

# nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE



## CAUGHT IN THE ACT

Dark-matter detector captures exotic nuclear decay in xenon [PAGES](#)

NATURE.COM

25 April 2019 £10  
Vol. 568, No. 7753



## Observation of two-neutrino double electron capture in $^{124}\text{Xe}$ with XENON1T



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Università di Bologna  
INFN Bologna  
XENON Dark Matter Project

# THE RAREST DECAY EVER OBSERVED



31 May 2019

Pietro Di Gangi | Aperitivo Scientifico Bologna

2

INTERACTIONS.ORG  
PARTICLE PHYSICS NEWS AND RESOURCES

A communication resource from the world's particle physics laboratories.

## XENON1T Scientists Observe the Rarest Decay Process Ever Measured in the Universe

24 April 2019 - Laboratori Nazionali del Gran Sasso - INFN

Forbes

Billionaires Innovation Leadership Money Consumer Industry Lifestyle

12,022 views | Apr 24, 2019, 01:00pm

## Dark Matter Search Discovers A Spectacular Bonus: The Longest-Lived Unstable Element Ever

sky | Esplora Sky TG24, Sky Sport, Sky Video

sky tg24

HOME VIDEO CRONACA ED LOCALI POLITICA ELEZIONI ECONOMIA MONDO

TRIBÙ - EUROPA 19 ELEZIONI: IL QUIZ

FISICA-MATEMATICA

Misurato in Italia uno dei processi più rari del cosmo

CANALI ANSA > Ambiente ANSA Viaggieri Legalità

ANSAS&T > Fisica&Matematica

News Multimedie RAGAZZI

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ANSAS.it • Scienza&Tecnica • Fisica&Matematica • Misurato sotto il Gran Sasso il processo più raro dell'universo

## Misurato sotto il Gran Sasso il processo più raro dell'universo

Aiuterà a capire la natura dei neutrini

≡ MENU | CERCA

la Repubblica

R+ | Rep: | ABONATI | ACCEDI

HOME POLITICA ECONOMIA SPORT SPETTACOLI TECNOLOGIA MOTORI TUTTE LE SEZIONI D REP TV

f t in e

## Misurato sotto il Gran Sasso il processo più raro di sempre



WIRED.it

HOT TOPIC WIRED NEXT FEST 2019

HOME SCIENZA LAB

## Al Gran Sasso hanno osservato uno degli eventi più rari dell'Universo

DISCOVER VIDEO PODCAST NEWSLETTERS

**BIG THINK**

## Scientists see 'rarest event ever recorded' in search for dark matter

The team caught a glimpse of a process that takes 18,000,000,000,000,000,000 years.

STEPHEN JOHNSON 24 April, 2019

**NEW ATLAS**

LIFESTYLE

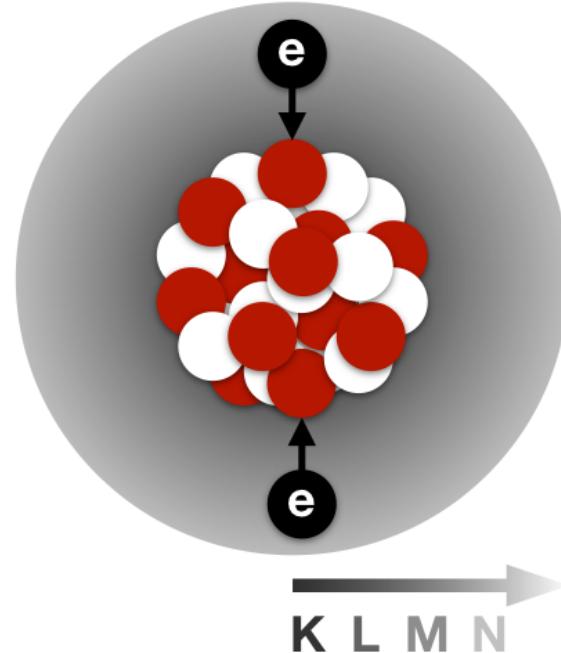
PHYSICS

## Dark matter detector reveals material with longest half-life ever – 18 sextillion years

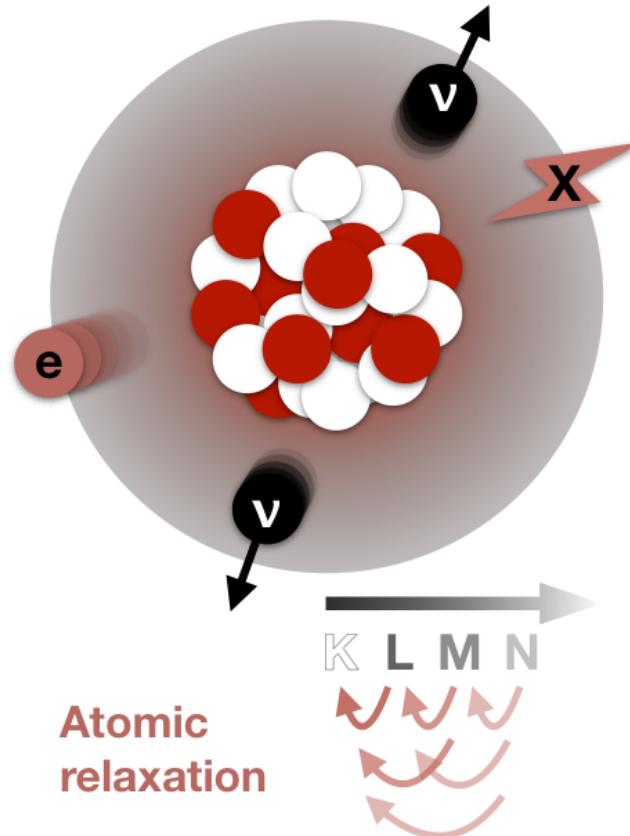
# THE RAREST DECAY EVER OBSERVED

## Double Electron Capture ( $2\nu$ ECEC)

Electron capture



Neutrino emission



# THE RAREST DECAY EVER OBSERVED

## Double Electron Capture ( $2\nu\text{ECEC}$ )

” Binding energy released:  $\sim 1 \text{ MeV}$  carried away mostly by neutrinos

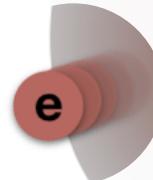
Electron capture



Neutrino emission

### DETECTABLE SIGNAL

AUGER  
ELECTRONS



X-RAYS



Atomic  
relaxation

” Experimental signature:  $\alpha(\text{keV})$   
cascade of X-rays and Auger electrons

# THE RAREST DECAY EVER OBSERVED

## Previous $2\nu$ ECEC experimental indications

” Quoted half-lives of the order of  $10^{20} - 10^{22}$  years

### DIRECT MEASUREMENTS for ${}^{78}\text{Kr}$

PHYSICAL REVIEW C 87, 035501 (2013)

#### Indications of $2\nu K$ capture in ${}^{78}\text{Kr}$

Yu. M. Gavriluk, A. M. Gangapshev, V. V. Kazalov, and V. V. Kuzminov  
*Baksan Neutrino Observatory INR RAS, Russia*

S. I. Panasenko and S. S. Ratkevich\*  
*V. N. Karazin Kharkiv National University, Kharkiv, Ukraine*  
(Received 6 August 2012; published 4 March 2013)

#### Comparative study of the double $K$ -shell-vacancy production in single- and double-electron capture decay

S.S. Ratkevich,<sup>1,2,\*</sup> A.M. Gangapshev,<sup>1</sup> Yu.M. Gavriluk,<sup>1</sup> F.F. Karpeshin,<sup>3</sup> V.V. Kazalov,<sup>1</sup> V.V. Kuzminov,<sup>1</sup> S.I. Panasenko,<sup>1,2</sup> M.B. Trzhaskovskaya,<sup>4</sup> and S.P. Yakimenko<sup>1</sup>  
<sup>1</sup>*Baksan Neutrino Observatory INR RAS, Neutrino 361609, Russia*  
<sup>2</sup>*V.N. Karazin Kharkiv National University, Kharkiv 61022, Ukraine*  
<sup>3</sup>*D.I. Mendeleev Institute for Metrology, Saint-Petersburg 190005, Russia*  
<sup>4</sup>*Petersburg Nuclear Physics Institute, NRC “Kurchatov Institute”, Gatchina 188300, Russia*  
(Dated: September 7, 2017)

### GEOCHEMICAL STUDIES for ${}^{130}\text{Ba}$

PHYSICAL REVIEW C, VOLUME 64, 035205

#### Weak decay of ${}^{130}\text{Ba}$ and ${}^{132}\text{Ba}$ : Geochemical measurements

A. P. Meshik,<sup>1</sup> C. M. Hohenberg,<sup>1</sup> O. V. Pravdiktseva,<sup>1</sup> and Ya. S. Kapusta<sup>2</sup>  
<sup>1</sup>*Physics Department, Washington University, St. Louis, Missouri 63130*  
<sup>2</sup>*Activation Laboratories, Ancaster, Ontario, Canada L9G 4V5*  
(Received 18 April 2001; published 22 August 2001)

#### Xenon in Archean barite: Weak decay of ${}^{130}\text{Ba}$ , mass-dependent isotopic fractionation and implication for barite formation

Magali Pujol<sup>a,b,\*</sup>, Bernard Marty<sup>a</sup>, Pete Burnard<sup>a</sup>, Pascal Philippot<sup>b</sup>

<sup>a</sup>*CRPG-CNRS, Nancy-Université, 15 rue Notre Dame des Pauvres, 54501 Vandoeuvre-lès-Nancy Cedex, France*  
<sup>b</sup>*Institut de Physique du Globe de Paris, IMPMC, Université Denis Diderot, CNRS, 4 Place Jussieu 75252 Paris Cedex 5, France*

Received 20 February 2009; accepted in revised form 6 August 2009; available online 11 August 2009

# THE RAREST DECAY EVER OBSERVED

## Key ingredients for discovery



### ” Very large detector

Huge number of atoms ( $^{124}\text{Xe}$ ) present in the LXe target

### ” Very silent detector

Extremely low and well characterized background level



# THE RAREST DECAY EVER OBSERVED

## Looking for ${}^{124}\text{Xe}$ decay with XENON1T

”  $2\nu\text{EC}\bar{\text{E}}\text{C}$  for  ${}^{124}\text{Xe} \rightarrow {}^{124}\text{Te} + \nu_e + \nu_e$

Isotopic abundance of  ${}^{124}\text{Xe}$  in natural Xenon  
**1‰**

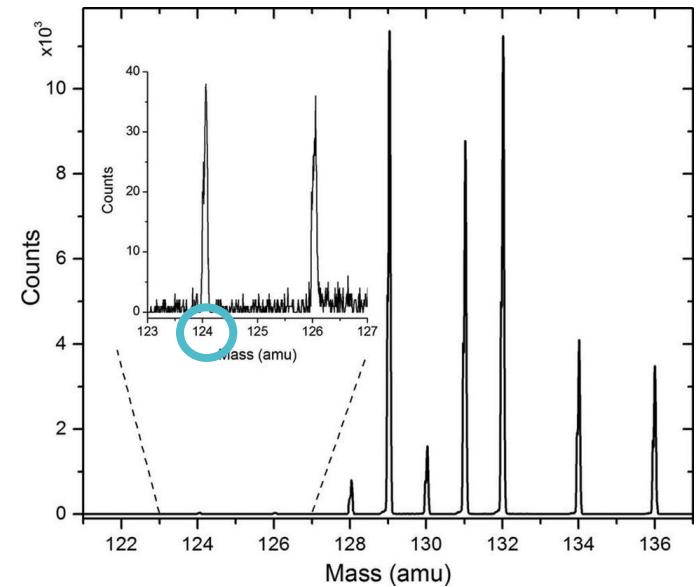
Total liquid Xenon in XENON1T  
**3.2 t**

Atoms of  ${}^{124}\text{Xe}$   
**~  $10^{25}$**

” **MEASURED HALF-LIFE  $1.8 \times 10^{22}$  years**

The longest half-life ever measured directly!  
About  $10^{12}$  times the age of the Universe ( $1.83 \times 10^9$  years)

Z. Y. ZHOU, Y. WANG, X. F. TANG, W. H. WU, AND F. QI, REV. SCI. INSTRUM. 84, 014101 (2013)



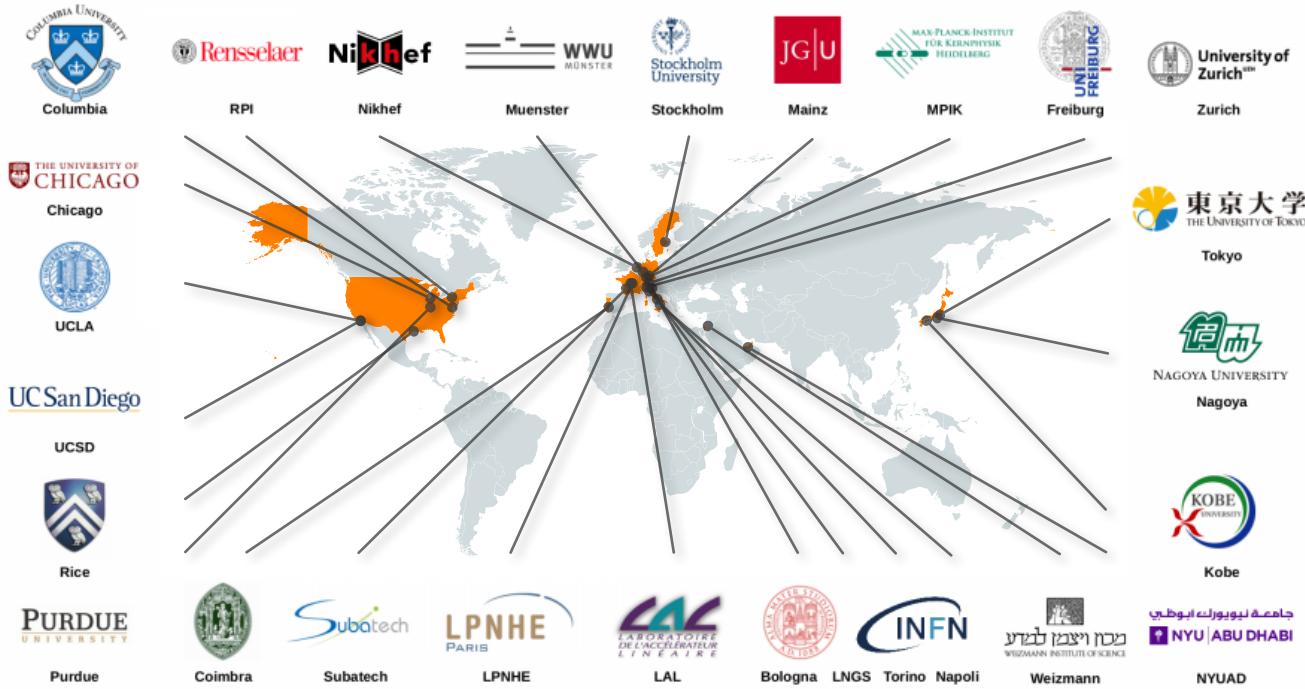
# THE XENON COLLABORATION



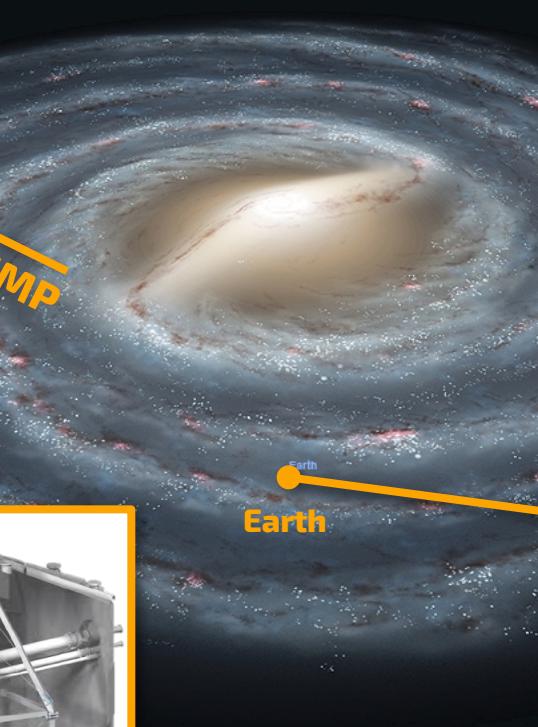
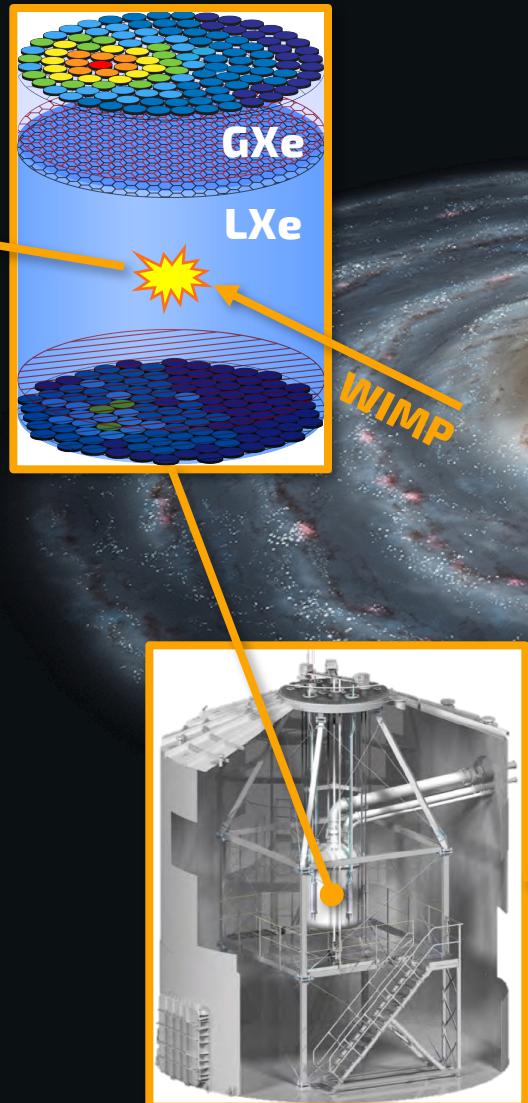
**170**  
SCIENTISTS

**27**  
INSTITUTIONS

**11**  
COUNTRIES



# DARK MATTER SEARCH WITH XENON1T



Earth

## 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 LABORATORI NAZIONALI DEL GRAN SASSO

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

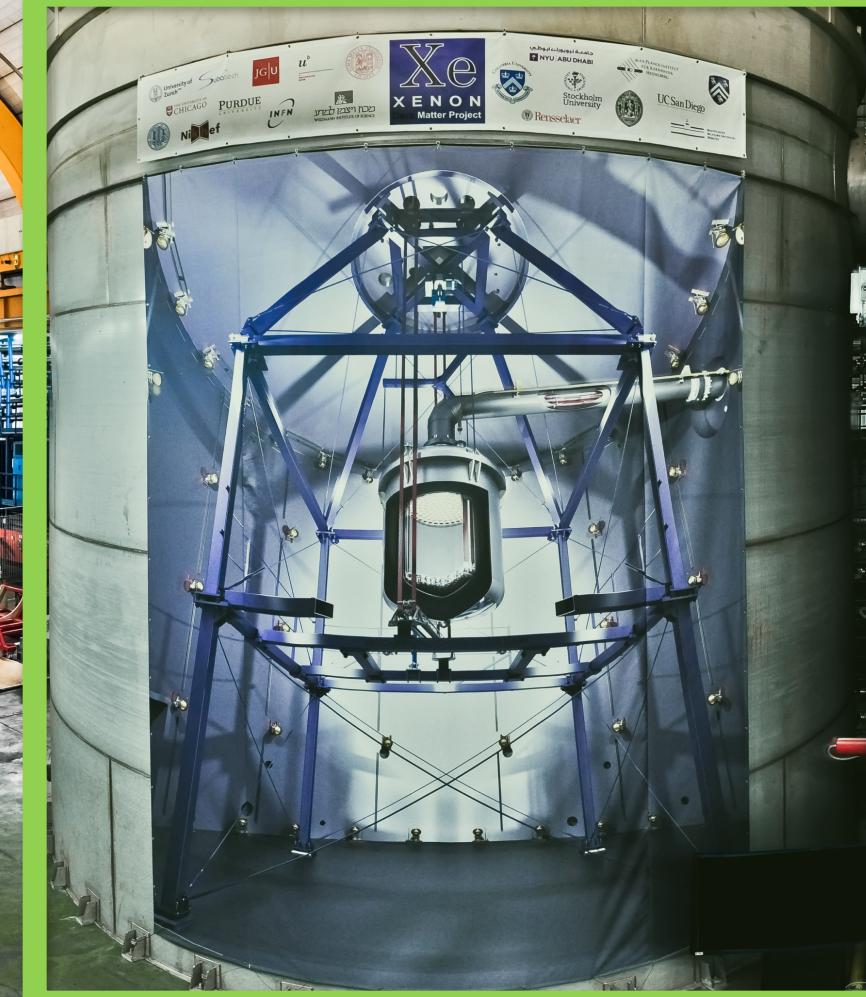


# THE XENON1T EXPERIMENT

AT LABORATORI NAZIONALI DEL GRAN SASSO

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

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



# THE XENON1T EXPERIMENT

AT LABORATORI NAZIONALI DEL GRAN SASSO

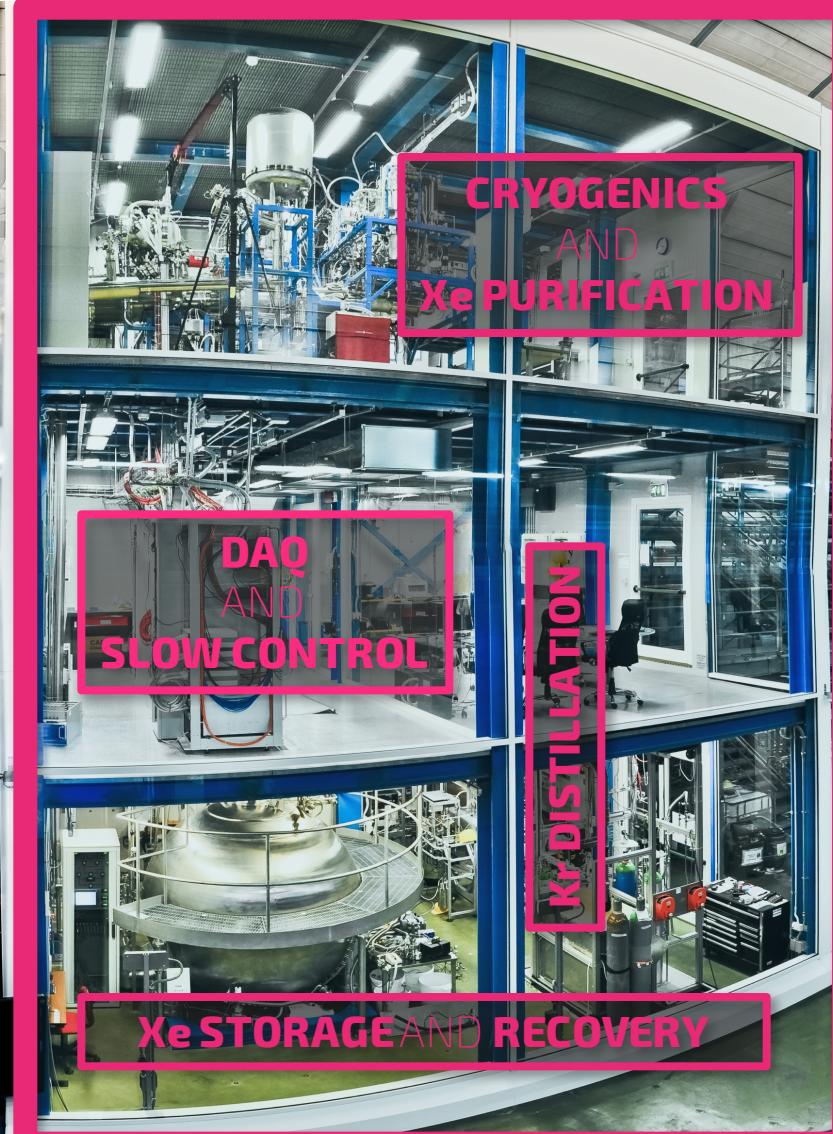
Eur. Phys. J. C. (2017) 77:881



# THE XENON1T EXPERIMENT

AT LABORATORI NAZIONALI DEL GRAN SASSO

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



# LIQUID XENON-BASED DETECTORS

## EVOLUTION OF SPECIES

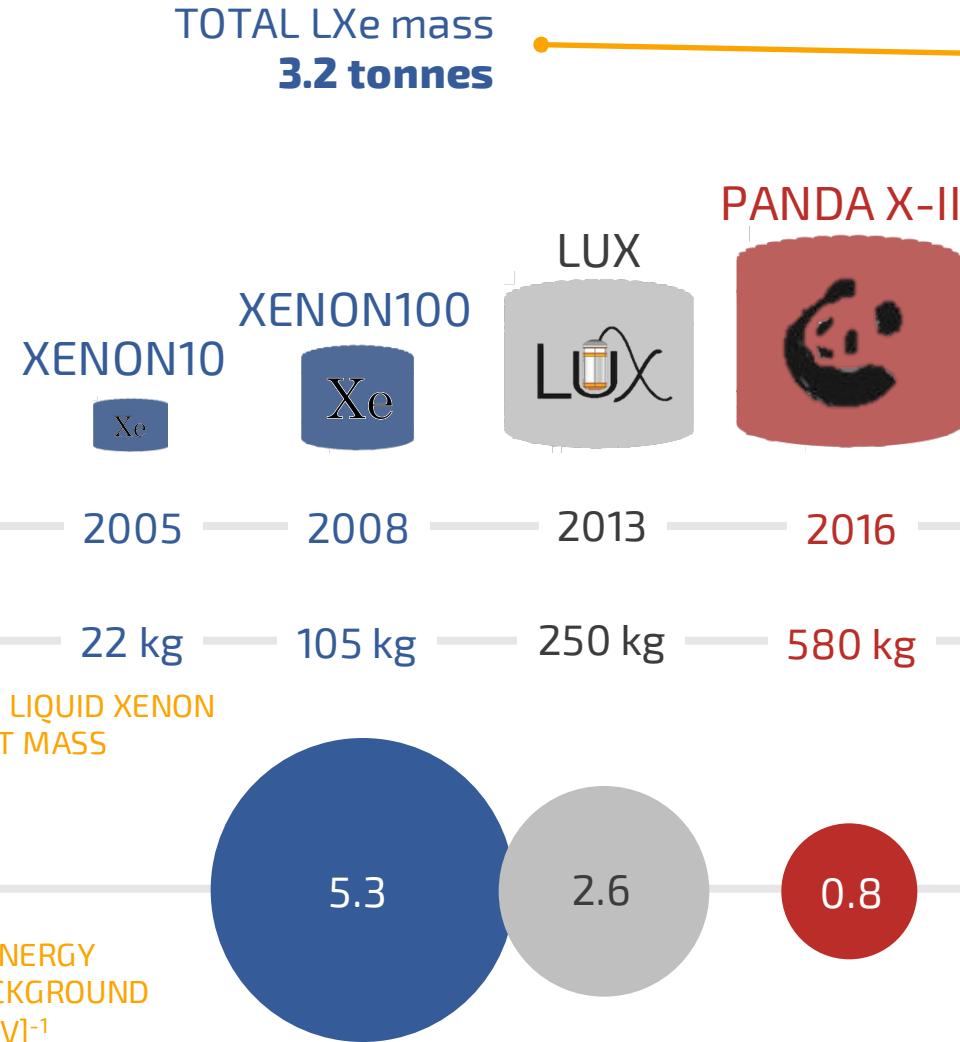


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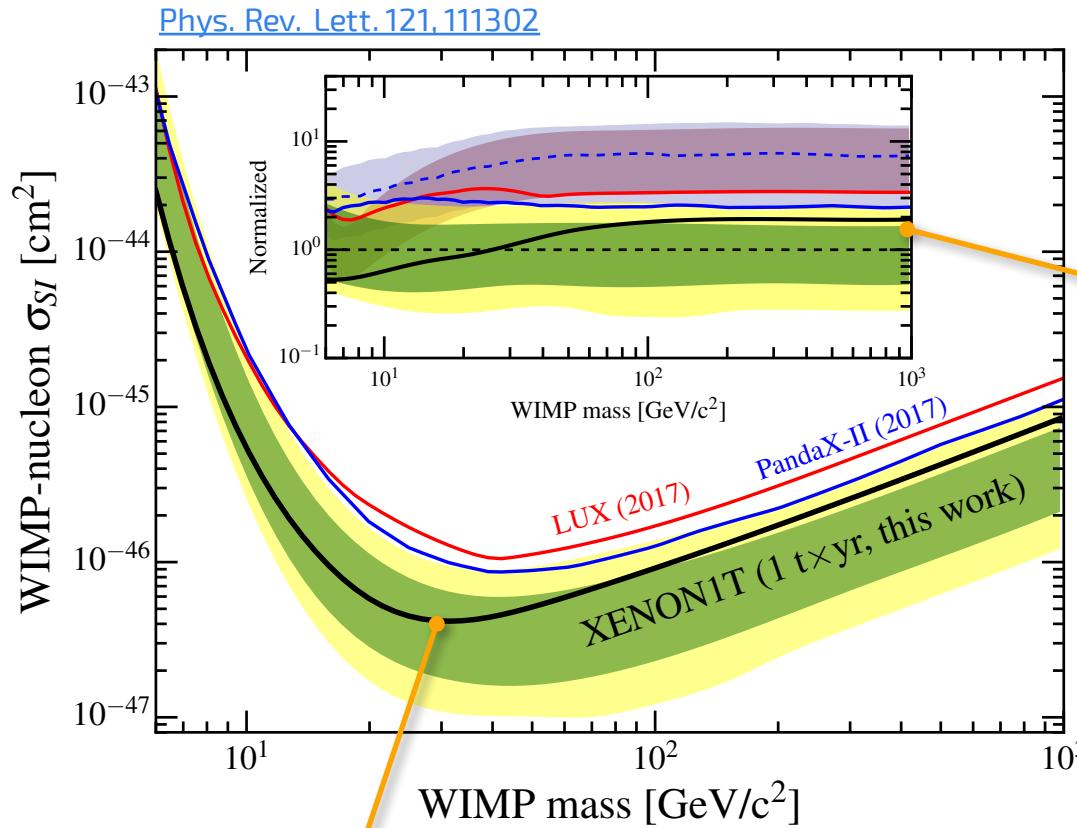
XENONnT



# LEADING THE DM DIRECT SEARCH

## “WORLD BEST CONSTRAINT ON WIMP DARK MATTER

Most stringent exclusion limits (at 90% CL) for WIMPs  $> 6 \text{ GeV}/c^2$



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

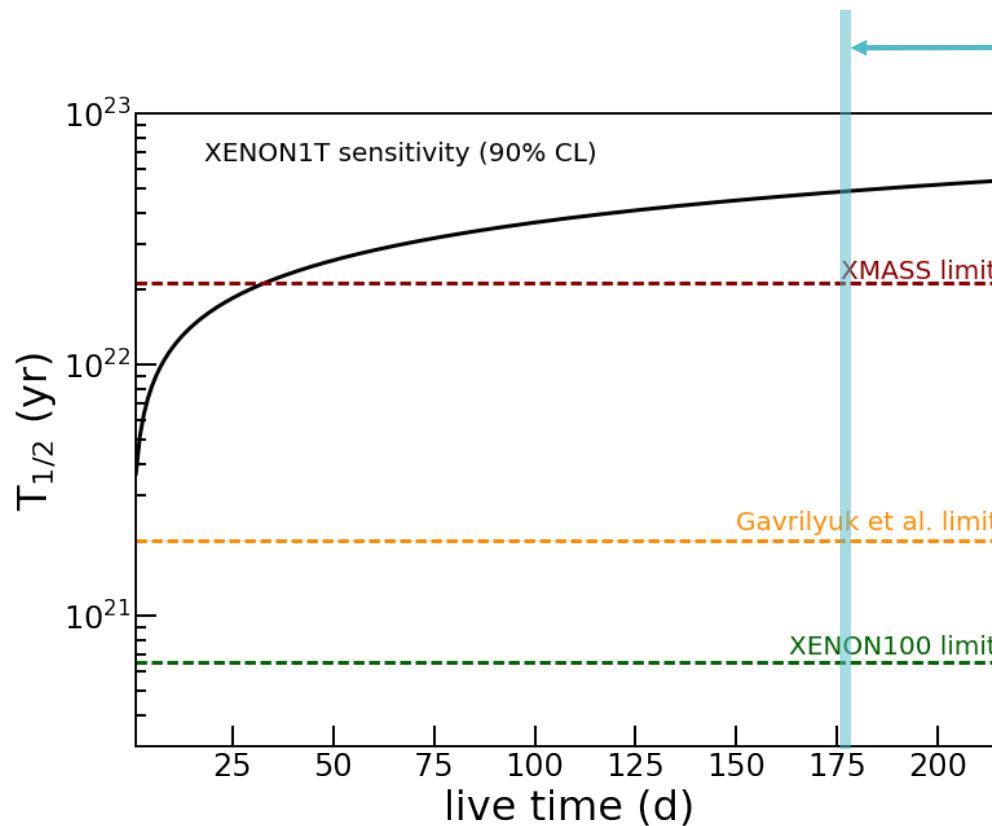
“**x7**  
**IMPROVED  
SENSITIVITY**  
with respect to  
previous  
experiments  
(LUX, PANDAX-II)

# HOW ABOUT $2\nu$ ECEC of $^{124}\text{Xe}$ ?

## XENON1T SENSITIVITY AND PREVIOUS LIMITS

### PREVIOUS SEARCHES OF $^{124}\text{Xe}$ DECAY

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



### XENON1T DATA FOR $2\nu$ ECEC SEARCH

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

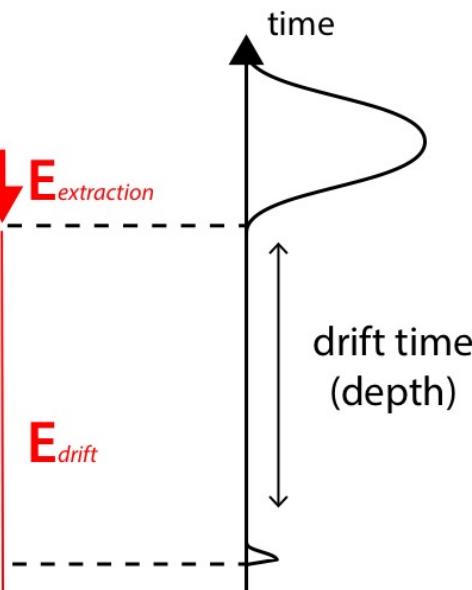
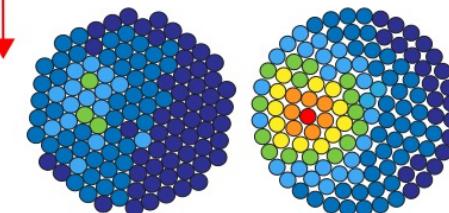
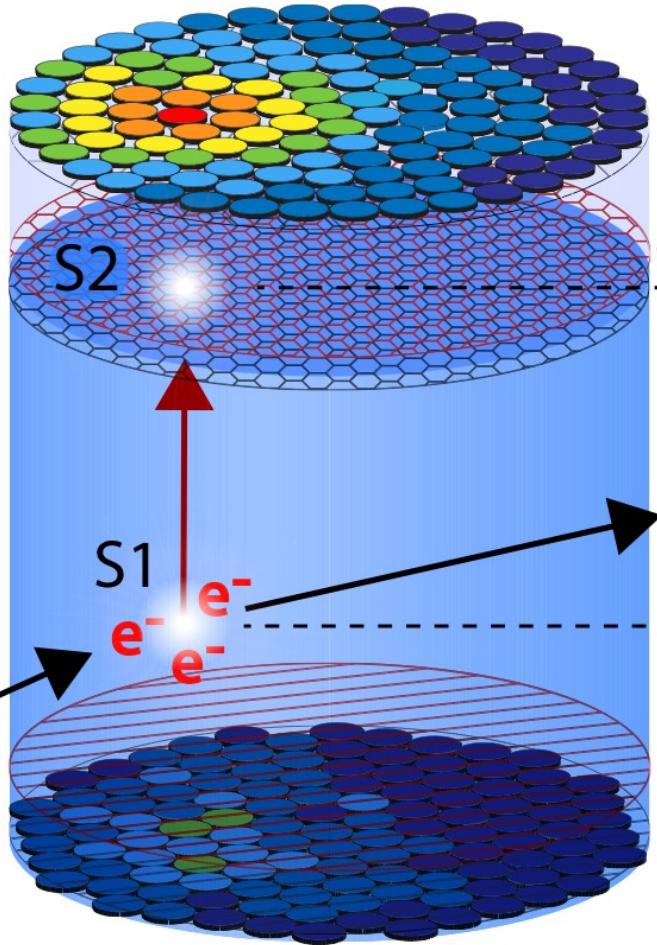
# DUAL PHASE TIME PROJECTION CHAMBER

## DETECTION PRINCIPLE

GXe

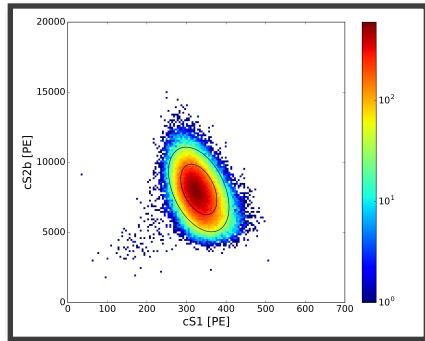
LXe

particle



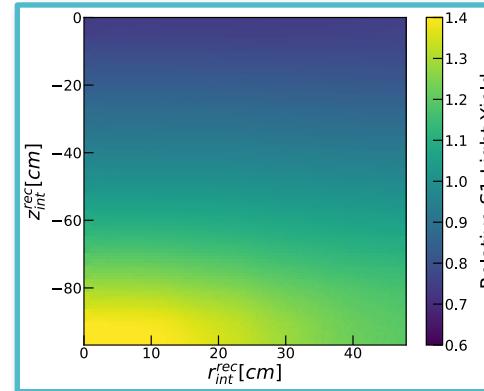
# S1 - S2 SIGNAL CORRECTIONS

## FOR SPATIAL-DEPENDENT DETECTOR EFFECTS



### 83mKr CALIBRATIONS

41.5 KeV line uniformly distributed in the TPC

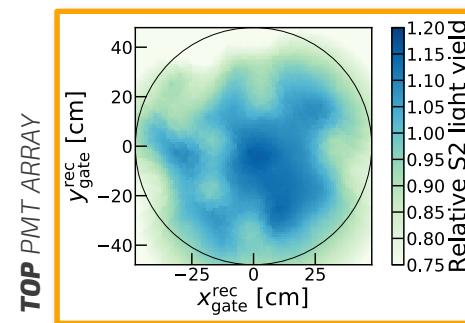
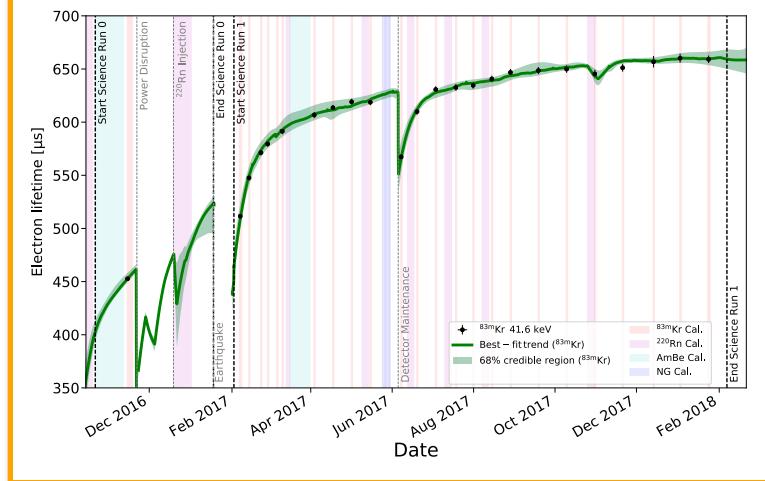


### S1 LCE

x-y-z-  
dependent  
correction

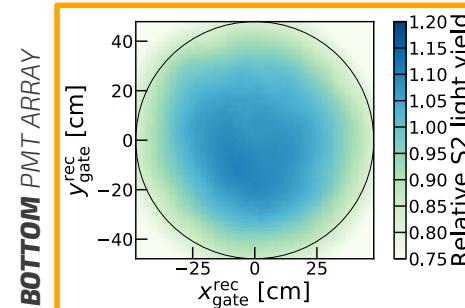
### ELECTRON LIFETIME

*z*-dependent S2 correction



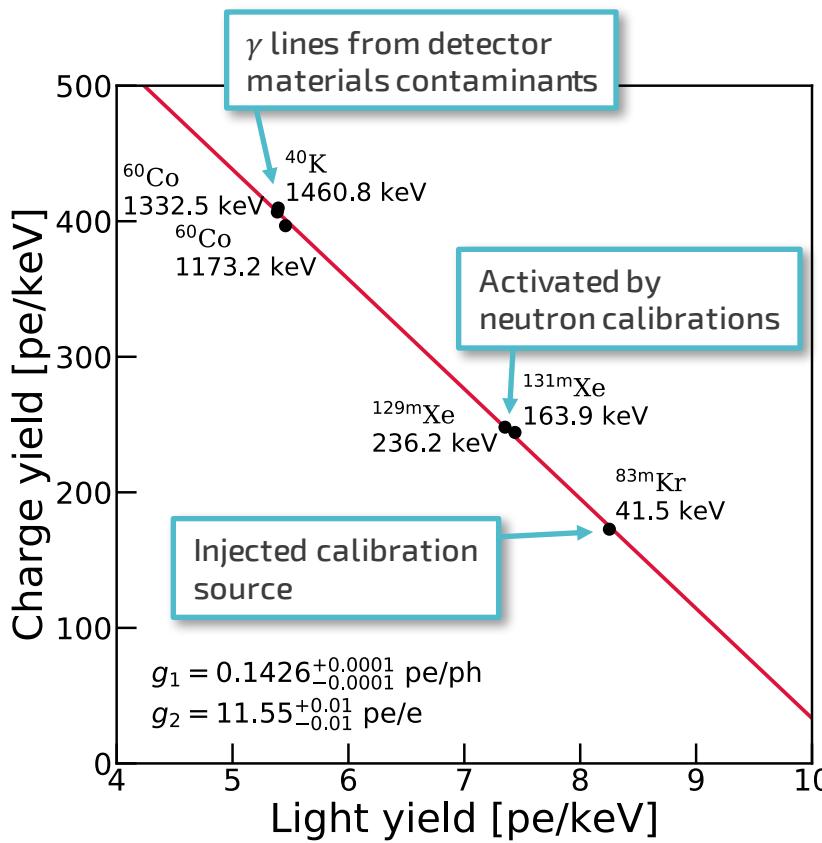
### S2 LCE

x-y-  
dependent  
correction



### BOTTOM PMT ARRAY

# XENON1T ENERGY SCALE



- “  $W = 13.7 \pm 0.2 \text{ eV}$   
Average energy to generate measurable quanta ( $\gamma, e^-$ ) in LXe
- “  $g_1 = cS1 / n_\gamma$   
Primary scintillation gain
- “  $g_2 = cS2_b / n_e$   
Secondary scintillation gain
- “ S1 and S2 signals are anti-correlated
- “  $g_1(z)$  and  $g_2(z)$  calibrated in 10 different z-slices along the TPC
- “ Excellent linearity from keV to MeV

## ENERGY RESOLUTION

Fitting Gaussian functions to mono-energetic peaks

“  $^{83m}\text{Kr}$  (41.5 keV)

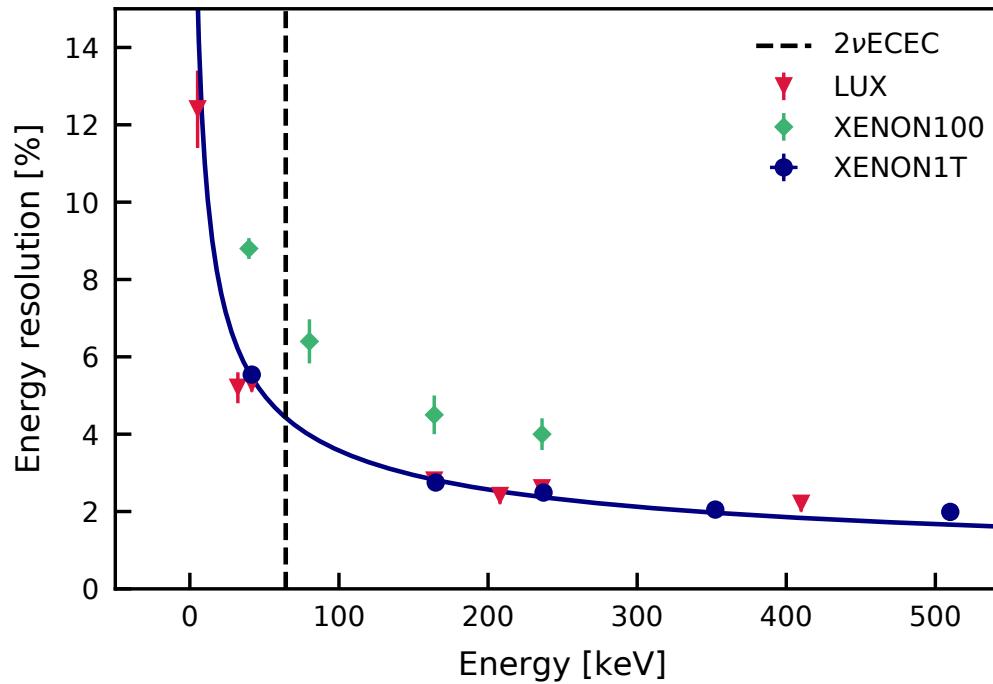
Injected calibration source

“  $^{131m}\text{Xe}$  (163.9 keV) and  $^{129m}\text{Xe}$  (236.2 keV)

Activated metastable isotopes during neutron calibrations

“  $^{214}\text{Pb}$  (351.9 keV) and  $^{208}\text{Tl}$  (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  $E_{2\nu\text{ECEC}} = 64.3$  keV  
 $(4.1 \pm 0.4) \%$

# $^{124}\text{Xe}$ $2\nu\text{ECEC}$ SIGNATURE

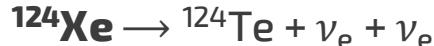
## MONO-ENERGETIC PEAK AT 64.3 keV



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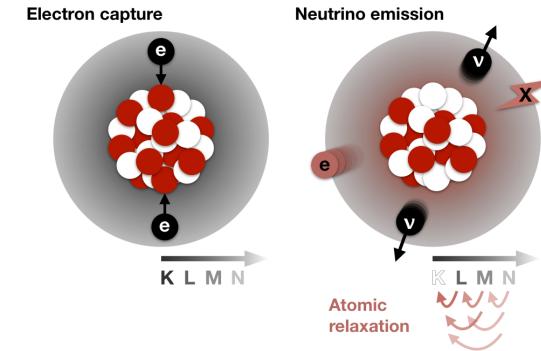
21



- ” Q-value (carried away by the two neutrinos)

**2.857 MeV**

- ” Energy released by recoiling nucleus  
(not detectable)  
 **$\alpha(10 \text{ eV})$**



- ” Total energy released by X-rays and Auger electrons for double K-shell electron capture (atomic relaxation)  
 **$(64.3 \pm 0.6) \text{ keV}$**

- ” Range of atomic X-rays and Auger electrons in LXe  
**< 1 mm** (not resolvable)

### SIGNATURE IN XENON1T

Single S1 + S2 pair

- ” Blinded energy range for the  $2\nu\text{ECEC}$  search  
**(56, 72) keV**

# BACKGROUNDS



## INTRINSIC RADIOACTIVE ISOTOPES

### ” **$^{222}\text{Rn}$ (10 $\mu\text{Bq/kg}$ )**

Most dangerous is  $\beta$ -decay of  $^{214}\text{Pb}$ . Emanated from inner surfaces in contact with Xenon.  
Extensive screening campaign and careful radiopure material selection.

### ” **$^{85}\text{Kr}$ (0.66 ppt)**

$\beta$ -emitter, Xenon contaminant.  
Reduced by a factor  $>10^3$  via cryogenic distillation.

### ” **$^{136}\text{Xe}$ (~9% of $^{\text{nat}}\text{Xe}$ )**

Double- $\beta$ -emitter.

## SOLAR NEUTRINOS

### ” Subdominant and well constrained from solar and nuclear physics. Irreducible background.

## RADIOACTIVE ISOTOPES IN DETECTOR MATERIALS

### ” **$\gamma$ -rays** from $^{238}\text{U}$ and $^{232}\text{Th}$ decay chains and from $^{60}\text{Co}$ and $^{40}\text{K}$ .

They can undergo forward Compton scattering before entering the LXe active mass and produce a flat spectrum at low energies.  
Multiple scatters in the active volume are rejected.

# BACKGROUND SPECTRUM

## DATA – MC SIMULATIONS MATCHING



- “ MC SIMULATIONS of all background components

Convolved with the measured energy resolution

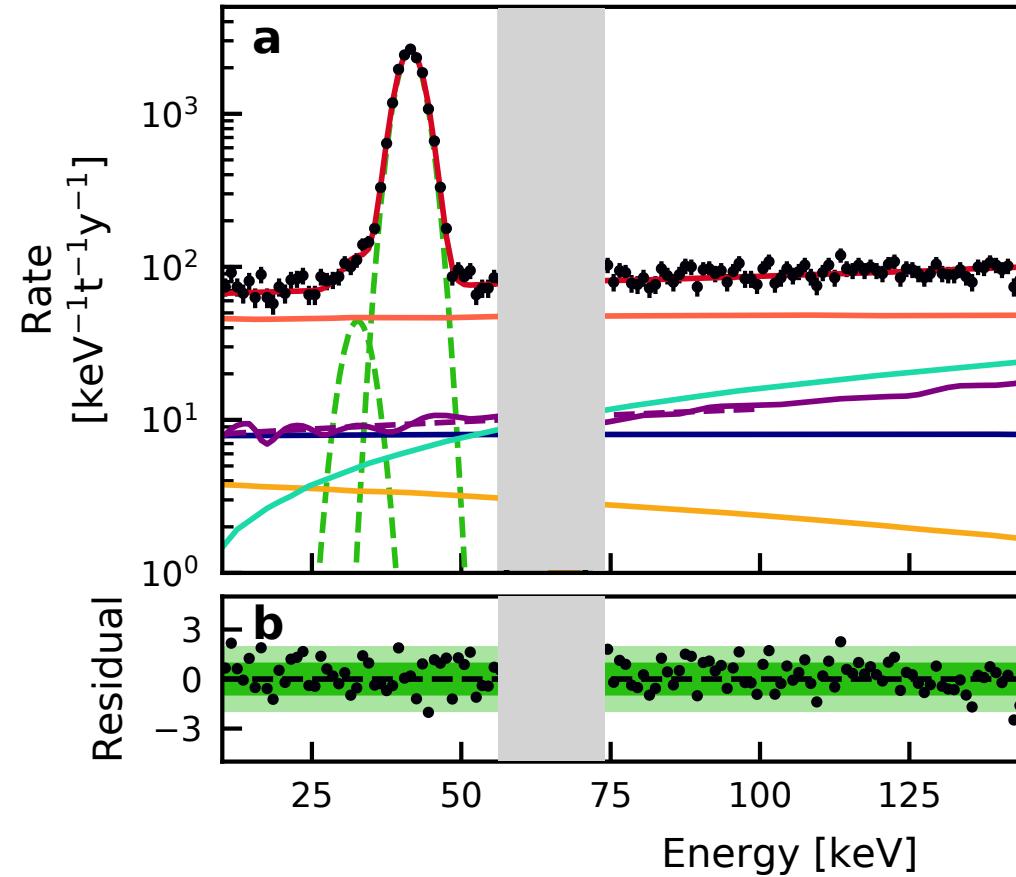
- “ BACKGROUND MODEL

Built by matching the measured energy spectrum with the MC simulations

- “ LOW ENERGY BACKGROUND RATE

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

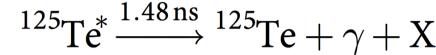
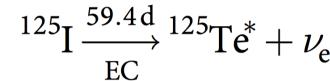
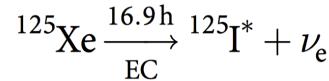
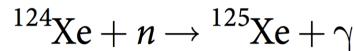
The lowest ever among DM detectors



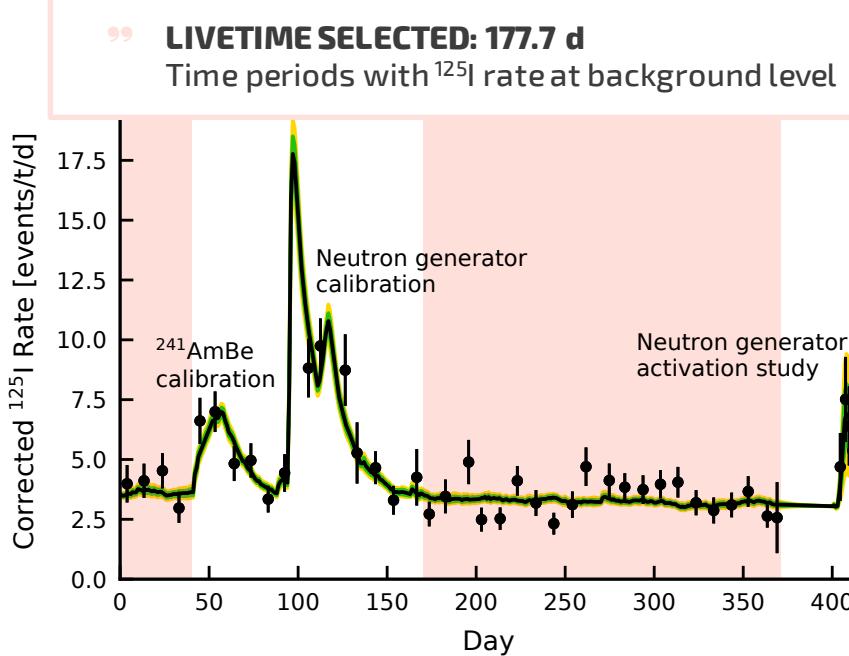
# THE $^{125}\text{I}$ BACKGROUND PEAK

## ACTIVATION AND REMOVAL MODEL

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



- $^{125}\text{I}$  DECAY:** mono-energetic peak at **67.3 keV** (very close to the  $2\nu\text{ECEC}$  peak)



“ ACTIVATION MODEL  
Based on  $^{125}\text{Xe}$  rate evolution

“  $^{125}\text{I}$  REMOVAL TIME CONSTANT  
 $(9.1 \pm 2.6)$  d  
Thanks to Xenon purification loop  
through hot Zirconium getters

“  $^{125}\text{I}$  EXPECTED EVENTS IN 177.7 d  
 $N_{^{125}\text{I}} = 10 \pm 7$

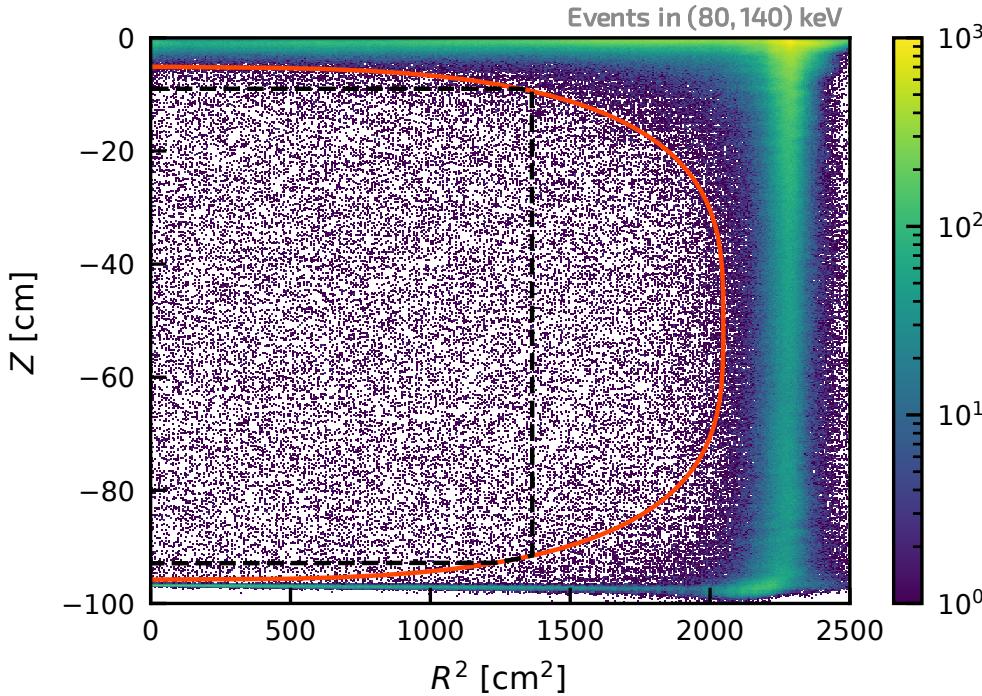


# FIDUCIAL MASS

## OPTIMIZED ON DISCOVERY SENSITIVITY

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

- ” Total fiducial volume  
**1.502 t superellipsoid**

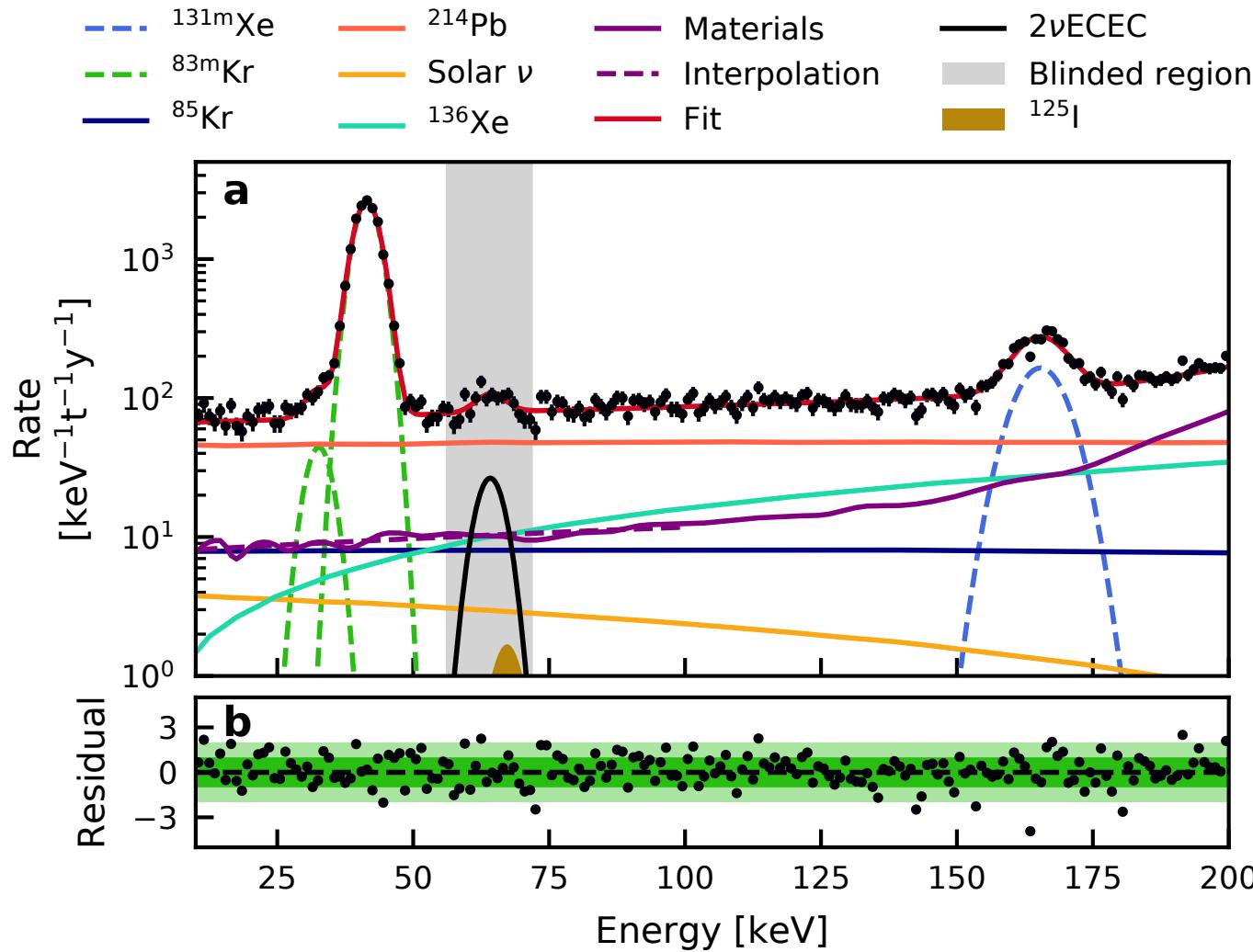


Volume segmented into  
” INNER volume (1.0 t)  
” OUTER volume (0.5 t)

Intrinsic background sources and solar neutrinos are homogeneously distributed.

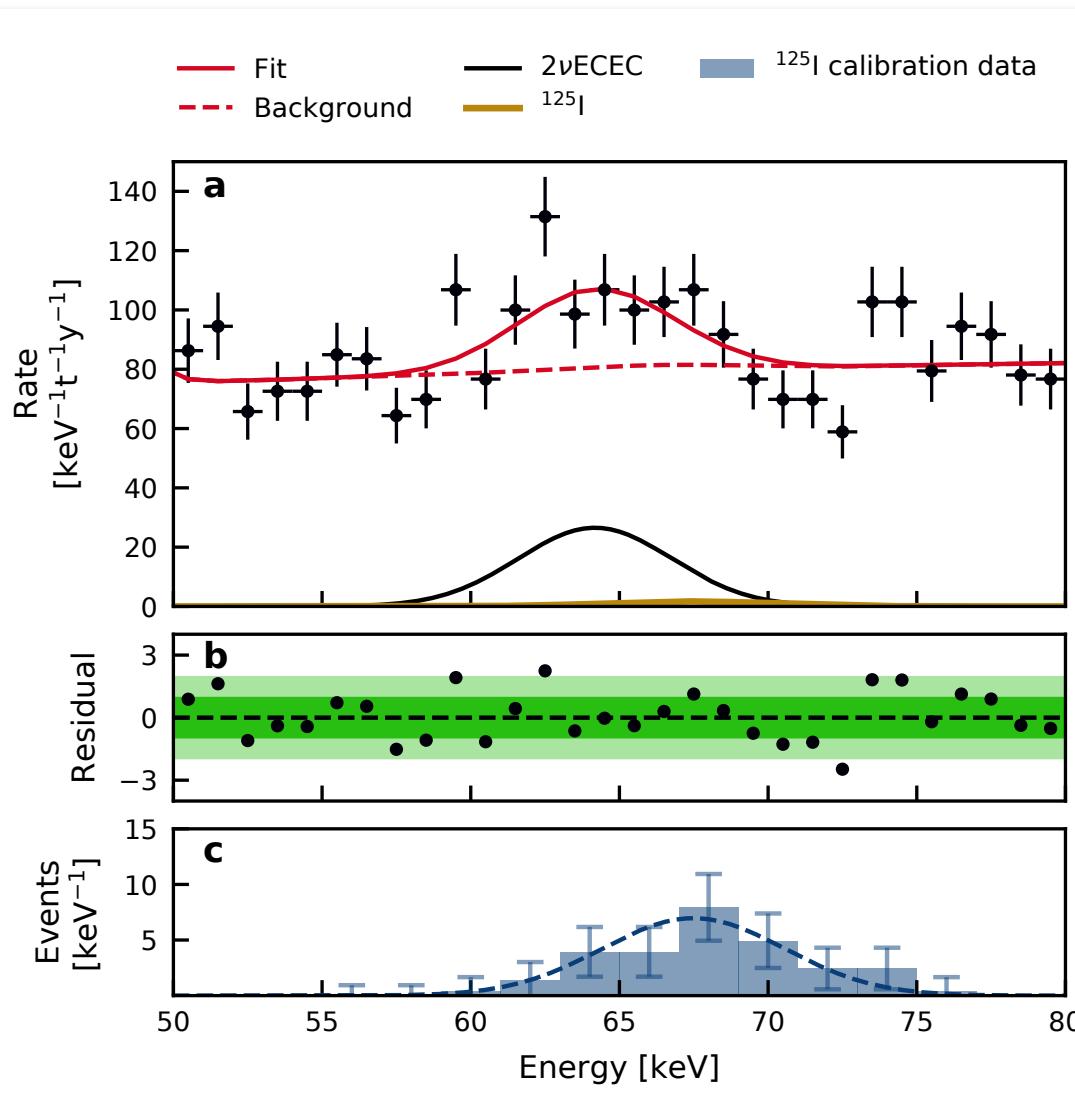
Background from materials is greatly reduced in the inner volume.

## UNBLINDING THE SIGNAL REGION



# UNBLINDING THE SIGNAL REGION

## THE $2\nu$ ECEC PEAK IS RIGHT THERE!



## FIT RESULTS

“  **$2\nu$ ECEC PEAK**  
 $\mu = (64.2 \pm 0.5) \text{ keV}$   
 $\sigma = (2.6 \pm 0.3) \text{ keV}$

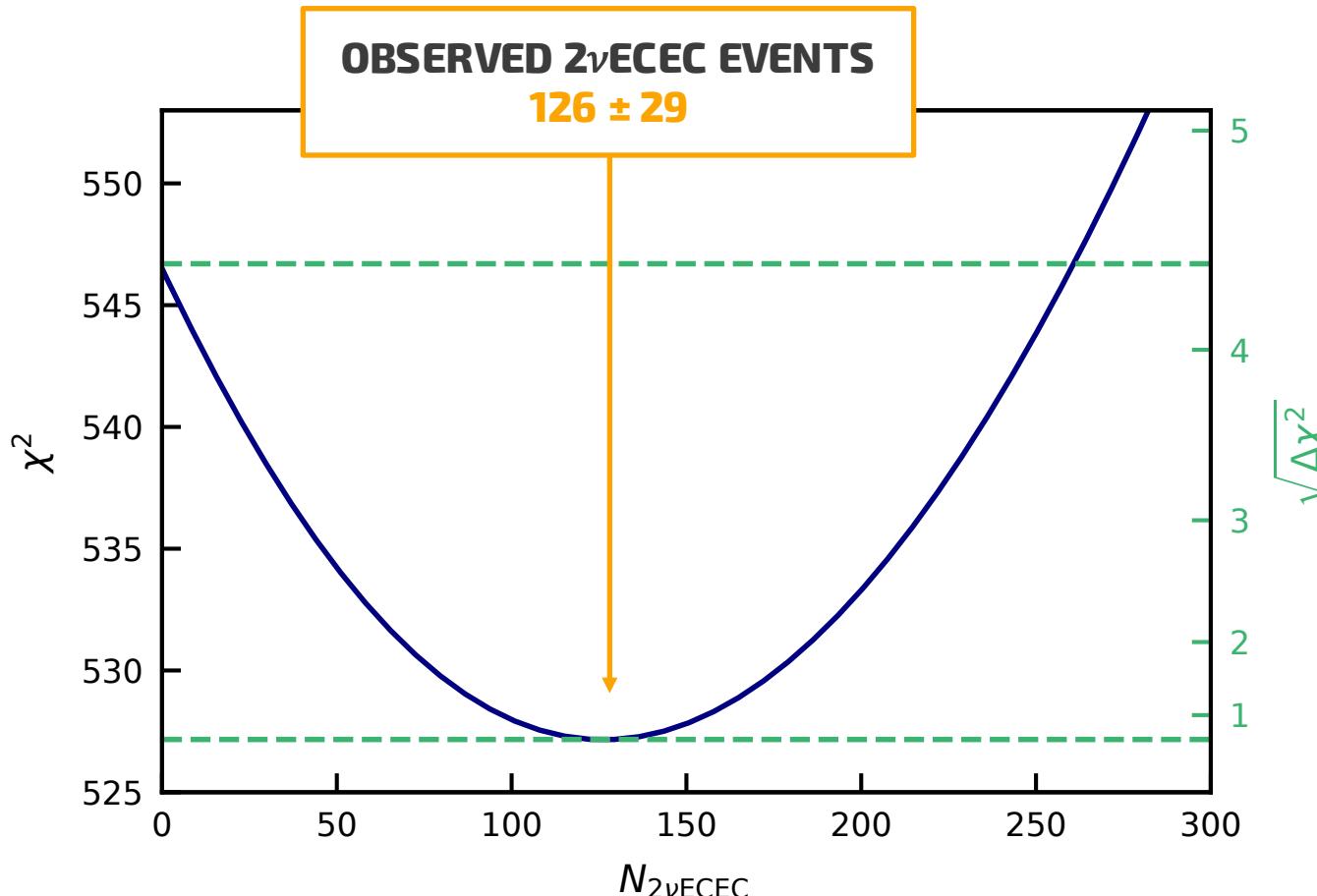
“  **$^{125}\text{I}$  EVENTS**  
 $N_{^{125}\text{I}} = 9 \pm 7$

Compatible with expectations

## DISCOVERY SIGNIFICANCE

4.4  $\sigma$ 

“ 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  $^{125}\text{I}$  peak observed at the expected position and separated from the  $2\nu\text{ECEC}$  peak by more than the energy resolution
- ✓ Systematic uncertainties on cut acceptance, fiducial mass and number of  $^{125}\text{I}$  events included as fit parameters
- ✓ Knowledge from external measurements (material screening,  $^{85}\text{Kr}$  concentrations measurements, elemental abundances) are incorporated through constraint terms
- ✓ No constrained fit parameters are pulled significantly ( $< 1\sigma$ ) away from the expected value

# 124Xe 2νECEC HALF-LIFE

## SYSTEMATIC UNCERTAINTIES AND DERIVATION



### “ 124Xe ABUNDANCE IN XENON1T

$$\eta = (9.94 \pm 0.14_{\text{stat}} \pm 0.15_{\text{sys}}) \times 10^{-4}$$

Molar isotopic abundance measured underground with a residual gas analyzer with 1.5% systematic uncertainty

### “ ACCEPTANCE

$$\varepsilon = 0.967 \pm 0.007_{\text{stat}} \pm 0.033_{\text{sys}}$$

Acceptance of data selection criteria in (55, 75) keV

### “ FIDUCIAL MASS

$$m = (1502 \pm 9_{\text{stat}}) \text{ kg}$$

Uncertainty due to finite position reconstruction resolution.

Constraining the mass fraction with:

- volume geometry, LXe density (2.862 g/cm<sup>3</sup>) and temperature (-96.1 °C)
- the fraction of <sup>83m</sup>Kr events in the fiducial volume

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

$$(1.8 \pm 0.5_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22} \text{ yr}$$

$t = 177.7 \text{ d}$  Lifet ime

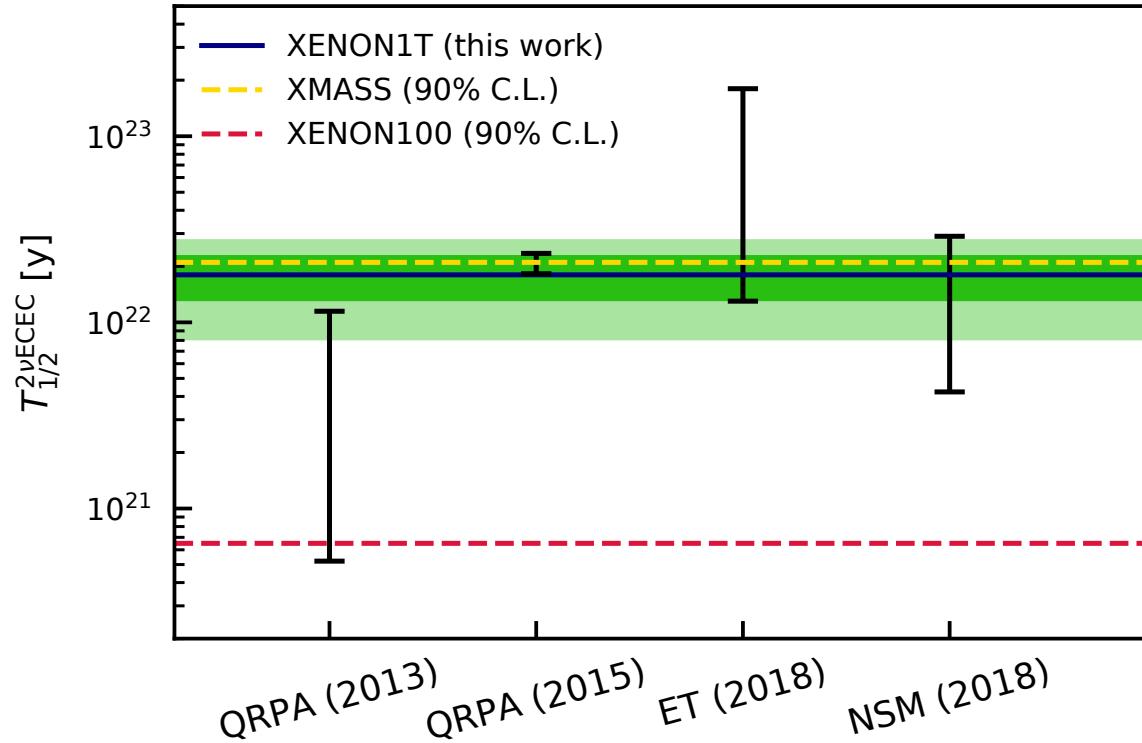
$M_{\text{Xe}} = 131.293 \text{ g/mol}$  Mean molar mass of xenon

$N_A = 6.022 \times 10^{22} \text{ mol}^{-1}$  Avogadro's number

# THEORETICAL PREDICTIONS

## FOR $2\nu$ ECEC HALF-LIFE

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



” It sets the stage for  $0\nu$ ECEC searches hunting for the Majorana neutrino

# WHAT'S NEXT: XENONnT



x4

## LXe TARGET

- Fiducial mass  $1\text{t} \rightarrow 4\text{t}$



## LARGER TPC

- $248 \rightarrow 476$  PMTs

÷10

## ER BACKGROUND

- Radon distillation
- Improved LXe purification



## NR BACKGROUND

- Neutron Veto



## FAST UPGRADE

- Installation ongoing

## DIRECT DARK MATTER SEARCHES

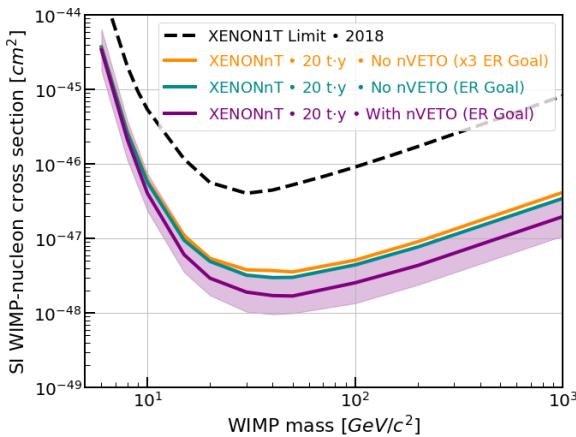
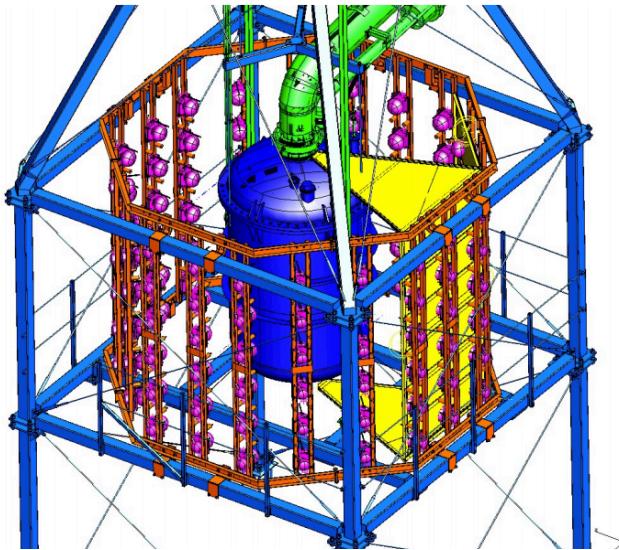
- Improve XENON1T results on WIMPs by 1 order of magnitude
- Test several DM hypotheses (ALPs, Dark Photons, Super WIMPs, ...)

## RARE PROCESS SEARCHES

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

# NEUTRON VETO

## A NEW SUB-DETECTOR FOR XENONnT



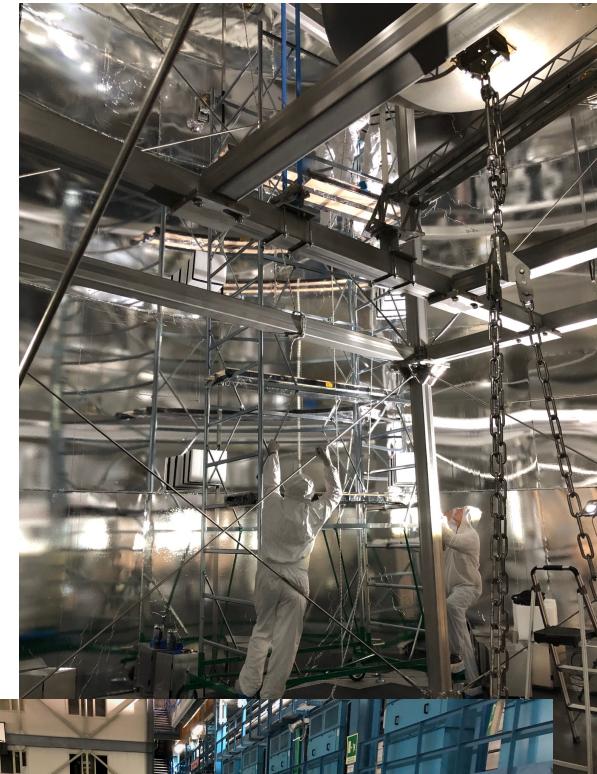
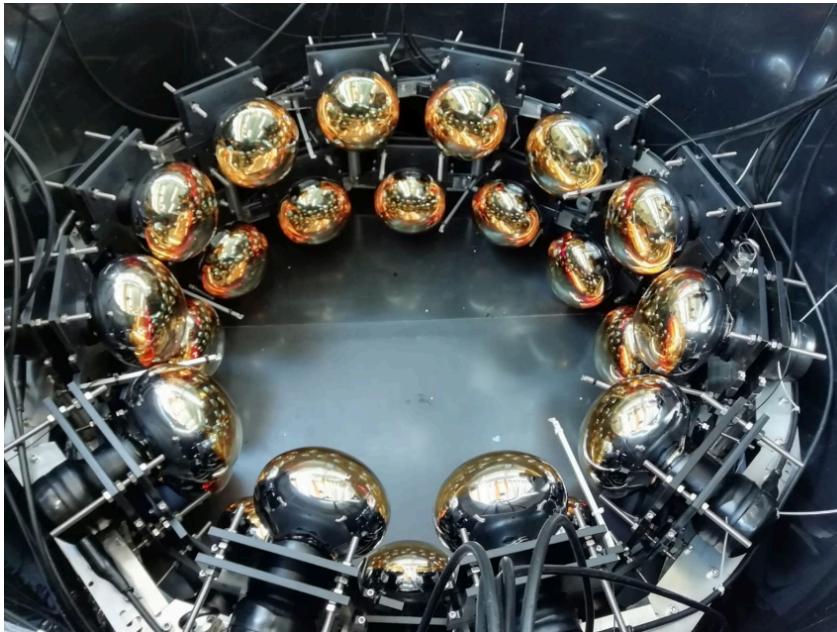
- ” Region outside the cryostat instrumented with additional 120 PMTs
- ” Doped water with 0.2% concentration of Gadolinium sulphate
- ” Optically separated from Muon Veto system by ePTFE reflector
- ” Reduction of neutron background thanks to ~85% neutron tagging efficiency
- ” Boost the sensitivity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

The Bologna Group is leading the mechanical design, simulations, development and PMT tests for the Neutron Veto system

# NEUTRON VETO

## ONGOING ACTIVITIES

- “ Design of mechanical support structure for nVeto PMTs and ePTFE reflector
- “ nVeto PMTs tests at LNGS
- “ MC simulations for design optimization and background studies





# BACKUP

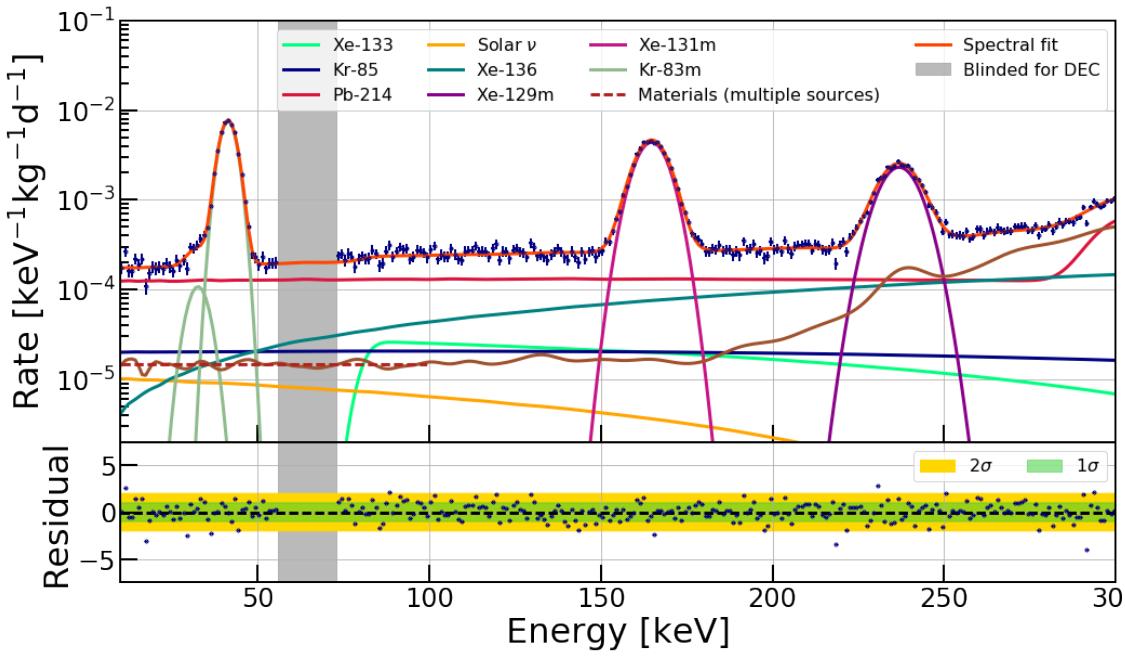
XENON

# FIT PARAMETERS

**b) Constrained fit parameter**

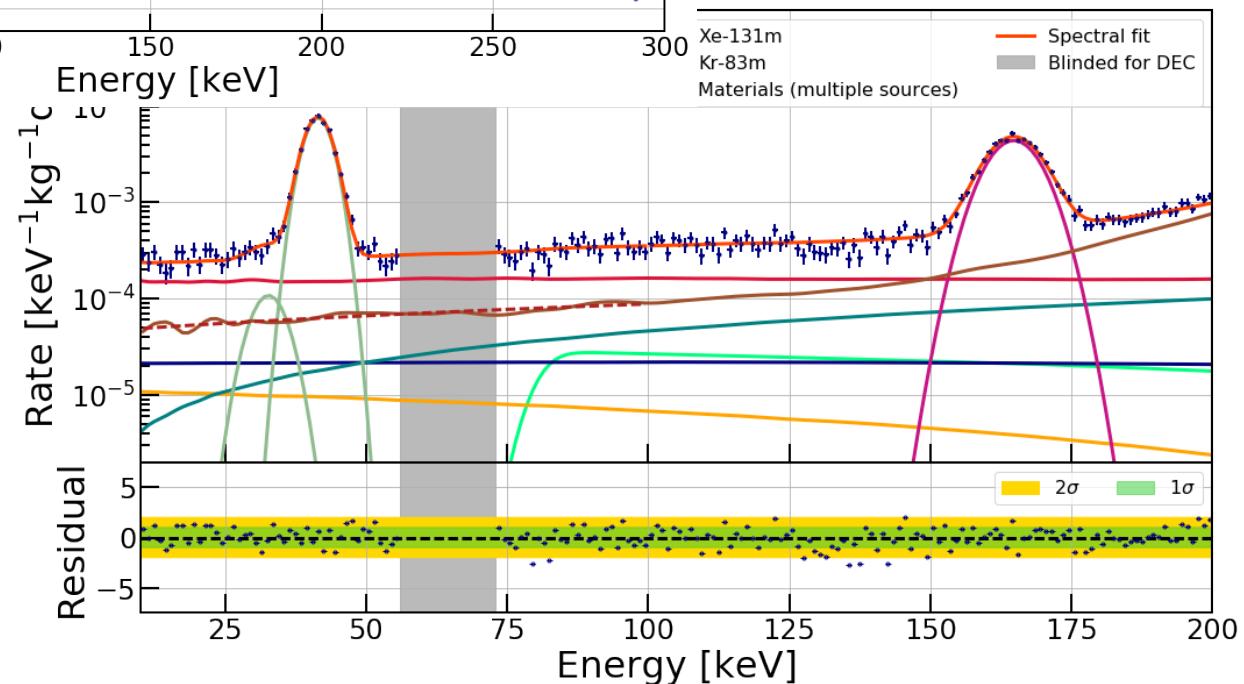
	Value $\pm$ uncertainty	Parameter pull [ $\sigma$ ]
$\nu_{\text{solar}}$ multiplier	$1.00 \pm 0.20$	0.3
$^{136}\text{Xe}$ $2\nu\beta\beta$ multiplier	$1.00 \pm 0.05$	-0.2
Volume <sub>inner,outer</sub> multipliers	$1.00 \pm 0.01$	$0.7_{\text{inner}}, -0.7_{\text{outer}}$
High energy acceptance <sub>inner,outer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

## INNER AND OUTER VOLUME FITS



INNER (1.0 T)

OUTER (0.5 T)



# 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  $\rho = 2.8 \text{ g/cm}^3$

## ► Scalability

👍 Compact detectors scalable to larger dimensions

## ► High purity

👍  $^{136}\text{Xe}$  decay rate negligible;  $^{85}\text{Kr}$  removed to <ppt level

## ► Light and charge yields

👍 Highest among noble liquids

## ► "Easy" cryogenics

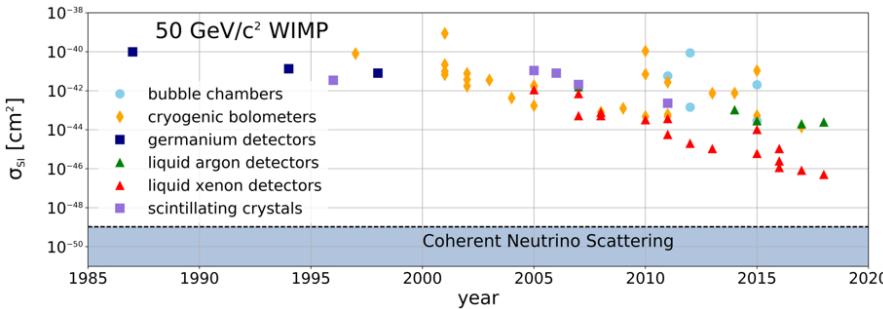
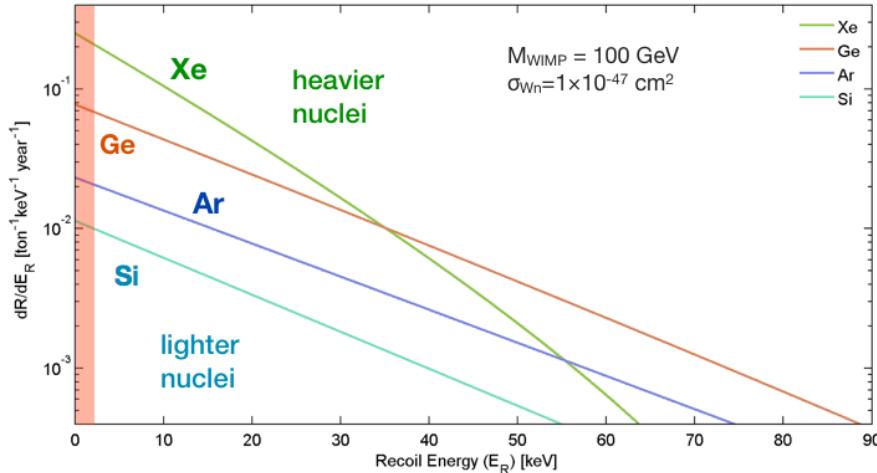
👍 Xenon is liquid at  $-95^\circ\text{C}$

## ► VUV scintillation light

👍 178 nm → no need for wavelength shifters

## ► Odd-nucleon isotopes

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

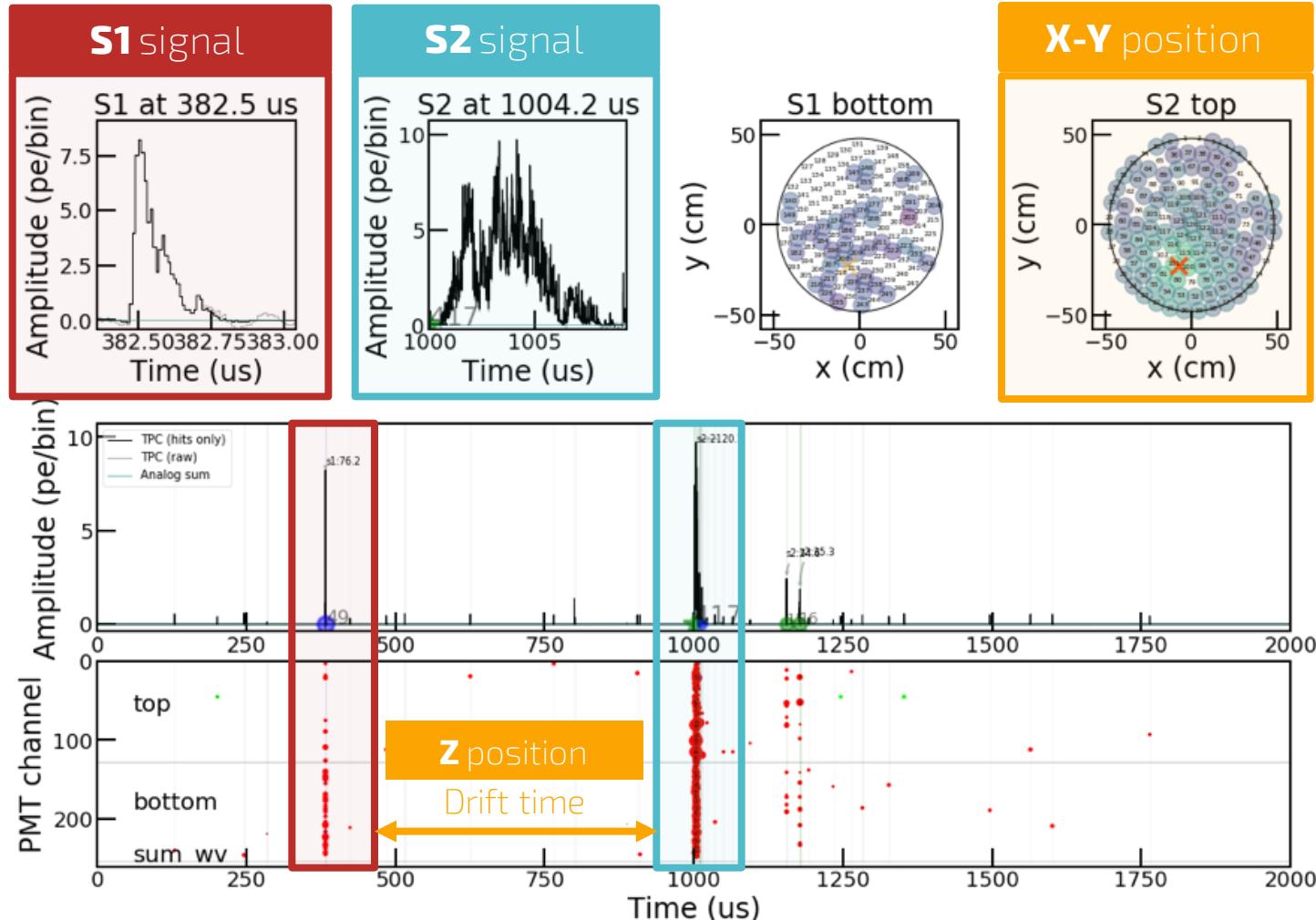


# FROM THE PRINCIPLE TO REALITY

## A TYPICAL LOW ENERGY EVENT

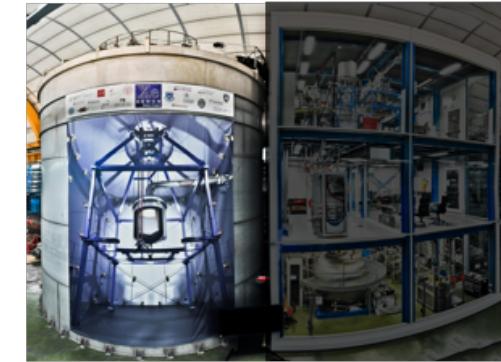
PAX  
Processor For Analyzing XENON

<https://github.com/XENON1T/pax>

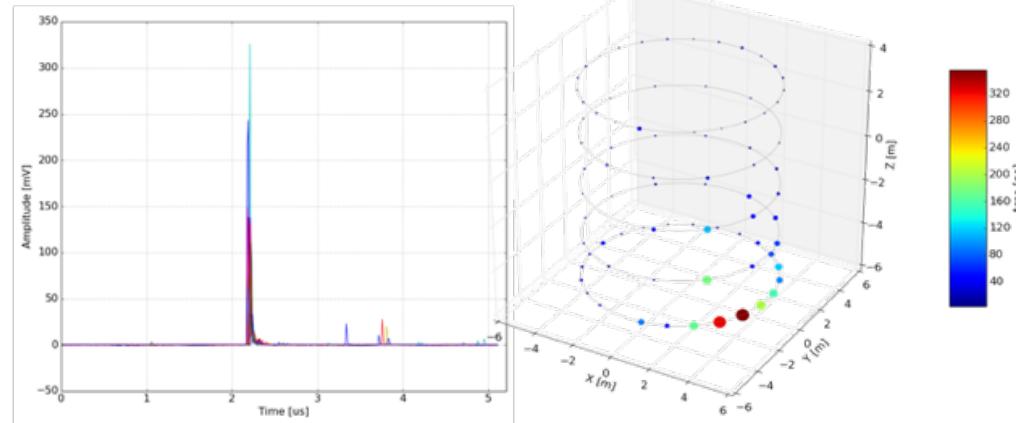


# MUON VETO

## WATER CHERENKOV SUB-DETECTOR

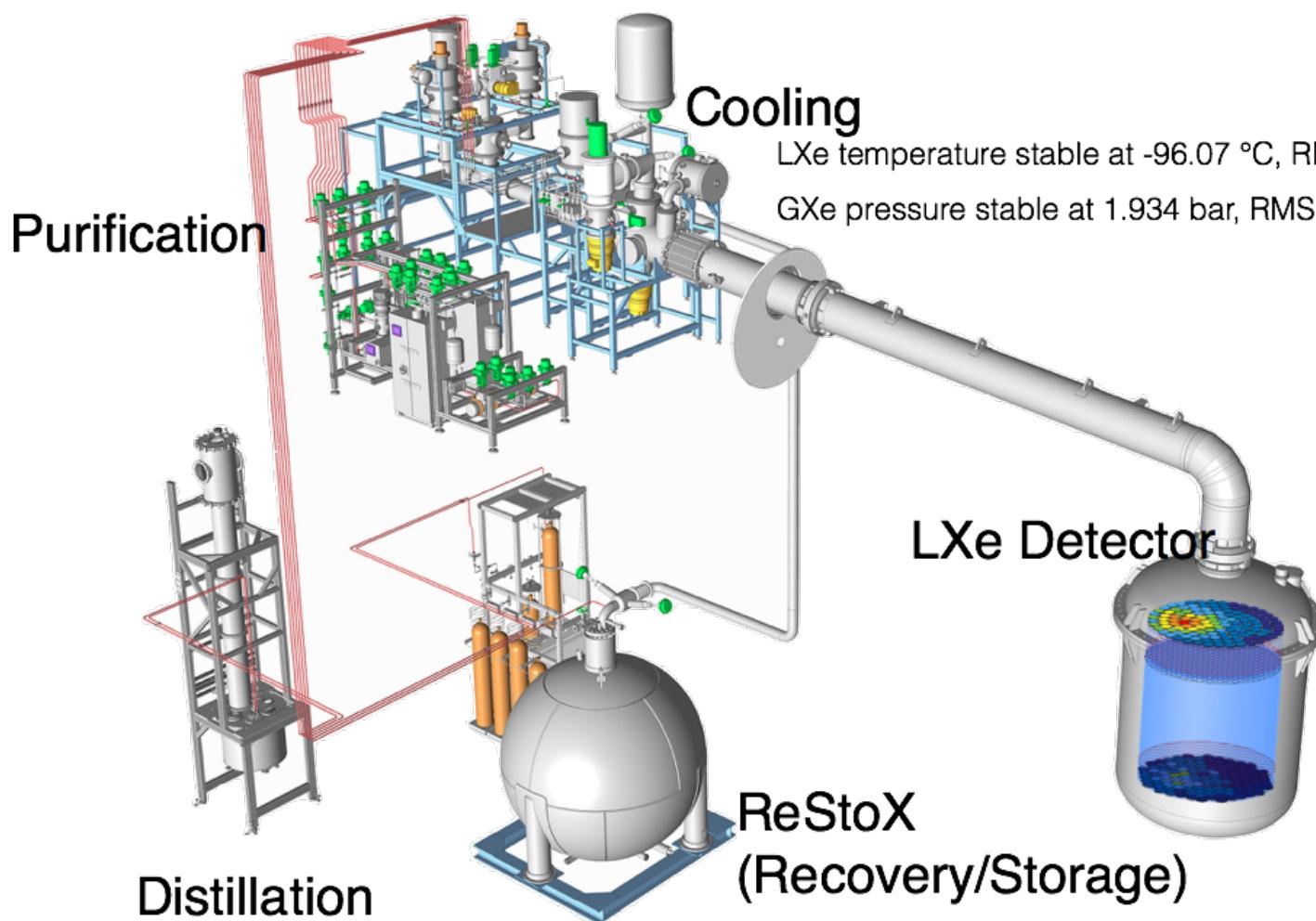


- 700 ton pure water instrumented with 84 high-QE 8" PMTs
- Active shield against muons
- Trigger efficiency > 99.5% for muons in water tank
- Cosmogenic neutron background suppressed to < 0.01 events/ton/yr



JINST 9, 11007 (2014)

# XENON SYSTEMS



ReStoX  
(Recovery/Storage)

LXe Detector

Purification

Distillation

Cooling

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

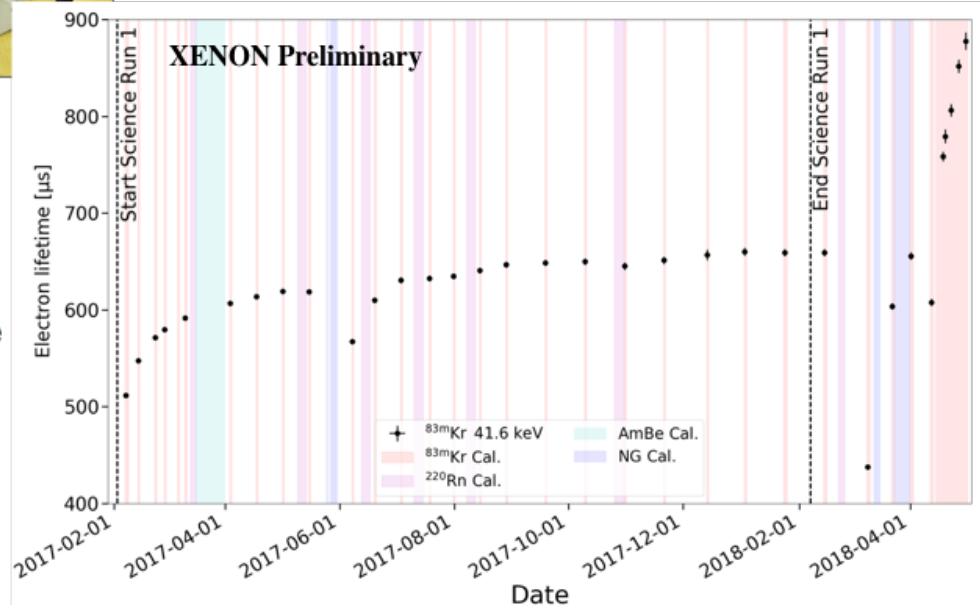
GXe pressure stable at 1.934 bar, RMS 0.001 bar

# XENON PURIFICATION

## ELECTRON LIFETIME

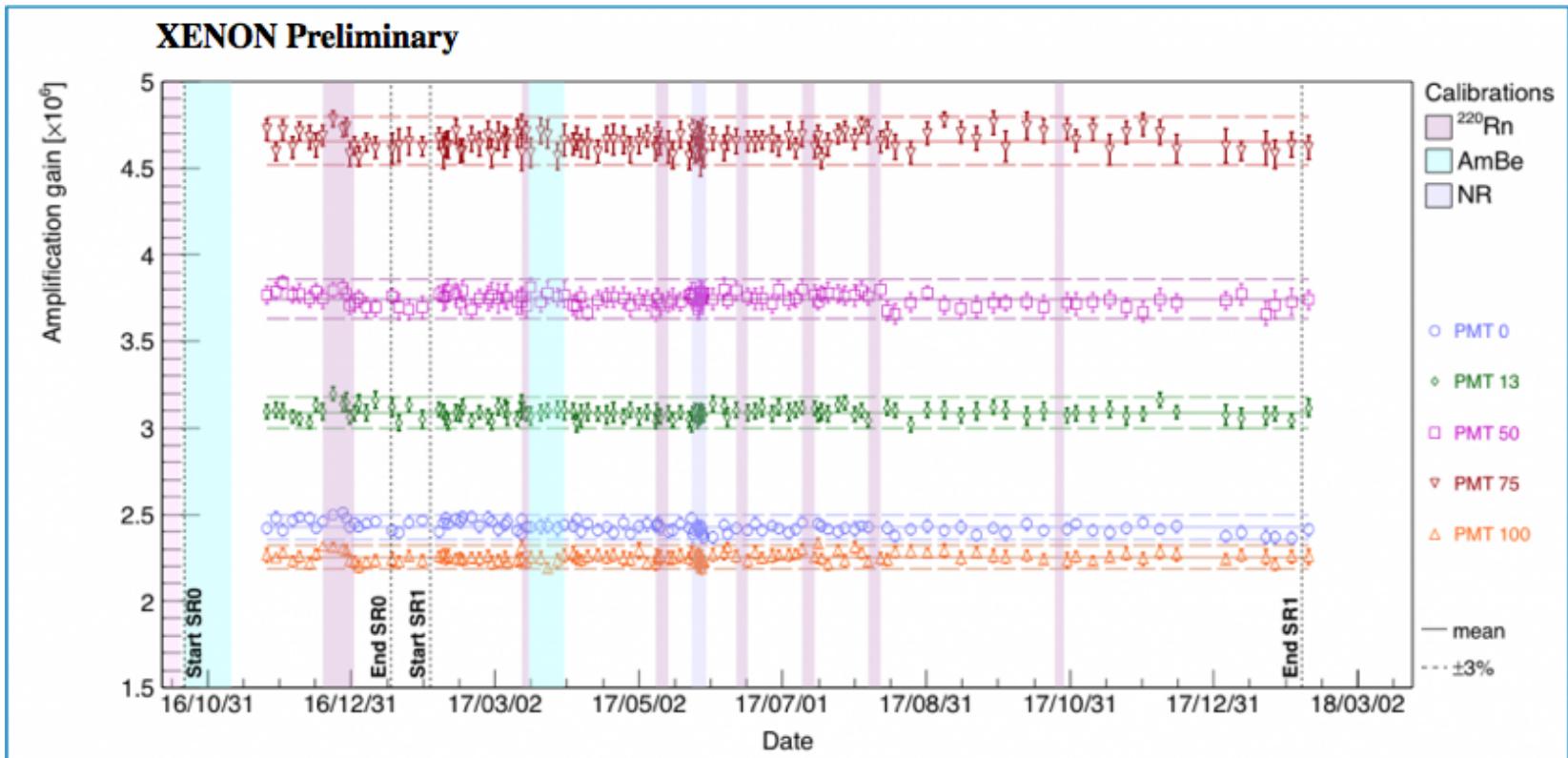


- electron lifetime is monitored regularly with ERs calibration sources.
- Current value, following increase in gas flow, approaches 1 msec



# LIGHT DETECTION SYSTEM

## PMT STABILITY

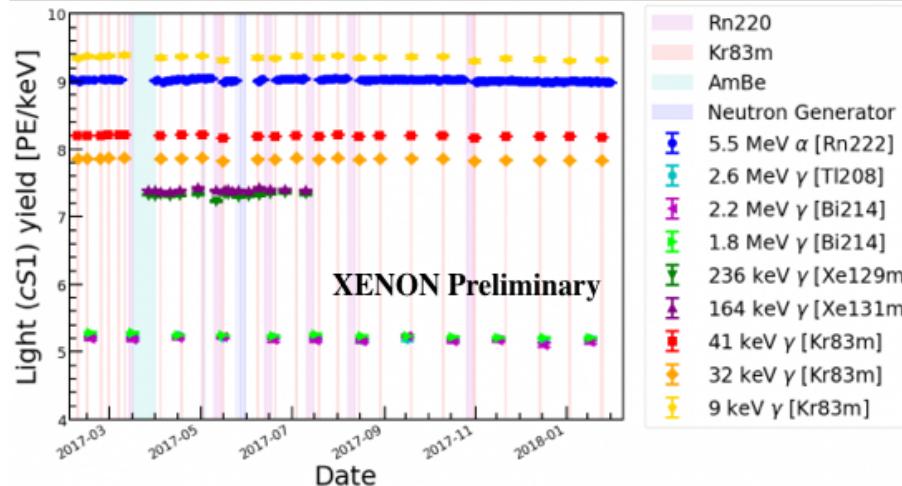
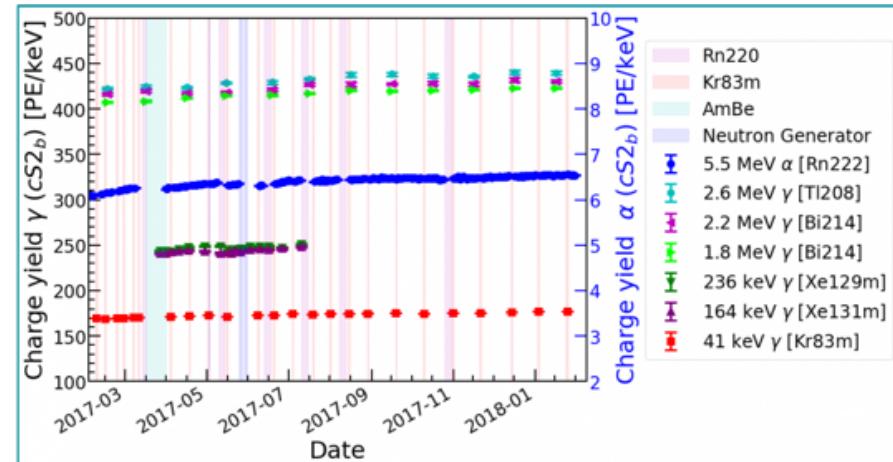


# LIGHT AND CHARGE SIGNALS

## TIME STABILITY



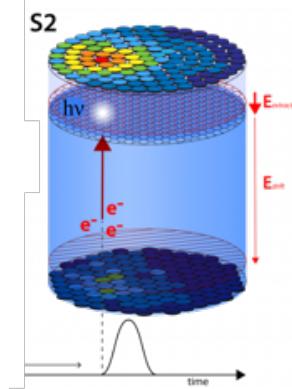
Position dependence of light (solid angle) and charge (attenuation length) signals very well understood through measurement with  $^{83m}\text{Kr}$ ,  $^{222}\text{Rn}$  alphas. Excellent agreement with optical Monte Carlo simulations and with model of purity evolution



Light and charge yield stability monitored with several sources:

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

# POSITION RECONSTRUCTION



## X-Y reconstruction via neural network:

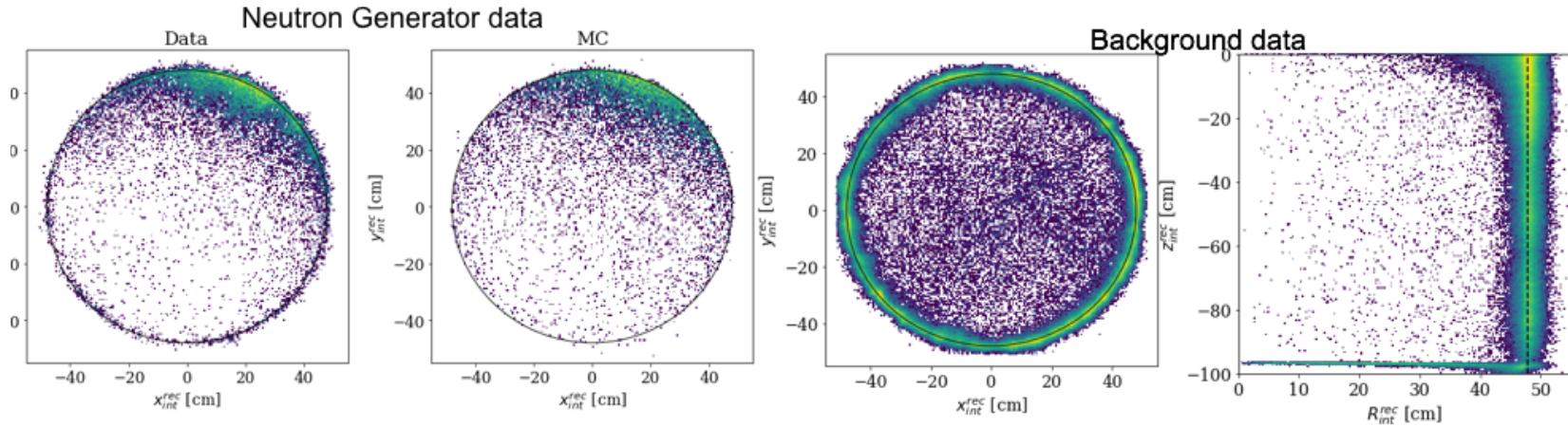
- **Input:** charge/channel top array
- **Training:** Monte Carlo simulation

## Position resolution using $^{83m}\text{Kr}$

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

## Position corrections using $^{83m}\text{Kr}$

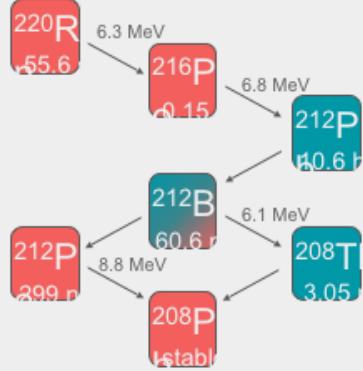
- **Drift field distortion**
- Localized inhomogeneities from inactive PMTs
- Data-derived correction verified by comparison to MC with several event sources



# CALIBRATIONS



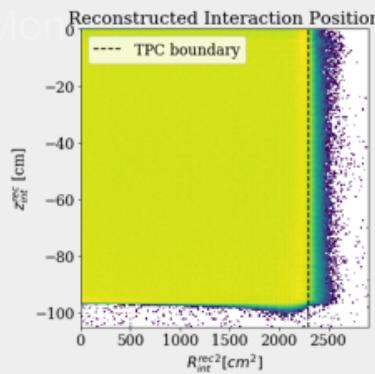
## $^{220}\text{Rn}$ : Low Energy ER



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

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

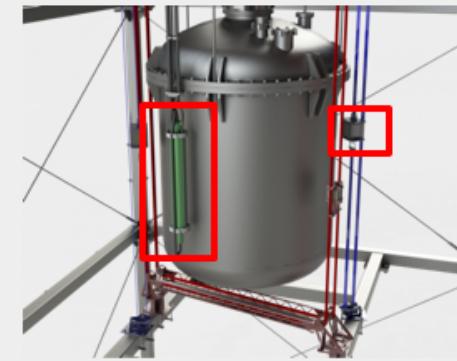
## $^{83\text{m}}\text{Kr}$ : Stability and



**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*

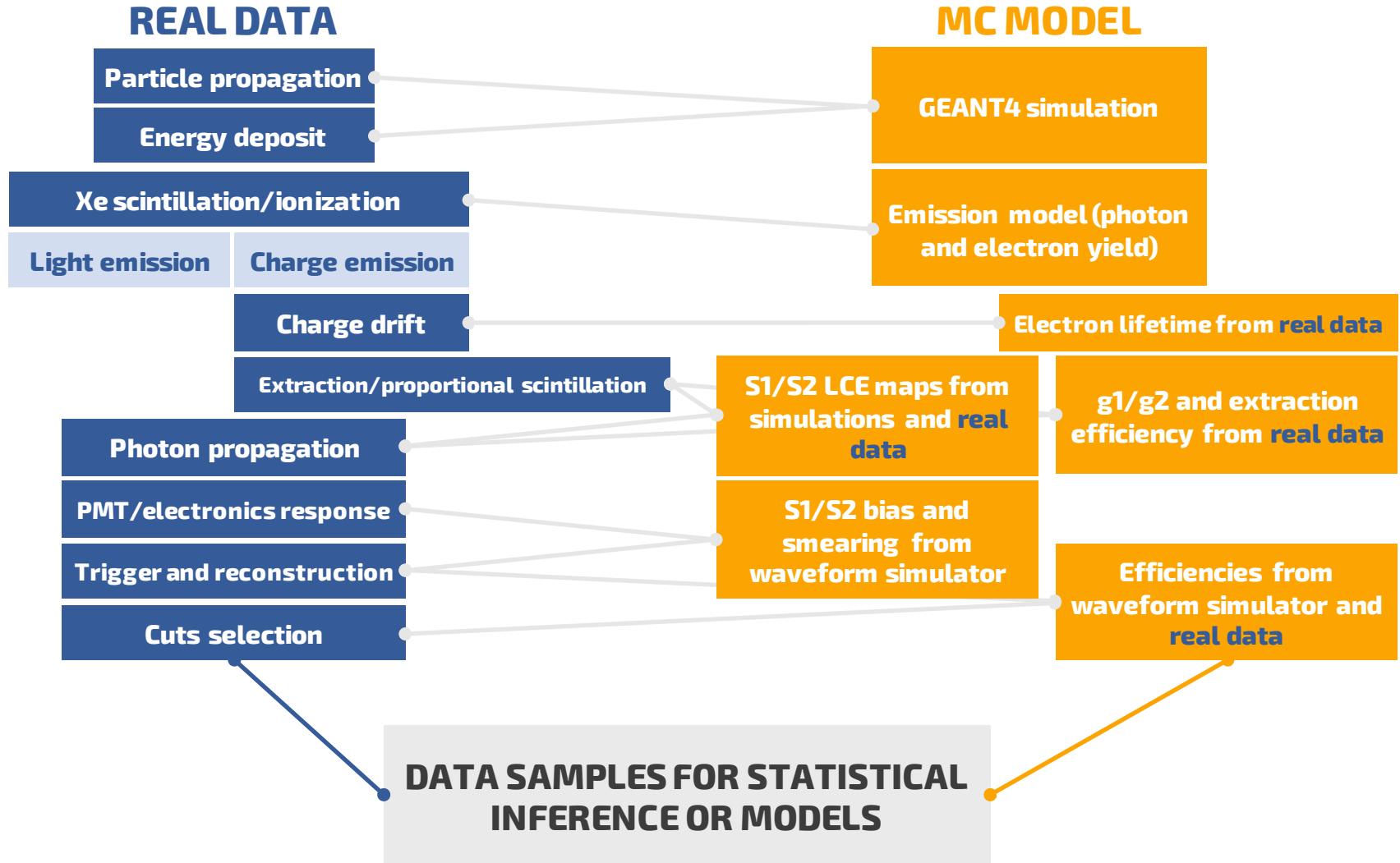
## Neutrons: Signal



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

# LER 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

