DarkSide-20k sensitivity to light dark matter particles

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On Behalf of the DarkSide-20k Collaboration

1. Motivation
2. DarkSide-20k detector
3. Background model for light DM searches
4. Prospect sensitivity (WIMP, leptophilic DM)
5. Conclusion

IRN Terascale meeting, November 13-15 2024

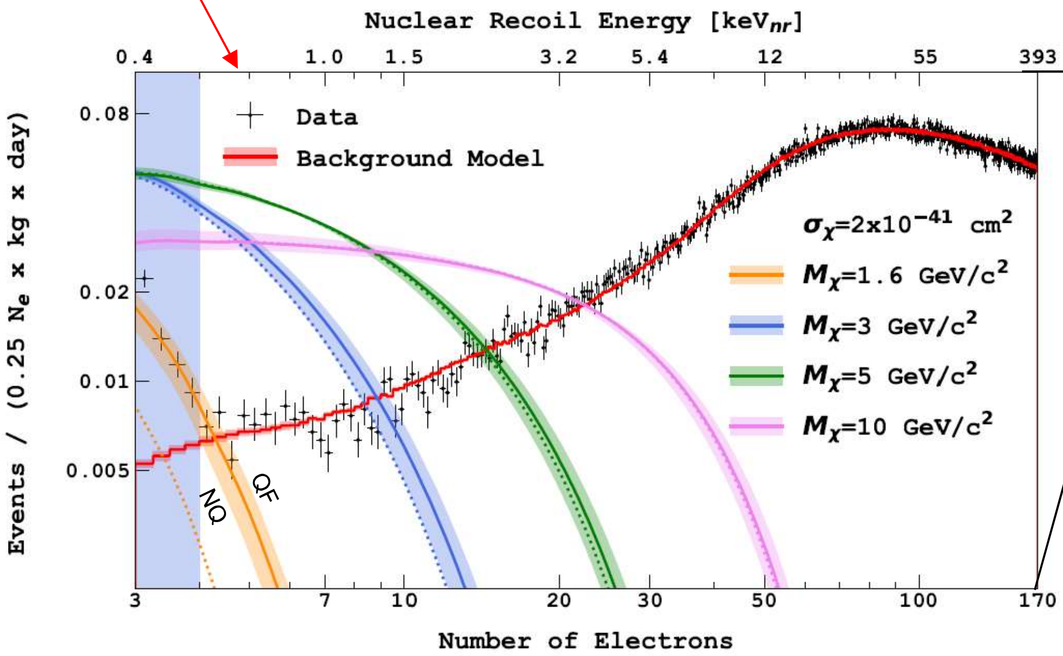
Motivation

- **DarkSide-50** (**2015-18**): double phase TPC, 50 kg low-radioactivity underground argon

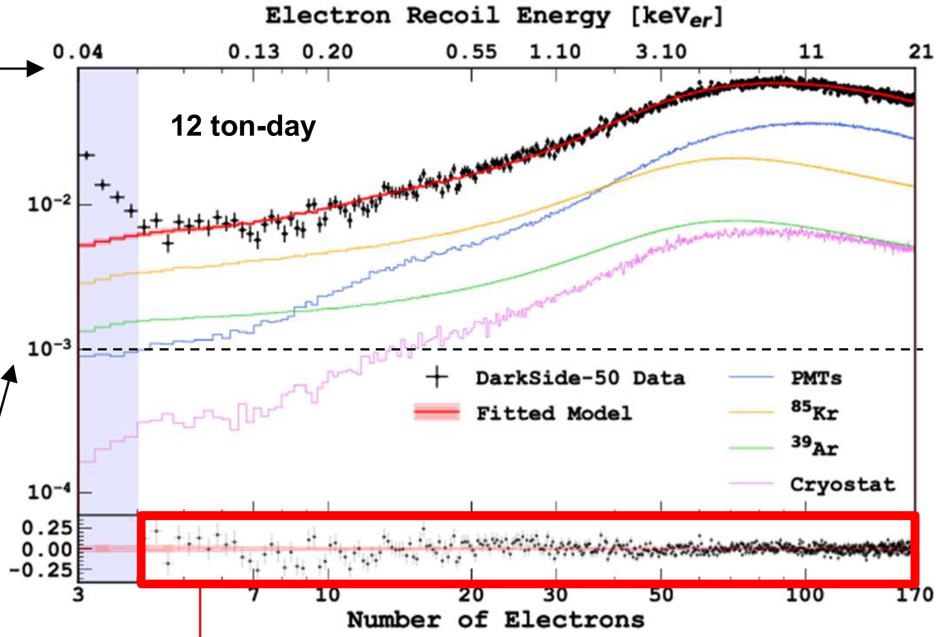
Very low deposited energy in TPC < O(1 keV$_{nr}$)

PRD 107 (2023) 063001

NR

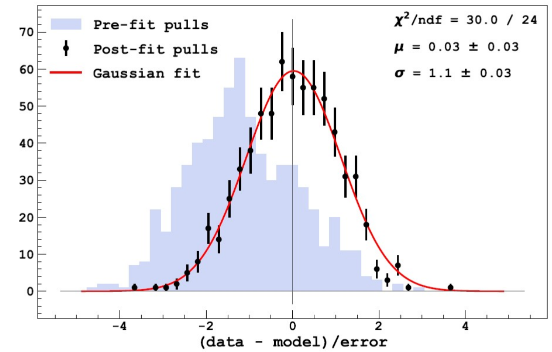


ER



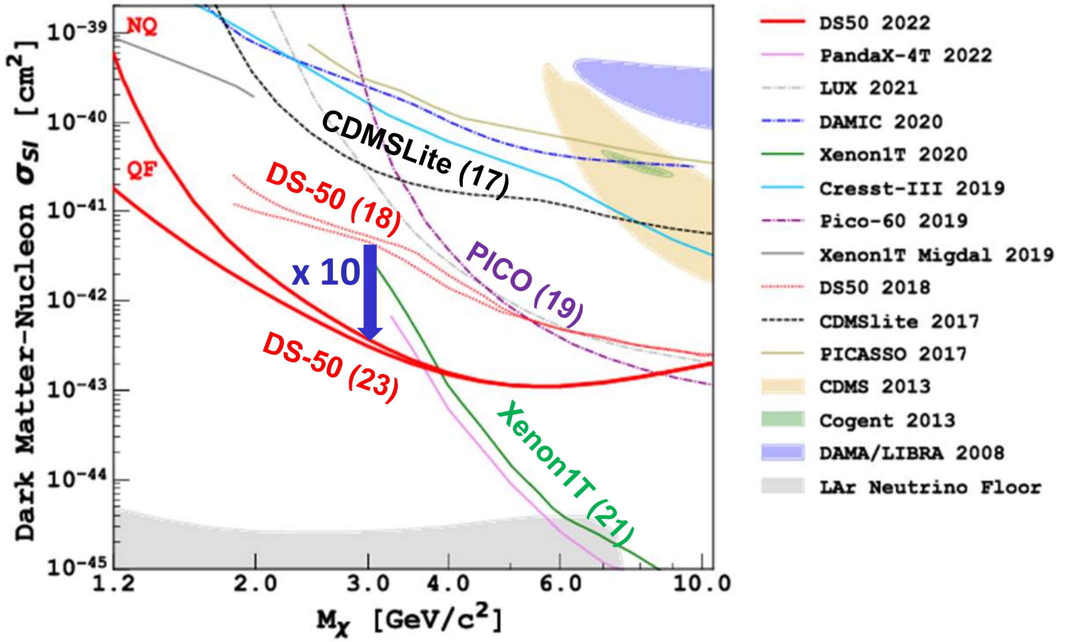
Counting the number of ionisation electron provides an intrinsic signal and background separation

Excellent background modelling of ionization spectrum (only fitted variable) for $N_e \geq 4$ [50 eV$_{er}$]



Motivation

- **DarkSide-50** (**2015-18**): double phase TPC, 50 kg low-radioactivity underground argon
  - ✓ Obtained world best limits on WIMP-nucleon σ_{SI} for light WIMPs (1.2-3.6 GeV) PRD 107 (2023) 063001



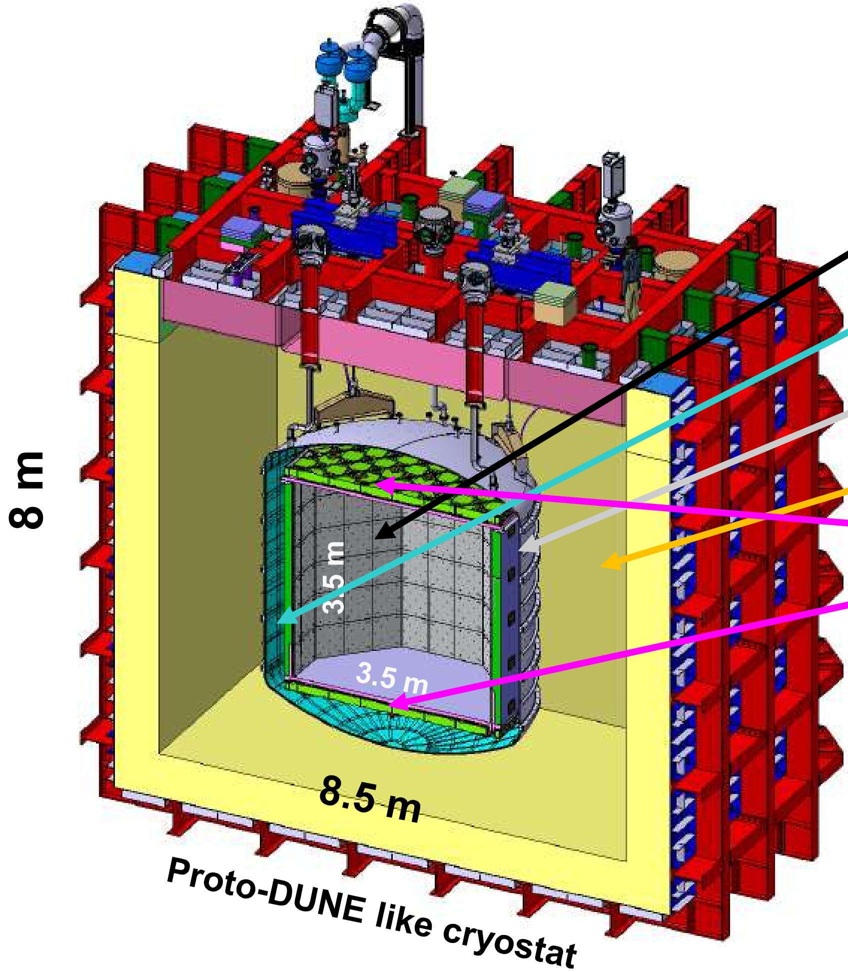
  - ✓ Extended down to 40 MeV using Migdal effect + limits on leptophilic light DM candidates

PRL 130 (2023) 101001 PRL 130 (2023) 101002

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

DarkSide-20k (DS-20k)

- Next generation LAr double phase TPC (unique world-wide collaboration)
  - ✓ Construction started at LNGS ➔ Should start data taking in **2027**



TPC: 50 t UAr

(low radioactivity argon extracted from deep mine and further purified in distillation column)

Neutron veto: 32 t UAr

Stainless-steel vessel

Outer μ veto: 650 t atmospheric argon

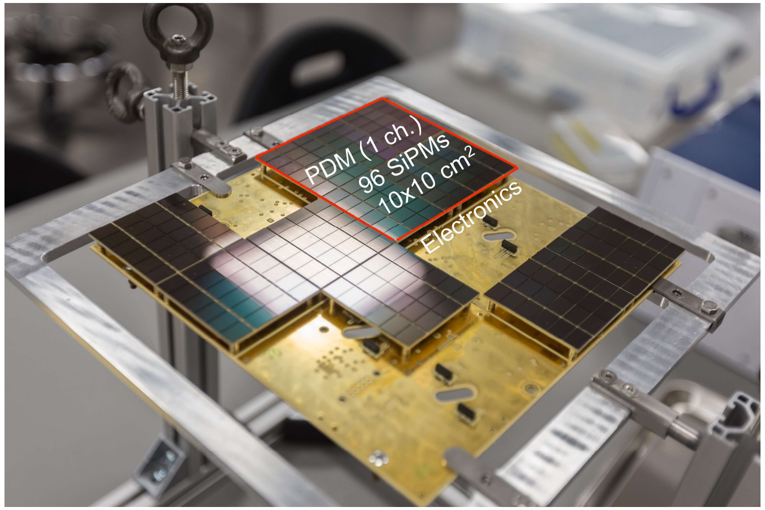
Acrylic TPC equipped with 2x10.5 m² SiPMs arrays (→ 2112 readout channels)

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

DS-20k in 2024

- Proto-Dune **cryostat** completed in LNGS Hall C

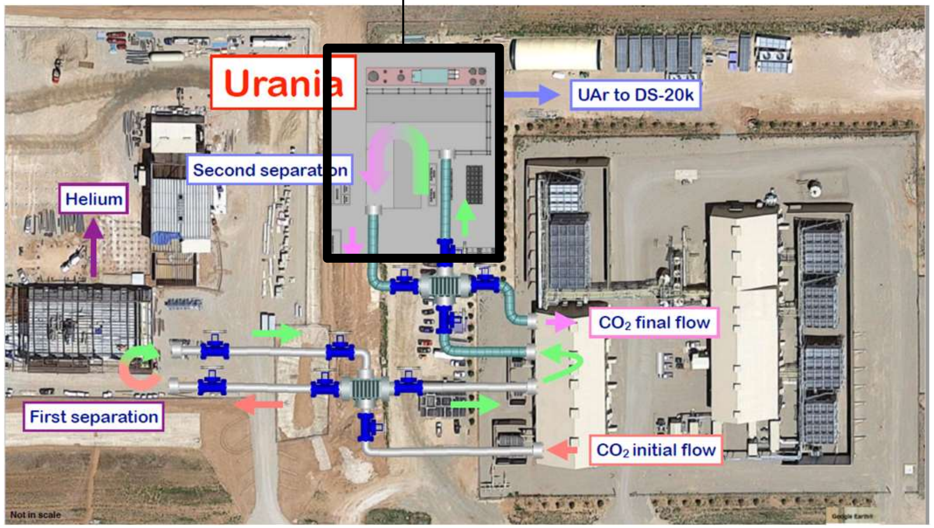
- TPC **Photo Detector** Modules *(PDMs)* production starting



- Plant for 100 t **Underground Argon** *(Urania)* extraction is ~ready

+ distillation column

Mine exploitation by Doe Canyon Facility (Cortez, CO, USA)

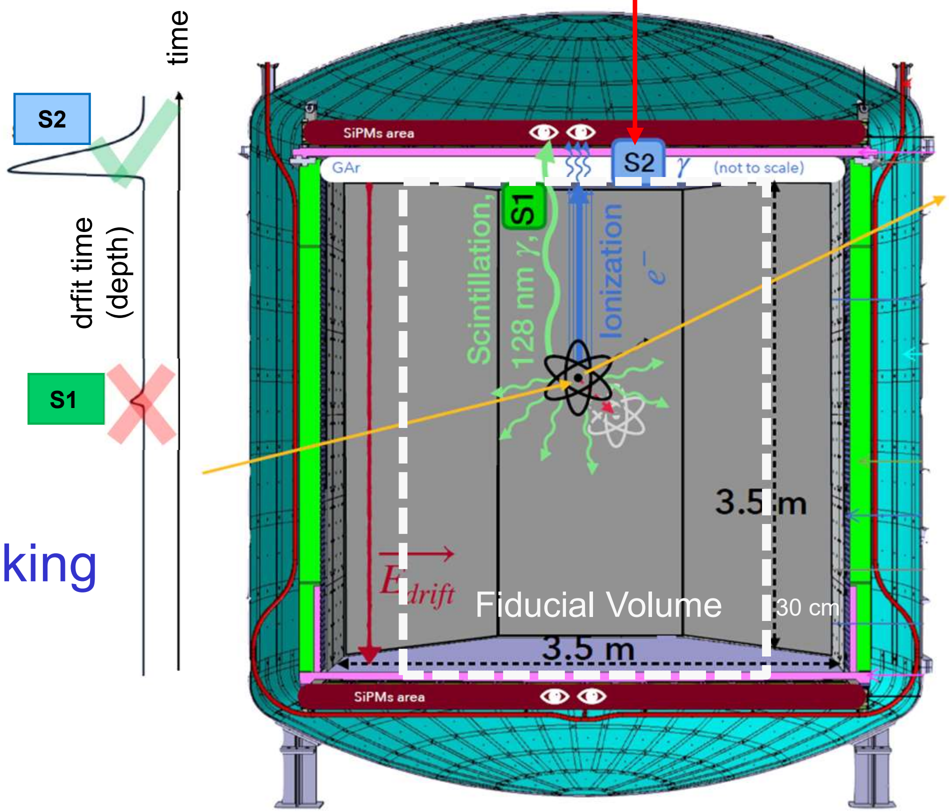


600 m

DS-20k: low mass DM analysis

- Scintillation signal **S1** threshold O(1 keV_{nr}) is too high for light DM search
  - Use only ionization signal **S2** →
    - Electrons drifted up (E=200 V/cm) and multiplied in gas phase → **electroluminescence light yield ~25 PE/e**
    - Max drift time = 3.7 ms, lifetime 16 ms

- Main bkg (ER): low energy e⁻ from β **&** X, γ
  - Fiducialize in transverse direction
    - → **68 %** signal efficiency
  - Remove pile-up events with this 80 Hz ER bkg by select isolated single S2 pulses (+/- 3.7 ms)
    - → **51 %** effective livetime

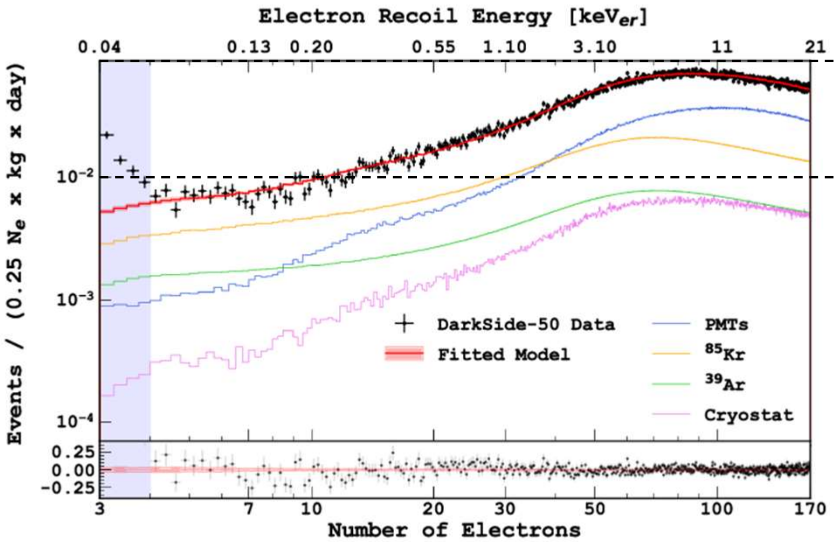


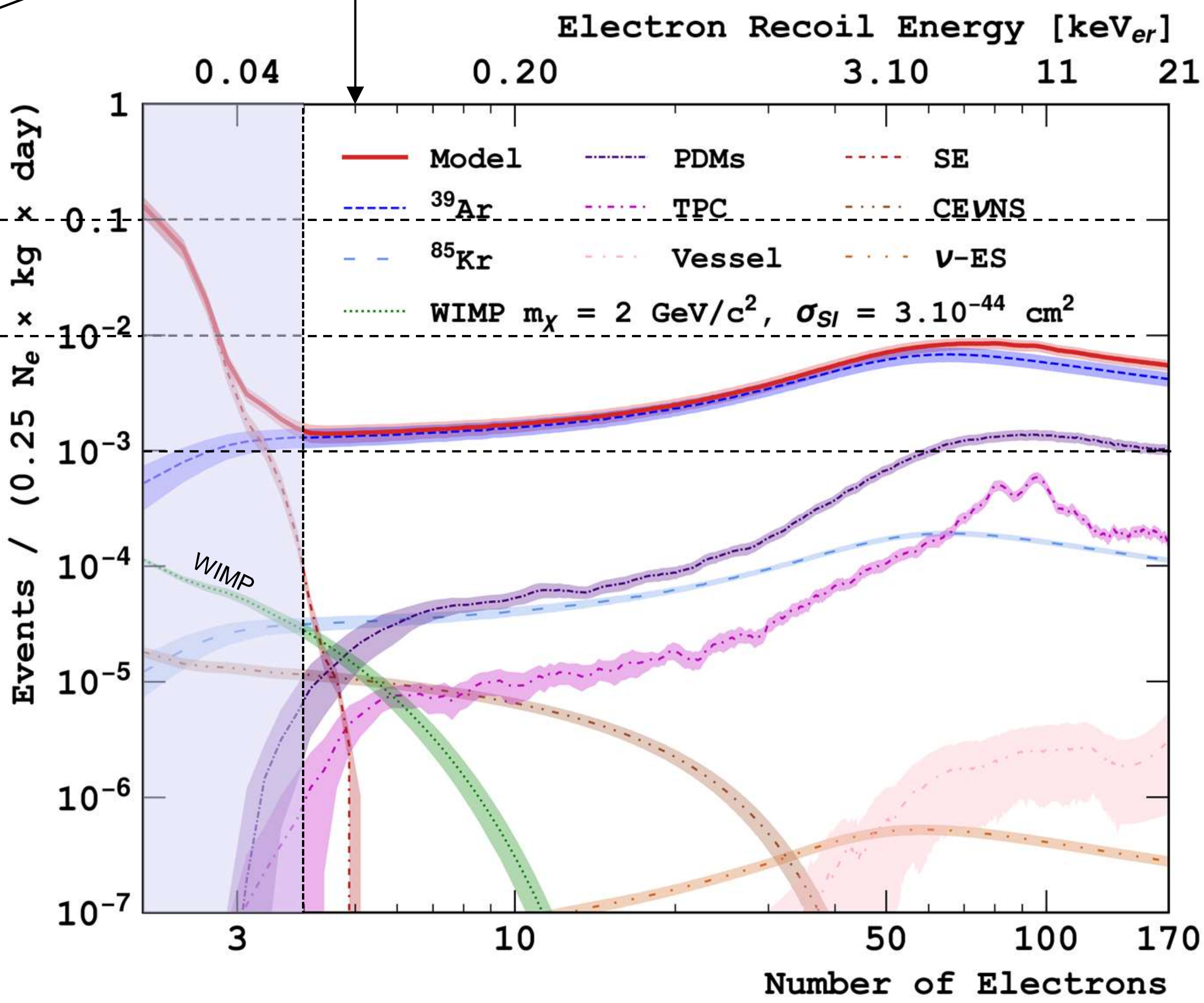
- exposure = 17.4 ton.year for 1 year of data taking

→ Need to accurately model ER background

Background model

- Normalized background model for DS-50 and DS-20k





➔ Effective mitigation of the DS-20k ER background wrt DS-50

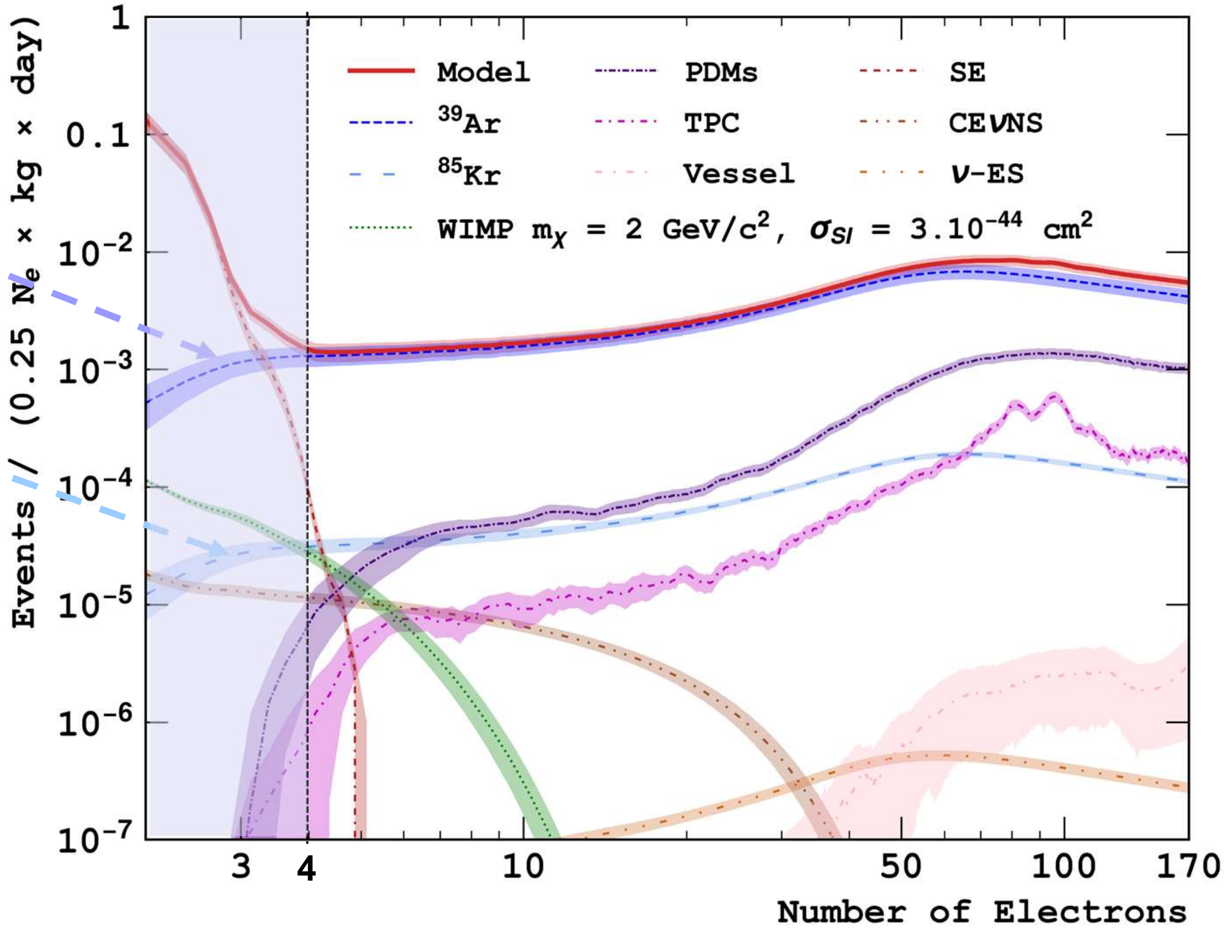
Internal UAr background

- **^{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 by 100 wrt DS-50, as new distillation column at extraction plant

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



Internal UAr background

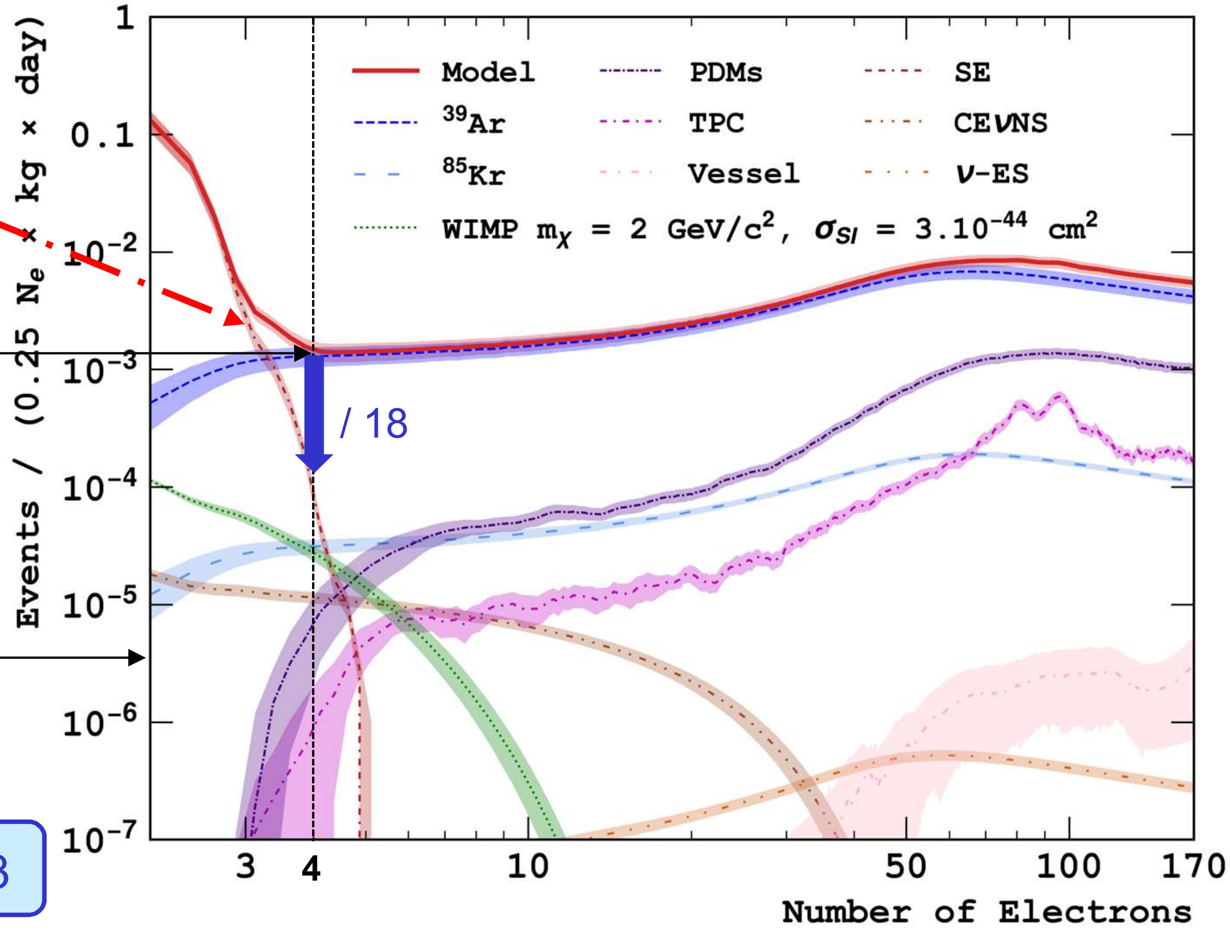
- **Spurious e⁻ (SE)** originated from UAr impurities, modeled with DS-50 data extrapolated to DS-20k
  50 x higher background rate wrt DS-50, 23% single electron response resolution

➢ Conservative: fit from N_e=4

Almost independent of SE modelling, as SE 18 x lower than ^{39}Ar at N_e=4 (DS-50 approach)

➢ Ultimate: fit from N_e=2

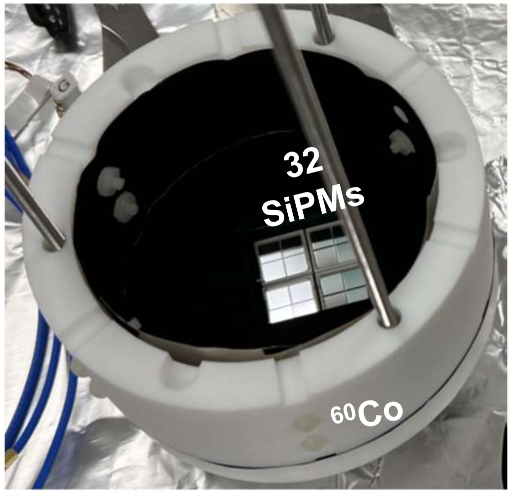
Assume good control of rate and spectral shape of SE in DS-20k

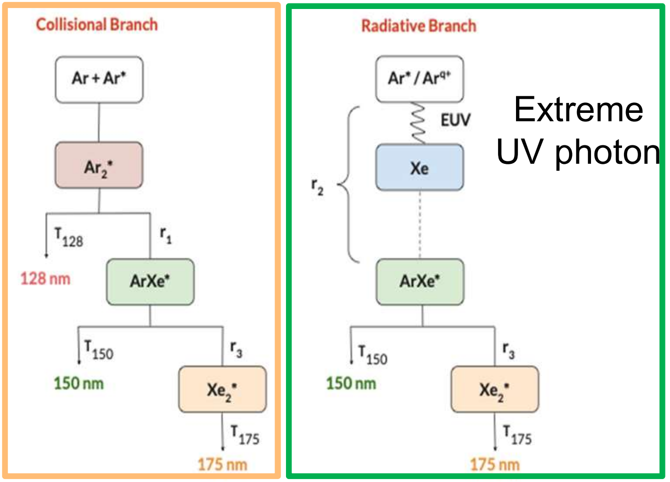


➔ SE background dominant for $N_e \leq 3$

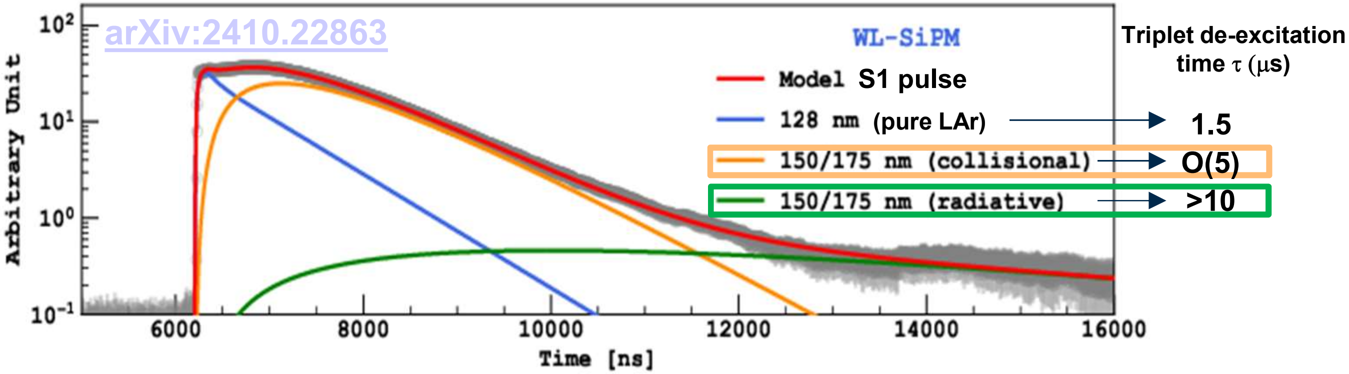
Spurious e⁻ origin

- Recent progresses in understanding the **origin of spurious e⁻** by X-ART collaboration arXiv:2410.22863
  - ✓ S1 study as a function of Xenon doping in Argon





  - ✓ EUV Photons identified for the first time → can ionize impurities and cause single SE



  - ✓ Understanding of multiple SE ongoing → could benefit DS-20k

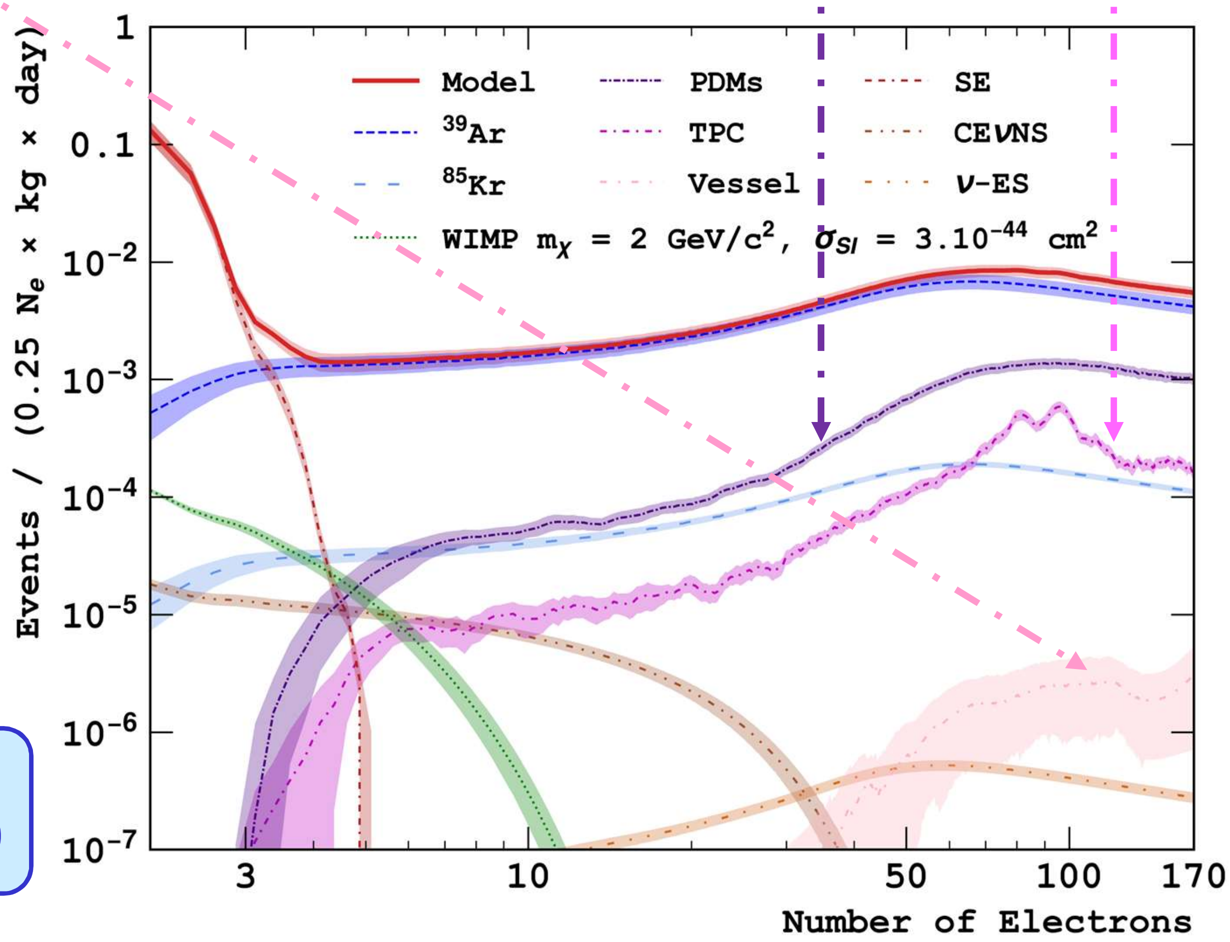
External background

- 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, normalized 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



Neutrino

- **Solar neutrinos** can scatter off the argon atom in two ways

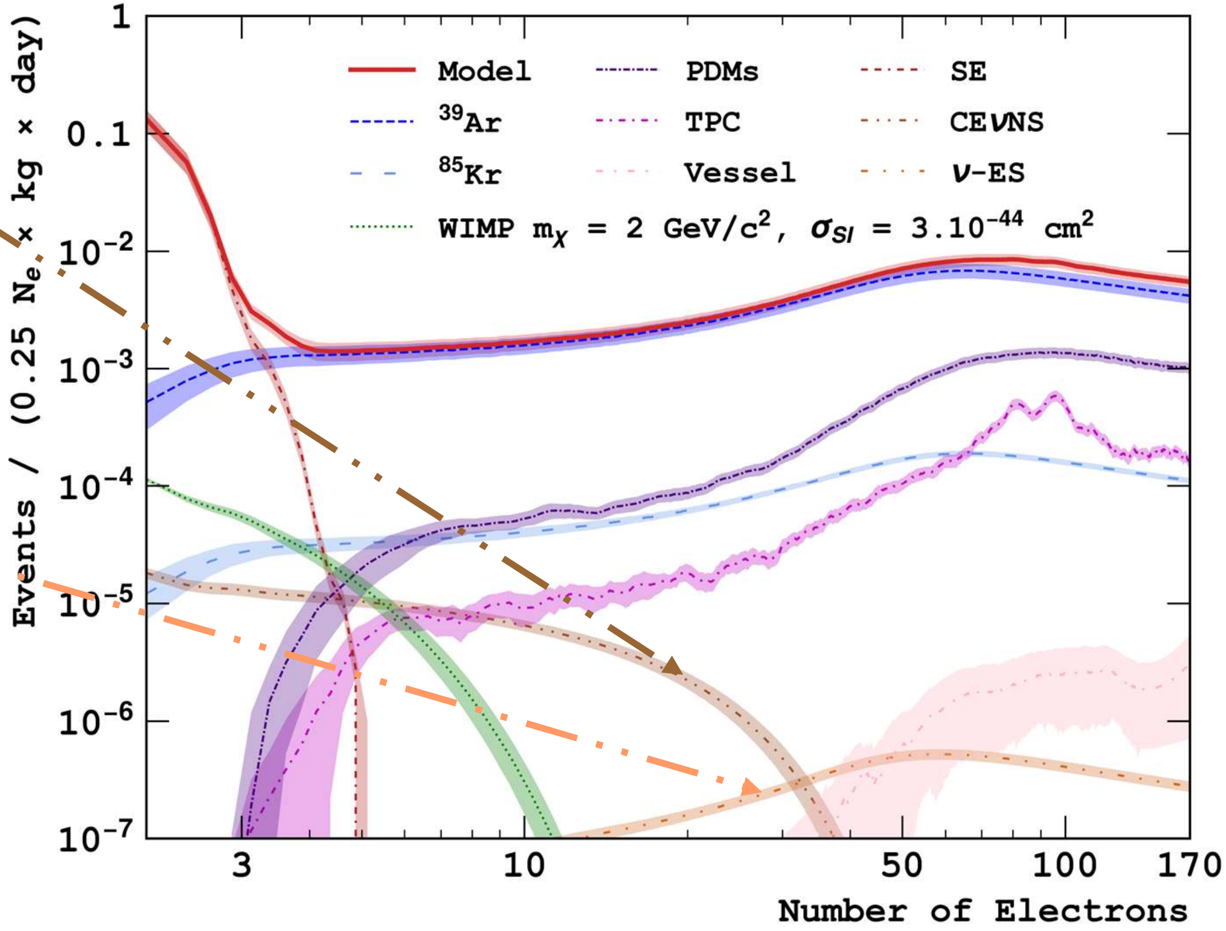
➢ Coherent elastic neutrino scattering off argon nucleus **(CEνNS)**

Mainly from solar ^{8}B ν with nuclear recoil and Edep < 10 keV$_{nr}$

➢ Elastic scattering of neutrinos off argon electrons **(ν-ES)**

Mainly from solar pp & ^{7}Be ν with electron recoil and Edep < 20 keV$_{er}$

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



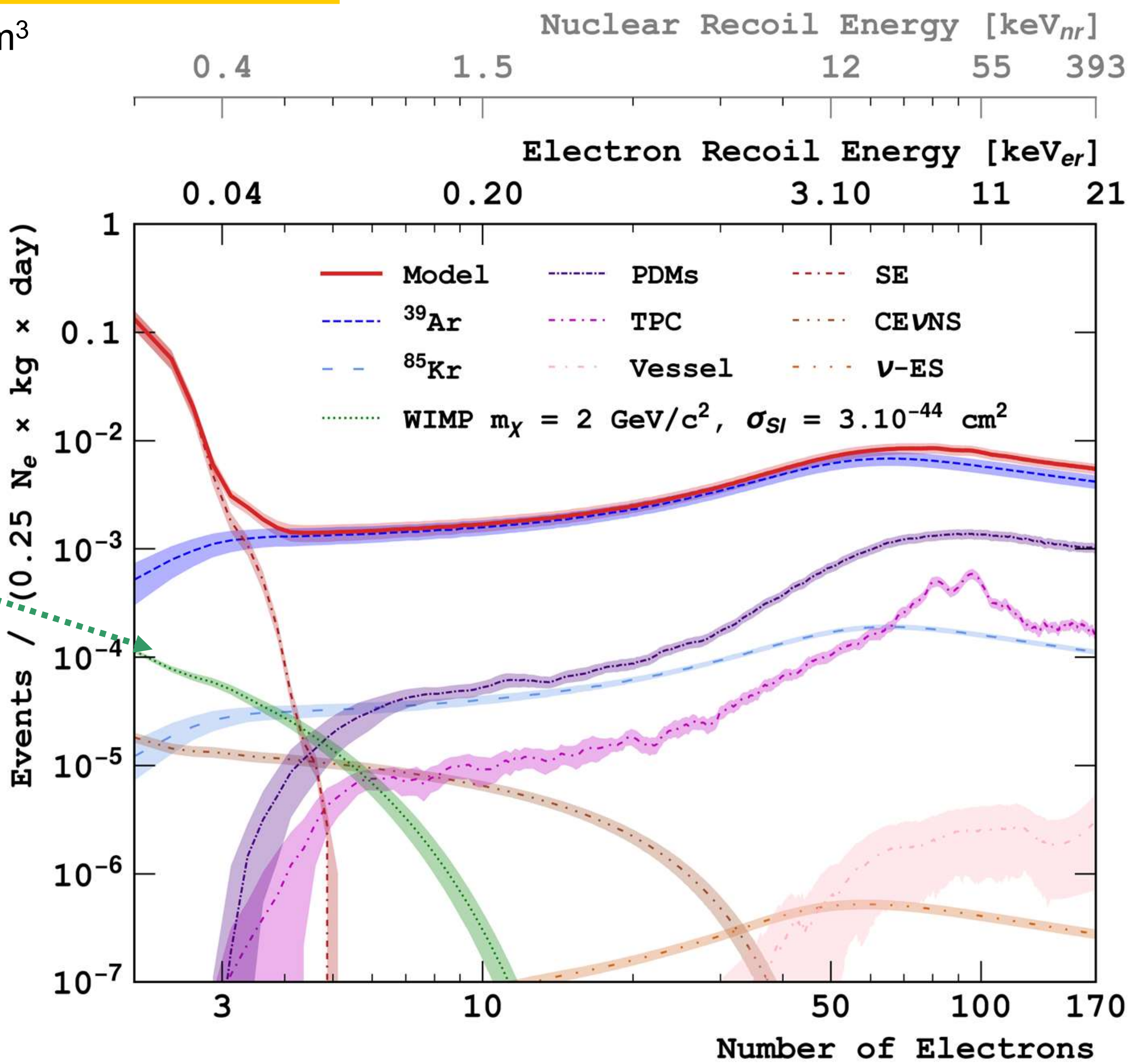
WIMP signal

- Signal assumes recommended **Standard Halo model**

EPJC 81 (2021) 907

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

- Illustrated for NR of 2 GeV mass WIMP with nucleon cross-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.

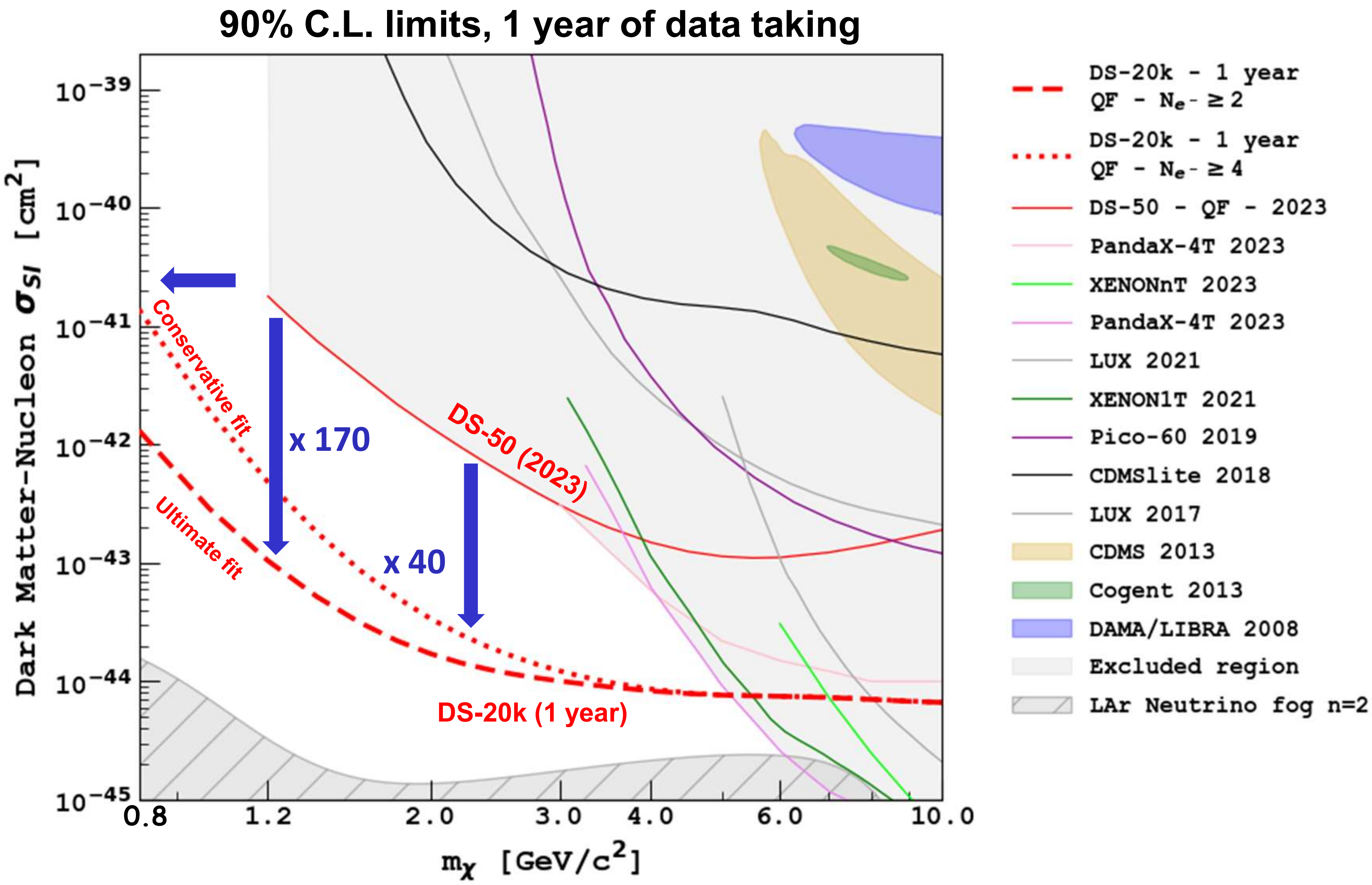
Gaussian penalties to account for the nuisance parameters (θ_0 and $\Delta\theta$ are the nominal central values and uncertainties)

Statistical uncertainties of the simulated sample

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

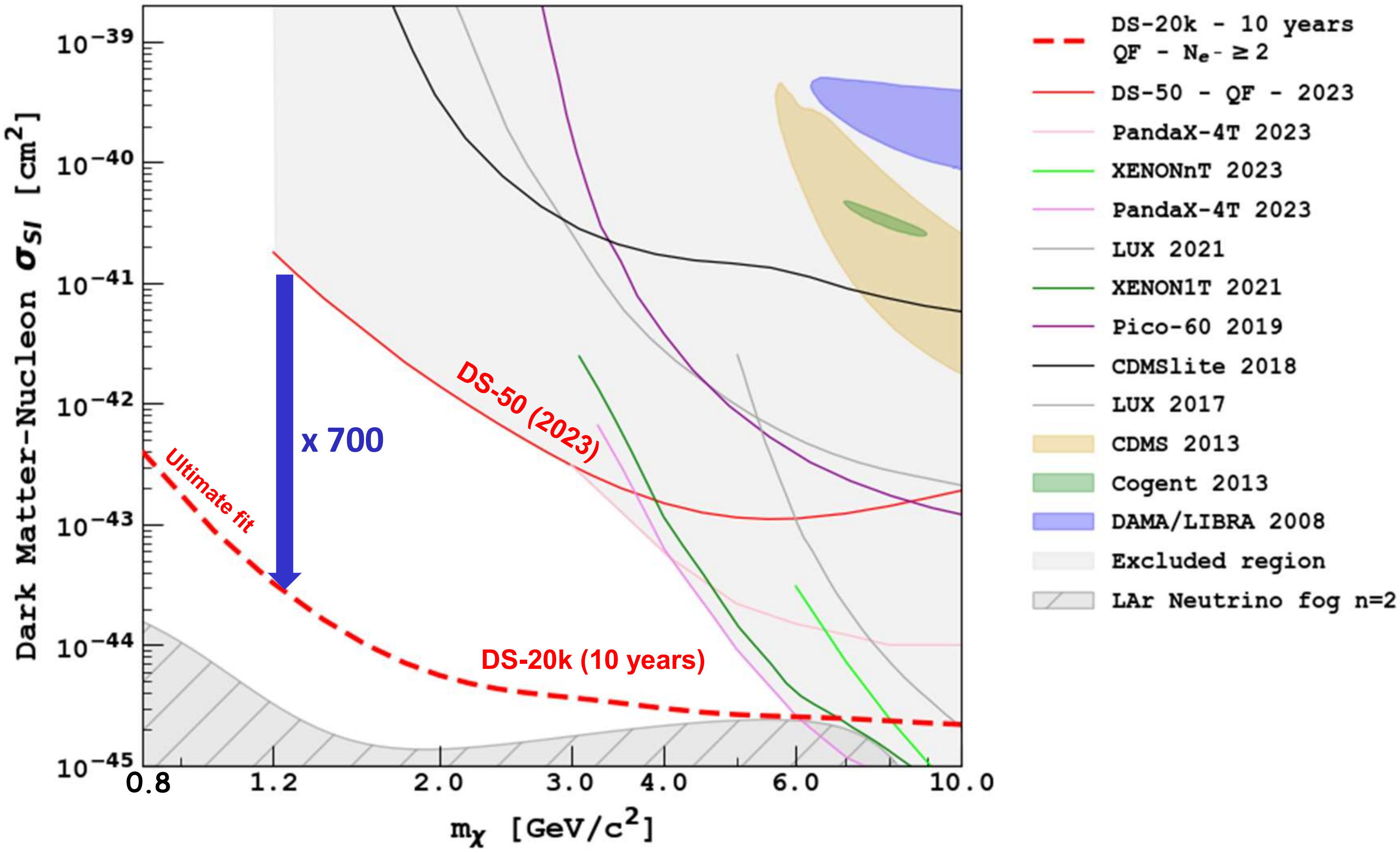
- 90% C.L. limits from binned profile-likelihood fit on N_e distribution, including amplitude uncertainties (activities, exposure) and shape systematics (β-decay shapes, LAr response calibration, SE)
- Strong constraints on nuisance parameters associated to dominant backgrounds and ER ionization yield

Sensitivity to low mass WIMPs (1/3)



- ➔ Sensitivity to WIMP-nucleon **$\sigma_{SI} < 1\times10^{-42}$ cm² for m_χ > 800 MeV**
- ➔ > 1 order of magnitude improvement wrt current experiments in 1 year

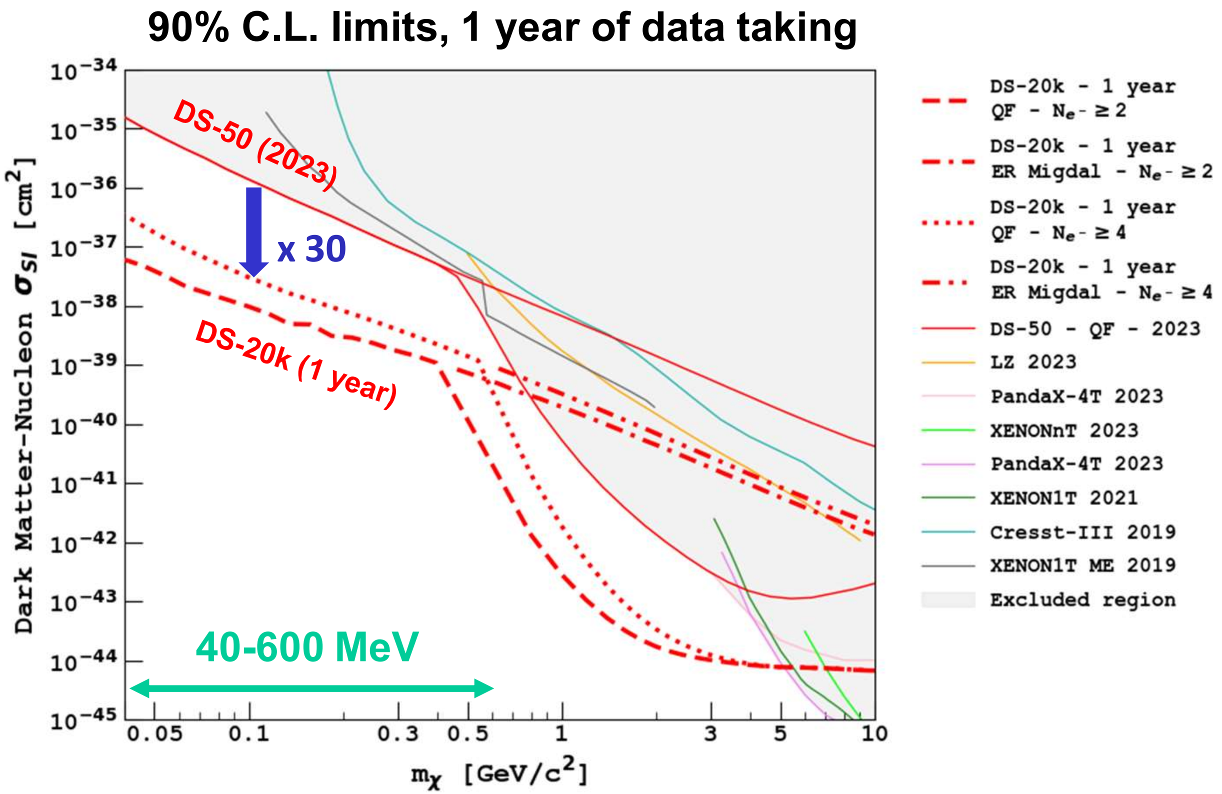
Sensitivity to low mass WIMPs (2/3)

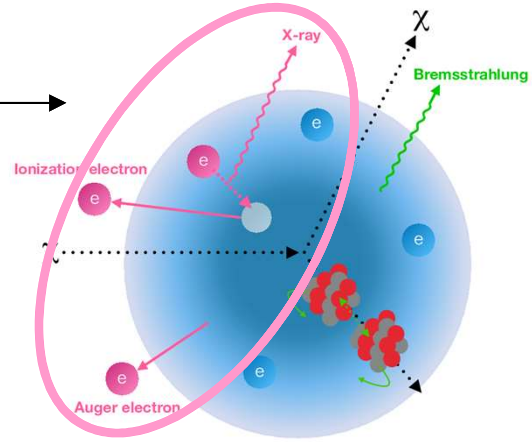


➔ With 10 years exposure, **neutrino fog** in LAr reached m_χ around 5 GeV

Sensitivity to low mass WIMPs (3/3)

- Including **Migdal effect** (not yet observed)
  - ✓ Additional electrons to NR signal
  - ✓ Enhanced sensitivity to low mass WIMPs



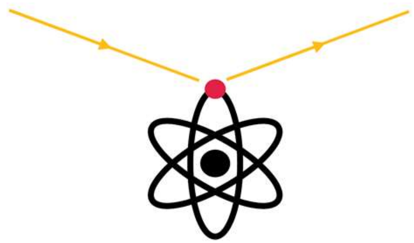


[from PRL123, 241803 (2019)]

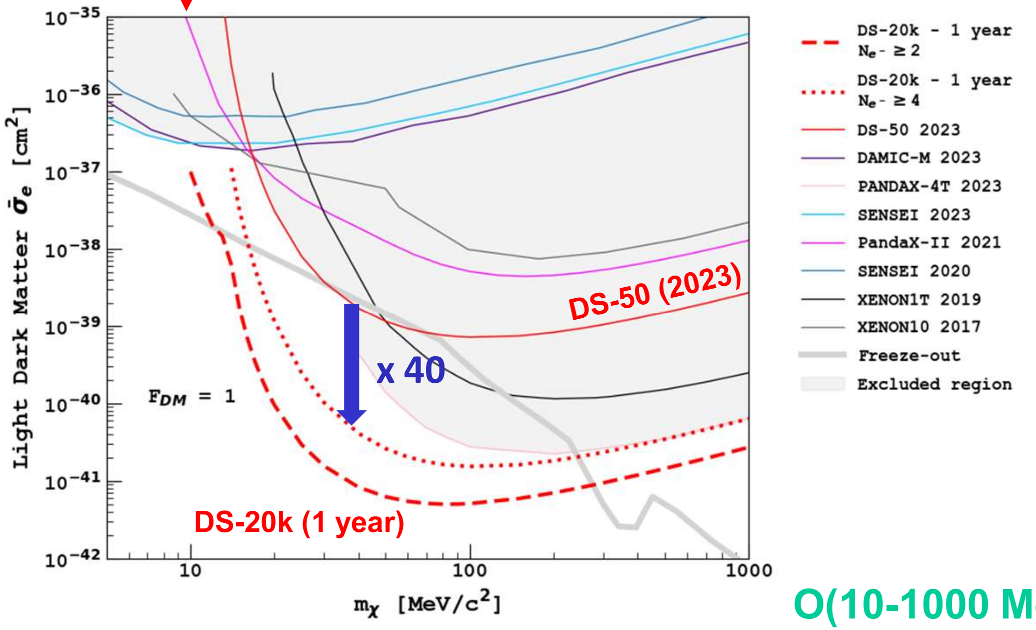
➔ > 1 order of magnitude improvement wrt current experiments in 1 year

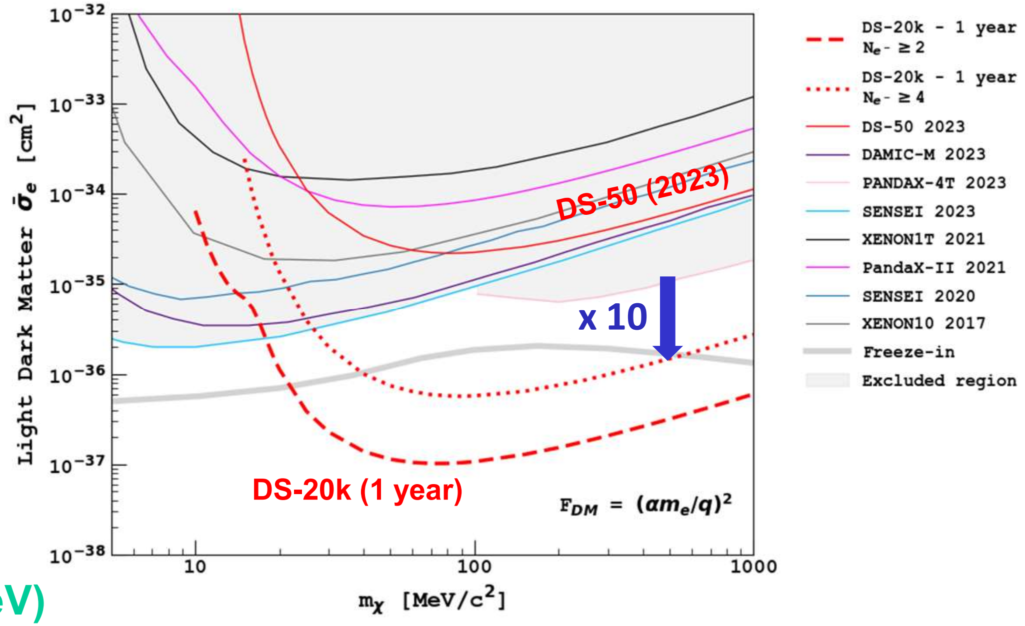
Sensitivity to leptophilic DM (1/3)

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



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



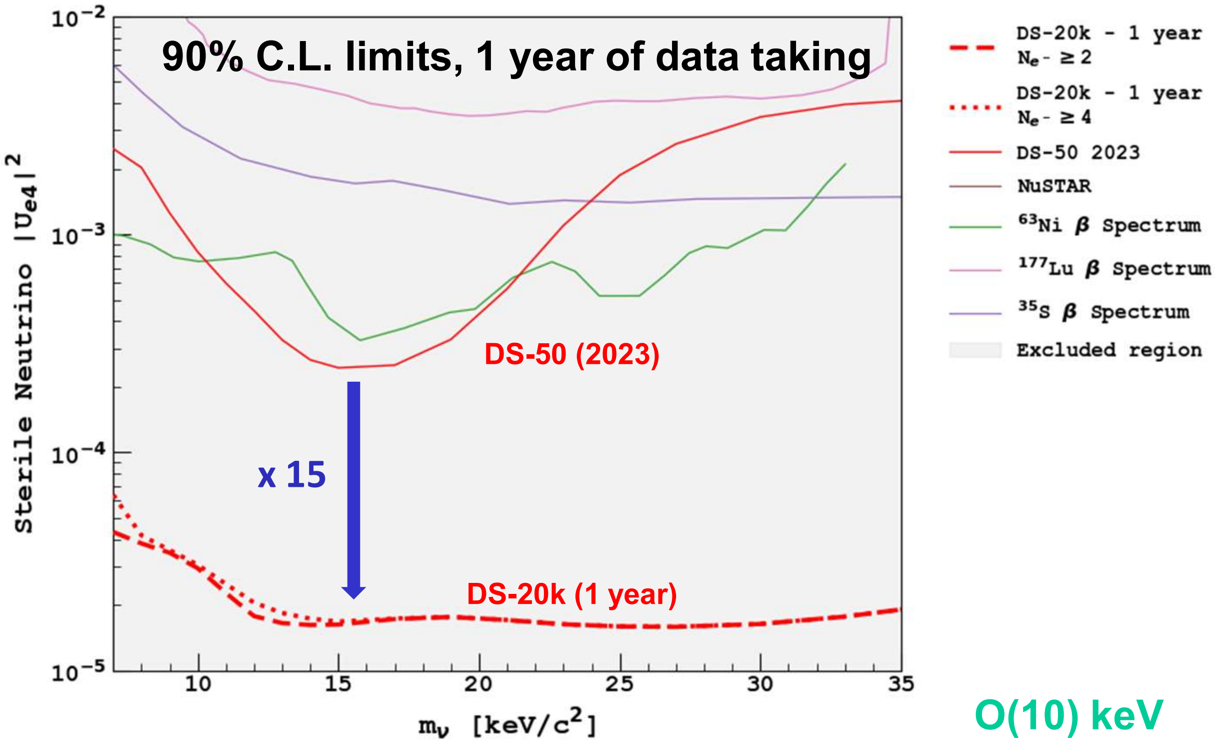


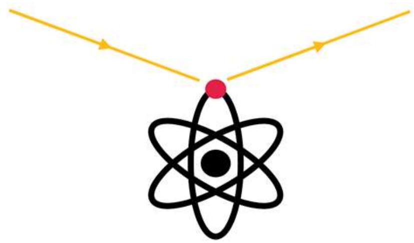
O(10-1000 MeV)

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

Sensitivity to leptophilic DM (2/3)

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





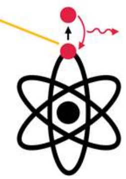
O(10) keV

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

➔ Phase space already rejected by indirect measurements (NuSTAR)

Sensitivity to leptophilic DM (3/3)

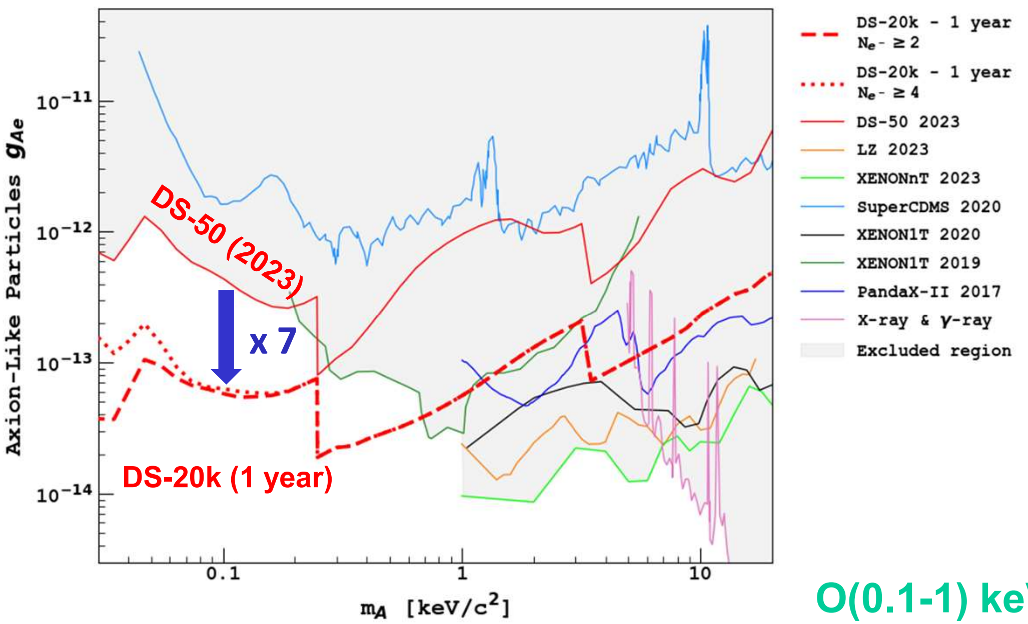
- Absorption by bound electrons of **Axion-Like Particle** (ALP) or **Dark Photon** (DP)



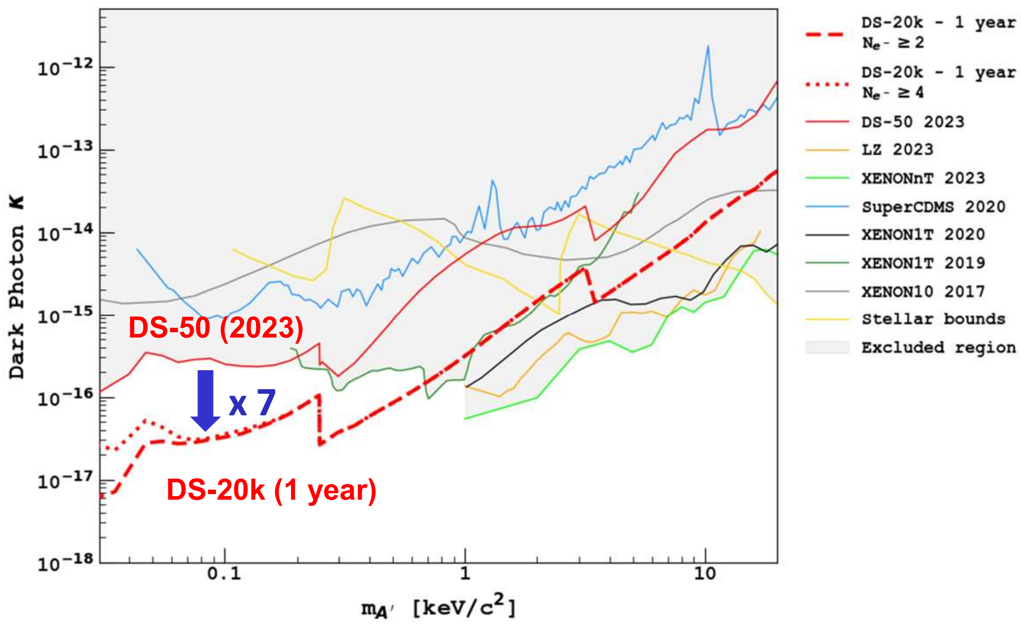
mono-energetic signal

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 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 + GDR DUPHY 2024

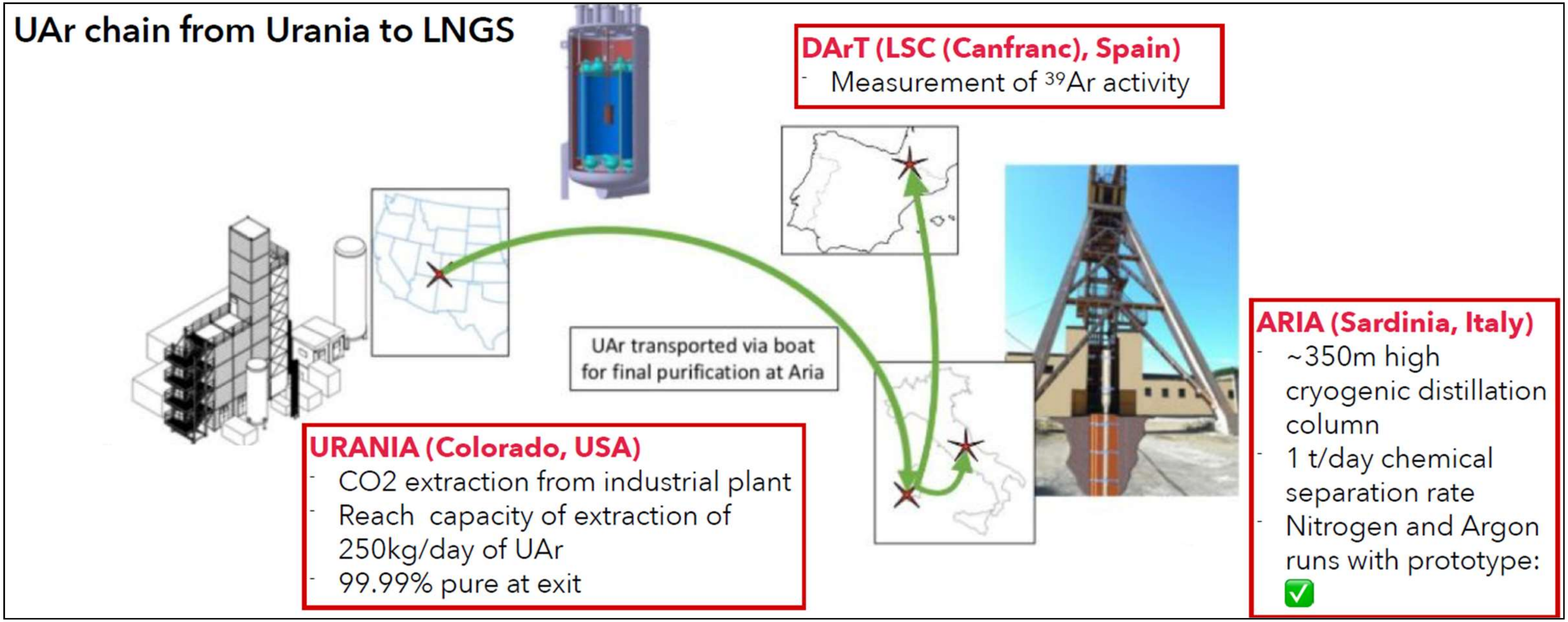
PRL 121 (2018) 081307	PRL 121 (2018) 111303	PRD 104 (2021) 082005	PRD 107 (2023) 063001	PRL 130 (2023) 101001	PRL 130 (2023) 101002	arXiv:2407.05813 (Nature Comm.)

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 → used for DS50 and DS20k



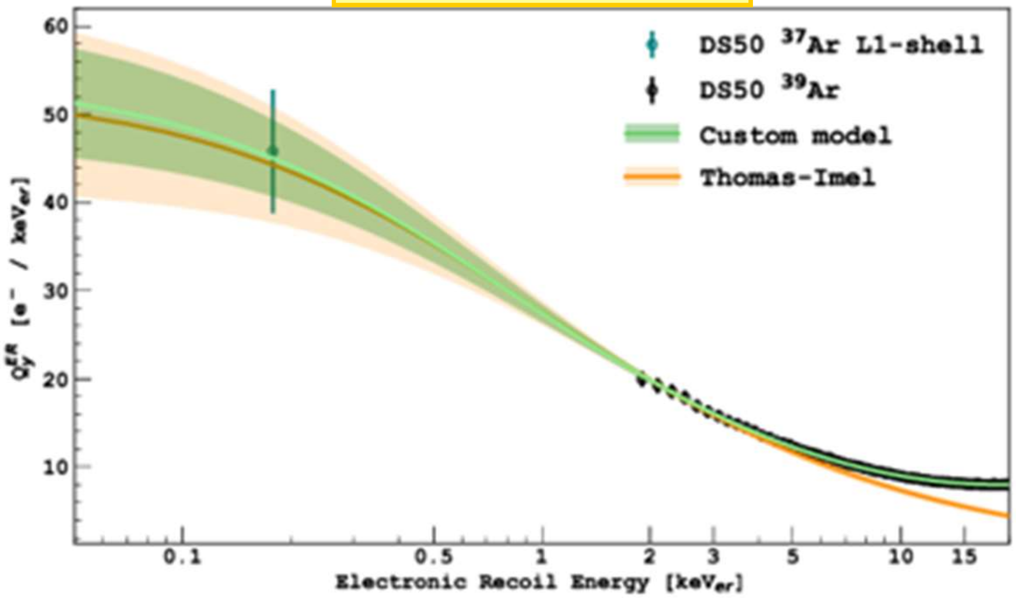
→ UAr extraction should start Q1 2025

LAr ionization response to ER / NR

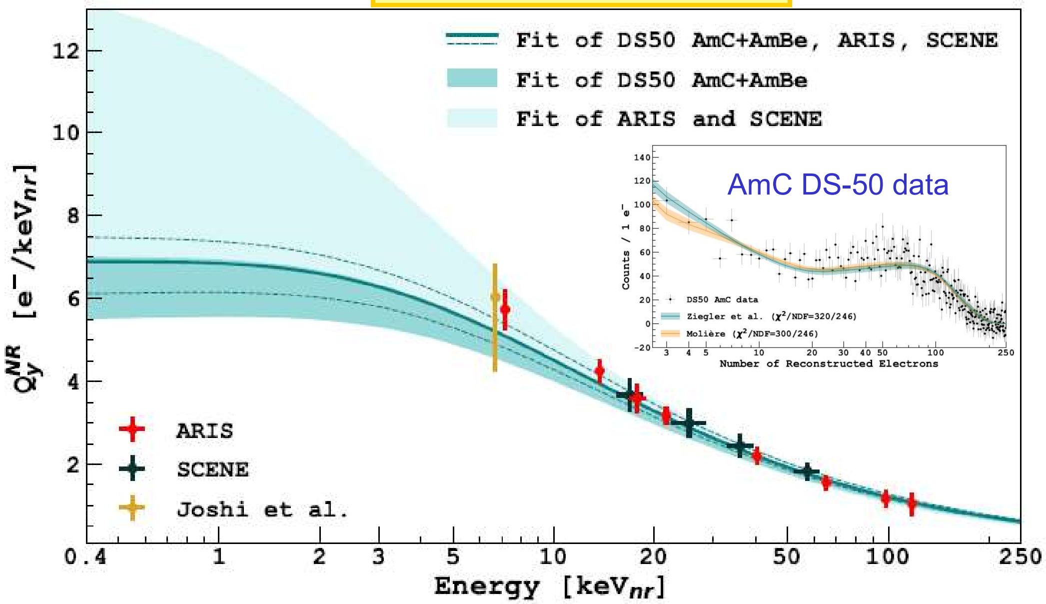
- Measurement of ionization yield at low E central for low mass WIMP search

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:

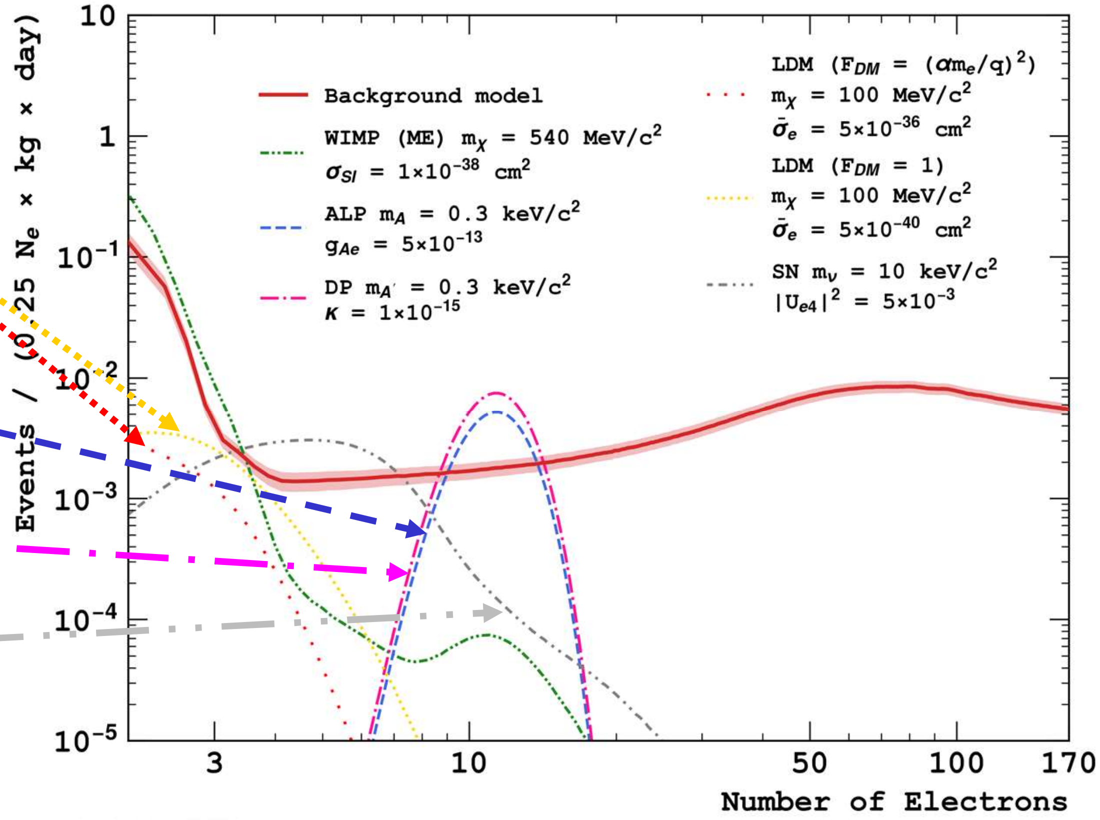
$$R = N_T \frac{\rho_{DM}}{m_A} \times \frac{3 m_A^2 g_{Ae}^2}{16\pi\alpha m_e^2} \sigma_{pe}(m_A c^2) c$$

DP:

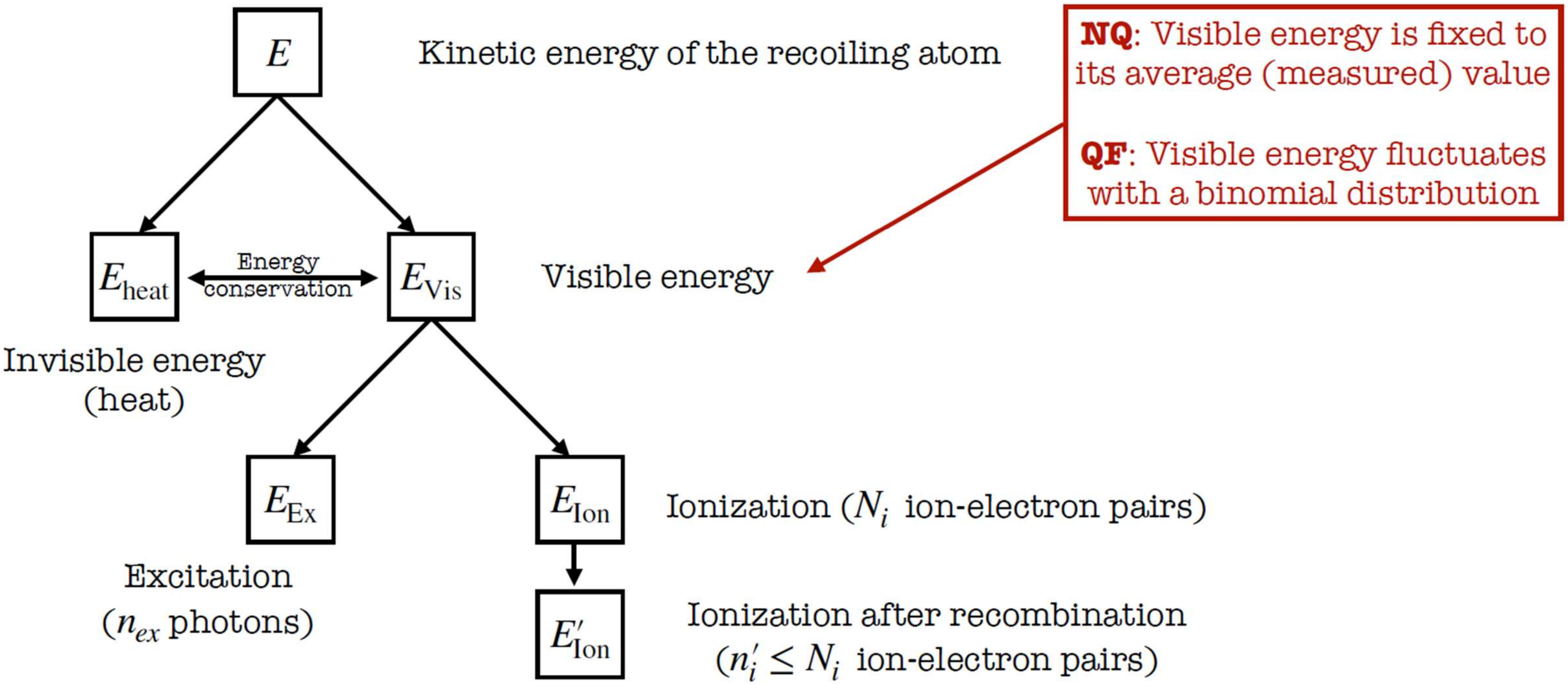
$$R = N_T \frac{\rho_{DM}}{m_{A'}} \times \kappa^2 \sigma_{pe}(m_A c^2) c$$

Sterile neutrinos:

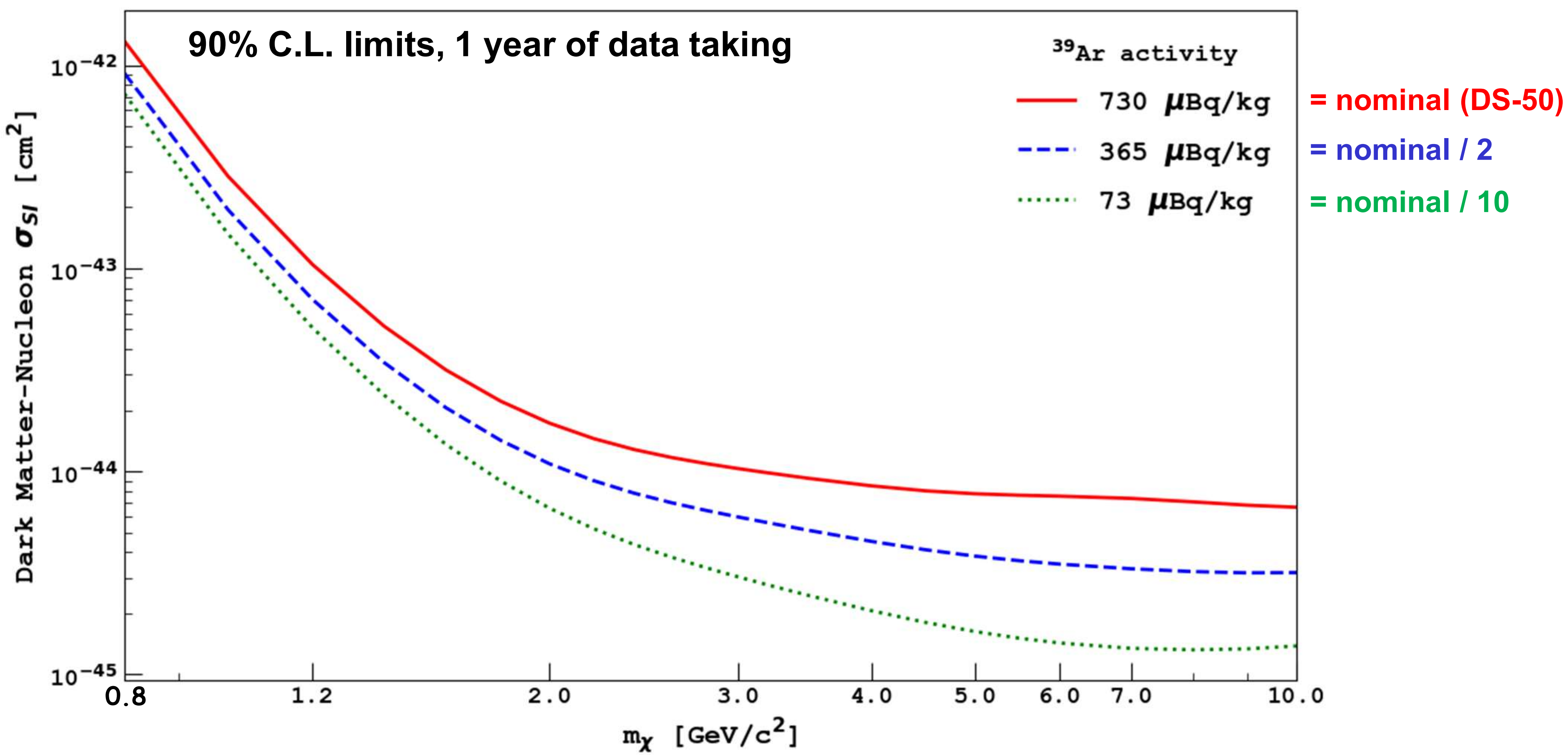
$$\frac{dR}{dE_{er}} = N_T \frac{\rho_{DM}}{m_\nu} \times \sum_{nl} 2(2l+1) \int \frac{d\sigma_{nl}}{dE_{er}} \left(v, m_\nu, |U_{e4}|^2\right) f(v)\ v\ dv$$



Quenching fluctuations in NR



Sensitivity vs ^{39}argon activity



Prospective experiments