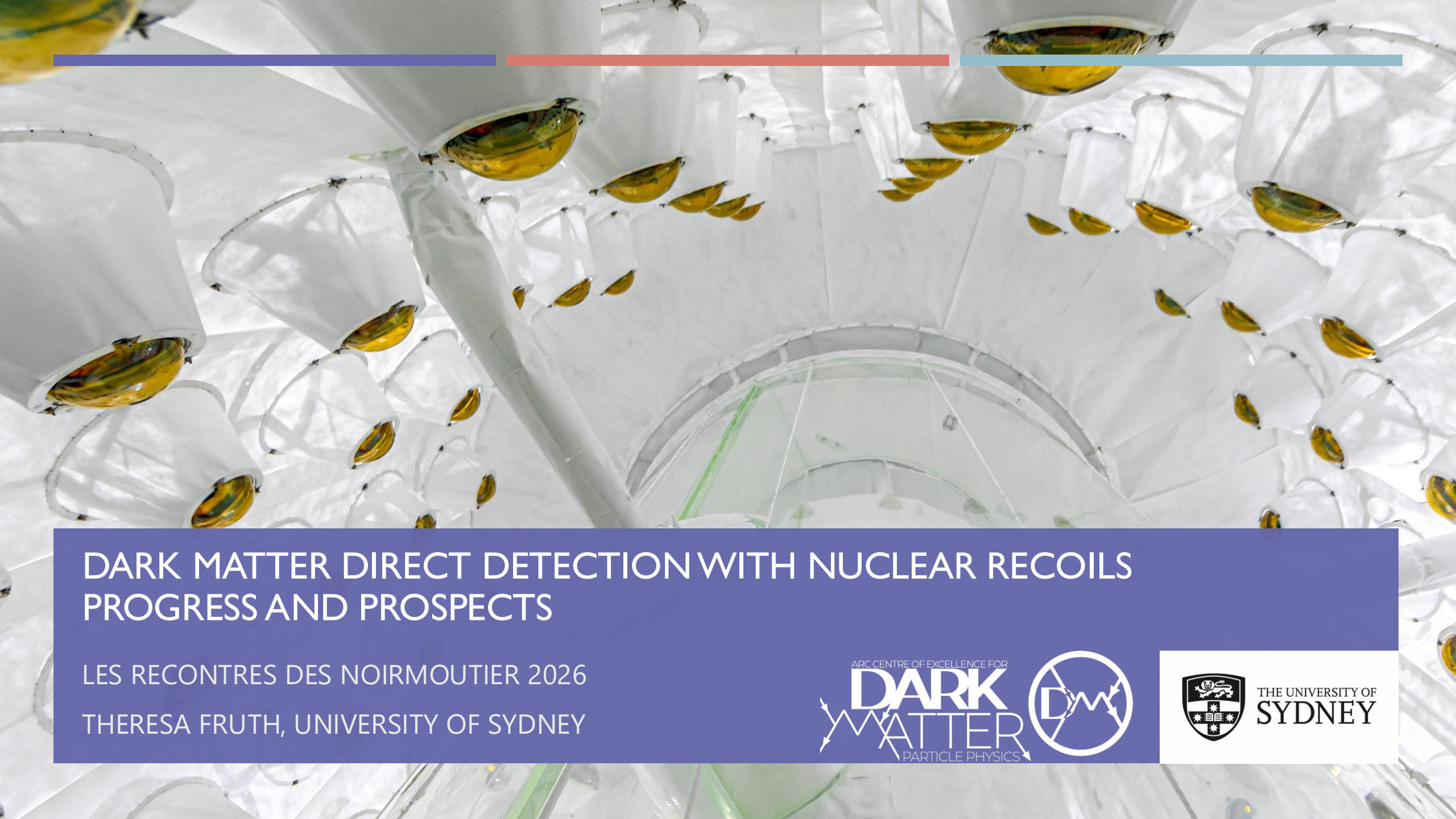


DARK MATTER DIRECT DETECTION WITH NUCLEAR RECOILS PROGRESS AND PROSPECTS

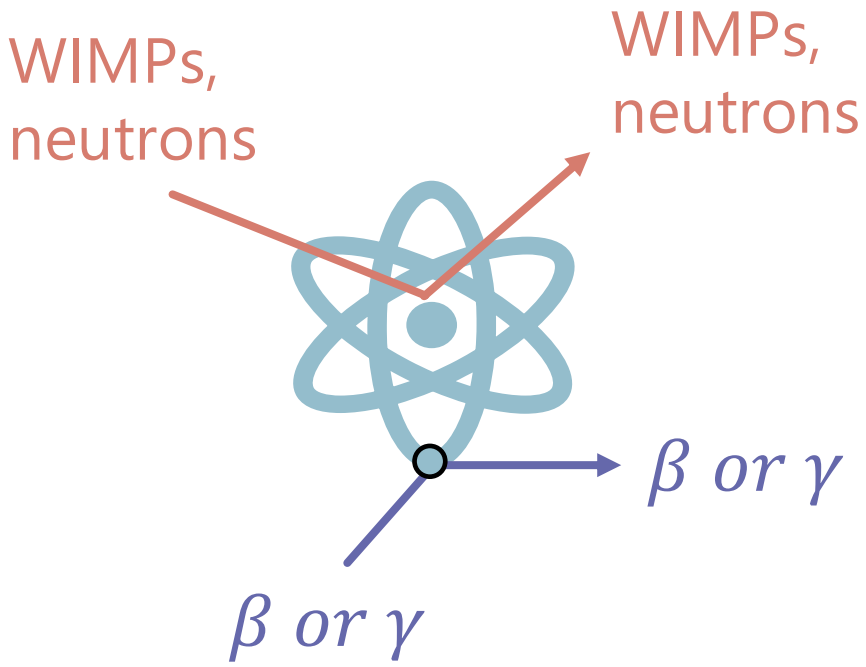
LES RECONTRES DES NOIRMOUTIER 2026

THERESA FRUTH, UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

THE UNIVERSITY OF SYDNEY

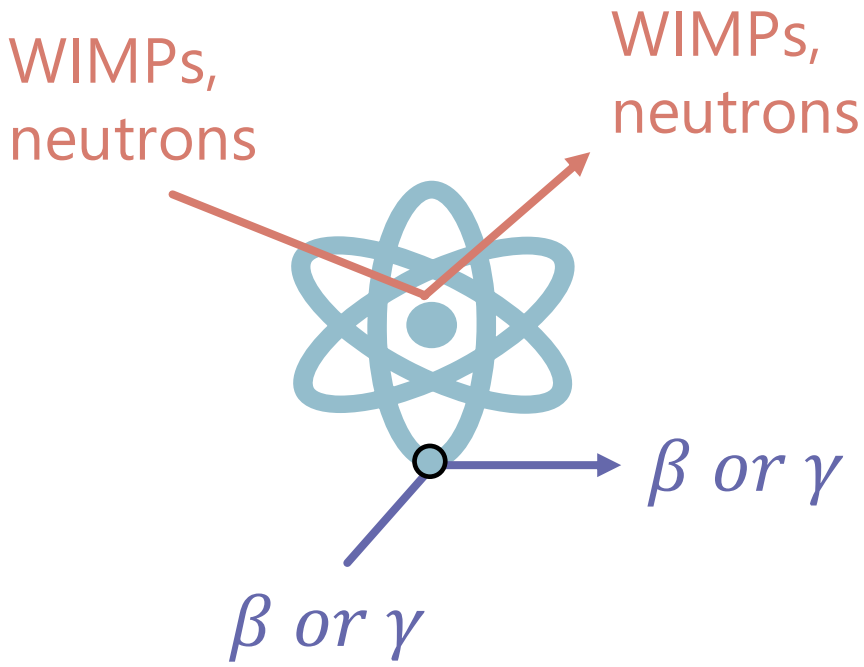
DARK MATTER – NUCLEUS SCATTERING



DM particle (mass: GeV-TeV) scatters elastically of nucleus causing a nuclear recoil

- Rare events (< 0.0001 evt/kg/day)
- Low energy (~ keV scattering)

DARK MATTER – NUCLEUS SCATTERING



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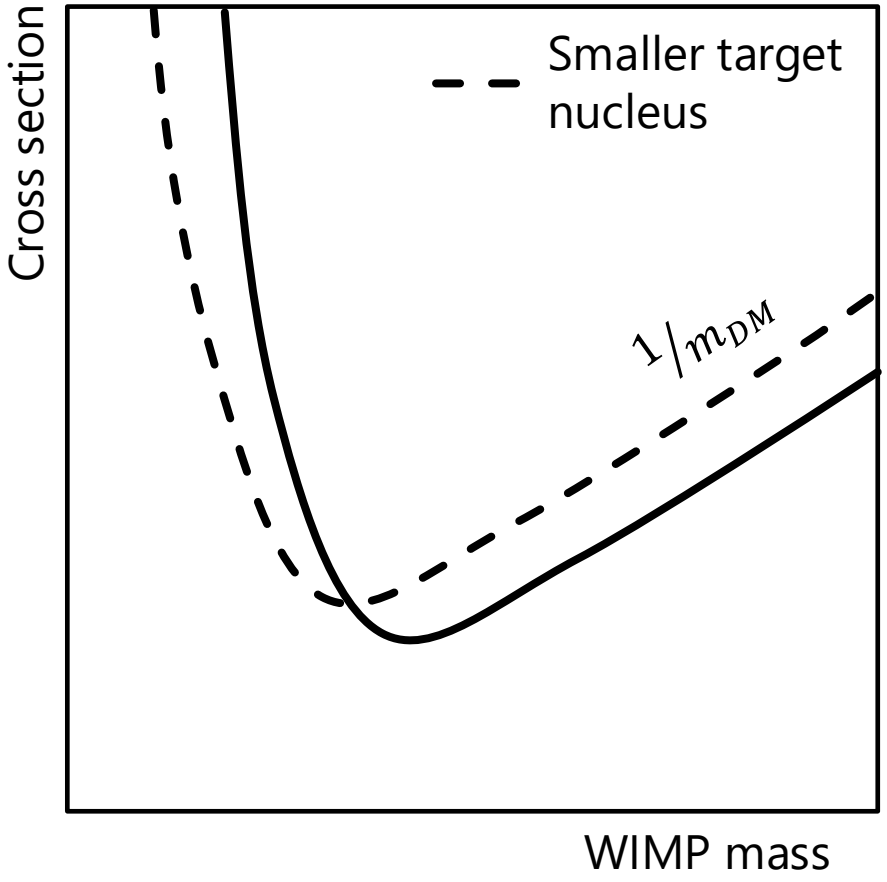
We need to:

- Reduce backgrounds
- Achieve low energy thresholds
- Maximise exposure

DARK MATTER – NUCLEUS SCATTERING



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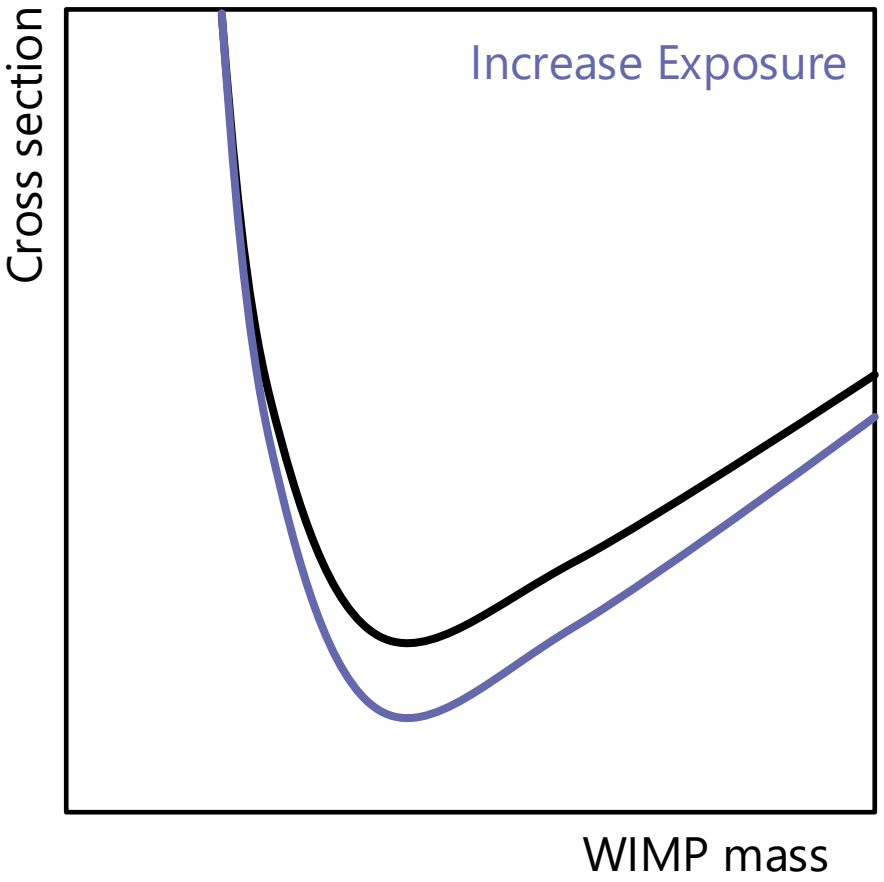

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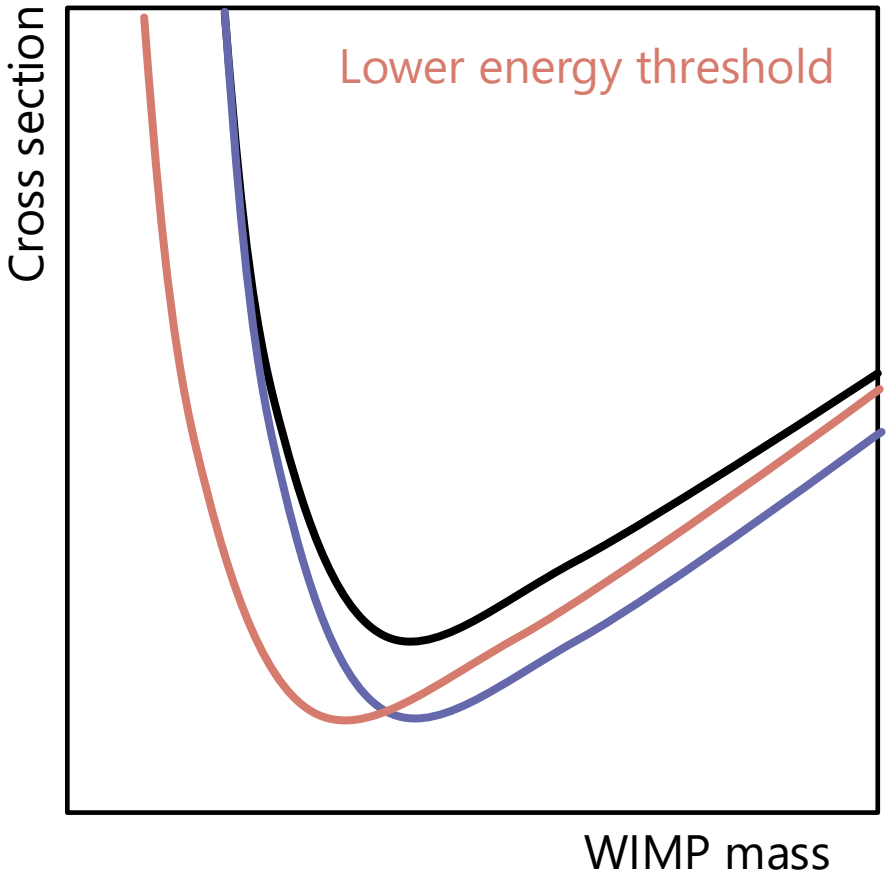

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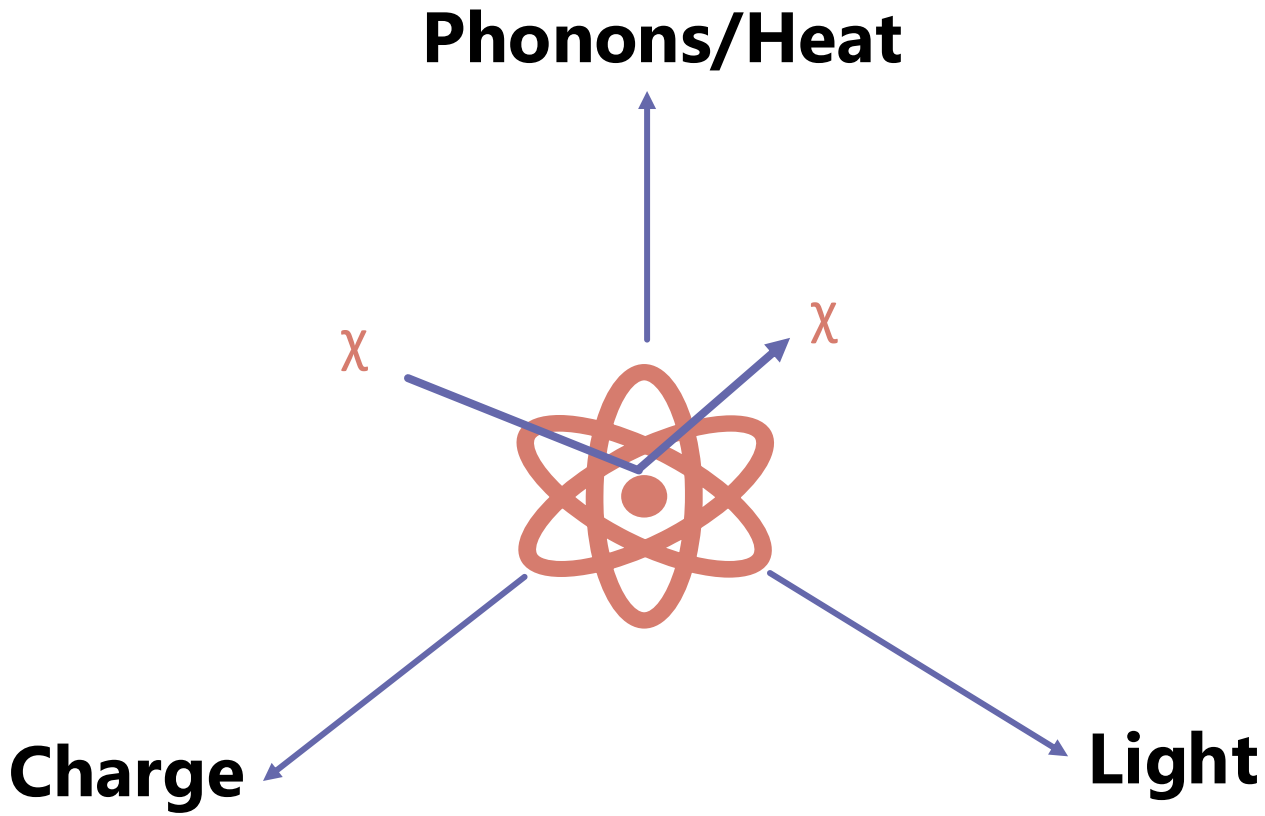
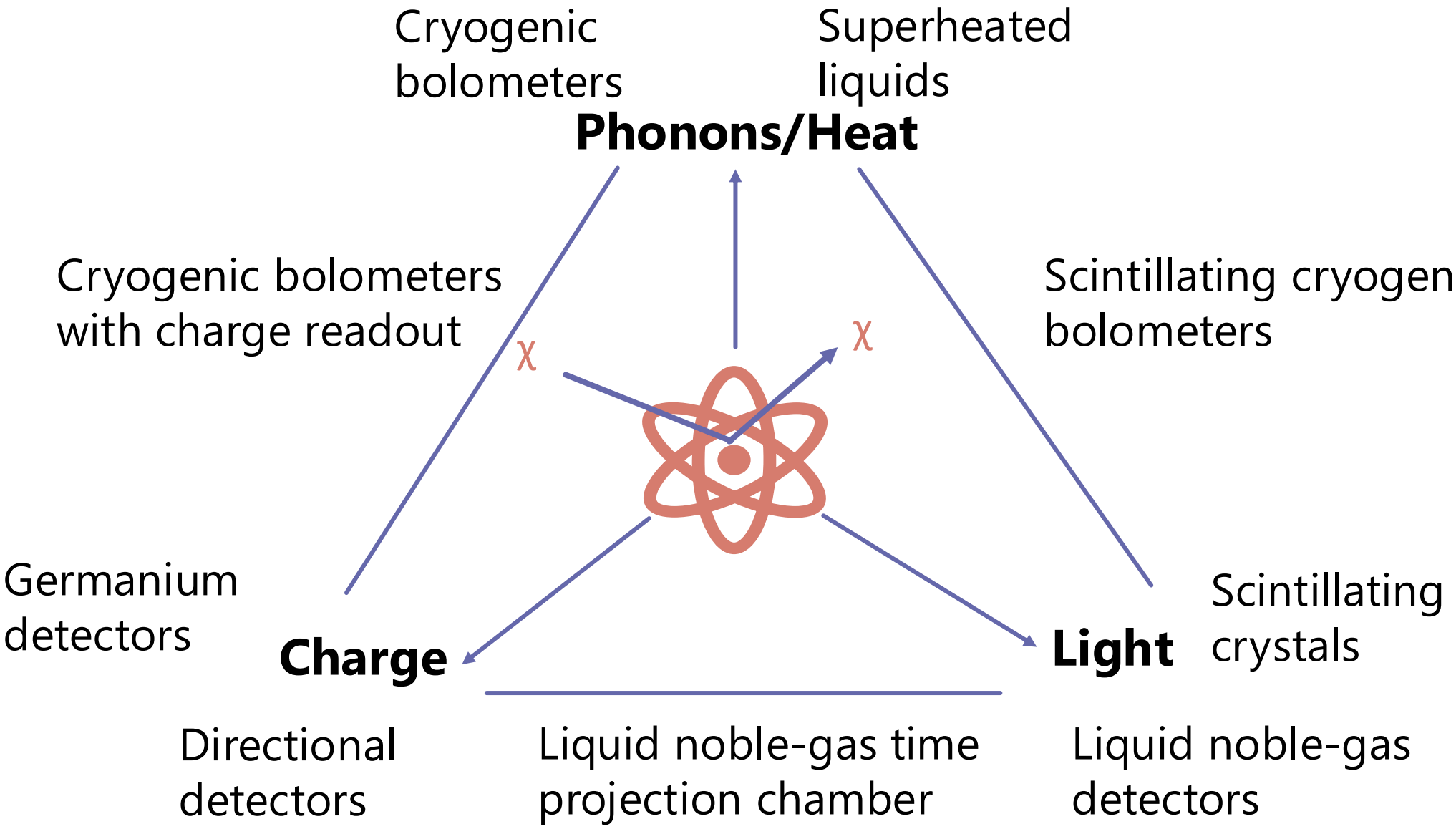
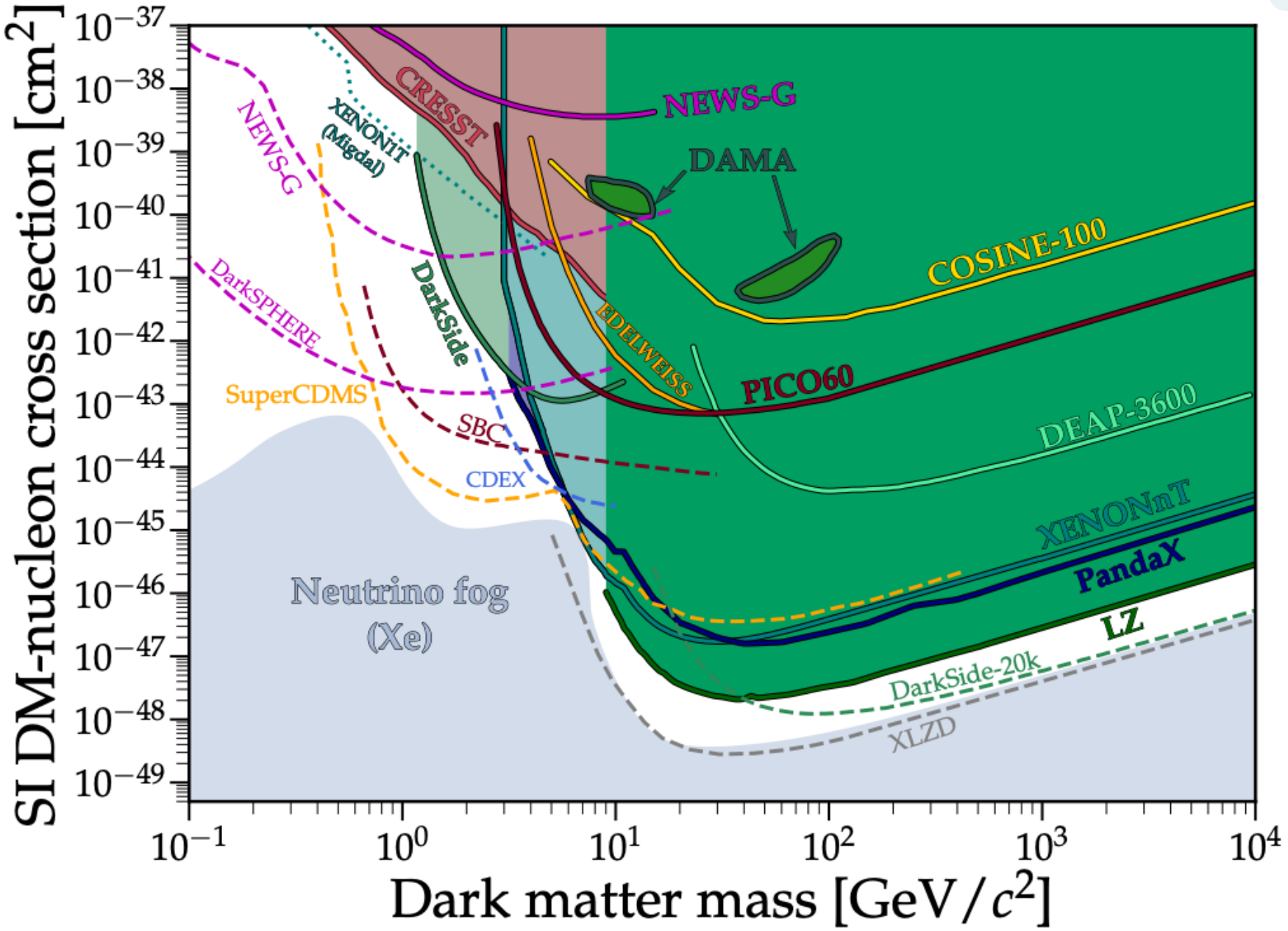
NUCLEAR RECOIL DETECTION



https://arxiv.org/pdf/2104.07634.pdf



Plot by Ciaran O'Hare
(https://github.com/cajohare)



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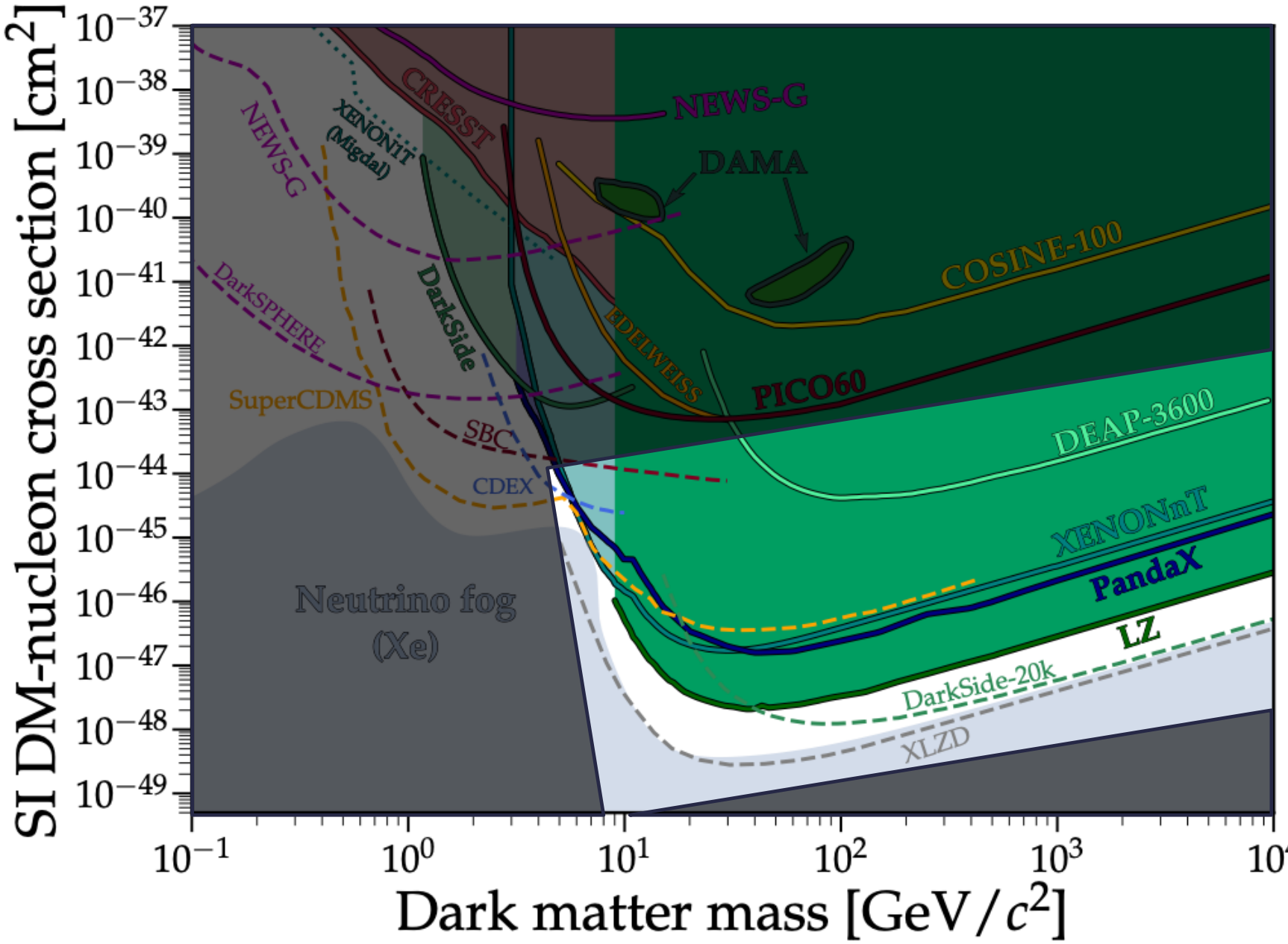
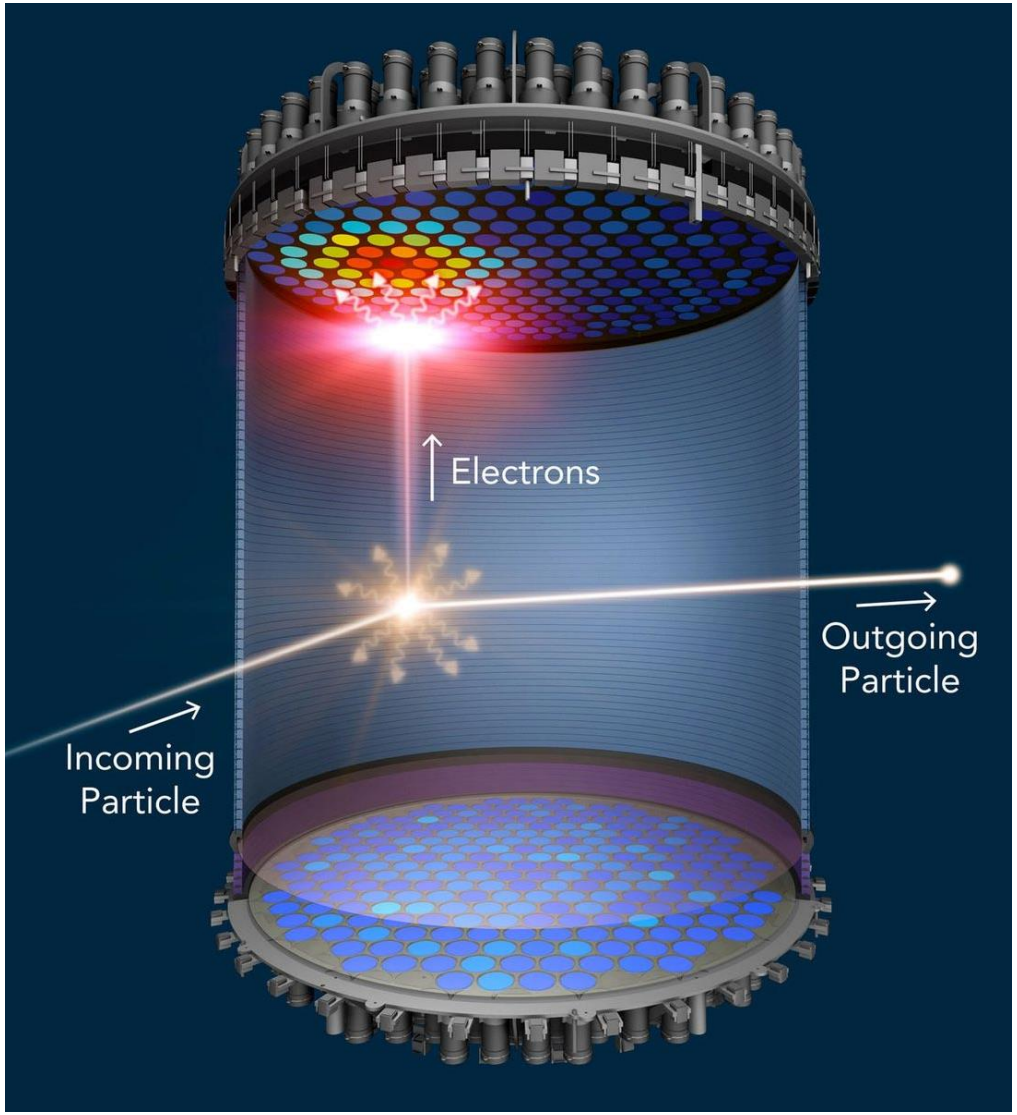


Liquid Noble Detectors

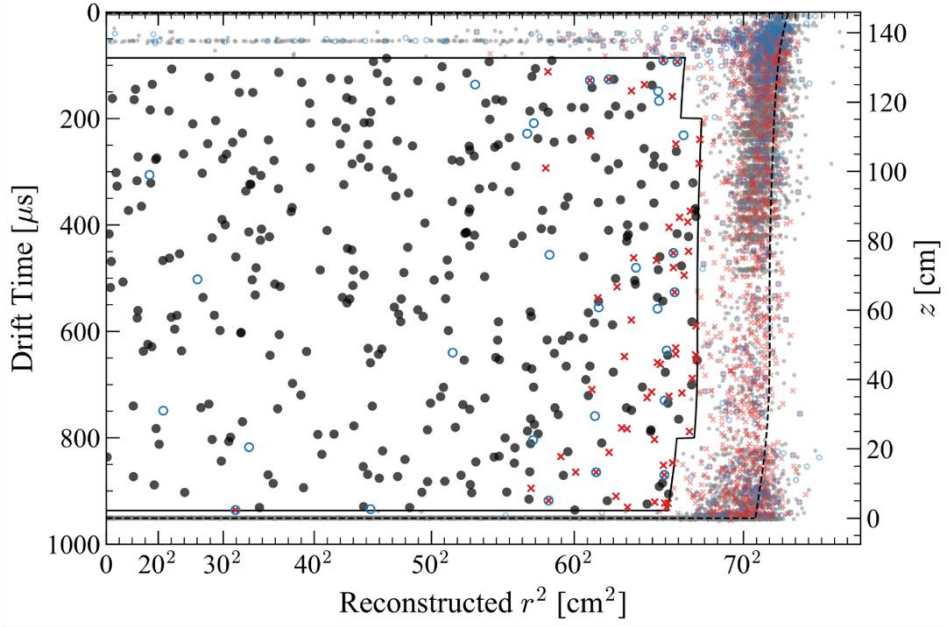
LIQUID NOBLE DETECTORS



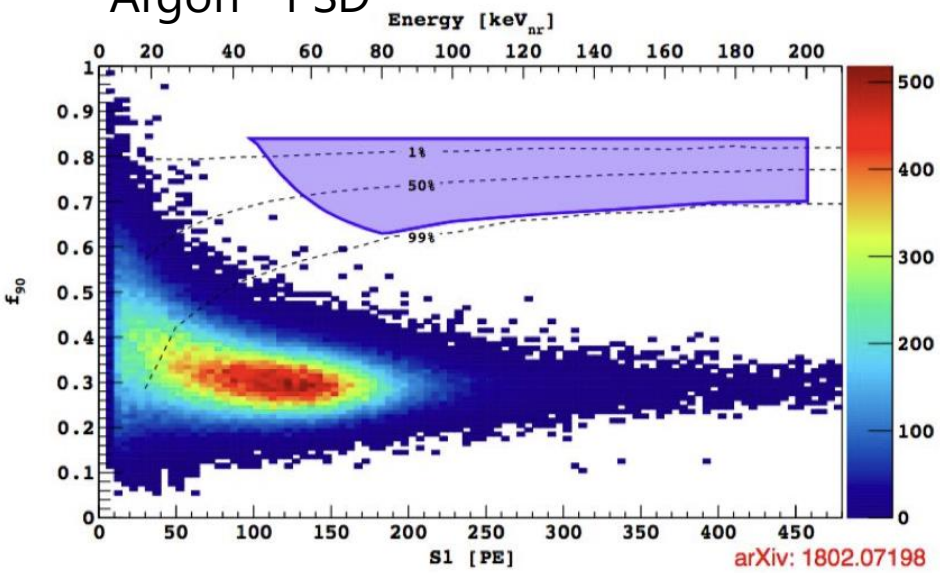
- Noble Liquids: Xe, Ar
- Good scintillators and easily ionized
- Scintillation signal & electroluminescence from ionization charge (in TPC configuration)
- Large target volume, fiducialisation possible
- Event-by-event discrimination by S2/S1 ratio (Xe) or pulse-shape (Ar)

LIQUID NOBLE DETECTORS

Xenon - Fiducialisation



Argon - PSD



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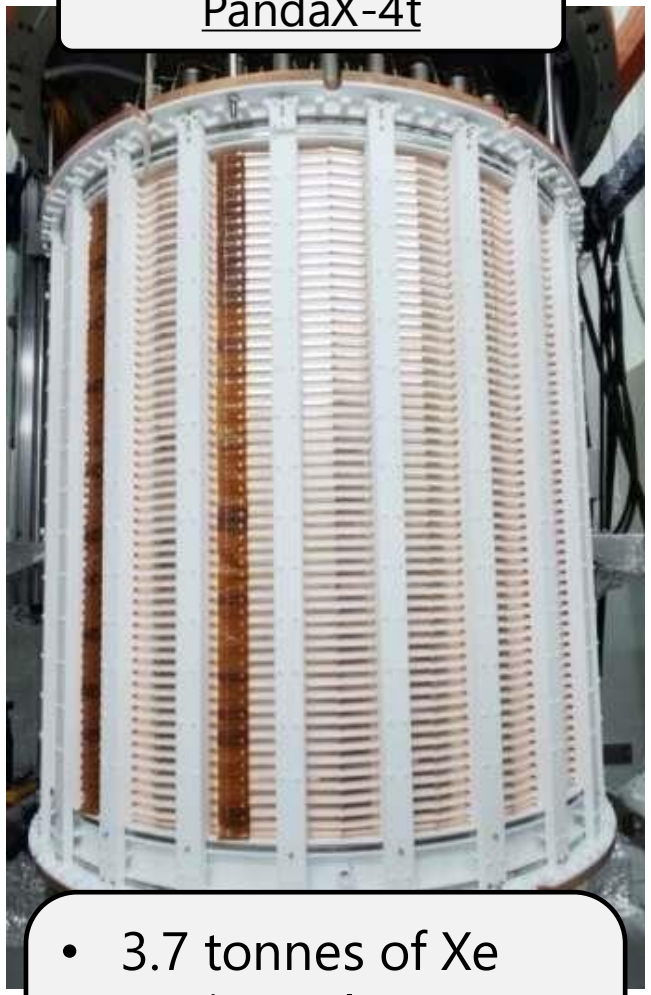
Xenon detectors

PandaX-4t



- 3.7 tonnes of Xe (active volume)
- 368 PMTs
- Status: running

XENONnT

- 5.9 tonnes of Xe (active volume)
- 494 PMTs
- Status: running

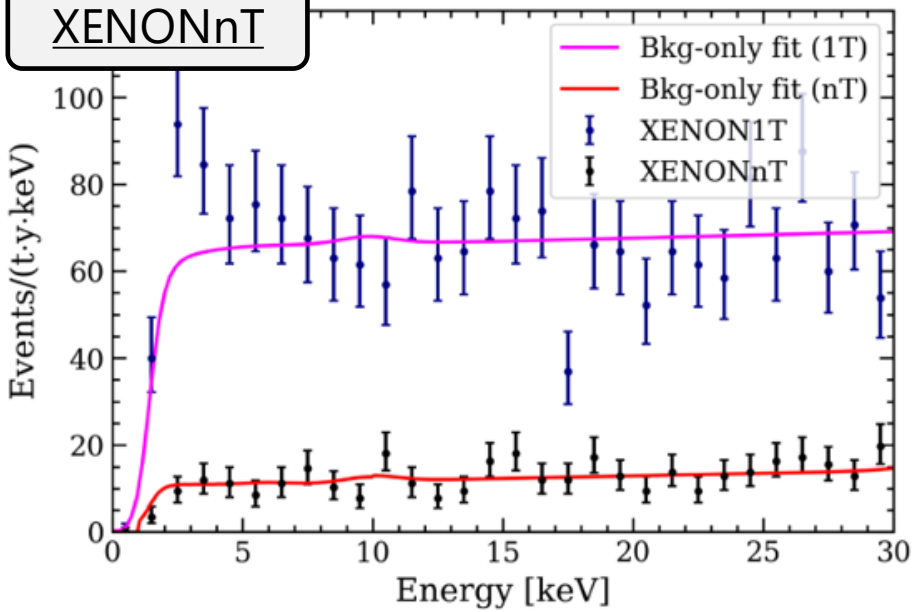
LZ

- 7 tonnes of Xe (active volume)
- 494 PMTs
- Status: running

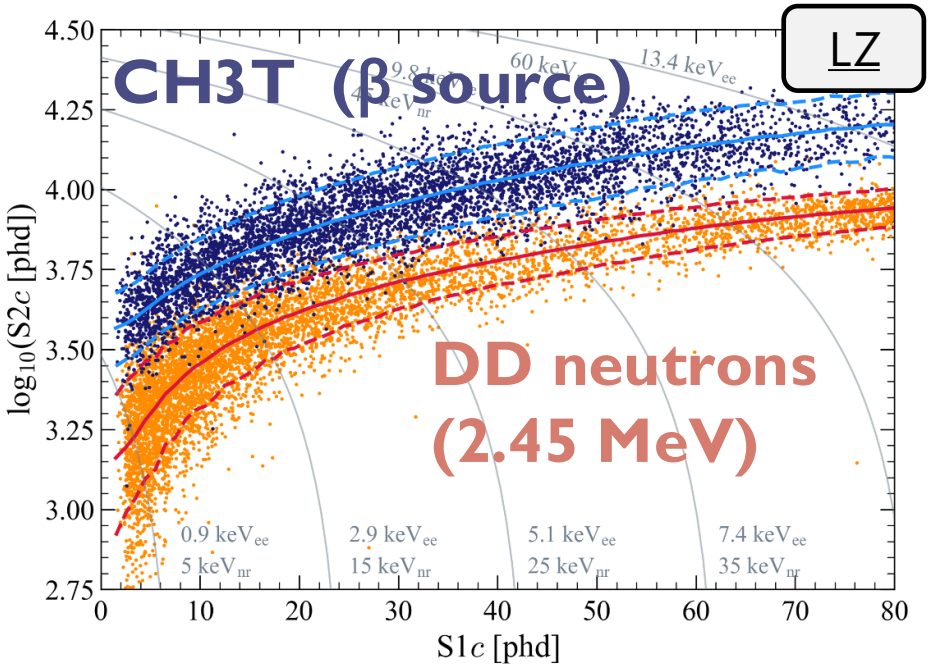
Xenon detectors

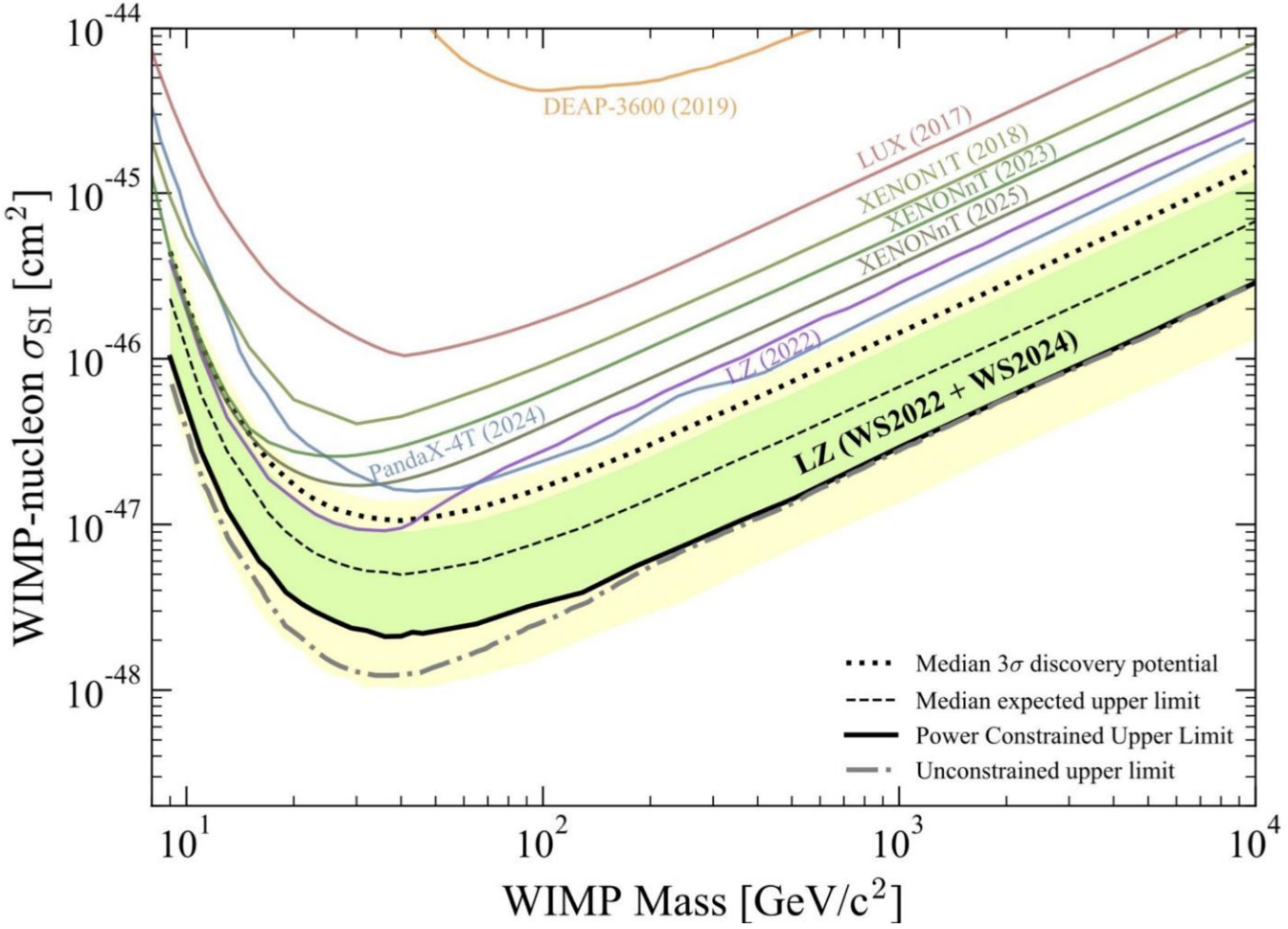
PandaX-4T: PRL134 (2025) 011805
LZ: PRL 135 (2025) 011802
XENONnT: arXiv:2502.18005 (2025)

XENONnT



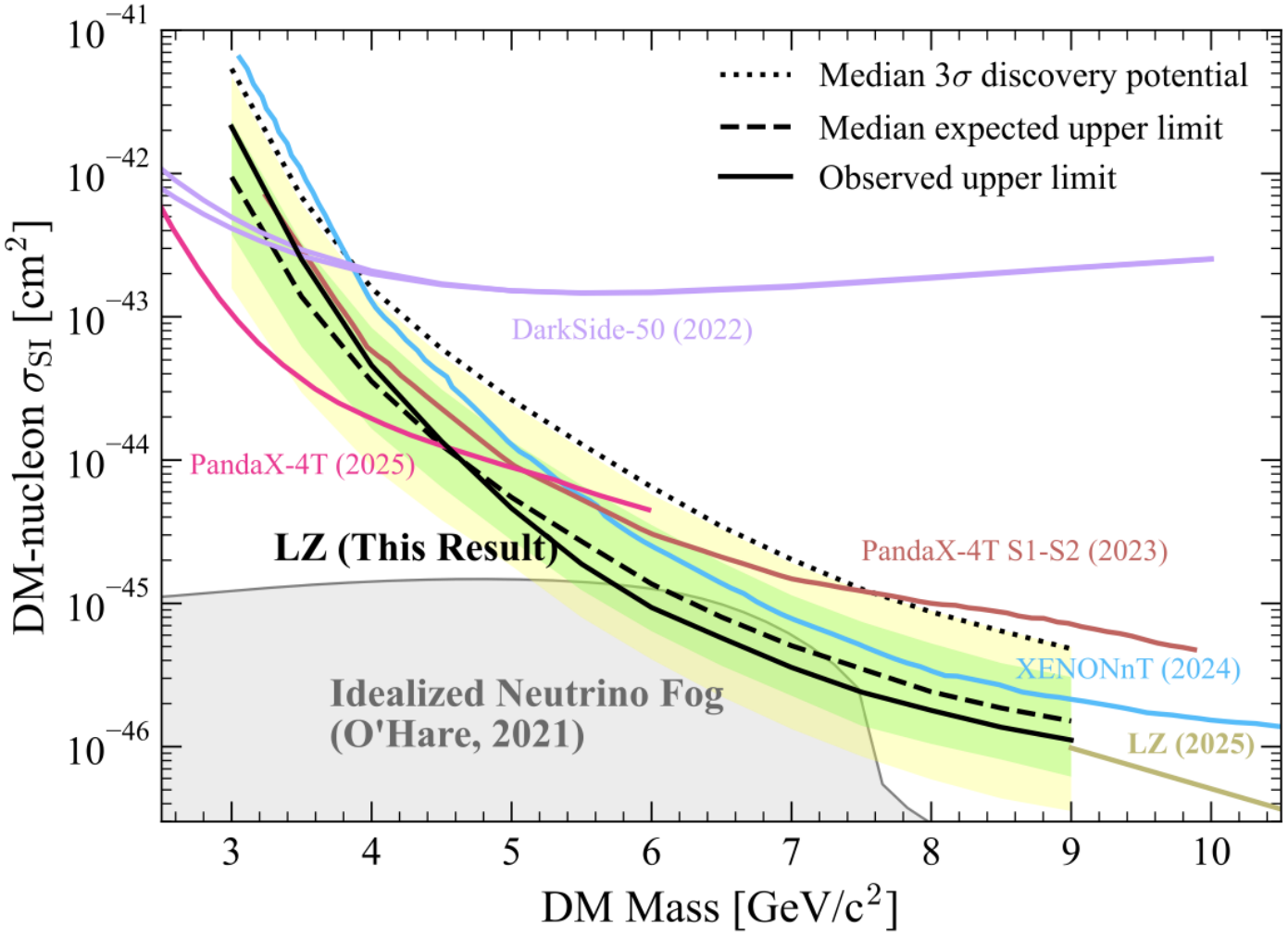
LZ



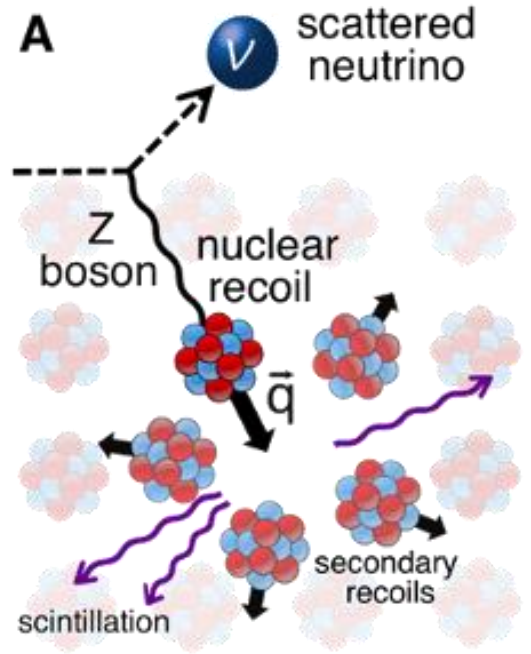


Xenon detectors – Beyond Dark Matter

XENONnT: PRL 123, 2024
PandaX-4T: PRL 123, 2024
LZ: arXiv:2512.08065

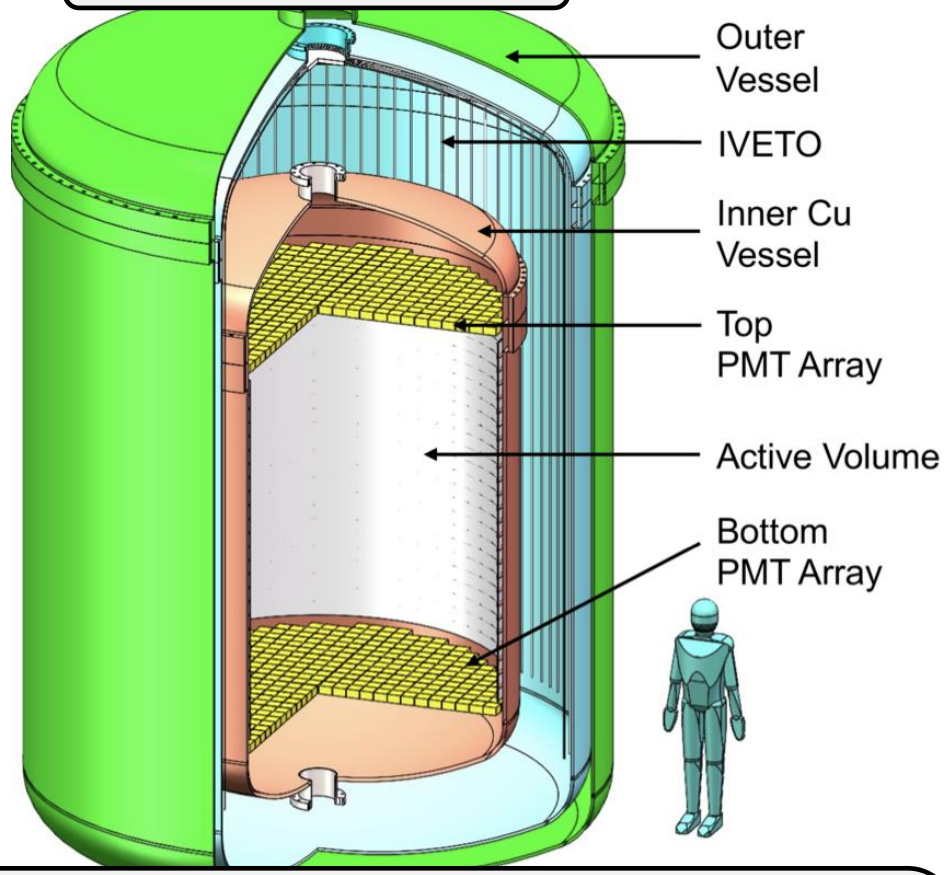


- At low energies, starting to push into the neutrino fog
- Coherent neutrino-nucleus scattering, a well-predicted neutral current SM process



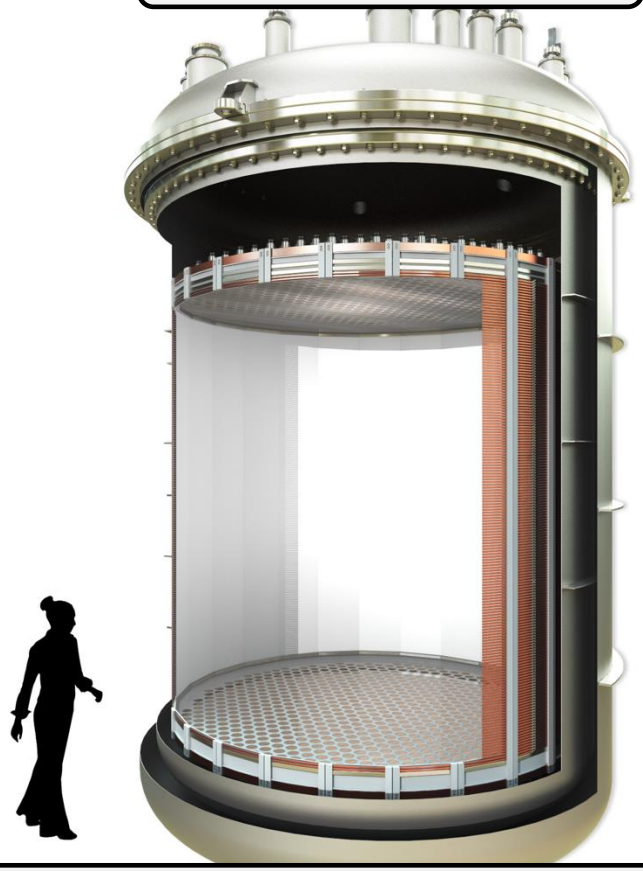
Next generation xenon detectors

PandaX-xt



- 43 tonnes of Xe (active volume)
- Panda collaboration
- Design paper: *Sci. China Phys. Mech. Astron.* 68 (2025) 2, 221011

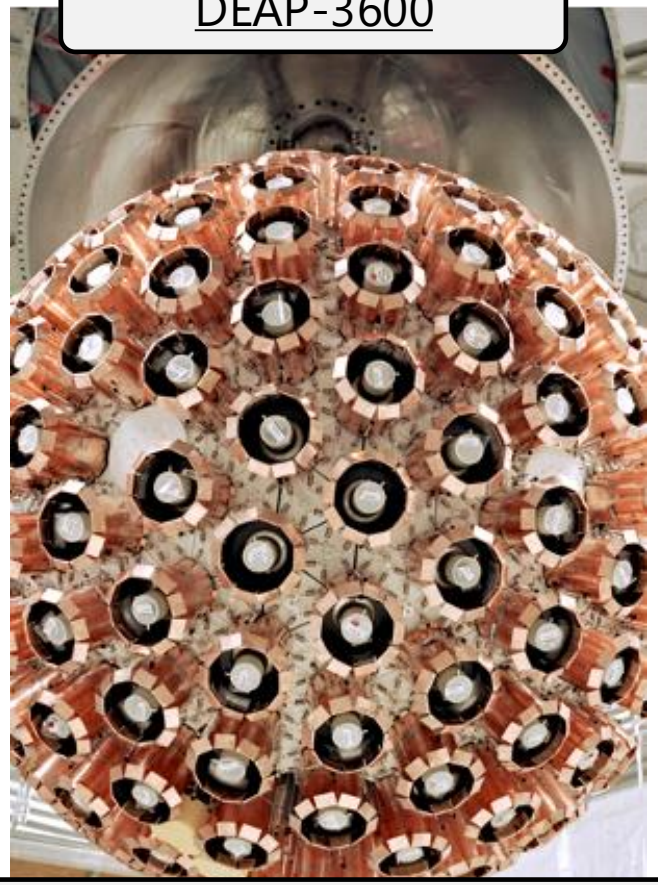
XLZD



- 60-80 tonnes of Xe (active volume)
- Xenon, LZ and DARWIN merged into a formal collaboration in 2024
- Design Book: EPJC (2025) 85: 1192

Argon detectors

DEAP-3600



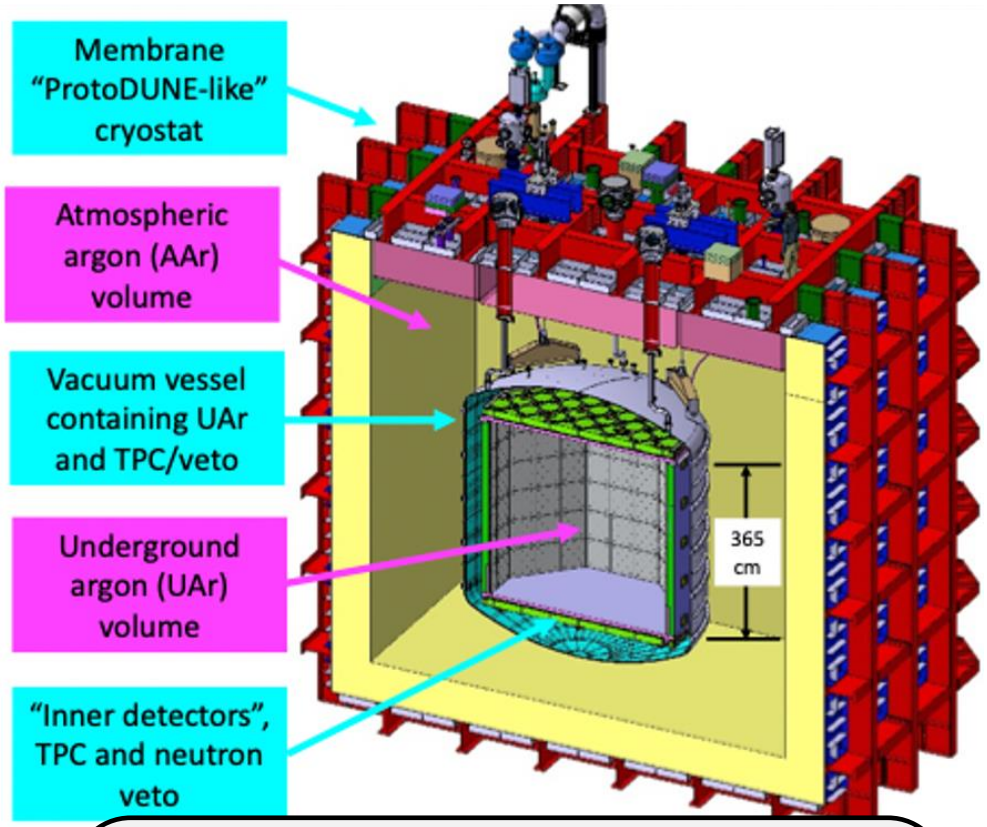
- 3.3 t of Argon
- 255 PMTs & light guides
- Status: running after hardware updates to reach design sensitivity

DarkSide-50

- 46 kg of UAr
- 38 PMTs
- Status: ended

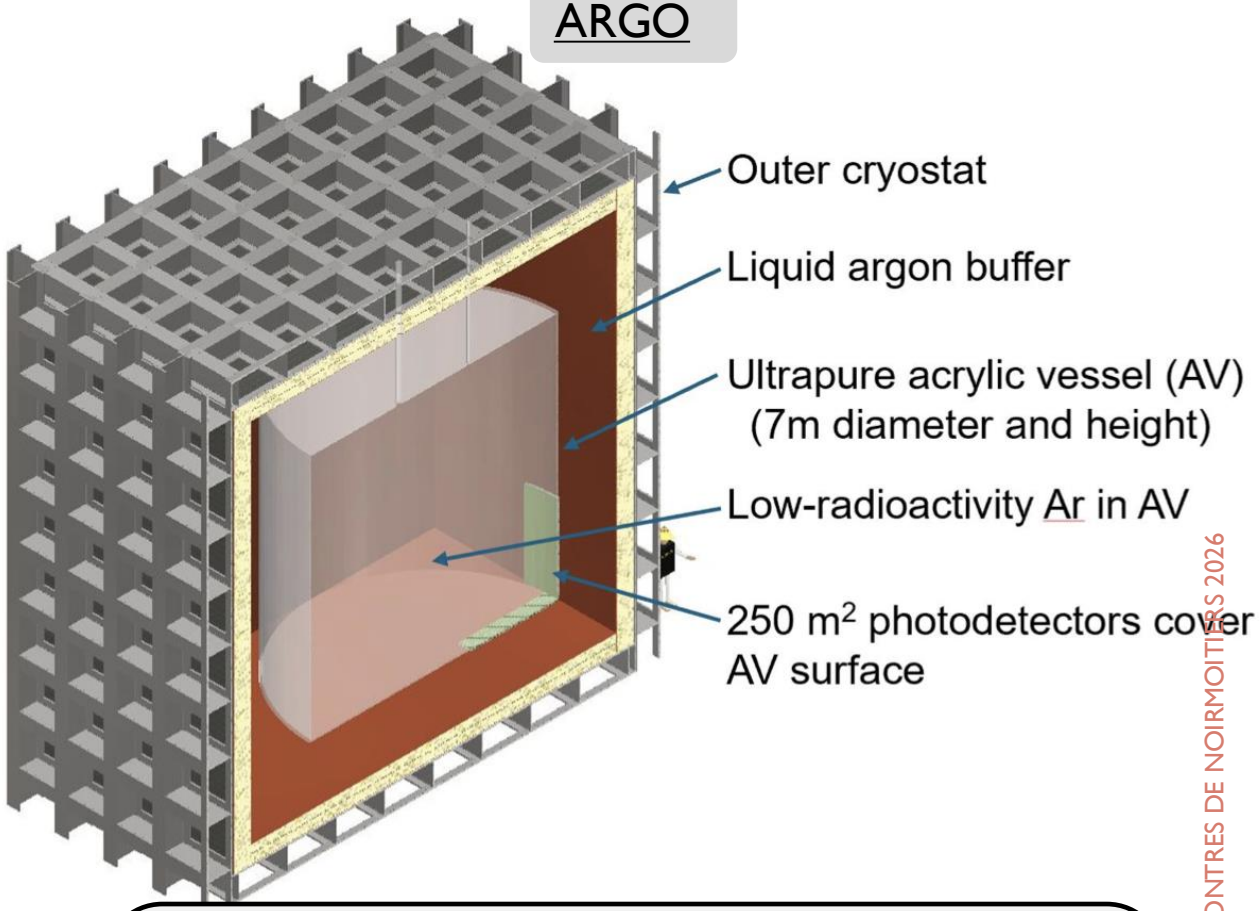
GLOBAL ARGON DARK MATTER COMMUNITY

DarkSide – 20k



- 50 tonnes active target
- 2-phase detector, switch to SiPMs
- Aim for 460 t-y exposure
- Status: under construction, data taking expected in 2028

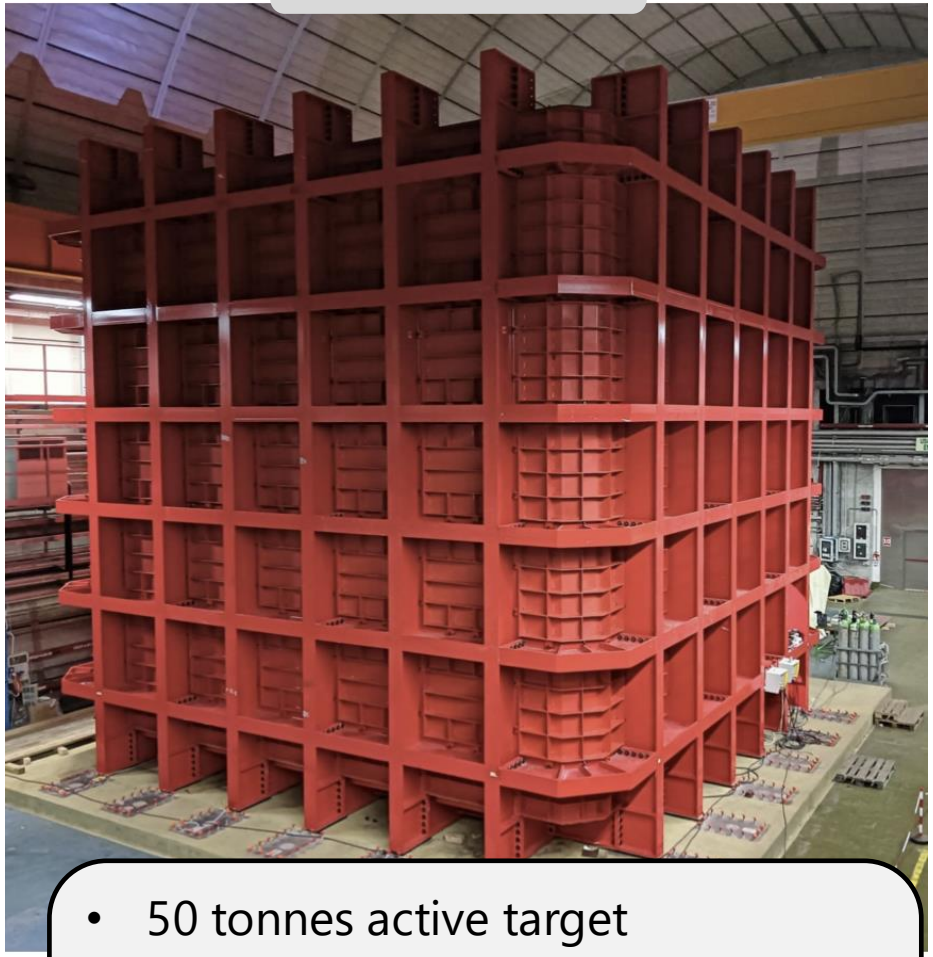
ARGO



- 400 tonnes total mass (300 t fiducial mass)
- Pixelated digital photodetector readout
- Both single-phase and TPC design being considered
- Status: Conceptual design

GLOBAL ARGON DARK MATTER COMMUNITY

DarkSide – 20k



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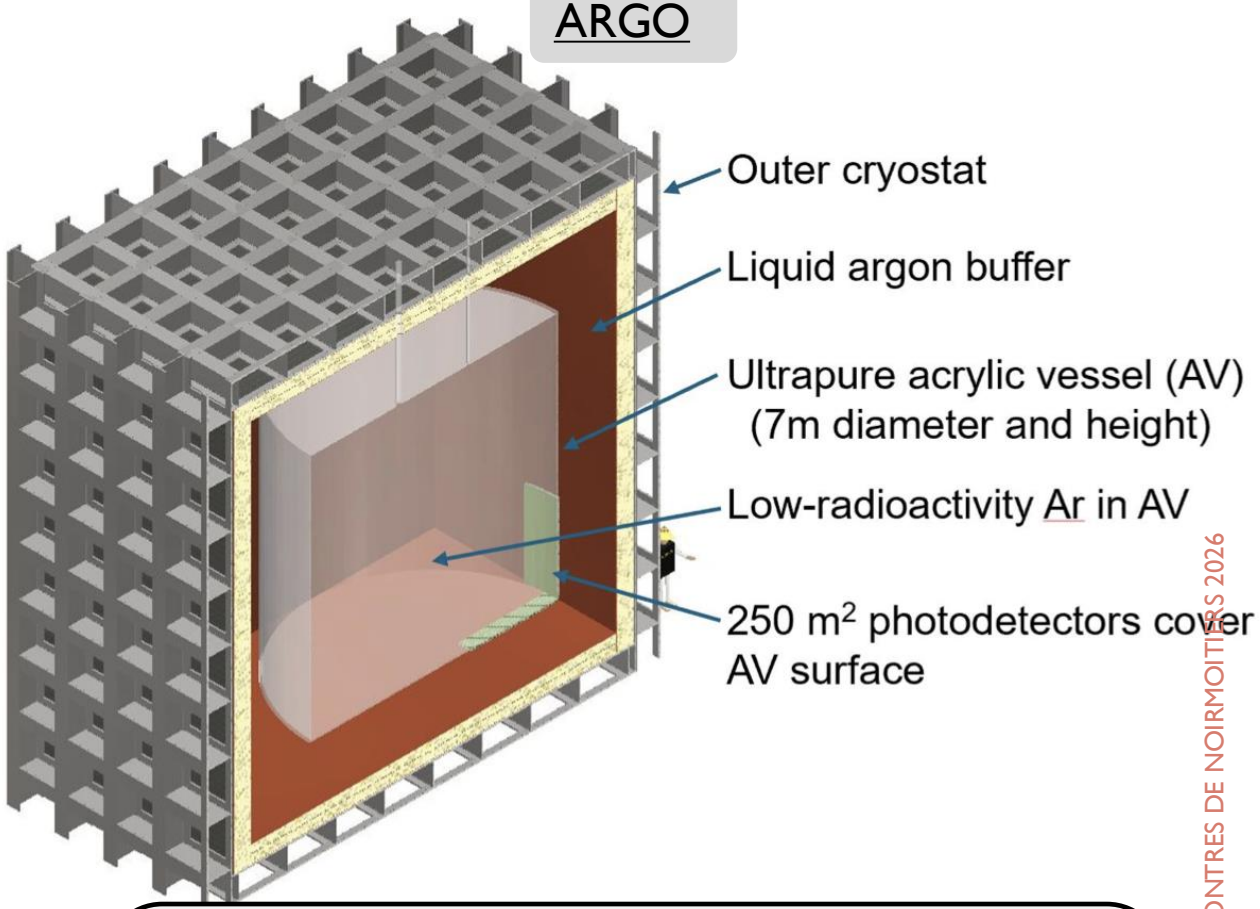

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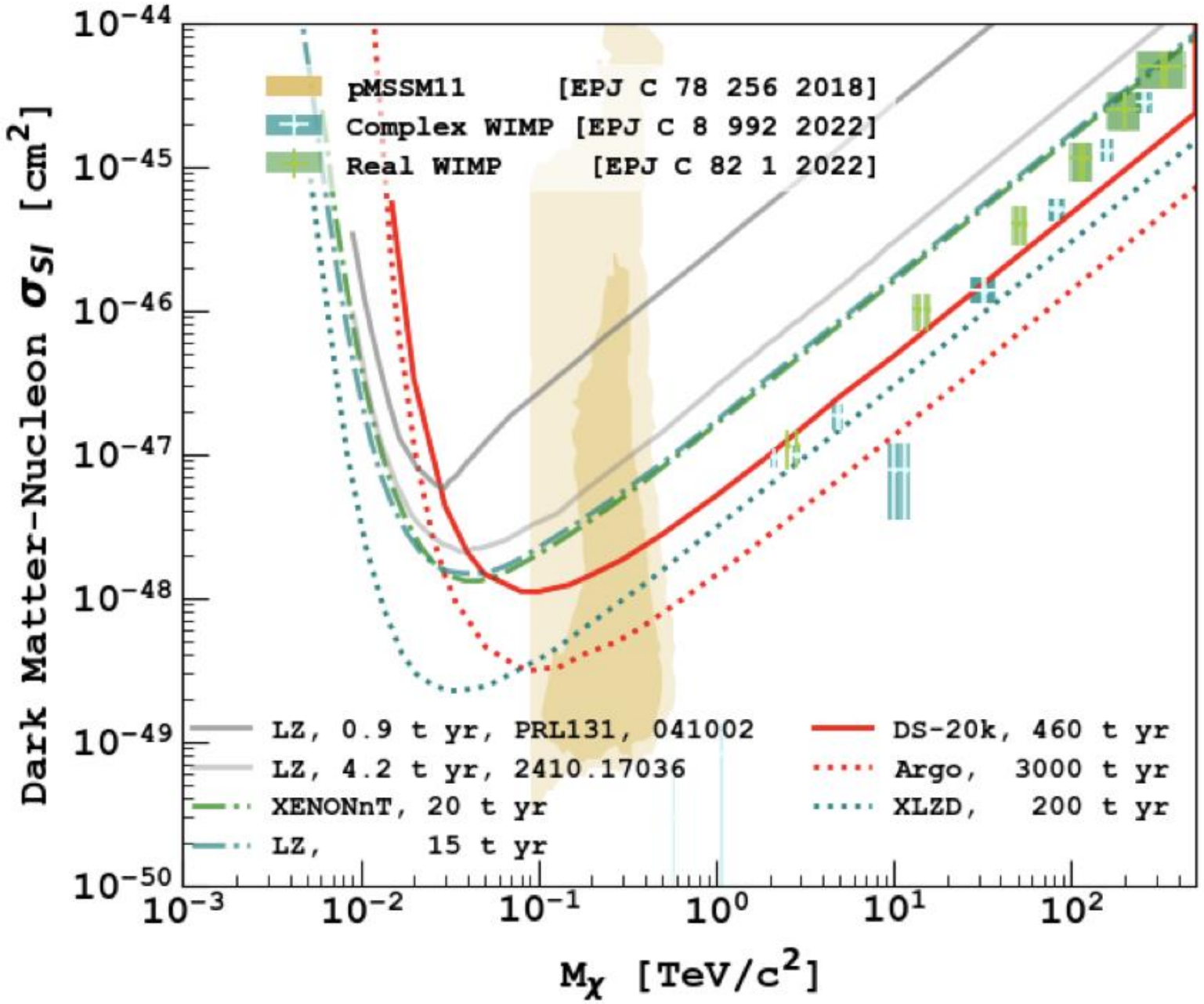
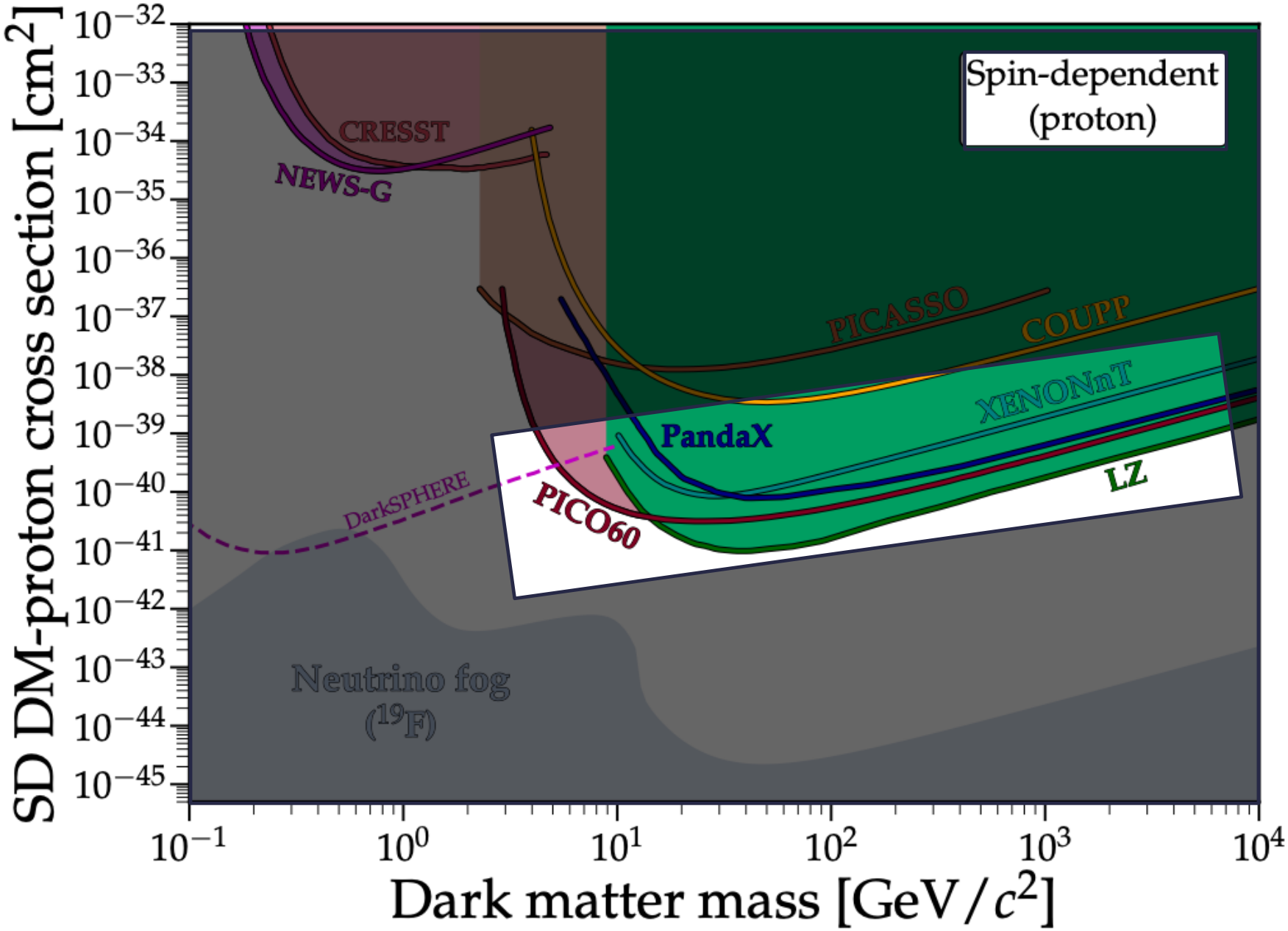
NEXT GENERATION

GADMC input to ESPP2025



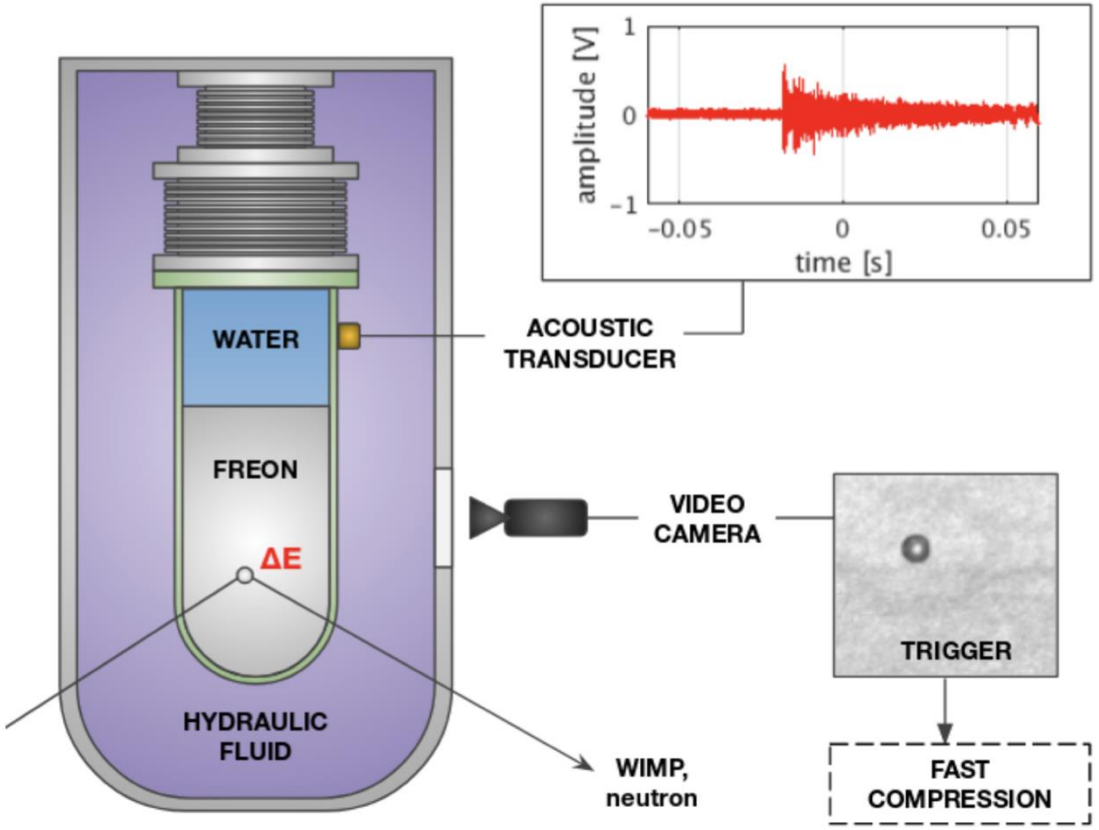
Plot by Ciaran O'Hare
(https://github.com/cajohare)



Bubble Chambers

BUBBLE CHAMBERS

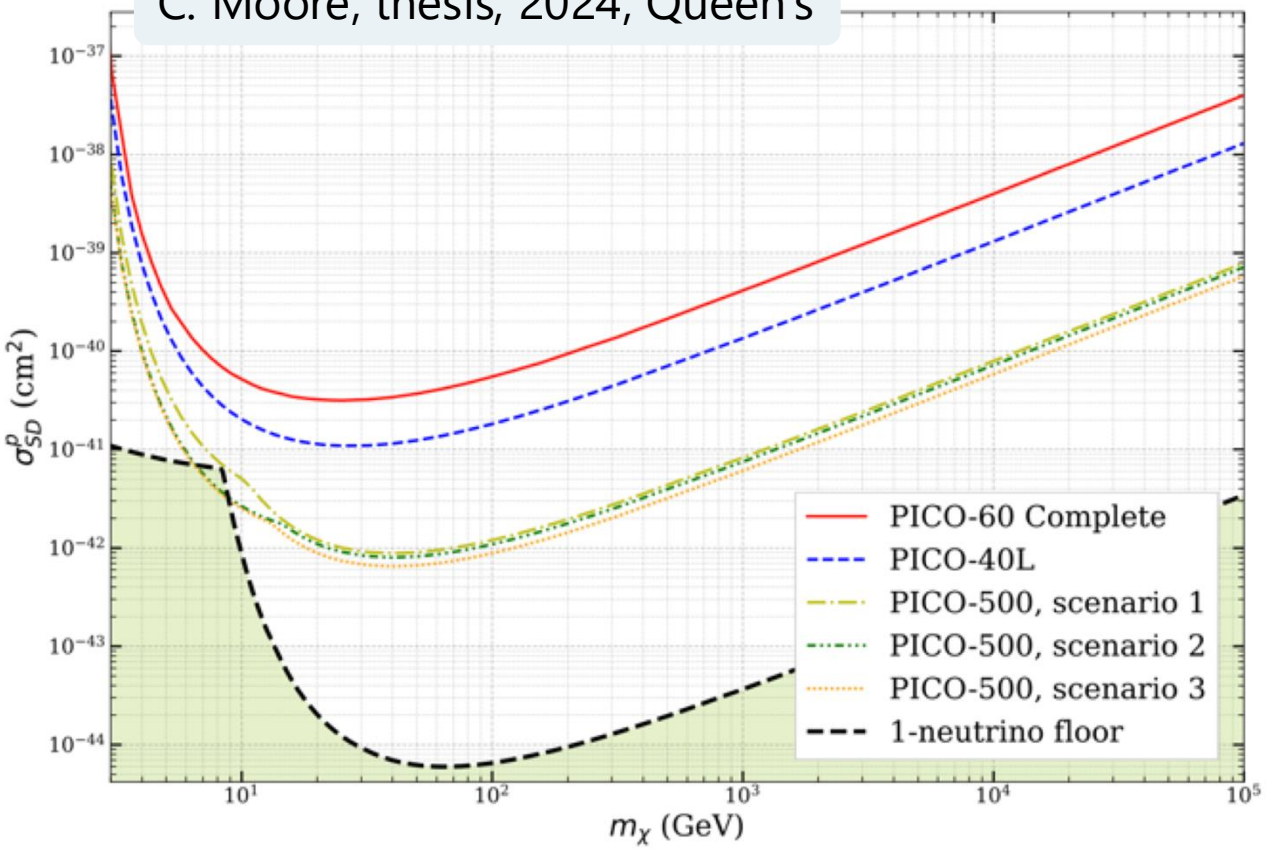
Guillaume Giroux 2021 J. Phys.: Conf. Ser. 2156 012068



- Bubble chambers using superheated liquids (Freon-based).
- Threshold detector, ER background suppression by energy tuning
- 3D event reconstruction

BUBBLE CHAMBERS

C. Moore, thesis, 2024, Queen's

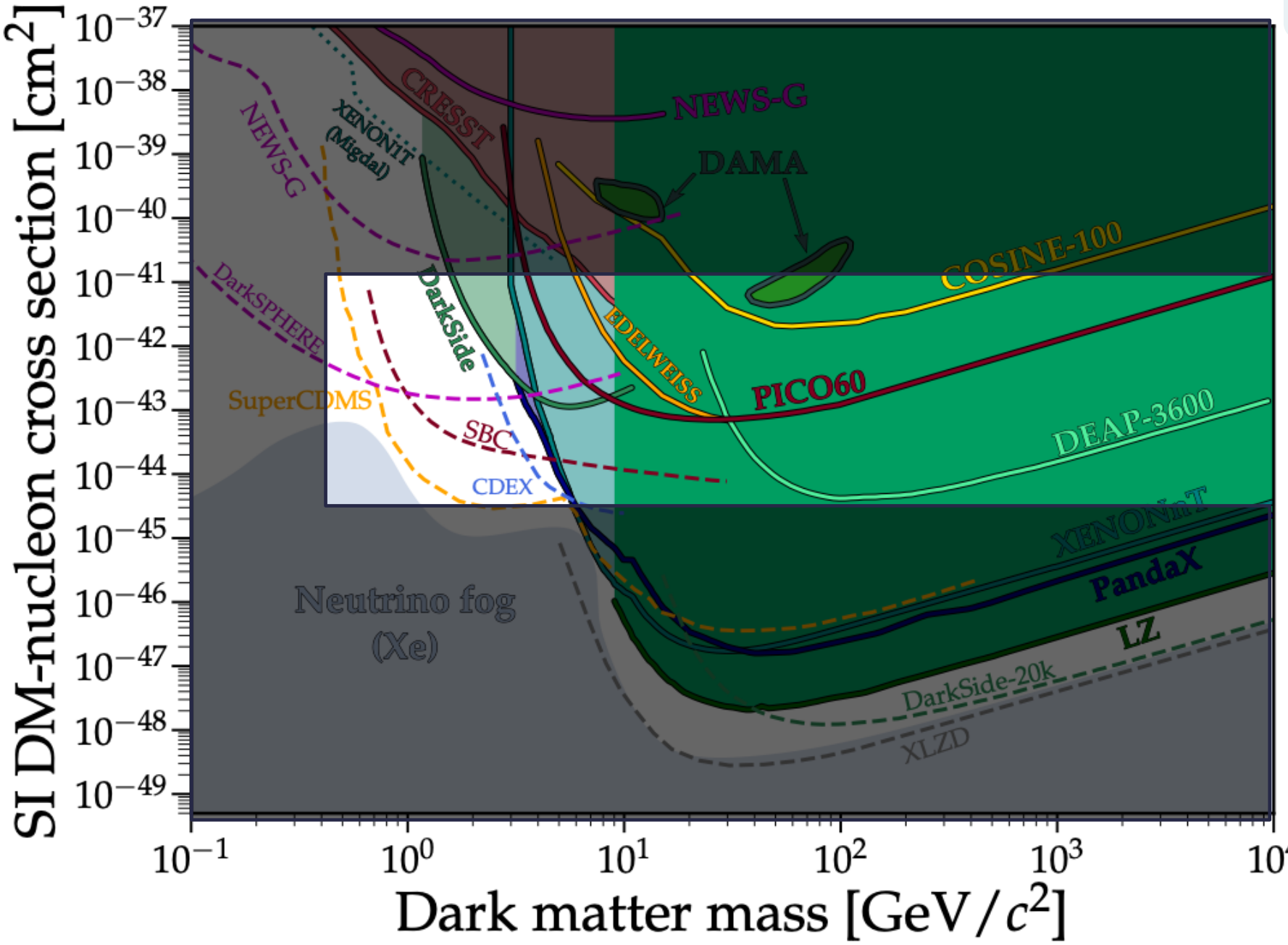


- Leading WIMP-proton spin-dependent limits with PICO-60
- PICO- 40L running (right-side-up design)
- Next generation: PICO-500 (commissioning expected 2026)

PICO – 40L

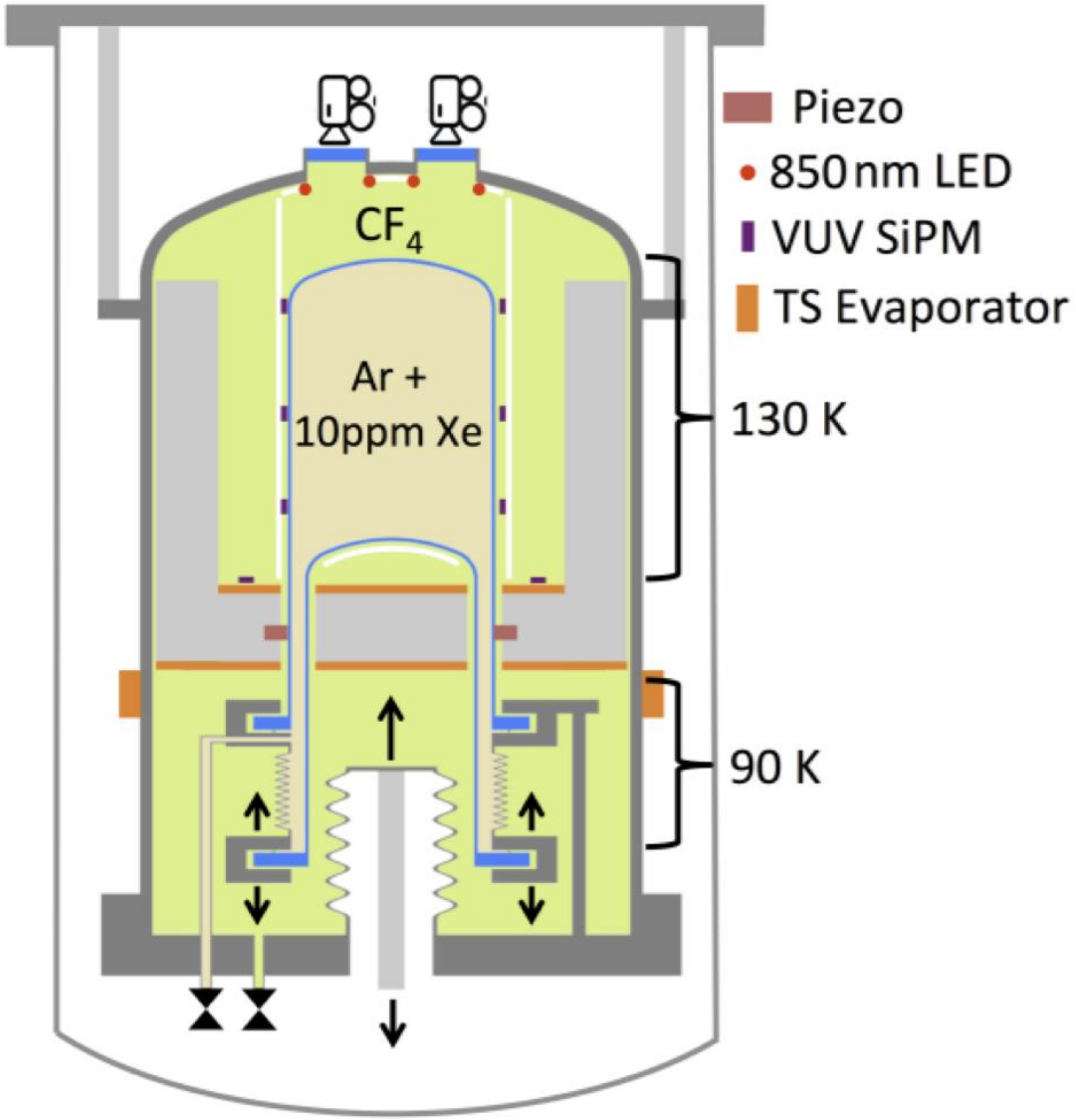
PICO – 500

Plots by Ciaran O'Hare
(https://github.com/cajohare)



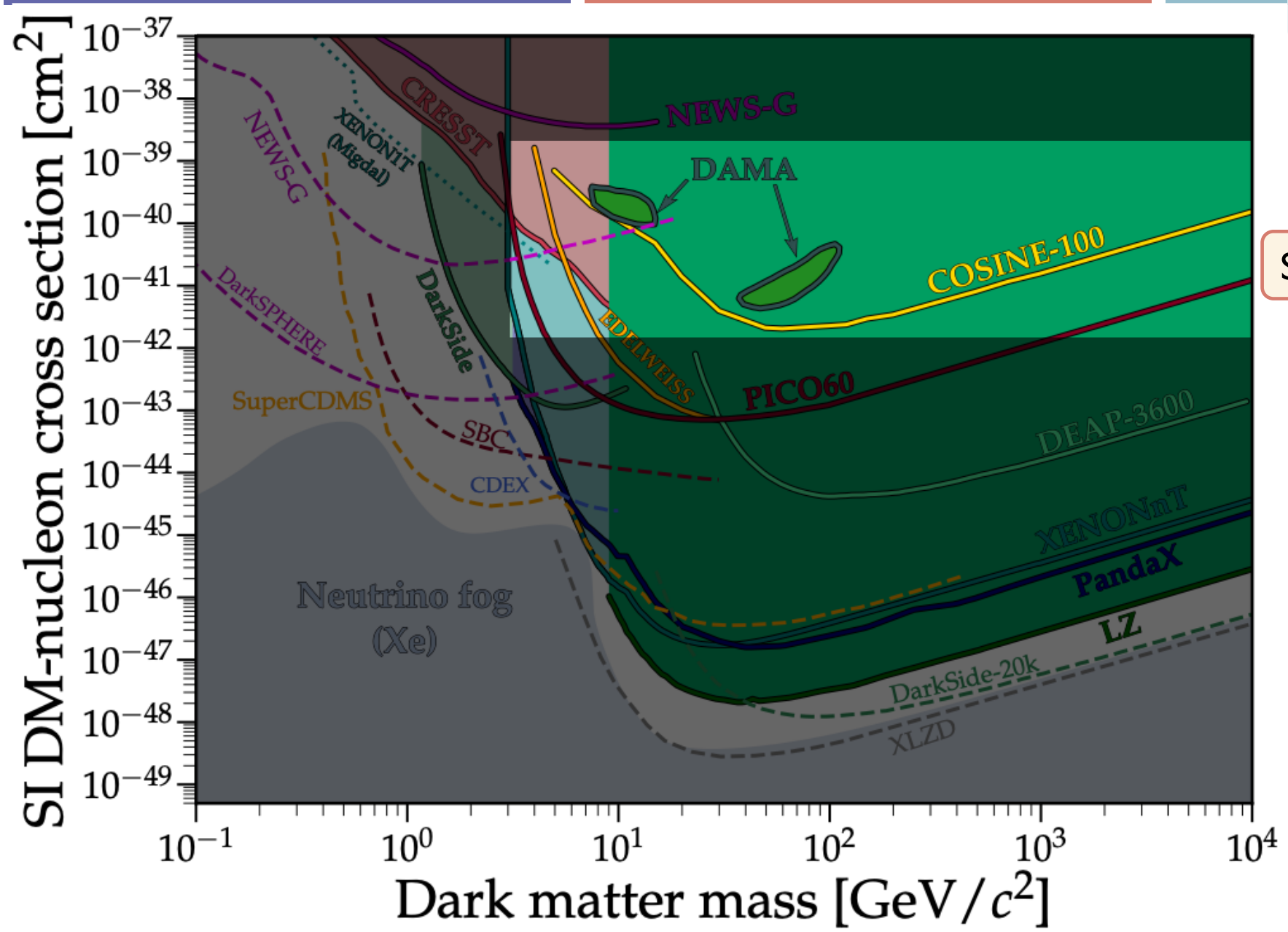
Scintillating Bubble Chambers

SCINTILLATING BUBBLE CHAMBERS



- Improved low energy ER rejection
- Scintillation as added signal channel, detected with VUV SiPMs to veto high-energy backgrounds and neutron calibration
- SBC LAr10 with 10 kg Ar target and 100 eV target threshold
- 10 ppm xenon to wavelength shift the scintillation light
- At Fermilab, eventually SNOLab

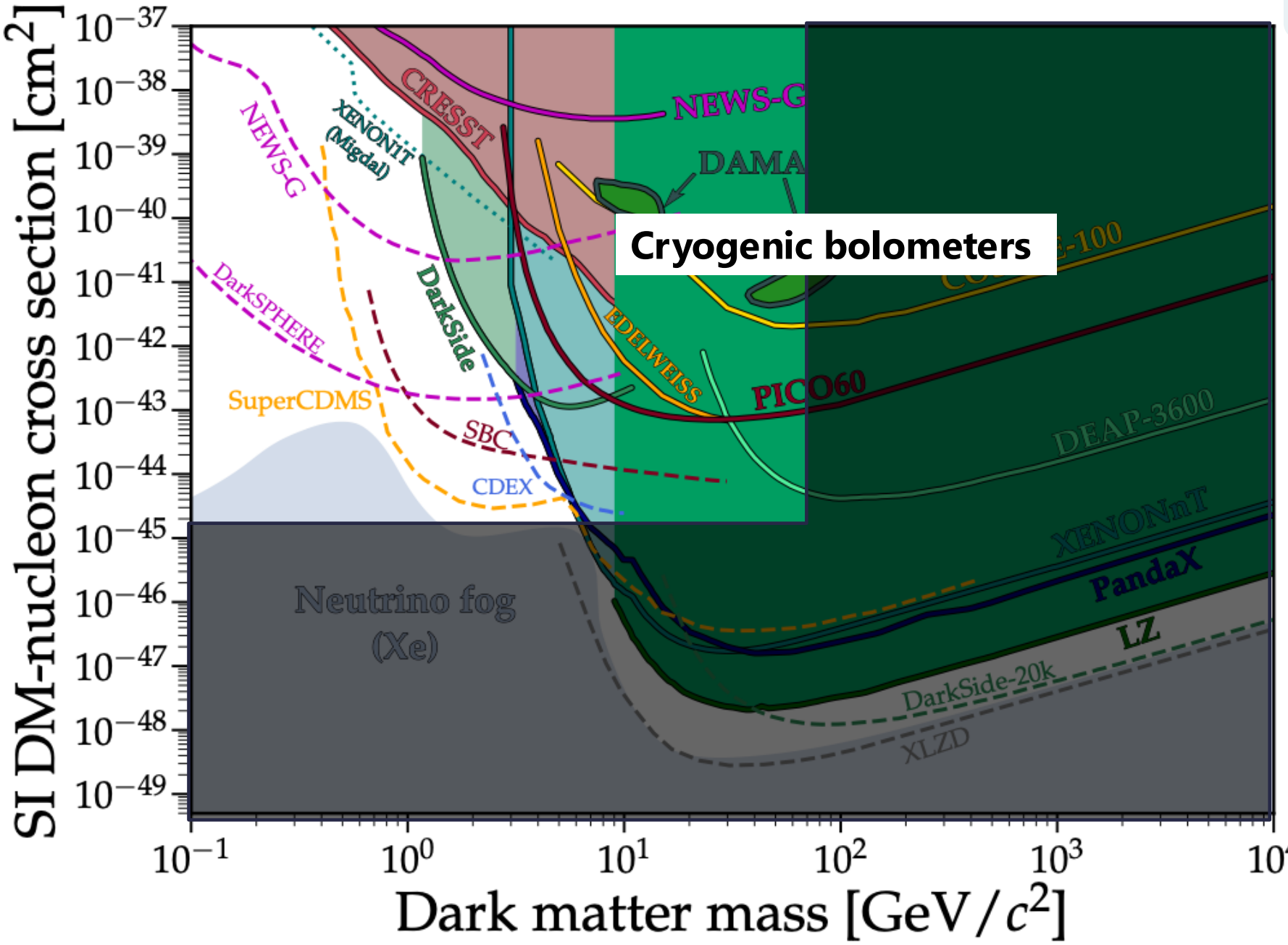
Plots by Ciaran O'Hare
(https://github.com/cajohare)



NaI efforts

See Florian Reindl's talk

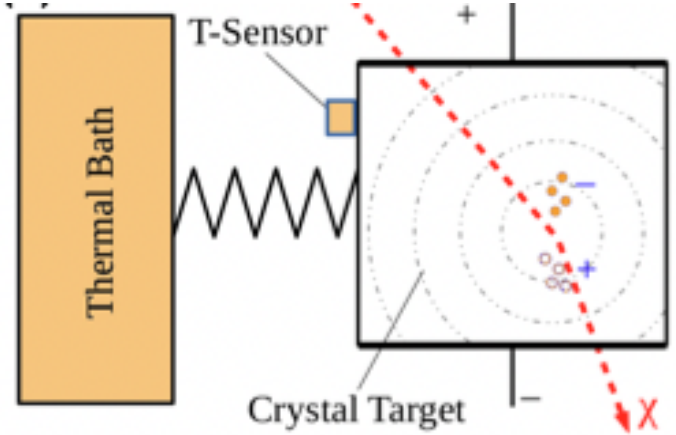
Plots by Ciaran O'Hare (https://github.com/cajohare)

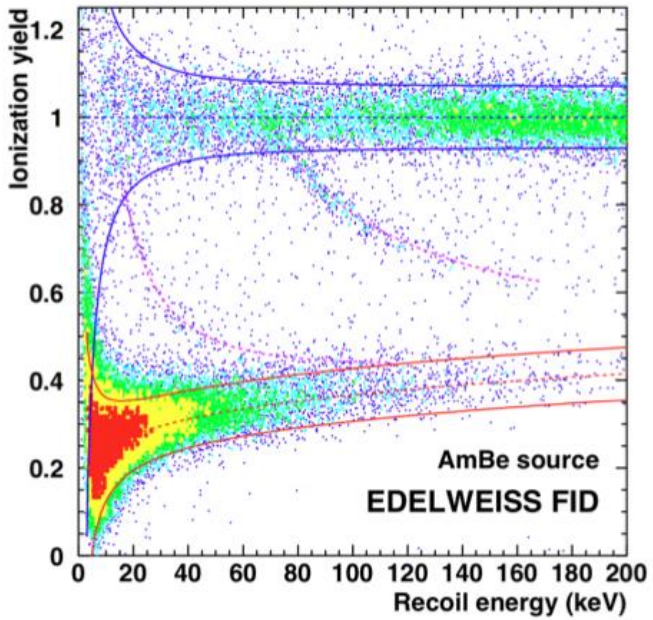


Migdal effect, see Chris McCabe's talk

CRYOGENIC BOLOMETERS

APPEC Committee Report 2021, arXiv:2104.07634
E. Armengaud *et al* 2017 *JINST* **12** P08010

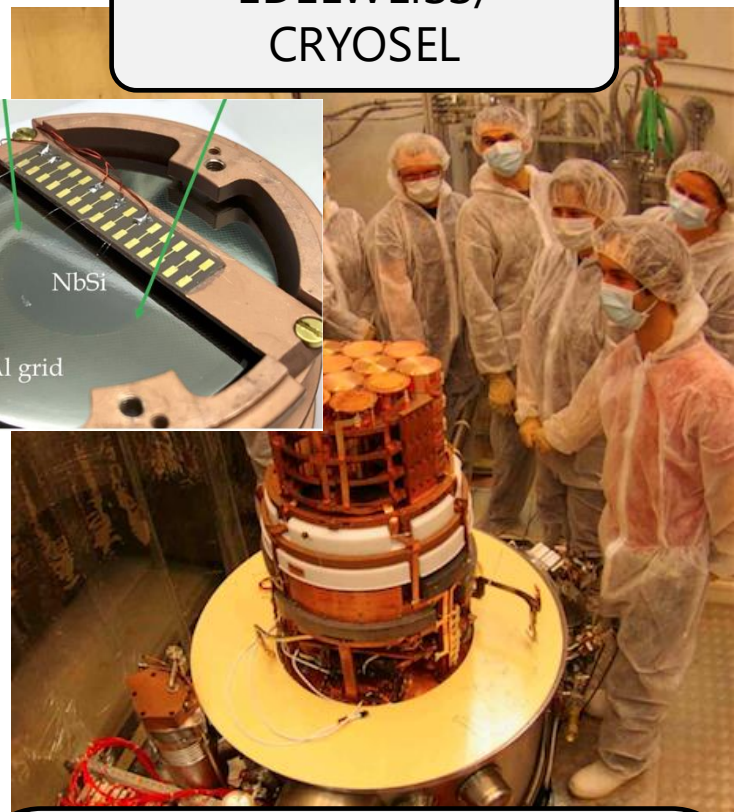




- Crystal targets (Ge, $CaWO_4$) operated < 50mK
- Phonon readout via NTD thermistors or transition edge sensors
- Simultaneous readout of ionization or scintillation signal allows background discrimination
- Excellent energy resolution

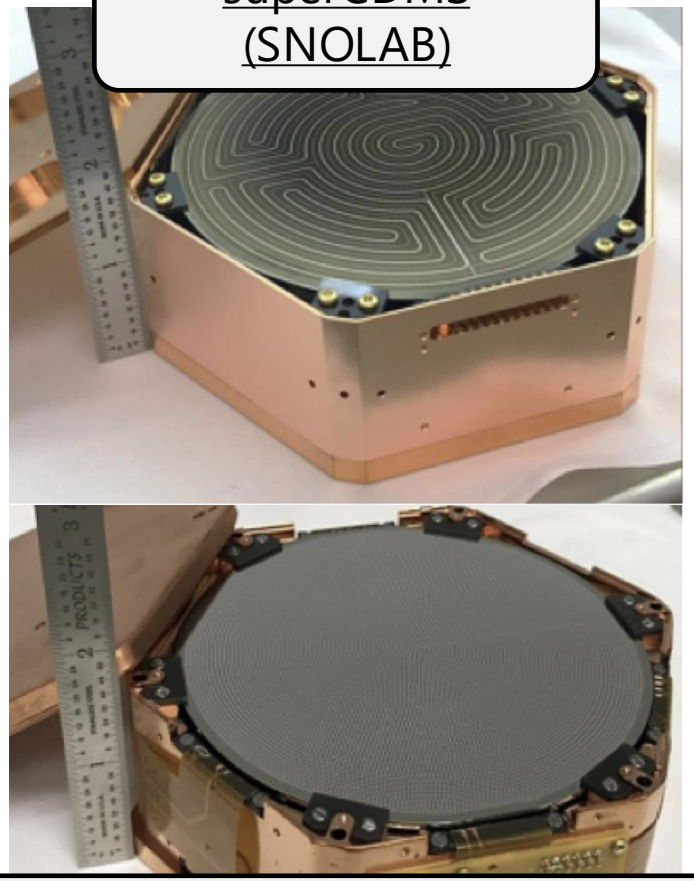
CRYOGENIC BOLOMETERS

EDELWEISS/ CRYOSEL



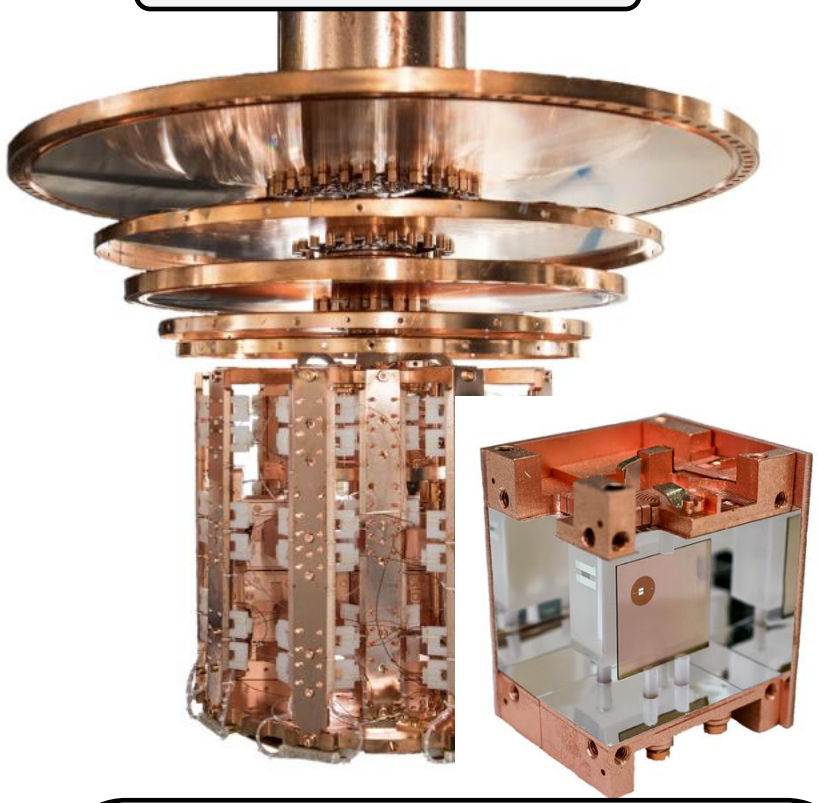
- Germanium crystals
- Moving towards Superconducting Single Electron Device (SSED) sensors
- Status: R&D for CRYOSEL

superCDMS (SNOLAB)



- Si and Ge crystals, total 30kg
- Phonons: QETES, Charge: interleaved electrodes
- Status: Cooled down for science search in March

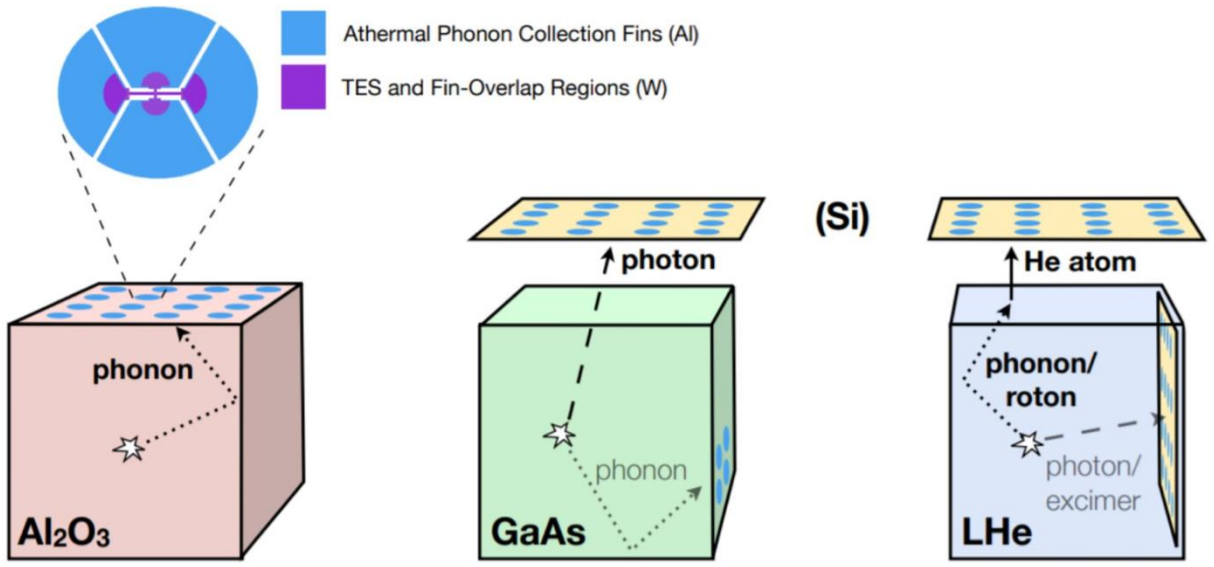
CRESST-III (LNGS)



- $CaWO_4$, Al_2O_3 LiAlO2, Si
- Phonons: W-TES
- Light: Silicon-on-Sapphire wafer
- Status: Running, electronics upgrade for more modules/channels

CRYOGENIC BOLOMETERS

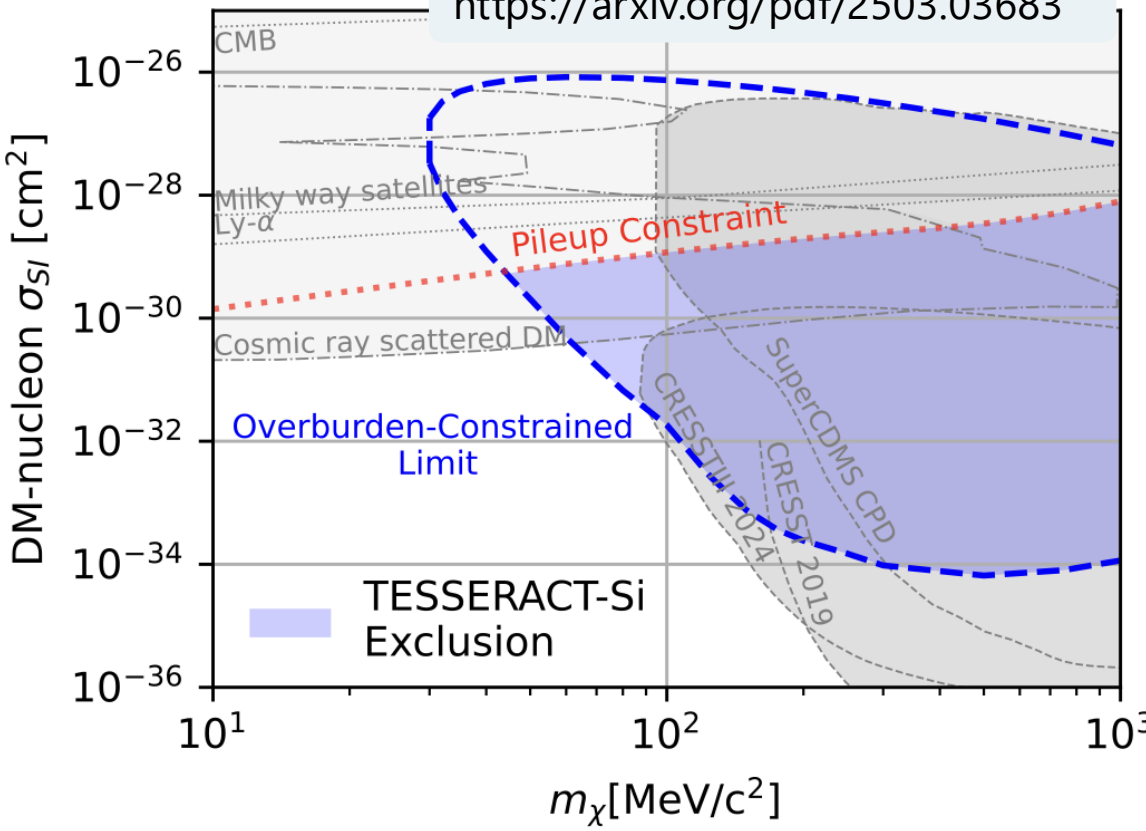
TESSERACT



- Apply diverse TES-based methods to the low-mass regime
- Push phonon sensors to sub-eV thresholds
- Diverse target materials
- Understand and mitigate Low Energy Excess (LEED)
- Status: Aiming for UG operations at LSM in 2028

24h DM search at LBNL

https://arxiv.org/pdf/2503.03683



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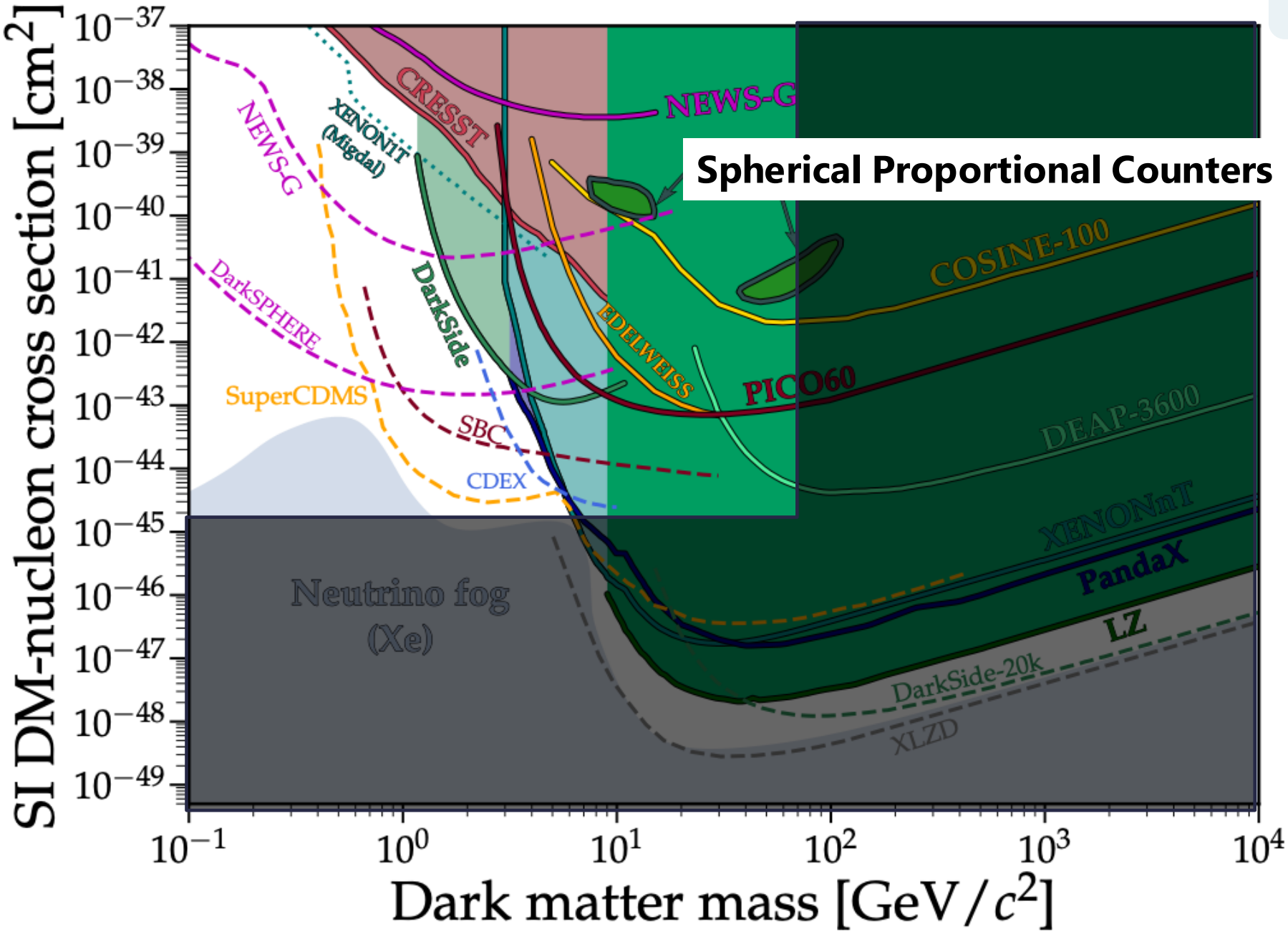
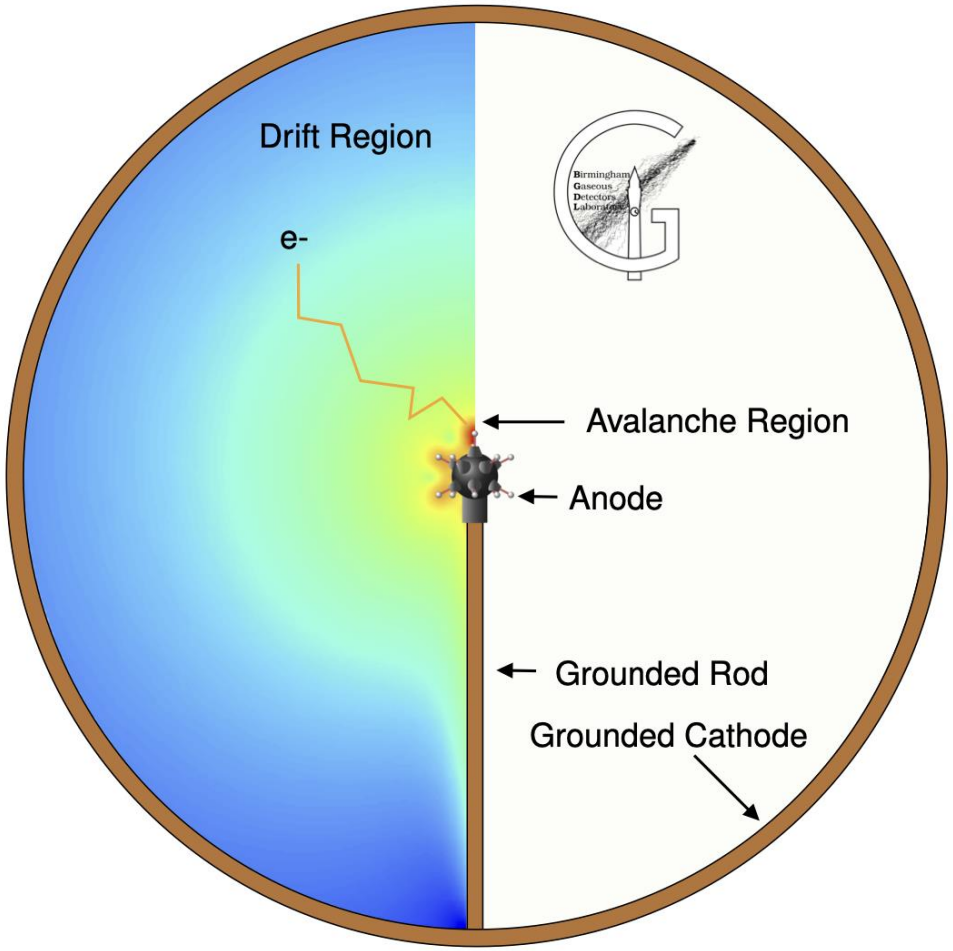


SPHERICAL PROPORTIONAL COUNTERS

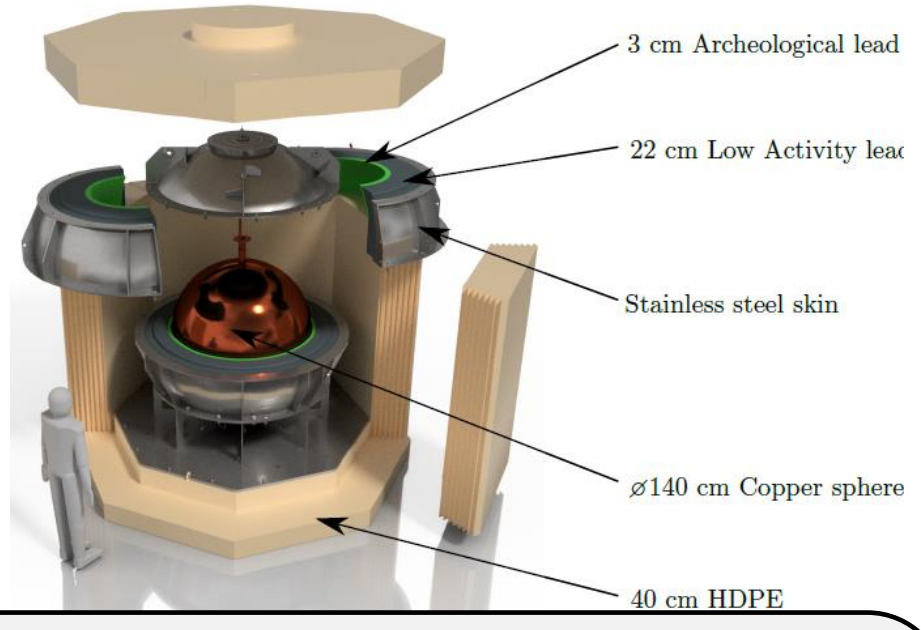
L. Balogh *et al* 2023 *JINST* 18 T02005
L. Balogh et al 2023 Phys. Rev. D 108, 112006



- Grounded, spherical, metallic vessel filled with gas
- Readout via central anode
- Interaction leads to ionisation of electrons and avalanche for signal amplification
- Small detector capacitance and high gas gains enable sub-keV energy threshold
- Detector scale-up possible without impacting energy threshold
- Simple design, allowing for low backgrounds
- Pulse shape for background rejection and fiducialisation

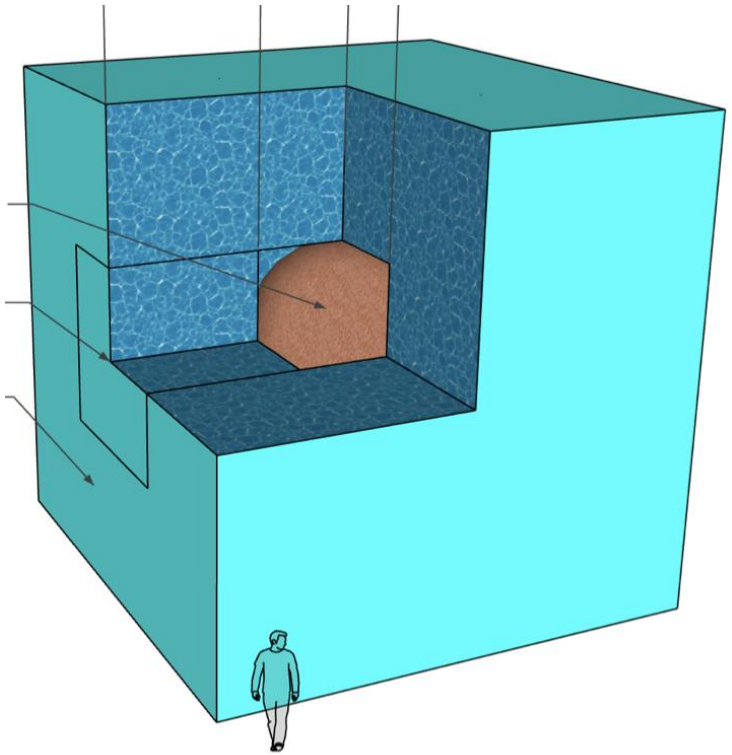
L. Balogh *et al* 2023 *JINST* 18 T02005
L. Balogh et al 2023 Phys. Rev. D 108, 112006

NEWS-G

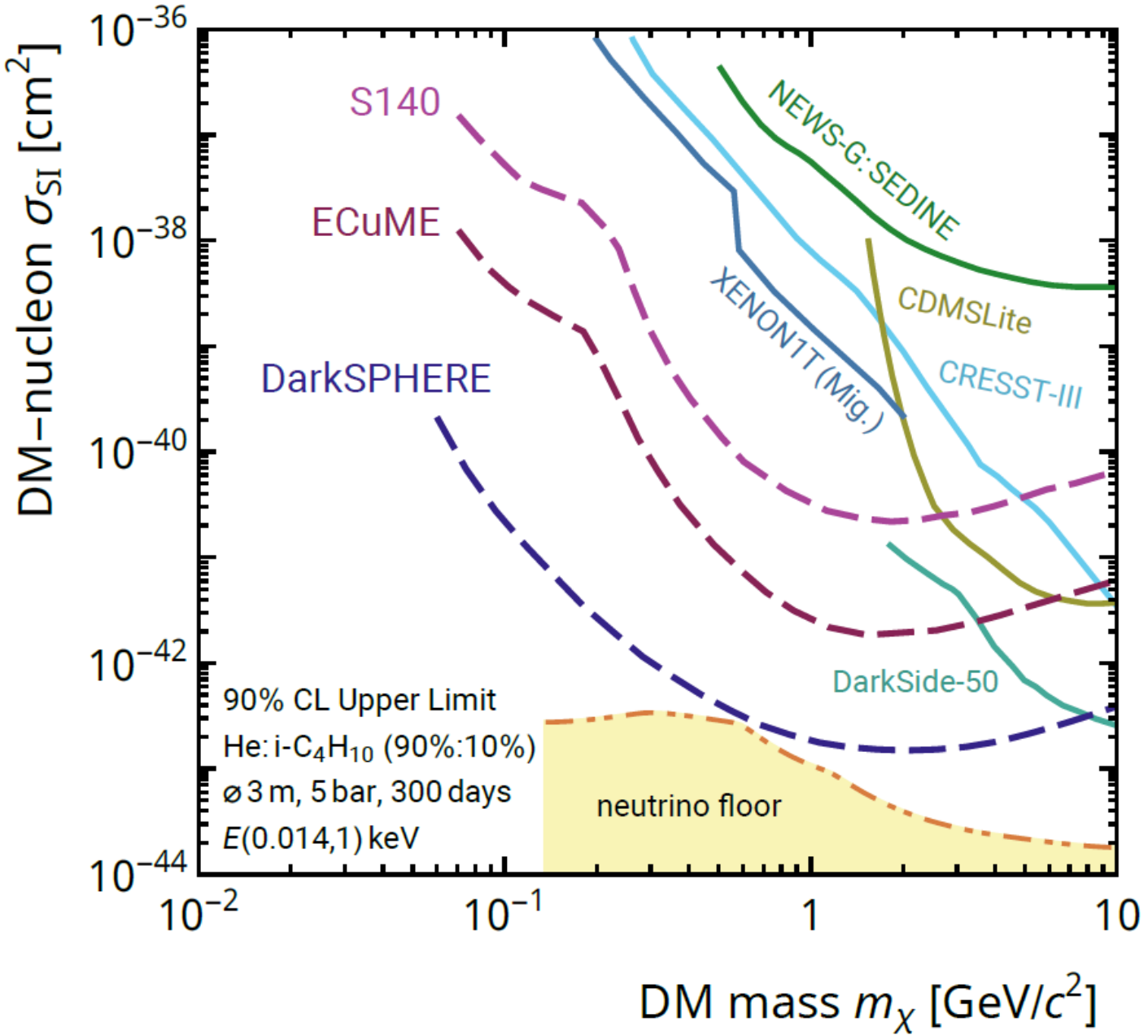


- SEDINE (2017): Prototype 60 cm detector @ LSM
- S140 (since 2021): 135 cm detector @ SNOLab
- Fully underground electroformed 140 cm ECuME detector @ SNOLab
- Status: Upgrade towards ECuME

DarkSPHERE



- 300 cm diameter detector @ Boulby
- Fully underground electroformed copper
- Status: Preparation

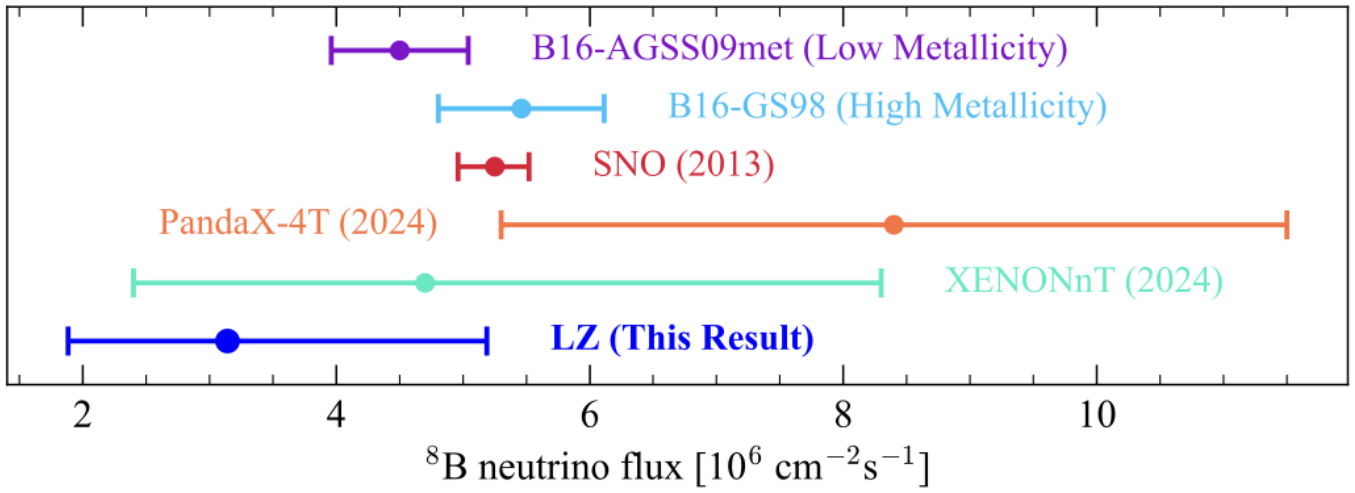

S140
ECuME
DarkSPHERE
NEWS-G:SEDINE
XENON1T (Mig.)
CDMSLite
CRESST-III
DarkSide-50
90% CL Upper Limit
He: i-C4H10 (90%:10%)
ø 3 m, 5 bar, 300 days
E(0.014,1) keV
neutrino floor
DM−nucleon σSI [cm2]
DM mass mχ [GeV/c2]
10−36
10−38
10−40
10−42
10−44
10−2
10−1
1
10

STAY TUNED! EXCITING TIMES AHEAD FOR DARK MATTER DIRECT DETECTION EFFORTS.

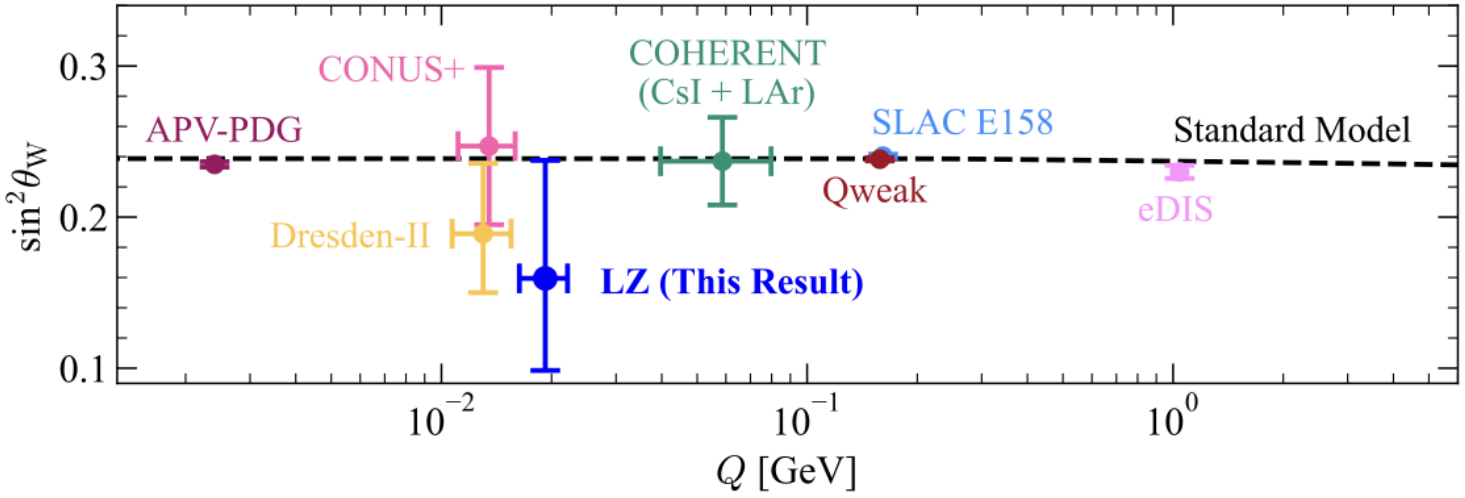
Xenon detectors – Beyond Dark Matter

XENONnT: PRL 123, 2024
PandaX-4T: PRL 123, 2024
LZ: arXiv:2512.08065

Flavour independent measurement of ^{8}B solar neutrino flux



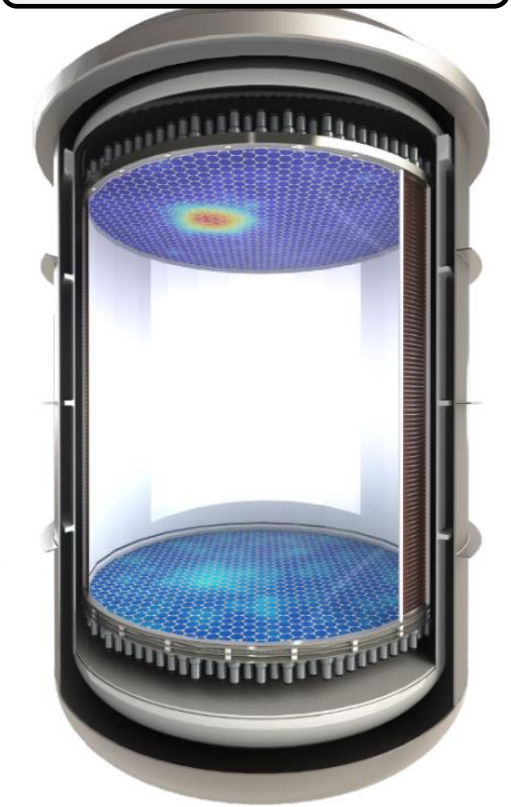
Measure weak-mixing angle ($\sin^2\theta_W$) at low momentum transfer



NEXT GENERATION

Dark Matter
WIMPs
Sub-GeV
Inelastic
Axion-like particles
Planck mass
Dark photons

XLZD



Neutrino nature
Neutrinoless double beta decay
Neutrino magnetic moment
Double electron capture

0νbb: J. Phys. G: Nucl. Part. Phys. 52 (2025) 045102

Supernovae
Early alert
Supernova neutrinos
Multi-messenger astrophysics

Sun
pp neutrinos
Solar metallicity
^{7}Be, ^{8}B, hep

NEXT GENERATION

XLZD Design Book
EPJC (2025) 85: 1192

XLZD