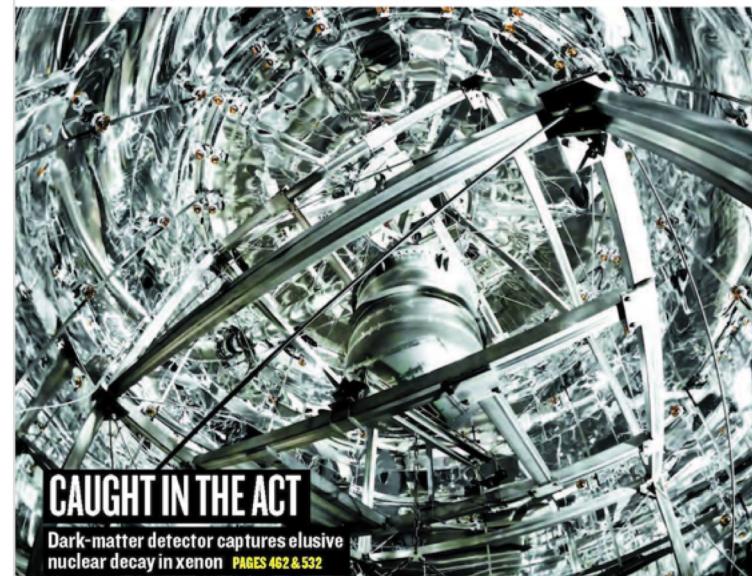


First observation of two-neutrino double electron capture in ^{124}Xe with XENON1T

nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE



Julien Masbou
Subatech – Université de Nantes

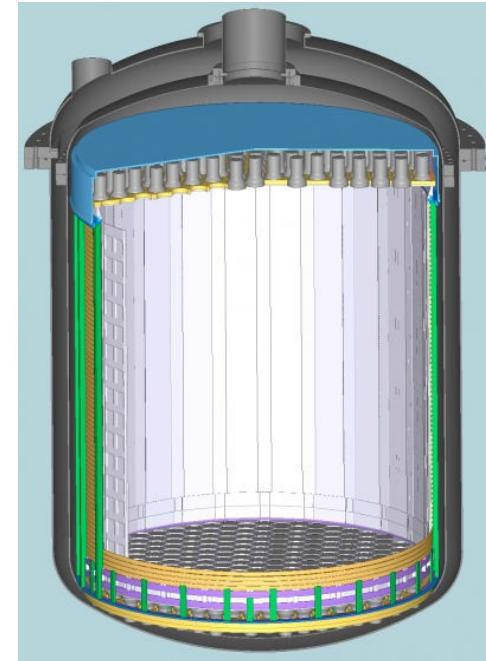
XENON World

27 Institutions
11 Countries
165 Scientists

Experiment
@LNGS (Italy)
- 3600 mwe
underground



XENON Program : timeline



XENON10

2005 – 2007

15 cm drift TPC

Total: 25 kg

Target: **14** kg

Fiducial: 5.4 kg

Achieved (2007)

$$\sigma_{\text{SI}} = 8.8 \cdot 10^{-44} \text{ cm}^2$$

@ 100 GeV/c²

XENON100

2008 – 2016

30 cm drift TPC

Total: 161 kg

Target: **62** kg

Fiducial: 34/48 kg

Achieved (2016)

$$\sigma_{\text{SI}} = 1.1 \cdot 10^{-45} \text{ cm}^2$$

@ 55 GeV/c²

XENON1T

2011 – 2018

100 cm drift TPC

Total: 3 200 kg

Target: **2 000** kg

Fiducial: 1 300 kg

Achieved (2018)

$$\sigma_{\text{SI}} = 4.1 \cdot 10^{-47} \text{ cm}^2$$

@ 30 GeV/c²

XENONnT

2019 – 2023

150 cm drift TPC

Total: 8 000 kg

Target: **6 000** kg

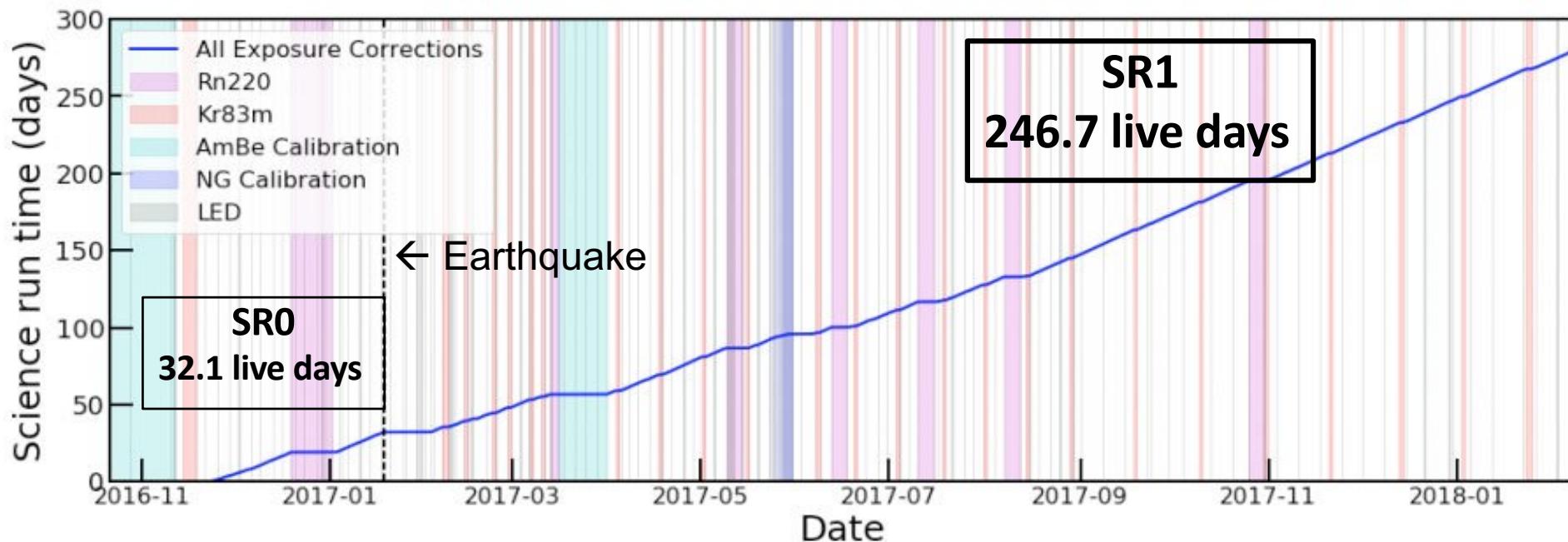
Fiducial: 4 500 kg

Projected (2022)

$$\sigma_{\text{SI}} = 1.6 \times 10^{-48} \text{ cm}^2$$

@ 50 GeV/c²

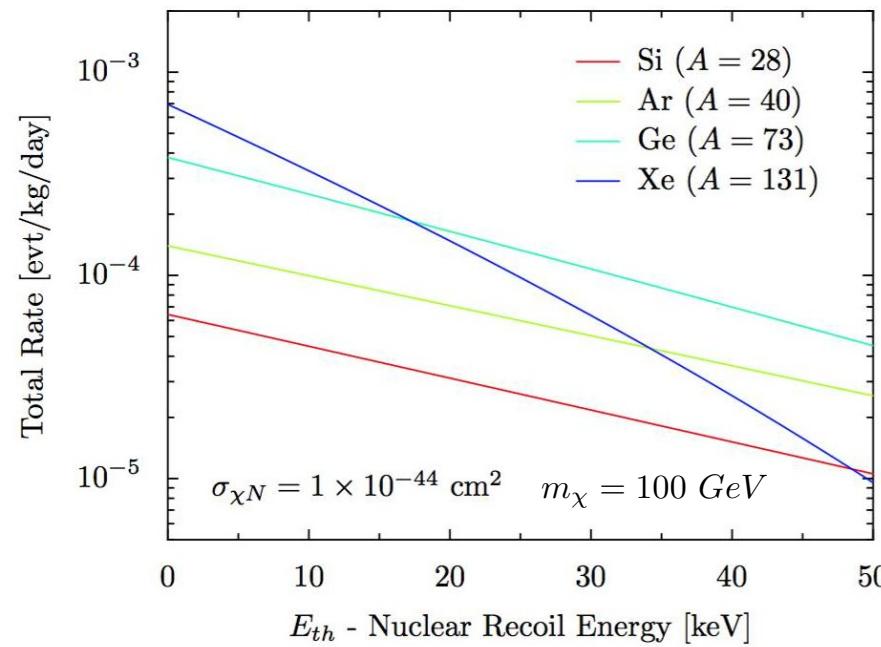
XENON1T Data Taking : a tale of two science runs



- DM total exposure SR0+SR1: 278.8 Live days
→ Largest exposure reported to-date with this type of detector
- Regular Calibration Data:
 - 83mKr → Spacial Response (electron lifetime,...)
 - 220Rn → ER-Band
 - 241AmBe & NG → NR-Band
 - LED → PMT gain monitoring

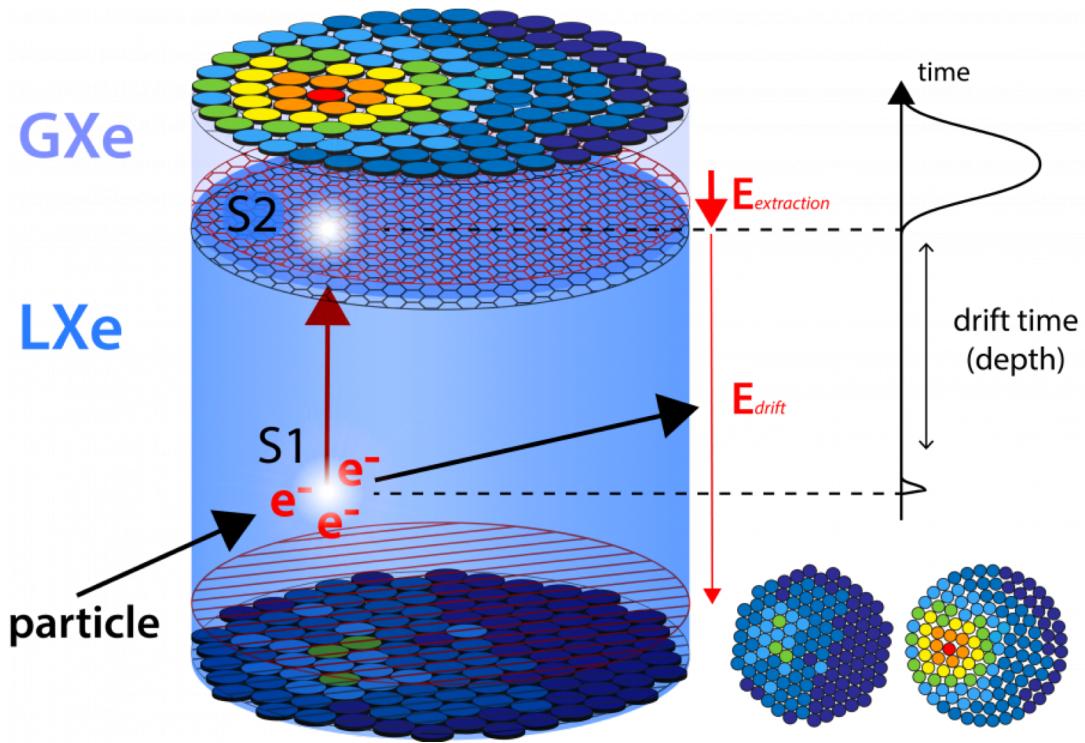
Why Xenon ?

- Large mass number A (131) (Interaction cross section $\propto A^2$)
- 50% odd isotopes (^{129}Xe , ^{131}Xe) for Spin-Dependent interactions
- Kr can be reduced to ppt levels
- High stopping power, i.e. active volume is self-shielding
- Efficient scintillator (178 nm)
- Scalable to large target masses
- Electronic recoil discrimination with simultaneous measurement of scintillation and ionization



Dual phase TPC: principle

TPC = Time Projection Chamber



S1:

→ Photon ($\lambda = 178$ nm)
from Scintillation process

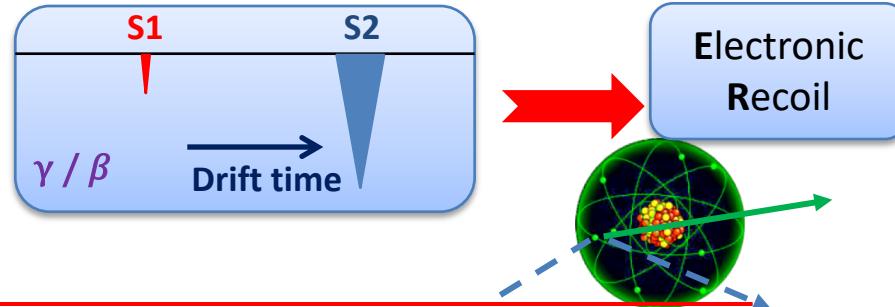
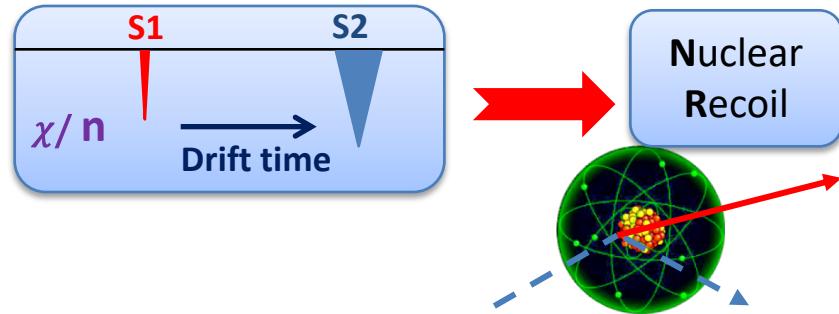
S2:

→ Electrons drift
→ Extraction in gaseous phase
→ Proportional scintillation light

3D reconstruction :

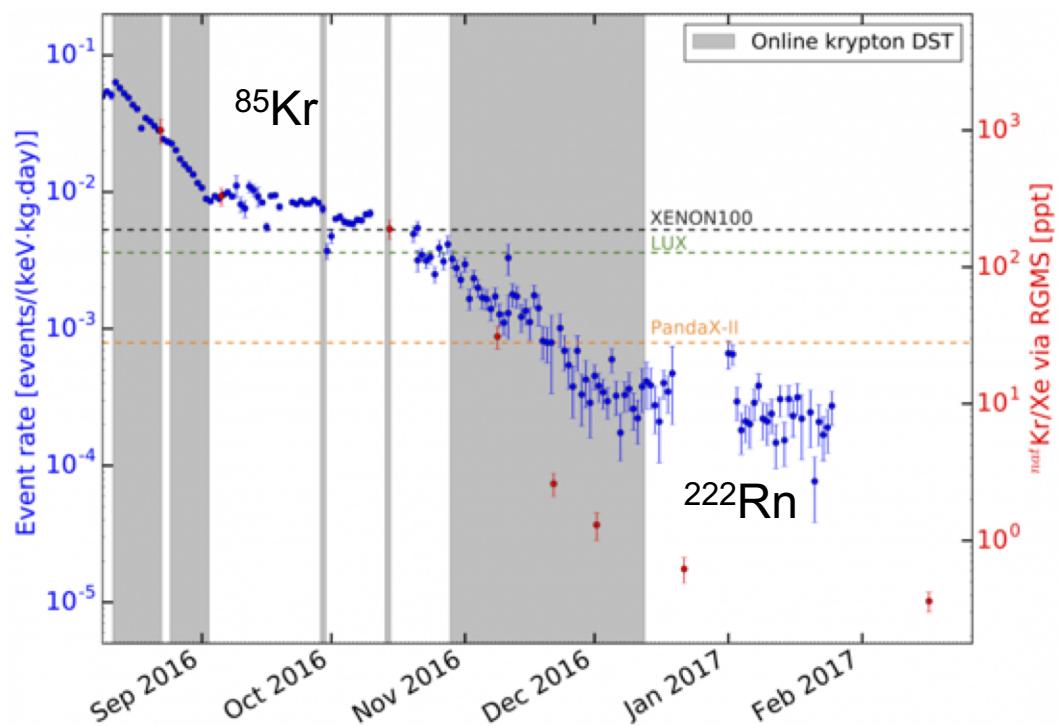
→ X,Y from top array
→ Z from Drift time

$$(S2/S1)_{WIMP,n} < (S2/S1)_{\gamma,\beta}$$



Electronic Recoil Background

- Initially ^{85}Kr dominated → distillation campaign → from 1 ppb to 0.66 ppt
- SR1 ^{222}Rn dominated from material emanation: $\sim 10 \mu\text{Bq/kg}$
- Lowest ER background in DM detector: $(82^{+5}_{-3} \text{ (syst)} \pm 3_{\text{(stat)}}) \text{ events}/(\text{t}\cdot\text{yr}\cdot\text{keV}_{\text{ee}})$

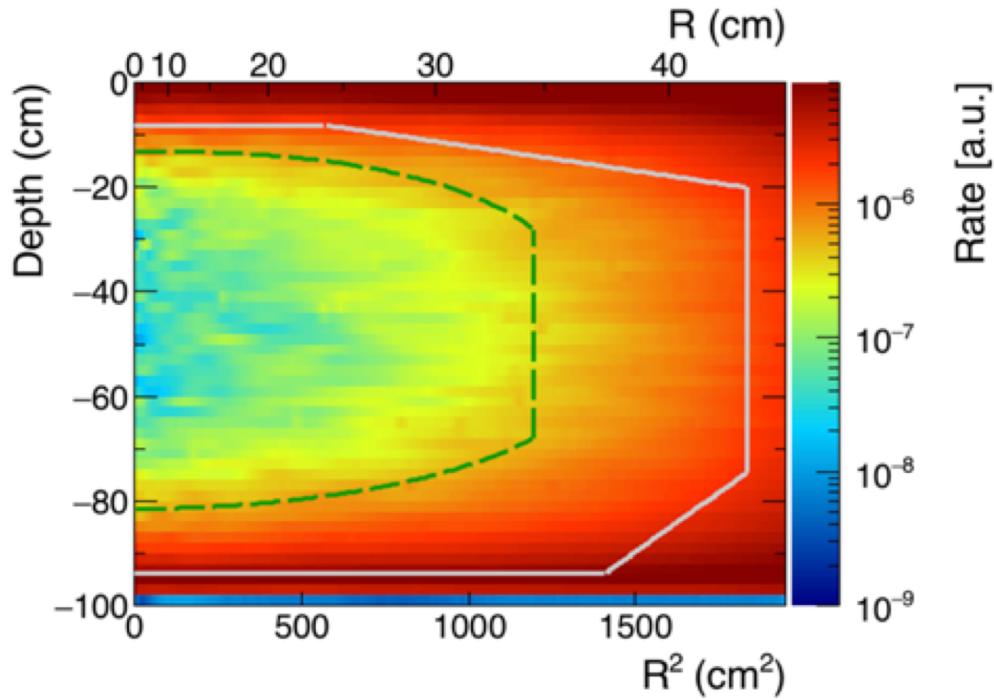


Source	Fraction [%]
^{222}Rn	85,4
^{85}Kr	4,3
Solar ν	4,9
Materials	4,1
^{136}Xe	1,4

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

Nuclear Recoil Background

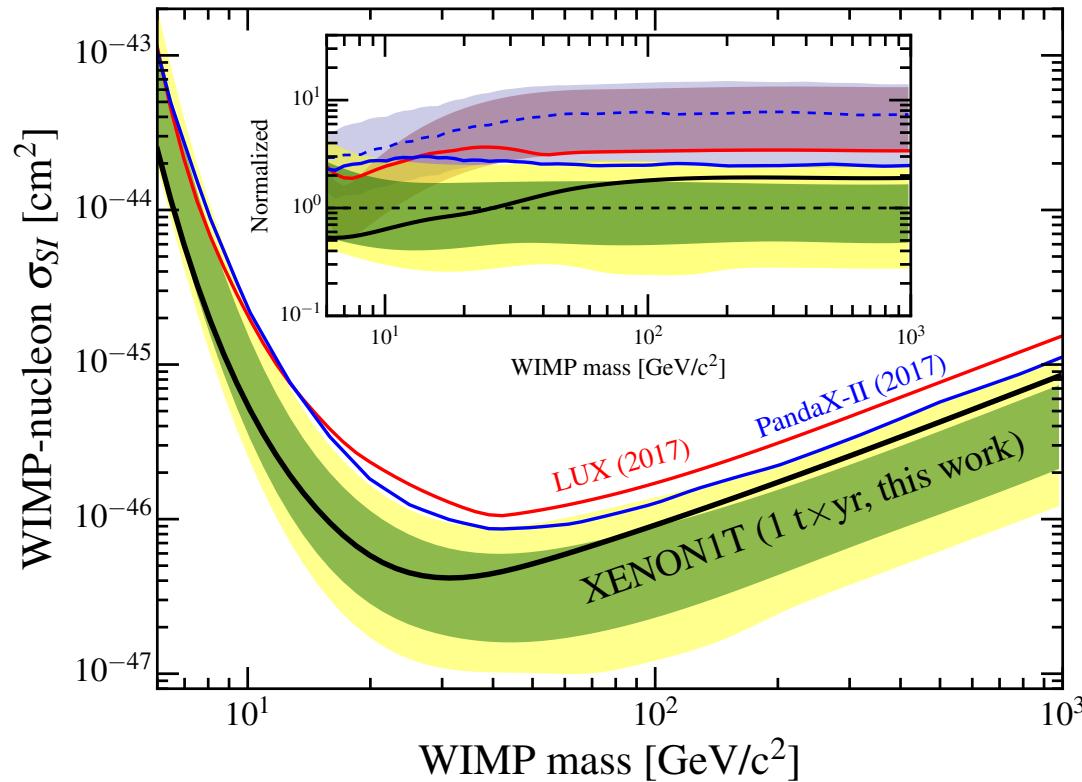
- **Radiogenic** neutrons from (α , n) reactions and fission from ^{238}U and ^{232}Th : reduced via careful materials selection, event multiplicity and fiducialization
- **Cosmogenic** μ -induced neutrons significantly reduced by rock overburden and muon veto
- **Coherent elastic ν -nucleus scattering**, constrained by ^8B neutrino flux and measurements, is an irreducible background at very low energy (1 keV)
- 9 neutron multiple scatters identified in the ROI



Source	Fraction [%]
Radiogenic n	96,5
CEvNS	2,0
Cosmogenic n	< 2,0

XENON1T Spin-independent Results

Strongest exclusion limits (at 90% CL) on WIMPs $> 6 \text{ GeV}/c^2$.



7 times better sensitivity
compared to previous
experiments (LUX, PANDAX-II)

World best limit:
First 1 ton \times years exposure !

$$\sigma_{\text{SI}} < 4.1 \cdot 10^{-47} \text{ cm}^2$$

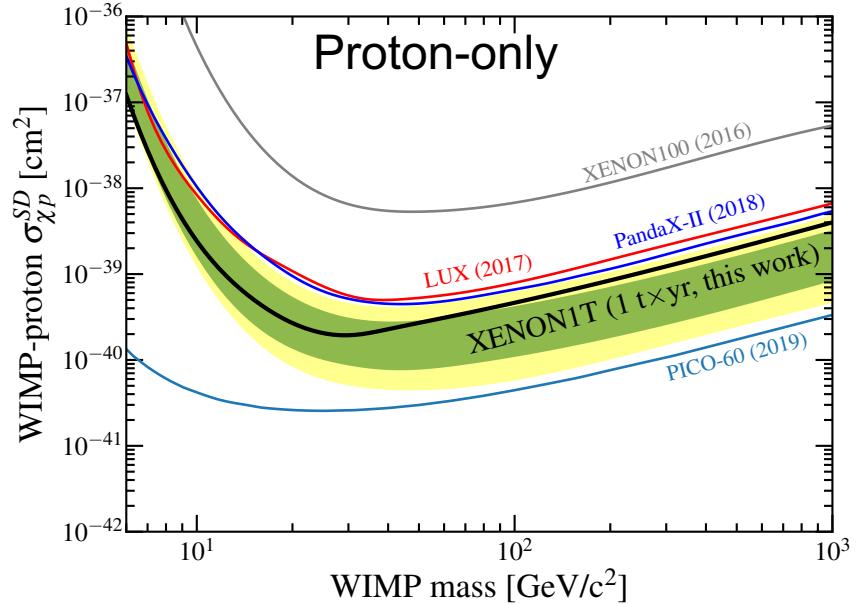
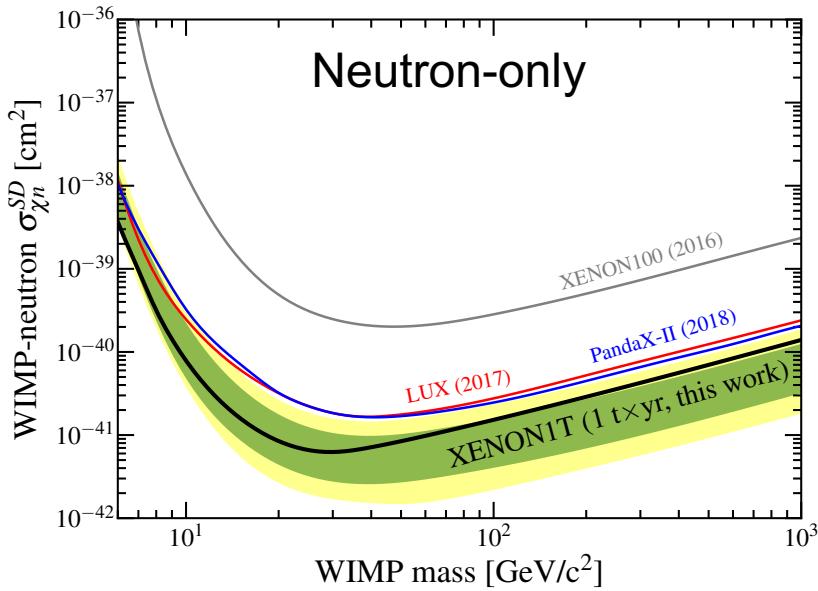
at 30 GeV/c^2

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

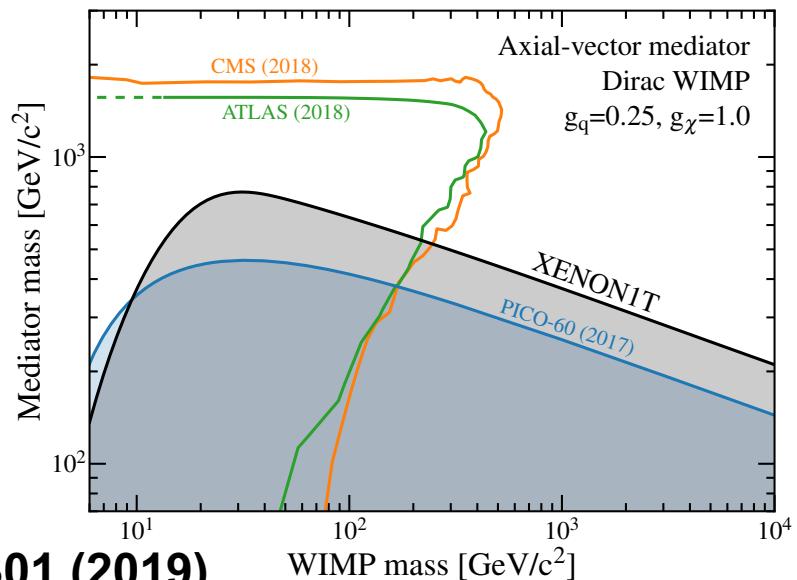
No significant excess (> 3 sigma) is observed.

Phys. Rev. Lett. 121, 111302 (2018)

XENON1T Spin-dependent Results

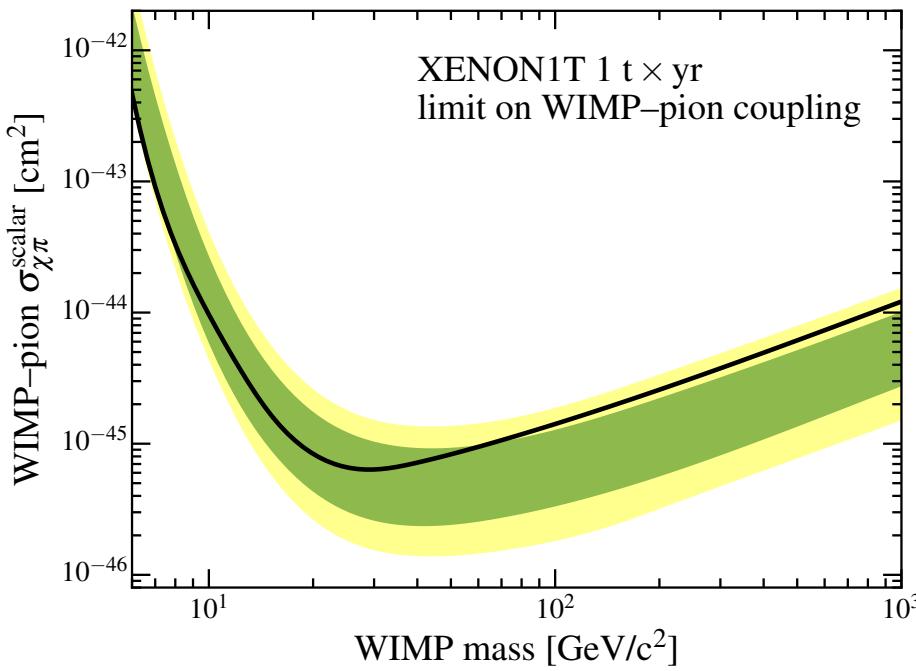
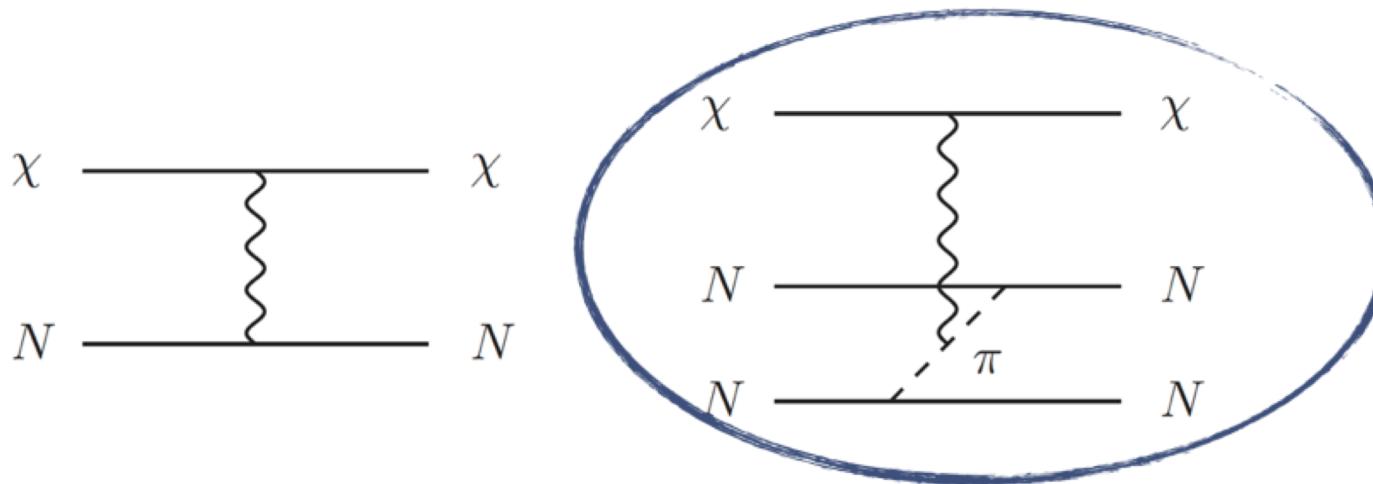


- WIMP-quark axial vector coupling
- WIMP-neutron scattering more sensitive for ^{129}Xe and ^{131}Xe
- Excluded new parameter space in isoscalar theory with axial vector mediator



Phys. Rev. Lett. 122, 141301 (2019)

XENON1T WIMP-Pion Coupling Results



- Coupling of WIMP with virtual pion-current between two nucleons
- Correction to SD WIMP analysis
- Same background model as SI analysis

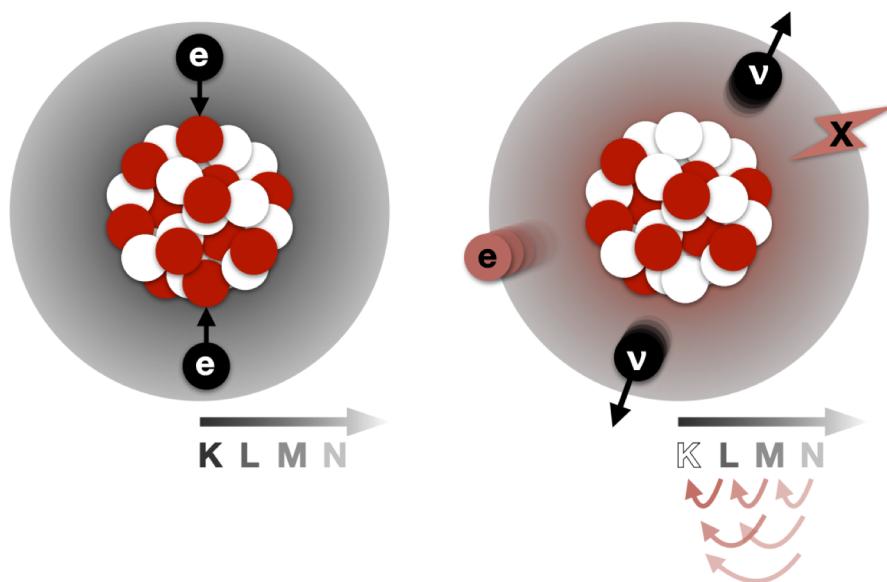
Phys. Rev. Lett. 122, 071301 (2019)

Double electron capture (DEC) with ^{124}Xe

- $^{124}\text{Xe} + 2\text{e}^- \rightarrow ^{124}\text{Te} + 2\nu_e$
- Vacancies on the K shell : Detectable cascade of X-rays and Auger electrons in the keV-range (64.3 keV)
- Large half-lives : $> 10^{12} \cdot T_{\text{univers}}$
- Needs very low background experiment

XENON1T

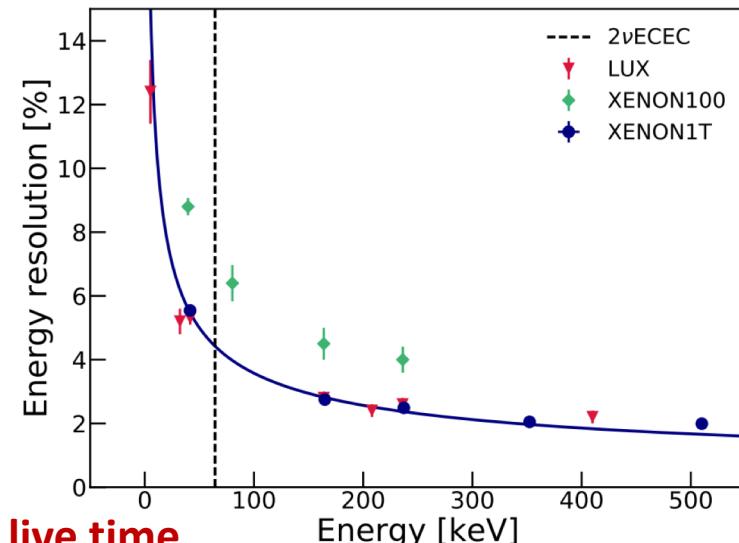
$^{124}\text{Xe} \sim 1 \text{ kg / t}$



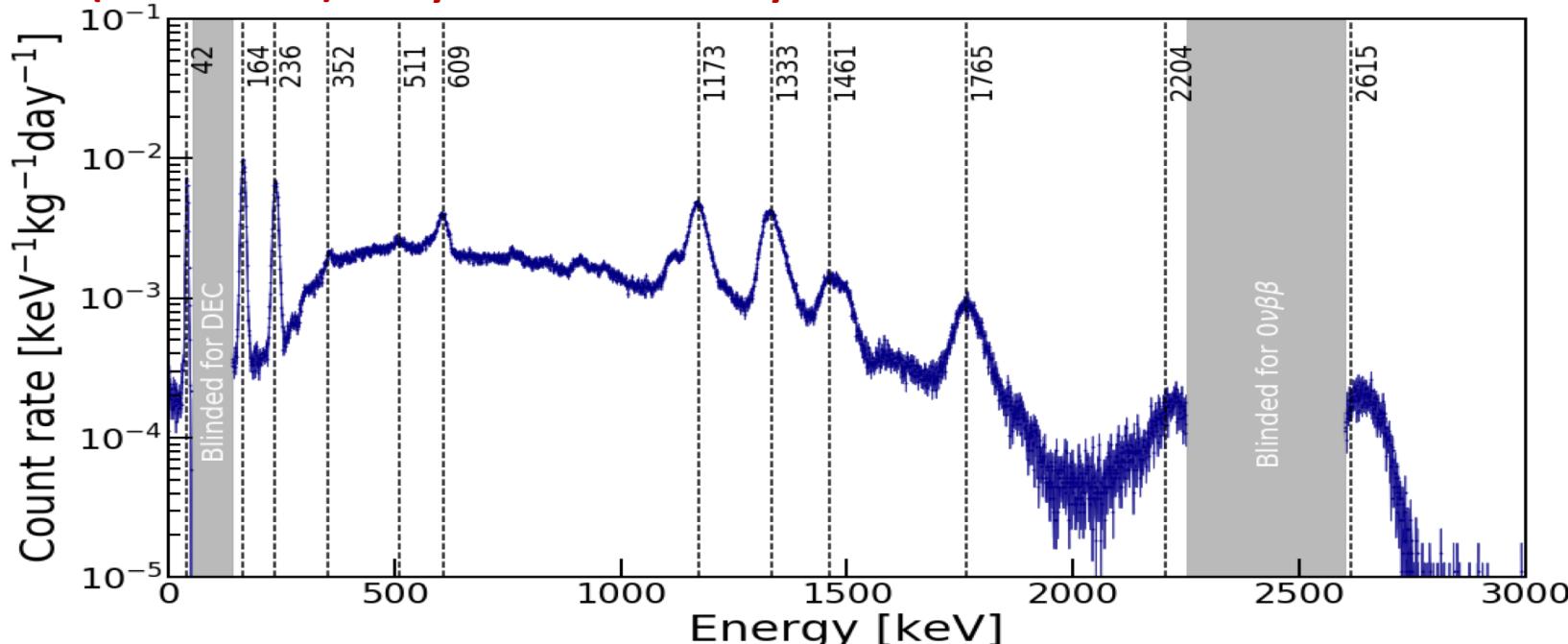
Double electron capture (DEC) with XENON1T

$^{124}\text{Xe} \Leftrightarrow$ Double K-shell capture :
X-rays and Auger electrons
Single peak @64.3 keV

Energy resolution @64.3 keV:
 $\frac{\sigma}{\mu} = (4.1 \pm 0.4) \%$



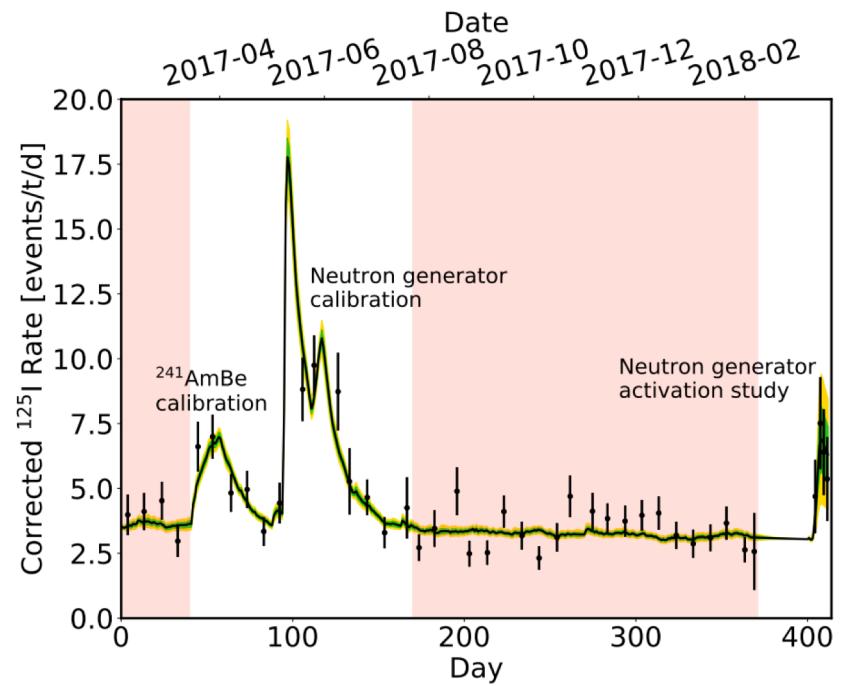
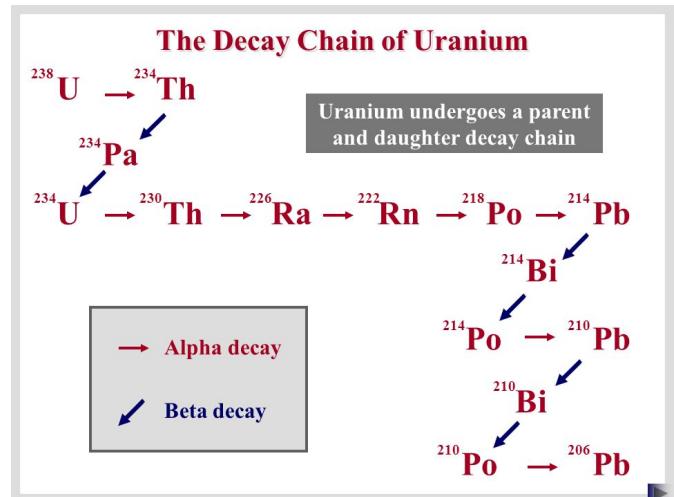
Blinded (56 – 72 keV) analysis with 177.7 days of live time



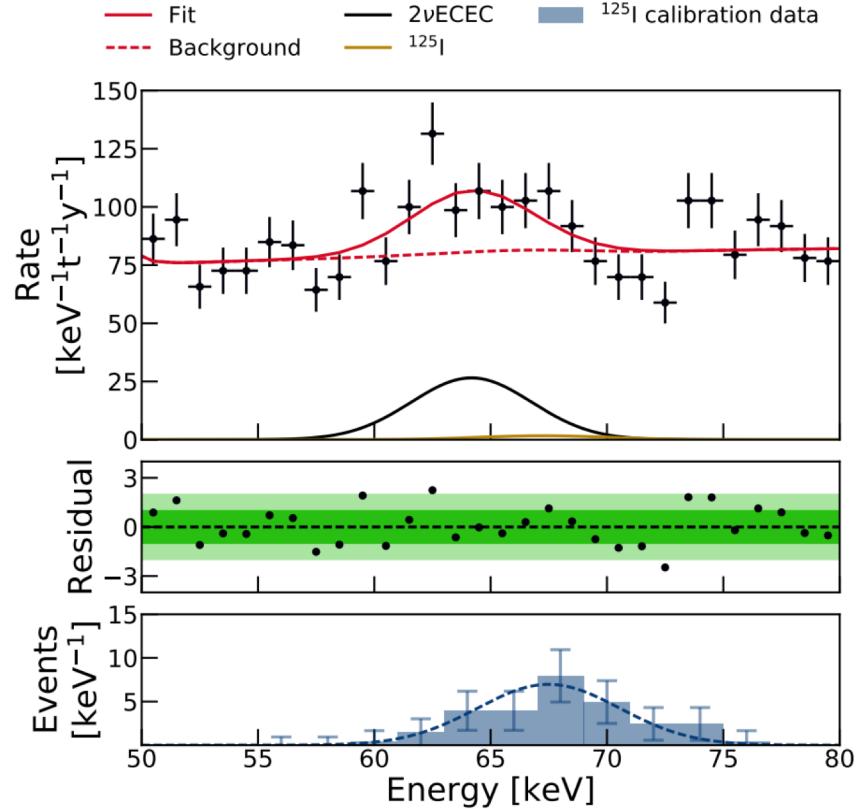
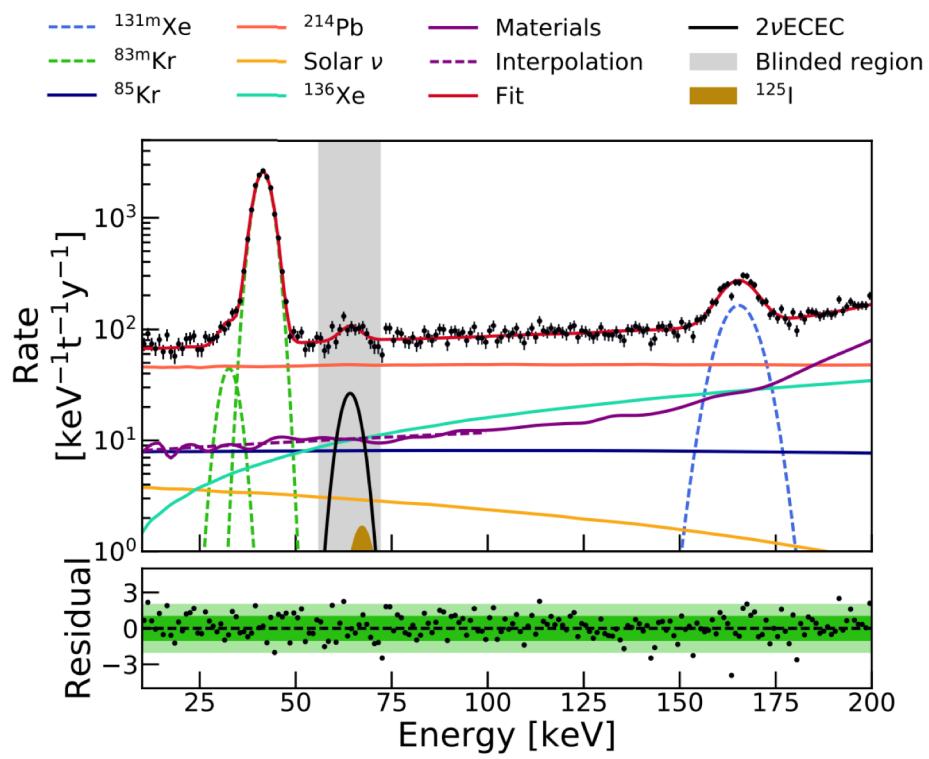
Double electron capture background

Most important background:

- Intrinsic ^{214}Pb :
 - ^{222}Rn daughter
 - β decay
- ^{125}I :
 - Peak @67.3 keV : close to the DEC peak
 - Half life of 59.4 d
 - Produced by calibration of XENON1T:
 - decay of ^{125}Xe which is produced by **neutron capture**
 - **Removed after ~ 9 days, by purification**
 - Predicted background : 10 ± 7 events
 - Measured background : 9 ± 7 events



Double electron capture (DEC) Results

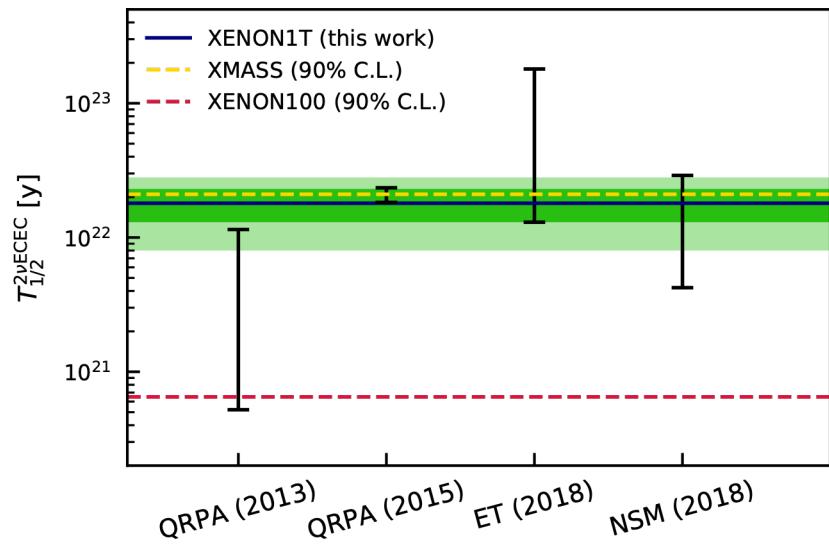
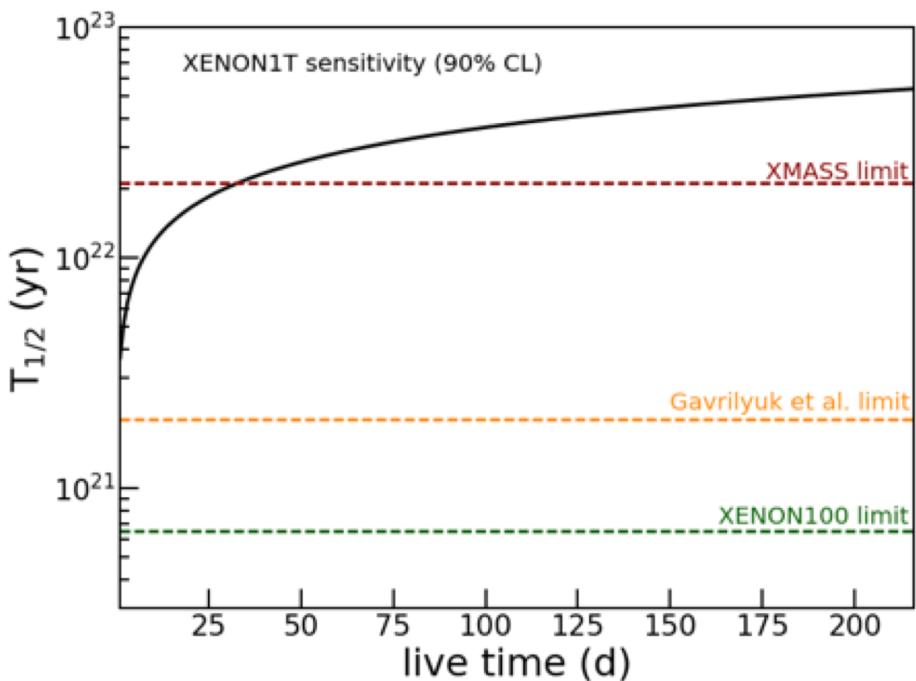


- Blinded region from 56 keV to 72 keV
- Ellipsoidal 1.5 t inner fiducial volume
- Peak at $E = (64.2 \pm 0.5)$ keV and $\sigma = (2.6 \pm 0.3)$ keV
- Significance 4.4σ

$$\text{Half-life } T_{1/2} = (1.8 \pm 0.5_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22} \text{ y}$$

Double electron capture (DEC) Results

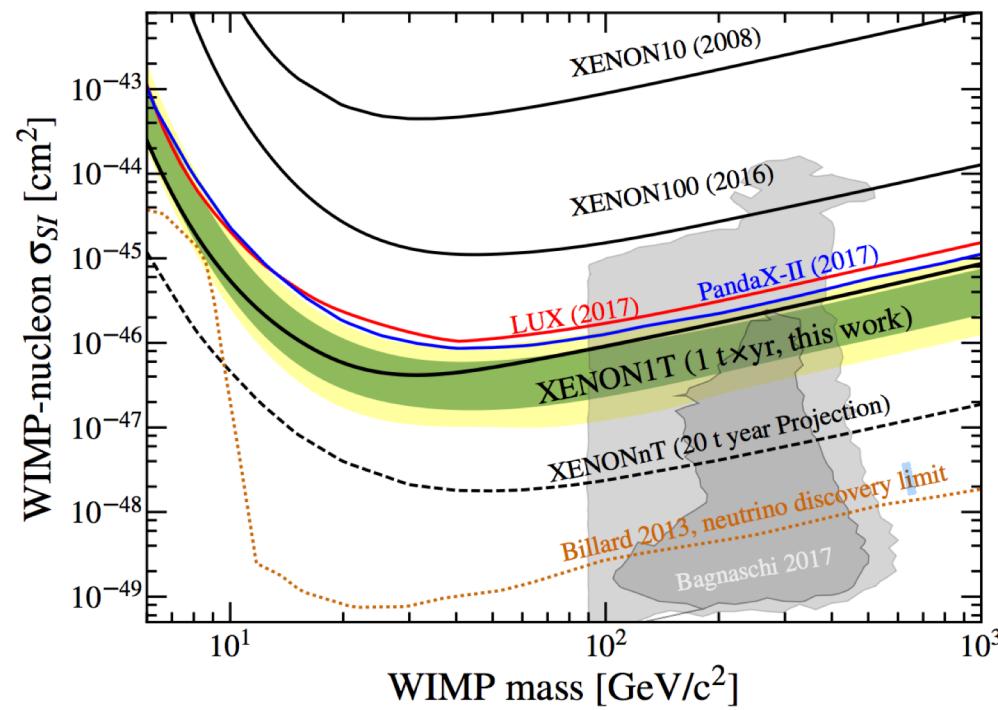
a) Variable in $T_{1/2}^{\text{ECEC}}$ calculation	Uncertainty [%]
Fiducial mass m	0.6
ROI cut acceptance ϵ	3.4
^{124}Xe abundance η	1.5



$$\text{Half-life } T_{1/2} = (1.8 \pm 0.5_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22} \text{ y}$$

Conclusions

- First multi-ton scale LXe-TPC successfully operated for more than 1 year
- **Strongest limit** on WIMP-nucleon SI cross-section above $6 \text{ GeV}/c^2$: minimum at $4.1 \cdot 10^{-47} \text{ cm}^2$ for a WIMP of $30 \text{ GeV}/c^2$
- Double Electron Capture detection : **longest half-life ever measured directly**
- Proof that xenon-based Dark Mater search experiments are sensitive for rare event searches

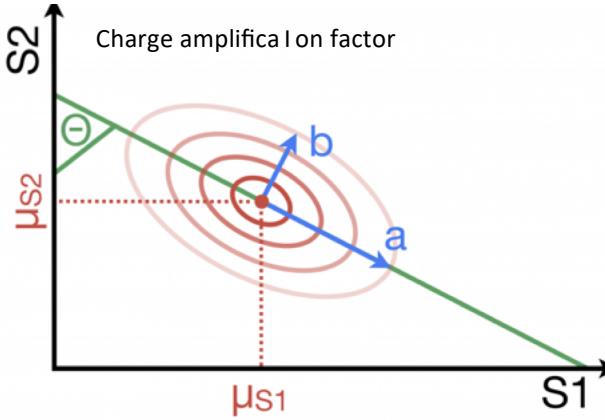
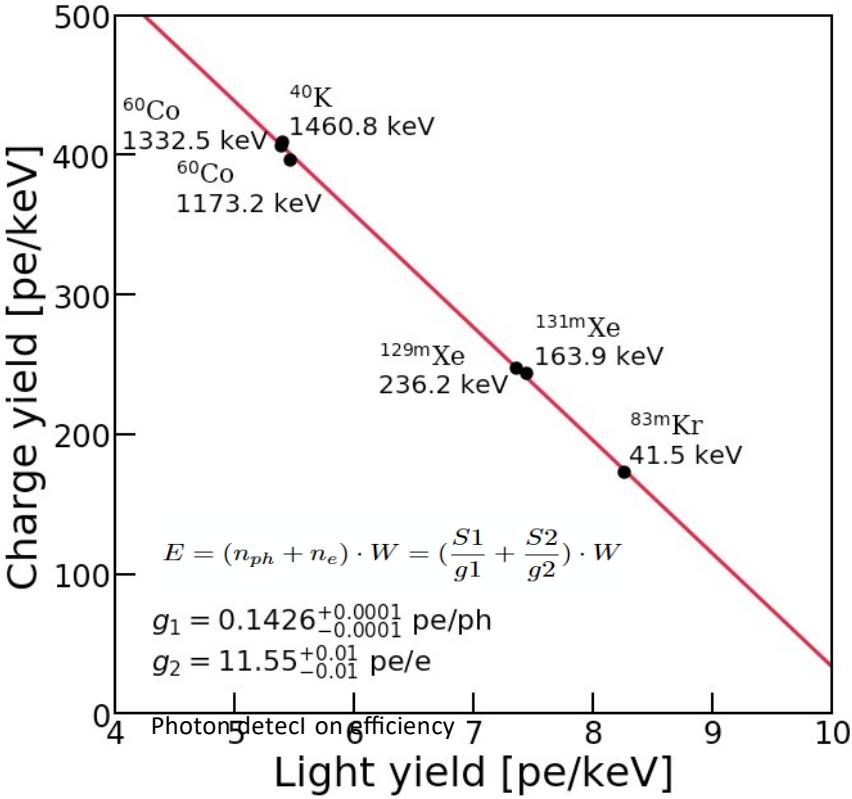


Other XENON1T analysis:

- S2 only analysis channel
- Annual modulation
- Migdal effect
- Light dark matter searches
- $0\nu\beta\beta$ of ^{136}Xe

Stay Tuned!

Energy Reconstruction



- Energy loss to either light or charge channel
→ S1/S2 anl correlation
- γ -lines from known sources
 - Internal source: ^{83m}Kr
 - Activated lines in NG: ^{129m}Xe , ^{131m}Xe
 - Detector material: ^{60}Co , ^{40}K
- Linear from keV to MeV

