Universität Münster

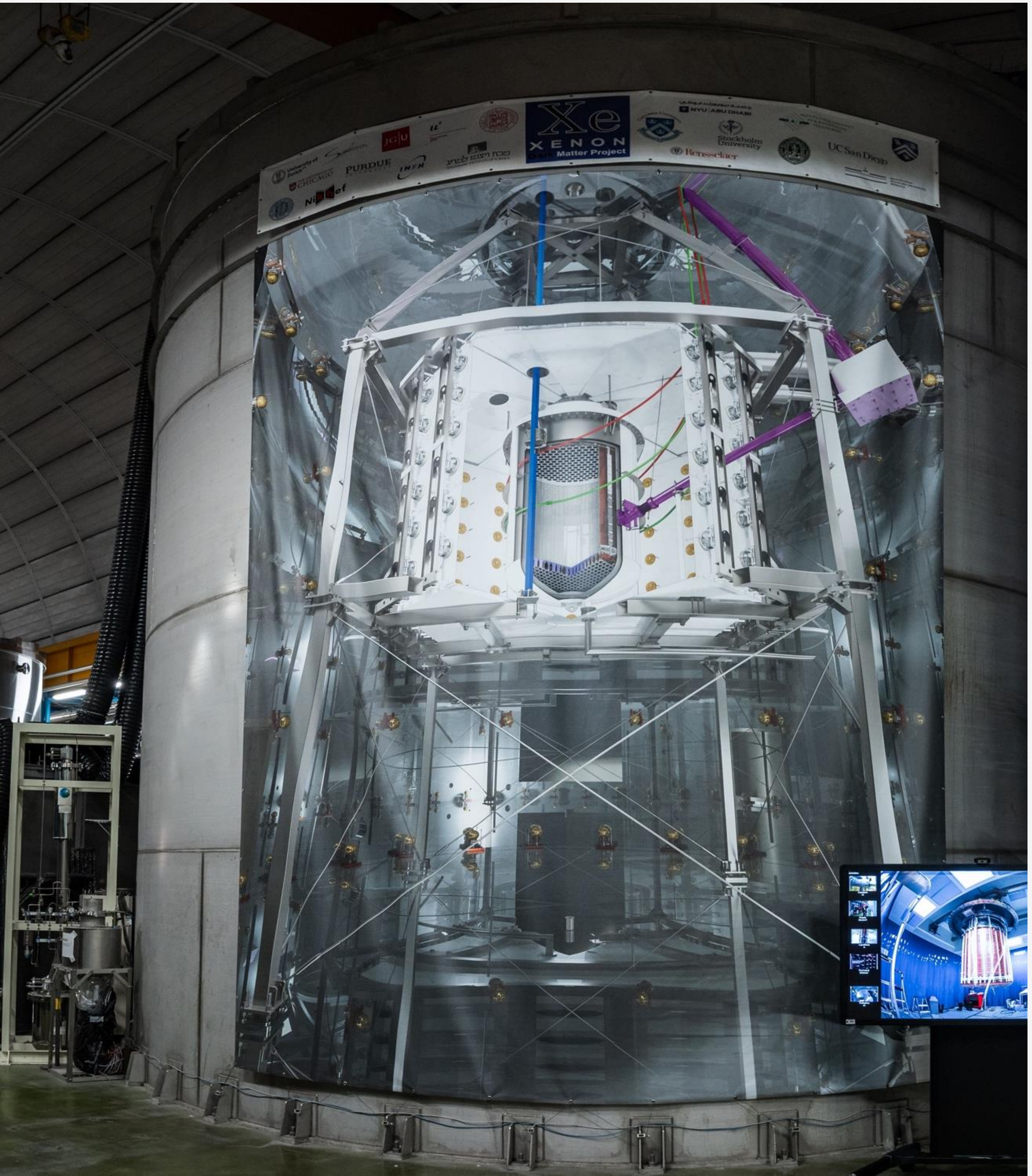
XENONnT:
Towards Solar *pp* Level Background in the Electron-Recoil Detection Channel

Ying-Ting Lin, on behalf of the XENON Collaboration
University of Münster, Institute for Nuclear Physics, Germany
IDM 2026 Zaragoza, Spain, 03.06.2026

erc LowRad

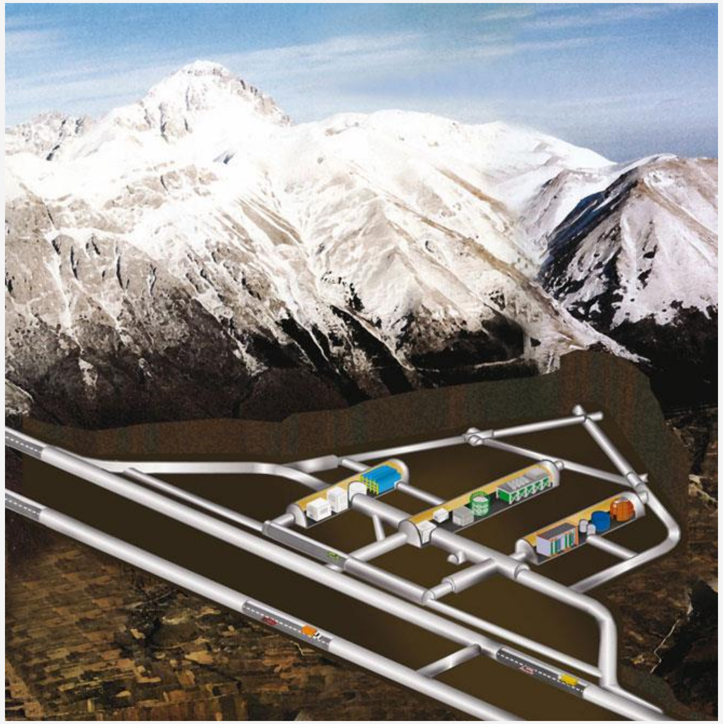
XENON

The XENON Collaboration



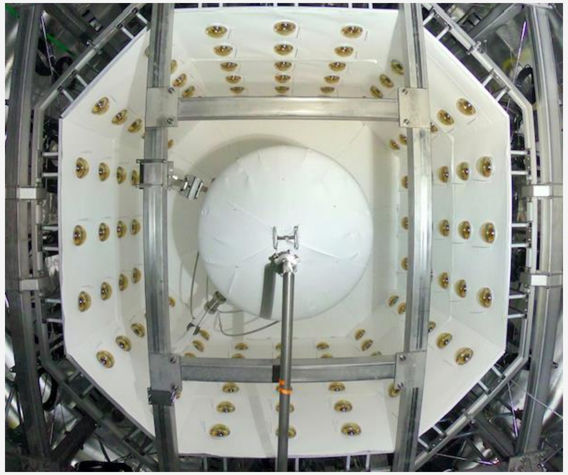
200+ members
31 institutes
12 countries

Background Reduction Prerequisites for Rare Event Searches

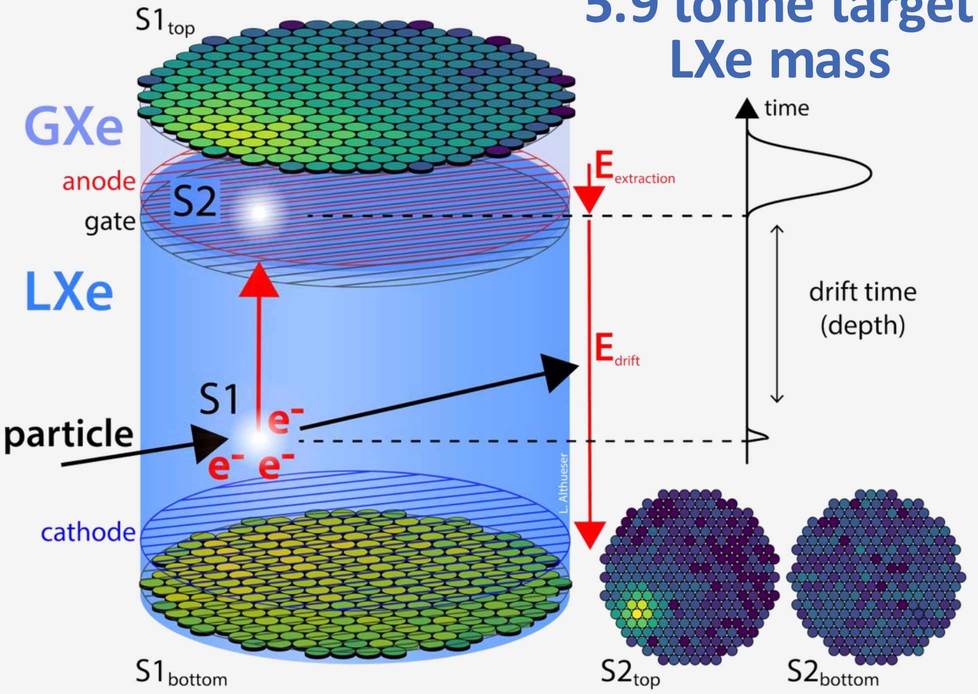


- Going underground (3.6 km water equivalent)
- Active muon and neutron vetoes / extra shielding
- Detector material: cleaning and screening
- Accurate position reconstruction: fiducial volume (FV)
  - **S1: prompt scintillation, light signal**
  - **S2: drift electrons, charge signal**

Gd-Loaded Neutron Veto: Emanuele Angelino, Jun 4th, 15:15, Pedro Cerbuna



5.9 tonne target LXe mass



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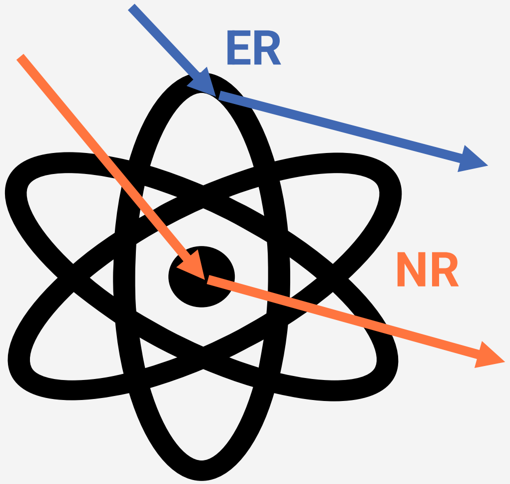
ER/NR Discrimination

➢ S2/S1 ratio is different for Electronic Recoils (ER) and Nuclear Recoils (NR), resulting in two separate bands

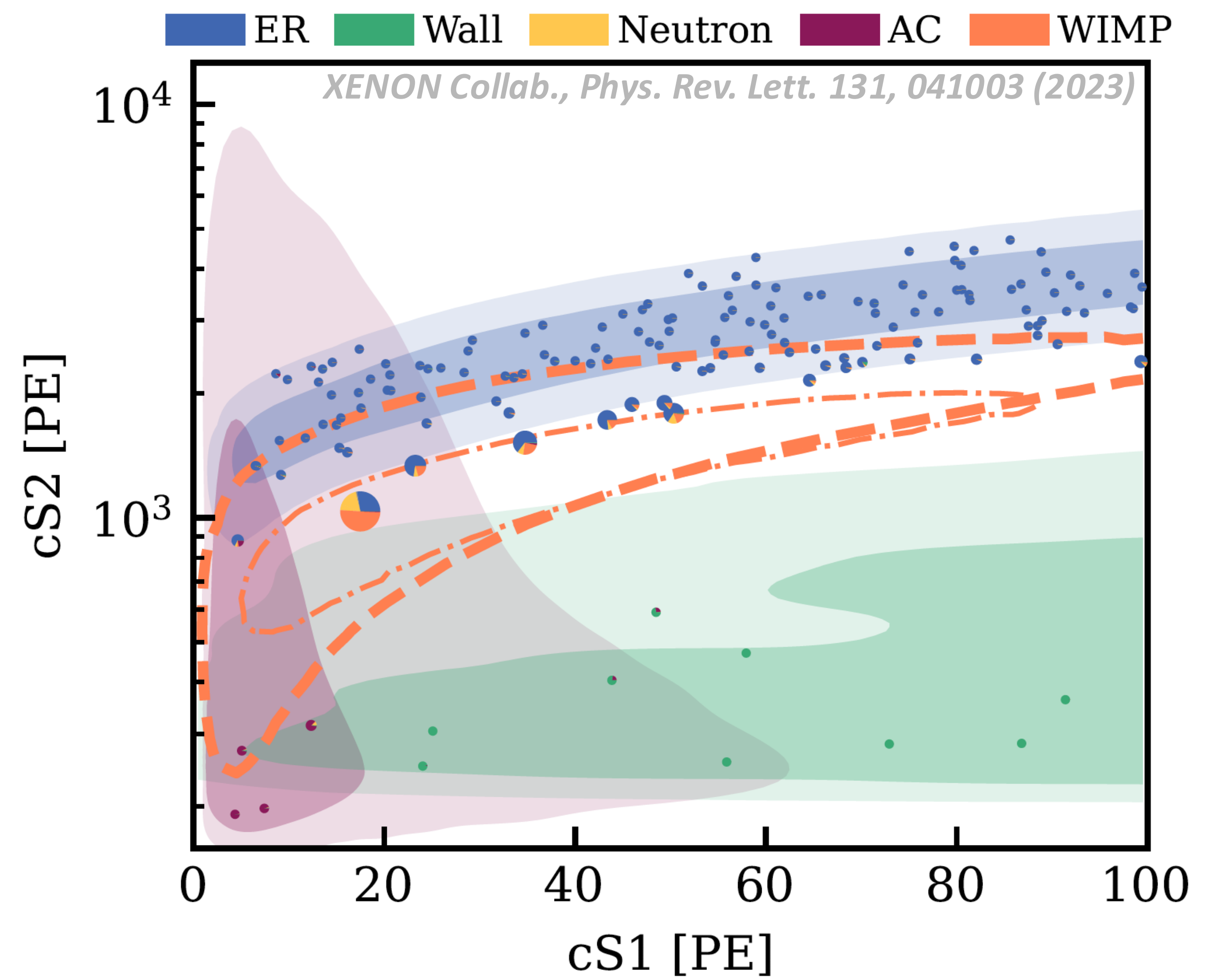


ER (Electronic Recoils):

electron, photon, neutrino, (axions…)

NR (Nuclear Recoils):

neutron, CEvNS, (WIMPs…)



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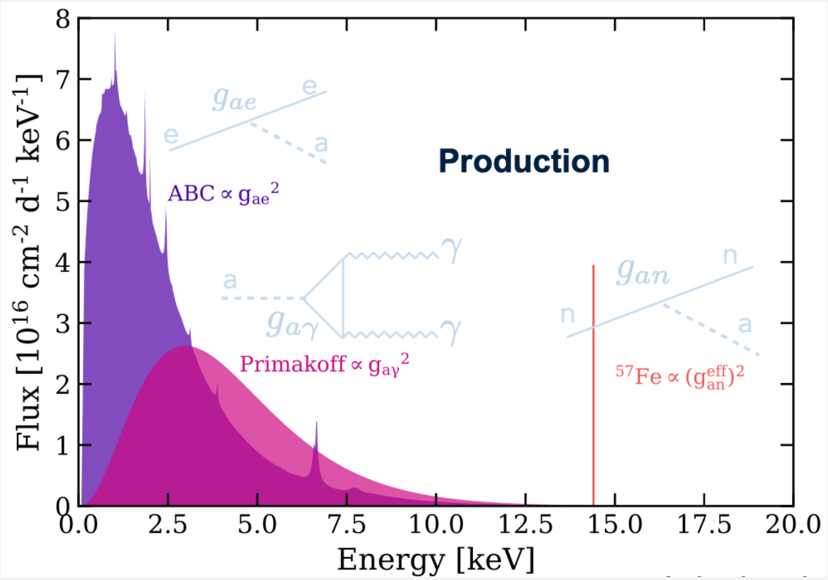
Dark Matter and New Physics Searches in the ER Channel

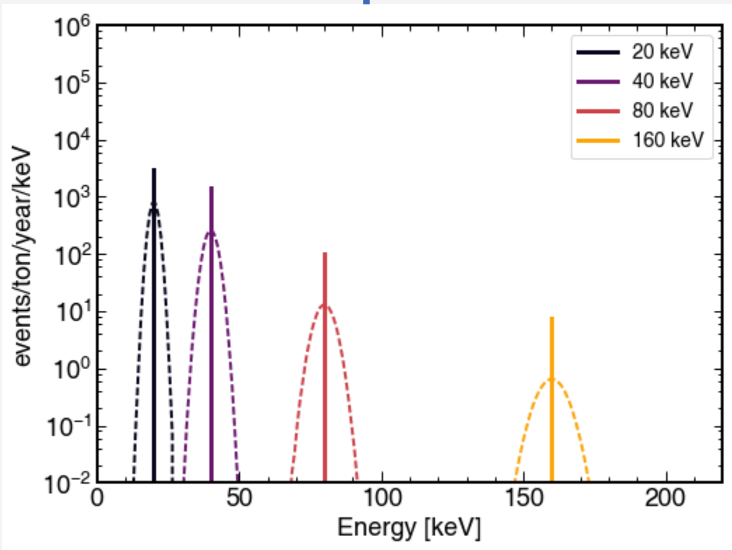
Solar Axion



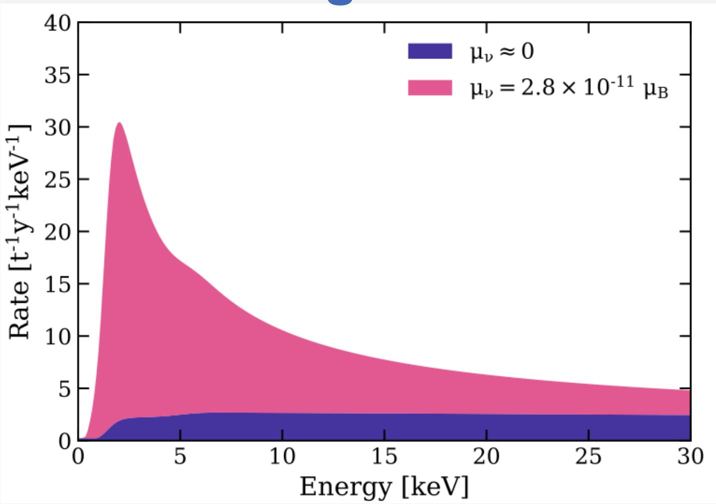
Updated from XENON Collab., Phys. Rev. D 102, 072004 (2020)

Peak-like Signals:

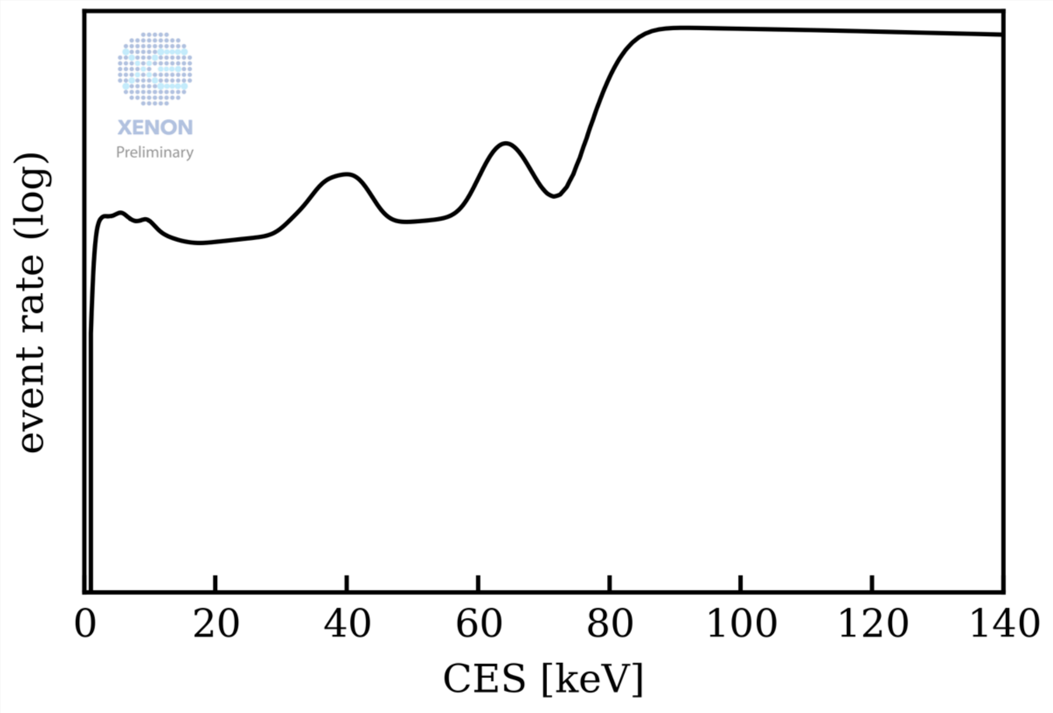
- Dark Photon
- Axion-like particles



Neutrino Magnetic Moment



Region of Interest (ROI):
ER channel in [1, 140] keV range



Prediction for XENONnT Science Run 1 (SR1)

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Backgrounds in ER Channel

ROI: ER channel in [1, 140] keV range

Noble gas backgrounds:

- ^{222}Rn/^{220}Rn
- ^{85}Kr

Xenon Isotopes:

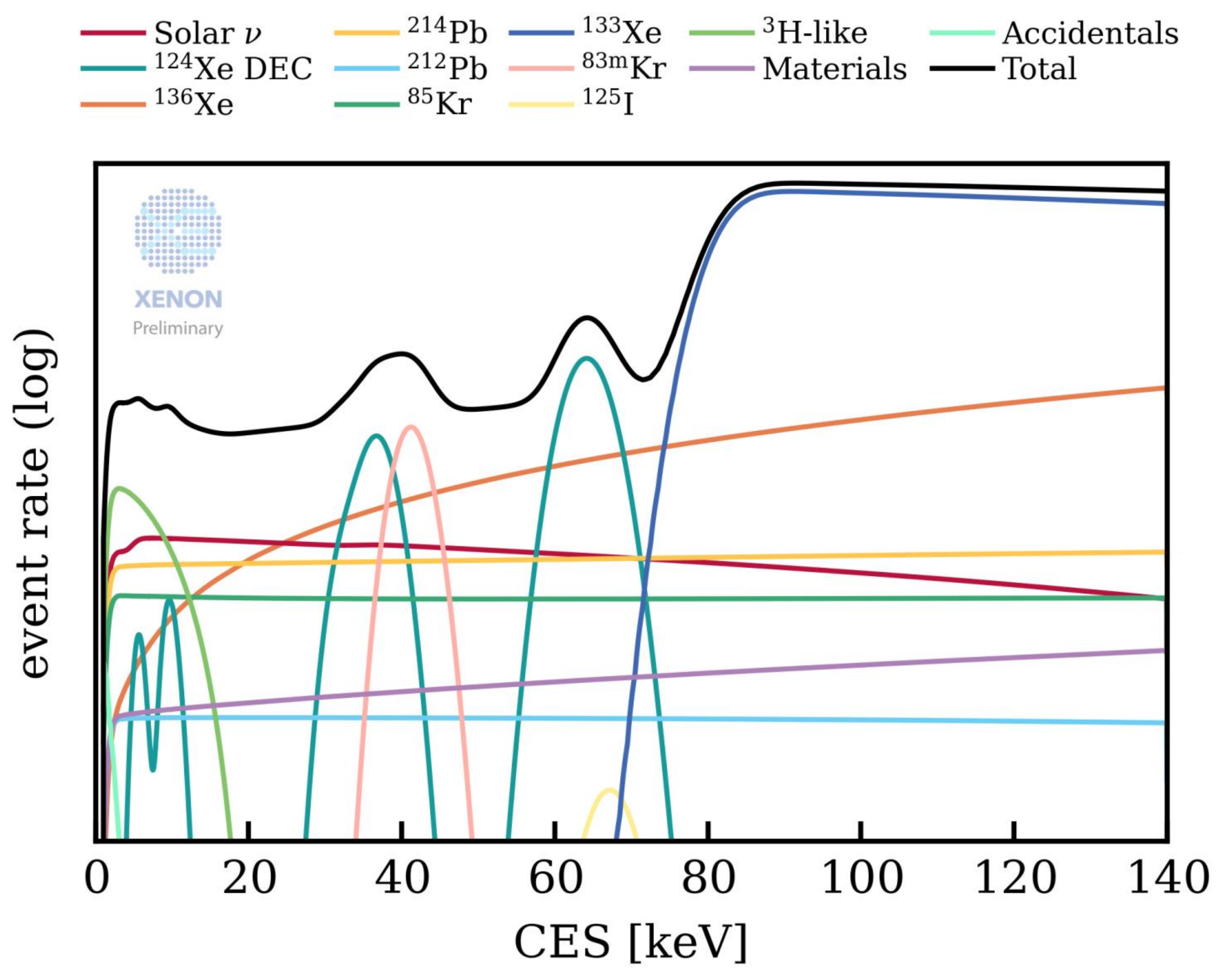
- ^{136}Xe/^{124}Xe
- ^{133}Xe/^{125}I

Other backgrounds:

- Materials
- ^{3}H-like
- ^{83m}Kr
- Accidentals

Neutrinos:

- Solar ν



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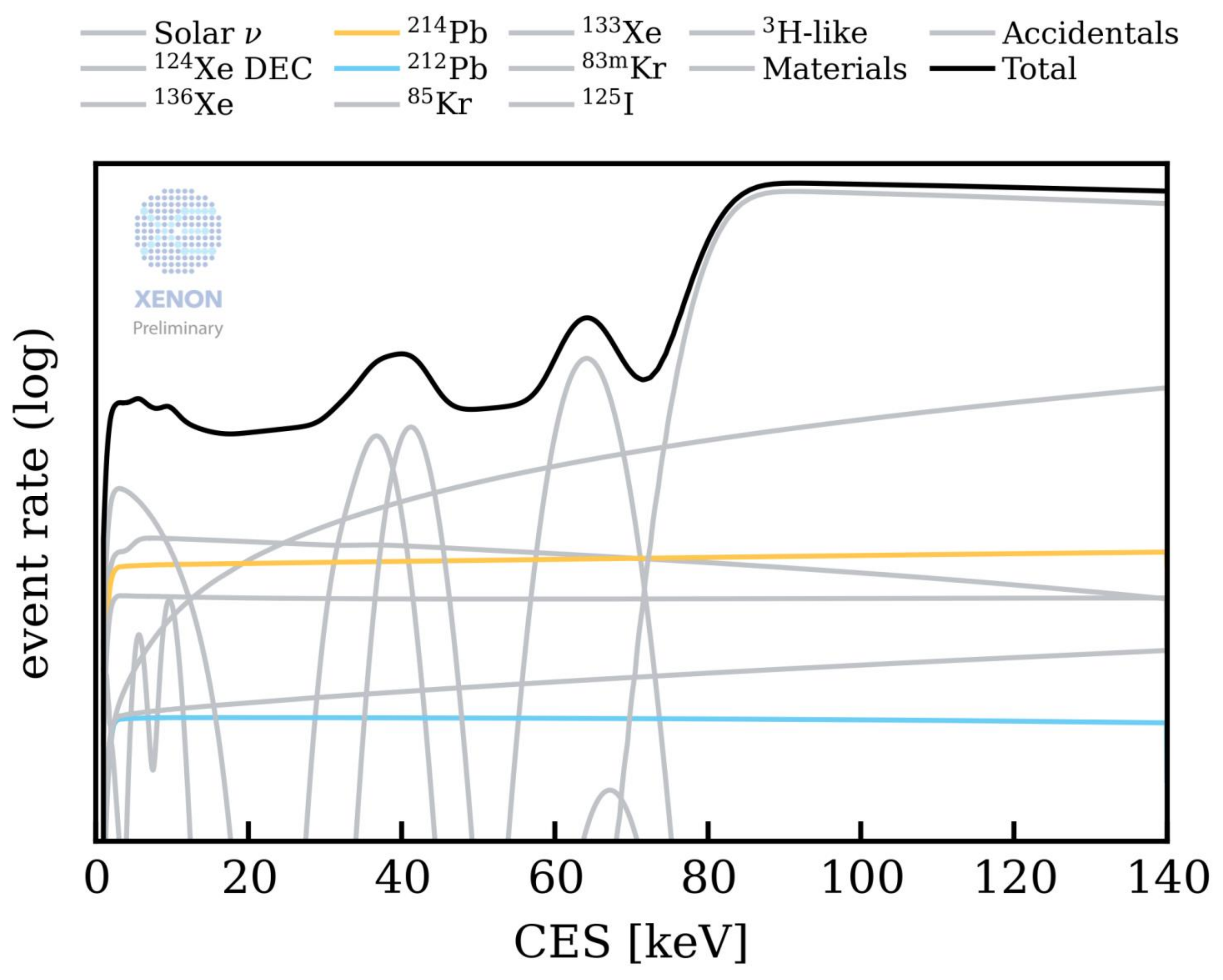
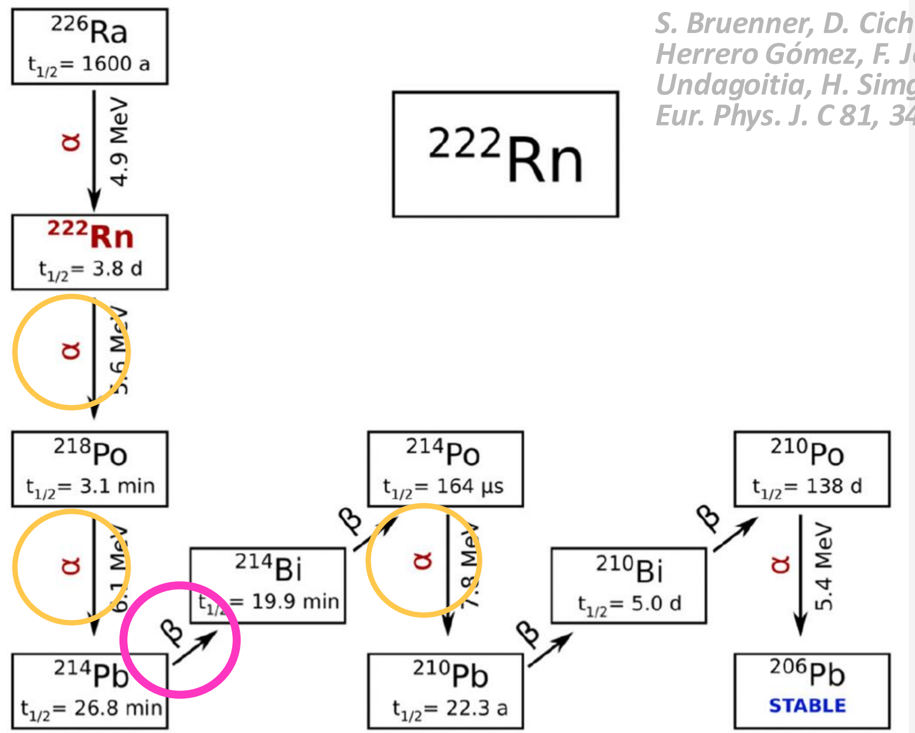
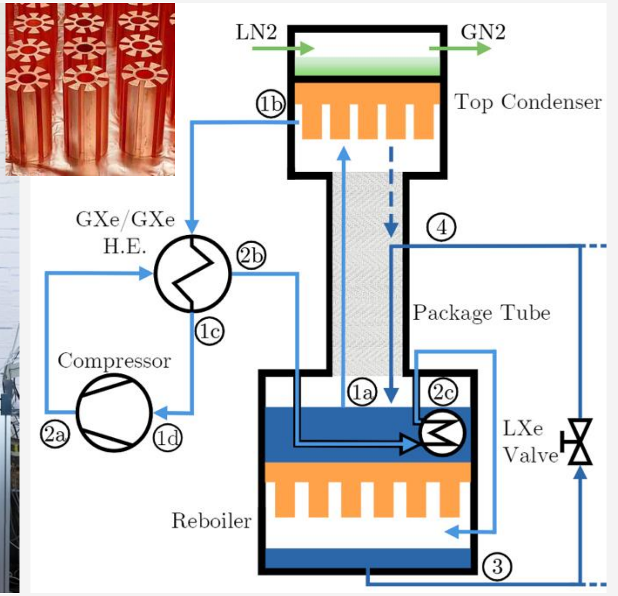


$^{222}Rn/^{220}Rn$: Removal & Monitor

- ER background comes from ^{214}Pb beta decay
- Continue radon removal with ~ 72kg/h high flow
- Alphas from decay chain to constrain ^{214}Pb

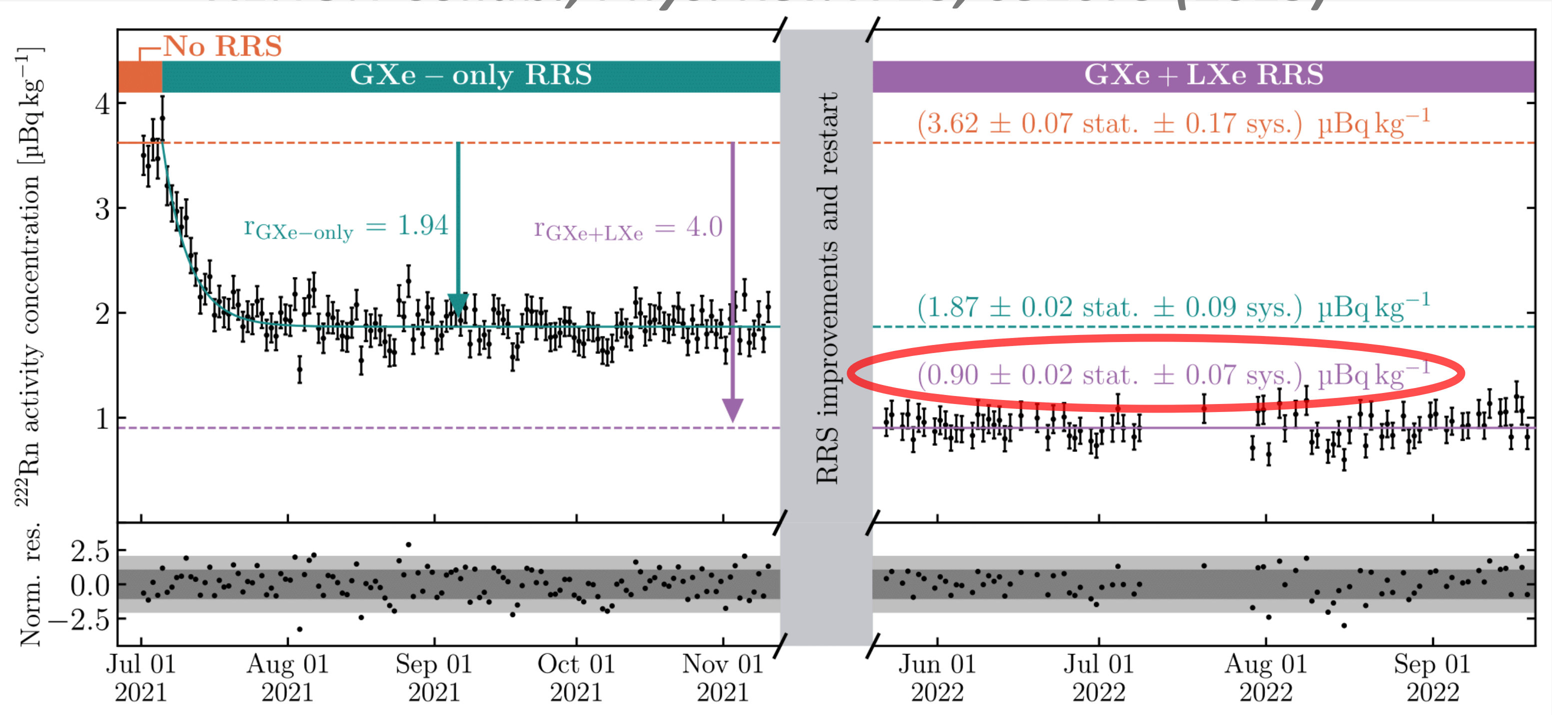


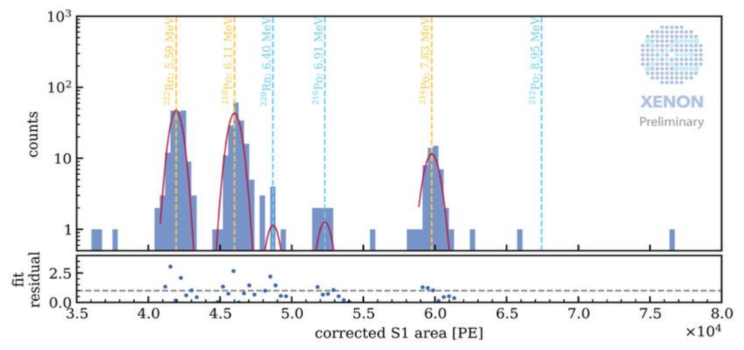
S. Bruenner, D. Cichon, G. Eurin, P. Herrero Gómez, F. Jörg, T. Marrodán Undagoitia, H. Simgen, N. Rupp, Eur. Phys. J. C 81, 343 (2021)



➢ **Reduced ^{222}Rn activity down to 1 µBq/kg level!**

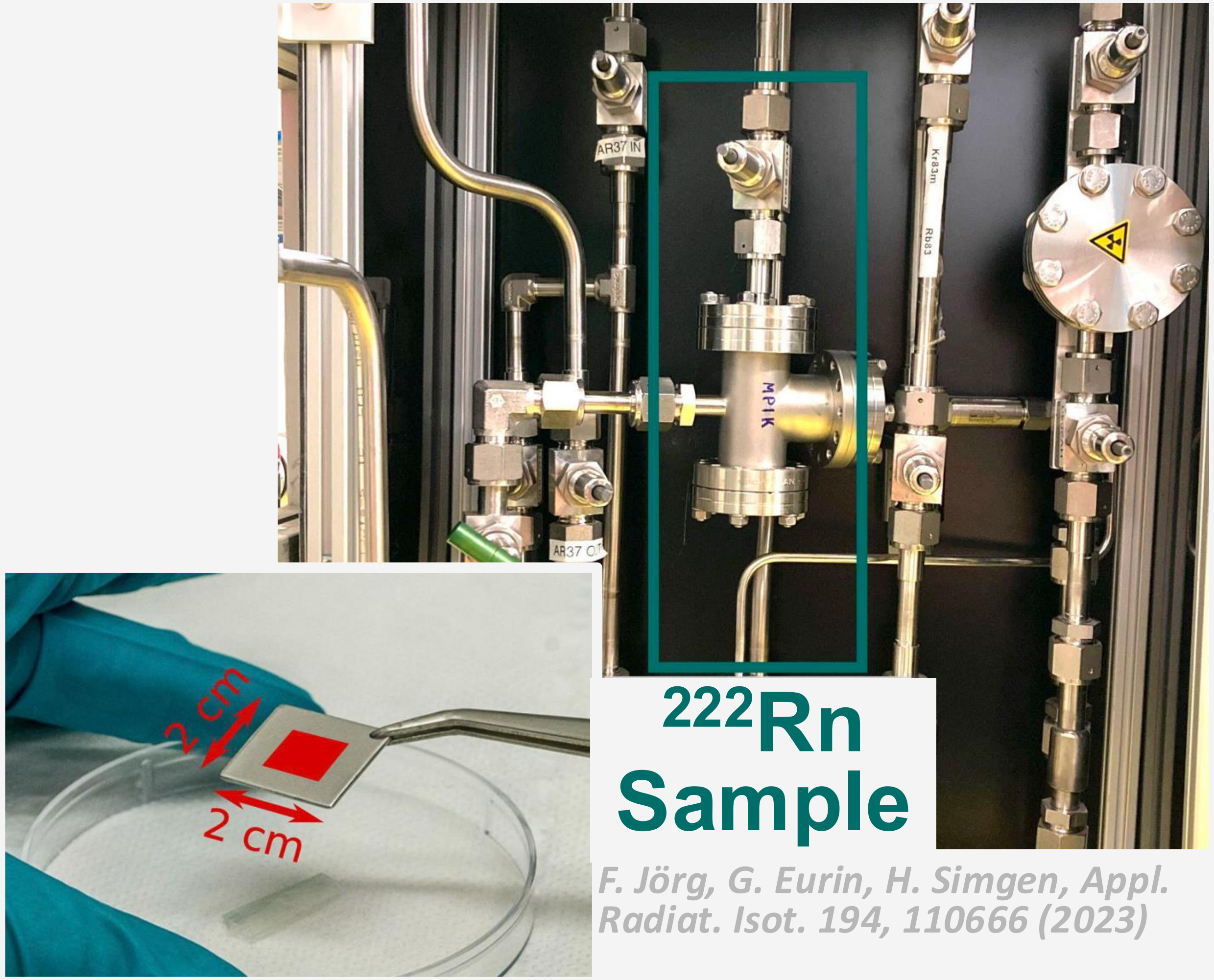
XENON Collab., Phys. Rev. X 15, 031079 (2025)



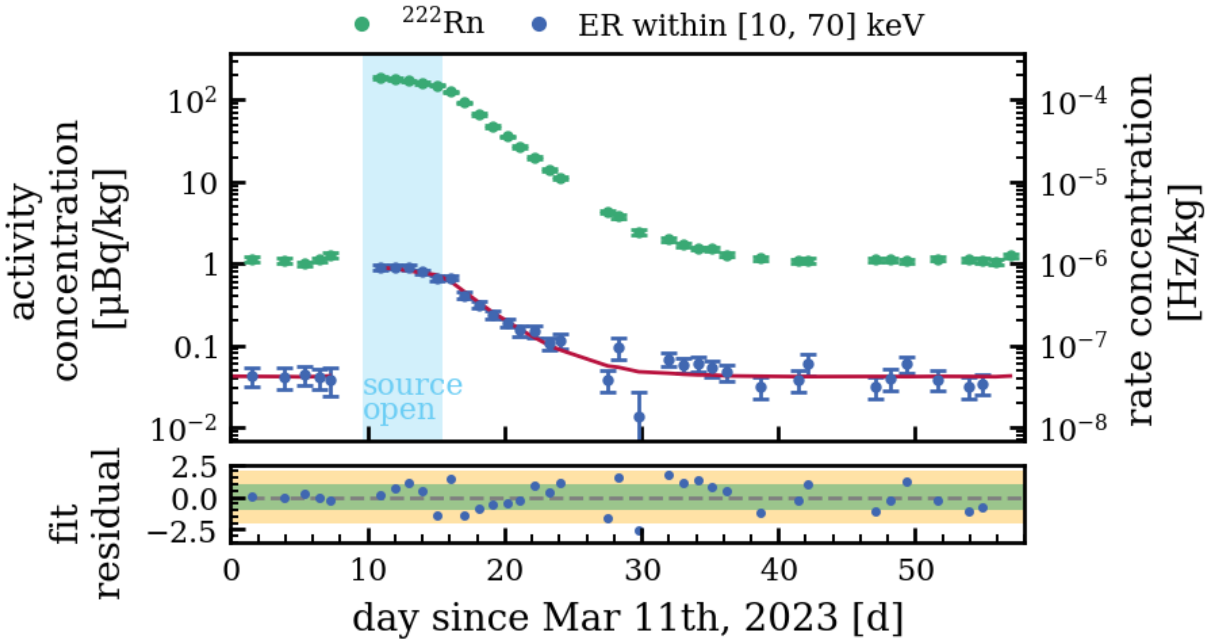


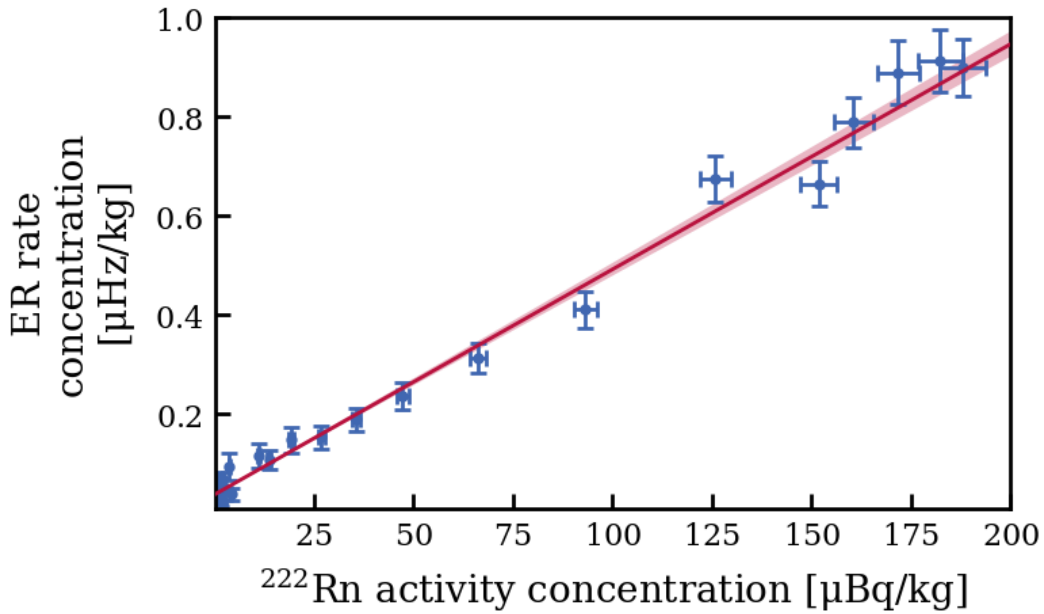
^{222}Rn: Estimation

- Decay chain one-to-one up to *plate-out*
- Utilizing the ^{222}Rn calibration sample
- Precise estimation of $^{214}Pb/^{222}Rn$ ratio
- **Total uncertainty for ^{214}Pb rate: < 5%**



F. Jörg, G. Eurin, H. Simgen, Appl. Radiat. Isot. 194, 110666 (2023)





XENON
Preliminary

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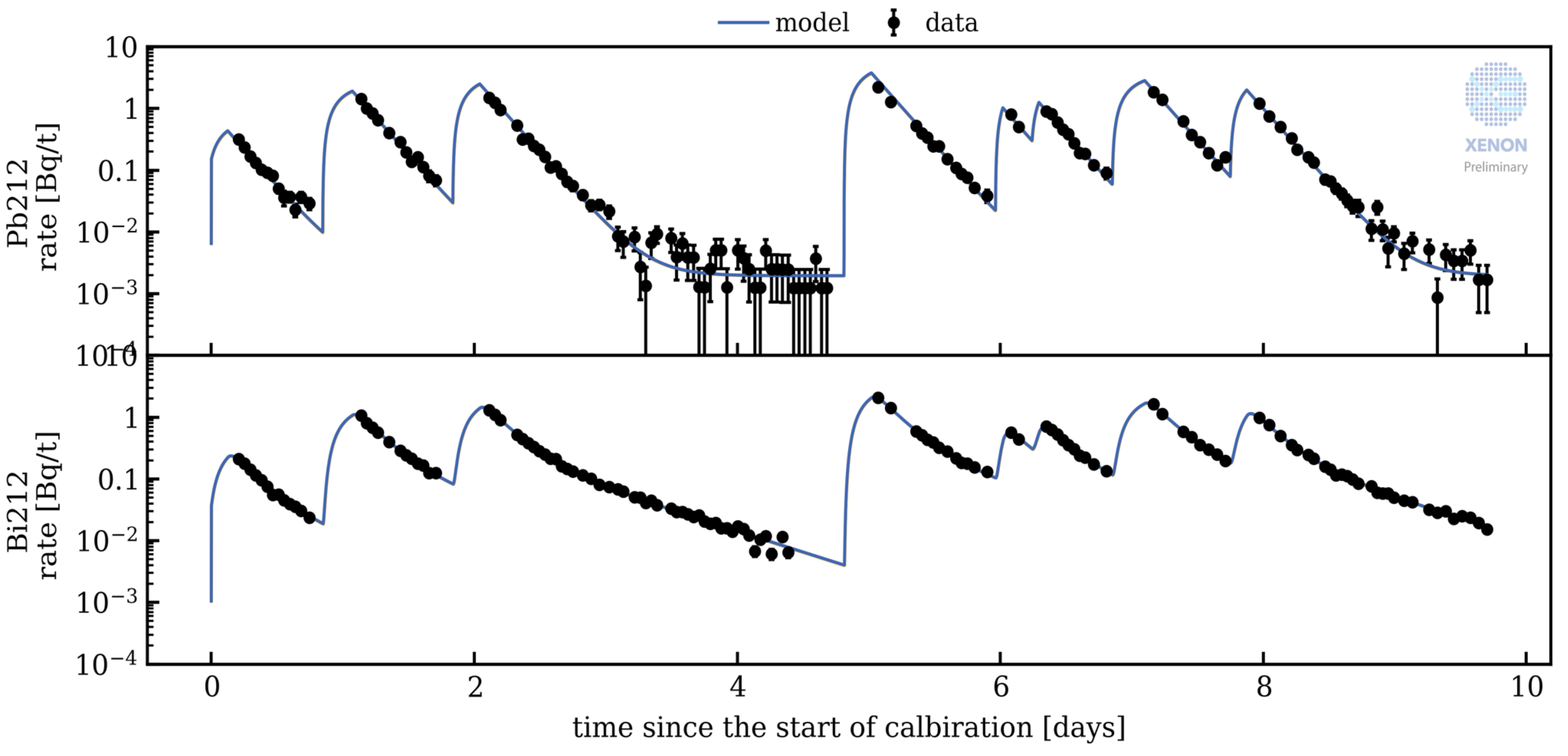
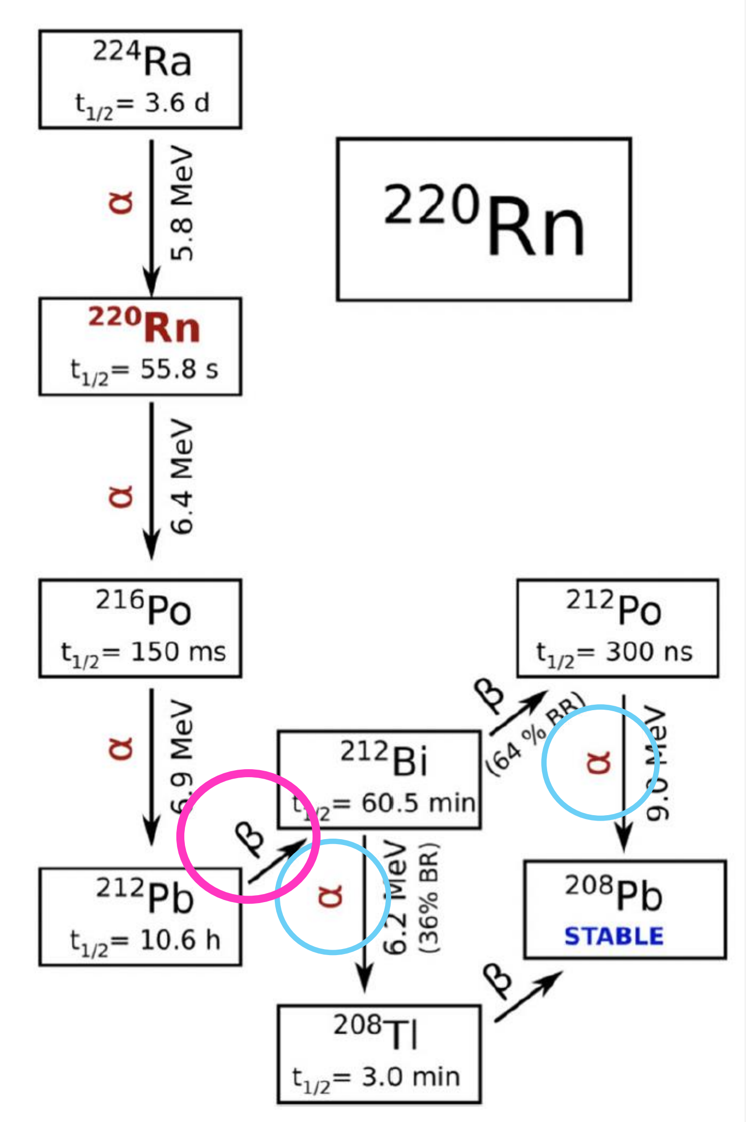
^{220}Rn: Estimation

S. Bruenner, D. Cichon, G. Eurin, P. Herrero Gómez, F. Jörg, T. Marrodán Undagoitia, H. Simgen, N. Rupp, Eur. Phys. J. C 81, 343 (2021)

- ER background comes from ^{212}Pb beta decay
- Tracing alphas from ^{220}Rn calibration (instant injections) by difference equations with decay constants and plate-out ratios
- Use asymptotic equilibrium to predict ^{212}Pb/(^{212}Bi, ^{212}Po) ratios





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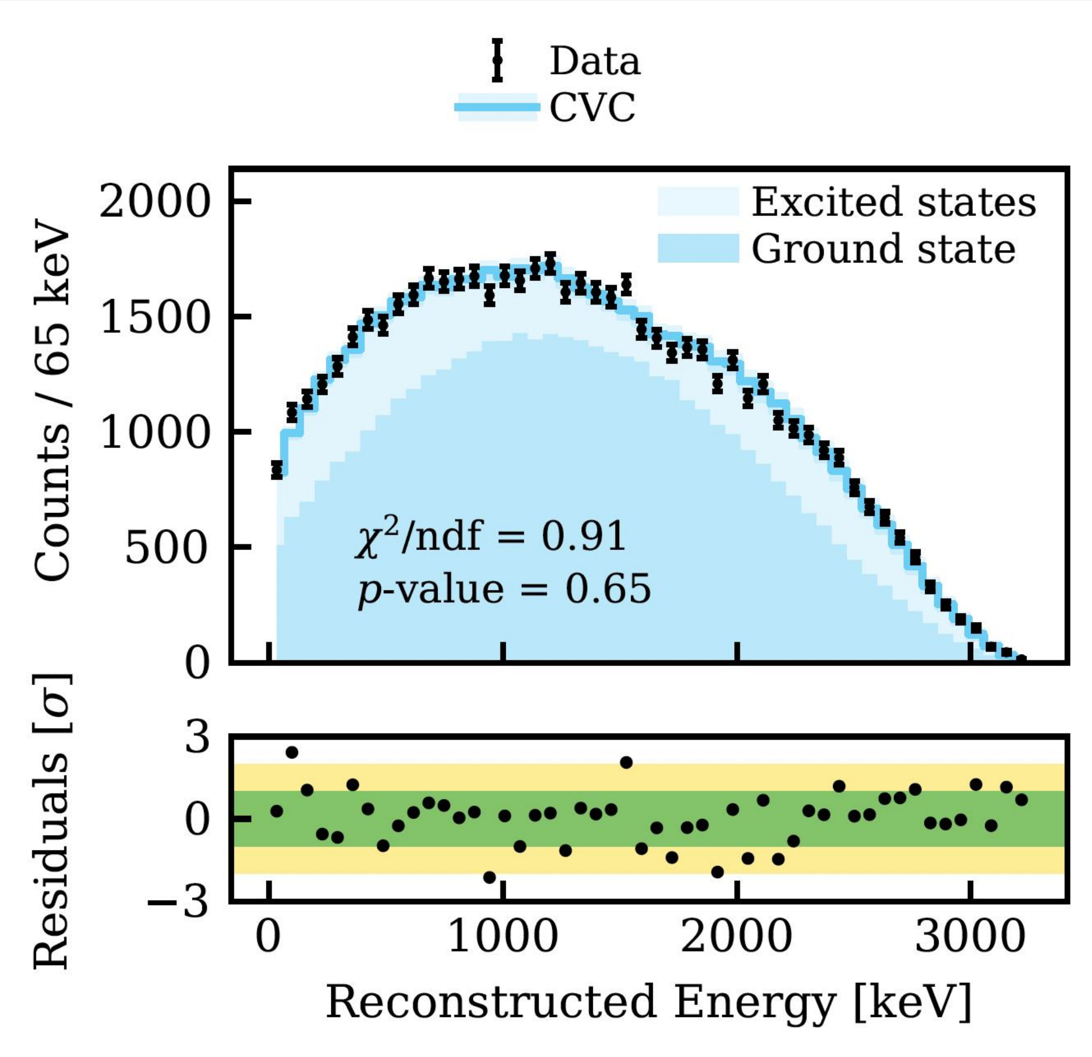
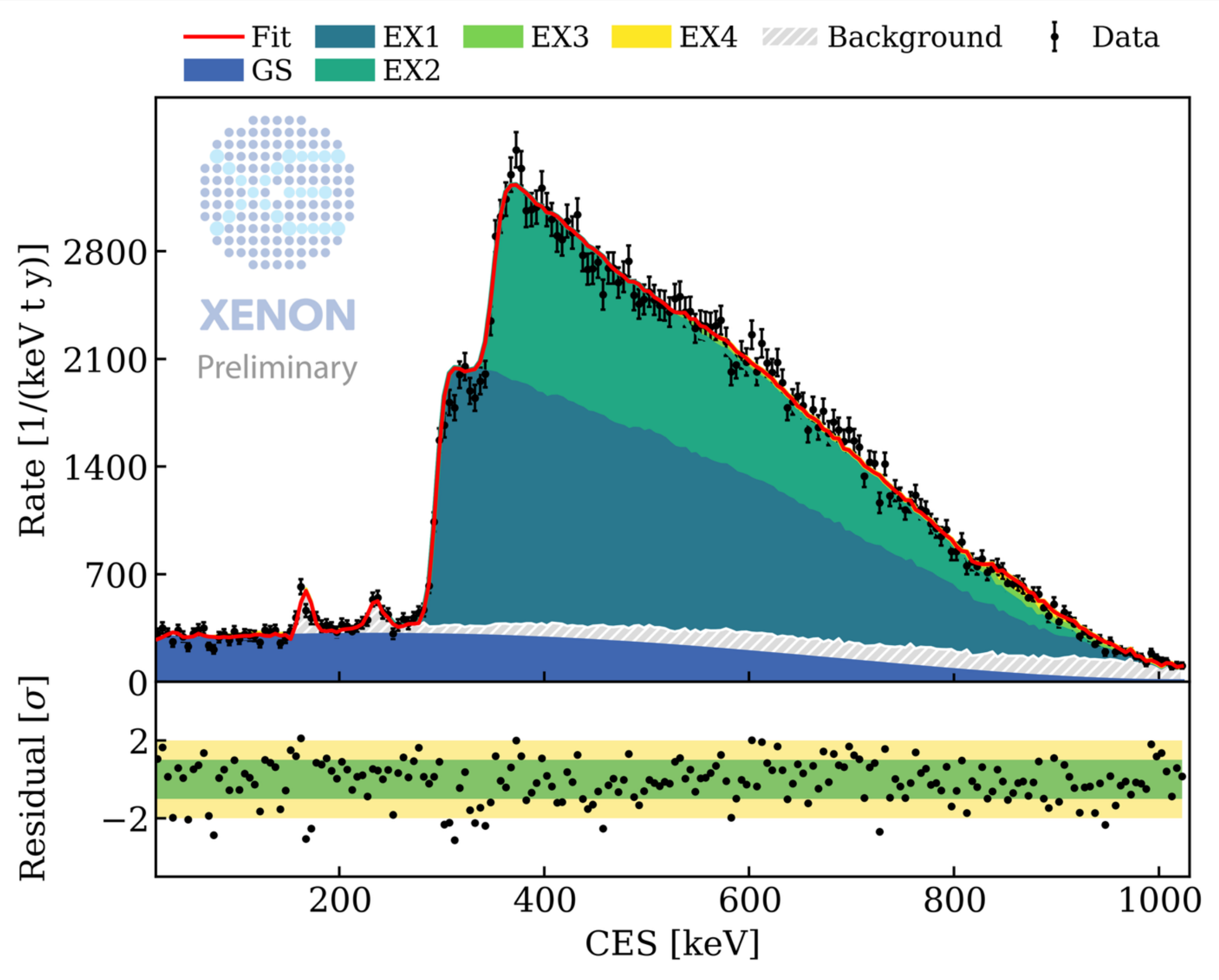
Radon Calibration Science Search

- Determination of ^{212}Bi beta spectrum shape



XENON Collab., Phys. Rev. C 113, 044303 (2026)

- Determination of ^{214}Pb/^{212}Pb beta decay branching ratio to ground/excited states



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Backgrounds in ER Channel

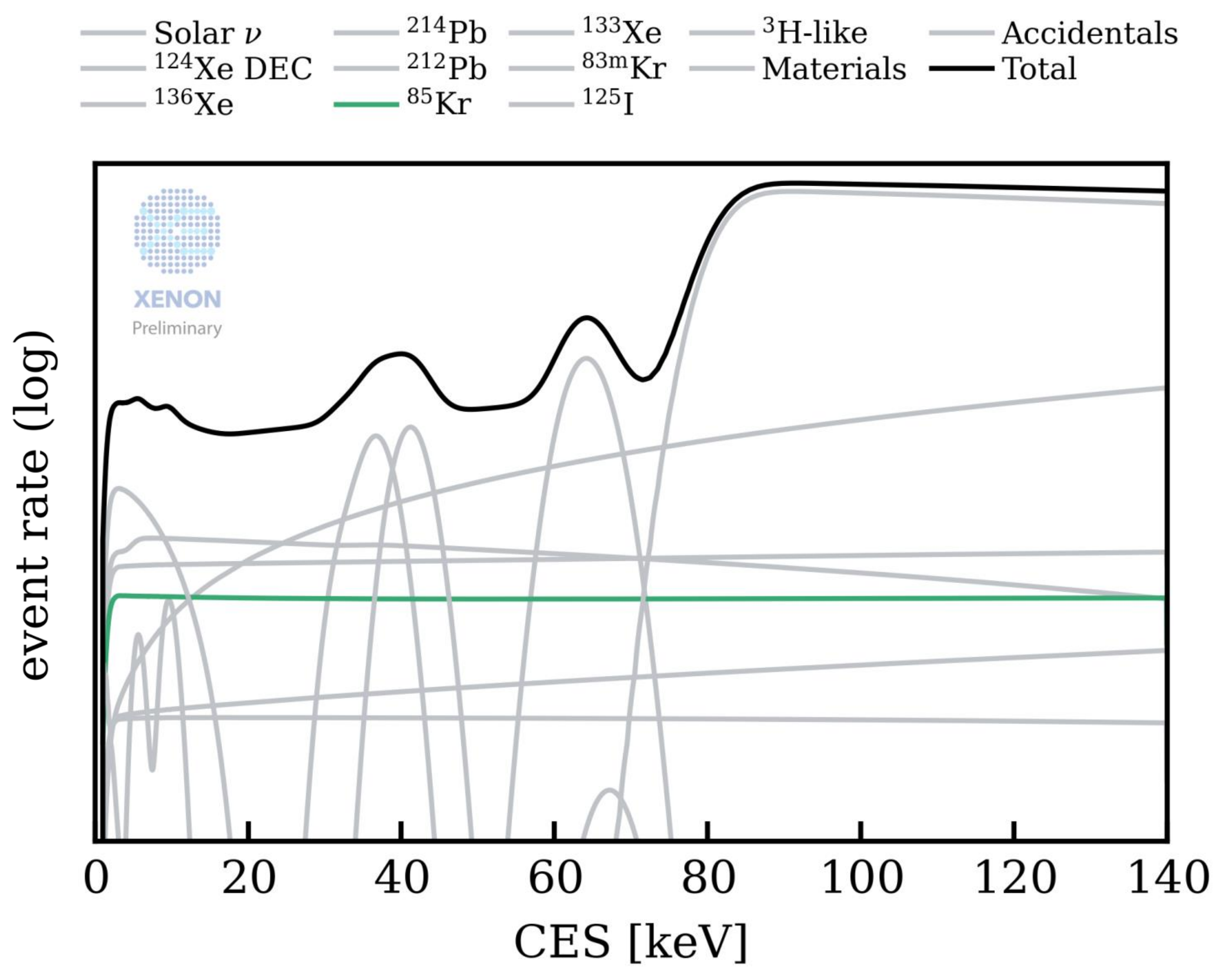
Noble gas backgrounds:
- ^{222}Rn/ ^{220}Rn: decay daughters of the material; dominant ER background
- ^{85}Kr: from ^{nat}Kr in the residual air in xenon inventory or after pump-down

Xenon Isotopes:
- ^{136}Xe/^{124}Xe
- ^{133}Xe/^{125}I

Other backgrounds:
- Materials
- ^{3}H-like
- ^{83m}Kr
- Accidentals

Neutrinos:
- Solar υ

ROI: ER channel in [1, 140] keV range



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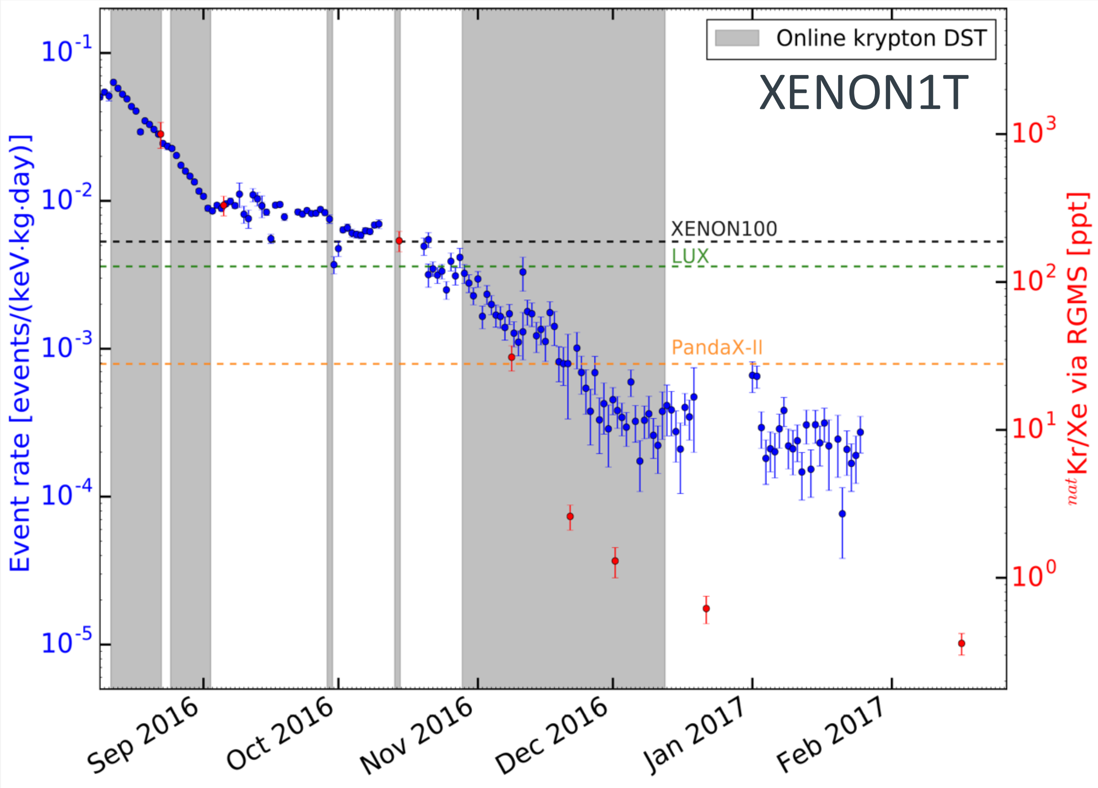
^{85}Kr: Krypton Distillation and RGMS Measurements



XENON Collab., Prog. Theor. Exp. Phys., 053H01 (2022)

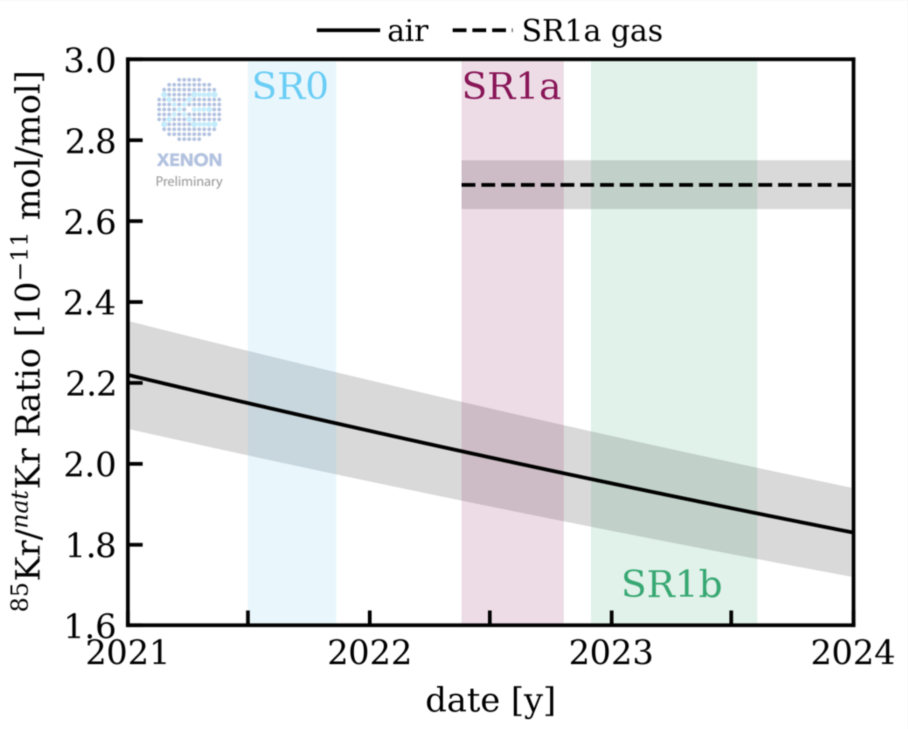
- Online krypton distillation column
- Measurements with Rare Gas Mass Spectrometer (RGMS) using chromatographic separation:

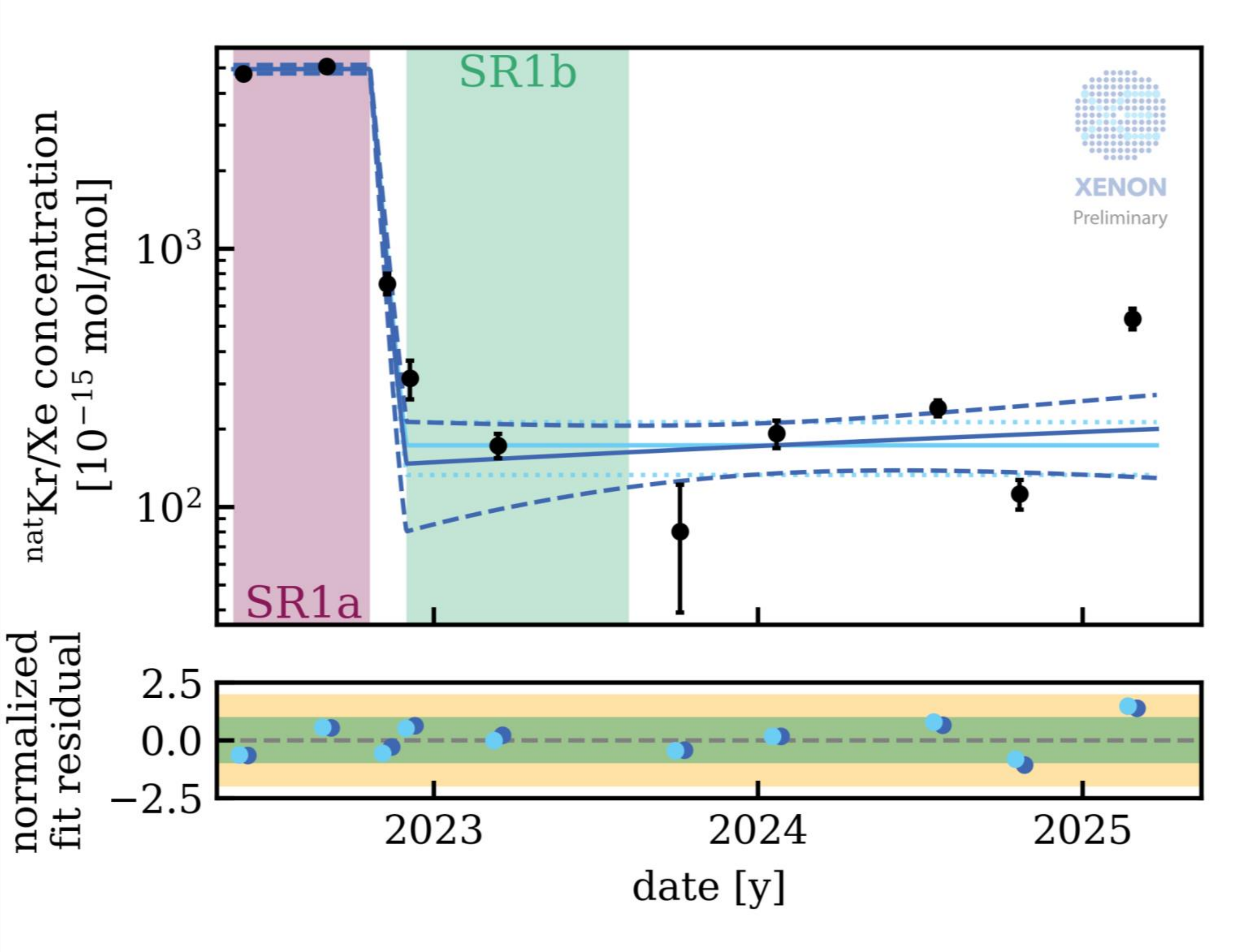
➢ **Capable of reduction to sub-100 ppq level ^{nat}Kr/Xe**

ppq = parts per quadrillion = 10^{-15}

^{85}Kr: RGMS Results for Science Run 1 (SR1)

- SR1a has unintended gas introduction
- Two models: ^{nat}Kr outgassing versus constant over time
- ^{85}Kr/^{nat}Kr abundance time evolution considered





M. Guida, Y.-T. Lin, and H. Simgen, Eur. Phys. J. C, 85, 14262 (2025)

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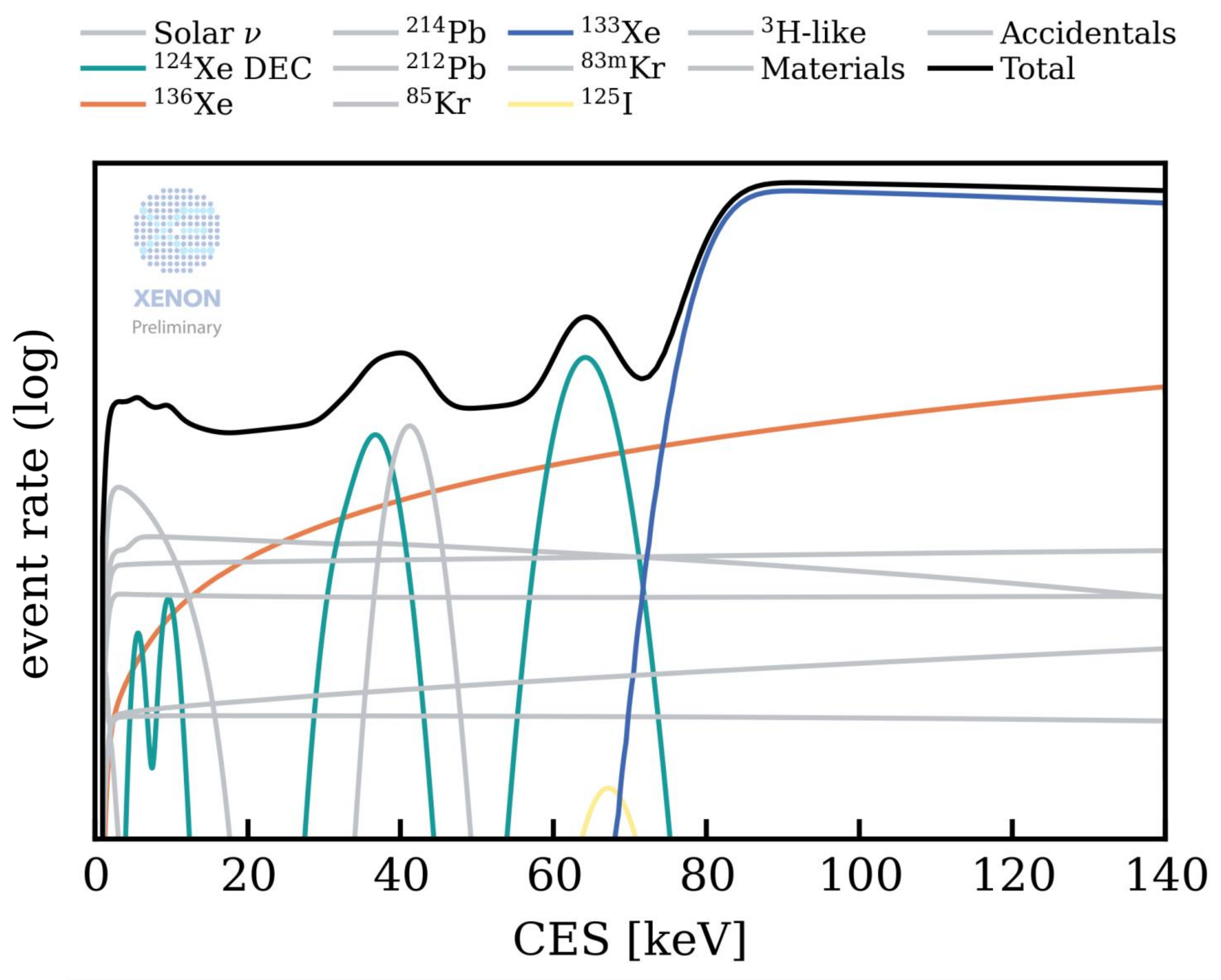

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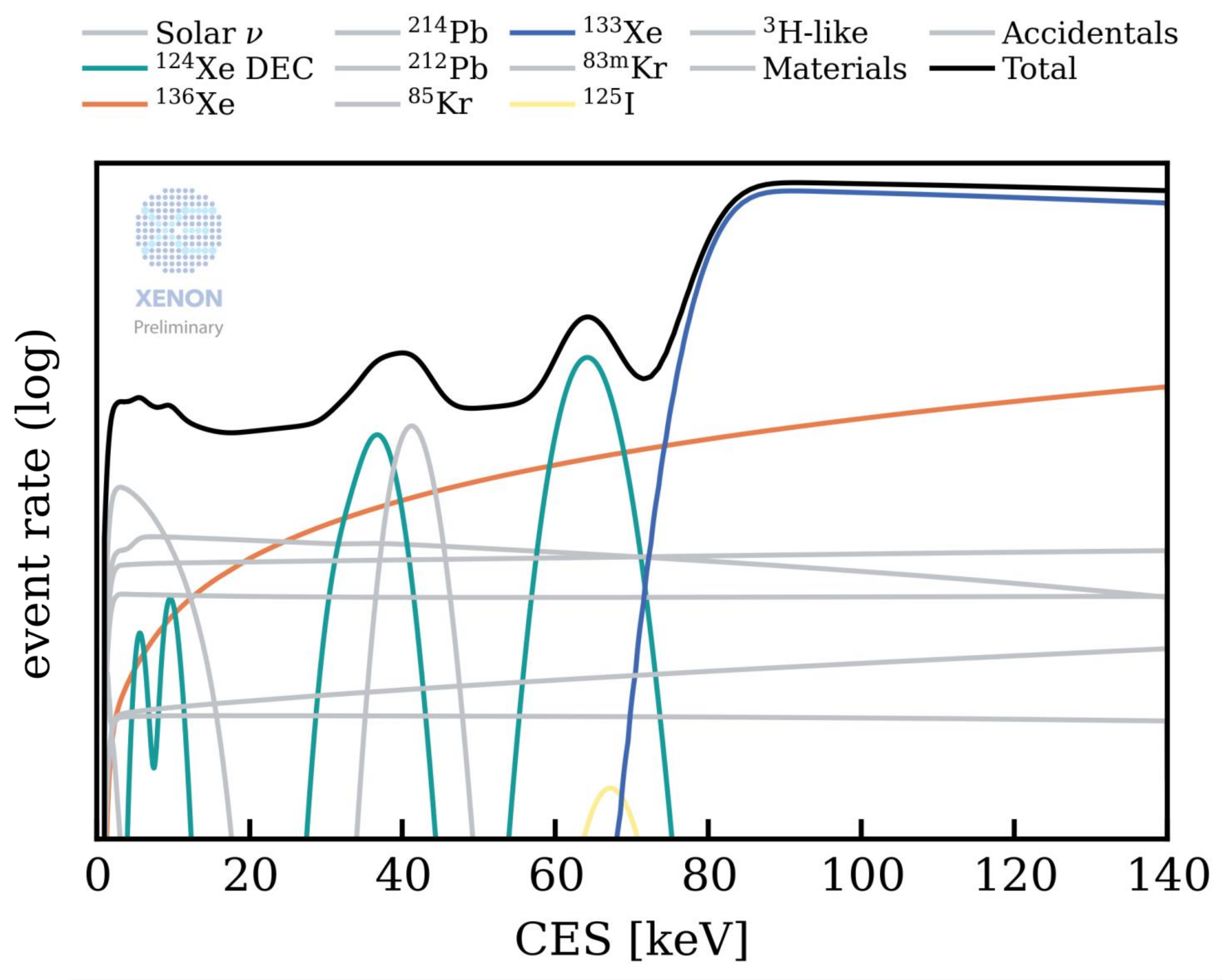
Xenon Isotopes

- ^{136}Xe: abundance estimated using residual gas analyzer
- ^{124}Xe: left free as a handle to the fit
- ^{133}Xe: from decay models since calibration and estimated activation rate outside detector
- ^{125}I: from decay models with ^{125}Xe

XENON Collab., Nature volume 568, pages 532–535 (2019)

ROI: ER channel in [1, 140] keV range



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Neutrinos:
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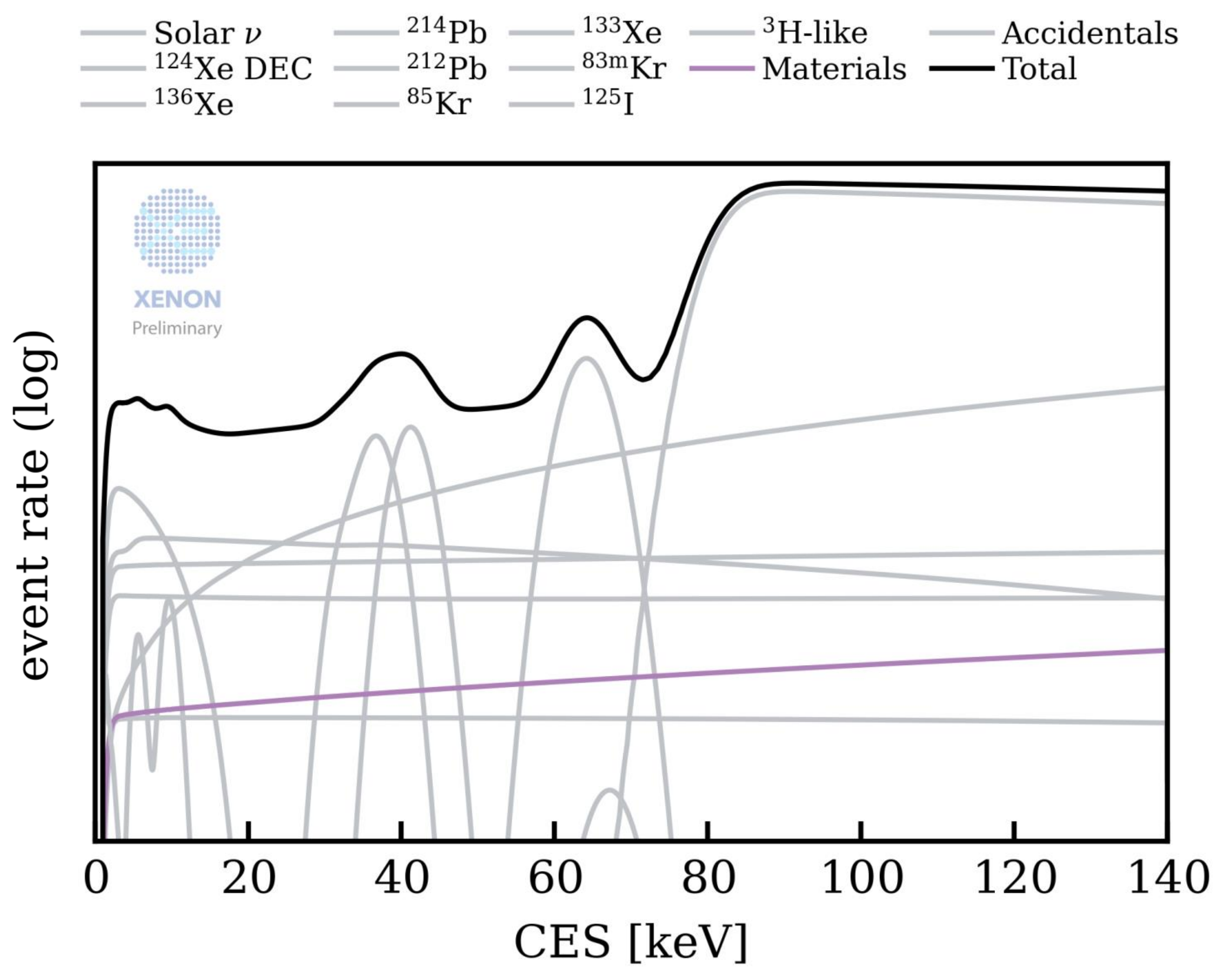

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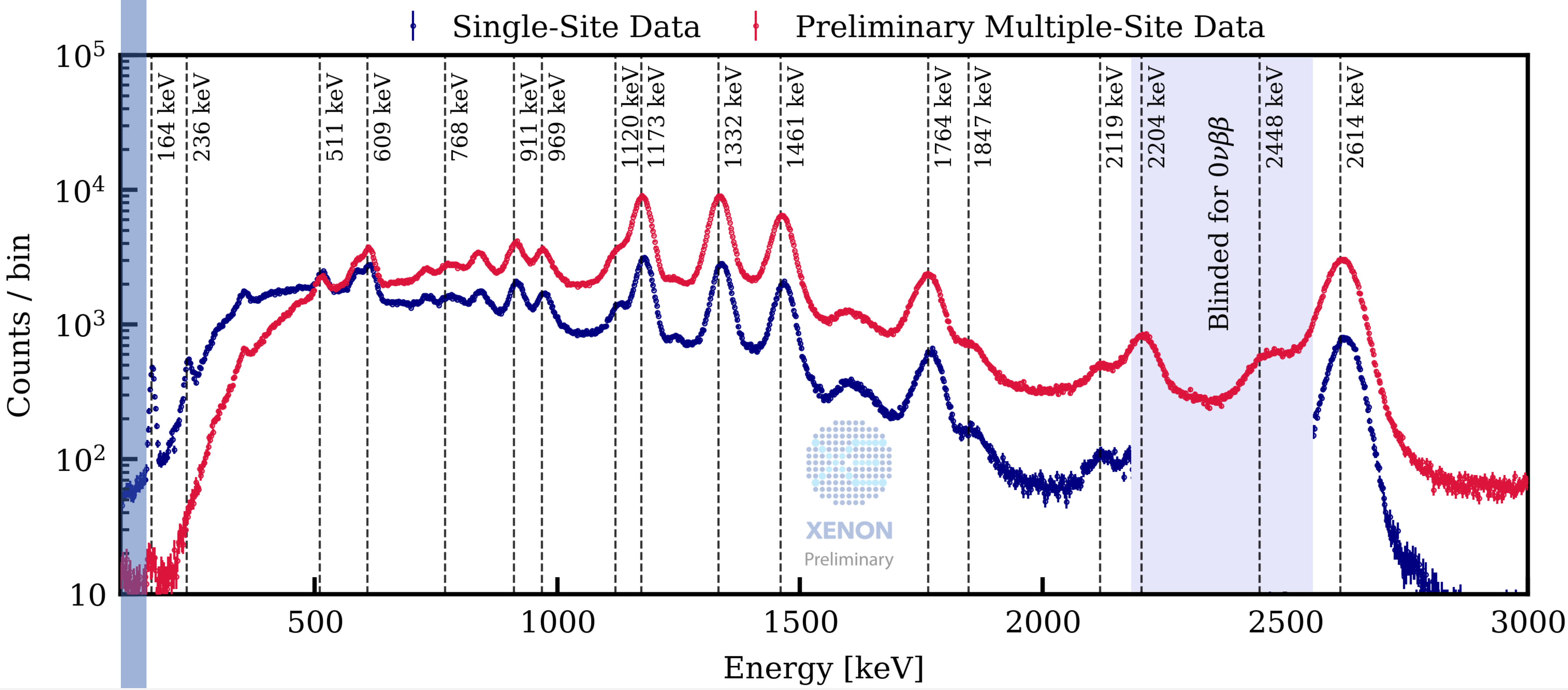
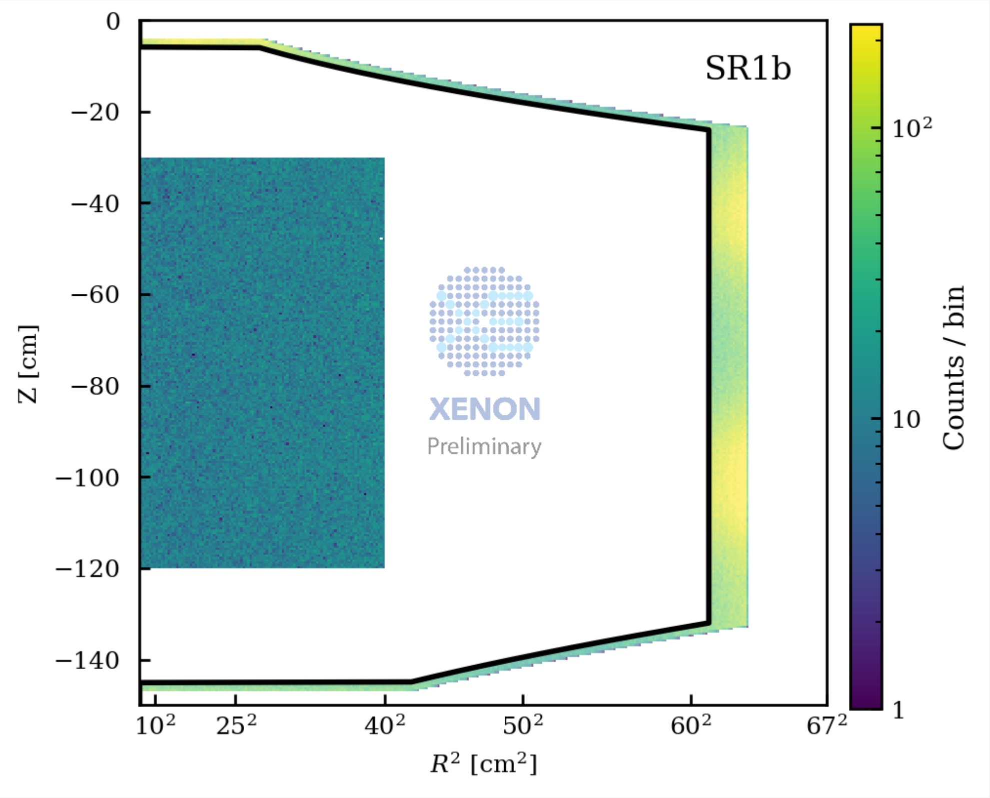
Materials: Full-chain Simulation

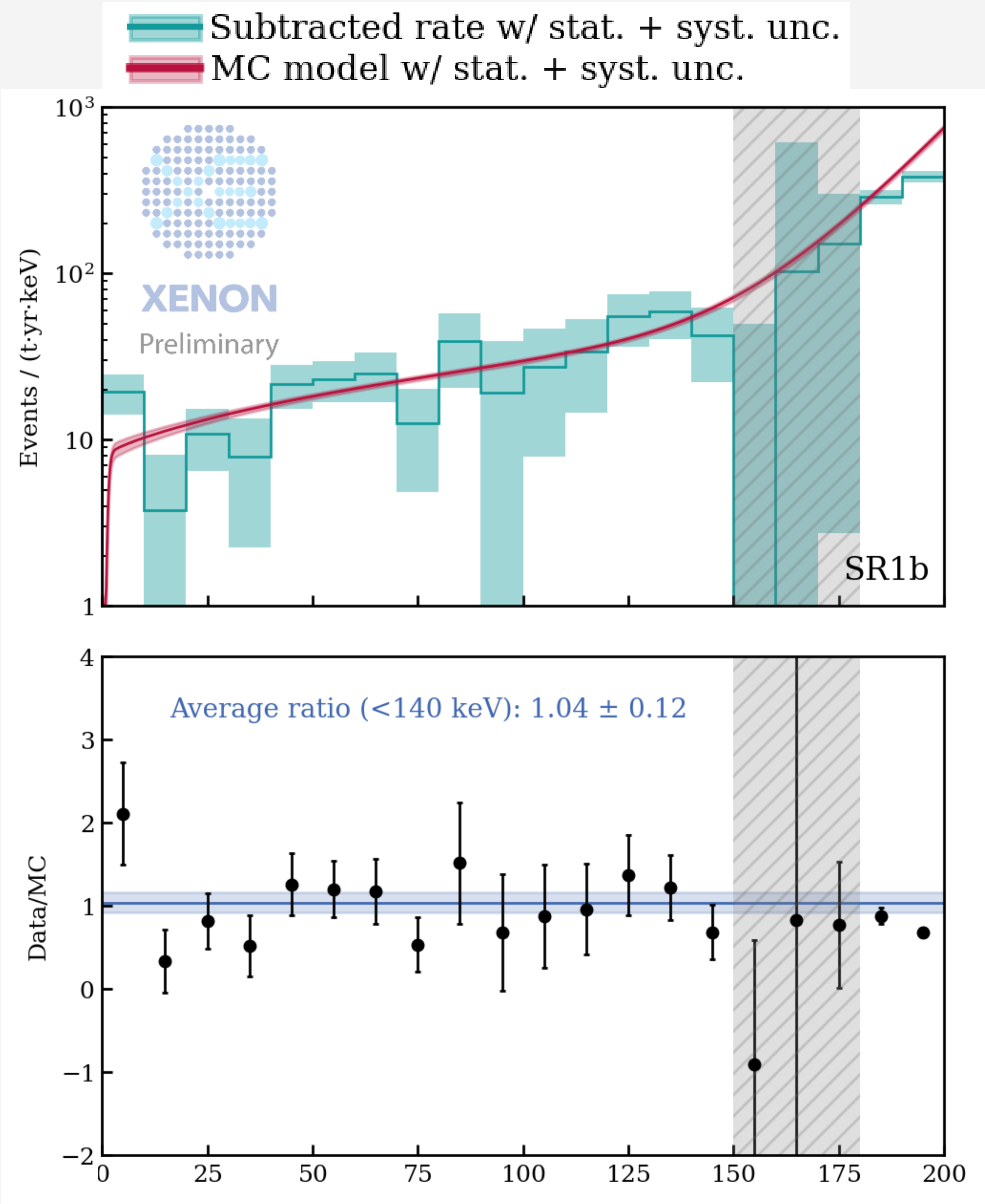
- Full-chain GEANT4 with waveform simulation (WFsim) using screening values
- Reconstructing both single-site and multi-site events



Materials: Estimation

- Investigating the data 2 cm outside the FV
- Using the rate comparison between the simulation and data as systematic uncertainty





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Other backgrounds:

- Materials: gamma with Compton scattering
- ^{3}H-like: potentially from operation
- ^{83m}Kr: residual from calibration
- Accidentals: accidental coincidences

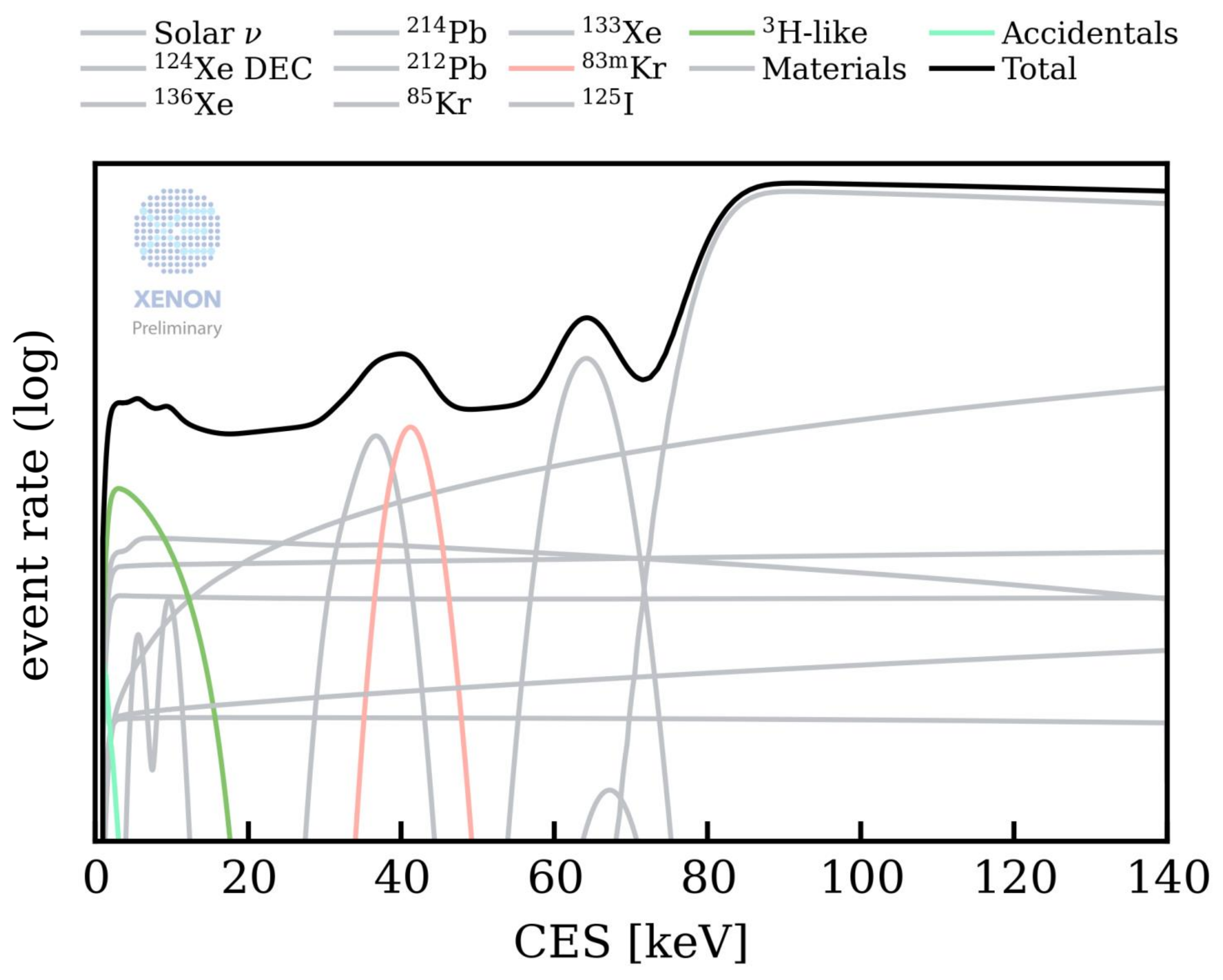
Neutrinos:

- Solar ν

➢ WIMP: Maxime Pierre, Jun 2nd, 12:10, Aula Magna

➢ CEνNS: Giovanni Volta, Jun 2nd, 11:30, Pedro Cerbuna

ROI: ER channel in [1, 140] keV range



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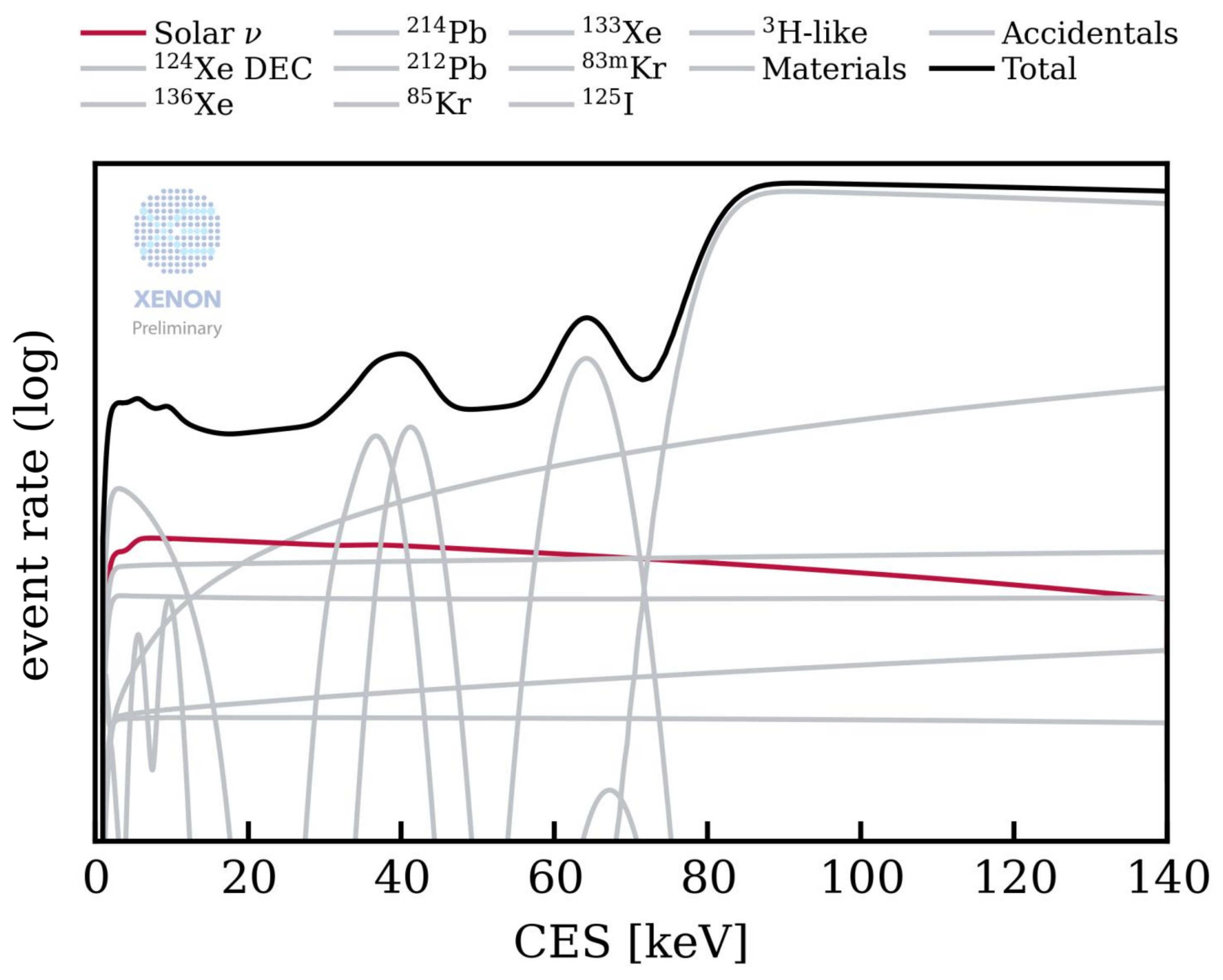

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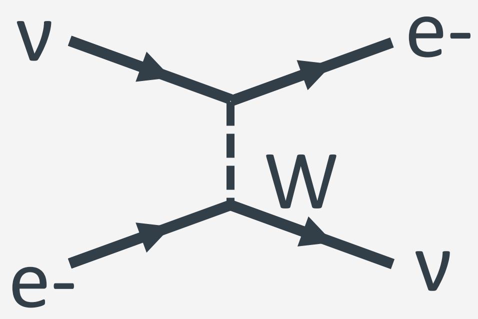
Neutrinos:

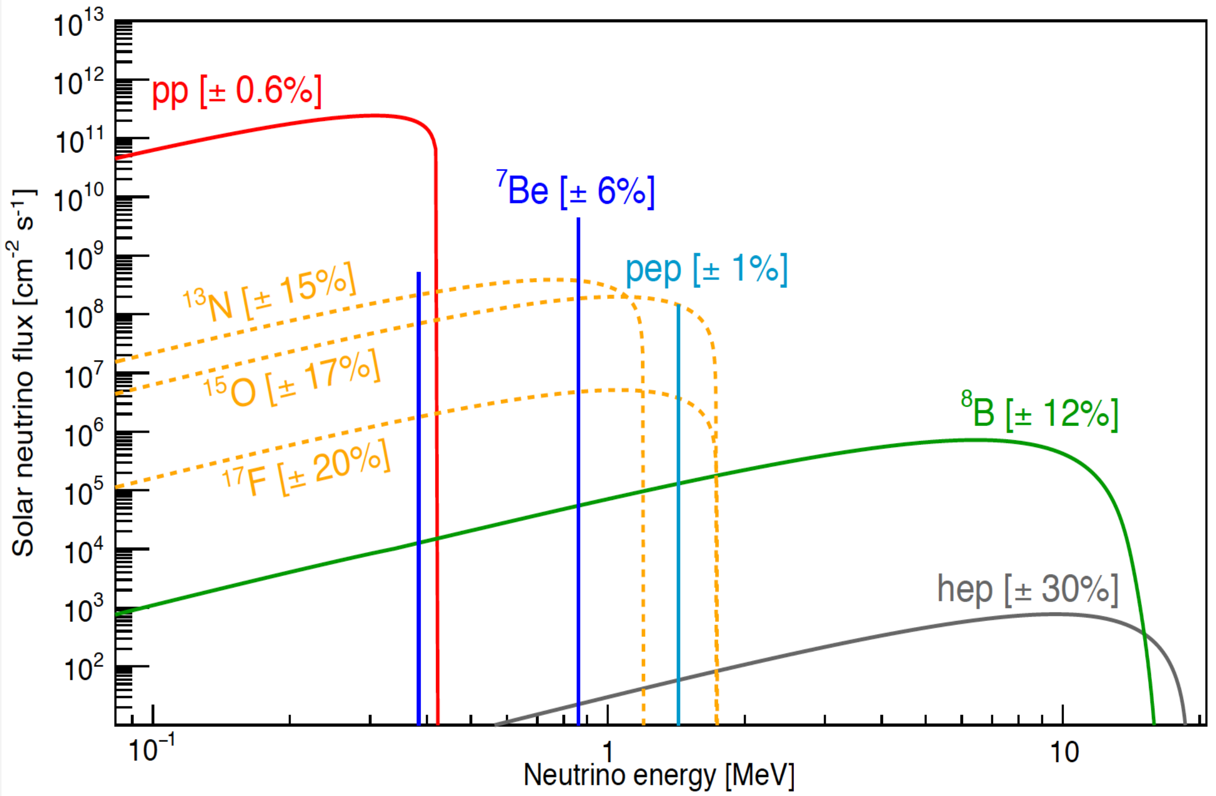
- Solar ν: non-shieldable, dominate by *pp* neutrinos in low-energy ROI

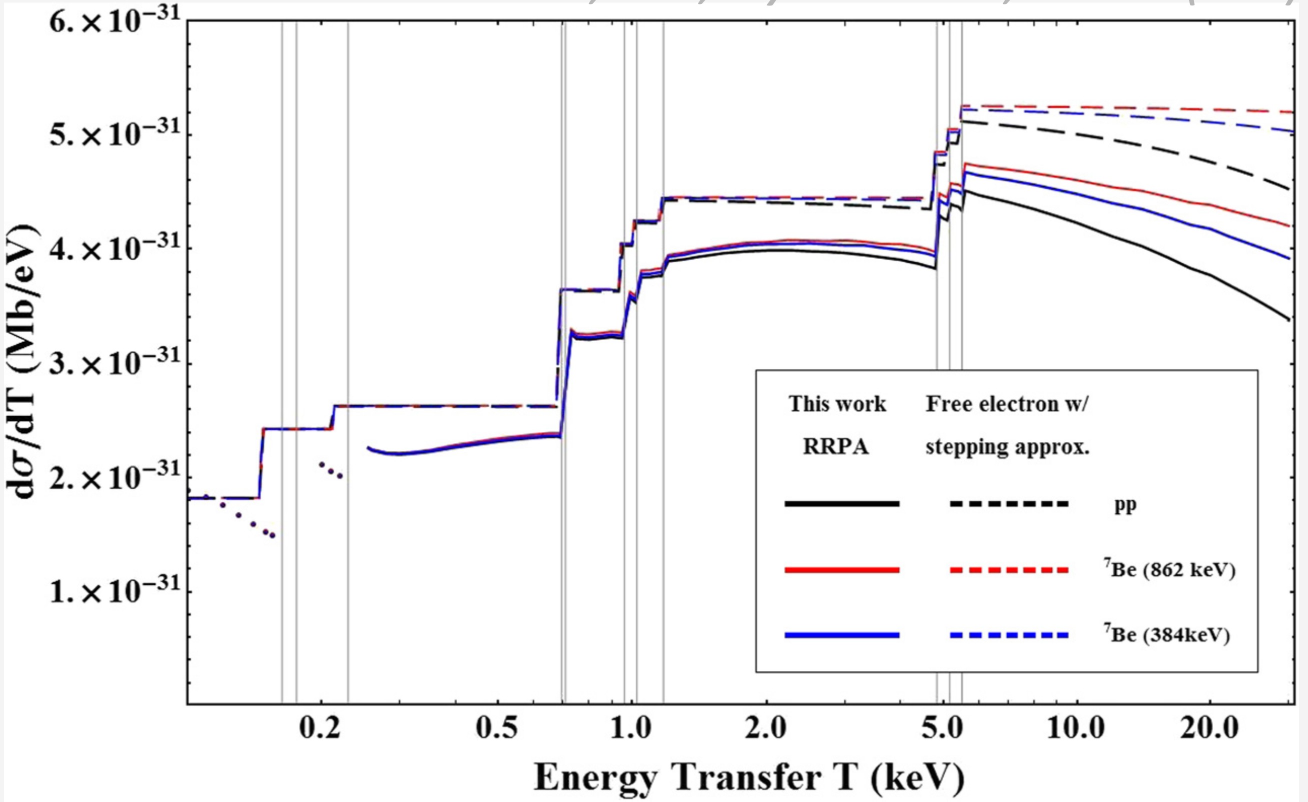
Low ER Region Search: pp-chain Solar Neutrino

- The low-energy region of ER channel will be dominated by the elastic electron-neutrino scattering of solar *pp* neutrinos
- The cross-section models in xenon:
    - Free Electron Approximation (FEA) with stepping correction
    - Relativistic Random Phase Approximation (RRPA)



J. -W. Chenetal, et al., Phy. Lett. B. 774, 656–661 (2017)





BOREXINO Collaboration, Nature 562, 505–510 (2018)

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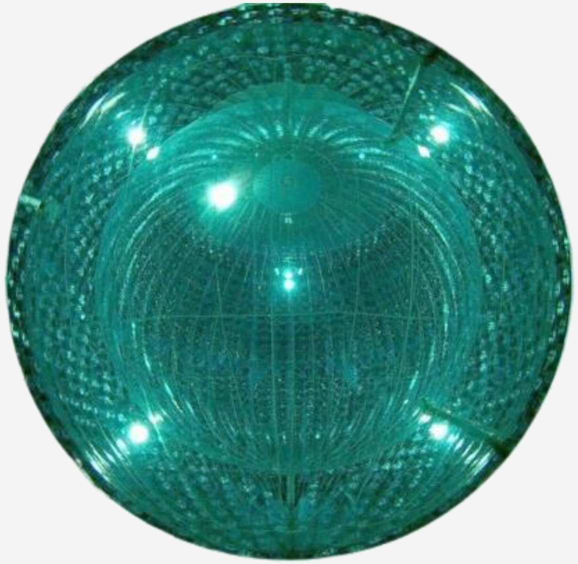
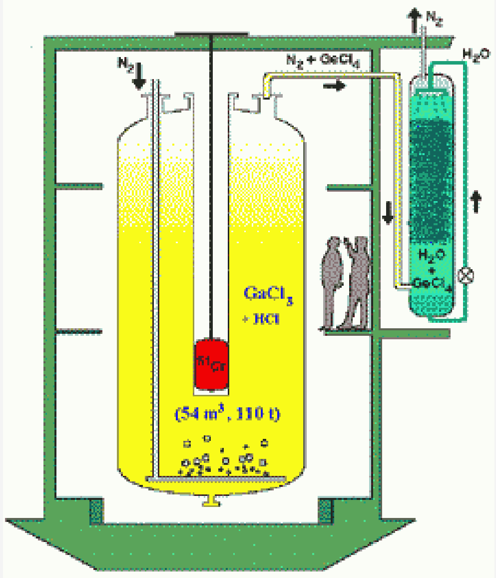
Backgrounds in ER Channel

- XENONnT ER channel background now reduced to solar *pp* level

XENONnT (5.9 tonne)

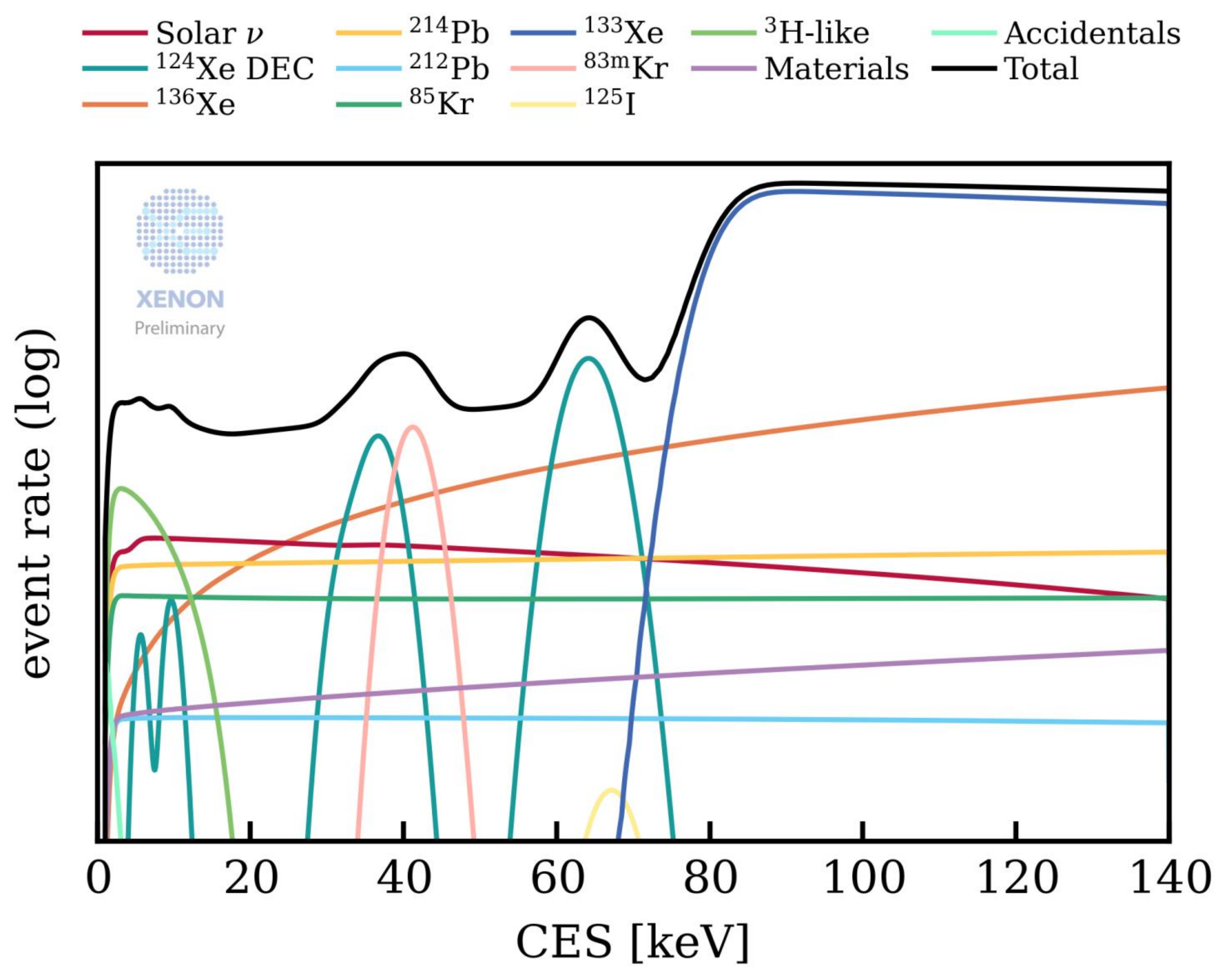


BOREXINO (280 tonne)



GALLEX/GNO SAGE (30-60 tonne)

ROI: ER channel in [1, 140] keV range



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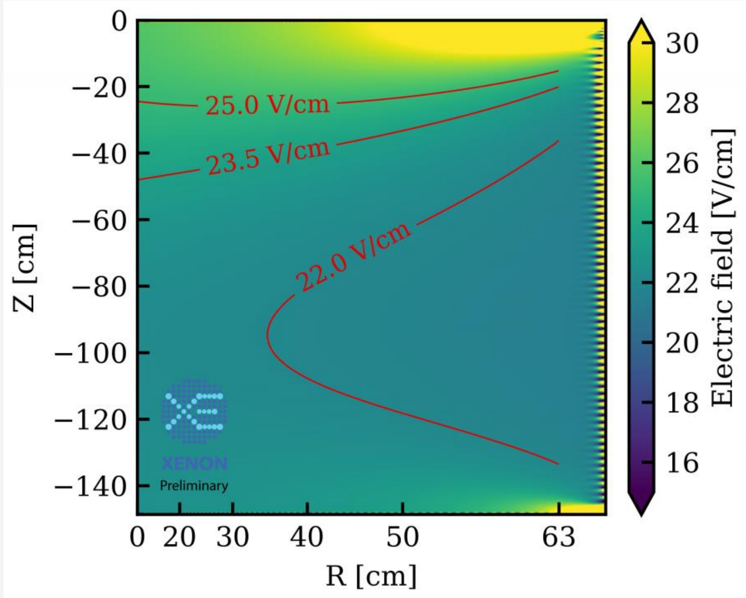
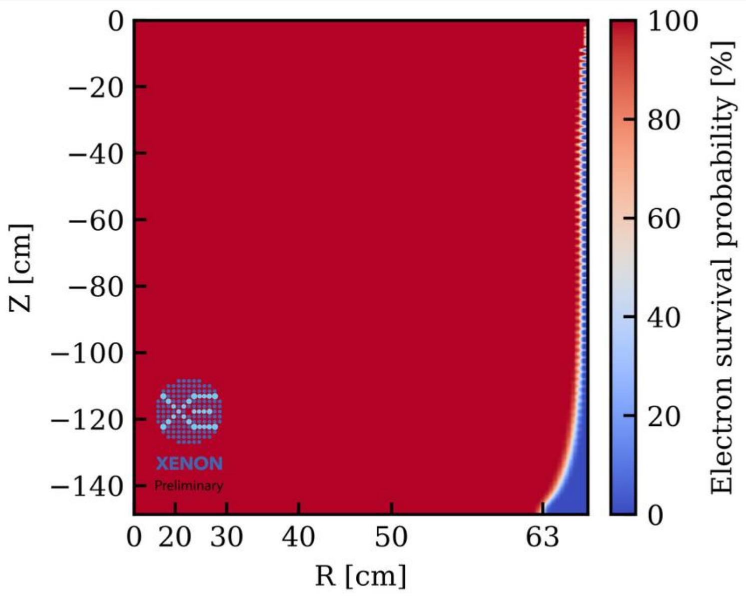
Fiducial Volume Estimation

- Field distortion correction
- Charge incentive area simulation

- FV optimized using simulated material background based on signal to background figure of merit

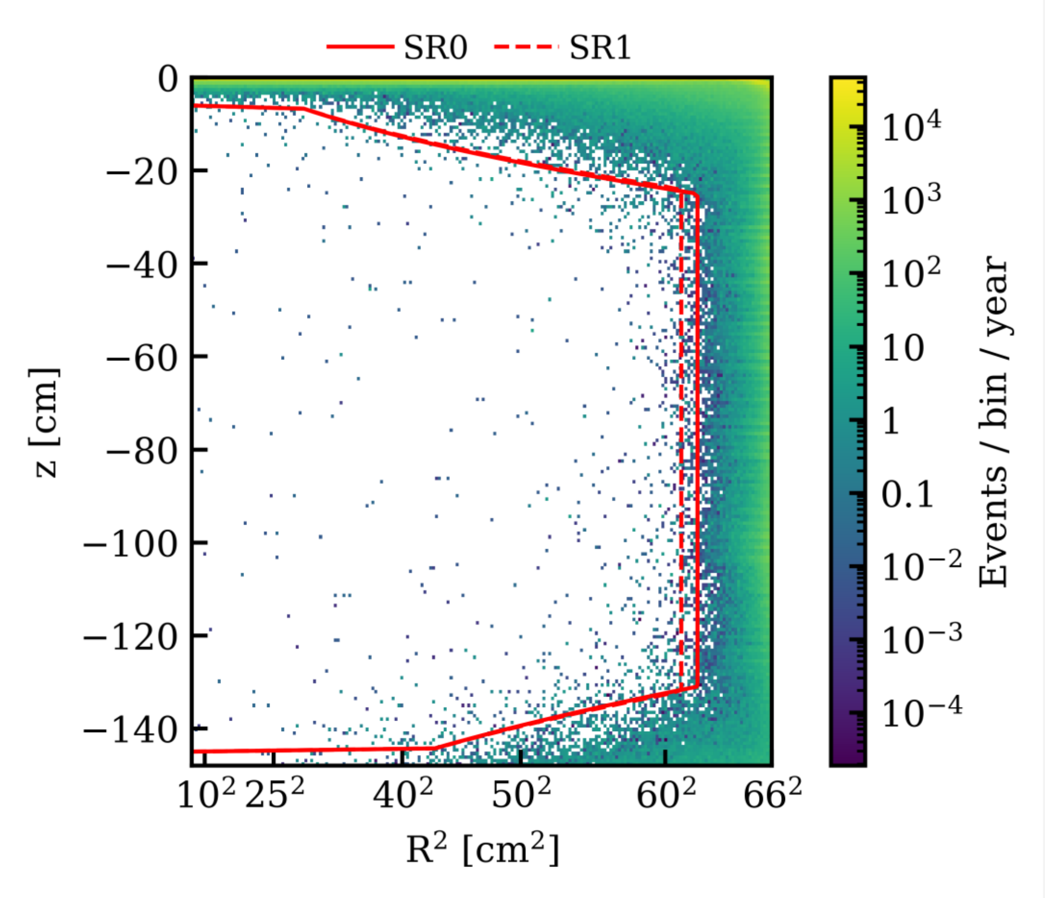
- FV value: overall 3% uncertainty from field map
- Event position resolution uncertainty is negligible





Uncertainty of Solar *pp* Measurement

	Lower (%)	Upper (%)
FV	9.7	10.0



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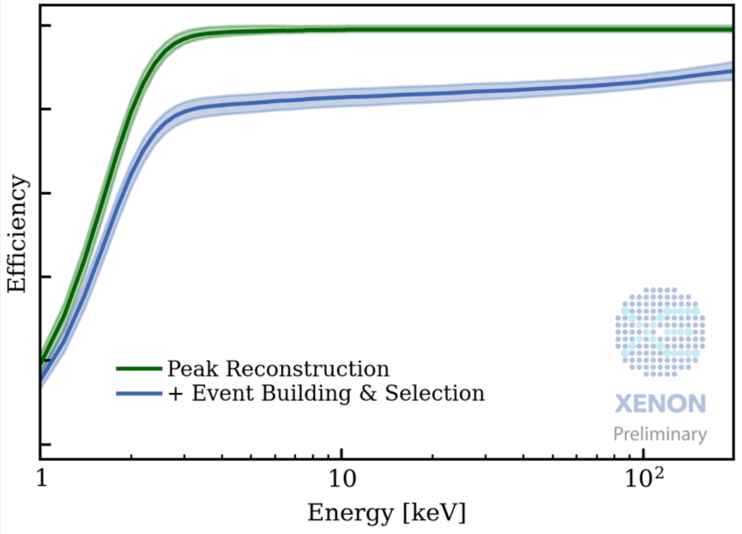
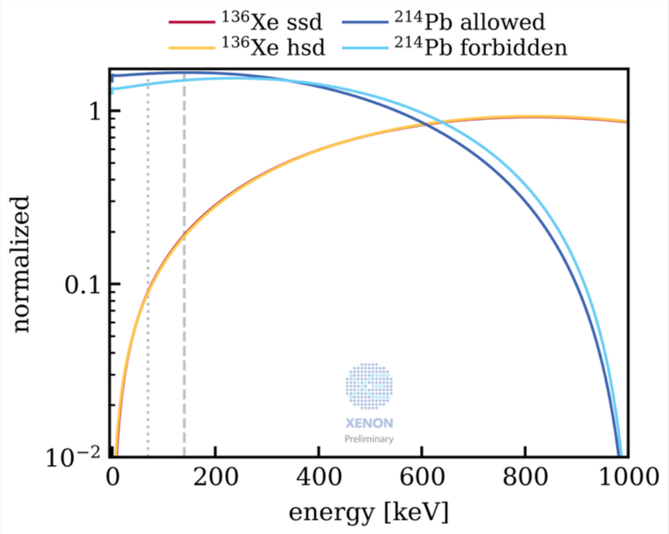
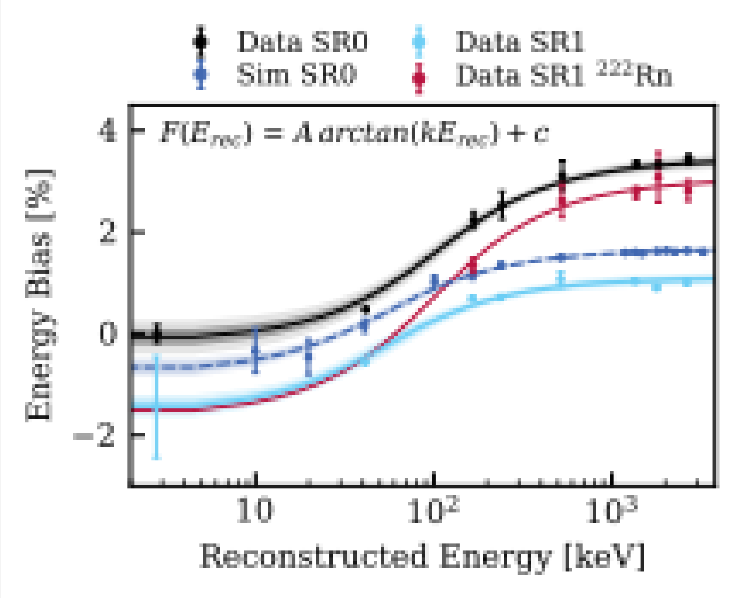
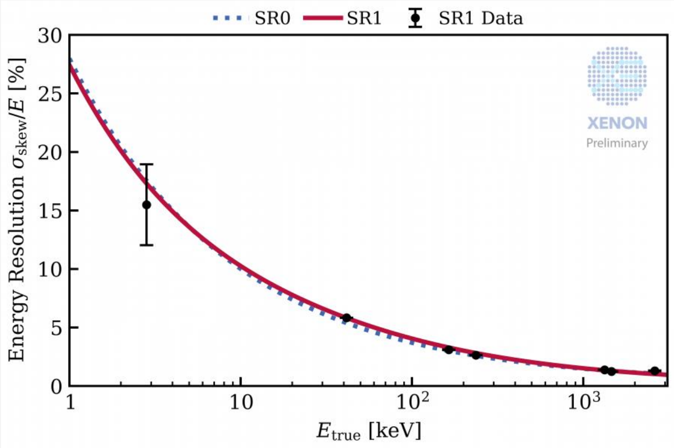
Uncertainty Budget for Solar *pp* Measurement (SR0+SR1)









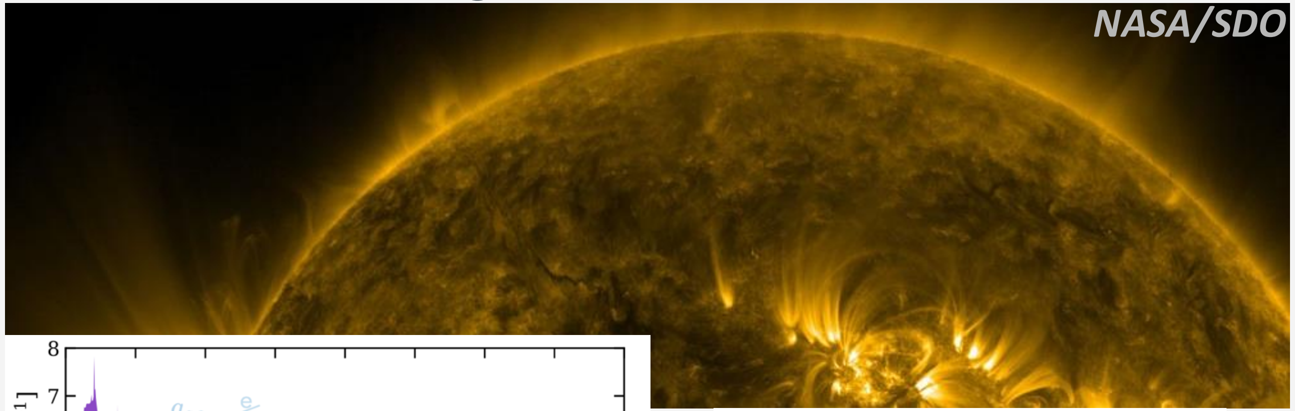
Uncertainty of Solar *pp* Measurement

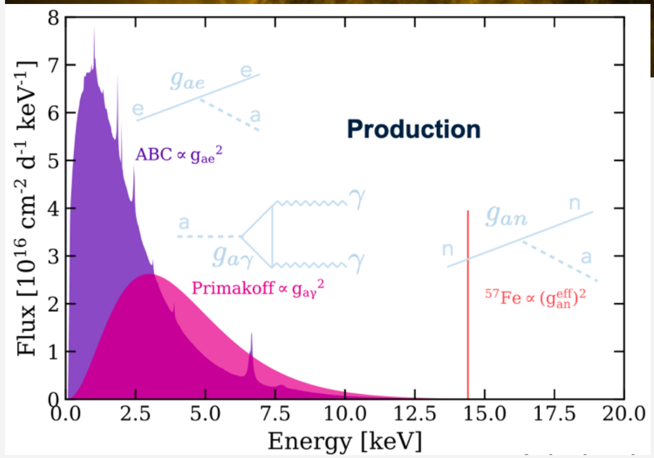
	Lower (%)	Upper (%)
FV	9.7	10.0
Efficiency	7.1	7.3
^{214}Pb rate	4.3	4.1
^{214}Pb spectrum	1.1	1.1
^{136}Xe spectrum	1.0	1.0
Energy Bias	2.8	4.0
Energy Resolution	1.2	1.4
Total Post-Inference Systematics	**13**	**14**

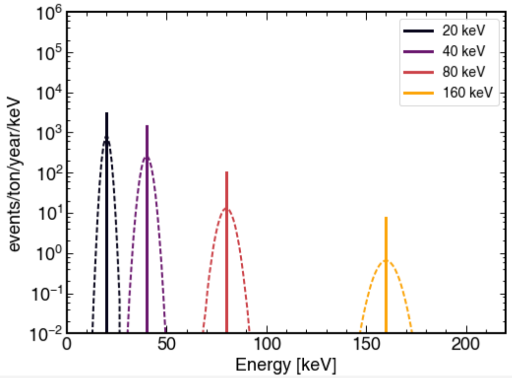
Ying-Ting Lin, ylin3@uni-muenster.de

Summary and Prospect

- Achieved the lowest ER background in direct dark matter experiments
- Precise determinations of the remaining ER background has been established along with comprehensive systematic budget
- Measurement of solar *pp* is within reach, opening to future dark matter searches in ER channel



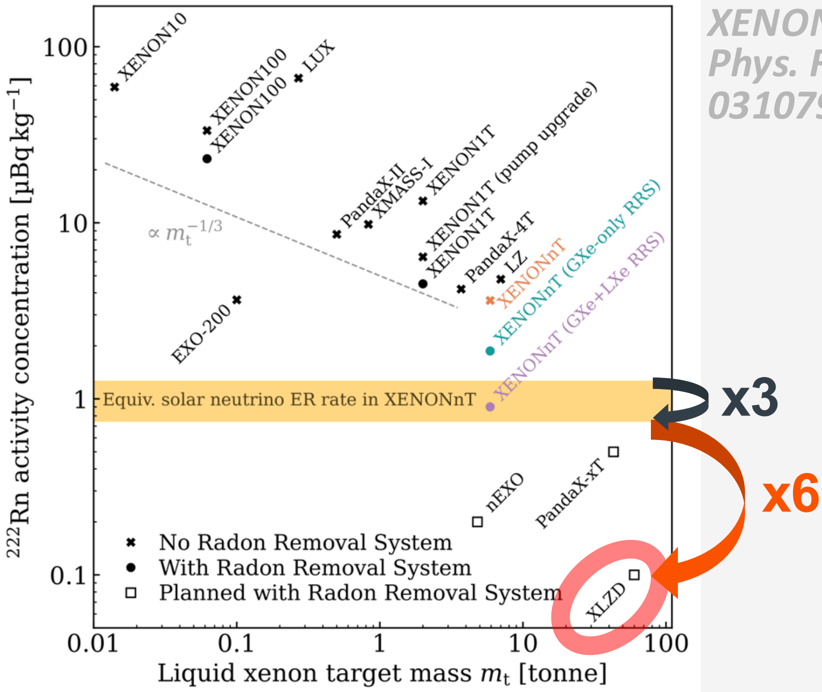




The Next Generation Experiment

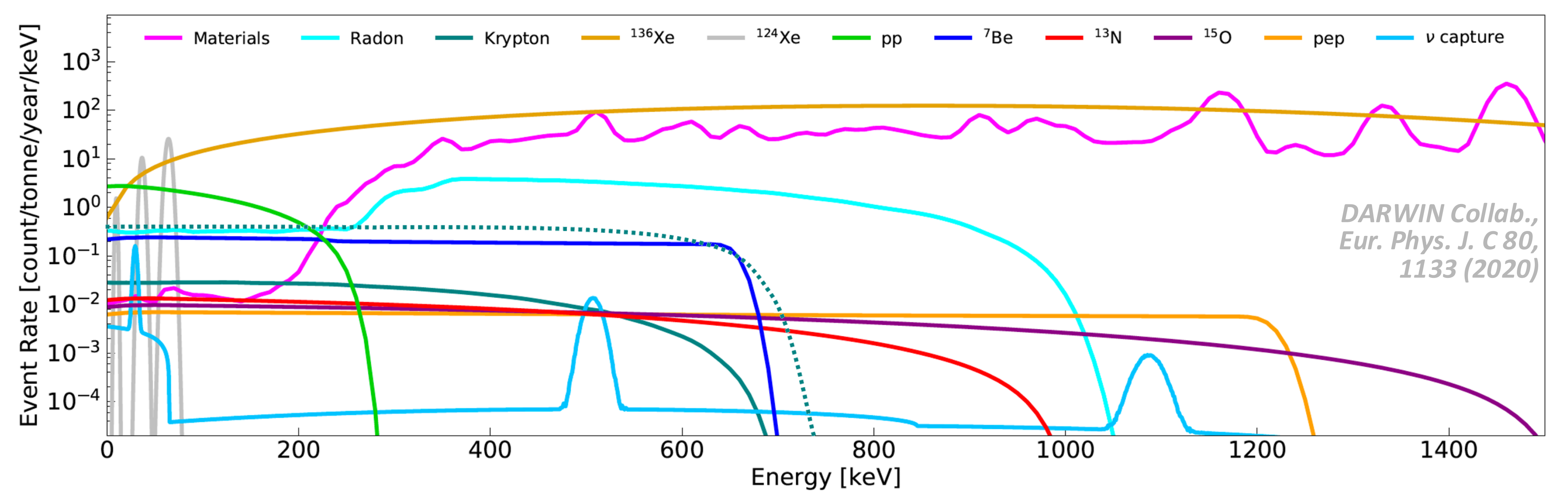
- Aiming for sub-% accuracy in solar *pp* flux measurement
  - **^{222}Rn: 0.1 μBq/kg**
    - **< 10% constraint to ^{214}Pb**
  - **^{nat}Kr/Xe: 30 ppq**
    - **< 10% constraint to ^{85}Kr**

XLZD Collab., The XLZD Design Book, Eur. Phys. J. C 85, 1192 (2025)



XENON Collab., Phys. Rev. X 15, 031079 (2025)

LowRad

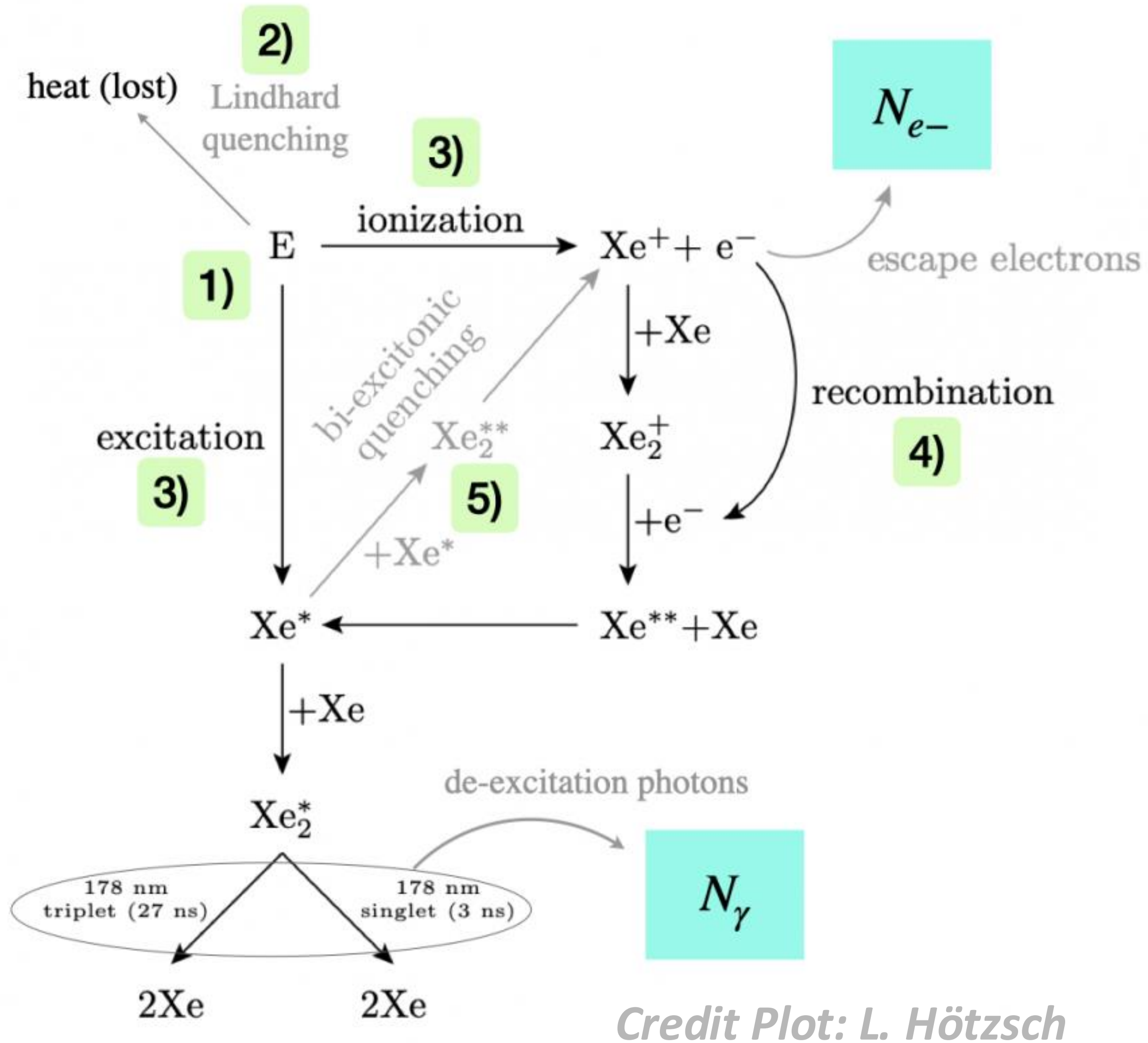


DARWIN Collab., Eur. Phys. J. C 80, 1133 (2020)

Backup Slides

Liquid Xenon Target

- scintillation yield ≃ 46 γ/keV$_{ee}$
- ionization yield ≃ 64 e$^-$/keV$_{ee}$

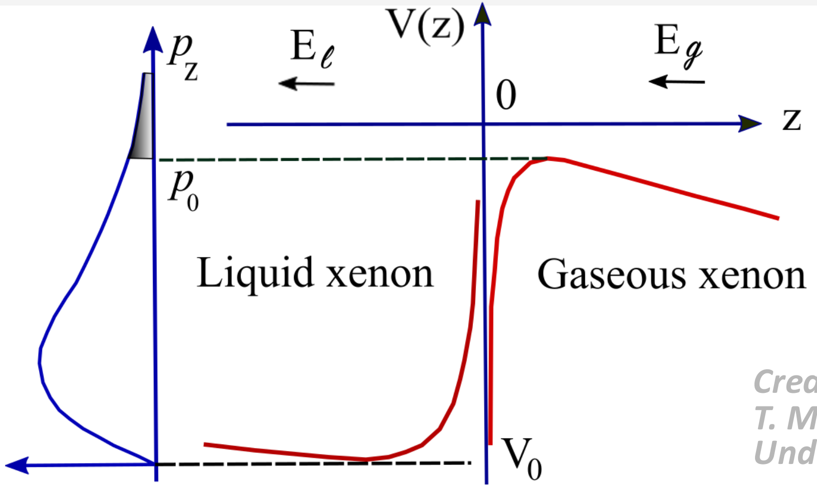


Credit Plot: L. Hötzsch

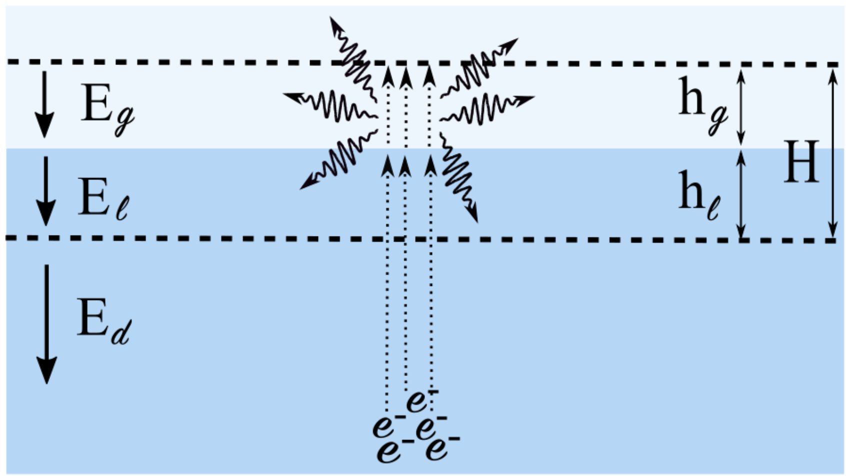
Isotope	Abundance	Decay mode and half-life
^{124}Xe	0.09 %	double-electron capture, 1.8×10^{22} y
^{125}Xe	synthetic	electron capture, 16.9 h
^{126}Xe	0.09 %	stable *
^{127}Xe	synthetic	electron capture, 36.35 d
^{128}Xe	1.92 %	stable
^{129}Xe	26.44 %	stable
^{130}Xe	4.08 %	stable
^{131}Xe	21.18 %	stable
^{132}Xe	26.89 %	stable
^{133}Xe	synthetic	beta decay β^-, 5.25 h
^{134}Xe	10.44 %	stable *
^{135}Xe	synthetic	beta decay β^-, 9.14 h
^{136}Xe	8.86 %	double-beta decay, 2.23×10^{21} y

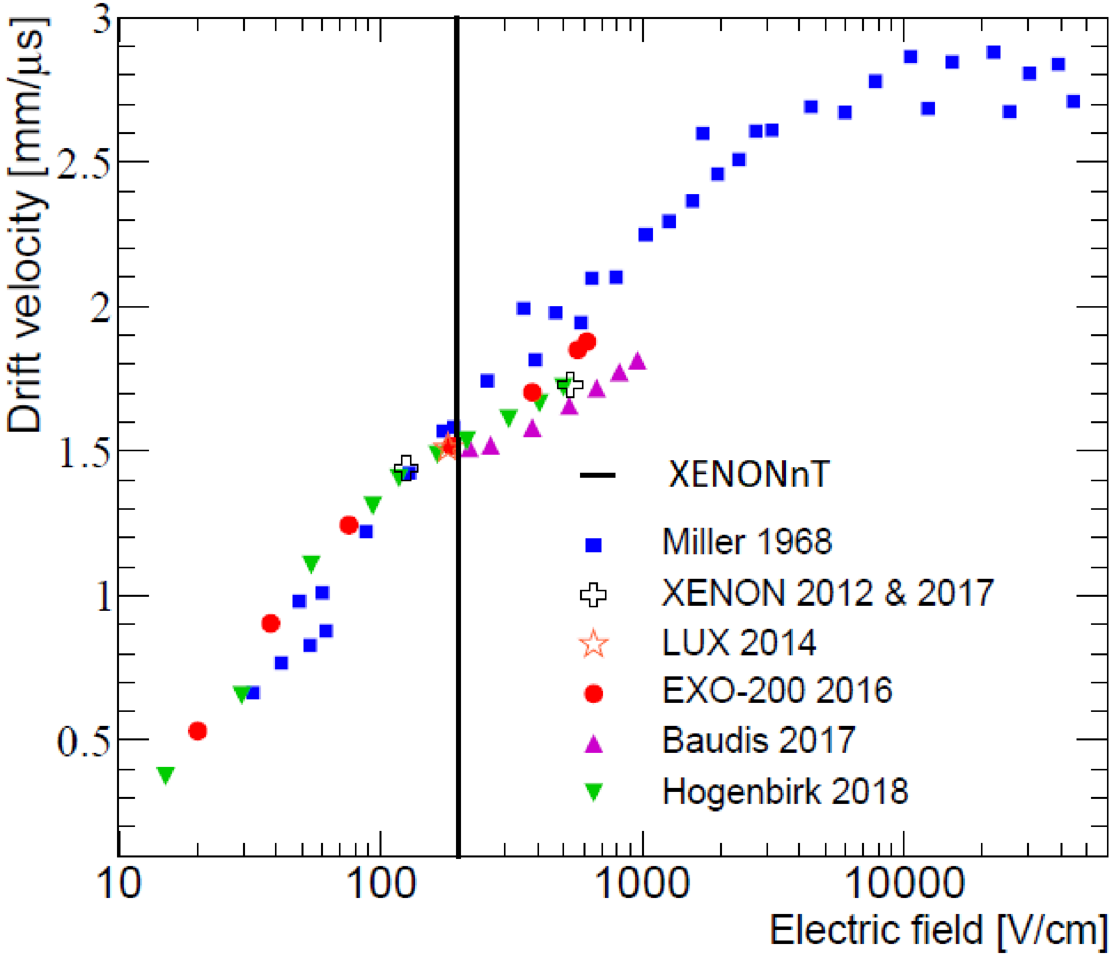
*Candidate for double-beta decay

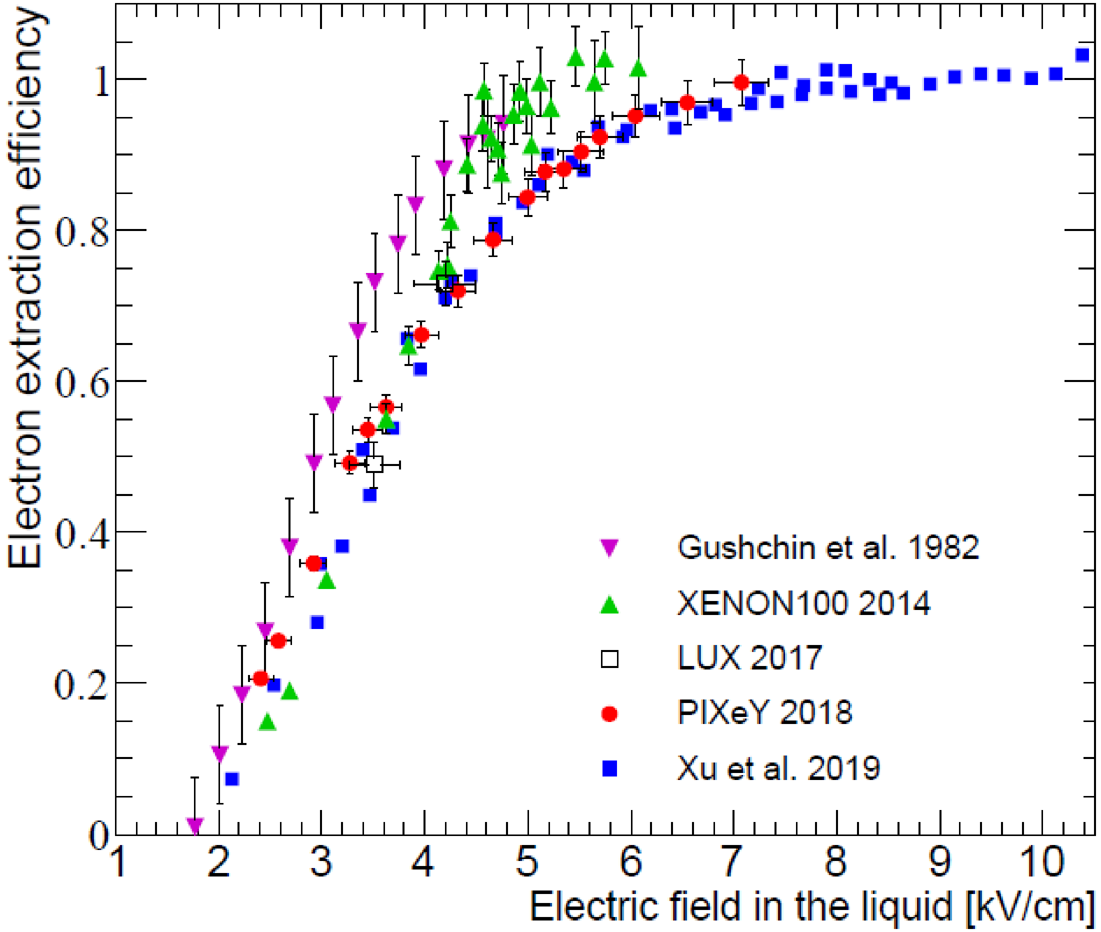
Electron Drift and Extraction



Credit Plot: T. Marrodán Undagoitia

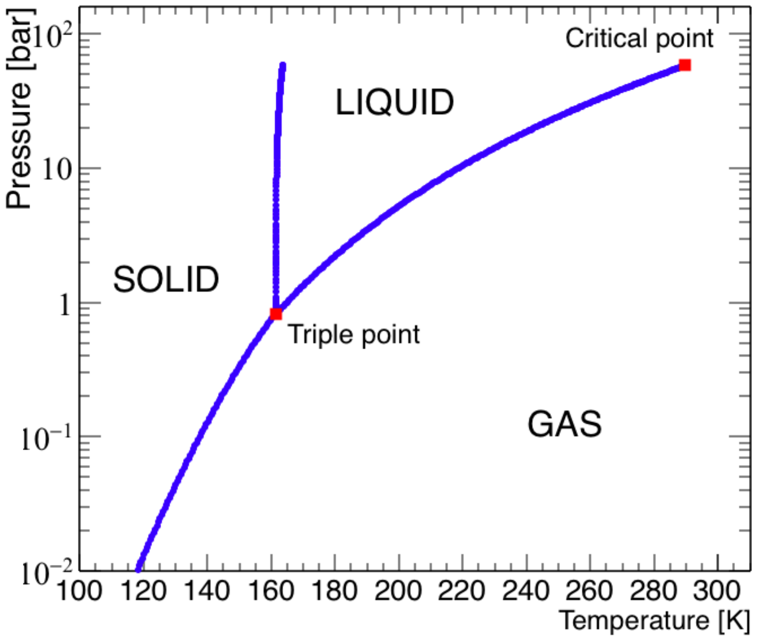




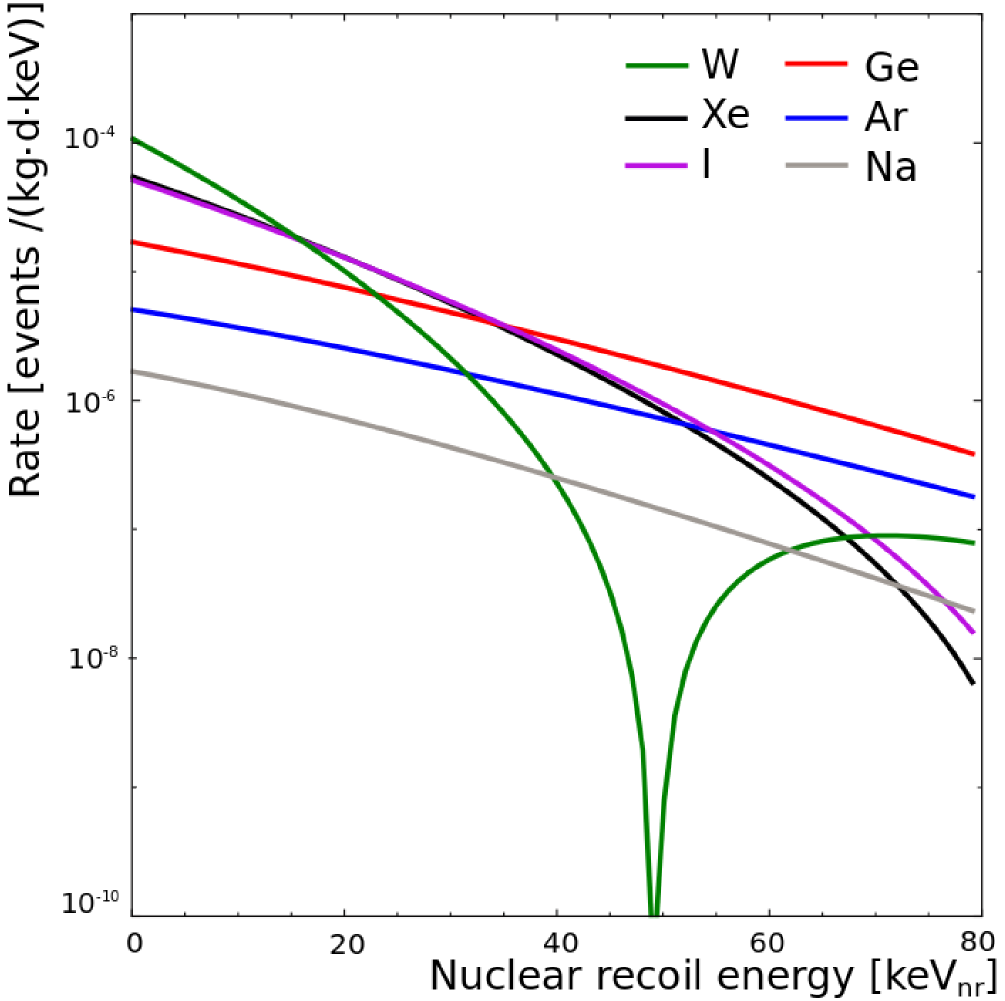


Liquid Xenon (LXe) Rare Event Detection

- High mass number: high density (3 g/cm^3), high nuclear interaction cross-section
- Homogeneity: liquid target under cryogenic temperature
- Noble gas: can achieve high purity
- Low intrinsic background
- Vacuum Ultra-violet (VUV) scintillation: high light/charge yield
- Time projection chamber (TPC) allow 3D position reconstruction



Data from Air Liquide Encyclopedia



T. Marrodán Undagoitia, L. Rauch, J. Phys. G: Nucl. Part. Phys. 43 013001 (2016)

Universität Münster
Ying-Ting Lin
ylin3@uni-muenster.de

Electronegative Impurity in LXe

- H_2O: resides on metal surfaces
  - Light attenuation at scintillation wavelength
  - Uniform reduction of S1 signal

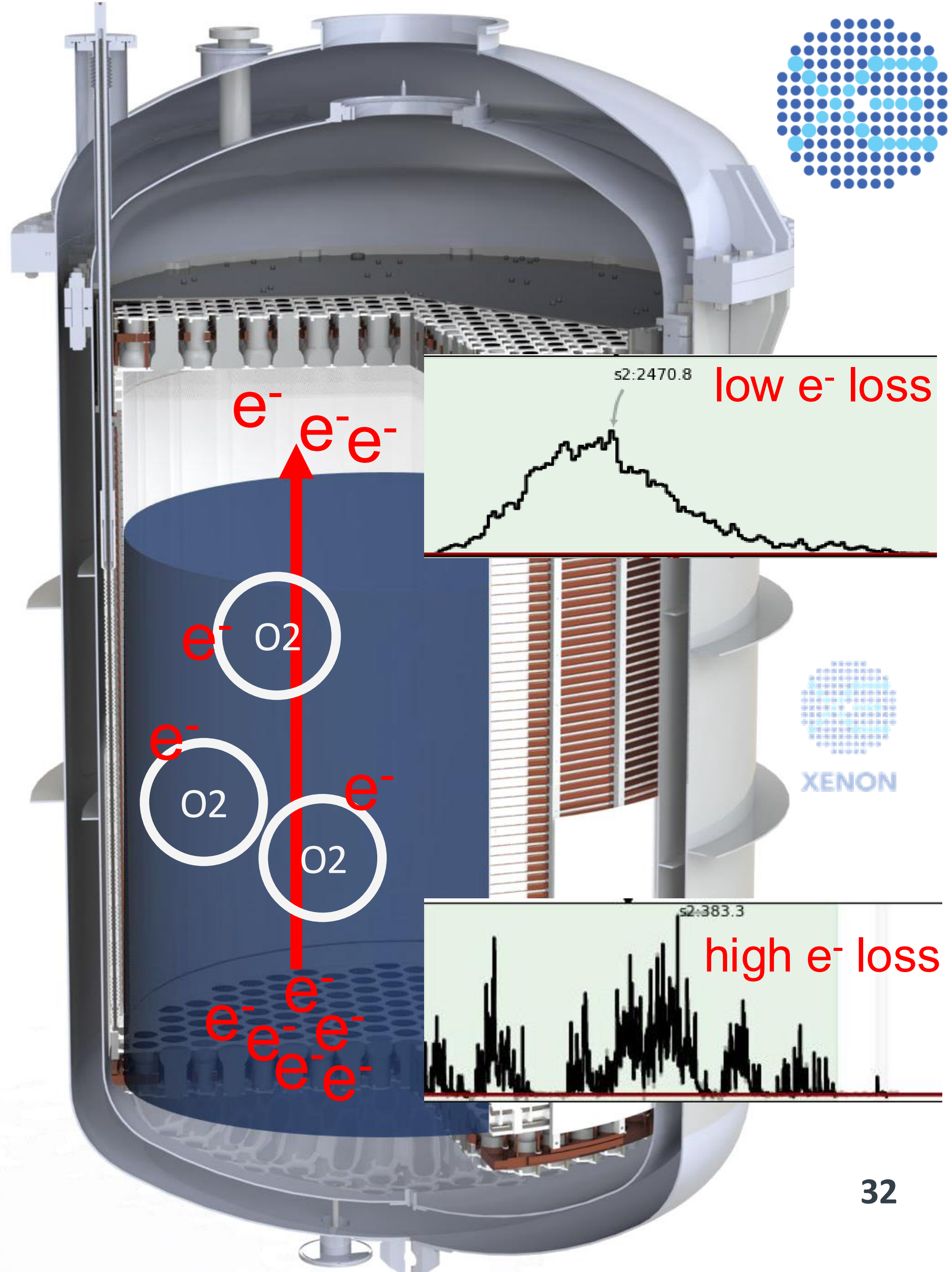
- O_2: resides within porous material such as PTFE
  - High electron attenuation; capturing drift electrons
  - Depth dependent loss of S2 signal
  - Quantified by **electron drift lifetime**:

$$\tau_e = \frac{1}{k_{O_2} C_{O_2}}$$

C_{O_2}: O_2 concentration, k_{O_2}: rate constant

  - Number of S2 electrons N_e lost at drift time t:

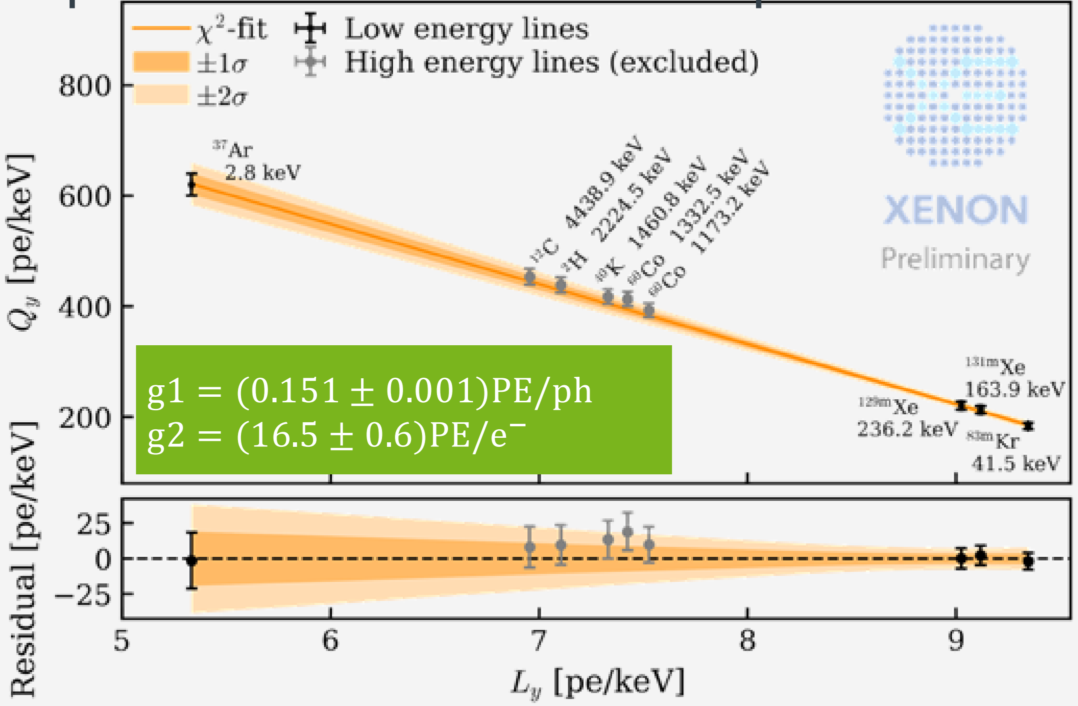
$$N_e(t) = N_e(0) e^{-\frac{t}{\tau_e}}$$

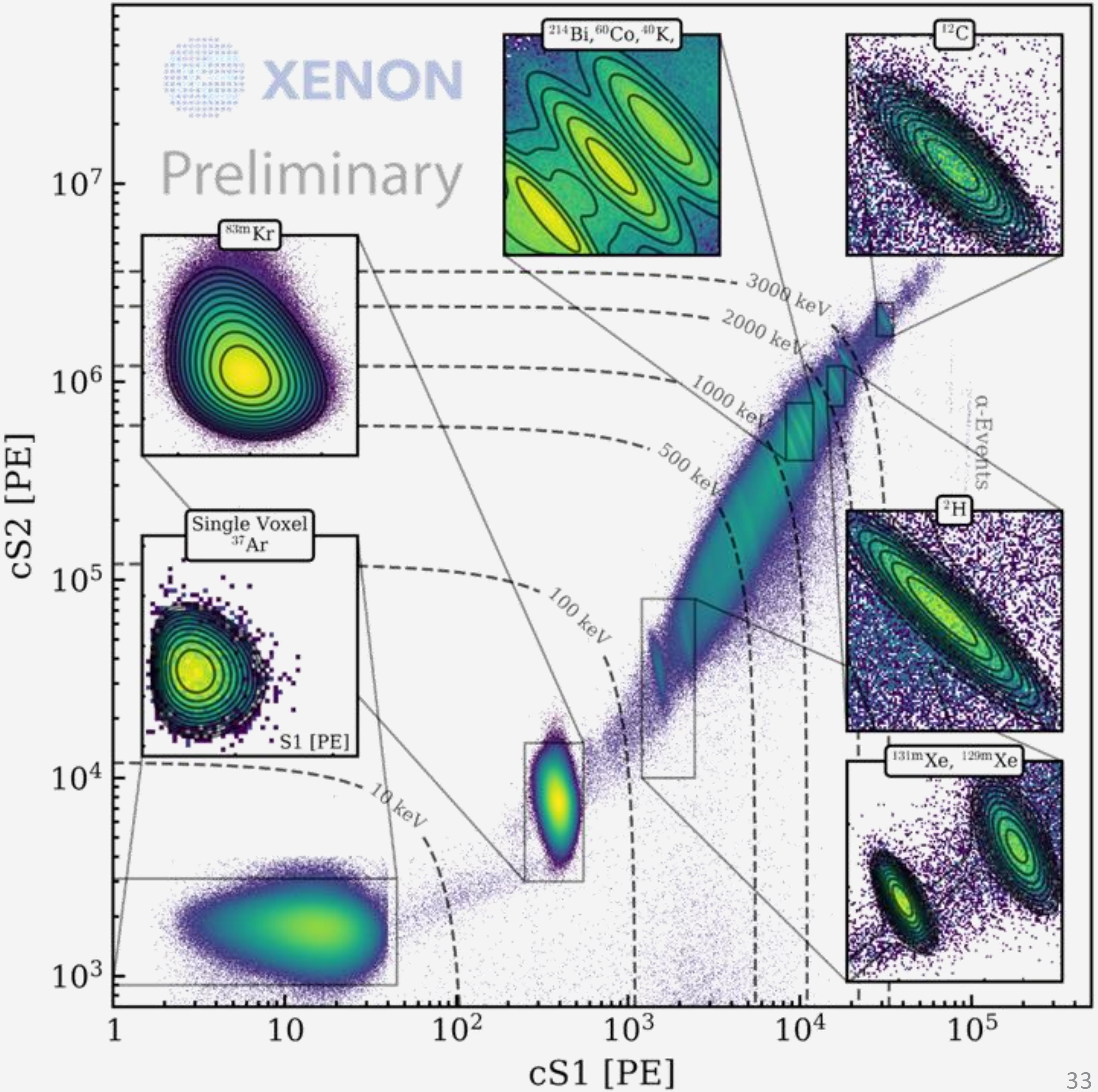


ER Calibration

$$E = W\left(\frac{cS1}{g_1} + \frac{cS2}{g_2}\right)$$

- W: work function
- g_1/g_2 : photon/electron detection efficiency: number of observed PMT photoelectrons (PE) per scintillation photon/ionization electron produced

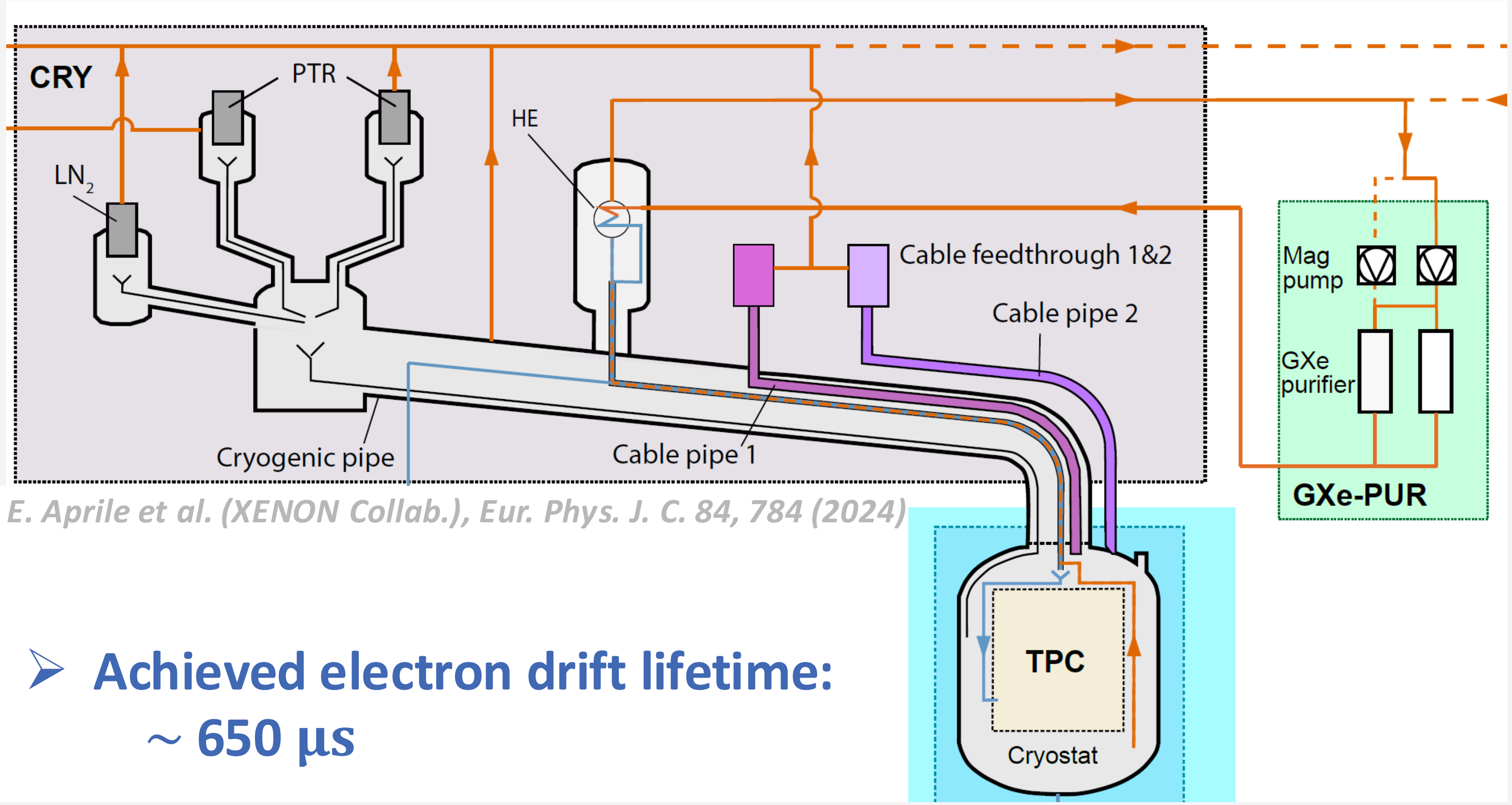




XENON1T/nT Gas Purification

- General purification performance equation: $x_\infty = \dfrac{\Lambda \tau_p}{n\varepsilon}$
- Hot getter purifiers
- Magnetic GXe pumps (mag-pumps): 22-36 kg/h ~ 60-100 slpm

x_∞: impurity at equilibrium
Λ: total impurity source inflow
τ_p: flow turnaround time from TPC
ε: purifier efficiency
n: total LXe



E. Aprile et al. (XENON Collab.), Eur. Phys. J. C. 84, 784 (2024)

➢ **Achieved electron drift lifetime: ~ 650 μs**

Hot Getter

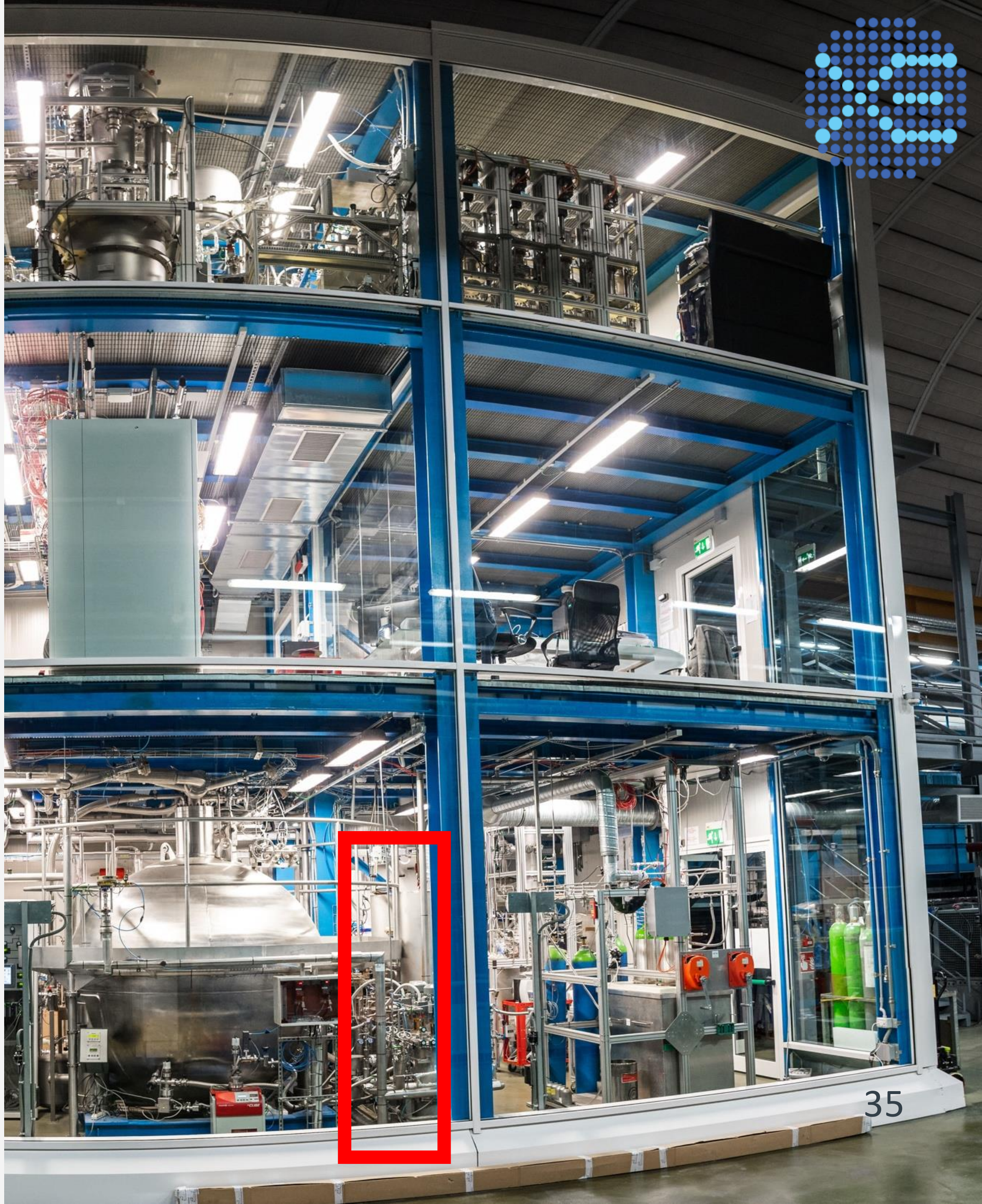
Mag-Pump

E. Brown et al., Eur. Phys. J. C. 78, 604 (2018)

XENONnT Liquid Purification

- Magnetically coupled cryogenic rotor pumps:
  180-720 kg/h ~ 1-4 LPM
  Barber-Nichols

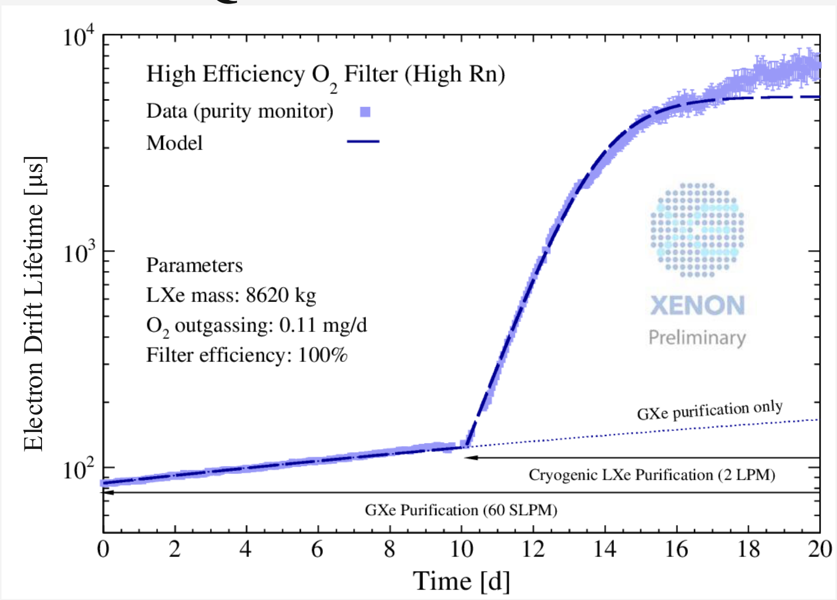
- Purifiers:
  - copper catalyst on high-surface-area alumina (Q5): **high ε, higher radon emanation**
  - sintered pellets of non-evaporable getter alloy (St707): **lower ε, low radon emanation**



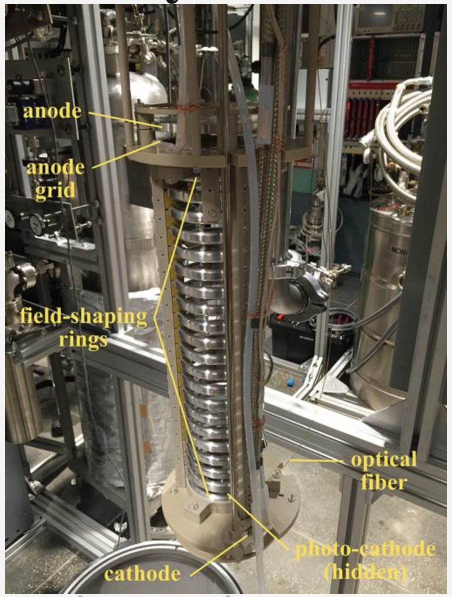
XENONnT Liquid Purification Performance

- With Q5, achieved 5 ms electron drift lifetime in 5 days
- In science run with St707, kept at 15 ms electron drift lifetime:
  ~90% full-drift electrons survive

Q5 Performance

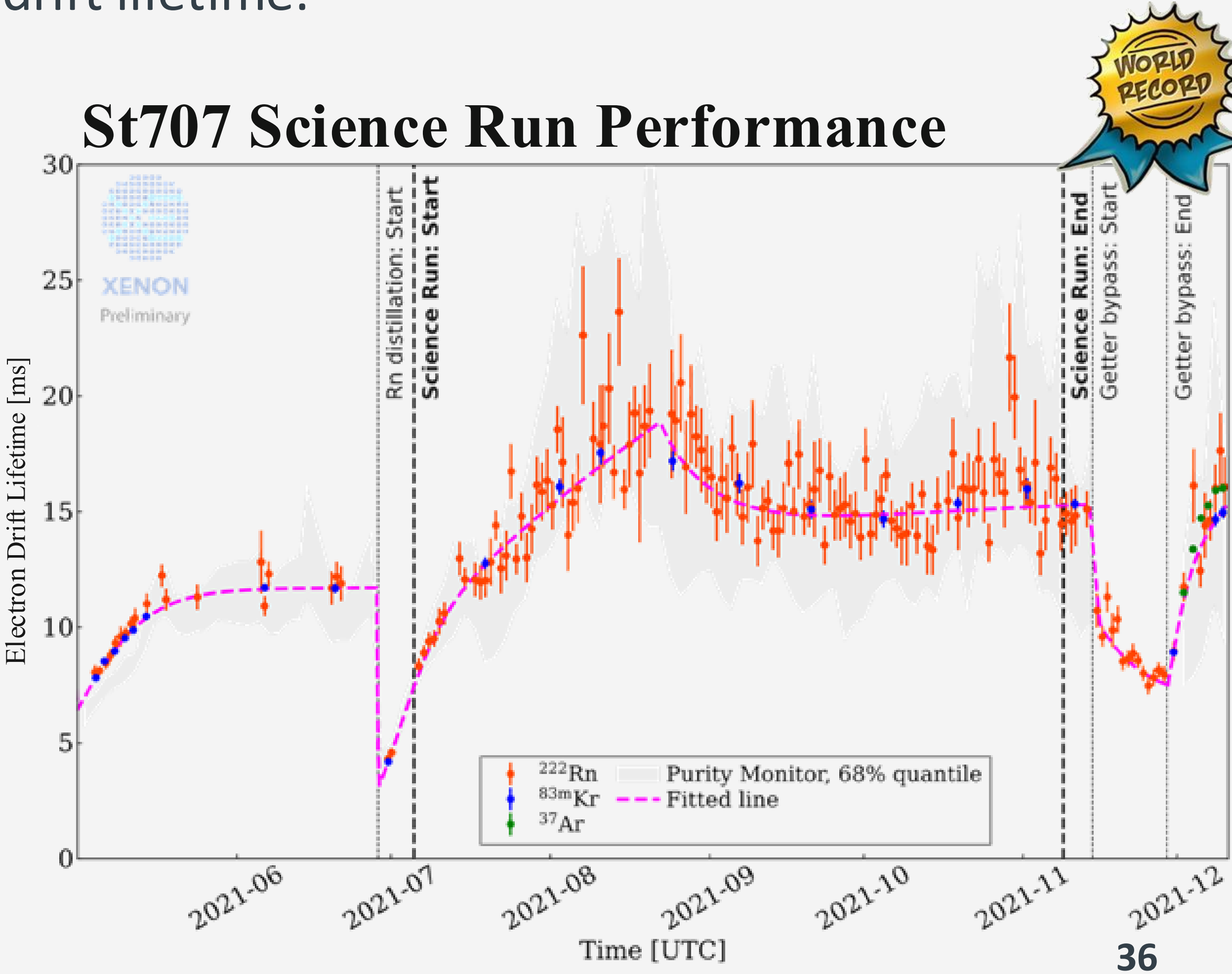


Xeclipse Purity Monitor



G. Plante et al, Eur. Phys. J. C 82, 860 (2022)

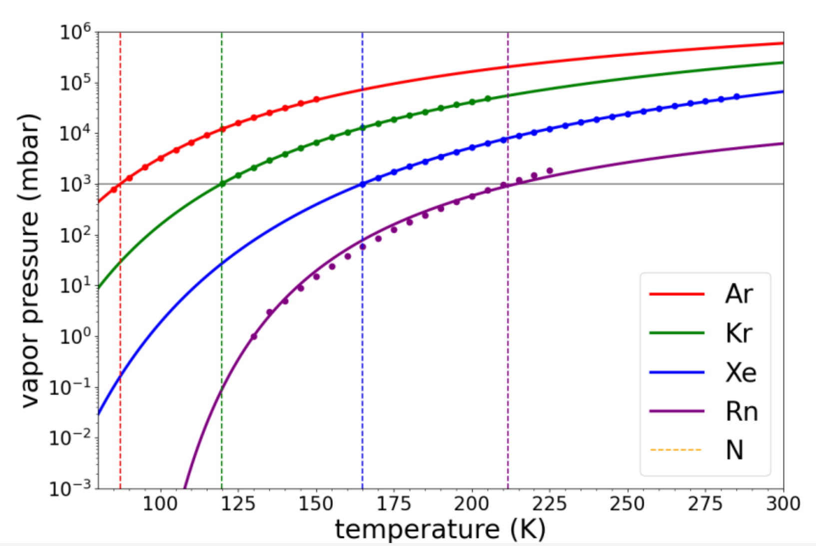
St707 Science Run Performance



Noble Gas Cryogenic Distillation

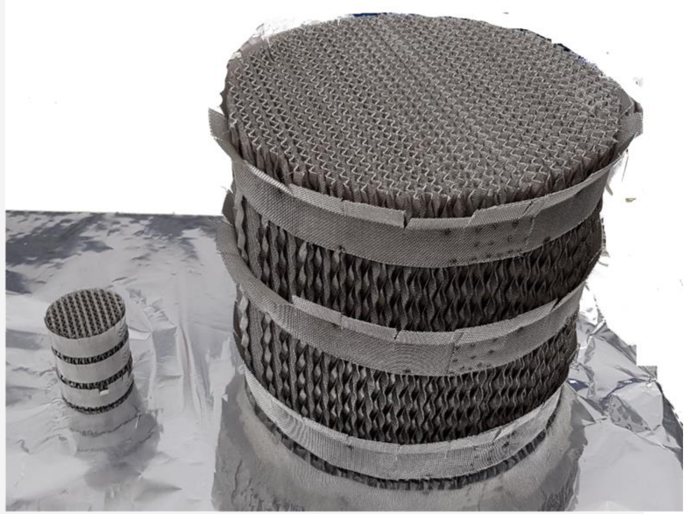
- Relative volatility as vapor pressure ratio:

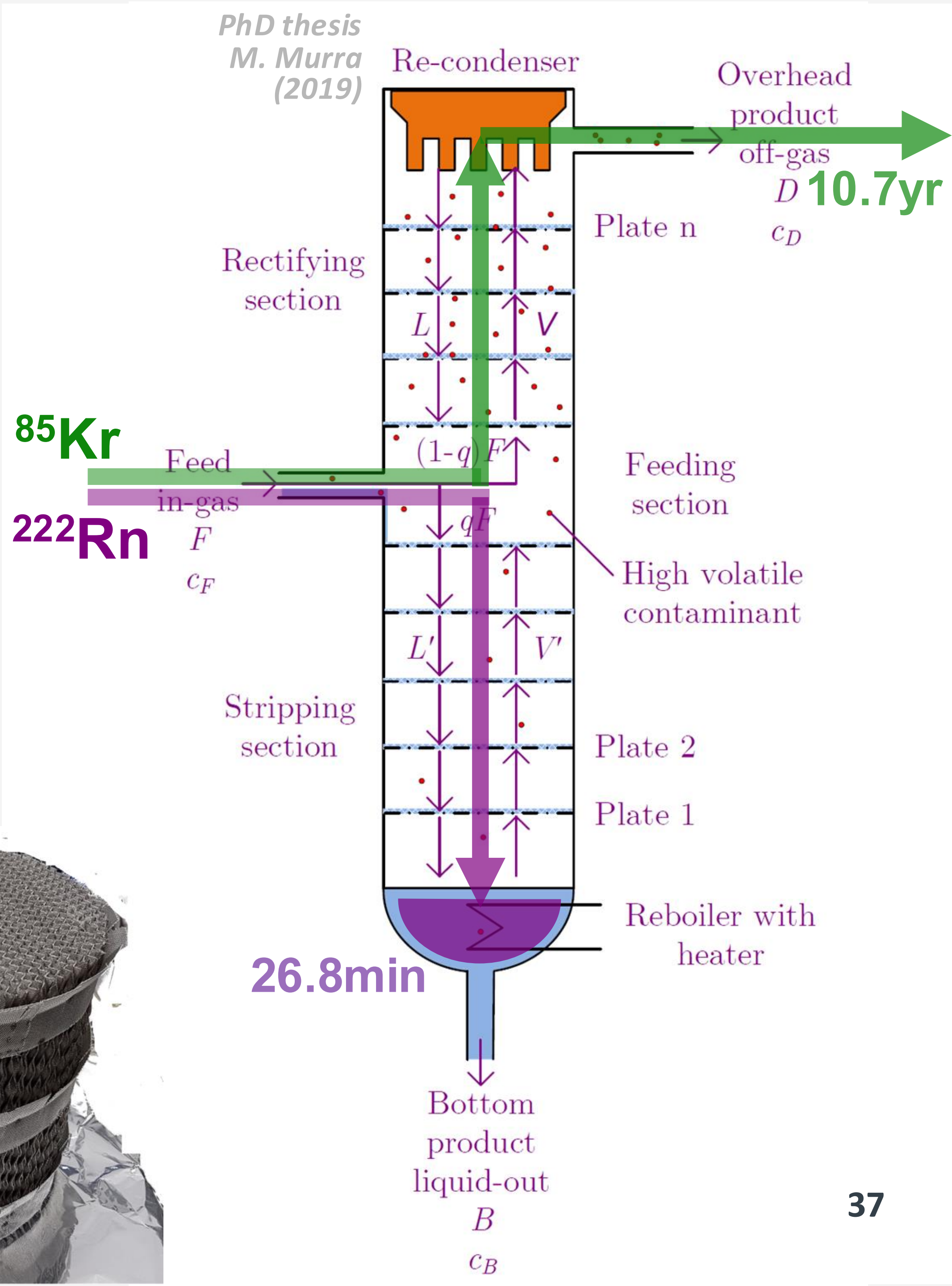
$$\alpha_i \equiv \frac{p_i}{p_{Xe}}$$



Data from CRC Handbook of Chemistry and Physics 95th Edition

- ^{85}Kr: $\alpha = 10.5$ (-100 °C)
  - Enriched at the top
  - **Remove through off-gas**
- ^{222}Rn: $\alpha = 0.1$ (-100 °C)
  - Enriched at the bottom
  - **Trapped in reboiler to decay**





XENONnT Krypton Distillation

- Distillation mode:
  Offline and online

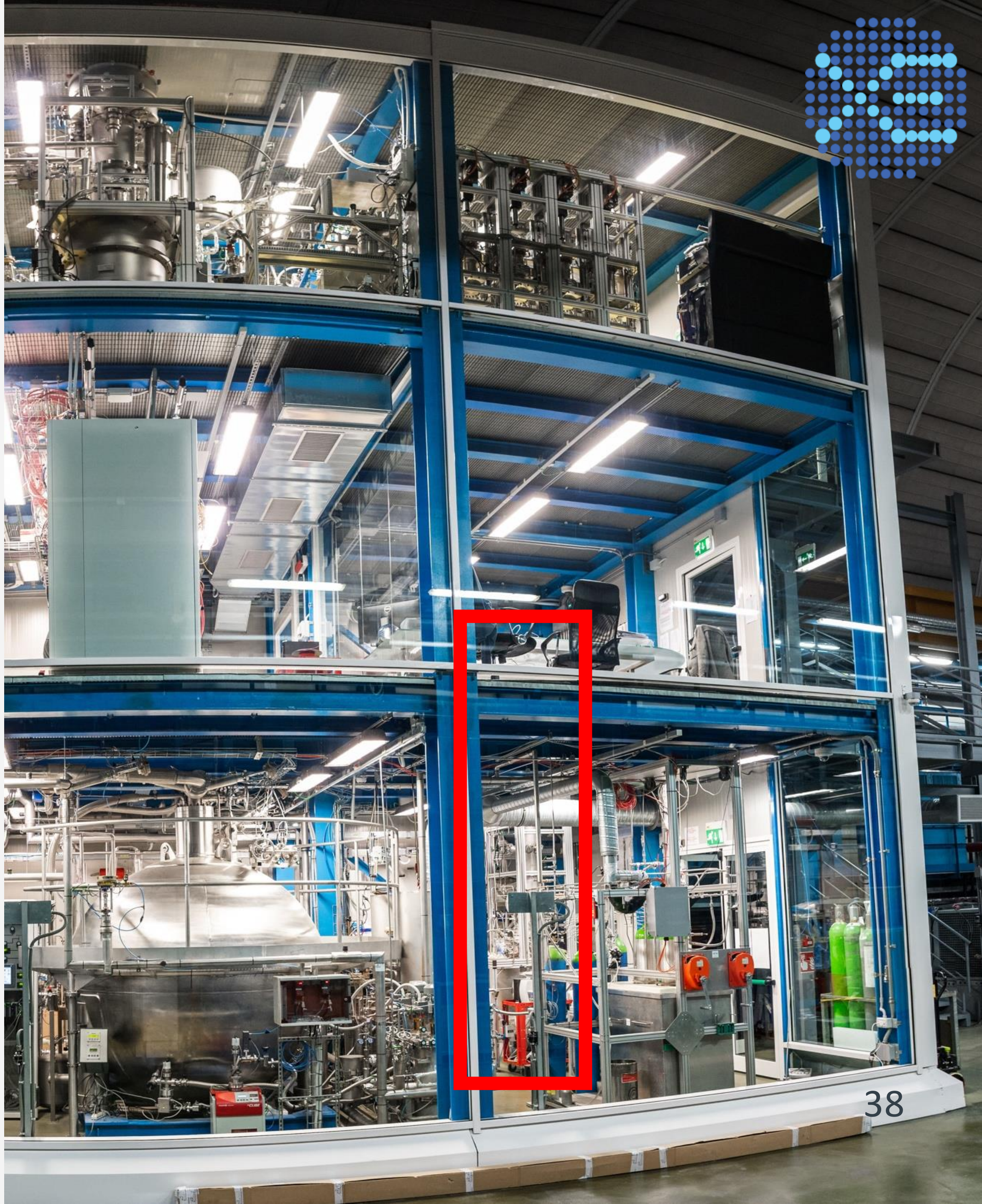
- Feeding flow:
  - 3 kg/h ~ 8.3 slpm
  - ➢ Achieved: 6.5 kg/h ~ 18 slpm

- Separation factor:
  - 10^4-10^5
  - ➢ Achieved: $6.4^{+1.9}_{-1.3} \times 10^5$

- Xe recovery:
  99%

5.5 m

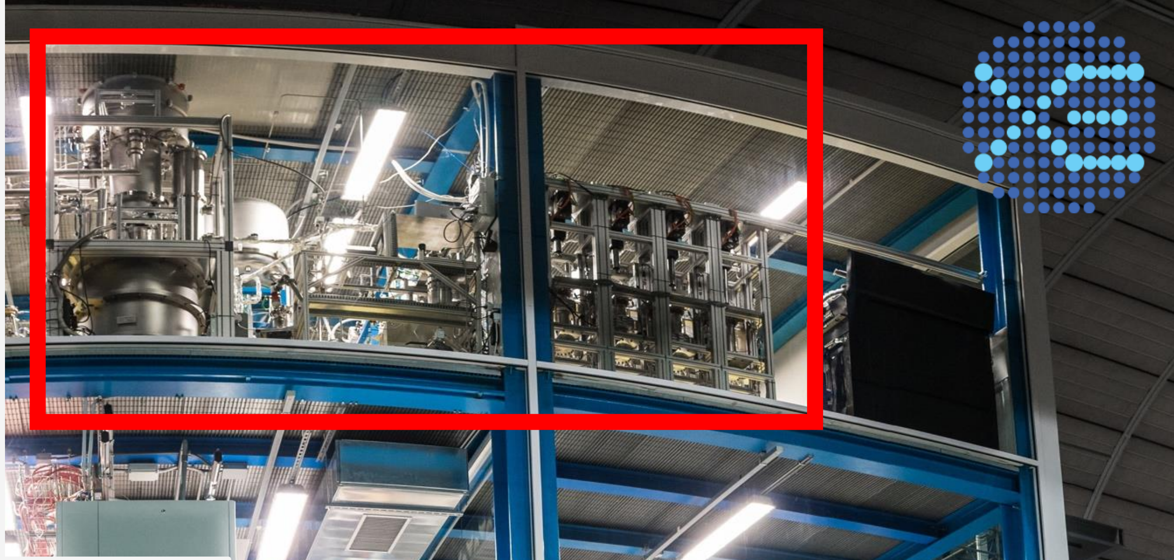
E. Aprile et al. (XENON Collab.), Eur. Phys. J. C. 77, 275 (2017)

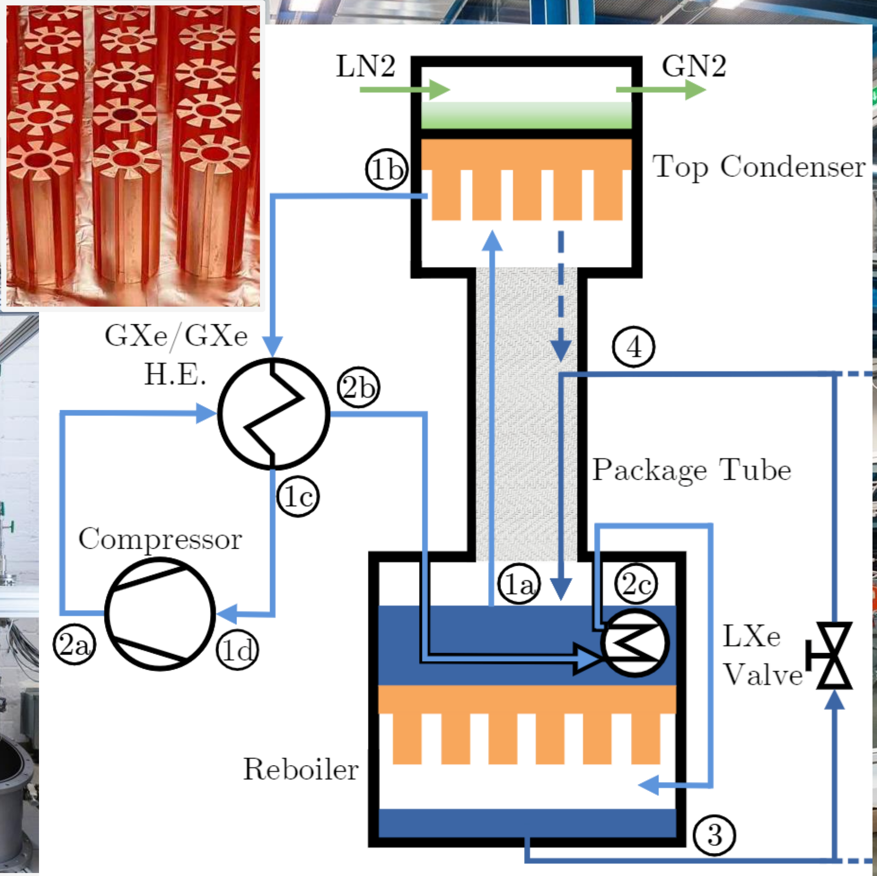


XENONnT Radon Removal

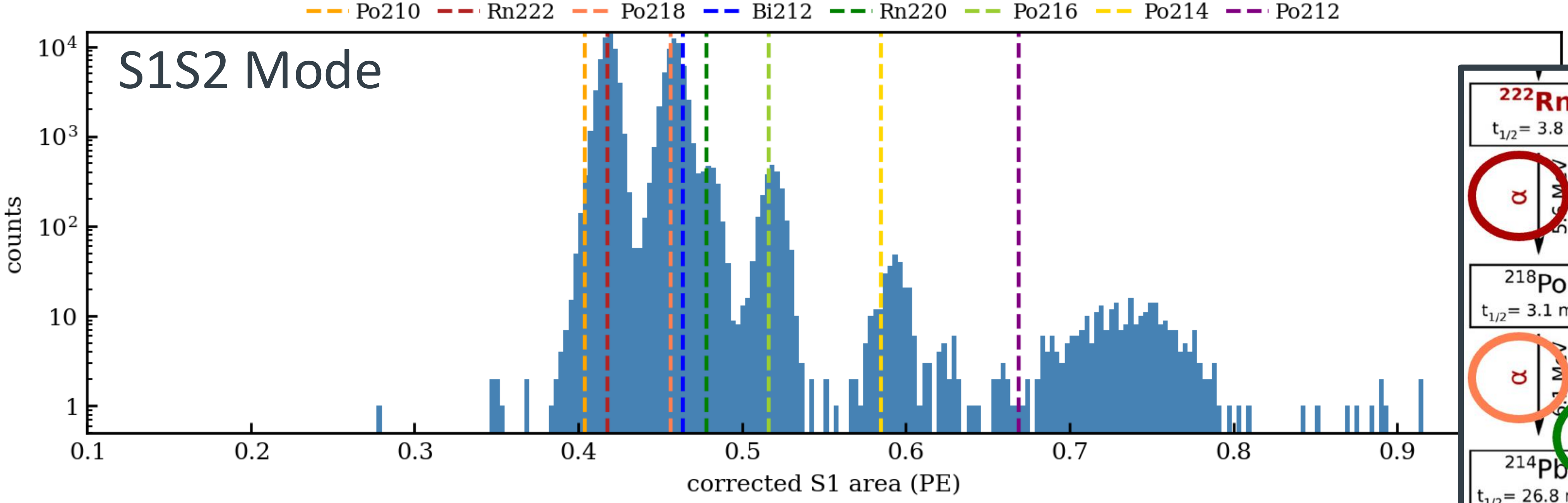
- Distillation mode:
  Continuous online
- Feeding flow (radon-free mag-pumps):
  targeting 72kg/h ~ 200 slpm (~15% of LXe flow)
- Separation factor:
  >156
- *XENON Collaboration, Phys. Rev. X 15, 031079 (2025)*
- Xe recovery:
  100%
- Reboiler heat exchanger (HE)
- Mag-pump compressor acts similar to a heat pump via another HE
- **Improve power consumption for cooling by a factor of 3!**

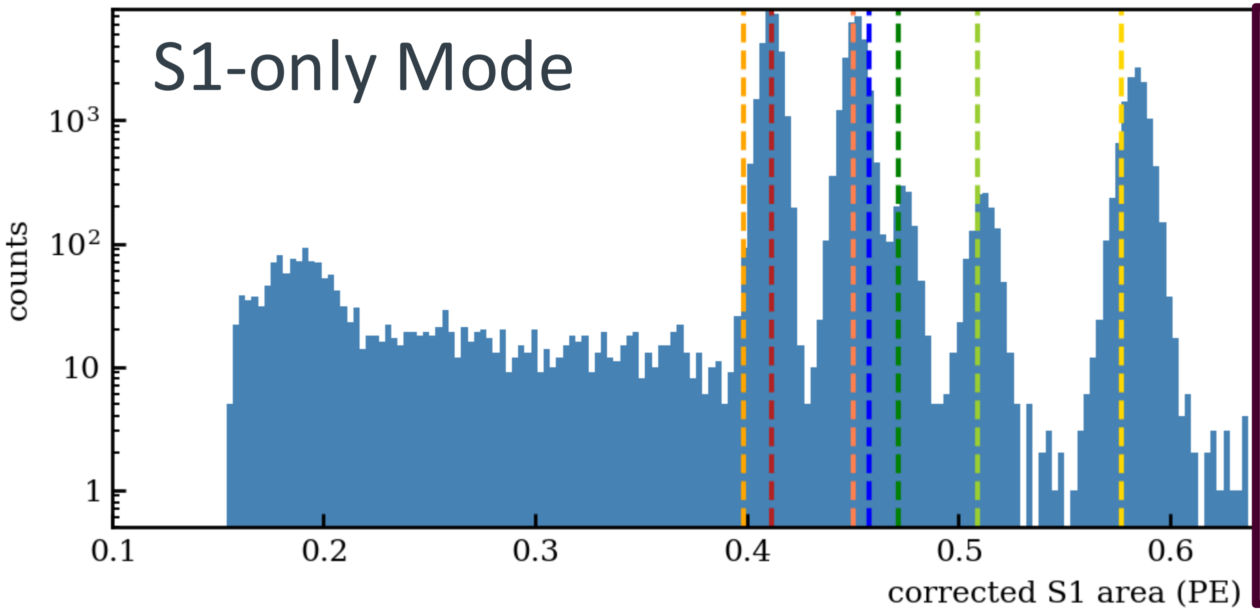
E. Aprile et al. (XENON Collab.), Eur. Phys. J. C. 82, 1108 (2022)

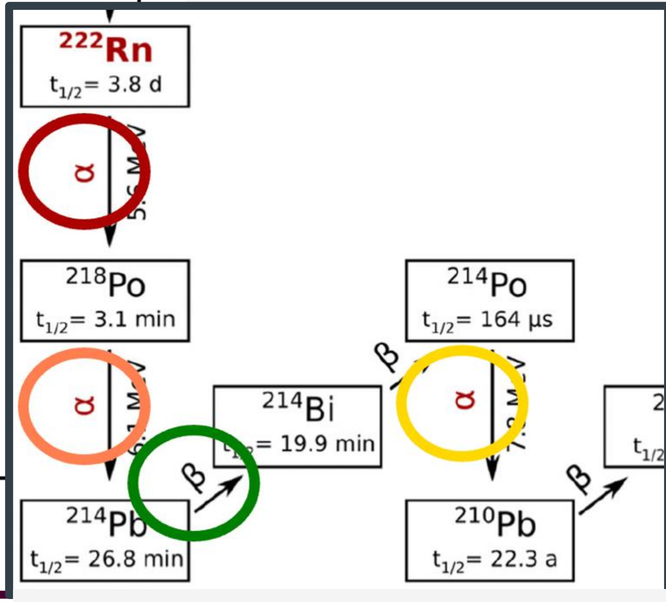


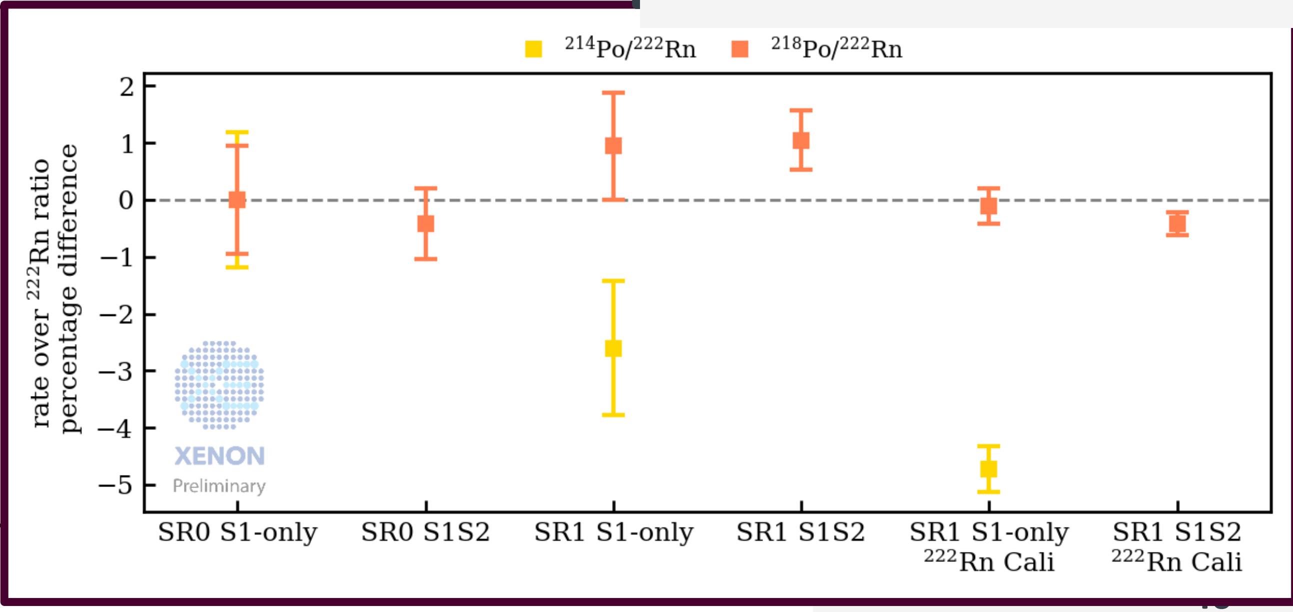


Alpha Analysis: S1S2 versus S1-Only Peak Comparison





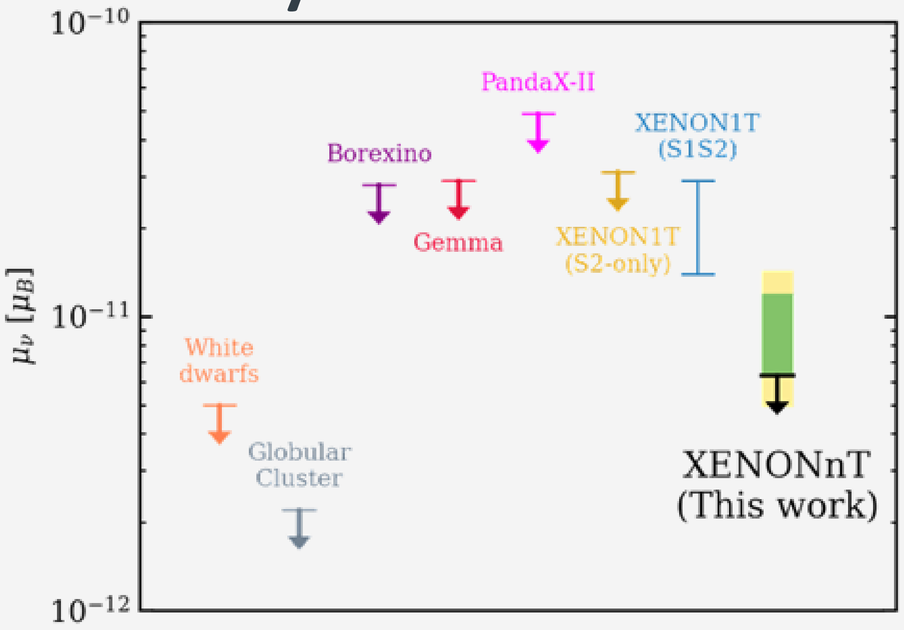




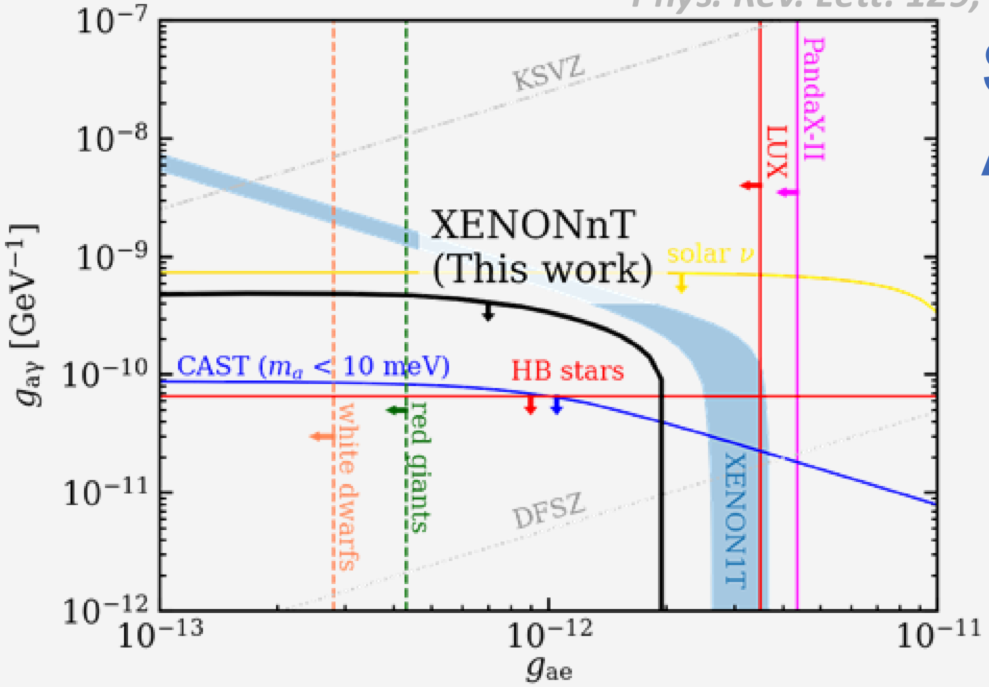
ER Region Analysis: XENON1T BSM Limits

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

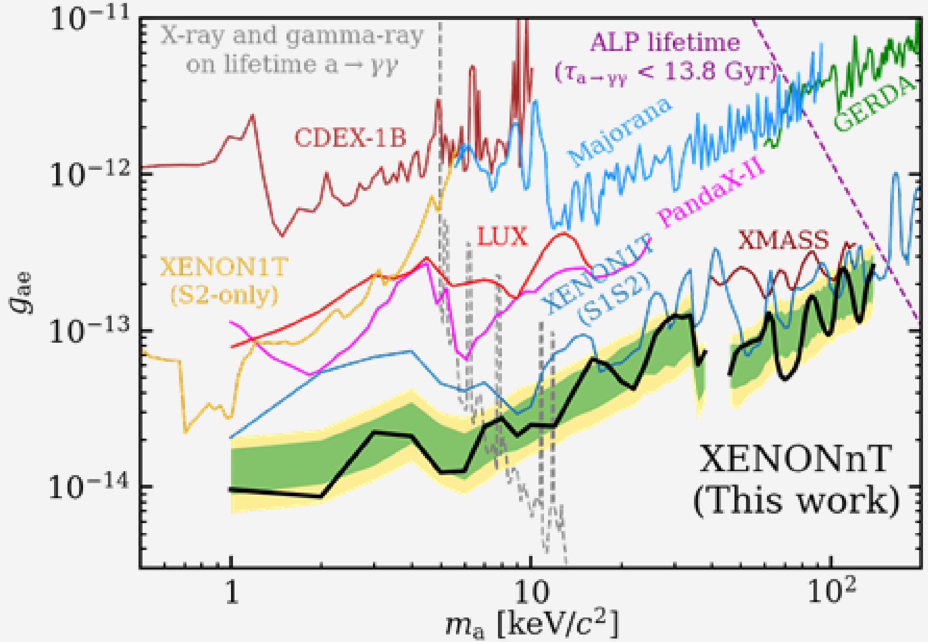
Neutrino Magnetic Moment



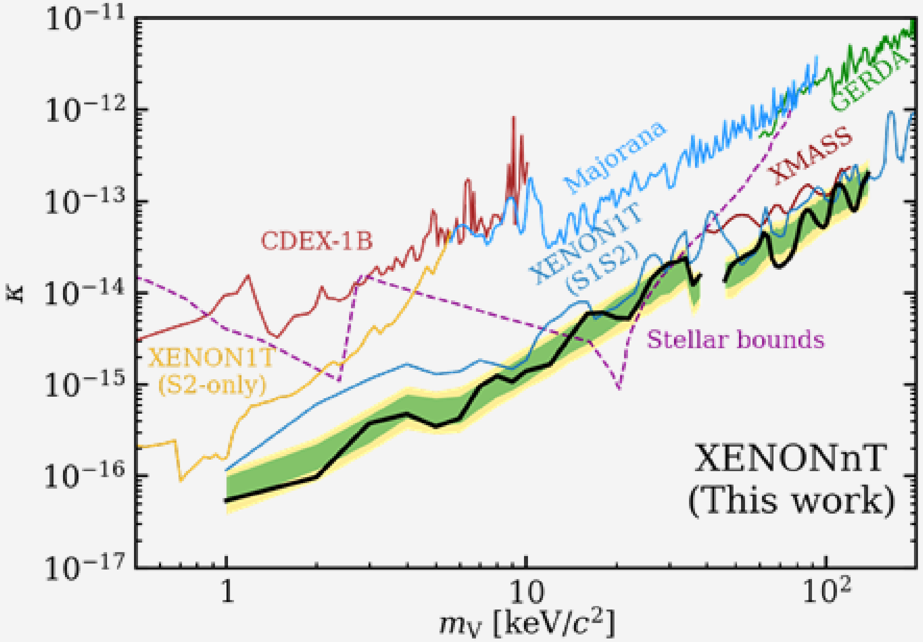
Solar Axion



Axion-like Particle

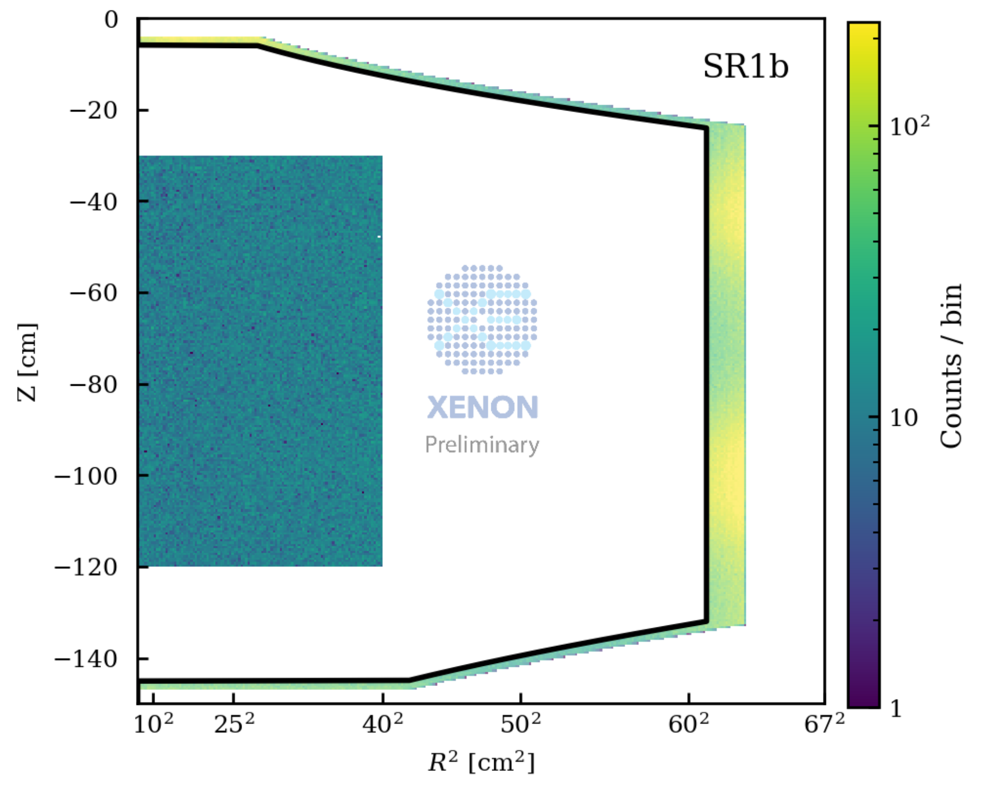


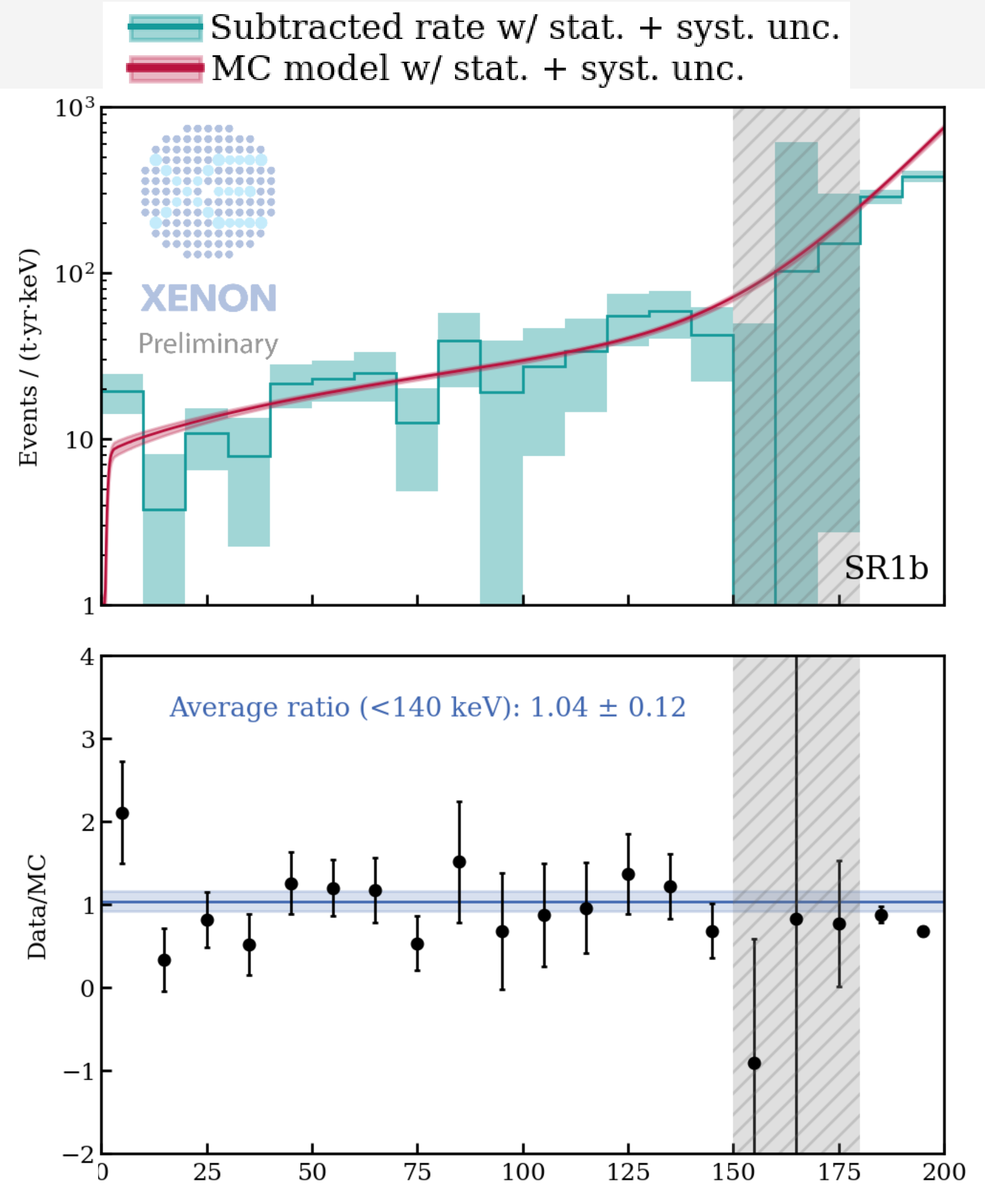
Dark Photon



Materials: Estimation

- Compton scattering of γ from trace radioactive material in detector surface
- Full-chain simulation using Geant4 and waveform simulation (WFsim) with screening values as input
- Side-band data from 2 cm outside the FV





Backgrounds in ER Channel

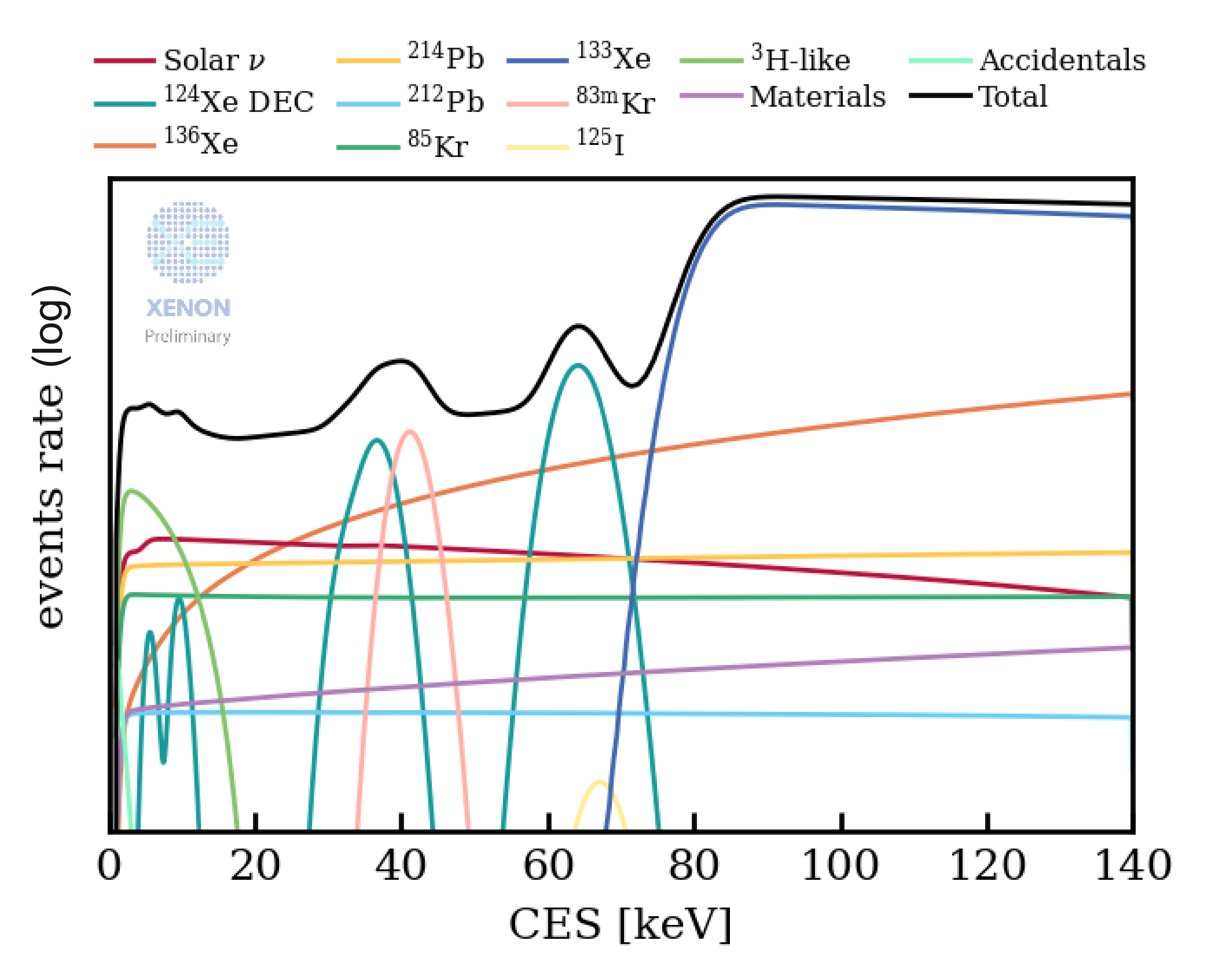
Noble gas backgrounds:
- ^{222}Rn/^{220}Rn: decay daughters of the material; dominant ER background
- ^{85}Kr: from ^{nat}Kr in Xe in the xenon inventory

Xenon Isotopes:
- ^{136}Xe/^{124}Xe: natural xenon isotopes
- ^{133}Xe/^{125}I: activation from neutron calibration

Other backgrounds:
- Materials: gamma with Compton scattering
- ^{3}H-like: potentially from operation
- ^{83m}Kr: residual from calibration
- Accidentals: accidental coincidences

Neutrinos:
- Solar υ: non-shieldable, dominate by *pp* neutrinos in low-energy ROI

ROI: ER channel in [1, 140] keV range

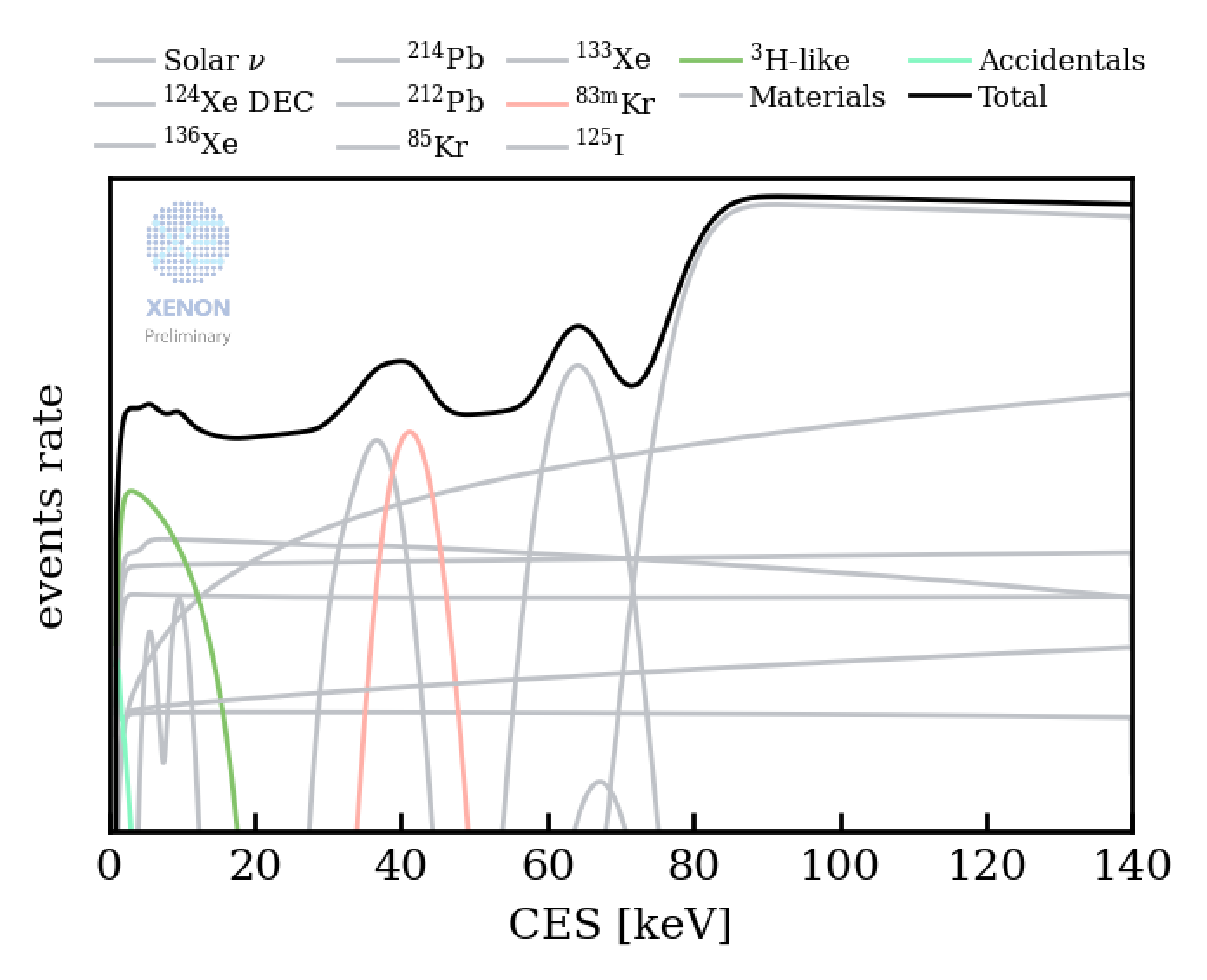


Ying-Ting Lin, ylin3@uni-muenster.de

Other Backgrounds

- ^{3}H-like: potentially introduced in SR1a along with ^{nat}Kr
- ^{83m}Kr: residual from ^{83m}Kr calibration, removing 24h of science data after injection
- Accidentals: accidental coincidences are negligible for science data, but important during ^{222}Rn/^{220}Rn calibrations due to pileups
- Critical for searches in other channels:
  - ➢ WIMP: Maxime Pierre, Jun 2nd, 12:10, Aula Magna
  - ➢ CEνNS: Giovanni Volta, Jun 2nd, 11:30, Pedro Cerbuna

ROI: ER channel in [1, 140] keV range



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LowRAD Project Goals

- **Low Rad**on and **Low** Internal **Radi**oactivity (LowRad) ERC Advanced Grant

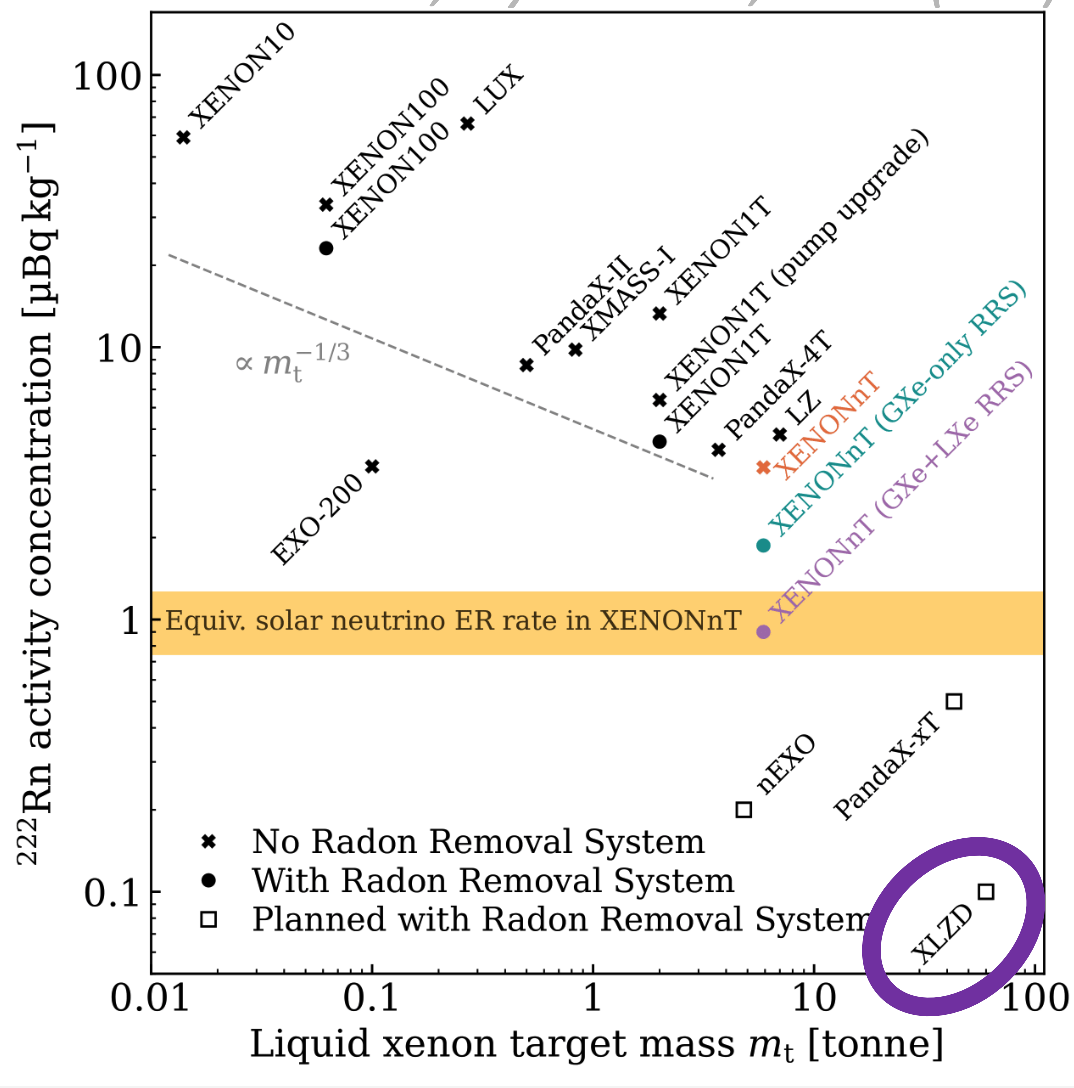
- **High flow radon** removal with **factor of 10** combined improvement in radon reduction to:
  0.1 µBq/kg of xenon

- **Lossless** online **krypton** removal at:
  30×10^{-15} (^{nat}Kr/Xe)

- **All-in-one** purification & distillation system

- R&D for novel purification methods
- Advancing analysis method for physics search

XENON Collaboration, Phys. Rev. X 15, 031079 (2025)



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Compact Solar Neutrino Detector