First WIMP Search Results from the XENONnT Experiment

Daniel Wenz on behalf of the XENON collaboration
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PRISMA+ Colloquium 2023

Mainz 28.06.2023

"How to bake delicious dark matter chip cookies"

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PRISMA+ Colloquium 2023
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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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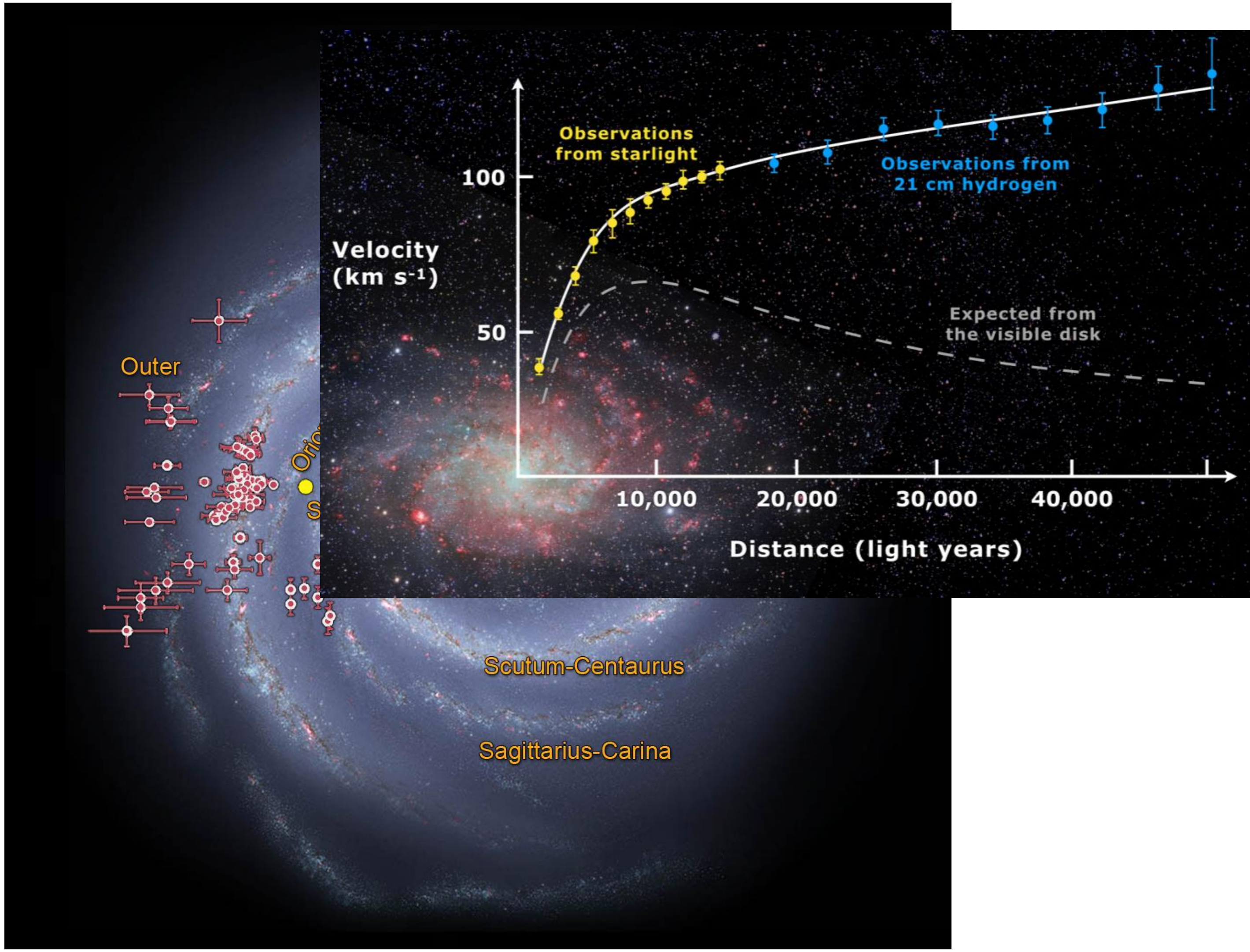
  ➡ Variety of evidence on different time and mass scales

- Local scale of galaxies and clusters:
  - Rotation curves



Dark Matter Evidence

- Decades of astronomical surveys

  ➔ Variety of evidence on different time and mass scales

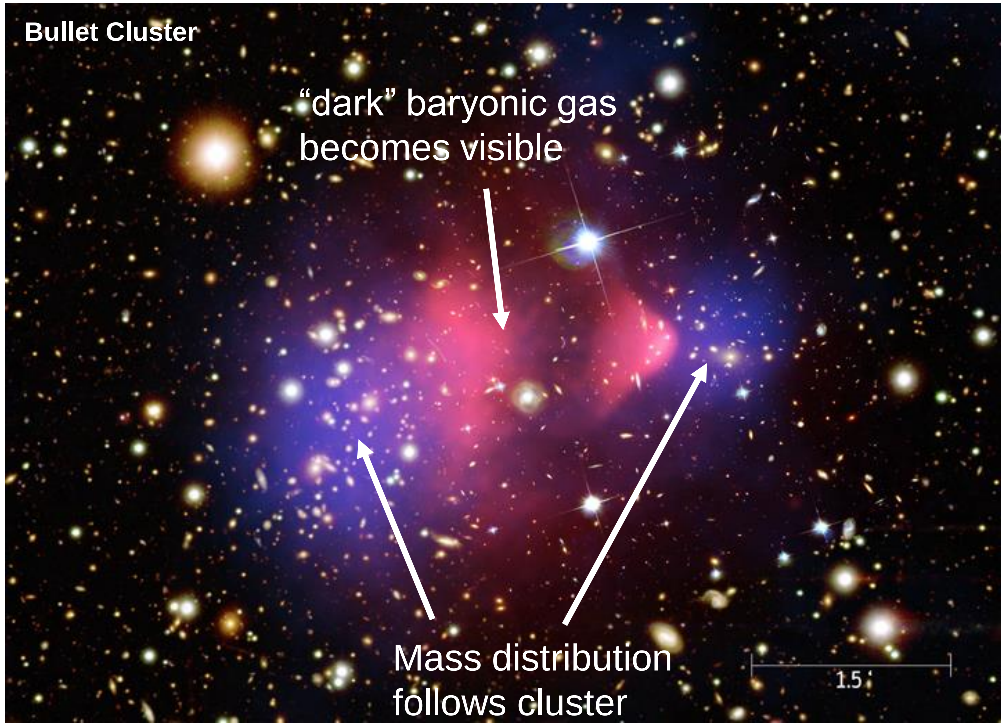
- Local scale of galaxies and clusters:
  - Rotation curves
  - Cluster movement, collisions and gravitational lensing

Virial Theorem:

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

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

➔ **More mass than visible**

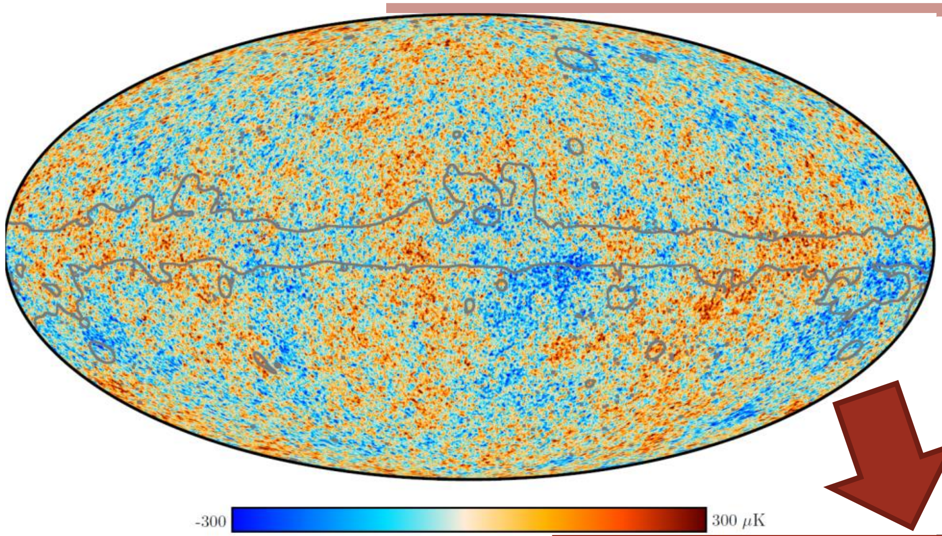


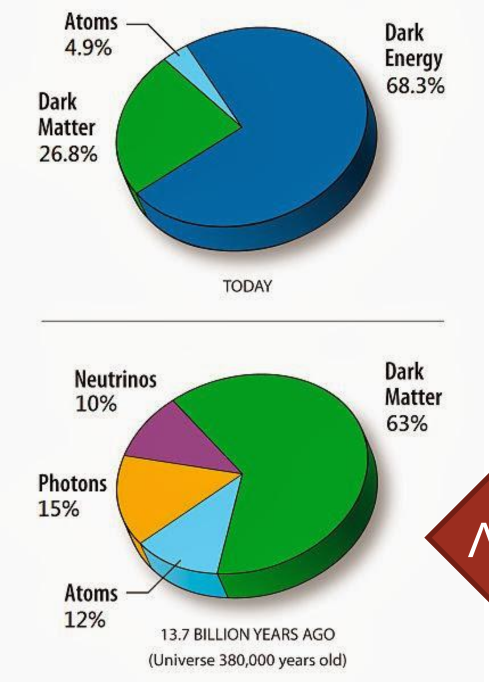
Dark Matter Evidence

- Decades of astronomical surveys

  Variety of evidence on different time and mass scales

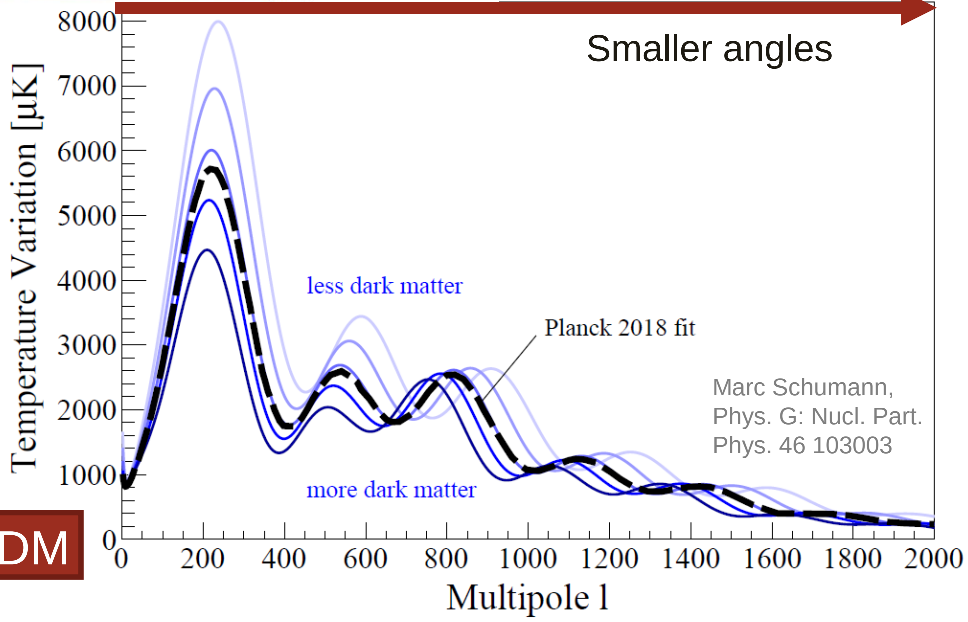
- Local scale of galaxies and clusters:
  - Rotation curves
  - Cluster movement, collisions and gra lensing
- Cosmic scales
  - Structure formation of the universe
  - Cosmic microwave background





ΛCDM

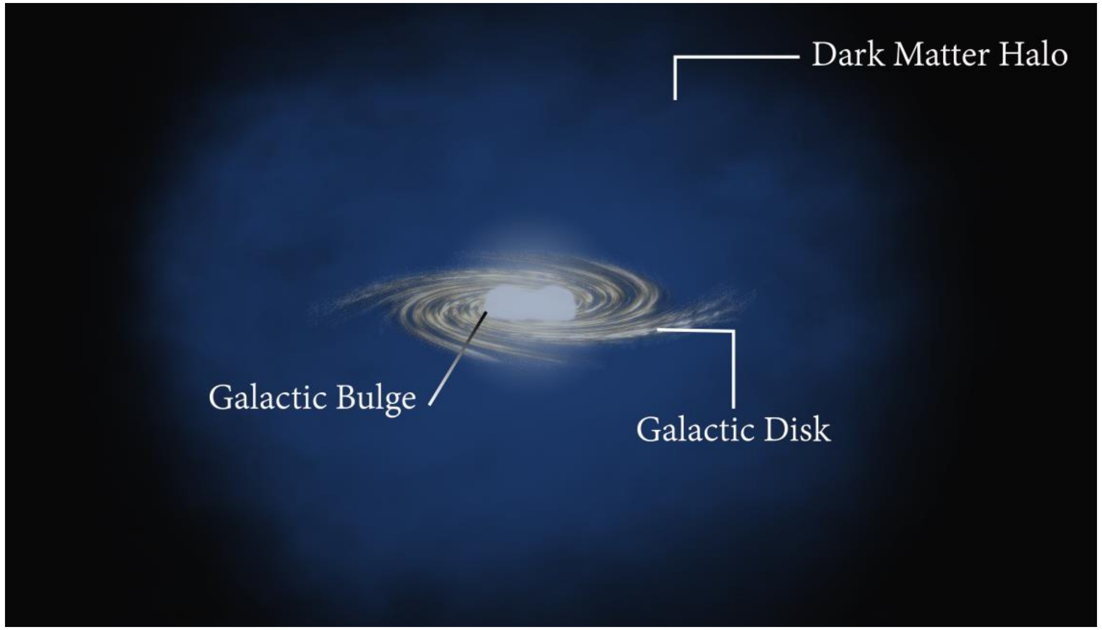
Smaller angles



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

DM detection

- What do we know based on astronomical observations?
  - Must be non-baryonic
  - 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?**



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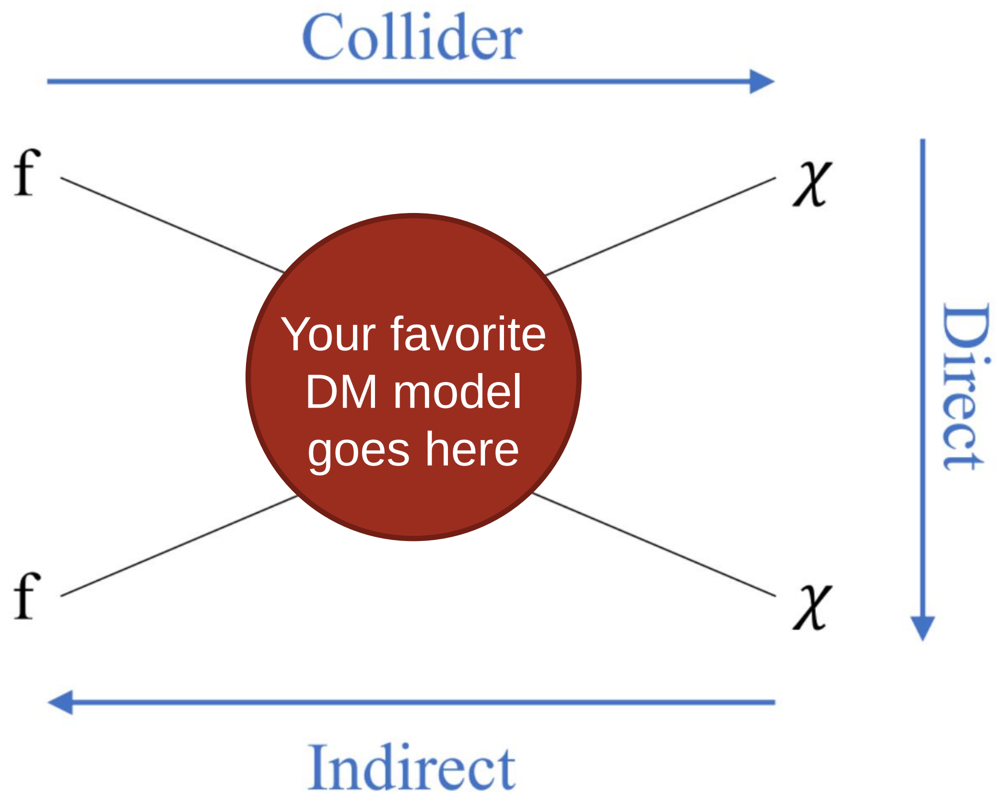

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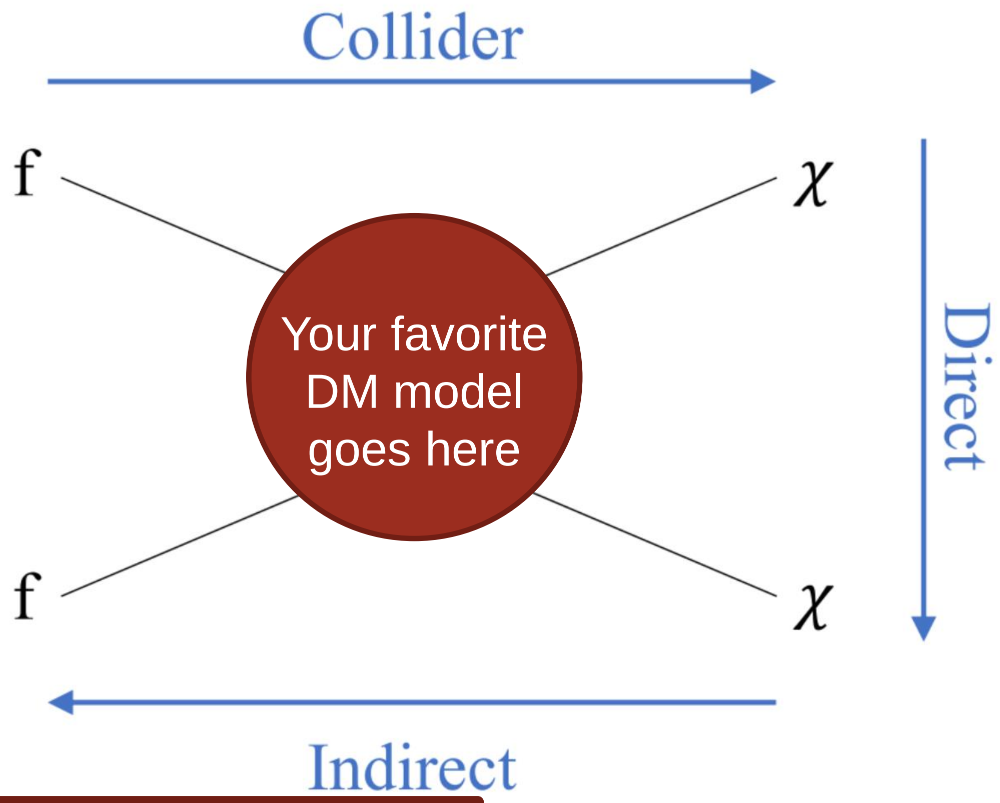
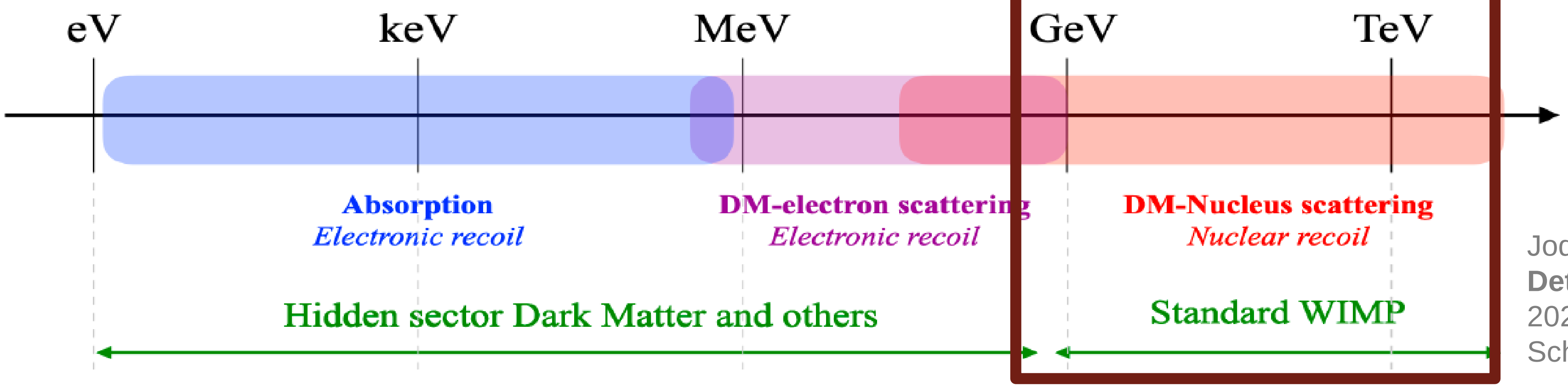


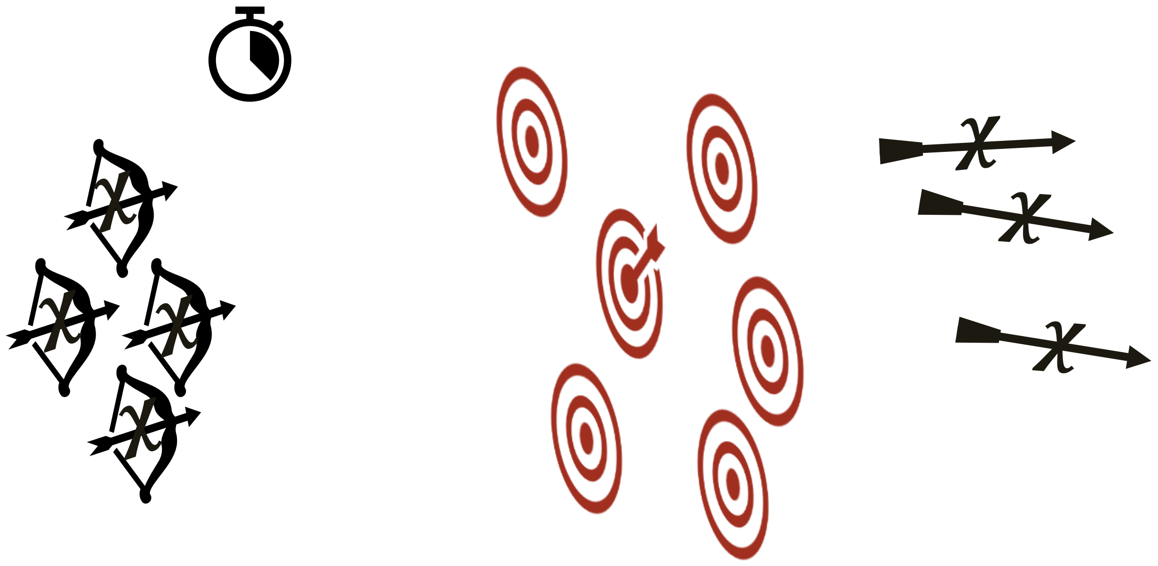


Jodi Cooley, **Dark Matter Direct Detection of Classical WIMPs**, 2021 Les Houches Summer School lecture manuscript

DM direct detection

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{M_T \cdot \rho_0}{m_\chi m_N} \int_{v_{min}}^{v_{esc}} v\, f(\vec{v})\, \frac{\mathrm{d}\sigma_{\chi,N}}{\mathrm{d}E_R}\, \mathrm{d}v$$

DM direct detection



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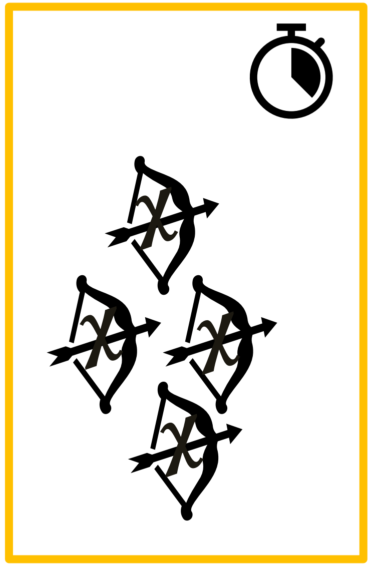
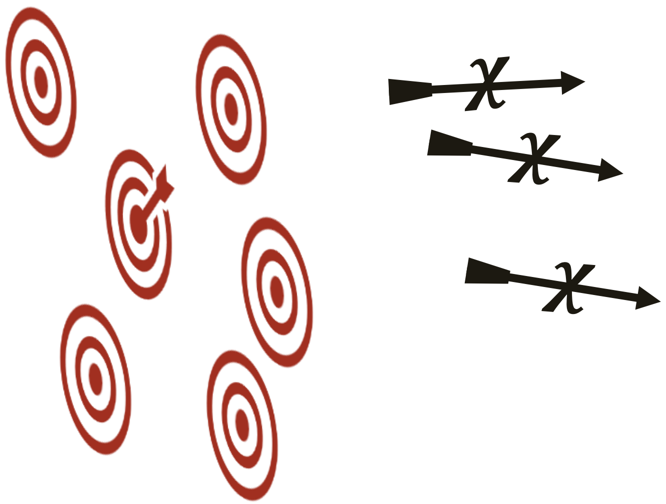
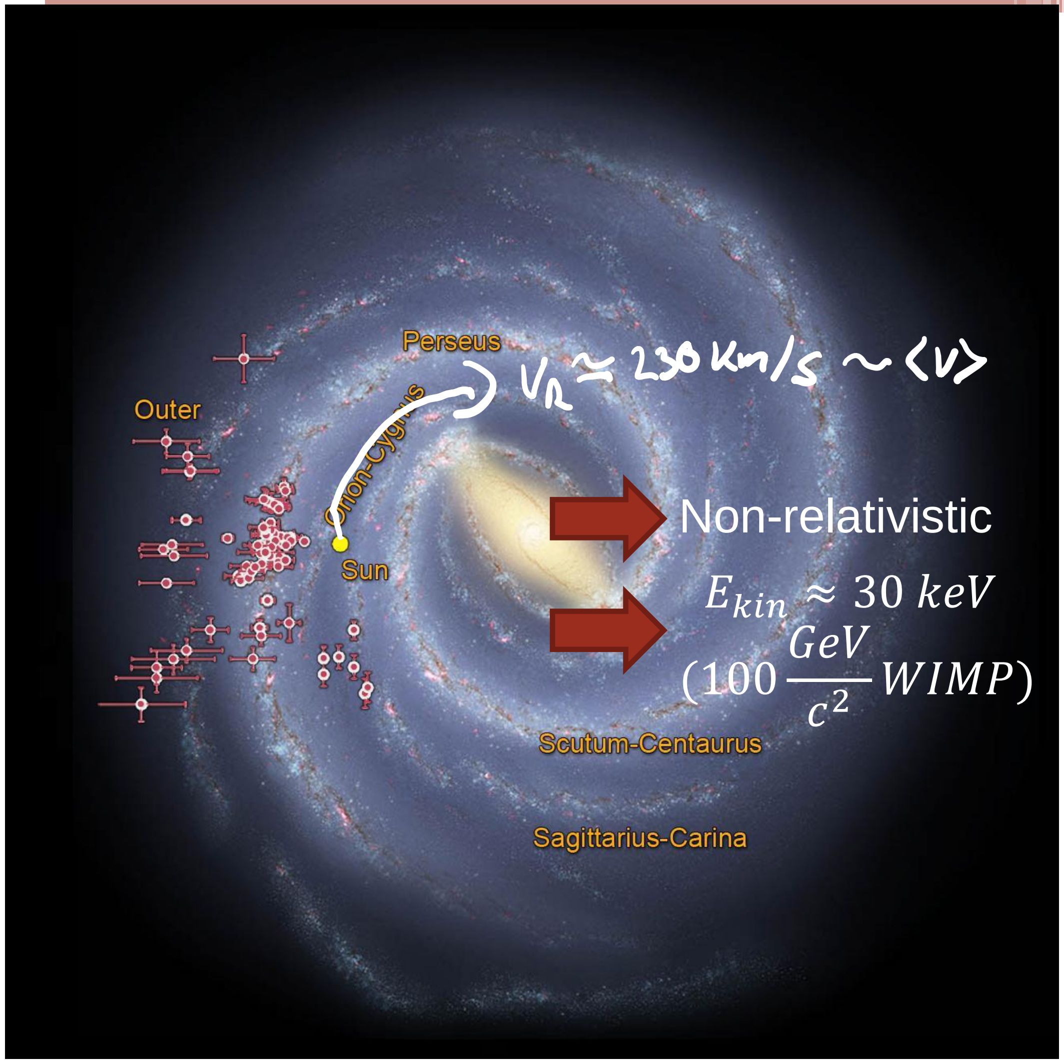
DM direct detection

Astrophysical inputs





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

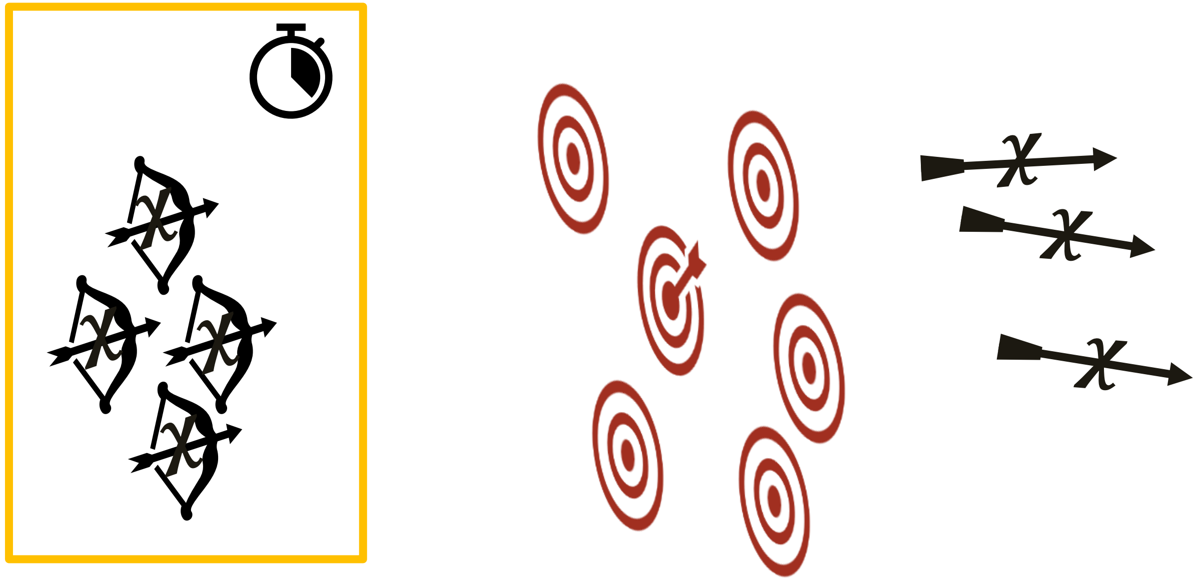


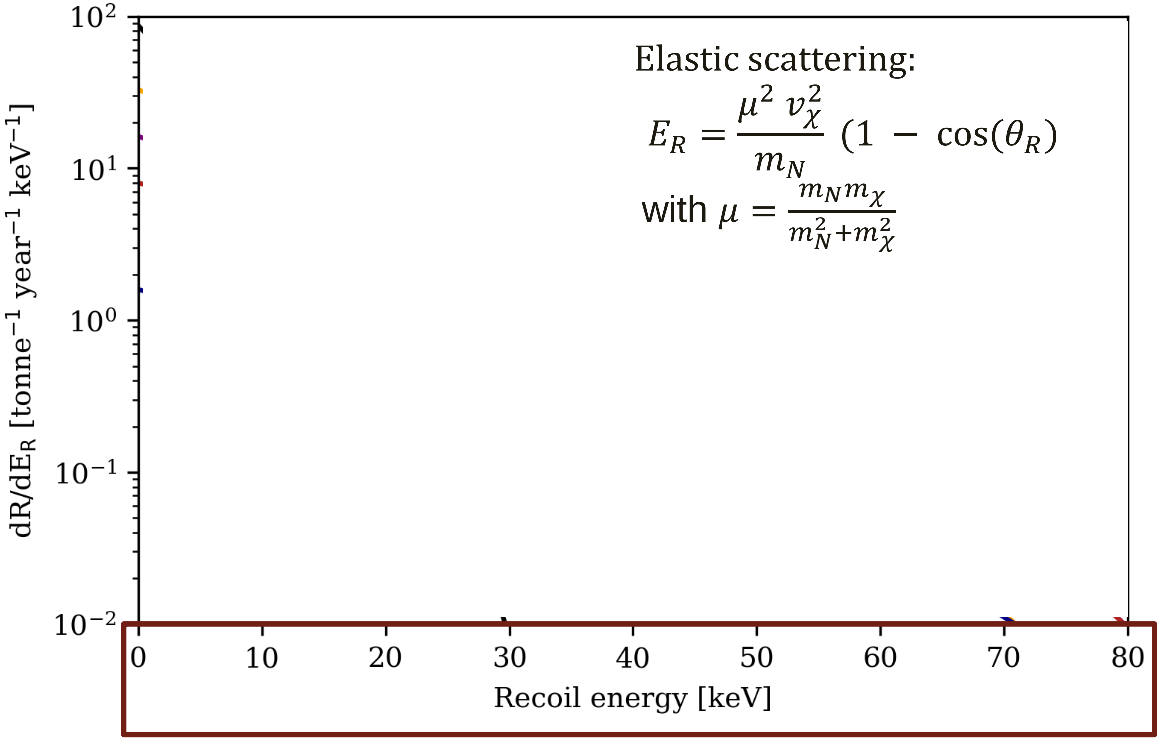
Canonical value:

$$\rho_0 = 0.3\,\mathrm{GeV/c^2/cm^3}$$

DM direct detection

Astrophysical inputs





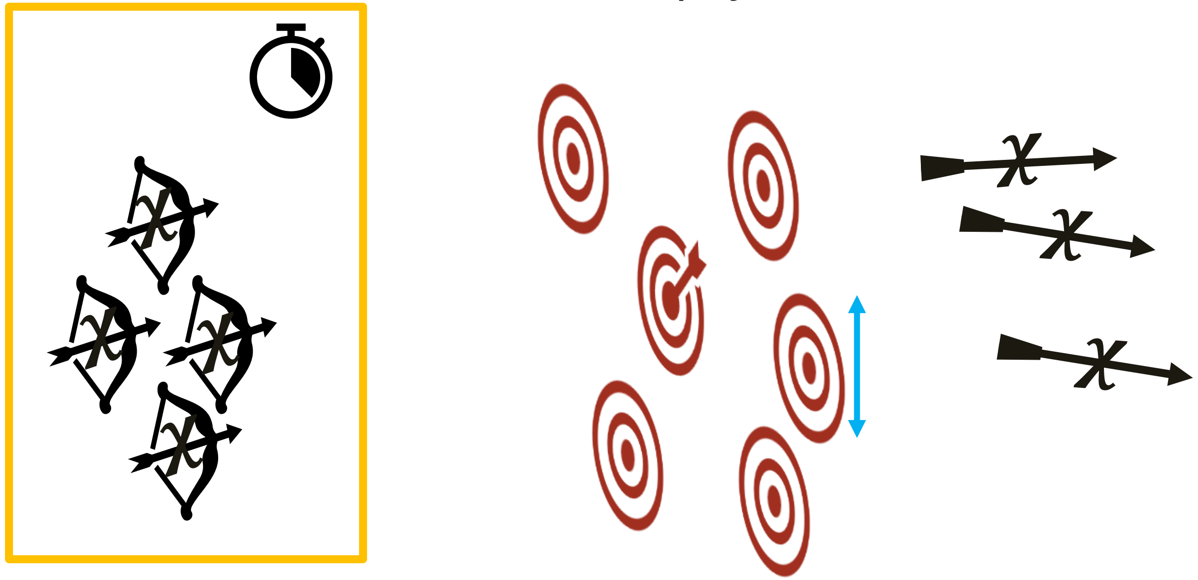
<< Binding energies nucleons interaction anticipated to be elastic

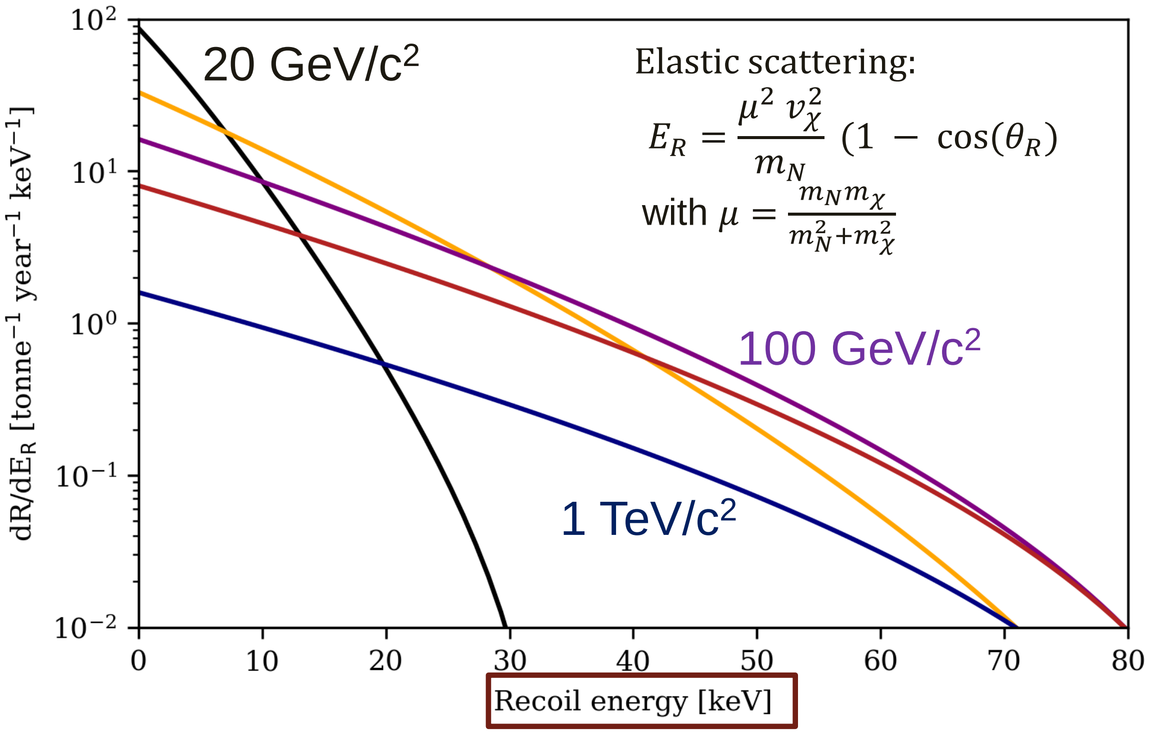
$$\frac{dR}{dE_R} = \frac{M_T \cdot \rho_0}{m_\chi m_N} \int_{v_{min}}^{v_{esc}} v\, f(\vec{v}) \frac{d\sigma_{\chi,N}}{dE_R}\, dv$$

DM direct detection

Astrophysical inputs

Nuclear and particle, and … physics





$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{M_T \cdot \rho_0}{m_\chi m_N} \int_{v_{min}}^{v_{esc}} v\, f(\vec{v}) \frac{\mathrm{d}\sigma_{\chi,N}}{\mathrm{d}E_R} \mathrm{d}v$$

de Brogile: $\lambda \cong 16.5\,\mathrm{pm}$

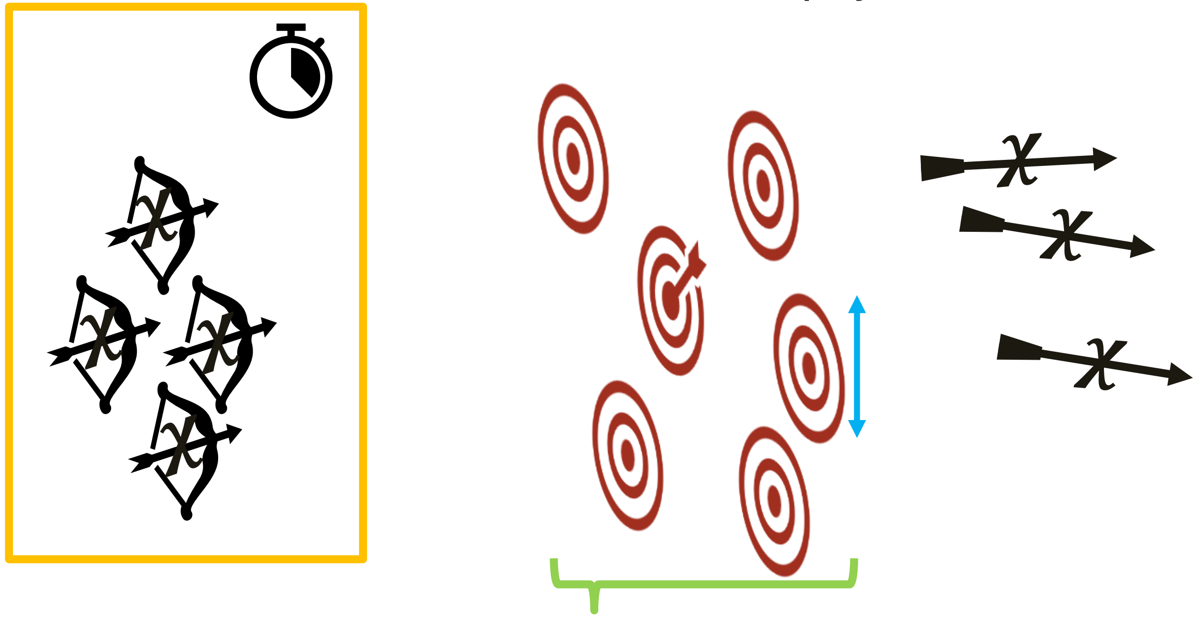
Nucleus not resolved, coherent elastic scattering

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_R} = \left[\underbrace{\left(\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}\right)_{\mathrm{SI}}}_{\propto A^2} + \underbrace{\left(\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}\right)_{\mathrm{SD}}}_{\propto j, S_n, S_p}\right]$$

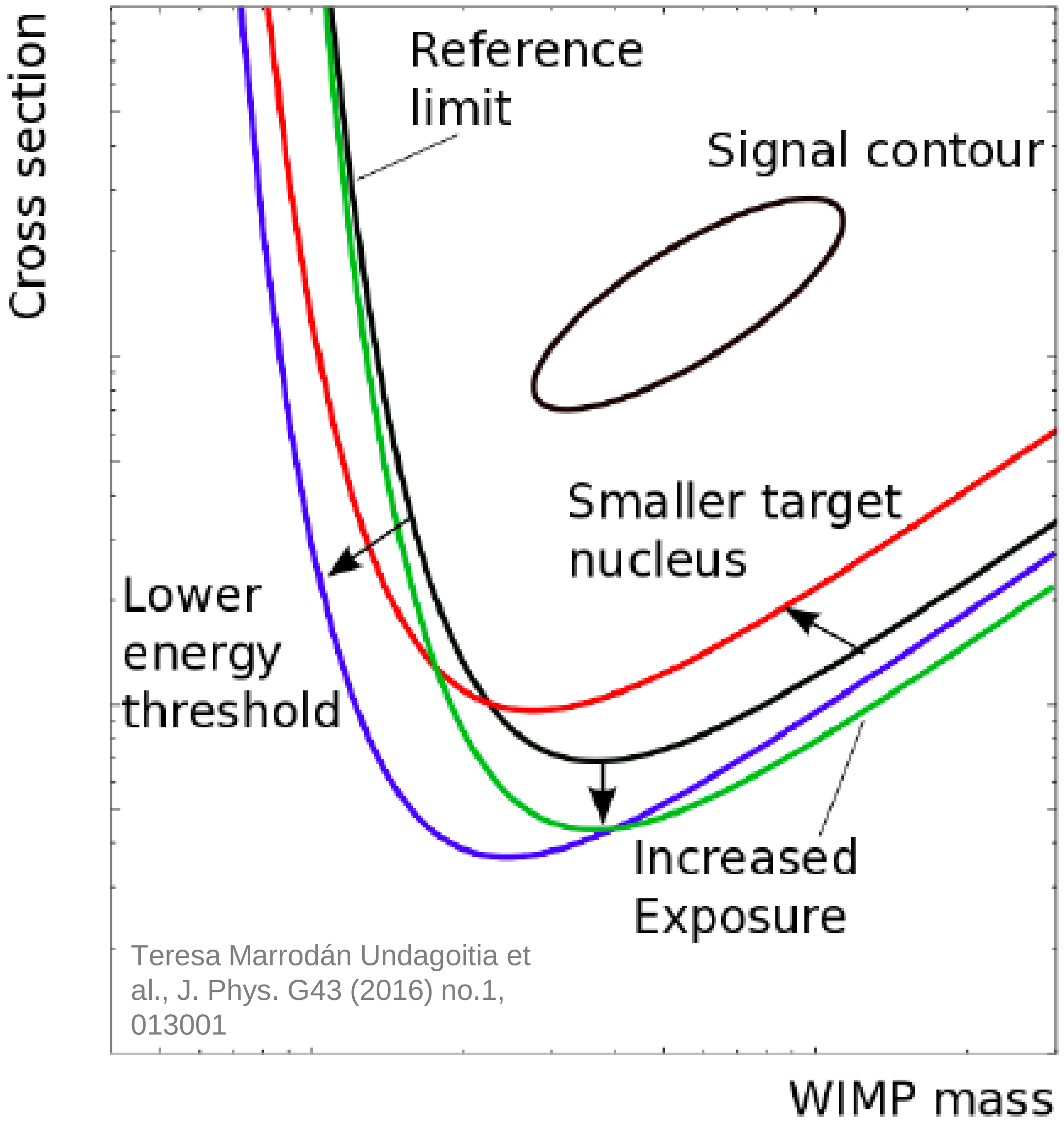
DM direct detection

Astrophysical inputs

Nuclear and particle, and detector physics



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



Teresa Marrodán Undagoitia et al., J. Phys. G43 (2016) no.1, 013001

Dark Matter Cookies

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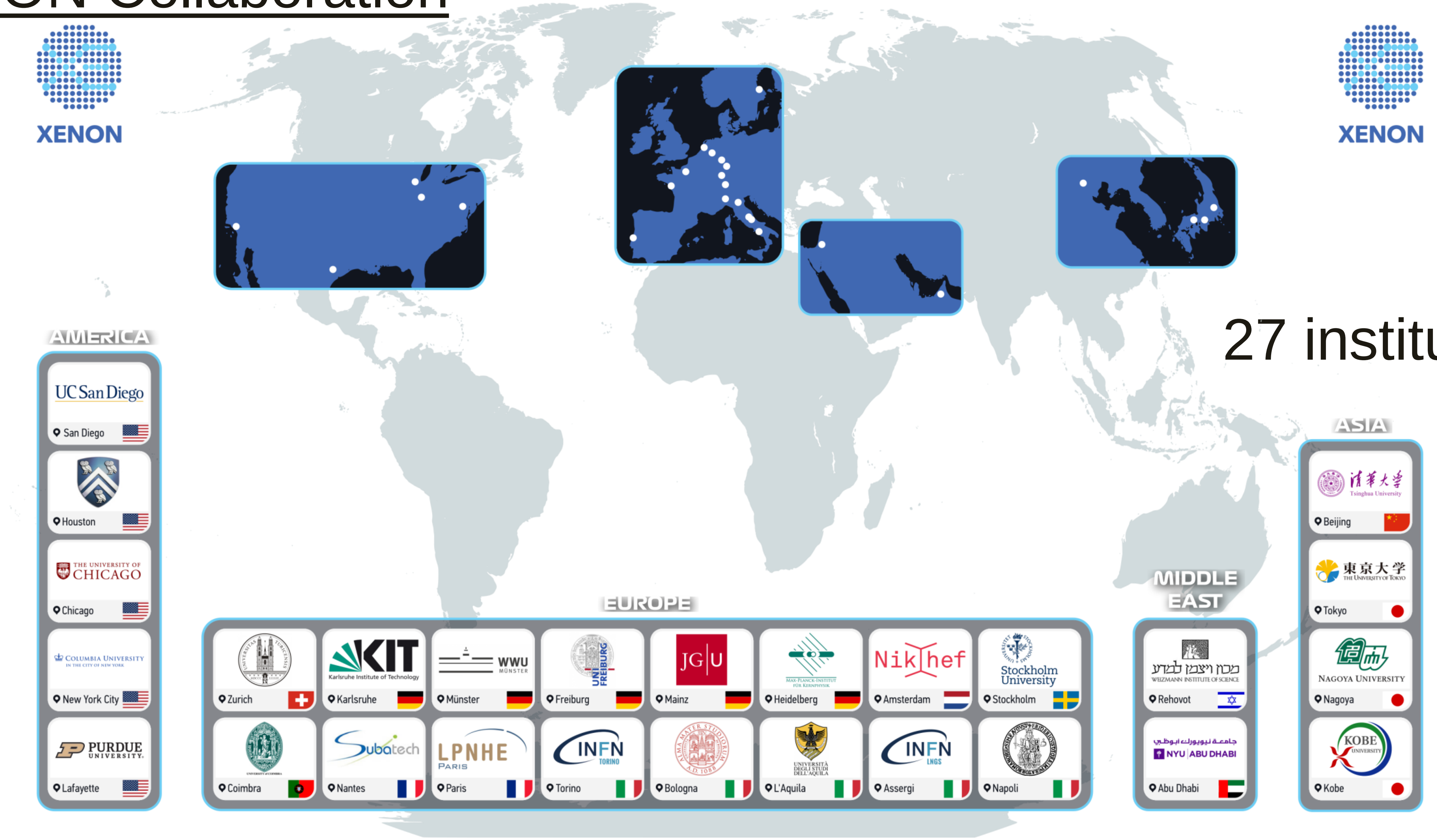
XENON Collaboration

XENON

XENON

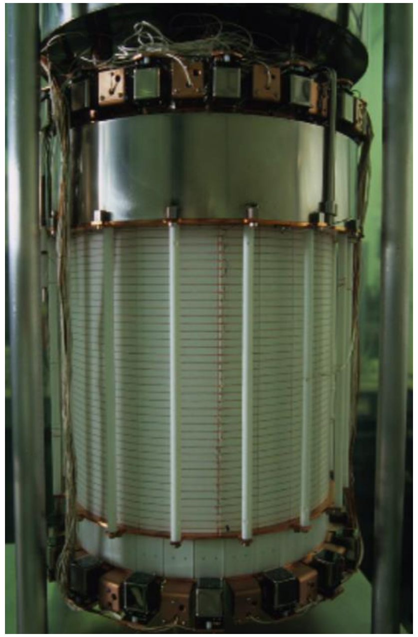
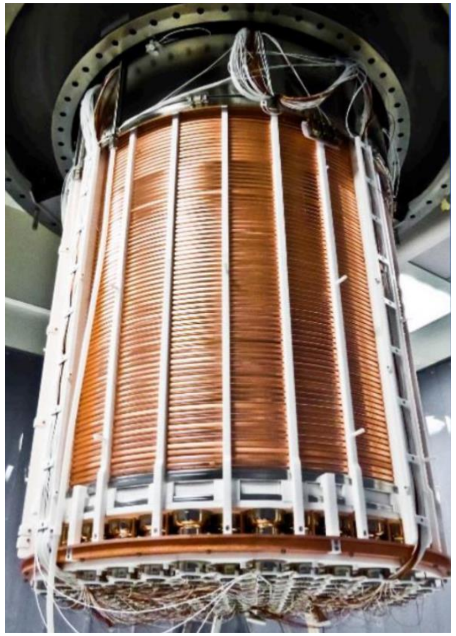
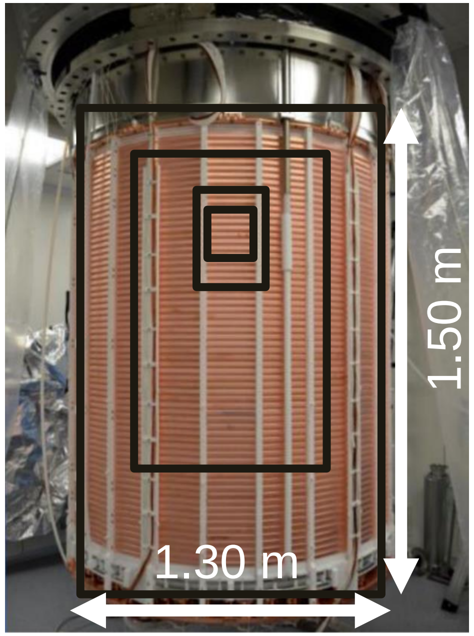


27 institutes

XENON Collaboration

~180 members

The XENON evolution

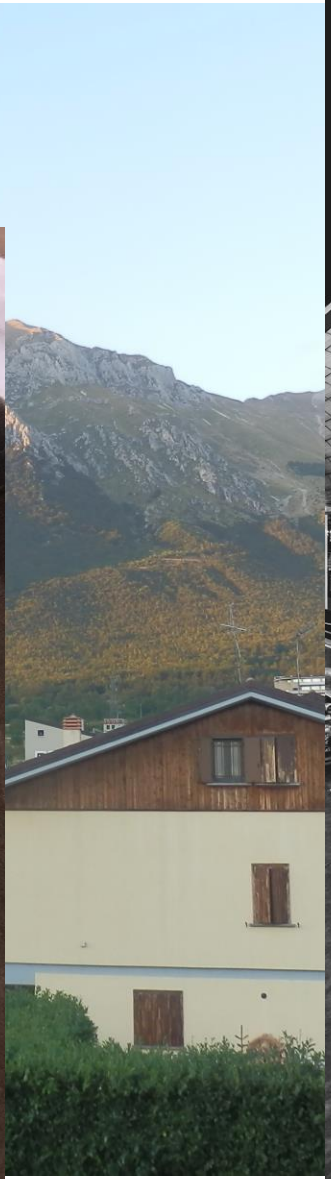
XENON10	XENON100	XENON1T	XENONnT
2005-2007	2008-2016	2012-2019	2020-2026
14 kg Xe target	62 kg Xe target	2 t Xe target	5.9 t Xe target, 8.5 t total mass
~10^{-43} cm^2	~10^{-45} cm^2	$4 \cdot 10^{-47}$ cm^2	$1.4 \cdot 10^{-48}$ cm^2 (projected for 20 t·y exposure) (Flea)
~2M background ER / (keV· t·y)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

^{40}K ~3500 decays per second

XENON @ LNGS

XENON @ LNGS

XENON @ LNGS



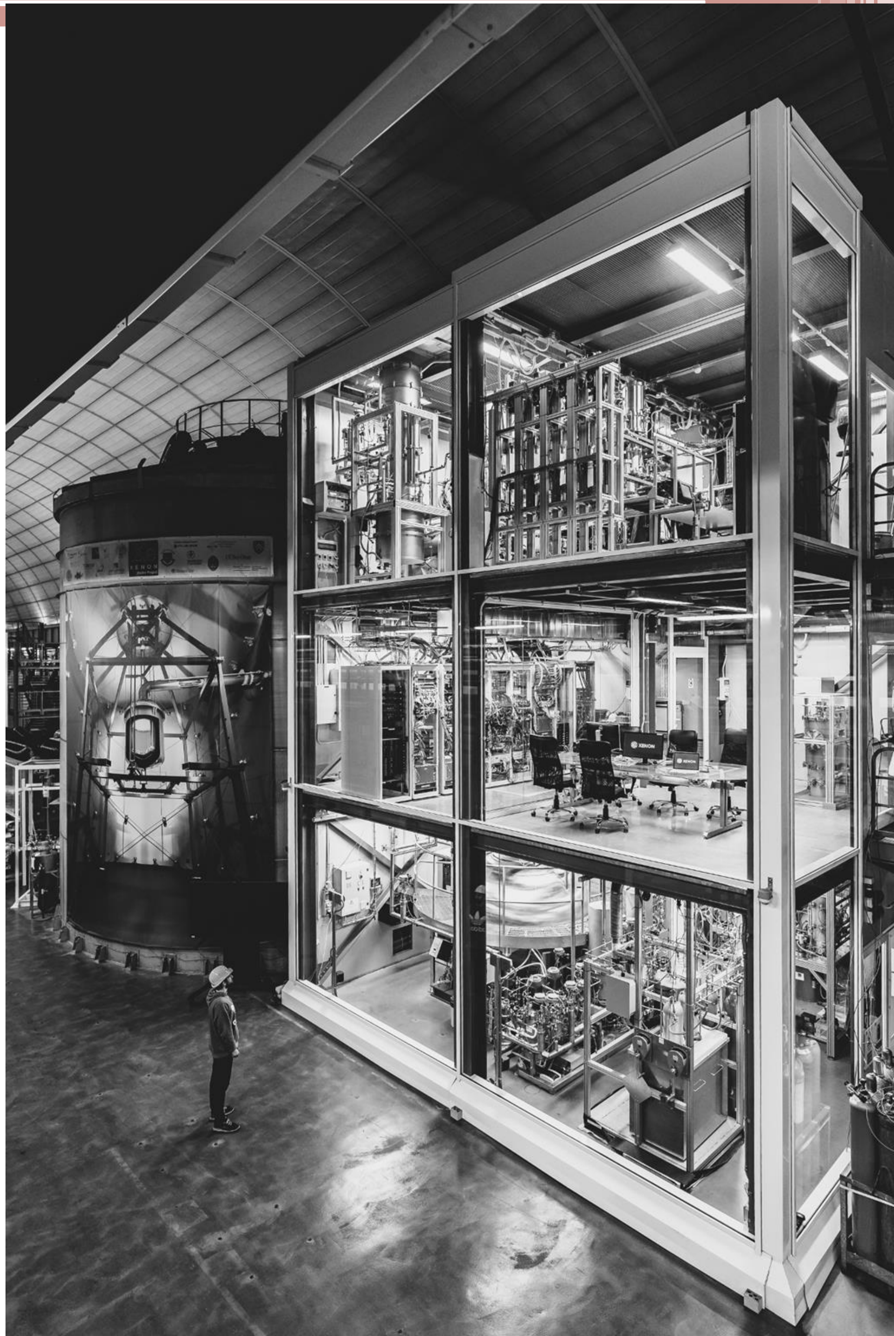
XENONnT experiment

XENON1T → XENONnT upgrades:

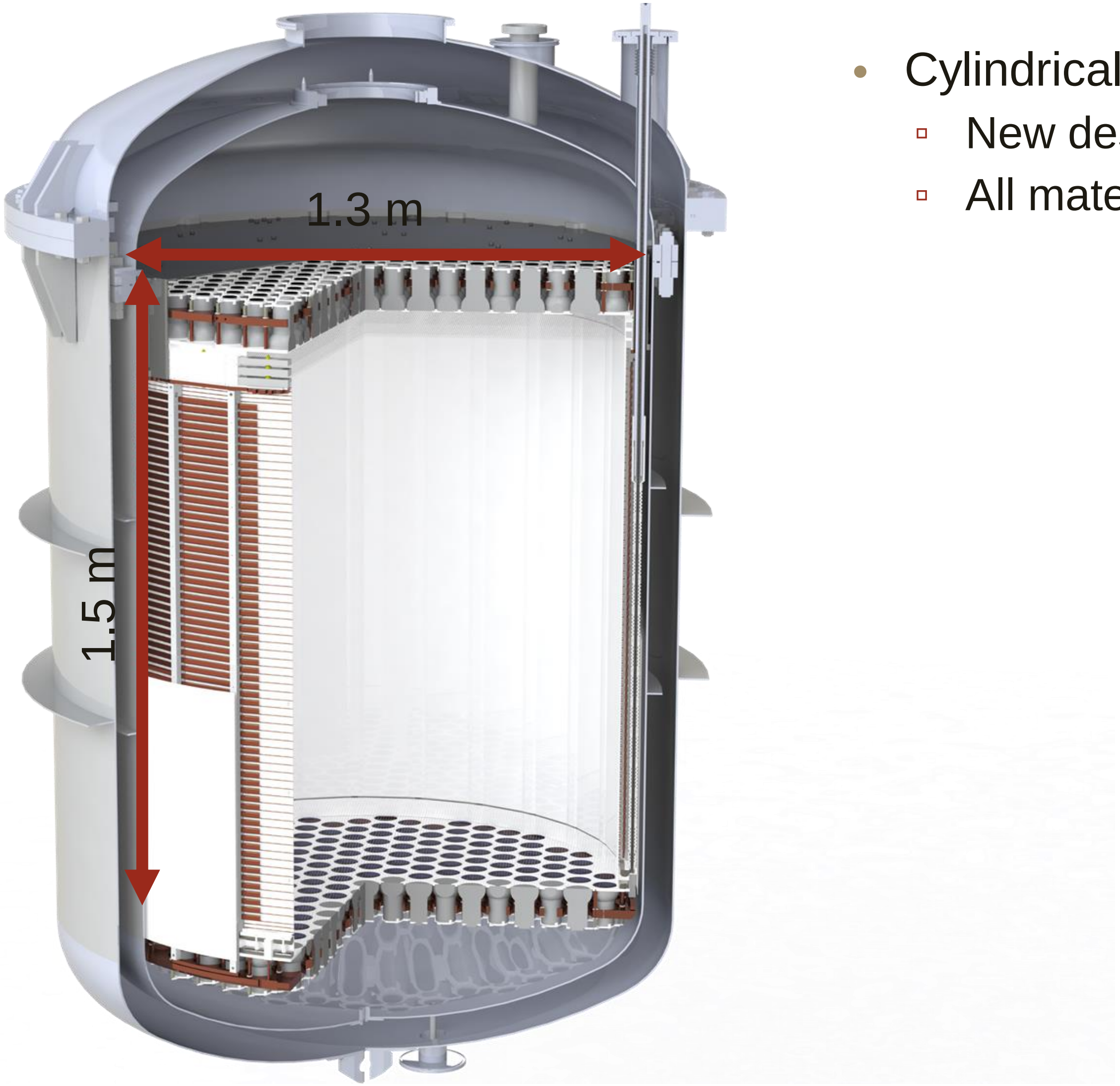
- Larger TPC and inner cryostat
- Improved cleanliness and radiopurity
- New purification and distillation system
- Additional water Cherenkov neutron-veto
- New calibration systems and techniques
- New analysis software package STRAXEN and triggerless data acquisition
- Improved analysis methods

E. Aprile *et al.* **The Triggerless Data Acquisition System of the XENONnT Experiment** arXiv:2212.11032 (accepted by JINST)

E. Aprile *et al.* **Signal characterization with a Bayesian Network in XENONnT** arXiv:2304.05428 (accepted by PRD)

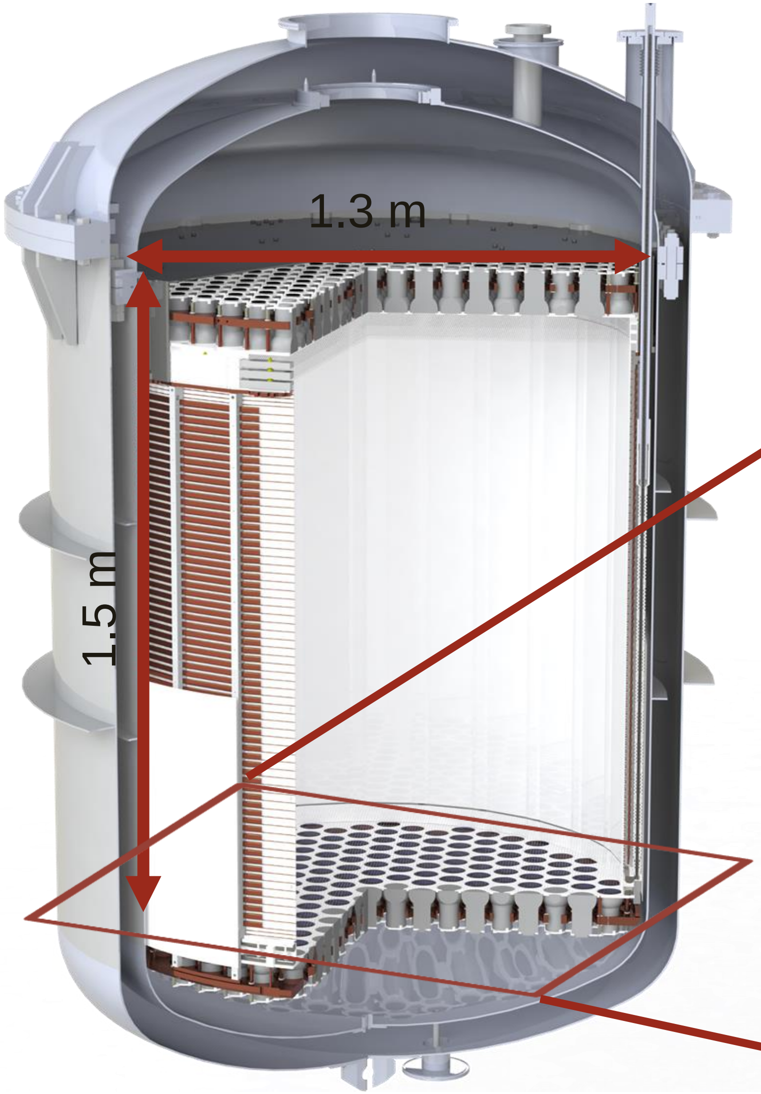


Liquid noble gas time projection chamber



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

Liquid noble gas time projection chamber



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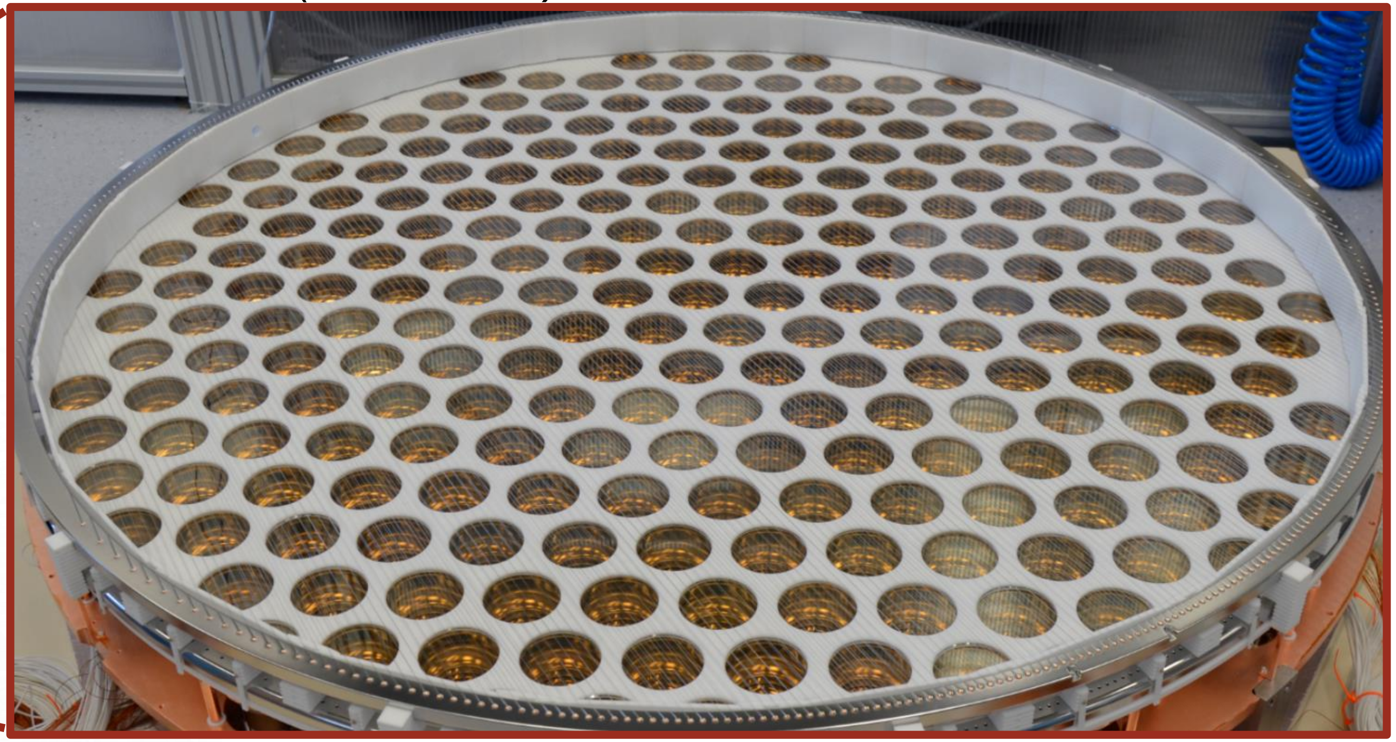
  - All materials carefully screened and selected
- 494 3” PMTs (R11410-21)



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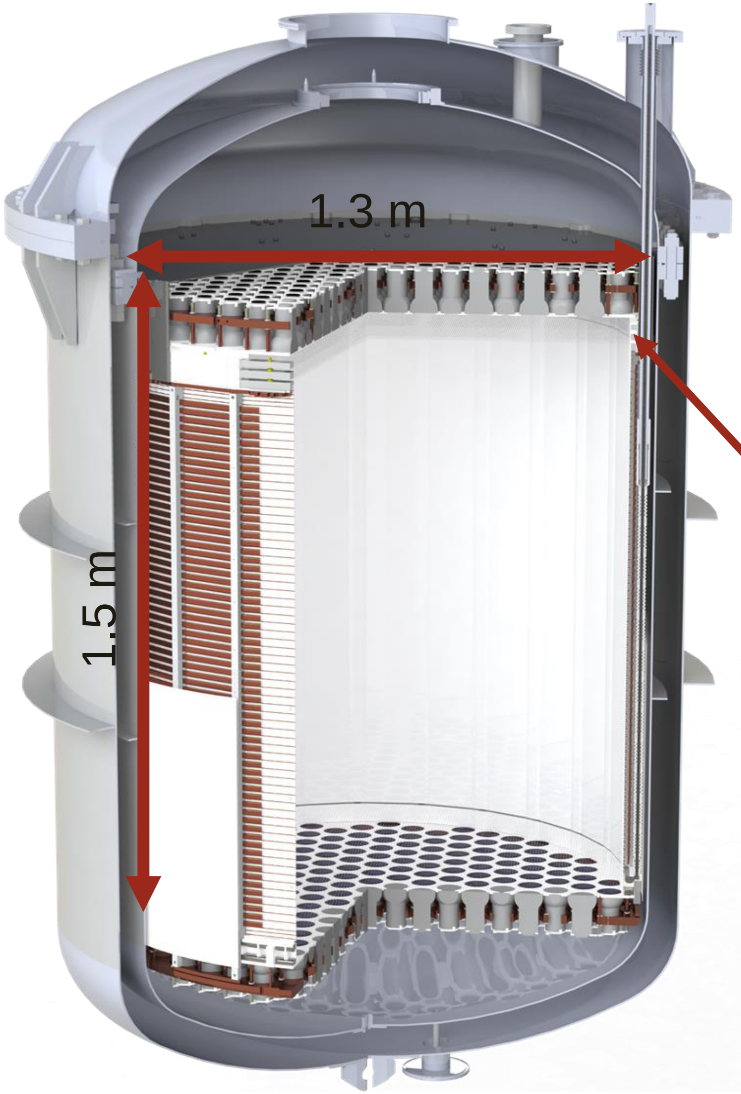
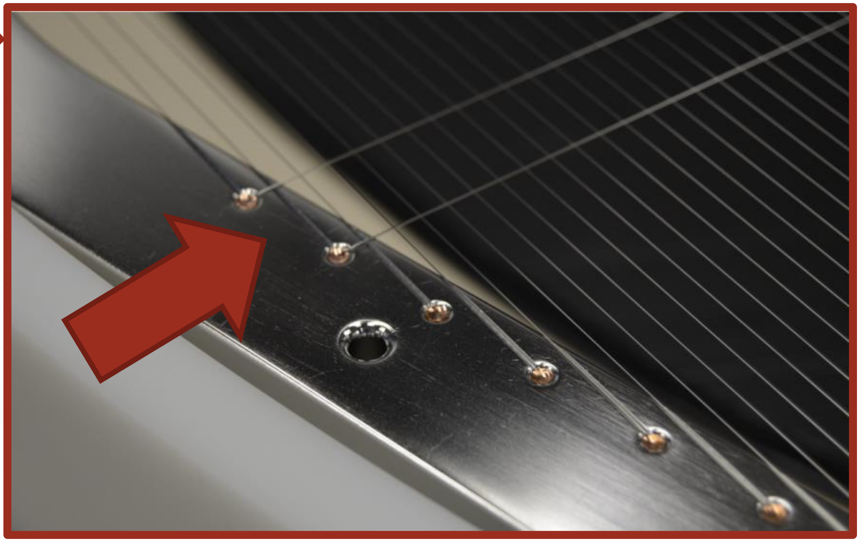


- Cylindrical PTFE walls for high reflectivity
  - New design compared to 1T, reduced relative amount of mass
  - All materials carefully screened and selected

- 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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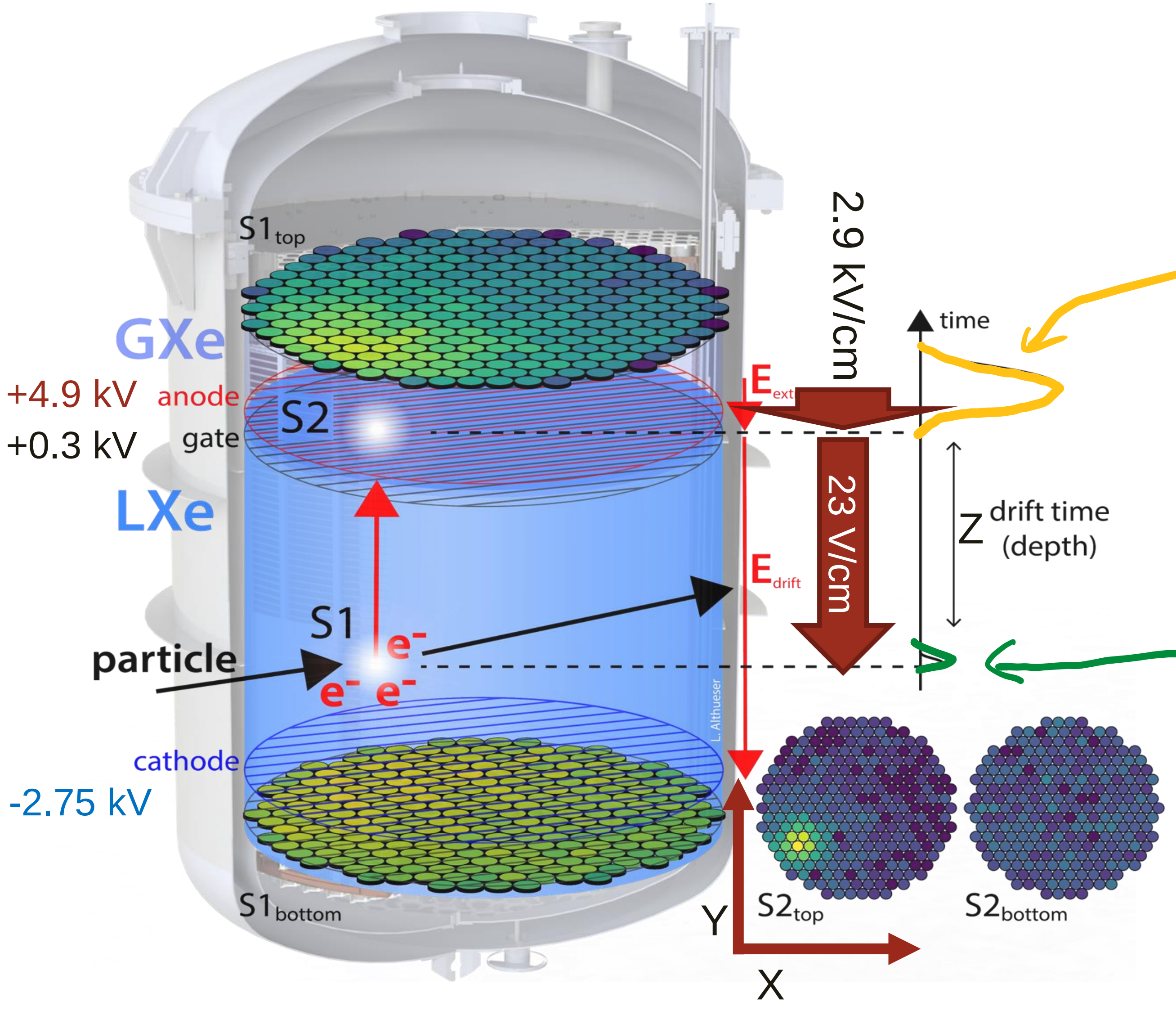


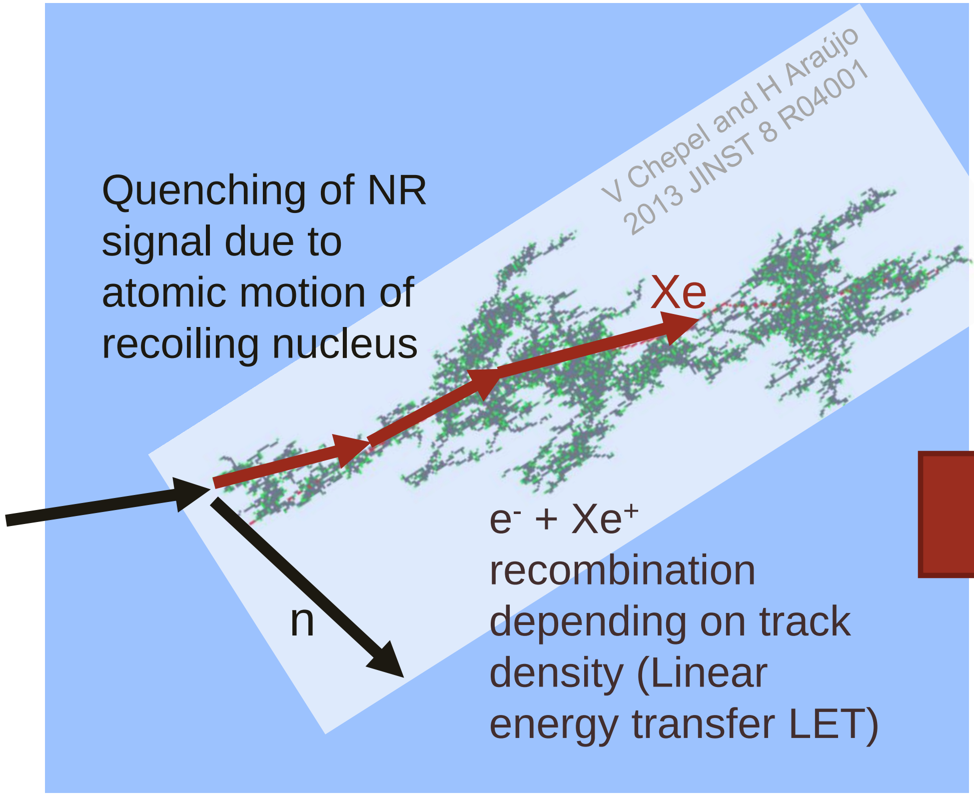
Secondary scintillation signal (S2)

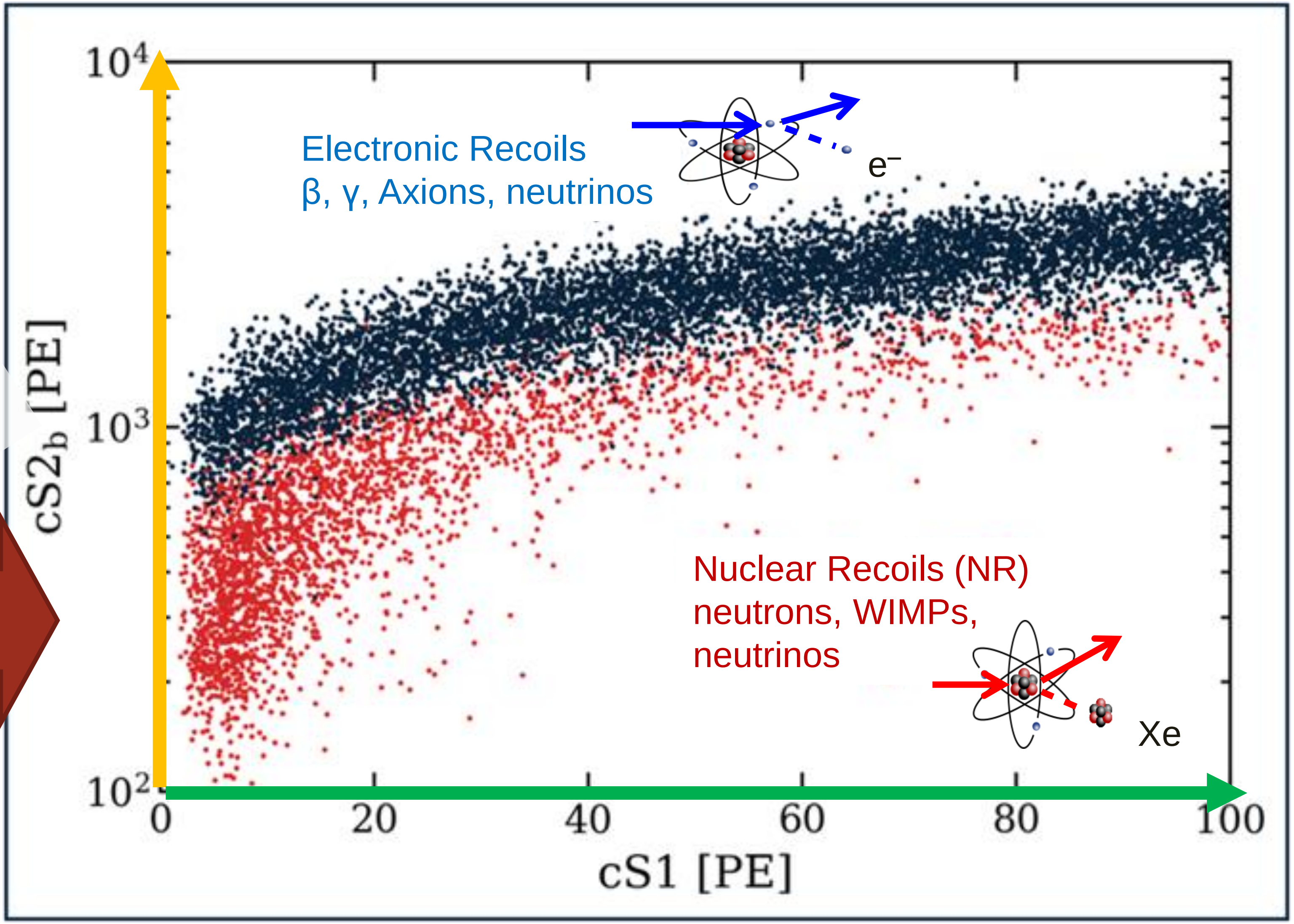
- Electrons from ionized Xe^+ drift upwards between anode and gate
- Extraction from LXe into GXe by stronger field
- Electroluminescence yields S2 prop. to $\#e^-$
- Signals 100 pe – 100000 pe

Primary scintillation signal (S1)

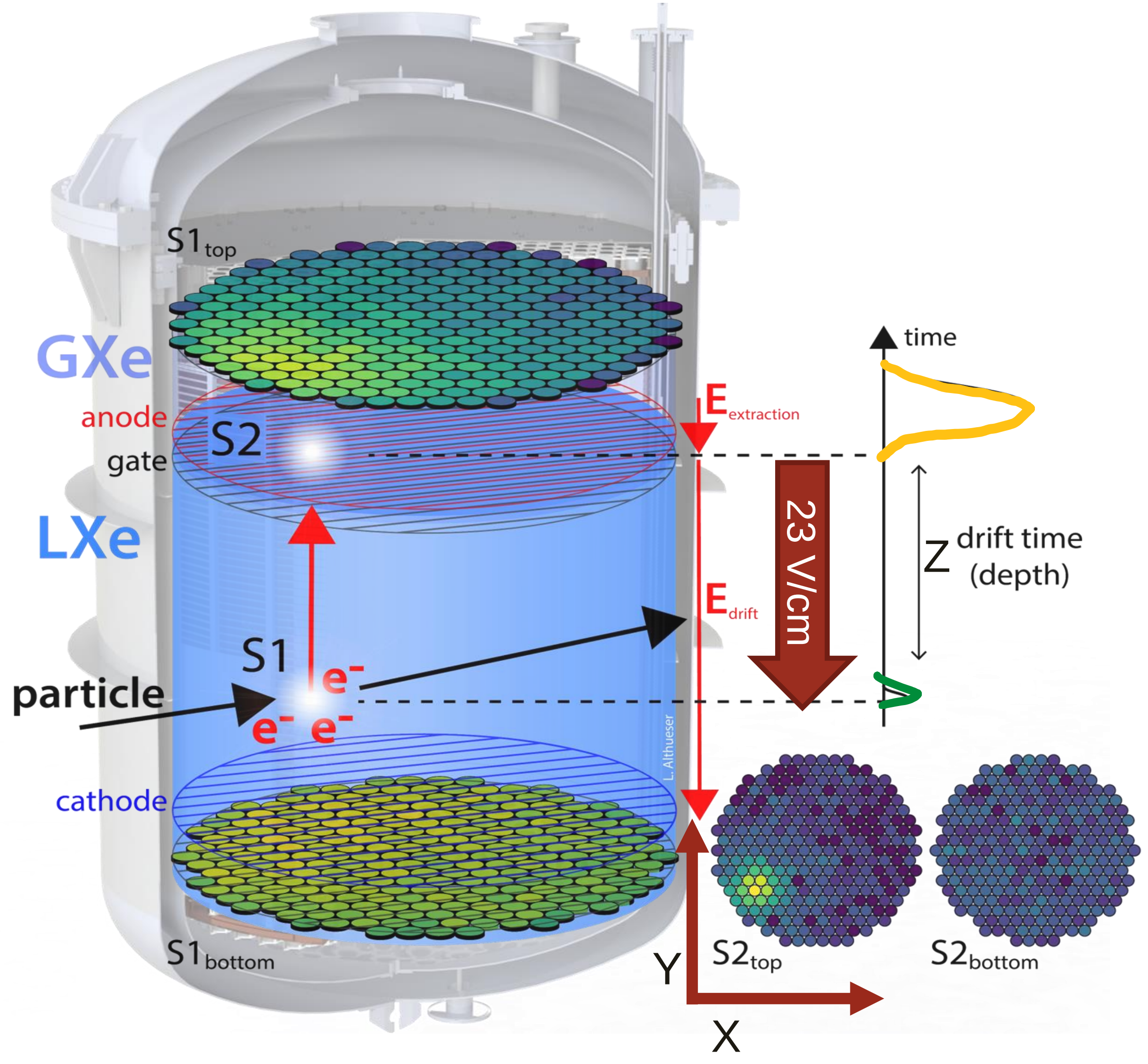
- Excited Xe atoms form excimers Xe_2^*
- Excimers emit VUV-photons (178 nm)
- Signals 3 pe – 1000 pe

Liquid noble gas time projection chamber



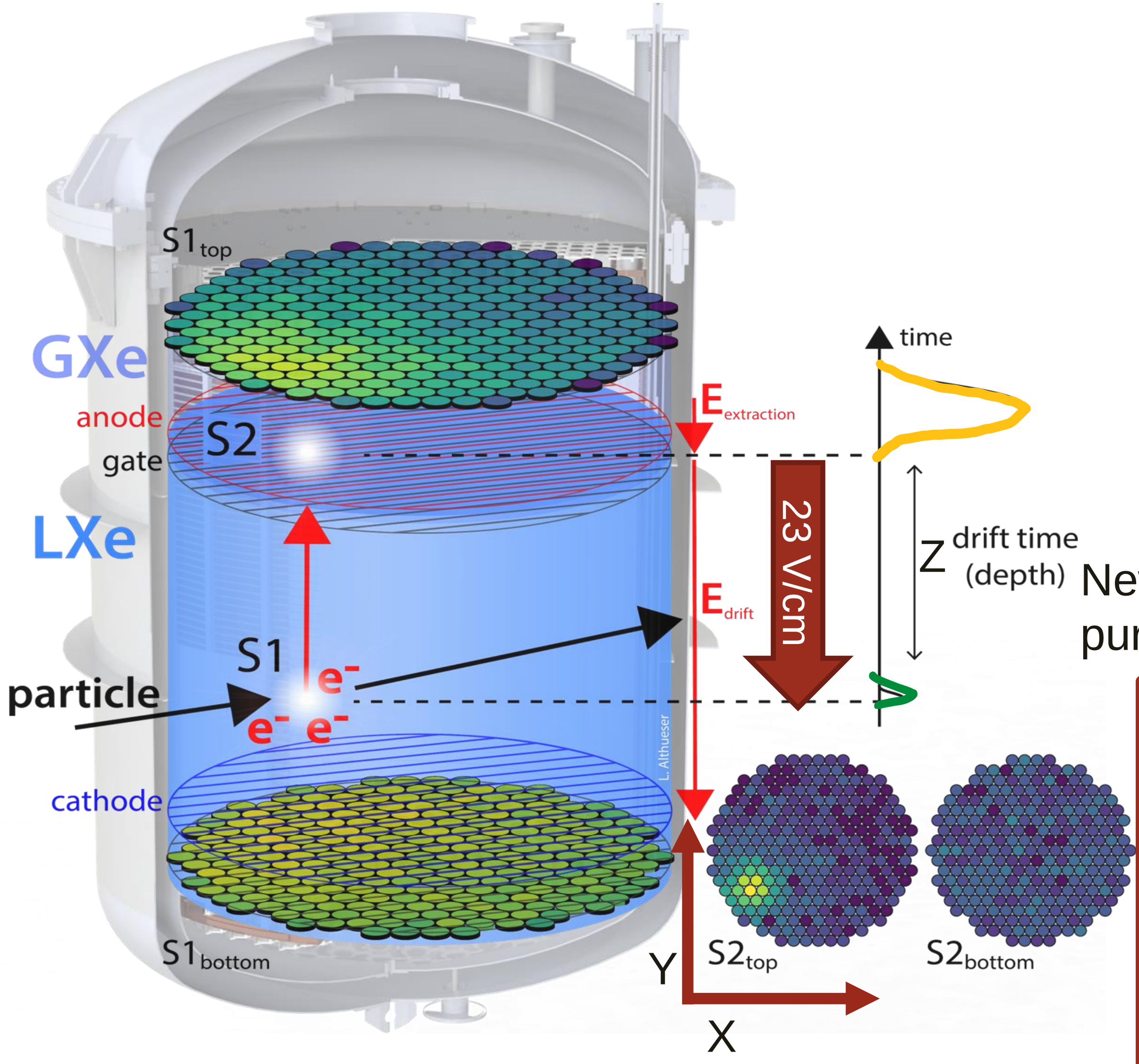


Liquid noble gas time projection chamber



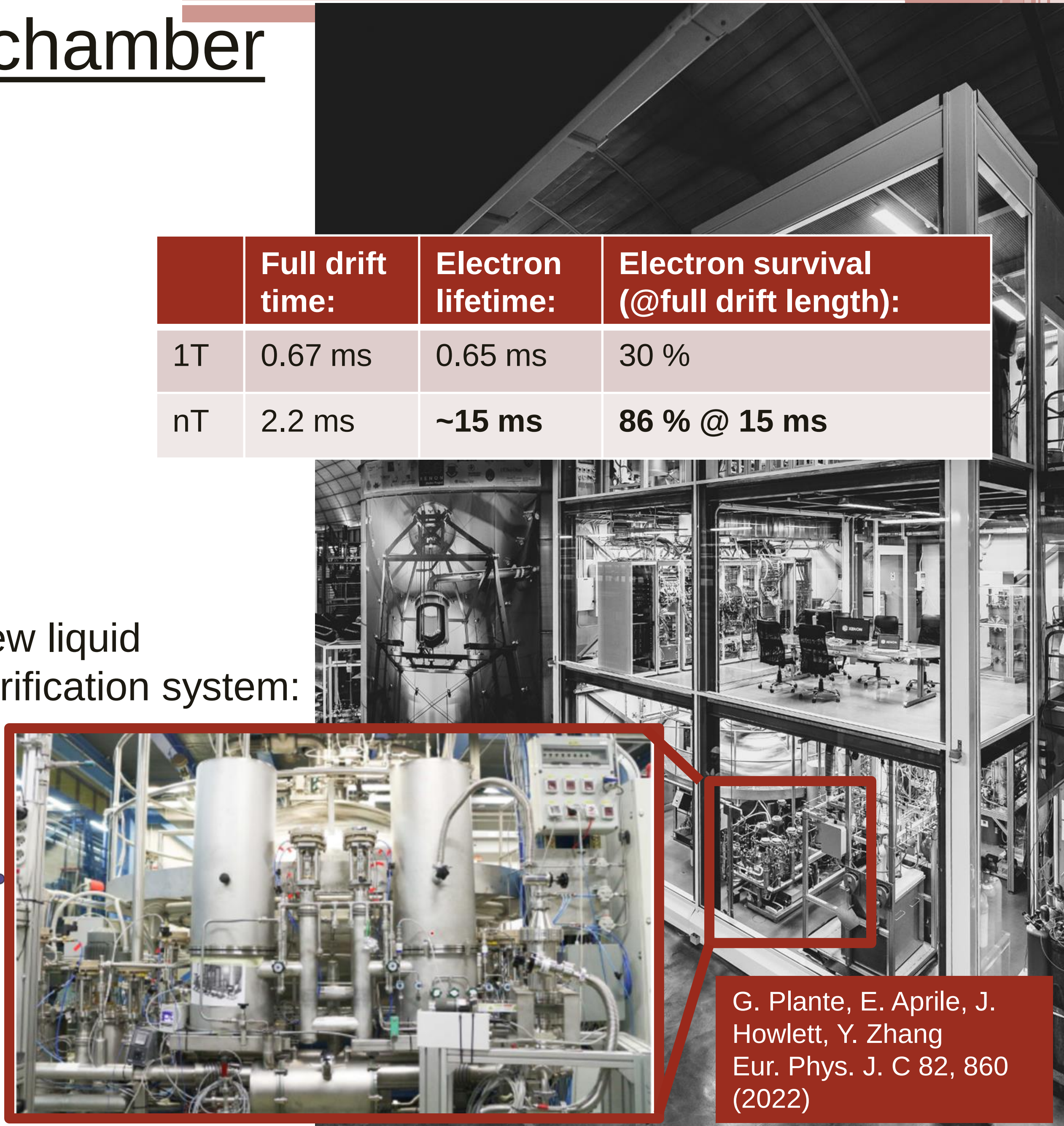
	Full drift time:	Electron lifetime:	Electron survival (@full drift length):
1T	0.67 ms	0.65 ms	30 %

Liquid noble gas time projection chamber



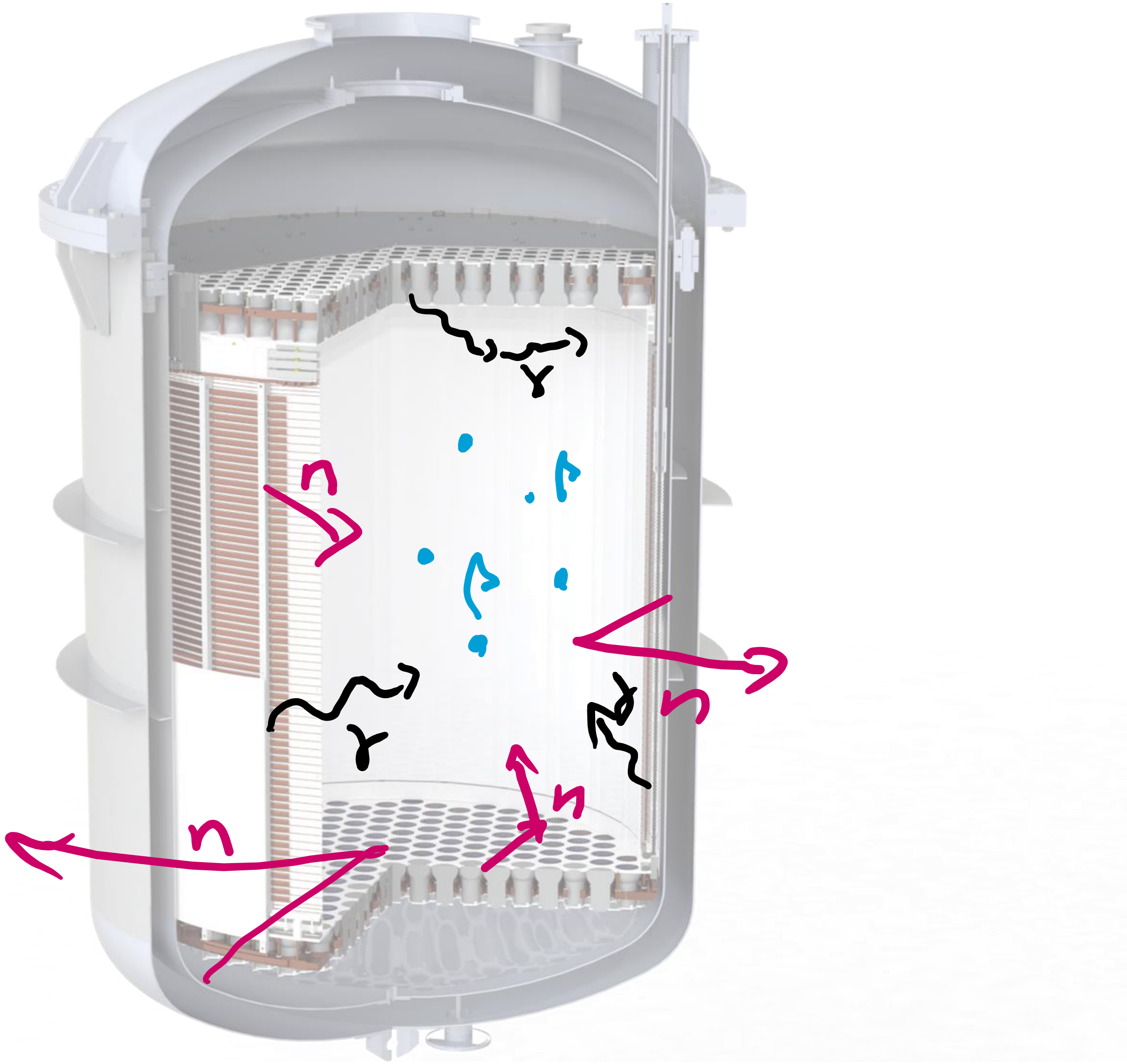
	Full drift time:	Electron lifetime:	Electron survival (@full drift length):
1T	0.67 ms	0.65 ms	30 %
nT	2.2 ms	**~15 ms**	**86 % @ 15 ms**

New liquid purification system:



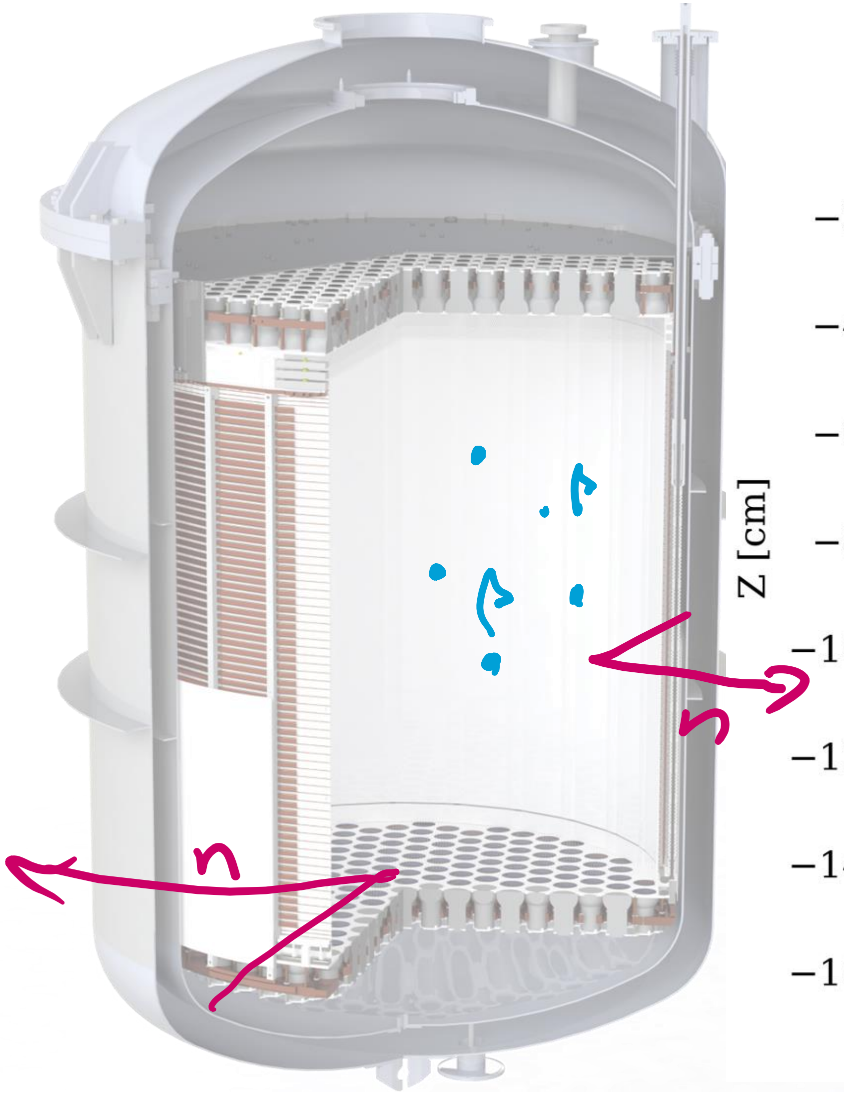
G. Plante, E. Aprile, J. Howlett, Y. Zhang Eur. Phys. J. C 82, 860 (2022)

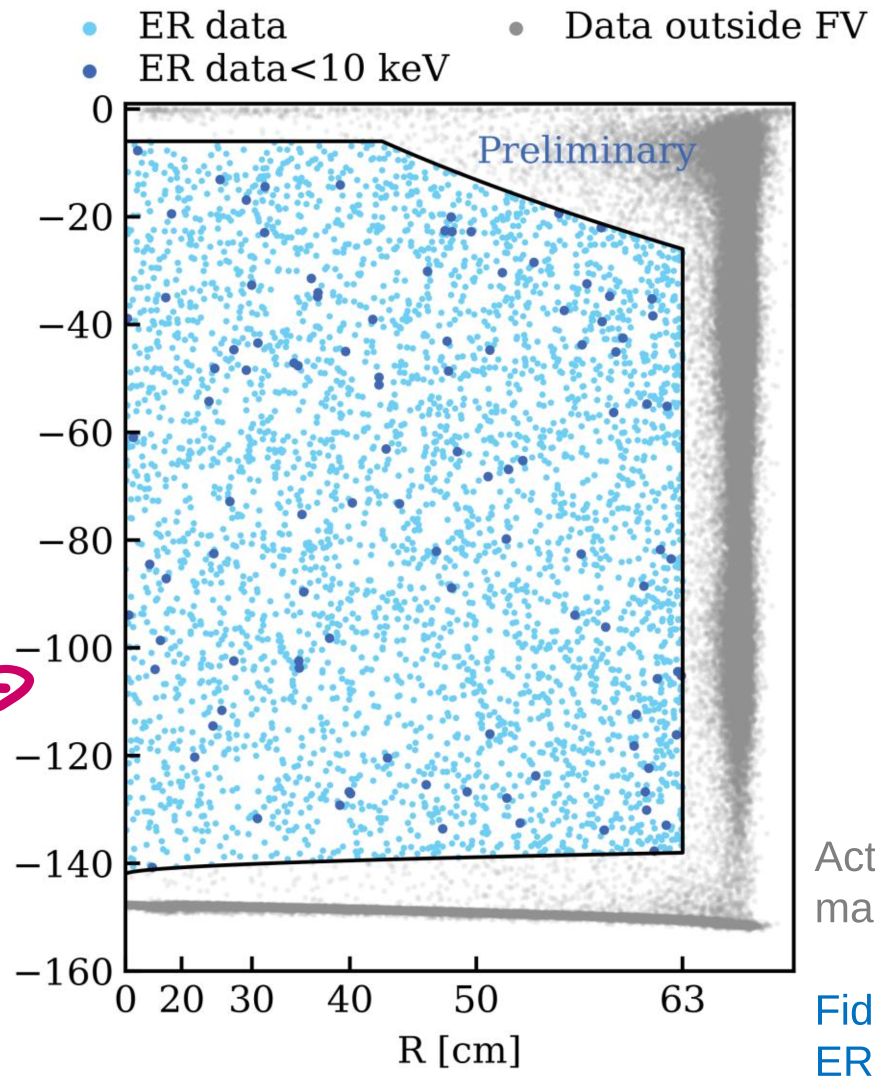
Liquid noble gas time projection chamber



E. Aprile *et al*
Search for New Physics in Electronic Recoil Data from XENONnT
Phys.Rev.Lett. 129 (2022) 16, 16 1805

Liquid noble gas time projection chamber





Active LXe mass: 5.9 t

Fiducial mass ER analysis: (4.37 ± 0.14) t

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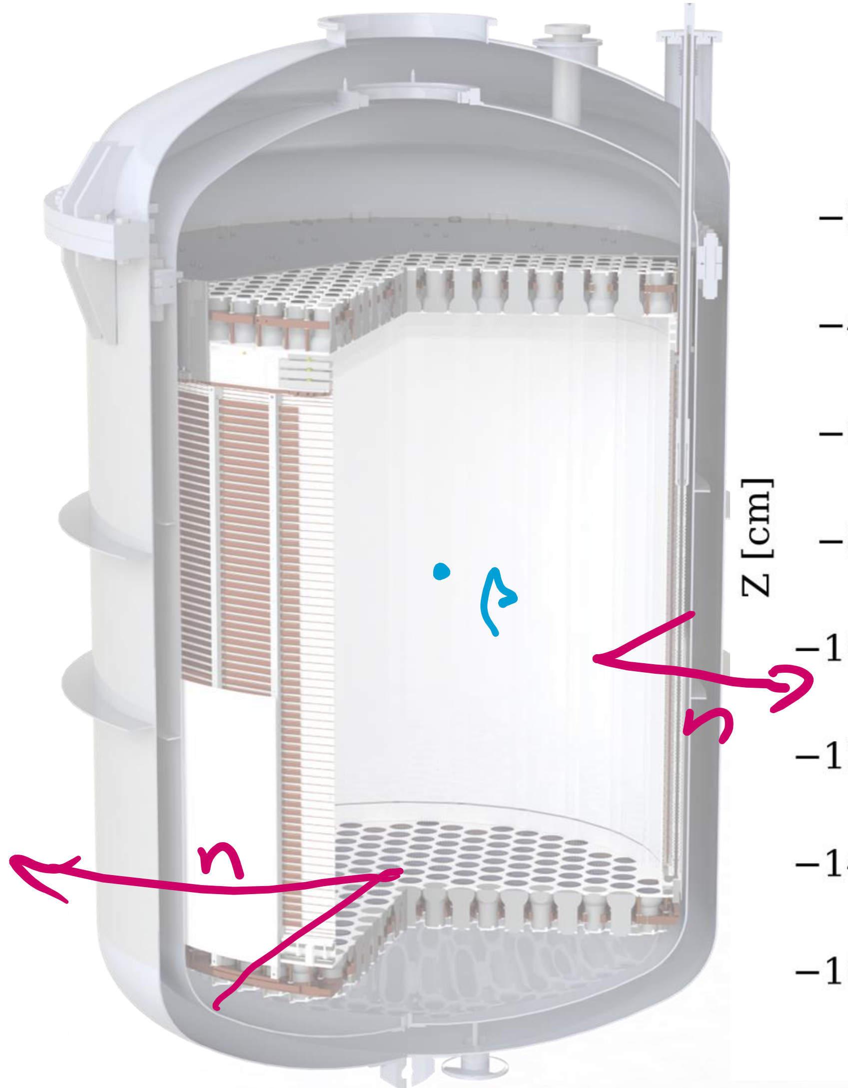
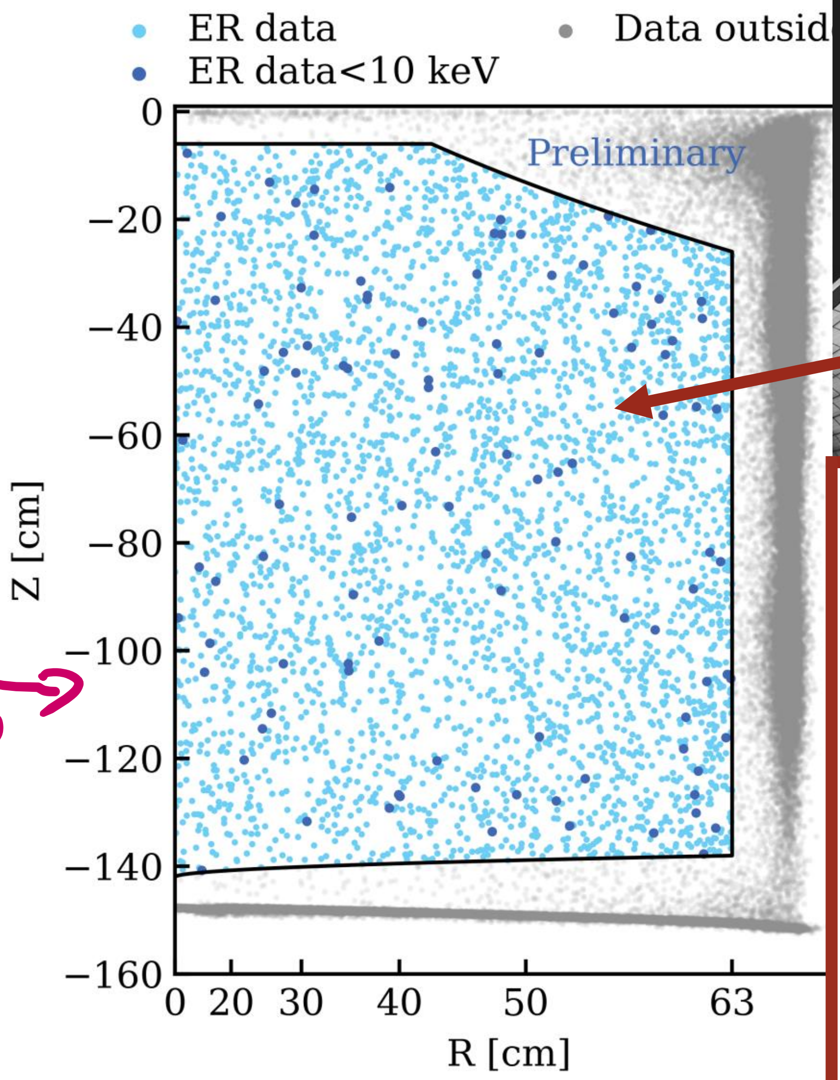
Liquid noble gas time projection chamber

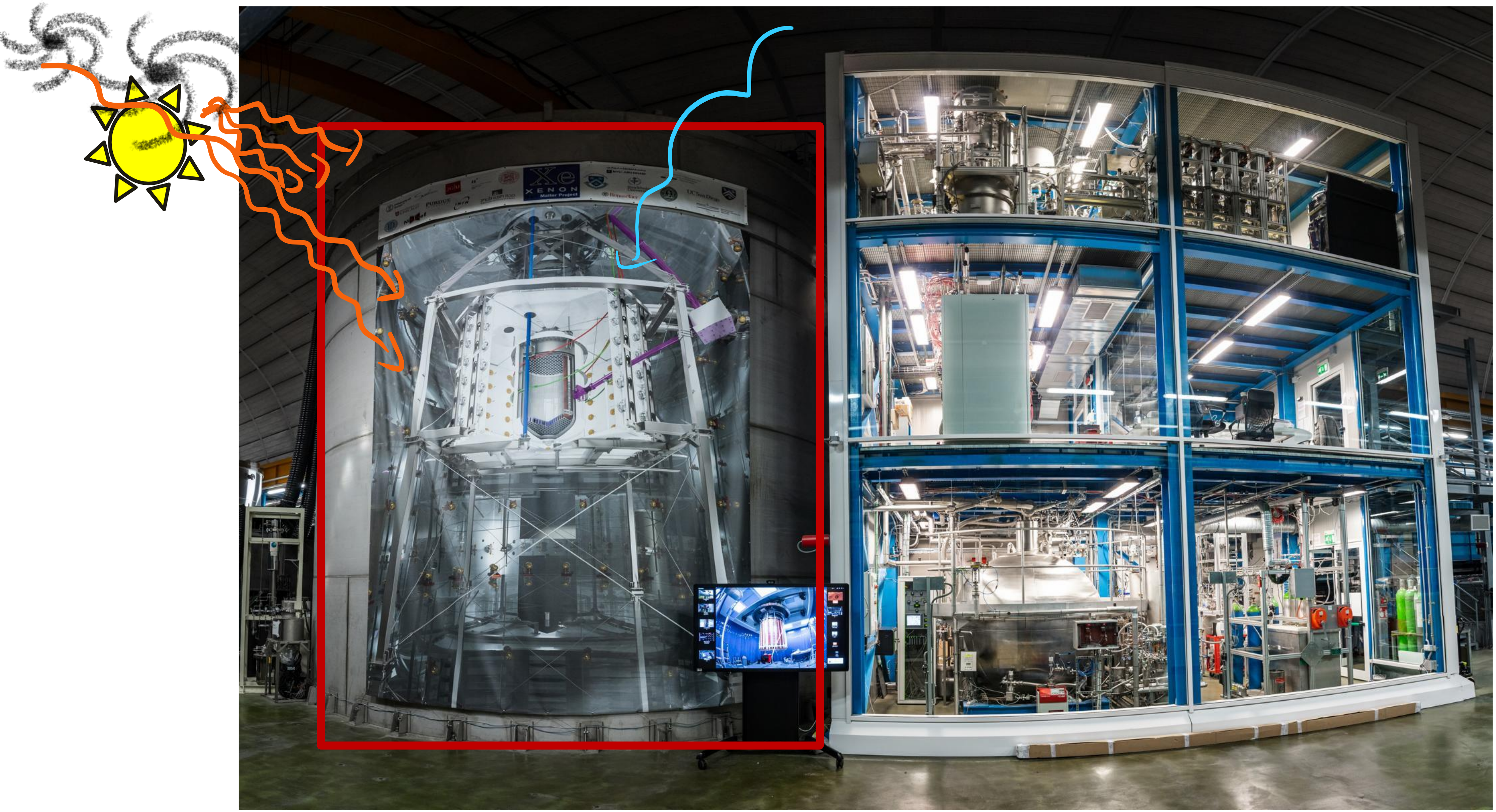




M. Murra, D. Schulte, C. Huhmann, C. Weinheimer

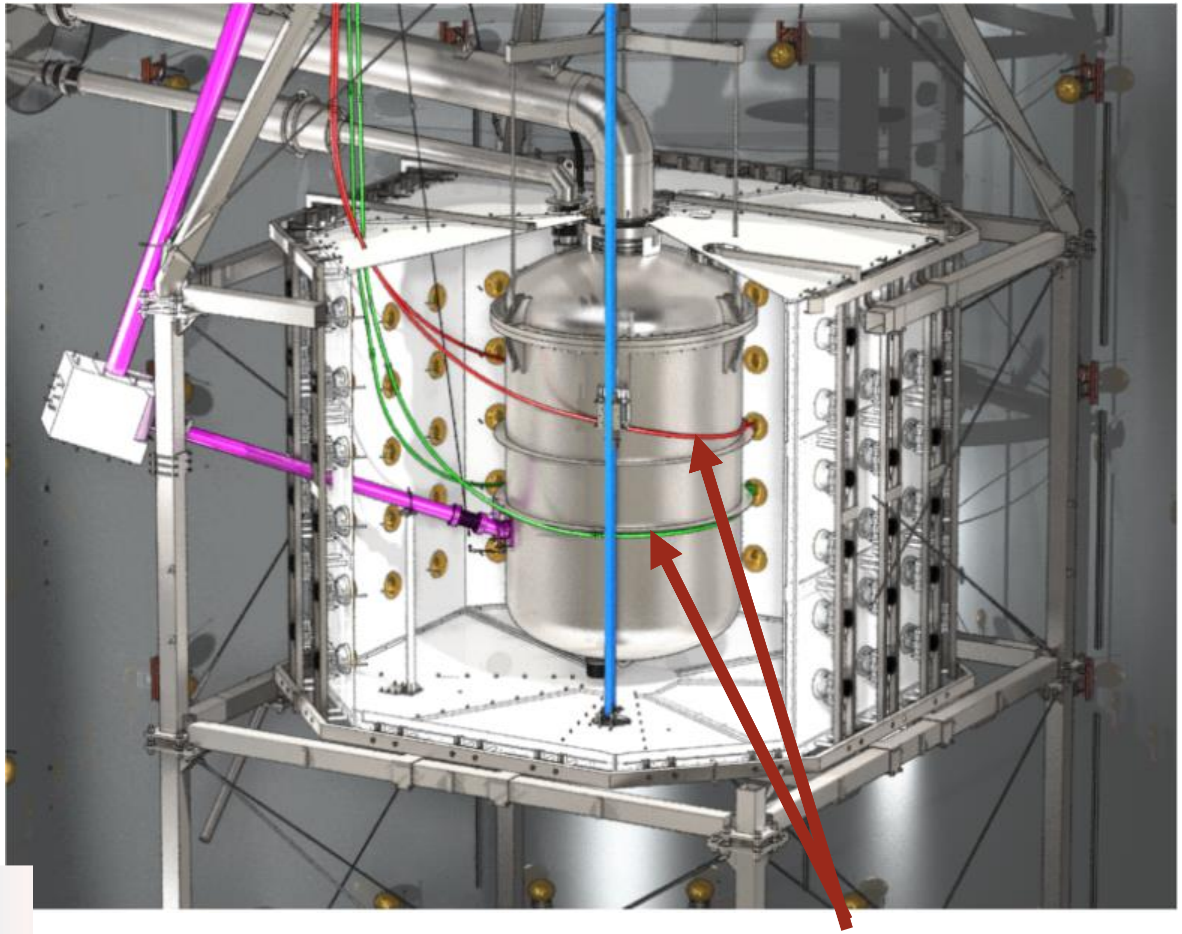
Eur. Phys. J. C 82, 1104 (2022)

XENONnT neutron-veto

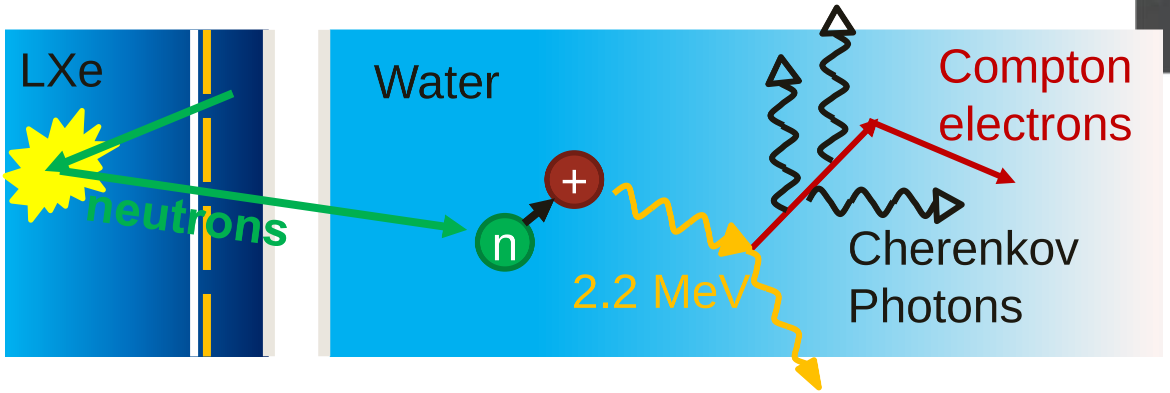


XENONnT neutron-veto

- 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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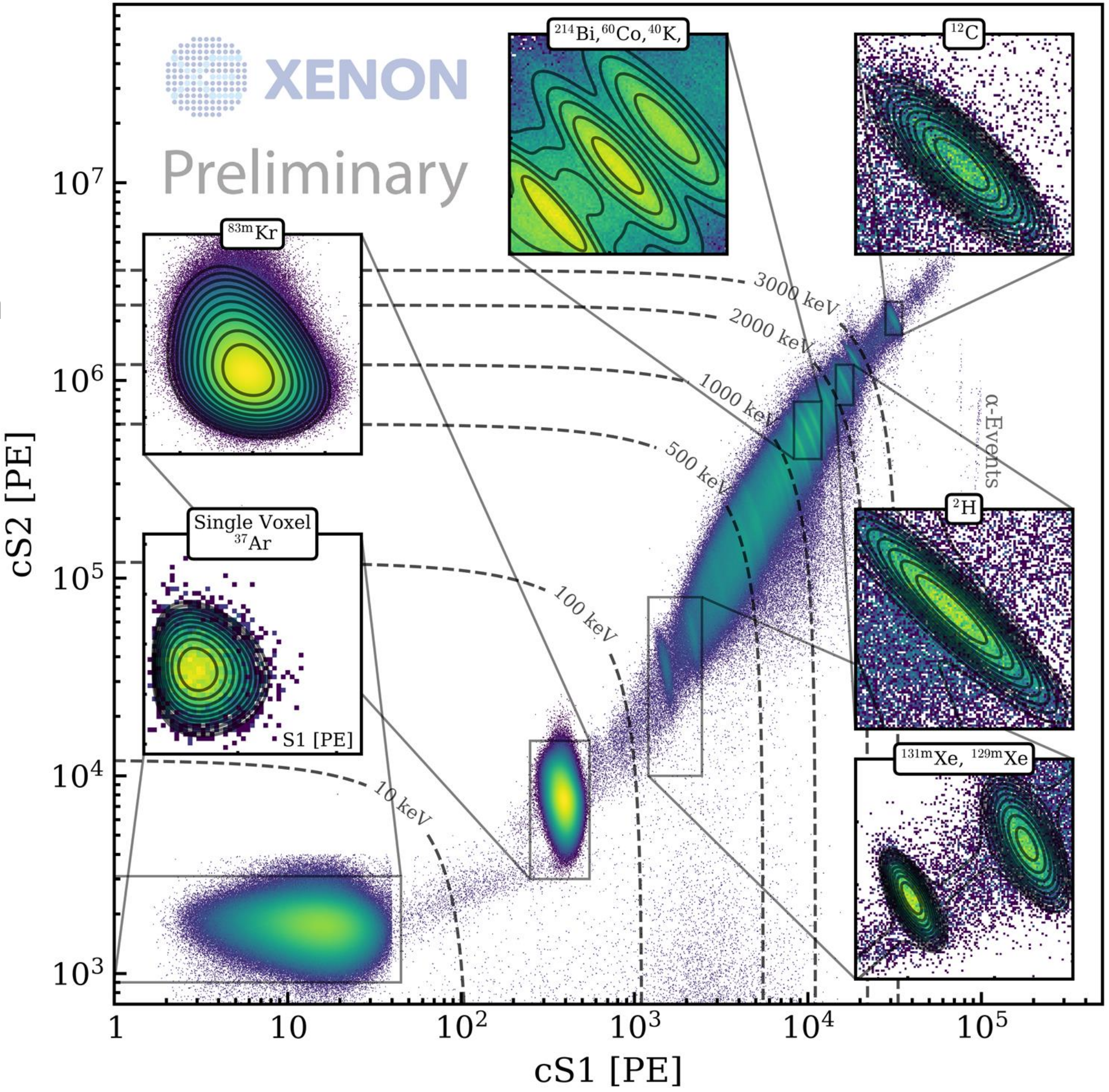
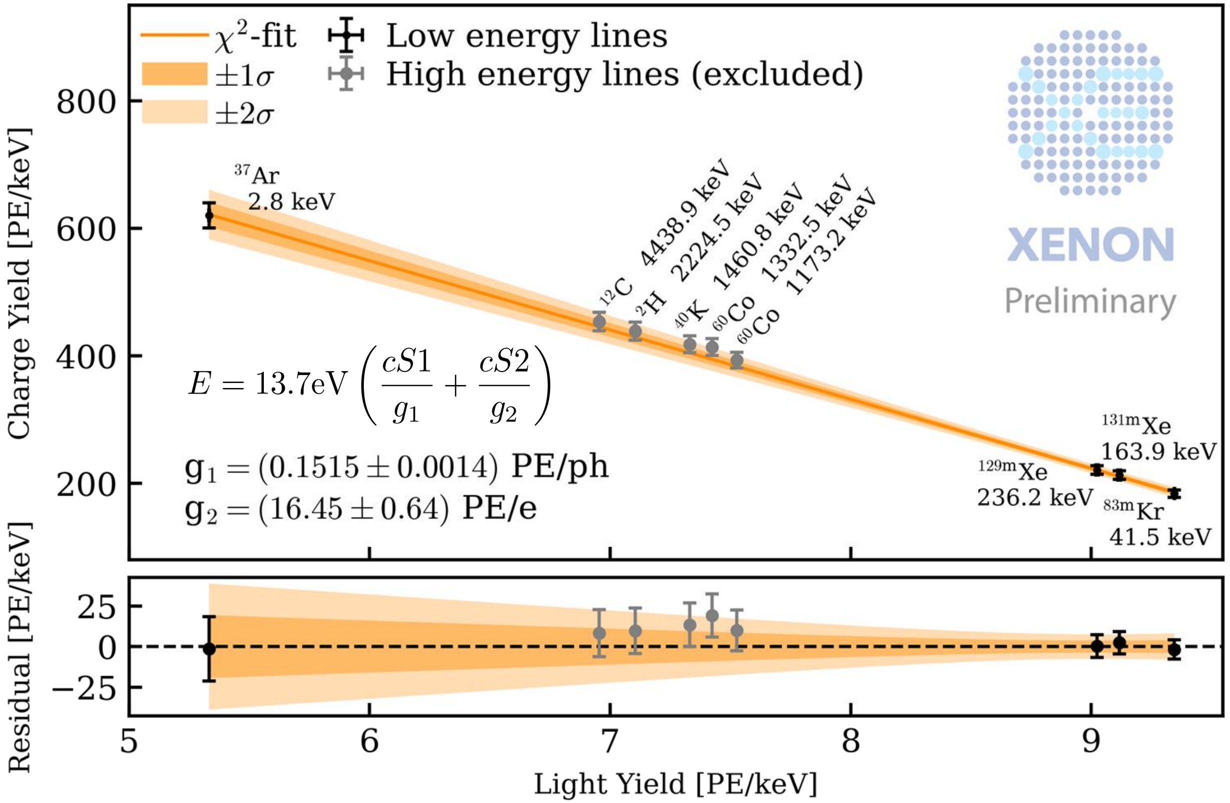
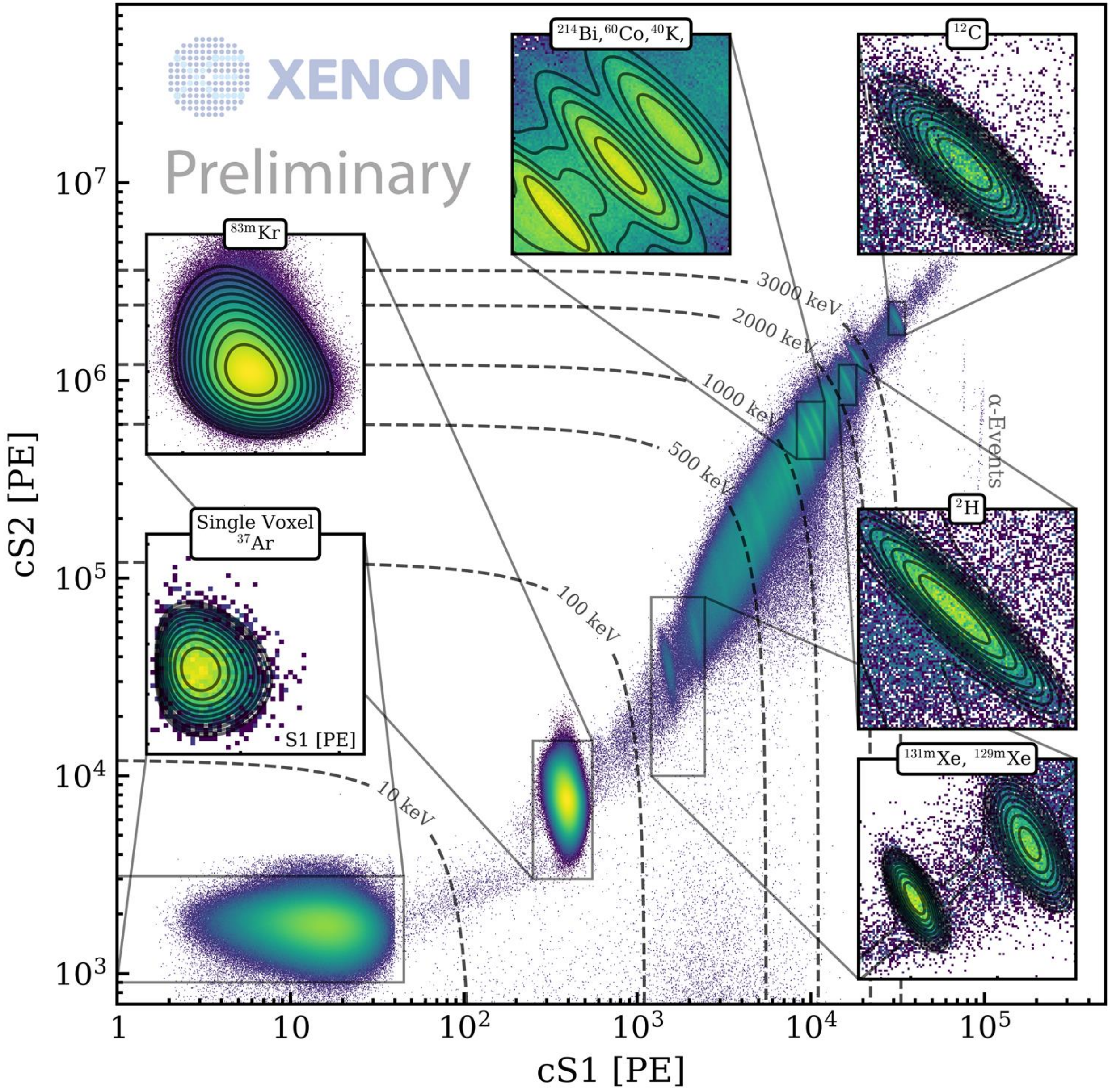
Calibration of XENONnT

- 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



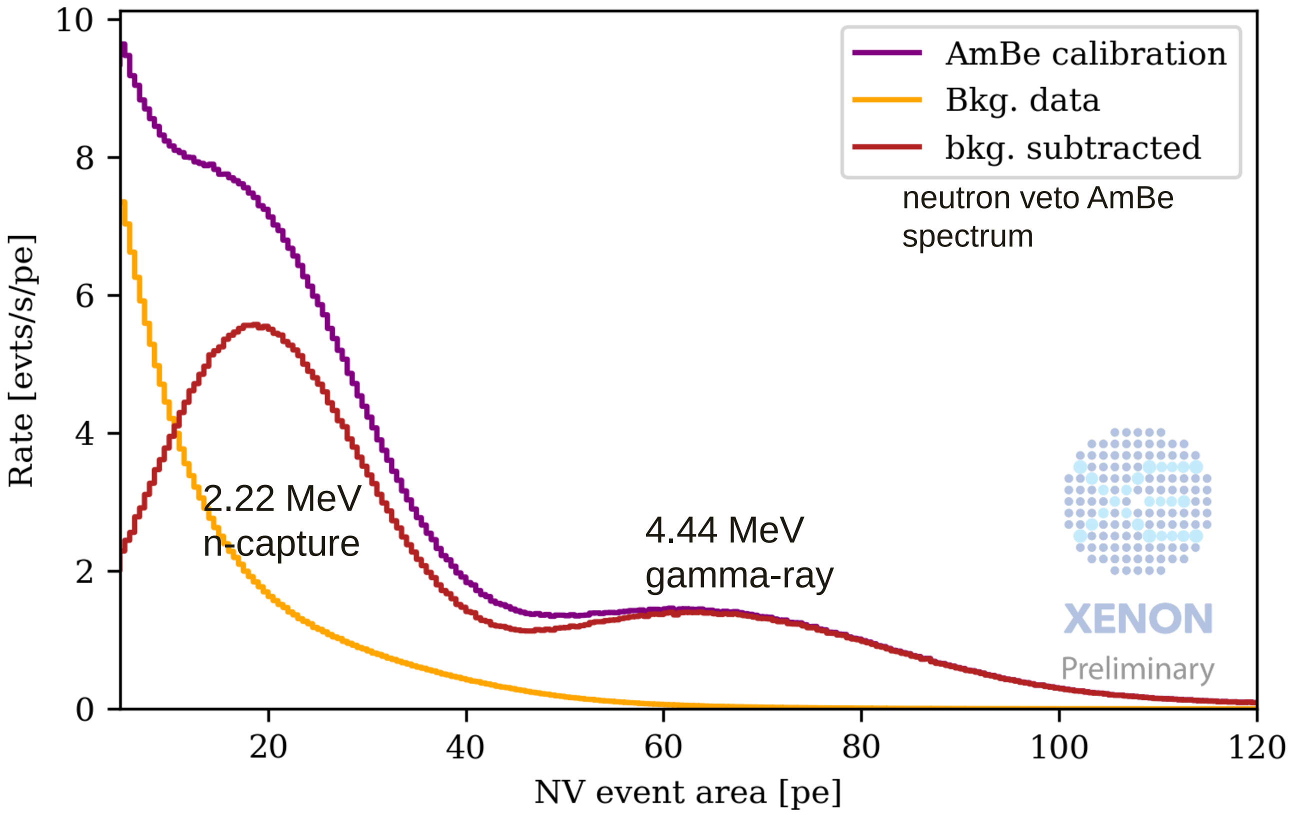


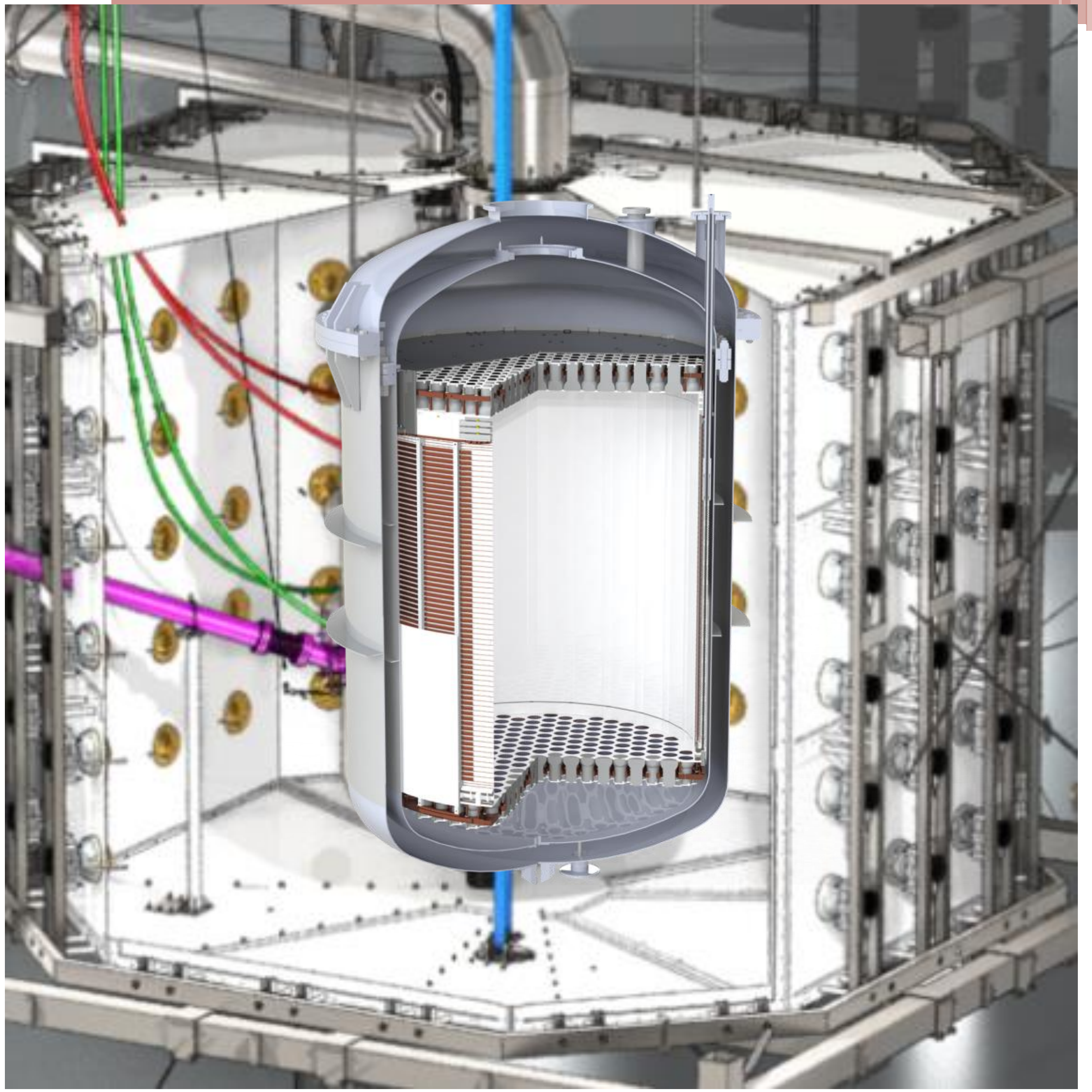
- Photon and electron gain g1/g2 used as prior in the LXe response model
- Energy scale important to forward fold WIMP spectrum into cS1 and cS2

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





Calibration of NR response

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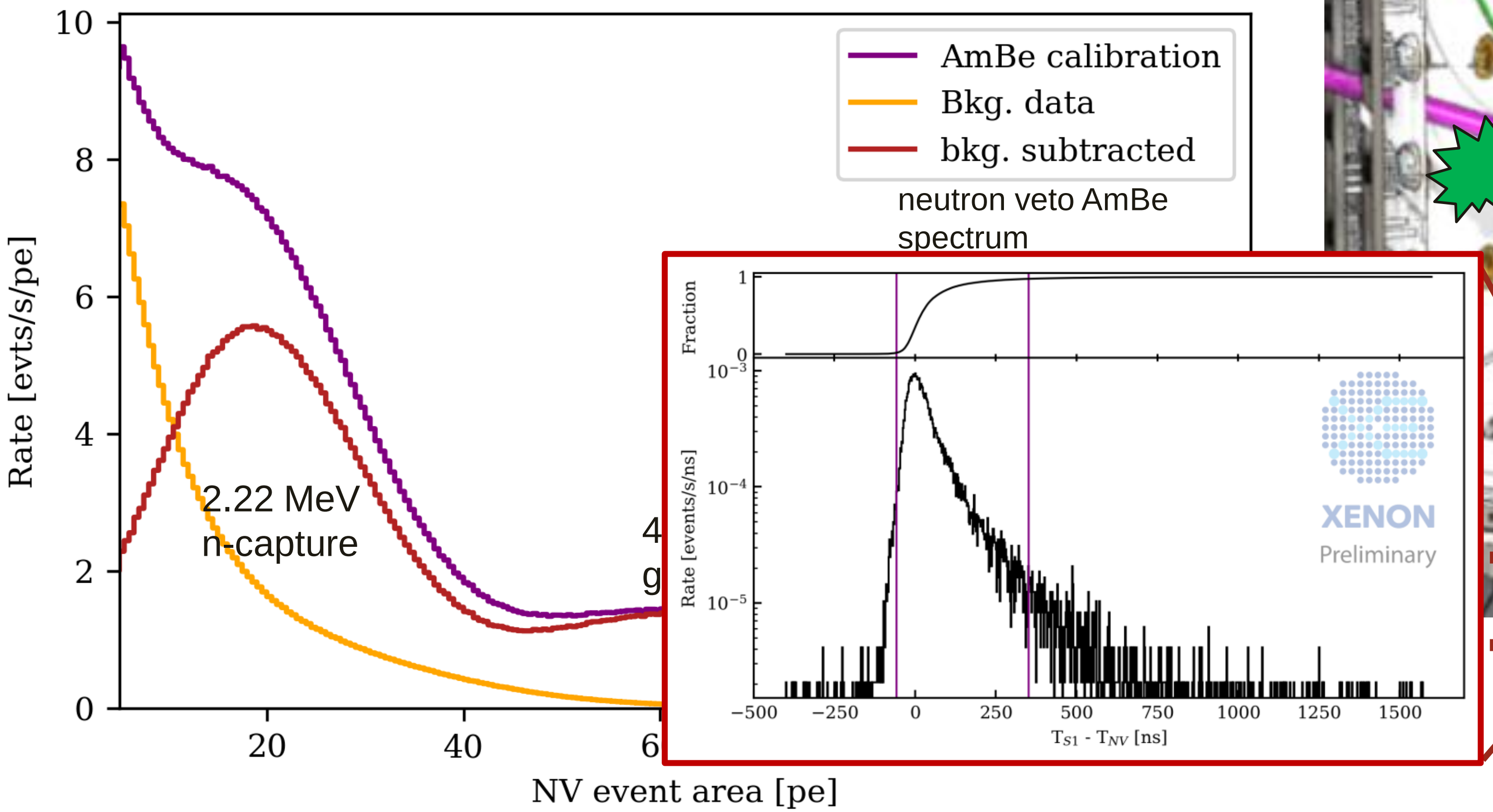
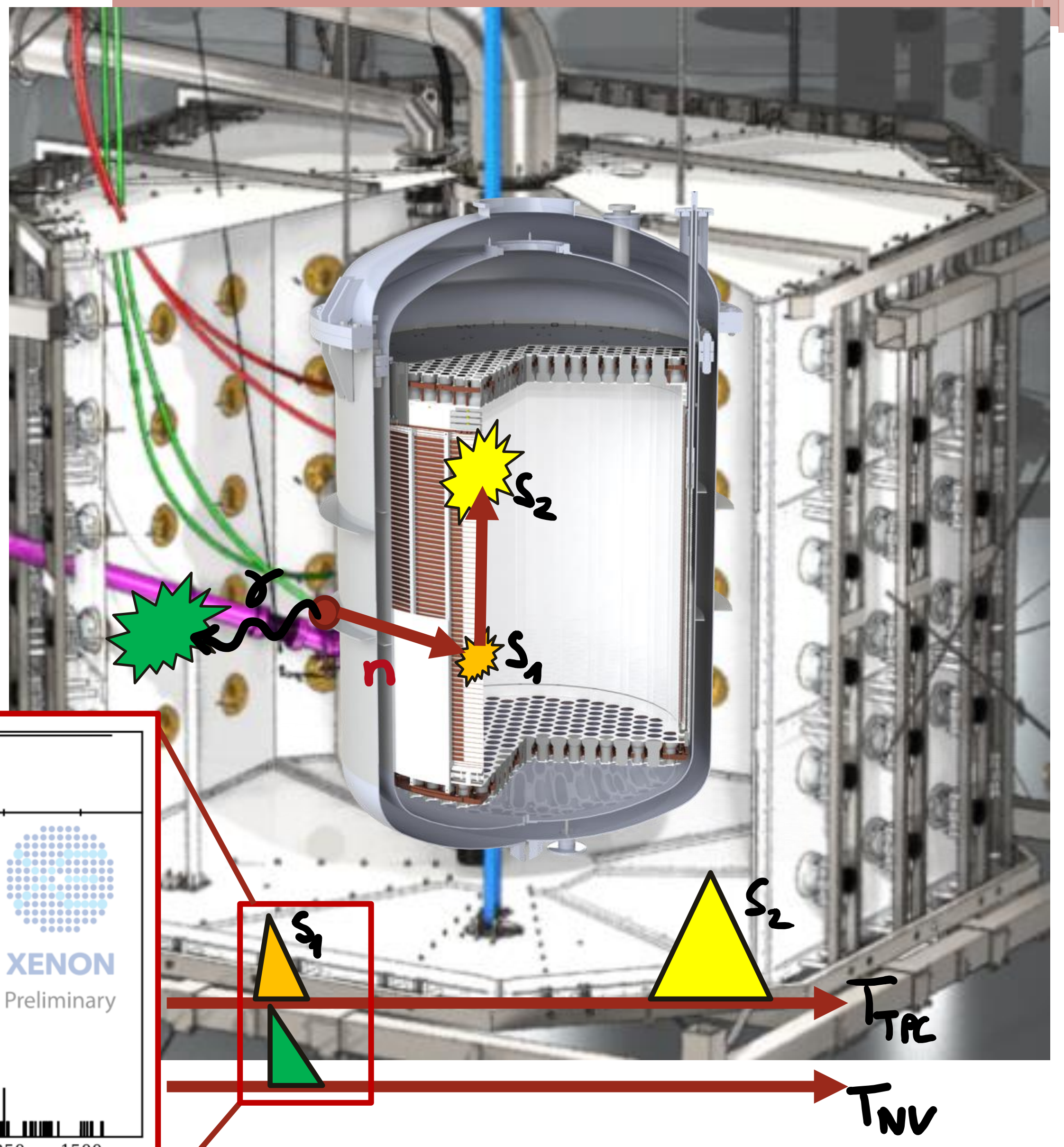




Calibration of NR response

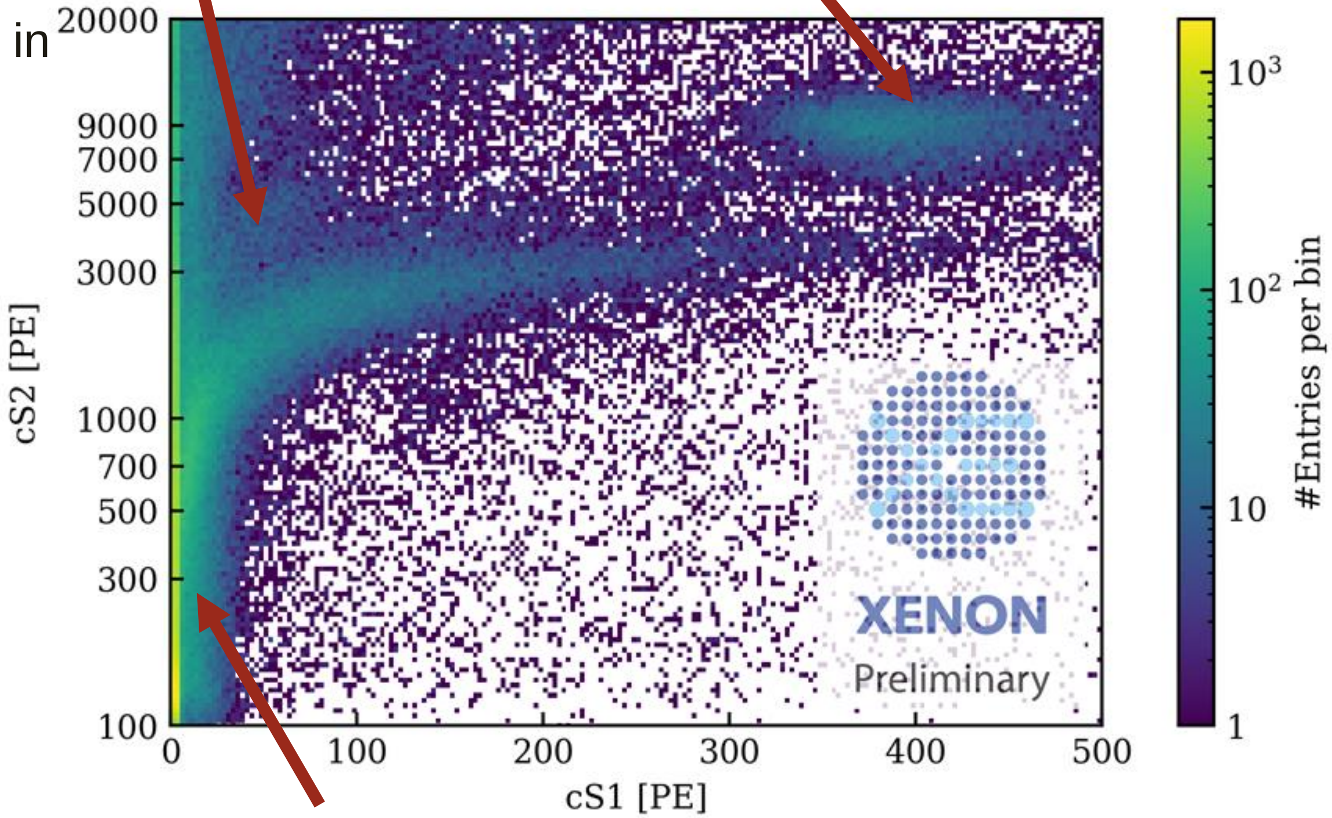
- $^{241}Am(\alpha, n)^{9}Be$ emits coincident 4.4 MeV gamma in ~60 % of all emitted neutrons

➡ Calibrate TPC and NV using tagged neutrons

- Build 400 ns wide coincidence between TPC and neutron veto

ER background

inelastic 39.6 keV line from ^{129}Xe



accidentally paired S1 S2 signals

Calibration of NR response

- ^{241}Am(α, 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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  ➡ Very strong background suppression

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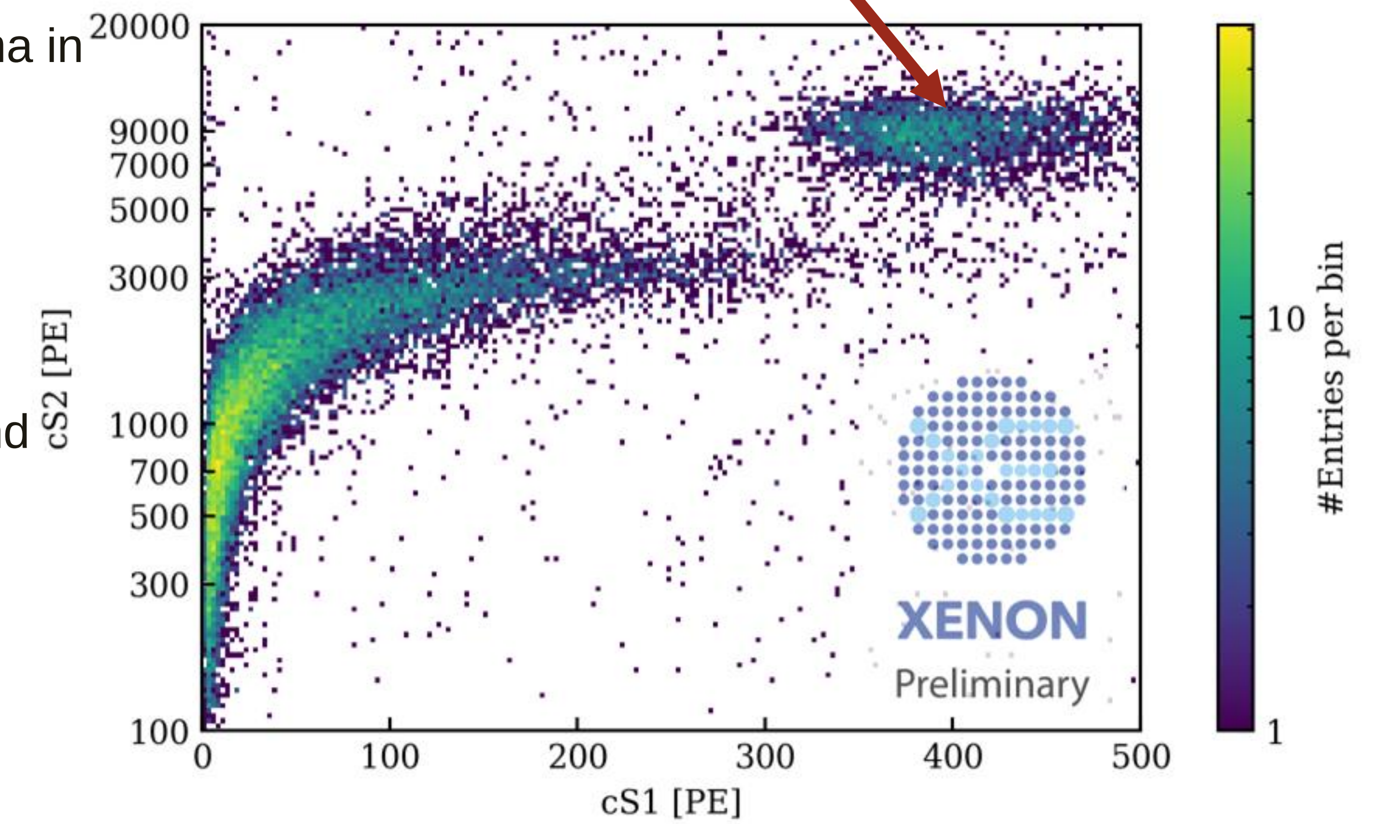


Calibration of NR response

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

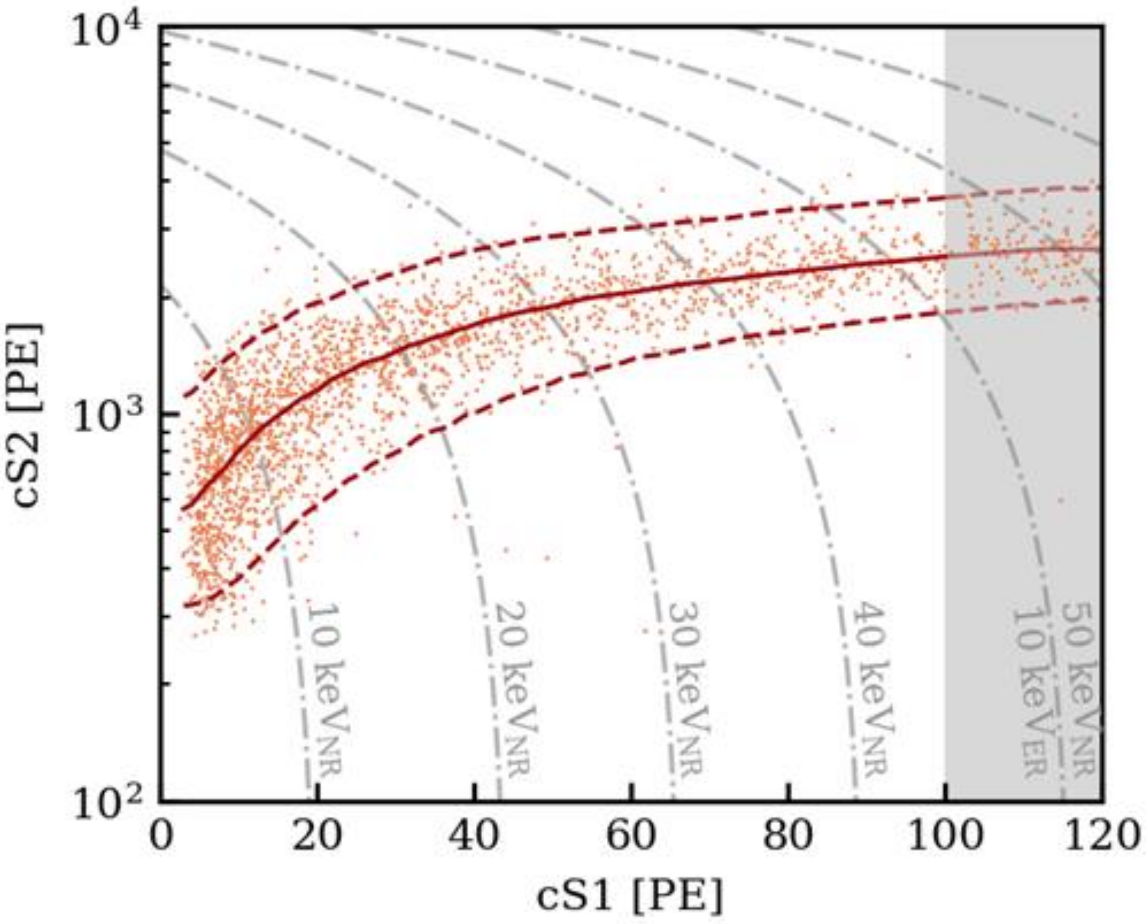
→ Calibrate TPC and NV using tagged neutrons

- Build 400 ns wide coincidence between TPC and neutron veto

→ Very strong background suppression

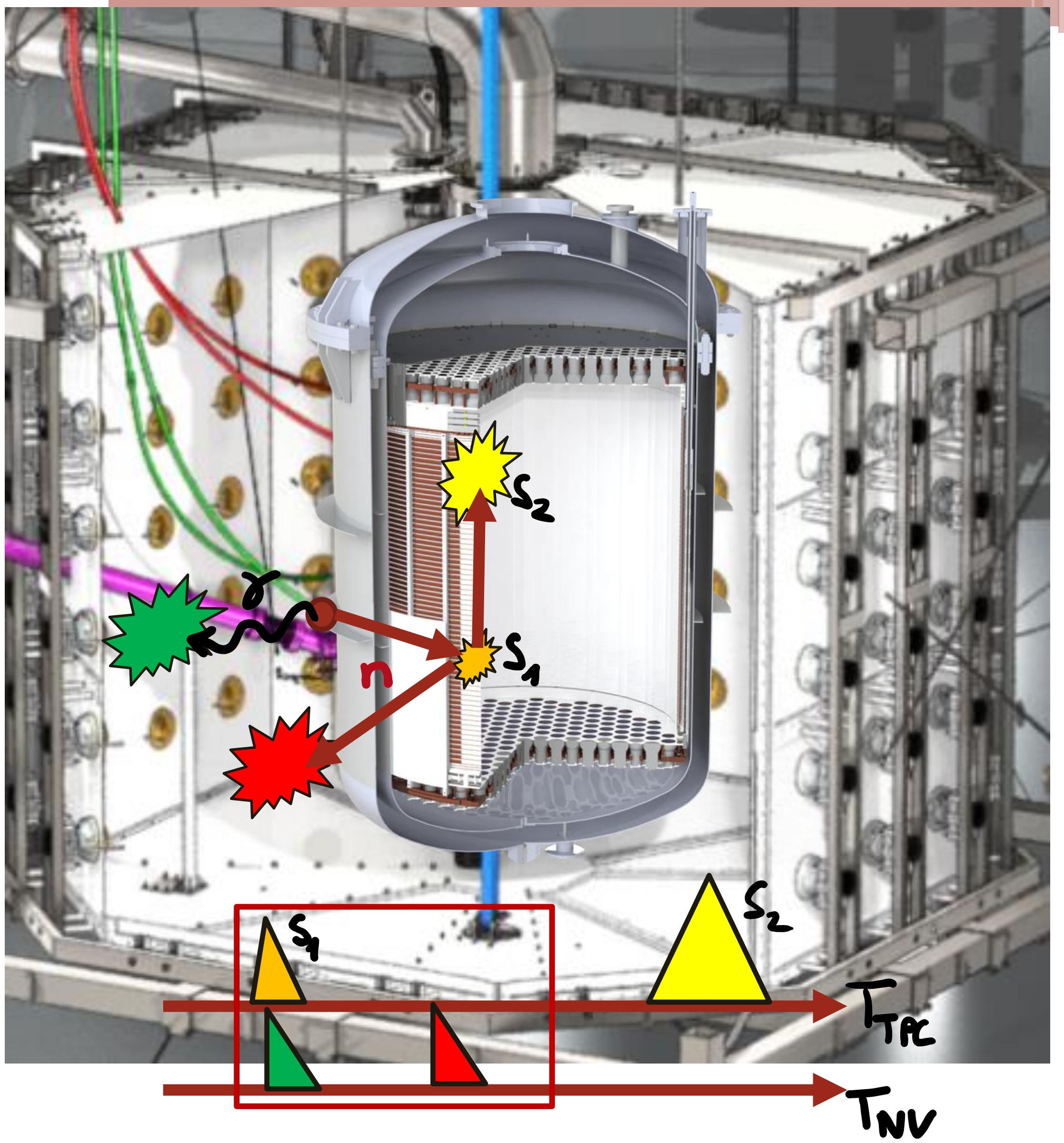
- Additional data-quality cuts to remove wrongly reconstructed events, mostly multi-scatter events

→ 99.9% purity of NR signals



Calibration of NV tagging

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

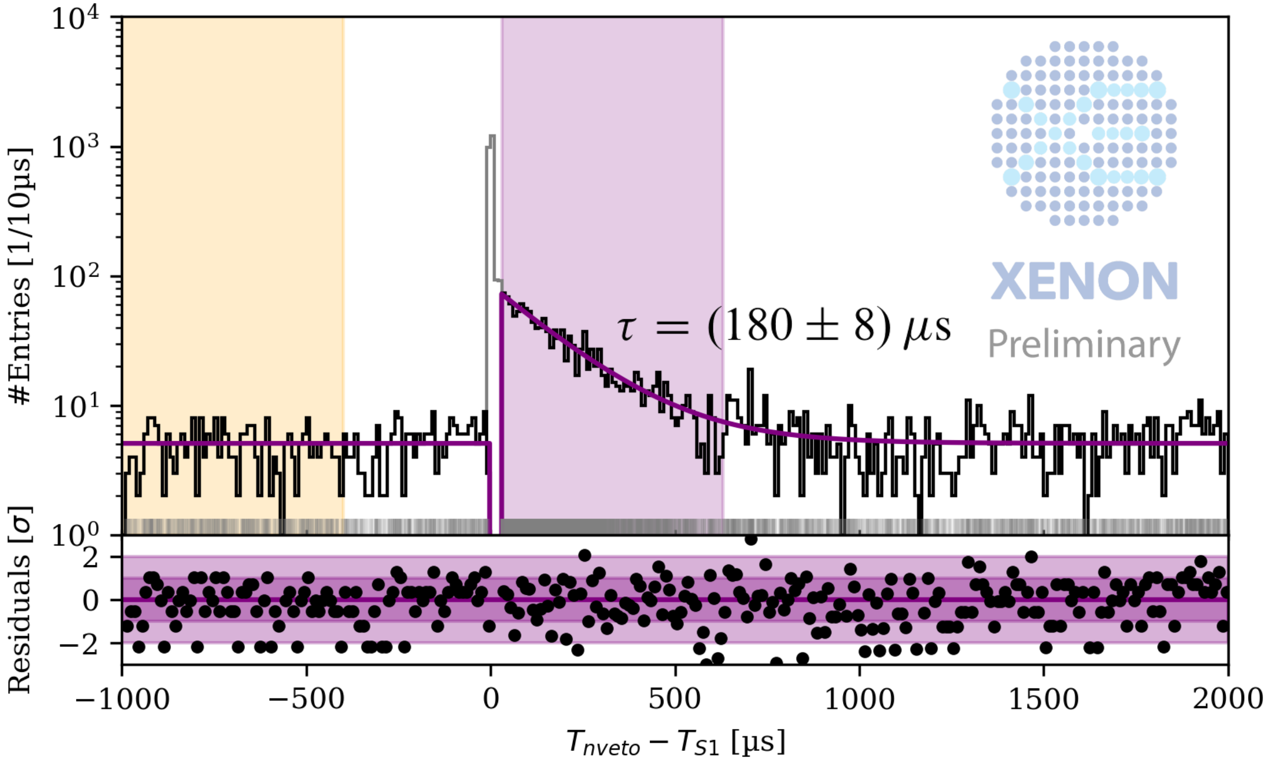


Calibration of NV tagging

- 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

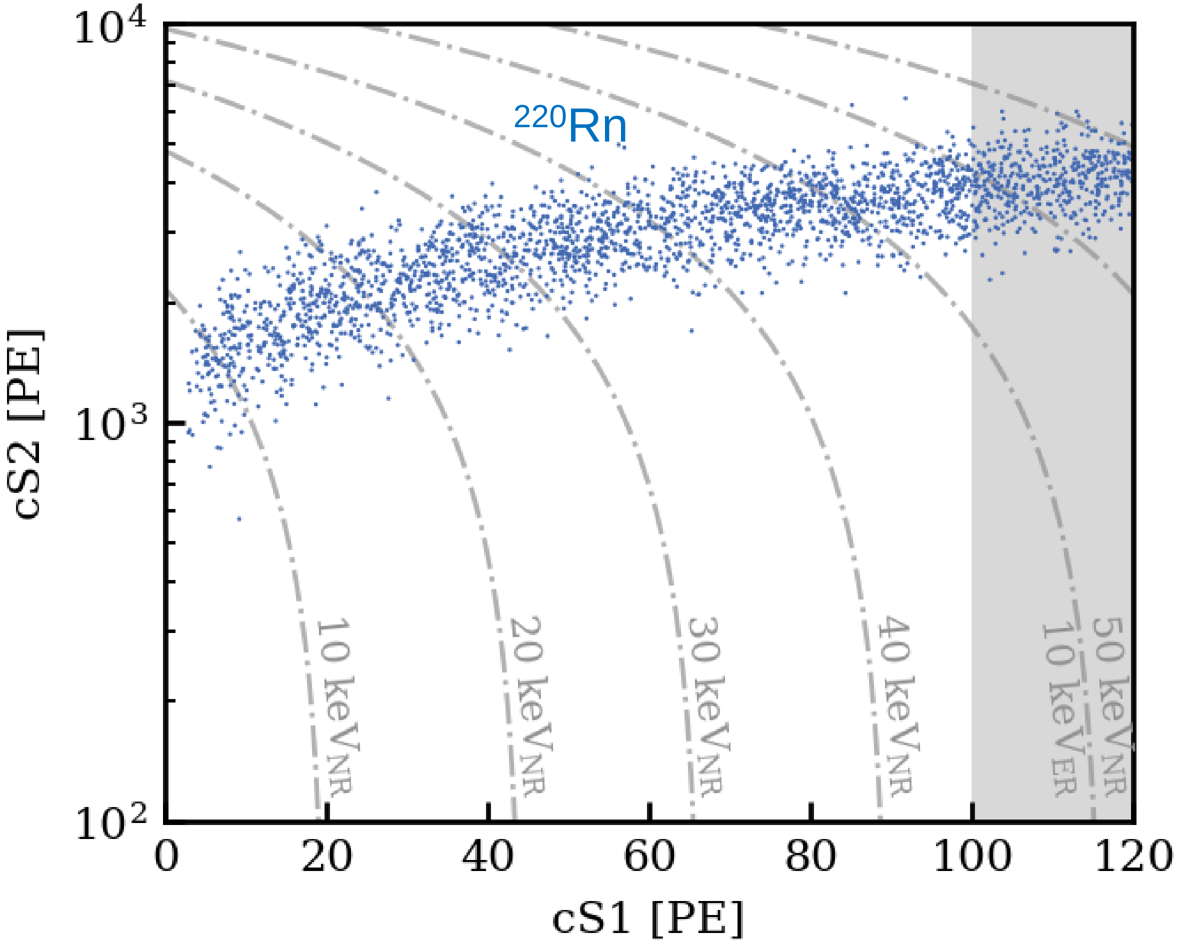
- Lifetime loss due to the veto of 1.6 %



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

- Calibration of ER response using ^{220}Rn
  - Gives approximately flat energy spectrum
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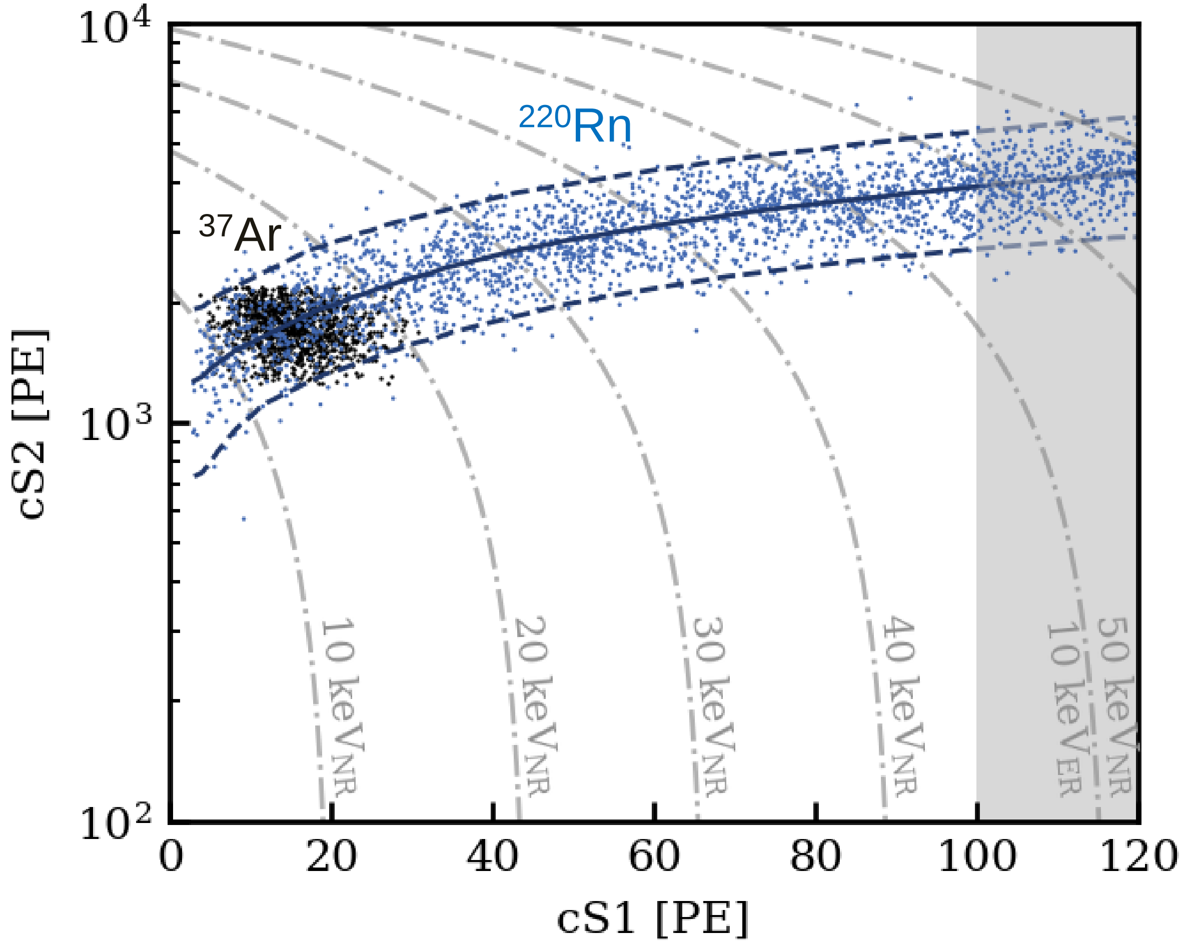
- Detector performance at low energies using ^{37}Ar
  - Mono-energetic line @2.8 keV
  - Allows to study performance with high resolution, due to high statistics
  - Removed via distillation
- ER response model based on a combined fit



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  - Allows to study performance with high resolution, due to high statistics
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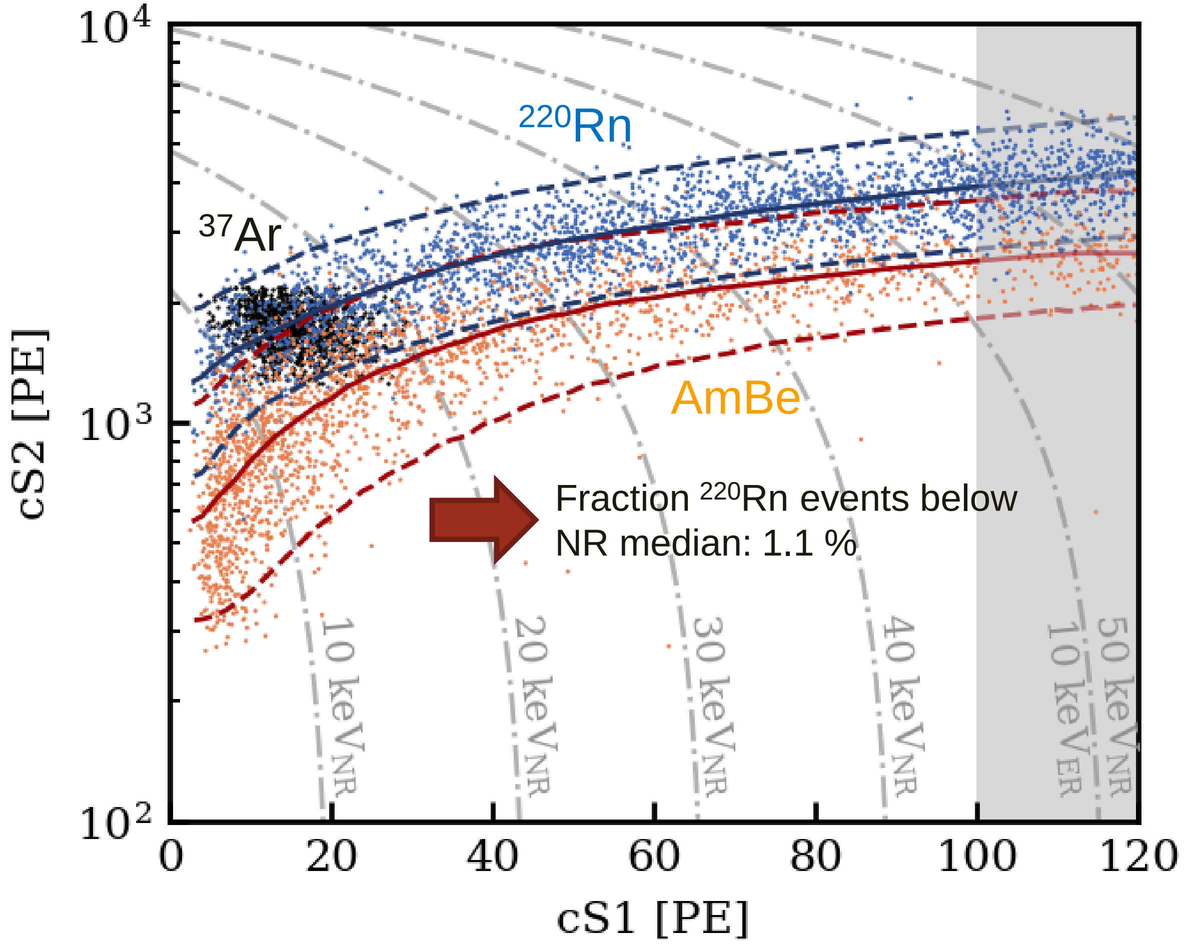
- ER response model based on a combined fit
- Uncertainties of the ER band shape propagated via a principal component analysis



Dark Matter Cookies

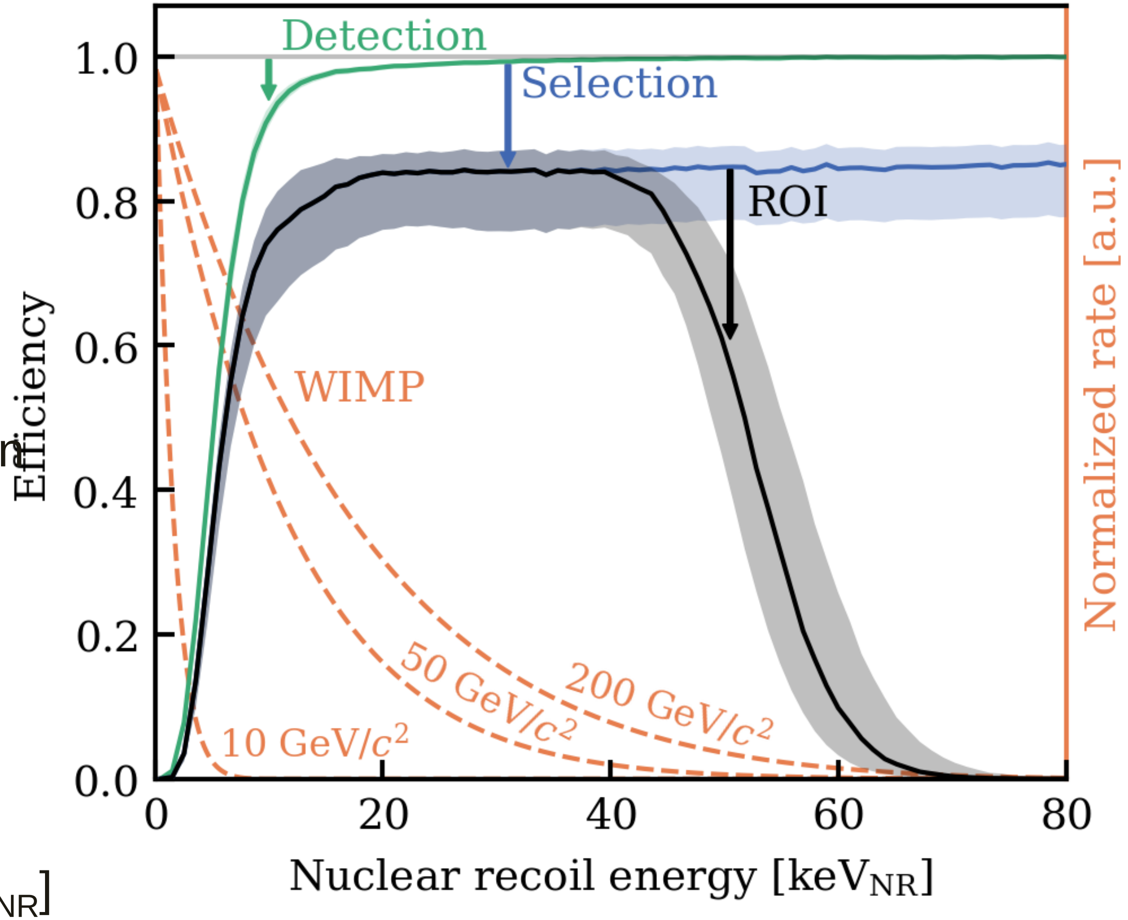
Dark Matter Chip Cookies (with extra big chunks of DM)

Ingredients:

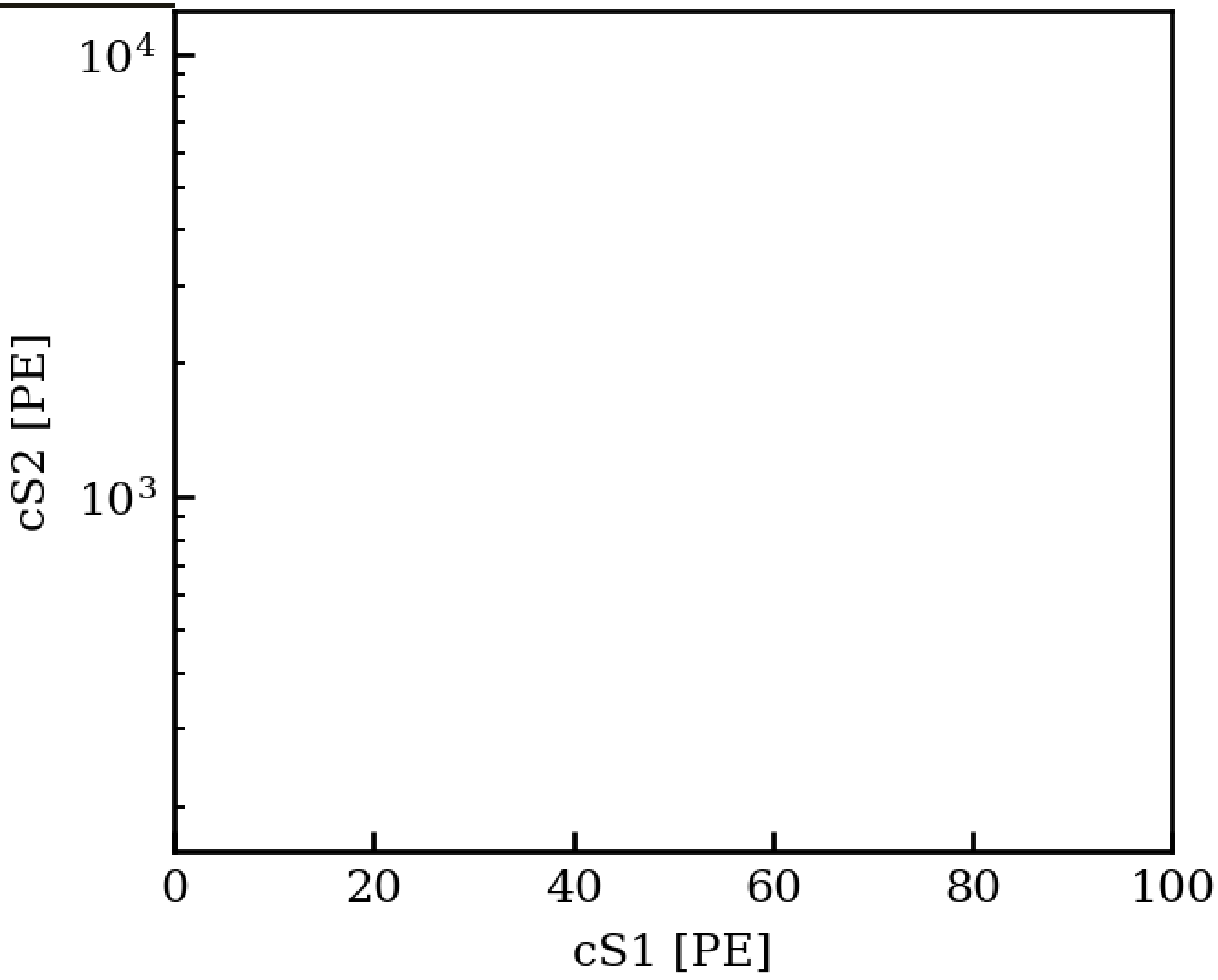
1. Dark Matter ✓
2. Detector ✓
3. Detector calibration ✓
4. Background and signal model
5. Enjoy the result

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 [3.3 keV_{NR}, 60.5 keV_{NR}]



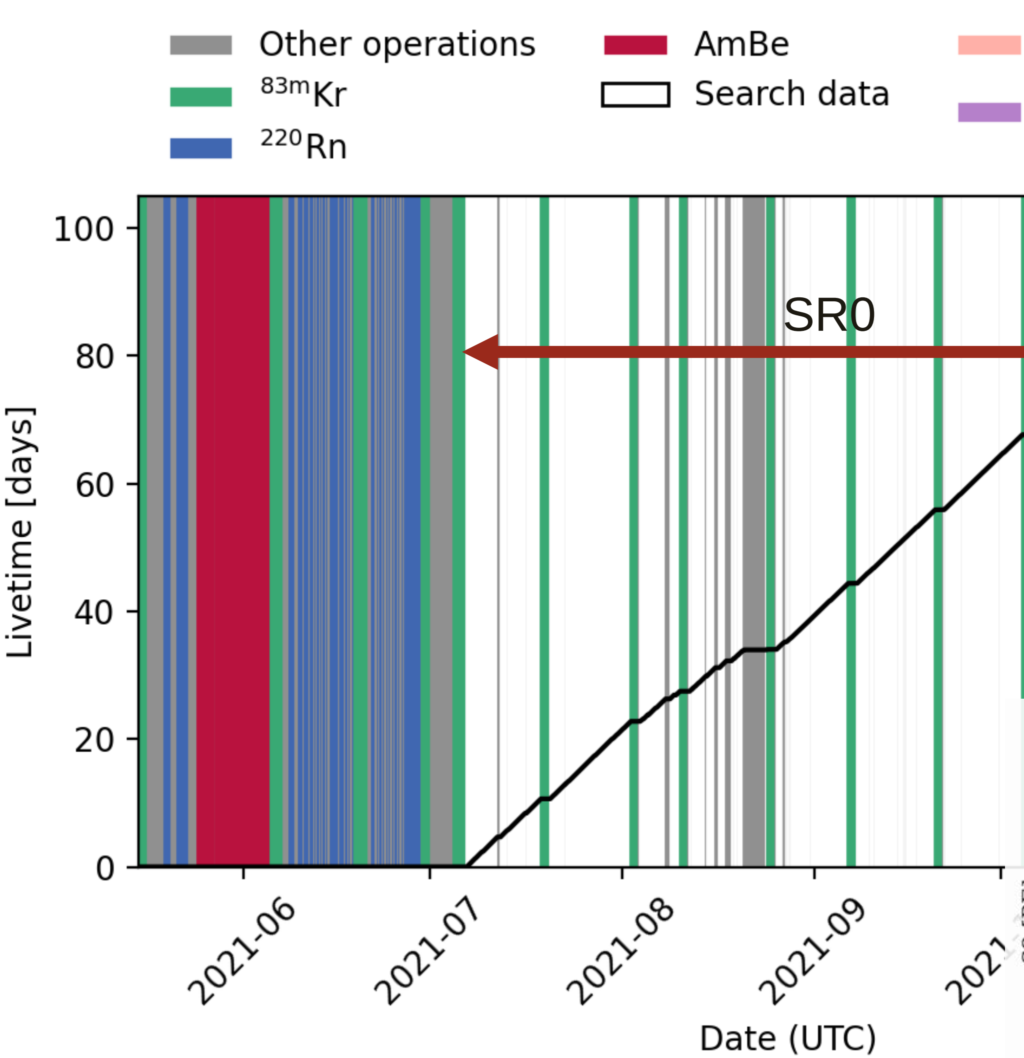
Dark Matter ROI

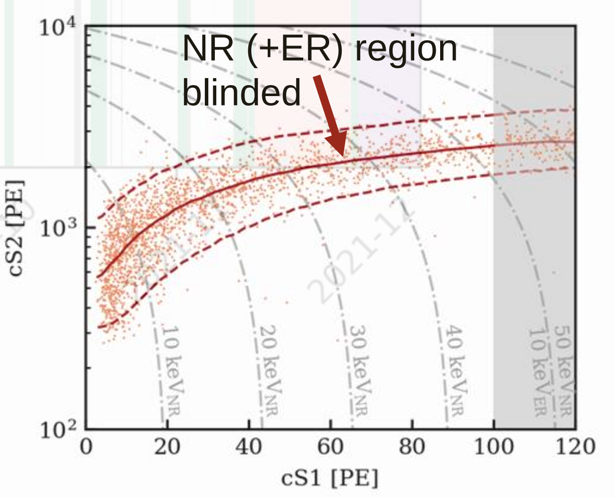


SR0 data taking

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**

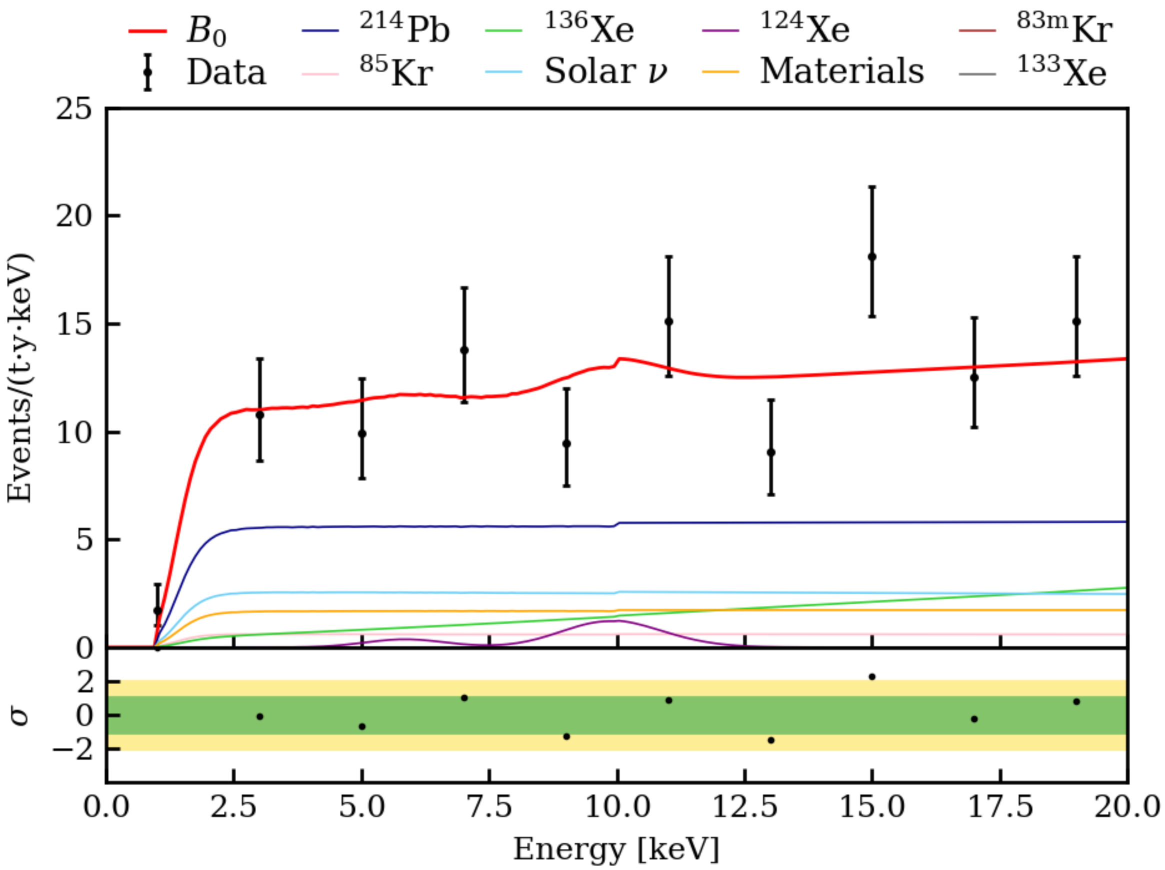




ER background

- 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

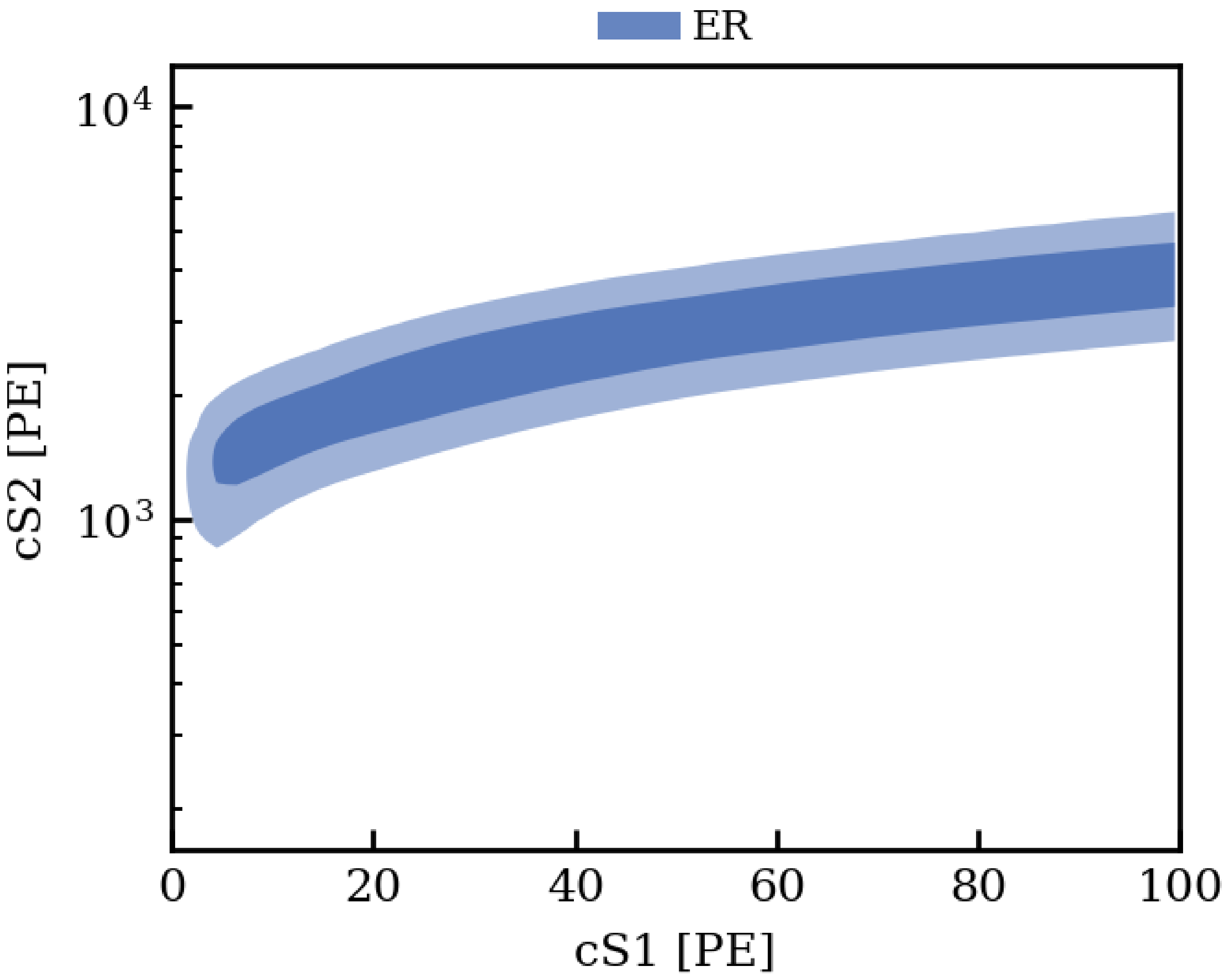
134 events in ER band of ROI
(15.8±1.3) events/(t · y · keV)



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

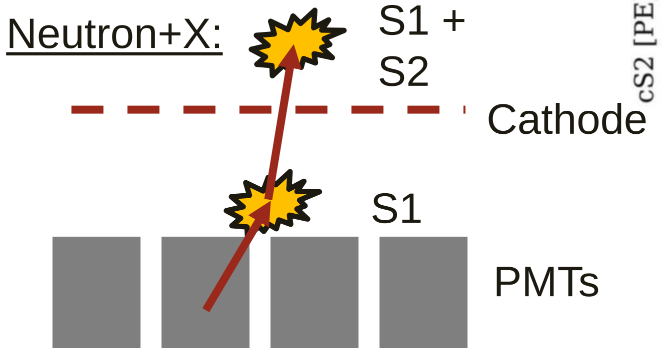


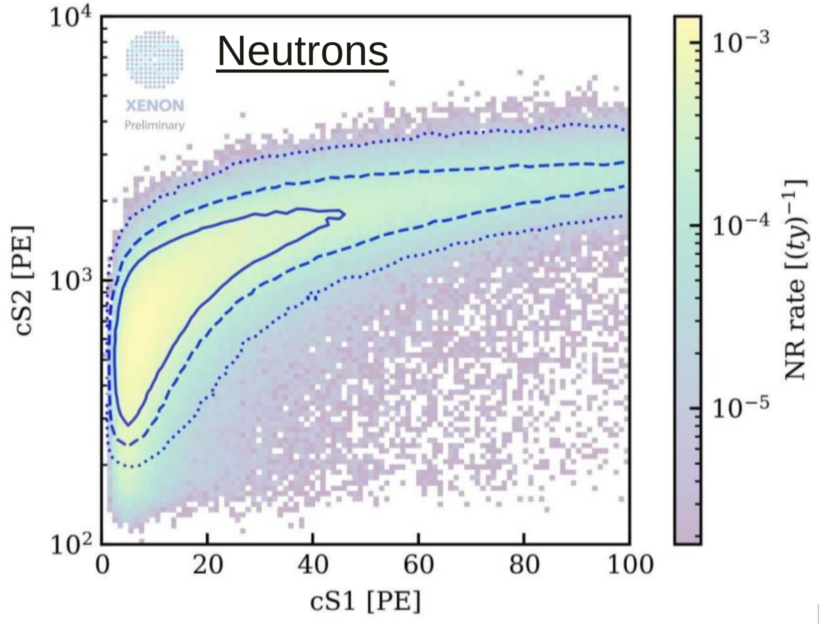
Background model NR search

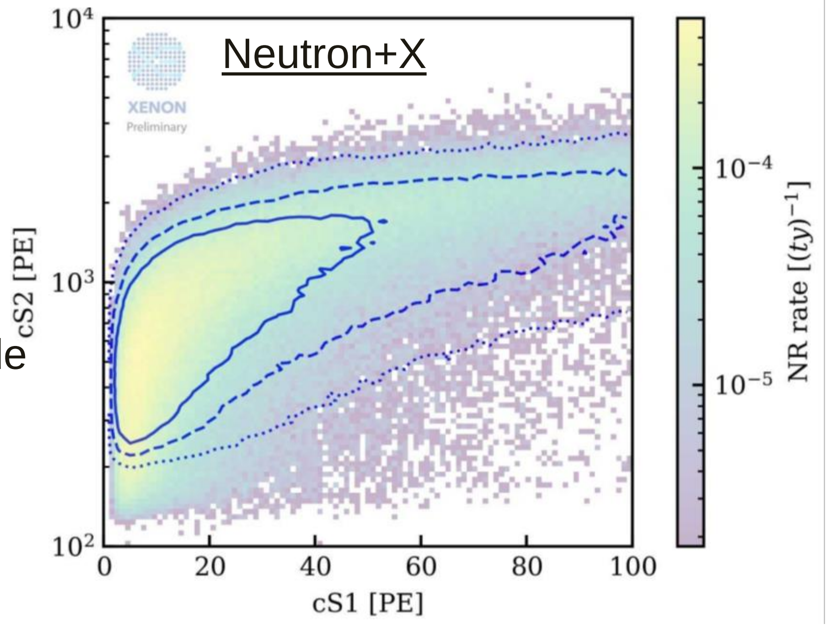
- Neutron background dominated by spontaneous fission and (α, n)-reactions
- Neutron yields estimated based on screening results
- Background templates generated via full-scale waveform simulations + analysis chain
- Background rate by NV tagged unblinding:

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

*determined after fixing a mistake in the NV tagging post unblinding the SR0 data



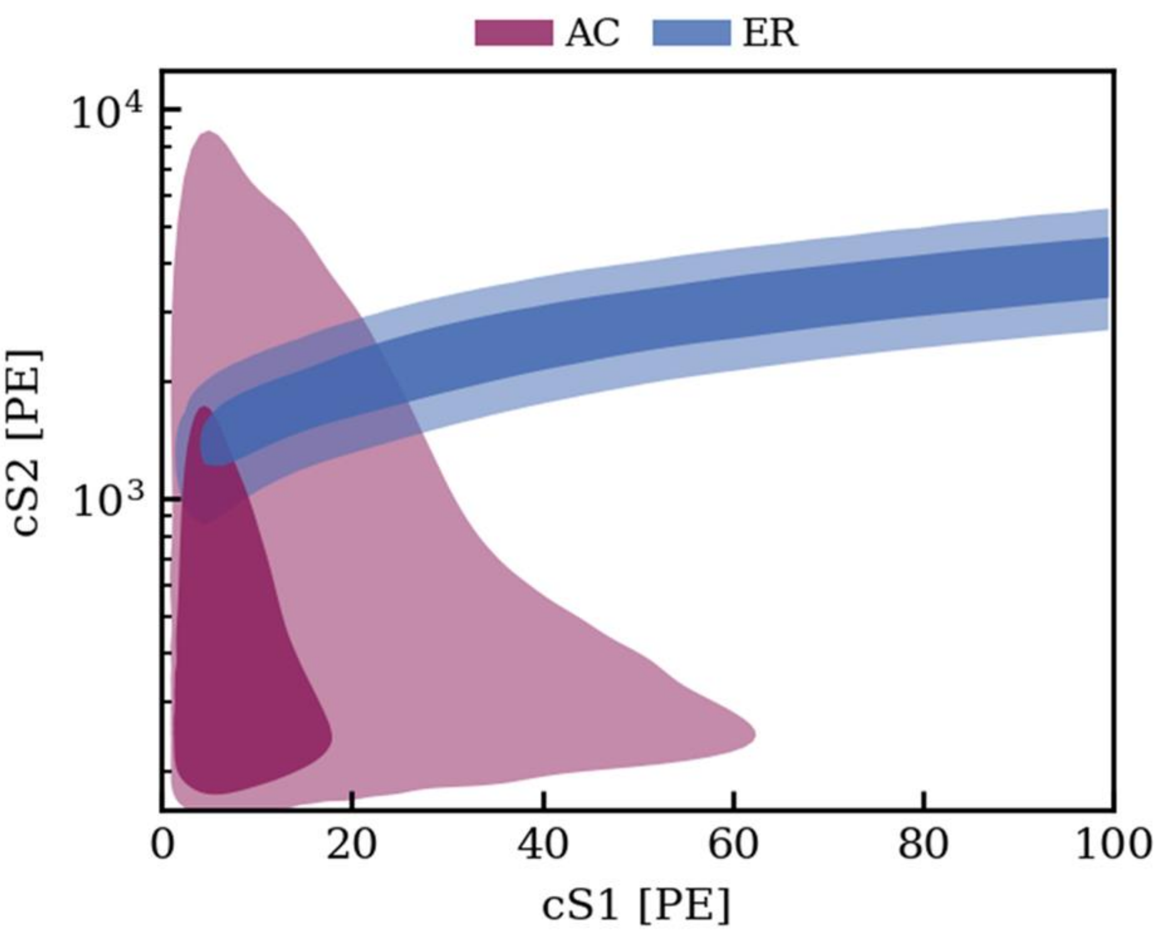




Detector backgrounds

Accidental coincidences (AC):

- Random pairing of S1 and S2 signals
- Model optimized on synthetic dataset due to triggerless DAQ approach



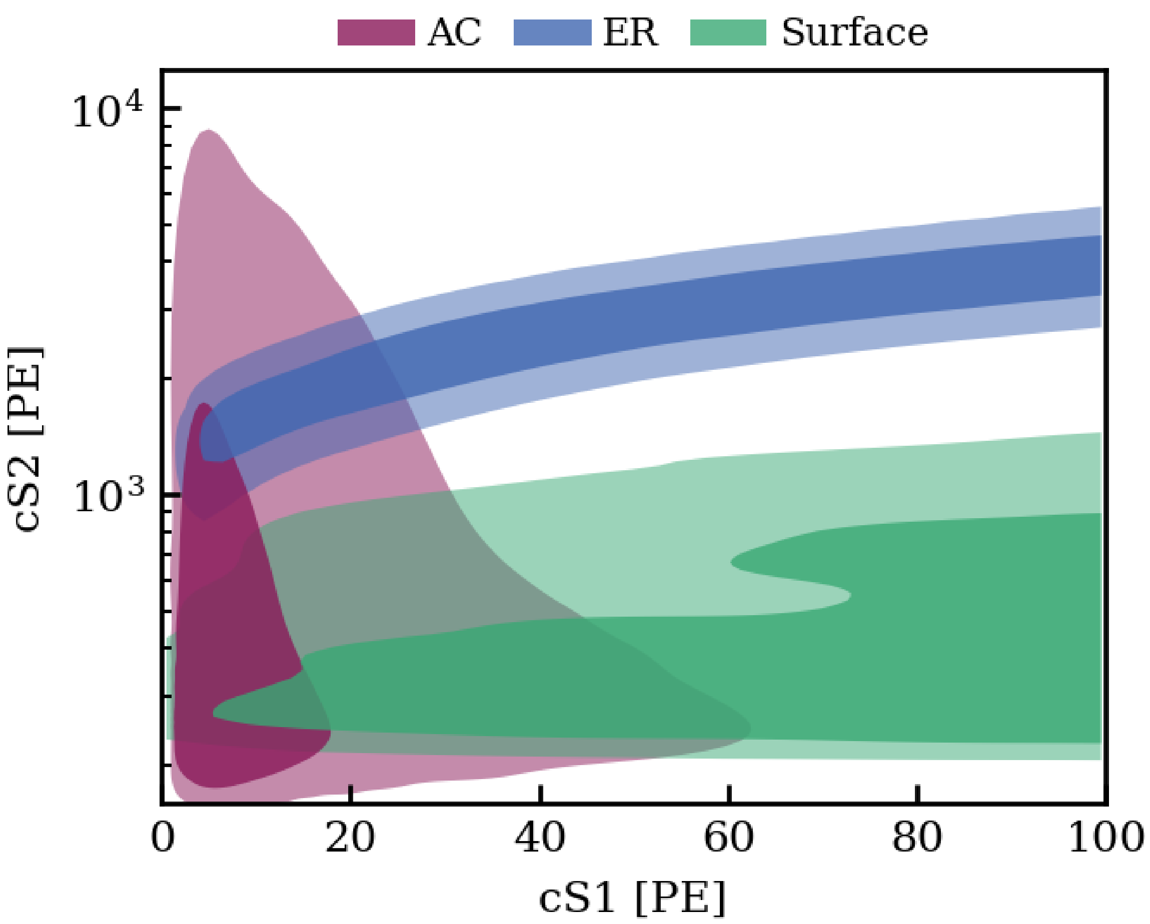
Detector backgrounds

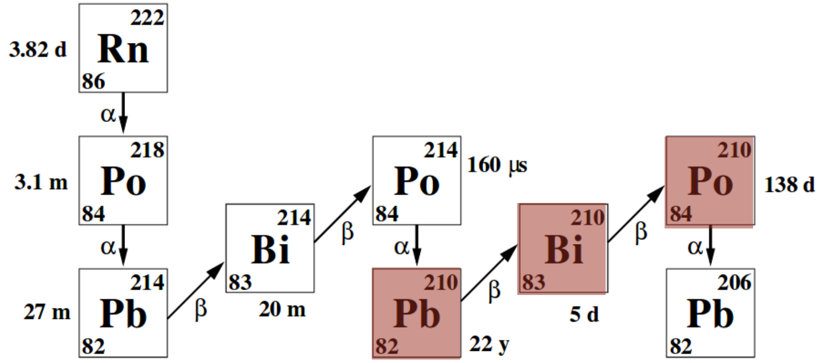
Accidental coincidences (AC):

- Random pairing of S1 and S2 signals
- Model optimized on synthetic dataset due to triggerless DAQ approach

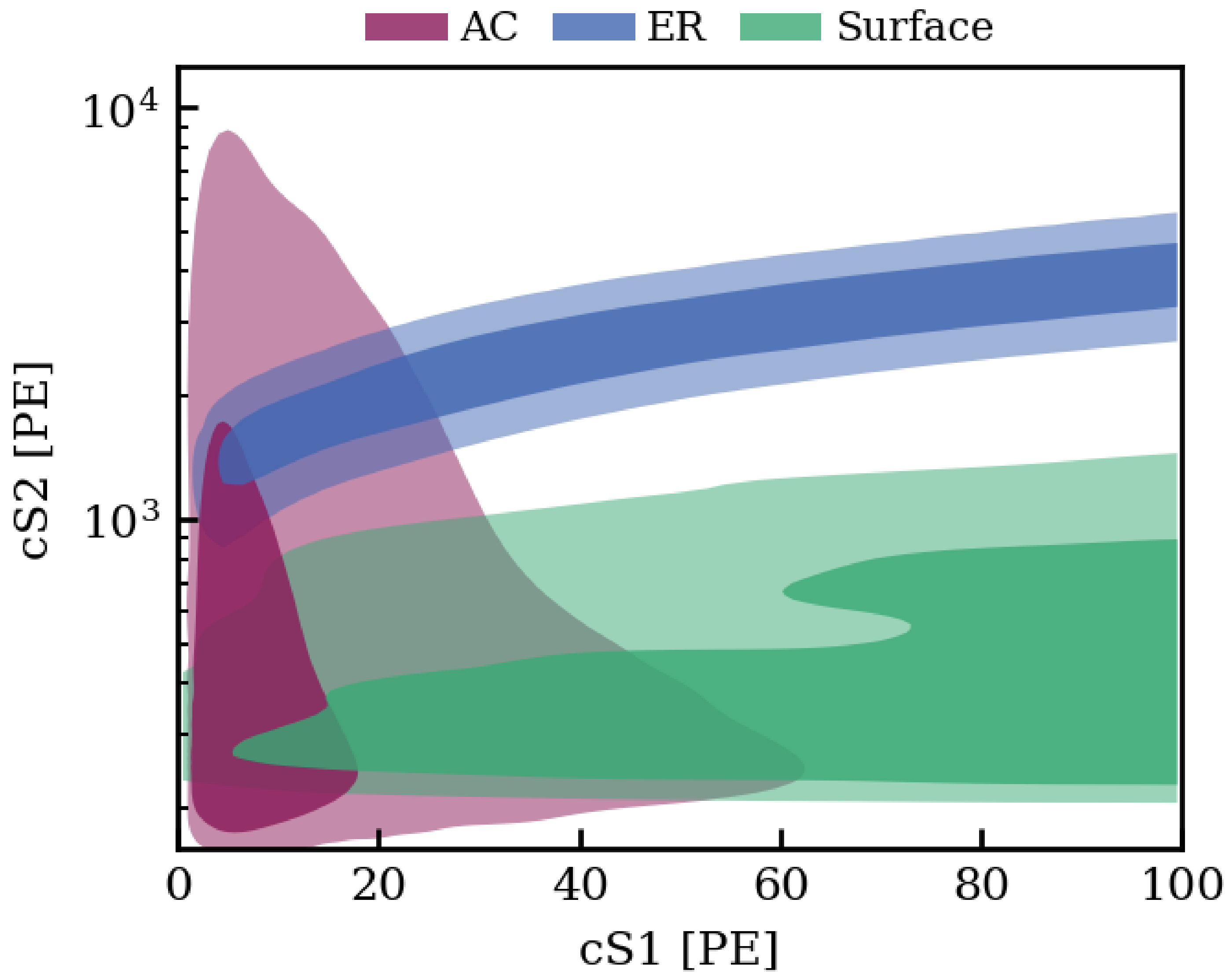
Surface Background:

- Due to ERs from ^{210}Pb plate out at detector walls
- Model based on events reconstructed outside the fiducial
- Absolute rate R,Z dependent
- Reduced R_{max} < 61.35 cm





Dark Matter ROI



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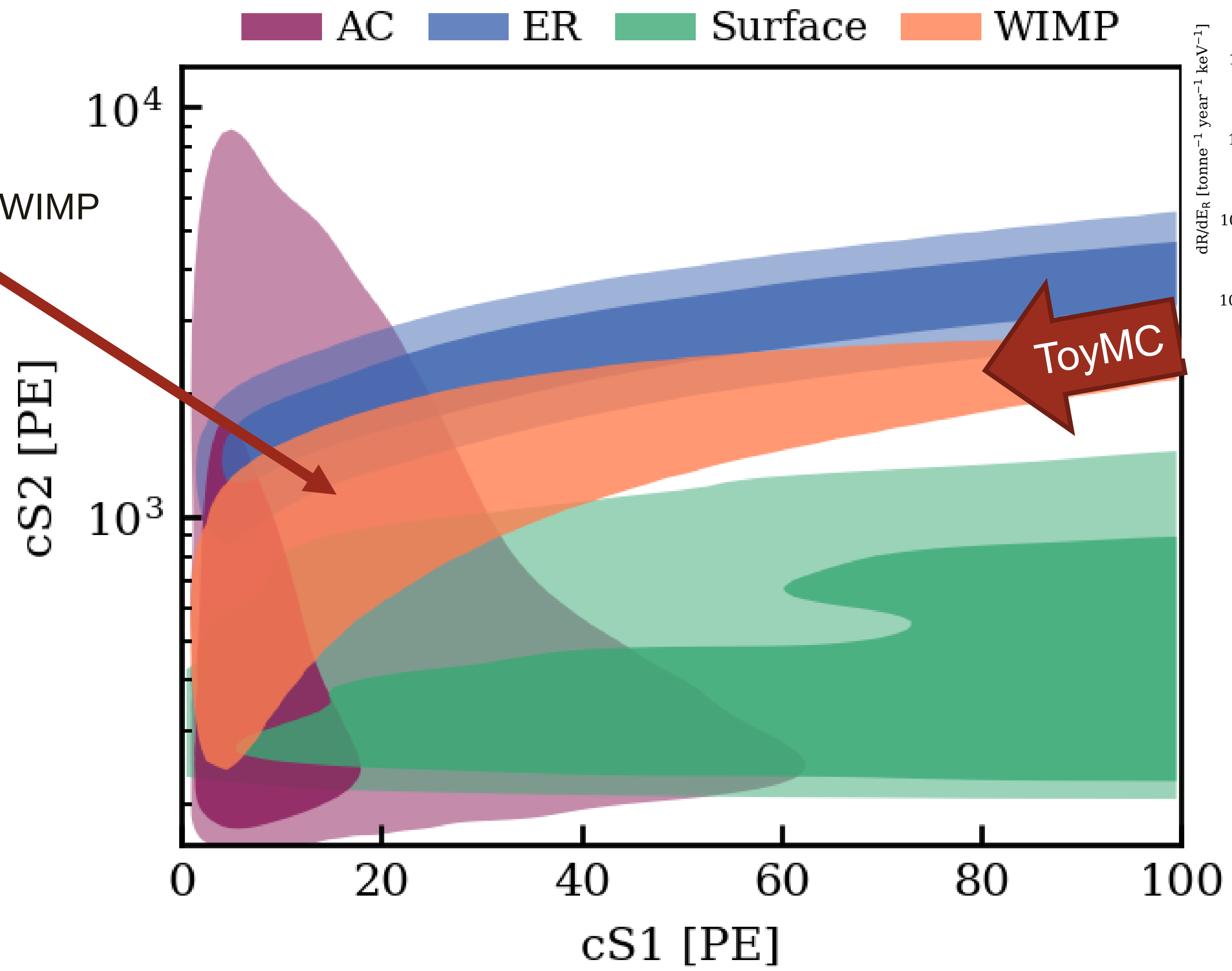
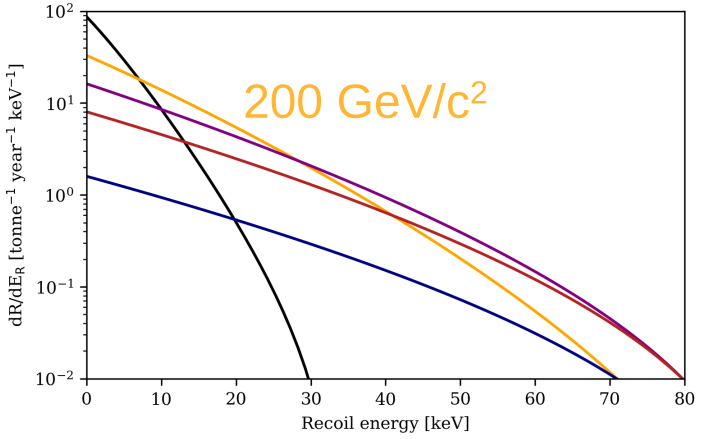
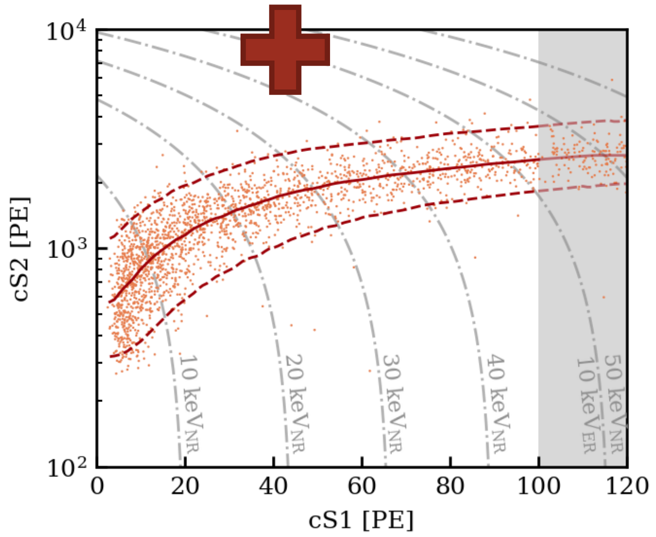
WIMP results

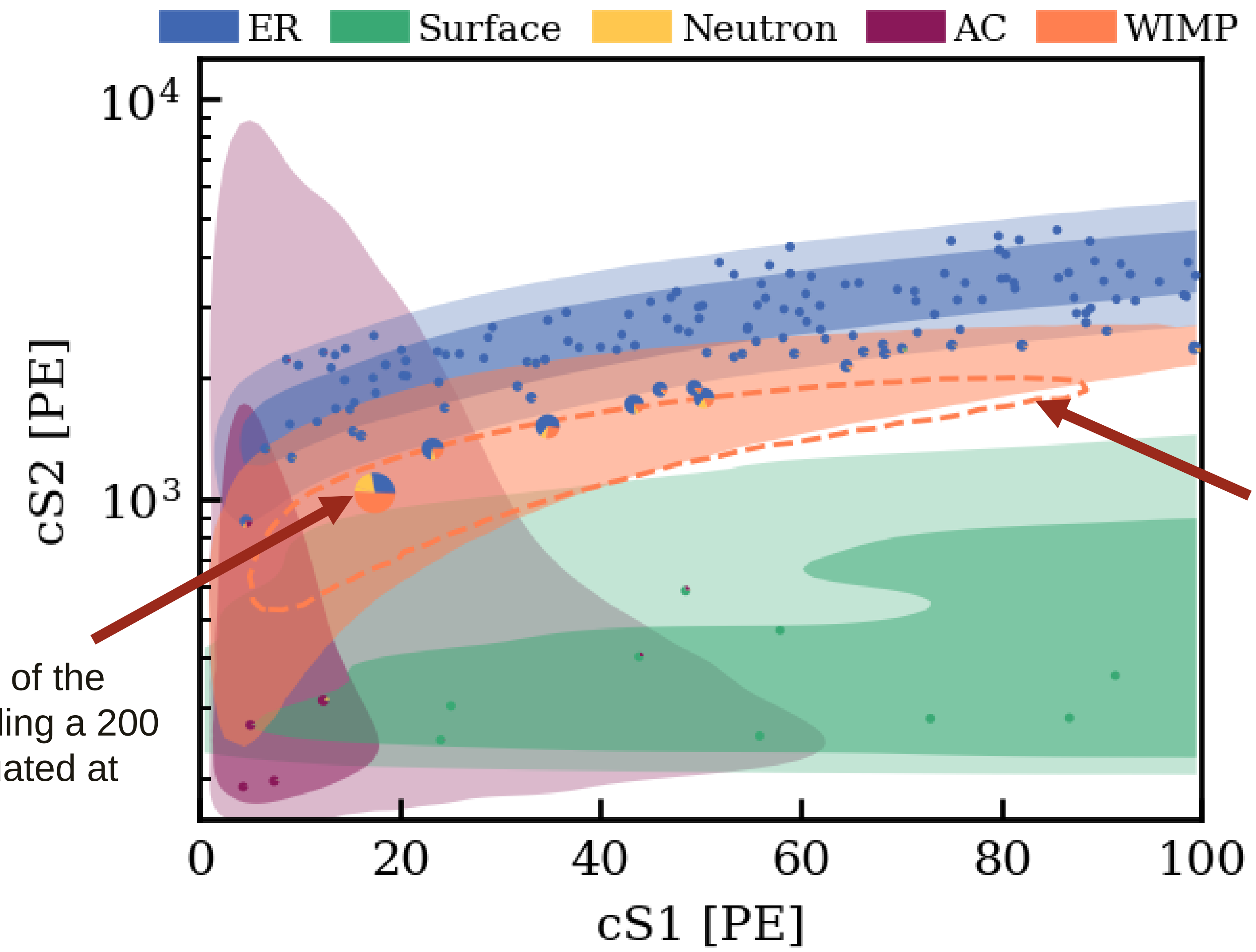
2 σ contour
200 GeV/c² WIMP







WIMP results

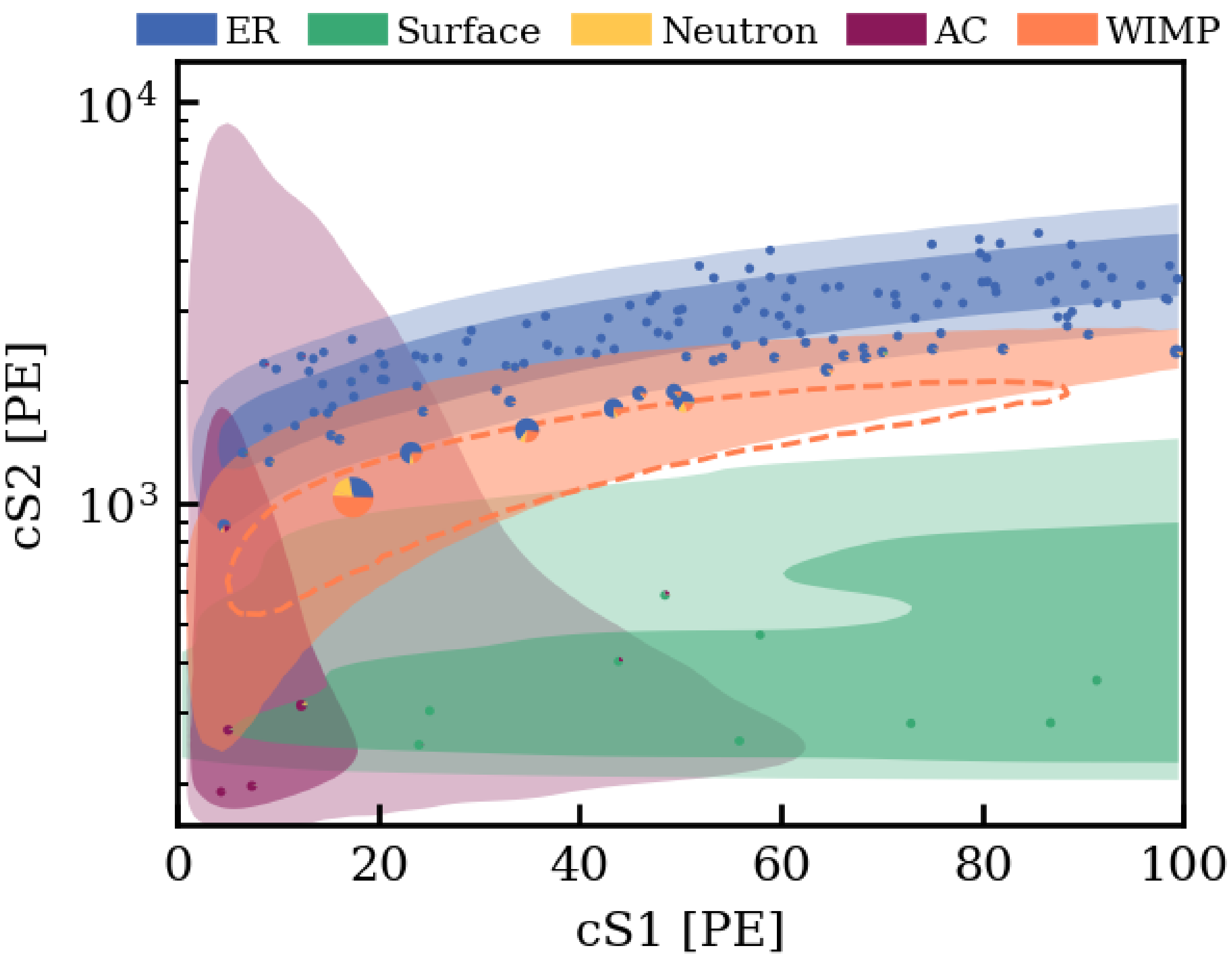


Component fraction of the best fit model including a 200 GeV/c² WIMP evaluated at event position

Signal-like region, containing 50% of a 200 GeV/c² WIMP signal with highest signal-to-noise ratio

WIMP results

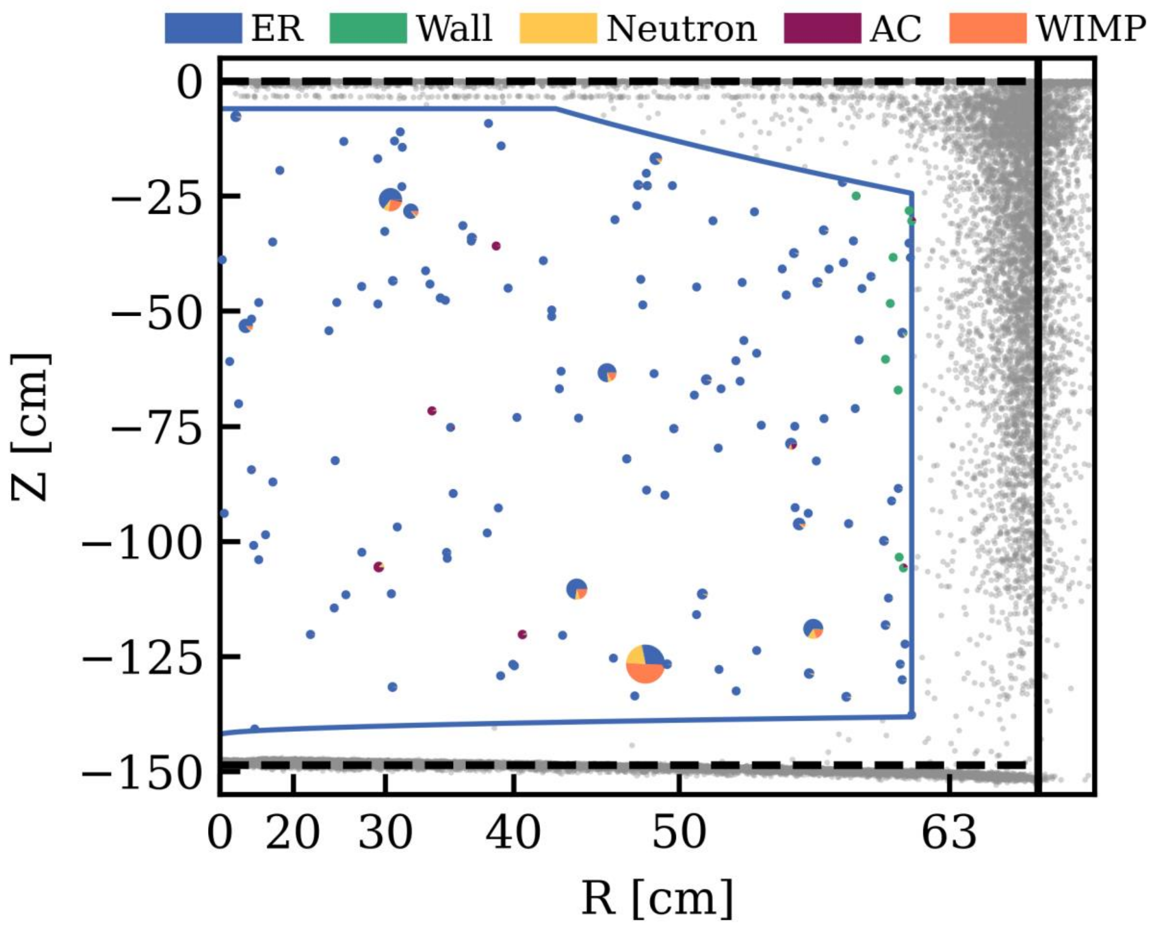
	Nominal	Best Fit	
		ROI	Signal-like
ER	134	135^{+12}_{-11}	0.81 ± 0.07
Neutrons	$1.1^{+0.6}_{-0.5}$	1.1 ± 0.2	0.42 ± 0.10
CEvNS	0.23 ± 0.06	0.23 ± 0.06	0.022 ± 0.011
AC	4.3 ± 0.2	4.32 ± 0.15	0.363 ± 0.013
Surface	14 ± 3	12^{+0}_{-4}	$0.34^{+0.01}_{-0.11}$
Total	154	152 ± 12	$1.95^{+0.12}_{-0.16}$
WIMP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

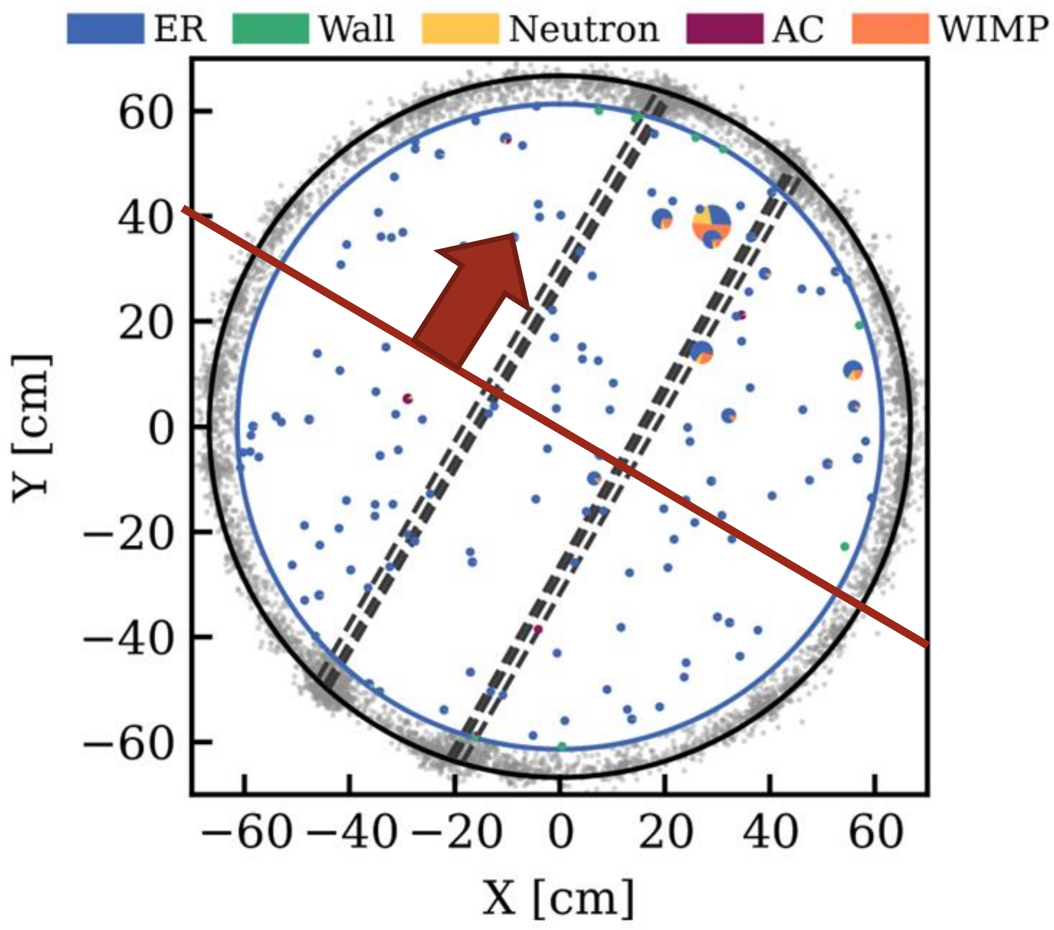


- 152 events in ROI, 16 in blinded region
- Best fit indicates **no significant excess**

WIMP results

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



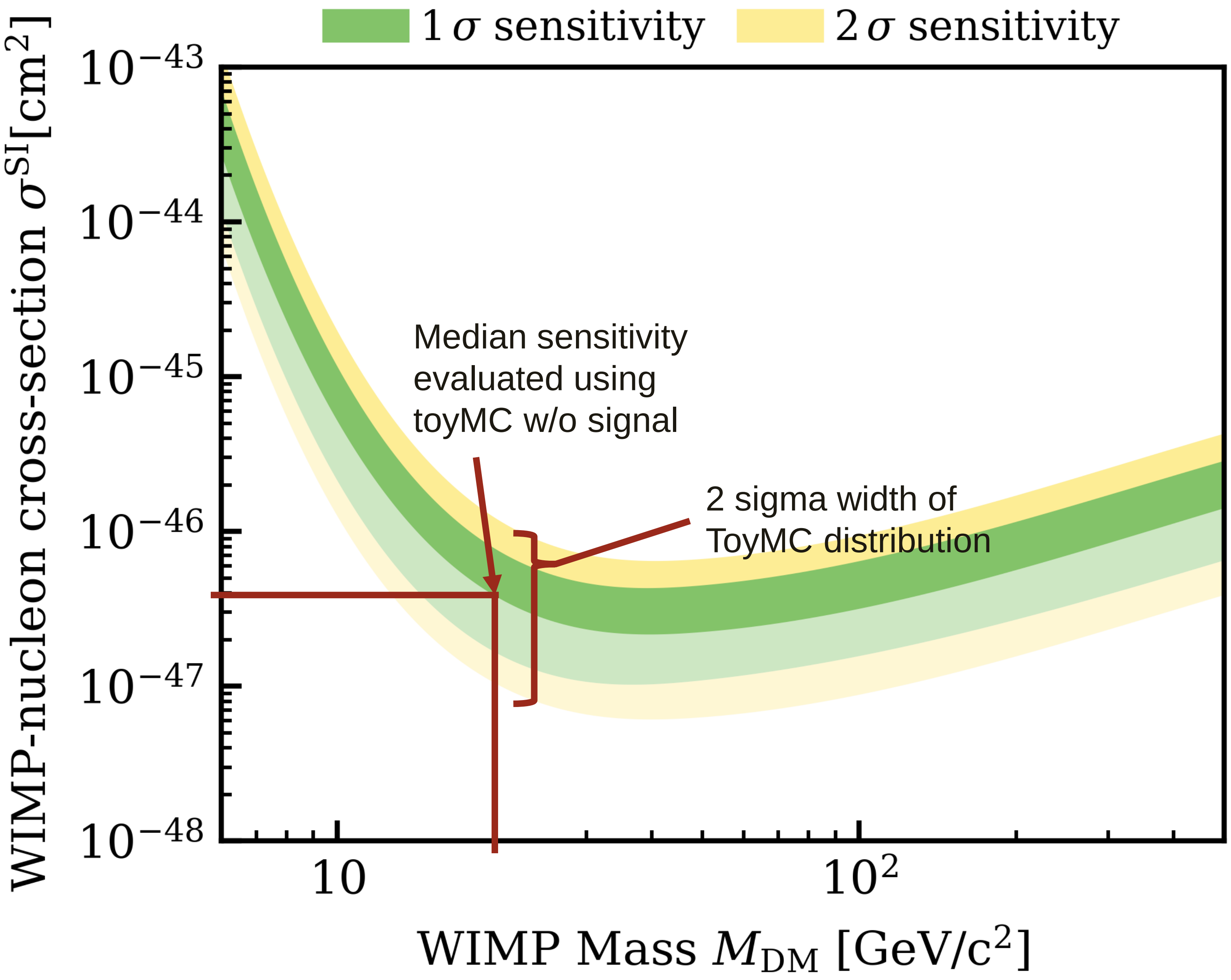


WIMP results

- Log-Likelihood-ratio as test statistics

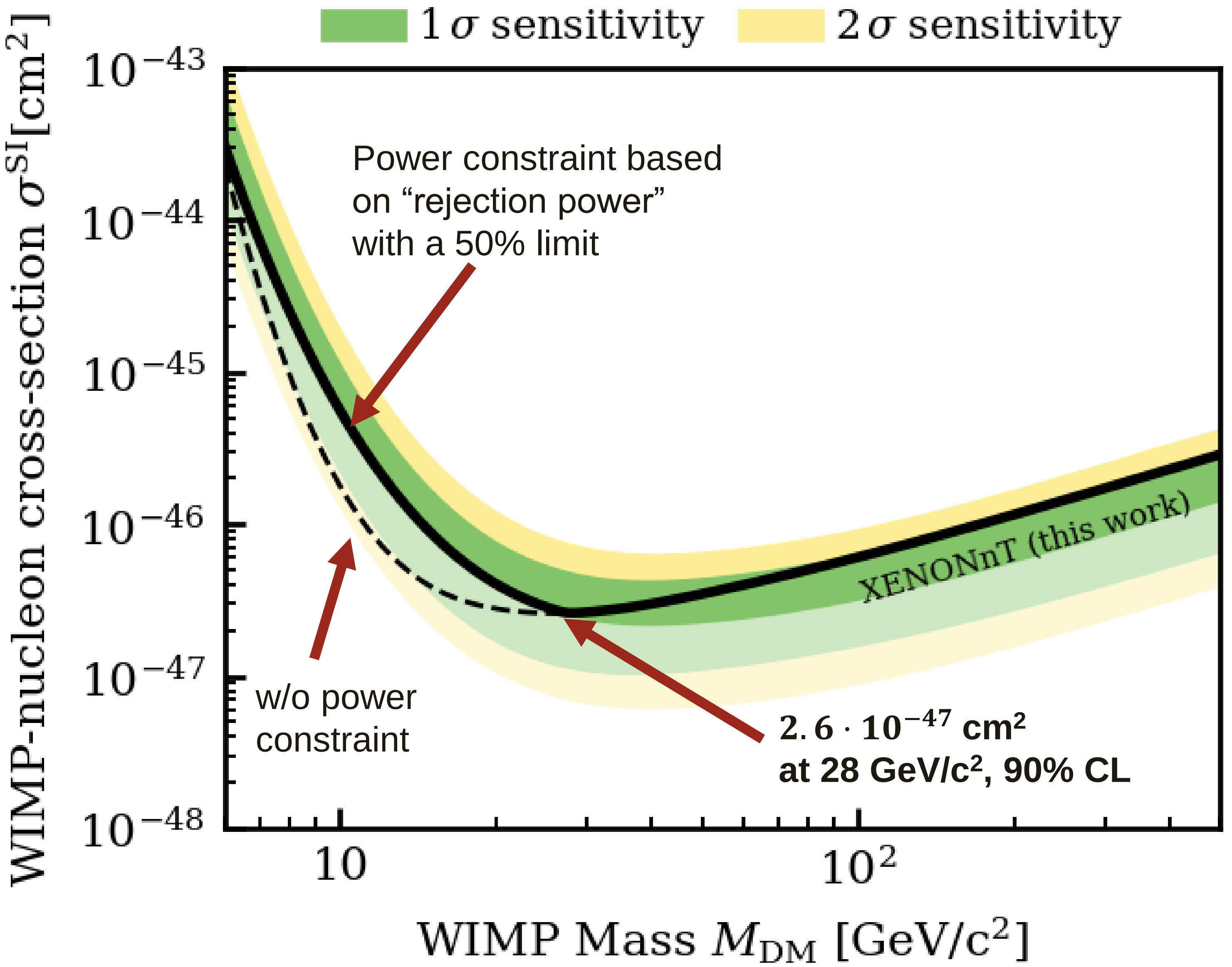
$$q(\sigma) = -2\log\frac{L(\sigma,\hat{\hat{\theta}})}{L(\hat{\sigma},\hat{\theta})}$$

- Median upper limit @ 90% confidence



WIMP results

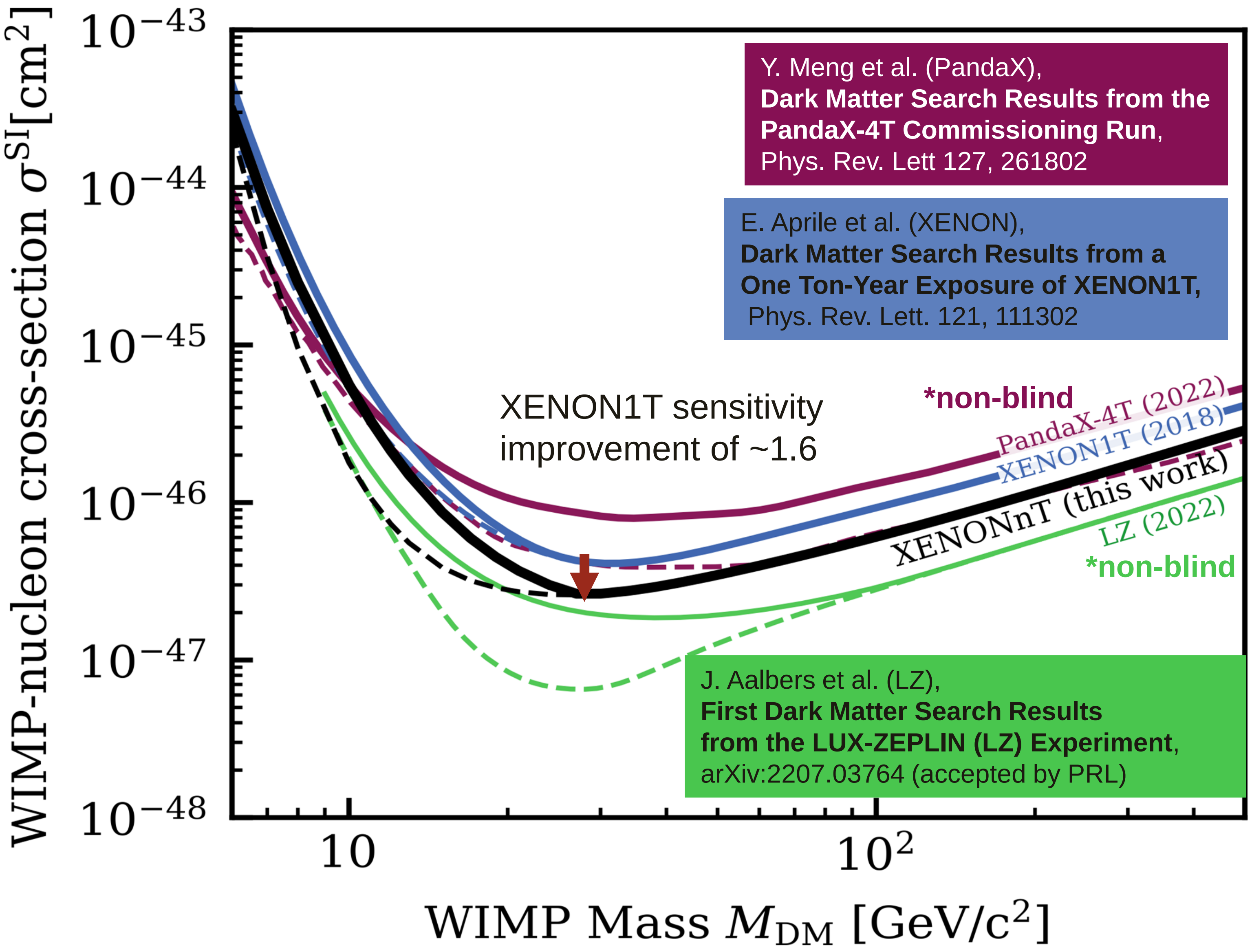
- Power constraint limits (PCL) to avoid exclusion limits, in region without sensitivity



WIMP results

Comparison

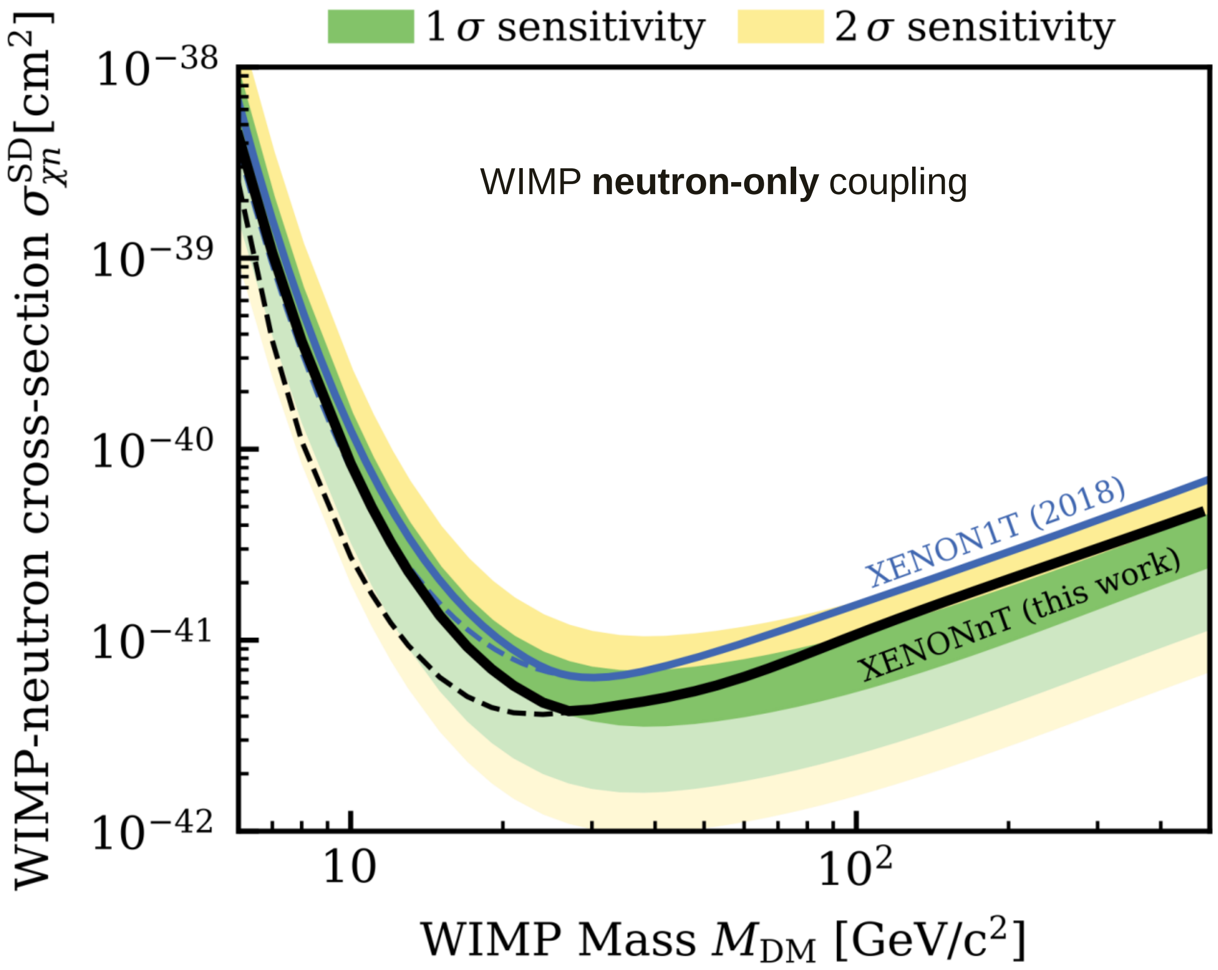
- Power constraint limits (PCL) to avoid exclusion limits, in region without sensitivity
- Same approach applied to other results to make limits comparable

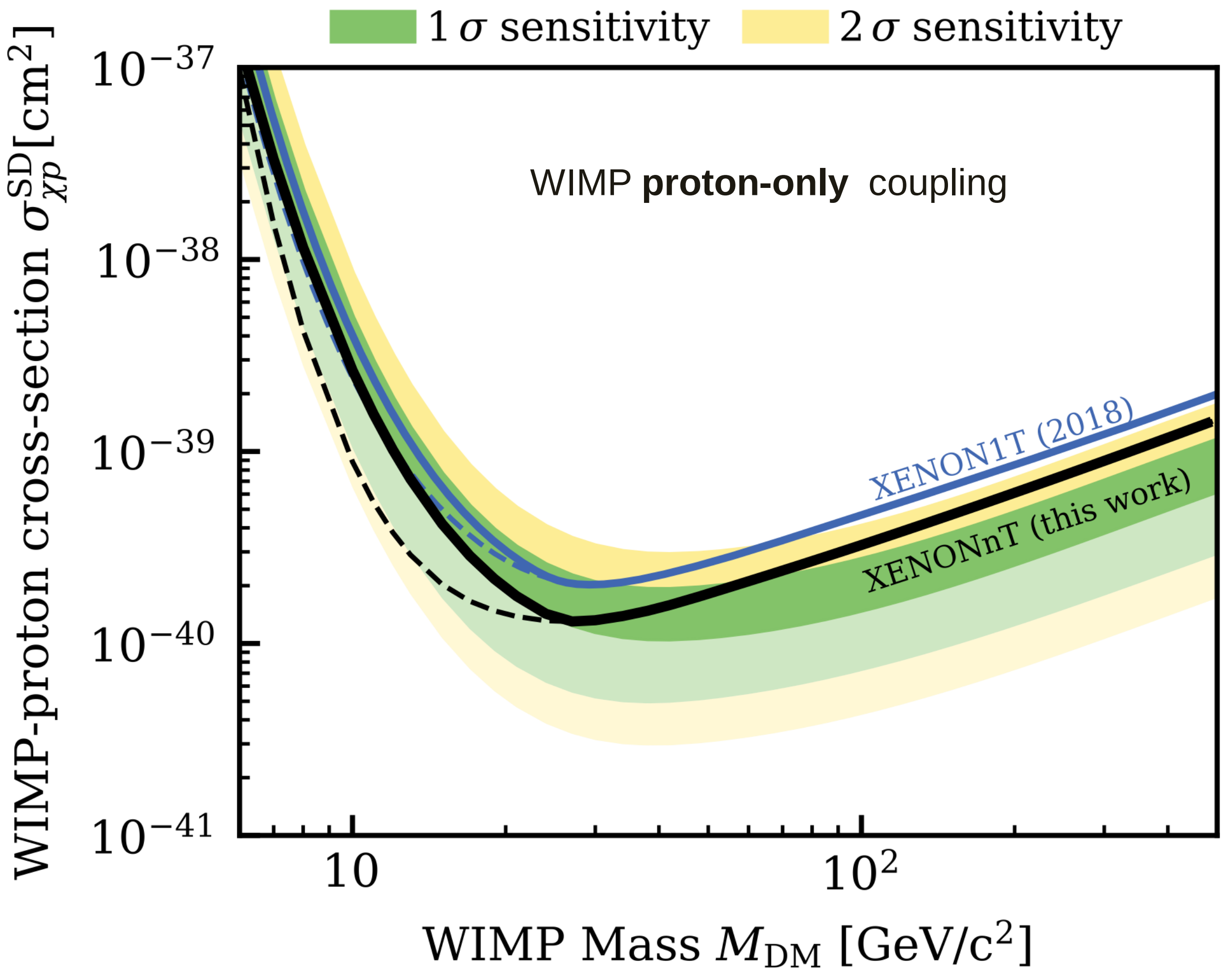


WIMP results

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**
- Despite low electric field, 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

Paper just accepted by PRL
arXiv:2303.14729