Physics Reach of the LZ Experiment

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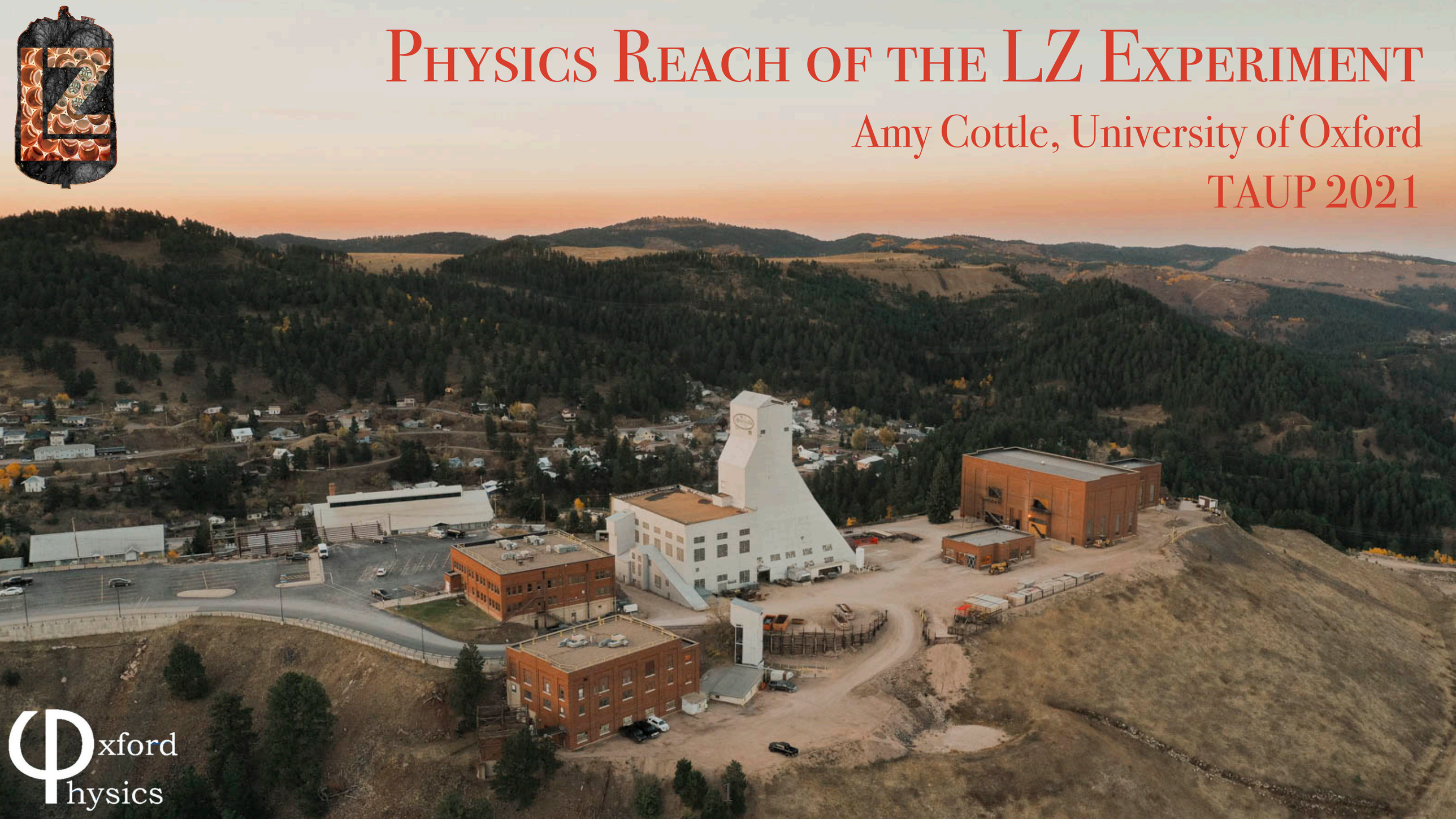
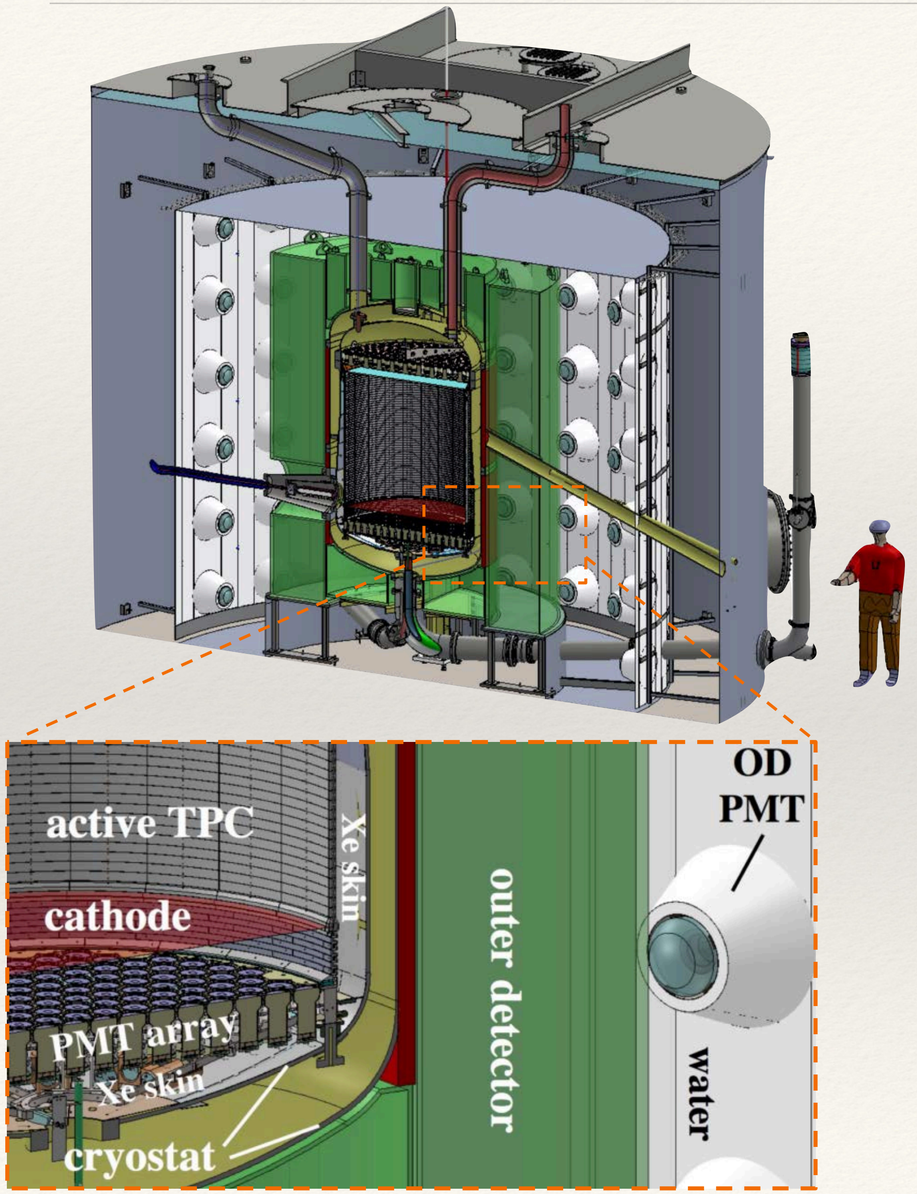
TAUP 2021



Oxford Physics

Introduction to LUX-ZEPLIN (LZ)

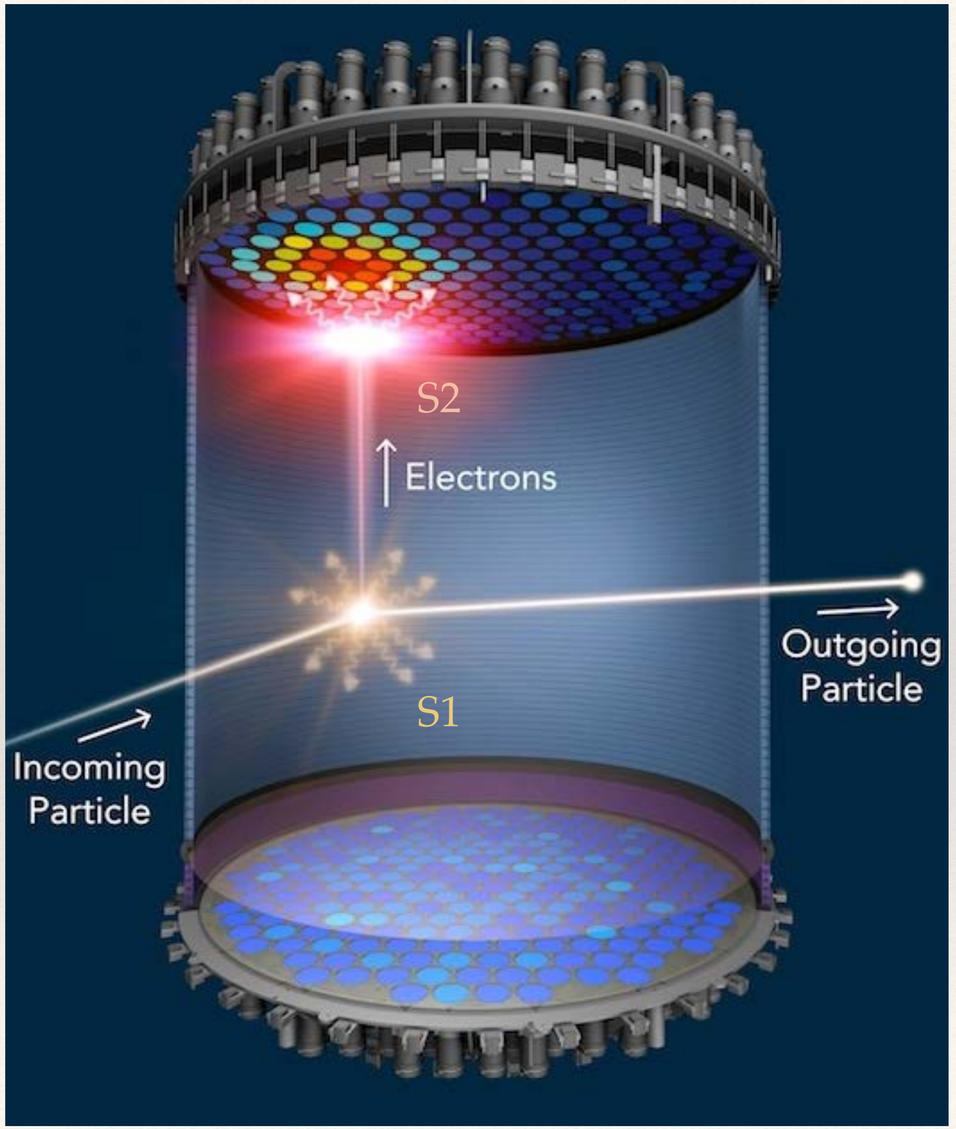


- LZ is a dark matter direct detection experiment based at the Sanford Underground Research Facility
  - 4850 ft underground -> cosmic ray reduction
- Dual-phase xenon time projection chamber (TPC)
  - 7 t active xenon viewed by 494 photomultiplier tubes
- Skin and Outer Detector (OD) active veto systems
- Commissioning started (see D. Woodward's talk)
- Primarily designed for WIMP detection, but has considerable sensitivity to other new physics

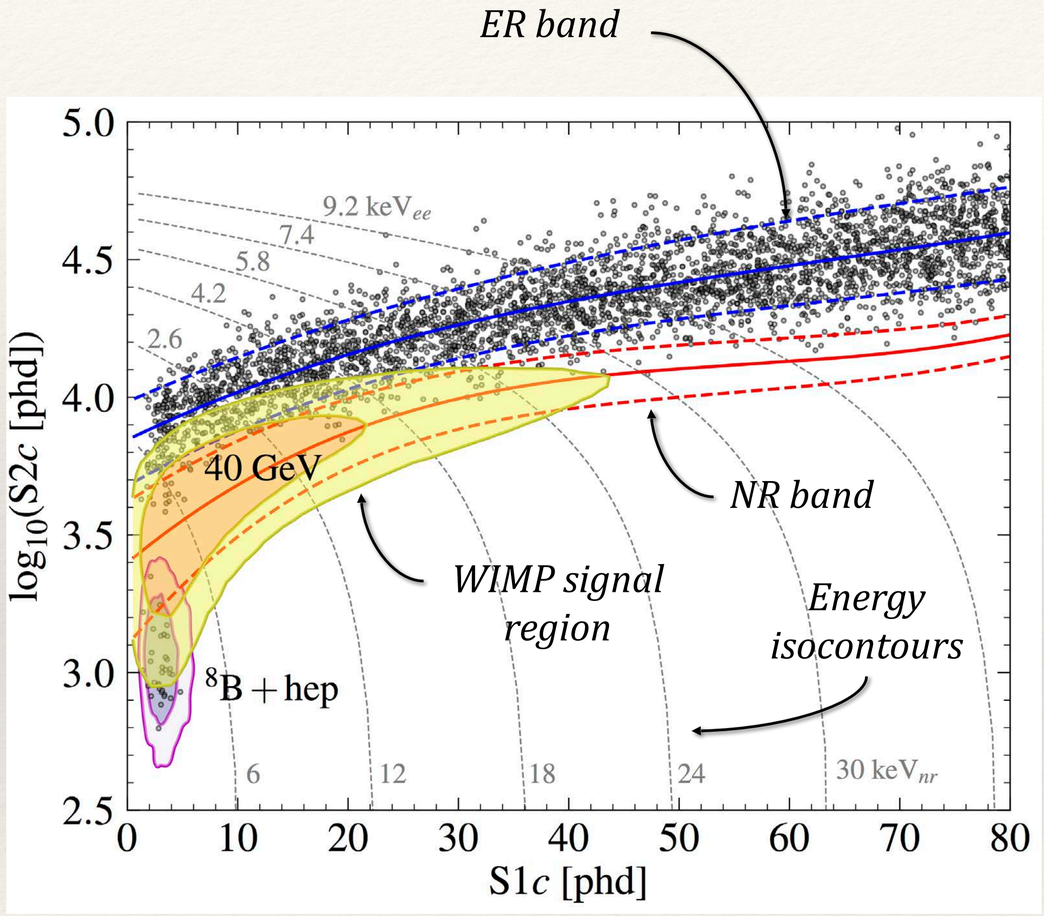
j.nima.2019.163047

TPC Detection Principle

- Interactions in the xenon create
  - Light - prompt scintillation (S1)
  - Charge - electrons drifted and extracted into gas -> proportional scintillation (S2)
- Excellent 3D position reconstruction (~mm)
  - Z from time difference between S1 and S2
  - XY from S2 hit pattern on top PMT array
- Signals can be used to determine energy of the event and for particle identification



WIMP Analysis Strategy

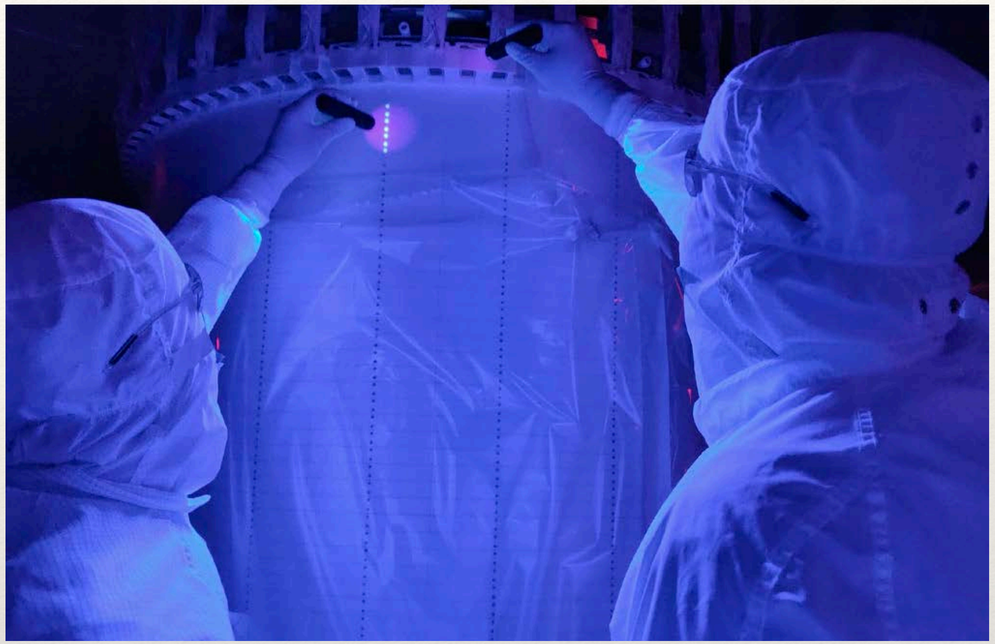


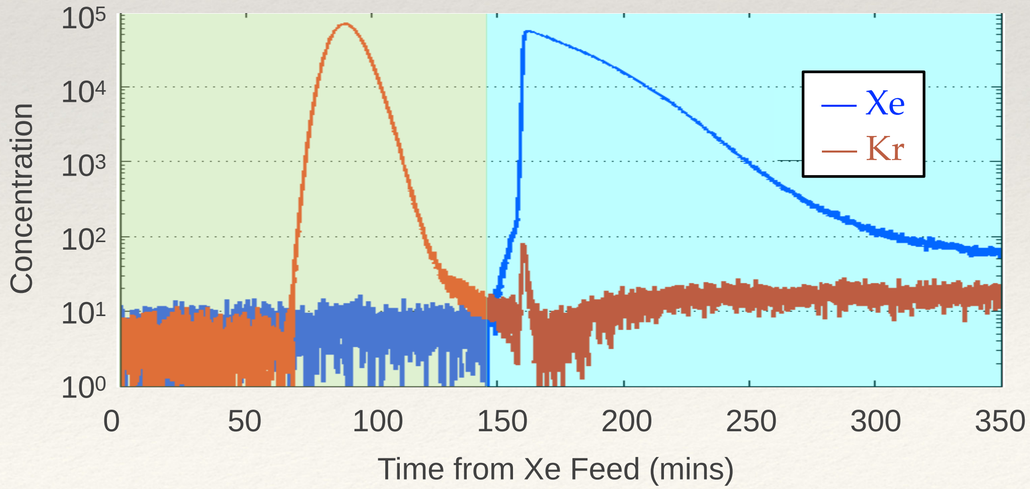
*Simulated data inside the fiducial volume for the full LZ exposure (1000 days * 5.6 t)*

- S2 to S1 ratio -> discrimination of electron recoil (ER) from nuclear recoil (NR) events
  - ER and NR bands obtained via calibration
  - Conduct search below NR band median -> predicted 99.5% ER event rejection
- Reduce background events via
  - Fiducialisation to cut external source contributions
  - Rejection if coincident veto response (Slide 7)
- Projected energy threshold of ~1.5 keVee

Background Control

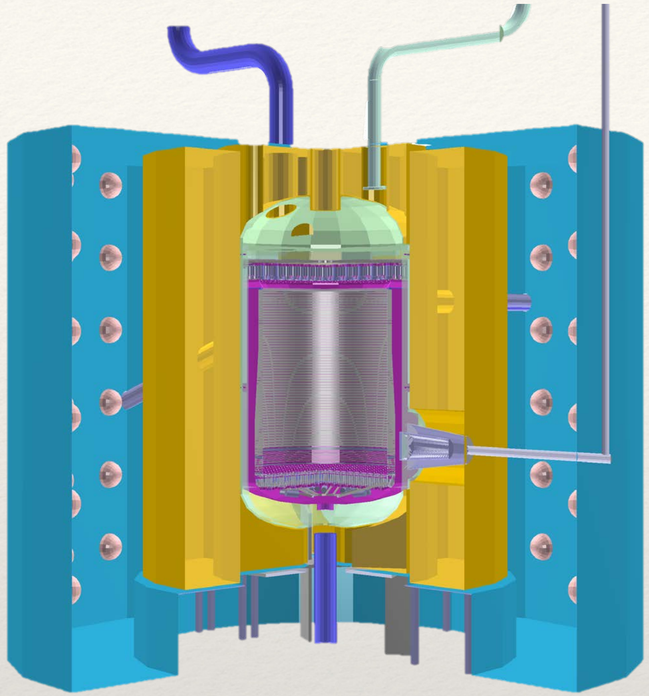
- Material selection based on ~2000 assays with 13 HPGe detectors, ICPMS, neutron activation analysis
- Four Rn emanation screening sites
- TPC assembly in Rn-reduced cleanroom
  - Cleanliness protocols limiting surface contamination
    - Dust (<500 ng/cm^3)
    - Plate-out (<0.5 mBq/m^2)
- Charcoal chromatography at SLAC to remove xenon contaminants (^{85}Kr, ^{39}Ar)
- Online radon reduction system and purification via getter

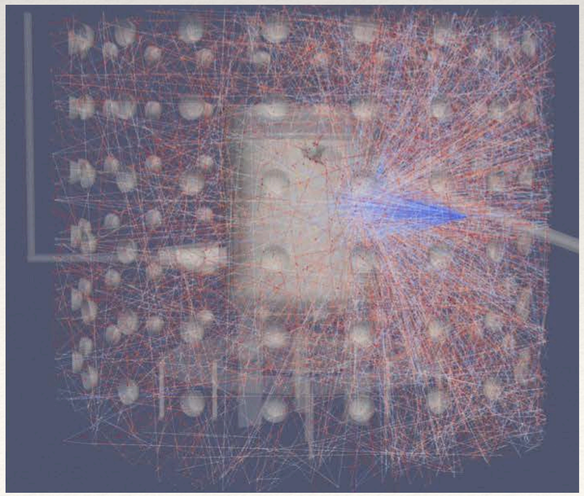




EPJC, Vol 80: 1044 (2020)

Background Simulations

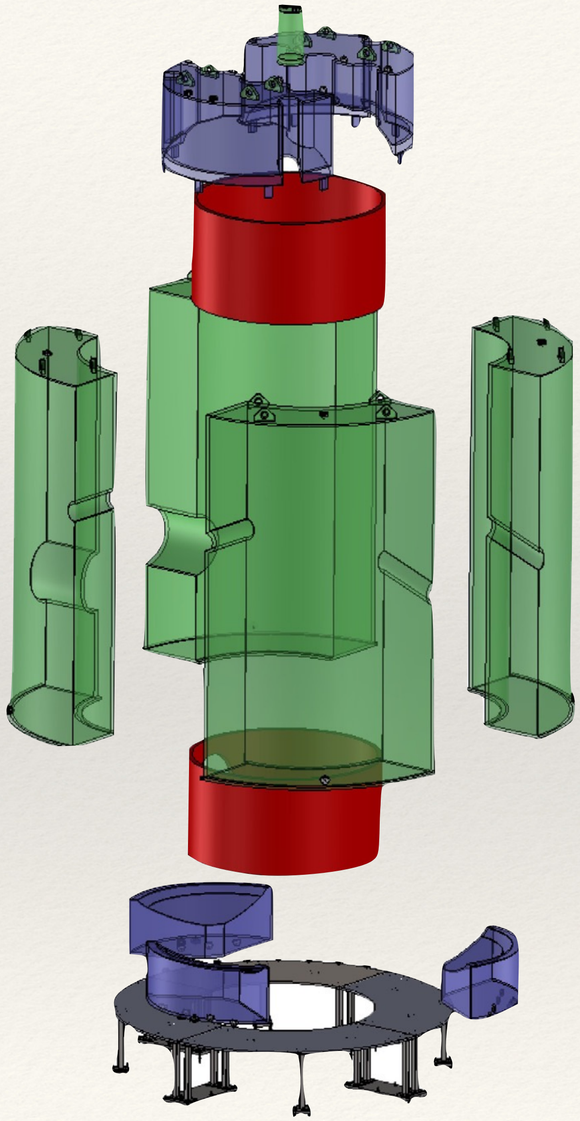




- Geant4-based simulation framework (BACCARAT)
  - Event generators written for specific backgrounds e.g.
    - Neutrons with coincident gammas (e.g. uranium spontaneous fission)
    - Laboratory and external backgrounds (e.g. muons, cavern gammas)
    - Surface backgrounds (e.g. embedded Po210 (alpha, n) on fluorine)
  - Custom physics lists e.g. OD Gd neutron capture with DICEBOX
- Energy depositions converted to S1s and S2s with NEST
  - Used for backgrounds estimates and sensitivity projections
- Detailed optical and electronics response simulations also possible to produce pulses and realistic scatter topologies for mock analyses

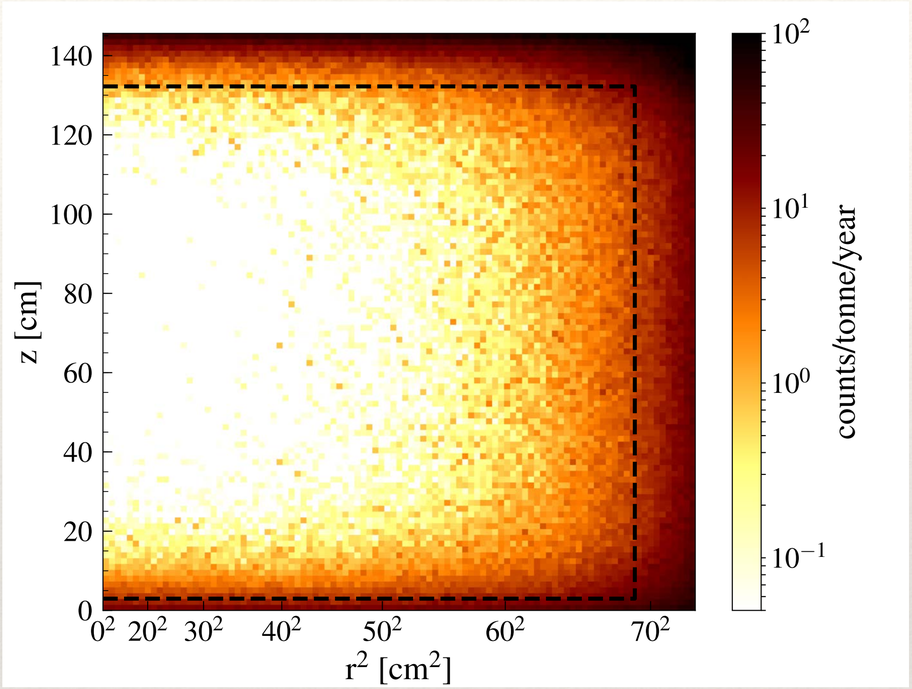
j.astropartphys.2020.102480

Veto Impact on Backgrounds

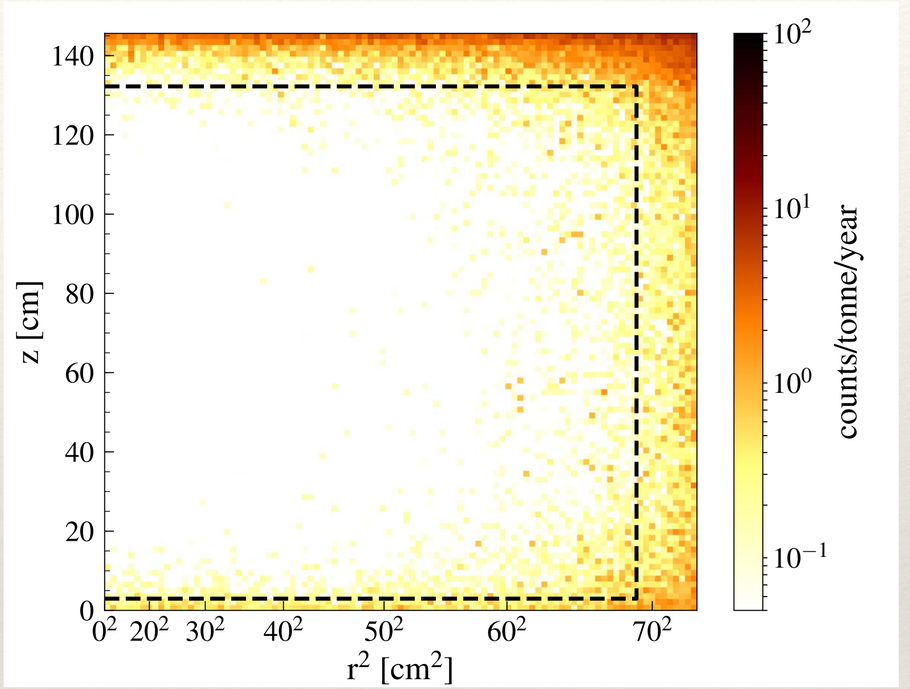


CAD view of the Outer Detector

No vetoes: 10.4 NR cts/1000 days

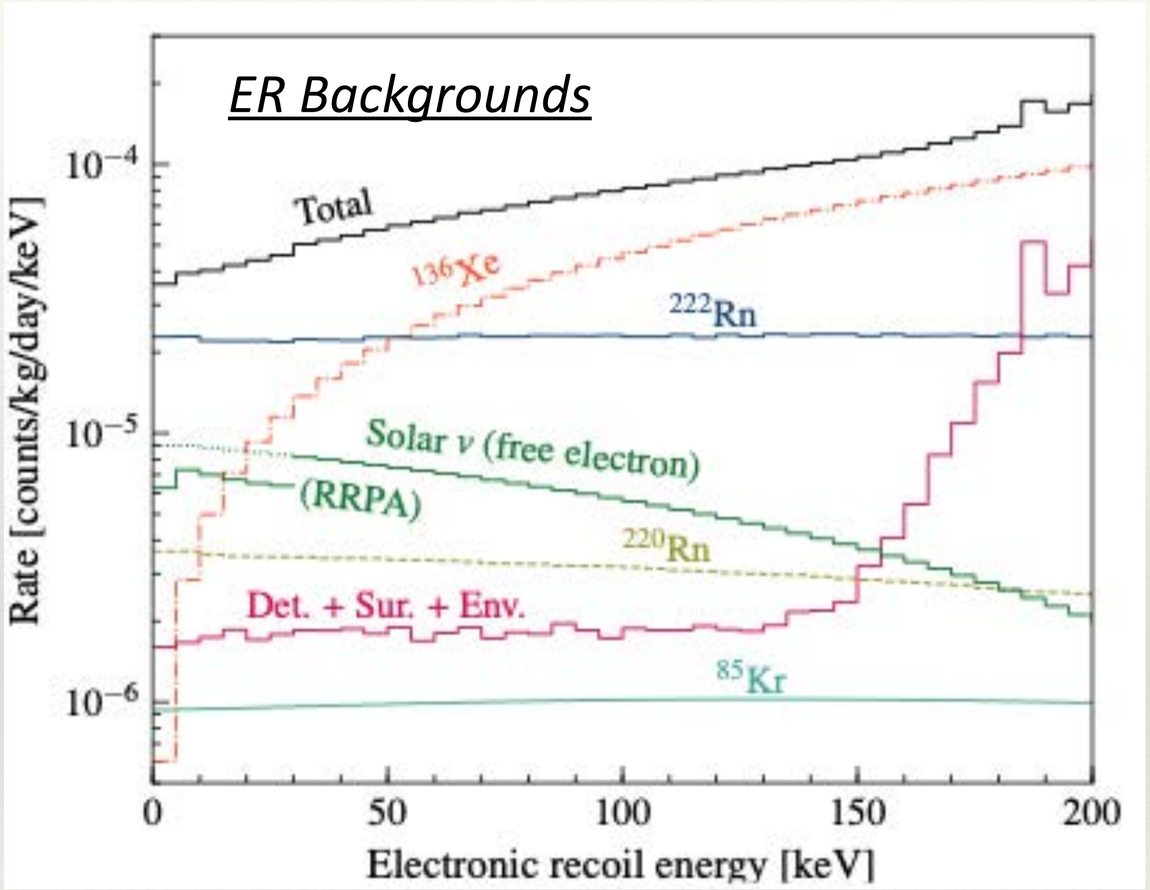


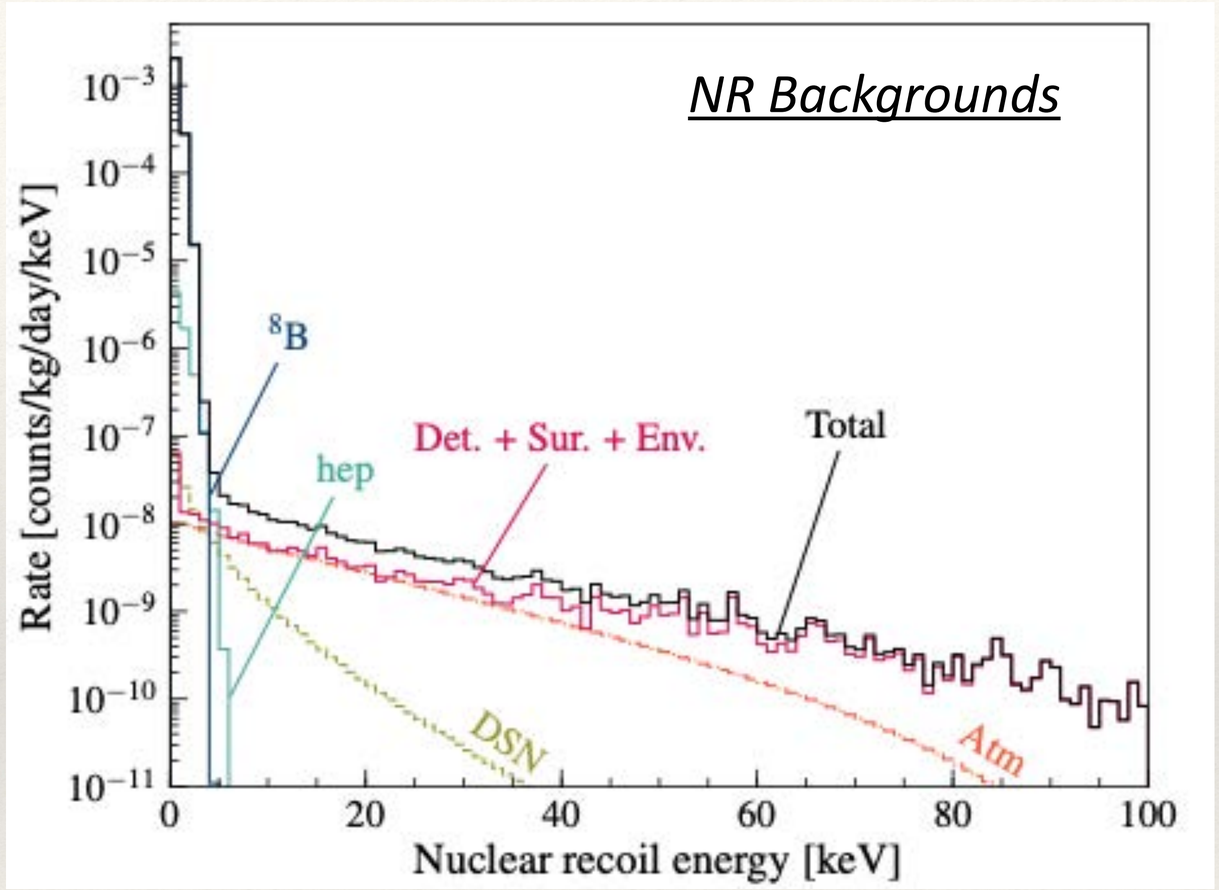
With vetoes: 1.0 NR cts/1000 days



- Combined veto system allows for a fiducial volume of 5.6 t (80% of active volume)
- See H. Birch's poster for more details

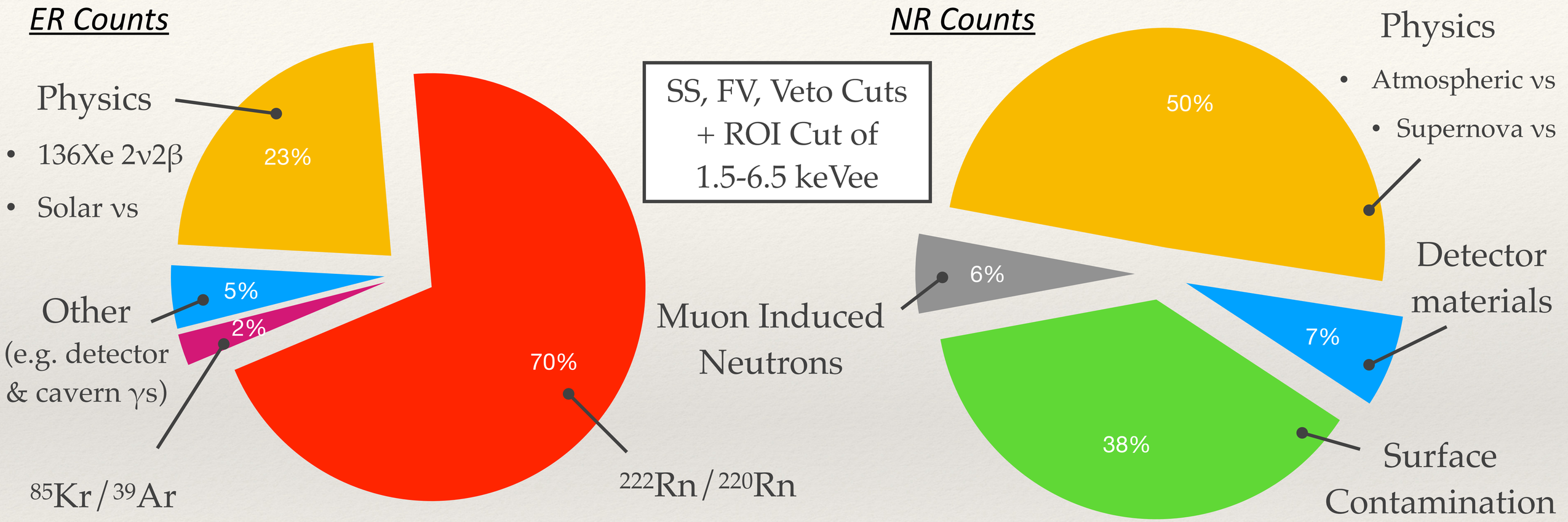
WIMP Search Backgrounds





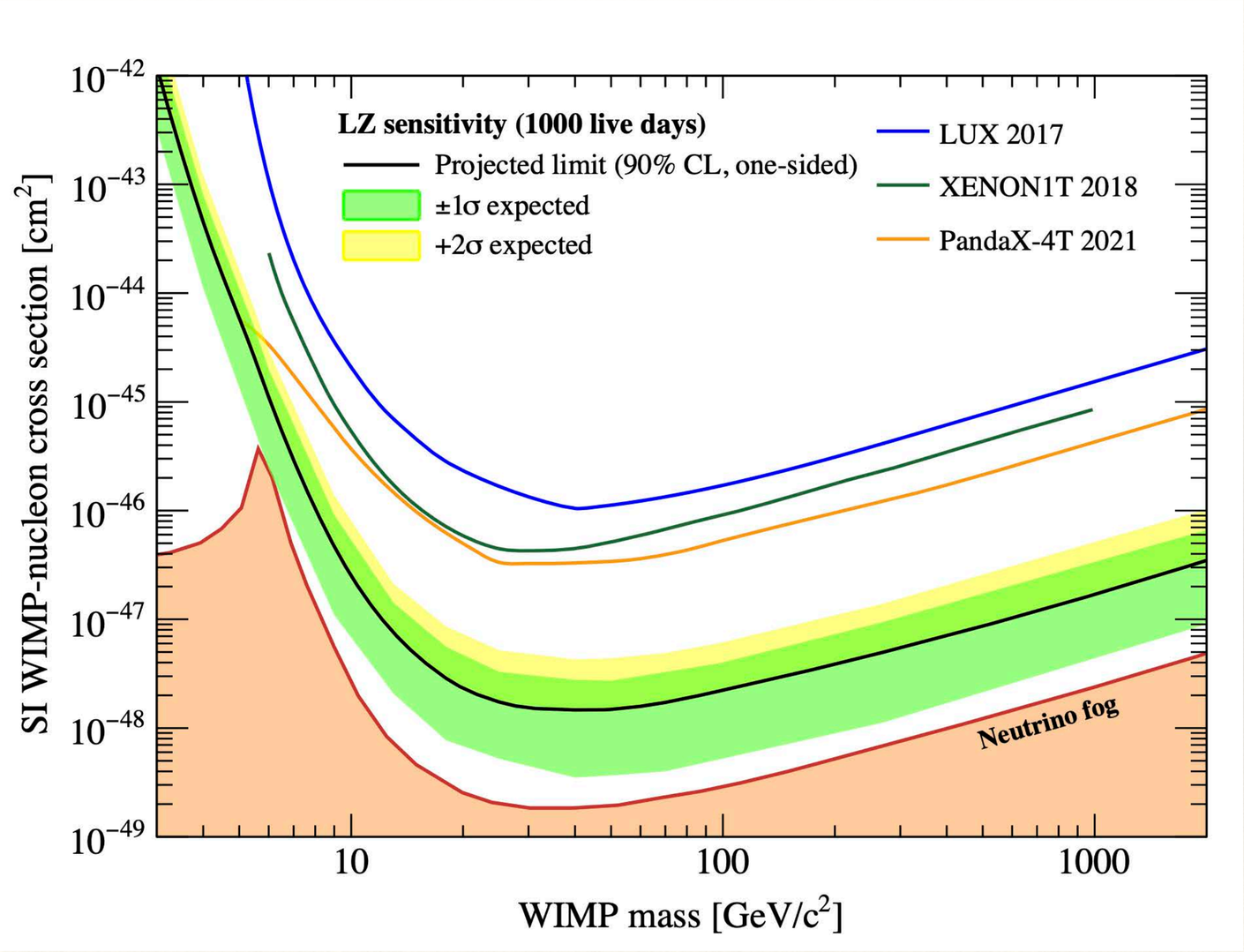
Expected contributions after analysis cuts
(single scatter (SS), 5.6 t fiducial volume (FV), veto anti-coincidence)

Backgrounds for a 40 GeV/c² WIMP



Source	ER [cts]	NR [cts]
Total	1131	1.03
+ 99.5% ER discrimination, 50% NR efficiency	**5.66**	**0.52**

WIMP Sensitivity



- Profile likelihood ratio analysis
  - S1, S2 (+ position) PDFs
    - Simulated backgrounds (Slide 6)
    - Analytical recoil spectra -> NEST (signal/physics)

90% CL minimum:

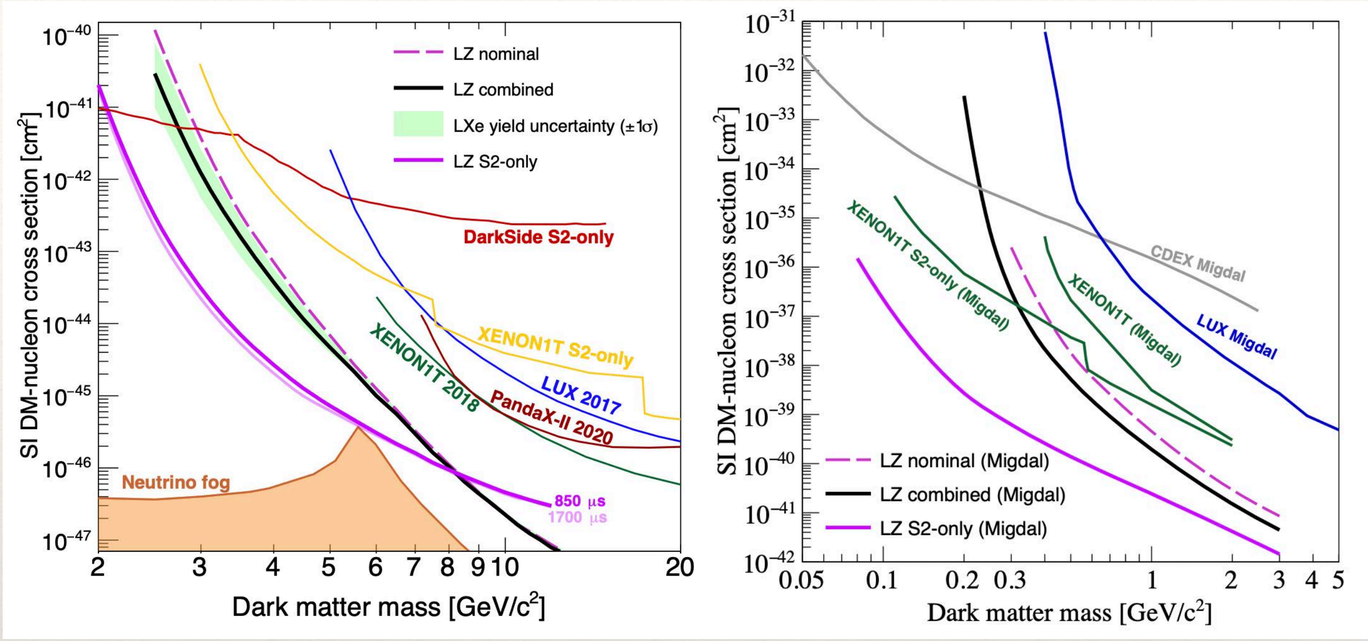
1.4×10^{-48} cm² at 40 GeV/c²

*For full LZ exposure (1000 days * 5.6 t)*

PRD 101, 052002 (2020)

Extension to Lower Mass Candidates

- Lowering the energy threshold
  - Exploit 2-phe effect to reduce S1 coincidence requirement from 3 to 2
    - ~4x sensitivity gain at 2.5 GeV/c^2
  - Conduct an S2-only search
    - Discriminate backgrounds based on S2 pulse shape/width
- Sub-GeV masses accessible when considering Migdal electron emission



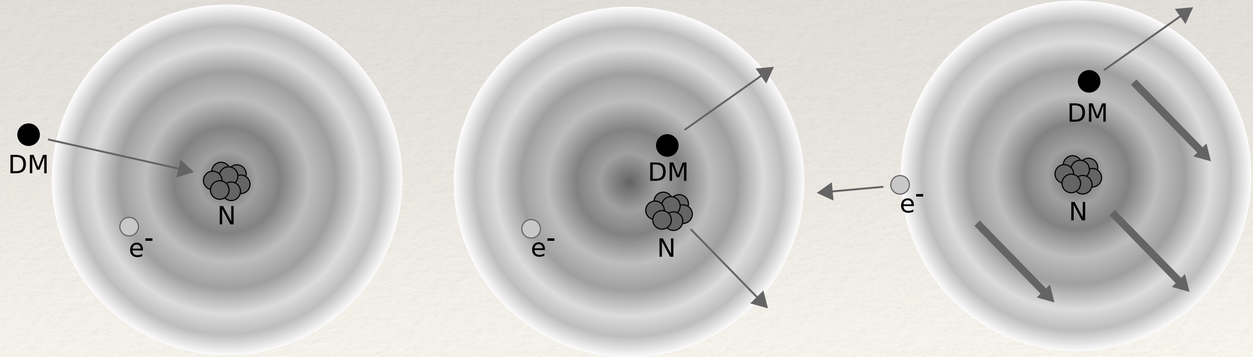
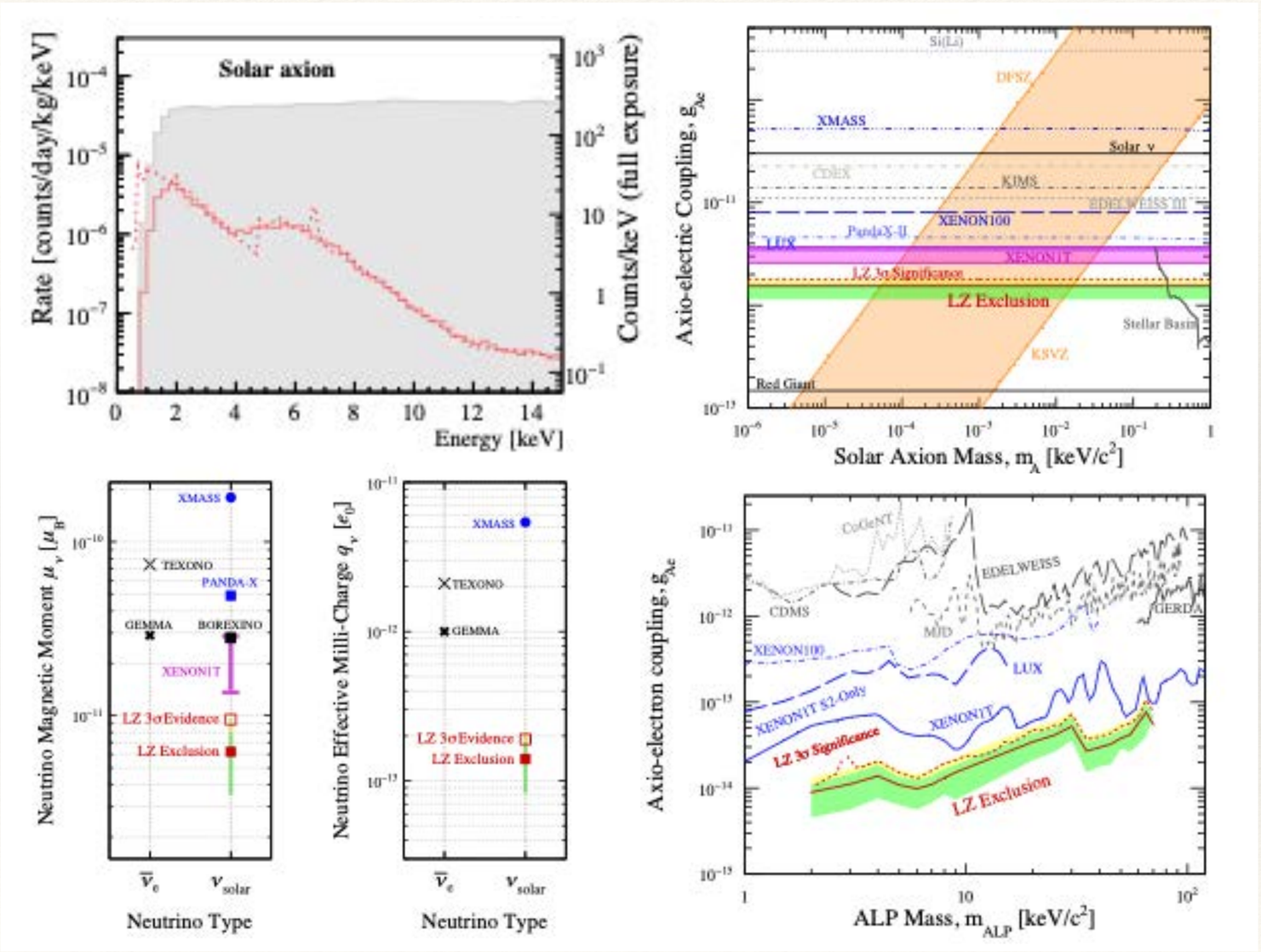


Image credit: [PRL 121, 101801]

[ArXiv: 2101.08753]

Low Energy ER Searches

- Signal & background models use NEST reconstructed energy, S1, S2
- Example 90% CL upper limits:
  - Solar axions - $g_{Ae} < 1.58 \times 10^{-12}$
  - Neutrino magnetic moment - $\mu_{\nu_{solar}} < 6.2 \times 10^{-12}\,\mu_B$
  - Neutrino electric millicharge - $q_{\nu_{solar}} < 1.4 \times 10^{-13}\,e_0$
- ^{37}Ar & ^{3}H included in likelihood fits
- Robustly test XENON1T excess

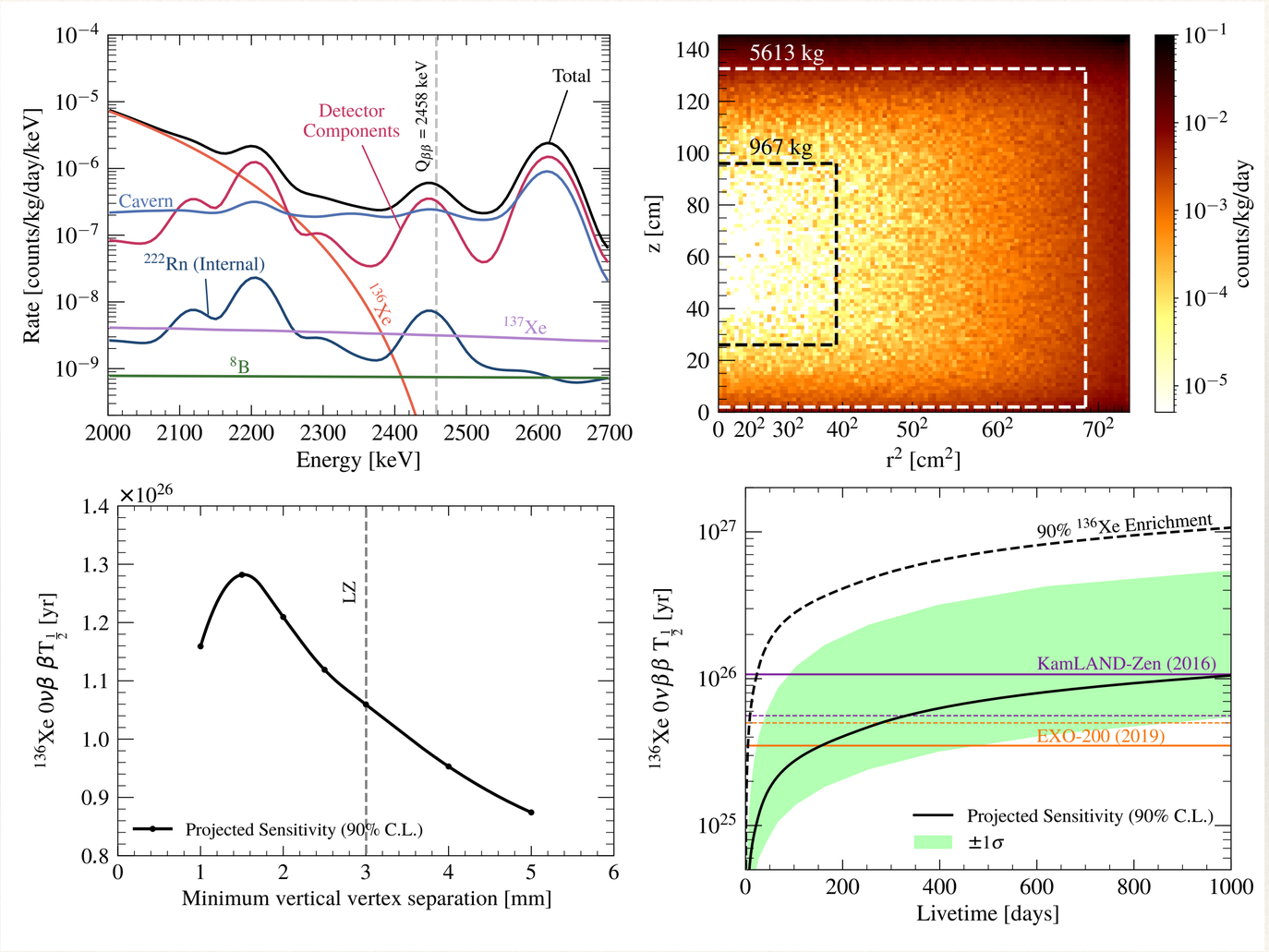


[ArXiv: 2102.11740]

^{136}Xe Neutrinoless Double Beta Decay

- Isotopic abundance of 8.9% ^{136}Xe
- Gamma backgrounds near $Q_{\beta\beta}$ (2458 keV)
- Energy and position dependent PDFs
- Requires good energy resolution (assume 1% or better at $Q_{\beta\beta}$)
- Needs good single vs multiple scatter discrimination (Z separation < 3 mm)

$T_{1/2}$ (90% C.L.) > 1 x 10^{26} years
in 1000 live days in 5.6 t fiducial volume



PRC 102, 014602 (2020)

Conclusions

- LZ is fully optimised for the direct detection of WIMPs
  - 20x more sensitive than the current best limits
- LZ is a multi-physics experiment, with competitive searches across a range of energies, in both NR & ER channels
- Long-term campaign of backgrounds control and continued assessment to ensure world-leading sensitivities
- Experiment is in its commissioning phase, with first science data expected this year
- This next year will be a pivotal one in dark matter physics - watch this space!

LZ (LUX-ZEPLIN) Collaboration

34 Institutions: 250 scientists, engineers, and technical staff

- Black Hills State University
- Brandeis University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial 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 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 Wisconsin, Madison

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