First results of the LUX-ZEPLIN Experiment

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November 21st, 2022

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Imperial College London

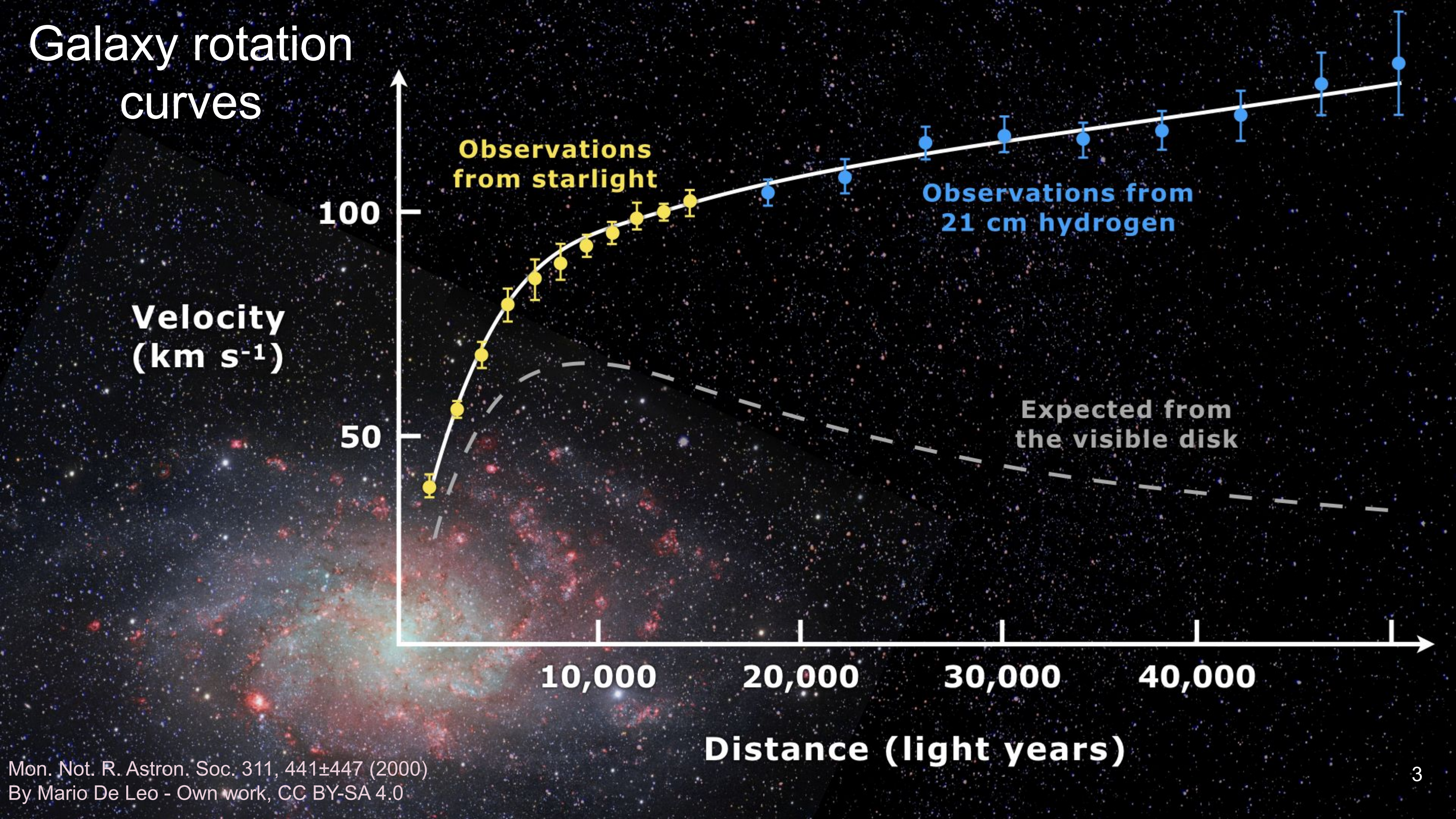
Outline

1. Introduction to dark matter

2. The LUX-ZEPLIN (LZ) experiment
    a. Detector design
    b. Construction and commissioning
    c. Dark matter search

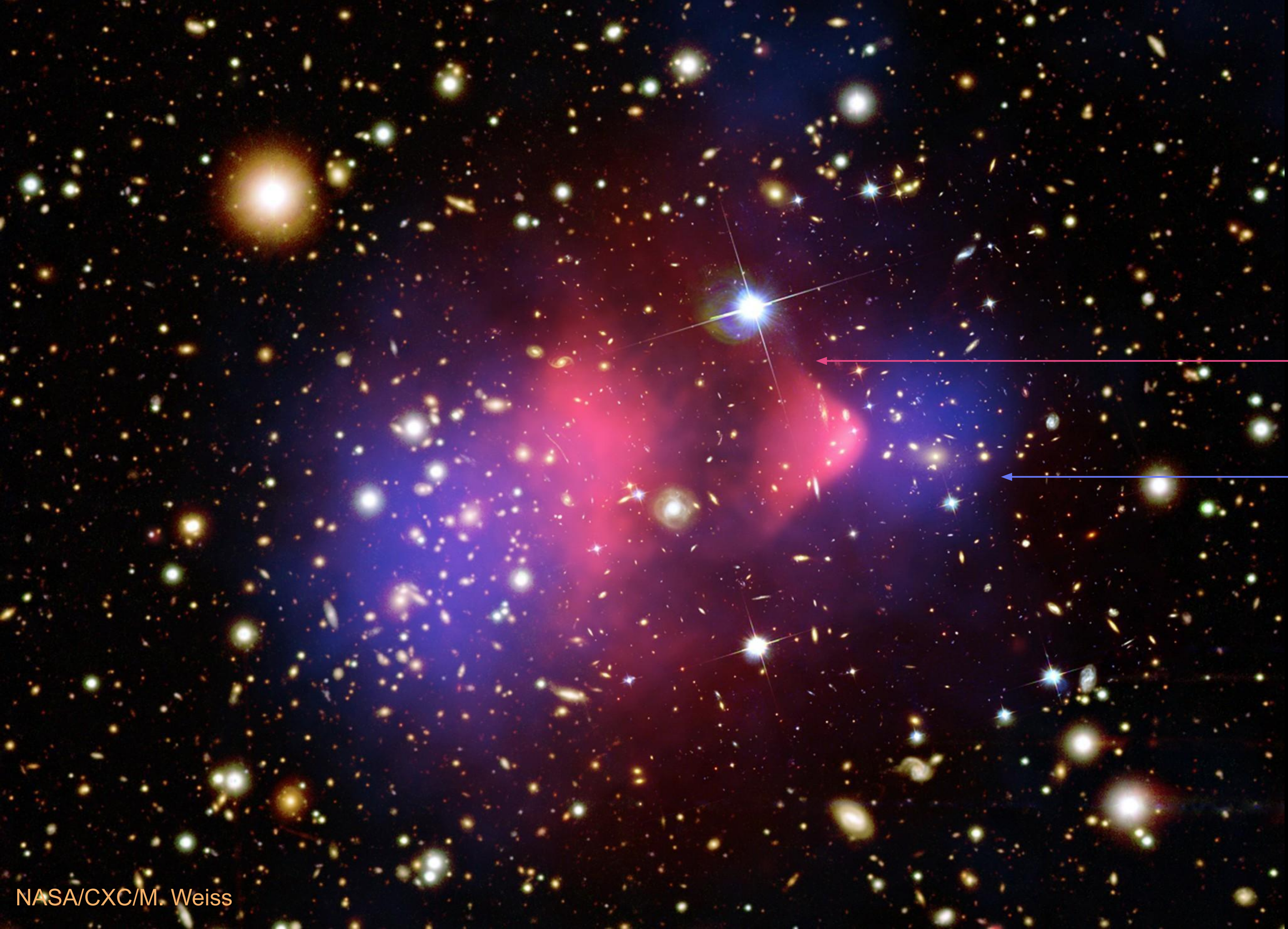
3. Future xenon observatory for dark matter and other rare events
    a. XLZD consortium
    b. Physics reach

Galaxy rotation curves



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

Bullet cluster



NASA/CXC/M. Weiss

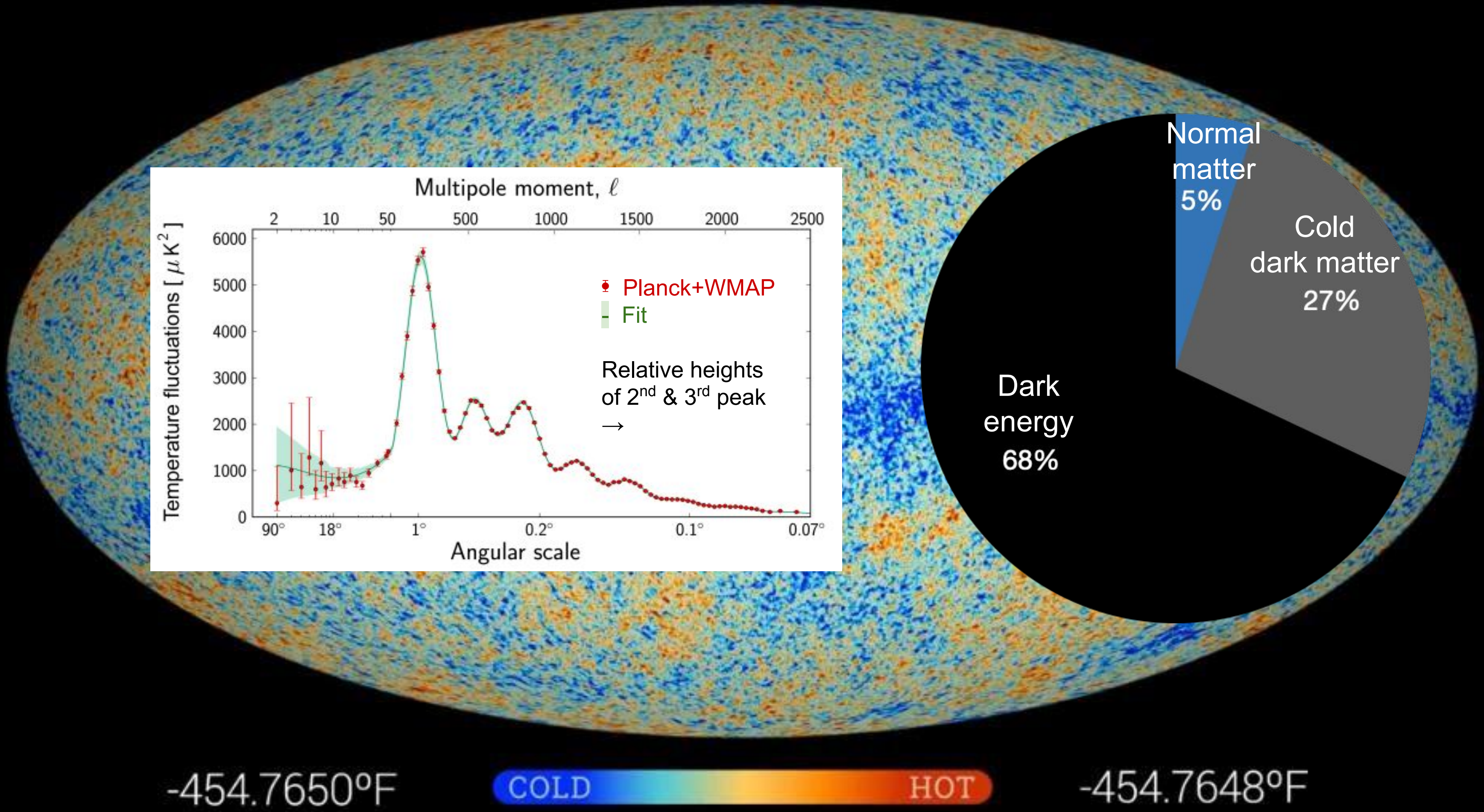
Colliding clusters of galaxies

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

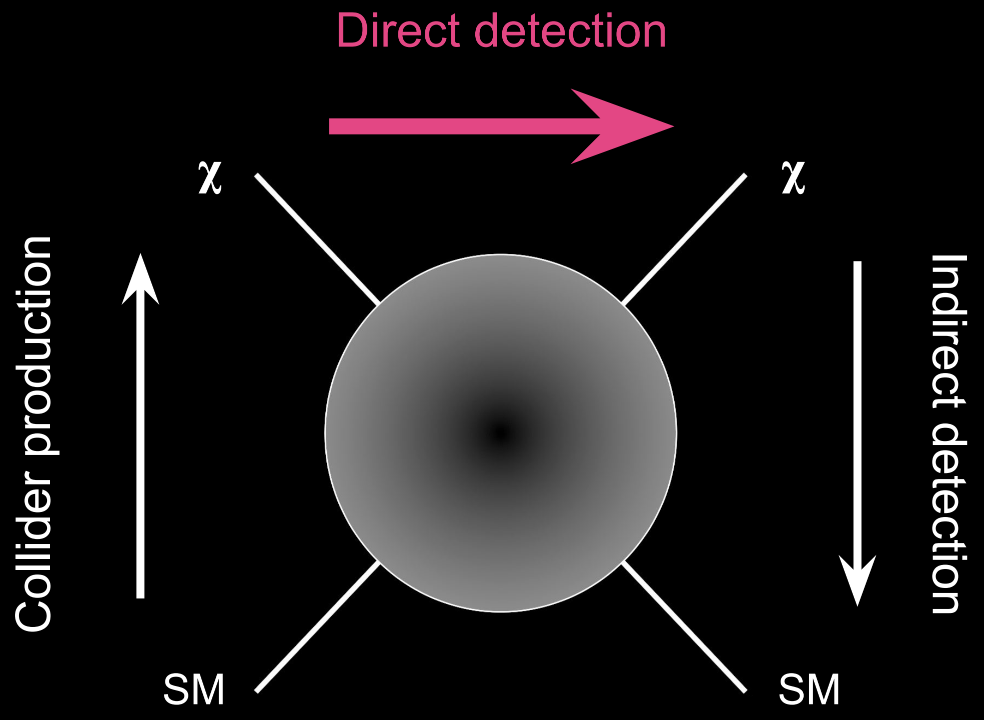
We are in the Milky Way →

Local dark matter density ~ 0.3 GeV/cm^3

Average dark matter velocity v ~ 220 km/s

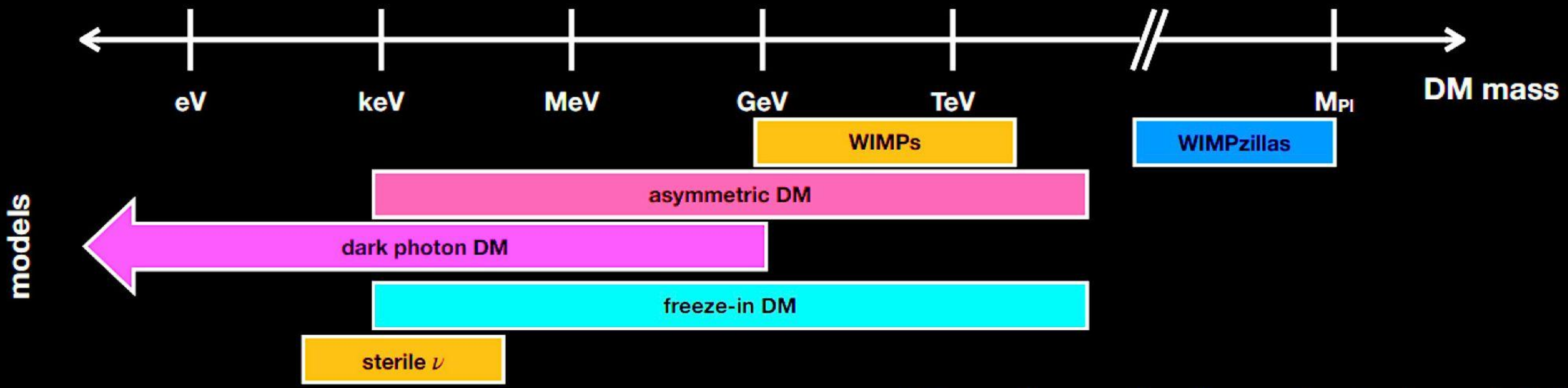
Assuming Maxwell-Boltzmann distribution of dark matter

Detecting particle dark matter



Possibilities for particle dark matter

Gravitational interactions ⟶ massive (particle)



Weakly interacting massive particles (WIMPs)

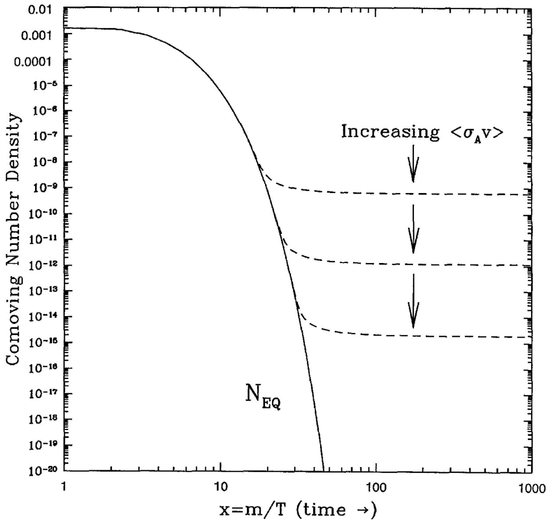
Dark matter freeze-out

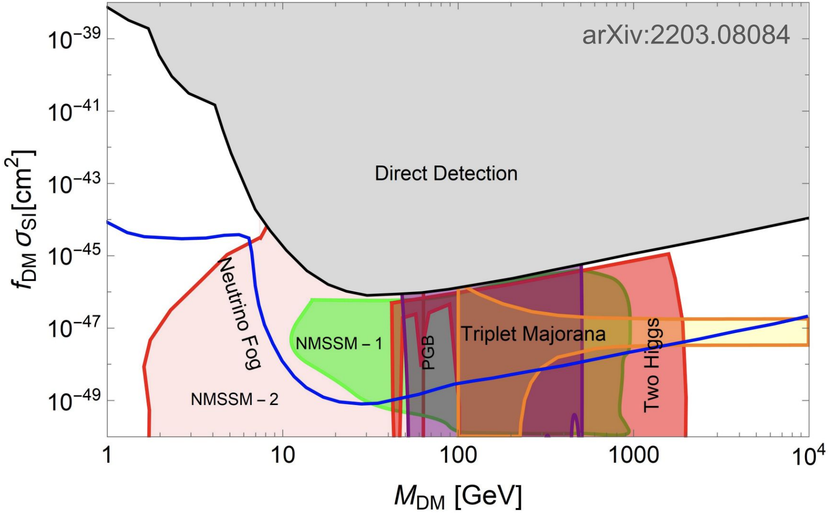
m_{DM} ~ 100 GeV

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

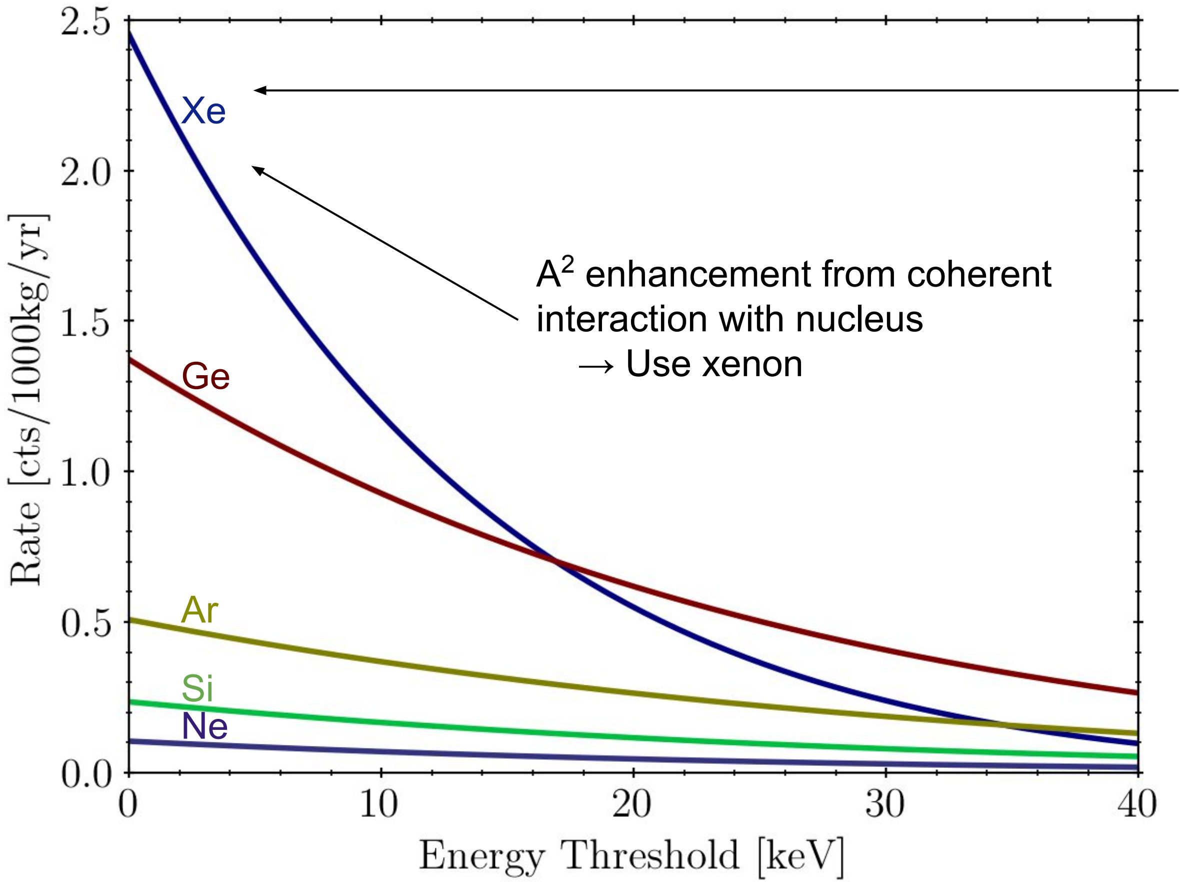
Supersymmetry provides candidates

Currently viable GeV-TeV dark matter models →





Dark matter scattering rate



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

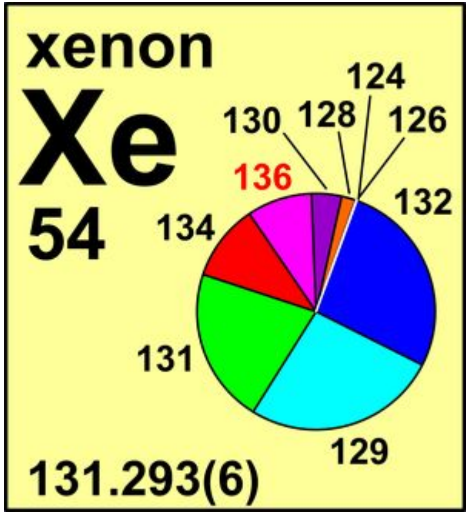
Spin-dependent scattering rate ~ $(J+1)/J\ (\alpha_p\langle S_p\rangle+\alpha_n\langle S_n\rangle)\ F_{SD}^2$

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 $0\nu\beta\beta$

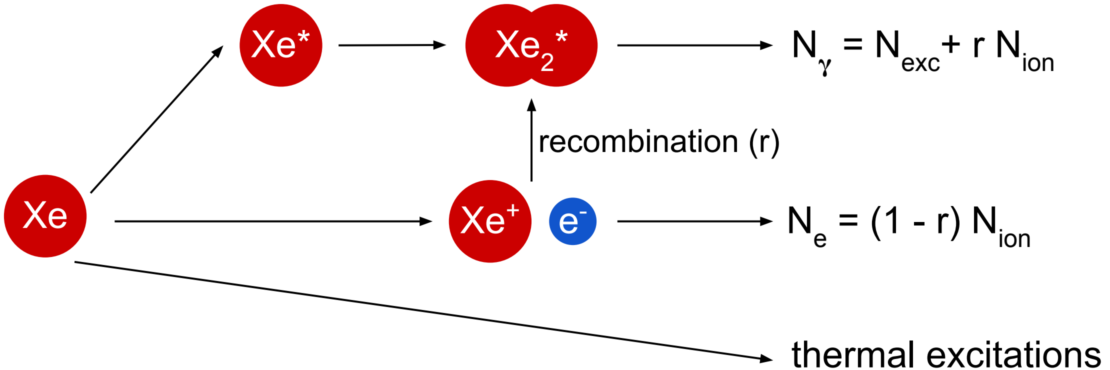
Few problematic radio-isotopes

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

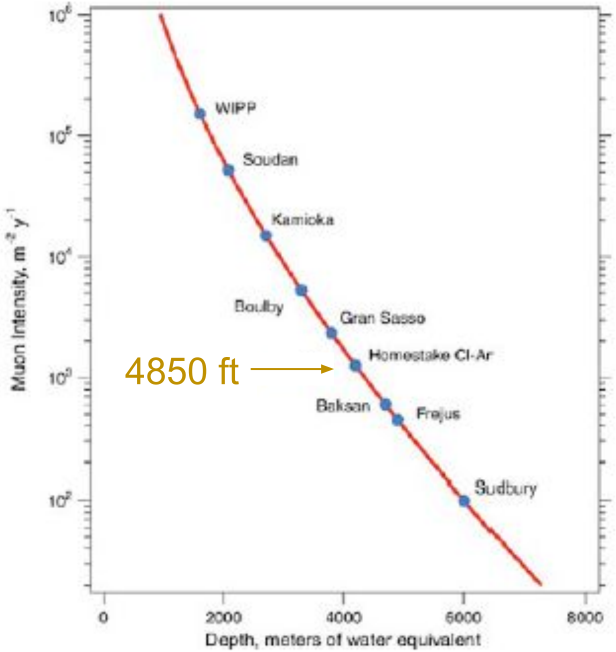
UKRI Science and Technology Facilities Council

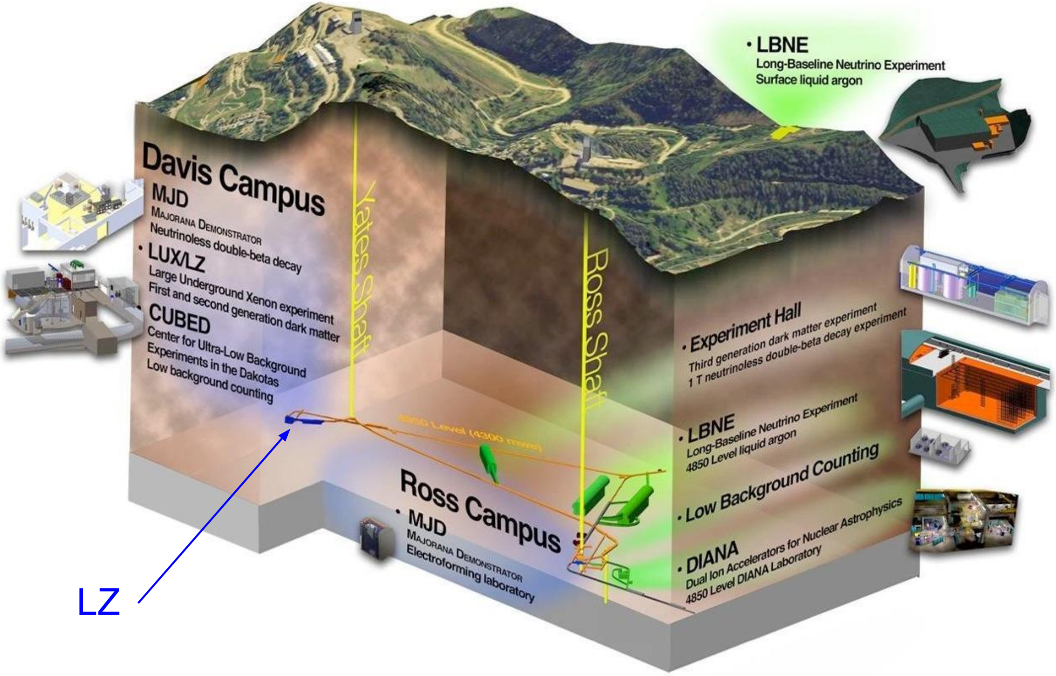
Sanford Underground Research Facility
South Dakota Science and Technology Authority

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

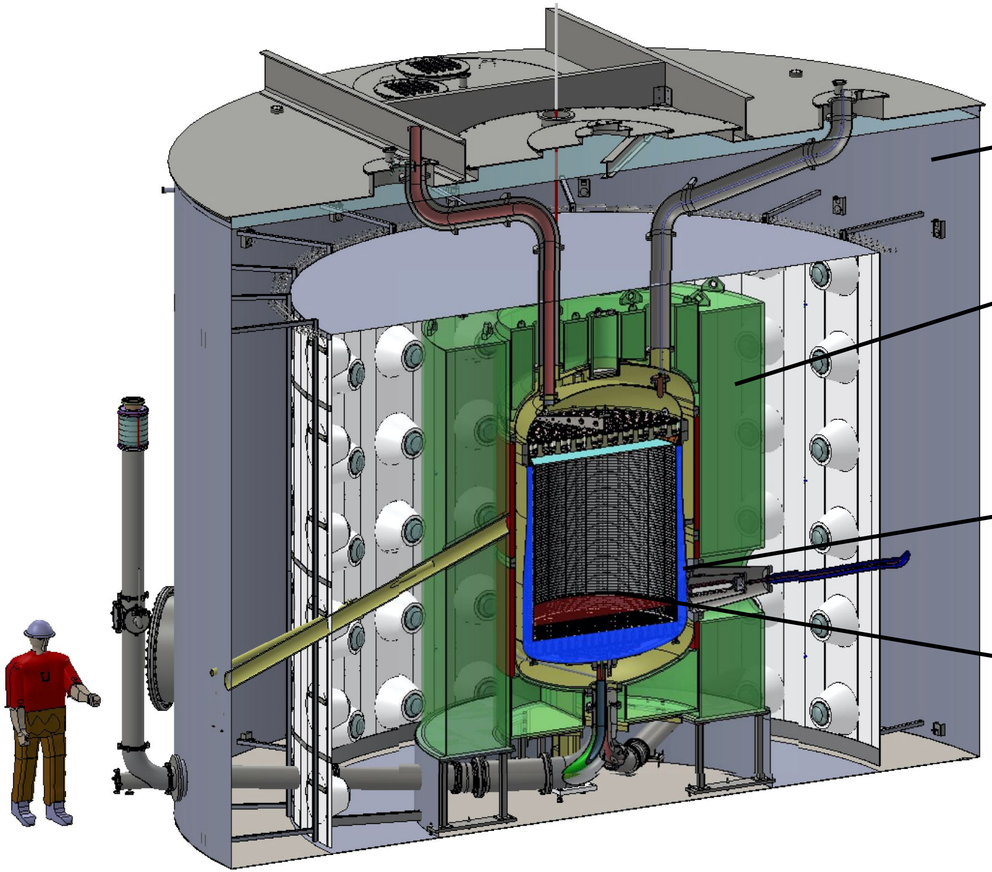
ibs Institute for Basic Science

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” 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

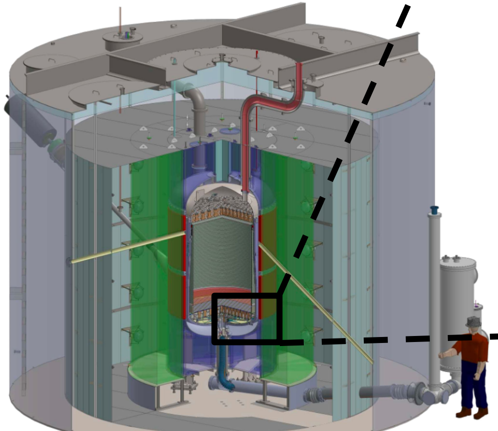
Veto detectors

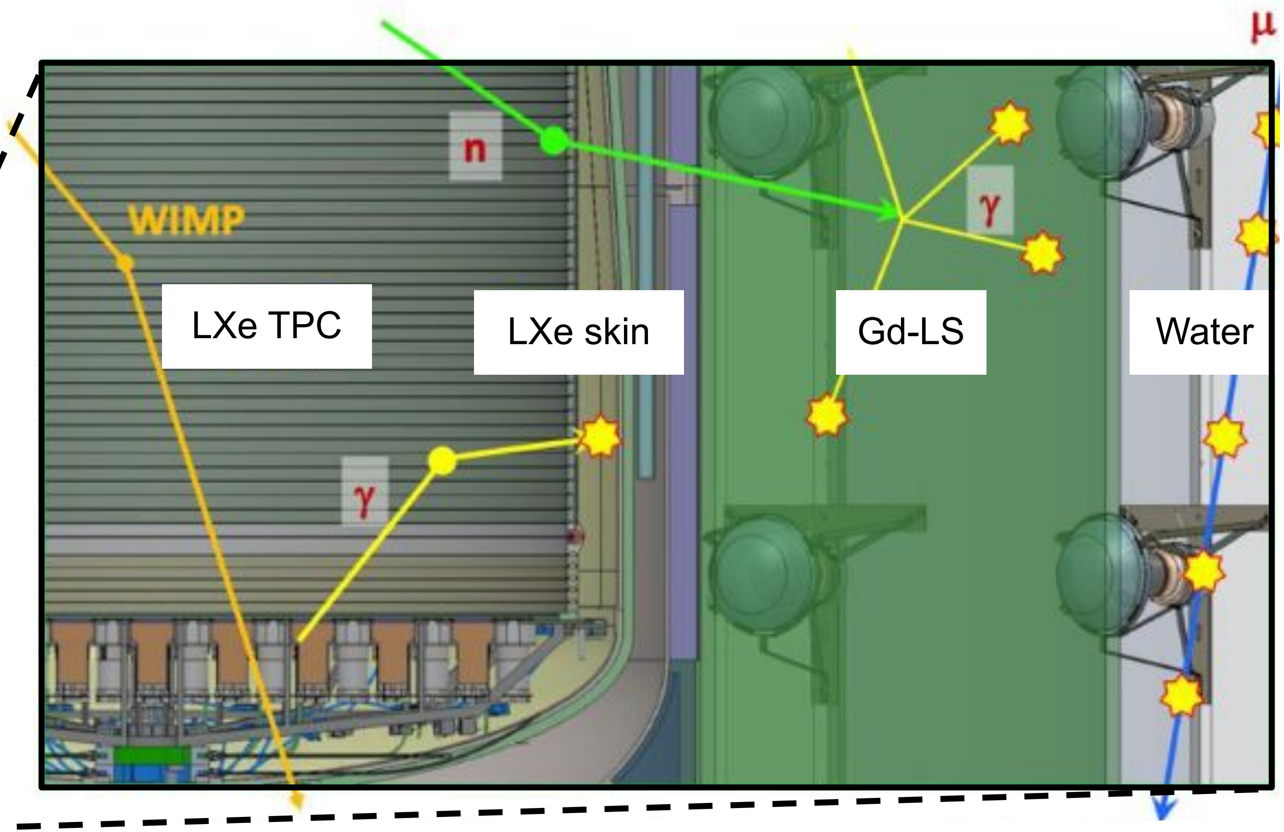
Lined with PTFE (skin) or tyvek (OD) to maximize light collection

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

88±0.7% neutron tagging efficiency

5% livetime reduction

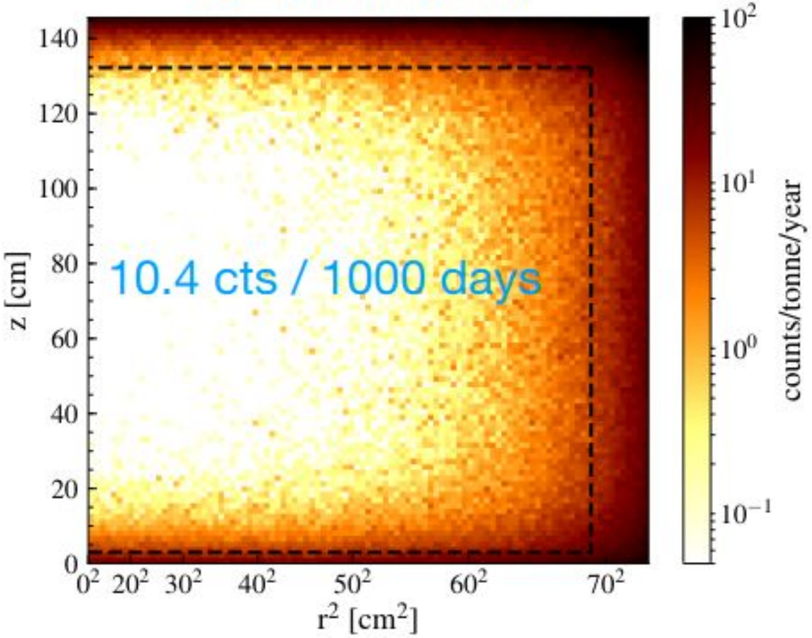




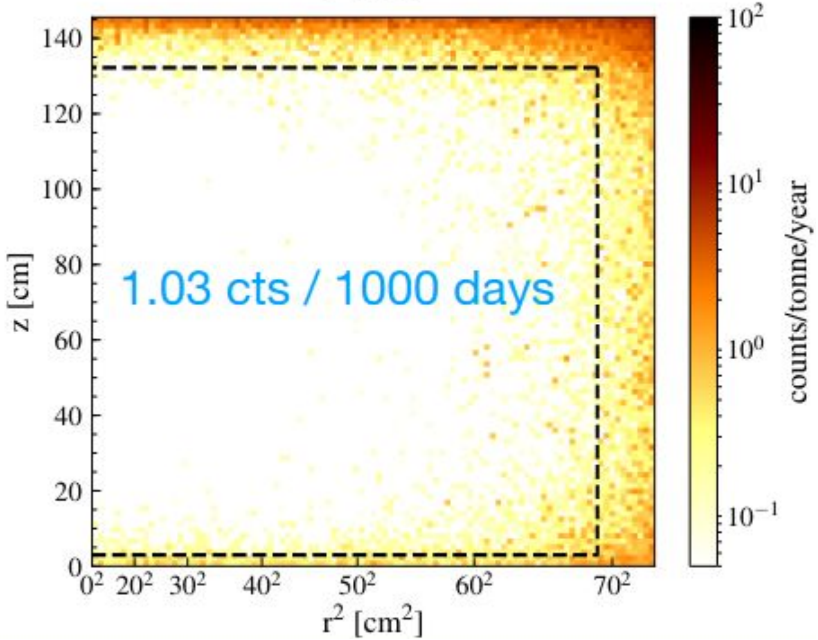
Veto detectors

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

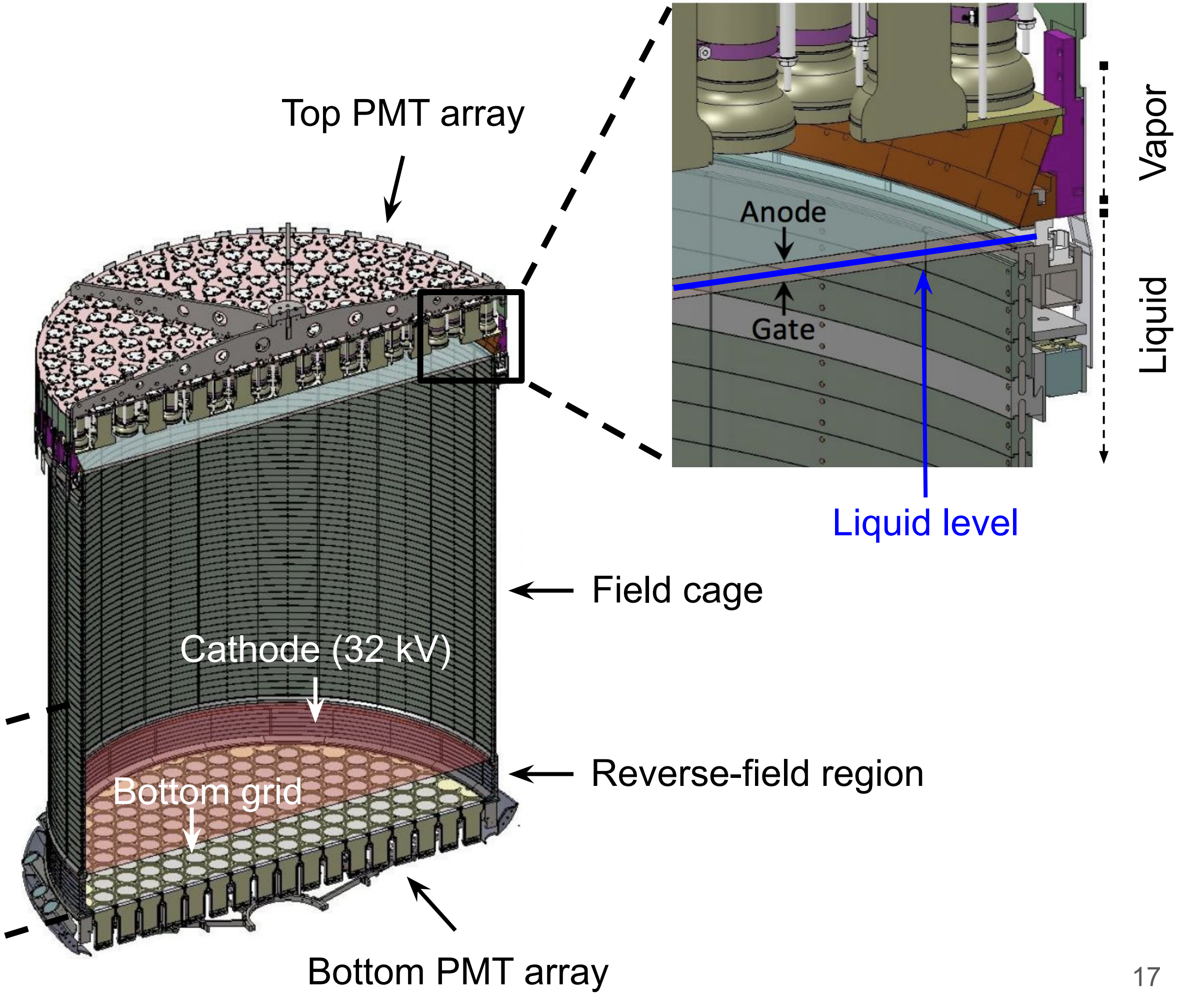
1.5 m dia x 1.5 m height

PTFE everywhere for light collection

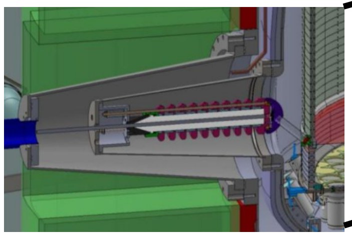
7 T active LXe (5.5 T fiducial)

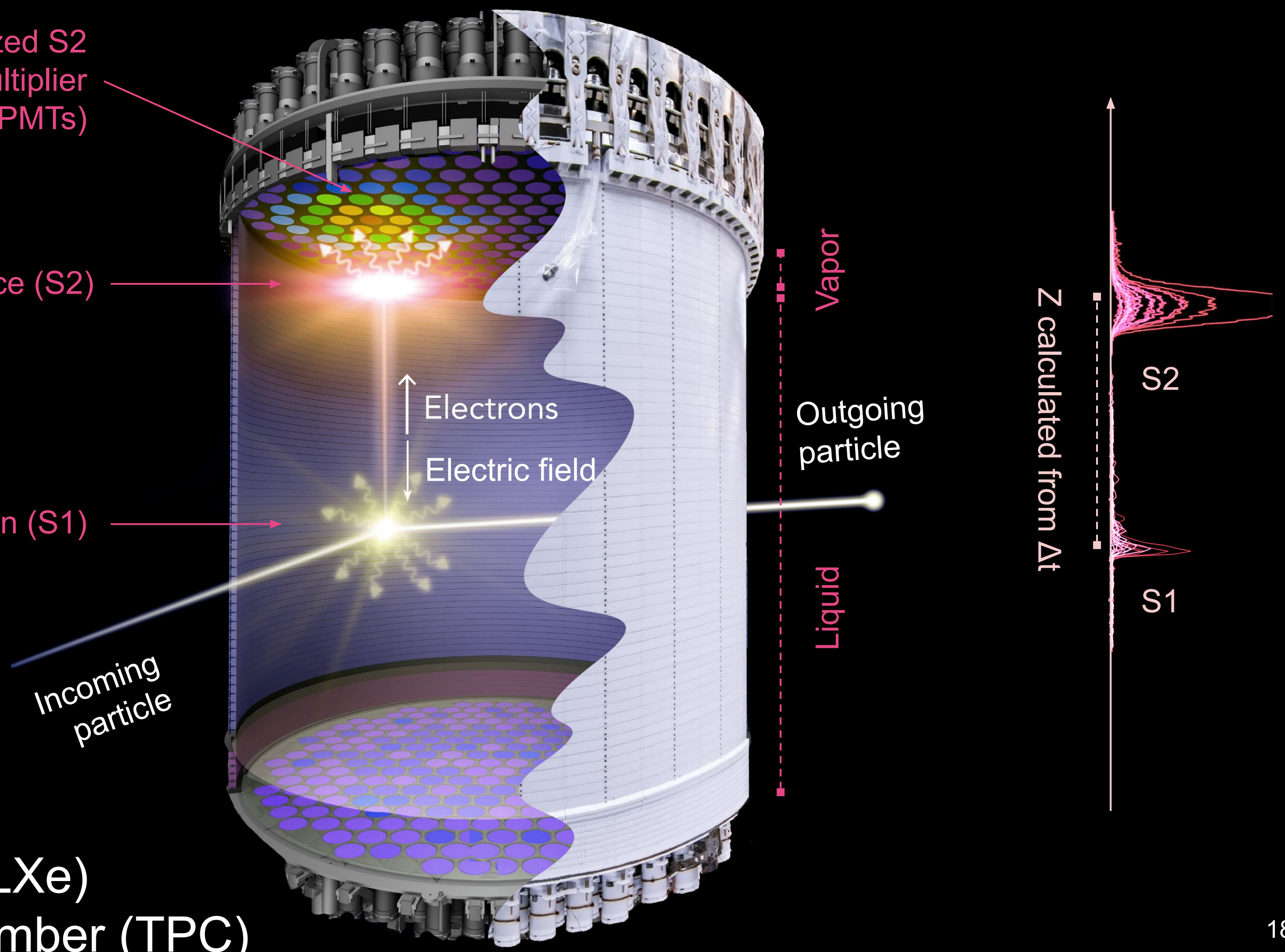
4x wire-grid electrodes

- 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)

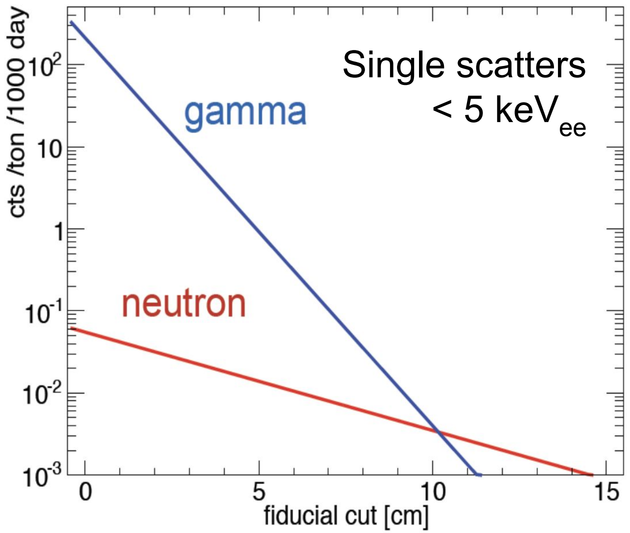
Fiducialization

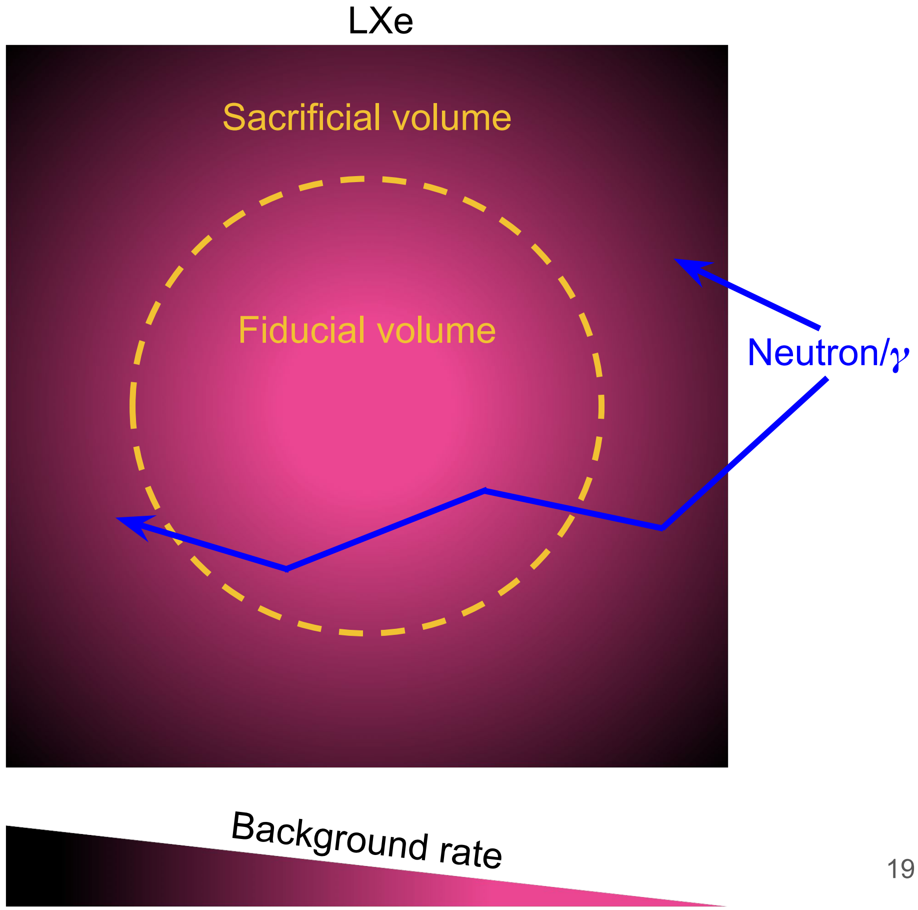
Xenon is dense, ~ 3 g/cm^3

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

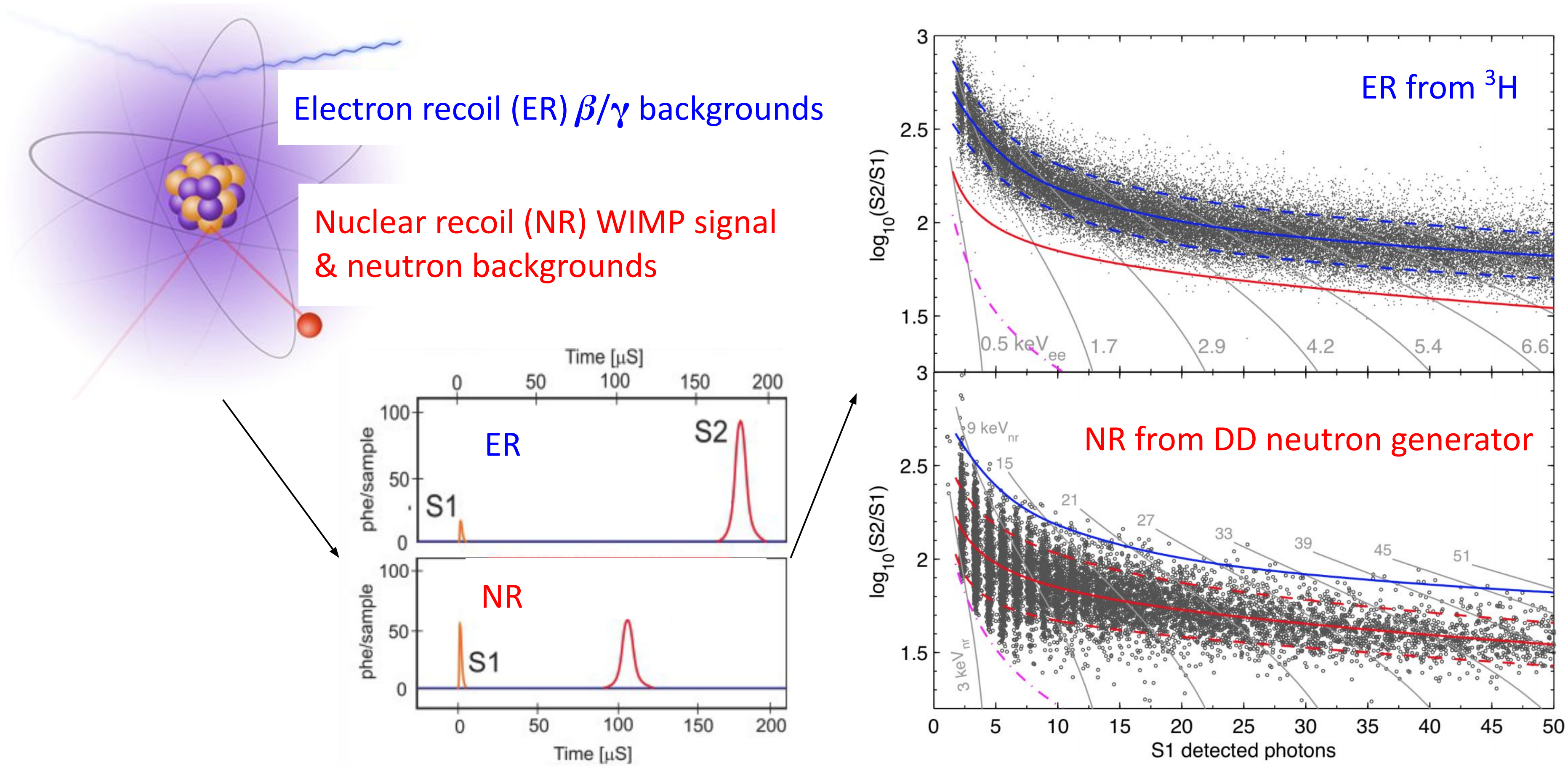
Reject events from the high-background rate regions near the edge of the TPC

Reject multiple scatters

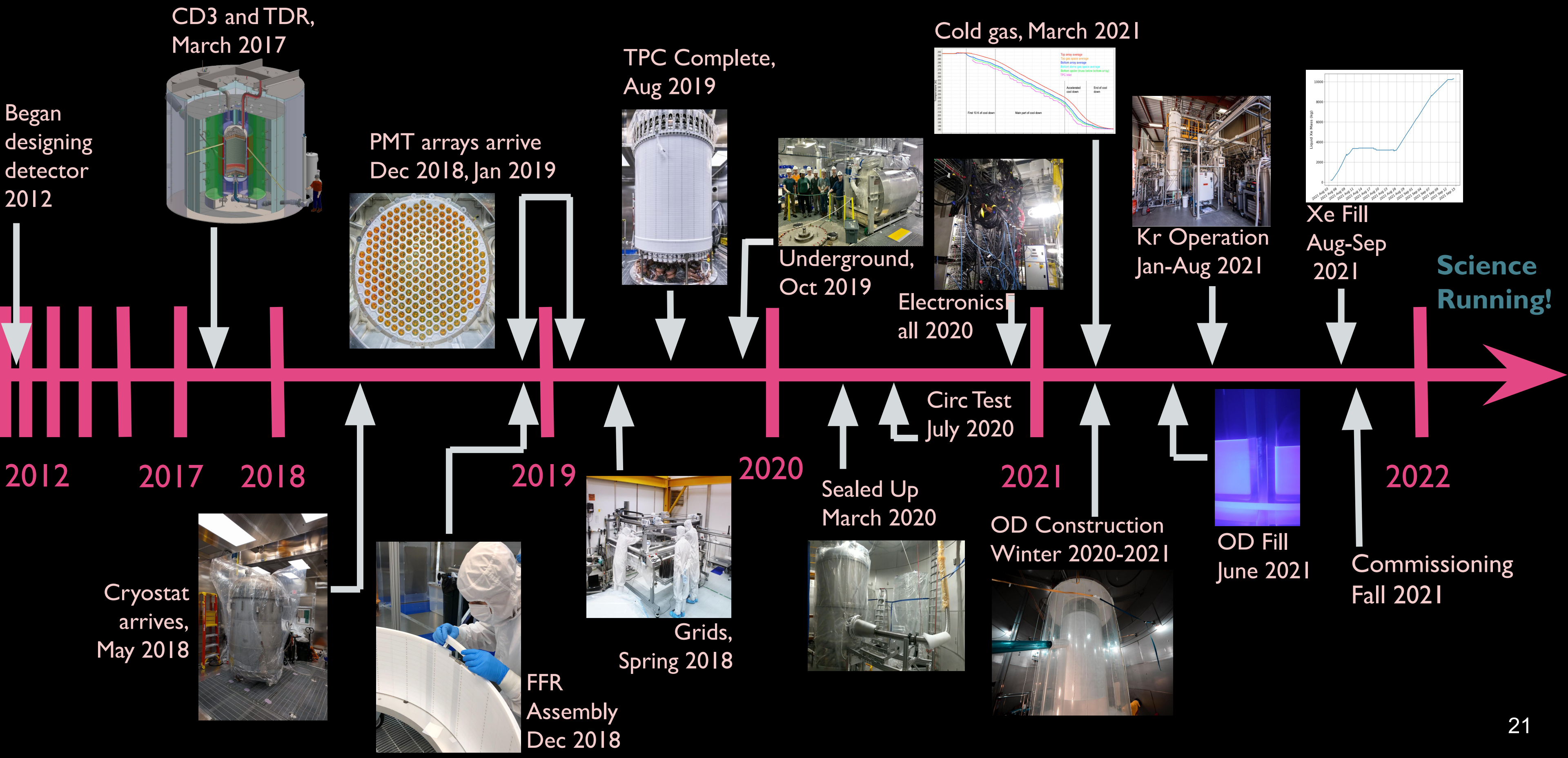




Electron/nuclear recoil discrimination



Timeline: Design→Construction→Operation



Construction of electric-field grids

Critical to achieve desired electrostatic parameters for high ER/NR discrimination and ~uniform electron extraction efficiency

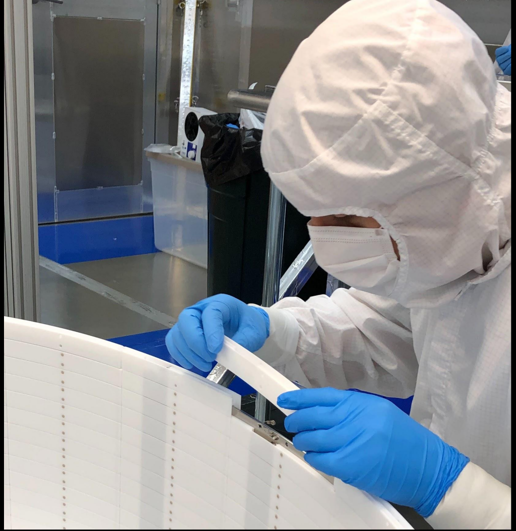
At SLAC, woven in custom loom, precise tensioning of wires, limit deflection of wires in electric field

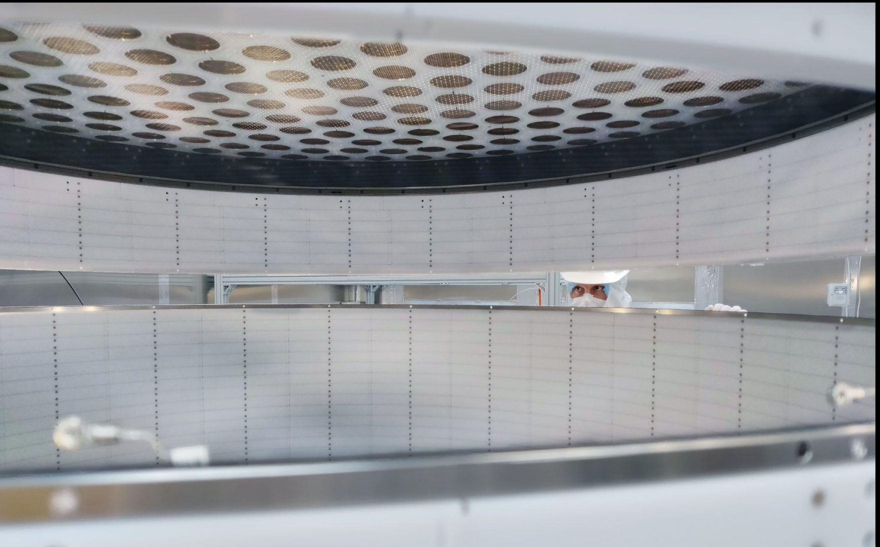
Citric acid passivation of the gate to mitigate field induced emission of electrons that limits fields we can apply in extraction region

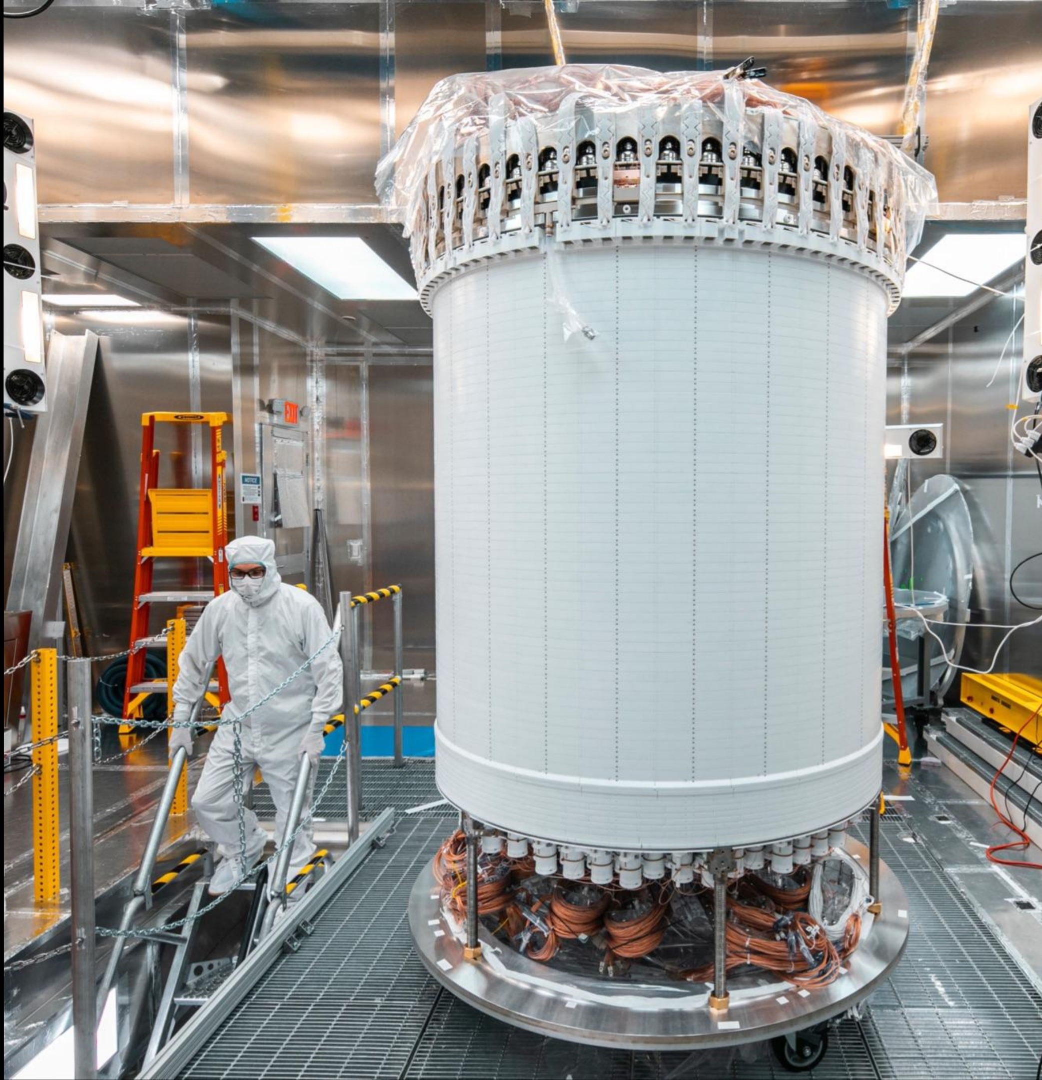
TPC construction

Surface level at SURF

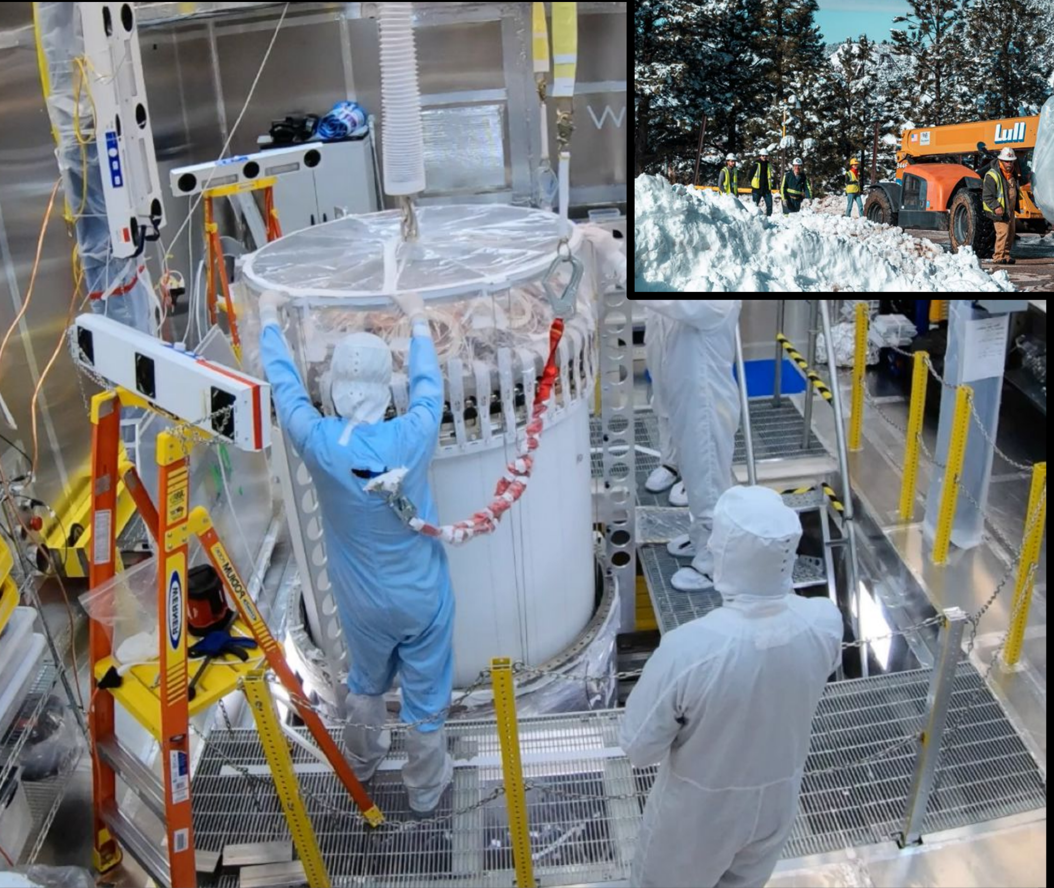
Class 100 (ISO 5) cleanroom with radon reduction, < 4 mBq/m^3



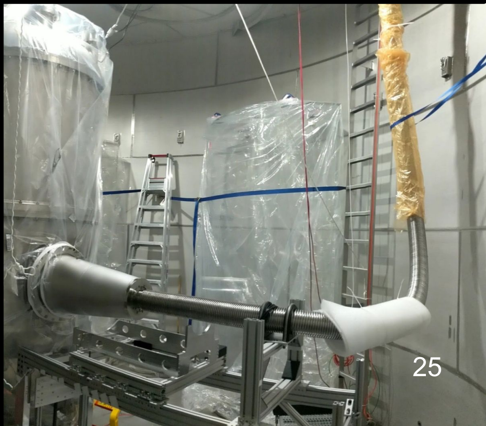




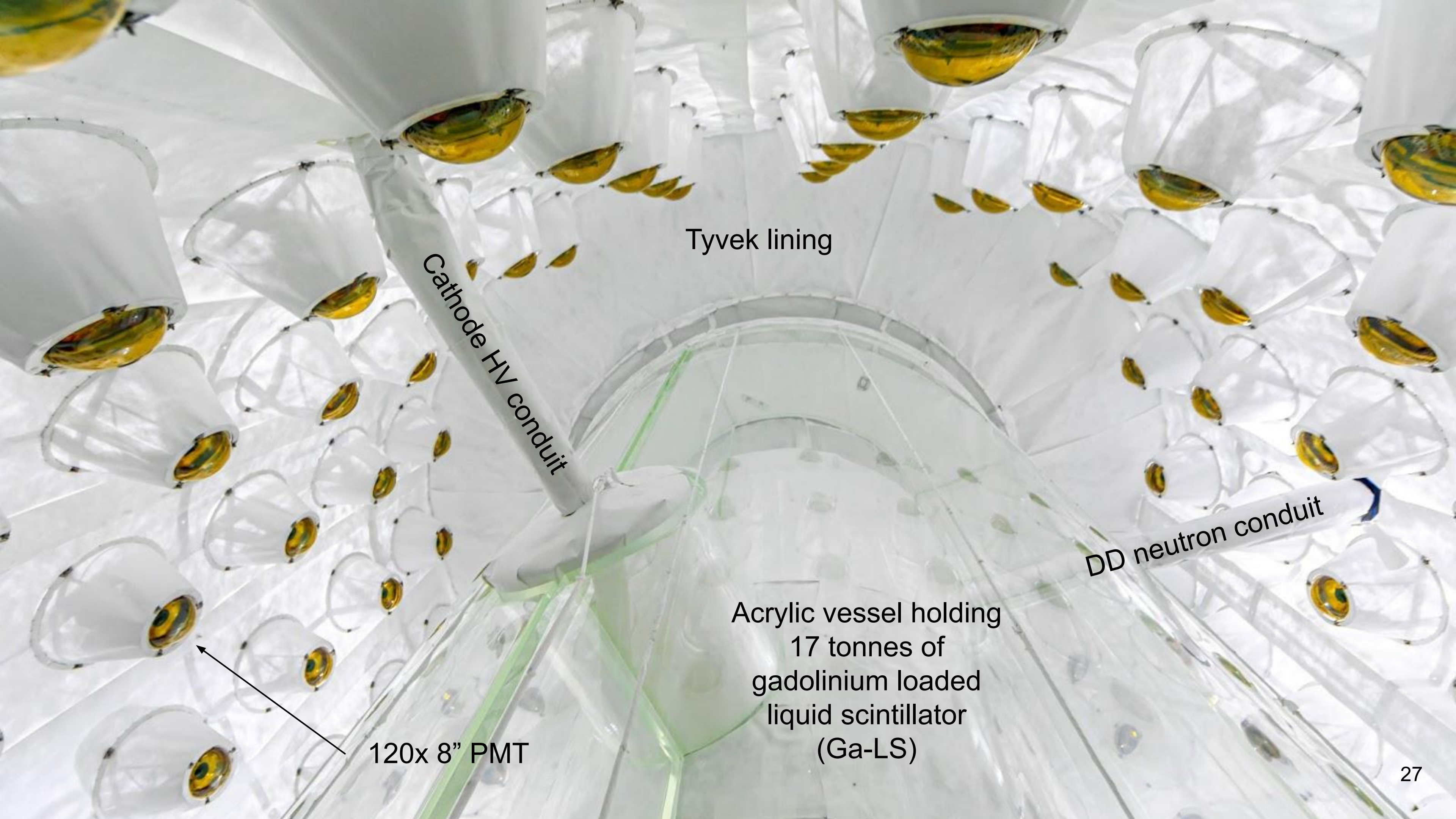
Transportation underground



Installing TPC underground



Installing OD


Tyvek lining
Cathode HV conduit
DD neutron conduit
Acrylic vessel holding
17 tonnes of
gadolinium loaded
liquid scintillator
(Ga-LS)
120x 8” PMT

Background mitigation

Material screening: HPGe, ICP-MS, NAA, radon emanation (arXiv:2006.02506)

Gas chromatograph to remove ^{85}Kr beta decay, reduced to 0.1 ppt g/g ^{nat}Kr/Xe (TDR, CDR)

Adsorption of xenon gas on charcoal for Rn removal

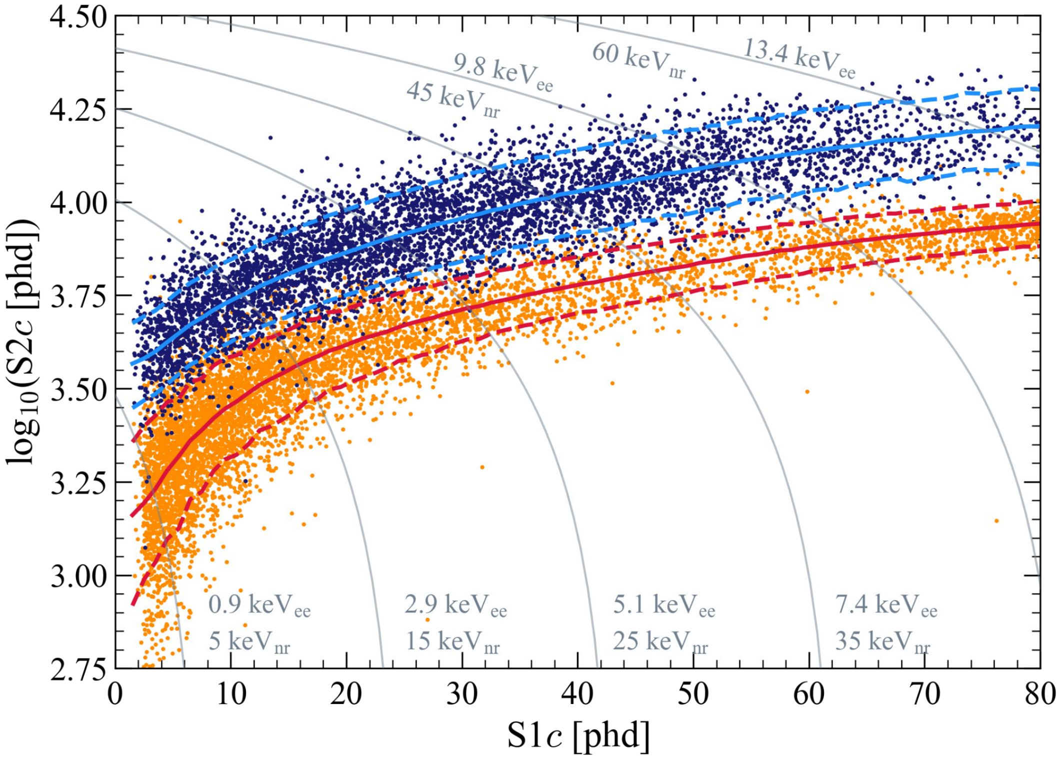
Clean assembly:

Rn reduce cleanroom

Deionizing fans

Nitrogen purge components in storage

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%**

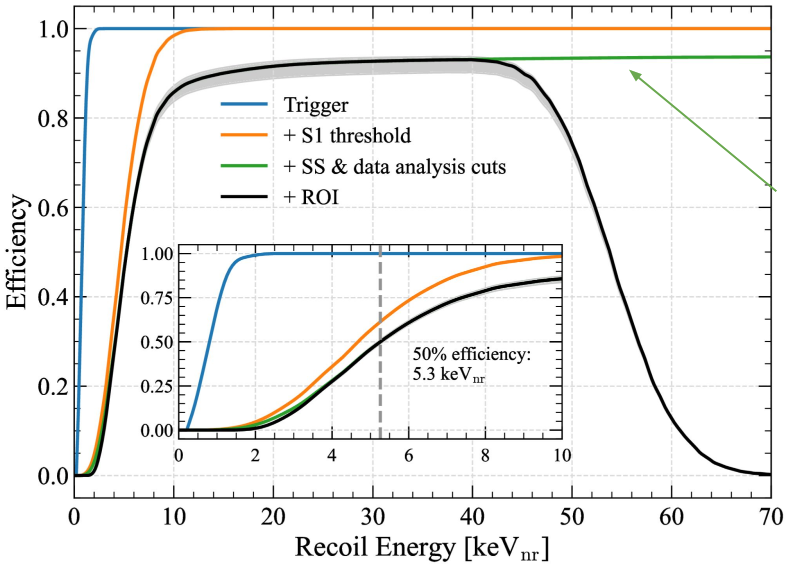
99.9% rejection of ERs below the median of a 40 GeV WIMP

Data quality

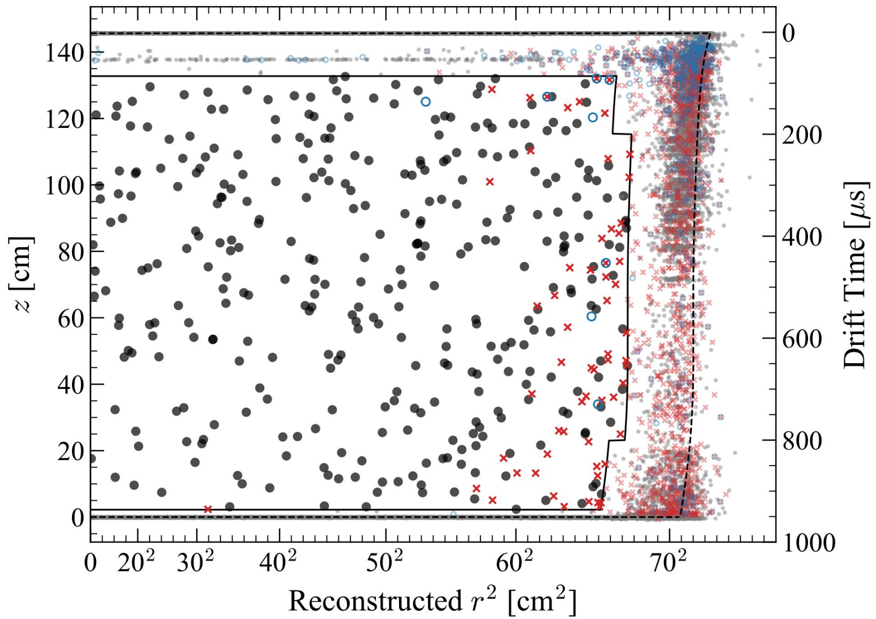
Fiducial volume cut: 5.5 ± 0.2 T

Livetime vetoes: 90 → 60 days

Waveform quality cuts



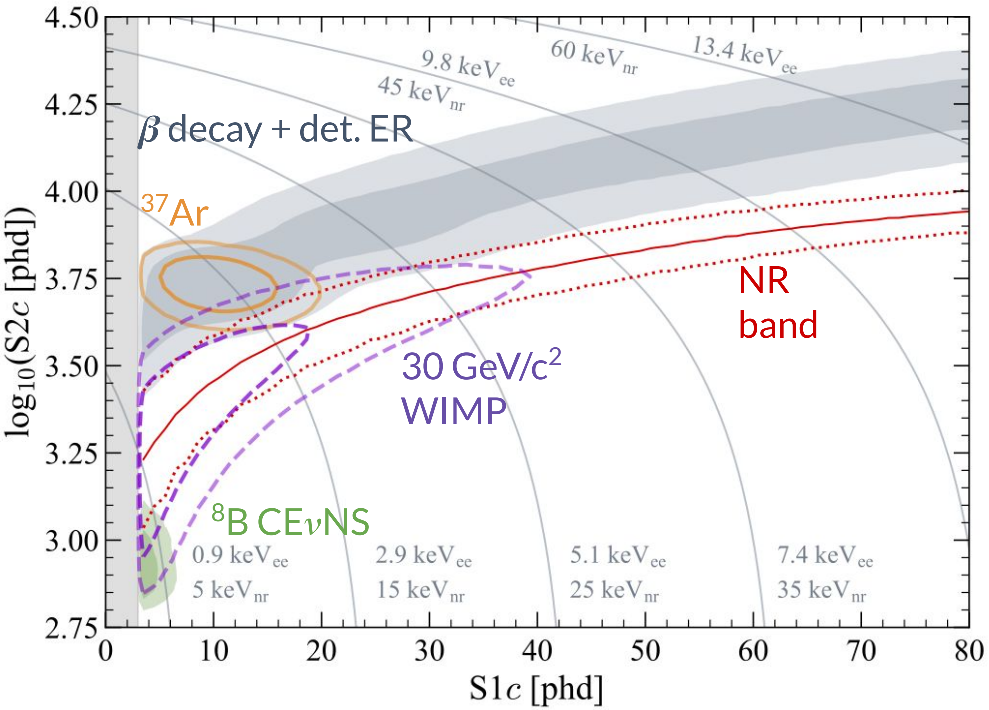
Measured with CH_3T and DD/AmLi



● Events surviving all selections
× Skin-prompt-tagged events
○ OD-prompt-tagged events

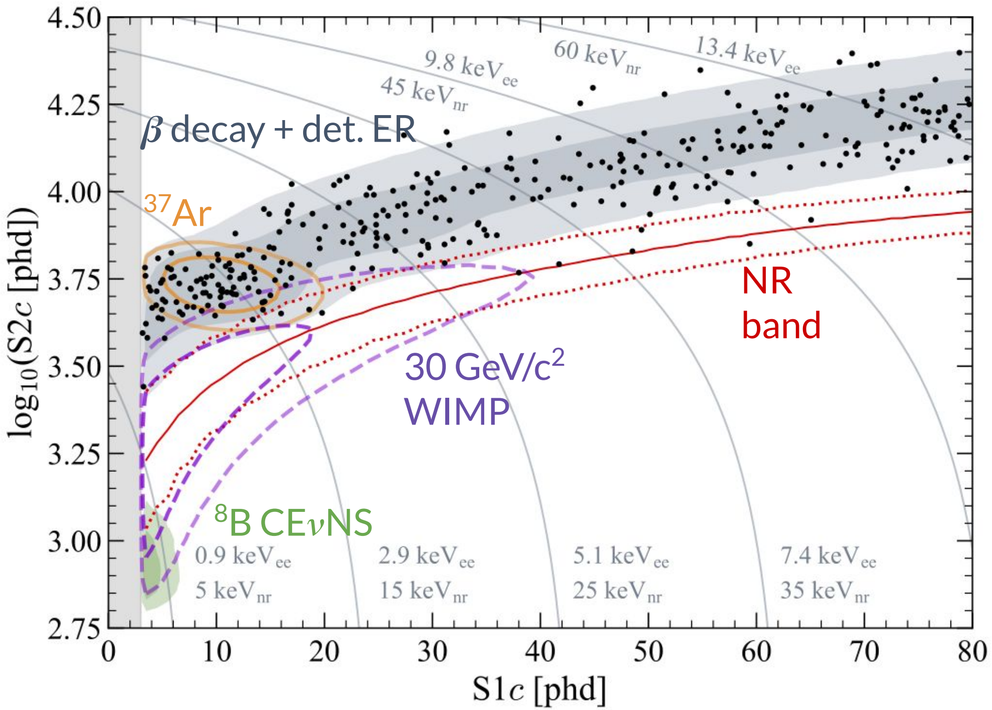
Background model

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

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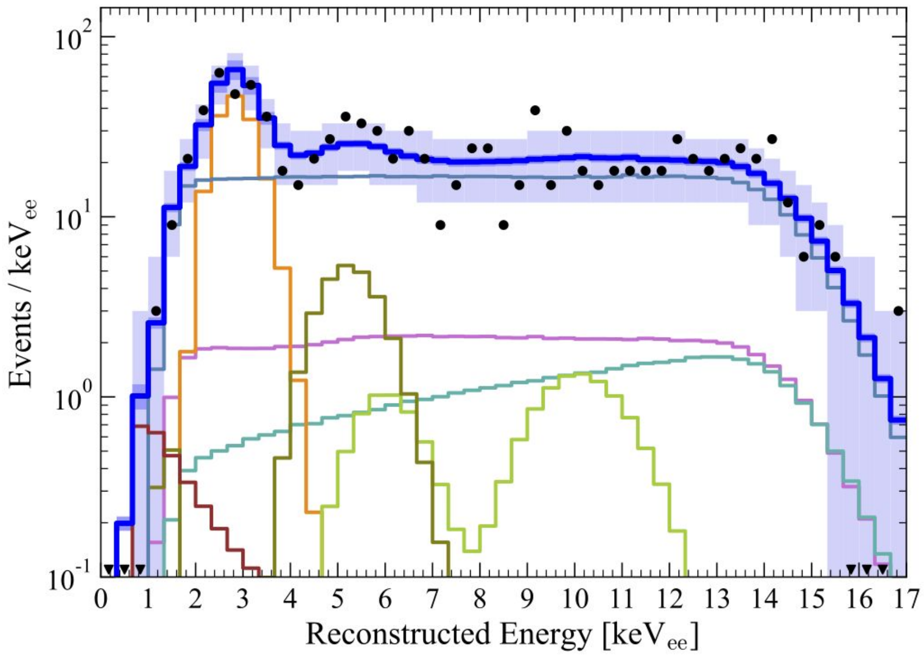
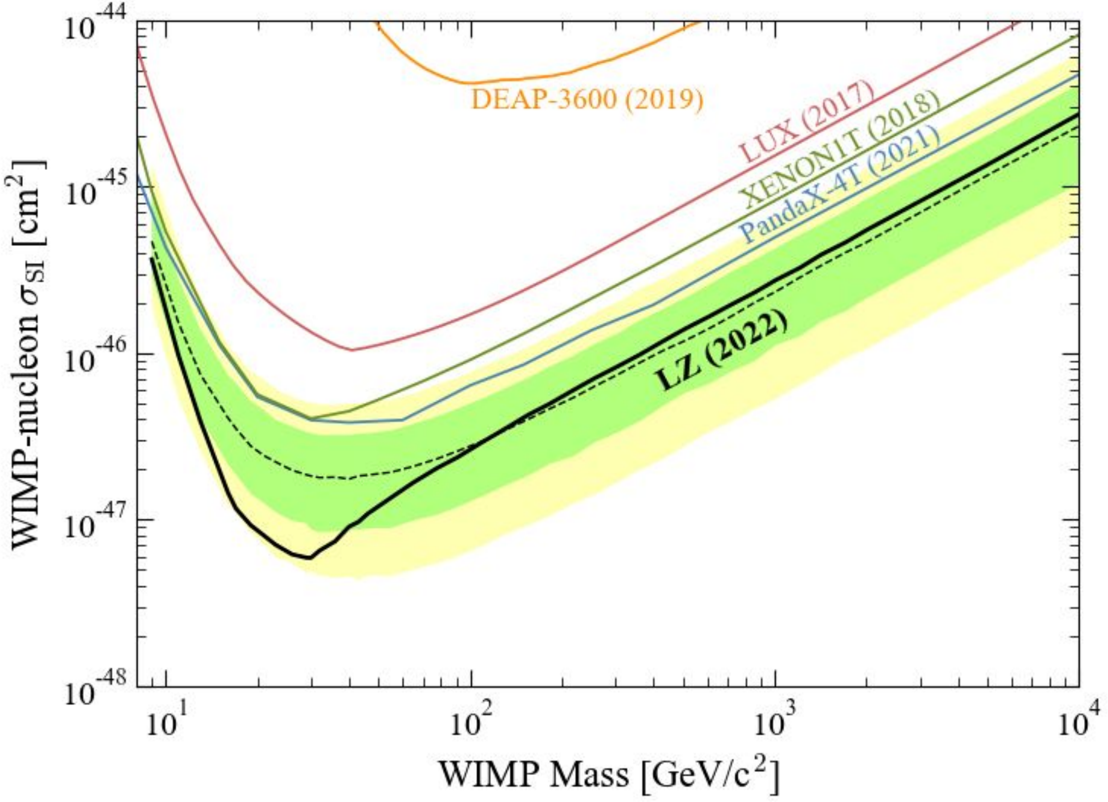
^{37}Ar ()



For every WIMP mass best fit result is consistent with 0

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

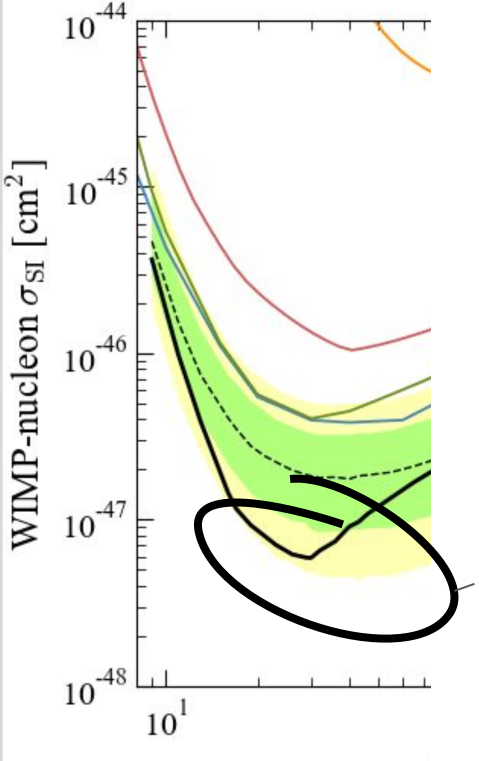
Signal rate must be non-negative
90% confidence bands

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

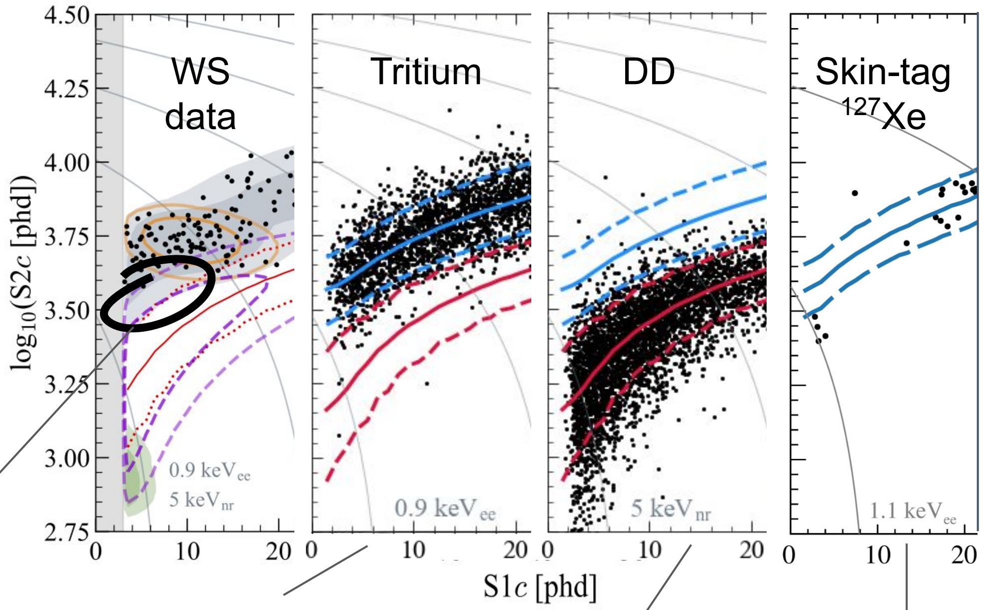
No salting or blinding

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 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 between members of XENON, LUX-ZEPLIN, and DARWIN (XLZD) towards a next generation liquid xenon experiment

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

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

Memorandum of Understanding between members of XENON, LUX-ZEPLIN, and DARWIN (XLZD) towards a next generation liquid xenon experiment

Website: https://xlzd.org/

First meeting held June 27-29, 2022

Science with liquid xenon

White paper released (arXiv:2203.02309)
(particular thanks to Rafael Lang, Purdue)

~600 authors from 146 institutes

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

A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

J. Aalbers,[1,2] K. Abe,[3,4] V. Aerne,[5] F. Agostini,[6] S. Ahmed Maouloud,[7] D.S. Akerib,[1,2] D.Yu. Akimov,[8] J. Akshat,[9] A.K. Al Musalhi,[10] F. Alder,[11] S.K. Alsum,[12] L. Althueser,[13] C.S. Amarasinghe,[14] F.D. Amaro,[15] A. Ames,[1,2] T.J. Anderson,[1,2] B. Andrieu,[7] N. Angelides,[16] E. Angelino,[17] J. Angevaare,[18] V.C. Antochi,[19] D. Antón Martin,[20] B. Antunovic,[21,22] E. Aprile,[23] H.M. Araújo,[16] J.E. Armstrong,[24] F. Arneodo,[25] M. Arthurs,[14] P. Asadi,[26] S. Baek,[27] X. Bai,[28] D. Bajpai,[29] A. Baker,[16] J. Balajthy,[30] S. Balashov,[31] M. Balzer,[32] A. Bandyopadhyay,[33] J. Bang,[34] E. Barberio,[35] J.W. Bargemann,[36] L. Baudis,[5] D. Bauer,[16] D. Baur,[37] A. Baxter,[38] A.L. Baxter,[9] M. Bazyk,[39] K. Beattie,[40] J. Behrens,[41] N.F. Bell,[35] L. Bellagamba,[6] P. Beltrame,[42] M. Benabderrahmane,[25] E.P. Bernard,[43,40] G.F. Bertone,[18] P. Bhattacharjee,[44] A. Bhatti,[24] A. Biekert,[43,40] T.P. Biesiadzinski,[1,2] A.R. 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Lopez Asamar,[53] W. Lorenzon,[14] C. Lu,[34] S. Luitz,[1] Y. Ma,[86] P.A.N. Machado,[70] C. Macolino,[73] T. Maeda,[98] J. Mahlstedt,[19] P.A. Majewski,[31] A. Manalaysay,[40] A. Mancuso,[6] L. Manenti,[25] A. Manfredini,[5] R.L. Mannino,[12] N. Marangou,[16] J. March-Russell,[10] F. Marignetti,[67] T. Marrodán Undagoitia,[66] K. Martens,[4] R. Martin,[7] I. Martinez-Soler,[109] J. Masbou,[39] D. Masson,[37] E. Masson,[7] S. Mastroianni,[67] M. Mastronardi,[67] J.A. Matias-Lopes,[15] M.E. McCarthy,[69] N. McFadden,[5] E. McGinness,[43] D.N. McKinsey,[43,40] J. McLaughlin,[72] K. McMichael,[56] P. Meinhardt,[37] J. Menéndez,[110,111] Y. Meng,[87] M. Messina,[45] R. Midha,[9] D. Milisavljevic,[9] E.H. Miller,[1,2] B. Milosevic,[21] S. Milutinovic,[21] S.A. Mitra,[82] K. Miuchi,[98] E. Mizrachi,[24,112] K. Mizukoshi,[98] A. Molinario,[17] A. Monte,[36,70] C.M.B. Monteiro,[15] M.E. Monzani,[1,2,42] J.S. Moore,[9] K. Morå,[23] J.A. Morad,[30] J.D. Morales Mendoza,[1,2] S. Moriyama,[3,4] E. Morrison,[28] E. Morteau,[39] Y. Mosbacher,[54] B.J. Mount,[113] J. Mueller,[37] A.St.J. Murphy,[105] M. Murra,[23] D. Naim,[30] S. Nakamura,[114] E. Nash,[30] N. Navaieelavasani,[82] A. Naylor,[102] C. Nedlik,[92] H.N. Nelson,[36] F. Neves,[53] J.L. Newstead,[9,35] K. Ni,[86] J.A. Nikoleyczik,[12] V. Niro,[115,116] U.G. Oberlack,[82] M. Obradovic,[21] K. Odgers,[56] C.A.J. O'Hare,[49] P. Oikonomou,[25] I. Olcina,[43,40] K. Oliver-Mallory,[16] A. Oranday,[78] J. Orpwood,[102]

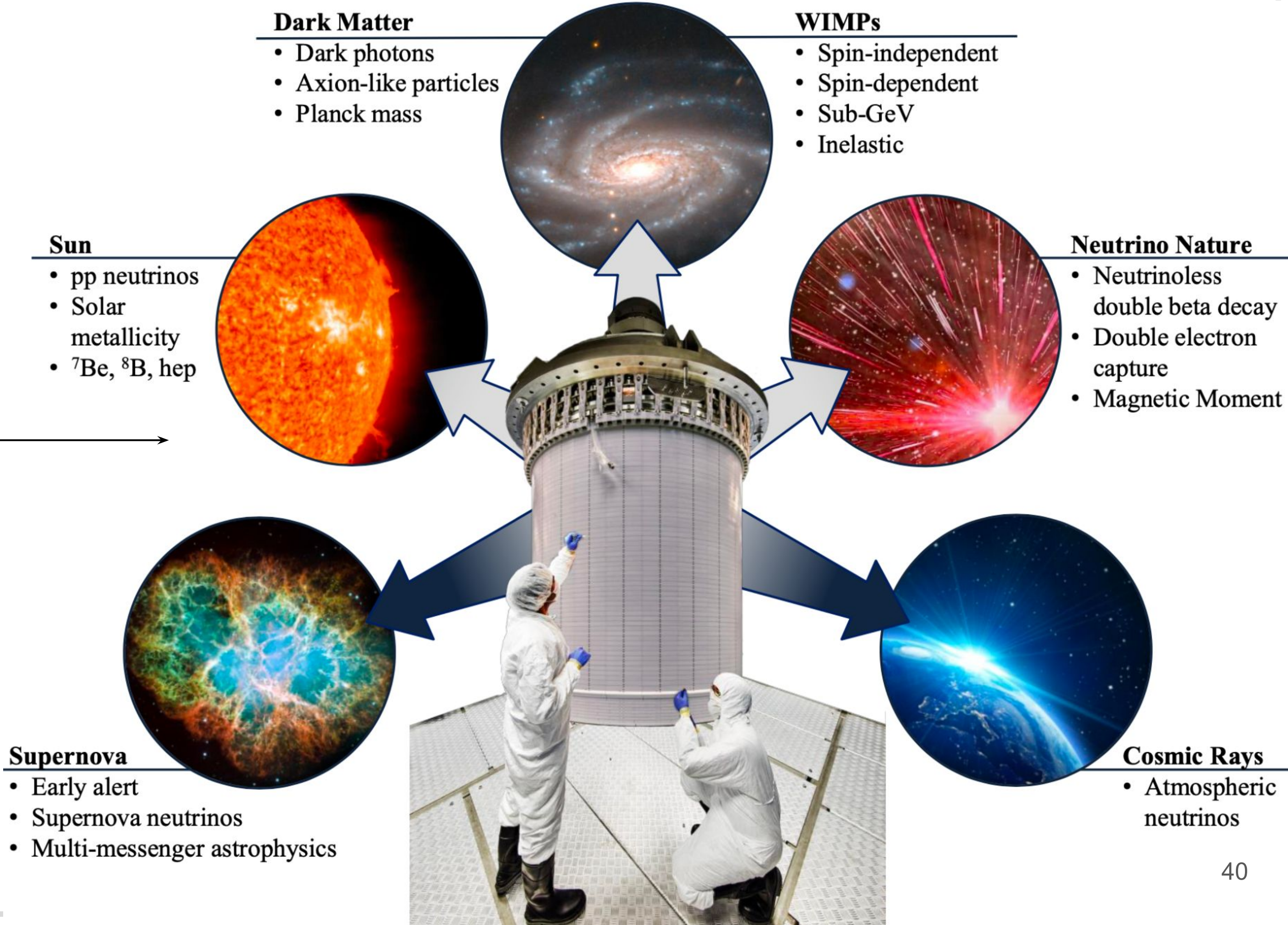
Massive

→ 50-100 tonnes

Yet compact

→ 2-4m height x diameter

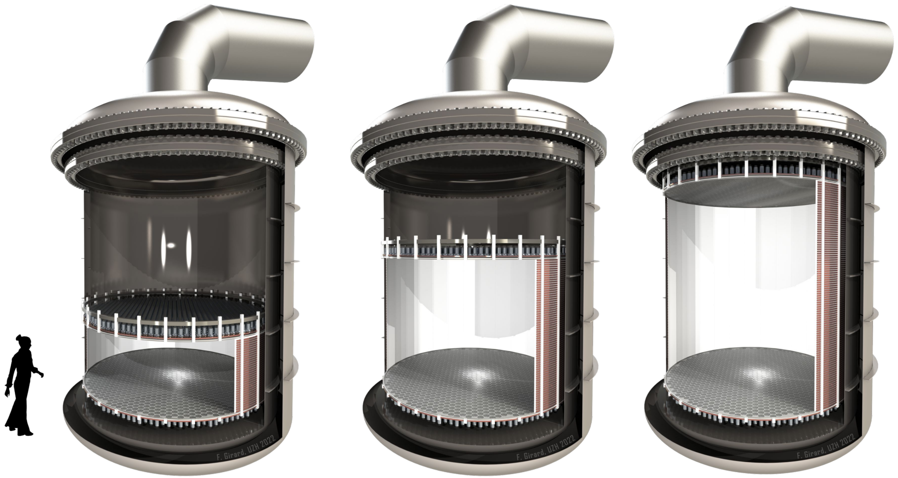
Science

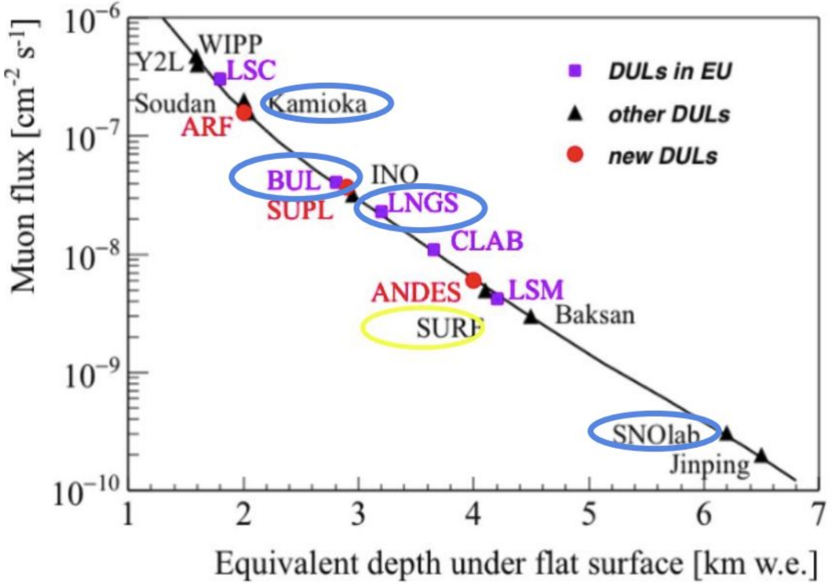


Detector and siting

Considering modifiable detector: 20→80 T

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





Considering 5 underground sites

Detector size requires significant space for underground fabrication

Backgrounds

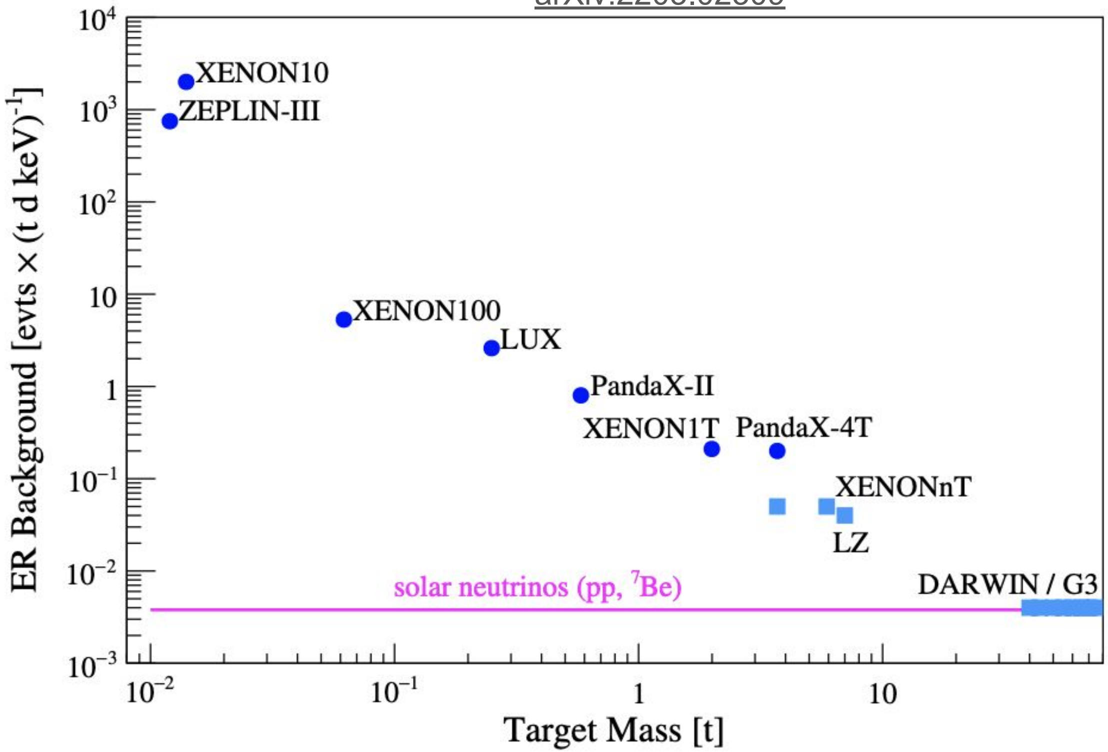
Goal is to be dominated by neutrino backgrounds

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

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

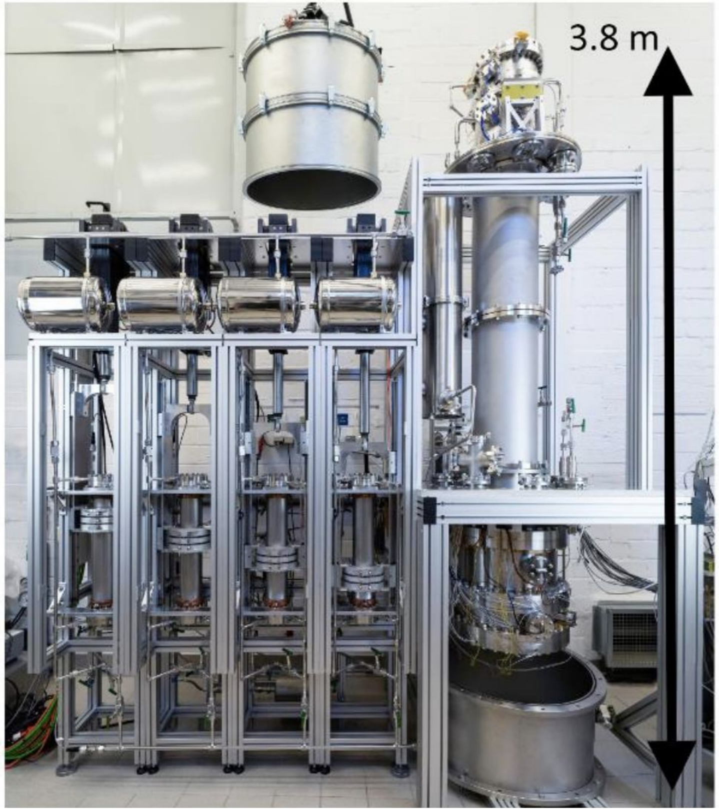
Self-shielding from γ-ray and neutron backgrounds

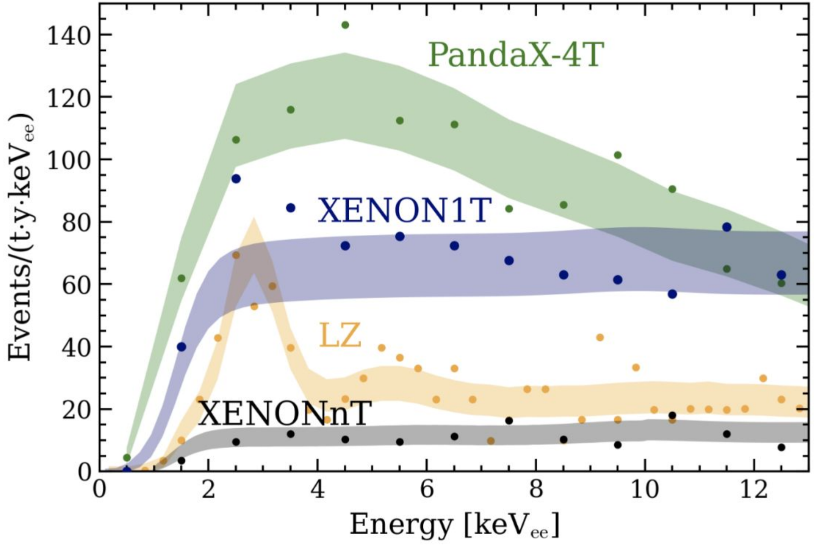
arXiv:2203.02309



Solutions for Rn removal

XENONnT system



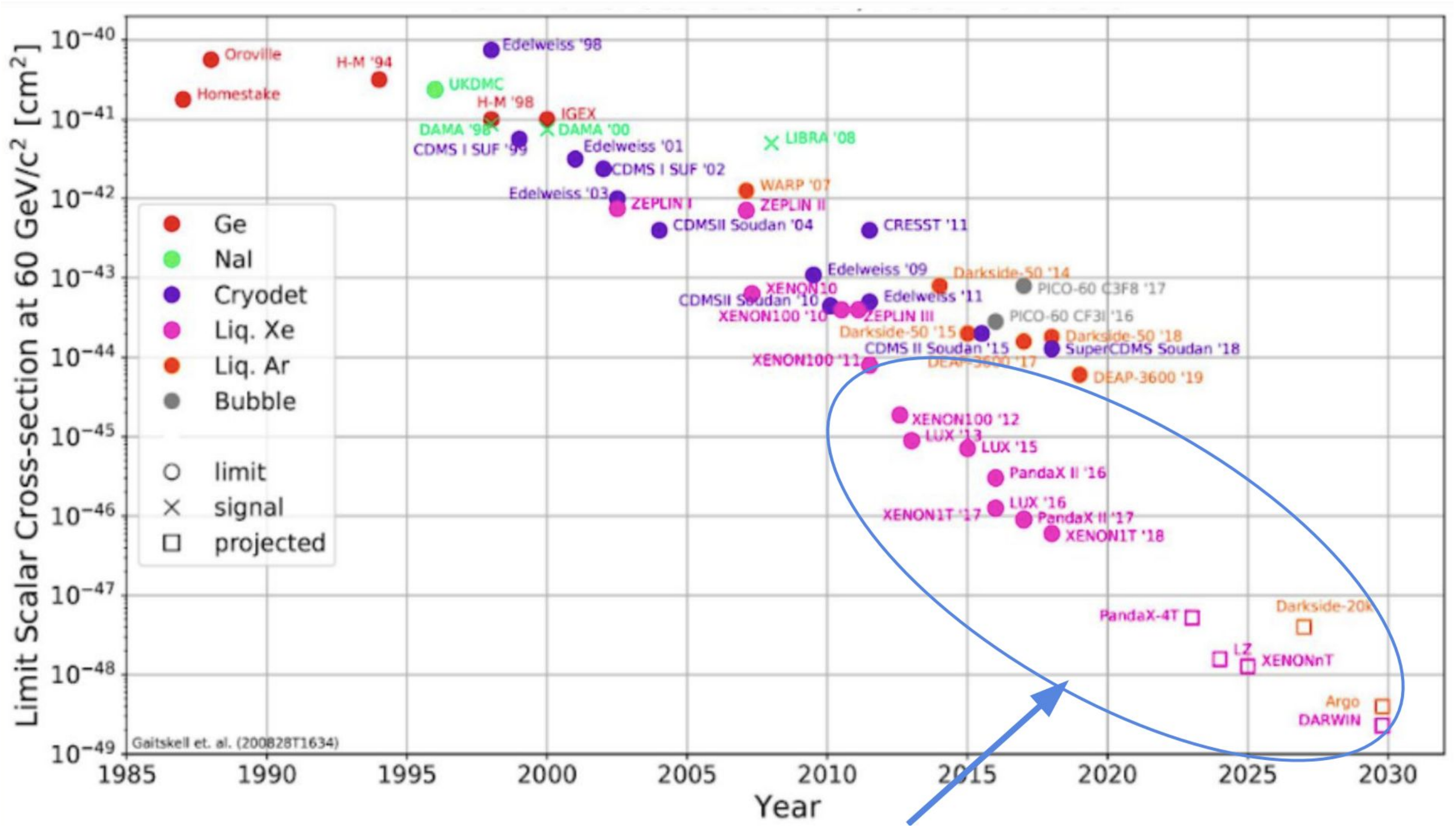


Two collaborations→two solutions to every problem

LZ uses adsorption of xenon gas on charcoal

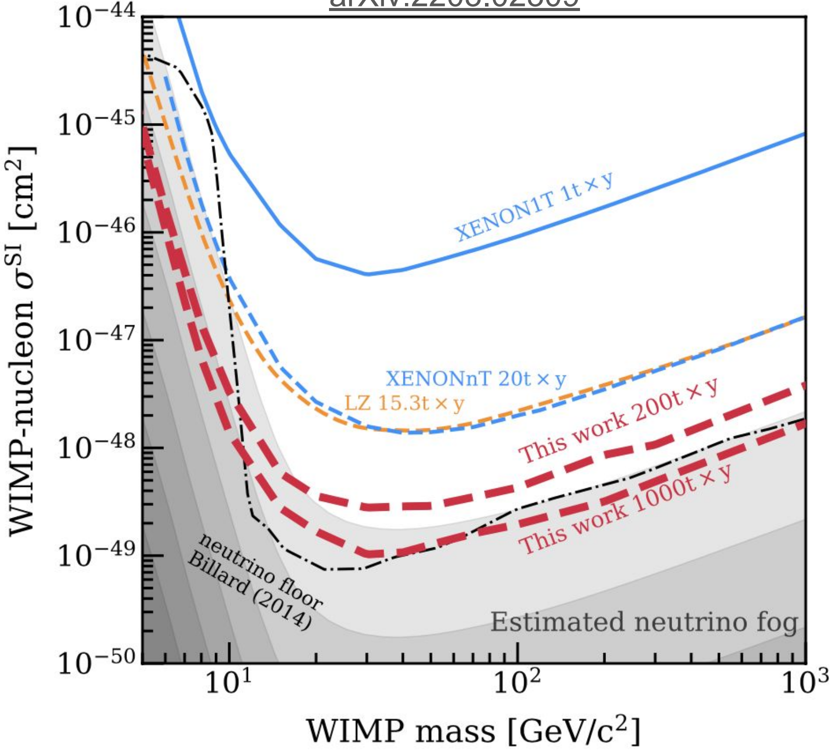
XENONnT uses cryogenic distillation enhanced for radon removal (arXiv2205.11492)

Evolution of sensitivity



Dominated by LXe TPCs for the last two decades

arXiv:2203.02309



Weakly Interacting Massive Particles

Spin independent interactions

Chase WIMPs to the neutrino floor!

Solar neutrino electron scattering

^{8}B, HEP, diffuse supernovae, atmospheric coherent neutrino-nucleus scattering

^{136}Xe double beta decay

Summary

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

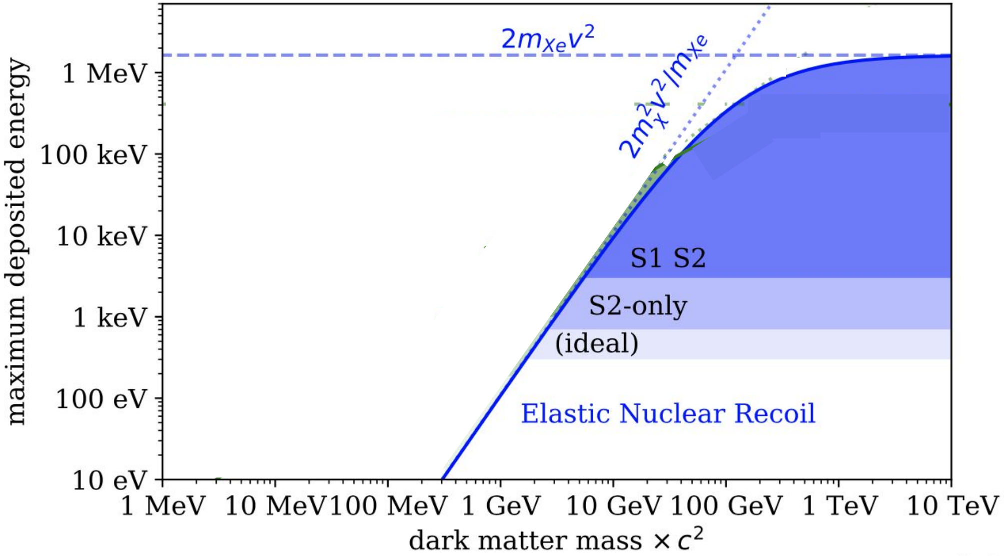
2. With its first run, LZ has achieved world-leading WIMP sensitivity

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

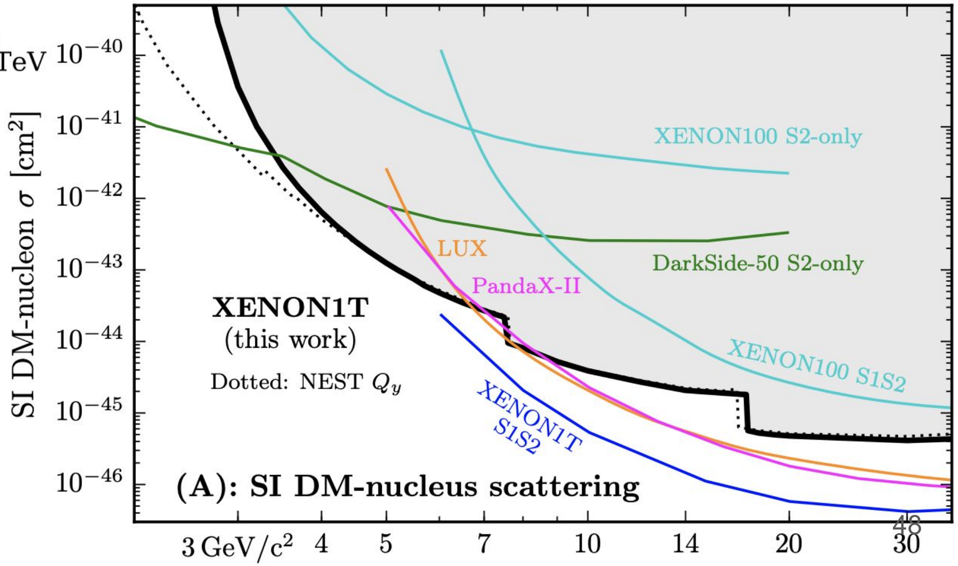
Additional Slides

arXiv:2203.02309



Light WIMPs

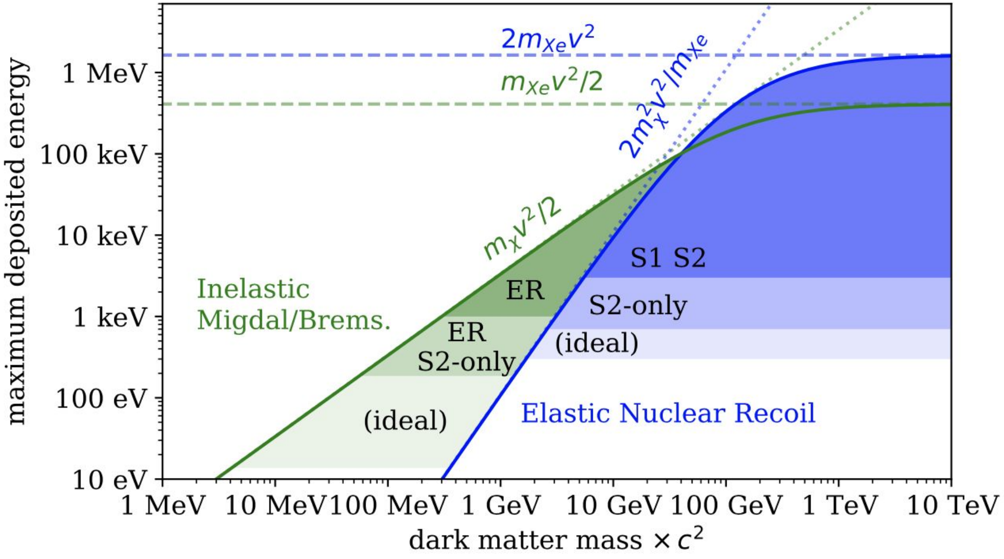
Phys. Rev. Lett. 123, 251801



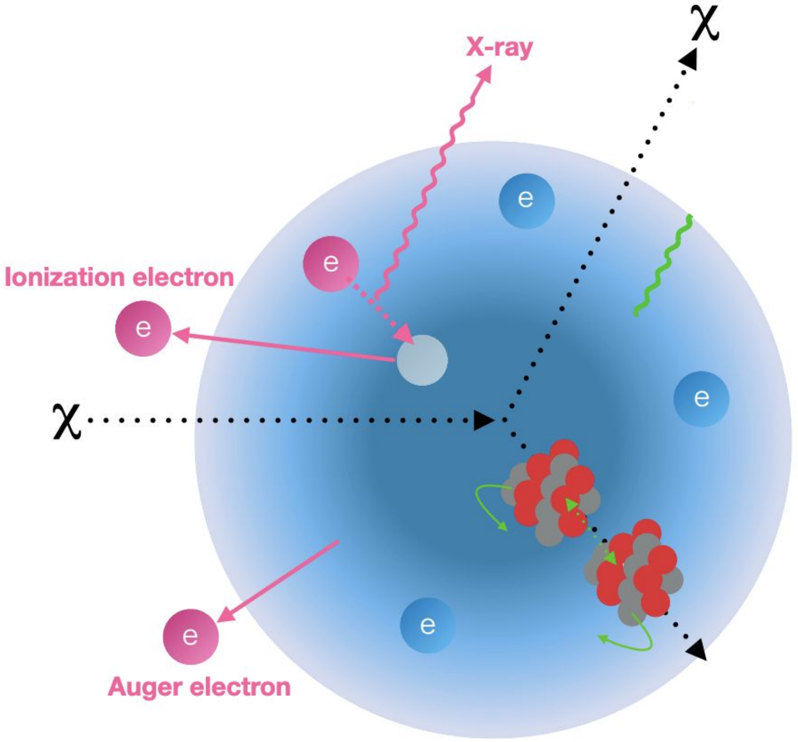
Scintillation agnostic

m_χ ~ few GeV

arXiv:2203.02309



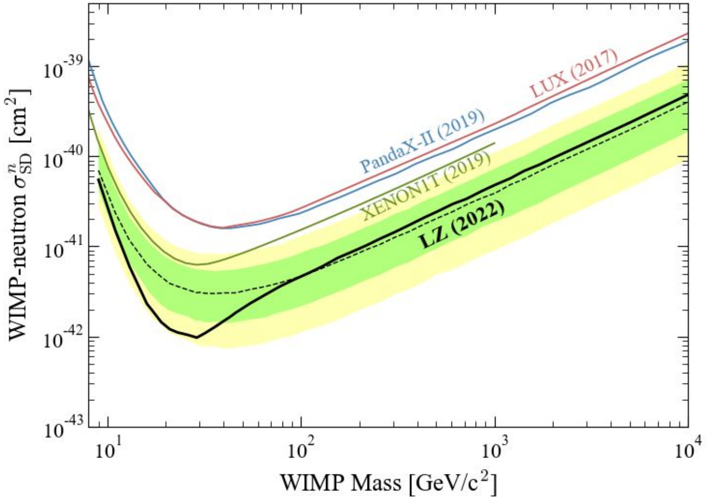
Light WIMPs



Migdal effect

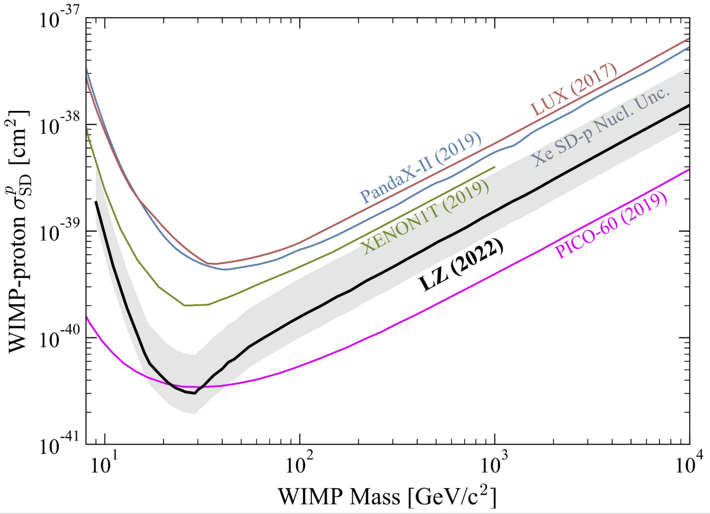
m_χ ~ few-hundred MeV

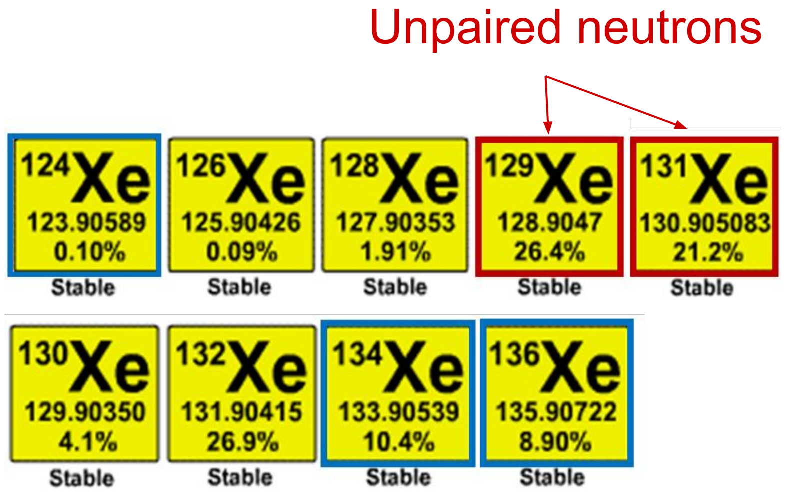
arXiv:1907.12771



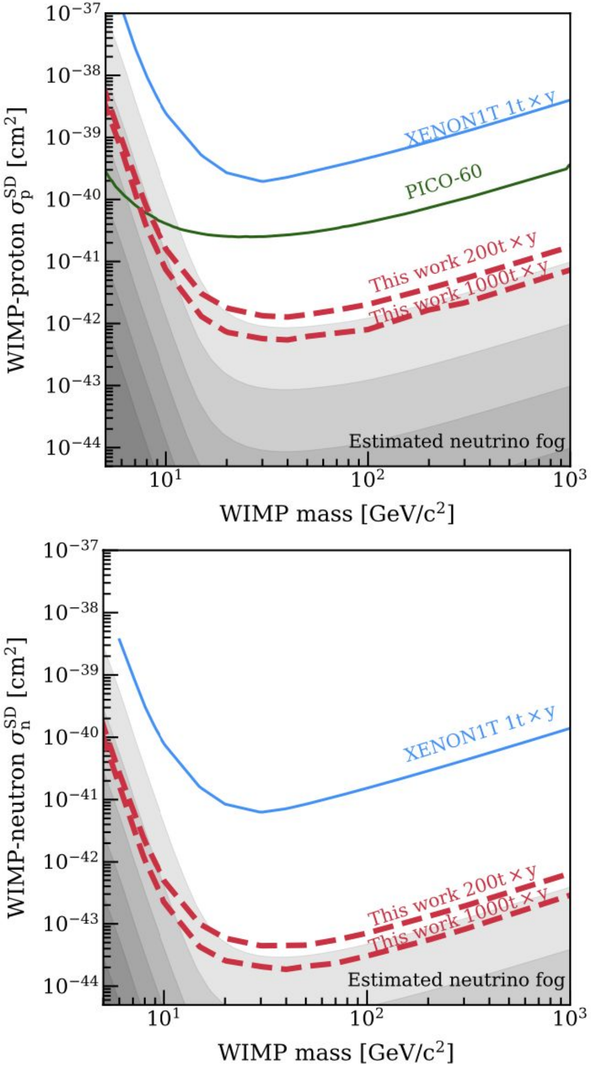
Spin-dependent WIMP sensitivity

LUX-ZEPLIN





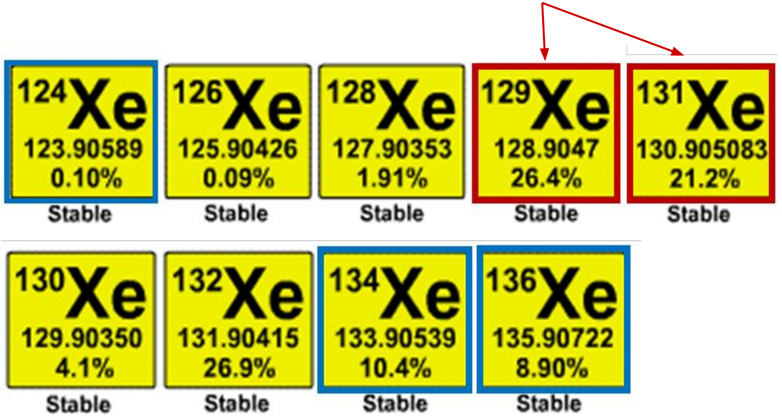
Spin-dependent WIMP sensitivity



arXiv:2203.02309

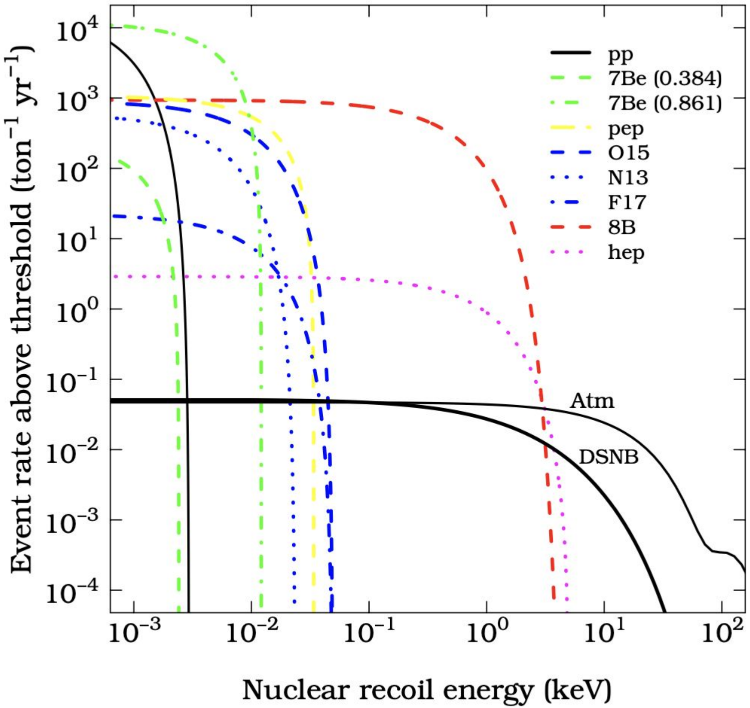
Next generation

Unpaired neutrons

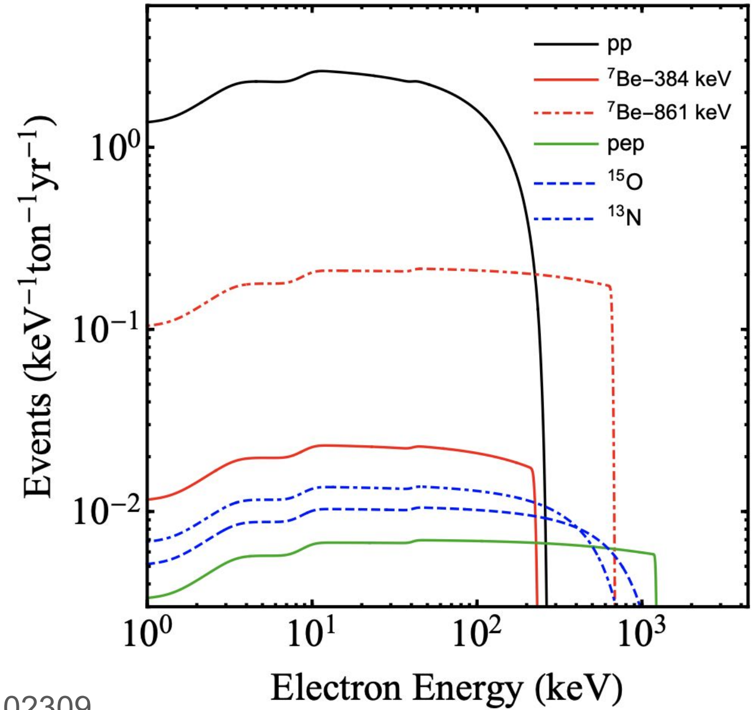


Astrophysical neutrinos

^{8}B solar neutrinos
→ ready for supernova neutrinos



pp solar neutrinos
300 t×yr→ new solar physics



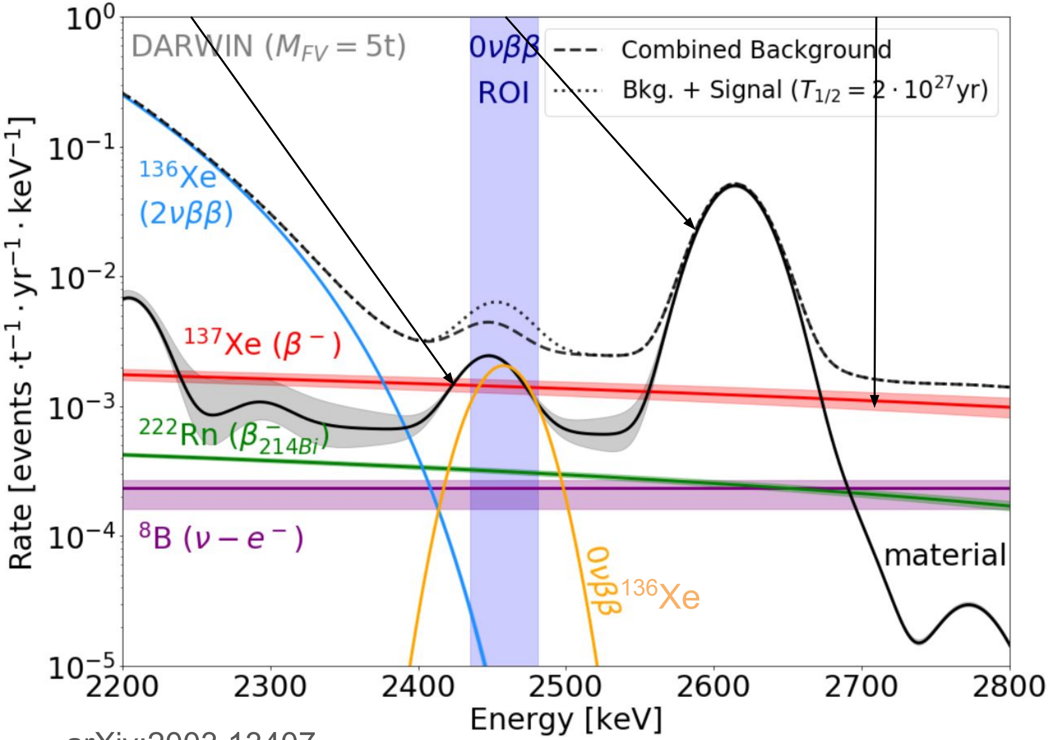
arXiv:2203.02309

Promising isotopes

^{214}Bi γ
2447 keV

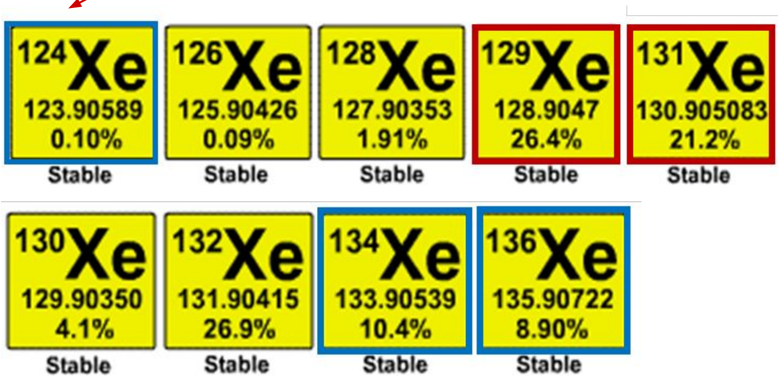
^{208}Tl γ
2614 keV

^{137}Xe β
Q=4173 keV



arXiv:2003.13407

Double electron capture



Neutrinoless double beta decay

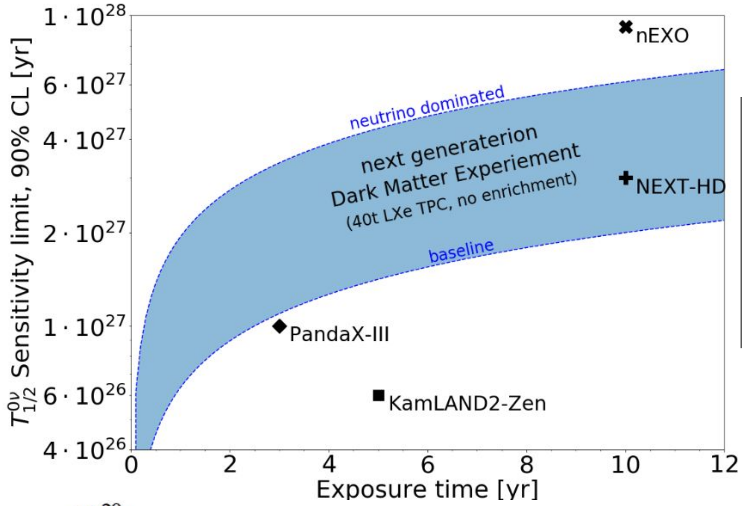
^{136}Xe neutrinoless double beta decay

γ-ray backgrounds from detector components and external environment

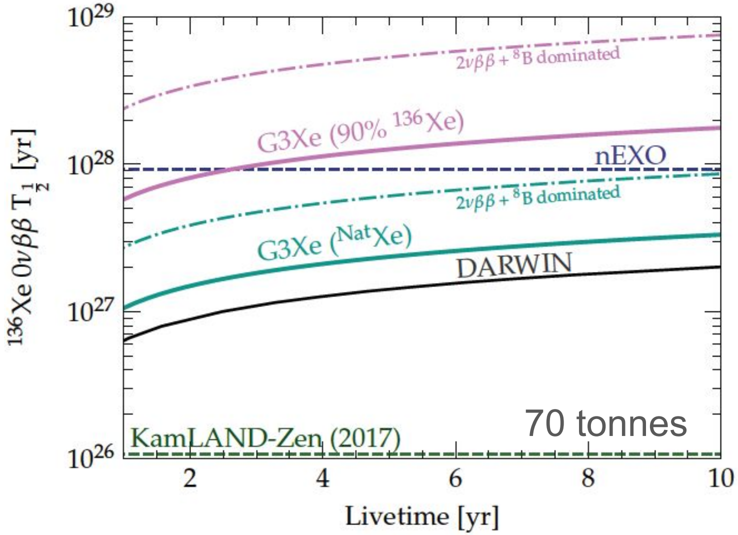
- ^{208}Tl 2614 keV → impact strongly mitagated by 1% **σ**/E
- ^{214}Bi 2447 keV → impact mitigated by self shielding of larger detector

^{137}Xe from neutron capture and cosmogenic activation

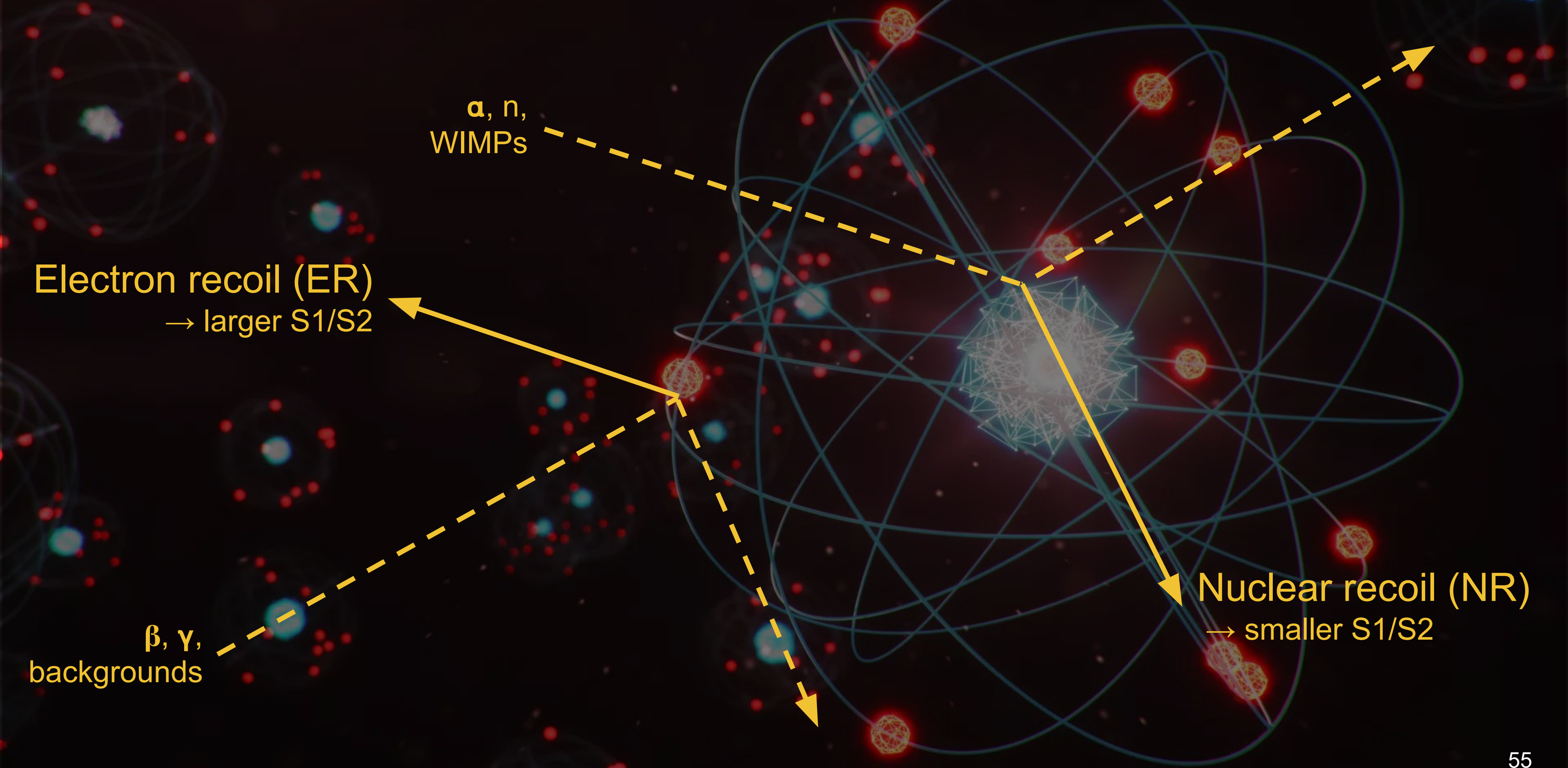
With major investment in controlling backgrounds (beyond DM needs) could match nEXO sensitivity



arXiv:2003.13407

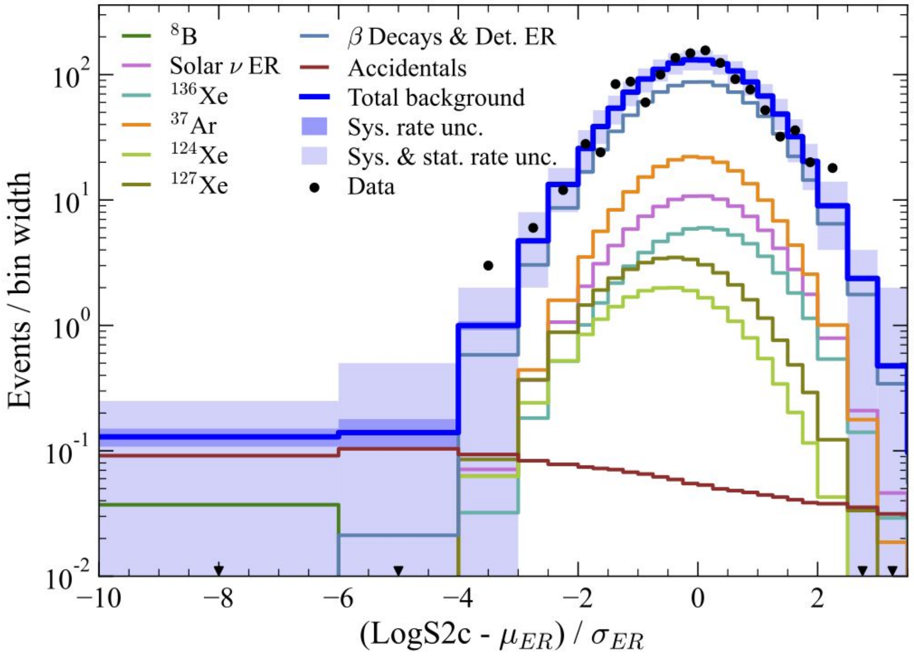


ER/NR discrimination

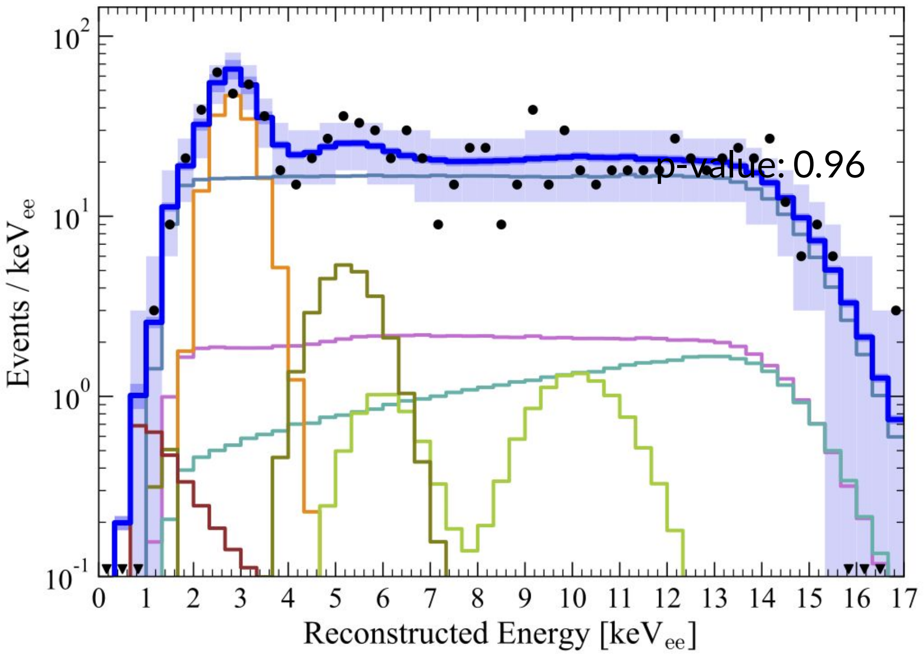


https://www.livescience.com/37206-atom-definition.html

Fit results



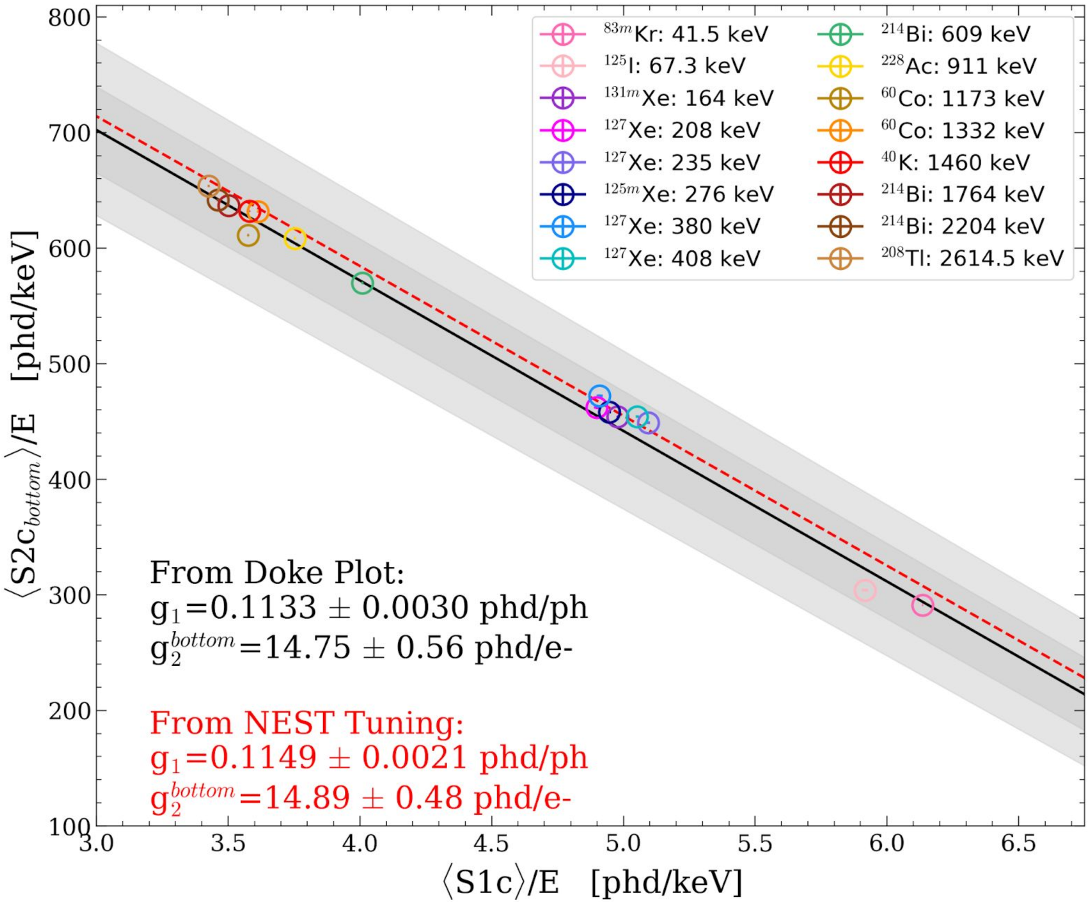
^{8}B
Solar ν ER
^{136}Xe
^{37}Ar
^{124}Xe
^{127}Xe
β Decays & Det. ER
Accidentals
Total background
Sys. rate unc.
Sys. & stat. rate unc.
Data
Events / bin width
(LogS2c - μ_{ER}) / σ_{ER}



p-value: 0.96
Events / keV$_{ee}$
Reconstructed Energy [keV$_{ee}$]

Doke Plot - energy calibration

E = W (S1/gs+S2/g2)



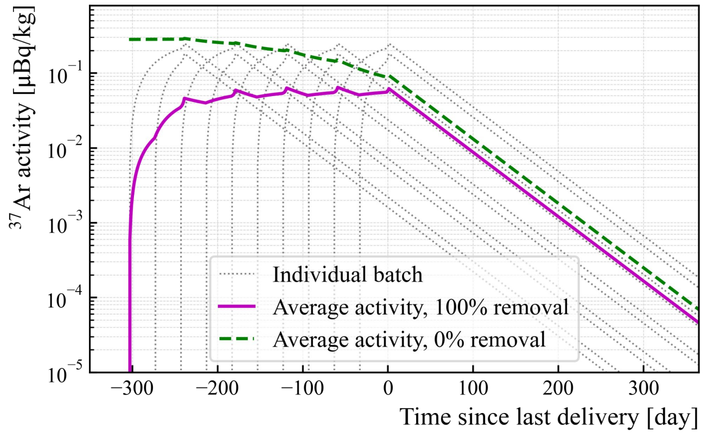
^{37}Ar

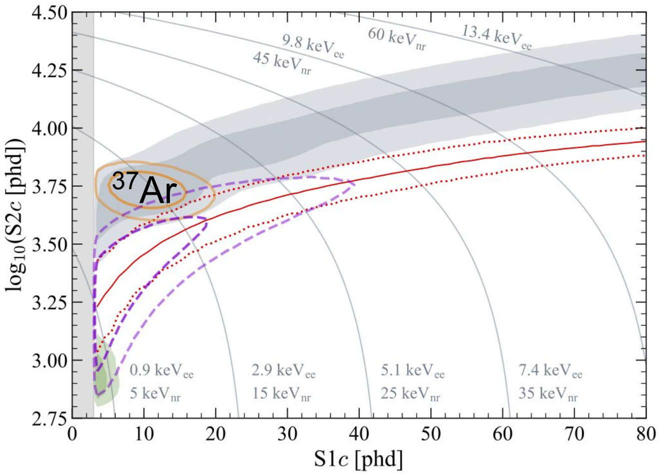
^{37}Ar decays ($T_{1/2}$ = 35 d, monoenergetic 2.8 keV ER deposition from electron capture)

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)

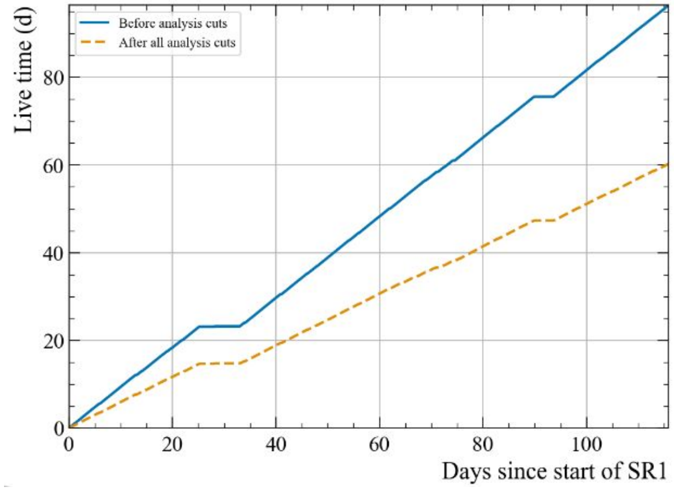




Livetime

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

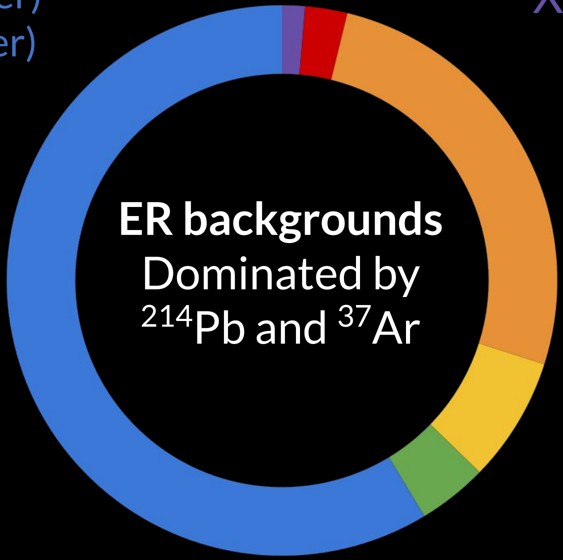
Backgrounds

~Flat energy spectra
within ROI

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

^{136}Xe ($2\nu\beta\beta$)

Solar neutrinos (ER)
- pp
- ^{7}Be
- ^{13}N



Mono-energetic spectra
dissolved electron captures

^{37}Ar (activation)

^{127}Xe

^{124}Xe (double e-capture)

NR backgrounds:
- Neutron emission from spontaneous fission and (α,n)
- ^{8}B solar neutrinos

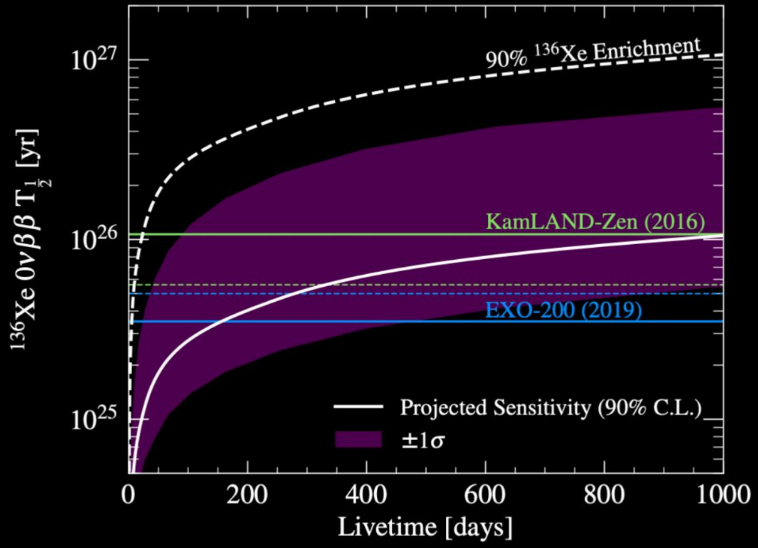
Expected in ROI:

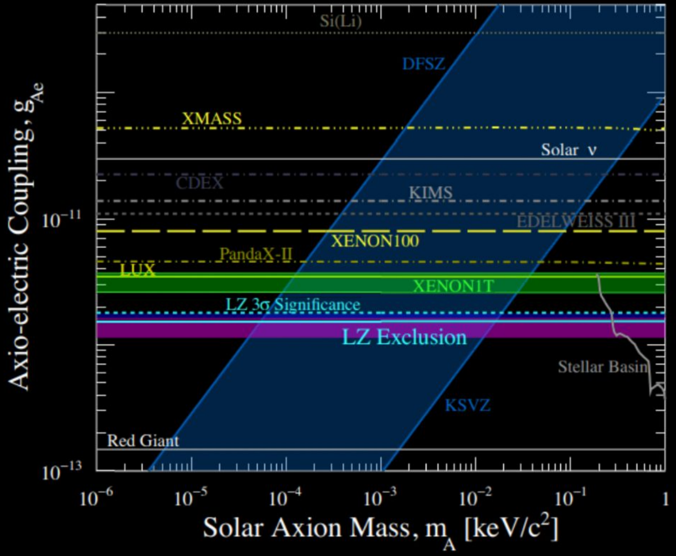
ER: 276 + [0, 291] for 37Ar
NR: 0.15

Next for LZ

LZ plans to take 1000 live days of data (x17 more exposure):

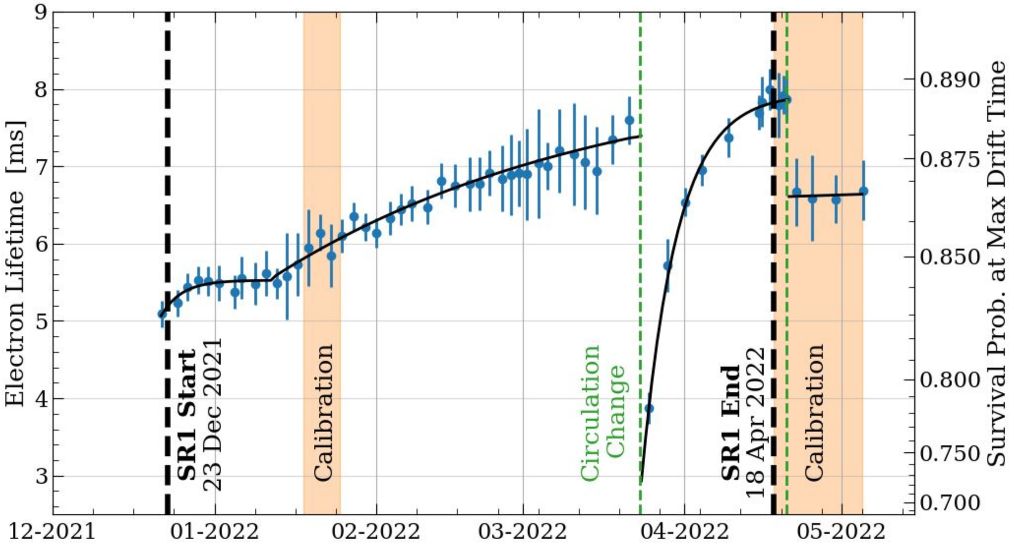
- Extending the reach: S2-only, Migdal effect, EFT
- Non-WIMP DM candidates
- Astrophysical neutrinos: 8B CEvNS, solar-pp, supernova, and more
- Rare decays: 0v$\beta\beta$ of 136Xe, 2v$\beta\beta$ and 0v$\beta\beta$ of 134Xe, and more





First science run

- Goals:
  1. Demonstrate physics capabilities of the detector (not blinded)
  2. Perform competitively with other similar experiments
- Key information:
  1. Livetime 60 days (Data from 23rd Dec 2021 to 12th May 2022)
  2. PMTs: >97% operational throughout run
  3. Liquid temperature: 174.1 K (0.02%)
  4. Gas pressure: 1.791 bar(a) (0.2%)
  5. Gas circulation: 3.3t/day
  6. Drift field: 193 V/cm (32 kV cathode, uniform to 4% in fiducial volume)
  7. Extraction field: 7.3 kV/cm in gas (8 kV gate-anode ΔV)



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
- Alphas
- 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