First Results from the LUX-ZEPLIN Dark Matter Experiment

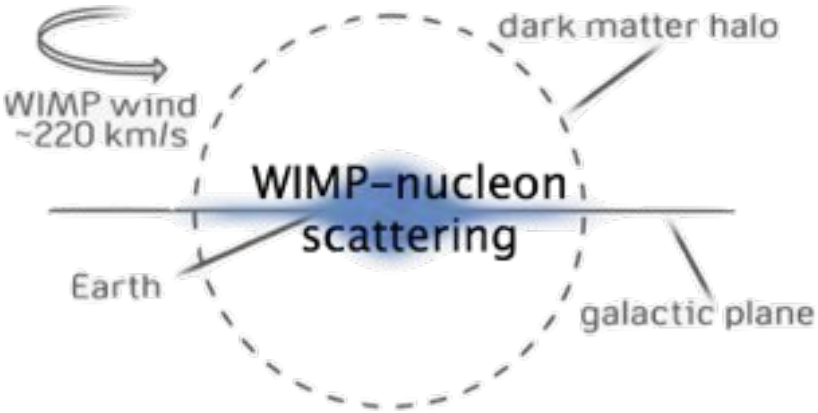
PATRAS 2023

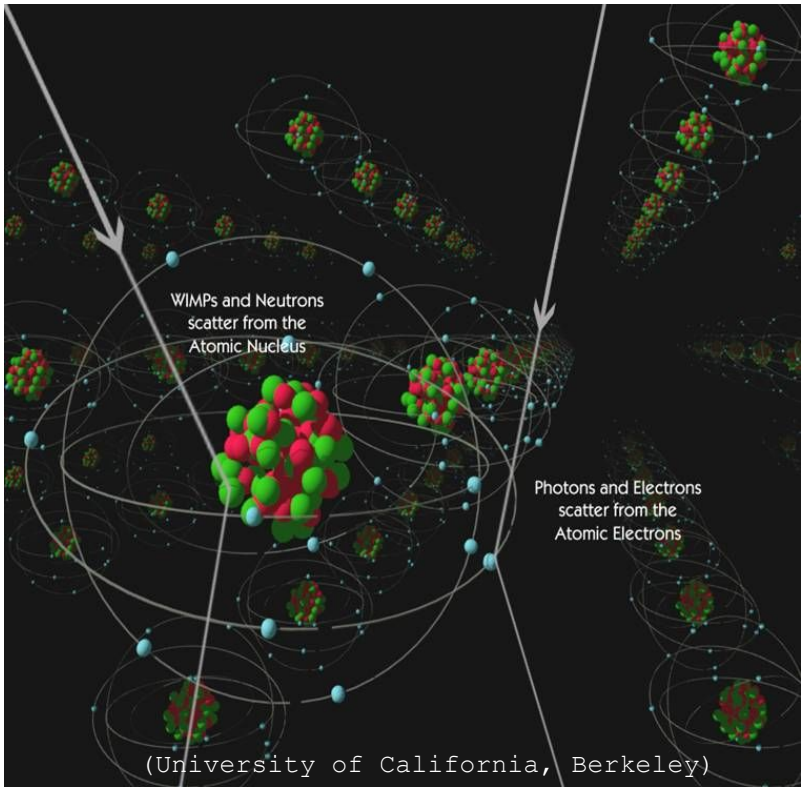
Jim Dobson* for the LZ Collaboration

* STFC Ernest Rutherford Fellow, King's College London

jim.dobson@kcl.ac.uk – 18th PATRAS - 3/7/23

Direct detection of Dark Matter

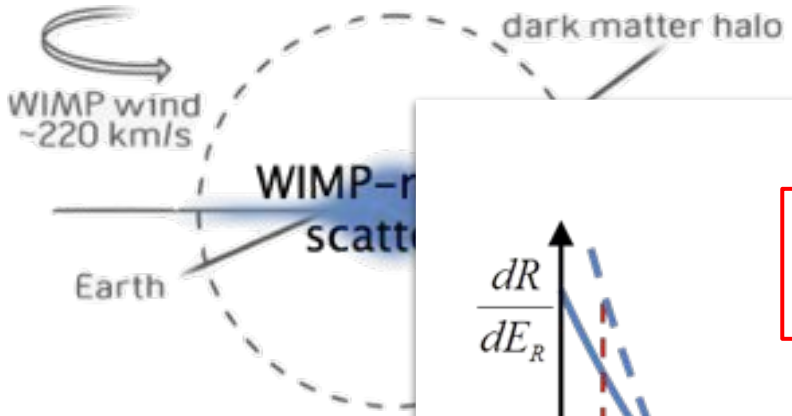


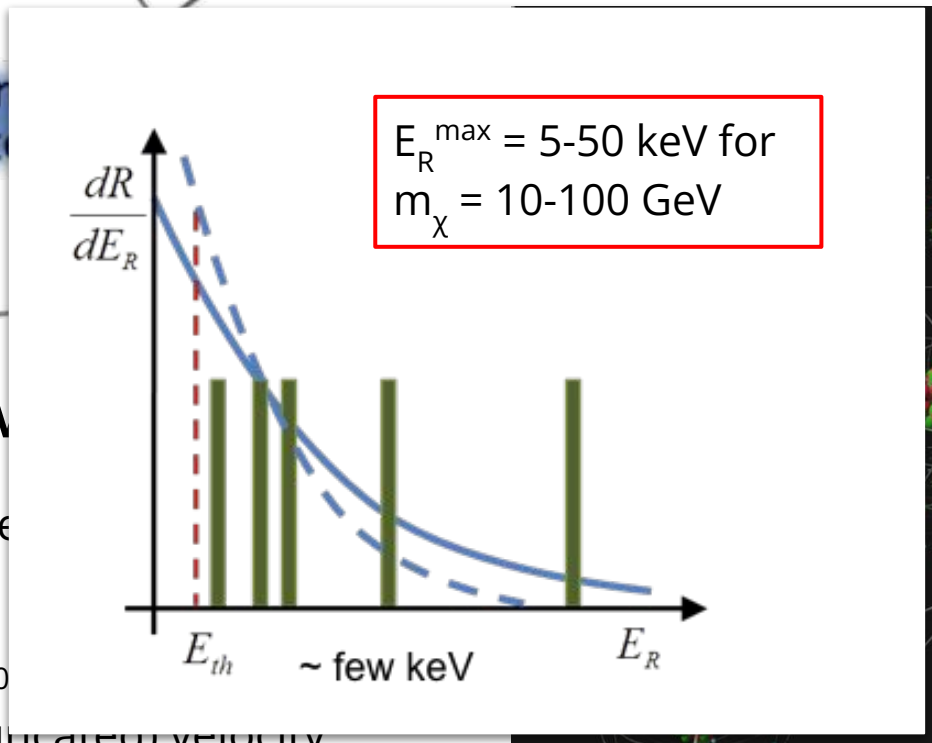


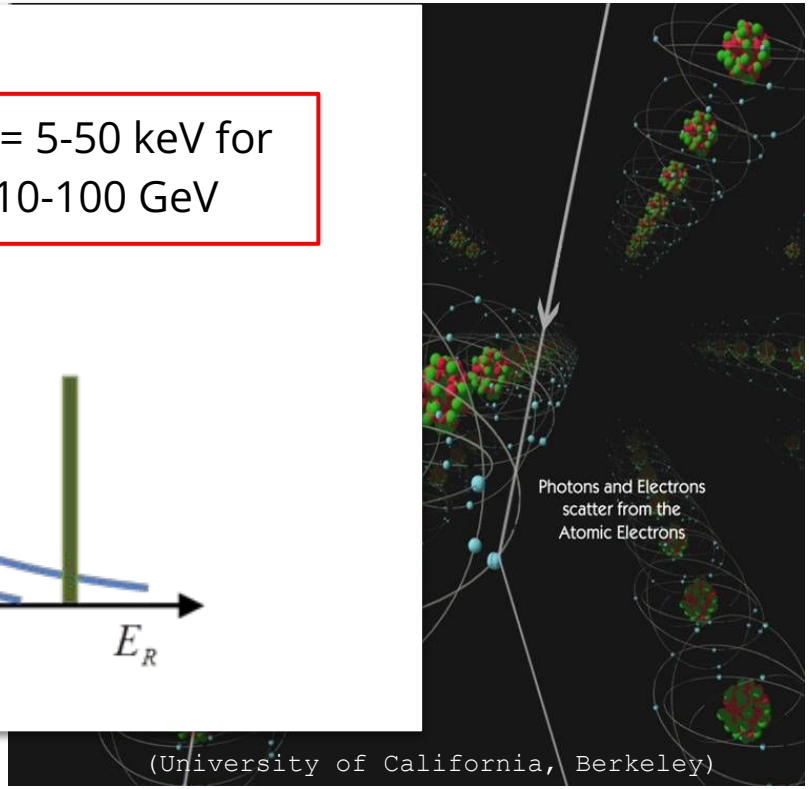
Standard Halo Model

- Isothermal sphere of DM, $\rho \propto r^{-2}$
- Local density ρ_0 ~ 0.3 GeV/cm3
- Maxwellian (truncated) velocity distribution
- Characteristic velocity v_0=220 km/s → non-relativistic!

Direct detection of Dark Matter







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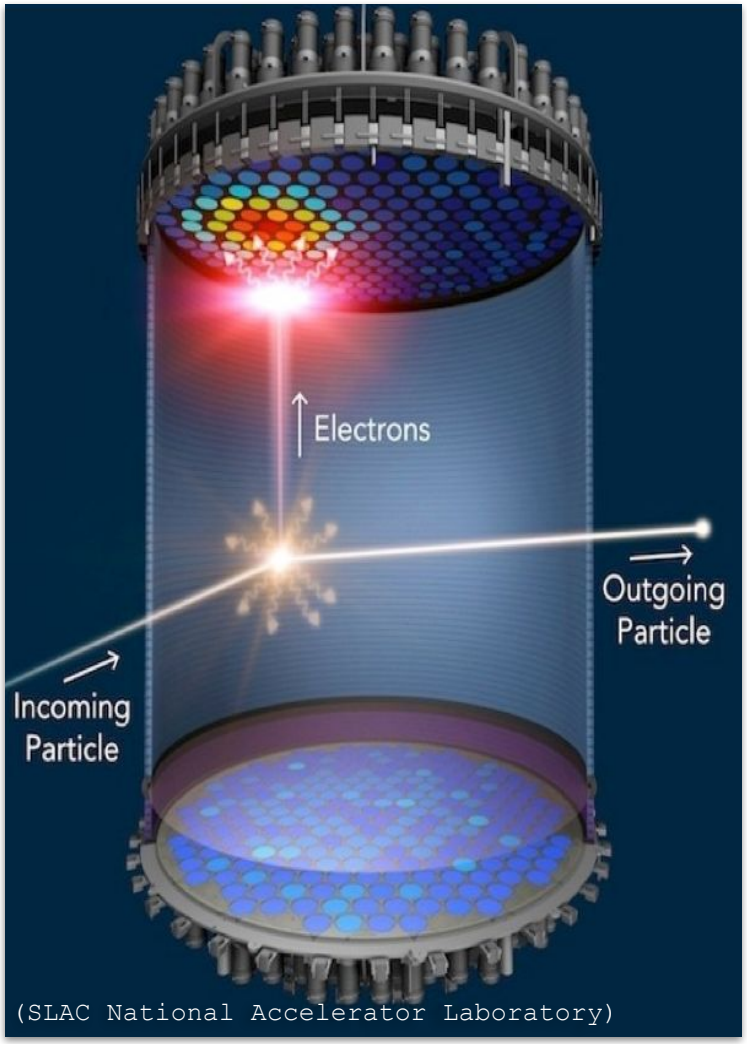
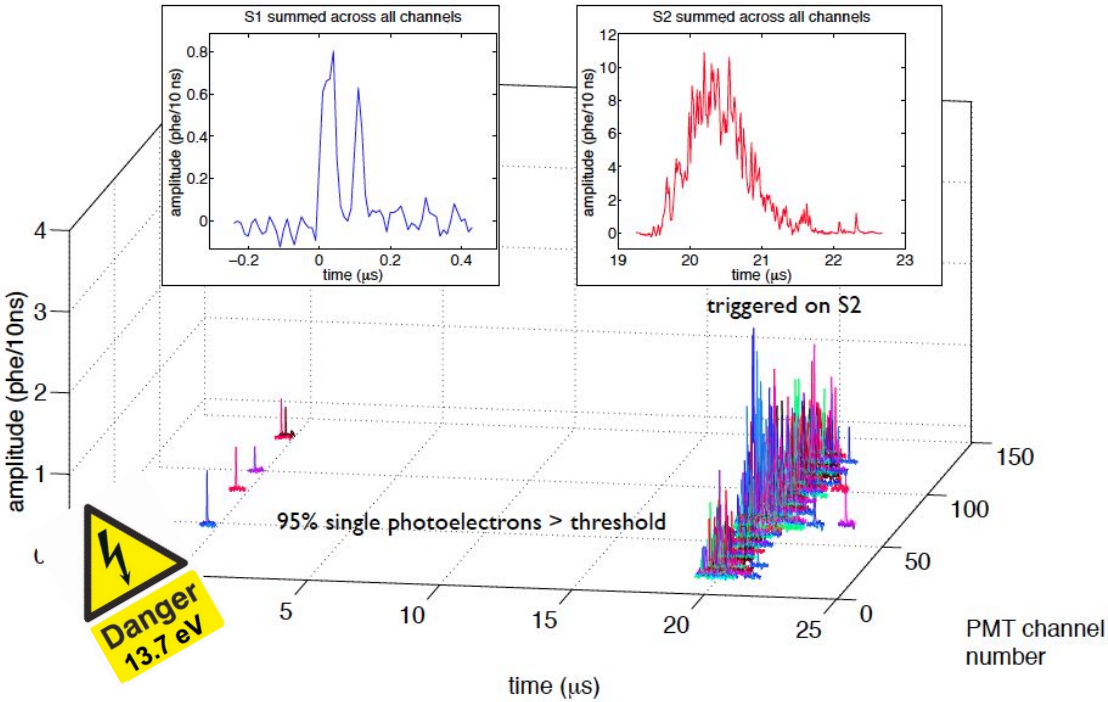
Liquid Xenon Time Projection Chambers





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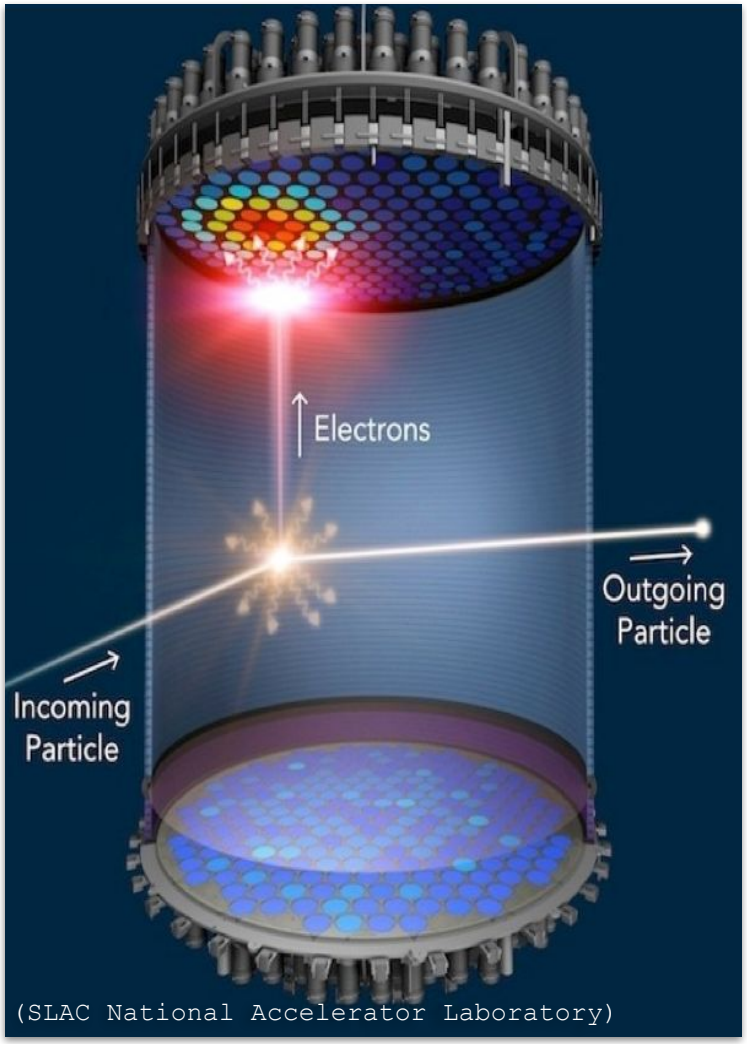

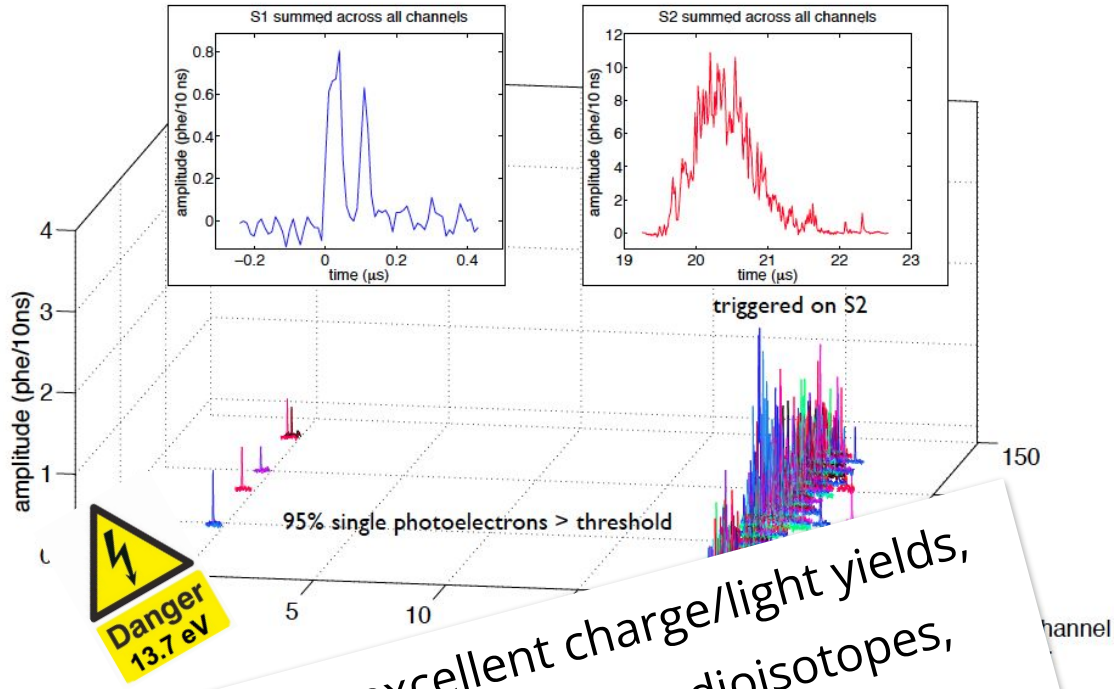

Key features: excellent charge/light yields, $\sigma \propto A^2$, lack of long-lived radioisotopes, fiducialisation →highly scalable.

Background suppression in LXe-TPC

3D position: σ_{xy}= O(cm), σ_z ~ O(mm) → fiducialisation + single-scatter ID

Background suppression in LXe-TPC

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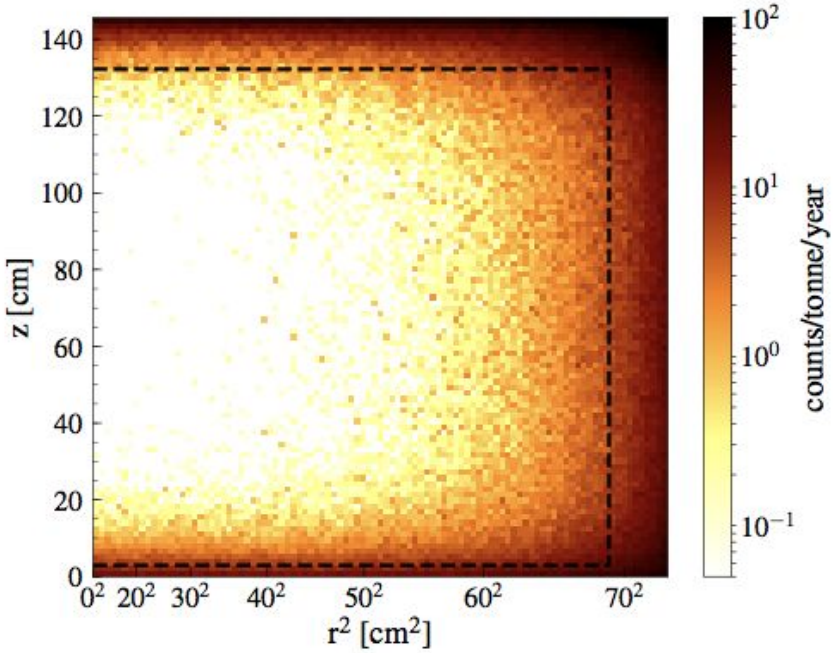
Self-shielding: here showing
low-energy neutron **single scatters**



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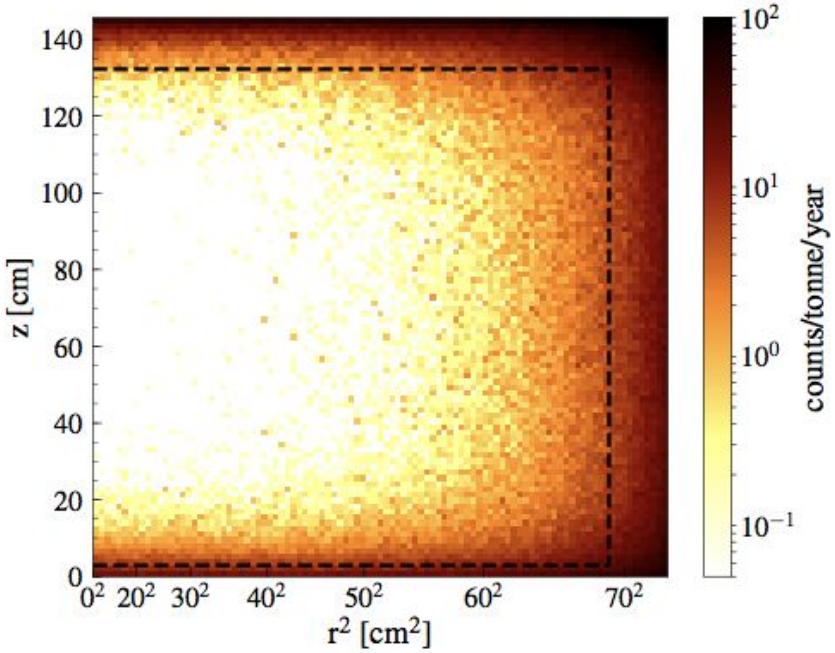
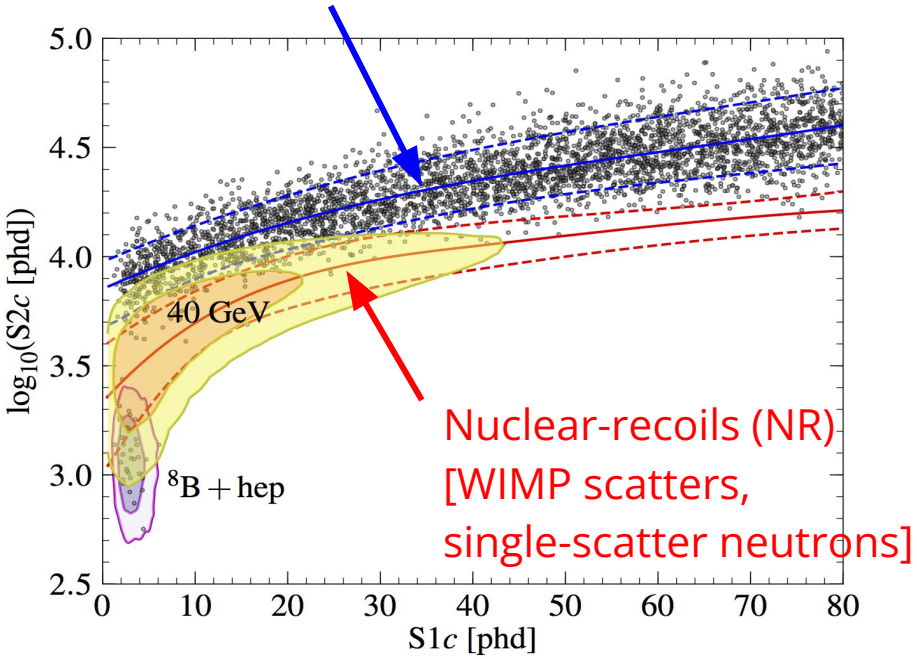


Electron-recoils (ER) [internal betas, auger/x-rays, external gammas]



LZ WIMP Sensitivity paper: Phys.Rev.D 101 (2020) 5, 052002

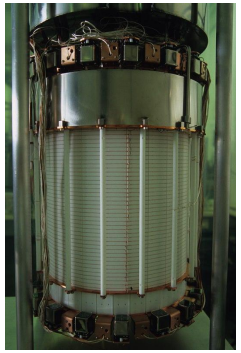
Leading technology above a ~few GeV

ZEPLIN-III

12 kg (7 kg)

2008

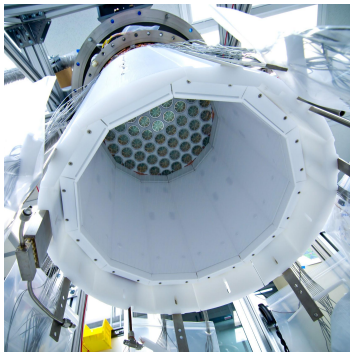
XENON100



62 kg (34 kg)

2013

LUX



250 kg (100 kg)

2016

PANDAX-II

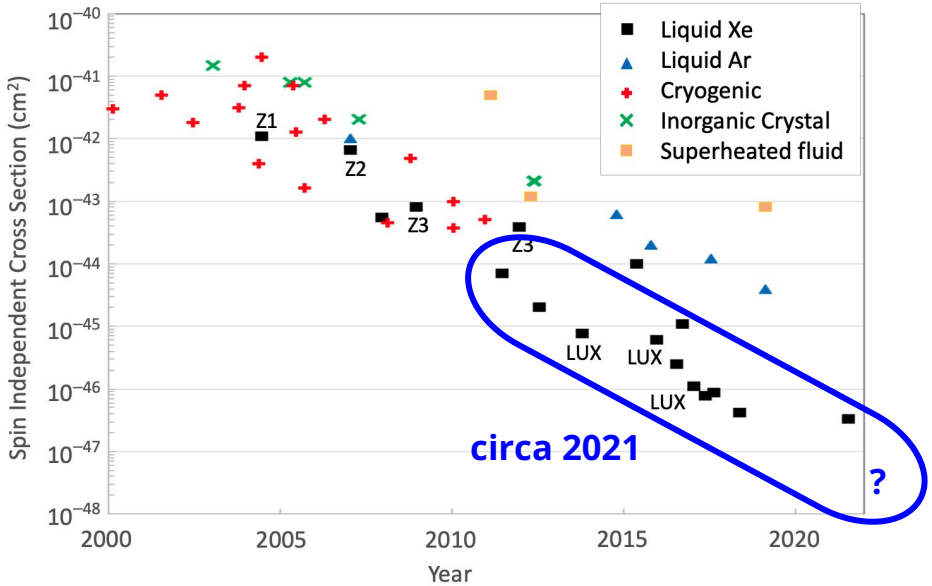
580 kg (362 kg)

2017

XENON1T

2,000 kg (1,042 kg)

2018



LUX-ZEPLIN

7,000 kg (5,600 kg)

2022-25

LZ (LUX-ZEPLIN) Collaboration, 37 Institutions

@lzdarkmatter

https://lz.lbl.gov/

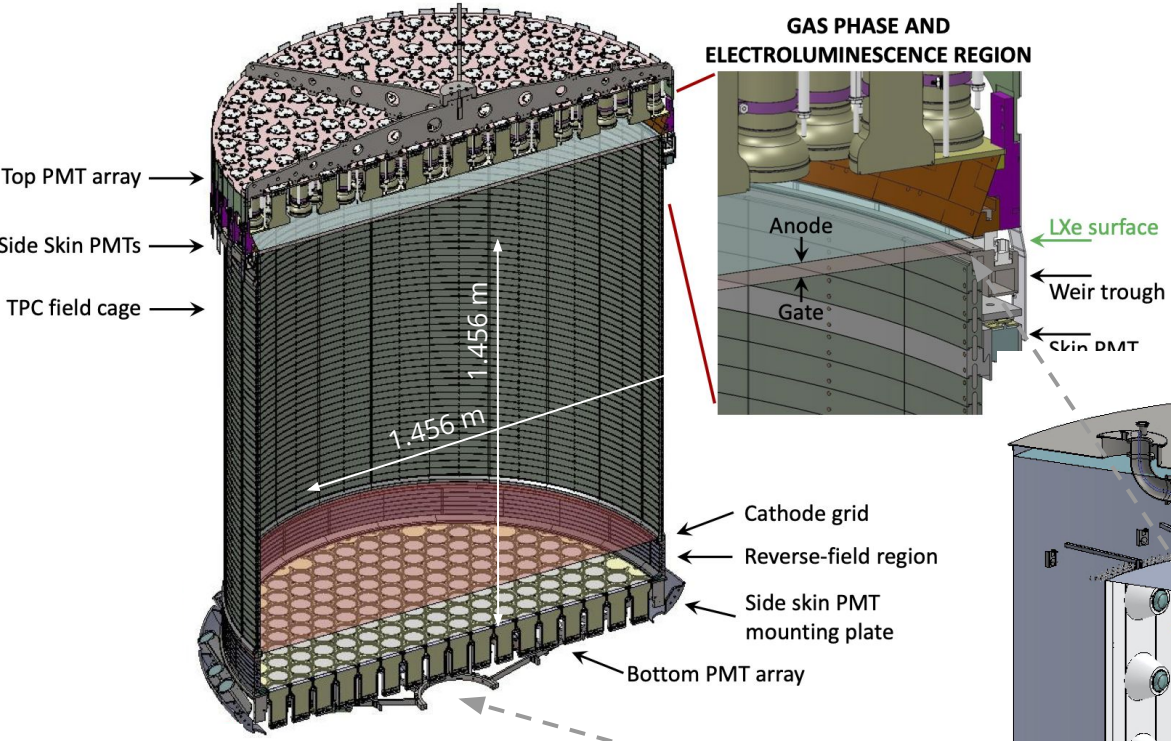
250 scientists, engineers, and technical staff

- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- King's College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- University of California Los Angeles
- University of California Santa Barbara
- University of Liverpool
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- University of Oxford
- University of Rochester
- University of Sheffield
- University of Sydney
- University of Texas at Austin
- University of Wisconsin, Madison

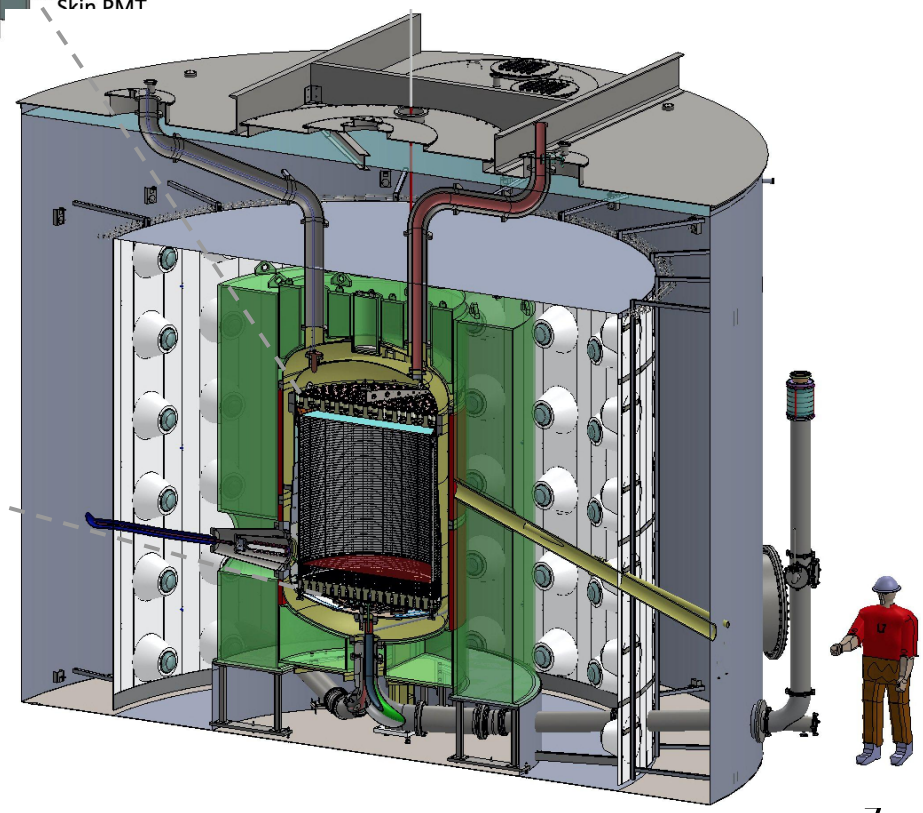
US UK Portugal Korea Australia

Thanks to our sponsors and participating institutions!

The LUX-ZEPLIN Detector



Nucl.Instrum.Meth.A 953 (2020) 163047

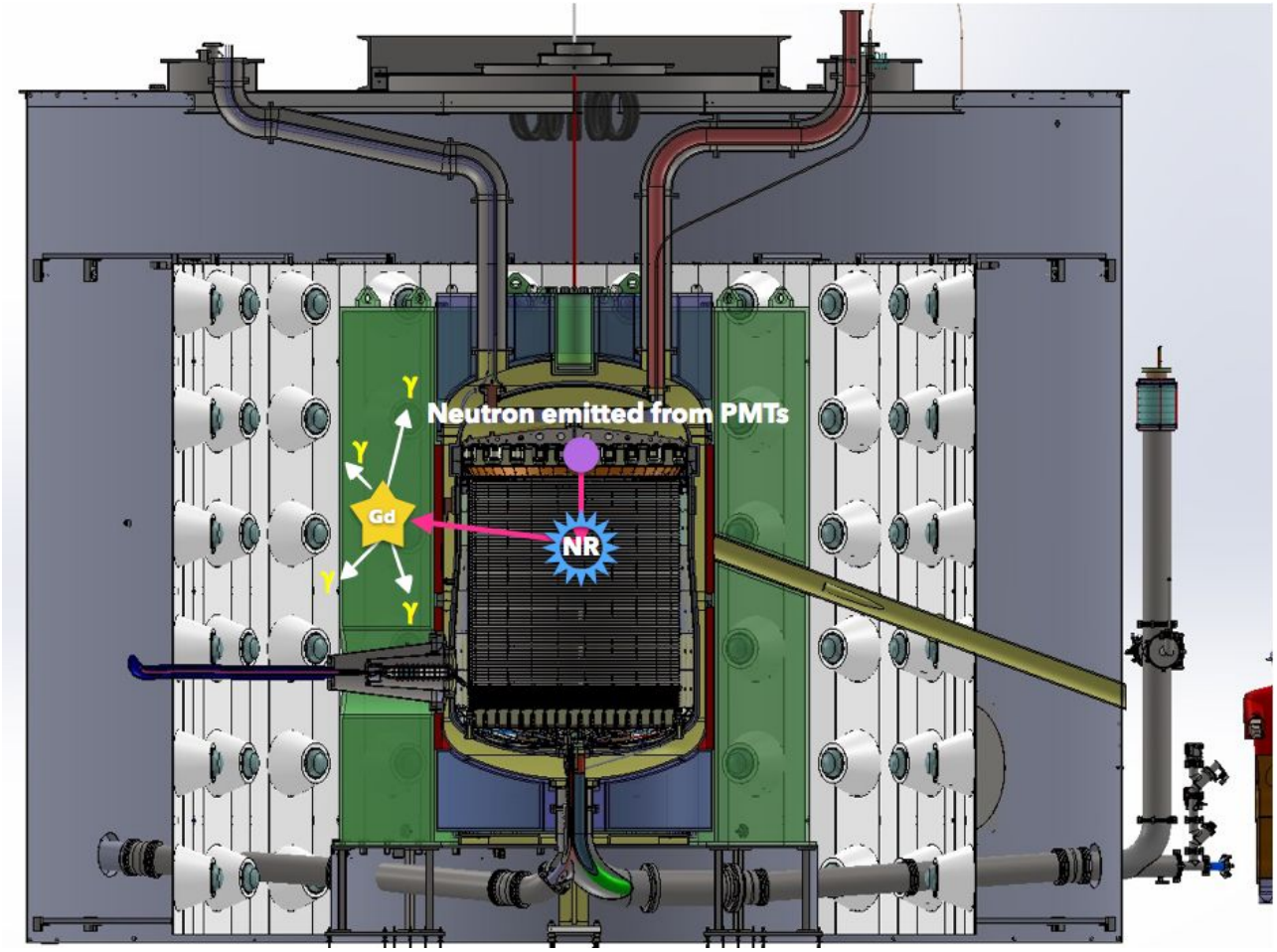


TPC key stats:

- 1.456 m between cathode and gate grid
- **7 tonne active region**
- 494 Hamamatsu R11410-22 3” PMTs
- High reflectivity PTFE for light collection

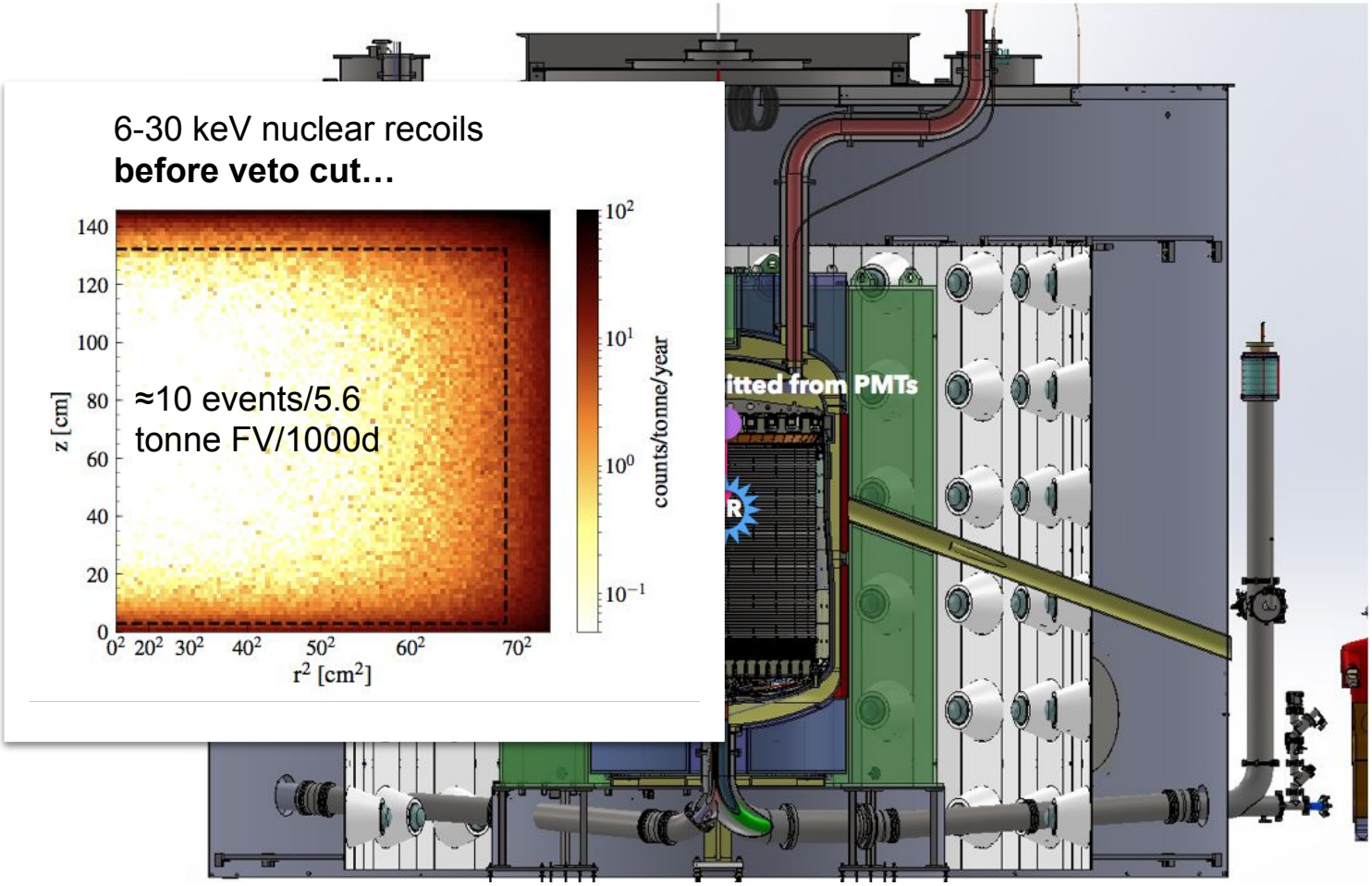
Multi-detector active veto system

Optically separated Xe **Skin** detector + Outer Detector (**OD**) with 17 tonnes of Gd-doped LS → <u>BG suppression and in-situ characterisation</u>



Multi-detector active veto system

Optically separated Xe **Skin** detector + Outer Detector (**OD**) with 17 tonnes of Gd-doped LS → <u>BG suppression and in-situ characterisation</u>



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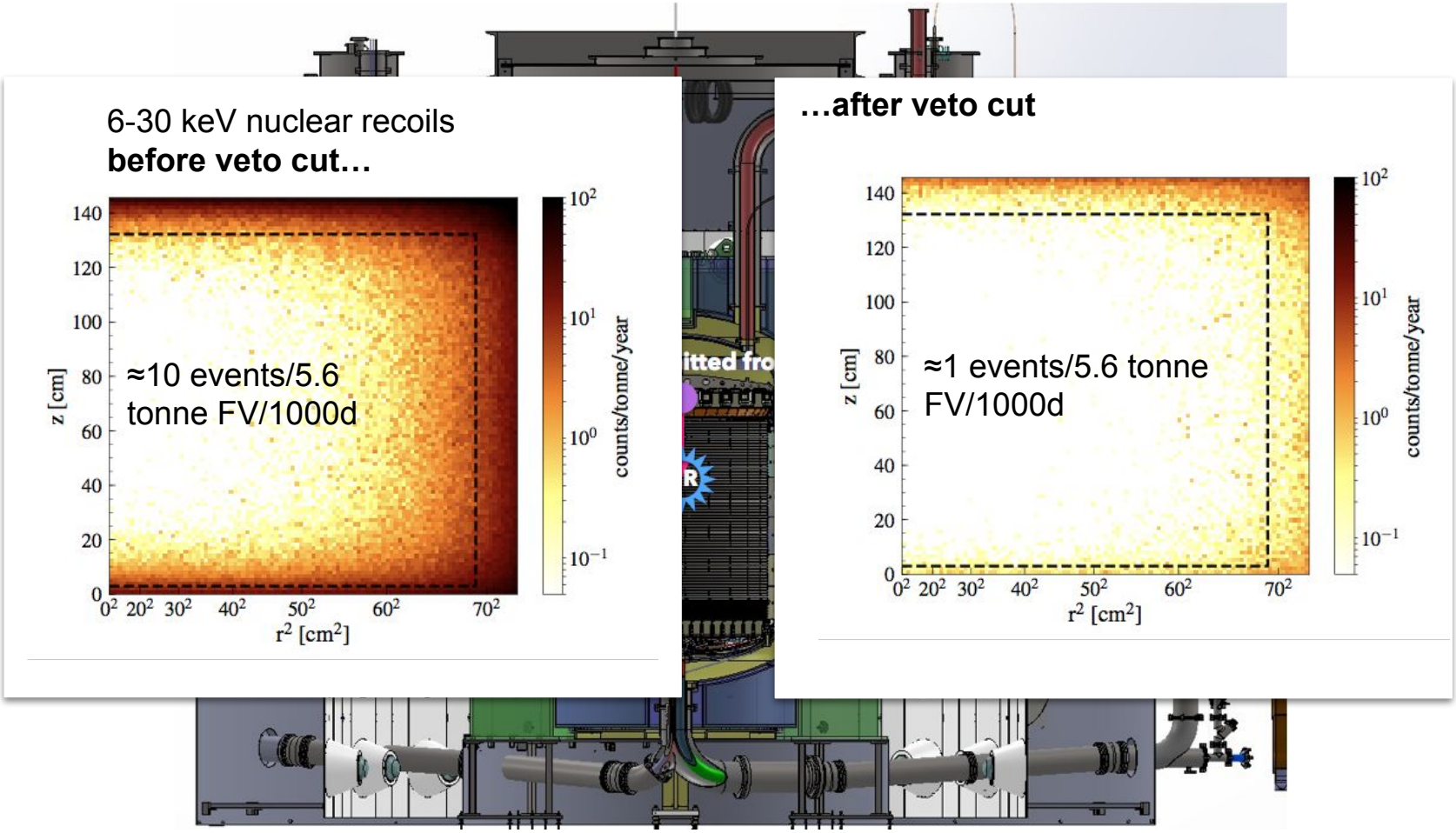
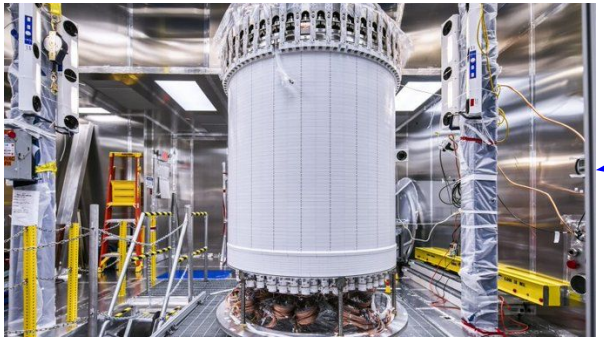
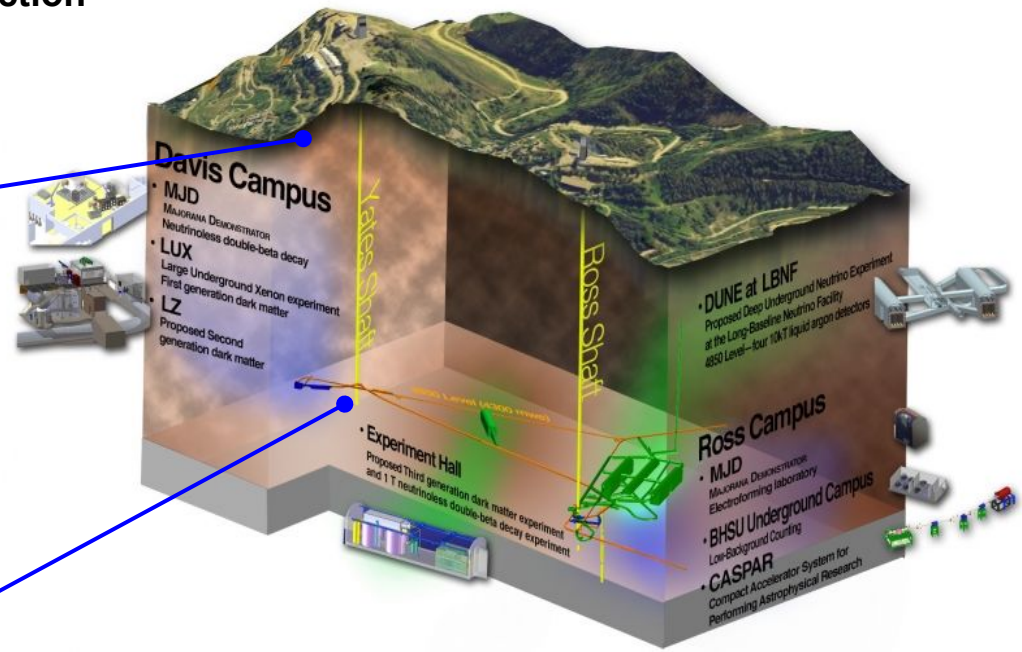


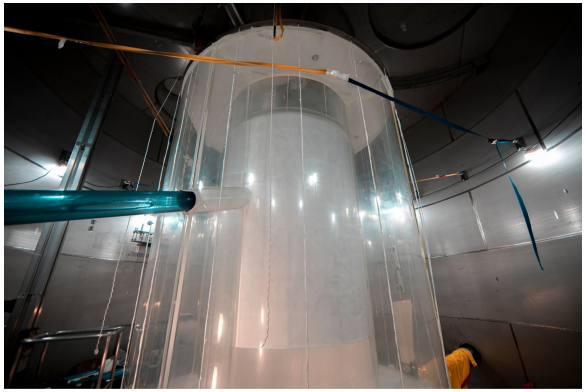
Backgrounds, backgrounds, backgrounds

1) **Ultra-radio pure materials and construction**





2) Take 1 mile underground



3) Run until background limited

Radiopurity is key:

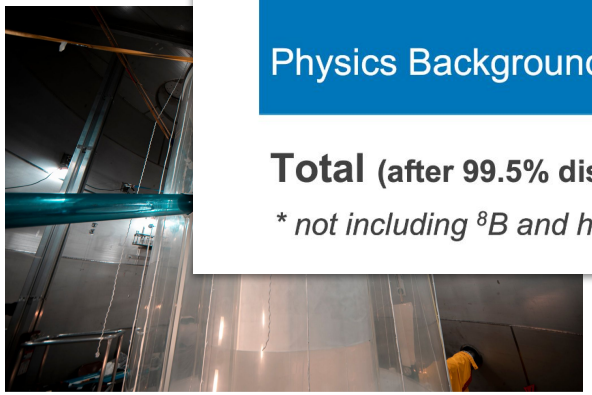
- ➔ Xe purification with chromatography
- ➔ Extensive radioassay campaign > 1000 assays
- ➔ Strict cleanliness controls

See Eur.Phys.J.C 80 (2020) 11

Backgrounds, backgrounds, backgrounds

1) Ultra-radio pure materials and construction

2) Take 1 m
undergrou



3) Run until background limited

Projected backgrounds: 5.6 ton fiducial, 1000 live-days

~1.5 - 6.5 keV, single scatters, no coincident veto

Background Source	ERs	NRs
Detector Components	9	0.07
Dispersed Radionuclides — Rn, Kr, Ar	819	—
Laboratory and Cosmogenics	5	0.06
Surface Contamination and Dust	40	0.39
Physics Backgrounds — 2β decay, neutrinos*	322	0.51
Total (after 99.5% discrimination and 50% NR efficiency)	**6.49**	

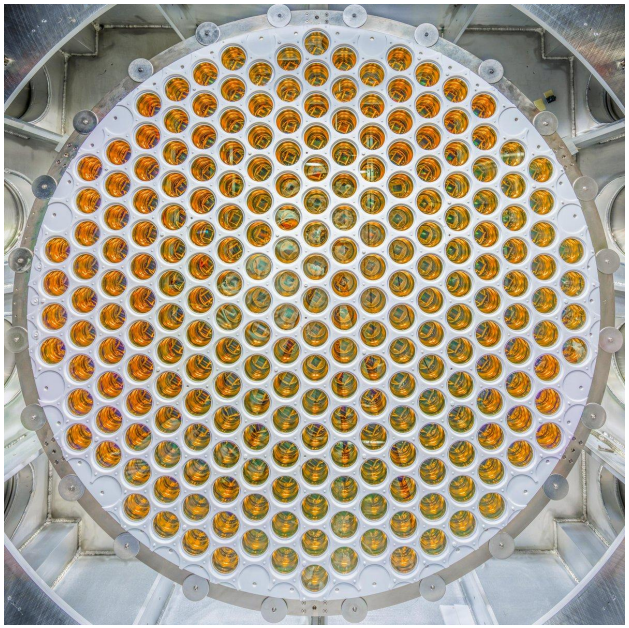
** not including ^{8}B and hep*

y
00 assays

See Eur.Phys.J.C 80 (2020) 11

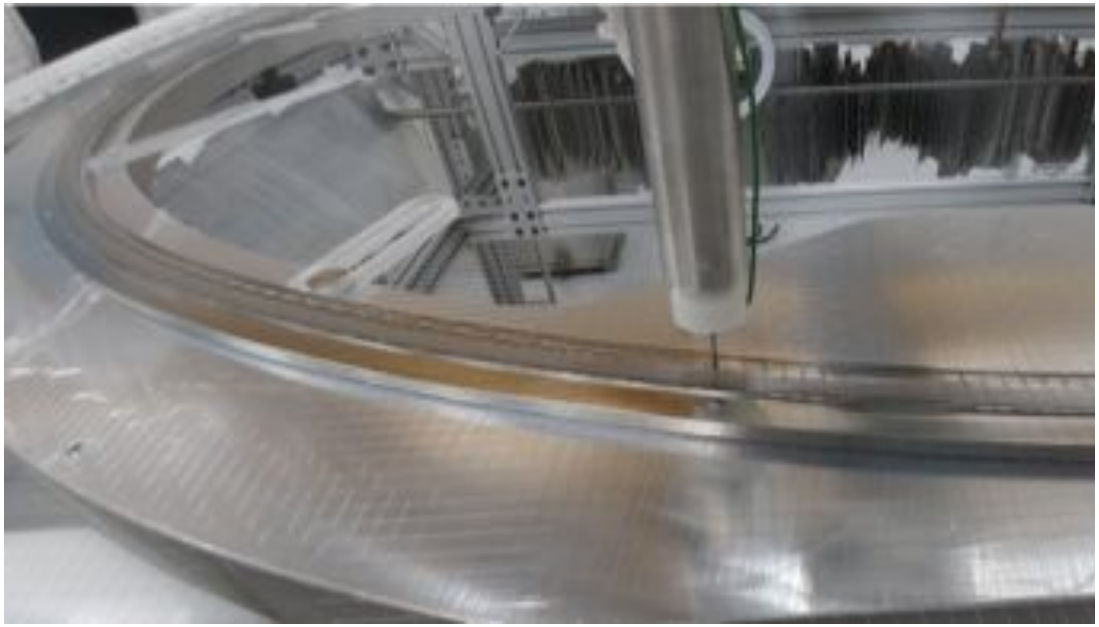
LUX-ZEPLIN Construction - a few highlights

2018



Bottom PMT array after assembly at Brown University

2019



HV grids production at SLAC, see Nucl.Instrum.Meth.A 1031 (2022) 165955

LUX-ZEPLIN Construction - a few highlights

In total, OD tanks will contain w/17 tonnes Gd-LS produced at BNL

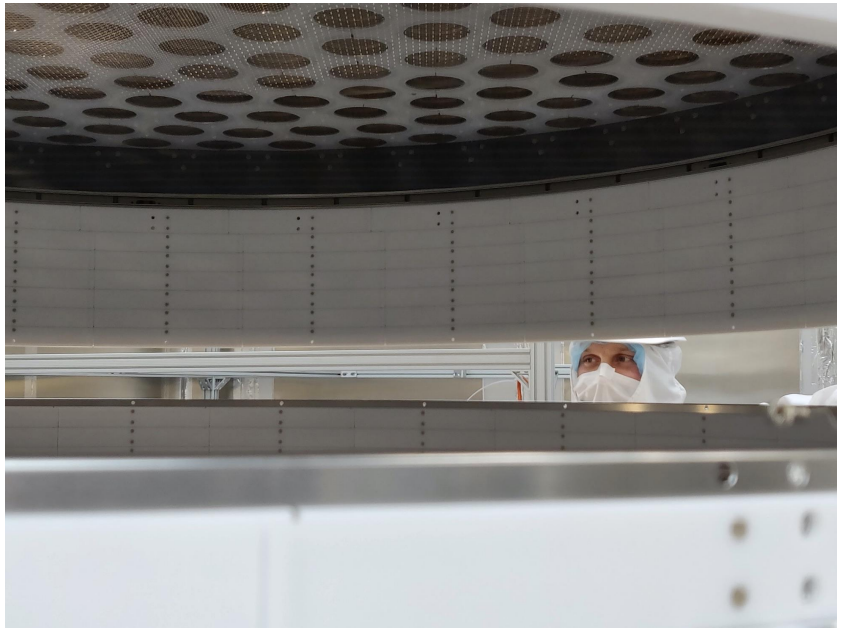
Completed outer detector tank at Reynolds Polymer Technology - USCB

Gas chromatography:
→ natKr reduced to 0.1 ppt g/g

Offsite Kr removal of 10 tonnes of LXe at SLAC

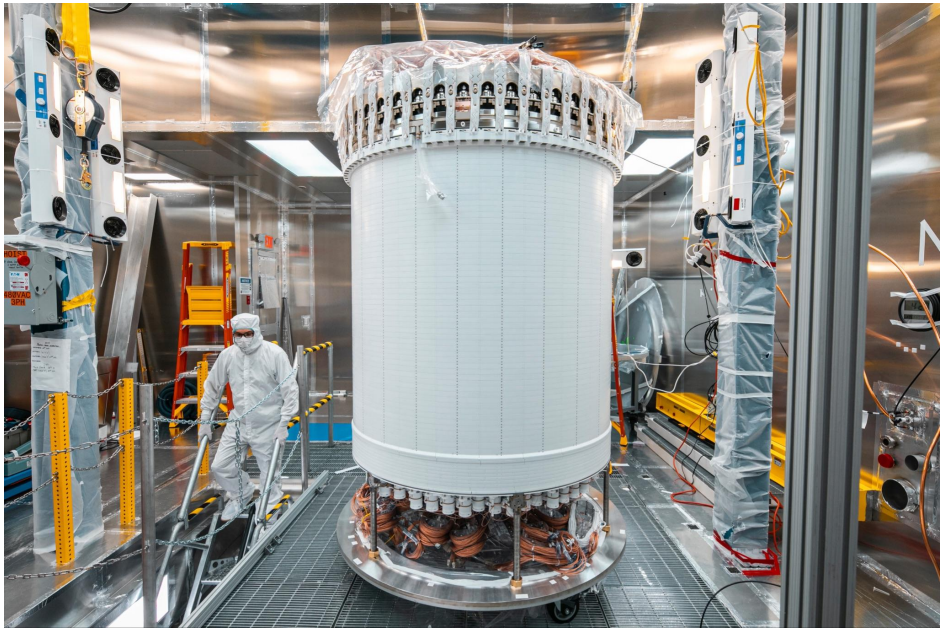
TPC Assembly at SURF surface laboratory

2019



Mating of the extraction region to central TPC

2019



Fully assembled TPC at SURF surface lab

Dust and Rn exposure control critical → assembly in Rn-reduced surface lab cleanroom

Moving to the Davis Campus

2021

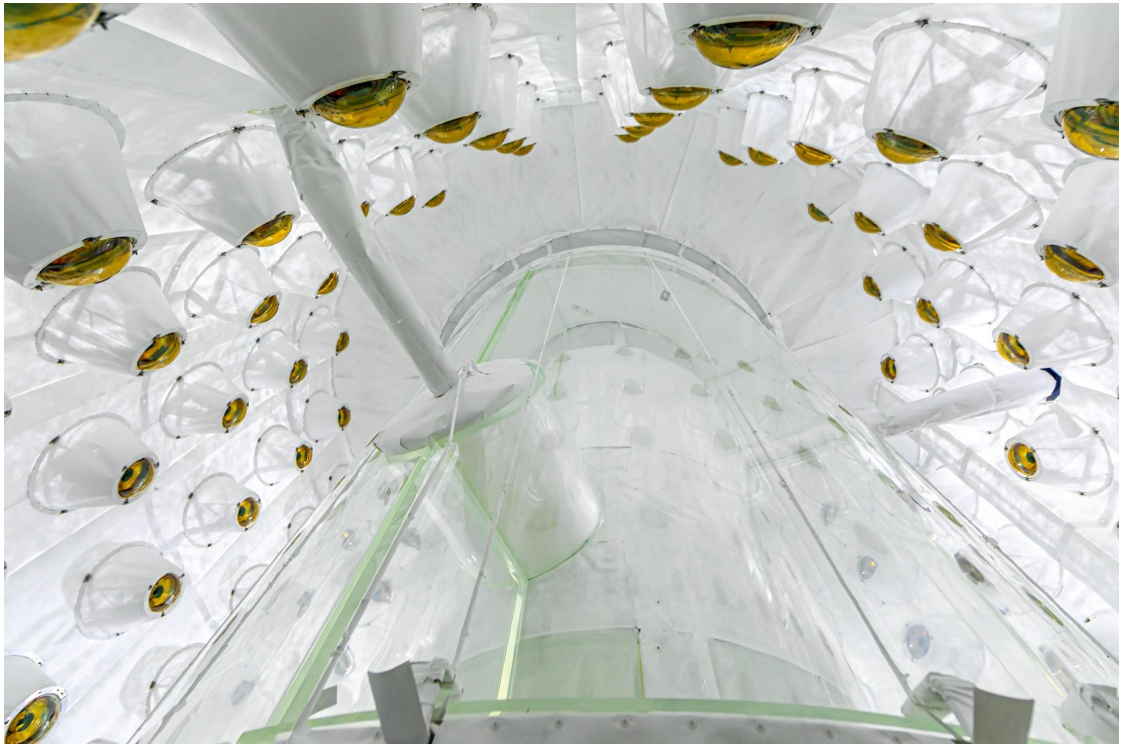
TPC inside inner cryostat vessel (ICV) being transported underground

2021

ICV being lowered into the outer vessel inside the water tank

Fully assembled 1 mile UG in Davis Campus

2021

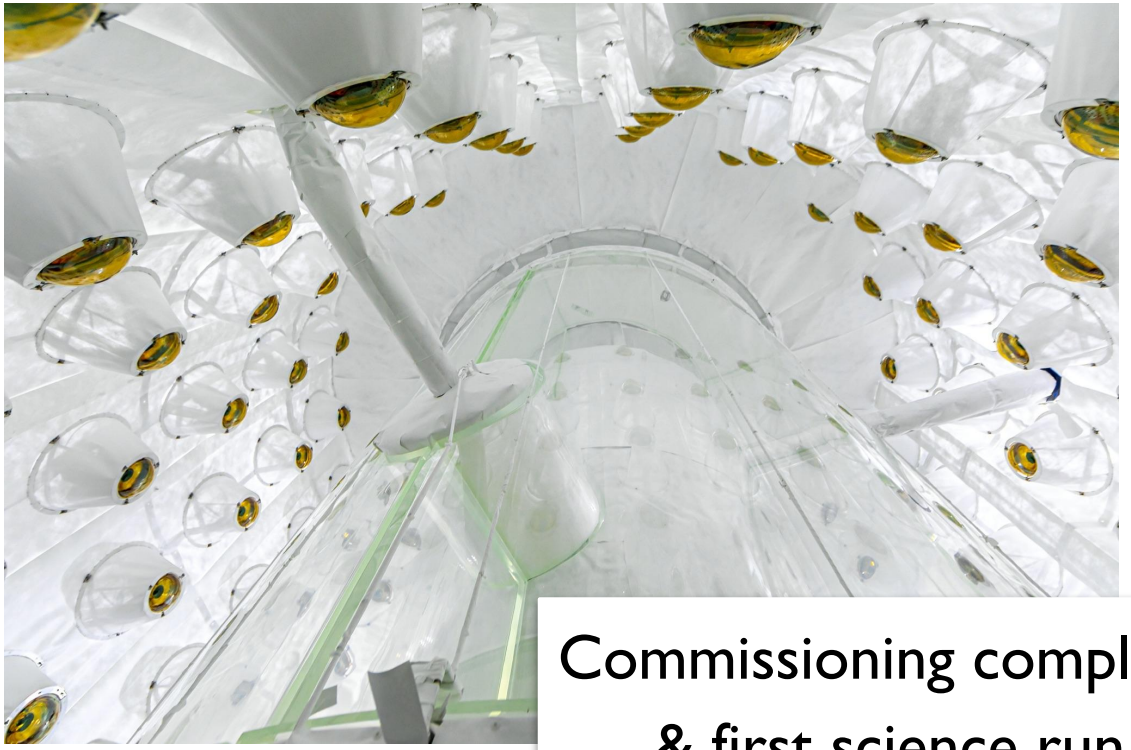


Fully assembled detector

- OD ready for GdLS + water fill (at same time)

Fully assembled 1 mile UG in Davis Campus

2021

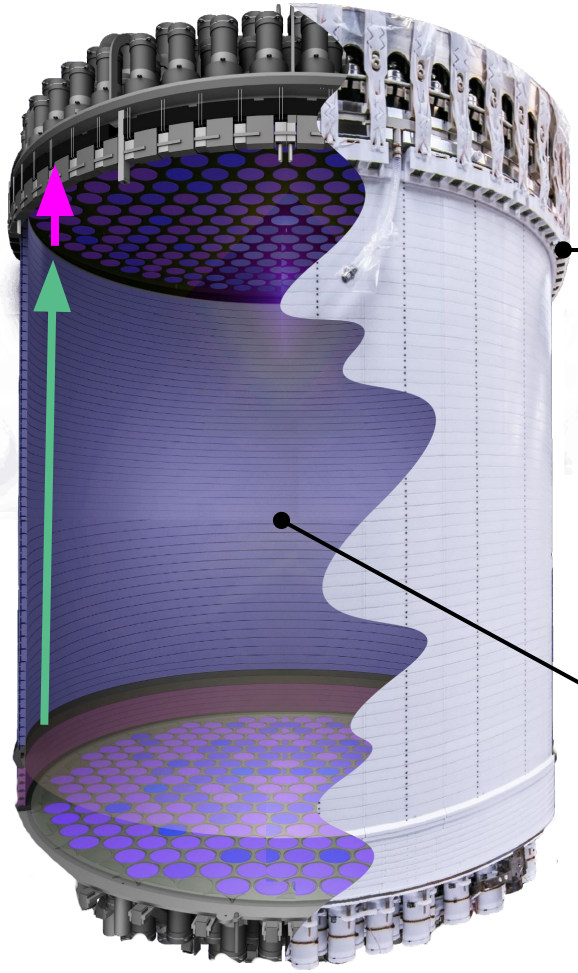


Fully assembled detector

- OD ready for GdLS + water fill (at same time)

Commissioning complete late 2021 -
& first science run started December

Detector state and stability



Gas extraction field of 7.3 kV/cm

(~60 phd/extracted electron)

193 V/cm between cathode-gate

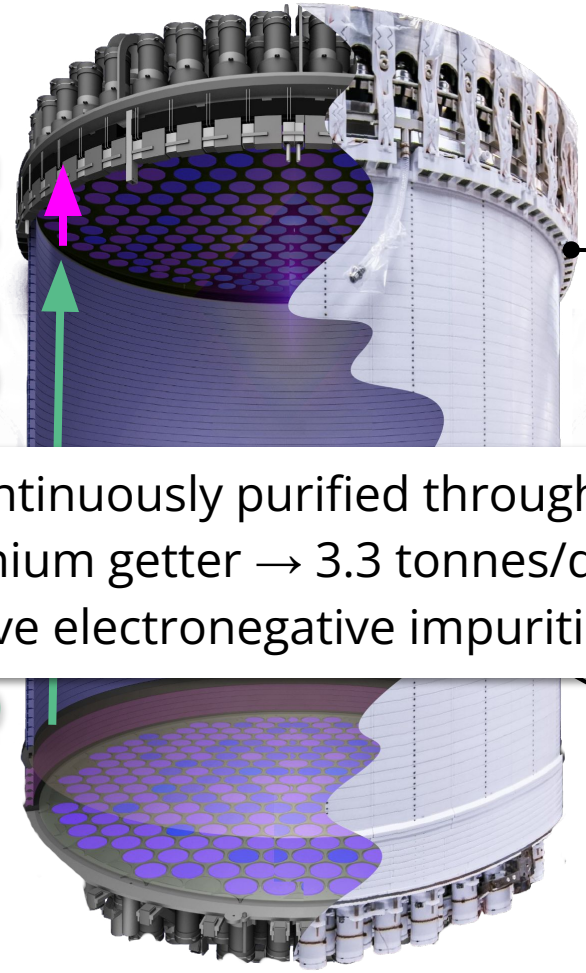
(951 μs drift time)

Liquid-level stable within 10 μm

LXe: 174.1 K and 1.791 bar(a) [stable within 0.2%]

Composite overlay courtesy of Nicolas Angelides, Imperial

Detector state and stability



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(~60 phd/extracted electron)

Liquid-level stable within 10 μm

Xe continuously purified through hot Zirconium getter → 3.3 tonnes/day to remove electronegative impurities

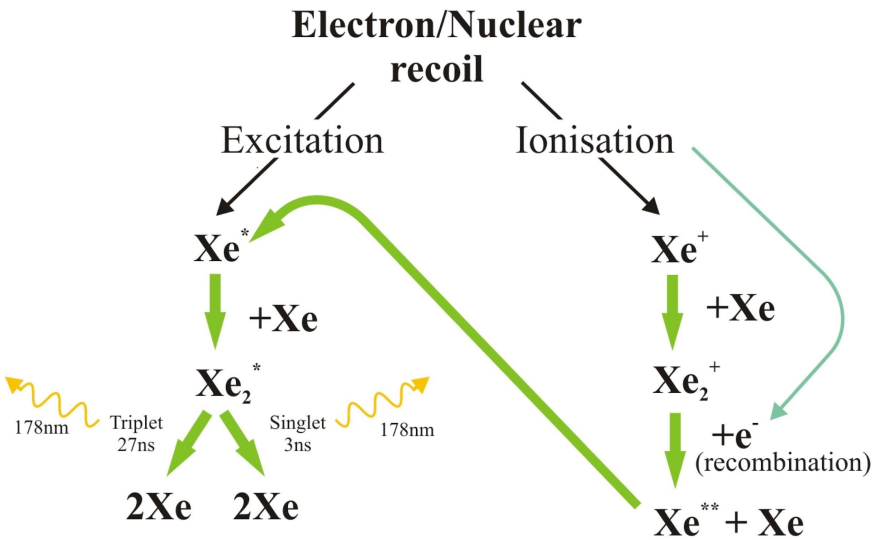
193 V/cm b
catho

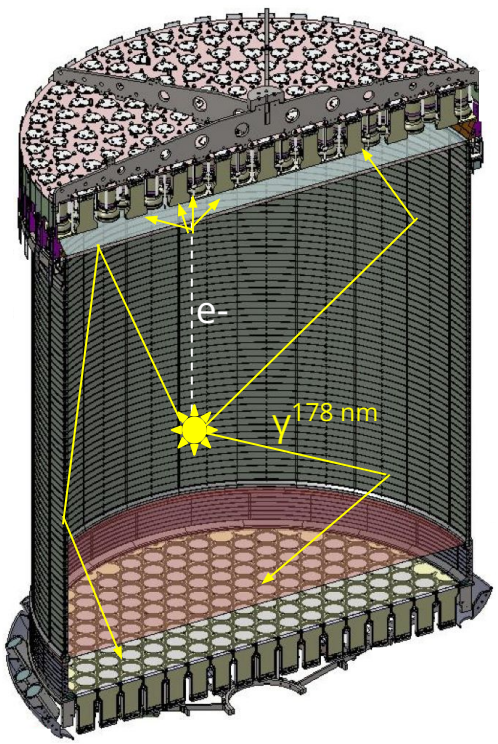
(951 μs drift time)

LXe: 174.1 K and 1.791 bar(a) [stable within 0.2%]

Composite overlay courtesy of Nicolas Angelides, Imperial

Light and Charge collection





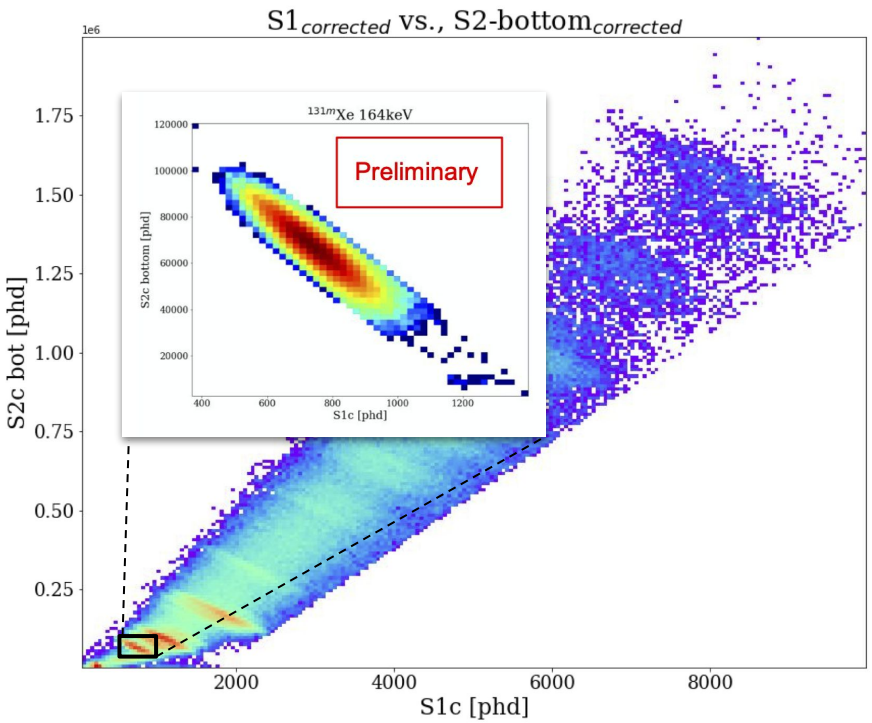
Xe microphysics → light and charge signals are anti-correlated:

$$E = W \cdot \left(\frac{S1_c}{g1} + \frac{S2_c}{g2}\right)$$

Where:
g1 = photon detection efficiency
g2 = electron gain phd/e-
W = work function = 13.5 eV/quanta

Detector response - monoenergetic sources

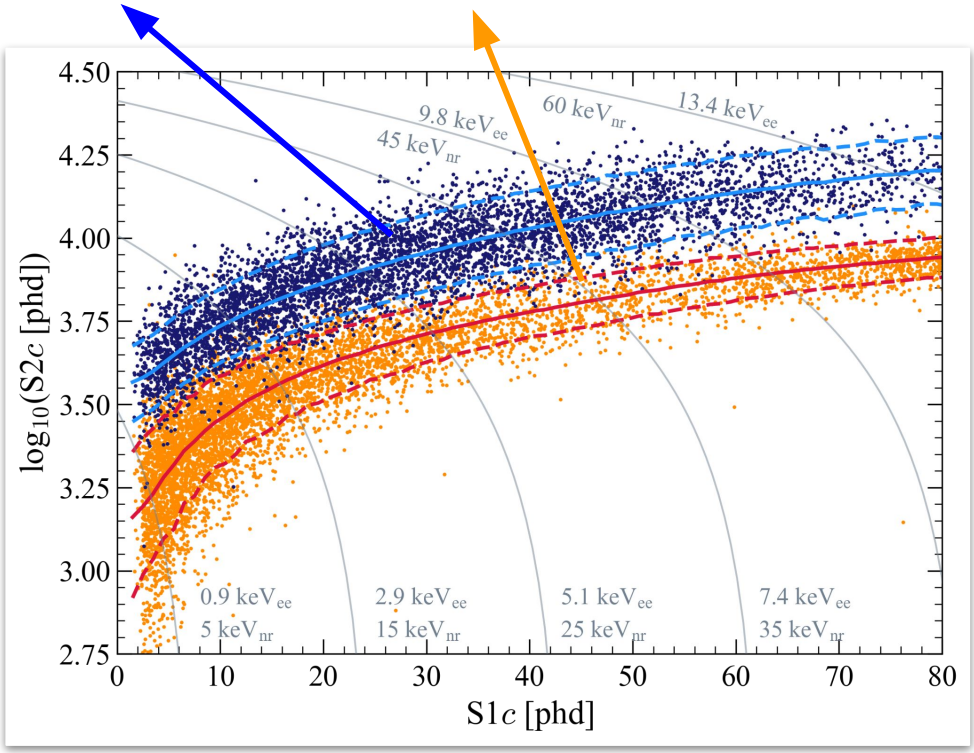
- Noble Element Scintillation Technique (NEST) 2.3.7
- Tuned to reconstruct ER mono-energetic sources:
  - ^{83m}Kr (41.5 keV)
  - ^{129m}Xe (236 keV)
  - ^{131m}Xe (164 keV)
- Detector (g1, g2) and Xe response parameters varied



Detector response - ER/NR bands

5343 tritium tagged methane (CH3T). β with Q value 18.6 keV

6324 DD neutron gun events - 2.45 MeV neutrons

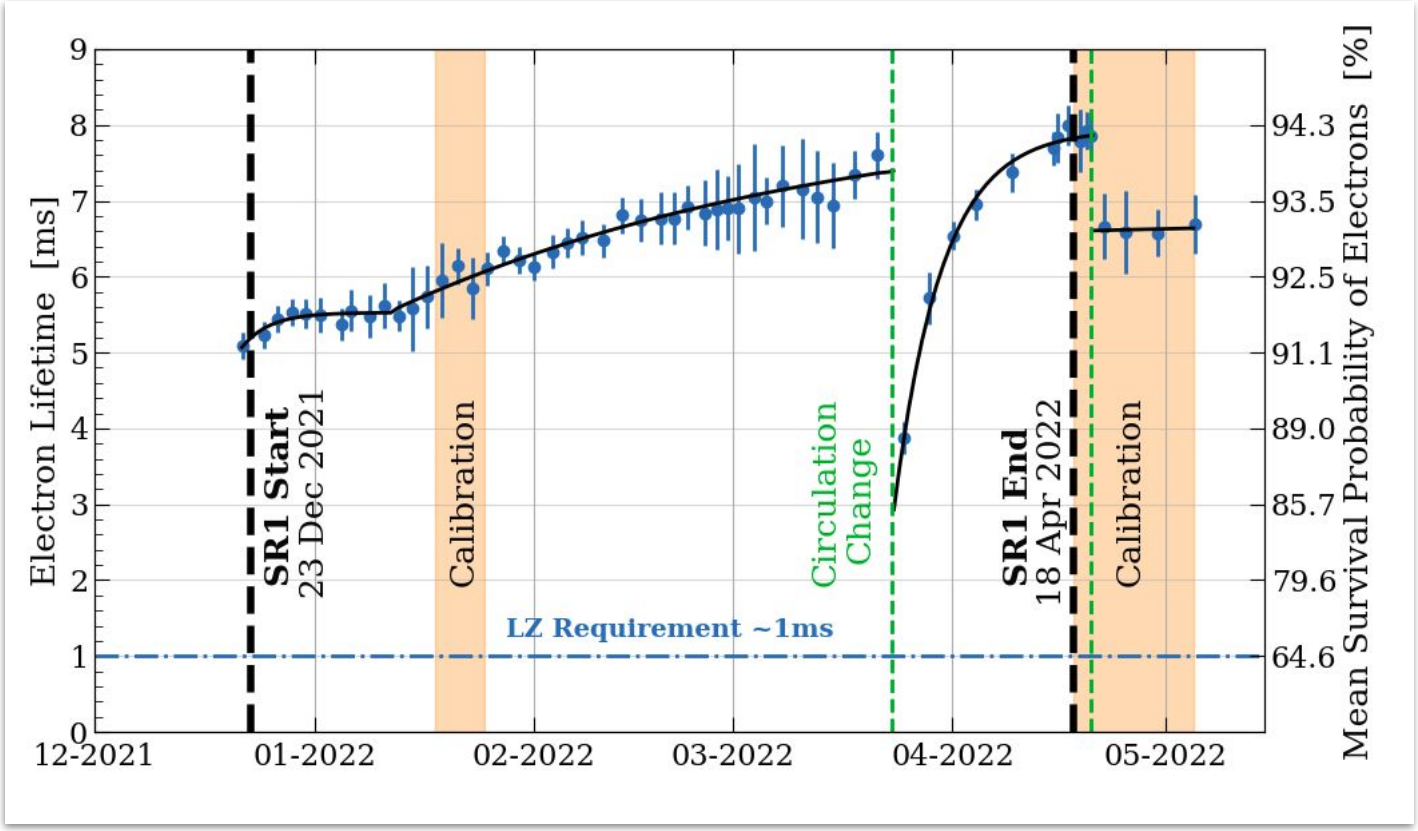


- NEST simultaneously tuned to reproduce ER band mean and widths
- Tuned parameters propagated into NR model
- Consistent at 1% with neutron calibration data (DD and AmLi)

Fitted det. parameters: g_1 = 11.4% and g_2 = 47.1 phd/liquid electron

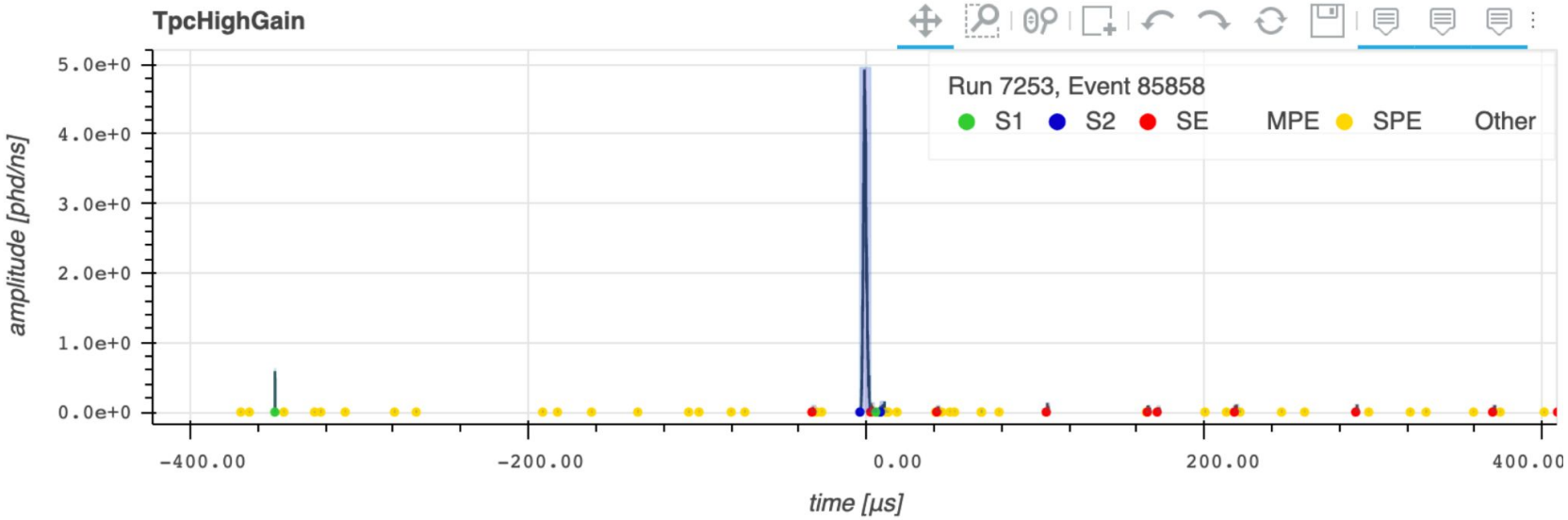
Science Run 1 (SR1)

23rd December 2021 to 11th May 2022



Remove DAQ deadtime (3%), anomalous trigger rates (7%)
→ 89 live-days left

Time hold-off following large S2s



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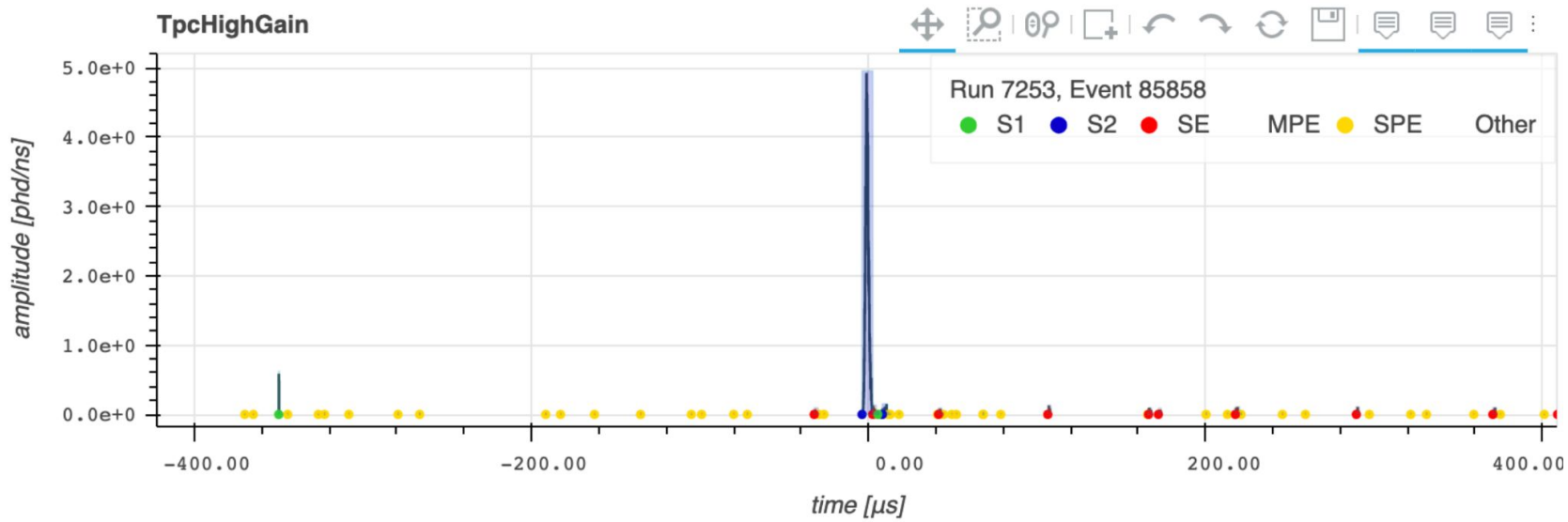

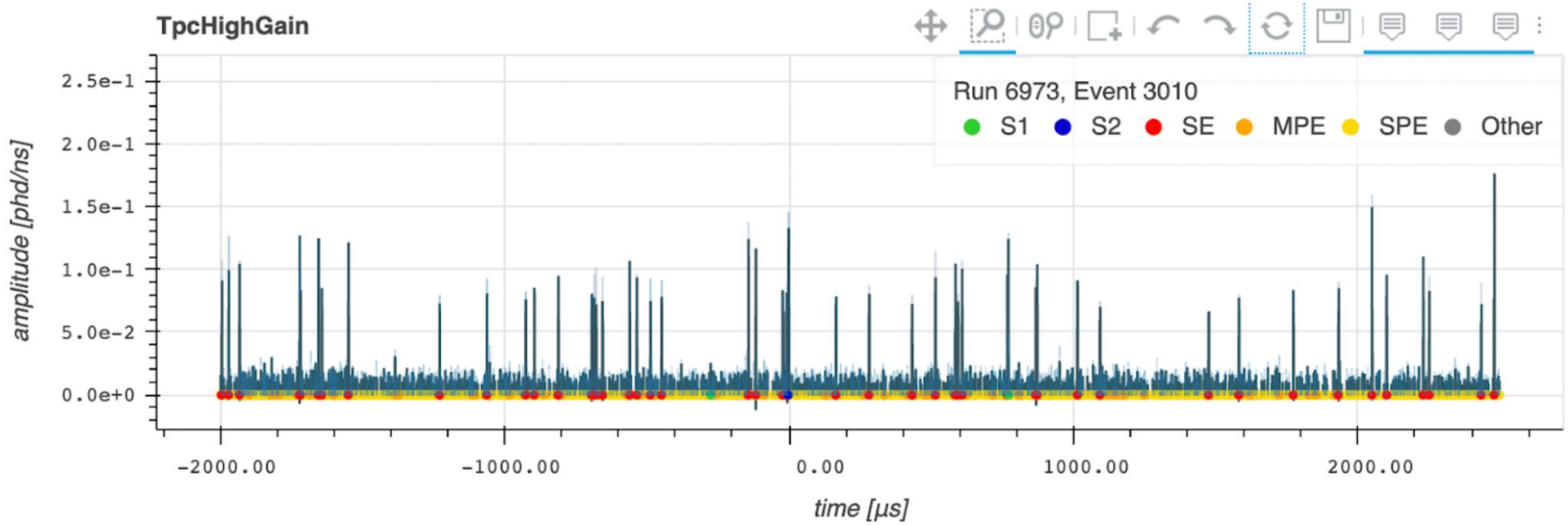

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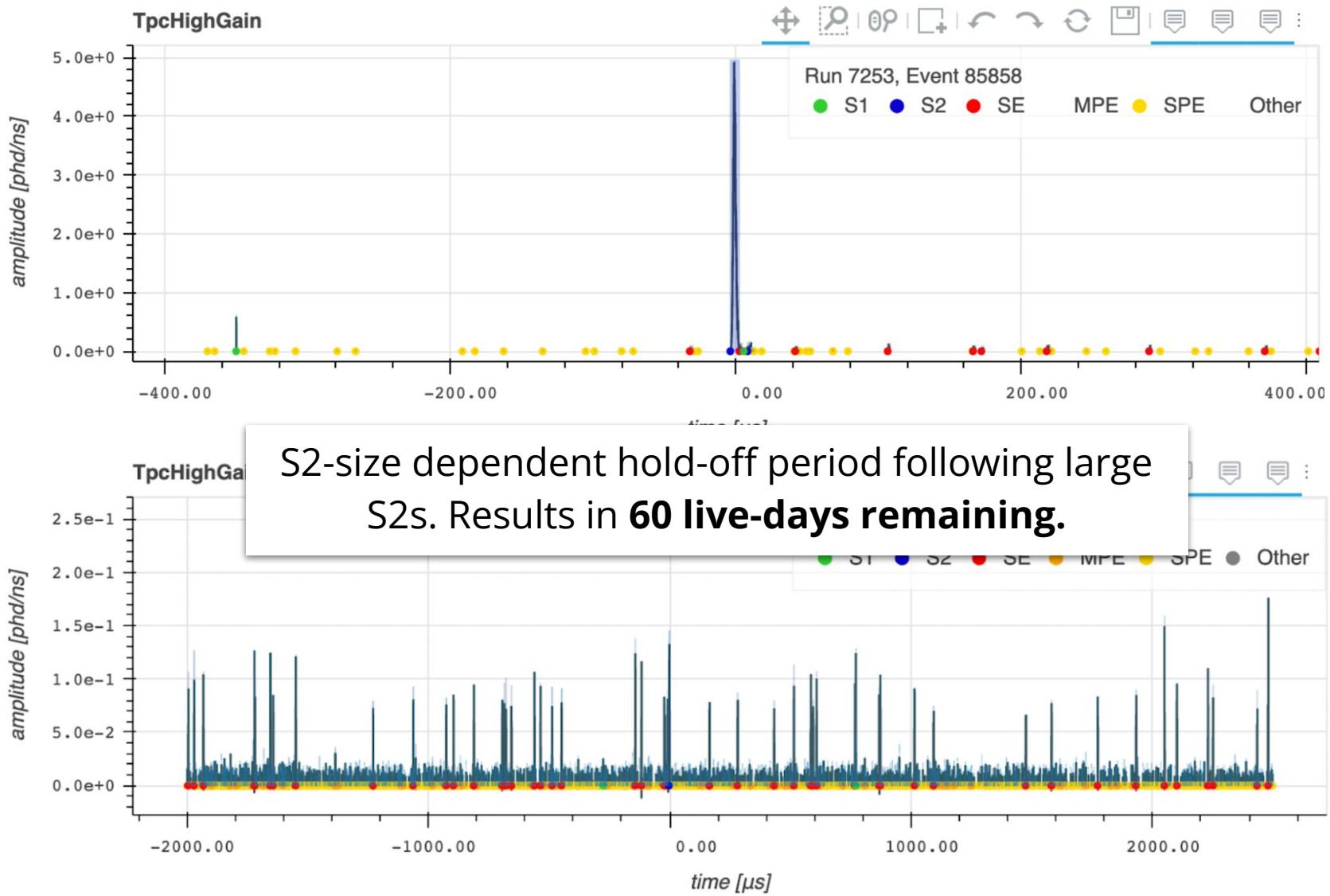
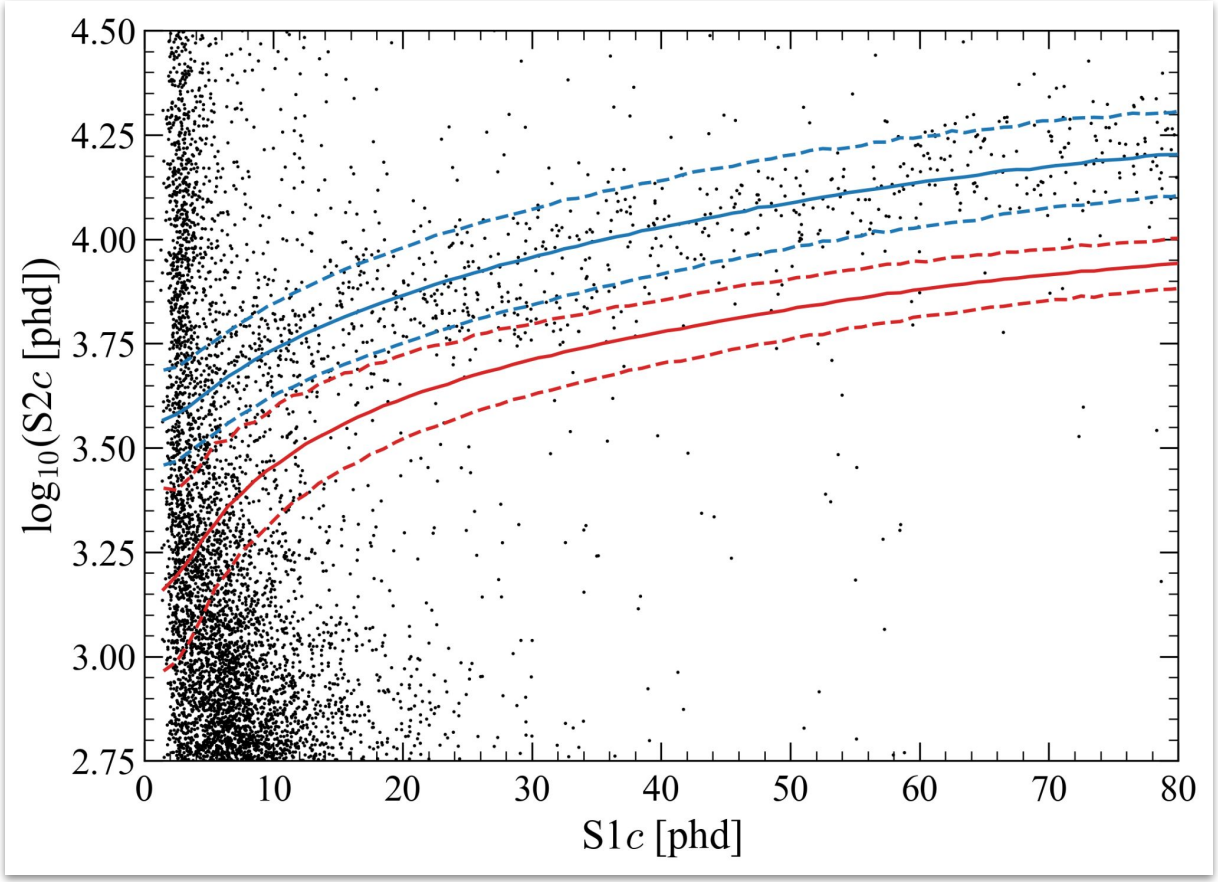


S2-size dependent hold-off period following large S2s. Results in **60 live-days remaining.**

SR1 WIMP-search data before analysis cuts

60 live-days and 5.5 tonne fiducial volume cut



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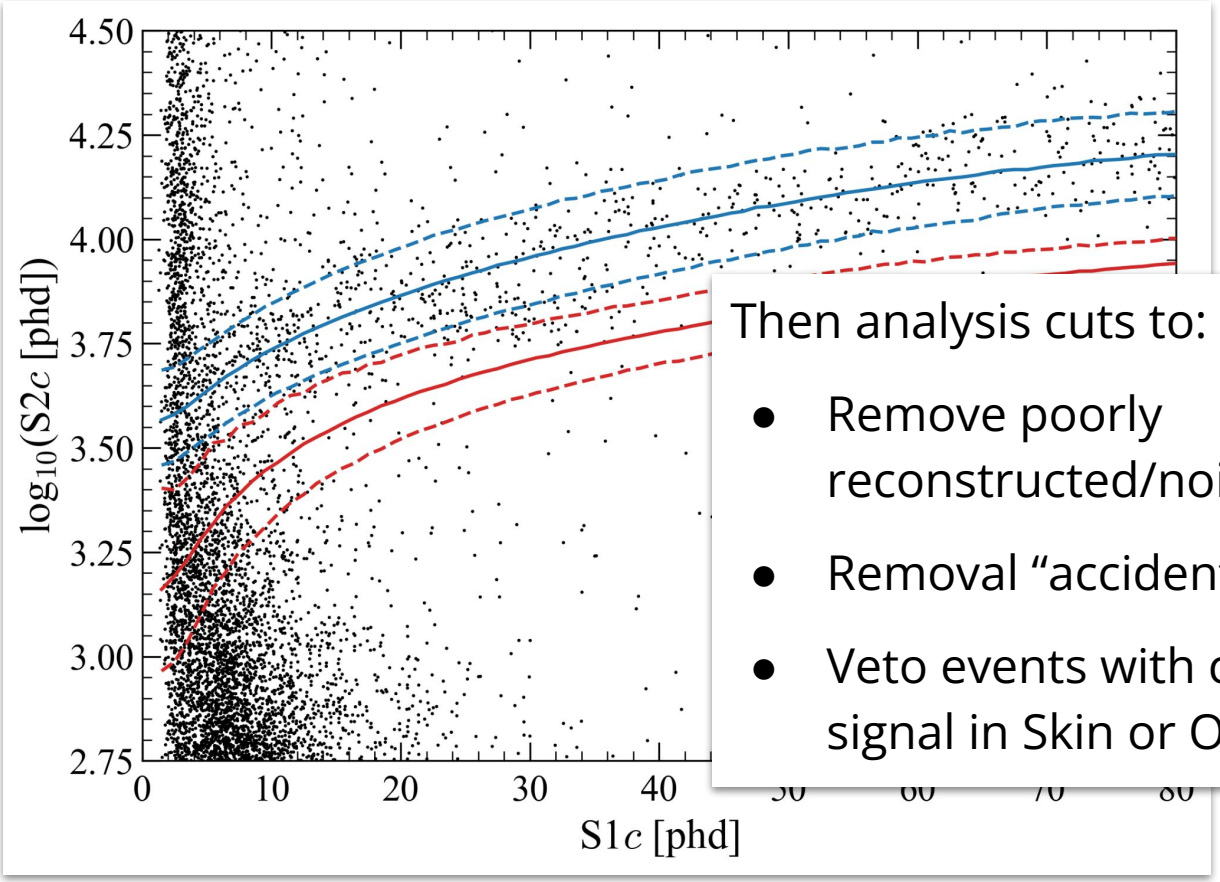
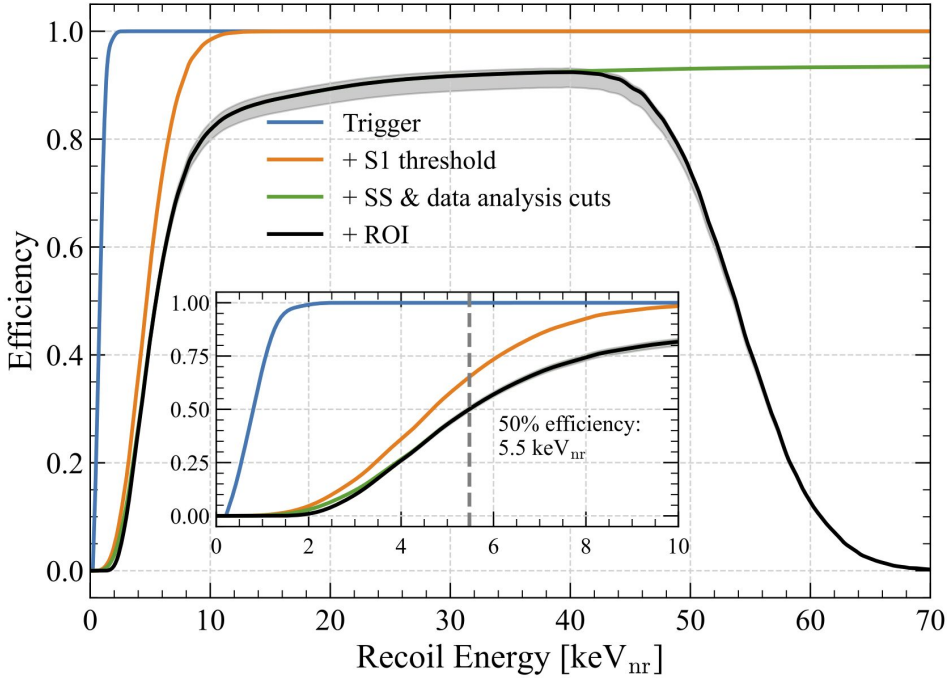


Then analysis cuts to:

- Remove poorly reconstructed/noisy events
- Removal “accidentals”
- Veto events with coincident signal in Skin or OD

Nuclear Recoil Efficiency - all cuts



- DD neutron data to evaluate trigge and reconstruction efficiency
- CH3T for S1-cuts
- AmLi(S2) + CH3T(S1) for S2-cuts
- **50% signal efficiency at 5.5 keV**

WIMP-search events surviving all cuts

60 live-days and 5.5 tonne fiducial volume cut

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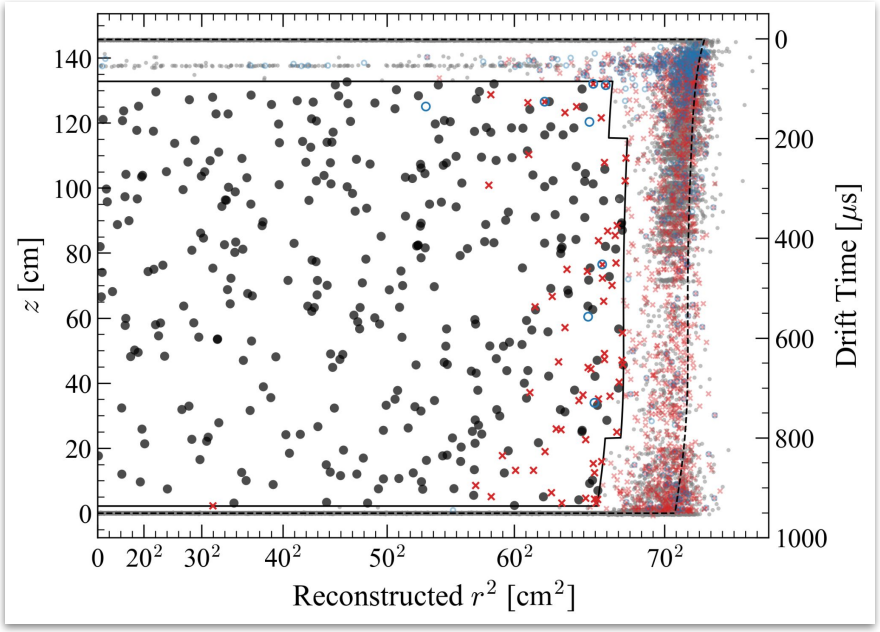

● = inside FV; ● = outside F

✕ = vetoed by skin; ○ = vetoed by OD

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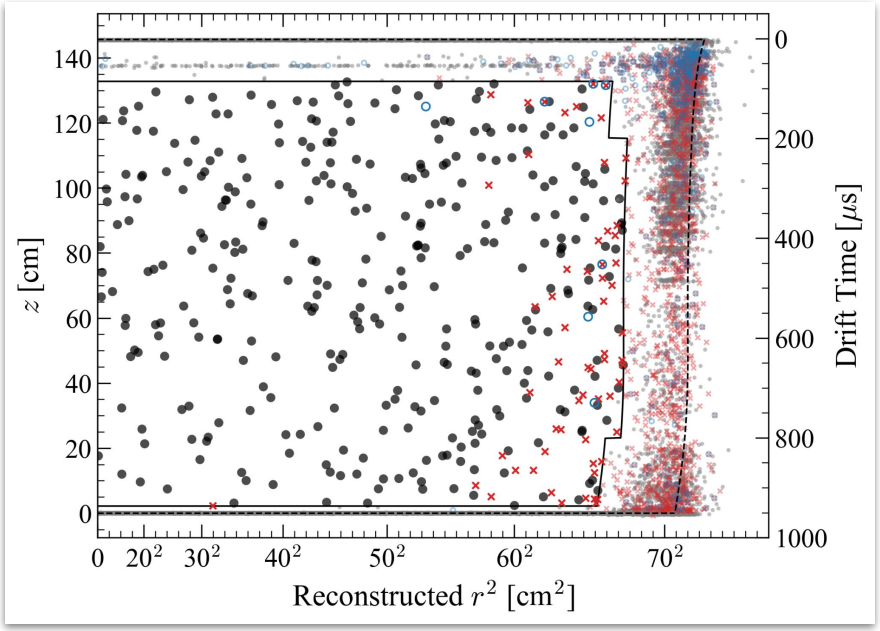
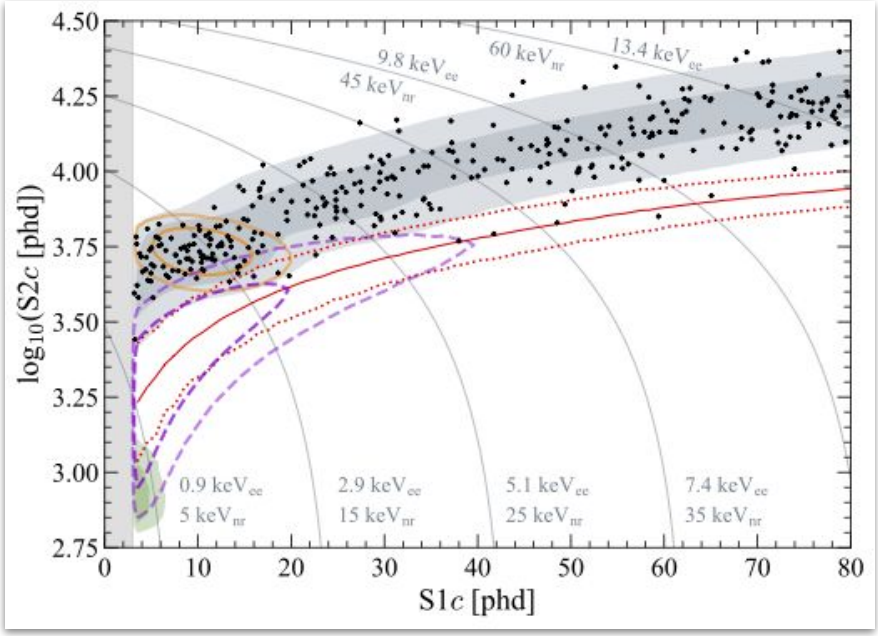
60 live-days and 5.5 tonne fiducial volume cut





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Backgrounds: pre-and post-fit

- Profile likelihood fit (in S1 vs S2 observable space)
- Pre-constraints on BGs (high-energy sideband, mass spec, OD tagged)

Source	Expected Events	Fit Result
β decays + Det. ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
^{8}B CEνNS	0.14 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	273 ± 36	280 ± 16
^{37}Ar	[0, 288]	$52.5^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17

"Background Determination for the LUX-ZEPLIN (LZ) Dark Matter Experiment" (11/2022), arxiv/2211.17120

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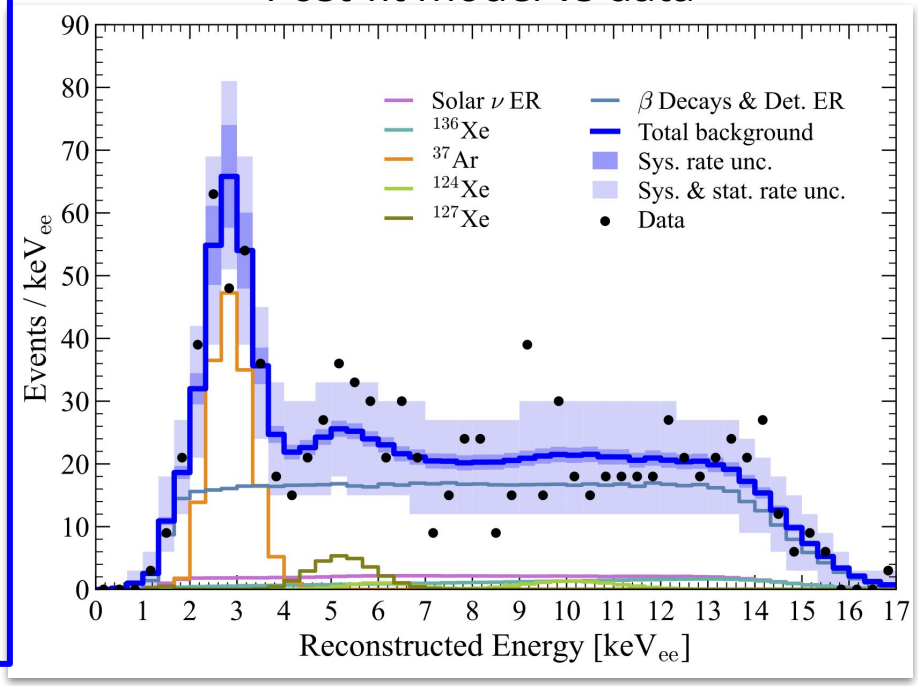
Post-fit model vs data



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Spin-independent WIMP-nucleon

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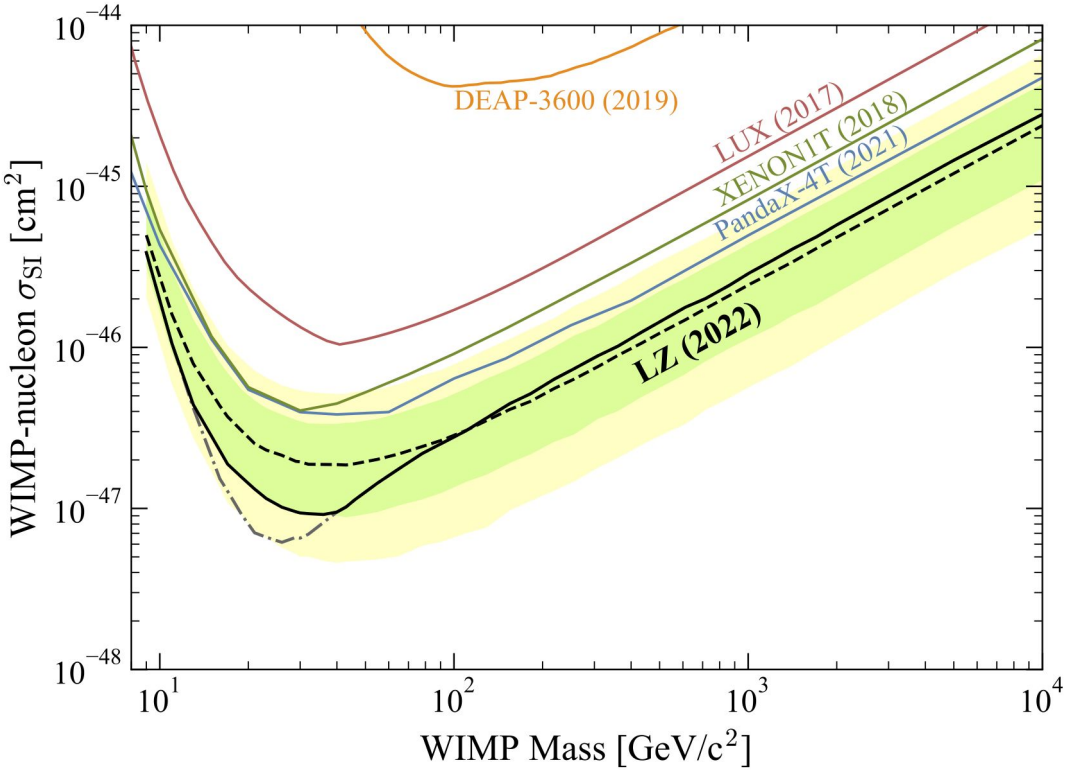

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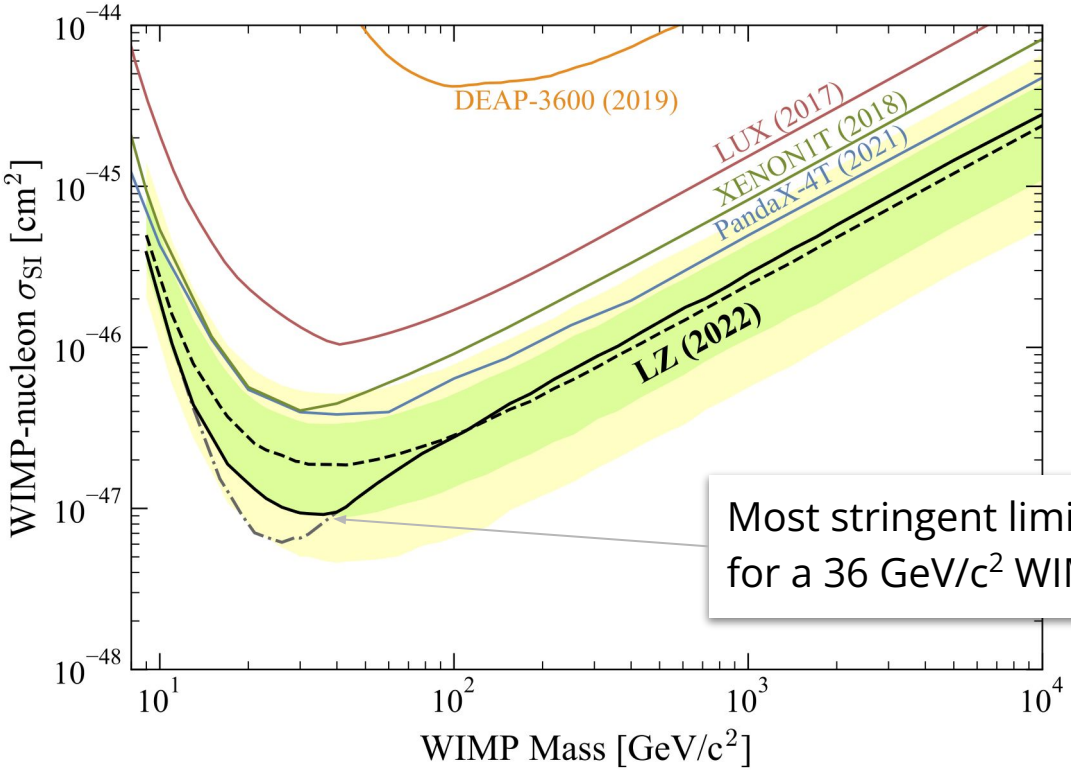

Most stringent limit of 9.2 x 10^{-48} cm^2 for a 36 GeV/c^2 WIMP

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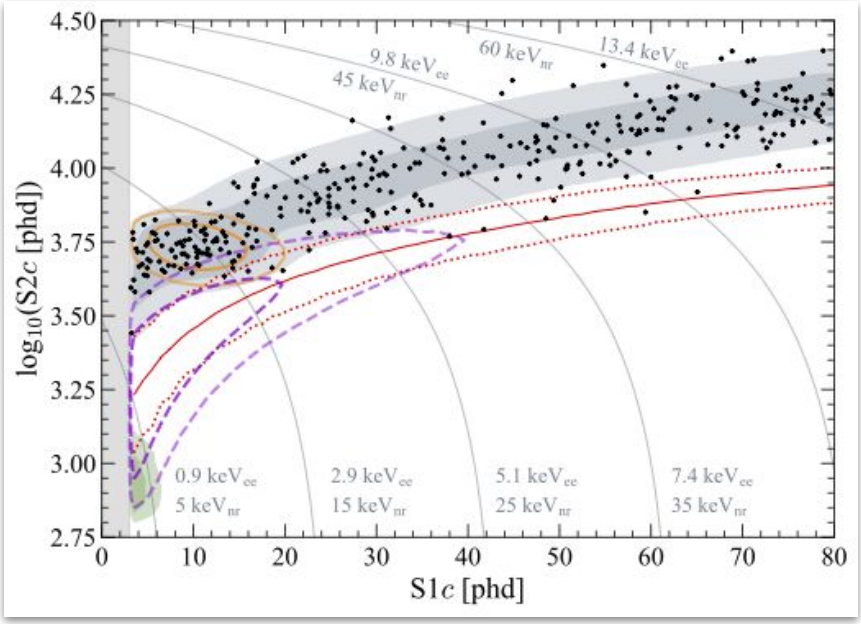
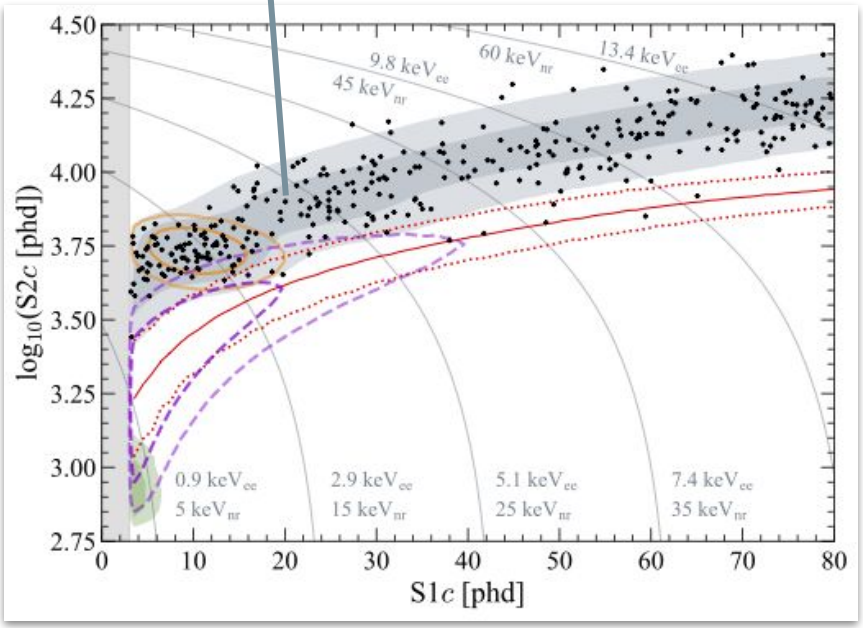
Not just WIMPs



Not just WIMPs

ER band searches: mirror dark matter, ALPs, hidden photons
Phys.Rev.D 104, 092009, 2021



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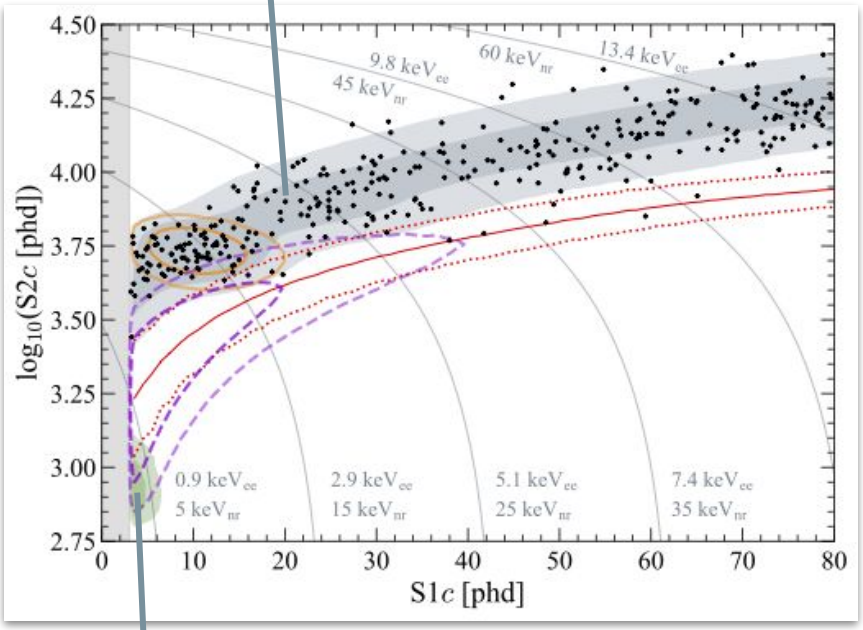

8B CEvNS; SN neutrinos

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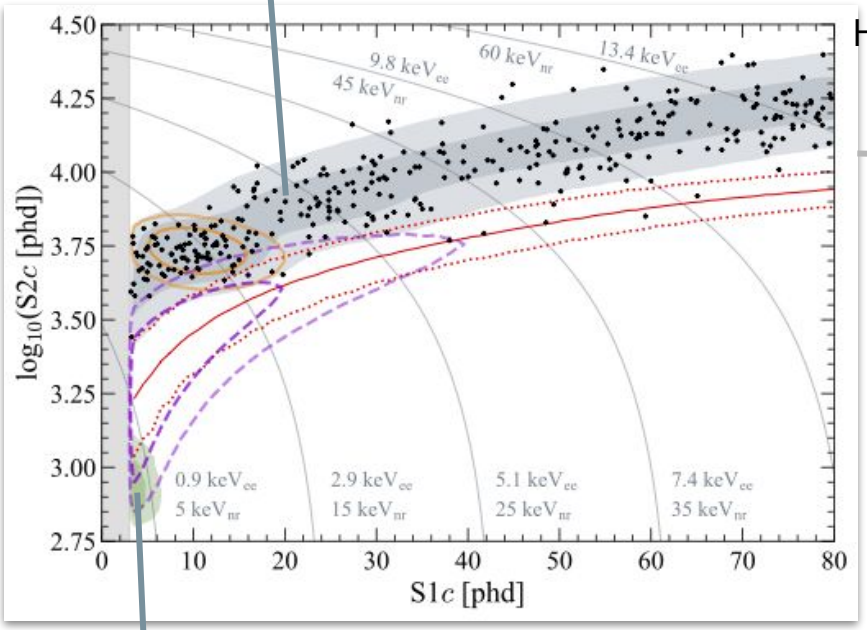

High energy NR/EFT (up to 400 keV)

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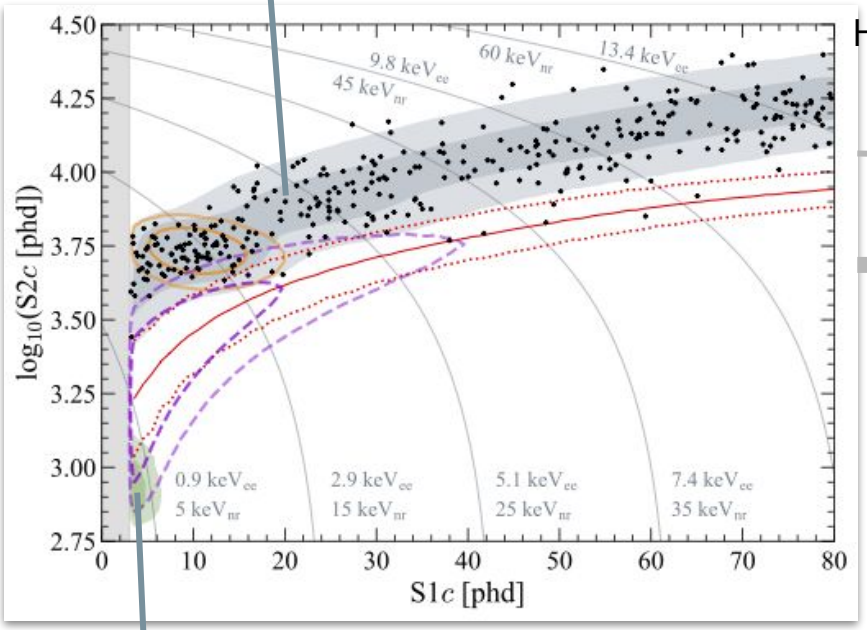

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0νββ (2.45 MeV/0.83 MeV) and 2νDEC (2.86 MeV)

Phys. Rev. C 102, 014602, 2020 and Phys. Rev. C 104, 065501 202

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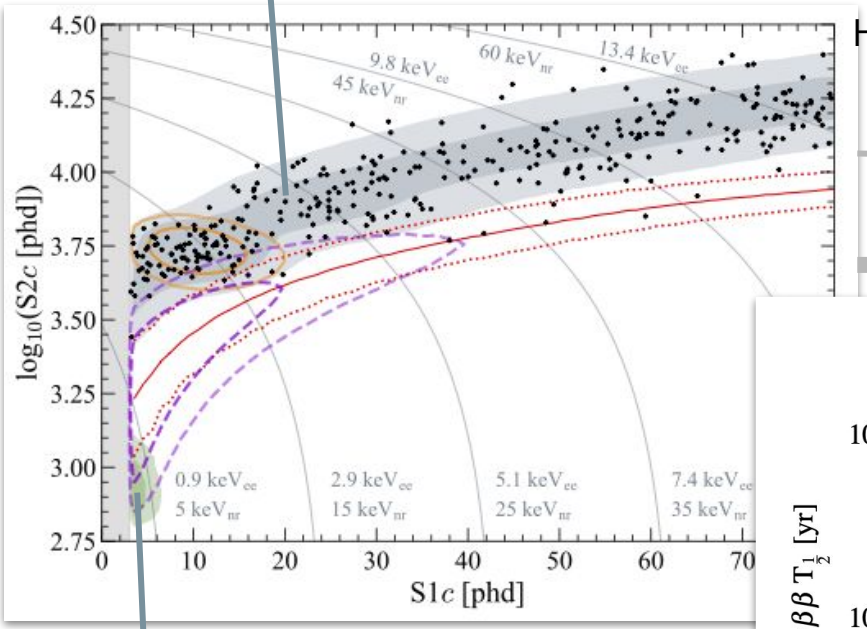

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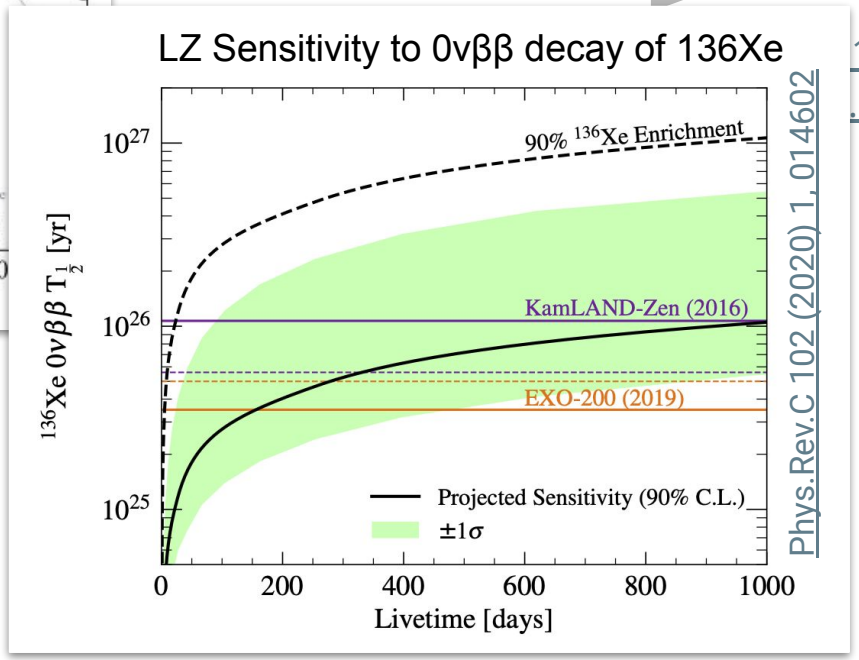

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Phys.Rev.C 102 (2020) 1, 014602

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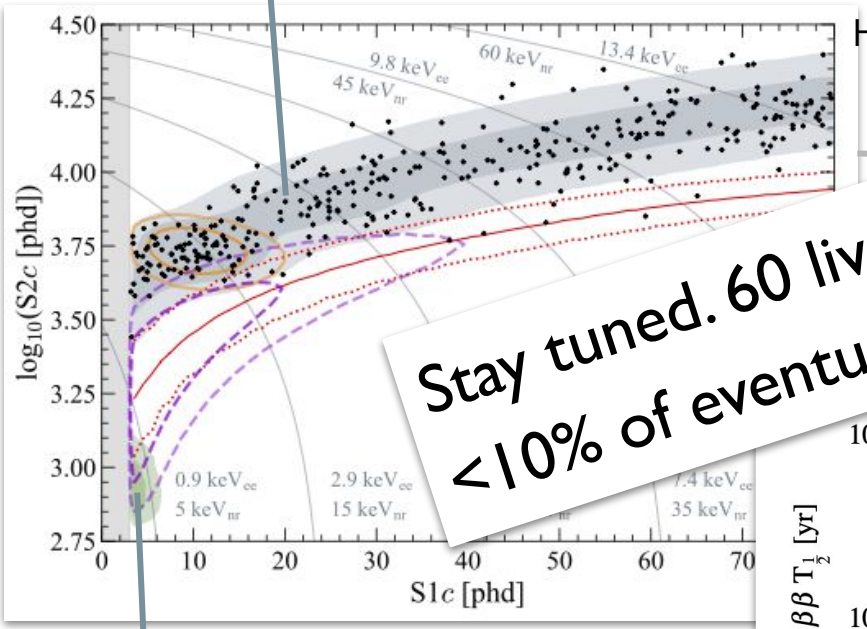

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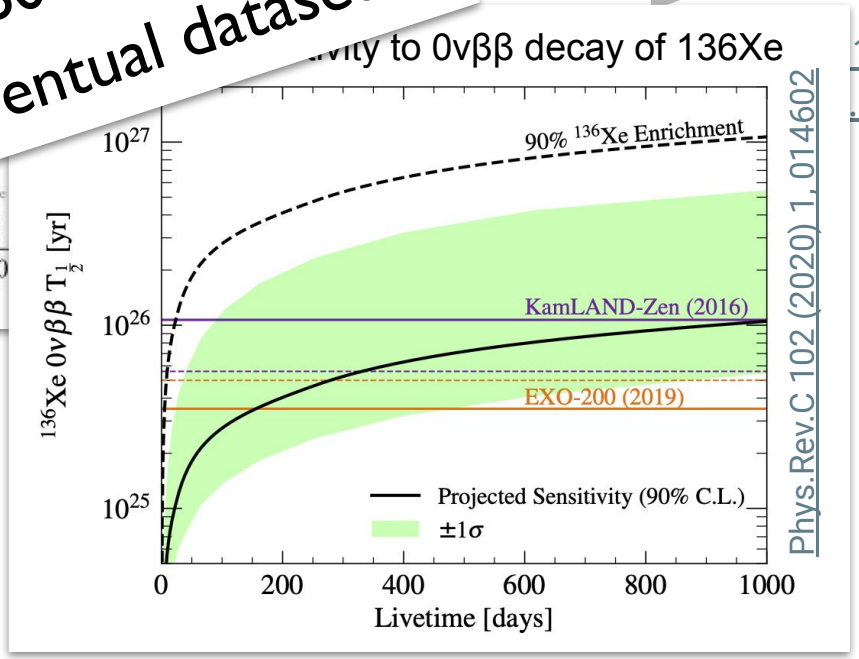
Stay tuned. 60 live-days is <10% of eventual dataset.



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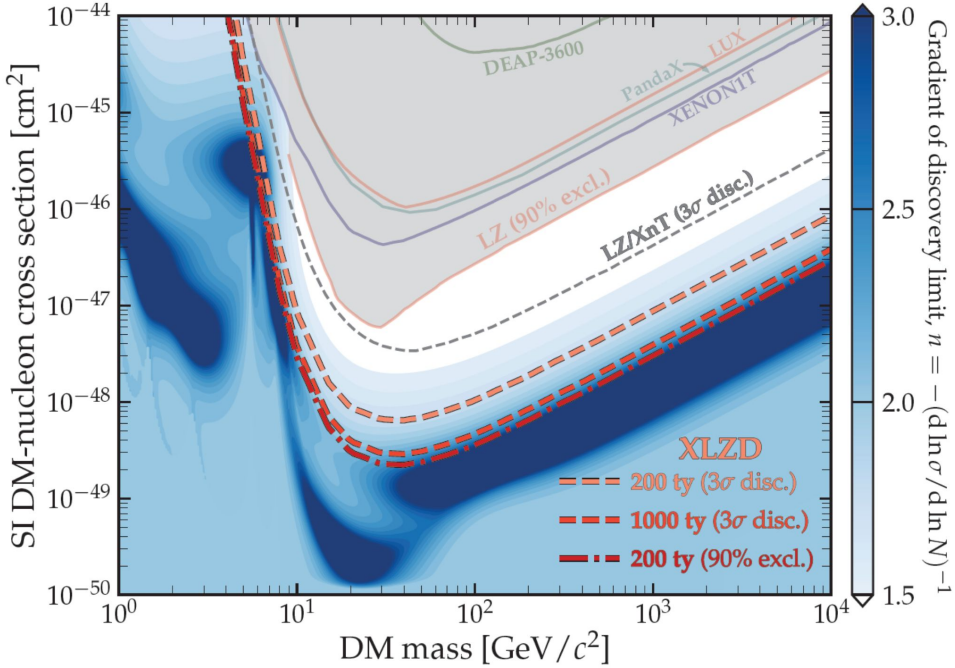
Phys.Rev.C 102 (2020) 1, 014602

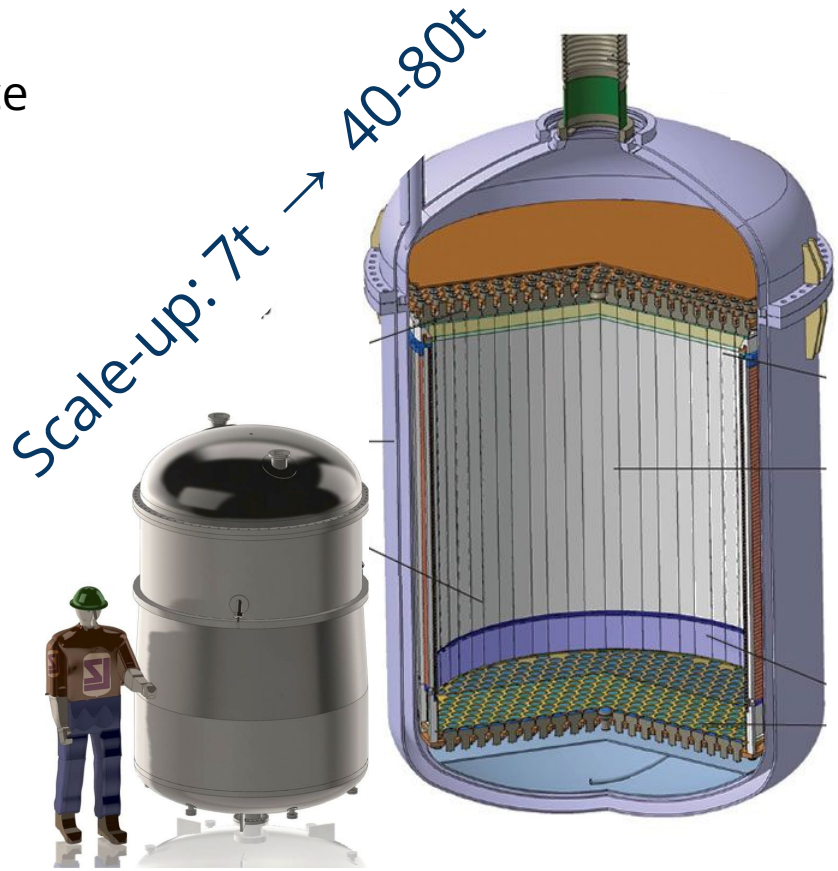
8B CEvNS; SN neutrinos

XLZD - a next-generation LXe observatory

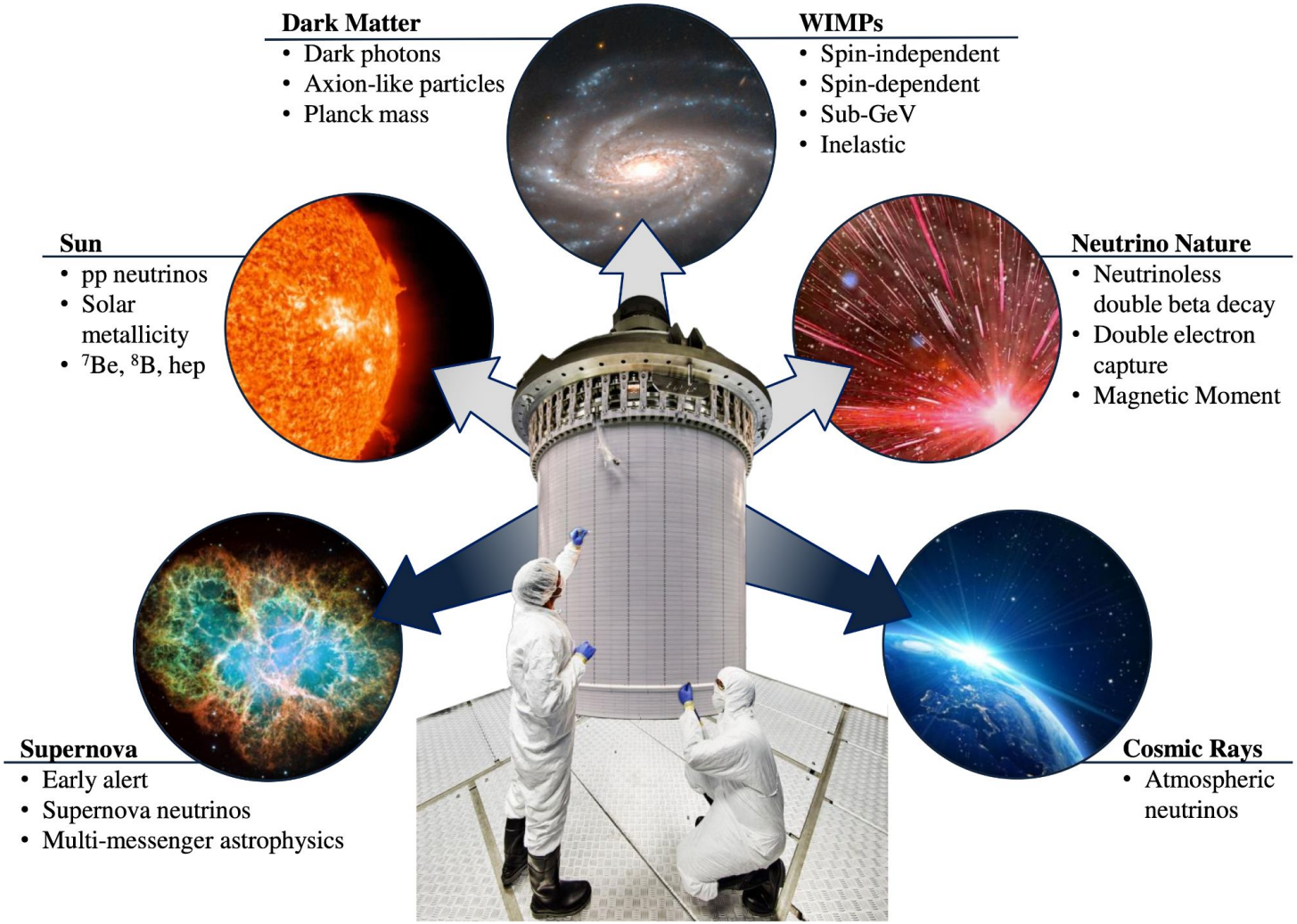
https://xlzd.org

- Consortium of **X**ENON, **L**UX-**Z**EPLIN & **D**ARWIN → MOU July 2021
- Explore electro-weak parameter space to neutrino fog in the 2030s





A broad range of physics with 300+ tonne.years



J Aalbers *et al* 2023 *J. Phys. G: Nucl. Part. Phys.*

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Thanks to our sponsors and 37 participating institutions!

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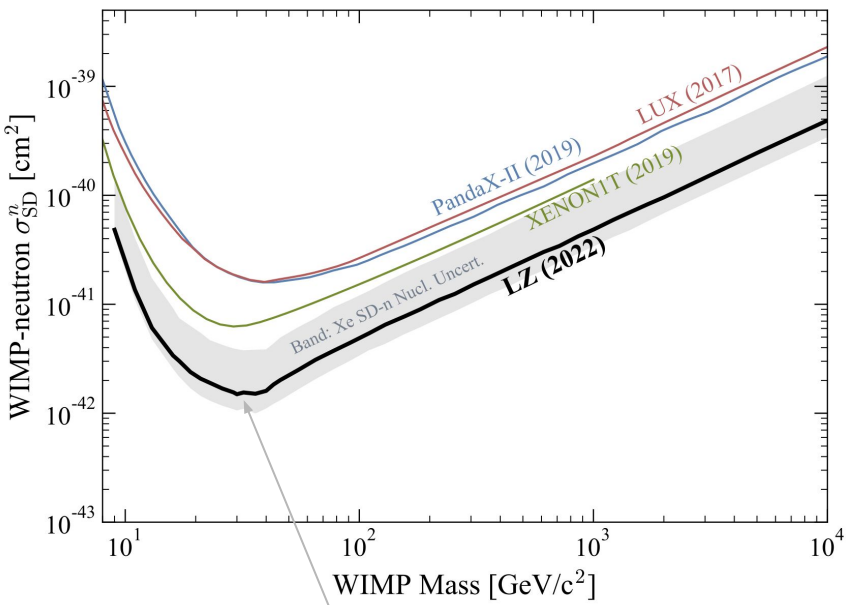
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

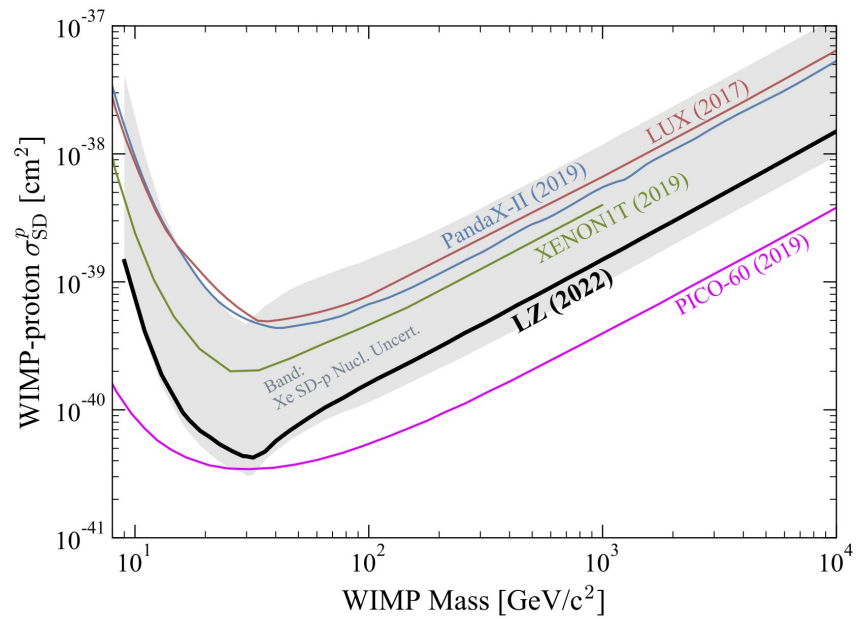
Institute for Basic Science

Backups - SD results

Spin-dependent WIMP-p(n)

- Structure functions from Hoferichter et al [Phys. Rev. D 102, 074018 (2020)]
- Gray band → uncertainty from range of theory models





Most stringent limit for SD-n of 1.49×10^{-42} cm^2 at 36 GeV/c^2