Double-weak decays of ^{124}Xe and ^{136}Xe in the XENON1T and XENONnT experiments

Group C (Neutrino Physics)

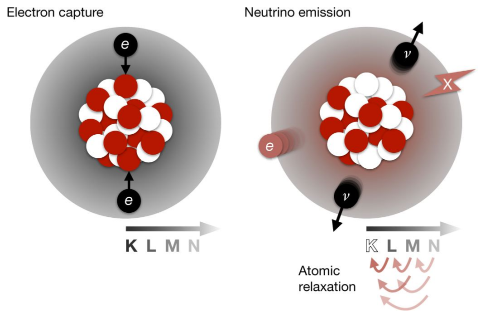
Featuring results from Phys. Rev. C **106**, 024328

Group Members:
Amandeep Kaur, Atakan Tugberk Akmete, Bongho Tae, Giorgi Kistauri, Harjot Kaur, HyonSan Seo, Jing Zhao, **José Pretel**, Juhee Song, Marcos Miralles, Mehdi Hajimaghsoud, Simran Gurdasani, Tong Pan, Vilius Čepaitis, Younghoon Lee, Wai Yuen Chan

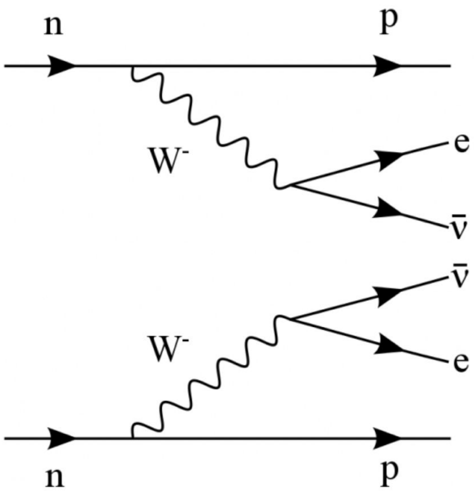
A neutrino was here
(and trillions more! :P)

Two-neutrino double electron capture (2νECEC)

- Important for nuclear structure models
- Second-order weak-interaction process.



- Nuclear binding energy released via the 2ν, which cannot be detected.



2νββ decay

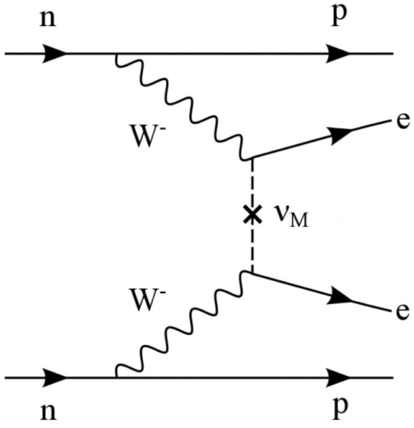
$\Delta L=0$

<u>Neutrinoless double-*β* decay (*0νββ*)</u>

- Possible if neutrino is Majorana
- Sensitive to
  - Neutrino mass
  - Lepton number violation
- Best lower limit on the ^{136}Xe half-life up-to-date from KamLAND-Zen

$$T^{0\nu}_{1/2} > 2.3 \times 10^{26} \text{ yr at } 90\% \text{ C.L.}$$

- Requirements for a *0νββ* decay of ^{136}Xe
  - Low background rate
  - Good energy reconstruction and resolution



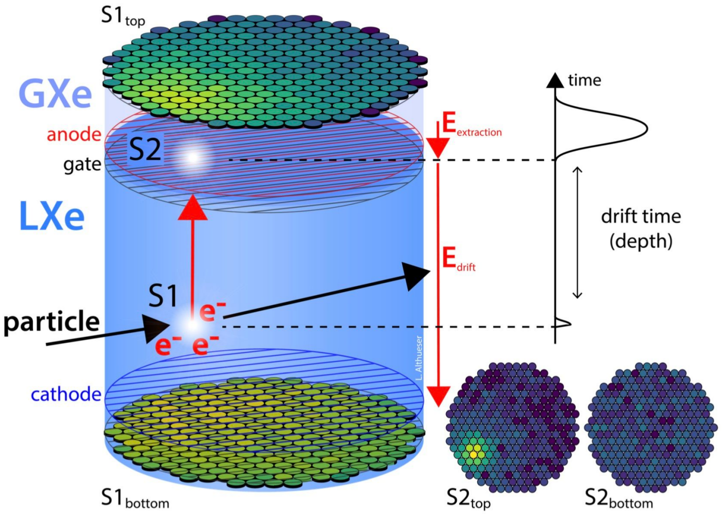
ΔL=2

0νββ decay

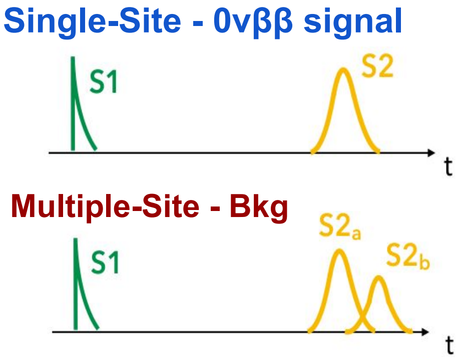
- **Signature in Xenon1T**: energy deposits on atomic electrons in xenon: electronic recoil (ER)

XENON1T Detector

- **Main goal**: Direct detection of WIMPs (DM candidates)
- Location: Laboratori Nazionali del Gran Sasso (LNGS), Italy,
    - ~1300m rock-equivalent wall
- 3.2 t detector ⇒ Target mass of 2.0 t
- **(Dual-phase) Time Projection Chamber (TPC) [1]**

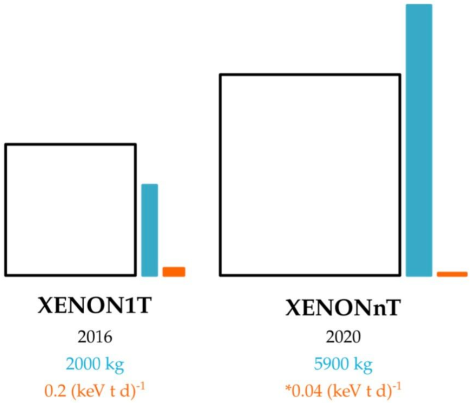


$$\frac{S2}{S1}(ER) > \frac{S2}{S1}(NR)$$



Upgrades for XENONnT:

- **More Xe**: 5.9 t LXe with a 8.4 t capacity
- **Less background**: Radon removal, LXe purification, neutron veto, …



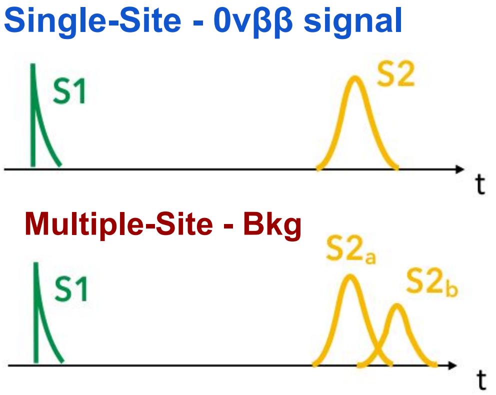
Event Selection

Dataset:

- Scan energies between 1600 and 3200 keV
  - 0νββ peak at $Q_{\beta\beta} = (2457.83 \pm 0.37)$ keV
- Isotope exposure of 36.16 kg yr

Analysis Strategy:

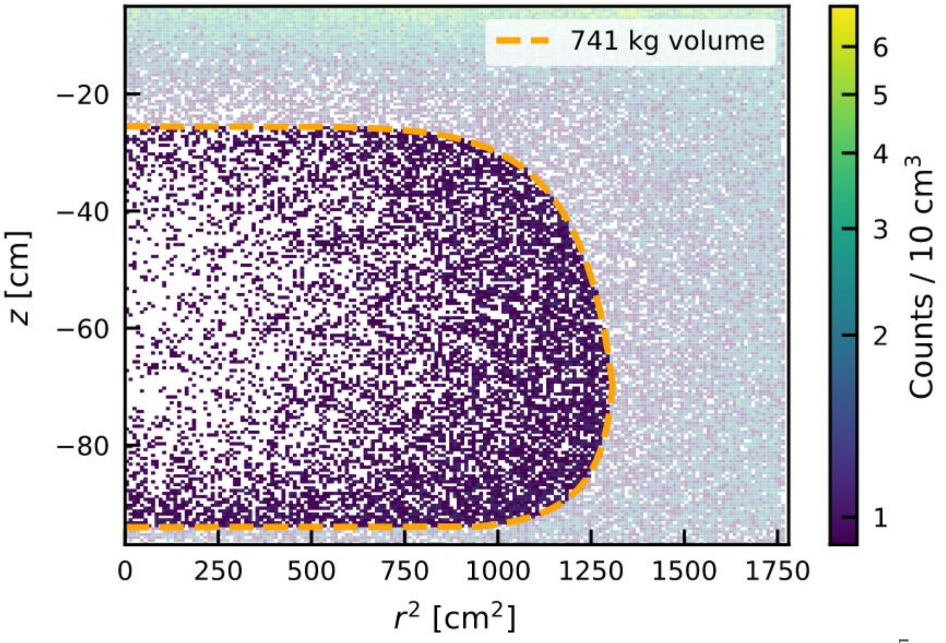
- Select events that have one S1 signal and one S2 signal with the correct shape pattern of the S2 signal



Ref: Xenon1T Public Talk

Signal Acceptance Optimization

- An FV (Fiducial Volume) in the detector is chosen that maximises signal-to-noise ratio:

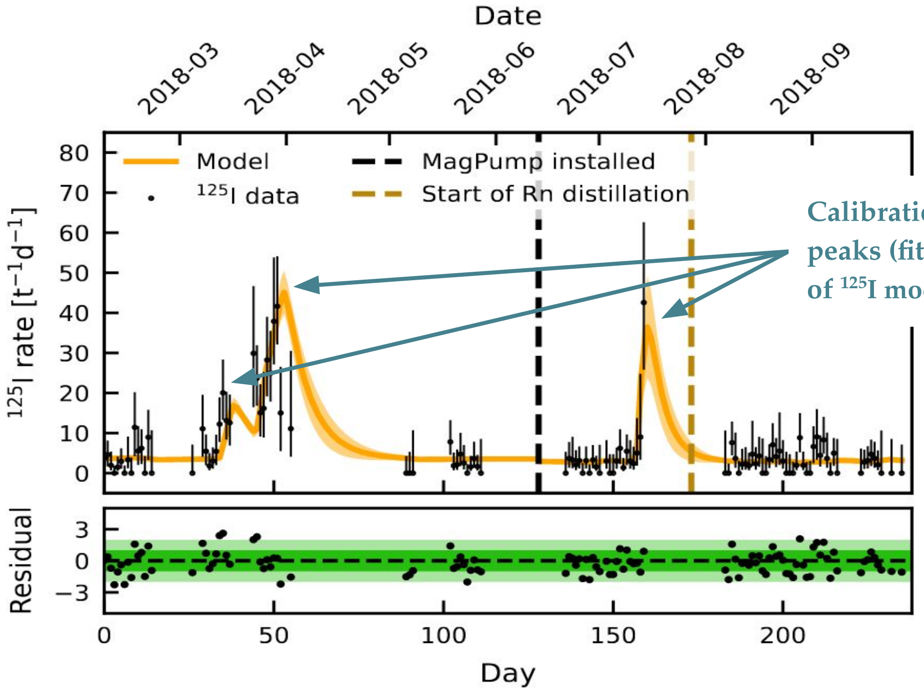


Search for ^{124}Xe Two-Neutrino double electron capture

AEPSHEP 2022 Group C

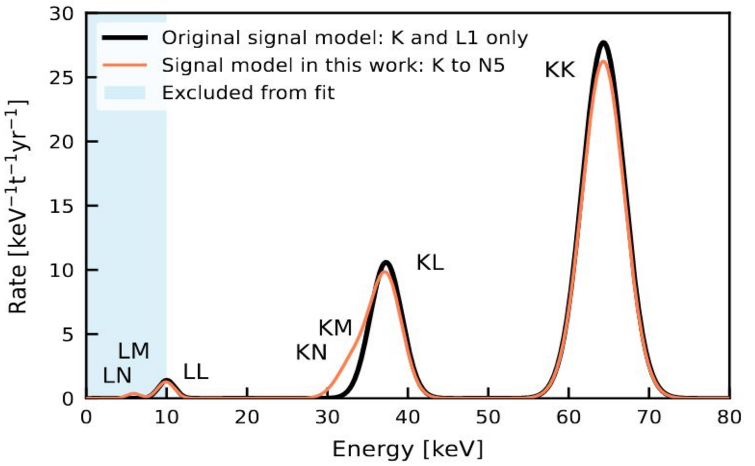
Background(s):

- Key background: **^{125}I** coming from neutron activation of ^{124}Xe ⇒ Peak at 67.3 keV. $$^{125}\mathrm{I} + e^- \rightarrow {}^{125}\mathrm{Te}^* + \nu_e$$
- Other backgrounds com from ^{214}Pb , ^{85}Kr and Elastic scattering of solar neutrinos off atomic electrons.



Signal model:

Account for additional shells (not only K+L) ⇒ Relative fraction of KK, KL, and LL captures slightly decreased.



Search for ^{124}Xe Two-Neutrino double electron capture (2/2)

Fitting strategy ⇒ **Binned log-likelihood:**

$$\mathcal{L}\left(\mu_s, \vec{\theta}\right) = \prod_i^{\text{bins}} \text{Poisson}\left(N_\text{i},\, \lambda_\text{i}(\vec{\theta}) + n_\text{i}^s(\mu_s, \vec{\theta})\right) \times \prod_\text{j}^{\text{constraints}} \text{Gauss}\left(\theta_\text{j},\, \mu_\text{j},\, \sigma_\text{j}\right).$$

Parameter of interest: 2νECEC event rate $A_{\beta\beta}$

$$T_{1/2}^{\beta\beta} = \ln 2 \times \frac{N_A \times \eta_{\text{Xe}} \times \epsilon_{\text{SS}}}{A_{\beta\beta} \times M_A}$$

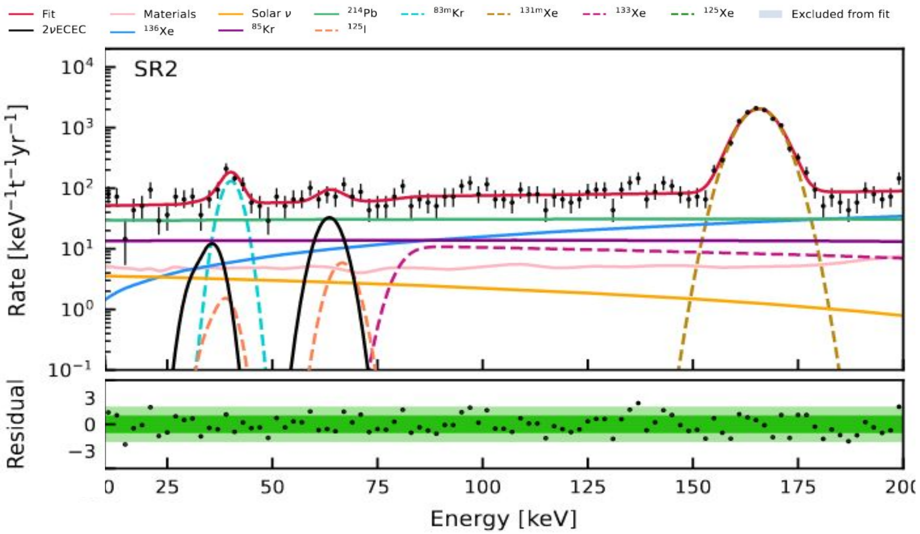
Fit Results:

The best-fit double-electron capture rate:

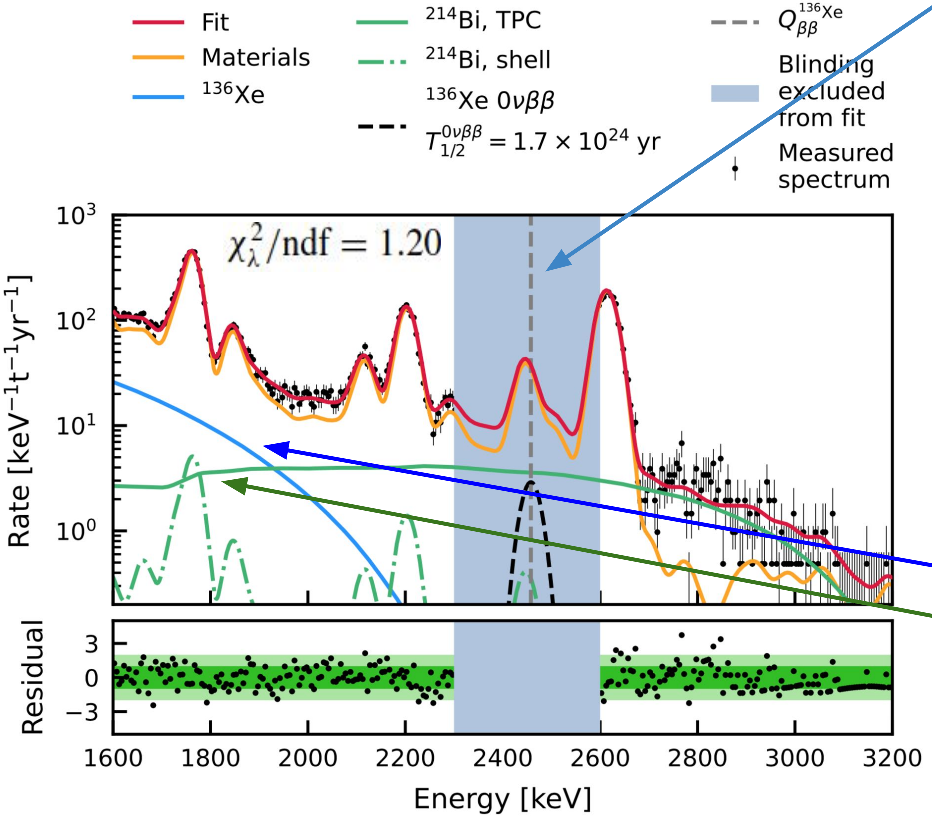
$$A_{2\nu\text{ECEC}} = (300 \pm 50)\ \text{t}^{-1}\text{yr}^{-1}$$

The resulting 2νECEC half-life (first >5σ in any isotope):

$$T_{1/2}^{2\nu\text{ECEC}} = (1.1 \pm 0.2_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{22}\ \text{yr}$$



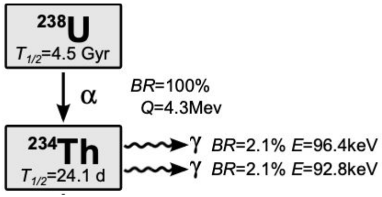
$0\nu\beta\beta$ search with XENON1T: Background sources



Background validation performed by excluding the blinded signal region (2300–2600 keV)

Materials (main) background

Originating from ^{238}U and ^{232}Th natural radioactive decays of the material

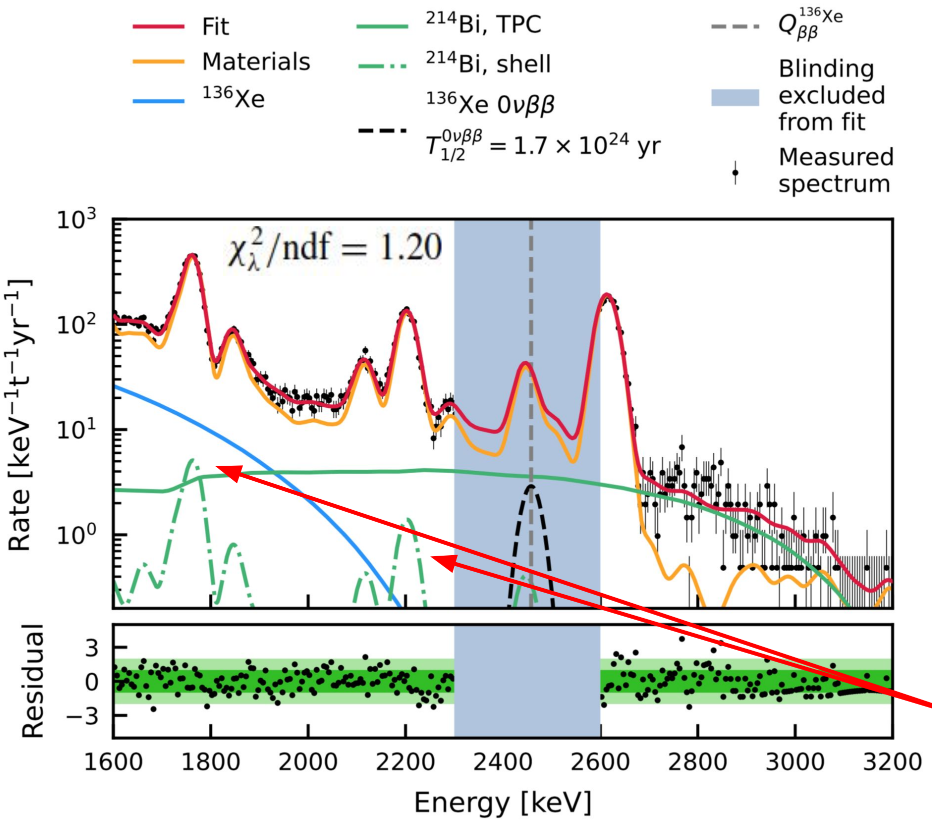


In the form of Compton scatter from radiated γ-rays

In particular, absorption peaks for

- ^{208}Tl,
- ^{214}Bi, and
- ^{60}Co γ-lines

Contributions obtained using radioassay



2νββ of ^{136}Xe

Continuous spectrum ending at signal peak
Modelled from theoretical calc.

^{222}Rn contamination

Rn emanation from materials to LXe target

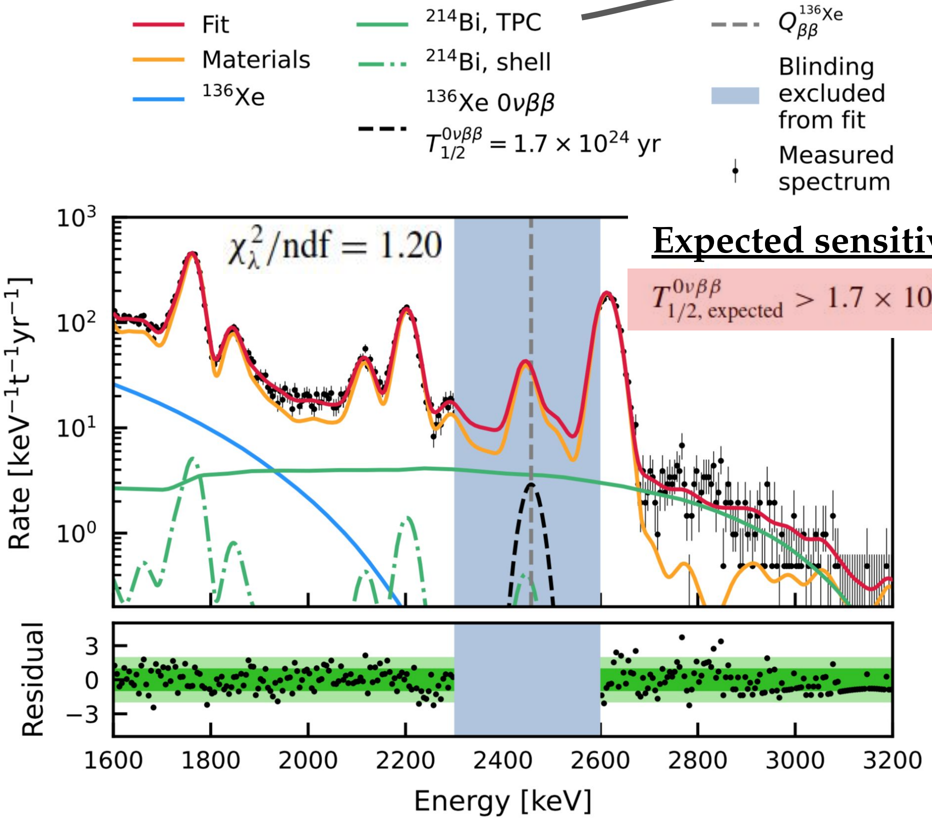
Internal TPC ^{214}Bi β-decays to ^{214}Po are easily tagged and have >99% rejection efficiency

- ^{214}Bi spectrum is continuous

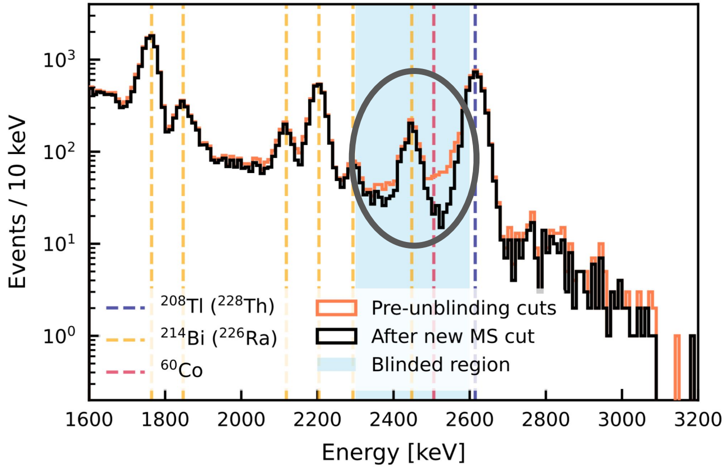
External (shell) ^{214}Bi β-decays with γ-rays in the active volume

- Several ^{214}Bi absorption peaks

Fit to blinded Data



Unblinding



Expected sensitivity:

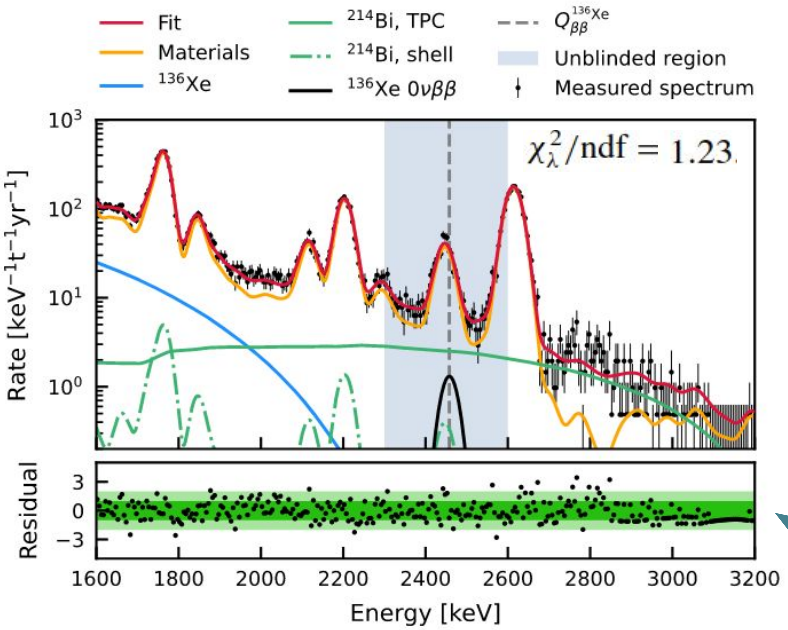
$T_{1/2,\text{ expected}}^{0\nu\beta\beta} > 1.7 \times 10^{24}$ yr at 90% CL.

Unexpected background leakage observed in blinded region (~2550 keV).

- **Source**: MS events not rejected by the cuts. ⇒ Misidentification as SS events
- An stricter cut on PMT signal collection time cut applied.

$0\nu\beta\beta$ search with XENON1T

Final unblinded result:



Residuals within 2σ

Best-fit $0\nu\beta\beta$ rate:

$$A_{\beta\beta} = (65 \pm 87)\ \text{t}^{-1}\text{yr}^{-1}$$

$$\langle m_{\beta\beta}\rangle \equiv \left|\Sigma_i U_{ei}^2 m_{\nu_i}\right|$$

$$\langle m_{\beta\beta}\rangle^2 = \frac{m_e^2}{G_{0\nu}|M_{0\nu}|^2 T_{1/2}^{0\nu}}$$

Observed exclusion limit:

$$T_{1/2}^{0\nu\beta\beta} > 1.2 \times 10^{24}\ \text{yr at 90\% CL}$$

Resulting neutrino mass range:

$$\langle m_{\beta\beta}\rangle < (0.8\text{–}2.5)\ \text{eV}/c^2$$

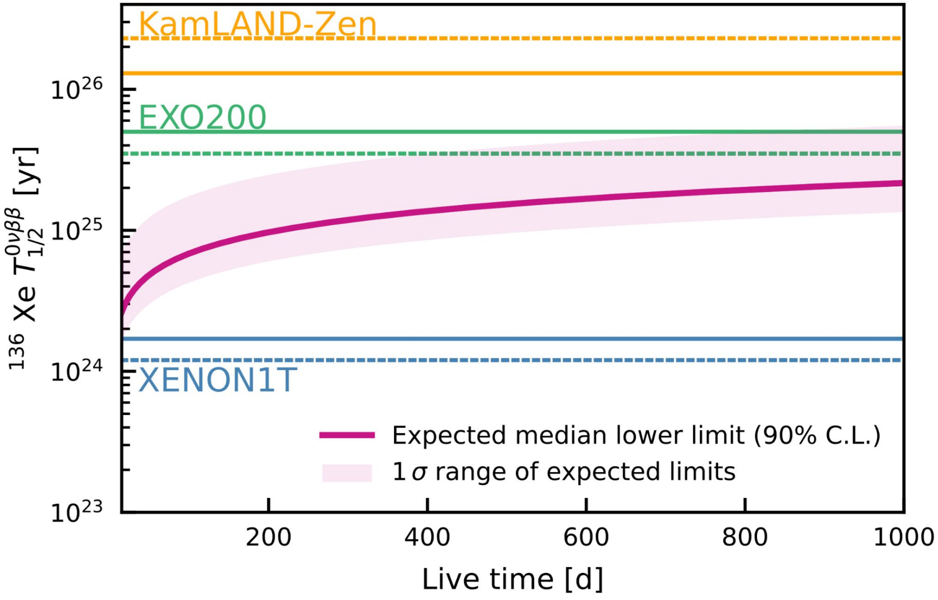
Large uncertainty due to nuclear ME

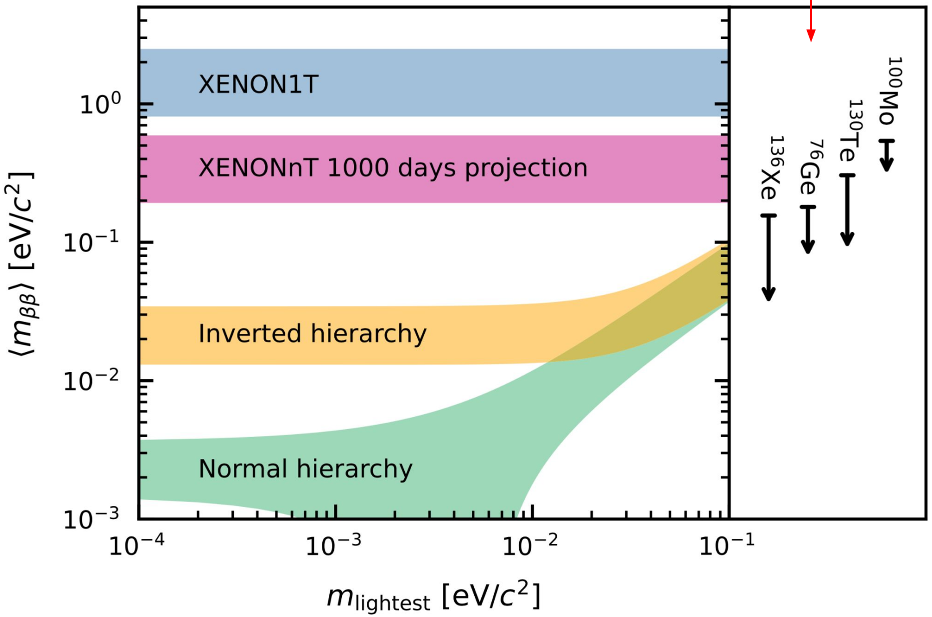
EXO-200 [2] and KamLAND-Zen [3] supersede this result by 2 orders of magnitude.

Projection of XENONnT sensitivity to 0νββ decay

AEPSHEP 2022 Group C

Best experimental limits for different isotopes





- XENONnT is not yet competitive with dedicated experiments
- However, future Xe DM detectors can also enter the game

Conclusions and prospects

- XENON1T is awesome
  - **Main goal**: Direct detection of Dark Matter
  - Nevertheless, **broader physics program** such as
    - First significant measurement of 2νECEC
    - **Searches of 0$\nu\beta\beta$** for experimental evidence of Majorana neutrinos
- XENONnT is n times more awesome!
  - Sensitivity studies to 0$\nu\beta\beta$ decay $\Rightarrow$ Closer to dedicated experiments
  - Exciting prospects for XENONnT, low background and optimized detection

Thank you very much for your attention!

Backup Slides

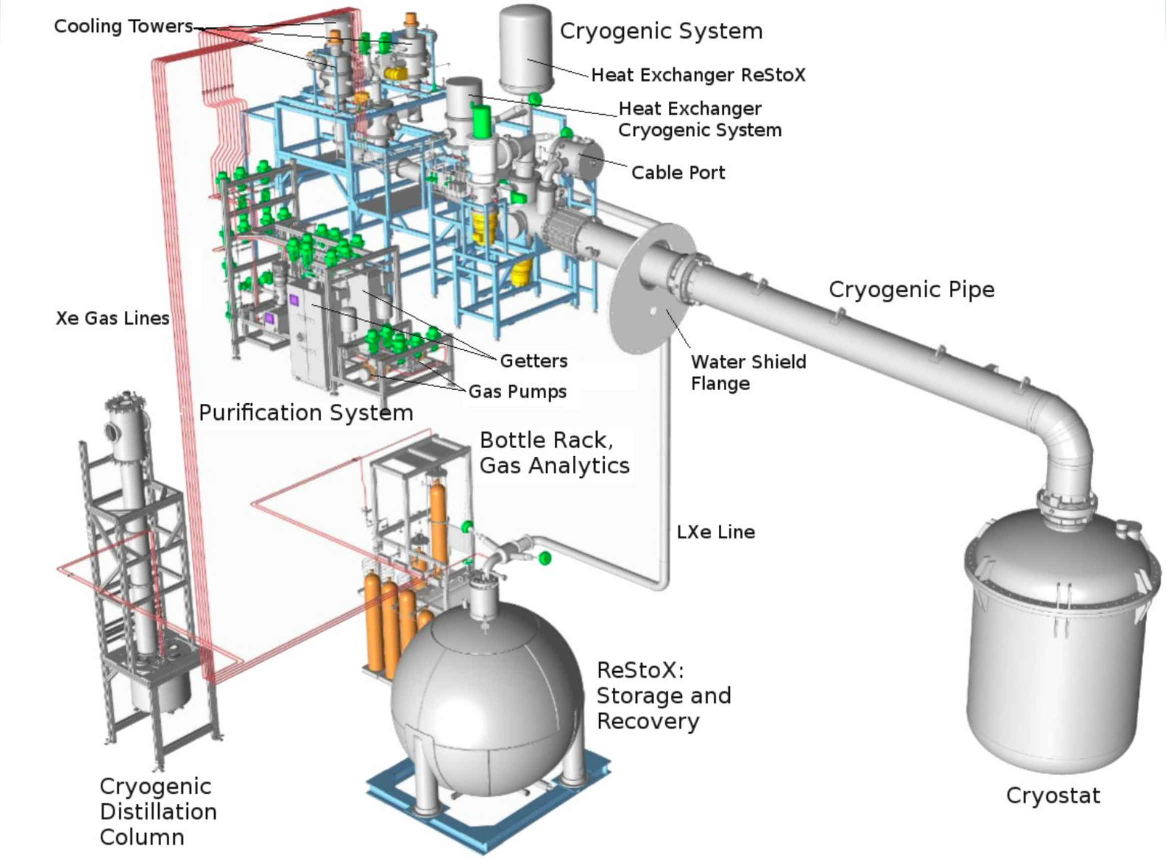
Reference

[1] E. Aprile et al. (XENON Collaboration), Eur. Phys. J. C 77, 881 (2017).

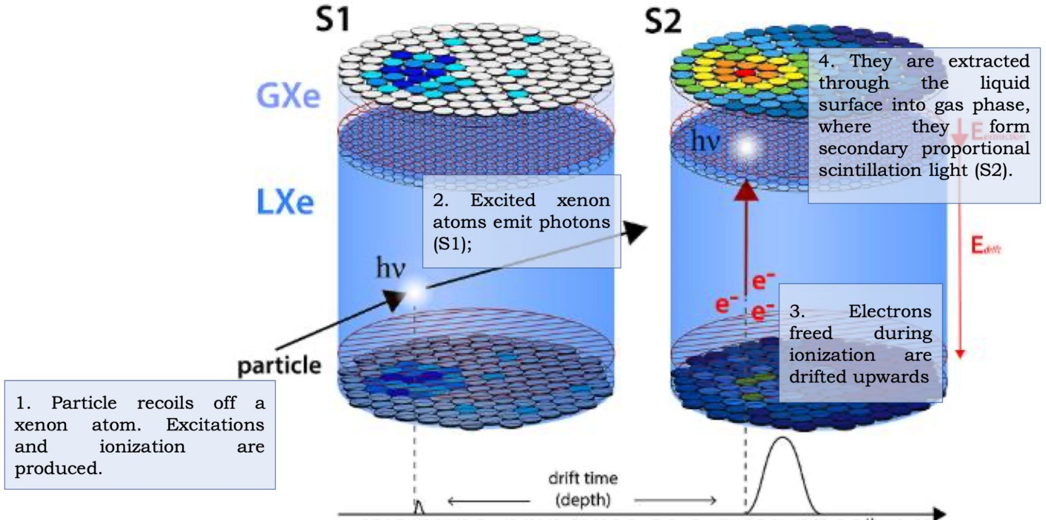
[2] G. Anton et al. (EXO-200 Collaboration), Phys. Rev. Lett. 123, 161802 (2019).

[3] S. Abe et al. (KamLAND-Zen Collaboration), arXiv:2203.02139

[4] Murra, M., et al. "Design, construction and commissioning of a high-flow radon removal system for XENONnT." arXiv preprint arXiv:2205.11492 (2022).

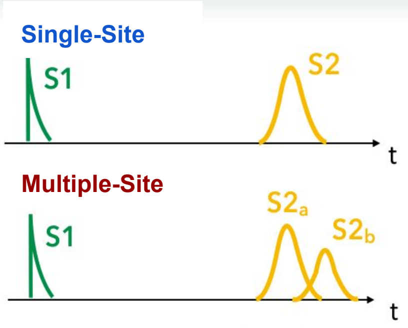

Cooling Towers
Cryogenic System
Heat Exchanger ReStoX
Heat Exchanger
Cryogenic System
Cable Port
Cryogenic Pipe
Xe Gas Lines
Getters
Gas Pumps
Water Shield
Flange
Purification System
Bottle Rack,
Gas Analytics
LXe Line
ReStoX:
Storage and
Recovery
Cryogenic
Distillation
Column
Cryostat

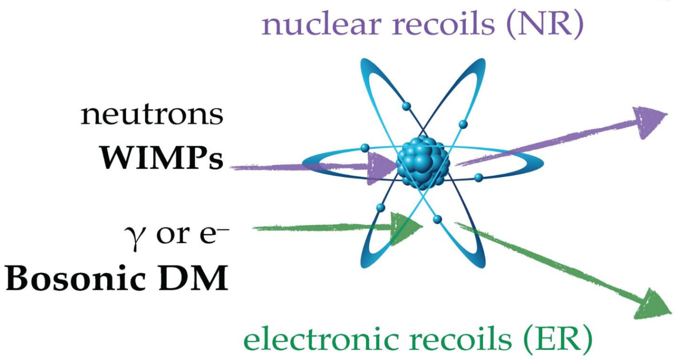
1. Recoil of ***a particle*** with the Xe atom excite and ionize which causes a release of photos and *e*
   1.1. ***WIMP, neutron* or ν** interacts with LXe: Nuclei scatter → Nuclear recoil (NR)
   1.2. **γ rays, charged particles or ν_e** interacts with LXe: Atomic electrons → Electronic recoil (ER)
2. First scintillation signal S1 is emitted from the first photons of the excited Xe atom that reach on the top and the bottom PMTs
3. Ionized electrons go upwards with the electric field and drift to the liquid-gas
4. Second scintillation signal S2 is emitted in GXe
5. Events can be reconstructed in 3D using the drift time between S1 and S2 to reconstruct the z coordinate and the S2 hit pattern on the top PMT array for the (x,y) coordinates.



Working principle of a dual-phase TPC

Eur.Phys.J.C 77 (2017) 12, 881

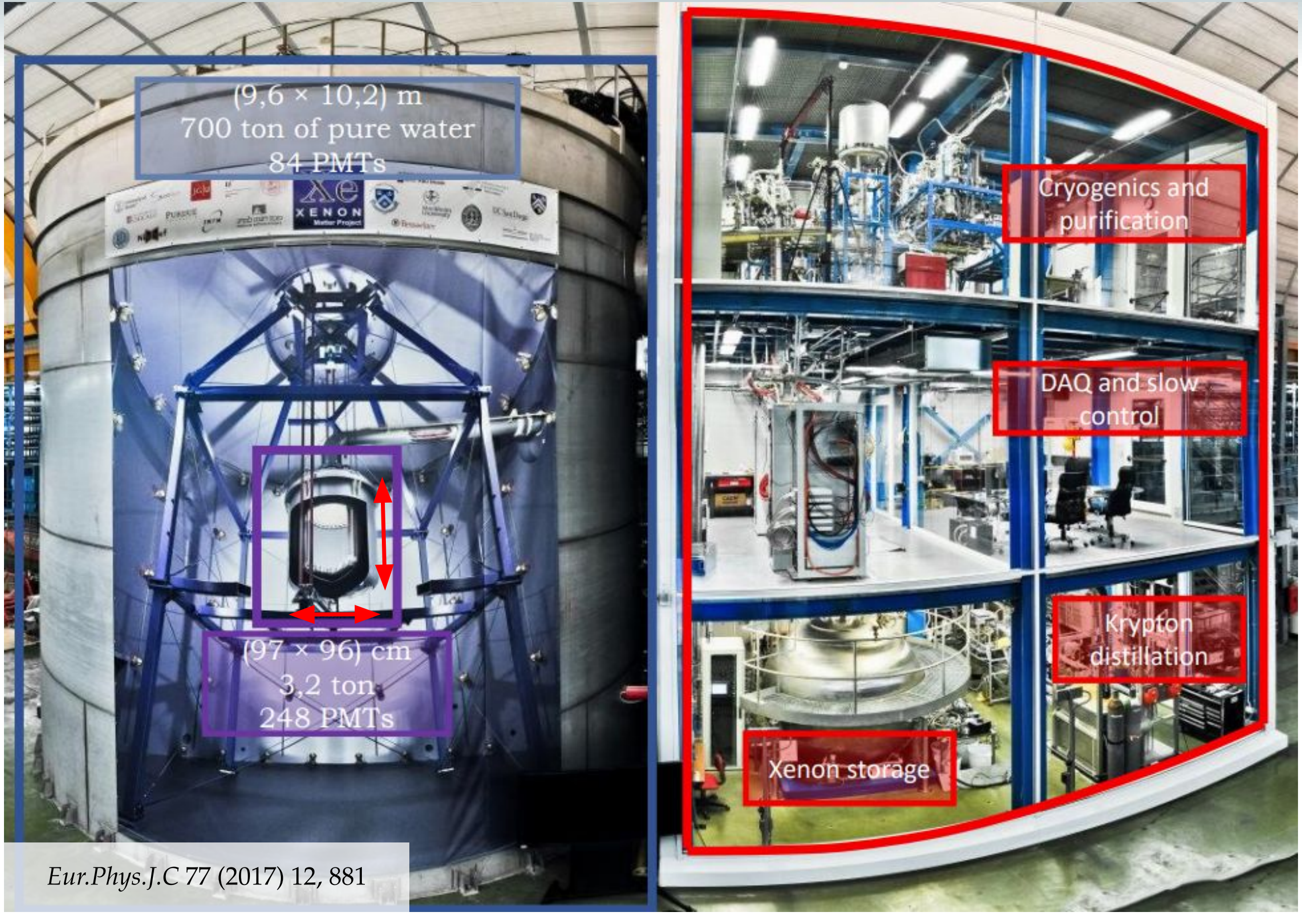




$$\frac{S2}{S1}(ER) > \frac{S2}{S1}(NR)$$

<u>**A particle interacting with LXe**</u>

XENON1T in LNGS



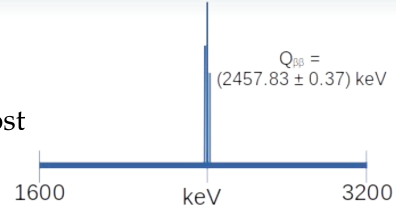
Eur.Phys.J.C 77 (2017) 12, 881

Event Selection

AEPSHEP 2022 Group C

Dataset:

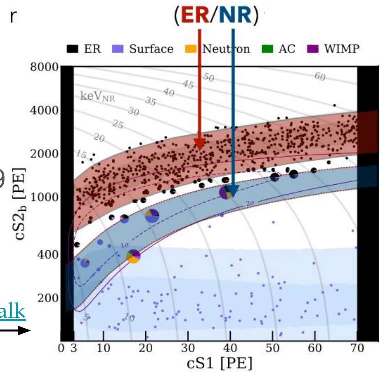
- Scan energies between 1600 and 3200 keV
  - $0\nu\beta\beta$ peak at $Q_{\beta\beta}$ = (2457.83 ± 0.37) keV
- Isotope exposure of 36.16 kg yr (current most sensitive – KamLand-ZEN 89.5 kg yr)



Cuts:

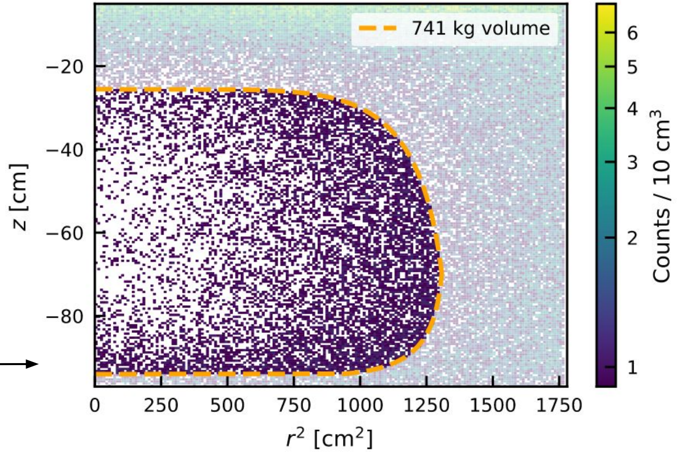
- Data cleaning cuts (busy periods, light emission etc.)
- Compton background removal
  - Shows up as **MS** events as opposed to $0\nu\beta\beta$ as **SS** events.
- Remove pileup events
  - example: ^{214}BiPo decay - shows up as multiple S1 signals
- Apply position reconstruction algorithm - Neural Net + S2 shape fit
  - removes events near edge of TPC or where bad PMTs were located
- Electron Recoils removed - 98% efficiency.
  - Done using S1/S2 ratio
- Restrict to events where S2 shape matches what we expect from drifted electron diffusion

Ref: Xenon1T Public Talk



Signal Acceptance Optimization

- An FV (Fiducial Volume) in the detector is chosen that maximises signal-to-noise ratio:



Mass of isotopes

	mass (g/mol)	delta m (keV)
Te124	123.9028179	-2864.437522
I124	123.9062099	295.1904819
Xe124	123.905893	0
Cs124	123.912258	5928.959979
Ba124	123.915094	8570.677261

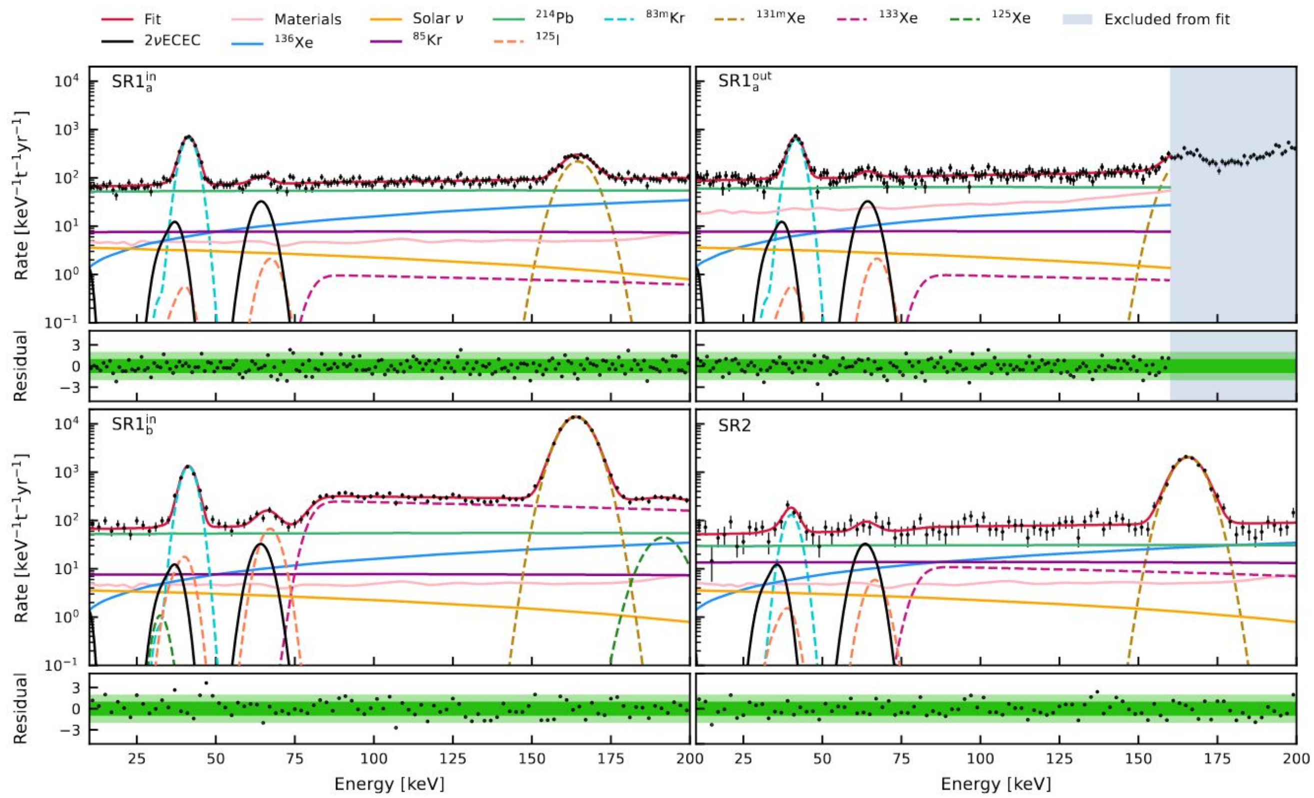
	mass (g/mol)	delta m (keV)
Te136	135.9201	11998.57557
I136	135.91465	6921.932695
Xe136	135.907219	0
Cs136	135.9073116	86.25635414
Ba136	135.9045759	-2462.032069

EXO-200 and KamLAND-Zen supersede this result by 2 orders of magnitude

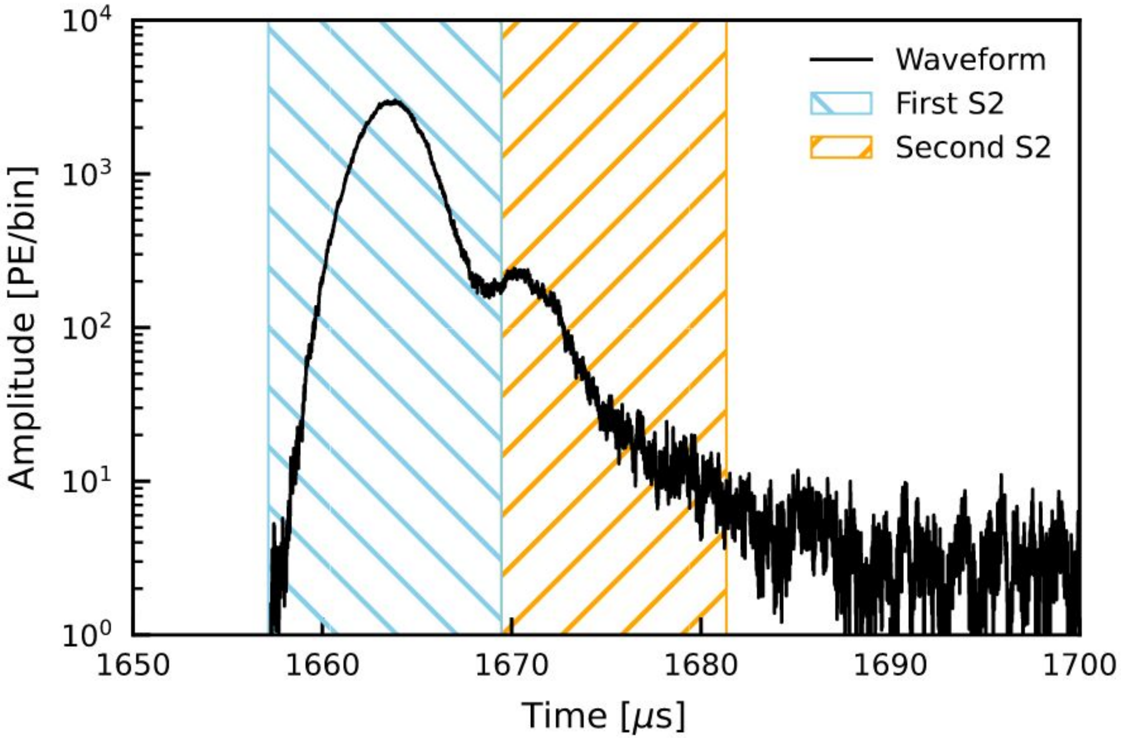
- EXO-200 [2]: $T_{1/2} > 3.5 \times 10^{25}$ yr $\langle m_{\beta\beta} \rangle < (93-286)$ meV
- KamLAND-Zen [3]: $T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ yr at 90% C.L. $\langle m_{\beta\beta} \rangle < (36 - 156)$ meV

Search for ^{124}Xe Two-Neutrino double electron capture (2/2)

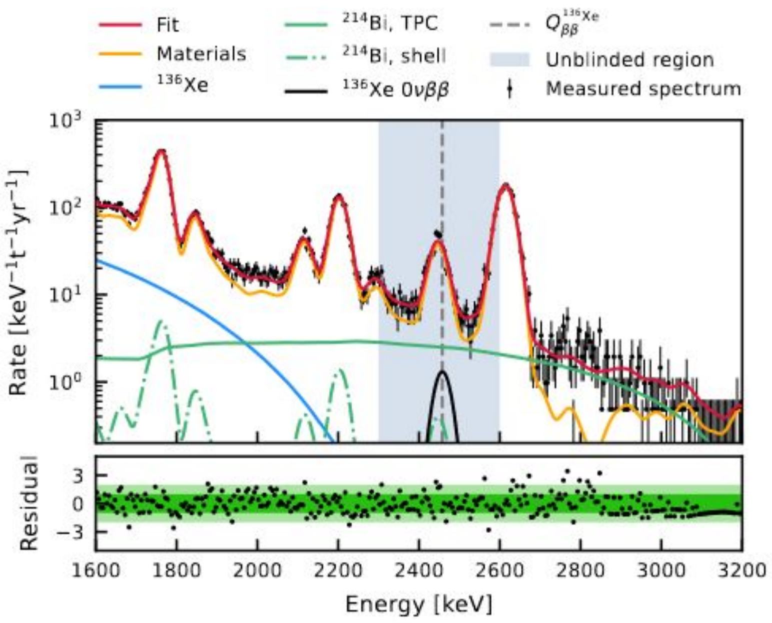
AEPSHEP 2022 Group C

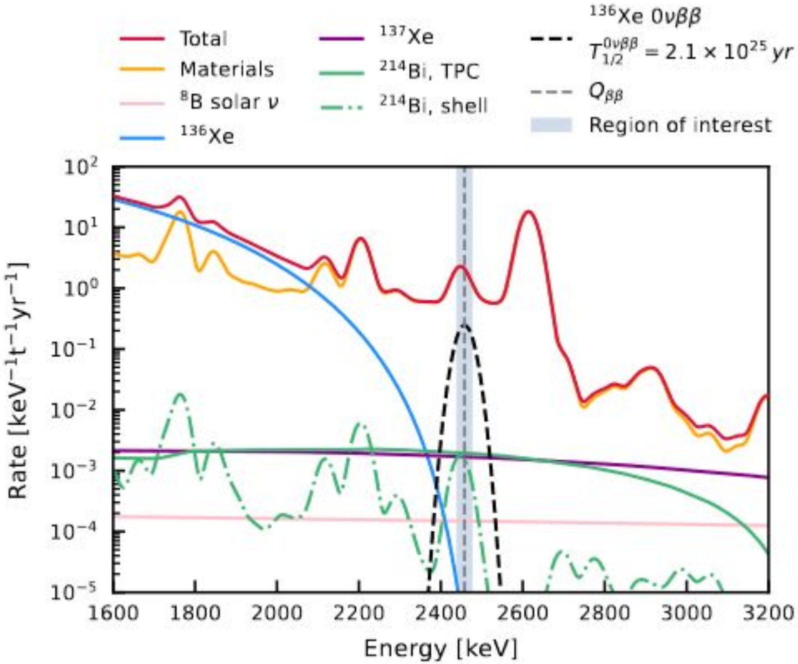


Limits $0\nu\beta\beta$ XENON1T: Background leakage into unblinded region



Projection of XENONnT: Background and signal





Background sources

AEPSHEP 2022 Group C

- Main background: radioactive impurities in the detector material, comprised of several radioactive decay chains
  - ^{238}U, ^{232}Th, ^{40}K, ^{60}Co
  - Their contributions are obtained using radioassay
- Intrinsic LXe backgrounds also play a (subdominant) role
  - Comes from ^{222}Rn emanation from detector materials to LXe target
  - Composed of ^{214}Pb and ^{214}Bi isotopes, >99% rejection using timing information

- Background modelling is validated in a fit that excludes the blinded signal region (2300–2600 keV)

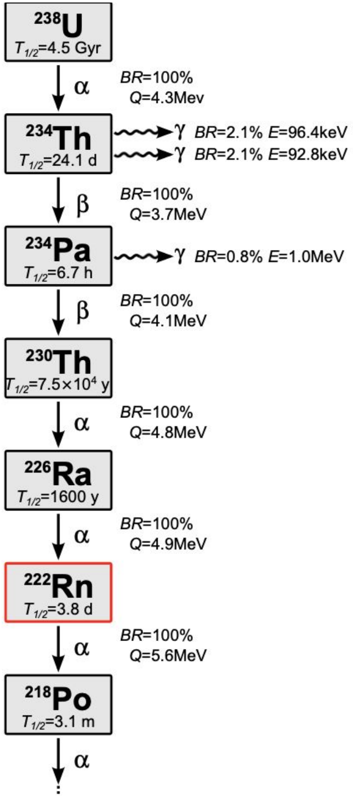


TABLE VII. Best-fit signal and background model parameters for the XENON1T 2νECEC search that were shared among all datasets. Unitless parameters state the relative change to the expected value. The meaning of the parameters is given in Sec. III D.

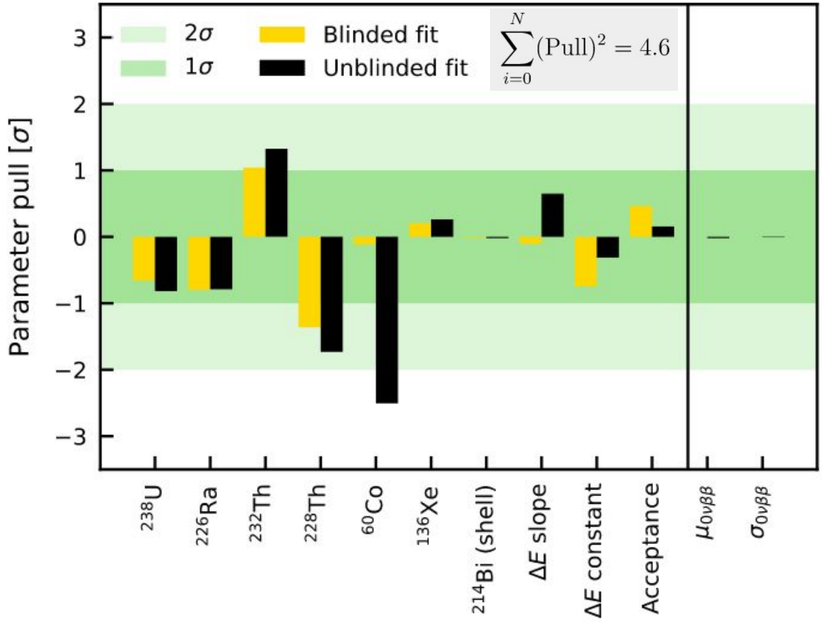
Parameter	Fit value	Constraint	Unit
$A_{2\nu\mathrm{ECEC}}$	300 ± 50	–	$\mathrm{t}^{-1}\mathrm{yr}^{-1}$
Solar ν	1.00 ± 0.02	1.00 ± 0.02	–
^{136}Xe	0.99 ± 0.03	1.00 ± 0.03	–
^{238}U	1.0 ± 0.5	1.0 ± 0.6	–
^{226}Ra	0.5 ± 0.3	1.0 ± 0.5	–
^{232}Th	0.9 ± 0.6	1.0 ± 0.6	–
^{228}Th	0.9 ± 0.6	1.0 ± 0.6	–
^{60}Co	0.6 ± 0.3	1.0 ± 0.4	–
^{40}K	1.0 ± 0.3	1.0 ± 0.3	–
$\mu_{^{83m}\mathrm{Kr,misID}}$	32.1 ± 0.6	32.1 ± 0.6	keV
$\sigma_{^{83m}\mathrm{Kr,misID}}$	1.3 ± 0.2	1.3 ± 0.2	keV
$f_{^{83m}\mathrm{Kr,misID}}$	2.6 ± 0.4	2.6 ± 0.4	10^{-4}

TABLE IX. Parameter constraints and best-fit parameters for the XENON1T $0\nu\beta\beta$ search. Best-fit parameters are given for the blinded and unblinded data. Unitless parameters state the relative change to the expected value. For the acceptance, the constrained and best-fit acceptances are given instead of the fit parameters. Due to the implementation of the acceptance, the Gaussian constraint on the acceptance scaling parameter yields an asymmetric acceptance range. Due to the internal processing of the thorium chain, the respective best-fit parameters cannot be translated directly to ^{228}Th event counts in Tab. V.

Parameter	Unit	Constraints	Blinded fit value	Unblinded fit value
^{238}U	–	1.0 ± 0.6	0.6 ± 0.1	0.5 ± 0.1
^{226}Ra	–	1.0 ± 0.5	0.620 ± 0.008	0.624 ± 0.008
^{232}Th	–	1.0 ± 0.6	1.6 ± 0.1	1.8 ± 0.1
^{228}Th	–	1.0 ± 0.6	0.2 ± 0.1	0.0 ± 0.1
^{60}Co	–	1.0 ± 0.4	1.0 ± 0.3	-0.1 ± 0.1
^{136}Xe	–	1.00 ± 0.03	1.01 ± 0.03	1.01 ± 0.03
^{214}Bi, TPC	μBq/kg	–	1.7 ± 0.1	1.25 ± 0.09
^{214}Bi, LXe shell	μBq/kg	10 ± 5	10 ± 5	10 ± 5
ΔE_{slope}	–	$(1.5 \pm 0.2) \times 10^3$	$(1.5 \pm 0.1) \times 10^3$	$(1.6 \pm 0.1) \times 10^3$
ΔE_{offset}	keV	-4.4 ± 0.3	-4.6 ± 0.3	-4.5 ± 0.2
ϵ	%	$88.6^{+8.9}_{-0.3}$	$88.3^{+0.6}_{-0.1}$	$85.2^{+4.6}_{-0.3}$
$\mu_{0\nu\beta\beta}$	keV	2457.8 ± 0.4	–	2457.8 ± 0.4
$\sigma_{0\nu\beta\beta}$	keV	19.7 ± 0.3	–	19.7 ± 0.3
$A_{0\nu\beta\beta}$	$\text{t}^{-1}\text{yr}^{-1}$	–	–	60 ± 90

Pulls

Fit to blinded data



Pulls:

- No pulls of the blinded fit >2σ.
- The pull on ^{60}Co - close to 0.
- No notable pulls on the systematic uncertainty parameters.