First WIMP Search Results from the XENONnT Experiment

Daniel Wenz on behalf of the XENON collaboration

dwenz@uni-mainz.de

L' Aquila Joint Astroparticle Colloquia 2023

LNGS 22.03.2023

XENON

PRISMA+

MPA MAINZ PHYSICS ACADEMY

“How to bake delicious dark matter chip cookies”

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Bundesministerium für Bildung und Forschung

Studienstiftung des deutschen Volkes

Dark Matter Cookies

Dark Matter Chip Cookies (with extra big chunks of DM)

Ingredients:

1. Dark Matter
2. Detector
3. Detector calibration
4. Background and signal model
5. Enjoy the result

Dark Matter Evidence

- Decades of astronomical surveys

➡ Variety of evidence on
different time and mass scales

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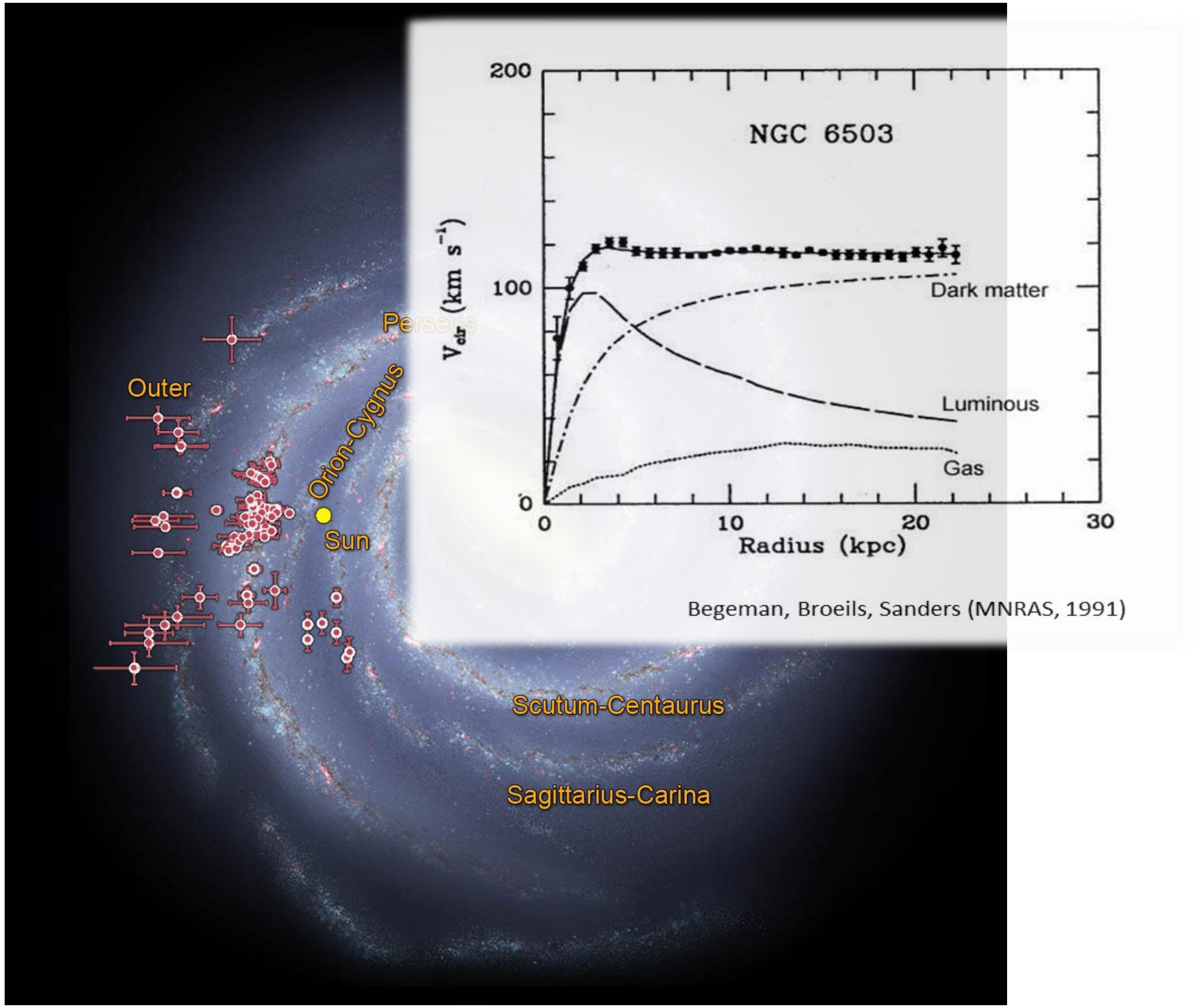
- Local scale of galaxies and clusters:
  - Rotation curves



Begeman, Broeils, Sanders (MNRAS, 1991)

Dark Matter Evidence

- Decades of astronomical surveys

  ➡ Variety of evidence on different time and mass scales

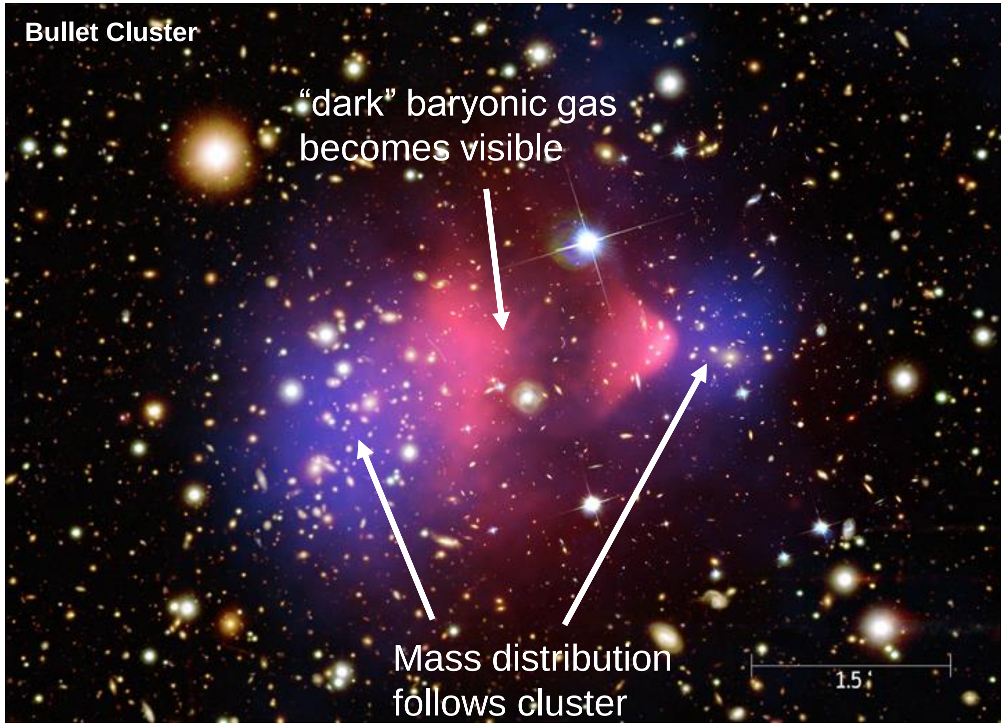
- Local scale of galaxies and clusters:
  - Rotation curves
  - Cluster movement, collisions and gravitational lensing

Virial Theorem:

$$2E_{kin} + E_{pot} = 0$$

➡ $M \propto R_G \langle v^2 \rangle / G$

➡ **More mass than visible**

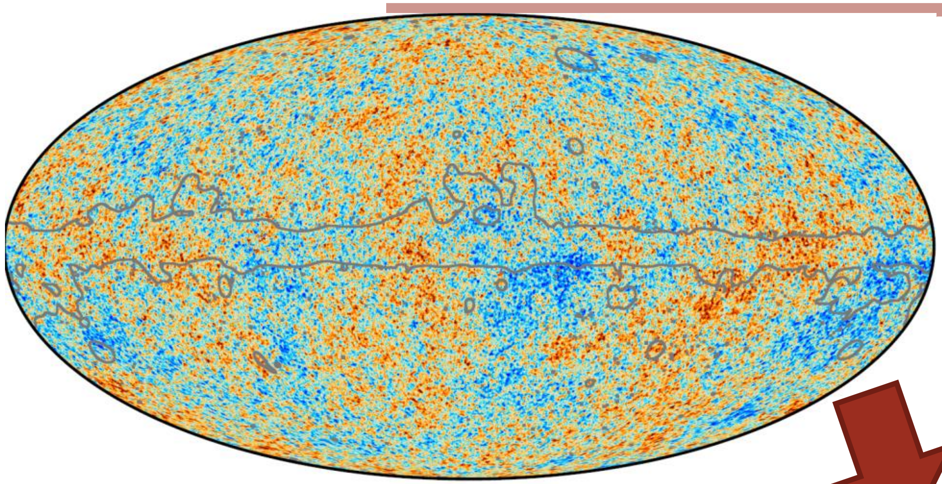


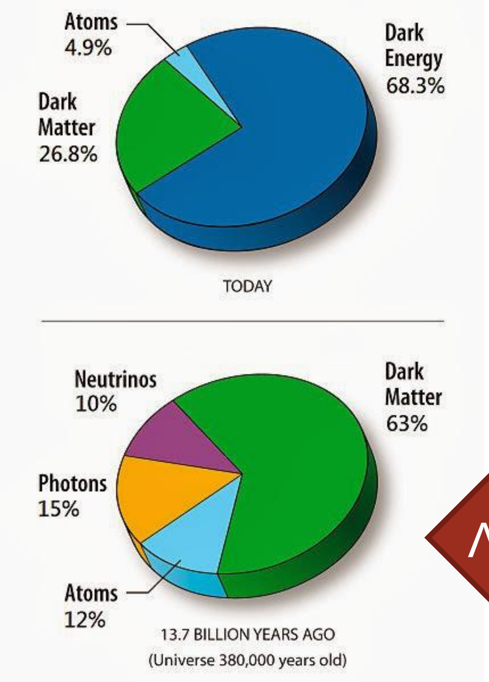
Dark Matter Evidence

- Decades of astronomical surveys

→ Variety of evidence on different time and mass scales

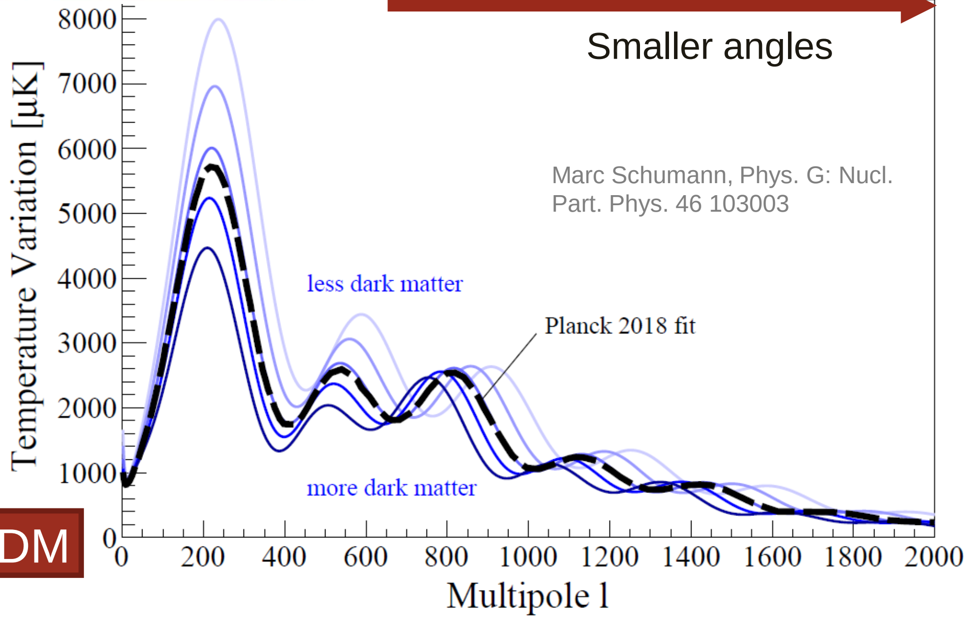
- Local scale of galaxies and clusters:
  - Rotation curves
  - Cluster movement, collisions and gra lensing
- Cosmic scales
  - Structure formation of the universe
  - Cosmic microwave background





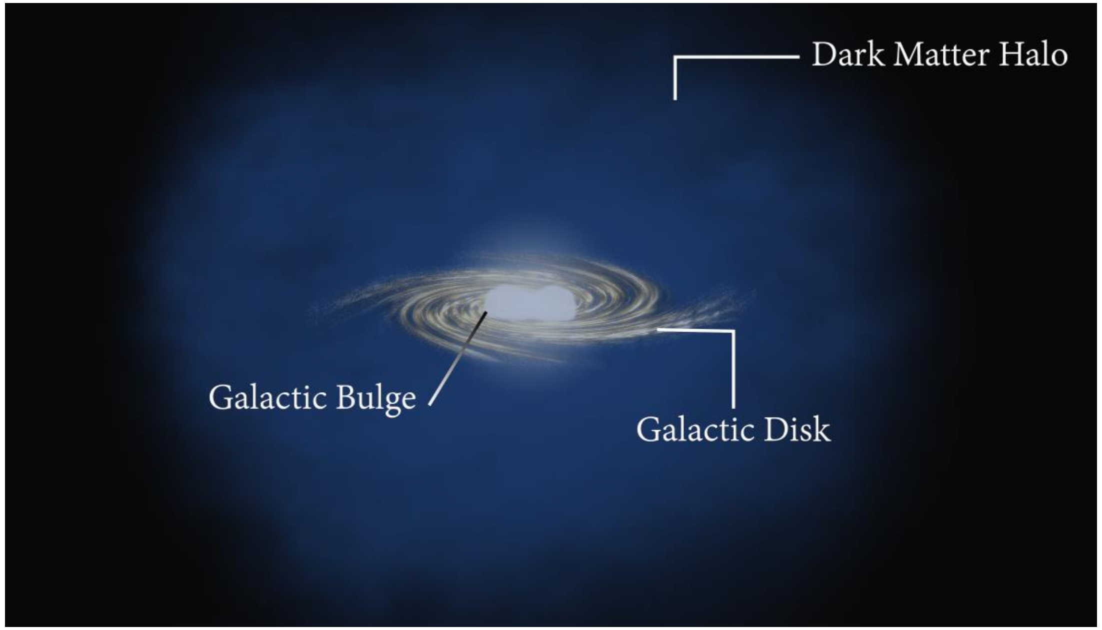
ΛCDM

Smaller angles



Marc Schumann, Phys. G: Nucl. Part. Phys. 46 103003

DM detection



- What do we know based on astronomical observations?
  - Electrically neutral
  - Small (self-)interaction cross section
  - Either long-lived/stable or produced
  - Must be cold/warm dark matter
  - Must exist within Galaxies!
- **What is dark matter and how can we search for it?**

DM detection

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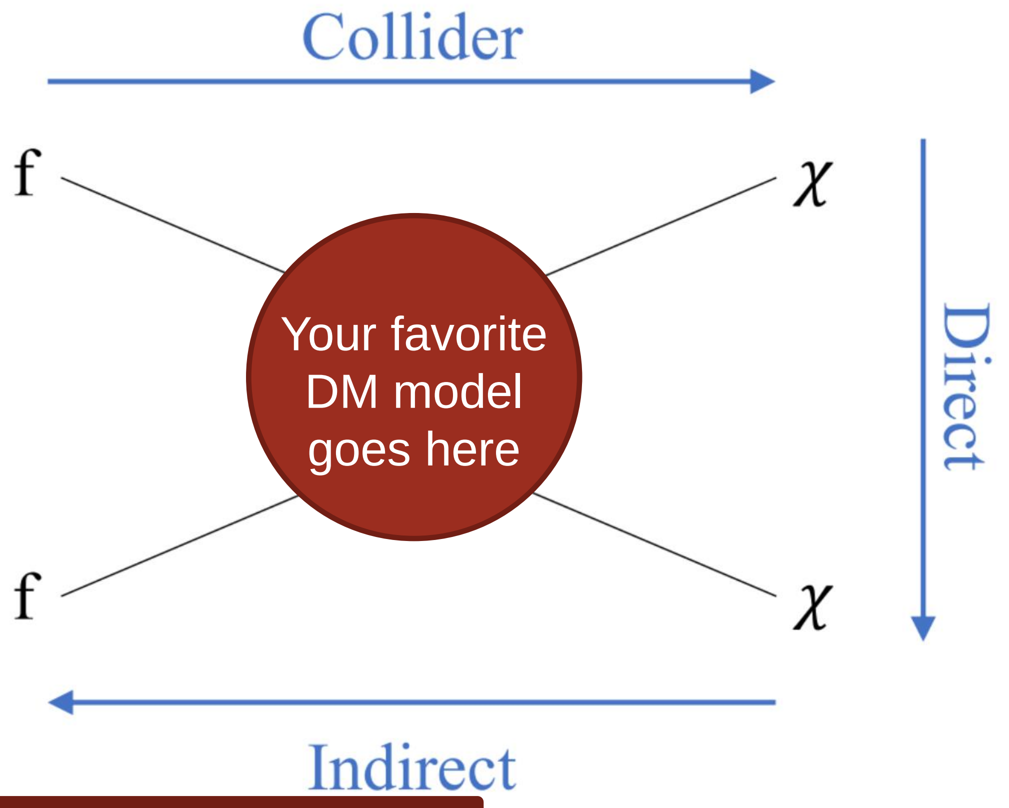
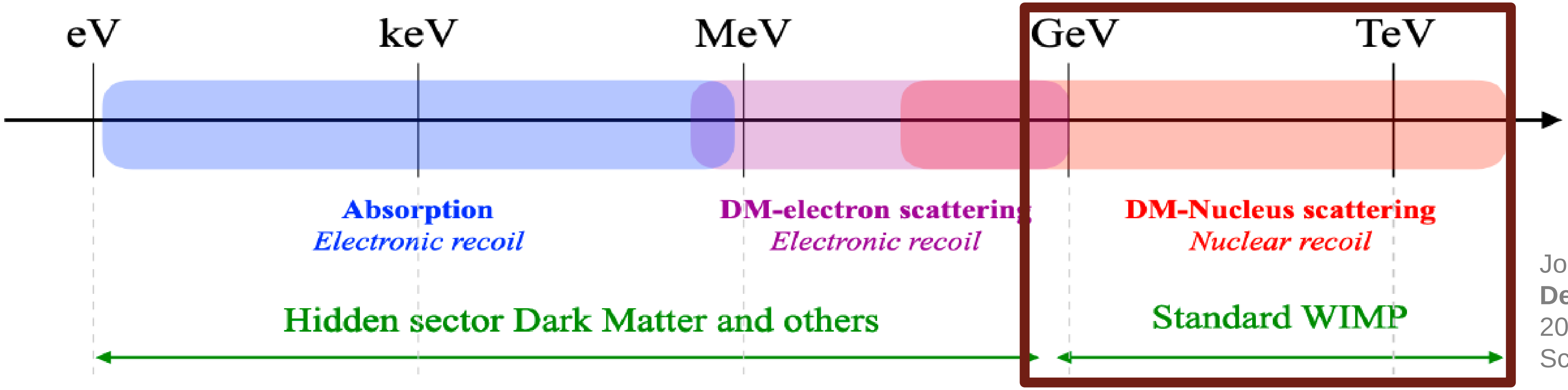


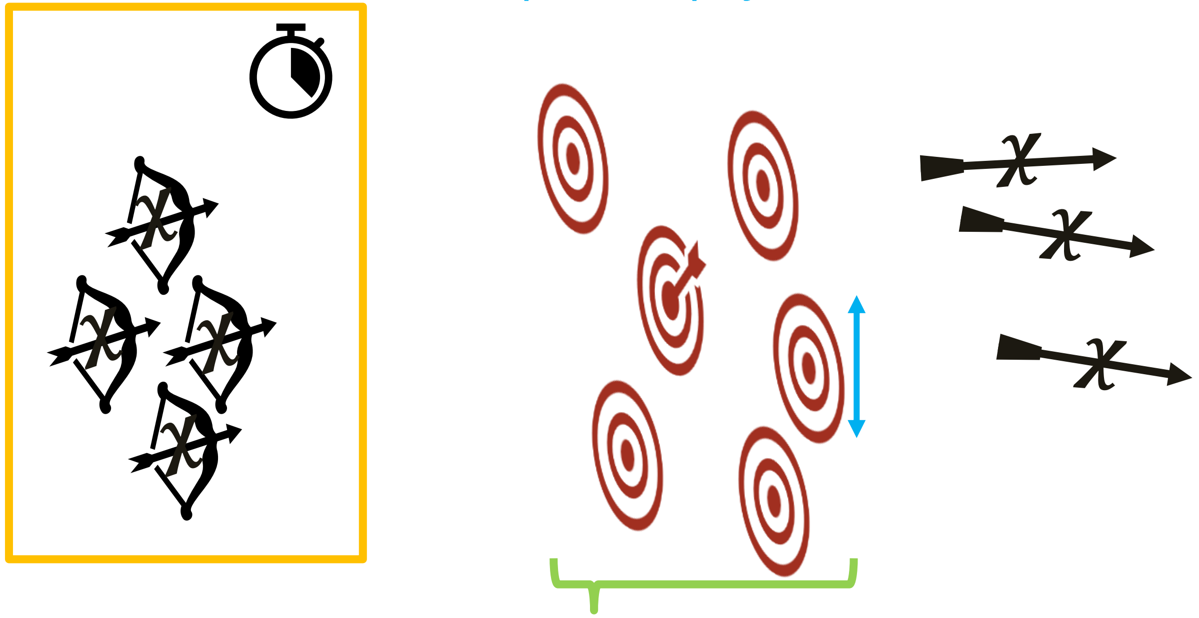


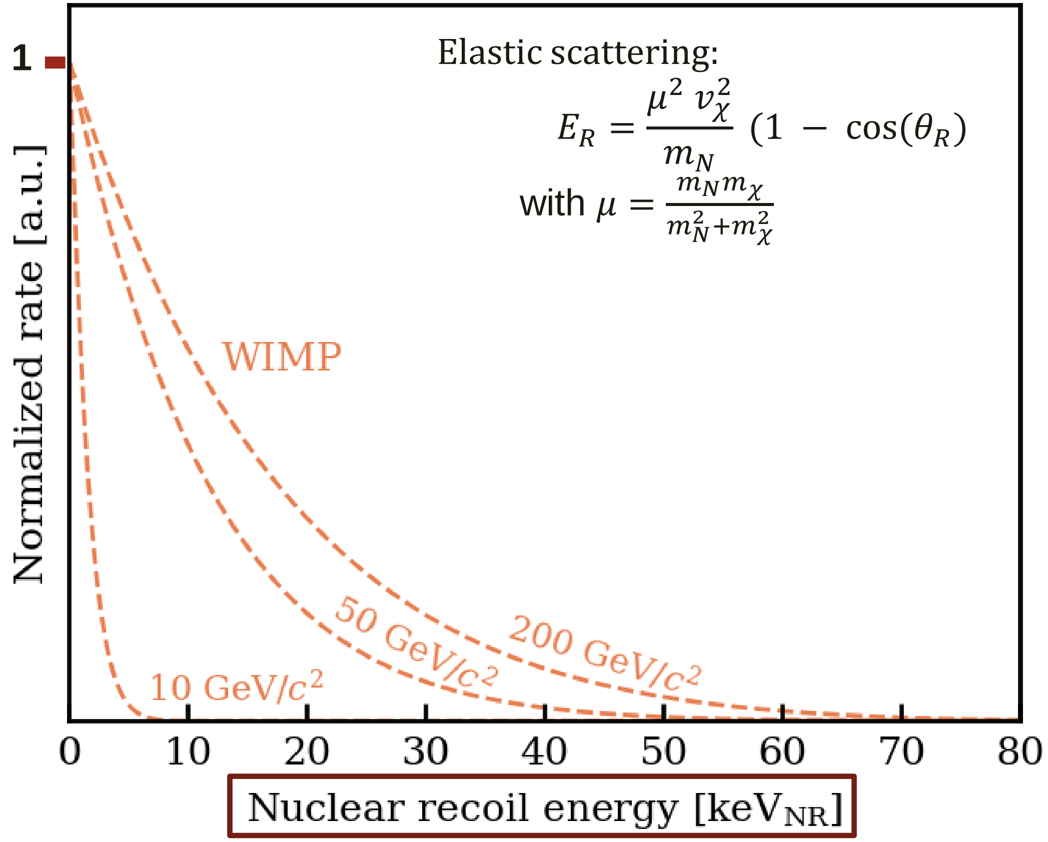
Jodi Cooley, **Dark Matter Direct Detection of Classical WIMPs**, 2021 Les Houches Summer School lecture manuscript

DM direct detection

Astrophysical inputs

Detector and particle physics





$$\frac{dR}{dE_R} = \frac{M_T \rho_0}{m_\chi m_N} \int_{v_{min}}^{v_{esc}} v\, f(\vec{v}) \frac{d\sigma_{\chi,N}}{dE_R} dv$$

DM direct detection

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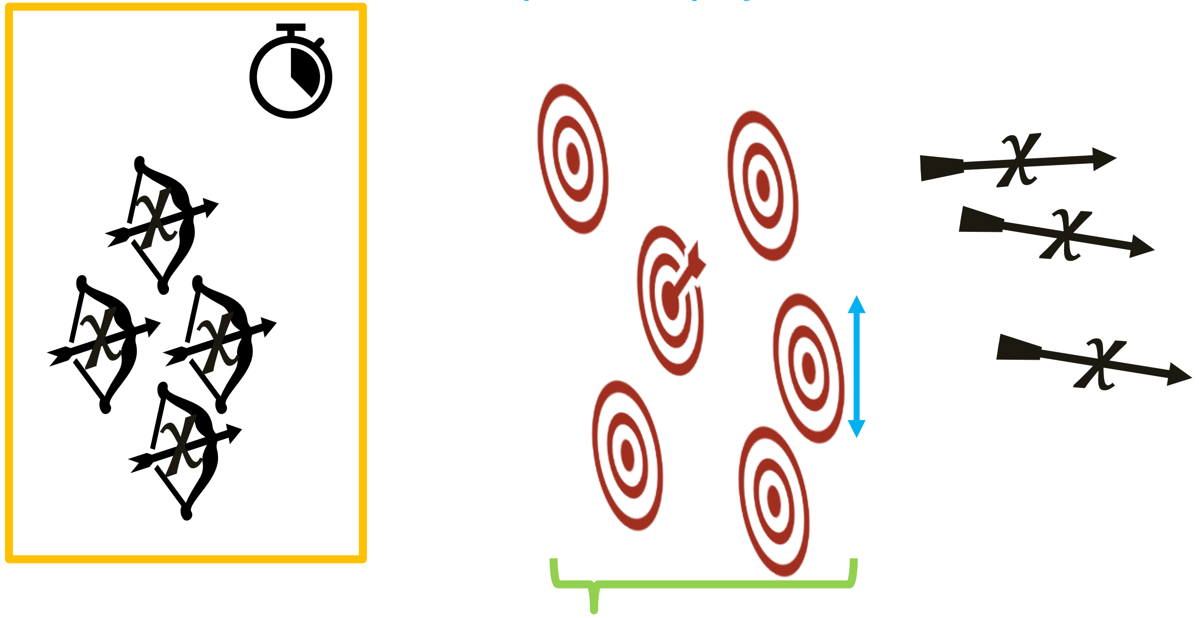
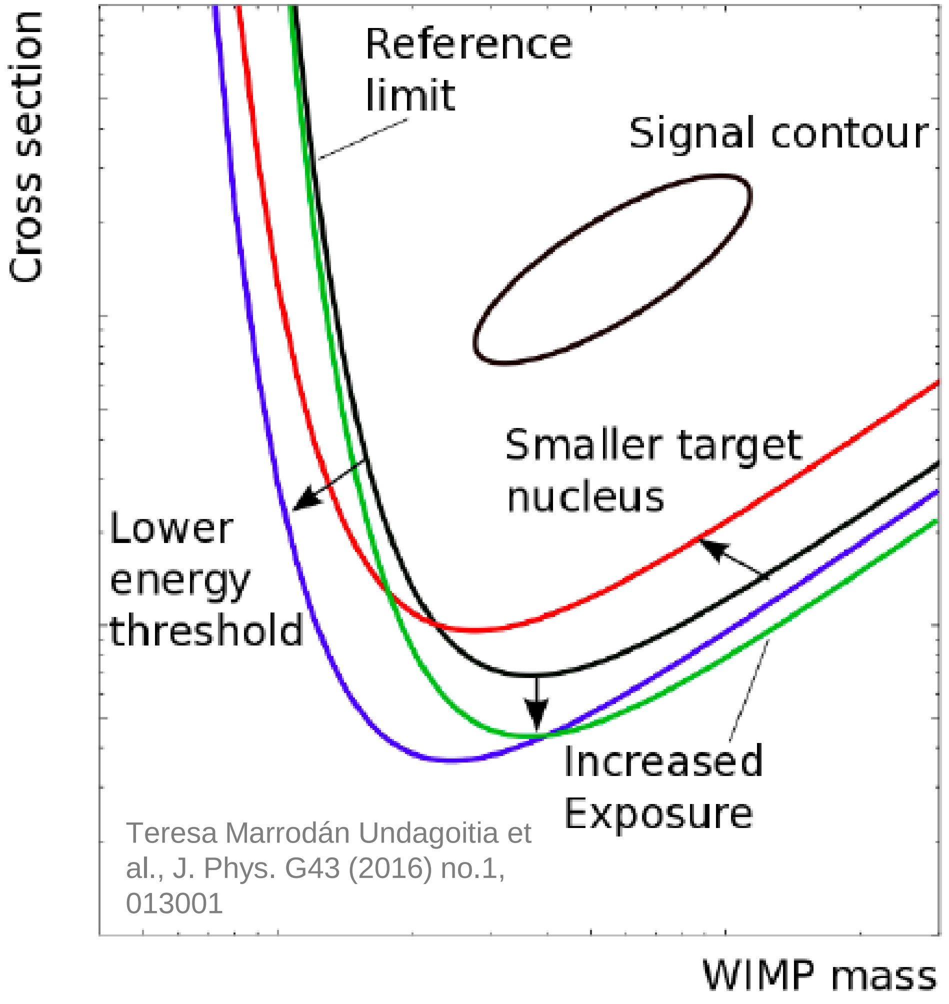


$$\frac{dR}{dE_R} = \frac{M_T \, \rho_0}{m_\chi m_N} \int_{v_{min}}^{v_{esc}} v \, f(\vec{v}) \frac{d\sigma_{\chi,N}}{dE_R} dv$$



$$\frac{d\sigma}{dE_R} = \left[\left(\frac{d\sigma}{dE_R} \right)_{SI} + \left(\frac{d\sigma}{dE_R} \right)_{SD} \right]$$

$\propto A^2$ $\propto j, S_n, S_p$

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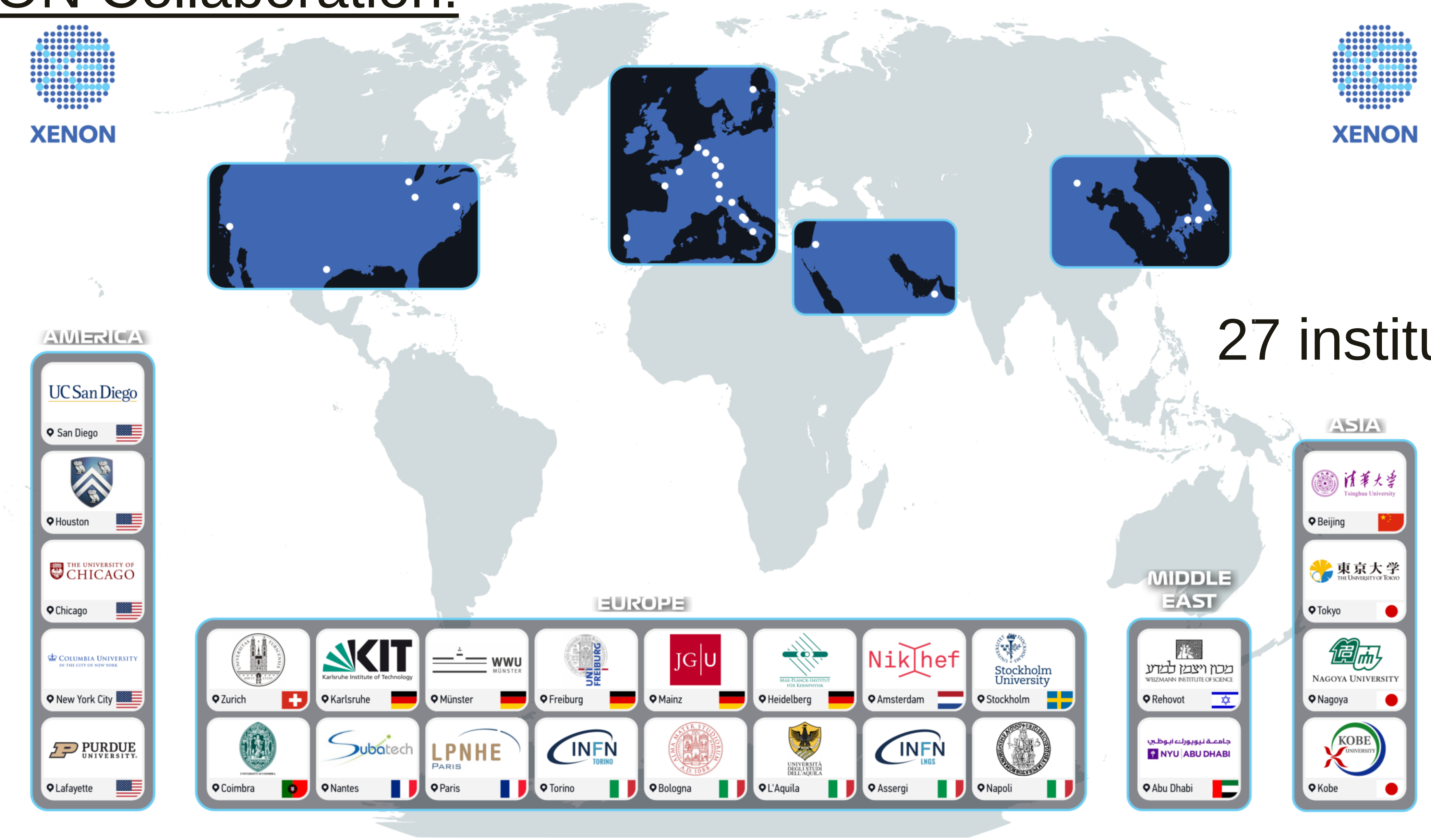
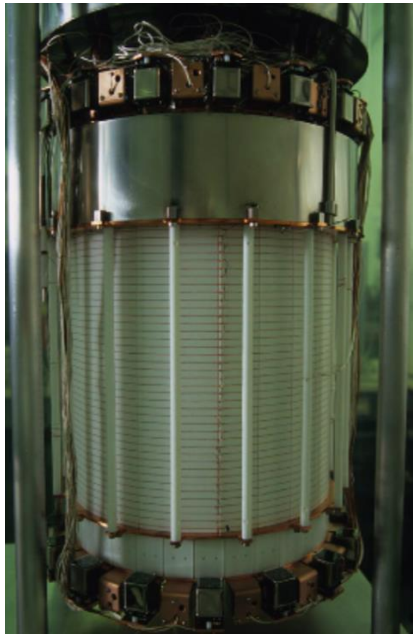
XENON Collaboration:

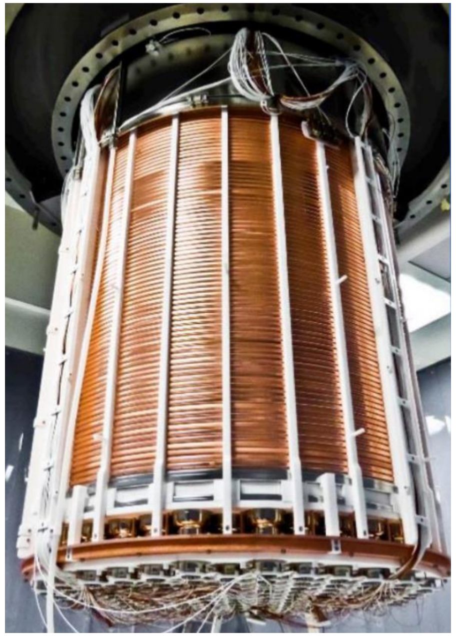


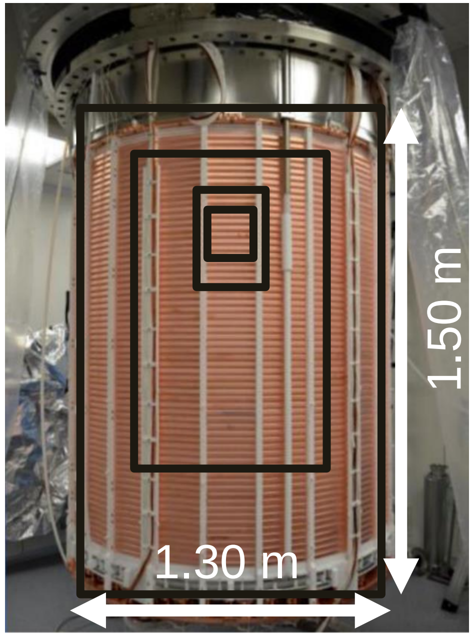
27 institutes

XENON Collaboration

The XENON evolution







XENON10	XENON100	XENON1T	XENONnT
2005-2007	2008-2016	2012-2019	2020-2026
14 kg Xe target	62 kg Xe target	2 t Xe target	5.9 t Xe target, 8.5 t total mass
~10^{-43} cm^2	~10^{-45} cm^2	$4{\cdot}10^{-47}$ cm^2	$1.4{\cdot}10^{-48}$ cm^2 (projected for 20 t·y exposure) (Flea)
~2M background ER / (keV· t·y)	1800 background ER / (keV· t·y)	82 background ER / (keV· t·y)	16.1 background ER / (keV· t·y)

XENON @ LNGS

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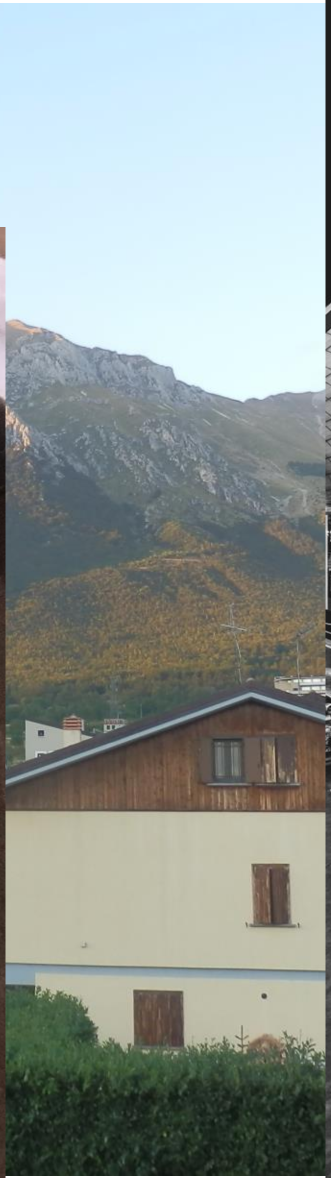
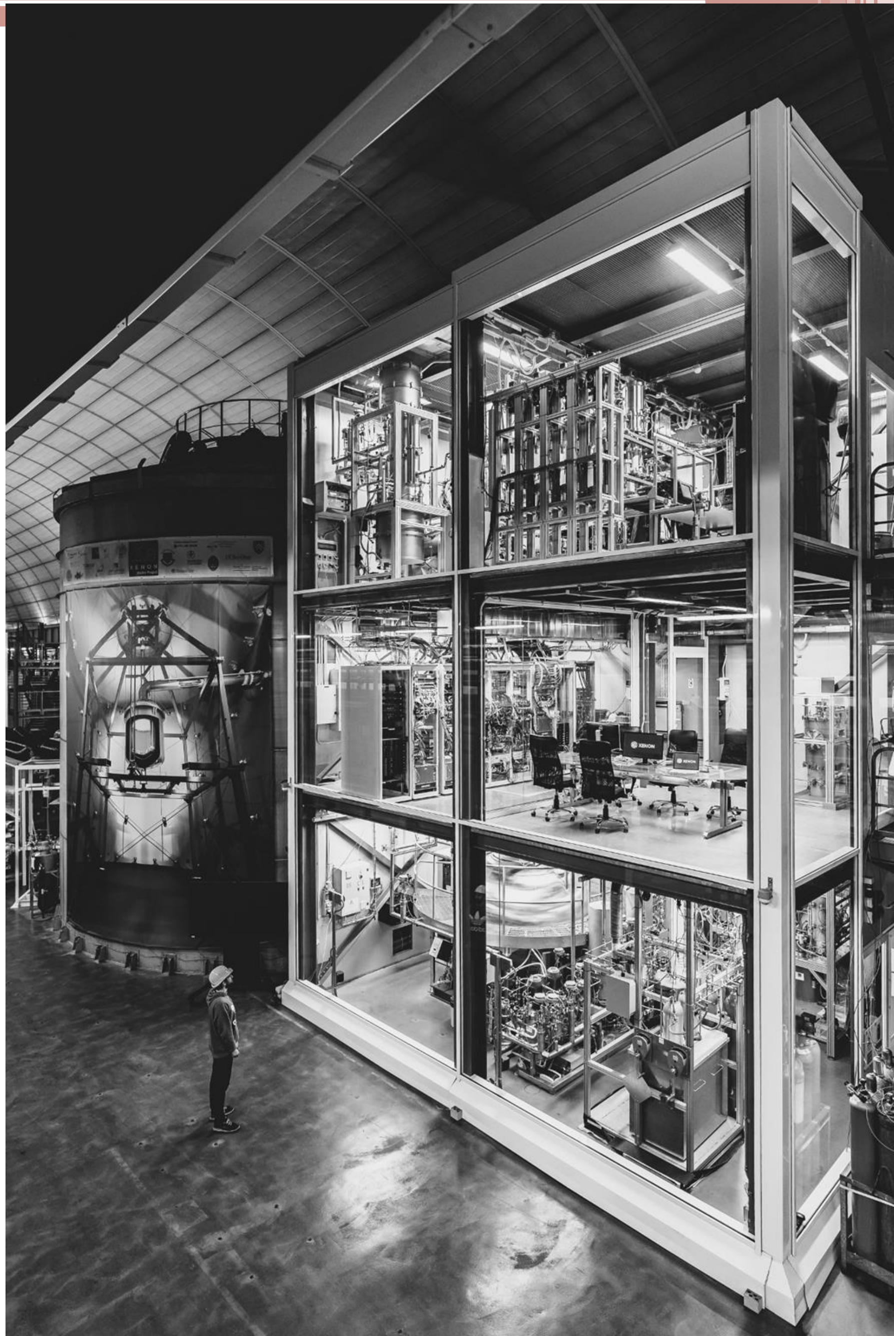


XENONnT experiment

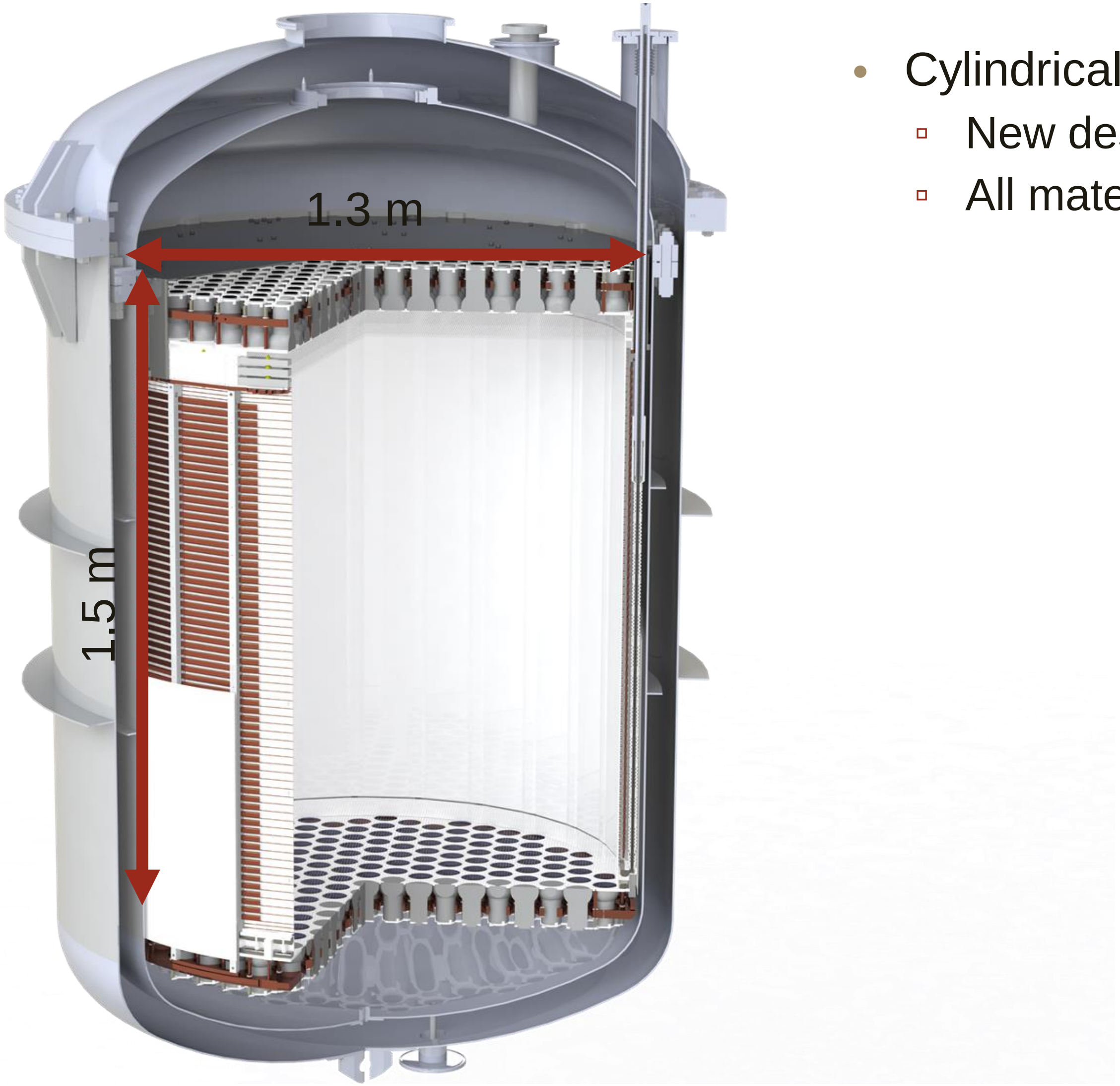
XENON1T → XENONnT upgrades:

- Larger TPC and inner cryostat
- Improved cleanliness and radiopurity
- New purification and distillation system
- Additional water Cherenkov neutron-veto
- New calibration systems and techniques
- New analysis software package STRAXEN and triggerless data acquisition
- Improved analysis methods

E. Aprile *et al.* **The Triggerless Data Acquisition System of the XENONnT Experiment** arXiv:2212.11032



Liquid noble gas time projection chamber



- Cylindrical PTFE walls for high reflectivity
  - New design compared to 1T, reduced relative amount of mass
  - All materials carefully screened and selected

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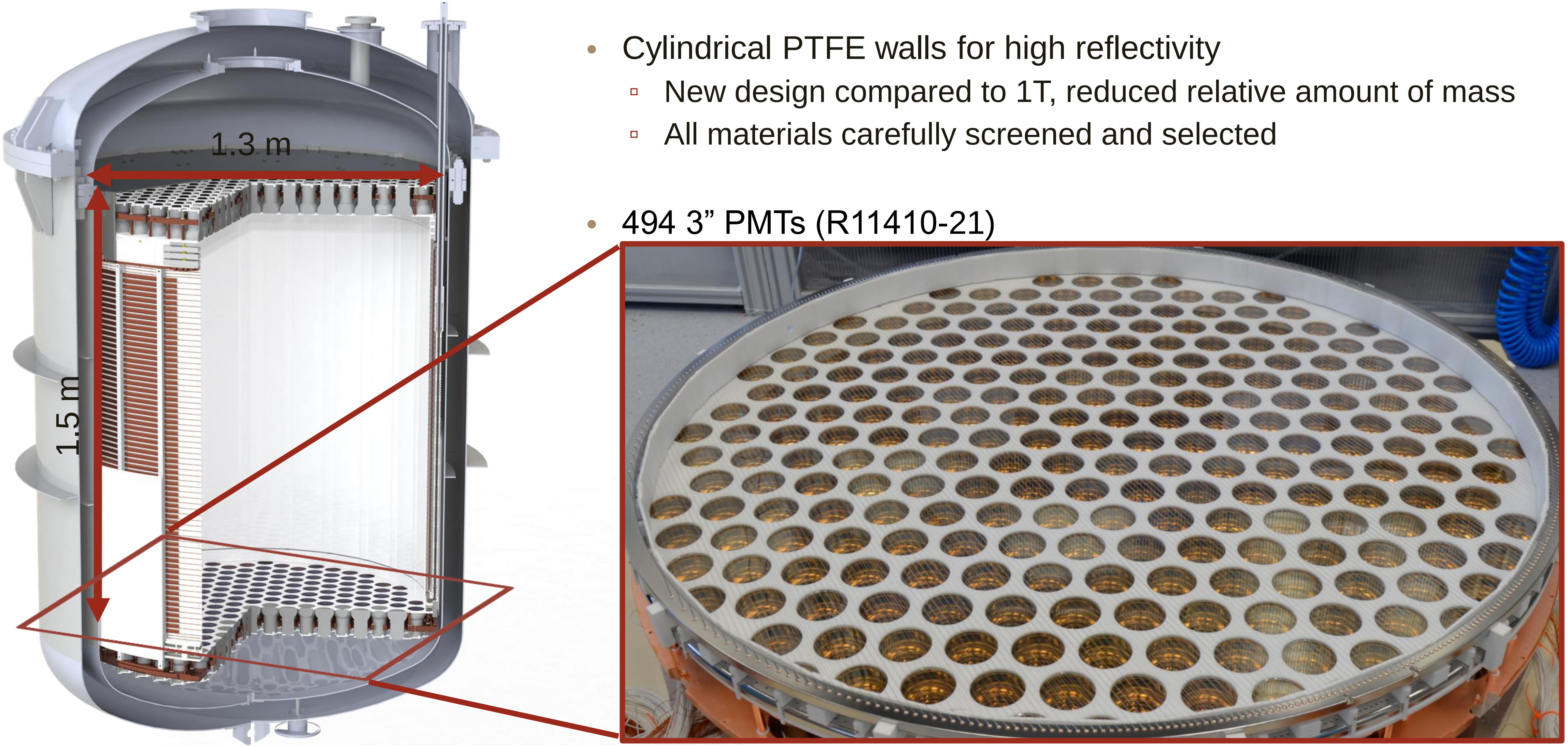
- 494 3" PMTs (R11410-21)



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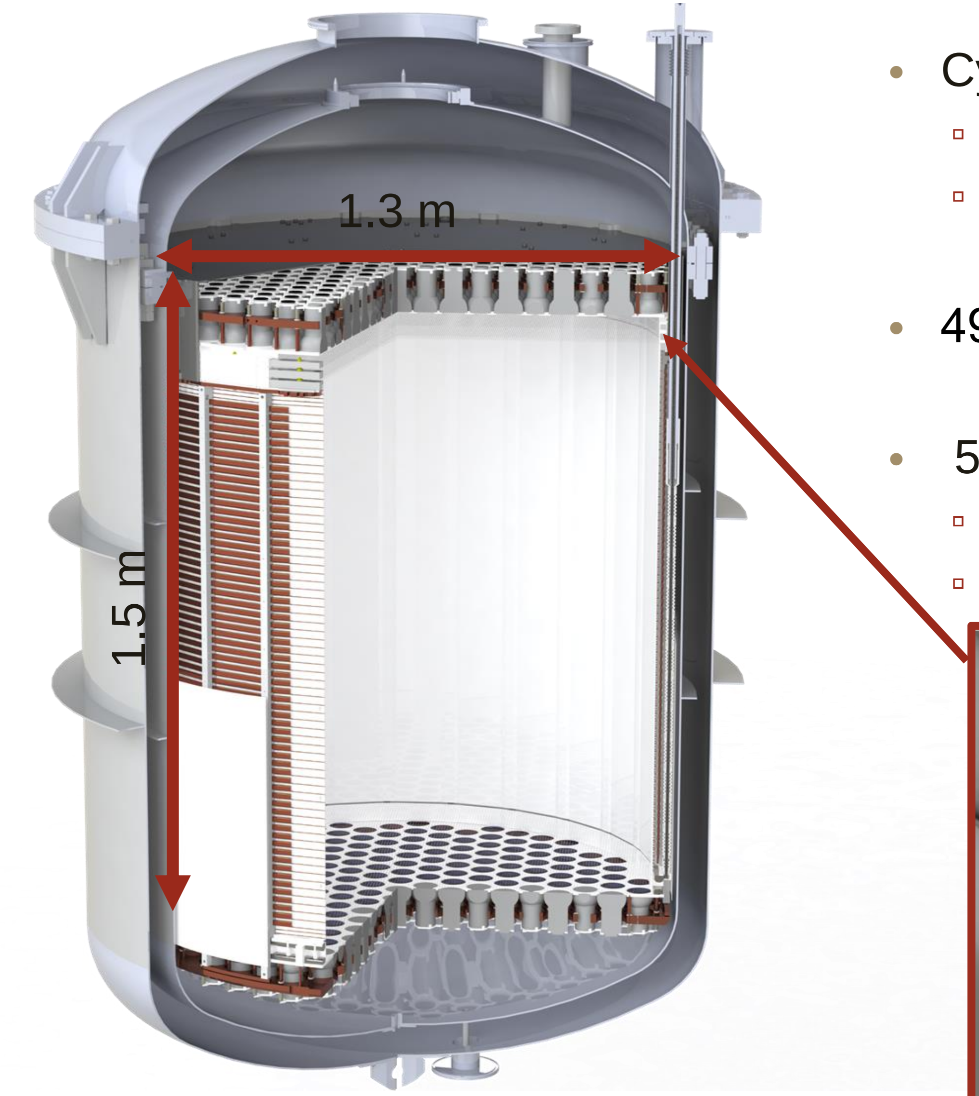
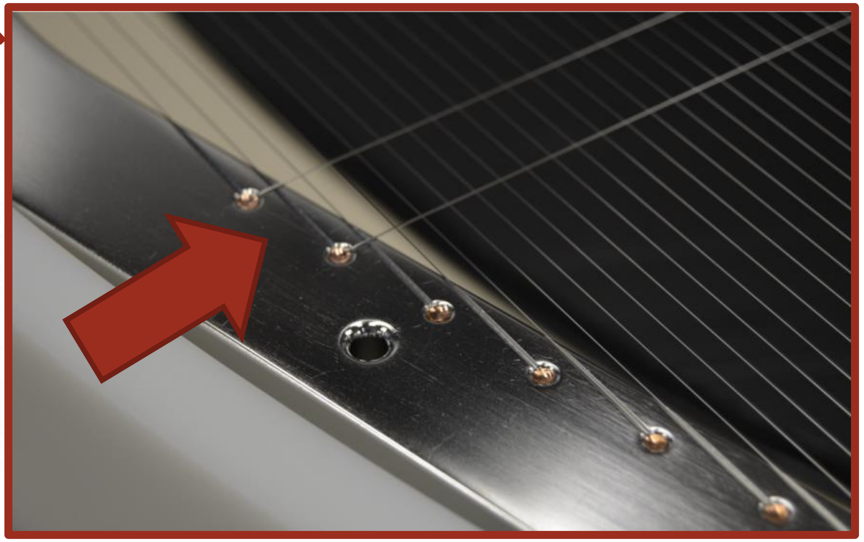


- Cylindrical PTFE walls for high reflectivity
  - New design compared to 1T, reduced relative amount of mass
  - All materials carefully screened and selected
- 494 3" PMTs (R11410-21)
- 5 meshes and a field cage to define electric fields and protect PMTs
  - cathode, gate and anode + 2 screening meshes
  - gate and anode reinforced by additional perpendicular wires



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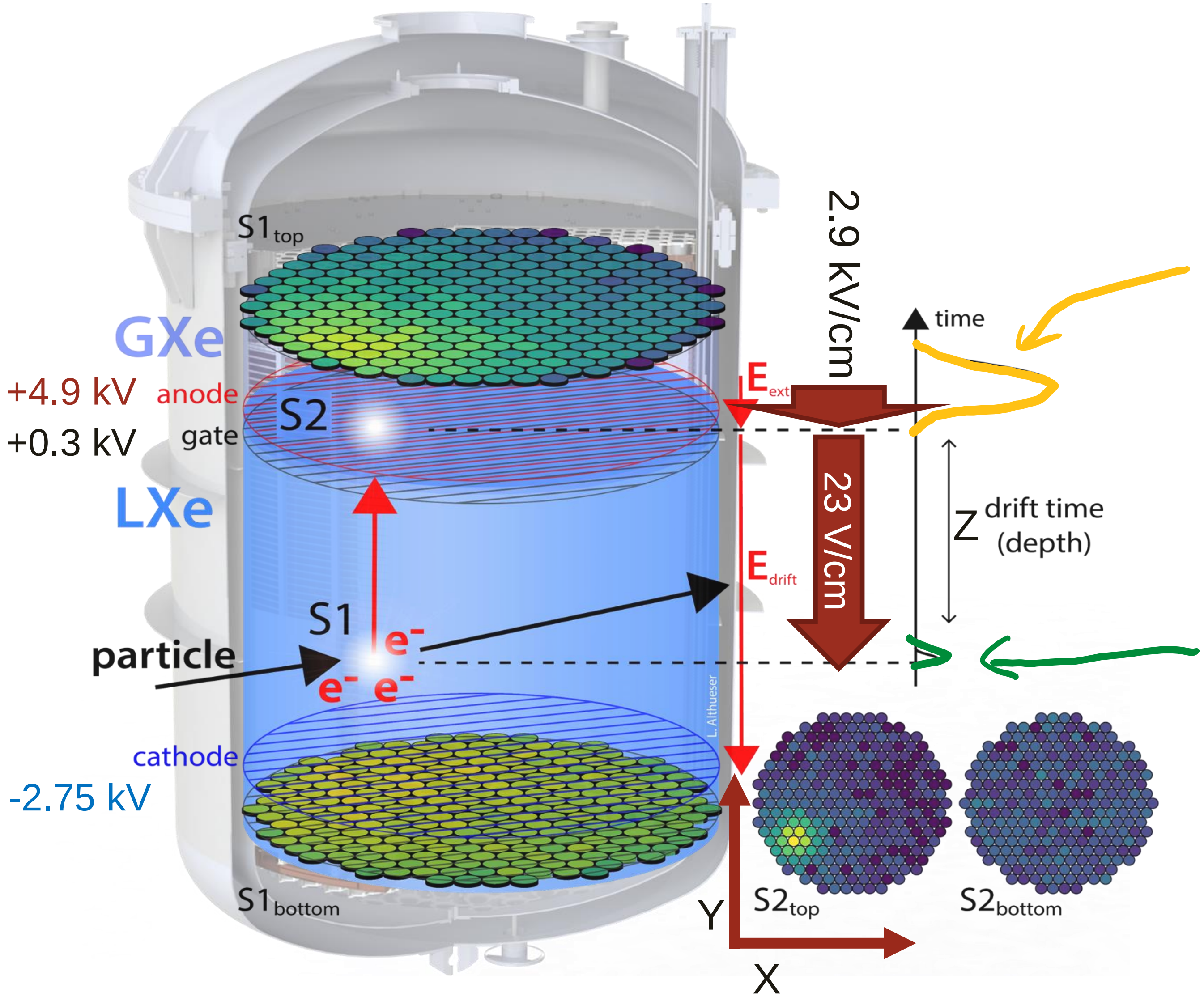

Secondary scintillation signal (S2)

- Electrons from ionized Xe^+ drift upwards between anode and gate
- Extraction from LXe into GXe by stronger field
- Electroluminescence yields S2 prop. to $\#e^-$
- Signals 100 pe – 100000 pe

Primary scintillation signal (S1)

- Excited Xe atoms form excimers Xe_2^*
- Excimers emit VUV-photons (178 nm)
- Signals 3 pe – 1000 pe

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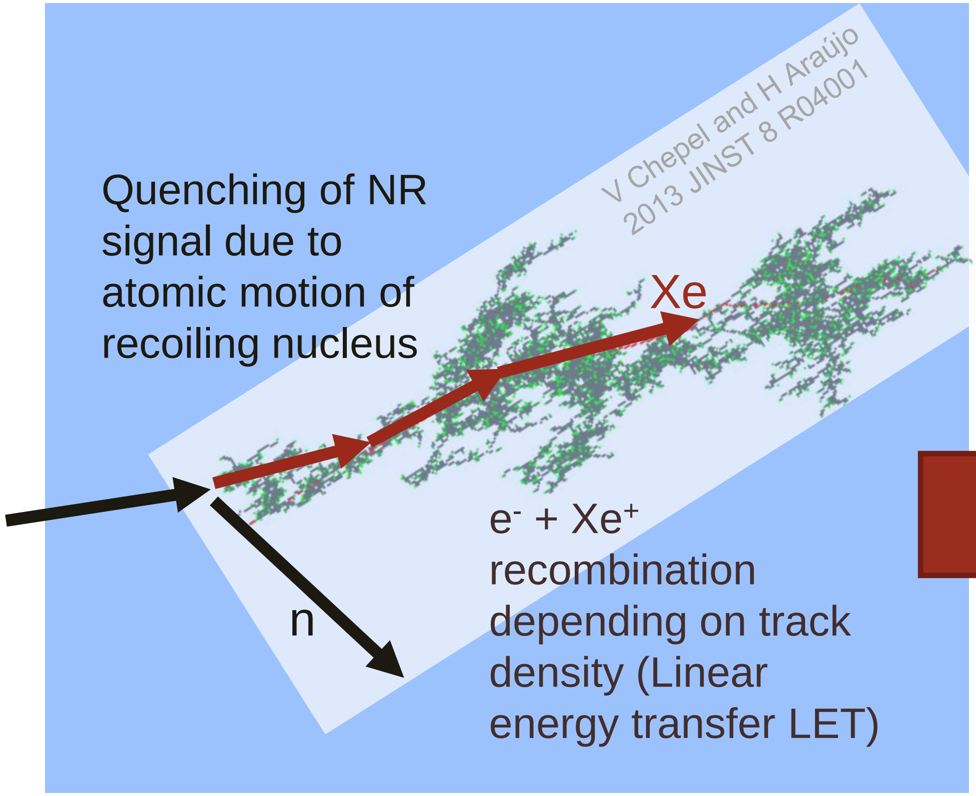

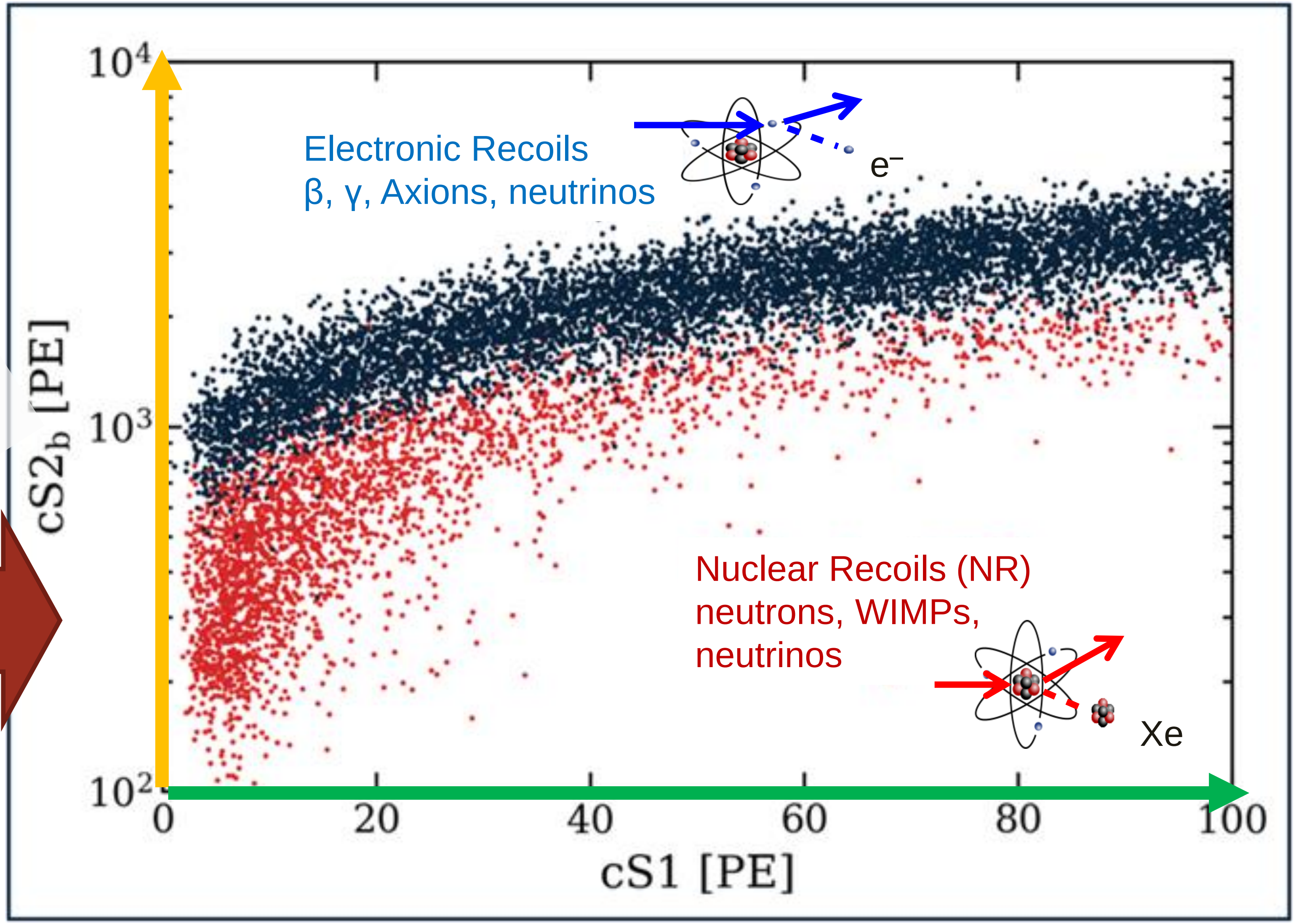

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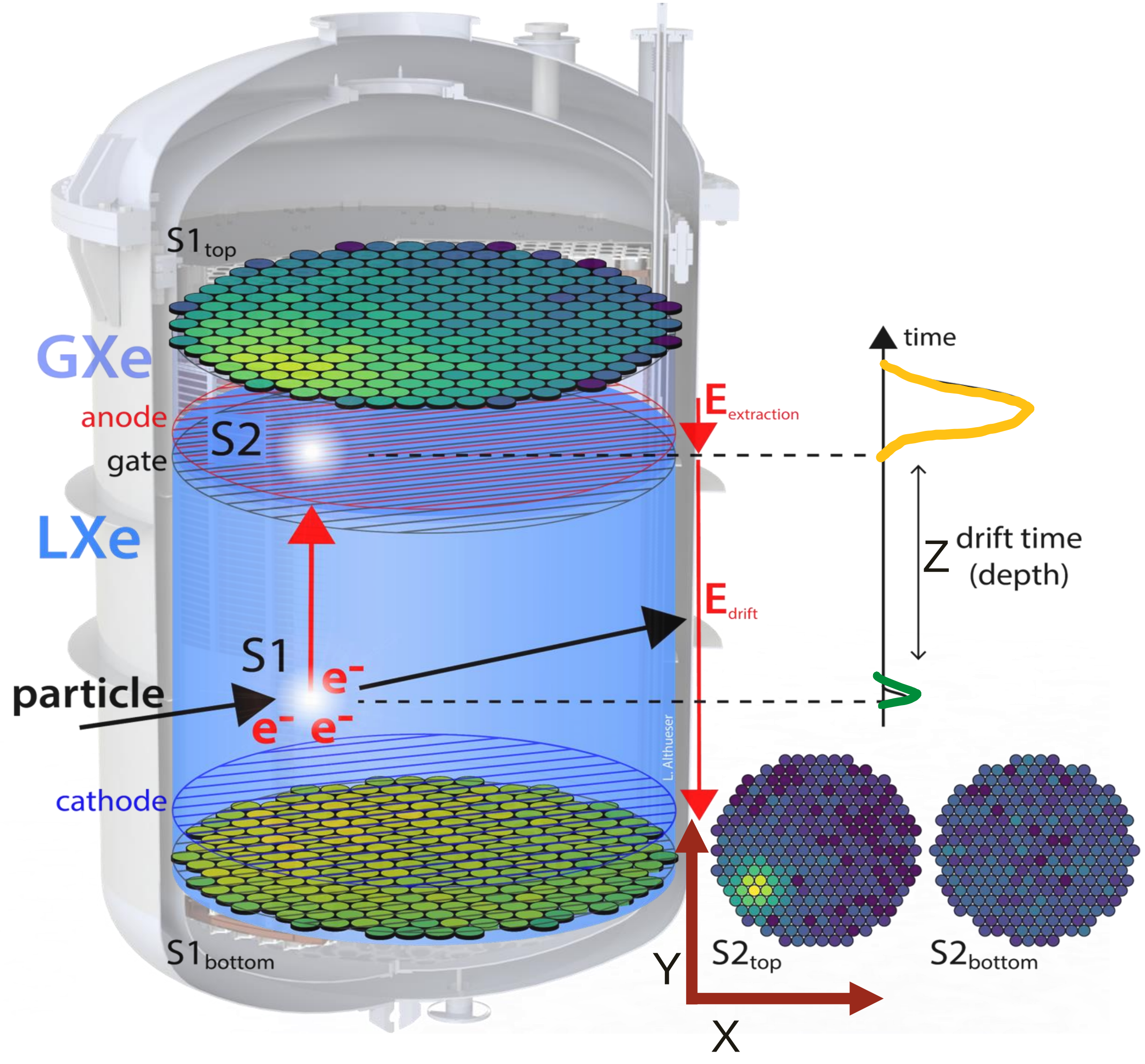

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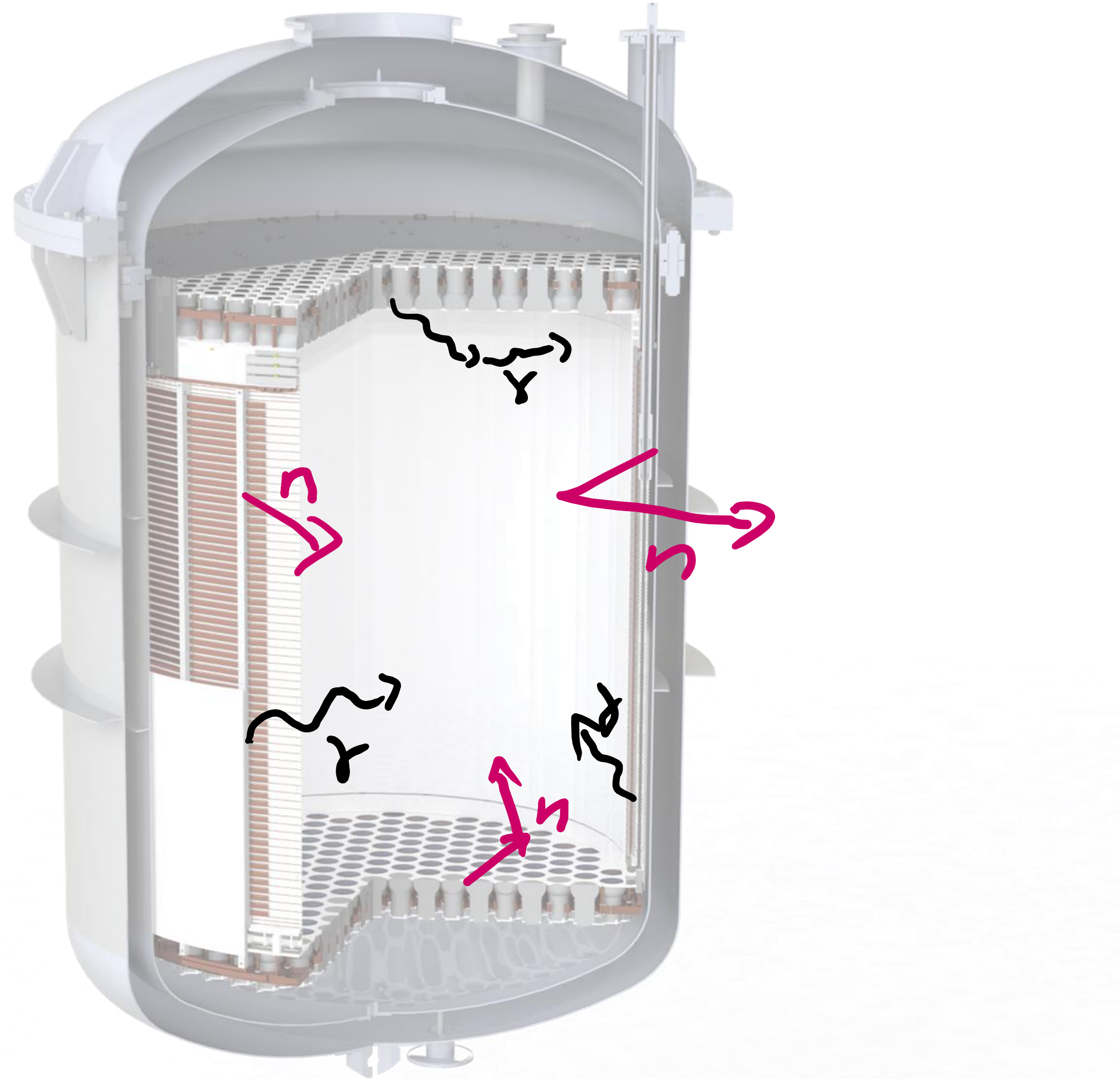

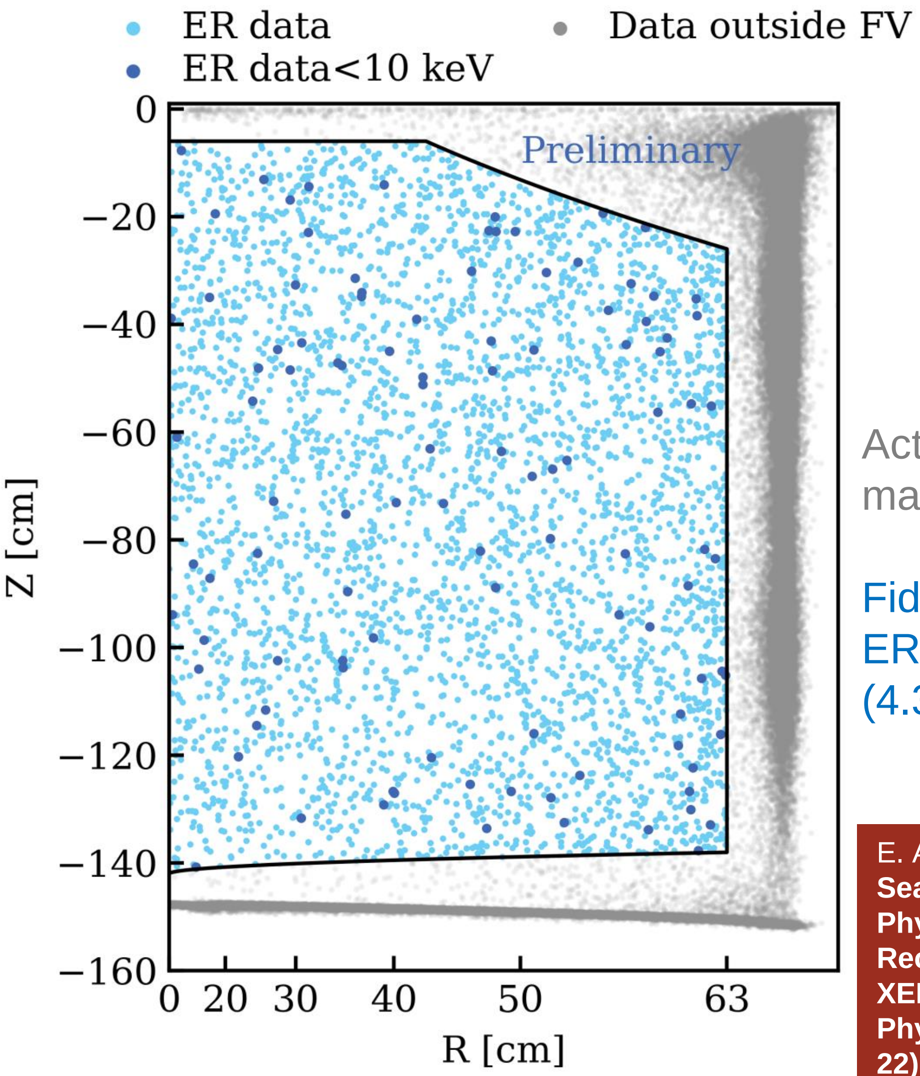

Active LXe mass: 5.9 t

Fiducial mass ER analysis: (4.37 ± 0.14) t

E. Aprile *et al*
Search for New Physics in Electronic Recoil Data from XENONnT Phys.Rev.Lett. 129 (2022) 16, 161805

Liquid xenon purification

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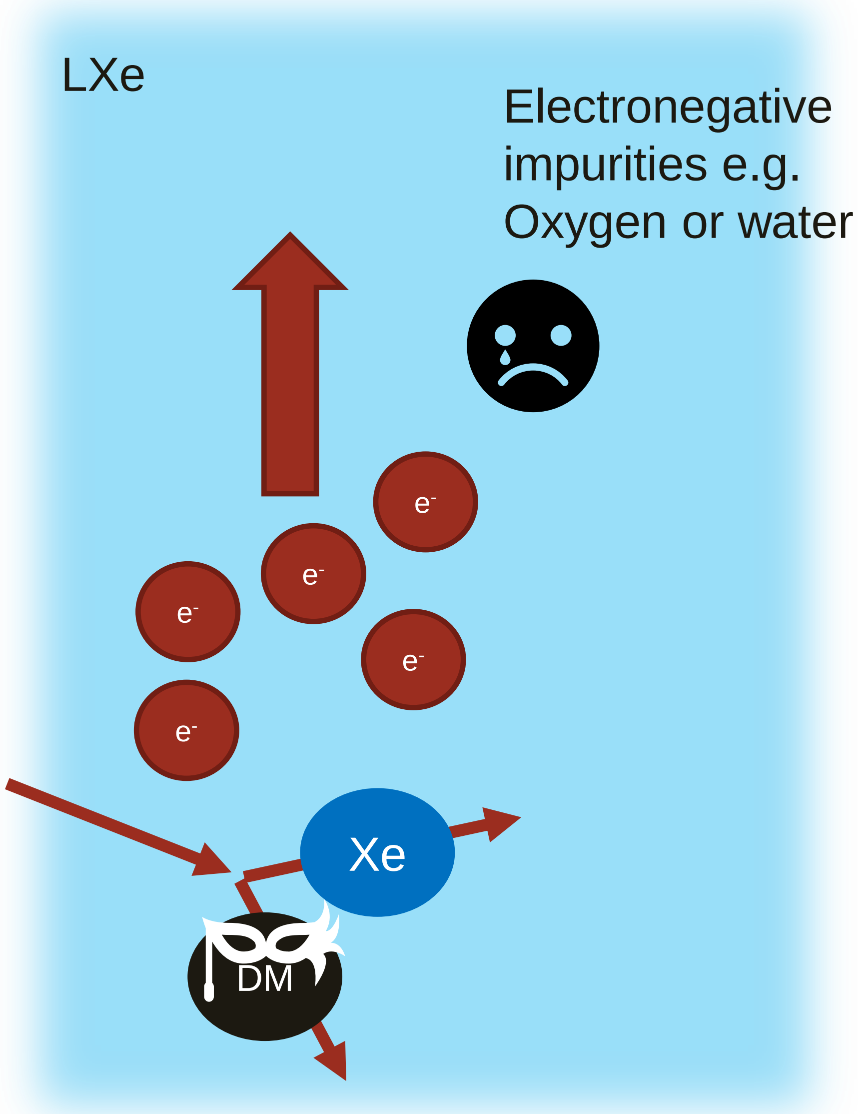
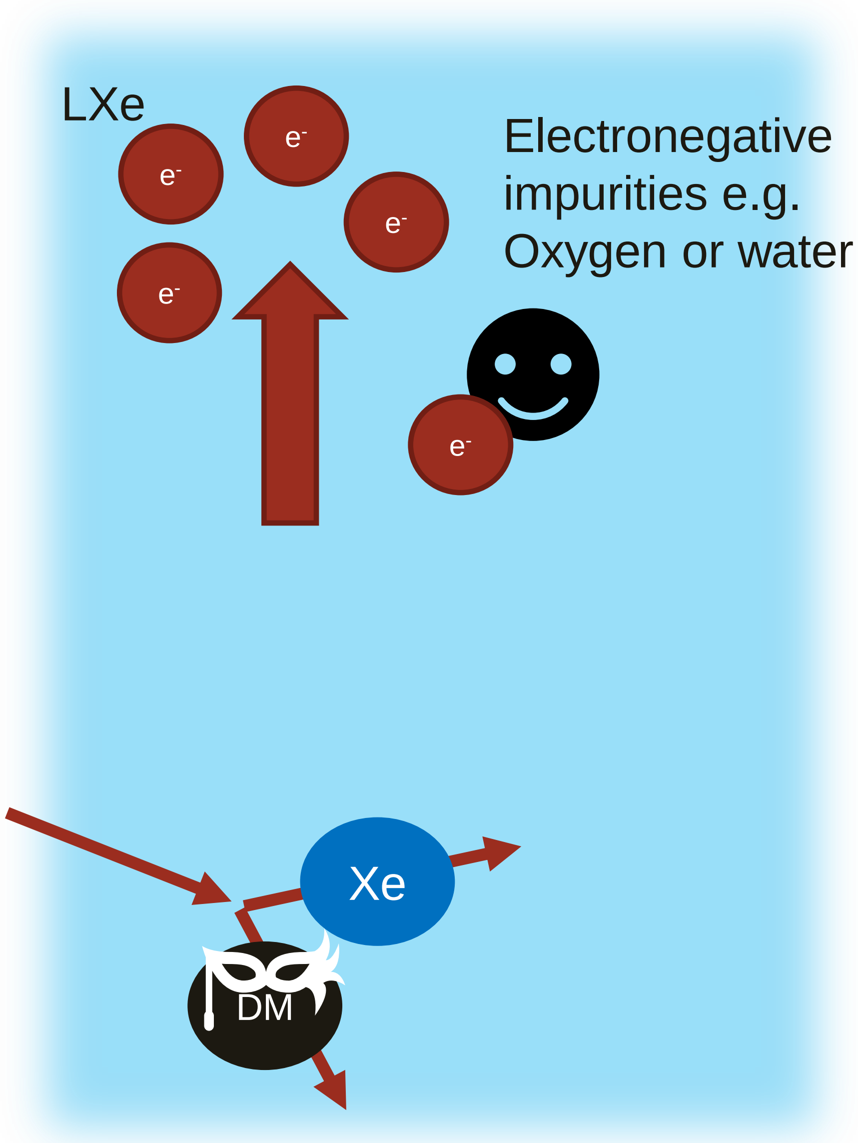


Liquid xenon purification



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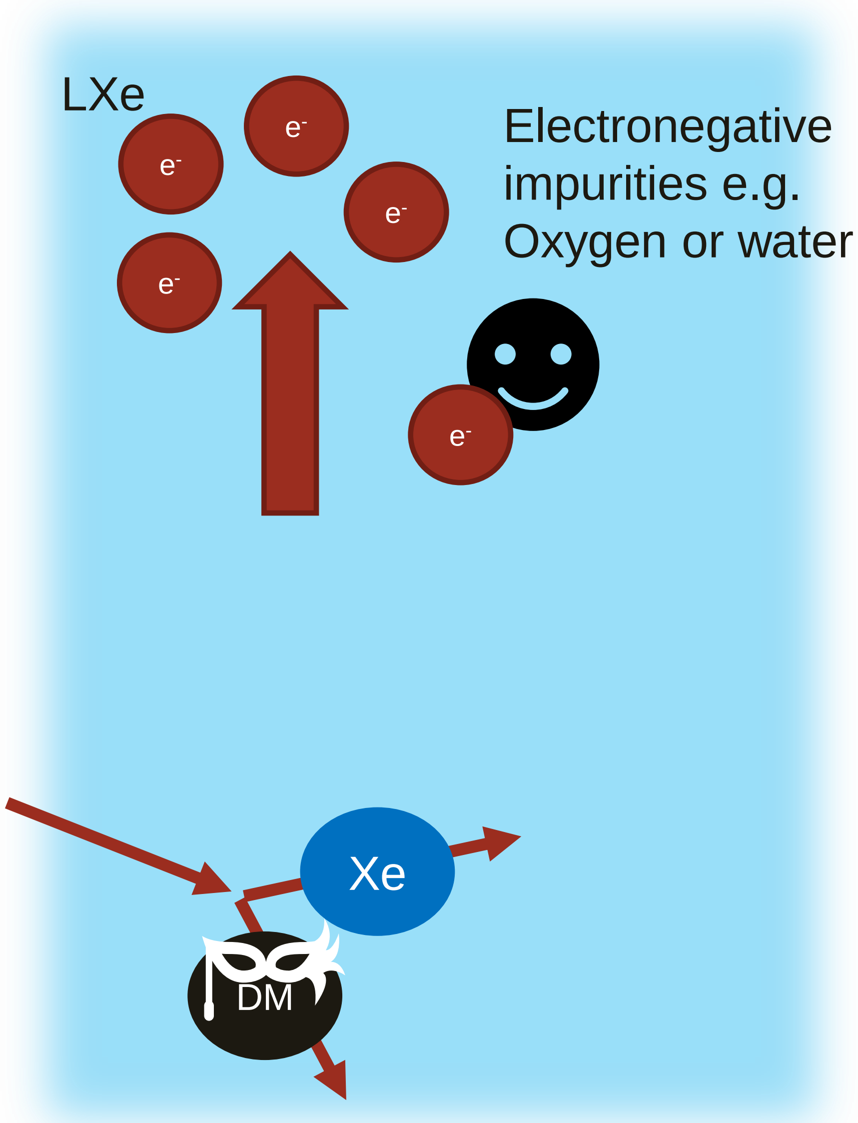
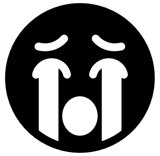
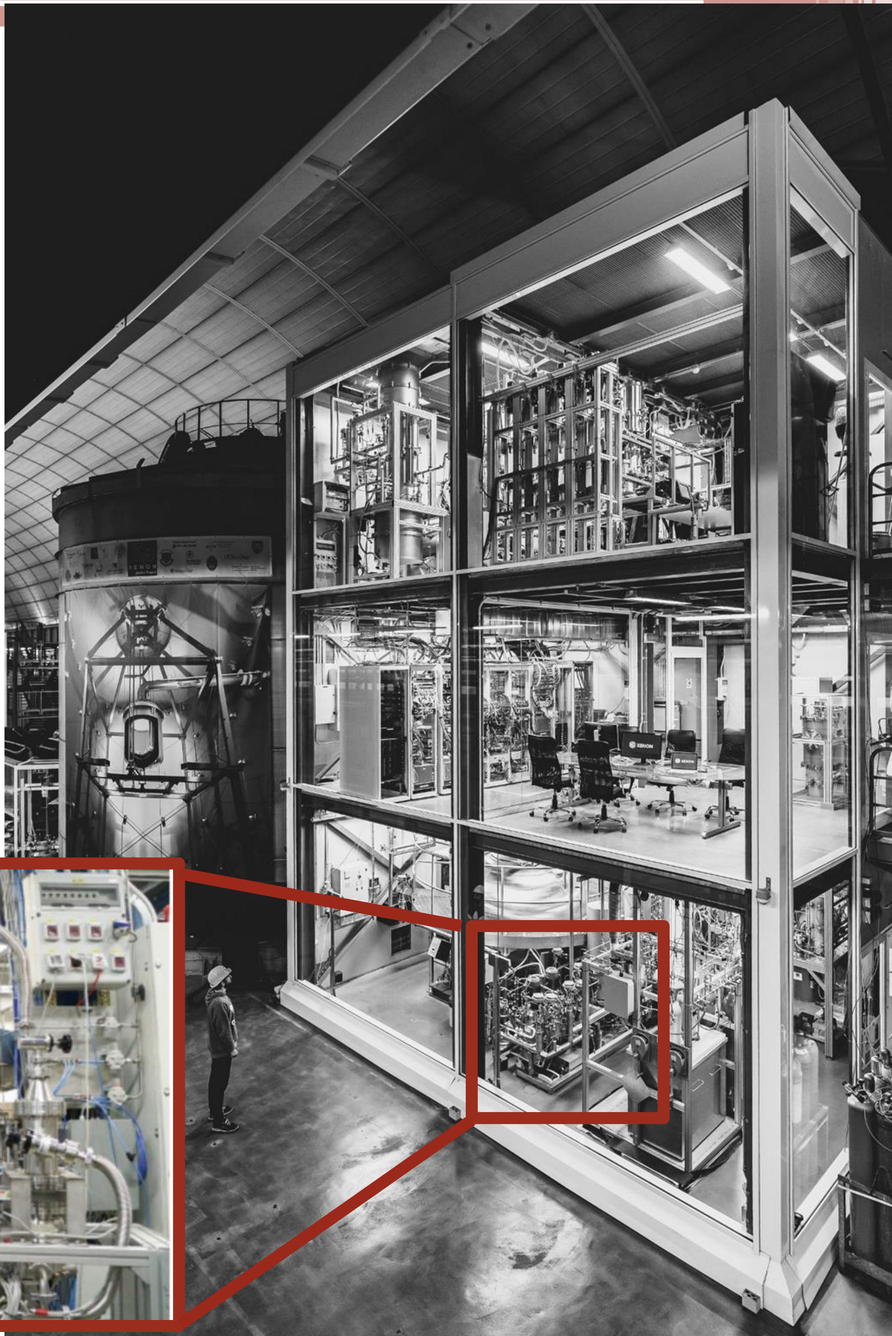


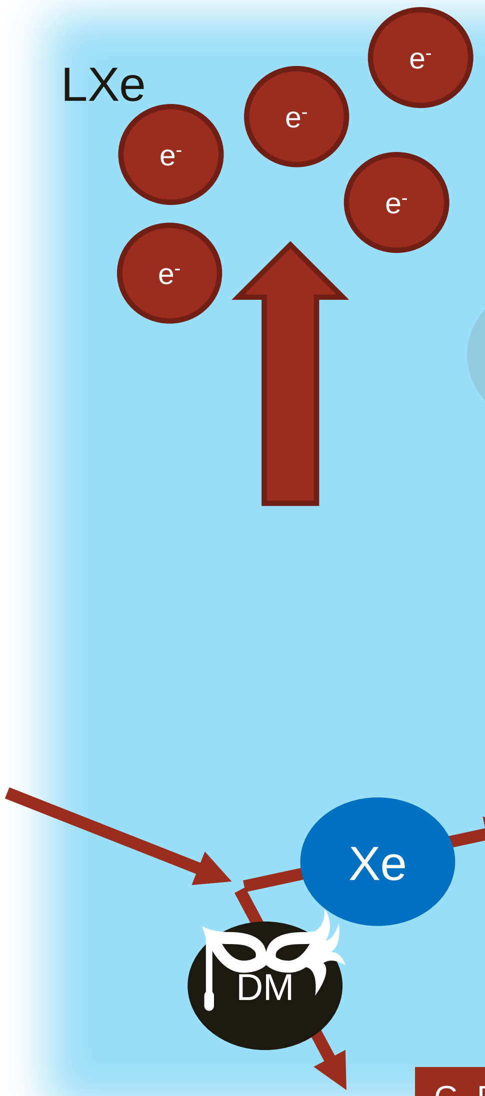


Analyst

New liquid purification system:

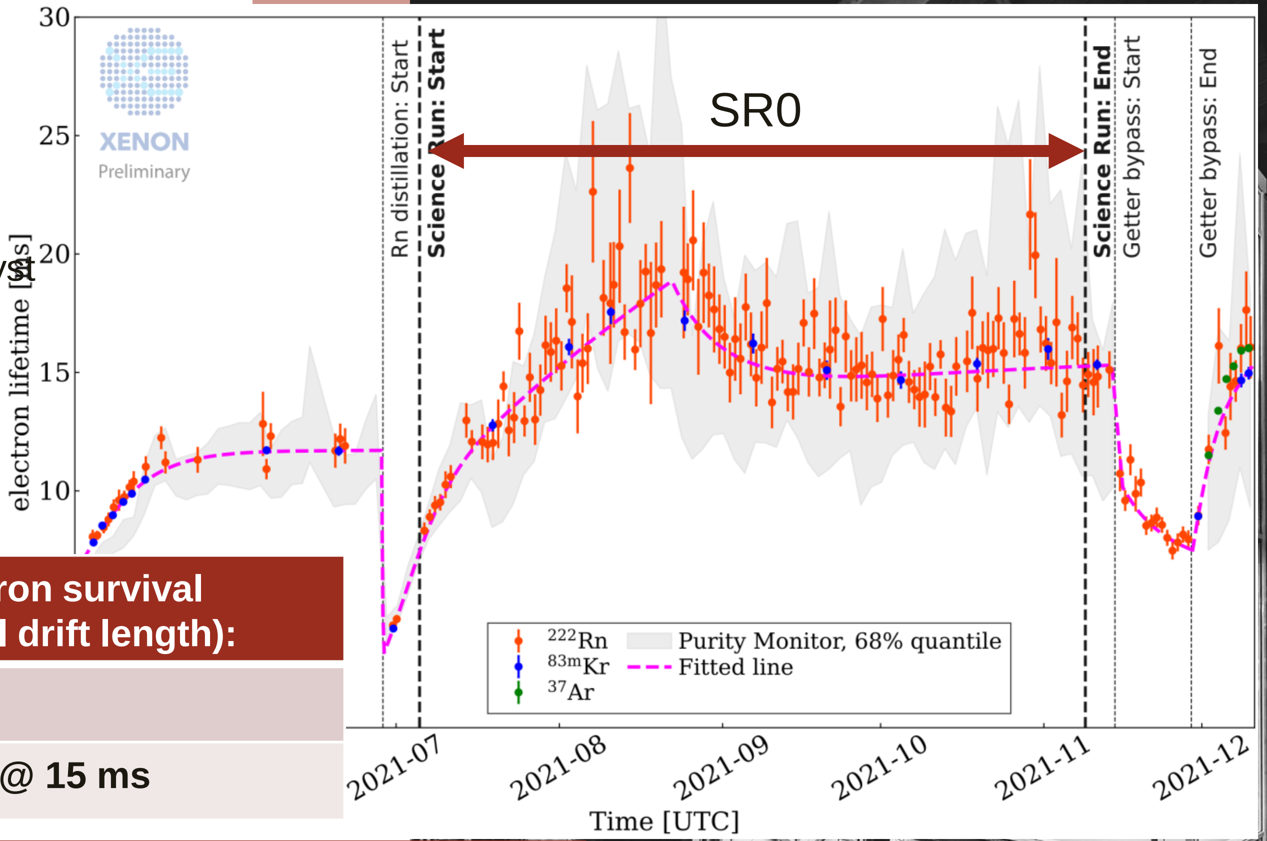


Liquid xenon purification



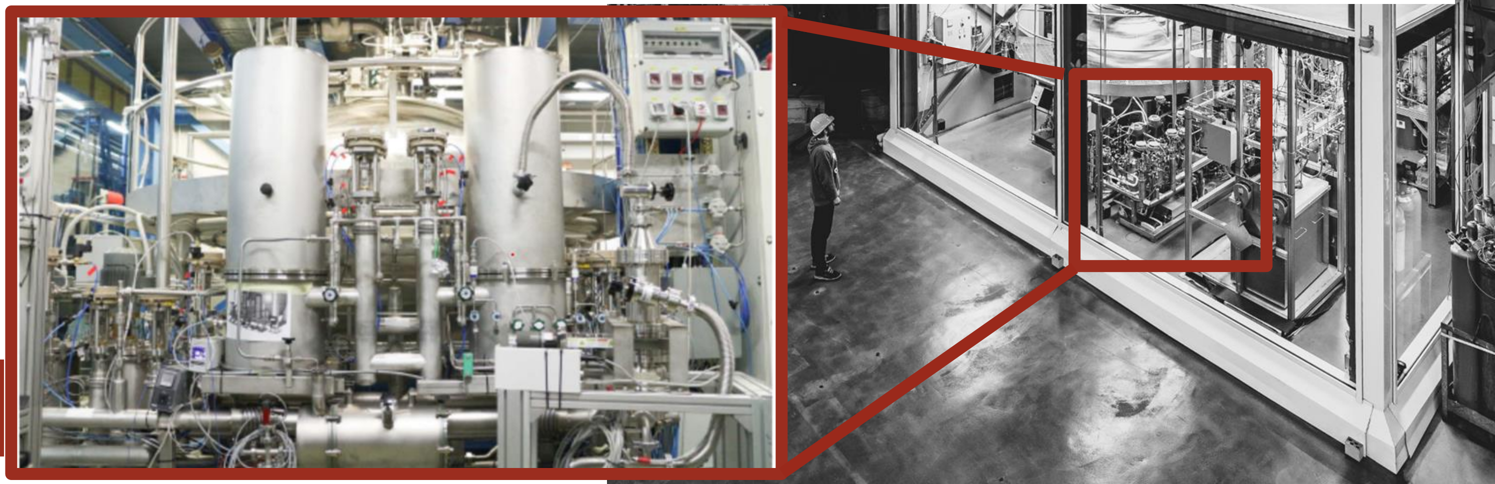
Electronegative impurities e.g. Oxygen or water

Analyst

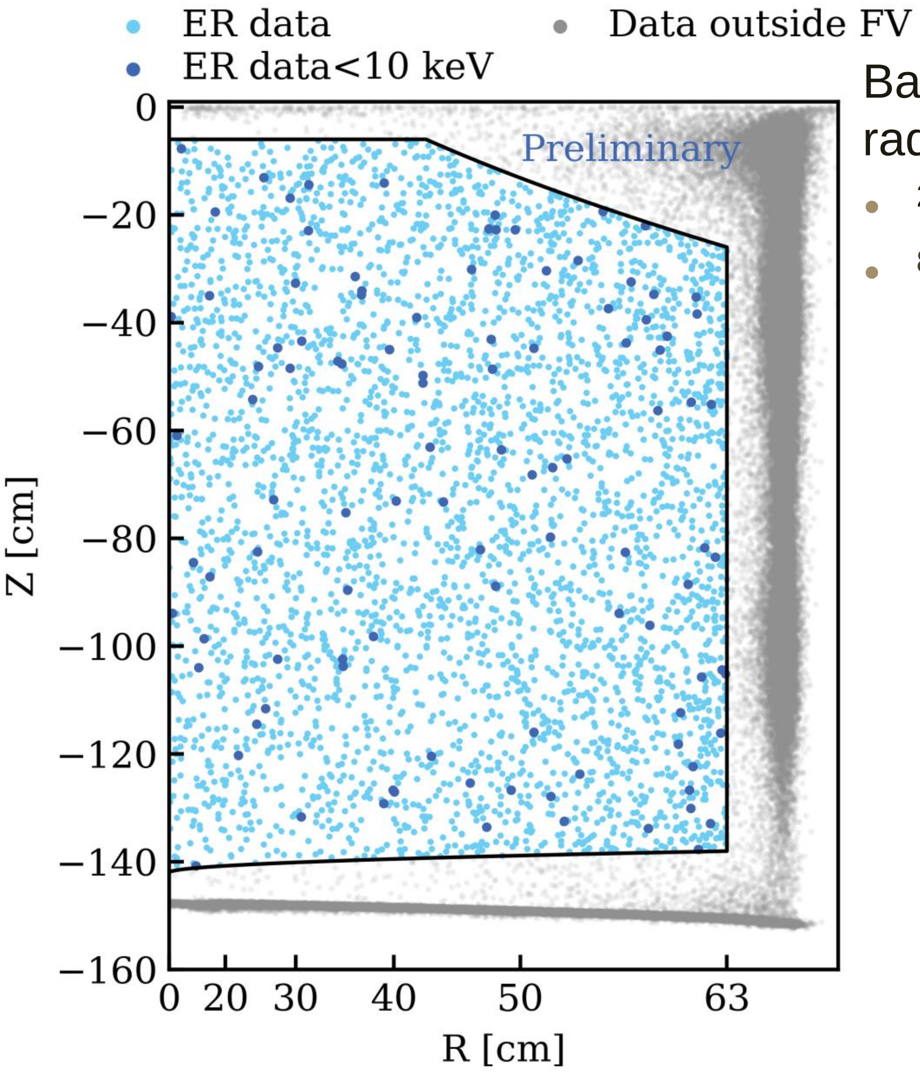


	Full drift time:	Electron lifetime:	Electron survival (@full drift length):
1T	0.67 ms	0.65 ms	30 %
nT	2.2 ms	**~15 ms**	**86 % @ 15 ms**

G. Plante, E. Aprile, J. Howlett, Y. Zhang
Eur. Phys. J. C 82, 860 (2022)



Cryogenic distillation



Background from intrinsic radioactive isotopes:

- ^{214}Pb (^{222}Rn daughter)
- ^{85}Kr

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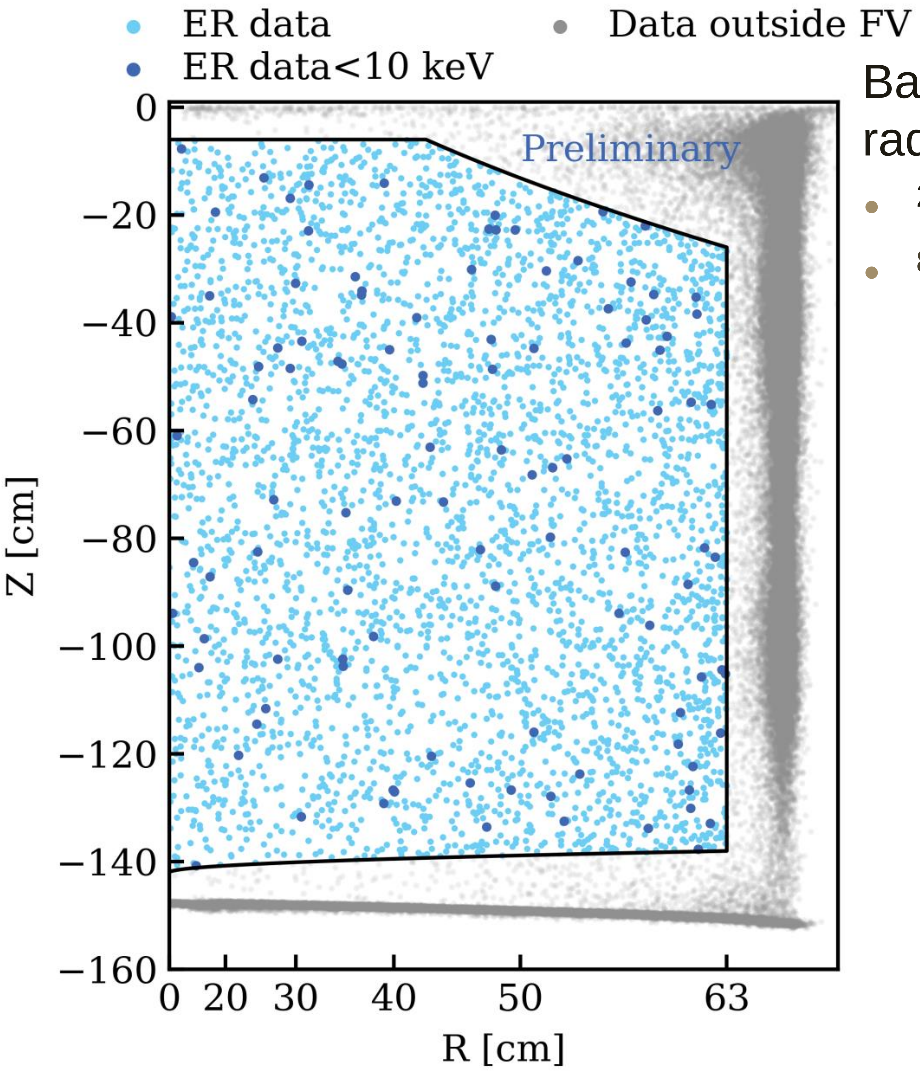

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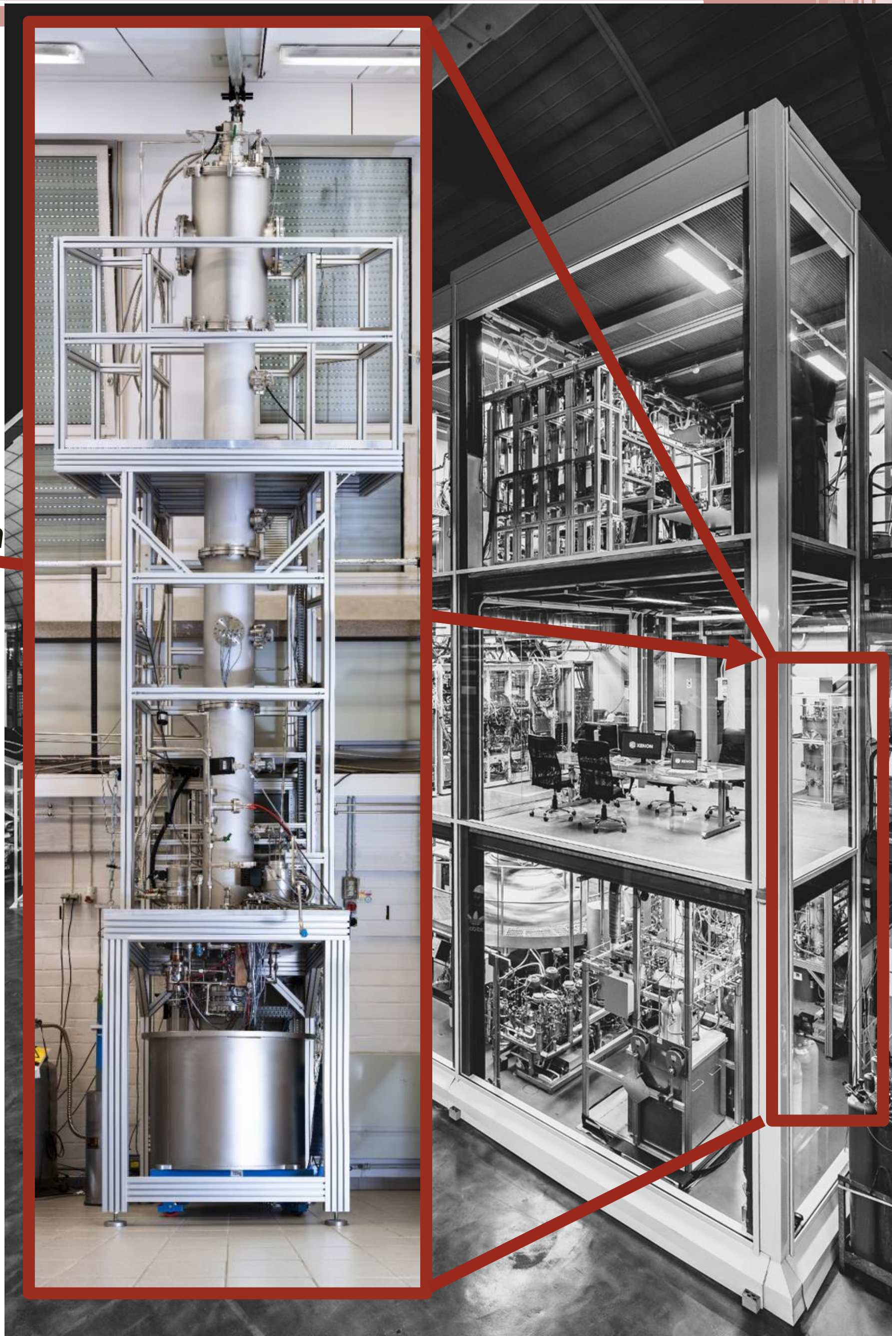
Remove by cryogenic distillation



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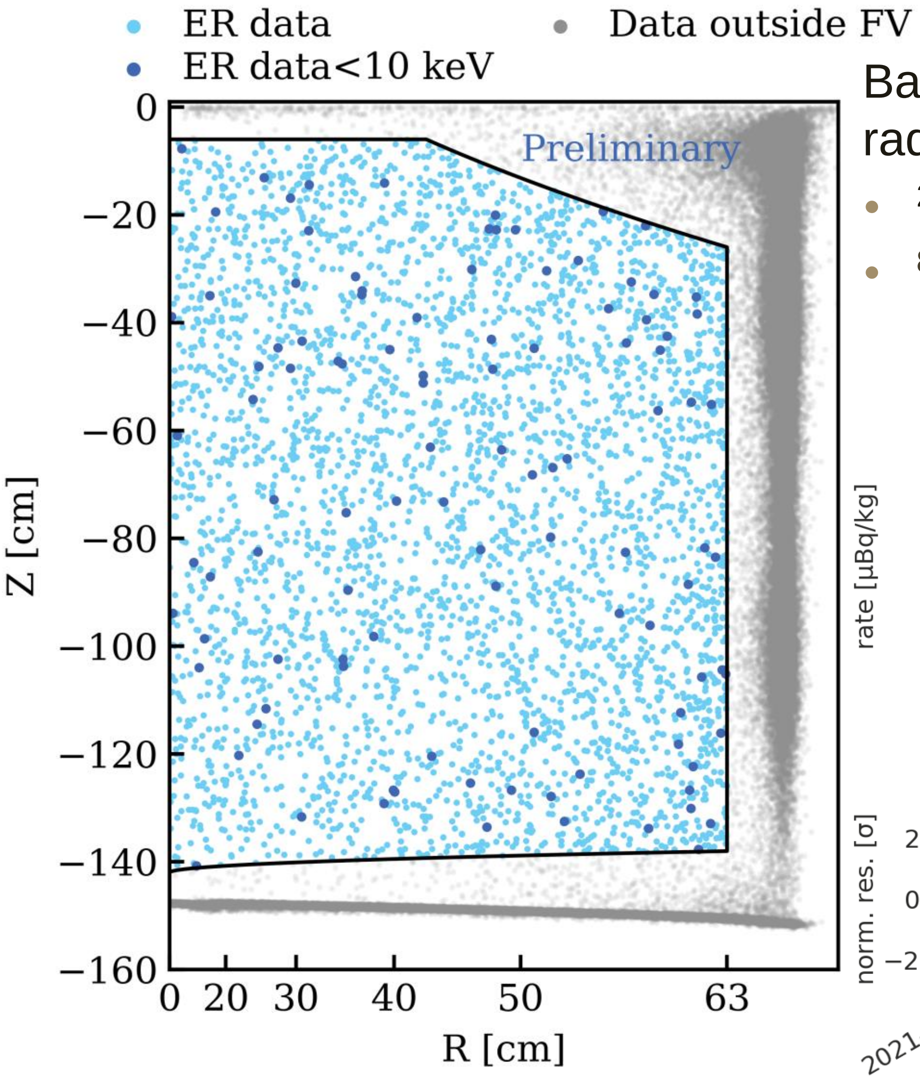

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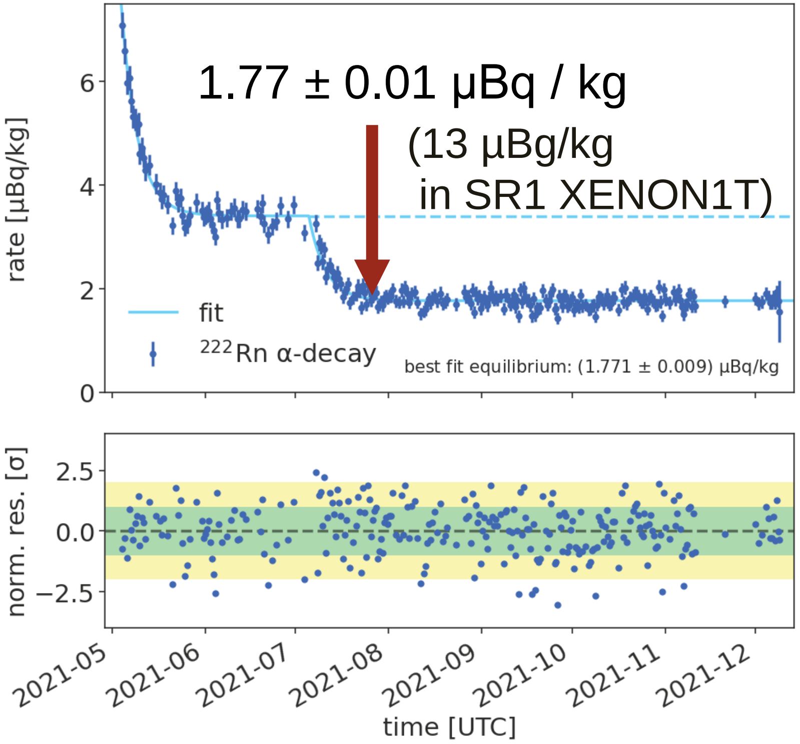
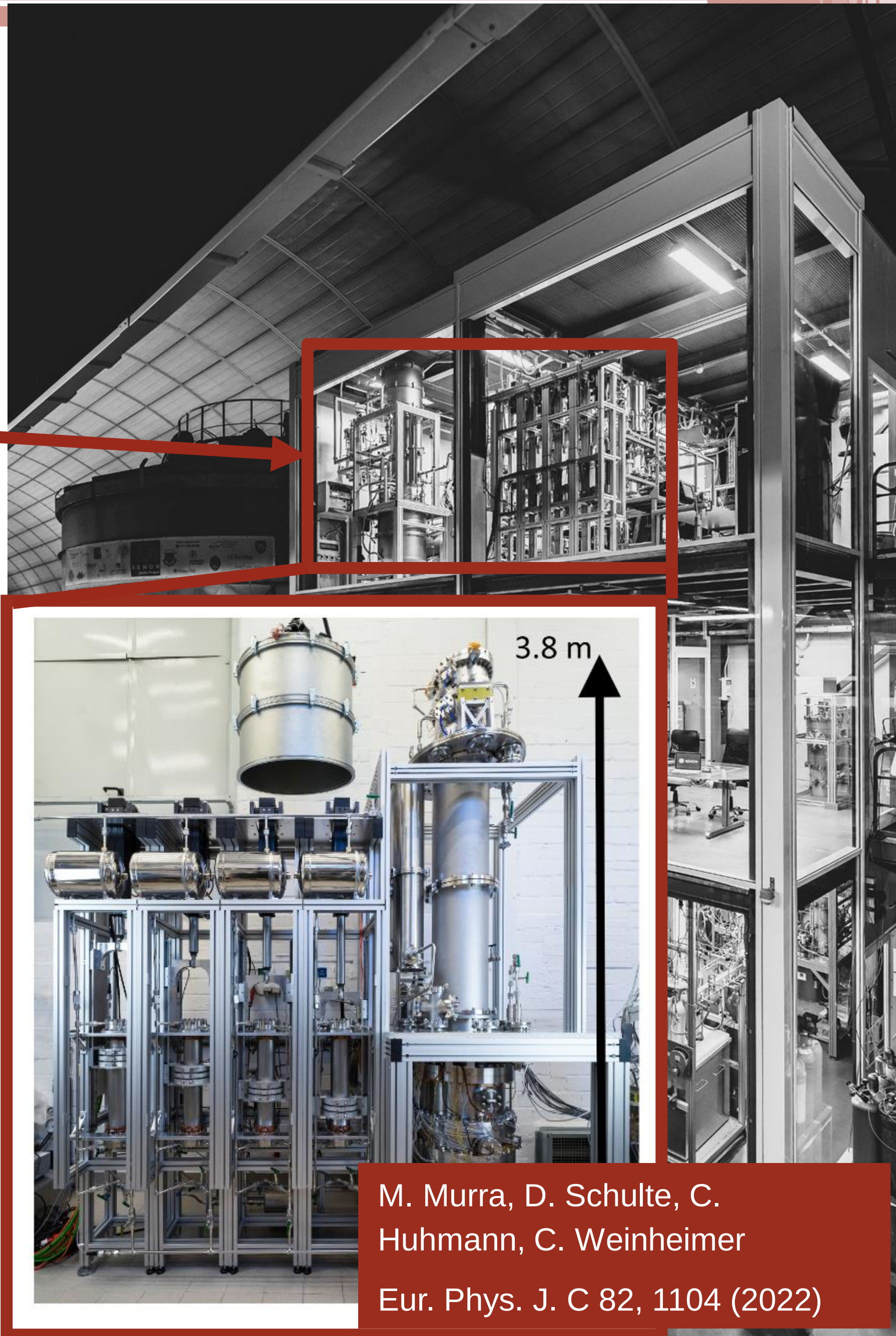
Distillation + New pumps

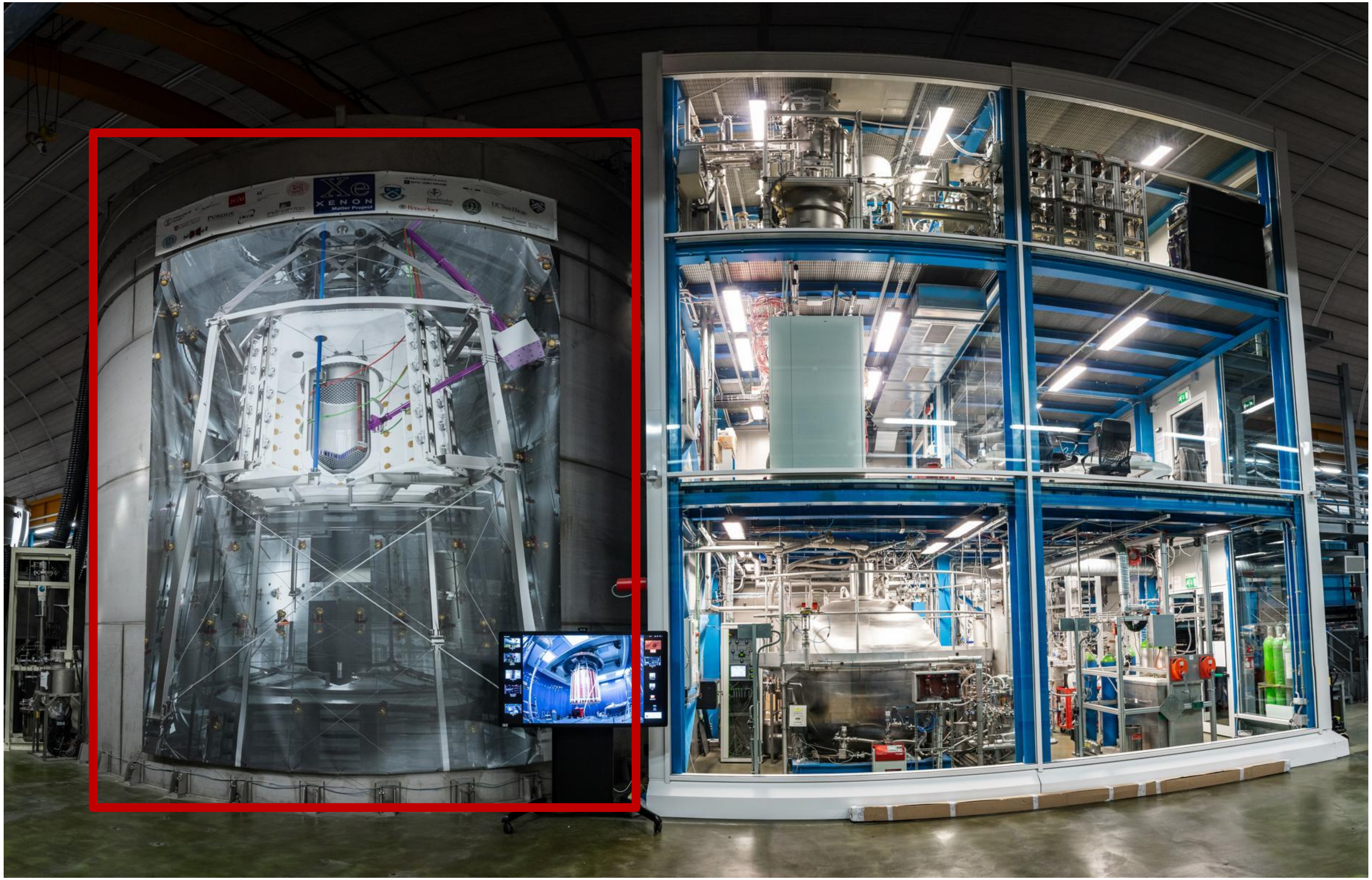




M. Murra, D. Schulte, C. Huhmann, C. Weinheimer

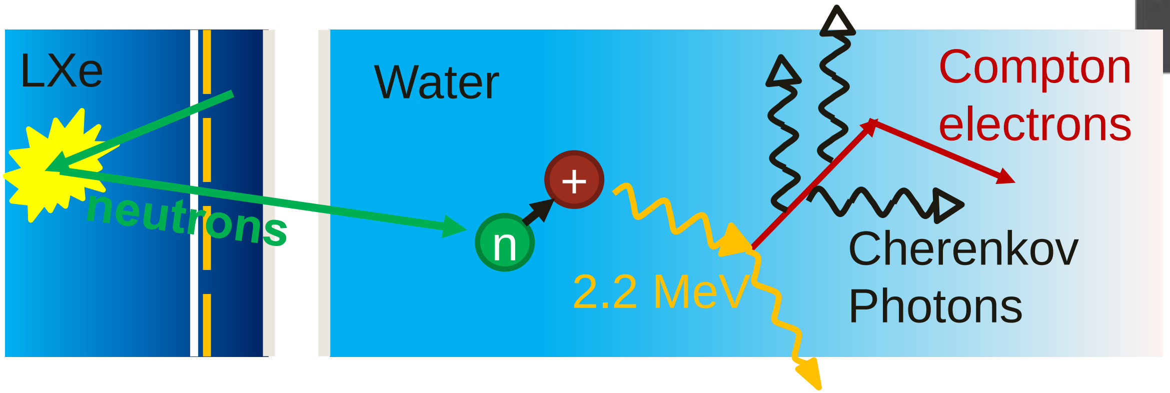
Eur. Phys. J. C 82, 1104 (2022)

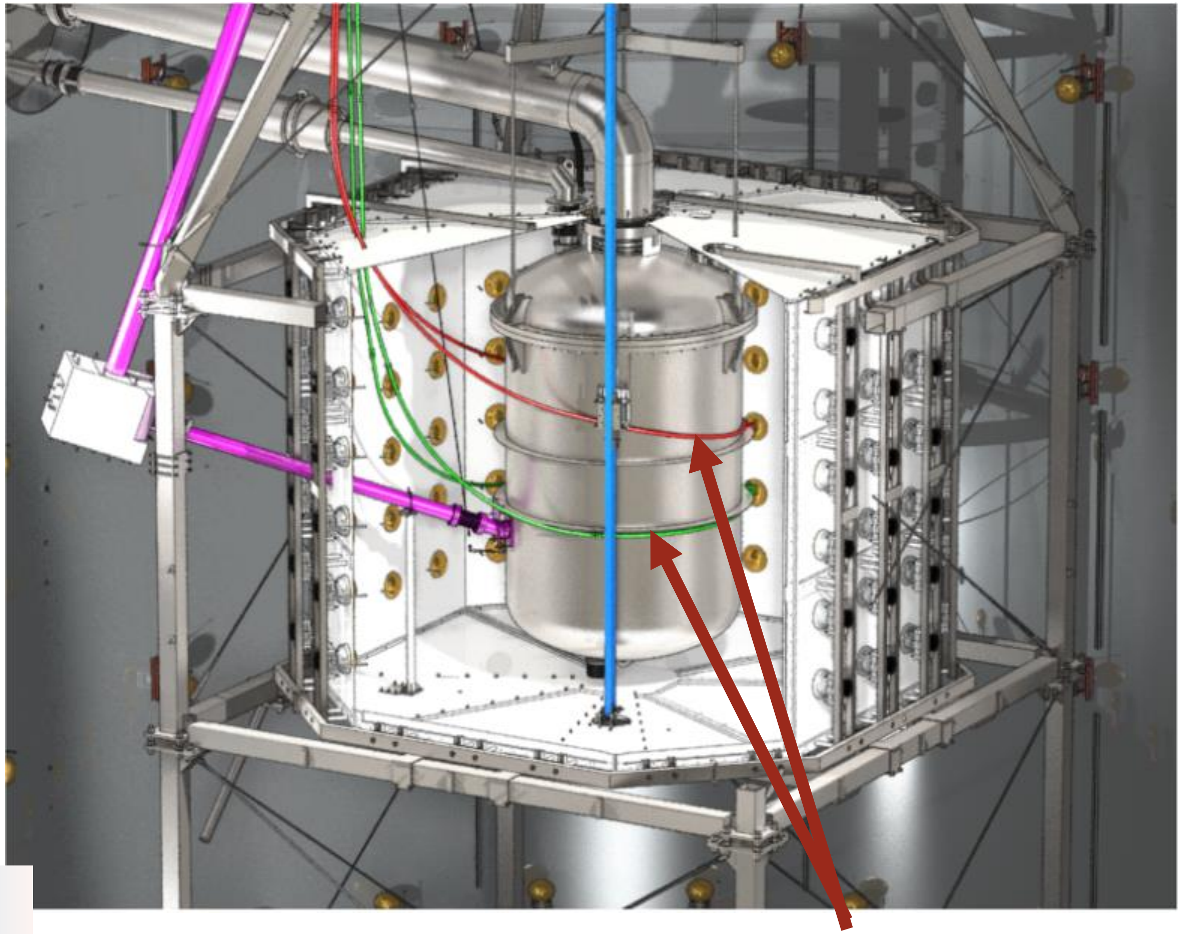
XENONnT neutron-veto



XENONnT neutron-veto

- Added the world's first water Cherenkov neutron veto inside existing muon veto
- 120 8" PMTs are watching the TPC cryostat
- Highly reflective ePTFE and ultra-pure water to maximize light-collection efficiency
- Tag neutrons through the neutron-capture on hydrogen which releases a 2.22 MeV γ-ray





„U-tubes", to place an AmBe neutron source close to TPC

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Dark Matter Chip Cookies
(with extra big chunks of DM)

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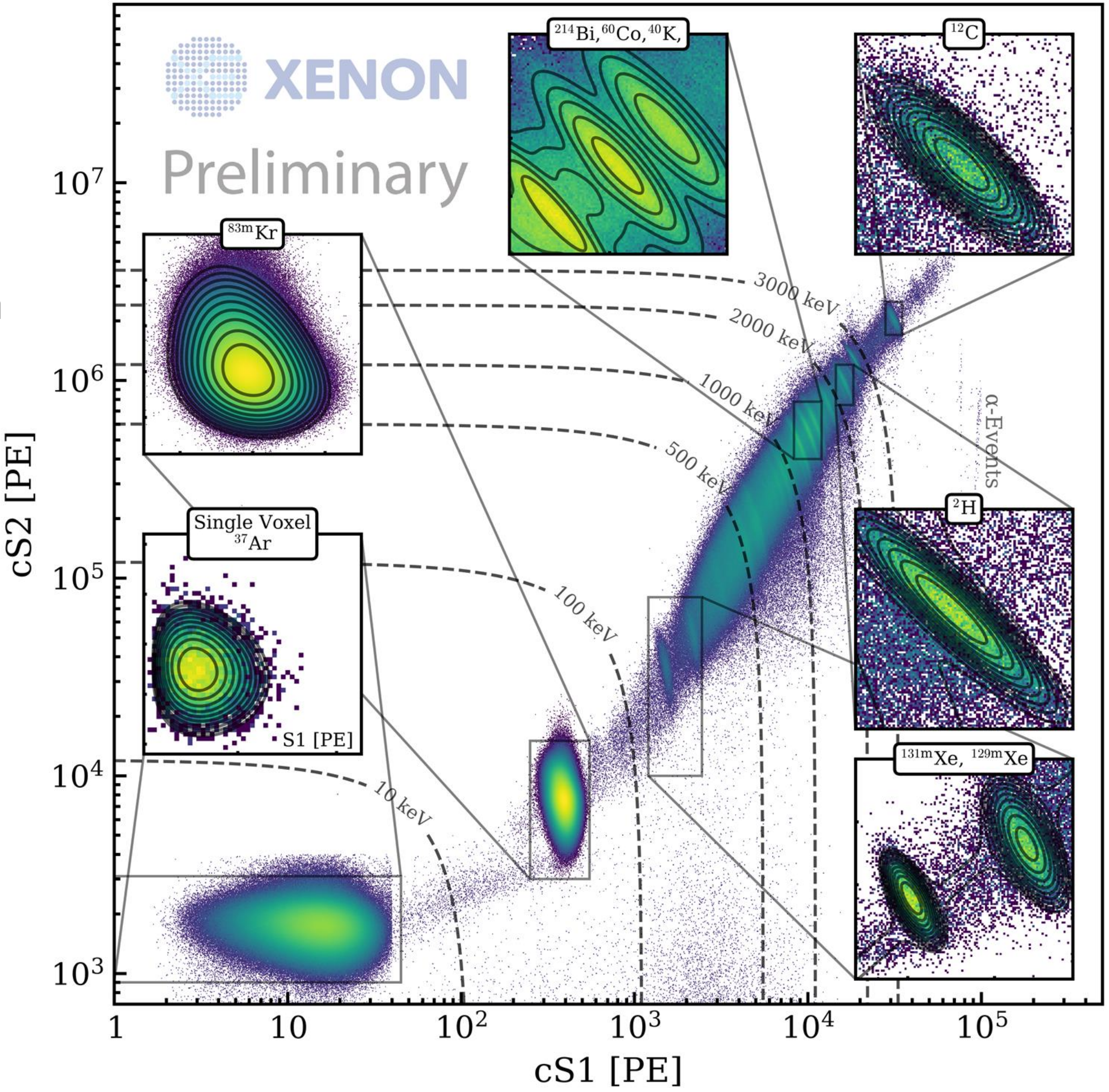
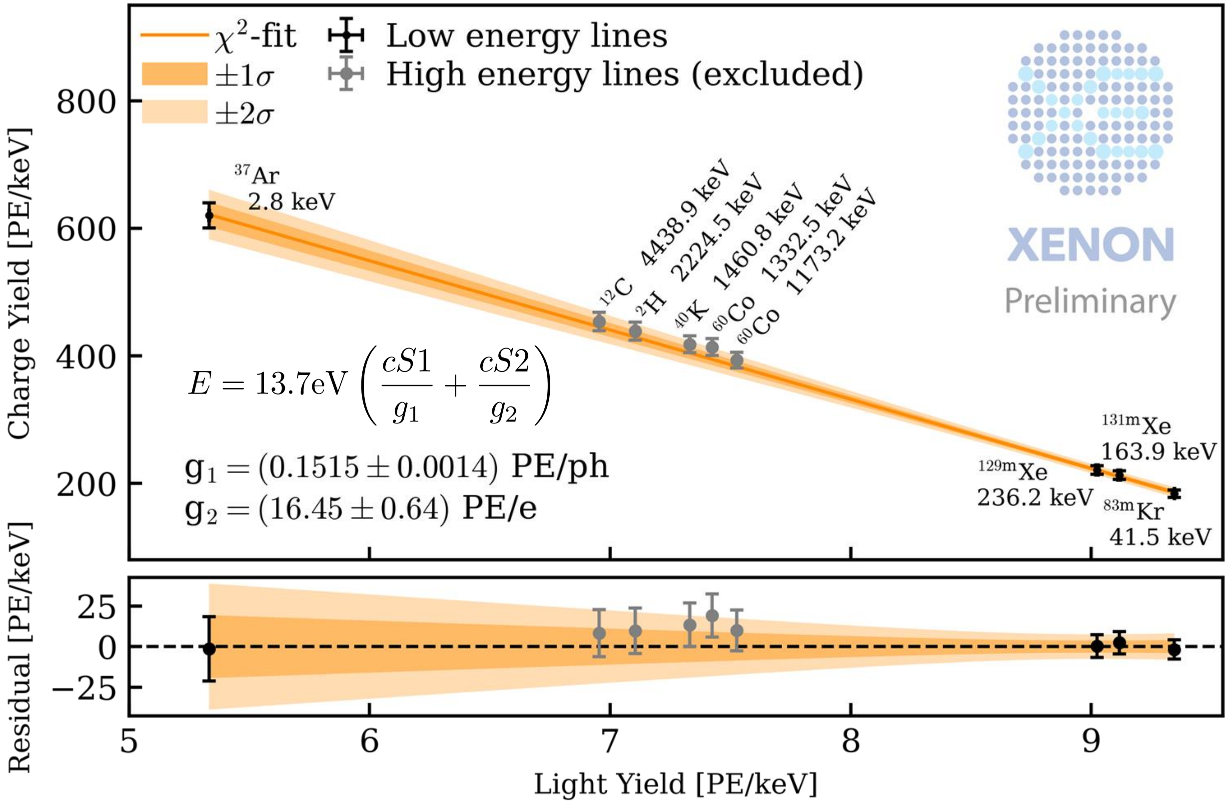
Calibration of XENONnT

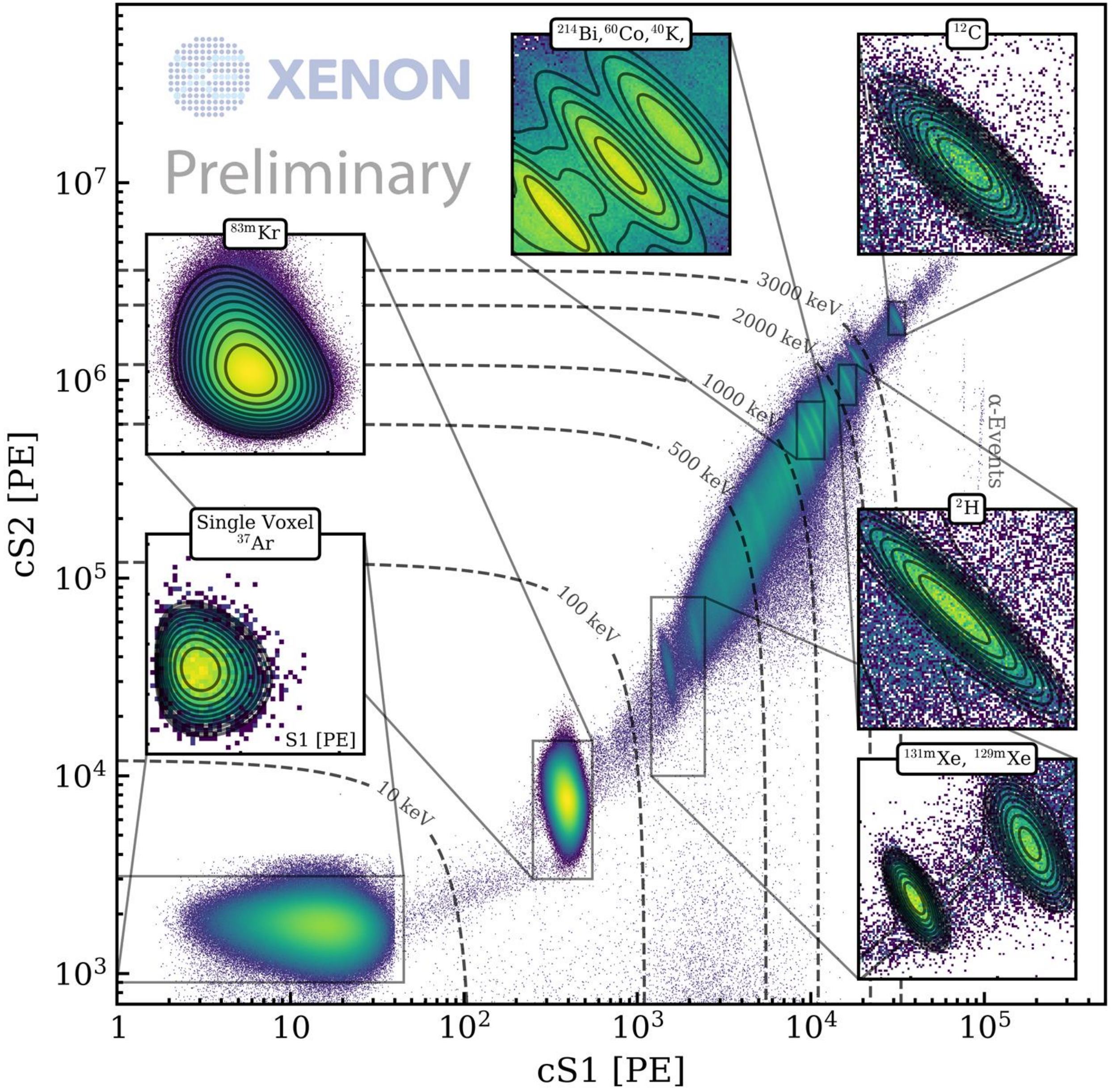
- Weekly PMT calibrations via LEDs
- Calibration of detector response and efficiency:
  - Internal source: ^{37}Ar, ^{83m}Kr, ^{129m}Xe, ^{131m}Xe, ^{220}Rn
  - External sources like: ^{241}Am(α, n)^{9}Be and Th
- Bi-weekly ^{83m}Kr and materials background **α** and **γ** are used for stability monitoring
- Correction of spatially dependent detector effects with ^{83m}Kr



Energy scale of XENONnT



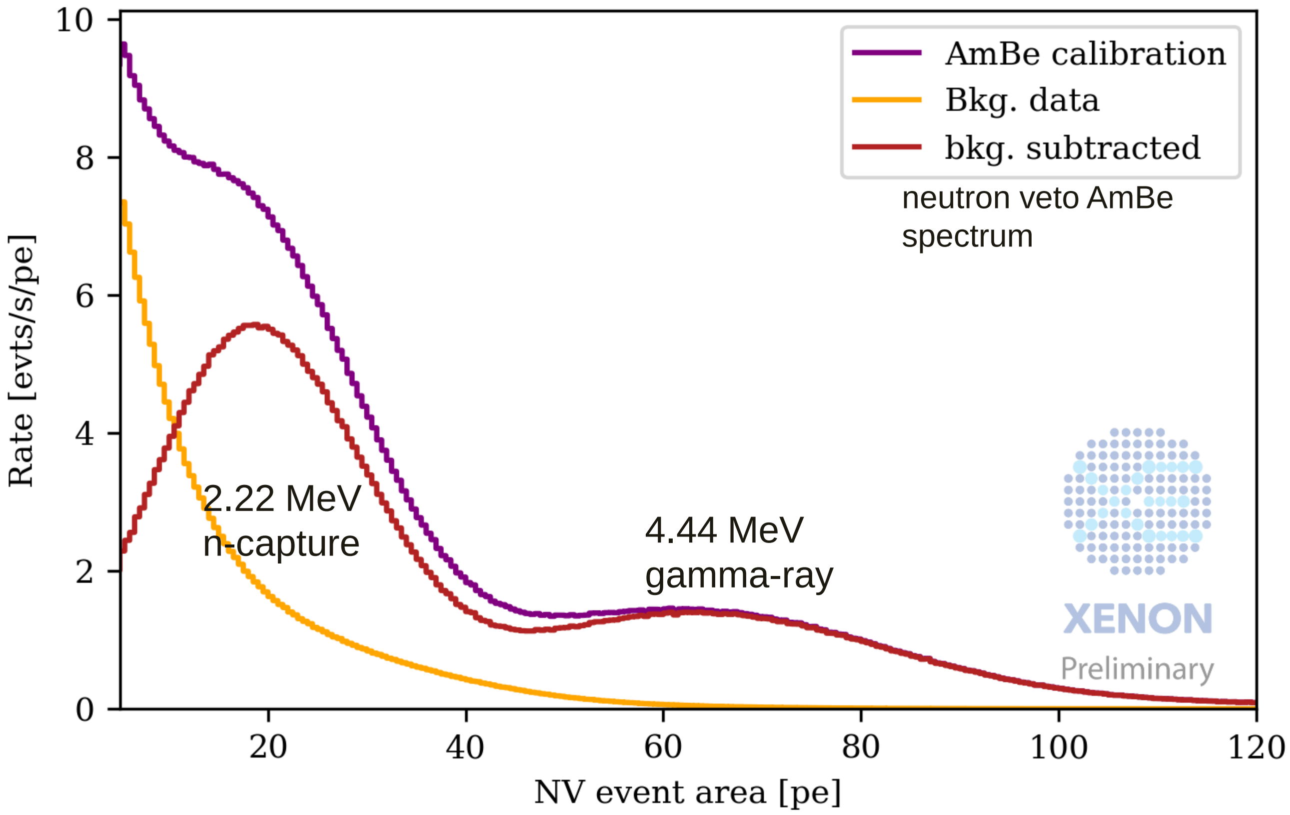
- Photon and electron gain g1/g2 used as prior in the LXe response model
- Energy scale important to forward fold WIMP spectrum into cS1 and cS2

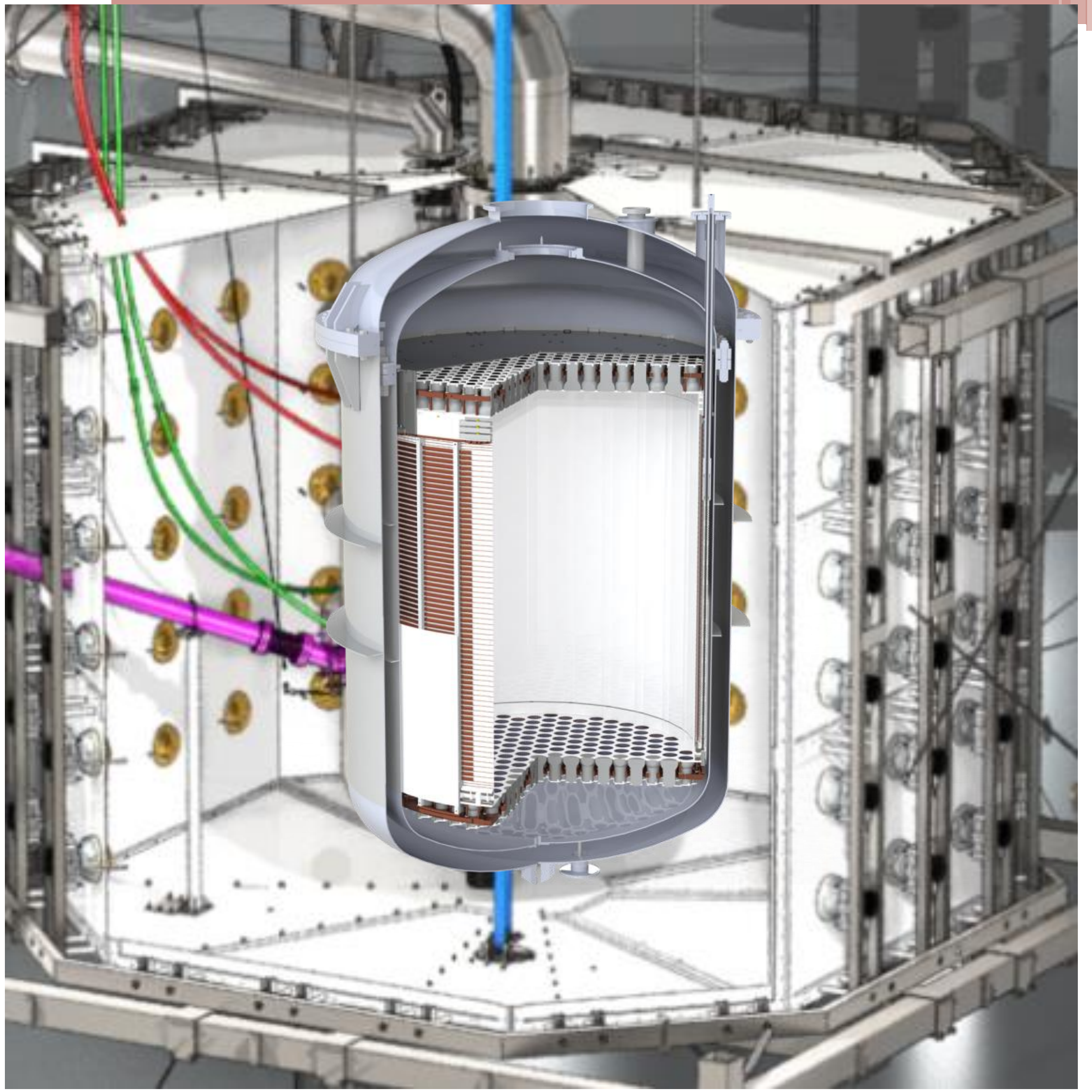


Calibration of NR response

- $^{241}Am(\alpha, n)^{9}Be$ emits coincident 4.4 MeV gamma in ~60 % of all emitted neutrons

➡ Calibrate TPC and NV using tagged neutrons





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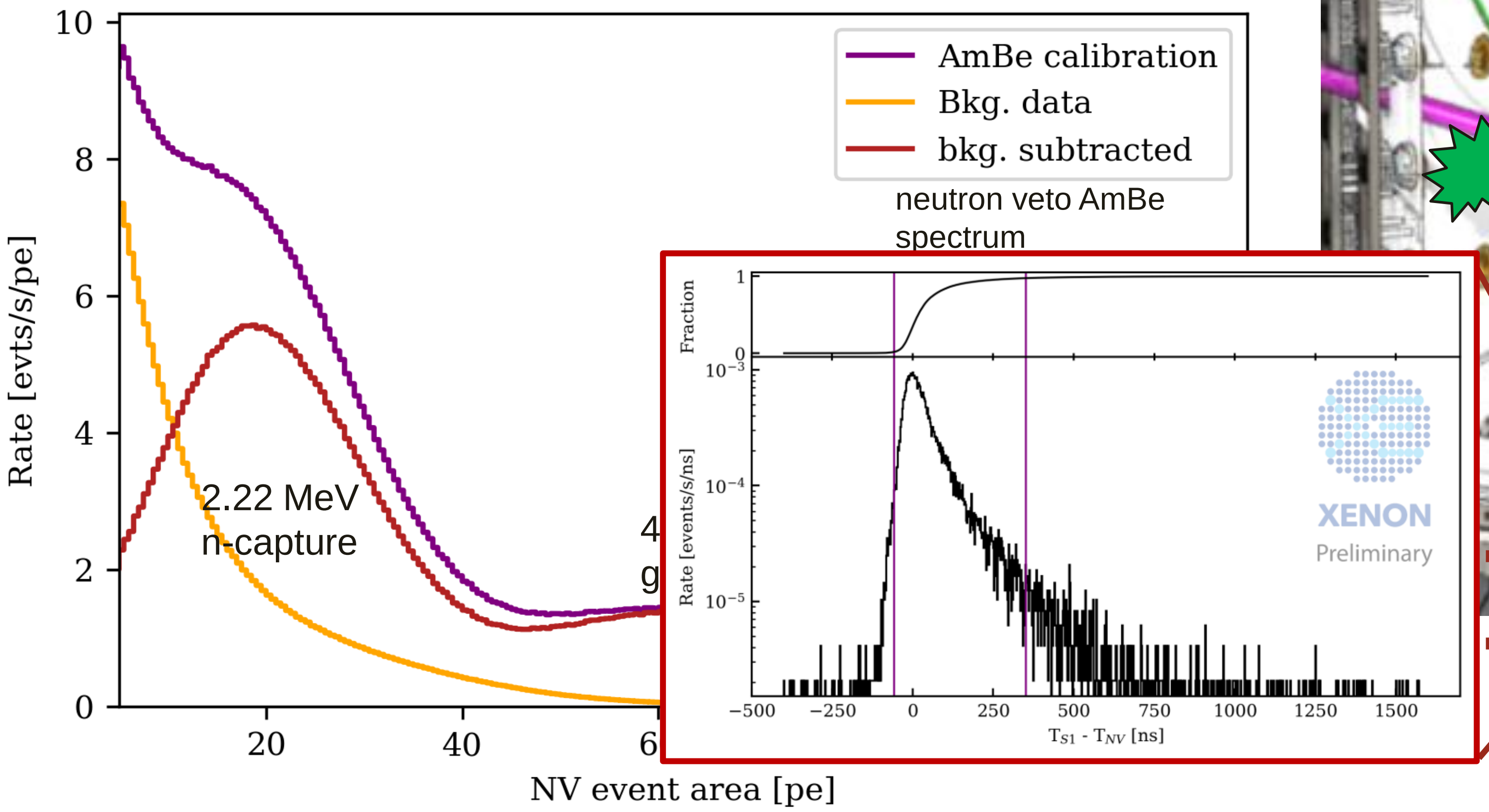

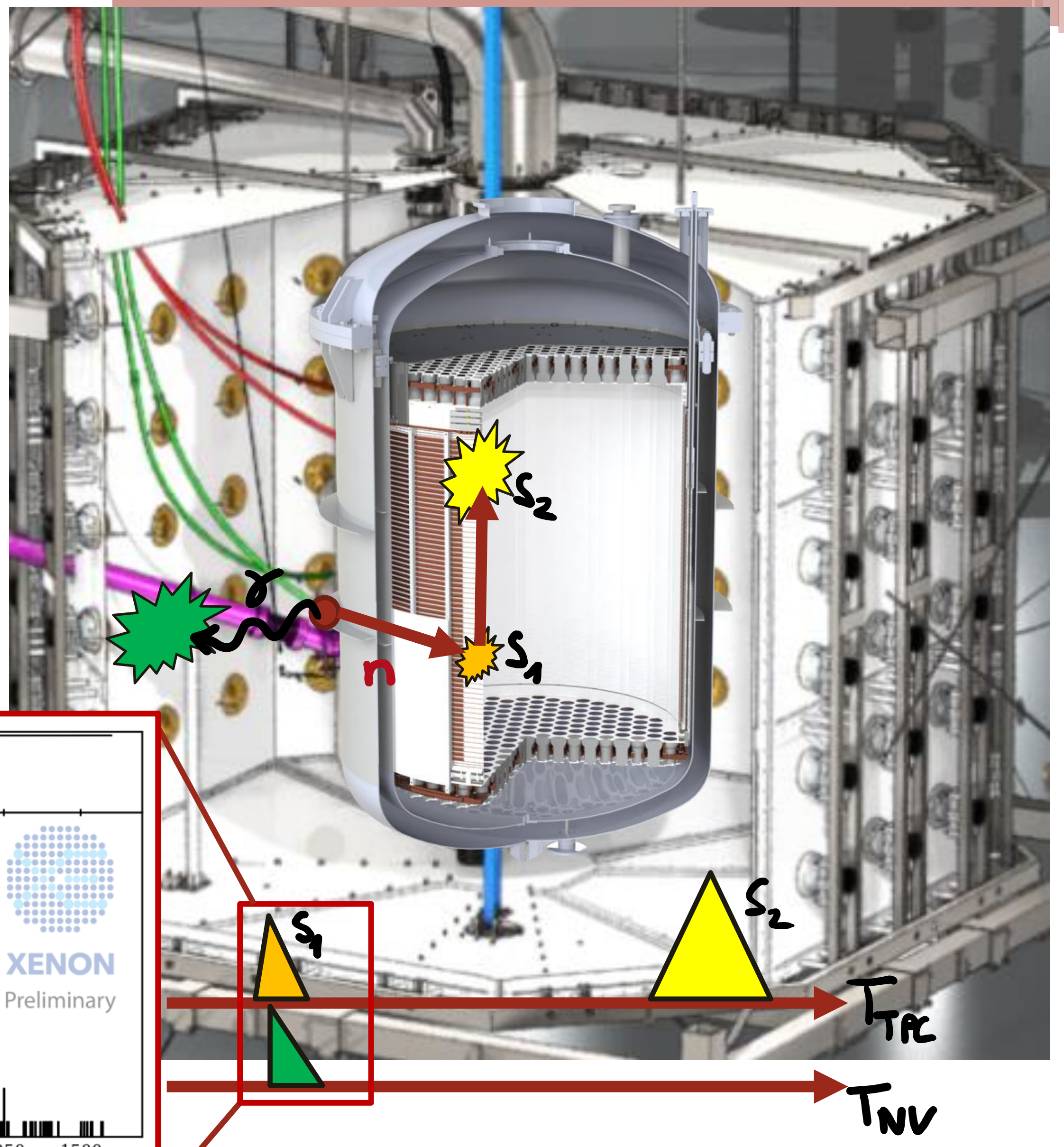

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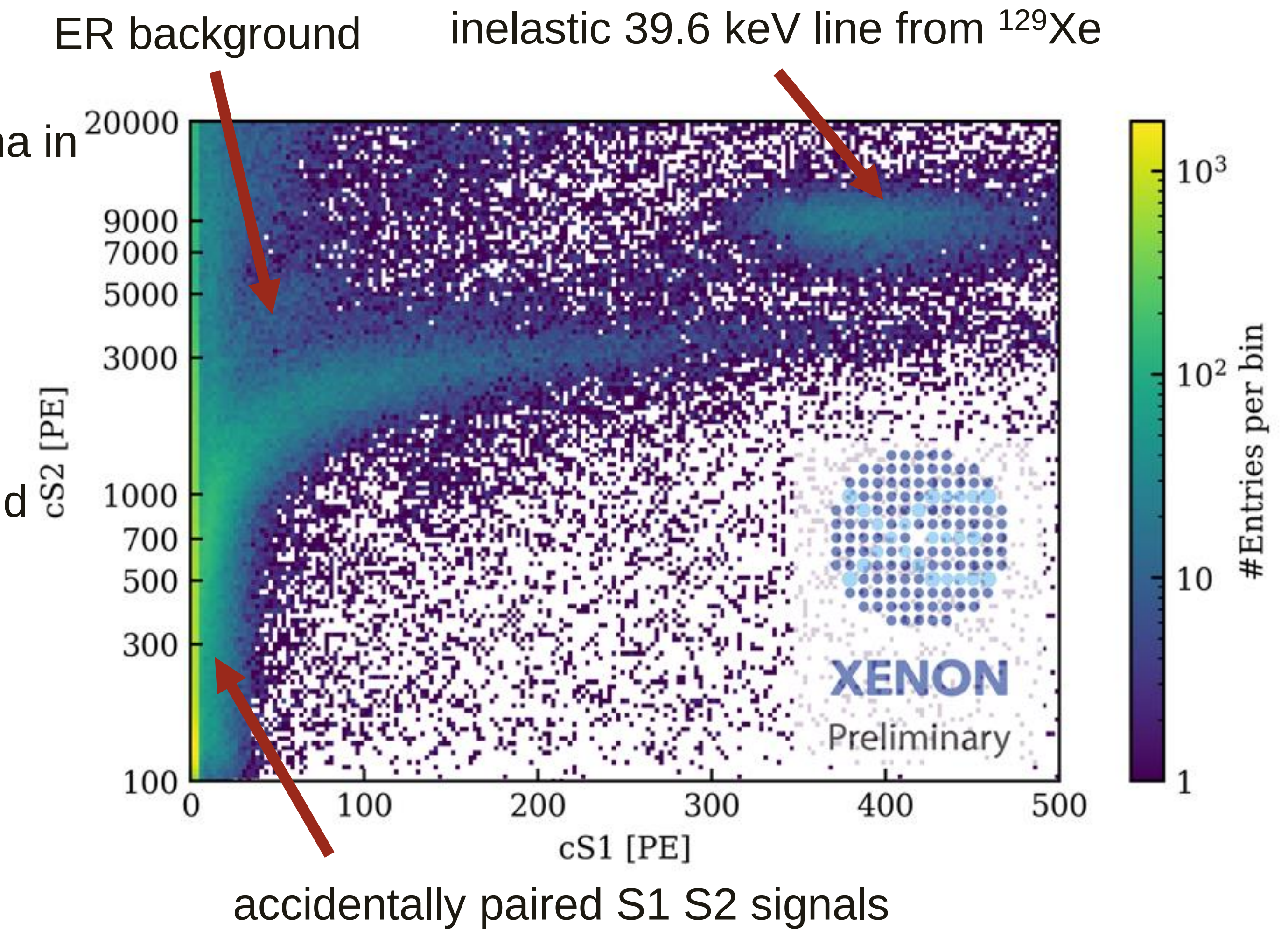
- Build 400 ns wide coincidence between TPC and neutron veto

  ➡ Very strong background suppression



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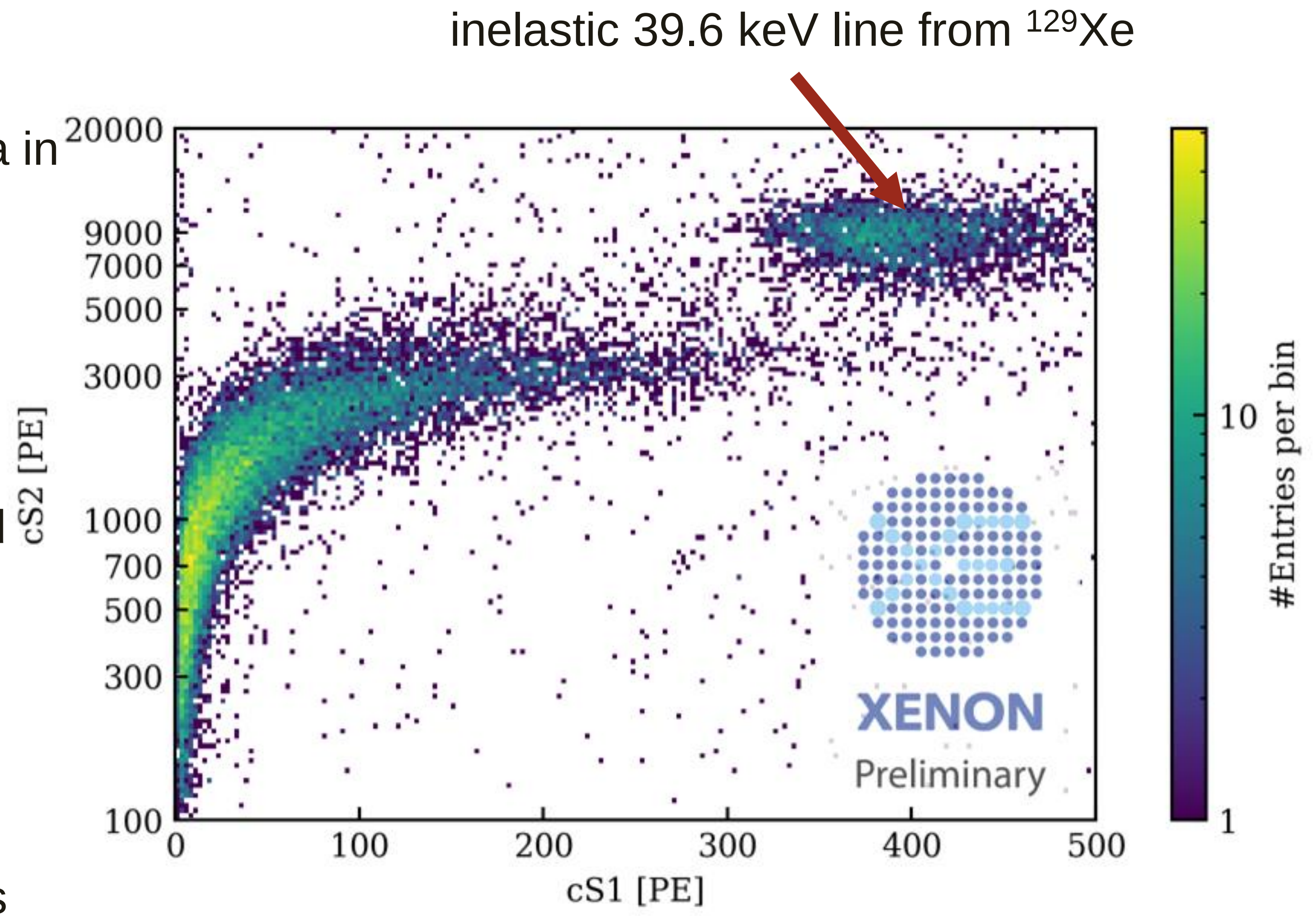

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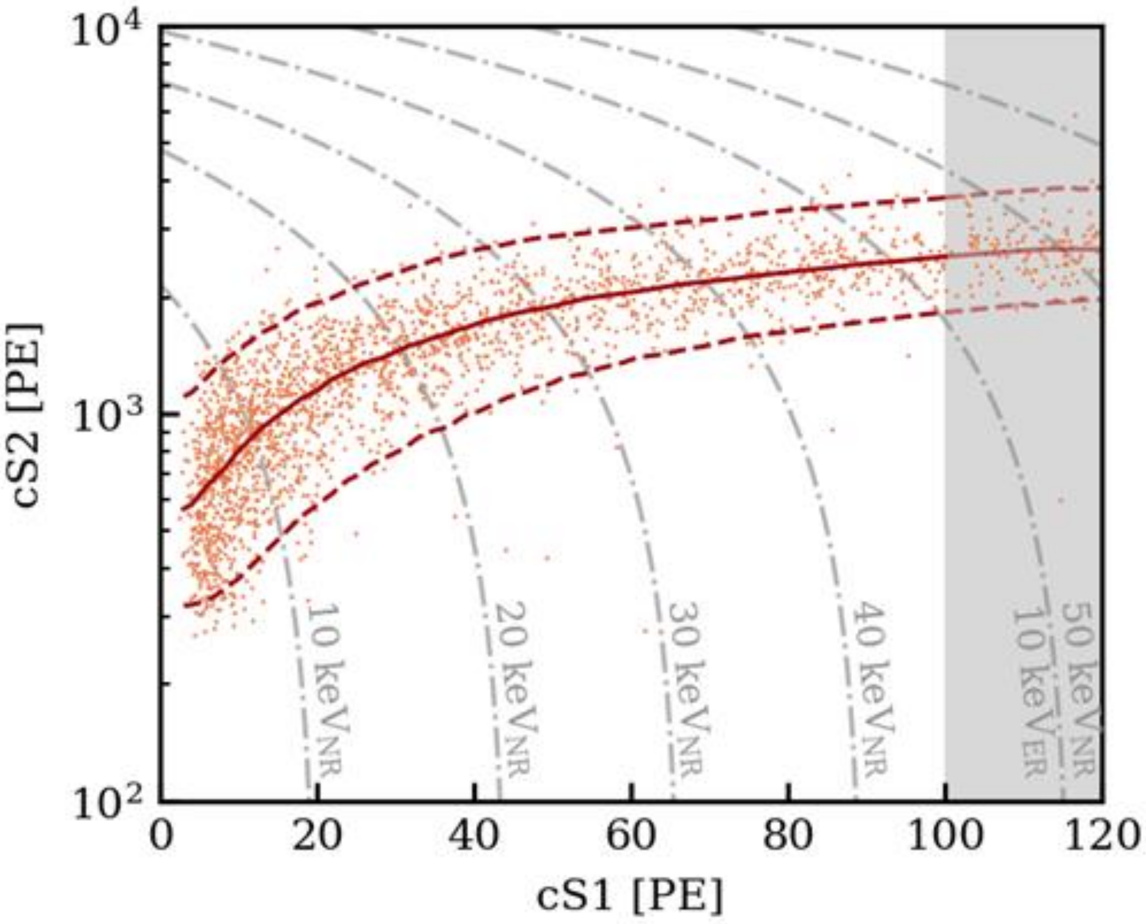
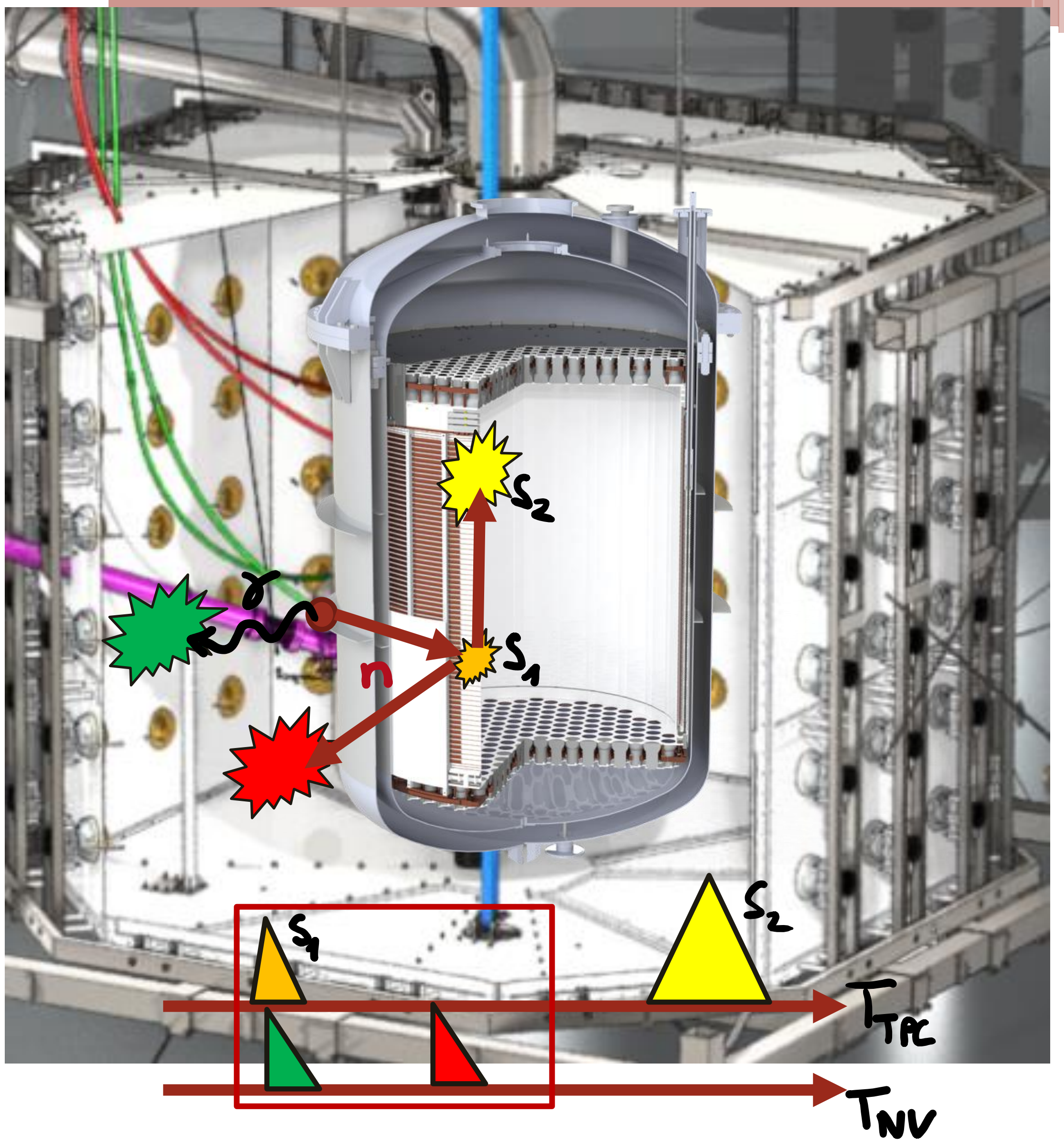


Calibration of NV tagging

- Use NR single-scatter data and search for neutron-capture signals in NV

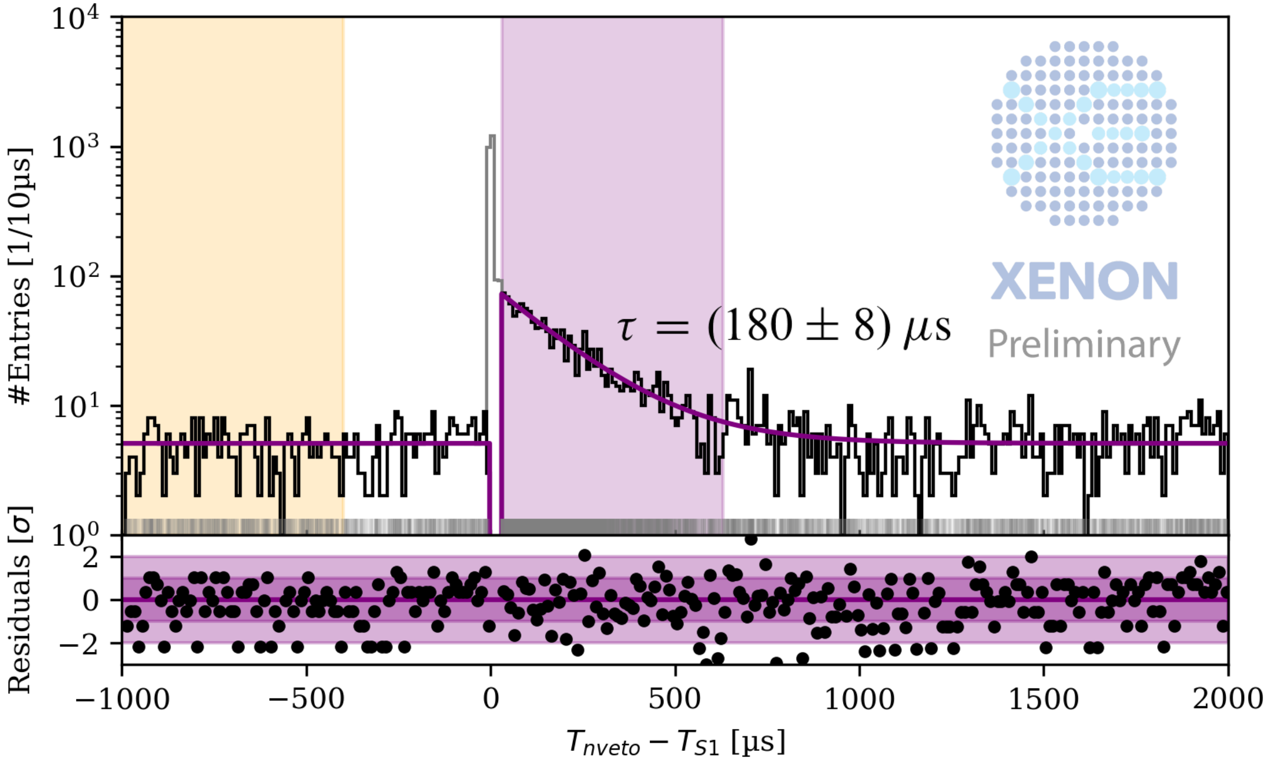


Calibration of NV tagging

- Use NR single-scatter data and search for neutron-capture signals in NV
- Time delay between γ-ray/S1 determined by neutron-capture time

(53 ± 3) % tagging efficiency
@ 250 μs window and a 5-fold PMT coincidence, and 5 pe threshold

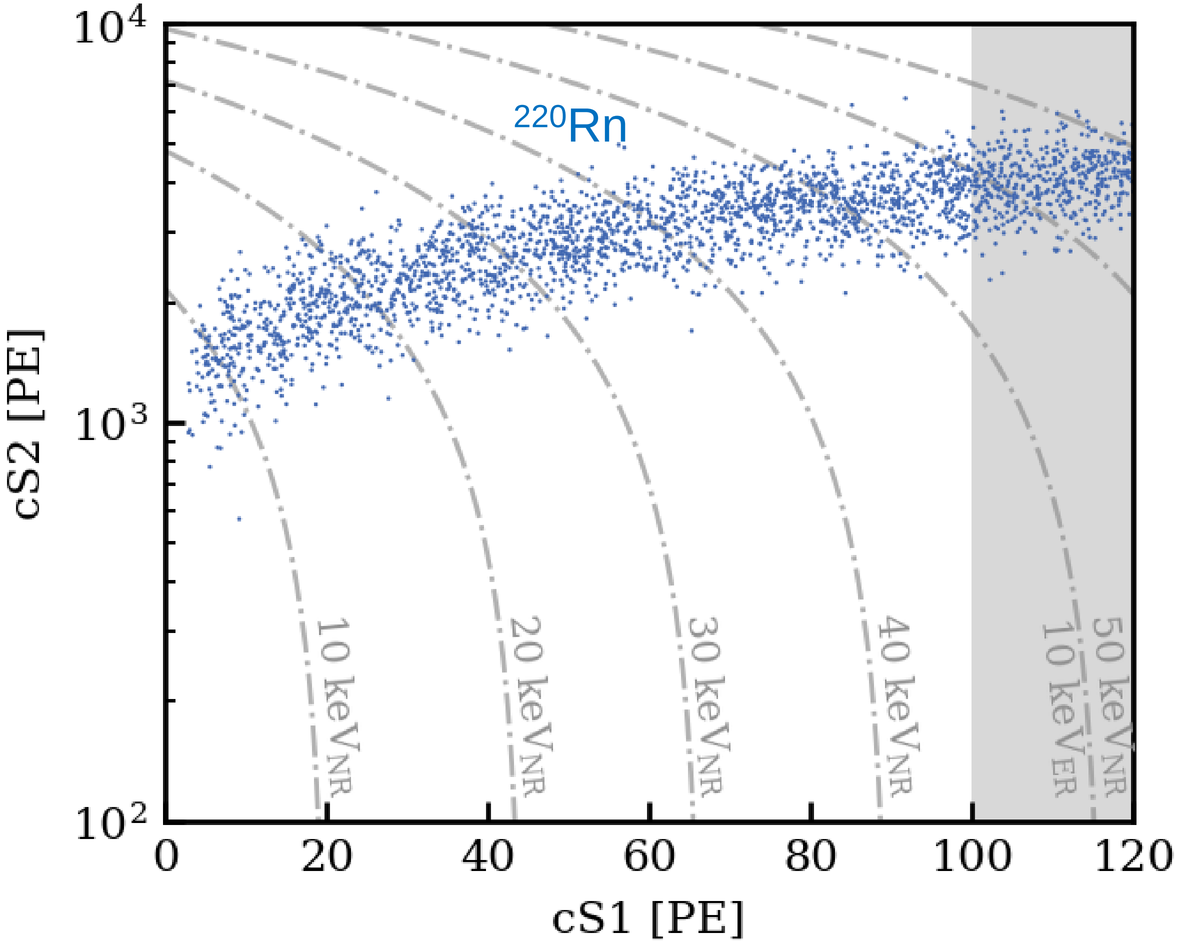
- Lifetime loss due to the veto of 1.6 %



Side mark neutron detection efficiency:
Detected neutrons over emitted neutrons (81 ± 1) % @ 600 μs **Highest neutron-detection efficiency ever measured in water Cherenkov detector!**

Calibration of XENONnT

- Calibration of ER response using ^{220}Rn
  - Gives approximately flat energy spectrum
  - Used to validate cut acceptances



Calibration of XENONnT

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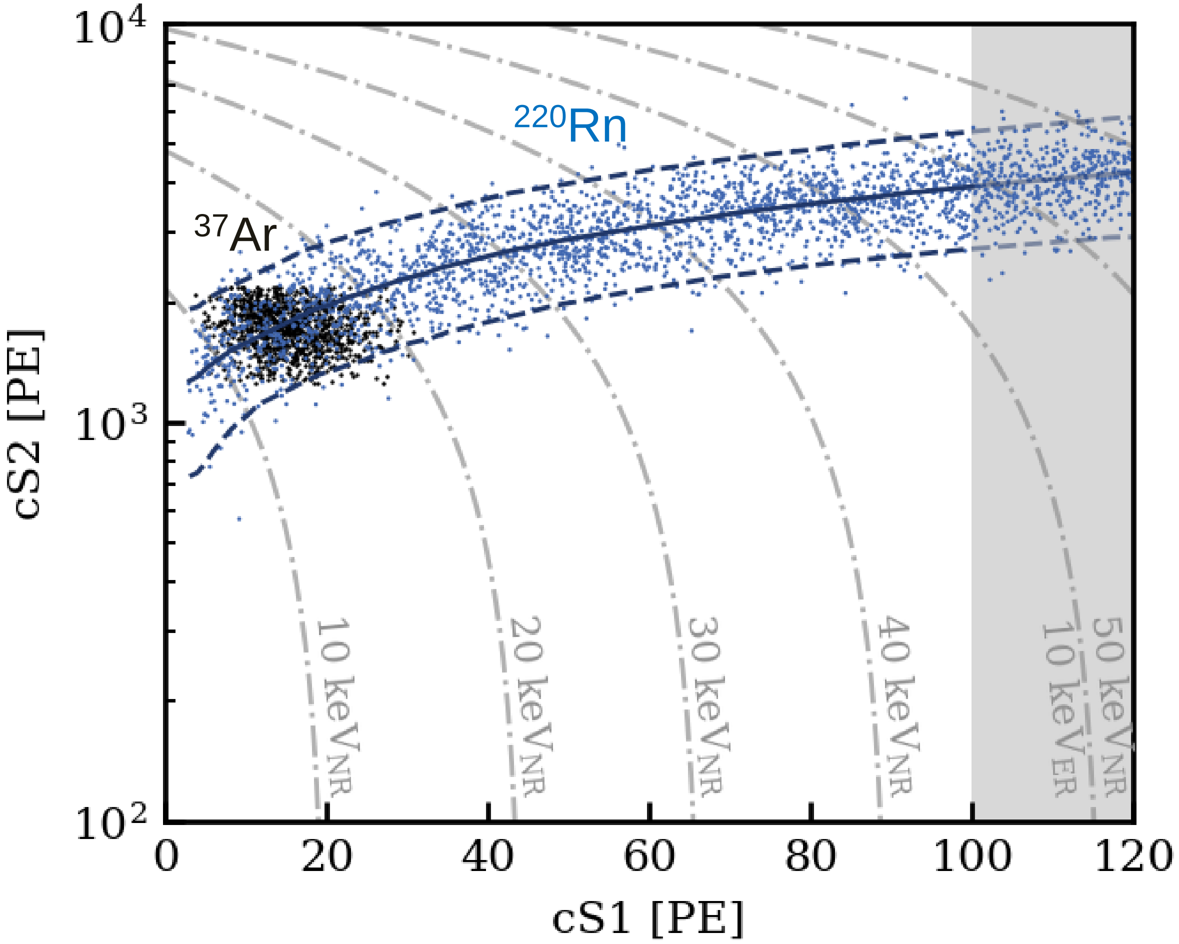
- Detector performance at low energies using ^{37}Ar
  - Mono-energetic line @2.8 keV
  - Allows to study performance with high resolution, due to high statistics
  - Removed via distillation
- ER response model based on a combined fit



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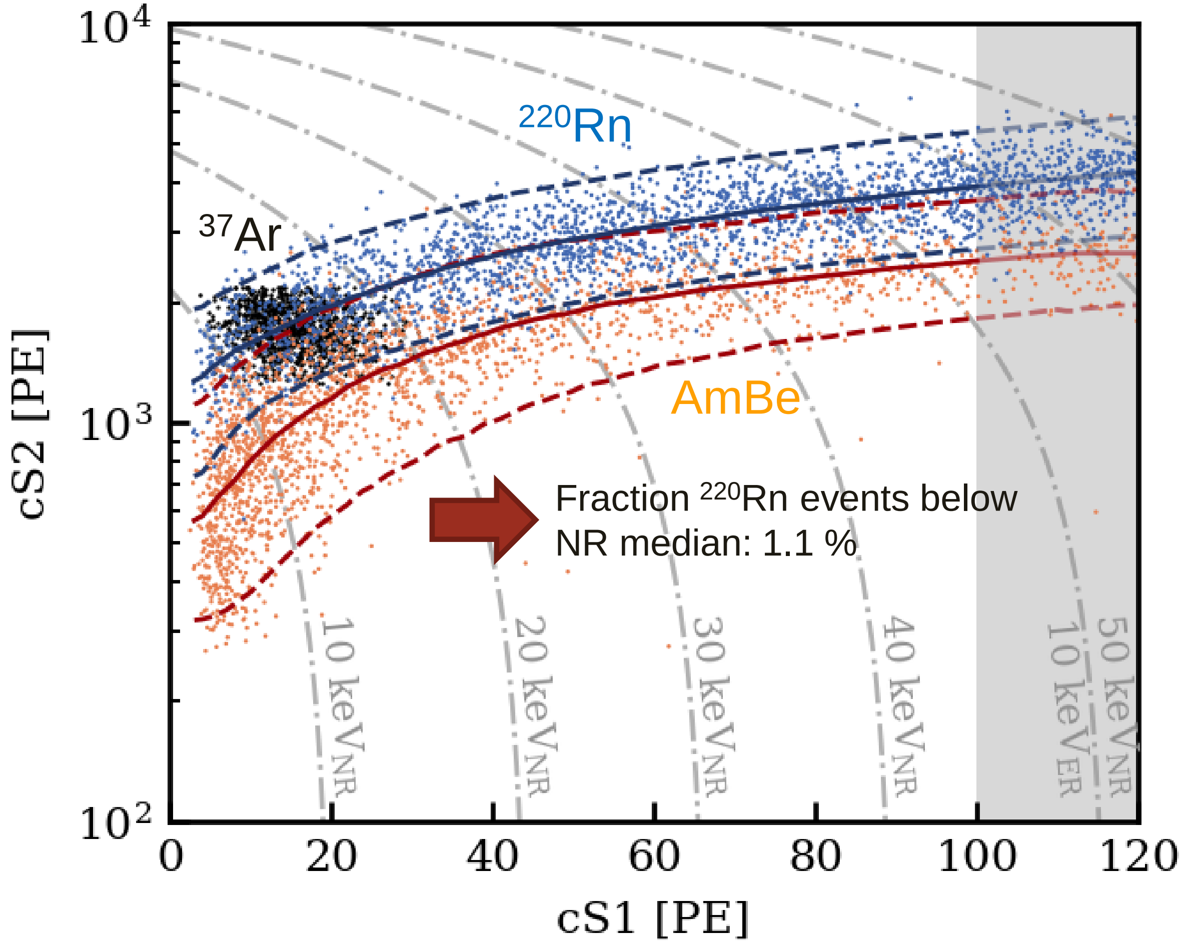
- ER response model based on a combined fit
- Uncertainties of the ER band shape propagated via a principal component analysis



Dark Matter Cookies

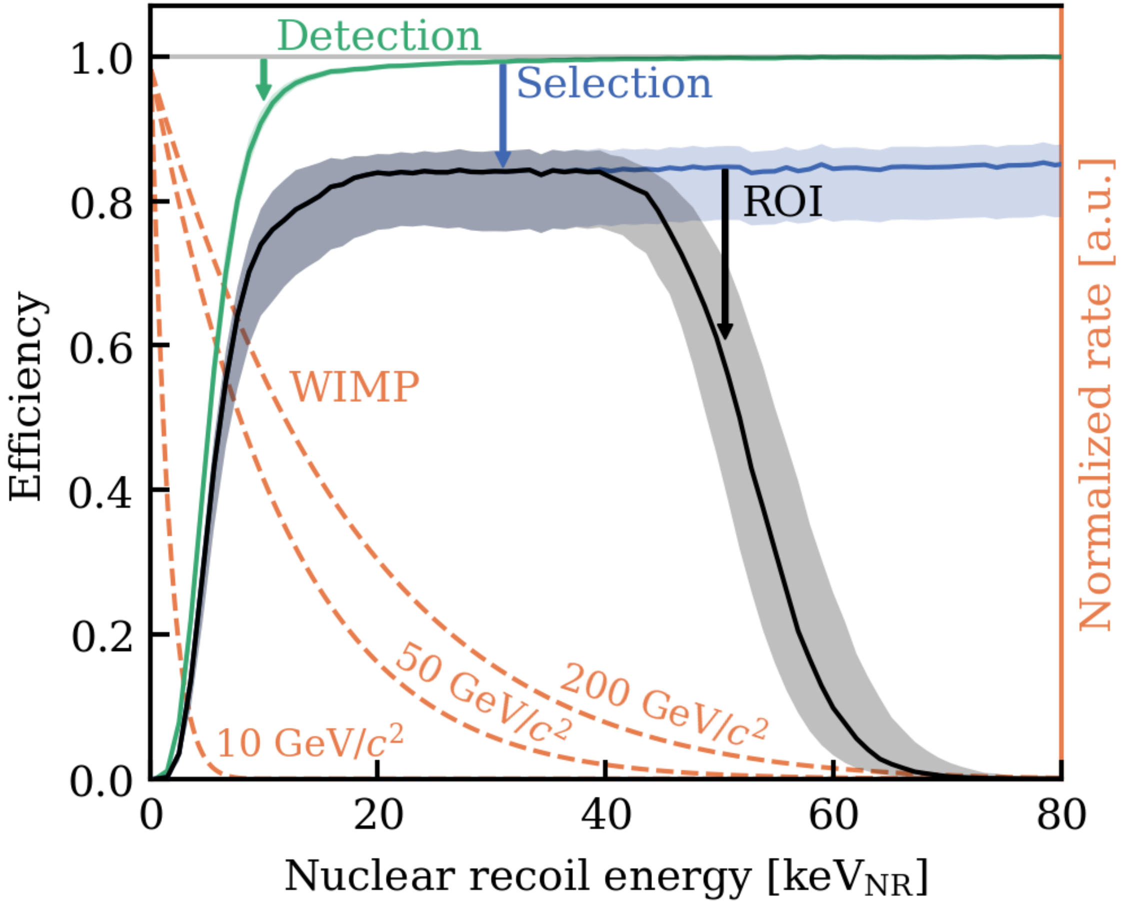
Dark Matter Chip Cookies (with extra big chunks of DM)

Ingredients:

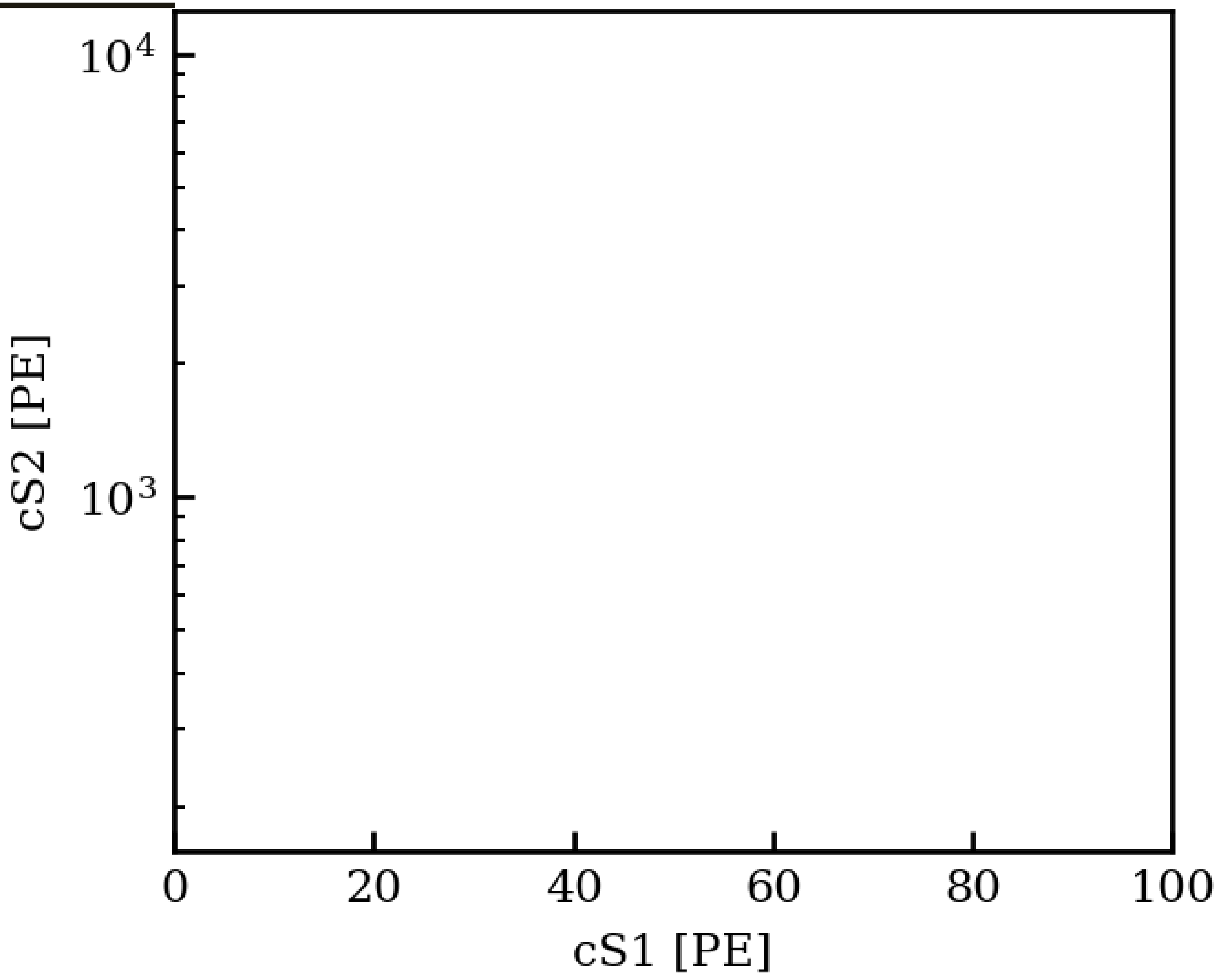
1. Dark Matter ✓
2. Detector ✓
3. Detector calibration ✓
4. Background and signal model
5. Enjoy the result

Detector threshold and acceptance

- Detection efficiency:
  - Threshold driven by a 3-fold PMT coincidence for S1
  - Simulation-driven: Full waveforms
  - Data-driven: Bootstrapping from ^{83m}Kr and ^{37}Ar S1
  - Both processed with analysis framework
- Data quality selection evaluated using ER/NR calibration data
- ROI defined to fully contain WIMP spectra
  - cS1 [0 pe, 100 pe]
  - cS2 [$10^{2.1}$ pe, $10^{4.1}$ pe]
- Total acceptance > 10 % between [3 keV_{NR}, 60 keV_{NR}]



Dark Matter ROI

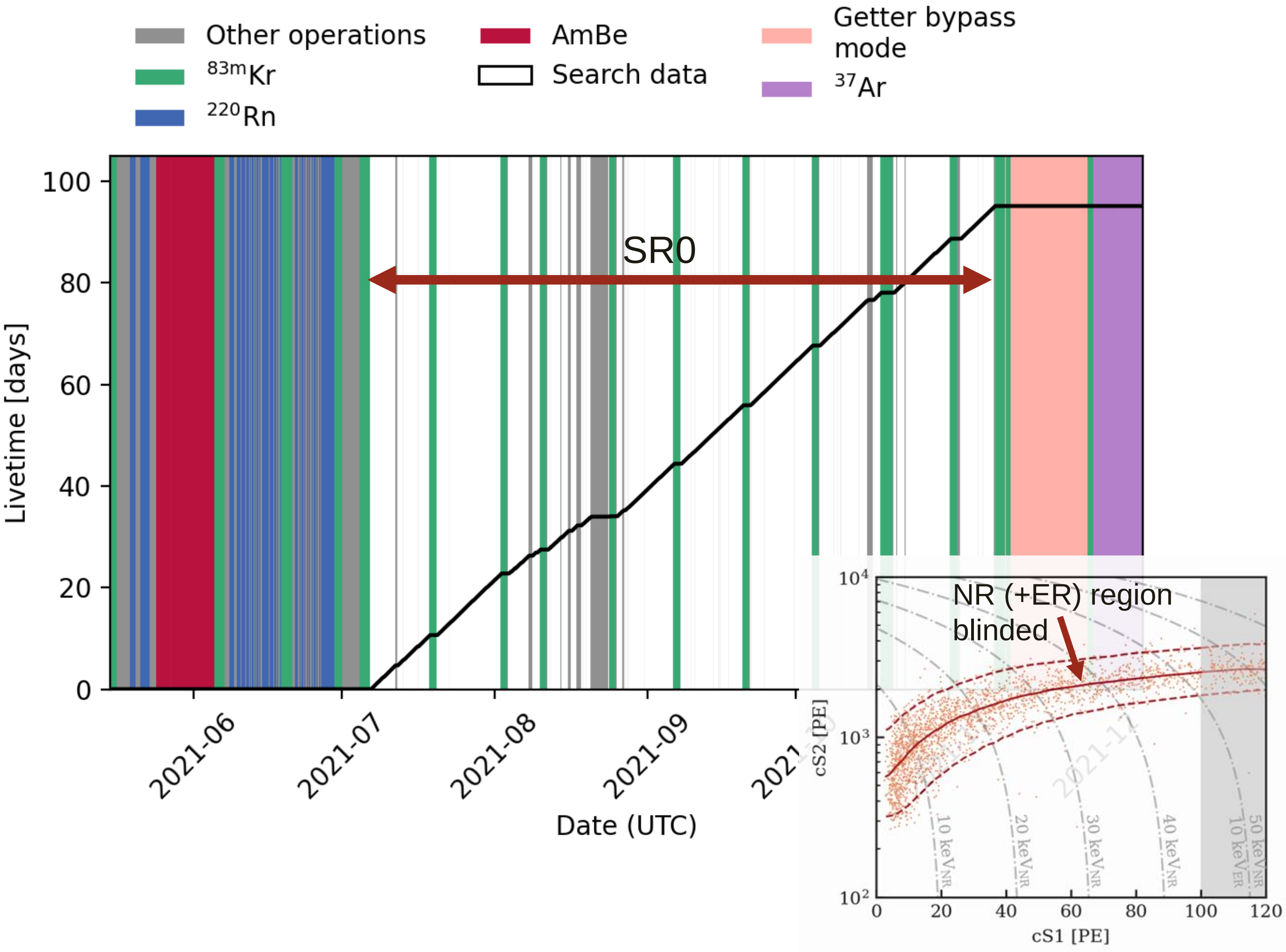


SR0 data taking

SR0 NR search data:

- July 6 – Nov 10, 2021 (97.1 days)
- **95.1 days** lifetime corrected
- **(4.18 ± 0.13) t fiducial volume**

  (Same shape as for ER, but with smaller R_{max} < 61.35 cm)
- exposure of **1.1 tonne-year**
- **blind analysis**



ER background

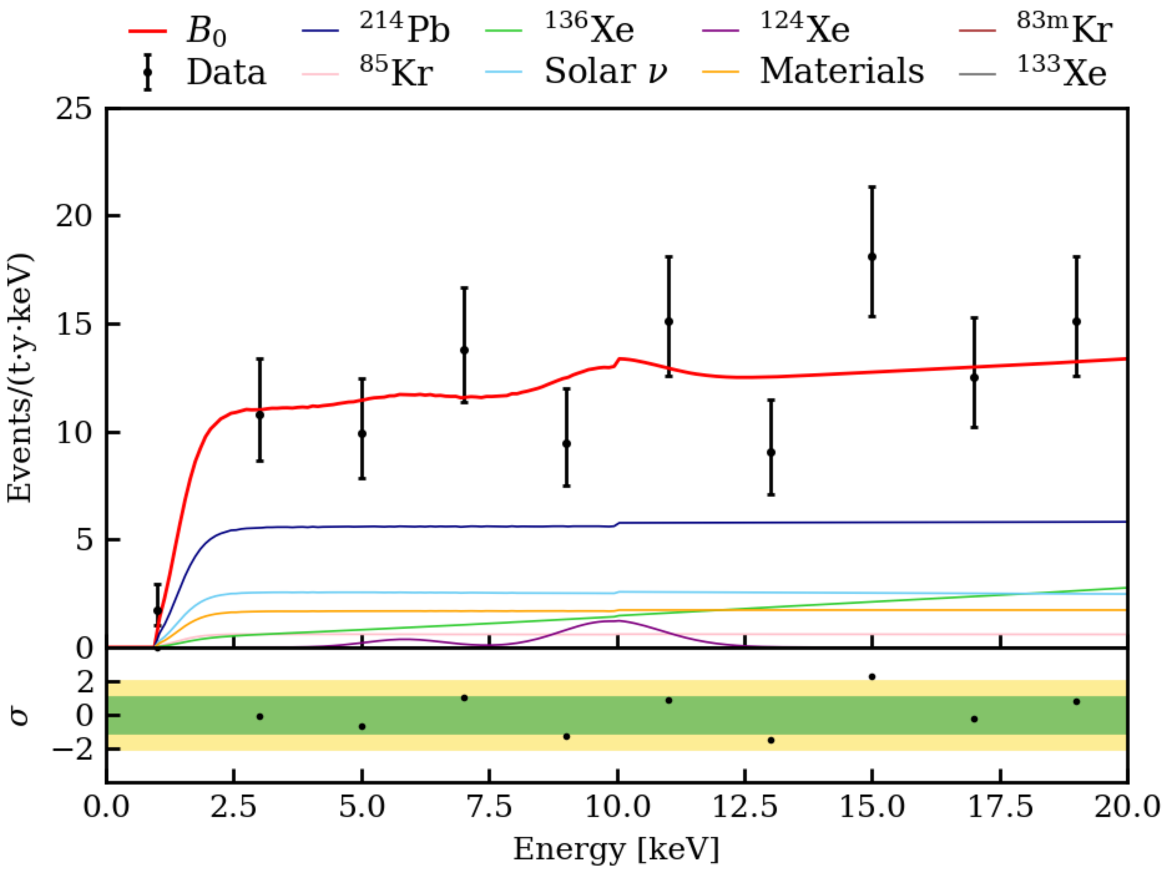
- Dominated by beta decays from ^{214}Pb a daughter of ^{222}Rn

- Additional components:
  - Solar neutrino electron-scattering
  - Beta decay of ^{85}Kr
  - Material backgrounds

- **Factor x5 improved** background compared to XENON1T

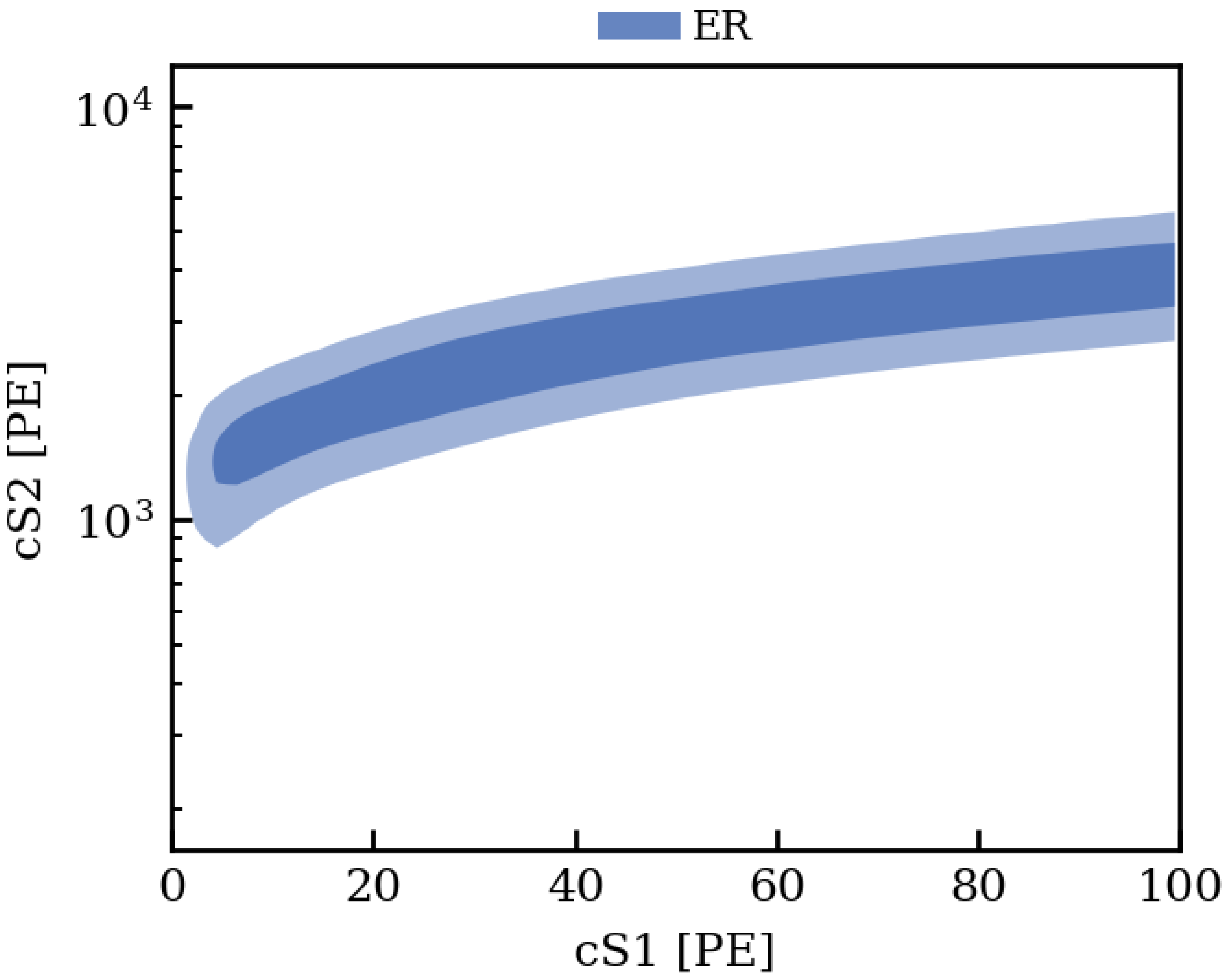
134 events in ER band of ROI
(15.8±1.3) events/(t · y · keV)

Assume **flat ER background** spectrum between 1 keV and 10 keV electronic recoil energies



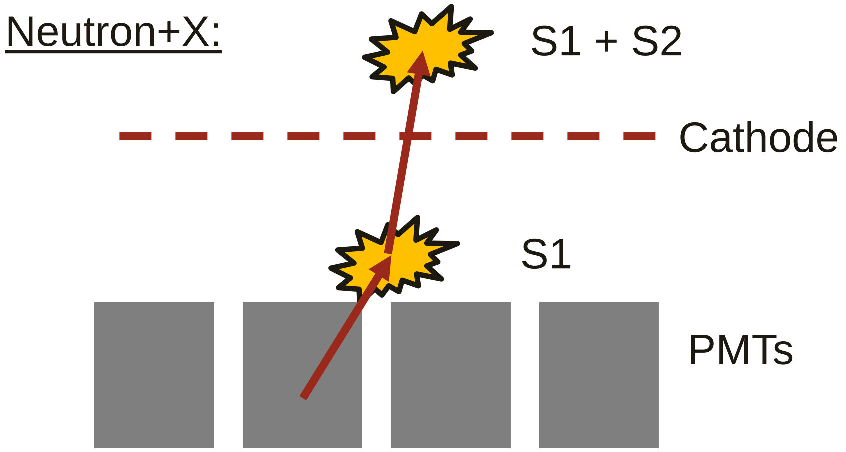
E. Aprile *et al*
Search for New Physics in Electronic Recoil Data from XENONnT
Phys.Rev.Lett. 129 (2022) 16, 161805

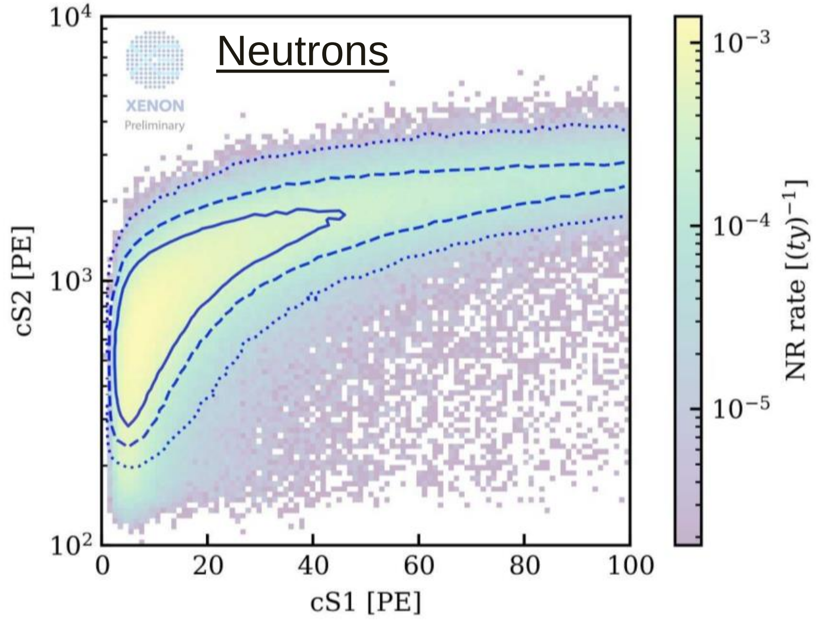
Dark Matter ROI

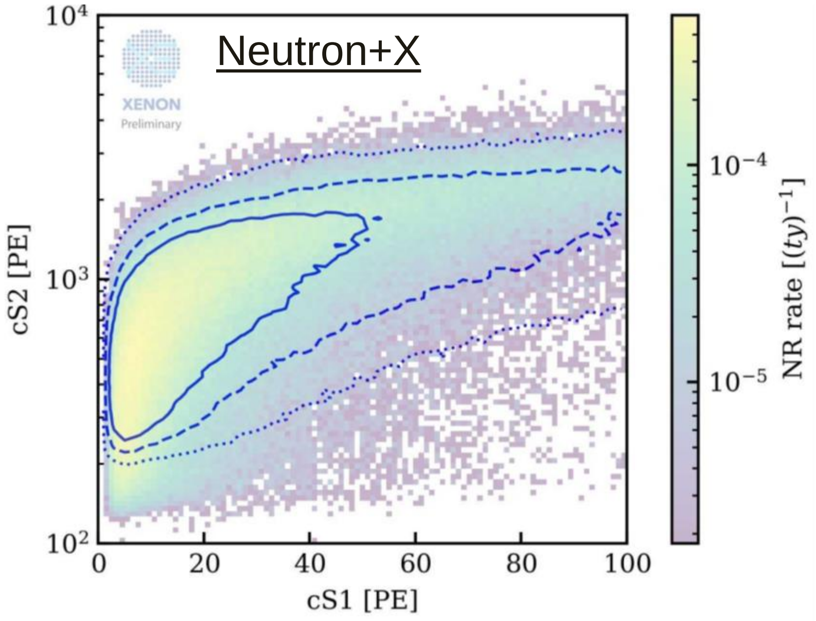


Background model NR search

- Neutron background from spontaneous fission and (α, n)-reactions
- Neutron yields estimated based on screening results
- Background templates generated via full-scale waveform simulations + analysis chain

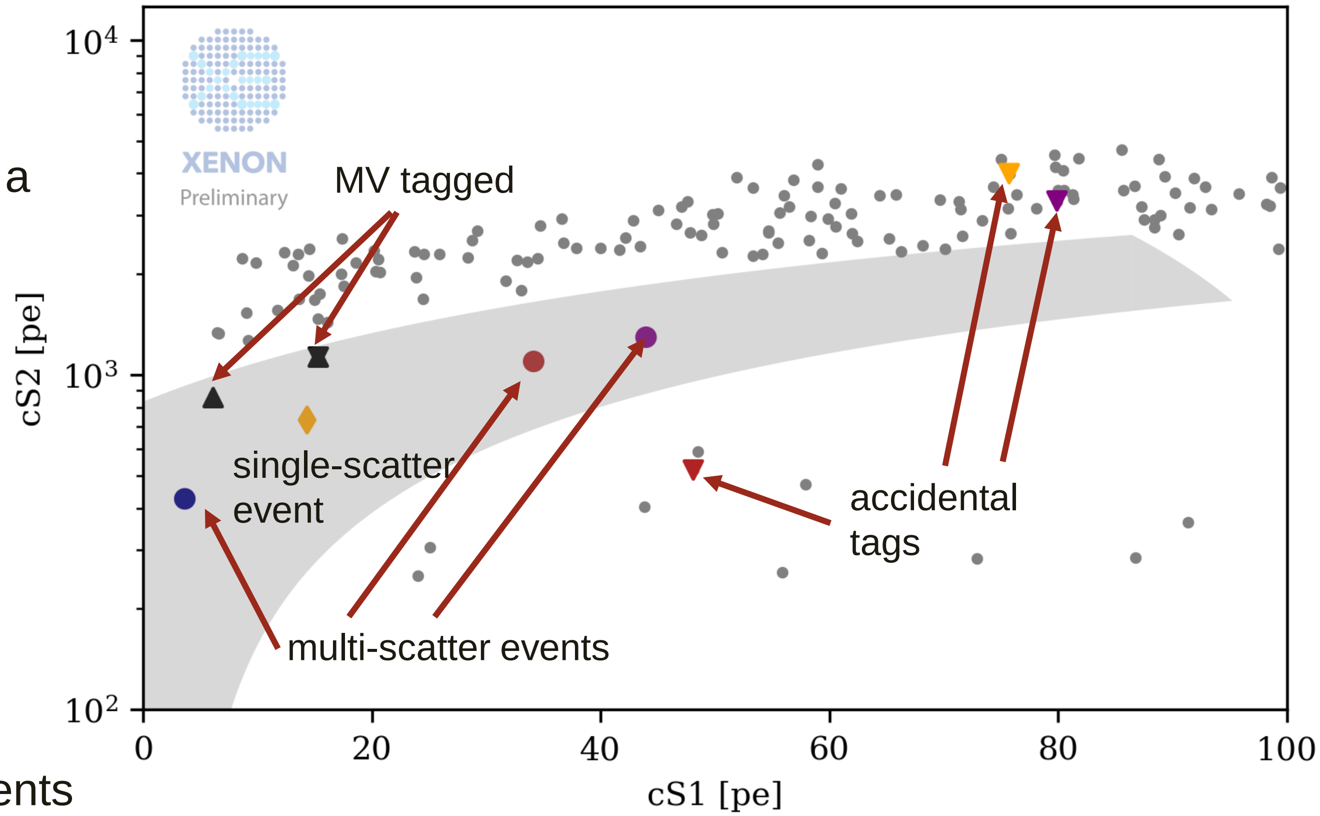






Background model NR search

- Validation with a NV tagged unblinding
  - Sign error in NV-TPC coincidence timing let to a wrong conclusion at first
  - Correct tagging predicts a ~x6 higher neutron background than simulations
- Background prediction based on a combined Poisson likelihood:
  - Number of tagged single- and multi-scatter events
  - Multi-to-single-scatter ratio (MS/SS) from simulations, validated with AmBe calibration data



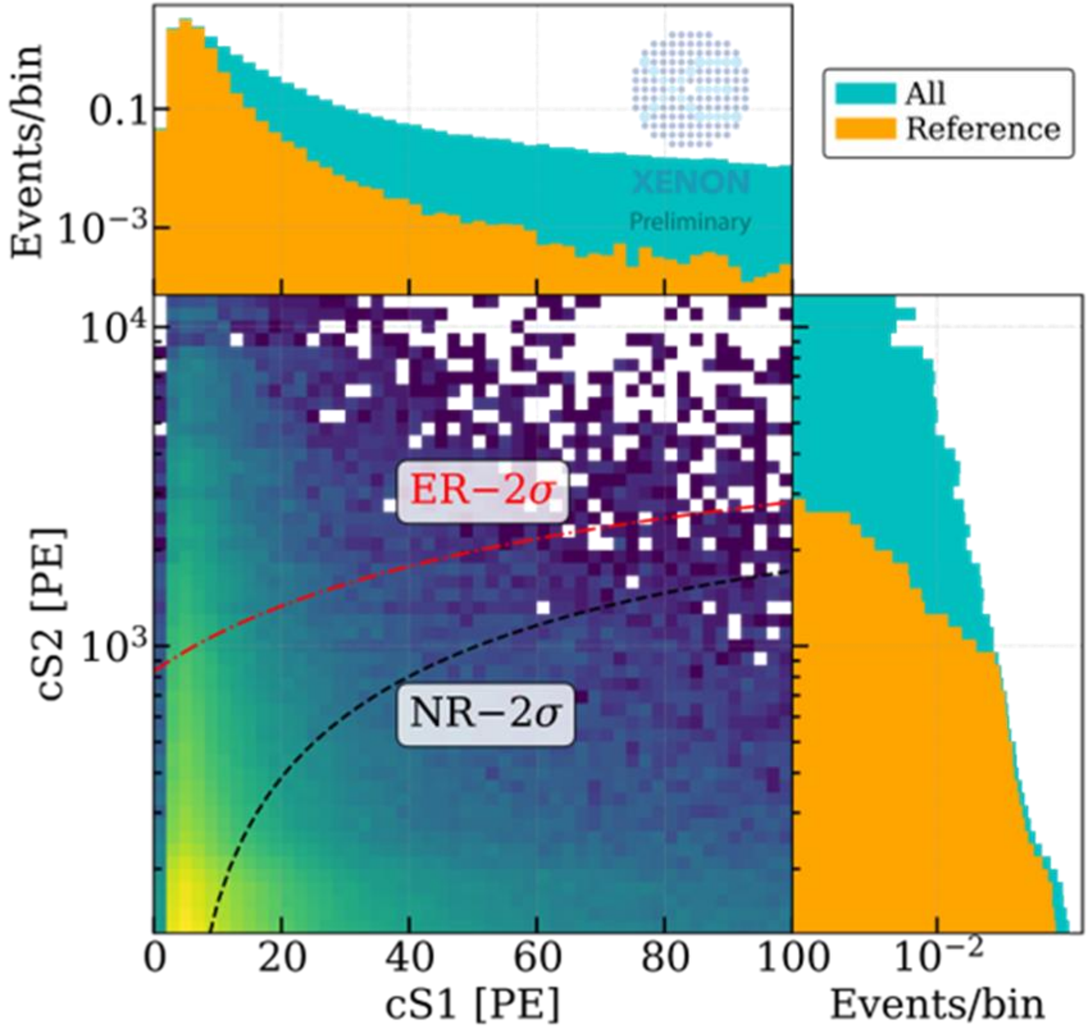
Total nominal neutron bkg.: $1.1^{+0.6}_{-0.5}$ evts

Background model NR search

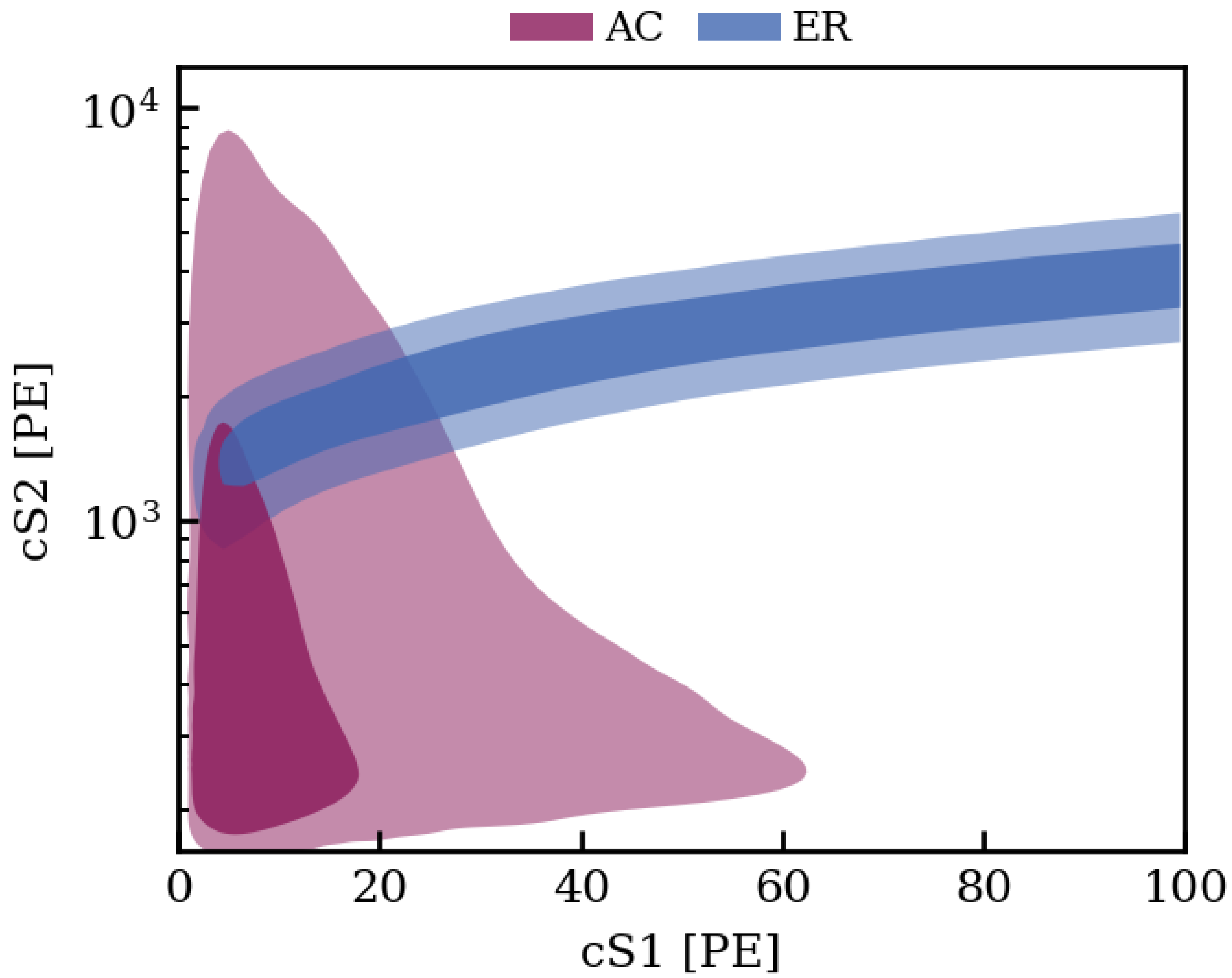
- Other NR background components:
  - Muons: Negligible, after MV tagging evaluated to be less than 0.01 events, w/o additional NV.
  - CEvNS: Constrained by ^{8}B neutrino flux, main uncertainty in rate due to uncertainties in the detector response model

Accidental coincidences

- Random pairing of S1 and S2 signals
- Model optimized on synthetic dataset due to triggerless DAQ approach
- Validate on sideband studies e.g., ^{37}Ar data
- **Dedicated cut** based on a **gradient boosted decision tree**, using S2 shape, are and Z information



Dark Matter ROI



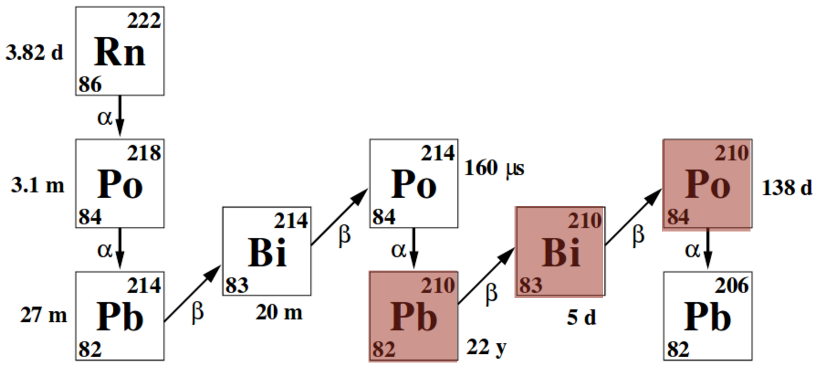
Surface background model

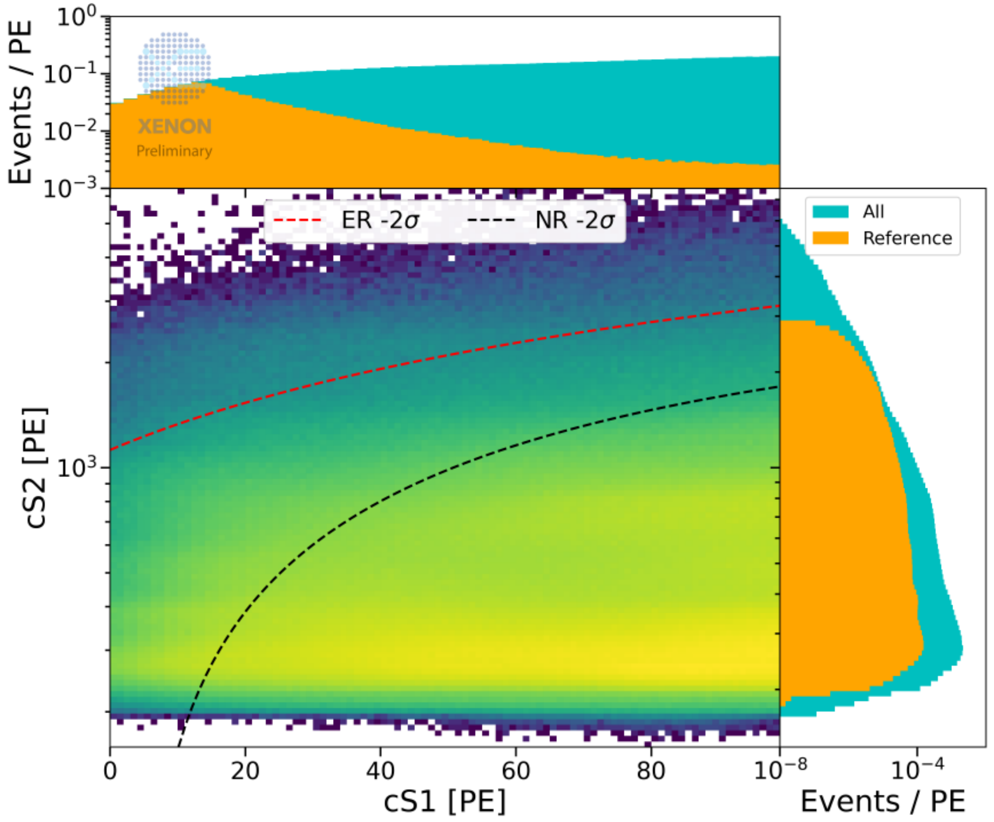
- **"Surface" events** due to ERs from **^{210}Pb plate out** at detector walls

- Use **events reconstructed outside the fiducial** volume and a KDE to create a **smooth template** for ROI

- Absolute rate **R,Z dependent**
  - Use events **reconstructed "below" blinded region**
  - Modeled based on a parametric likelihood fit
  - Rate estimated by counting events "inside"/"outside"

- **Reduced R_{max} < 61.35 cm** for **fiducial volume** compared to low ER analysis





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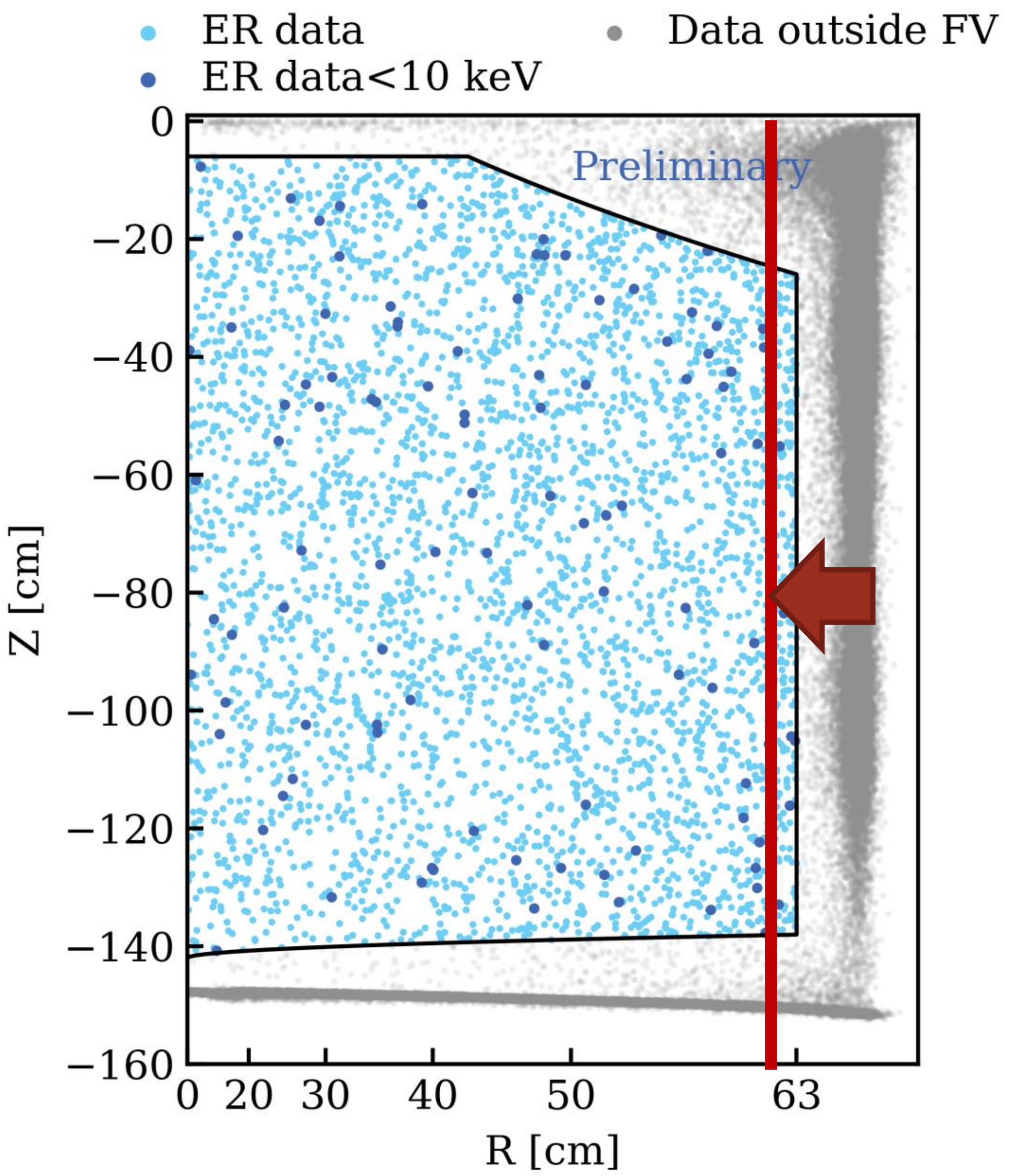

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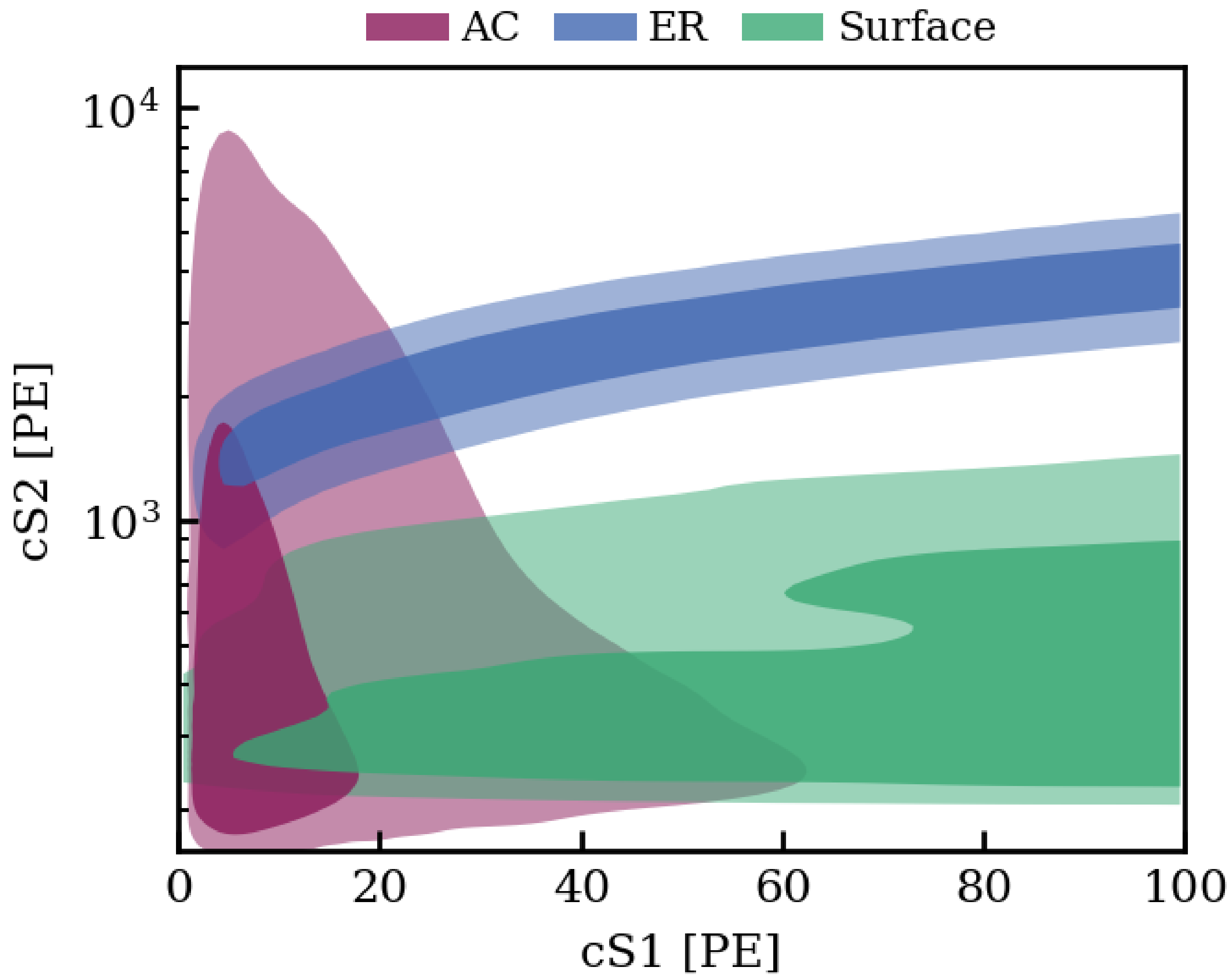

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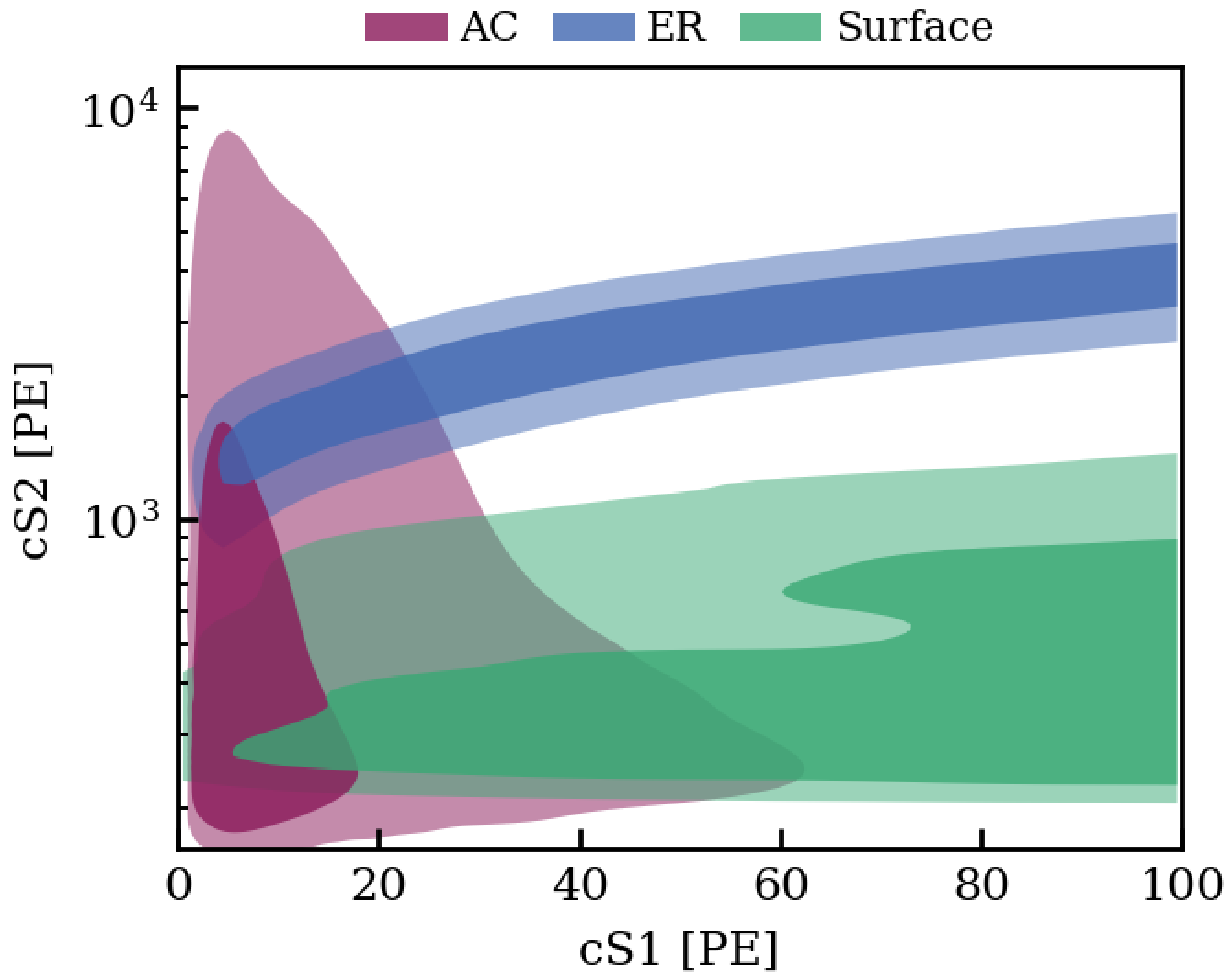
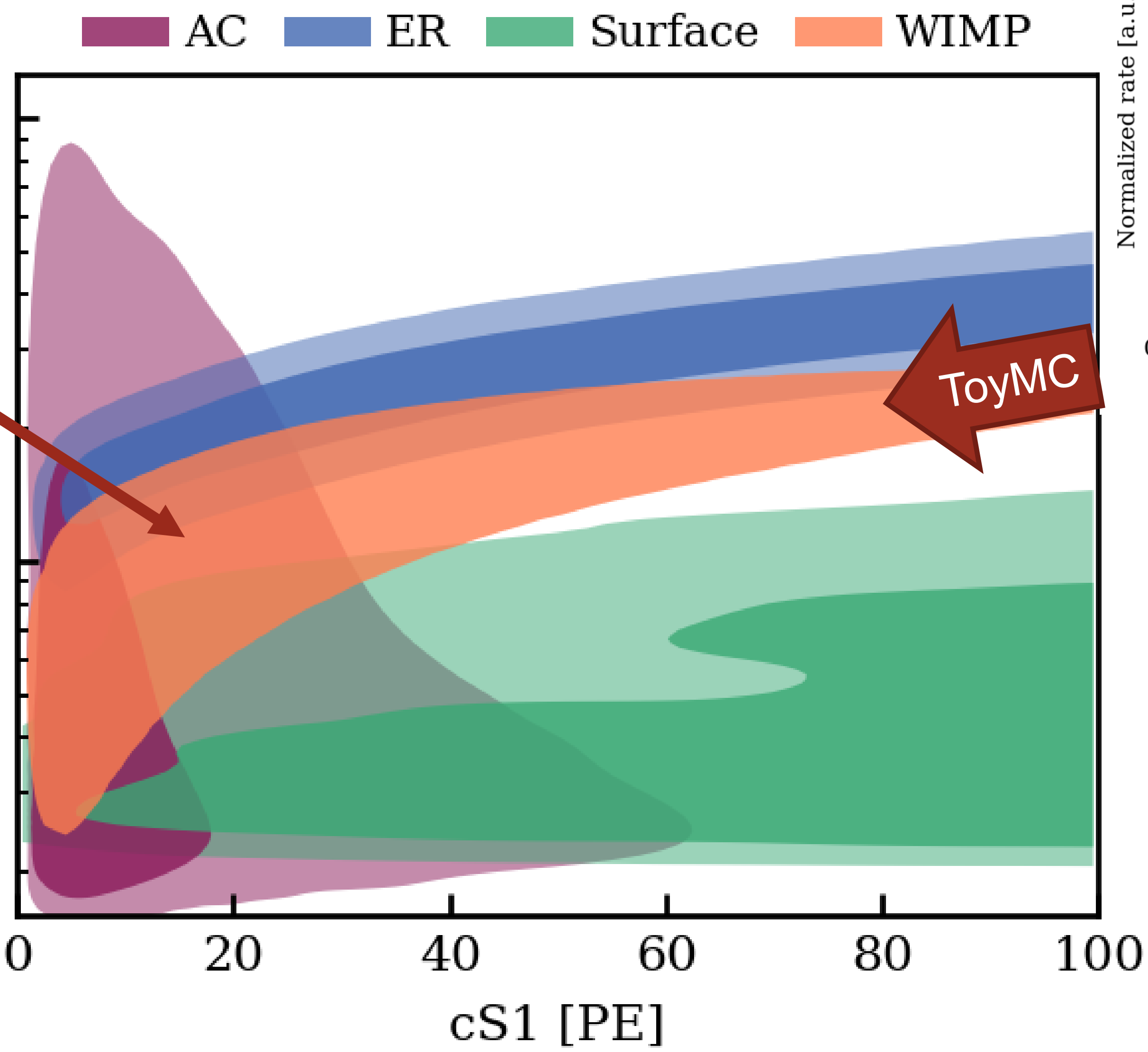
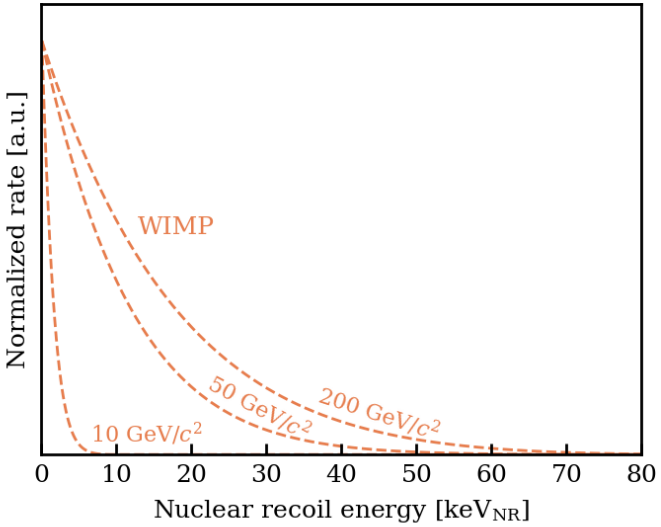
WIMP results

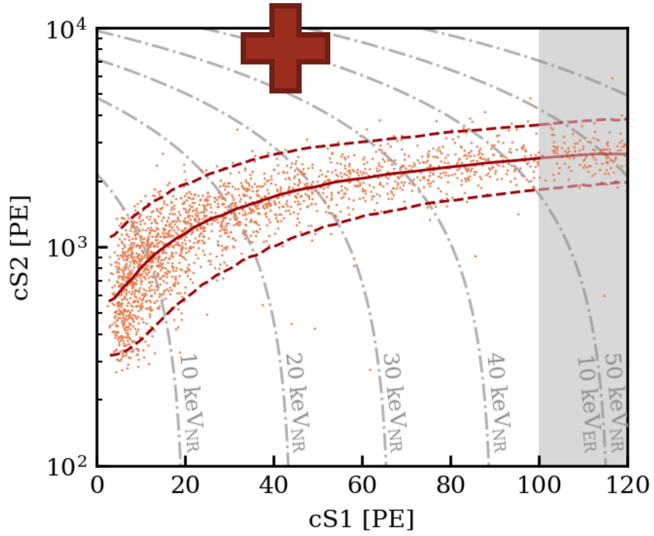


WIMP results

2 σ contour
200 GeV/c^2 WIMP







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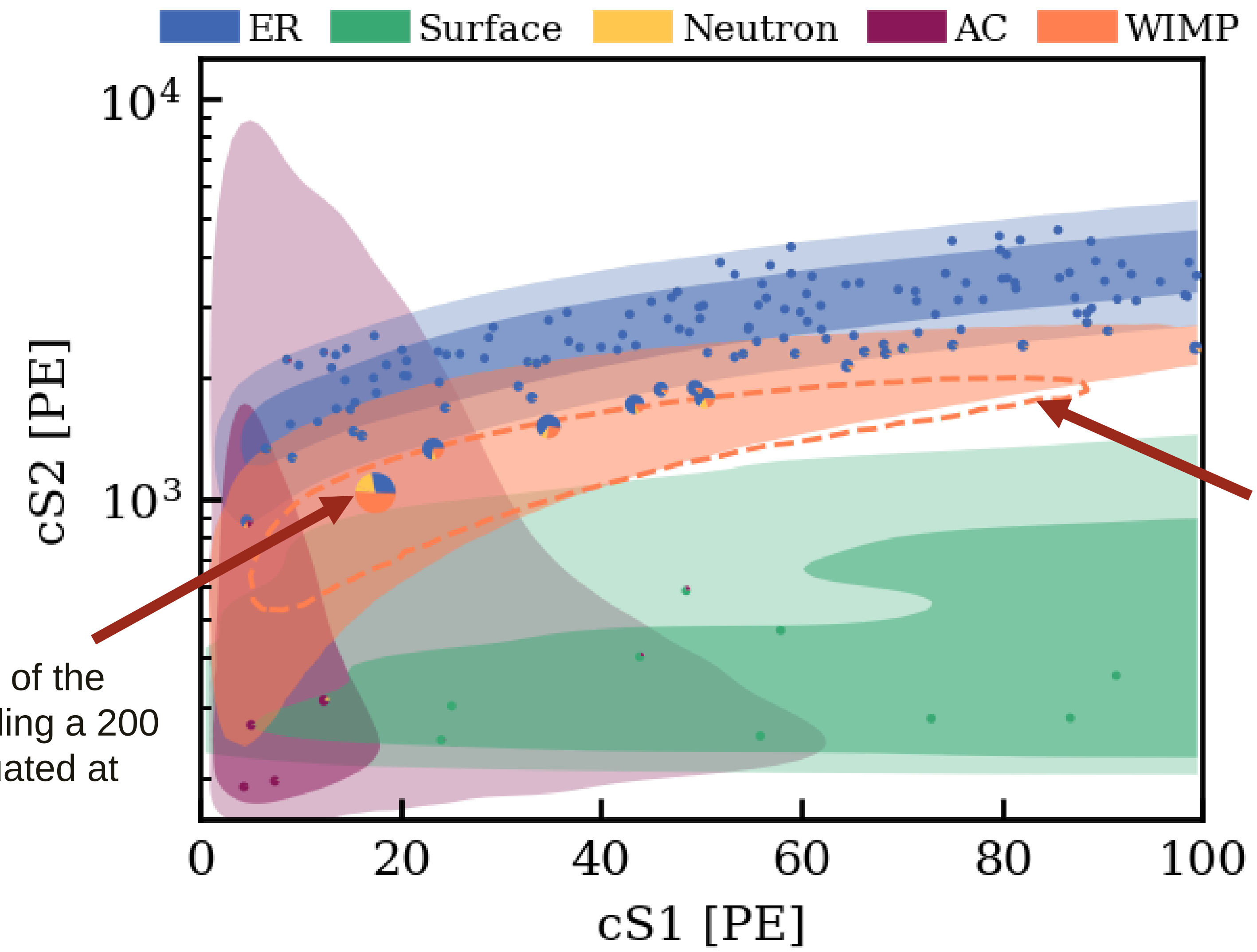


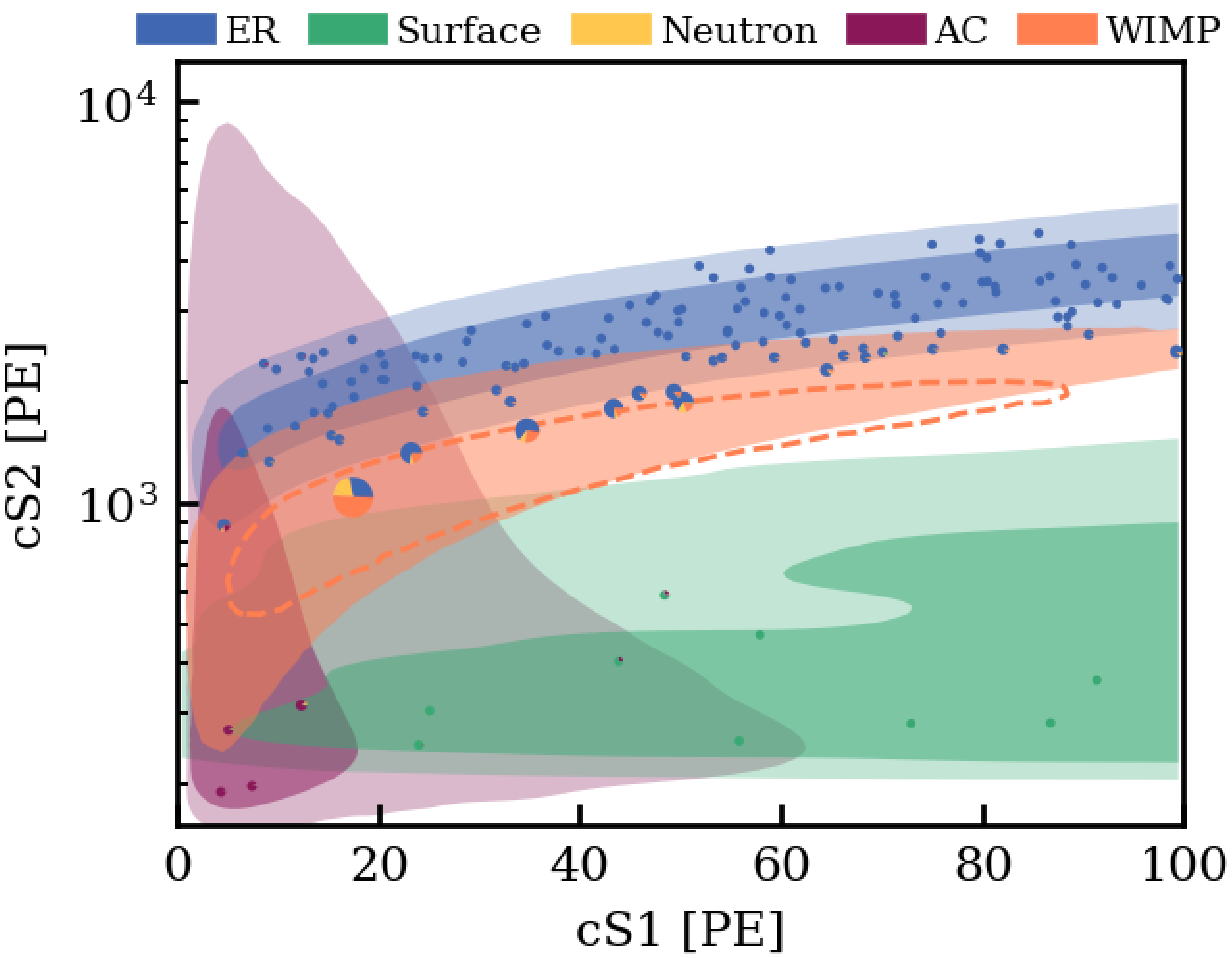
Signal-like region, containing 50% of a 200 GeV/c^2 WIMP signal with highest signal-to-noise ratio

Component fraction of the best fit model including a 200 GeV/c^2 WIMP evaluated at event position

WIMP results

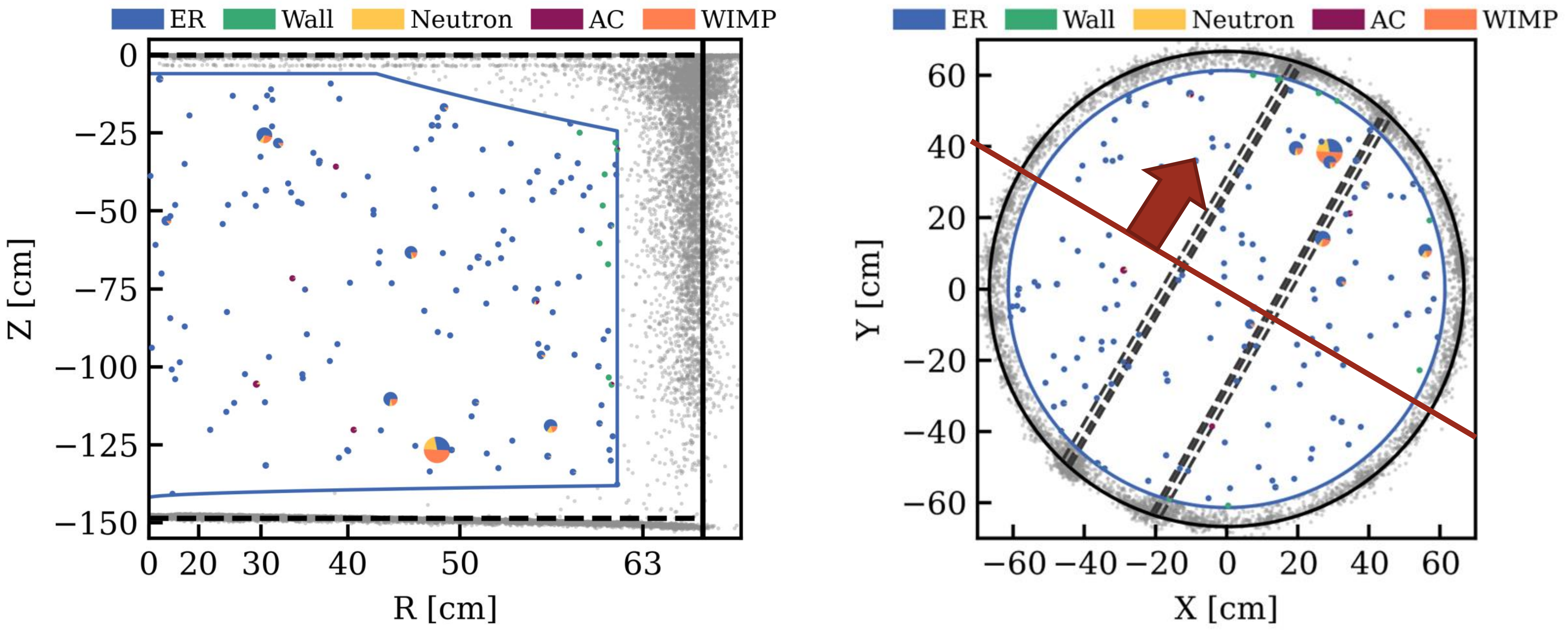
	Nominal	Best Fit	
	ROI		Signal-like
ER	134	135^{+12}_{-11}	0.81 ± 0.07
Neutrons	$1.1^{+0.6}_{-0.5}$	1.1 ± 0.2	0.42 ± 0.10
CEvNS	0.23 ± 0.06	0.23 ± 0.06	0.022 ± 0.011
AC	4.3 ± 0.2	4.32 ± 0.15	0.363 ± 0.013
Surface	14 ± 3	12^{+0}_{-4}	$0.34^{+0.01}_{-0.11}$
Total	154	152 ± 12	$1.95^{+0.12}_{-0.16}$
WIMP	-	2.4	1.2
Observed:	-	152	3

- 152 events in ROI, 16 in blinded region
- Best fit indicates **no significant excess**



WIMP results:

- XY asymmetry in unblinded data
- Not observed in corrections, data quality selections, or calibration data

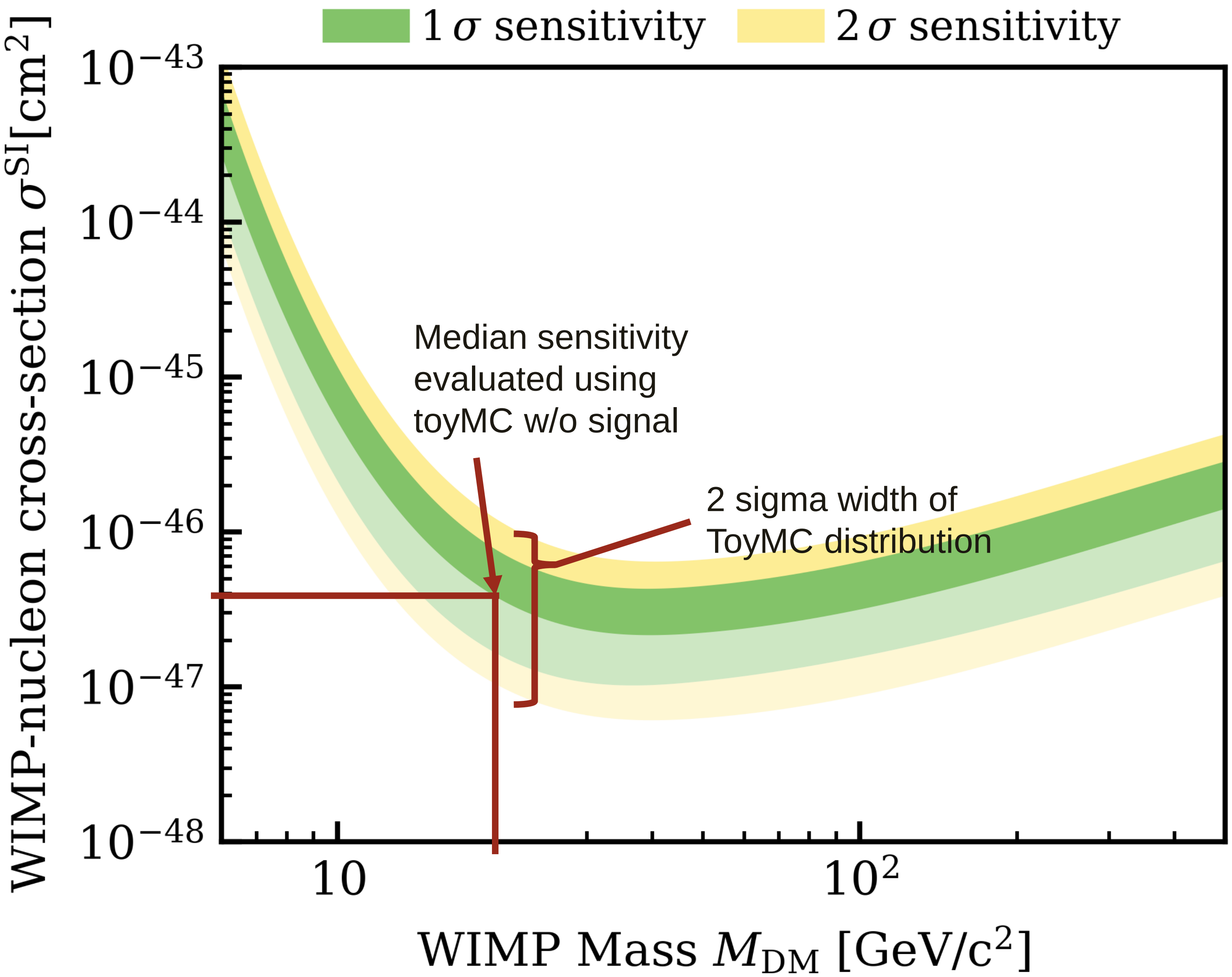


WIMP results

- Log-Likelihood-ratio as test statistics

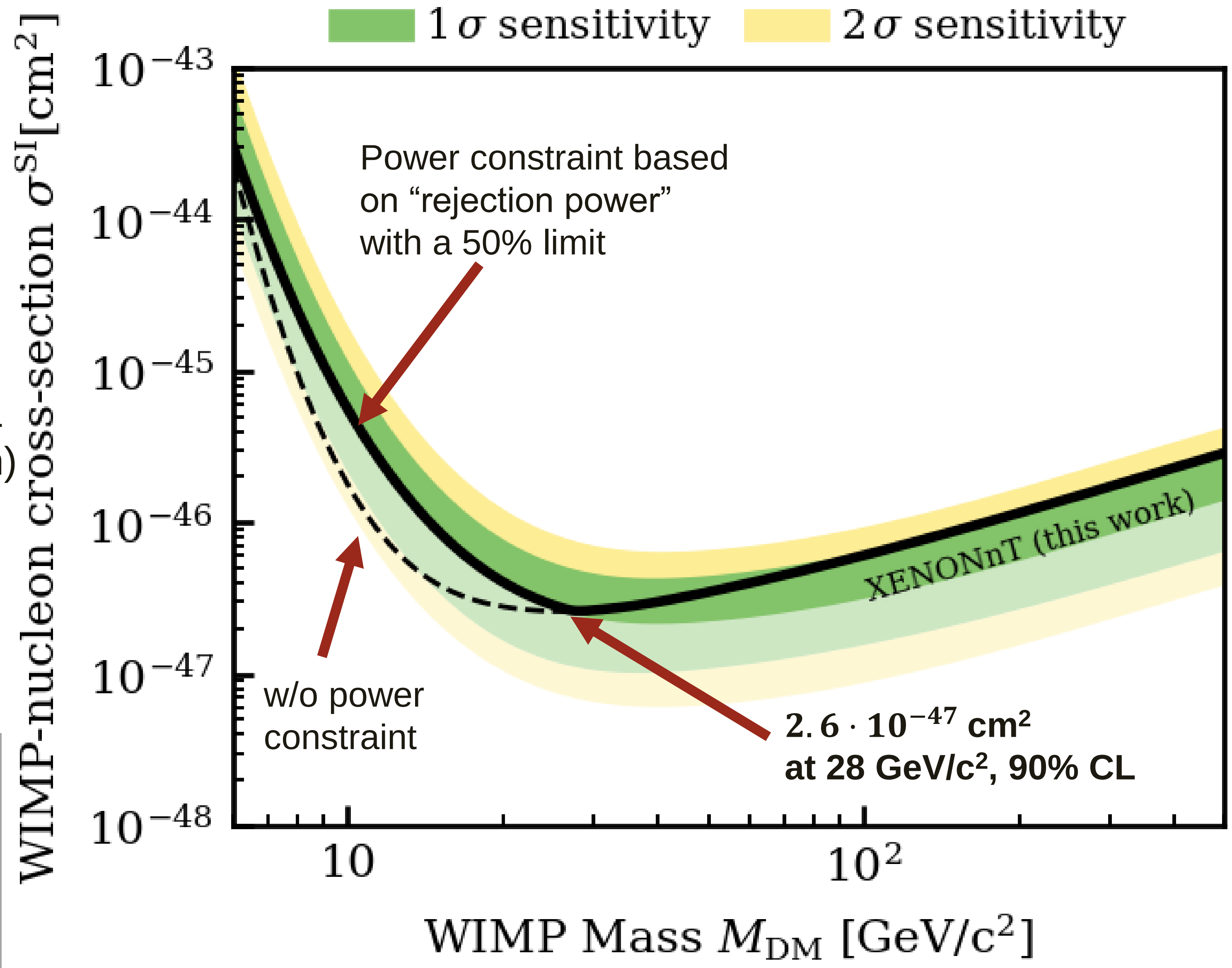
$$q(\sigma) = -2\log\frac{L(\sigma,\hat{\hat{\theta}})}{L(\hat{\sigma},\hat{\theta})}$$

- Median upper limit @ 90% confidence



WIMP results

- Power constraint limits (PCL) to avoid exclusion limits
- Before, defined on discovery power, now correct on rejection power
- Critical threshold raised from 0.16 (1 σ in asymptotic case) to 0.5 (median) as $\beta_r >> \alpha$
- 0.5 choice is too conservative, but needs to be discussed within the community



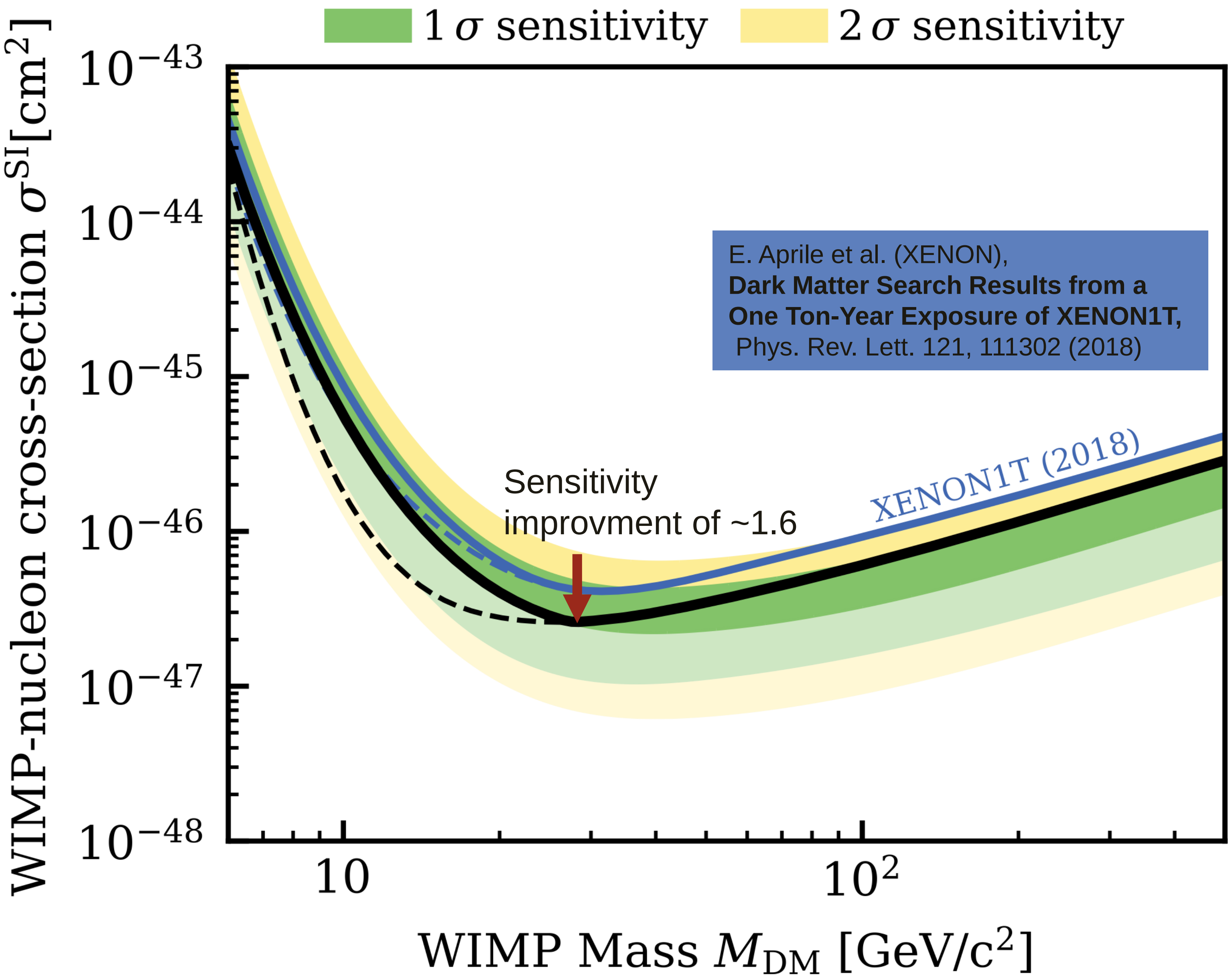
G. Cowan, K. Cranmer, E. Gross, O. Vitells, **Power-Constrained Limits** arxiv:1105.3166.

D. Baxter, et al. **Recommended conventions for reporting results from direct dark matter searches** European Physical Journal C, 81, 907 (2021)

WIMP results

Comparison

- Same approach applied to other results to make limits comparable



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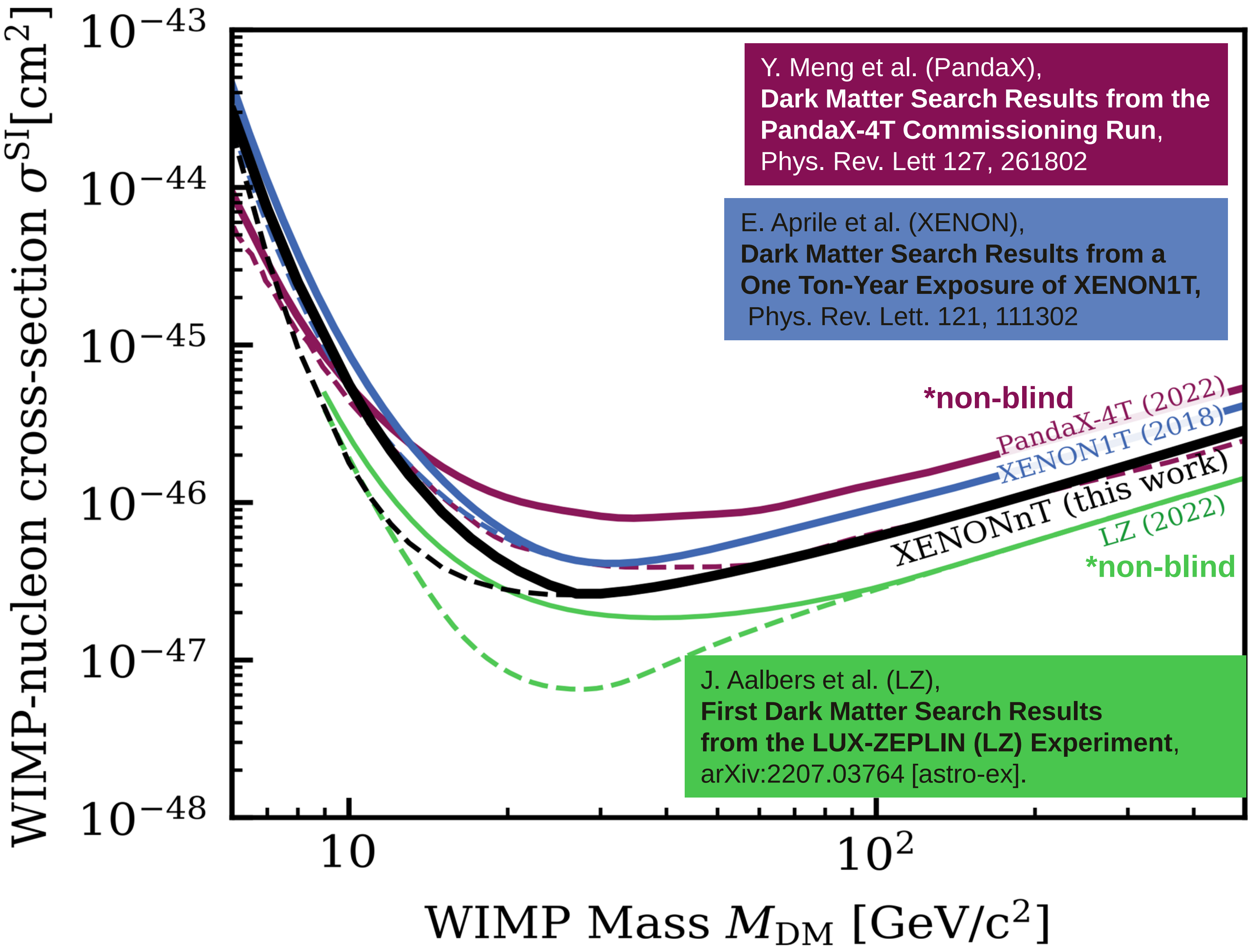
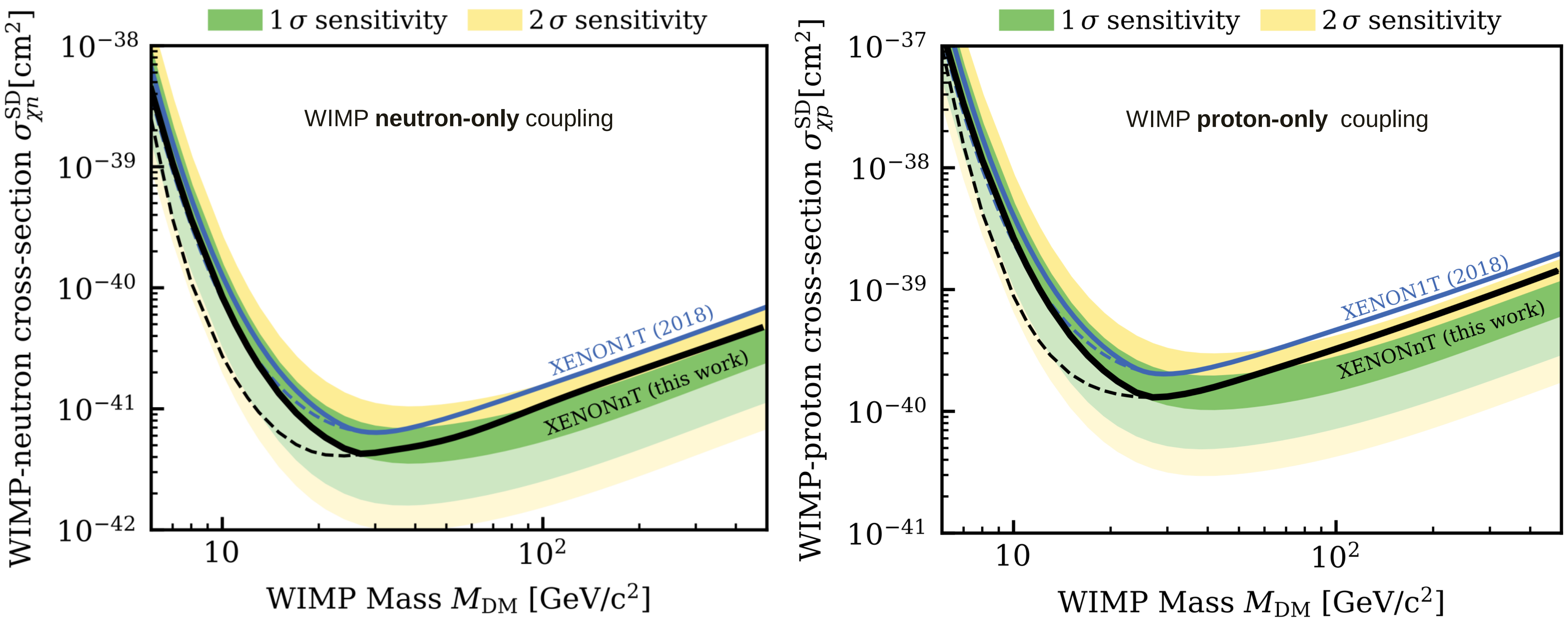


WIMP results

Spin-dependent interactions

- Non-zero spin operator for ^{129}Xe and ^{131}Xe, due to unpaired neutrons
- In general, more sensitive to neutron-spin coupling



Conclusion and Outlook

- Blinded WIMP dark matter search with **1.1 tonne-year exposure**
- Unprecedented low **ER background (15.8±1.3) events/(t·y·keV)**
- Best **limit for SI** at $\mathbf{2.6 \cdot 10^{-47}}$ **cm² at 28 GeV/c²** and 90% CL
- Data taking on going:

→ Further reduction of ^{222}Rn content due to GXe + LXe radon distillation

→ Gd-loading of NV: Increased tagging efficiency of 87% with a shorter 150 µs tagging window

E. Aprile *et al.*
Projected WIMP sensitivity of the XENONnT dark matter experiment
JCAP11(2020)031

Thank you very much

The paper will be available on arxiv and https://xenonexperiment.org/ soon…