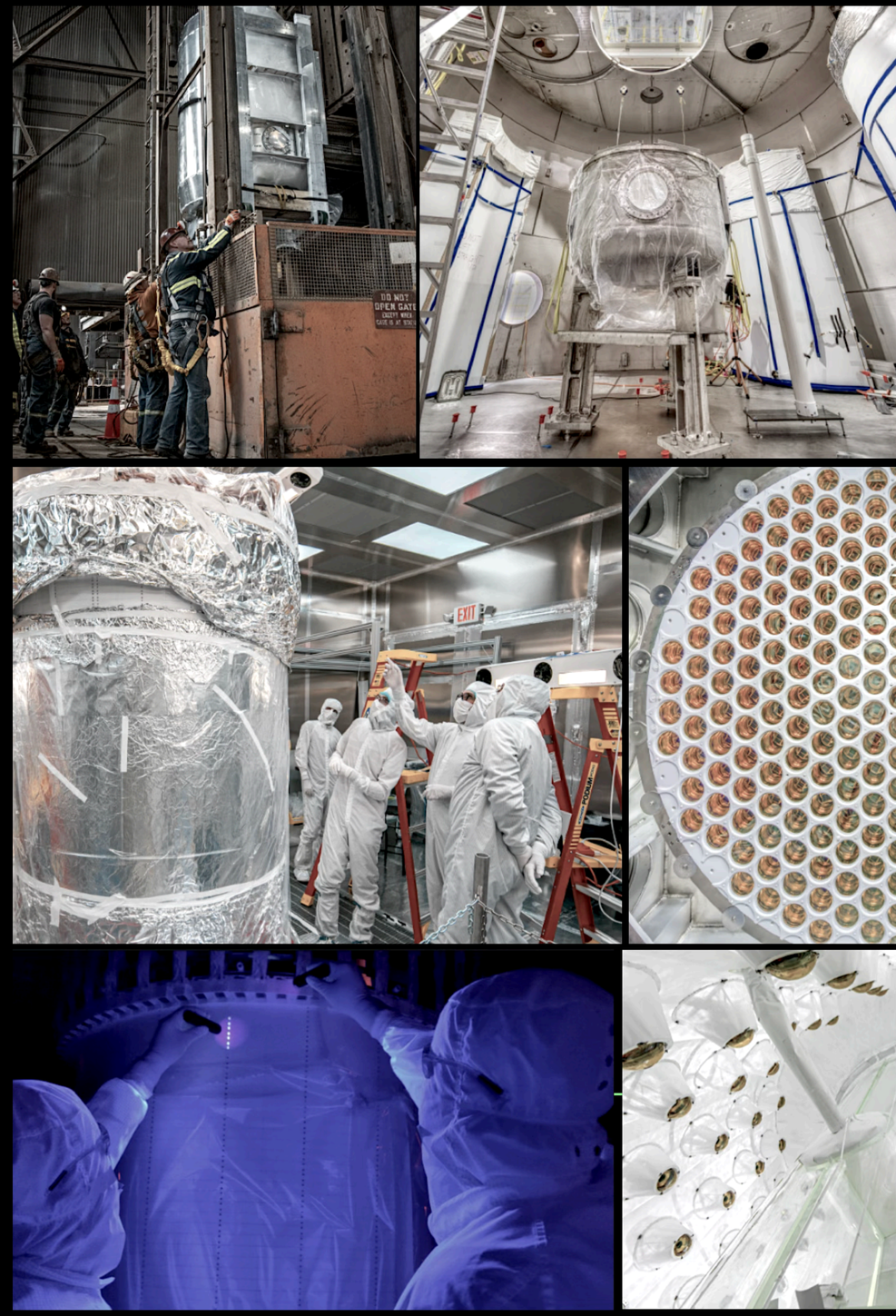
IMPERIAL
Department of Physics

News from the Halo – Recent Developments in Dark Matter Searches

IOP Annual APP and HEPP Conference
Edinburgh 8–10 April 2026

Christian Wittweg
Department of Physics
Imperial College London

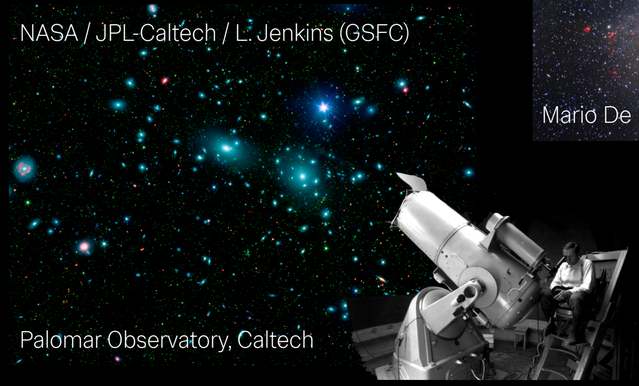


Dark matter evidence

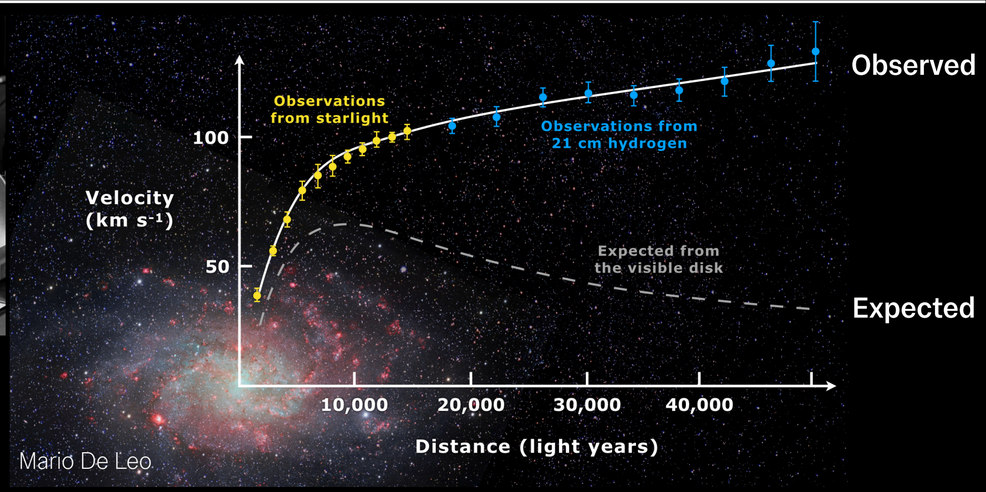
Evidence at all scales:

- Galactic rotation curves (Rubin and Ford, 1970s)
- Dynamics of galaxy clusters (Fritz Zwicky, 1930s)
- Cluster collisions (“Bullet cluster”)
- Large scale structure of the Universe
- Cosmic microwave background (Planck)

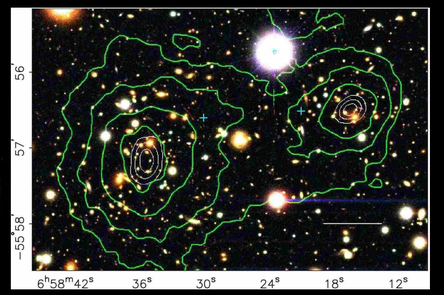

Carnegie Institution of Washington

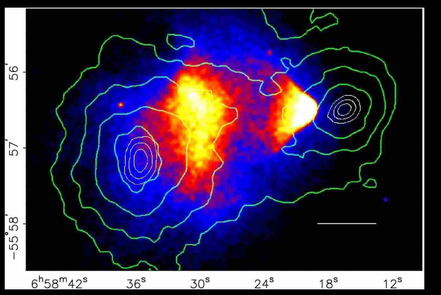

NASA / JPL-Caltech / L. Jenkins (GSFC)

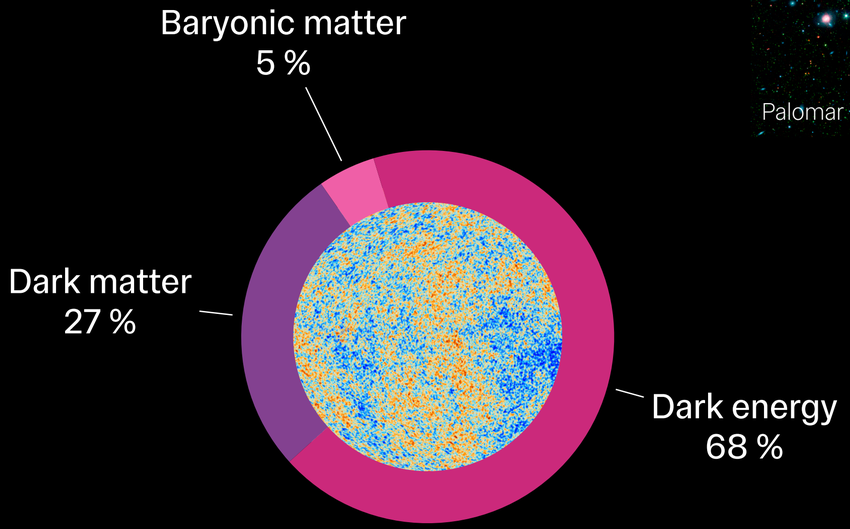
Palomar Observatory, Caltech

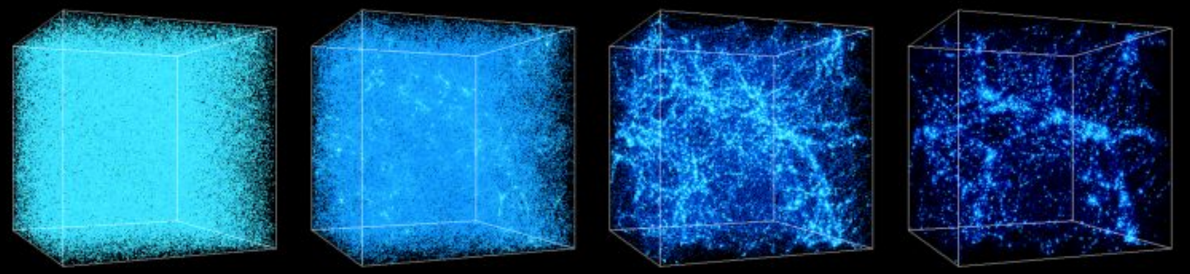


Mario De Leo

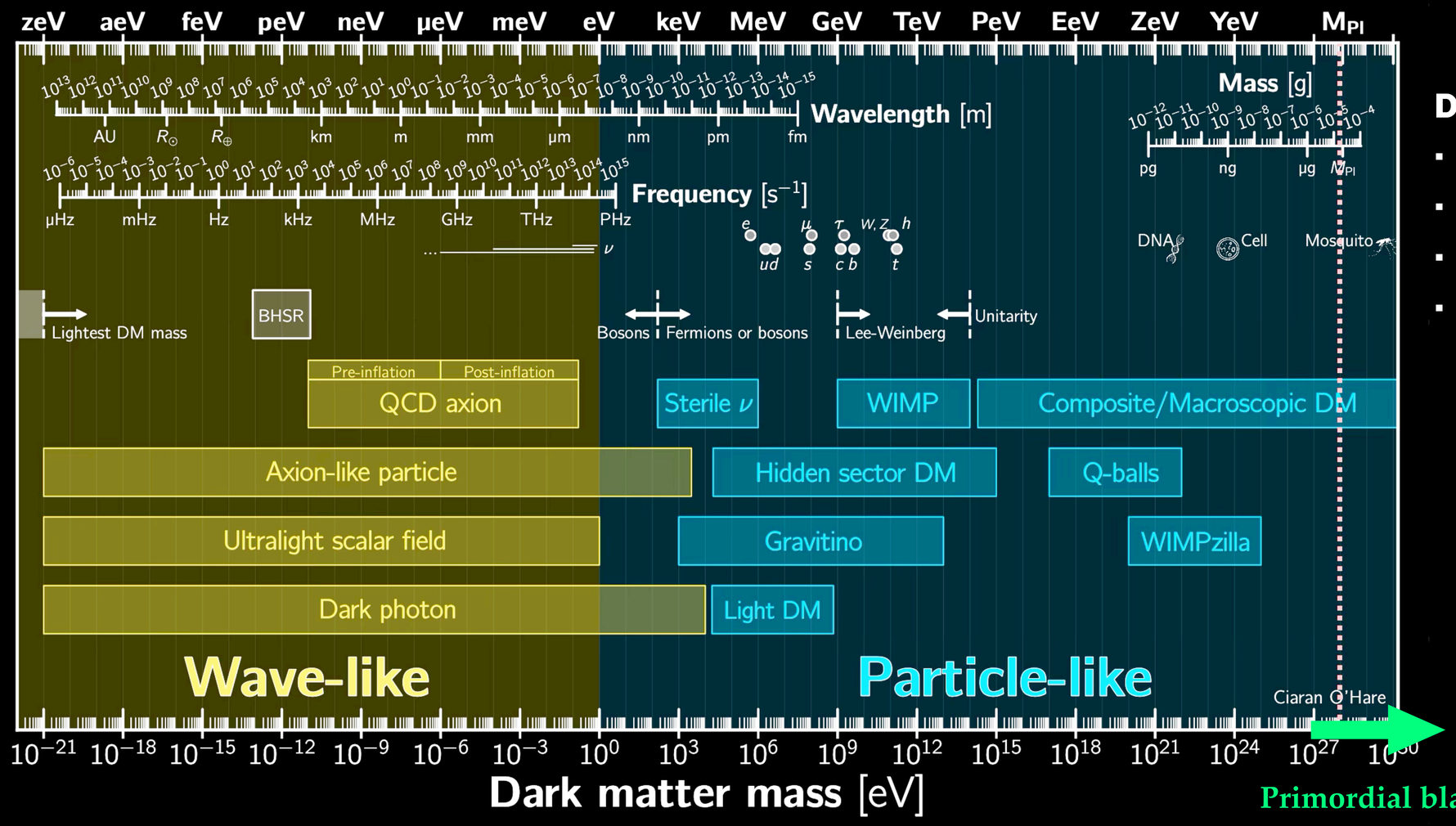







Dark Energy Survey

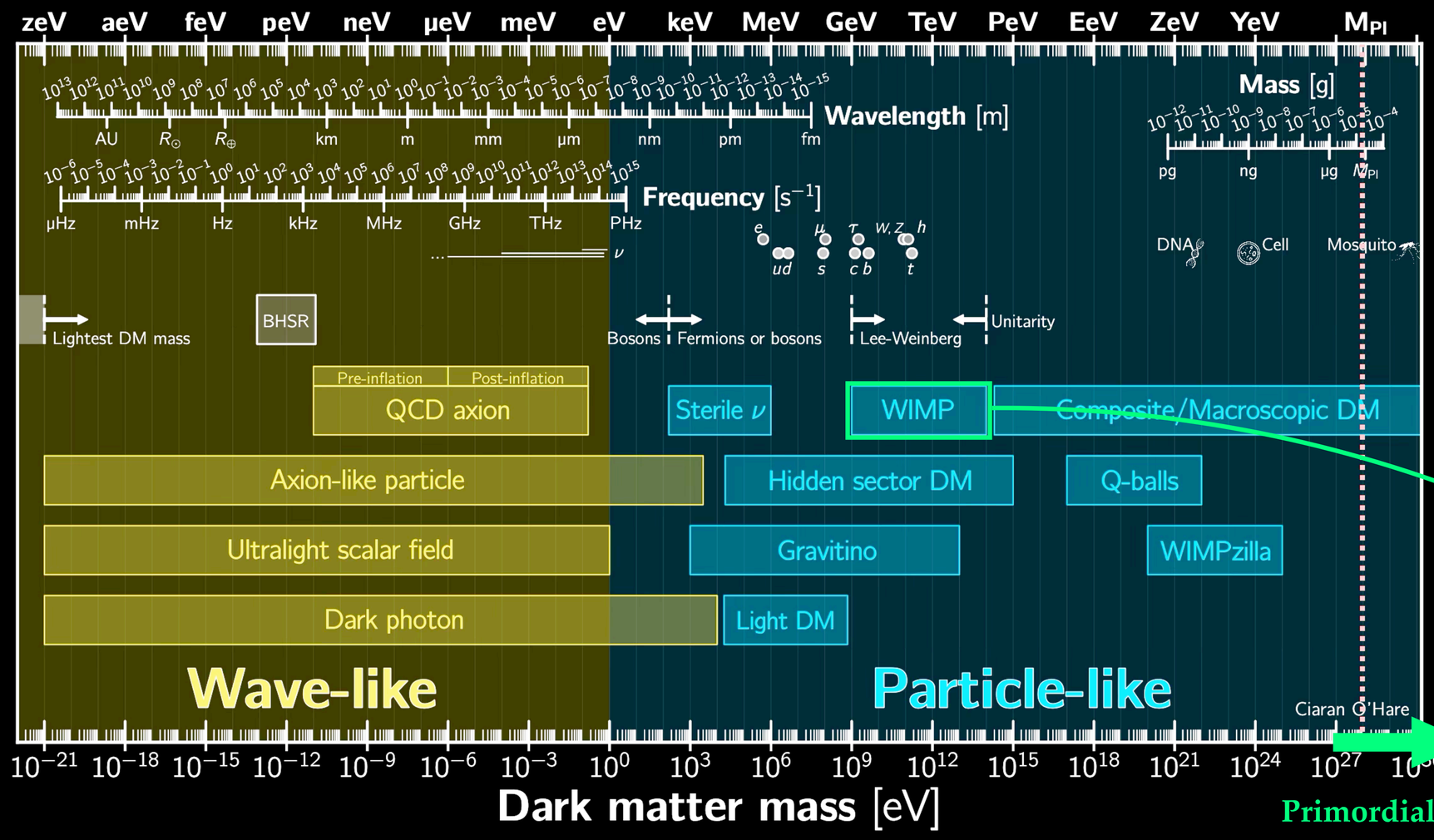
Dark matter candidates



Dark matter particles:

- Non-relativistic (massive)
- Stable/long-lived
- Non-baryonic
- Small coupling to Standard Model matter

Dark matter candidates



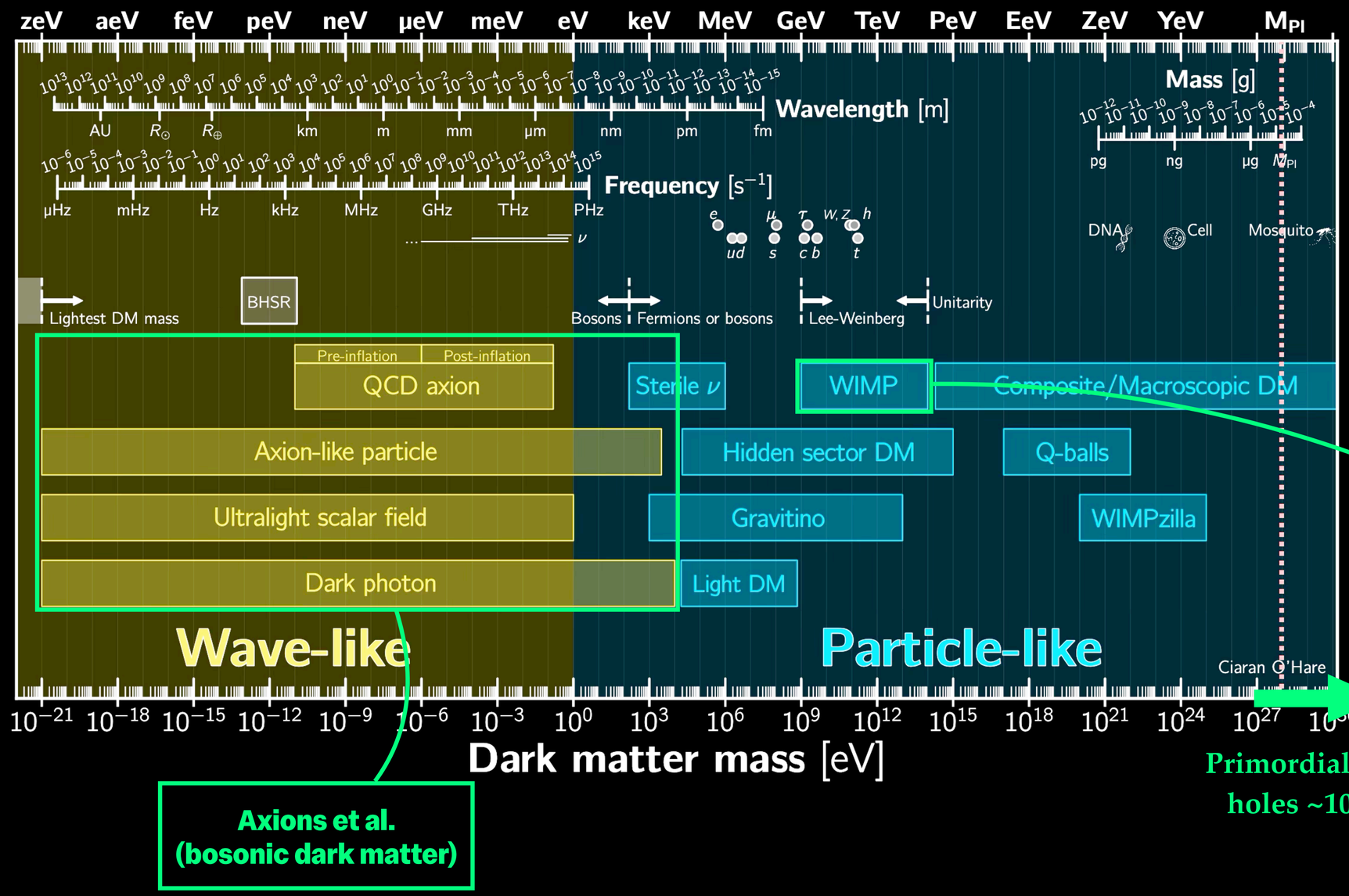
Dark matter particles:

- Non-relativistic (massive)
- Stable/long-lived
- Non-baryonic
- Small coupling to Standard Model matter

Weakly Interacting Massive Particles

Primordial black holes ~10 $M_\odot$

Dark matter candidates



Dark matter particles:

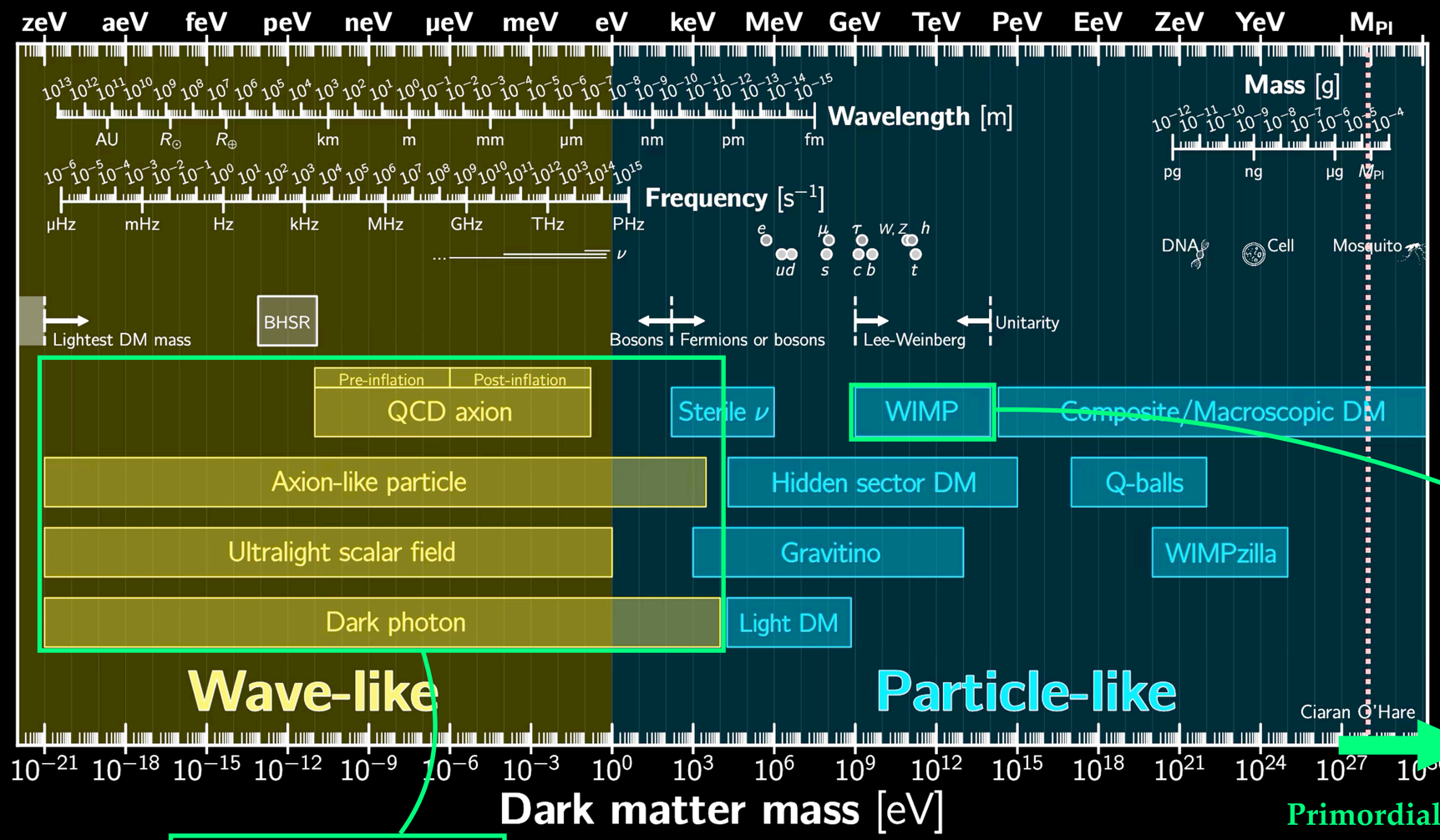
- Non-relativistic (massive)
- Stable/long-lived
- Non-baryonic
- Small coupling to Standard Model matter

Weakly Interacting Massive Particles

Axions et al. (bosonic dark matter)

Primordial black holes ~10 $M_\odot$

Dark matter candidates



Dark matter particles:

- Non-relativistic (massive)
- Stable/long-lived
- Non-baryonic
- Small coupling to Standard Model matter

Weakly Interacting Massive Particles

Axions et al. (bosonic dark matter)

Primordial black holes ~10 $M_\odot$

Dark matter particles permeate our Galaxy. This means, we could detect them on Earth!

Dark matter in the UK

Astronomy & Cosmology:

- **Active:**
  - Euclid (VIS, NISP)
  - Dark Energy Survey (DES)
  - VLT MUSE, MOONS
  - Rubin-LSST
  - Gemini (GMOS)
  - VISTA
  - Square Kilometre Array (SKA), MeerKAT, LOFAR-UK
- **Legacy:**
  - Kilo-Degree Survey (KiDS)
  - Planck
  - Gaia

Where is the dark matter?
What are its dynamics?
How did it influence the evolution of cosmic structures?
What can we learn about its properties?

Theory & Phenomenology:

- Particle theory, BSM models, collider phenomenology
- Astroparticle and cosmology theory
- Dark-matter detection theory and quantum-sensing concepts
- Indirect-detection interpretation and astrophysical signal modelling
- Collider and long-lived/portal phenomenology for dark sectors

How does dark matter fit into our models? What should we look for and how?

Experiment:

- **Collider:**
  - ATLAS, CMS, LHCb, FASER, SHiP
  - Belle II
  - Electron-Ion Collider (EIC)
- **Indirect detection**
  - HESS, HAWC, CTAO, SWGO
  - LOFAR-UK, MeerKAT
- **Direct detection:**
  - LUX-ZEPLIN (LZ), MIGDAL, DarkSide 20k, XLZD
  - NEWS-G, DarkSPHERE
  - QSHS, QUEST-DMC, AION, QSNET, QuEPA, MOLeQuTE, Levitated Quantum Sensors

Produce or detect dark matter by particle interactions.

Dark matter in the UK

Astronomy & Cosmology:

- **Active:**
  - Euclid (VIS, NISP)
  - Dark Energy Survey (DES)
  - VLT MUSE, MOONS
  - Rubin-LSST
  - Gemini (GMOS)
  - VISTA
  - Square Kilometre Array (SKA), MeerKAT, LOFAR-UK
- **Legacy:**
  - Kilo-Degree Survey (KiDS)
  - Planck
  - Gaia

Where is the dark matter?
What are its dynamics?
How did it influence the evolution of cosmic structures?
What can we learn about its properties?

Theory & Phenomenology:

- Particle theory, BSM models, collider phenomenology
- Astroparticle and cosmology theory
- Dark-matter detection theory and quantum-sensing concepts
- Indirect-detection interpretation and astrophysical signal modelling
- Collider and long-lived/portal phenomenology for dark sectors

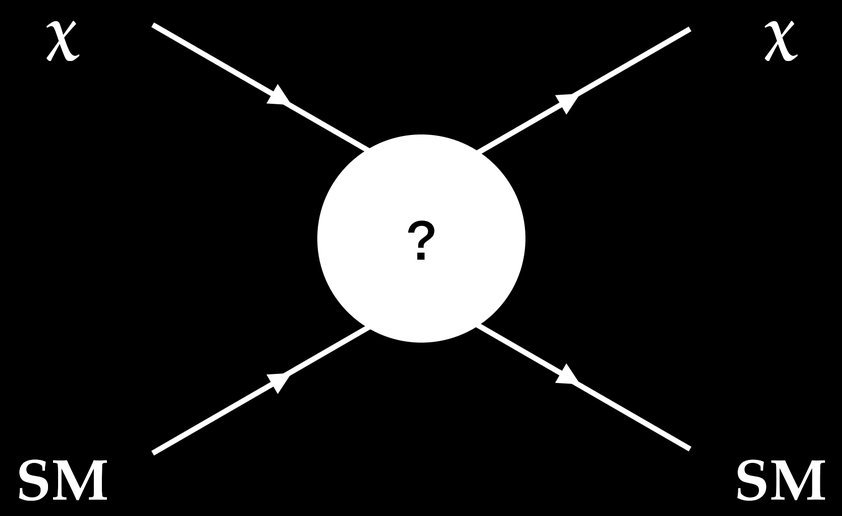
How does dark matter fit into our models? What should we look for and how?

Experiment:

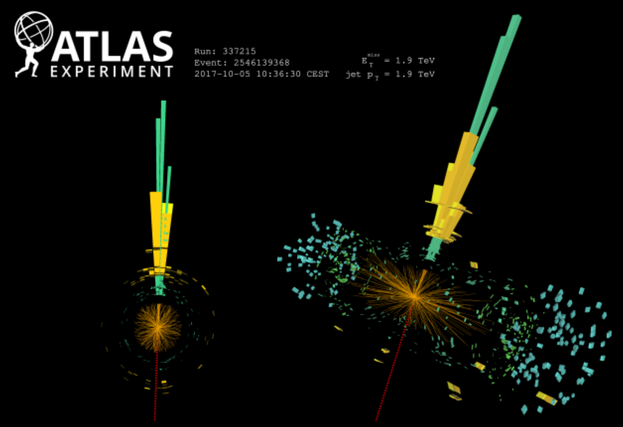
- **Collider:**
  - ATLAS, CMS, LHCb, FASER, SHiP
  - Belle II
  - Electron-Ion Collider (EIC)
- **Indirect detection**
  - HESS, HAWC, CTAO, SWGO
  - LOFAR-UK, MeerKAT
- **Direct detection:**
  - LUX-ZEPLIN (LZ), MIGDAL, DarkSide 20k, XLZD
  - NEWS-G, DarkSPHERE
  - QSHS, QUEST-DMC, AION, QSNET, QuEPA, MOLeQuTE, Levitated Quantum Sensors

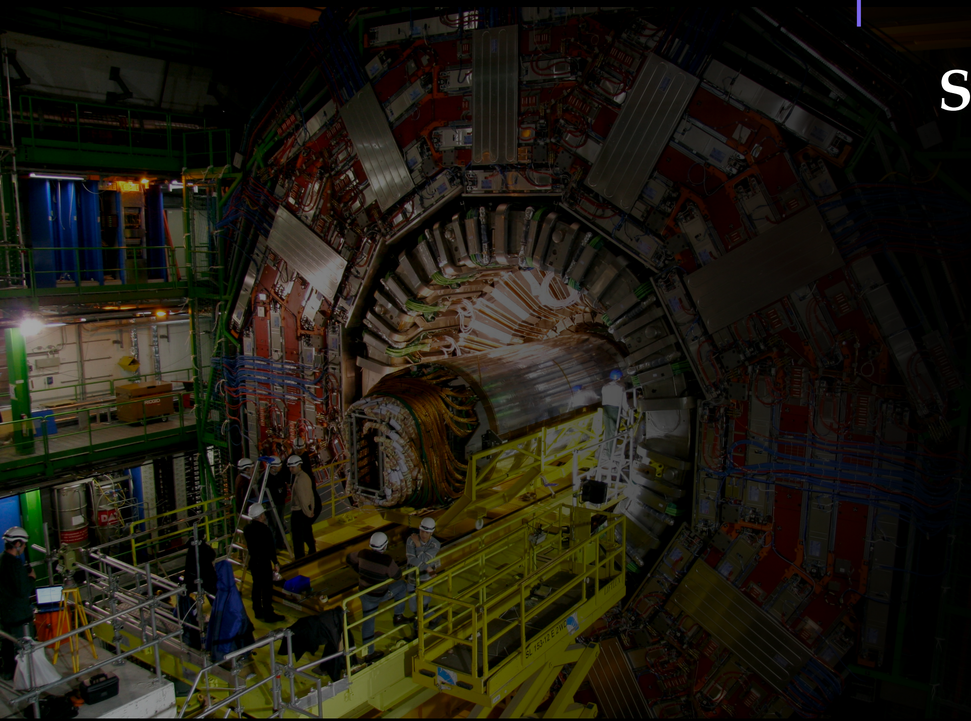
Produce or detect dark matter by particle interactions.

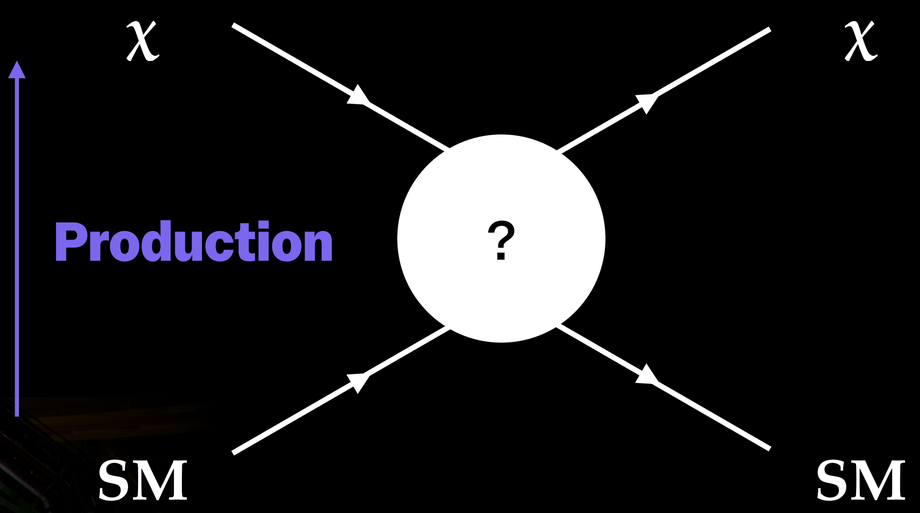
Experimental dark matter searches



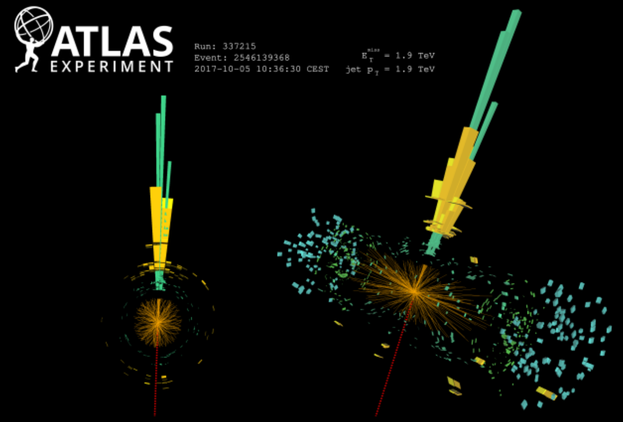
Experimental dark matter searches

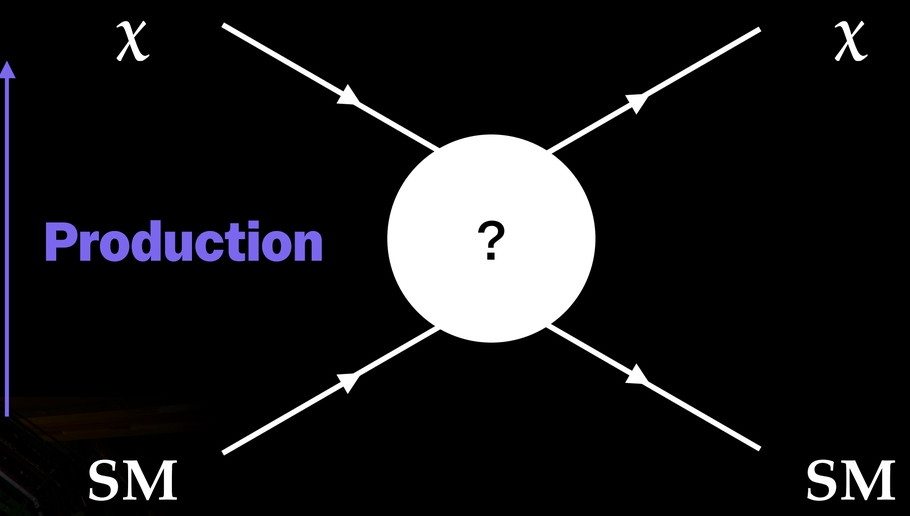






Experimental dark matter searches





Shu Chen
Wed 16:00

Rachel Pickering
Wed 17:00

Joseph Bateman
Wed 16:00

Miguel Bernal
Thur 10:45

Julian Wack
Wed 16:30

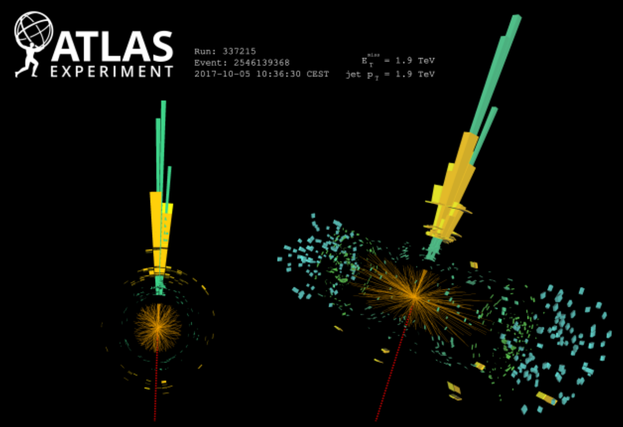
Holly Pacey
Fri 9:30 plenary

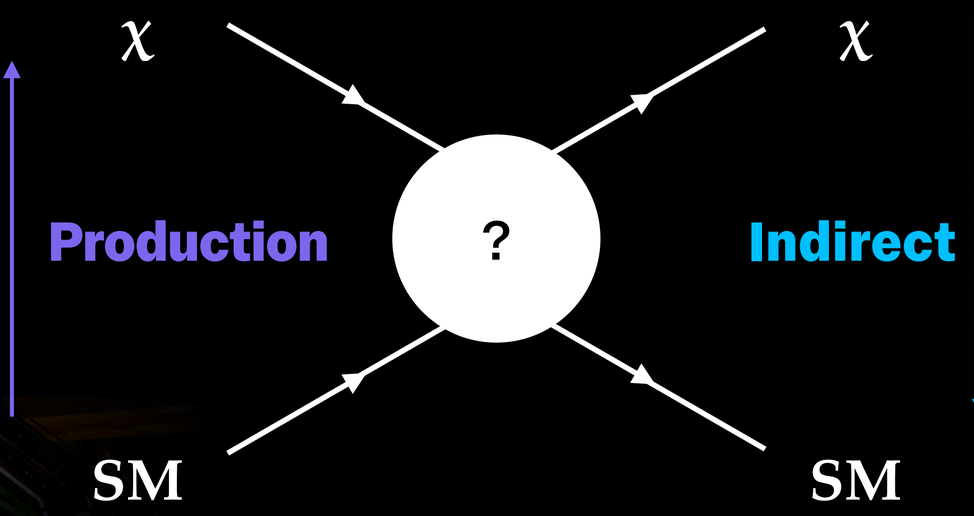
Saashiv Valjee
Wed 16:45

Tom Elliot
Fri 11:15

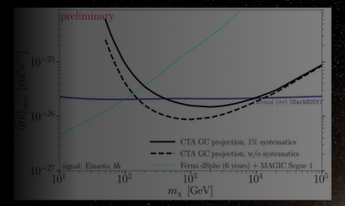
Alex Veltman
Fri 11:45

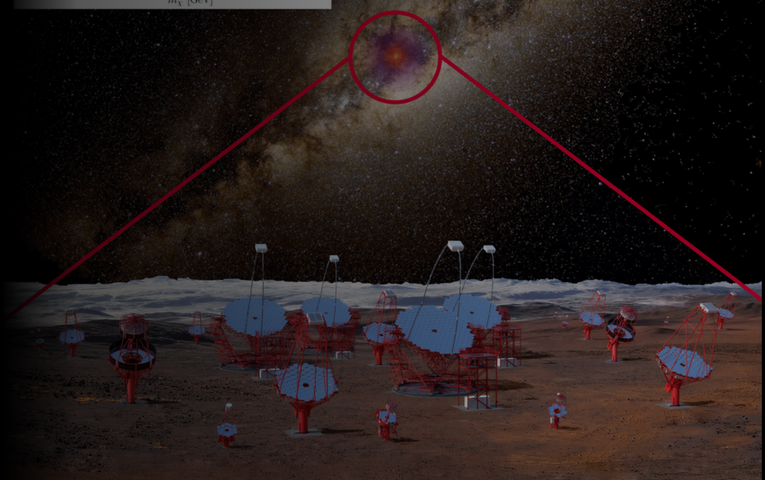
Experimental dark matter searches





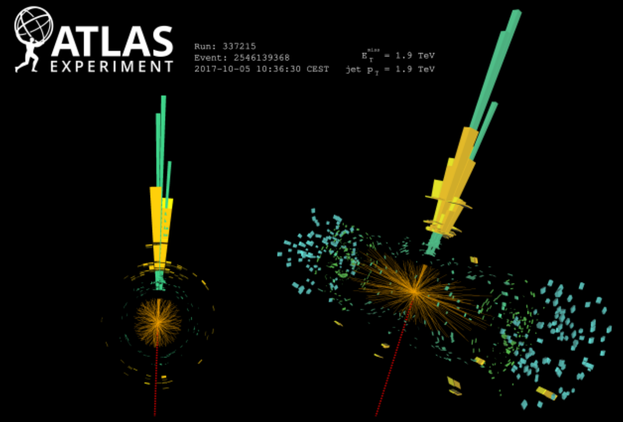


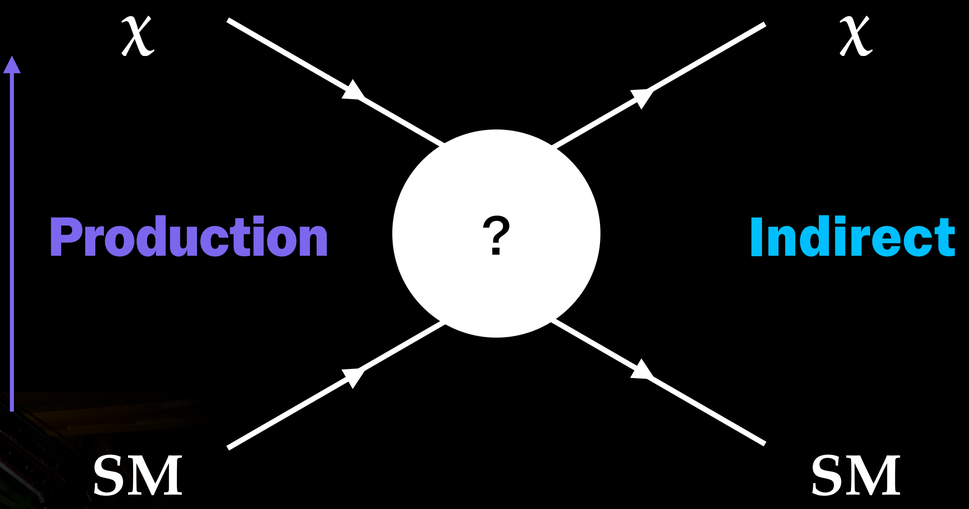


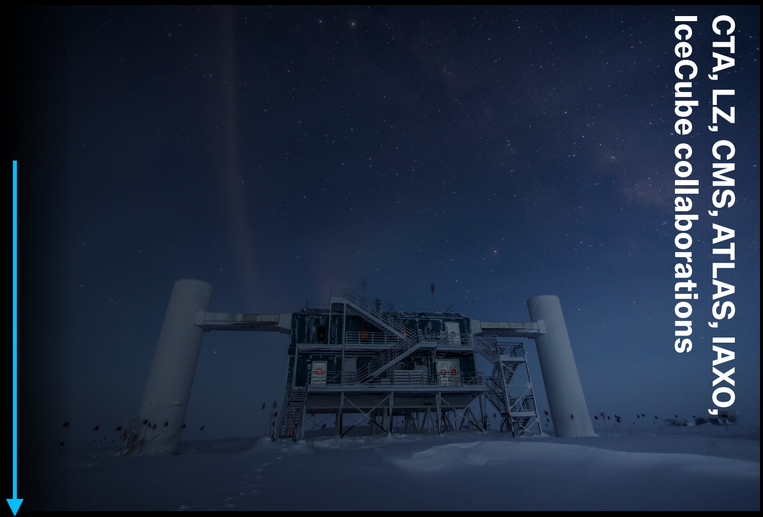


Shu Chen Wed 16:00	Rachel Pickering Wed 17:00
Joseph Bateman Wed 16:00	Miguel Bernal Thur 10:45
Julian Wack Wed 16:30	Holly Pacey Fri 9:30 plenary
Saashiv Valjee Wed 16:45	Tom Elliot Fri 11:15
Alex Veltman Fri 11:45	

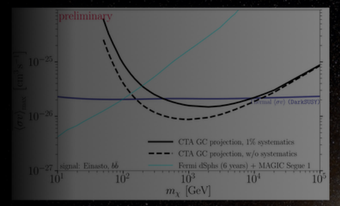
Experimental dark matter searches

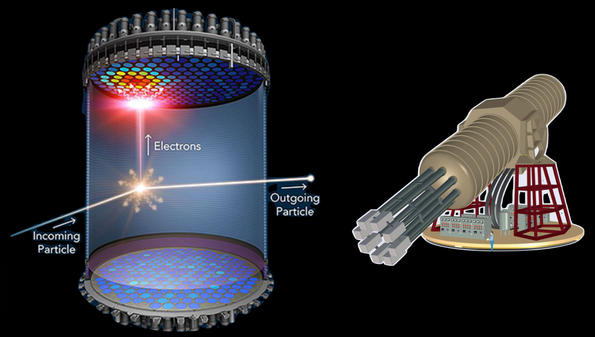


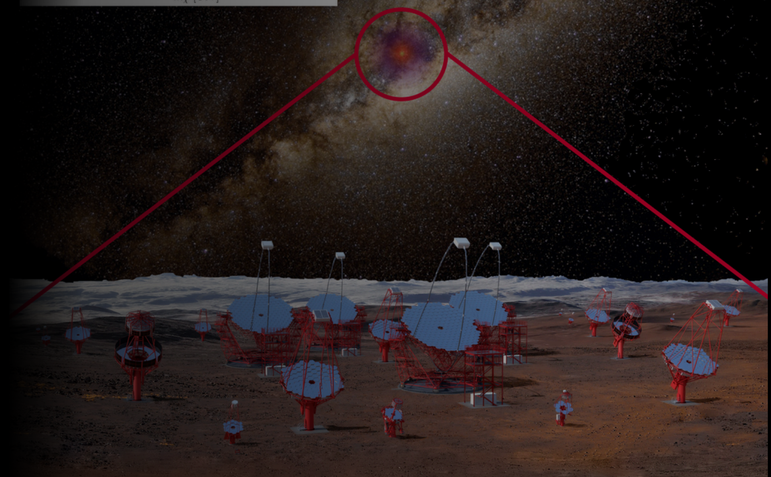




CTA, LZ, CMS, ATLAS, IAXO, IceCube collaborations







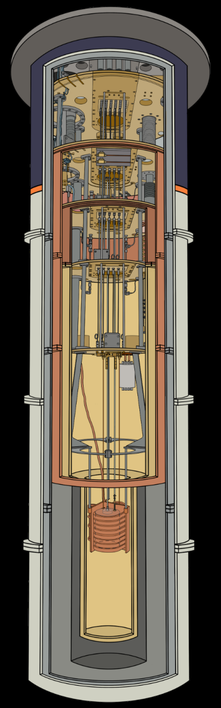
Shu Chen Wed 16:00	Rachel Pickering Wed 17:00
Joseph Bateman Wed 16:00	Miguel Bernal Thur 10:45
Julian Wack Wed 16:30	Holly Pacey Fri 9:30 plenary
Saashiv Valjee Wed 16:45	Tom Elliot Fri 11:15
Alex Veltman Fri 11:45	

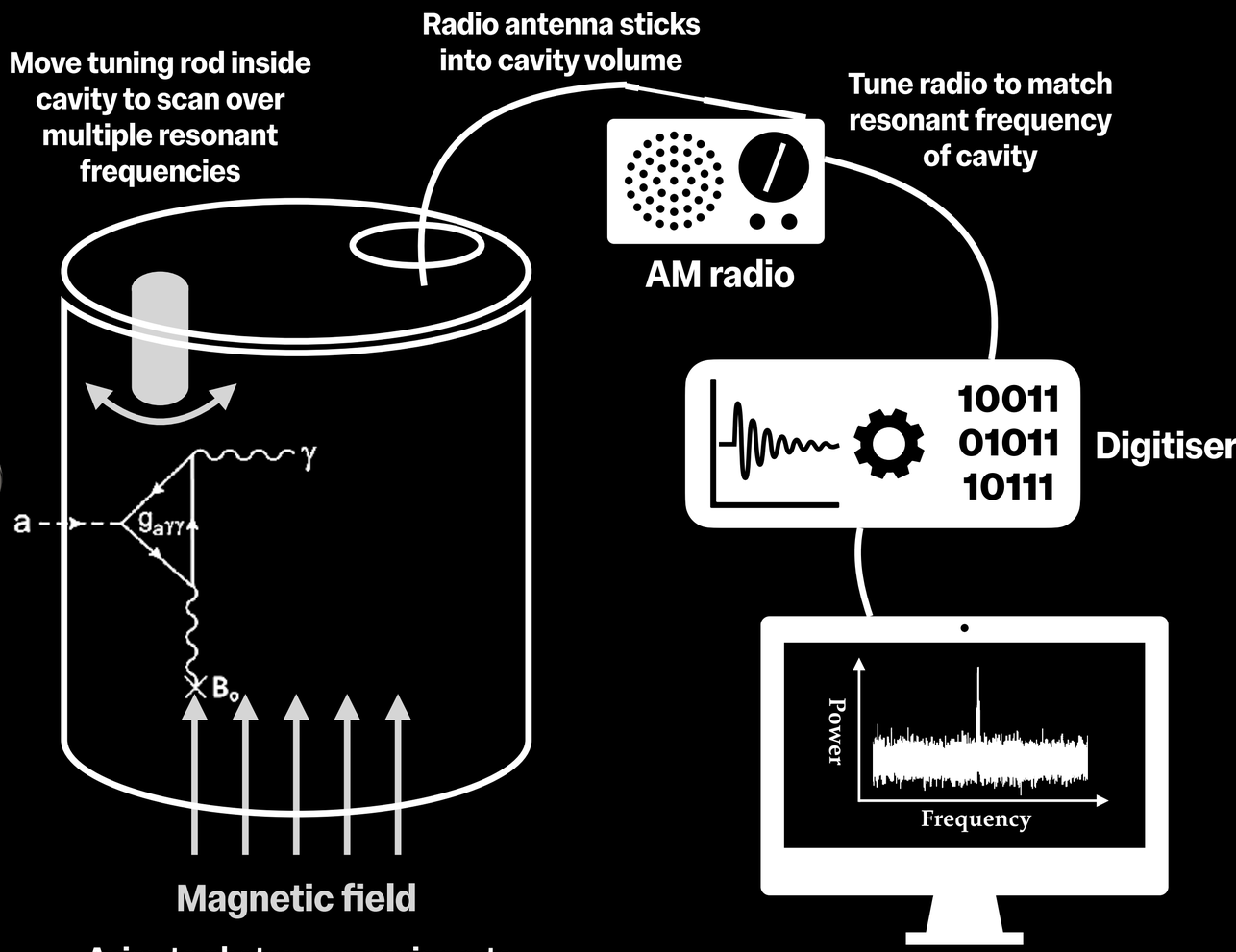
Quantum Sensors for the Hidden Sector

Many thanks to Ed Daw for providing material!



- Condensed matter physicists, quantum technologists, theorists and experimental astro-particle physicists from NPL, Sheffield, Oxford, Lancaster, UCL, RHUL.
- Halo axions convert to radio waves in a magnetic field via the inverse Primakoff effect, exciting a tunable high-Q resonant cavity.
- Measure excess power from axions over noise from blackbody radiation (**mK temperatures**) and amplifier noise (**quantum electronics**).

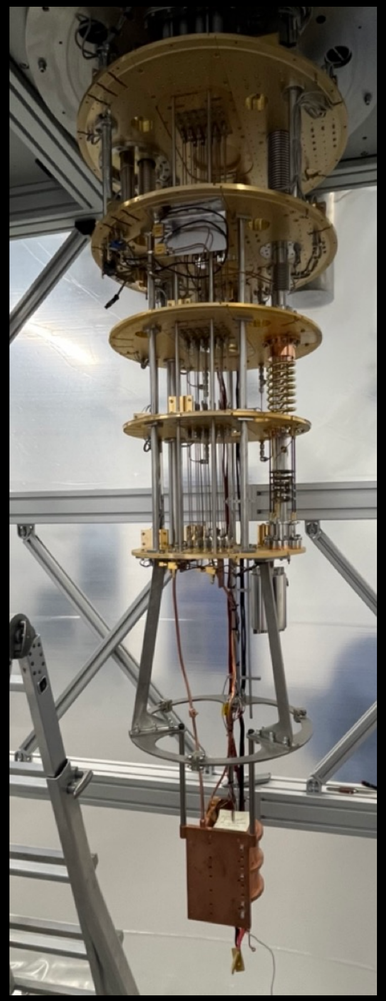


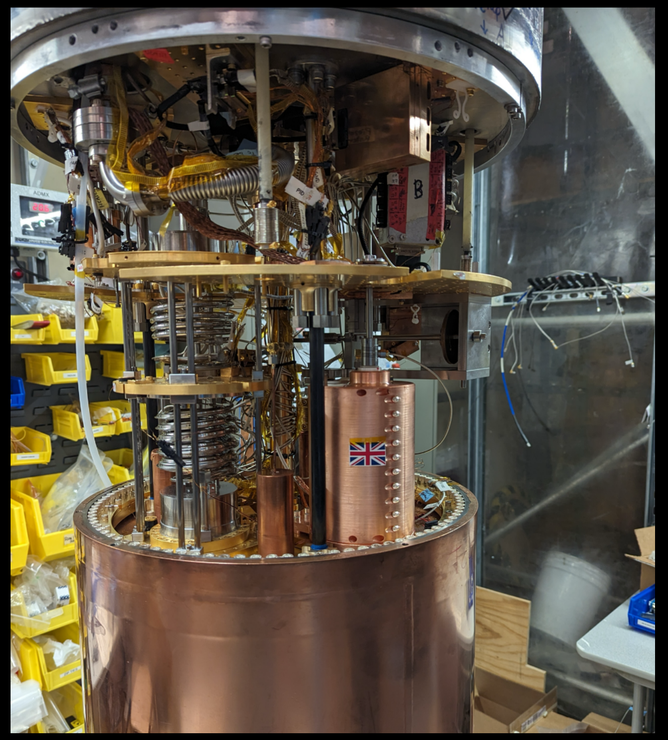


Status of QSHS

- One cavity in QSHS and the other running as sidecar of ADMX.
- Apparatus assembled and commissioned.
- Currently preparing for tests of first quantum amplifiers, one from Boon Kok Tan (Oxford), the other from VTT and the Lancaster group.
- Some issues with mechanical tuning rod mechanism and antenna insertion mechanism getting jammed at low temperatures. Newly polished and aligned hardware may resolve the issue.
- In-situ measurement of stage 2 HFET amplifier yielded a noise temperature of 3.2K.
- First axion search run with HEMT amplifier imminent.
- First two Ph.D. students (Claude Mostyn, Mitch Perry) writing up to submit this year.

In collaboration with ADMX AXION DARK MATTER EXPERIMENT

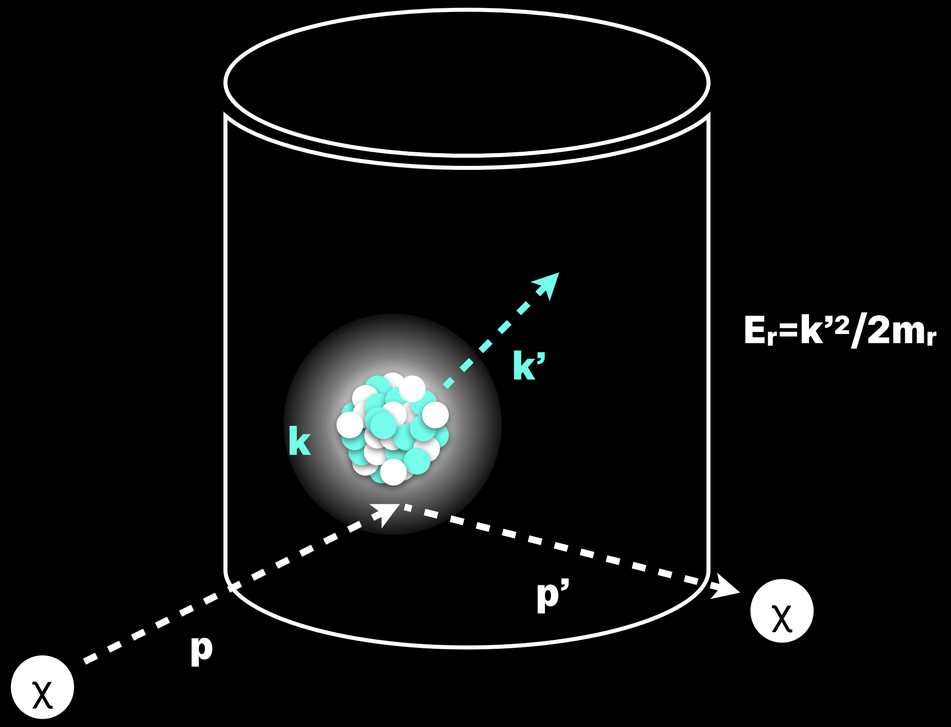




Annora Sundararajan
Poster A2

Jamie MacDonald
Thur 10:45

Direct WIMP detection



$E_r = k'^2/2m_r$

$$\frac{dR}{dE_r} = M \times \frac{\rho_0 \sigma_0}{m_\chi m_r^2} F^2(E_r) \int_{v_{min}} \frac{f(\vec{v})}{v} d^3v$$

WIMP properties

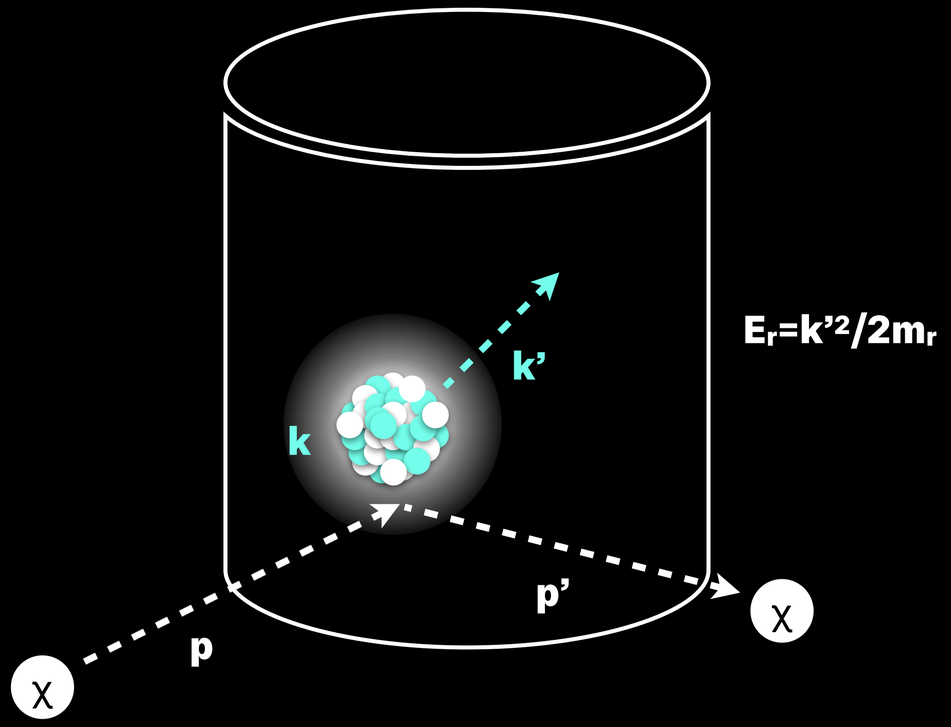
Astrophysics

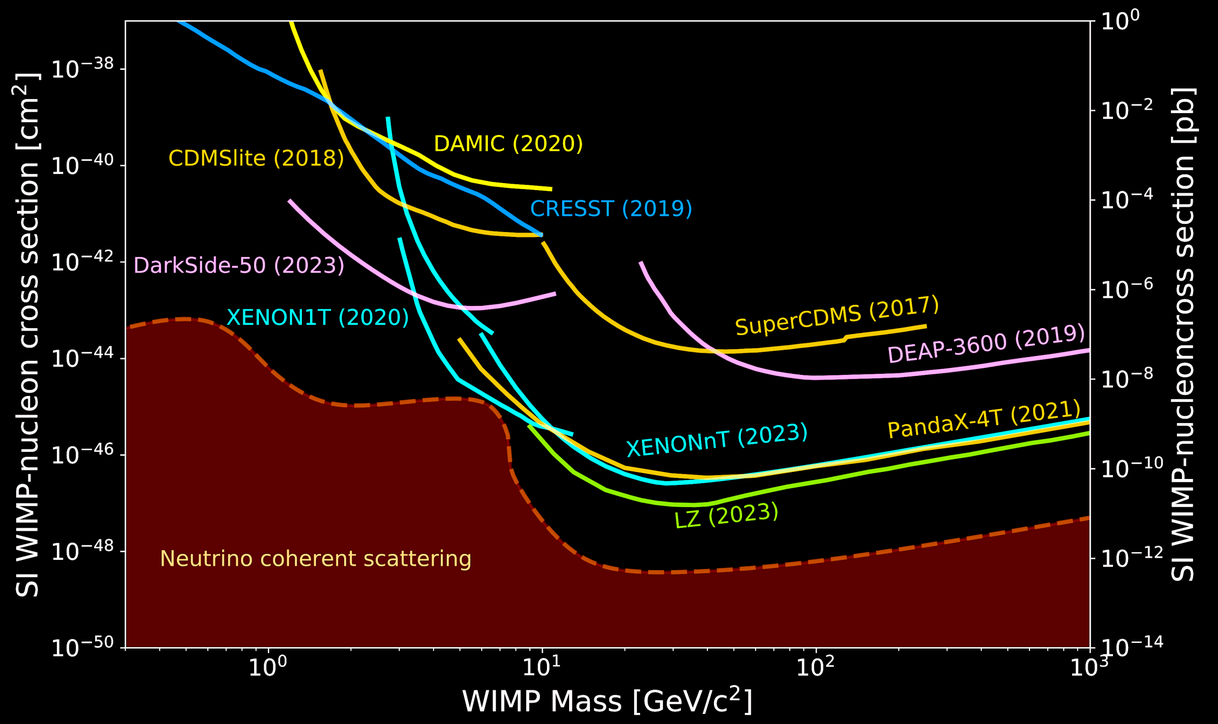
Detector

Detect WIMPs directly by measuring a **O(1) keV nuclear recoil** after scattering in a detector with:

- **large exposure**
- **low background**
- **low threshold**

Direct WIMP detection

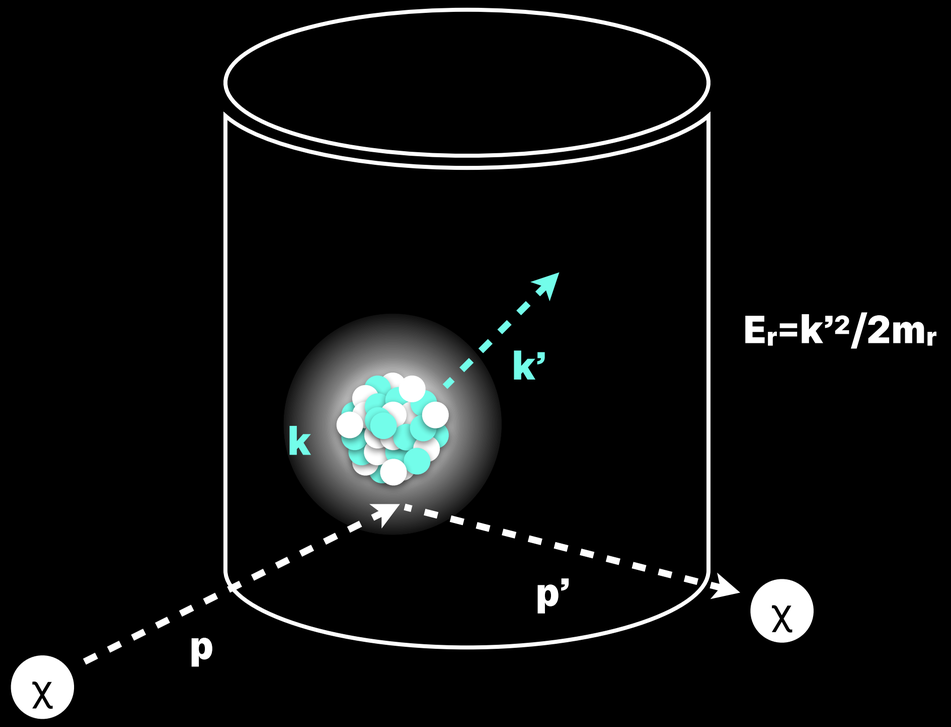




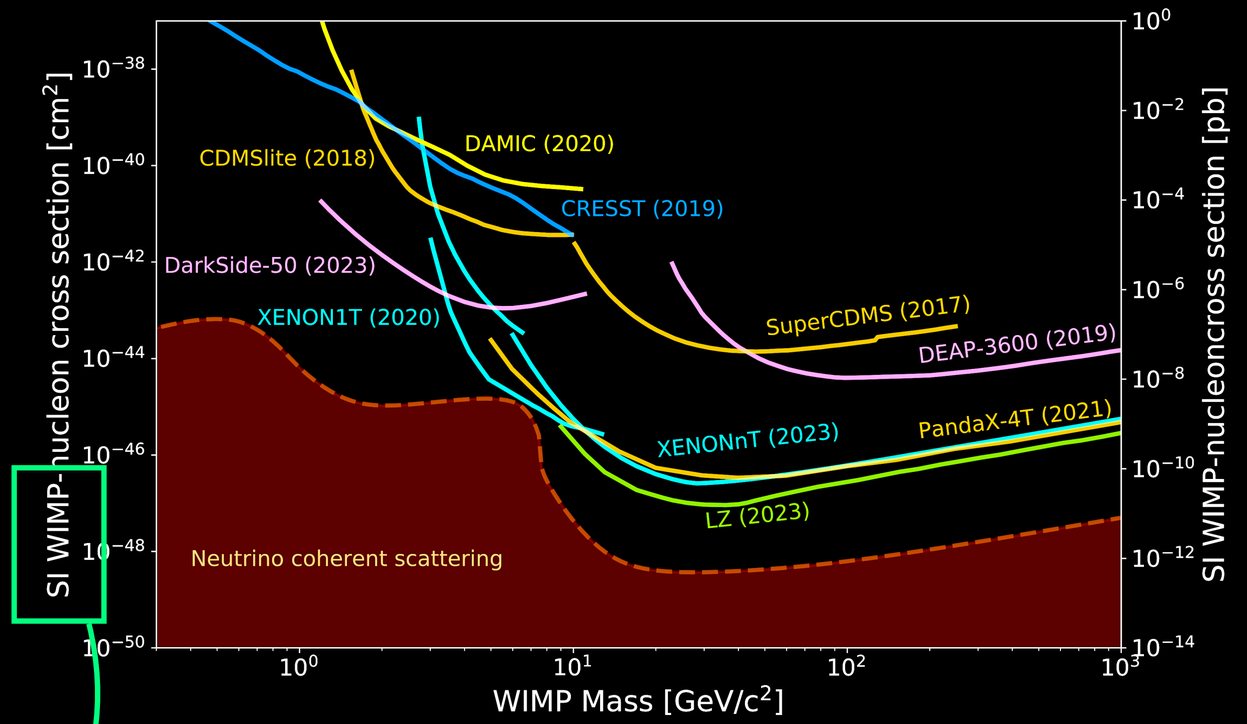
Detect WIMPs directly by measuring a **O(1) keV nuclear recoil** after scattering in a detector with:

- **large exposure**
- **low background**
- **low threshold**

Direct WIMP detection



$E_r = k'^2/2m_r$

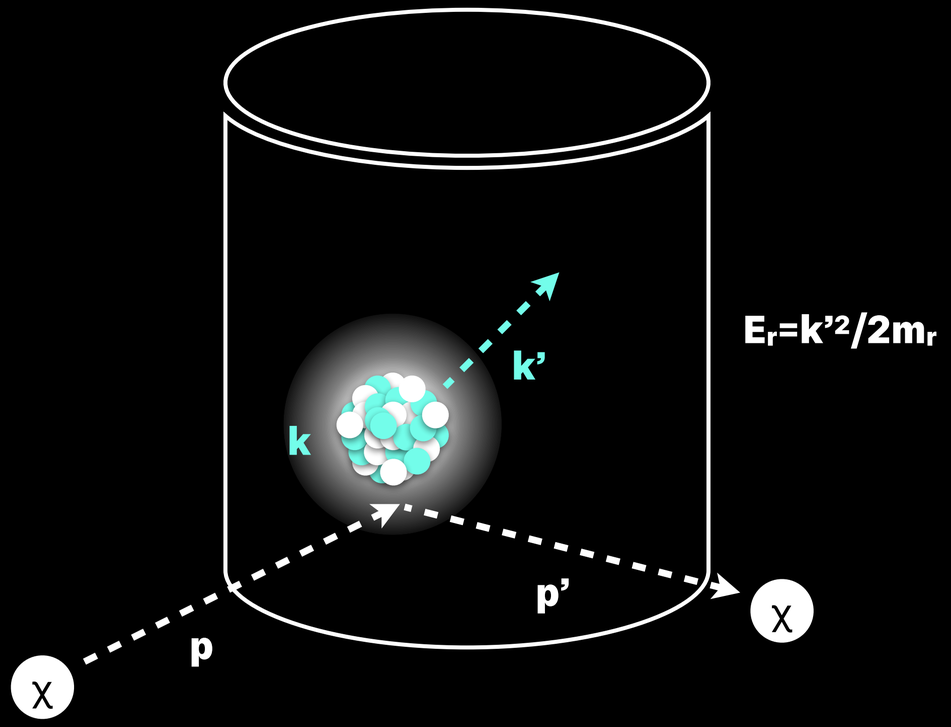


Detect WIMPs directly by measuring a **O(1) keV nuclear recoil** after scattering in a detector with:

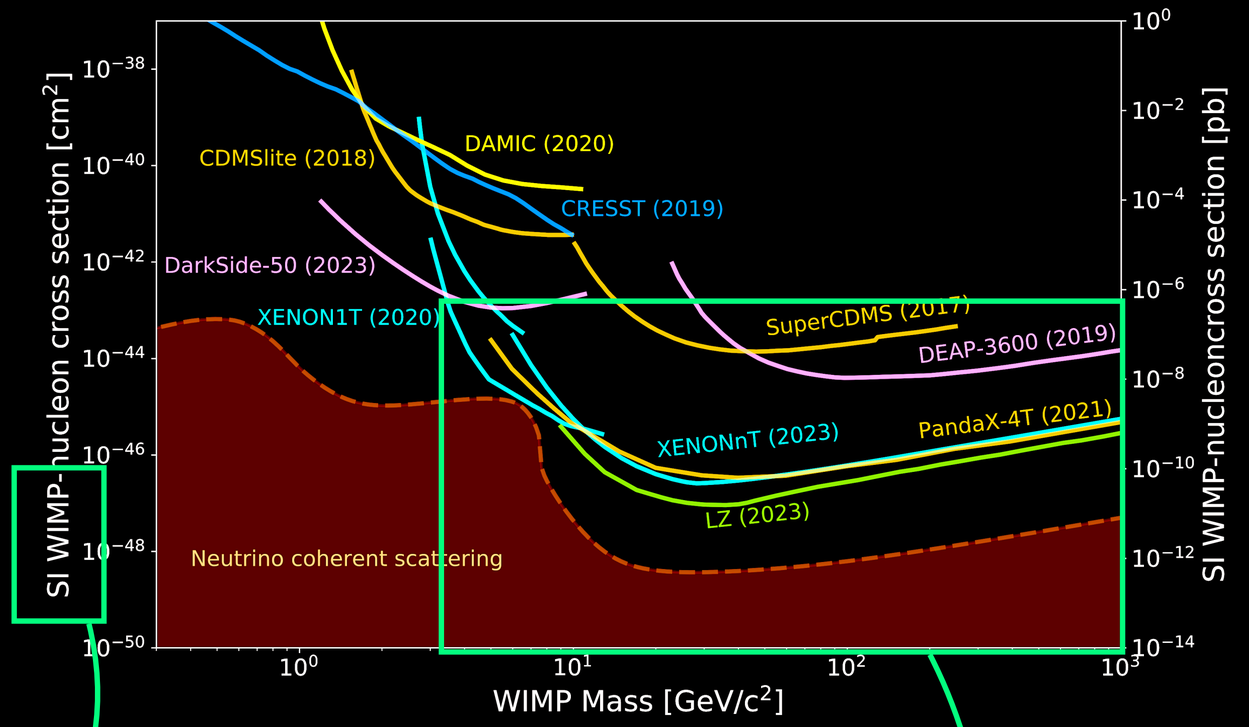
- **large exposure**
- **low background**
- **low threshold**

- **SI:** spin-independent coherent scattering with a nucleus
- **SD:** coupling to unpaired nucleon spins

Direct WIMP detection



$E_r = k'^2/2m_r$



Detect WIMPs directly by measuring a **O(1) keV nuclear recoil** after scattering in a detector with:

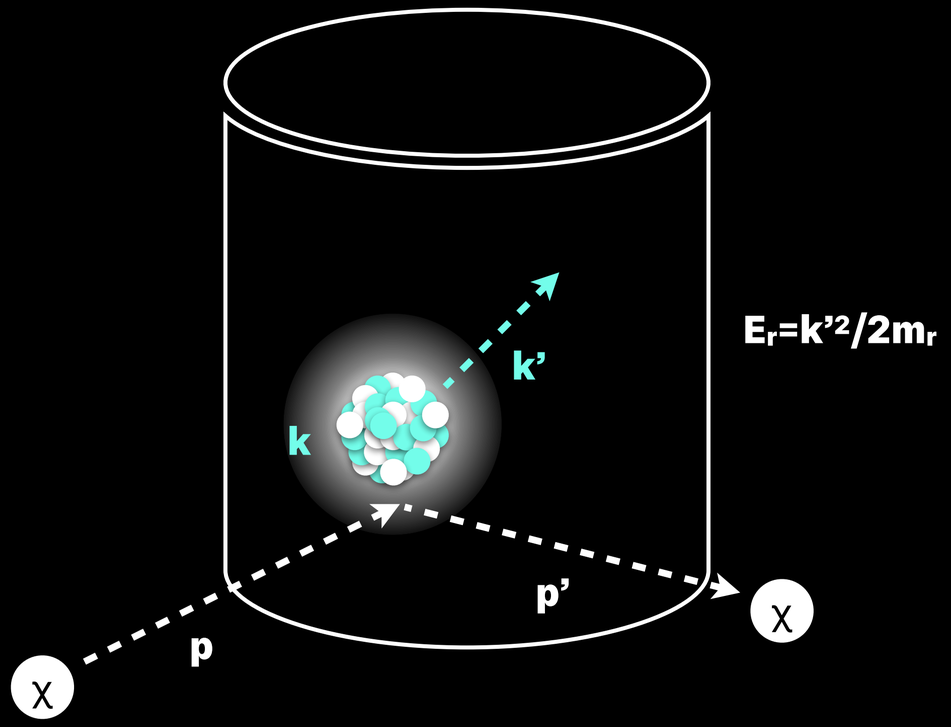
- **large exposure**
- **low background**
- **low threshold**

- **SI:** spin-independent coherent scattering with a nucleus
- **SD:** coupling to unpaired nucleon spins

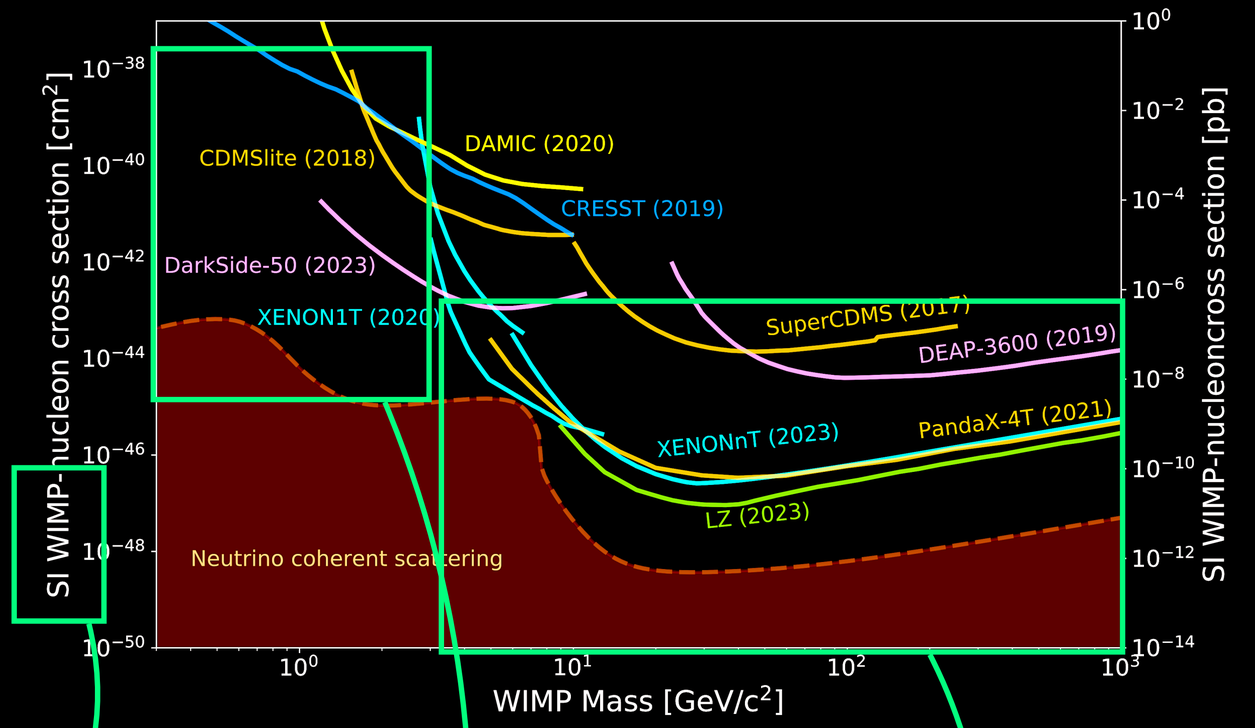
Xenon dual-phase TPCs are world-leading here:

- **Thermal relics**
- **SUSY (bino, higgsino), minimal DM**
- **Complementarity to collider searches**

Direct WIMP detection



$E_r = k'^2/2m_r$



Detect WIMPs directly by measuring a **O(1) keV nuclear recoil** after scattering in a detector with:

- **large exposure**
- **low background**
- **low threshold**

- **SI:** spin-independent coherent scattering with a nucleus
- **SD:** coupling to unpaired nucleon spins

What About low-mass WIMPs?

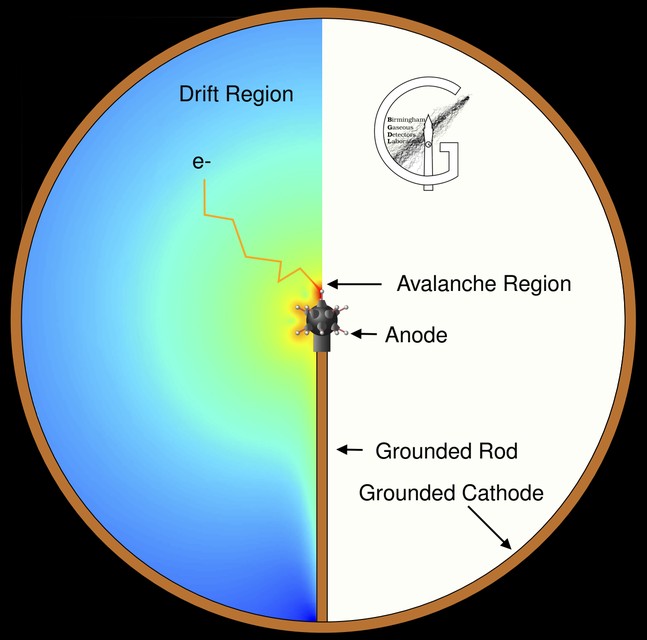
- **Production more complicated than thermal relic at weak scale?**
- **Asymmetric DM**

Xenon dual-phase TPCs are world-leading here:

- **Thermal relics**
- **SUSY (bino, higgsino), minimal DM**
- **Complementarity to collider searches**

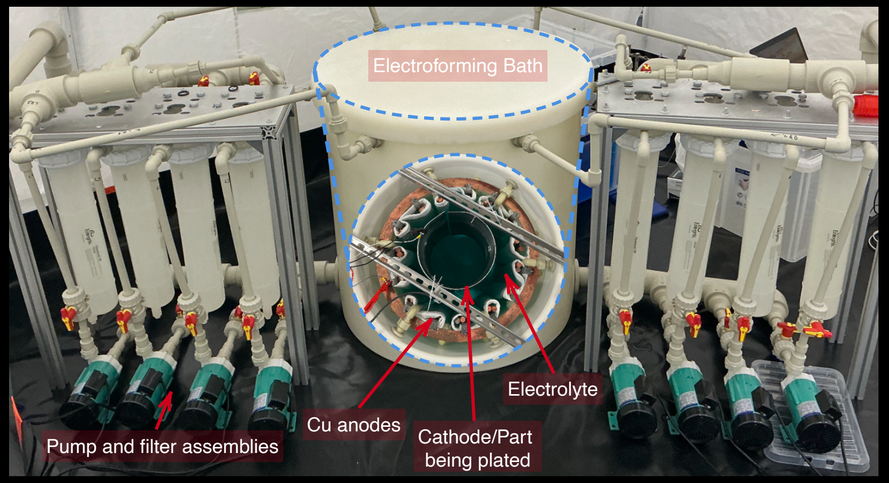
Spherical proportional counters

Many thanks to Patrick Knights and Kostas Nikolopoulos for providing material!







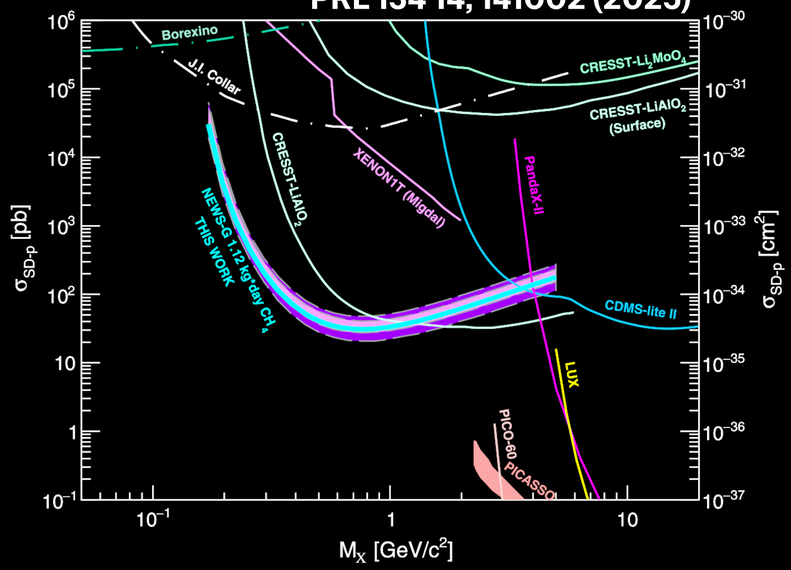


- Light target gases for kinematic matching to light particle DM
- First results from NEWS-G ⌀1.3m detector
- World-leading constraint on spin-dependent proton coupling
- DarkSPHERE: Proposed ⌀3m, fully electroformed Cu detector in Boulby
- Sensitivity to SI, SD-p and SD-n interactions
- Awaiting outcome of STFC medium-scale DM call

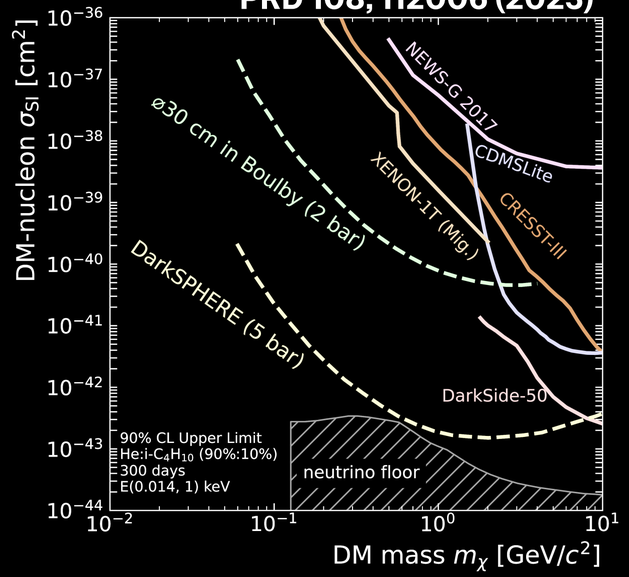
Lachlan Milligan Wed 16:45

Peter Walters Thur 10:45

PRL 134 14, 141002 (2025)



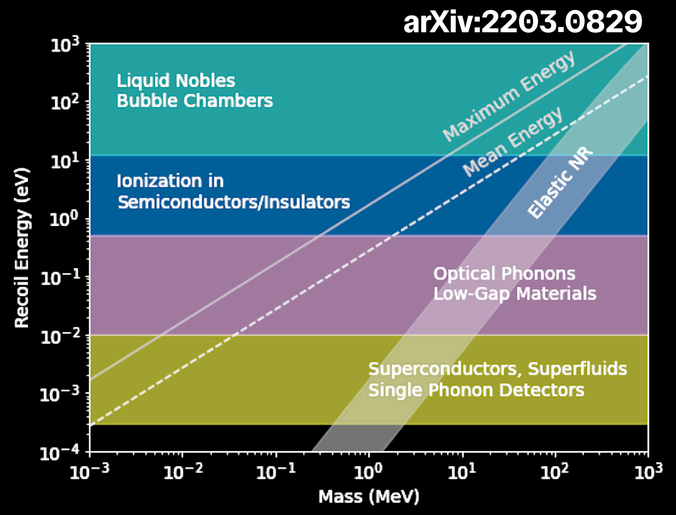
PRD 108, 112006 (2023)



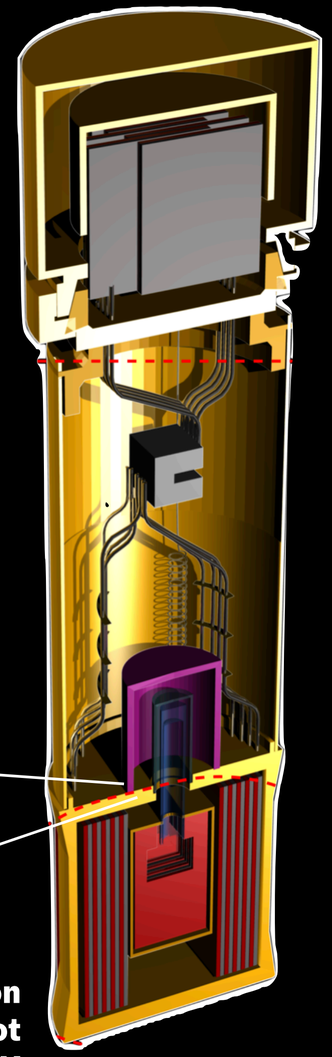
Light DM with superfluid ^{3}He: QUEST-DMC

Many thanks to Jocelyn Monroe for providing material!

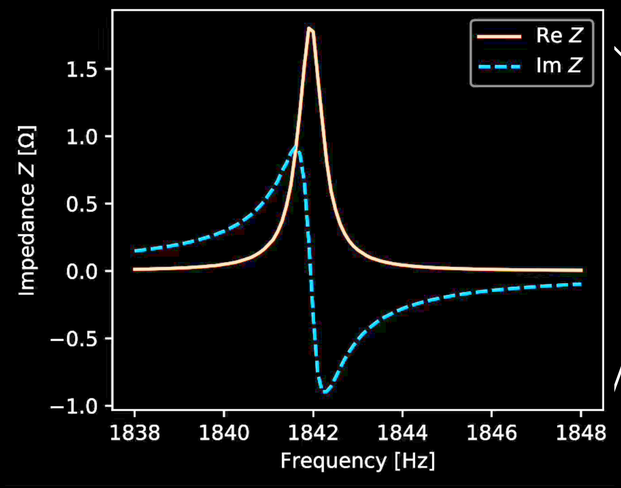
- DM masses in MeV range only kinematically accessible with new technologies
- Quantum Technology for Fundamental Physics (QTFP) collaboration: RHUL, Lancaster, Liverpool, Oxford, RAL PPD, Rheinmann Hochschule, Sussex, radioassay at Boulby
- Detection of sub-GeV dark matter with quasiparticles (heat) in superfluid ^{3}He target using superconducting nanowires
- SQUID readout of nanowire resonators

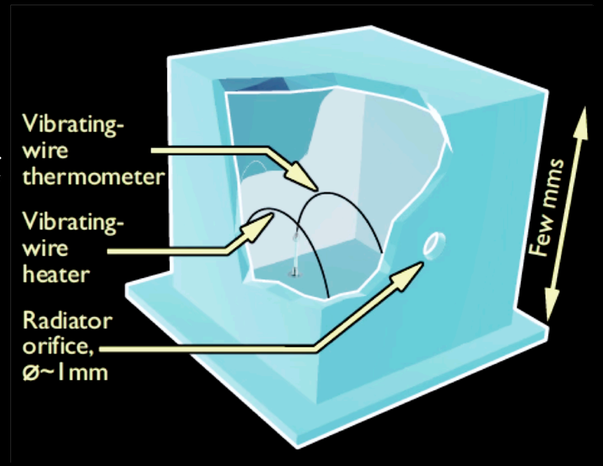


Dilution refrigerator going to 2 mK



Change in resonance width proportional to deposited energy.





Bolometer cell

Copper demagnetisation stage for single-shot cooling to 100 μK

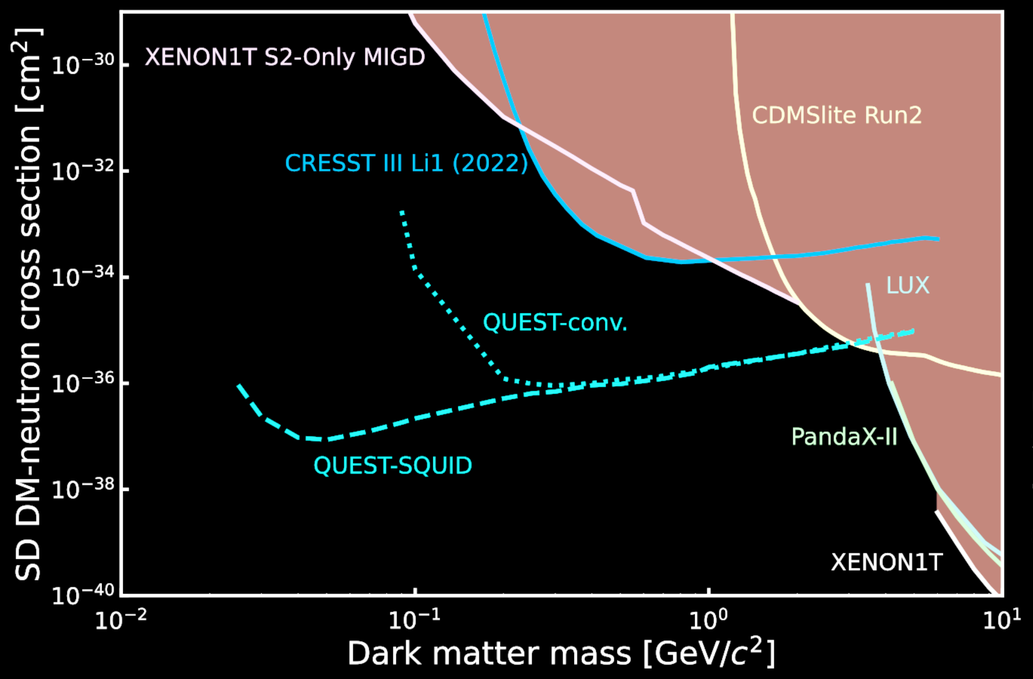
Eur. Phys. J. C (2024) 84:248

Light DM with superfluid ^{3}He: QUEST-DMC

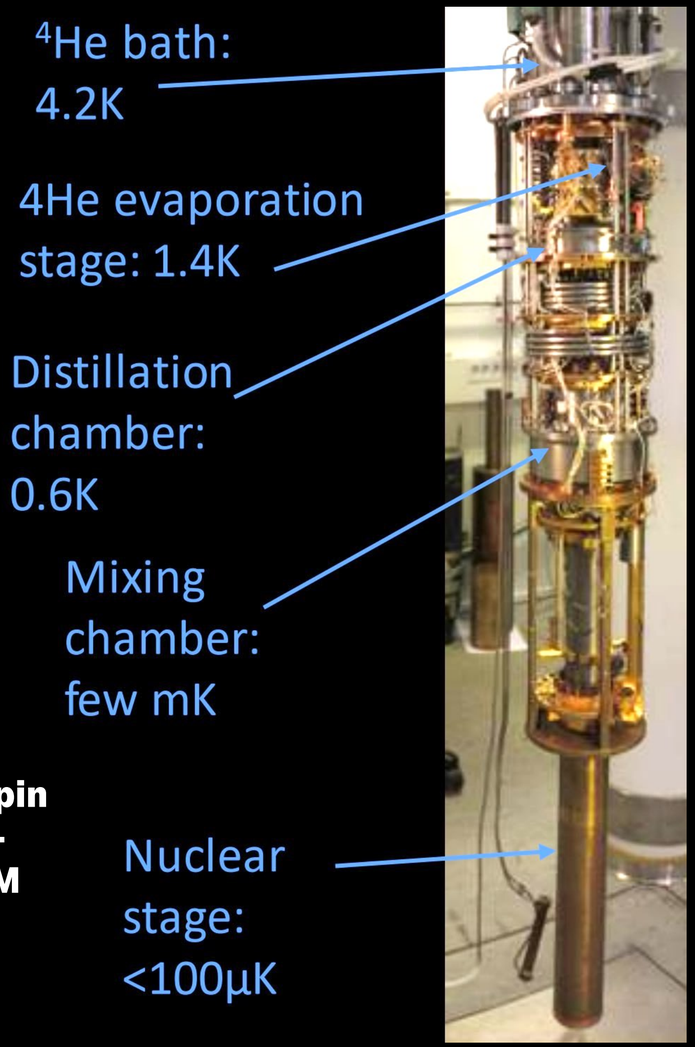
Many thanks to Jocelyn Monroe for providing material!

- 4 prototype detector runs, most recently reaching 110 μK
- Development of veto technology compatible with operation at 10 mK stage – Relevant to radiation impact on superconducting qubits. **arXiv:2512.16769**
- Next step: nano-fabricated resonators

arXiv:2310.11304



Use unpaired ^{3}He nuclear spin to probe spin-dependent DM interactions.



Neda Darvishi Wed 16:30

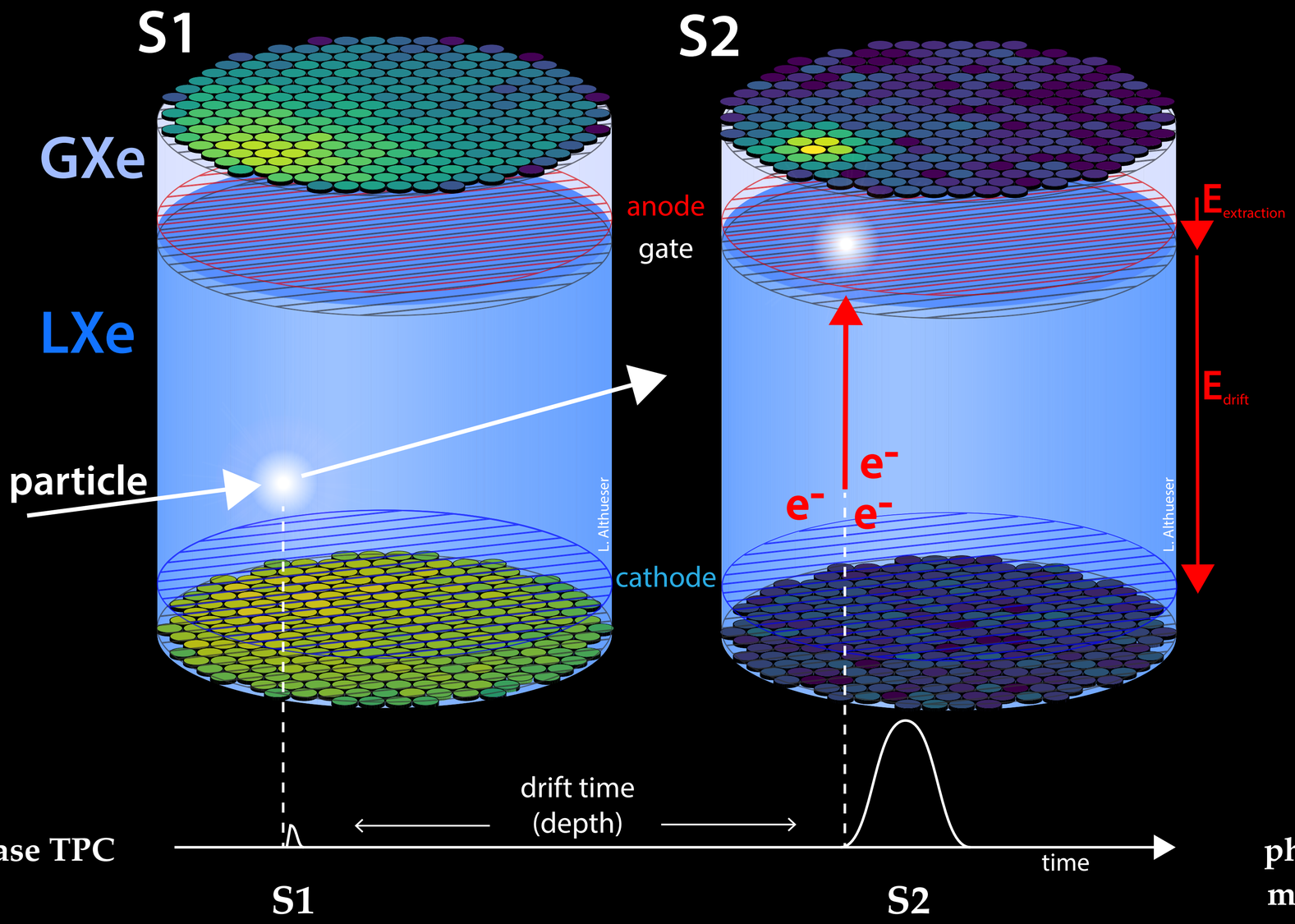
Adam Ting Poster A1

Lizzie Bloomfield Poster A6

Lizzie Bloomfield Fri 11:30

Eur. Phys. J. C. 84 (2024) 3, 248
JCAP 10 (2025) 044
J. Low Temp. Phys. 222 (2026) 2, 39

Heavy WIMPs with dual-phase TPCs



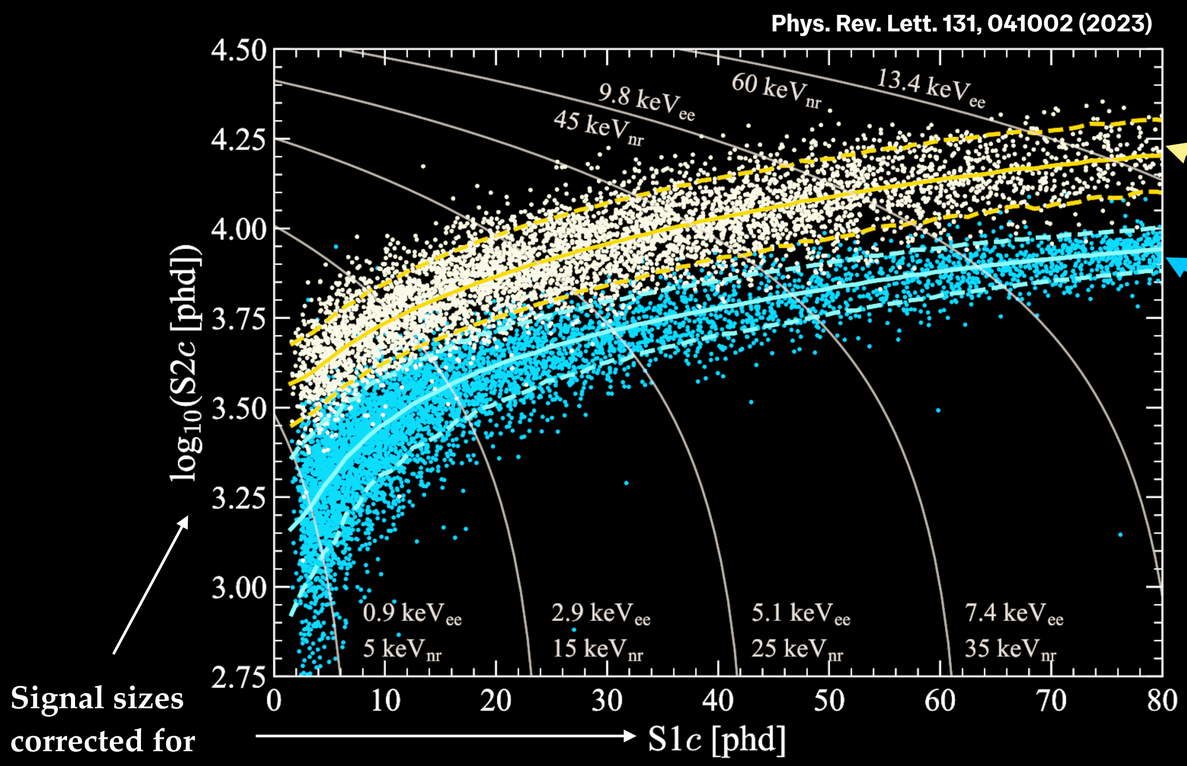
“Event" in a dual-phase TPC

Signal sizes in photoelectrons (PE) measured by PMTs

What does the data look like?

Combine scintillation (S1) and ionization (S2) for:

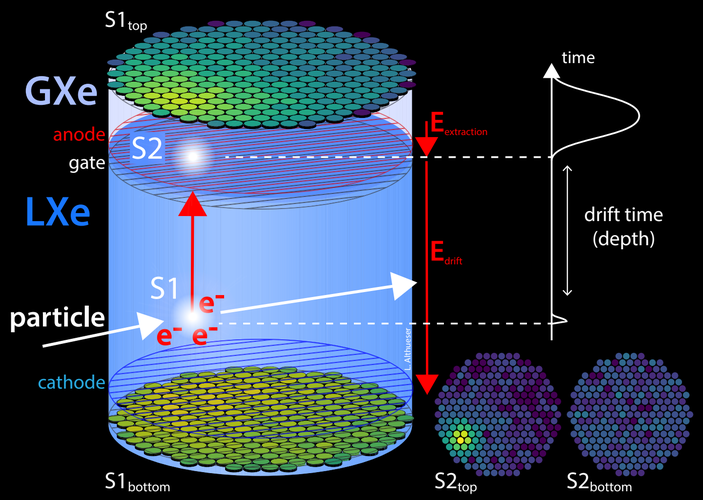
- **Position reconstruction from hit pattern and drift delay (x, y, z)**
- **Energy measurement from signal sizes**
- **Background discrimination by interaction type (ER/NR)**

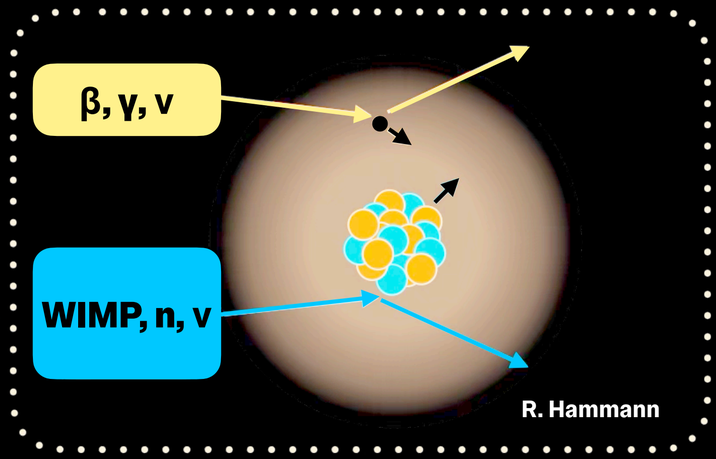


Signal sizes corrected for collection and detection effects

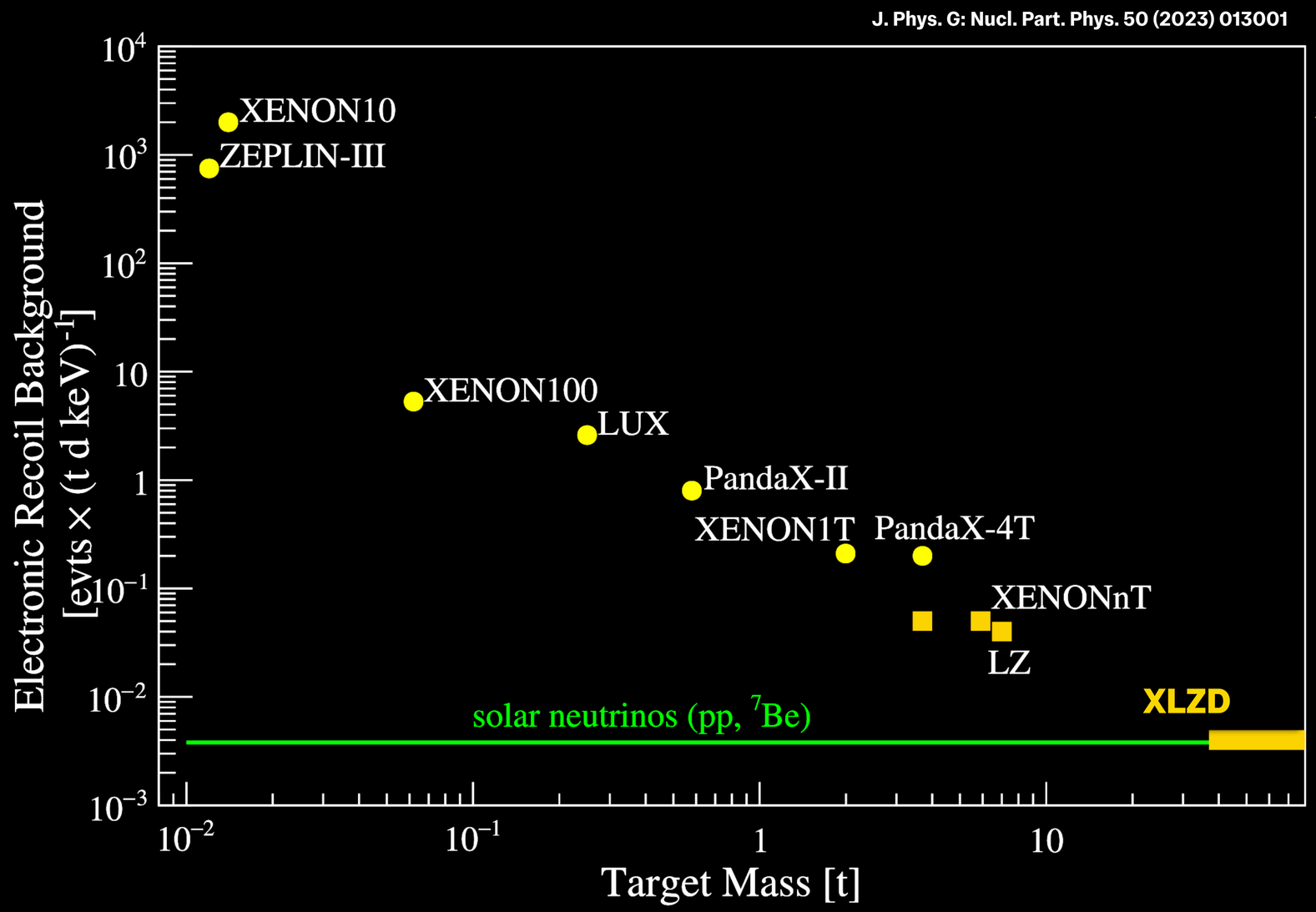
Electronic recoil (ER)

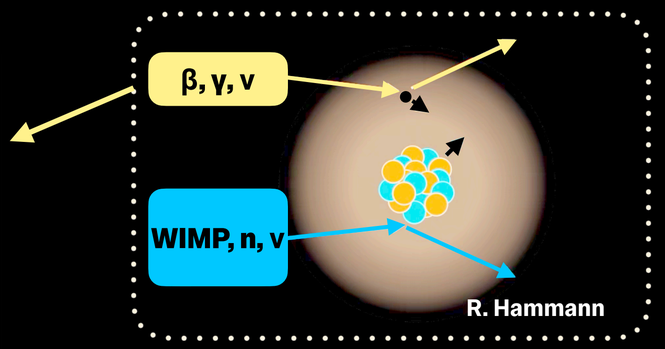
Nuclear recoil (NR)





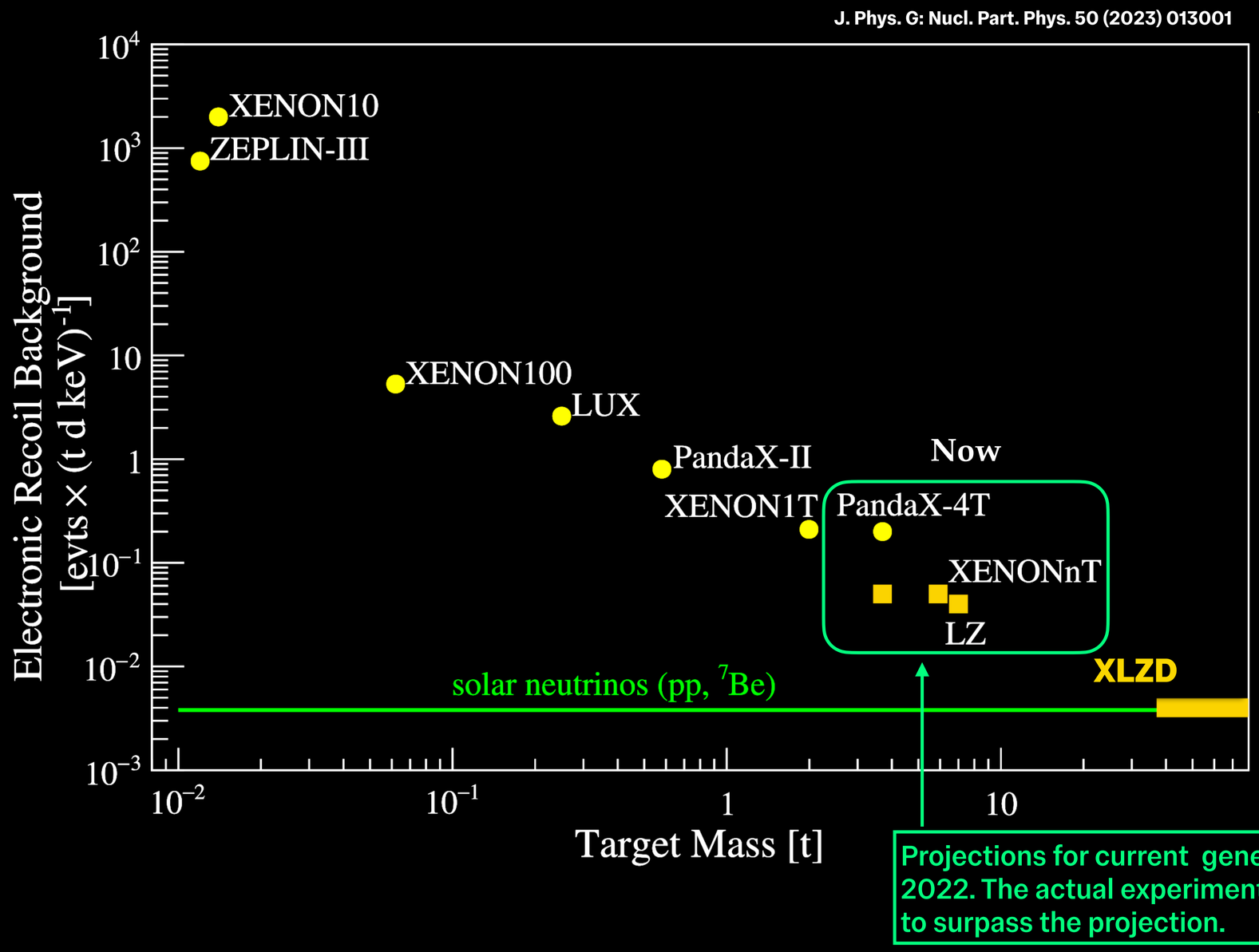
Large exposure, low background

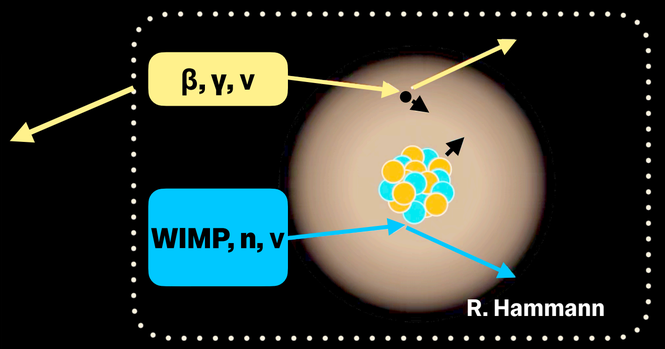




- From few kg to few t in 20 years
- Exponential decrease in electronic recoil background
- Getting close to irreducible solar neutrino background

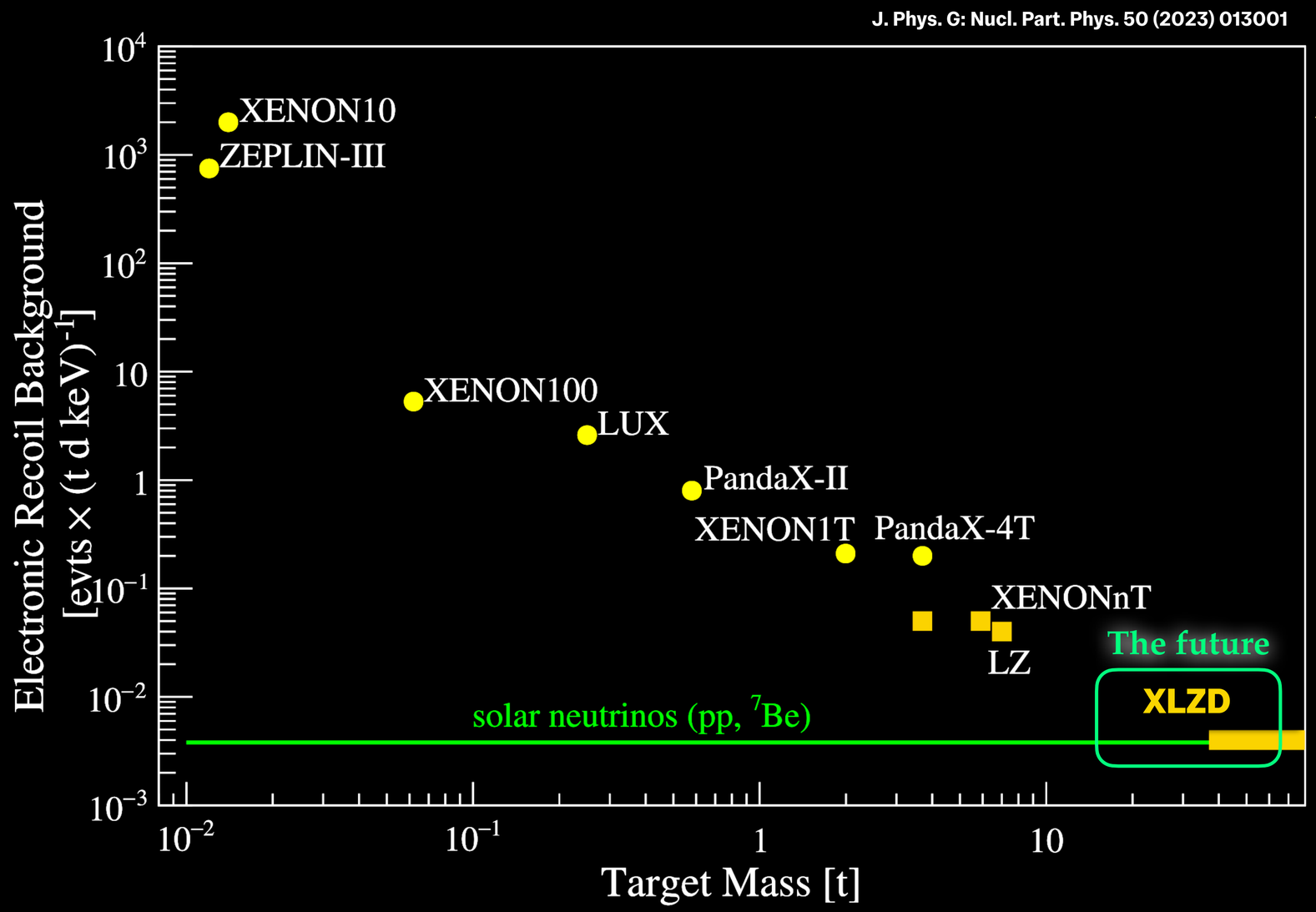
Large exposure, low background

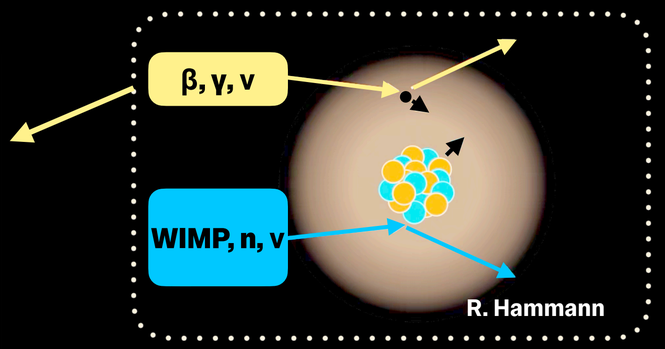




- From few kg to few t in 20 years
- Exponential decrease in electronic recoil background
- Getting close to irreducible solar neutrino background

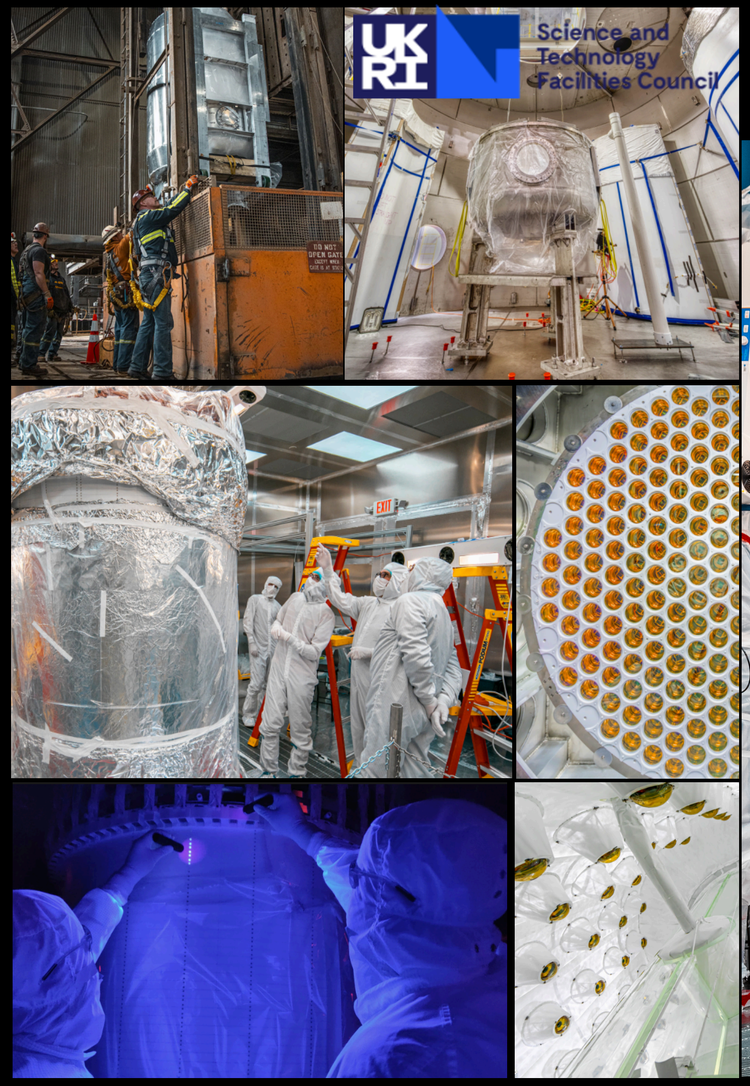
Large exposure, low background





- From few kg to few t in 20 years
- Exponential decrease in electronic recoil background
- Getting close to irreducible solar neutrino background

LUX-ZEPLIN



^{122}Xe	^{123}Xe	^{124}Xe	^{125}Xe	^{126}Xe	^{127}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{133}Xe	^{134}Xe	^{135}Xe	^{136}Xe	^{137}Xe
e- capture	β+	2β+	β+	2β+	e- capture	Stable	Stable	Stable	Stable	Stable	β-	2β-	β-	2β-	β-

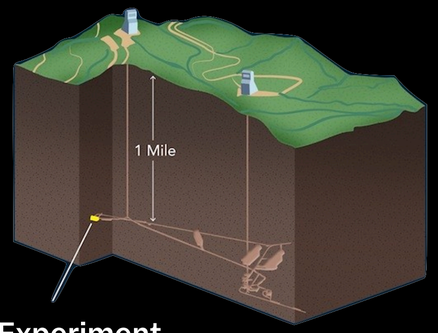




- 38 institutions
- 250 scientists, engineers, technical staff
- UK: Edinburgh, Imperial, King's College, RHUL, STFC Rutherford Appleton Lab, Bristol, UCL, Liverpool, Oxford, Sheffield
- Science operations since 2021

The LZ experiment at SURF

Sanford Underground Research Facility (SURF)

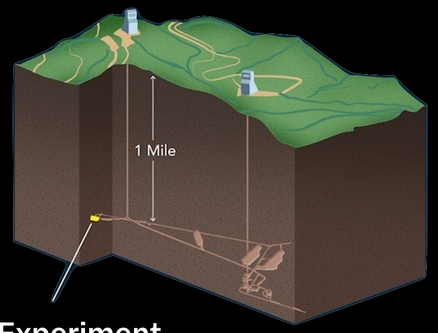


- 4300 $m_{w.e.}$ overburden
- Three nested detectors inside water tank:
  - Outer detector with Gd-loaded liquid scintillator
  - Instrumented xenon veto outside of TPC
  - TPC with 7 t active Xe volume
- 92 ± 4 % neutron veto efficiency

NIM A Volume 953, 163047 (2020)

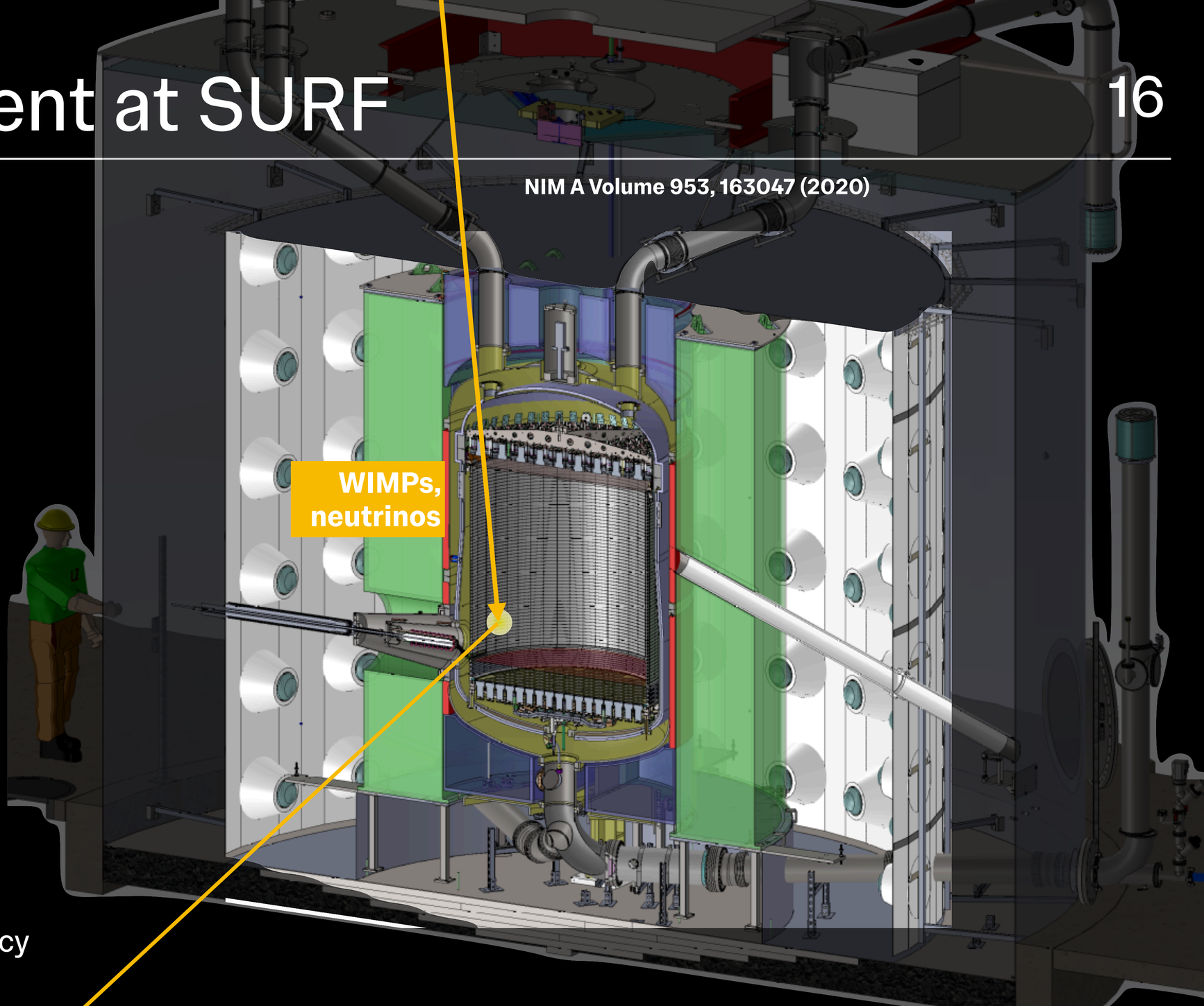
The LZ experiment at SURF

Sanford Underground Research Facility (SURF)



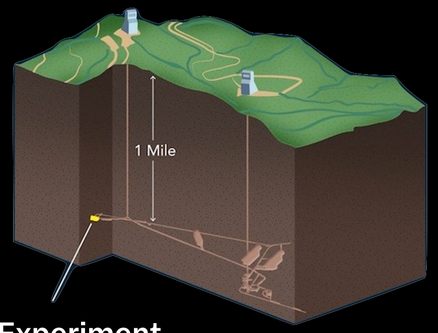
- 4300 $m_{w.e.}$ overburden
- Three nested detectors inside water tank:
  - Outer detector with Gd-loaded liquid scintillator
  - Instrumented xenon veto outside of TPC
  - TPC with 7 t active Xe volume
- 92 ± 4 % neutron veto efficiency

NIM A Volume 953, 163047 (2020)



The LZ experiment at SURF

Sanford Underground Research Facility (SURF)

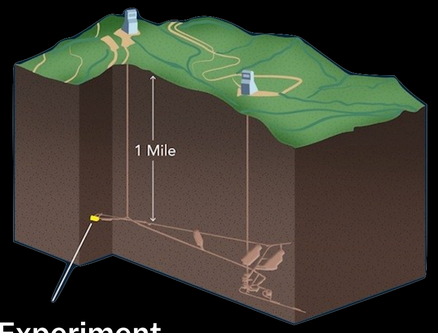


- 4300 $m_{w.e.}$ overburden
- Three nested detectors inside water tank:
  - Outer detector with Gd-loaded liquid scintillator
  - Instrumented xenon veto outside of TPC
  - TPC with 7 t active Xe volume
- 92 ± 4 % neutron veto efficiency

NIM A Volume 953, 163047 (2020)

The LZ experiment at SURF

Sanford Underground Research Facility (SURF)

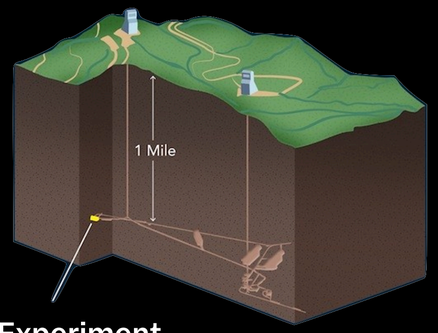


- 4300 $m_{w.e.}$ overburden
- Three nested detectors inside water tank:
  - Outer detector with Gd-loaded liquid scintillator
  - Instrumented xenon veto outside of TPC
  - TPC with 7 t active Xe volume
- 92 ± 4 % neutron veto efficiency

NIM A Volume 953, 163047 (2020)

The LZ experiment at SURF

Sanford Underground Research Facility (SURF)

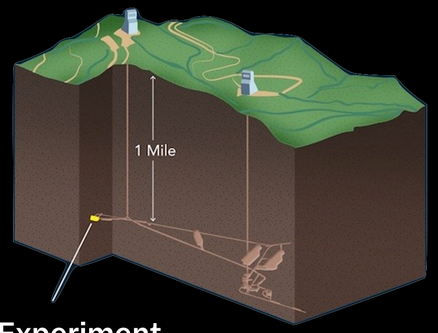


- 4300 $m_{w.e.}$ overburden
- Three nested detectors inside water tank:
  - Outer detector with Gd-loaded liquid scintillator
  - Instrumented xenon veto outside of TPC
  - TPC with 7 t active Xe volume
- 92 ± 4 % neutron veto efficiency

NIM A Volume 953, 163047 (2020)

The LZ experiment at SURF

Sanford Underground Research Facility (SURF)

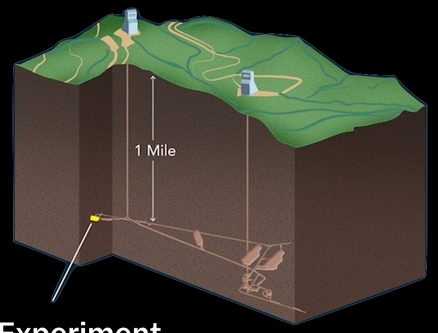


- 4300 $m_{w.e.}$ overburden
- Three nested detectors inside water tank:
  - Outer detector with Gd-loaded liquid scintillator
  - Instrumented xenon veto outside of TPC
  - TPC with 7 t active Xe volume
- 92 ± 4 % neutron veto efficiency

NIM A Volume 953, 163047 (2020)

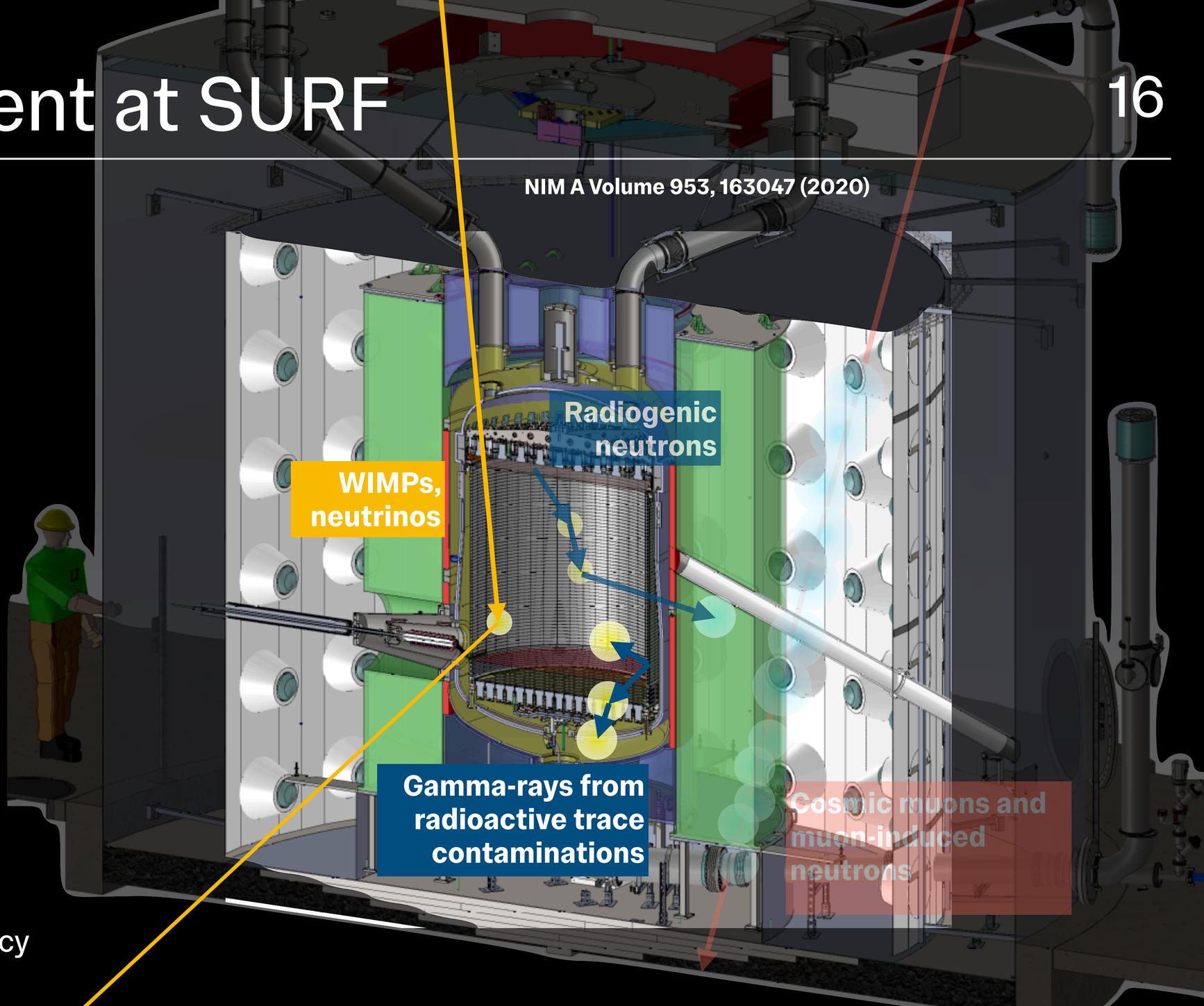
The LZ experiment at SURF

Sanford Underground Research Facility (SURF)



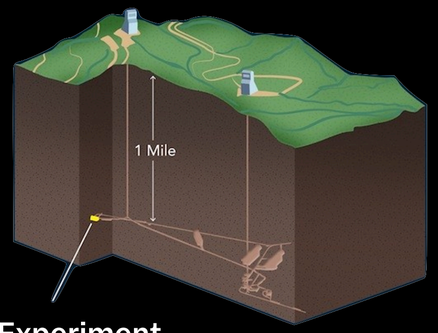
- 4300 $m_{w.e.}$ overburden
- Three nested detectors inside water tank:
  - Outer detector with Gd-loaded liquid scintillator
  - Instrumented xenon veto outside of TPC
  - TPC with 7 t active Xe volume
- 92 ± 4 % neutron veto efficiency

NIM A Volume 953, 163047 (2020)



The LZ experiment at SURF

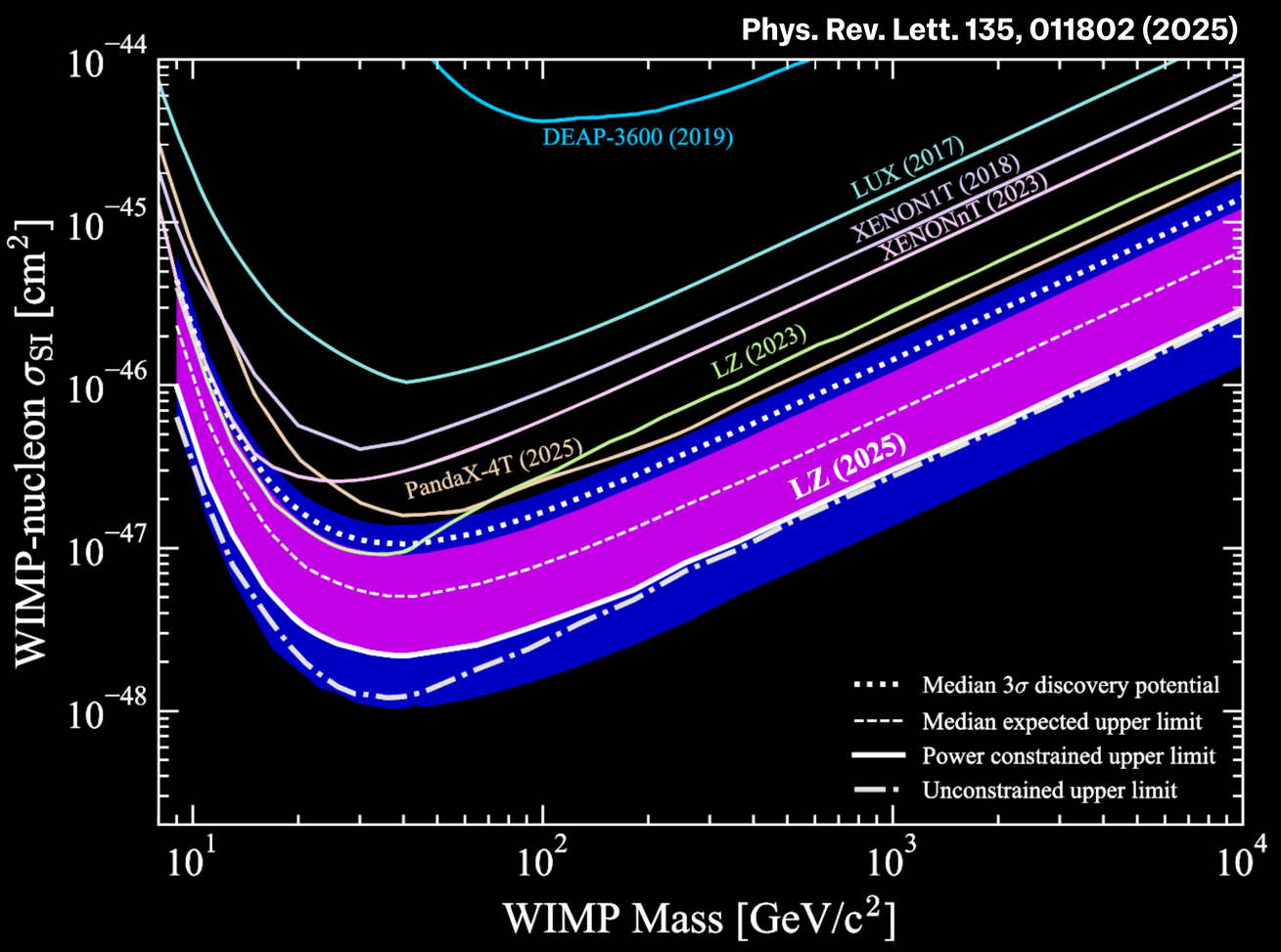
Sanford Underground Research Facility (SURF)



- 4300 $m_{w.e.}$ overburden
- Three nested detectors inside water tank:
  - Outer detector with Gd-loaded liquid scintillator
  - Instrumented xenon veto outside of TPC
  - TPC with 7 t active Xe volume
- 92 ± 4 % neutron veto efficiency

NIM A Volume 953, 163047 (2020)

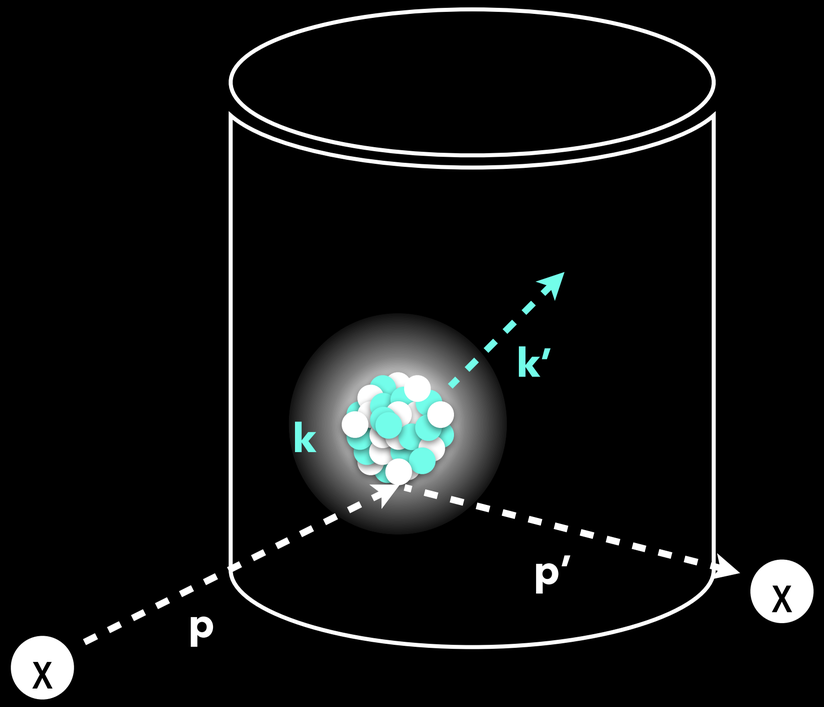
LZ physics



- WIMP search in 4.2 tonne x years of data from second WIMP science campaign
- Data salting for bias mitigation
- Active tagging of ^{214}Pb beta decay backgrounds
- World-leading constraints for WIMP masses above 9 GeV/c^2
- LZ as a multi-purpose observatory:
  - High-energy nuclear recoils, inelastic scattering
  - Axion-like particles, dark photons or neutrino magnetic moment
  - Neutrinoless double-beta decay
  - Coherent elastic neutrino-nucleus scattering

Robyn Evren Poster A8	Simran Dave Fri 11:00	Kate Lawes Fri 11:15

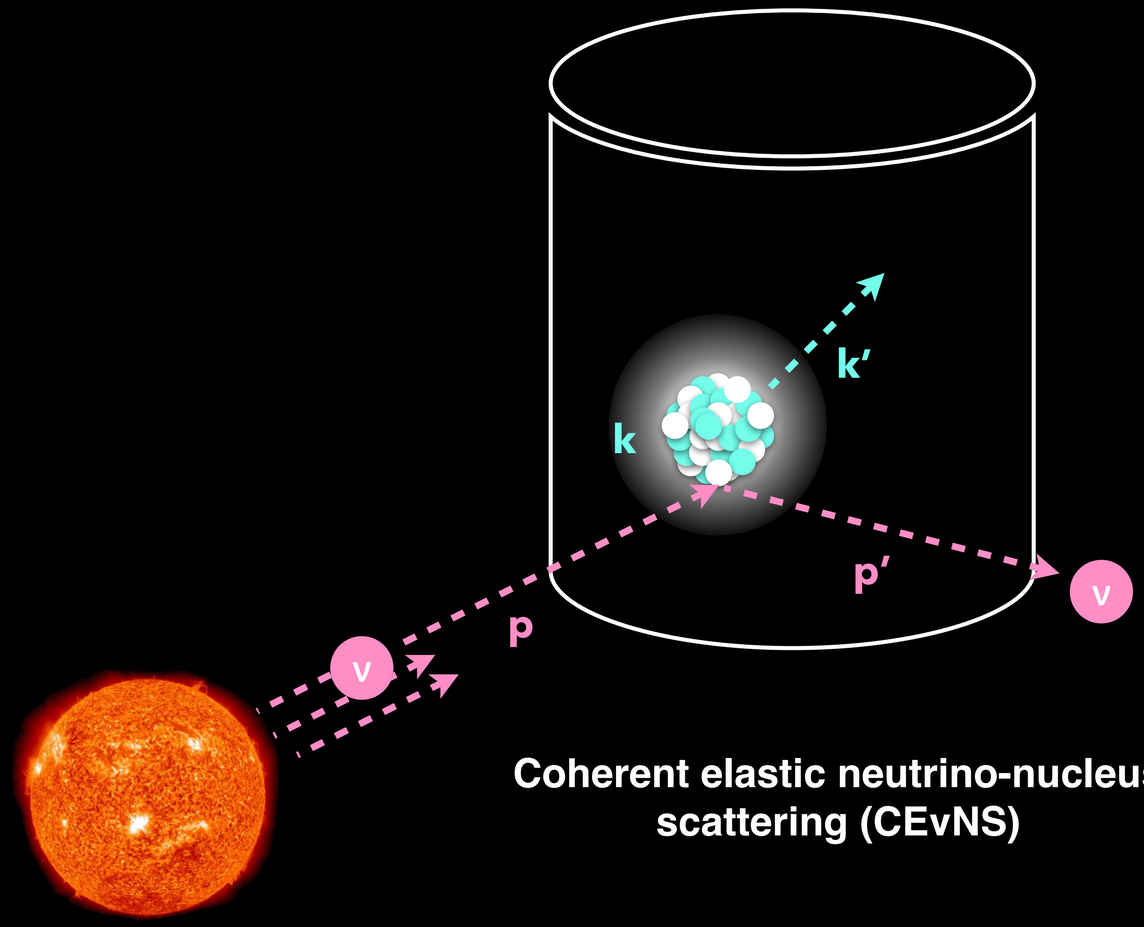
Beyond WIMPs: coherent neutrino scattering



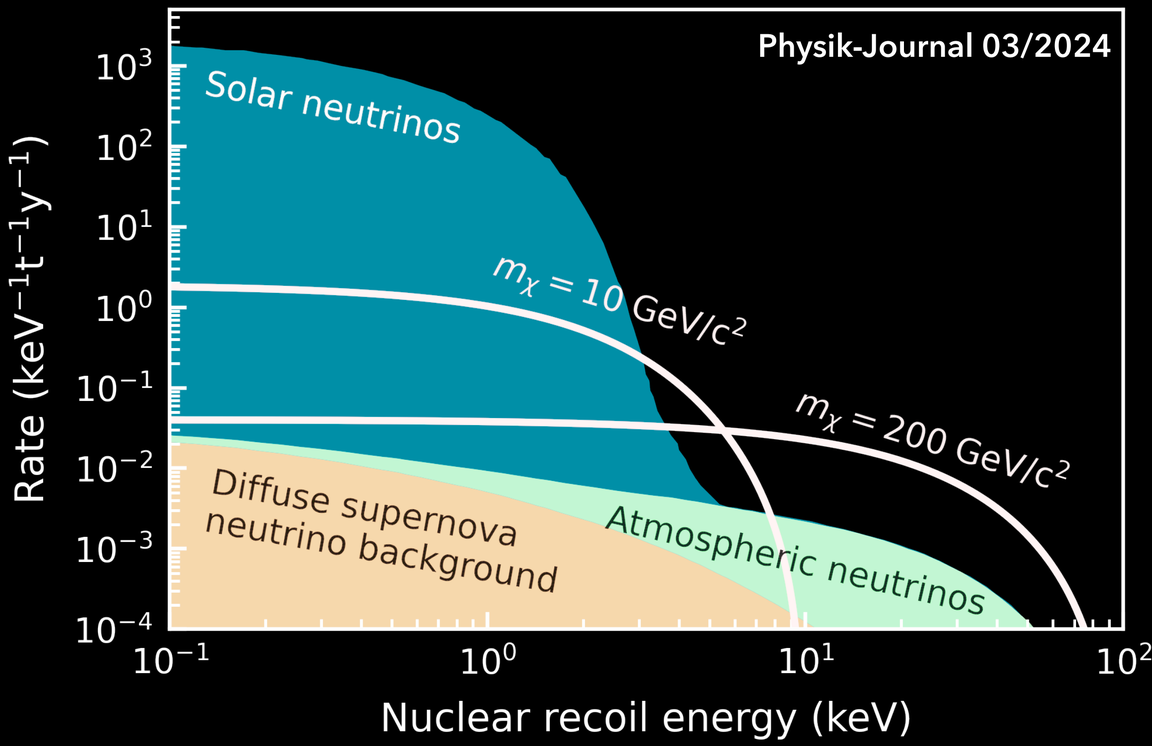
Detect WIMPs directly by measuring a **O(1) keV nuclear recoil** after scattering in a detector featuring:

- **large exposure**
- **low background**
- **low threshold**

Beyond WIMPs: coherent neutrino scattering

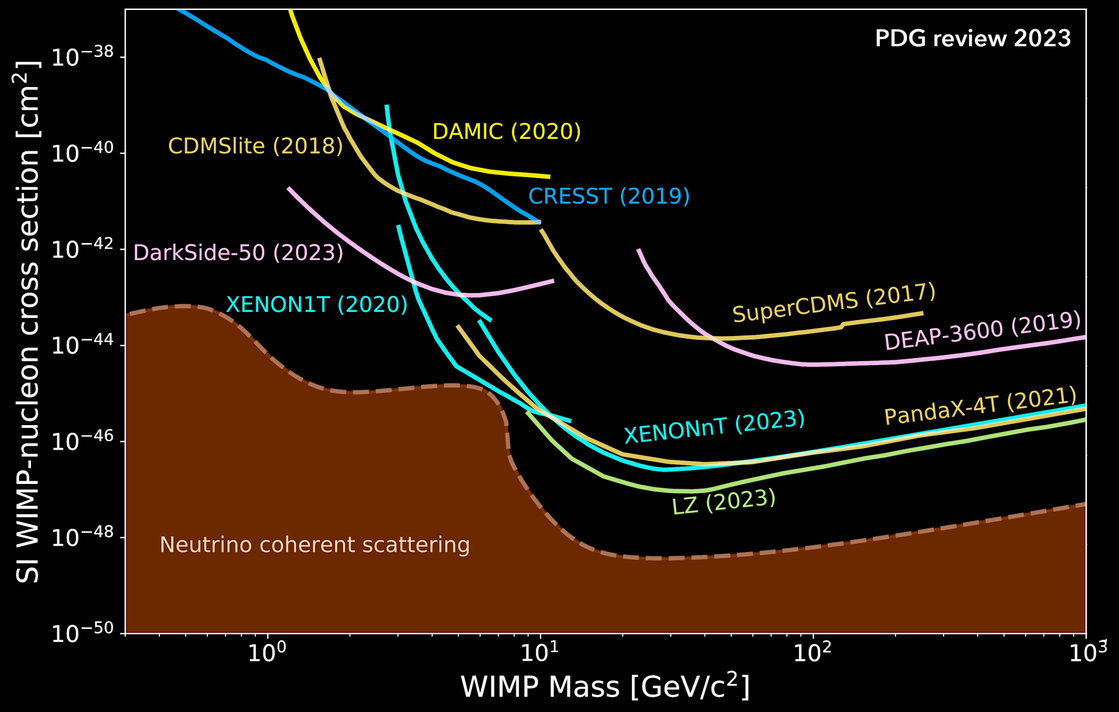


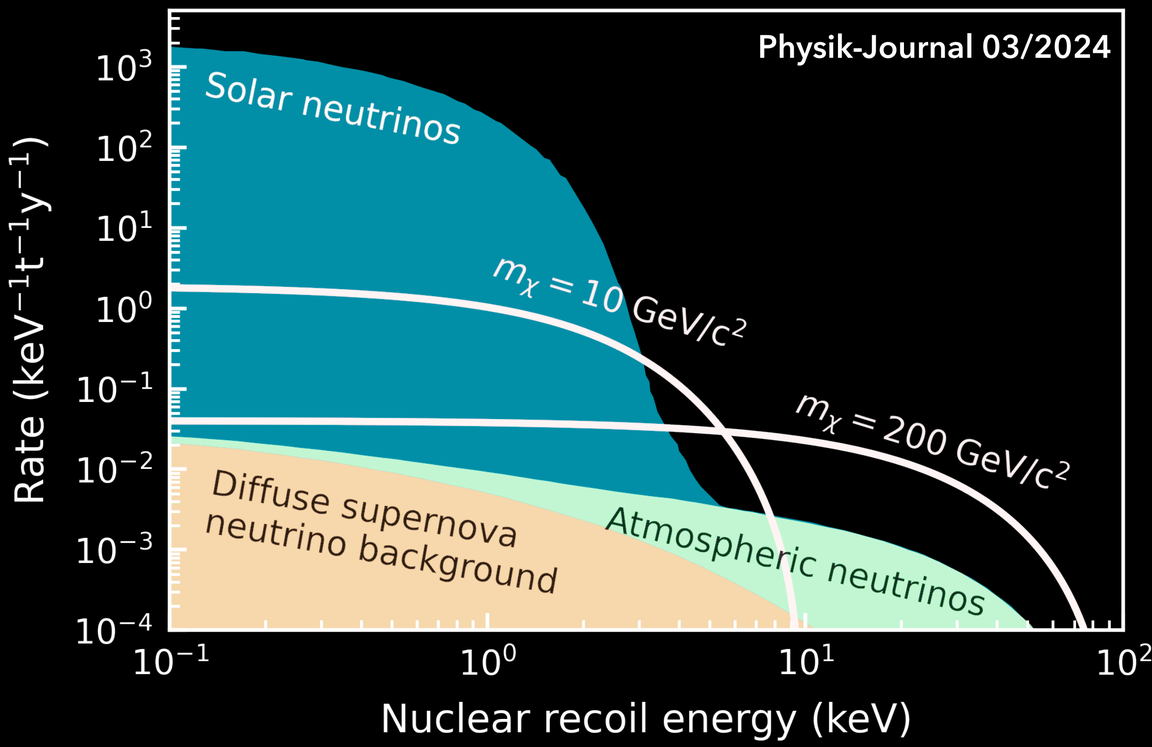
Coherent elastic neutrino-nucleus scattering (CEvNS)



Coherent elastic neutrino nucleus scattering (CEvNS) of solar ^{8}B neutrinos mimics light WIMP scattering.

Beyond WIMPs: coherent neutrino scattering





Not only a background, but a signal: neutrinos from the sun, atmosphere and supernovae.

Coherent elastic neutrino nucleus scattering (CEvNS) of solar ^{8}B neutrinos mimics light WIMP scattering.

LZ CEvNS search

Isolated S1s…

…get paired with **isolated S2s**



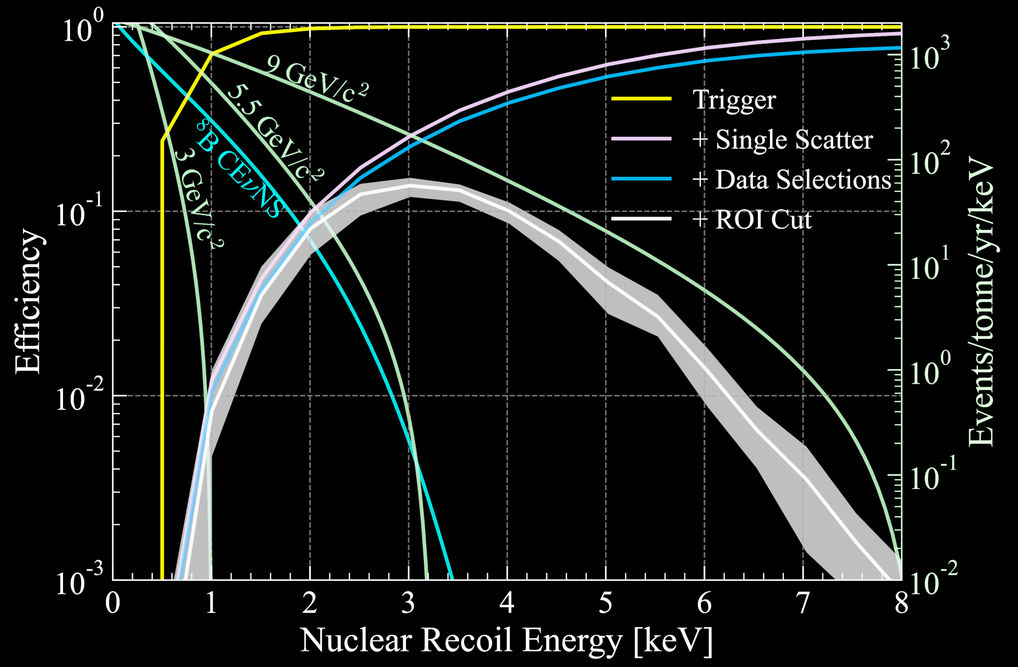
S1

Mostly PMT dark counts

S2

Spurious electron emission from high-voltage electrodes

arXiv:2512.08065



Balancing act of energy threshold vs. accidental coincidence background

- Salted analysis
- Extended ROI
- New data selection criteria
- Large exposure: 417 live days, 5.09 ±0.15 t

LZ CEvNS search

Isolated S1s…

…get paired with **isolated S2s**

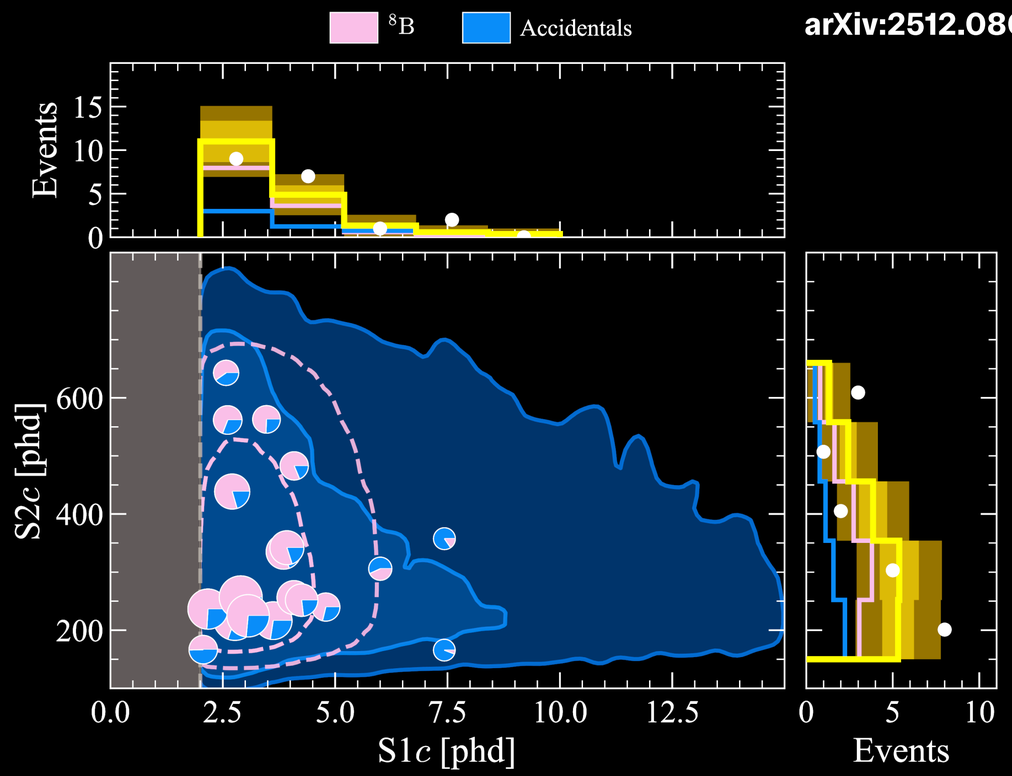


S1

Mostly PMT dark counts

S2

Spurious electron emission from high-voltage electrodes



arXiv:2512.08065

Expected background

$6.6^{+0.4}_{-0.3}$

Expected signal

$20.6^{+8.9}_{-6.8}$

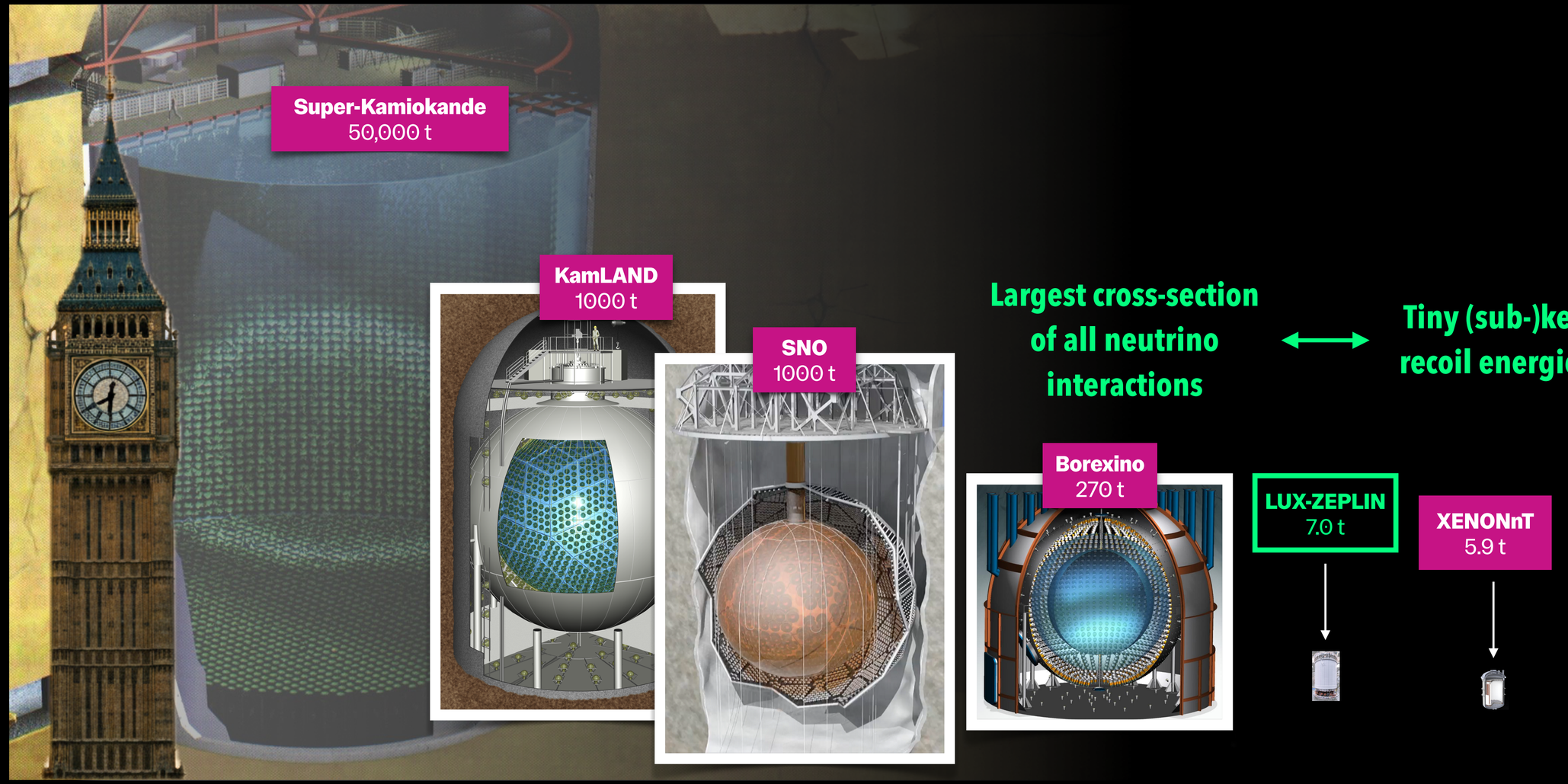
Observed

$18.9^{+7.0}_{-5.5}$

Best-fit number of ^{8}B signal events

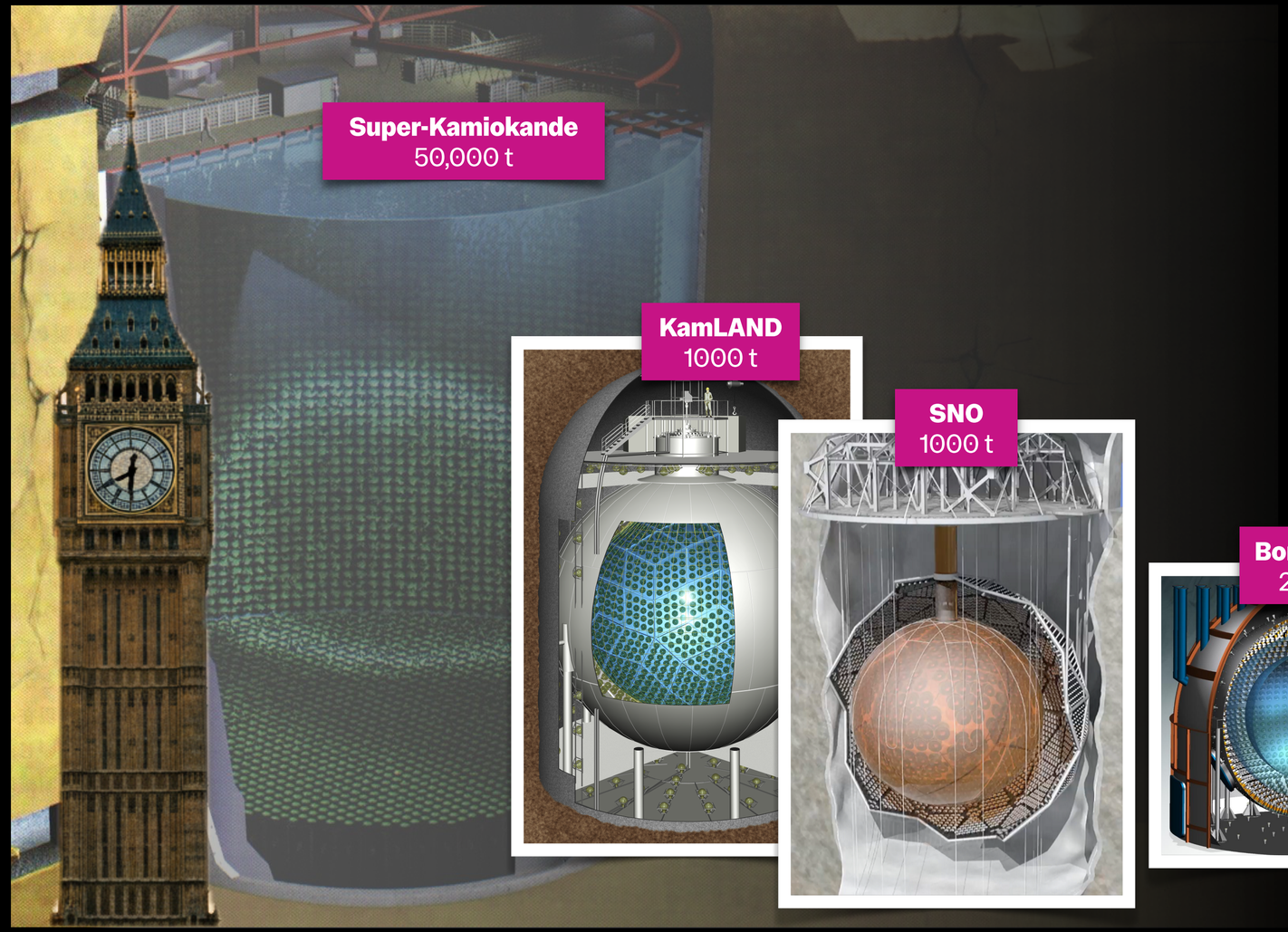
$12.3^{+7.0}_{-5.4}$

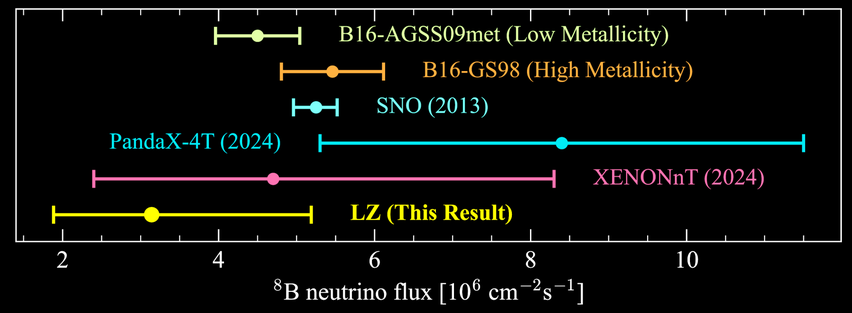
World’s smallest solar neutrino detectors

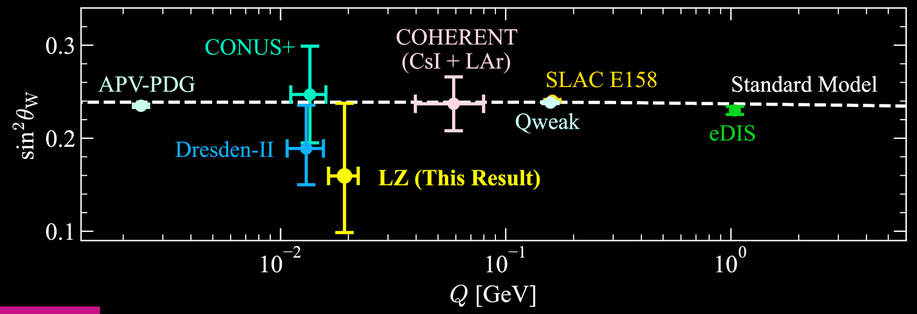


Slide courtesy of R. Hammann (modified)

World's smallest solar neutrino detectors

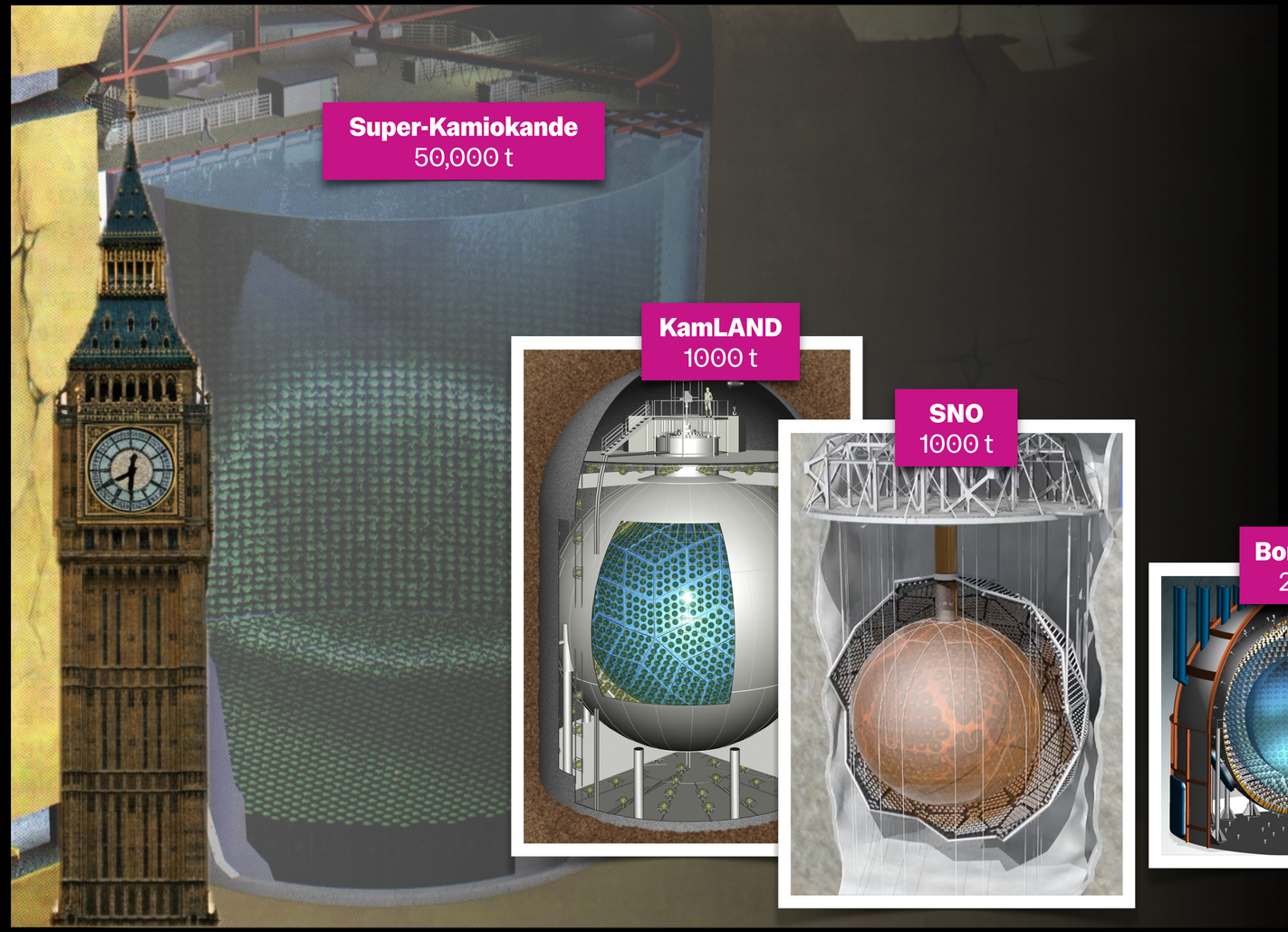


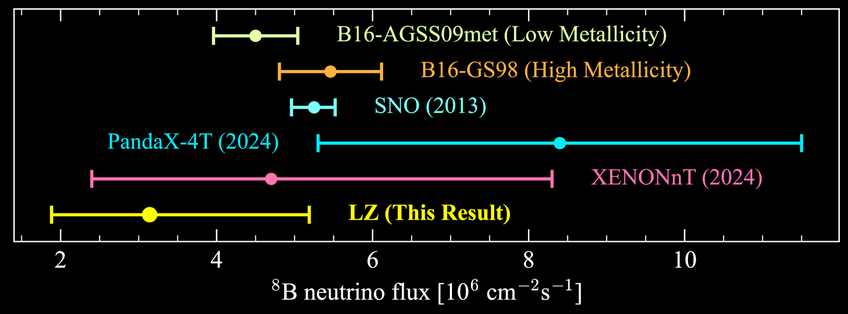


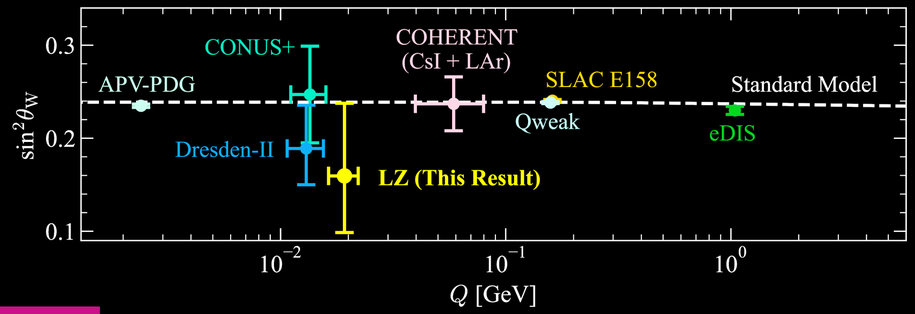


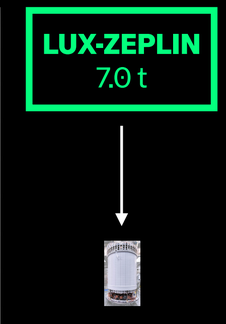
Slide courtesy of R. Hammann (modified)

World's smallest solar neutrino detectors











Slide courtesy of R. Hammann (modified)

Issy Darlington
Wed 16:15

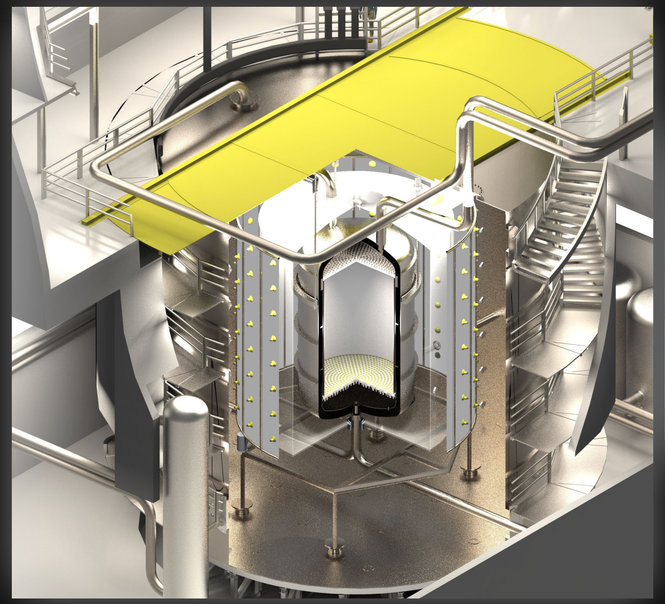
Leah Wolf
Fri 11:00

XENON, LZ and DARWIN become



XLZD meeting at LNGS, July 2025

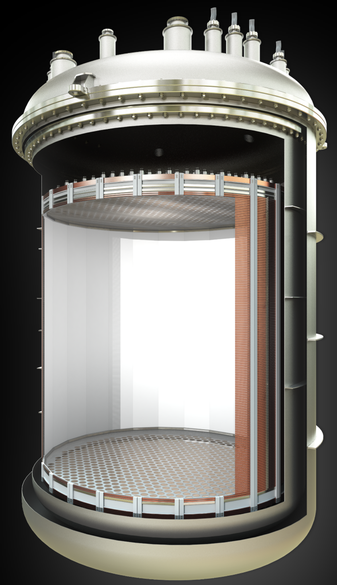
- Three world-leading collaborations joining forces to build the ultimate dark matter detector
- ≈500 scientists from 84 institutions in 16 countries
- Four possible underground sites:
  - SURF (USA)
  - **Boulby (UK)**
  - LNGS (IT)
  - Snolab (Canada)





TPC baseline design

- 60–80 t xenon target
- Phased approach 40 t – 60 t – 80 t considered
- 2362 PMTs
- 240 – 290 V/cm drift field
- ≈3 m height and diameter
- Double-walled Ti cryostat

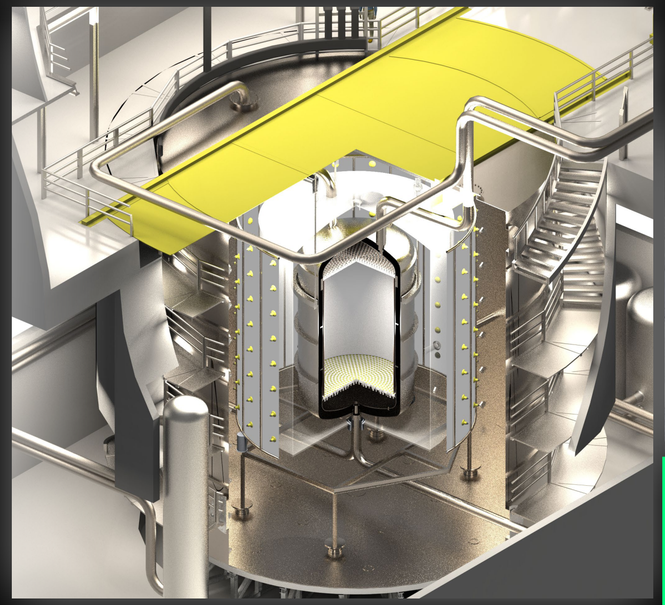


XENON, LZ and DARWIN become



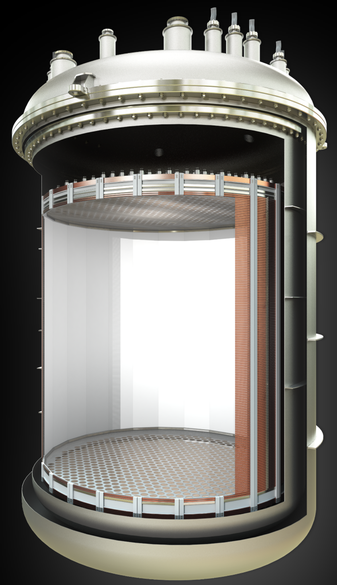
XLZD meeting at LNGS, July 2025

- Three world-leading collaborations joining forces to build the ultimate dark matter detector
- ≈500 scientists from 84 institutions in 16 countries
- Four possible underground sites:
  - SURF (USA)
  - **Boulby (UK)**
  - LNGS (IT)
  - Snolab (Canada)



TPC baseline design

- 60–80 t xenon target
- Phased approach 40 t – 60 t – 80 t considered
- 2362 PMTs
- 240 – 290 V/cm drift field
- ≈3 m height and diameter
- Double-walled Ti cryostat



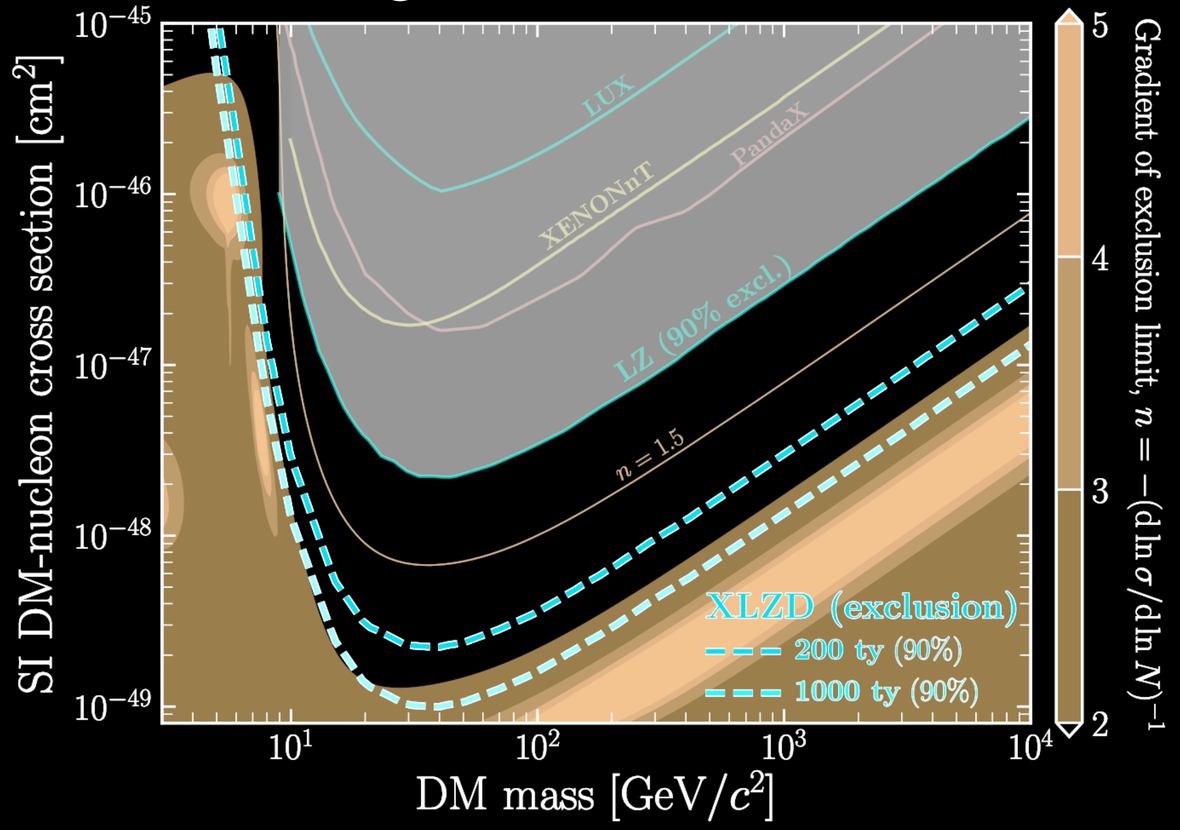


XLZD@Boulby Pre-Construction project:

- **Develops UK contribution to XLZD**
- **Prepares possible hosting at Boulby**
- **~100 people at 14 UK institutes**

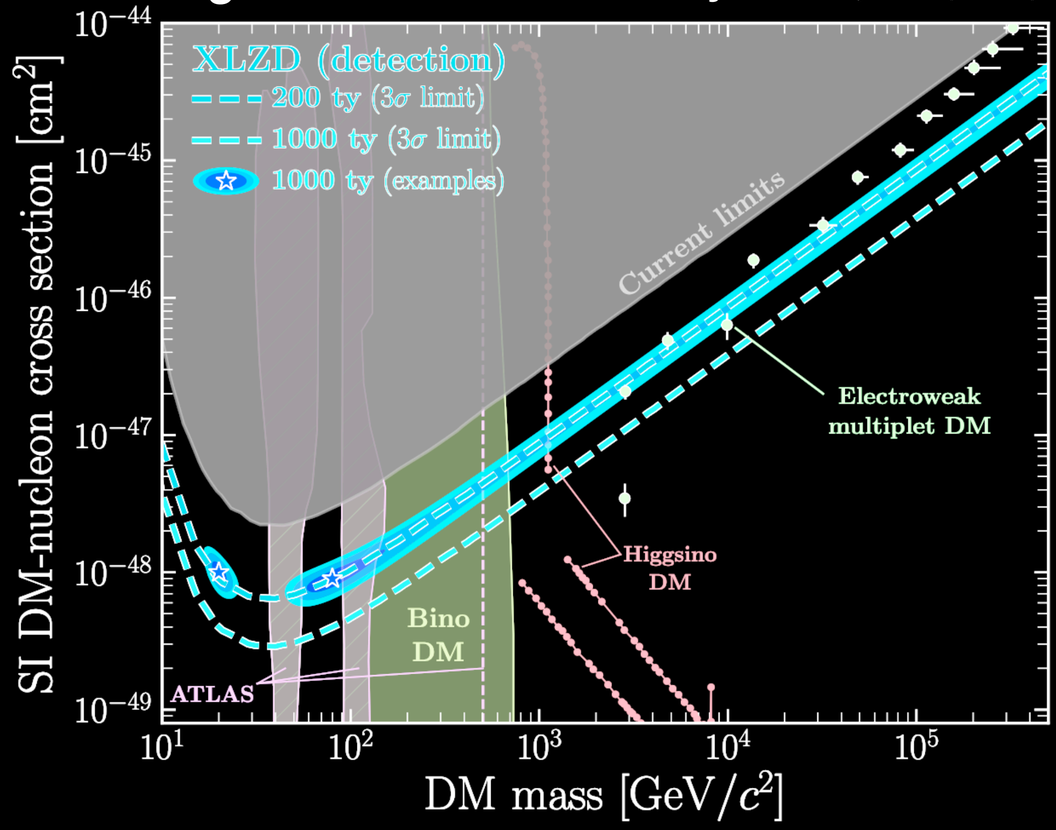
WIMP dark matter sensitivity

Exclusion @ 90 % CL



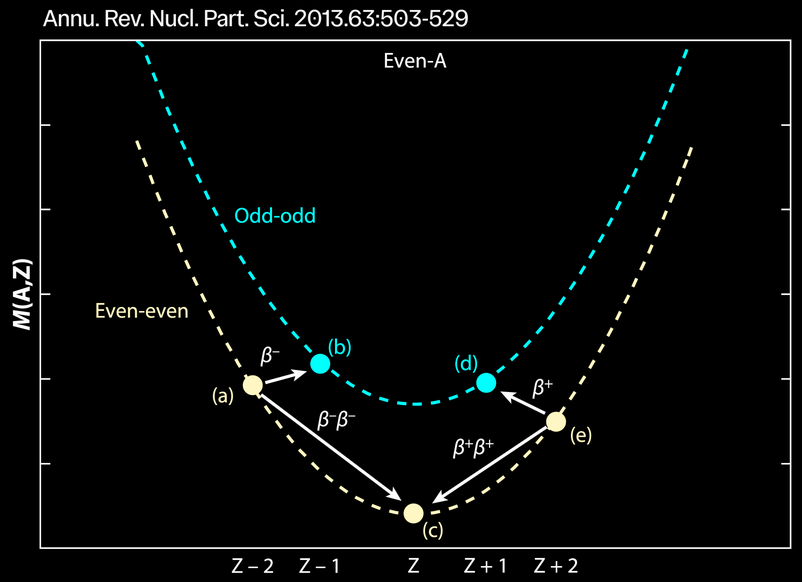
Signal at 3σ

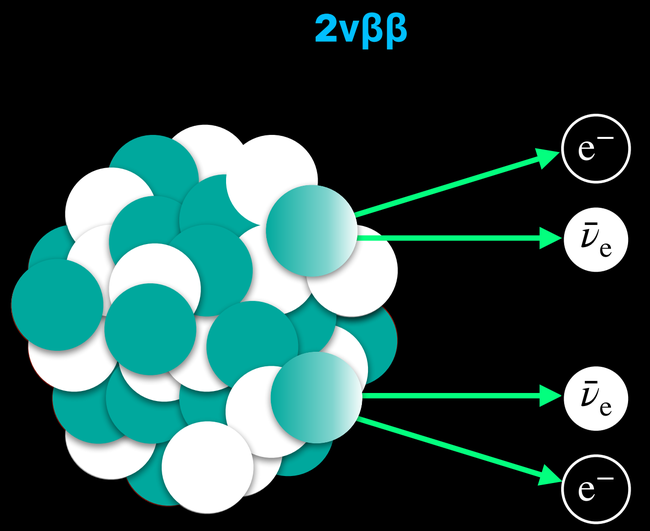
Eur. Phys. J. C 85, 1192 (2025)



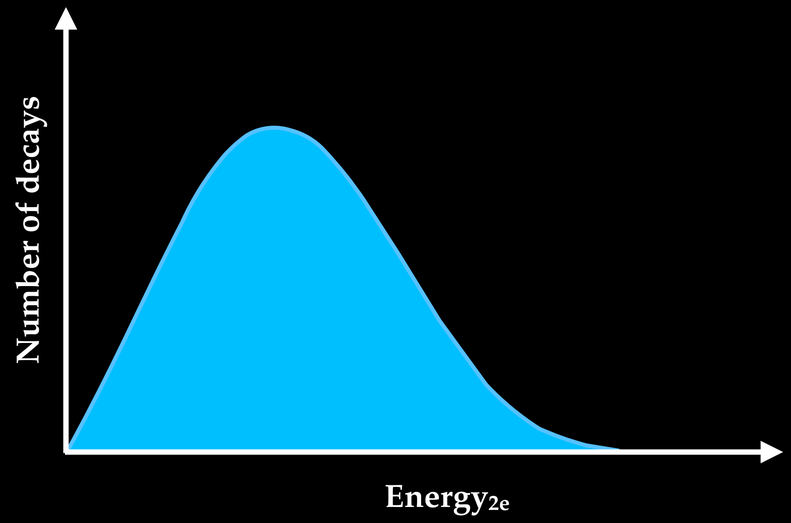
Probe WIMP dark matter down to the neutrino fog.

Beyond WIMPs: neutrinoless double-beta decay

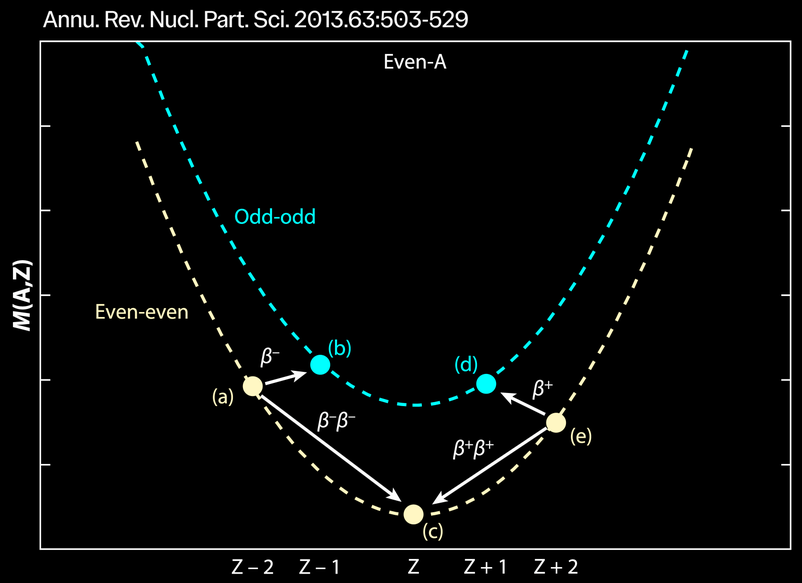


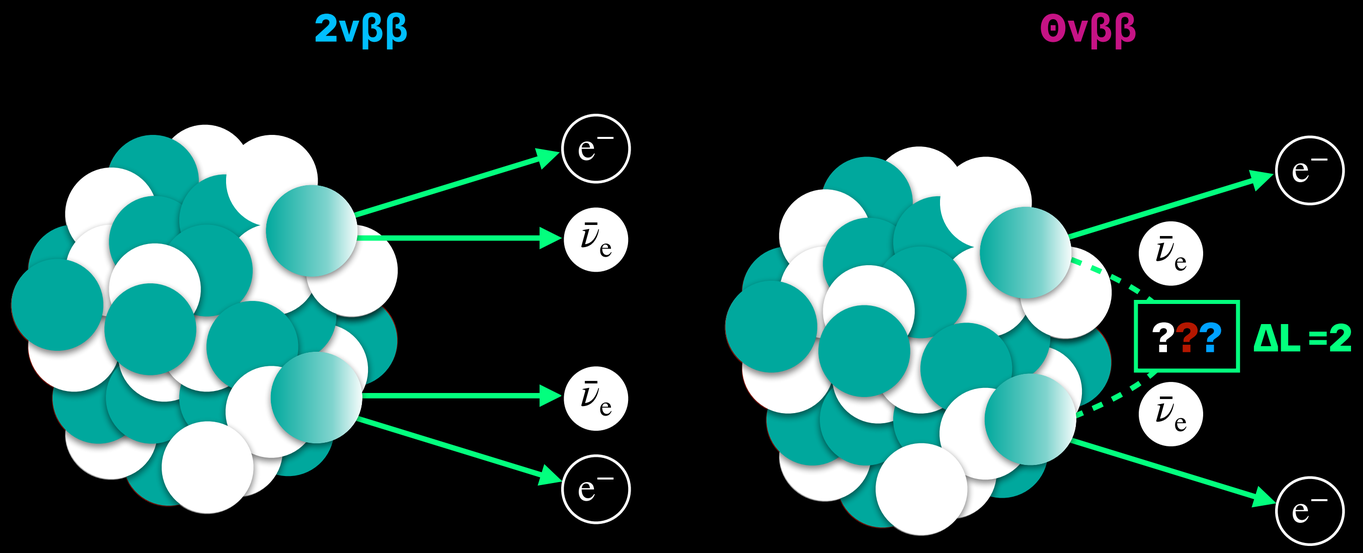


- In double-even nuclei where a lower energy state on the isobar cannot be reached via a single beta decay
- Two neutrino Standard Model process with extremely long half lives ~10^{20} yr
- BSM process without neutrinos

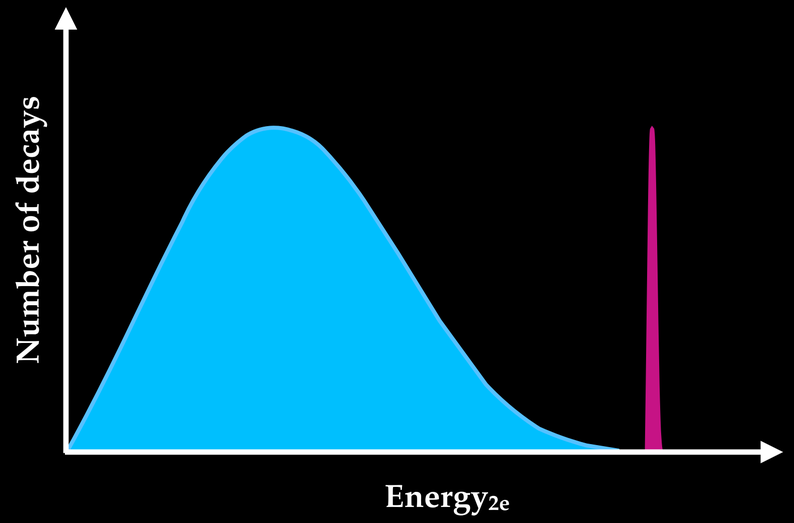


Beyond WIMPs: neutrinoless double-beta decay

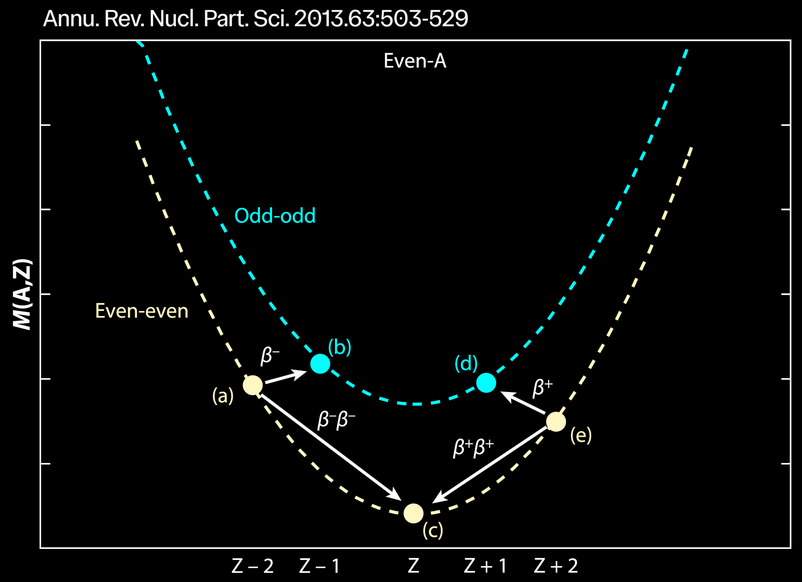




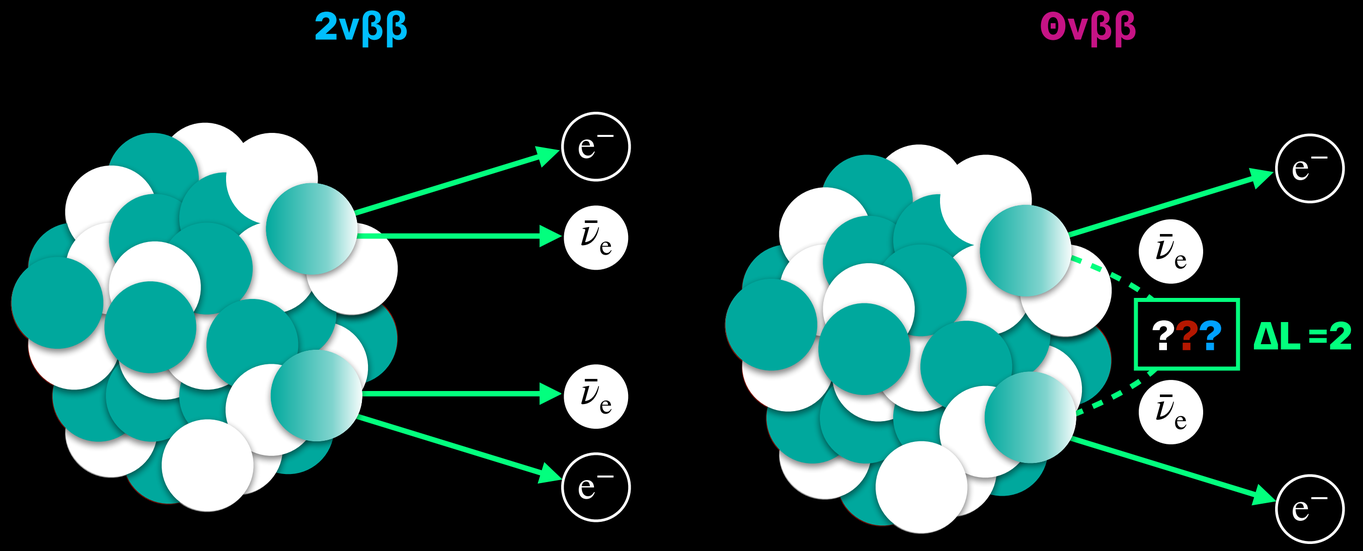
- In double-even nuclei where a lower energy state on the isobar cannot be reached via a single beta decay
- Two neutrino Standard Model process with extremely long half lives ~10^{20} yr
- BSM process without neutrinos

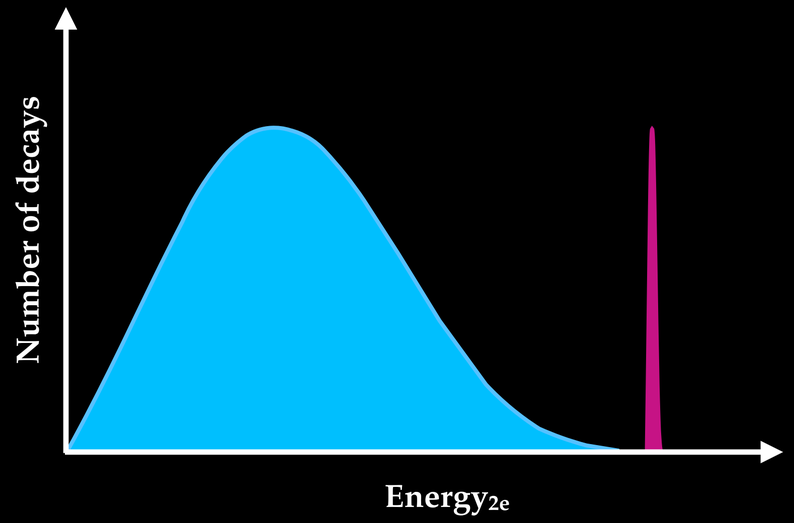


Beyond WIMPs: neutrinoless double-beta decay



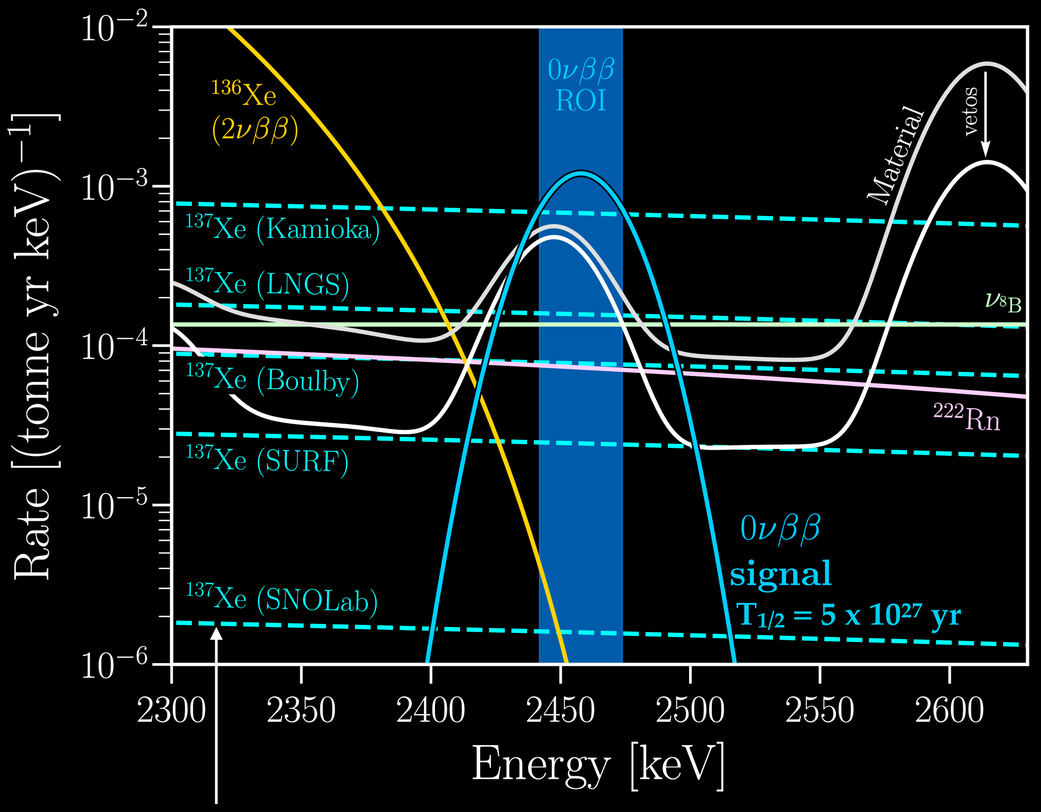
- In double-even nuclei where a lower energy state on the isobar cannot be reached via a single beta decay
- Two neutrino Standard Model process with extremely long half lives ~10^{20} yr
- BSM process without neutrinos



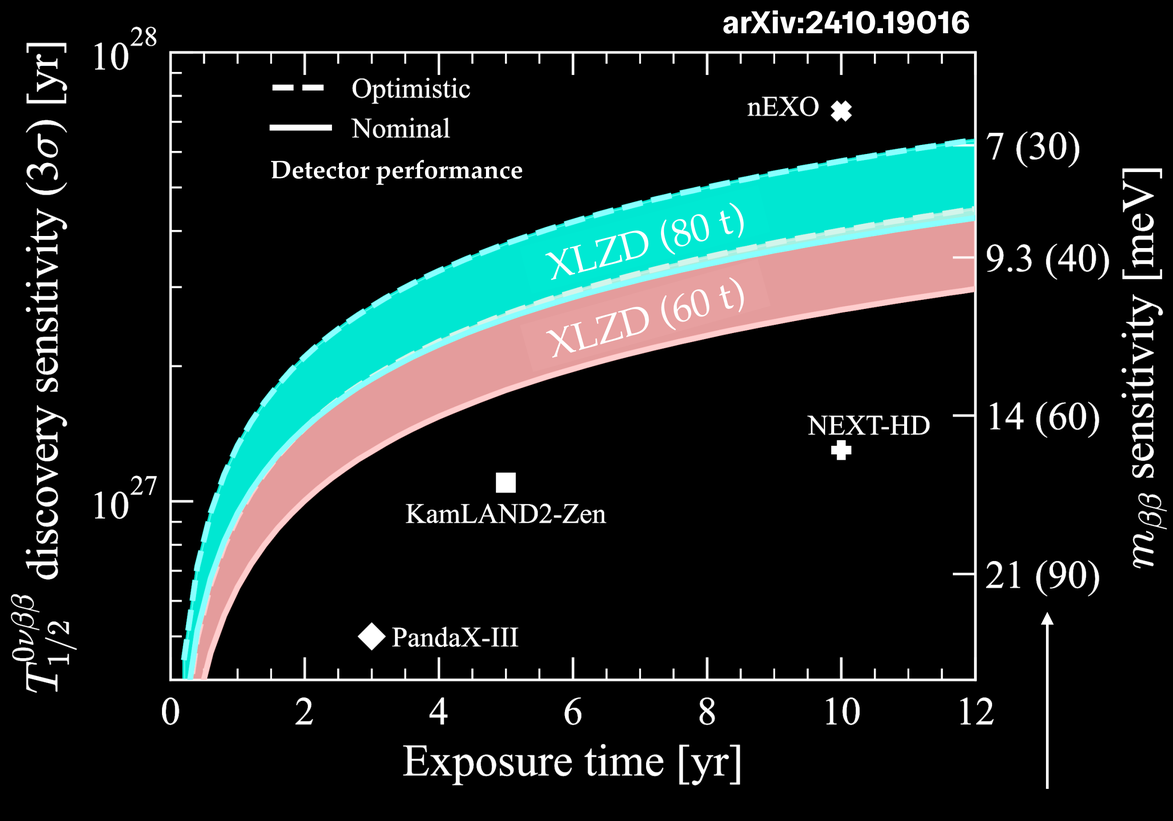


- Majorana neutrinos give access to neutrino masses.
- Lepton number violation related to matter-antimatter asymmetry of the Universe.

^{136}Xe neutrinoless double-beta decay in XLZD



Cosmogenic xenon activation background depends on depth of underground lab

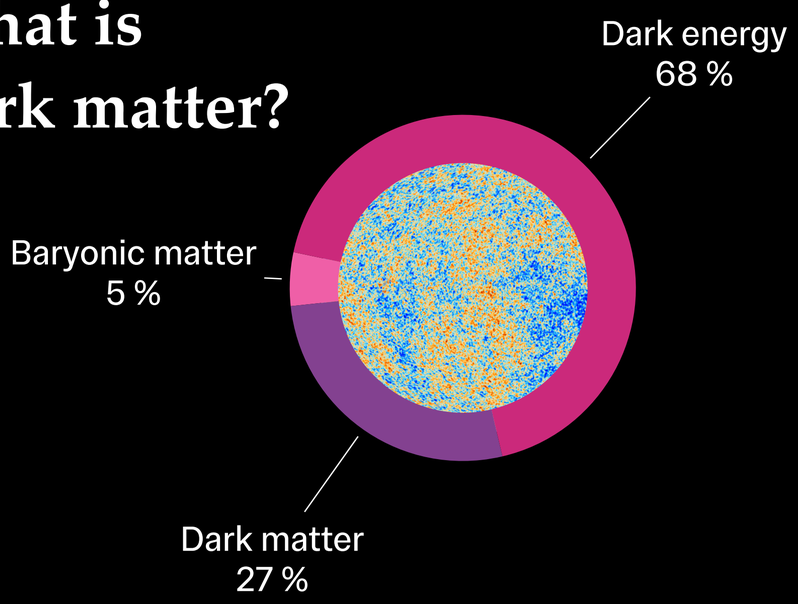


Optimistic and pessimistic NMEs for converting half-life to neutrino mass

- **Compete with purpose-built ^{136}Xe 0νββ experiments.**
- **Cover inverted neutrino mass hierarchy.**

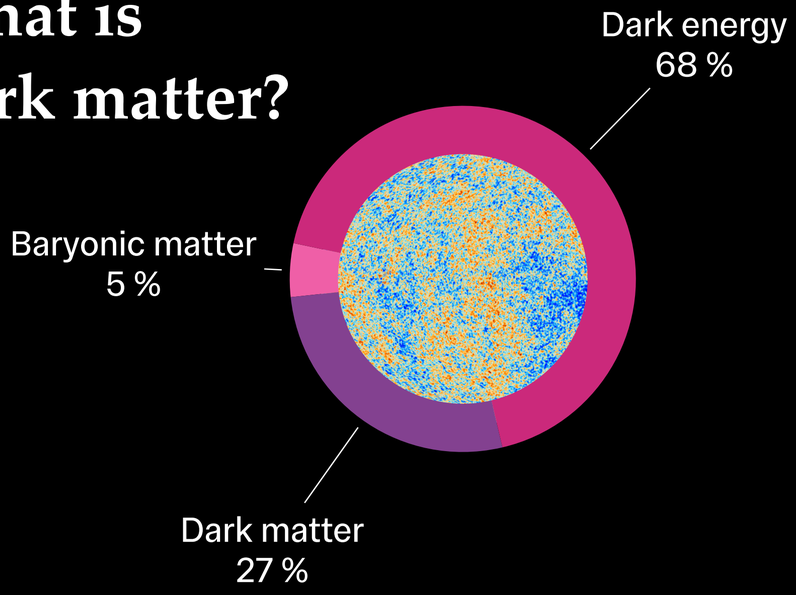
Astroparticle physics with XLZD

What is dark matter?

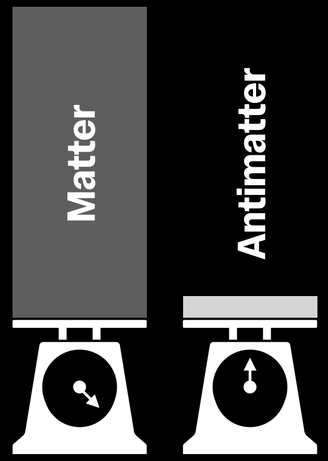


Astroparticle physics with XLZD

What is dark matter?

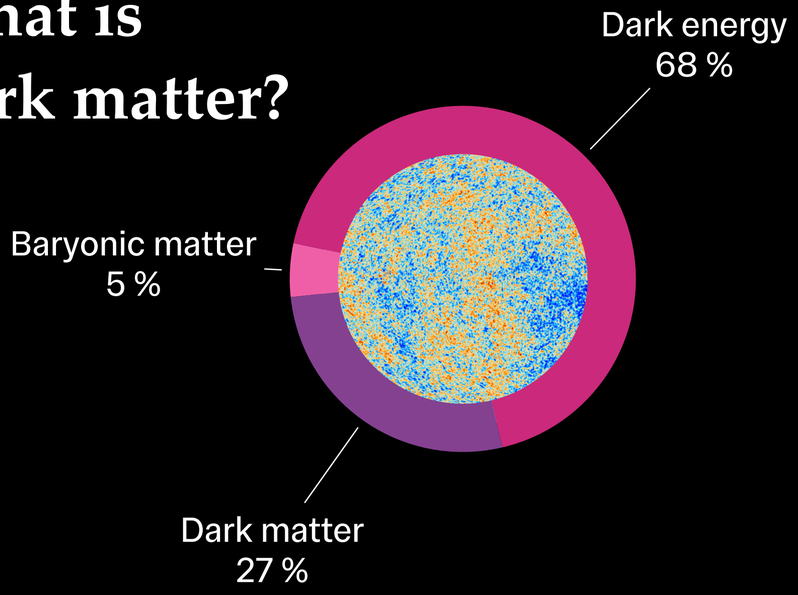


Why is there matter in the Universe?

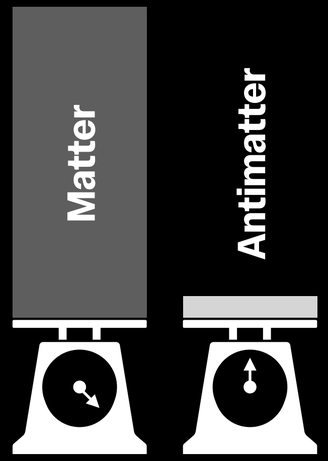


Astroparticle physics with XLZD

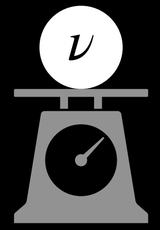
What is dark matter?



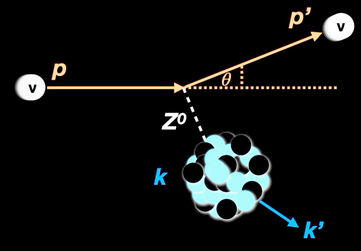
Why is there matter in the Universe?



$\nu = \bar{\nu}$?



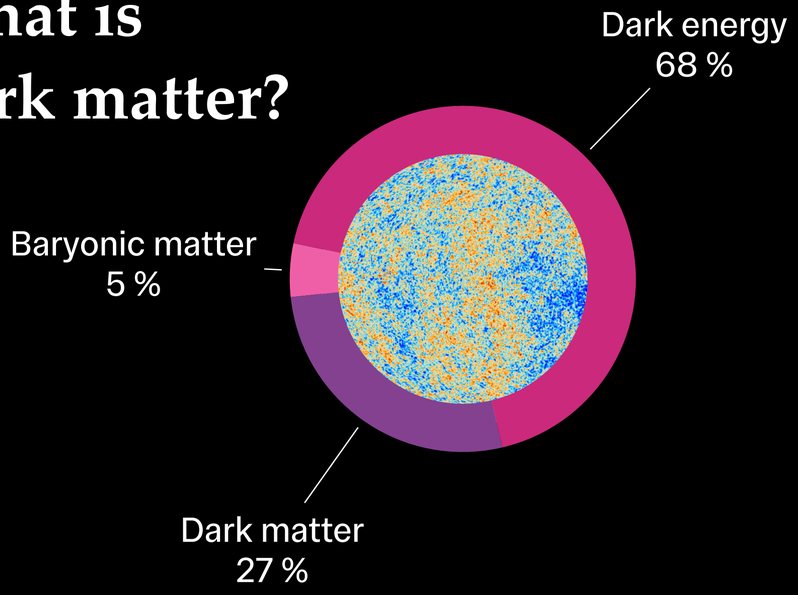
What is the nature of neutrinos and their interactions?



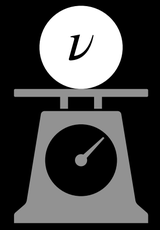
Huan Zhang
Wed 15:45

Astroparticle physics with XLZD

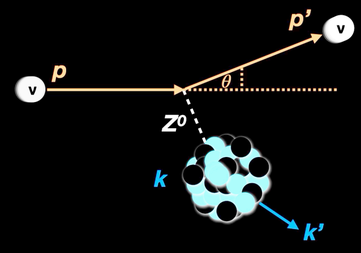
What is dark matter?



$\nu = \bar{\nu}$?

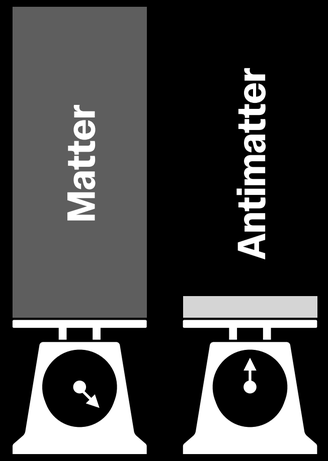


What is the nature of neutrinos and their interactions?



Huan Zhang
Wed 15:45

Why is there matter in the Universe?



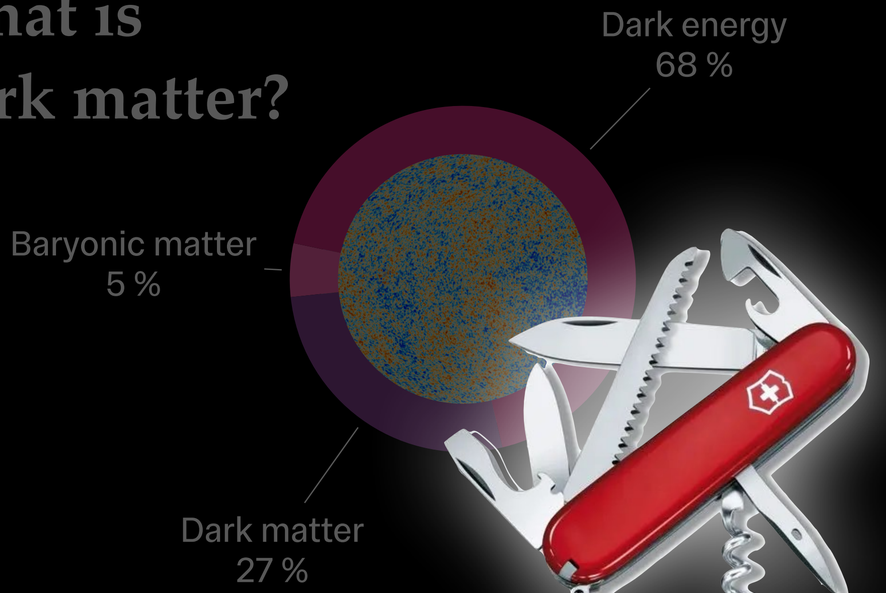




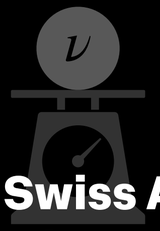
What are the properties of cosmic neutrino sources?

Astroparticle physics with XLZD

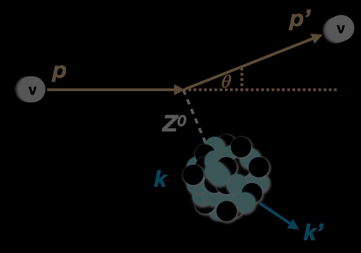
What is dark matter?



$\nu = \bar{\nu}$?

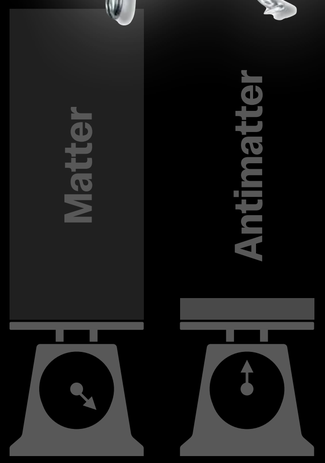


What is the nature of neutrinos and their interactions?



Huan Zhang
Wed 15:45

XLZD will be the the Swiss Army knife of low-energy astro-particle physics!



Why is there matter in the Universe?





What are the properties of cosmic neutrino sources?

IMPERIAL
Department of Physics

www.xlzd.org

- Abundant evidence for particle dark matter at all scales
- UK groups heavily involved in theory, astronomy and particle physics
- Direct searches:
  - Axions: cavity searches, quantum-limited readout electronics
  - Low masses: spherical proportional counters, quantum sensors
  - High masses: xenon and argon dual-phase time projection chambers
  - Large upcoming experiments with XLZD possibly hosted in the UK

DarkSide 20k

Ash Ritchie-Yates Wed 17:15	Angus Thompson Wed 17:00
Haoxiang Zhan Poster A4	Emma Ellingwood Thur 11:15
Emma Ellingwood Thur 11:30	Daria Santone Fri 11:45
Paolo Franchini Fri 12:00	

Levitated quantum sensors

Andrzej Gawdzik
Wed 16:00

Underground physics at Boulby

Alice Hamer
Wed 16:30

Beth Green
Poster A3

Jonathan Gutteridge
Poster H7

Kayleigh Johnson
Poster A5

Thank you very much for listening!

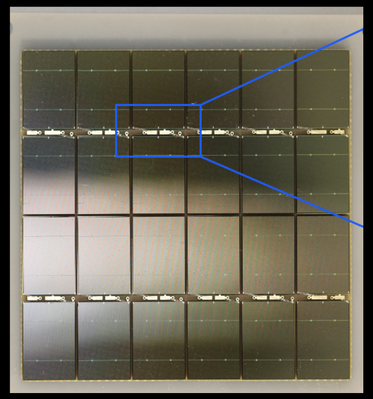
Backup

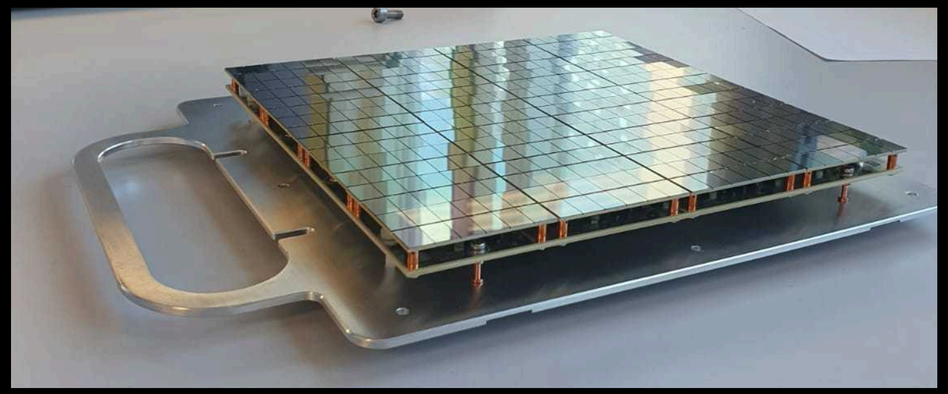
Argon TPCs: DarkSide 20k

Many thanks to Jocelyn Monroe for providing material!

- 54 institutes in 14 countries, UK ~10% of collaboration
- Construction advanced:
  - Cryostat and cryogenics infrastructures in LNGS Hall C complete
  - Major infrastructures for extraction + purification of 130 tonnes of underground argon target complete
  - Fabrication of huge acrylic components of TPC complete

- DarkSide-UK STFC project delivering 7 m² of SiPM array detectors (>50,000 sensors!)
  - Production/qualification: Birmingham, Edinburgh, Lancaster, Liverpool, Manchester, Oxford, RAL PPD, RHUL, STFC Interconnect, Warwick + radioassay at Boulby.
  - UK production **complete**, with 95% yield, exceeding target.

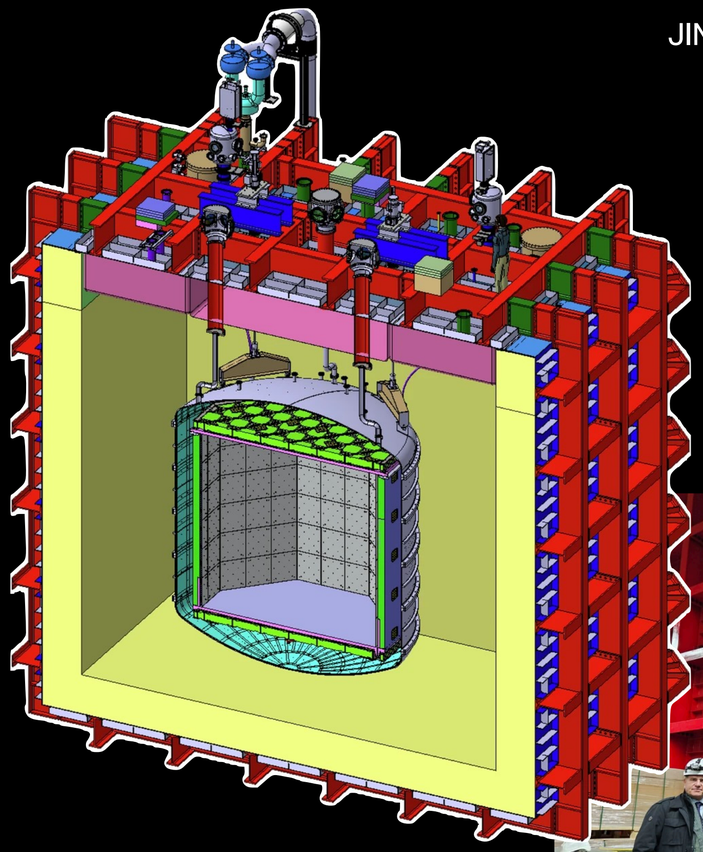


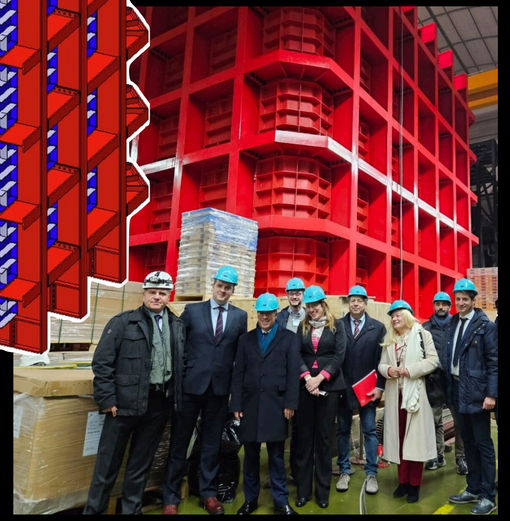


Low noise + radioactivity, high photon detection efficiency

^{34}Ar	^{35}Ar	^{36}Ar	^{37}Ar	^{38}Ar	^{39}Ar	^{40}Ar	^{41}Ar
β+	β+	2β+	e- capture	Stable	β-	Stable	β-

JINST 19 C03058 (2024)

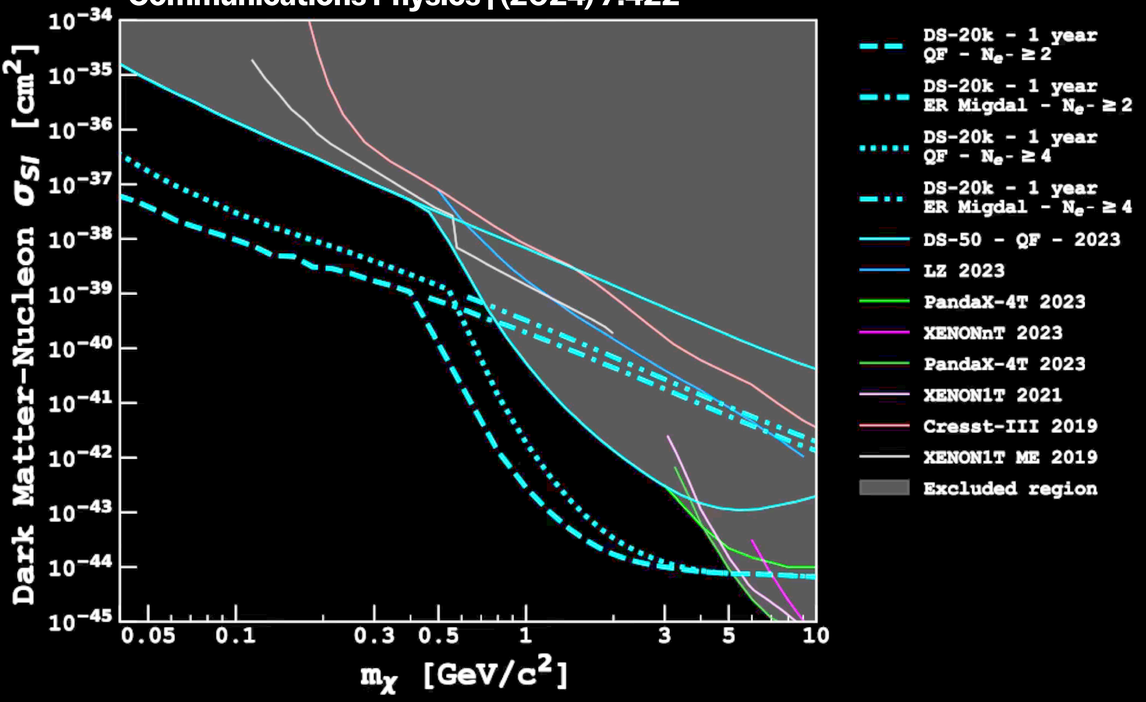




UK ambassador to Italy visits DarkSide-20k

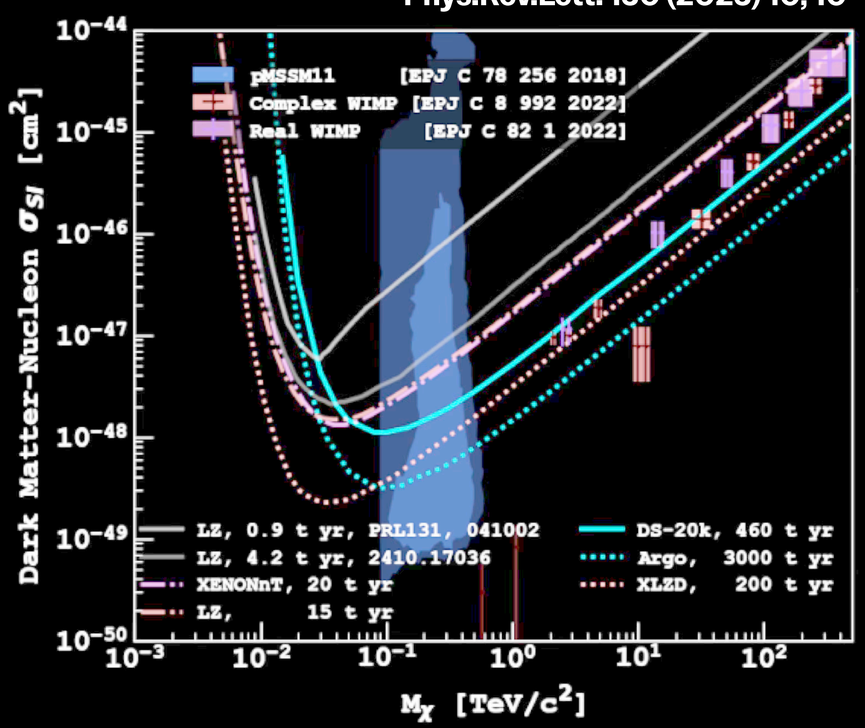
Argon TPCs: DarkSide 20k

Communications Physics | (2024) 7:422



DM electron scattering

Phys.Rev.Lett. 130 (2023) 10, 10

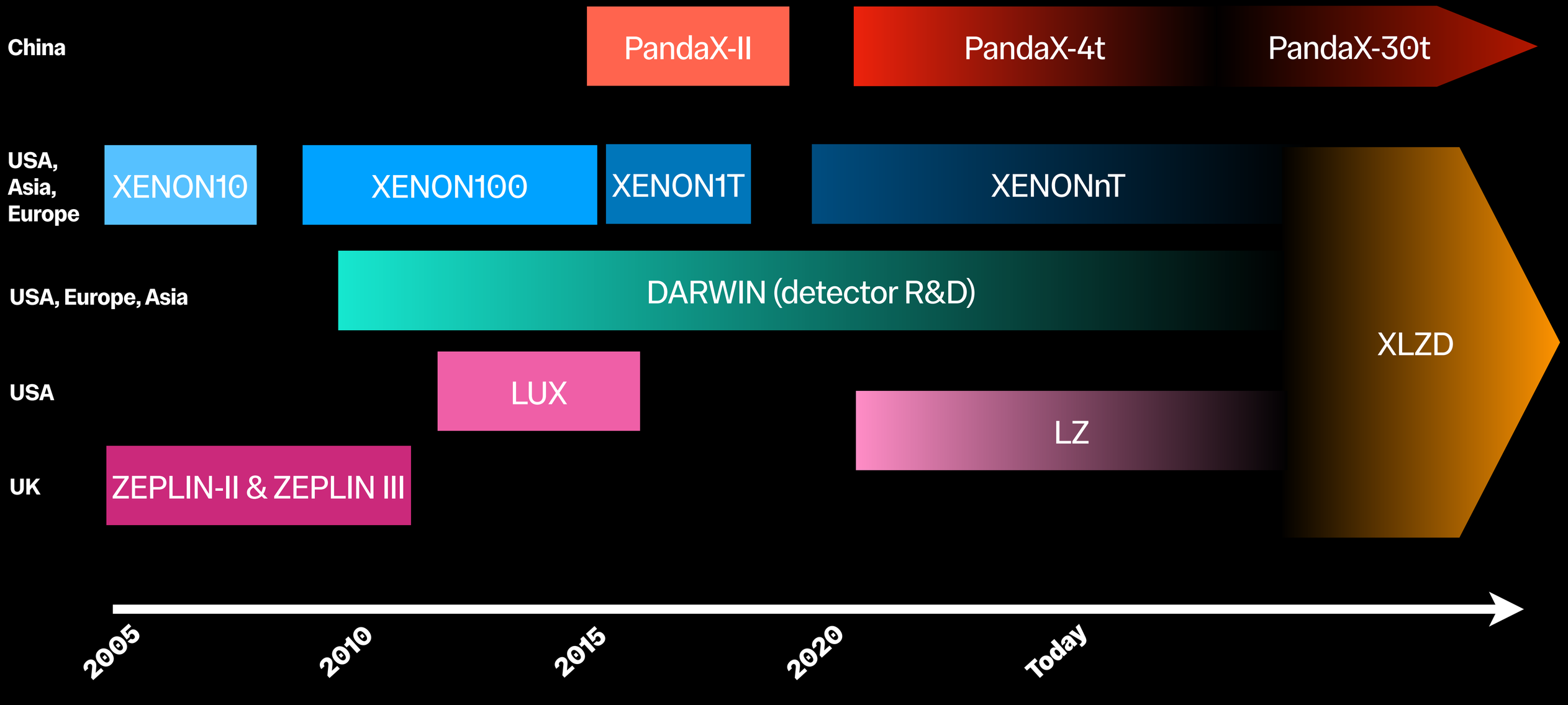


DM nucleus scattering

Probe dark matter candidates from keV/c² to Planck mass ≈10²⁸ eV/c².

- Hidden sector DM, warm DM: Nat.Comms. Phys.7 422 (2024)
- Elastic DM: CERN Yellow Rep.Monogr. 8 (2025),
- Composite DM: arXiv:2602.09421,
- Primordial black hole DM: Phys.Rev.D 112 (2025) 12, 123058,
- Spin-dependent DM: Eur. Phys. J. C 83, 914 (2023)

Evolution of xenon dual-phase TPCs



Where do we go from here?

Now

- No evidence for WIMPs, but stringent exclusion of parameter space
- First indication of solar neutrino coherent scattering
- Demonstrated neutrinoless double-beta decay search
- Many other physics searches in nuclear and electronic recoils

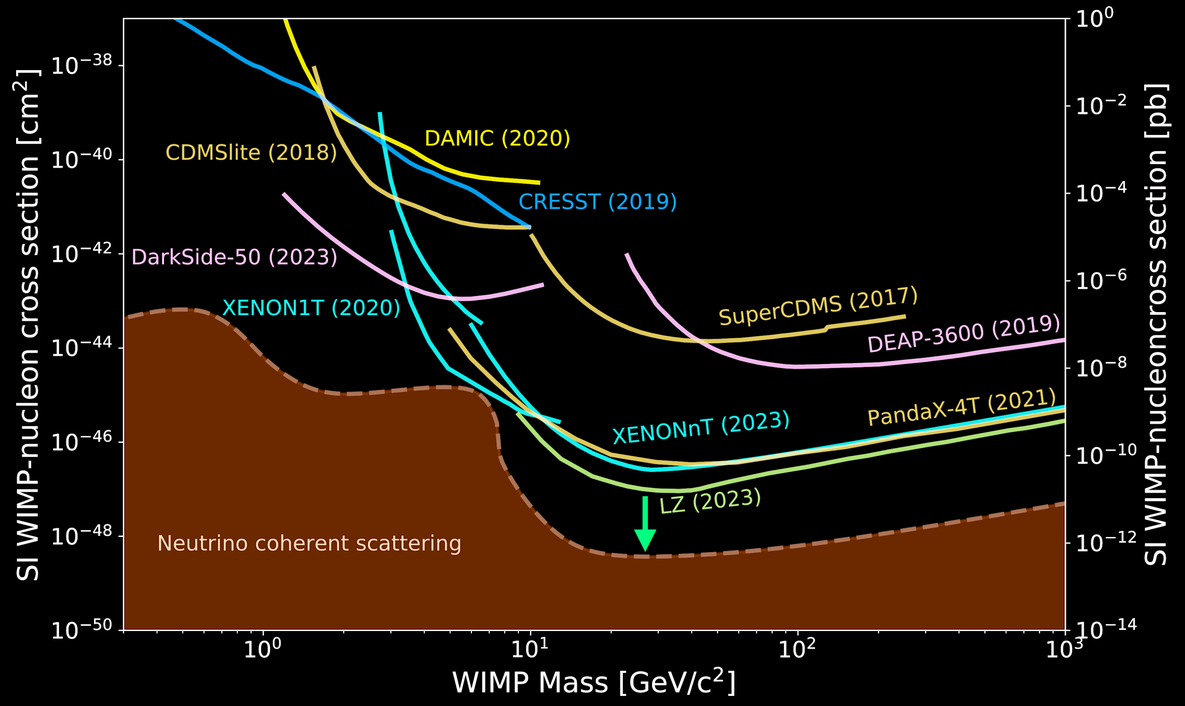
Future

Measure down to neutrino fog.

Measure solar neutrinos comprehensively and be ready for the next supernova.

Become world-leading experiment for these searches.

Improve all existing results and probe exciting new physics!



Where do we go from here?

Now

- No evidence for WIMPs, but stringent exclusion of parameter space
- First indication of solar neutrino coherent scattering
- Demonstrated neutrinoless double-beta decay search
- Many other physics searches in nuclear and electronic recoils

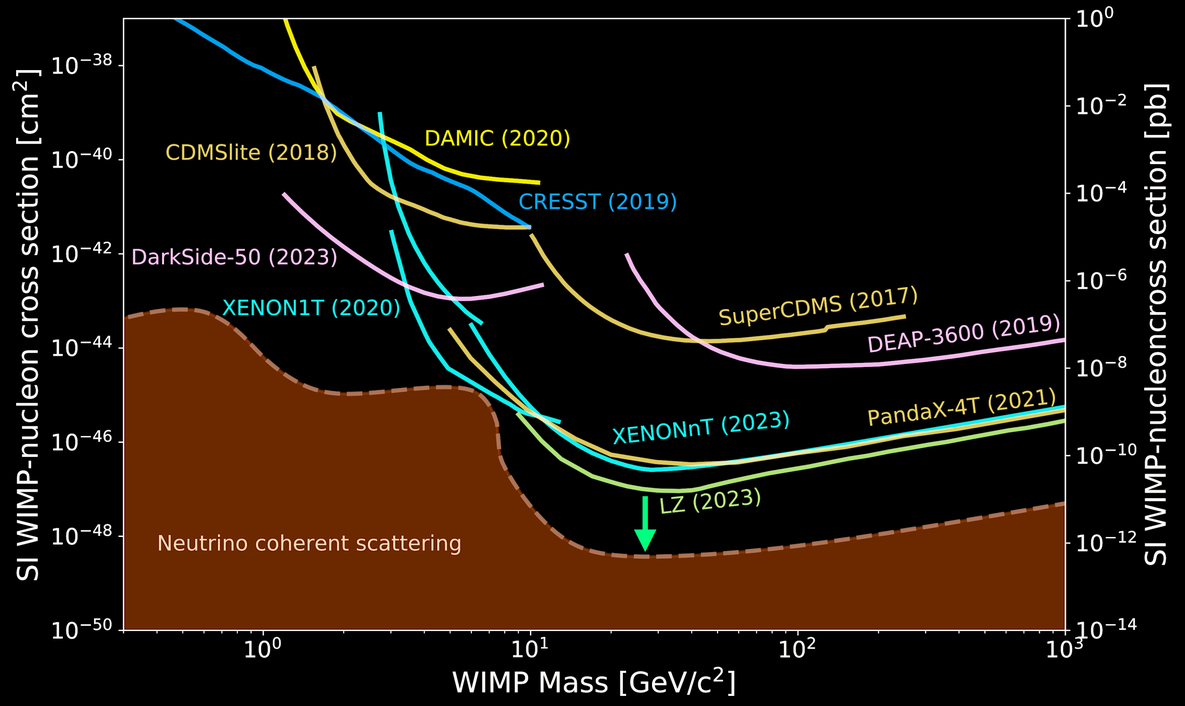
Future

Measure down to neutrino fog.

Measure solar neutrinos comprehensively and be ready for the next supernova.

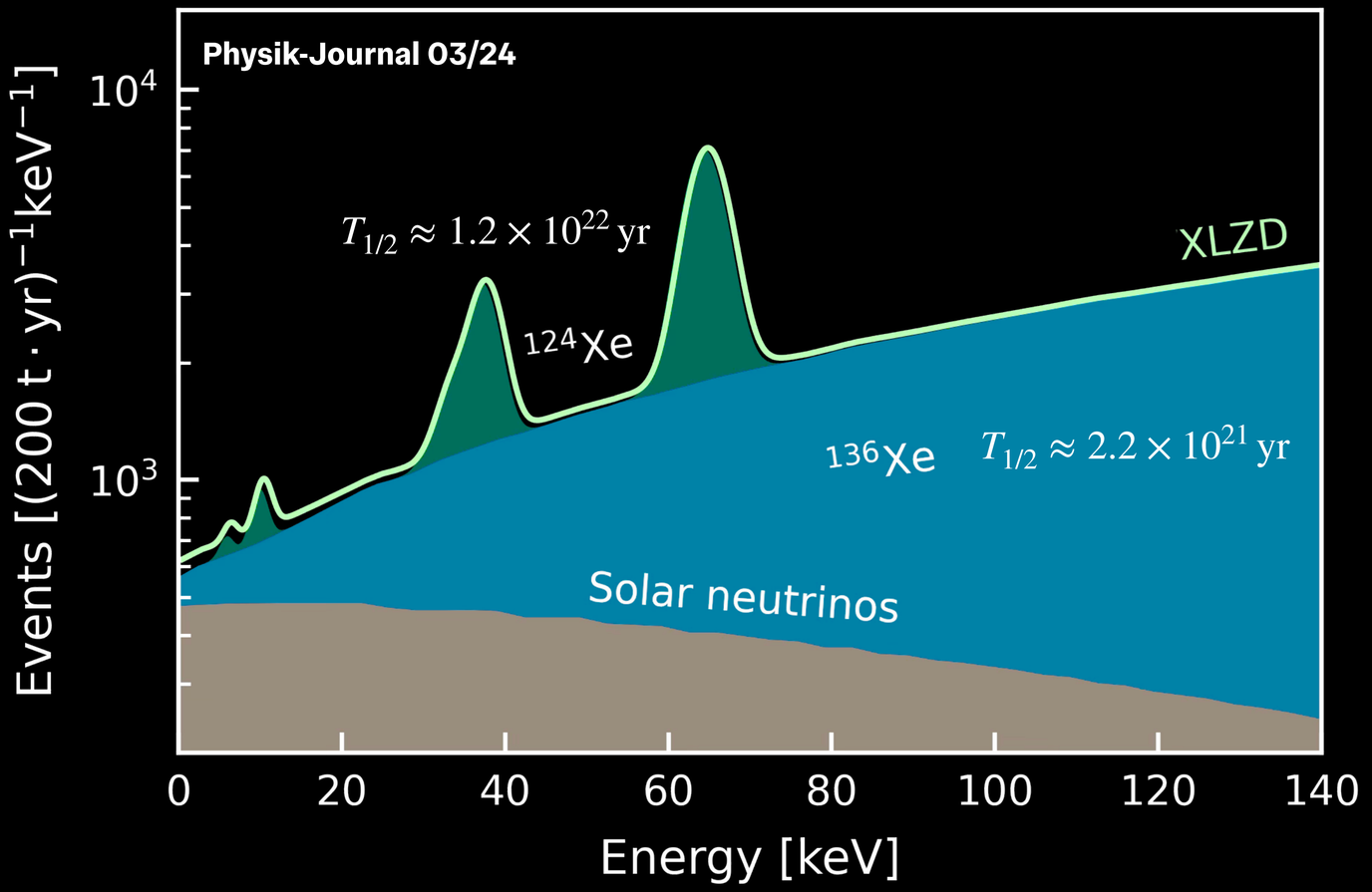
Become world-leading experiment for these searches.

Improve all existing results and probe exciting new physics!





Low-energy electronic recoils in XLZD



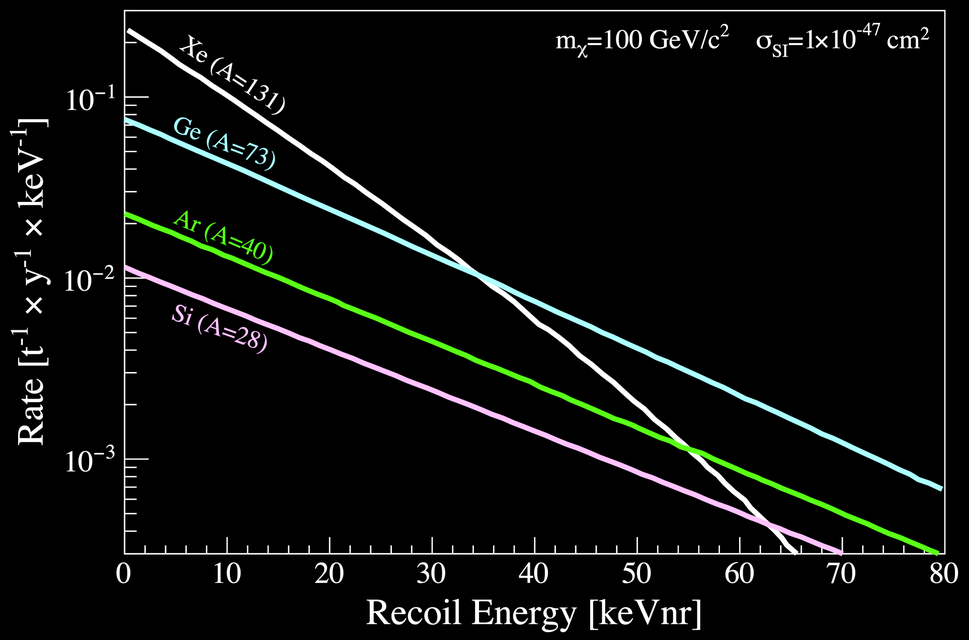
- Unprecedentedly low background at few keV dominated by **neutrinos** and **double-beta decays of xenon**
- Physics searches:
  - **Neutrino magnetic moment**
  - **Axions, axion-like particles, dark photons**
  - Solar **pp-neutrinos** below Borexino energy threshold Eur. Phys. J C 80, 1133 (2020
  - Precision measurements of **rare SM processes** (e.g. ^{124}Xe double-electron capture with longest half-life measured to date by XENON1T/nT)

Why xenon?

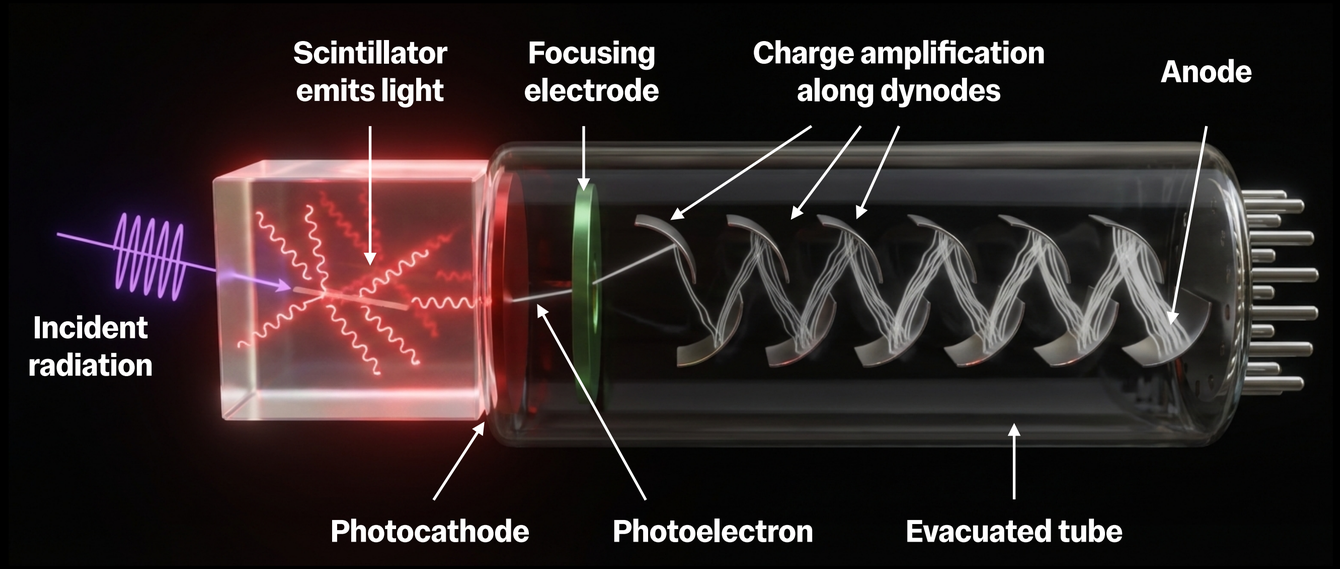
^{124}Xe	^{125}Xe	^{126}Xe	^{127}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{133}Xe	^{134}Xe	^{135}Xe	^{136}Xe
2β+	β+	2β+	e- capture	Stable	Stable	Stable	Stable	Stable	β-	2β-	β-	2β-

- Inert and purifiable
- Scalable
- “Easy” cryogenics
- No relevant radioactive isotopes; naturally occuring double-beta emitters have extremely long half-lives and their own physics potential
- Excellent scintillator and ionization medium (**W ≈ 13.7 eV**)
- Transparent to its own scintillation light
- No wavelength shifters needed with **λ ≈ 175 nm**
- Self-shielding with high atomic number (**Z = 54**)
- Different nuclear spins allow probing spin-dependent dark matter interactions
- Coherent WIMP interaction rate goes with ~ **A²**

Marc Schumann 2019 J. Phys. G: Nucl. Part. Phys. 46 103003



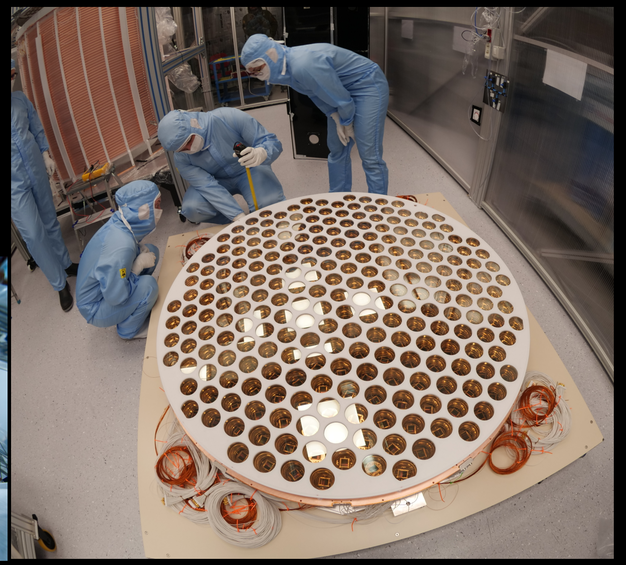
Measuring light: photosensors

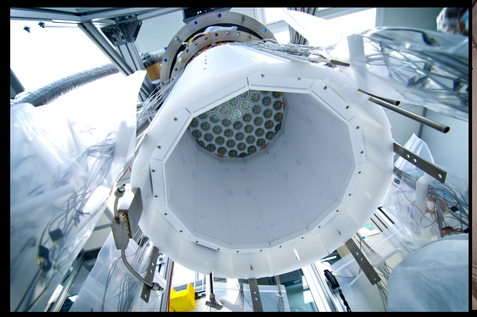


Made with Google Gemini



LZ collaboration, LUX collaboration, XENON collaboration



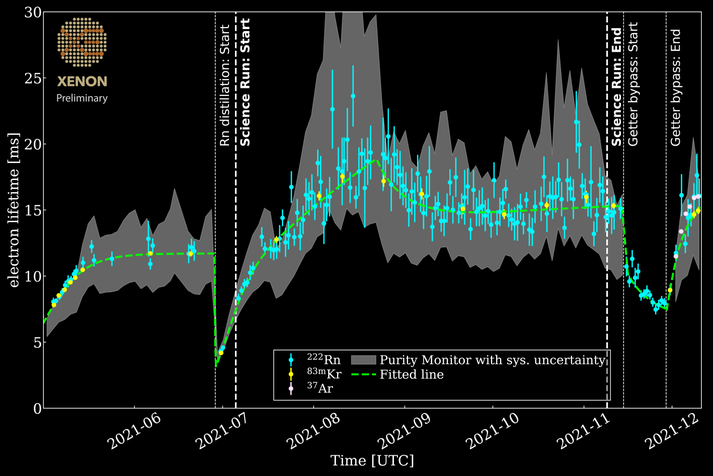


- “See“ individual photons.
- Convert measured photons to measurable electric current.
- Reflectors ensure maximum light collection

Measuring electrons

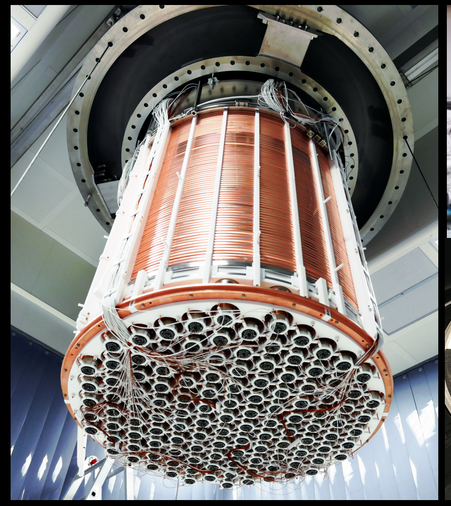
Xenon purity



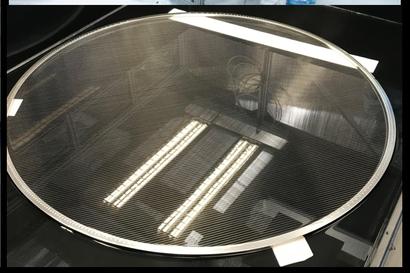


- Electrons and photons may by lost due to chemical impurities inside the xenon.
- Effective electron drift lifetime
- Need: liquid and gas purification with turnaround cycle of few days
- **Challenges:**
  - Clean pumps
  - Liquefaction for gas purification
  - Low-radon materials for liquid cleaning

Drift and extraction fields





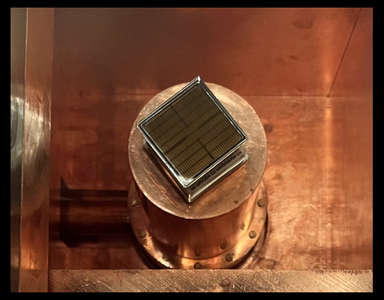


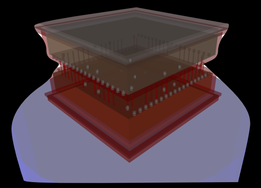
Farrin Abbott/ SLAC National Accelerator Laboratory, LZ collaboration, XENON collaboration

- Need homogeneous electric field for straight drift of electrons.
- Large parallel wire, hexagonal mesh or woven electrodes
- High-voltage delivery:
  - Drift: ~100 V/cm
  - Extraction: few kV/cm

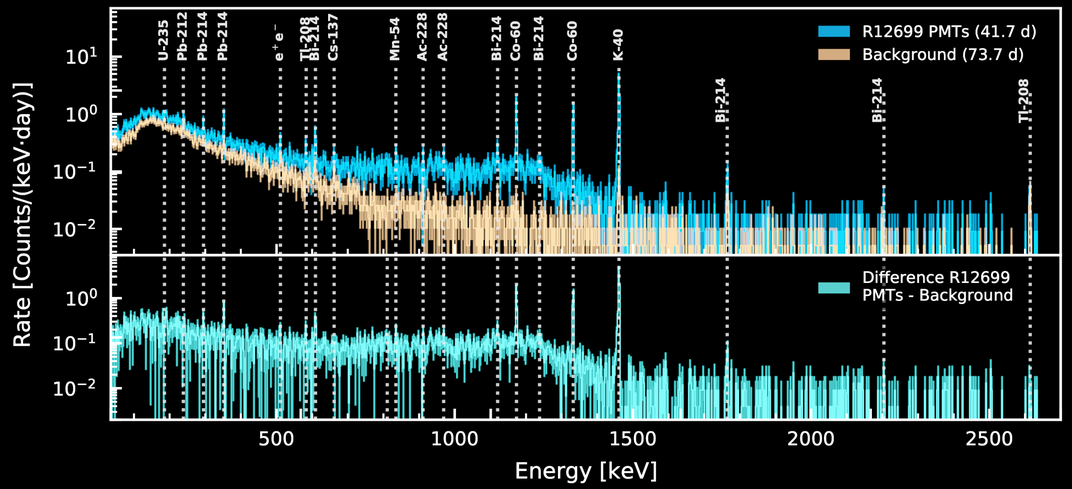
Low background: radiopure materials

- Neutrons and γ-rays come from radioactive trace contaminations in detector construction materials
- ^{40}K, ^{60}Co, ^{238}U, ^{232}Th, ...
- Measure activity of every material in underground HPGe detectors and select most radiopure materials





G. R. Araujo et al 2022 JINST 17 P08010



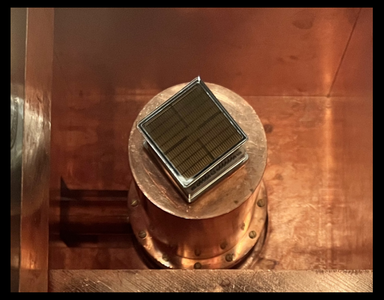
Goal: 1 μBq/kg – 1 mBq/kg

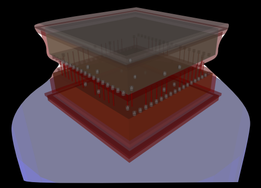
1 decay/kg/12 days – 1 decay/kg/hour



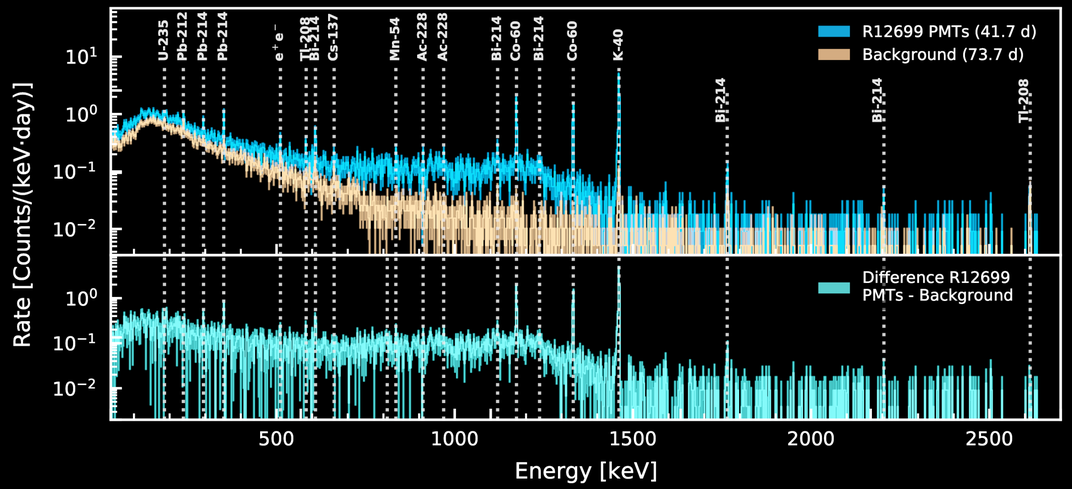
Low background: radiopure materials

- Neutrons and γ-rays come from radioactive trace contaminations in detector construction materials
- ^{40}K, ^{60}Co, ^{238}U, ^{232}Th, ...
- Measure activity of every material in underground HPGe detectors and select most radiopure materials





G. R. Araujo et al 2022 JINST 17 P08010



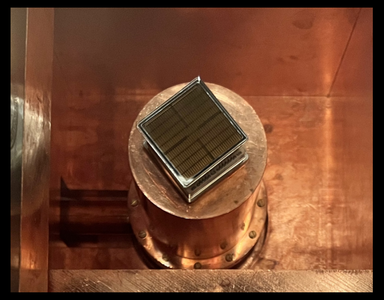
Goal: 1 μBq/kg – 1 mBq/kg

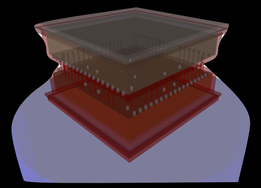
1 decay/kg/12 days – 1 decay/kg/hour



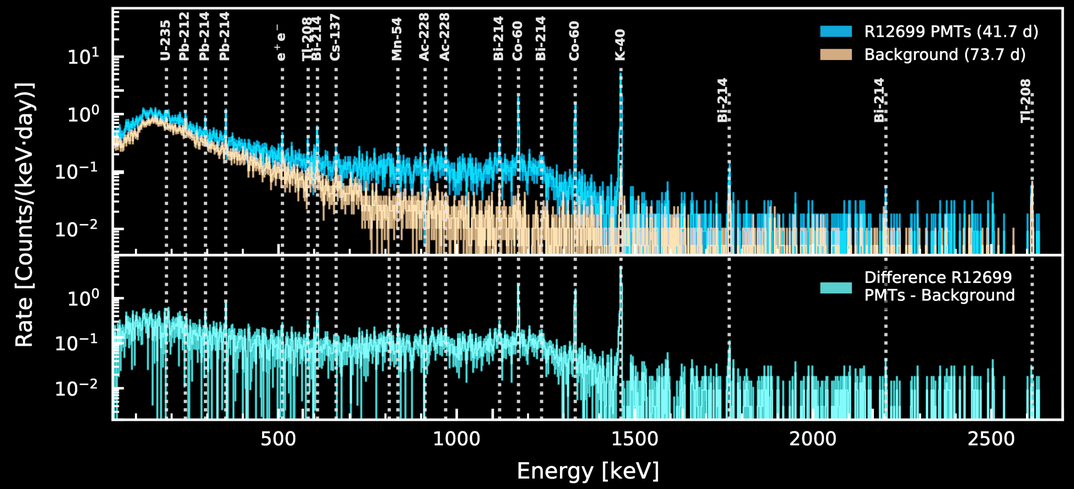
Low background: radiopure materials

- Neutrons and γ-rays come from radioactive trace contaminations in detector construction materials
- ^{40}K, ^{60}Co, ^{238}U, ^{232}Th, ...
- Measure activity of every material in underground HPGe detectors and select most radiopure materials





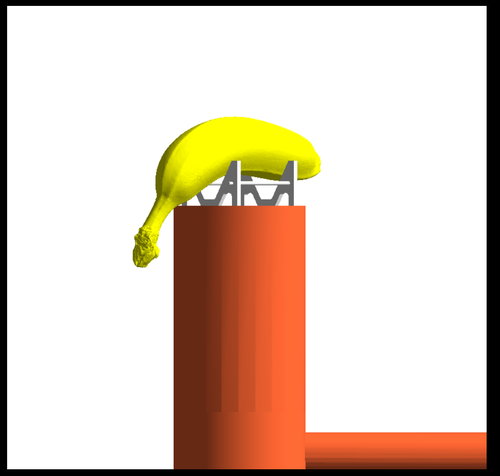
G. R. Araujo et al 2022 JINST 17 P08010



Goal: 1 μBq/kg – 1 mBq/kg

1 decay/kg/12 days – 1 decay/kg/hour





D. Ramírez García et al 2022 JINST 17 P04005

Active intrinsic background removal

- ^{85}Kr from atmospheric nuclear testing and nuclear reprocessing entered xenon during extraction from air.
- Radon continuously emanated from all detector materials as part of the natural uranium and thorium chains.
- Remove by cryogenic distillation.



Air Liquide

^{85}Kr



PTEP, 053H01 (2022)

Remove once

^{222}Rn



EPJC 82, 1104 (2022), 2205.11492

Remove continuously before it decays to reach <1 µBq/kg (4 decays per tonne per hour)

Radon concentration in air ~ 8 Bq/kg

Active intrinsic background removal

- ^{85}Kr from atmospheric nuclear testing and nuclear reprocessing entered xenon during extraction from air.
- Radon continuously emanated from all detector materials as part of the natural uranium and thorium chains.
- Remove by cryogenic distillation.



Air Liquide

^{85}Kr **^{222}Rn**

Krypton

Xenon



PTEP, 053H01 (2022)



EPJC 82, 1104 (2022), 2205.11492

Remove once

Remove continuously before it decays to reach <1 μBq/kg (4 decays per tonne per hour)

Radon concentration in air ~ 8 Bq/kg

Active intrinsic background removal

- ^{85}Kr from atmospheric nuclear testing and nuclear reprocessing entered xenon during extraction from air.
- Radon continuously emanated from all detector materials as part of the natural uranium and thorium chains.
- Remove by cryogenic distillation.



Air Liquide

^{85}Kr **^{222}Rn**

Krypton

Xenon





Xenon

Radon

PTEP, 053H01 (2022)

EPJC 82, 1104 (2022), 2205.11492

Remove once

Remove continuously before it decays to reach <1 μBq/kg (4 decays per tonne per hour)

Radon concentration in air ~ 8 Bq/kg

Active intrinsic background removal

- ^{85}Kr from atmospheric nuclear testing and nuclear reprocessing entered xenon during extraction from air.
- Radon continuously emanated from all detector materials as part of the natural uranium and thorium chains.
- Remove by cryogenic distillation.

^{222}Rn down to the level of irreducible solar pp-neutrino background!

^{85}Kr **^{222}Rn**

Krypton

Xenon



PTEP, 053H01 (2022)



EPJC 82, 1104 (2022), 2205.11492

Xenon

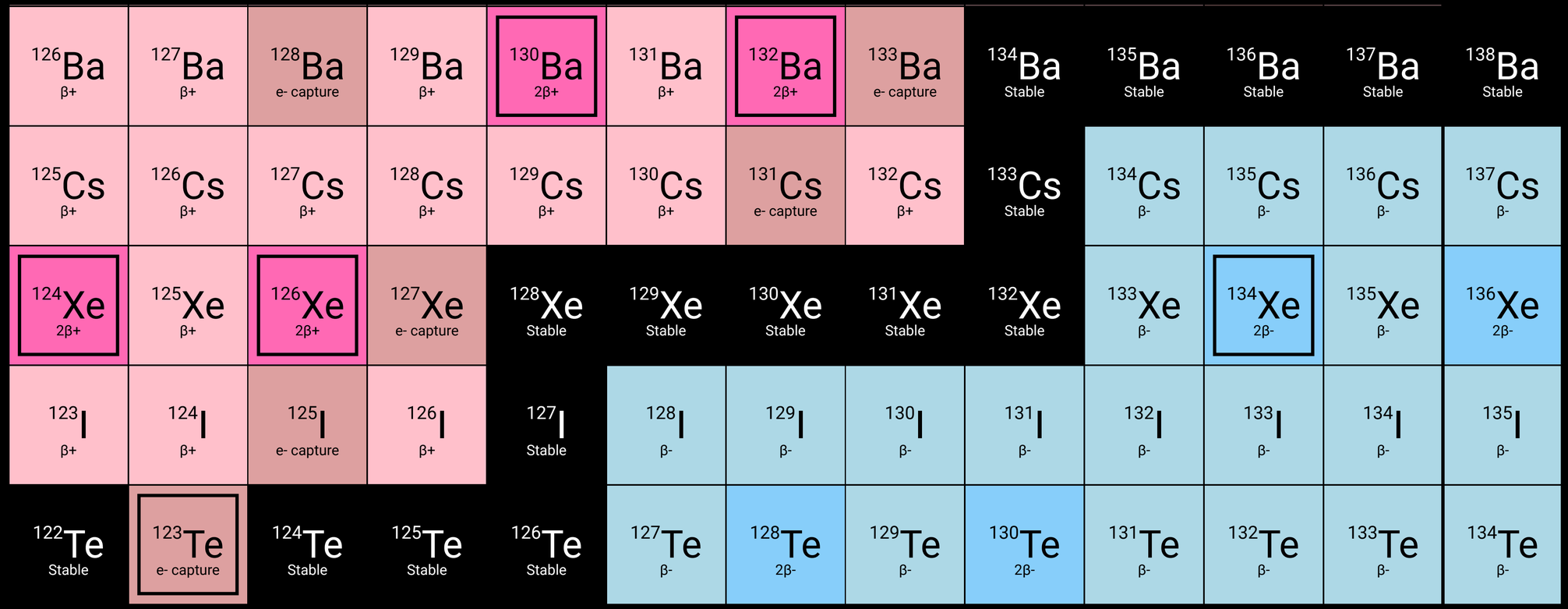
Radon

Remove once

Remove continuously before it decays to reach <1 µBq/kg (4 decays per tonne per hour)

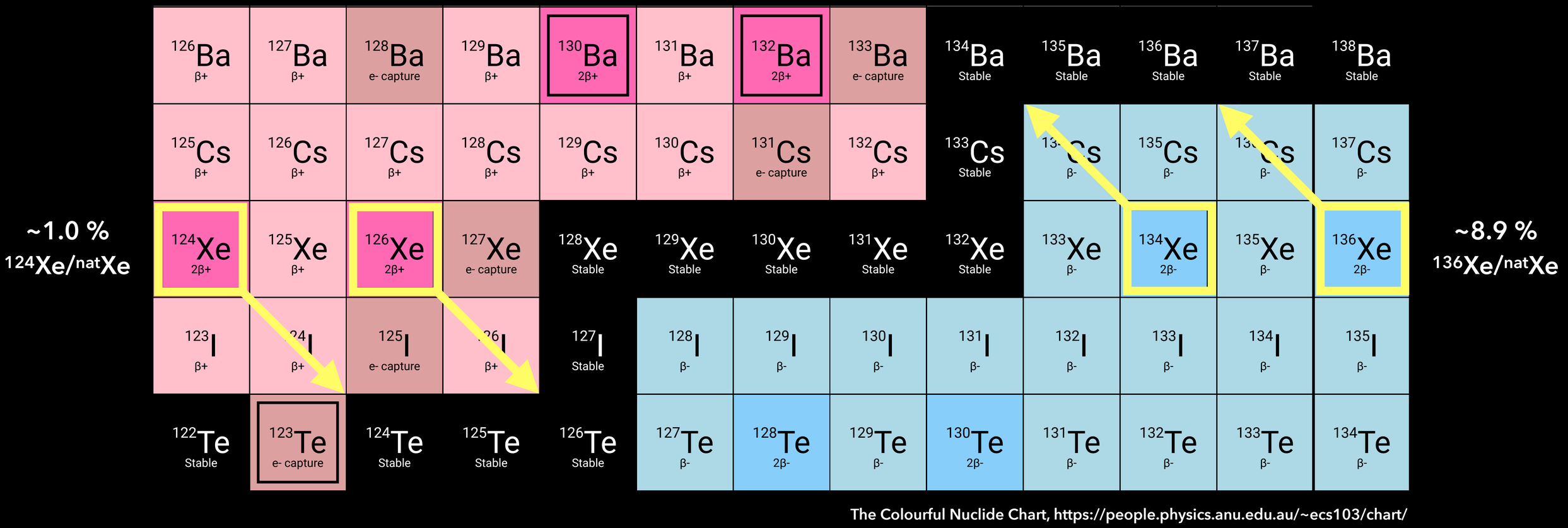
Radon concentration in air ~ 8 Bq/kg

Neutrinoless double-beta decay in xenon



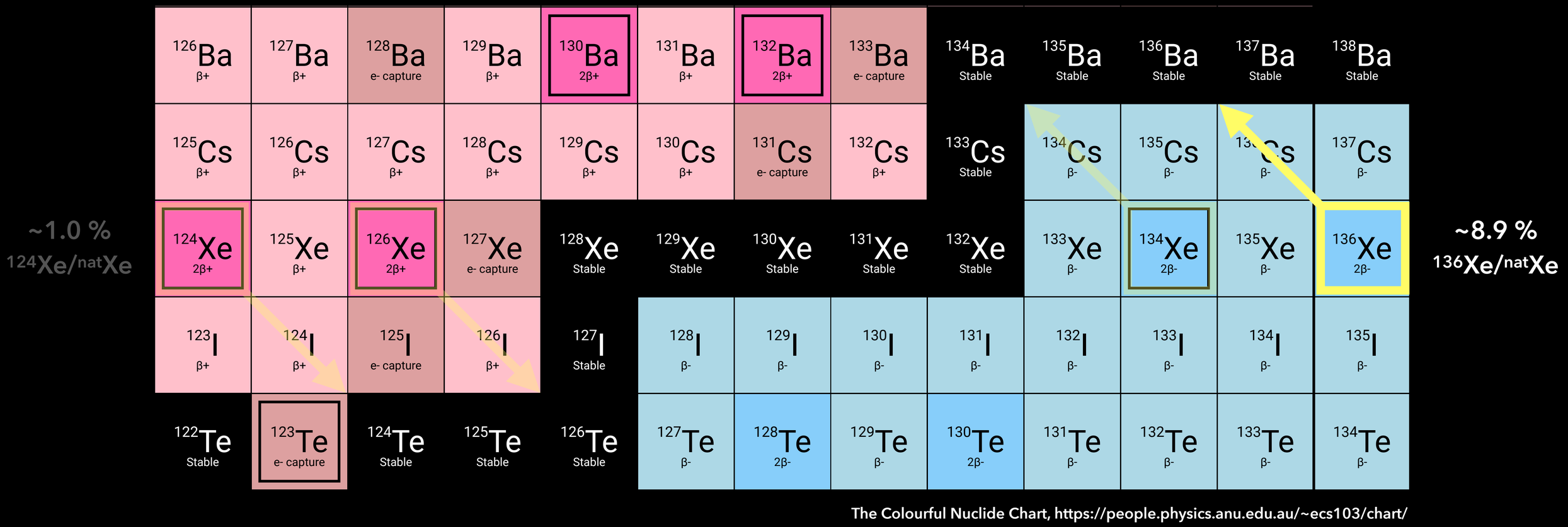
The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

Neutrinoless double-beta decay in xenon



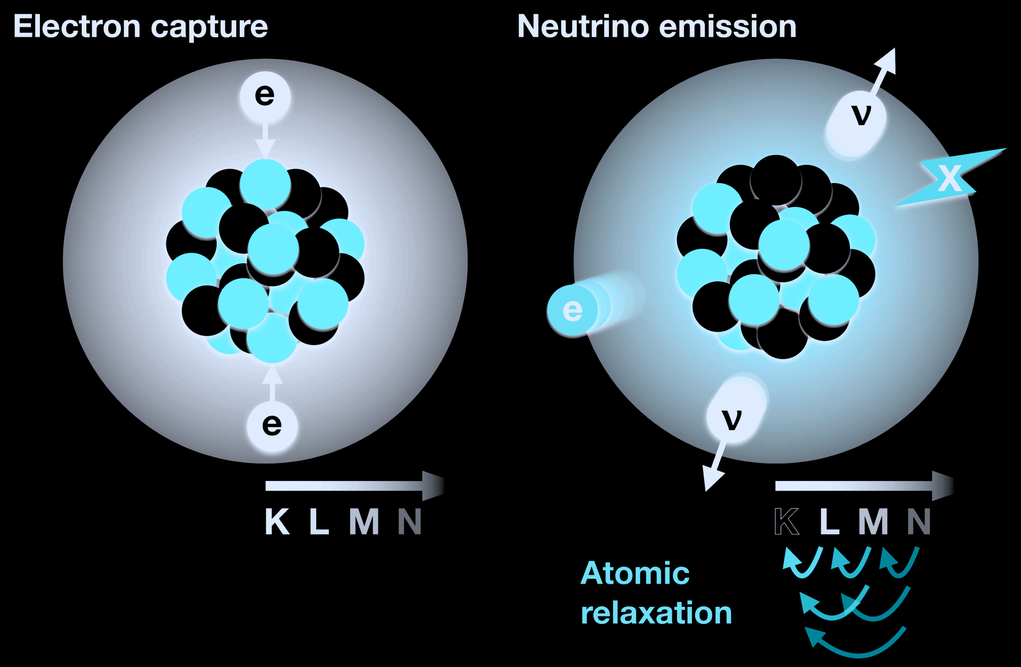
The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

Neutrinoless double-beta decay in xenon



The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

Double-electron capture of ^{124}Xe

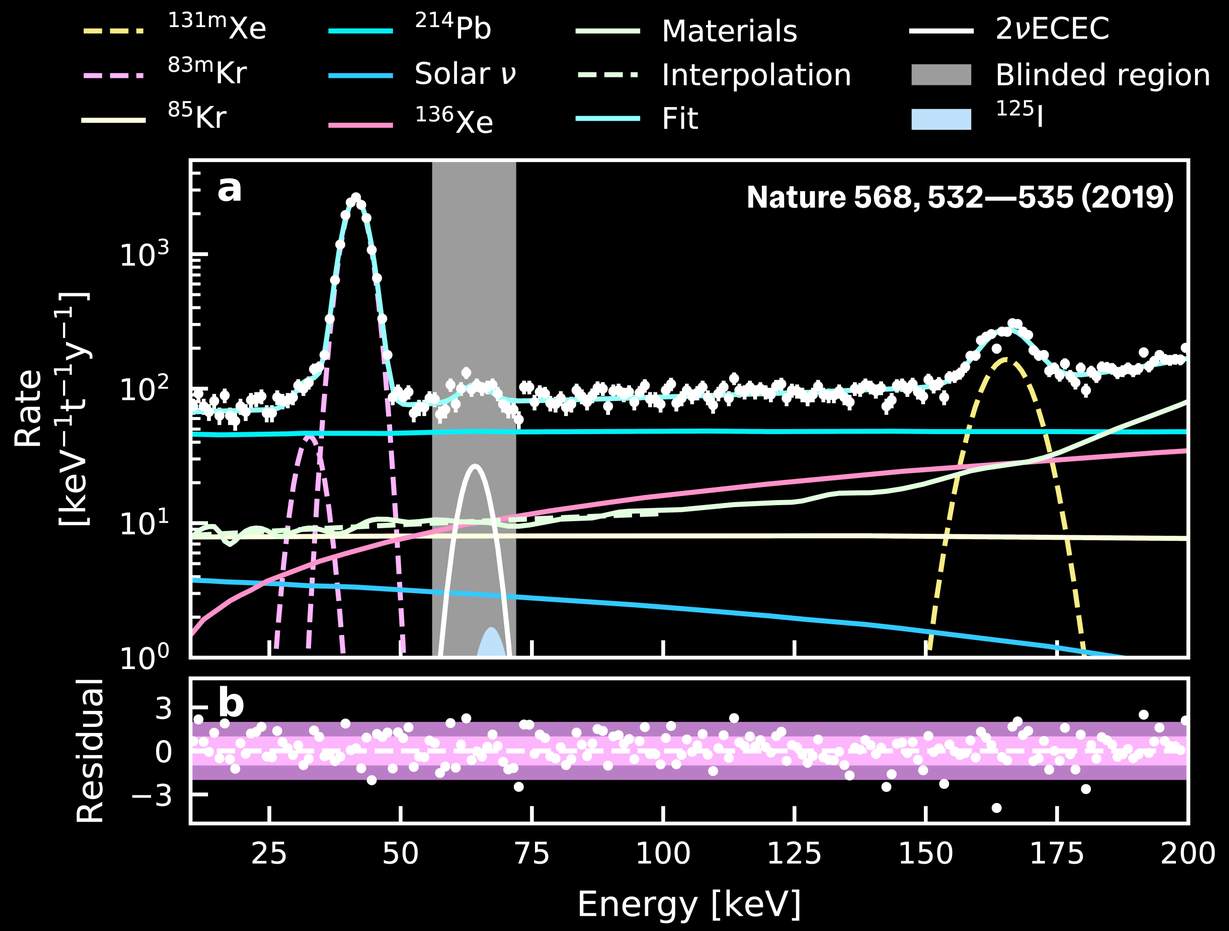


Measure X-rays and Auger-Meitner electrons from atomic relaxation:

KK-capture: 64.3 keV (72.4 %)

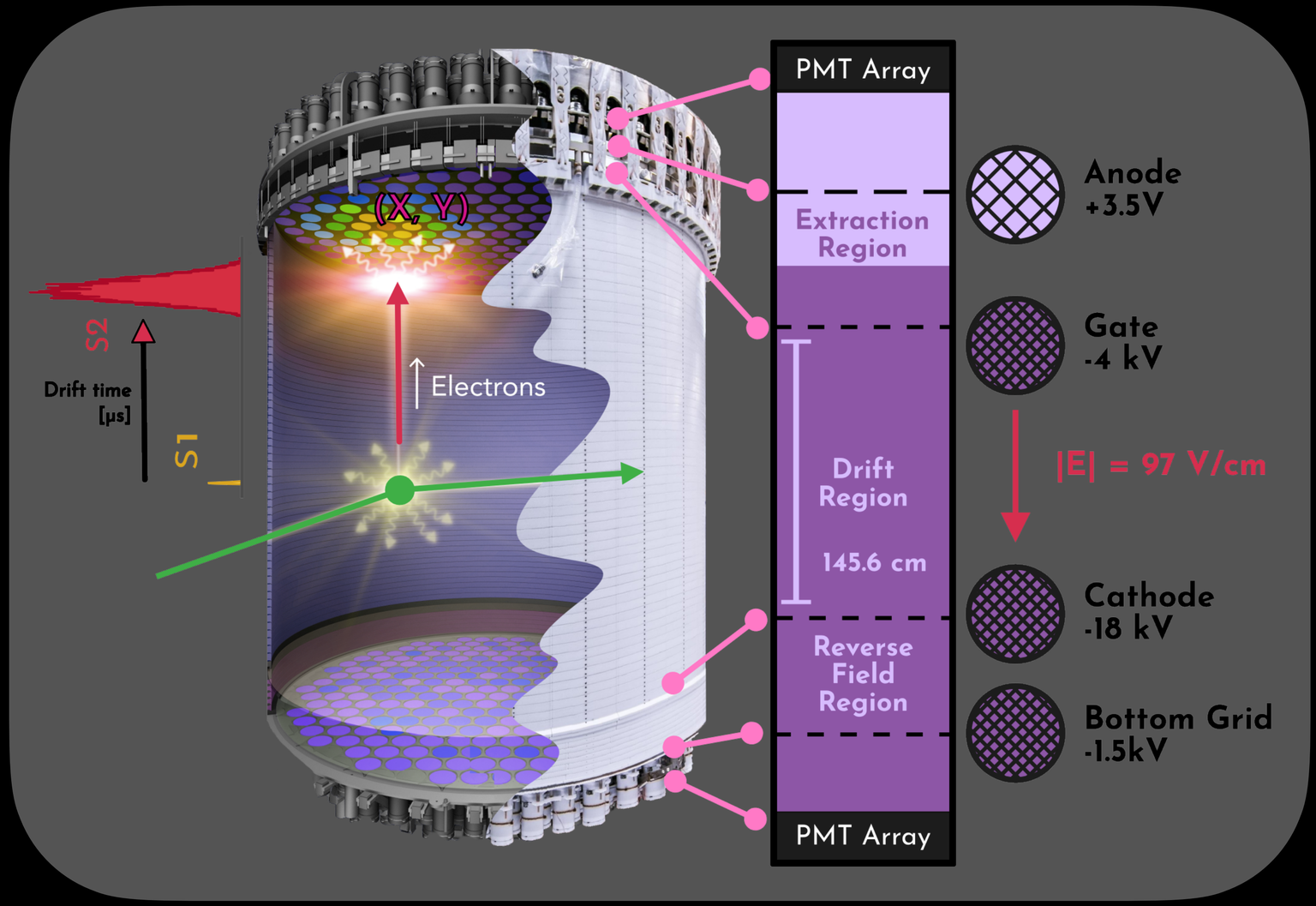
KL-, **KM**-, **KN**-capture: 32.4 – 37.3 keV (25.3 %)

LL-capture: 8.8 – 10.0 keV (1.4 %)

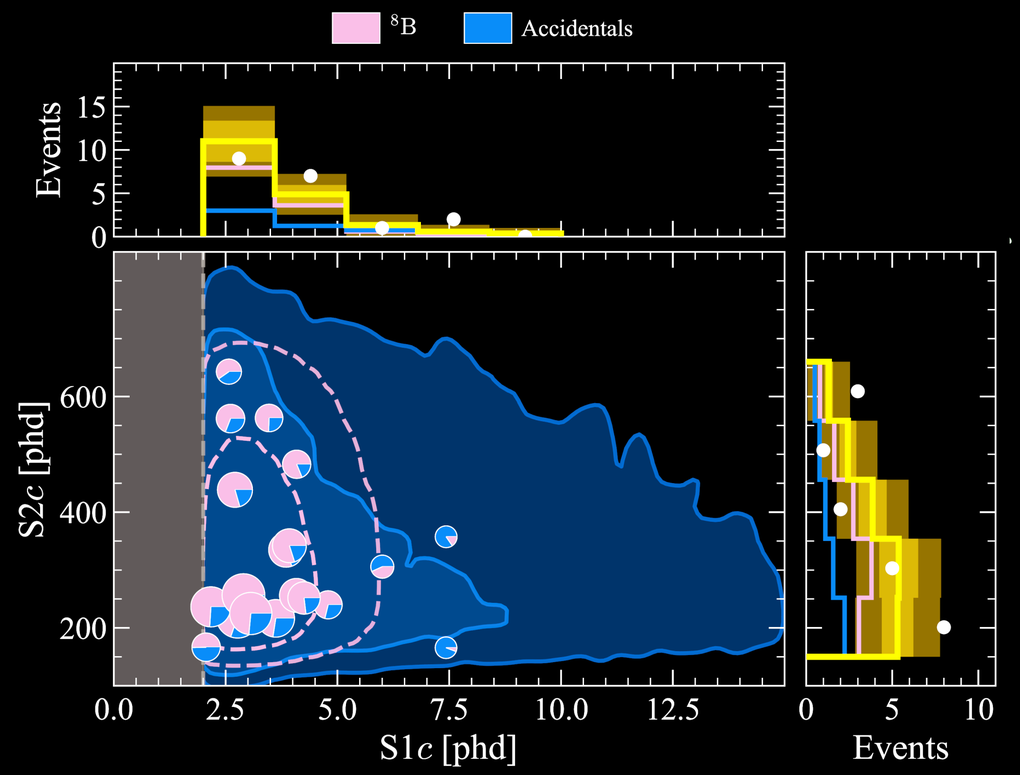


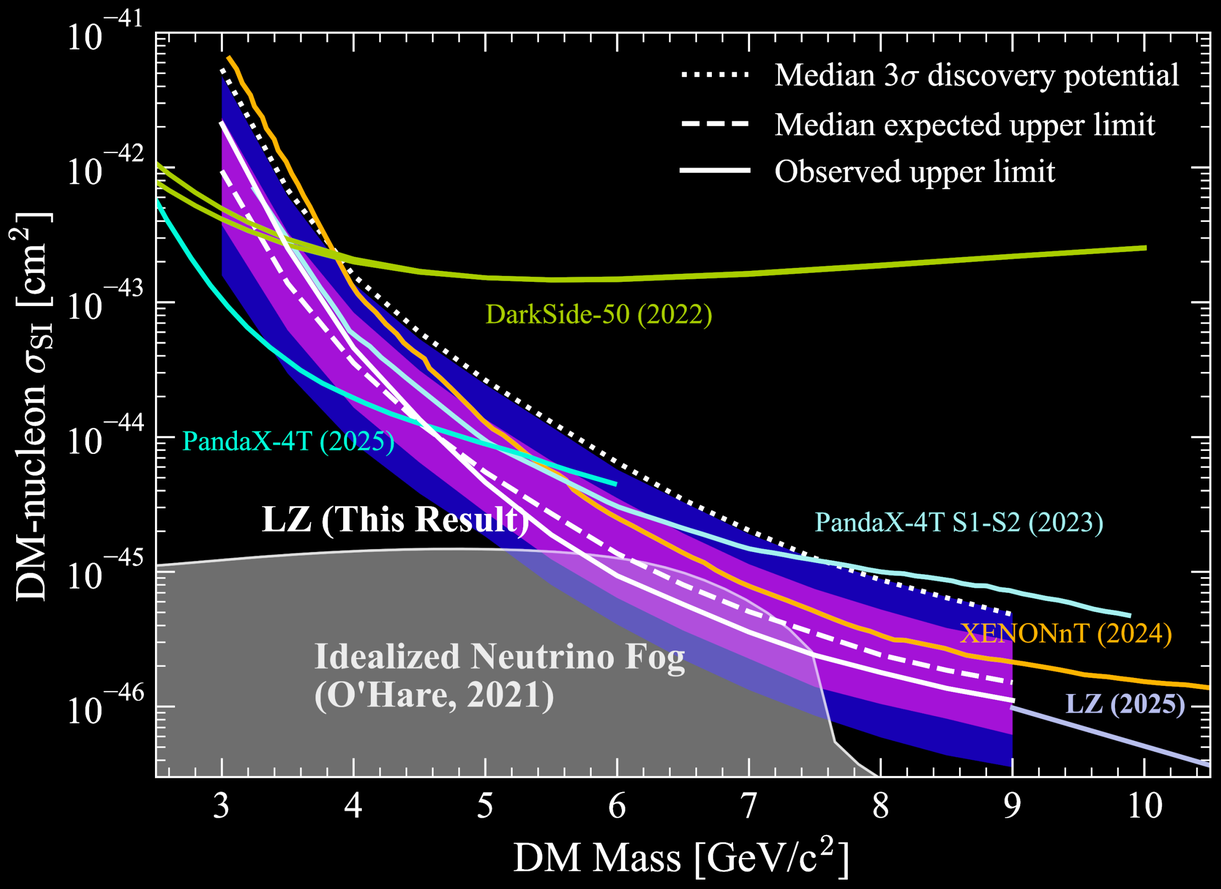
1.8×10^{22} yr longest half-life measured to date.

Xenon TPCs: LUX-ZEPLIN

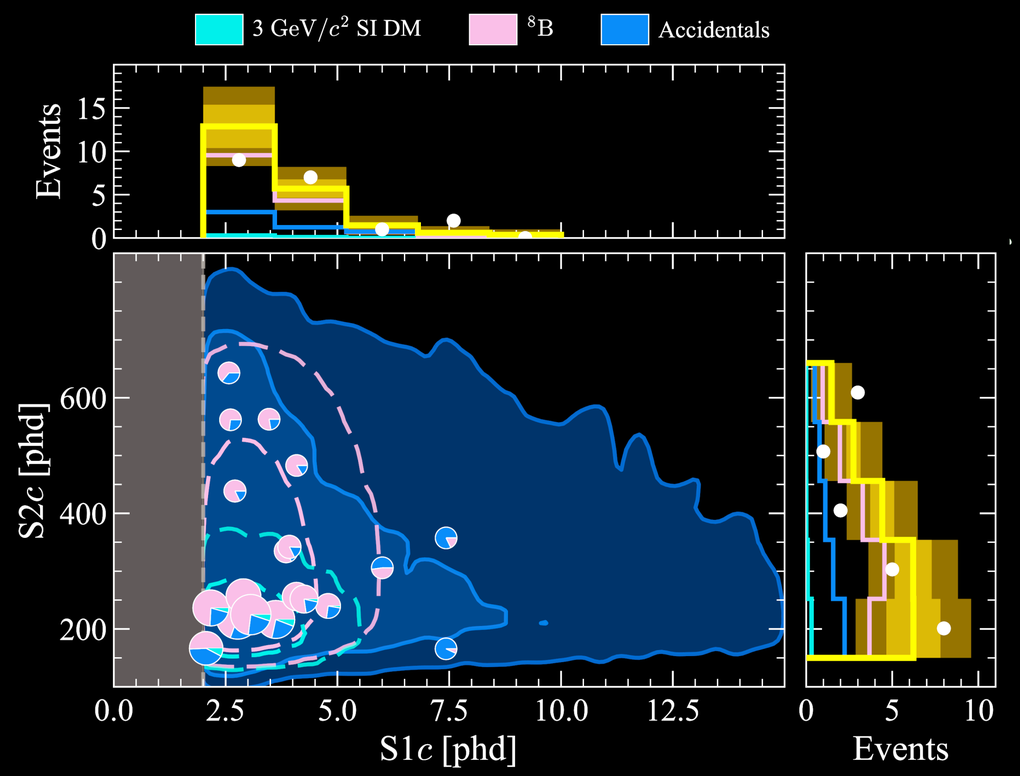


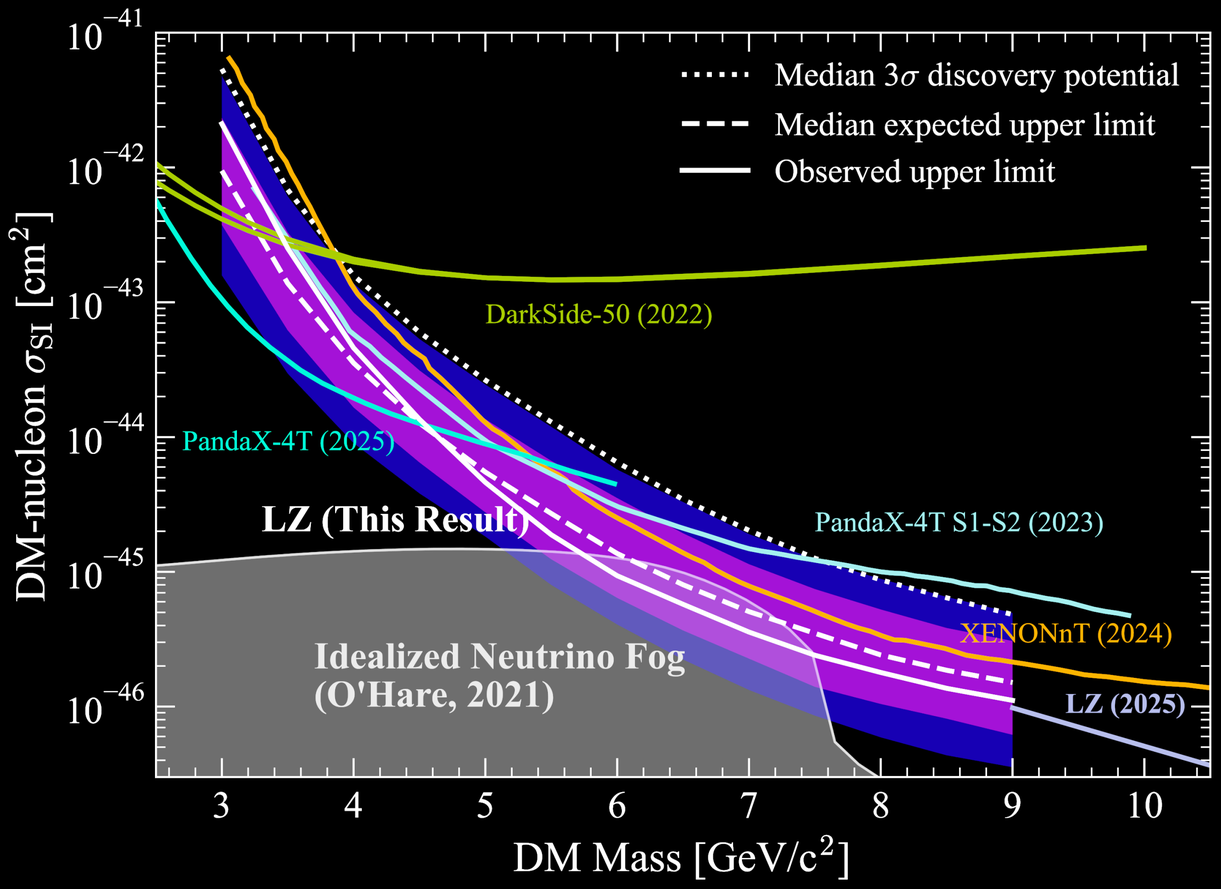
CEvNS to light dark matter in LZ





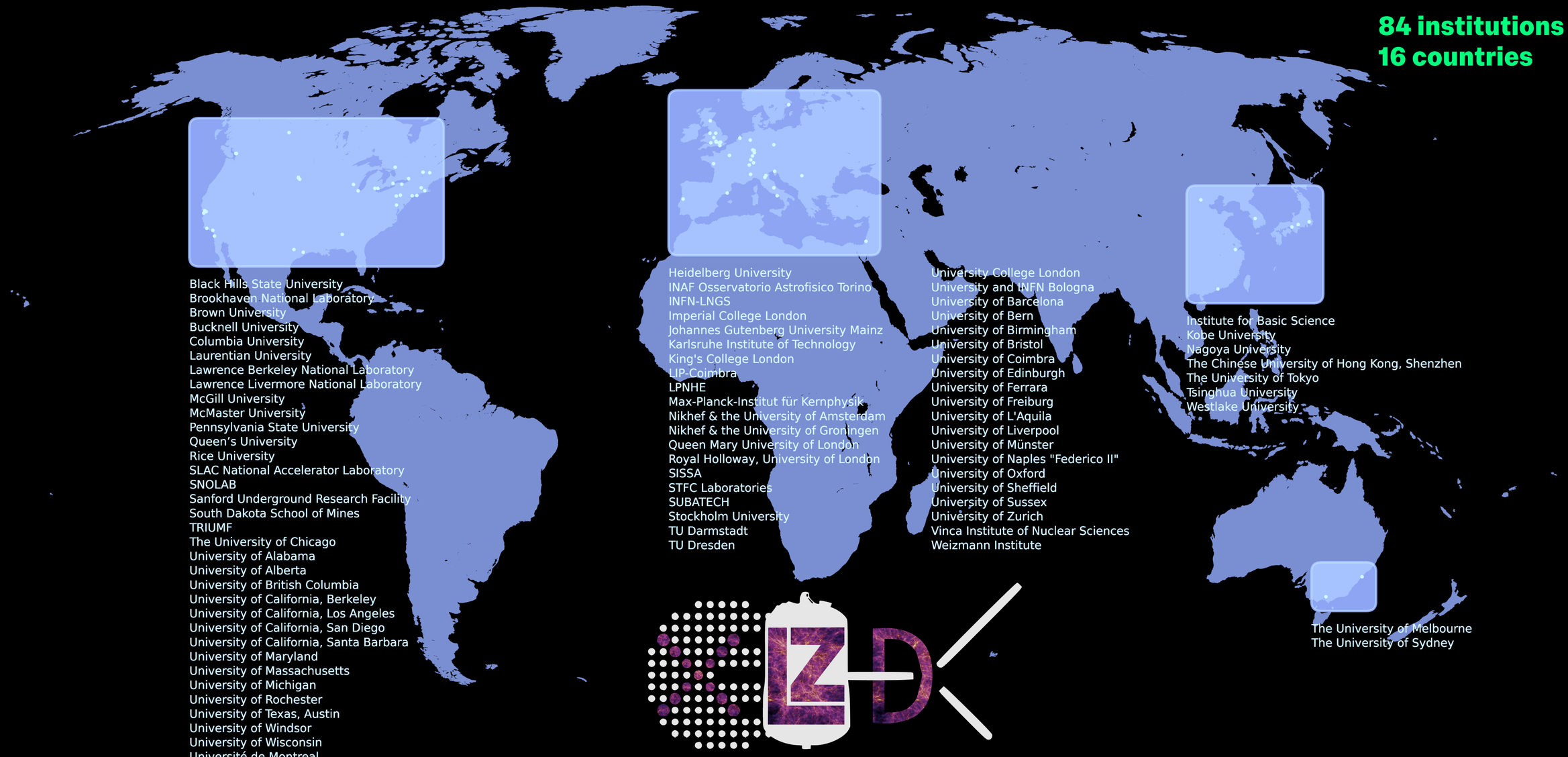
CEvNS to light dark matter in LZ





XENON, LZ and DARWIN become XLZD

84 institutions
16 countries



Black Hills State University
Brookhaven National Laboratory
Brown University
Bucknell University
Columbia University
Laurentian University
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
McGill University
McMaster University
Pennsylvania State University
Queen's University
Rice University
SLAC National Accelerator Laboratory
SNOLAB
Sanford Underground Research Facility
South Dakota School of Mines
TRIUMF
The University of Chicago
University of Alabama
University of Alberta
University of British Columbia
University of California, Berkeley
University of California, Los Angeles
University of California, San Diego
University of California, Santa Barbara
University of Maryland
University of Massachusetts
University of Michigan
University of Rochester
University of Texas, Austin
University of Windsor
University of Wisconsin
Université de Montreal
Université de Sherbrooke

Heidelberg University
INAF Osservatorio Astrofisico Torino
INFN-LNGS
Imperial College London
Johannes Gutenberg University Mainz
Karlsruhe Institute of Technology
King's College London
LIP-Coimbra
LPNHE
Max-Planck-Institut für Kernphysik
Nikhef & the University of Amsterdam
Nikhef & the University of Groningen
Queen Mary University of London
Royal Holloway, University of London
SISSA
STFC Laboratories
SUBATECH
Stockholm University
TU Darmstadt
TU Dresden

University College London
University and INFN Bologna
University of Barcelona
University of Bern
University of Birmingham
University of Bristol
University of Coimbra
University of Edinburgh
University of Ferrara
University of Freiburg
University of L'Aquila
University of Liverpool
University of Münster
University of Naples "Federico II"
University of Oxford
University of Sheffield
University of Sussex
University of Zurich
Vinca Institute of Nuclear Sciences
Weizmann Institute

Institute for Basic Science
Kobe University
Nagoya University
The Chinese University of Hong Kong, Shenzhen
The University of Tokyo
Tsinghua University
Westlake University

The University of Melbourne
The University of Sydney