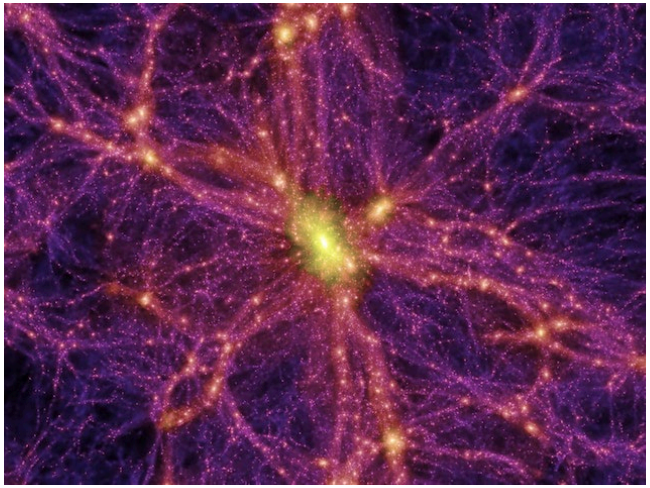
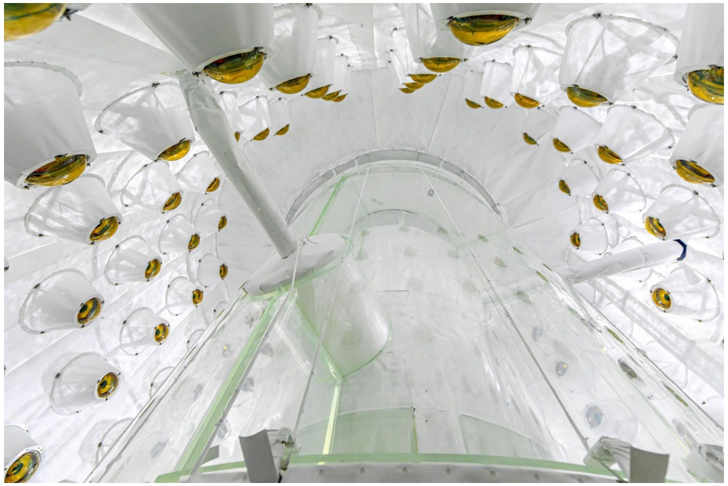
What's next in direct detection

Generation 3 dark matter searches, axions, and direct detection of dark matter

DPF/Pheno meeting, Pittsburgh, PA, May 15, 2024

Carter Hall, University of Maryland

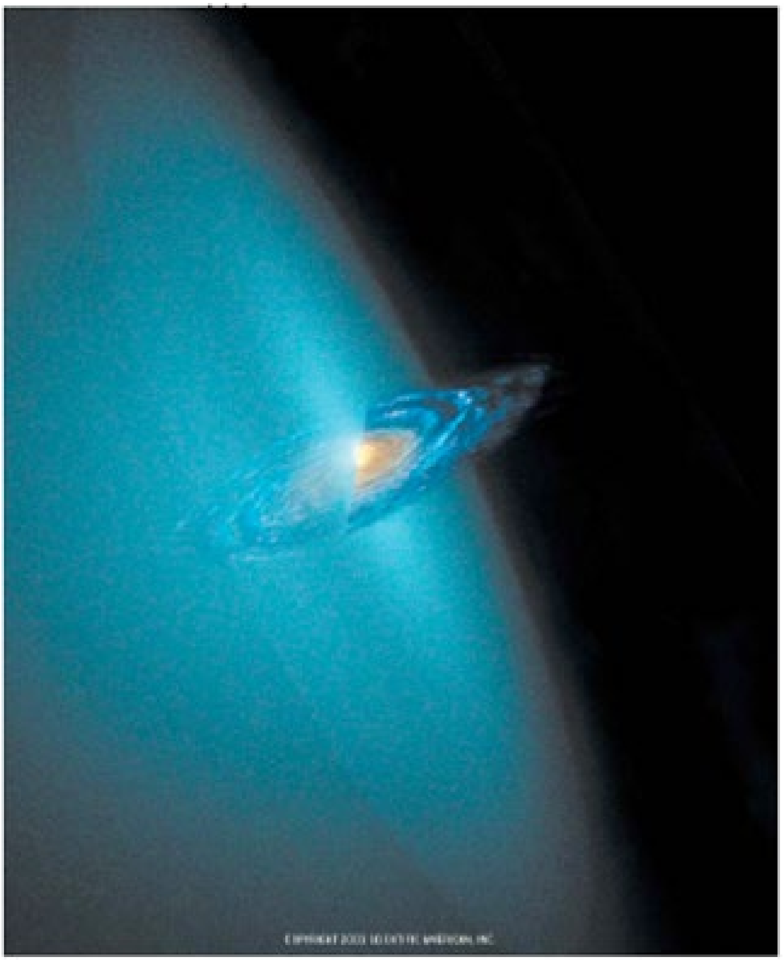




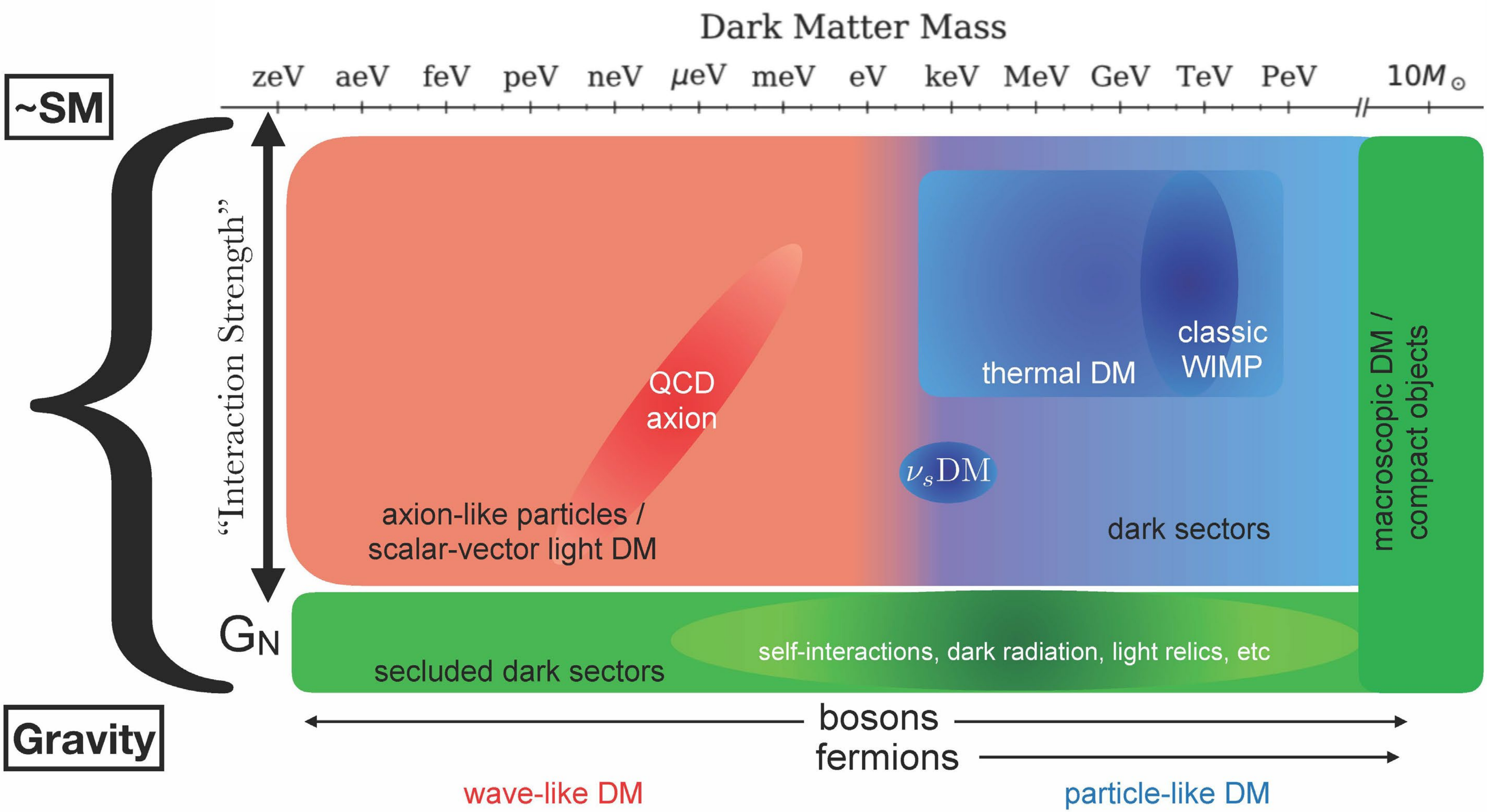
“The particle physicists’ assignment is to learn whether the dark matter is detectable.”

Jim Peebles, Nuclear Physics B (Proc. Suppl.) 138 (2005) 5–9

- **Typical orbital vel.** = 230 km/sec
  ~ 0.1% speed of light
- **Density:** ~ 300 GeV / liter
- For particle mass of 100 GeV, every liter of space has 3 WIMPs.

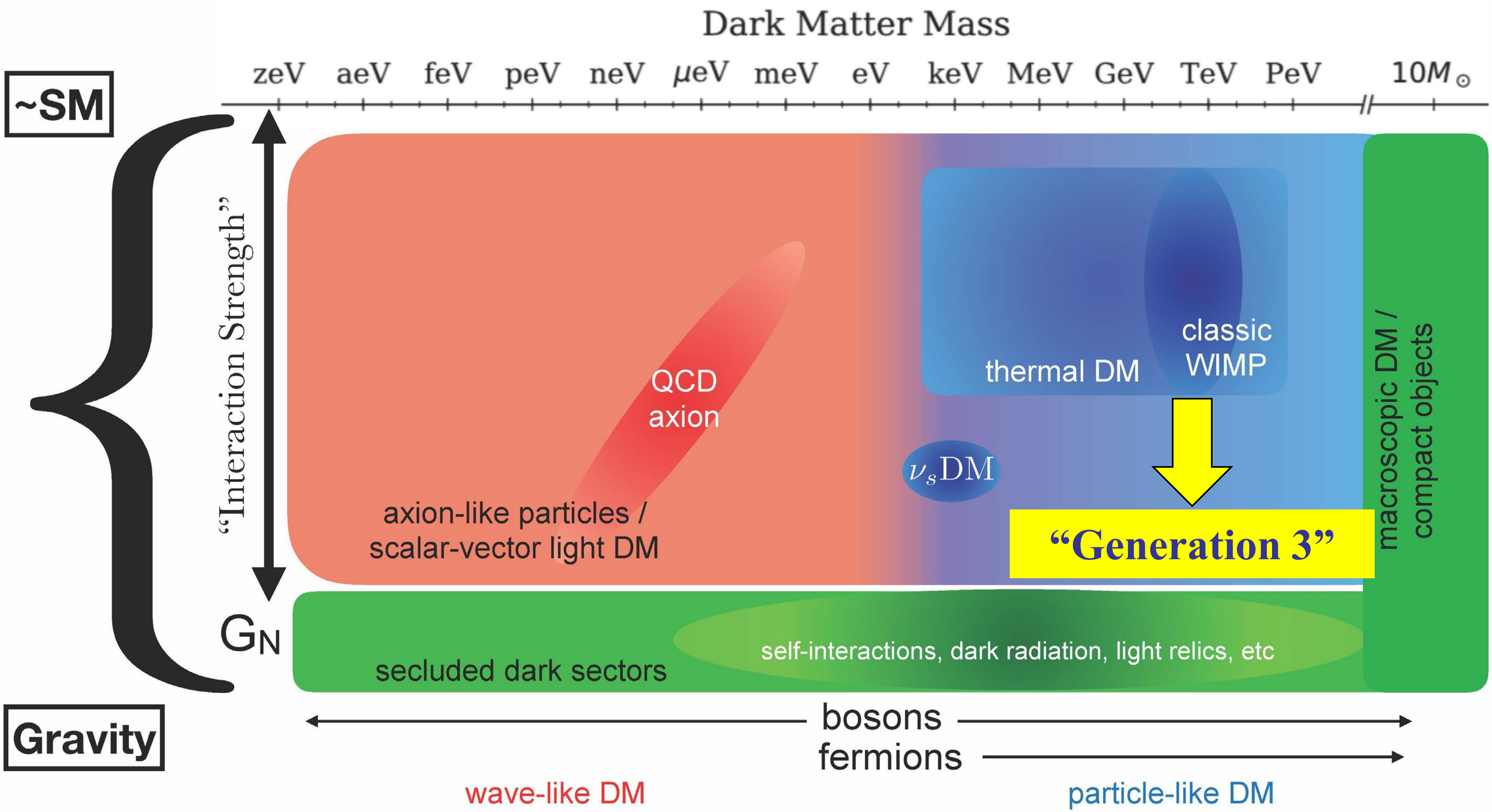


Possible interaction strengths range from the scale of the standard model to the scale of gravity



Credit: Aaron Chou, Snowmass 2022

Possible interaction strengths range from the scale of the standard model to the scale of gravity



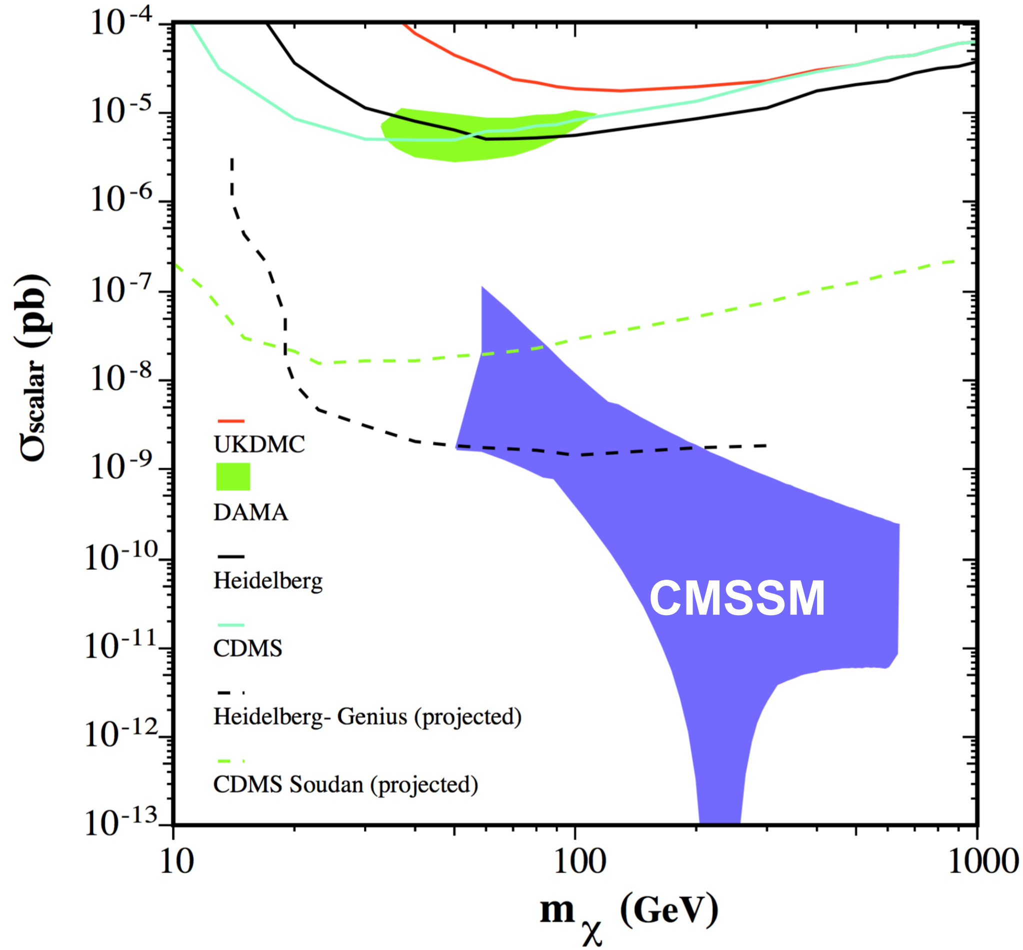
Credit: Aaron Chou, Snowmass 2022

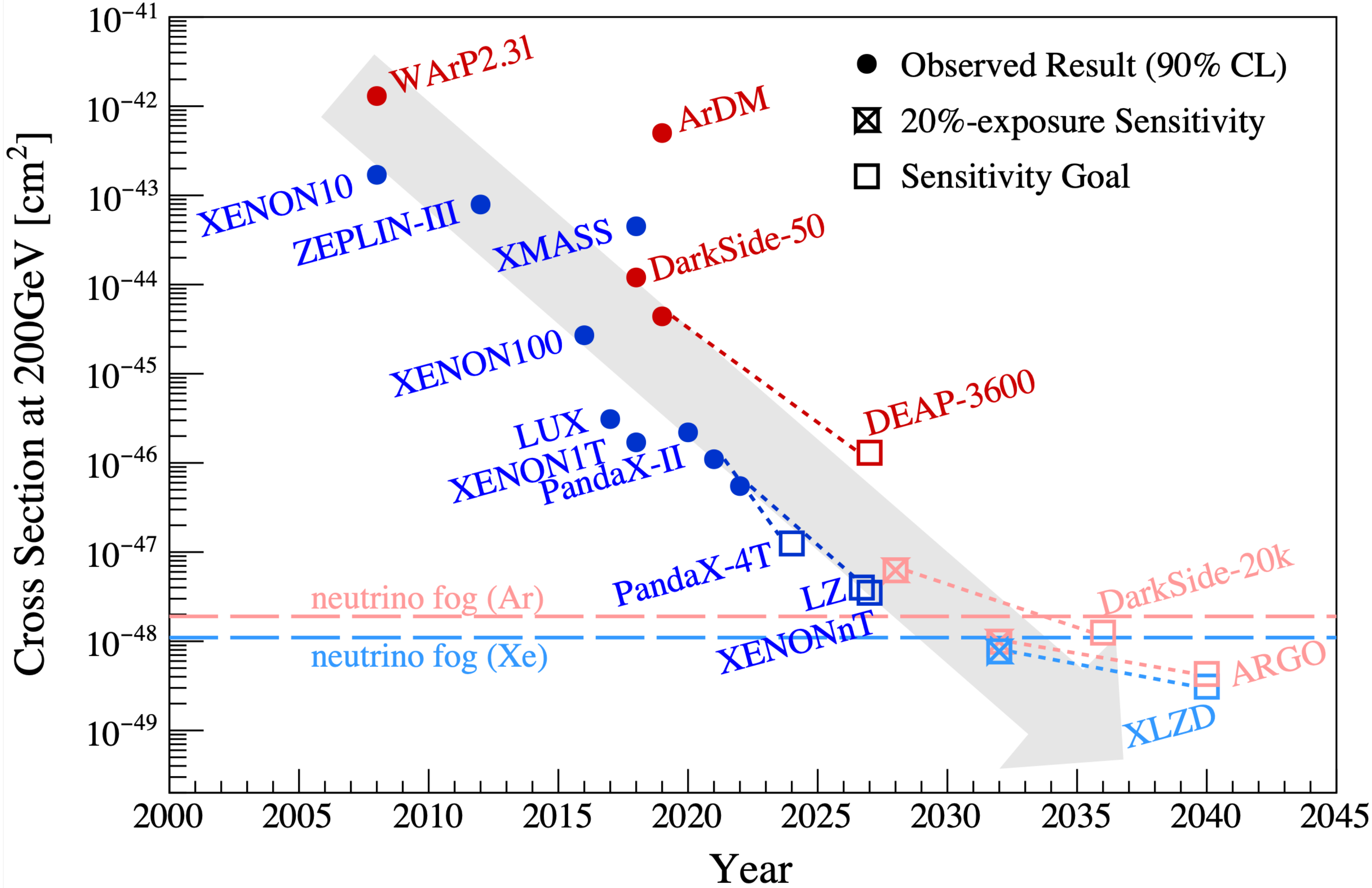
Historical perspective: Ellis, Ferstl, Olive (2000);

‘Re-Evaluation of the Elastic Scattering of Supersymmetric Dark Matter’; hep-ph/0001005.

‘Our results fall considerably below many of the possible predictions in the literature [10], and may discourage some faint-hearted experimentalists. ’

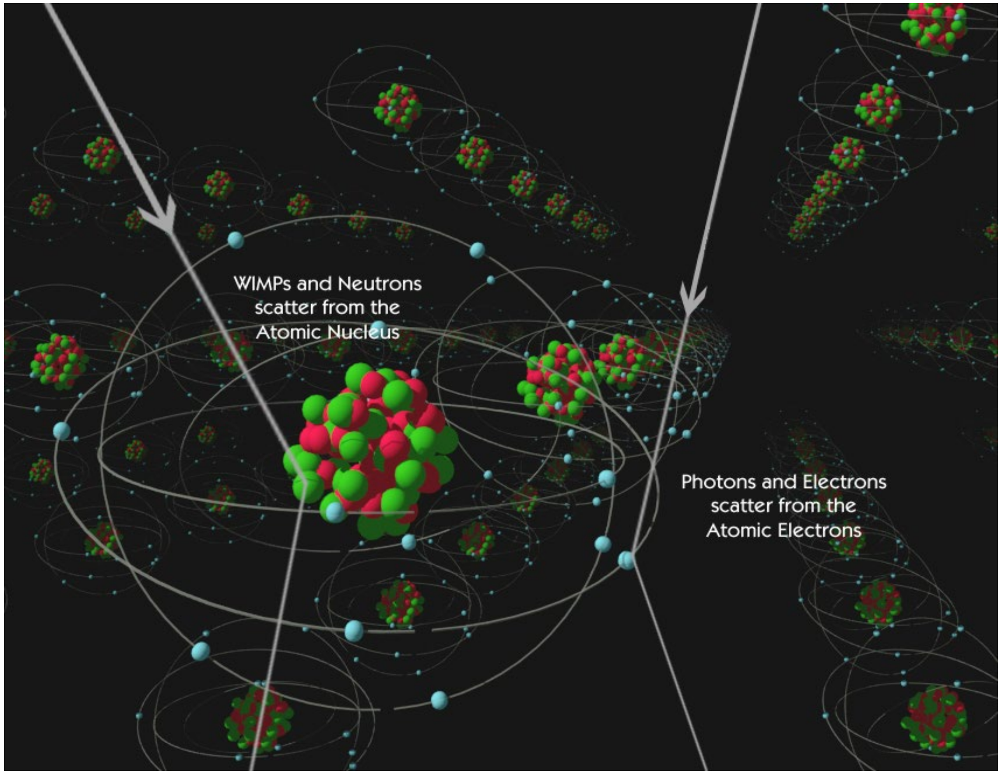
‘We should not want our experimental colleagues to be too downcast by the long road they appear to have to cover…. However, we think it best to have in mind a plausible and realistic target sensitivity….’

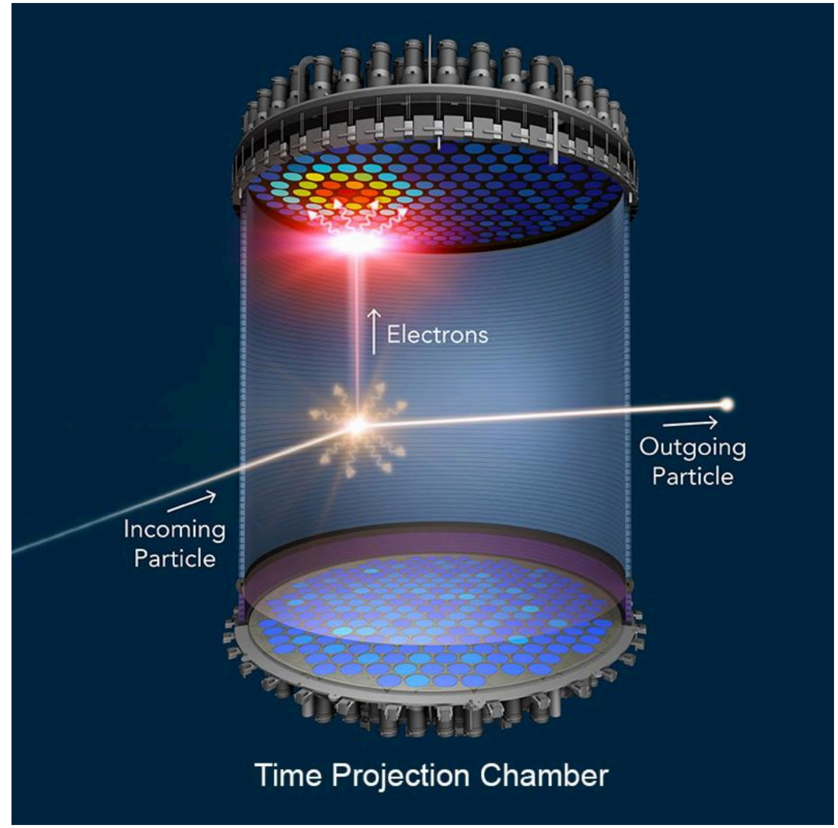




Observed Result (90% CL)
20%-exposure Sensitivity
Sensitivity Goal
WArP2.31
ArDM
XENON10
ZEPLIN-III
XMASS
DarkSide-50
XENON100
LUX
XENON1T
PandaX-II
DEAP-3600
PandaX-4T
LZ
DarkSide-20k
neutrino fog (Ar)
neutrino fog (Xe)
XENONnT
ARGO
XLZD
Cross Section at 200GeV [cm^2]
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
Year

Generation 2 WIMP searches: 5 to 10 tonnes of Liquid Xenon

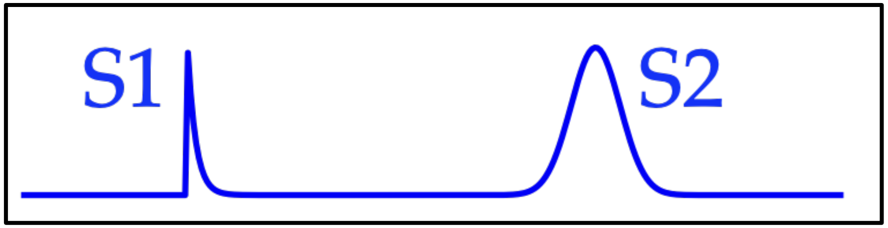


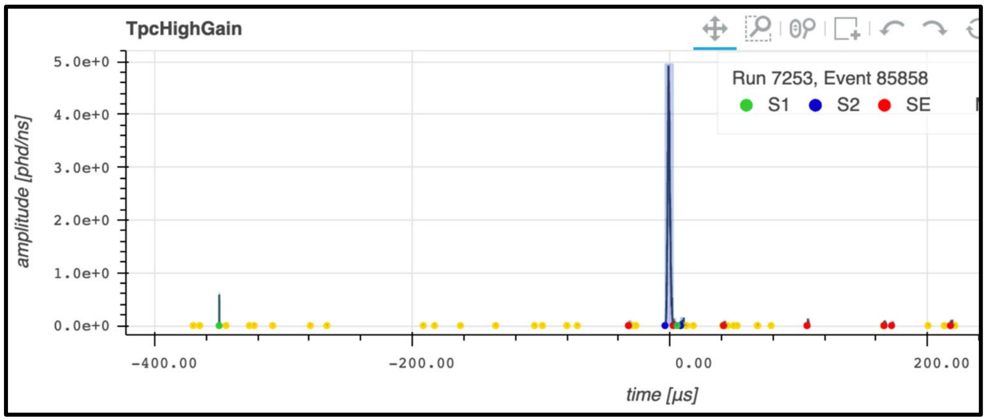


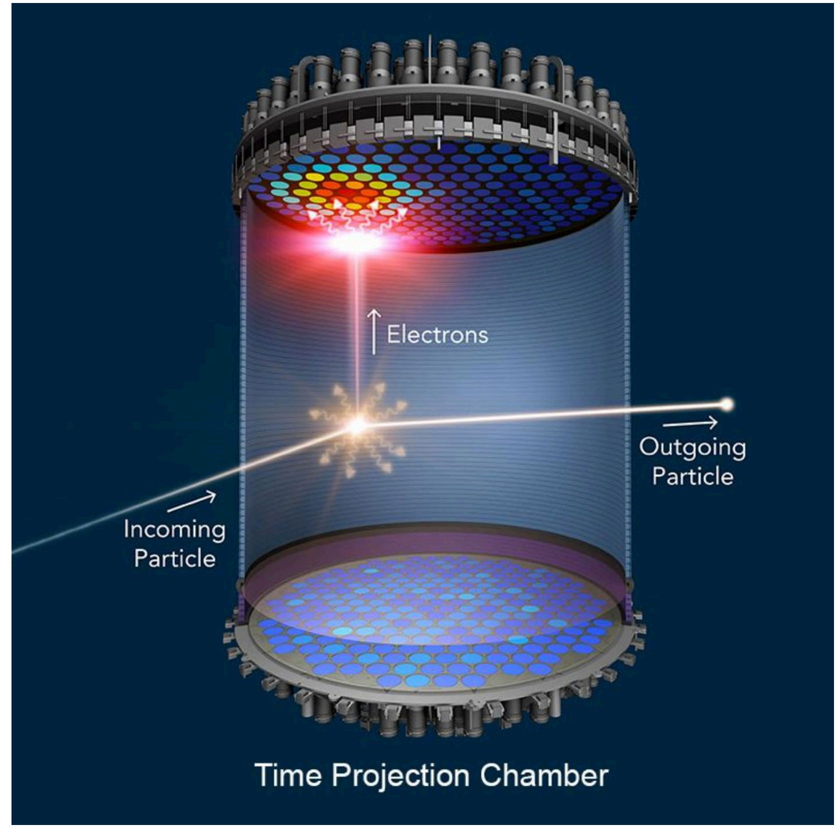
Search for anomalous low-energy nuclear recoils

Requirements: large target mass + low energy threshold + background control.

Generation 2 WIMP searches: 5 to 10 tonnes of Liquid Xenon





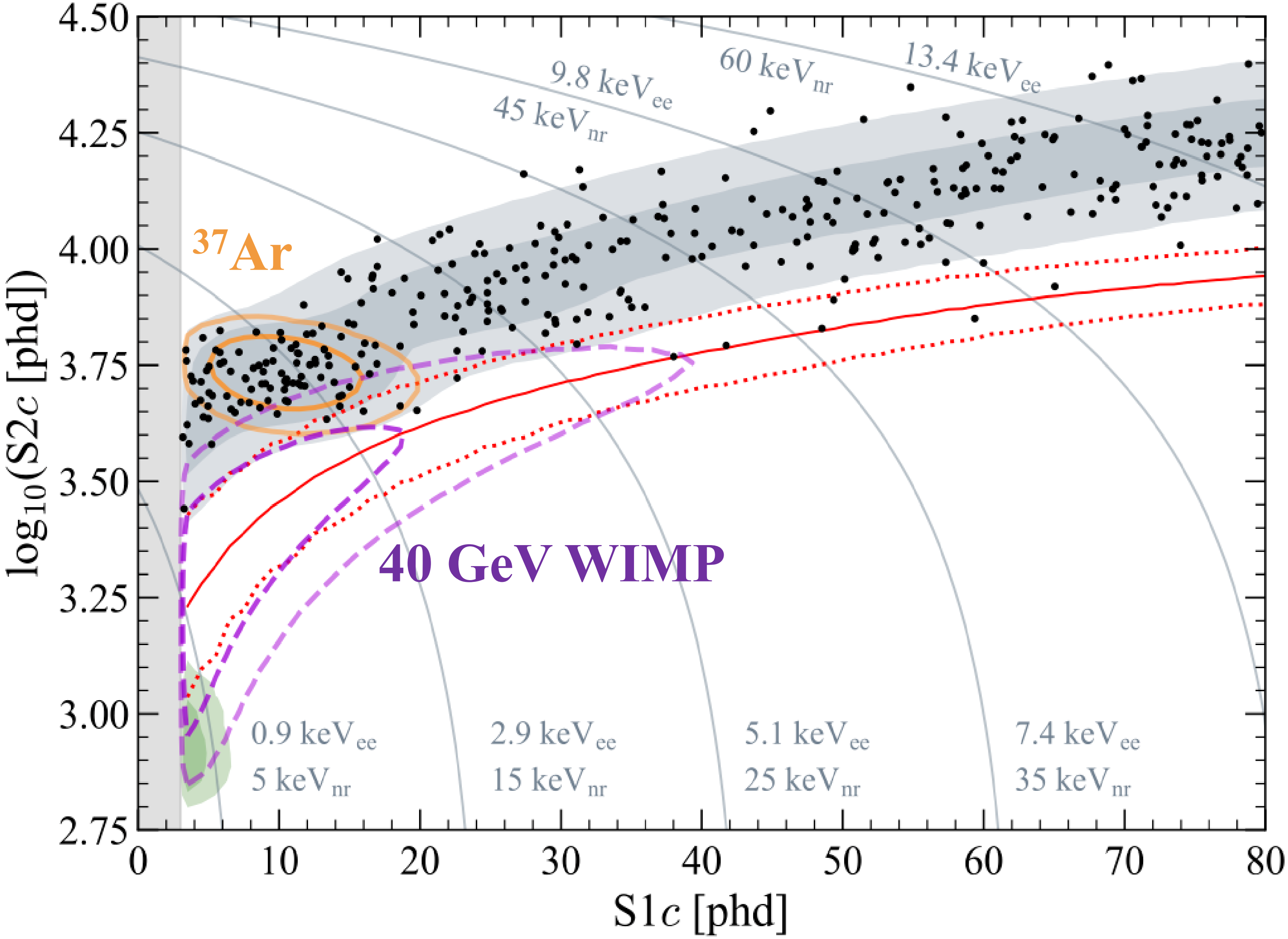


Search for anomalous low-energy nuclear recoils

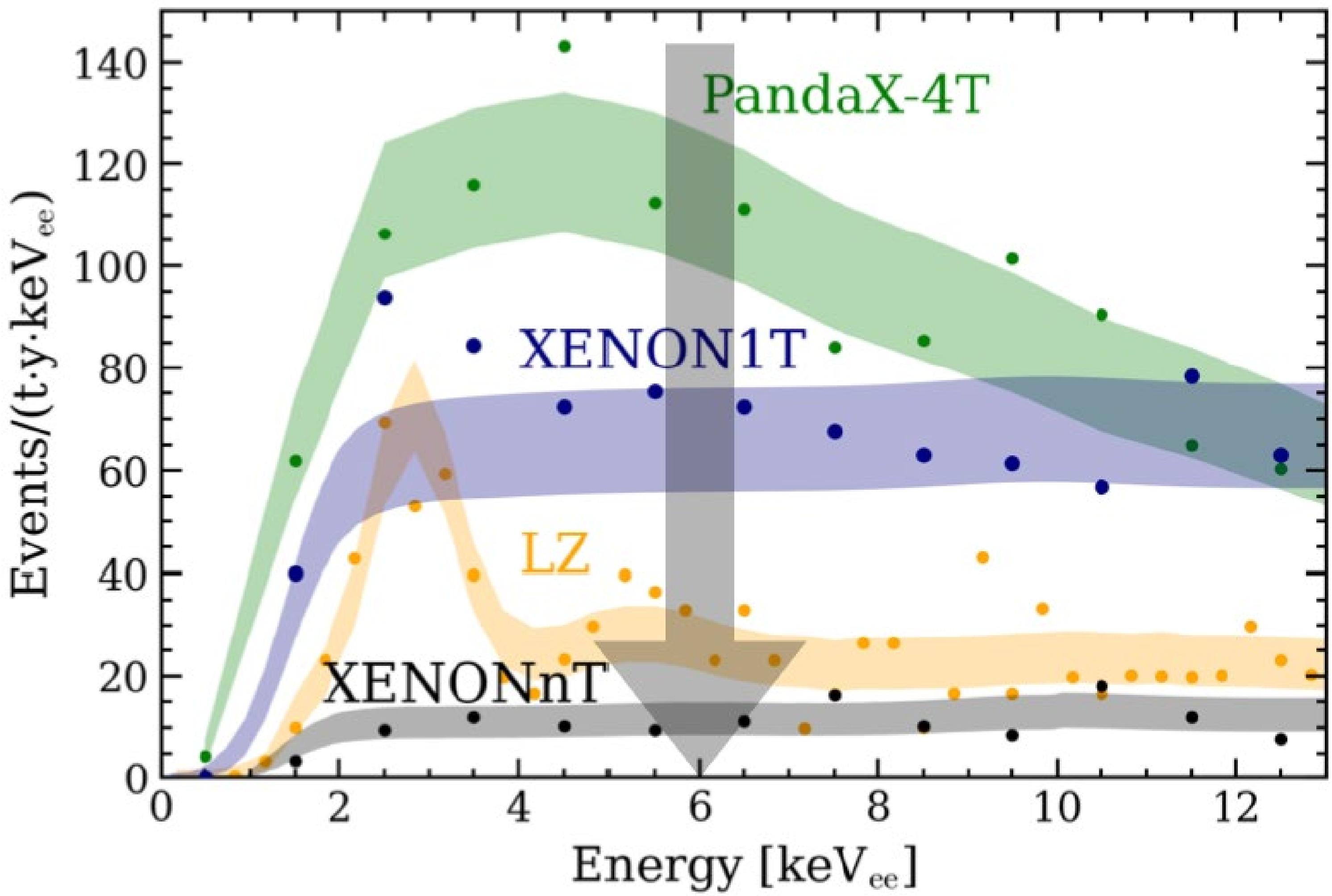
Requirements: large target mass + low energy threshold + background control.

Initial WIMP Search Data from LZ – only 60 days

Final dataset will be 10 times larger

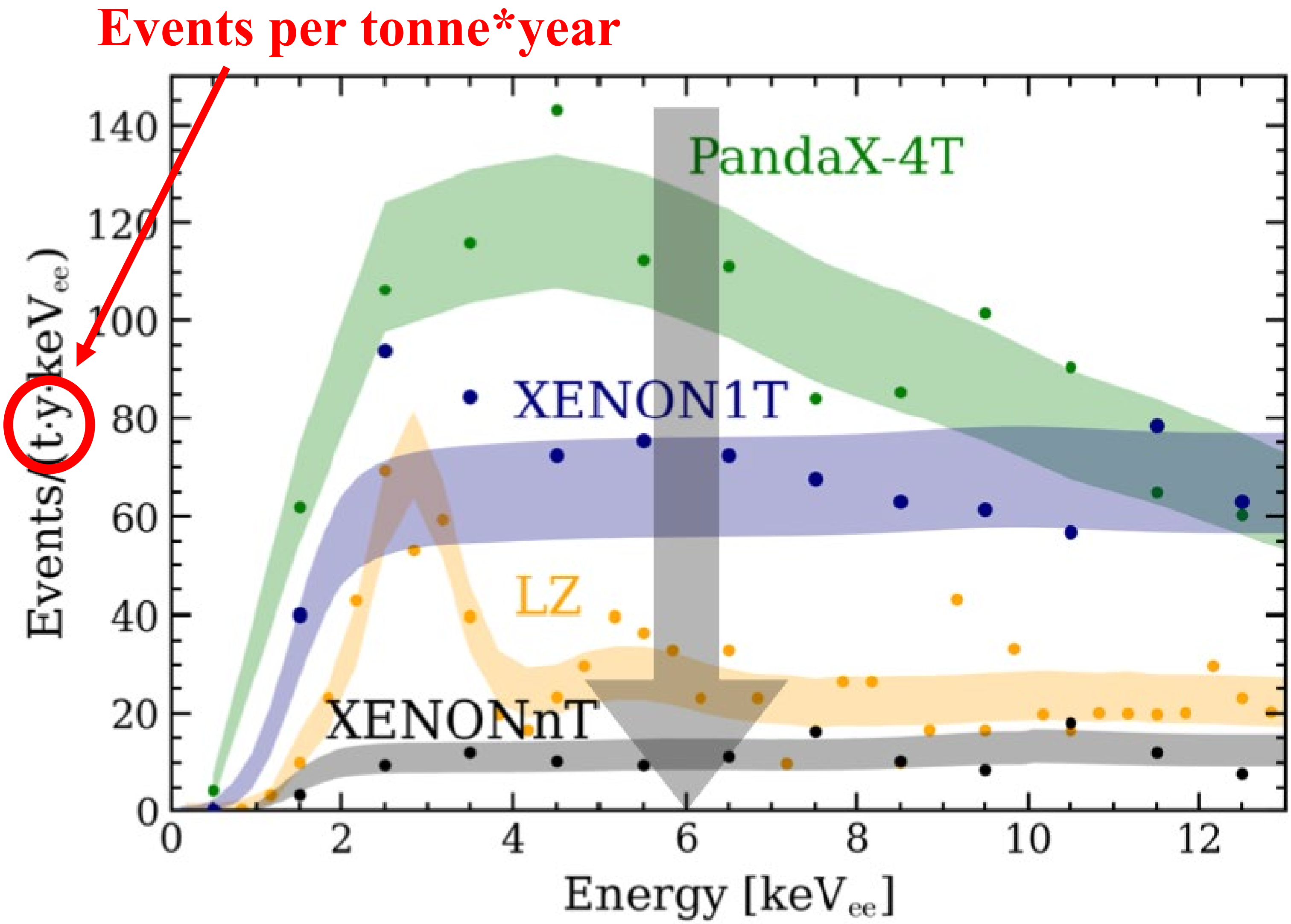


Notable background reduction even within the last five years



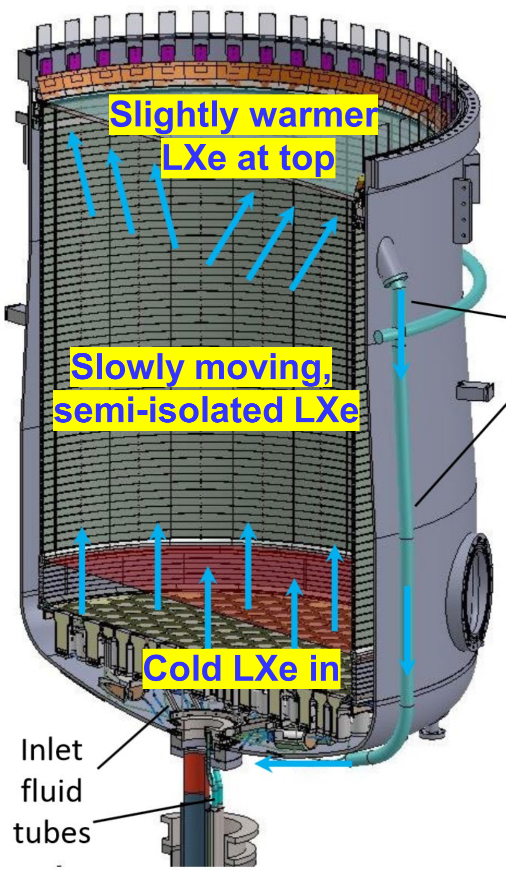
Gamma backgrounds are now negligible (self-shielding)
Radon daughters (^{214}Pb) are currently the largest contributor.

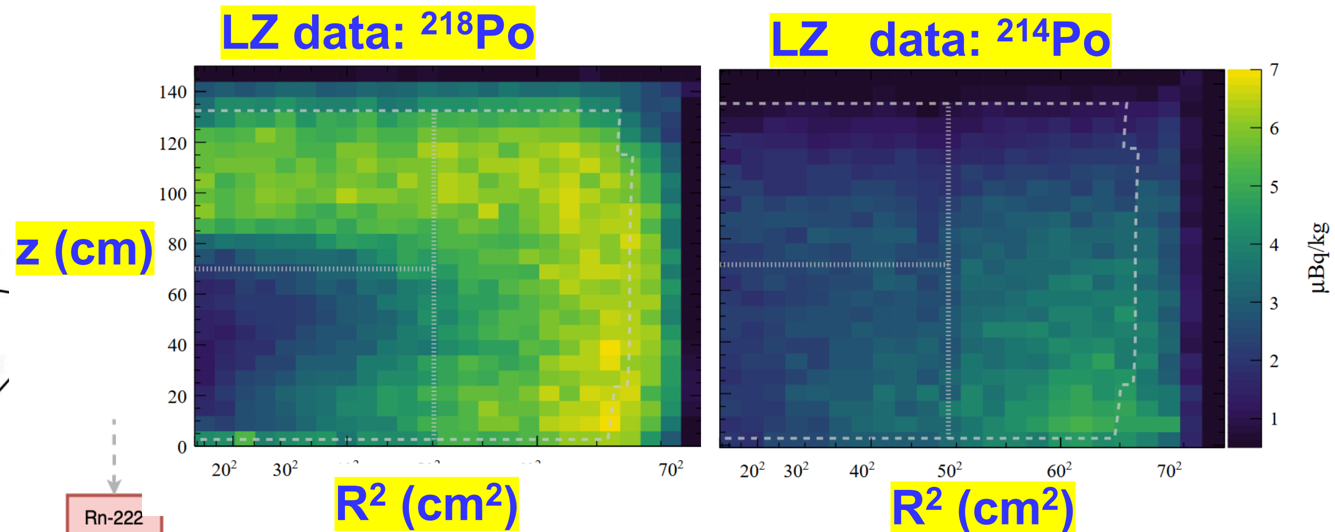
Notable background reduction even within the last five years

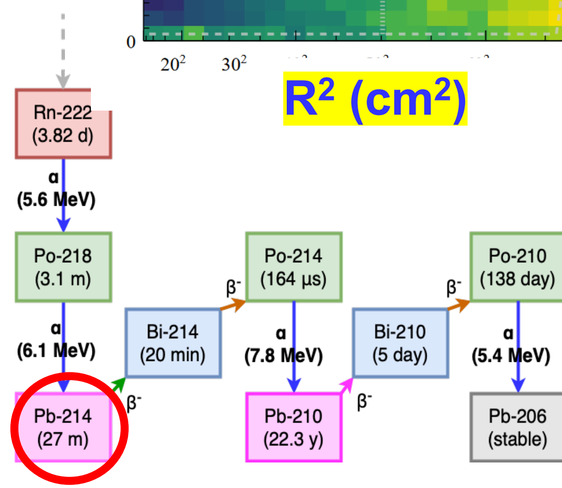


Gamma backgrounds are now negligible (self-shielding)
Radon daughters (^{214}Pb) are currently the largest contributor.

^{222}Rn and its daughters are not fully mixed in LZ: This enables event-by-event rejection of Rn daughters.

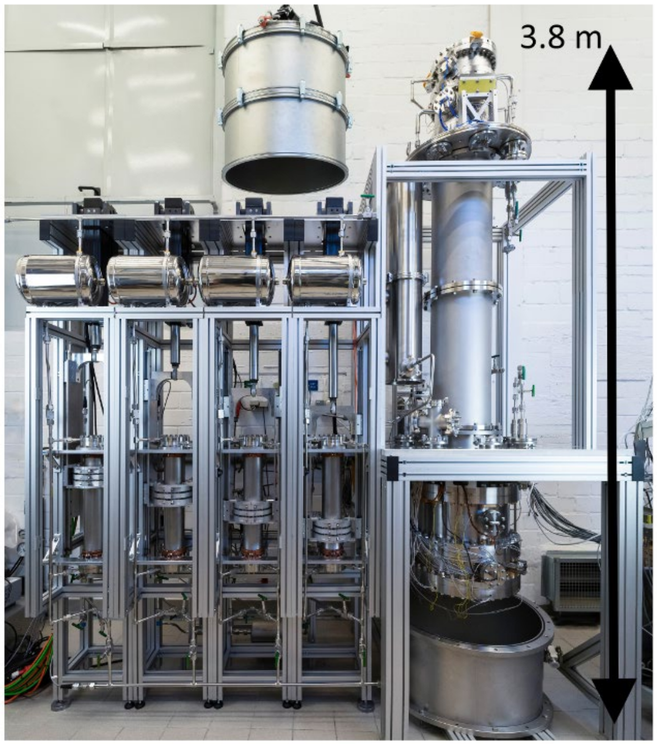


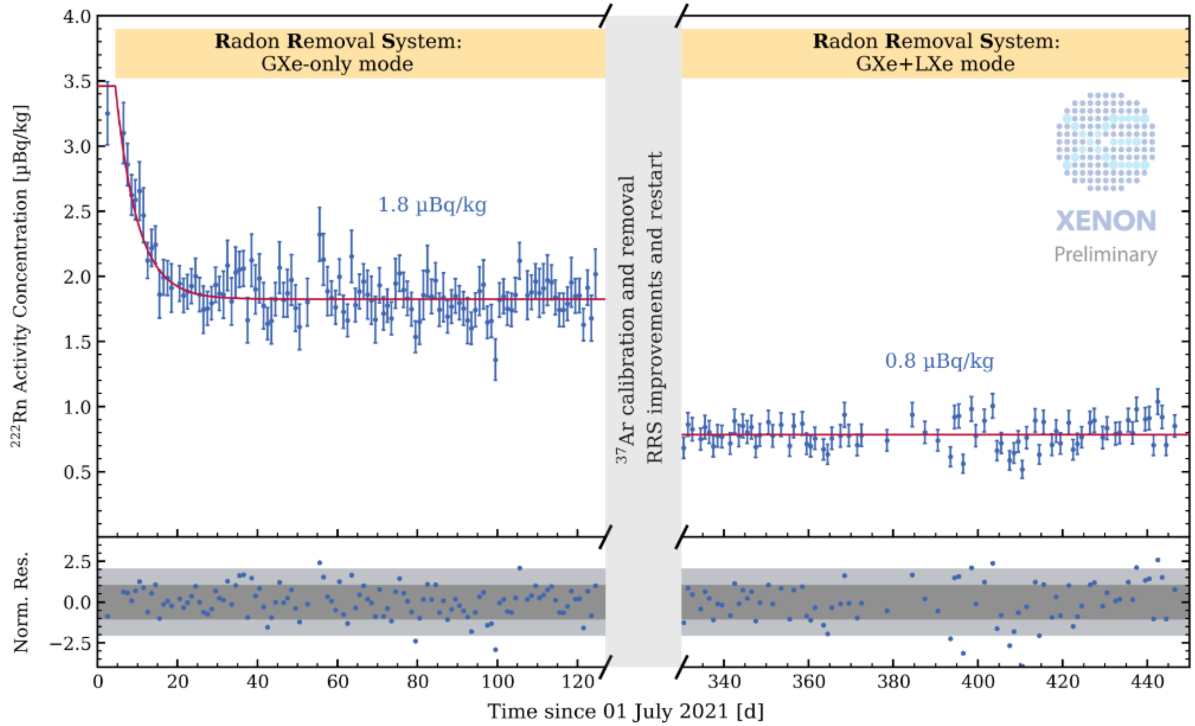




Rn222 (μBq/kg)	Pb214 (μBq/kg)	Po214 (μBq/kg)
4.37 ± 0.31 (stat)	**3.26 ± 0.13(stat) ± 0.57(sys)**	2.56 ± 0.21 (stat)

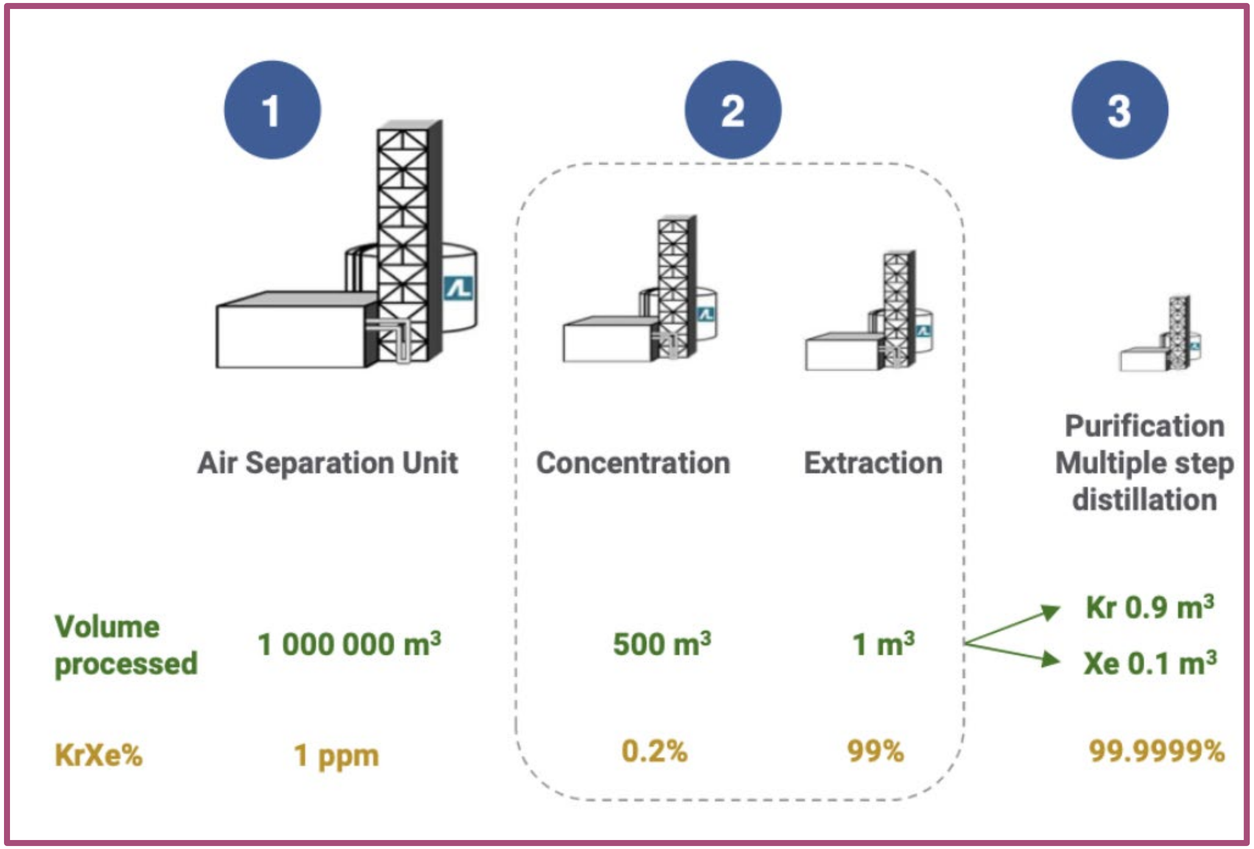
Radon removal via distillation: the XenonNT experiment





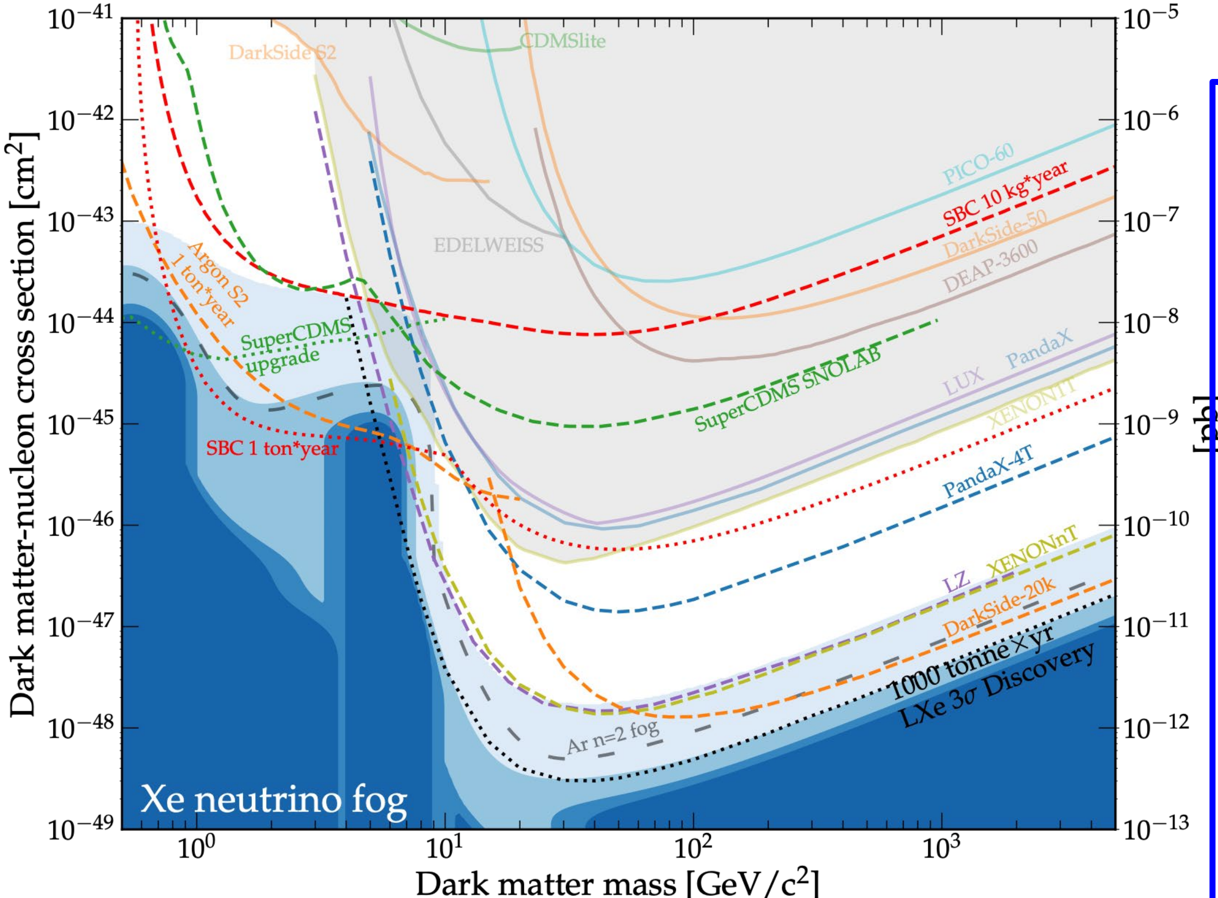
Credit: Koke, D, et al. 'Radon Removal System for the XENONnT experiment and beyond', Topics in Astroparticle and Underground Physics 2023 (poster)

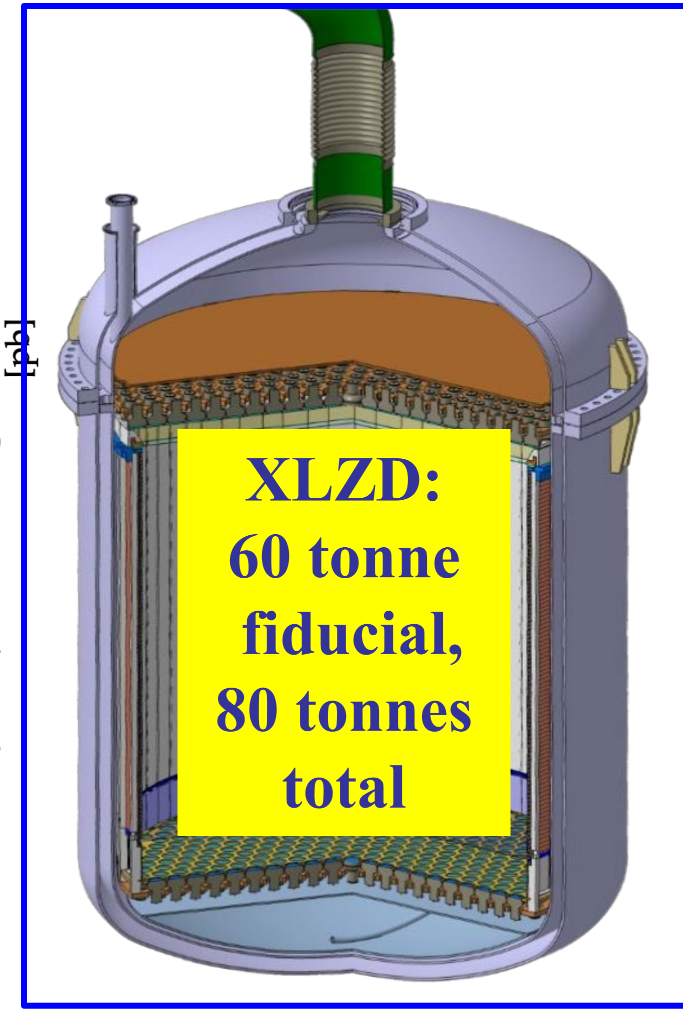
Global Xe production: 60 tonnes/year and increasing.



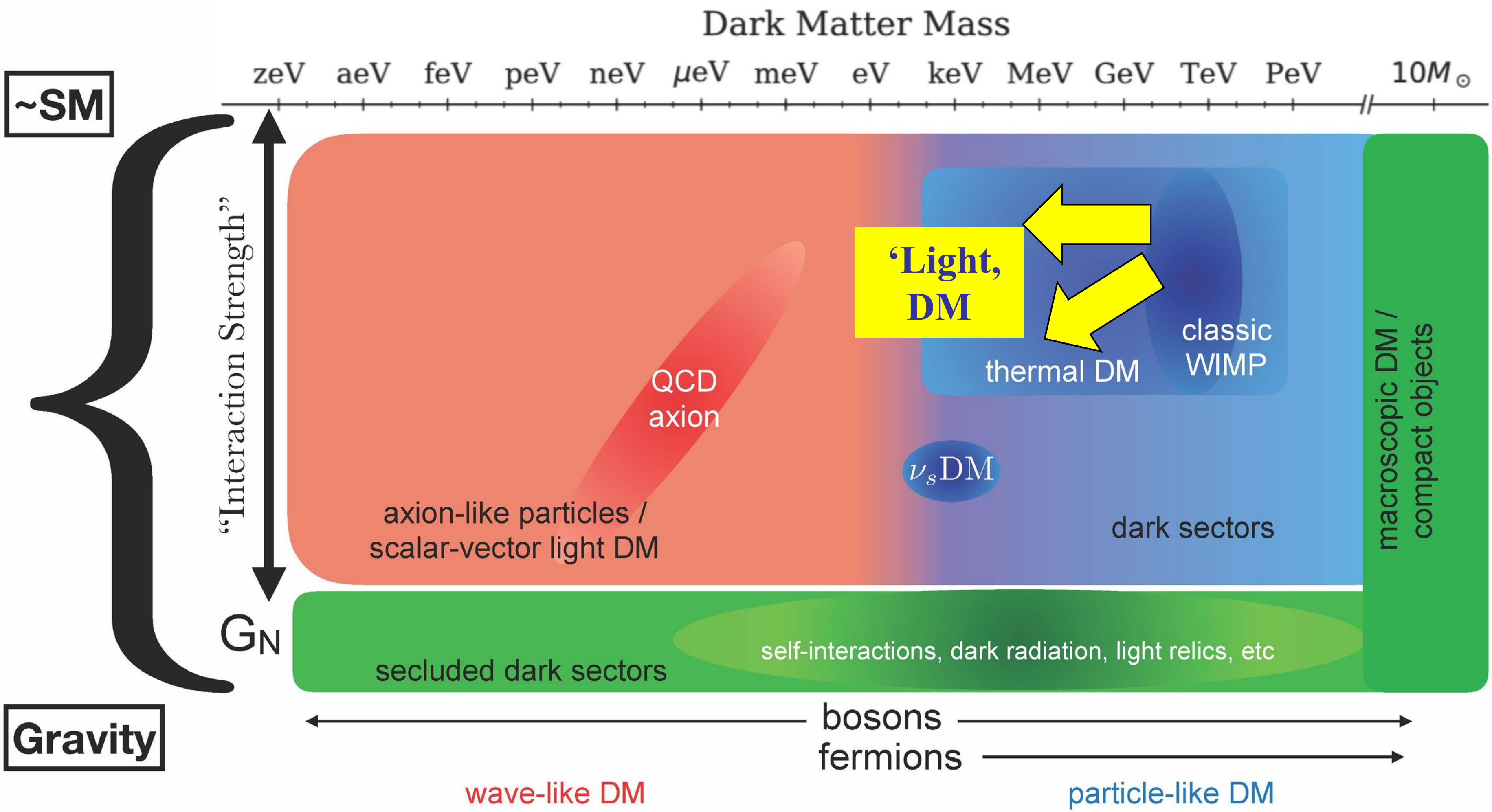
- New Xe production capacity comes online in response to market demand.
  - As a large customer, XLZD can sign a favorable long-term contract.
  - Xe procurement for XLZD may take 8 – 10 years.
- Other large Xe customers are the electronics industry; aerospace; and the lighting industry.

If a thermal WIMP exists above the neutrino fog, XLZD will see it





Possible interaction strengths range from the scale of the standard model to the scale of gravity

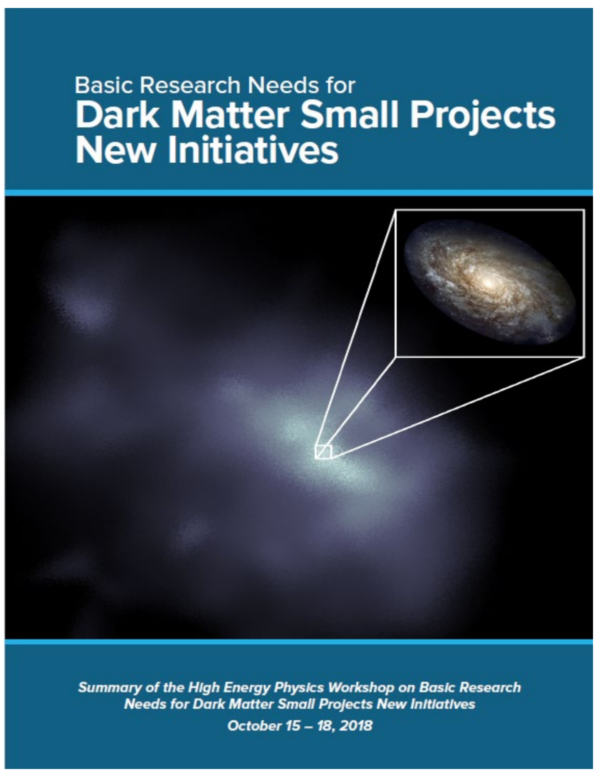


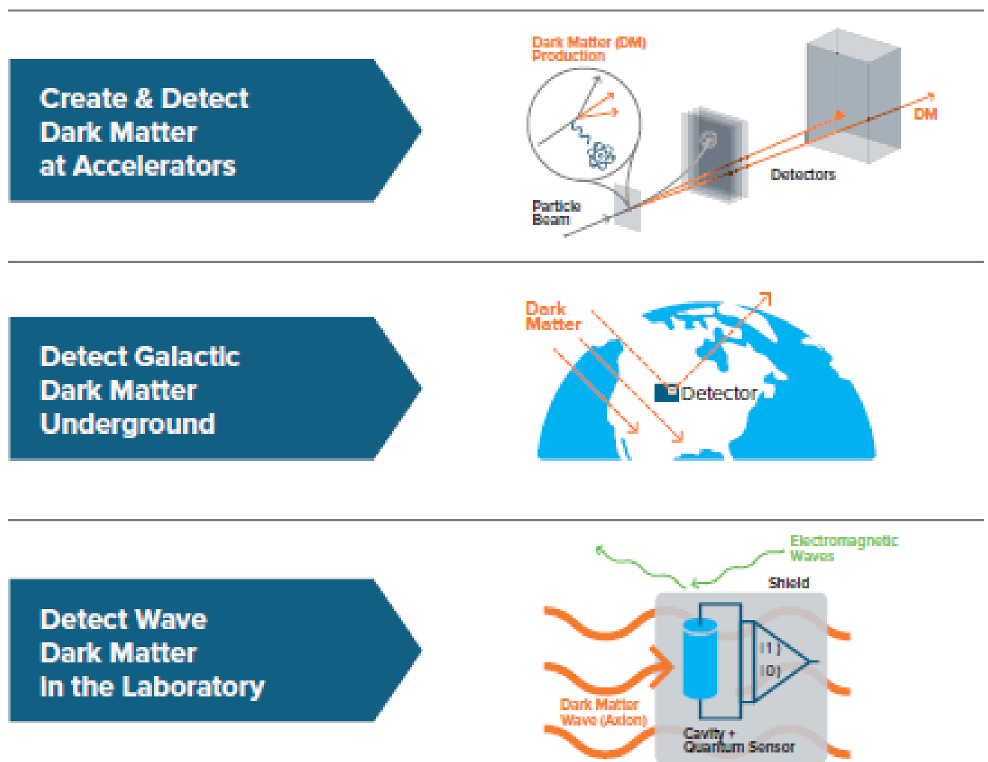
Credit: Aaron Chou, Snowmass 2022

2018 – Basic Research Needs – Dark Matter New Initiatives

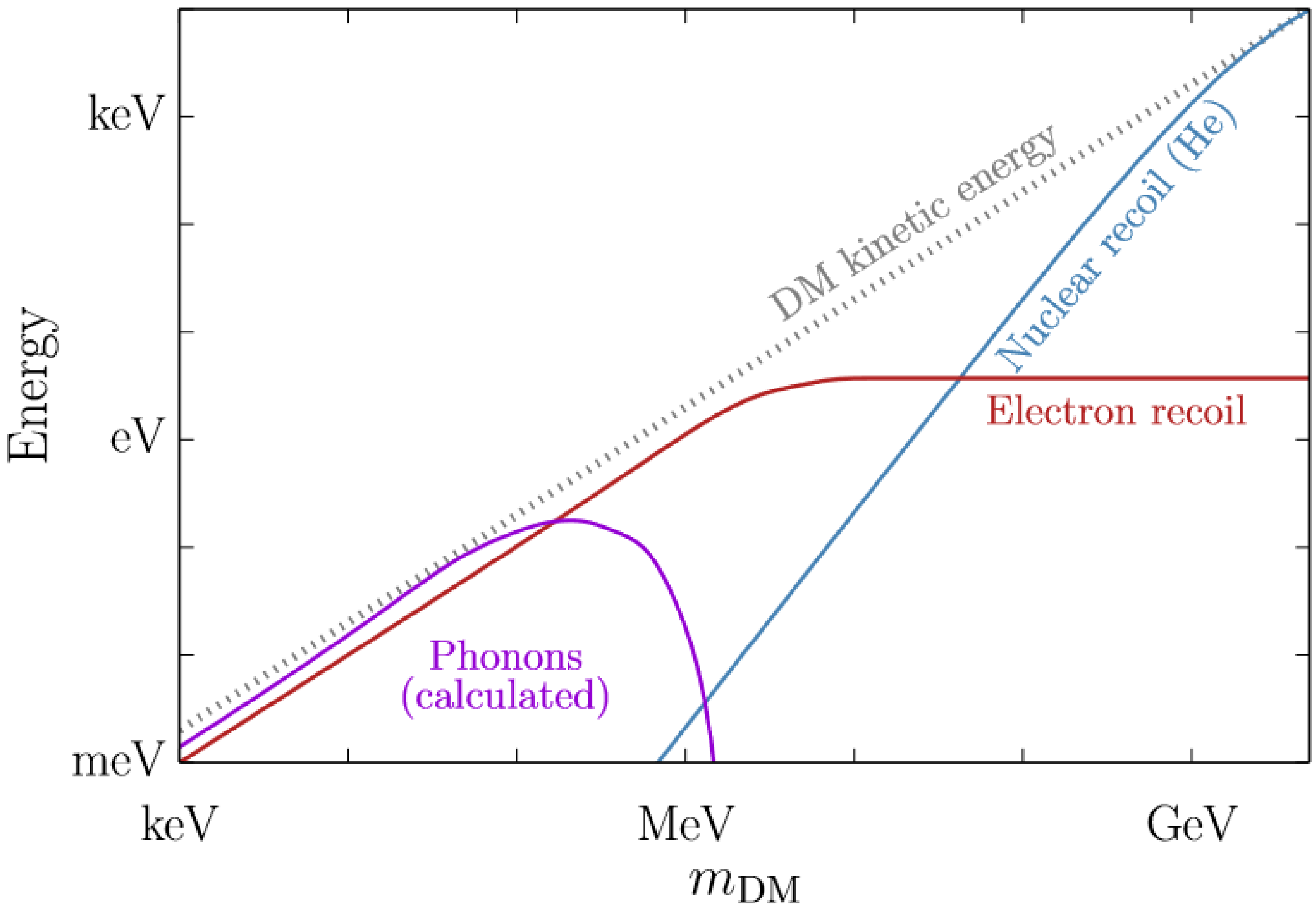
Priority Research Direction #2: Detect individual galactic dark matter particles below the proton mass.

Priority Research Direction #3: Detect wave dark matter using innovative technologies with emphasis on resolving a decades-old mystery of the physics inside the nucleus, the so-called "QCD axion."





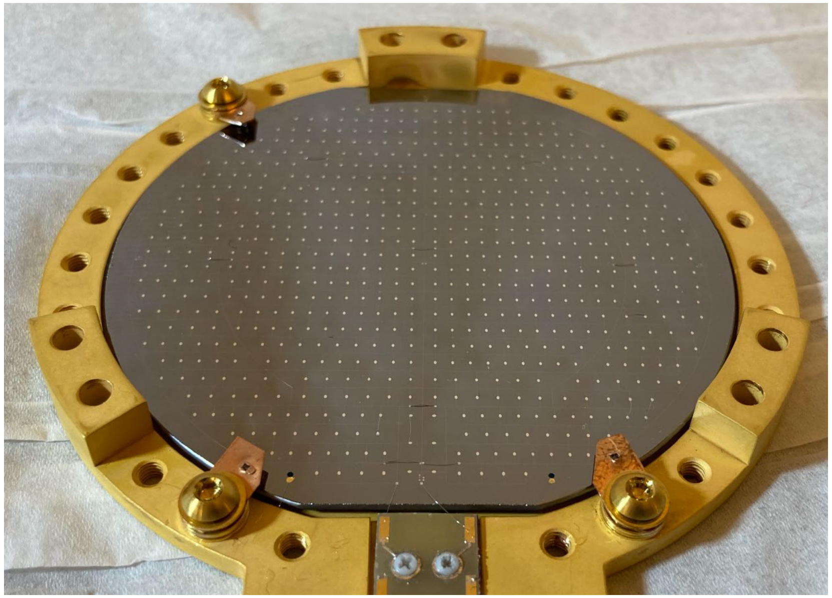
Kinematics of momentum transfer for light dark matter below 1 GeV



Credit: Tongyan Lin, TASI 2018 lectures; arXiv:1904.07915

Transition Edge Sensors: The TESSERACT project

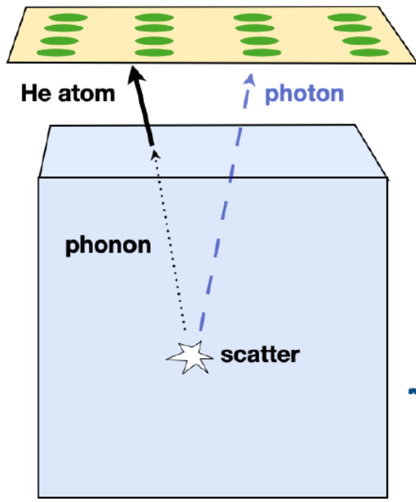
SPICE: TES on Crystals. Sapphire, GaAs, Si

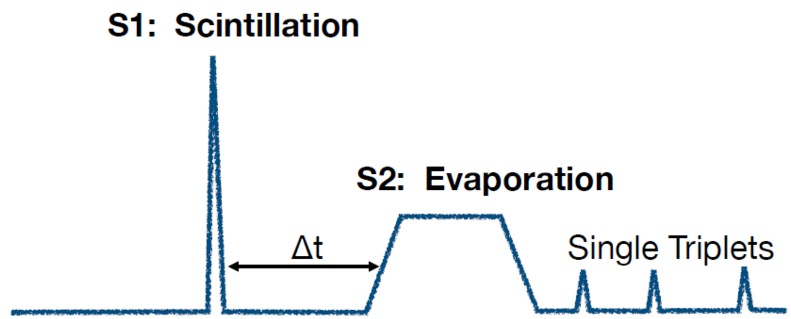


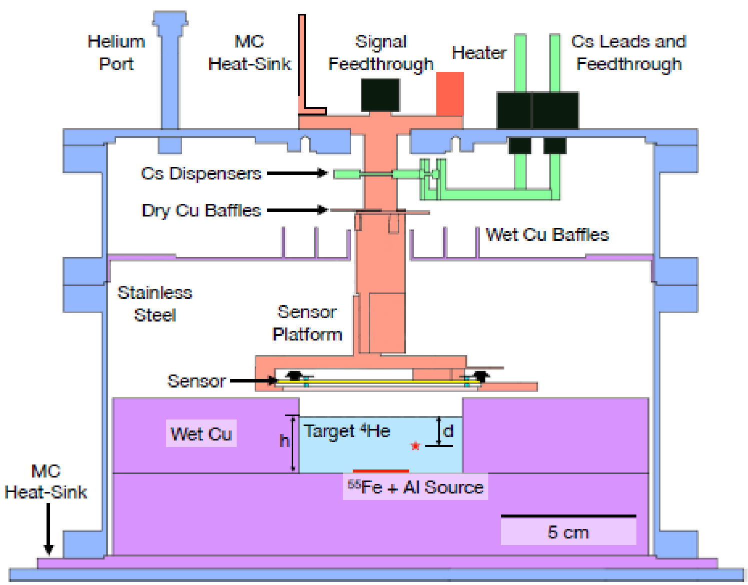
HERALD: TES on Silicon, observing superfluid liquid helium.

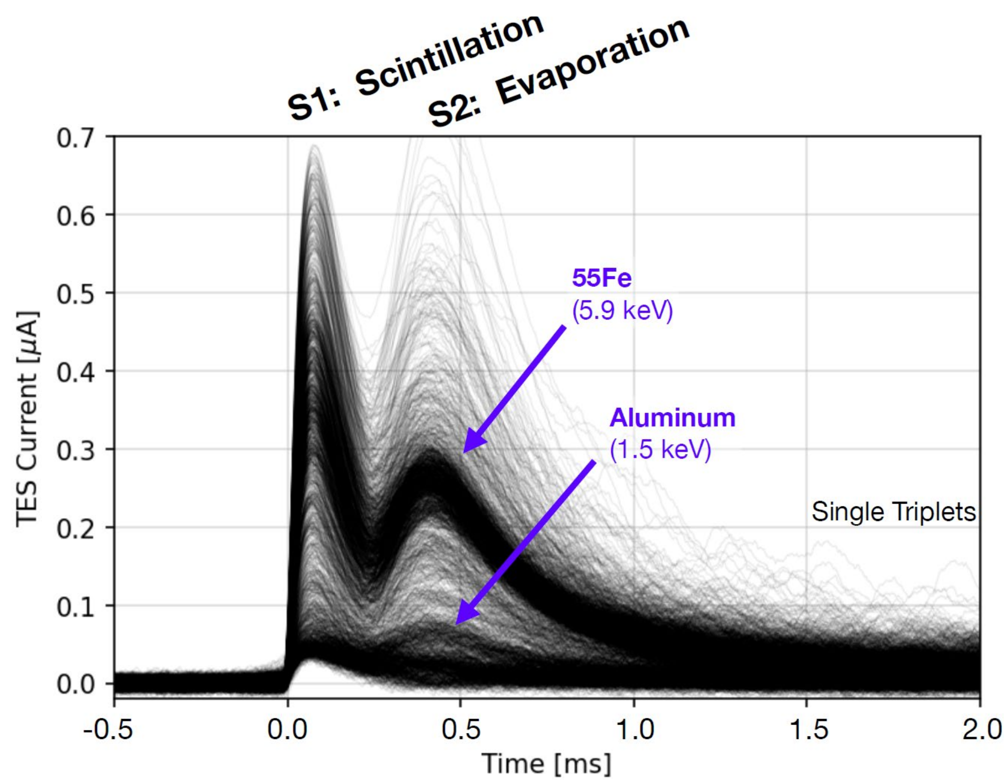
To be hosted at the Modane Underground Lab in France.

HEARLD: Superfluid liquid helium as a dark matter target

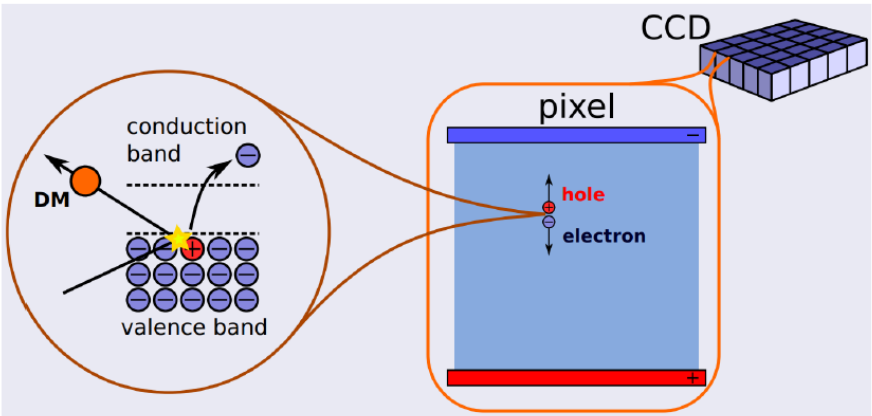


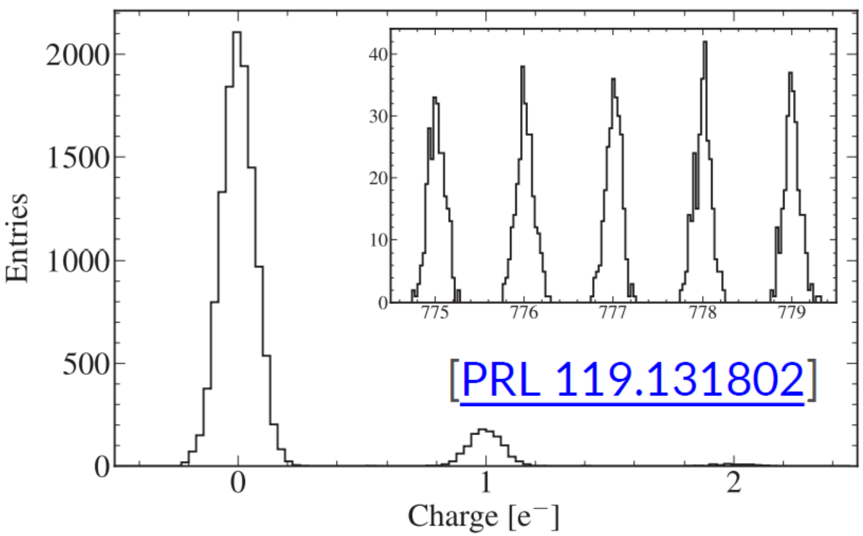


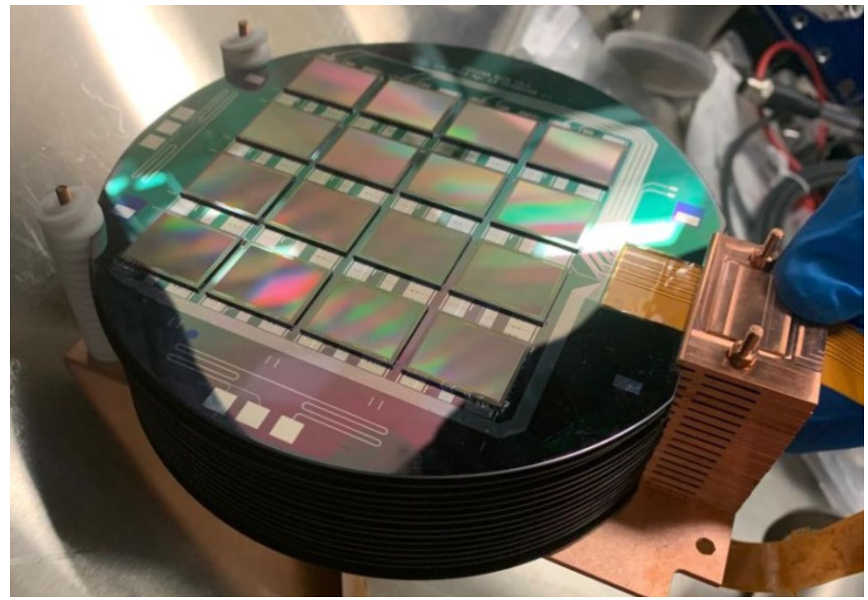




OSCURA: light dark matter scattering on electrons
10 kg of skipper CCDs.
Joint effort of the DAMIC + SENSEI collaborations

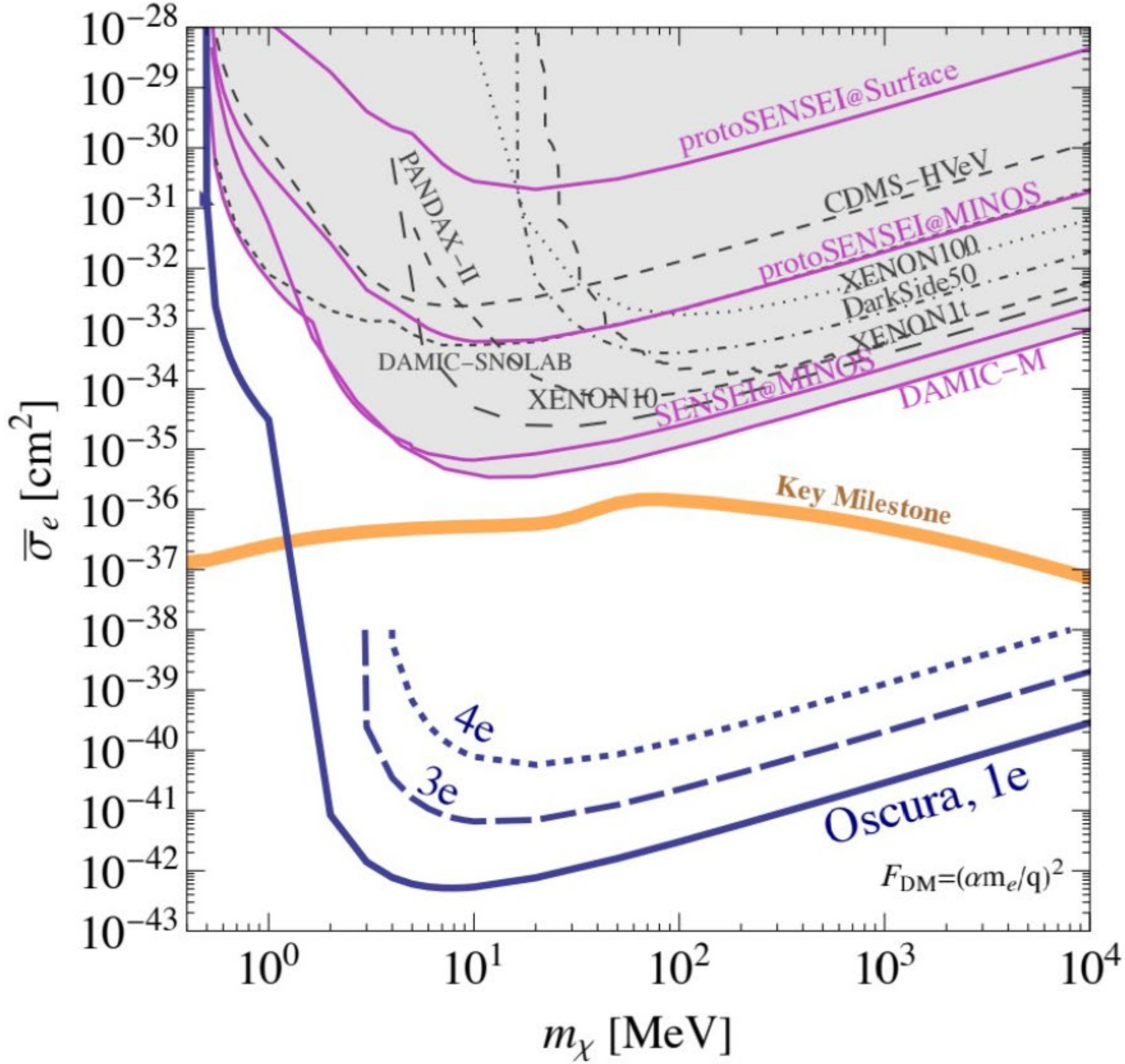




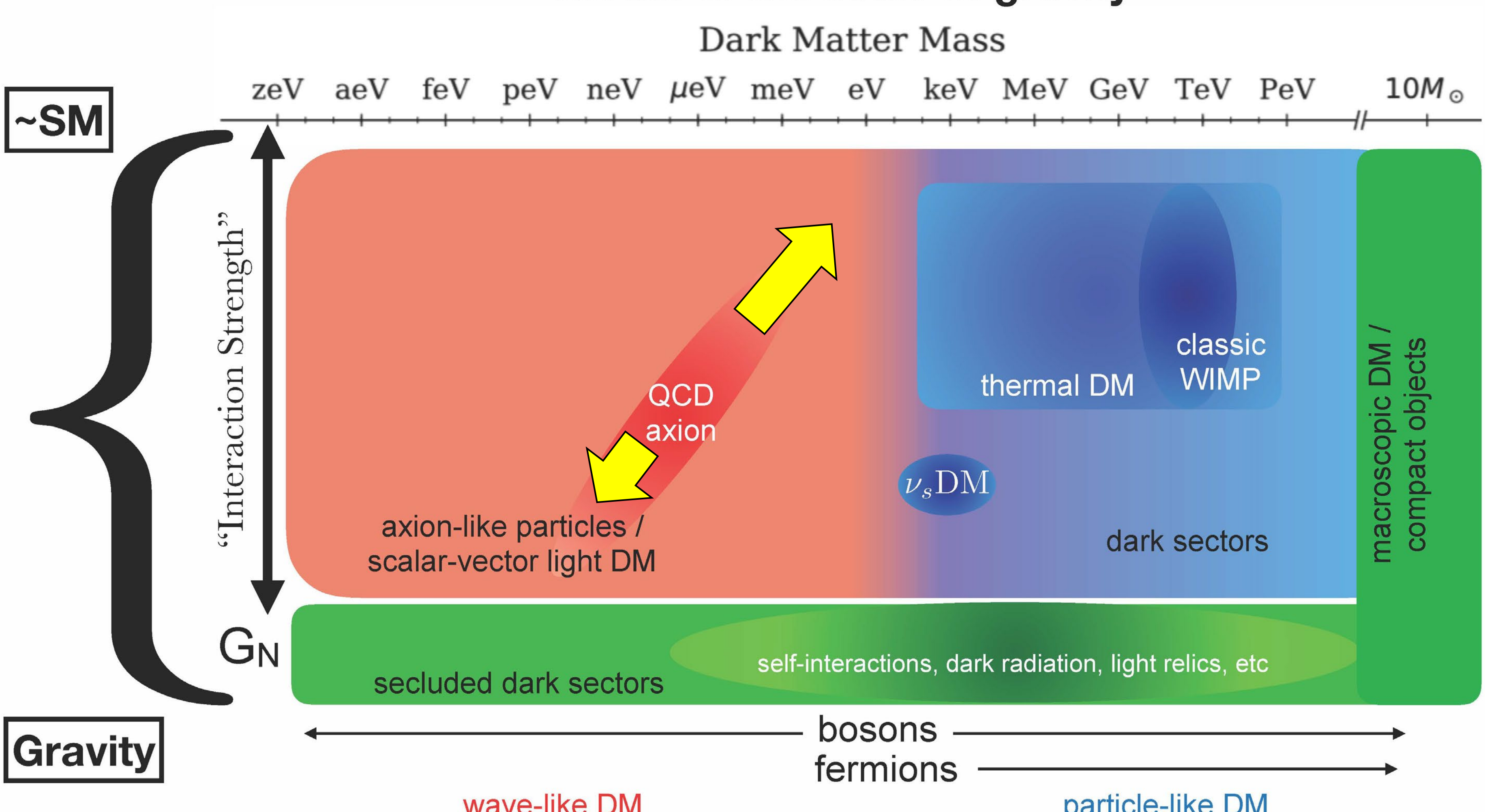


Credit: Nate Saffold, TAUP 2023

Oscura sensitivity: light mediator scenario



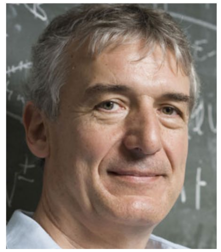
Possible interaction strengths range from the scale of the standard model to the scale of gravity



Credit: Aaron Chou, Snowmass 2022

The pioneering ADMX Axion Haloscope

2020 J. J. Sakurai Prize for Theoretical Particle Physics Recipient



Pierre Sikivie
University of Florida

Citation:

"For seminal work recognizing the potential visibility of the invisible axion, devising novel methods to detect it, and for theoretical investigations of its cosmological implications."

Background:

Pierre Sikivie was born in Sint-Truiden, Belgium, on October 29, 1949. He did his undergraduate studies at the University of Liege and obtained the degree of "Licencie en Sciences Physiques" in 1970. He did his graduate studies at Yale University and obtained a PhD in Physics in 1975. His PhD advisor was Professor

2024 W.K.H. Panofsky Prize in Experimental Particle Physics Recipient

David B. Tanner
University of Florida

Citation:

"For leading the synthesis of precision microwave cavity techniques, superconducting quantum sensing, and cryogenic technology into the modern axion haloscope, and for the subsequent demonstration of experimental sensitivity to high-priority models of axions as dark matter."

Background:

David Tanner attended the University of Virginia (B.A. 1966, M.S. 1967) and Cornell University (Ph.D. 1972). He held a postdoctoral position at the University of Pennsylvania and then, in 1974, joined the Physics Department at the Ohio State University. He came to the

2024 W.K.H. Panofsky Prize in Experimental Particle Physics Recipient

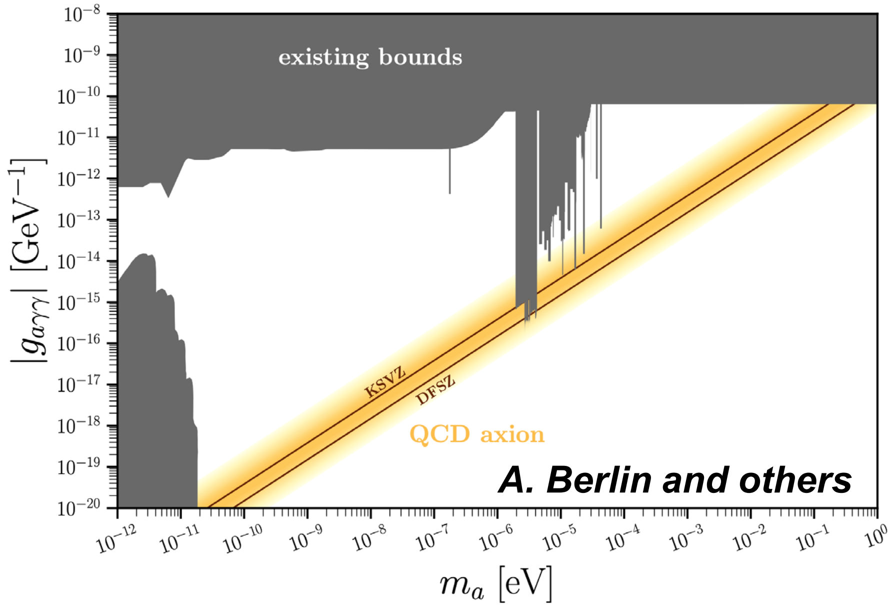
Leslie J Rosenberg
University of Washington

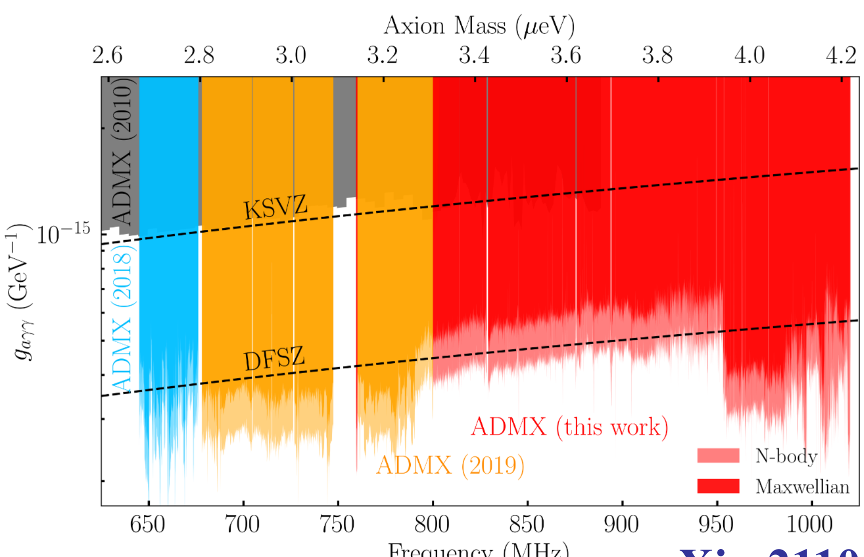
Citation:

"For leading the synthesis of precision microwave cavity techniques, superconducting quantum sensing, and cryogenic technology into the modern axion haloscope, and for the subsequent demonstration of experimental sensitivity to high-priority models of axions as dark matter."

Background:

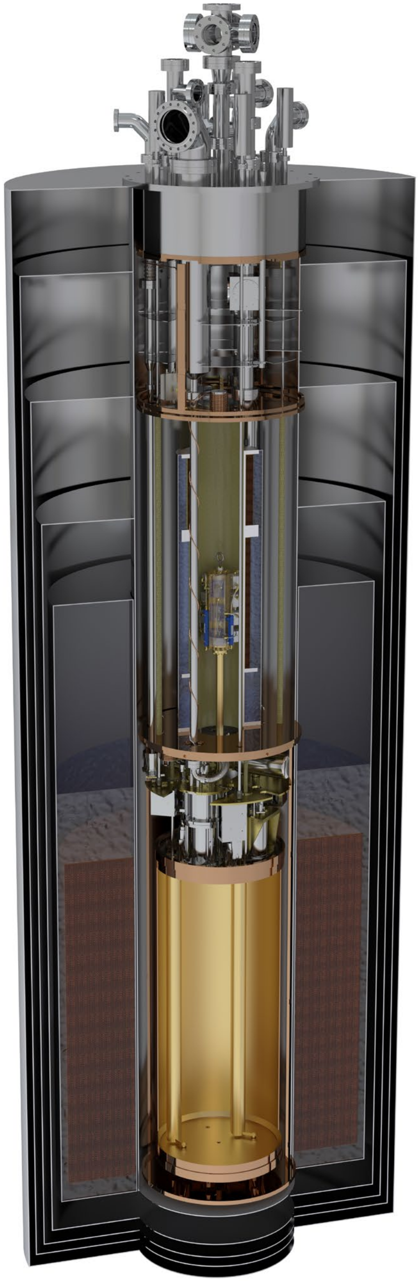
Leslie Rosenberg graduated from UCLA in 1977 and became a research assistant at LBL. He received his Ph.D. from Stanford University in 1985 with the MAC Detector group at SLAC's PEP storage ring. There, his research focus was the strong-interaction coupling

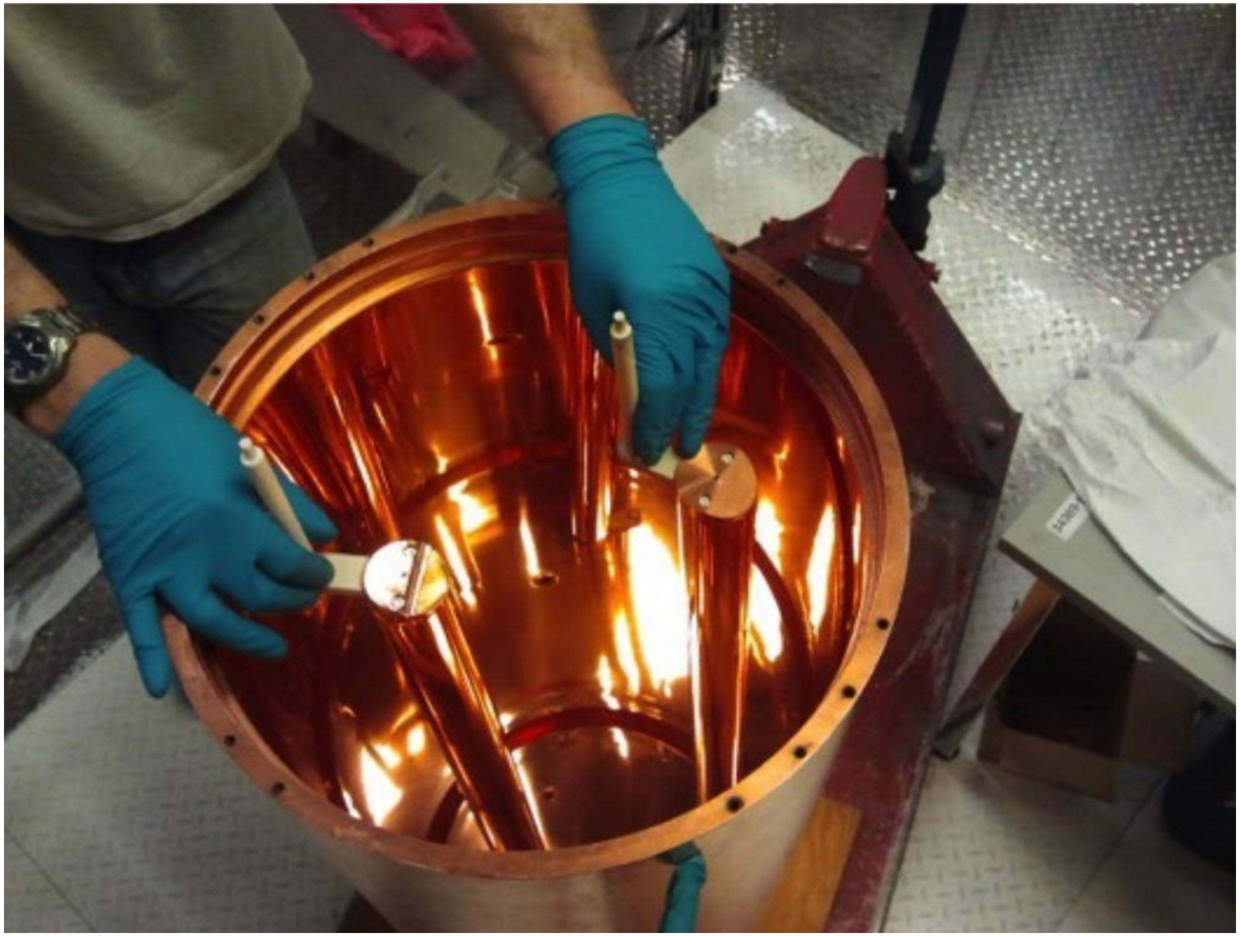




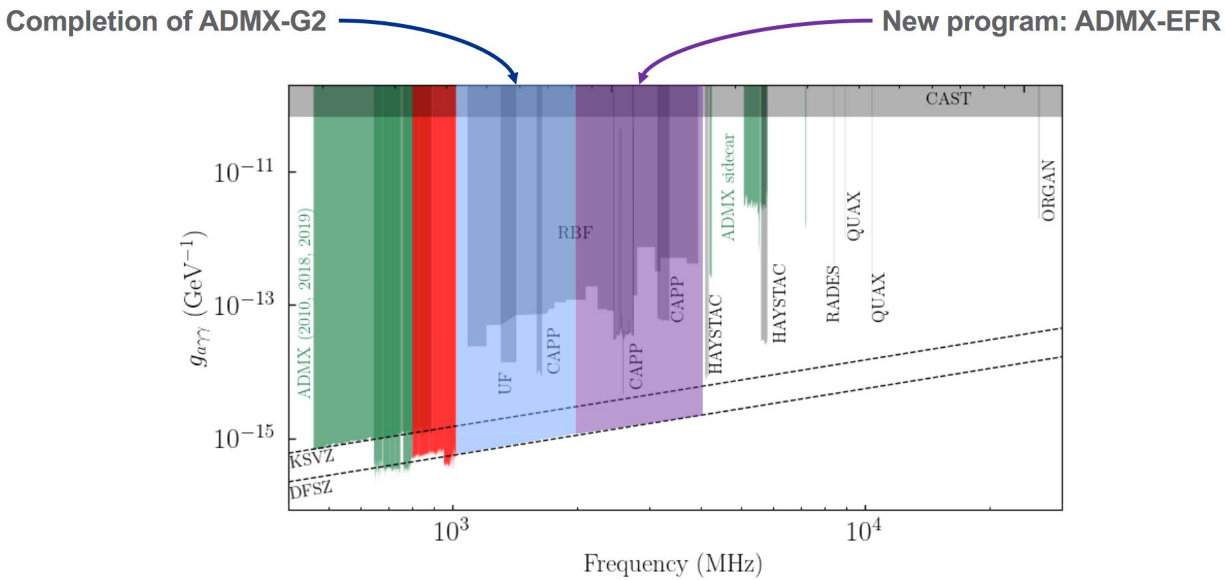
arXiv:2110.06096

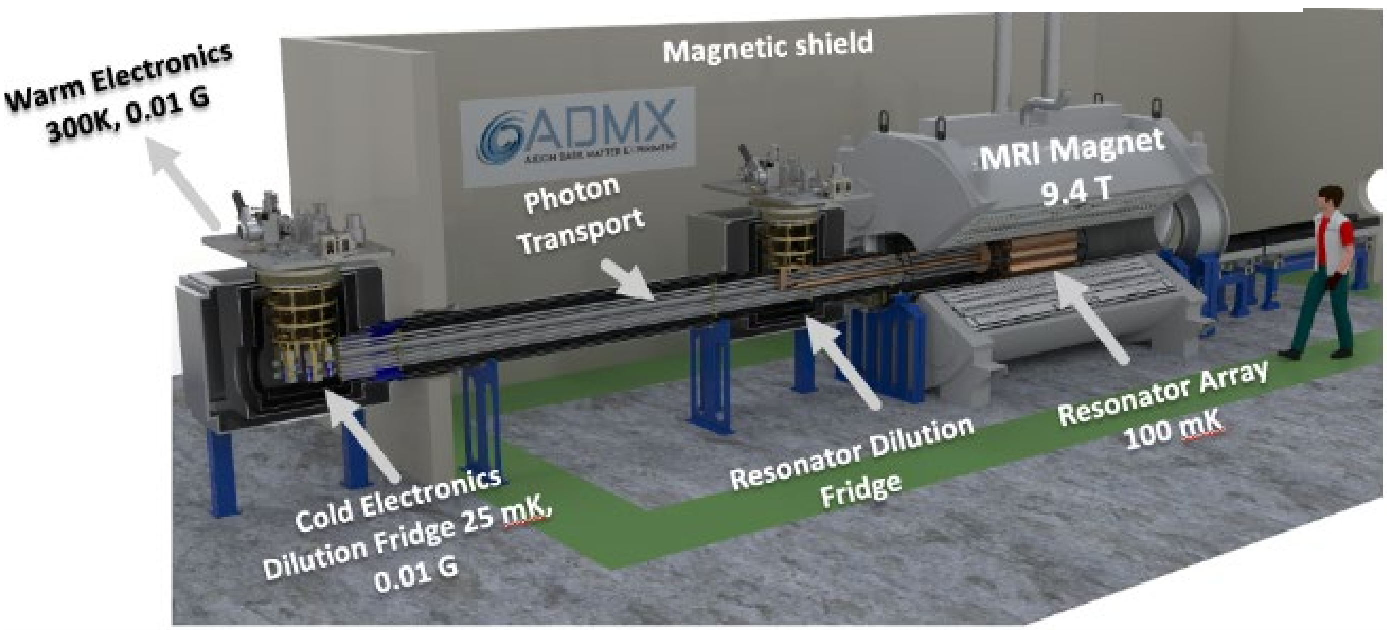
ADMX-G2 Axion Haloscope

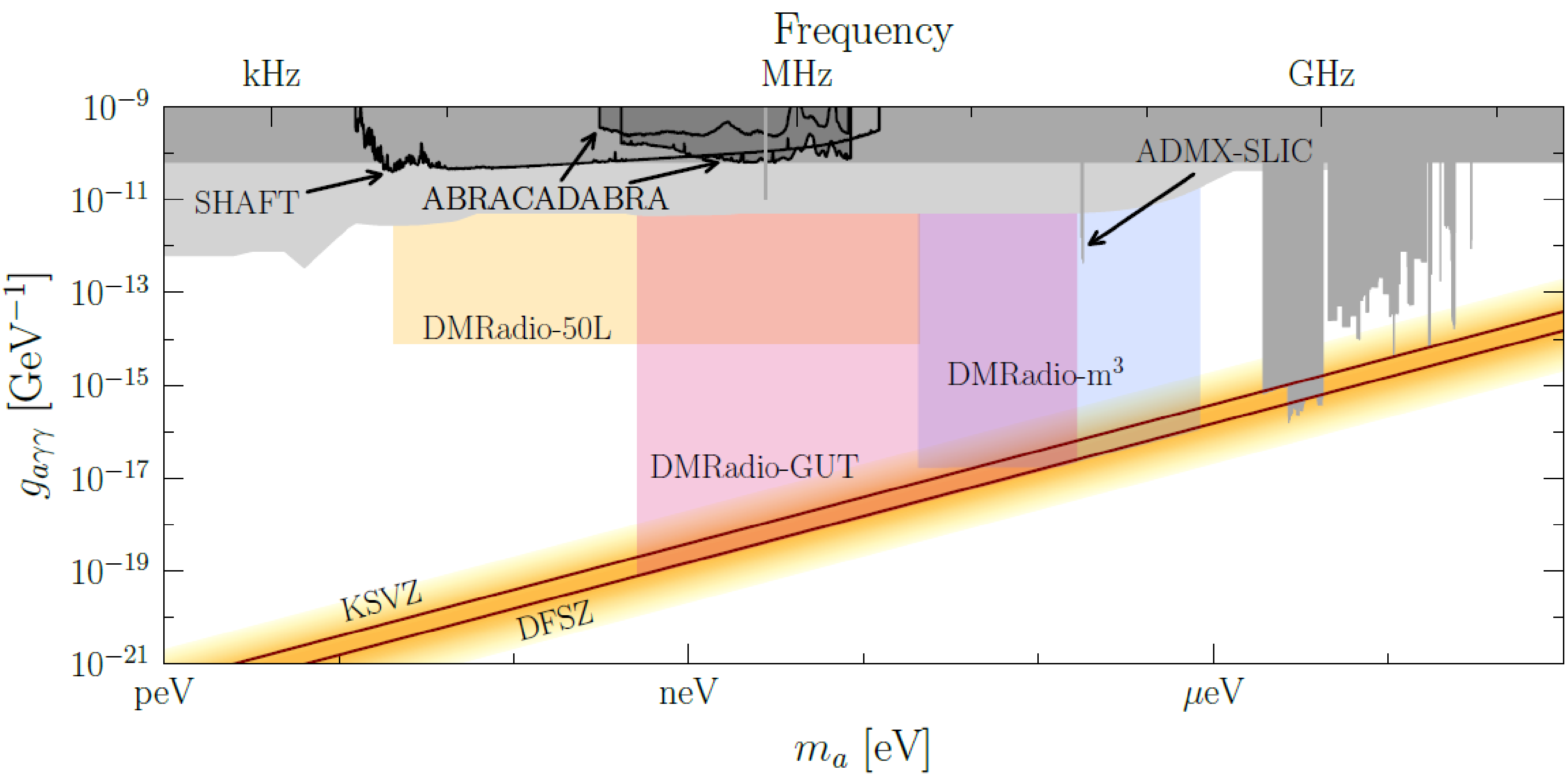




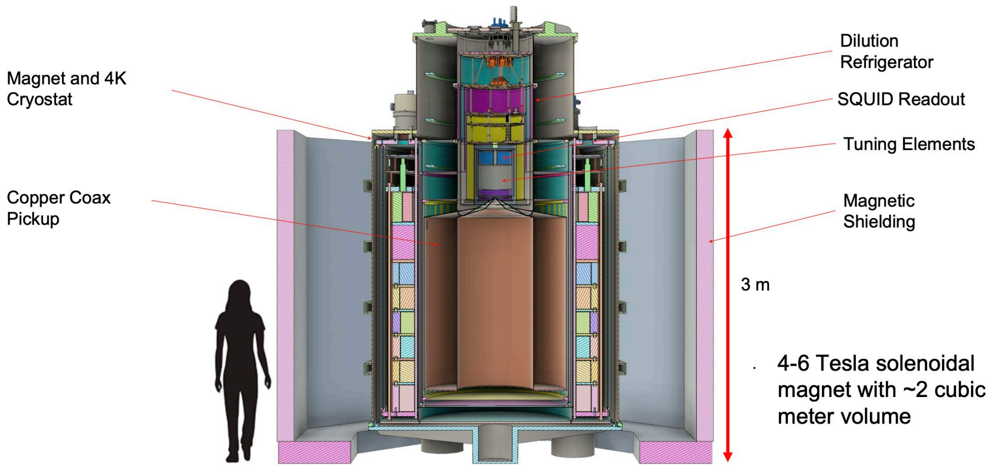
ADMX – Extended Frequency Range (EFR)



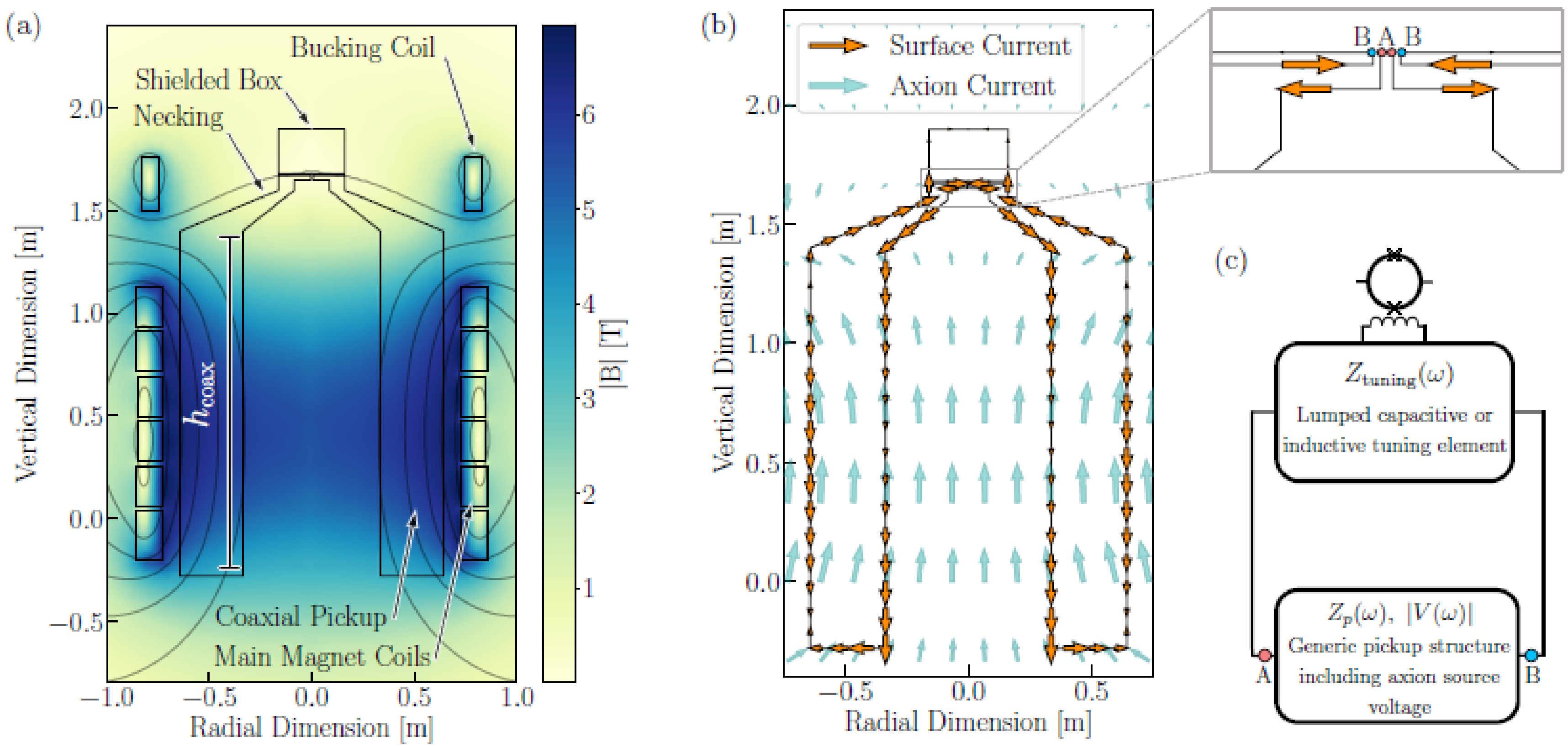




Phys.Rev.D 106 (2022) 11, 112003, arXiv:2203.11246



The DMRadio-m^3 experiment arxiv:2302.1408



P5 recommendations

Recommendation 2d: An ultimate Generation 3 (G3) dark matter direct detection experiment reaching the neutrino fog.

Recommendation 3a: Implement a new small-project portfolio at DOE (ASTAE)….. This program should start with the construction of experiments from the Dark Matter New Initiatives (DMNI) by DOE-HEP.

BACKUP SLIDES

DMNI Status

Concept	DM type	Mass range	Lead lab	Orig R&D request ($K)	R&D $K thru FY24	Est. Fab. cost ($M)
ADMX-EFR	Axions	9-17 μeV	FNAL	1,976	3,140	$20
DM-Radio	Axions	<μeV	SLAC	993	1,560	$24
LDMX	Hidden sector	10-300 MeV	SLAC	1,960	2,250	$21
OSCURA	WIMPs	1MeV-1GeV	FNAL	3,943	3,544	$15
TESSERACT	WIMPs	>10 MeV	LBNL	3,975	1,815	<$10
Total				12,847	12,309	$90

- These are the remaining DMNI proposals.
  - CCM at LANL was funded, fabricated and is operating.
- The French have funded a proposal to host TESSERACT.
- DOE has decided to fund TESSERACT starting in FY25 based on its cost effectiveness and the French offer to host.
  - These considerations made it the ideal concept to go next.
- We are still working on the process to select other DMNI proposals.
  - Most likely start will be in FY 26
- HEP will try to select 2 additional DMNI's to move to fabrication, with the rest folded into the ASTAE program competition. This will also allow new dark matter proposals to be considered.

ASTAE

- From P5 Report recommendation #3 *: Implement a new small-project portfolio at DOE,* ***Advancing Science and Technology through Agile Experiments (ASTAE)****, across science themes in particle physics with a competitive program and recurring funding opportunity announcements. This program should start with the construction of experiments from the Dark Matter New Initiatives (DMNI) by DOE-HEP (section 6.2).*
- DOE response and actions :
  - DOE will initiate fabrication of 1-3 DMNI projects (5 projects remain under consideration)
  - The key word for new projects is AGILE

P5's call for *agile* implies that we should complete these experiments quickly, and shift course when it comes time to start new ones.

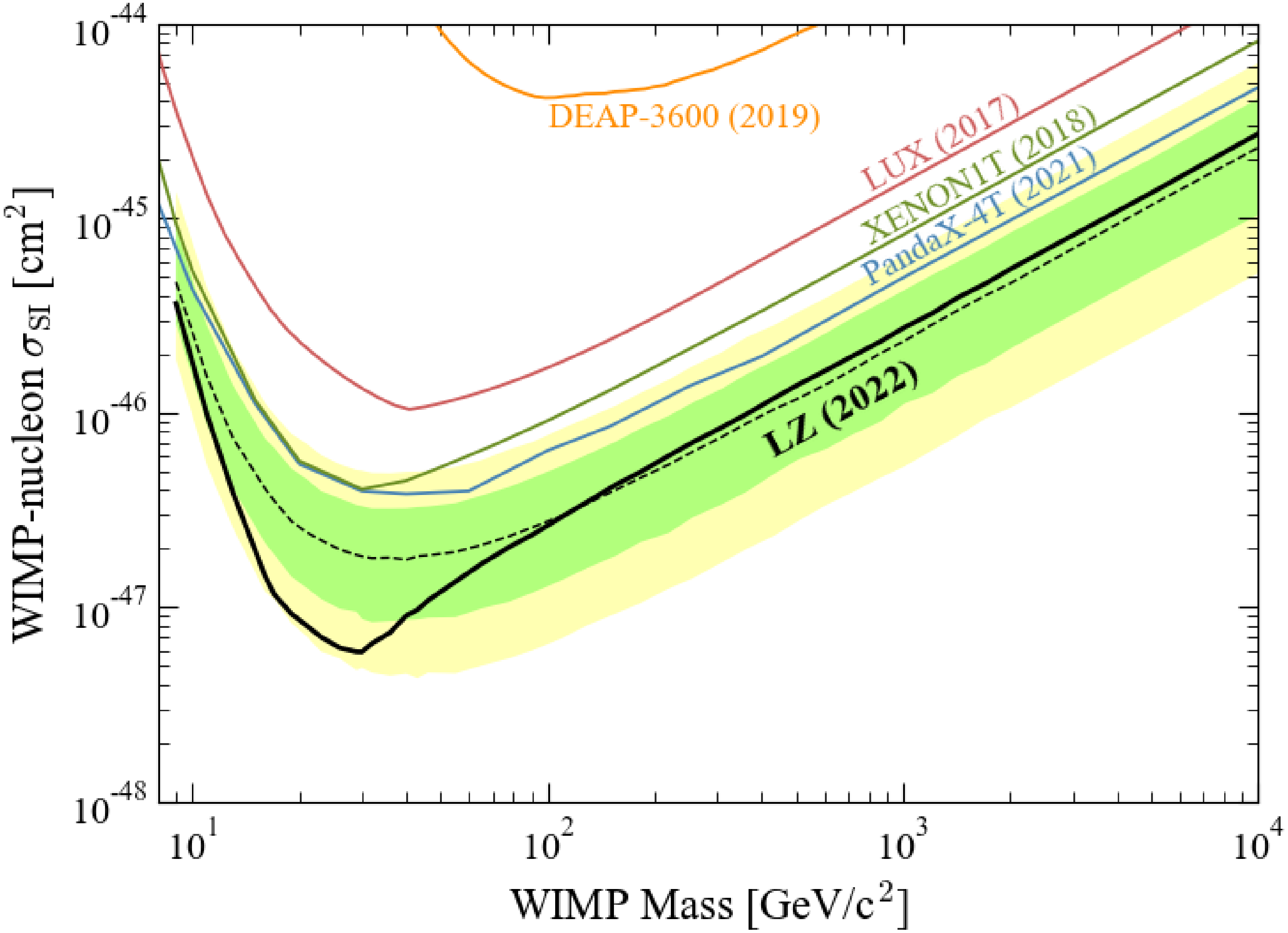
To do this:

- Keep FOA's and # of reviews limited. Select a few (2?) concepts at a time to develop into projects.
- Short R&D/design phase to finalize technology, concept development.
- Keep projects within a set funding envelope and schedule.
- We expect the lead laboratories to develop project execution plans to keep the initiatives on track and within budget

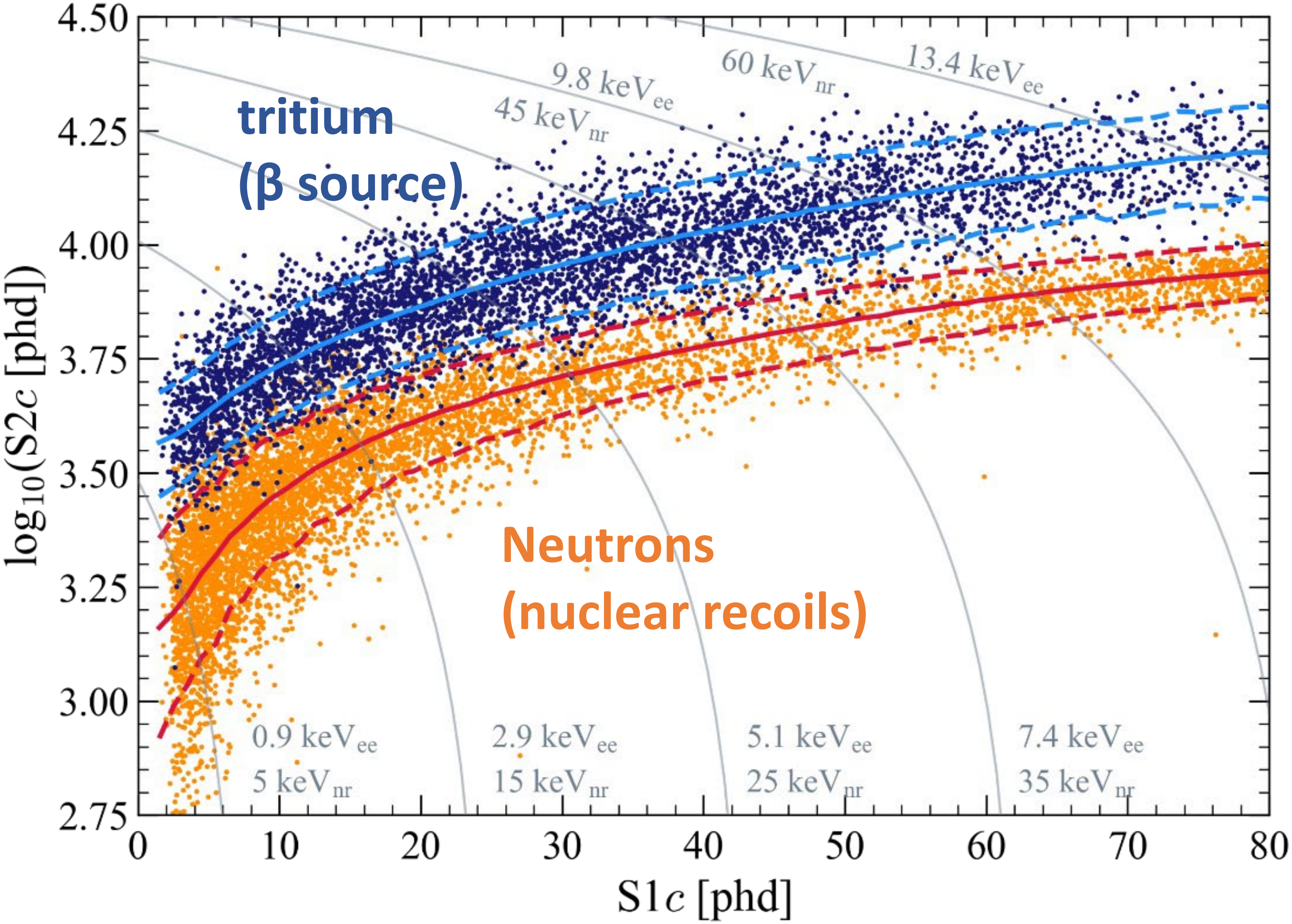
G3 Dark Matter

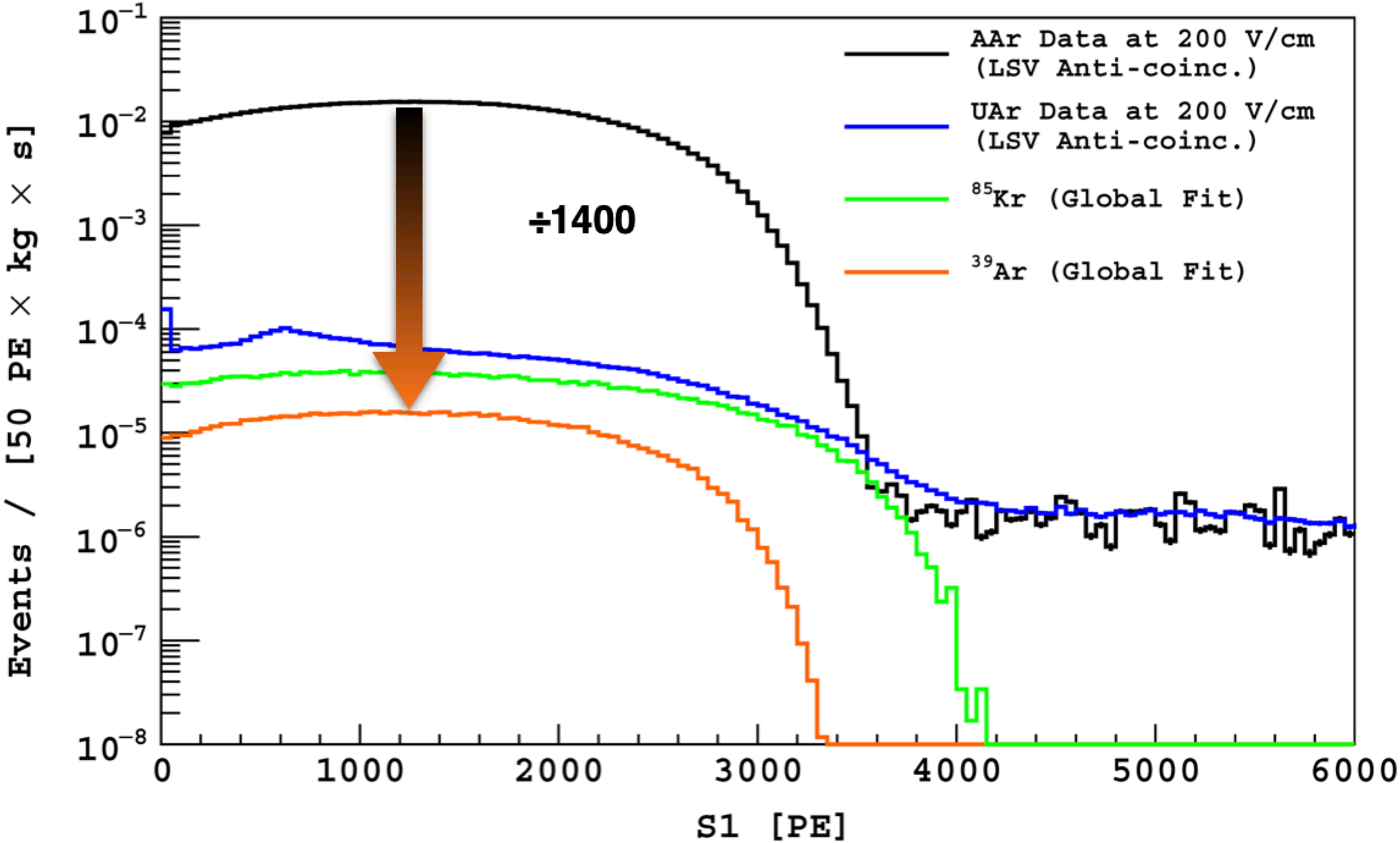
- From P5 Recommendation 2, Priority 4 out of 5 :
  - An **ultimate Generation 3 (G3) dark matter** direct detection experiment reaching the neutrino fog, in coordination with international partners and **preferably sited in the US** (section 4.1).
- DOE response and actions :
  - At the present time, based on the Snowmass Community Summer Study, there have been two proposals for G3 Dark Matter detectors : XLZD and ARGO
  - Each concept has explored potential sites both within the US and off-shore.
  - At the present time, DOE is supportive of the development of the off-shore concepts.
  - DOE will entertain proposals by U.S. groups for pre-project R&D consistent with experiment deployment at an off-shore site.

LZ WIMP Search Result
60 days – July 2022

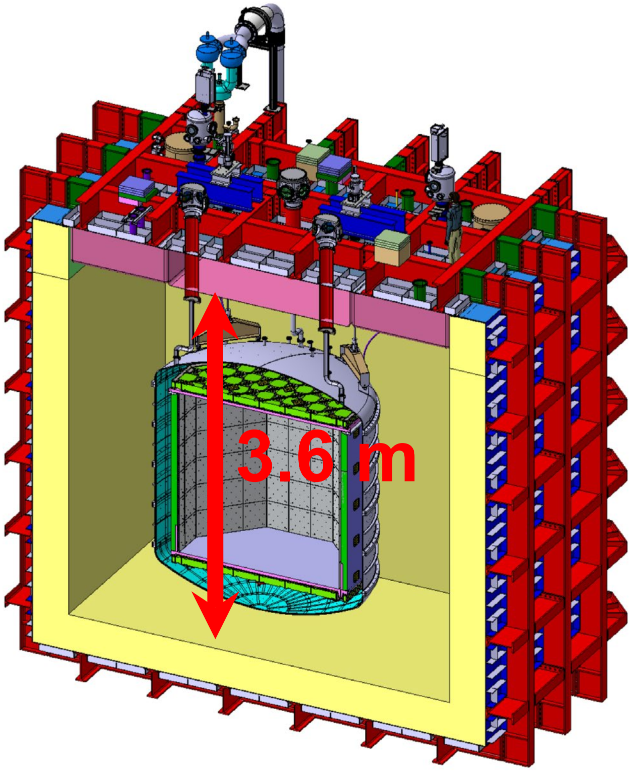


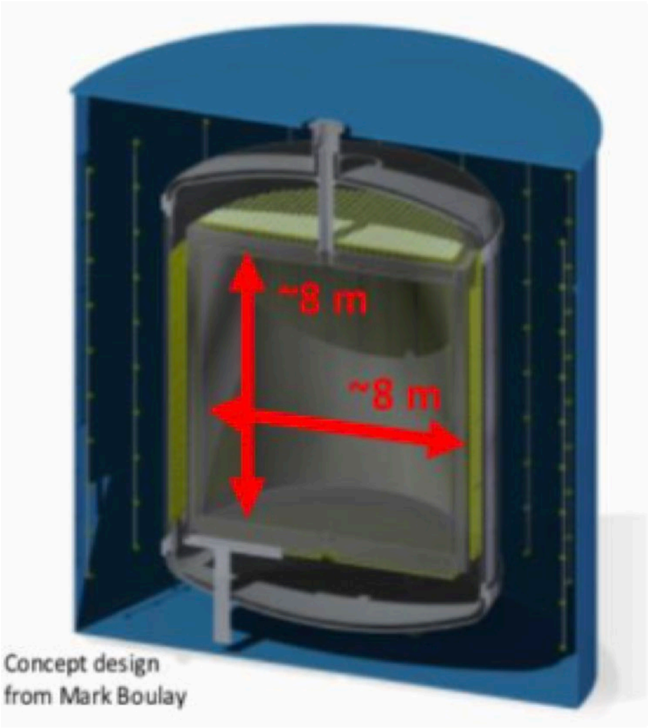
LZ calibration data – April 2022




AAr Data at 200 V/cm
(LSV Anti-coinc.)
UAr Data at 200 V/cm
(LSV Anti-coinc.)
85Kr (Global Fit)
39Ar (Global Fit)
÷1400
Events / [50 PE × kg × s]
S1 [PE]
0
1000
2000
3000
4000
5000
6000
10−1
10−2
10−3
10−4
10−5
10−6
10−7
10−8

GADMC: Future LAr TPCs → DS20k → ARGO





DarkSide-20k @ LNGS

ARGO @ SNOLAB
Construction 2030-203
Operations 2035-2051