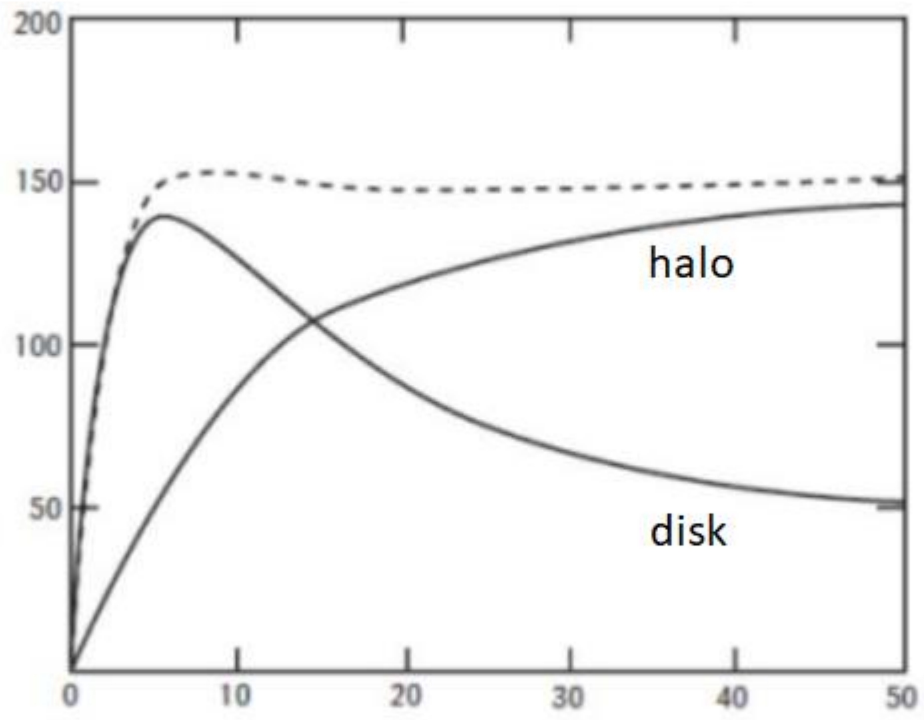
# Direct search for low mass dark matter

*Sergey Chashin (SINP MSU)*

**Nucleus-2025, 2nd July 2025, Saint-Petersburg, Russia**

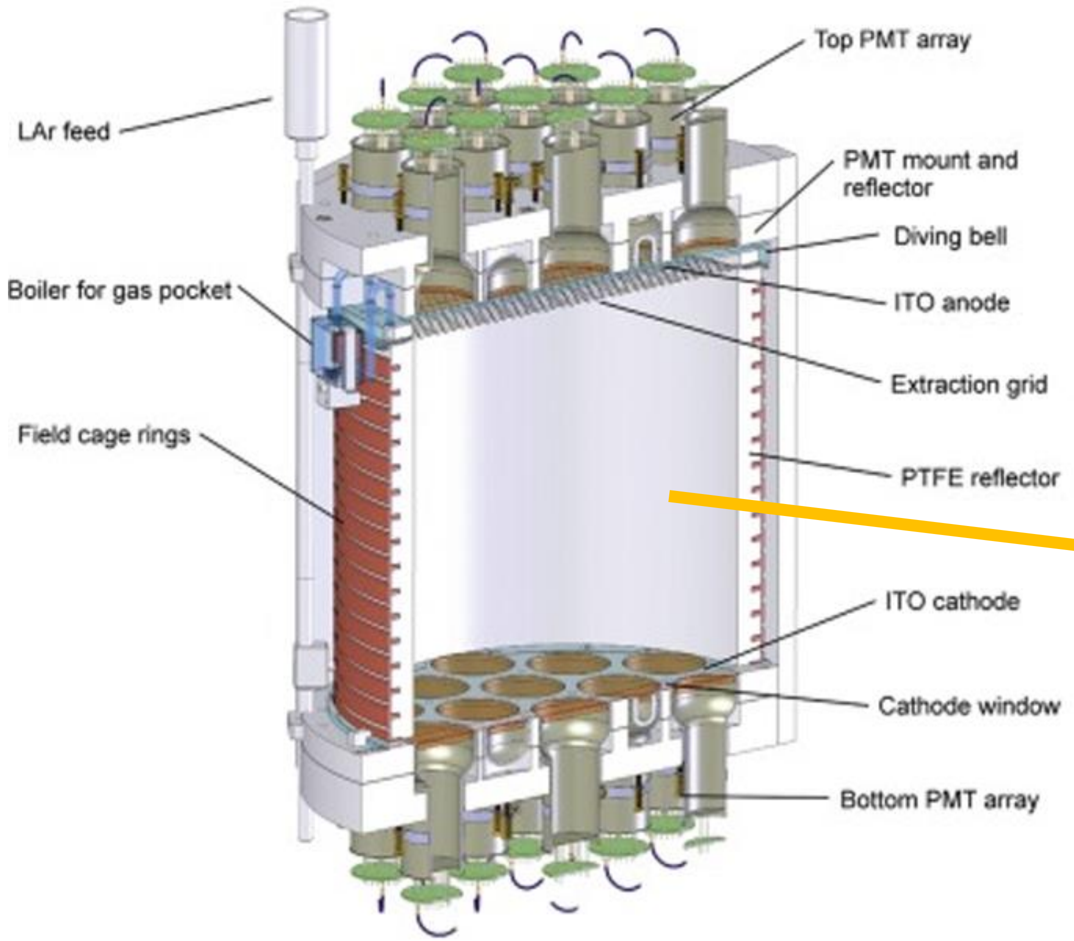
# Dark matter



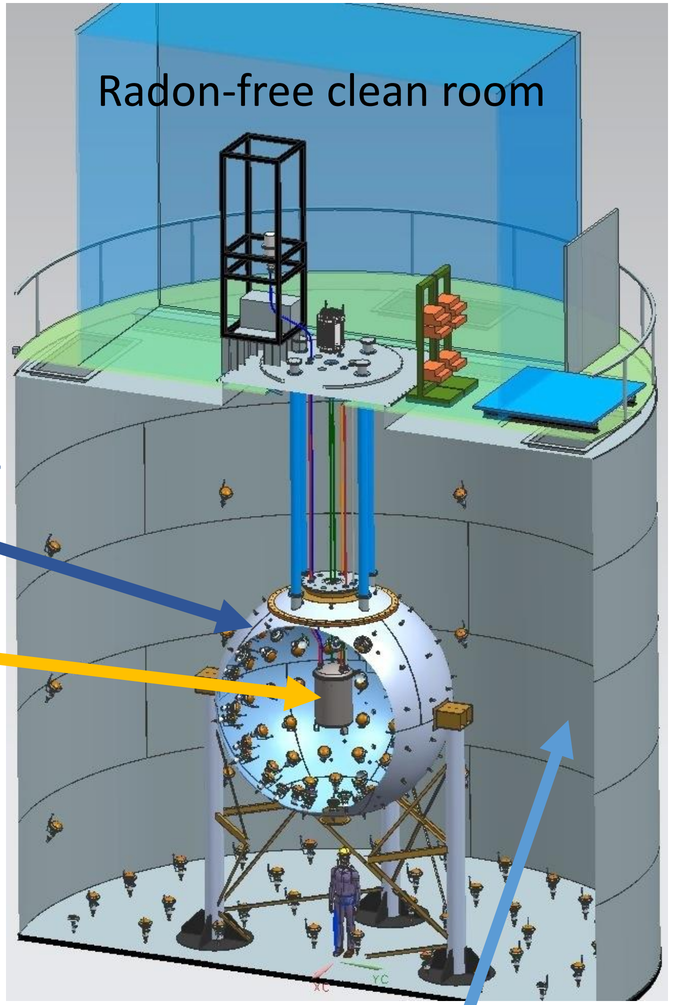

The rotation curve of M33 galaxy

Optical and X-ray images of the 1E0657 558 cluster. Lines highlight mass density contours based on weak gravitational lensing

# The DarkSide-50




Dual-Phase Argon Time Projection Chamber



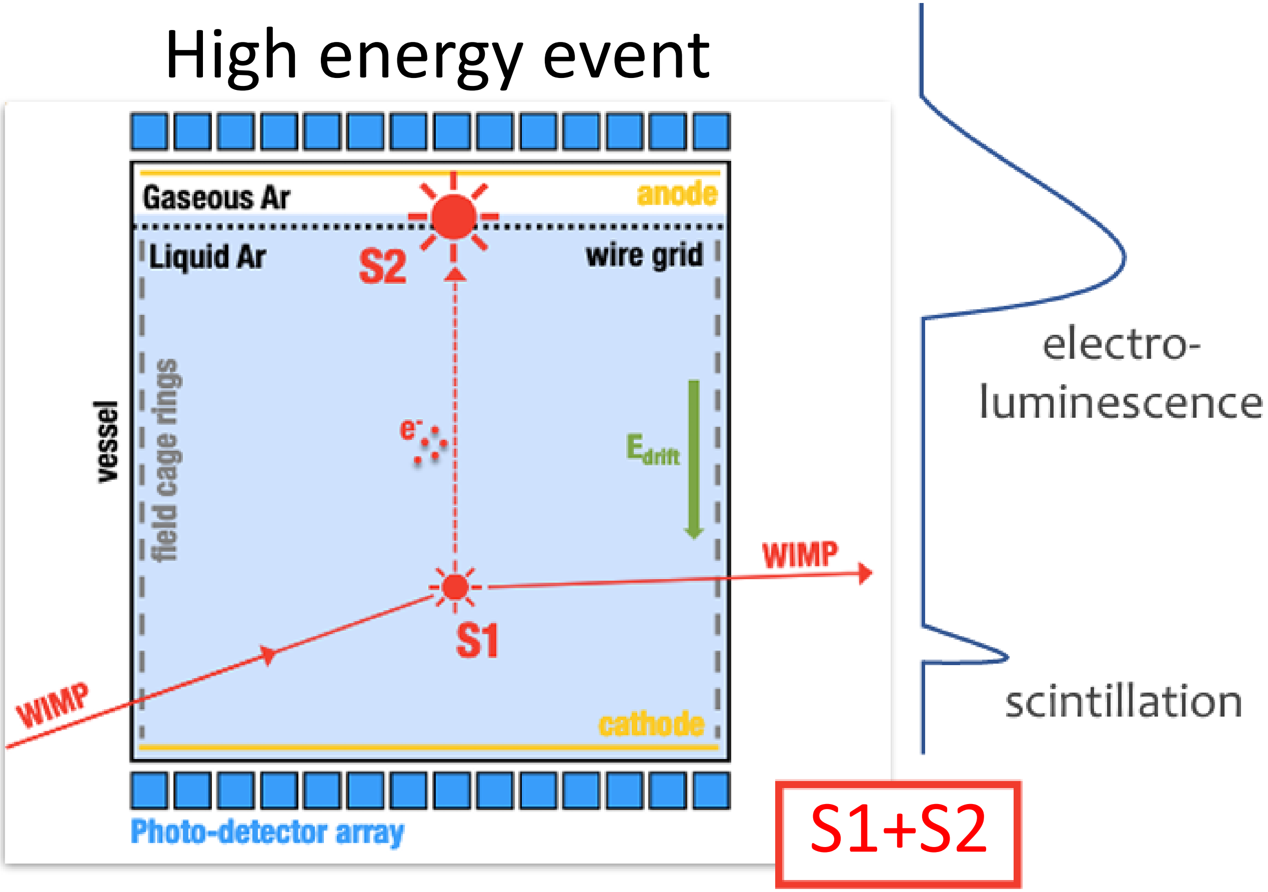

Liquid Scintillator Veto

Water Cherenkov Veto

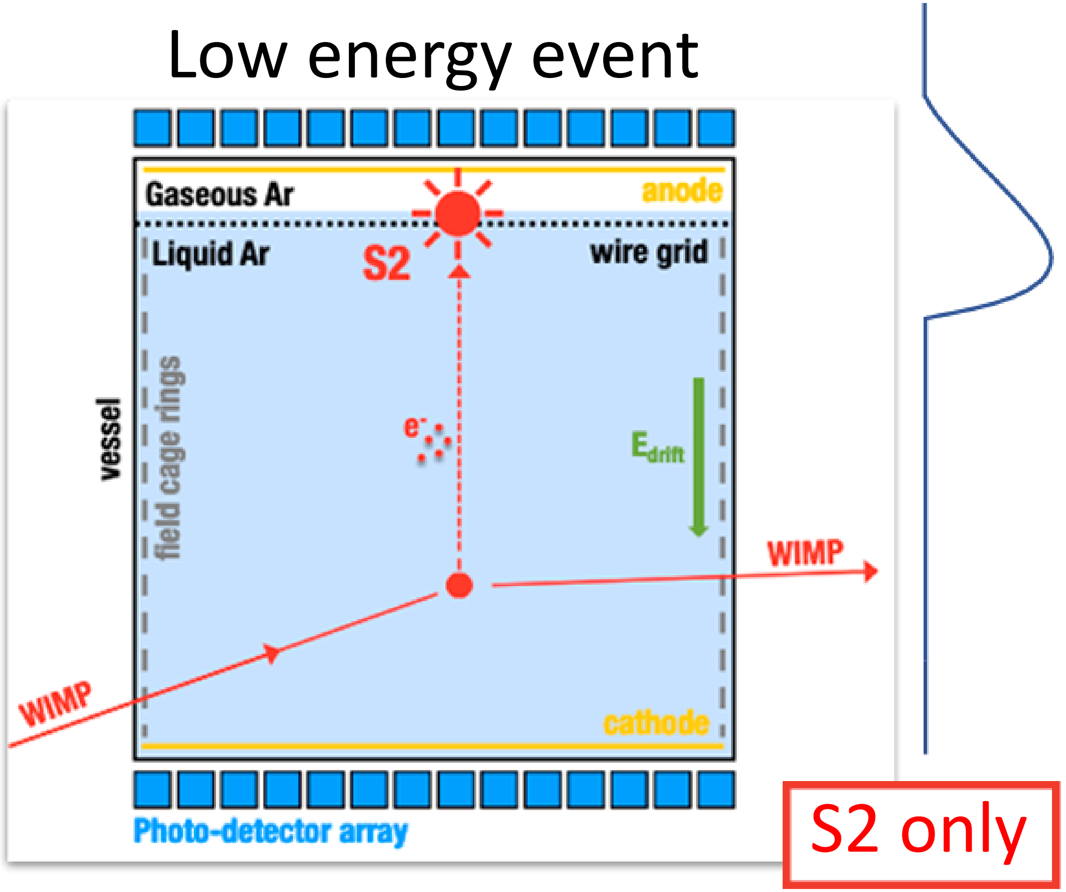
(Images credit: DarkSide collaboration)

# Dual-Phase Argon Time Projection Chamber (TPC)

## High energy event




## Low energy event



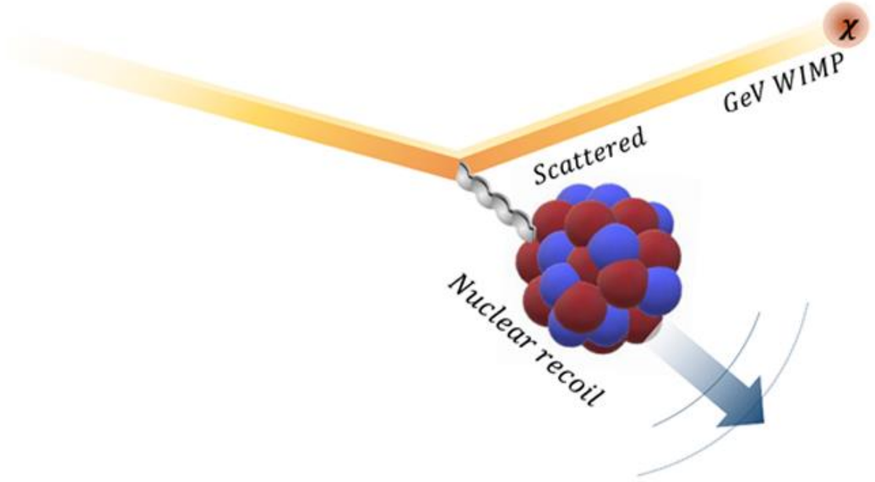

- Recoil energy → scintillation photons and ionization $e^-$
- Amplitude of S1+S2 → calorimetery
- Particle identification via pulse shape discrimination (PSD)
- Drift time (between S1 and S2) → Z coordinate

- Amplification in GAr lets us detect signals with high efficiency above photoelectronic noise → lower energy threshold
- PSD, and drift time are not available

(Images credit: DarkSide collaboration)

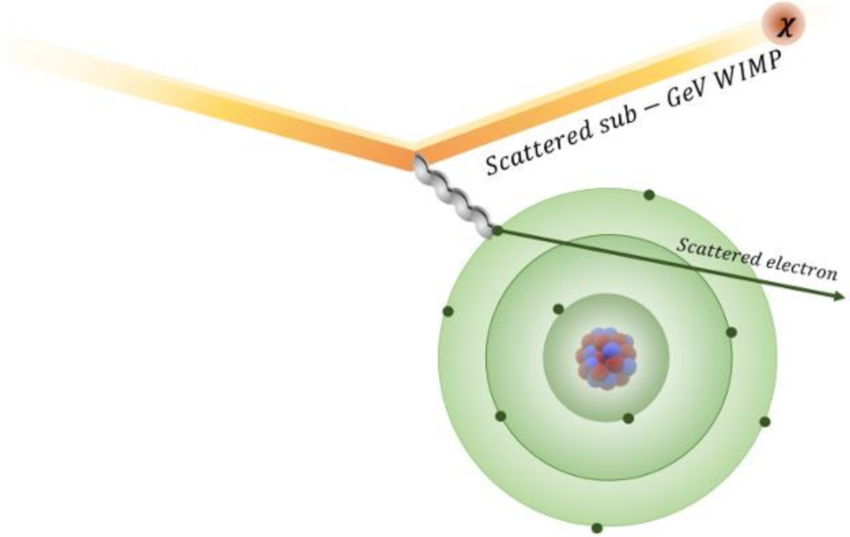
# Detection channels: elastic scattering

## Nuclear Recoil (NR)




DM high-mass range: ~5 GeV/$c^2$ to 10 TeV/$c^2$

## Electron Recoil (ER)



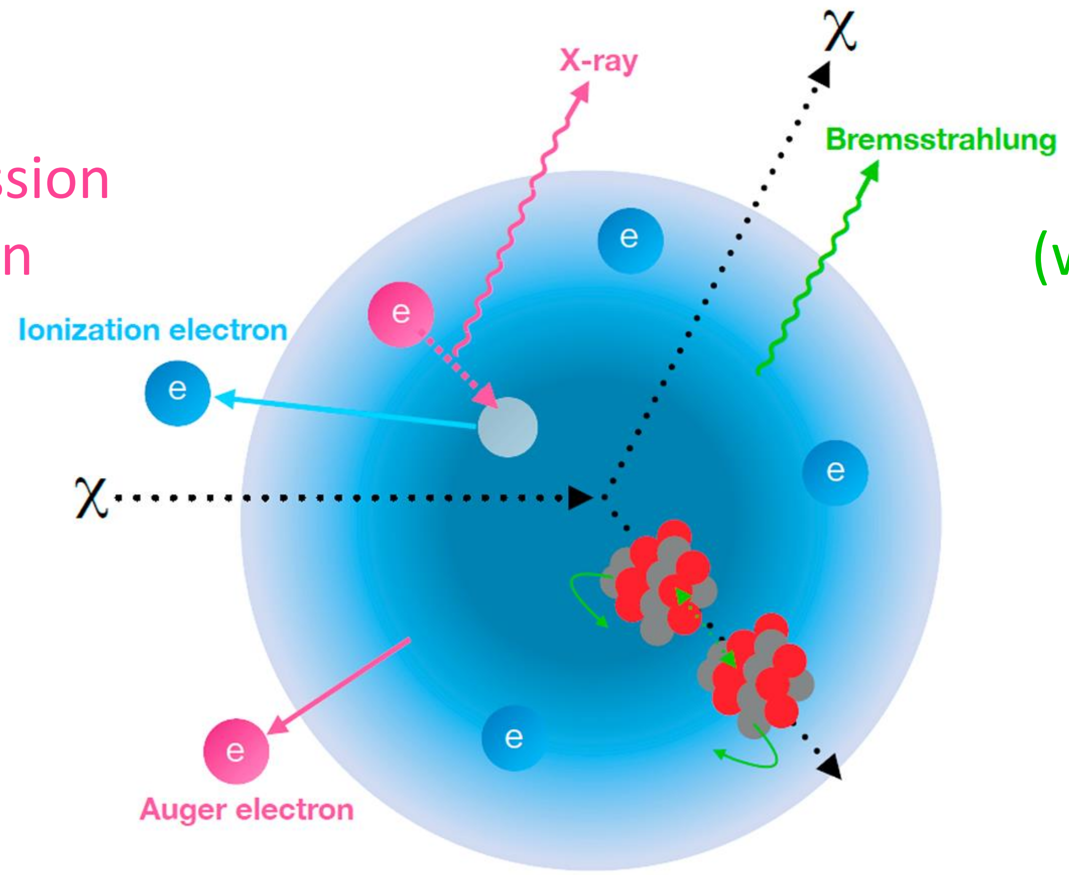

DM low-mass range: ~30 MeV/$c^2$ to 5 GeV/$c^2$

(Images credit: DarkSide collaboration)

# Detection channels: inelastic scattering

Electron shell follows the recoiling nucleus with delay, so the atom after a DM-nucleus interaction can become polarized, which can lead to the following effects:

**Migdal Effect:**
keV-range electron emission
X-ray photon emission




**Bremsstrahlung:**
X-ray photon emission
(weak effect, low sensitivity)

DM low-mass range: ~30 MeV/$c^2$ to 5 GeV/$c^2$

(Images credit: XENON1T collaboration)

# DarkSide-50 dataset

The dataset consists of 653.1 live-days (12 ton-days) of underground argon data, taken from December 12, 2015, to February 24, 2018, with an average trigger rate of 1.54 Hz

Detector showed reasonable stability for the whole period of 26 months:

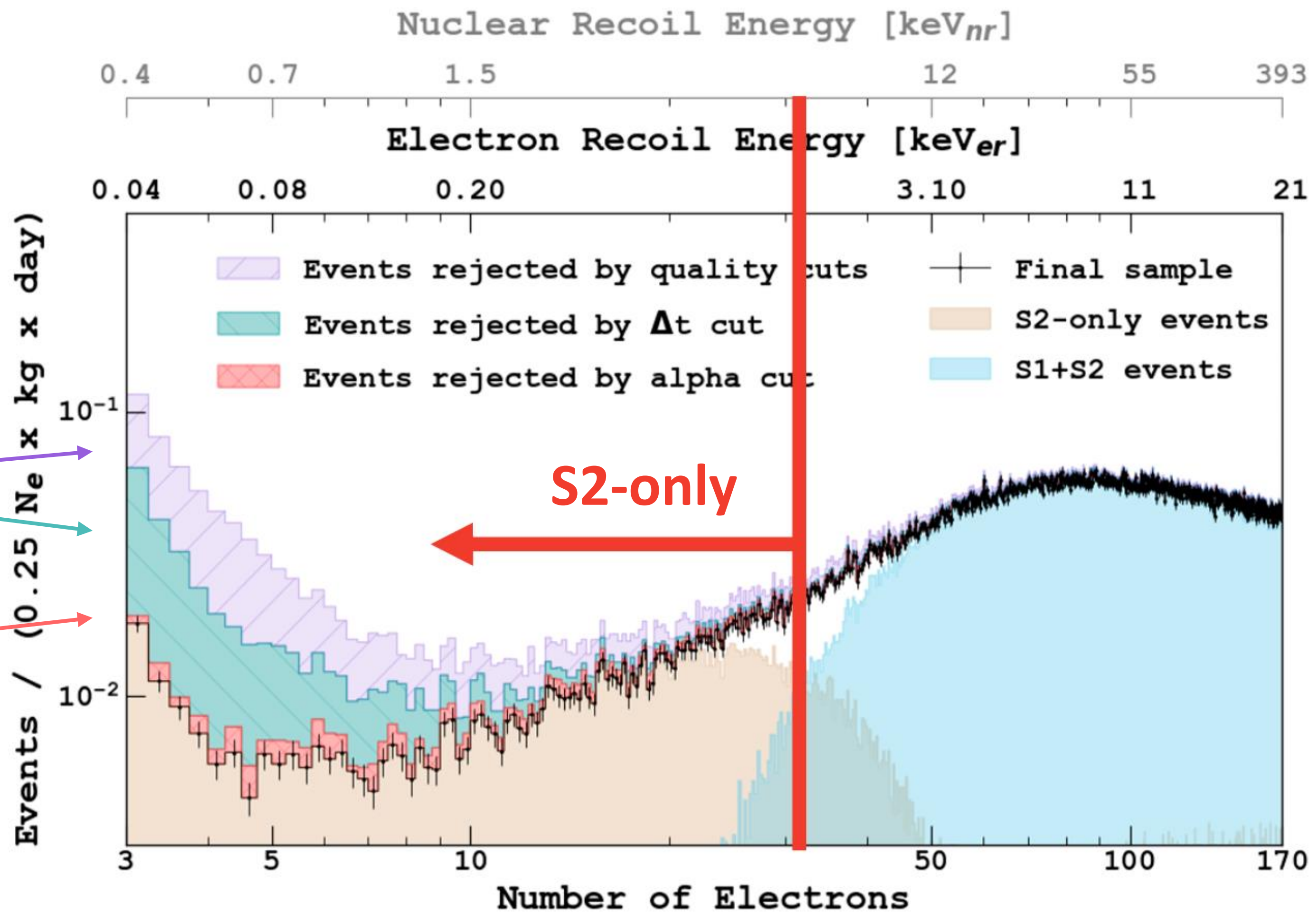
- δT = ±0.02 K, δP < ±0.005 psi,
- δ(S1) ~0.4%, δ(S2) <1%

Multiple-pulses & pileup events

Improperly triggered events

& SE events (delayed electron signals)

Surface-α events

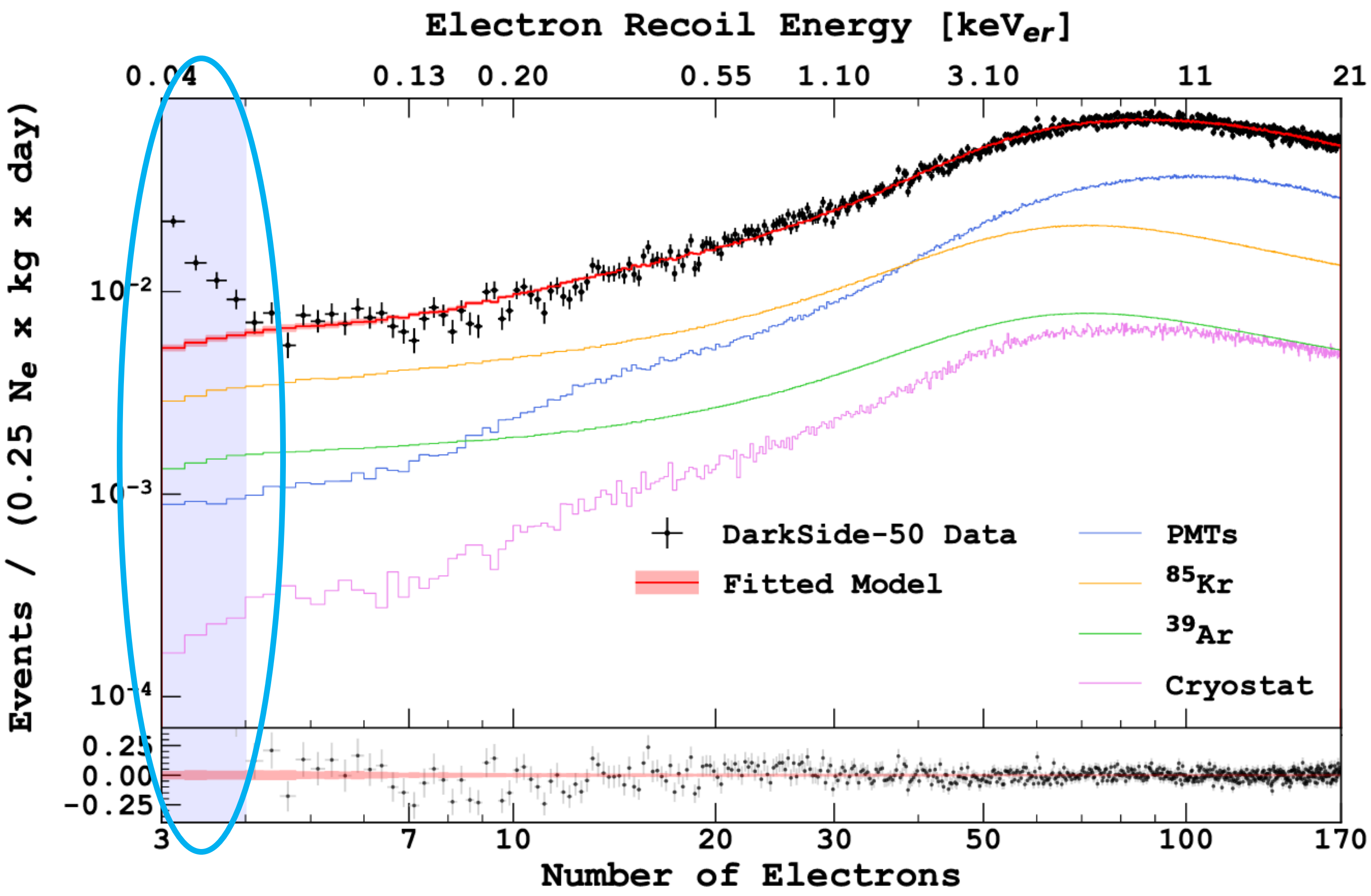


Phys. Rev. D 107, 063001 (2023)

Signal efficiency is >95% for the region of interest (low energy analysis threshold is equal to 4 Ne)

# DarkSide-50 background model

- Internal background consists of $^{39}Ar$ and $^{85}Kr$
- External background consists of impurities in PMT and cryostat materials
- Spurious electrons (SE), that follow large S2 pulses



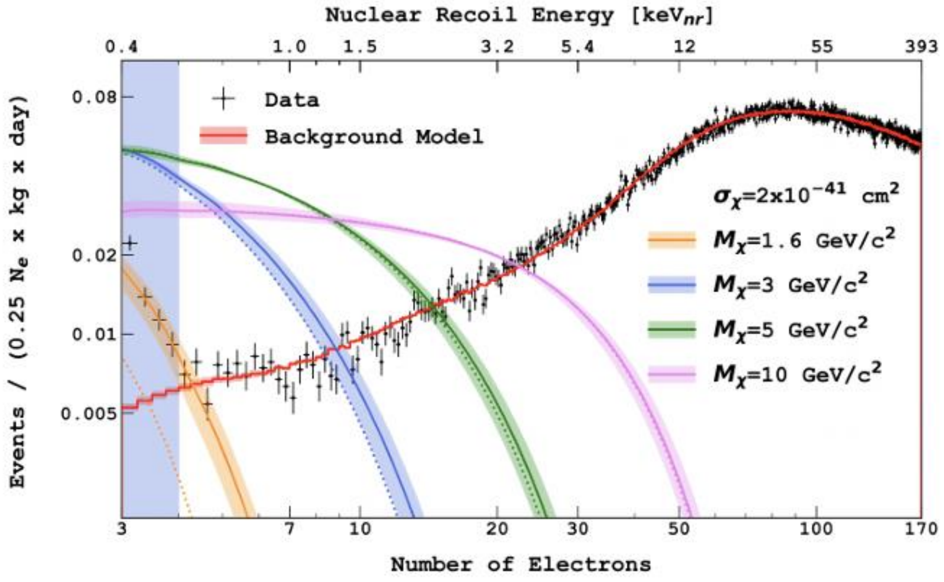

Phys. Rev. D 107, 063001 (2023)

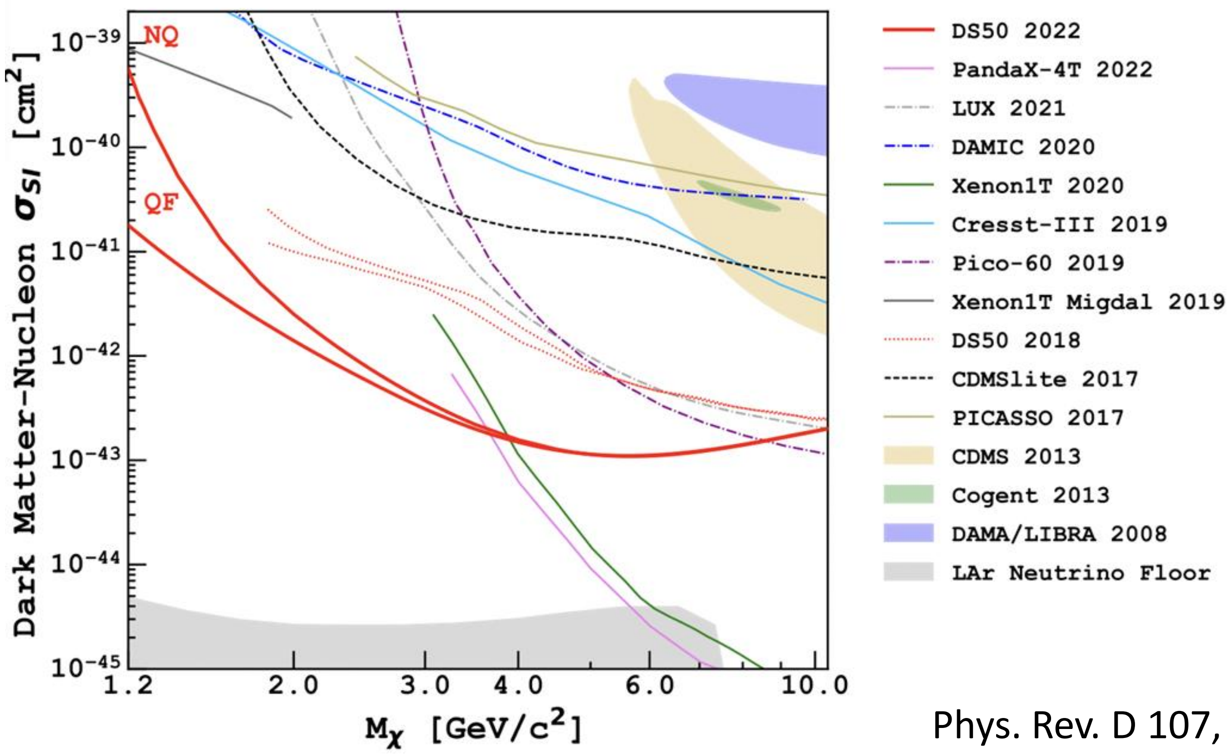
# Standard low mass wimp search

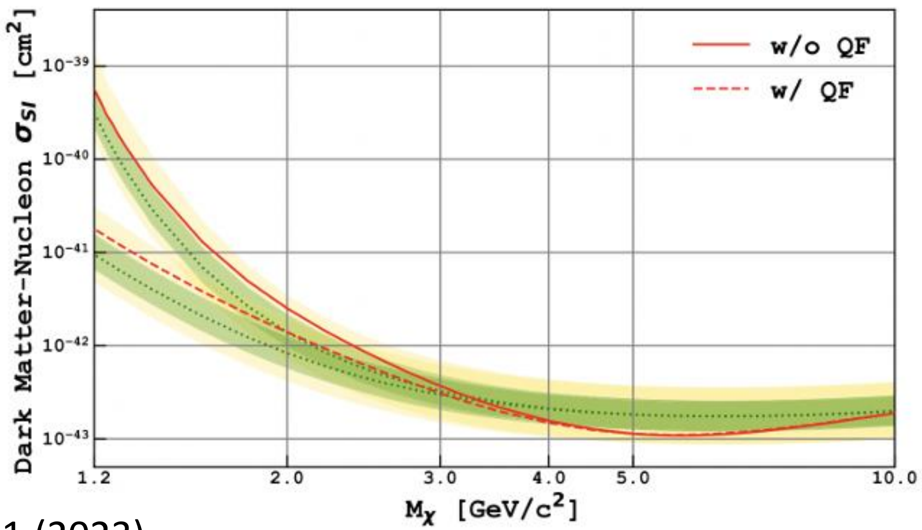
S1+S2 analysis, search for NR with PSD

Approaches used to improve sensitivity in low mass region:

- Extended exposure
- Improved data selection criteria
- More accurate detector calibration
- Better background modeling



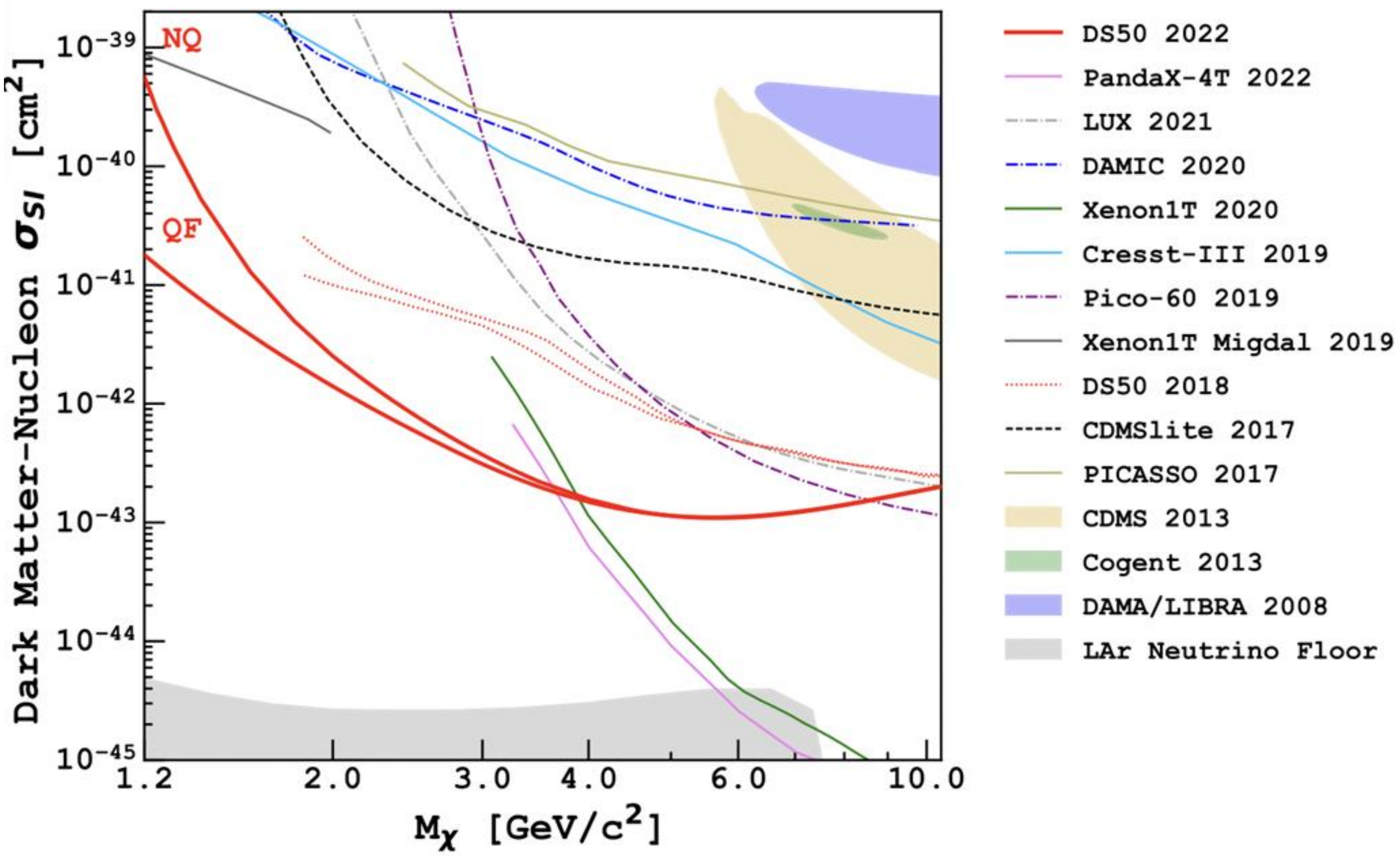




Phys. Rev. D 107, 063001 (2023)

# Standard low mass wimp search

This approach allowed us to set the most stringent exclusion limit at Mχ = [1.2, 3.6] GeV/$c^2$

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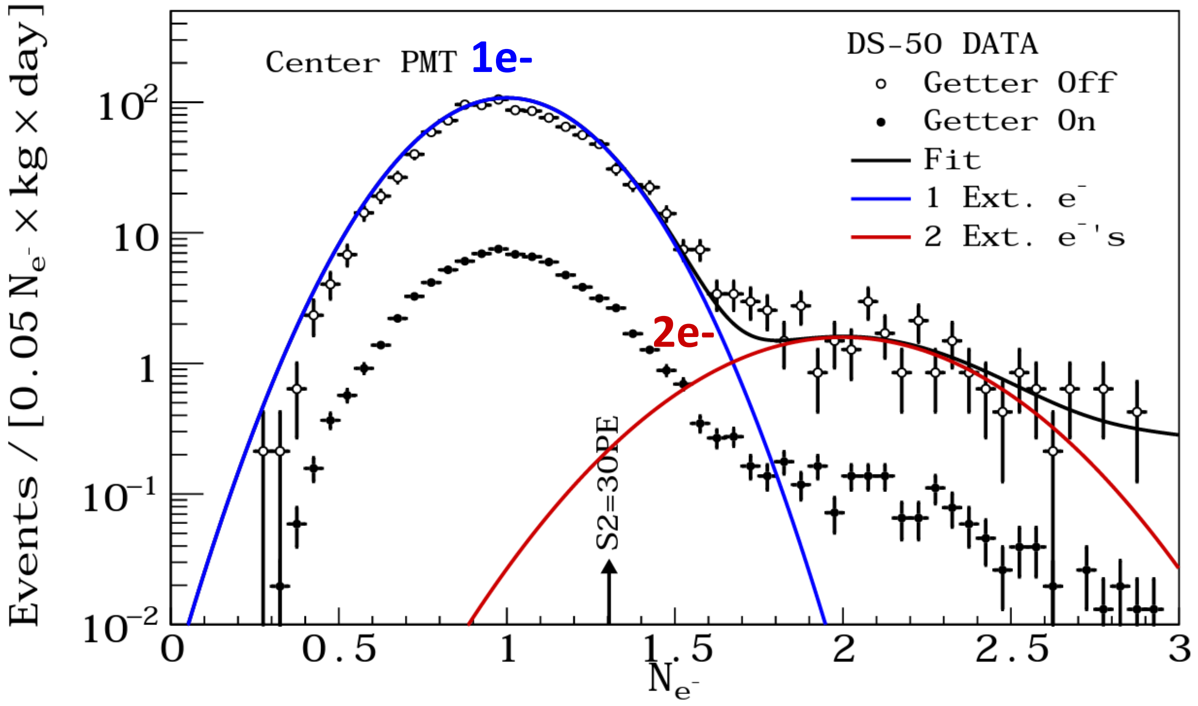
# S2-only low mass wimp search

- Using only S2 signal in analysis allows to increase sensitivity to low-energy interactions (which is crucial for low mass DM search), but PSD and Z-coordinate reconstruction become unavailable
- S2 signals, amplified in GAr, allow to identify even the single ionization electron

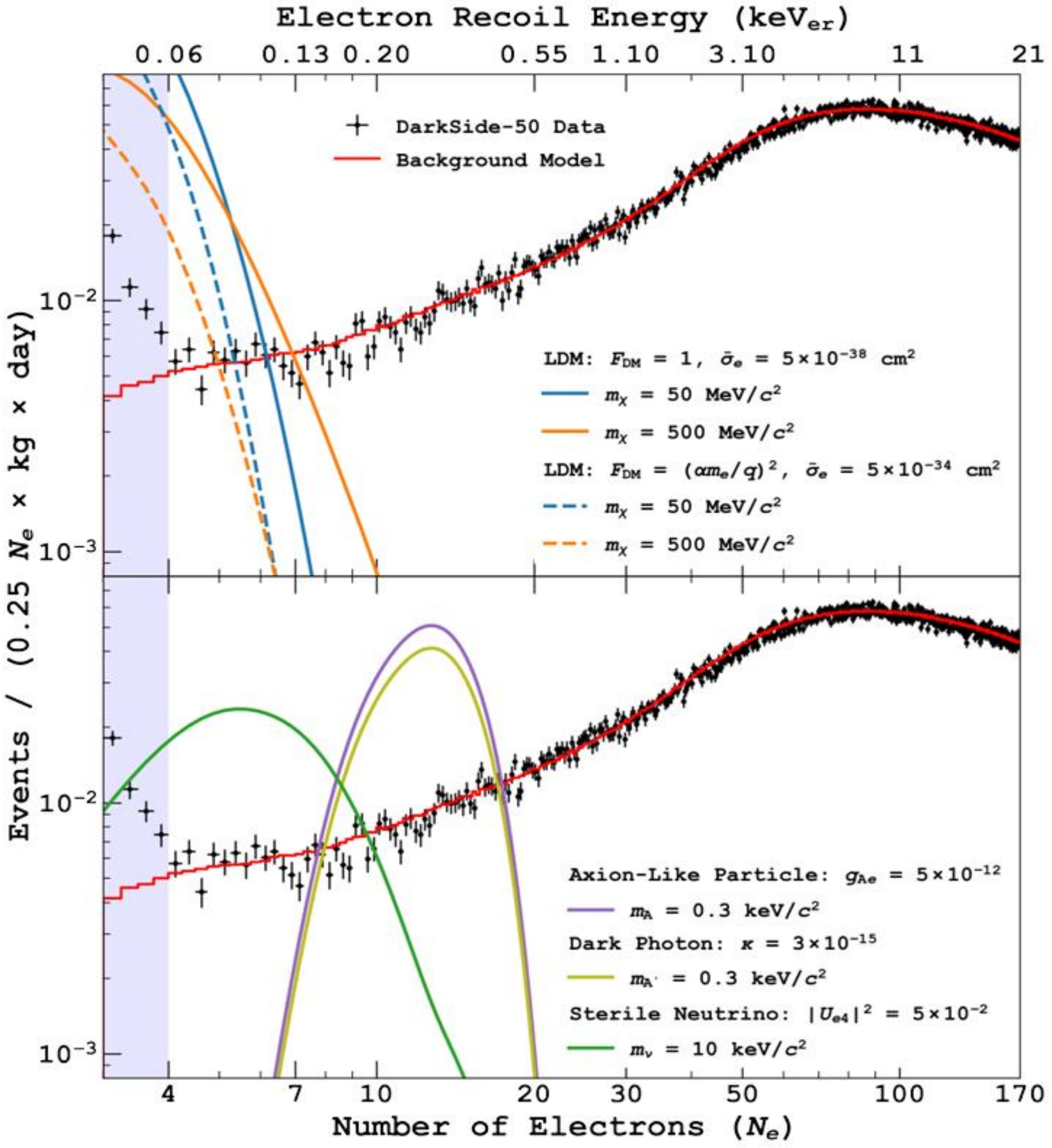



Phys. Rev. Lett. 121, 081307 (2018)

# DM-electron scattering

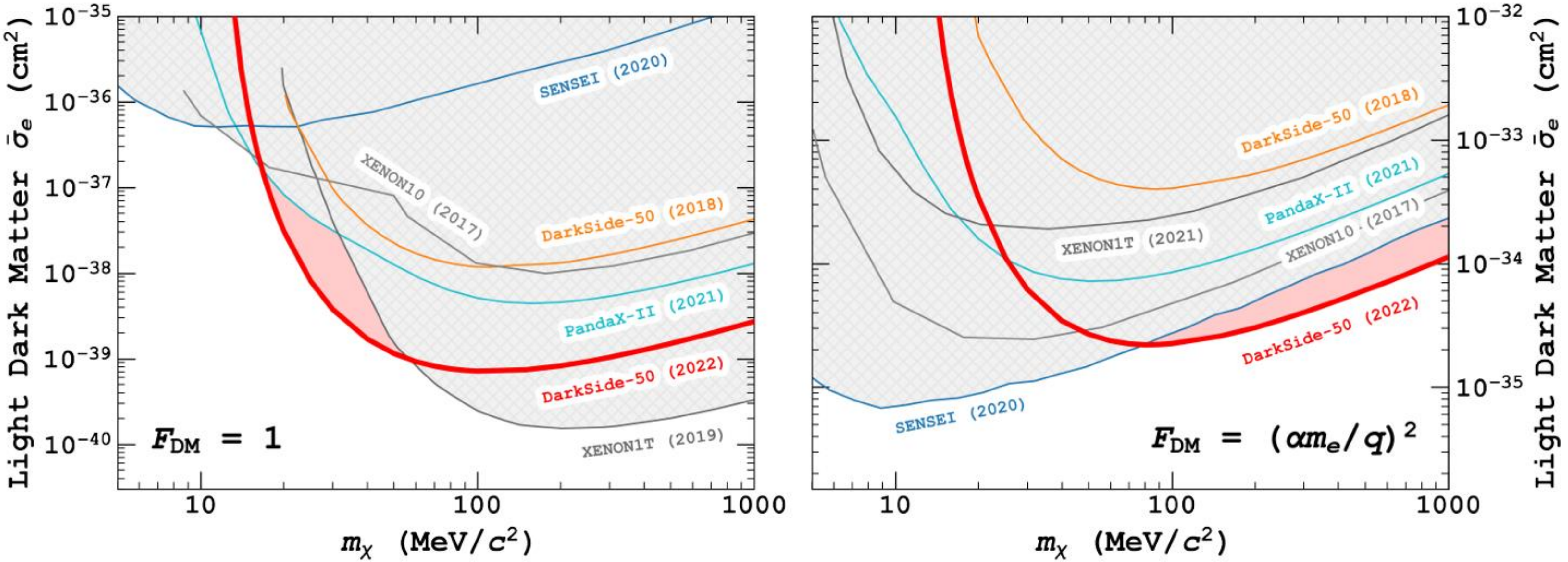
This mechanism describes interactions between several DM candidates and bound electrons of a target atom:

- Fermion or scalar boson light DM (LDM) interact via a vector mediator → ionization
- Pseudo-scalar DM (Axion-Like Particles) or vector boson DM (Dark Photons) are absorbed by argon shell electrons → monoenergetic signal at the particle’s rest mass
- Sterile neutrinos inelastically scatter of bound electrons → ionization




Phys. Rev. Lett. 130, 101002 (2023)

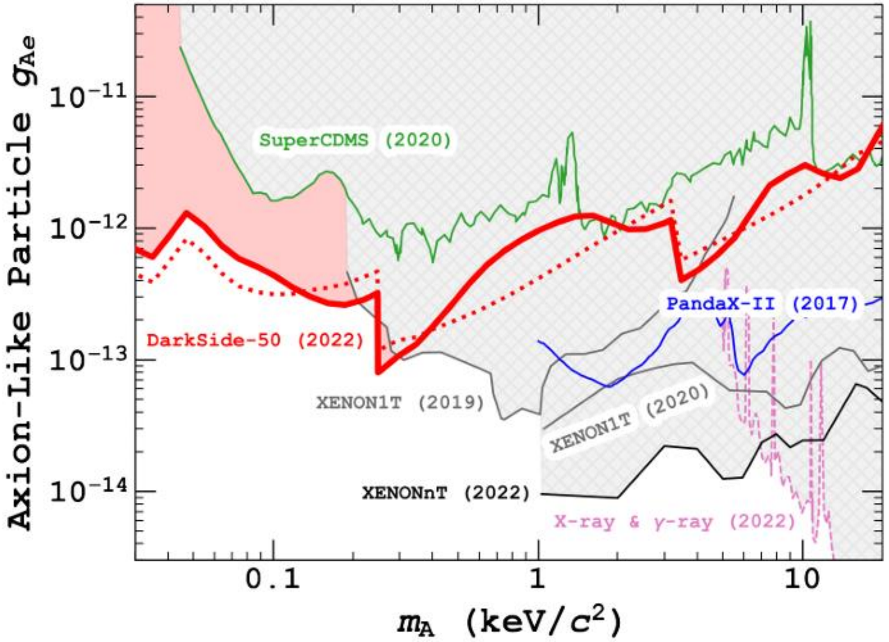
# DM-electron scattering

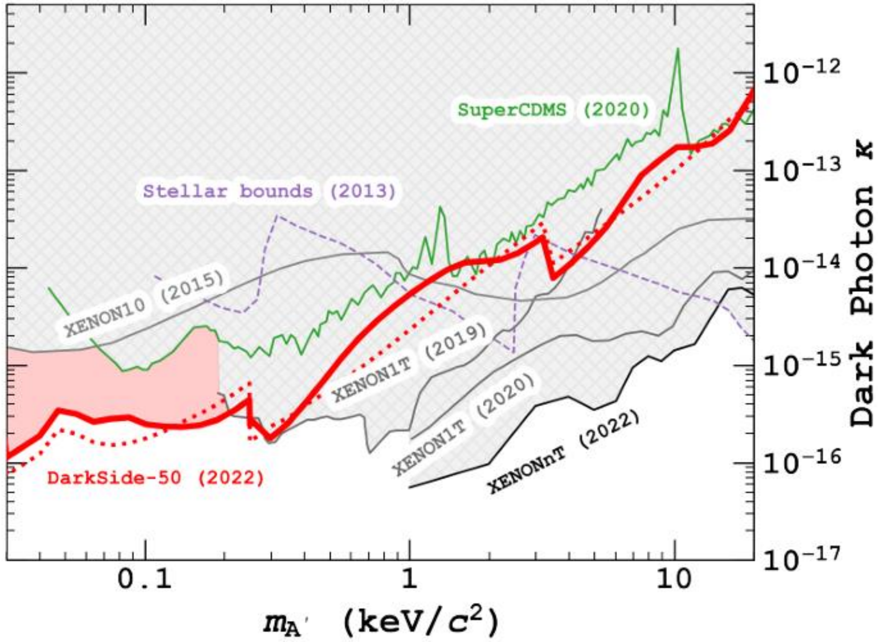



Phys. Rev. Lett. 130, 101002 (2023)

The most stringent exclusion limit on DM-electron interaction cross section was set in the mass region of [16, 56] MeV/$c^2$ for a heavy mediator and above 80 MeV/$c^2$ for a light mediator

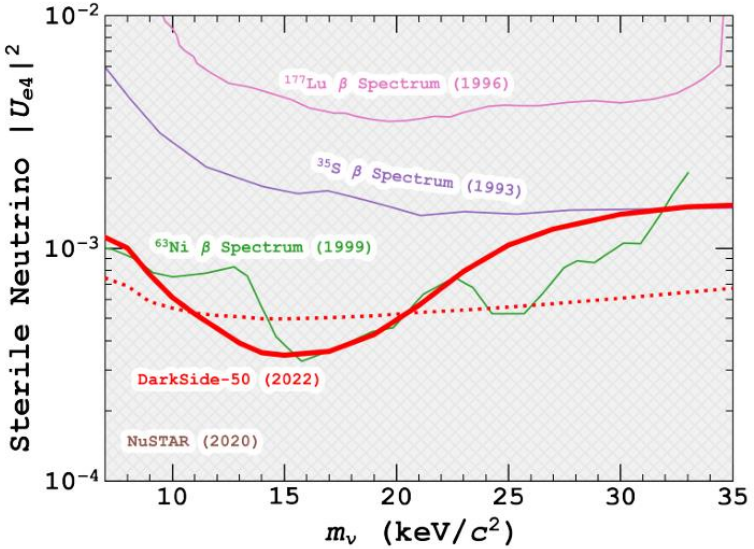
# DM-electron scattering




For different DM candidates the exclusion limit was calculated for model parameters:

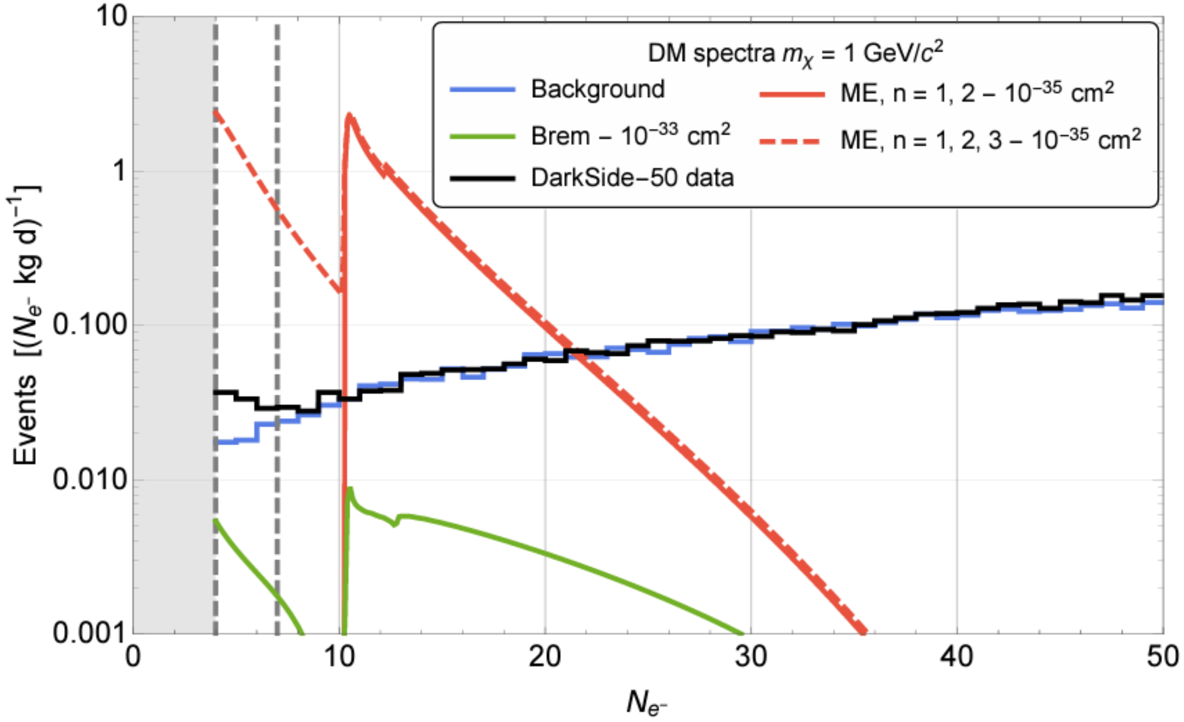
- Axion-electron coupling strength $g_{Ae}$
- Dark photon-photon kinetic mixing strength $\kappa$
- Sterile neutrino mixing angle $|U_{e4}|^2$




Phys. Rev. Lett. 130, 101002 (2023)

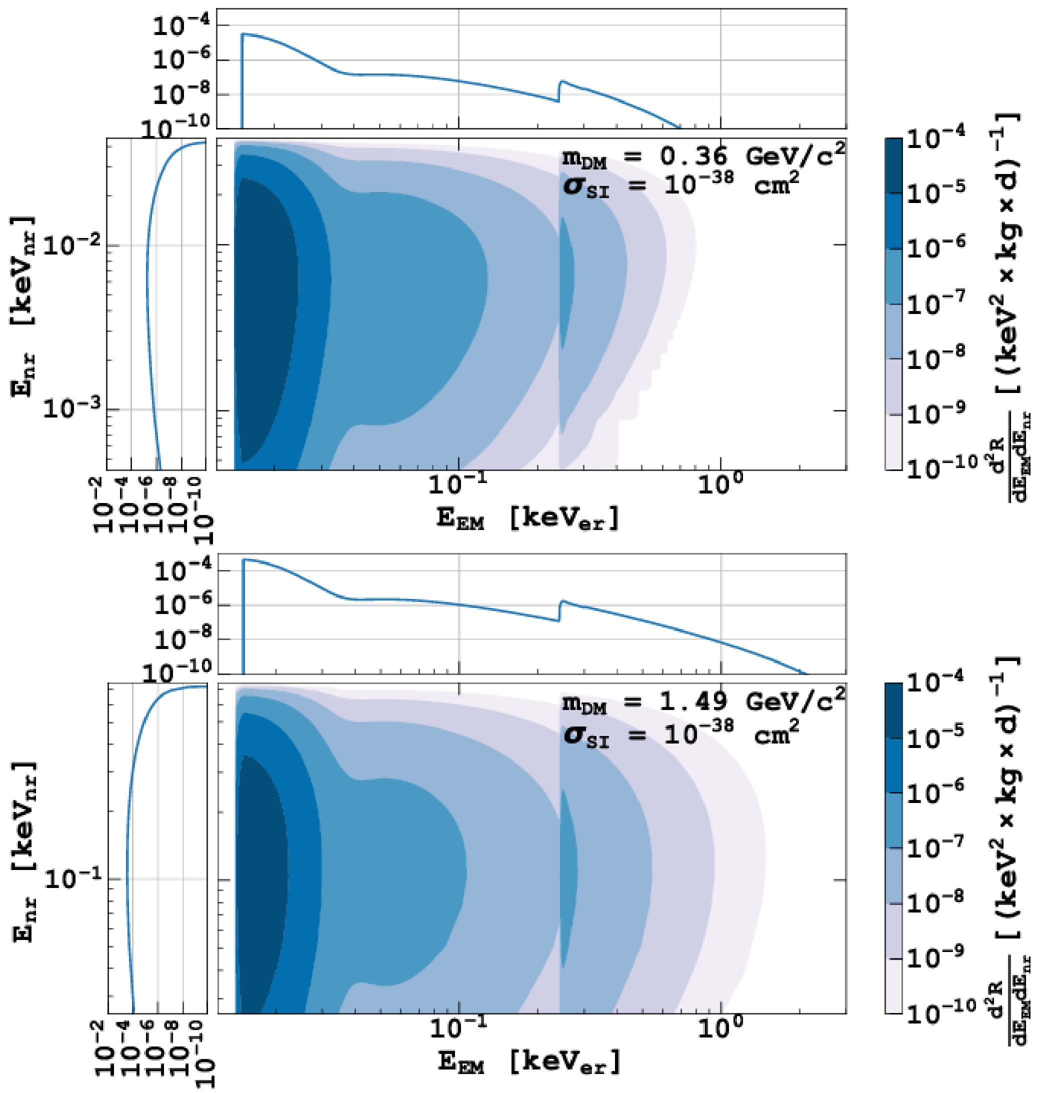
# Migdal effect and bremsstrahlung

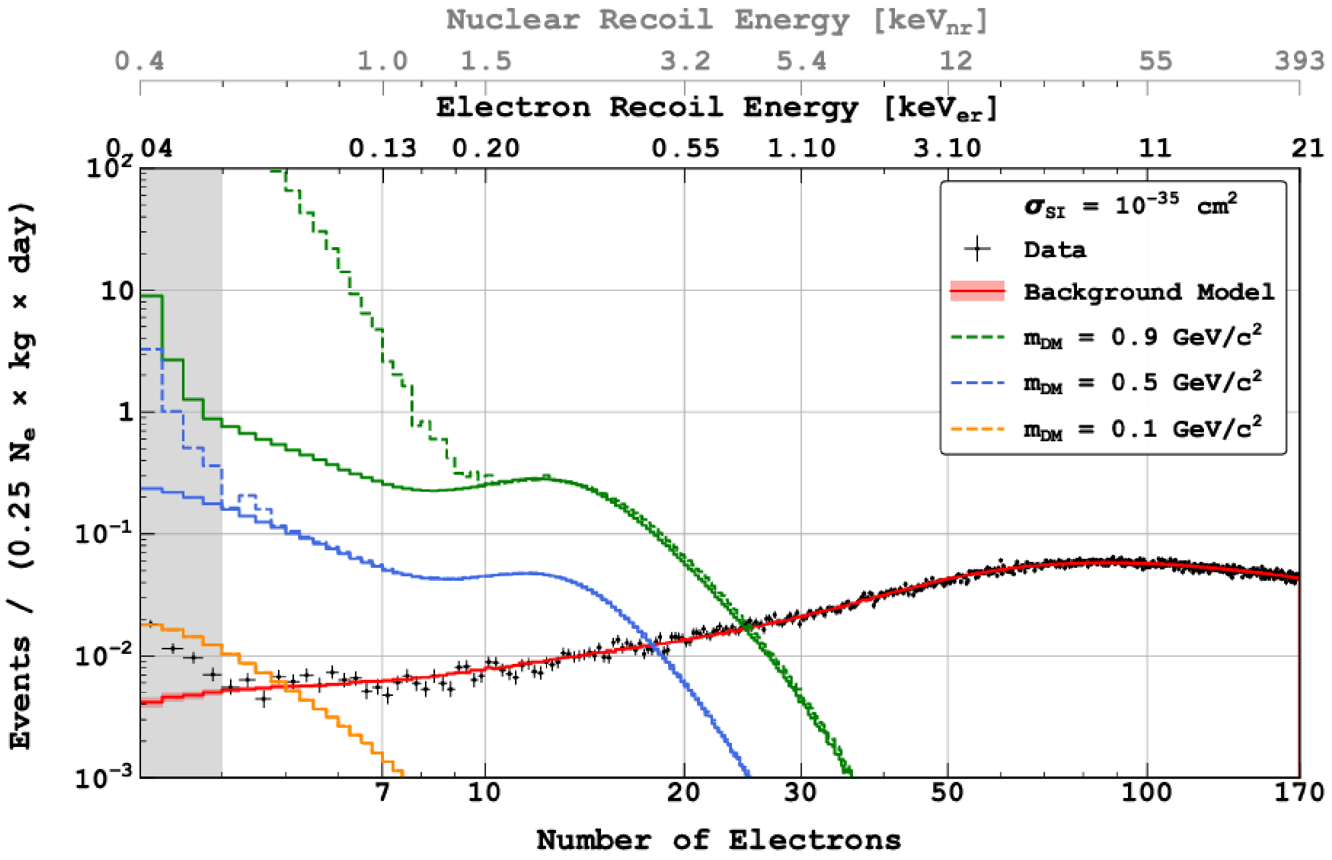
- Migdal effect (ME): delayed movement of the electron shells after the recoiling nucleus→ polarization of the atom → ionization and photon emission
- Bremsstrahlung: accelerated movement of the recoiling nucleus in the electric field of its electron shells → photon emission (weak effect)




JHEP 11 (2020) 034 (with old dataset)

# Migdal effect

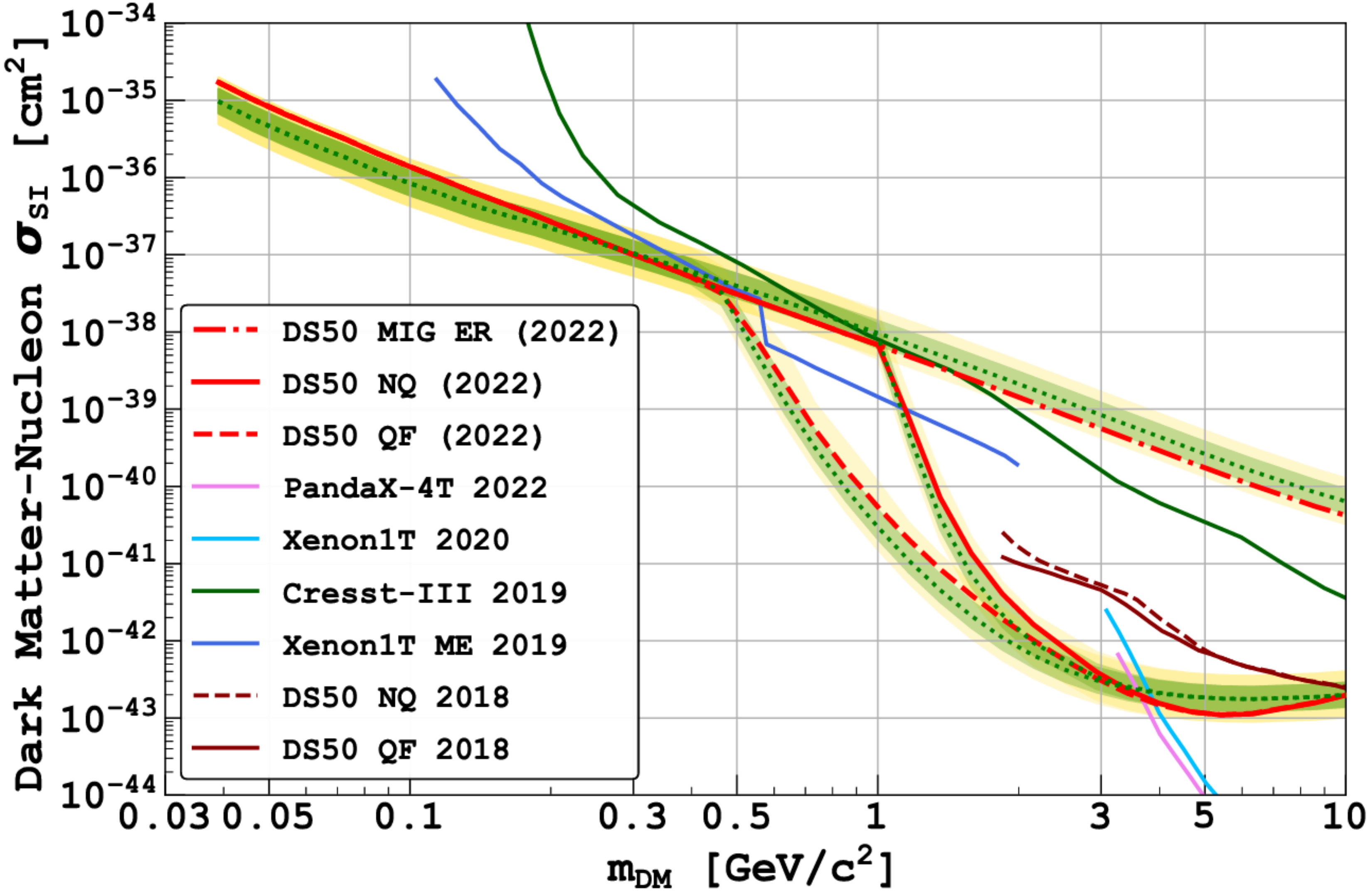



Phys. Rev. Lett. 130, 101001 (2023)

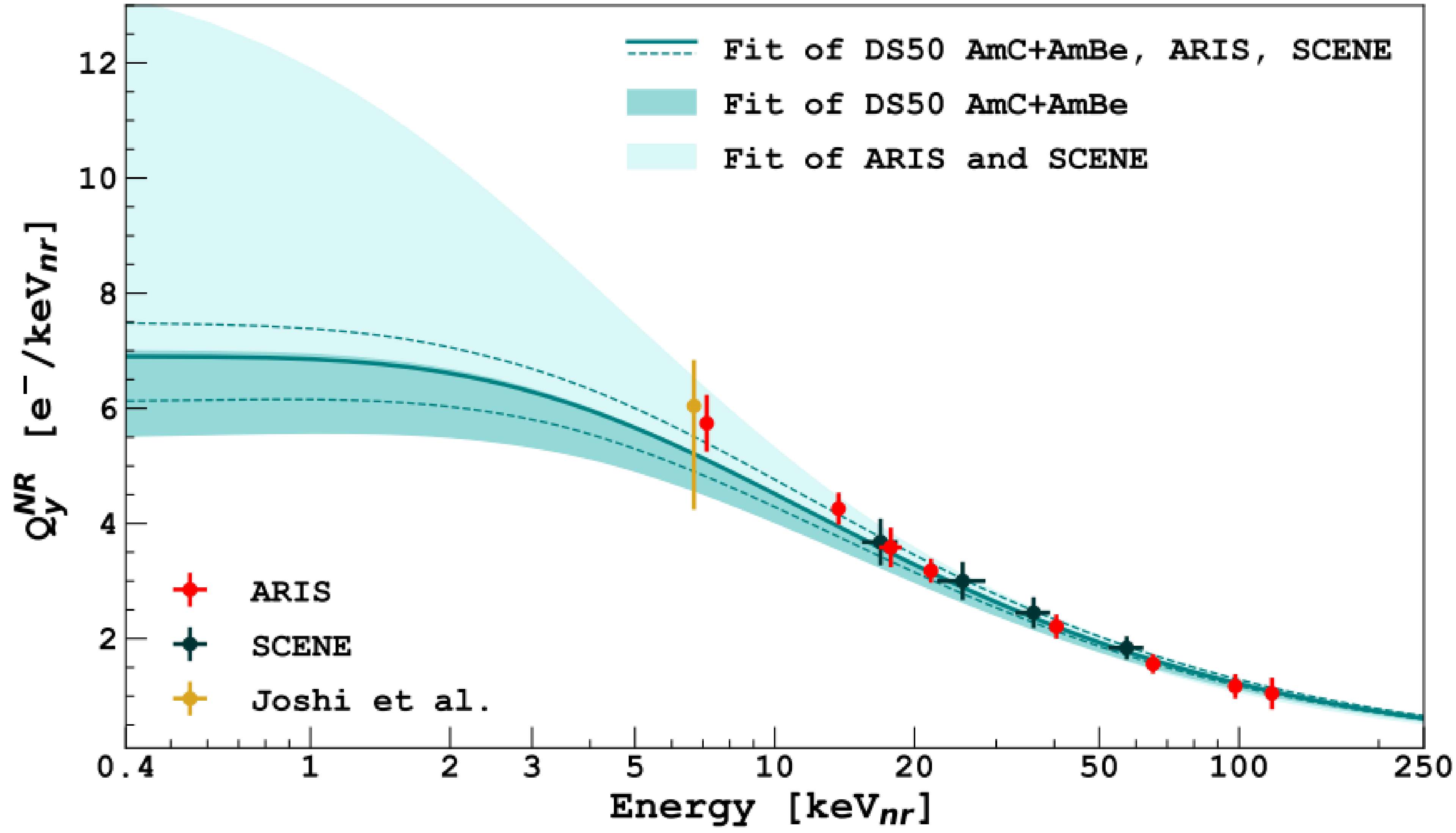
# Migdal effect

- This approach allowed us to set the most stringent exclusion limit at Mχ = [0.04, 3.6] GeV/$c^2$
- The limit is entirely driven by ME up to 0.5 GeV/$c^2$; also, the limit in this mass region is not affected by choice of quenching fluctuation model



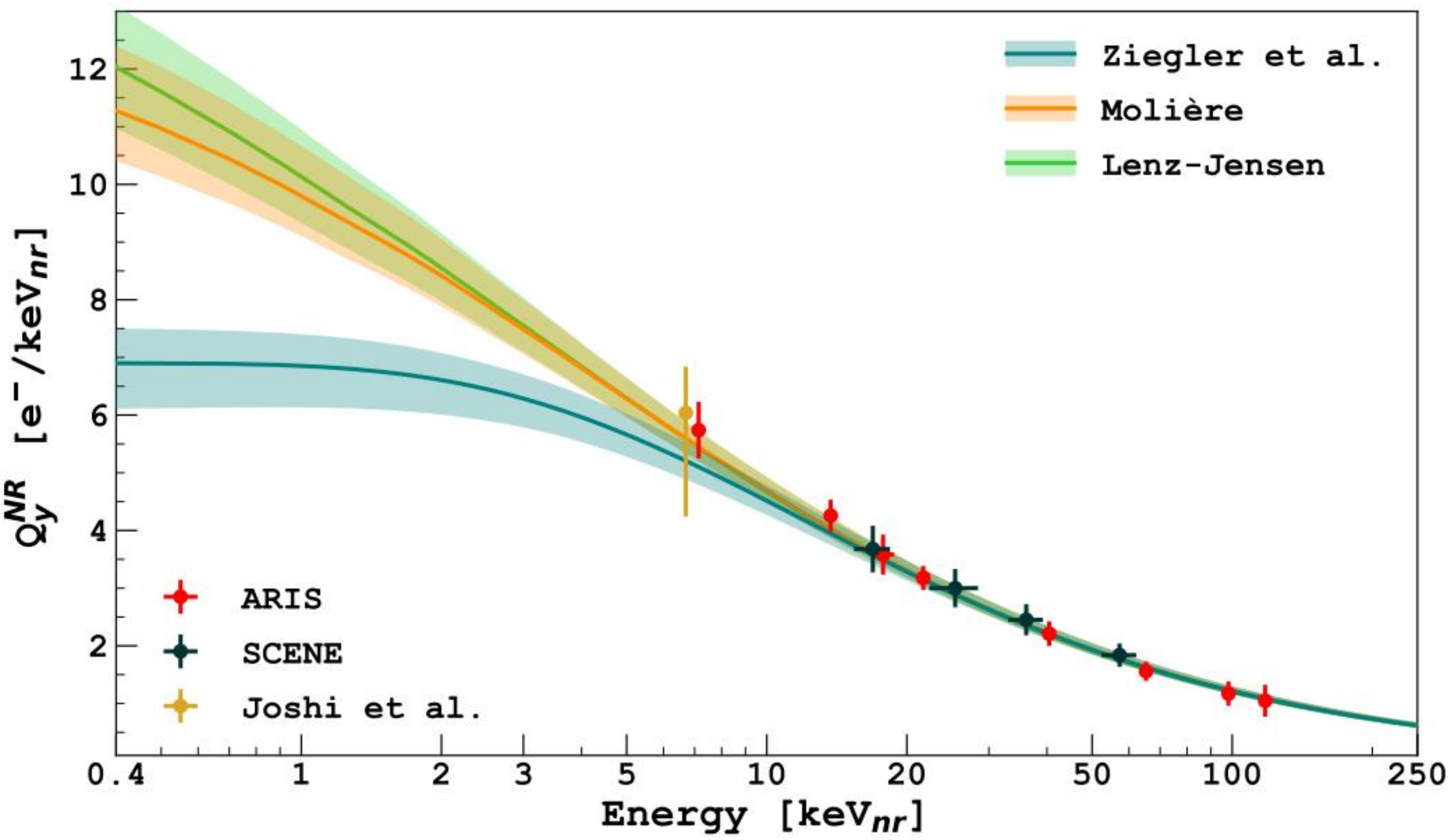

Phys. Rev. Lett. 130, 101001 (2023)

# Low energy calibration




Phys. Rev. D 104, 082005 (2021)

# Atomic screening models




Phys. Rev. D 104, 082005 (2021)

# Project of the experiment

- The main goal of the proposed experiment is to study low-energy recoils of neutral particles in argon
- The experiment will use a two-phase argon time projection chamber (TPC) and a neutron beam produced by $^{7}Li(p,n)^{7}Be$ reaction with protons accelerated to ≈ 2 MeV by VITA tandem accelerator at the Budker Institute of Nuclear Physics in Novosibirsk, Russia
- To determine neutron energy, time of flight and geometry (scattering angle) methods will be used
- This approach is expected to allow us to register recoils with energies down to tenths of a keV

# Conclusions

- Detectors with dual-phase argon TPCs, such as DarkSide-50, are able to significantly increase the dark matter search capabilities in low mass region
- Advanced analysis methods and implementation of atomic effects, such as the Migdal effect, in the analysis can furthermore increase sensitivity of low mass dark matter search
- Increasing of exposure is crucial for low mass dark matter search, which will be achieved by experiments with much greater target mass, such as DarkSide-20k and DarkSide-LowMass – the next stages of the DarkSide program
- To increase the sensitivity for the low mass dark matter search experiments, the project for the experiment to study low-energy recoils in argon was developed