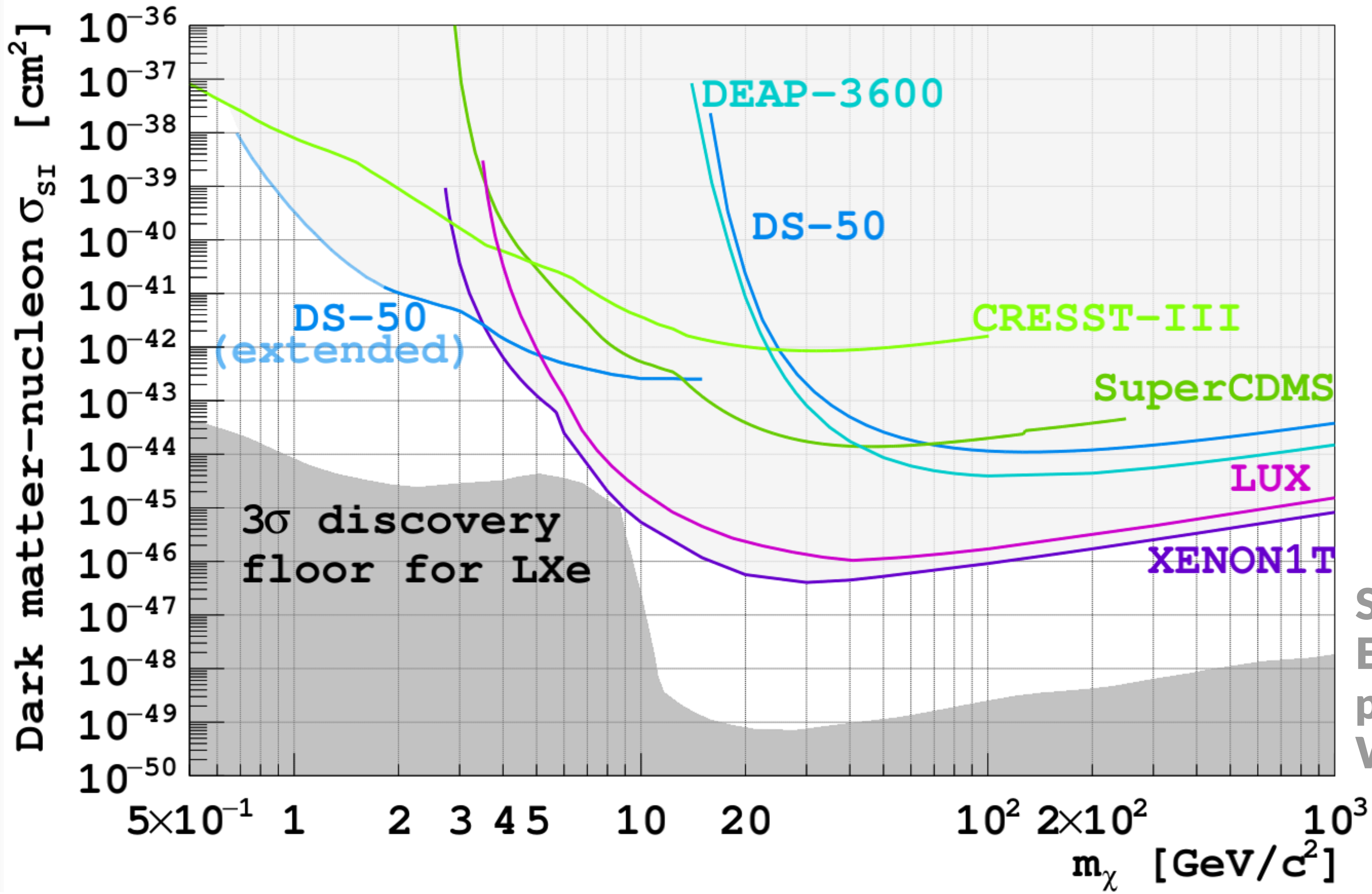
Direct search for low-mass dark matter with DarkSide-LowMass

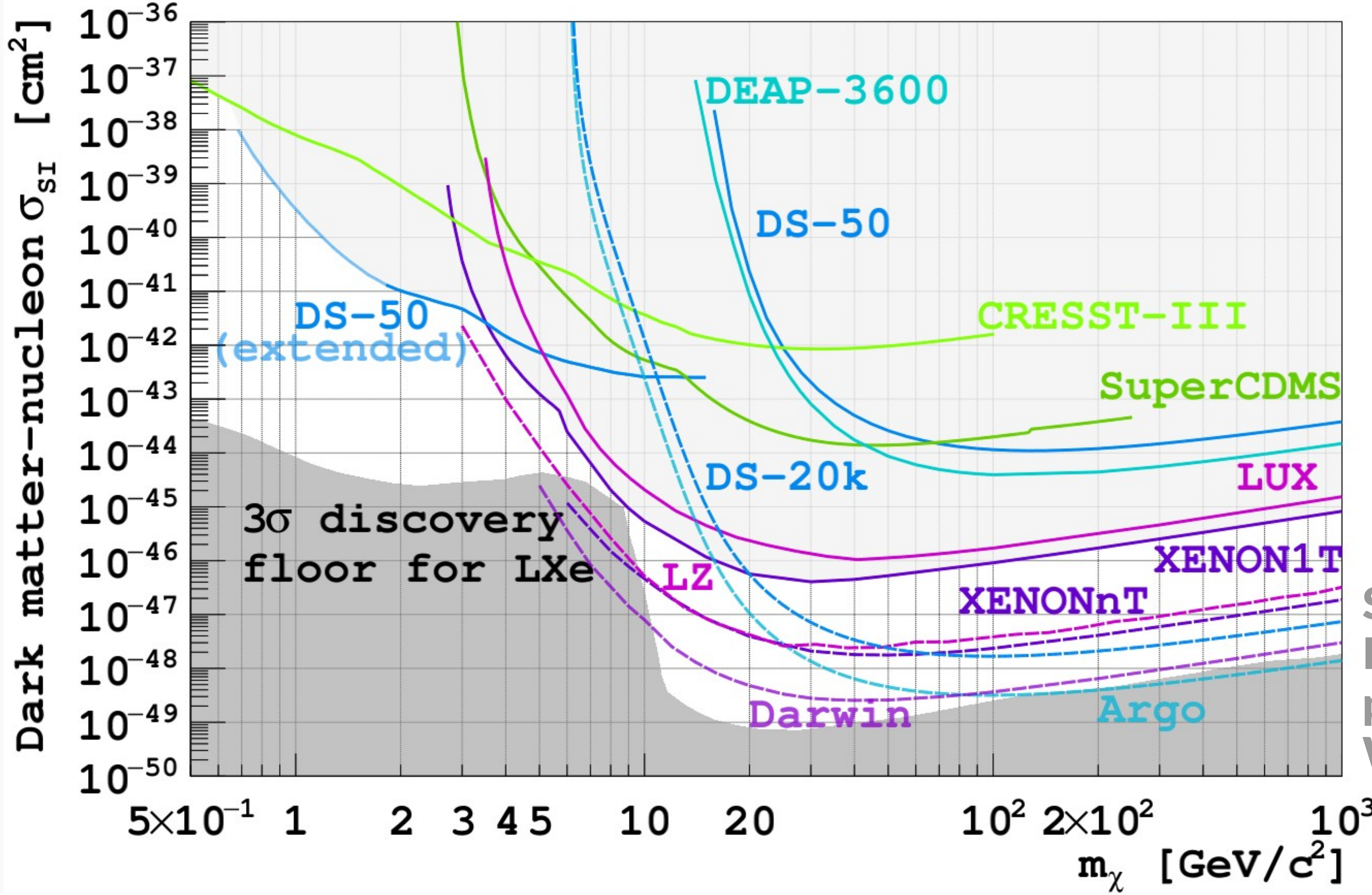
Shawn Westerdale - INFN Cagliari
(on behalf of the Global Argon Dark Matter Collaboration)
TAUP2021 Valencia/Online
August 2021

Current experiments have paved the way by excluding much of the detectable WIMP parameter space



See talk by E. Pantic on DS-20k plans for high-mass WIMP search

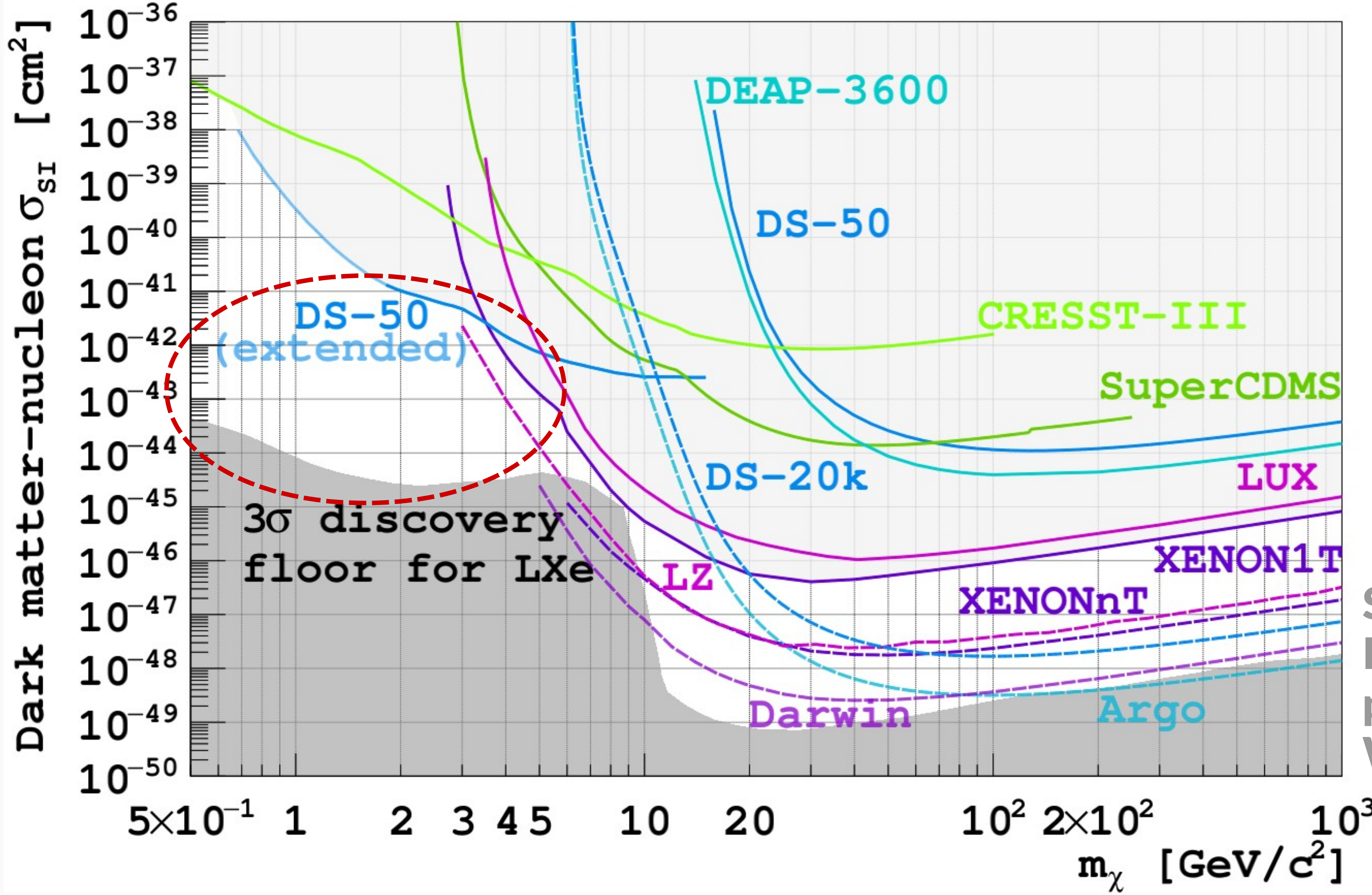
Future high-mass detectors will probe the accessible parameter space above the atmospheric neutrino floor



DS-20k: 200 t·yr
Argo: 3000 t·yr
XENONnT: 20 t·yr
LZ: 2.7 live-yrs
DARWIN: 200 t·yr

See talk by E. Pantic on DS-20k plans for high-mass WIMP search

Lower masses require sensitivity to ~ionization energy scales, which requires dedicated studies

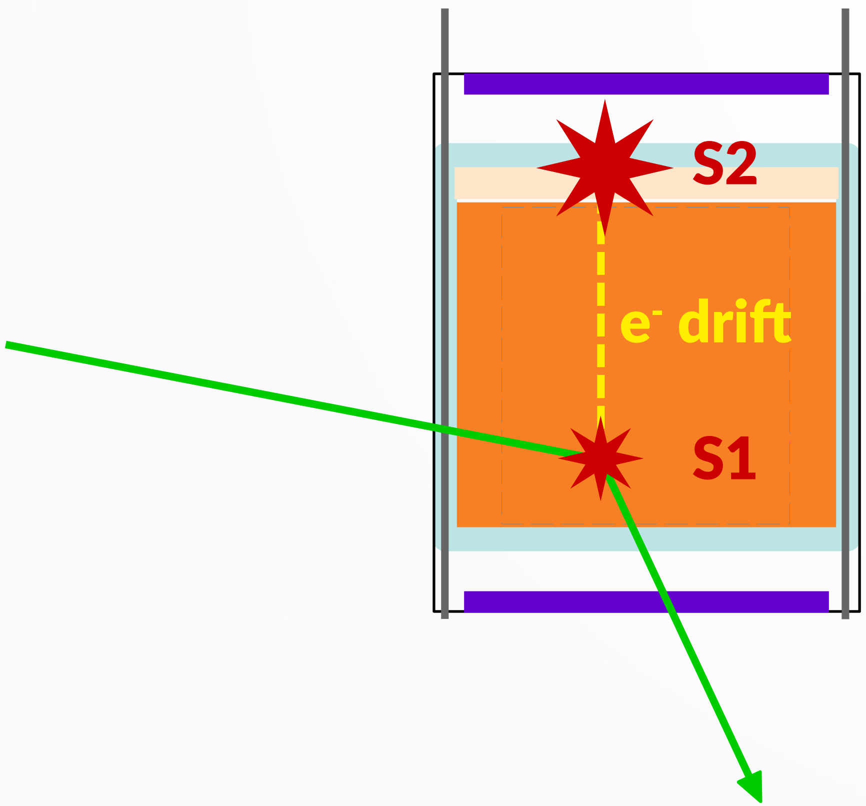


DS-20k: 200 t·yr
Argo: 3000 t·yr
XENONnT: 20 t·yr
LZ: 2.7 live-yrs
DARWIN: 200 t·yr

See talk by E. Pantic on DS-20k plans for high-mass WIMP search

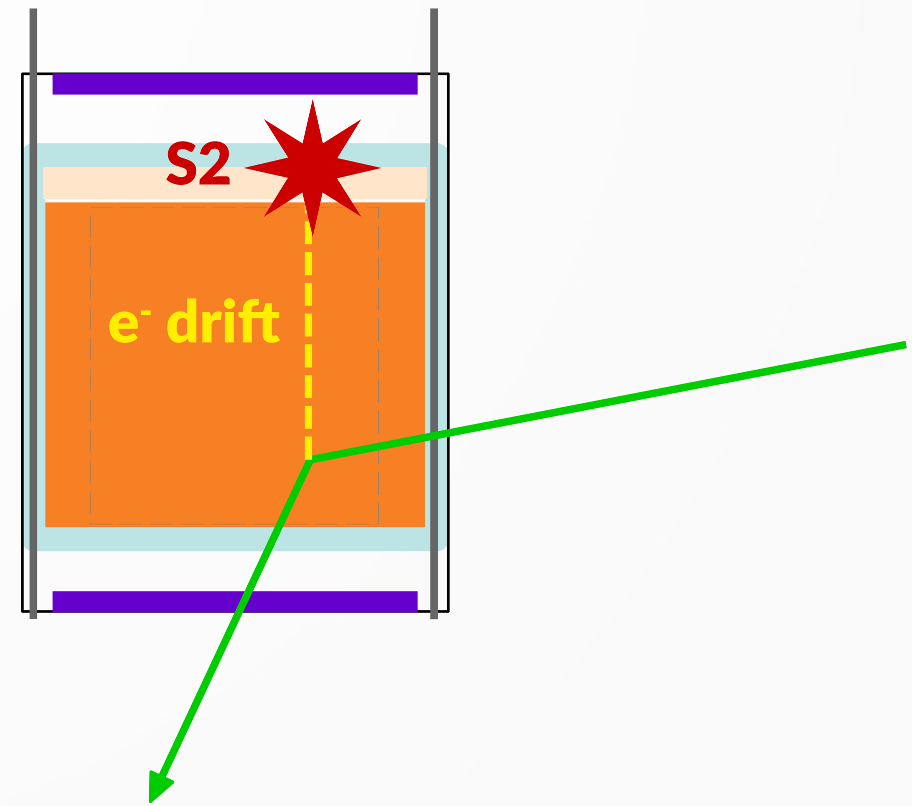
DarkSide-50 demonstrated the use of dual-phase LAr TPCs for WIMP searches and the power of S2-only channel in LAr

High energy event



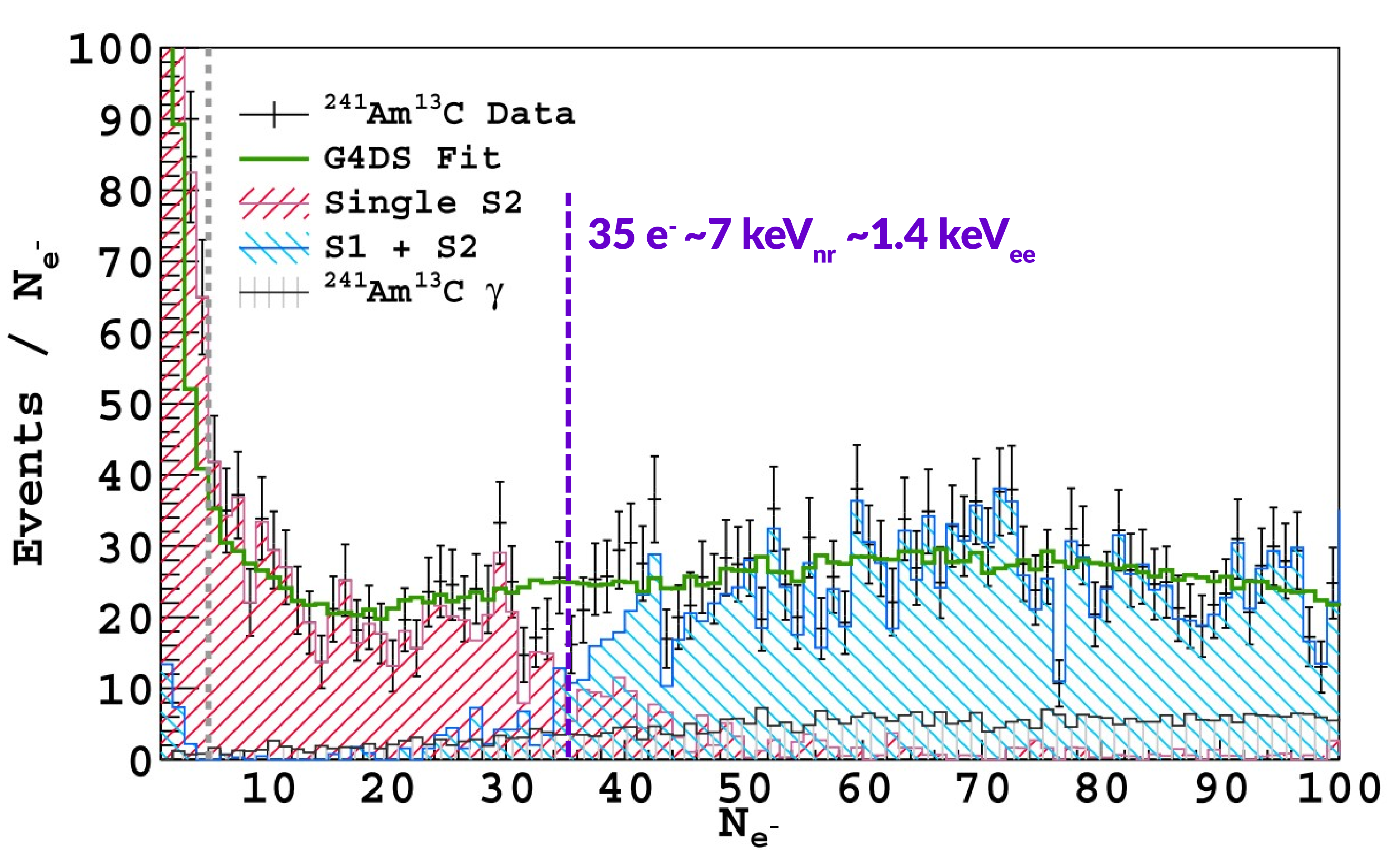
Energy dep.→scintillation photons & ionization e^-
~20% of photons detected → S1
e^-'s drift to GAr, amplified, ~100% detected→S2

Low energy event



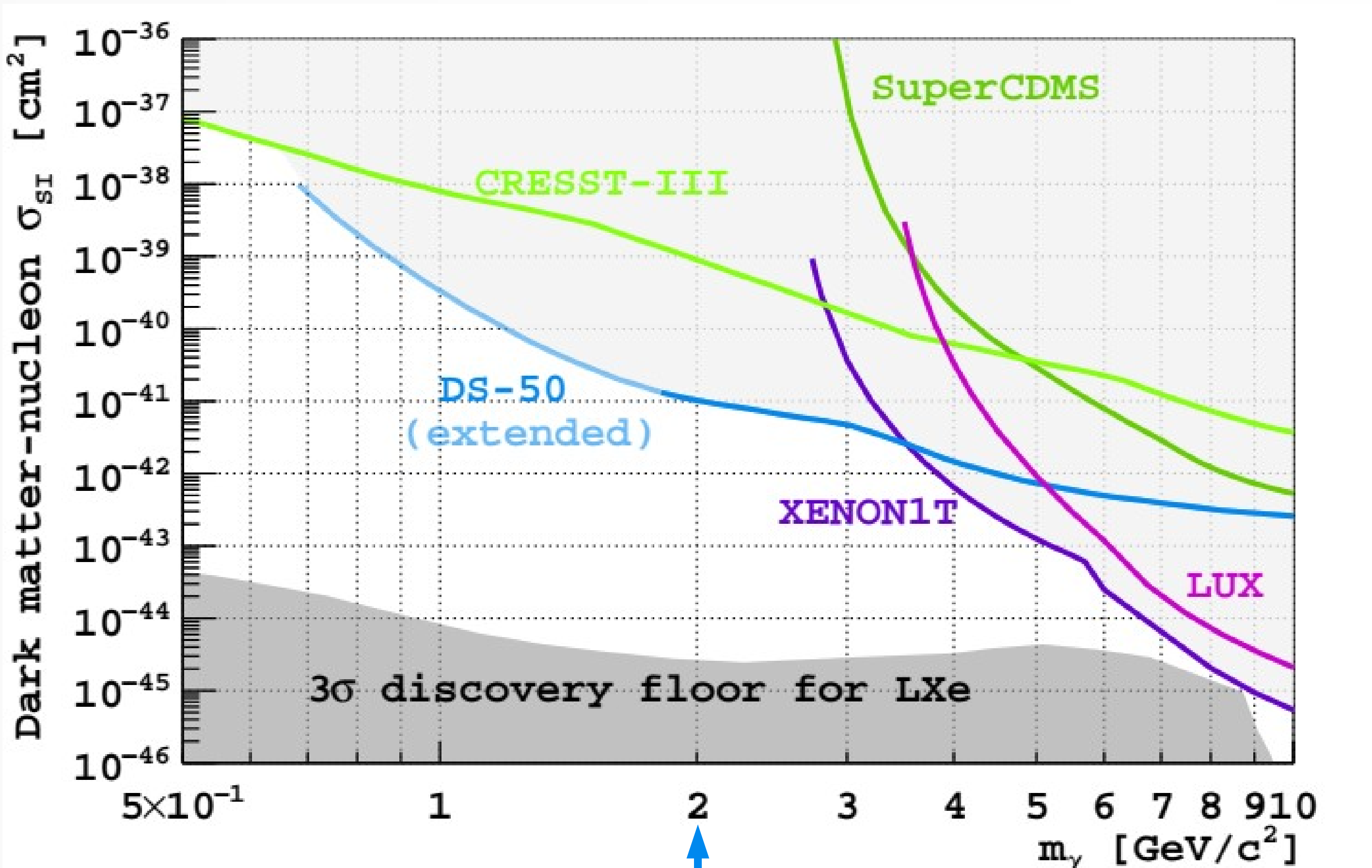
Amplification in GAr lets us detect e^-'s with high efficiency above photoelectronic noise
→Lower energy threshold
No pulse shape discrimination
No vertical position reconstruction

Sensitivity of S2-only channel to low-energy nuclear recoils demonstrated in DS-50 neutron calibration data



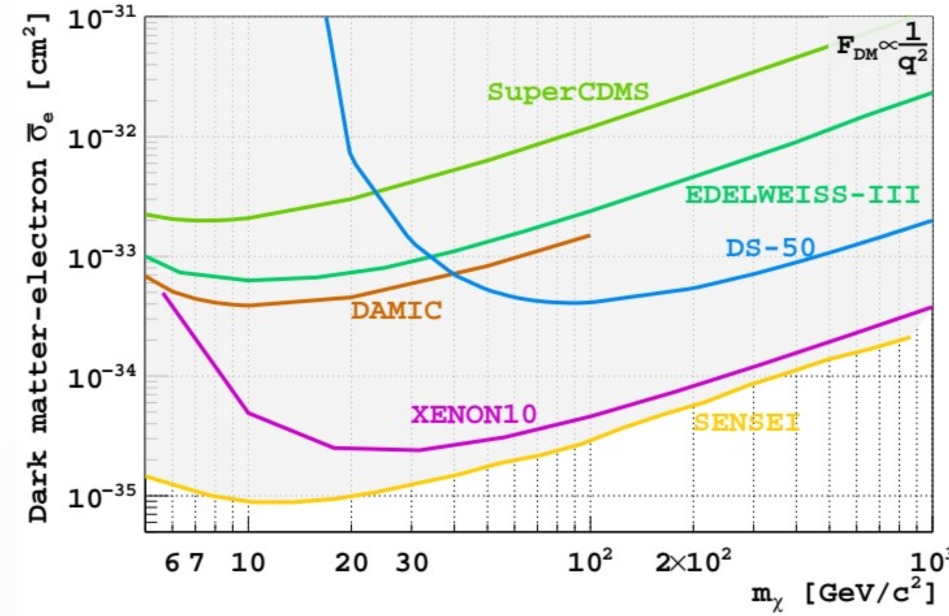
DarkSide Collaboration. "Low-Mass Dark Matter Search with the DarkSide-50 Experiment" Phys. Rev. Lett. 121 081307 (2018)

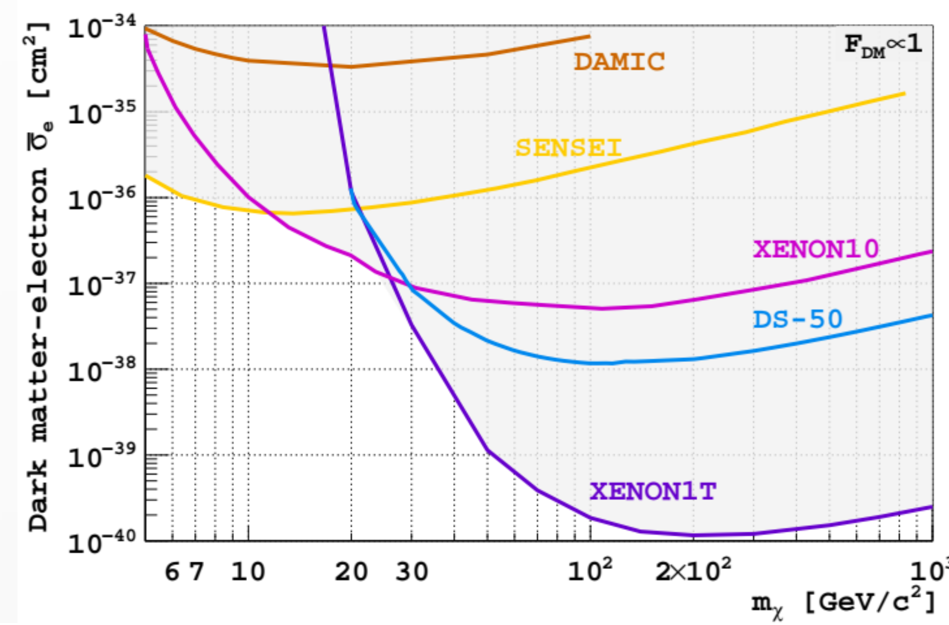
DarkSide-50 demonstrated the success of this technique for low-mass DM interactions with nucleons and electrons



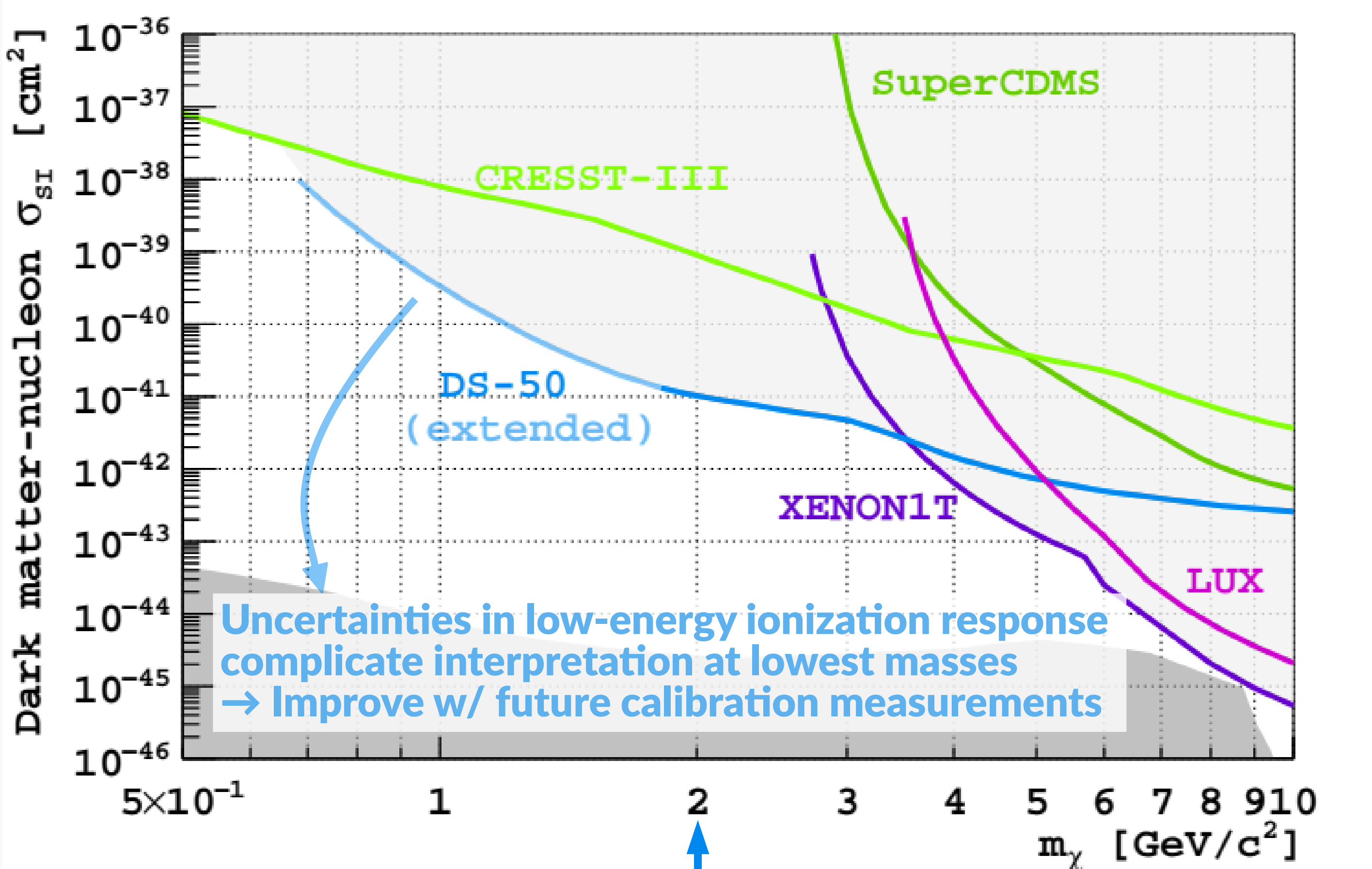
DarkSide Collaboration. "Low-Mass Dark Matter Search with the DarkSide-50 Experiment" Phys. Rev. Lett. 121 081307 (2018)

DarkSide Collaboration. "Constraints on Sub-GeV Dark-Matter-Electron Scattering from the DarkSide-50 Experiment". Phys. Rev. Lett. 121 111303 (2018)



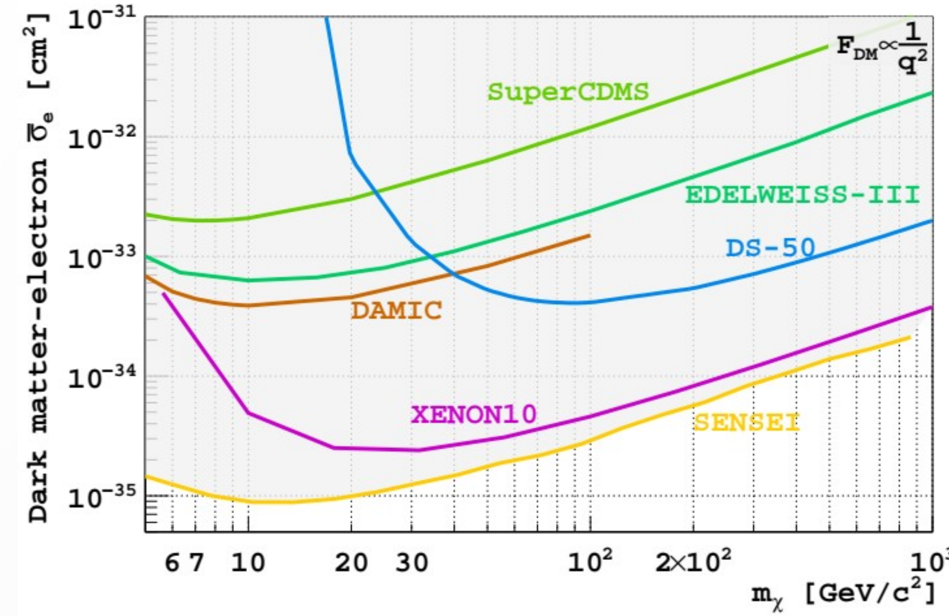


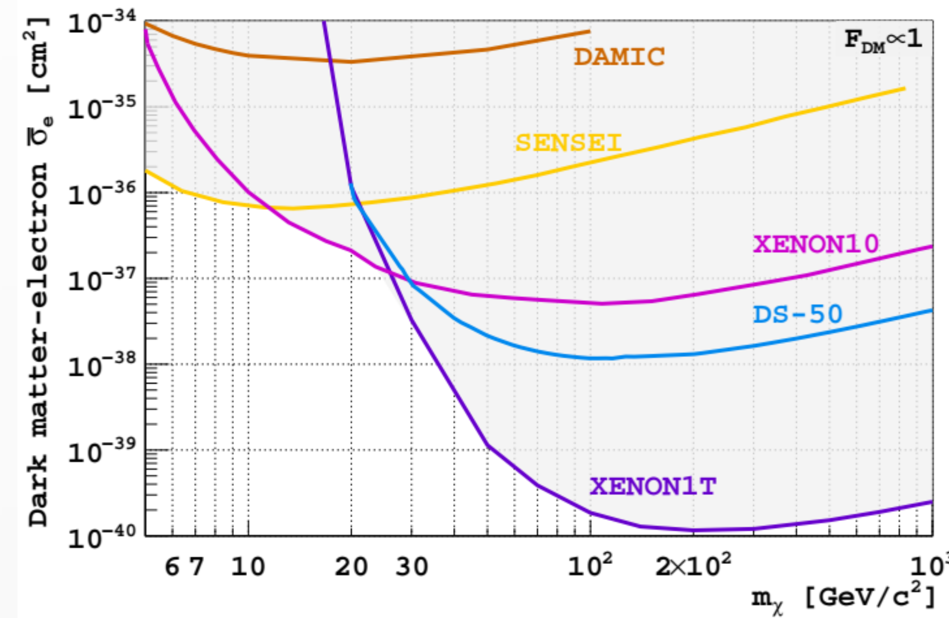
DarkSide-50 demonstrated the success of this technique for low-mass DM interactions with nucleons and electrons



DarkSide Collaboration. "Low-Mass Dark Matter Search with the DarkSide-50 Experiment" Phys. Rev. Lett. 121 081307 (2018)

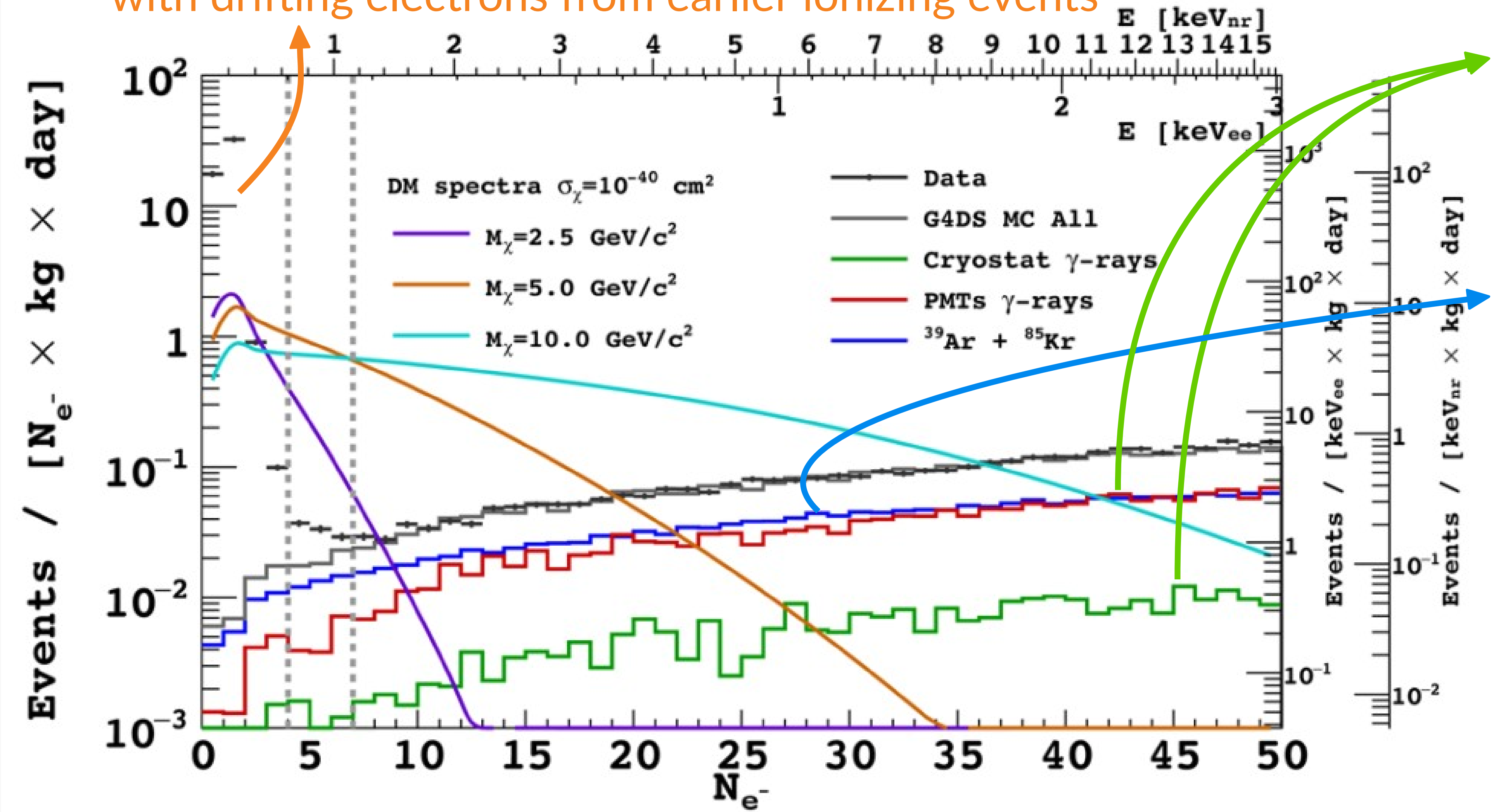
DarkSide Collaboration. "Constraints on Sub-GeV Dark-Matter-Electron Scattering from the DarkSide-50 Experiment". Phys. Rev. Lett. 121 111303 (2018)





Success of DS-50 due to great ultra-low backgrounds achievable with LAr

Energy threshold set by **spurious electron (SE)** backgrounds, due to chemical impurities interacting with drifting electrons from earlier ionizing events



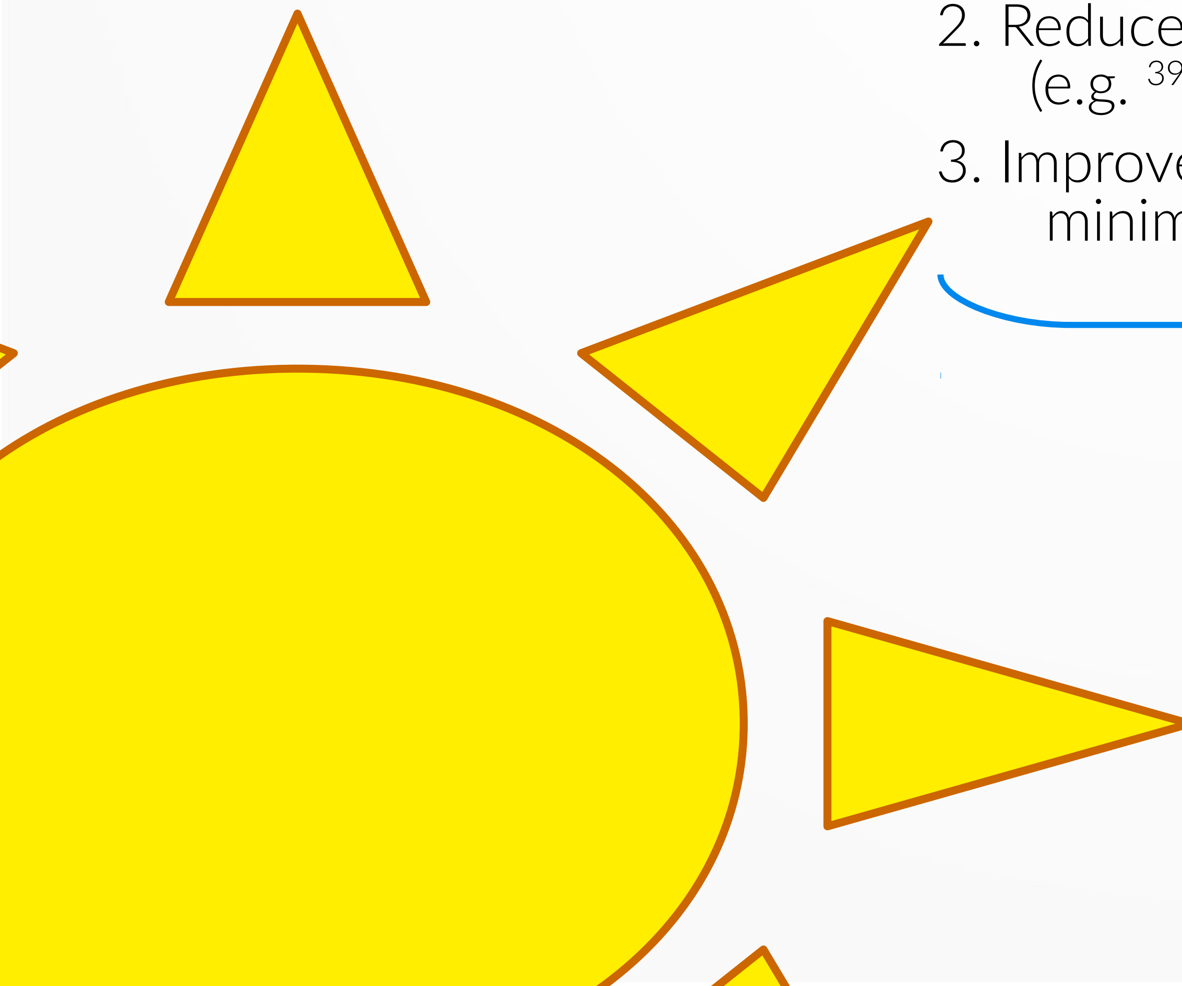
γ-ray backgrounds from from PMTs and cryostat

β-decay backgrounds from ^{39}Ar and ^{85}Kr in LAr

Loss of pulse shape discrimination in S2-only channel means electronic recoils dominate background

DarkSide Collaboration. "Low-Mass Dark Matter Search with the DarkSide-50 Experiment" Phys. Rev. Lett. 121 081307 (2018)

The path to the solar neutrino floor

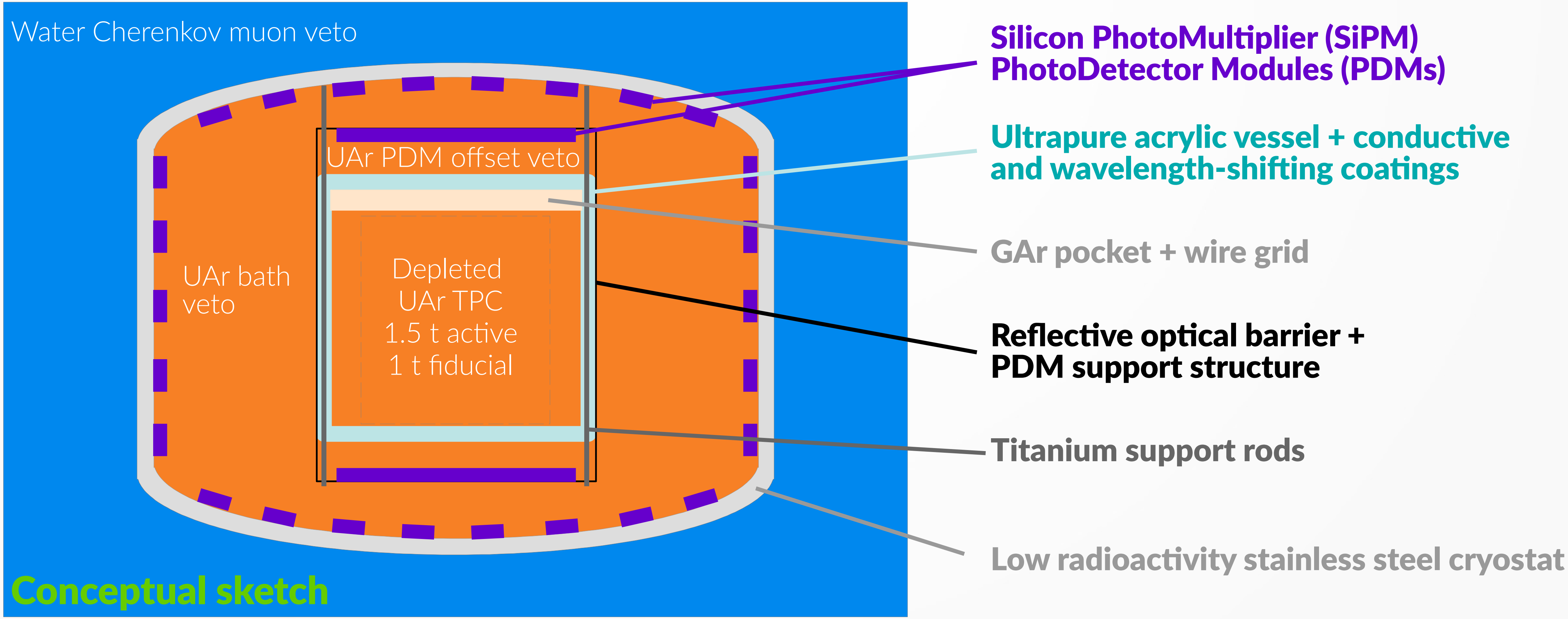


A dedicated detector is needed to...

1. Reduce γ-ray backgrounds to rate comparable w/ solar ν's
2. Reduce LAr radioactivity to rate comparable with solar ν's (e.g. ^{39}Ar and ^{85}Kr)
3. Improve UAr chemical purity and optimize electric field to minimize spurious electrons and maximize S2 signal

DarkSide-LowMass

DarkSide-LowMass: A LAr TPC optimized for a low-energy electron-counting analysis

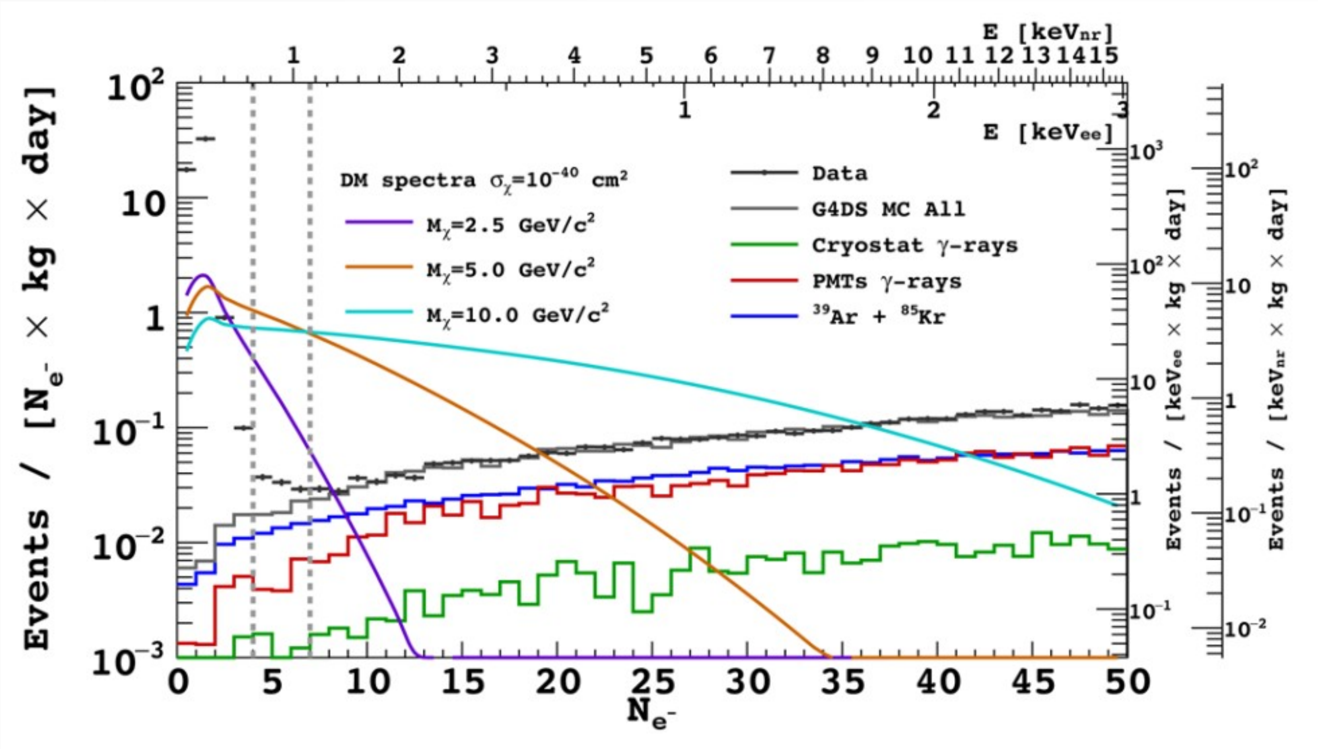


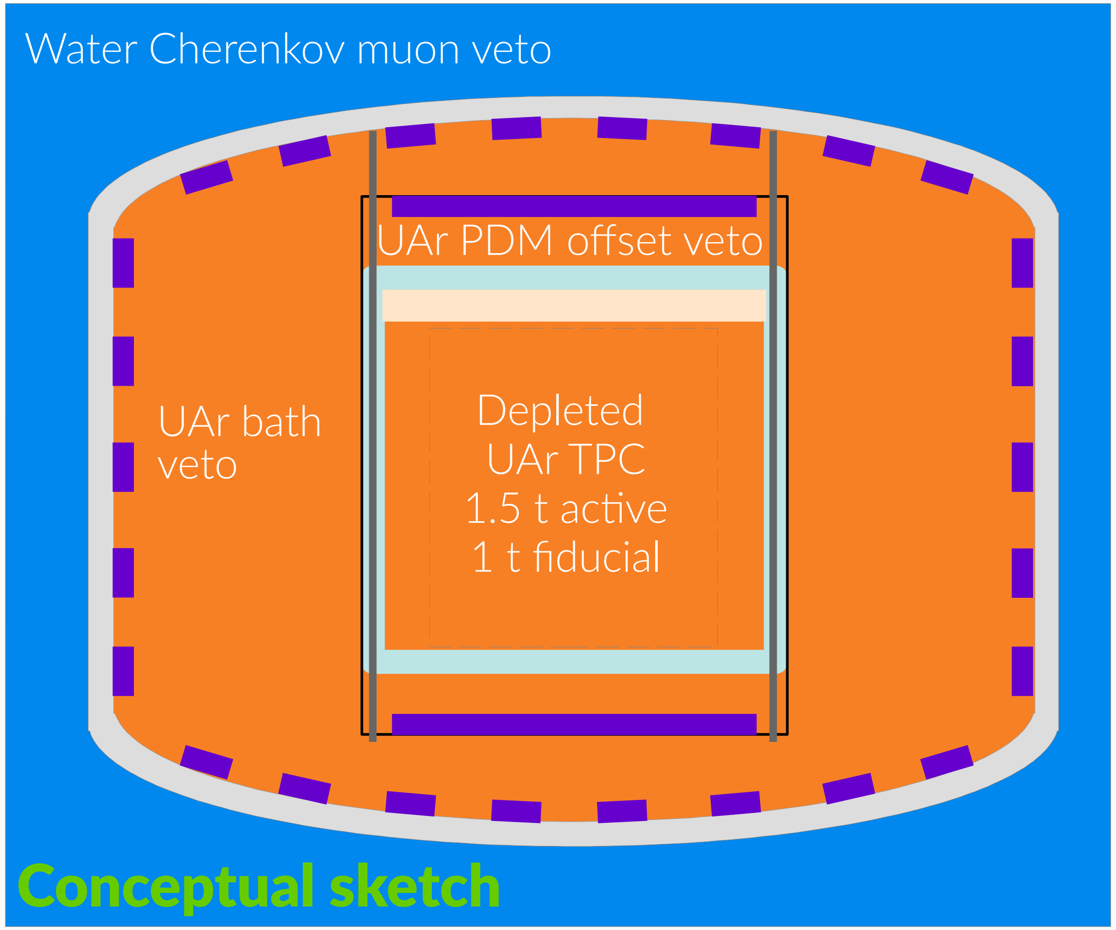
DarkSide-50 measured Underground Argon (UAr) ^{39}Ar activity of 700 µBq/kg (1400× depletion factor). Improvements to UAr extraction may achieve significantly lower activities

Fiducialization in horizontal plane only, due to lack of S1. Conservative 2 cm resolution from optical simulations, used to reduce surface and γ-ray backgrounds

Design centered around reducing γ/β and spurious electron backgrounds

- Greatly decreased γ-ray backgrounds + γ-ray vetoes
- Radiopure Ar for low β-decay backgrounds
- Extreme chemical purity to minimize SE backgrounds and maximize ionization signal





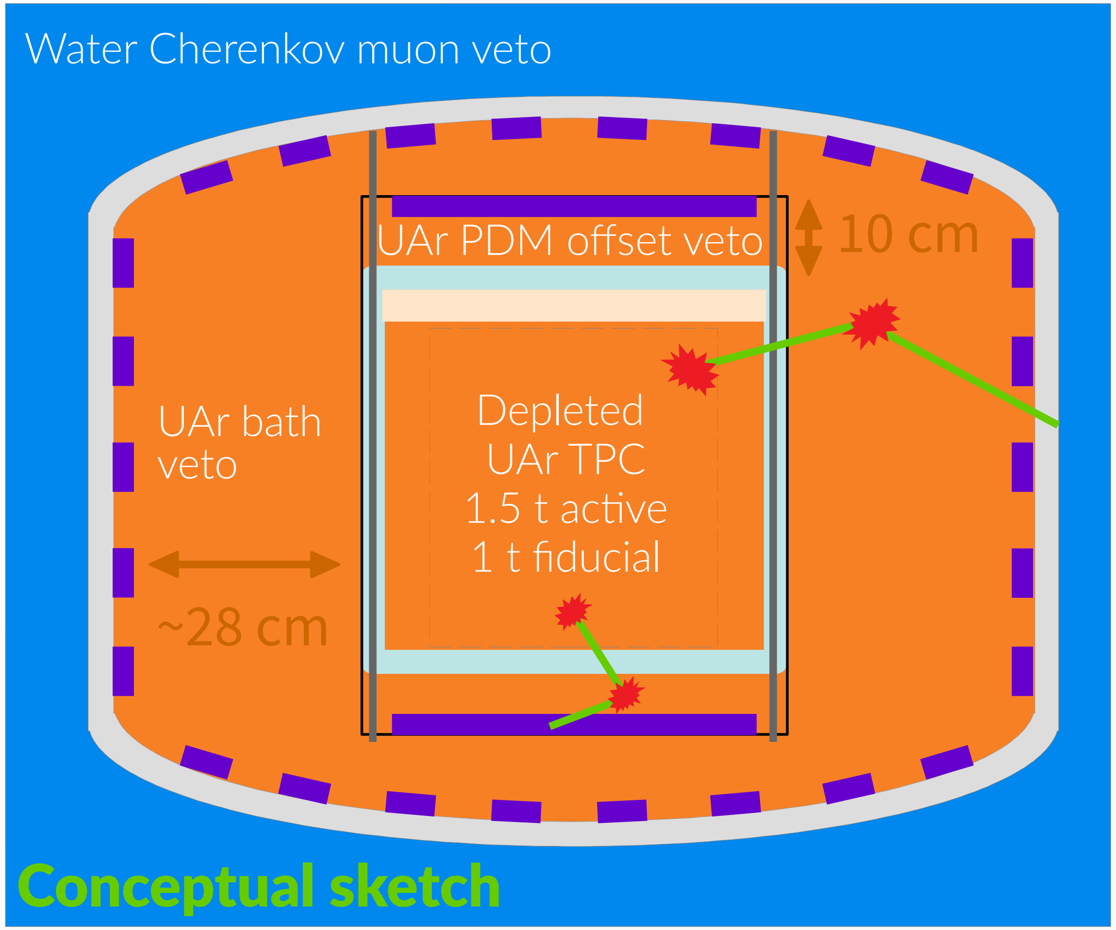
Design centered around reducing γ/β and spurious electron backgrounds

Greatly decreased γ-ray backgrounds

- Ultra radiopure acrylic, stainless steel, and other materials
- Low-background SiPMs
- Water Cherenkov muon veto shields from external neutrons and γ-rays from rock walls, tags passing muons
- UAr bath veto suppresses cryostat γ-rays ~10×
- UAr PDM offset veto suppresses PDM γ-rays by ~10×

Radiopure Ar for low β-decay backgrounds

Extreme chemical purity to minimize SE backgrounds & maximize ionization signal



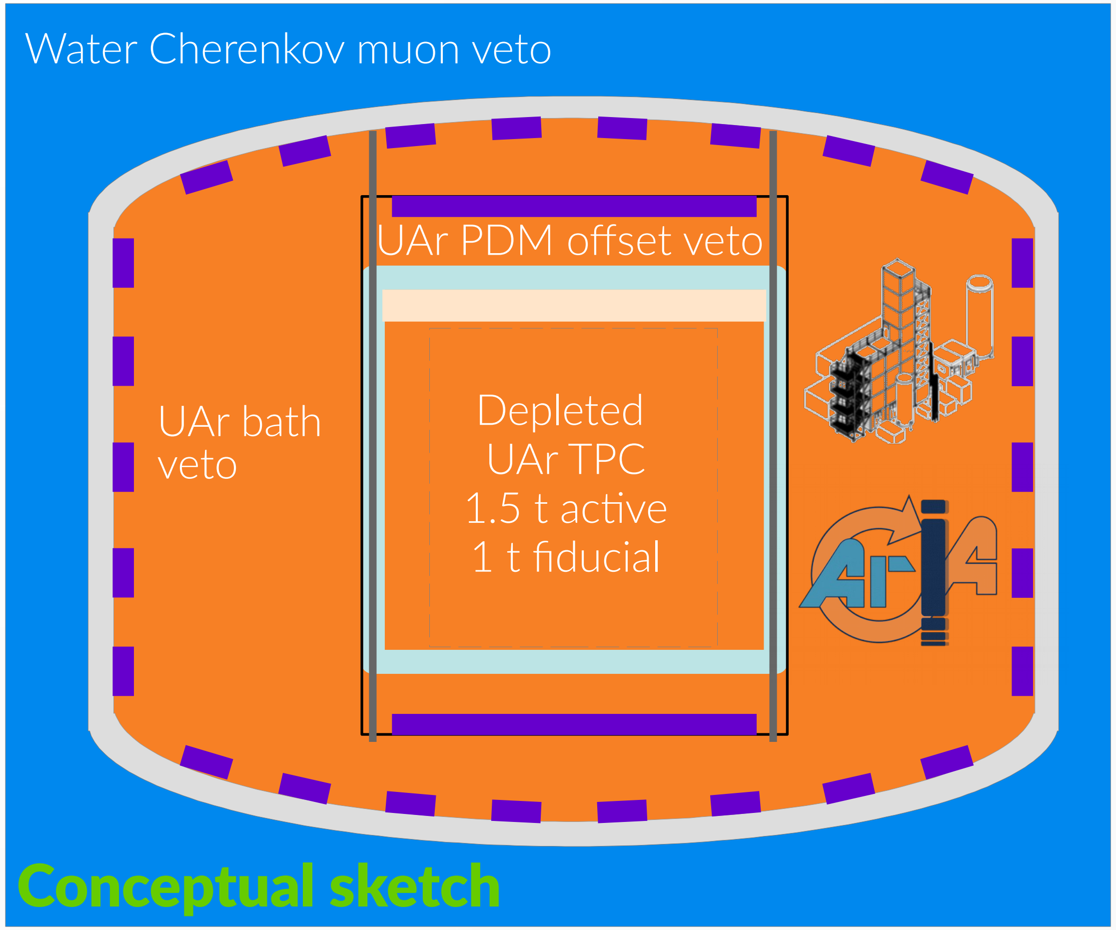
Design centered around reducing γ/β and spurious electron backgrounds

Greatly decreased γ-ray backgrounds

Radiopure Ar for low β-decay backgrounds

- UAr extracted with Urania plant (1400× in DS-50)
- Additional ^{39}Ar reduction from extraction improvements
- Further ^{39}Ar depletion & complete ^{85}Kr removal with Aria

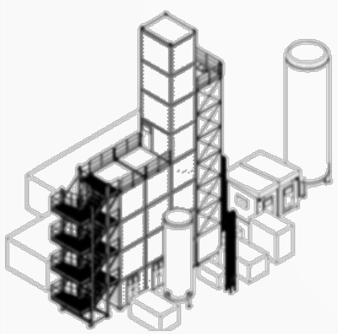
Extreme chemical purity to minimize SE backgrounds & maximize ionization signal

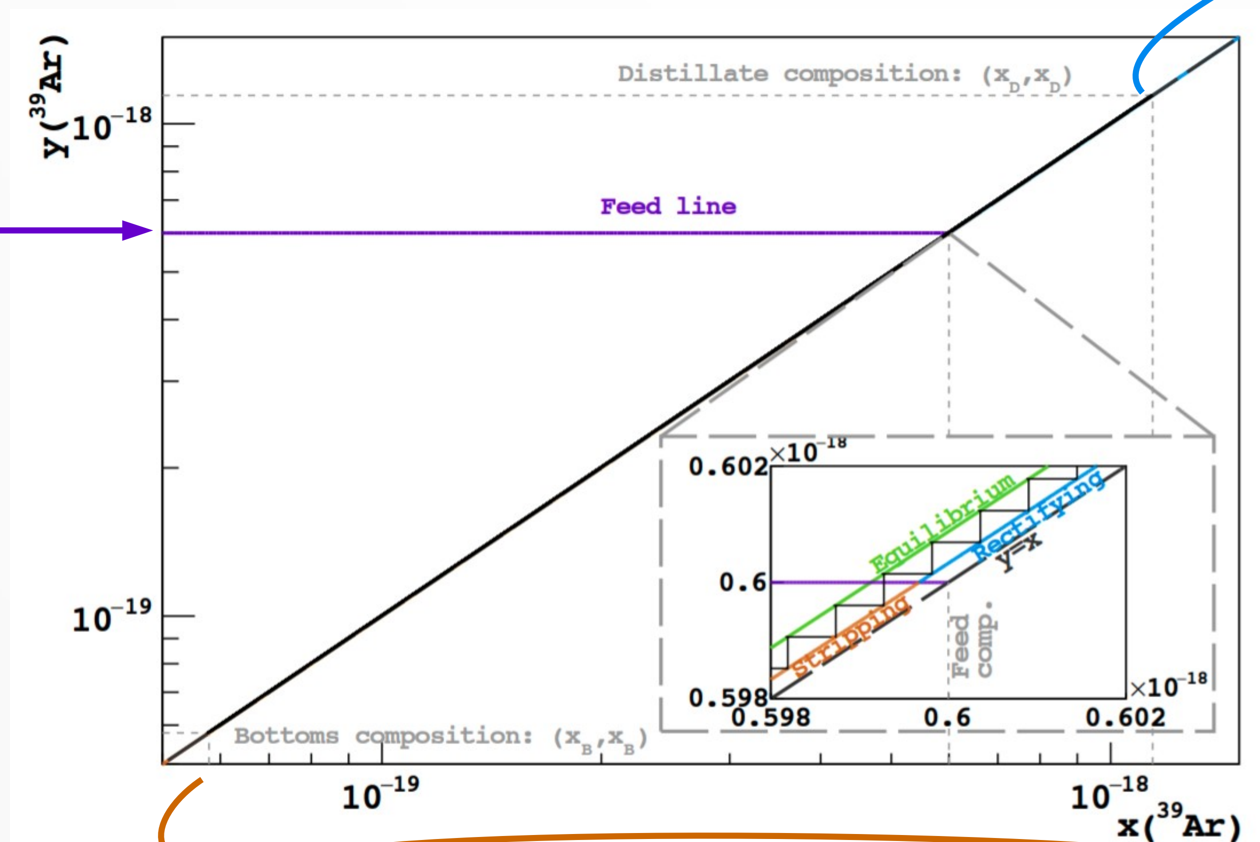


UAr extracted from Urania (Colorado) will be isotopically distilled in Aria (Sardinia) and assayed by DArT in ArDM (Canfranc Laboratory)

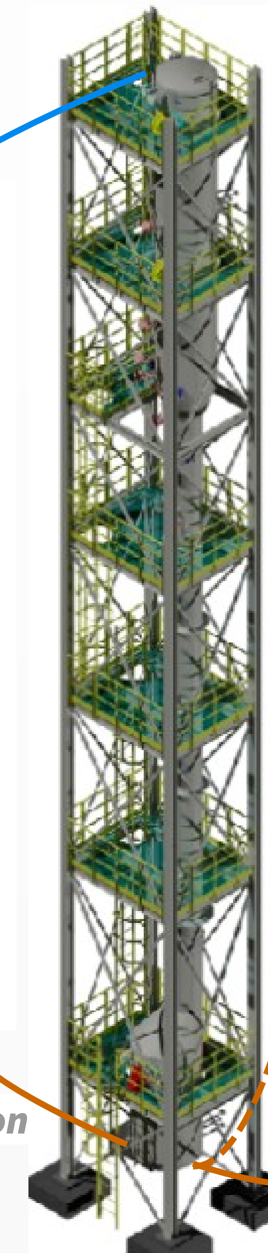
Simulations predict a 10× depletion factor at a throughput of 8.1 kg/day

Urania

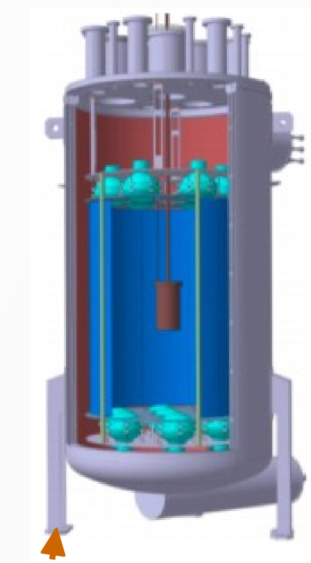




DarkSide Collaboration. "Separating ^{39}Ar from ^{40}Ar by cryogenic distillation with Aria for dark-matter searches" Eur. Phys. J. C 81 359 (2021)

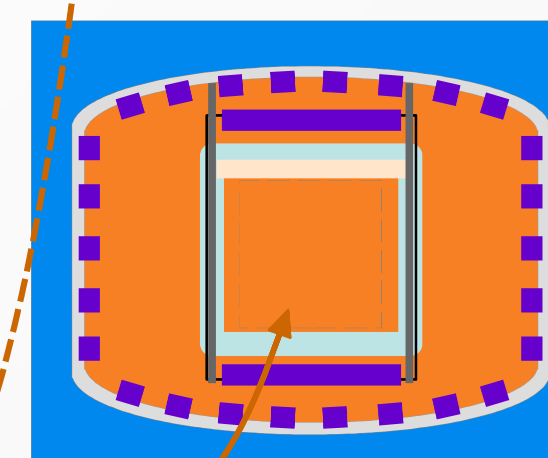


DArT in ArDM



See talk by V. Pesudo

DarkSide Collaboration. JINST 15 P02 024 (2020)



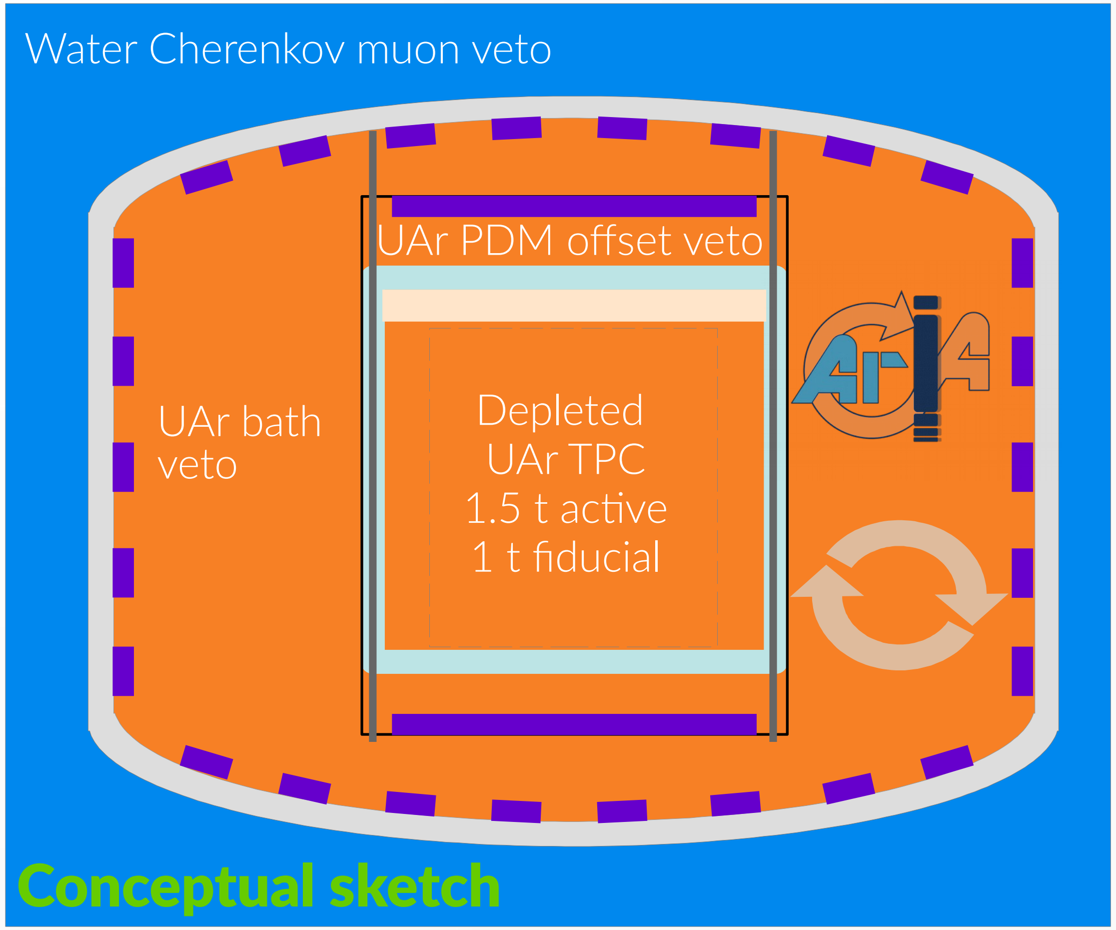
Design centered around reducing γ/β and spurious electron backgrounds

Greatly decreased γ-ray backgrounds

Radiopure Ar for low β-decay backgrounds

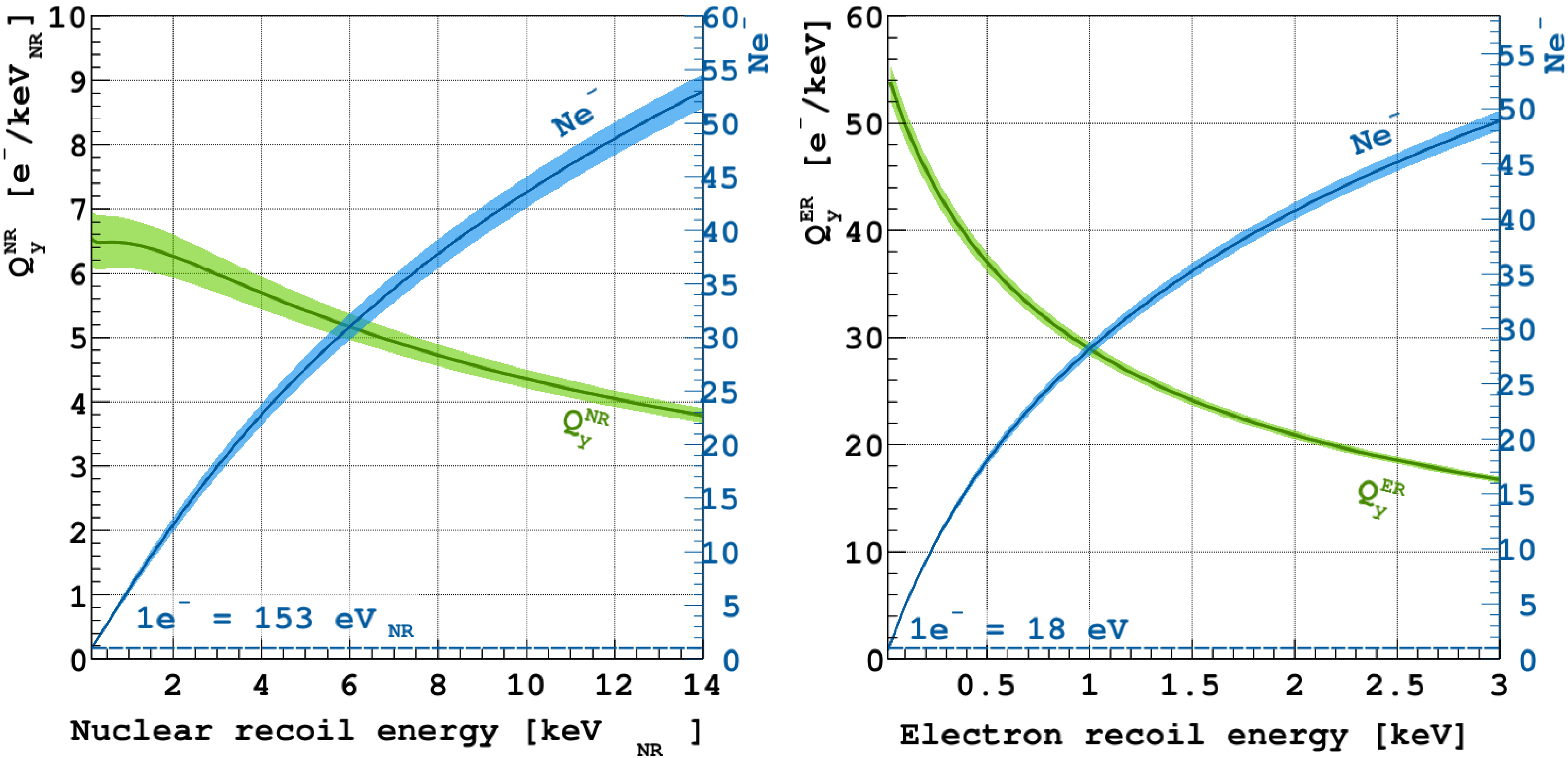
Extreme chemical purity to minimize SE backgrounds & maximize ionization signal

- High initial purity from distillation in Aria
- *In situ* purification with re-circulation
- Ongoing R&D to study relationship between SE backgrounds, impurities, and field configuration for future improvements



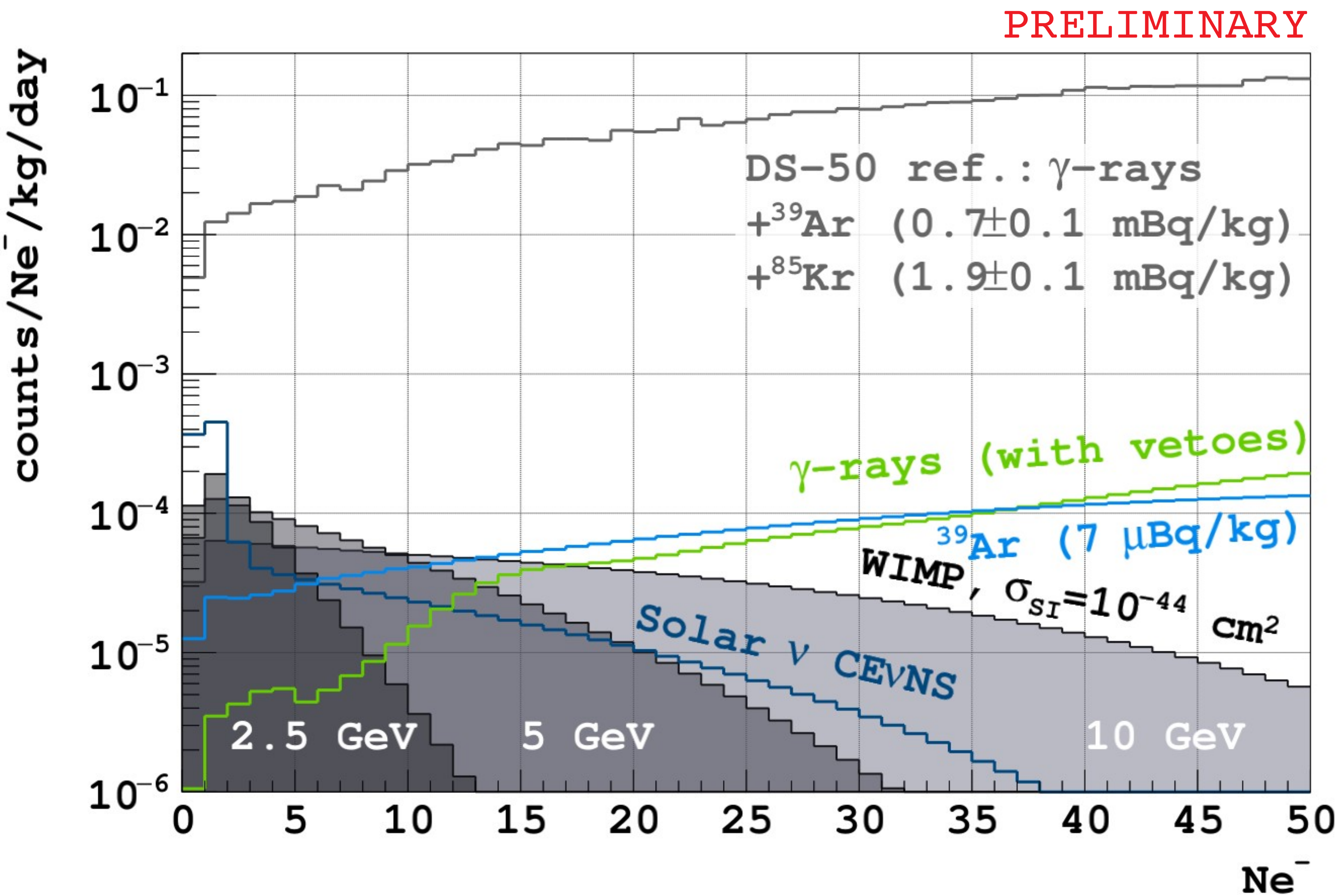
LAr ionization yield model tuned on dedicated measurements and DarkSide-50 data

PRELIMINARY



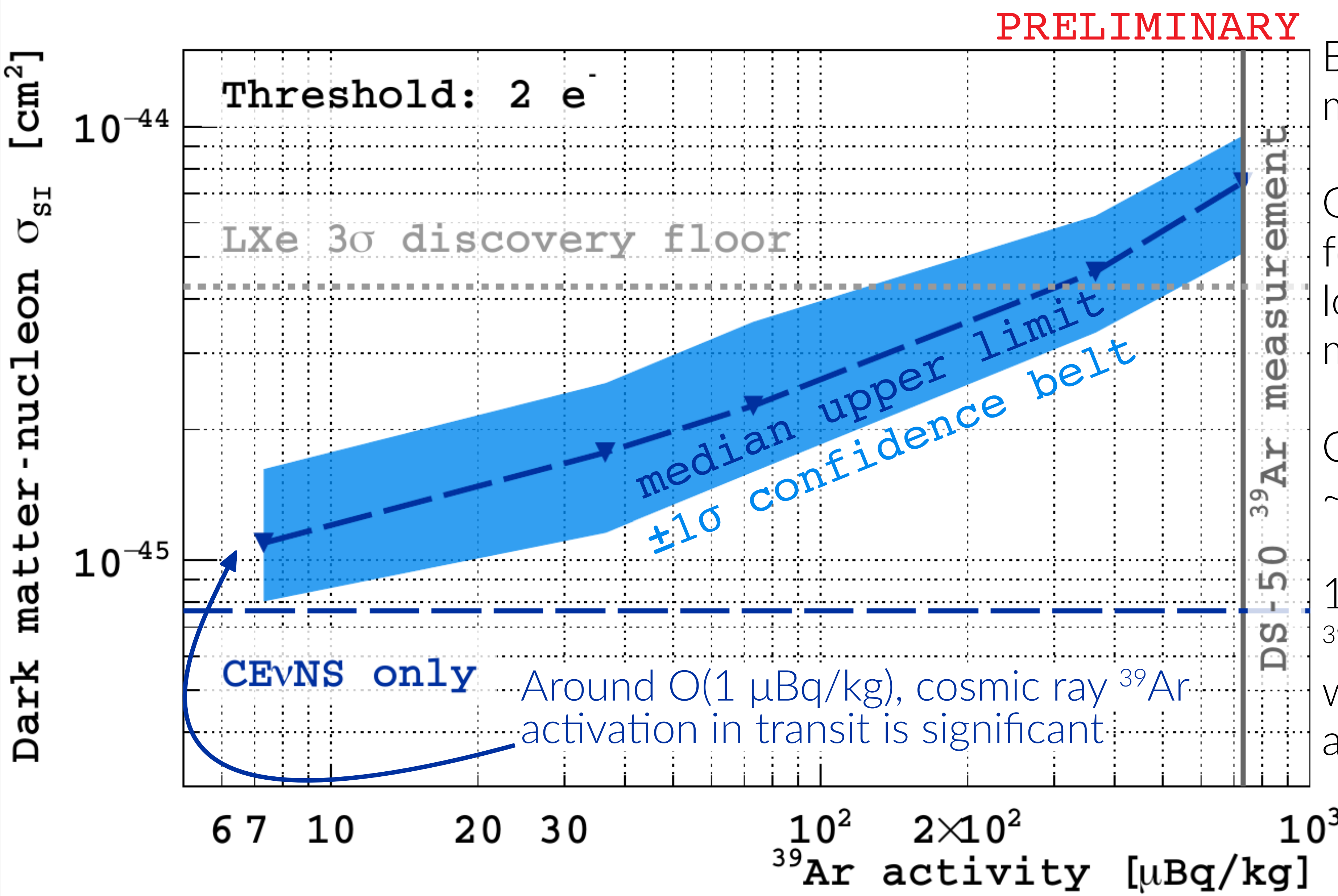
Based on model in *DarkSide Collaboration. "Calibration of the liquid argon ionization response to low energy electronic and nuclear recoils with DarkSide-50" arXiv:2107.08087 (2021)*

With realistic models of γ-ray backgrounds and ^{39}Ar reduction, solar neutrino CEvNS become major background



- Spurious electrons (SEs) impose a low-energy analysis threshold.
- Rate is proportional to total event rate
- DS-50 used a 4e⁻ threshold to avoid SEs
- A 2e⁻ threshold requires a 10^5 reduction in SEs
- SEs expected to decrease w/ lower β/γ rate and better chemical purity
- Ongoing R&D is investigating further reduction

Expected 90% C.L. upper limits for $m_\chi = 5$ GeV/c²: Sensitivity varies significantly with the ^{39}Ar specific activity



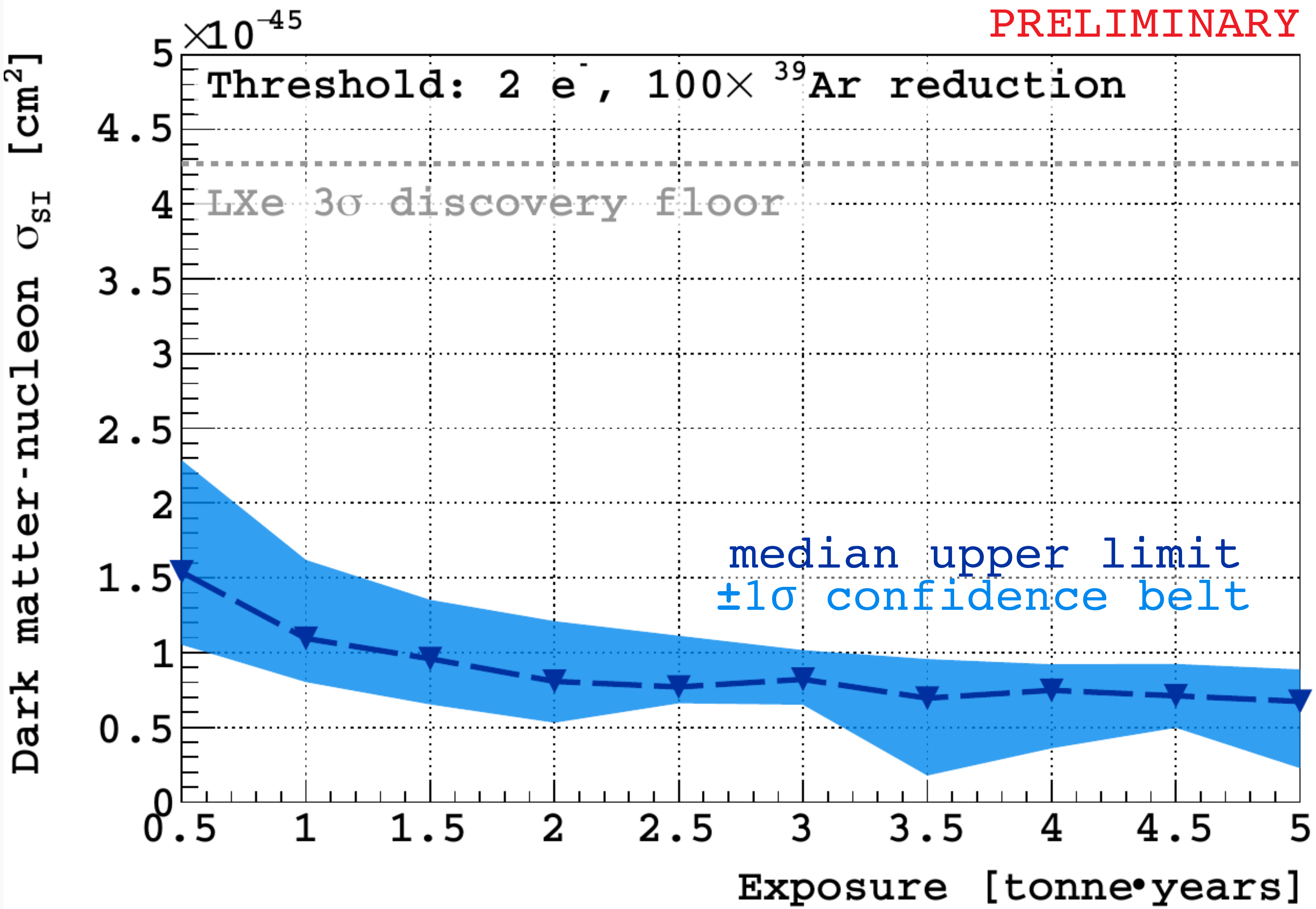
Based on background model in previous slide…

Given Aria's throughput for isotopic separation, lower target masses allow more ^{39}Ar removal.

Can reduce by 10× in ~0.5 yrs for 1.5 t target

100× reduction brings ^{39}Ar to a comparable rate w/ solar neutrinos, and we approach neutrino floor

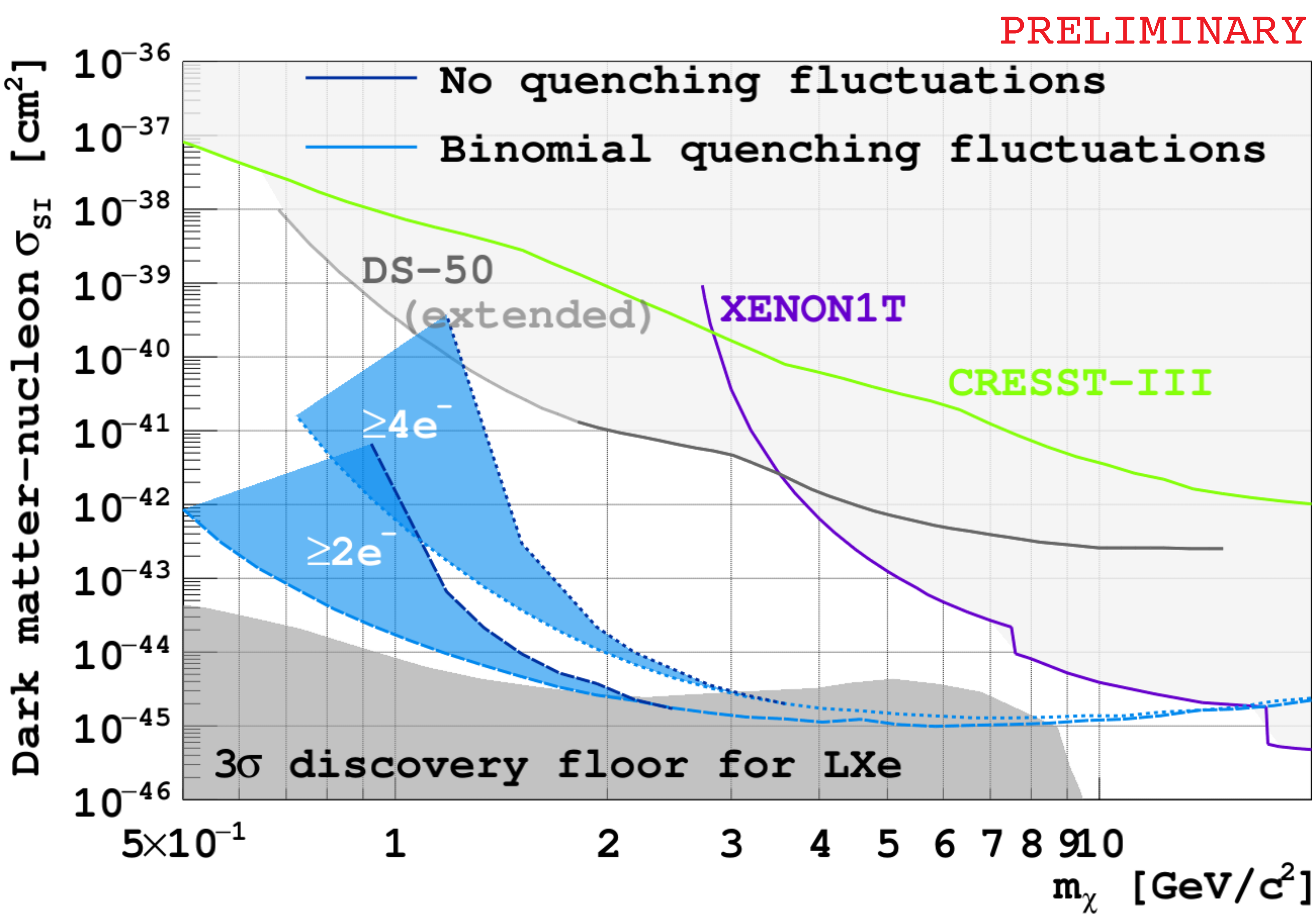
Expected 90% C.L. upper limits for m_X = 5 GeV/c^2: Sensitivity varies very little with exposure after 1.5 t·yrs



Sensitivity improvement with larger exposures become marginal as irreducible backgrounds become limiting.

Little motivation to go far larger than 1 t fiducial mass

Low-mass reach in 1 t·yr strongly depends on analysis energy threshold and low-energy ionization response



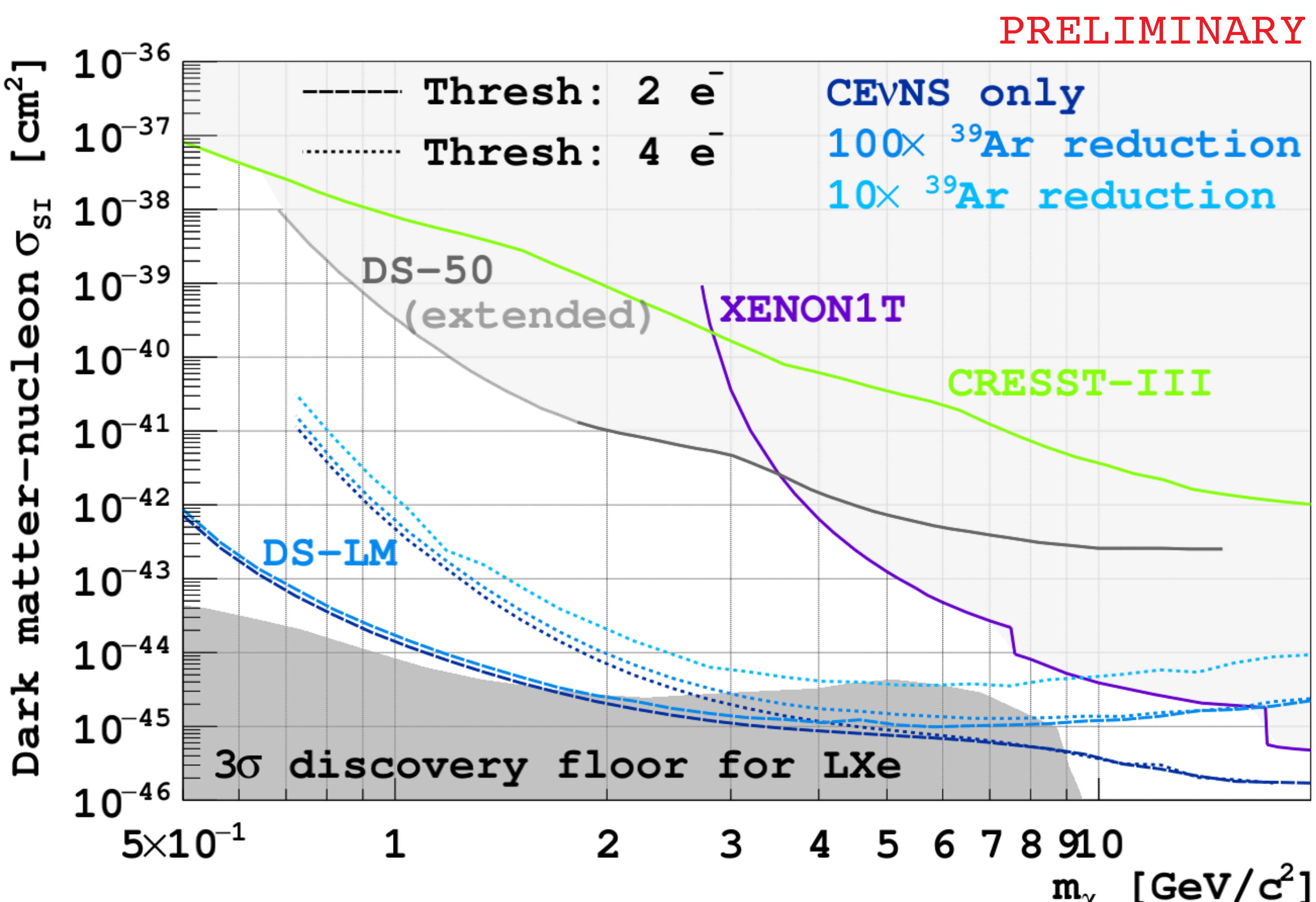
Assuming 100× ^{39}Ar suppression

Analysis threshold set by SE rate ($2e^-$ & $4e^-$ used as case studies)

Significant uncertainties on ionization response to low-energy nuclear recoils. Uncertainty on quenching fluctuations impact sensitivity below 2 GeV/c^2

Calibration measurements are being planned

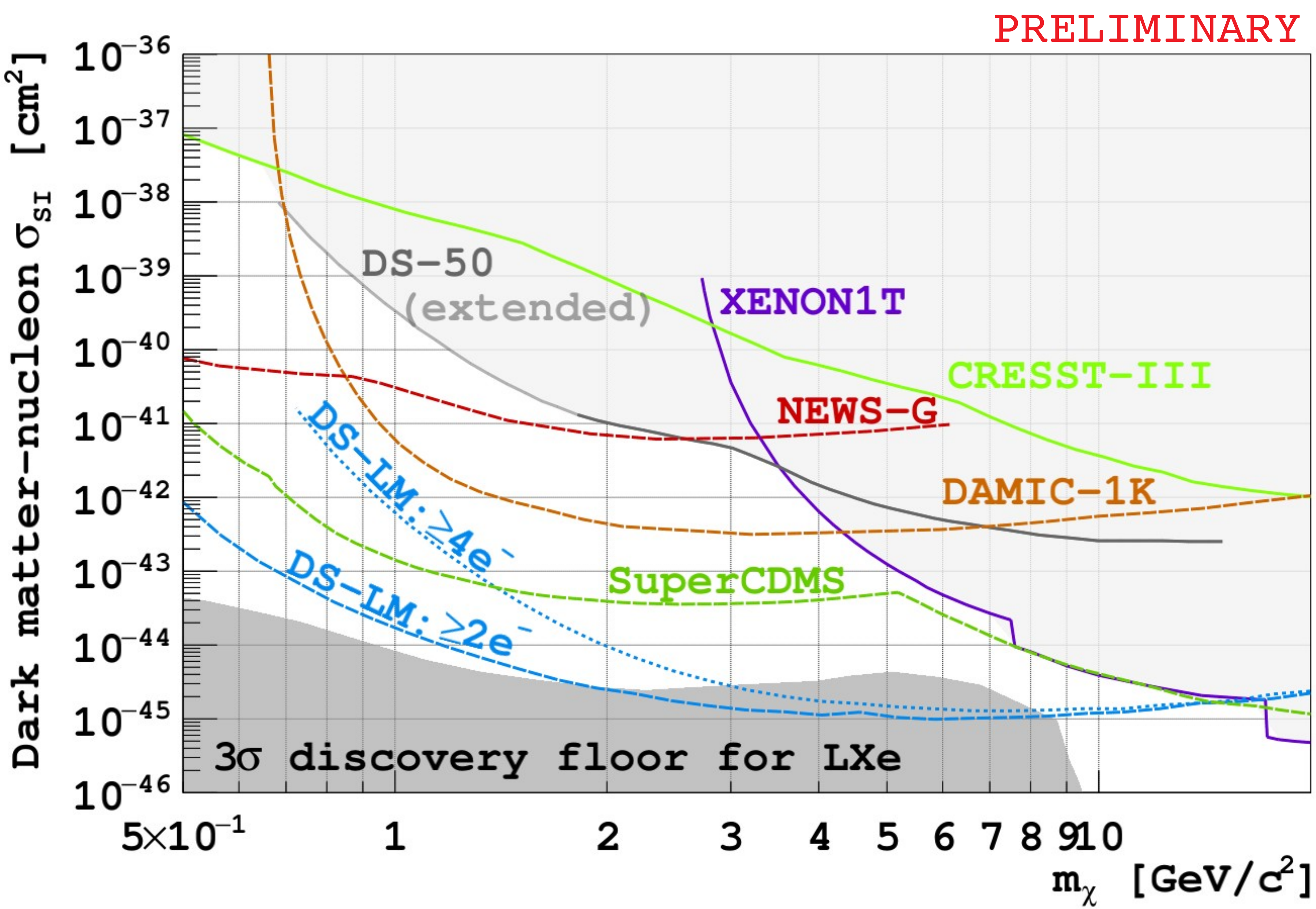
Sensitivity in 1 t·yr most significantly improved by reducing backgrounds and lowering energy threshold



Assuming binomial fluctuations in nuclear recoil quenching.

Active R&D underway to explore methods of decreasing SE backgrounds and lowering energy threshold

With realistic assumptions, solar neutrino floor is in reach with 1 t·yr exposure



Example projections for:
- 100✕ ^{39}Ar reduction
- Binomial nuclear recoil quenching fluctuations

Final remarks

- DarkSide-LowMass has a clear path to the neutrino floor, benefiting from developments of the Global Argon Dark Matter Collaboration
  - Upcoming paper on these sensitivity projections with more details
- Significant γ-ray background reduction due to low-γ materials and two-fold veto system
- Biggest room for additional sensitivity gains from:
  - **^{39}Ar reduction:** Improvements in UAr extraction with the Urania plant and isotopic purification with the Aria cryogenic distillation column
  - **Lower energy threshold:** Lower SE backgrounds, better UAr purity, and optimized field design
- Ongoing R&D for spurious electron suppression, low-energy recoil calibration measurements, and further energy threshold reduction
- Spurious electron background studies with DarkSide-50 data
  - *DarkSide Collaboration, "A study of events with photoelectric emission in the DarkSide-50 liquid argon Time Projection Chamber". arXiv:2107.08015 (2021)*
  - Upcoming paper on isolated spurious electron signals
- With low thresholds, sensitivity to supernova burst neutrinos may also be achievable
  - *DarkSide Collaboration, "Sensitivity of future liquid argon dark matter search experiments to core-collapse supernova neutrinos." JCAP03(2021)043*

Thank you