University of Zurich[UZH]

Measurement of two-neutrino double-electron capture in the XENON experiments

NME 2023

Osaka, Japan | Dec 22 2023

Christian Wittweg on behalf of the XENON Collaboration

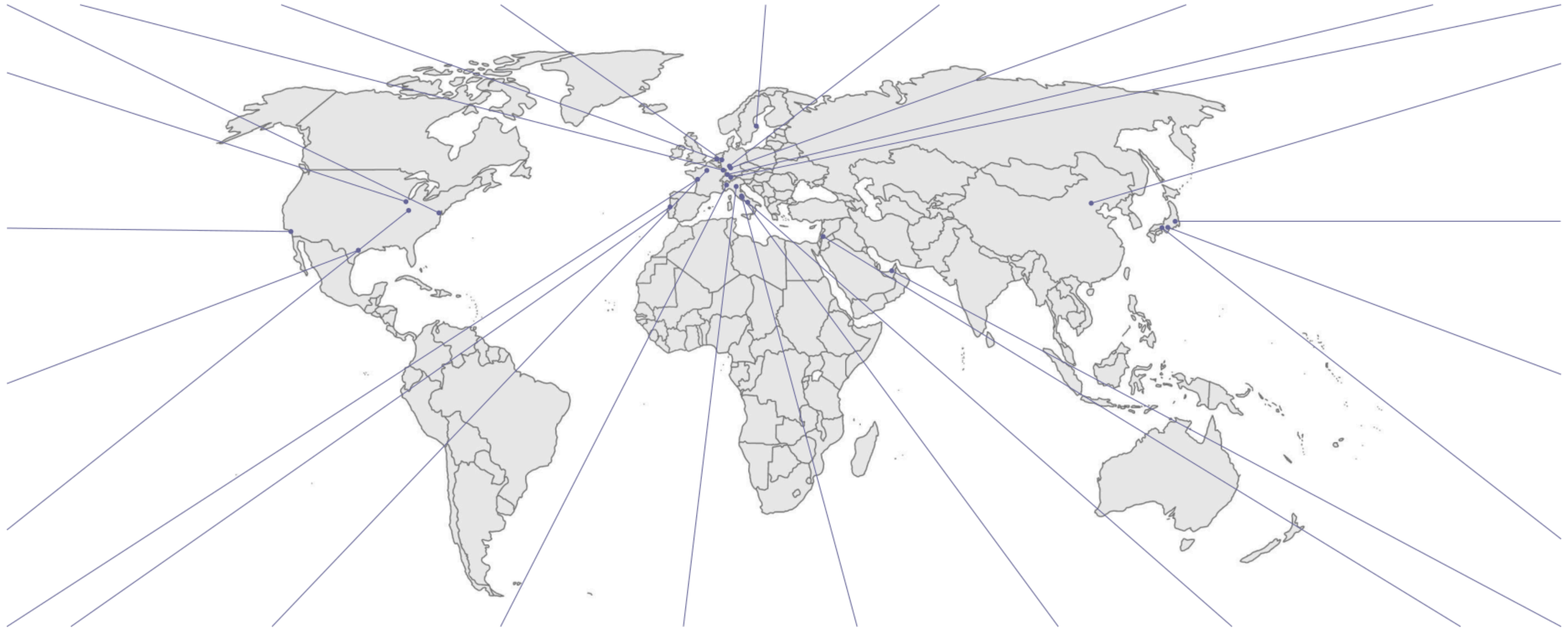
The XENON Collaboration

Columbia | KIT | Nikhef | Muenster | Stockholm | Mainz | MPIK, Heidelberg | Freiburg | Zurich

Chicago | UCSD | Rice | Purdue

Tsinghua | Tokyo | Nagoya | Kobe

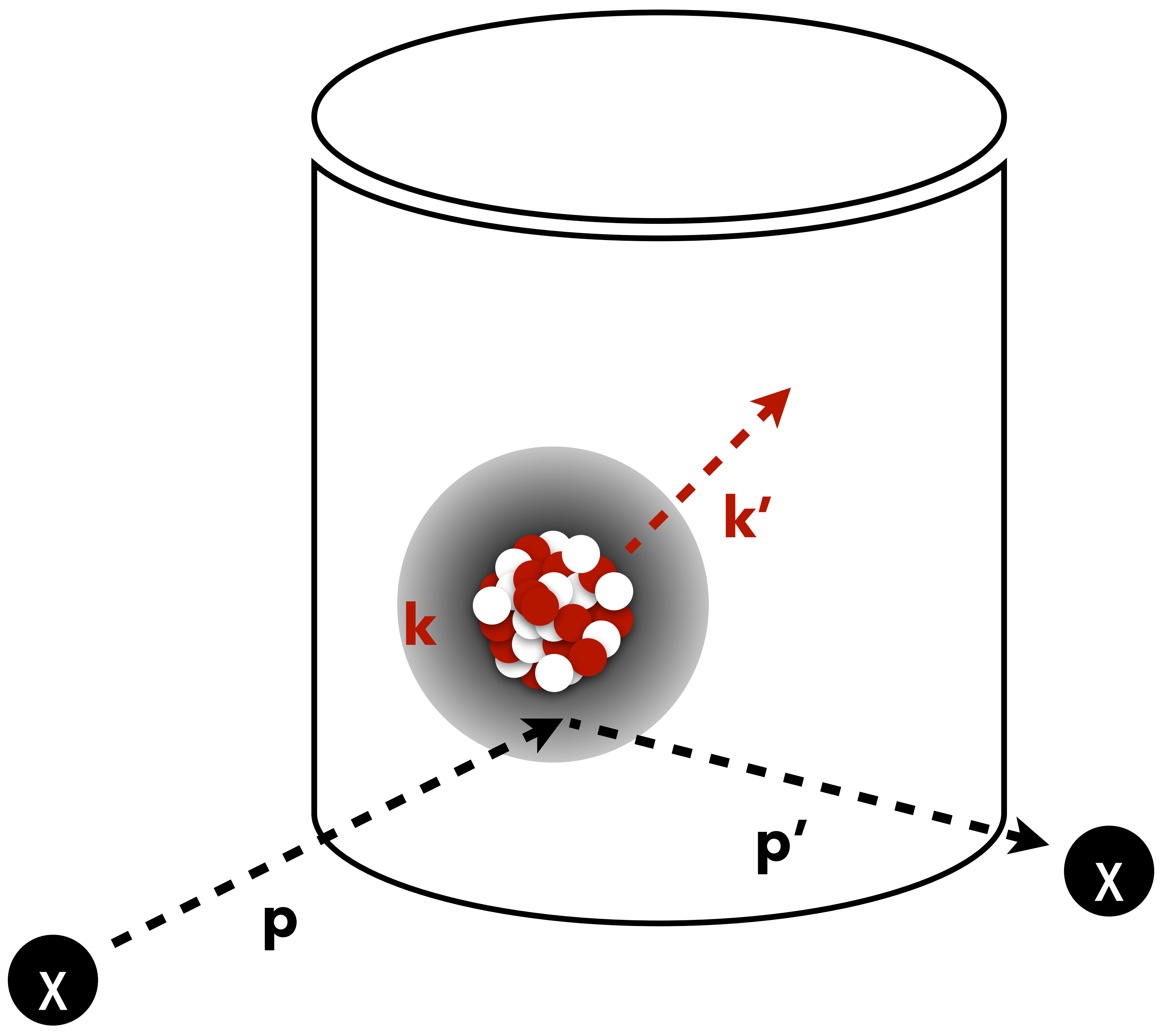
Subatech | Coimbra | LPNHE | Torino | Bologna | L'Aquila | LNGS | Napoli | Weizmann | NYUAD



XENON

- ~170 scientists
- 27 institutions
- 12 countries

Direct dark matter detection



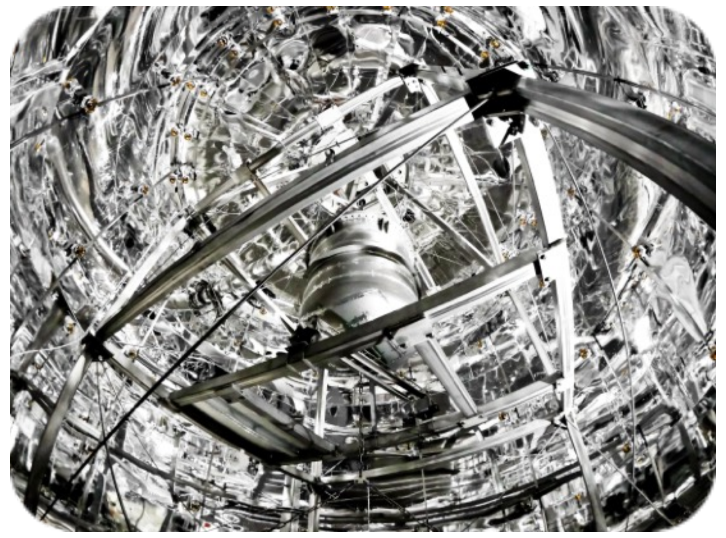
Detect weakly interacting massive particles (**WIMP**s) **directly** by measuring the **O(1) keV nuclear recoil** after scattering in a **large, low background, low threshold detector.**

XENON Dark Matter Project

XENON1T at LNGS

1500 m overburden
(3600 m.w.e.)

TPC



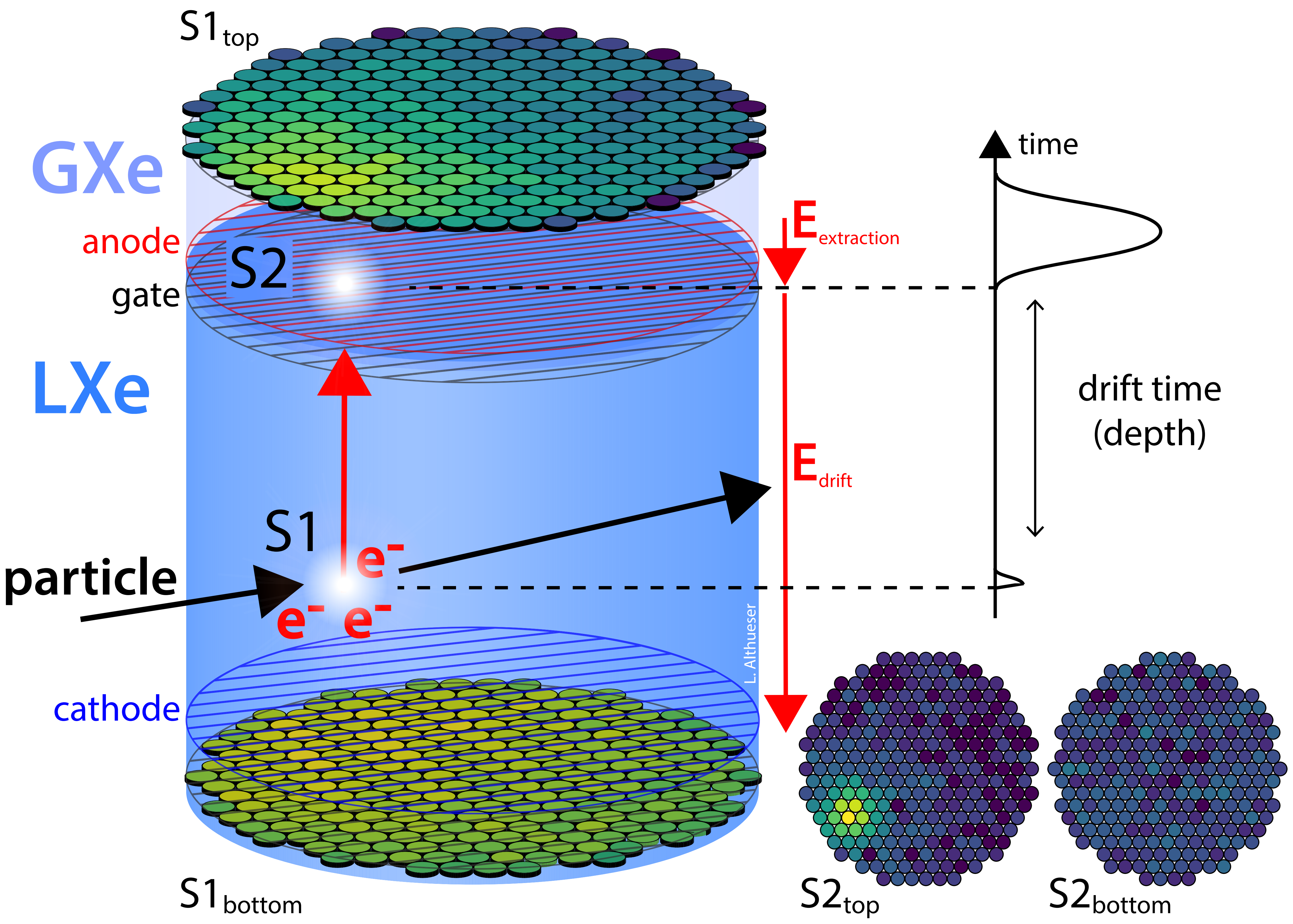
84
8" PMTs as water
Cherenkov muon
veto

LNGS hall B

700 t
demi-water

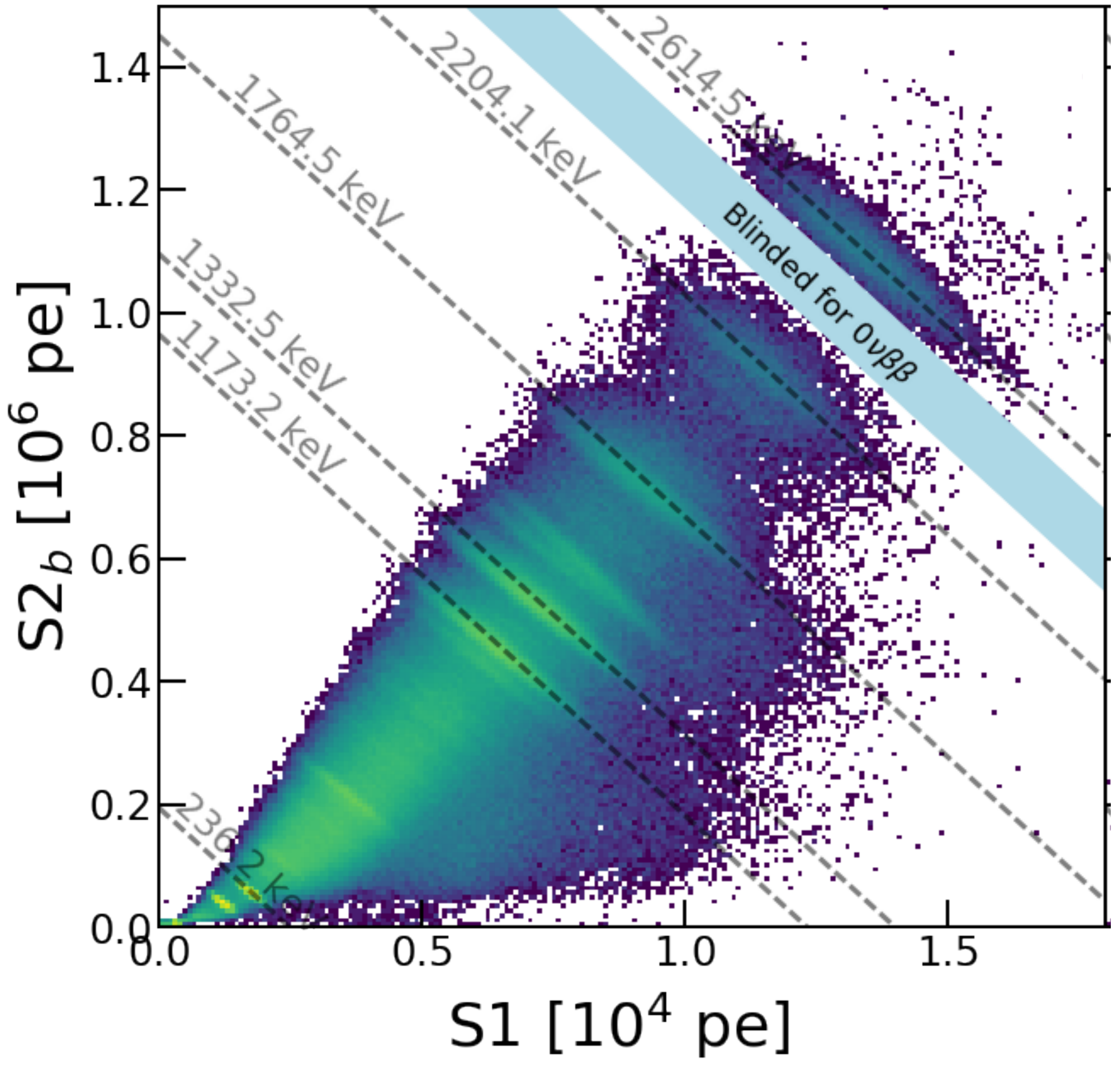
Cryostat

Dual-Phase Time Projection Chamber



Scintillation and **ionization**:

- Prompt light signal (**S1**)
- Secondary light in GXe from drifted charges (**S2**)
- Position reconstruction (**x, y, z**), calorimetry (**E**) and interaction type (**ER**/**NR**)



XENON Physics Programme

WIMP DARK MATTER

PRL 119, 181301
PRL 121, 111302
PRL 122, 071301
PRL 122, 141301
PRL 126, 091301
PRD 103, 063028

BOSONIC DARK MATTER

PRD 102, 072004

LIGHT DARK MATTER

PRL 123, 241803
PRL 123, 251801

SOLAR AXIONS

PRD 102, 072004

SOLAR ^{8}B CEvNS

PRL 126, 091301

NEUTRINO MAGNETIC MOMENT

PRD 102, 072004

DOUBLE ELECTRON CAPTURE

Nature 568, 532
Phys. Rev. C 106, 024328

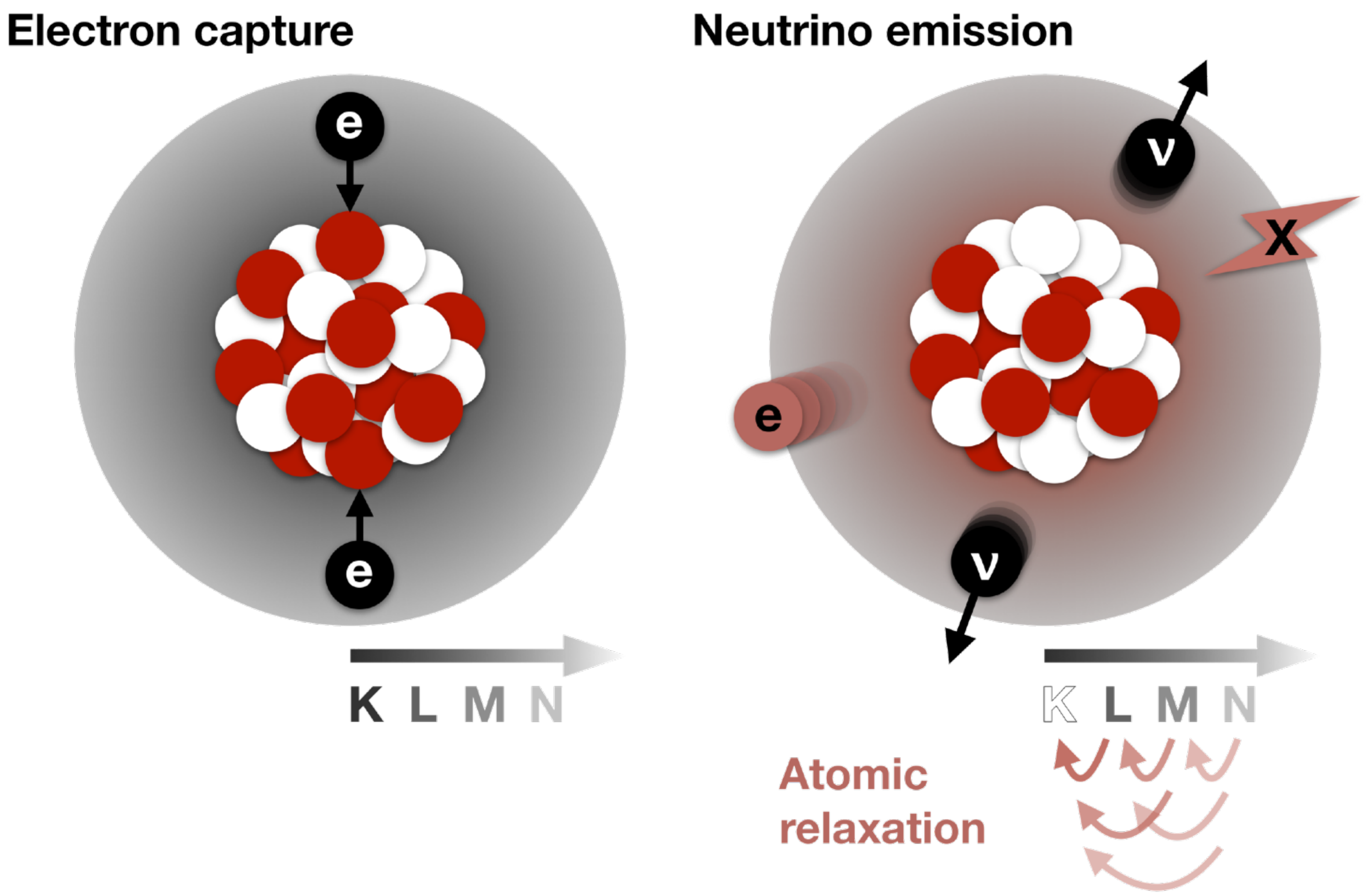
TECHNICAL ANALYSIS PAPERS

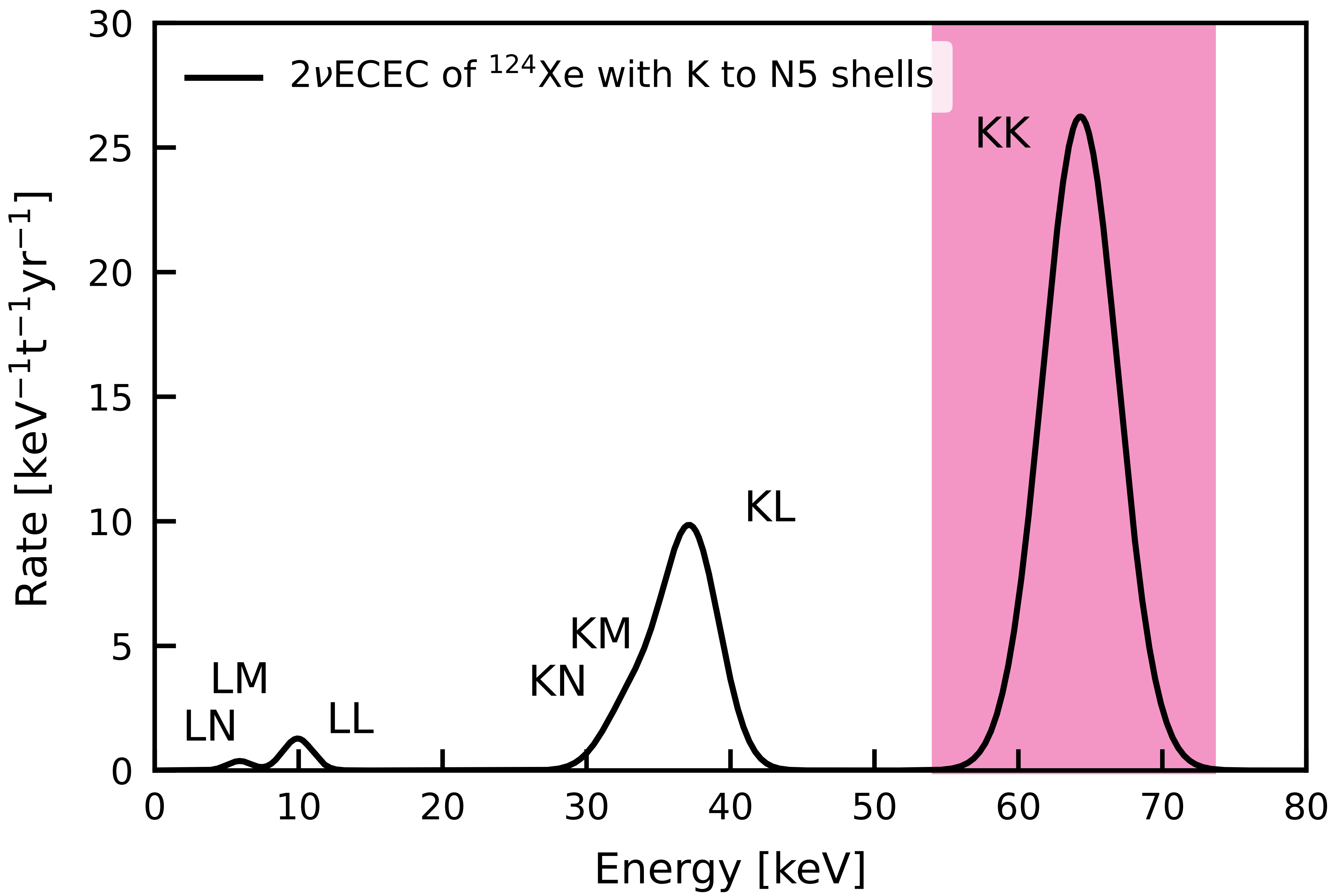
PRD 99, 112009
PRD 100, 052014

NEUTRINOLESS DOUBLE-β DECAY

EPJ C (2020) 80:785 (analysis R&D)

Two-Neutrino Double-Electron Capture





KK-capture: 64.3 keV (72.4 %)

KL-, **KM**-, **KN**-capture: 32.4 – 37.3 keV (25.3 %)

LL-capture: 8.8 – 10.0 keV (1.4 %)

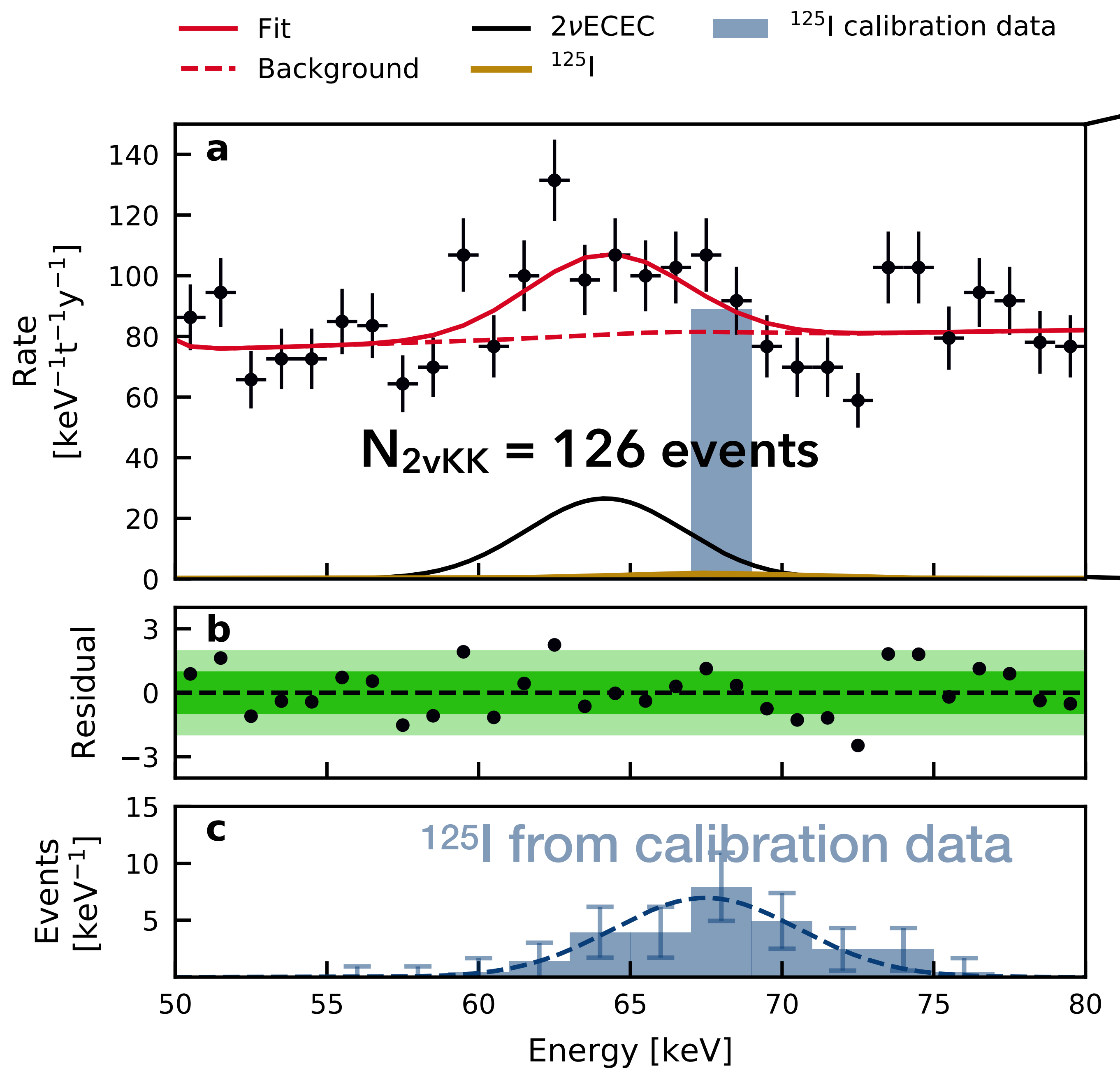
Other: < 10 keV (0.8 %)

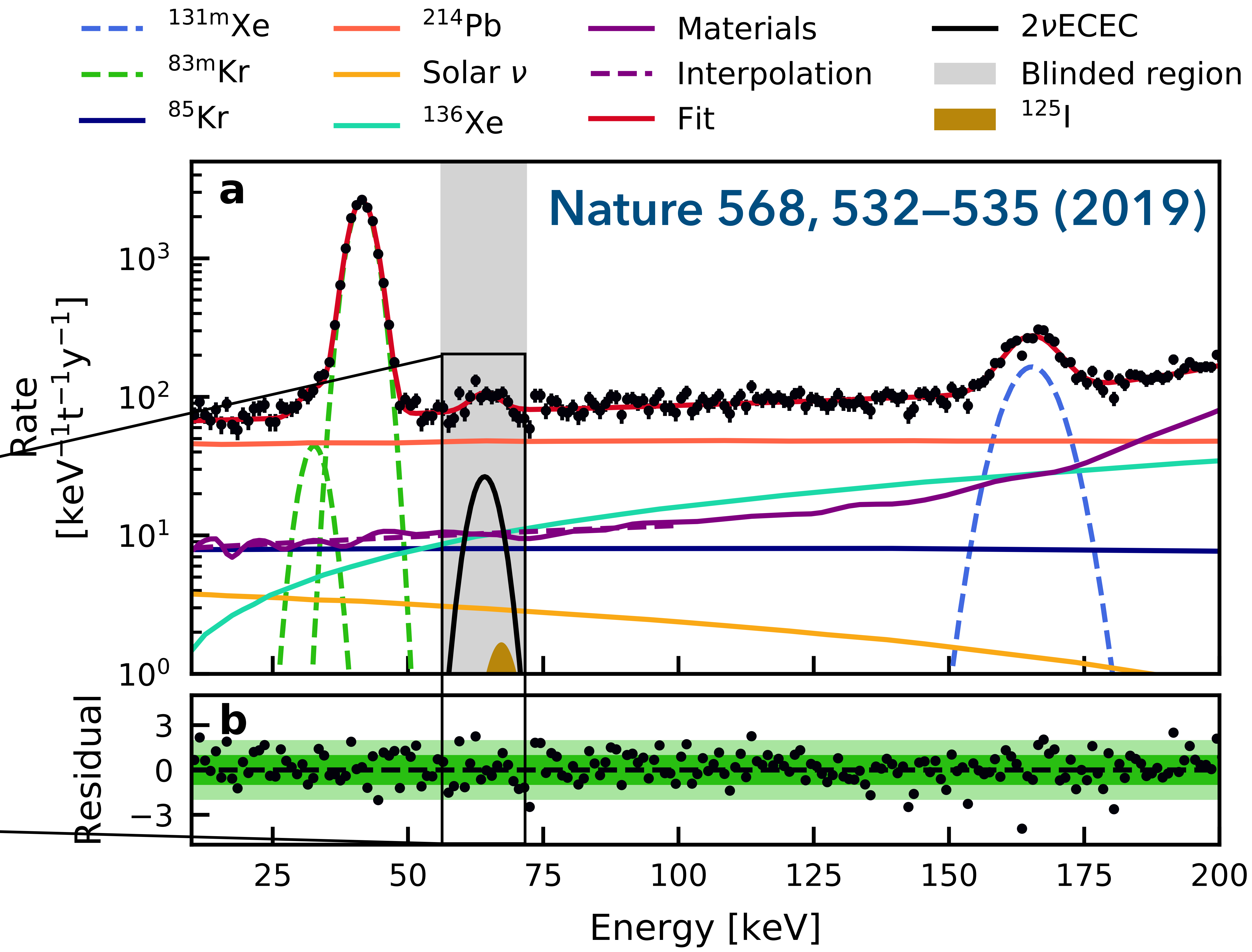
Relative capture ratios calculated from overlap of K to N5 electron and nuclear wave functions.

$$^{124}\mathrm{Xe}/^{\mathrm{nat}}\mathrm{Xe} = (9.94 \pm 0.14_{\mathrm{stat}} \pm 0.15_{\mathrm{sys}}) \cdot 10^{-4}\ \frac{\mathrm{mol}}{\mathrm{mol}}$$

First XENON1T Result

- Observed KK-capture at **4.4σ** significance.
- LL-capture too low in rate and outside ROI.
- KL-, KM- and KN-capture obscured by ^{83m}Kr



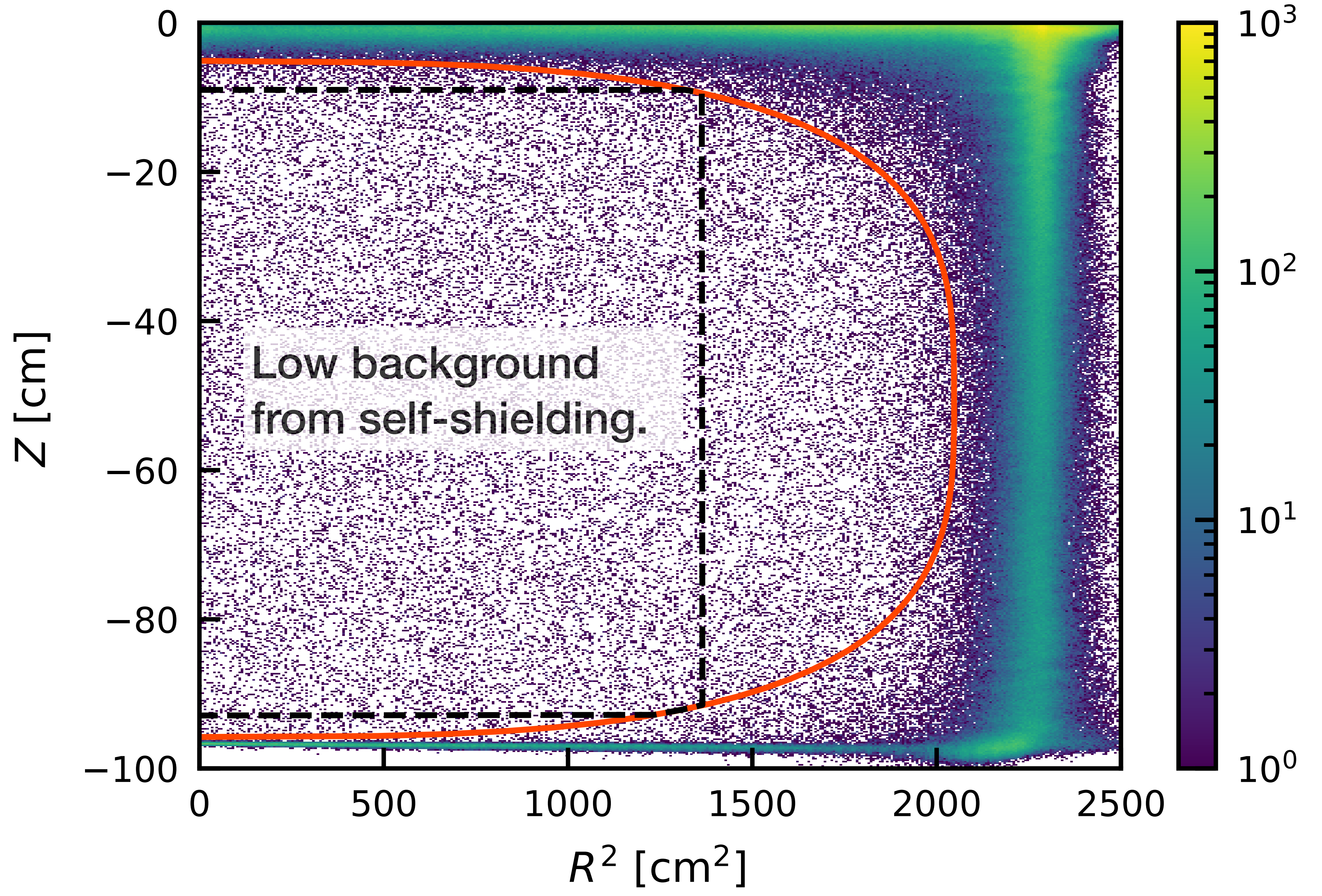


$$T_{1/2}^{2\nu KK} = (1.8 \pm 0.5_{stat} \pm 0.1_{sys}) \times 10^{22}\ \text{yr}$$

Analysis Upgrades

- Improved cuts for ^{83m}Kr events allow inclusion of KL-, KM-, KN-peaks.
- Updated data processor and energy reconstruction.
- Increase exposure to 0.93 tonne × years using four datasets
  - **SR1a**: 171.2 d
    - 1.0 t inner cylinder
    - 0.5 t outer fiducial volume
  - **SR1b**: 55.8 d in 1 t cylinder
  - **SR2**: 24.3 d in 1 t cylinder

Nature 568, 532–535 (2019)



Separation in time due to time-dependent ^{125}I background!

Background from ^{125}I

Neutron capture

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

^{125}Xe decay

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

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

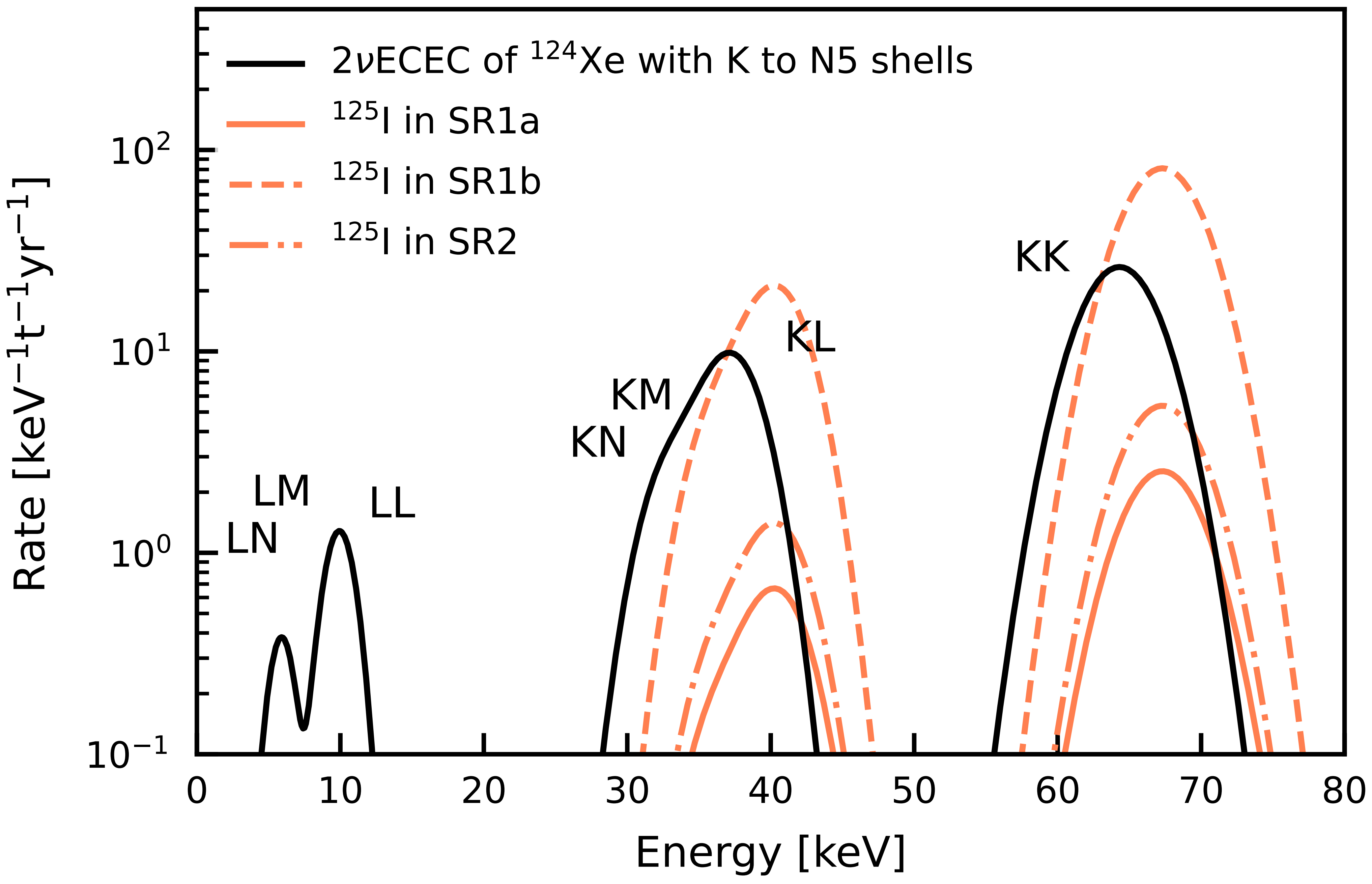
Line at 276.5 keV

^{125}I decay

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

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

Lines at 67.3 keV, 40.4 keV, 36.5 keV



Background from ^{125}I

Neutron capture

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

^{125}Xe decay

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

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

Line at 276.5 keV

^{125}I decay

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

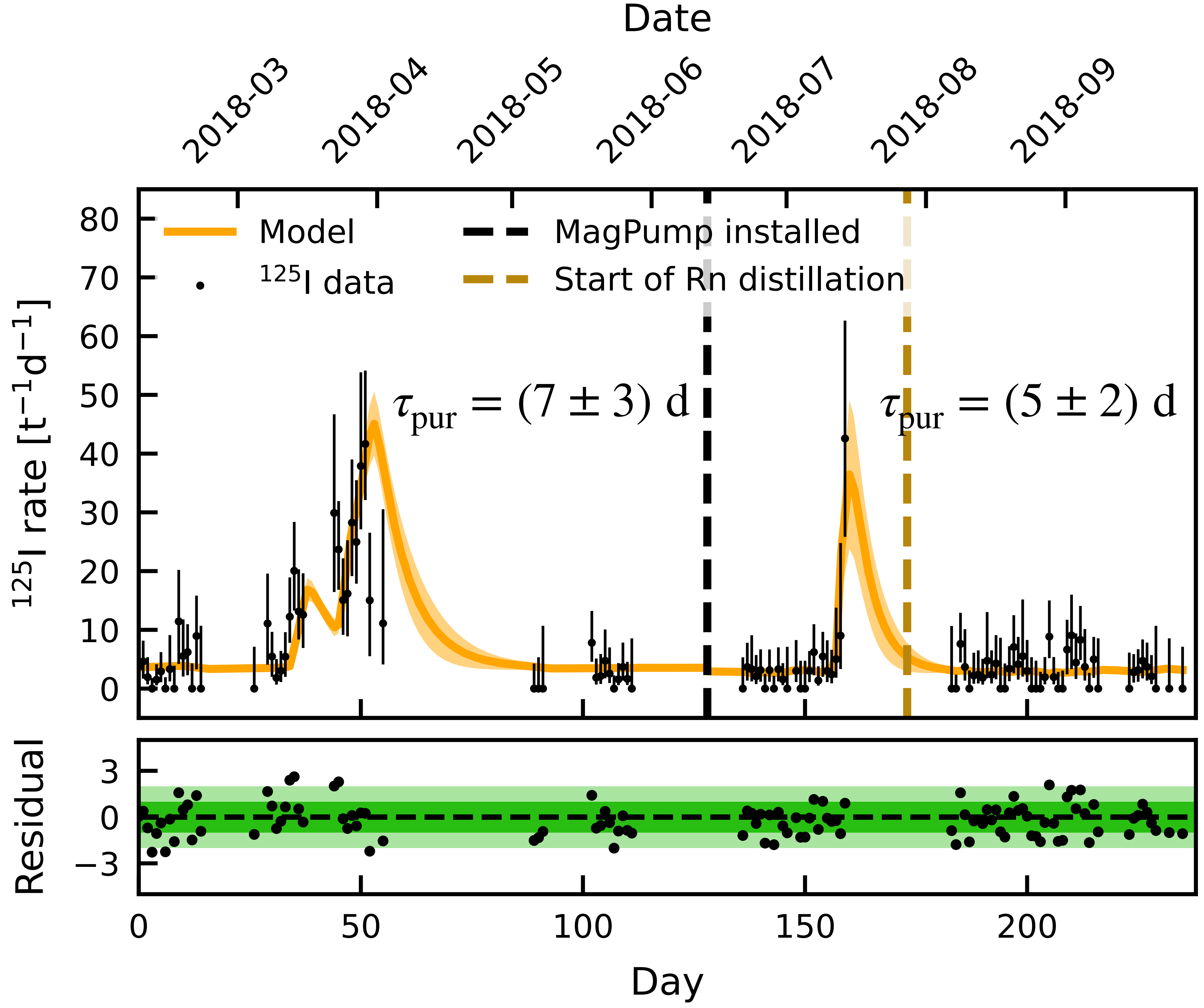
$$^{125}\mathrm{Te}^* \xrightarrow{1.48\ \mathrm{ns}} {}^{125}\mathrm{Te} + \gamma + \mathrm{X}.$$

Lines at 67.3 keV, 40.4 keV, 36.5 keV

Monitor ^{125}Xe activity and predict ^{125}I activity:

$$\frac{\mathrm{d}N_{^{125}\mathrm{I}}}{\mathrm{d}t} = \lambda_{^{125}\mathrm{Xe}} N_{^{125}\mathrm{Xe}}(t) - \left(\lambda_{^{125}\mathrm{I}} + \frac{1}{\tau_{\mathrm{pur}}}\right) N_{^{125}\mathrm{I}}(t)$$

Consider iodine removal by purification!

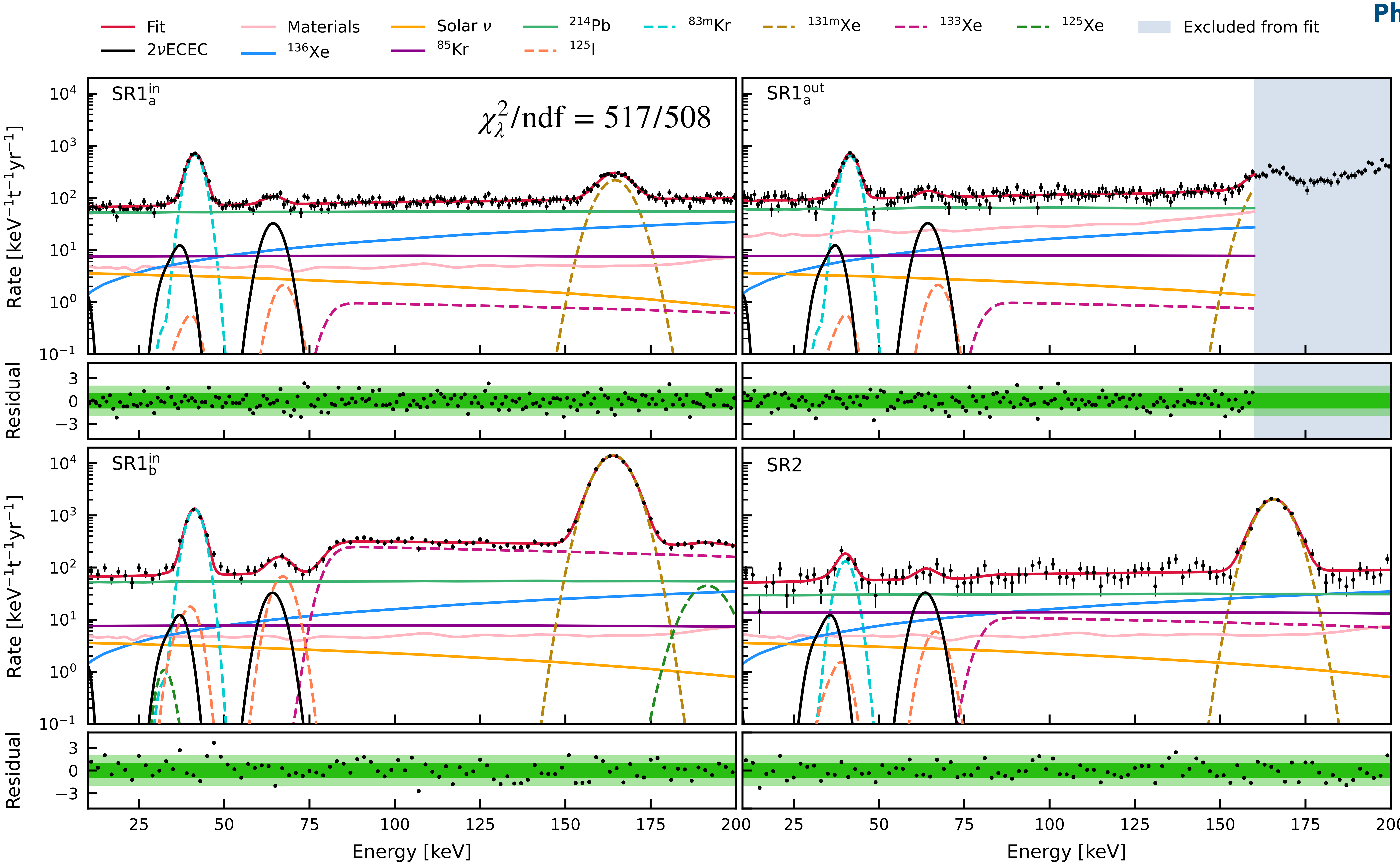


Combined Signal + Background Fit

Phys. Rev. C 106, 024328

SR1a:
- 171.2 d
- 1.0 t

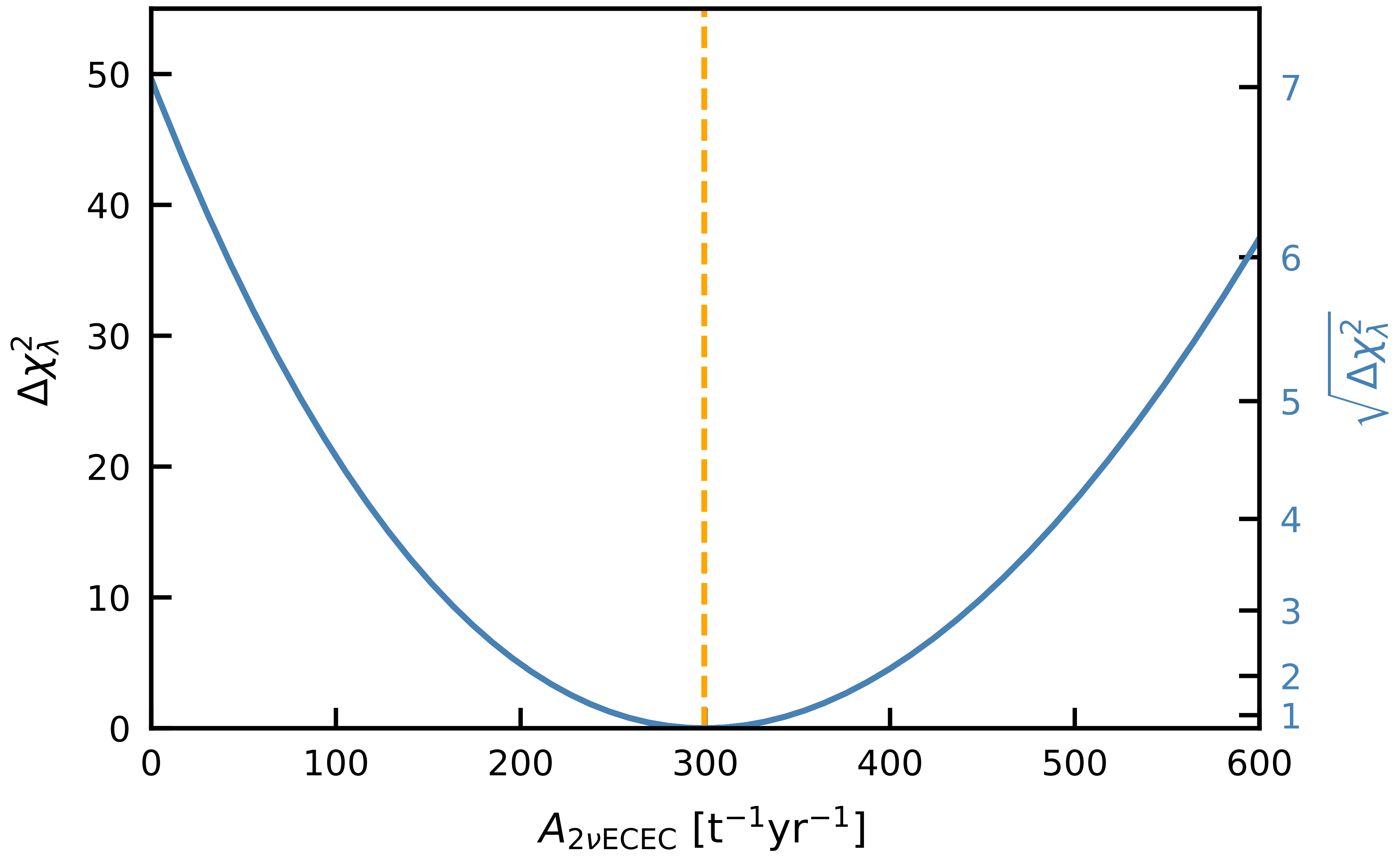
SR1b:
- 171.2 d
- 1.0 t

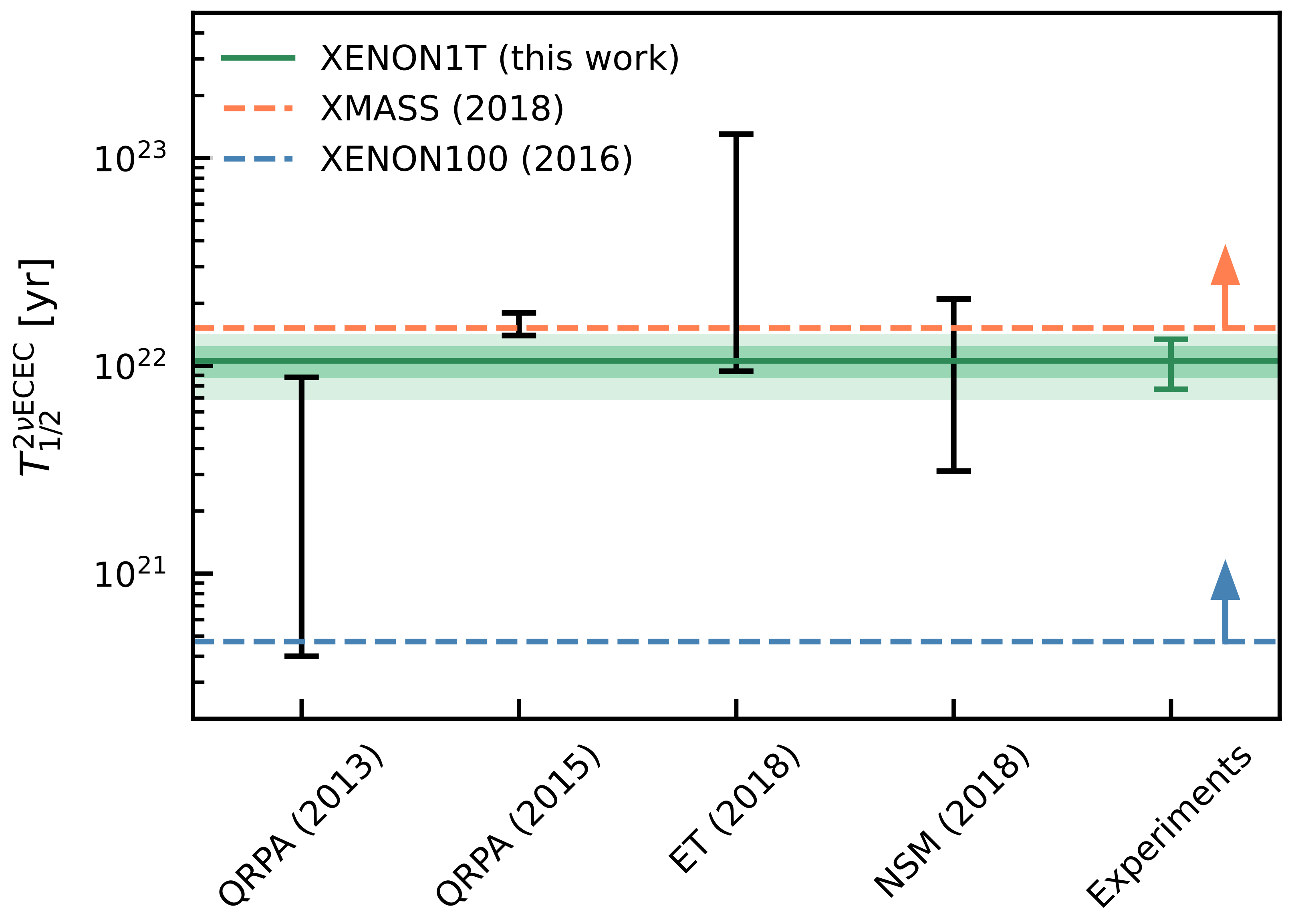


SR1a:
- 171.2 d
- 0.5 t

SR2:
- 24.3 d
- 1.0 t

Comparing to Nuclear Models





- Observed 2vECEC at **7.0σ** significance with a best-fit rate of **(300 ± 50) events/t/yr**.
- Longest half-life measured directly to date.

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

Exposure (0.3 %)
Abundance (1.8 %)
Signal acceptance (4.5 %)
Relative capture fractions (6.3 %)

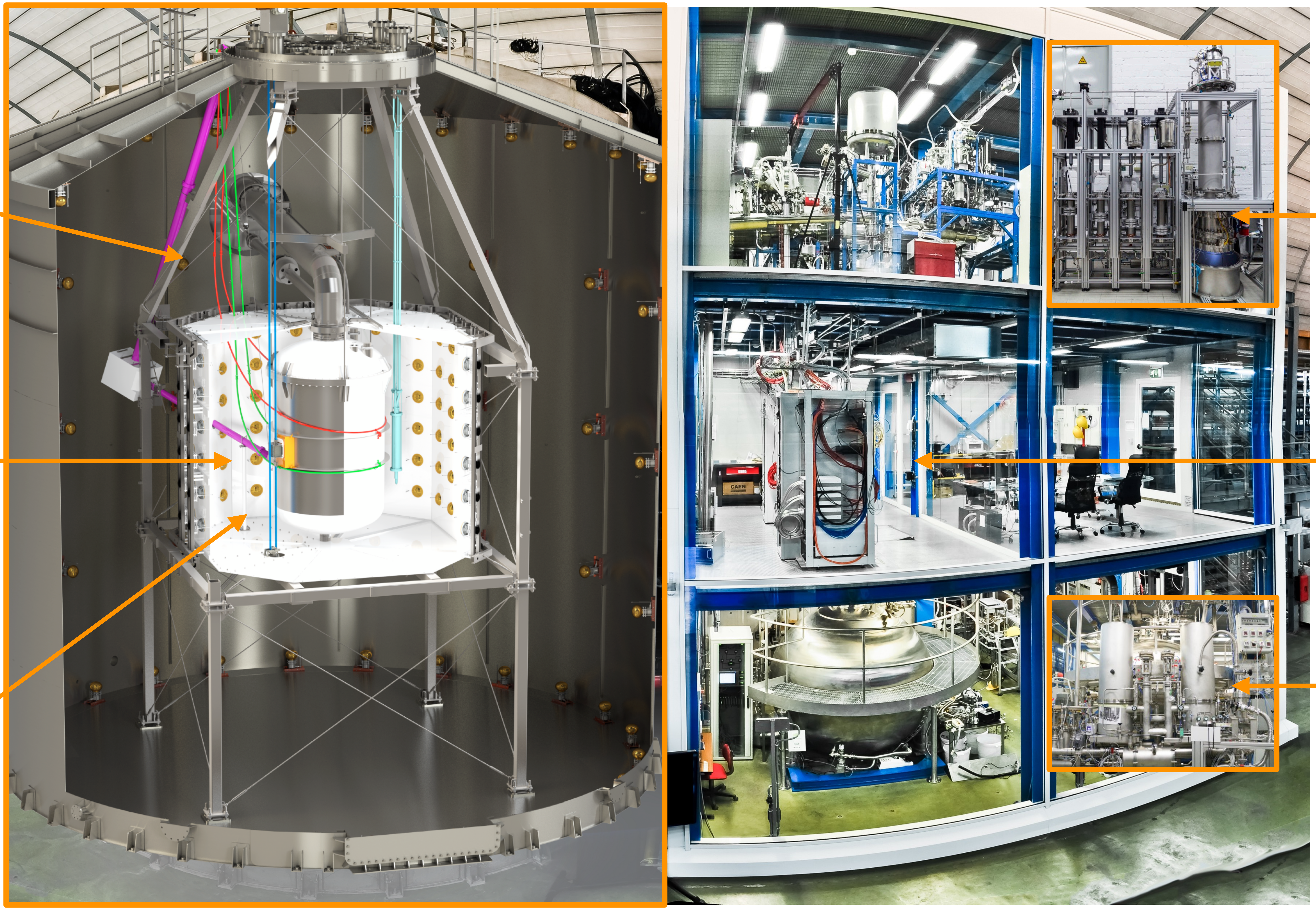
- Compatible with theoretical models.
- Approximately 2σ below XMASS lower limit.

Upgrading to XENONnT

New ER and NR calibration systems

Larger TPC with 3x active volume

Gd-loaded water Cherenkov neutron veto



Radon distillation column

Upgraded DAQ with high-energy readout

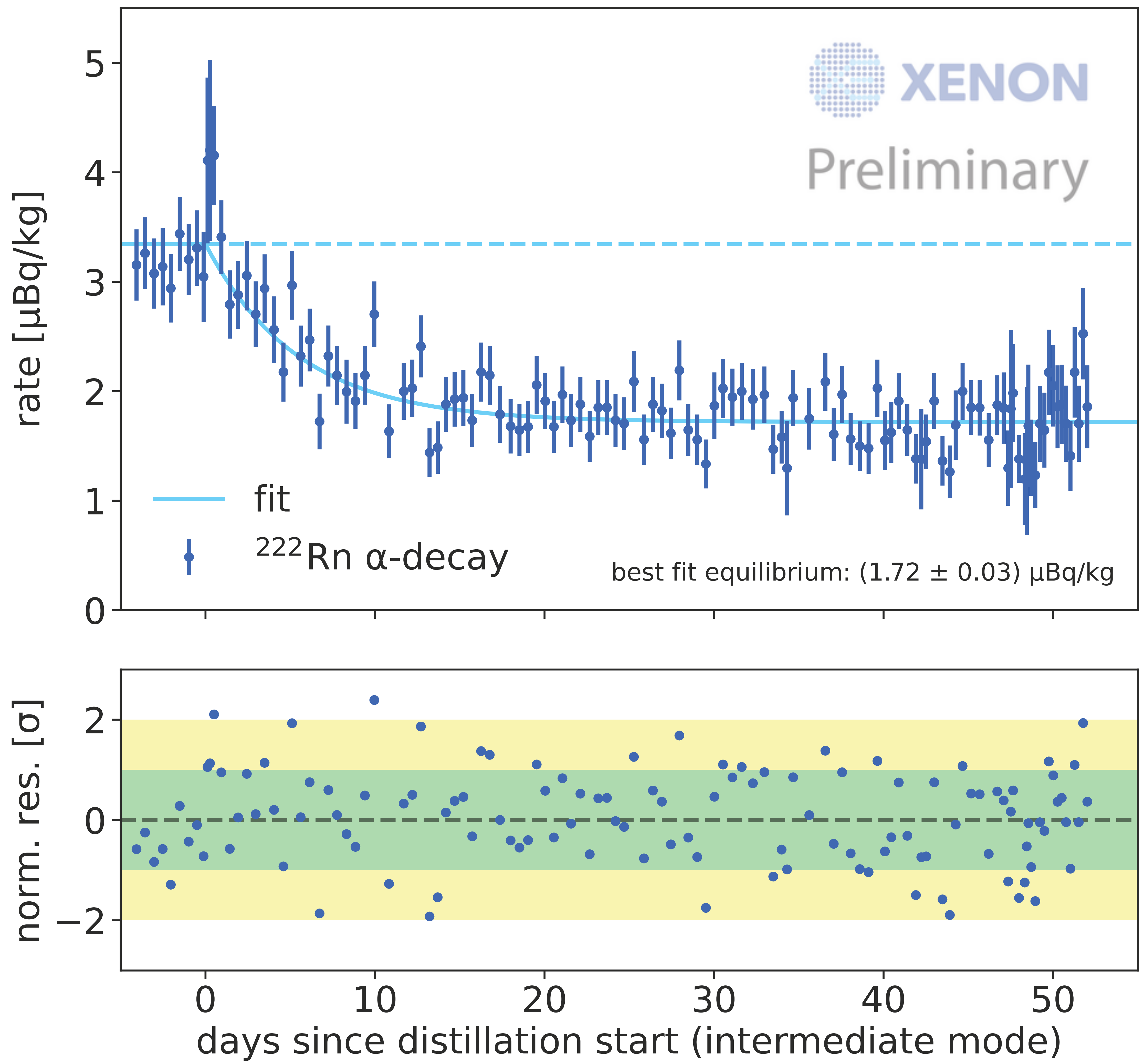
Liquid xenon purification

XENONnT Radon Distillation Column

- Main background for low-energy ER searches from ^{222}Rn progeny
- Constantly remove emanating radon from xenon using difference in vapor pressure
- Remove radon faster than it decays ($T_{1/2}$ = 3.8 d)
- Liquid xenon inlet and outlet with 0.4 l/min ≈ 70 kg/h LXe

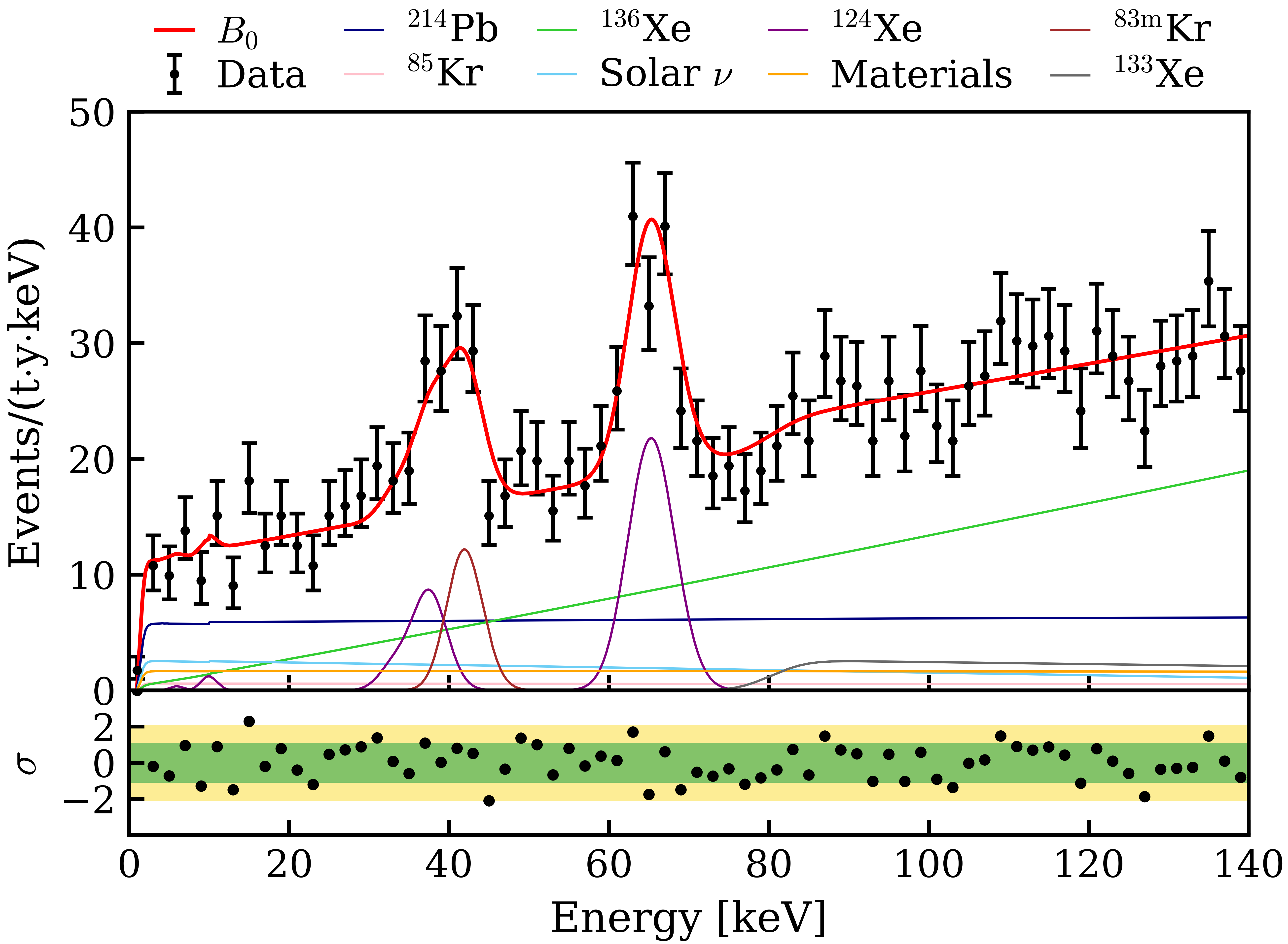
XENONnT Radon Distillation Column

- Reached equilibrium concentration of 1.72 μBq/kg by gas extraction only
- Additional factor 2 in Rn removal achieved for second science run using originally planned liquid extraction
- Achieved background goal 1 μBq/kg



XENONnT low-energy ER results

Phys. Rev. Lett. 129, 161805 (2022)

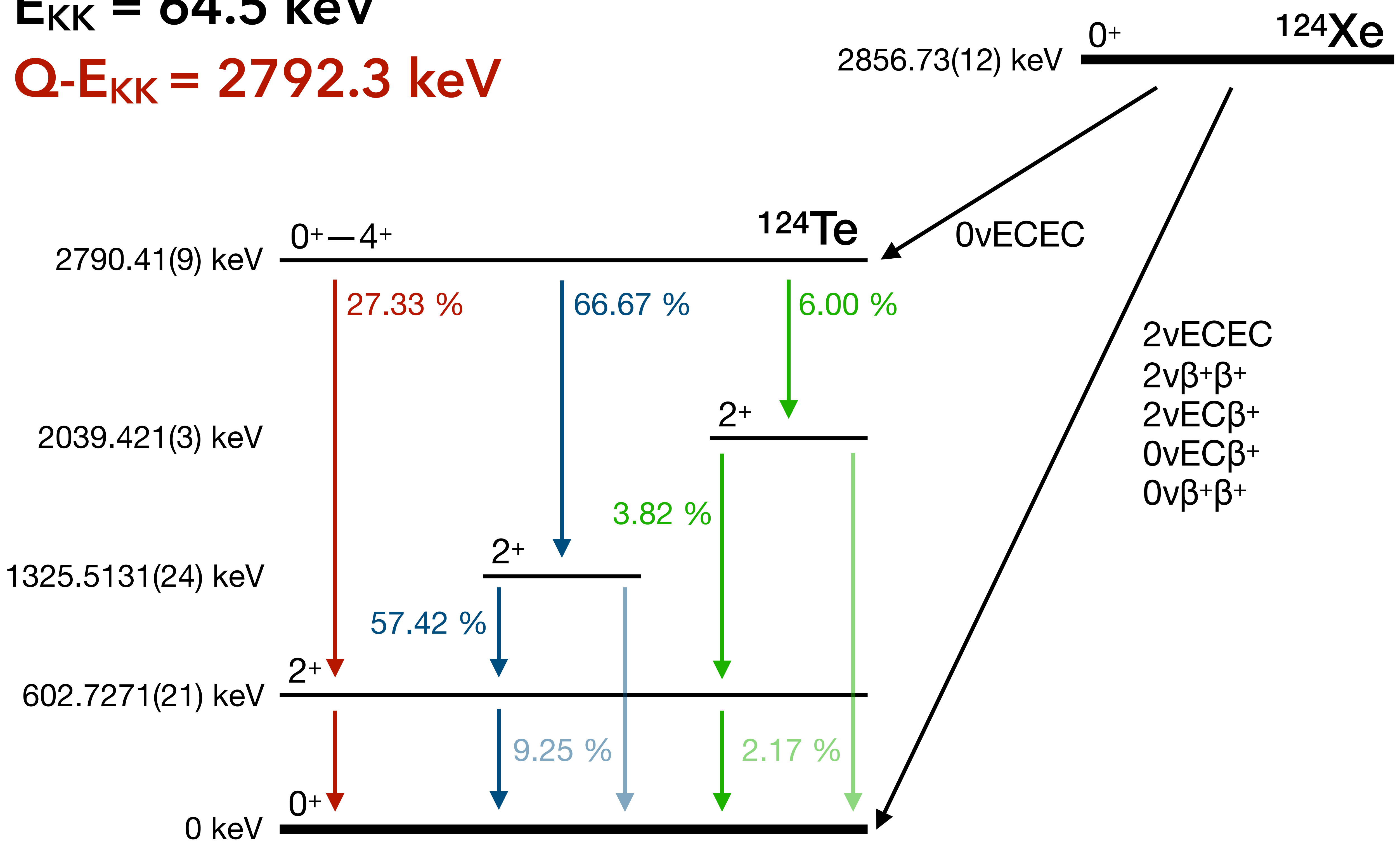


- First XENONnT 2vECEC measurement as a spin-off from a search for new physics with low-energy electronic recoils.
- 97.1 live days of data in a (4.37 ± 0.14) tonne fiducial volume => 1.16 tonne-years
- Lowest ever background in a Xe TPC for dark matter searches.

$$T_{1/2}^{2\nu\mathrm{ECEC}} = (1.18 \pm 0.13_{\mathrm{stat}} \pm 0.14_{\mathrm{sys}}) \cdot 10^{22}\ \mathrm{yr}$$

Neutrinoless double-electron capture

Q = 2856.7 keV
E_{KK} = 64.5 keV
Q-E_{KK} = 2792.3 keV



Eur. Phys. J. C 80 (2020) 12, 1161

- Resonant decay needed in order to conserve energy and momentum.
- ^{124}Te state at 2790.41 keV is 1.9 keV off and J^P unknown.

BSM physics, e.g. light neutrino exchange

$$(T_{1/2}^{0\nu ECEC})^{-1} = G_{0\nu}\,|M_{0\nu}|^2\,|f(m_i, U_{ei})|^2\,R$$

PSF and NME **Resonance factor**

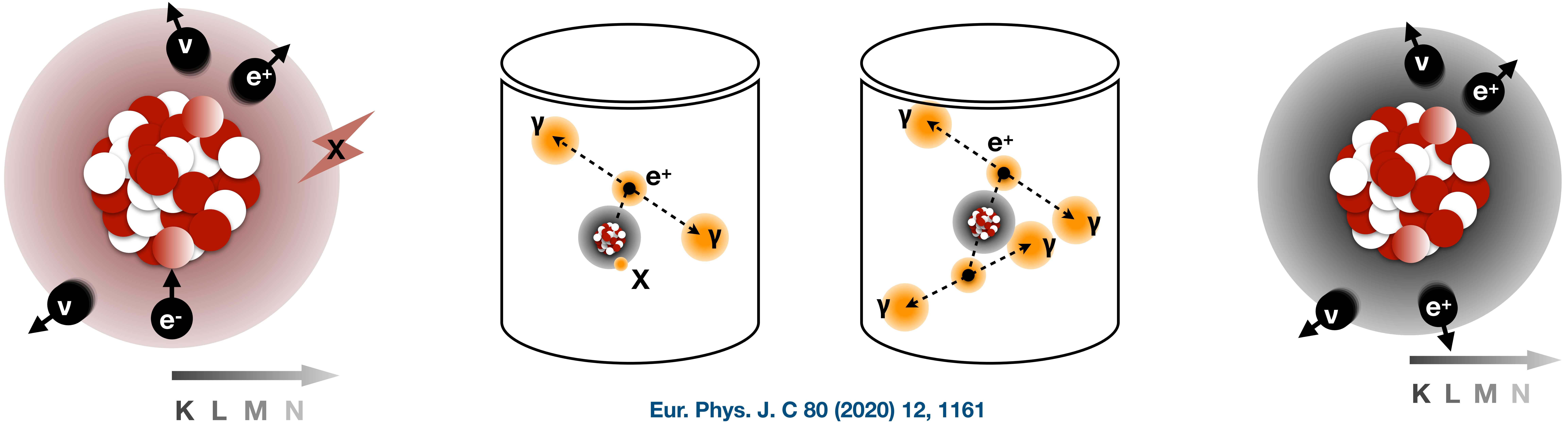
$$R = \frac{m_e c^2 \Gamma}{\Delta^2 + \Gamma^2/4} = 2.92 \pm 0.47$$

$$T_{1/2}^{0\nu} > 1.8 \cdot 10^{29}\ \mathrm{yr}\ -\ 3.9 \cdot 10^{32}\ \mathrm{yr}\quad (90\,\%\ \mathrm{C.L.})$$

Undetected ^{124}Xe decays

With $Q_{2\nu ECEC}$ = 2856.7 keV two positronic decay modes for ^{124}Xe:

0ν/2νECβ⁺ **0ν/2νβ⁺β⁺**



Eur. Phys. J. C 80 (2020) 12, 1161

$T^{2\nu}_{1/2} = (1.7 \pm 0.6) \cdot 10^{23}$ yr

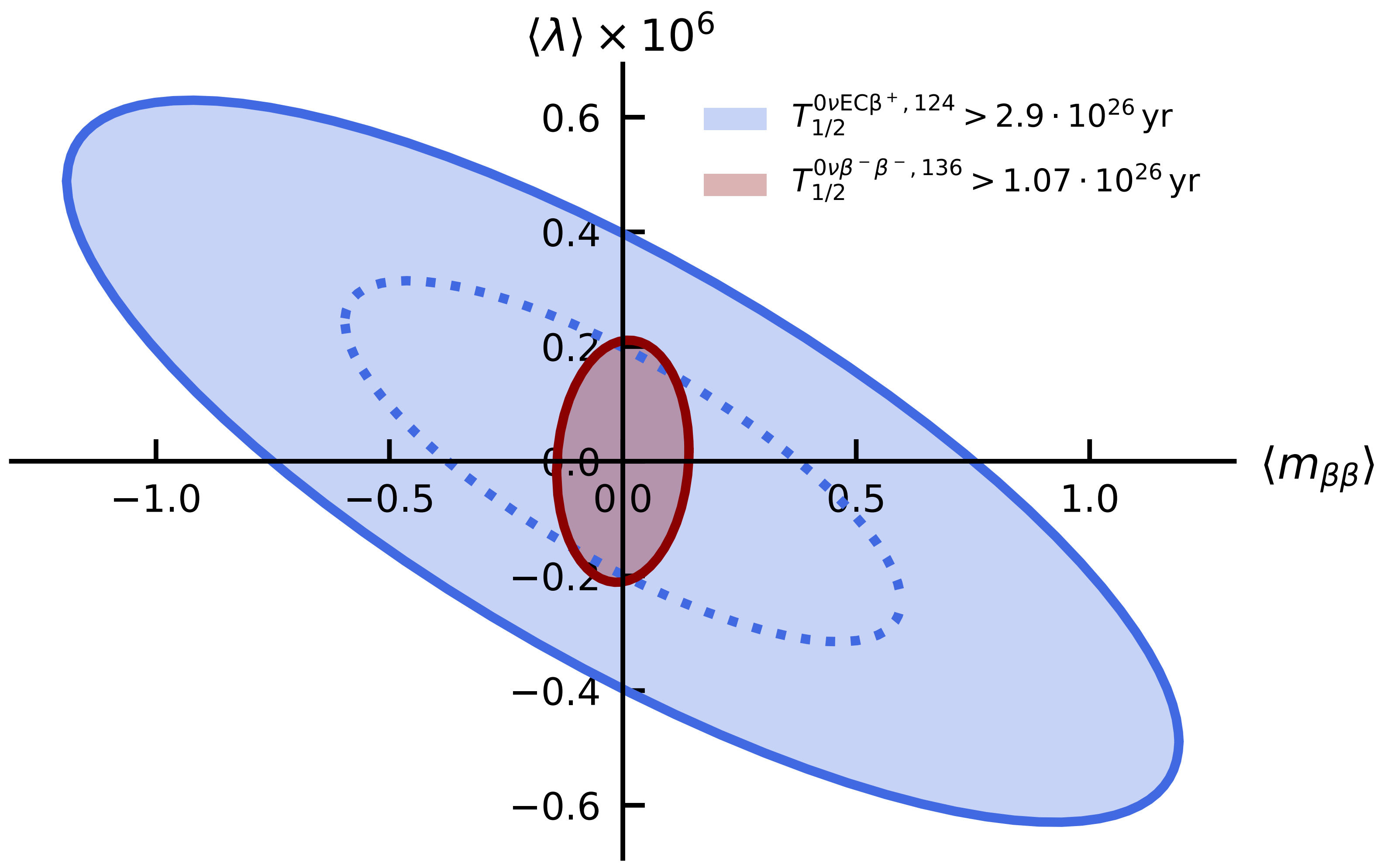
$T^{0\nu}_{1/2} > 4.8 \cdot 10^{25}$ yr $-$ $5.3 \cdot 10^{28}$ yr (90 % C.L.)

$T^{2\nu}_{1/2} = (2.2 \pm 0.7) \cdot 10^{28}$ yr

$T^{0\nu}_{1/2} > 8.6 \cdot 10^{26}$ yr $-$ $9.3 \cdot 10^{29}$ yr (90 % C.L.)

What if it is not light neutrino exchange?

M. Hirsch et al.: Zeitschrift für Physik A Hadrons and Nuclei 347, 151 (1994)

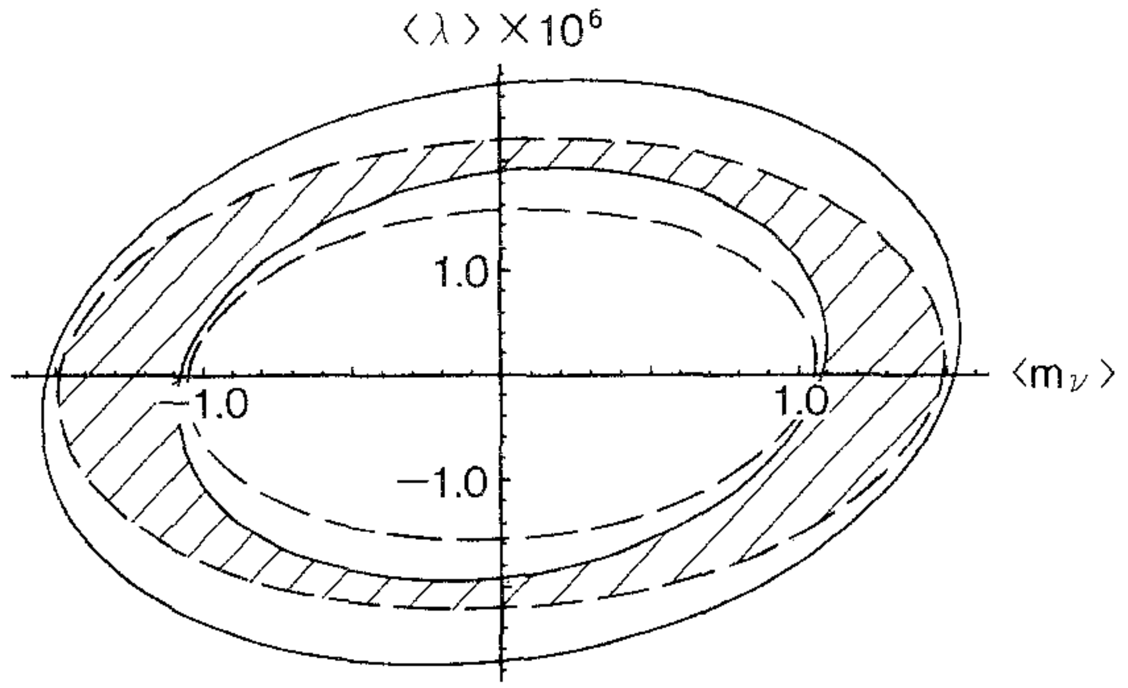


Matrix elements

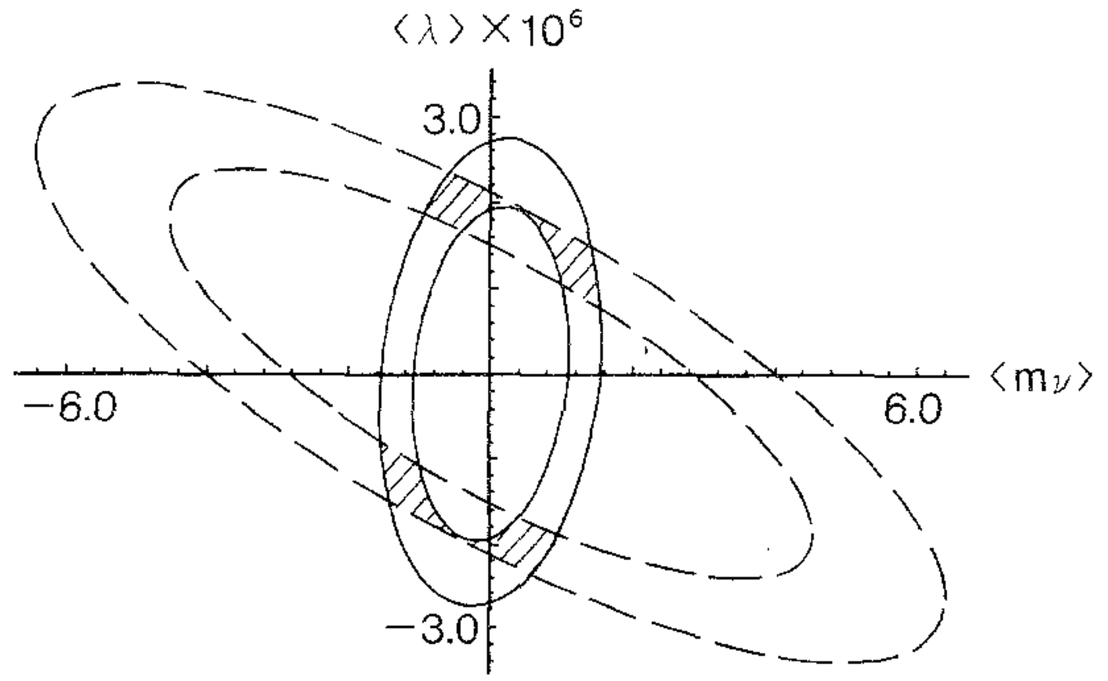
$$[T^{\alpha}_{1/2}(0_i^+ \to 0_f^+)]^{-1} = C^{\alpha}_{mm}\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2 + C^{\alpha}_{\eta\eta}\langle\eta\rangle^2 + C^{\alpha}_{\lambda\lambda}\langle\lambda\rangle^2 + C^{\alpha}_{m\eta}\frac{\langle m_\nu\rangle}{m_e}\langle\eta\rangle + C^{\alpha}_{m\lambda}\frac{\langle m_\nu\rangle}{m_e}\langle\lambda\rangle + C^{\alpha}_{\eta\lambda}\langle\eta\rangle\langle\lambda\rangle$$

Couplings and mixing

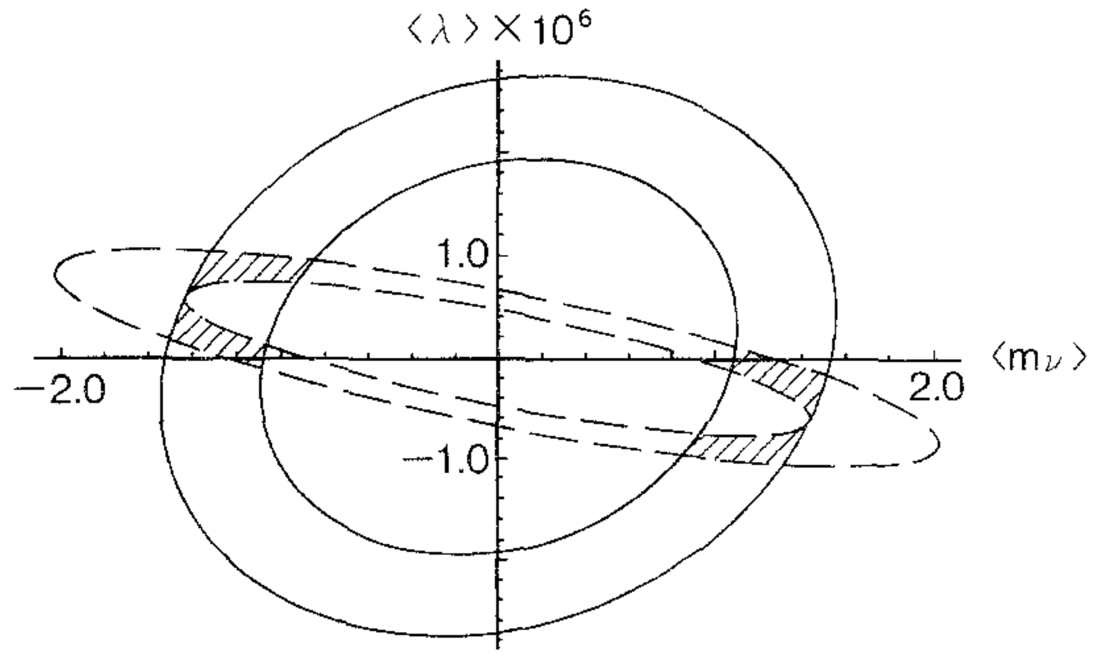
Observation of 0νβ⁻β⁻ in ^{76}Ge (full) and ^{136}Xe (dashed) with $T_{1/2} = (1.5 \pm 0.5) \times 10^{24}$ yr



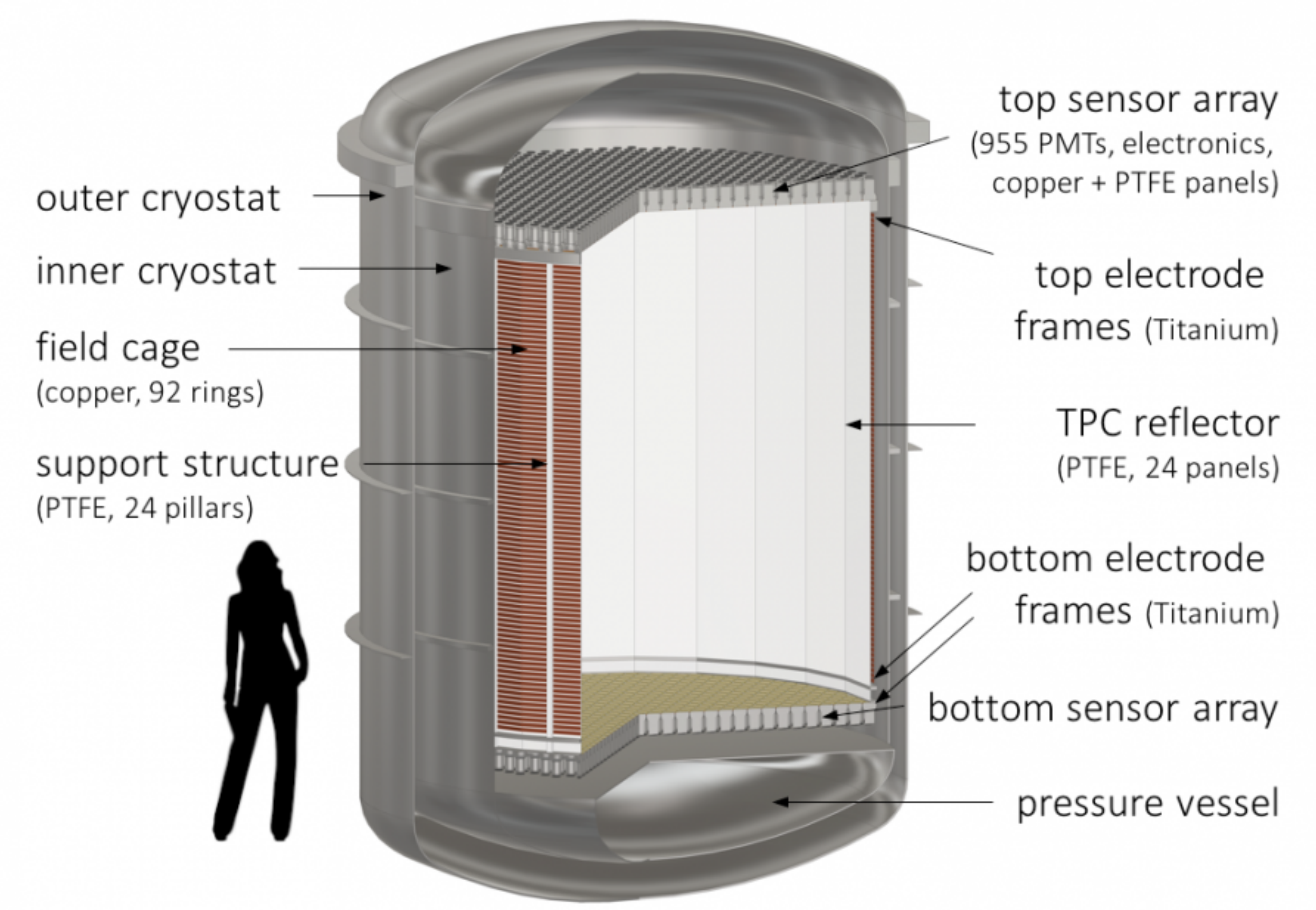
Observation of 0νβ⁻β⁻ in ^{76}Ge and 0νECβ⁺ of ^{124}Xe with $T_{1/2} = (1.5 \pm 0.5) \times 10^{25}$ yr



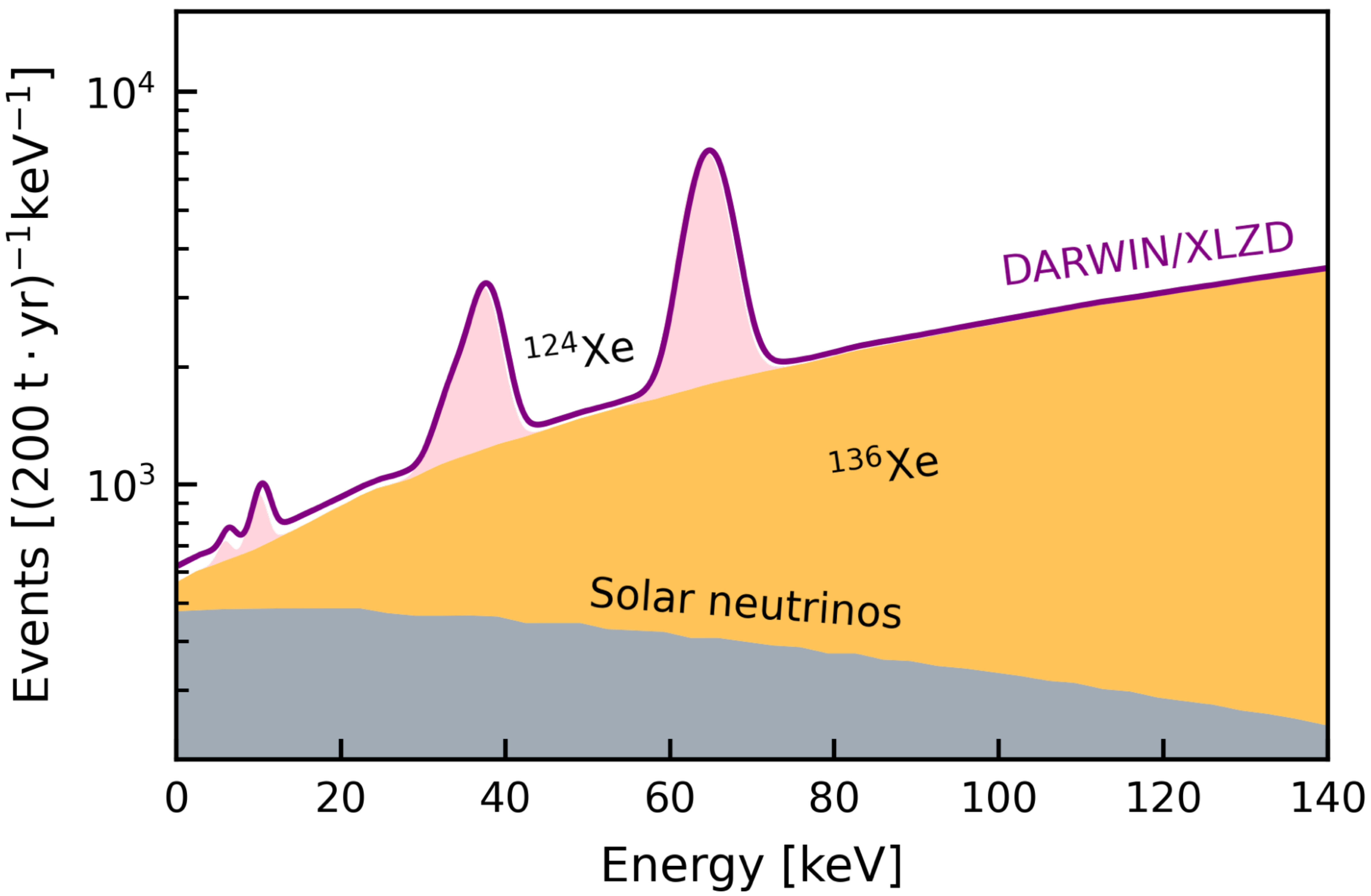
Observation of 0νβ⁻β⁻ in ^{76}Ge and 0νECβ⁺ of ^{124}Xe with $T_{1/2} = (1.5 \pm 0.5) \times 10^{26}$ yr



The Future: DARWIN + XLZD



Based on DARWIN Collaboration., Aalbers, J., Agostini, F. et al., Eur. Phys. J. C 80, 1133 (2020).



- Make ^{124}Xe 2νECEC, ^{136}Xe 2νββ and solar neutrinos dominant backgrounds
- Multi-purpose physics observatory:
  - Dark matter, 0νββ, axions, neutrinos, …

Summary

University of Zurich[UZH]

- XENON1T measured 2νECEC directly for the first time in 2018
- First significant measurement of 2νECEC in ^{124}Xe with a half-life of **$(1.1 \pm 0.2_{stat} \pm 0.1_{sys}) \times 10^{22}$ yr** at **7.0σ**.
- XENONnT will improve the measurement precision further for a better benchmark of nuclear models.
- Neutrinoless and positronic decay modes of ^{124}Xe provide intriguing event signatures.

www.xenonexperiment.org

instagram.com/xenon_experiment

twitter.com/xenonexperiment