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

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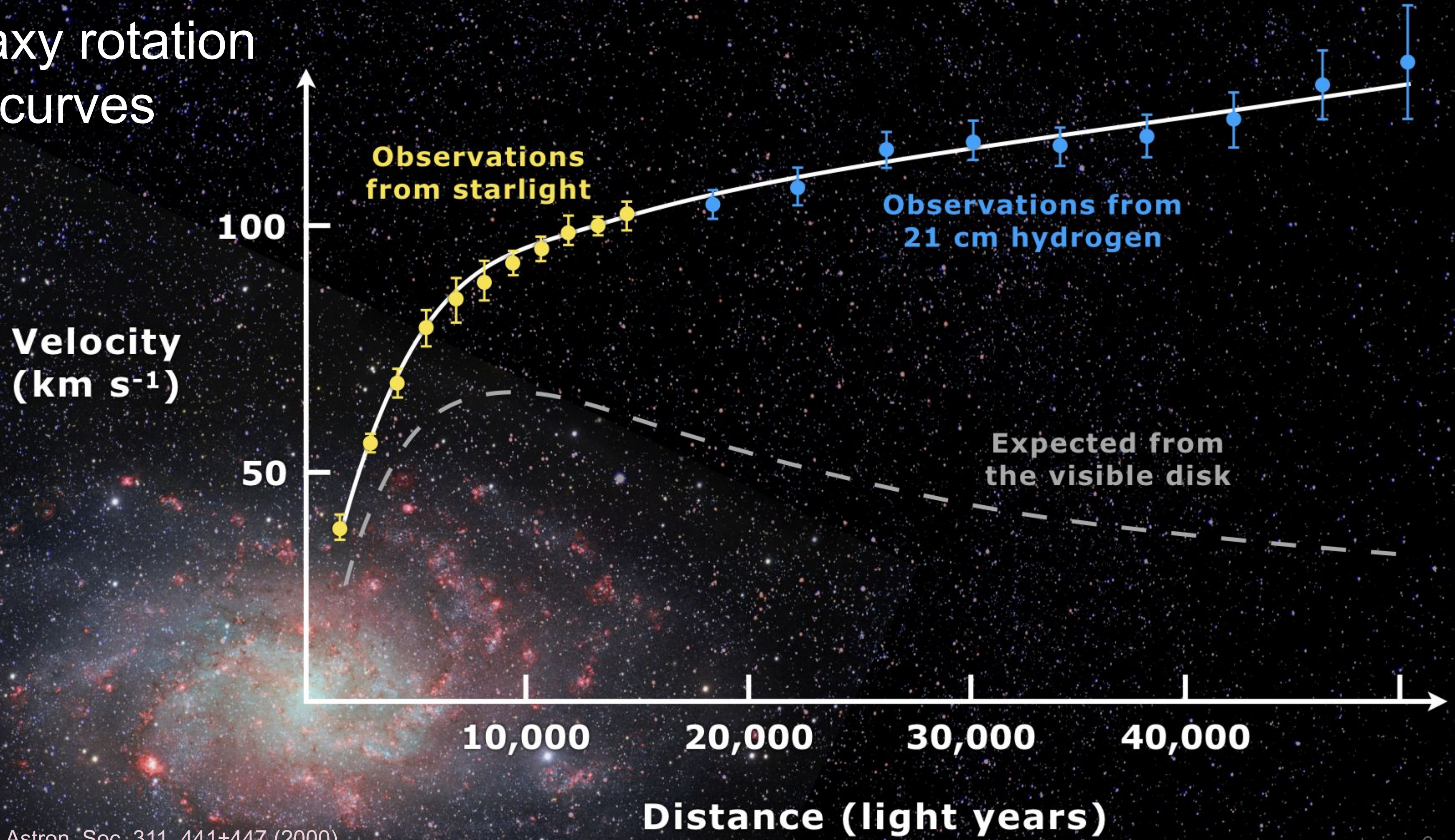
March 1st, 2023
University of Birmingham Particle Physics Seminar Programme

Imperial College London

Outline

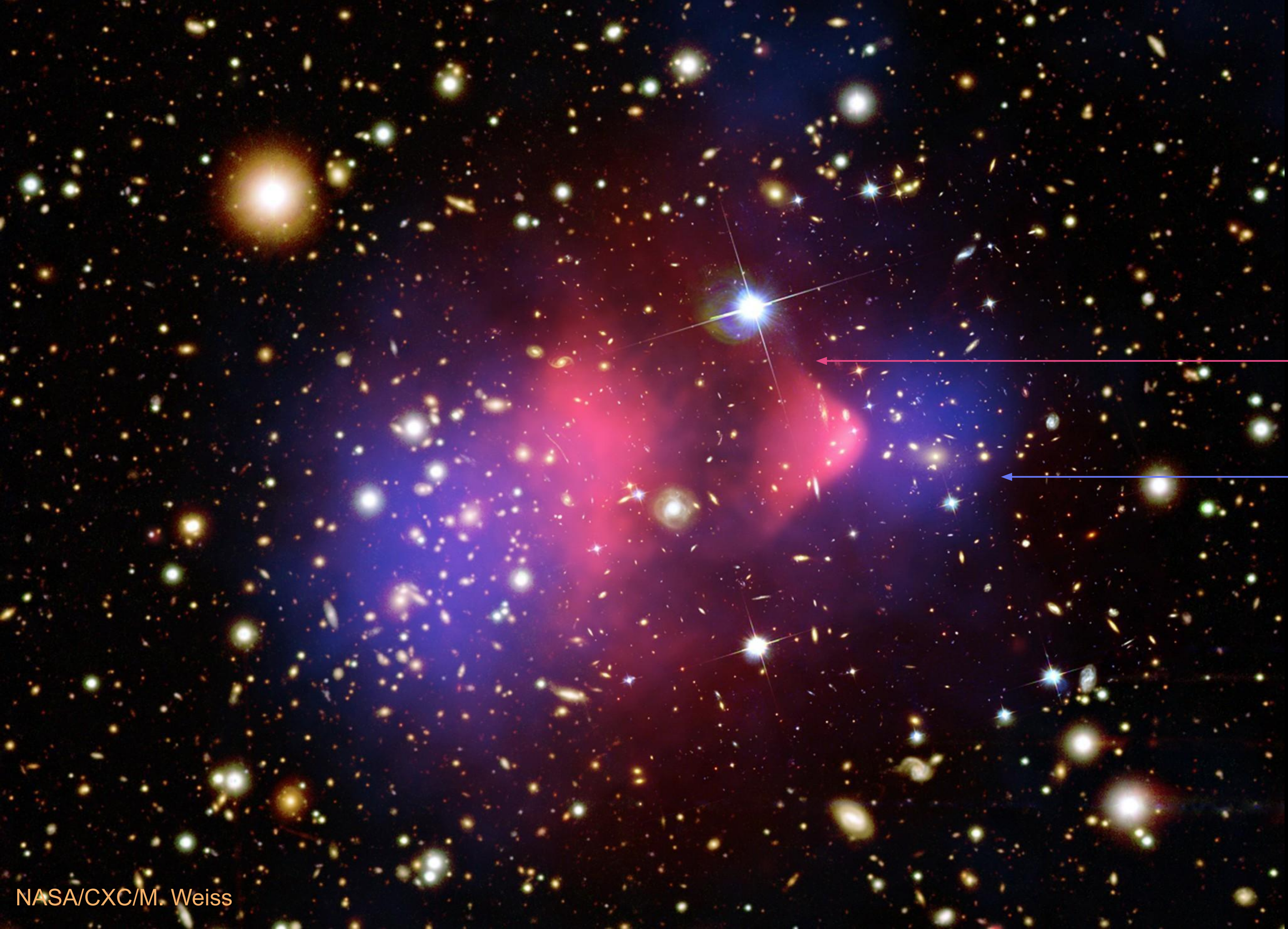
1. Introduction to dark matter
2. Liquid xenon time projection chambers (LXe TPCs)
3. Recent results from the LUX-ZEPLIN (LZ)
4. Future xenon observatory for dark matter and other rare events

Galaxy rotation curves



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

Bullet cluster



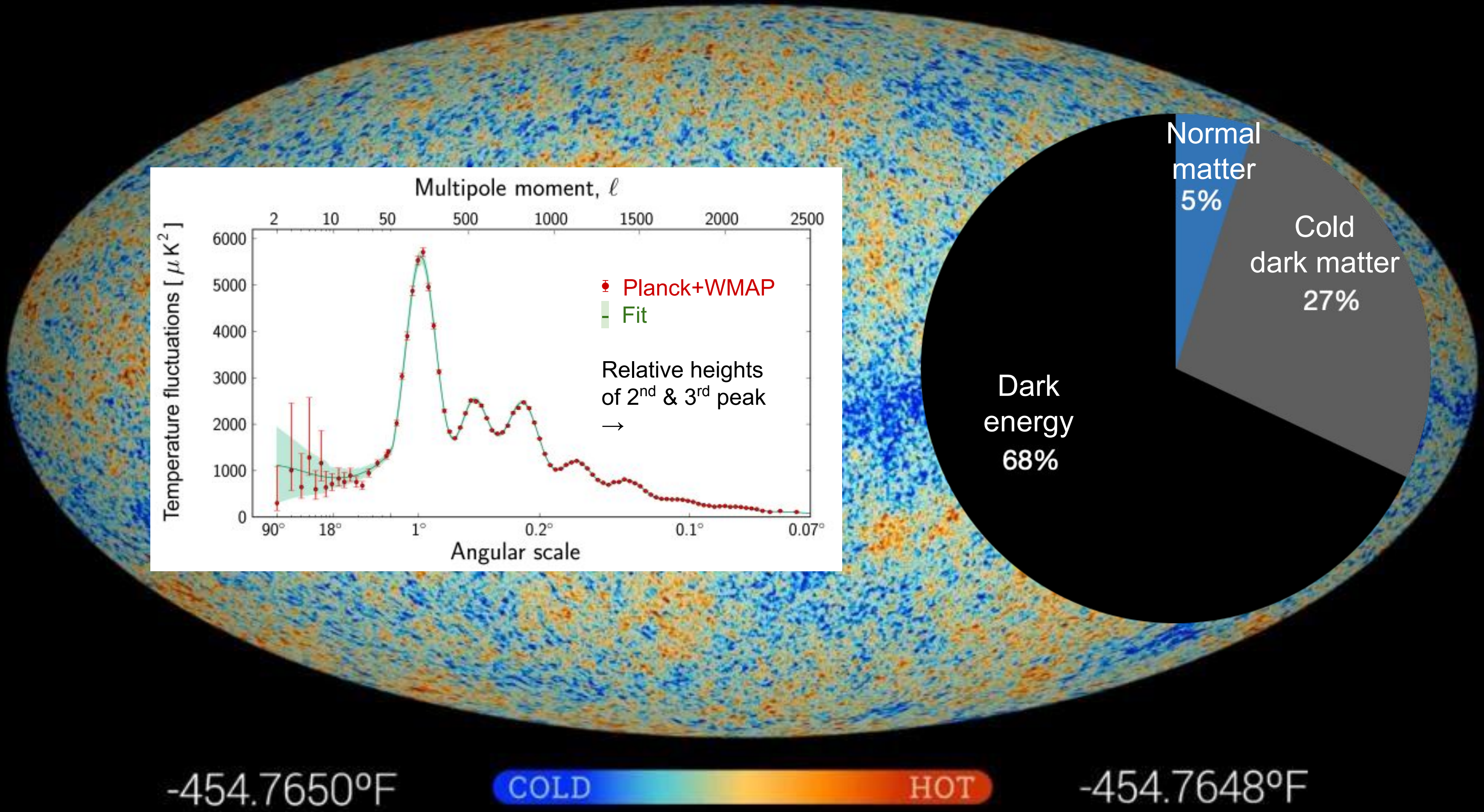
Colliding galaxy clusters

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

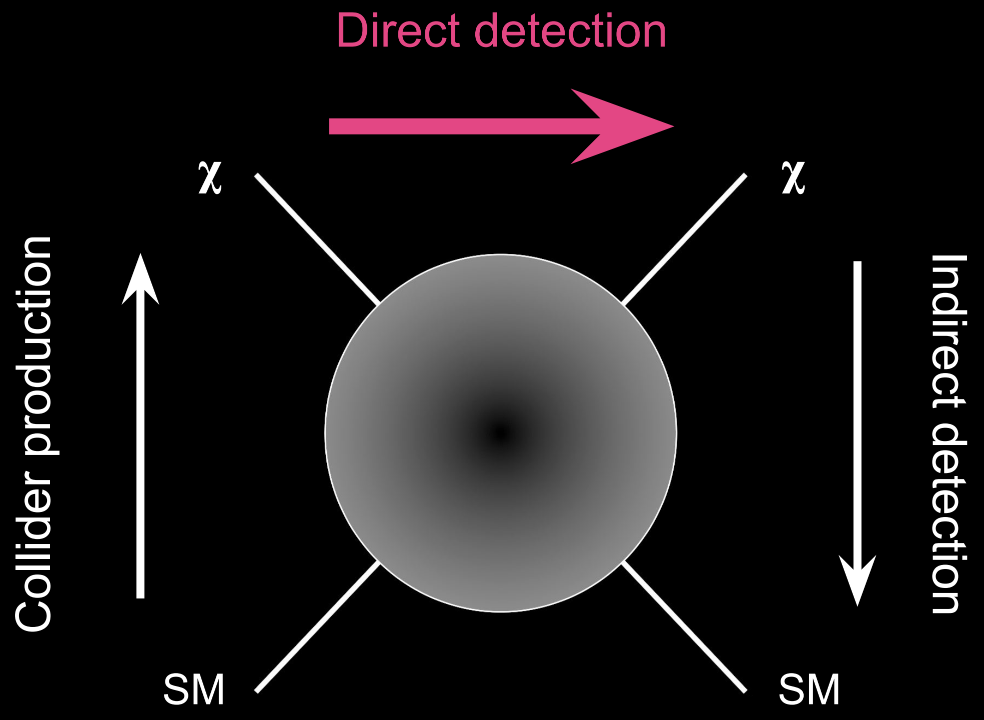
We are in the Milky Way →

Local dark matter density ~ 0.3 GeV/cm^3

Average dark matter velocity v ~ 220 km/s

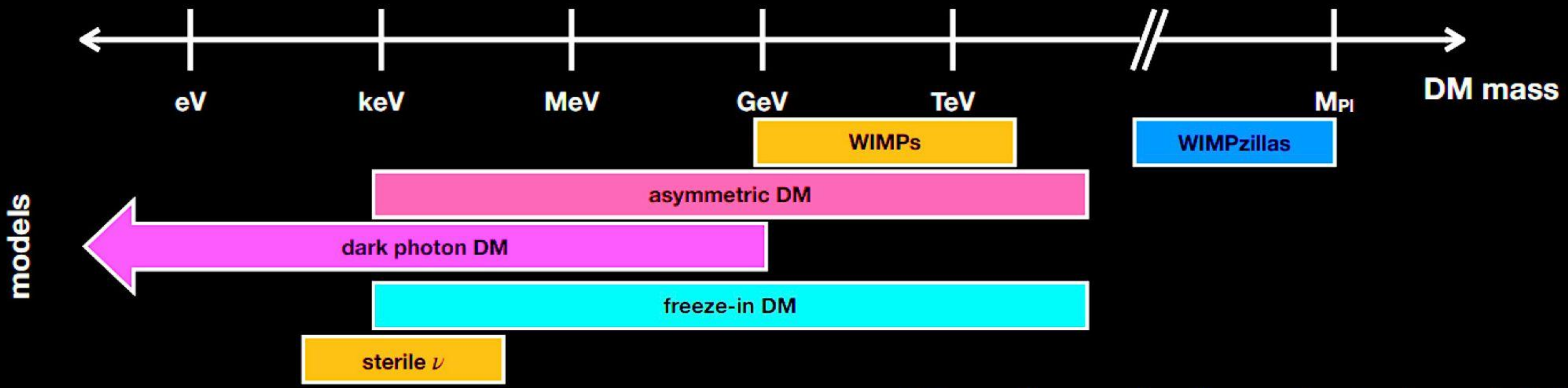
Assuming Maxwell-Boltzmann distribution of dark matter

Detecting dark matter particles



Possibilities for particle dark matter

Gravitational interactions ⟶ massive (particle)



Weakly interacting massive particles (WIMPs)

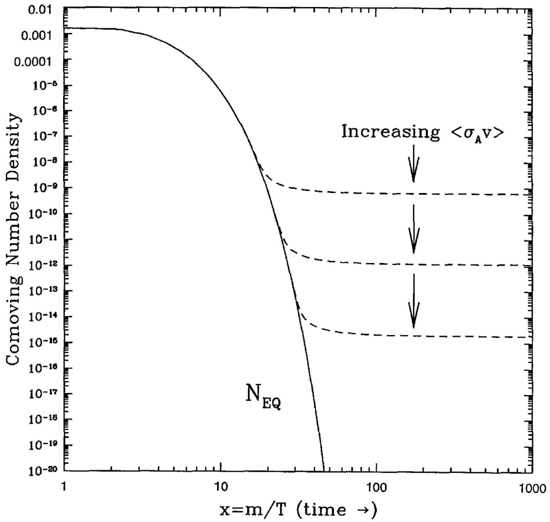
Dark matter freeze-out

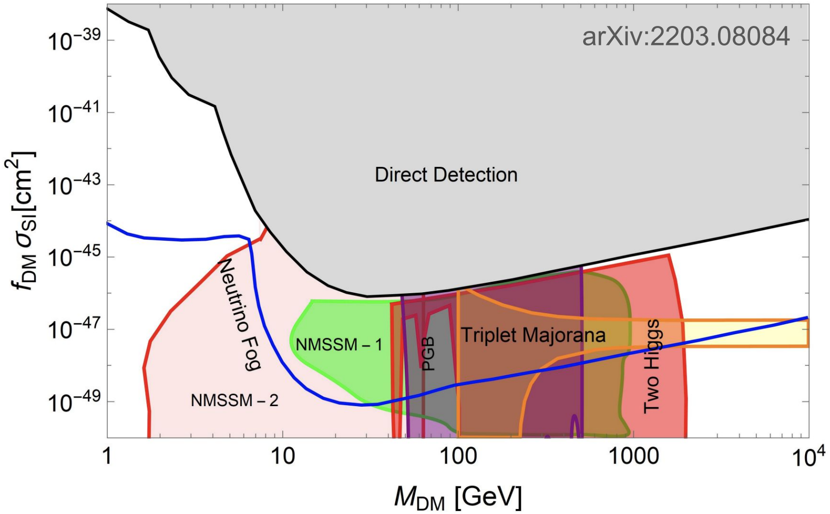
m_{DM} ~ 100 GeV

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

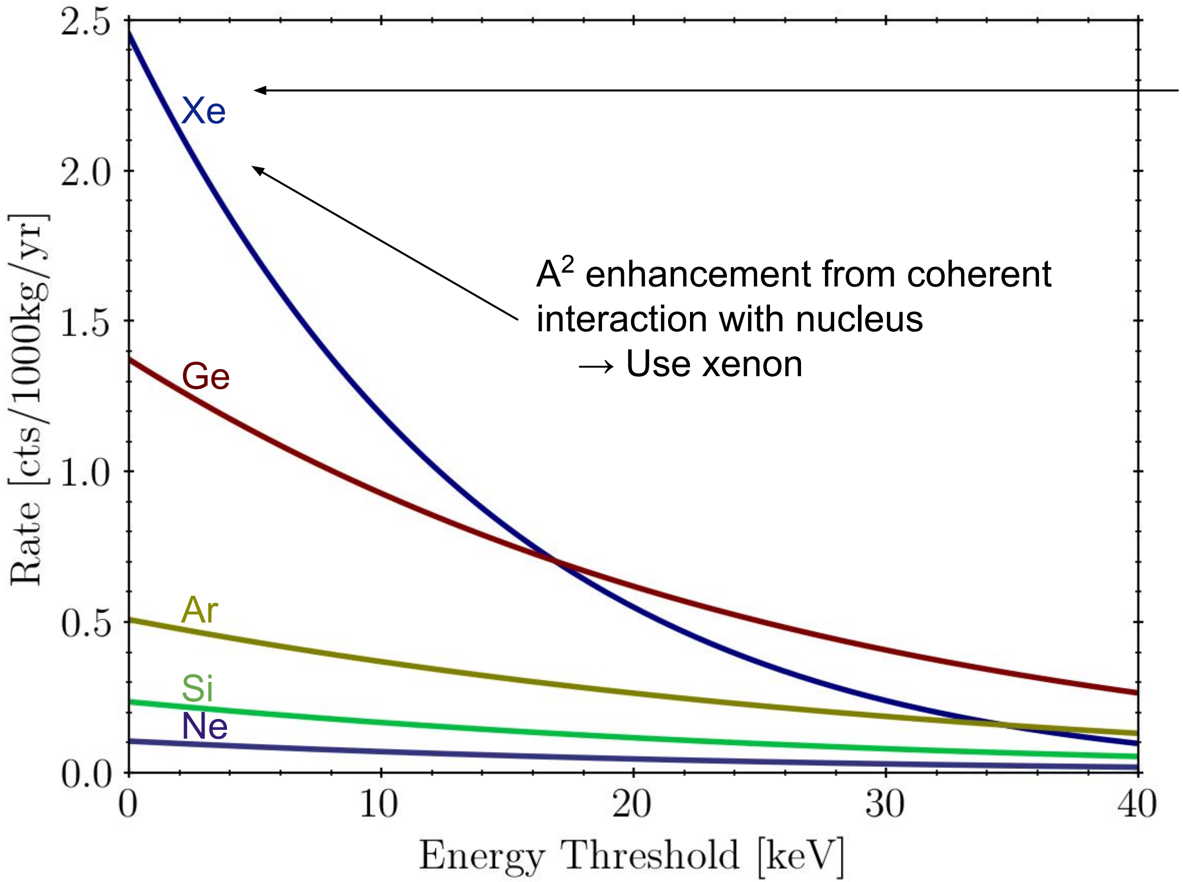
Supersymmetry provides candidates

Currently viable GeV-TeV dark matter models →





Dark matter scattering rate



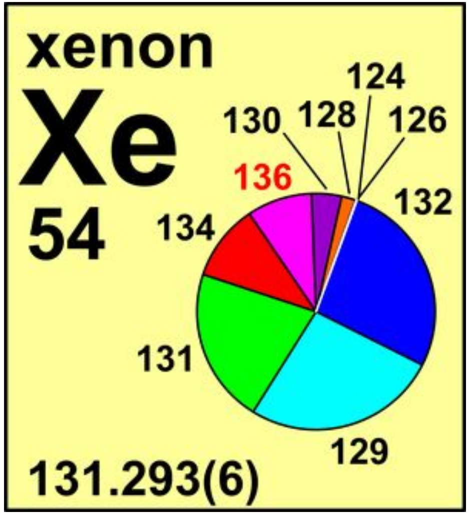
Coherent nuclear scattering rate ~ $\sigma_{SI}\, A^2\, F_{SI}^{\;2}$

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

Xenon



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

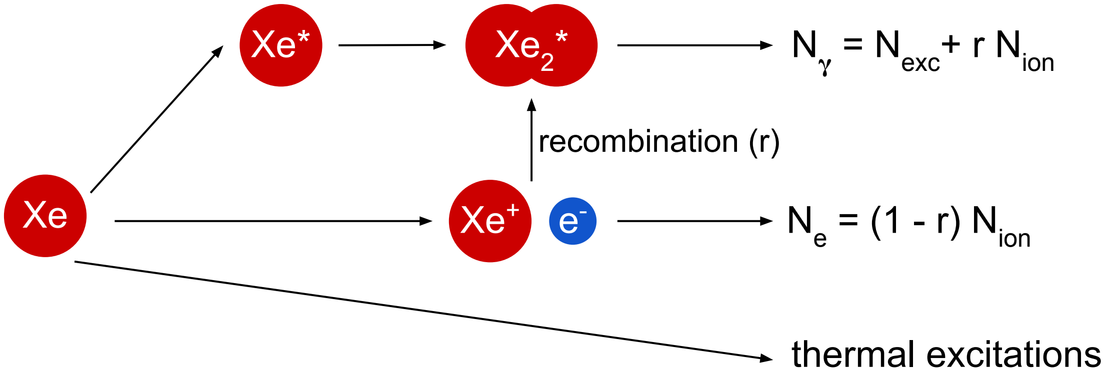
Few problematic radio-isotopes

Boils at cryogenic temperatures (~ -110 C)

Dense (~3 g/cm^3)

Inert

Scintillates



LUX-ZEPLIN (LZ) collaboration

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 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 Wisconsin, Madison

US UK Portugal Korea

U.S. Department of Energy
Office of Science

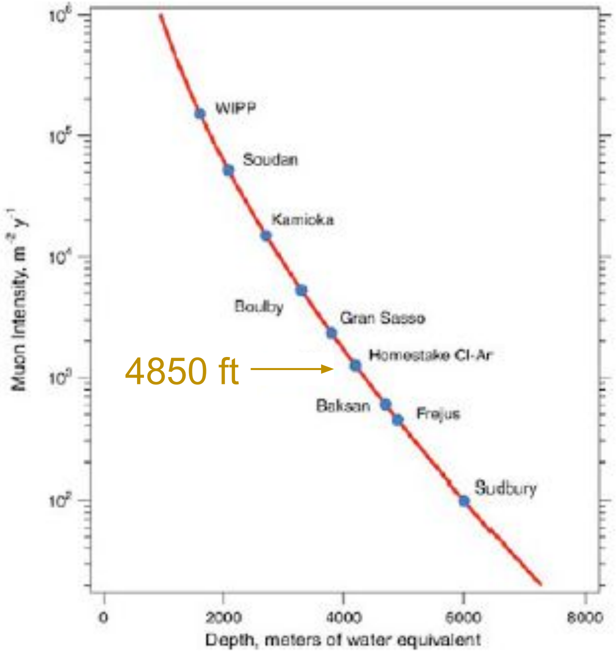
Science and Technology Facilities Council

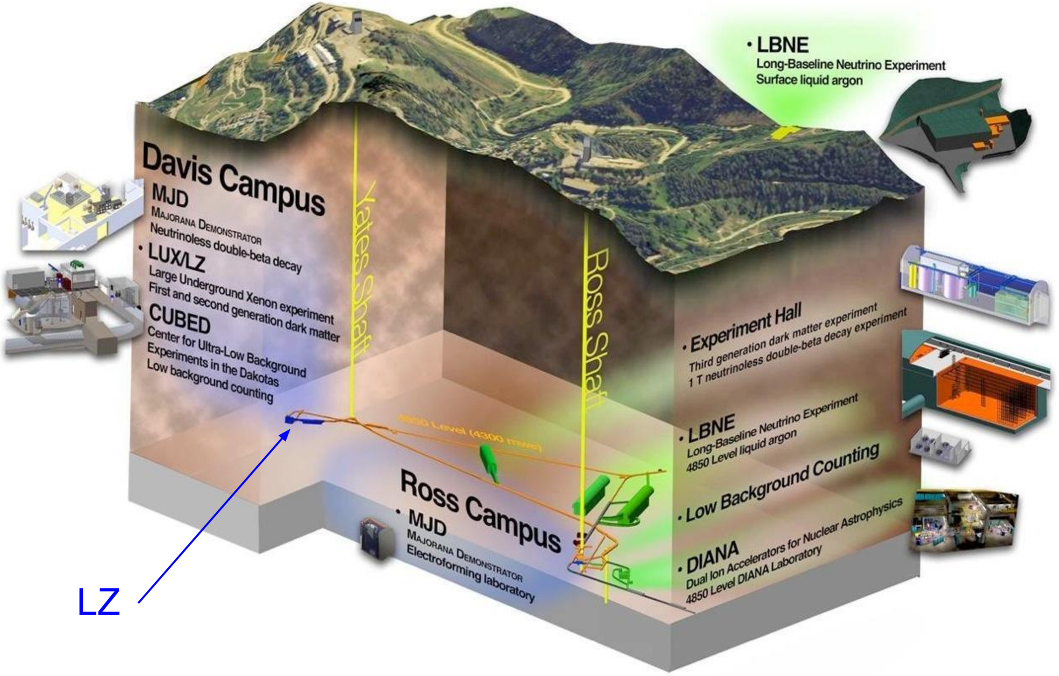
Sanford Underground Research Facility
South Dakota Science and Technology Authority

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

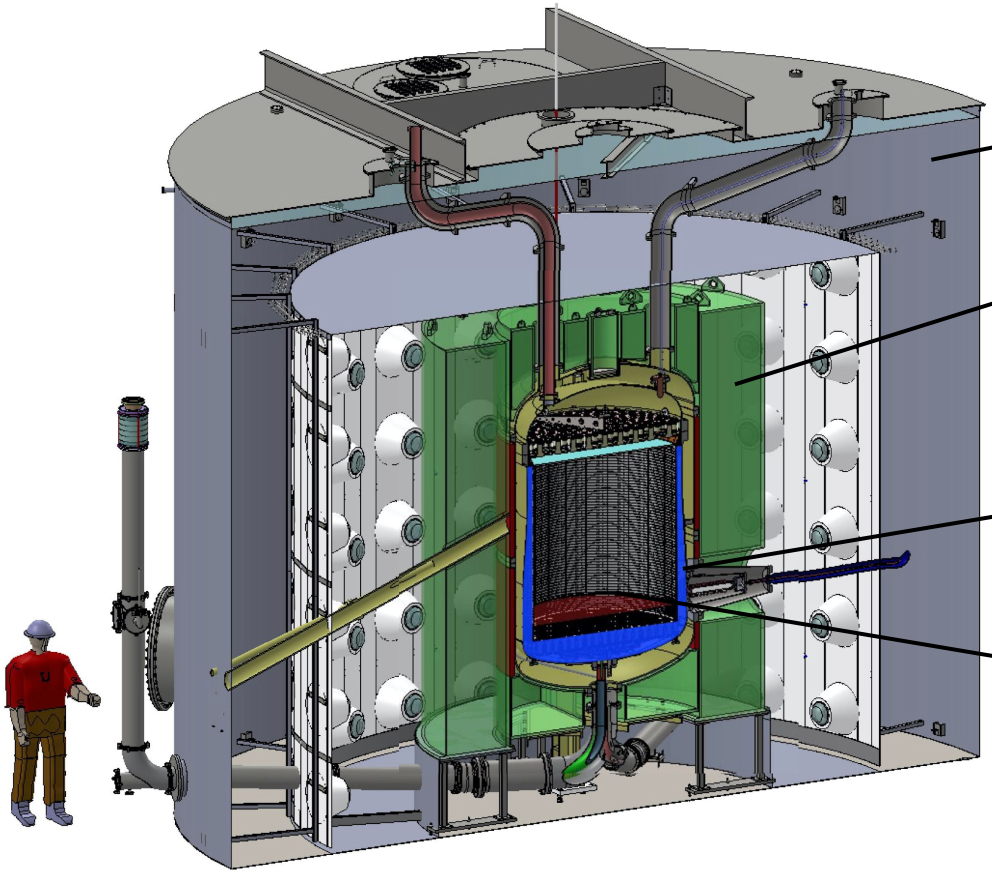
Institute for Basic Science

Sanford Underground Research Facility (SURF) in Lead South Dakota





Layered detector



Tank
- High purity (HP) water

Outer detector (OD)
- Gadolinium loaded liquid scintillator (Gd-LS)
- 120x 8” photomultiplier tubes (PMTs)

Skin
- 2 T liquid xenon
- 93x 1” and 38x 2” PMTs

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

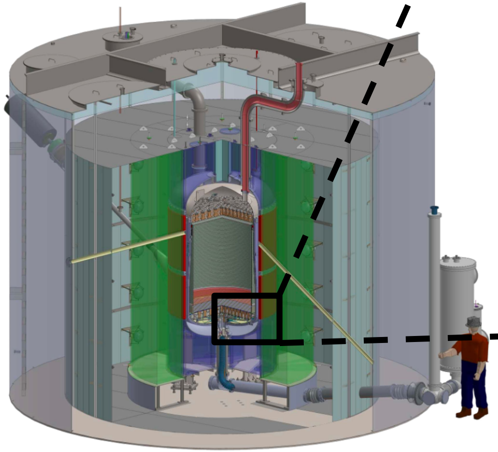
Veto detectors

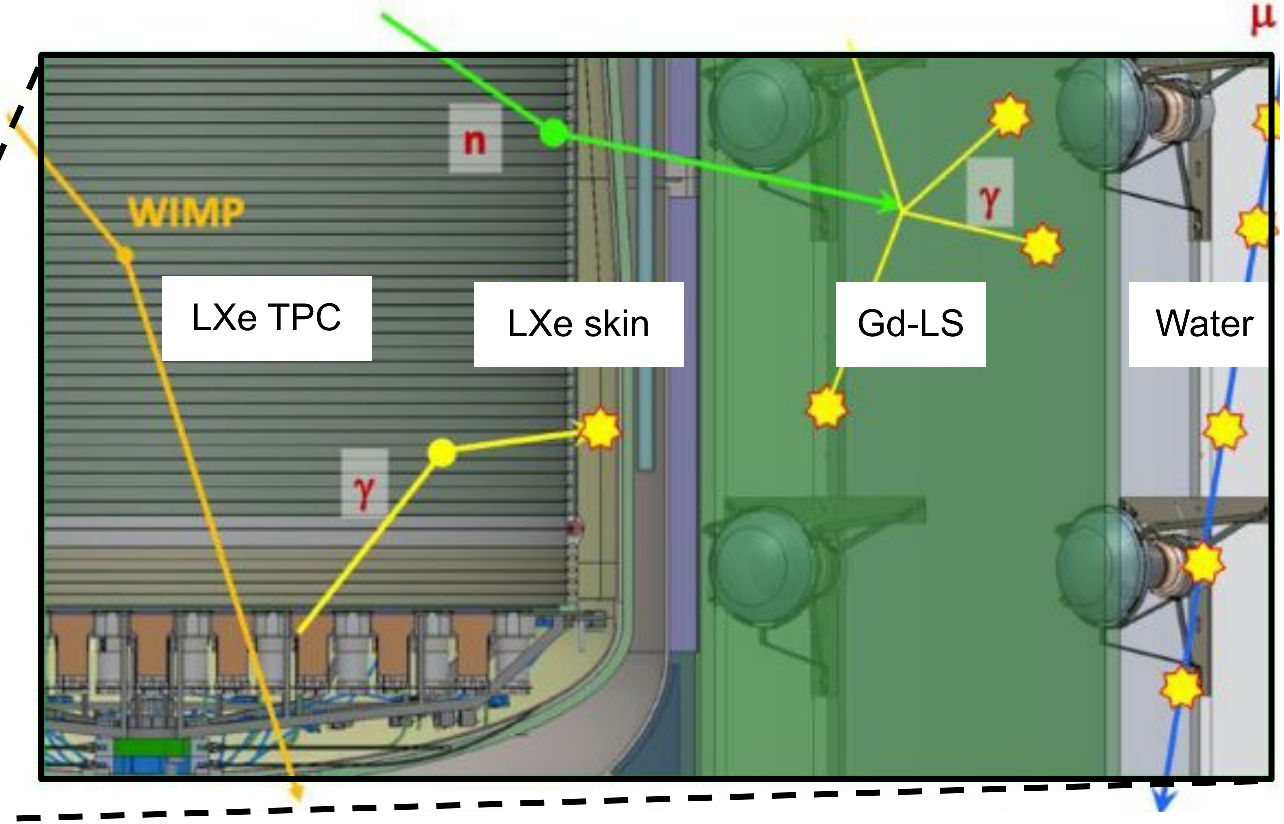
Lined with PTFE (skin) or tyvek (OD) to maximize light collection

~8/2.2 MeV of γ-rays from thermal neutron capture on ^{155}Gd/H

88±0.7% neutron tagging efficiency

5% livetime reduction

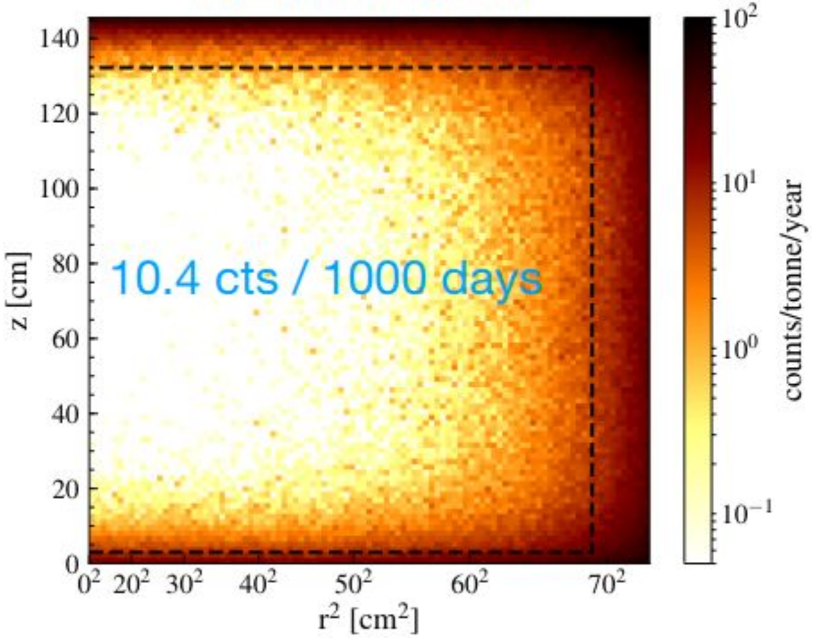




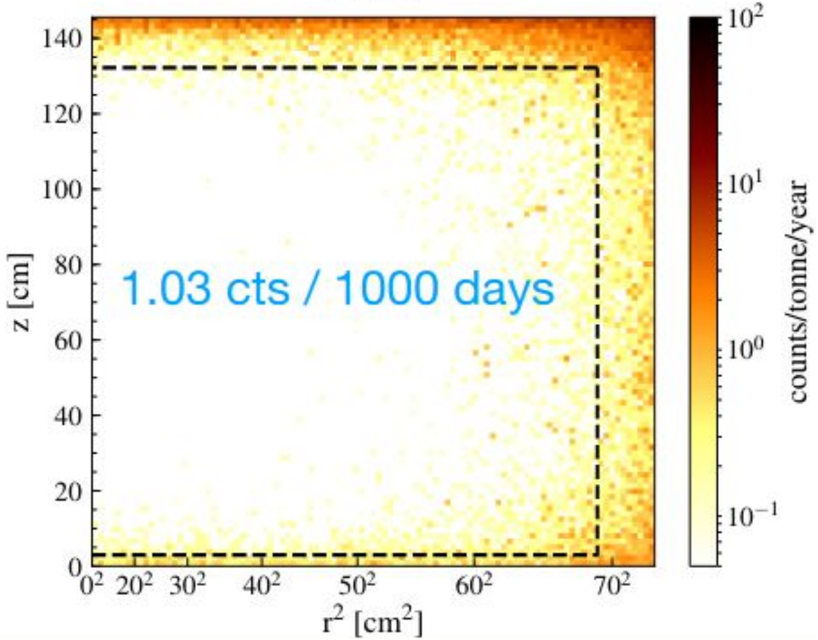
Outer detector veto

Simulated single-scatter nuclear recoils in region of interest relevant to a 40 GeV WIMP, 6-30 keV_{nr}

Before vetoing



After vetoing



TPC design

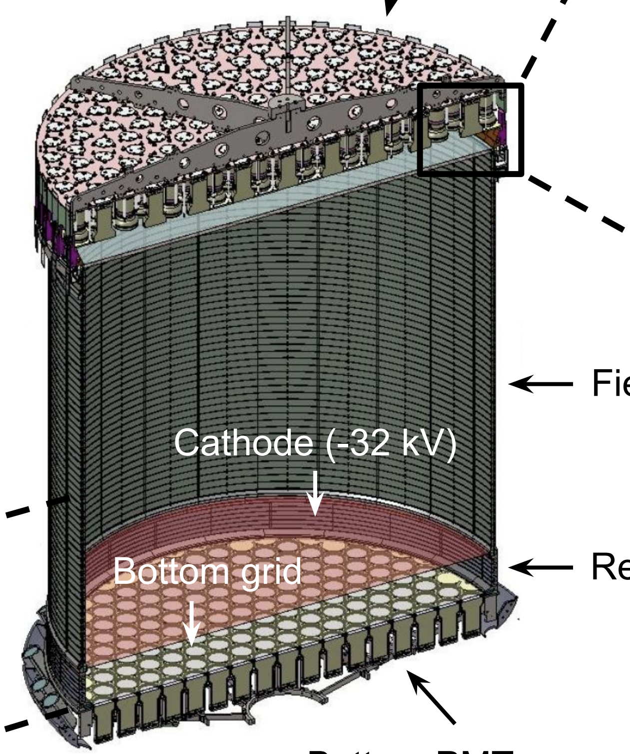
1.5 m dia x 1.5 m height

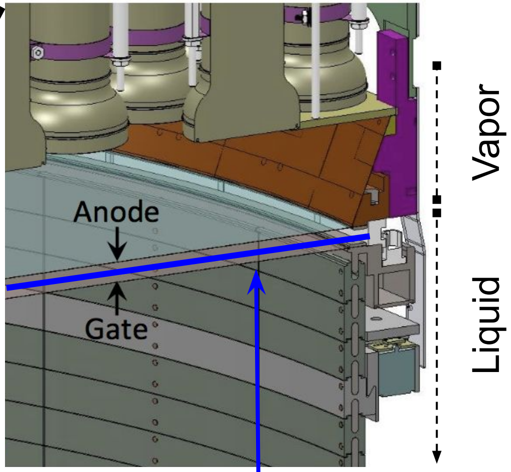
PTFE everywhere for light collection

7 T active LXe (5.5 T fiducial)

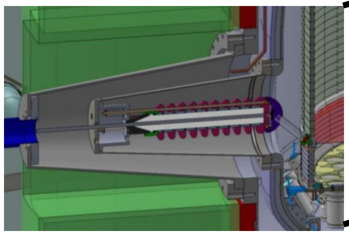
4x wire-grid electrodes

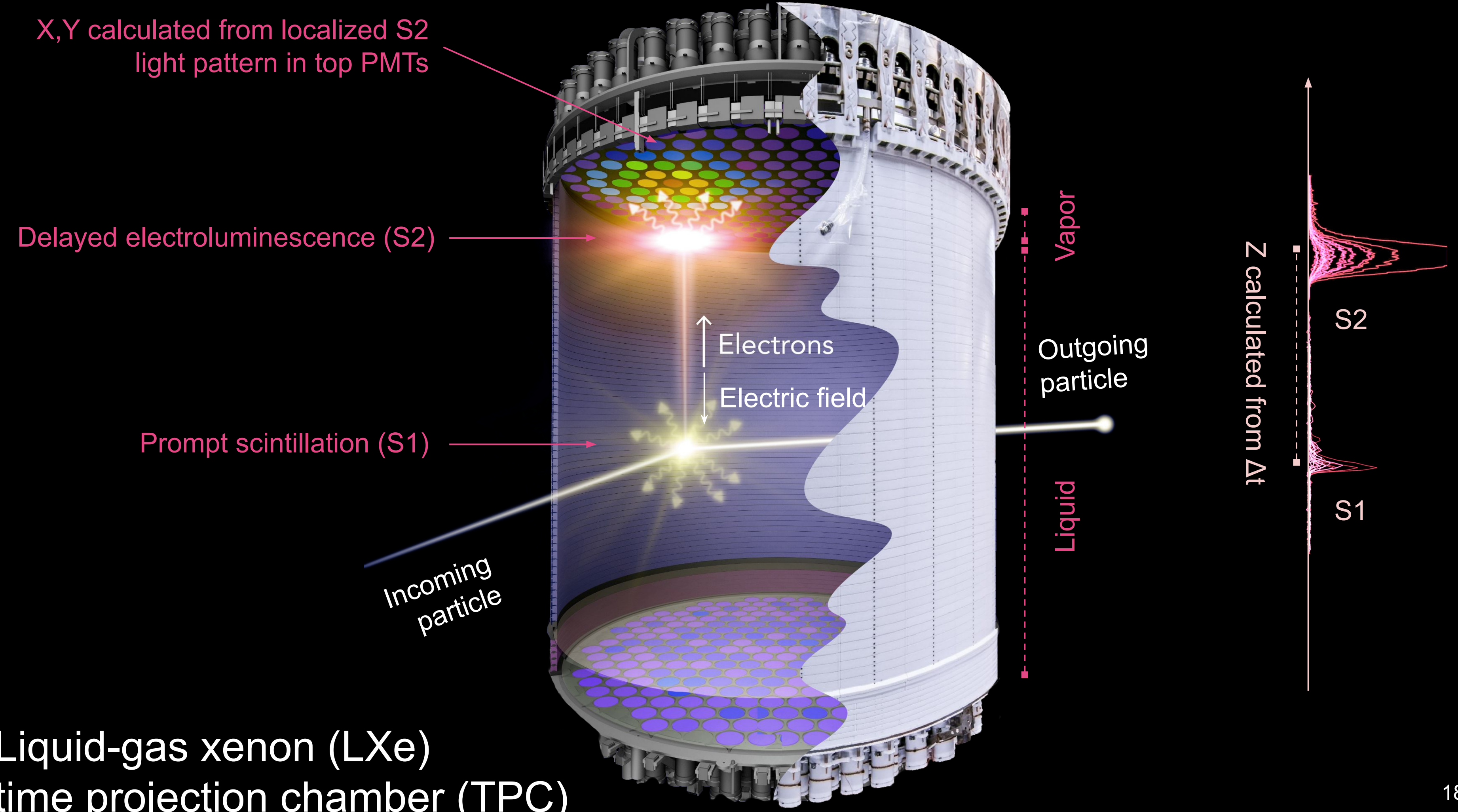
- E_{drift} = 190 V/cm
- ER/NR discrimination = 99.9%
- $E_{ext,gas}$ = 7.7 kV/cm
- Extraction efficiency = 80.5%





Cathode HV connection





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

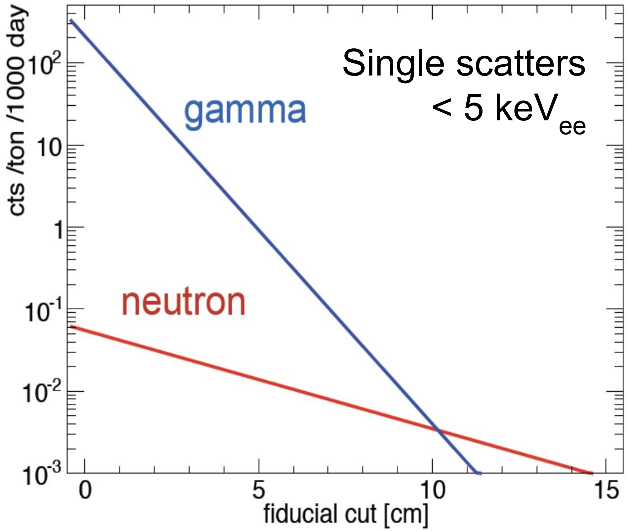
Fiducialization

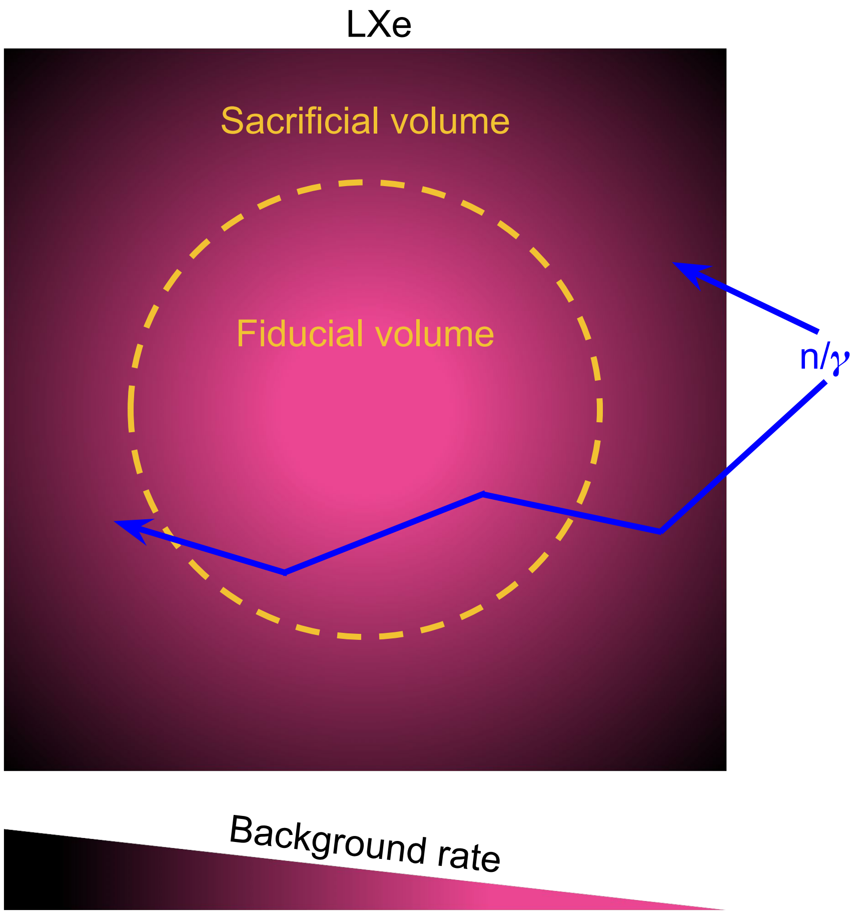
Xenon is dense, ~ 3 g/cm^3

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

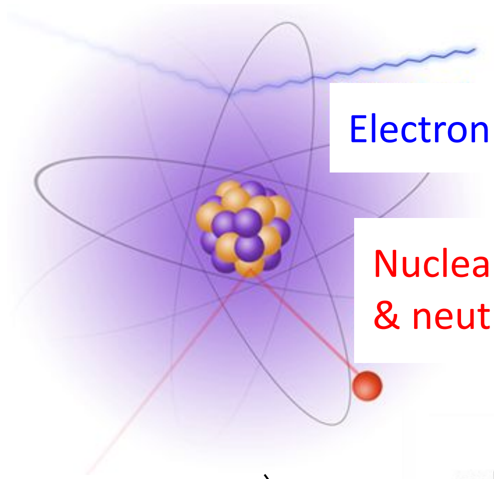
Reject events from the high-background rate regions near the edge of the TPC

Reject multiple scatters



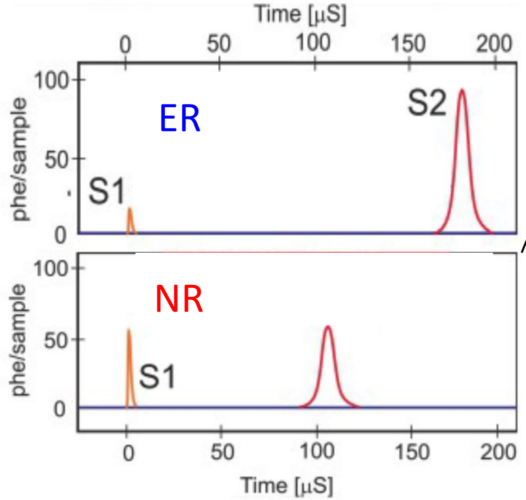


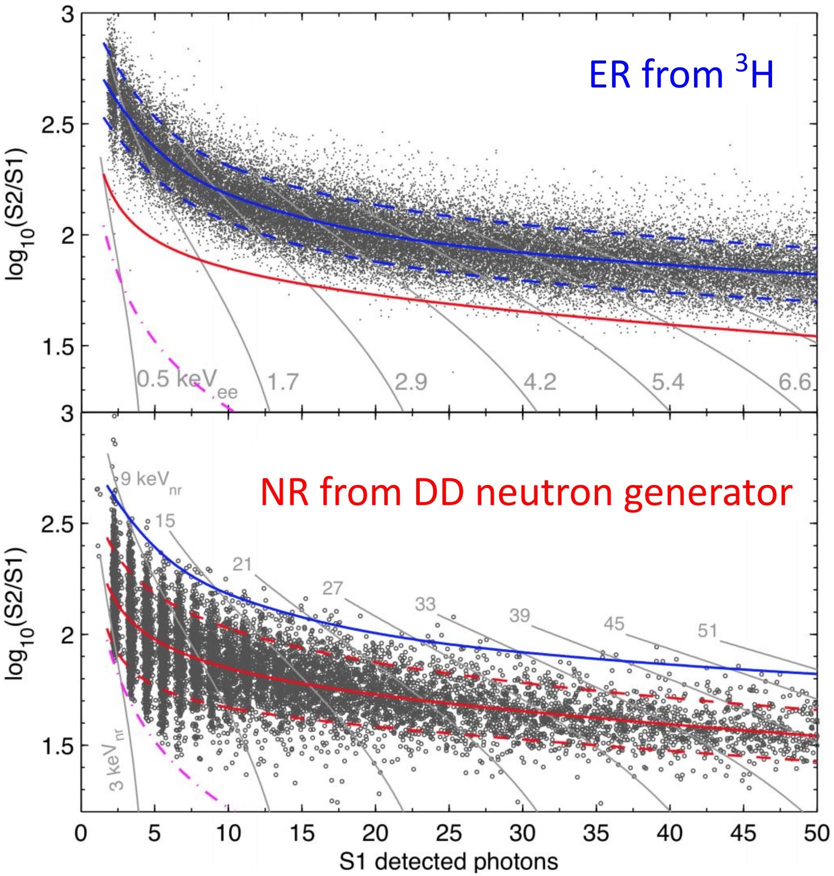
Electron/nuclear recoil discrimination



Electron recoil (ER) β/γ backgrounds

Nuclear recoil (NR) WIMP signal
& neutron backgrounds

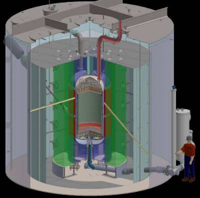




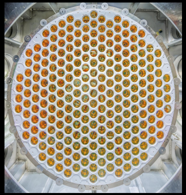
Timeline: Design→Construction→Operation

Began designing detector 2012

CD3 and TDR, March 2017



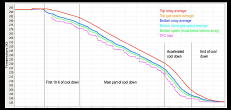
PMT arrays arrive Dec 2018, Jan 2019

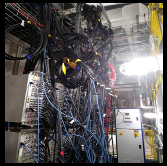


TPC Complete, Aug 2019

Underground, Oct 2019

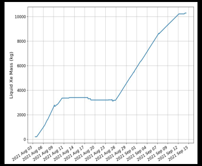
Cold gas, March 2021





Electronics all 2020

Kr Operation Jan-Aug 2021

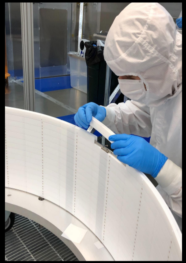


Xe Fill Aug-Sep 2021

Science Running!

2012 2017 2018 2019 2020 2021 2022

Cryostat arrives, May 2018



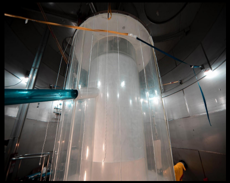
FFR Assembly Dec 2018

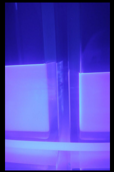
Grids, Spring 2018

Sealed Up March 2020

Circ Test July 2020

OD Construction Winter 2020-2021

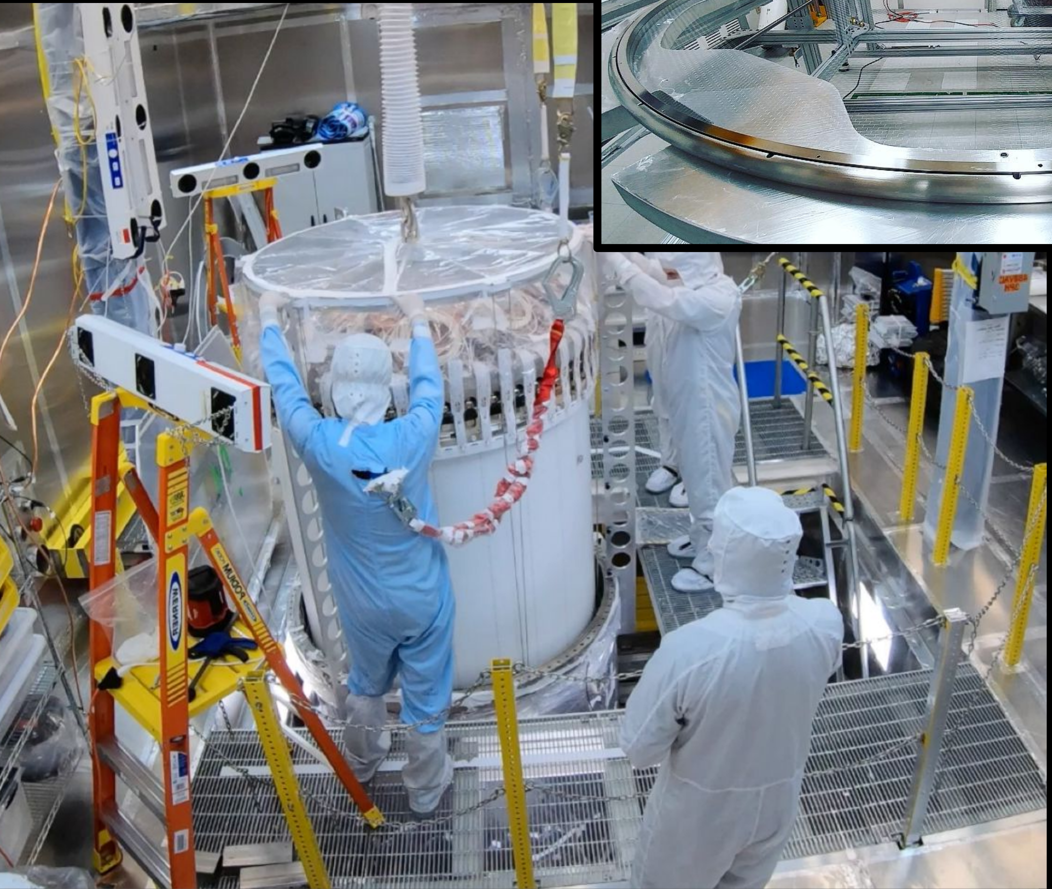


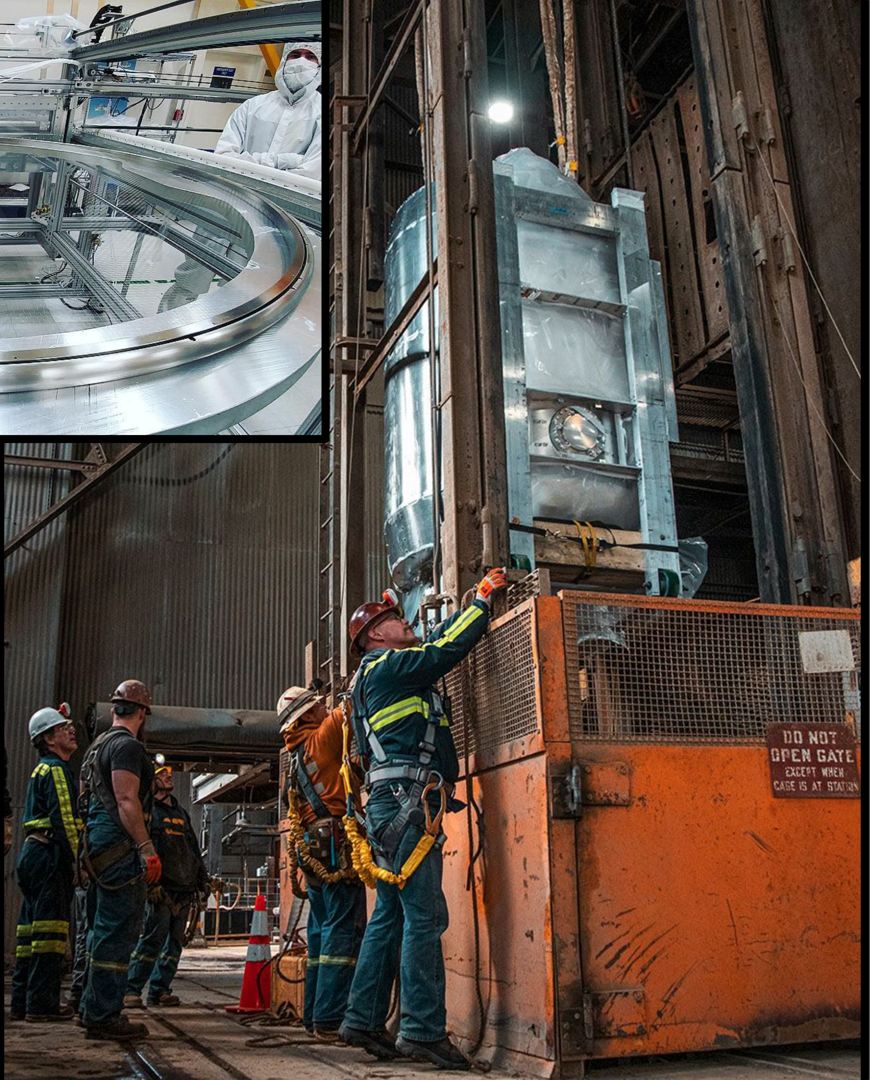


OD Fill June 2021

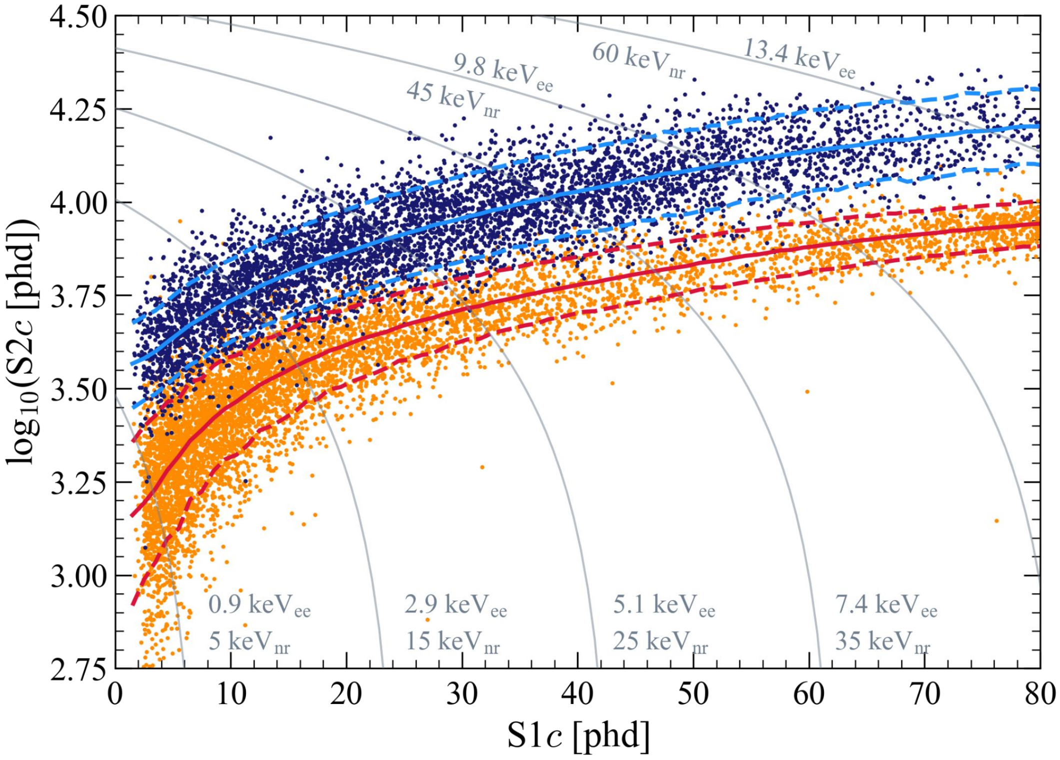
Commissioning Fall 2021

Construction highlights





Calibration



Noble Element Simulation Technique (NEST) to model detector response

CH_3T to validate accuracy of ER leakage model to 4σ

DD neutrons to validate NR band model

- ER/NR mean

- - 10 & 90% contours

Light gain g1: **0.114 ± 0.002 phd**
Charge gain g2: **47.1 ± 1.1 phd**
Single electron size: **58.5 phd**
Extraction efficiency: **80.5%**

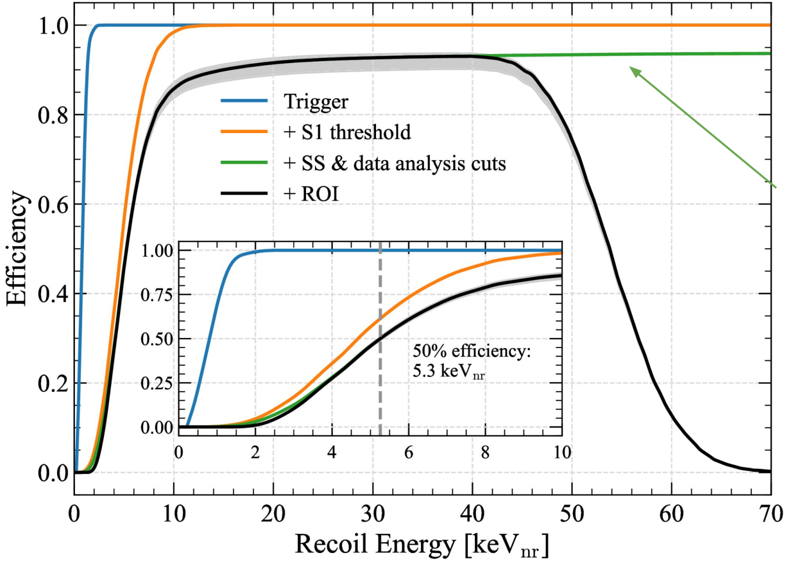
99.9% rejection of ERs below the median of a 40 GeV WIMP

Data quality

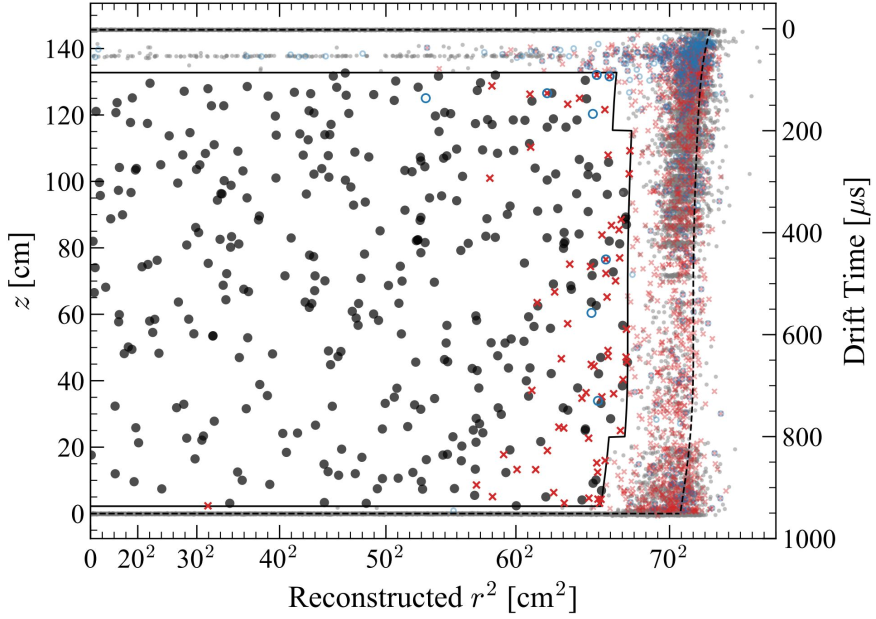
Fiducial volume cut: 5.5 ± 0.2 T

Livetime vetoes: 90 → 60 days

Waveform quality cuts



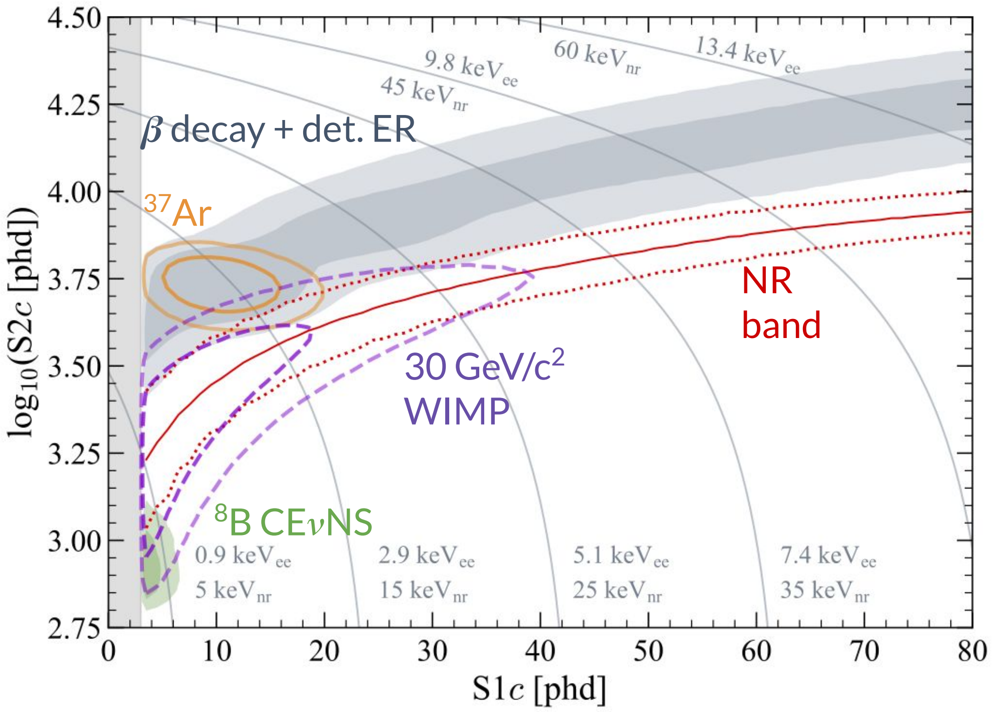
Measured with CH_3T and DD/AmLi



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

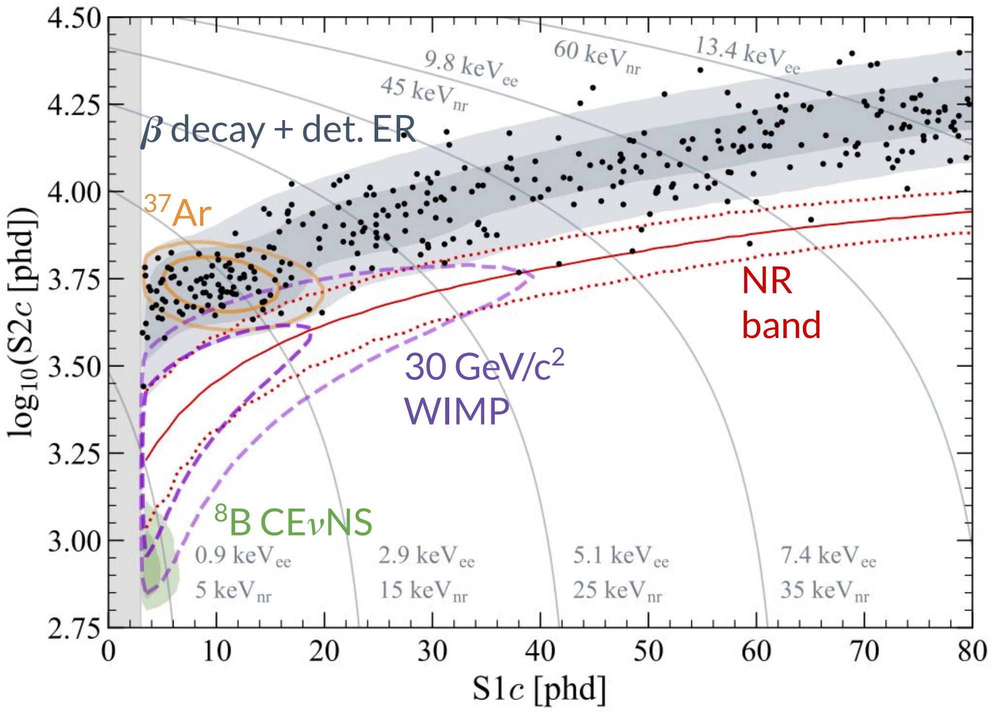
Background model

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	–



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



For every WIMP mass best fit result is consistent with 0

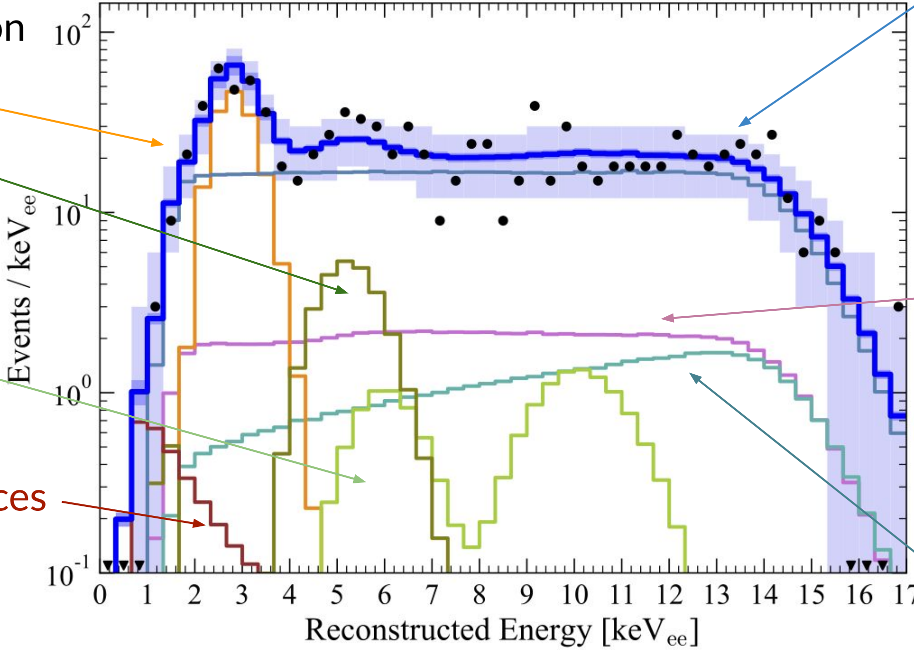
Fit results

Cosmogenic activation

- ^{37}Ar
- ^{127}Xe

^{124}Xe (2νECEC)

Accidental coincidences



Dissolved radiogenic contaminants

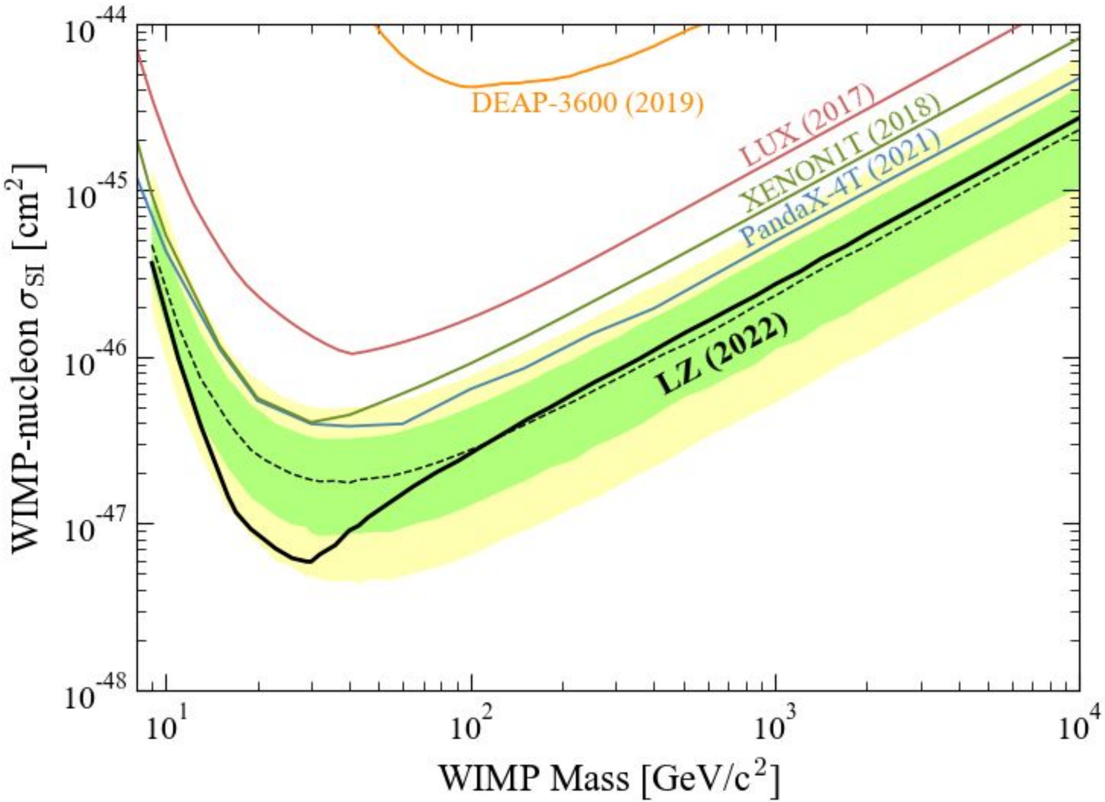
- ^{214}Pb (^{222}Rn daughter)
- ^{212}Pb (^{220}Rn daughter)
- ^{85}Kr

Solar neutrinos (ER)

- pp
- ^{7}Be
- ^{13}N

^{136}Xe (2νββ)

WIMP sensitivity



90% CL upper limit on WIMP-nucleon σ_{SI} is 5.9×10^{-48} cm^2 at 30 GeV

Frequentist, two-sided profile-likelihood-ratio (PLR) test statistic

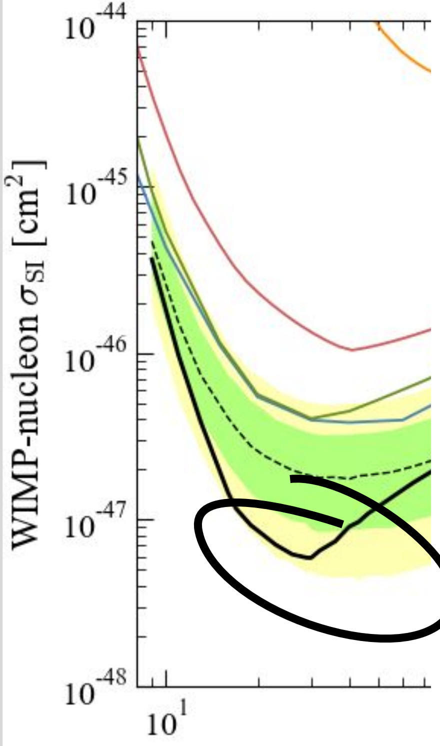
Signal rate must be non-negative
90% confidence bands

Power constraint at $\pi_{crit} = 0.32$

No salting or blinding

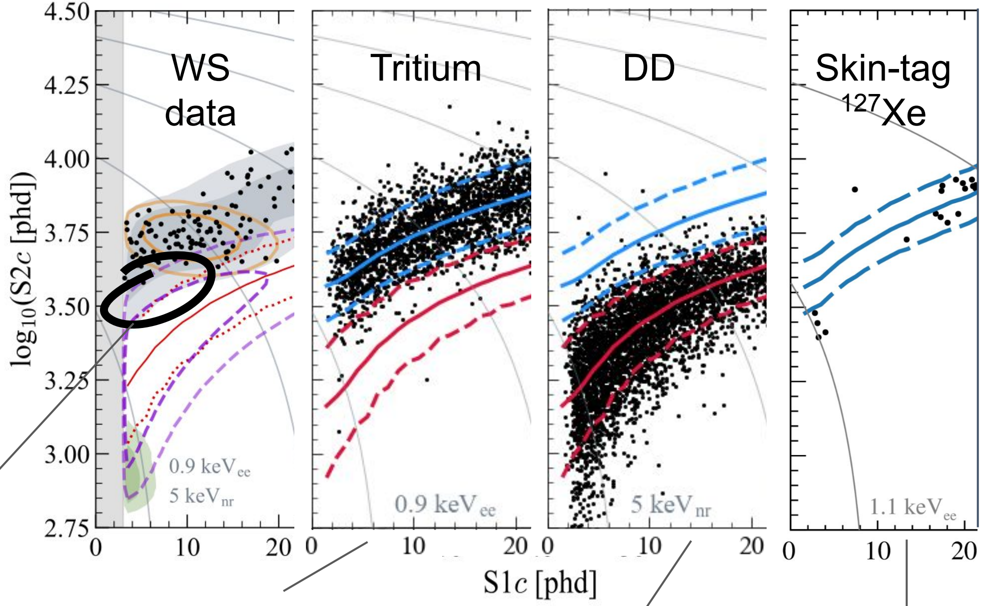
Recommended conventions for reporting results from direct dark matter searches (arXiv:2105.00599)

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

Next steps for LZ

1. First 90 day science run complete
2. Ultimate goal to accumulate 1000 livedays
3. Continue producing science 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 July 6, 2021

XENON + LUX-ZEPLIN + DARWIN → XLZD

First XLZD consortium meeting in June 27-29, 2022

Website: https://xlzd.org/

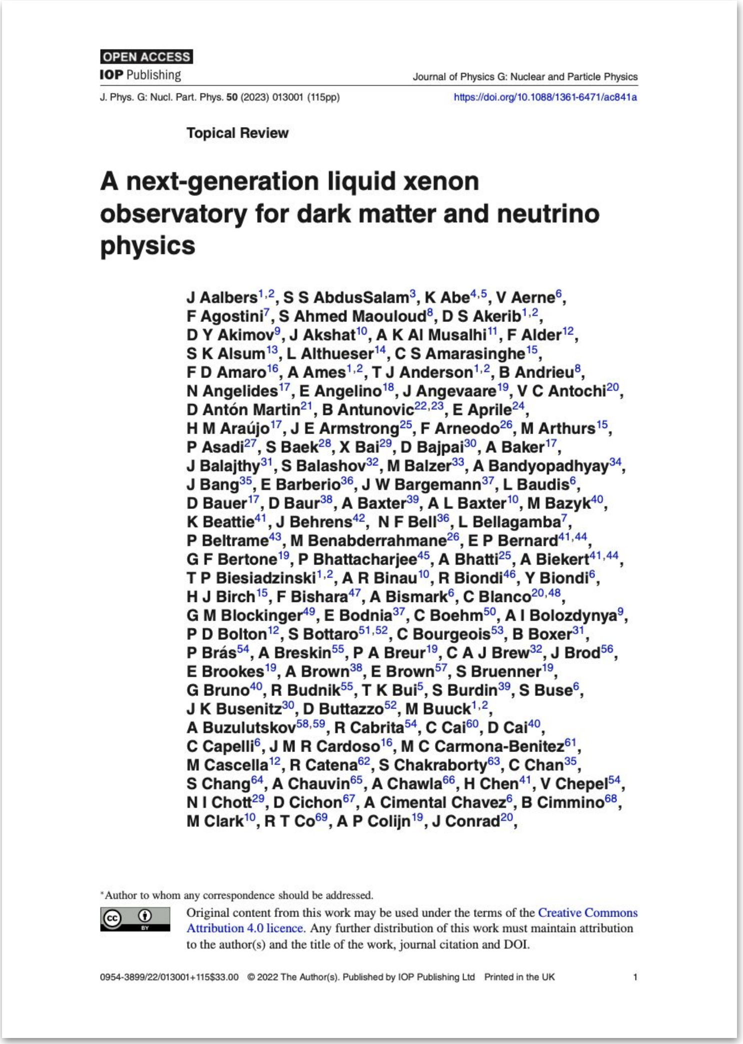
Science with liquid xenon

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



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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

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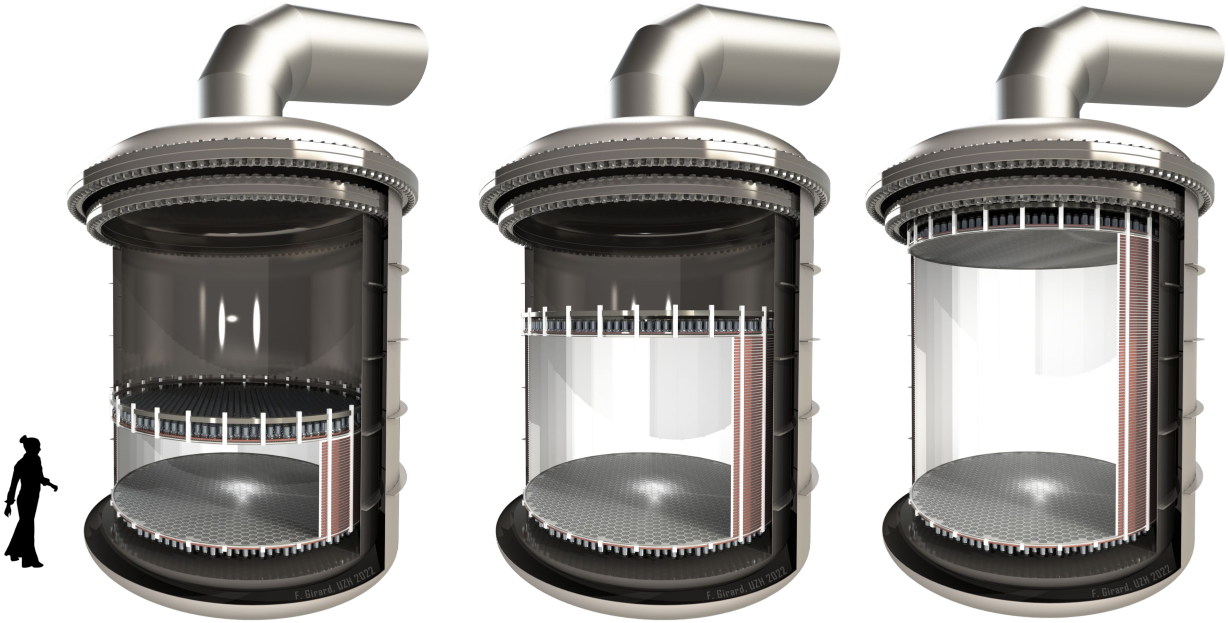
Detector

Ultimate mass: 50-80 T

Compact: 2-4 m diameter x height

Considering modifiable detector: 20→80 T

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

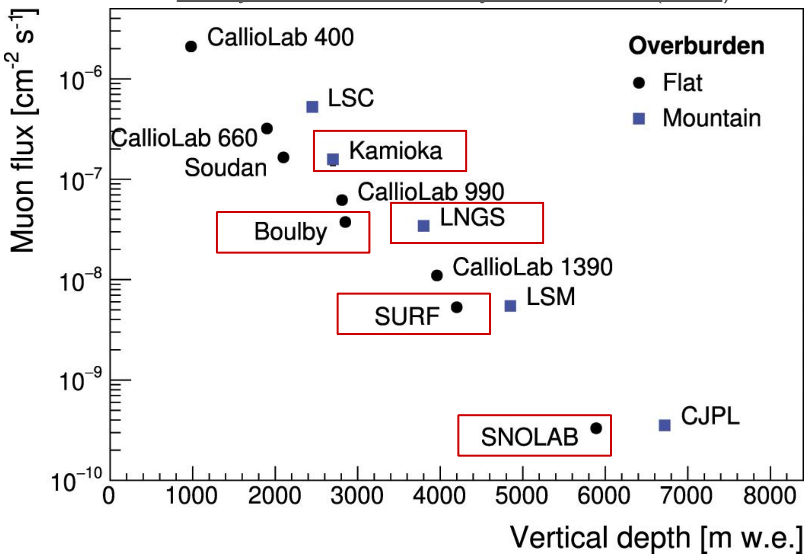


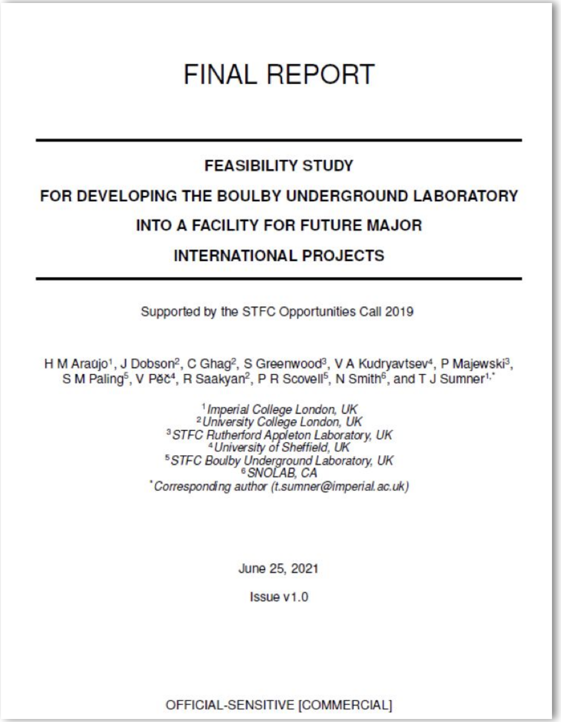
Siting

Considering 5 underground sites

Detector size requires significant space for underground fabrication

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





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

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Issue v1.0

OFFICIAL-SENSITIVE [COMMERCIAL]

Boulby feasibility study indicates technical viability

A challenge, but a great opportunity

Backgrounds

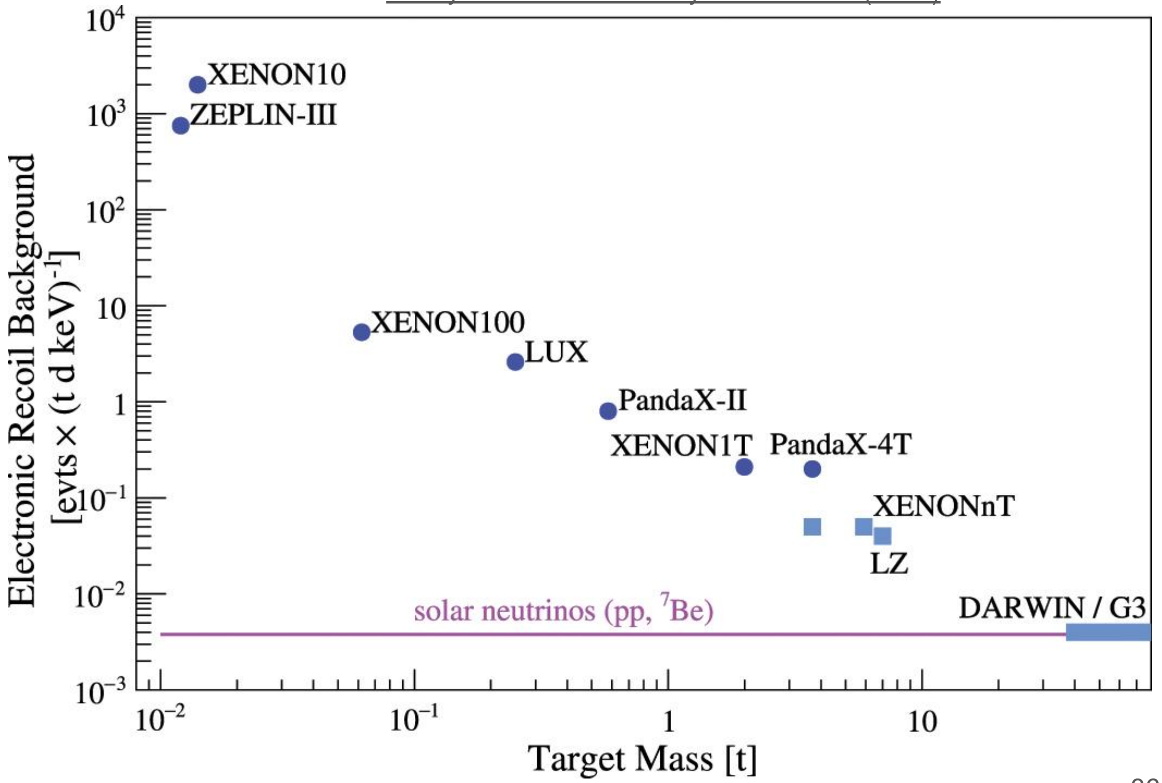
Goal is to be dominated by neutrino backgrounds

Self-shielding from γ-ray and neutron backgrounds

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

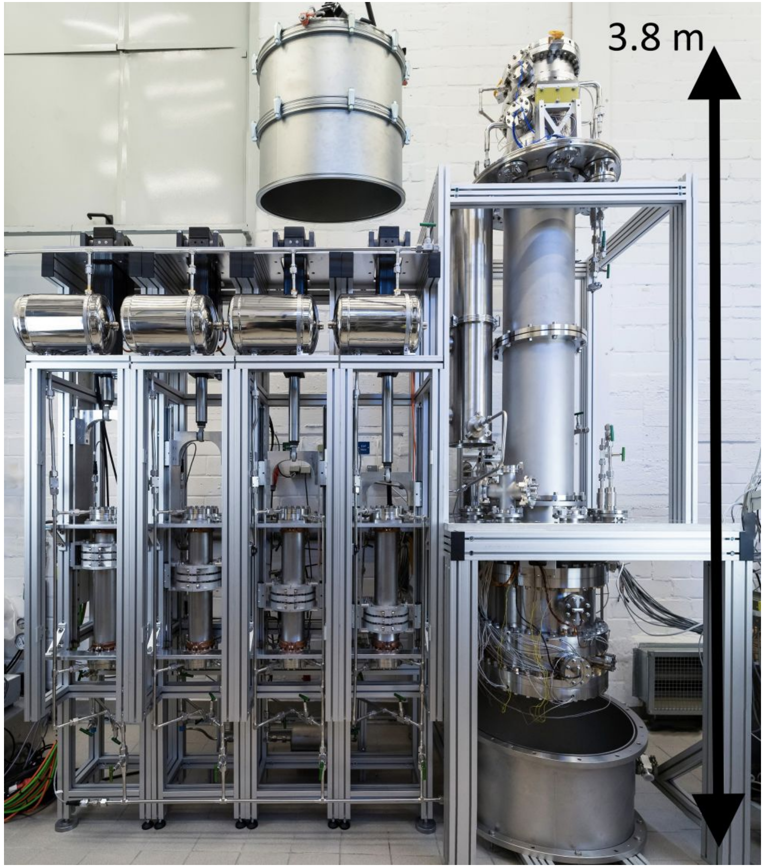
^{222}Rn challenging but there is R&D to fix it

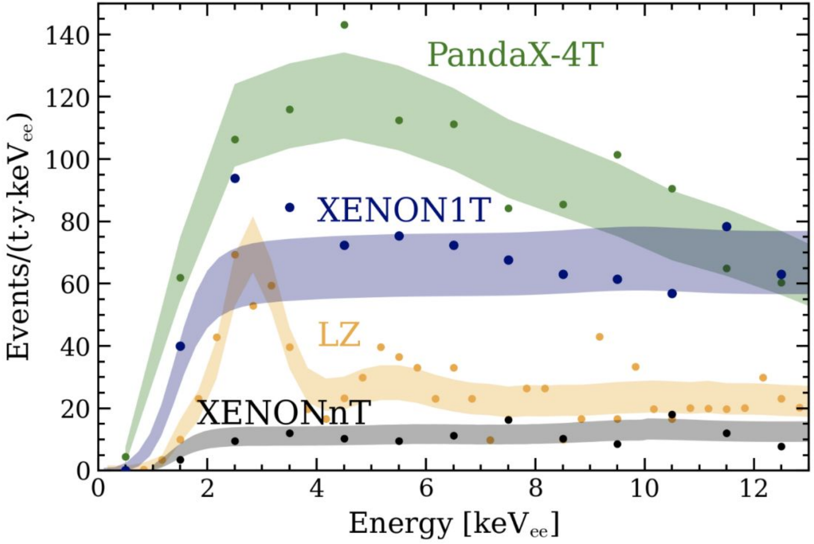
J. Phys. G: Nucl. Part. Phys. 50 013001 (2023)



Solutions for Rn removal

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





2 ongoing experiments → 2 solutions to every problem

LZ uses adsorption of xenon gas on charcoal

XENONnT uses cryogenic distillation enhanced for radon removal

WIMP projected sensitivity

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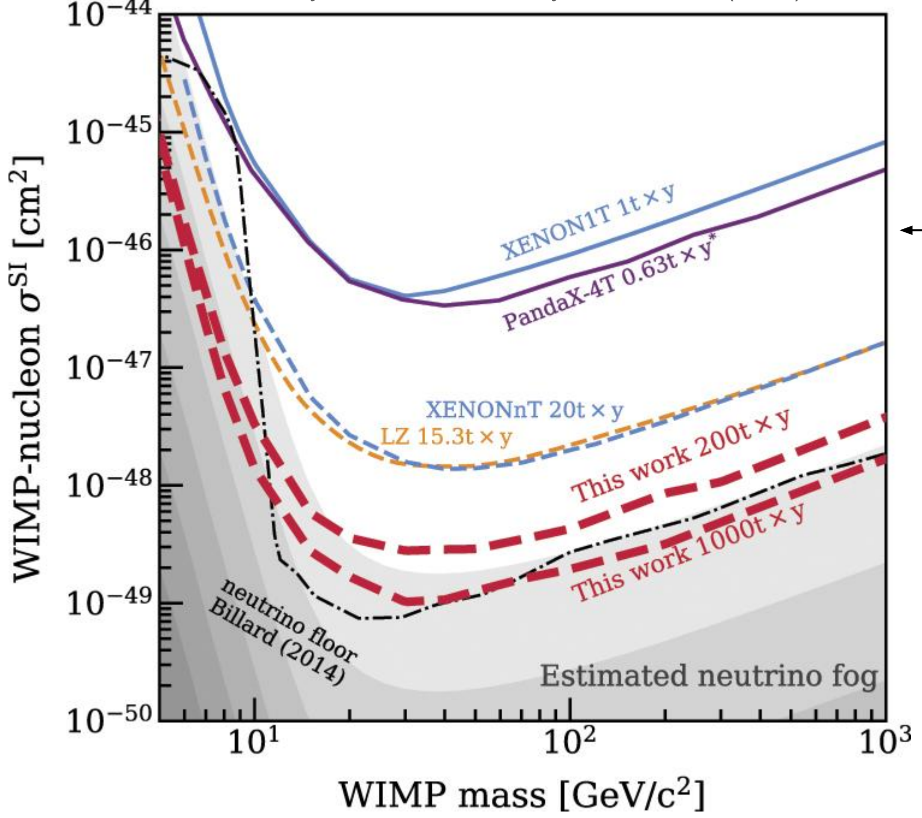
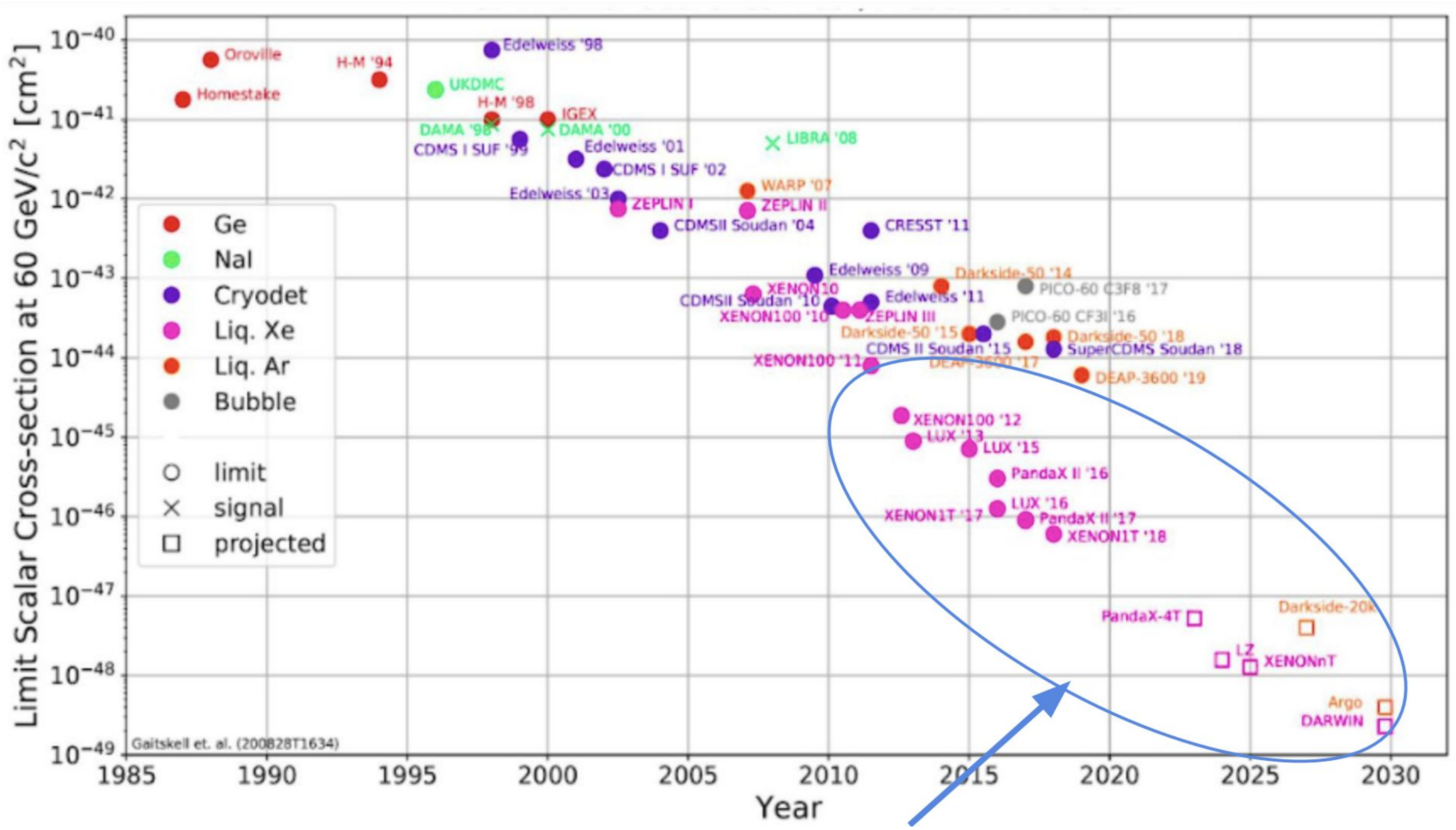


Chase WIMPs to the neutrino fog!

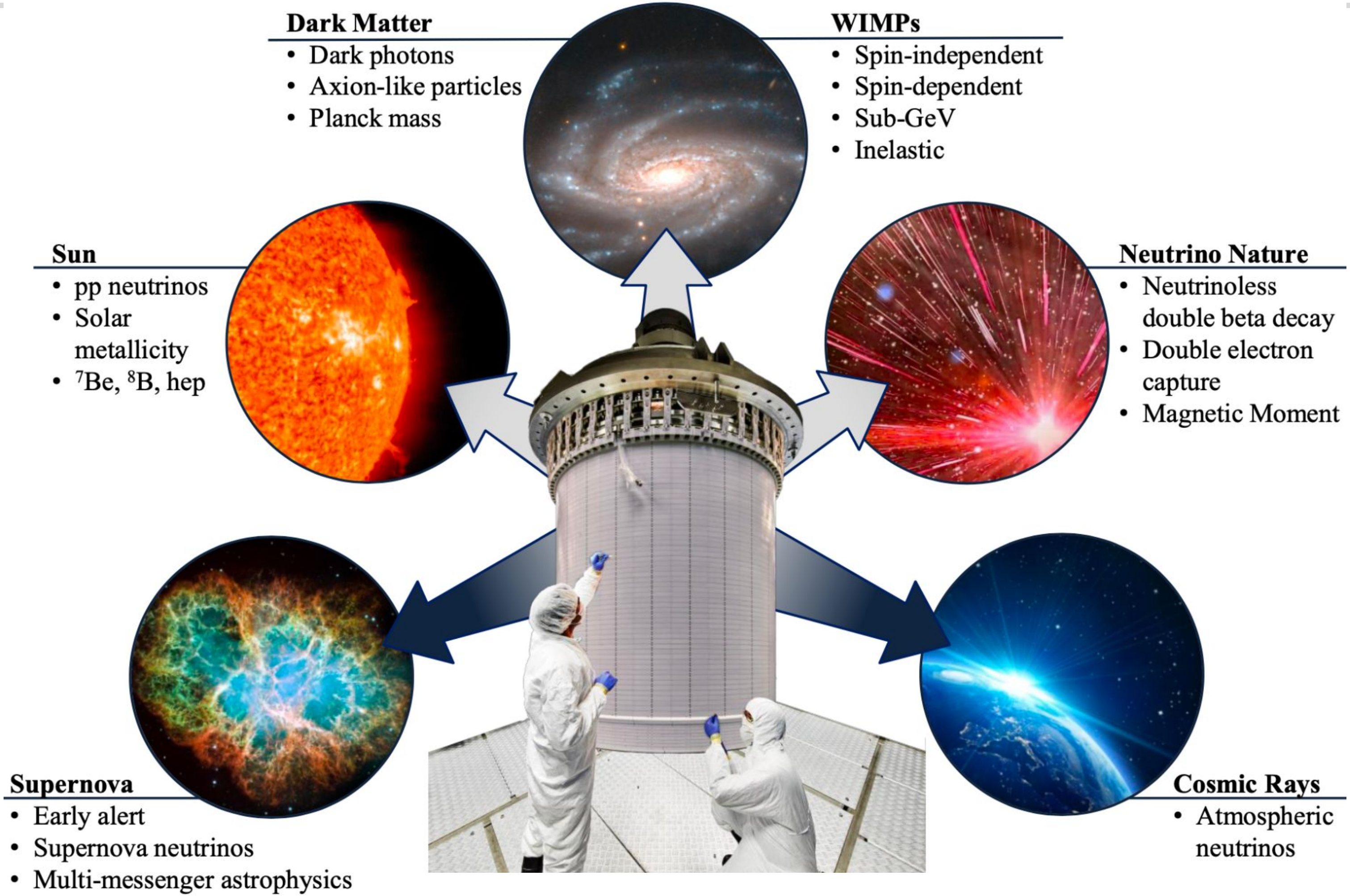
Background assumptions

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

Evolution of sensitivity

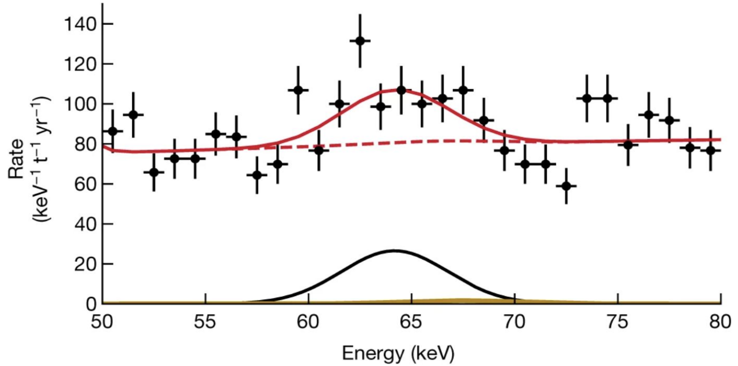


Dominated by LXe TPCs for the last two decades

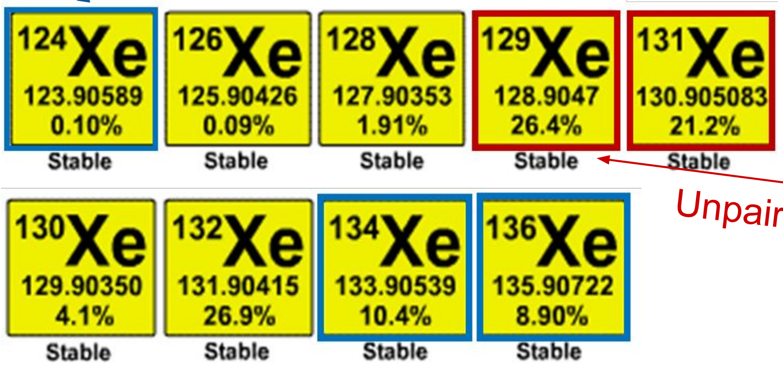


Scientific reach

XENON1T Collaboration. Nature 568, 532–535 (2019)

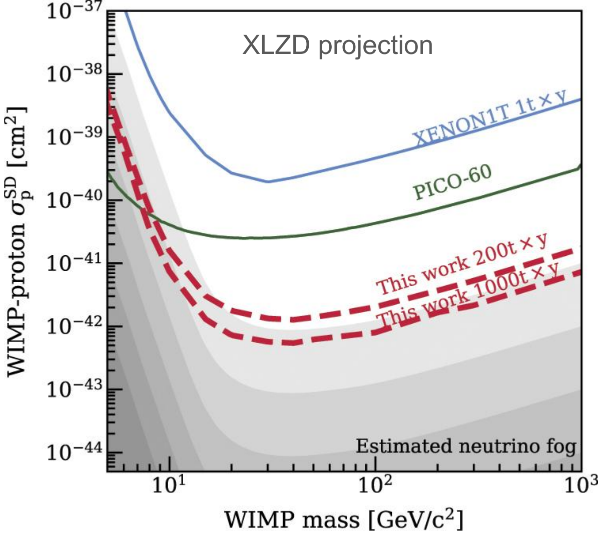


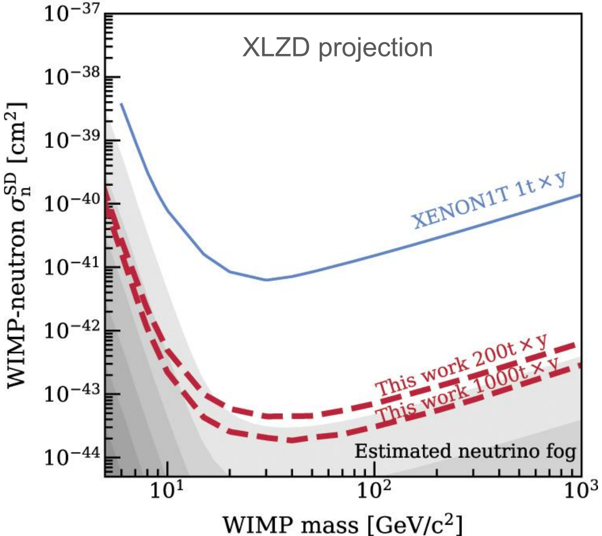
2ν double electron capture



Unpaired neutrons

$0\nu\beta\beta$ decay





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^{136}Xe $0\nu\beta\beta$ backgrounds

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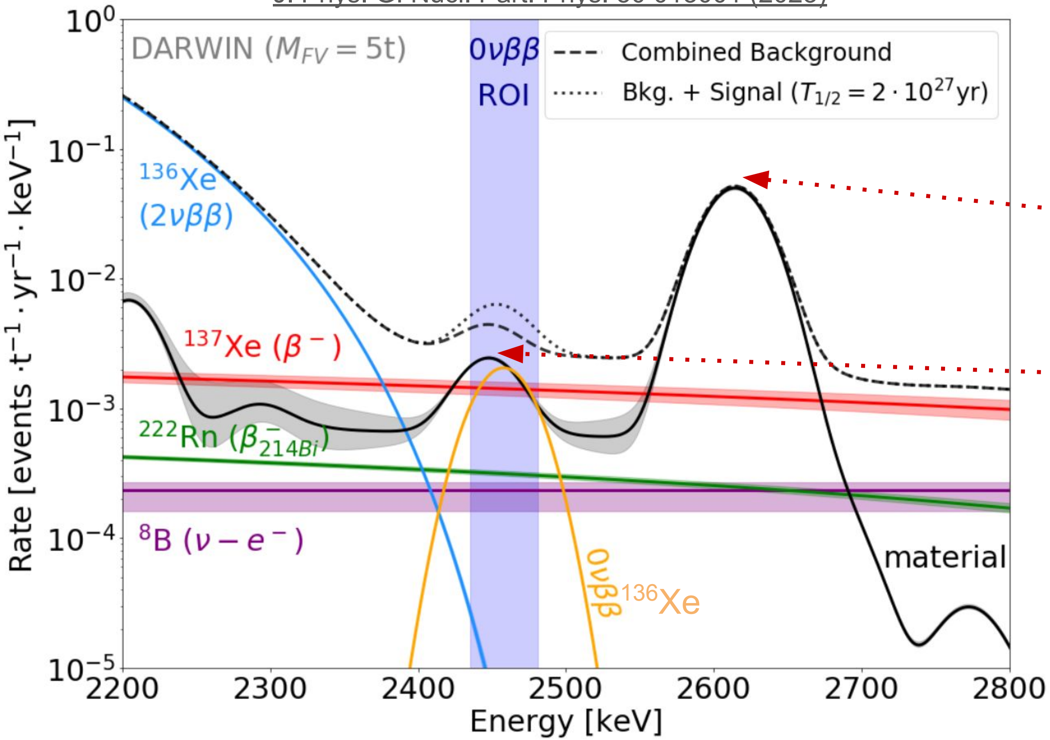

Primary backgrounds: γ rays from detector components

- ^{208}Tl 2614 keV → impact strongly mitaged by ~1% **σ**/E
- ^{214}Bi 2447 keV → impact mitigated by self shielding of larger detector

^{137}Xe β (Q=4173 keV) from neutron capture and cosmogenic activation

^{136}Xe $0\nu\beta\beta$ projected sensitivity

With major investment controlling backgrounds (beyond DM needs) could match nEXO sensitivity

DARWIN: 40 T

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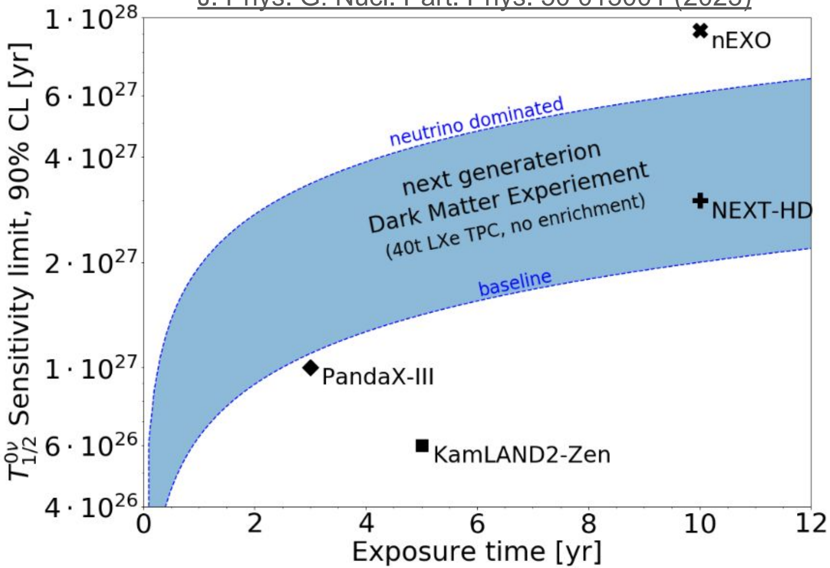
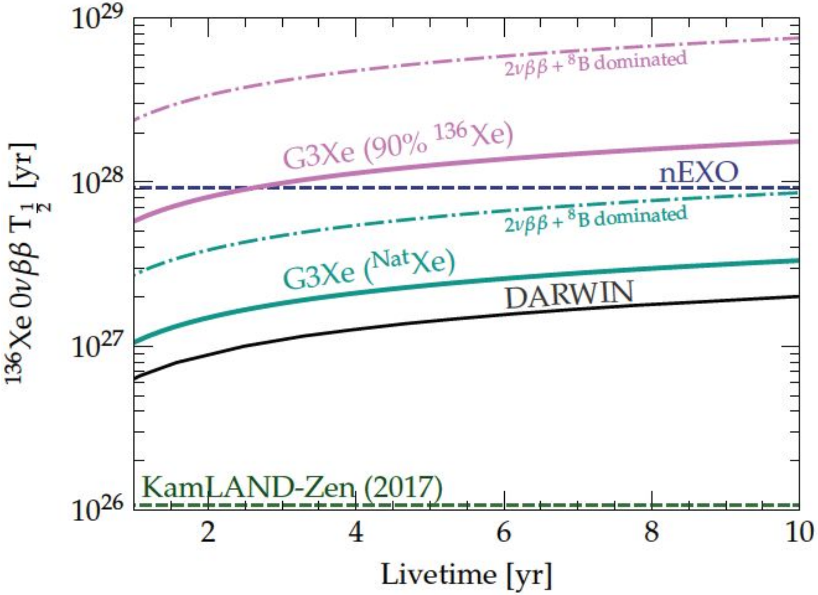


Next-gen (G3): 70 T



Xenon Futures R&D Programme

UK has started the R&D phase towards a next generation experiment

Exploring SiPM readout for γ-ray and radon background reduction (Xenia)

Cold radon emanation facility (CREF)

Attempting observation of the Migdal effect from nuclear recoils (MIGDAL)

University of BRISTOL

The University Of Sheffield.

Science & Technology Facilities Council Rutherford Appleton Laboratory

KING'S College LONDON

UNIVERSITY OF LIVERPOOL

Imperial College London

UCL

UNIVERSITY OF OXFORD

ROYAL HOLLOWAY UNIVERSITY OF LONDON

THE UNIVERSITY of EDINBURGH

Summary

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

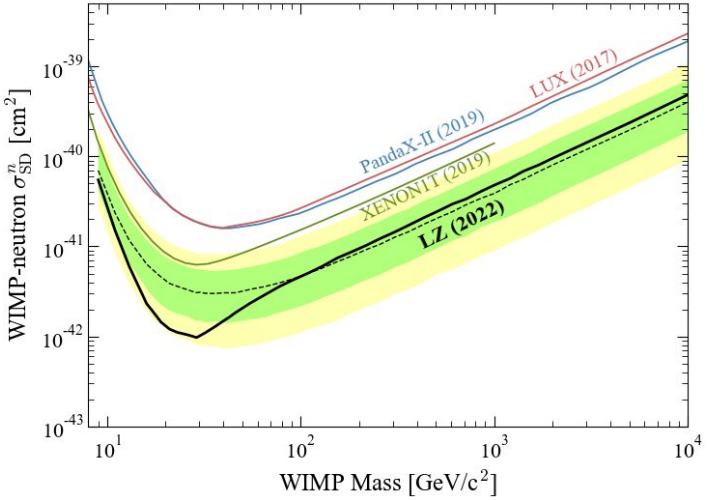
2. With its first run, LZ has achieved world-leading WIMP sensitivity

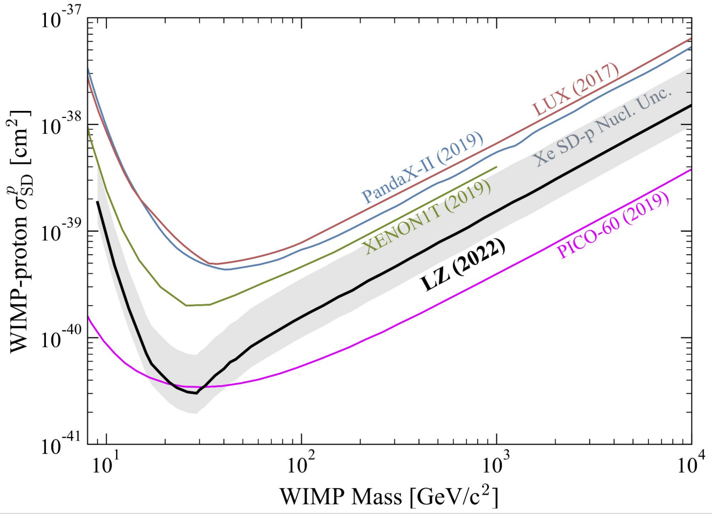
3. Broad physics program still lies ahead for LZ

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

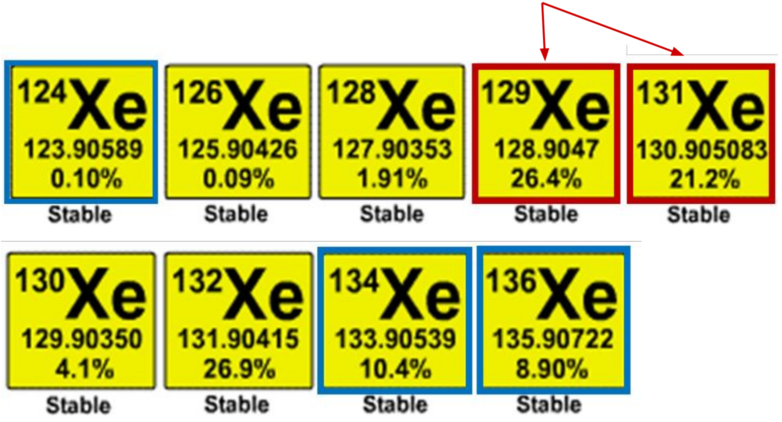
Additional Slides

Spin-dependent WIMP sensitivity





Unpaired neutrons



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

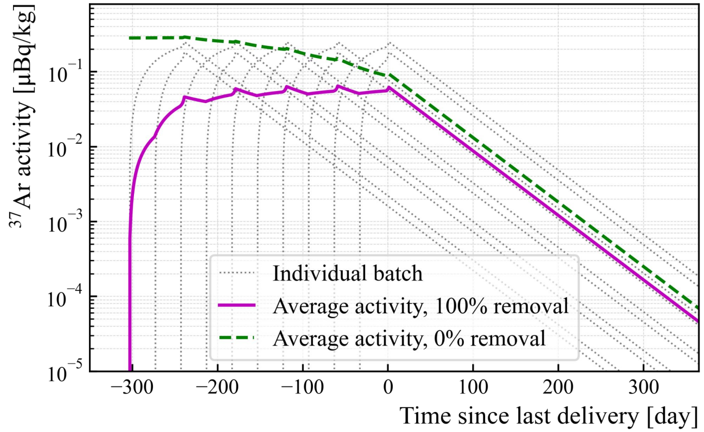
^{37}Ar

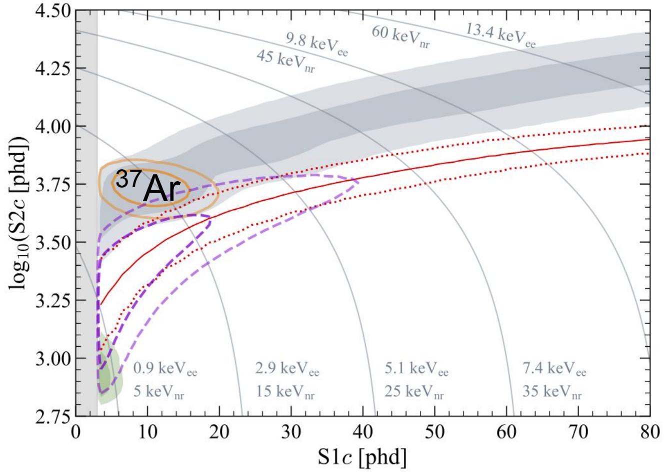
^{37}Ar decays ($T_{1/2}$ = 35 d, monoenergetic 2.8 keV ER deposition from electron capture)

Predominant source of argon in LZ is through cosmogenic spallation

LZ Collaboration, Phys. Rev. D 105, 082004 (2022), 2201.02858

Activity estimates can be formed showing approximately 100 decays in data (large uncertainty)

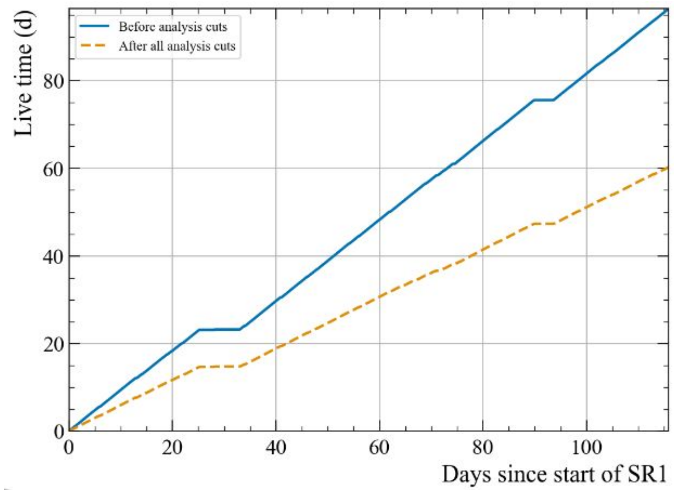




Livetime

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 (S1/g1+S2/g2)

W = average energy required to prejudice one quantum