DarkSide-20k sensitivity to light dark matter particles

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On Behalf of the DarkSide-20k Collaboration

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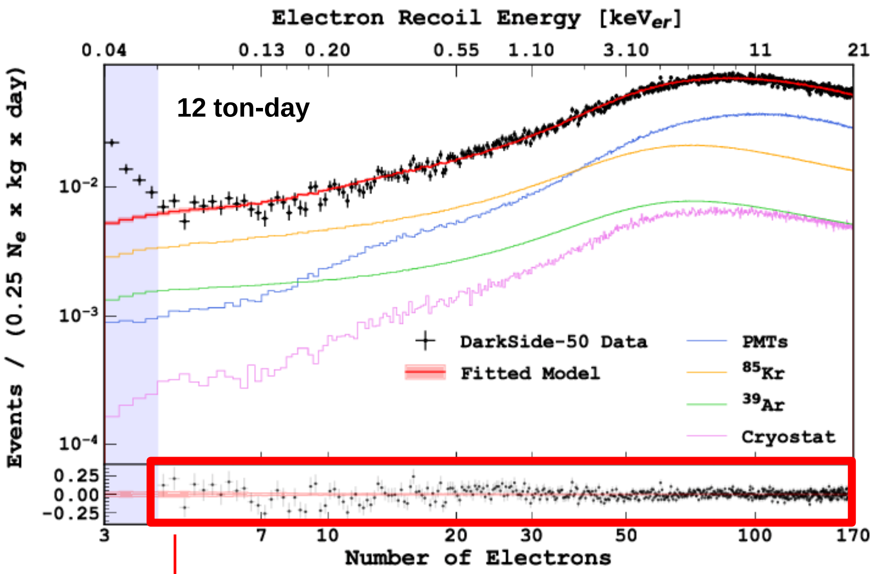
Introduction

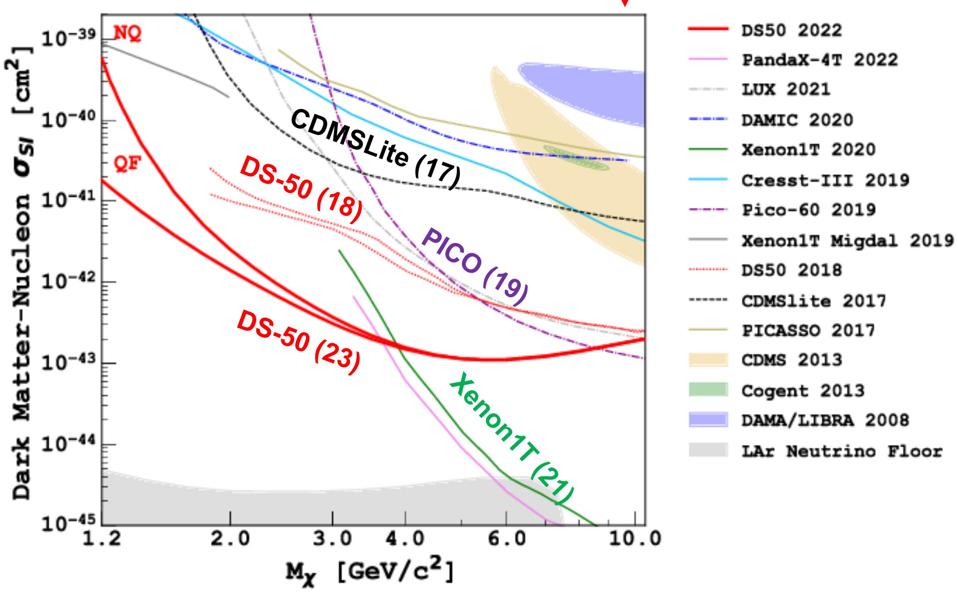
- DarkSide-50, double phase TPC, used 50 kg of low-radioactivity underground argon (UAr)
- Obtained world best limits on WIMP-nucleon σ_{SI} for light WIMPs (1.2-3.6 GeV)
- Extended down to 40 MeV using Migdal effect + limits on leptophilic light DM candidates

PRD 107 (2023) 063001

PRL 130 (2023) 101001

PRL 130 (2023) 101002



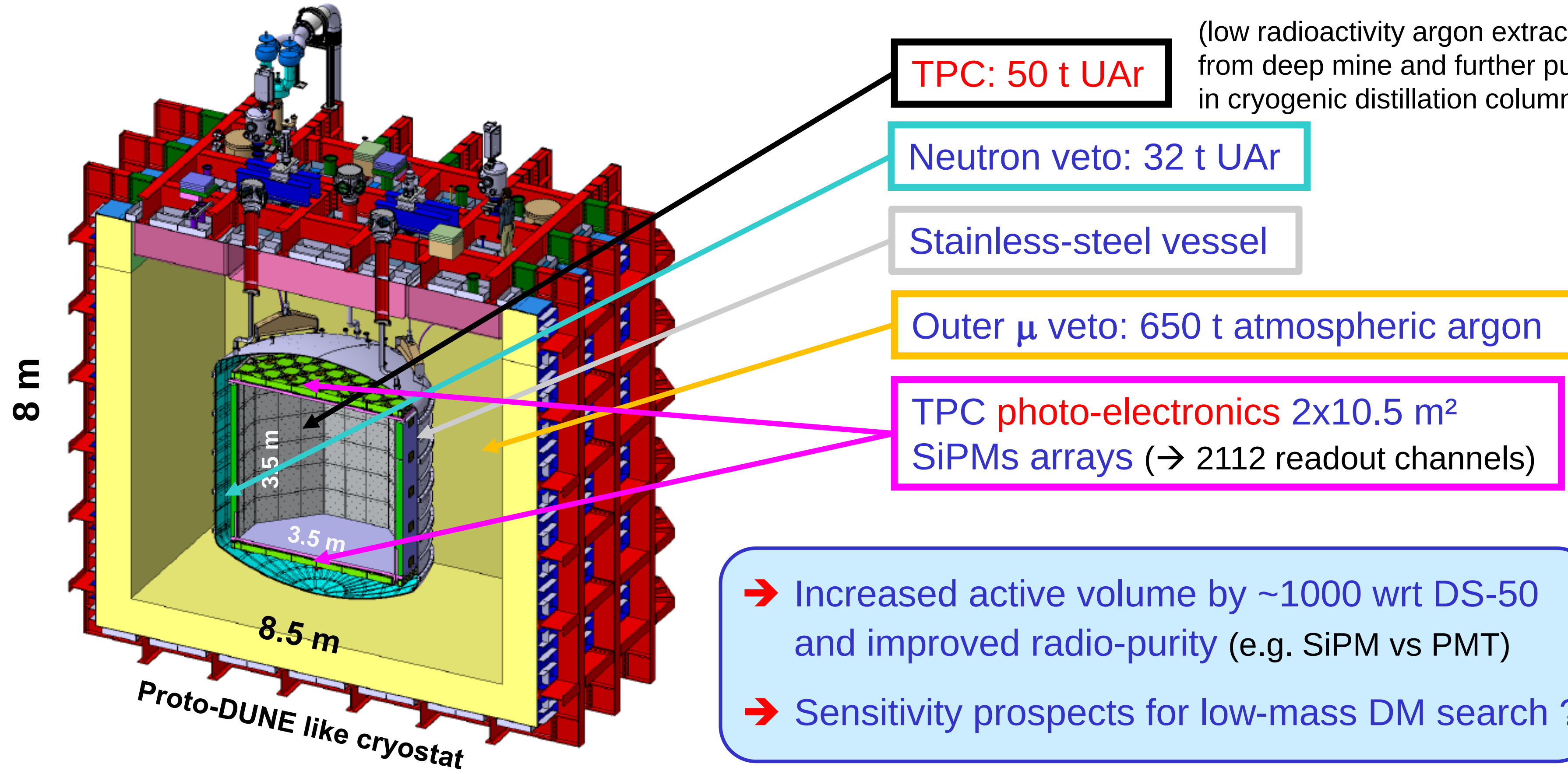


Excellent background modelling of ionization spectrum (only fitted variable)

➔ Asset of argon TPC technology to search for light (<10 GeV) DM

DarkSide-20k in a nutshell

- **DarkSide-20k** = next generation LAr double phase TPC (unique world-wide collaboration)
- Construction started at LNGS ➔ Should start data taking in 2027



➔ Increased active volume by ~1000 wrt DS-50 and improved radio-purity (e.g. SiPM vs PMT)

➔ Sensitivity prospects for low-mass DM search ?

DS-20k: low mass DM analysis

- Scintillation signal **S1** threshold O(5 keV_{nr}) is too high for light DM search → Can only use ionization signal **S2** →

electrons drifted upwards (E=200 V/cm, max drift time = 3.7 ms, lifetime 16 ms) and multiplied in gas phase → electroluminescence light yield ~25 PE/e-

  - ➢ No S1 Pulse Shape Discrimination to reject electron recoil (ER) background

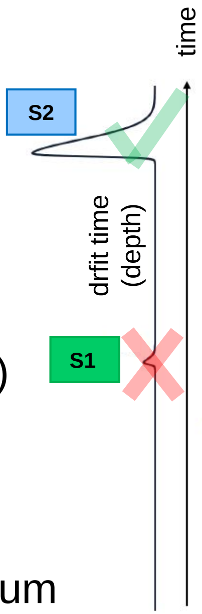
    → not a background free analysis
    (unlike the search for high mass WIMPs)

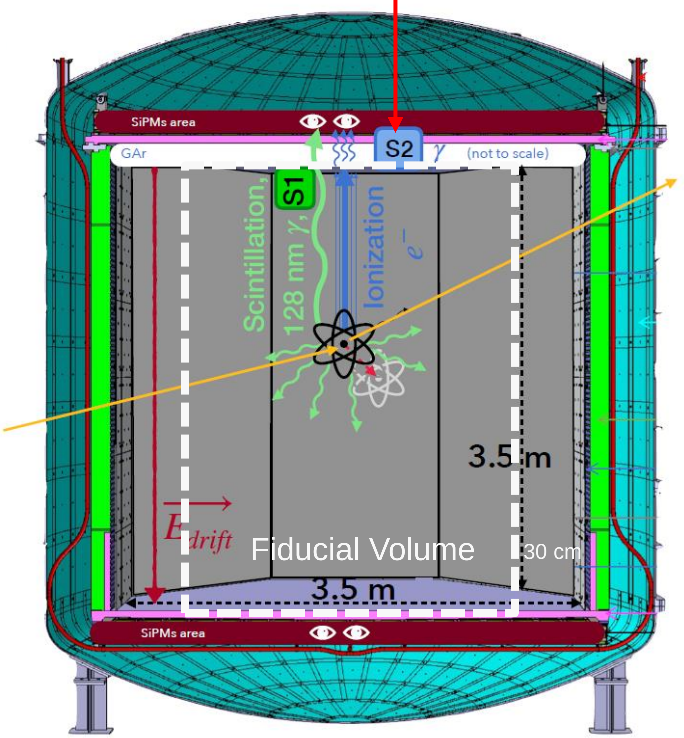
  - ➢ No fiducialization along drift direction

    → fiducialize in transverse direction (30 cm)

- Pile-up of β, X and γ backgrounds (80 Hz rate)

  → select single S2 pulses isolated from other S2 occurring at times greater than one maximum drift time (3.7 ms) → 51% of effective livetime





→ **exposure** = 17.4 ton.year for 1 year of data taking

→ Need to mitigate and accurately model ER background

Model: internal LAr background

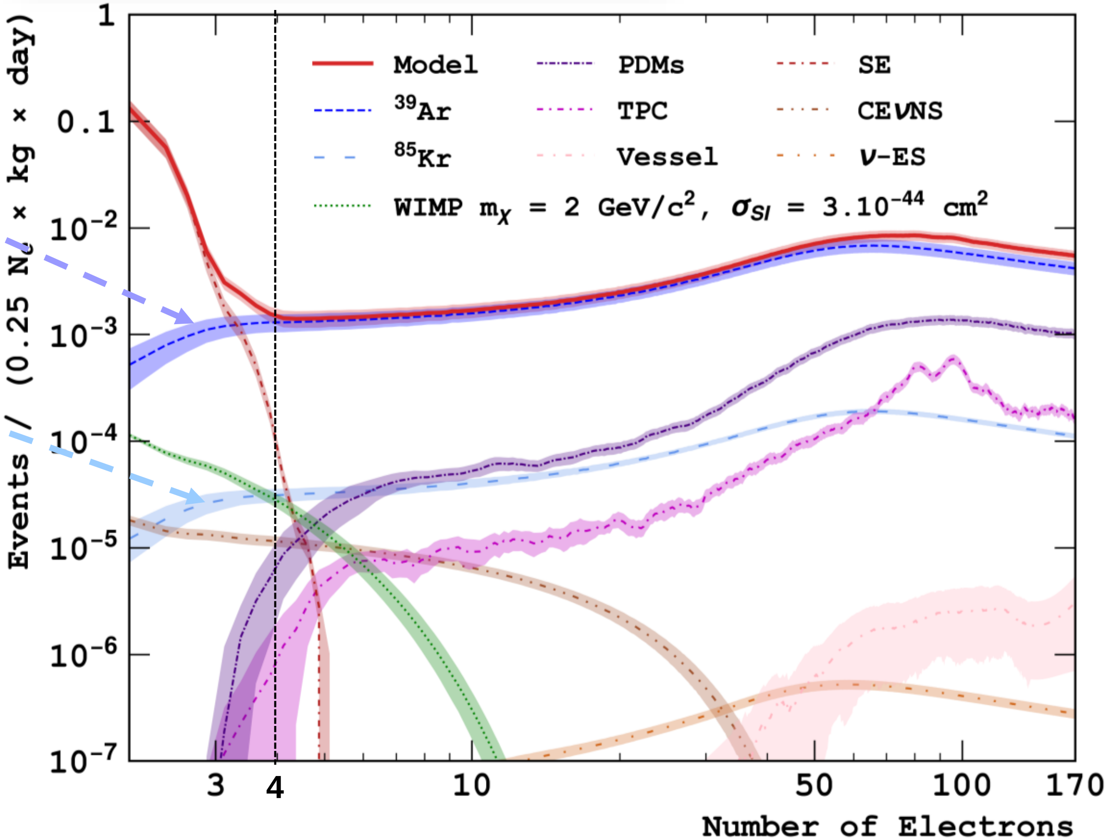
- **^{39}Ar and ^{85}Kr → β-emitters** uniformly distributed in LAr active volume
- Both unique first-forbidden β-decays → spectra from latest calculations of atomic exchange and screening effects

Phys.Rev.A 90 (2014) 012501, Phys.Rev.C 102 (2020) 065501

➢ ^{39}Ar activity: 0.73 mBq/kg
[same as DS-50, as same UAr mine]

➢ ^{85}Kr activity: 0.019 mBq/kg
[reduced wrt DS-50, as new distillation column at extraction plant]

→ Internal ^{39}Ar background dominant for $N_e \geq 4$



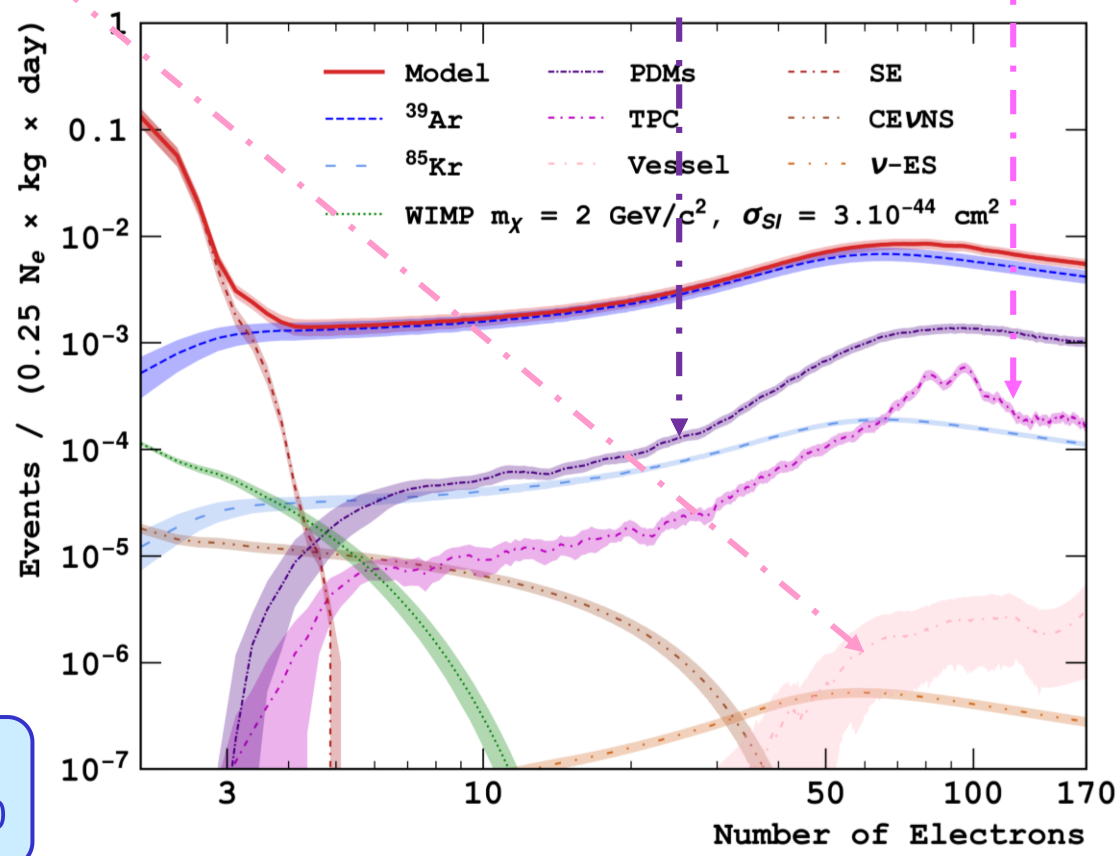
Model: external background

- Sources of **γ and X-rays from inner detector material**: photo-electronics (PDM), TPC structure and stainless-steel vessel

➢ Spectra from GEANT-4 based simulations

➢ Normalisation from material screening campaigns

Radio-contaminant	Activity (Bq) TPC	PDMs	SS vessel
^{238}U up	16.1	38.8	21
^{238}U mid	11.5	18.4	8.8
^{238}U low	16.4	449	62
^{232}Th	4.2	17.8	33
^{235}U	0.7	1.8	1.0
^{137}Cs	2.5	2.9	5.0
^{60}Co	2.0	5.1	13
^{40}K	102	269	49



➔ 2.5x reduced bkg contamination per surface area ⊥ to drift wrt DS-50

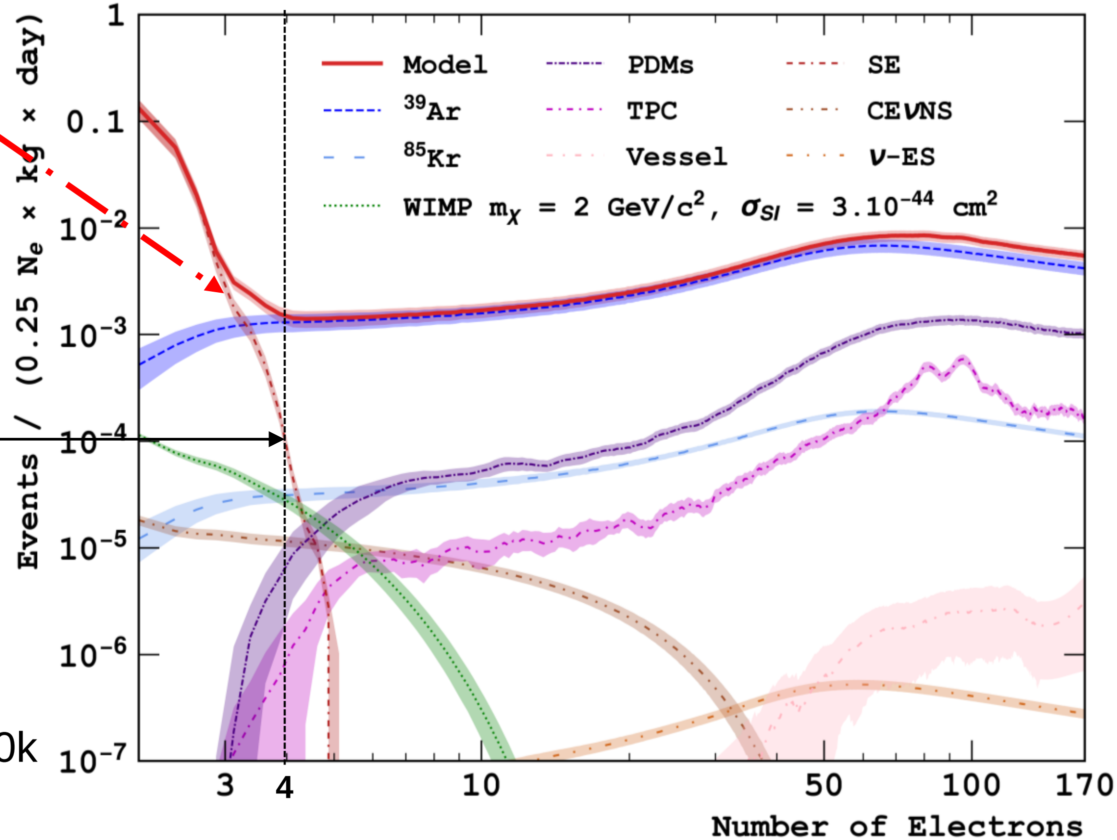
Model: spurious e⁻ background

- **Spurious e⁻ (SE)** origin might be electrons trapped by impurities and released later
- Model built by fitting DS-50 data and extrapolating to DS-20k (50x higher background rate and 10x larger drift length. 23% single electron response resolution)

➔ SE background dominant for $N_e \leq 3$

➢ Conservative approach: fit from N_e=4 → almost indep. of SE modelling, as SE 18x lower than ^{39}Ar at N_e=4 (DS-50 approach)

➢ Ultimate approach: fit from N_e=2 → assume good control of rate and spectral shape of SE in DS-20k

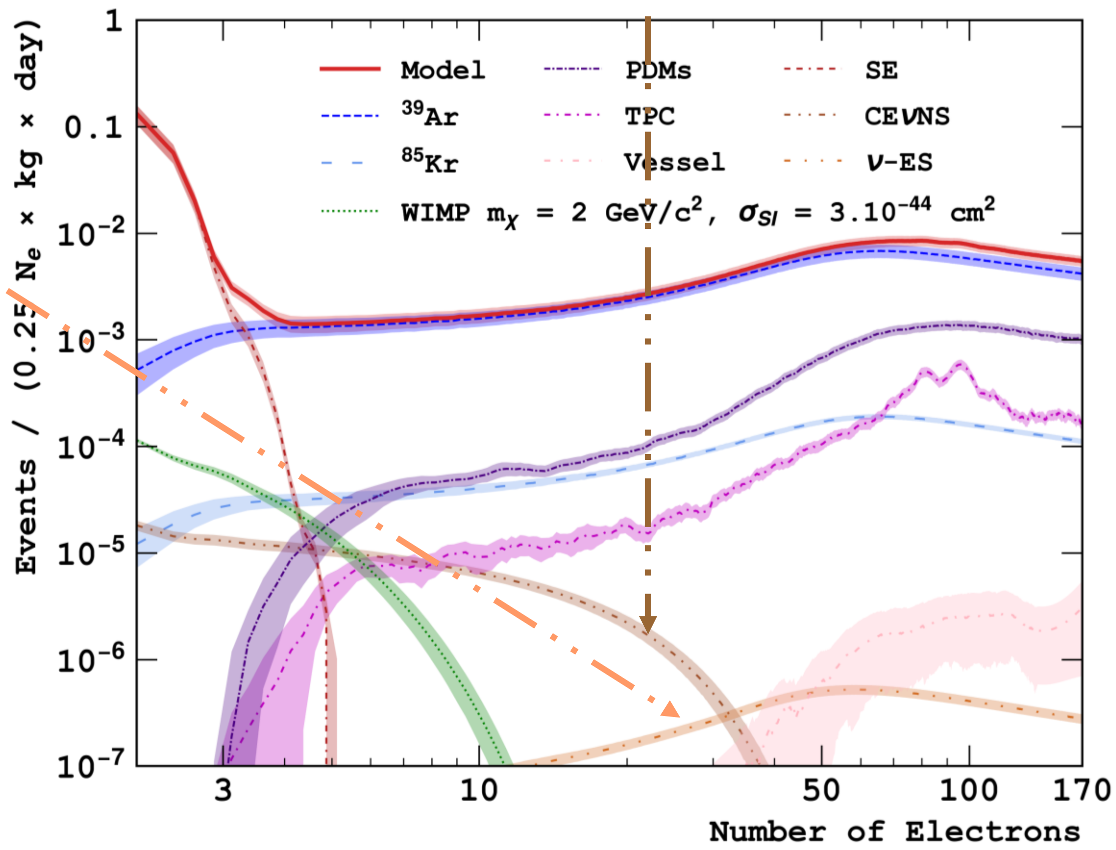


Model: neutrino background

- Coherent elastic scattering of solar neutrinos off argon nucleus **(CEνNS)** (mainly from solar ^{8}B ν) → nuclear recoil (NR) with Edep < 10 keV$_{nr}$

- Elastic scattering of solar neutrinos off argon electrons **(ν-ES)** (mainly from solar pp & ^{7}Be) → electron recoil(ER) with Edep < 20 keV$_{er}$

→ 2 to 4 orders of magnitude below ^{39}Ar background



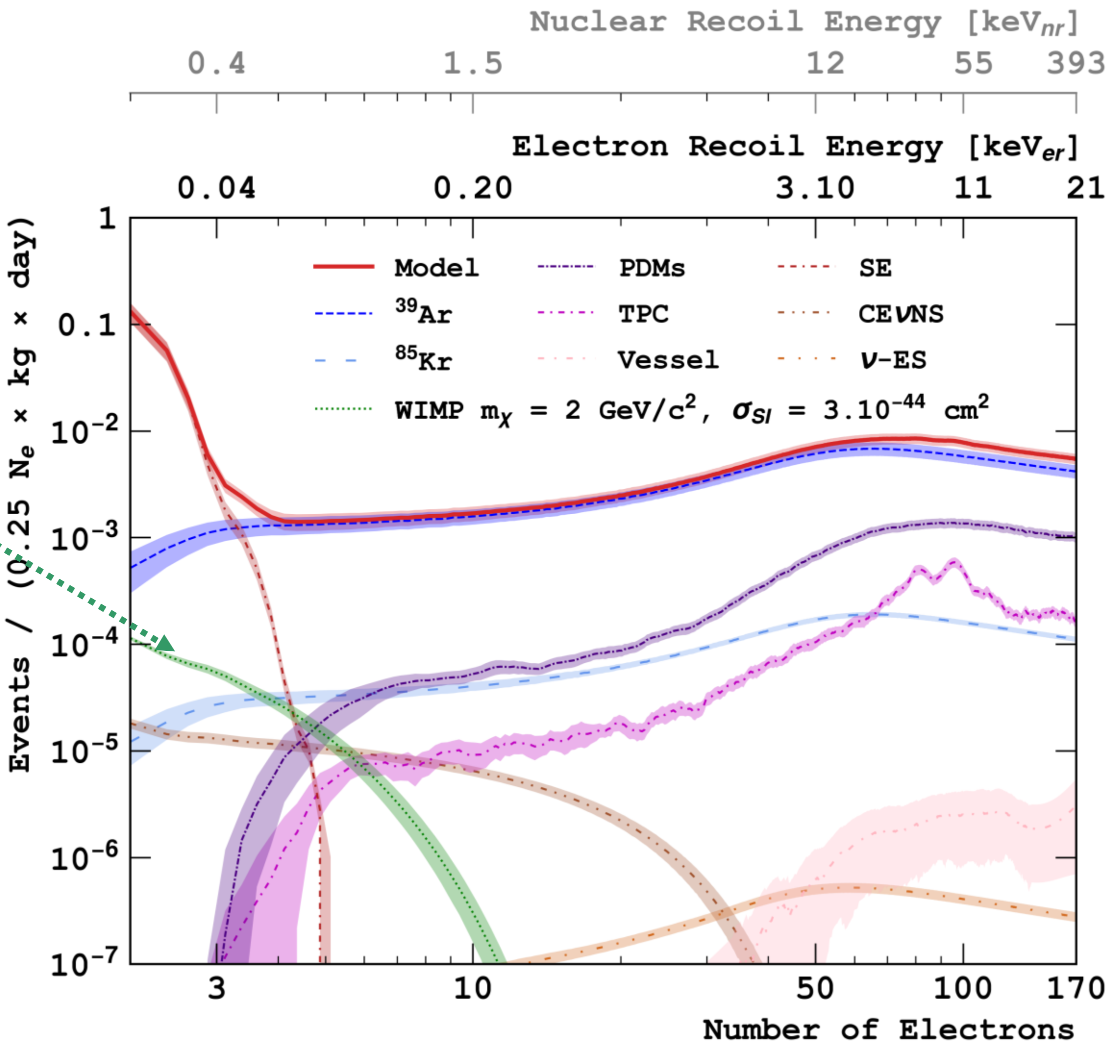
Model: WIMP signal

- Signal assumes recommended **Standard Halo model**

[v_{esc}=544 km/s, v_0=238 km/s, ρ=0.3 GeV/cm^3]

EPJC 81 (2021) 907

- Illustrated here for NR of 2 GeV mass WIMP with nucleon x-section $\sigma_{SI} = 3\times10^{-44}$ cm^2



Profile Likelihood and systematics

$$\mathcal{L} = \prod_{i \,\epsilon\, \text{bins}} \mathcal{P}\left(n_i | m_i(\mu_s, \Theta)\right) \times \prod_{\theta_i \,\epsilon\, \Theta} \mathcal{G}(\theta_i^0 | \theta_i, \Delta\theta_i) \times \prod_{i \,\epsilon\, \text{bins}} \mathcal{G}\left(m_i^0 | m_i(\Theta), \delta m_i(\Theta)\right)$$

Poisson probability of observing n_i events in the i^{th}-bin with respect to the expected ones, $m_i(\mu_s,\Theta)$, with μ_s the signal strength.

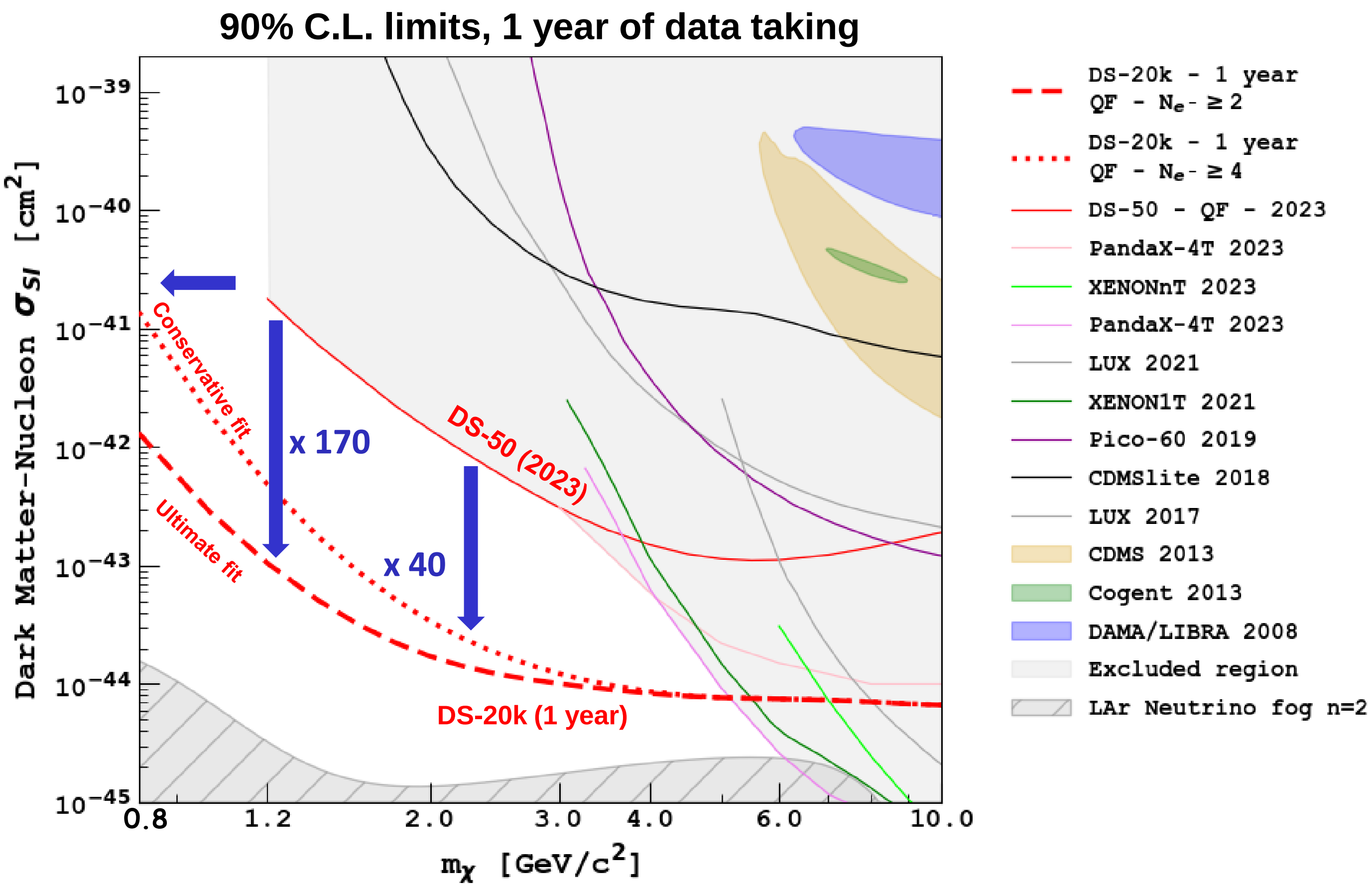
Gaussian penalties to account for the nuisance parameters (θ_0 and $\Delta\theta$ are the nominal central values and uncertainties)

Statistical uncertainties of the simulated sample

	Source uncertainty	Affected components
Amplitude	5% on the exposure	All
	15% on ^{39}Ar activity	^{39}Ar
	15% on ^{85}Kr activity	^{85}Kr
	20% on SE normalization	SE
	10% on activity from PDMs	PDMs
	10% on activity from the vessel	Vessel
	10% on activity from the TPC	TPC
	10% on neutrinos normalization	Neutrinos
Shape	atomic exchange and screening	^{39}Ar
	atomic exchange and screening	^{85}Kr
	1% on the ^{39}Ar-decay Q-value	^{39}Ar
	0.4% on the ^{85}Kr-decay Q-value	^{85}Kr
	SE modelling	SE
	ER ionization response	All backgrounds but CEνNS, SE
	NR ionization response	WIMP, CEνNS

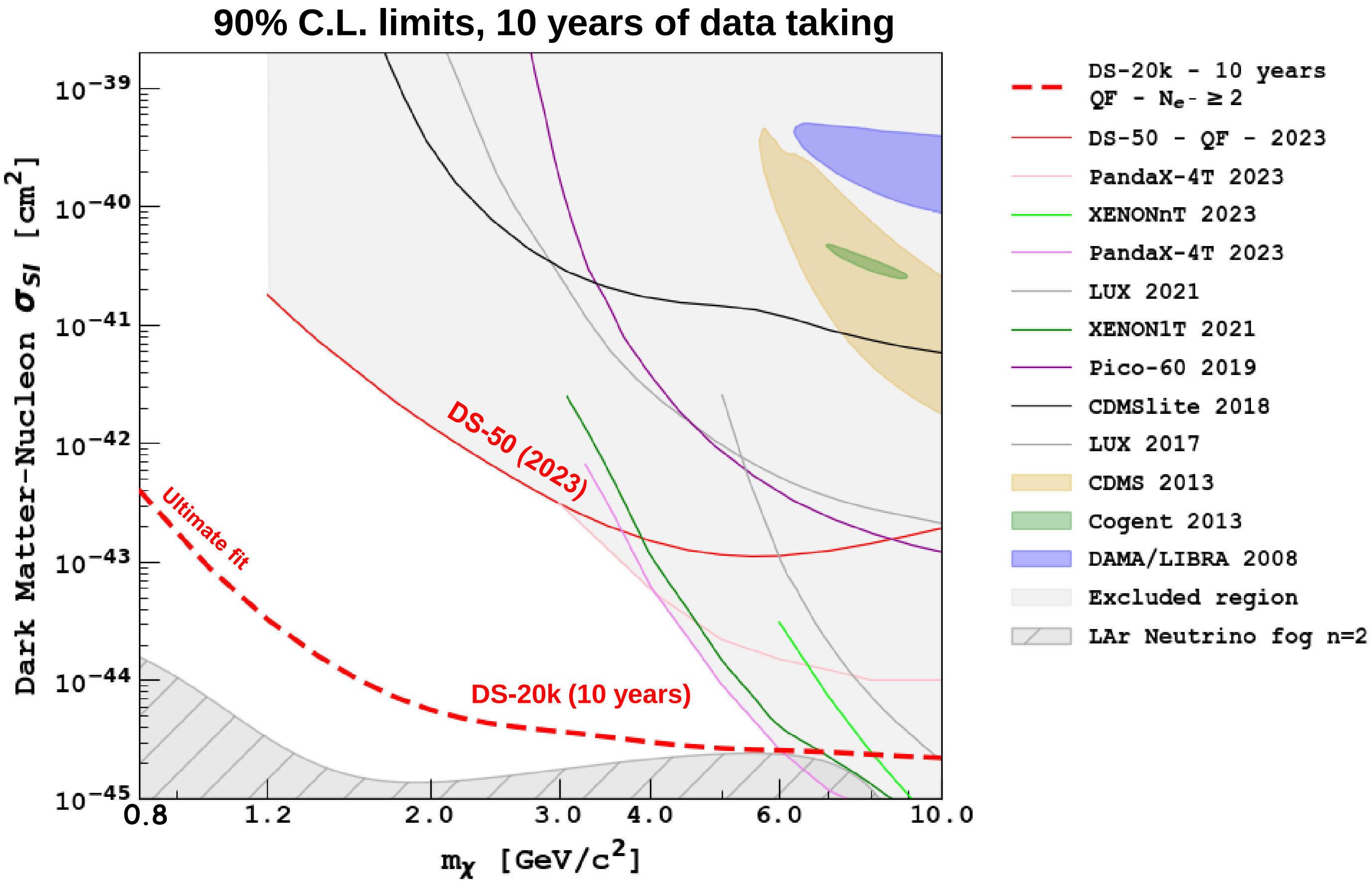
- 90% C.L. limits from binned profile-likelihood fit on N_e distribution, including amplitude uncertainties (activities, exposure) and shape systematics (β-decay shapes, LAr response calibration, SE)
- Strong constraints on nuisance parameters associated to dominant backgrounds and ER ionization yield

Sensitivity to low mass WIMPs (1/3)



- ➔ Sensitivity to WIMP-nucleon $\sigma_{SI} < 1\times10^{-42}$ cm^2 for $m_\chi > 800$ MeV
- ➔ > 1 order of magnitude improvement wrt to current experiments in 1 year

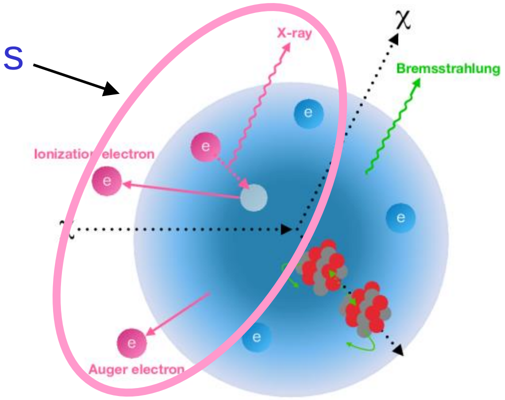
Sensitivity to low mass WIMPs (2/3)



➔ With 10 years exposure, **neutrino fog** in LAr reached m_χ around 5 GeV

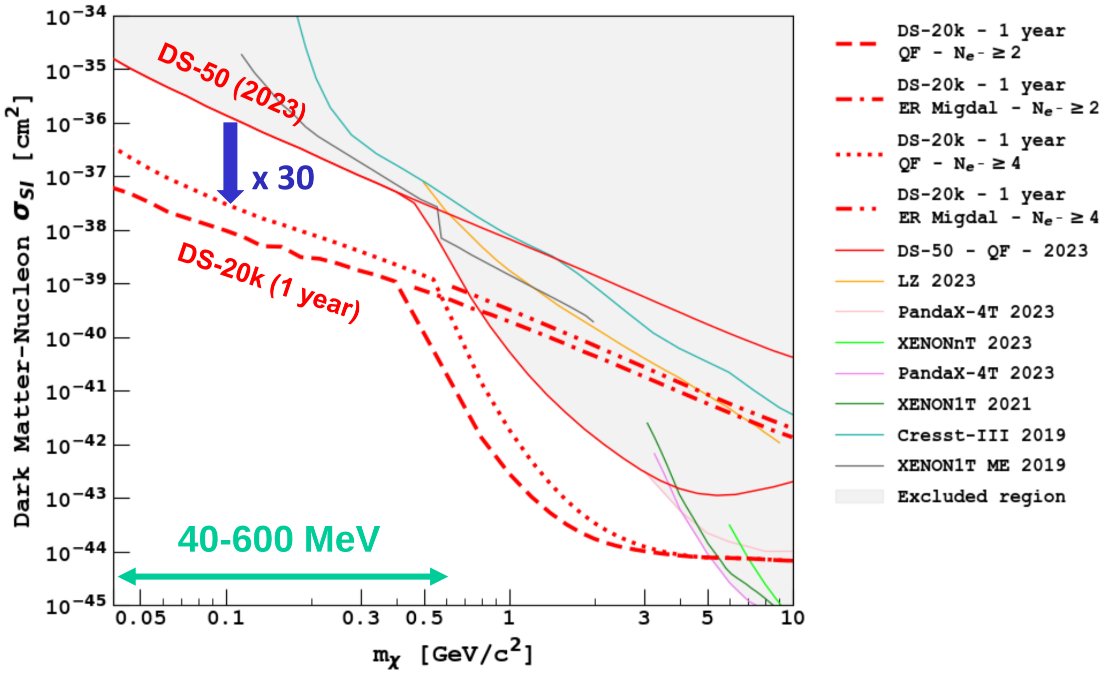
Sensitivity to low mass WIMPs (3/3)

- Including **Migdal effect** (not yet observed) ➔ additional electrons to NR signal ➔ enhanced sensitivity to low mass WIMPs



[from PRL123, 241803 (2019)]

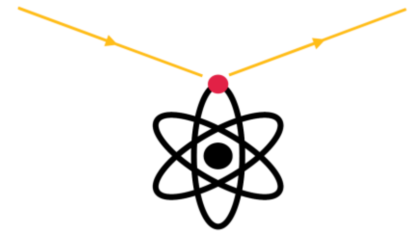
90% C.L. limits, 1 year of data taking



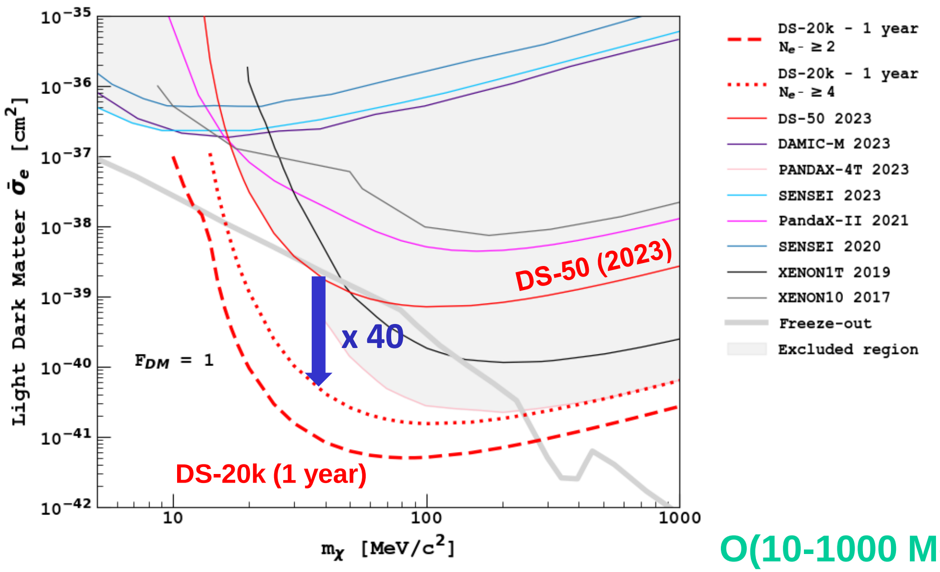
➔ > 1 order of magnitude improvement wrt to current experiments in 1 year

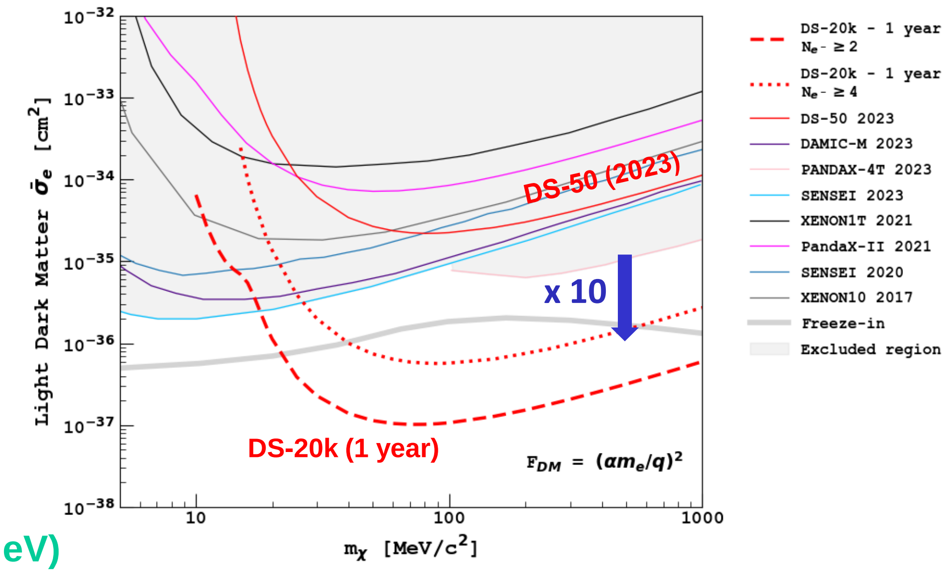
Sensitivity to leptophilic DM (1/3)

- Elastic scattering of **Light Dark Matter** (sub-GeV fermion or scalar boson) off bound electrons via heavy or light vector mediator



90% C.L. limits, 1 year of data taking



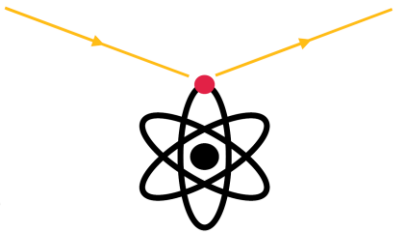


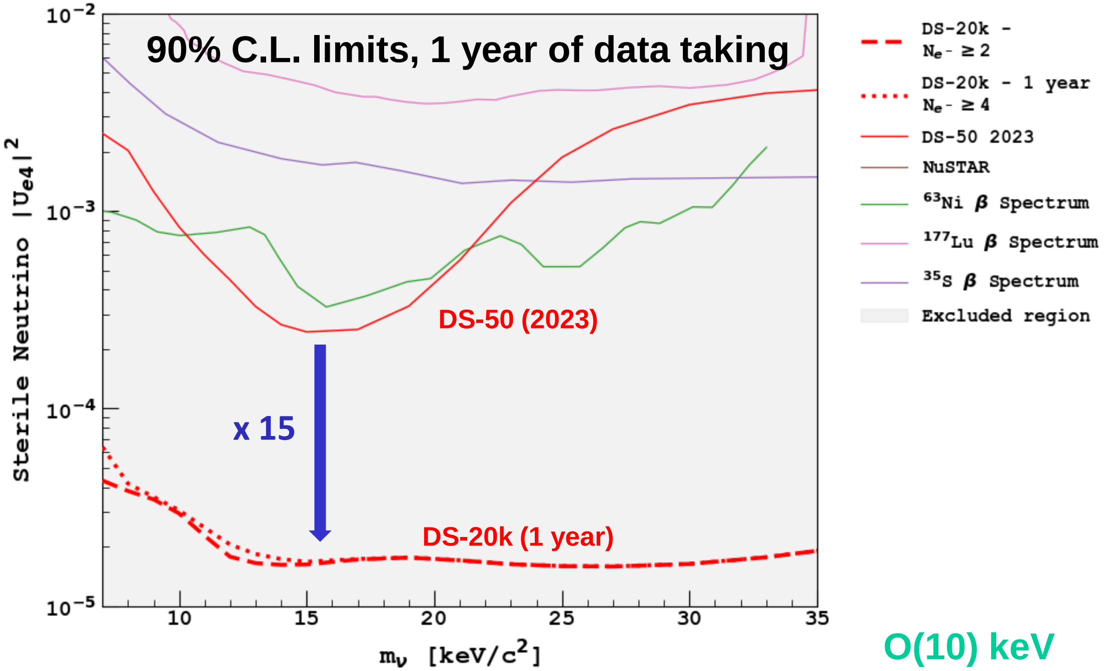
O(10-1000 MeV)

➔ > 1 order of magnitude improvement wrt to current experiments in 1 year

Sensitivity to leptophilic DM (2/3)

- Inelastic scattering of **sterile neutrino**, mixing with active neutrino through angle $|U_{e4}|^2$, off bound electrons





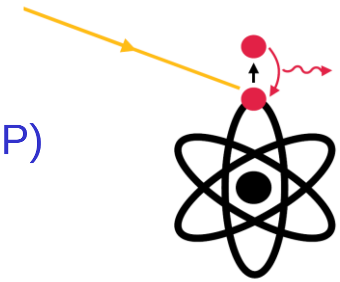
O(10) keV

➔ > 1 order of magnitude improvement wrt to current direct limits in 1 year

➔ Phase space already rejected by indirect measurements (NuSTAR)

Sensitivity to leptophilic DM (3/3)

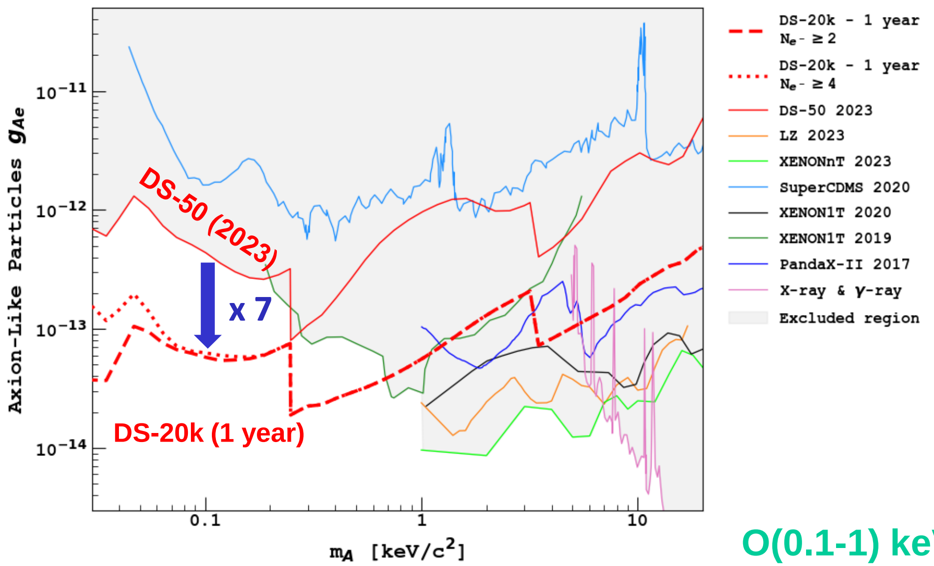
- Absorption by bound electrons of pseudo-scalar **Axion-Like Particle** (ALP) or vector-boson **Dark Photon** (DP)



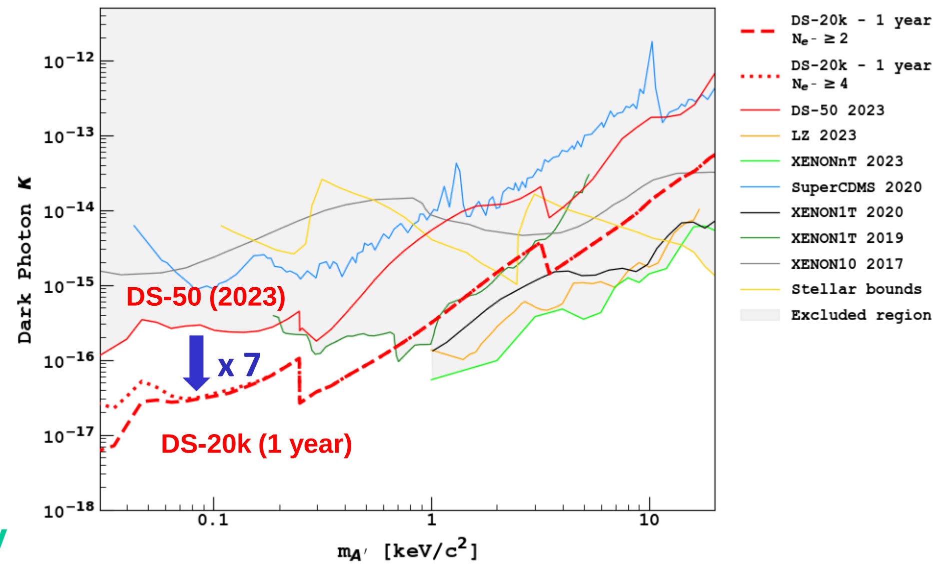
mono-energetic signal

90% C.L. limits, 1 year of data taking

ALP-electron coupling strength $\mathbf{g_{Ae}}$



Strength of kinetic mixing **κ** between photon and DP



O(0.1-1) keV

➔ O(1) order of magnitude improvement wrt to current experiments in 1 year

Conclusions

❑ Dual phase LAr TPC = one of leading techno for light (<10 GeV) DM search

- Demonstrated by DS-50 → world best limits for WIMPs & leptophilic DM phase spaces
- Next generation DS-20k under construction → start data taking in 2027
- In 1 year, expect >1 order of magnitude sensitivity improvement for a variety of DM models

[WIMPs w/wo Migdal in MeV-GeV mass range – LDM, ALP, DP, SN in keV or sub-keV mass range]

arXiv:2407.05813 (submitted to Nature Communications)

❑ IN2P3 = leader of DarkSide light DM searches

- Calibration of LAr ionisation response at low energy ➢ see talk at GDR DUPHY 2021
- DS-50 light dark matter searches ➢ see talks at GDR DUPHY 2022, 2023
- DS-20k sensitivity to light dark matter particles ➢ this talk at GDR DUPHY 2024

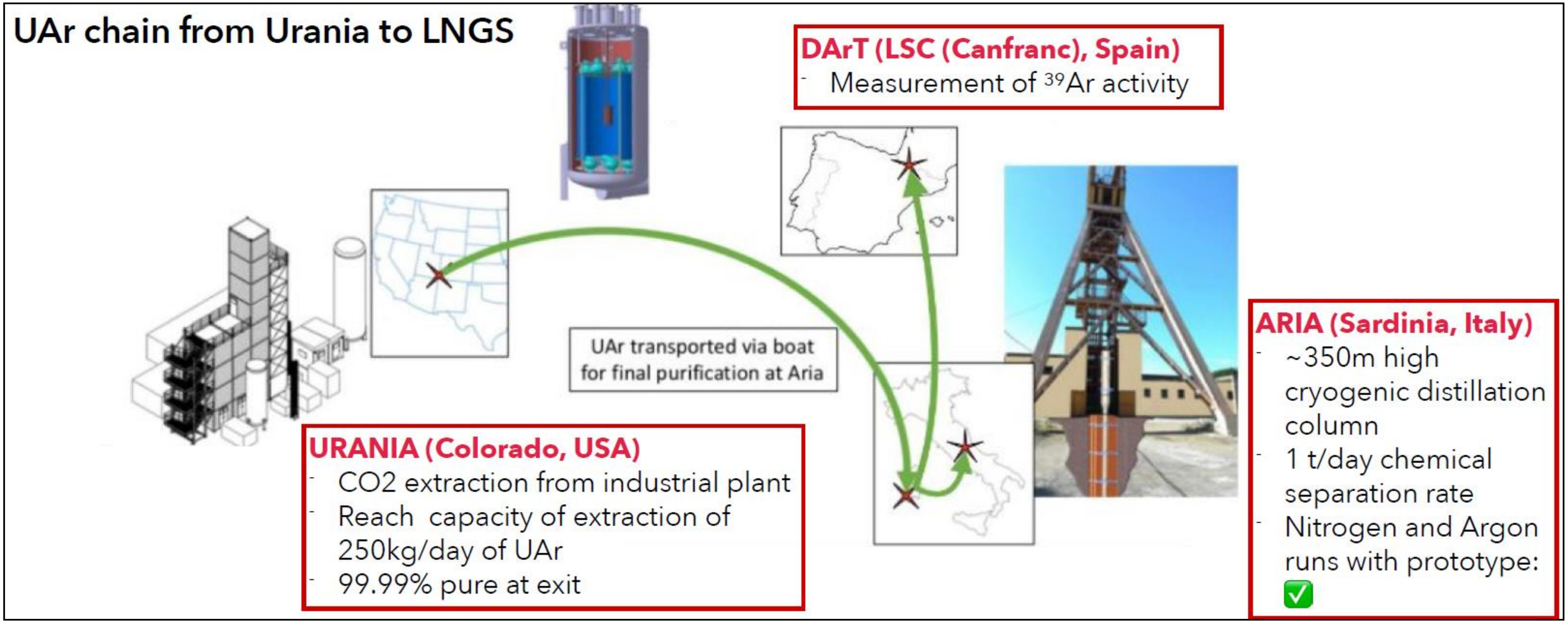
PRL 121 (2018) 081307	PRL 121 (2018) 111303	PRD 104 (2021) 082005	PRD 107 (2023) 063001	PRL 130 (2023) 101001	PRL 130 (2023) 101002	arXiv:2407.05813 (Nature Comm.)

SPARES

$m_{\gamma\gamma}$=125.4 GeV

Purified underground argon

- Argon isotopes: ^{40}Ar (stable) and ^{39}Ar (β emitter)
- Atmospheric ^{40}Ar is cosmogenically activated by cosmic rays → ~1 Bq/kg in AAr
- ^{40}Ar present in underground wells (1400x depleted in ^{39}Ar) of CO_2 in Colorado → used for DS50 and DS20k



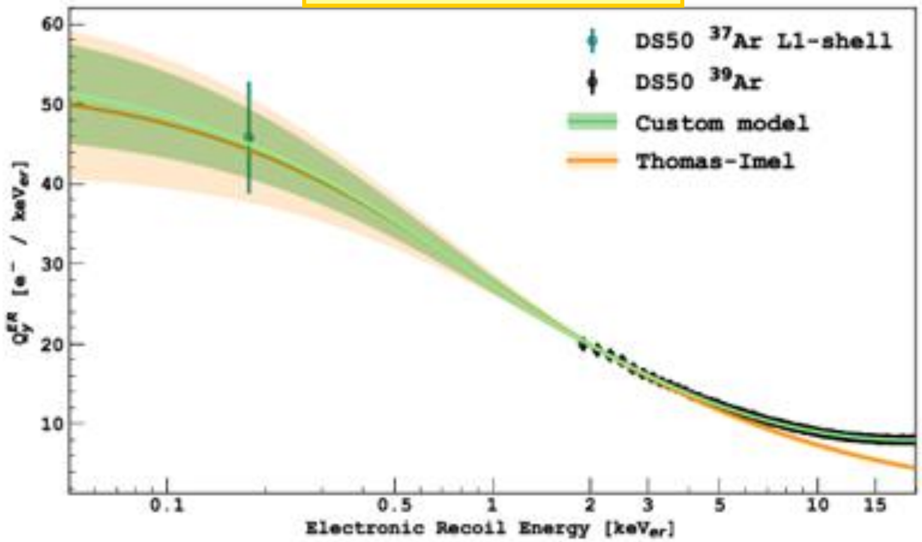
➢ **UAr extraction should start Q1 2025**

LAr ionization response to ER / NR

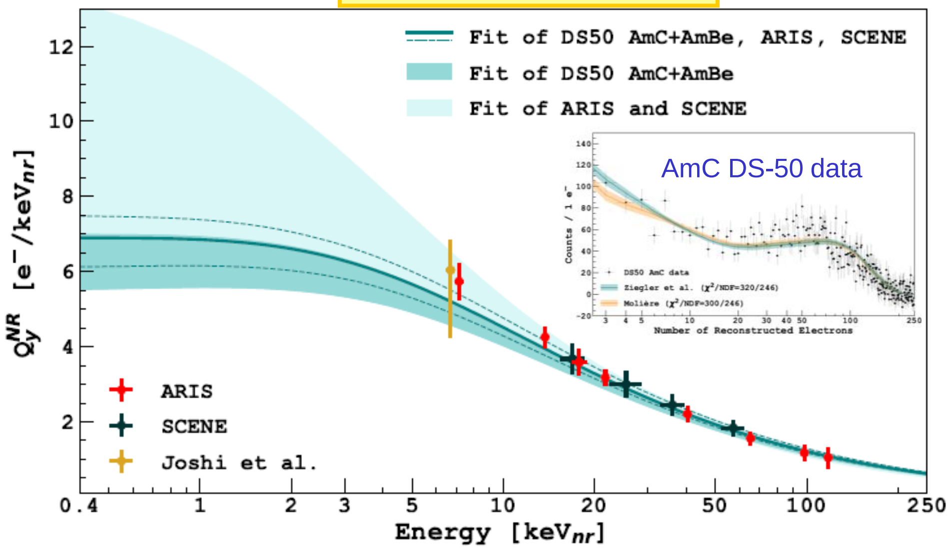
- Measurement of ionization yield at low E central for low mass WIMP search

PRD 104 (2021) 082005

Electronic recoil



Nuclear recoil



➔ ER ionization yield measured down to 180 eV$_{er}$ and extrapolated to a few ionization electrons

➔ NR ionization yield measured down to ~500 eV$_{nr}$, the lowest ever achieved in liquid argon

Other signal models

Rates

e⁻ in a given orbital (n, l)

LDM:

$$\frac{dR}{d\ln E_{er}} = N_T \frac{\rho_{DM}}{m_\chi} \times \frac{\bar{\sigma}_e}{8\mu_{\chi e}^2} \times \sum_{nl} \int |f_{ion}^{nl}(k', q)|^2 |F_{DM}(q)|^2 \eta(v_{min}) q dq$$

ALPs:

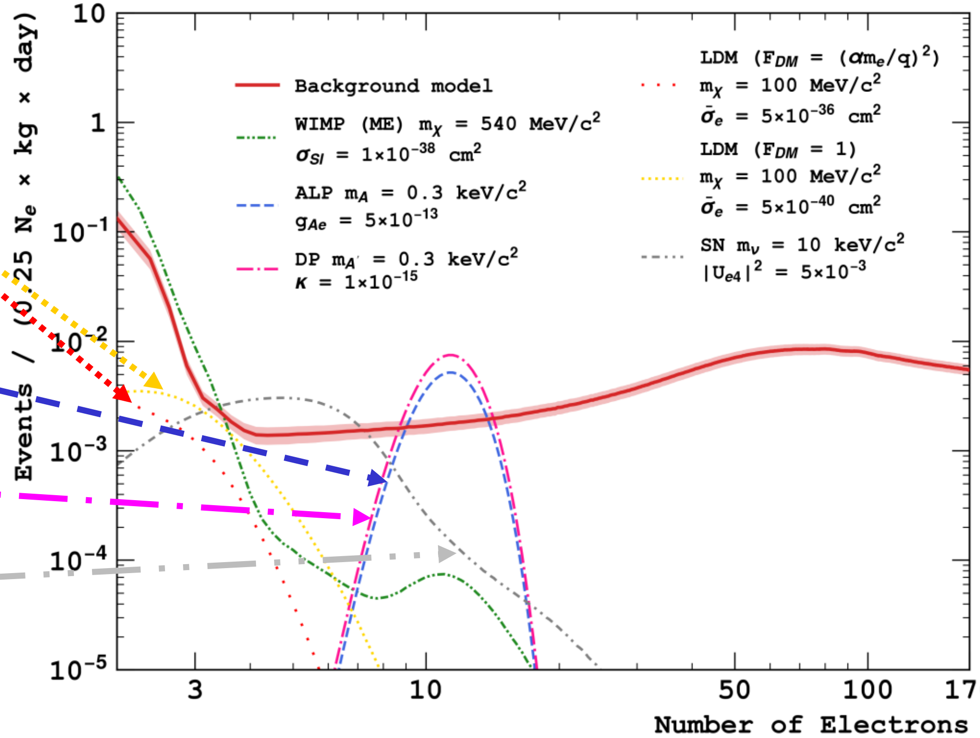
$$R = N_T \frac{\rho_{DM}}{m_A} \times \frac{3 m_A^2 g_{Ae}^2}{16\pi\alpha m_e^2} \sigma_{pe}(m_A c^2) c$$

DP:

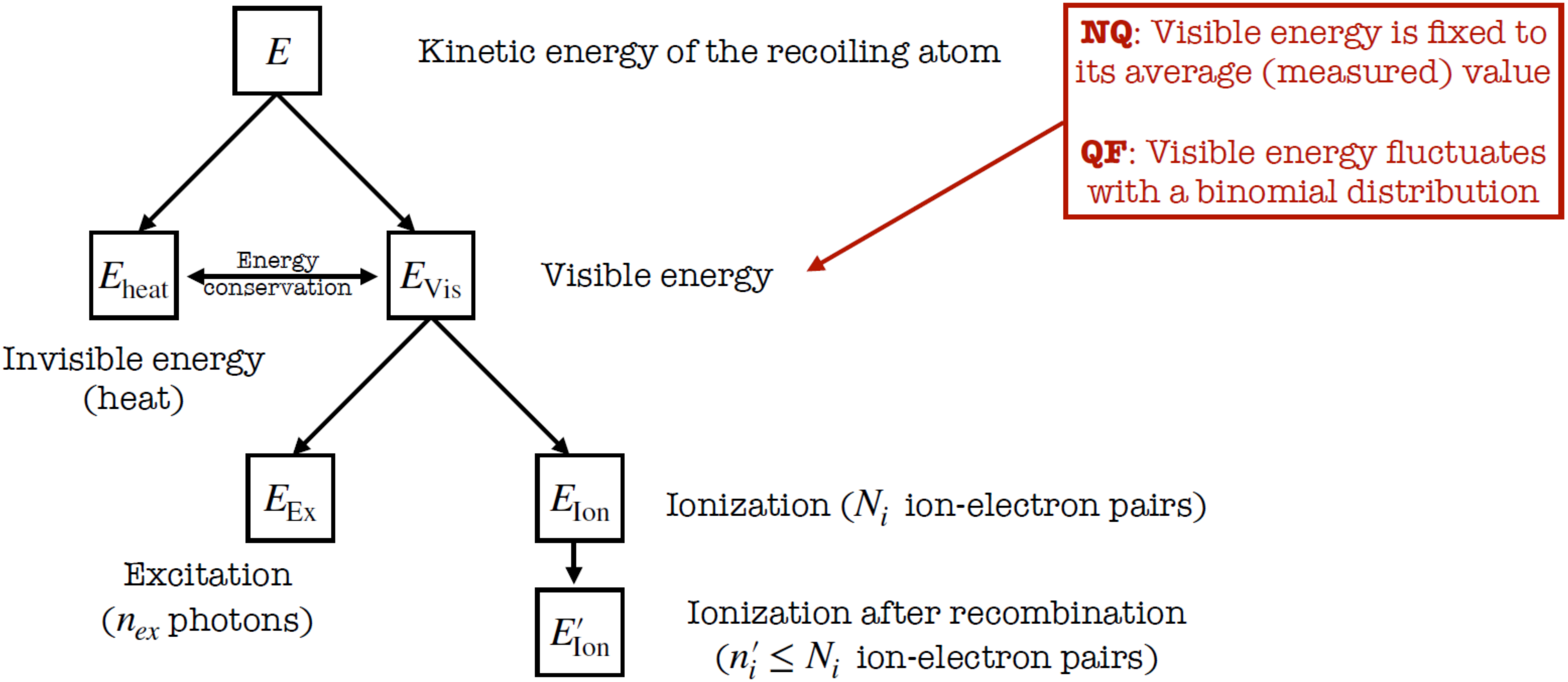
$$R = N_T \frac{\rho_{DM}}{m_{A'}} \times \kappa^2 \sigma_{pe}(m_A c^2) c$$

Sterile neutrinos:

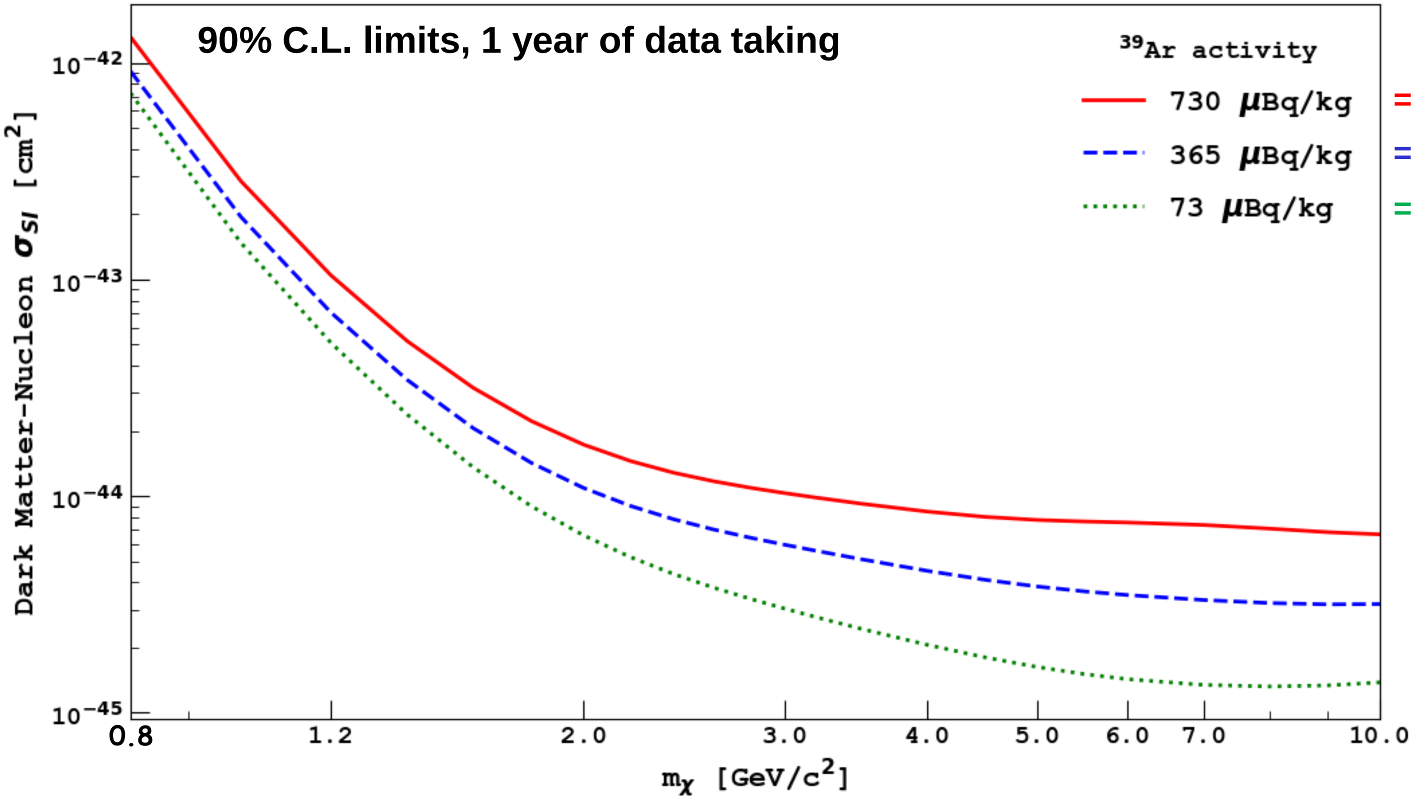
$$\frac{dR}{dE_{er}} = N_T \frac{\rho_{DM}}{m_\nu} \times \sum_{nl} 2(2l+1) \int \frac{d\sigma_{nl}}{dE_{er}} \left(v, m_\nu, |U_{e4}|^2\right) f(v)\, v\, dv$$



Quenching fluctuations in NR



Sensitivity vs ^{39}argon activity



= nominal (DS-50)

= nominal / 2

= nominal / 10

Prospective experiments