
# Observation of two-neutrino double electron capture in Xe-124 with XENON1T

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Xe
XENON
Dark Matter Project

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XENON Collaboration*

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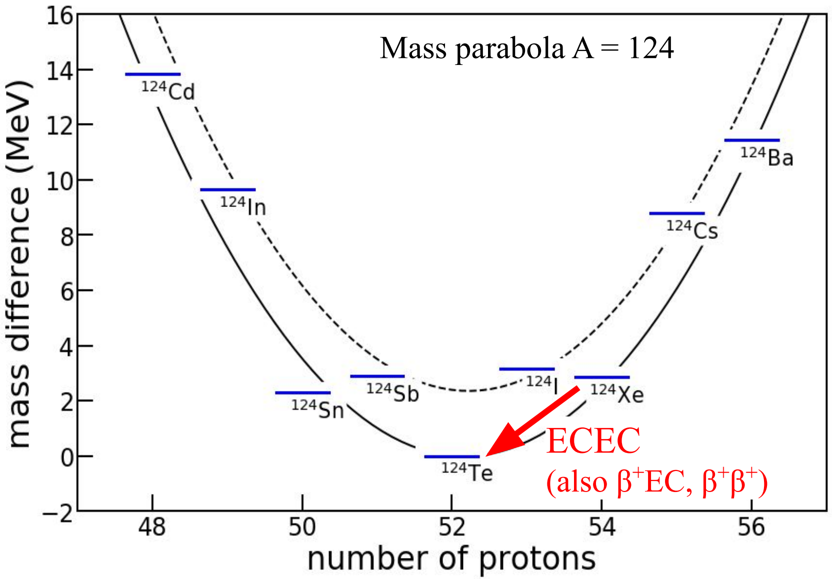
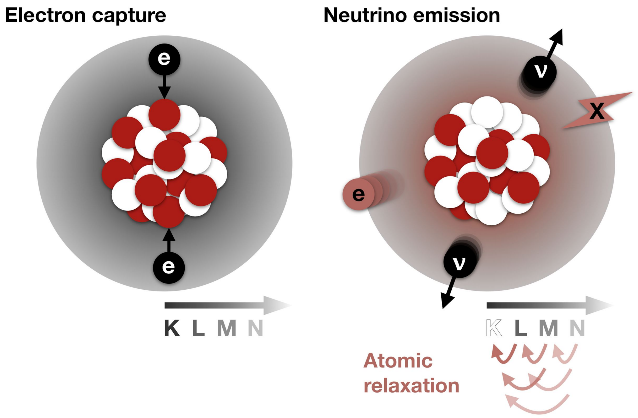
# What is 2-Neutrino Double Electron Capture (2νDEC)?



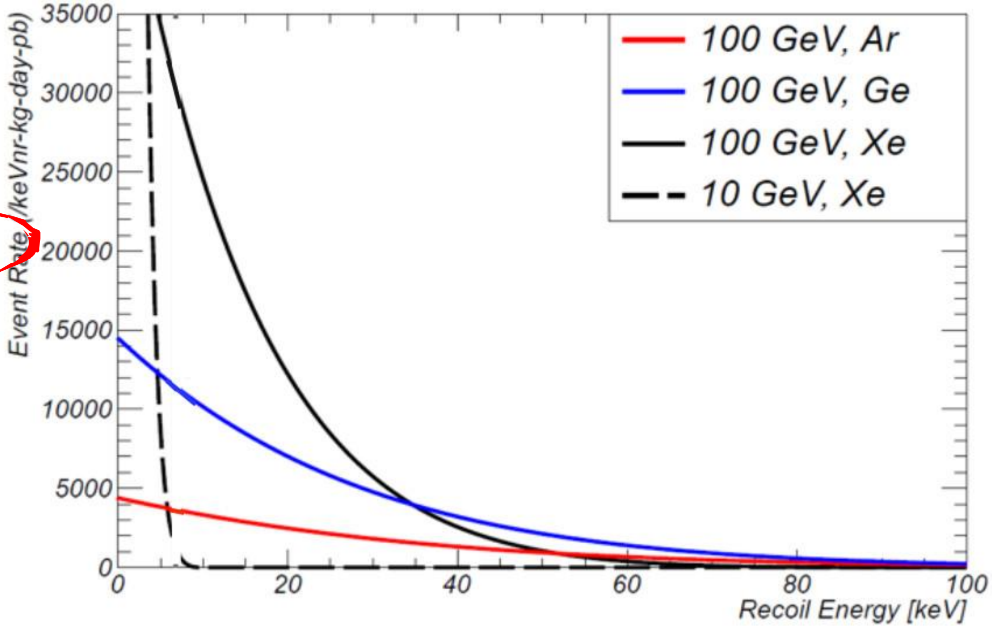

$$^{124}\mathrm{Xe} + 2e^- \rightarrow {}^{124}\mathrm{Te} + 2\nu_e \quad (Q_{DEC} = 2857\ \mathrm{keV})$$

- Nucleus captures two atomic shell electrons
- Recoil of nucleus O(10 eV) negligible
- Observe X-rays and Auger electrons
  - double K-shell capture: **$E_{DEC} = 64.3$ keV**

# Why looking for 2νDEC in $^{124}$Xe? (1)

## Rare event search: Liquid xenon (LXe) as detection medium

- Large mass number **A(131)**, higher rates for **SI** interactions (proportional to $A^2$)
- **50% odd** isotopes ($^{129}$Xe, $^{131}$Xe) for **SD** interactions
- No long-lived radioisotopes (with exception of $^{136}$Xe, $T_{1/2} = 2.2\times10^{21}$ y), **low intrinsic bg**
- High stopping power ($Z=54$, $\rho = 3$ g/cm$^3$), **self shielding**
- **Efficient scintillator** (80% light yield of NaI)
- Light output @ 178 nm (**no WLS needed**)
- Liquid at ~182K @ 2 bar, **easy cryogenics**



# Why looking for 2νDEC in $^{124}$Xe? (2)

## Nuclear matrix element computation

$$\left(T_{1/2}^{2\nu\mathrm{ECEC}}\right)^{-1} = G^{2\nu\mathrm{ECEC}} g_A^4 \left|M^{2\nu\mathrm{ECEC}}\right|^2$$

Phase-space factor
$G^{2\nu ECEC} = 1.72 \times 10^{-20}\ \mathrm{yr}^{-1}$
(e.g., Phys. Rev. C 87, 024313)

Effective axial-vector coupling constant
($g_A = 1.27$)

Nuclear matrix element
(e.g., arXiv:1809.04443)

- Large uncertainty
- Discrepancy between models
  QRPA: quasiparticle random-phase approximation
  ET: effective theory
  NSM: nuclear shell model

➔ **Detection of decay sheds light on calculations**

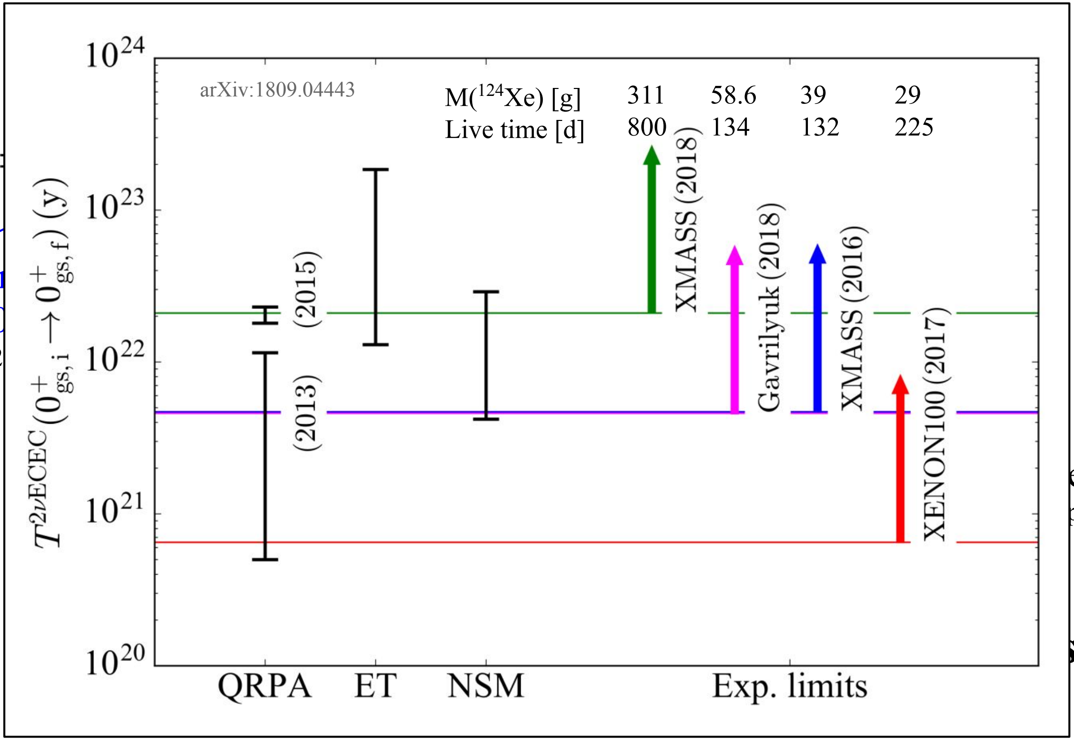
➔ **$M^{0\nu ECEC}$ related to $M^{2\nu ECEC}$**

# Why looking for 2νDEC in $^{124}$Xe? (2)

Nuclear matrix element computation

$$\left(T_{1/2}^{2\nu\mathrm{ECEC}}\right)^{-1}$$

Phase-space factor
$G^{2\nu ECEC}$ = 1.72×10
(e.g., Phys. Rev. C 87, 02




els
pproximation

**sheds light**

➔ **$M^{0\nu ECEC}$ related to $M^{2\nu ECEC}$**

# Why looking for 2νDEC in $^{124}Xe$? (3)

Rare event search: Liquid xenon (LXe) as detection medium

Because we can.

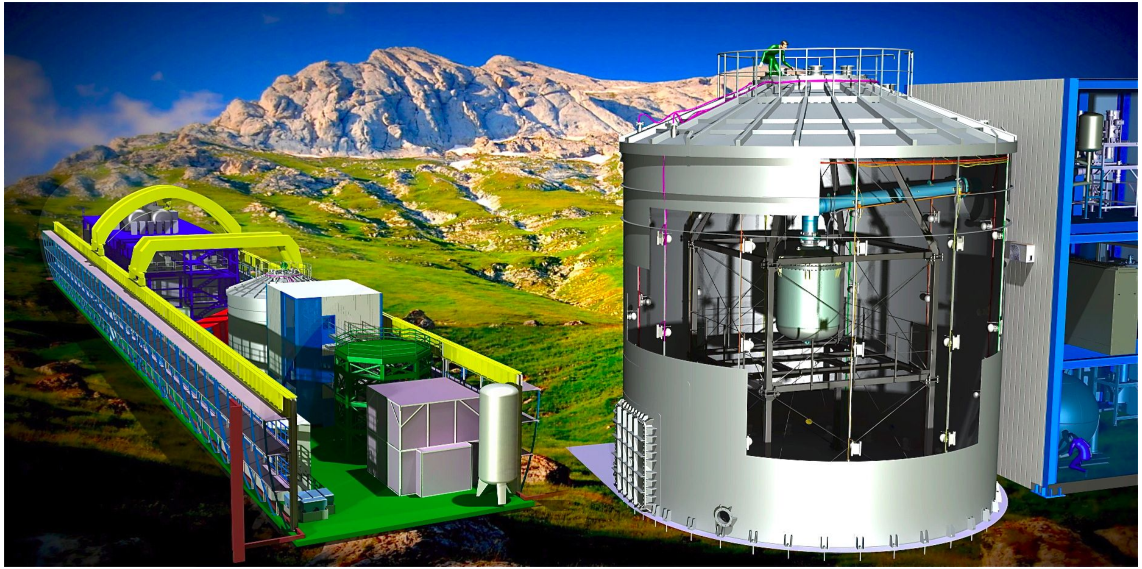
- Isotopic abundance of $^{124}Xe$: $\eta_{124Xe} \approx 0.1\%$
  ➜ ~ **1.5 kg of $^{124}$Xe target mass** (1.5 t total)
- Good energy resolution < 5%
- Low background < $10^{-3}$ cts $keV^{-1}$ $kg^{-1}$ $day^{-1}$
- Live time > 100 days

# XENON1T

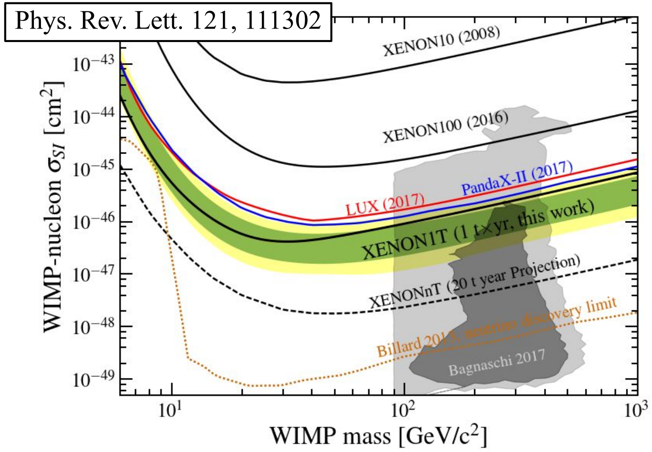
- ~160 scientists
- 27 institutions


# XENON1T

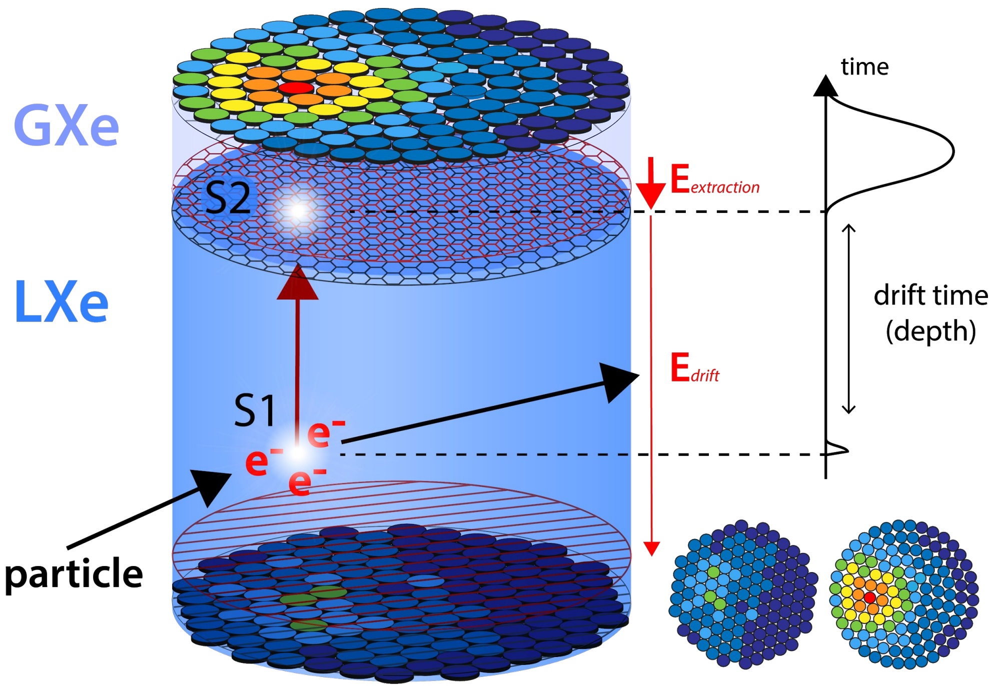
- Build for searching dark matter in form of WIMPs
- First tonne scale LXe detector
- Located at LNGS, Italy
- Most stringent limit on WIMP-nucleon spin-independent elastic scatter cross-section for WIMP masses above 6 GeV/$c^2$

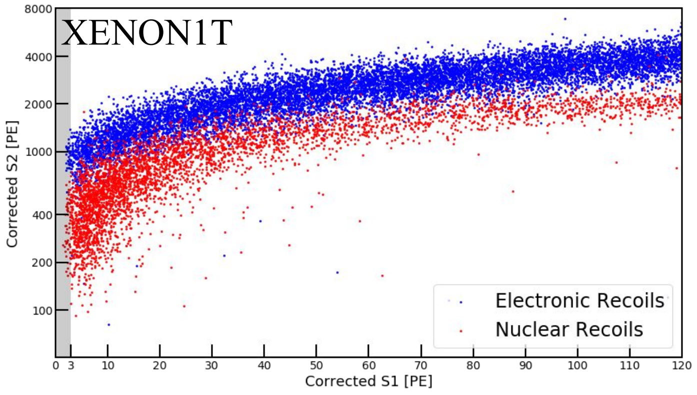


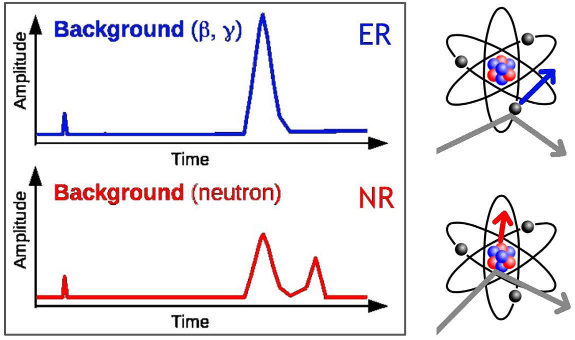
Talk by A. Molinario



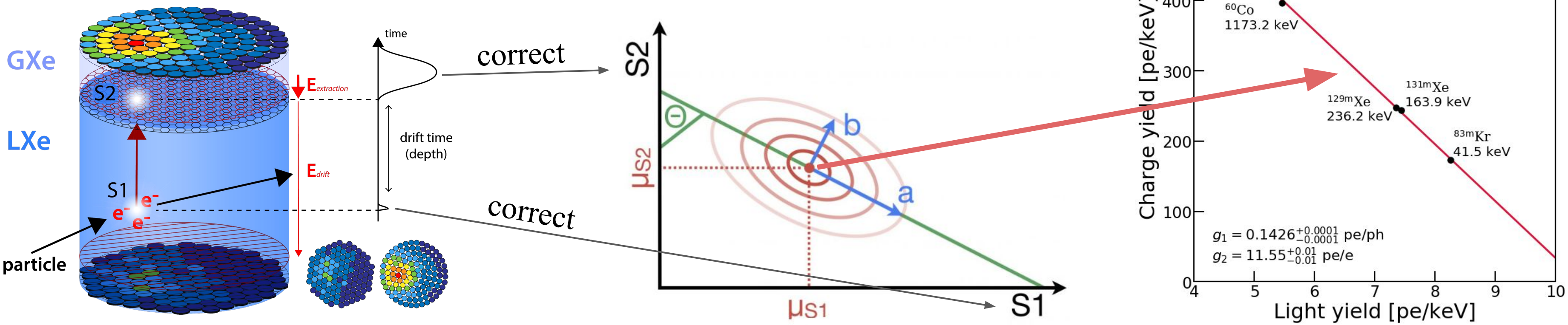
# Detection principle of 2-phase LXe TPC



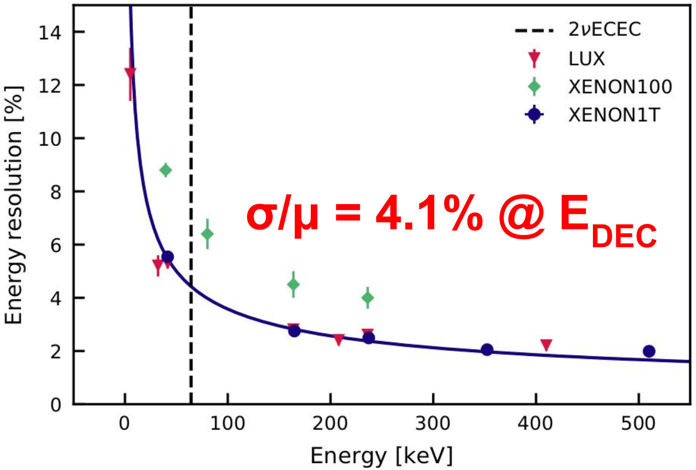
# Energy scale determination



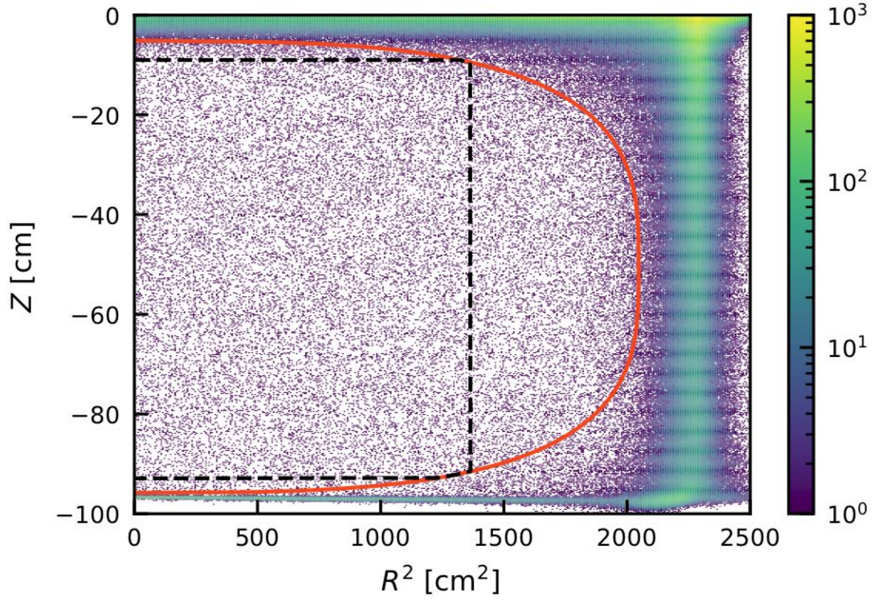

Combined Energy Scale (CES):

$$E = (N_{ph} + N_e) \times W$$
$$= (S1/g_1 + S2/g_2) \times W$$

(average energy to generate measurable quanta in LXe: W = 13.7 eV)



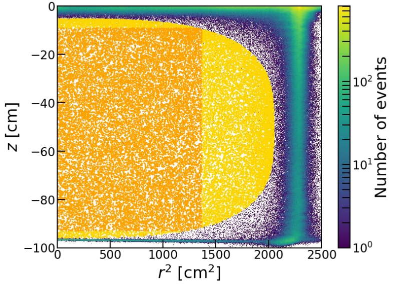
# Exposure and Fiducial Volume (FV)

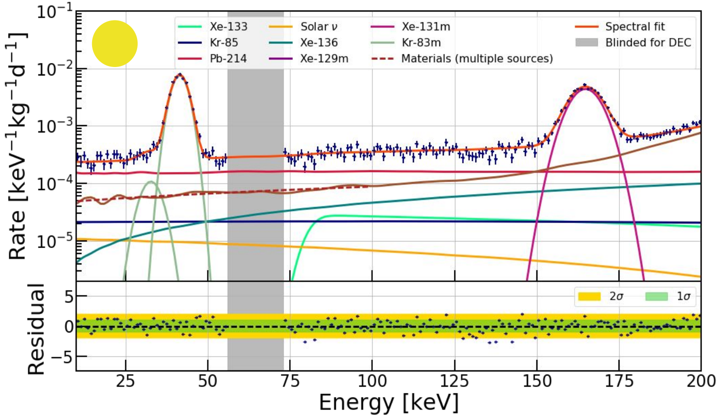



Optimize sensitivity $\propto$ $\text{mass}_{FV} \times (N_{Bg})^{-1/2}$
(in energy range [80, 140] keV)

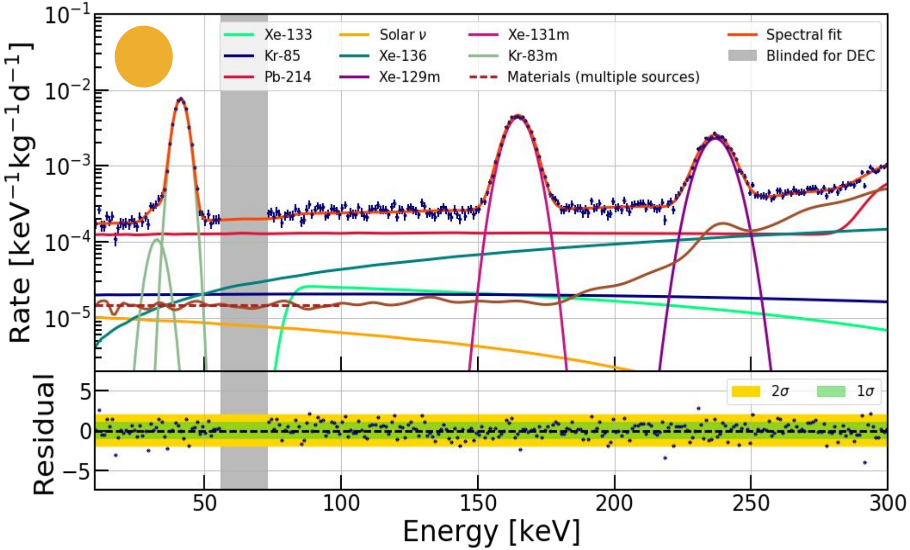
- 1.5 t FV (red)
- 1.0 t inner / 0.5 t outer (dashed black)
- In-situ abundance measurement:
  $^{124}\text{Xe}/^{nat}\text{Xe} = (9.94 \pm 0.14_{stat} \pm 0.15_{sys}) \times 10^{-4}$
  ➜ $\mathbf{m_{124Xe} = 1.49\ kg}$
- **177.7 days** total live time

# Background Model




- XENON1T MC:
  - physical processes (Geant4)
  - detector specific response
- MC spectra matched to measured data
  - simultaneously in both volumes (orange/yellow)
  - including all known backgrounds
  - linear interpolation of material backgrounds (below 100 keV)
  - 27 fit parameters in total



# $^{125}$I Background

(1) artificial activation during calibration campaigns
(DD-fusion neutron generator and/or $^{241}$AmBe source)

(2) (radiogenic) activation outside the water shield
by environmental thermal neutrons.

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

capture of thermal neutrons

$$^{125}\mathrm{Xe} \xrightarrow[EC]{16.9\,\mathrm{h}} {}^{125}\mathrm{I}^* + \nu_e$$

$$^{125}\mathrm{I}^* \xrightarrow{<1\,\mathrm{ns}} {}^{125}\mathrm{I} + \gamma + X$$

→ tag/model background
(Lines at 222 keV and 277 keV)

$$^{125}\mathrm{I} \xrightarrow[EC]{59.4\,\mathrm{d}} {}^{125}\mathrm{Te}^* + \nu_e$$

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

→ Gaussian line at 67.3 keV

# $^{125}$I Background

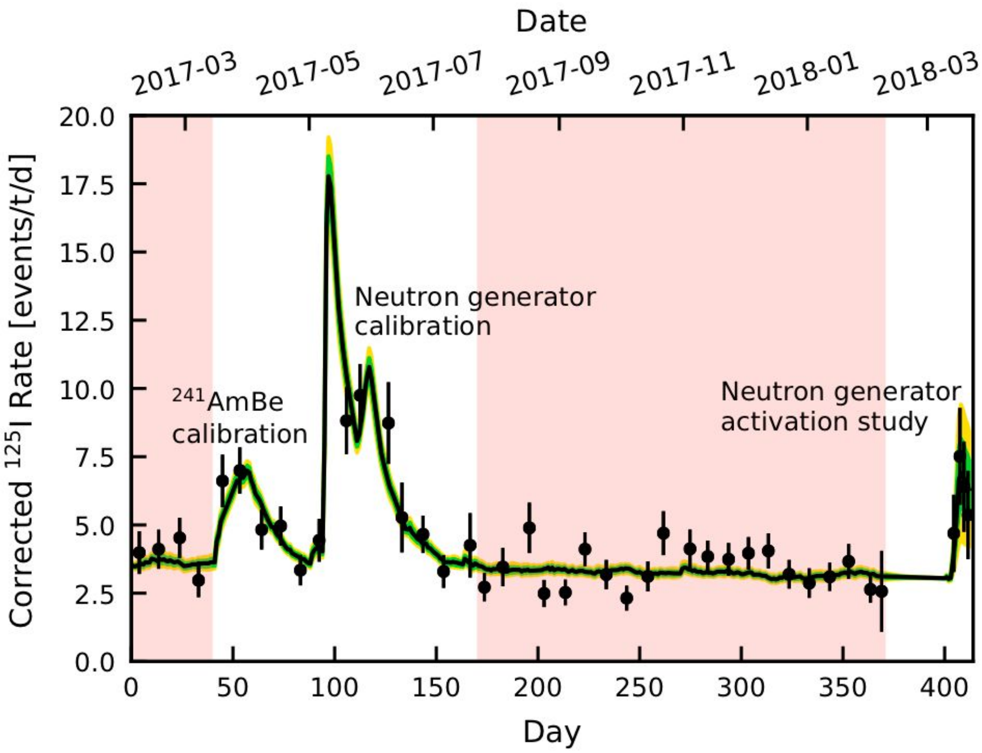
$$^{124}\mathrm{Xe} + n \rightarrow {}^{125}\mathrm{Xe} + \gamma$$

$$^{125}\mathrm{Xe} \xrightarrow[EC]{16.9\,\mathrm{h}} {}^{125}\mathrm{I}^{*} + \nu_e$$

$$^{125}\mathrm{I}^{*} \xrightarrow{<1\,\mathrm{ns}} {}^{125}\mathrm{I} + \gamma + X$$

$$^{125}\mathrm{I} \xrightarrow[EC]{59.4\,\mathrm{d}} {}^{125}\mathrm{Te}^{*} + \nu_e$$

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




**Artificial** (DD, AmBe) $^{125}$I:
Fit $^{125}$Xe model to $^{125}$I data

➔ $\tau_{eff}$ = (9.1 ± 2.6) d

➔ $N_{125\text{-I,art}}$ = (6 ± 6) events

**Radiogenic** $^{125}$I:
(measured neutron flux, 5kg Xe outside water tank):

➔ $N_{125\text{-I,rad}}$ = (4 ± 3) events

➔ **$N_{125\text{-I,tot}}$ = (10 ± 7) events**

# Fitting method

$$\chi^2_{\text{combined}}(\boldsymbol{p}) = \sum_i \frac{[R_i - f(E_i, \boldsymbol{p})]^2}{(\Delta R_i)^2}$$

$$f(E_i, \boldsymbol{p}) = \left[ \sum_k^{\text{materials}} p_k R_k(E_i) \right]_{\text{interpolated} < 100\,\text{keV}} + \sum_l^{\text{intrinsic}} p_l R_l(E_i) + \sum_m^{\text{Gaussians}} \text{Gaussian}_m(\boldsymbol{p}_m, E_i)$$

$$\chi^2_{\text{combined}}(\boldsymbol{p}, \boldsymbol{V}, \boldsymbol{\kappa}) = \chi^2_{\text{inner}}(\boldsymbol{p}, V_{\text{inner}}, \kappa_{\text{inner}}) + \chi^2_{\text{outer}}(\boldsymbol{p}, V_{\text{outer}}, \kappa_{\text{outer}}) + \text{constraint}_{\boldsymbol{p}} + \text{constraint}_V + \text{constraint}_\kappa$$

Backgrounds

Fiducial Volume

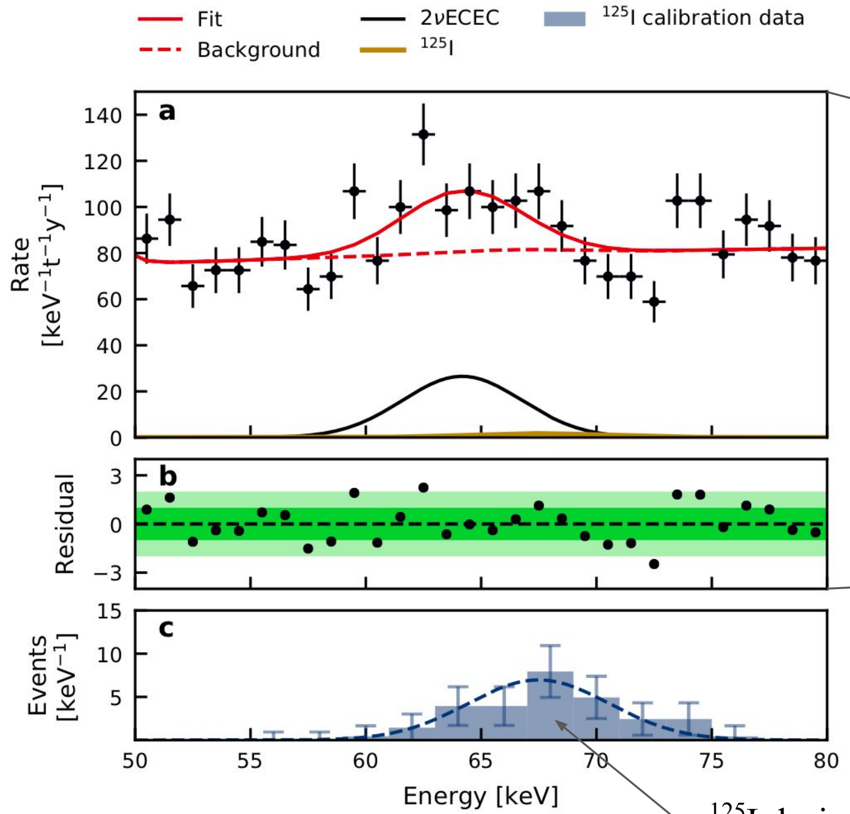
Cut acceptance

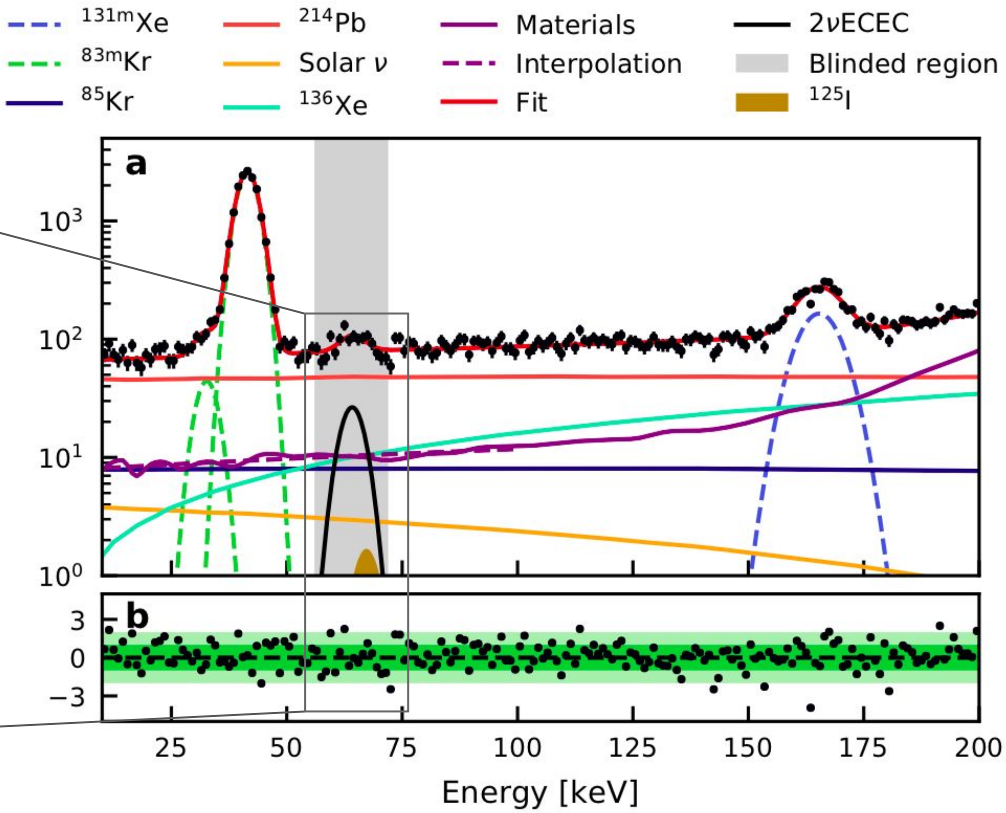
$$\text{constraint}_j = \frac{(\text{parameter}_j - \text{expectation}_j)^2}{\text{uncertainty}_j^2}$$

(Penalty terms)

$R_i$ - measured event rate
$R_{k,l}$ - MC rates
$p_{k,l,m}$ - fit parameters

# Results



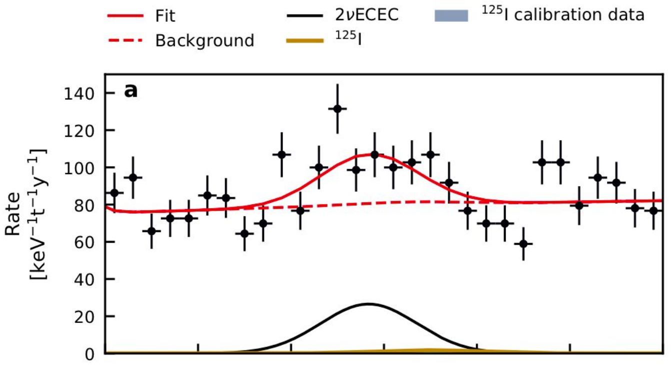



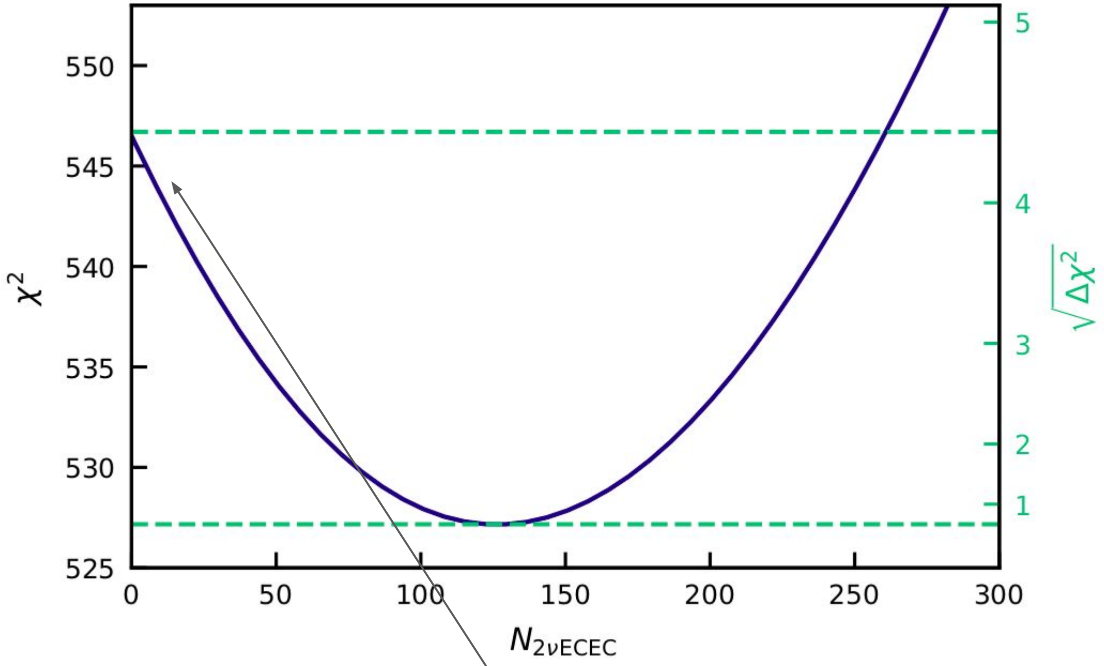

$^{125}$I during/after neutron calibrations

Best-fit results:

- $N_{DEC}$ = 126 (black)
- $N_{125I}$ = 9 (gold)

# Results

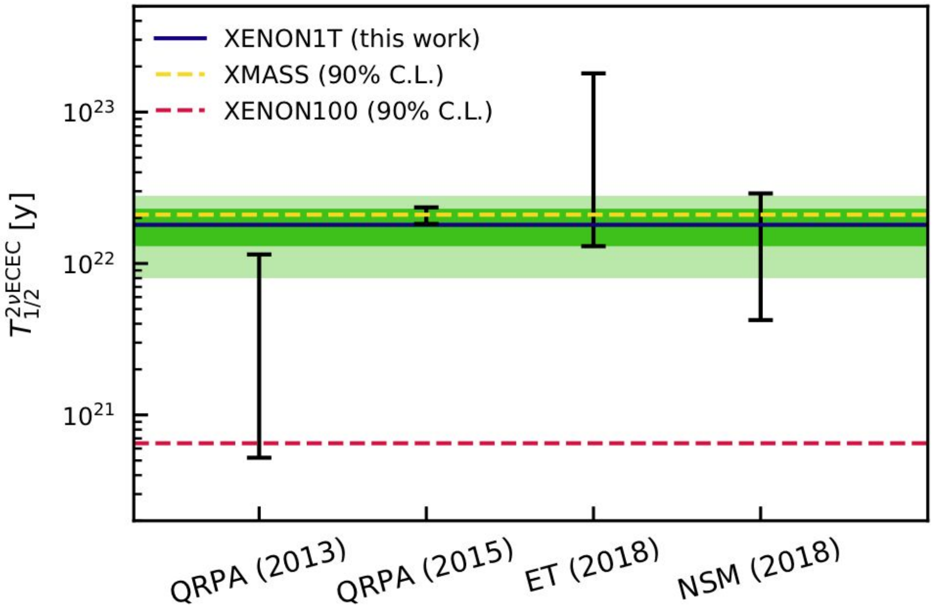


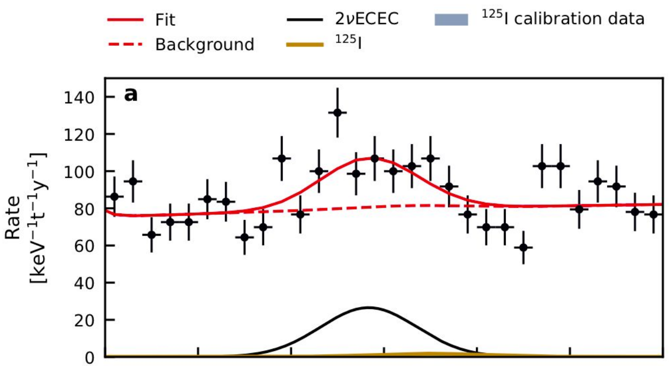




Compare local ($N_{2\nu ECEC}$ fixed) best-fit to global best-fit ($N_{2\nu ECEC}$= 126)

Null hypothesis excluded at 4.4σ

# Results




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

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

E. Aprile et al., Nature 568 (2019), no.7753, 532535

Cut acceptance

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

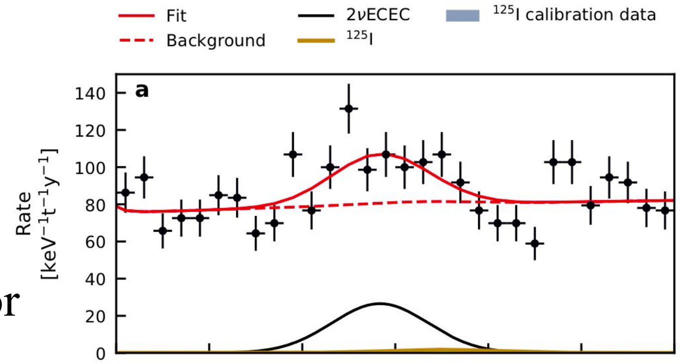
$^{124}$Xe abundance

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

$^{nat}$Xe target mass

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

# Summary




- 2νDEC is second-order weak interaction
- Measurement of 2νDEC half-life is important input for nuclear structure models

- We analysed a total of 177.7 life-days with 1.49 kg of $^{124}Xe$ target mass
- Half-life of $1.8 \times 10^{22}$ yr measured with 4.4 σ significance

  ➜ **Longest half-life measured directly so far**

  ➜ **LXe-TPCs can detect (not only exclude) signals**

# Backup

# Background model details

In total the MC/data matching is performed using **27 fit parameters** for the background isotopes:

- 6 parameters for the material contributions (Co-60, K-40, U-238, Ra-226, Th-232, Th-228). The material component is linearly interpolated between 10 keV and 100 keV. This avoids overfitting the wiggles introduced to an expectedly featureless spectrum by low MC statistics to data.

- 3 intrinsics in the liquid xenon (Pb-214, Kr-85, Xe-136).

- 1 from solar neutrinos.

- 2 for neutron activated components with multiple peaks or a continuous spectrum (Xe-125 and Xe-133).

- 6 for Kr83m (area, width and position for the peak and its mis-modeled low energy signal).

- 6 for the meta-stable isotopes from neutron activation (Xe-131m and Xe-129m).

- 3 for I-125 (area, width and position).