Dark Matter Searches with Noble Liquids

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Conference on Science at the Sanford Underground Research Facility

South Dakota Mines, Rapid City, SD

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LLNL-PRES- 864111

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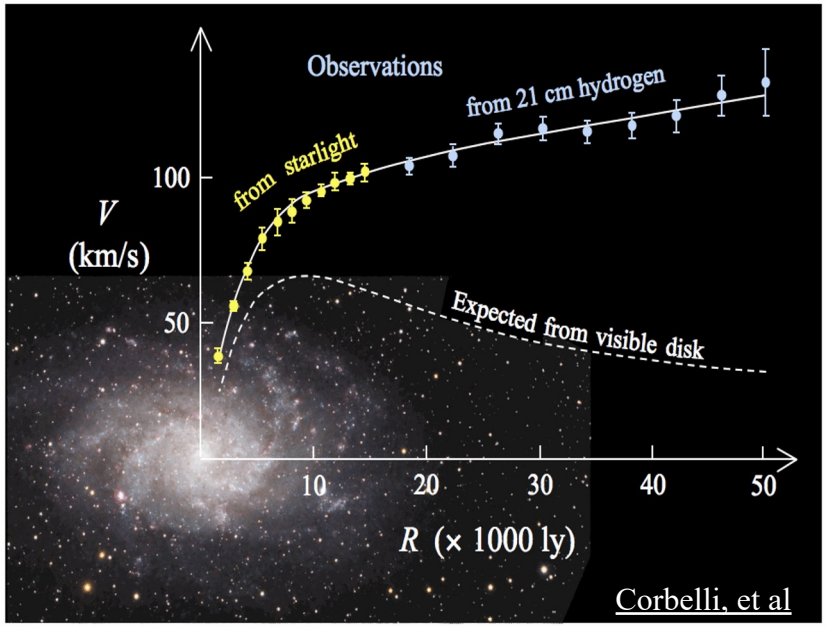
Lawrence Livermore National Laboratory

The Hunt for Dark Matter

- We need dark matter
  - A lot of it (~5X atomic matter)
- We know very little about dark matter
  - Probably new particle(s)
  - Likely slow moving (0.001c)
  - Convenient if its mass is at weak-scale, but it does not have to be
- Detection of dark matter is hard
  - It doesn't interact much
  - Even if it does, the energy transfer should be small



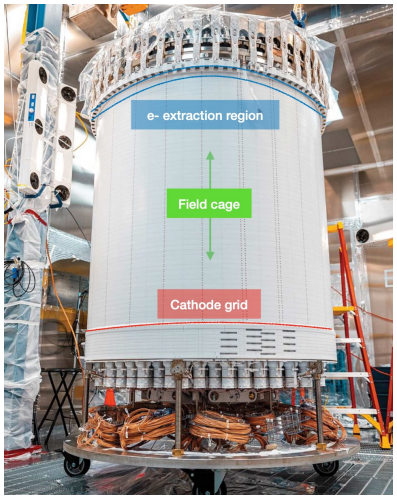
Expected and observed galactic rotation curves

Noble Liquid Dark Matter Experiments

- We need large, low-background and low-threshold detectors in search for dark matter
- We have a class of such detectors using liquid xenon or liquid argon as the target

XENONnT, LNGS
6t active LXe

Zhong, Tuesday, 3pm

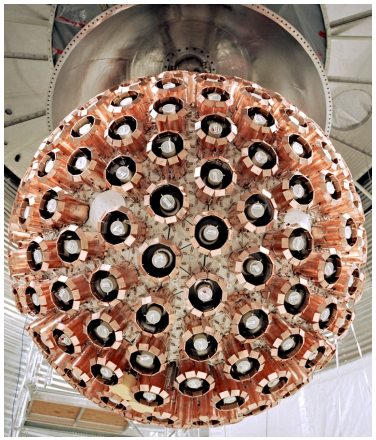


LZ, SURF
7t active LXe

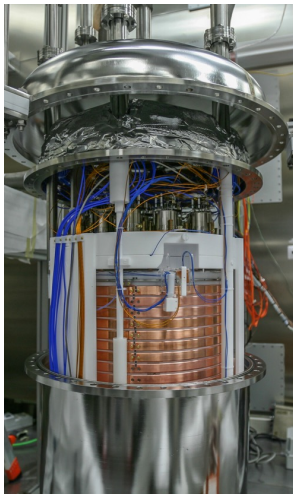
Xia, Wednesday, 2:25pm

PandaX-4T, CJPL
4t active LXe

Qian, Wednesday, 2pm



DEAP-3600, SNOLAB
3.6t active LAr

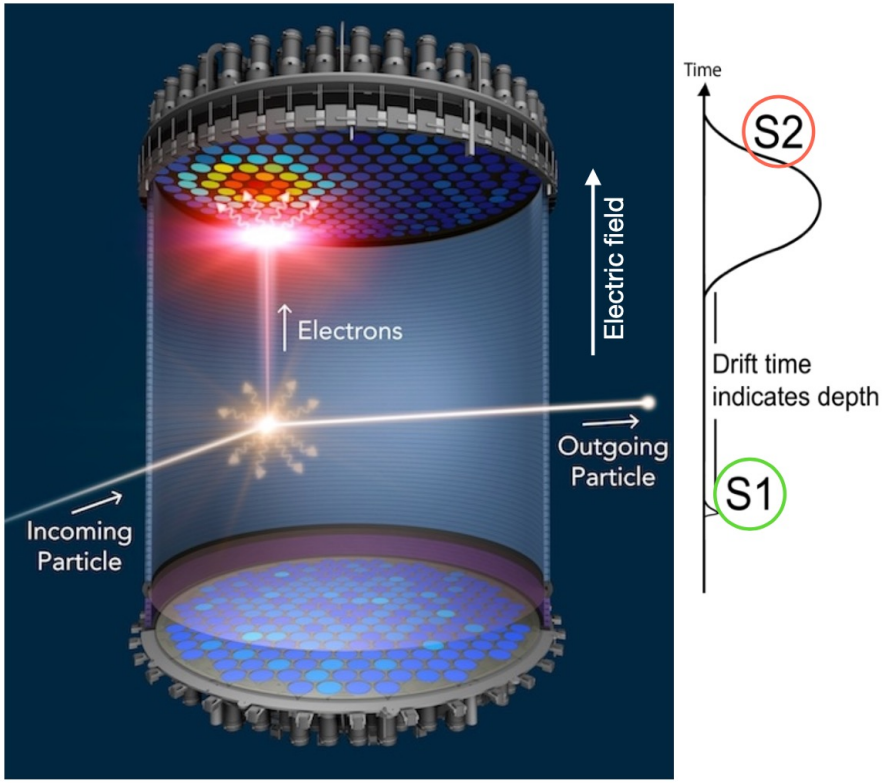


DarkSide-50, LNGS
46kg active LAr
20t upgrade (DS-20K)
under construction

Lai, Wednesday, 3:15pm

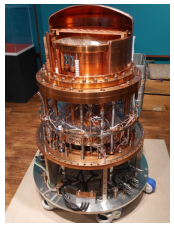
Benefits of Noble Liquids

- Scintillation photons
  - High light yield
  - Little self absorption
- Ionization electrons
  - Similar high yield to that of photons
  - Low electron affinity, long drift distance
  - Amplification of ionization signals possible
- Particle identification
  - Energy partition between photon/electron
  - Time profile of scintillation
- Position reconstruction
  - Accurate 3D position possible
- Scalable liquid volume



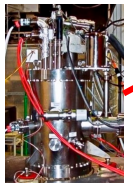
An illustration of signal generation in a dual-phase xenon TPC detector.

History of Xenon Experiments



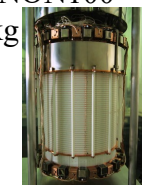
ZEPLIN
12kg

LUX
250kg

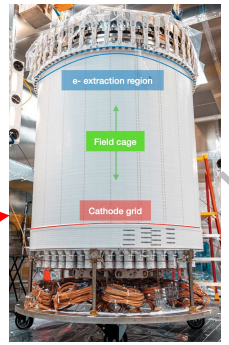


XENON10
15kg

XENON100
62kg



XENON1T
1t



LZ
7t

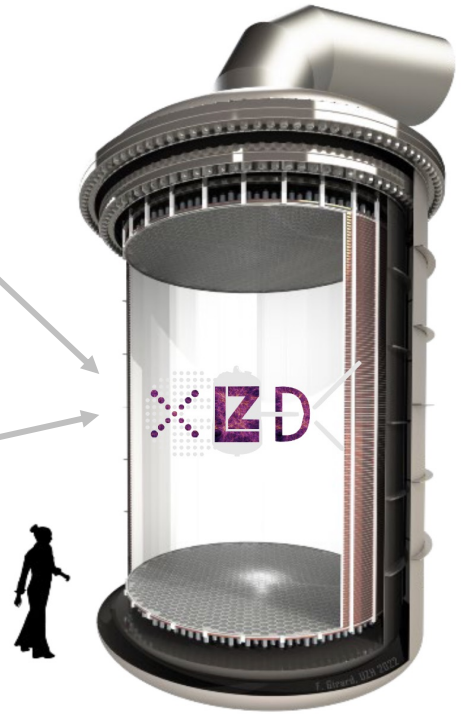
XENONnT
6t

XMASS
800kg

PandaX-II
300kg

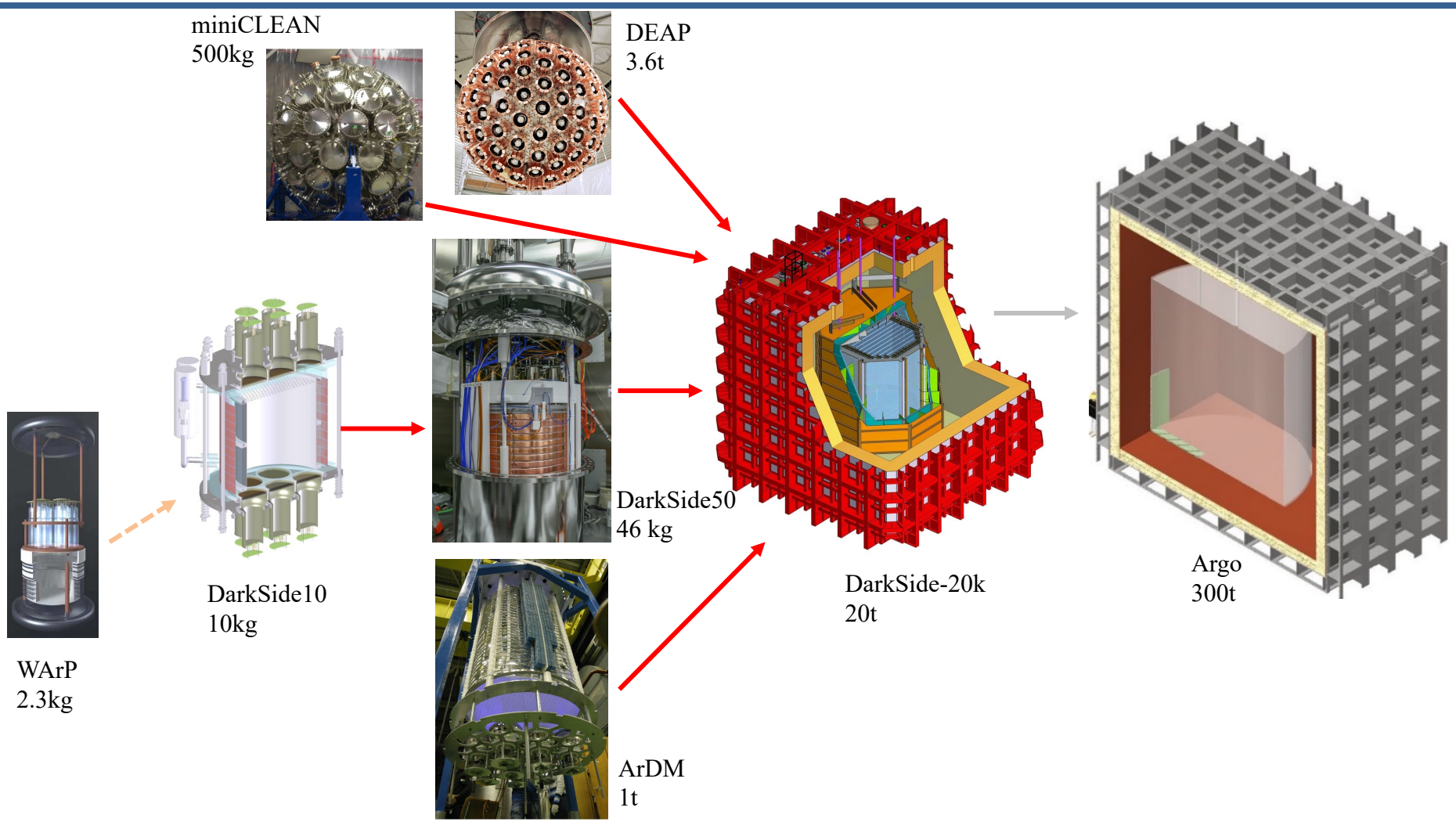
PandaX-I
54kg

PandaX-4T
4t



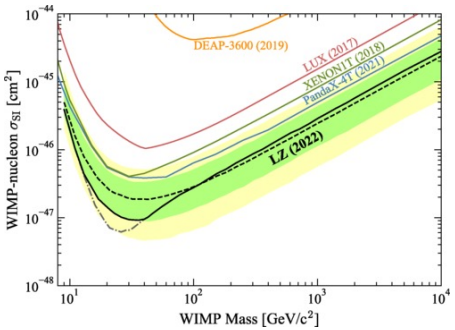
XLZD, 60-80t

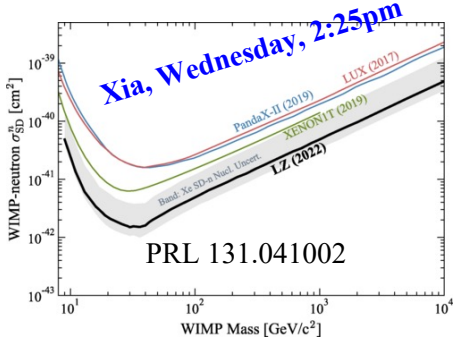
History of Argon Experiments

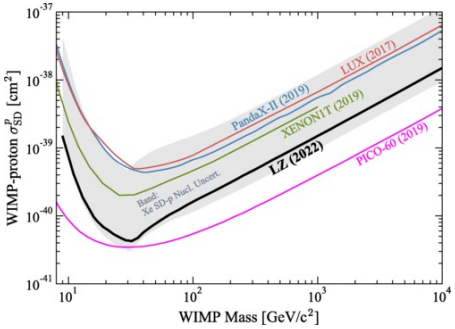


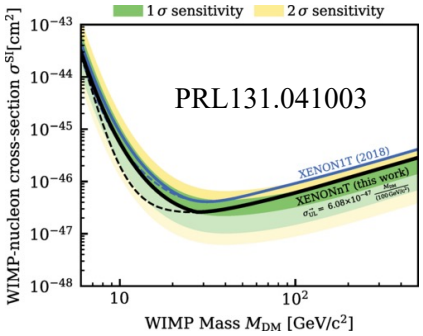
Most Recent Results

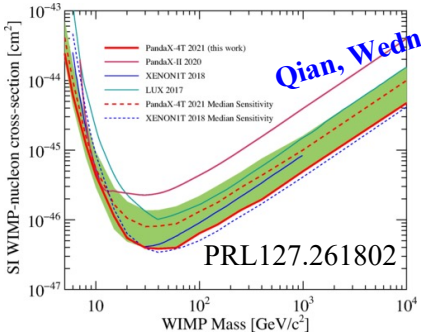
- WIMP searches
- EFT analyses
- Exotic studies
- Low-energy frontier

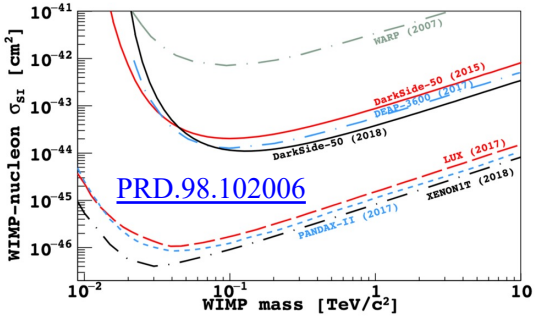


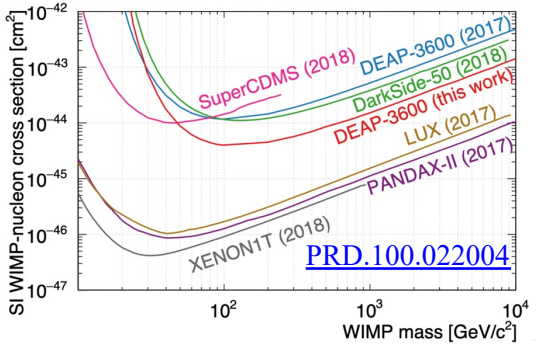












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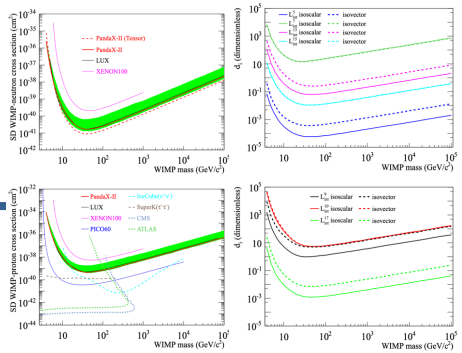
PLB.2019.02.043



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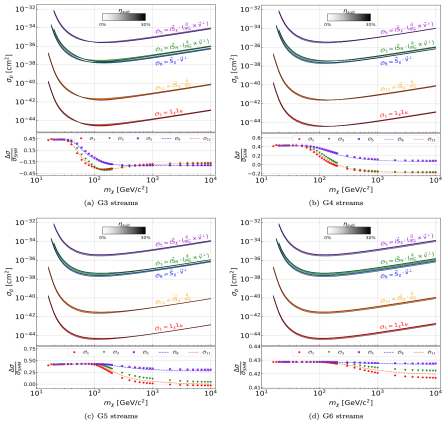
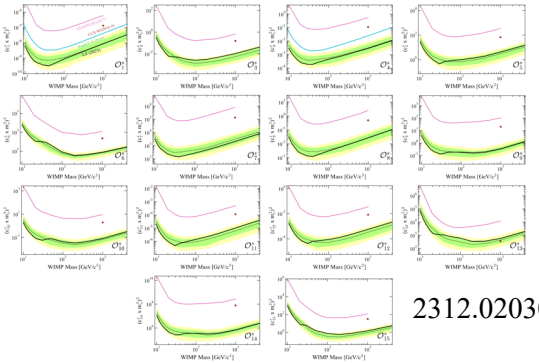
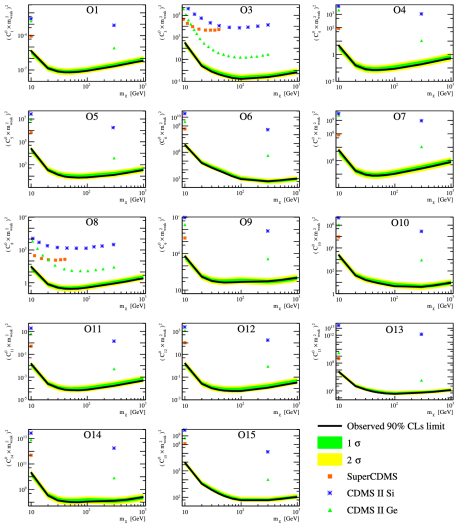
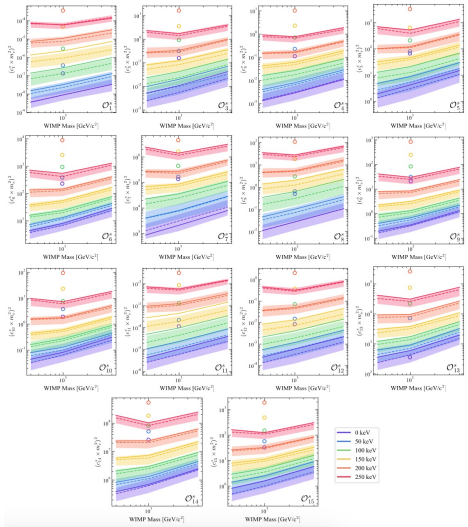




2312.02030

PRD.96.042004





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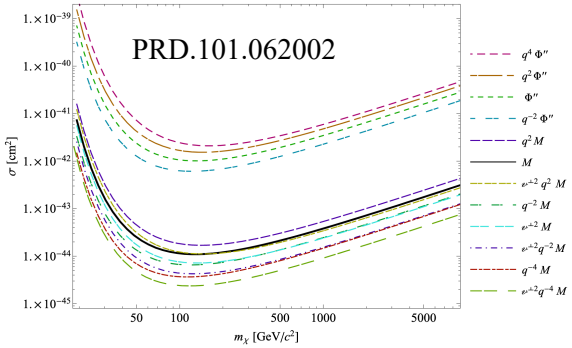

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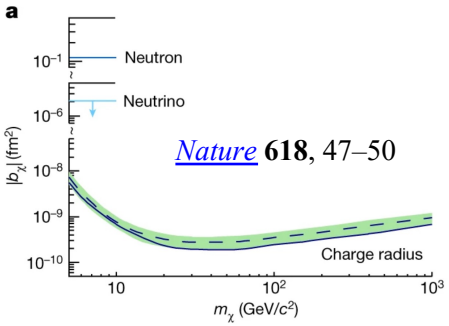
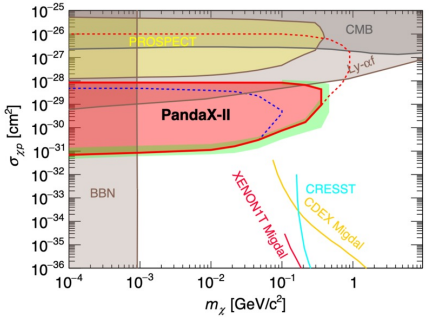
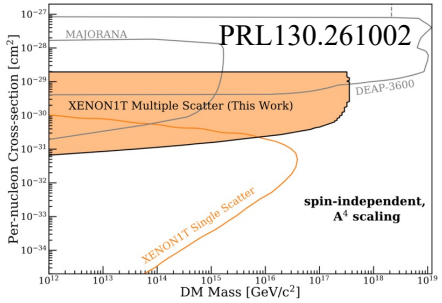


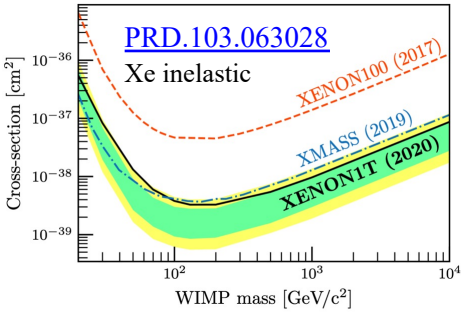
Nature **618**, 47–50

PRL128.171801



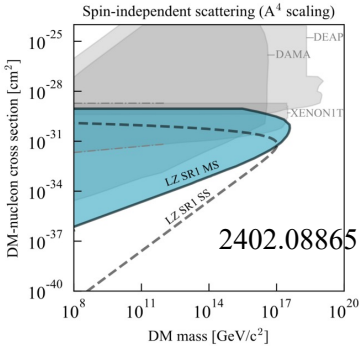


PRL130.261002



PRD.103.063028

Xe inelastic



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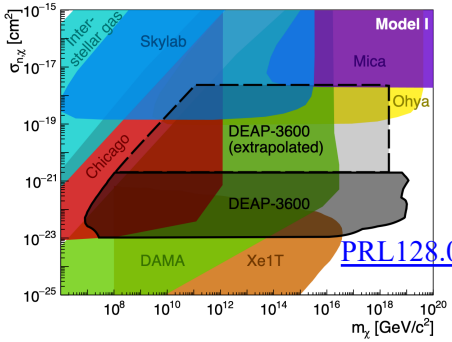

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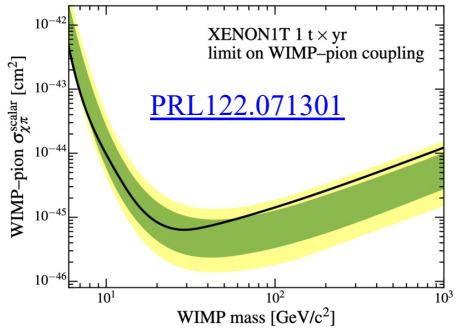

PRL122.071301

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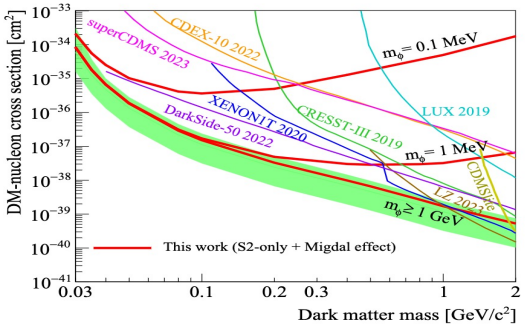
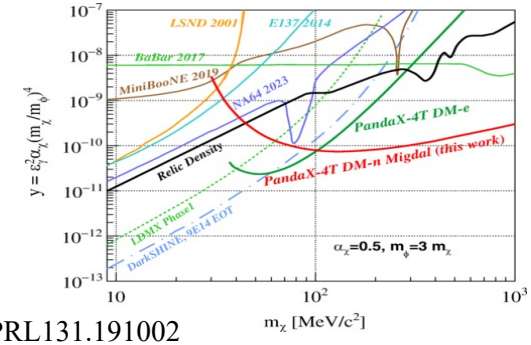
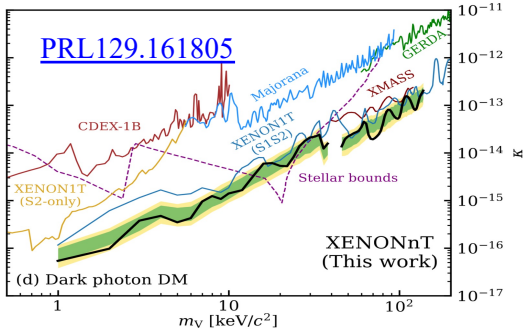
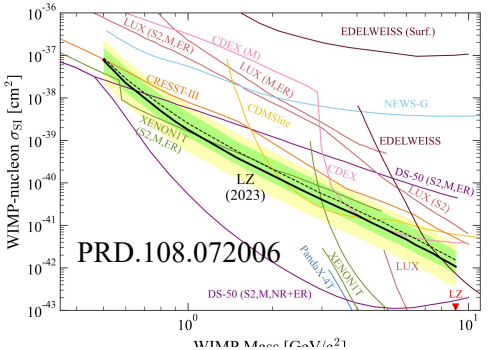
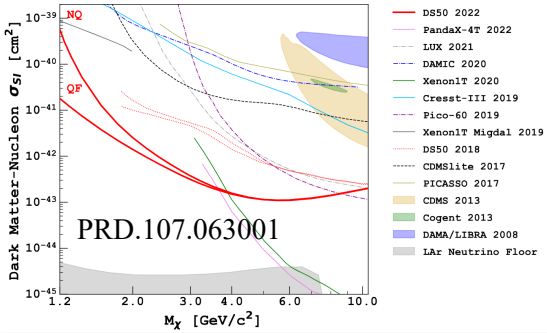


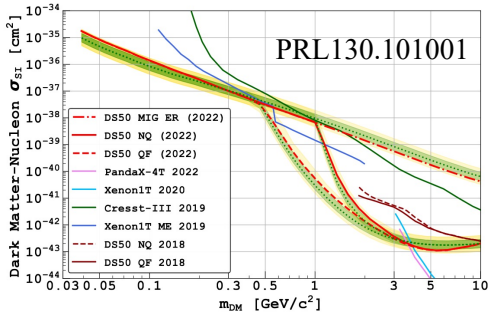


PRL131.191002



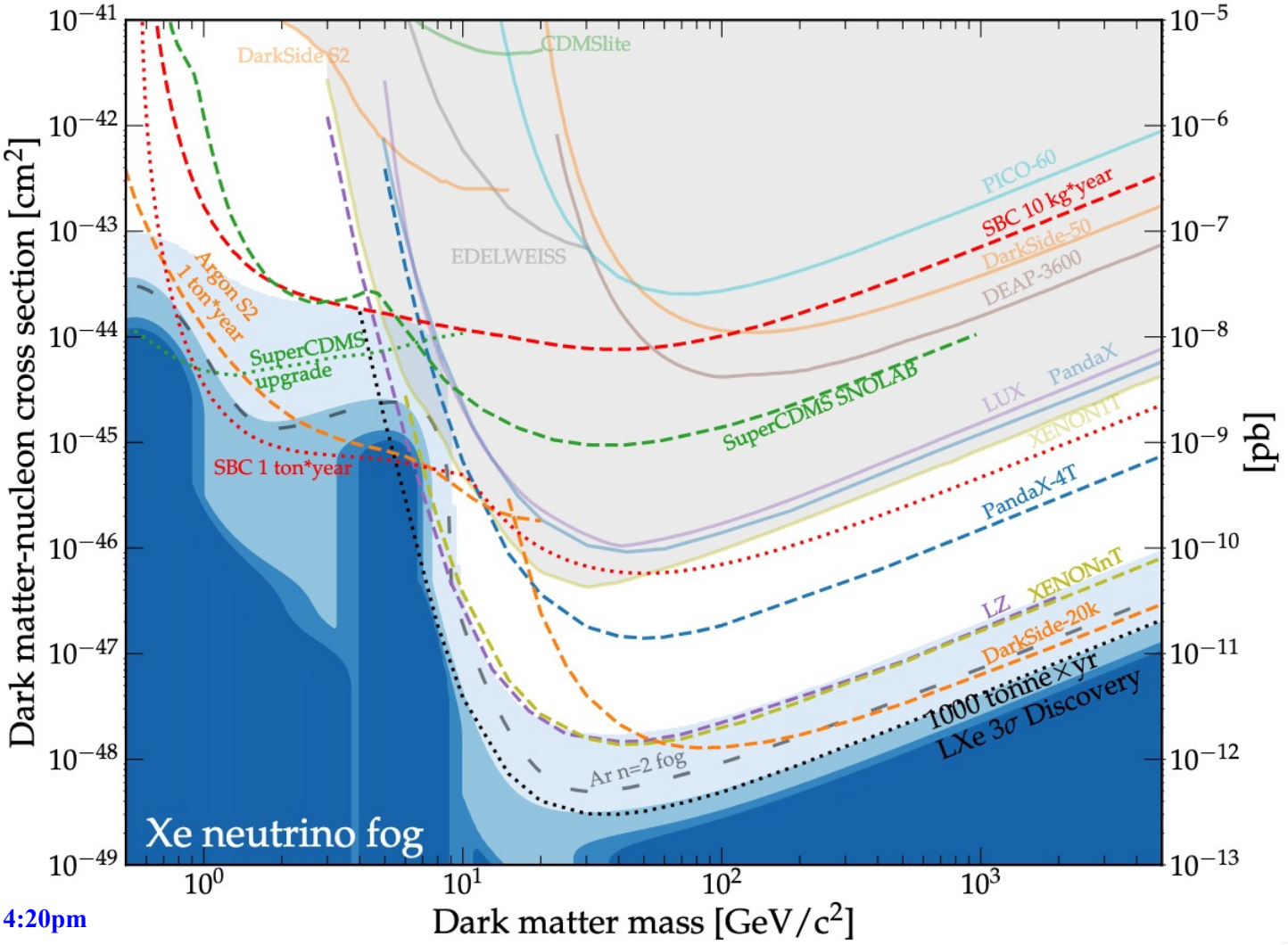






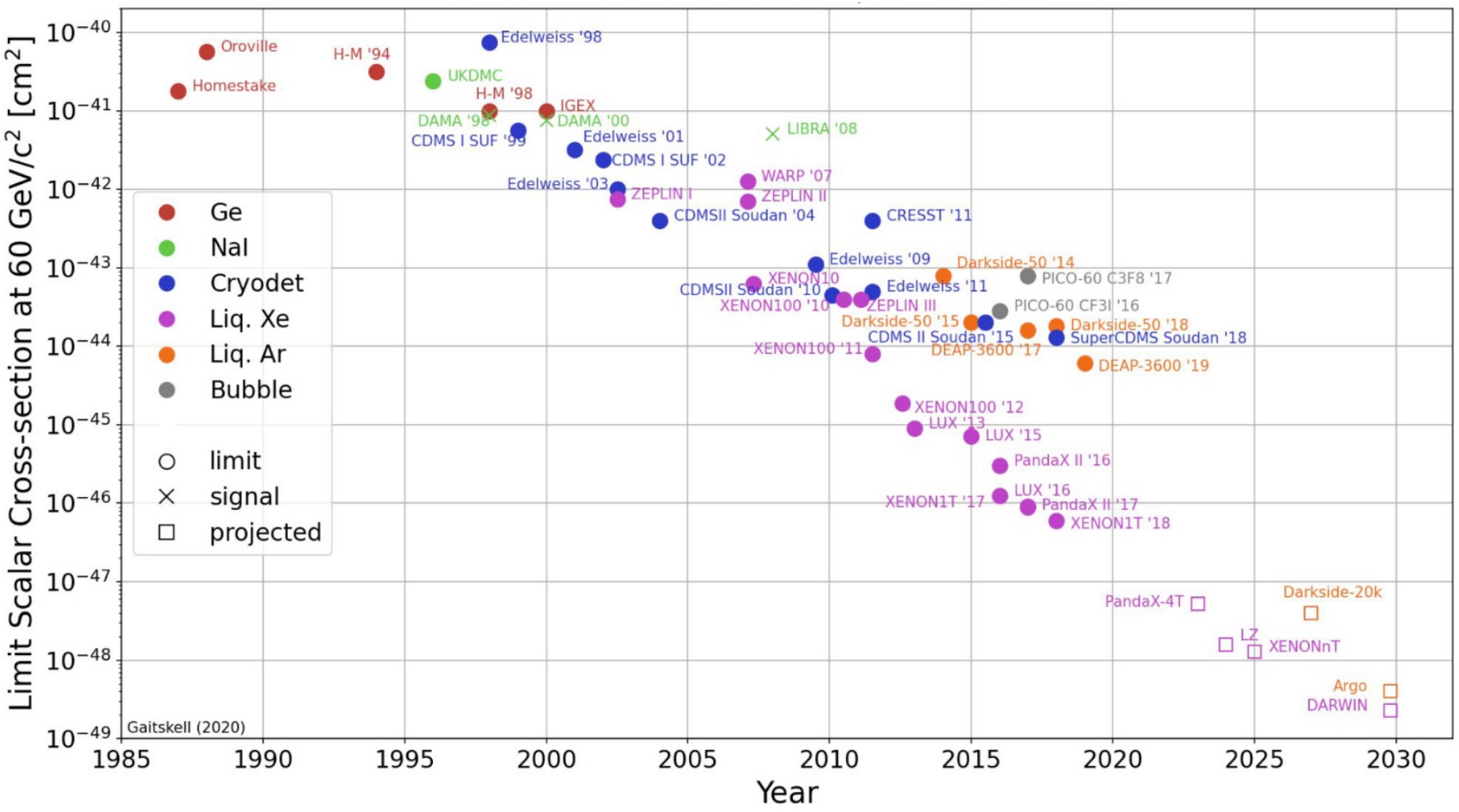
Direct Detection Summary (as of 2021)

- Benchmark model
- No definitive signal yet
- We are approaching solar neutrino background-dominated regions

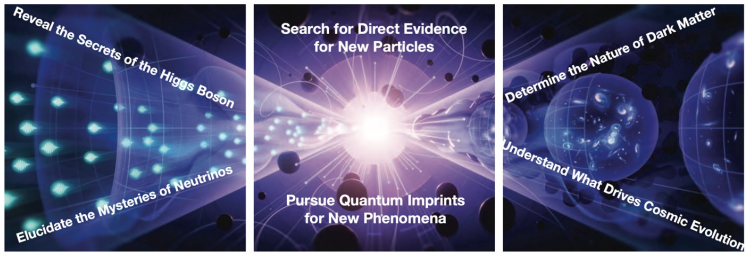


Directional search
Baracchini, Thursday, 4:20pm

Progress in Sensitivity Improvements

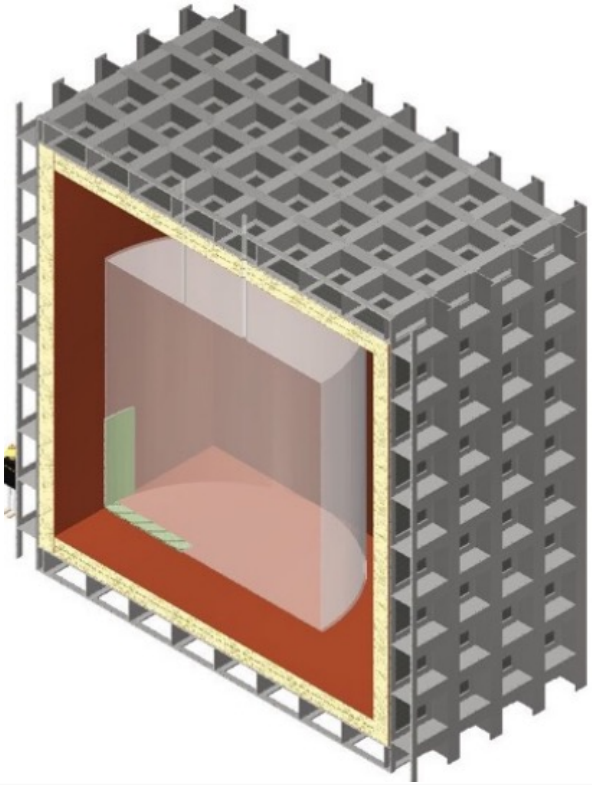


The Need for G3 WIMP Experiment(s)



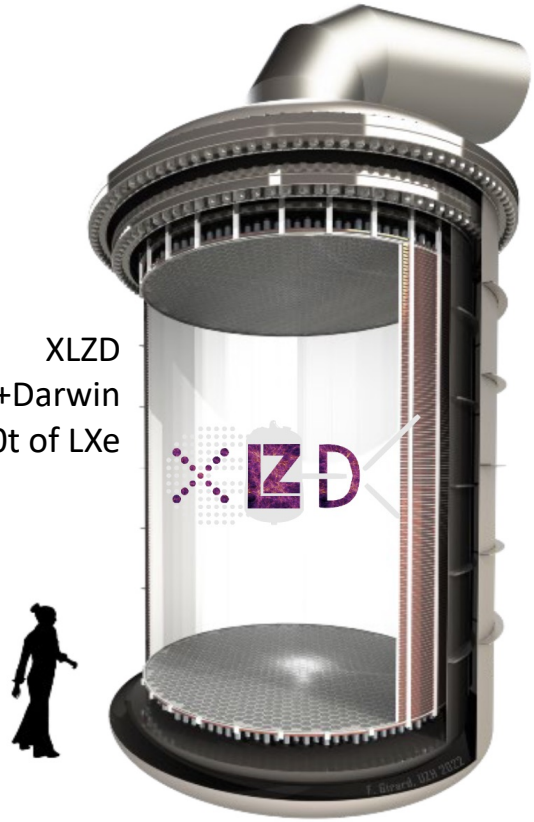
2023 P5 Recommendation 4.d:

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

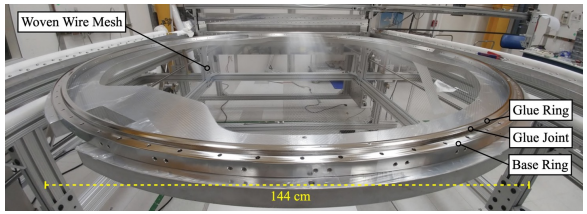


Argo
GADMC
(DarkSide+DEAP+CLEAN+ArDM)
300t of LAr

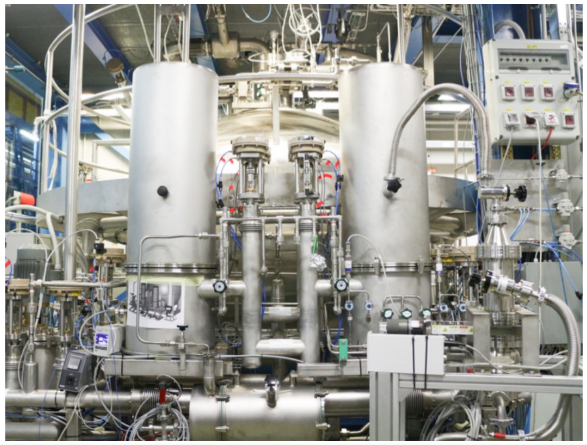
XLZD
XENON+LZ+Darwin
60-80t of LXe

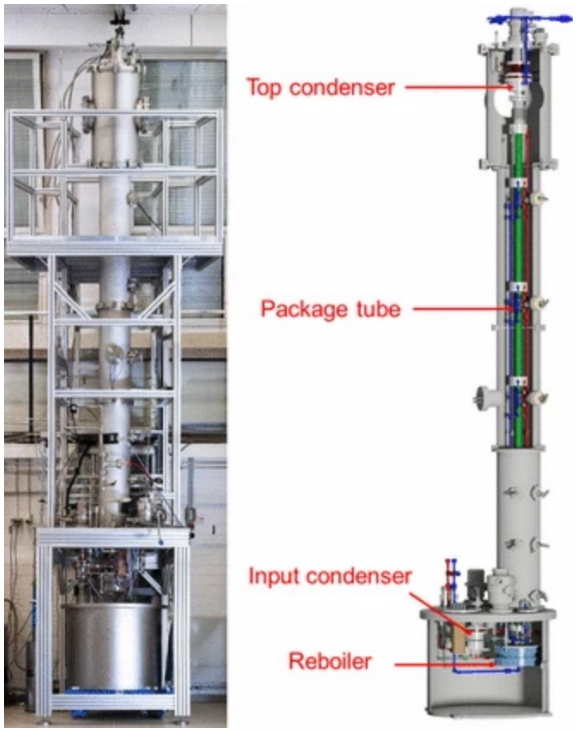


Challenges to Address for G3 Experiments



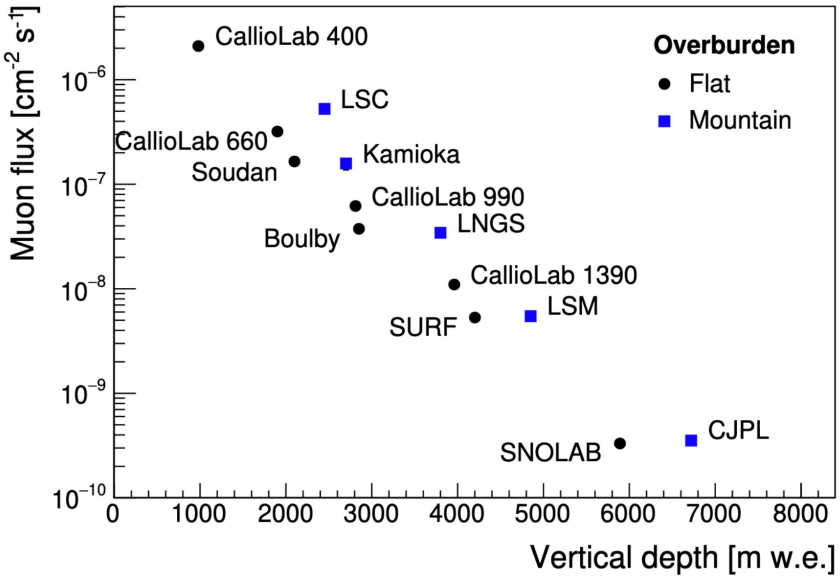
- Substantial high voltage development (feedthrough, grids, etc)
- Stringent purity requirement (radio-purity and chem-purity)
- Xenon production and cost
- Argon intrinsic radioactivity (^{39}Ar)

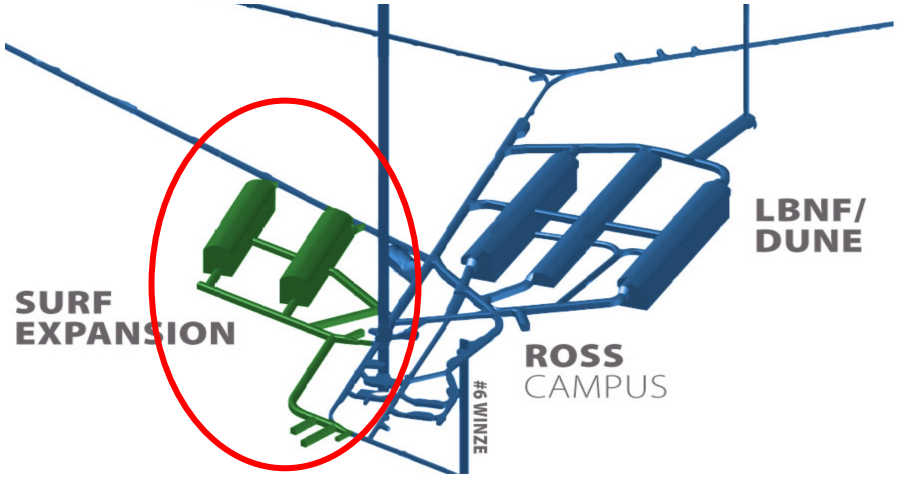




To SURF or not to SURF

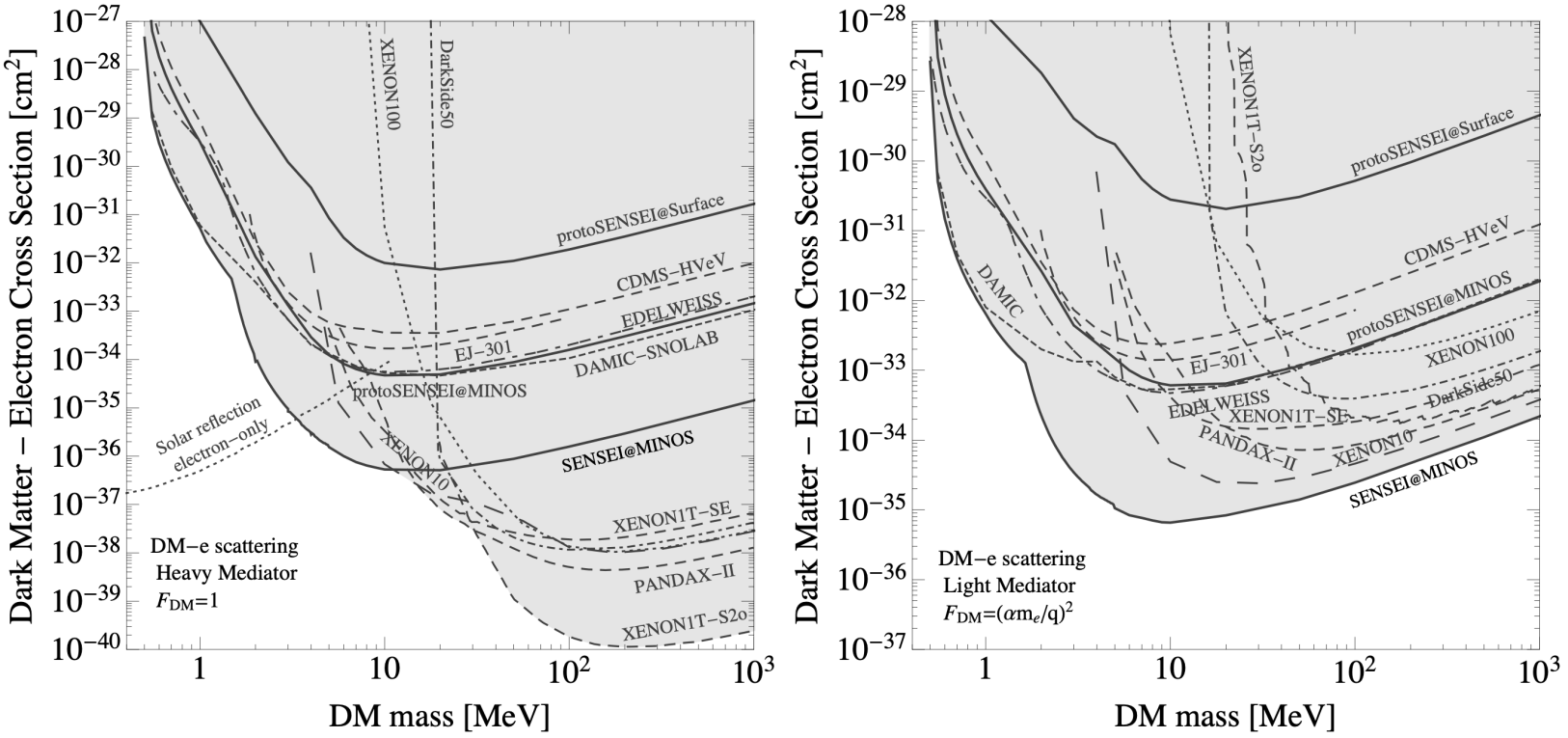
- SURF successfully hosted LUX and LZ; viable option for XLZD and/or Argo
- Expansion of underground lab space is needed – major investment
- DOE response to P5 recommendation on G3:
  - "At the present time, DOE is supportive of the development of the off-shore concepts." – May 9th, 2024
  - "Start with site independent R&D as we understand the funding that will be available. Engage with partners who are interested in hosting." – May 13th, 2024





Meanwhile, in Low-Mass Dark Matter Searches

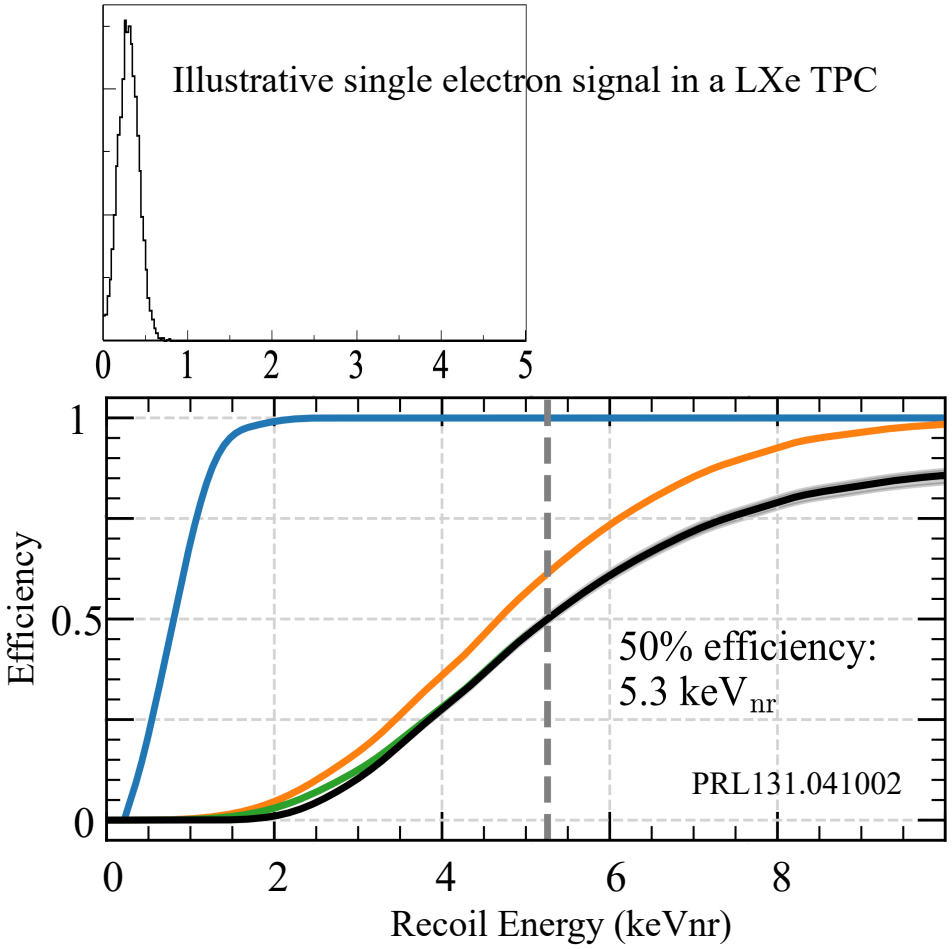
Liquid argon and xenon detectors have also demonstrated compelling sensitivities to dark matter candidates below 1GeV/c^2 mass



Compilation of low-mass dark matter sensitivity, SNOWMASS, 2203.08297

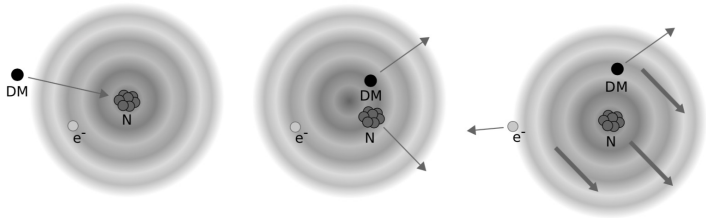
Ionization-only Searches with LXe and LAr

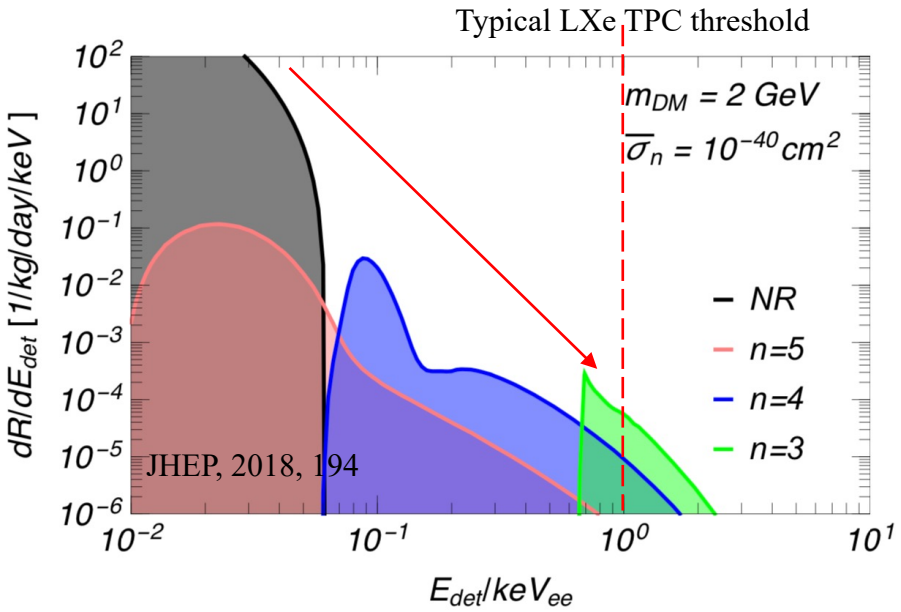
- Energy thresholds of argon and xenon TPCs (~keV) mainly limited by light detection
- Ionization signals <<1keV energy can be detected efficiently
- Ionization-only searches suffer elevated background levels
  - Extensive studies of background sources
  - Coherent explanation of background is being reported



Sensitivity Boost from the Migdal Effect

- A nucleus is coupled to shell electrons
- Nuclear recoils can lead to atomic excitation/ionization
- Low energy NRs can be accompanied by keV ERs, which can be collected more efficiently in LXe and LAr





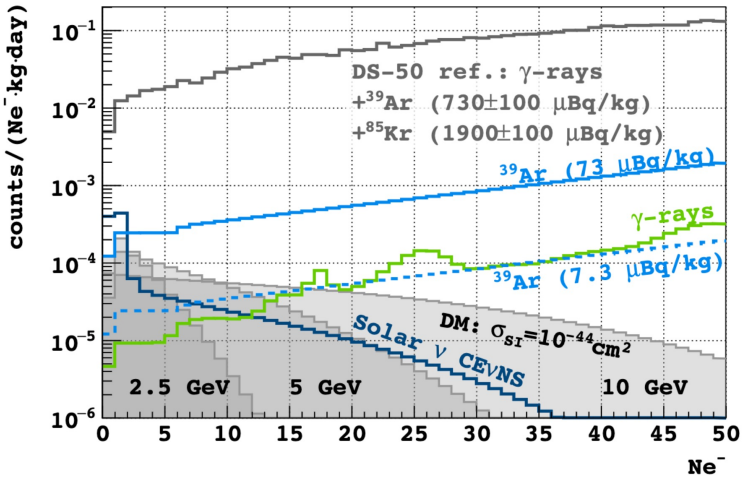
Predicted nuclear recoil and Migdal electron recoil energy distributions for 2 GeV WIMP interactions.

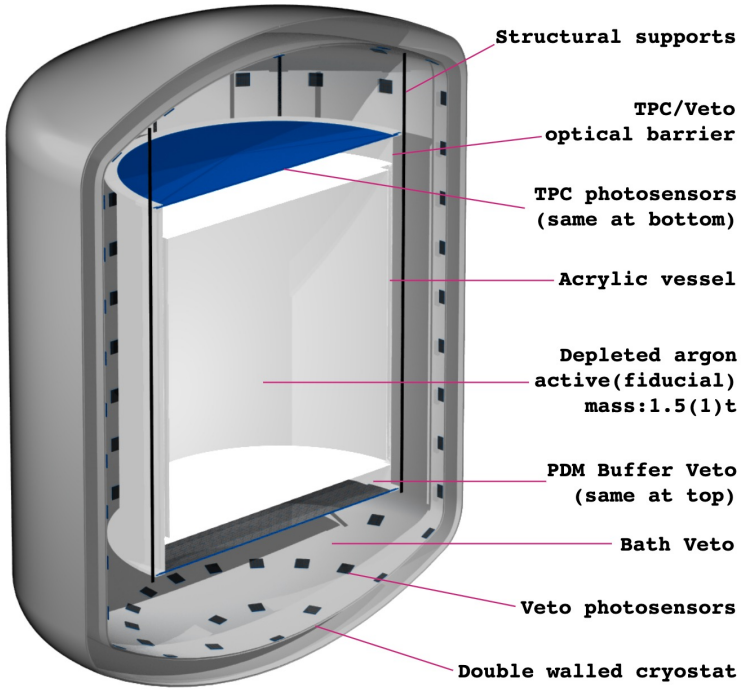
LLNL search for the Migdal Effect in liquid xenon. Result in PRD.109.L051101

DarkSide-LowMass: Argon w/ Dopants

A ton-scale LAr detector dedicated to ionization-only dark matter search

- Further reduction of ^{39}Ar
- Optimization of electric field for S2 detection
- Possible dopants to enhance ionization signals

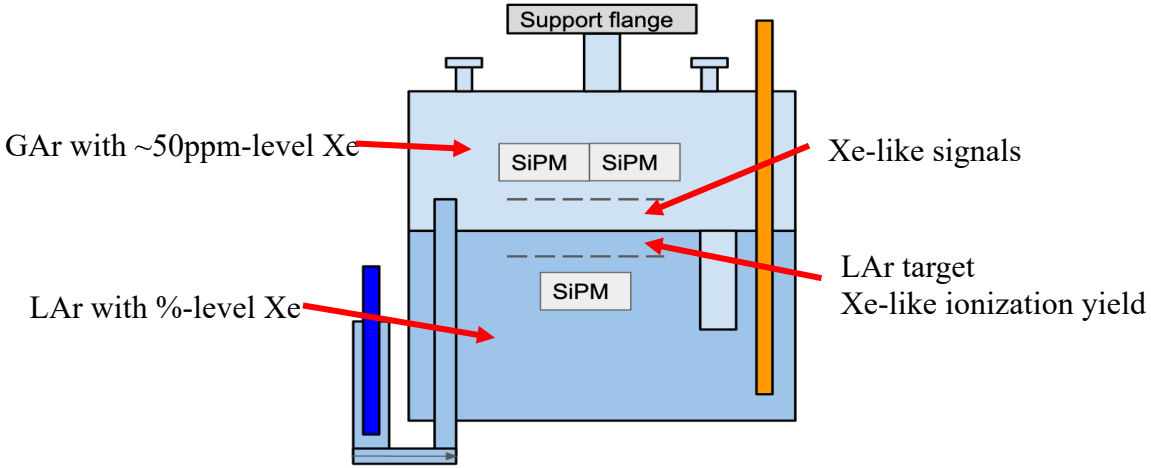


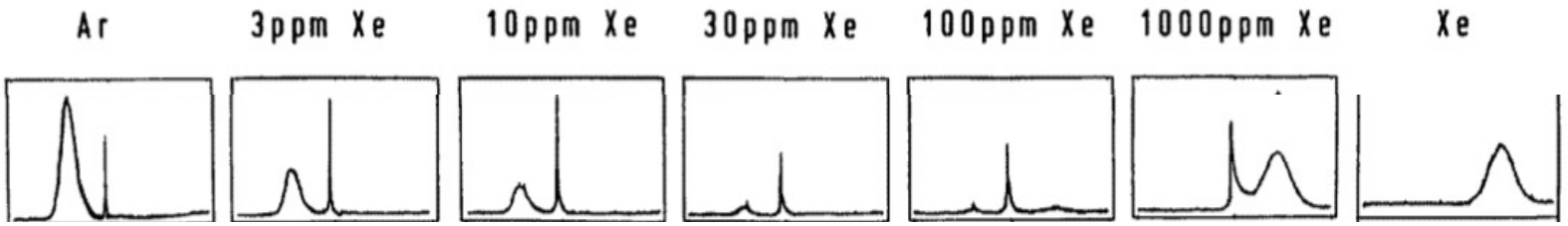


CHILLAX: Argon with Heavy Xenon Doping

A single detector to combine benefits of both Ar and Xe

- Heavy xenon doping capability demonstrated
- Signal benefits under active study



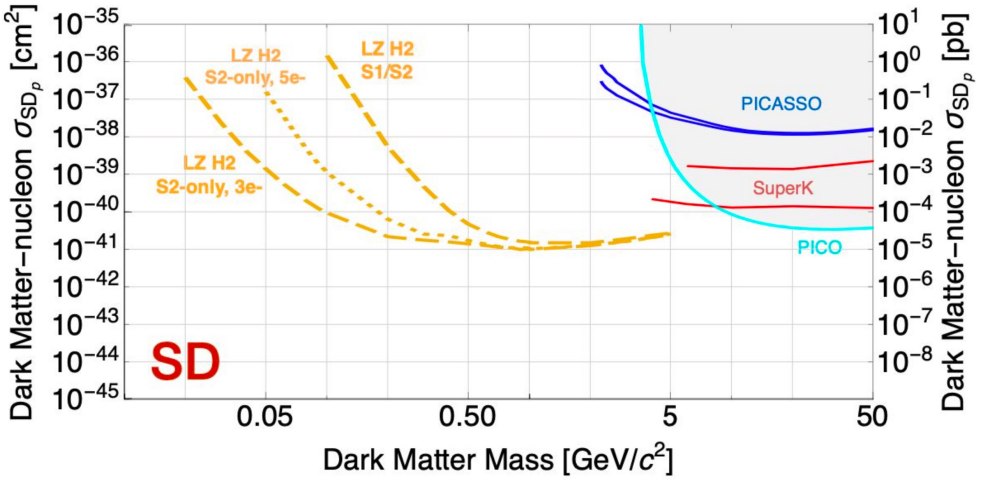


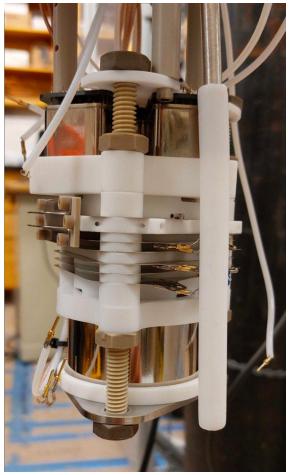
Xe doping in gaseous argon, T Efthimiopoulos et al 1997 J. Phys. D: Appl. Phys. 30 1746

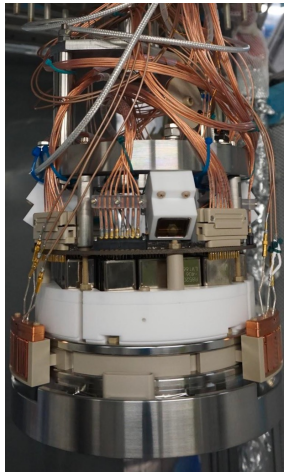
HydroX: Hydrogen-doped Xenon

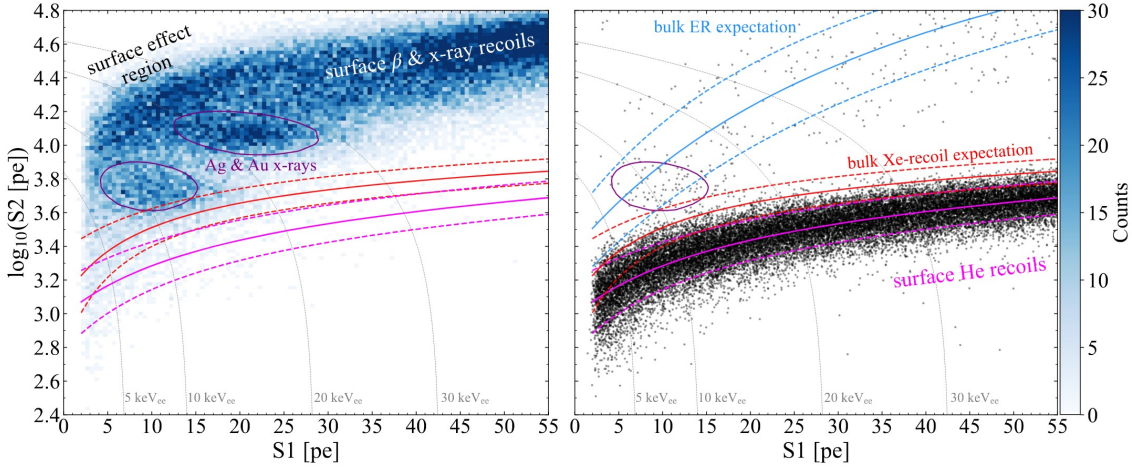
Doping Xe TPCs (LZ) with H_2

- Xe TPCs have low-background levels and powerful signal-background discrimination
- Hydrogen has kinematic benefits for low mass dark matter candidates
- Particularly sensitive to spin-dependent channel
- Demonstrated possible discrimination between NRs and ERs with H-doping





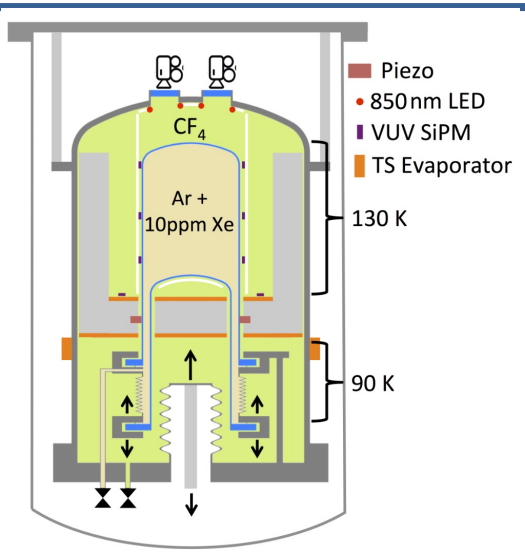


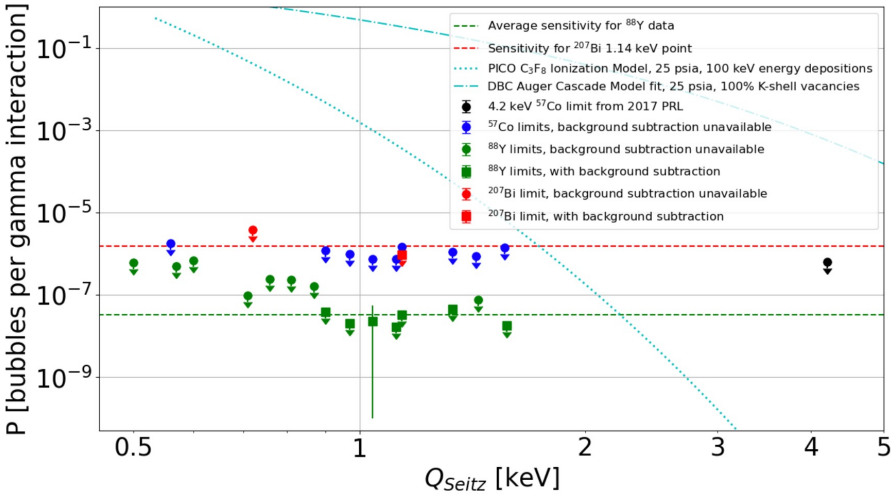


Measured ER and (surface) NR responses in H-doped xenon, PRL132.111801

Scintillating Bubble Chamber (Ar w/ Xe)

- Bubble chambers have intrinsic NR/ER discrimination
- Noble liquids are less prone to bubble formation from ERs, and can achieve lower NR energy thresholds
- LXe and LAr offer additional scintillation signals for background rejection (Xe-doping helps LAr light collection)
- Actively evaluating the achievable energy threshold for argon recoils with ER discrimination

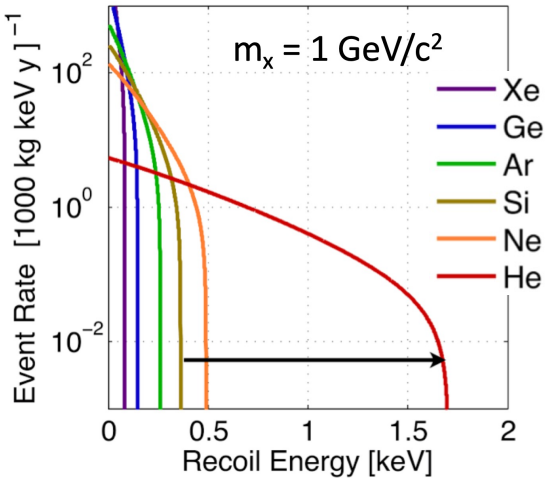


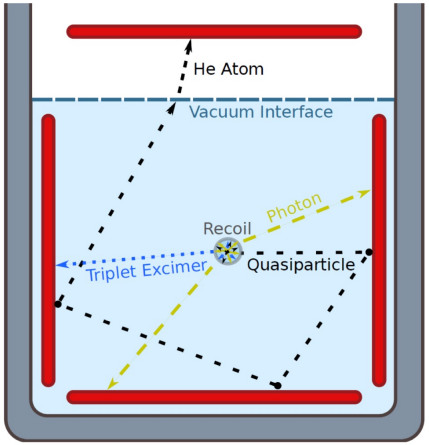


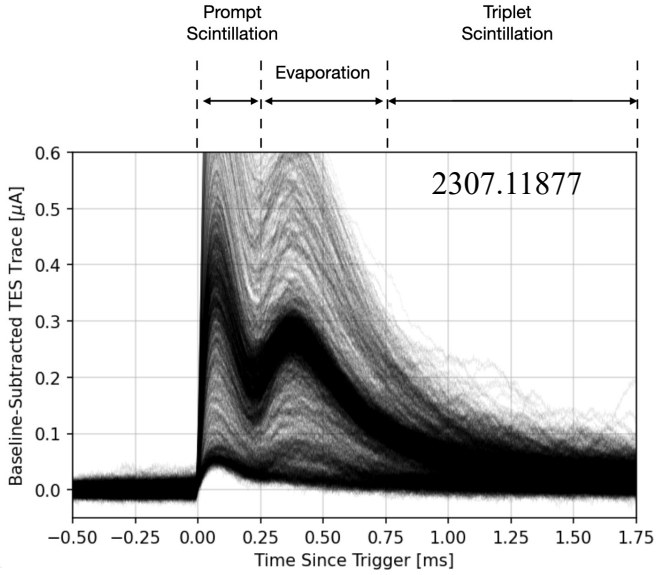
HeRALD: Detecting Quasiparticles in Helium

- Multi-channel signal readout with a superfluid He target: scintillation light and quasiparticles
- A He target has kinematic advantage for light dark matter detection over heavier elements
- Quantum evaporation provides additional signal amplification
- Demonstrated simultaneous detection of light and quasiparticles through a single TES sensor

Matava, Wednesday, 5:40pm







Outlook

- Noble liquid technologies enable experiments to achieve large target masses, low background rates, and low energy thresholds
- Liquid argon and liquid xenon detectors have been leading the searches for medium- to high-mass dark matter candidates
- Argo and XLZD are strong contenders for the G3 dark matter experiment, which aims test WIMP dark matter parameter space down to the neutrino background
- Noble liquid experiments also demonstrated competitive sensitivities to low-mass dark matter candidates below 1GeV/c^2
- New noble liquid technologies being developed will further expand the low-mass sensitivities for future experiments