IFAE 2019 | Napoli | 9 Aprile 2019

PIETRO **DI GANGI**

Università di Bologna
INFN Bologna
XENON Dark Matter Project

RICERCA DI **MATERIA OSCURA** CON **XENON1T**

digangi@bo.infn.it

L'UNIVERSO

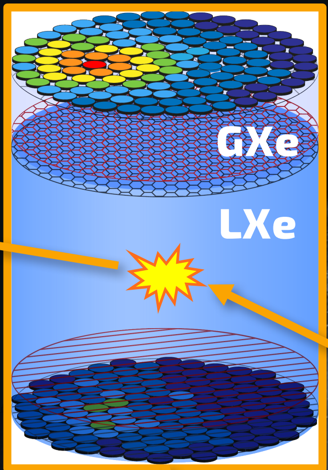
15^{th} floor of Wilson Hall at the U.S. Department of Energy's Fermilab America's national laboratory for particle physics research

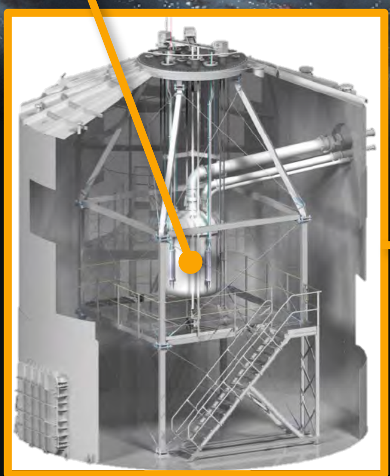
5%
MATERIA BARIONICA

26.5%
MATERIA OSCURA

68.5%
ENERGIA OSCURA

RICERCA DI WIMP CON XENON





UNDERGROUND LNGS (ITALY)

3600 m.w.e. rock shielding

MUON VETO CHERENKOV DETECTOR

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

Xe XENON Dark Matter Project

INFN

LA COLLABORAZIONE XENON

170 SCIENTISTS

27 INSTITUTIONS

11 COUNTRIES

Columbia | RPI | Nikhef | Muenster | Stockholm | Mainz | MPIK | Freiburg | Zurich

Chicago

UCLA

UCSD

Rice

Tokyo

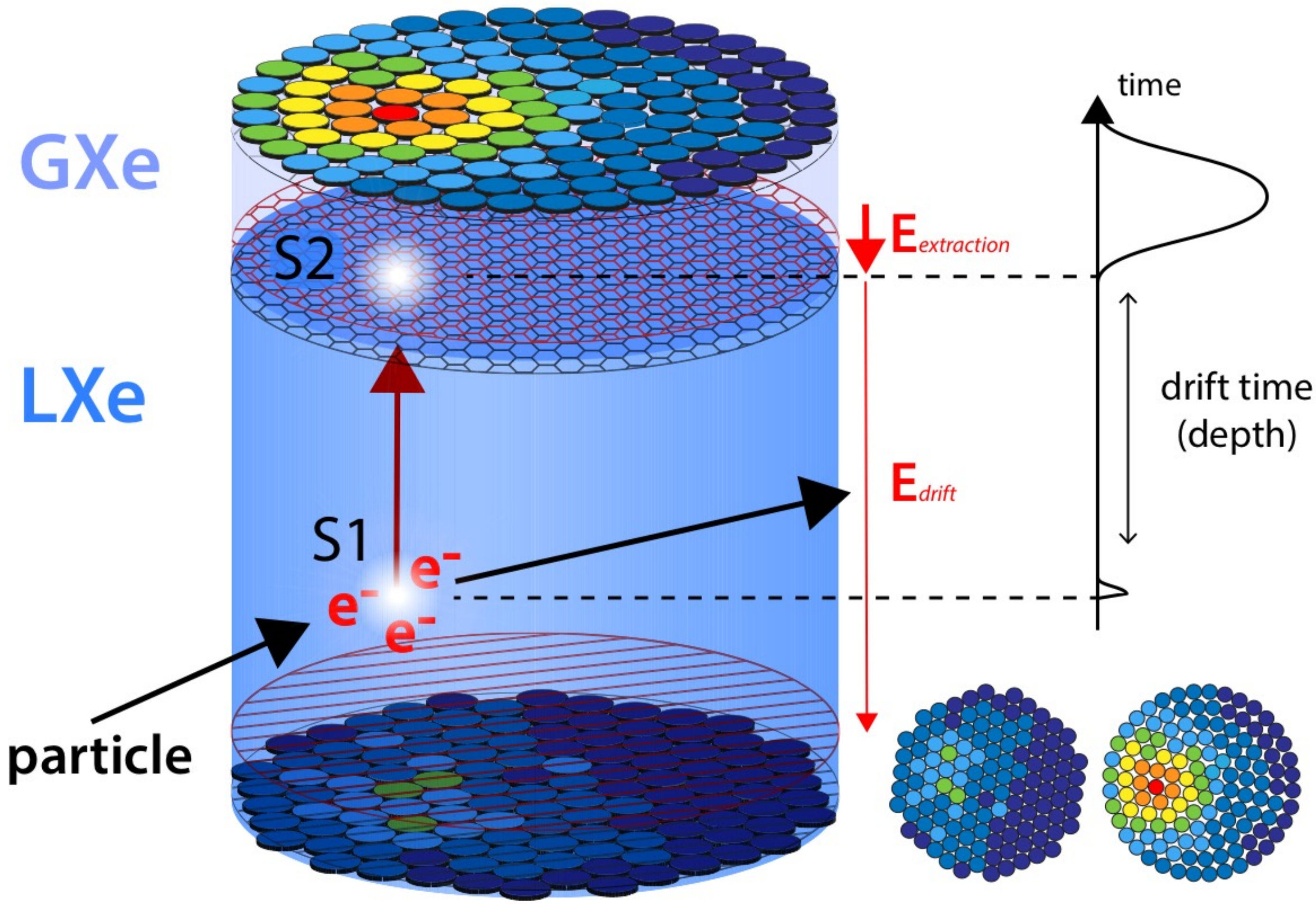
Nagoya

Kobe

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

TPC A DOPPIA FASE

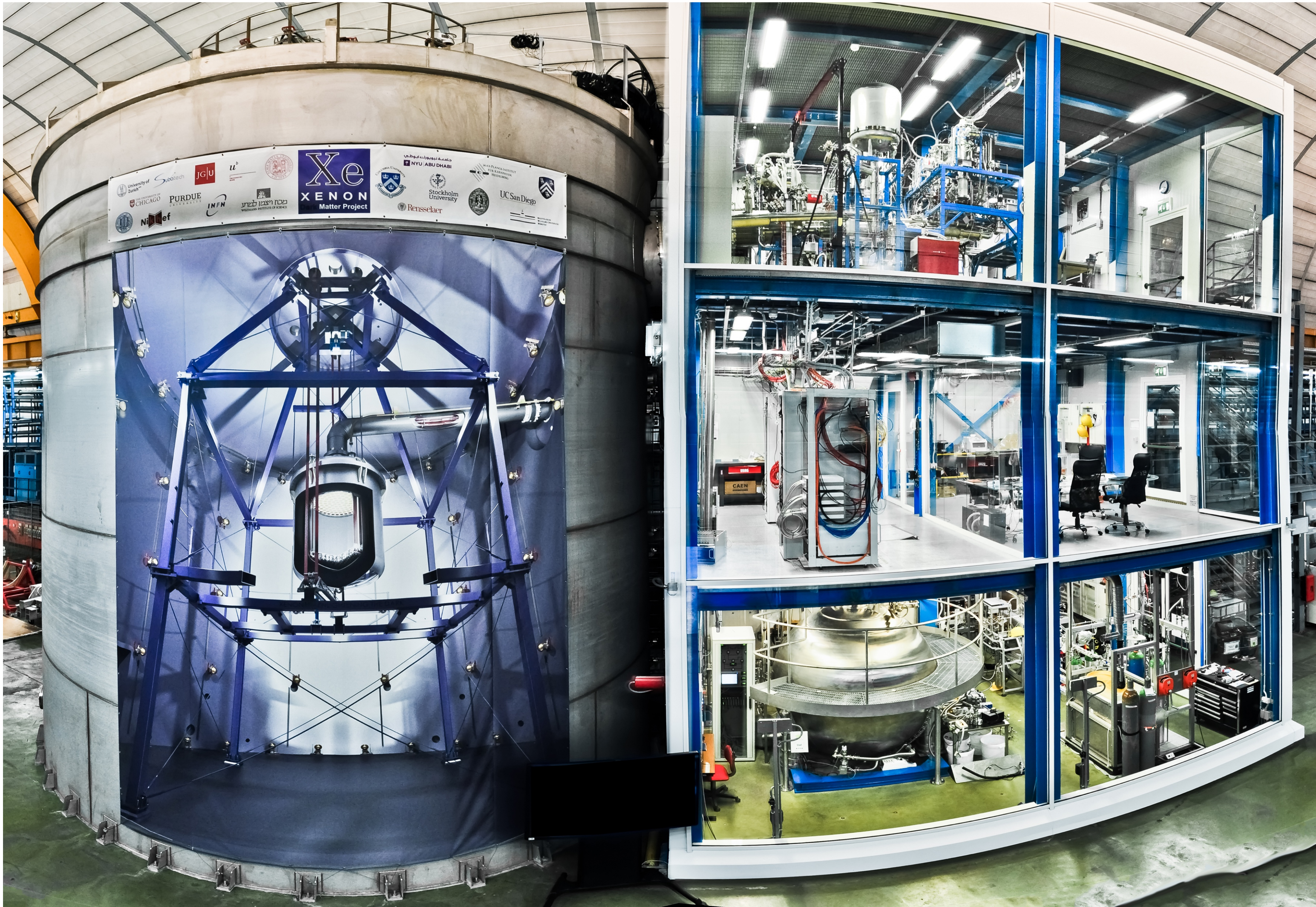
PRINCIPIO DI RIVELAZIONE



L'ESPERIMENTO XENON1T

AI LABORATORI NAZIONALI DEL GRAN SASSO

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



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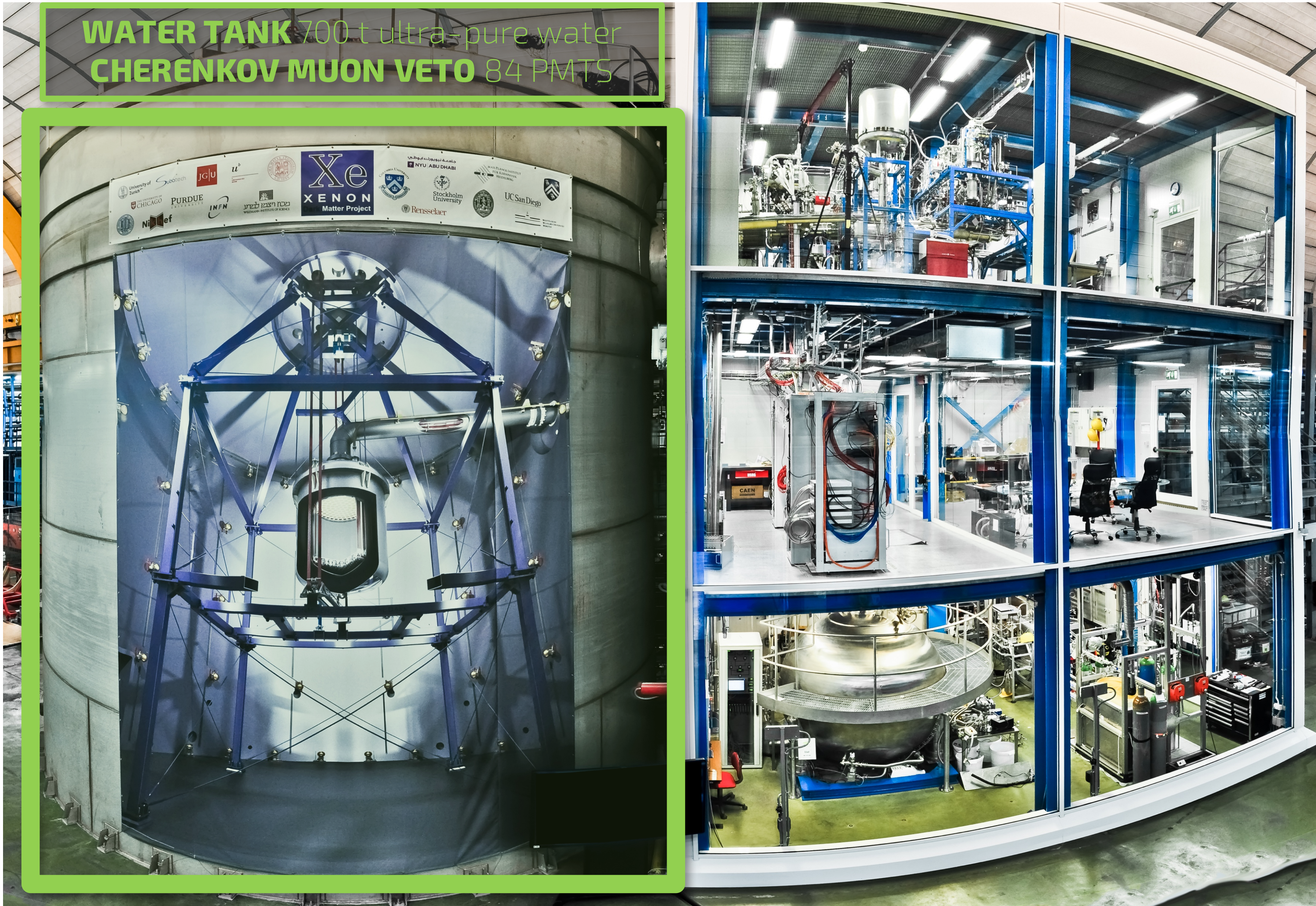

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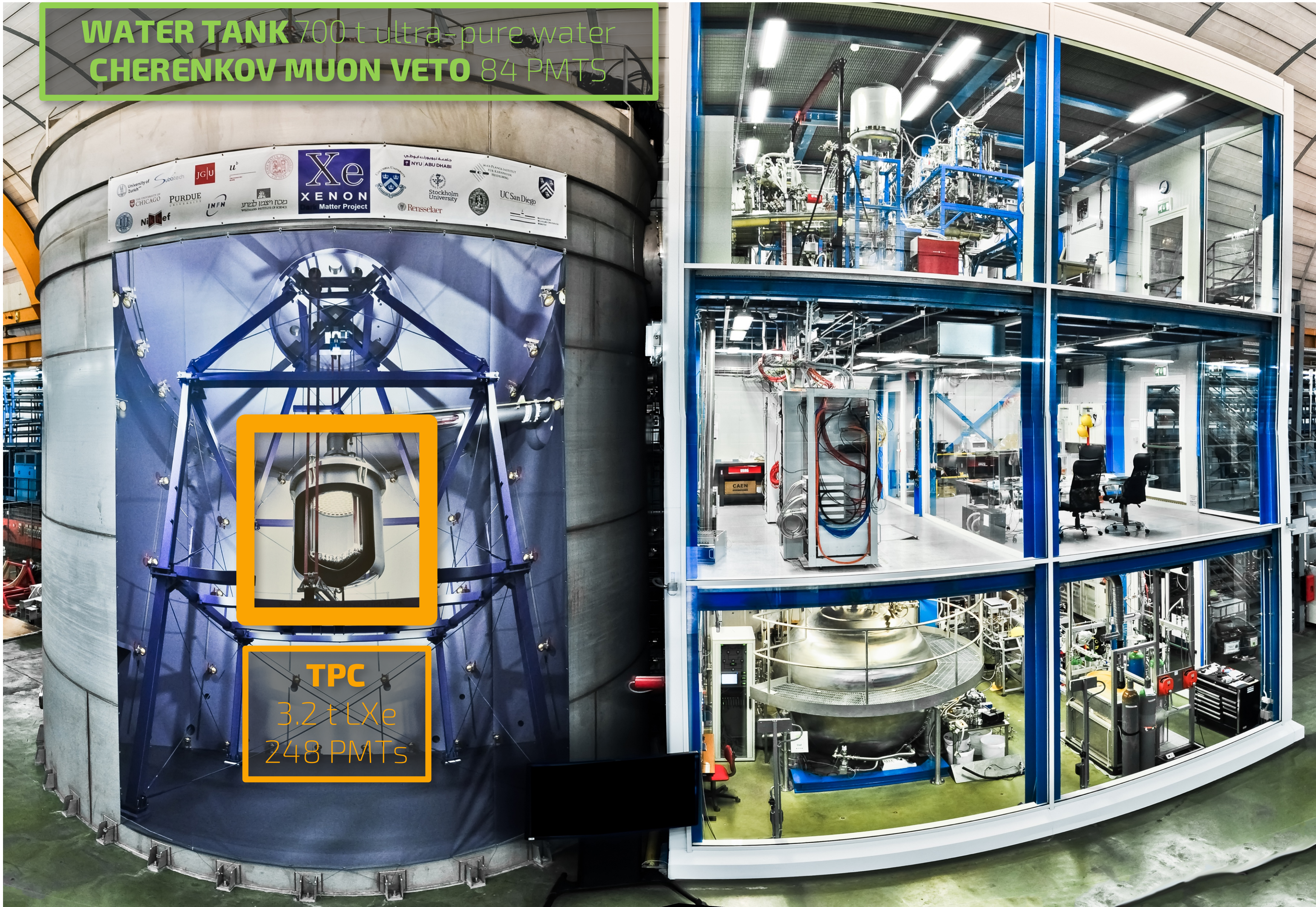

L'ESPERIMENTO XENON1T

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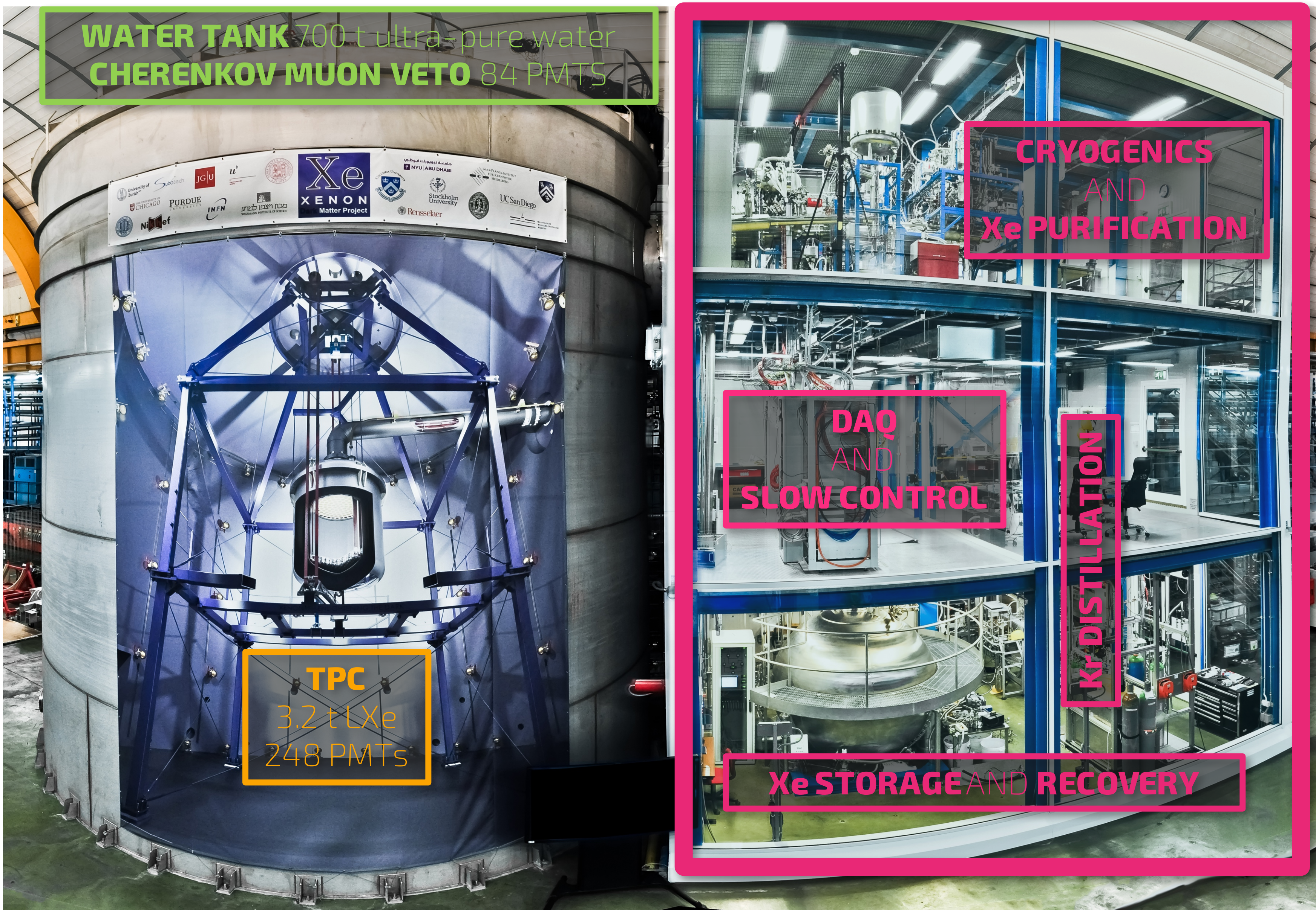


RIVELATORI BASATI SU LXe

L'EVOLUZIONE DELLA SPECIE

Massa TOTALE di LXe **3.2 t**

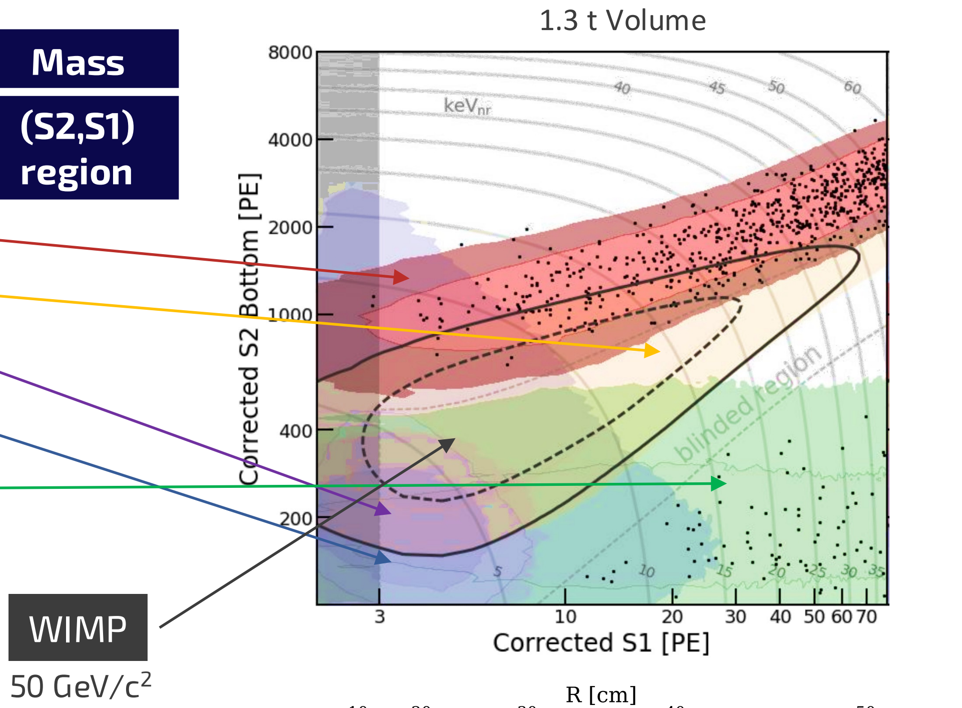
	XENON10	XENON100	LUX	PANDA X-II	**XENON1T**	XENONnT
Anno	2005	2008	2013	2016	**2016**	2019
MASSA ATTIVA DI XENON LIQUIDO	22 kg	105 kg	250 kg	580 kg	**2000 kg**	6000 kg
FONDO ER DI BASSA ENERGIA $[t \cdot d \cdot keV]^{-1}$		5.3	2.6	0.8	**0.2**	0.02 (Goal)

RISULTATI DI XENON1T
in 1 tonnellata-anno

XENON

BACKGROUND

278.8 days live-time	1.3 t Full ROI	0.65 t NR Reference	Mass (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**	



▸ MODELLI DI BACKGROUND

Spazio 4-dimensionale: S1, S2, r, z

▸ INFERENZA STATISTICA

Analisi **Profile Likelihood Ratio**

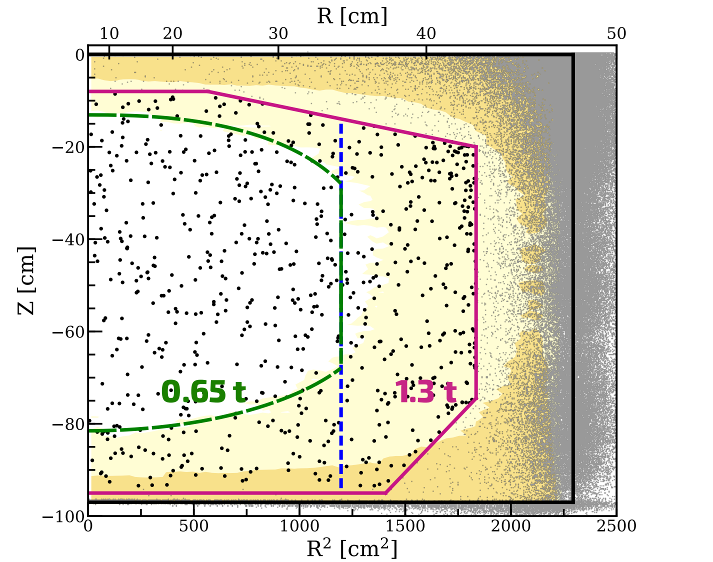
1.3 t Massa fiduciale

Spazio (S1,S2) completo: [4.9, 40.9] keV$_{nr}$ e [1.4, 10.6] keV$_{ee}$

▸ REGIONE DI REFERENZA NR

Fra mediana NR e quantile -2σ

I numeri in tabella sono rappresentativi; Risultato finale da inferenza PLR sull'intero spazio di analisi

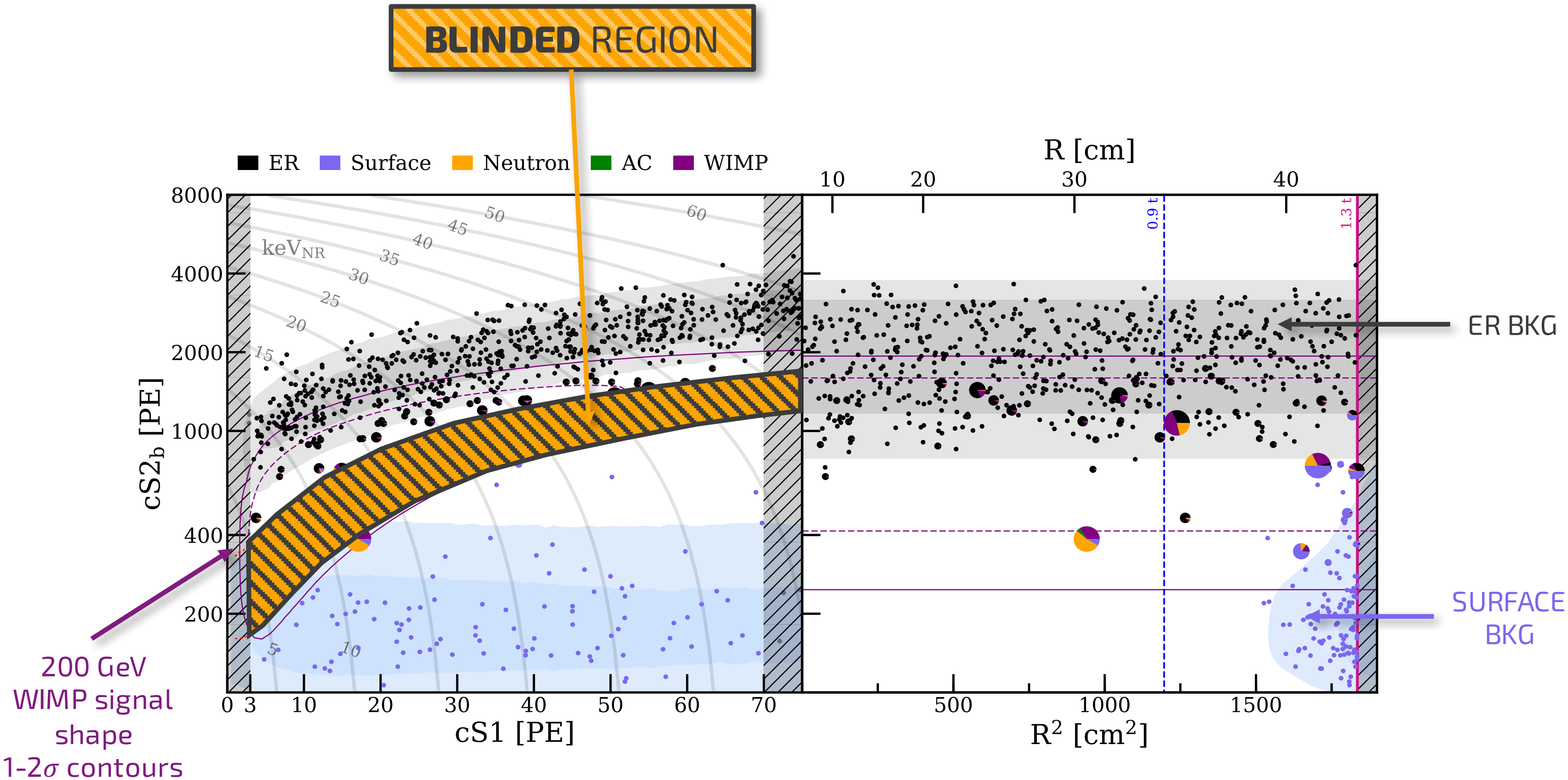


UNBLINDING

XENON1T DATASET

▸ BLINDING E SALTING

I dati sono stati tenuti segreti nella regione NR di segnale e “salted” con un numero sconosciuto di eventi fake



UNBLINDING

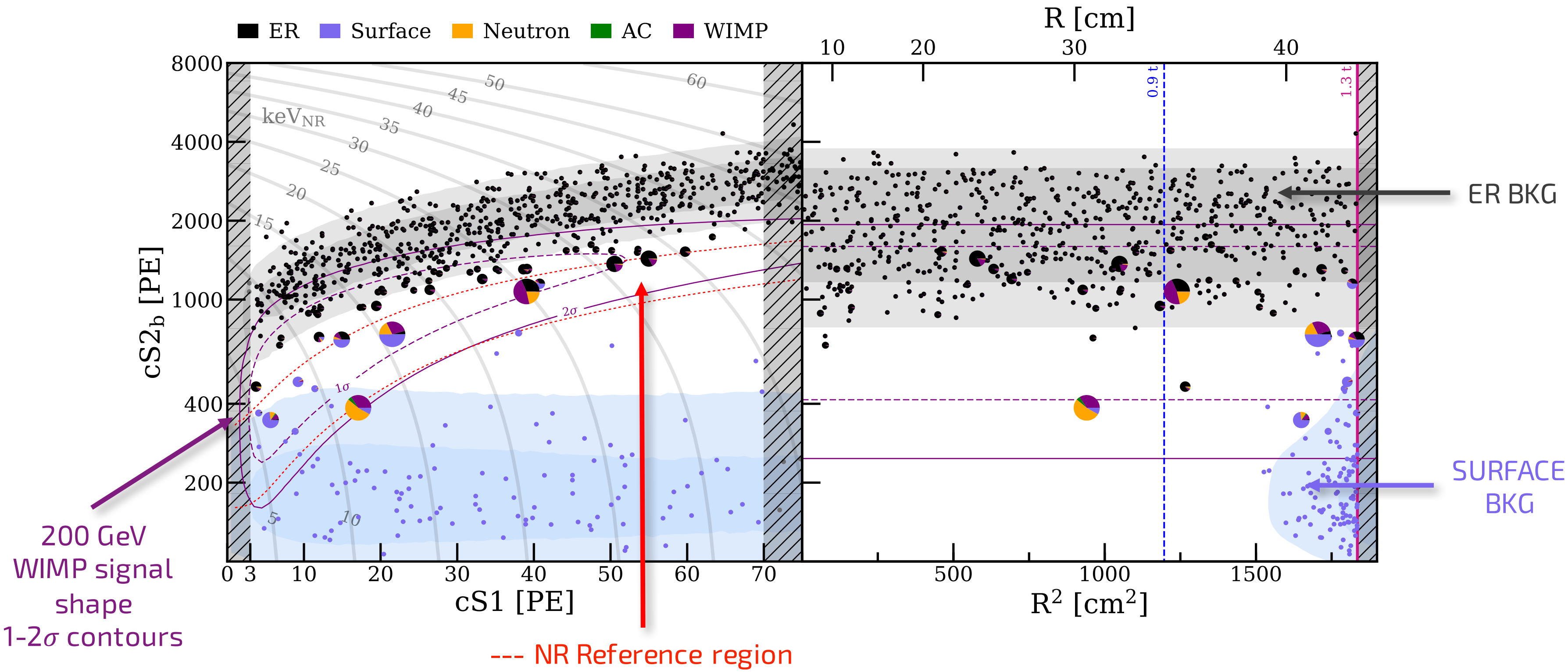
XENON1T DATASET

PIE CHARTS

Gli eventi che superano tutti i tagli di selezione sono mostrati come pie charts che rappresentano la PDF relativa da ciascun componente per il modello di best-fit per WIMP da 200 GeV/c^2 (σ_{SI}=4.7•10^{-47} cm^2).

INTERPRETAZIONE STATISTICA

Profile likelihood non binnata con le incertezze dei modelli incluse come nuisance parameters.

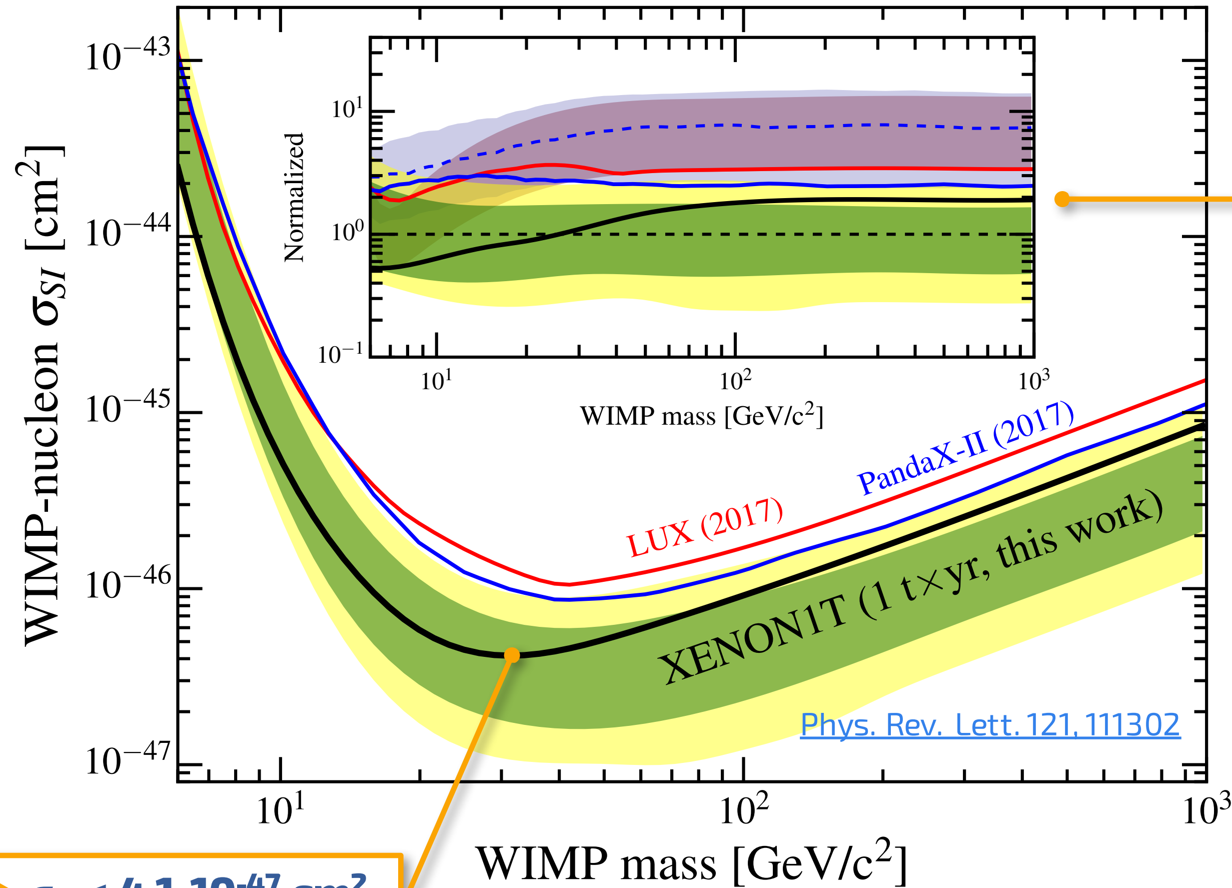


RISULTATO FINALE

MIGLIOR LIMITE AL MONDO SU WIMP

- **SEZIONE D'URTO SPIN-INDEPENDENT WIMP-NUCLEONE**

Limiti di esclusione più stringenti (al 90% CL) per WIMP > 6 GeV/c^2



- **x7 SENSIBILITA' MIGLIORATA** rispetto a esperimenti precedenti (LUX, PANDAX-II)

- $\sigma_{SI} < 4.1 \cdot 10^{-47}$ **cm²** a 30 GeV/c^2

XENONnT

PROSSIMO STEP

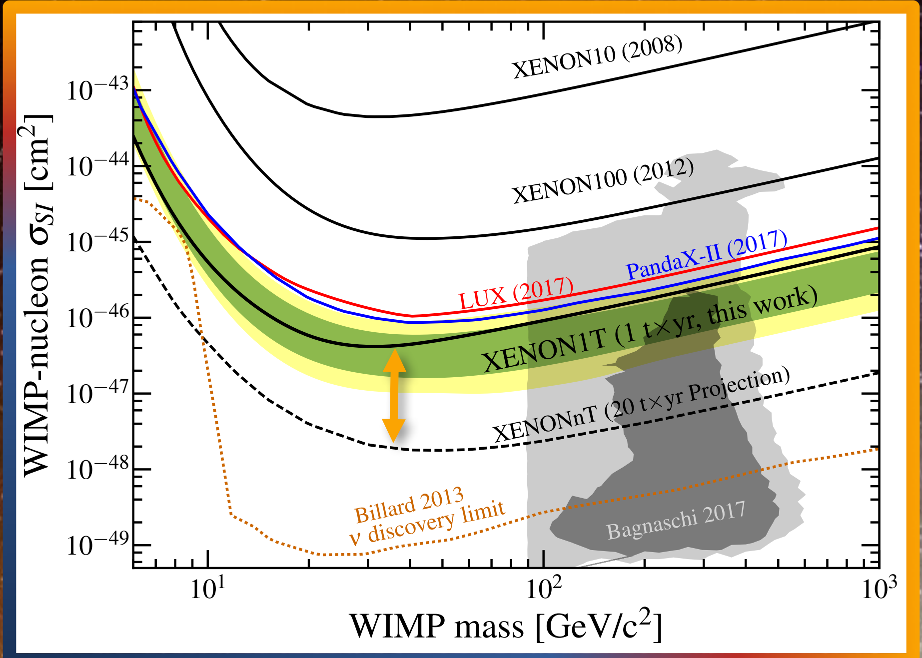
x4 **LXe TARGET**
- Massa fiduciale 1 t → 4 t

NEW TPC
- 248 → 476 PMTs

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

BACKGROUND NR
- Neutron Veto

UPGRADE VELOCE
- Commissioning entro 2019



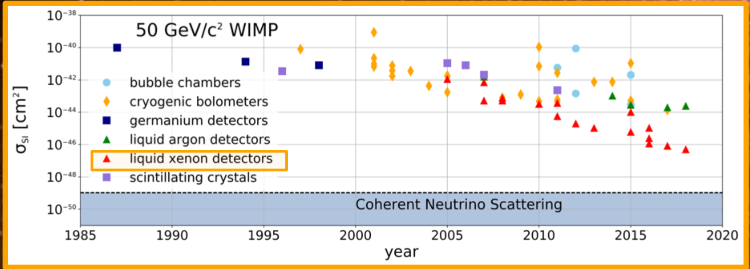
SENSIBILITÀ MIGLIORE DI 1 ORDINE DI GRANDEZZA IN 5 ANNI

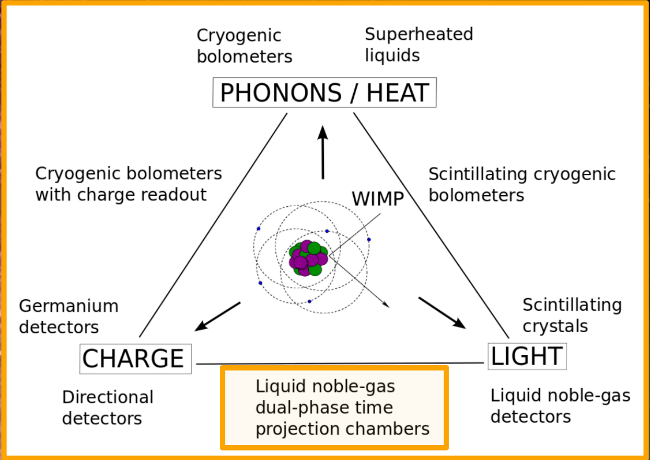
BACKUP

XENON

COME RIVELARE LA MATERIA OSCURA

- **RIVELAZIONE DIRETTA**
- **RIVELAZIONE INDIRETTA**
- **PRODUZIONE AI COLLIDER**



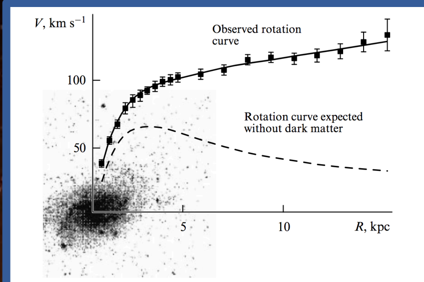


XENONnT Time Projection Chamber

EVIDENCES OF DARK MATTER

GALAXY AND CLUSTERS SCALE

ROTATION CURVES



M33 Galaxy

BULLET CLUSTER

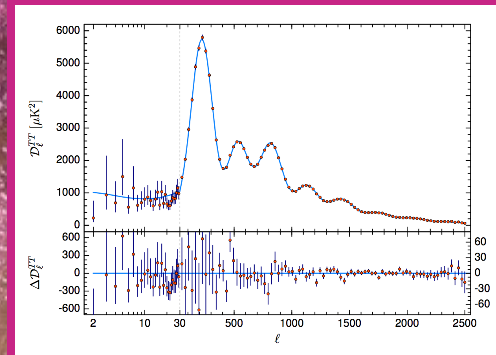
Luminous vs Dark matter

LENSING

SDSS J1038+4849 Clusters

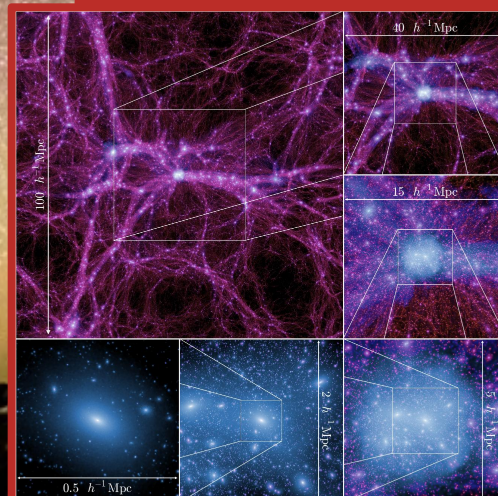
COSMOLOGICAL SCALE

CMB + ΛCDM



PLANCK 2018

STRUCTURE FORMATION

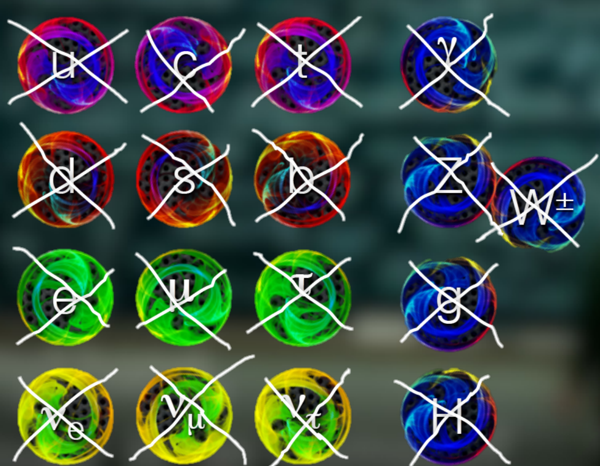


Millennium-II Simulation

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***

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

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

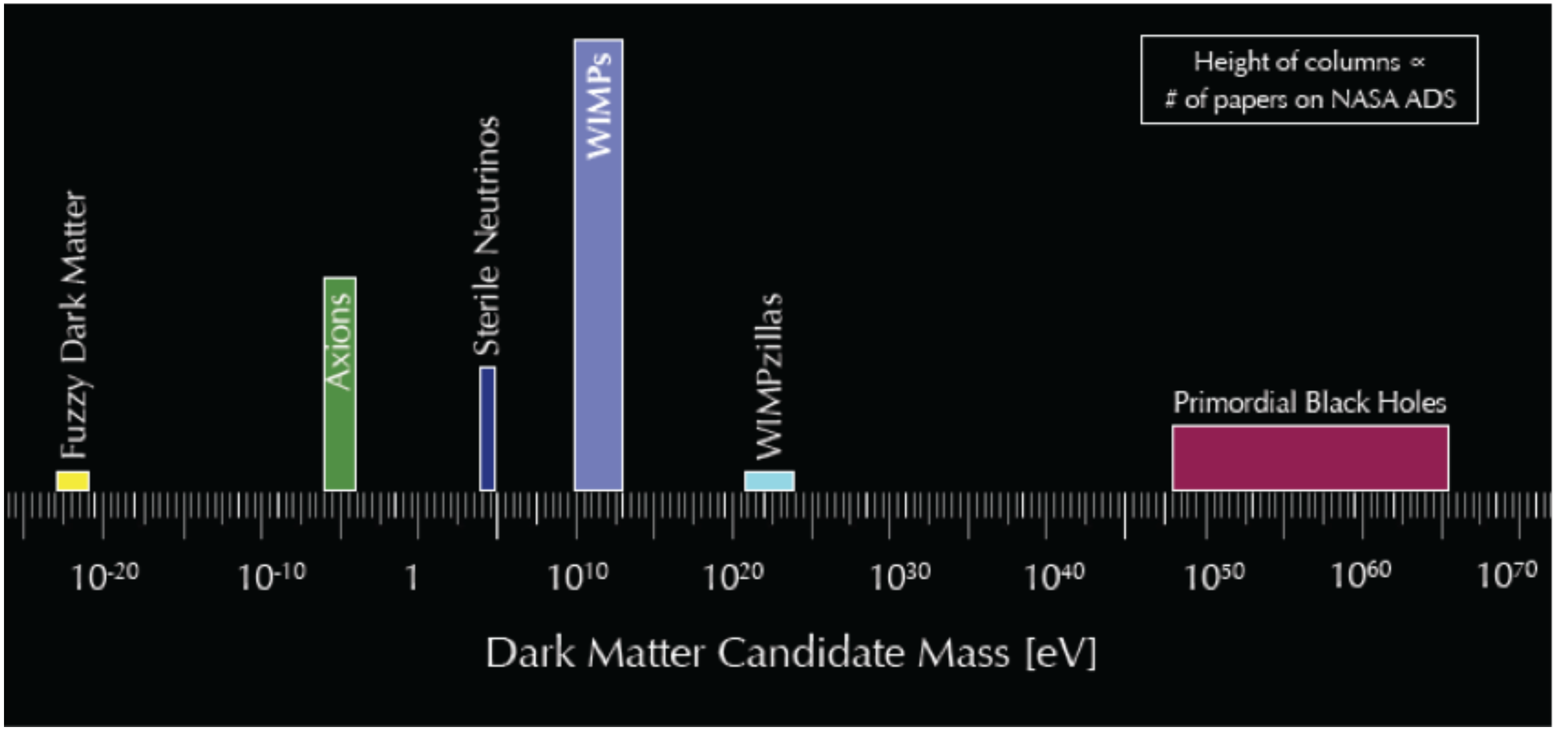
Other candidates

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

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

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**
👍 $\sigma_{WIMP-N} \sim A^2$ → 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

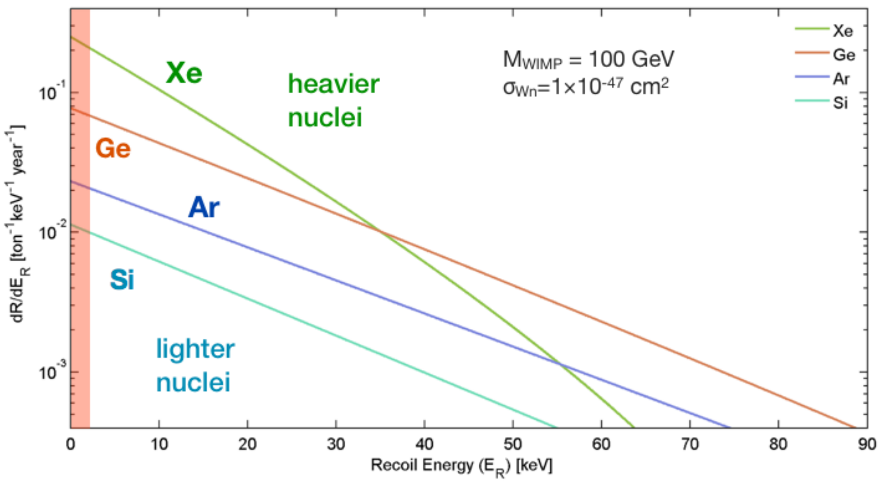
▸ **High purity**
👍 ^{136}Xe decay rate negligible; ^{85}Kr removed to <ppt level

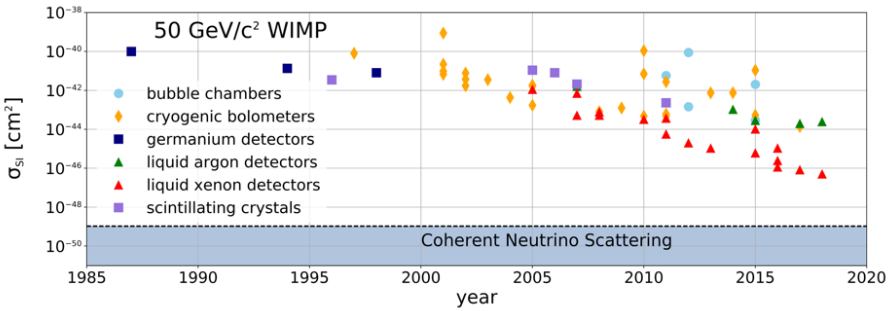
▸ **Light and charge yields**
👍 Highest among noble liquids

▸ **"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

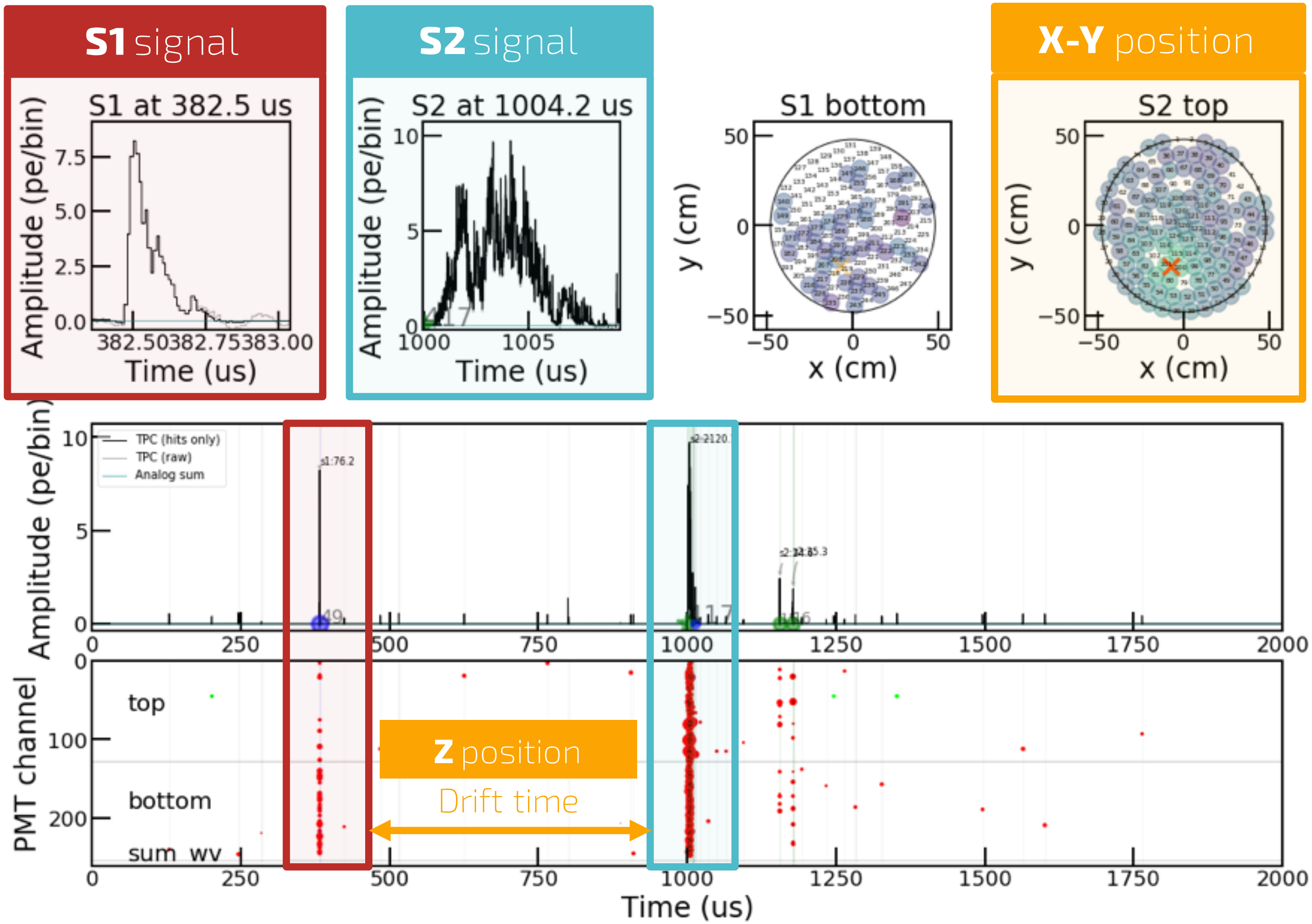




FROM THE PRINCIPLE TO REALITY

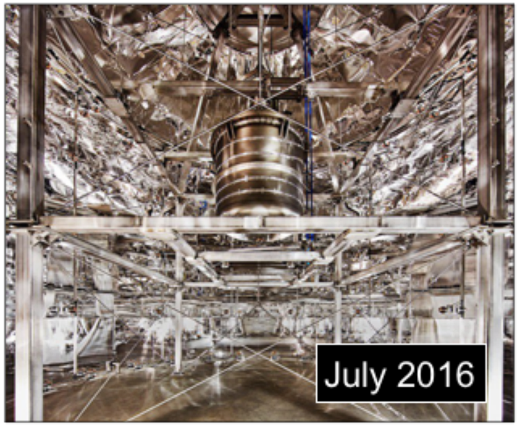
A TYPICAL LOW ENERGY EVENT

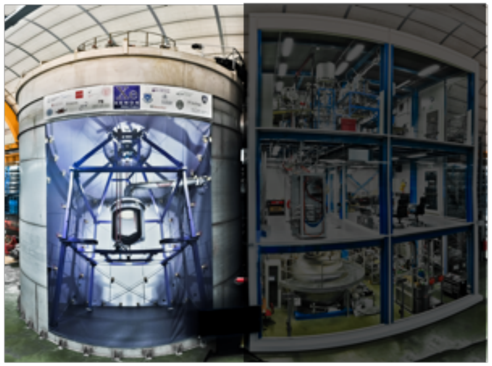
PAX
Processor for Analyzing XENON
https://github.com/XENON1T/pax



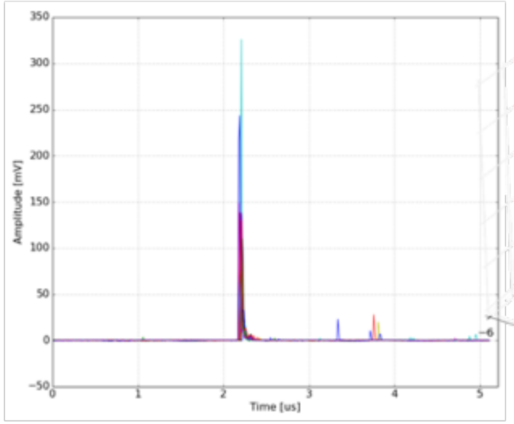
MUON VETO

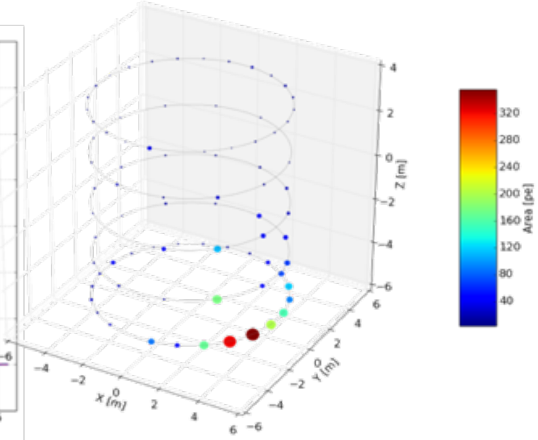
WATER CHERENKOV SUB-DETECTOR





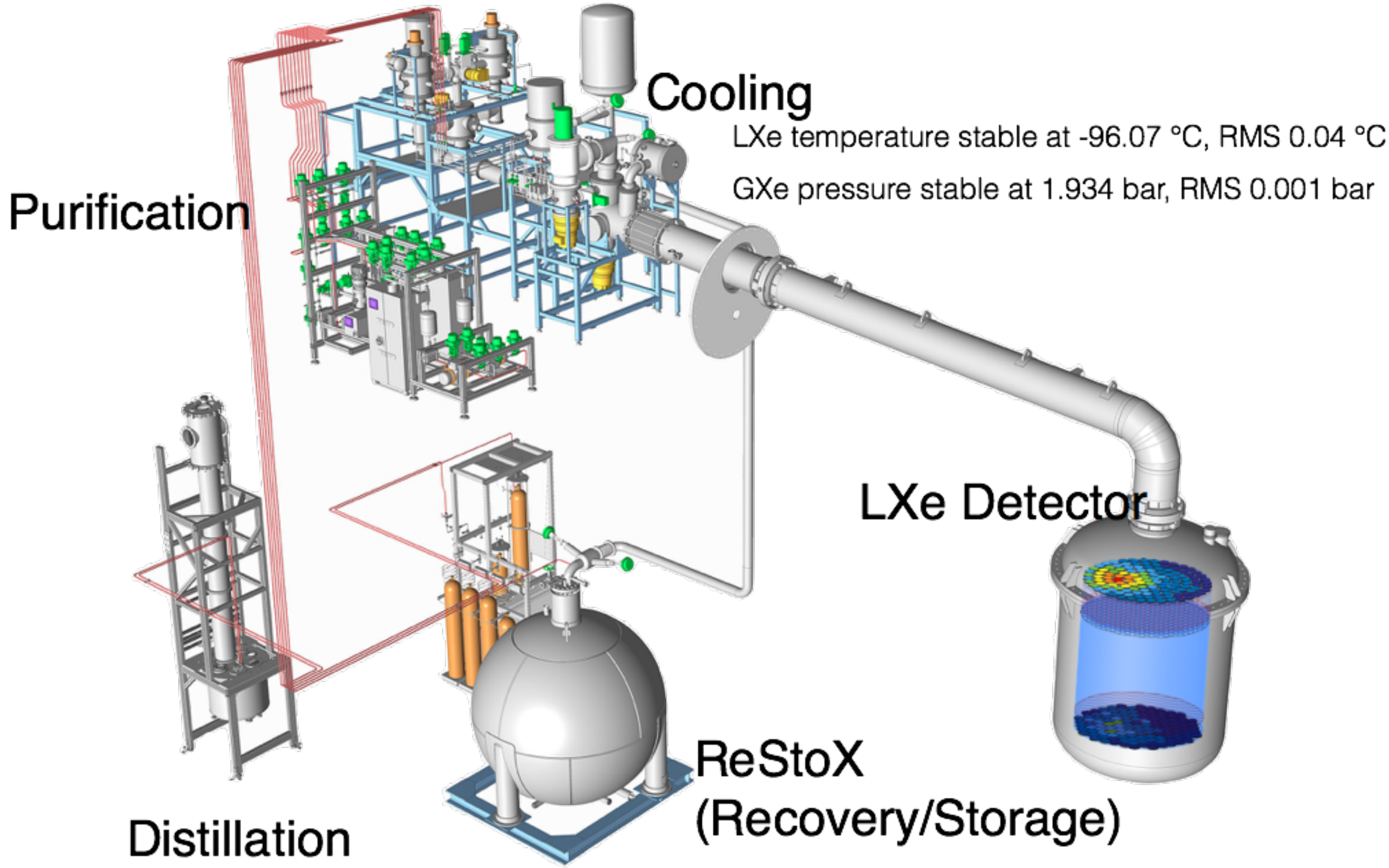
- 700 ton pure water instrumented with 84 high-QE 8" PMTs
- Active shield against muons
- Trigger efficiency > 99.5% for muons in water tank
- Cosmogenic neutron background suppressed to < 0.01 events/ton/yr





JINST 9, 11007 (2014)

XENON SYSTEMS

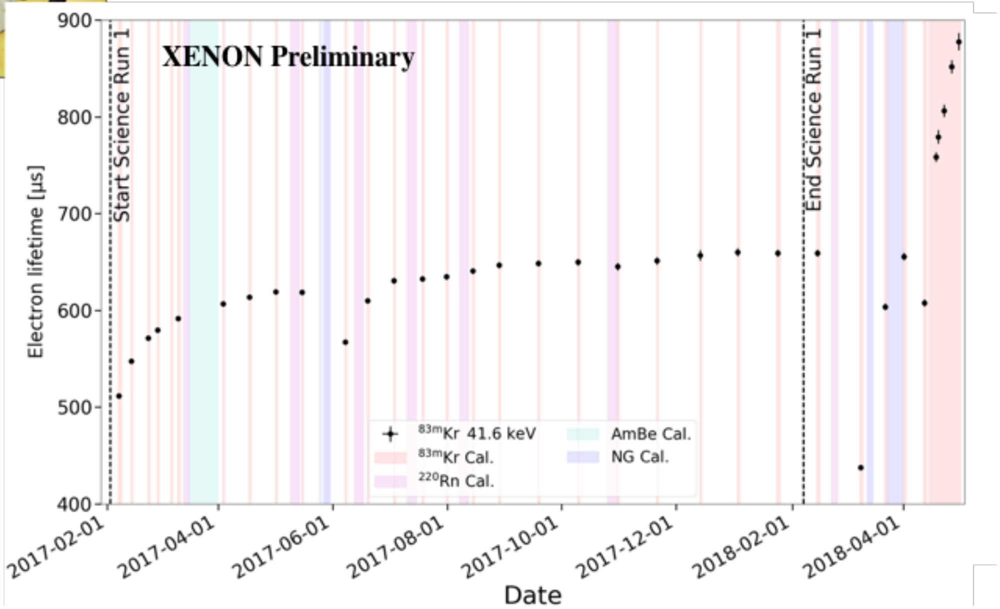


XENON PURIFICATION

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

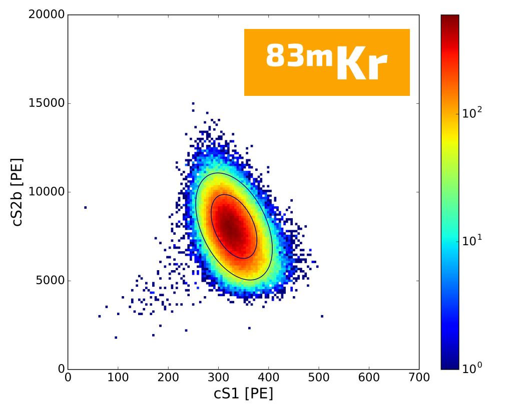
- electron lifetime is monitored regularly with ERs calibration sources.
- Current value, following increase in gas flow, approaches 1 msec



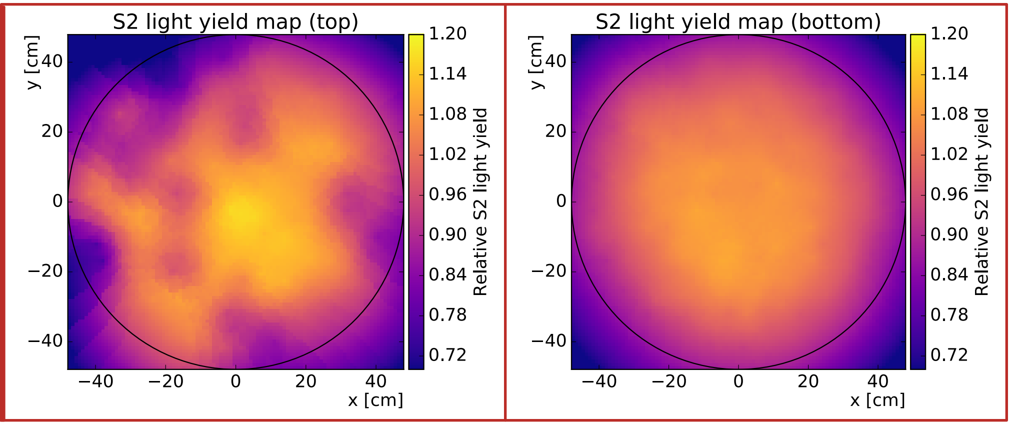
SIGNAL SPATIAL CORRECTIONS

VOLUME CALIBRATIONS WITH ^{83m}Kr

Plots just for illustration

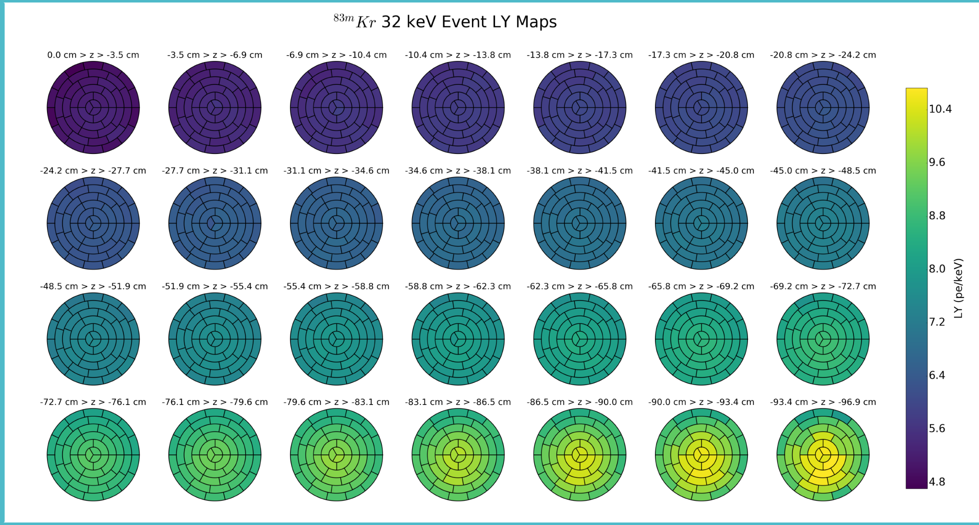


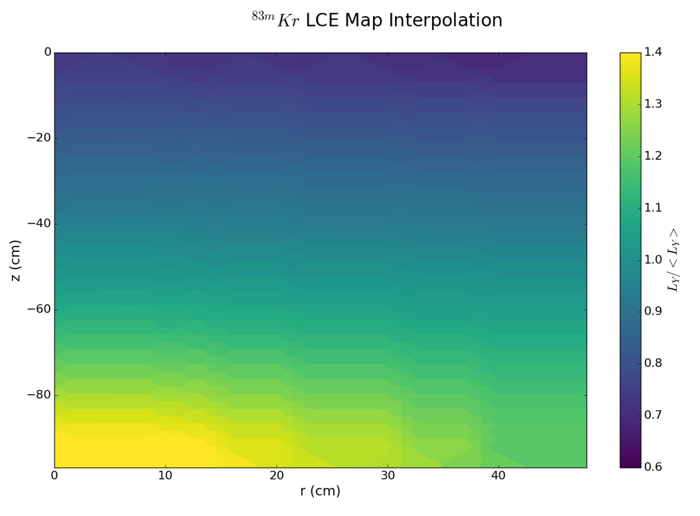
S2 XY correction map



^{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.

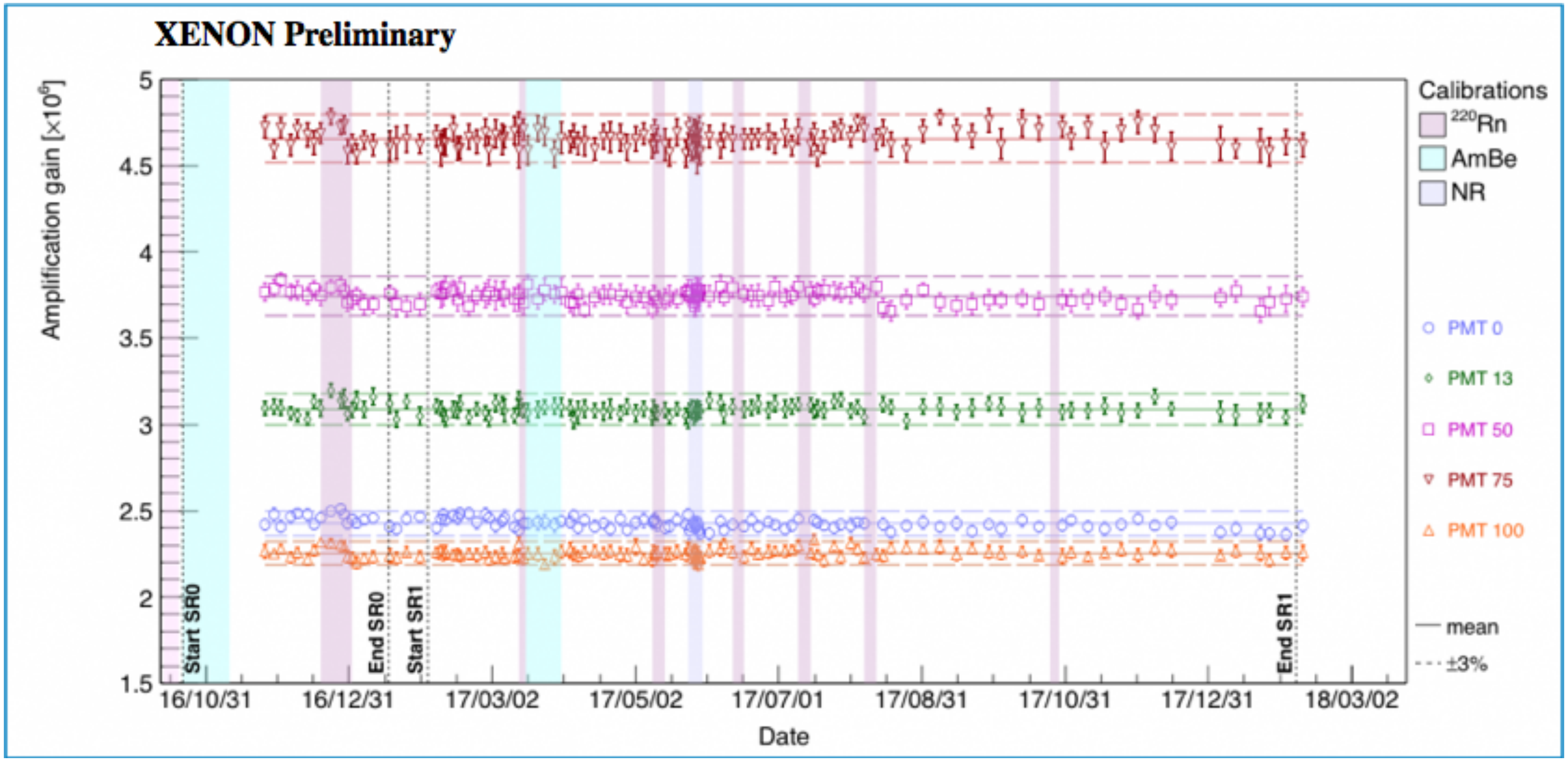
S1 XYZ correction map





LIGHT DETECTION SYSTEM

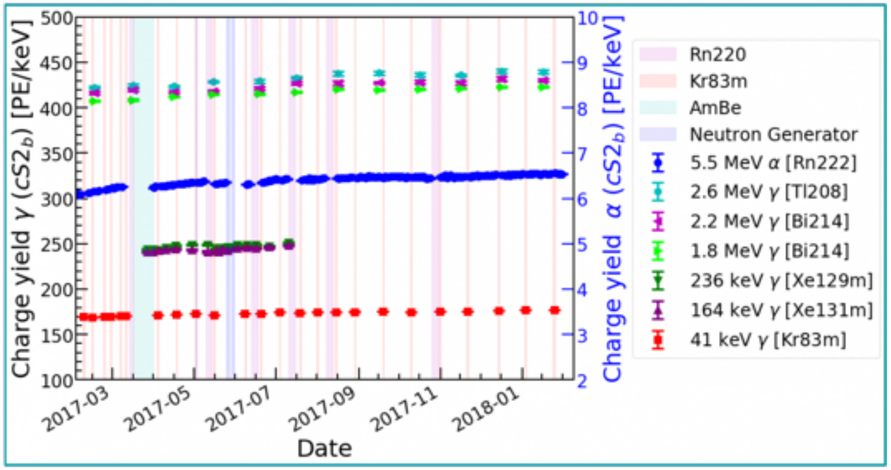
PMT STABILITY

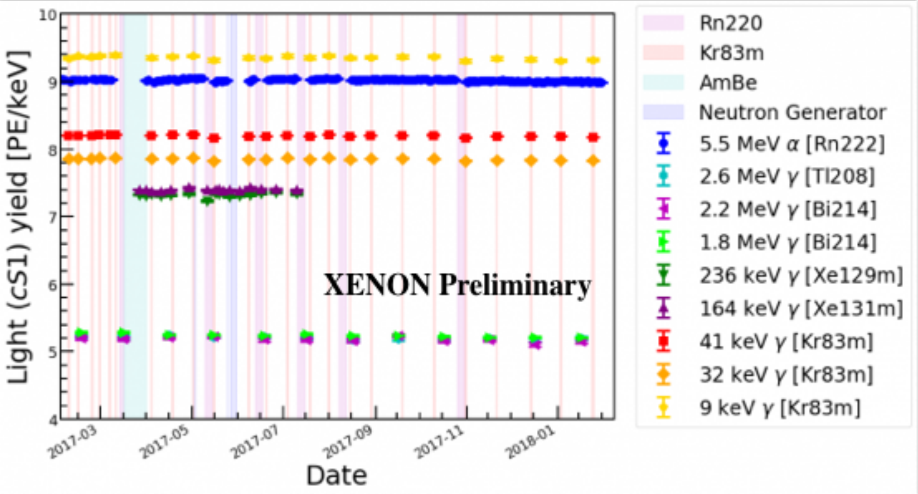


LIGHT AND CHARGE SIGNALS

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

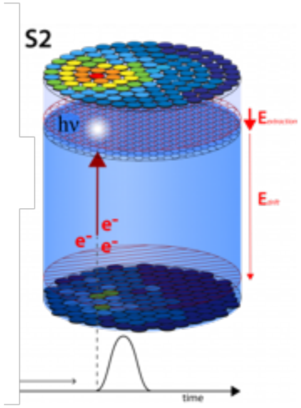




Light and charge yield stability monitored with several sources:

- ^{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

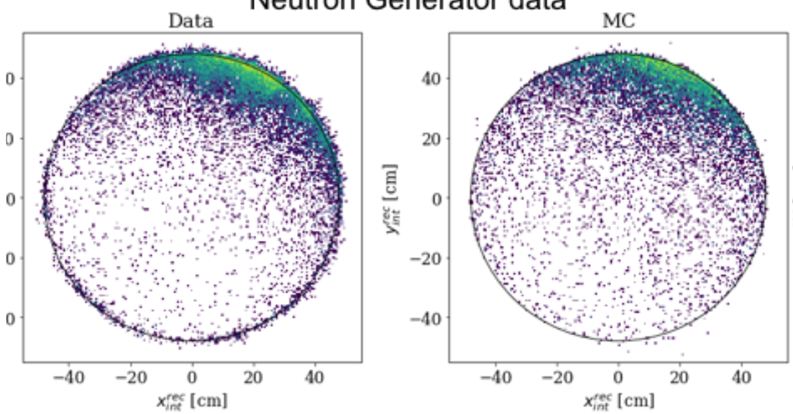
Position resolution using ^{83m}Kr

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

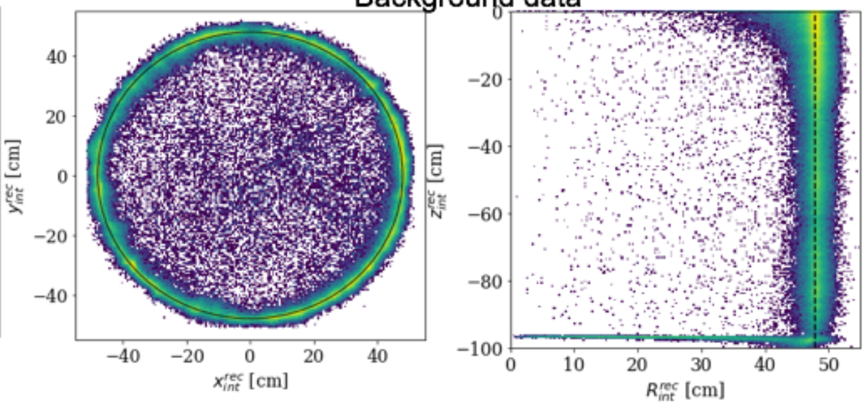
Position corrections using ^{83m}Kr

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

Neutron Generator data

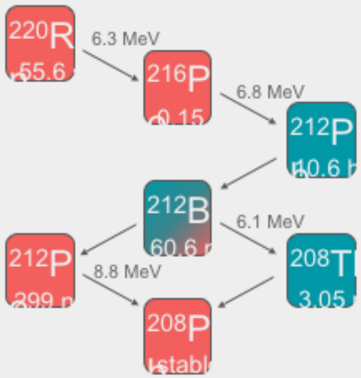


Background data



CALIBRATIONS

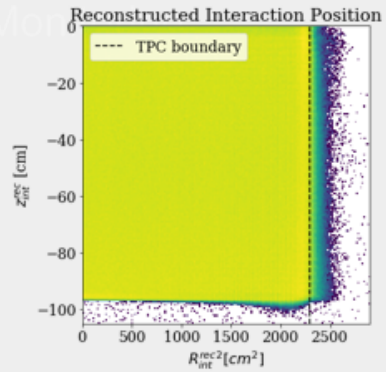
^{220}Rn: Low Energy ER



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

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

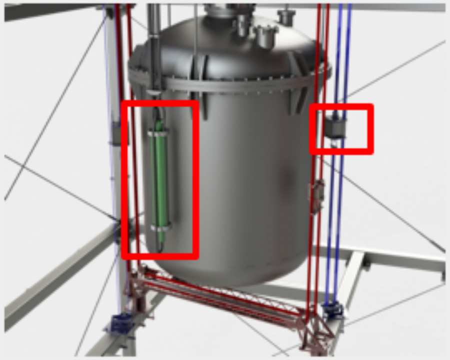
^{83m}Kr: Stability and Mon



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

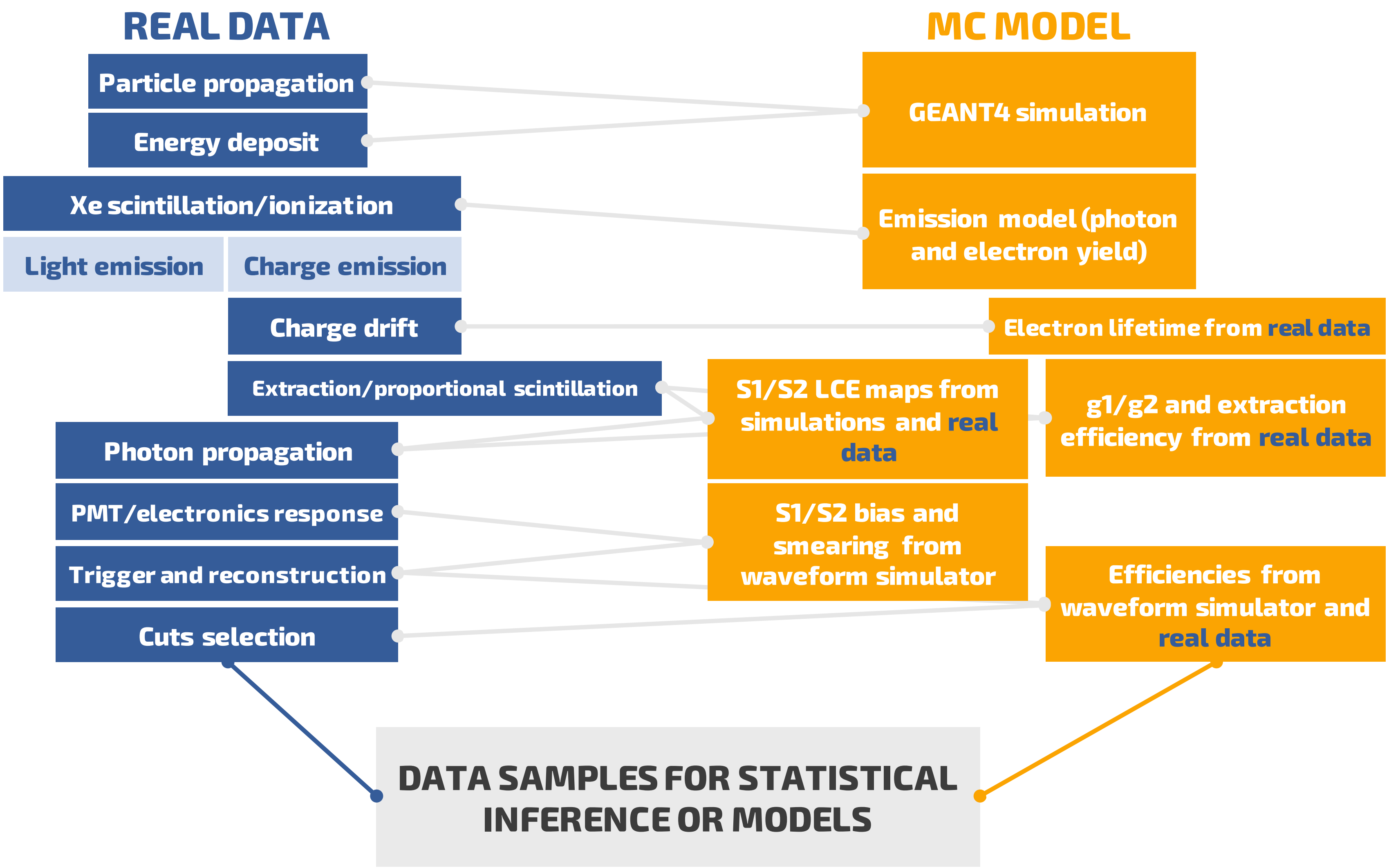
Neutrons: Signal Response



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

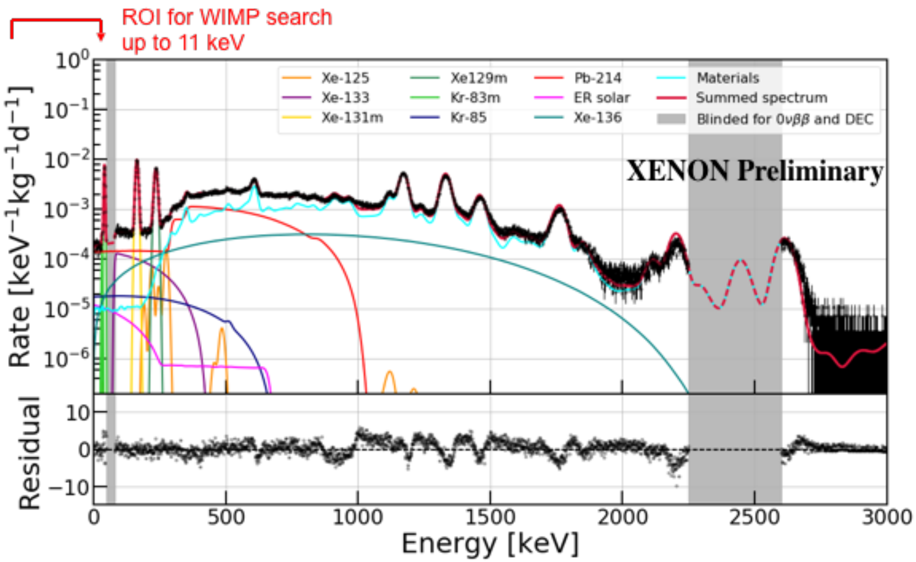
ER AND NR MODELING

REAL DATA AND MC SIMULATIONS

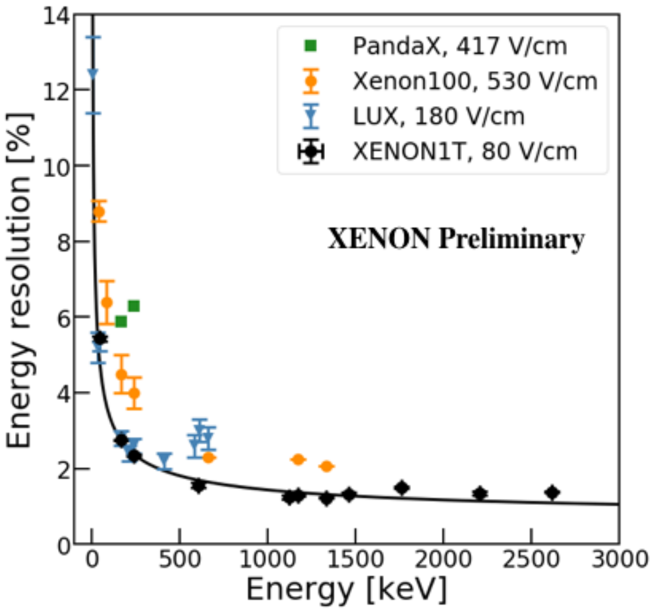


BACKGROUND SPECTRUM

ENERGY RESOLUTION AND MC MATCHING



- 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

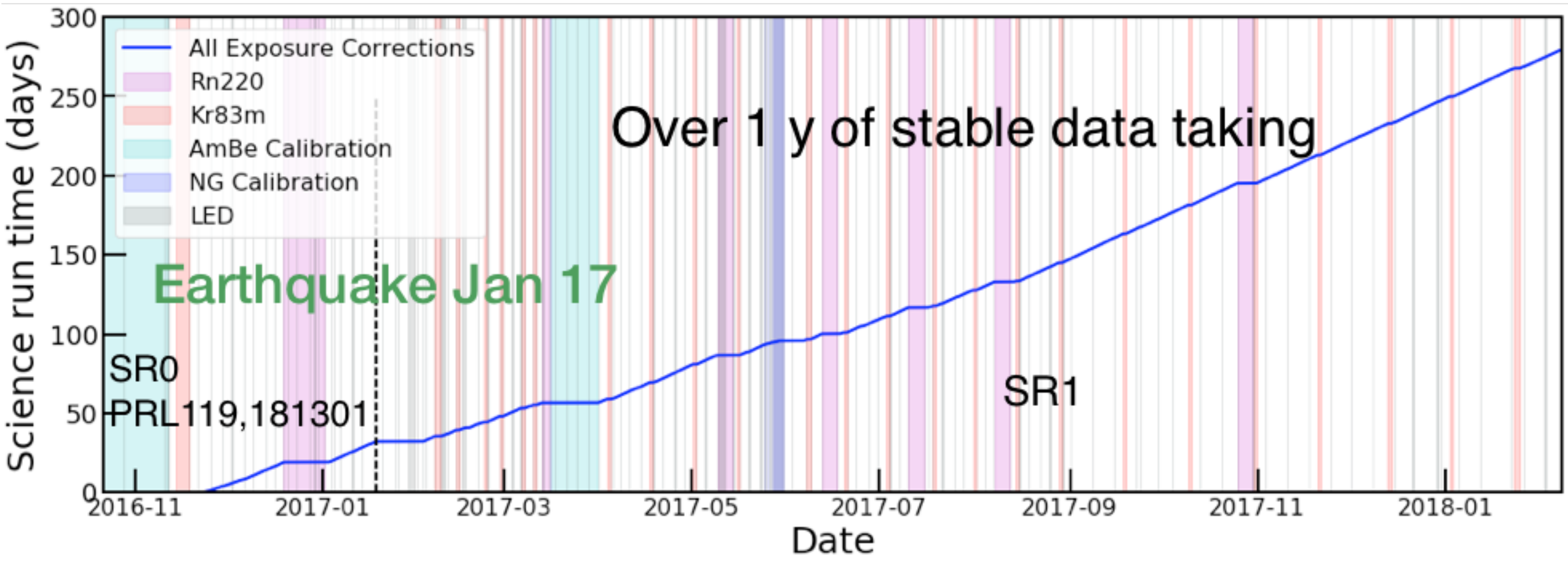


- Good agreement between predicted and measured background spectrum
- Kr: ~0.45 ppt; Pb214: ~ 10 uBq/kg
- Gammas based on screening measurements

XENON1T TIMESCALE

SCIENCE AND CALIBRATION DATA

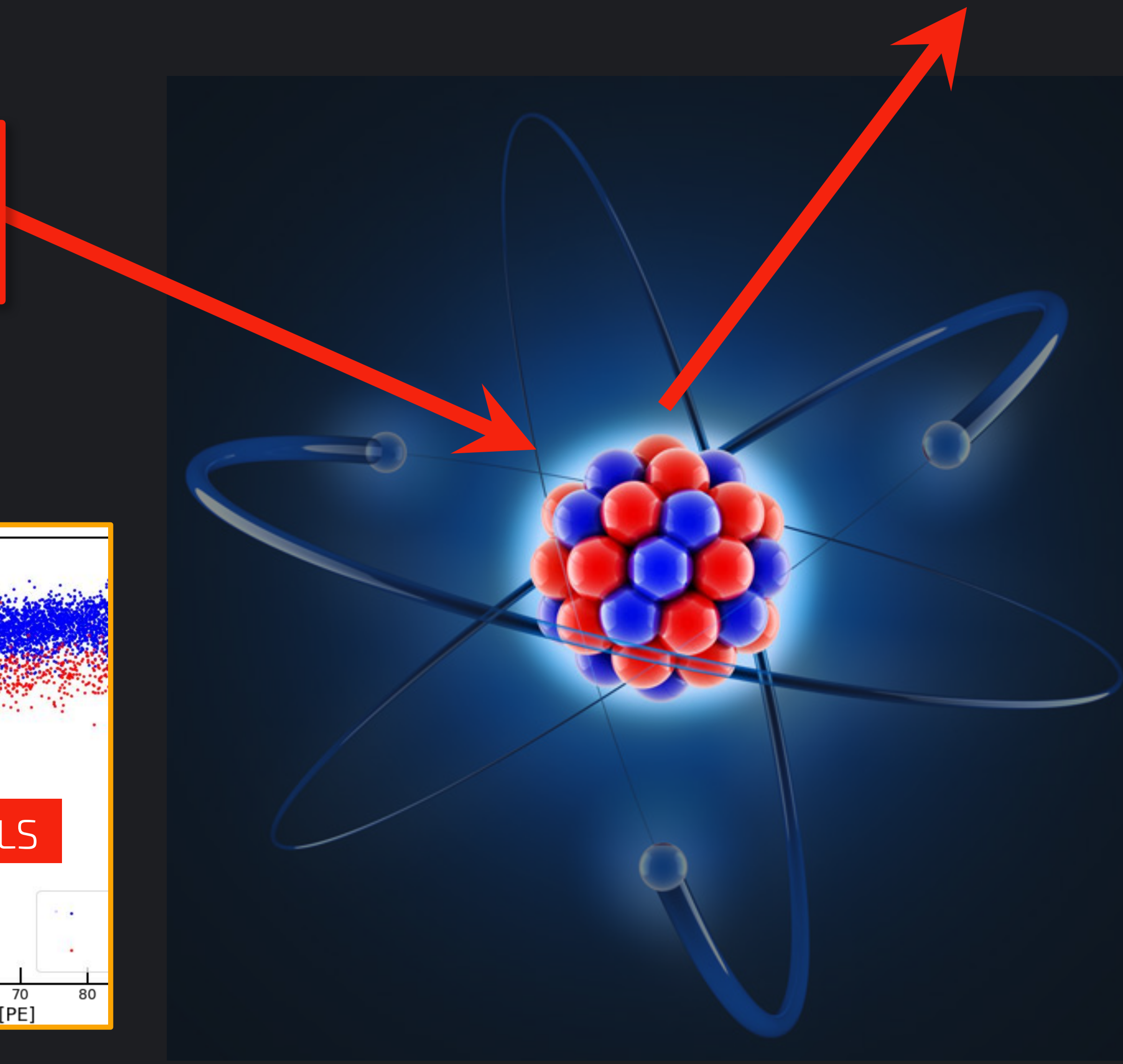
- 279 days high quality data (livetime-corrected) spanning more than 1 year of stable detector's operation. The LXeTPC has been "cold" since Summer 2016
- 1 tonne x year exposure given 1.3 tonne fiducial volume- the largest reported to-date with this type of detector
- Experiment still running smoothly and collecting more data

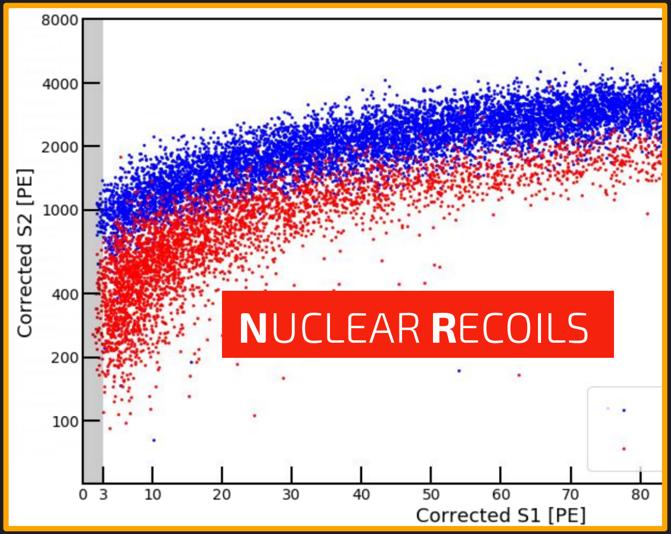


RECOIL TYPE DISCRIMINATION

NUCLEAR RECOILS

WIMP
Neutron
Neutrino (CNNS)

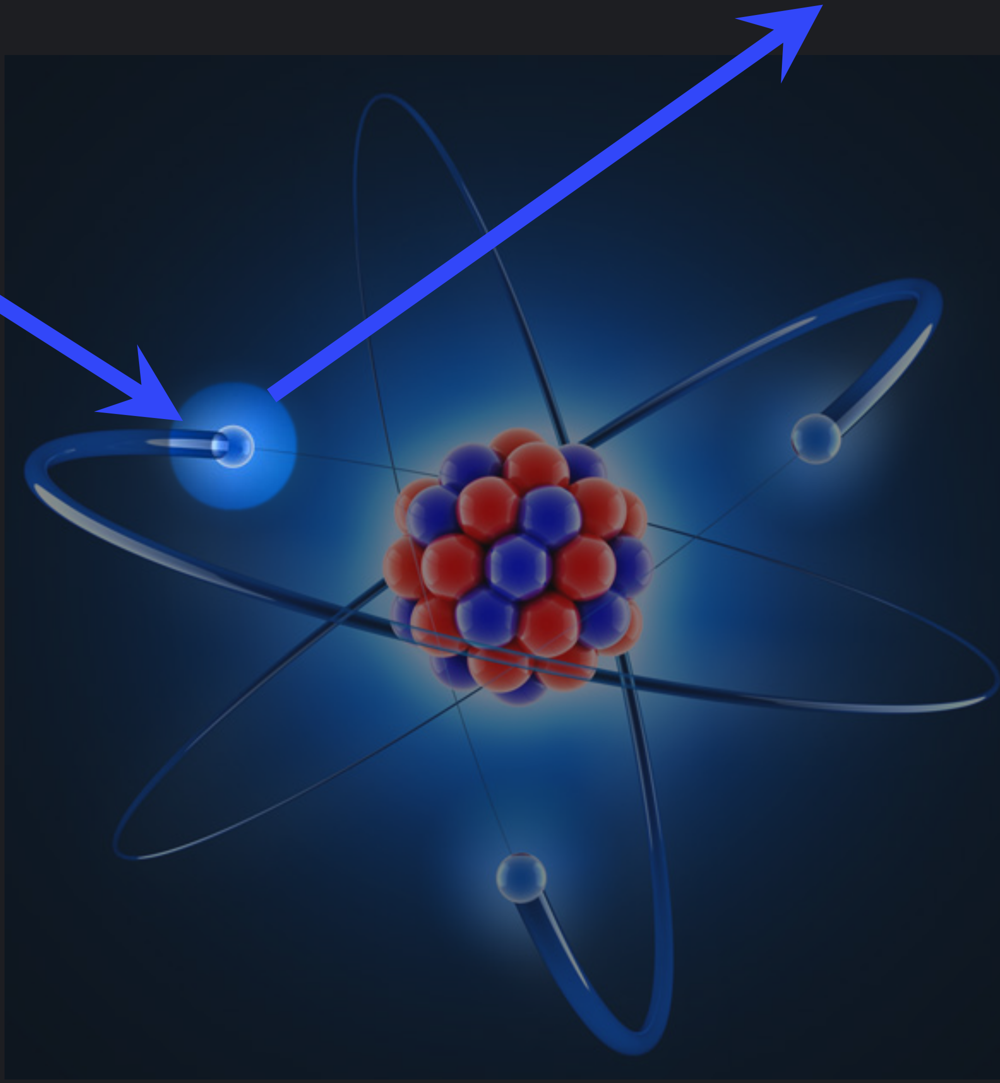


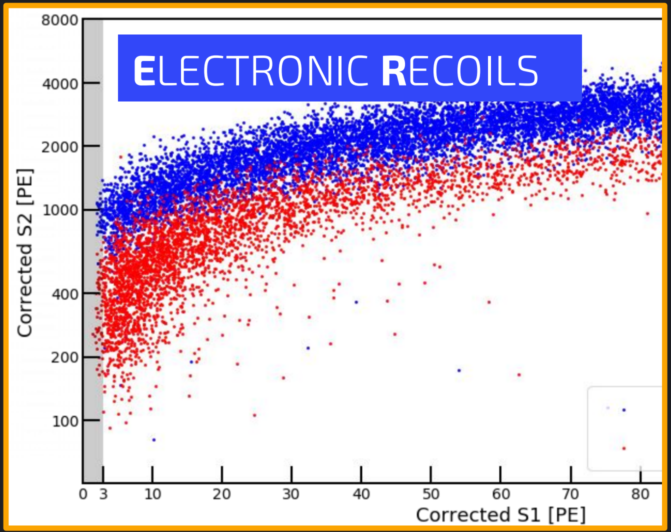


RECOIL TYPE DISCRIMINATION

ELECTRONIC RECOILS

Gamma
Beta
Neutrino





NUCLEAR RECOIL BACKGROUND

Cosmogenic neutrons

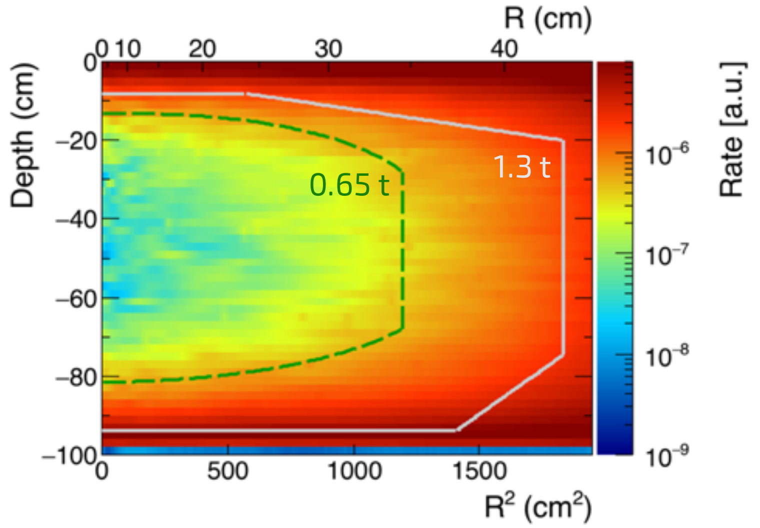
Induced by cosmic muons.
Reduced to negligible contribution by rock overburden, water passive shield and active Cherenkov Muon Veto. JINST 9, P11006 (2014)

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)



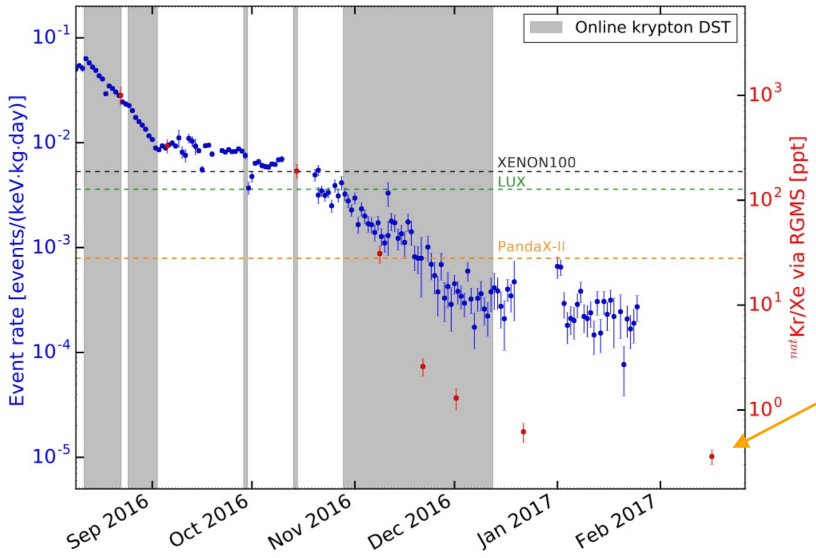
JCAP 04, 027 (2016)

	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



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.

- **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

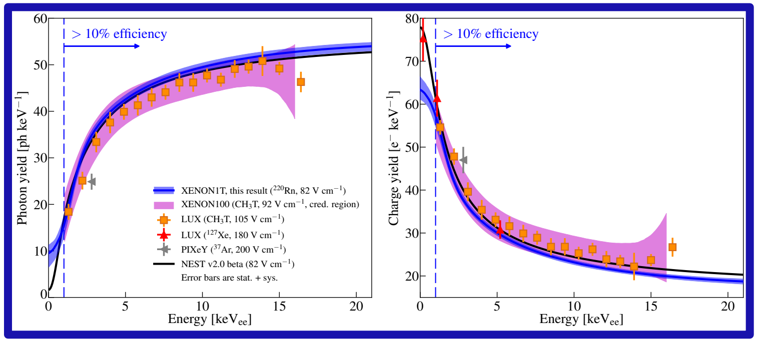
JCAP 04, 027 (2016)

	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

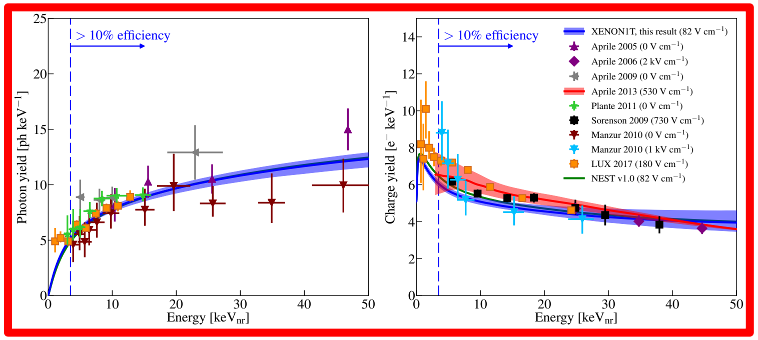
Expectations in 1 t FV, in [1,12] keV$_{ee}$, single scatters, **before ER/NR discrimination**

DETECTOR RESPONSE MODEL

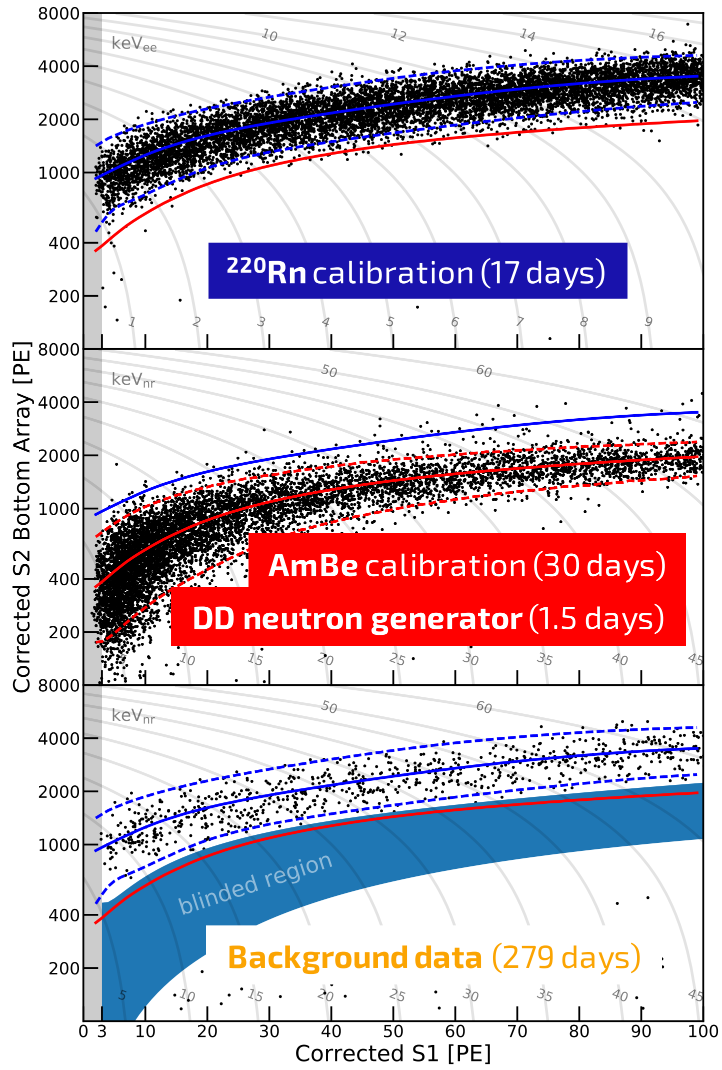
ER AND NR CALIBRATIONS



ER



NR



- **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

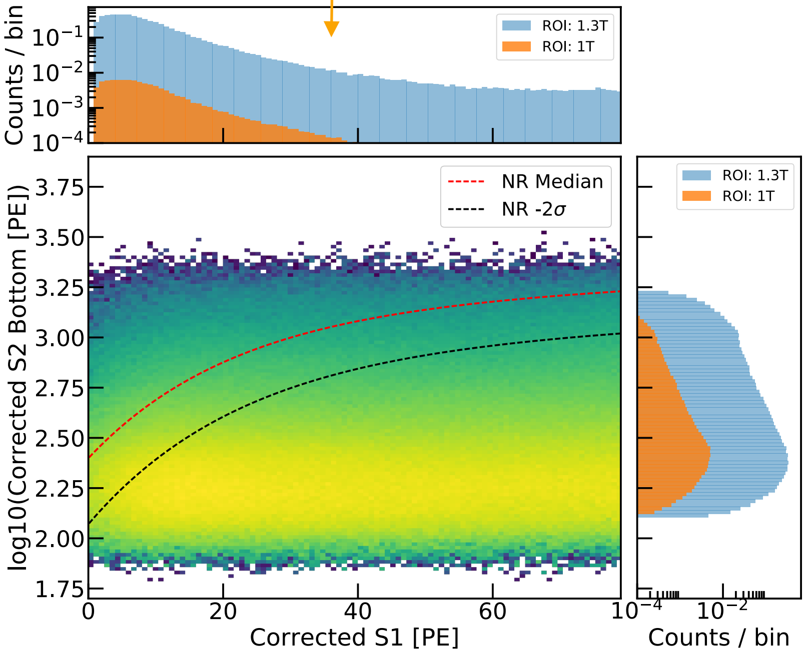
SURFACE BACKGROUND

- **Radioactivity on PTFE surface and charge loss**

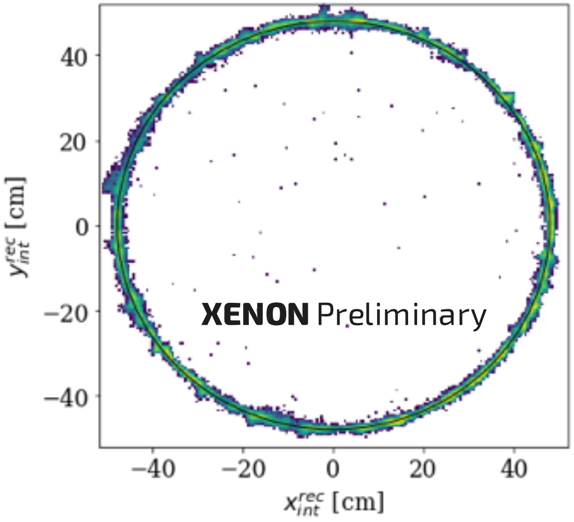
Events can fall in the NR energy region due to abnormally small S2. And due to position reconstruction resolution they can be reconstructed inwards.
Reduced by volume fiducialization.

- **Data driven model**

Derived from event surface control samples.

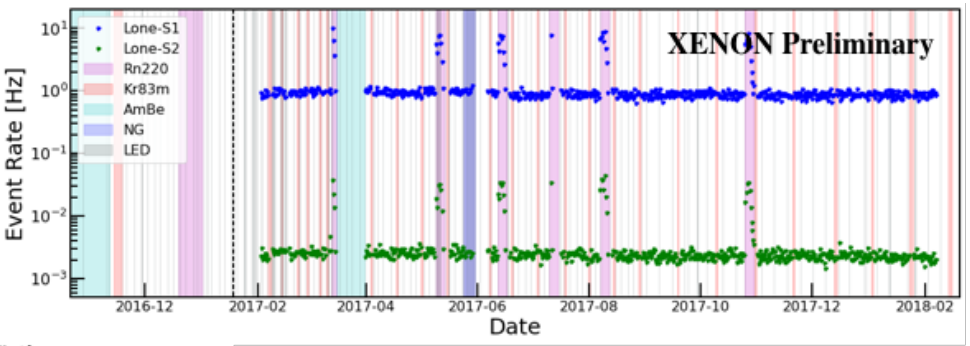


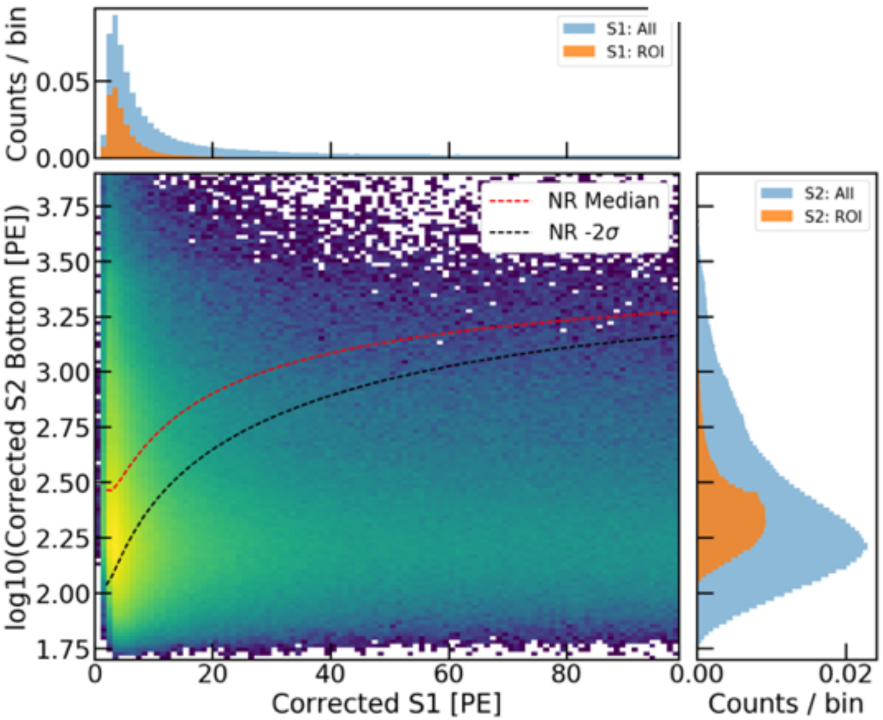
^{210}**Po** control sample



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



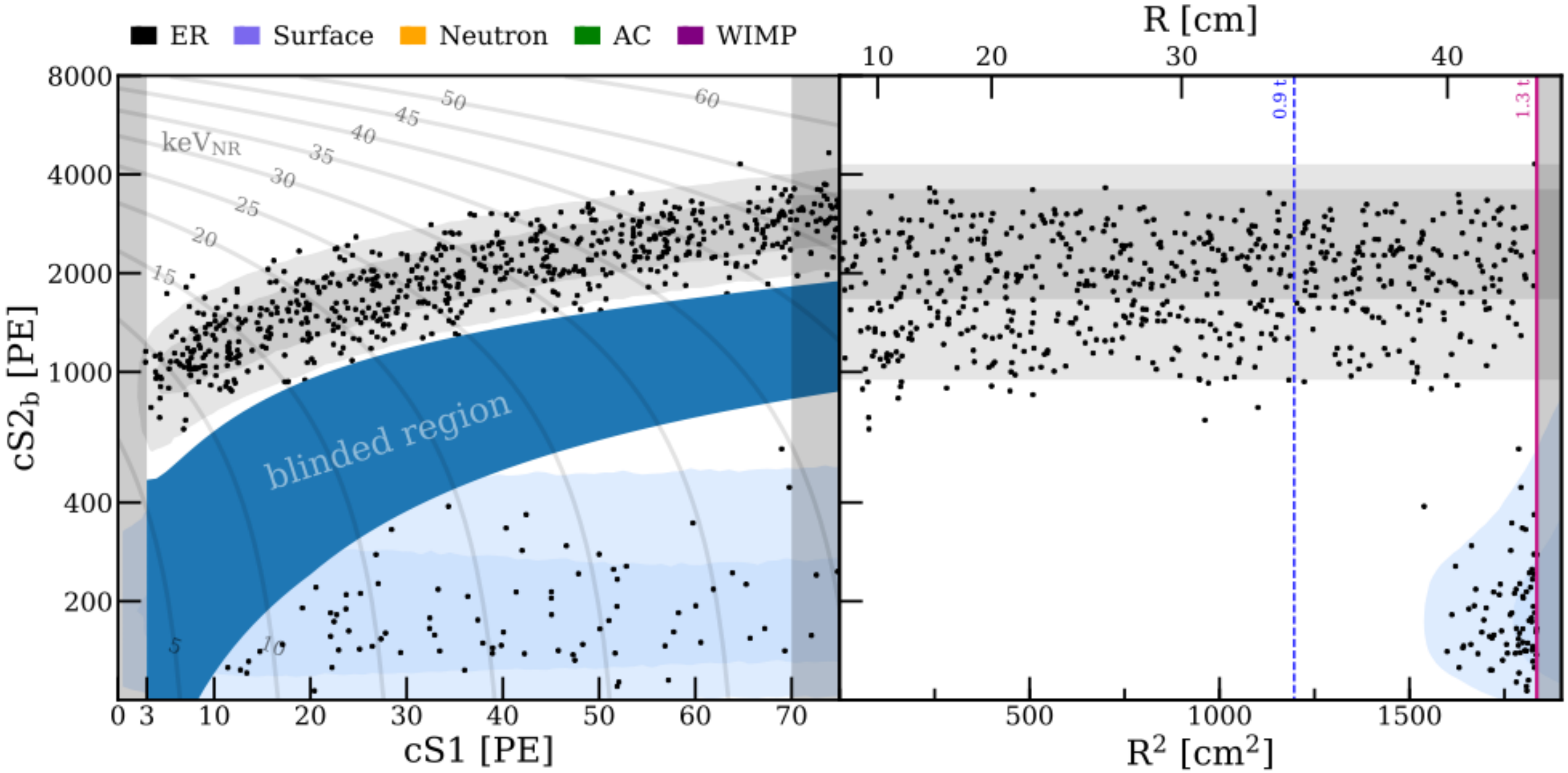


Empirical model shows an overall small rate in the ROI for NRs

- 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

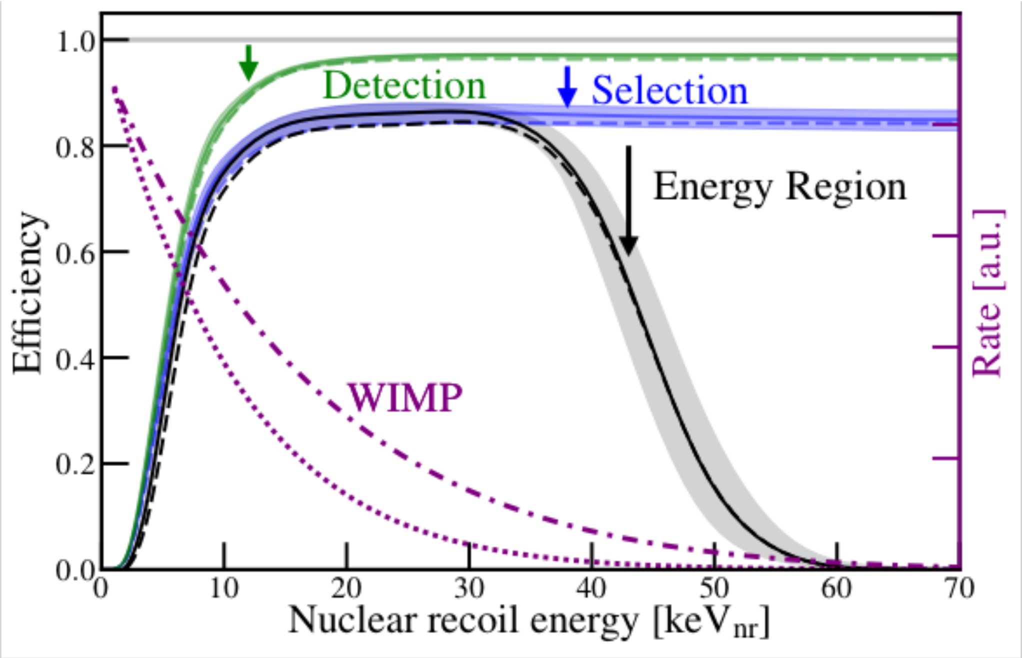
WIMP SEARCH
BLINDING AND SALTING

- 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
$WIMP_{\text{best-fit}}$	3.56	1.70	1.16	0.83
Data	739	14	2	2

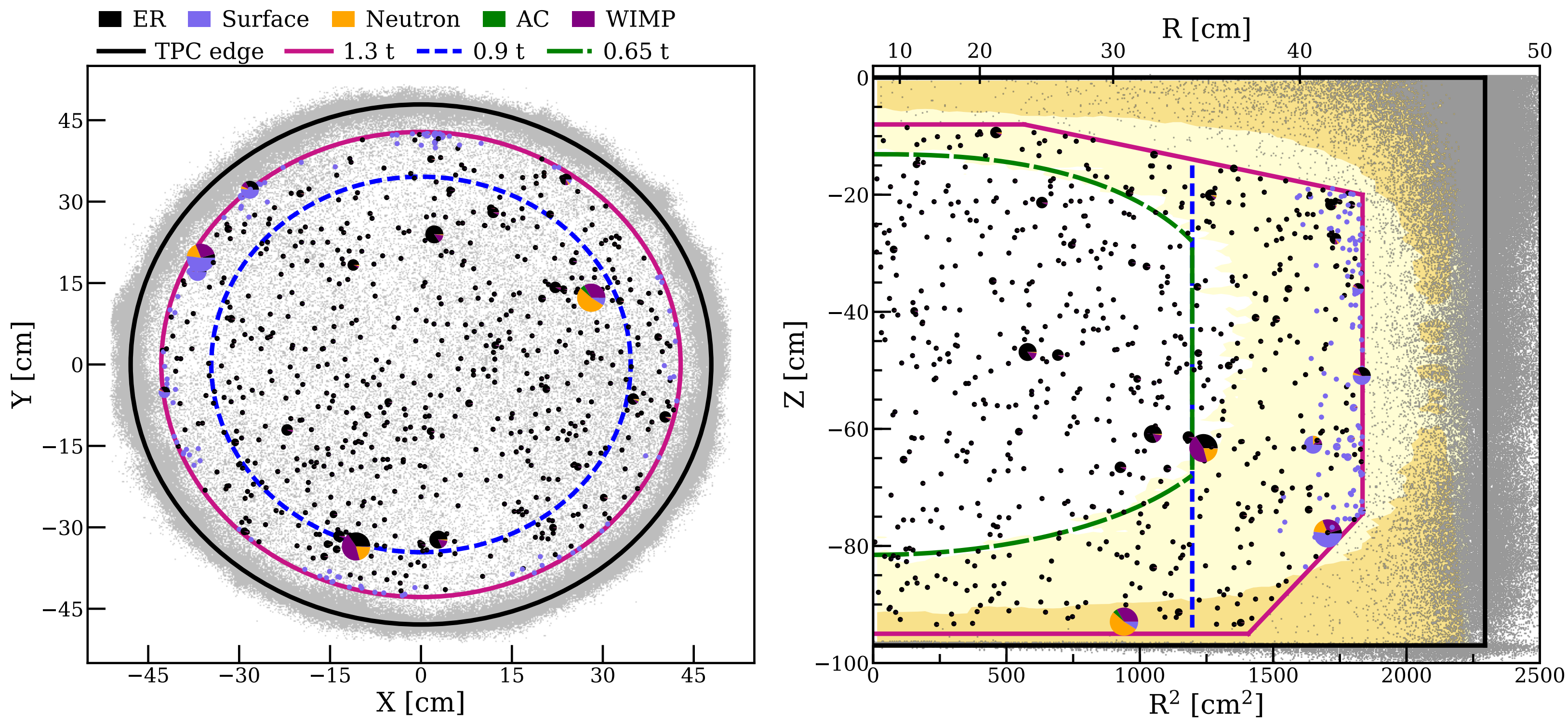
WIMP expectation under best-fit model at m=200 GeV (cross-section = 4.7×10^{-47} cm^2)

RESULTS

SPATIAL DISTRIBUTION

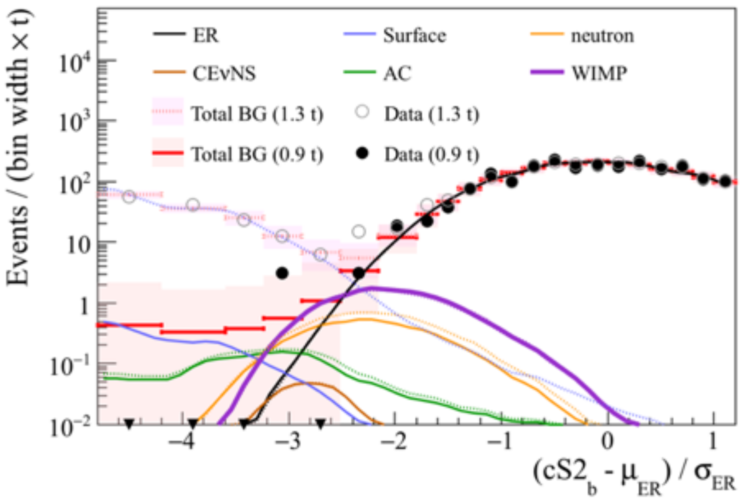
- **Core volume**

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

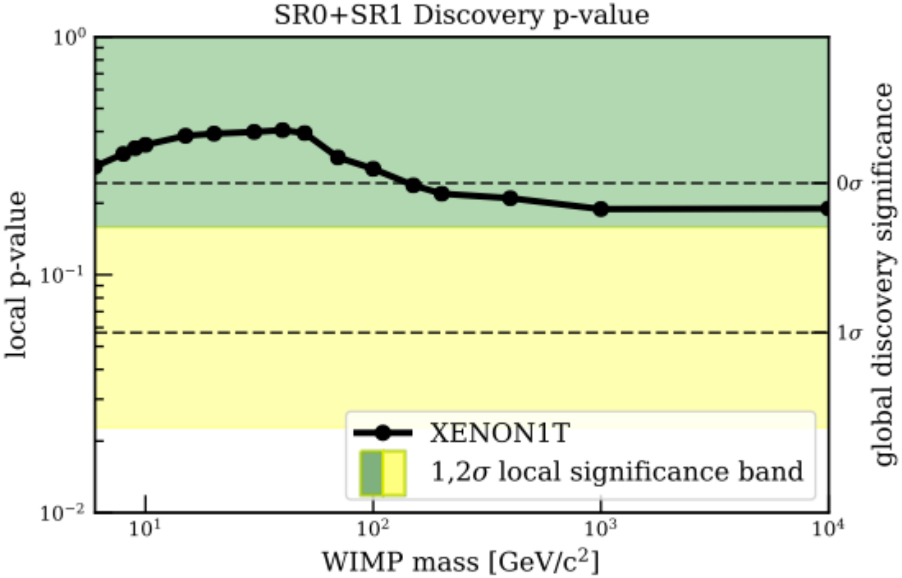


STATISTICAL INTERPRETATION

< 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