LAr and LXe searches for Sub-GeV Dark Matter

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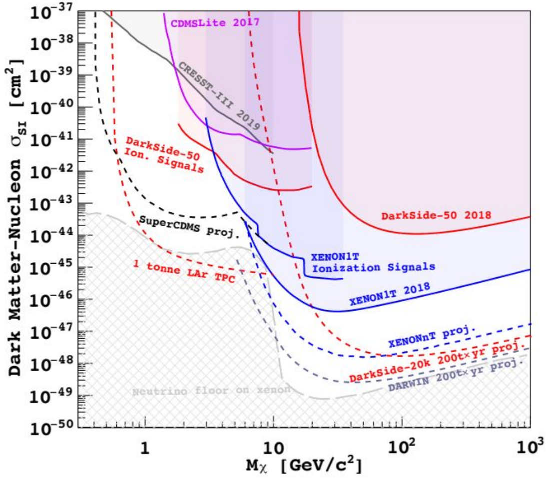
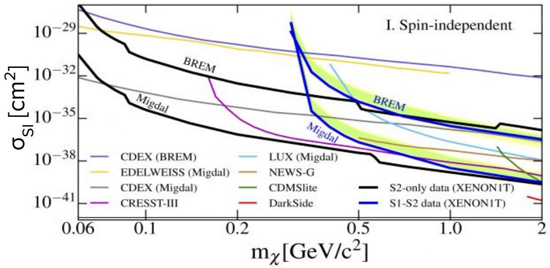
Where we're going (for sub-GeV DM searches)

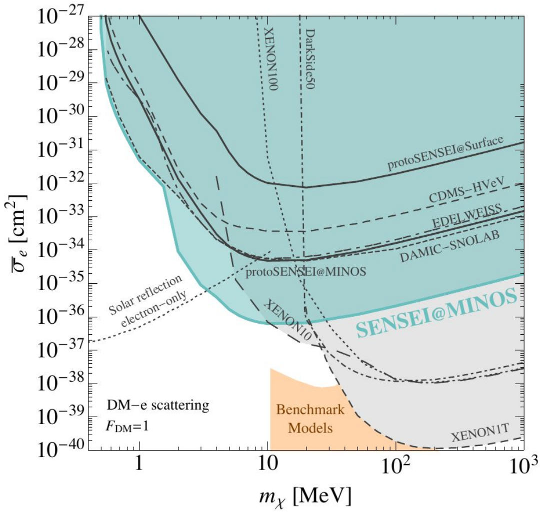
DM scattering on nuclei,
down to ~500 MeV/c^2
to ~50 MeV/c^2 (assuming Migdal)





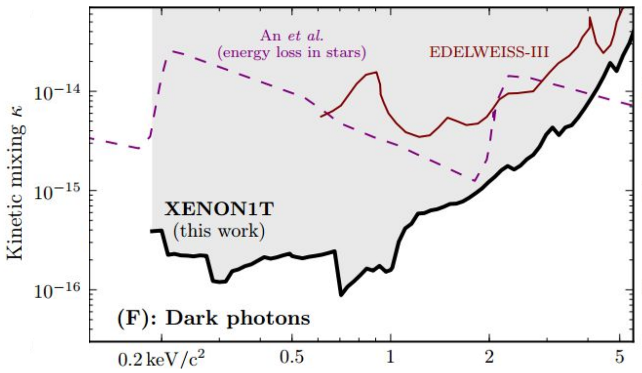
XENON Collaboration. [PRL 123, 241803 (2019)]

DM scattering on electrons,
down to ~10 MeV/c^2



SENSEI Collaboration. [arXiv:2004.11378]

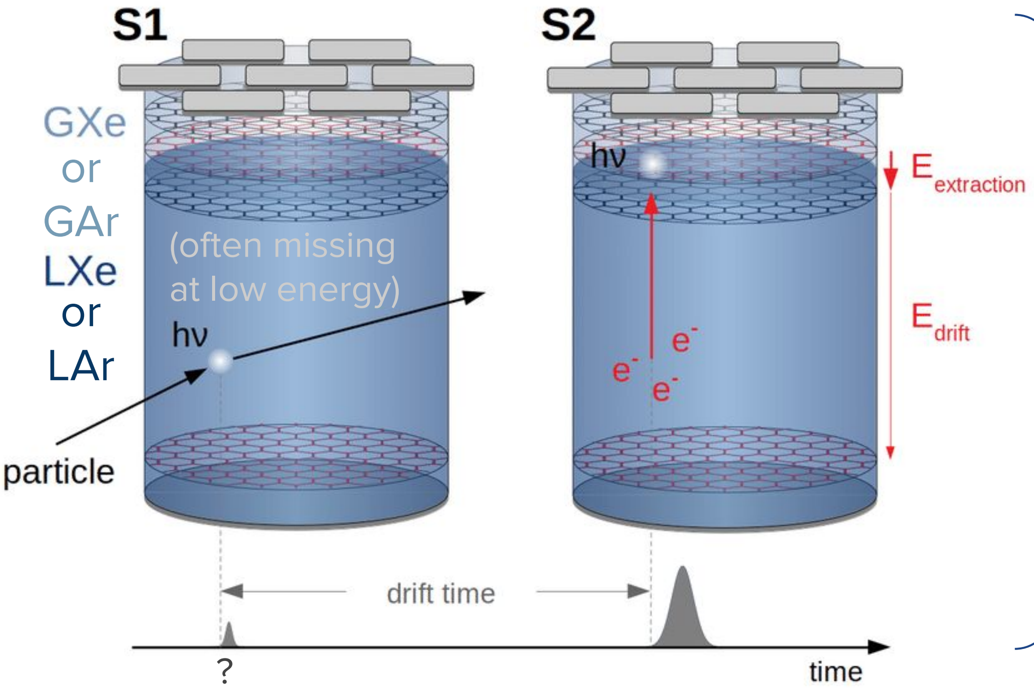
Dark photon and
Axion-like particle absorption,
down to the keV/c^2-scale



XENON Collaboration. [PRL 123, 251801 (2019)]

How we'll get there:
Low-threshold LAr and LXe detectors

TPCs optimized for S2, accepting events w/ small or absent S1



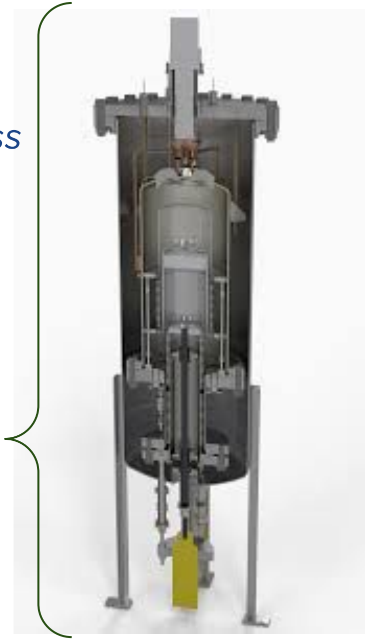
Neat LXe:
- › *e.g. LBECA*

Neat and doped LAr:
- › *e.g. DarkSide-LowMass*

Doped LXe:
- › *e.g.* HydroX

LAr bubble chamber doped with Xe

Scintillating Bubble Chamber (SBC) (rather than S2, detects heat -- similar threshold, but only for NRs)

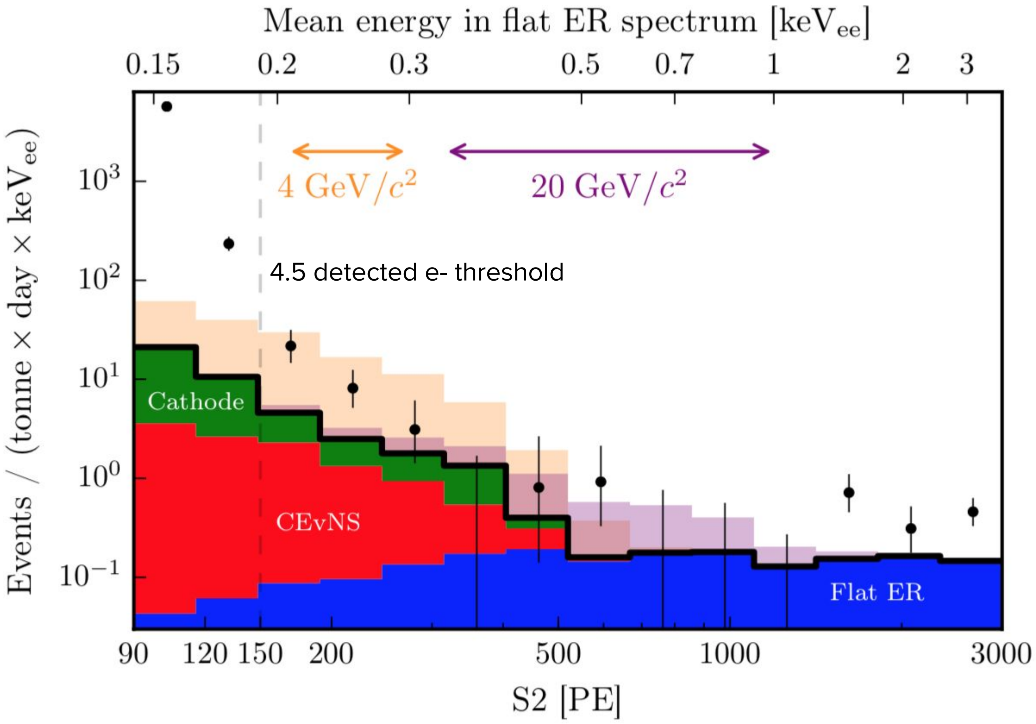


Scintillation photon detection efficiency: ~10--20%, Ionization electron detection efficiency: ~100%

Low-energy ionization background in LXe

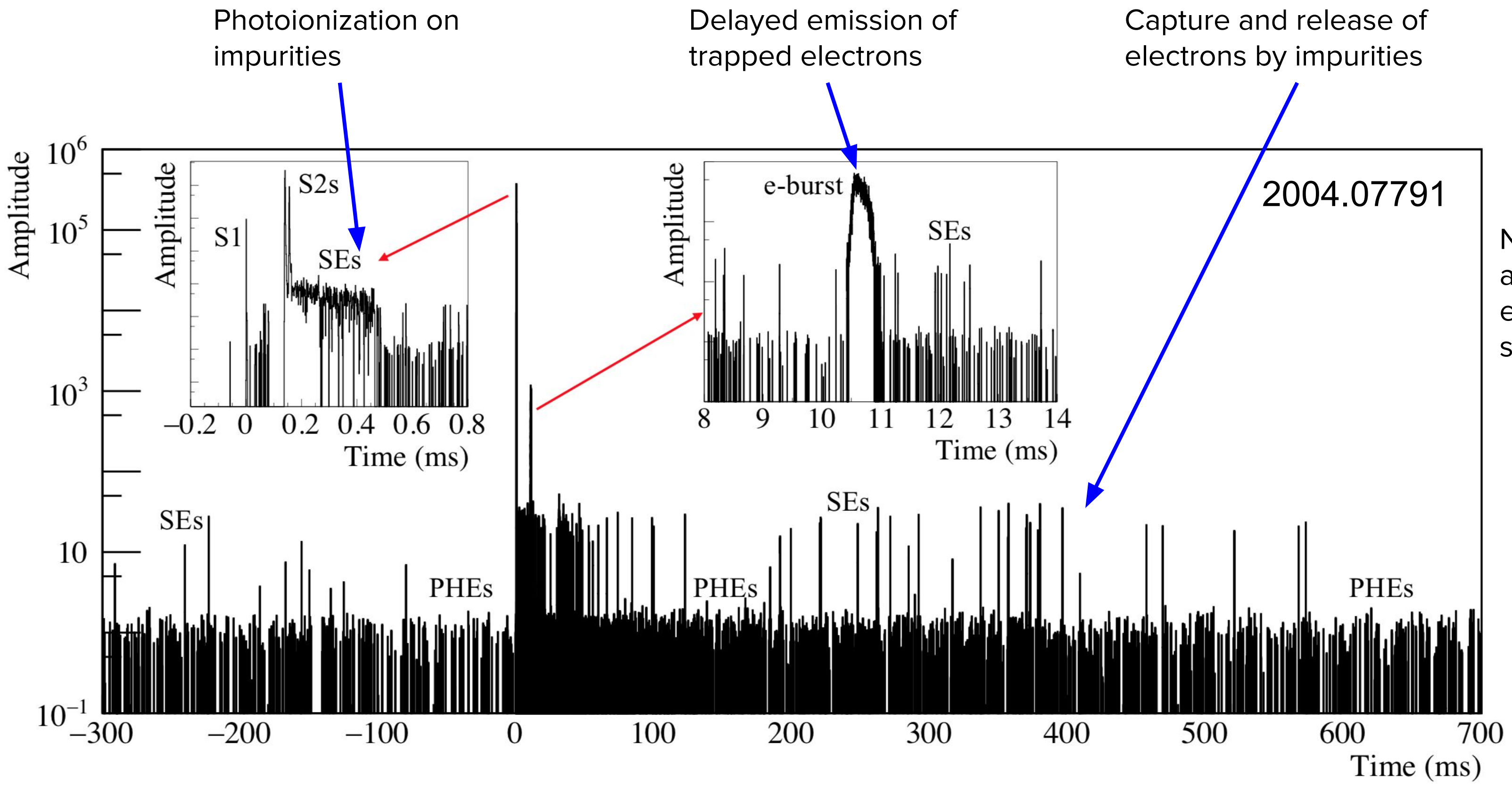
More to be gained in the ionization-only signals in LXe

- Analysis thresholds in such searches have been limited at ~>5 e-
  - Collection efficiency
  - Background limited
- Ionization background near the threshold is orders of magnitude higher than that from radioactivity
  - See next slide



XENON Collaboration. PRL 123, 251801 (2019)

LXe background diagnostics with LUX data



Not shown: single and multi-electron emission from grid surfaces

What is new with LBECA?

LBECA: Low Background Electron Counting Apparatus

- Substantial effort to improve LXe purity (“*plastic-free”/sealed TPC*)
  - Increase electron signal detection efficiency
  - Reduce background due to impurity-captured and released electrons
- High electric field at liquid surface
  - High electron extraction efficiency and low background from trapped electrons
  - High electroluminescence gain and better energy resolution
- Acid passivation and coated grids to reduce spurious electron emission
- Use of SiPMs for improved position sensitivity

Sub-GeV dark matter searches with LAr TPCs

Benefits

Light nucleus: Stronger kinematic couplings for light nucleus-scattering DM

Small atomic size: Very efficiently separated from Rn and Kr with charcoal trap

Lower temperature: Low impurity outgassing rates and highly efficient purification, less SiPM noise

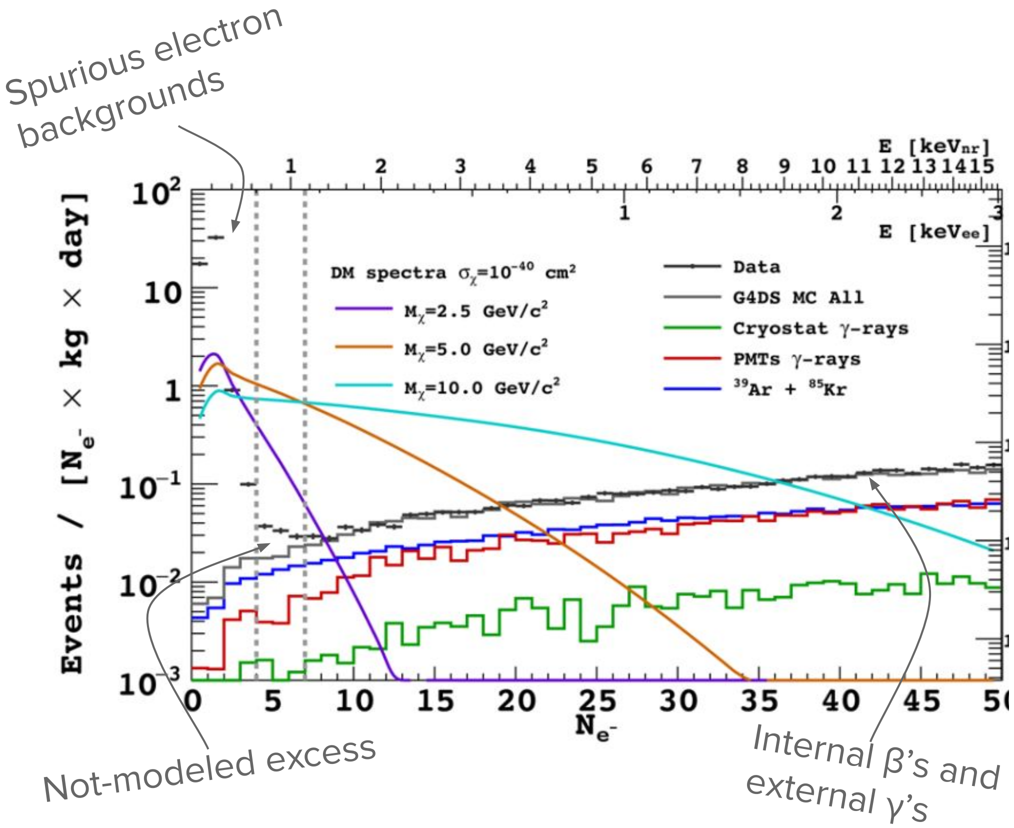
Widely used: Well-established technology (significant complementary work for DS-20k)

Complementary to LXe: Signals and backgrounds vary differently in LAr and LXe; a necessary comparison between detectors can test signals

Challenges

Intrinsic ^{39}Ar: must reduce using UAr (Urania plant) and isotopic distillation (Aria facility)

Higher ionization threshold: Lower ionization yield



DS-50: Design was not optimized to minimize these backgrounds; significantly reducible in dedicated low-threshold detector

DarkSide-50 SE's: Mostly from chemical impurities

OBSERVED spurious electrons (SE)'s:

Photoionization events: VUV scintillation photons ionize cathode, walls, or chem. impurities

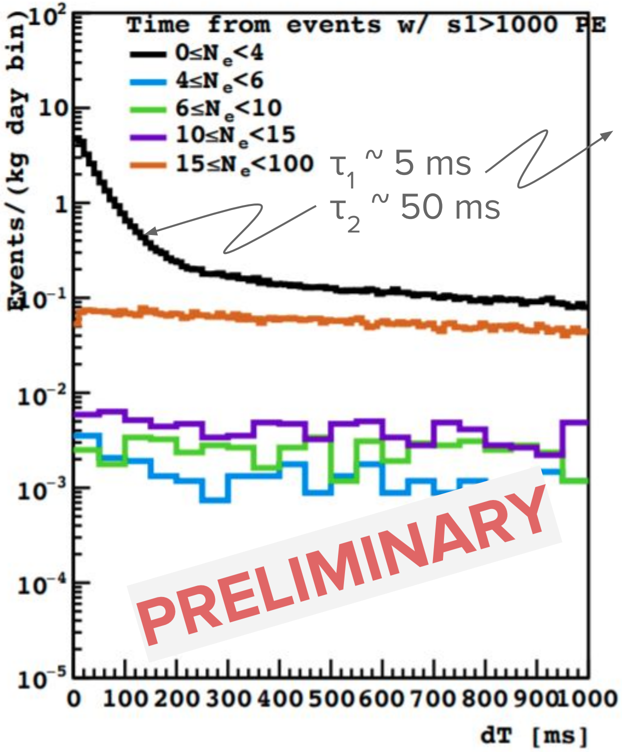
- Easily taggable with known Δt:
  - Cathode: $\Delta t = t_{drift,max}$
  - Others: $\Delta t < t_{drift,max}$
- Subdominant in DS-50 DM search

Chem. impurities: e^- capture + delayed re-emission

- Dominant source of SE bkgd

NOT OBSERVED (can't rule out, but small):

- Grid photo-ionization
- Grid spontaneous electron emission from E-field
- e^- trapping on GAr-LAr interface ("e-bursts")



SE's have same xy as preceding event, with delayed coincidence; not so for higher N_e events

Dominant SE backgrounds from chemical impurities.
LAr cold + small atomic size ➔ better chem. purification than other nobles (cleaner using Aria distillation facility)

Plans for DarkSide-LowMass

Phase I

Goal: Design TPC optimized for S2 signal in neat LAr, based on dedicated and well-defined R&D goals

- Optimize field configuration for S2 signal
- Develop low-γ materials, including SiPMs, design light collectors to decrease channels
- Reduce spurious electron backgrounds via improved chemical purification and optimized electric field configuration
- Measure scintillation and ionization response of LAr to low energy electronic and nuclear recoils

Phase II

Goal: Dope LAr (e.g. Xe, allene, He). Benefits of dopant with...

... low ionization energy: more efficient ionization
➔ lower energy threshold

... low-A nucleus: stronger kinematic coupling to light DM

... odd-A nucleus: sensitivity to spin-dependent couplings

Testing signals: Spurious electron, electron recoil, and nuclear recoil signals will all change differently when dopant is added
➔ allows for testing potential signals

R&D needs: Clean, stable doping techniques and effects of doping on signal to be further studied -- synergy w/ HydroX, SBC

Significant R&D required to develop doping and purification techniques, & measure effects on S1 and S2

R&D requirements for LAr and LXe

BACKGROUND REDUCTION: need factor of ~10^3 reduction before solar neutrinos to dominate background

- **External γ-rays:** radiopure low-γ material development (incl. SiPM substrates and electronics); decreased channel count; LAr-based γ-veto
- **Internal β-decays:** purification improvements (incl. Rn and Kr removal); ^{39}Ar removal for LAr (UAr from Urania extraction plant, chemical and isotopic purification with Aria distillation column)
- **Spurious electron backgrounds:** (from chemical impurities, ionization of detector components, and electric field effects) need to better understand and develop mitigation techniques

LOW ENERGY CALIBRATION TECHNIQUES: need to understand noble liquid response near quantum limit

- ***Ex-situ*:** measure low-energy electronic & nuclear recoil responses in different configurations
- ***In-situ*:** develop low-energy detector calibration strategies

ENHANCING SIGNAL YIELD

- **Electric field:** optimize field configuration to enhance ionization yield, suppress SE backgrounds
- **Migdal effect:** test the Migdal effect to validate its use for low-energy nuclear recoils
- **Doping:** load LAr/LXe with dopants with favorable kinematic properties and/or lower ionization yields; measure effects and develop clean and stable doping techniques

Conclusions

- R&D is being performed to develop low-threshold LAr/LXe detectors with energies set by the scale of the atomic ionization energies, involves
  - reducing β/γ and SE backgrounds -- chemical purity of medium highly important!
  - improving low energy calibration -- for nuclear and electronic recoils
  - enhancing signal yield -- may be able to further improve with doping
- Ultimately, sensitivities are expected to all be background limited
  - Several different complementary efforts are underway
  - Comparisons between detectors will ultimately be needed to identify signals over background
- Detectors are expected to probe a wide-range of DM models below 10 GeV/c^2, including a rich array below 1 GeV/c^2
- Potential for promising neutrino studies via CEvNS, as well

END

Case for Ar/Xe in detecting Sub-GeV DM

- Ar/Xe TPCs are commonly perceived as GeV-TeV DM detectors
- Ionization-only DM searches in Ar/Xe TPCs dominate $m_\chi > 10$ MeV/c^2 by ~$\times$10
- There is significant potential to further improve searches with Ar/Xe detectors
- Relevant properties:
  - Energy threshold set by ionization energy scale: O(10 eV)
  - Readily purified to high degrees, both chemically and radiologically
  - Established technology, scalable to large fiducial masses