Light Dark Matter Searches with Liquid Xenon

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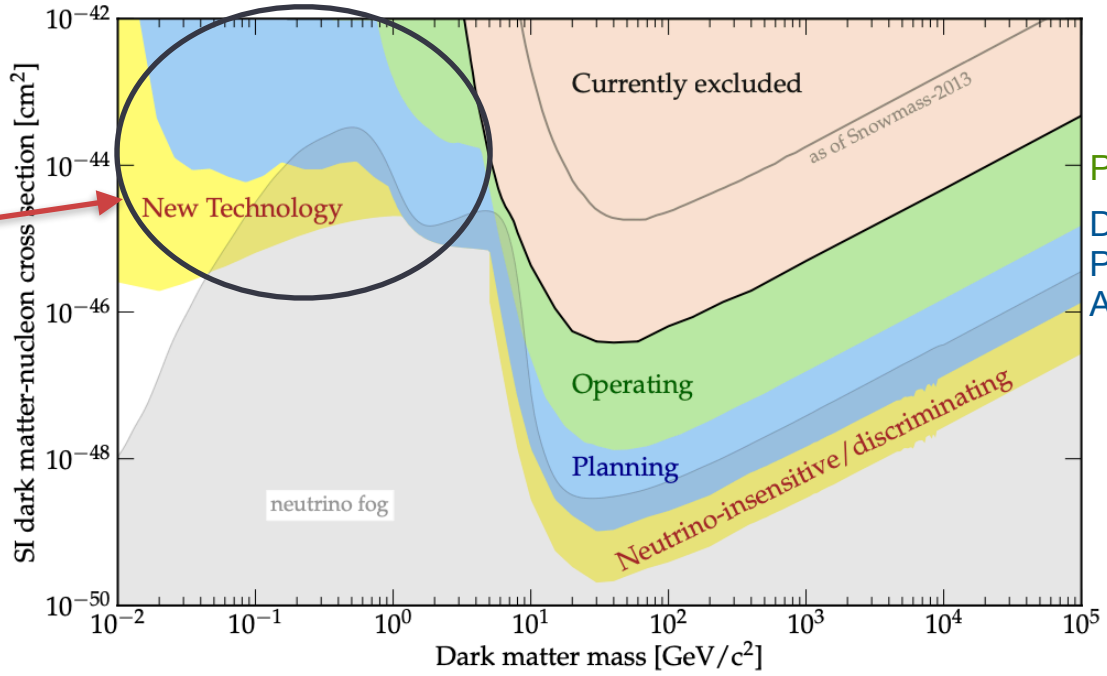
Two-phase xenon time projection chamber (XeTPC) is the leading technology for heavy WIMP dark matter searches

- PandaX-4T, XENONnT, LZ placed new limits on WIMPs in the past two years and the future PandaX-xT and DARWIN/XLZD will further improve the sensitivity for both SI and SD interactions
- The other complimentary technology for heavy WIMPs include liquid argon (DarkSide-20k) for SI, and bubble chamber (PICO) for SD-proton interactions

How wide/deep LXe detectors can probe into this region?

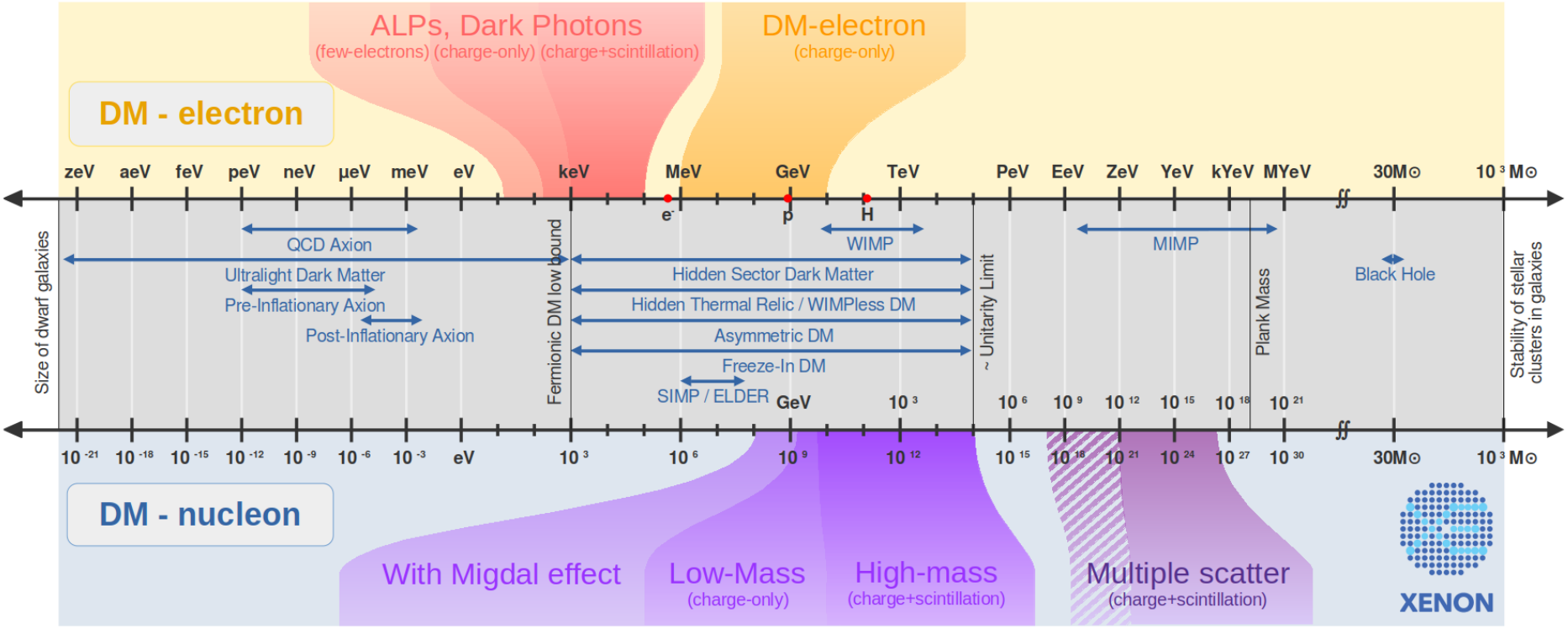


PandaX-4T, XENONnT, LZ

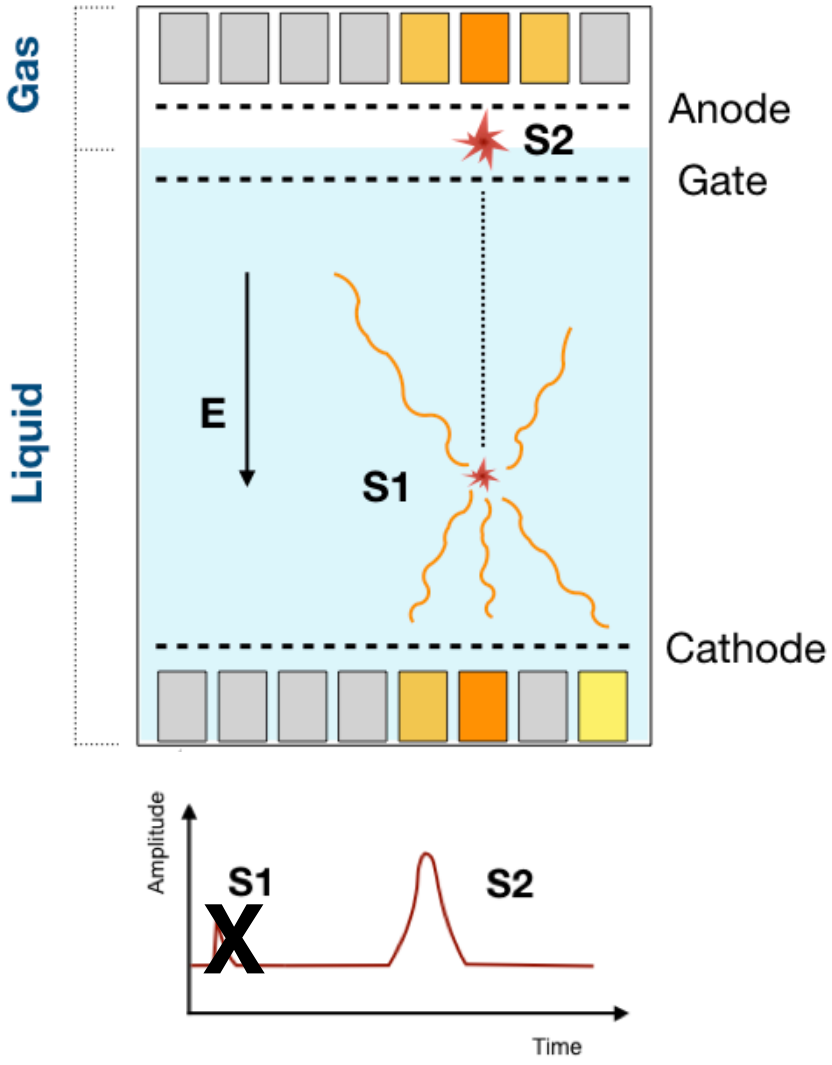
DarkSide-20k
PandaX-xT, DARWIN/XLZD
ARGO

Snowmass Report on Particle Dark Matter (arXiv:2209.07426)

Dark Matter Landscape: the XENON perspective



Two-phase xenon detector for dark matter search



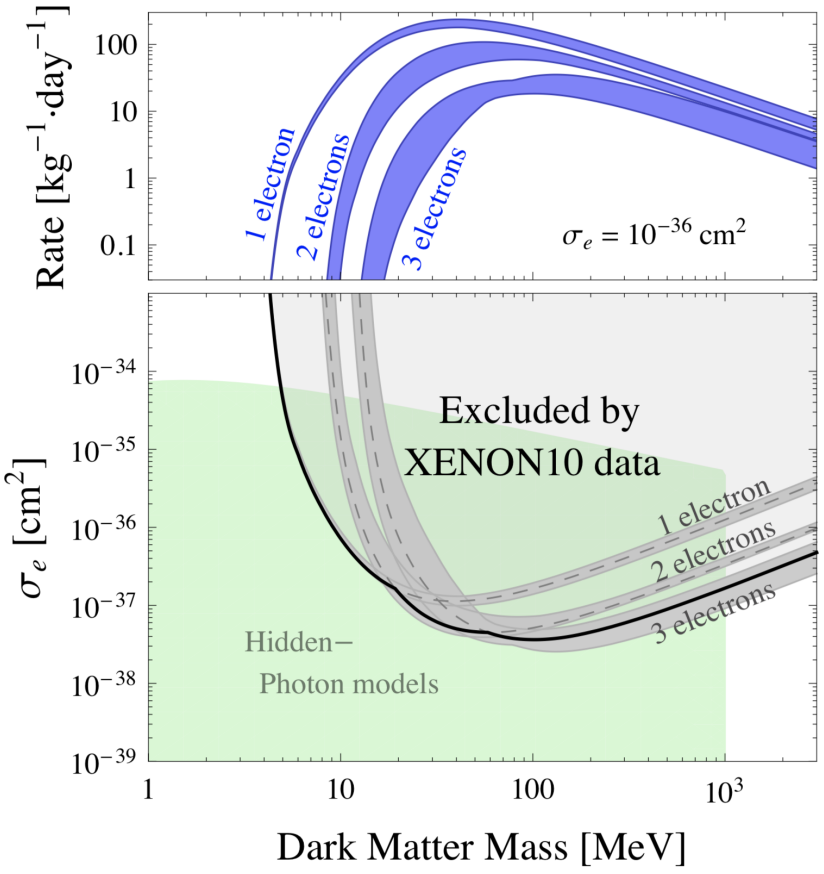
With both S1 and S2 signals: for WIMPs

- Low threshold: keV (set by S1)
- Large target mass (currently 1-10 tons)
- Ultra-low background
  - 3D fiducialization
  - ER/NR discrimination with S2/S1

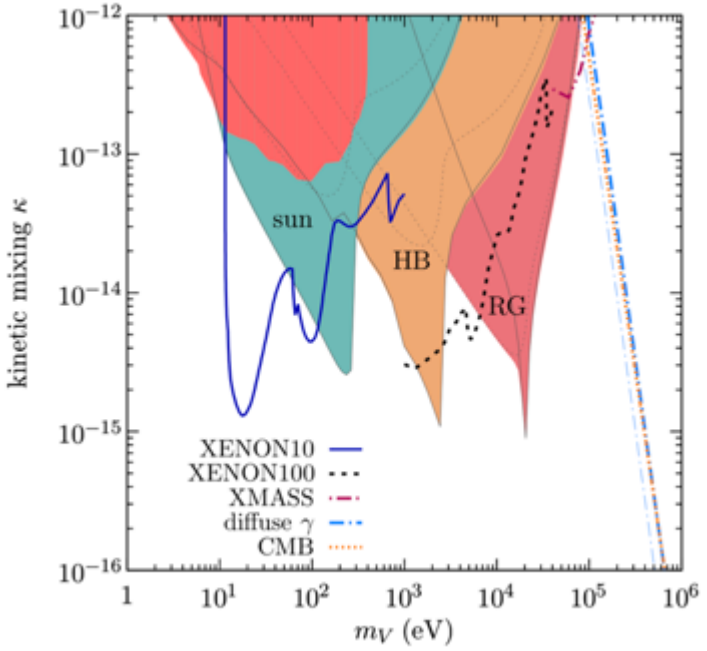
With S2 only signal: for light DMs

- Ultra-low threshold: 10-100 eV (set by S2 down to single ionization e-)
- Background control a challenge:
  - No ER/NR discrimination
  - Only XY position determined, no Z
  - **Known/unknown source of single/few electrons**

LXe detector was the pioneering technique to search for light dark matter & dark photons interacting with electrons

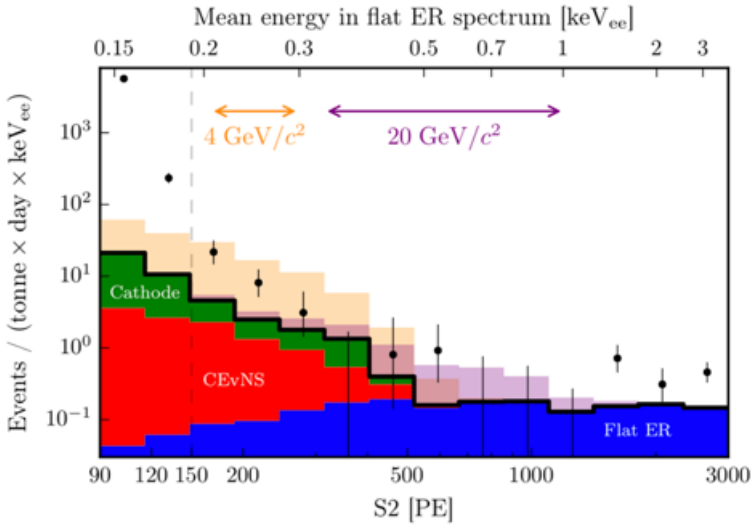


Essig et al., arXiv:1206.2644 (PRL 2012)

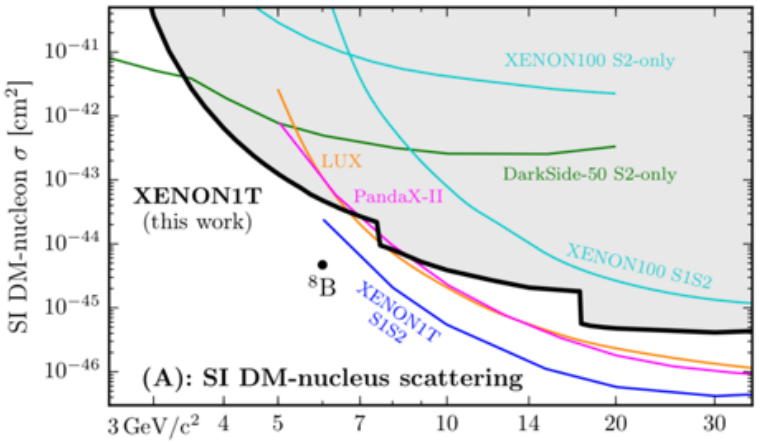


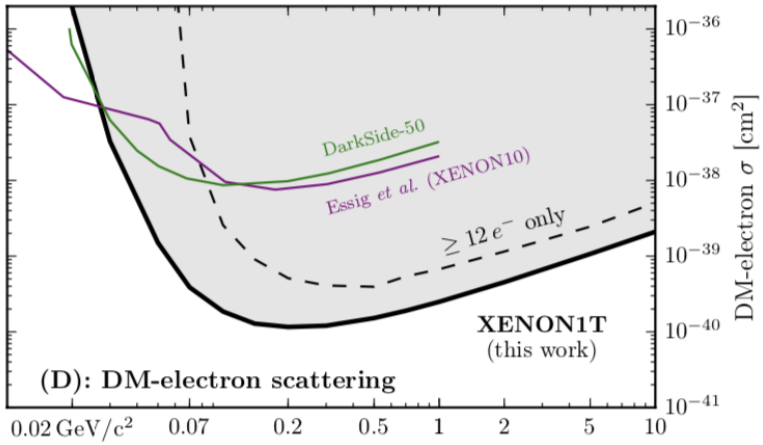
An et al., arXiv:1412.8378 (PLB 2015)

XENON1T S2-only search set strong limits for low-mass (GeV) and light (sub-GeV) dark matter

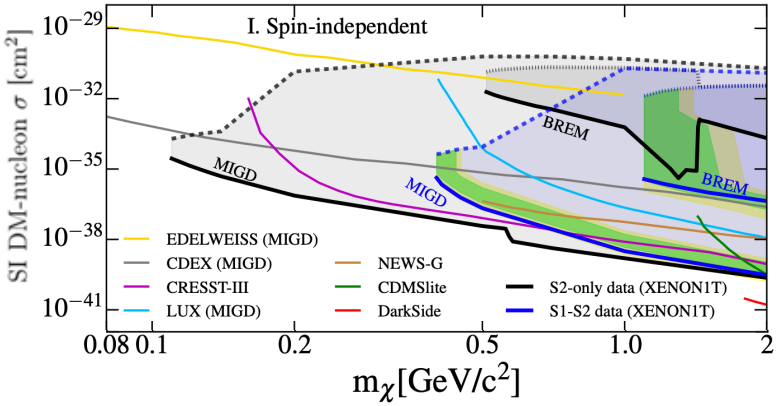


XENON1T: 1907.11485 (S2-only PRL 2019)

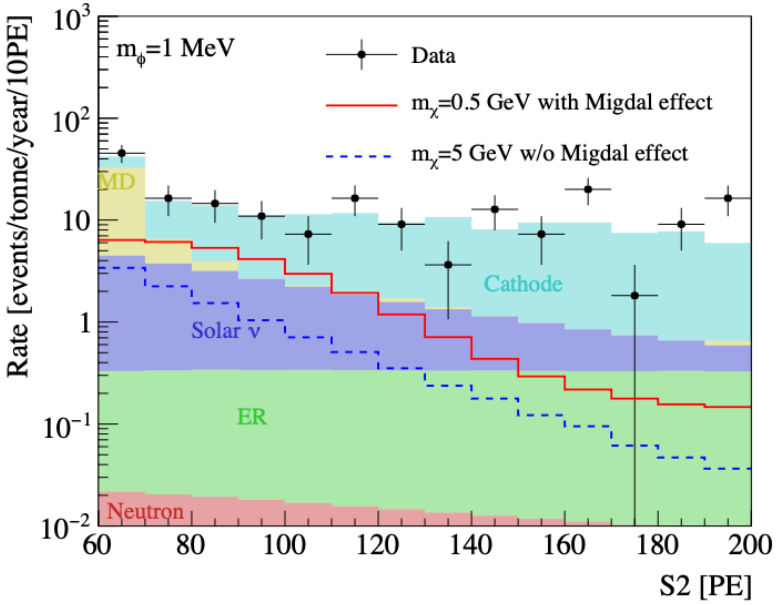




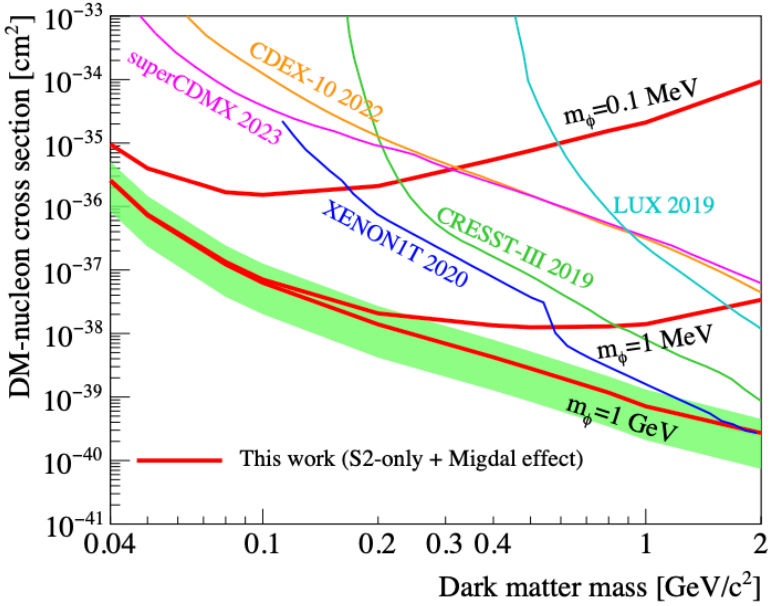
XENON1T: 1907.12771 (Migdal, PRL 2019)



Recent S2-only results from PandaX-4T



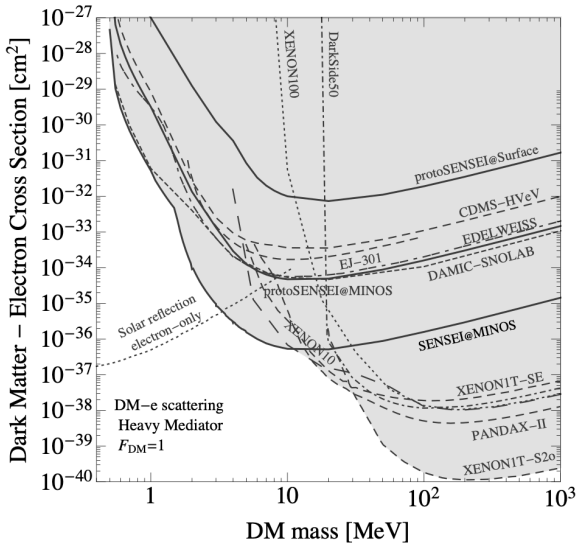
arXiv:2308.01540

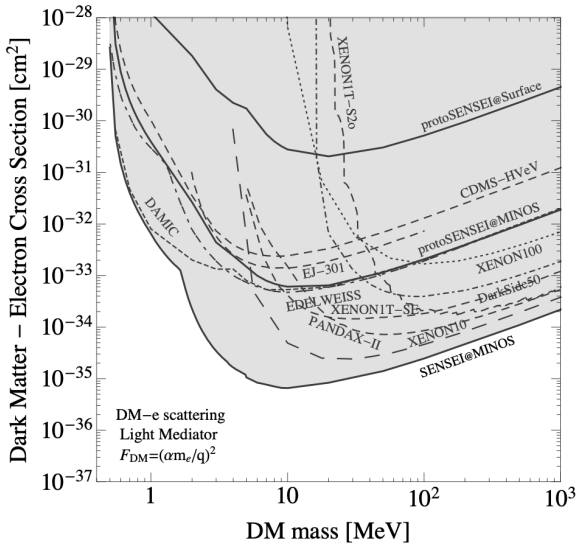


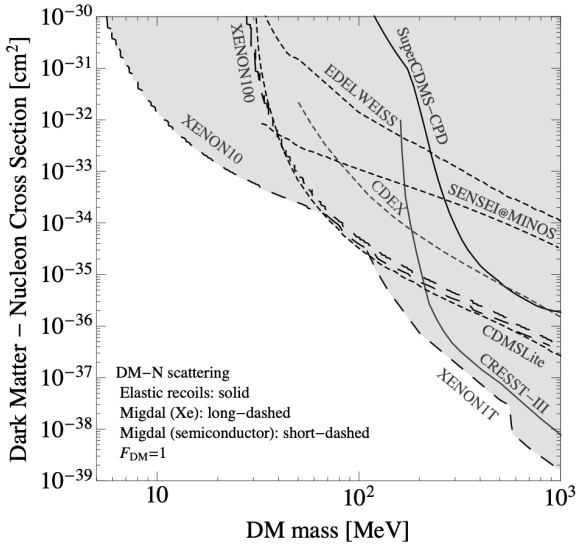
- **Placed some of the most stringent limits on light dark matter below 1 GeV**.
- background from Cathode, Solar v CEvNS and ERs, similar to XENON1T S2-only,
- discussed a new type of background MD - micro-discharges from electrodes.
- similar to other LXe experiments, only limit setting, because of irreducible few-electron background,

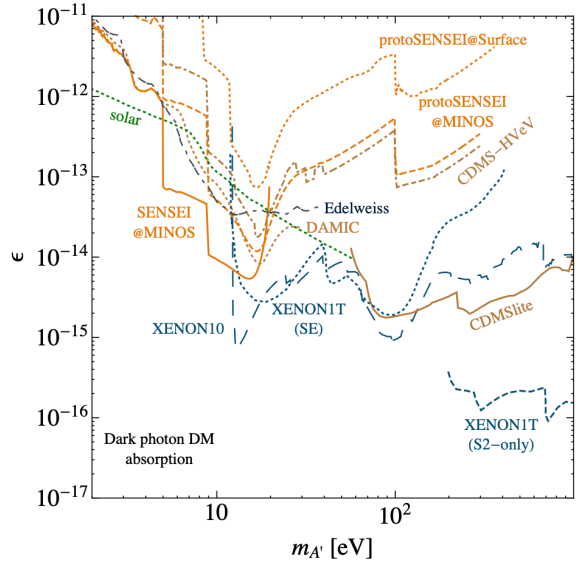
Current limits on light dark matter/dark photon DM

Snowmass2021 Cosmic Frontier:
The landscape of low-threshold dark matter direct detection in the next decade
arXiv:2203.08297









- **As a by-product, LXe are already the most sensitive target in the search for certain light dark matter**
- **This is thanks to the very low electron recoil (and S2-only) background achieved in the LXe detectors.**
- **Can we improve further?**

An R&D Program towards a **L**ow **B**ackground **E**lectron **C**ounting **A**pparatus

Lawrence Livermore National Laboratory

BERKELEY LAB Lawrence Berkeley National Laboratory

PURDUE UNIVERSITY

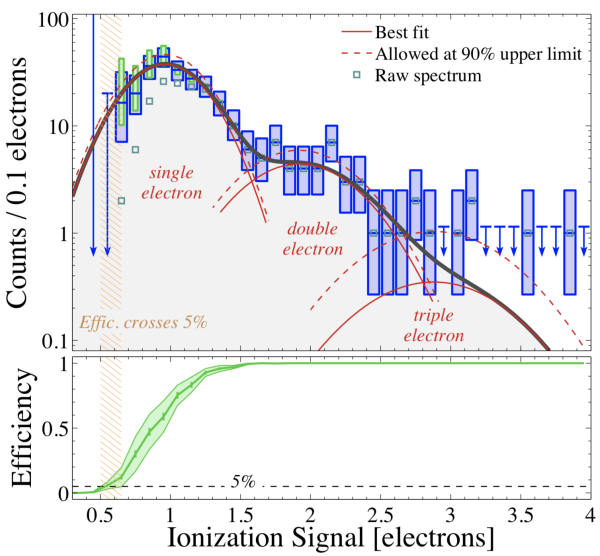
Stony Brook University

UC San Diego

- R&D program supported by DOE (2018-2020)
  - investigate single-and-few e- background in liquid xenon detectors
  - Dedicated setups to test various ideas to mitigate the electron background
  - Accurate calculations and modeling of expected low energy signals
- Following the R&D program, propose/build a liquid xenon detector with much reduced single e- background for Light DM Search

Single and a few electron background rate in the LXe bulk

XENON10, arXiv:1206.2644 (PRL 2012)



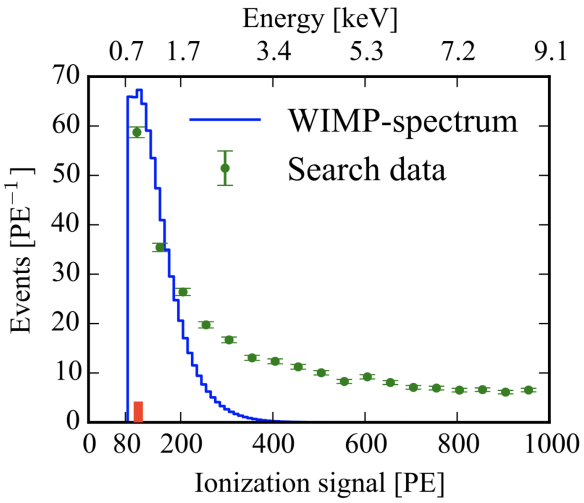
15 kg-day

Rate: 0.1~10/kg/day at 2~3 e-

10~100/kg/day at single e-

XENON100

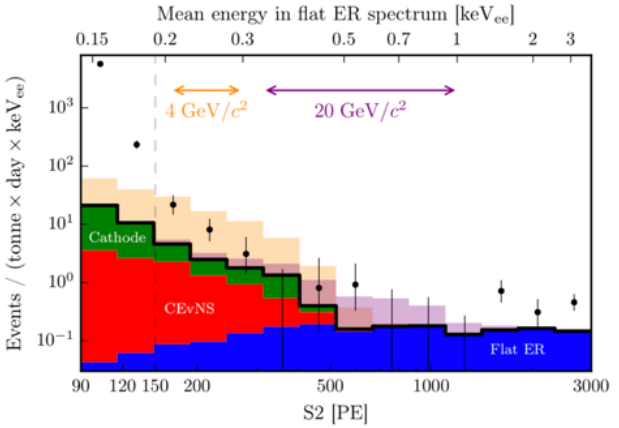
arXiv:1605.06262 (PRD 2016)



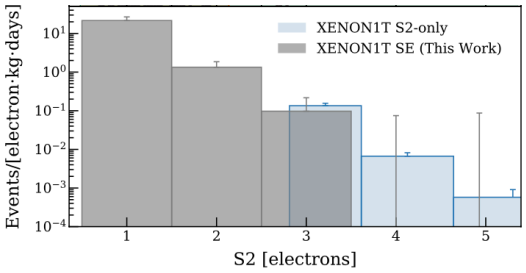
11,000 kg-day

Rate: 0.1/kg/day at ~4 e-

XENON1T (PRL 2019)



arXiv:2112.12116 (PRD 2022)



22,000 kg-day

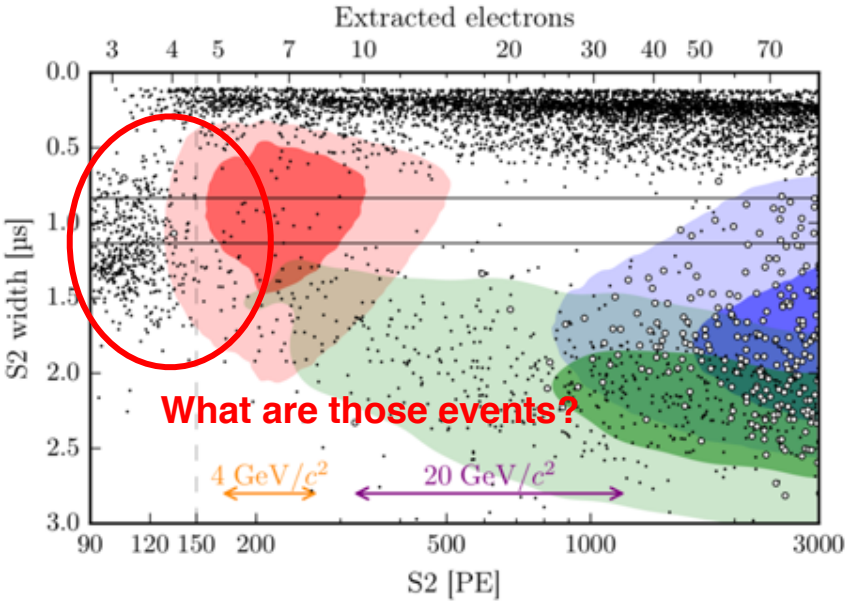
0.01~1/kg/day at 3~4 e-

~20/kg/day at single e-

- **Background at a few electron level is not always going down with increasing target mass.**
- **We have now understood much better the sources of these background electrons.**

Challenge: single-and-few electron background for Light DM search with LXe

XENON1T, arXiv:1907.11485 (PRL 2019)



XENON1T, arXiv:2112.12116 (PRD 2022)

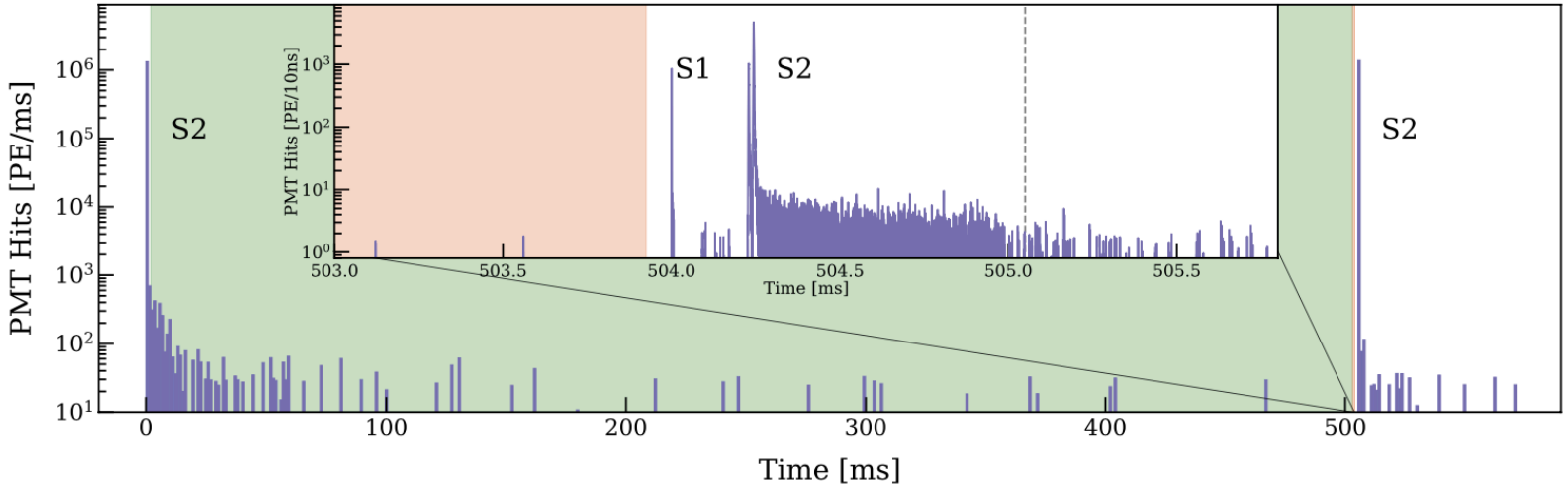
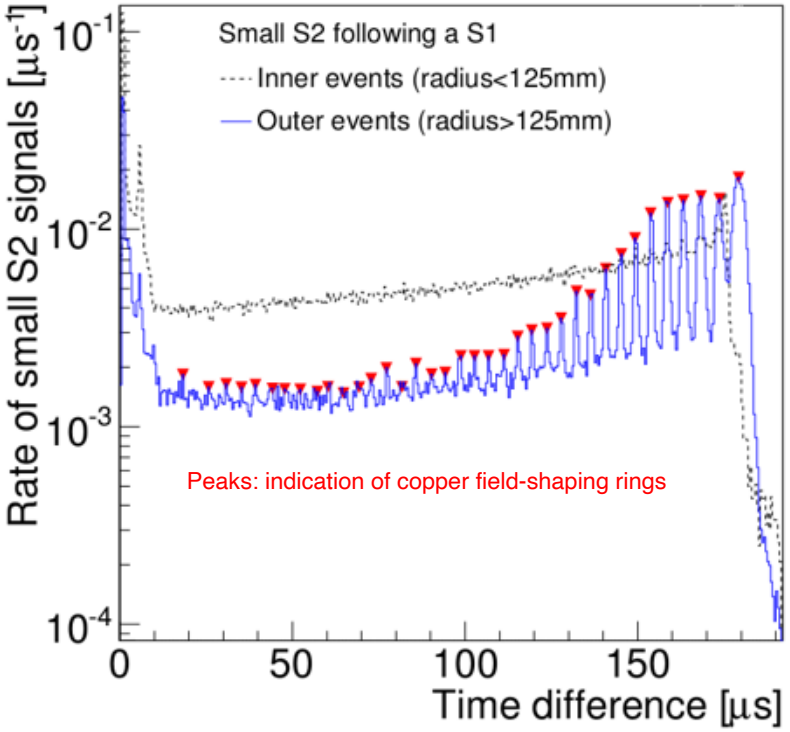
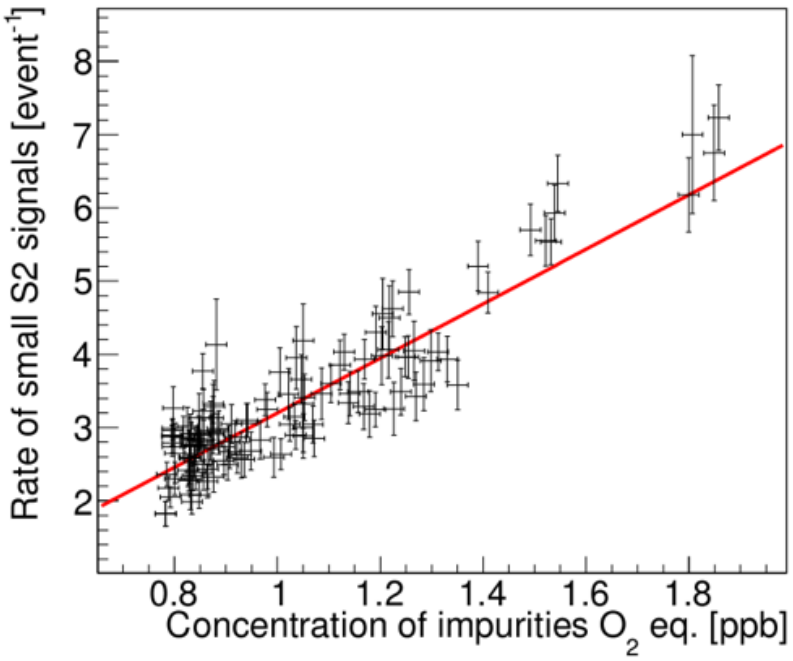


Photo-ionization of metal surfaces and impurities in the bulk LXe

Observation and applications of single-electron charge signals in the XENON100 experiment

arXiv:1311.1088 (J.Phys.G 2014)



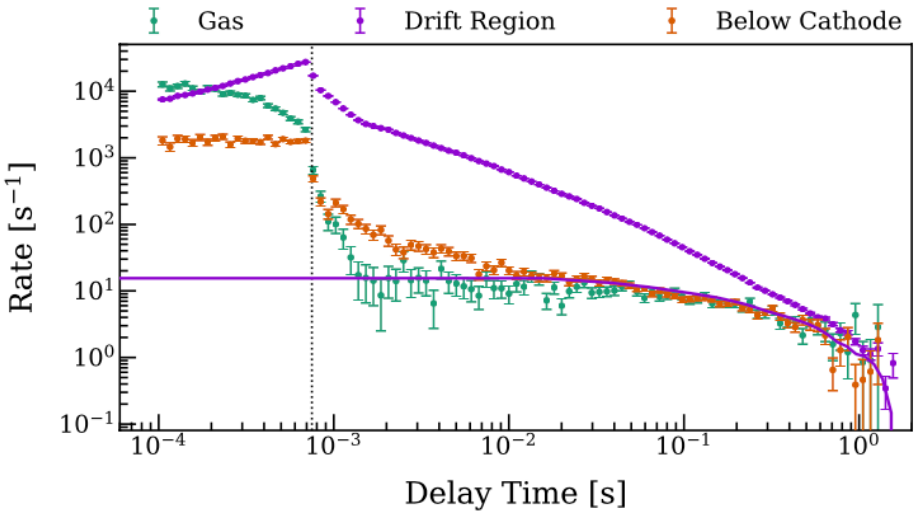


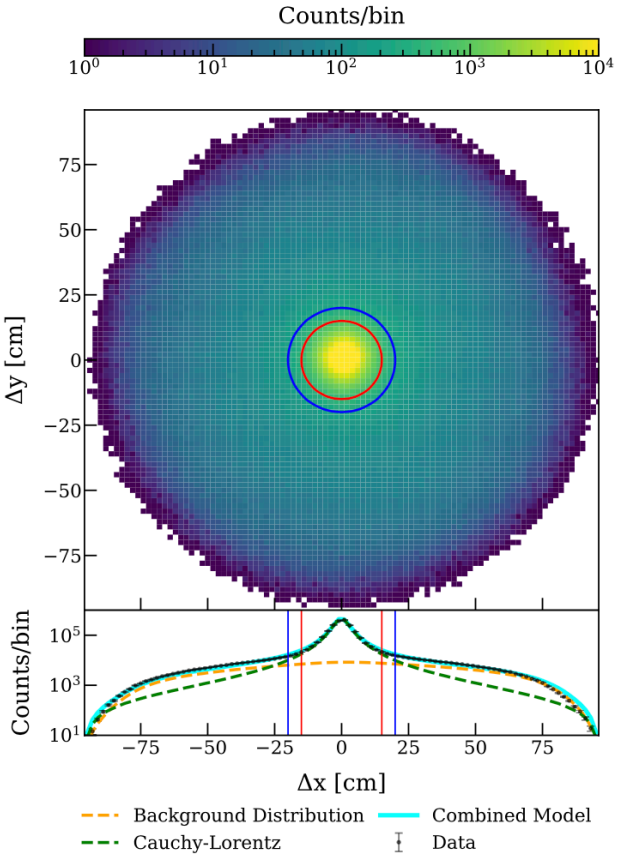
Mitigation solutions:

- **reduce metal components directly contacting the LXe target in the TPC**
- **significantly improve the purity of LXe target**

Investigating these single-and-few electrons bkg

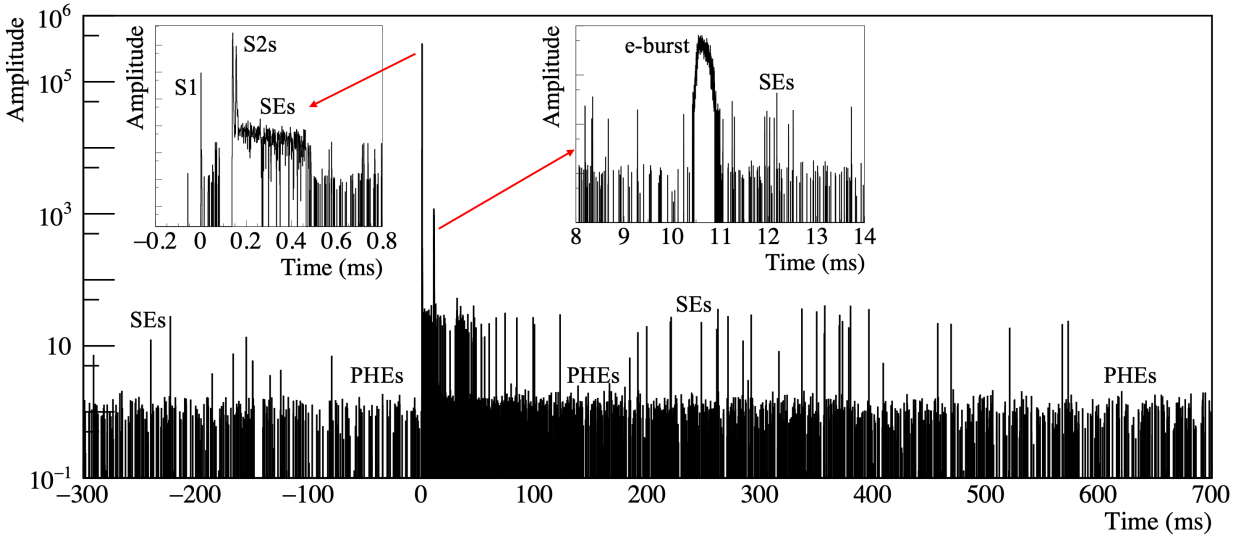
XENON1T, arXiv:2112.12116 (PRD 2022)



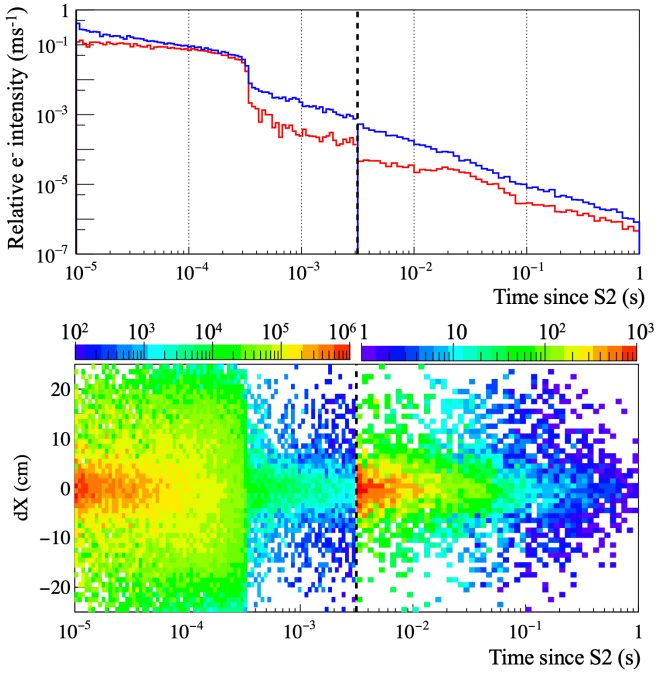


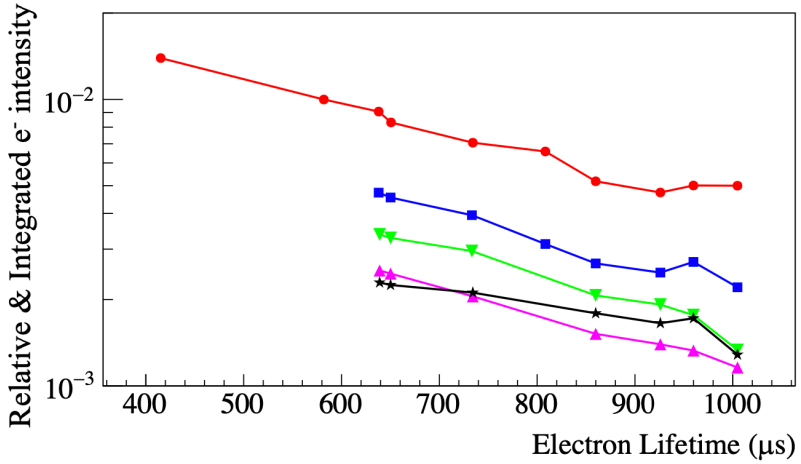
- single electron rate slowly decay long time after the max drift time
- most of these single electron positions correlate with the primary S2 position
- diffused one become constant background

LUX also observed similar phenomenon



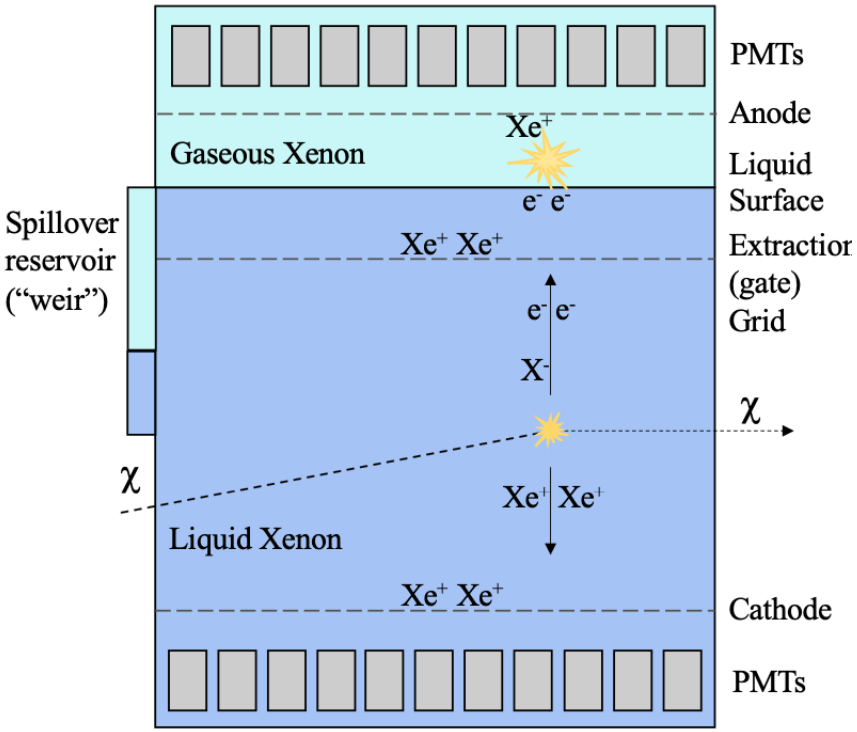
LUX,
arXiv:2004.07791
(PRD 2020)





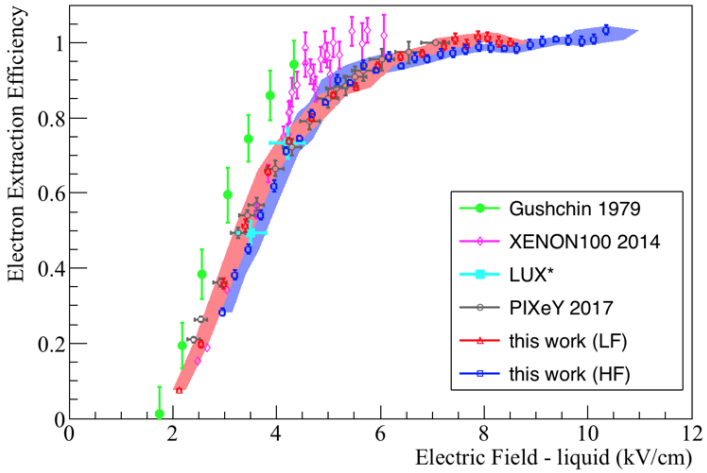
Delayed extraction of electrons trapped at the liquid-gas interface

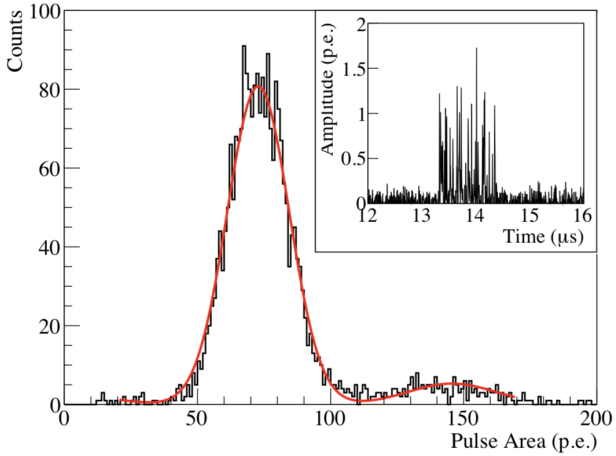
Mitigation solution with two-phase TPC: apply strong emission field: 7.5 kV/cm in the liquid to fully extract the electrons!



arXiv:2004.07791 (PRD 2020)

J. Xu et al., arXiv:1904.02885 (PRD 2019)





Very high gain (~72 p.e./e-) for single electrons obtained.

Sources of single/few e- background and mitigation methods

Problems

- Photoionization from metal surfaces
- Photoionization of impurities in the LXe bulk
- Delayed extraction of drifting electrons:
  - Attached on impurities
  - Trapped at liquid-gas interface
  - “ripples” at liquid-surface (Kopec et al 2021 JINST)
- Micro-discharges (MD) in PandaX-4T

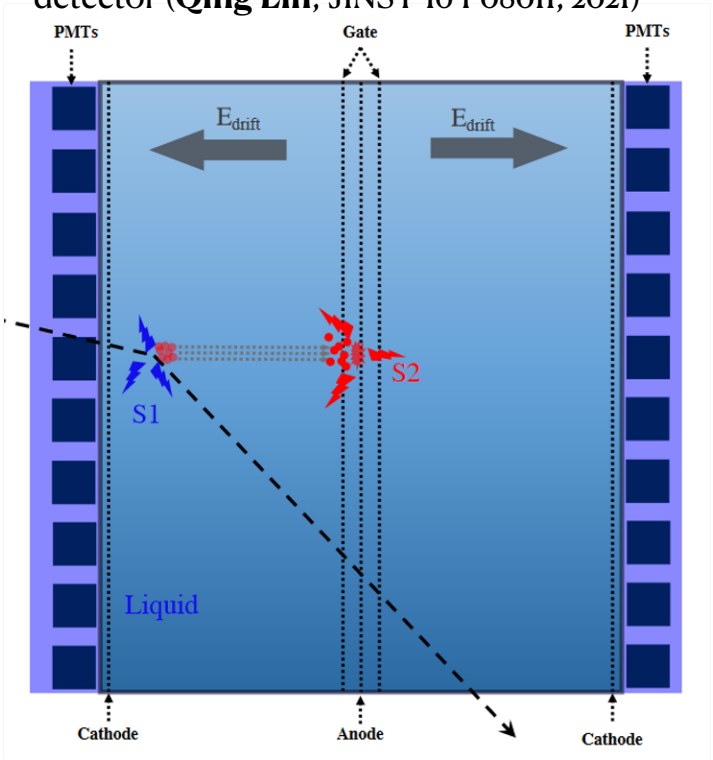
Solutions

- ➡ reduce metal surface area, use high work function metal coating
- ➡ significantly improve the liquid purity (now achieved by XENONnT/LZ)
- ➡ reduce the S2 size
- ➡ high extraction field to achieve complete electron extraction (small-scale demonstrated at LLNL, arXiv:1904.02885)
- ➡ reduce and surface treatment of electrode surface

Can we design a detector to solve all these problems at once?

A **Single-Phase LXe** detector for Light Dark Matter

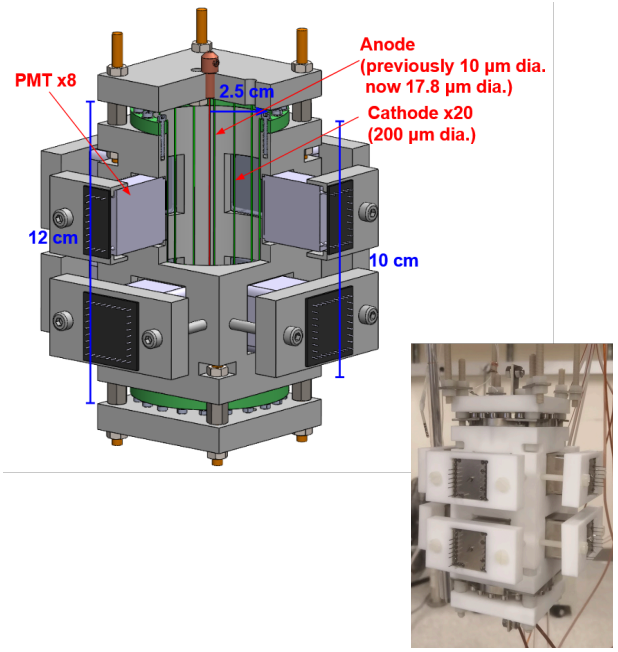
Principle of a cylindrical Single-Phase LXe detector (**Qing Lin**, JINST 16 P08011, 2021)



- **Generating proportional scintillation (S2) directly in liquid xenon** was previously studied by several groups (e.g. Aprile et al., 1408.6206, Juyal, Giboni et al., 2107.07798, Kuger et al. 2112.11844)
- A cylindrical Single-Phase LXe detector design (thin anode wire in the center) was **first proposed by Lin (2102.06903, JINST).**
  - **No liquid-gas interface: No trapped electrons!**
  - **S2 in LXe (~20 photon/e-) is typically much smaller than S2 in GXe: induce less delayed e-**
  - **Weak field on the cathode: less micro discharges; anode/gate surface area is very small: less e- from metal surface**
  - **More photosensor coverage, no reflection at liquid/gas interface: higher light collection (lower S1 threshold, better sensitivity for low-mass DM)**
  - **Fast liquid-phase purification; scalability.**
- This design could solve most (if not all) problems related to the single-and-few e- background in the two-phase TPCs! But first we need to demonstrate:
  - detection of S2-only signal down to single ionization electron (~10 eV)
  - significant reduction of the background rate down to single electrons

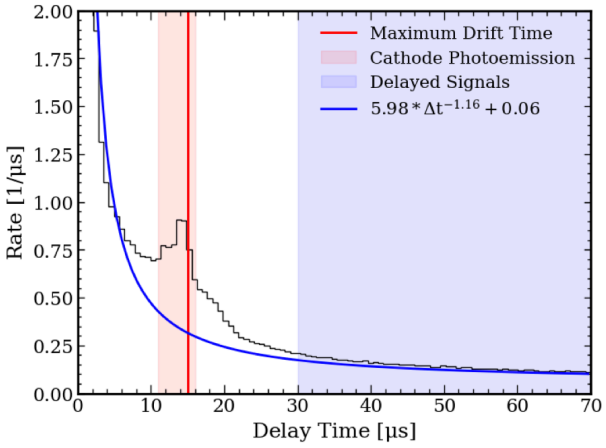
Demonstration of a Single-Phase LXe Proportional Scintillation Counter (LXePSC)

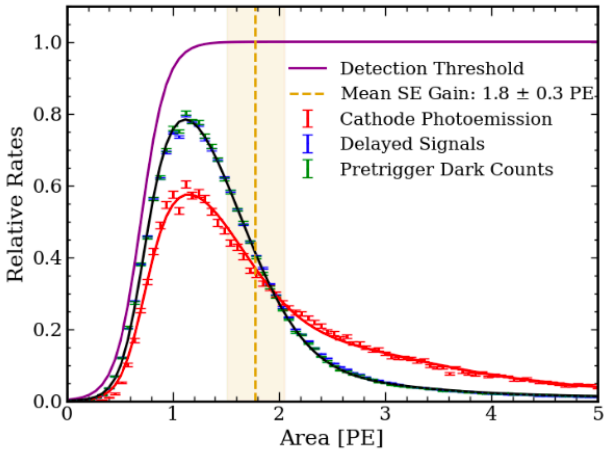
a LXePSC (0.6-kg active target) viewed by 8 R8520 PMTs (**Yuehuan Wei et al. arXiv: 2111.09112, JINST 2022**)



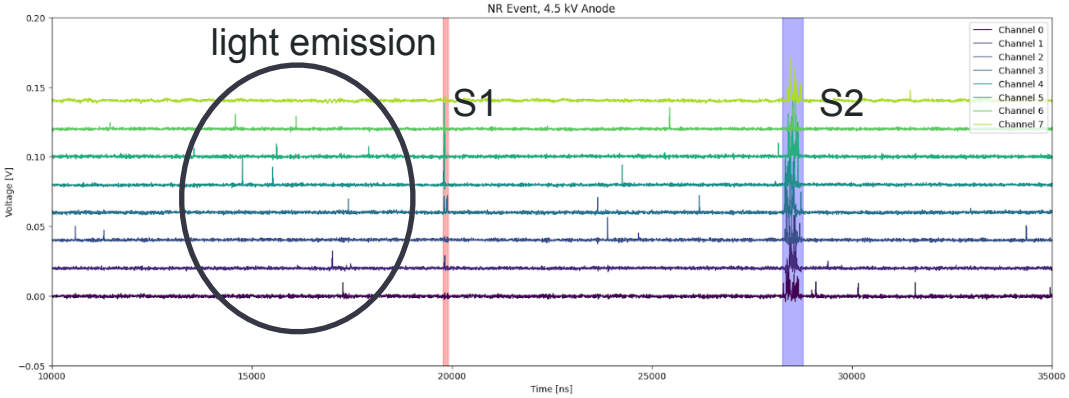
Previous work at UCSD
(Jianyang Qi et al. arXiv: 2301.12296, JINST 2023)

delayed 1-2 PE signals





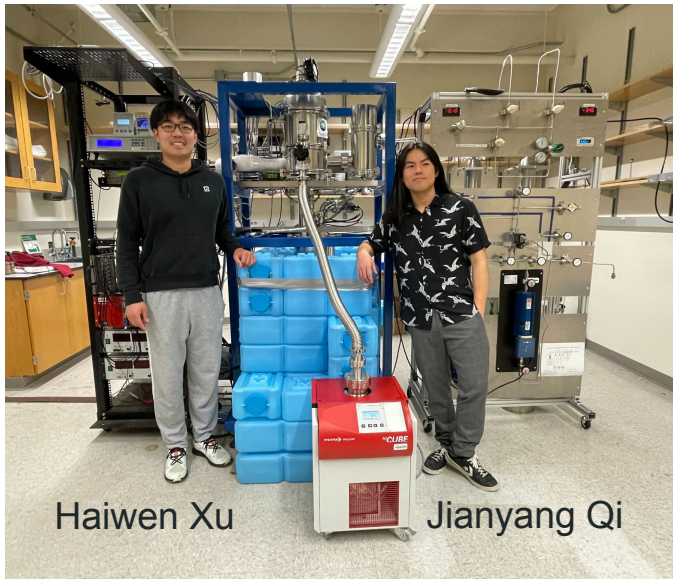
a low energy nuclear recoil event (Anode: 4.5 kV)

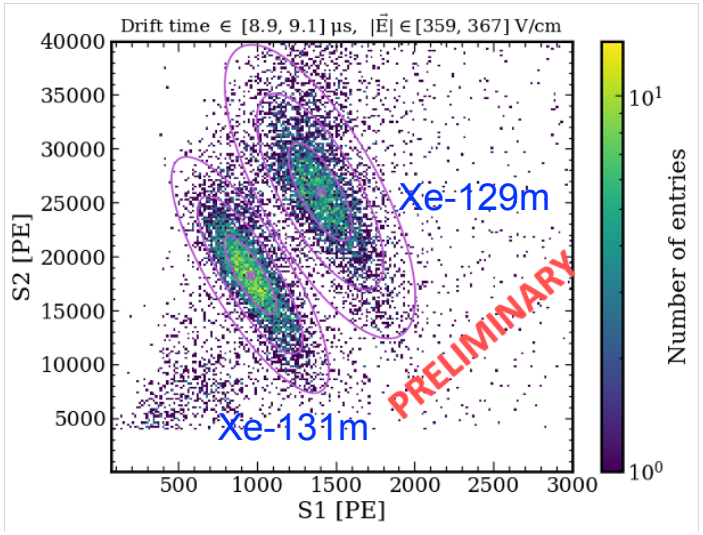


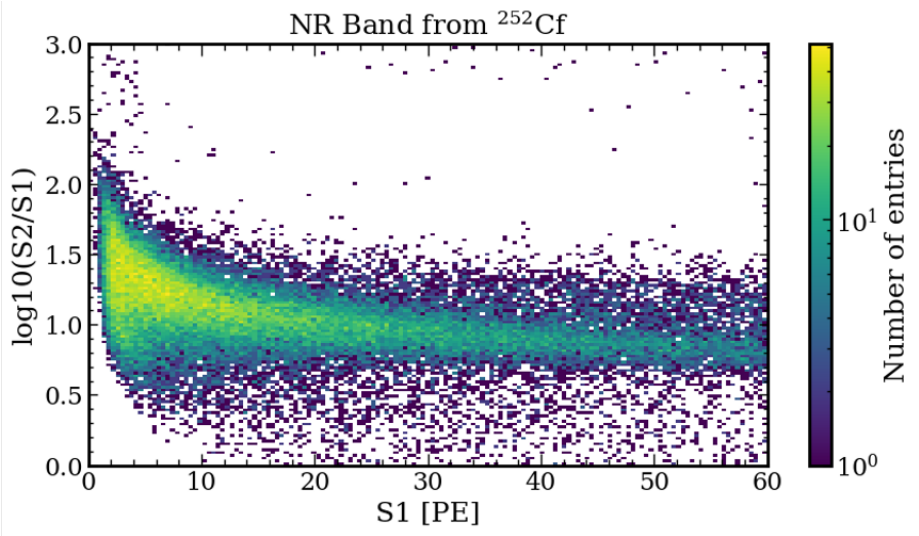
- Delayed pulses show a feature not like the “single e-” from cathode photoemission, but rather like dark counts
  - ➡higher single e- gain (g2) is needed to separate single e- from dark counts

First nuclear recoil calibration in a **single-phase** LXePSC

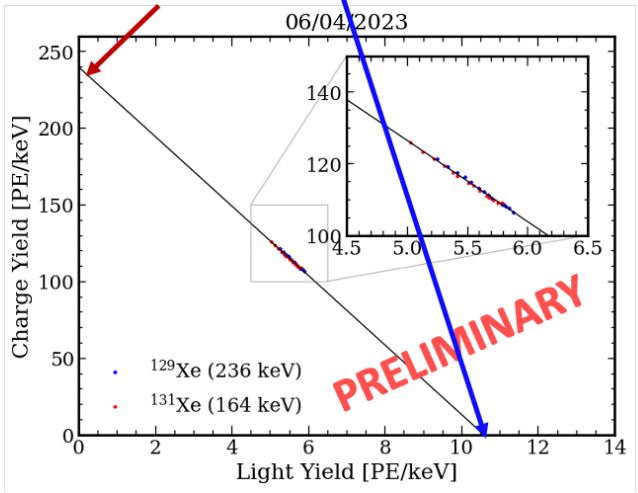
More recent work at UCSD (preliminary, analysis on-going)





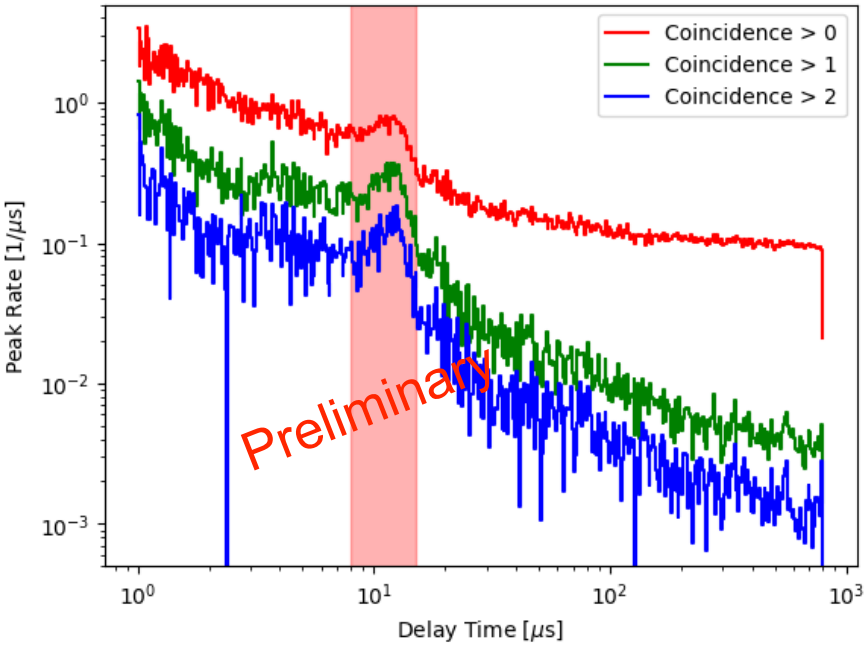


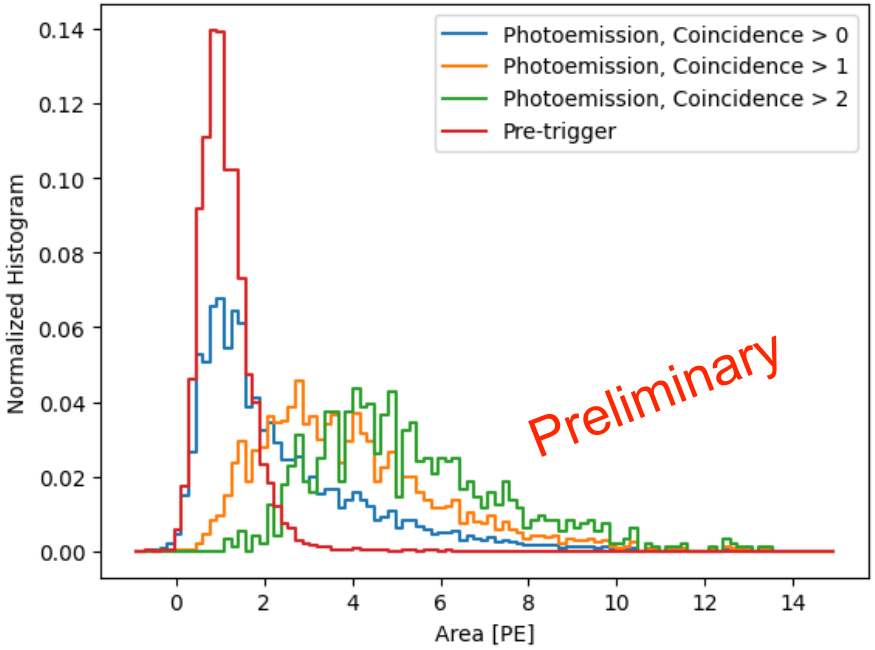
Maximum charge and light producible per keV



- g1 ~0.14 PE/photon, g2~3.5 PE/e- (from Doke plot fitting of Xe-131m, Xe-129m lines)

Detecting the single electrons with improved g2

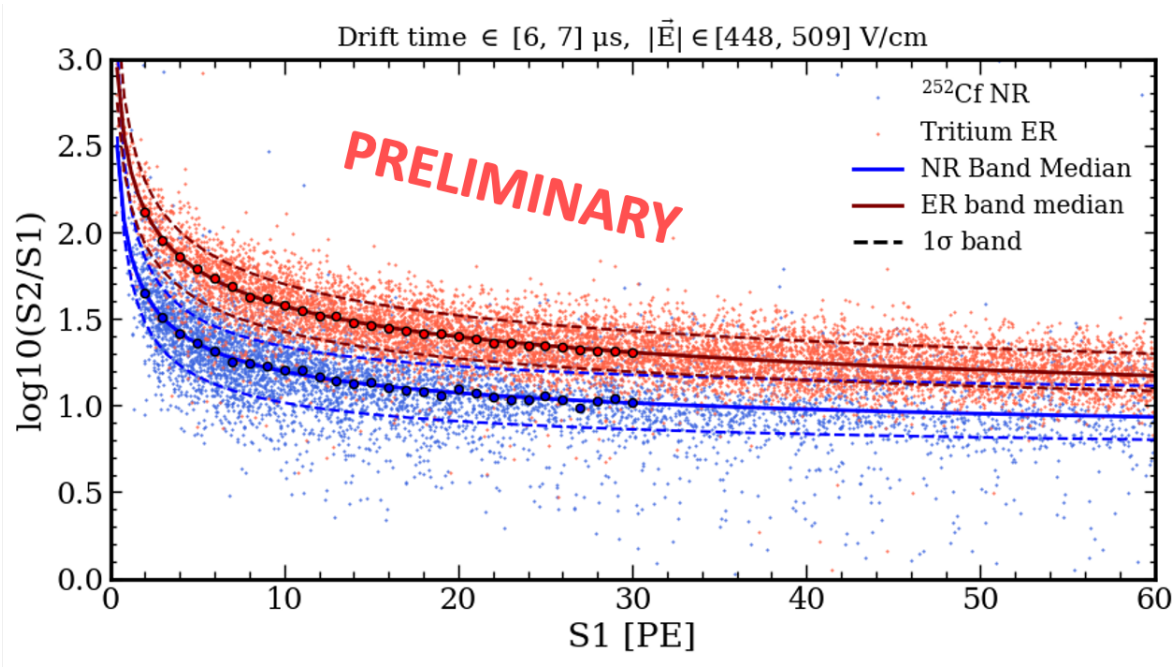


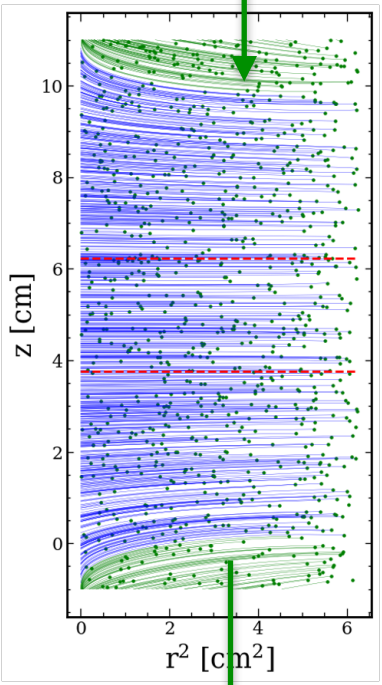


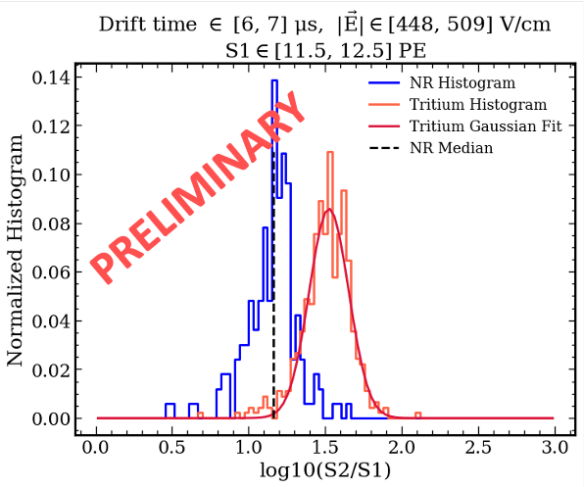
Higher g2 will help resolving the single and few electrons signals for low energy event detection

How about the ER/NR discrimination?

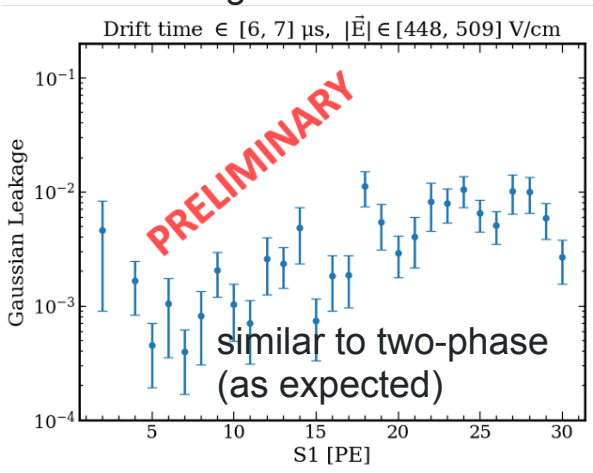
charge in-sensitive volume
(need field shaping!!)





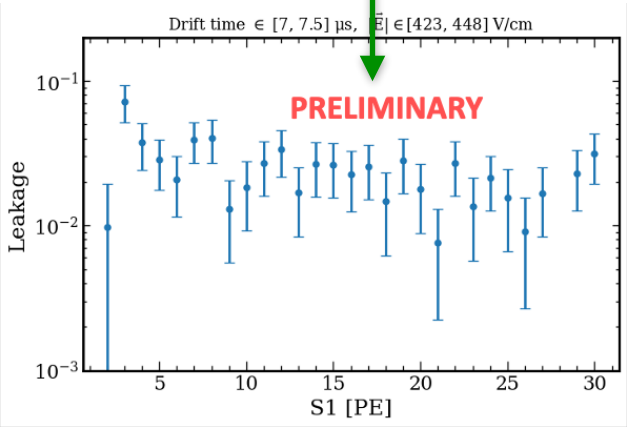


ER leakage from Gaussian tail



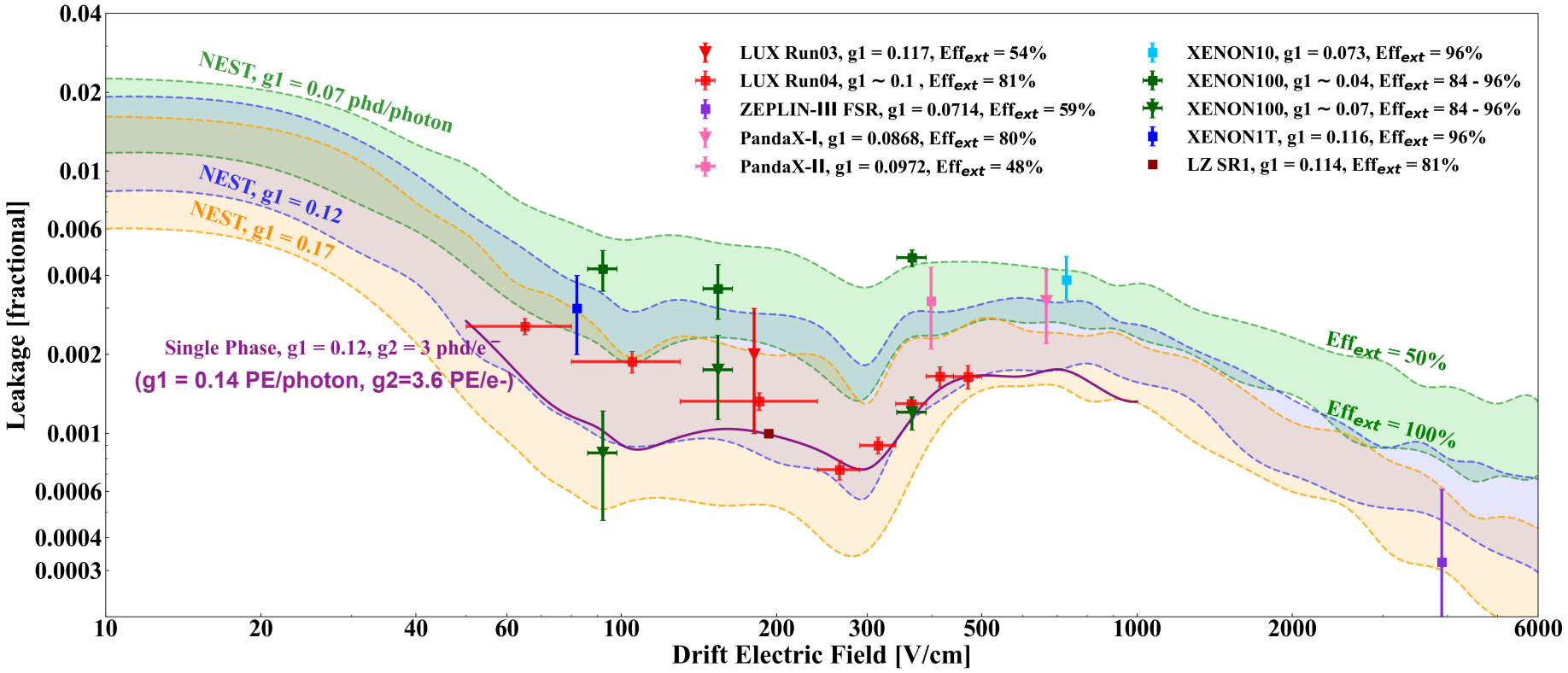
similar to two-phase
(as expected)

ER leakage from counting



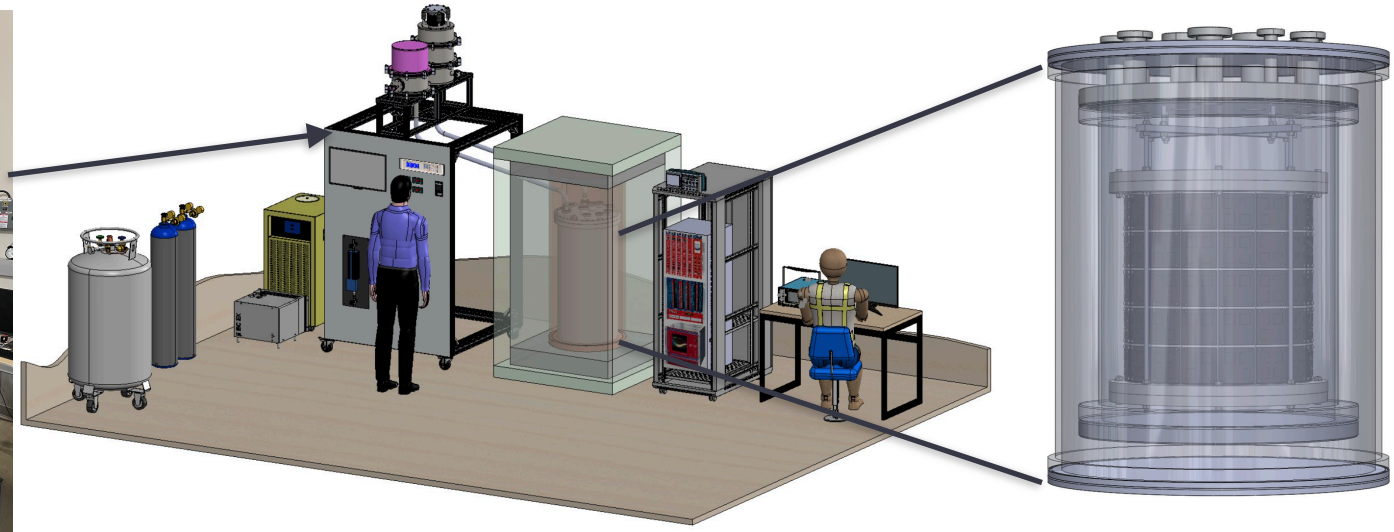
ER/NR discrimination predicted by NEST (compare a single-phase LXePSC with low g2 but 100% electron detection efficiency with two-phase TPCs)

Szydagis et al., arXiv:2211.10726 (submitted to PRD)



- It is **g1** and the **e- extraction efficiency**, NOT single e- gain, that have big impact on the ER/NR discrimination!
- Higher g1 and ER/NR discrimination will also help searching the standard WIMPs down to the lowest mass (1-10 GeV).

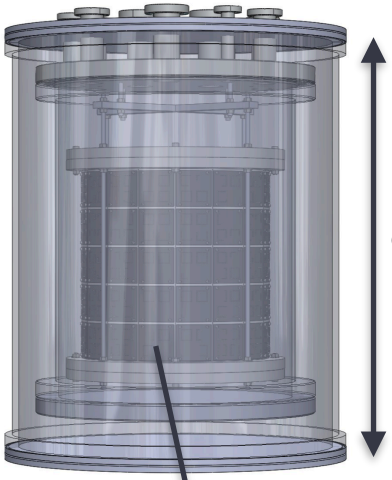
NUXE: a single e- sensitive reactor neutrino experiment with Xenon



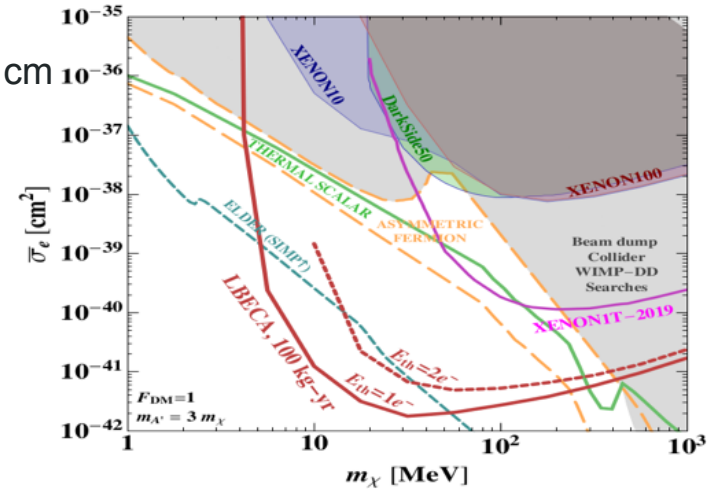
- **NUXE** is a planned reactor neutrino CEvNS experiment using ~100 kg LXe (or Xe-doped LAr) single-phase PSC
- Single-and-few e- will be the major background at surface for two-phase TPCs: we intend to reduce such background significantly with a single-phase PSC
- **The same detector system can be moved underground for light dark matter search** after detecting reactor neutrinos.

This research is sponsored by the US Defense Advanced Research Projects Agency (DARPA) under grant number HR00112010009, the content of the information does not necessarily reflect the position or the policy of the Government, and no official endorsement should be inferred.

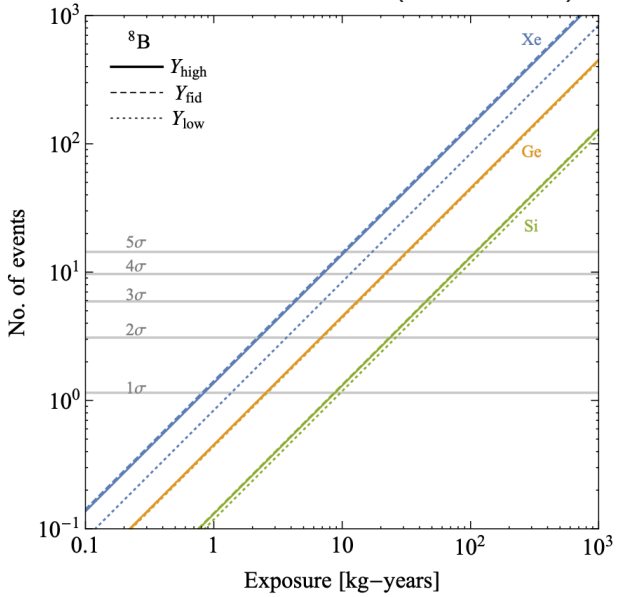
NUXE as **LBECA**: Demonstrating the LXePSC for Light Dark Matter Searches



LBECA, TAUP 2019 (arXiv:2001.09311)

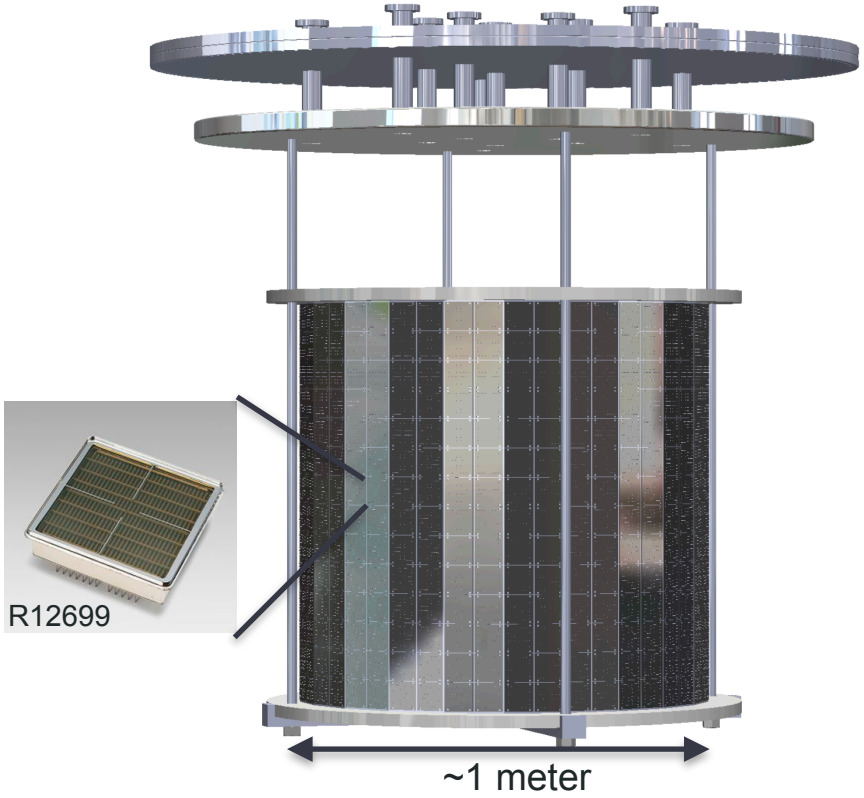


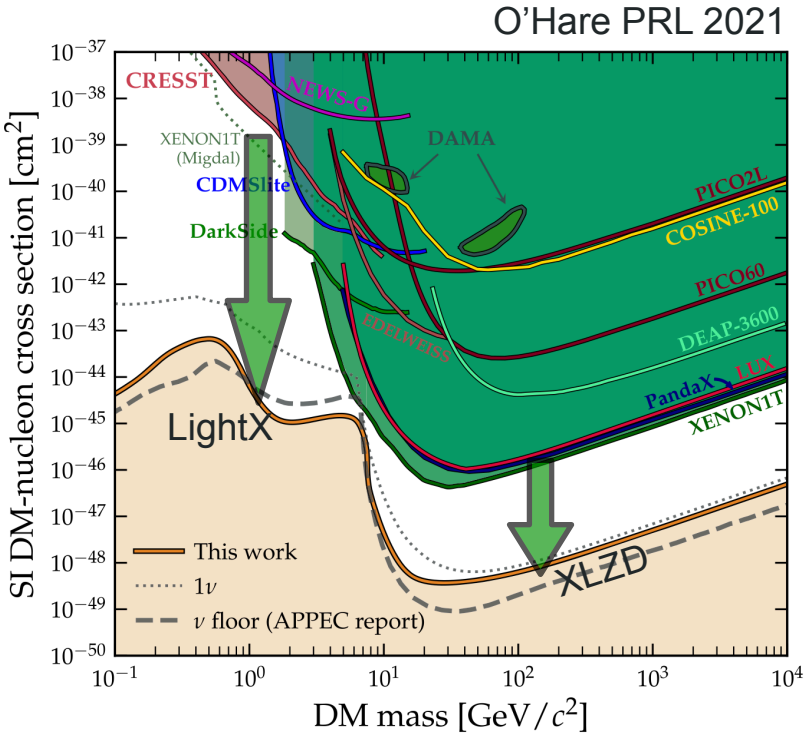
Essig, Sholapurkar, Yu
arXiv:1801.10159 (PRD 2018)



- ~**100-kg sensitive LXe (33cm D x 38cm H)** in the single-phase target
- **90 R12699** (2”x2”) PMTs
- **Demonstrate: >3 orders of magnitude** reduction of single-and-few e- background compared to the two-phase TPCs (XE10/100/1T/nT/LZ/PandaX) once it’s placed underground.
- **Physics reach (100 kg-yr exposure):**
  - cover most light dark matter electron interaction models between 5MeV-1GeV
  - >5σ detection of 8B solar neutrinos (with a much smaller target than PandaX-4T/nT/LZ)

LightX: A Ton-Scale **Light** Dark Matter Search Experiment with **X**enon

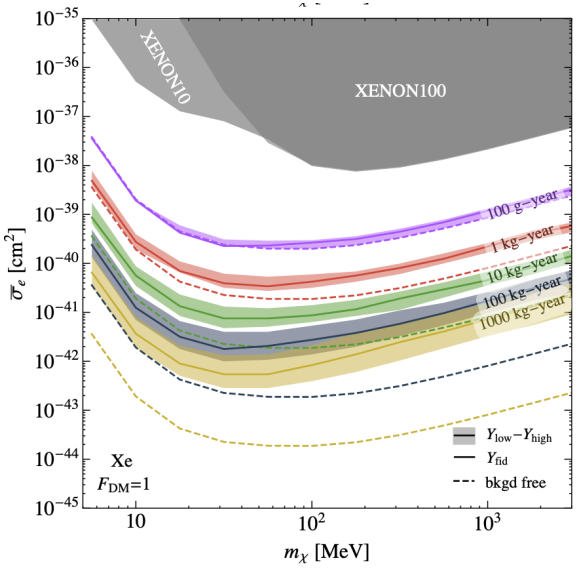


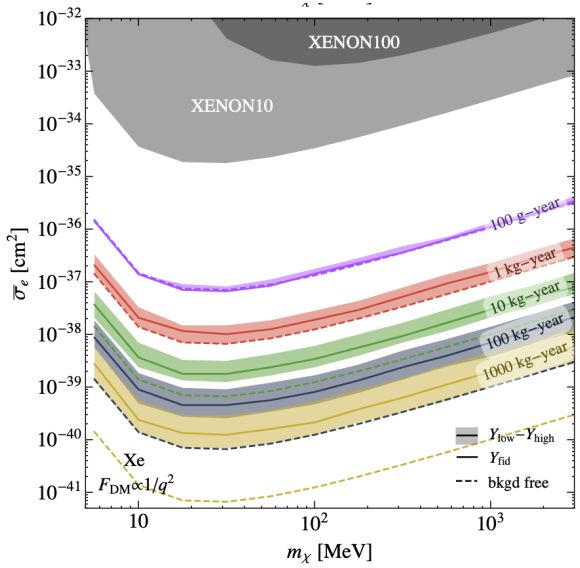


- **~2 tonnes sensitive LXe (1m D x 1m H)** in a **single-phase** target
- **616** 2"x2" **R12699 (or equivalent high QE)** PMTs (**g1: 0.2~0.3 PE/photon**, **g2: 7~10 PE/e-**)
- Ultra-low S2-only background down to single e-
- **Physics reach (1~10 ton-yr exposure):**
  - increase discovery significance of **light (sub-GeV) DM** if any signal is observed in the demonstration phase
  - search for **light and low-mass (0.1-10 GeV) dark matter** down to the neutrino floor
  - solar neutrino physics
- **Complementary to the XLZD/PandaX-xT programs for heavy WIMP searches**
- Lifetime (including construction/commissioning/operation): **10 years**

LightX's sensitivity to sub-GeV DM, dark photon and Solar neutrinos

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

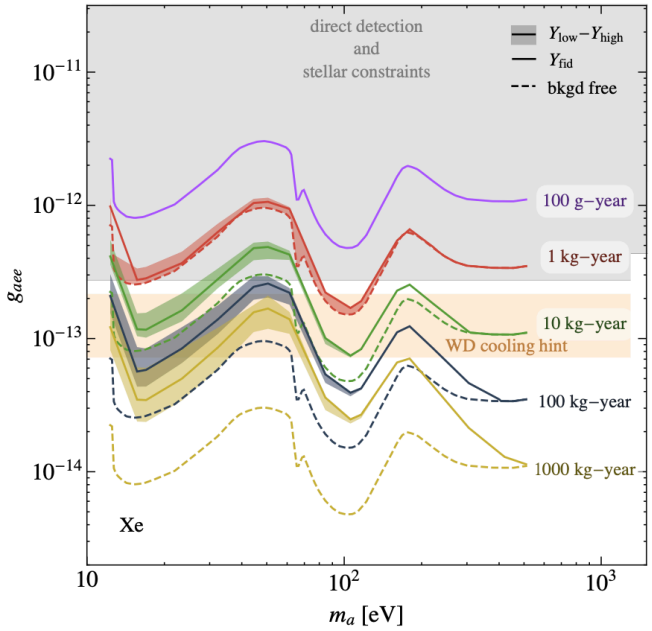


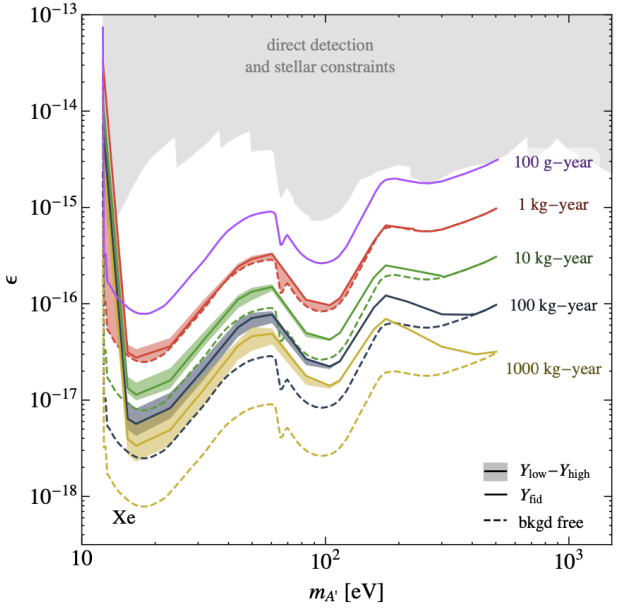


A lot of new physics and parameter space to explore with a ton-scale LXe detector with ultra-low background at single e- threshold!

solid: 2σ discovery sensitivity

dashed: bkg-free 90% C.L. sensitivity





Summary

- **Two-Phase Xenon detectors** made significant progress in the last two decades in searching for heavy WIMP dark matter, and also touching the parameter space for light and low-mass dark matter.

- **A Single-Phase Liquid Xenon detector (ton-scale)** will unleash the full potential of liquid xenon to probe many orders of unexplored parameter space for light and low-mass dark matter in the next decade.