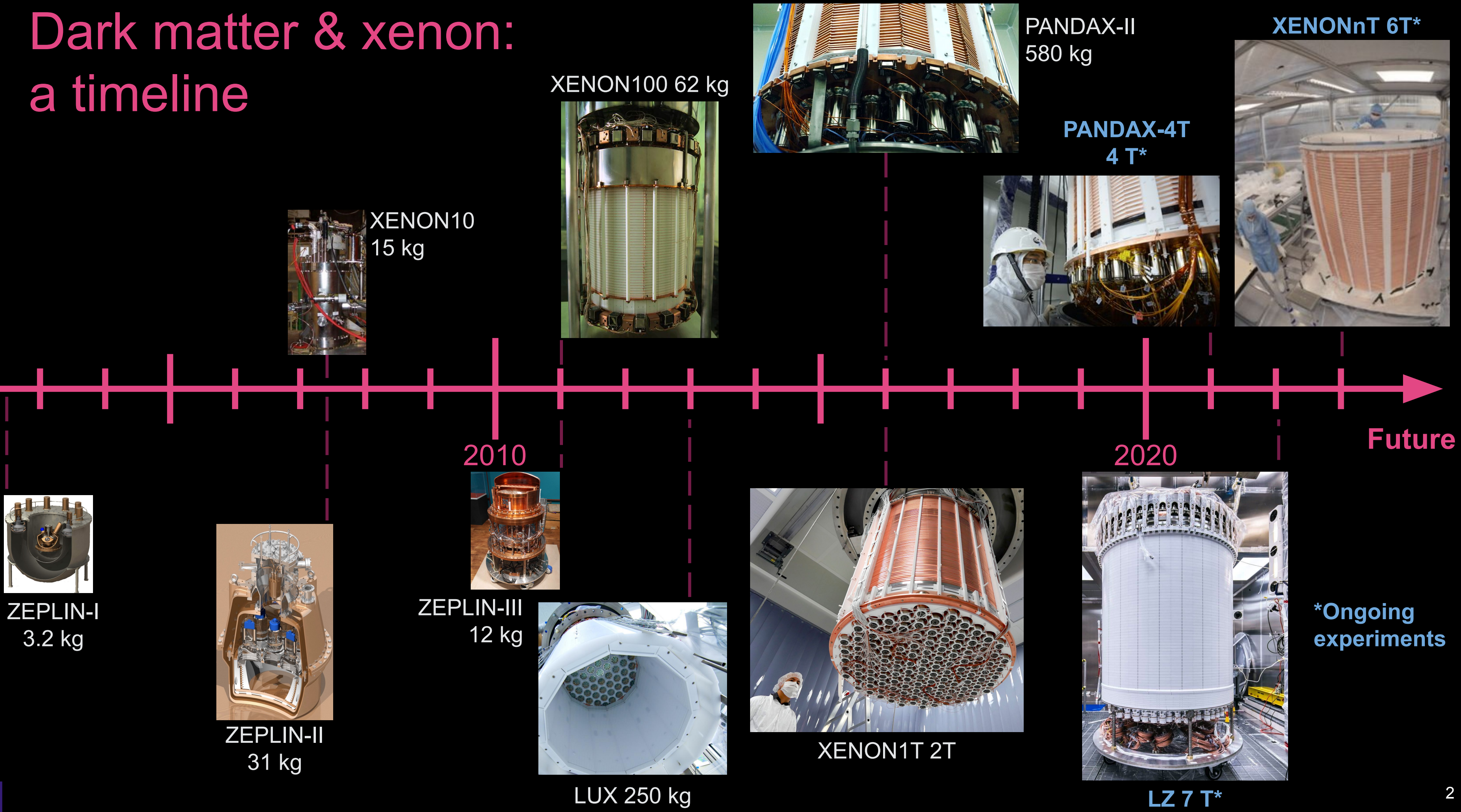
WIMPs and beyond: from LUX-ZEPLIN to a future liquid xenon observatory

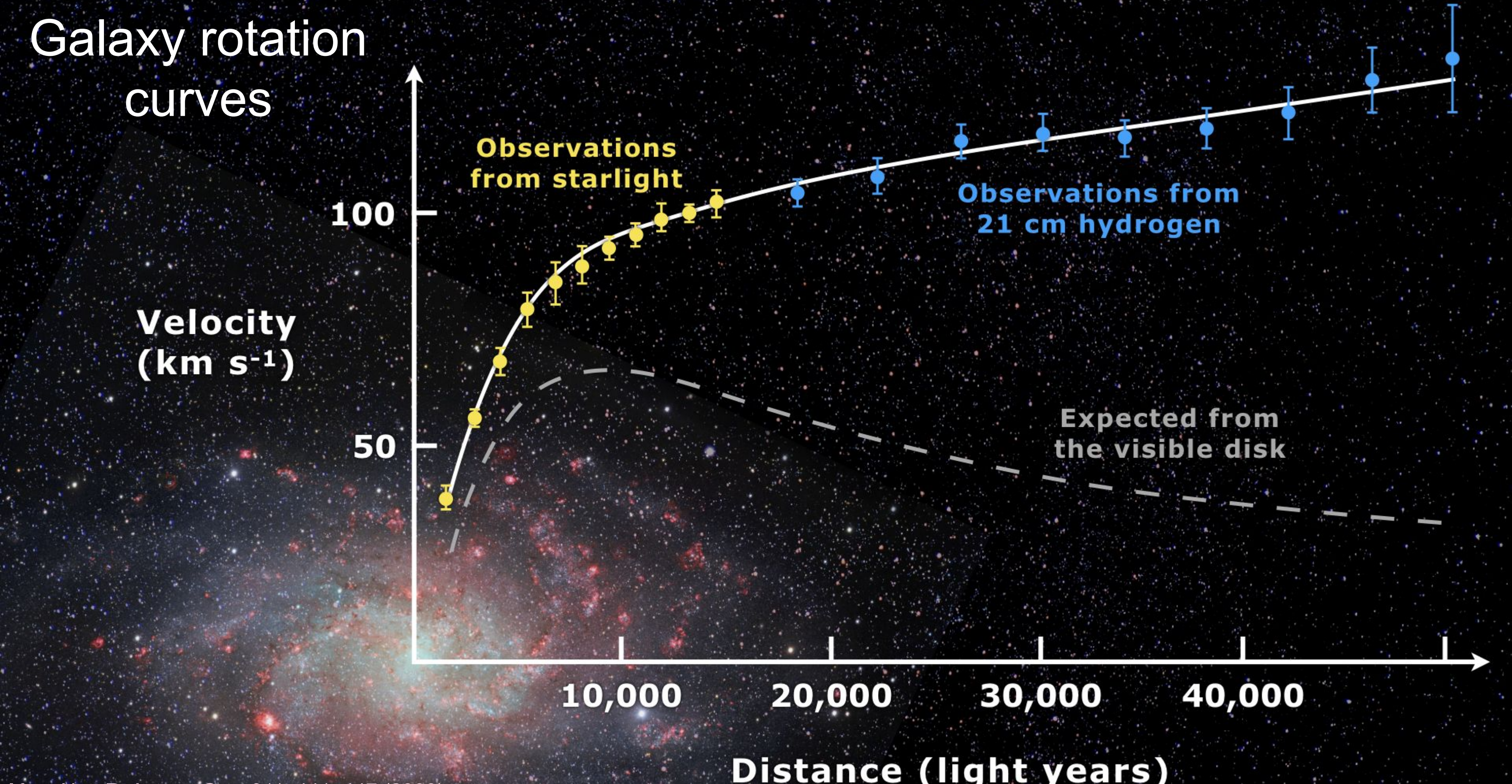
Kelsey C Oliver Mallory
Imperial College London
May 22nd, 2024
Rutherford Appleton Laboratory Particle Physics Department Seminar

IMPERIAL

Dark matter & xenon: a timeline

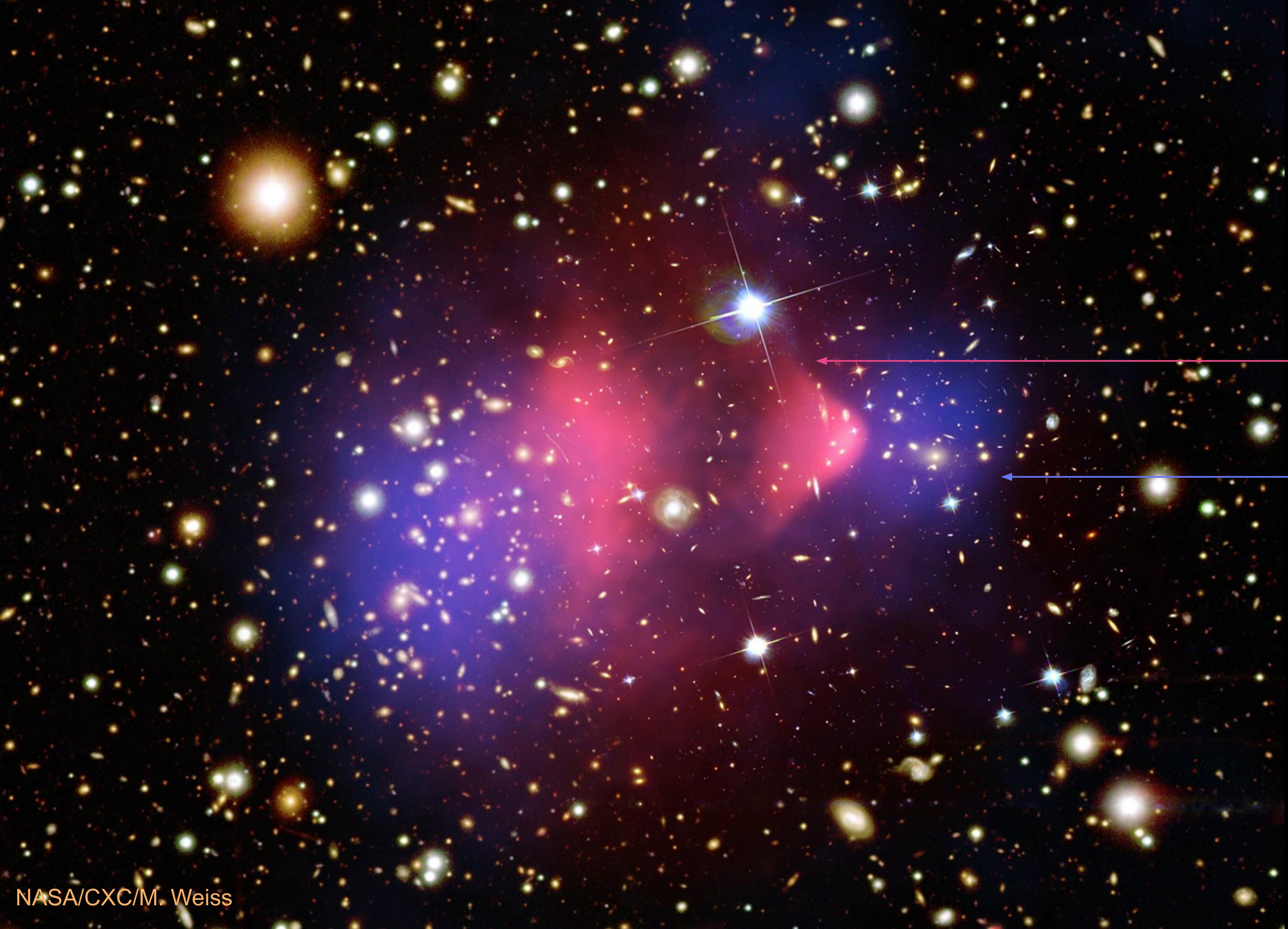


Galaxy rotation curves



Mon. Not. R. Astron. Soc. 311, 441±447 (2000)

Bullet cluster



NASA/CXC/M. Weiss

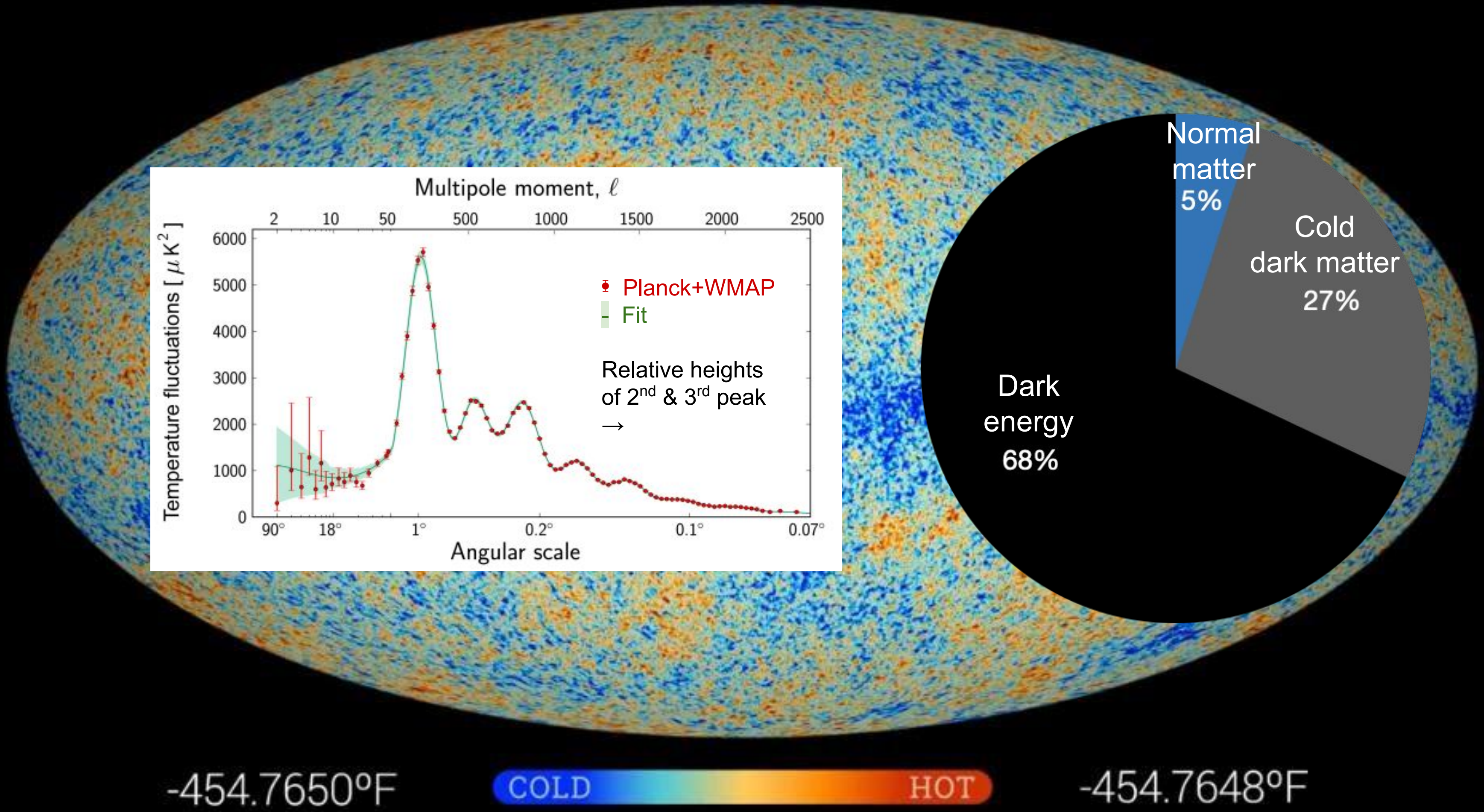
Colliding galaxy clusters

X-rays reveal location of hot baryonic gas

Gravitational lensing reveals distribution of mass, showing it is coincident with collisionless galaxies

Majority of matter is collisionless

Cosmic microwave background



Planck 2018 results

Dark matter properties

Dark: does not interact electromagnetically

Stable over the lifetime of the universe

Cold: moves slowly enough for galaxy formation

A particle could meet these criteria

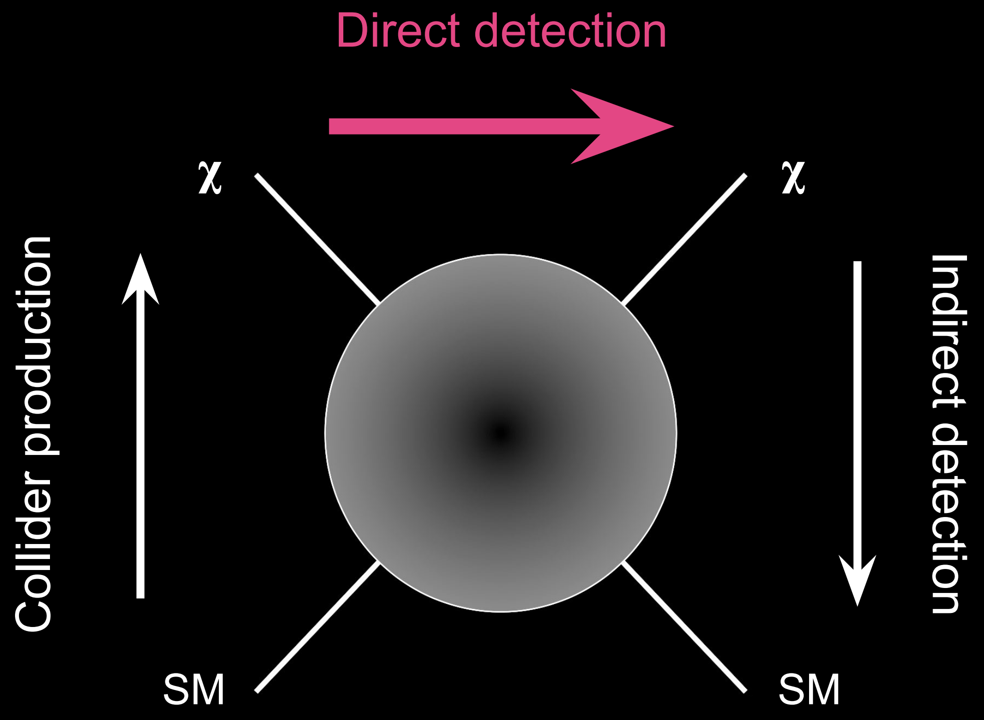
We are in the Milky Way →

Local dark matter density ~ 0.3 GeV/cm^3

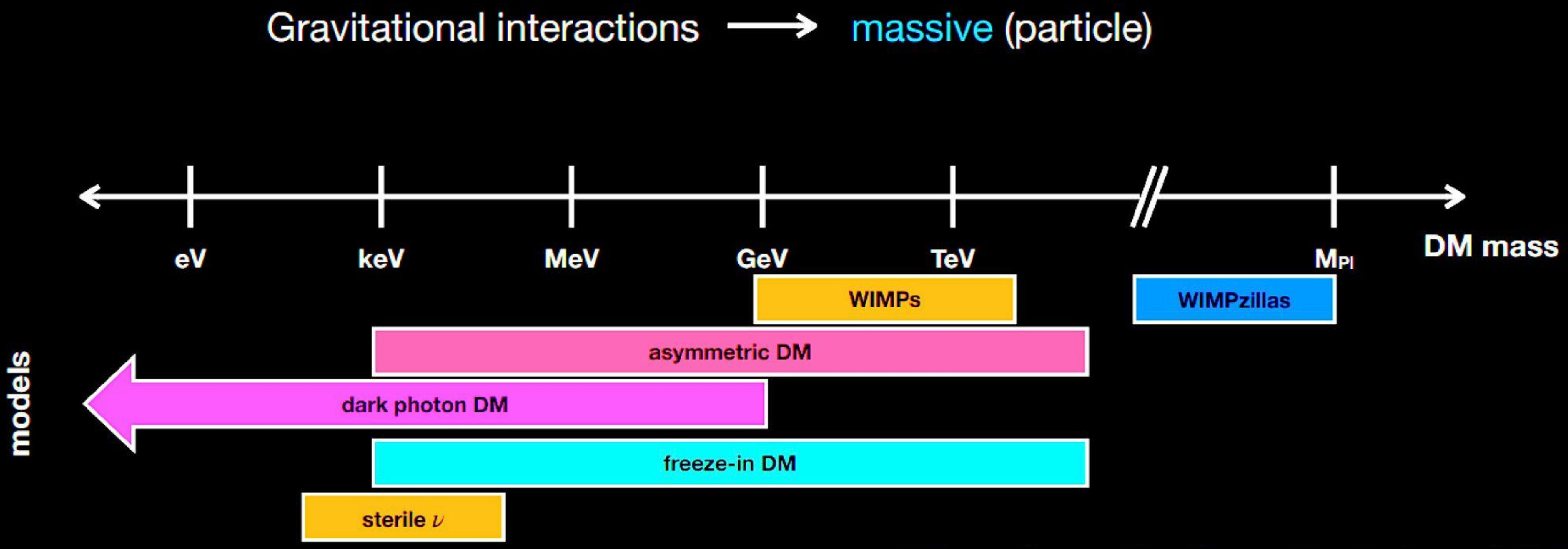
Average dark matter velocity v ~ 220 km/s

Assuming Maxwell-Boltzmann distribution of dark matter

Detecting dark matter particles



Theoretical possibilities for particle dark matter



Weakly interacting massive particles (WIMPs)

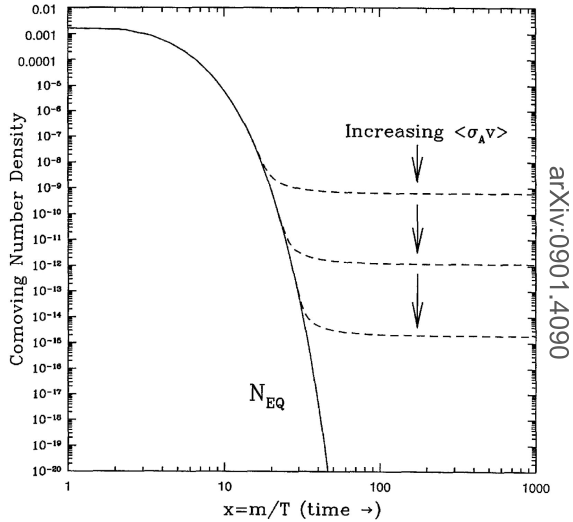
Dark matter freeze-out

m_{DM} ~ 100 GeV

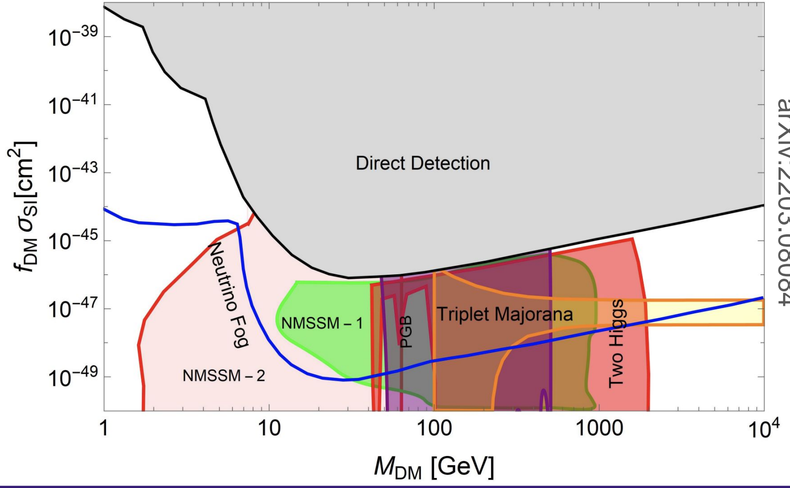
$\langle \sigma_A v \rangle$ ~ weak-scale

Supersymmetry provides candidates

Currently viable GeV-TeV dark matter models ⟶

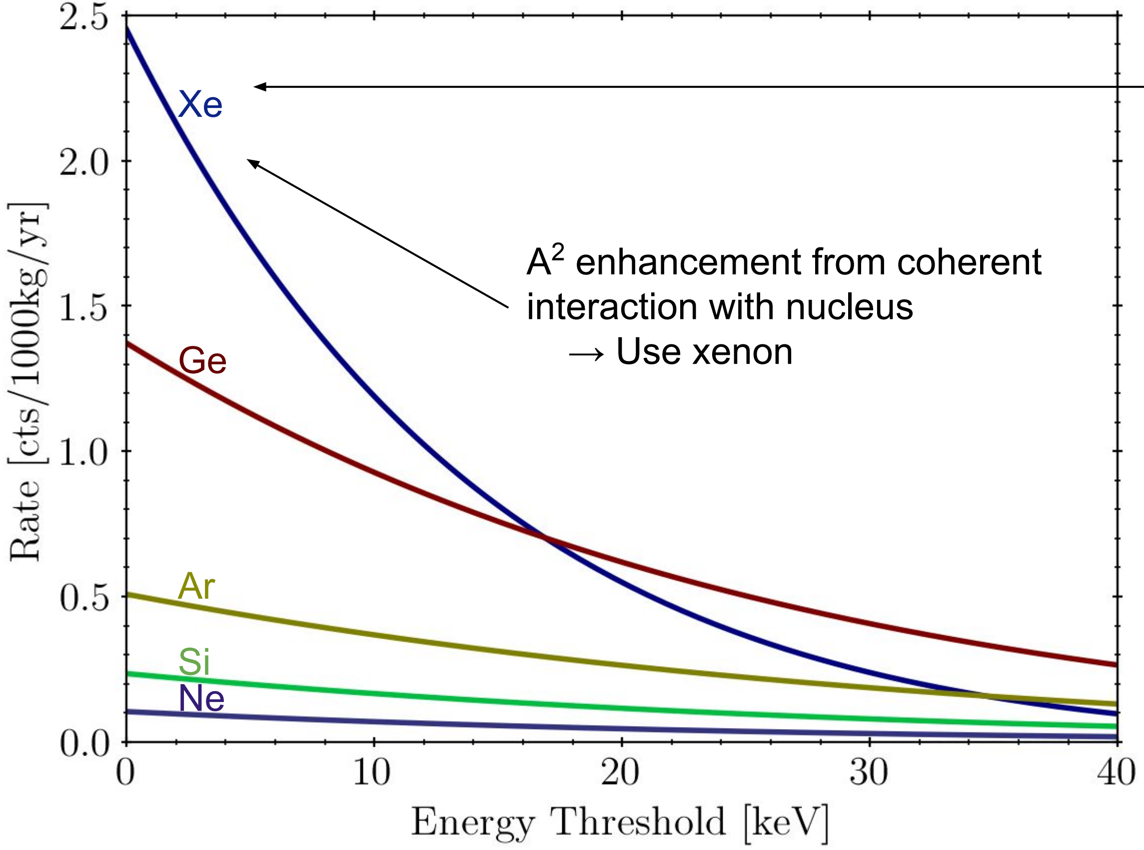


arXiv:0901.4090



arXiv:2203.08084

Dark matter scattering rate



Coherent nuclear scattering rate ~ $\sigma_{SI}\, A^2\, F_{SI}^{\;2}$

Spin-dependent scattering rate ~ $(J+1)/J\ (\alpha_p\langle S_p\rangle+\alpha_n\langle S_n\rangle)\ F_{SD}^{\;2}$

Current best limits at $\sigma_{\chi,N}$~10^{-47} cm^2 for m_χ~ 100 GeV

Looking for just a few events per tonne per year!

→ Large detector
→ Low threshold
→ Low background rate

Properties of Xe

Many isotopes including $^{129}Xe/^{131}Xe$ (26.4/21.2%) with unpaired neutrons and ^{136}Xe, a candidate for $0\nu\beta\beta$

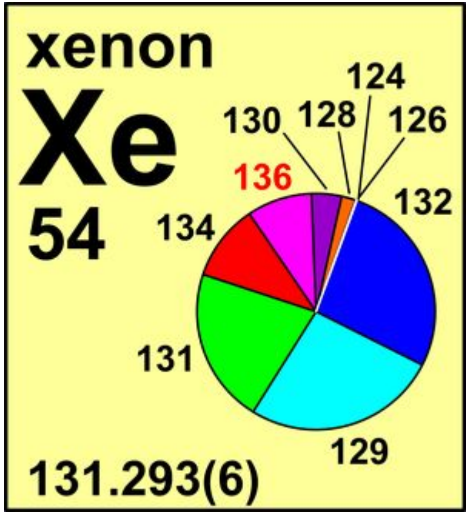
Boils at cryogenic temperatures (~ -110 C)

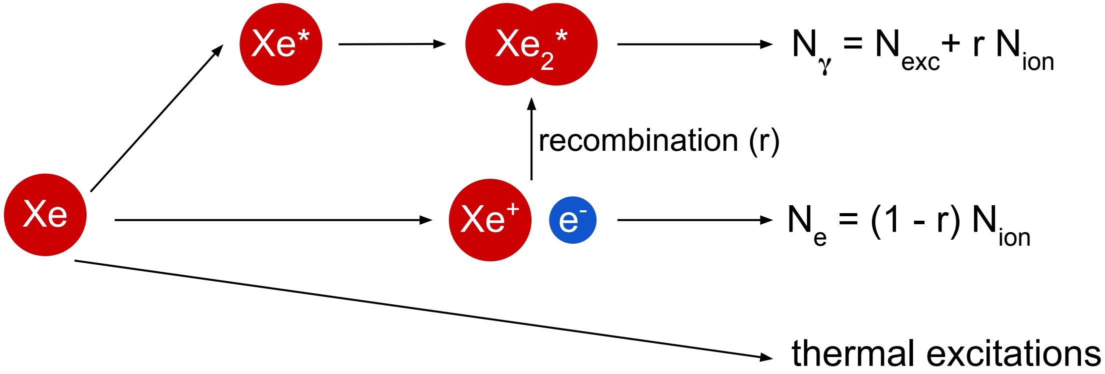
Few problematic radio-isotopes

Dense (~3 g/cm^3)

Inert

Scintillates





LUX-ZEPLIN (LZ) collaboration

@lzdarkmatter
https://lz.lbl.gov/

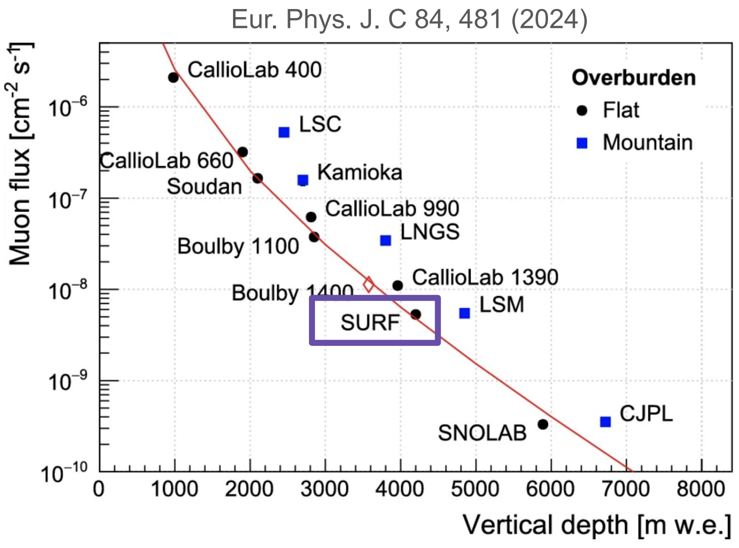
38 institutions, 250 scientists, engineers, and technical staff

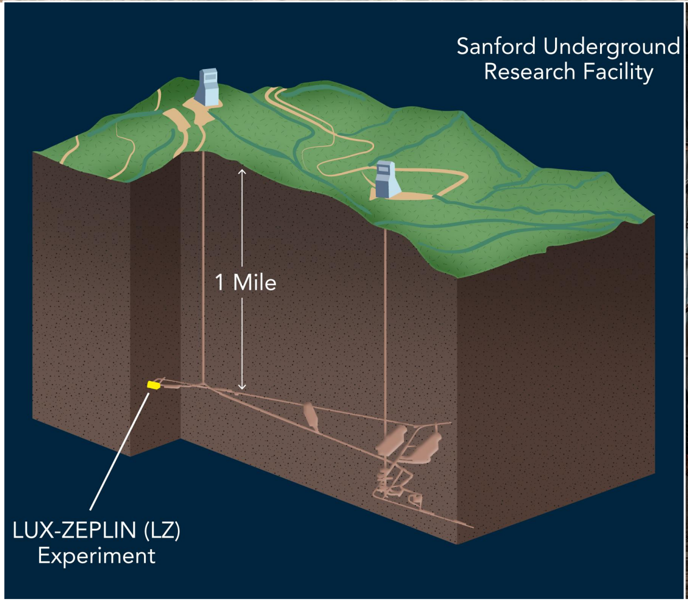
- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- King's College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- 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
- University of Zürich

US Europe Asia Oceania

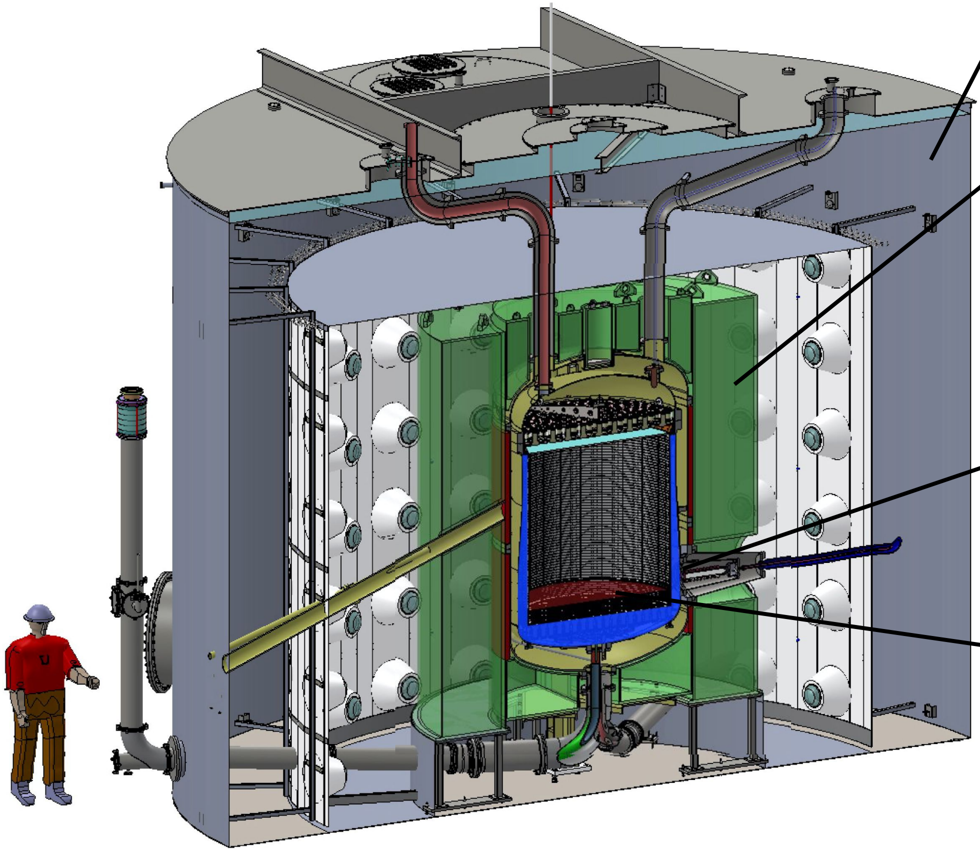
Science and Technology Facilities Council
FCT Fundação para a Ciência e a Tecnologia
SANFORD UNDERGROUND RESEARCH FACILITY
Institute for Basic Science

LZ at Sanford Underground Research Facility (SURF) in Lead South Dakota





LZ layered detector



Tank
- 238 T high purity water
- Passive shielding from external radioactivity

Outer detector (OD)
- 17.3 T gadolinium loaded liquid scintillator
- 120x 8” photomultiplier tubes (PMTs)
- Veto neutrons from detector materials (88±0.7% tagging efficiency with 5% livetime reduction)

Skin
- 2 T liquid xenon
- 93x 1” and 38x 2” PMTs
- Veto γ rays from detector materials

Liquid-gas Xe time projection chamber (TPC)
- 7 T liquid xenon
- 494 3” PMTs
- Dark matter detector

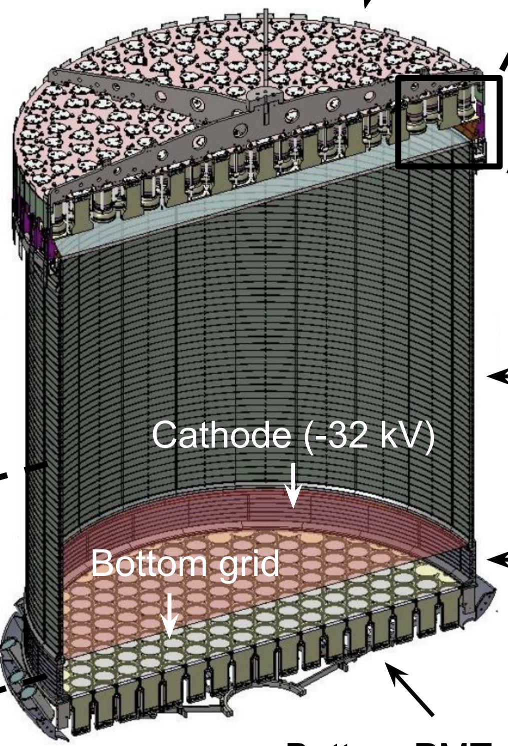
LZ TPC design

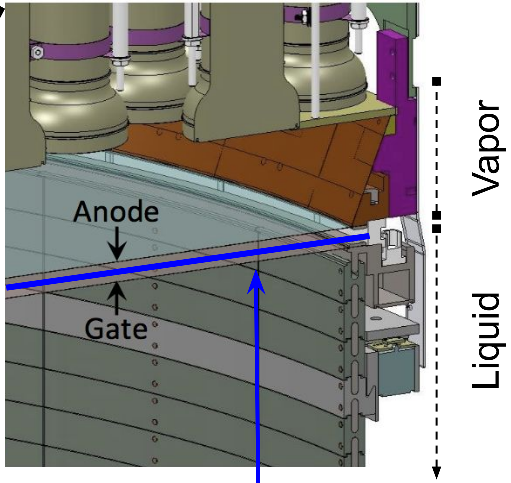
1.5 m dia x 1.5 m height

PTFE everywhere for light collection

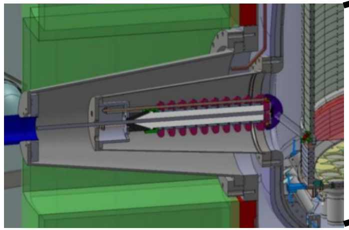
7 T active LXe (5.5 T fiducial)

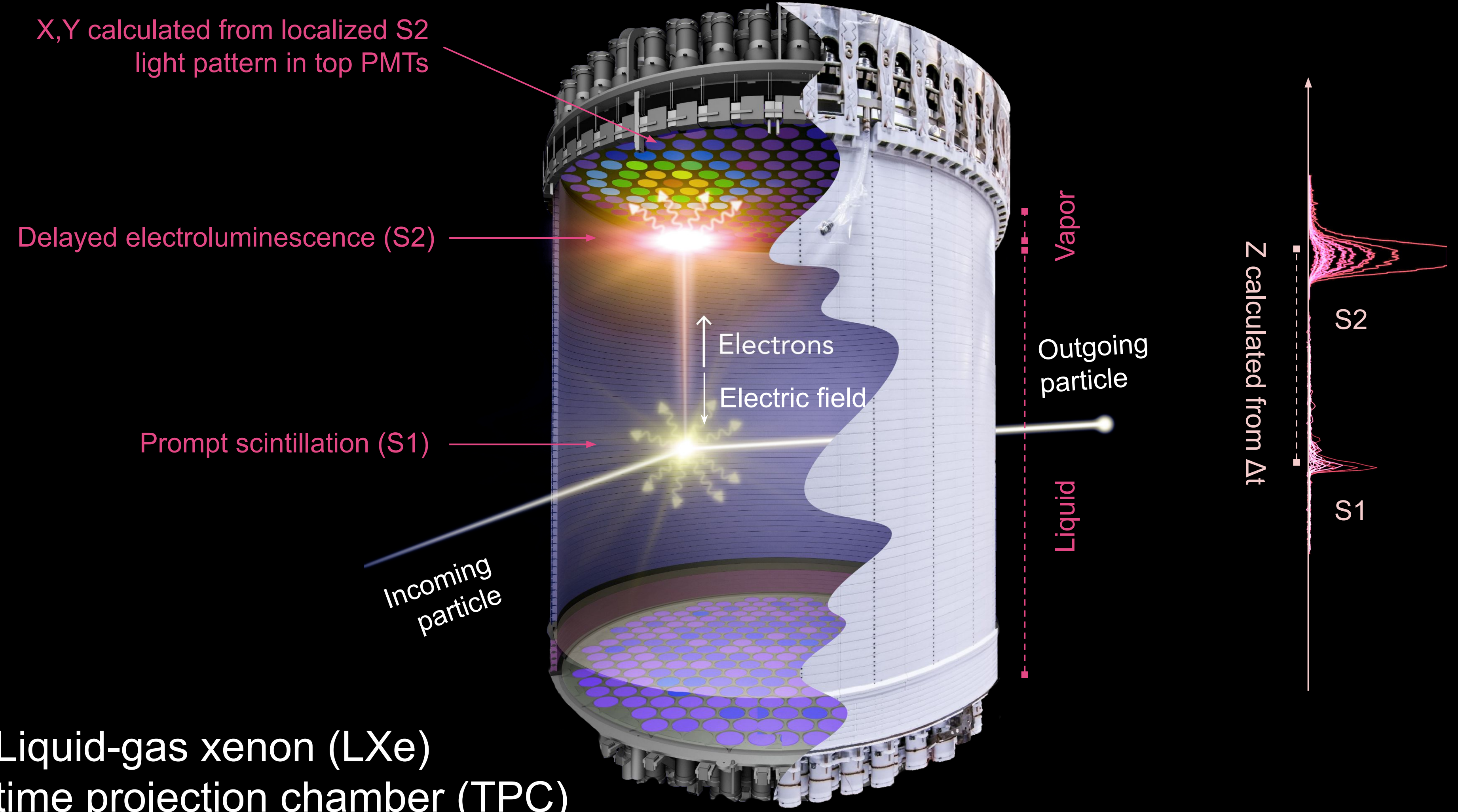
4x wire-grid electrodes
- E_{drift} = 193 V/cm
- ER/NR discrimination = 99.9%
- $E_{ext,gas}$ = 7.3 kV/cm
- Extraction efficiency = 80.5%





Cathode HV connection





Liquid-gas xenon (LXe) time projection chamber (TPC)

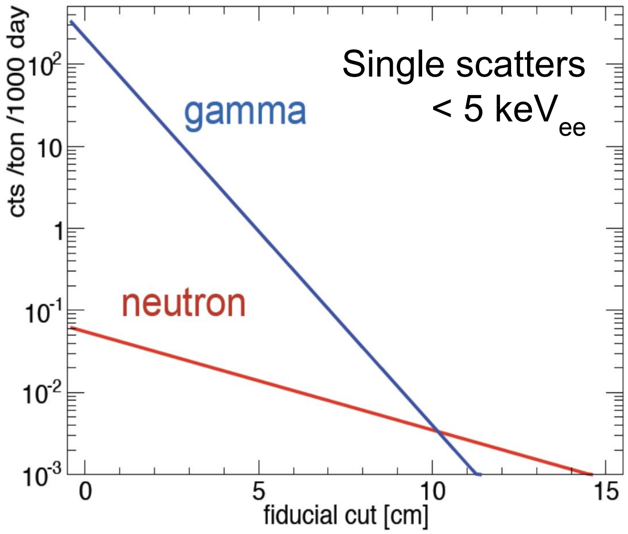
Fiducialization

Xenon is dense, ~ 3 g/cm^3

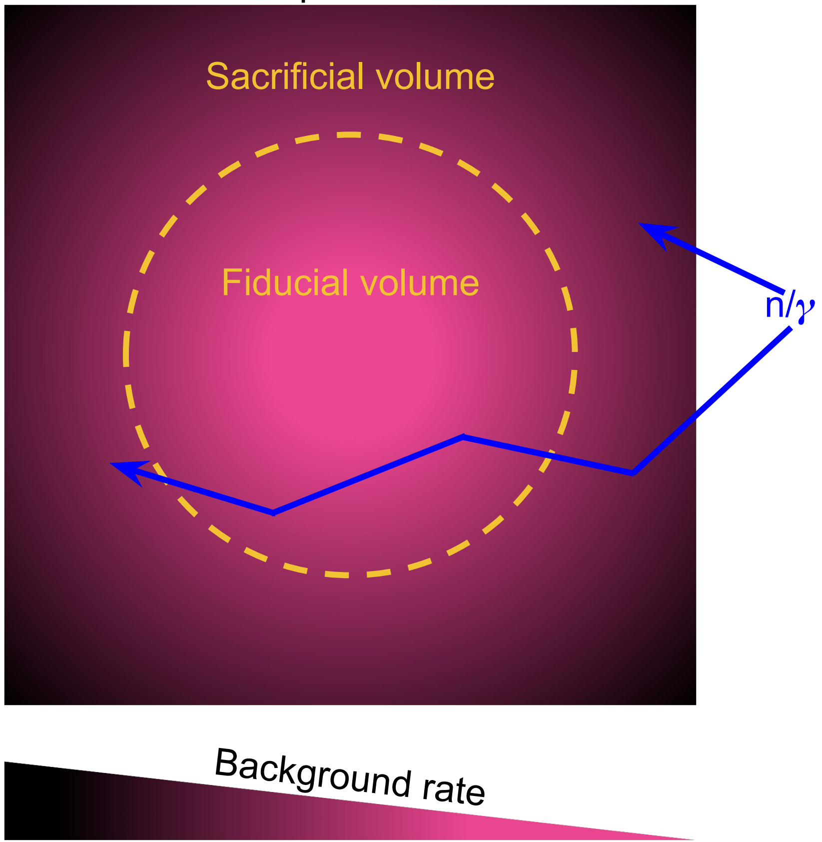
Short n/γ attenuation length (~few cm for γ) compared to size of LZ TPC (1.5 m x 1.5 m)

Reject events from the high-background rate regions near the edge of the TPC

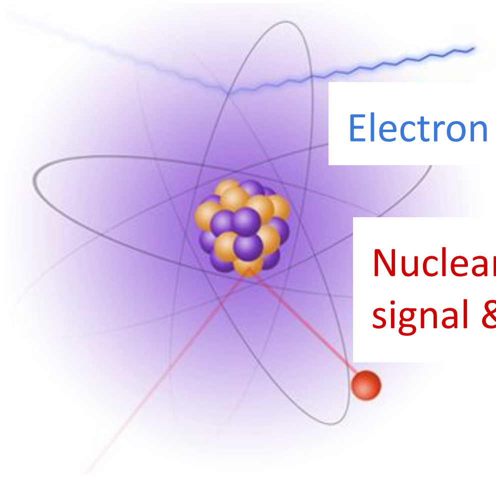
Reject multiple scatters



Liquid xenon

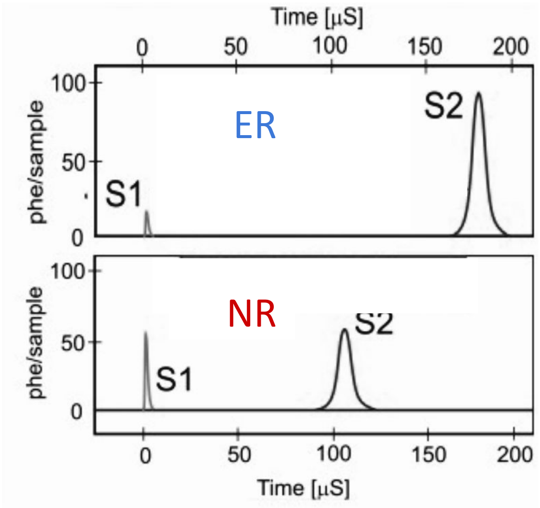


Electron/nuclear recoil discrimination

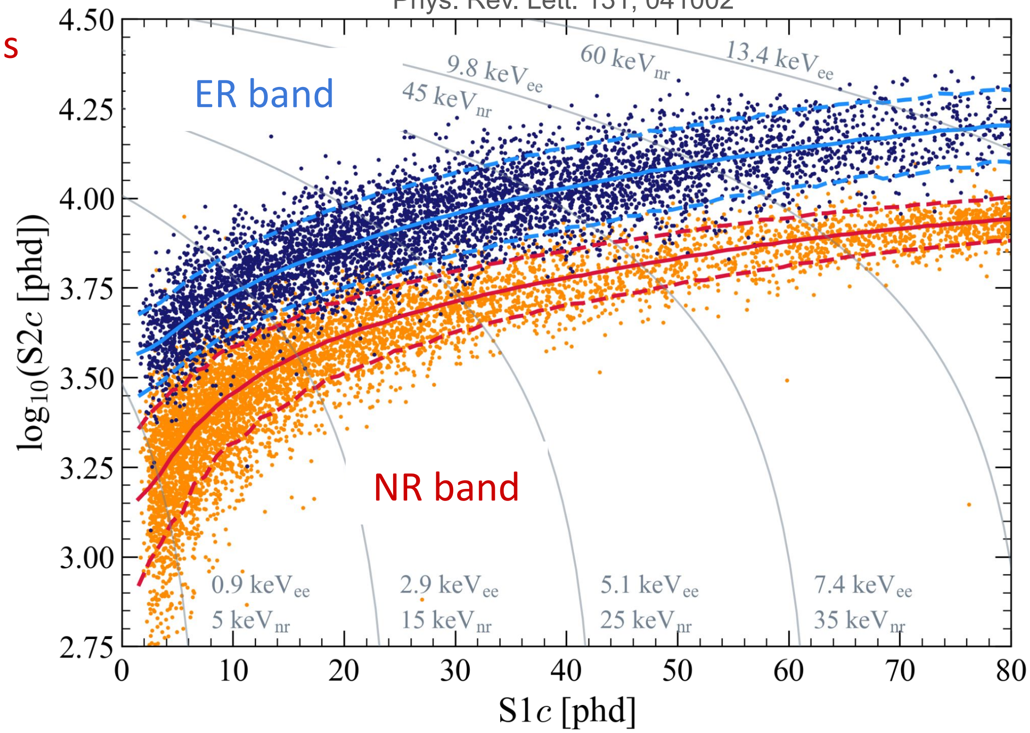


Electron recoil (ER) γ/β backgrounds

Nuclear recoil (NR) WIMP signal & neutron backgrounds



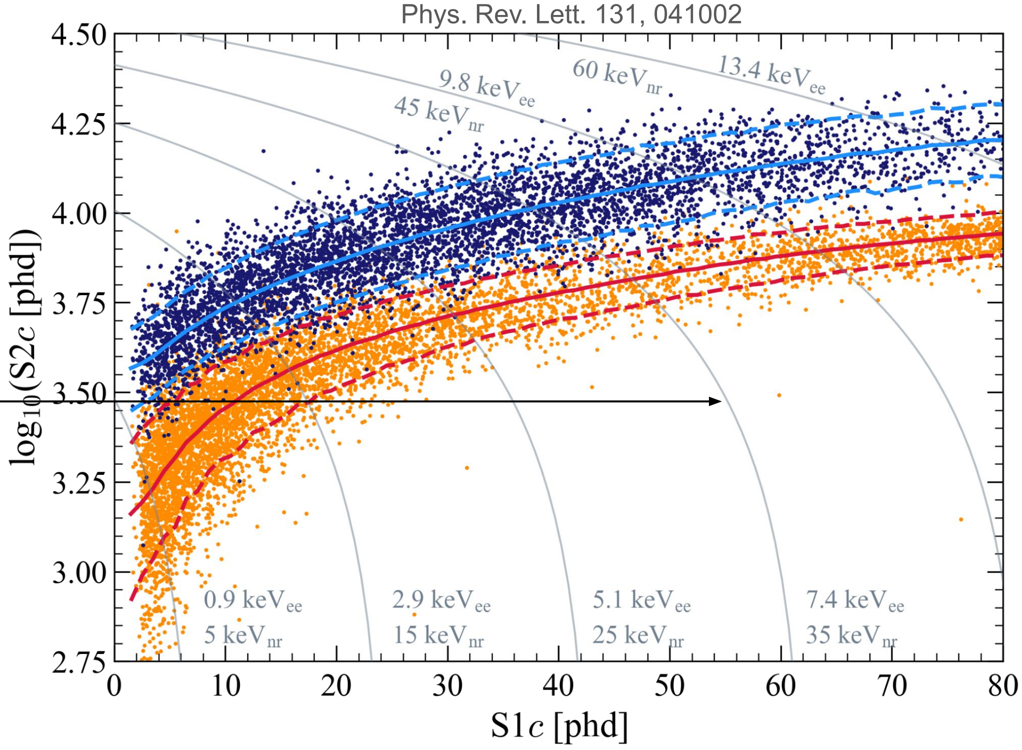
Phys. Rev. Lett. 131, 041002



LZ calibrations

Parameter	Value
g_1^{gas}	0.0921 phd/photon
g_1	0.1136 phd/photon
Effective gas extraction field	8.42 kV/cm
Single electron	58.5 phd
Extraction Efficiency	80.5 %
g_2	47.07 phd/electron

$$E = W\left(\frac{S_1}{g_1} + \frac{S_2}{g_2}\right)$$



W = *average energy per quantum*

g_1 = *light gain*

g_2 = *charge gain*

LZ calibrations

Noble Element Simulation Technique (NEST) to model response of the detector to electron/nuclear recoils
https://doi.org/10.5281/zenodo.6634896

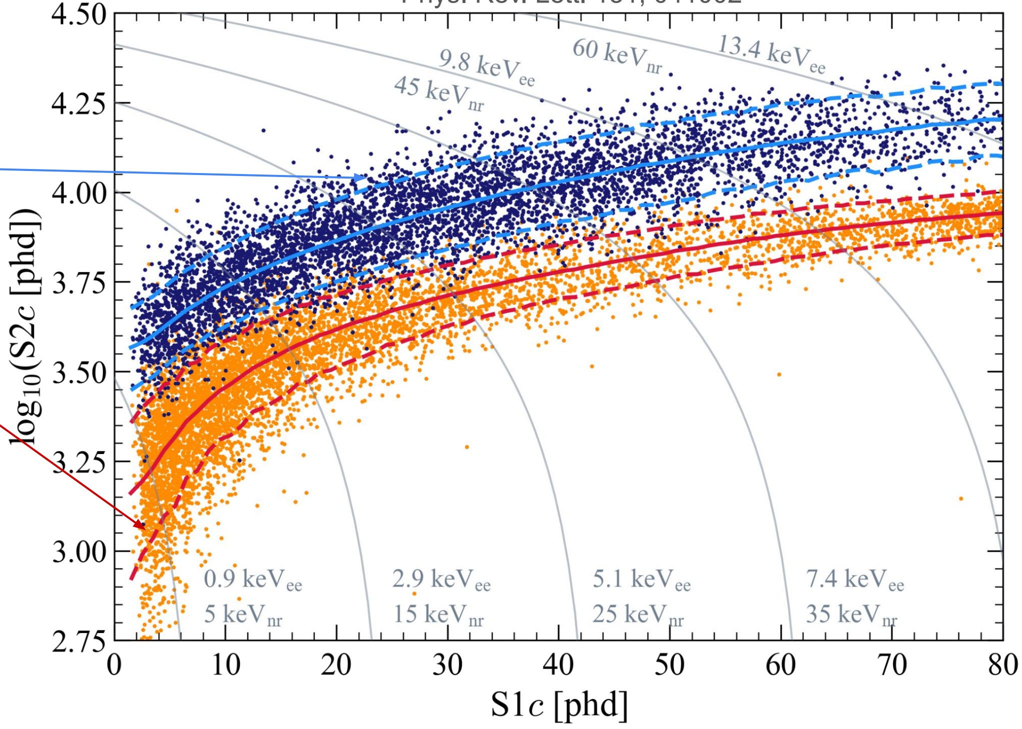
CH_3T (Q_β=18.6 keV) used to tune parameters of NEST

DD neutrons (2.45 MeV) to validate NR band model

- ER/NR band mean
- - 10 & 90% contours

99.9% rejection of ERs below the median of a 40 GeV WIMP signal

Phys. Rev. Lett. 131, 041002



LZ background model

Detector material γ rays (< 1%)

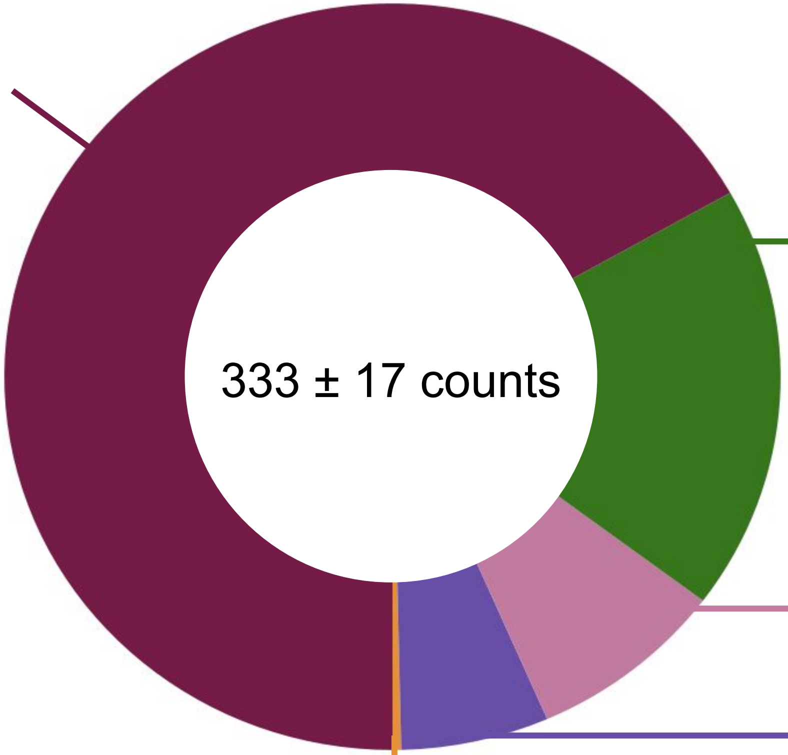
- ^{238}U
- ^{232}Th
- ^{40}K
- ^{60}Co

Dissolved radio-contaminates

- 76% ^{214}Pb (^{222}Rn daughter)
- 8% ^{212}Pb (^{220}Rn daughter)
- 15% ^{85}Kr

Accidental coincidences of isolated S1s and S2s

Neutrons (^{235}U & α,n reactions)



Activation of the xenon

- ^{37}Ar ($t_{1/2}$= 35 d)
- ^{127}Xe ($t_{1/2}$= 36 d)

Solar ν-e/-nuclear scattering

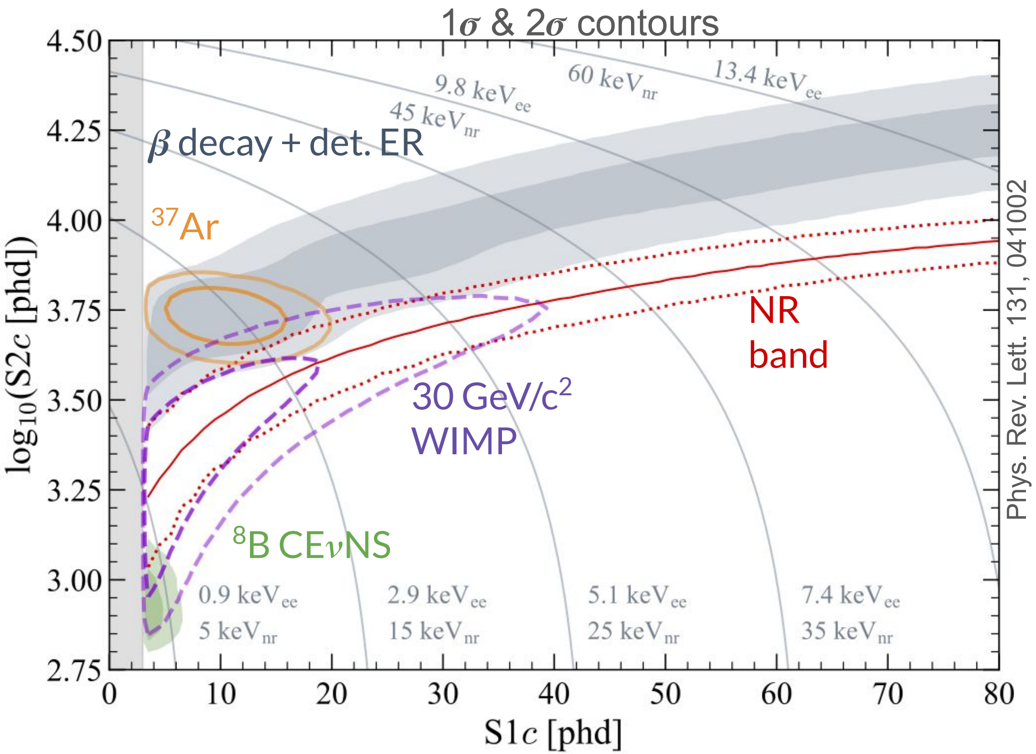
- pp
- ^{7}Be
- CNO
- ^{8}B

Rare decays

- ^{124}Xe ($t_{1/2}$=1.8x10^{22} y)
- ^{136}Xe ($t_{1/2}$=2.1x10^{21} y)

LZ background model

Source	Expected Events
β decays + Det. ER	218 ± 36
ν ER	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8
^{124}Xe	5.0 ± 1.4
^{136}Xe	15.2 ± 2.4
^{8}B CEνNS	0.15 ± 0.01
Accidentals	1.2 ± 0.3
Subtotal	276 ± 36
^{37}Ar	[0, 291]
Detector neutrons	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–
Total	–

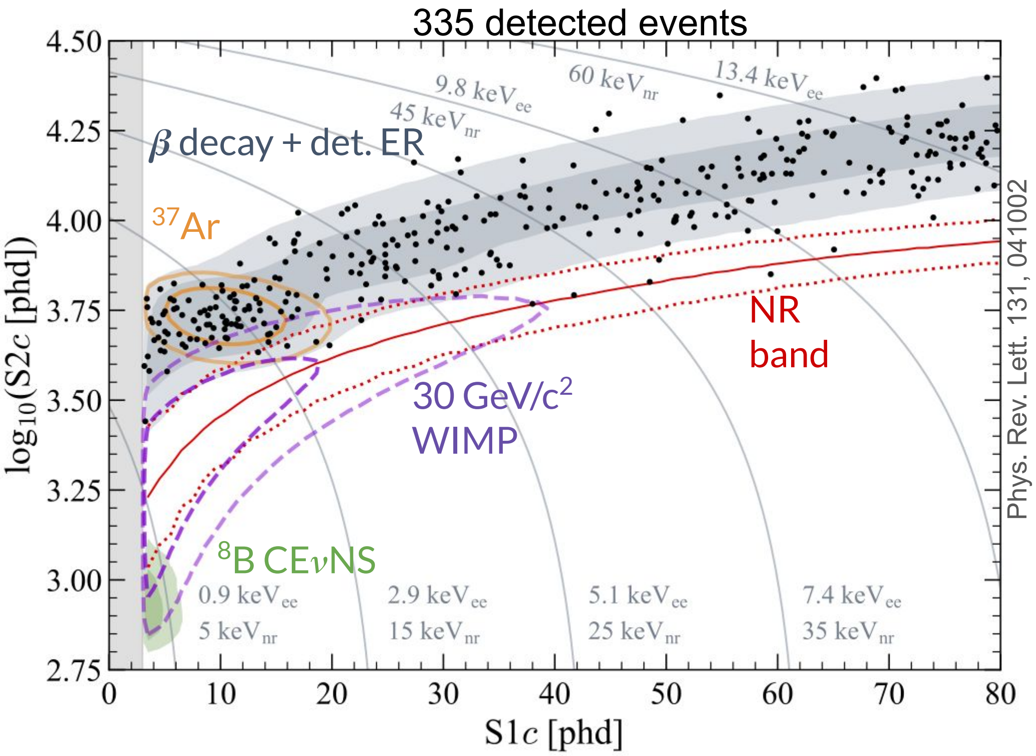


Predictions from:

- Material radioassays
- Calculations of cosmogenic activation
- Side bands of LZ data

LZ fit results

Source	Expected Events	Best Fit
β decays + Det. ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.2 ± 2.4	15.3 ± 2.4
^{8}B CEνNS	0.15 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	276 ± 36	281 ± 16
^{37}Ar	[0, 291]	$52.1^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17

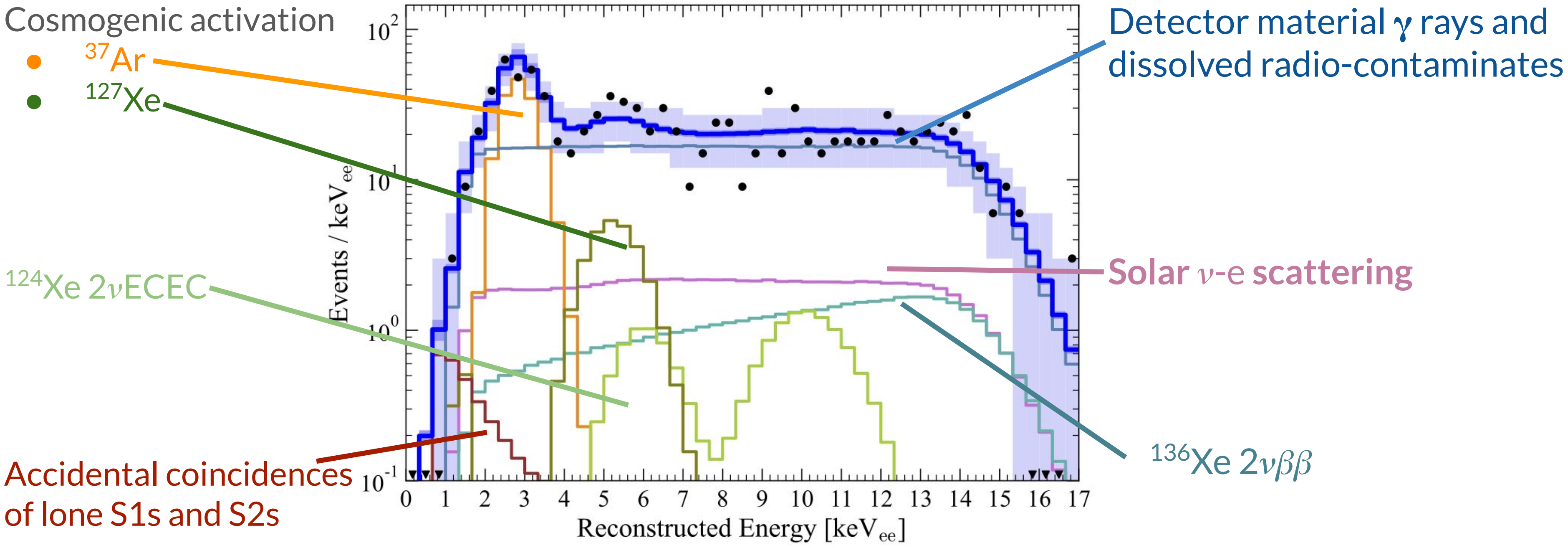


Phys. Rev. Lett. 131, 041002

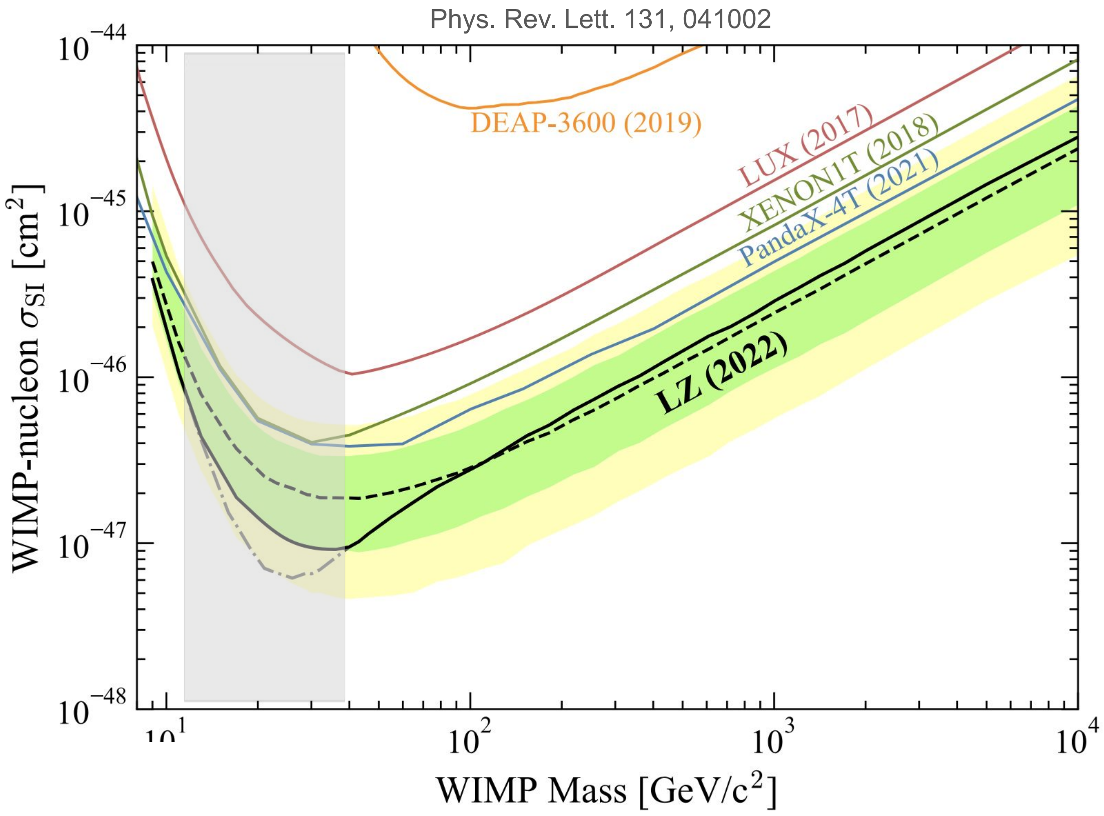
For every WIMP mass best fit result is consistent with 0

LZ fit results

Phys. Rev. Lett. 131, 041002



World-leading WIMP sensitivity



Extended unbinned profile likelihood statistic in $\log_{10}$S2-S1 observable space

Two-sided with 90% CL bounds

Power constrained with $\pi_{crit} = 0.16$

-- Median projected sensitivity
– Limit

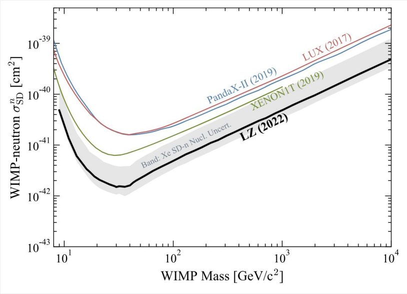
5.5 T fiducial volume, 60 livedays, 5.2 keV_{nr} threshold

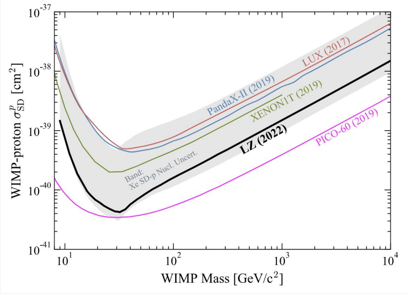
Probing new parameter space even with only 6% of the final exposure

Did NOT perform bias mitigation by salting or blinding but did define our cuts on sidebands and calibration data

Many additional DM searches!

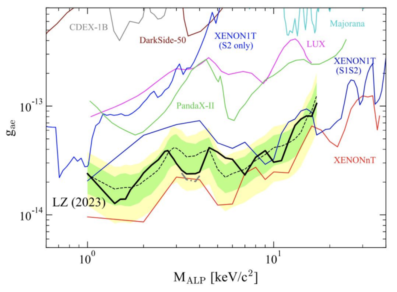
Spin-dependent WIMP interactions

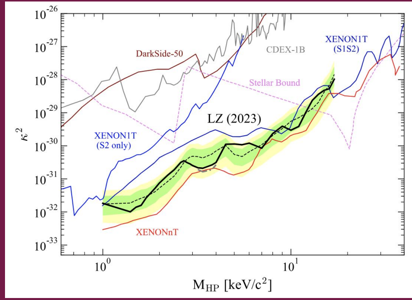




Phys. Rev. Lett. 131, 041002

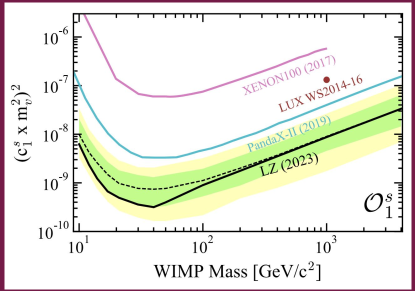
New physics in low-energy ERs

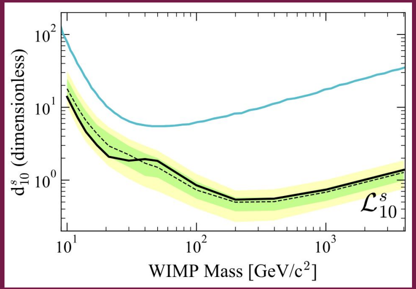




Phys. Rev. D 108, 072006

WIMP-nucleon EFT couplings

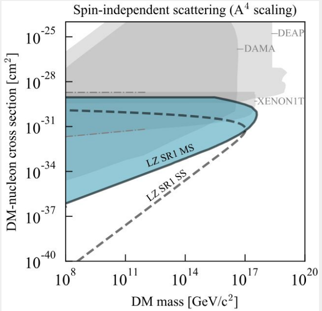


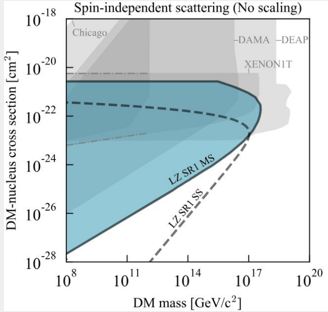


Phys. Rev. D 109, 092003

arXiv:2404.17666

Ultra-heavy dark matter

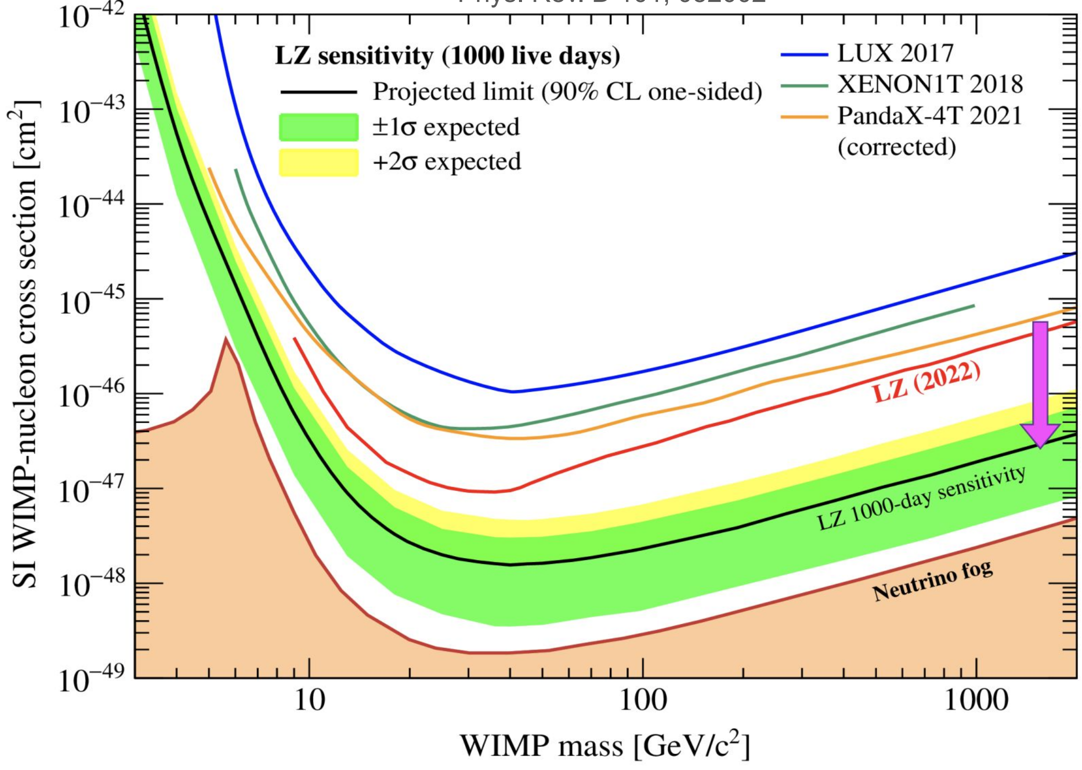




Accepted to Phys. Rev. D

LZ and beyond

Phys. Rev. D 101, 052002



1. Completed first 90 day engineering run but this corresponds to just 6% of our target exposure
2. Ultimate goal to accumulate 1000 livedays
3. Continue producing scientific results with existing data
4. Look further into the future

Memorandum of understanding towards a next-generation LXe experiment

XENON

Currently operating with 8.5 tonnes of liquid Xenon at Gran Sasso in Italy

LUX-ZEPLIN

Currently operating with 10 tonnes of liquid Xenon at SURF in South Dakota

DARWIN

Leading many R&D projects designing a future 50 tonnes liquid Xenon detector

More than 100 senior scientists from 16 countries signed MoU on 6th of July 2021

XENON + LUX-ZEPLIN + DARWIN → XLZD

First meeting of the XLZD consortium in June 2022

Two additional meetings, including one at RAL in 2024

Website: https://xlzd.org/

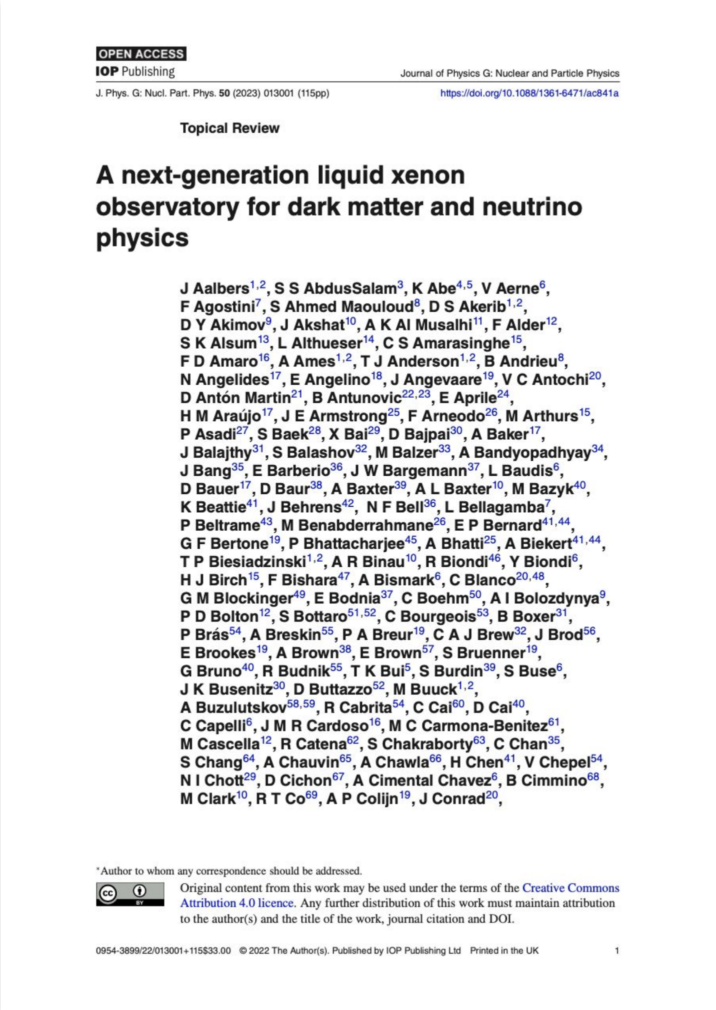
Science with liquid xenon

White paper published in J. Phys. G: Nucl. Part. Phys. 50 013001 (2023) (particular thanks to Rafael Lang, Purdue)

~600 authors from 145 institutes

72 UK authors from 13 institutes

Details the breadth of physics enabled by a next-generation xenon observatory


OPEN ACCESS
IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 50 (2023) 013001 (115pp)
https://doi.org/10.1088/1361-6471/ac841a

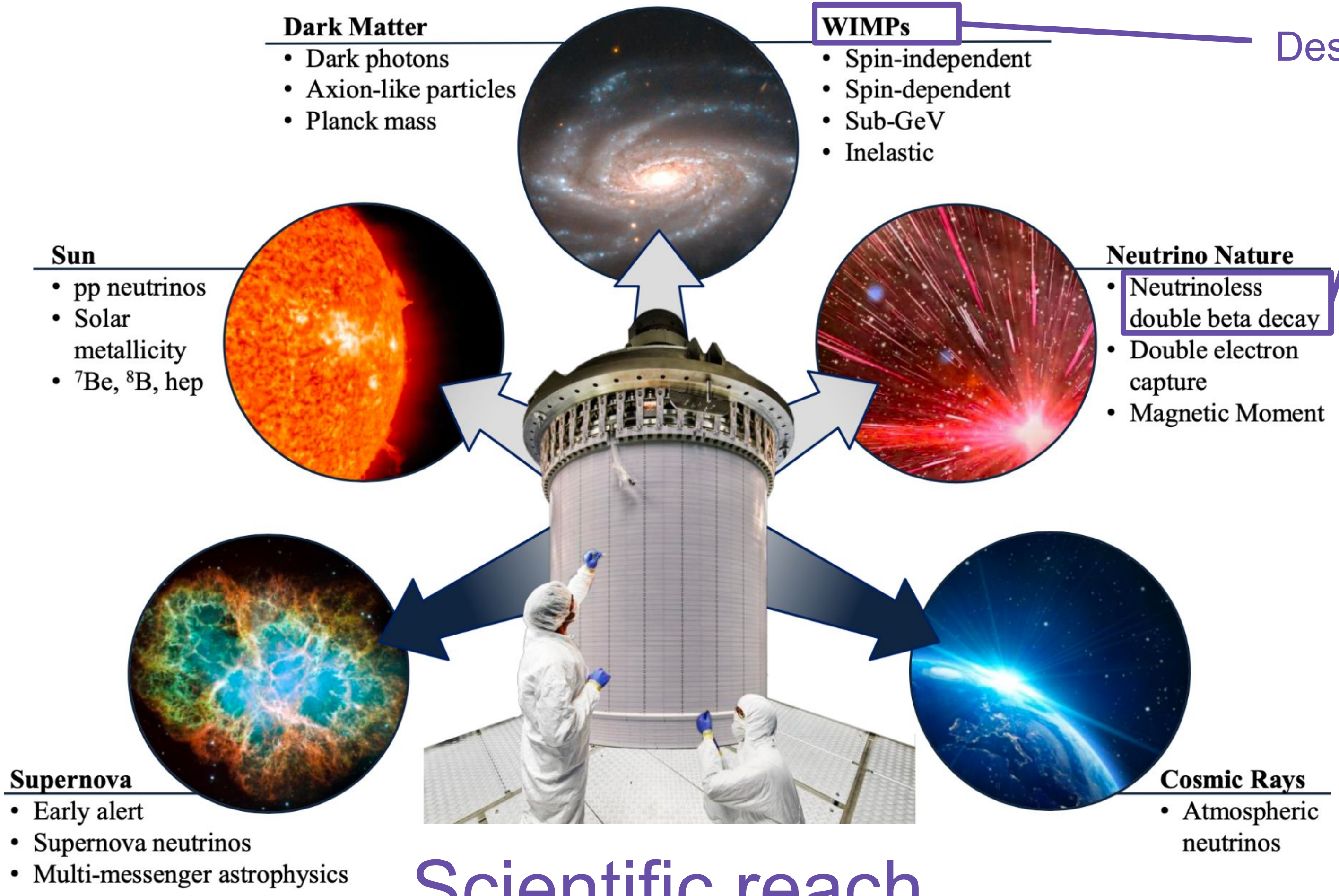
Topical Review

A next-generation liquid xenon observatory for dark matter and neutrino physics

J Aalbers[1,2], S S AbdusSalam[3], K Abe[4,5], V Aerne[6], F Agostini[7], S Ahmed Maouloud[8], D S Akerib[1,2], D Y Akimov[9], J Akshat[10], A K Al Musalhi[11], F Alder[12], S K Alsum[13], L Althueser[14], C S Amarasinghe[15], F D Amaro[16], A Ames[1,2], T J Anderson[1,2], B Andrieu[8], N Angelides[17], E Angelino[18], J Angevaare[19], V C Antochi[20], D Antón Martin[21], B Antunovic[22,23], E Aprile[24], H M Araújo[17], J E Armstrong[25], F Arneodo[26], M Arthurs[15], P Asadi[27], S Baek[28], X Bai[29], D Bajpai[30], A Baker[17], J Balajthy[31], S Balashov[32], M Balzer[33], A Bandyopadhyay[34], J Bang[35], E Barberio[36], J W Bargemann[37], L Baudis[6], D Bauer[17], D Baur[38], A Baxter[39], A L Baxter[10], M Bazyk[40], K Beattie[41], J Behrens[42], N F Bell[36], L Bellagamba[7], P Beltrame[43], M Benabderrahmane[26], E P Bernard[41,44], G F Bertone[19], P Bhattacharjee[45], A Bhatti[25], A Biekert[41,44], T P Biesiadzinski[1,2], A R Binau[10], R Biondi[46], Y Biondi[6], H J Birch[15], F Bishara[47], A Bismark[6], C Blanco[20,48], G M Blockinger[49], E Bodnia[37], C Boehm[50], A I Bolozdynya[9], P D Bolton[12], S Bottaro[51,52], C Bourgeois[53], B Boxer[31], P Brás[54], A Breskin[55], P A Breur[19], C A J Brew[32], J Brod[56], E Brookes[19], A Brown[38], E Brown[57], S Bruenner[19], G Bruno[40], R Budnik[55], T K Bui[5], S Burdin[39], S Buse[6], J K Busenitz[30], D Buttazzo[52], M Buuck[1,2], A Buzulutskov[58,59], R Cabrita[54], C Cai[60], D Cai[40], C Capelli[6], J M R Cardoso[16], M C Carmona-Benitez[61], M Cascella[12], R Catena[62], S Chakraborty[63], C Chan[35], S Chang[64], A Chauvin[65], A Chawla[66], H Chen[41], V Chepel[54], N I Chott[29], D Cichon[67], A Cimental Chavez[6], B Cimmino[68], M Clark[10], R T Co[69], A P Colijn[19], J Conrad[20],

*Author to whom any correspondence should be addressed.

0954-3899/22/013001+115$33.00 © 2022 The Author(s). Published by IOP Publishing Ltd Printed in the UK 1



Design drivers

Scientific reach

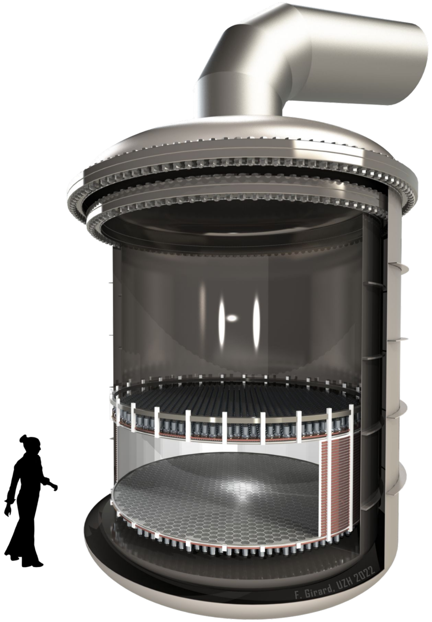
XLZD detector

Baseline target mass: 60 T

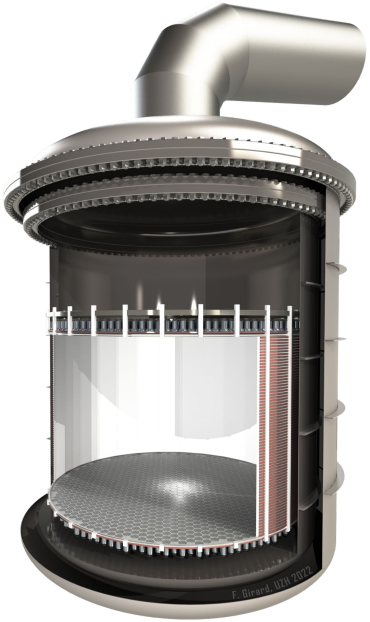
Compact: ~4 m diameter x height

Adjustable detector: options for shorter or taller TPC

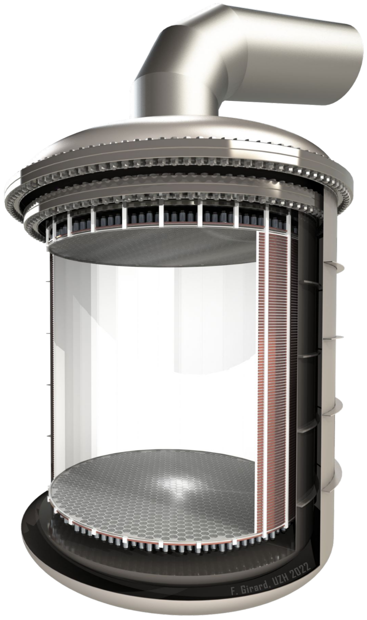
Allows us to operate initially with a smaller amount of xenon: identify and fix problems



Interim (20+ T)



Baseline (60 T)

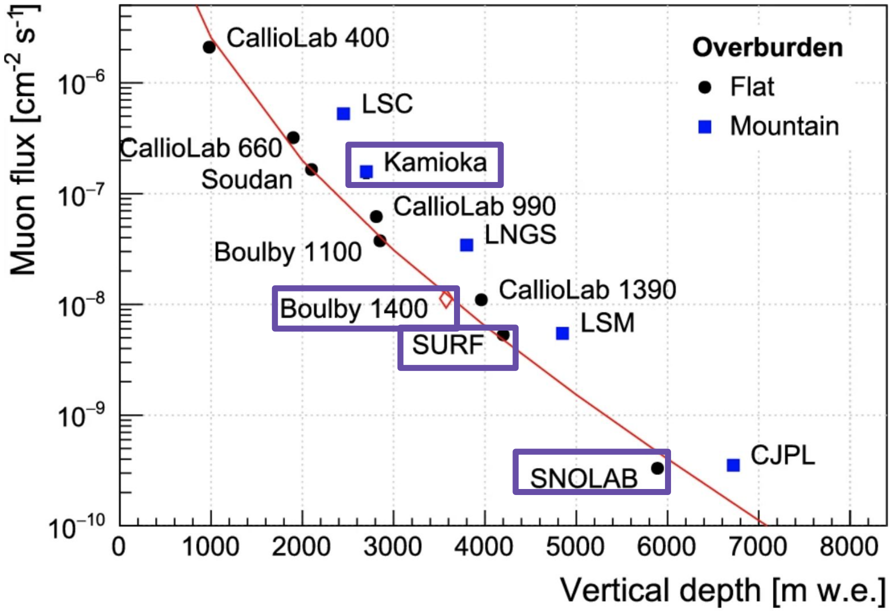


Optimistic (80 T)

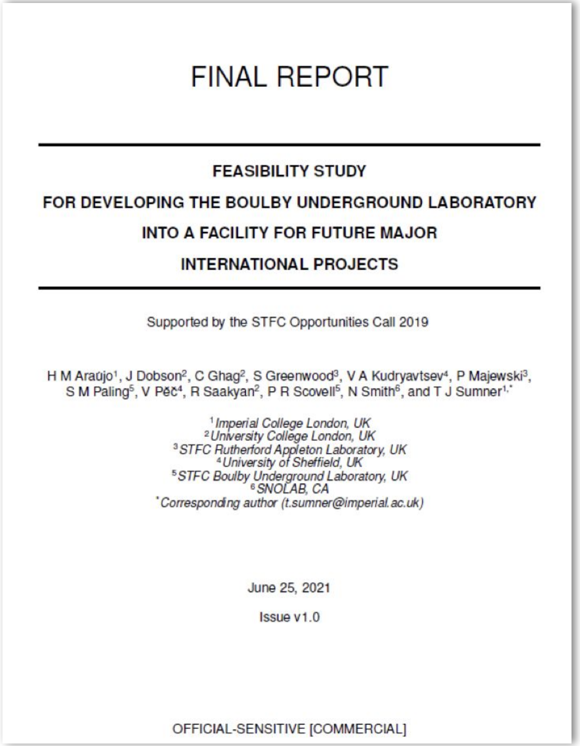
Siting

Considering 5 underground sites

Detector size requires significant space for clean underground fabrication



Eur. Phys. J. C 84, 481 (2024)


FINAL REPORT

FEASIBILITY STUDY

FOR DEVELOPING THE BOULBY UNDERGROUND LABORATORY

INTO A FACILITY FOR FUTURE MAJOR

INTERNATIONAL PROJECTS

Supported by the STFC Opportunities Call 2019

H M Araújo[1], J Dobson[2], C Ghag[2], S Greenwood[3], V A Kudryavtsev[4], P Majewski[3], S M Paling[5], V Pěč[4], R Saakyan[2], P R Scovell[5], N Smith[6], and T J Sumner[1,*]

[1] *Imperial College London, UK*
[2] *University College London, UK*
[3] *STFC Rutherford Appleton Laboratory, UK*
[4] *University of Sheffield, UK*
[5] *STFC Boulby Underground Laboratory, UK*
[6] *SNOLAB, CA*
[*] *Corresponding author (t.sumner@imperial.ac.uk)*

June 25, 2021

Issue v1.0

OFFICIAL-SENSITIVE [COMMERCIAL]

2019-21 Boulby feasibility study indicated technical viability

A challenge, but a great opportunity

XLZD WIMP Backgrounds

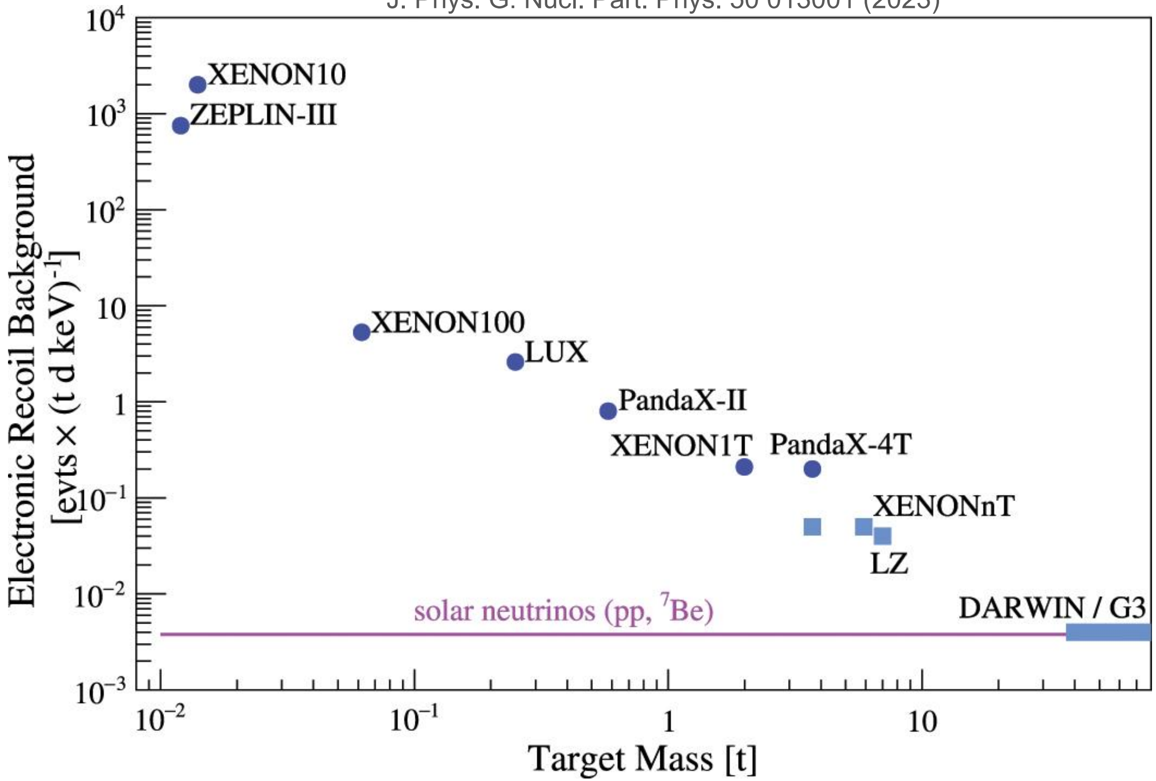
Goal is to be dominated by astrophysical neutrino backgrounds

Self-shielding from γ-ray and neutron backgrounds

^{85}Kr purity levels sufficient for next generation achieved

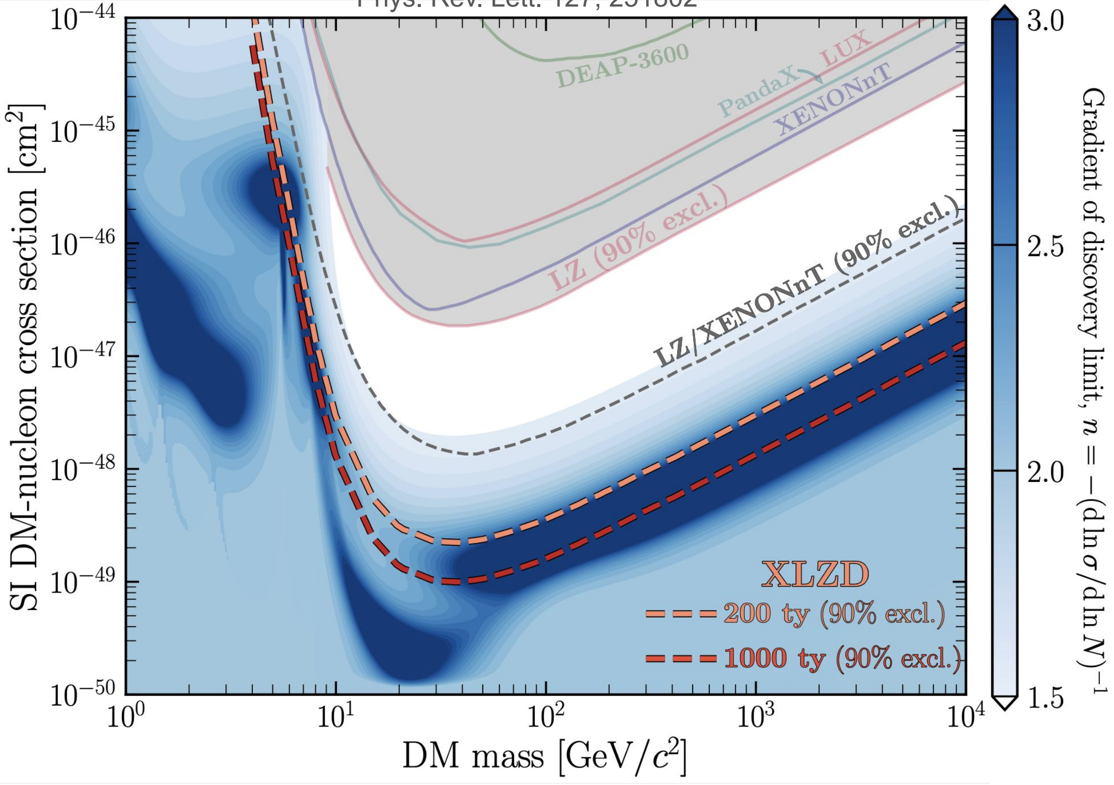
^{222}Rn is challenging but there is ongoing R&D

J. Phys. G: Nucl. Part. Phys. 50 013001 (2023)



Chasing WIMPs to the Neutrino Fog

J. Phys. G: Nucl. Part. Phys. 50 013001 (2023)
Phys. Rev. Lett. 127, 251802



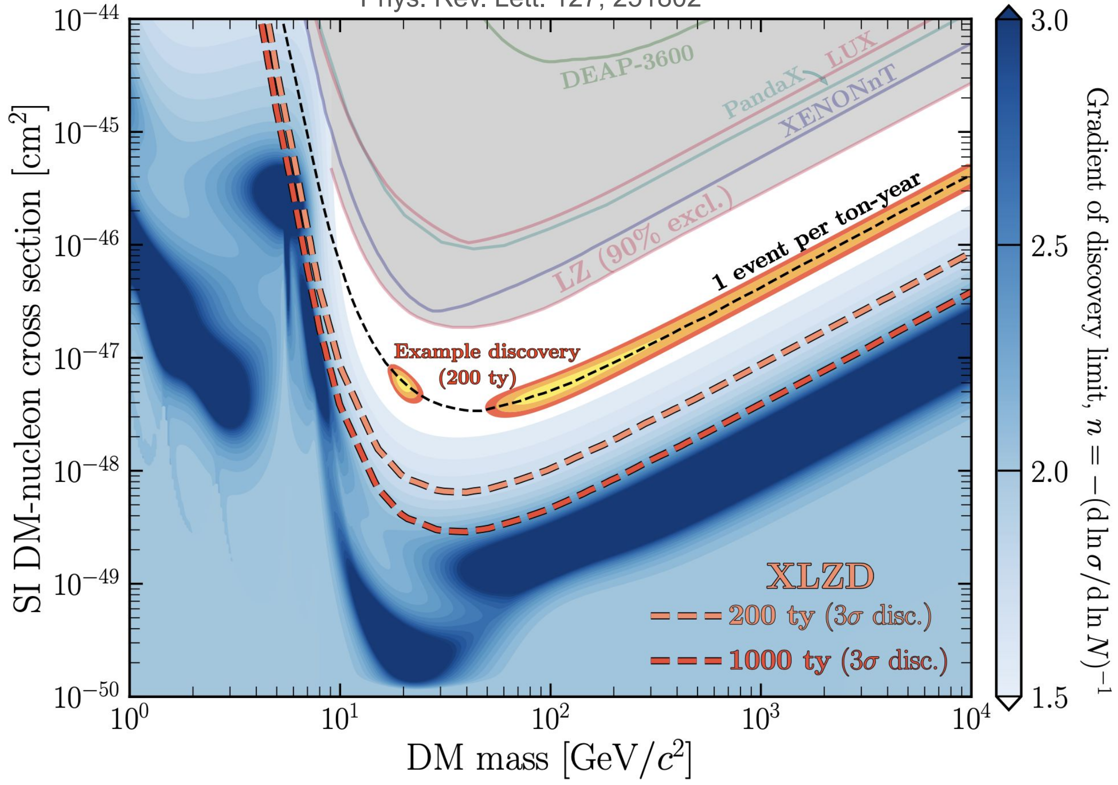
WIMP projected sensitivity

Background assumptions

- Coherent ^{8}B, HEP, diffuse supernovae, atmospheric ν-nucleus scattering
- Solar ν-e scattering
- $2\nu\beta\beta$ of ^{136}Xe at natural abundance

Chasing WIMPs to the Neutrino Fog

J. Phys. G: Nucl. Part. Phys. 50 013001 (2023)
Phys. Rev. Lett. 127, 251802

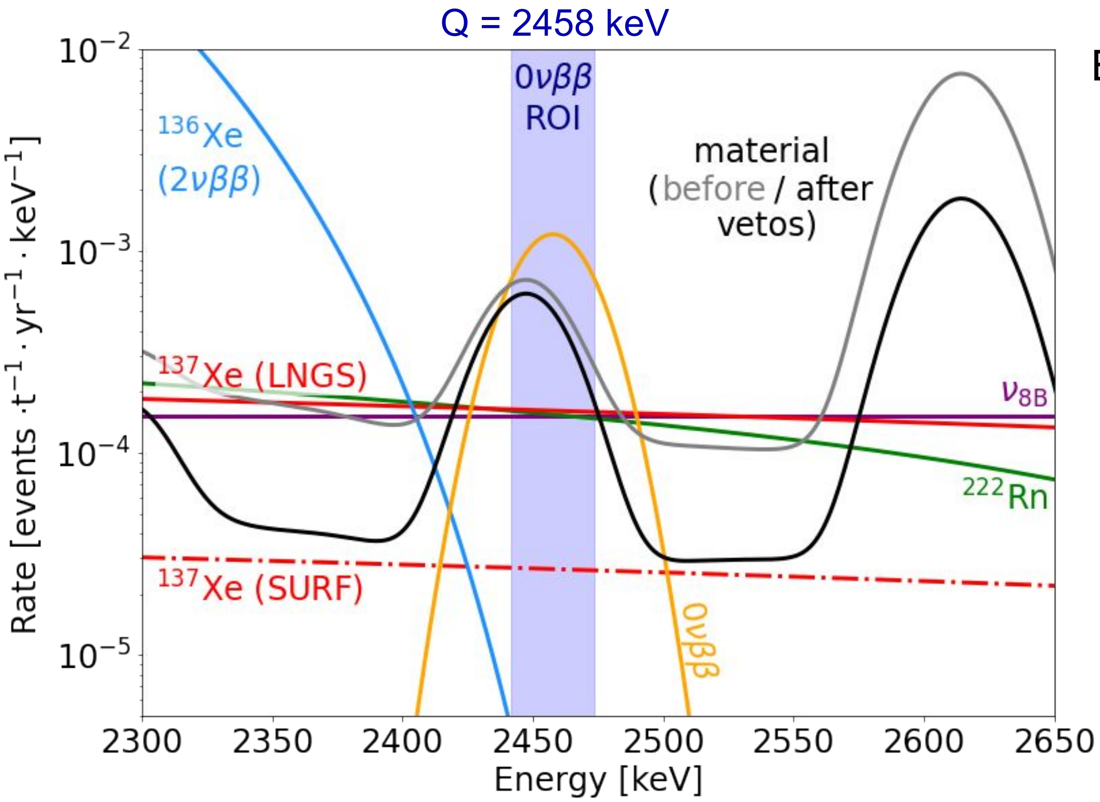


WIMP 3σ discovery potential

Background assumptions

- Coherent ^{8}B, HEP, diffuse supernovae, atmospheric ν-nucleus scattering
- Solar ν-e scattering
- $2\nu\beta\beta$ of ^{136}Xe at natural abundance

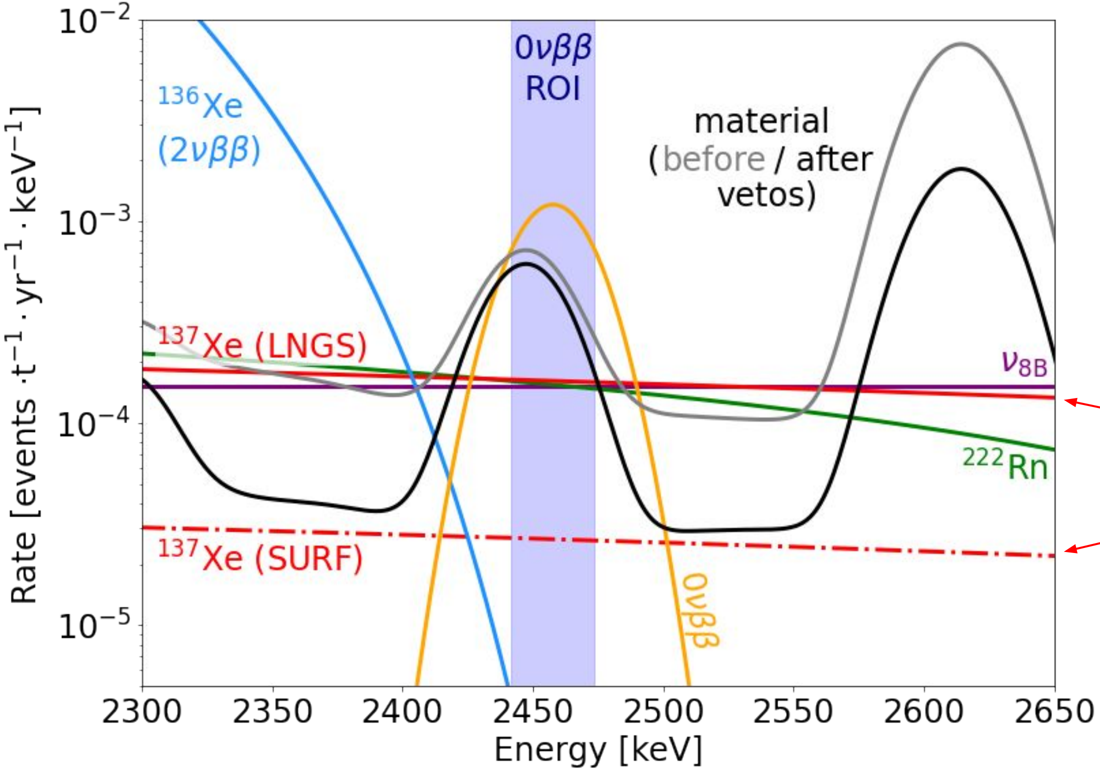
Chasing ^{136}Xe $0\nu\beta\beta$ to Exhaustion



Background assumptions

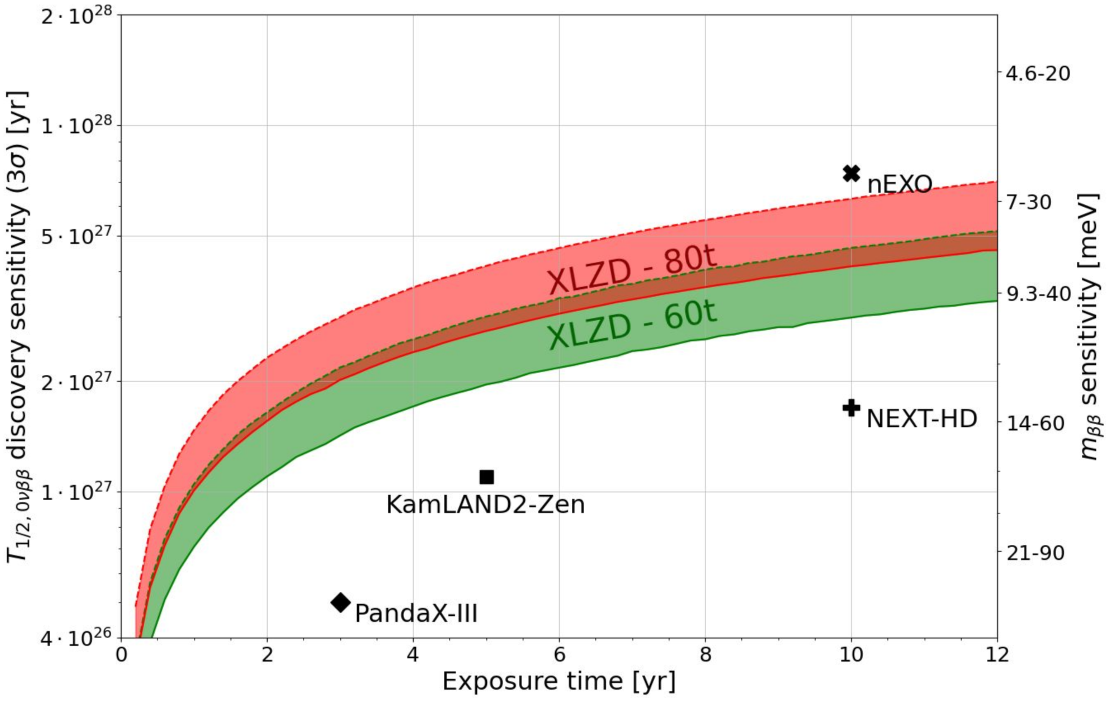
- $2\nu\beta\beta$ impact mitigated by ~0.6 σ/E
- 0.1 μBq/kg ^{222}Rn chain → ^{214}Bi (Q_β=3270 keV)
- ^{214}Bi γ ray (2447 keV) from materials mitigated by self shielding of large detector
- ^{137}Xe (Q_β=4173 keV) from capture of cosmogenic muon induced neutrons on ^{136}Xe

Chasing ^{136}Xe $0\nu\beta\beta$ to Exhaustion



Location	Muon flux ($m^{-2}d^{-1}$)
Kamioka	128
LNGS	29.7
Boulby	14.6
SURF	4.6
SNOLAB	0.3

Chasing ^{136}Xe $0\nu\beta\beta$ to Exhaustion



Baseline (-) and optimistic (---) scenarios

- 0.65% → 0.6% σ/E
- LNGS → SURF cosmogenics
- 99.95% → 99.99% ^{214}Bi β tagging
- 3x improvement in material backgrounds, primarily photosensors

Summary

1. LZ is operating and taking high quality physics data
   a. All detectors are performing well
   b. Backgrounds are within expectation

2. With 6% of final exposure, we’ve achieved world-leading WIMP sensitivity

3. Broad physics program still lies ahead for LZ

4. The xenon community is uniting into the XLZD Consortium to build the ultimate xenon rare event observatory

Thank you

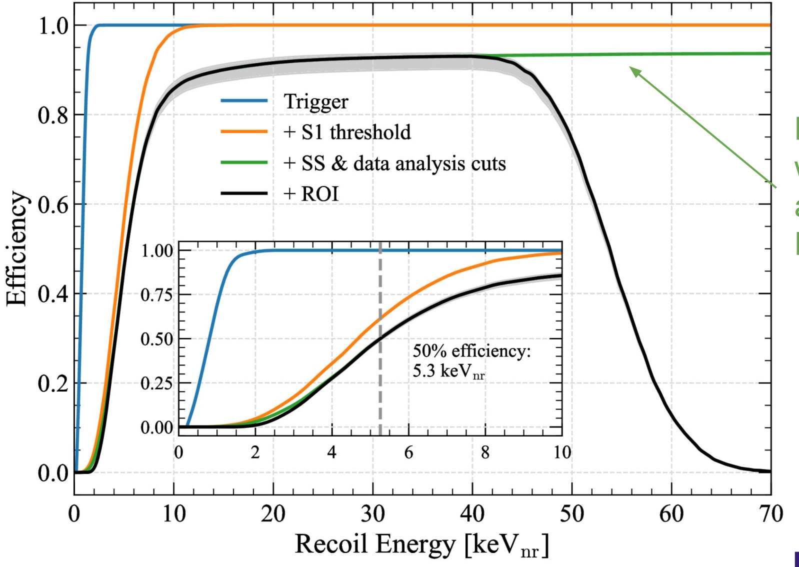
Additional Slides

LZ data quality

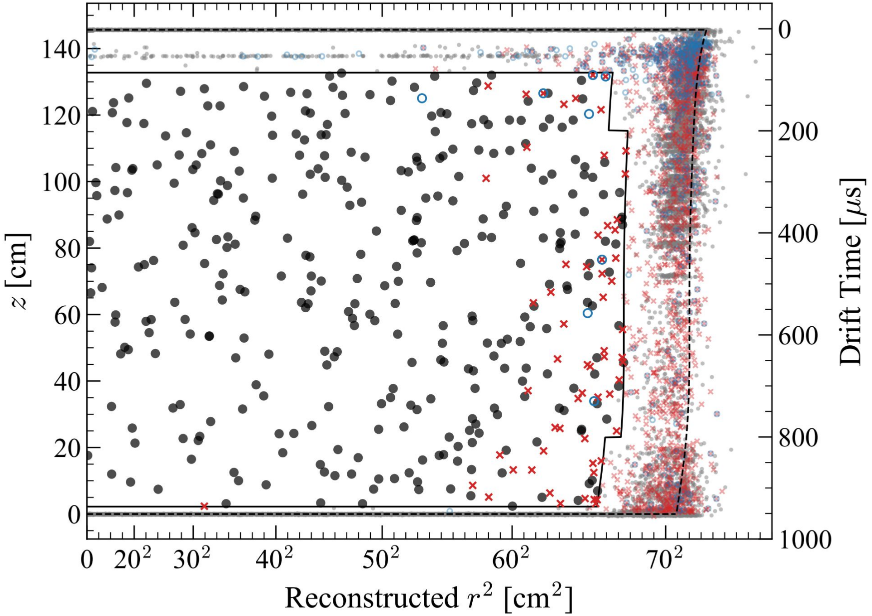
Fiducial volume cut: 7 → 5.5 ± 0.2 T

Livetime vetoes: 90 → 60 days

Waveform quality cuts



Measured with CH_3T and DD/AmLi

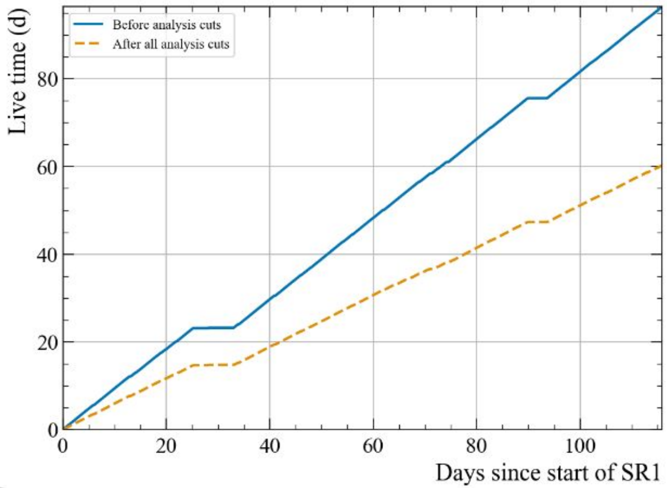


- Events surviving all selections
- Skin-prompt-tagged events
- OD-prompt-tagged events

Livetime

60 live days exposure after cuts collected over the beginning of 2022

The cuts form high rates of photons and electrons following larger S2 signals is dominant



Cause	Impact (%)
Hotspot cut	3.1
Muon event veto	0.2
Electron train	29.8
High S1 rates	0.2
Undetected muons	0.5
Electronics noise	<0.001
Veto cuts	5

Calibrations

- Many sources:
- **^{83m}Kr: monoenergetic ERs, 32.1 keV and 9.4 keV**
- **^{131m}Xe: monoenergetic ER, 164 keV**
- **CH_3T (tritium): beta spectrum - Q-value: 18.6 keV**
- **Deuterium-deuterium (DD): triggered 2.45 MeV neutrons**
- Activation lines
- AmLi: continuum neutrons, isotropic
- Radon chain alpha decays
- And more (^{220}Rn, YBe, ^{252}Cf, ^{22}Na, ^{228}Th, etc)
- Some uses:
  - Tune the position reconstruction algorithm in horizontal plane
  - Flat fielding of S1 and S2 signals
  - Energy reconstruction and detector response
  - Measure efficiencies

- Light gain g1: 0.114 ± 0.002 phd/photon
- Charge gain g2: 47.1 ± 1.1 phd/electron
- Single electron size: 58.5 phd

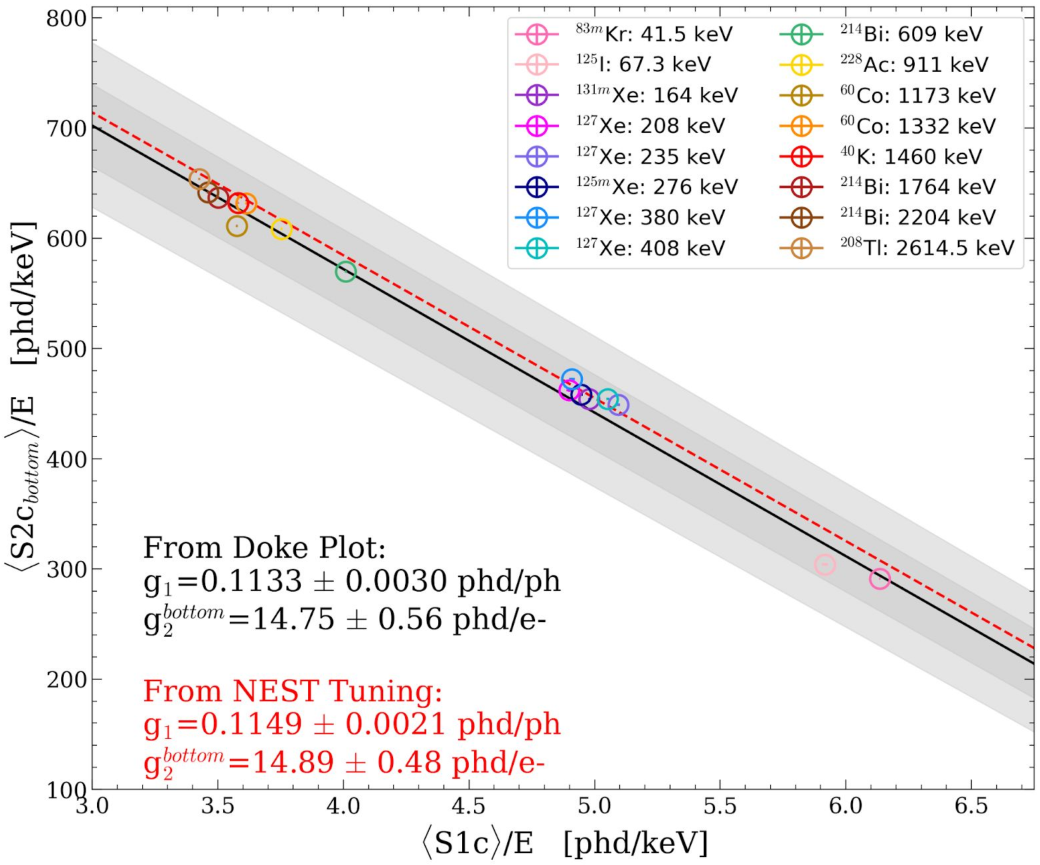
Doke Plot: energy calibration

$$E = W\left(\frac{S_1}{g_1} + \frac{S_2}{g_2}\right)$$

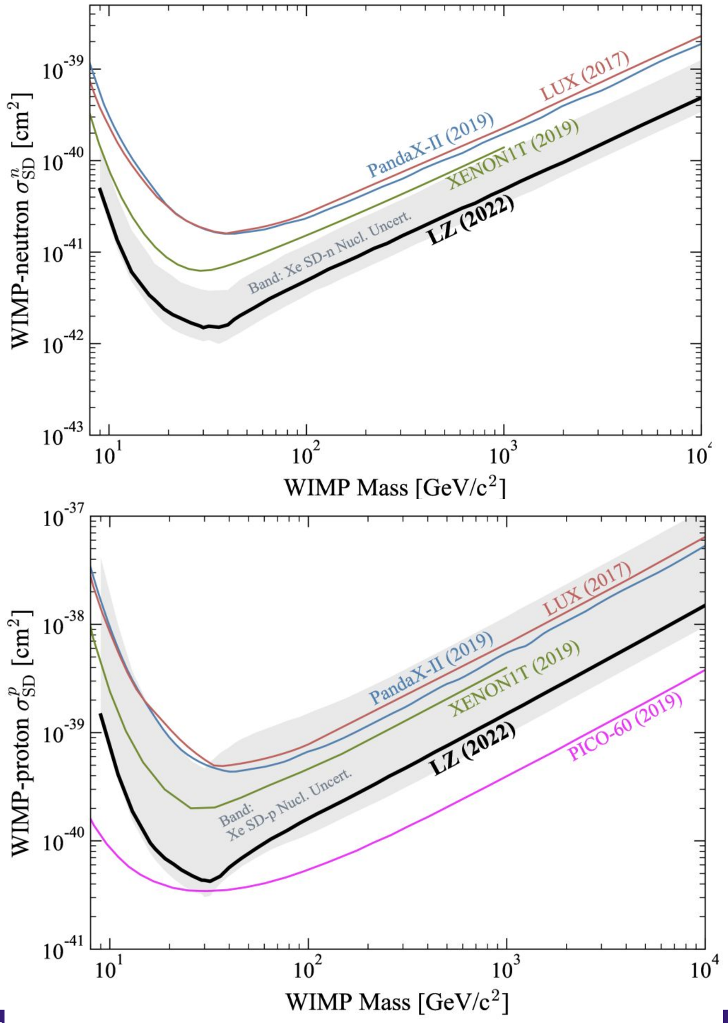
W = *average energy per quantum*

g_1 = *light gain*

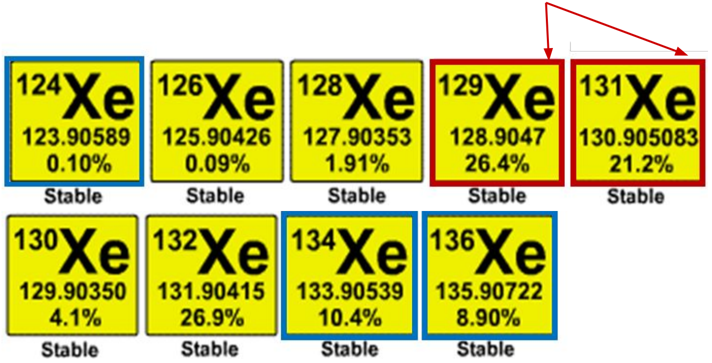
g_2 = *charge gain*



LZ spin-dependent WIMP sensitivity



Unpaired neutrons



Sensitivity to WIMP-p interactions through higher order nuclear effects, albeit with large uncertainty

Uncertainty bands represent theoretical uncertainty on nuclear form factor

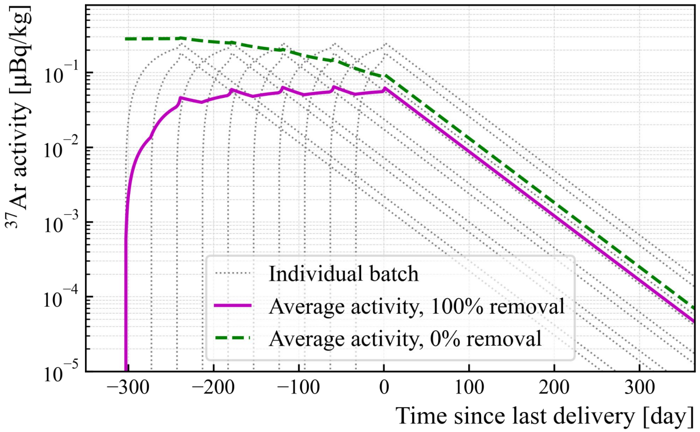
Xenon activation to ^{37}Ar

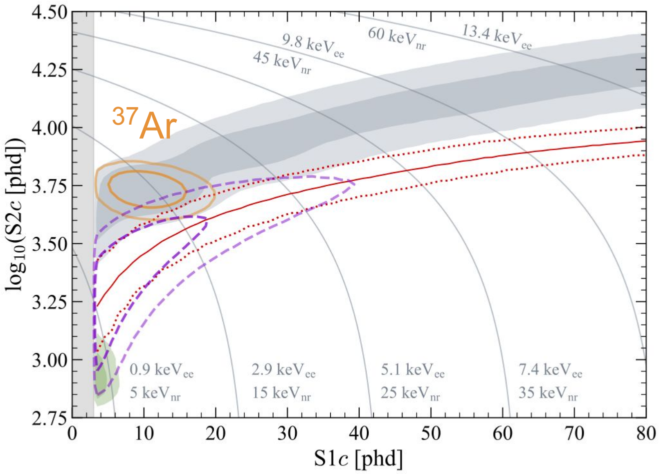
^{37}Ar decays ($T_{1/2}$ = 35 d, monoenergetic 2.8 keV ER deposition from electron capture)

Predominant source of argon in LZ is through cosmogenic spallation
LZ Collaboration, Phys. Rev. D 105, 082004 (2022), 2201.02858

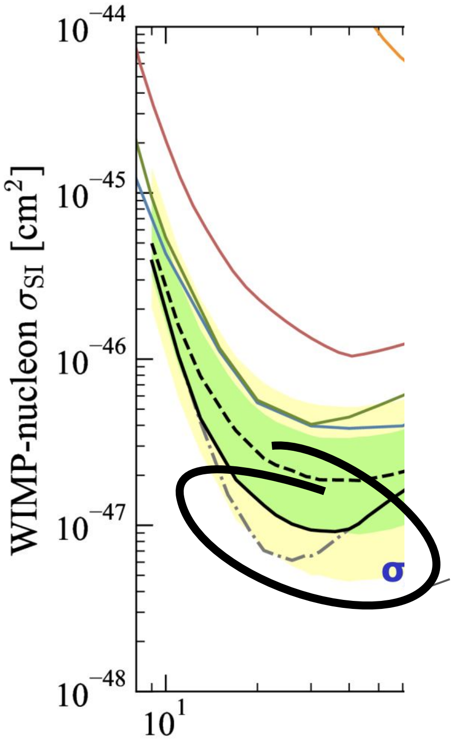
Estimates of the activity show approximately 100 decays in data, with a large uncertainty

PLR constraints [0,291]



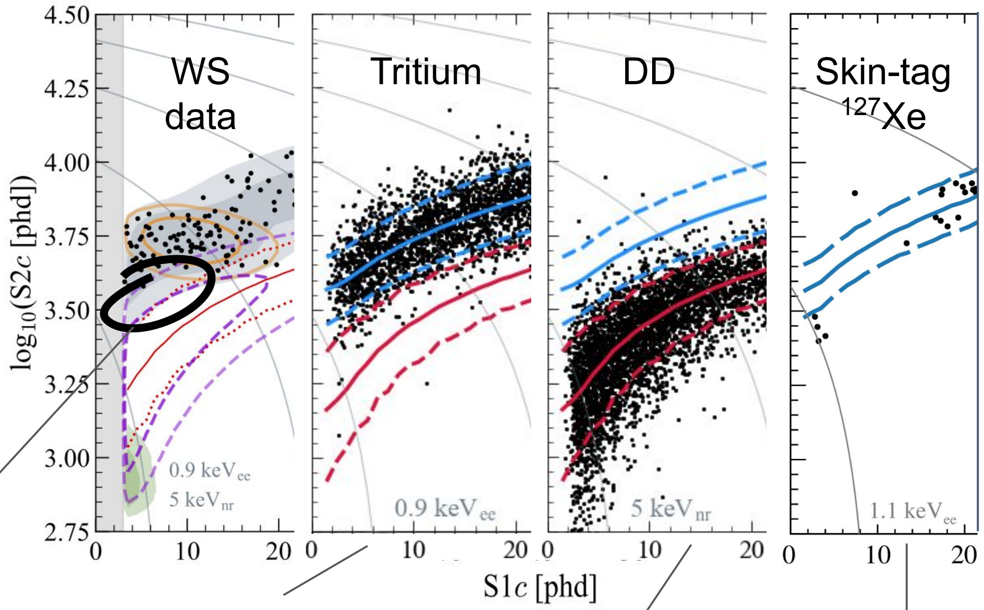


Downward fluctuation



Downward fluctuation of observed upper limit

Downward fluctuation in background rate



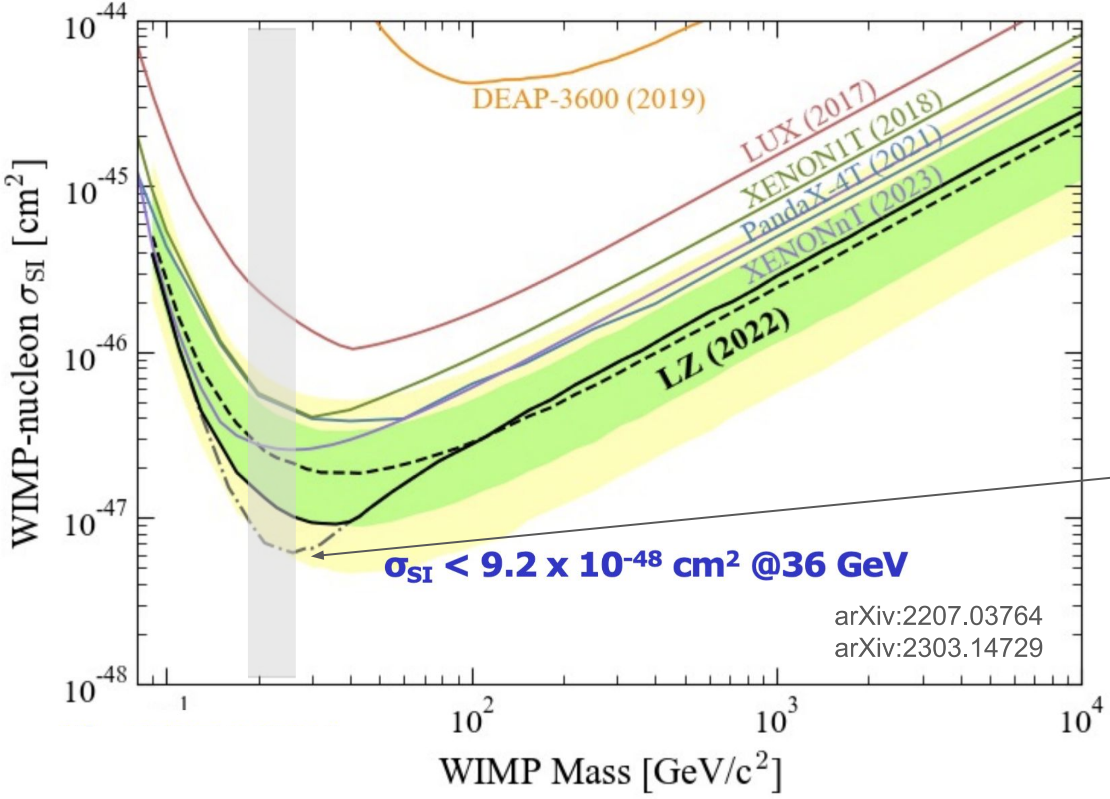
Analyzed identically to WS data

Source of NR signal-like events

Electron captured from M-shell (1.1 keV)

Three calibration sources cover this region
→ efficiency is NOT compromised

World-leading WIMP sensitivity

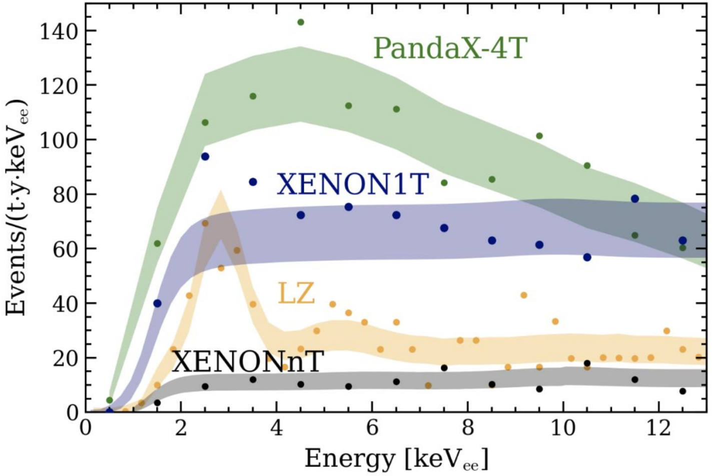


Downward fluctuation in background rate → Power constrain to avoid overstating our rejection power

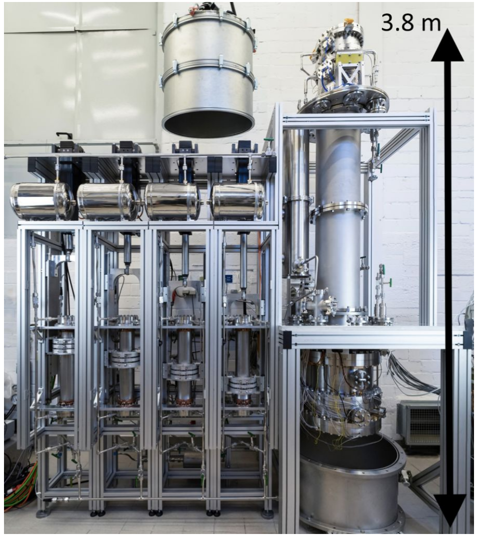
Recommended conventions for reporting results from direct dark matter searches
Eur. Phys. J. C 81, 907 (2021)

This indicated power-constraining limit using discovery power
Eur. Phys. J. C 81, 907 (2021)

Now updated to use rejection power
arXiv:1105.3166



Eur. Phys. J. C 82, 1104 (2022)
2021 JINST 16 P07047



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

Solutions for Rn removal

Rn sources inside the detector → continuous removal

2 ongoing experiments → 2 solutions to every problem

- LZ uses adsorption of xenon gas on cold charcoal
- XENONnT uses cryogenic distillation enhanced for radon removal

Most Rn sources are in the gaseous xenon

Cryogenic distillation in gas phase reduces by ~2

Cryogenic distillation by extracting LXe at a rate comparable to the Rn half live, 2 tonnes per day

XLZD would require 10 tonnes per day

Radioassay and emanation measurements to reduce the total radon load, e.g. Cold Radon Emanation Facility

Kr removal

arXiv:2112.12231

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

Required purity of <100 ppq

2 ongoing experiments → 2 solutions to every problem

- LZ uses offline gas chromatography
- XENONnT demonstrated online cryogenic distillation enhanced for krypton removal

Both techniques provide efficient removal

No sources of Kr in the detector but outgassing of air from components can introduce Kr well running

The Kr level will be monitored with a RGA and if it should rise above a certain level we can use online removal

Discovery limit at neutrino fog

CNS of ^{8}B solar and atmospheric neutrinos is indistinguishable from a WIMP signal

^{8}B solar neutrino flux has ~2% uncertainty

Atmospheric neutrino flux ~20% uncertainty

Discovery limit scale as: background free → Poissonian → limited by uncertainty in flux

Any reduction in uncertainty from other experiments will improve our ability to dig deeper in the WIMP parameter space

- SNO+
- JUNO
- DUNE

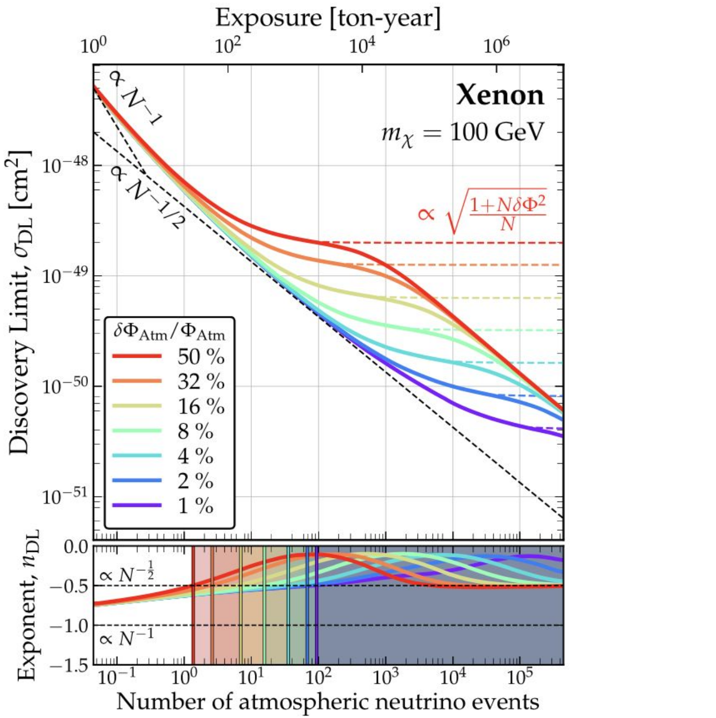


Figure 14. Spin-independent discovery limits at $m_\chi = 100$ GeV as a function of the expected number of atmospheric CEνNS events N, and the fractional uncertainty on the atmospheric neutrino flux, $\delta\Phi_{Atm}/\Phi_{Atm}$. Reprinted (figure) with permission from [474], Copyright (2020) by the American Physical Society. Three scaling regimes as a function of N are shown with dashed lines: (1) 'background-free' $\sigma \sim N^{-1}$, (2) Poissonian $\sigma \sim N^{-1/2}$, and (3) saturation $\sigma \sim \sqrt{(1+\delta\Phi^2 N)/N}$. The bottom panels in each case show the logarithmic scaling exponent defined as: $n_{DL} \equiv \mathrm{d}\ln\sigma_{DL}/\mathrm{d}\ln N$. This figure shows the importance of the neutrino flux systematic uncertainty in extending the dark matter physics reach below the neutrino fog.