# First WIMP search results from XENONnT

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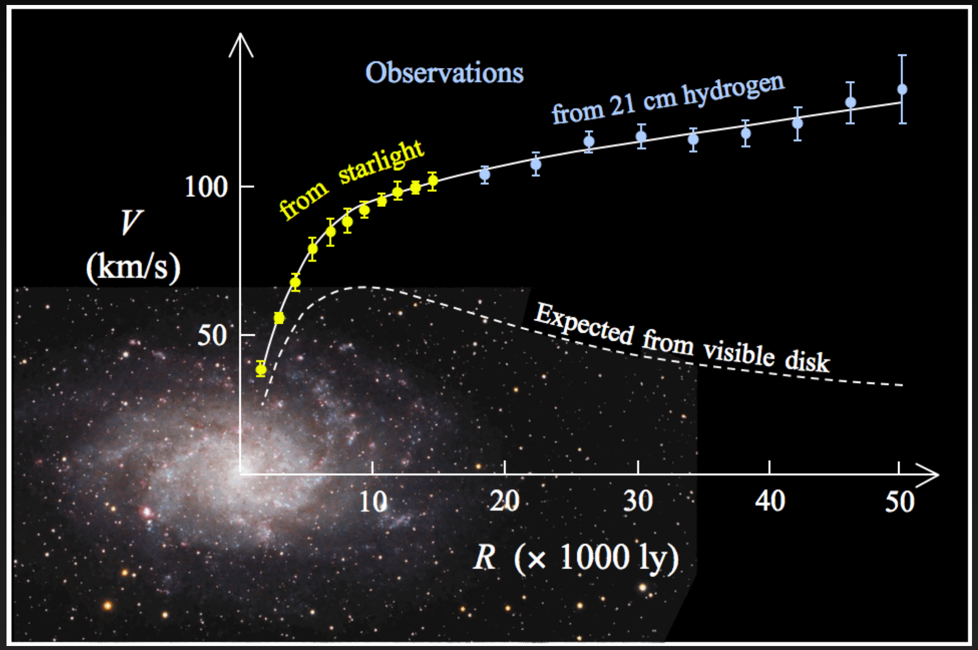
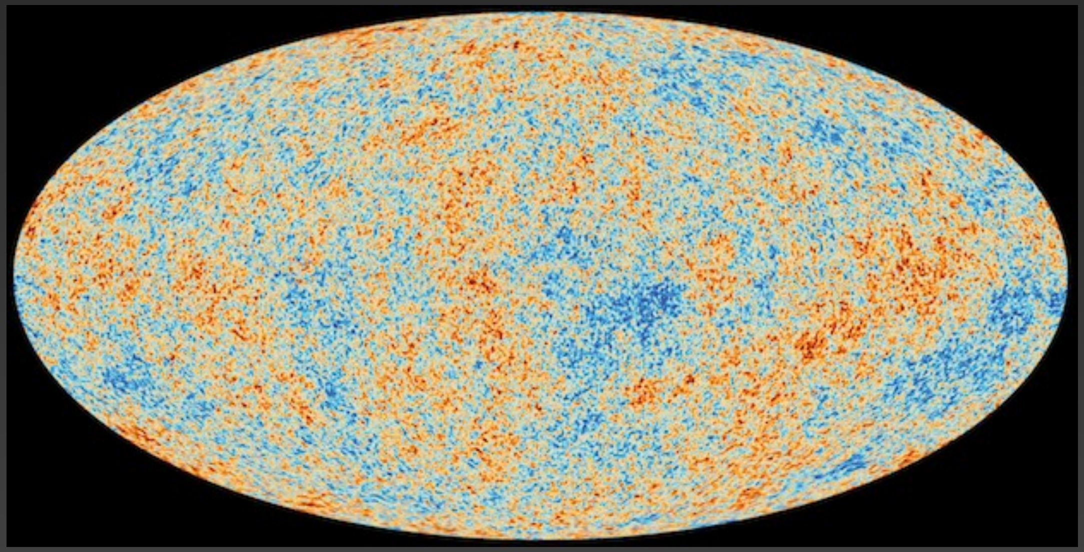
May 5, 2023

# Evidence of dark matter

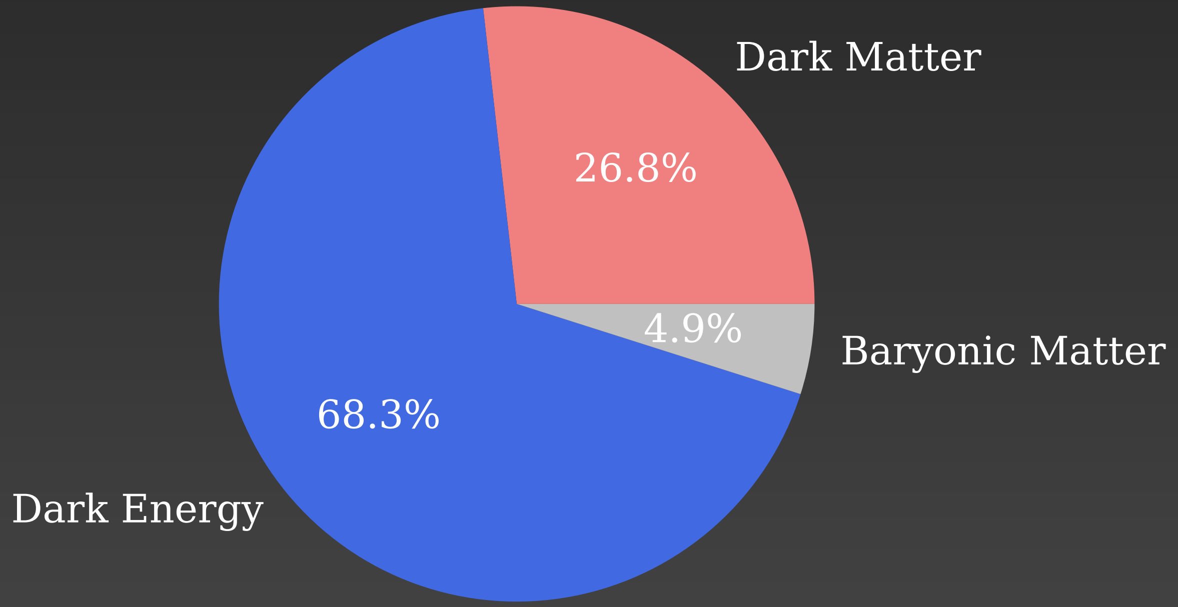



Rotation curve


Bullet cluster

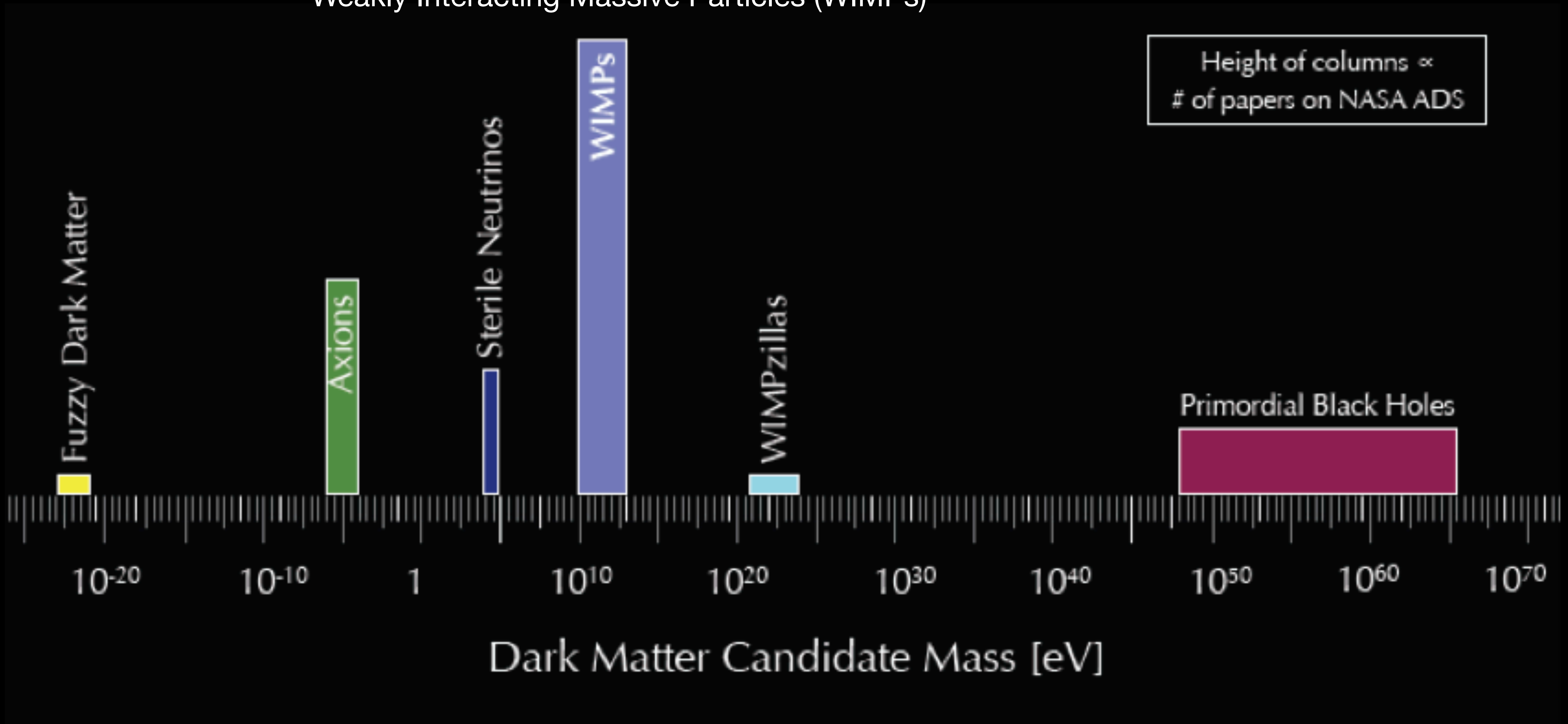


CMB background



# Dark matter particle candidates

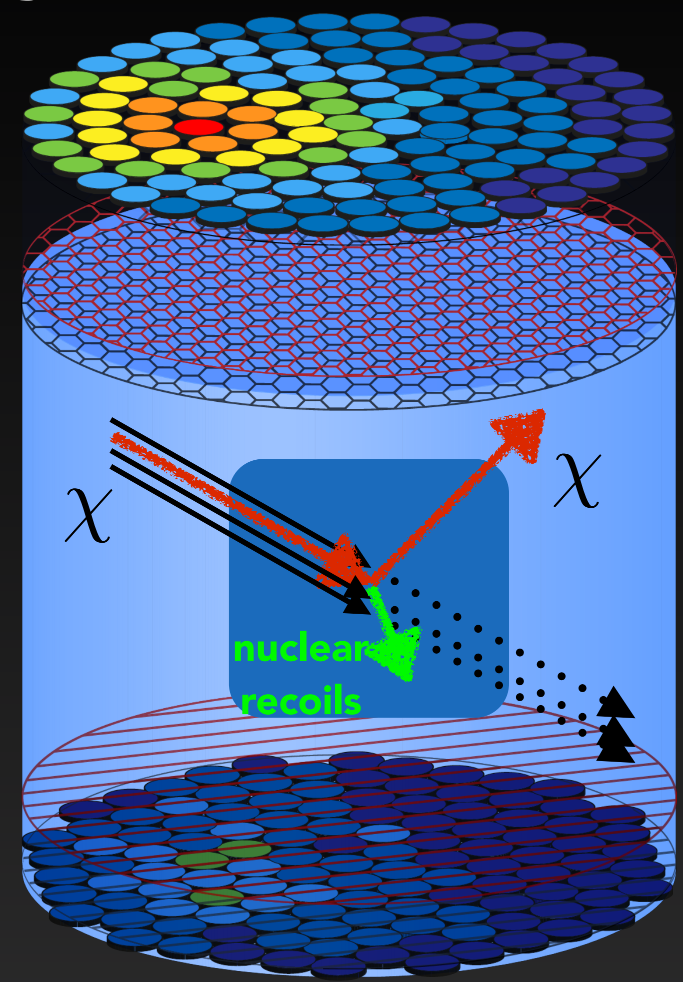
Weakly Interacting Massive Particles (WIMPs)



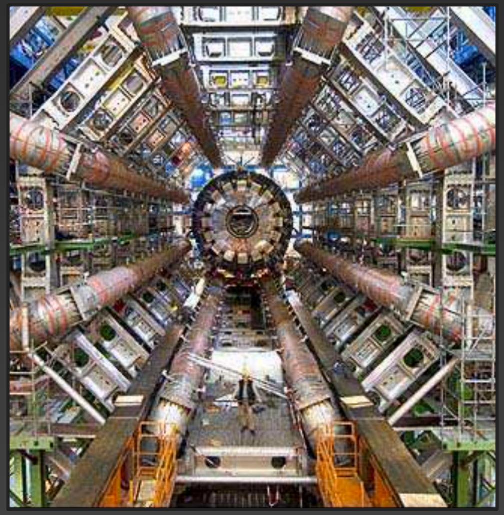

“Standard” assumptions for WIMPs:

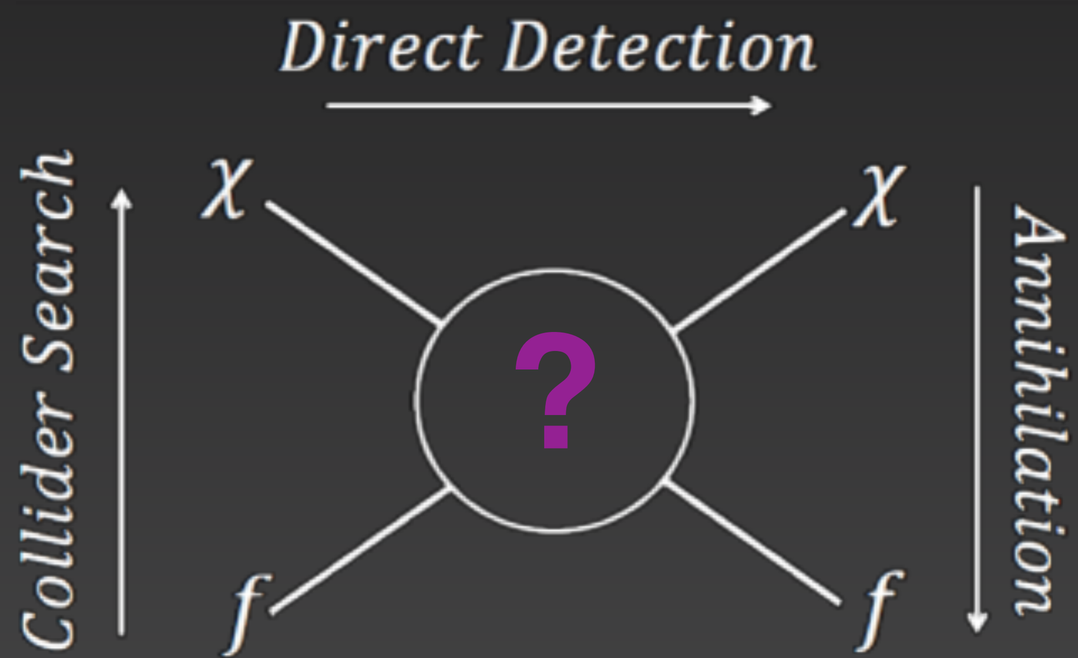
- Mass range: GeV~TeV
- Standard channels: elastic SI and SD scattering
- local WIMP density: 0.3 GeV/cm$^3$
- Isothermal velocity distribution: $v_0$~220 km/s
- WIMP escape velocity ~544 km/s

# Three ways to detect dark matter

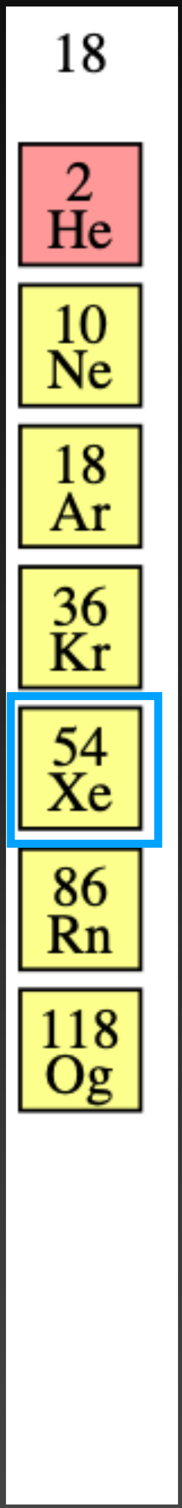



XENONnT is a direction detection experiment using two-phase time projection chamber with a xenon target



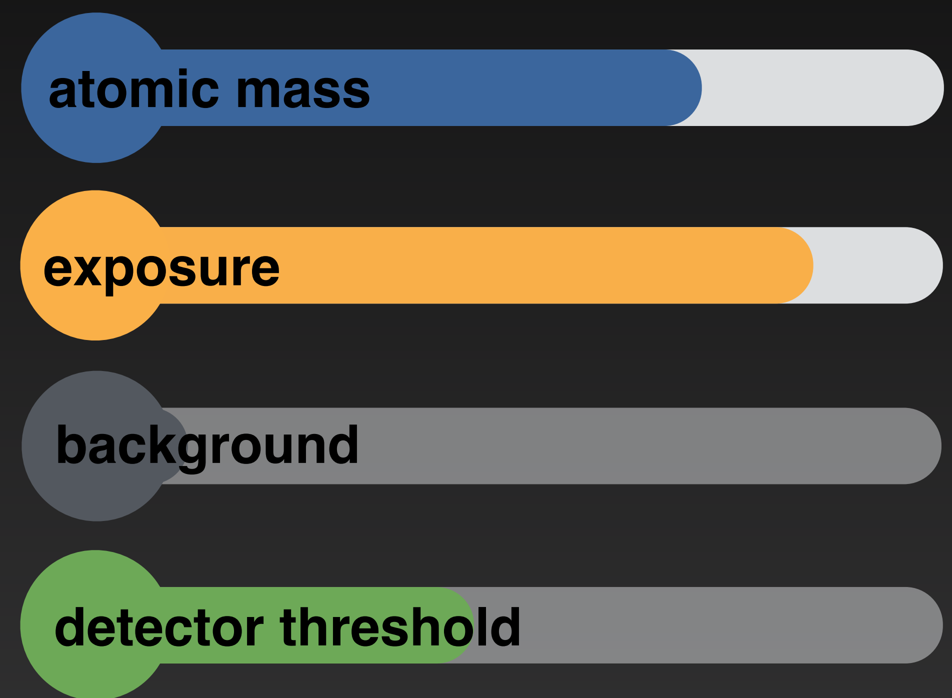



# Why xenon?

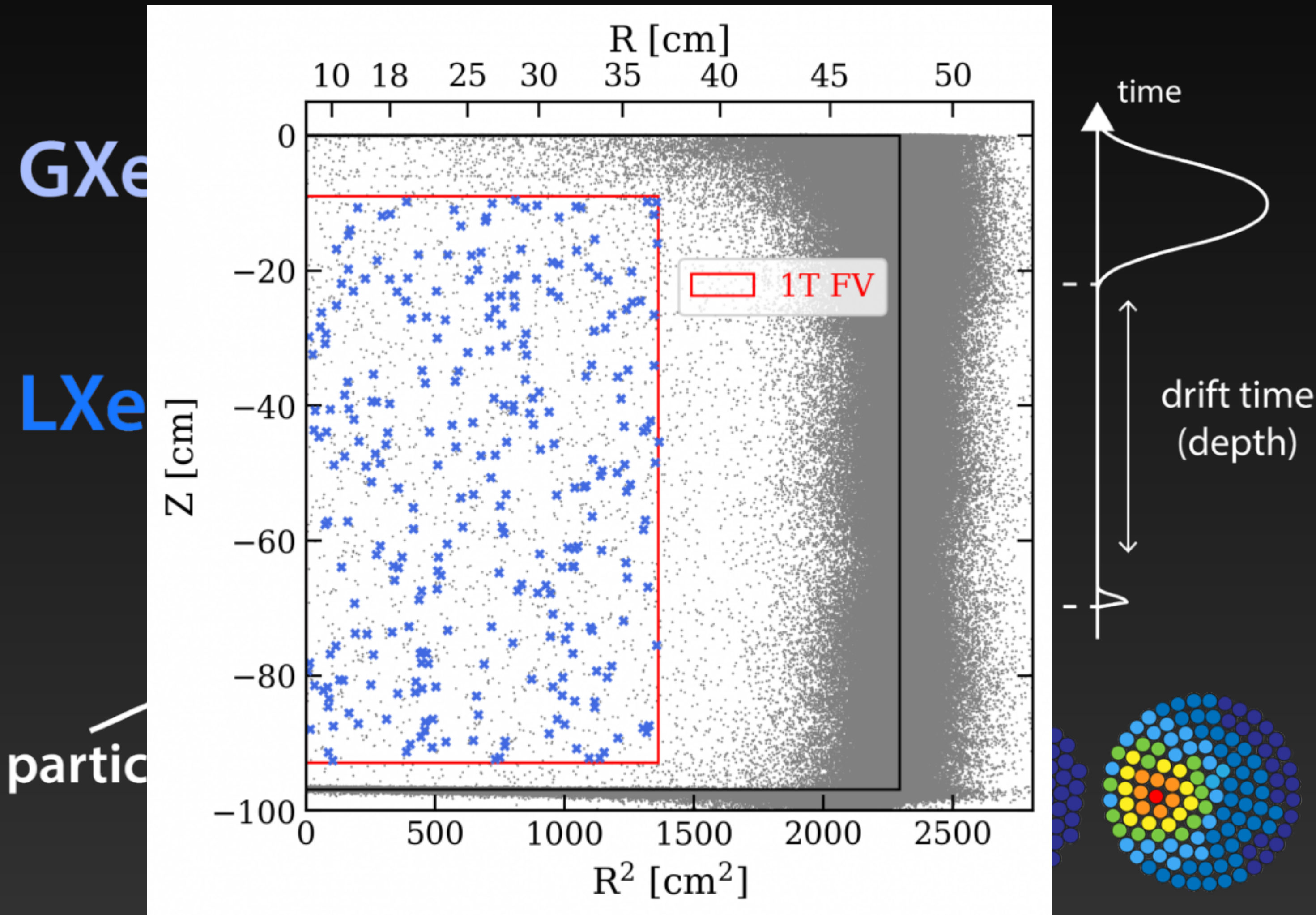


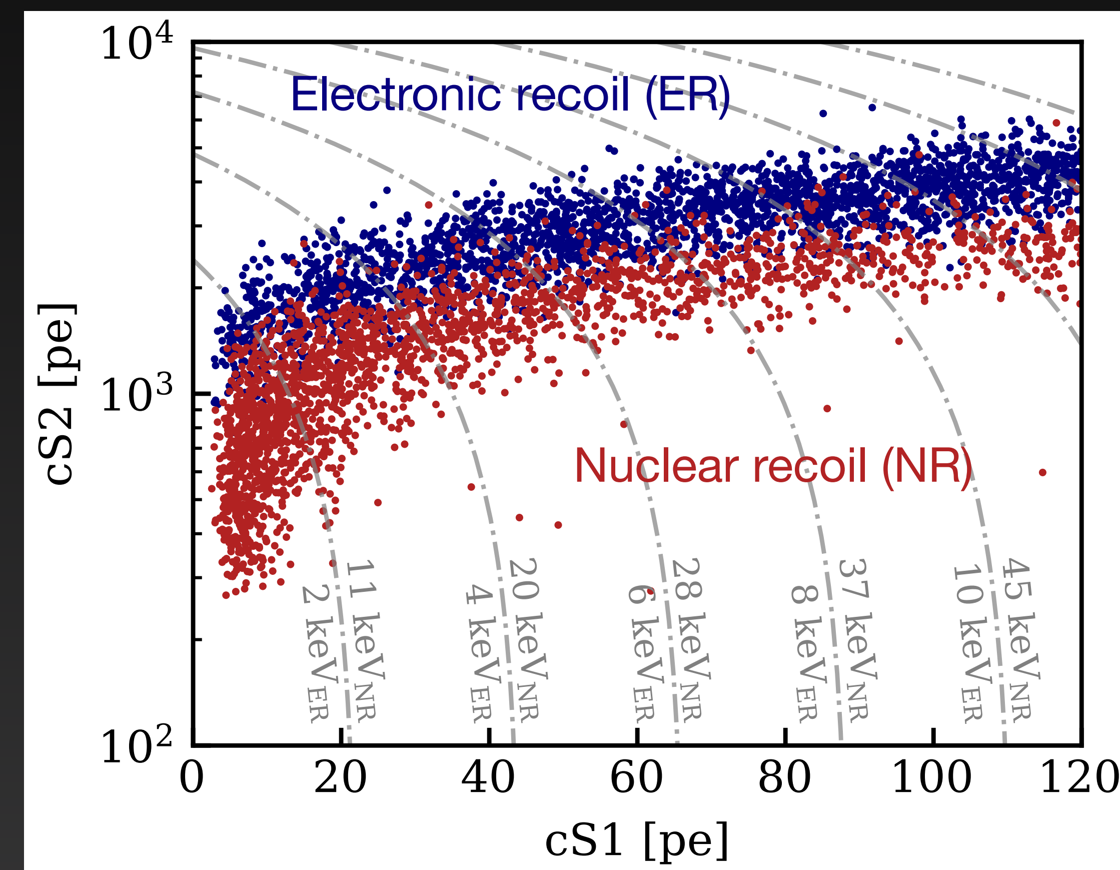

Facts about xenon:

- Large atomic mass ($A \approx 131$ u), $\sigma \propto A^2$
- Scalability and demonstrated stable operation
- Ultrapure (noble gas) and no stable 'radioactive' isotopes
- O(keV) threshold



# Why two-phase time projection chamber (TPC)?

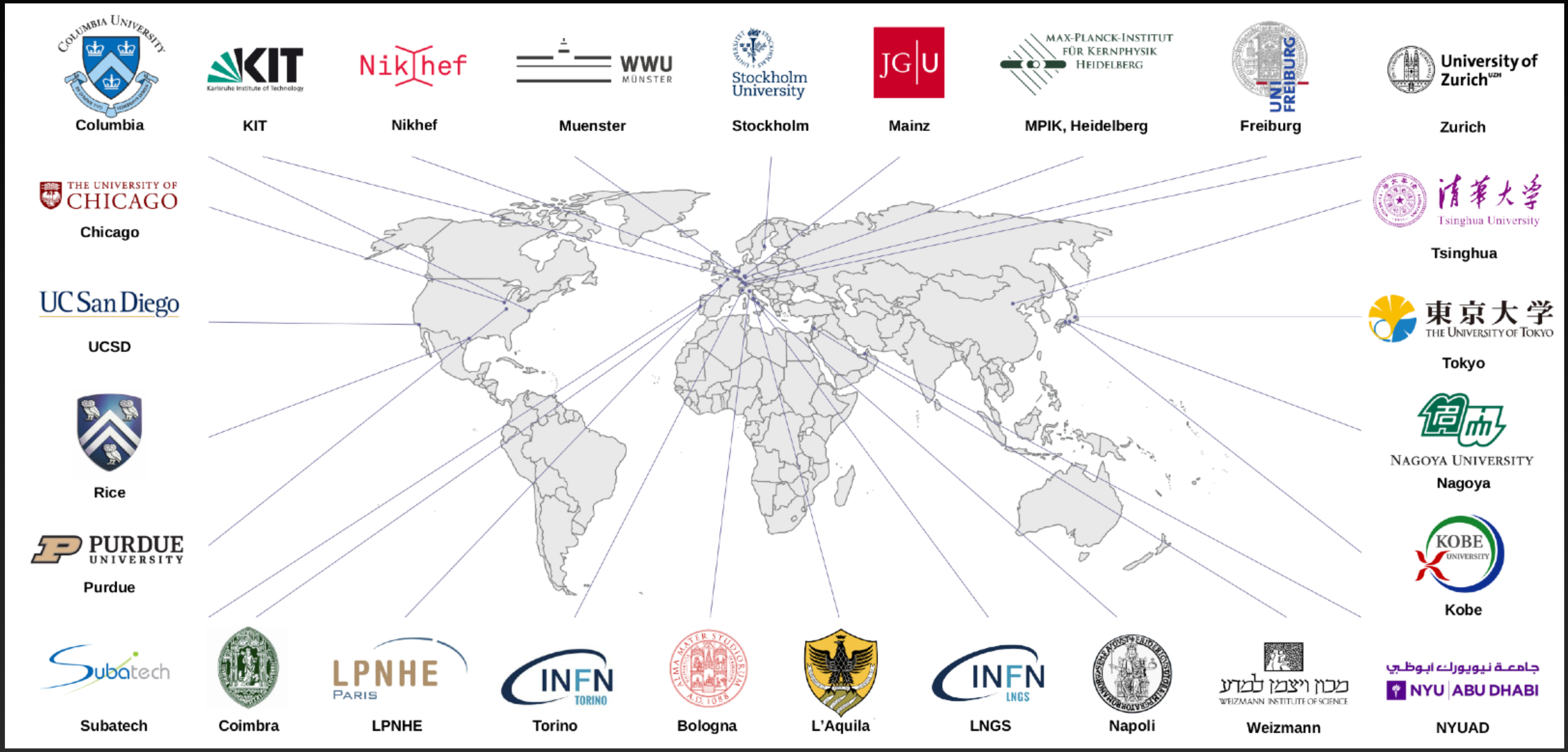



- Signal detection
Light signal (S1)
Charge signal (S2)
- Energy reconstruction
- 3D position reconstruction

Particle interaction identification
- S2/S1 ratio: ER/NR discrimination

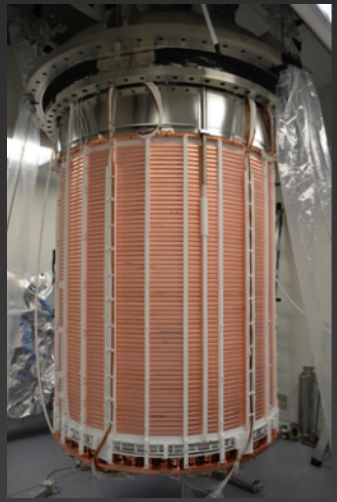
# XENON Collaboration: ~200 scientists




XENON10
2005—2007

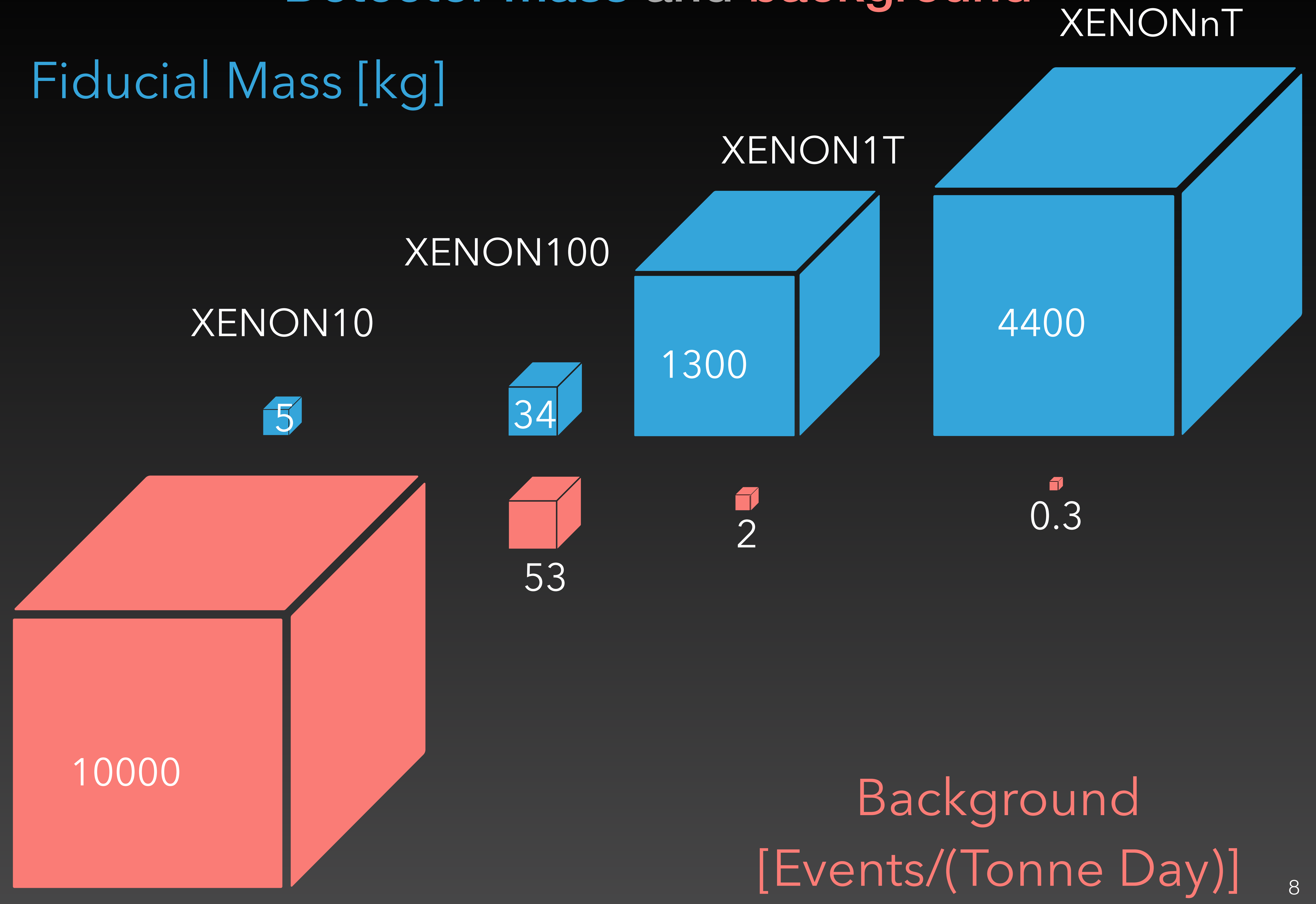
XENON100
2008—2016

XENON1T
2012—2018

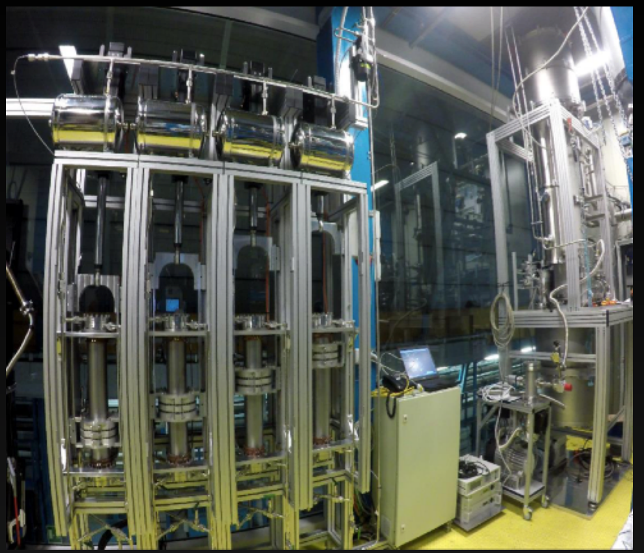


XENONnT
2019—2026

# Detector mass and background



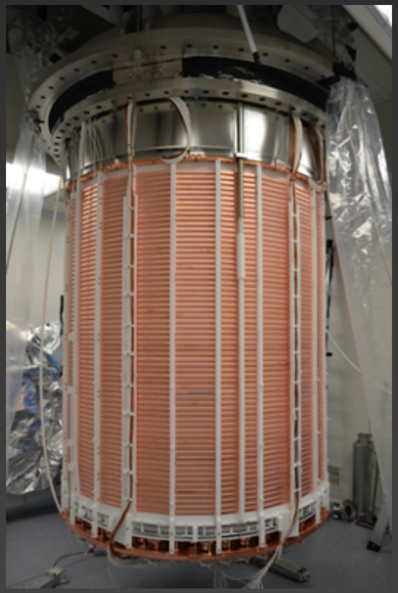
# The XENONnT experiment



Radon distillation column

Neutron veto

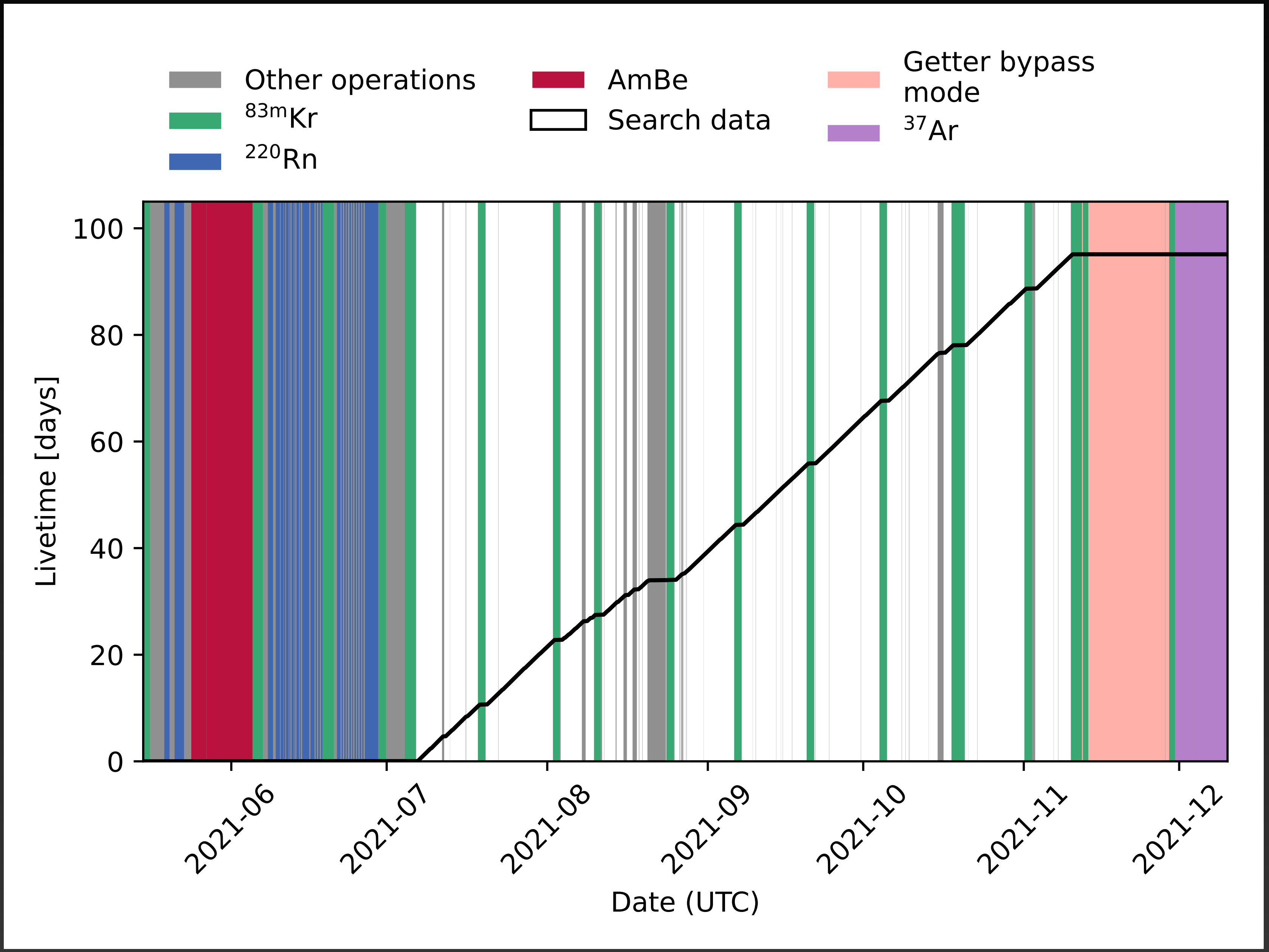
Krypton distillation column



XENONnT TPC

Liquid xenon purification system

# XENONnT first science run (SR0)

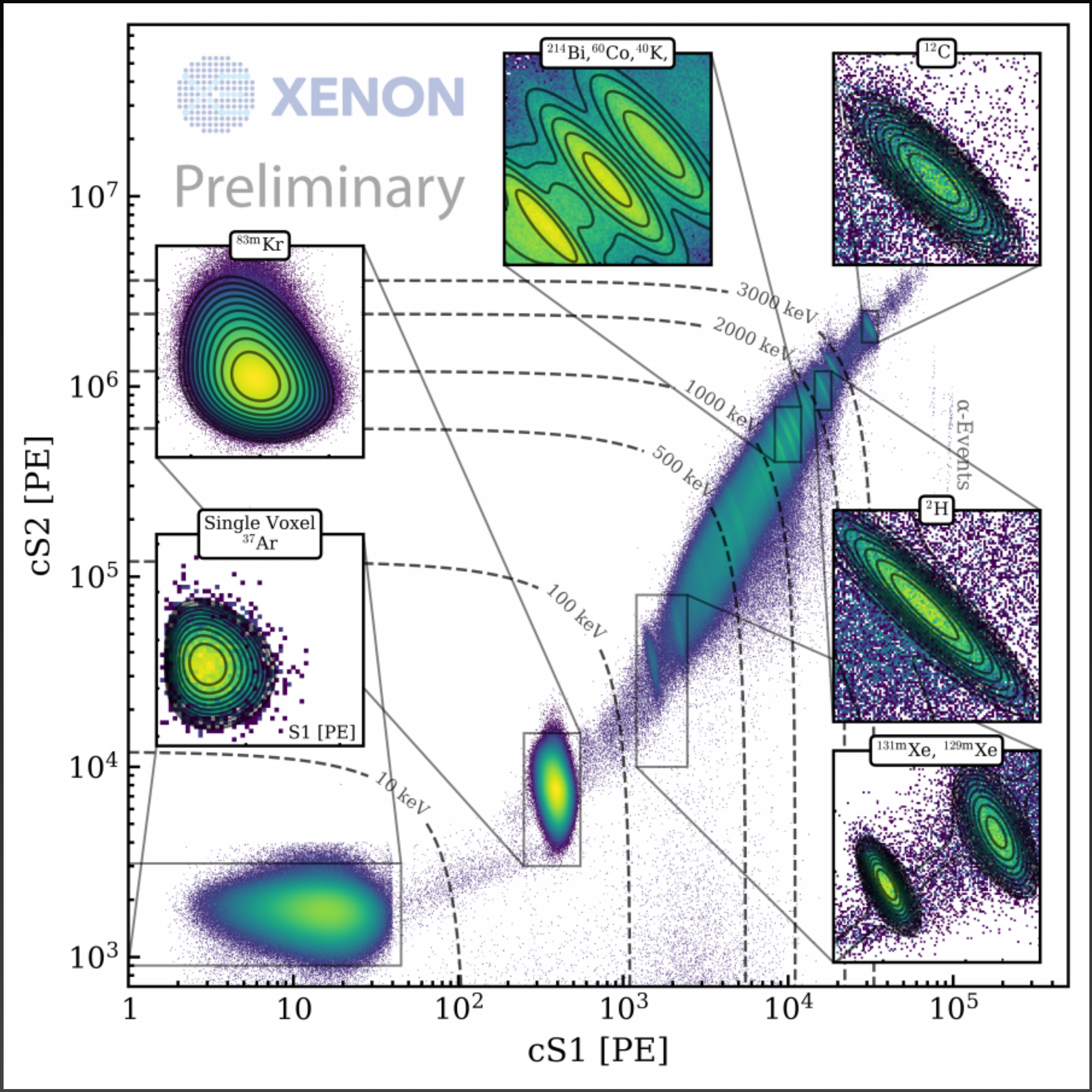



- Livetime: 95.1 days
- Exposure: $(1.09 \pm 0.03)$ tonne $\cdot$ year

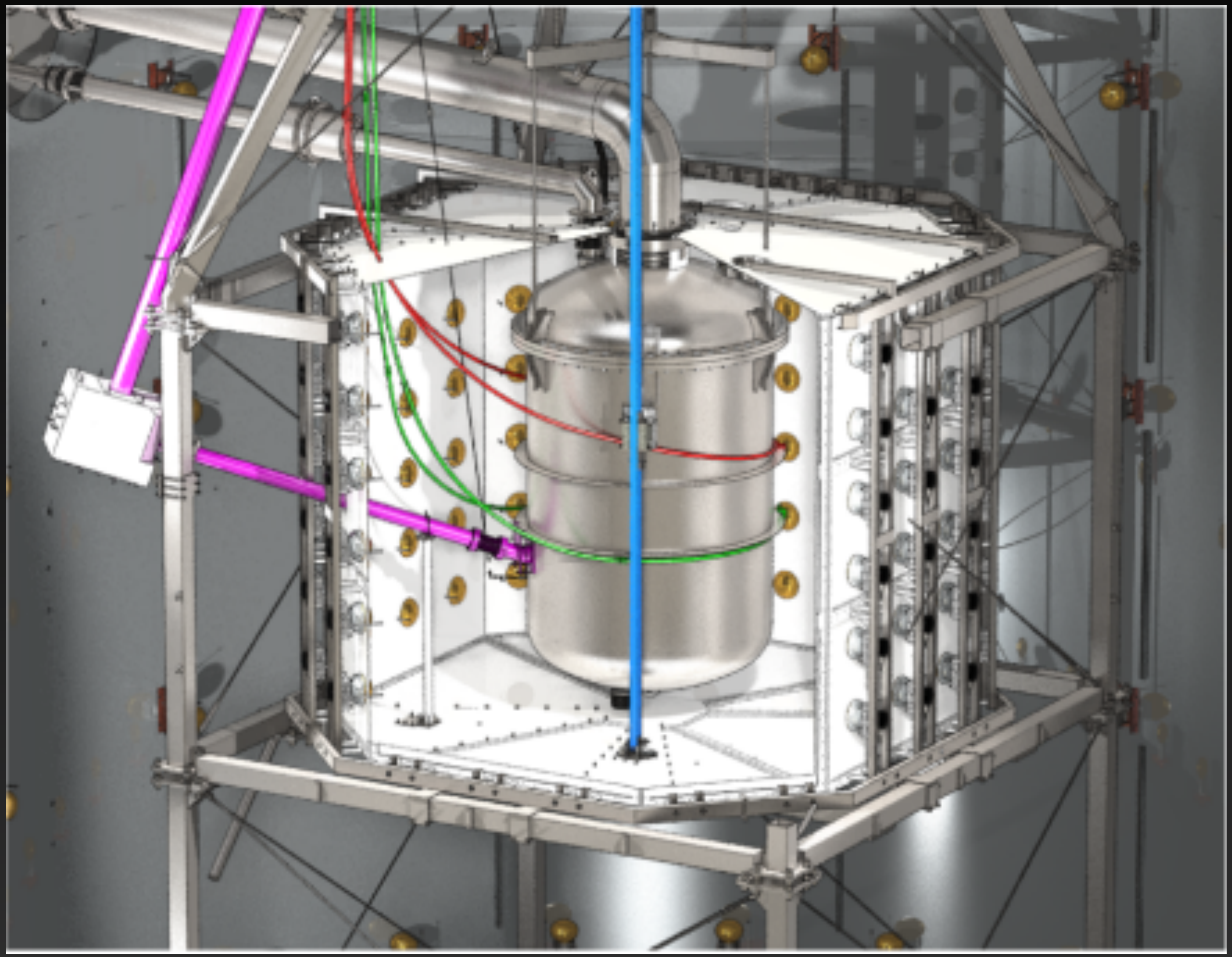
- Active mass: 5.9 tonne
- Fiducial mass: $(4.18 \pm 0.13)$ tonne
- 494 3-inch PMTs

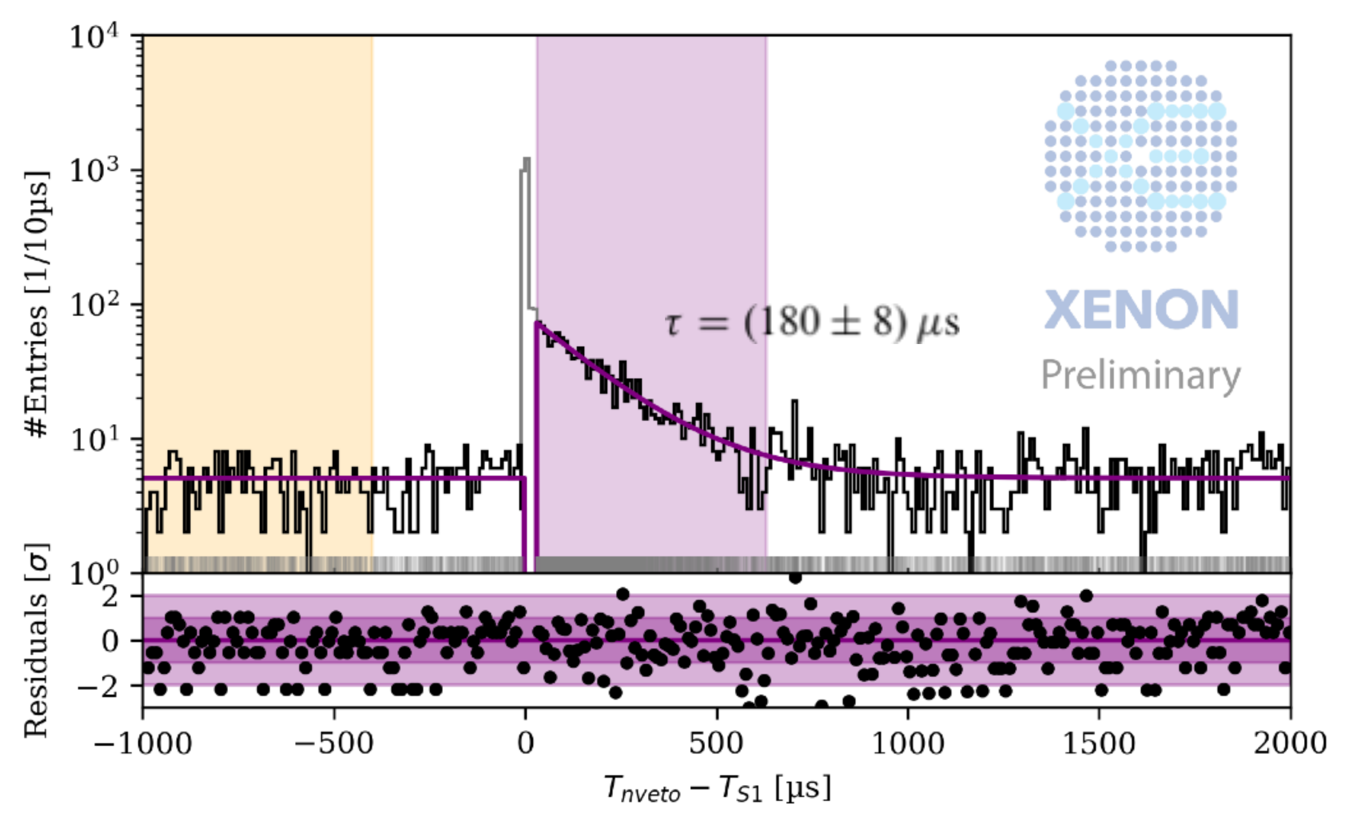
# Calibrations

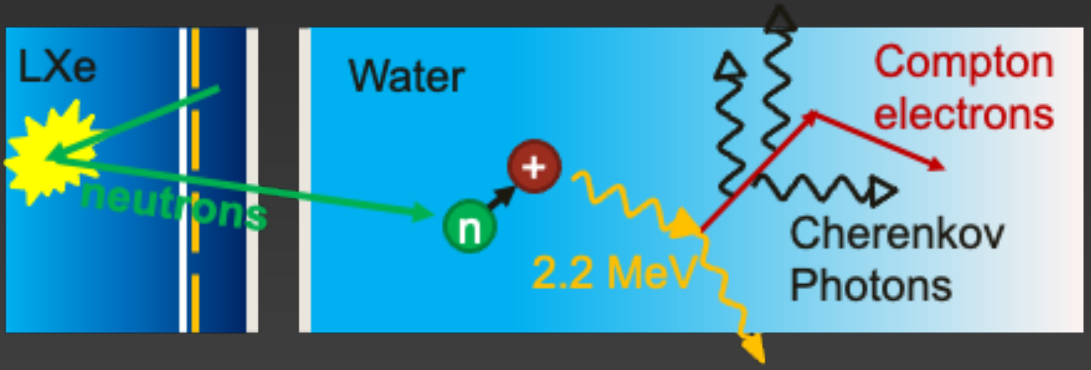
- AmBe
- $^{220}$Rn
- $^{37}$Ar



# AmBe: calibrate neutron veto



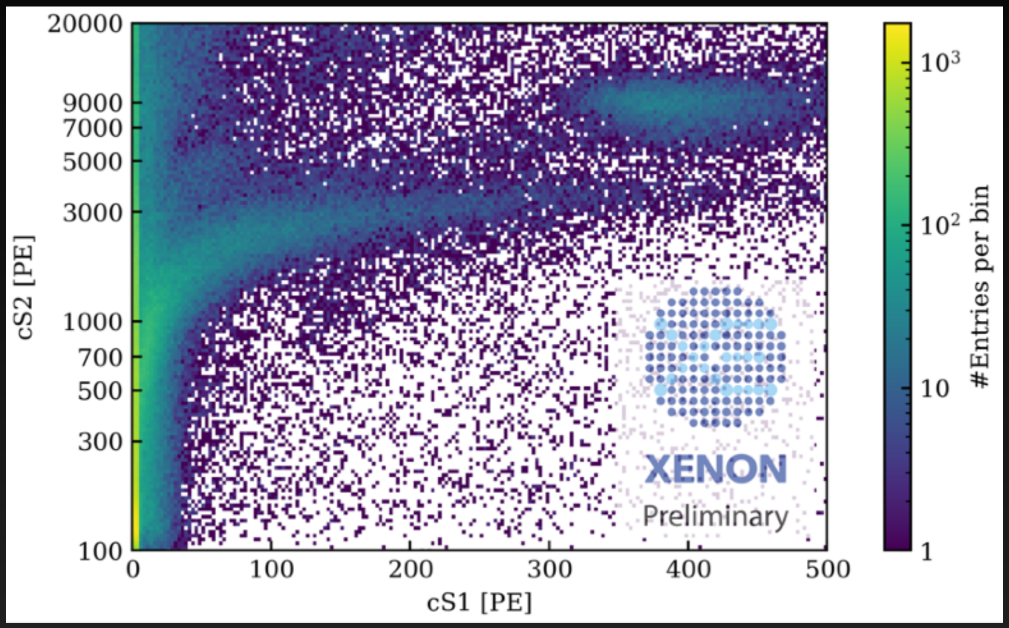



- $^{241}$Am ($\alpha$, n) $^{9}$Be emits neutrons with coincident 4.4 MeV gammas
- Neutron veto can tag neutrons via the neutron capture on hydrogen that releases a 2.22 MeV gamma ray
- Half-life for neutron capture in water is (180±8) $\mu$s

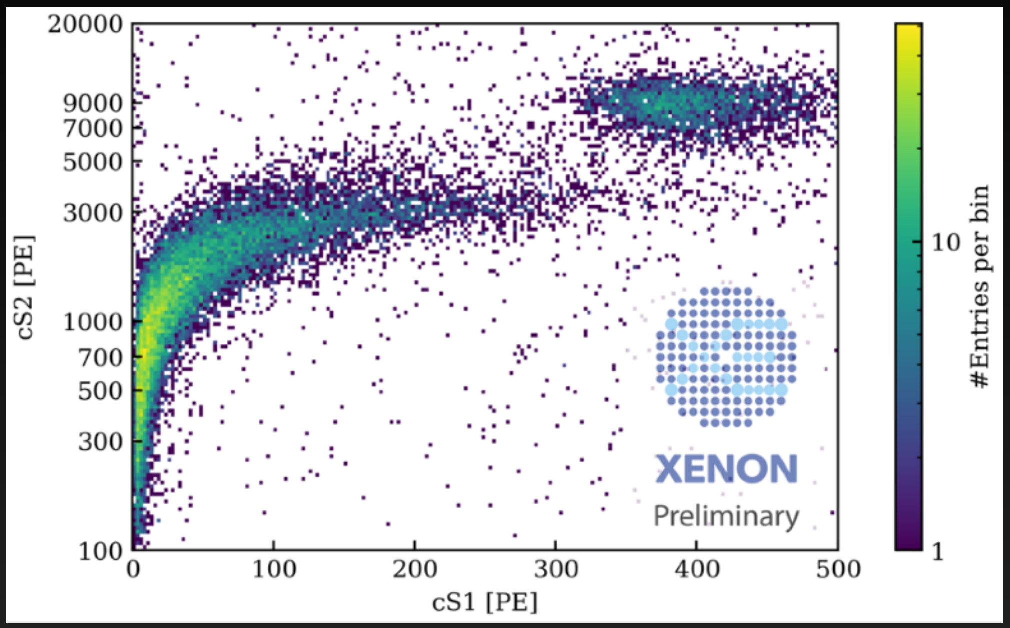
# AmBe calibration: NR response

before tagging

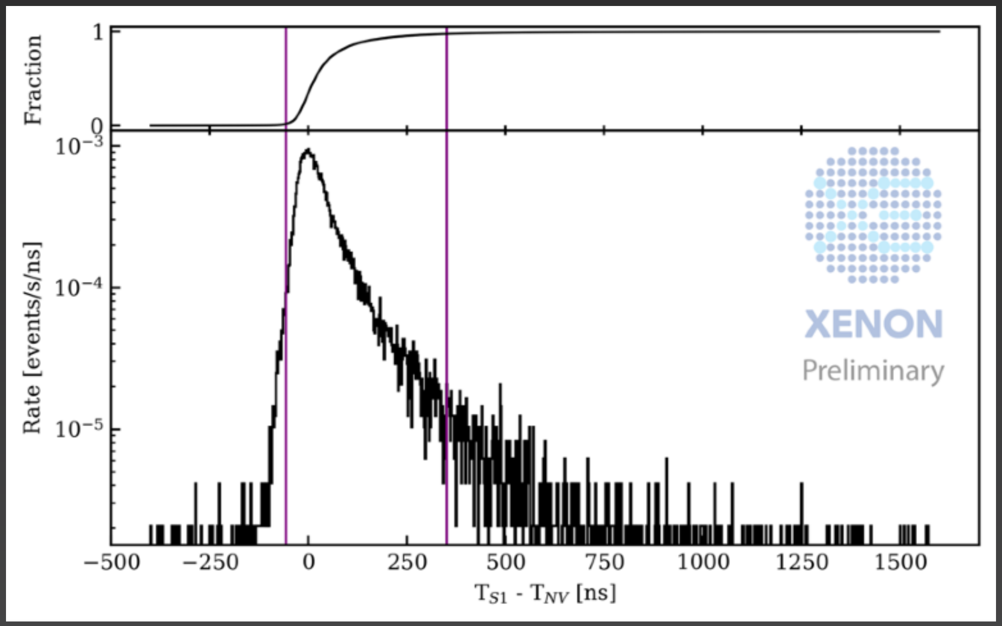


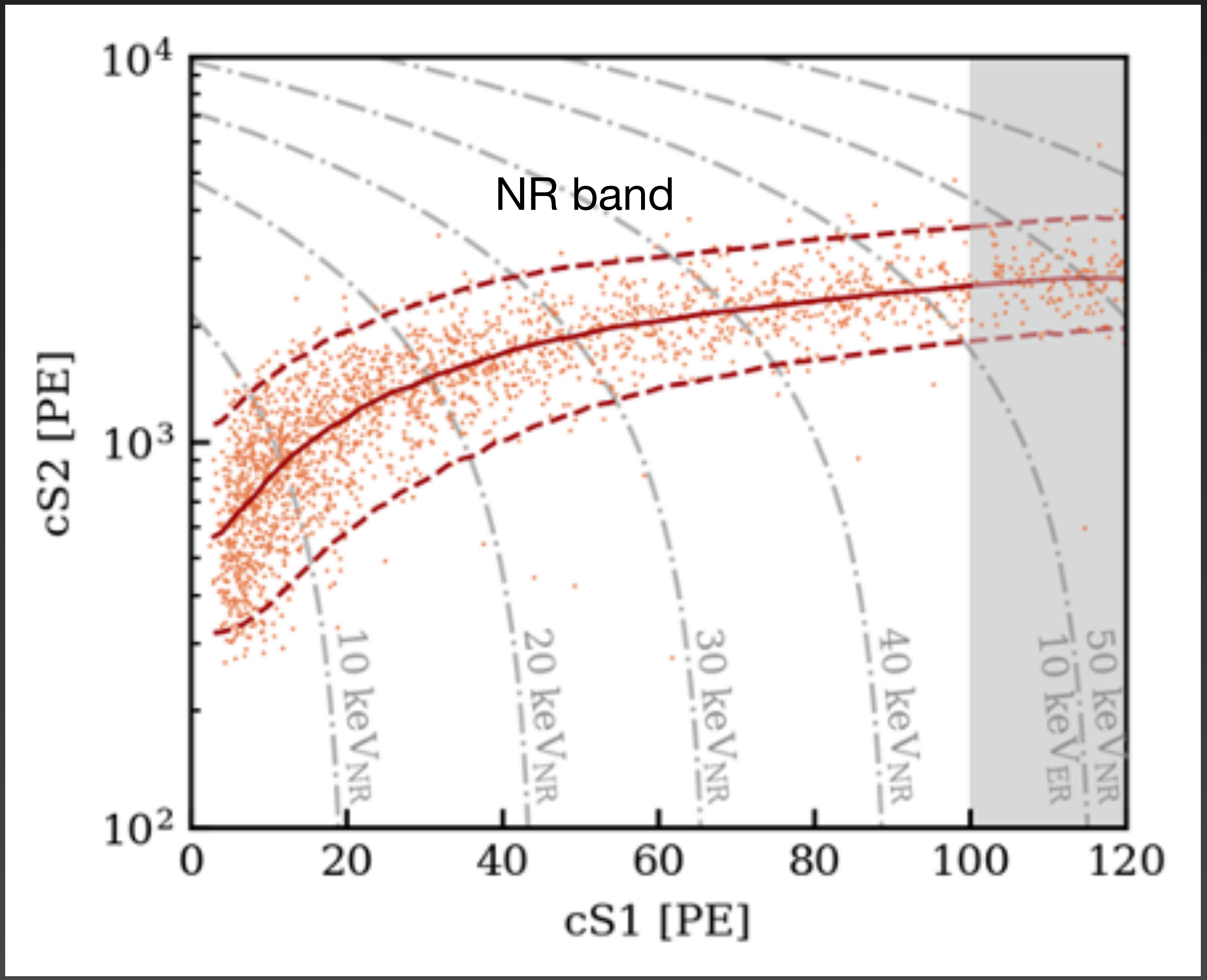

Strong background suppression

after tagging

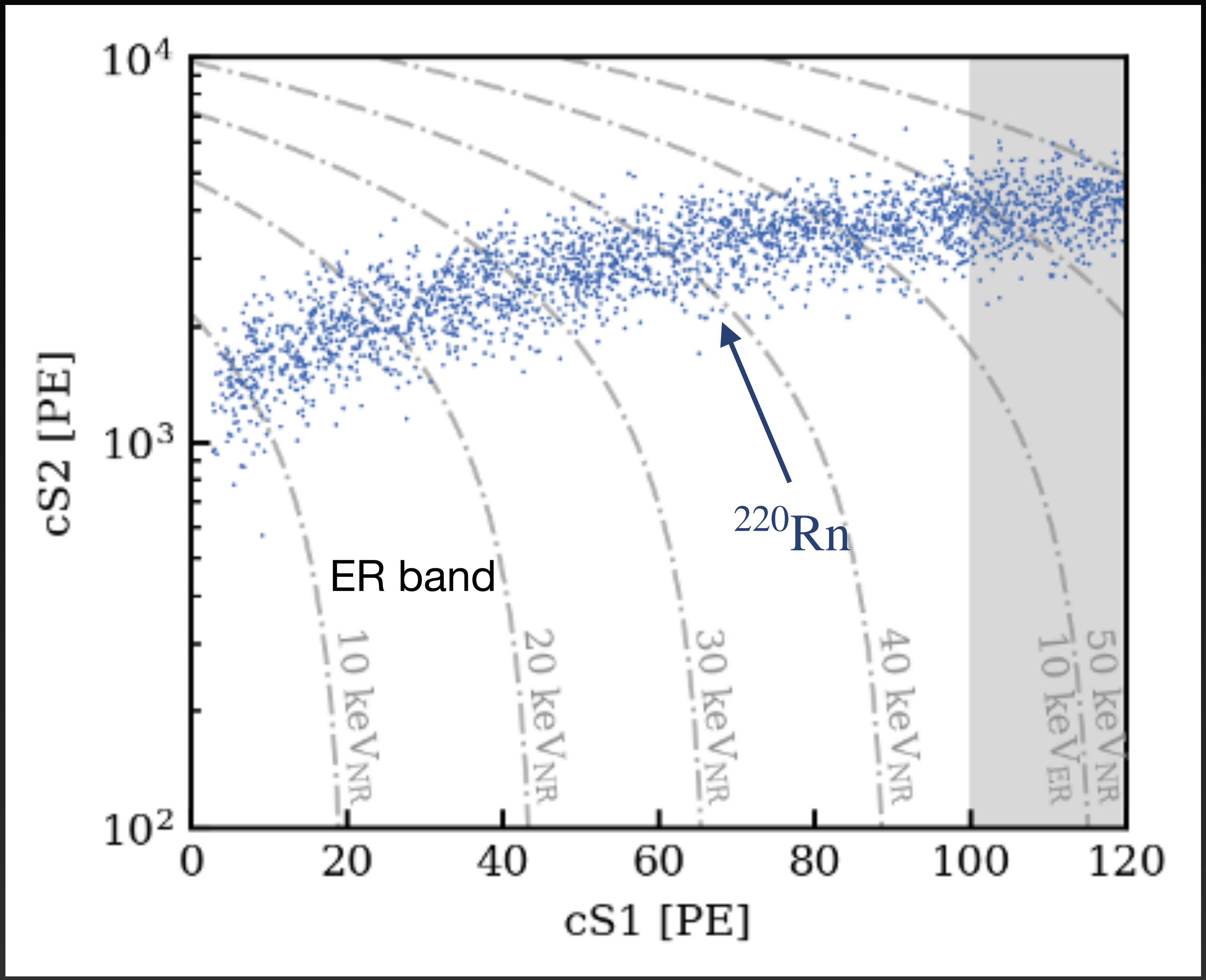


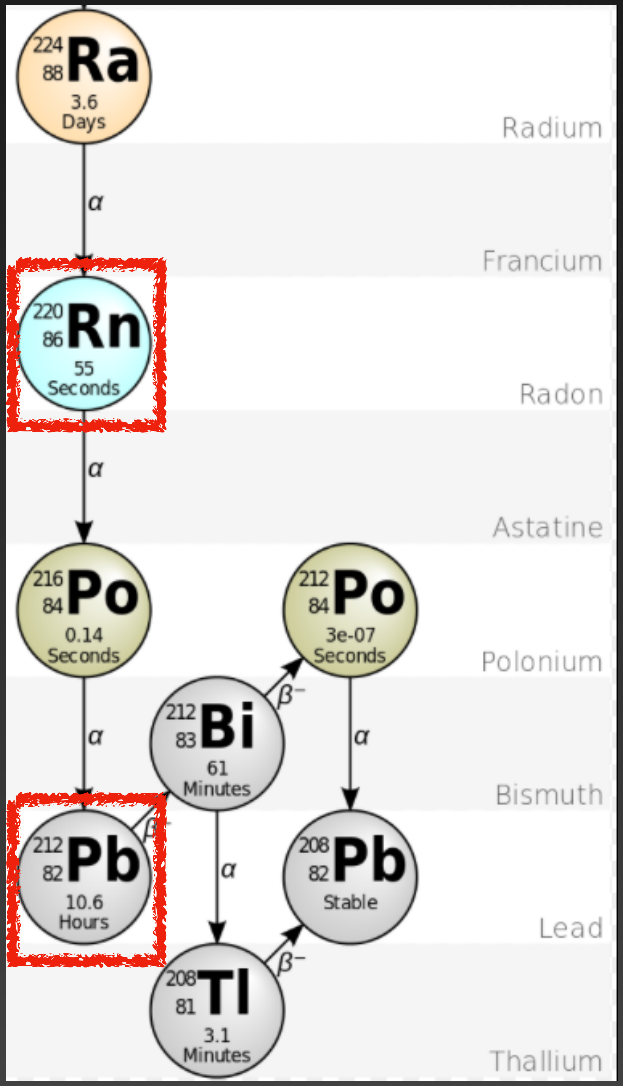

- Use neutron veto to tag NR events 400 ns coincident with 4.4 MeV gamma
- Tagging efficiency: ~60%



# $^{220}$Rn calibration: ER response

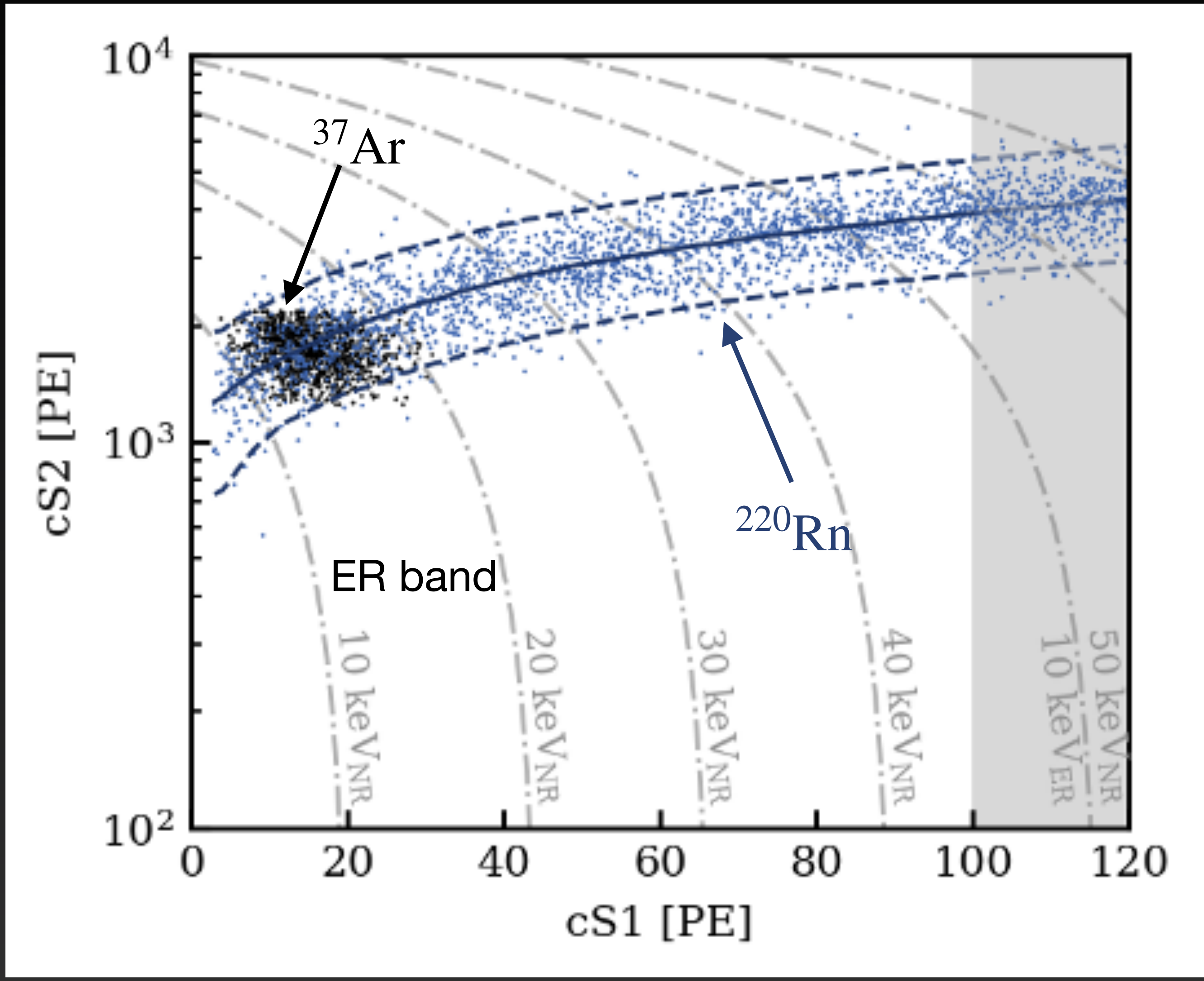



$^{220}$Rn

- Internal source
- Naked low-energy $^{212}$Pb betas from the $^{220}$Rn chain
- Energy spectrum is almost flat at low energies

# $^{37}$Ar calibration: ER response



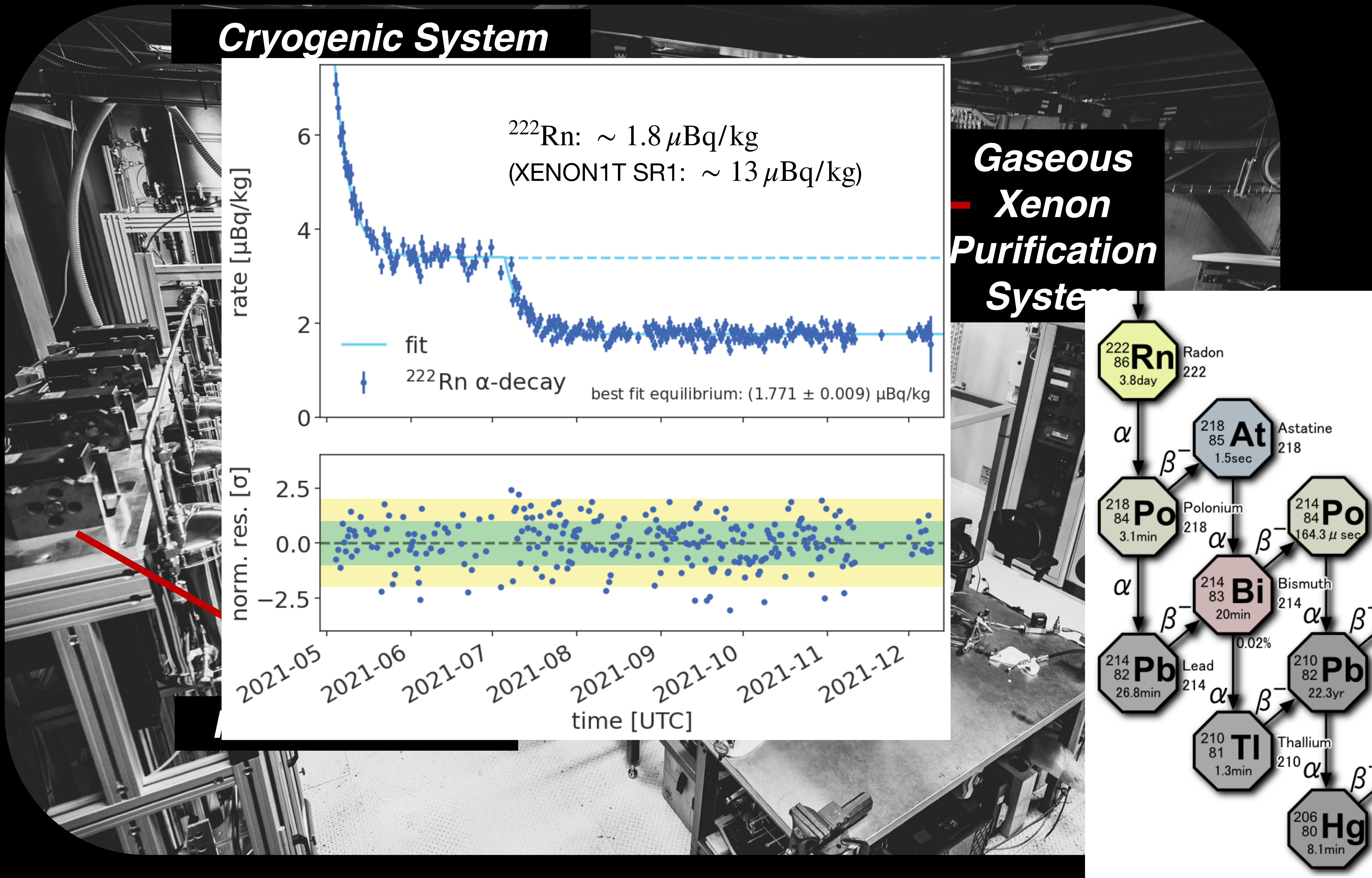

$^{37}$Ar

- Internal source
- Mono-energetic line @2.8 keV
- Half-life: 35 days
- Removed by krypton distillation column

# Backgrounds

- ER backgrounds
- NR backgrounds
- Accidental coincidence

# Radon distillation column

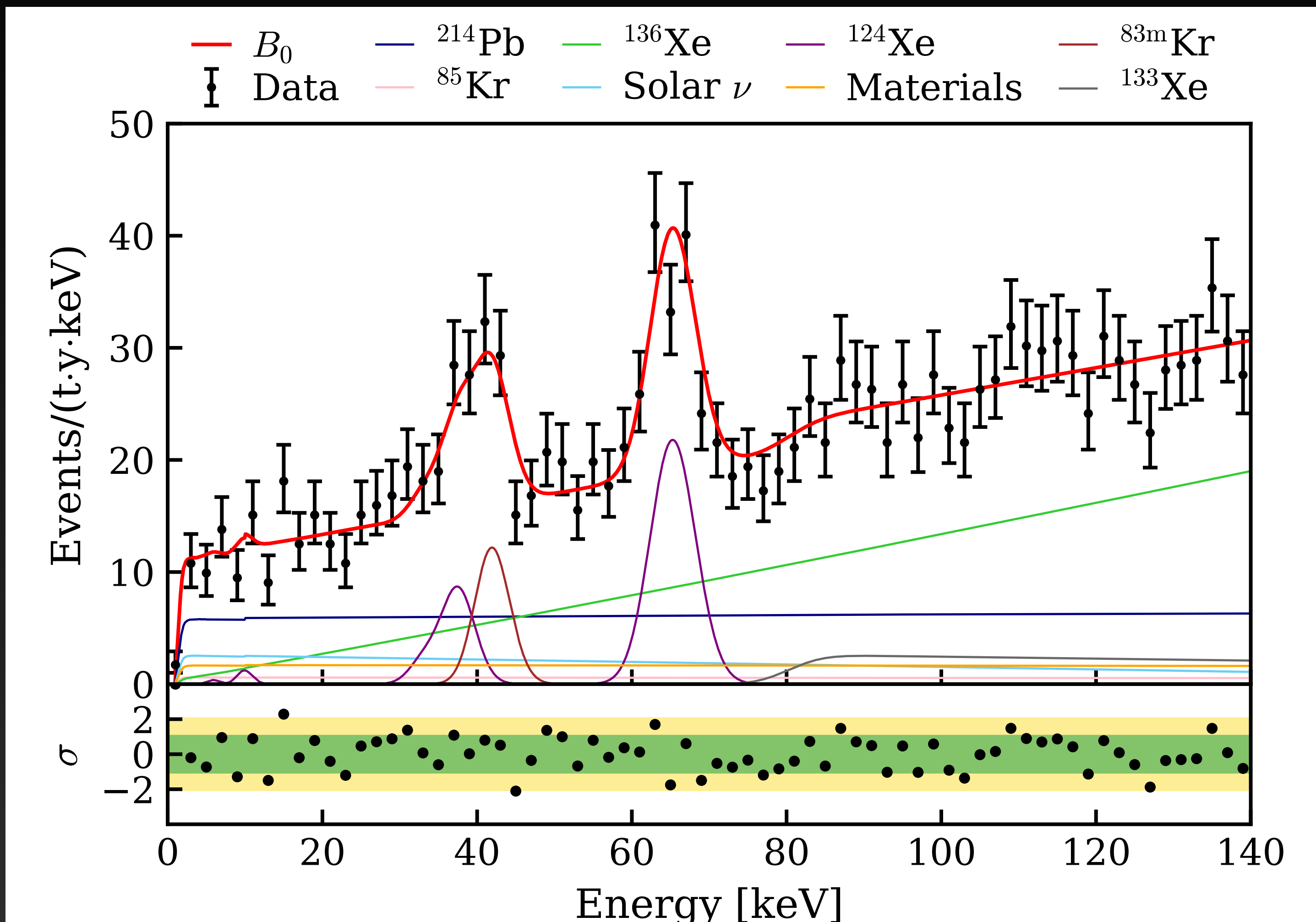


# Krypton distillation column

$^{85}Kr$

- Decrease krypton concentration by cryogenic distillation
- $^{nat}Kr$: $(56 \pm 36)$ ppq (XENON1T SR1: $(660 \pm 110)$ ppq)
- It can also reduce argon concentration, which enables the usage of $^{37}Ar$ calibration source

# ER backgrounds



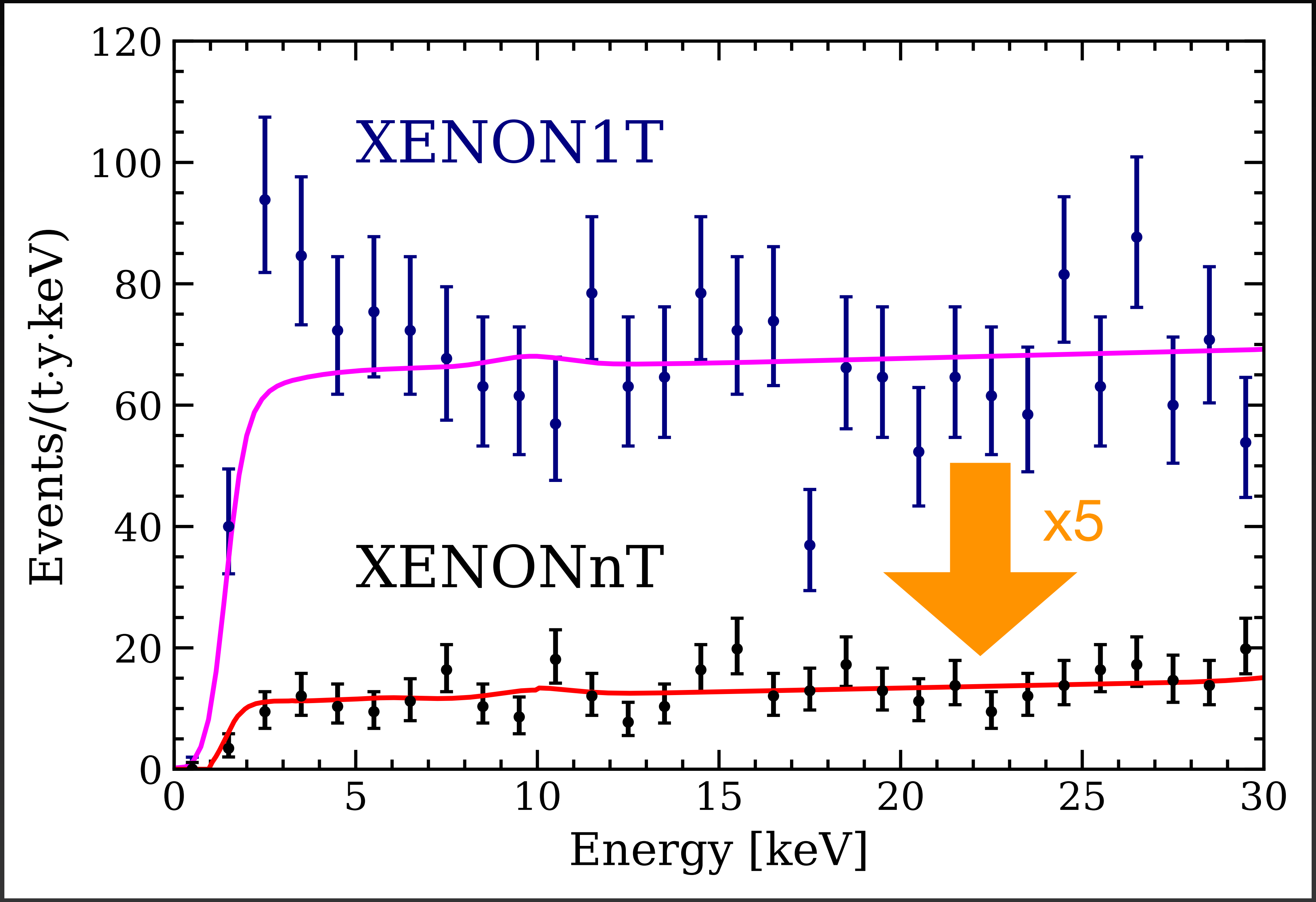

Best-fit values

| | (1, 10) keV | (1, 140) keV |
|---|---|---|
| $^{214}$Pb | $55 \pm 7$ | $960 \pm 120$ |
| $^{85}$Kr | $6 \pm 4$ | $90 \pm 60$ |
| Materials | $16 \pm 3$ | $270 \pm 50$ |
| $^{136}$Xe | $8.8 \pm 0.3$ | $1550 \pm 50$ |
| Solar neutrino | $25 \pm 2$ | $300 \pm 30$ |
| $^{124}$Xe | $2.6 \pm 0.3$ | $250 \pm 30$ |
| AC | $0.70 \pm 0.03$ | $0.71 \pm 0.03$ |
| $^{133}$Xe | - | $150 \pm 60$ |
| $^{83m}$Kr | - | $80 \pm 16$ |

- $^{214}$Pb is still the dominant background below 10 keV
- $^{222}$Rn: $\sim 1.8\ \mu$Bq/kg, decreased by radon distillation column (XENON1T SR1: $\sim 13\ \mu$Bq/kg)
- $^{nat}$Kr: $(56 \pm 36)$ ppq, decreased by krypton distillation column (XENON1T SR1: $(660 \pm 110)$ ppq)
- Spectral shape dominated by two double-weak decays:
  - $^{136}$Xe $2\nu\beta\beta$
  - $^{124}$Xe $2\nu$ECEC

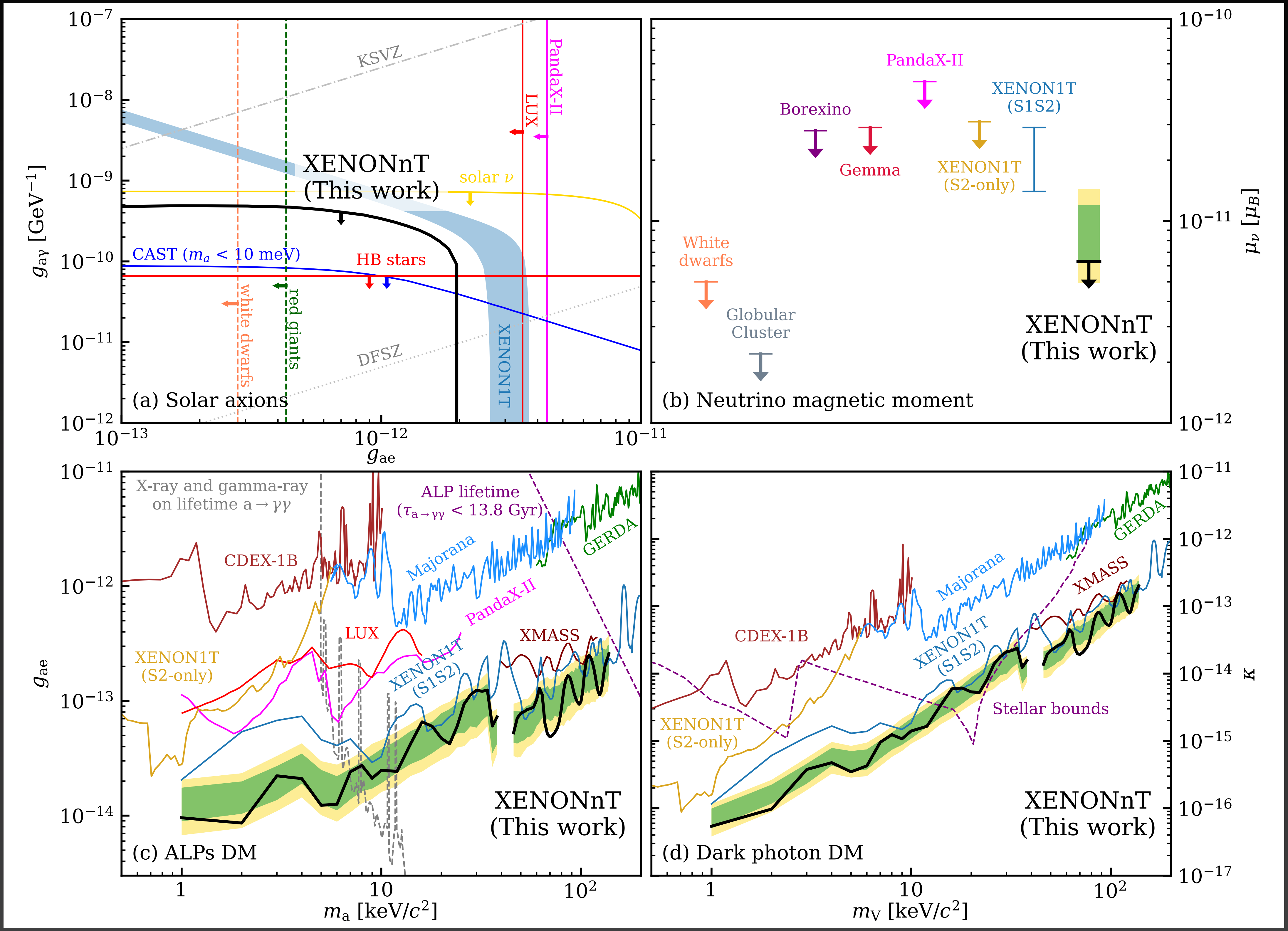
PRL 129, 161805 (2022)

# ER backgrounds




- The total ER rate below 30 keV is $(15.8 \pm 1.3_{\text{stat}})$ events/$(\text{t} \cdot \text{y} \cdot \text{keV})$, the lowest background ever achieved in a dark matter detector, a factor of ~5 lower than XENON1T ER background.
- No ER excess is found in XENONnT, which rejects new physics interpretations of the XENON1T excess.

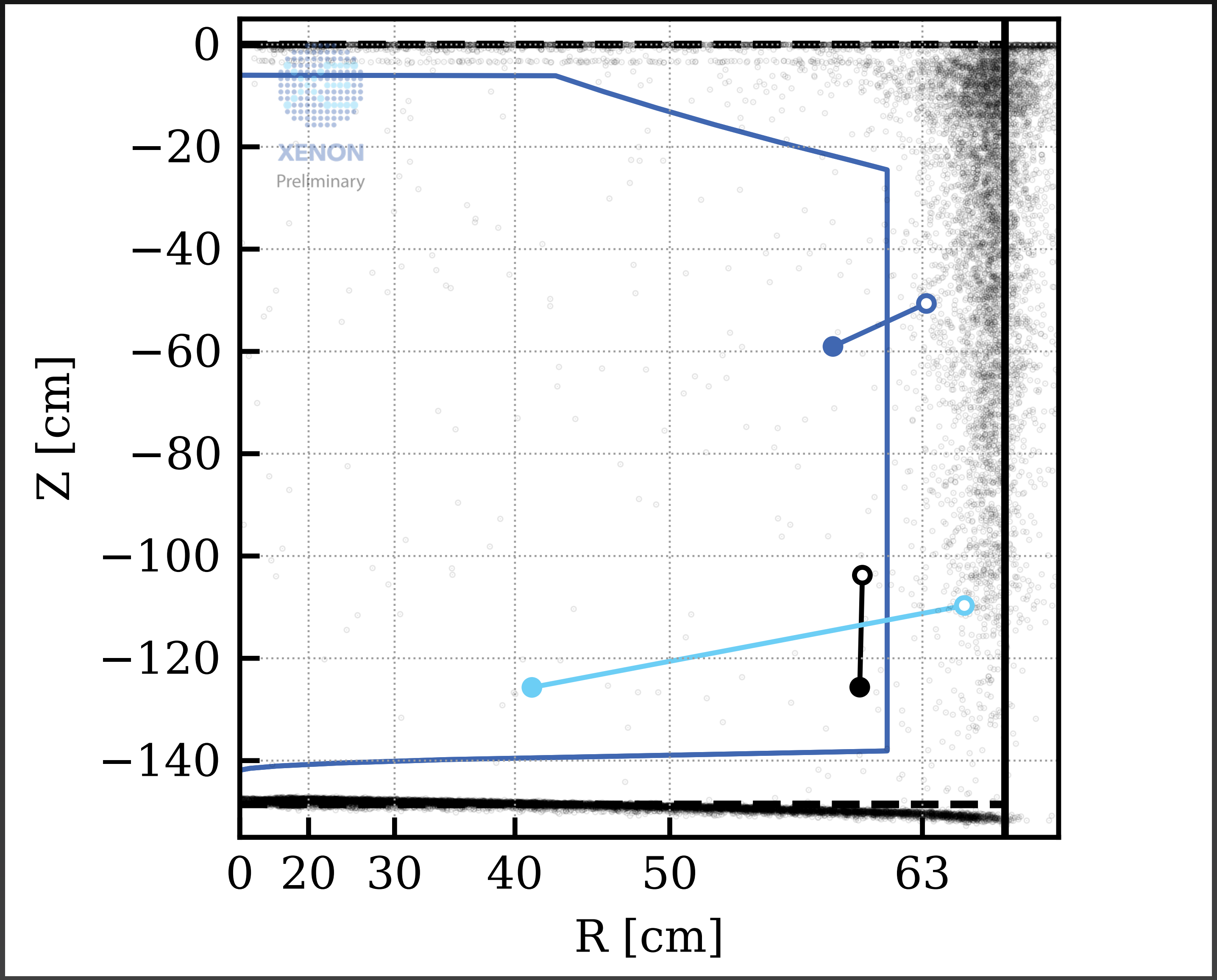
# New physics results with ER data



# NR backgrounds

Two NR backgrounds:

- Coherent Elastic Neutrino Nucleus Scattering (CEvNS) from solar $^8\mathrm{B}$ neutrinos
  - Relatively small, see more later
- Neutrons from spontaneous fission and ($\alpha$, n) reactions

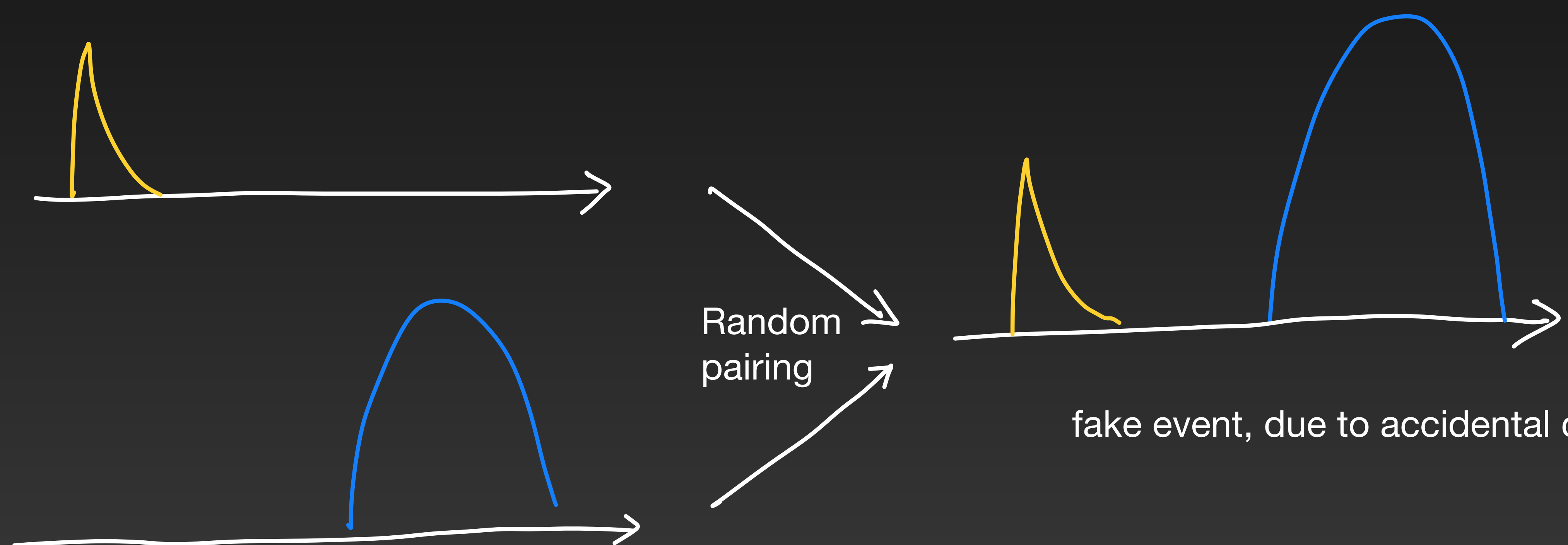



Neutron suppression methods

- Fiducialization
- multiple scatter rejection
- Neutron veto
  - (53 ± 3) % tagging efficiency @ 250 μs window
  - Lifetime loss: 1.6%

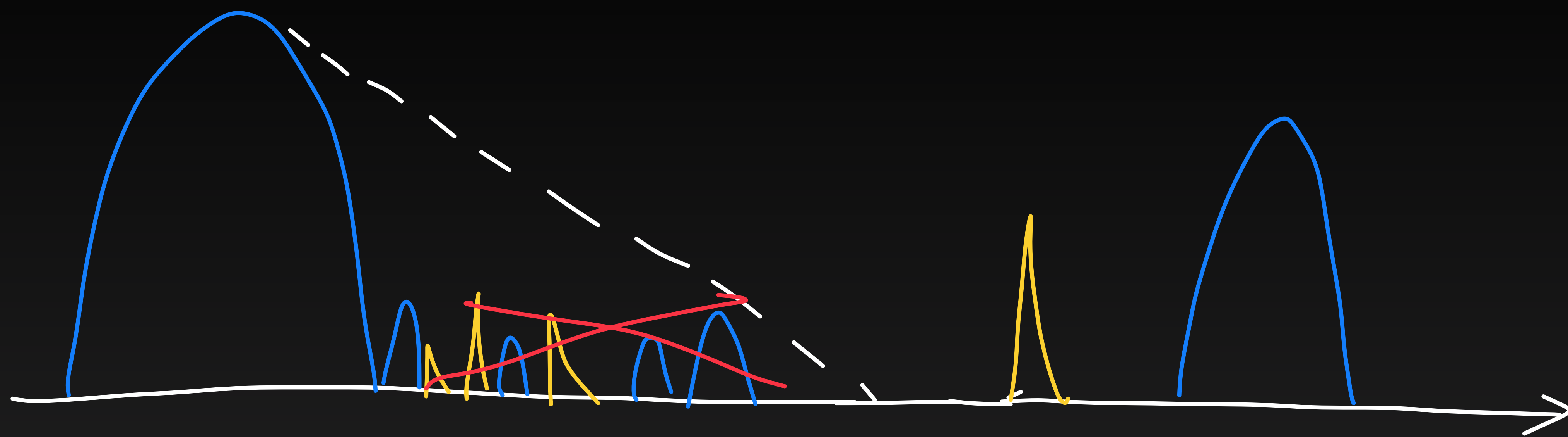
# Accidental coincidence (AC)

lone S1
- Dark current in PMTs
- S1 signal below cathode
- …




lone S2
- Single electron pile up
- …

# AC background suppression: reduce lone S1/S2 rate

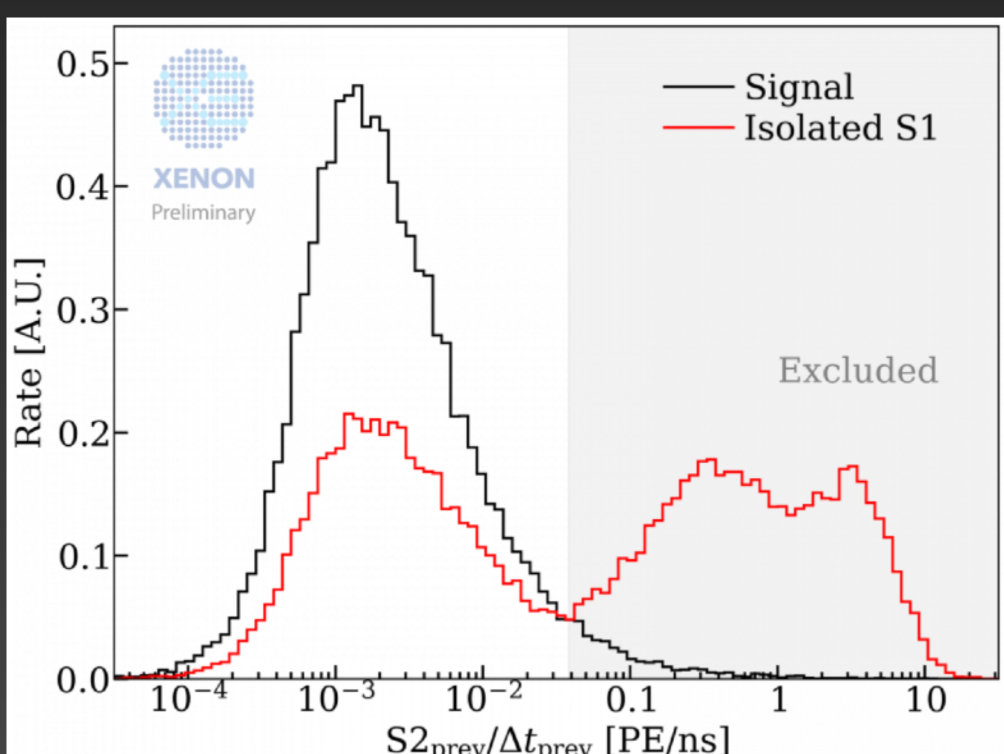


Lone S1:

- Time correlation with big previous S2s

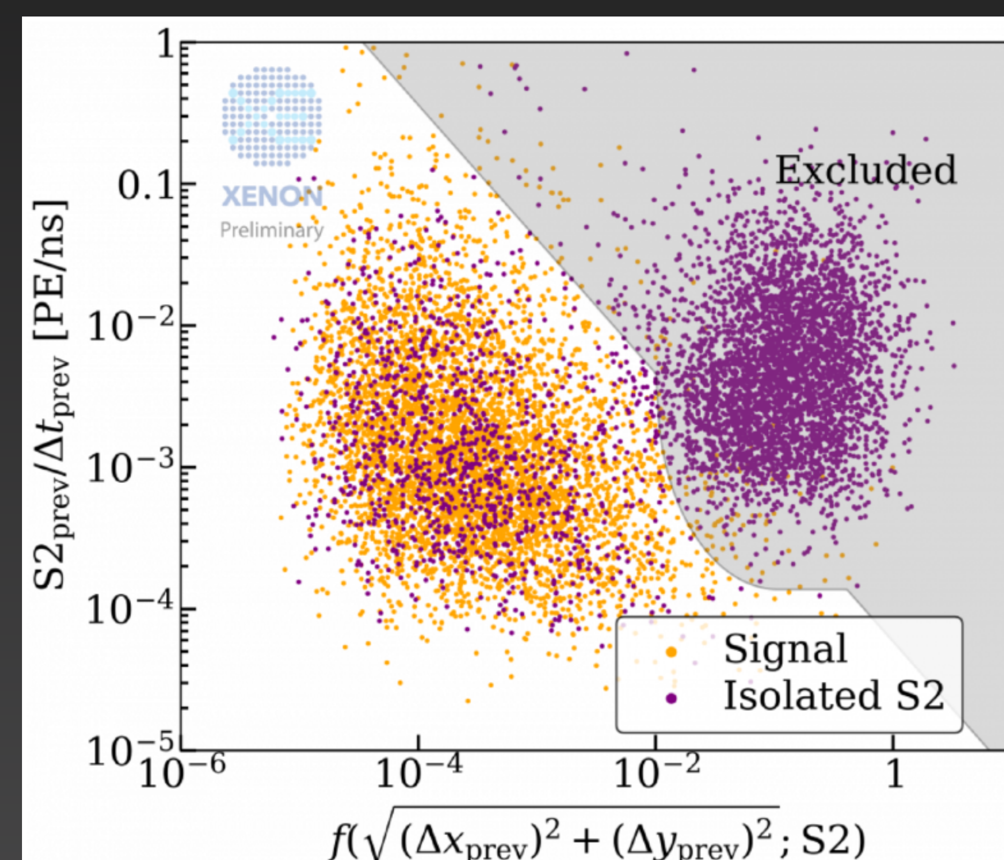
Lone S2:

- Time and position correlation with big previous S2s



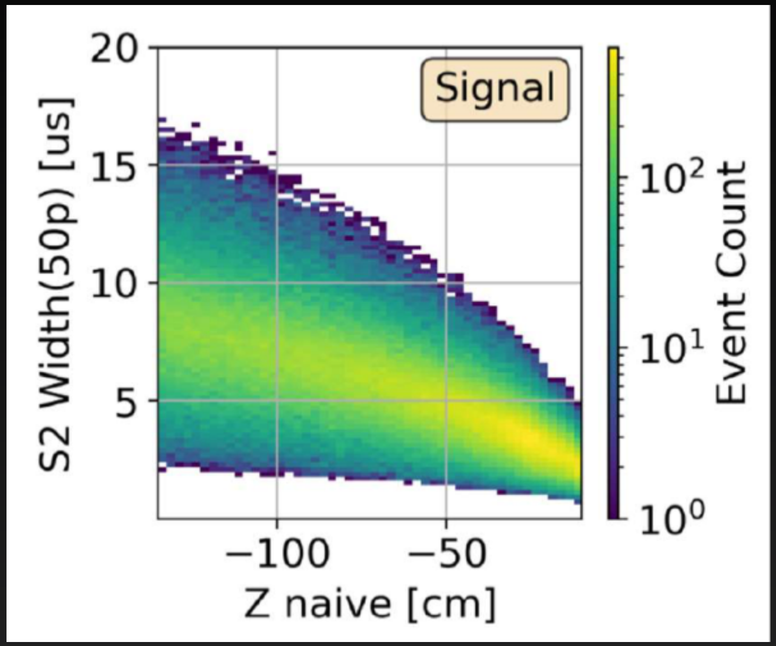

Time correlation

Time correlation

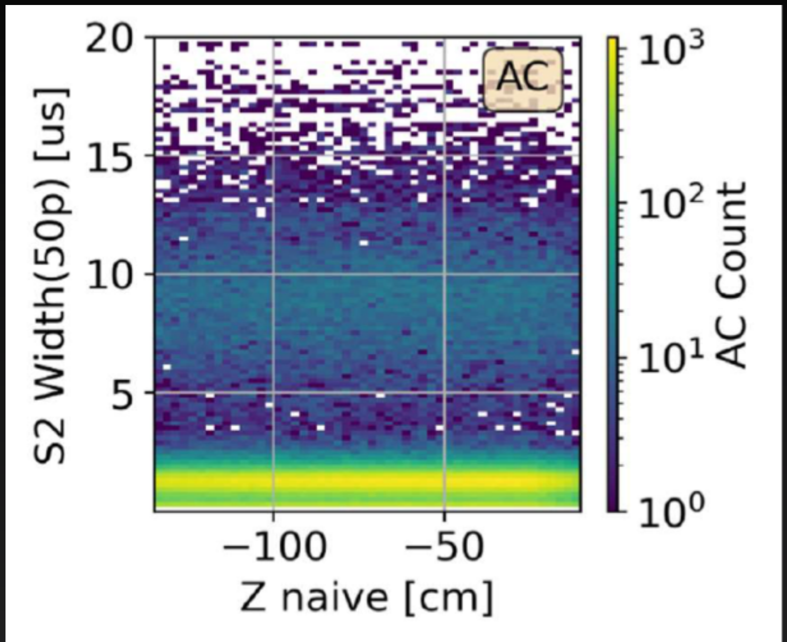



Position correlation

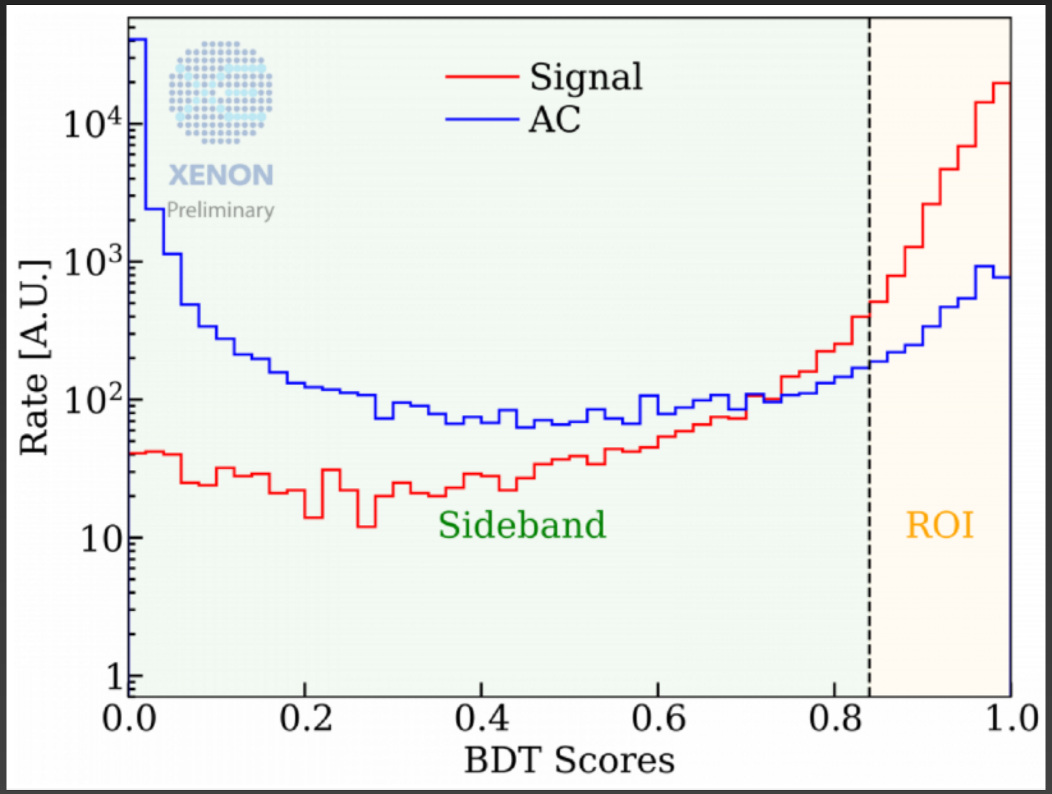
# AC background suppression: check s1/s2 pairing

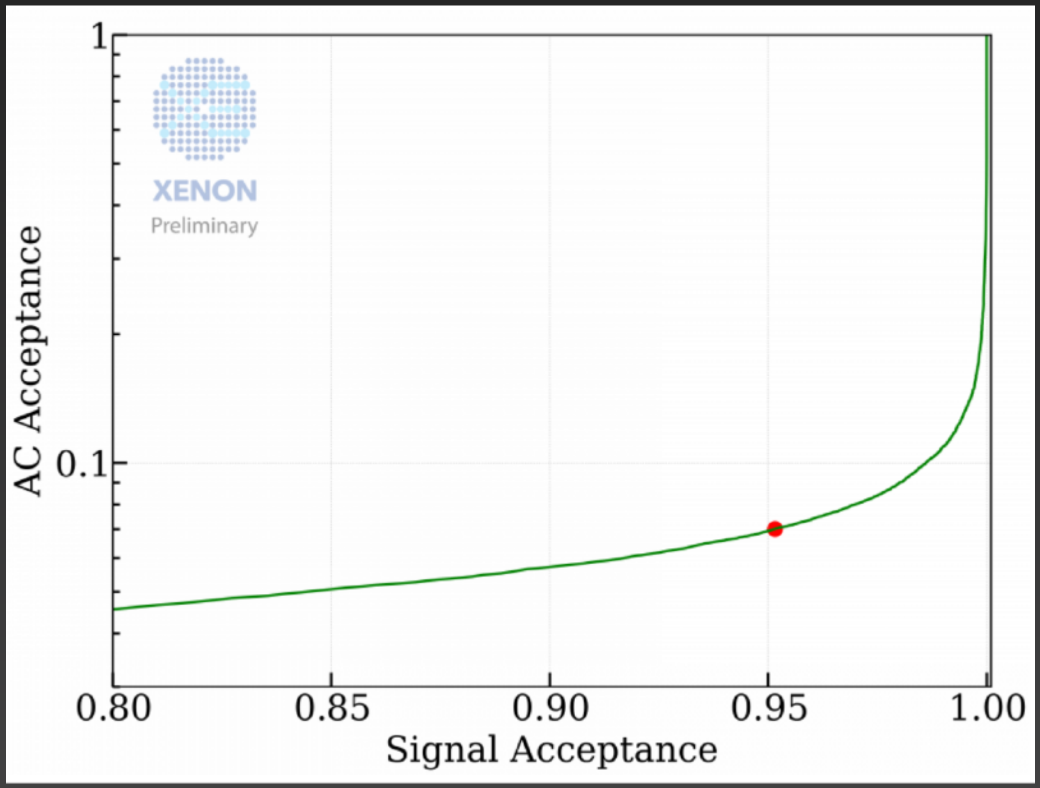



Correct pairing




Random pairing

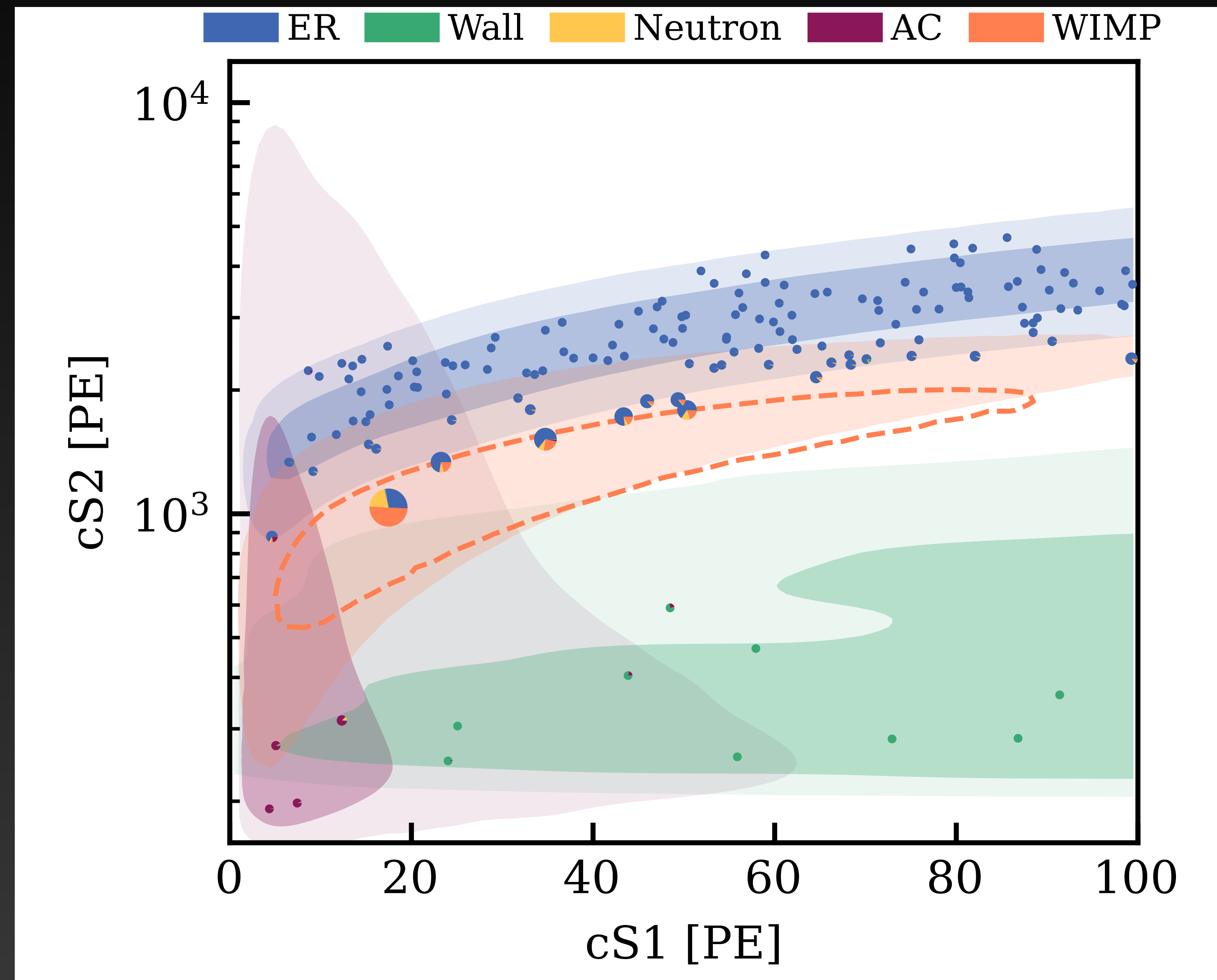



Boosted decision tree (BDT) features:
s2 width (diffusion), z, rise time, s2 size

# WIMP results

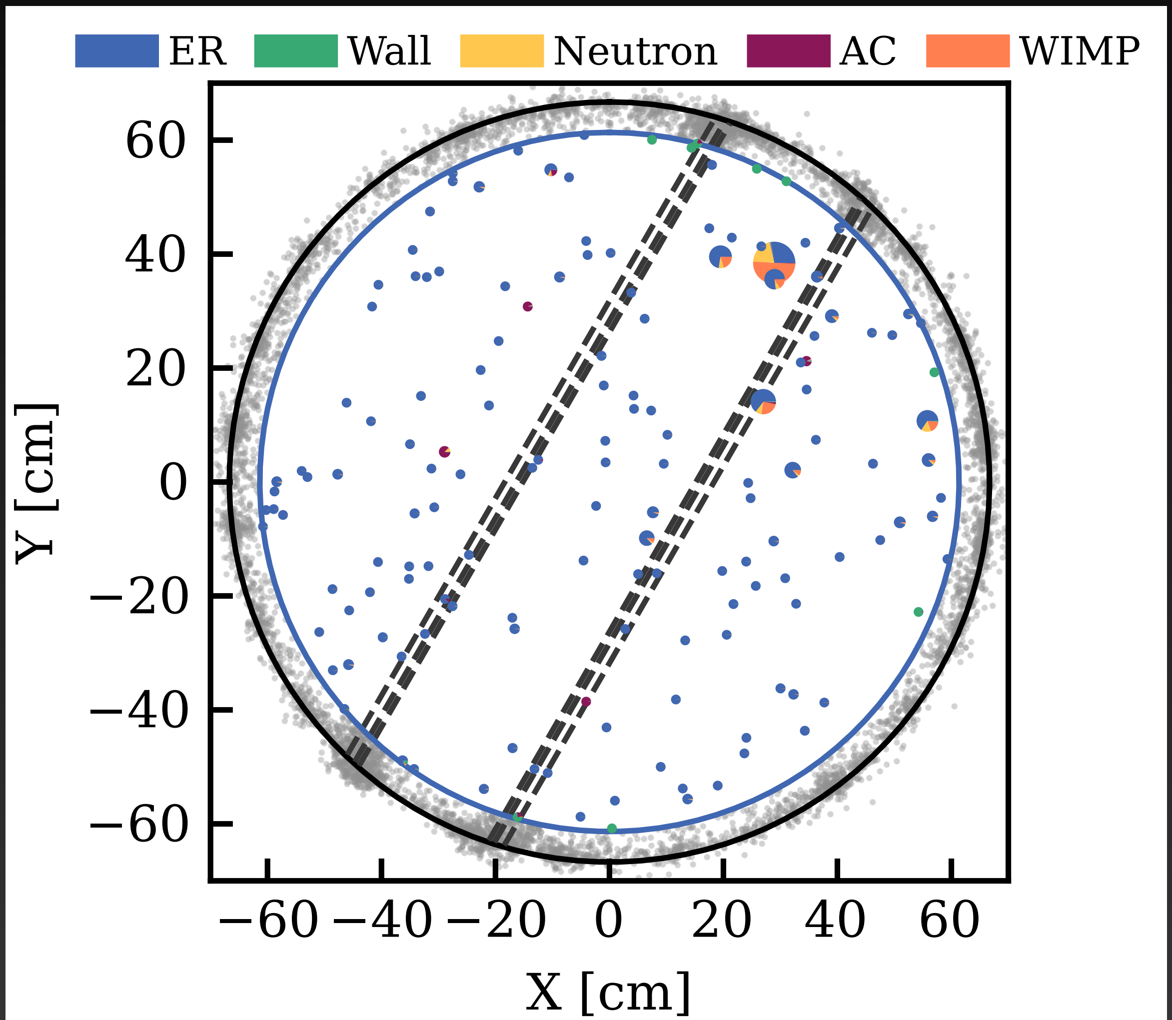
| | Nominal | Best Fit | |
|---|---|---|---|
| | ROI | | Signal-like |
| ER | 134 | $135^{+12}_{-11}$ | $0.86^{+0.08}_{-0.07}$ |
| Neutrons | $1.1^{+0.6}_{-0.5}$ | $1.1 \pm 0.4$ | $0.42 \pm 0.17$ |
| CE$\nu$NS | $0.23 \pm 0.06$ | $0.23 \pm 0.06$ | $0.022 \pm 0.011$ |
| AC | $4.3 \pm 0.2$ | $4.32 \pm 0.15$ | $0.366 \pm 0.013$ |
| Surface | $14 \pm 3$ | $12^{+0}_{-4}$ | $0.35^{+0.01}_{-0.11}$ |
| Total Background | 154 | $152 \pm 12$ | $2.0 \pm 0.2$ |
| WIMP | - | 2.6 | 1.3 |
| Observed | - | 152 | 3 |

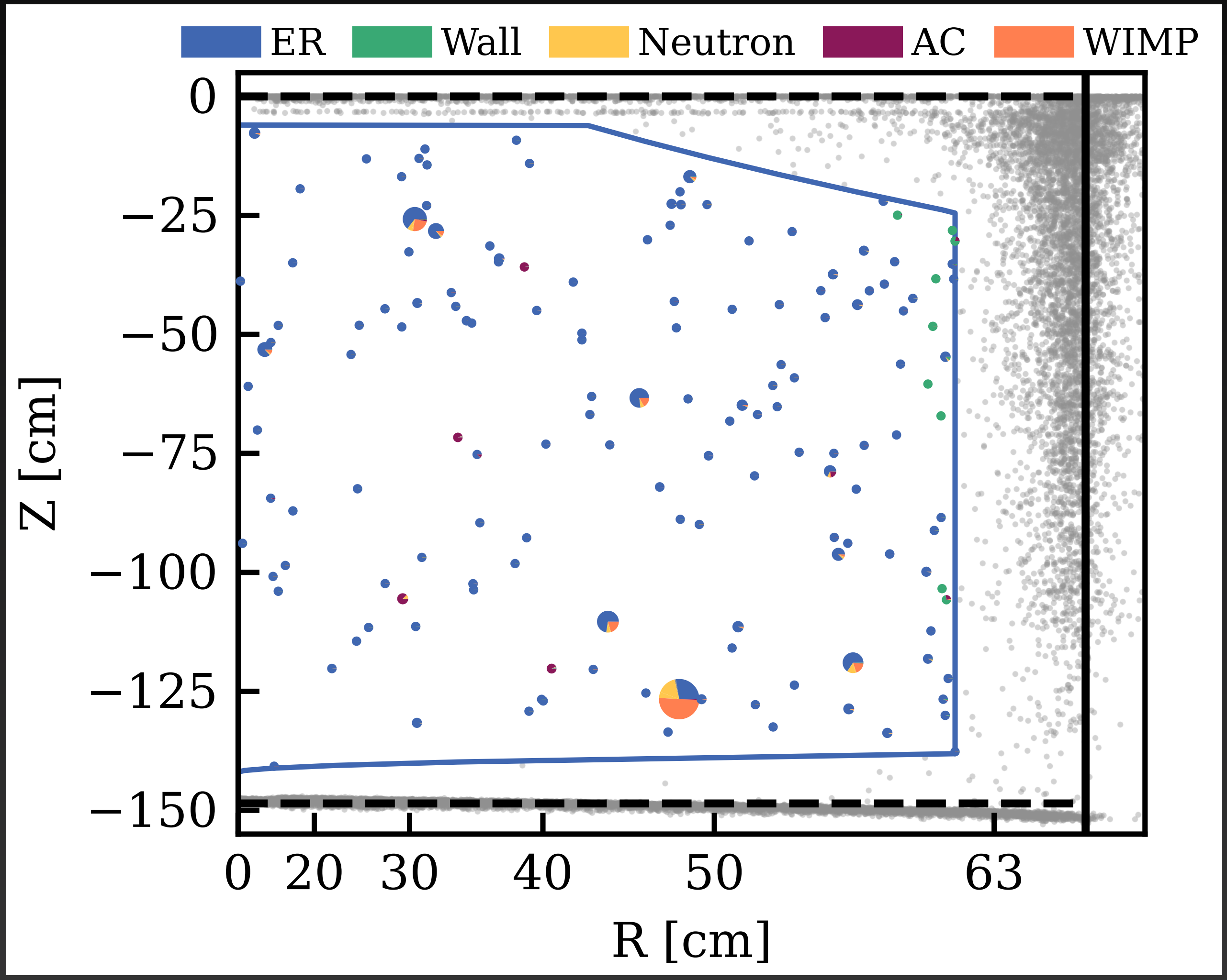



- 152 events in ROI, 16 in blinded region
- P-value indicates no significant excess

arXiv: 2303.14729

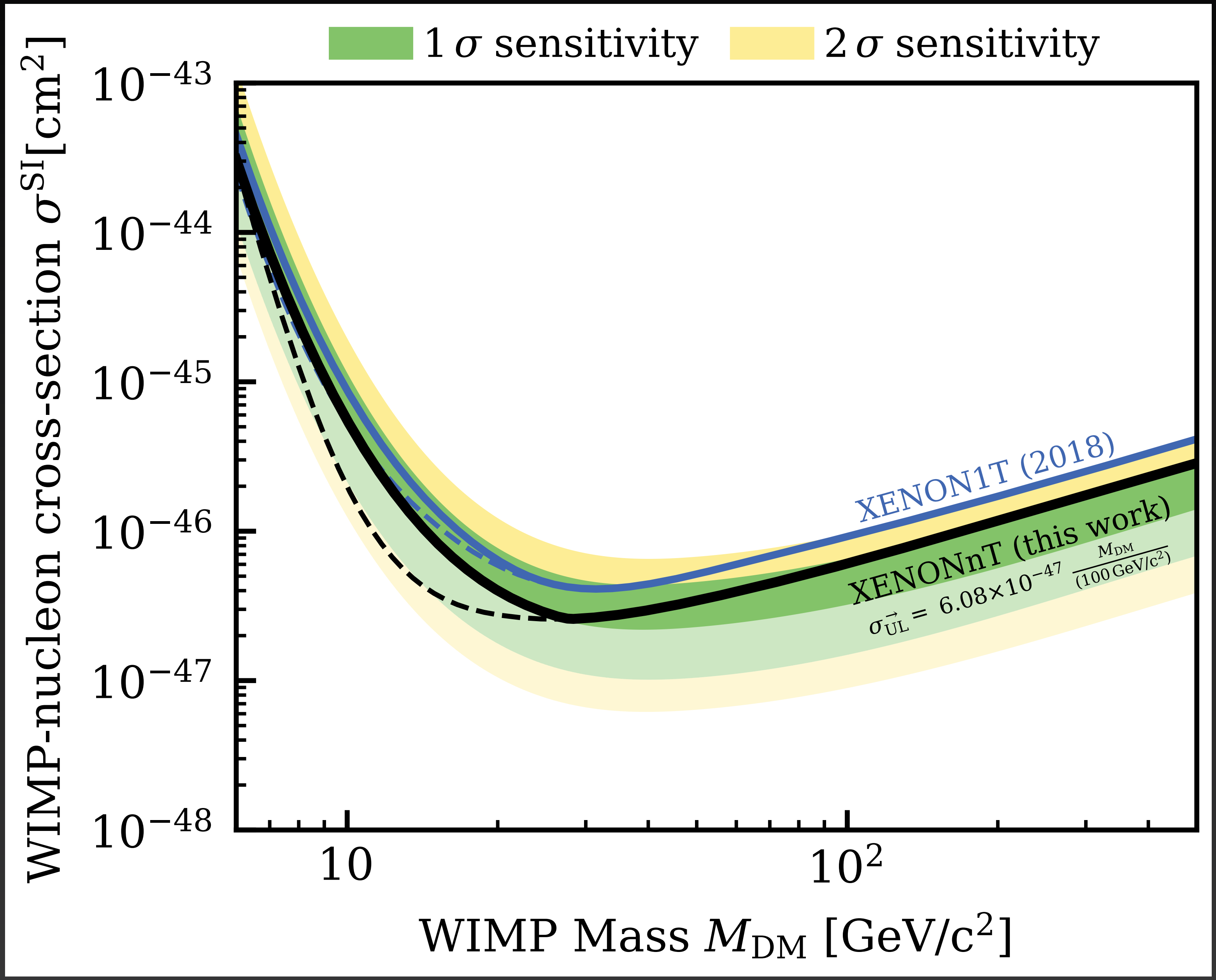
# Spatial distribution




arXiv: 2303.14729

# WIMP results

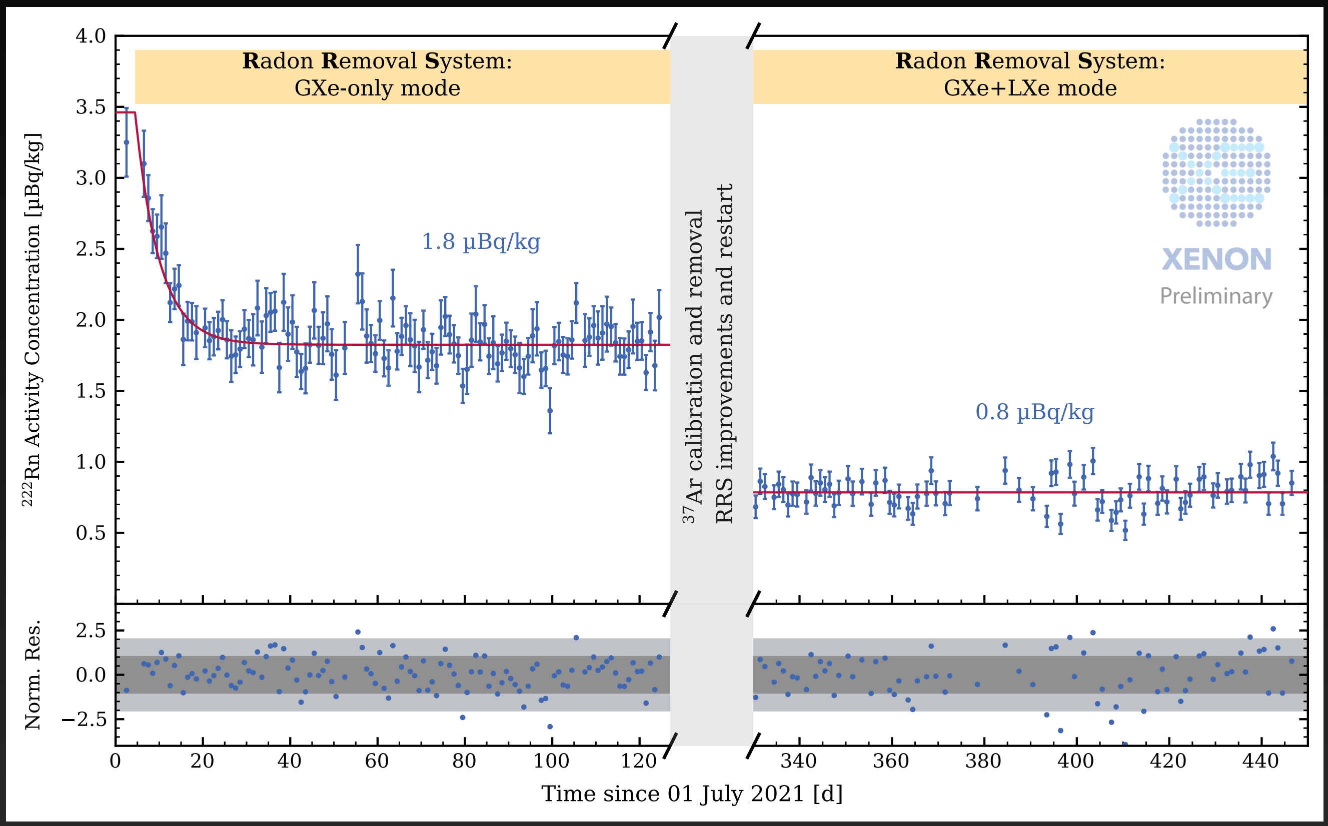


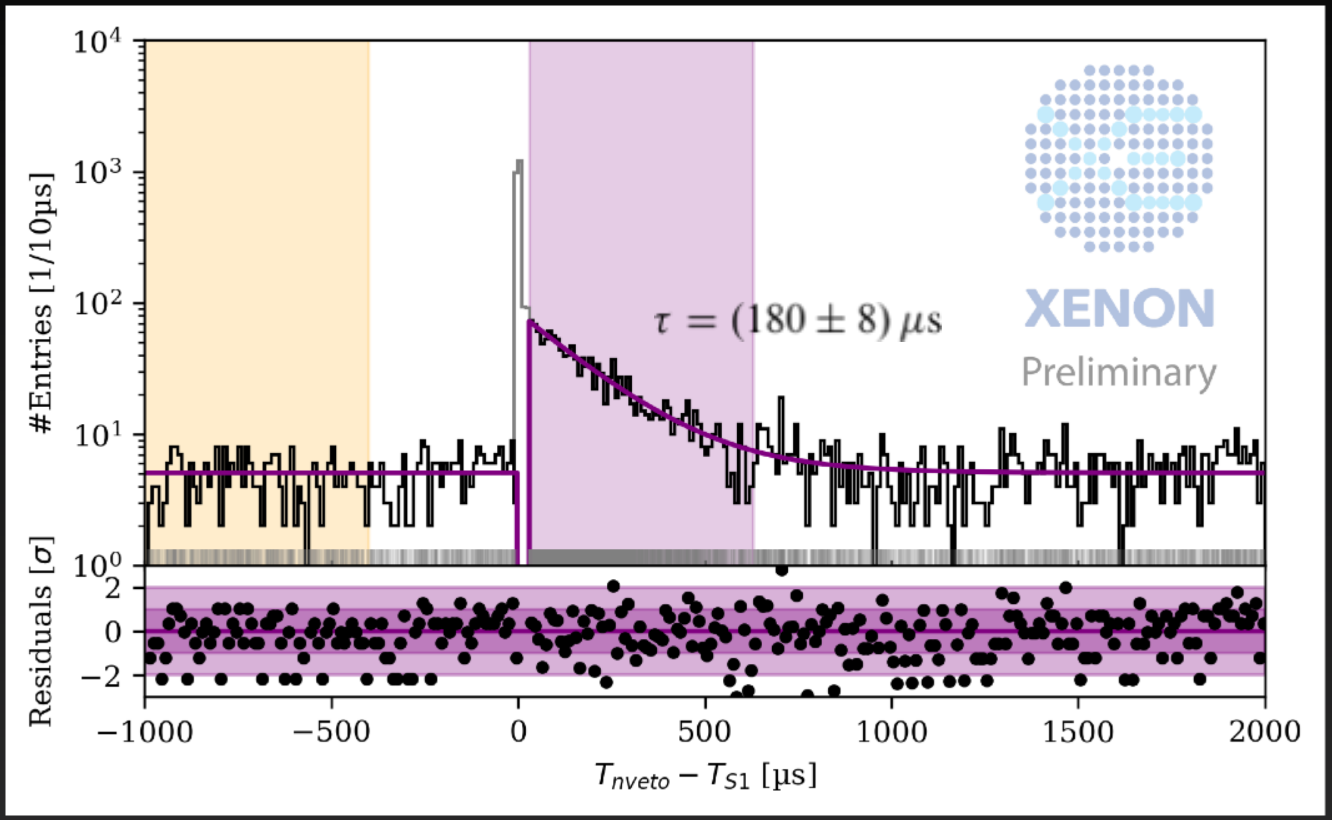

- Use power-constraint limit (PCL), currently set at median (50%)
- Minimum upper limit for spin-independent (SI) WIMP-nucleon cross sections is $2.58 \times 10^{-47}\ \mathrm{cm}^2$ for a mass of 28 GeV/$c^2$

arXiv: 2303.14729

# What's next?

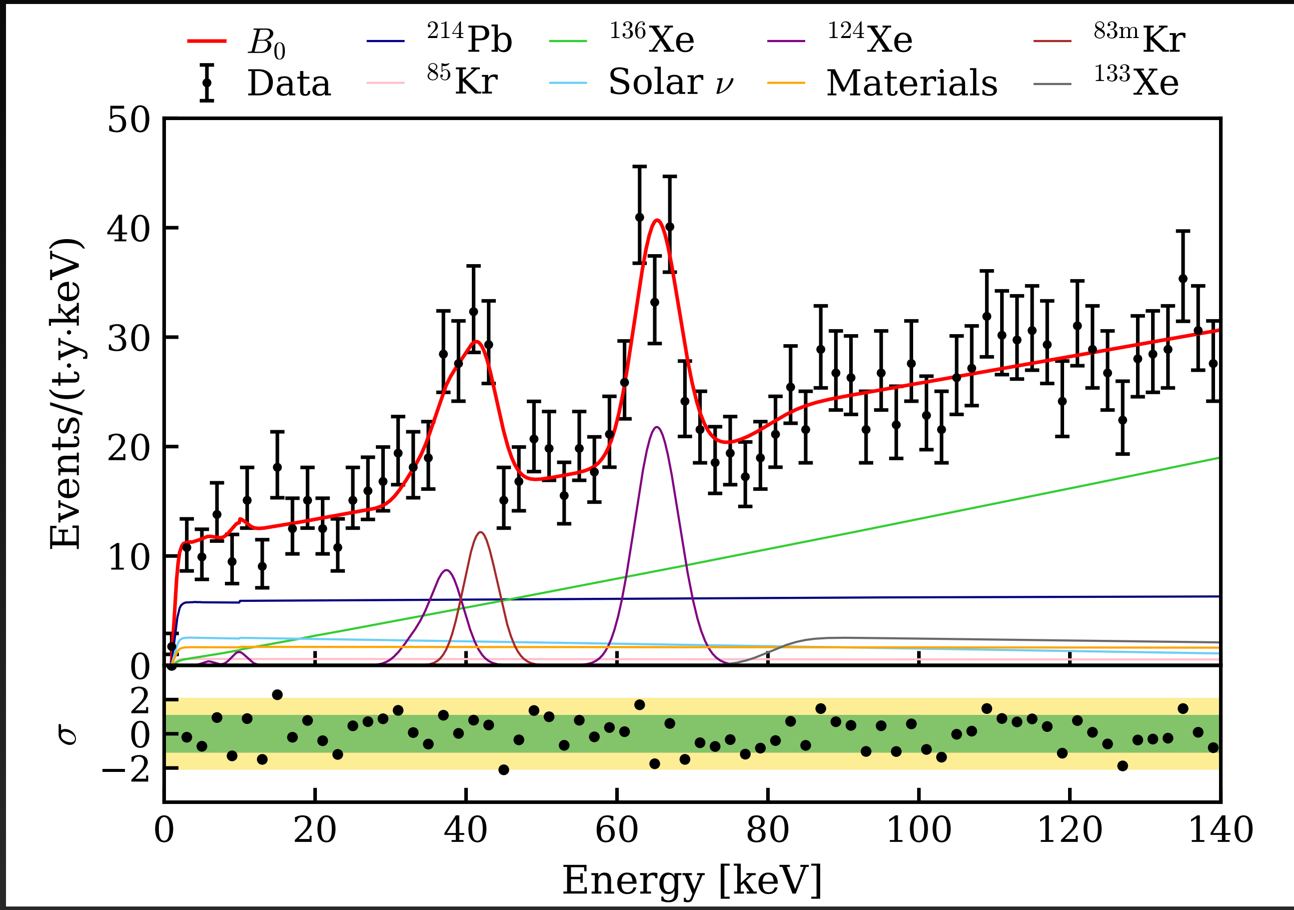
# Continue WIMP search

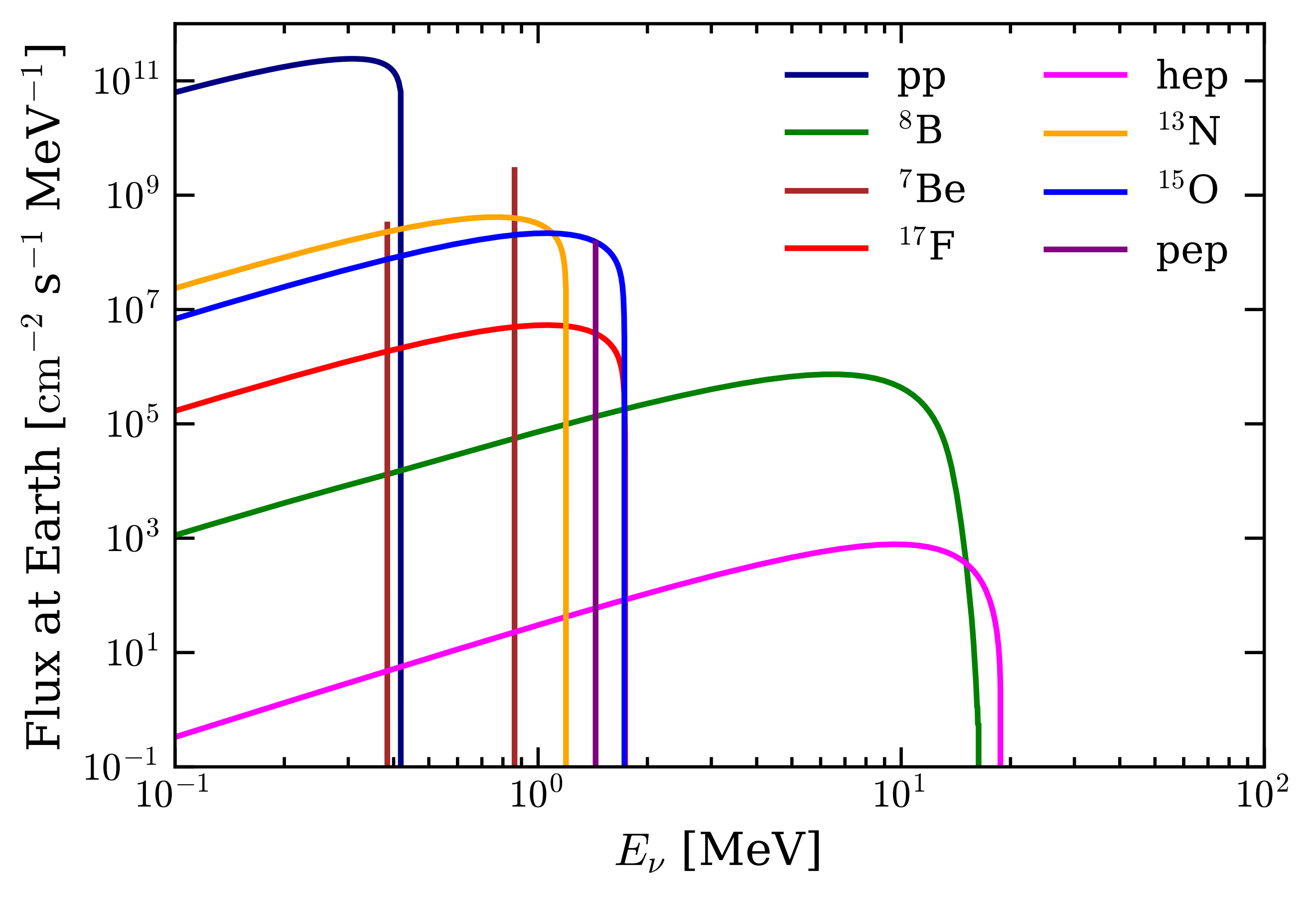



- Data taking is ongoing
- $^{222}$Rn is further reduced by a factor of ~2 due to GXe + LXe mode -> reduced ER background
- Optimize neutron veto tagging window and FV -> reduce NR background

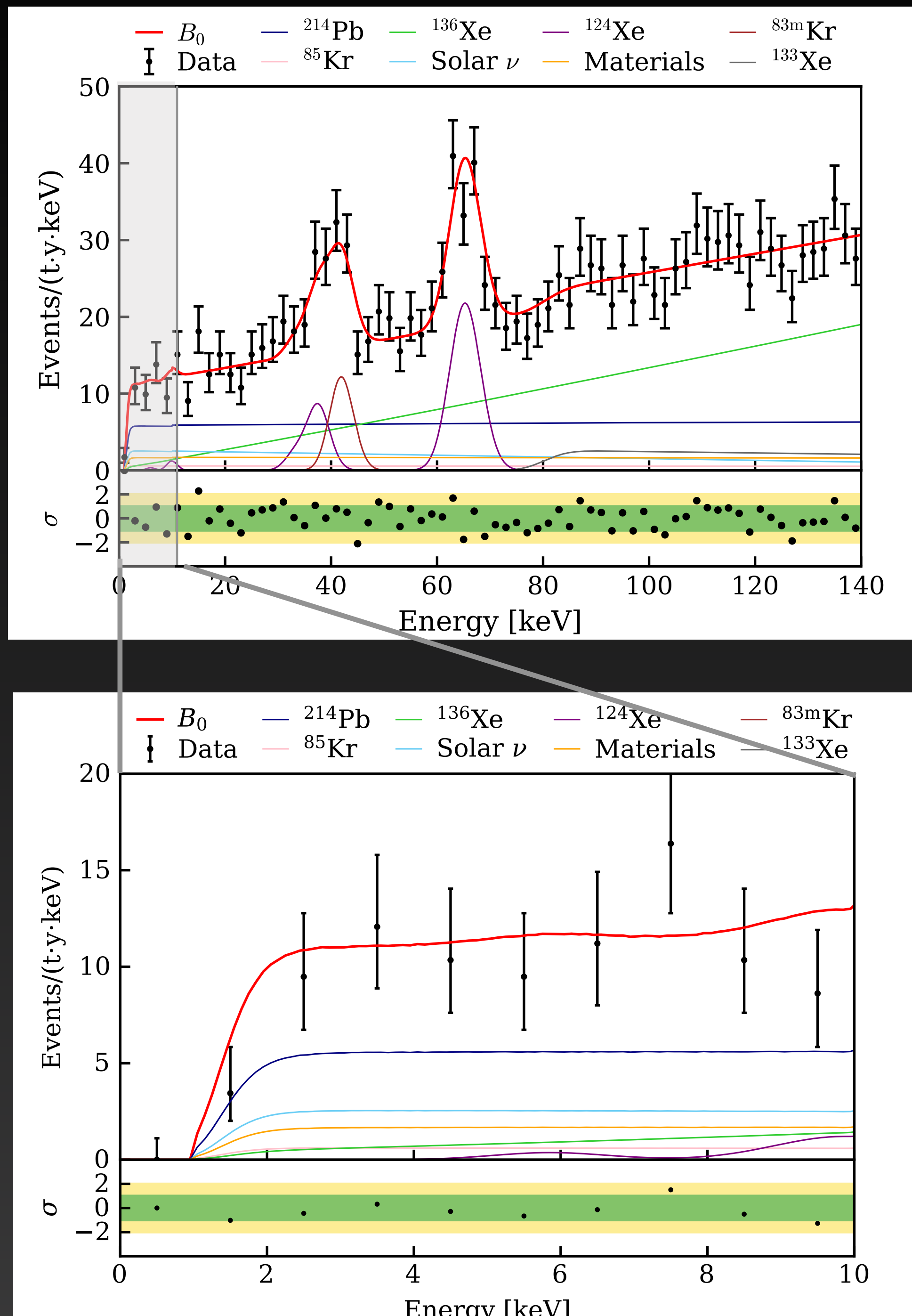
# Solar pp neutrinos




- Solar neutrinos can scatter elastically with electrons and produce ER events
- This interaction is dominated by Solar pp neutrinos (>99%)

# Search for solar pp neutrinos with XENONnT




Best-fit values in SR0

| | (1, 10) keV | (1, 140) keV |
|---|---|---|
| $^{214}$Pb | $55 \pm 7$ | $960 \pm 120$ |
| $^{85}$Kr | $6 \pm 4$ | $90 \pm 60$ |
| Materials | $16 \pm 3$ | $270 \pm 50$ |
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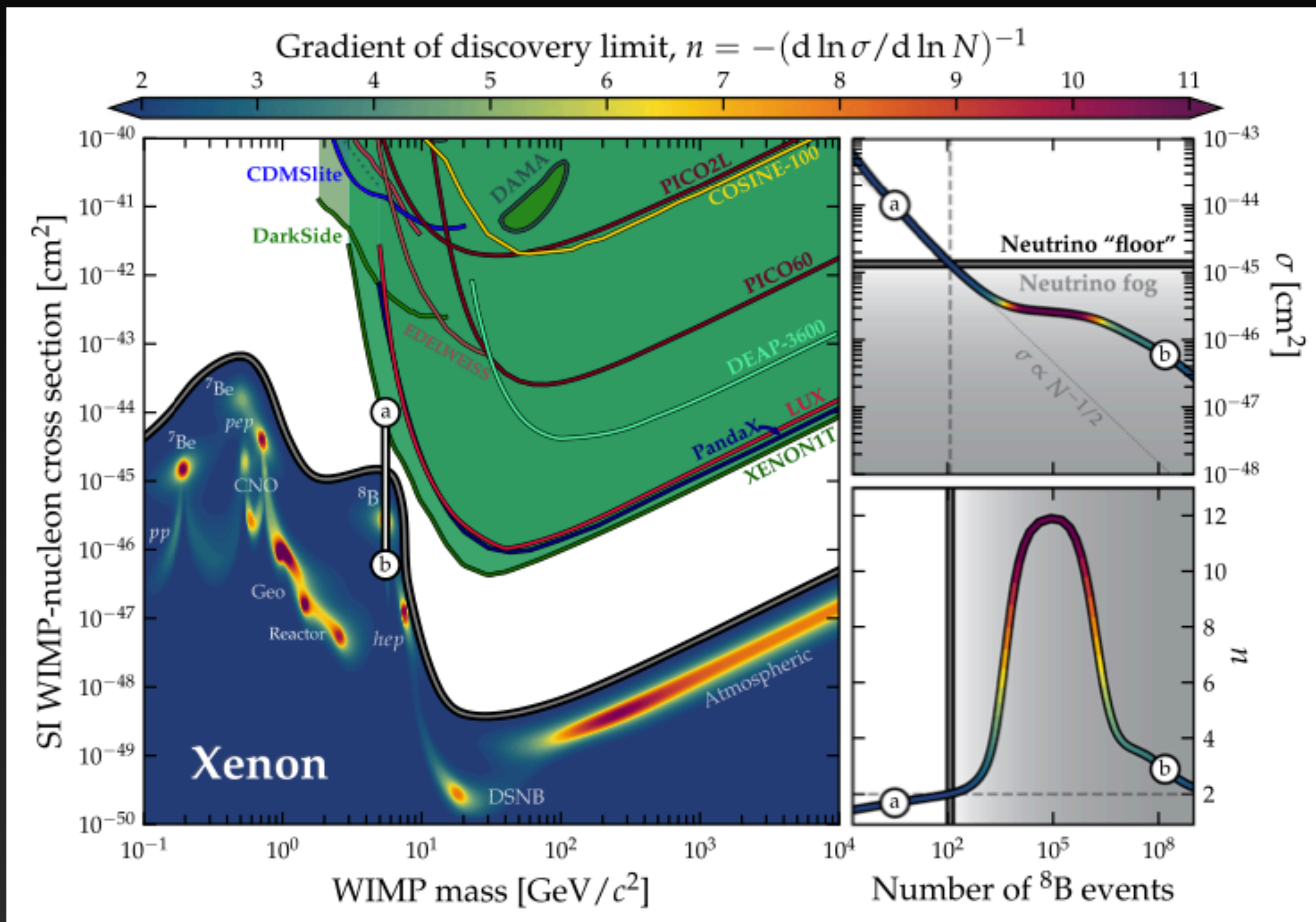
| $^{133}$Xe | - | $150 \pm 60$ |
| $^{83m}$Kr | - | $80 \pm 16$ |

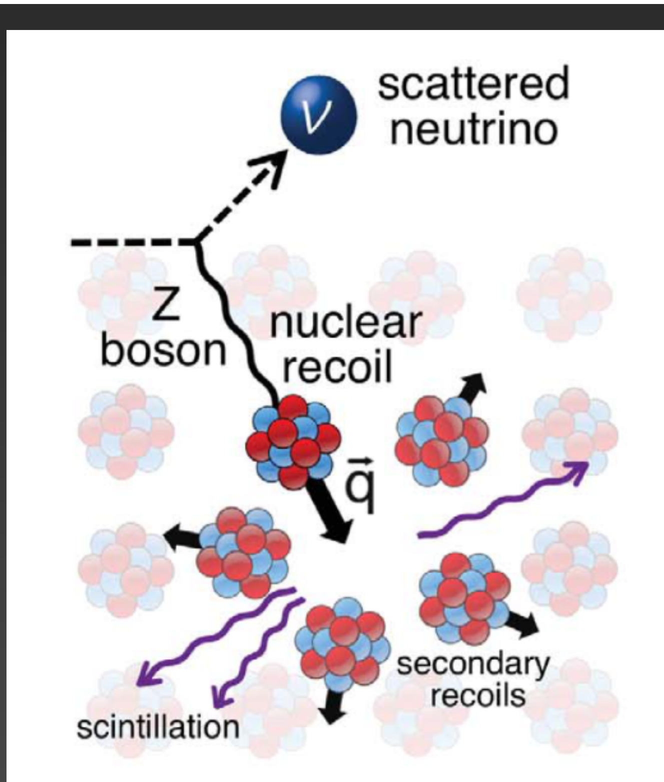
- This is the 2nd largest ER component below 10 keV in SR0 and at comparable with $^{214}$Pb in SR1 as radon backgrounds have been reduced by a factor of ~2
- It is very possible to make the first solar pp neutrino detection in a dark matter detector and give more precise measurement in the future that is meaningful to the Standard Solar Model and neutrino oscillation
- Constraining the $^{214}$Pb rate will further improve the sensitivity to solar pp neutrinos

# Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

Neutrino fog (floor) PRL 127, 251802 (2021)








- Neutrinos can coherently scatter with nuclei when its wavelength is similar to the size of nuclei
- CEvNS is a process predicted by the Standard Model, therefore a good probe for new physics
- CEvNS from solar $^8$B neutrinos is a “known” background for WIMPs, better to be measured beforehand!

# How to detect CEvNS?

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

**Coherent effects of a weak neutral current**

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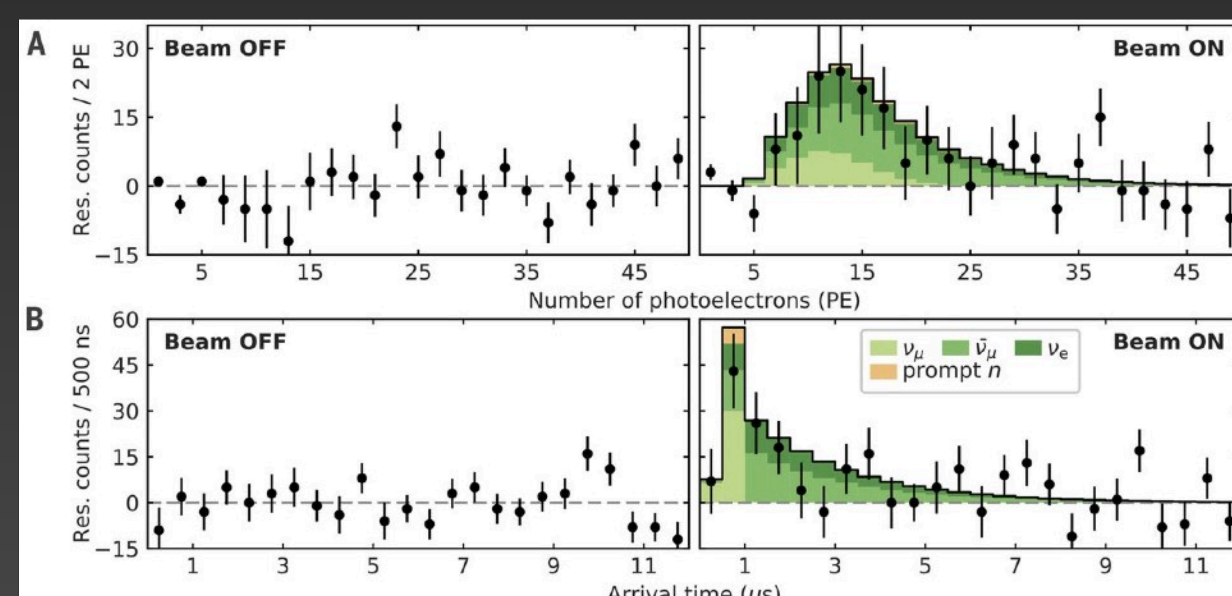
Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.

- Theory prediction made in 1974 while the first experimental observation is 43 years later by the COHERENT Collaboration
- So far only observed in CsI and argon
- The keys for CEvNS detection are
  - low threshold
  - low backgrounds

Main Background: AC background
- Suppress lone S1/S2 rate
- Check event (S1S2) pairing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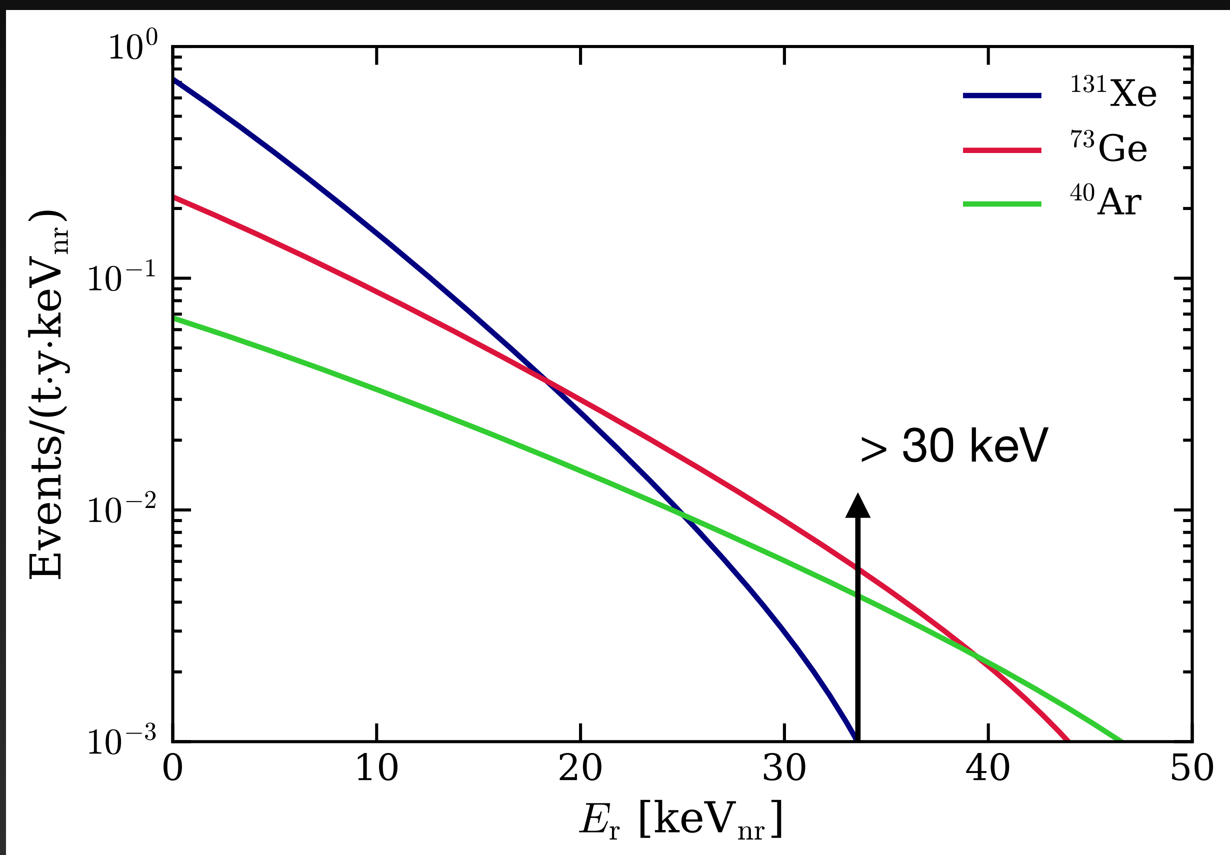
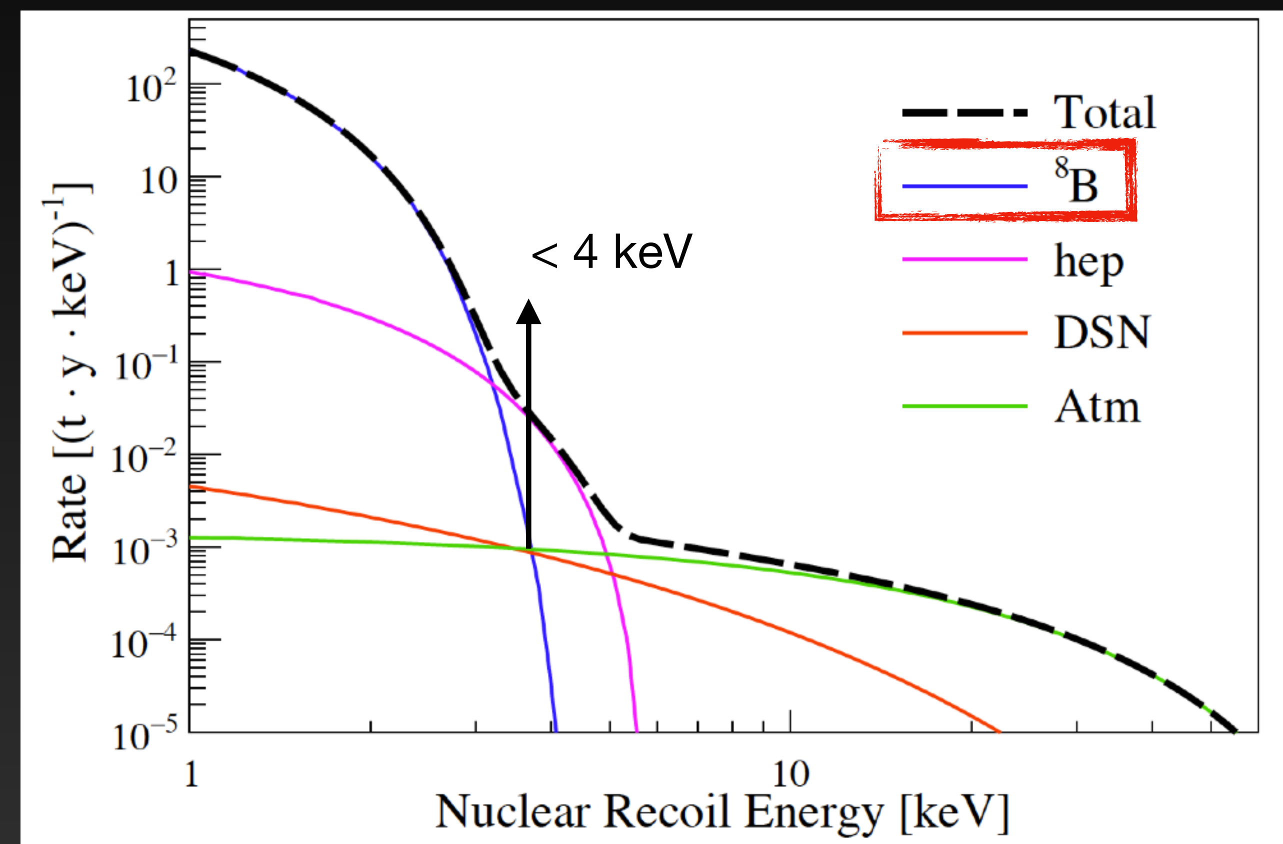
# Why lower detection threshold?

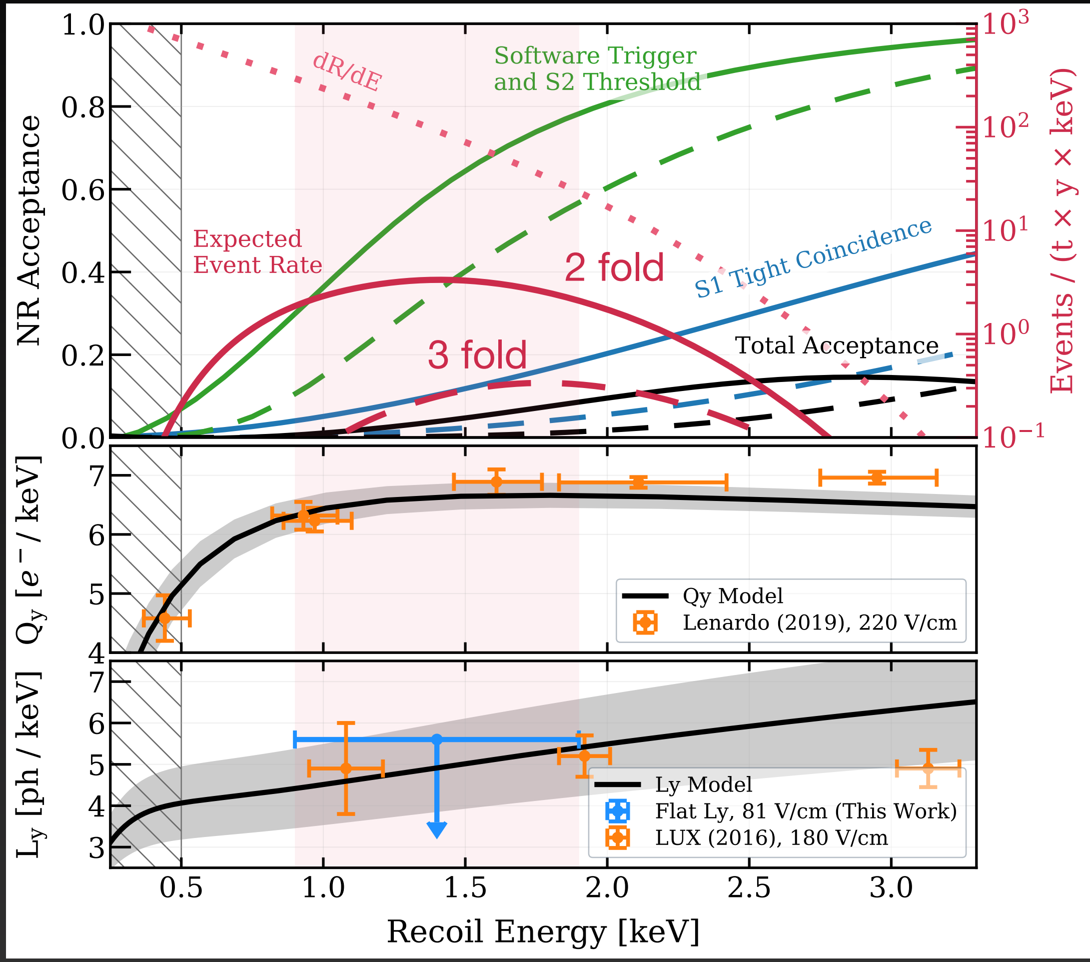



Nuclear recoil spectrum of 30 GeV/$c^2$ WIMPs




Nuclear recoil spectrum of solar B-8 neutrinos, similar to that of 6 GeV/$c^2$ WIMPs

# How to lower threshold?

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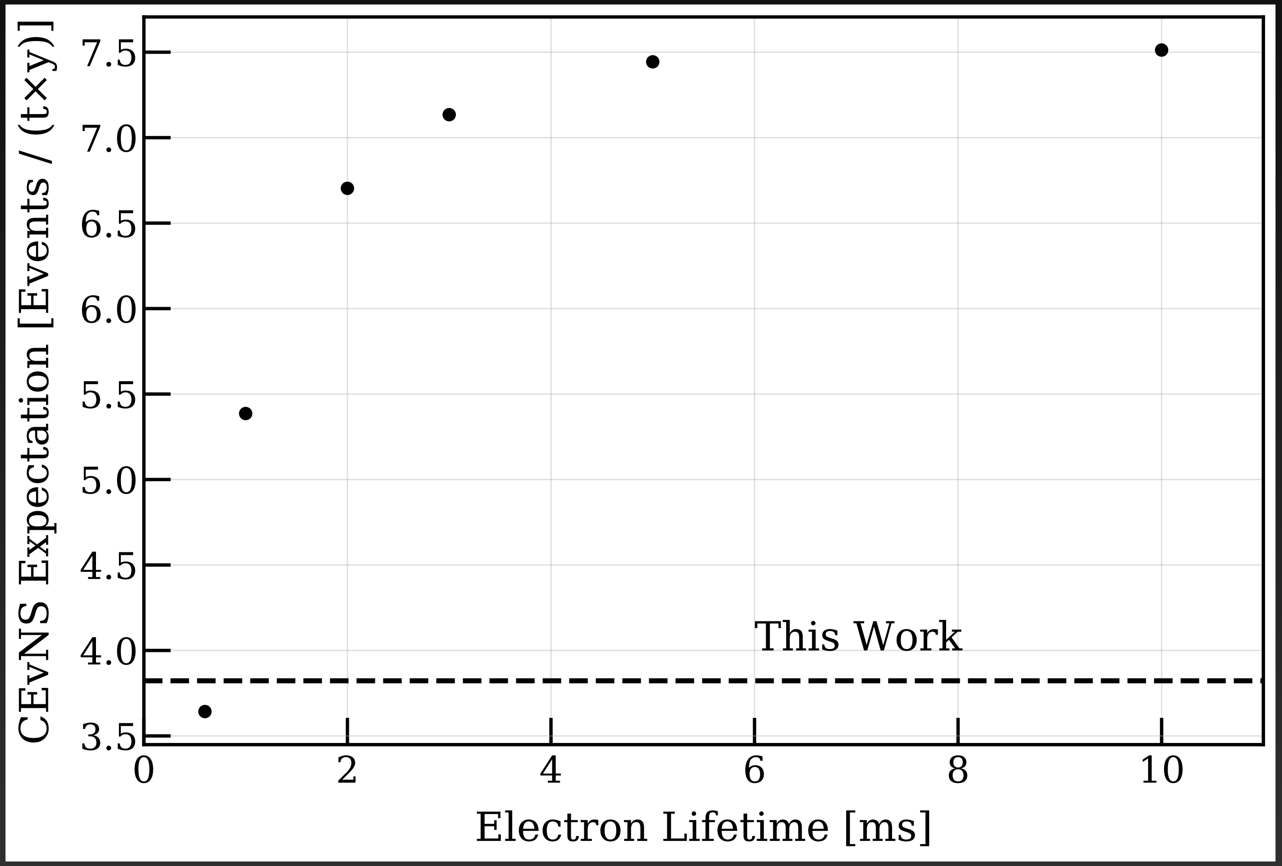
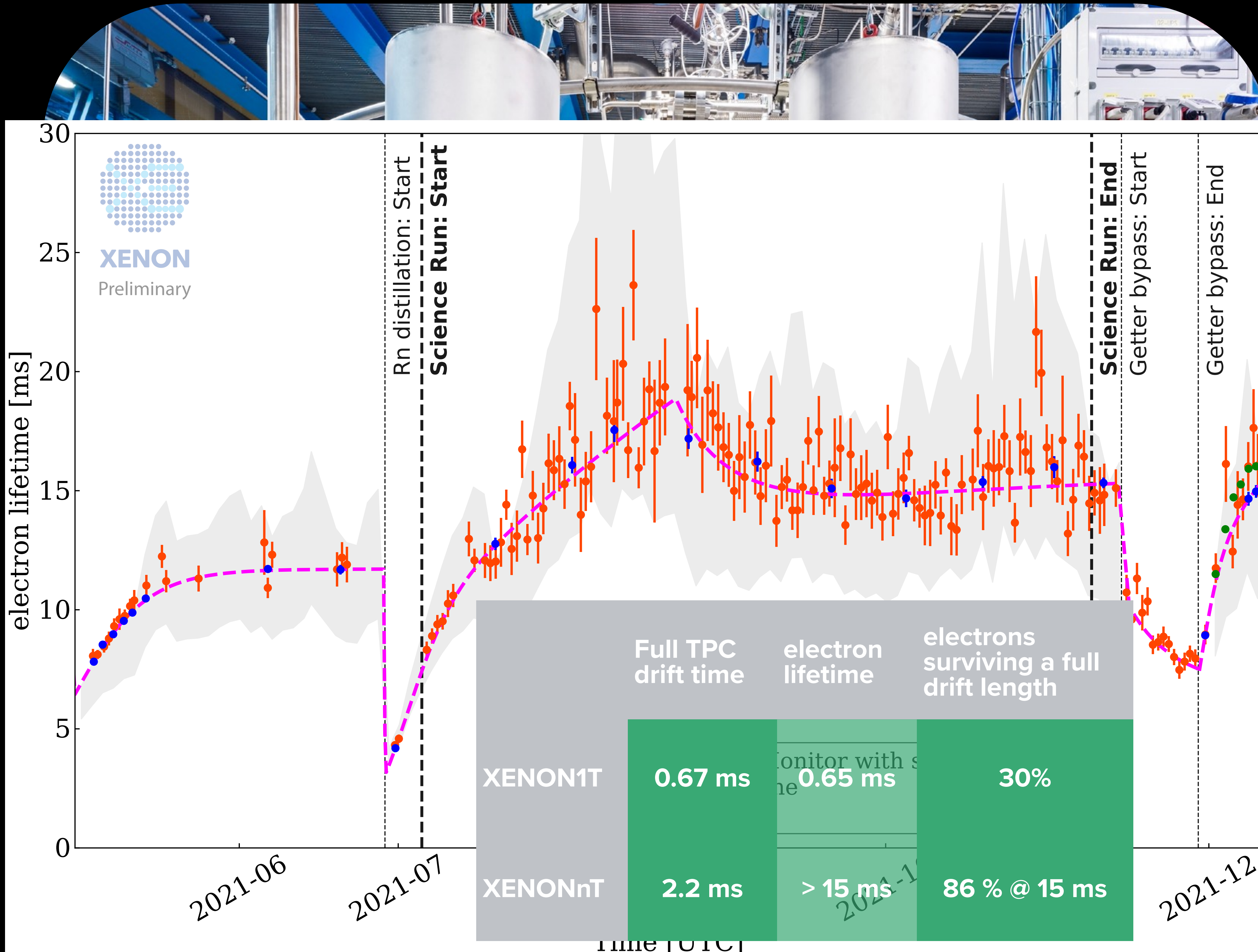



Lower S1 detection threshold:
Tight coincidence requirement for S1: 3 fold -> 2 fold
=> Signal rate increases by a factor of ~20

Increase electron lifetime:
Increase S2 detection efficiency by increasing electron lifetime (effectively lower S2 detection threshold)

# Liquid xenon purification system




| | Full TPC drift time | electron lifetime | electrons surviving a full drift length |
|---|---|---|---|
| XENON1T | 0.67 ms | 0.65 ms | 30% |
| XENONnT | 2.2 ms | > 15 ms | 86 % @ 15 ms |

# Summary

- XENONnT has achieved an unprecedented ER background rate of (15.8±1.3) events/(t y keV) below 30 keV, the lowest in a dark matter detector

- The first WIMP result from XENONnT has placed stringent limits for WIMPs with the minimum of $2.58 \times 10^{-47}\ \mathrm{cm}^2$ for a mass of 28 GeV/$c^2$

- XENONnT is currently taking data and extending its science potential to solar $^8\mathrm{B}$ neutrinos via CEvNS and solar pp neutrinos via electron scattering. Stay tuned!