CAP Congress 2026

AURORA: R&D for Low-Mass Dark Matter Detection in Argon

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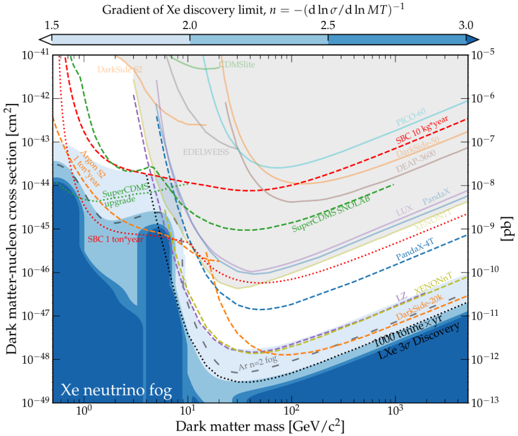
Dark Matter Search Has Two Frontiers

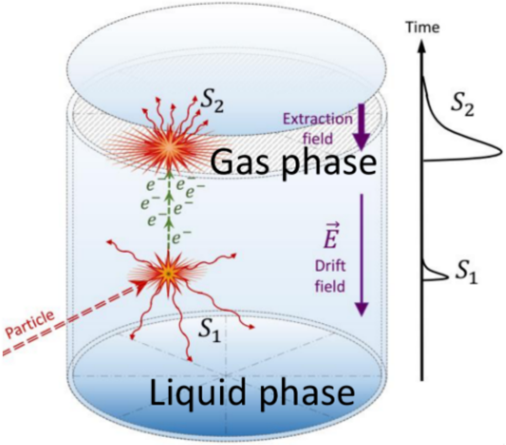


arXiv:2203.08084, Fig. 1.

- High-mass searches push exposure toward neutrino backgrounds.
- Low-mass searches push detector thresholds downward.

Message: The question is not only how much argon, but how little energy argon can measure reliably.

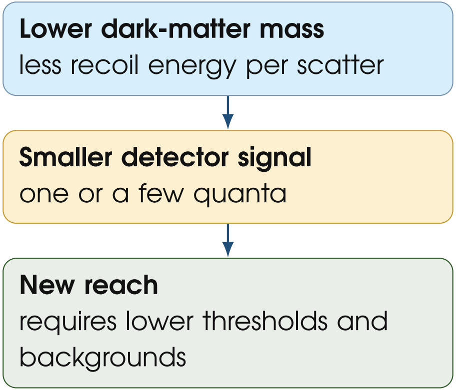
Signal Formation in a Dual-Phase Noble Liquid TPC



Source: deap3600.ca

- Energy deposit produces **excitation** and **ionization**
- **S1**: Prompt scintillation, energy, PSD
- **S2**: Delayed electroluminescence from extracted electrons in gas, position, n scatters
- $\Delta t \rightarrow z$
- S1 + S2 : energy and position reconstruction and background rejection

Why Low-Mass Searches Move to S2-Only



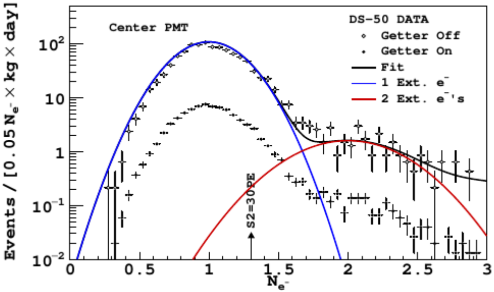
Lower dark-matter mass
less recoil energy per scatter

Smaller detector signal
one or a few quanta

New reach
requires lower thresholds and backgrounds

- Sub-GeV dark matter transfers very little energy to nuclei or electrons
- S1 signal can fall below the detection threshold
- S2 signal still exists as even a single extracted electron can produce many photons in the gas
- **Challenges**:
  - No PSD $\rightarrow$ weaker ER rejection
  - Cannot measure Δt $\rightarrow$ cannot fiducialize in z
  - Limited timing resolution
  - Spurious electron backgrounds

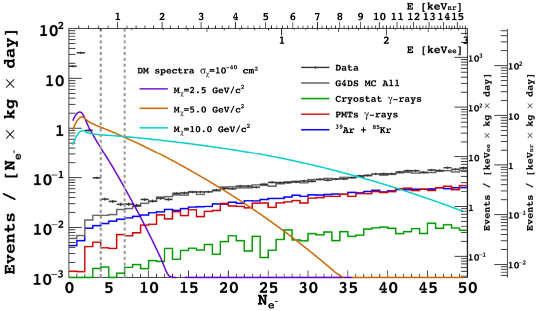
DarkSide-50: Lessons From the S2-Only Analysis



Phys. Rev. Lett. 121, 081307 (2018), Fig. 2.

- DarkSide-50 demonstrated a low-mass argon search using S2-only analysis
- Impurities caused delayed single electrons which allowed distinction between single- and double-electron populations

How Do We Lower the Threshold?

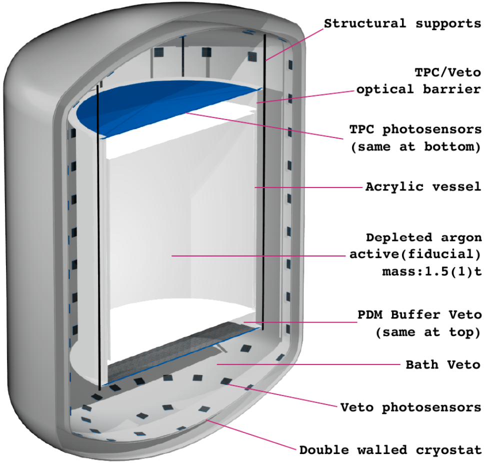


Phys. Rev. Lett. 121, 081307 (2018), Fig. 7.

- Threshold is set by
  - Electromagnetic backgrounds
  - Spurious electrons
  - Medium’s ionization energy
  - Deposited energy partitioning between scintillation, ionization, and heat

Takeaway: The analysis proved that few-electron argon data are usable, while showing that delayed/spurious electrons and response calibration set the practical threshold.

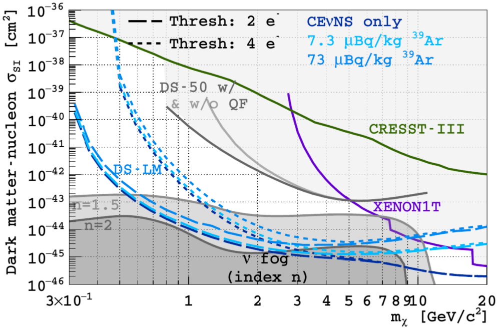
DarkSide-LowMass: Optimized For S2-Only Analyses



Phys. Rev. D 107, 112006 (2023), Fig. 1.

- DS-LowMass: A proposed detector and sensitivity study
- DS-LowMass strategy
  - Enhance few-electron S2 response
    Higher EL gain + uniform extraction + cleaner Ar
  - Reduce few electron backgrounds
    Depleted Ar + radiopure materials + γ vetoes + fewer spurious electrons

DarkSide-LowMass: Optimized For S2-Only Analyses

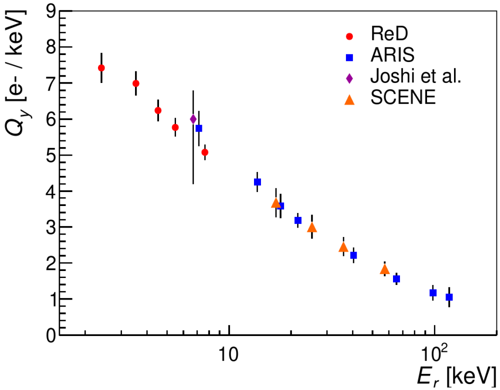


Phys. Rev. D 107, 112006 (2023), Fig. 9.

- DS-LowMass: A proposed detector and sensitivity study
- DS-LowMass strategy
  - Enhance few-electron S2 response
    Higher EL gain + uniform extraction + cleaner Ar
  - Reduce few electron backgrounds
    Depleted Ar + radiopure materials + γ vetoes + fewer spurious electrons

Takeaway: The 2023 study turns the DS-50 lesson into requirements for **ionization yield**, **gain**, backgrounds, and single-electron control.

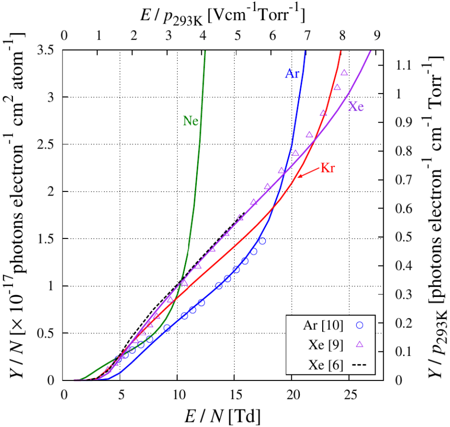
Ionization Yield



Eur. Phys. J. C 86, 220 (2026), Fig. 9.

- Ionization yield Q_y: electrons produced per deposited energy
- Better ionization yield gives more S2 light for the same energy deposit
- Careful measurements are necessary to assess effect of methods to improve ionization yield

Gas Electroluminescence (gain)



Phys. Lett. B 703, 217 (2011), Fig. 7.

- Extracted electrons produce S2 light while crossing the gas
- The gas properties and electric field set the photon yield per electron

Doped Argon

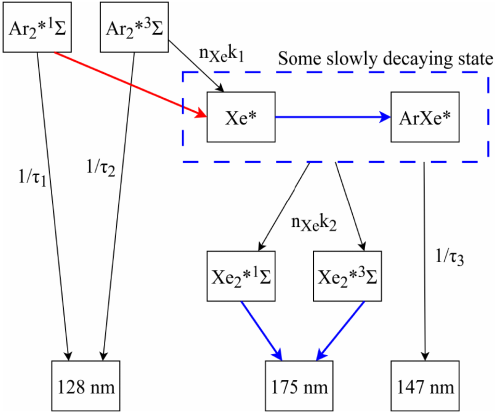
Xenon

Xenon's lower excitation and ionization energies can produce more photons or electrons for the same deposited energy, and its longer-wavelength light can give a larger detected signal.

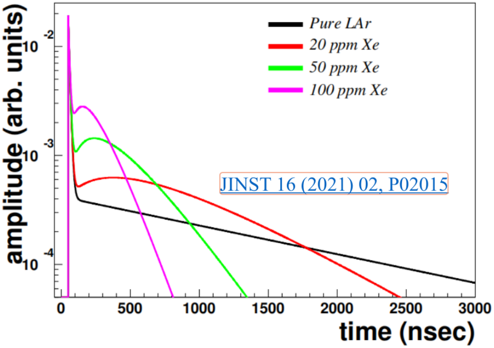
Hydrogenous Organic Dopants

Molecules such as TMA, TEA, TMG, and allene contain H and have low ionization potentials. They are candidates for photoionization or Penning-like charge production.

Xenon Doping: S1/PSD Response

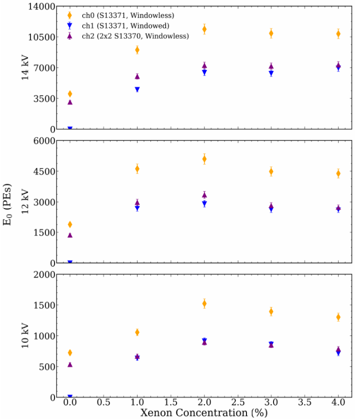


PRD 113, 032016 (2026), Fig. 9.



JINST 16 (2021) 02, P02015

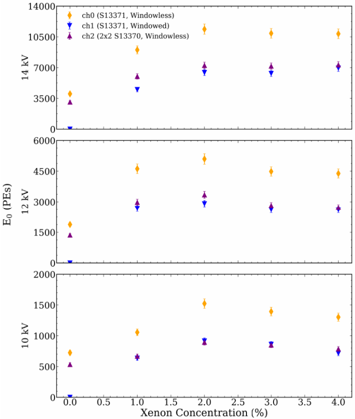
Xenon Doping: S2 Response



PRD 113, 032016 (2026), Fig. 5.

- Phys. Lett. A 49(5), 1974 reported a $\sim 13\%$ ionisation yield increase in Xe-doped LAr

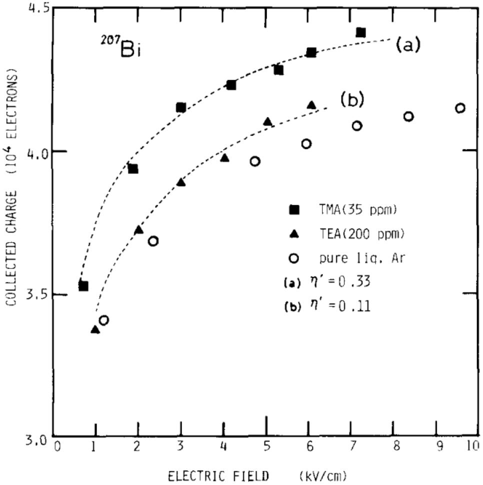
Xenon Doping: S2 Response



PRD 113, 032016 (2026), Fig. 5.

- Phys. Lett. A 49(5), 1974 reported a $\sim 13\%$ ionisation yield increase in Xe-doped LAr
- CHILLAX measured a larger detected S2 signal in xenon-doped argon
- About 2% Xe in liquid argon produced only ~ 34 ppm Xe in the gas
- That small gas concentration still gave roughly a $2.5\times$ S2 enhancement
- Gas-phase Xe drives EL gain; liquid-phase Xe may affect Q_y via Penning-like ionization.

Hydrogenous Photoionizing Dopants



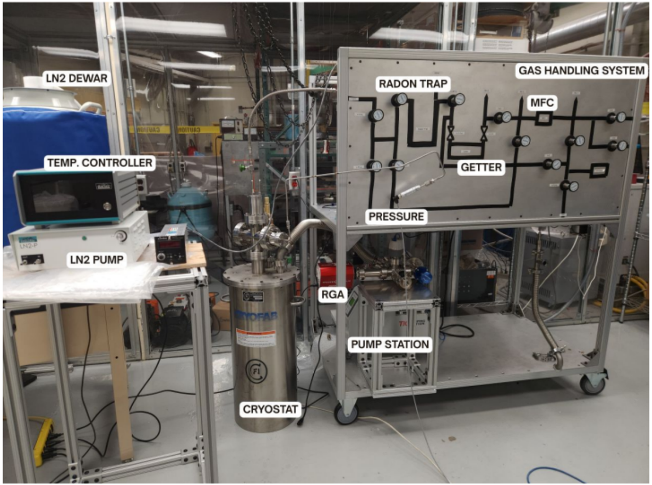
Nucl. Instr. Meth. A 245 (1986)

- Candidate dopants include TMA, TEA, TMG, and allene-like additives
- **Charge-conversion handle:** Ar VUV light can photoionize the dopant, producing extra electrons for S2
- **Light-target handle:** H nuclei in the dopant provide lighter scattering targets, improving kinematic reach for MeV-scale DM
- Main challenges: freezing, solubility, attachment, purity, and backgrounds

AURORA: R&D Program at Queen’s

- **A**rgon **U**ltra **R**adiopure **O**bservatory for **R**are **E**vents **D**ata **A**nalyses
- Using doped argon to detect sub-GeV DM and MeV-scale neutrinos
- New design with more radiopure materials for the inner vessel and TPC
- Pixelated SiPMs as ideal photosensors
- Radon mitigation with zeolite filtration
- Single-e^- backgrounds: measure in AURORA, then study source ID and rejection in a low-background environment.

The Scintillation Characterization And Liquid Argon Research Test Bed at Queen's (SCALAR)



Digital Silicon-Photomultiplier

Conventional Analog Silicon-Photomultiplier Readout

Many microcells are summed into an analog waveform. The waveform is compact, but photon timing, local saturation, correlated noise, and channel-level effects are harder to separate.

Sherbrooke 3D Digital Silicon-Photomultiplier Readout

Photon detections are digitized closer to the sensor, preserving timing and pixel-level information that can be used for noise rejection and low-light triggering.

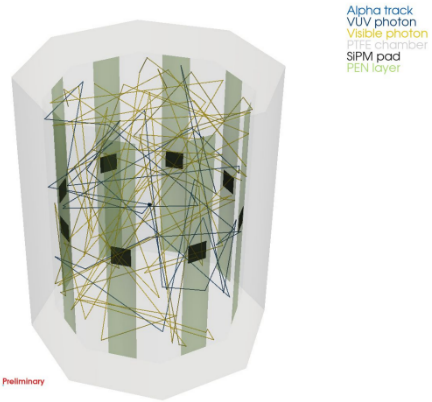
- *See talk by Anantha Padmanabhan, Tuesday*

AURORA Prototype Hardware and Materials Validation

Queen's AURORA single-phase prototype hardware, 2026.

- Initial square PTFE-wall prototype for cryogenic validation
- Test material stack: PTFE + PCB/SiPM + acrylic + PEN
- Main goal: verify fit, contraction, light leaks and optical response

AURORA Prototype Hardware and Materials Validation



Simulation snapshot for single-phase chamber.

- Initial square PTFE-wall prototype for cryogenic validation
- Test material stack: PTFE + PCB/SiPM + acrylic + PEN
- Main goal: verify fit, contraction, light leaks and optical response
- Next design iteration: octogonal geometry, closer to the final TPC design

Simulation and Background Requirements

Establish Cryogenics
SCALAR argon operation, then xenon addition

Build AURORA Response
single-phase optics, then dual-phase S2 response

Project Requirements
threshold, dopant concentration, exposure, radiopurity

- Low-radon, radiopure materials and clean surfaces
- Adsorbents compatible with pure/doped argon
- Purification built into the doped-argon design
- Single-e^- backgrounds: measure in AURORA, then study rejection in low-background conditions

Outlook

SCALAR
cryogenic commissioning

AURORA Prototype
single-phase optics

Dopants
xenon and organics

AURORA TPC
dual-phase S2 design

- Commission SCALAR as the cryogenic and readout test bed.
- Use AURORA prototype data for single-phase optical response.
- Quantify xenon partitioning and hydrogenous dopant behavior.
- Measure single-electron and material-background limits.

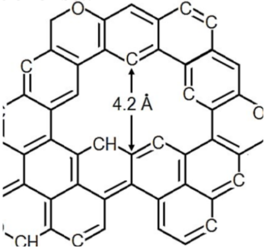
Message: A measured response model is the next milestone for AURORA

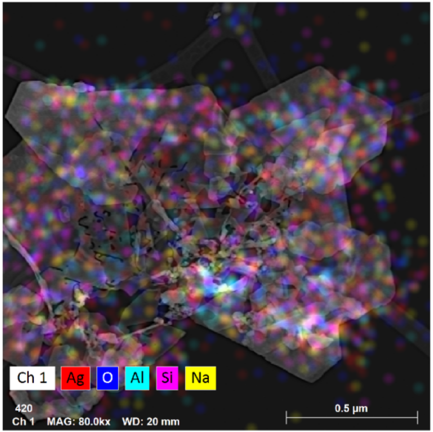
Backup Slides

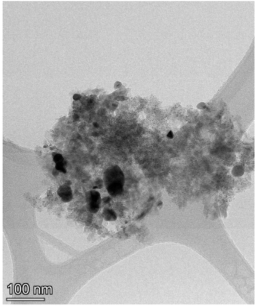
Atom	Atomic Diameter [A]
Ar	3.8
Rn	4.16
Xe	4.10

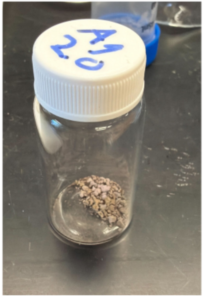
In-house developed Ag-Zeolites tested at SNOLAB
Next in line, samples from Extraordinary Adsorbents Inc.

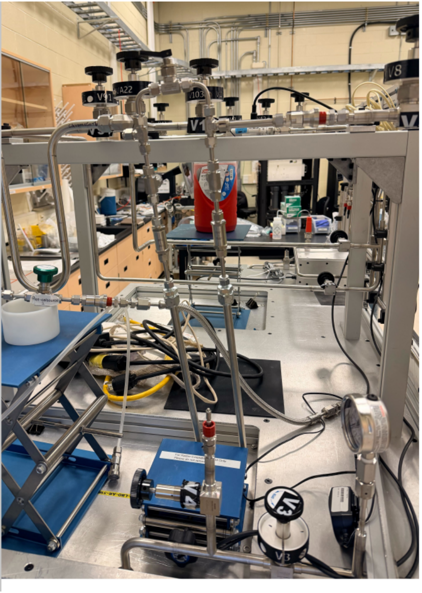
R. Curtis, S. Mohanty, M.Lai, N. Fatemighomi, MacNeil, P. Duchense..







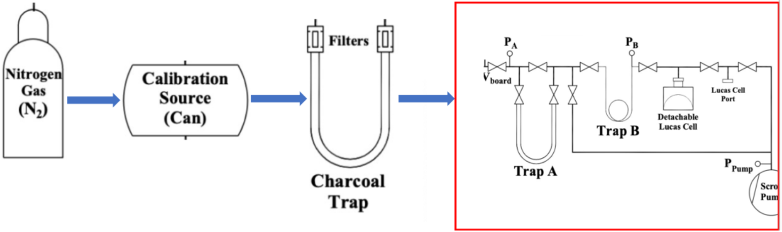




- N_2 flow through the source introduces radon atoms to trap
- Zeolite cooled with LN_2–alcohol mix to trap radon
- Radon released from charcoal trap by heating to 150 °C
- Released radon were extracted using the radon board

Trap Efficiency Test Set-up

Slide from N. Fatemighomi, SNOLAB



SCALAR and AURORA Serve Different Roles

SCALAR: Cryogenic Test Bed

SCALAR is the local cryogenic platform for controlled liquid-argon operation, purification, slow control, and photosensor readout.

- Current medium: argon.
- Possible extension: xenon-doped argon operation.
- Purpose: establish stable cryogenic and readout conditions before TPC measurements.

AURORA: Time-Projection Chamber

AURORA is the detector program: a time-projection chamber now being developed in a single-phase prototype, with a planned dual-phase design focused on S2.

- Current prototype: optical materials and sensor response.
- Planned detector: dual-phase doped-argon TPC.
- Physics focus: few-electron S2 response for low-mass searches.

Queen's SCALAR and AURORA development program, 2026.