

Direct Detection of Particle Dark Matter

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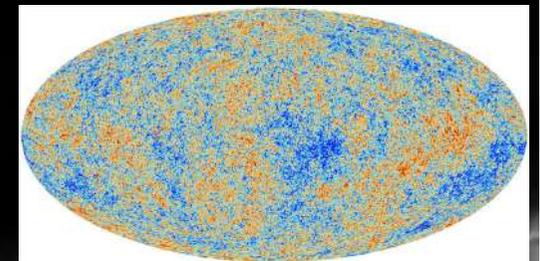
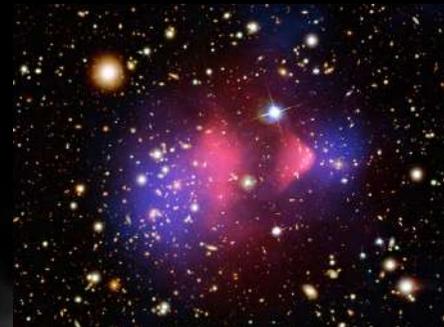
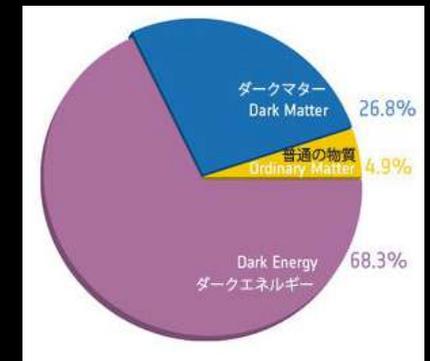
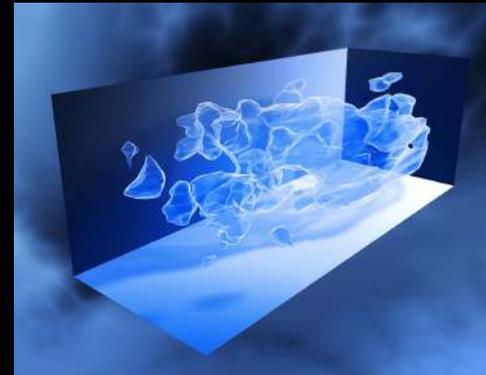
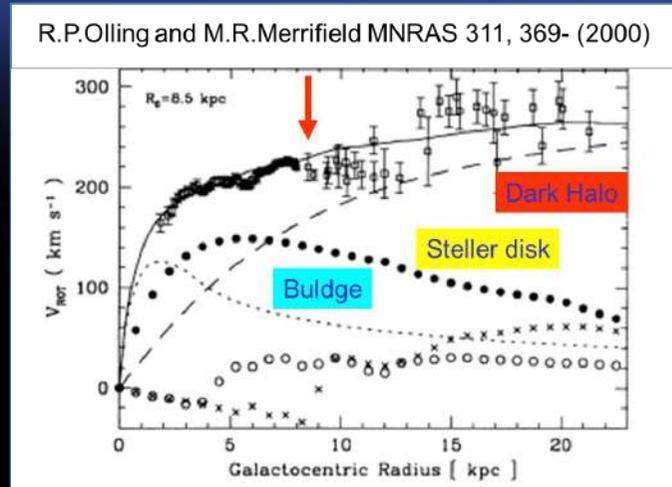


Scientific Importance of detection of dark matter

Understanding the nature of dark matter is one of the most important issues in particle astrophysics.

Strong evidence on dark matter: Cluster of galaxies, rotation curve of galaxies, lensing effect, large scale structure, cosmic microwave background, etc.

Identifying dark matter must be a breakthrough in understanding the universe filled with “unknowns”.



Particle dark matter

Size of galaxy **Mass ~totally unknown** 1000 solar mass
Interaction ~totally unknown
2-dimensional search



Neutrino physics: interaction predicted
Gravitational wave: interaction predicted

Proton decay: lifetime unknown (1-dim)

0ν double beta decay: lifetime unknown (1-dim)

- **Target mass range as “particle dark matter”**

- Less than 1 DM / (de Broglie wavelength)³: **> 30 eV**

<https://arxiv.org/pdf/2101.11735.pdf>

- More than 1 DM coming into m² detector/yr: **< 10¹⁶ GeV**

Basic kinematics

- Velocity of dark matter particles
 - $\beta \sim 10^{-3}$ \sim rotation velocity of the sun inside the galaxy
 - Fully non-relativistic unless boosted
- Expected energy deposition
 - Elastic scattering (DM mass $> \sim$ target mass):
 - **Nuclear** target: $m = 1-100 \text{ GeV} \rightarrow E_{\text{kin}} \sim m\beta^2/2 \sim \mathcal{O}(\text{keV-MeV})$
 - **Electron** target: $m = 511 \text{ keV} \rightarrow E_{\text{kin}} \sim m\alpha\beta/2 \sim \mathcal{O}(\text{eV})$
 - **Quasi-particle** target (\sim electron): useful for smaller mass
 - Absorption case:
 - **Rest mass of dark matter**

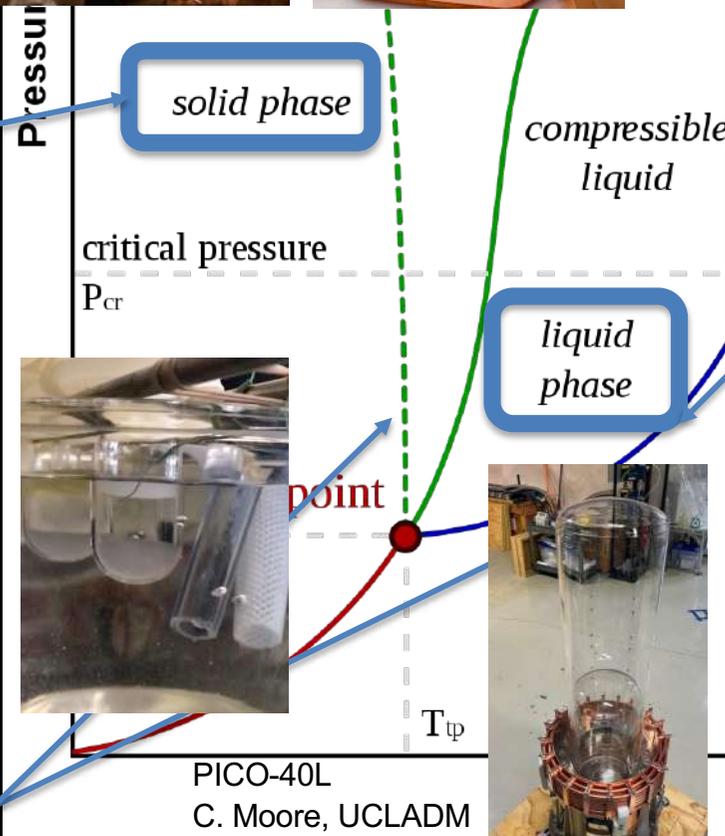
Target materials

DAMA
P. Belli, UCLA DM 2023
Super-CDMS
E. Michielin, UCLA DM

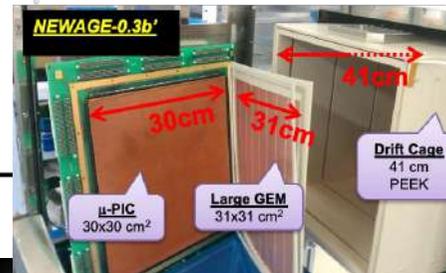


LHe
LAr
LKr
LXe (+H₂)
Monolithic

Optical crystals
Semiconductor
Material
Low excitation E
Multi modules



The snowball Chamber
M. Szydagis, UCLA DM



XENONnT

gaseous phase

CF₄ etc.
Directional

Superheated liq
Supercooled liq.
Particle ID

NEWAGE, K. Miuchi

Credit: wikipedia

There are still large "phase" space to be explored.

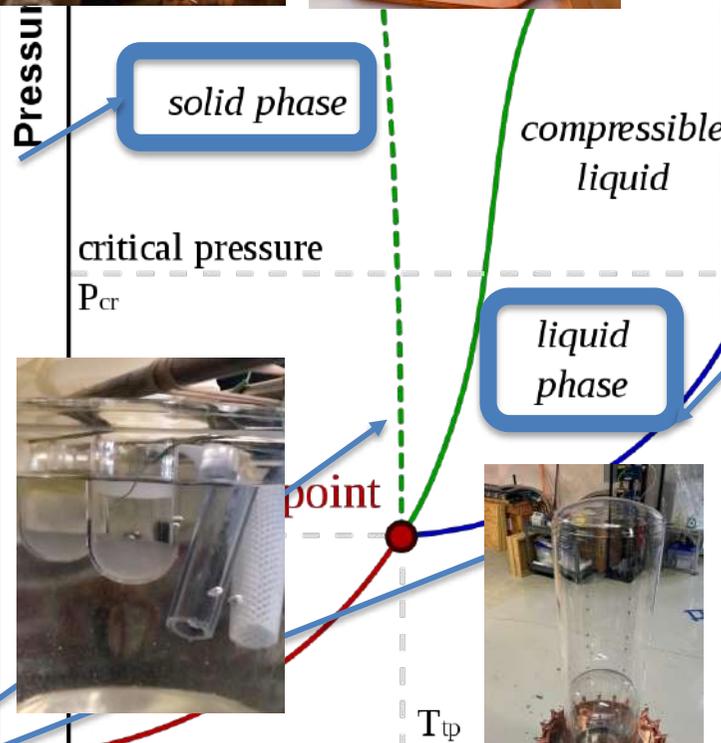
Quanta and their excitation energy

DAMA
P. Belli, UCLADM
Super-CDMS
E. Michielin, UCLADM



Photon $\sim 10\text{eV}$
Charges $\sim 10\text{eV}$
Roton $\sim \text{meV}$
Monolithic

Photon $\sim 10\text{eV}$
Charges $\sim 10\text{eV}$
Phonon $1\text{-}10^2\text{meV}$
Cooper $\sim \text{meV}$
Low excitation E
Multi modules

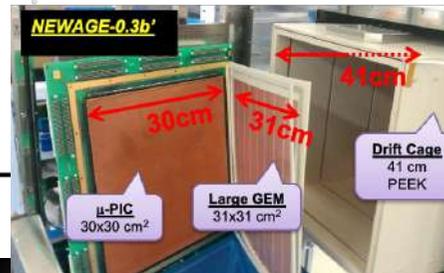


PICO-40L
C. Moore, UCLADM



XENONnT

gaseous phase



NEWAGE, K. Miuchi

Photon $\sim 10\text{eV}$
Charge $\sim 10\text{eV}$
Directional

Credit: wikipedia

Acoustic
Images
Particle ID

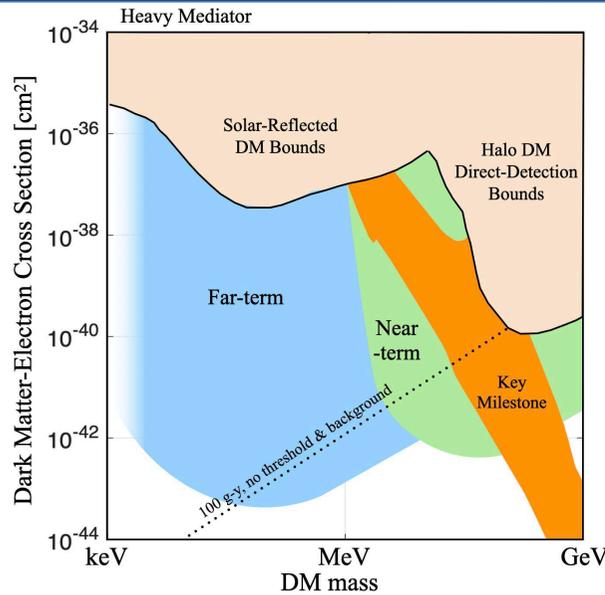
Low-energy quanta are suitable for low-mass WIMP search.⁶

Further developments of “particle dark matter” search

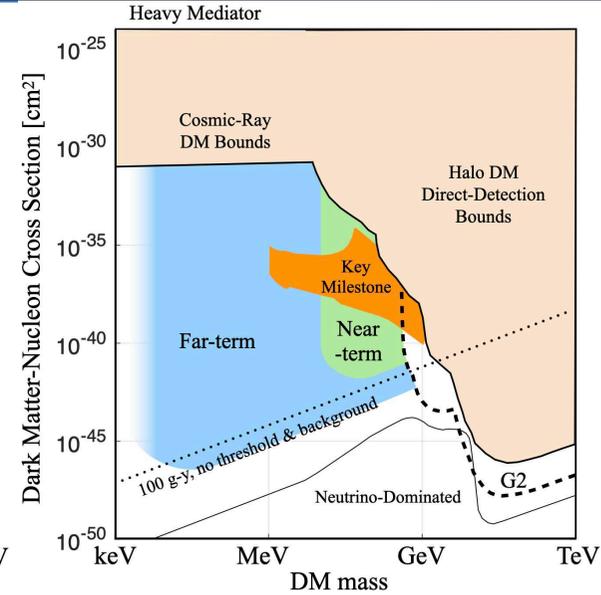
- By considering available quanta
 - Light DM, small $E \rightarrow$ e recoil, multi-modules
 - Efforts to delve deep.

Constraints and future

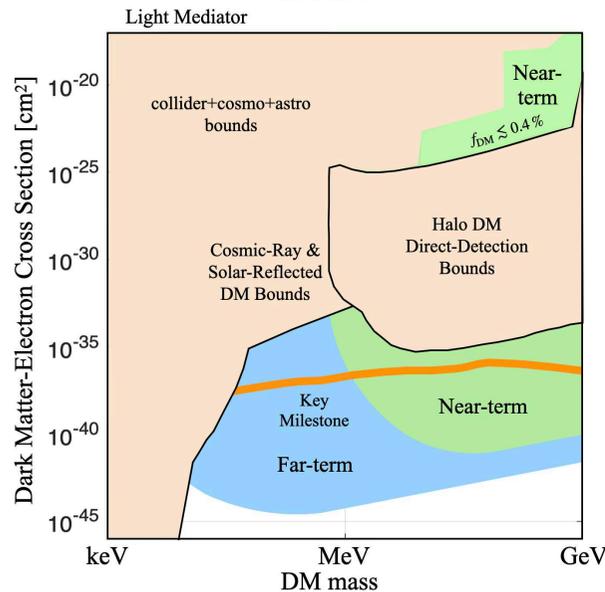
DM-electron
xsec
heavy mediator



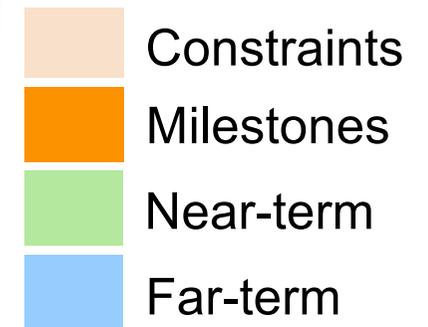
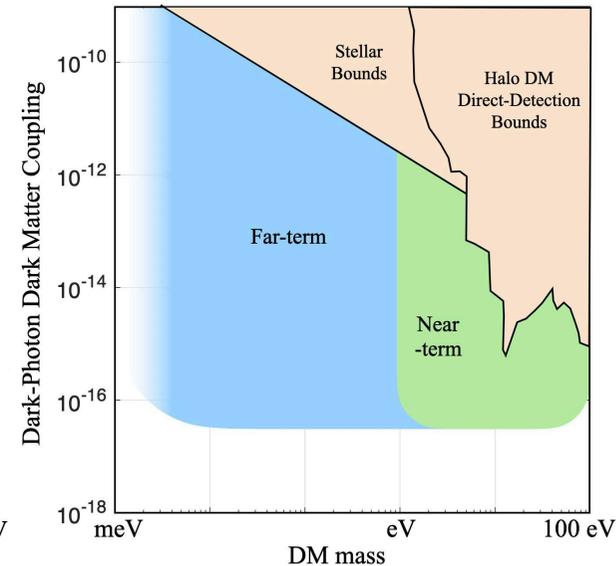
DM-nucleon
xsec
heavy mediator



DM-electron
xsec
light mediator



Dark photon
DM coupling



Further developments of “counter” experiments

- By considering available quanta
 - Light DM, small $E \rightarrow e$ recoil, multi-modules
 - Efforts to delve deep.
 - Heavy DM, large $E \rightarrow N$ recoil, monolithic
 - Atm. neutrino fog
 - Efforts to extend to low-mass range.

Constraints and future

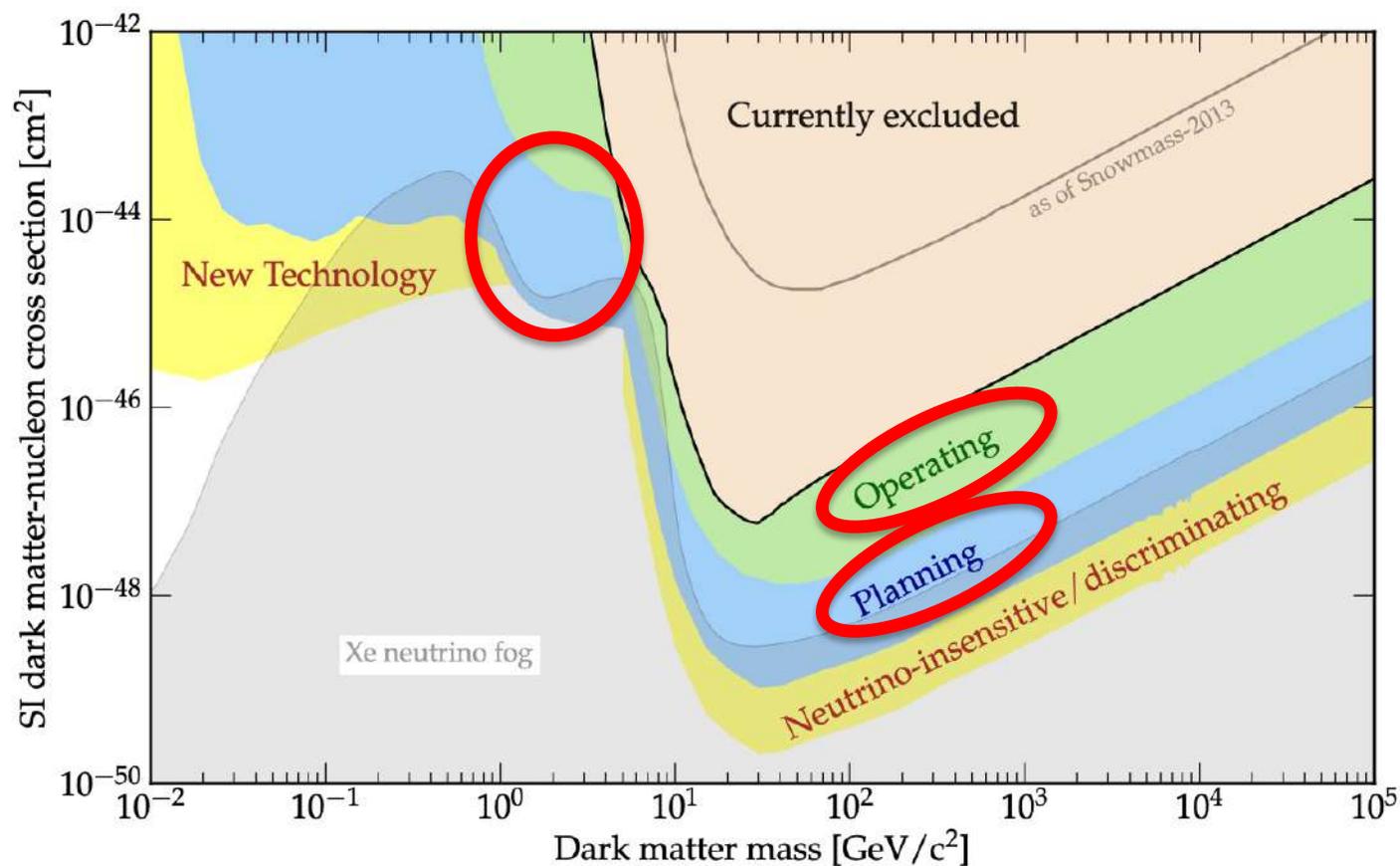
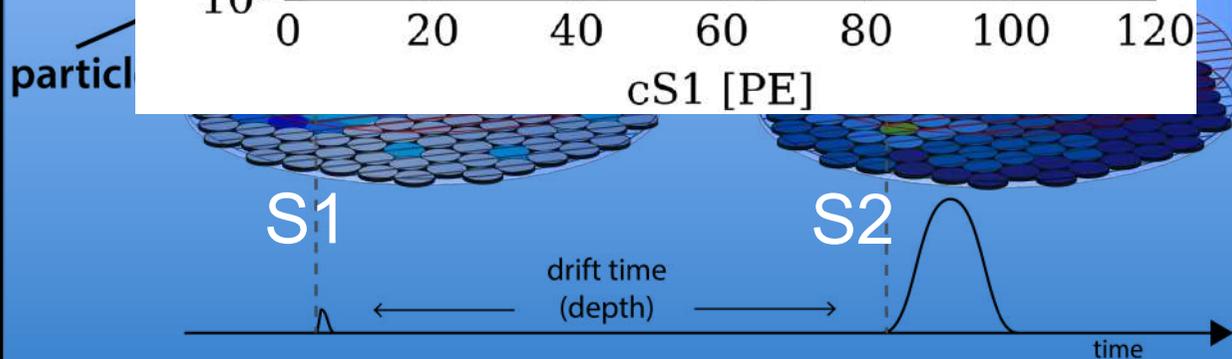
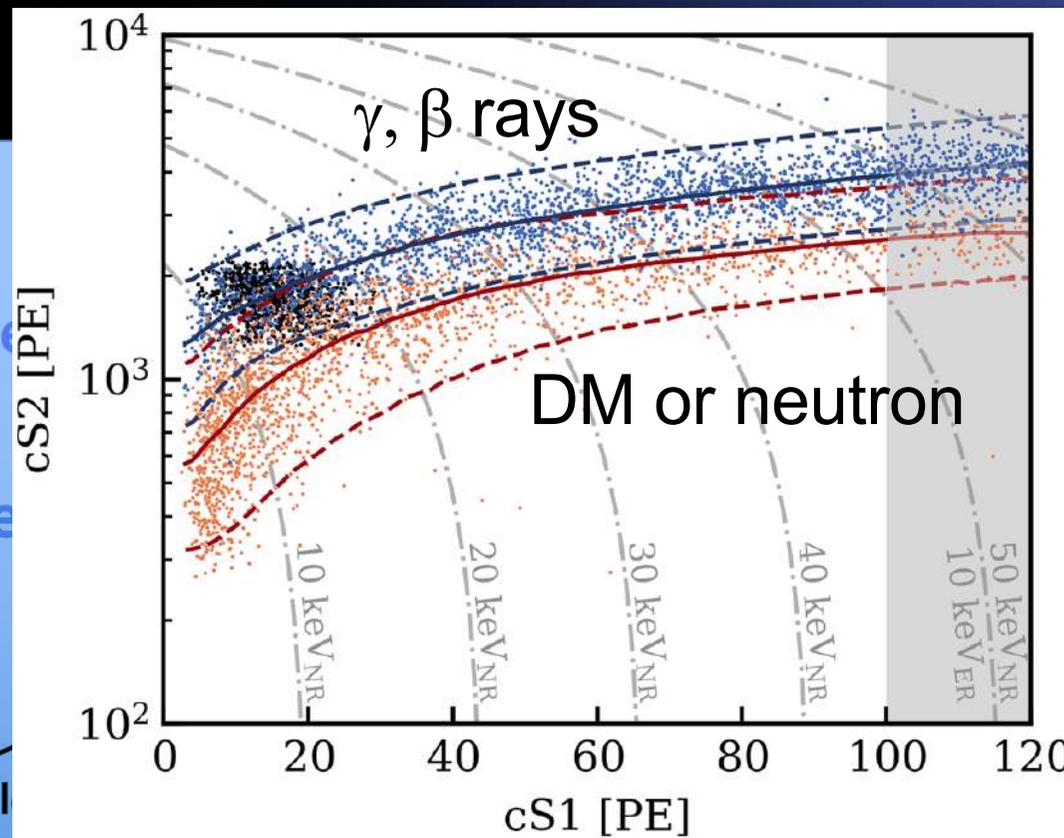


Figure 5-18. Combined Spin-independent dark-matter nucleon scattering cross section space. Current 90% c.l. constraints are shaded beige, while the reach of currently operating experiments are shown in green (LZ, XENONnT, PandaX-4T, SuperCDMS SNOLAB, SBC). Future experiments are shown in blue (SuperCDMS, DarkSide-20k, DarkSide-LowMass, SBC, XLZD, ARGO) and yellow (Snowball and Planned \times 5). The neutrino fog for a xenon target is shaded light grey. From Ref. [97].

detector



Drift time: Z position
 Photon distribution
 of S2:
 X&Y position
 determination

S1 and S2:
 Energy & particle
 identification

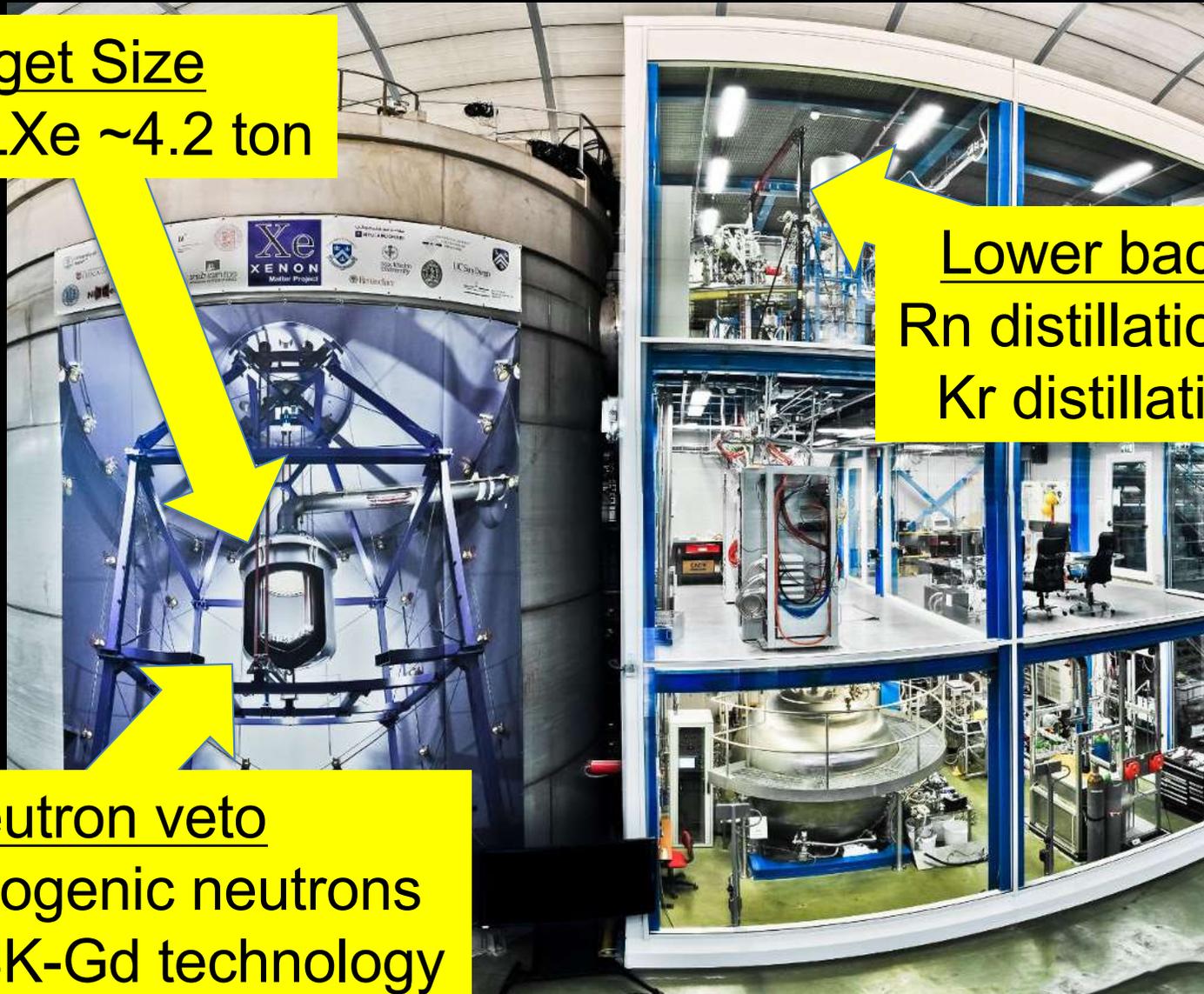
~13.7eV/quantum

Energy deposition in TPC
 causes **scintillation light**
S1 in liquid xenon target

Electrons from ionization
extracted into the gas phase
and amplified: S2.

XENONnT: overview

Target Size
Target LXe ~4.2 ton

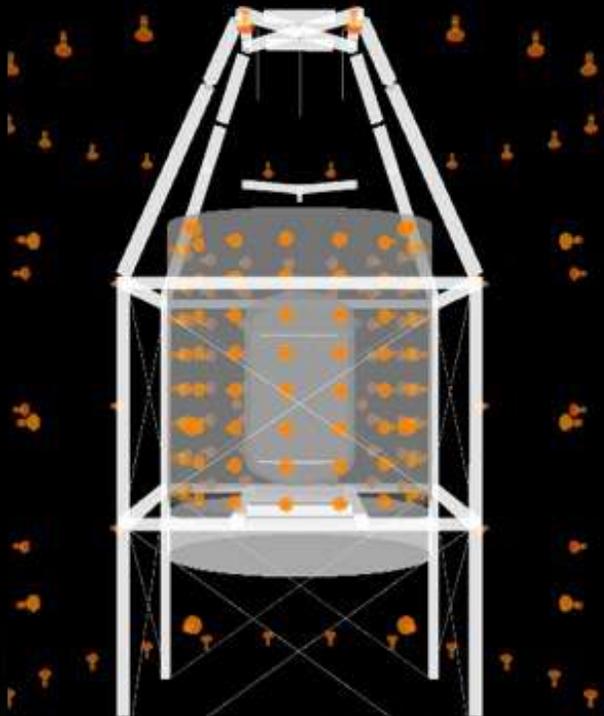


Lower background
Rn distillation (^{222}Rn)
Kr distillation (^{85}Kr)

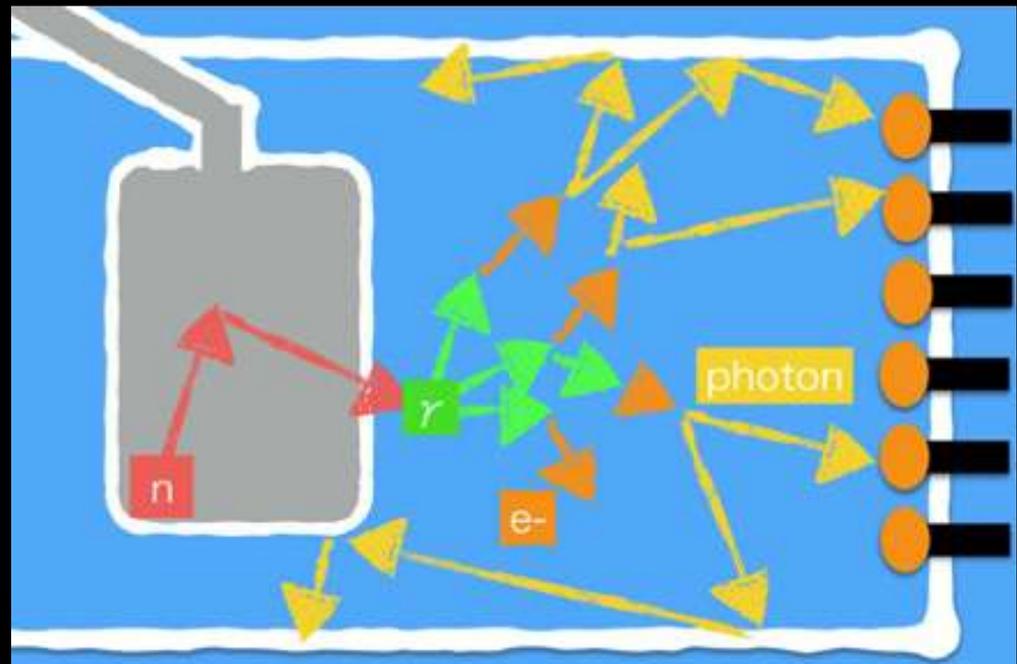
Neutron veto
tags radiogenic neutrons
utilizing SK-Gd technology

Key for the discovery: neutron veto

The neutron veto aims to detect radiogenic neutrons from the TPC. Adding 0.2% Gd by weight to the water in the muon veto, ~95% of these neutrons get captured on Gd rather than H in the water. Total 8 MeV gamma cascade from the Gd greatly improves the tagging efficiency.

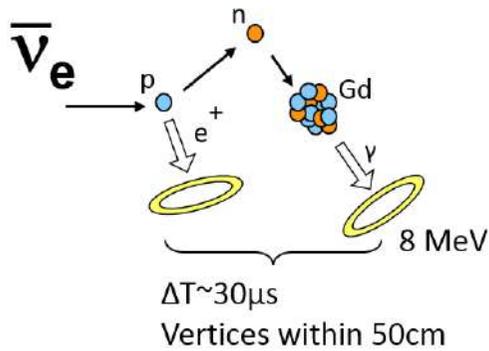


Covered by reflector sheets

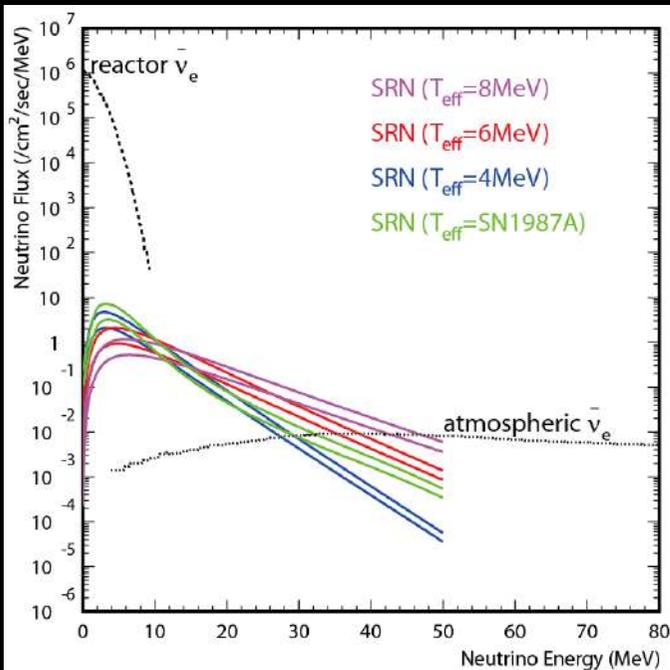


Reflector sheets will contain the Cherenkov emission from the γ conversions. - 120 PMTs will collect the light inside the reflector volume.

Key for the discovery: neutron veto

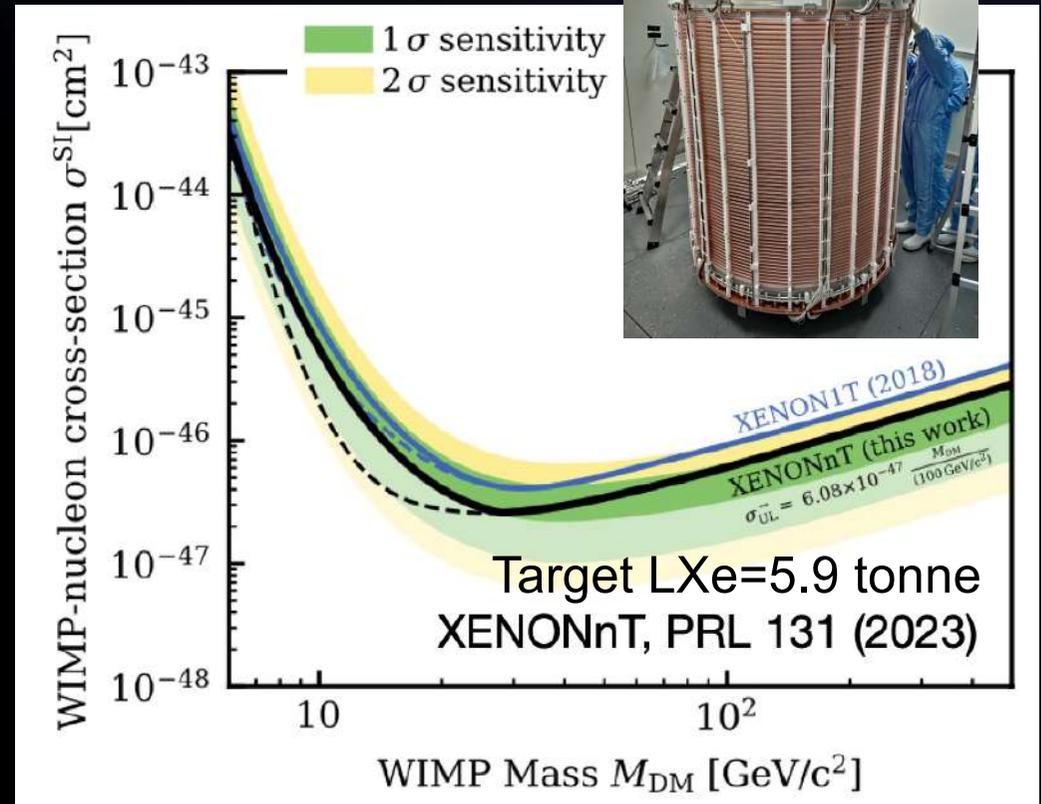
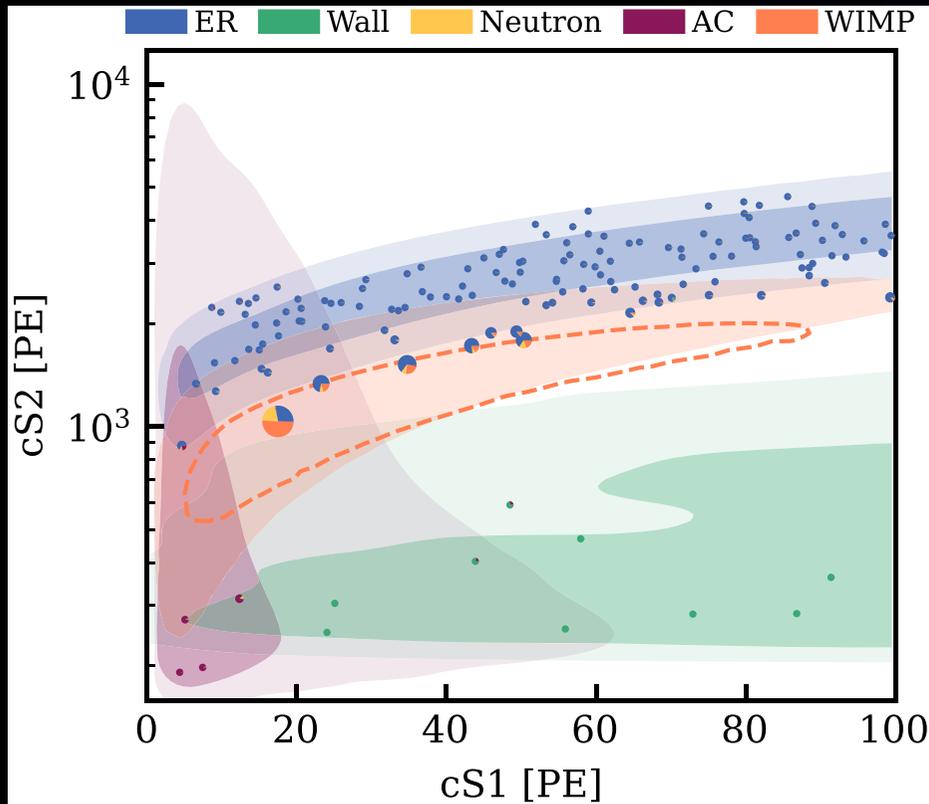


Super-K Gd technology, developed to observe the diffused supernova background, is applied in a dark matter experiment for the first time. XENON also uses the G4 Gd gamma ray code developed for EGADS and Super-K.



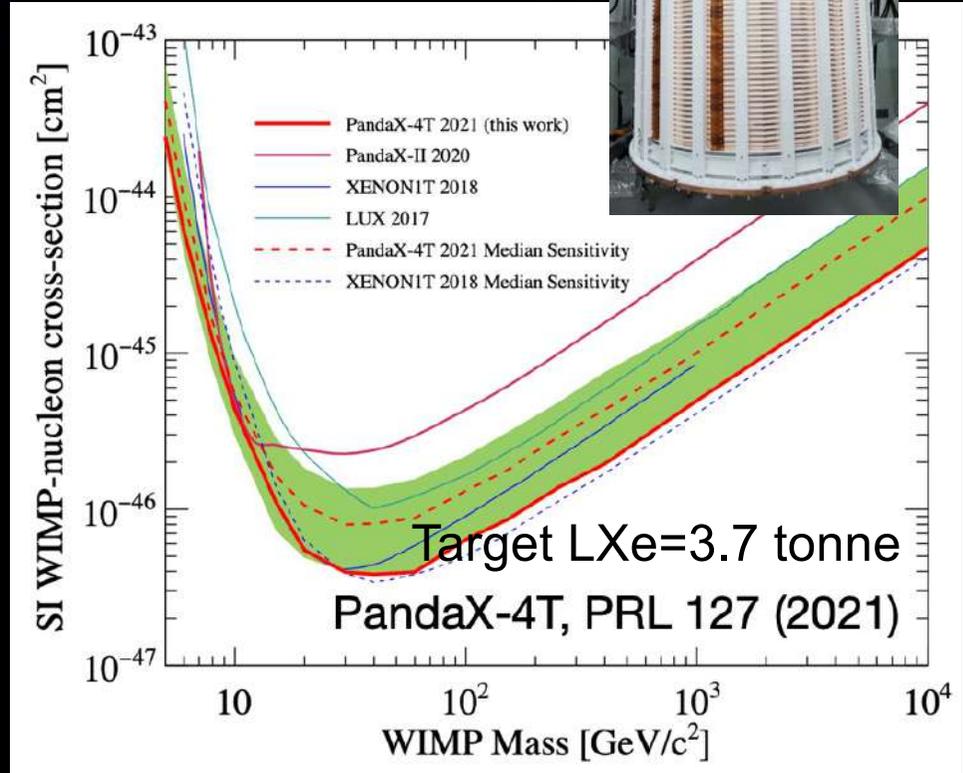
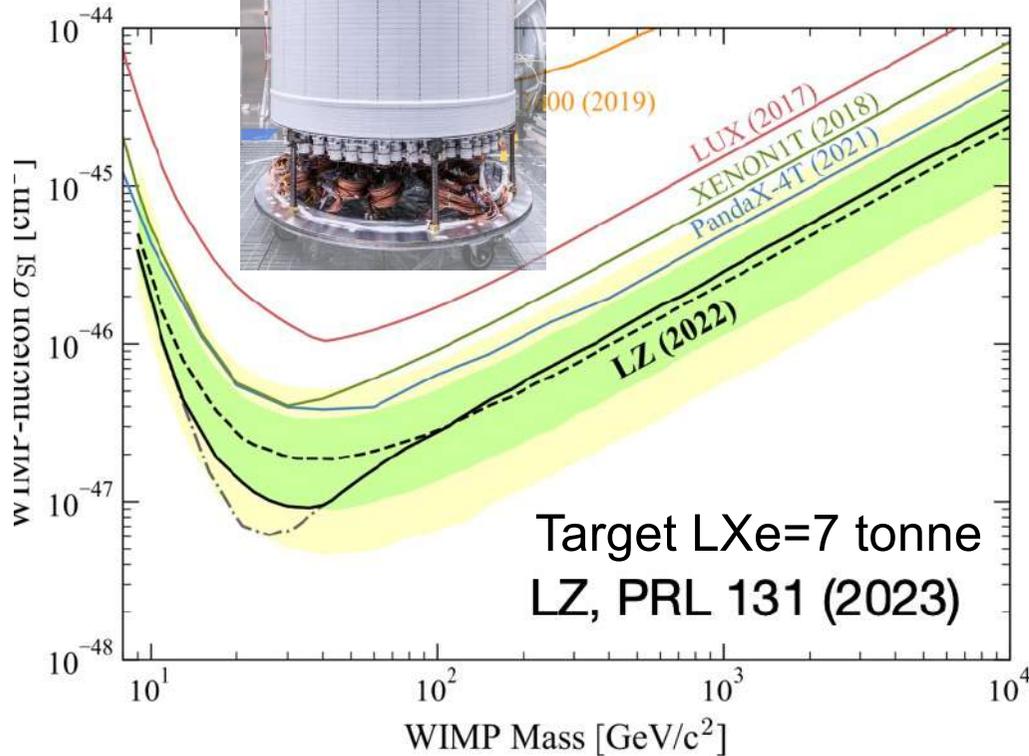
Super-K Gd and EGADS
Technology to detect neutron
in a water Cherenkov detector

Latest results of XENONnT



95.1 days of data ~ similar exposure of XENON1T: ~1 t yr
 Electron recoil BG dominates: world best radon BG, < 1/2 now
 Neutron BG: pure water nveto → Gd loaded nveto is necessary
 5 yrs data can explore WIMP dark matter ~ $2 \times 10^{-48} \text{cm}^2$

LZ and Panda-X



Aiming at 1000 live days data
x 17 more exposure than SR0

Tritium removal, Run 1, hall construction,
Expect to resume by the end of 2023

Three experiments are competing to discover
particle dark matter in following years!

Future: XLZD



The XLZD Consortium

- LZ and XENONnT are operating and leading experiments
- DARWIN: planned after the XENON program. R&D and design studies for next-generation LXe TPC.
- Formed by
 - XENONnT + LUX-ZEPLIN + DARWIN

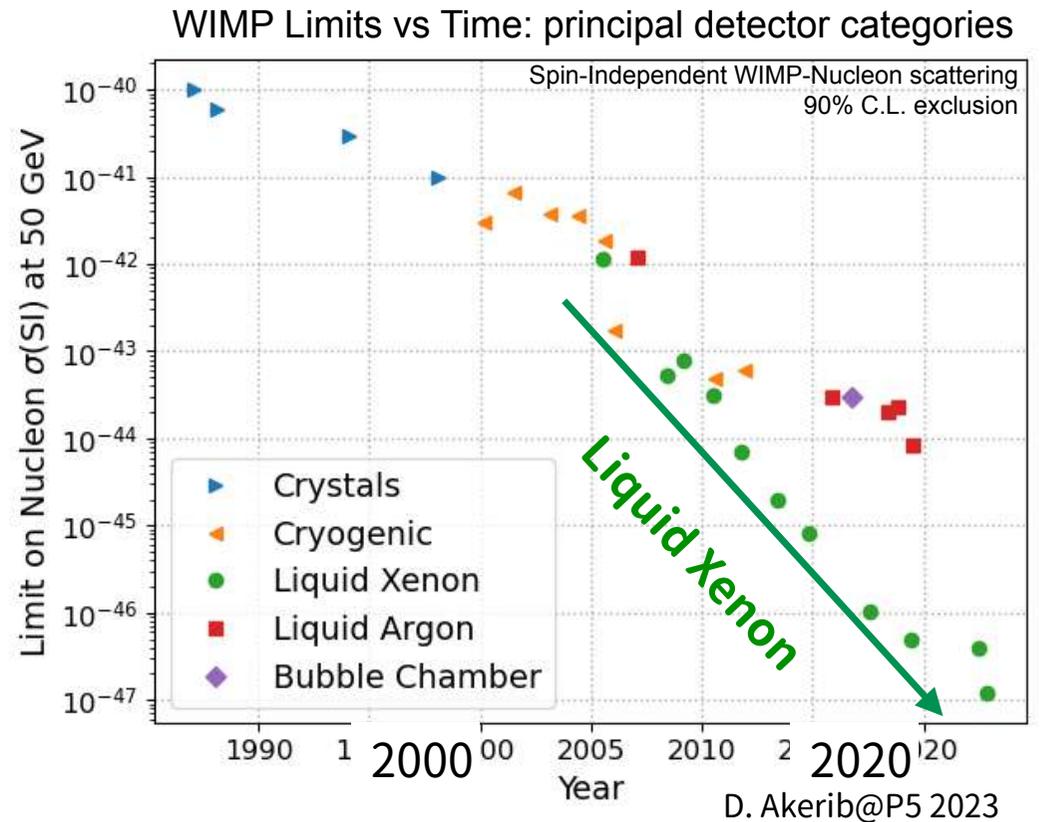
- 2021 XENON/DARWIN, LUX-ZEPLIN meeting
<https://indico.cern.ch/event/1028794/>
- 2021 **MOU signed**: 16 countries, 104 scientists
- 2022 1st Summer Meeting at **KIT in Germany**
- 2023 2nd meeting at **UCLA**

White Paper : 2023 J. Phys. G: Nucl. Part. Phys. 50 013001

OPEN ACCESS
IOF Publishing Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 50 (2023) 013001 (115pp) <https://doi.org/10.1088/1361-6471/ac841a>

Topical Review

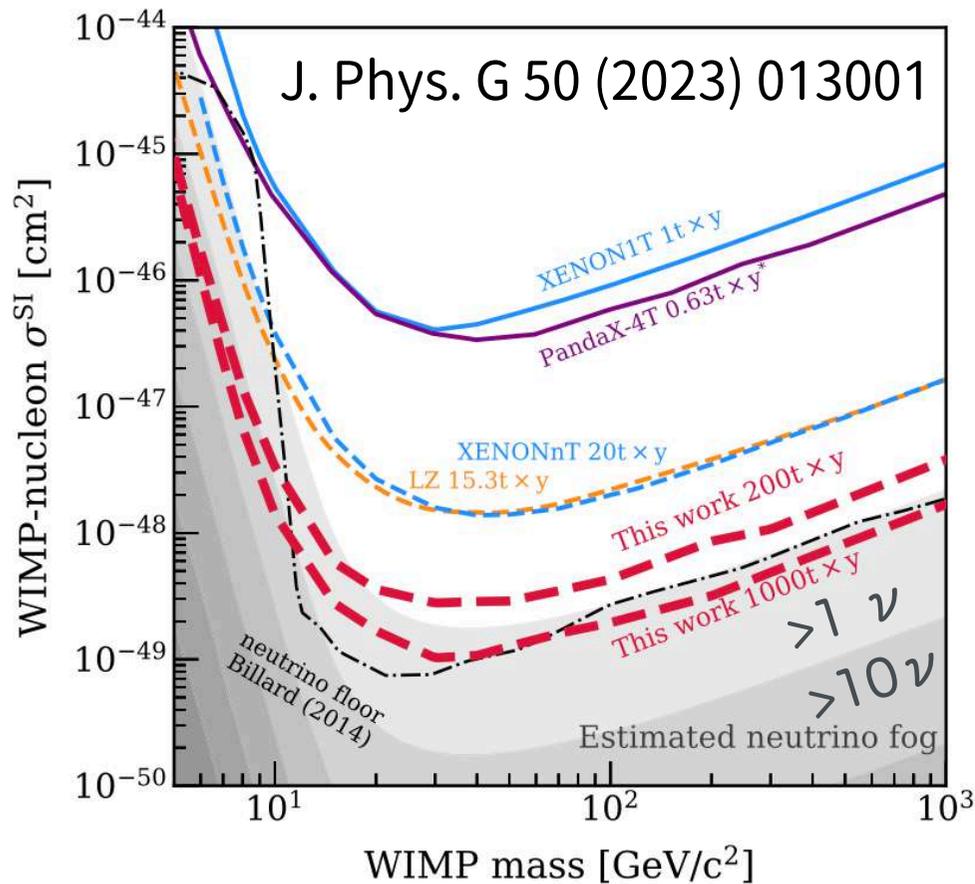
A next-generation liquid xenon observatory for dark matter and neutrino physics



Future: XLZD



A staged approach



reference design

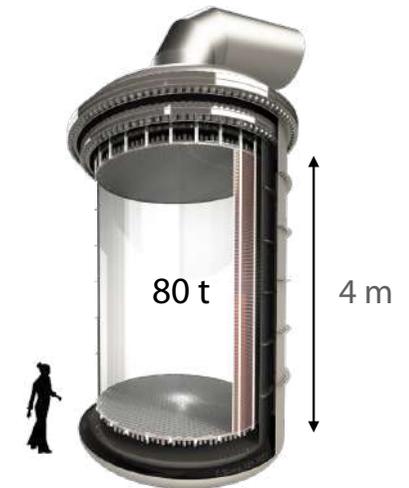


1step

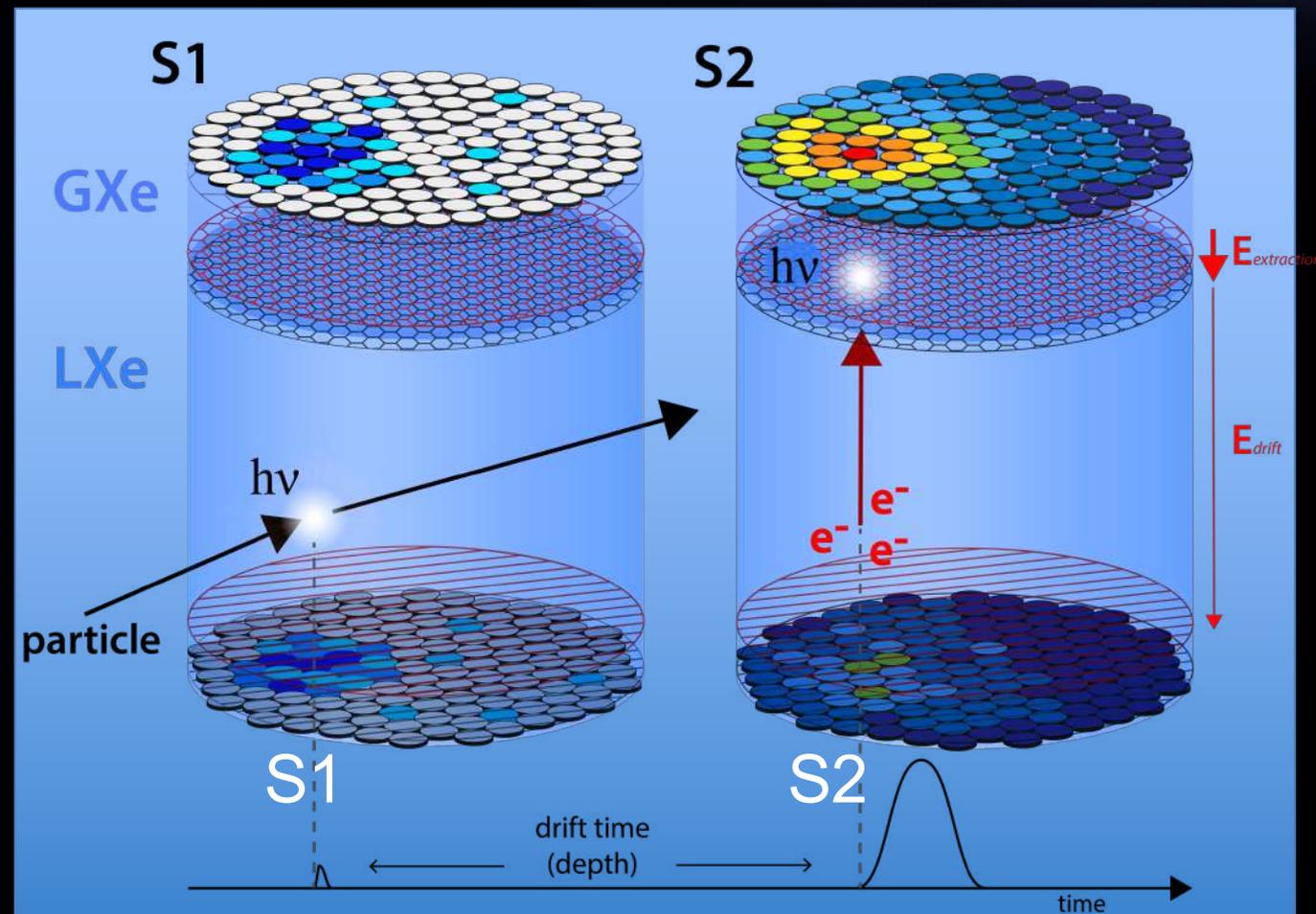
aggressive design



Next step



Low-mass WIMP search in LXe detectors

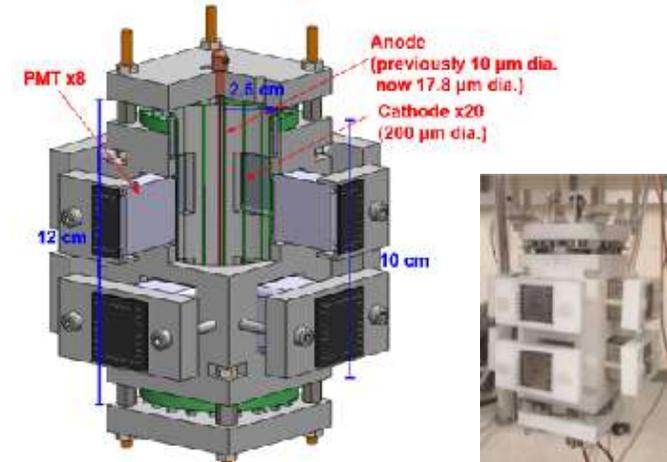
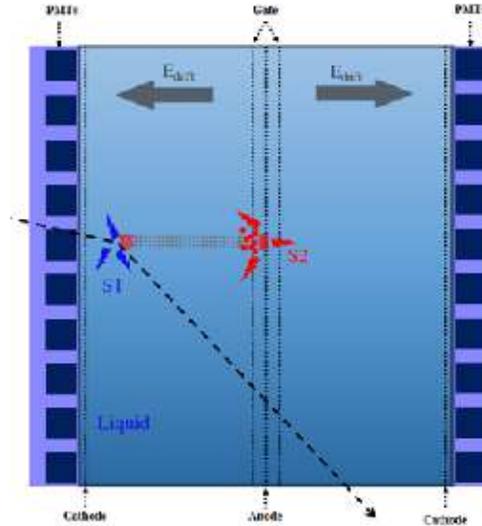
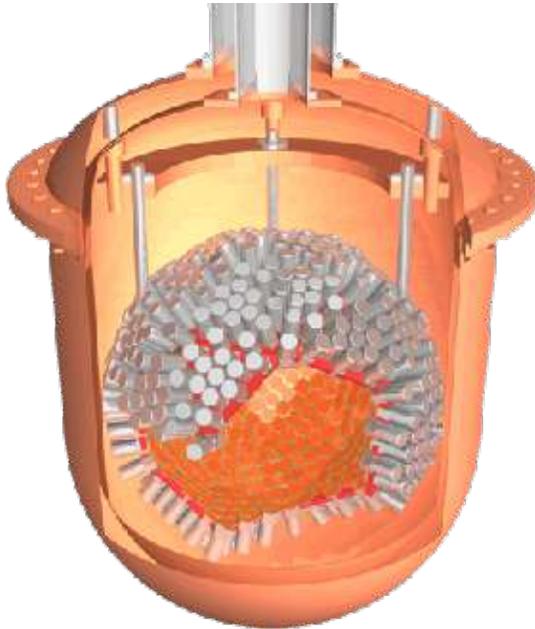


S1 determines the threshold of S1-S2 analyses → increase sensor area
S2 only analysis → reduce single electron background

A single-phase approach to lower the energy threshold

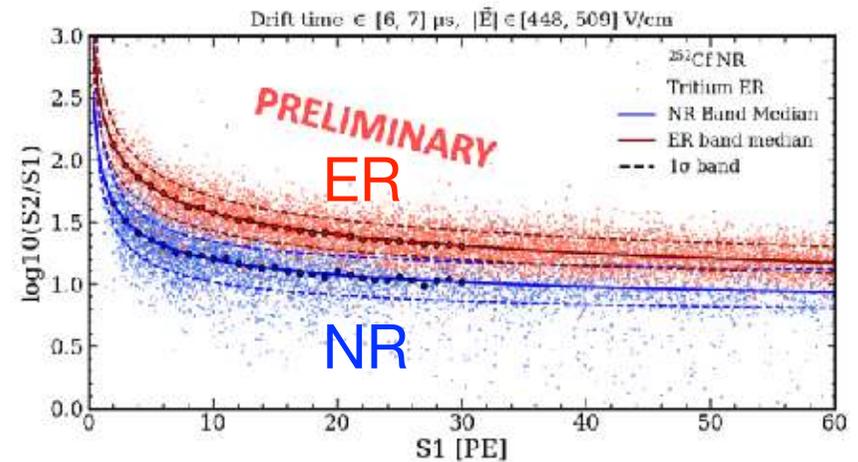
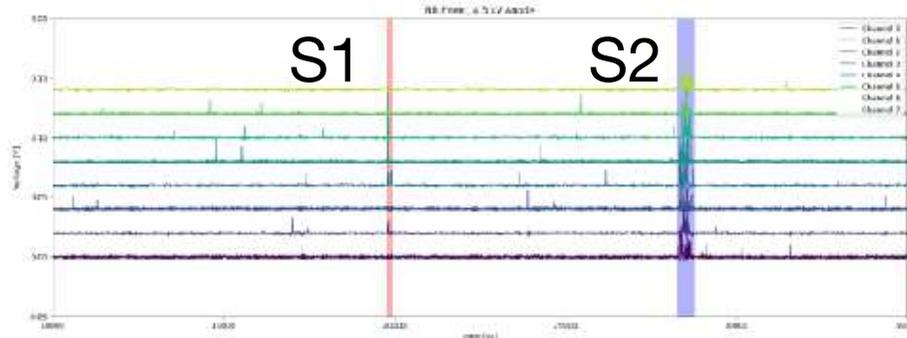
Proposal of a Single-Phase LXe detector with S2/S1 discrimination (Qing Lin, JINST 16 Po8o11, 2021)

Principle demonstration at UCSD
arXiv: 2111.09112, JINST 2022
arXiv: 2301.12296, JINST 2023
more new results coming...



XMASS: high S1 yield, but no S2

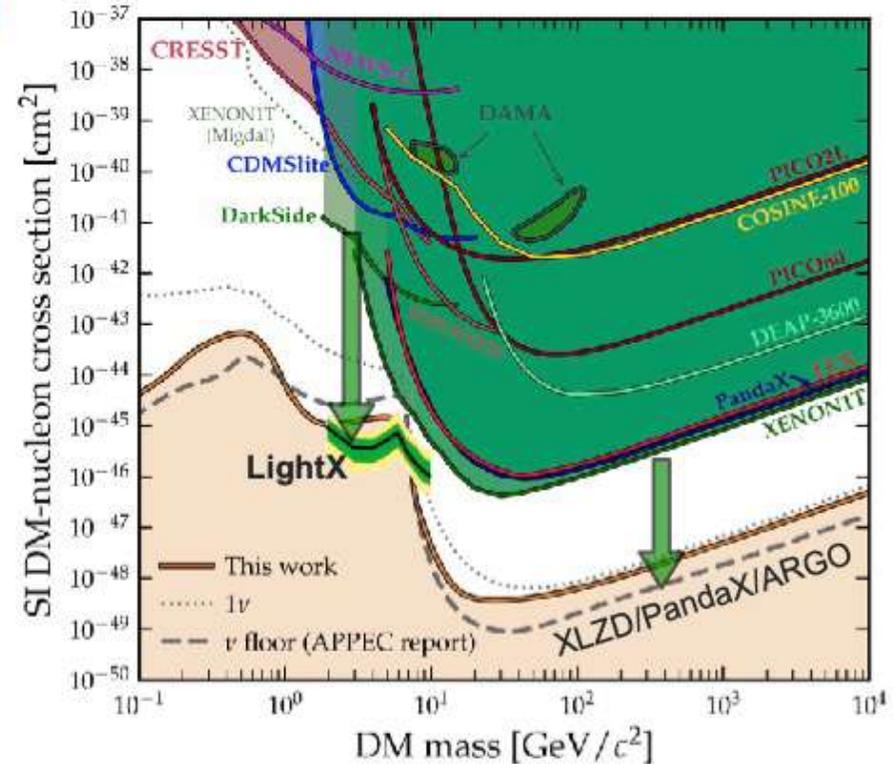
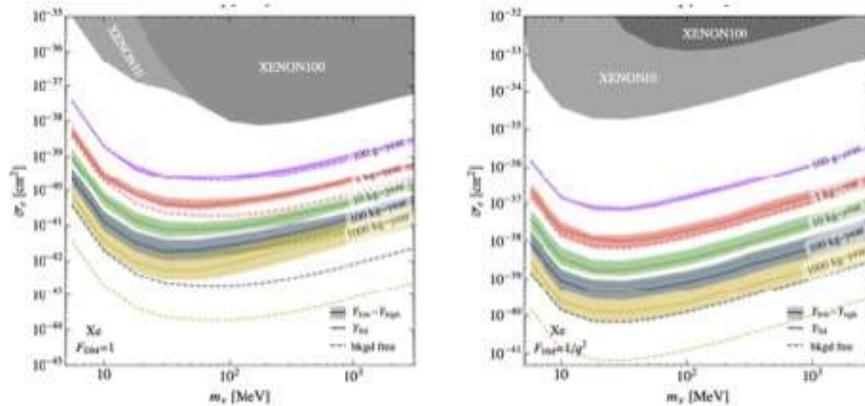
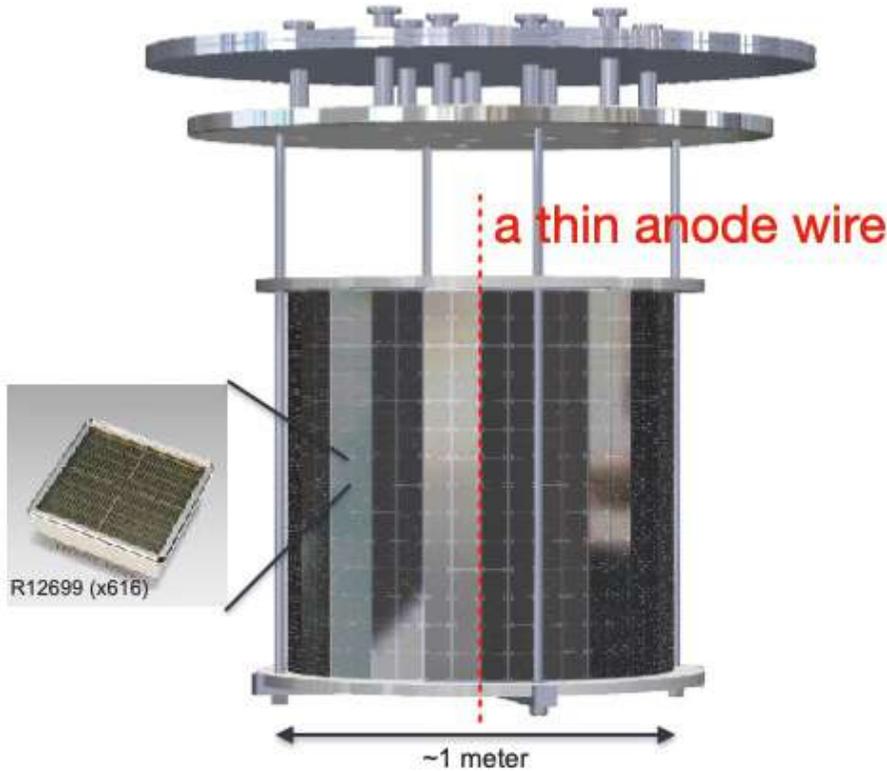
a low energy nuclear recoil event (Anode: 4.5 kV)



LightX: a conceptual ton-scale single-phase LXe detector for Light/Low-Mass Dark Matter

Sensitivity Projection Assumptions:

- g1: **0.3 PE/photon** (~x2 achieved in nT/LZ)
- g2: 7~10 PE/e-
- 2-fold coincidence
- 10 ton-year exposure



also improves significantly DM-e scattering for sub-GeV DM with “background free”

Essig, Sholapurkar, Yu, arXiv:1801.10159 (PRD 2018)

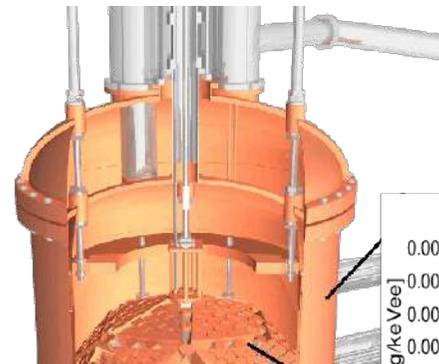
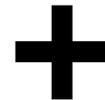
Towards S2 Signal in Spherical LXe TPC

Similarities between the spherical proportional counter and XMASS are striking

→ SPC: Charge-only, and gas.

XMASS: Light-only, liquid Xenon

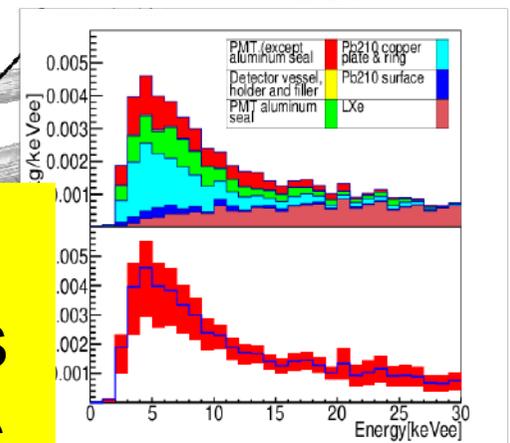
Question: Could sensitivity be improved further if fiducialisation/background rejection improved? → Can this be done by adding charge-amplification to get S2 signal



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1 phase LXe detectors may also mitigate possible issues in large dual-phase detectors.



Summary

- Particle dark matter with a broad mass range (30 eV- 10^{16} GeV), is expected to be explored by counter experiments.
- Various excitation modes in various material phases enable us to explore it. Further combinations can be studied.
- Efforts using rare-gas liquid, LXe, made significant progress at > 10 GeV range and extended to lower mass ranges.
 - XENON, LZ, and Panda-X are leading the exploration.
 - XLZD is expected to enter the neutrino fog.
 - 1-phase LXe detector is technically important. Interests in utilizing the XMASS site for R&D/low-mass WIMP search.