Direct Dark Matter Search with the XENON1T EXPERIMENT

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XENON Dark Matter Project
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INFN Bologna

WIN2019 | Bari | 5 June 2019
DARK MATTER DETECTION STRATEGY

- DIRECT DETECTION
- INDIRECT DETECTION
- PRODUCTION AT COLLIDERS
XENON TARGET FOR WIMP INTERACTION

- **HIGH A=131**
  \[ \sigma_{\text{WIMP-N}} \sim A^2 \rightarrow \text{Larger probability of SI WIMP-nucleon interactions} \]

- **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° C

- **VUV SCINTILLATION LIGHT**
  178 nm \( \rightarrow \) no need for wavelength shifters

- **ODD-NUCLEON ISOTOPES**
  \(^{131}\text{Xe}\) and \(^{129}\text{Xe}\) allow to study also the Spin-Dependent interaction

**WIMP SIGNATURE**

- Single elastic scatter on target nucleus
- Recoil energy <50 keV

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**Graphs**

- Comparison of detector materials:
  - Ge, Ar, Si, Xe
  - Xe is heavier nuclei
  - Ge, Ar, Si are lighter nuclei

- Recoil energy vs. energy flux for Xe target.

DARK MATTER SEARCH WITH XENON1T

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

MUON VETO CHERENKOV DETECTOR
700 tonnes active ultra-pure water shield instrumented with 84 PMTs
THE XENON1T EXPERIMENT
AT LNGS

THE XENON1T EXPERIMENT

AT LNGS

WATER TANK 700 t ultra-pure water
CHERENKOV MUON VETO 84 PMTs
THE XENON1T EXPERIMENT AT LNGS

- WATER TANK 700 t ultra-pure water
- CHERENKOV MUON VETO 84 PMTs
- TPC 3.2 t LXe 248 PMTs
THE XENON1T EXPERIMENT
AT LNGS

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

**TPC**
- 3.2 t Xe
- 248 PMTs

**CRYOGENICS AND Xe PURIFICATION**

**DAQ AND SLOW CONTROL**

**Kr DISTILLATION**

**Xe STORAGE AND RECOVERY**
LIQUID XENON-BASED DETECTORS

EVOLUTION OF SPECIES

TOTAL LXe mass
3.2 tonnes

XENON10
2005
22 kg
ACTIVE LIQUID XENON TARGET MASS

XENON100
2008
105 kg

LUX
2013
250 kg

PANDA X-II
2016
580 kg

XENON1T
2016
2000 kg

XENONnT
2019
6000 kg

LOW ENERGY ER BACKGROUND [t•d•keV]^{-1}

5.3
2.6
0.8
0.2
0.02 (Goal)

Xe
LXe

LUX
PANDA X-II

Xe
Xe

3.2 tonnes

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WIN2019 Bari
5 June 2019
A REAL XENON1T WAVEFORM

**S1 signal**
- S1 at 382.5 us

**S2 signal**
- S2 at 1004.2 us

**X-Y position**
- S1 bottom
- S2 top

**Z position**
- Drift time

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S1 - S2 SIGNAL CORRECTIONS
FOR SPATIAL-DEPENDENT DETECTOR RESPONSE

83mKr CALIBRATIONS
41.5 KeV line uniformly distributed in the TPC

83mKr CALIBRATIONS
x-y-z-dependent correction

83mKr CALIBRATIONS
S1 LCE

S2 LCE
x-y-dependent correction

ELECTRON LIFETIME
z-dependent S2 correction

TOP PMT ARRAY

BOTTOM PMT ARRAY
RECOIL TYPE DISCRIMINATION

NUCLEAR RECOILS

WIMP
Neutron
Neutrino (CNNS)

NUCLEAR RECOILS

WIN2019 Bari | 5 June 2019
RECOIL TYPE DISCRIMINATION
ELECTRONIC RECOILS

Gamma
Beta
Neutrino

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

RADIOGENIC NEUTRONS

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

COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING (CNNS)

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

<table>
<thead>
<tr>
<th></th>
<th>Rate [t⁻¹ y⁻¹]</th>
<th>Fraction [%]</th>
</tr>
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<tbody>
<tr>
<td>Cosmogenic neutrons</td>
<td>&lt;0.01</td>
<td>&lt;2.0</td>
</tr>
<tr>
<td>Radiogenic neutrons</td>
<td>0.6 ± 0.1</td>
<td>96.5</td>
</tr>
<tr>
<td>CNNS</td>
<td>0.012</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Expectations in 1 t FV, in [4,50] keVₙᵣ, single scatters
ELECTRONIC RECOIL BACKGROUND

INTRINSIC RADIOACTIVE ISOTOPES

- $^{222}$Rn (10 $\mu$Bq/kg)
  Most dangerous is $\beta$-decay of $^{214}$Pb.
  Emanated from inner surfaces in contact with Xenon.
  Extensive screening campaign and careful radiopure material selection.

- $^{85}$Kr (0.66 ppt)
  $\beta$-emitter, Xenon contaminant.
  Reduced by a factor $>10^3$ via cryogenic distillation.

- $^{136}$Xe (~9% of $^{\text{nat}}$Xe)
  Double-$\beta$-emitter.

SOLAR NEUTRINOS

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

RADIOACTIVE ISOTOPOES IN DETECTOR MATERIALS

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

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Rate [$^{\text{t}^{-1} \cdot ^{\text{y}^{-1}}}$]</th>
<th>Fraction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{222}$Rn</td>
<td>$620 \pm 60$</td>
<td>85.4</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>$31 \pm 6$</td>
<td>4.3</td>
</tr>
<tr>
<td>Solar $\nu$</td>
<td>$36 \pm 1$</td>
<td>4.9</td>
</tr>
<tr>
<td>Materials</td>
<td>$30 \pm 3$</td>
<td>4.1</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>$9 \pm 1$</td>
<td>1.4</td>
</tr>
</tbody>
</table>

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

JCAP 04, 027 (2016)
XENON1T BACKGROUND LEVEL

THE LOWEST EVER FOR DARK MATTER DETECTORS

**GEANT4 SIMULATIONS**

of all known background components
Convolved with the measured energy resolution

**LOW ENERGY BACKGROUND RATE**

82^{+5}_{-3} \text{(sys)} \pm 3 \text{(stat)} (t \text{y keV})^{-1}
The lowest ever among DM detectors

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

**SIMULATION PREDICTION**

71 \pm 7 (t \text{y keV})^{-1}
Very well understanding of background
Combined ER/NR fit

Detailed MC simulations of LXe microphysics and detector processes

99.7% ER rejection in NR reference region [NR median, -2σ]
**BACKGROUND MODELS**
In 4-dimensional space: $S_1, S_2, r, z$

**STATISTICAL INFERENCE**
Done with PLR analysis in 1.3 t fiducial volume and full $(S_2,S_1)$ space, corresponding to $[4.9, 40.9]$ keV$_{nr}$ and $[1.4, 10.6]$ keV$_{ee}$.

**NR REFERENCE REGION**
Between NR median and $-2\sigma$ quantile. Numbers in table are for illustration; final results from complete PLR statistical inference.
DATA UNBLINDING

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

"PIE CHARTS"
Events passing all selection criteria are shown as pie charts representing the relative PDF from each component for the best-fit model for 200 GeV WIMP ($\sigma_{SI}=4.7\cdot10^{-47}$ cm$^2$)

"STATISTICAL INTERPRETATION"
Unbinned profile likelihood with all model uncertainties included as nuisance parameters.
WORLD BEST CONSTRAINT ON WIMP DARK MATTER
Most stringent exclusion limits (at 90% CL) for WIMPs > 6 GeV/c^2

\[ \sigma_{SI} < 4.1 \times 10^{-47} \text{ cm}^2 \]
at 30 GeV/c^2

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

\( \sigma_{SI} < 4.1 \times 10^{-47} \text{ cm}^2 \)
**SPIN-DEPENDENT WIMP SEARCH**

*Phys. Rev. Lett. 122, 141301*

- Same data selection
- Different interpretation

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

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**WIMP interaction on $^{129}$Xe and $^{131}$Xe**

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![Graph showing WIMP-neutron and WIMP-proton cross sections](image)

- Axial-vector mediator
- Dirac WIMP $g_q=0.25$, $g_\chi=1.0$

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![Graph showing mediator mass vs. WIMP mass](image)

- CMS (2018)
- ATLAS (2018)
- PICO-60 (2017)
- XENON100 (2016)
- LUX (2017)
- PandaX-II (2018)
- XENON1T (1 t×yr, this work)

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![Graph showing efficiency and excluded parameter space](image)

- Excluded new parameter space in isoscalar theory with axial-vector mediator (restricted model for comparison with LHC)
WIMP coupling to a virtual pion exchanged between nucleons in a nucleus

Pion-exchange currents can be coherently enhanced by total number of nucleon

May dominate in scenarios where SI WIMP-nucleon interaction is suppressed

First ever result on WIMP-pion coupling

Signal model similar to SI WIMP-nucleon coupling
DISCOVERY OF DOUBLE ELECTRON CAPTURE IN $^{124}$Xe

- First observation of $2\nu$ECEC decay
- Measured half-life $(1.8 \pm 0.5_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22}$ yr
  The longest ever!
- ~$10^{12}$ times larger than the age of the Universe
$^{124}\text{Xe} \rightarrow ^{124}\text{Te} + \nu_e + \nu_e$

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

Blinded search in $(56, 72)$ keV

Total fiducial mass $(1502 \pm 9_{\text{stat}})$ kg

Dataset livetime 177.7 days

$^{124}\text{Xe}$ isotopic abundance $(9.94 \pm 0.14_{\text{stat}} \pm 0.15_{\text{sys}}) \times 10^{-4}$

Close $^{125}\text{I}$ peak at 67.3 keV
Expectation derived from $^{125}\text{Xe}$ activation model (during neutron calibrations)

Energy resolution at $E_{2\nu\text{ECEC}} (4.1 \pm 0.4\%)$
**UNBLINDING RESULTS**

**2νECEC PEAK**
\[\mu = (64.2 \pm 0.5) \text{ keV}\]
\[\sigma = (2.6 \pm 0.3) \text{ keV}\]

**125I BACKGROUND**
\[N_{125} = 9 \pm 7\]
Expected 10 ± 7

**2νECEC EVENTS OBSERVED**
\[126 \pm 29\]

**DISCOVERY SIGNIFICANCE**
4.4 \(\sigma\)
THE RAREST DECAY EVER OBSERVED

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

This measurement is the first benchmark for nuclear structure models of proton-rich nuclei.

It sets the stage for 0νECEC searches hunting for the Majorana neutrino.
WHAT'S NEXT: XENONnT

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

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

**LXe TARGET**
- Fiducial mass 1 t $\rightarrow$ 4 t

**LARGER TPC**
- 248 $\rightarrow$ 494 PMTs

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

**NR BACKGROUND**
- Neutron Veto

**FAST UPGRADE**
- Installation ongoing
Region outside the cryostat instrumented with additional 120 PMTs

Doped water with 0.2% concentration of Gadolinium sulphate

Optically separated from Muon Veto system by ePTFE reflector

Reduction of neutron background thanks to ~85% neutron tagging efficiency

Boost in the sensitivity to WIMPs by a factor ~2
FIRST MULTI-TON LXe-TPC
Operated > 1 year

LOWEST BACKGROUND
ever among DM detectors

BEST WIMP LIMITS
SI > 6 GeV/c^2

^{124}Xe 2νECEC DISCOVERY
Rarest decay ever observed directly

XENON1T ANALYSES
Many DM and rare processes searches ongoing

XENONnT GOAL:
x10 BETTER SENSITIVITY
Larger detector, lower background, 5 years data taking
EVIDENCES OF DARK MATTER

**ROTATION CURVES**
- M33 Galaxy
- SDSS J1038+4849 Clusters

**BULLET CLUSTER**
- Luminous vs Dark matter

**LENSING**
- SDSS J1038+4849 Clusters

**CMB + ΛCDM**
- PLANCK 2018

**STRUCTURE FORMATION**
- Millennium-2 Simulation

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GALAXY AND CLUSTERS SCALE

COSMOLOGICAL SCALE
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*

$$\Omega_{DM}h^2 = \frac{3 \times 10^{-27} \text{ cm}^3\text{s}^{-1}}{\langle \sigma_{\text{ann}}v \rangle} = 0.120 \pm 0.001$$

is obtained with mass (~100 GeV/c²) and annihilation cross section (~10⁻²⁵ cm³s⁻¹) typical of the weak scale

Weakly Interacting Massive Particles

- 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%
Purification

Cooling

LXe temperature stable at -96.07 °C, RMS 0.04 °C
GXe pressure stable at 1.934 bar, RMS 0.001 bar

Distillation

LXe Detector

ReStoX (Recovery/Storage)
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
- 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)
X-Y reconstruction via **neural network**:
- **Input**: charge/channel top array
- **Training**: Monte Carlo simulation

**Position resolution** using $^{83}\text{mKr}$
- Two interactions (9, 31 keV), same x-y
- Position resolution (1-2 cm)
- PMT diameter (7.62 cm)

**Position corrections** using $^{83}\text{mKr}$
- Drift field distortion
- Localized inhomogeneities from inactive PMTs
- Data-derived correction verified by comparison to MC with several event sources
**Calibrations**

**220Rn:** 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})**

**83mKr:** Stability and Response

- 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)
ER AND NR MODELING
REAL DATA AND MC SIMULATIONS

REAL DATA
- Particle propagation
- Energy deposit
- Xe scintillation/ionization
- Light emission
- Charge emission
- Charge drift
- Extraction/proportional scintillation
- Photon propagation
- PMT/electronics response
- Trigger and reconstruction
- Cuts selection

MC MODEL
- GEANT4 simulation
- Emission model (photon and electron yield)
- Electron lifetime from real data
- S1/S2 LCE maps from simulations and real data
- S1/S2 bias and smearing from waveform simulator
- g1/g2 and extraction efficiency from real data
- Efficiencies from waveform simulator and real data

DATA SAMPLES FOR STATISTICAL INFERENCE OR MODELS
• 279 days high quality data (livetime-corrected) spanning more than 1 year of stable detector’s operation. The LXeTPC has been “cold” since Summer 2016

• 1 tonne x year exposure given 1.3 tonne fiducial volume - the largest reported to-date with this type of detector

• Experiment still running smoothly and collecting more data
LIGHT DETECTION SYSTEM

PMT STABILITY

XENON Preliminary

Date

Amplification gain \([10^6]\]

Calibrations

\(^{220}\)Rn
AmBe
NR

PMT 0
PMT 13
PMT 50
PMT 75
PMT 100

mean
\(\pm 3\%\)
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 %
• 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
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 $4.2 \times 10^{-47}$ 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
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.

<table>
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<tr>
<th>Mass</th>
<th>1.3 t</th>
<th>1.3 t</th>
<th>0.9 t</th>
<th>0.65 t</th>
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<tr>
<td>(cS1, cS2_b)</td>
<td>Full</td>
<td>Reference</td>
<td>Reference</td>
<td>Reference</td>
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<tr>
<td>ER</td>
<td>627±18</td>
<td>1.62±0.30</td>
<td>1.12±0.21</td>
<td>0.60±0.13</td>
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<td>neutron</td>
<td>1.43±0.66</td>
<td>0.77±0.35</td>
<td>0.41±0.19</td>
<td>0.14±0.07</td>
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<tr>
<td>CEνNS</td>
<td>0.05±0.01</td>
<td>0.03±0.01</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>AC</td>
<td>0.47±0.27</td>
<td>0.10±0.06</td>
<td>0.06±0.03</td>
<td>0.04±0.02</td>
</tr>
<tr>
<td>Surface</td>
<td>106±8</td>
<td>4.84±0.40</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Total BG</td>
<td>735±20</td>
<td>7.36±0.61</td>
<td>1.62±0.28</td>
<td>0.80±0.14</td>
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<tr>
<td>WIMP_{best-fit}</td>
<td>3.56</td>
<td>1.70</td>
<td>1.16</td>
<td>0.83</td>
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<tr>
<td>Data</td>
<td>739</td>
<td>14</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

WIMP expectation under best-fit model at m=200 GeV (cross-section = 4.7x10^{-47} cm^2)
THE RAREST DECAY EVER OBSERVED

Double Electron Capture (2νECEC)

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

Detectable signal:

- Auger electrons
- X-rays

Experimental signature: \( \sigma(\text{keV}) \)

cascade of X-rays and Auger electrons
THE RAREST DECAY EVER OBSERVED

Key ingredients for discovery

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

"Very silent detector"
Extremely low and well characterized background level
HOW ABOUT $2\nu$ECEC of $^{124}$Xe?

XENON1T SENSITIVITY AND PREVIOUS LIMITS

PREVIOUS SEARCHES OF $^{124}$Xe DECAY

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

XENON1T DATA FOR $2\nu$ECEC SEARCH

* Data taking period
  2 February 2017 - 8 February 2018
* Final live time
  177.7 days
Fitting Gaussian functions to mono-energetic peaks

- $^{83m}\text{Kr} (41.5 \text{ keV})$
  Injected calibration source
- $^{131m}\text{Xe} (163.9 \text{ keV})$ and $^{129m}\text{Xe} (236.2 \text{ keV})$
  Activated metastable isotopes during neutron calibrations
- $^{214}\text{Pb} (351.9 \text{ keV})$ and $^{208}\text{Tl} (510.8 \text{ keV})$
  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 $E_{2\nu\text{ECEC}} = 64.3 \text{ keV}$
(4.1 ± 0.4) %
**ACTIVATION AND REMOVAL MODEL**

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

$$^{124}\text{Xe} + n \rightarrow ^{125}\text{Xe} + \gamma$$

$$^{125}\text{Xe} \xrightarrow{16.9\text{h}} ^{125}\text{I}^* + \nu_e$$

$$^{125}\text{I} \xrightarrow{59.4\text{d}} ^{125}\text{Te}^* + \nu_e$$

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

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

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

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

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

**$^{125}$I EXPECTED EVENTS IN 177.7 d**
$$N_{l-125} = 10 \pm 7$$
Sensitivity $\propto \frac{\text{Mass}}{\sqrt{N_{\text{background}}}}$

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

![Graph showing rate vs energy, with peaks at different energies for various isotopes and materials, and residual plot below.]
4.4 $\sigma$

Chi-square difference between background and signal hypothesis

OBSERVED 2$\nu$ECEC EVENTS

$126 \pm 29$
✓ Signal homogeneously distributed in space

✓ Signal events accumulated linearly with exposure

✓ Fits of inner (1.0 t) and outer (0.5 t) fiducial volumes yield consistent results

✓ Linearity of the energy response is ensured by the $^{125}$I peak observed at the expected position and separated from the $2\nu$ECEC peak by more than the energy resolution

✓ Systematic uncertainties on cut acceptance, fiducial mass and number of $^{125}$I events included as fit parameters

✓ Knowledge from external measurements (material screening, $^{85}$Kr concentrations measurements, elemental abundances) are incorporated through constraint terms

✓ No constrained fit parameters are pulled significantly ($<1\sigma$) away from the expected value
### DEC FIT PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value ± uncertainty</th>
<th>Parameter pull [σ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_{\text{solar}}$ multiplier</td>
<td>$1.00 \pm 0.20$</td>
<td>0.3</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$ 2νββ multiplier</td>
<td>$1.00 \pm 0.05$</td>
<td>−0.2</td>
</tr>
<tr>
<td>Volume$_{\text{inner}}$,outer multipliers</td>
<td>$1.00 \pm 0.01$</td>
<td>0.7$<em>{\text{inner}}$, −0.7$</em>{\text{outer}}$</td>
</tr>
<tr>
<td>High energy acceptance$_{\text{inner}}$,outer multipliers</td>
<td>$0.67 \pm 0.33$</td>
<td>0.1$<em>{\text{inner}}$, −1.0$</em>{\text{outer}}$</td>
</tr>
<tr>
<td>$^{85}\text{Kr}$ concentration</td>
<td>$(0.66 \pm 0.12)$ ppt $^{\text{nat}}\text{Kr}/\text{Xe}$</td>
<td>0.3</td>
</tr>
<tr>
<td>$N_{125}\text{I}$</td>
<td>$(10 \pm 7)$ events</td>
<td>−0.2</td>
</tr>
<tr>
<td>$\mu_{125}\text{I}$</td>
<td>$(67.3 \pm 0.5)$ keV</td>
<td>−0.1</td>
</tr>
<tr>
<td>$\sigma_{125}\text{I}$</td>
<td>$(2.8 \pm 0.5)$ keV</td>
<td>−0.1</td>
</tr>
<tr>
<td>$\mu_{2\nu\text{ECEC}}$</td>
<td>$(64.3 \pm 0.6)$ keV</td>
<td>−0.3</td>
</tr>
<tr>
<td>$\sigma_{2\nu\text{ECEC}}$</td>
<td>$(2.6 \pm 0.3)$ keV</td>
<td>−0.2</td>
</tr>
<tr>
<td>$\mu_{83}\text{mKr,1}$</td>
<td>$(32.2 \pm 0.6)$ keV</td>
<td>0.7</td>
</tr>
<tr>
<td>$\mu_{83}\text{mKr,2}$</td>
<td>$(41.5 \pm 0.6)$ keV</td>
<td>−0.1</td>
</tr>
<tr>
<td>$\mu_{131}\text{mXe}$</td>
<td>$(163.9 \pm 0.6)$ keV</td>
<td>2.4</td>
</tr>
<tr>
<td>$\mu_{129}\text{mXe}$</td>
<td>$(236.2 \pm 0.6)$ keV</td>
<td>1.0</td>
</tr>
</tbody>
</table>
UPGRADED Xe PURIFICATION SYSTEM

REDUCING $^{222}$Rn CONTAMINATION

Electron Lifetime $[\mu s]$ vs Date

- Jan 2018
- Feb 2018
- Mar 2018
- Apr 2018
- May 2018
- Jun 2018
- Jul 2018

- $^{85m}$Kr

- end Science Run 1
- Power Outage
- Pur. upgrade: 1” OD pipes
- Pur. upgrade: mag. pump installation

- ~48 SLPM
- ~70 SLPM
- ~80 SLPM