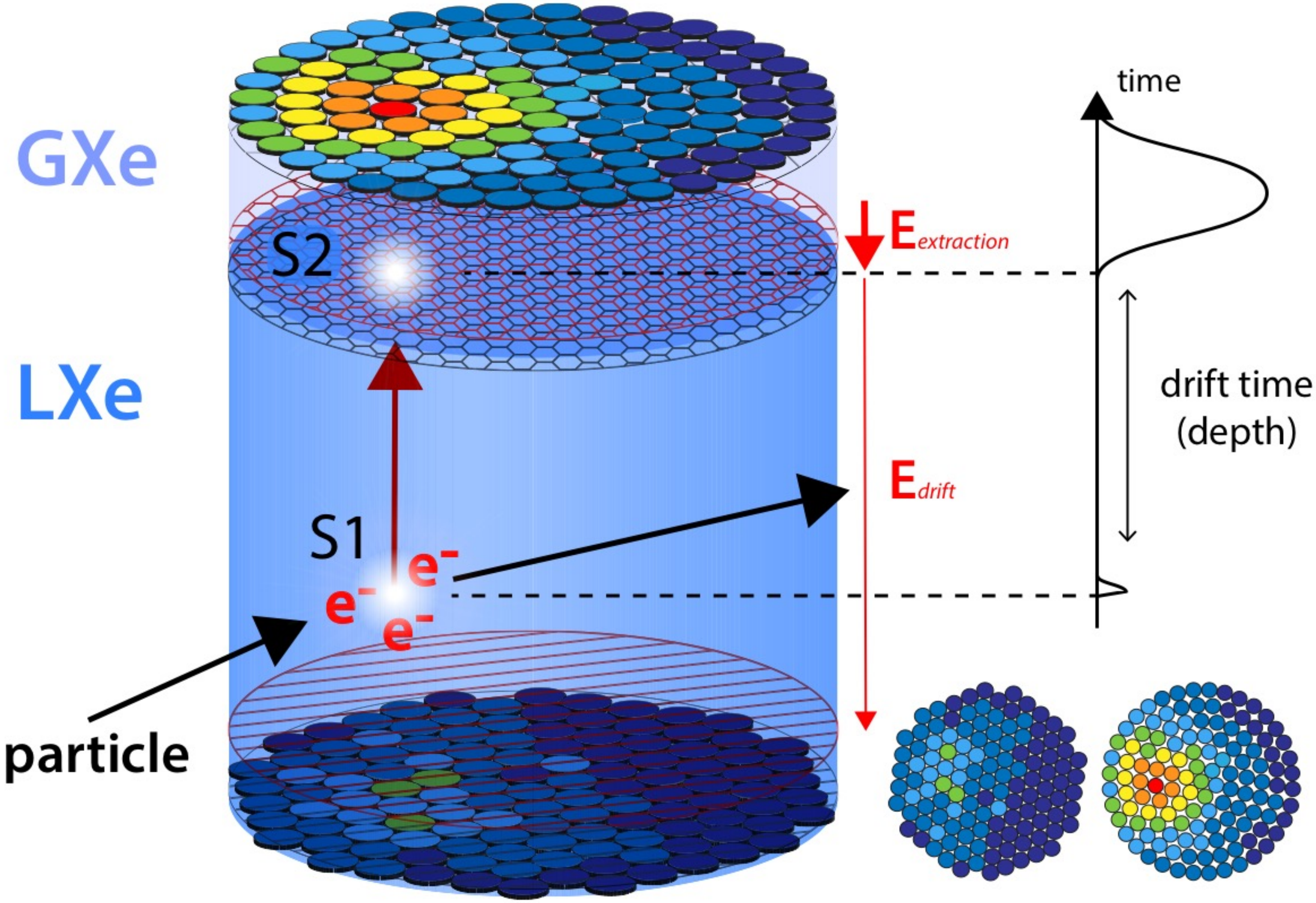


UNDERGROUND LNGS (ITALY)
3600 m.w.e. rock shielding

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

DUAL PHASE TPC

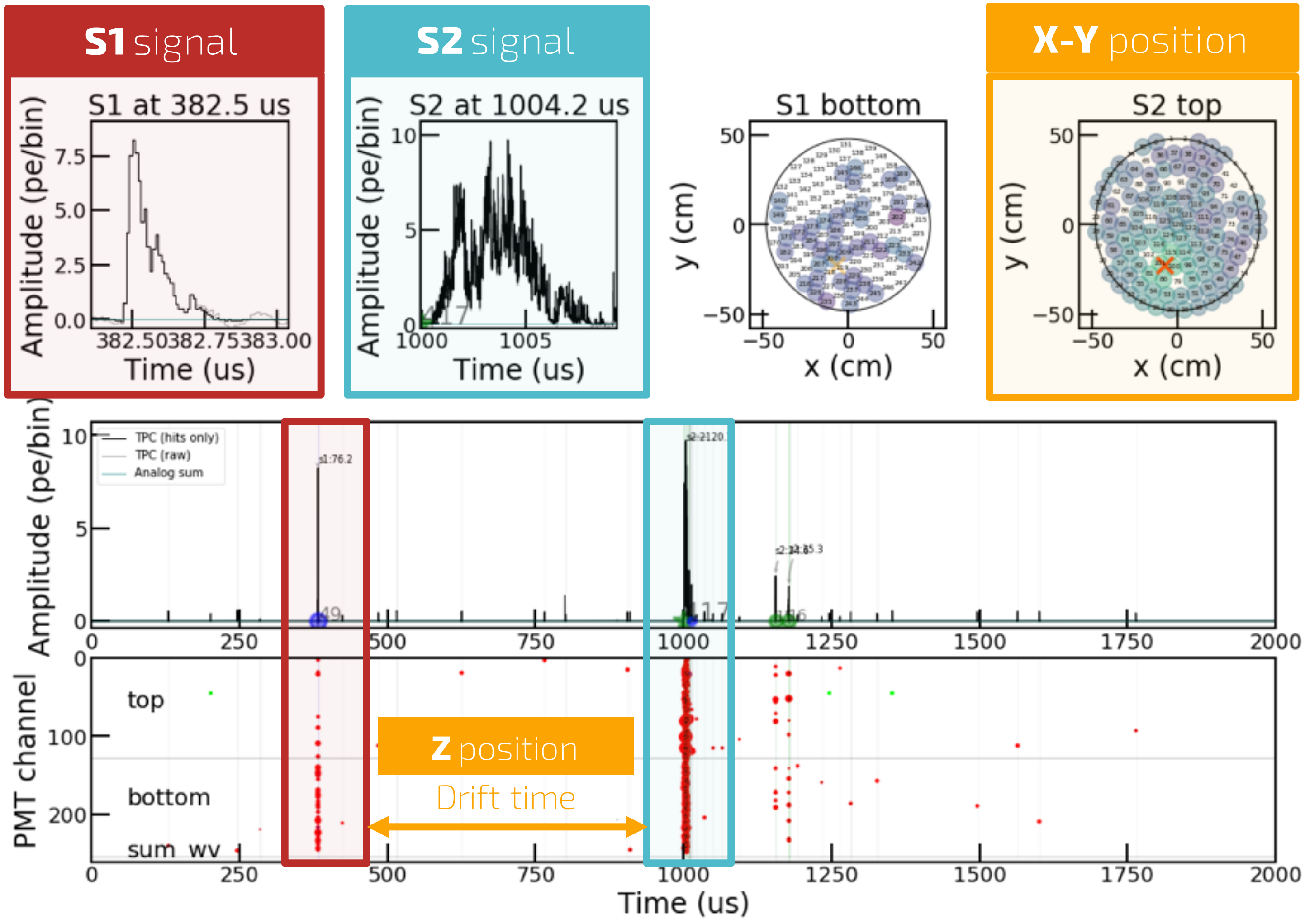
DETECTION PRINCIPLE



FROM THE PRINCIPLE TO REALITY

A TYPICAL LOW ENERGY EVENT

PAX
Processor for Analyzing XENON
https://github.com/XENON1T/pax



S1 signal

S2 signal

X-Y position

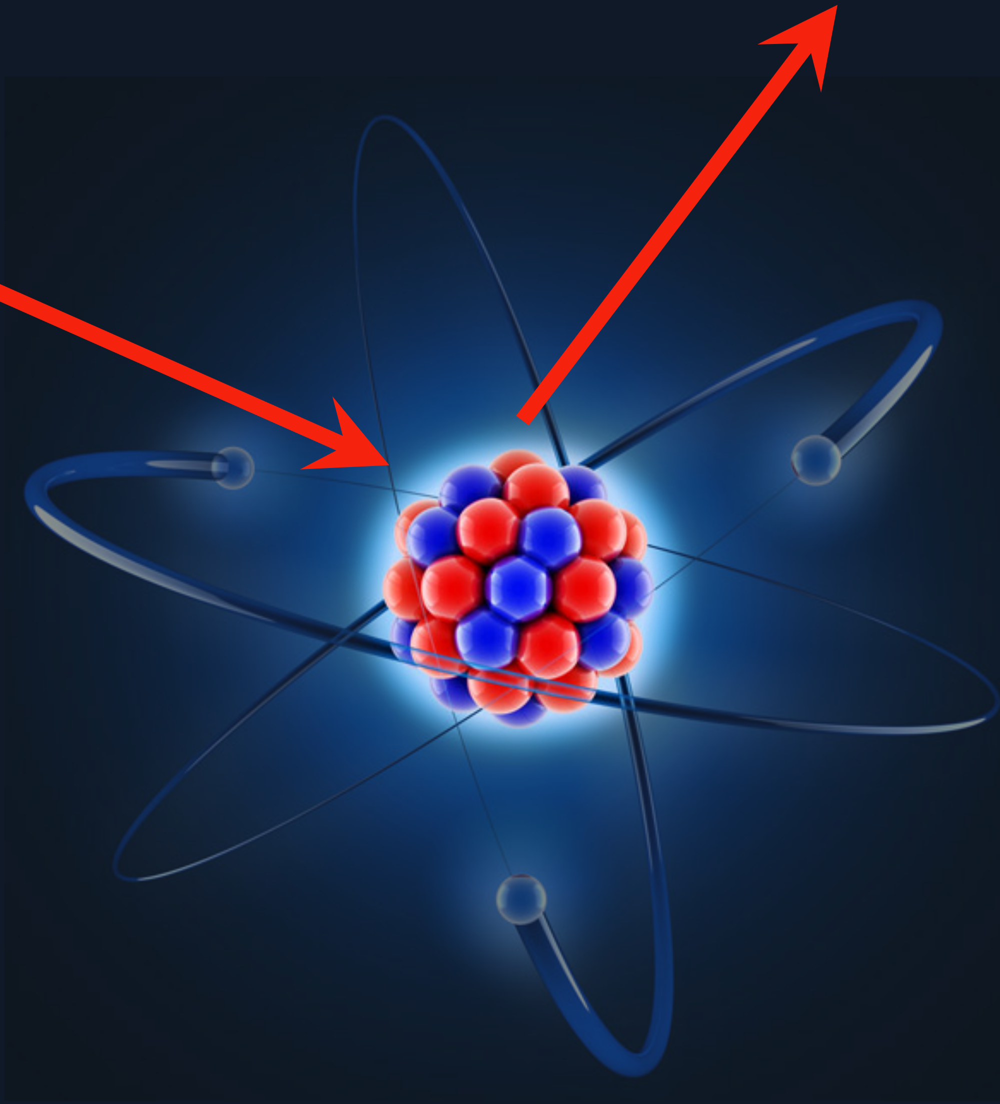
Z position

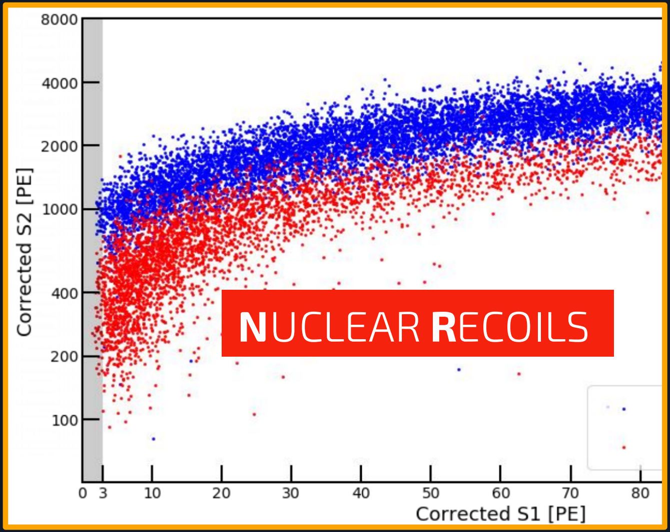
Drift time

RECOIL TYPE DISCRIMINATION

NUCLEAR RECOILS

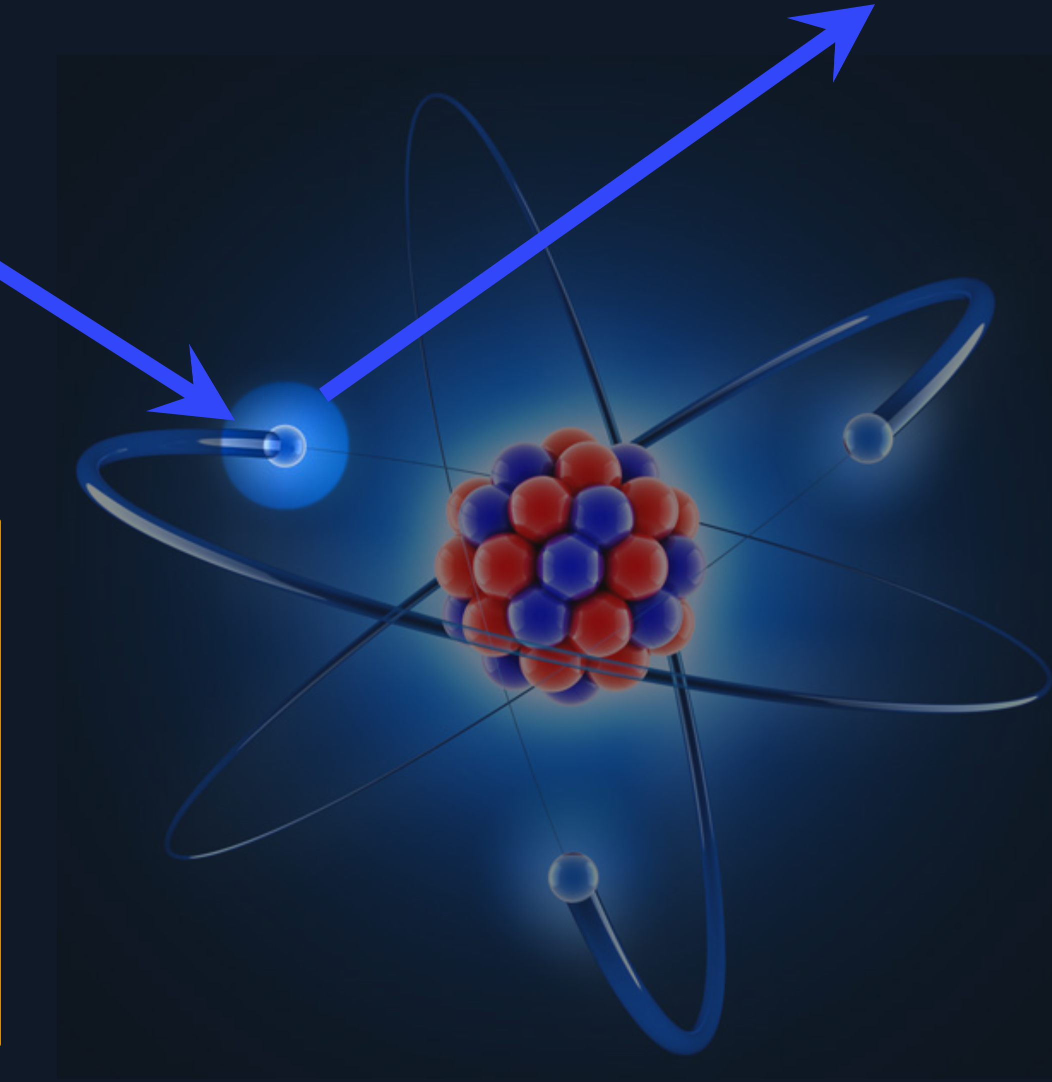
WIMP
Neutron
Neutrino (CNNS)



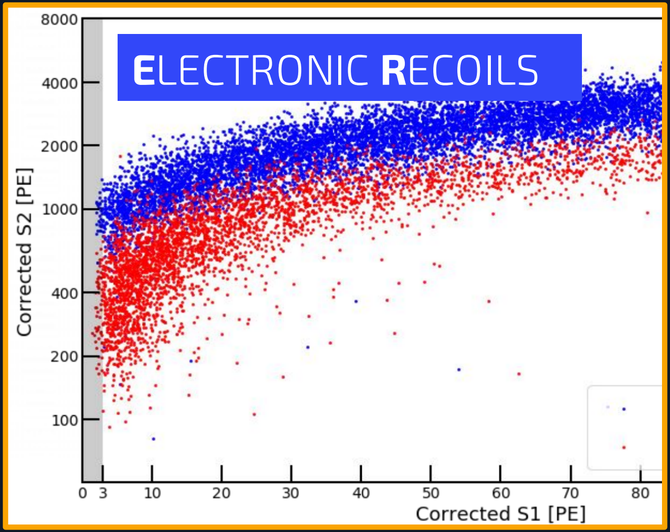


RECOIL TYPE DISCRIMINATION

ELECTRONIC RECOILS

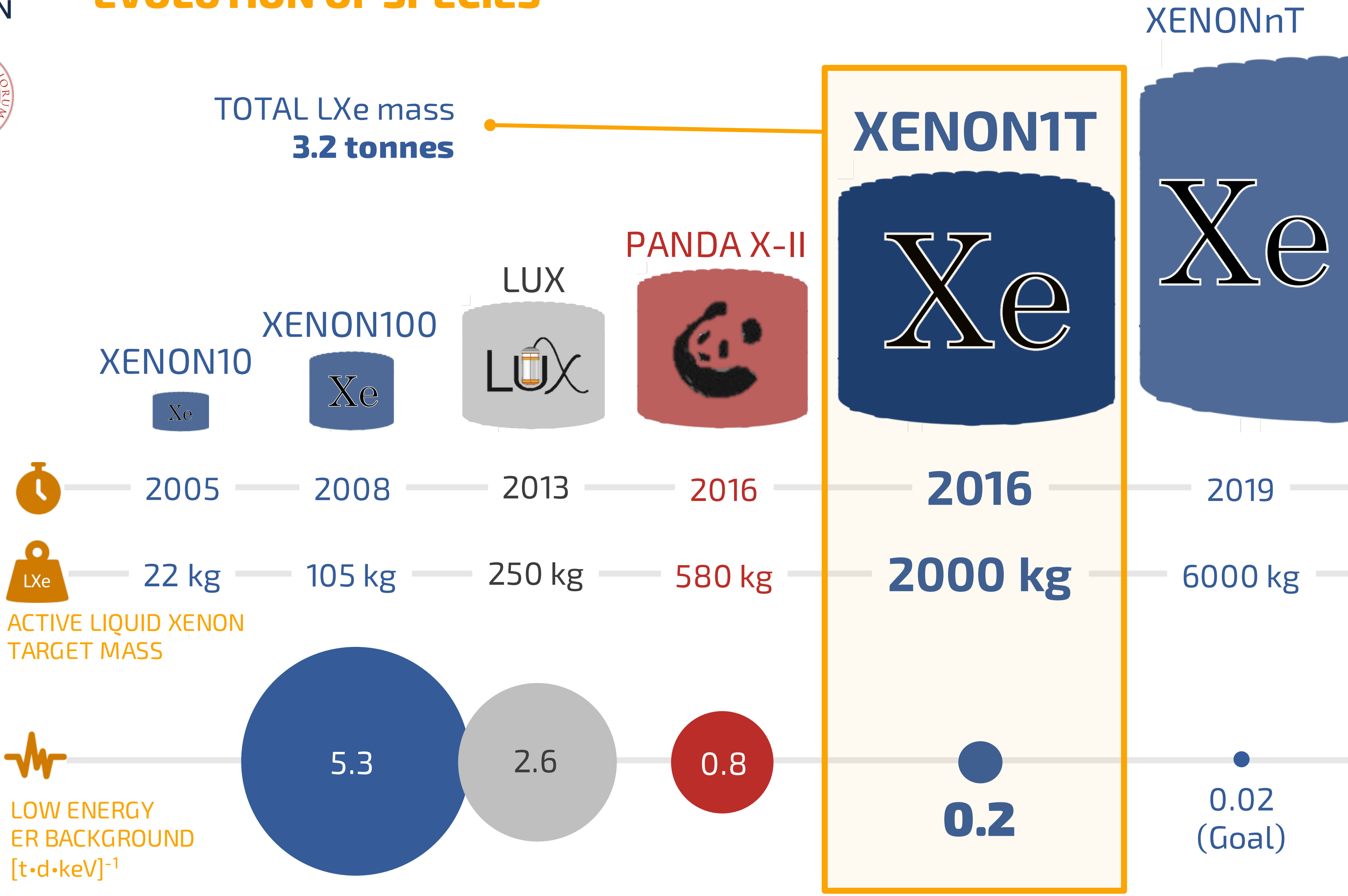


Gamma
Beta
Neutrino



LXe-BASED DM DETECTORS

EVOLUTION OF SPECIES



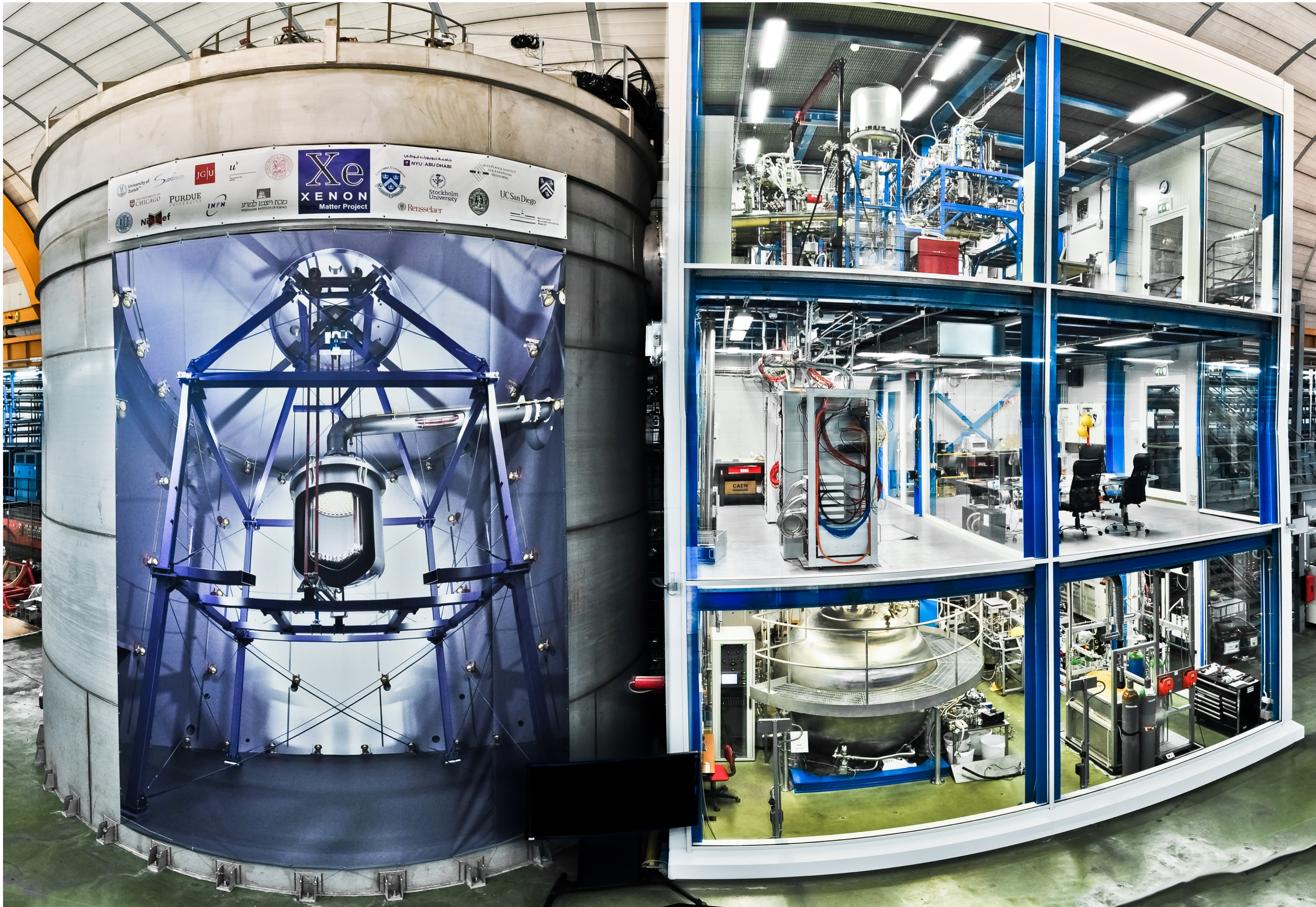
TOTAL LXe mass
3.2 tonnes

	XENON10	XENON100	LUX	PANDA X-II	**XENON1T**	XENONnT
	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)

THE XENON1T EXPERIMENT

AT LNGS (ITALY)

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



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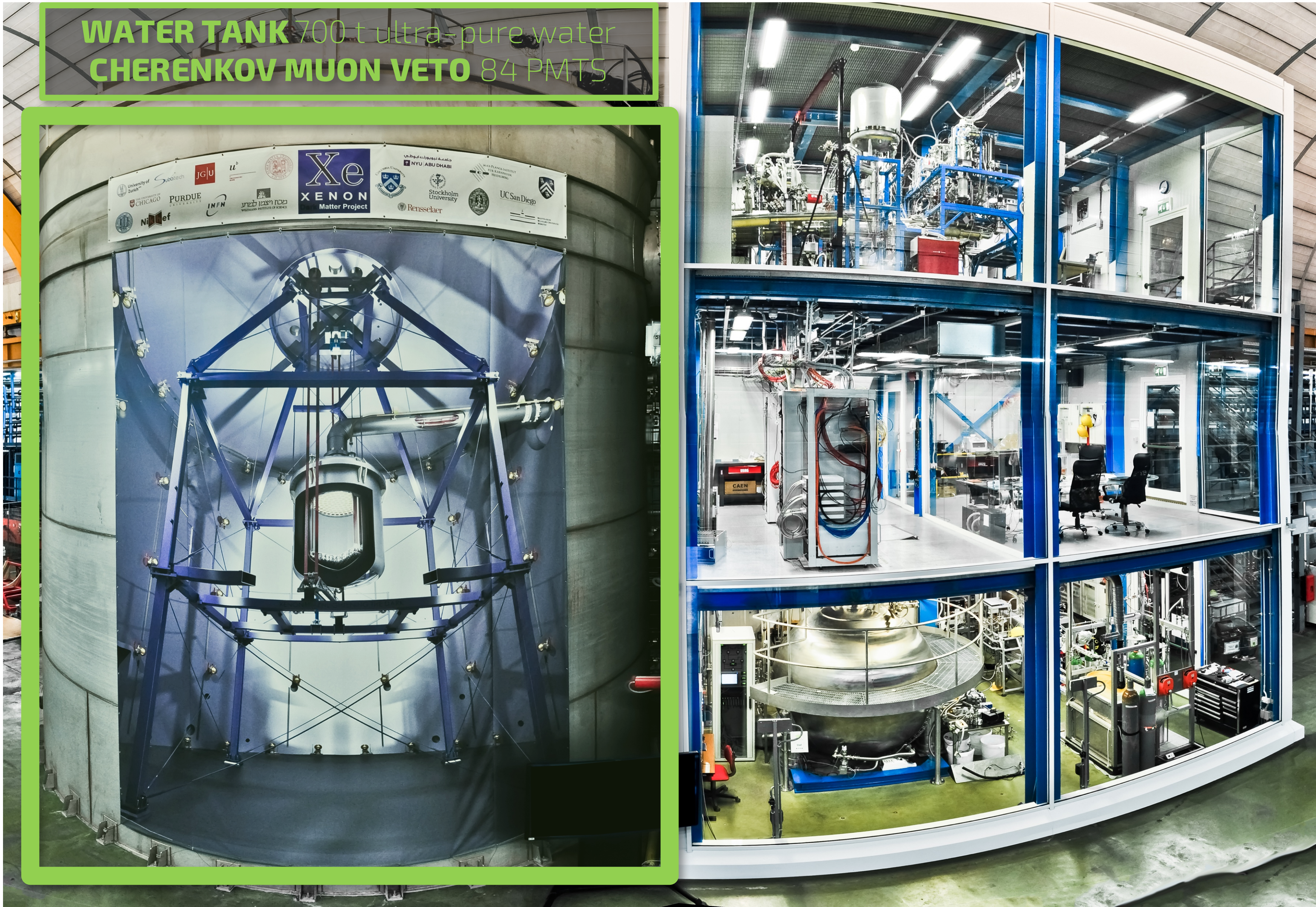

WATER TANK 700 t ultra-pure water

CHERENKOV MUON VETO 84 PMTS

THE XENON1T EXPERIMENT

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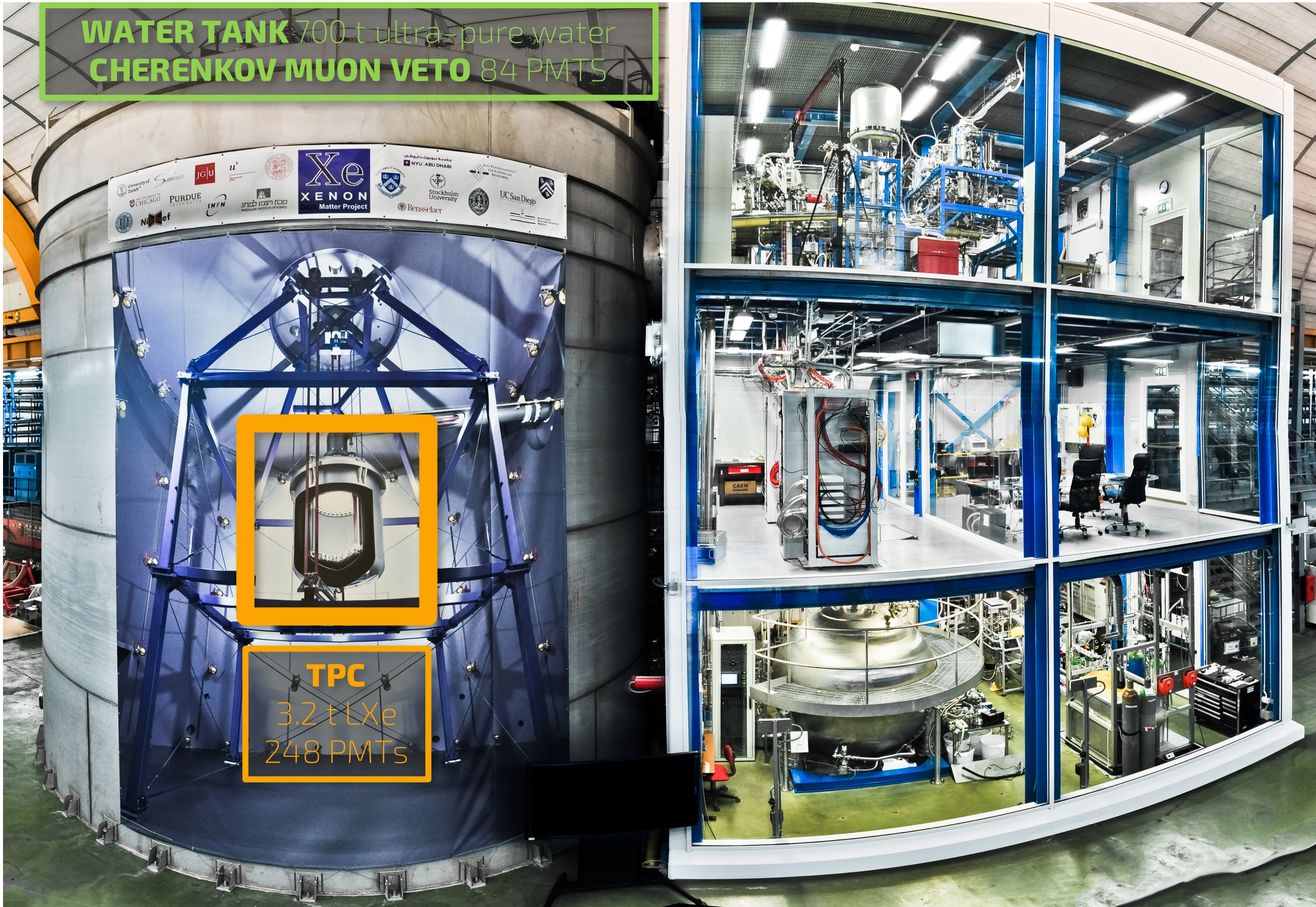

WATER TANK 700 t ultra-pure water

CHERENKOV MUON VETO 84 PMTS

TPC

3.2 t LXe

248 PMTs

THE XENON1T EXPERIMENT

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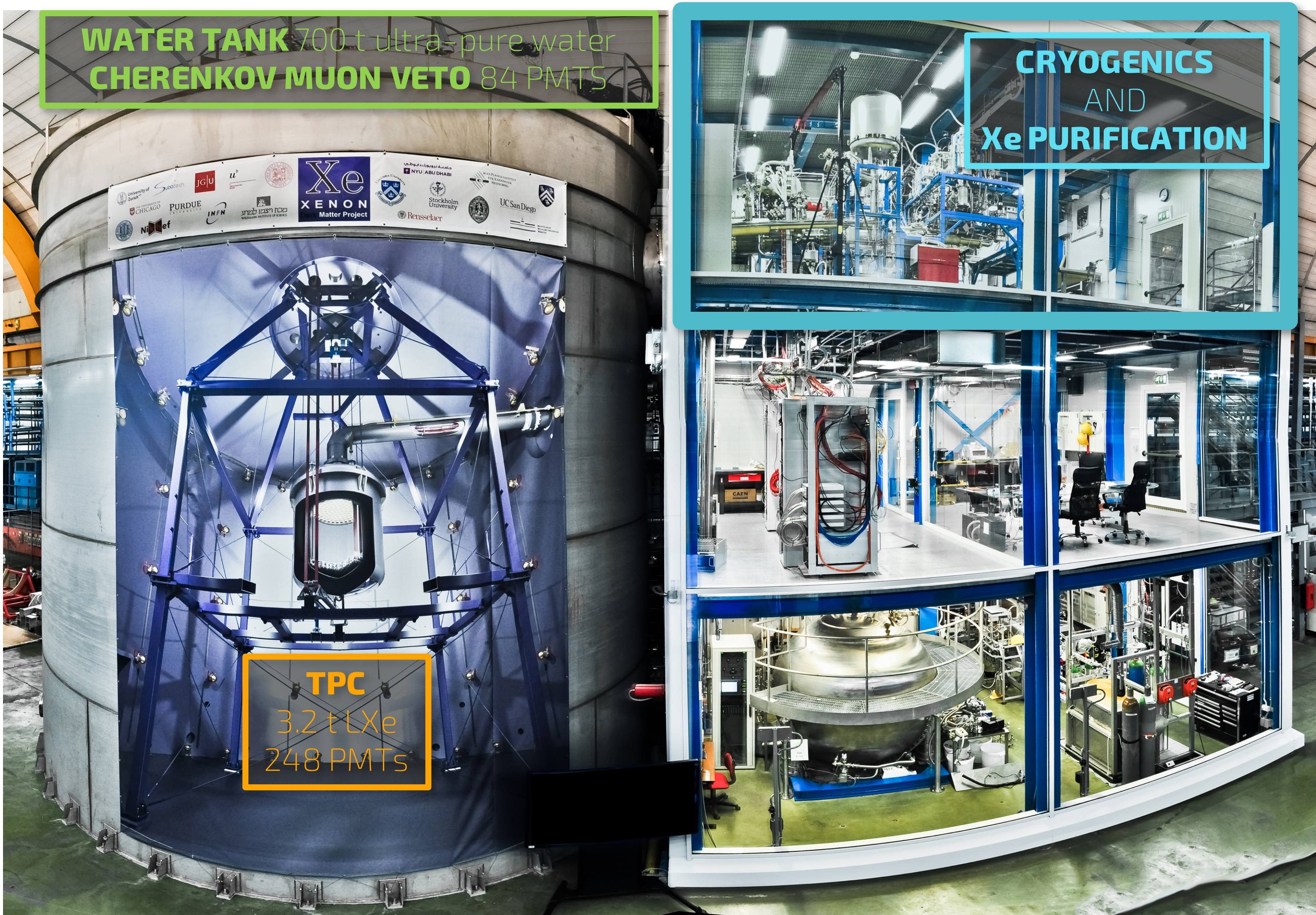

WATER TANK 700 t ultra-pure water

CHERENKOV MUON VETO 84 PMTS

CRYOGENICS
AND
Xe PURIFICATION

TPC
3.2 t LXe
248 PMTs

THE XENON1T EXPERIMENT

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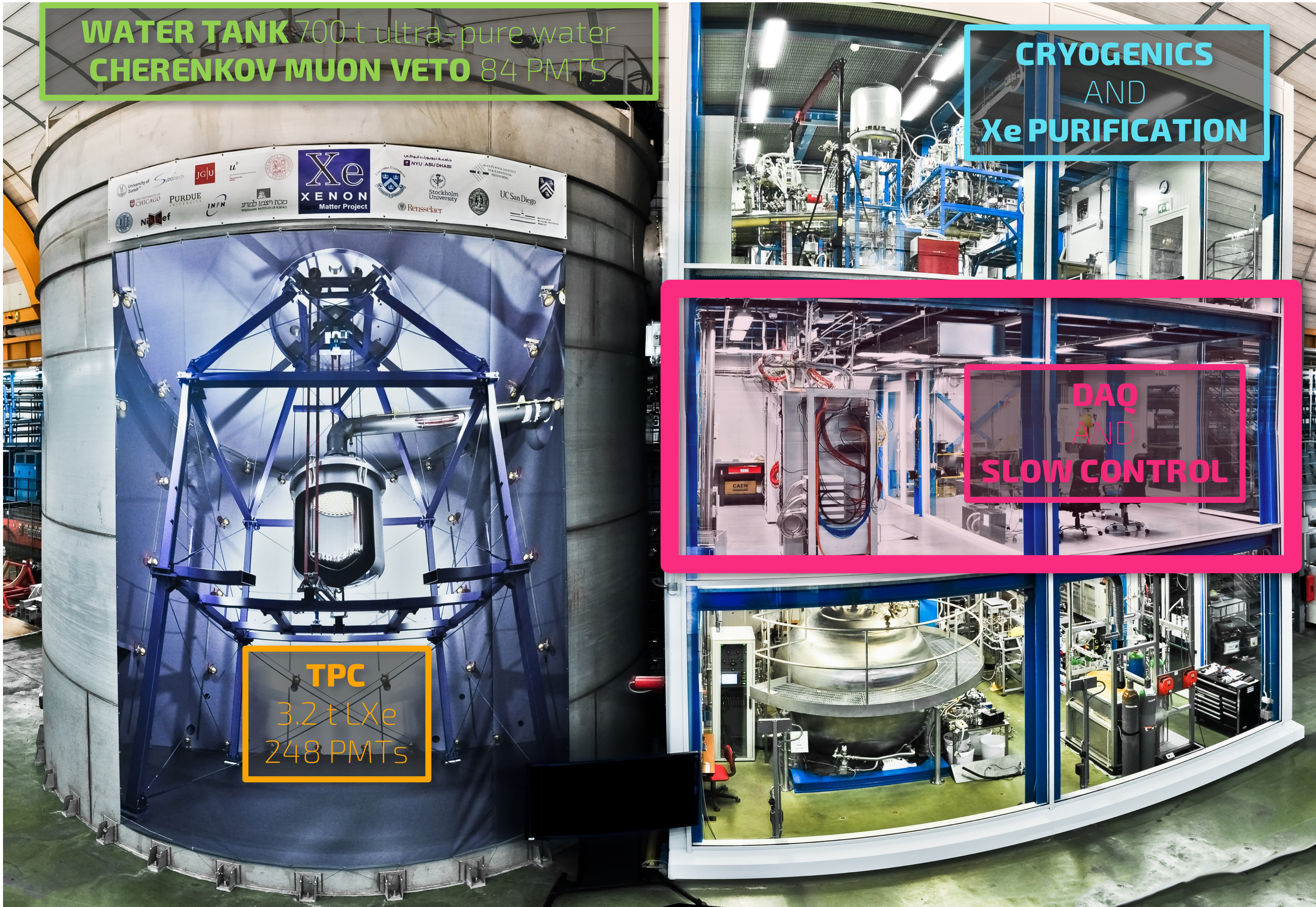


WATER TANK 700 t ultra-pure water
CHERENKOV MUON VETO 84 PMTS

CRYOGENICS
AND
Xe PURIFICATION

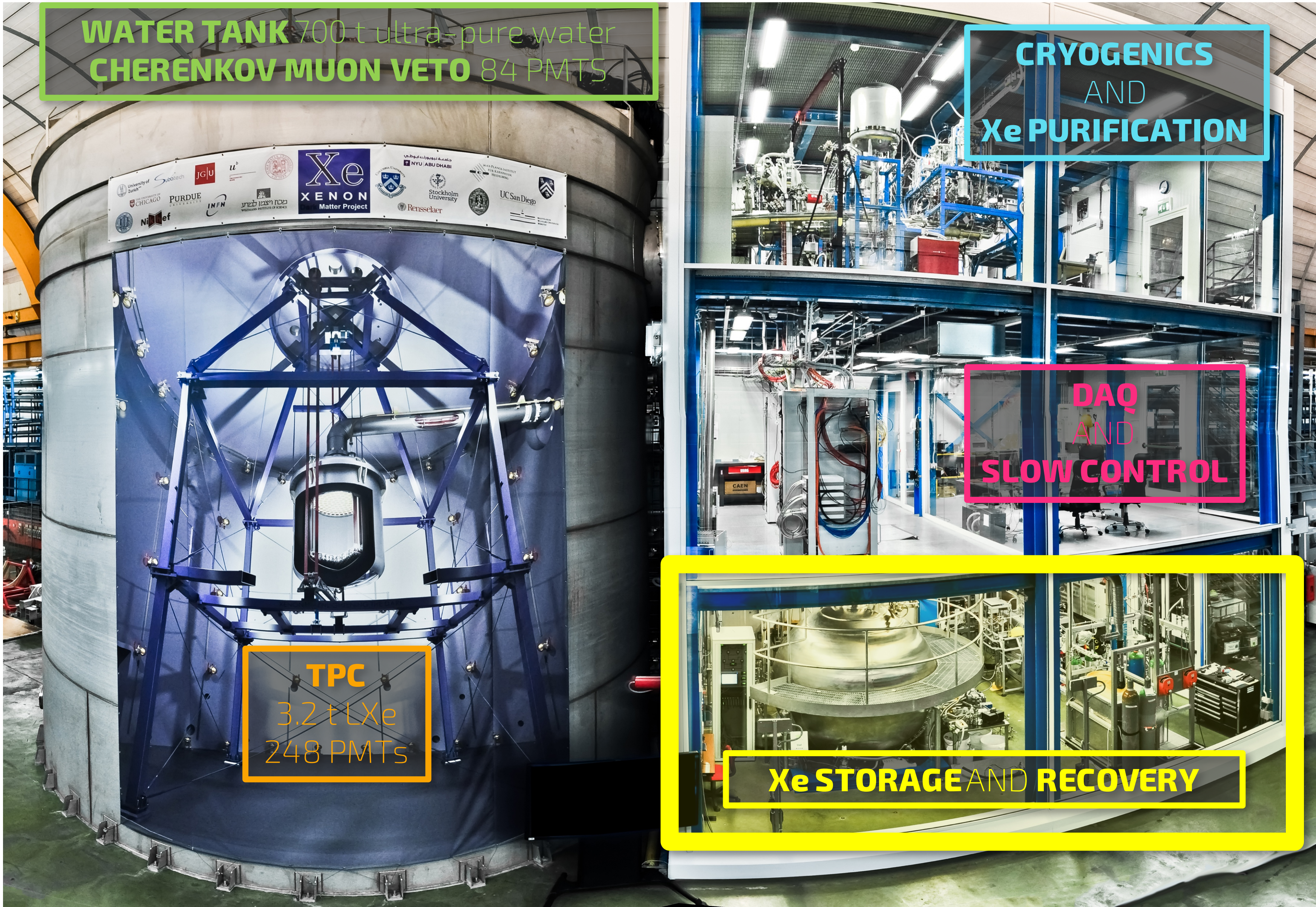
DAQ
AND
SLOW CONTROL

TPC
3.2 t LXe
248 PMTs

THE XENON1T EXPERIMENT

AT LNGS (ITALY)

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



BACKGROUNDS

NUCLEAR RECOIL BACKGROUND

- **Cosmogenic neutrons**

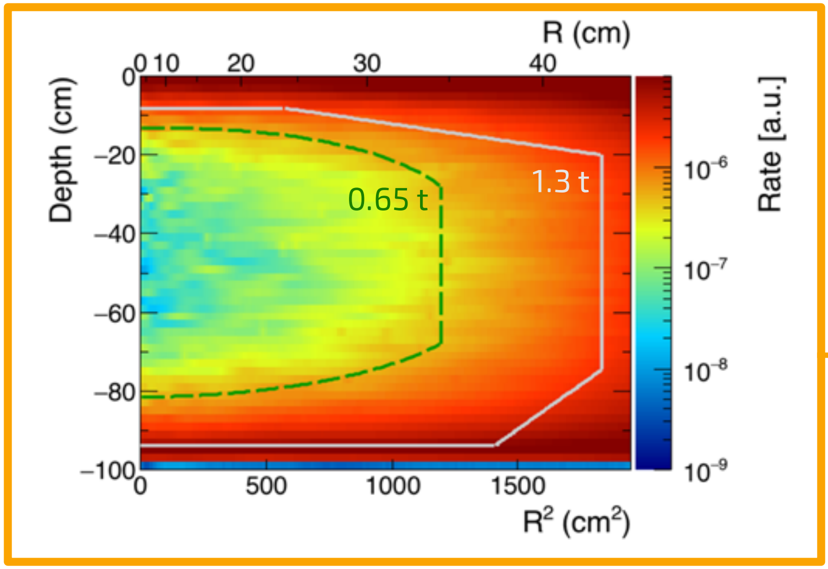
Induced by cosmic muons.
Reduced to negligible contribution by rock overburden, water passive shield and active Cherenkov Muon Veto. JINST 9, P11006 (2014)

- **Radiogenic neutrons**

From (α,n) and spontaneous fission in detector's materials.
Reduced via radiopure material selection, scatter multiplicity and fiducialization.
Eur. Phys. J. C. (2017) 77:890

- **Coherent Elastic neutrino-nucleus scattering (CNNS)**

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



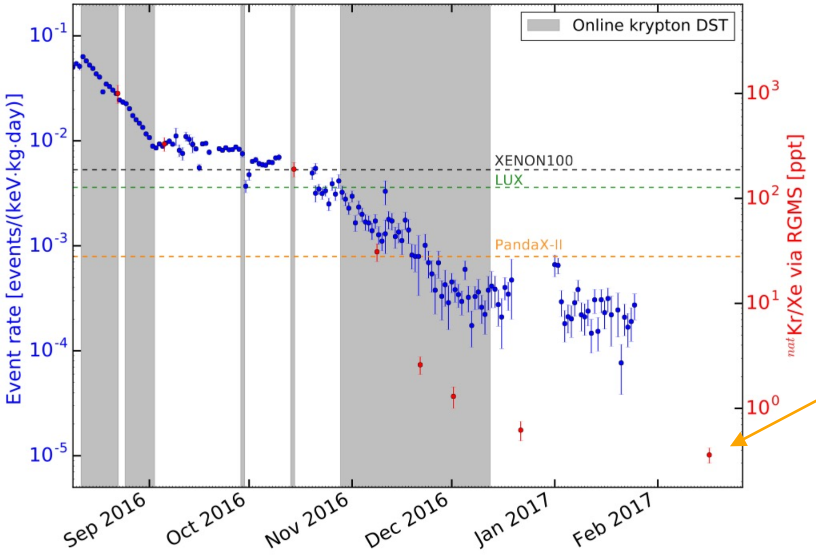
JCAP 04, 027 (2016)

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

Expectations in 1 t FV, in [4,50] keV$_{nr}$, single scatters

BACKGROUNDS

ELECTRONIC RECOIL BACKGROUND



- **Predicted:**

71 ± 7 events / (t•y•keV)

MC simulations assuming the average 0.66 ppt Kr concentration

- **Measured:**

82^{+5}_{-3} (sys) ± 3 (stat) events / (t•y•keV)

Data in 1300 kg FV and below 25 keV_{ee}

Lowest ER background

ever achieved in a DM detector

Eur. Phys. J. C (2017) 77: 358

- **^{222}Rn: 10 μBq/kg**

Careful surface emanation control and further reduction by online cryogenic distillation.

Eur. Phys. J. C. (2017) 77, 275

- **^{85}Kr: ~0.3 ppt (Kr/Xe)**

More than 3 orders of magnitude reduction via online cryogenic distillation.

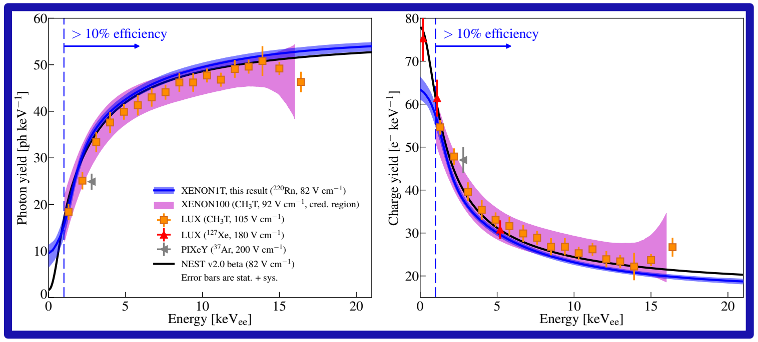
JCAP 04, 027 (2016)

	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

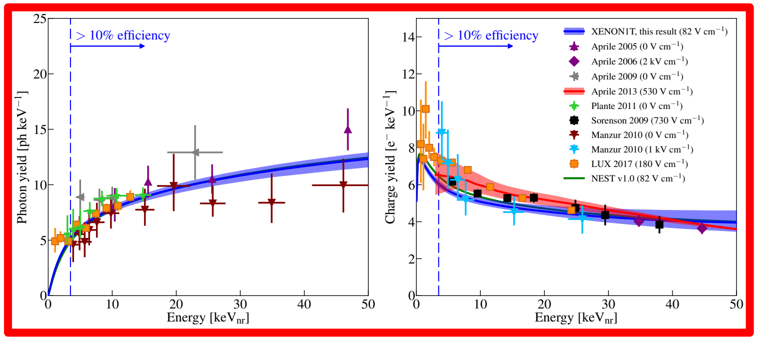
Expectations in 1 t FV, in [1,12] keV_{ee}, single scatters, **before ER/NR discrimination**

DETECTOR RESPONSE MODEL

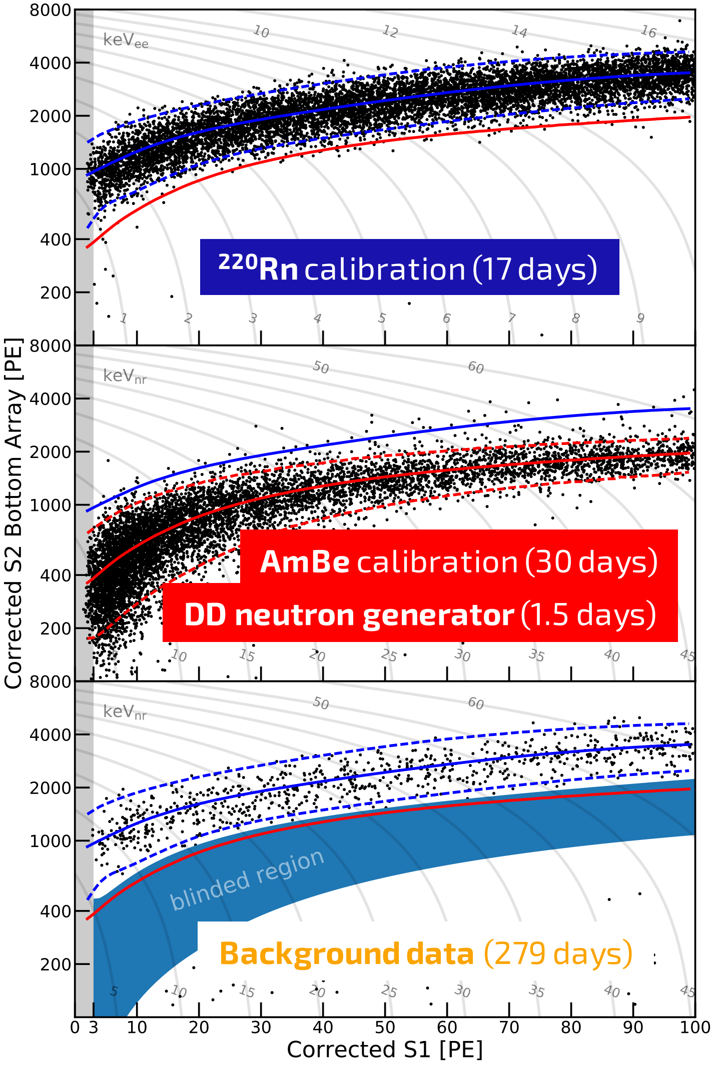
ER AND NR CALIBRATIONS



ER



NR



^{220}Rn calibration (17 days)

AmBe calibration (30 days)

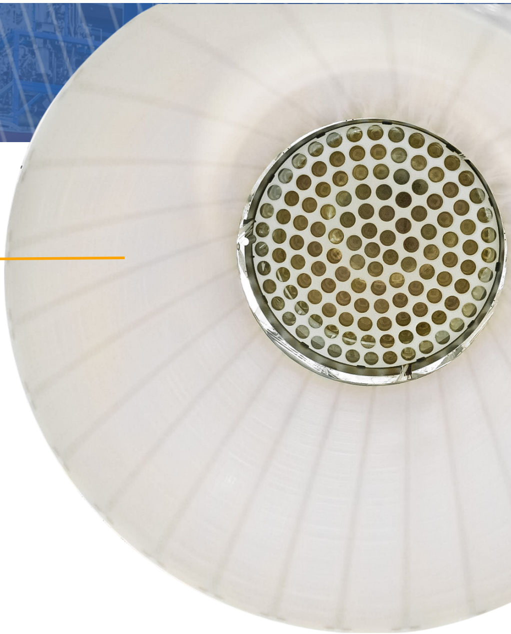
DD neutron generator (1.5 days)

Background data (279 days)

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

BACKGROUNDS

SURFACE BACKGROUND

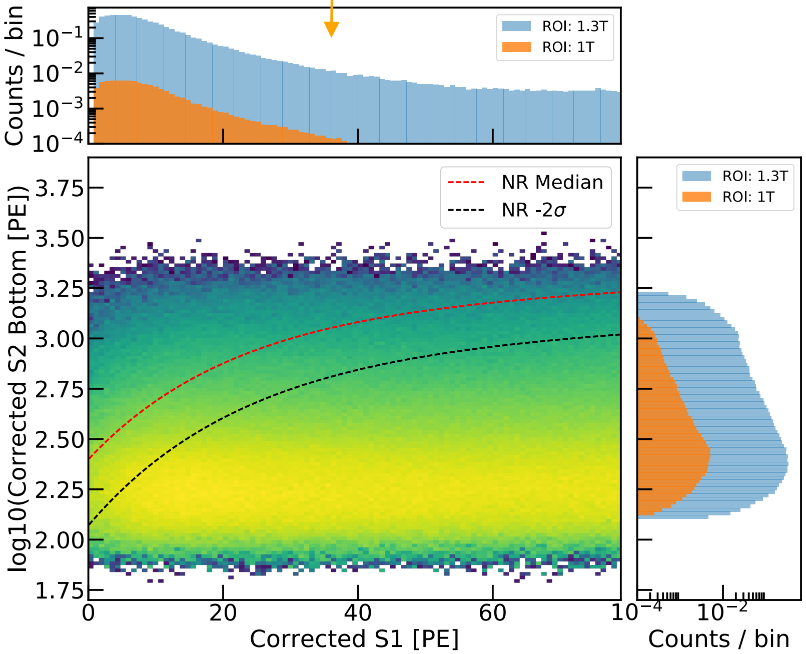


▸ Radioactivity on PTFE surface and charge loss

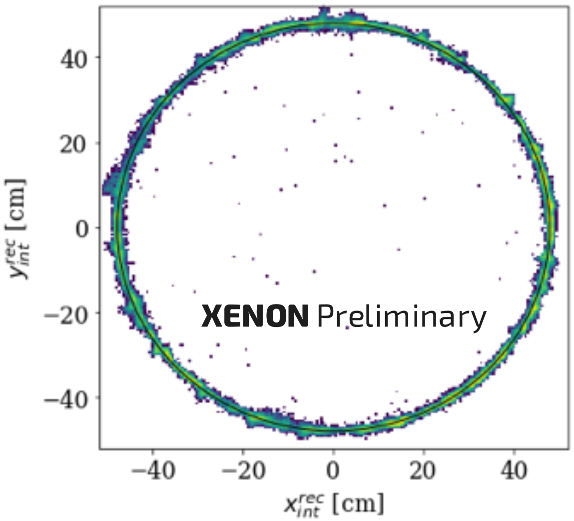
Events can fall in the NR energy region due to abnormally small S2. And due to position reconstruction resolution they can be reconstructed inwards.
Reduced by volume fiducialization.

▸ Data driven model

Derived from event surface control samples.



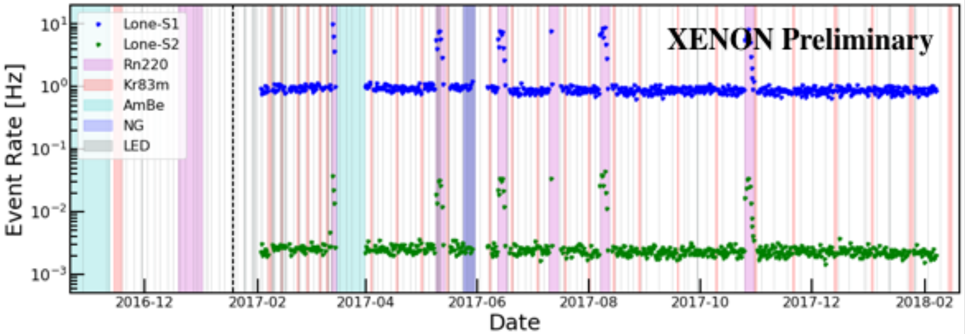
^{210}**Po** control sample

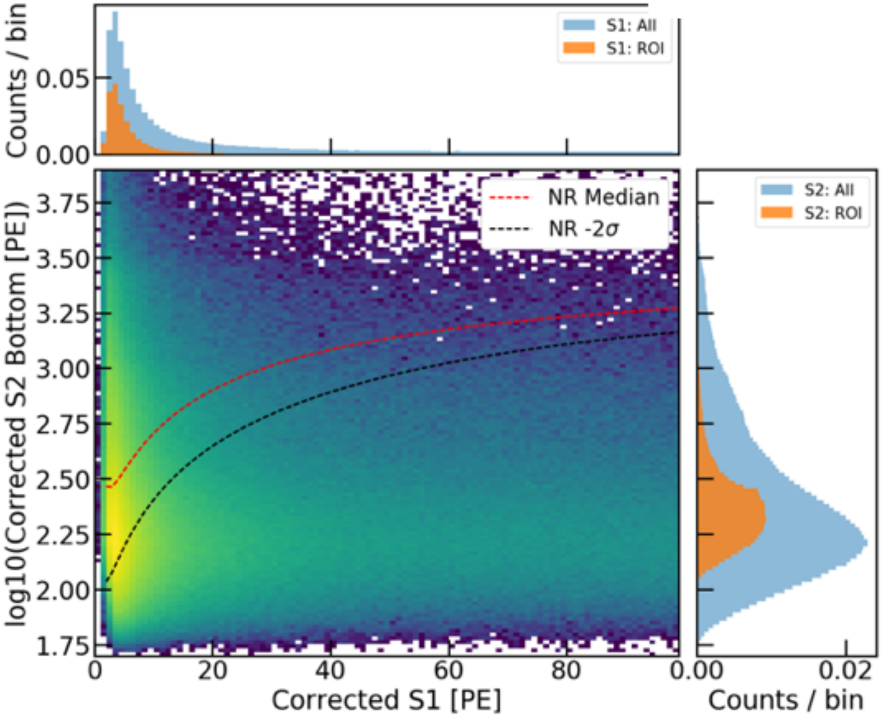


BACKGROUNDS

ACCIDENTAL COINCIDENCES

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

DARK MATTER SEARCH RESULTS

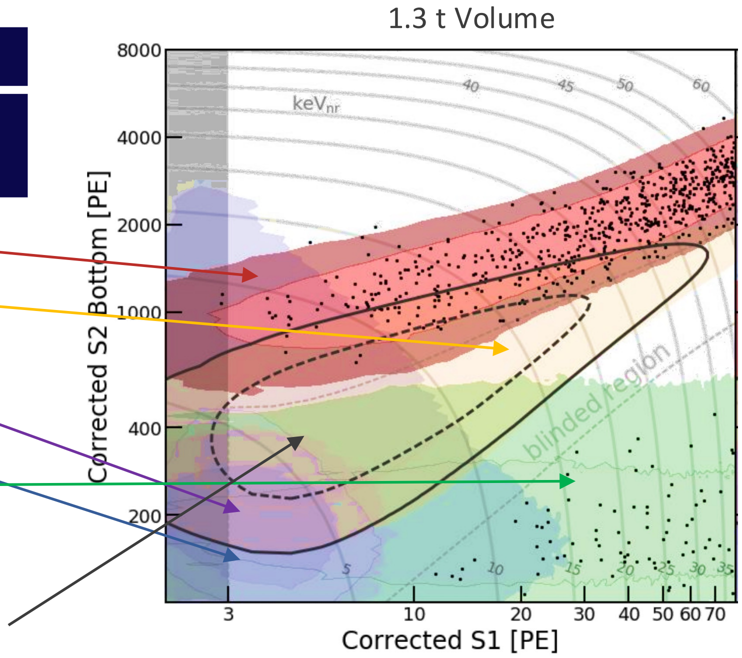
1 tonne-year Exposure:

278.8 live-days x **1.3 t** Fiducial Mass

XENON1T

BACKGROUND PREDICTIONS

	1.3 t	0.65 t	Mass
278.8 days live-time	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**	



WIMP

50 GeV/c^2

- **Background models**

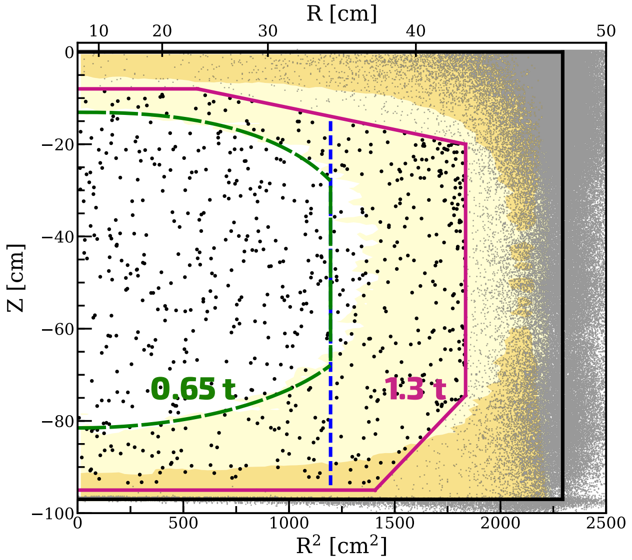
  In 4-dimensional space: S1, S2, r, z

- **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.



RESULTS

UNBLINDED DATA SET

▸ Blinding and salting

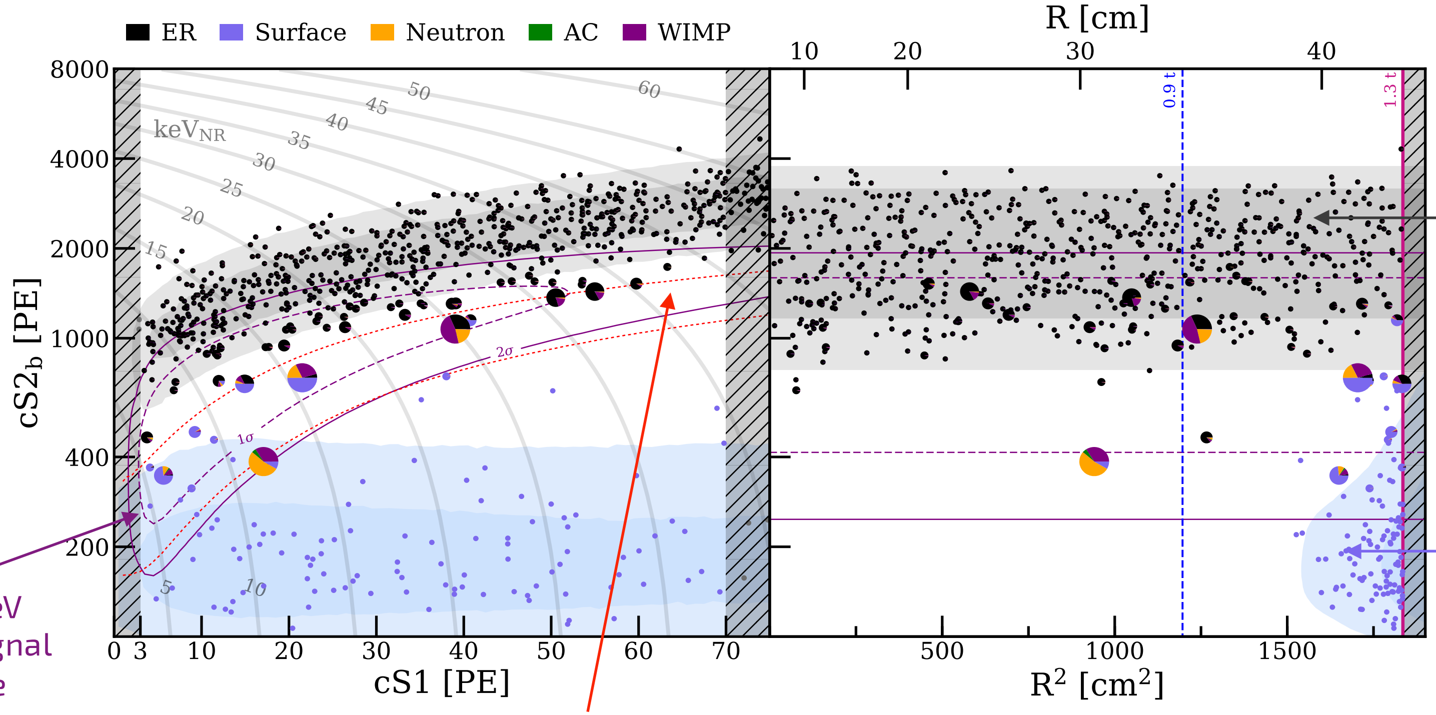
Data were blinded in the NR signal region and salted with unknown number of fake events.

▸ 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.



ER BKG

SURFACE BKG

200 GeV WIMP signal shape 1-2σ contours

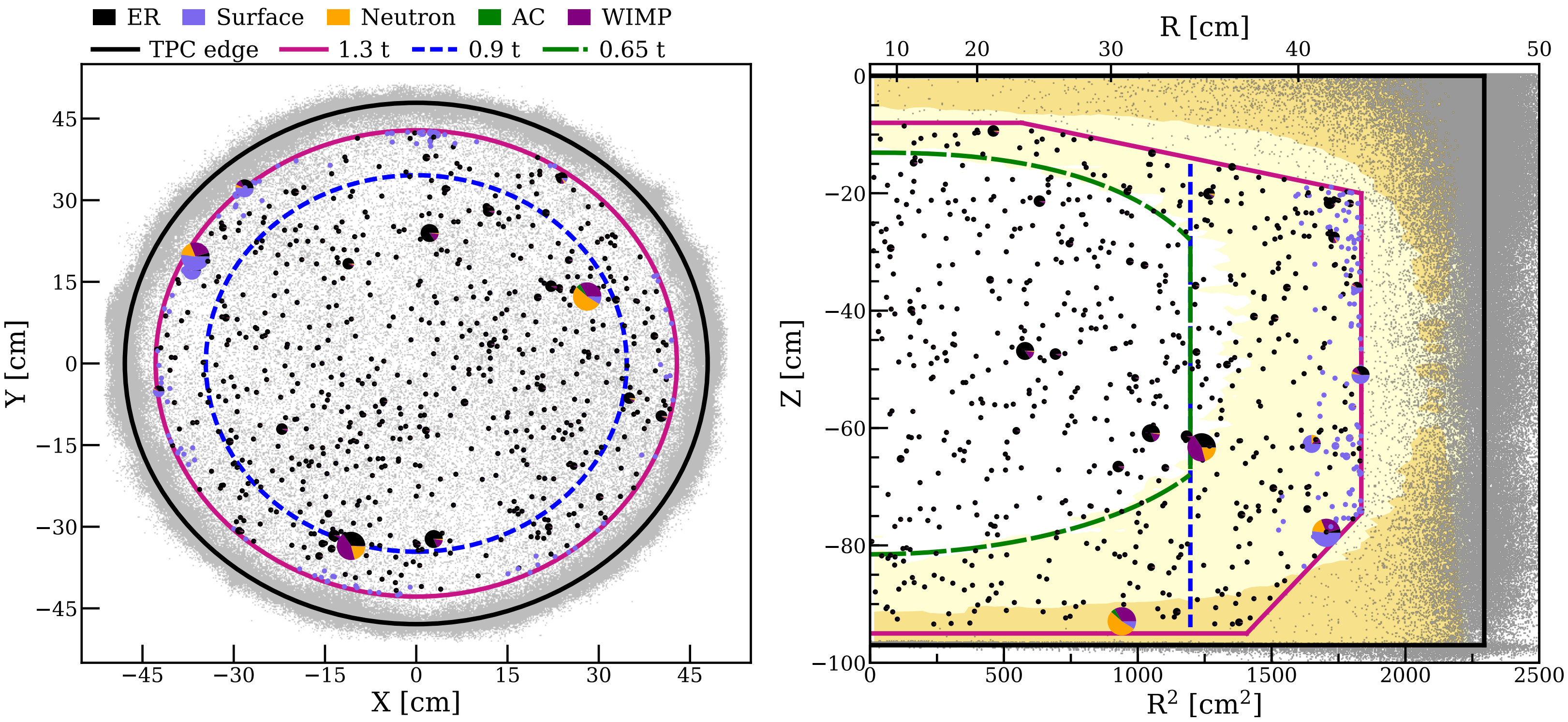
--- NR Reference region

RESULTS

SPATIAL DISTRIBUTION

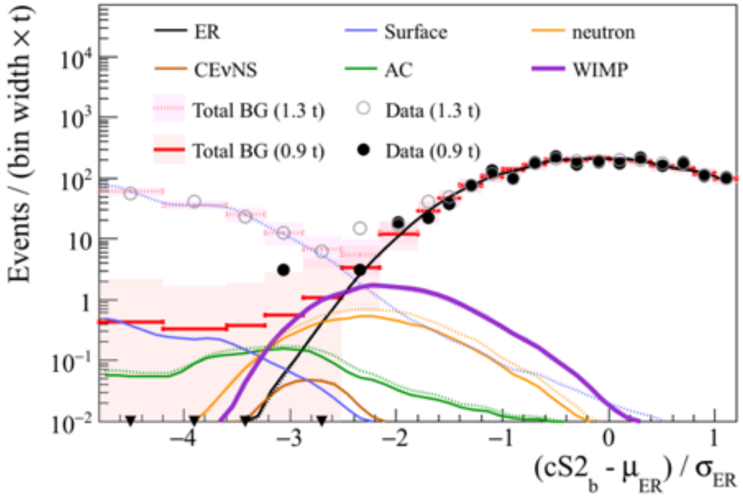
▸ Core volume

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

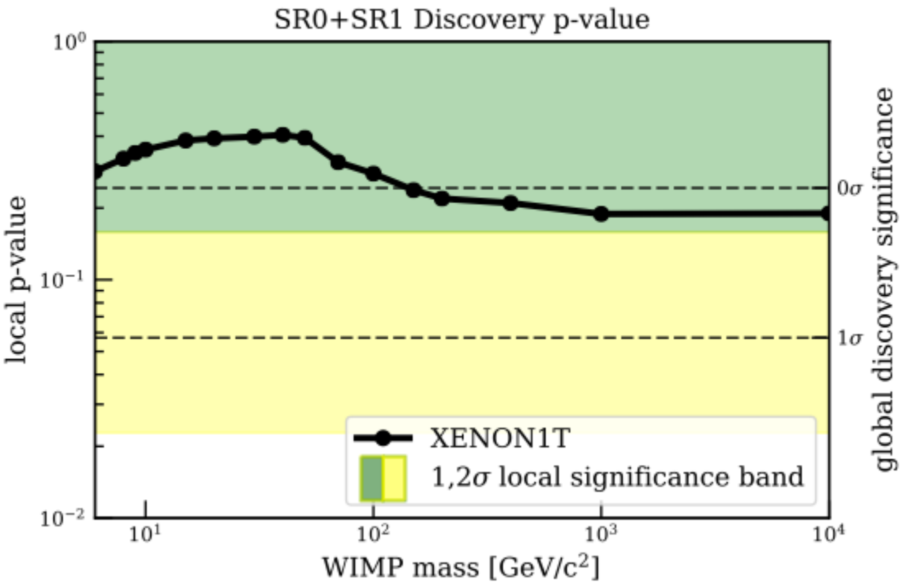


STATISTICAL INTERPRETATION

< 1 SIGMA DISCOVERY SIGNIFICANCE



- Extended unbinned profile likelihood analysis
- Example left: Background and 200 GeV WIMP signal best-fit predictions, assuming 4.2 x 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

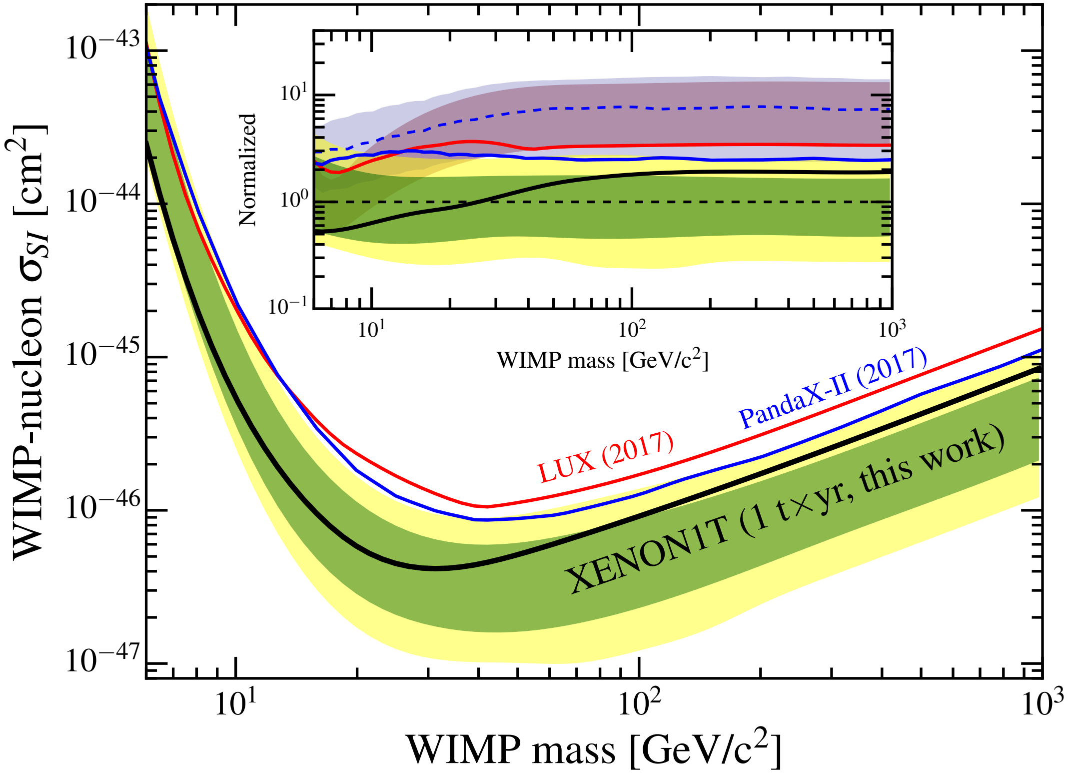
RESULTS

WORLD-BEST CONSTRAINTS ON WIMPS

- **Spin-independent WIMP-nucleon cross section**

  Strongest exclusion limits (at 90% CL) on WIMPs > 6 GeV/c^2.

Phys. Rev. Lett. 121, 111302



- **x7 better sensitivity**

  compared to previous experiments (LUX, PANDAX-II)

- **σ_{SI} < 4.1·10^{-47} cm^2**

  at 30 GeV/c^2

- **1 sigma upper fluctuation at higher WIMP masses**

  Local p-value ~0.2 (at 200 GeV/c^2). No significant excess (>3 sigma) is observed.

RESULTS

WORLD-BEST CONSTRAINTS ON WIMPS

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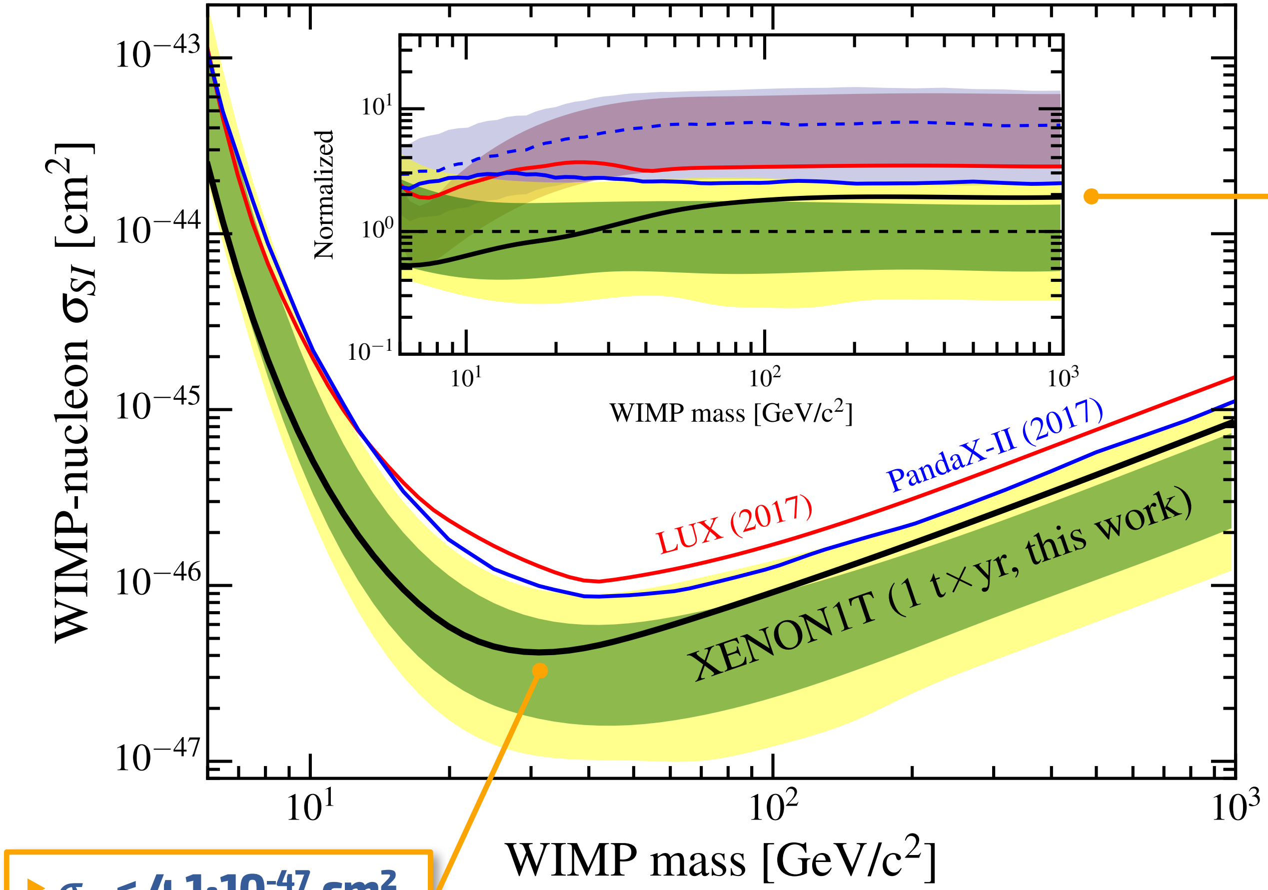
Phys. Rev. Lett. 121, 111302



- **x7 BETTER SENSITIVITY** compared to previous experiments (LUX, PANDAX-II)

- **$\sigma_{SI} < 4.1 \cdot 10^{-47}$ cm^2** at 30 GeV/c^2

MOVING FURTHER

XENONnT

▸ MINIMAL UPGRADE

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

x4

▸ FIDUCIAL Xe TARGET

Fiducial mass: ~4 t

Target LXe mass: 5.9 t

Total LXe mass: 8 t

1/10

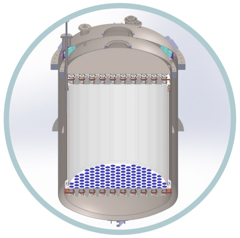
▸ BACKGROUND

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

▸ FAST TURNAROUND

Installation starts in 2018

Commissioning in 2019



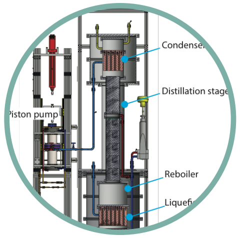
▸ NEW TPC

Larger inner cryostat

476 PMTs

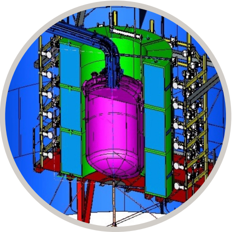
▸ LXe PURIFICATION

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

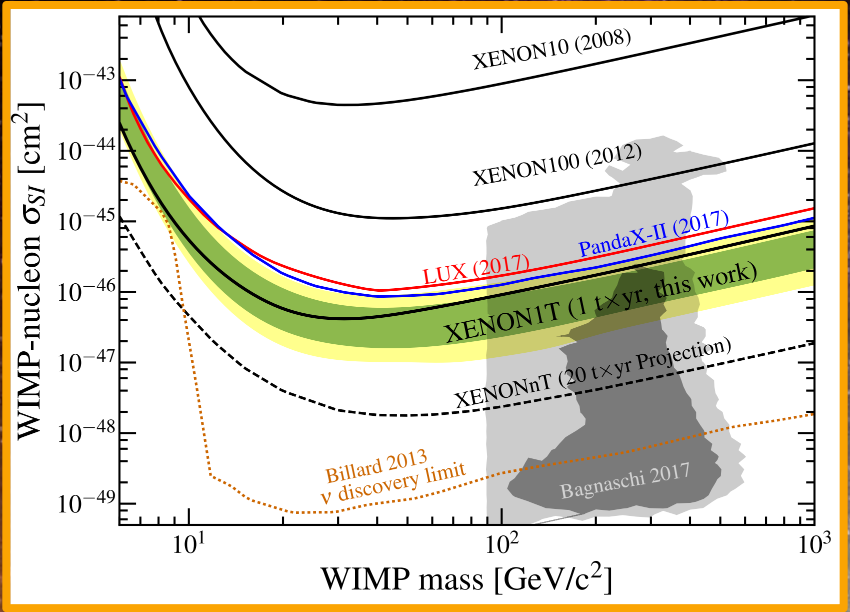
SUMMARY

- **XENON1T: THE FIRST MULTI-TON SCALE LXe-TPC**
  Successfully operated for > 1 year

- **LOWEST BACKGROUND EVER**
  Among all DM detectors

- **Strongest limit on WIMP-nucleon SI cross-section**
  Above 6 GeV/c^2
  Minimum at 4.1·10^{-47} cm^2 for 30 GeV/c^2 WIMP

- **XENONnT:**
  A larger and better detector will enable a further boost in sensitivity



APPENDIX

XENON1T

THE XENON COLLABORATION

- **~165** SCIENTISTS
- **27** INSTITUTIONS
- **11** COUNTRIES

Columbia

RPI

Nikhef

Muenster

Stockholm

Mainz

MPIK

Freiburg

Zurich

Chicago

UCLA

UCSD

Rice

Tokyo

Nagoya

Kobe

Purdue

Coimbra

Subatech

LPNHE

LAL

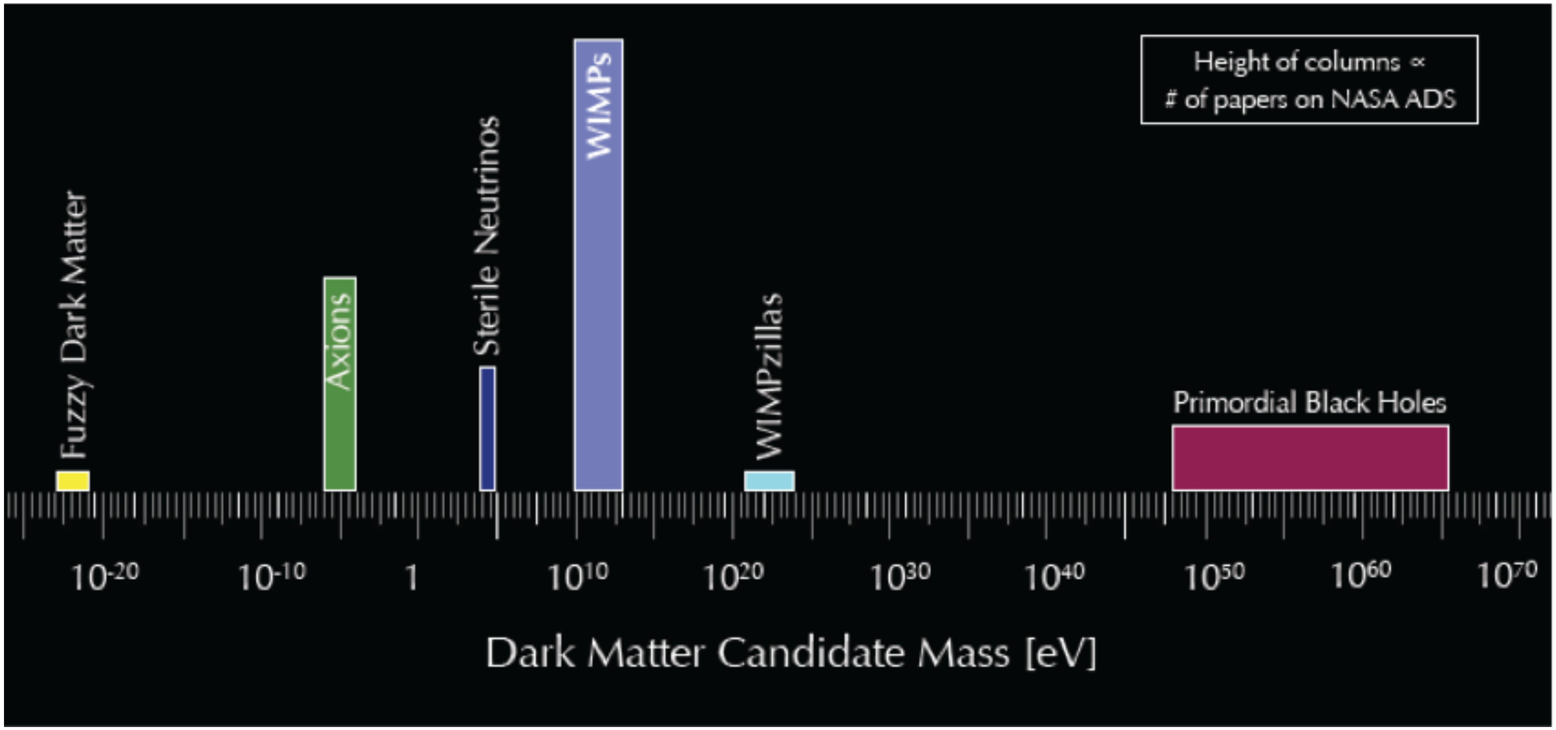
Bologna LNGS Torino Napoli

Weizmann

NYUAD

WHAT IS DARK MATTER

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



WHY DO WE CHOOSE XENON?

▸ **High A=131**

👍 $\sigma_{\text{WIMP-N}} \sim A^2$ → 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**

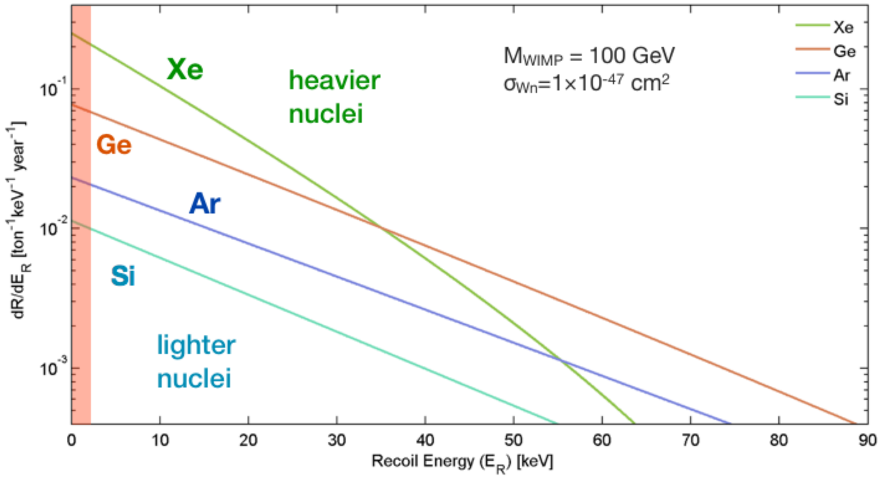
👍 Xenon is liquid at -95° C

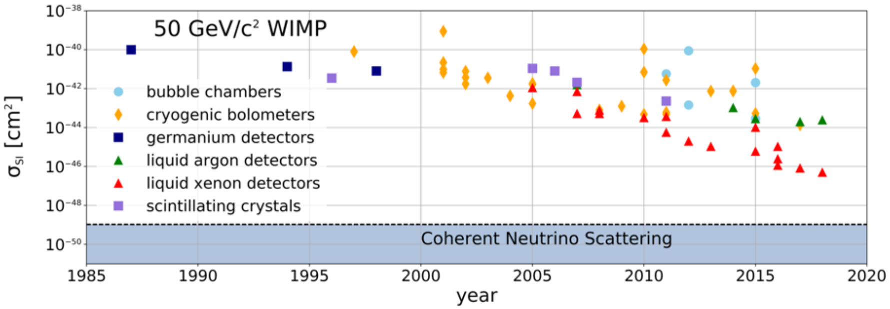
▸ **VUV scintillation light**

👍 178 nm → no need for wavelenght shifters

▸ **Odd-nucleon isotopes**

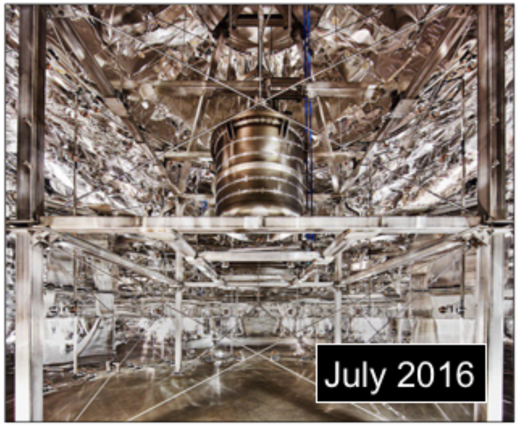
👍 ^{131}Xe and ^{129}Xe allow to study also the SD interaction

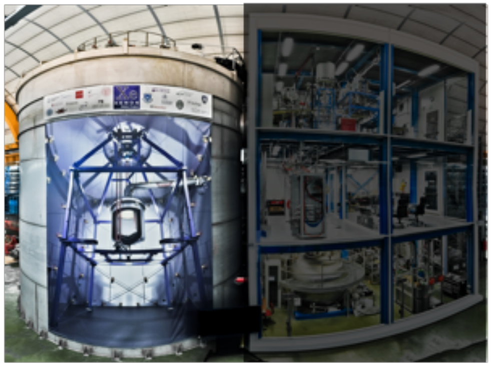




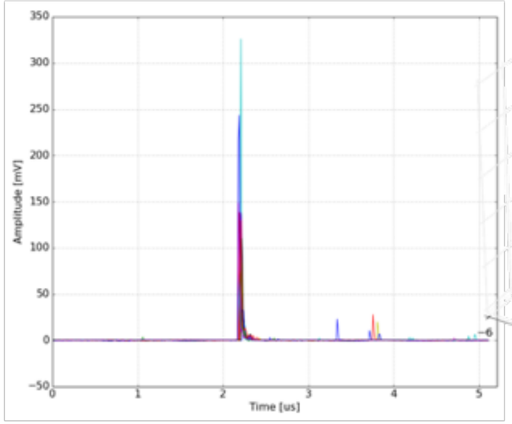
MUON VETO

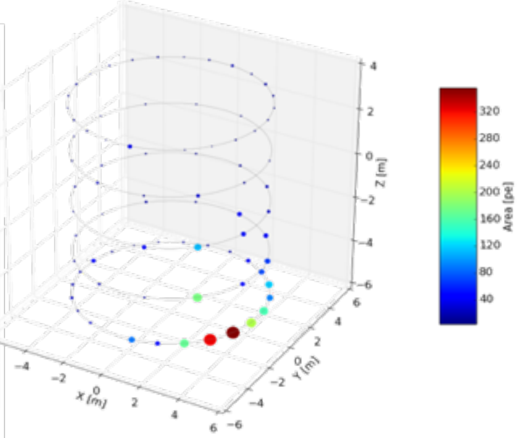
WATER CHERENKOV SUB-DETECTOR





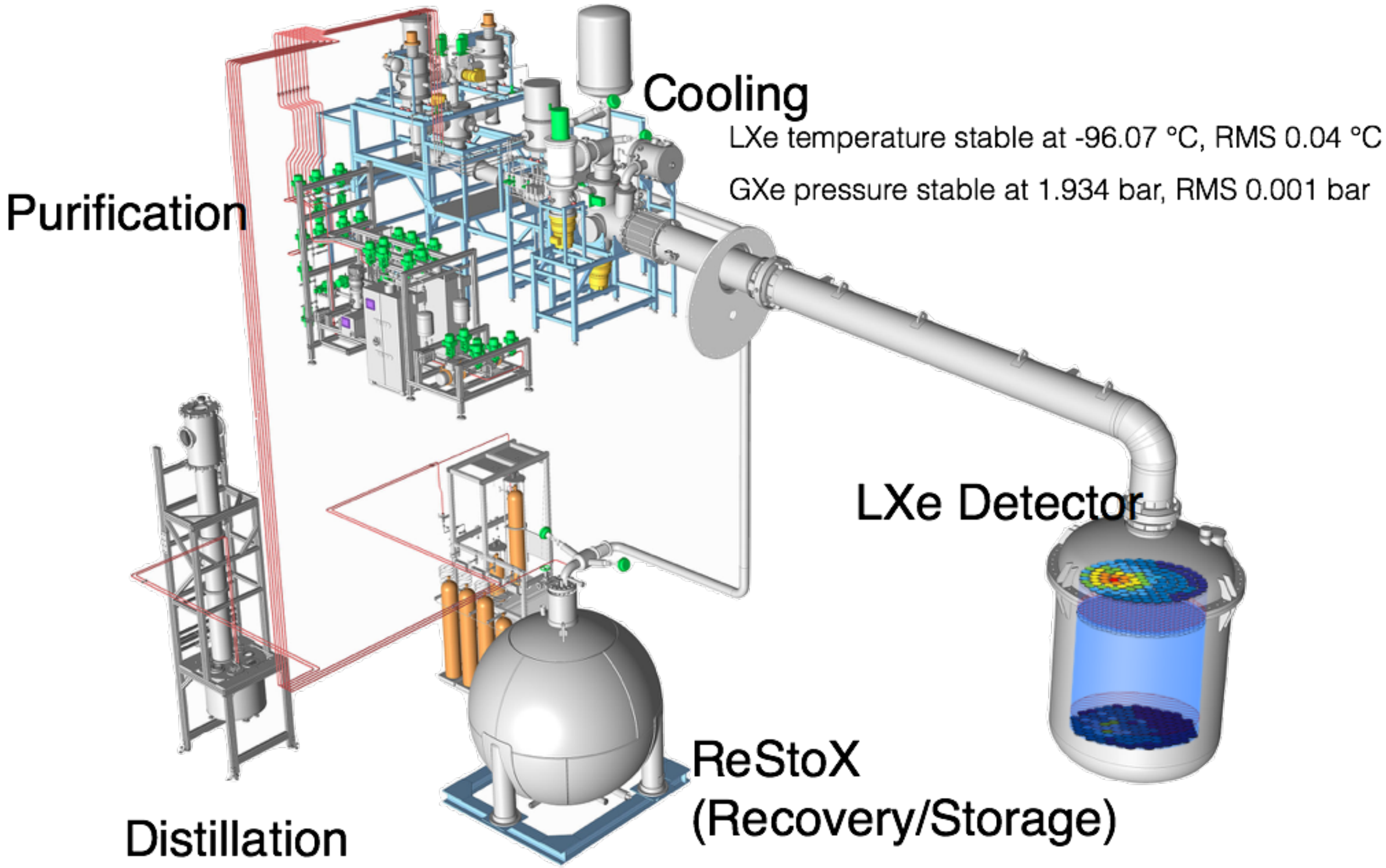
- 700 ton pure water instrumented with 84 high-QE 8" PMTs
- Active shield against muons
- Trigger efficiency > 99.5% for muons in water tank
- Cosmogenic neutron background suppressed to < 0.01 events/ton/yr





JINST 9, 11007 (2014)

XENON SYSTEMS

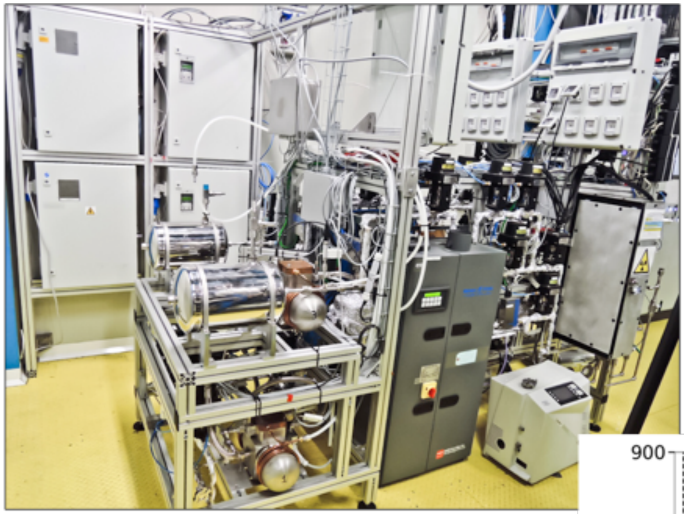


LXe temperature stable at -96.07 °C, RMS 0.04 °C

GXe pressure stable at 1.934 bar, RMS 0.001 bar

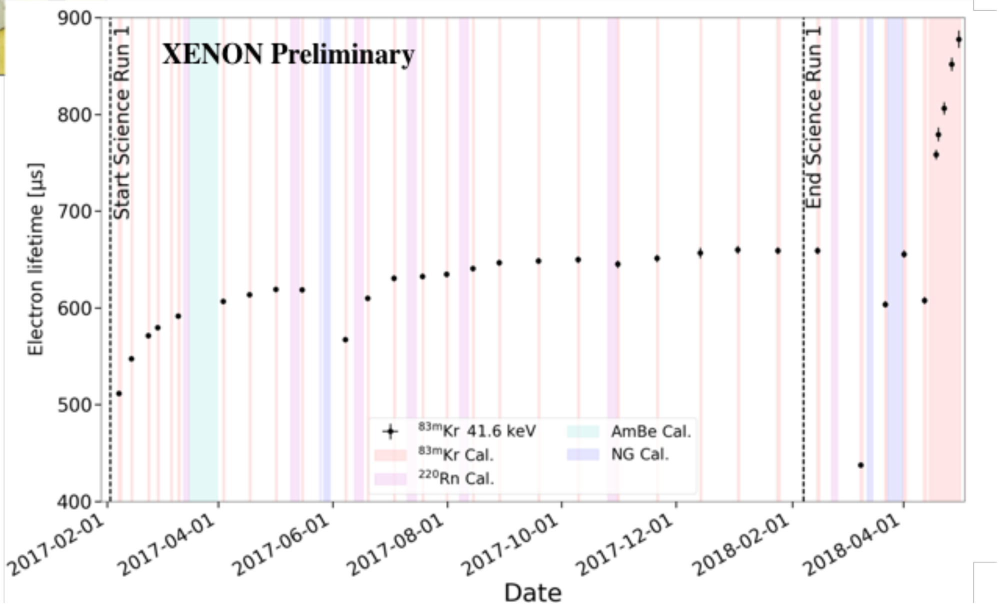
XENON PURIFICATION

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

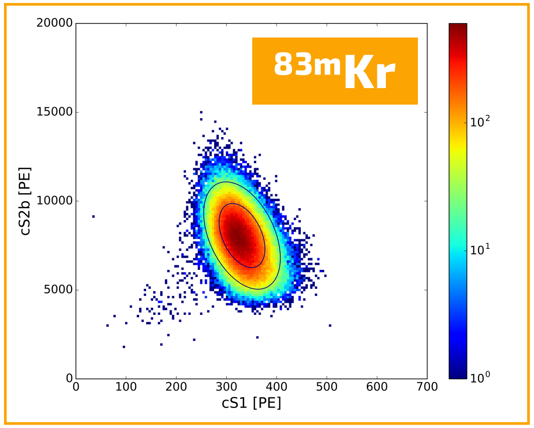
- electron lifetime is monitored regularly with ERs calibration sources.
- Current value, following increase in gas flow, approaches 1 msec



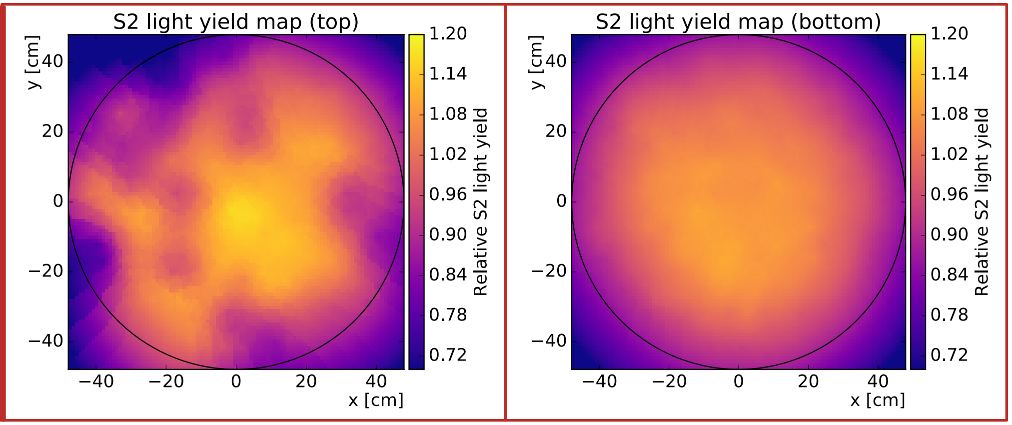
SIGNAL SPATIAL CORRECTIONS

VOLUME CALIBRATIONS WITH ^{83m}Kr

Plots just for illustration

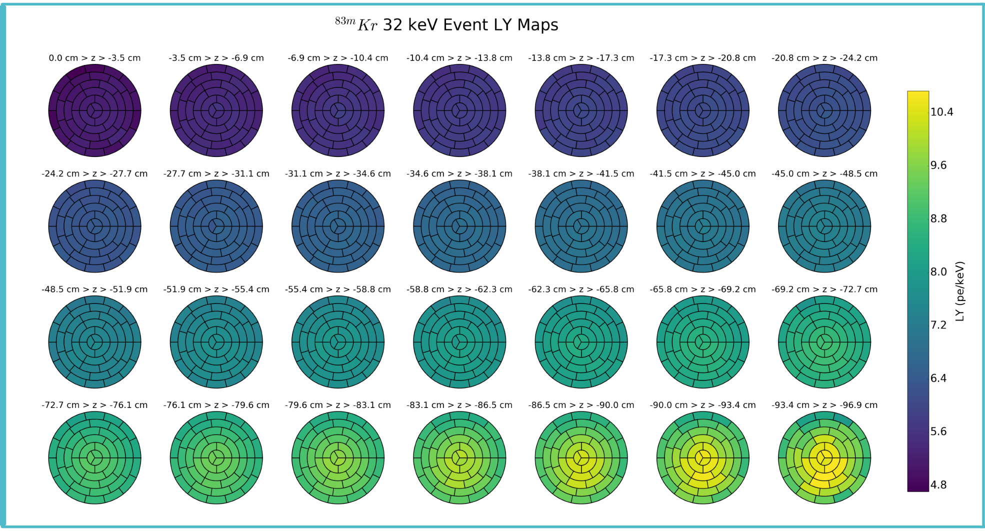


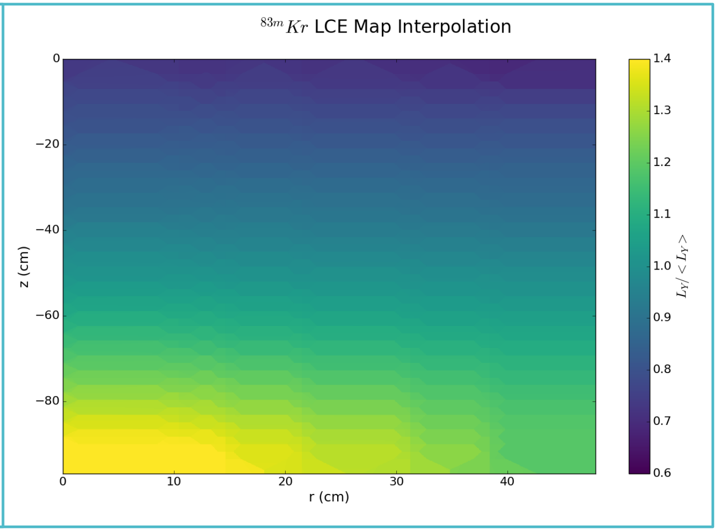
S2 XY correction map



^{83m}Kr source injected in LXe which uniformly distributes in the whole TPC volume → Ideal to understand spatial dependence of the light (S1) and charge (S2) signals.

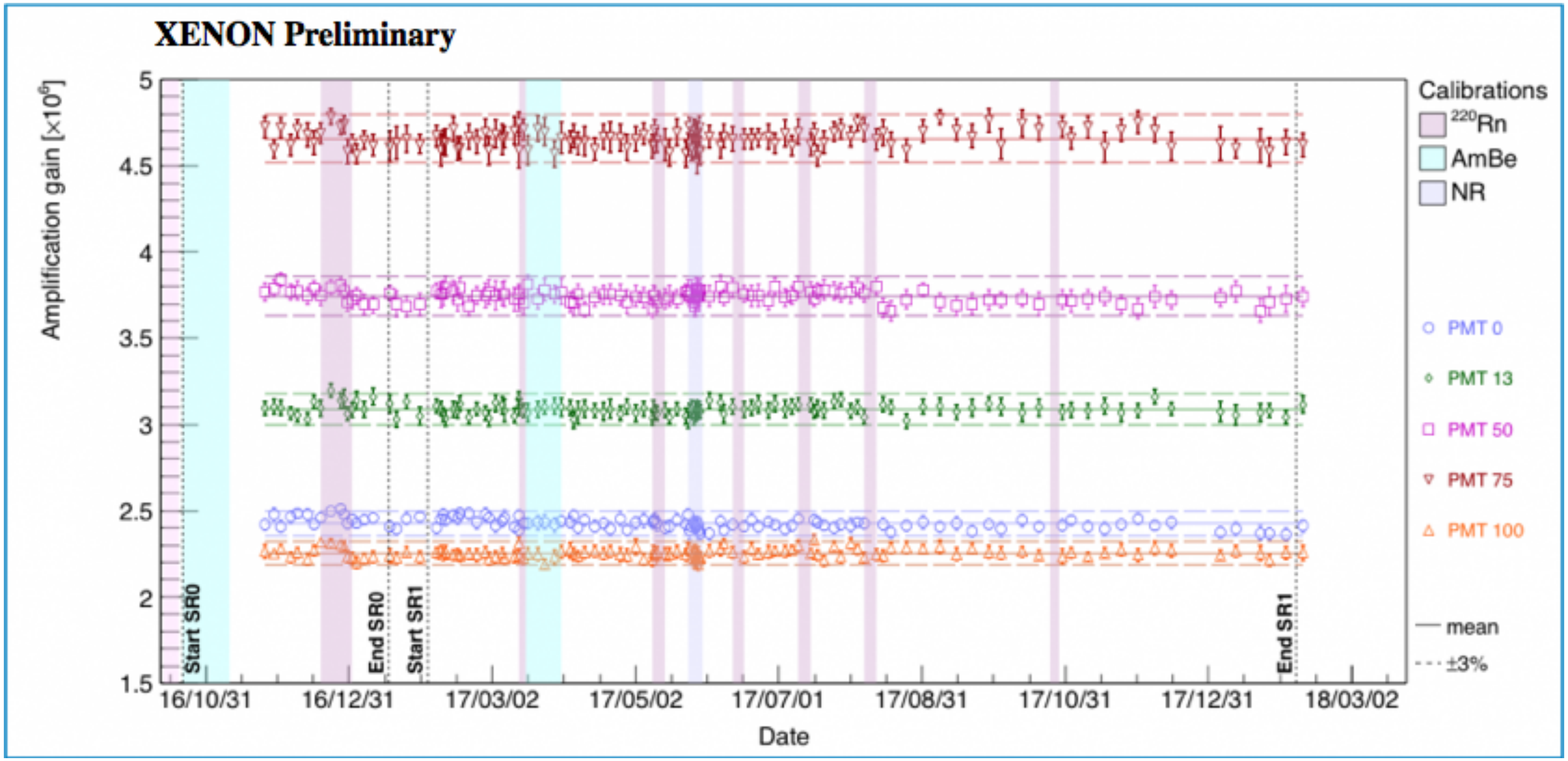
S1 XYZ correction map





LIGHT DETECTION SYSTEM

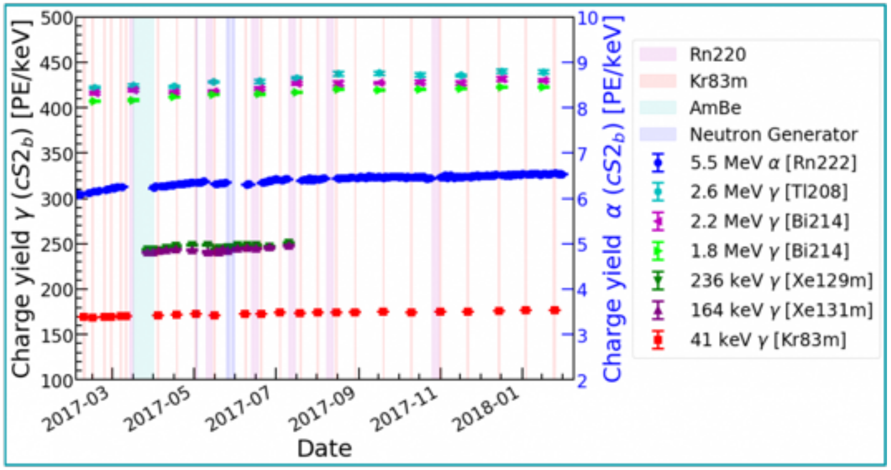
PMT STABILITY

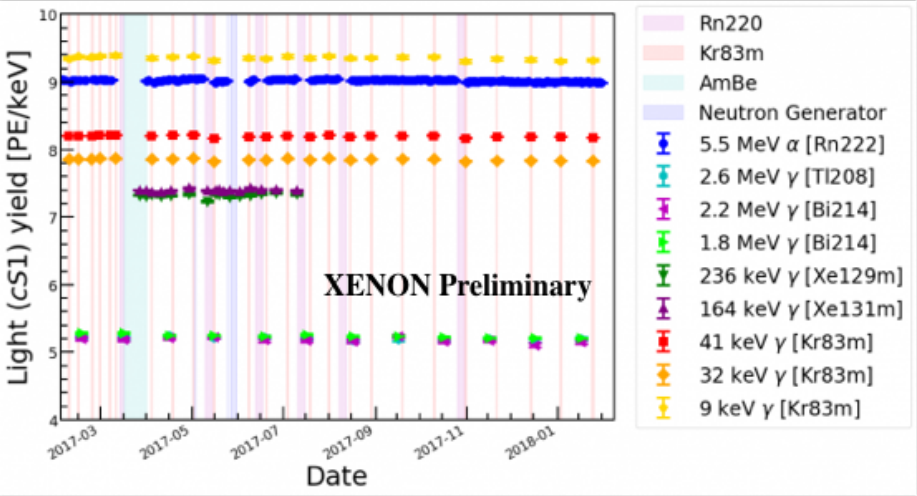


LIGHT AND CHARGE SIGNALS

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

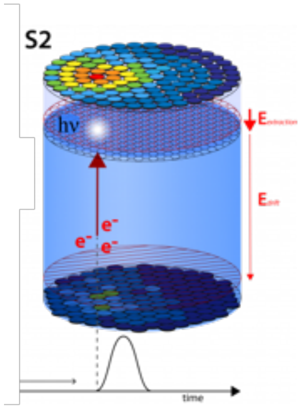




Light and charge yield stability monitored with several sources:

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

POSITION RECONSTRUCTION



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

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

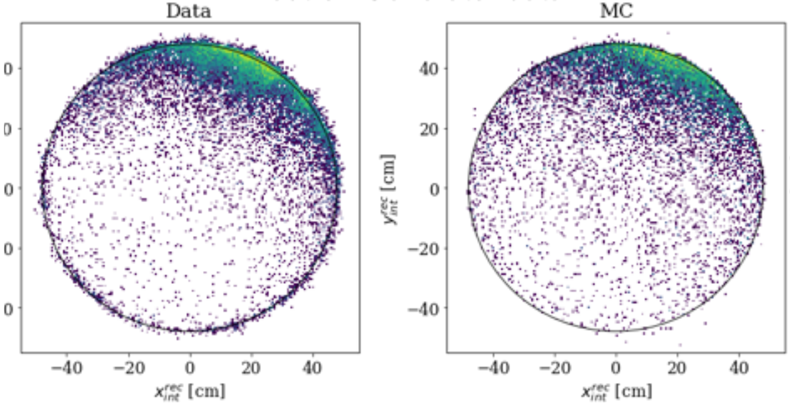
Position resolution using ^{83m}Kr

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

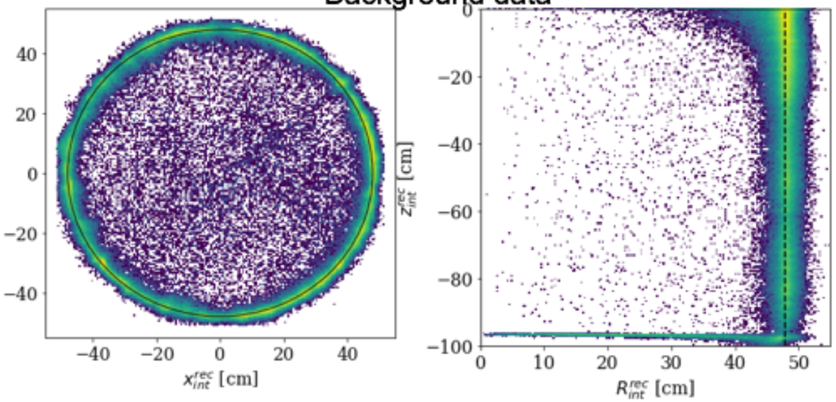
Position corrections using ^{83m}Kr

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

Neutron Generator data

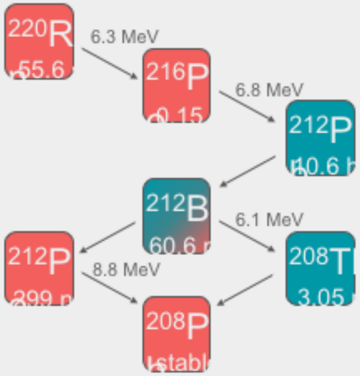


Background data



CALIBRATIONS

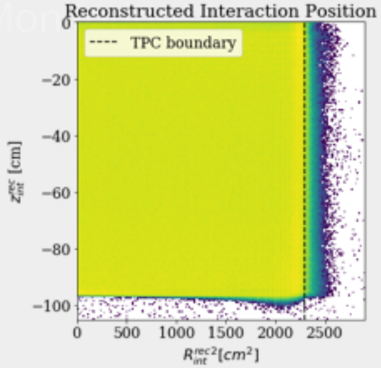
^{220}Rn: Low Energy ER



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

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

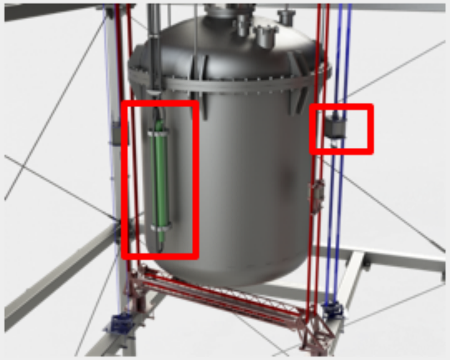
^{83m}Kr: Stability and Mon



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

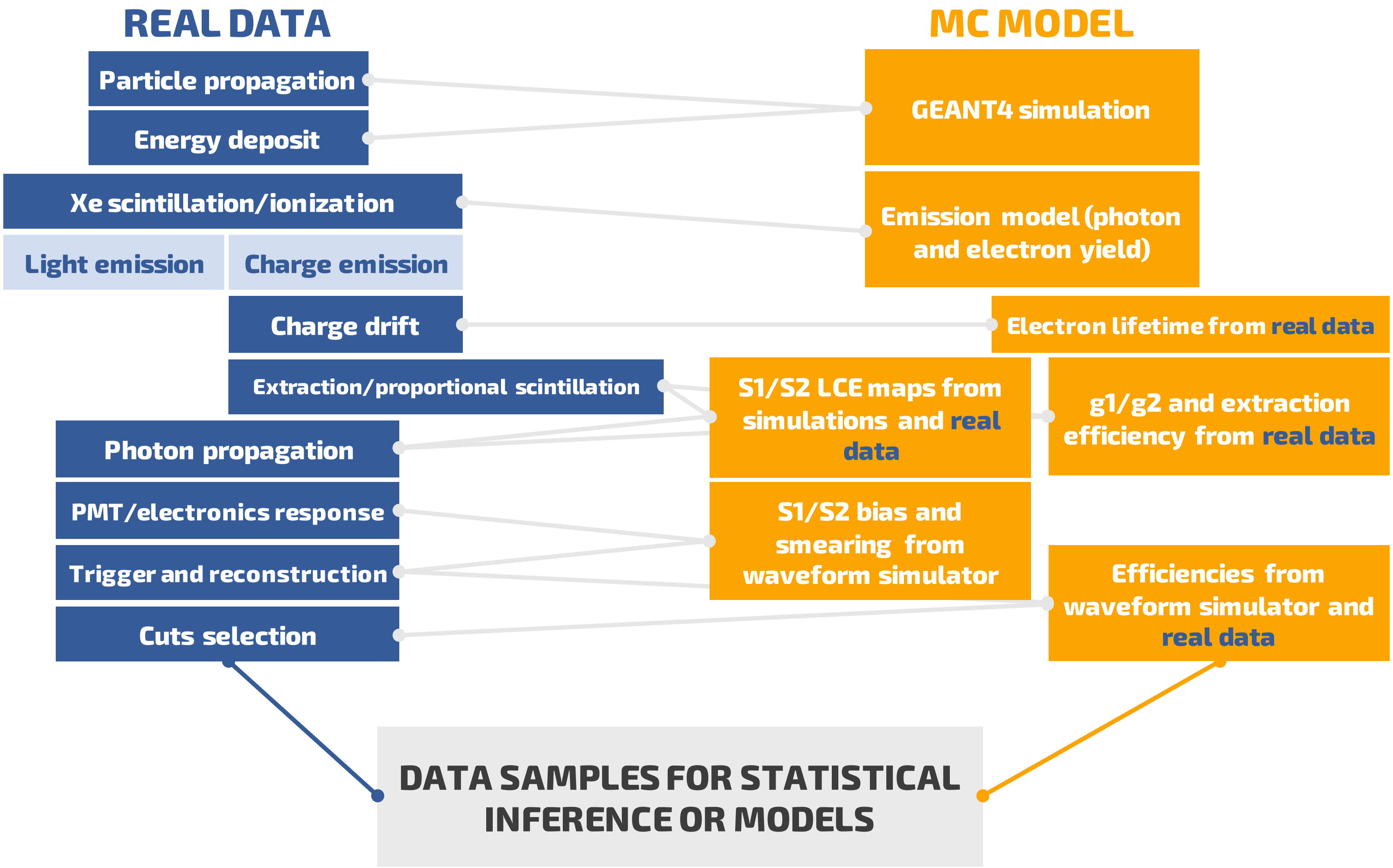
Neutrons: Signal Response



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

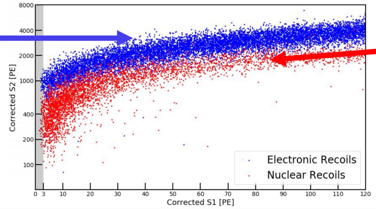
ER AND NR MODELING

REAL DATA AND MC SIMULATIONS



DETECTOR RESPONSE MODEL

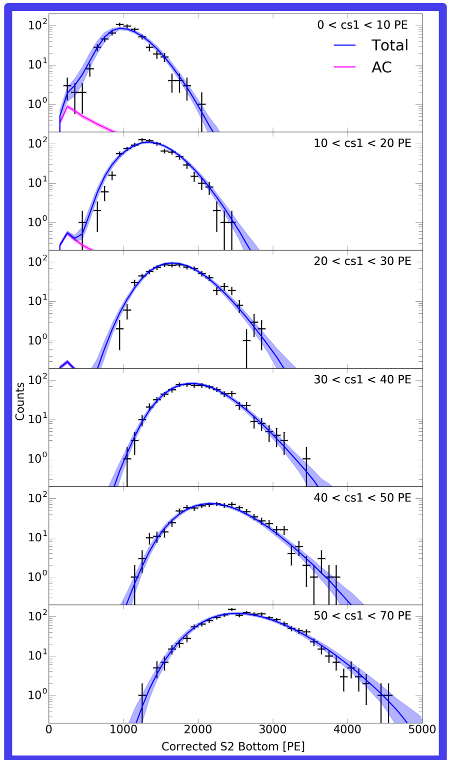
ER AND NR CALIBRATIONS



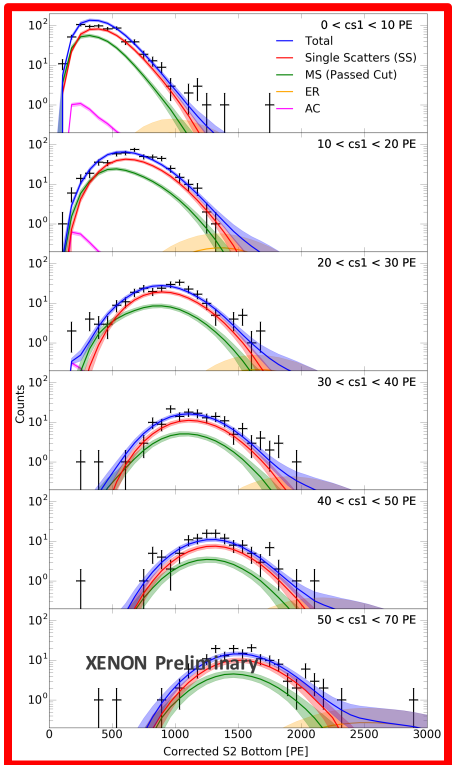
- Detailed MC simulations of **LXe microphysics** and **detector processes**
- Parameters tuned and constrained to calibration data

~99.7% ER rejection in NR reference region [NR median,-2σ]

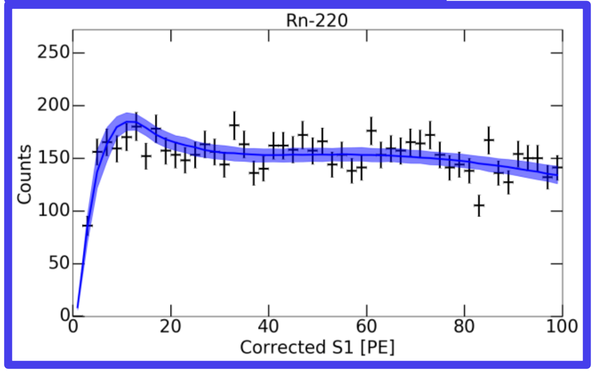
ER ^{220}Rn



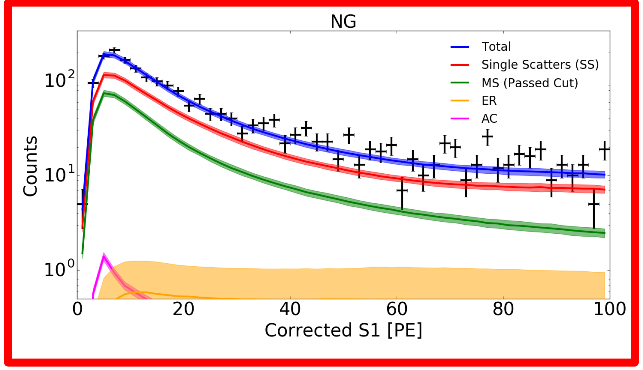
NR neutron generator



S2 projections in S1 slices

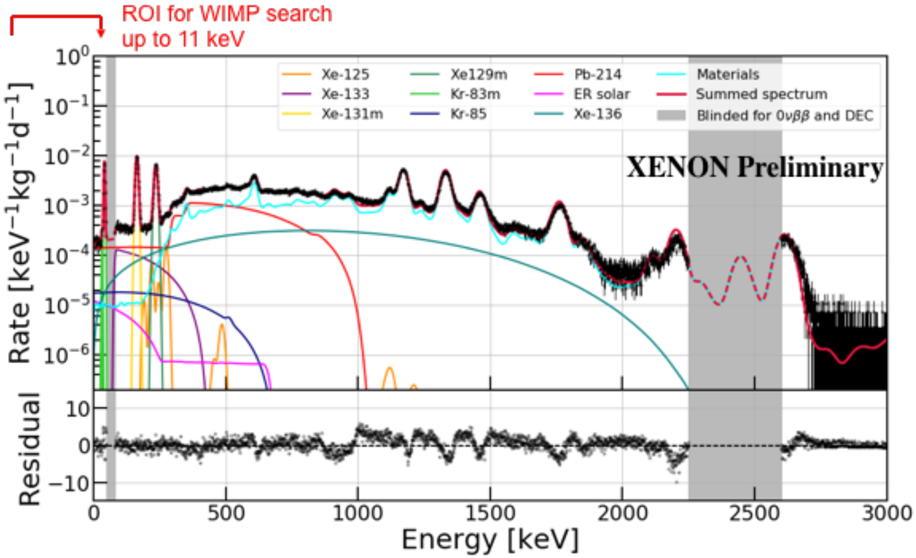


S1 projection

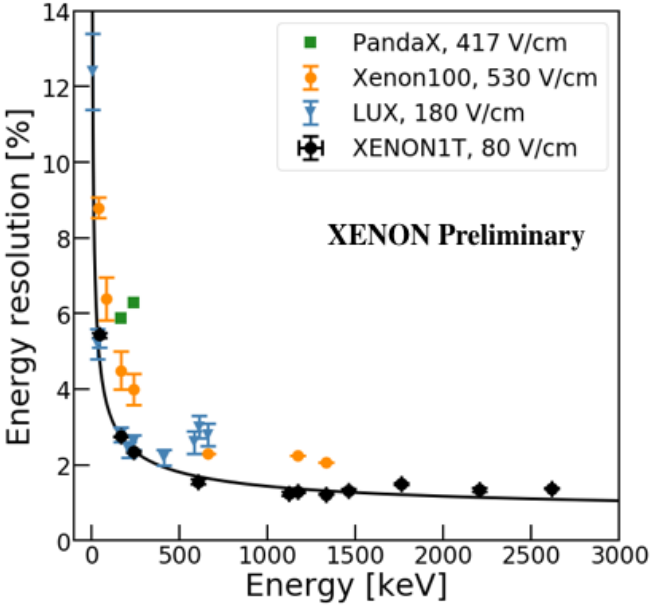


BACKGROUND SPECTRUM

ENERGY RESOLUTION AND MC MATCHING


ROI for WIMP search
up to 11 keV

- 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: ~0.45 ppt; Pb214: ~ 10 uBq/kg
- Gammas based on screening measurements

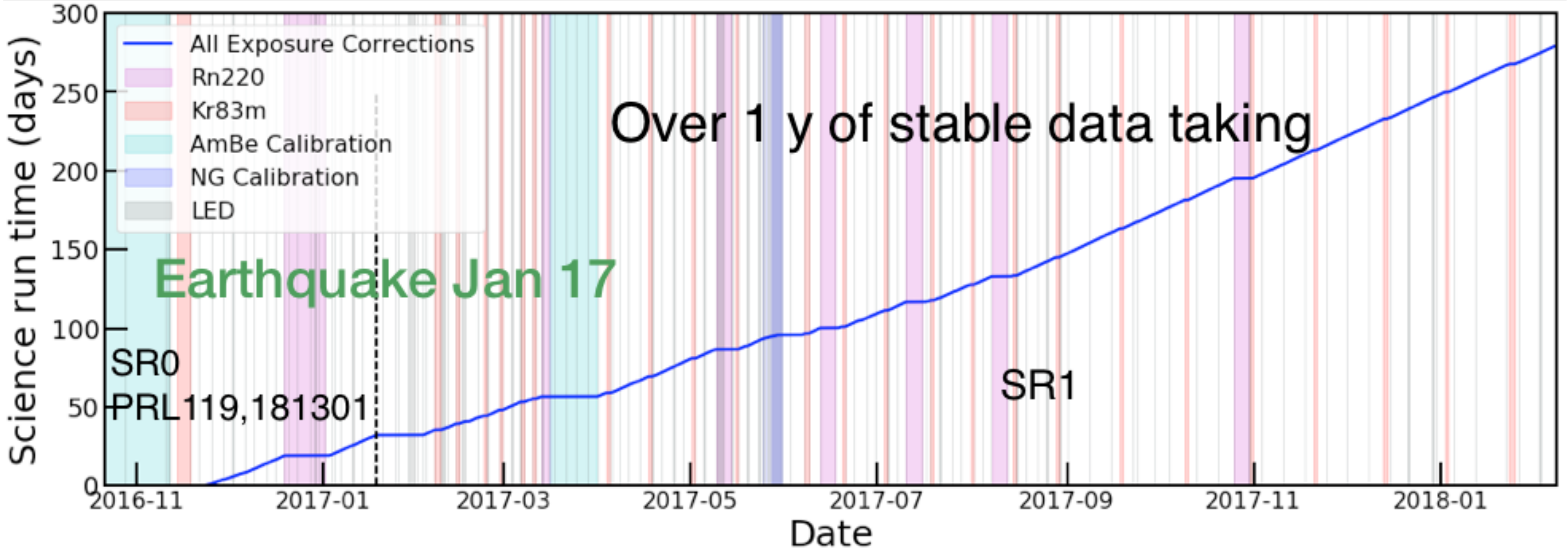
XENON1T TIMESCALE

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

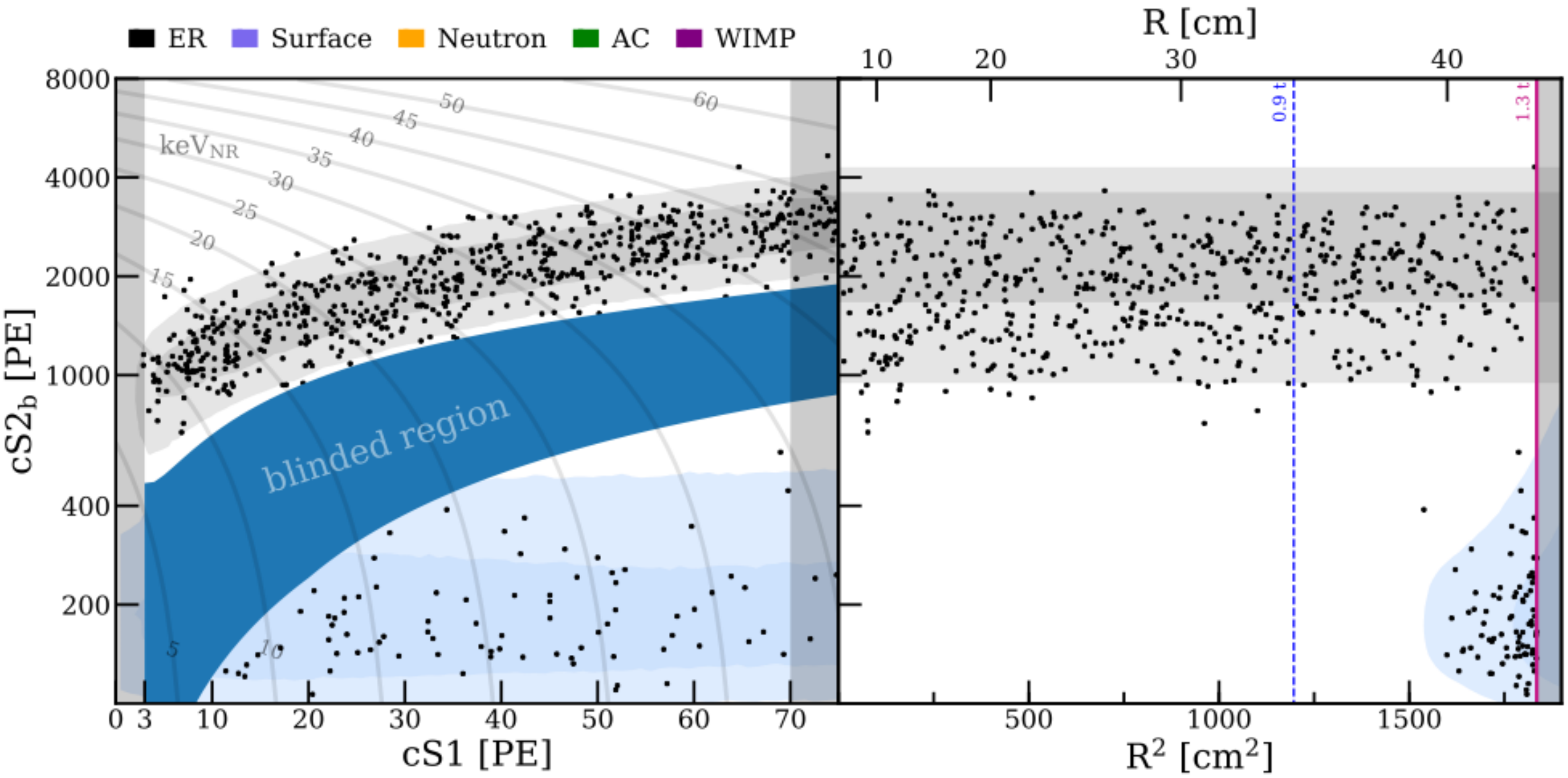
- Experiment still running smoothly and collecting more data



WIMP SEARCH

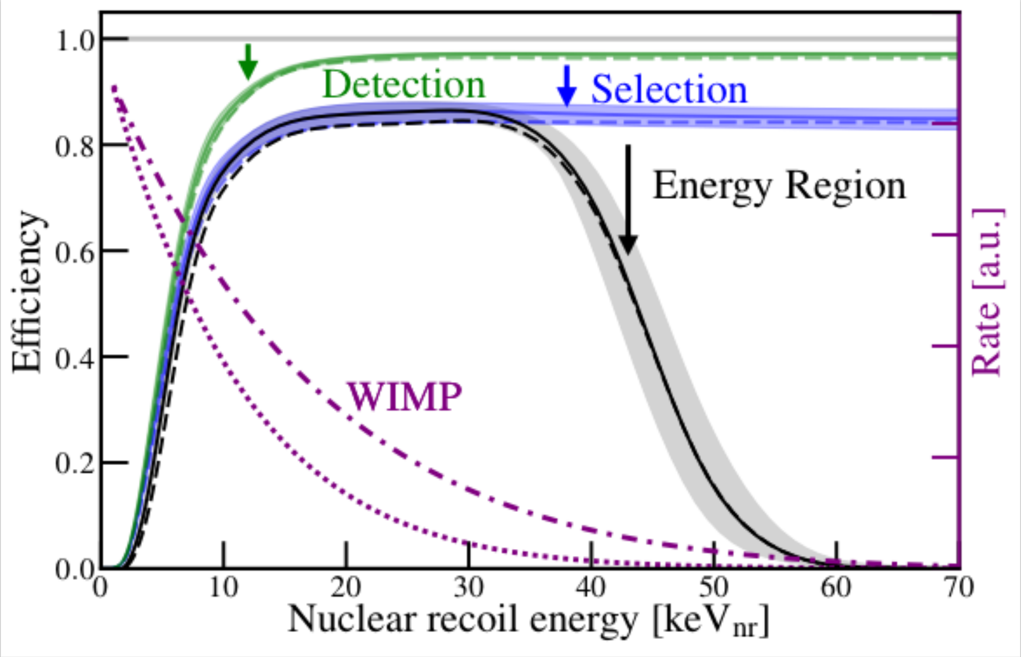
BLINDING AND SALTING

- 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



WIMP SEARCH

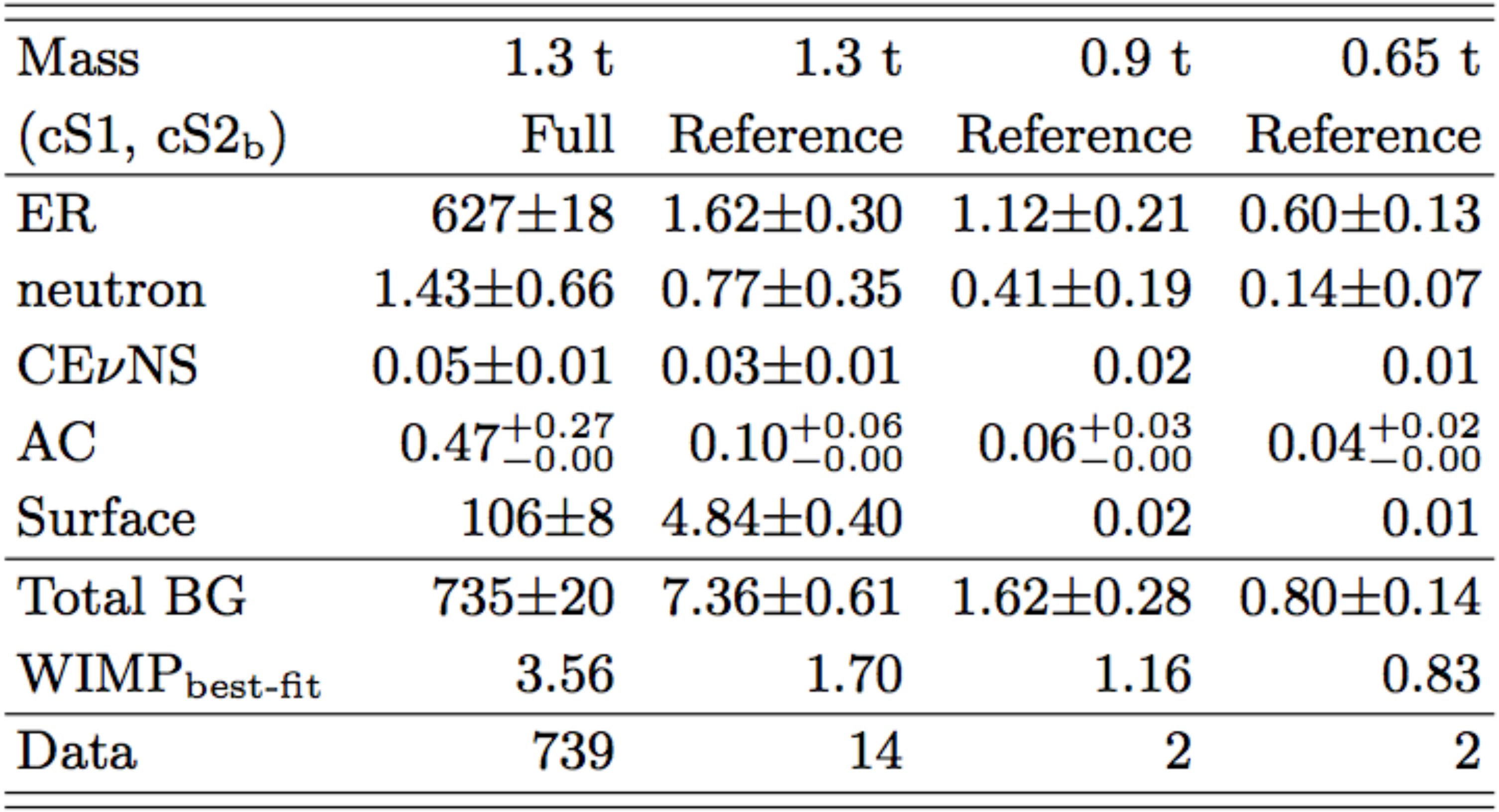
DATA SELECTION AND DETECTION EFFICIENCY



- 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

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.

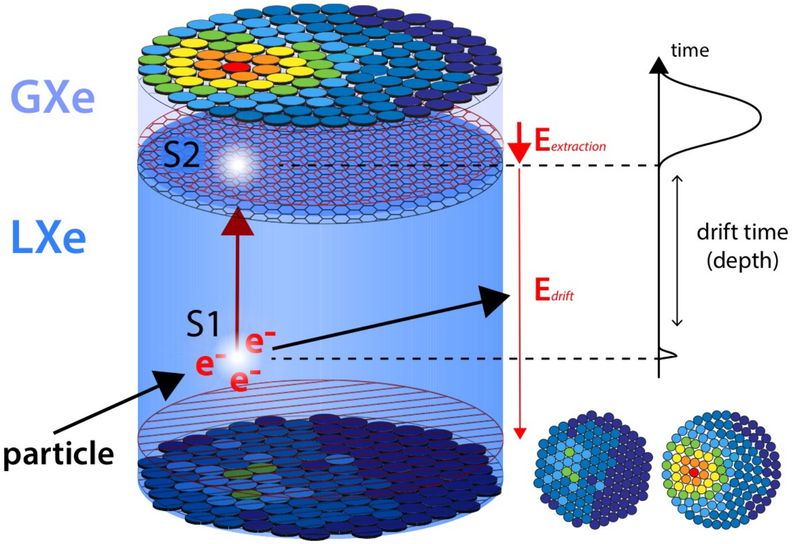


Mass	1.3 t	1.3 t	0.9 t	0.65 t
($cS1$, $cS2_b$)	Full	Reference	Reference	Reference
ER	627±18	1.62±0.30	1.12±0.21	0.60±0.13
neutron	1.43±0.66	0.77±0.35	0.41±0.19	0.14±0.07
CEνNS	0.05±0.01	0.03±0.01	0.02	0.01
AC	$0.47^{+0.27}_{-0.00}$	$0.10^{+0.06}_{-0.00}$	$0.06^{+0.03}_{-0.00}$	$0.04^{+0.02}_{-0.00}$
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)

DETECTION PRINCIPLE

WITH A DUAL PHASE TPC



- **S1** Light signal

Prompt scintillation photons

- **S2** Charge signal

Secondary scintillation in GXe from drifted electrons

👍 Energy reconstruction from combined S1 and S2

- **3D** vertex reconstruction

X,Y from S2 pattern in top PMT array

Z from drift time

👍 Volume fiducialization

👍 Single/multiple scatters discrimination

- **NR (Nuclear Recoils)**

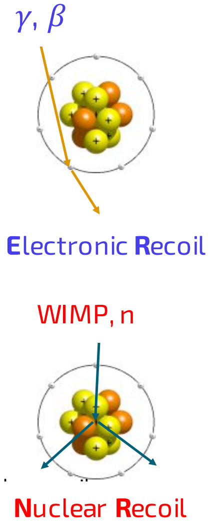
WIMP signal, neutrons, CNNS

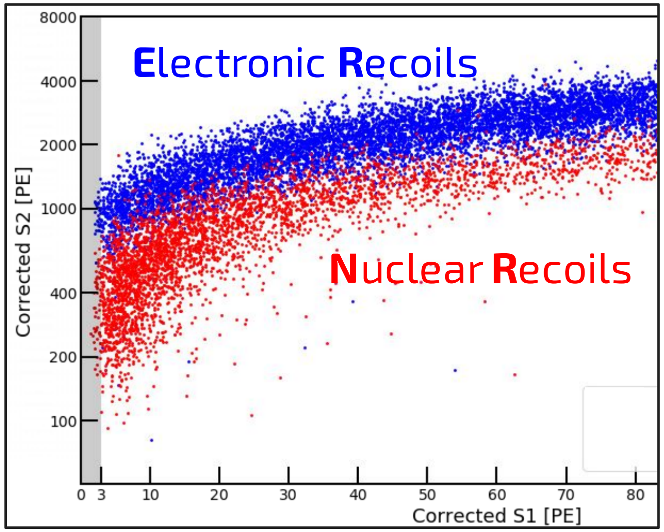
- **ER (Electronic Recoils)**

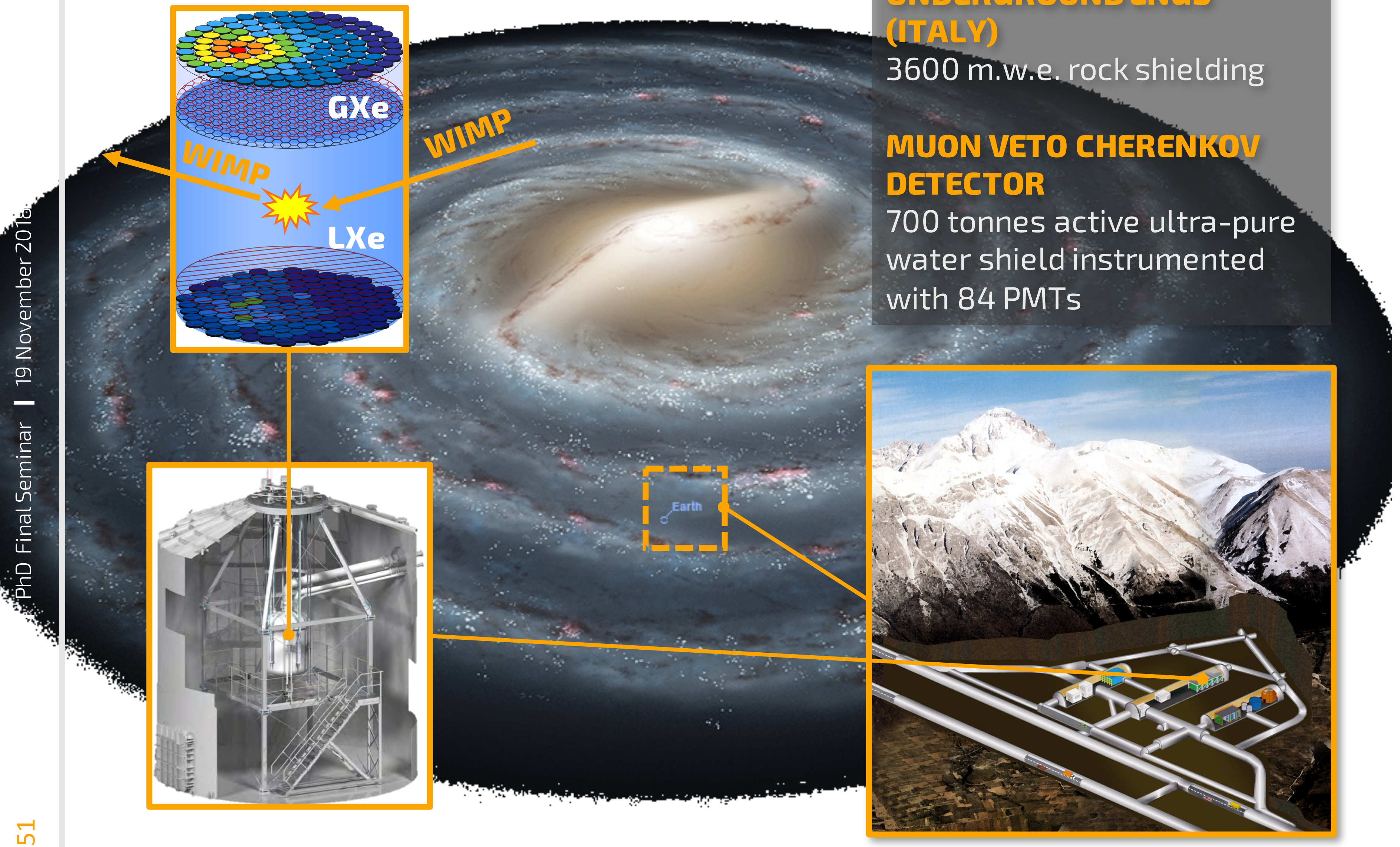
γ, β backgrounds

👍 **Recoil type identification from S2/S1**

Larger for ER than NR







UNDERGROUND LNGS (ITALY)

3600 m.w.e. rock shielding

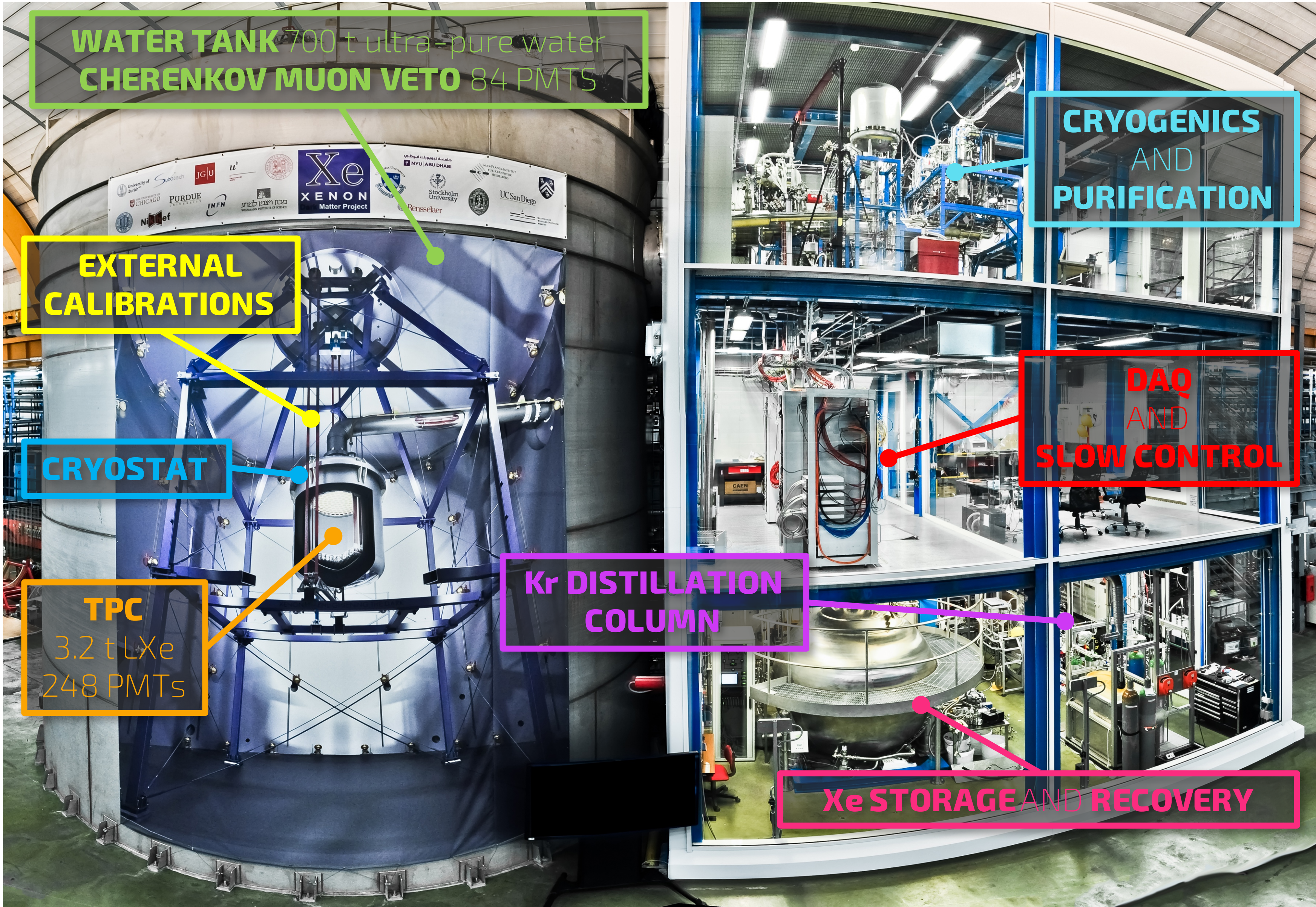
MUON VETO CHERENKOV DETECTOR

700 tonnes active ultra-pure water shield instrumented with 84 PMTs

THE XENON1T EXPERIMENT

AT LNGS (ITALY)

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



WATER TANK 700 t ultra-pure water
CHERENKOV MUON VETO 84 PMTS

CRYOGENICS AND **PURIFICATION**

EXTERNAL CALIBRATIONS

DAQ AND **SLOW CONTROL**

CRYOSTAT

TPC
3.2 t LXe
248 PMTs

Kr DISTILLATION COLUMN

Xe STORAGE AND **RECOVERY**

SUMMARY

- **XENON1T: first multi-ton scale LXe-TPC**
  Successfully operated for > 1 year

- **Lowest background ever**
  Among all DM detectors

- **Strongest limit on WIMP-nucleon SI cross-section**
  Above 6 GeV/c^2; minimum at $4.1{\cdot}10^{-47}$ cm^2 for 30 GeV/c^2 WIMP

- **XENONnT:**
  A larger and better detector will enable a further boost in sensitivity