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DarkSide-20k sensitivity to light dark matter particles

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On behalf of the DarkSide-20k collaboration

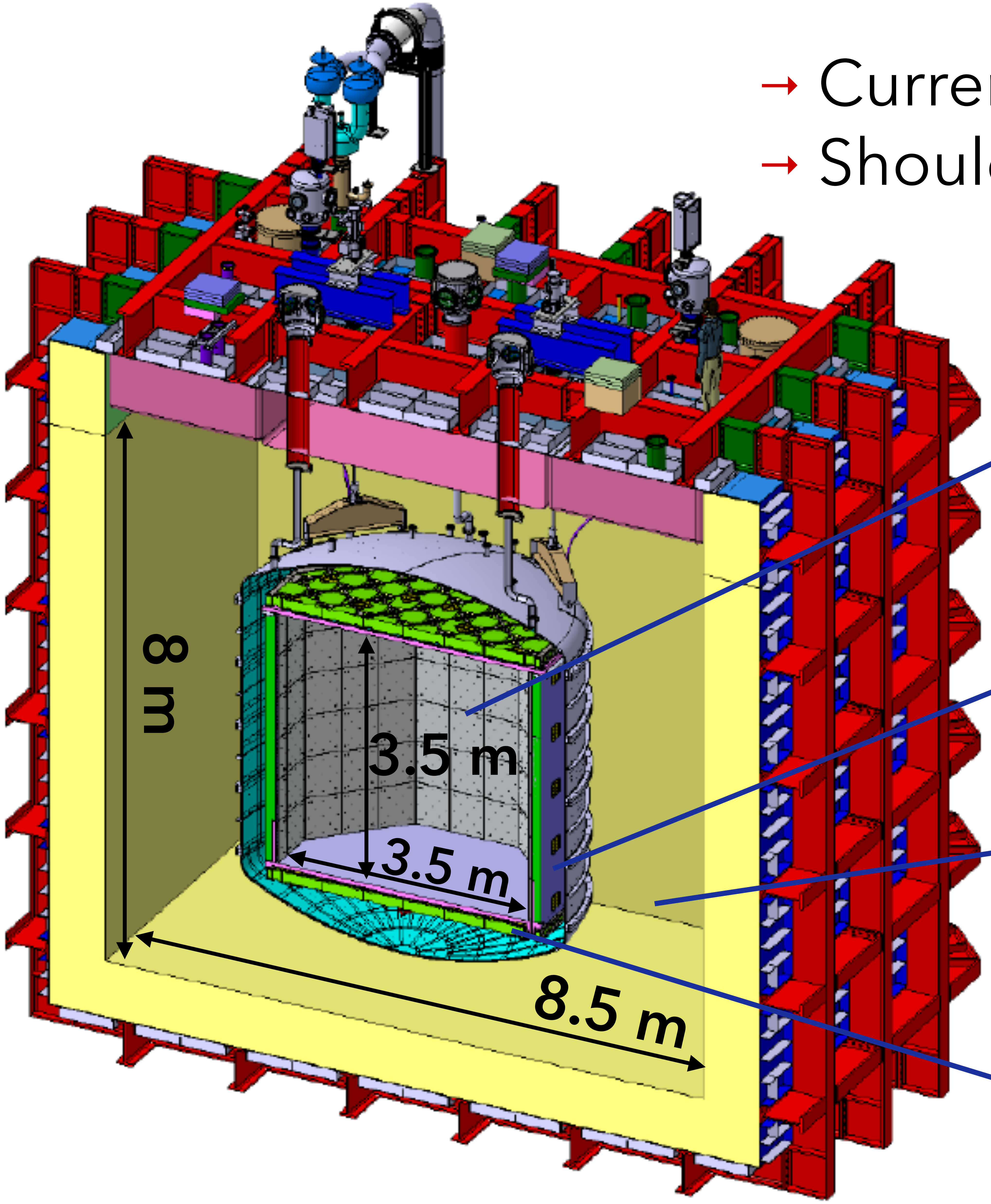
15th International Workshop on the Identification of Dark Matter 2024

Institut Physique de l'Univers
Aix*Marseille Université

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

The DarkSide-20k experiment 1/2

→ Currently under construction
→ Should start data taking in 2027



TPC: 50 t
Underground argon
(UAr)

Inner veto: 32 t UAr

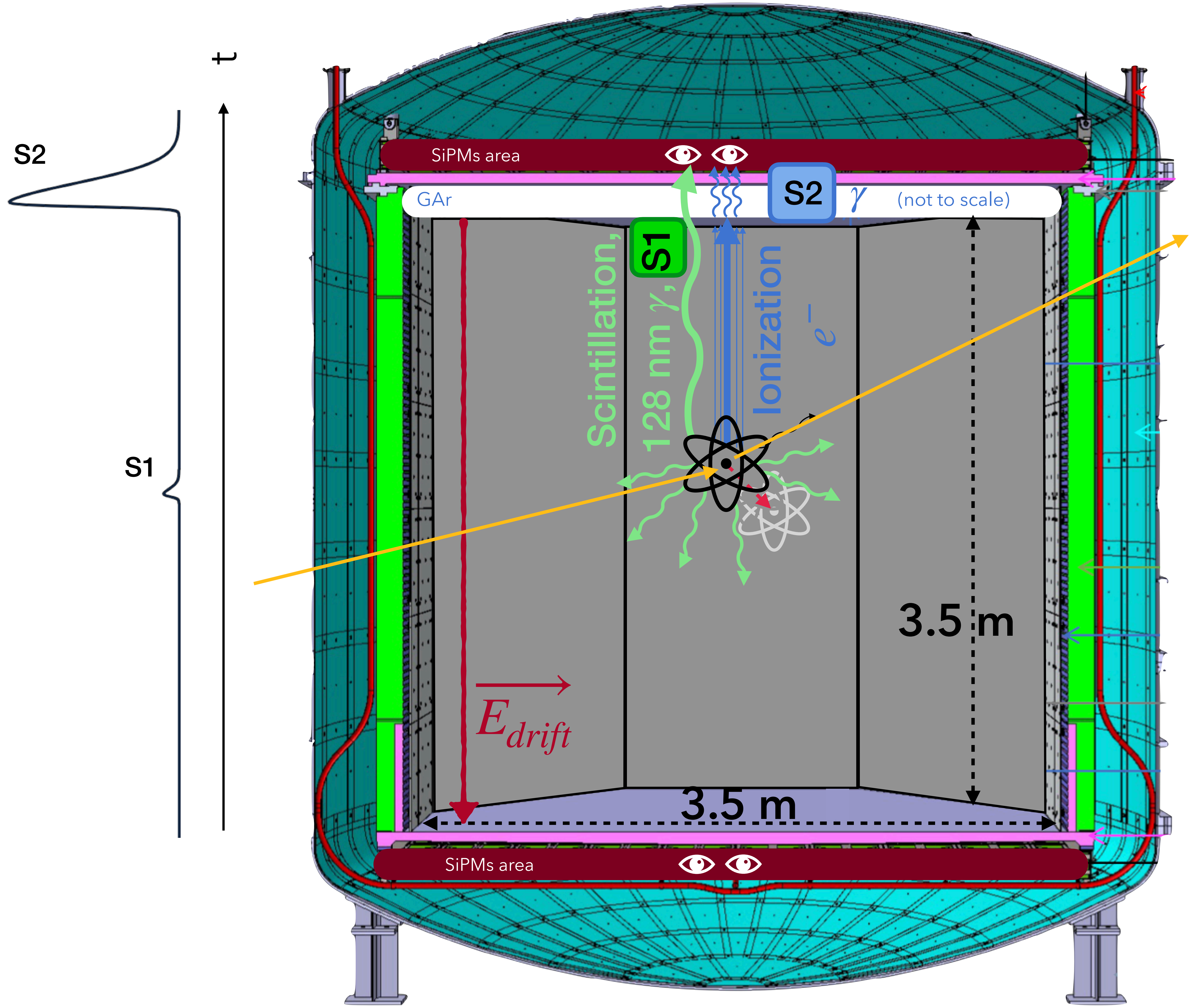
Outer veto: 650 t
Atmospheric argon

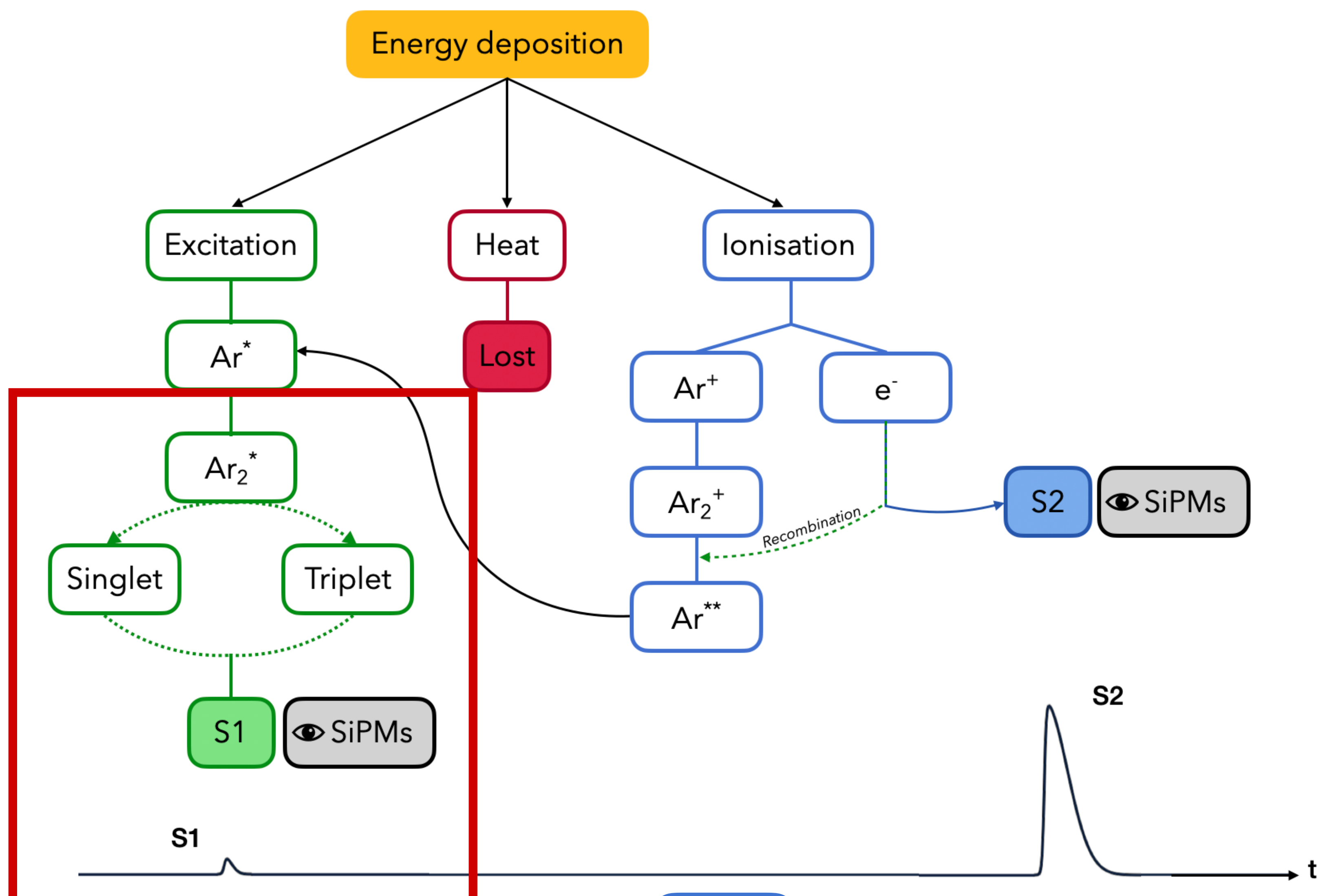
Photo-electronics
2x10.5 m² SiPMs
arrays

See talk by
I. Ahmad for more
details on
DarkSide-20k

See poster by
A. Marasciulli

The DarkSide-20k experiment 2/2





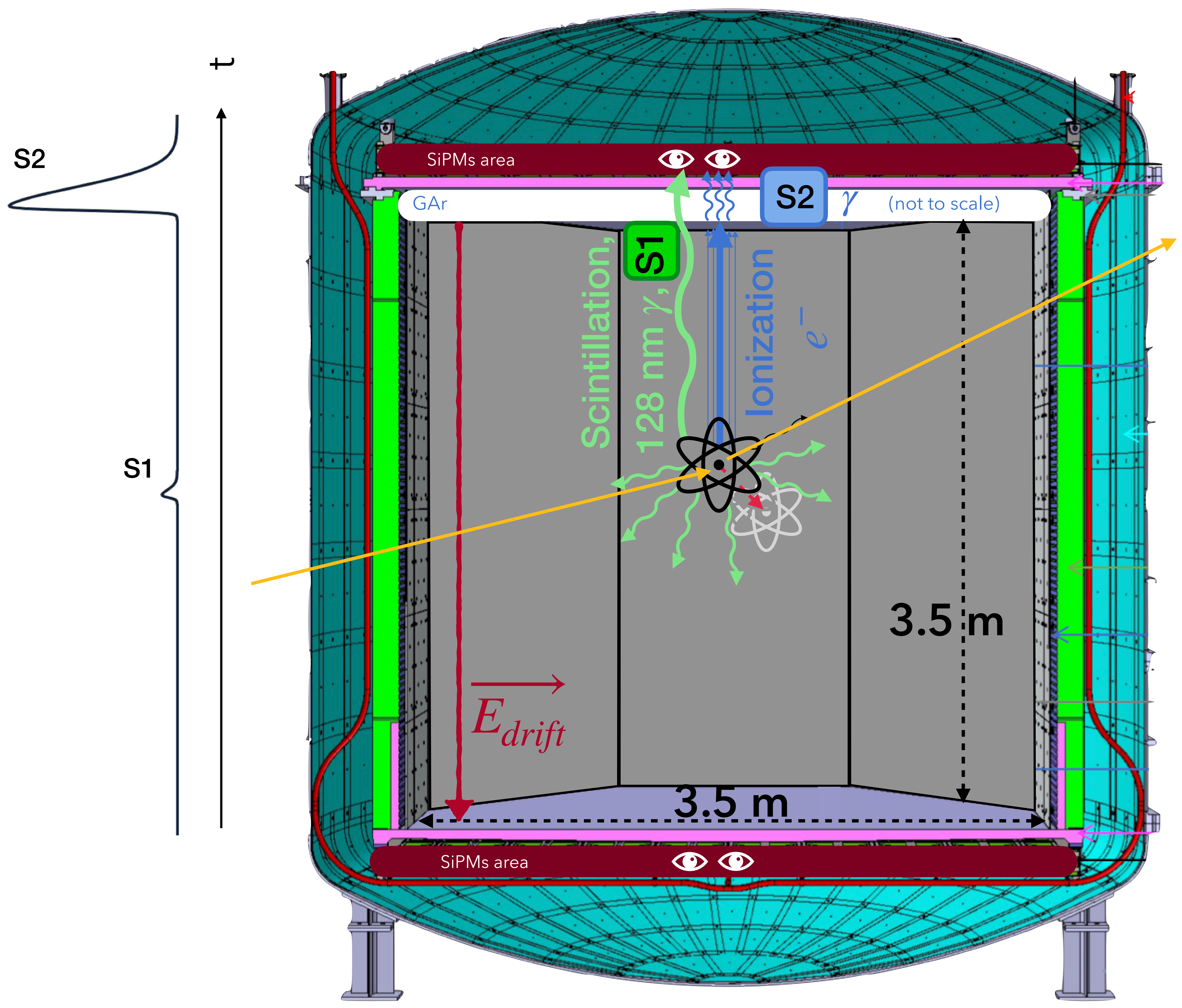
PSD
$10^7 - 10^9$ signal-bkg discrimination power

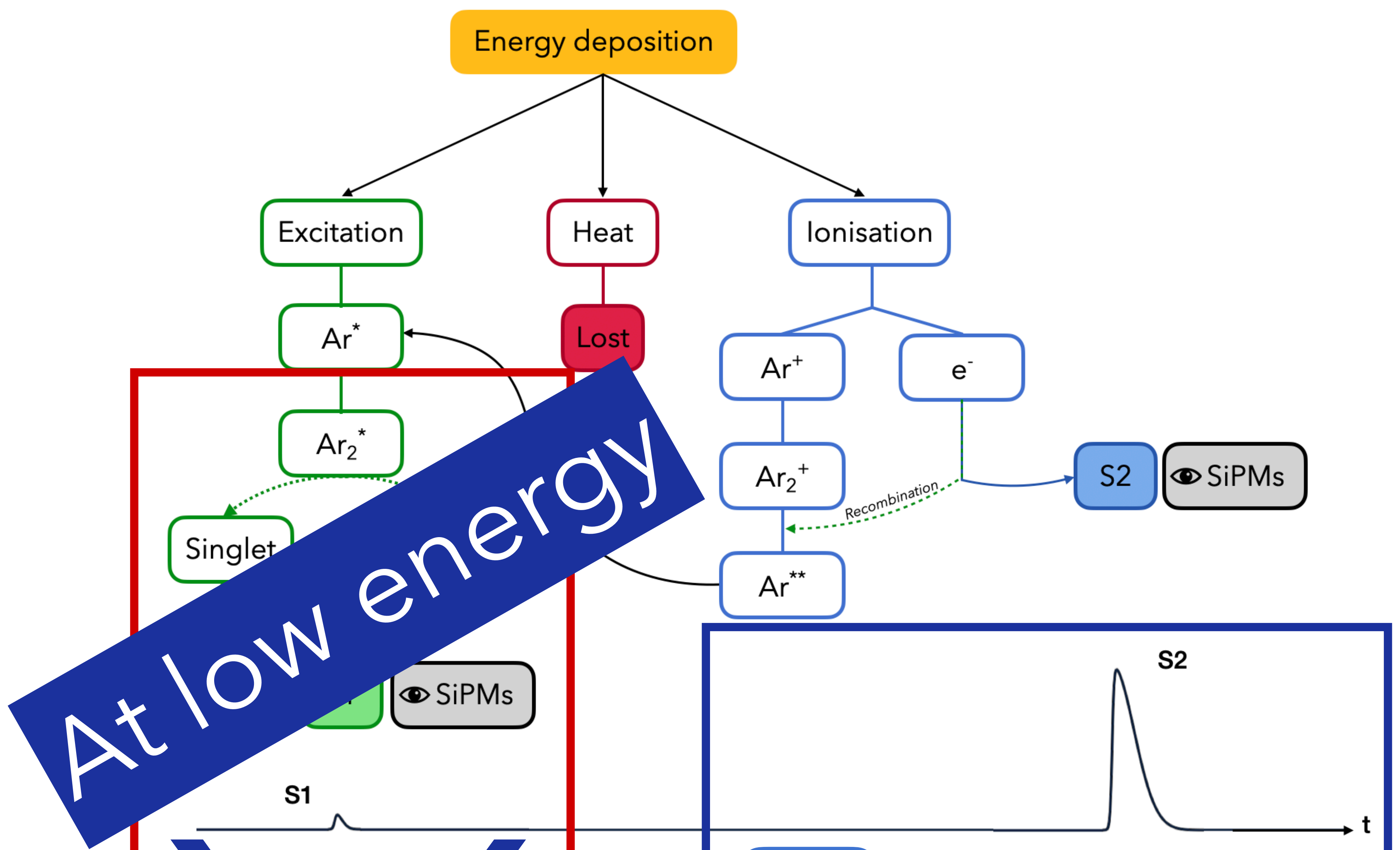
S2 ionization signal (delayed)

S1 scintillation signal (prompt)

See talk by I. Ahmad for more details on DarkSide-20k

The DarkSide-20k experiment 2/2





~~**PSD**~~

~~10^7 — 10^9 signal/bkg discrimination power~~

S1 scintillation signal

$\lesssim 1 keV_{ee}$ } *From DS-50*

$\lesssim 5 keV_{nr}$

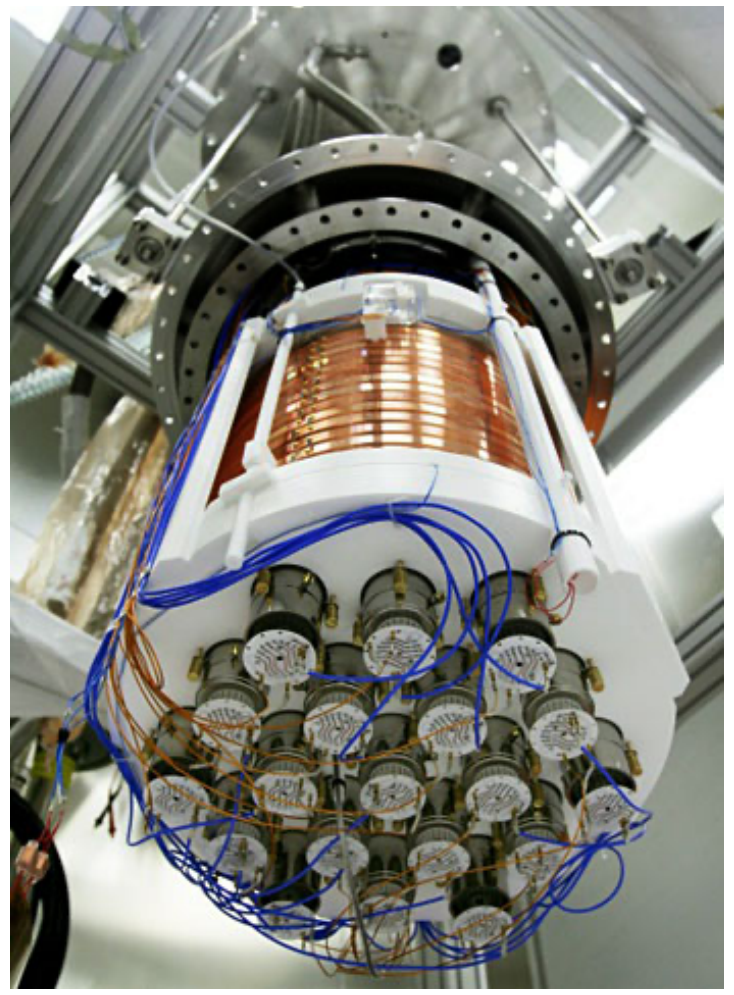
S2 ionization signal (delayed)

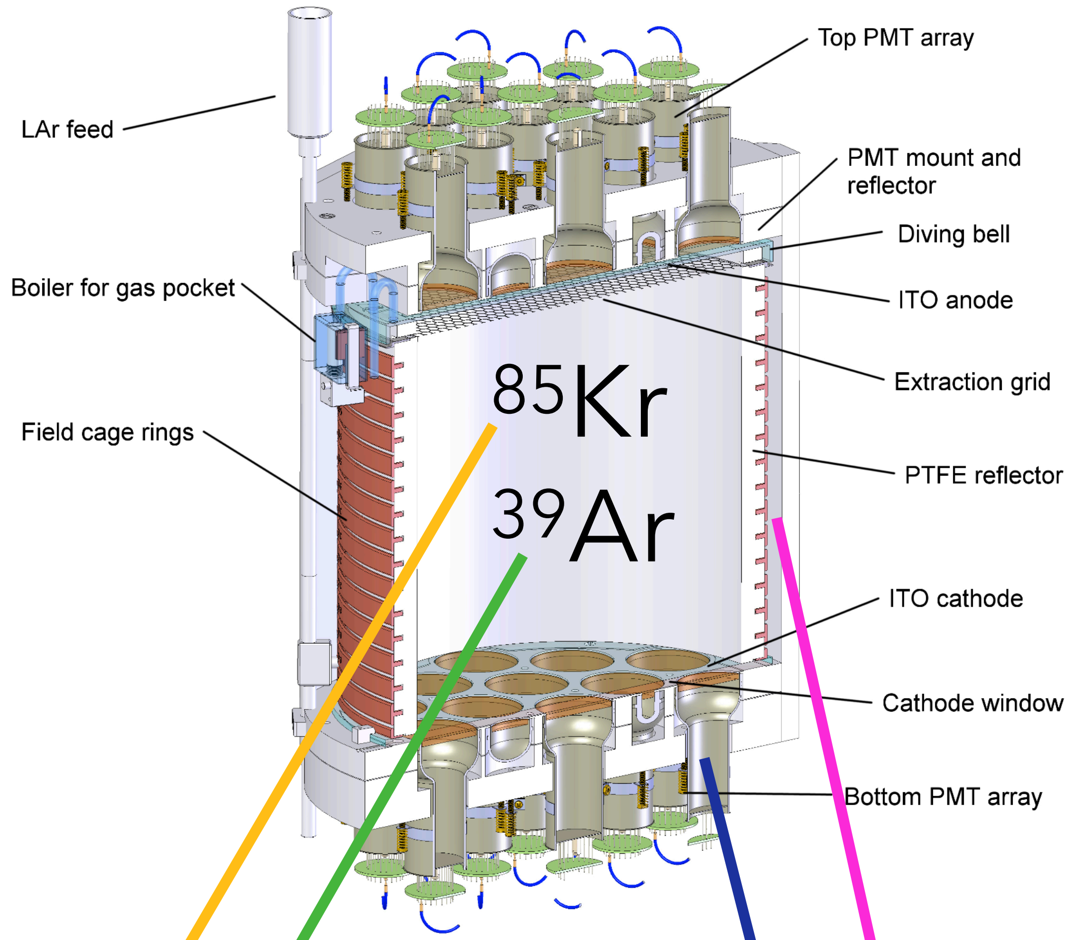
Only information

☑ Sub-keV threshold to extract S2

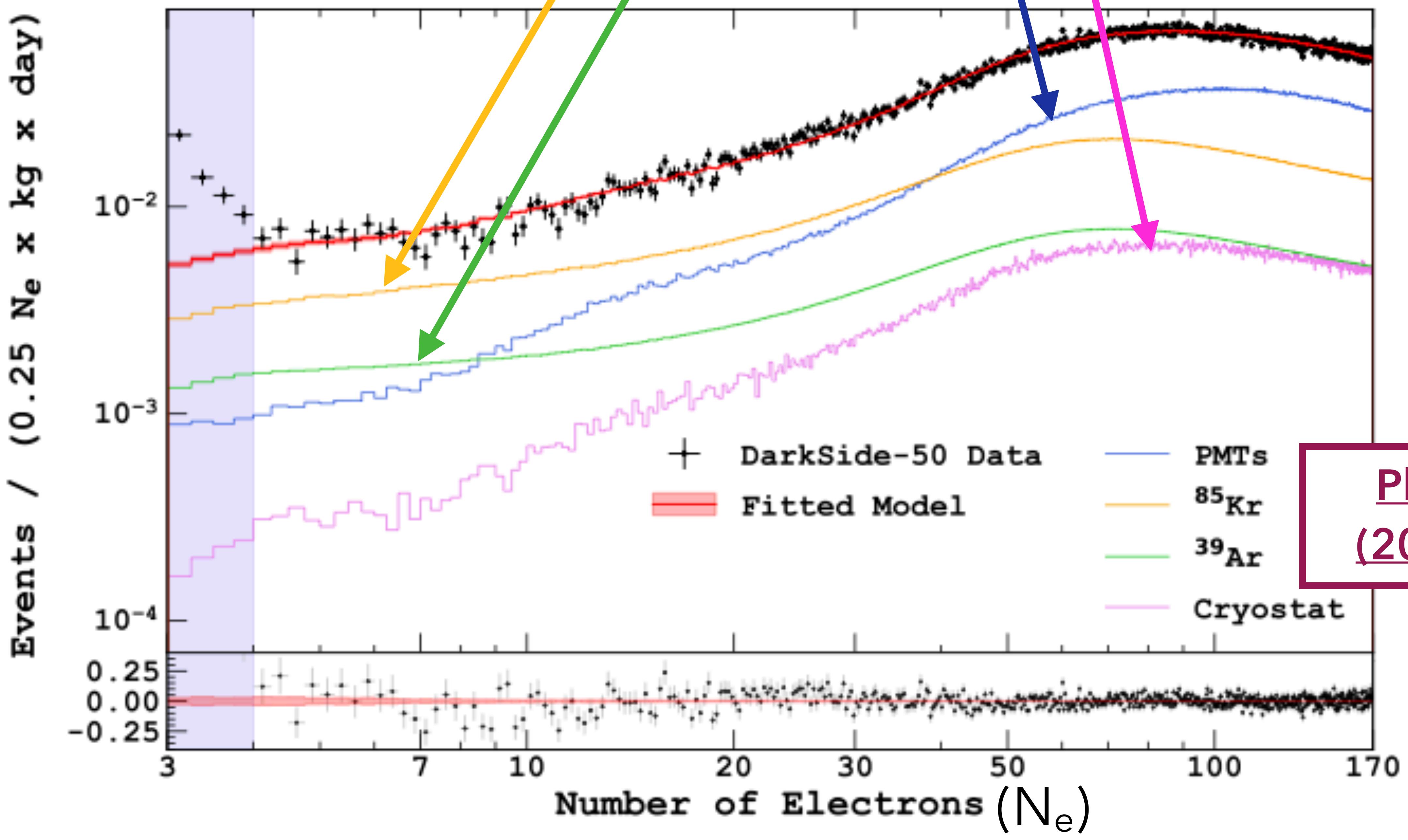
☒ (ER) bkg-dominated analysis

From DarkSide-50 to DarkSide-20k



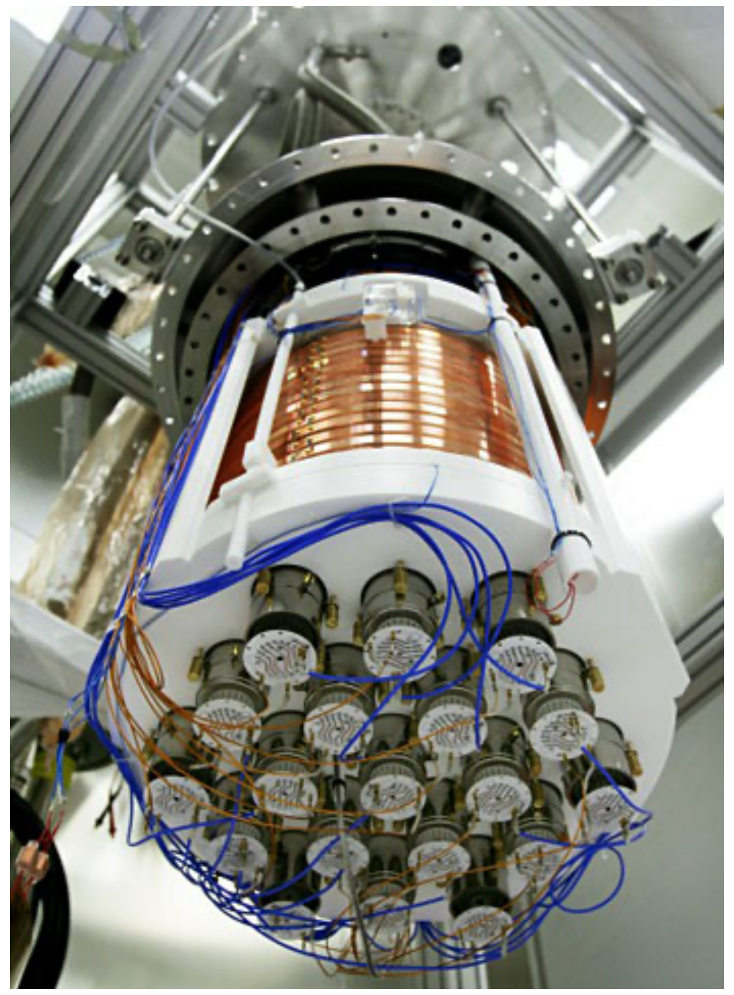


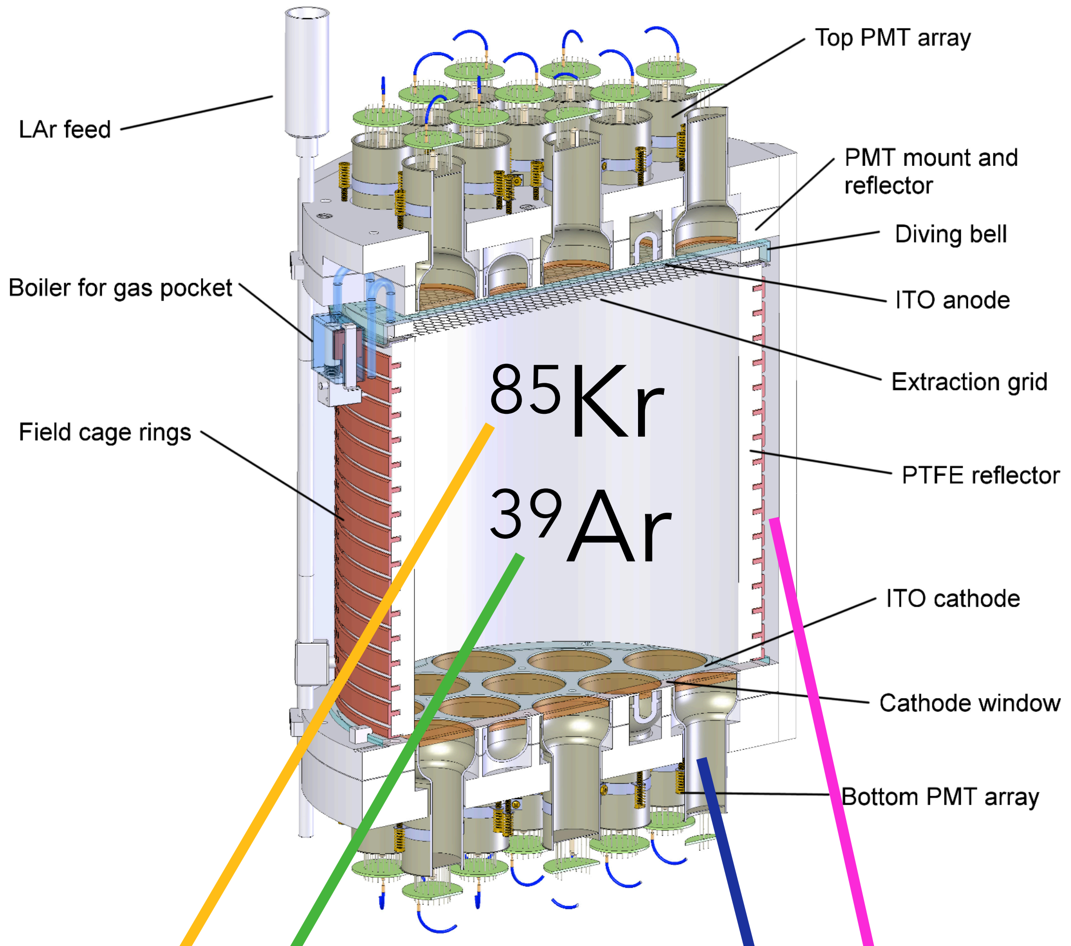
DarkSide-50



Phys.Rev.D 107 (2023) 6, 063001

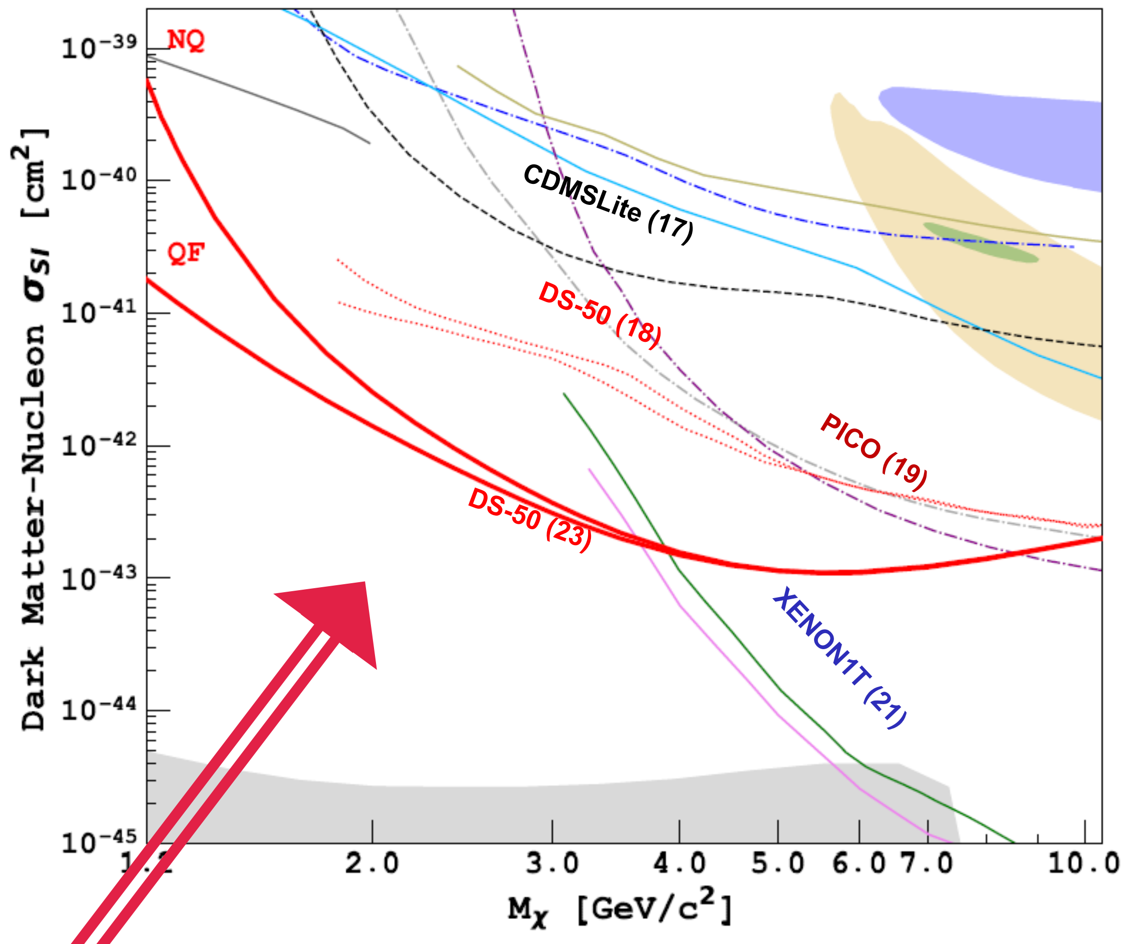
From DarkSide-50 to DarkSide-20k

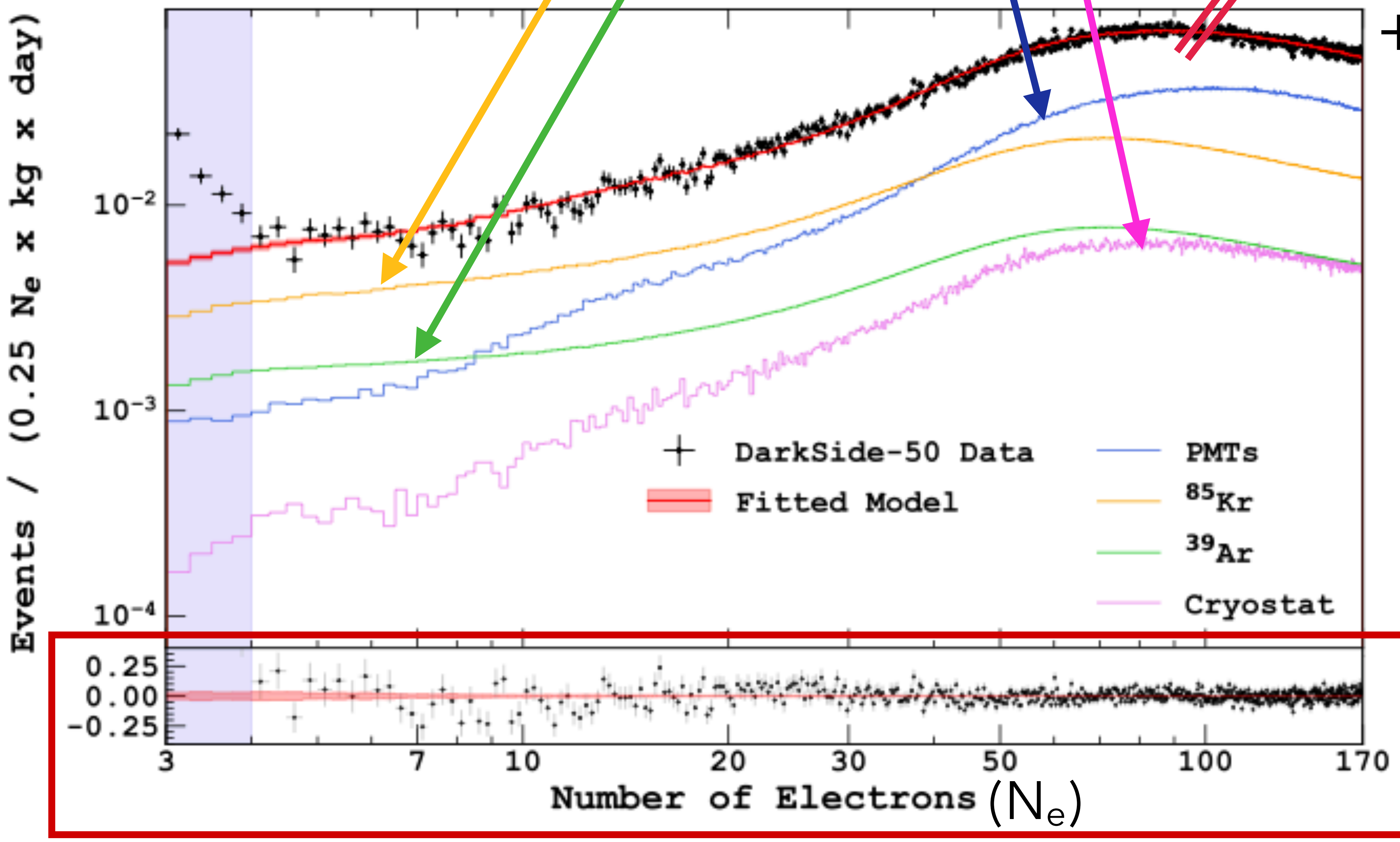




DarkSide-50

[Phys.Rev.D 107 (2023), 063001]





+ Migdal :

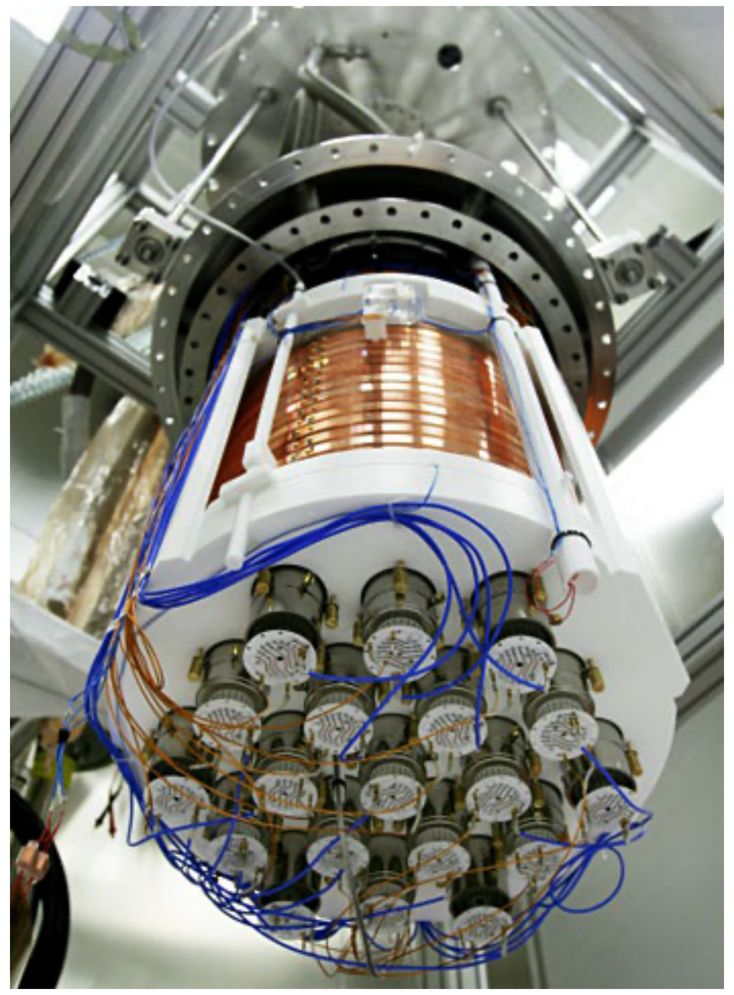
[Phys.Rev.Lett. 130 (2023), 101001]

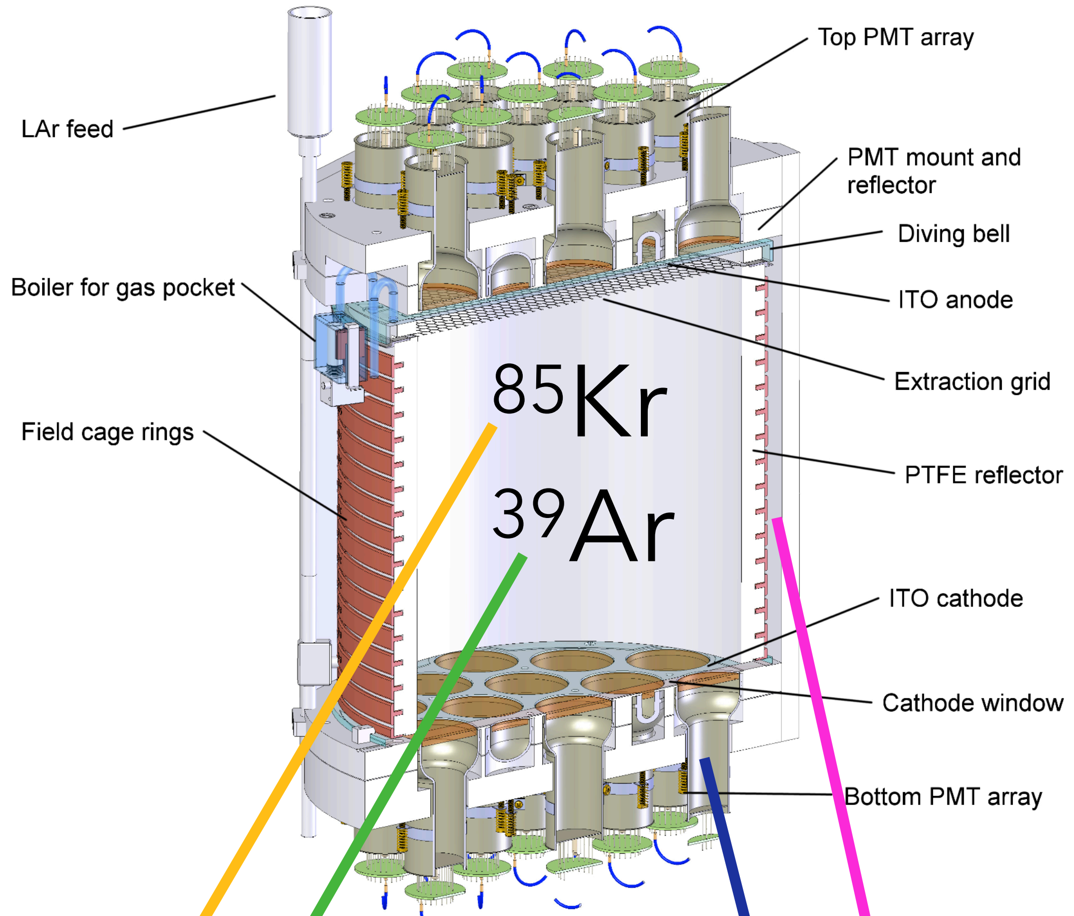
+ Other light DM :

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

Excellent bkg modelling above 4 N_e

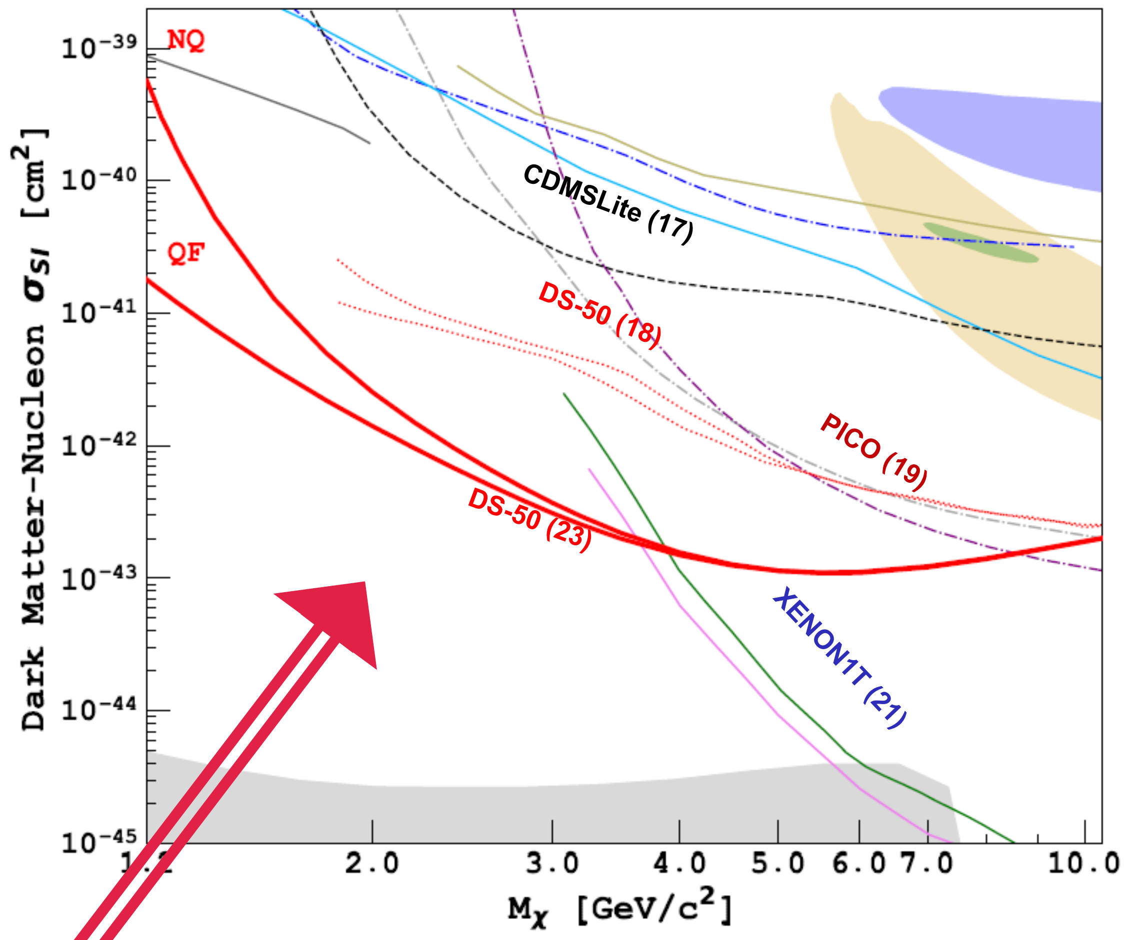
From DarkSide-50 to DarkSide-20k

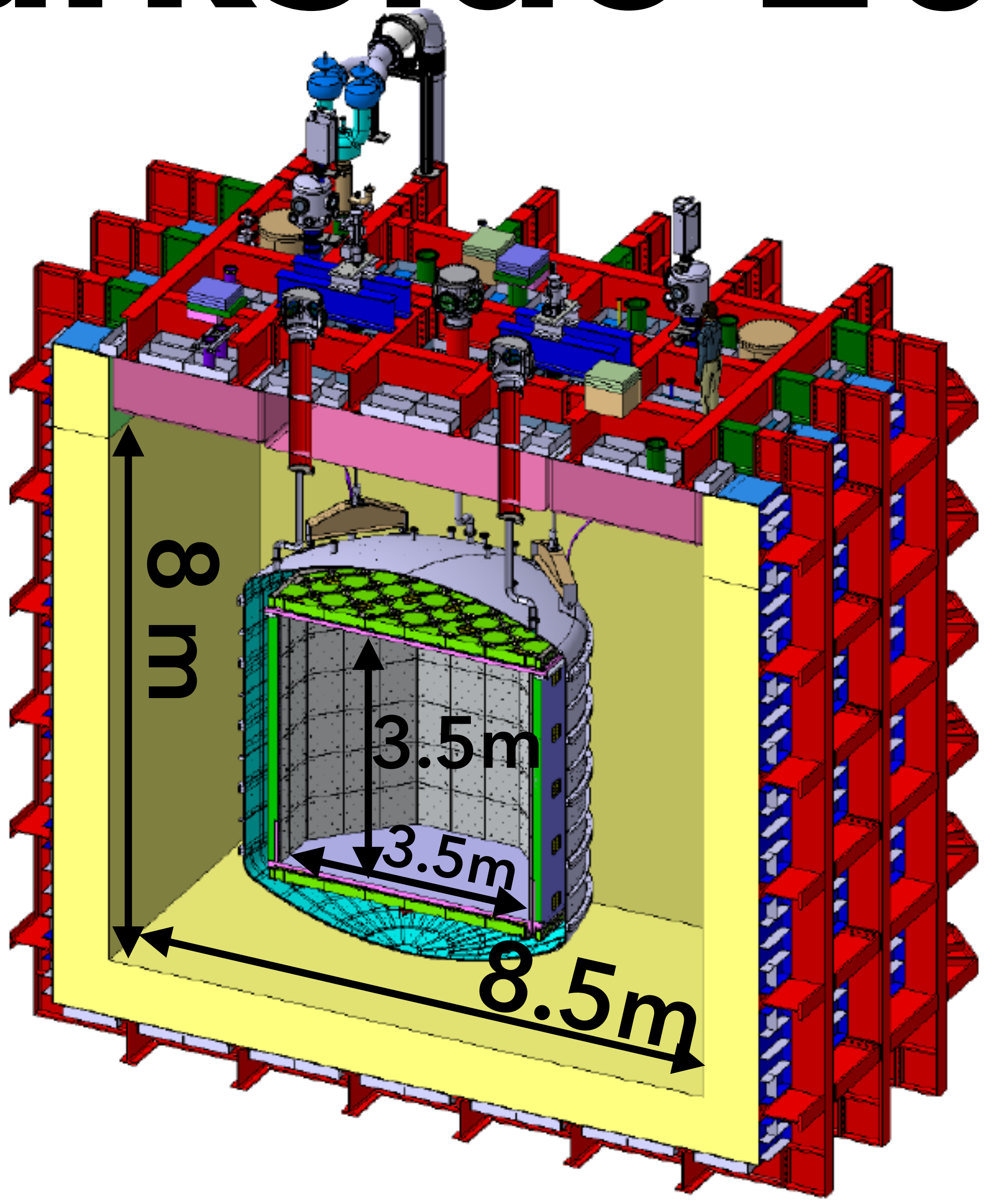




DarkSide-50

Phys.Rev.D 107 (2023), 063001

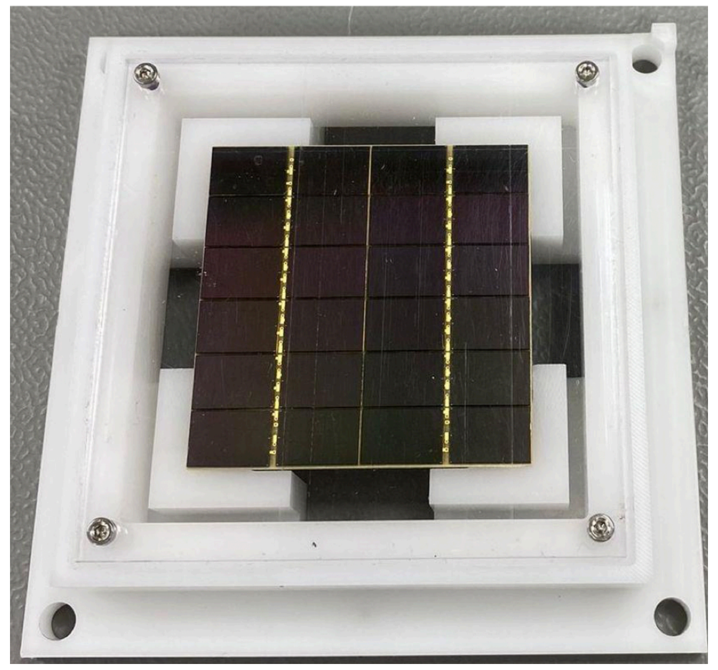


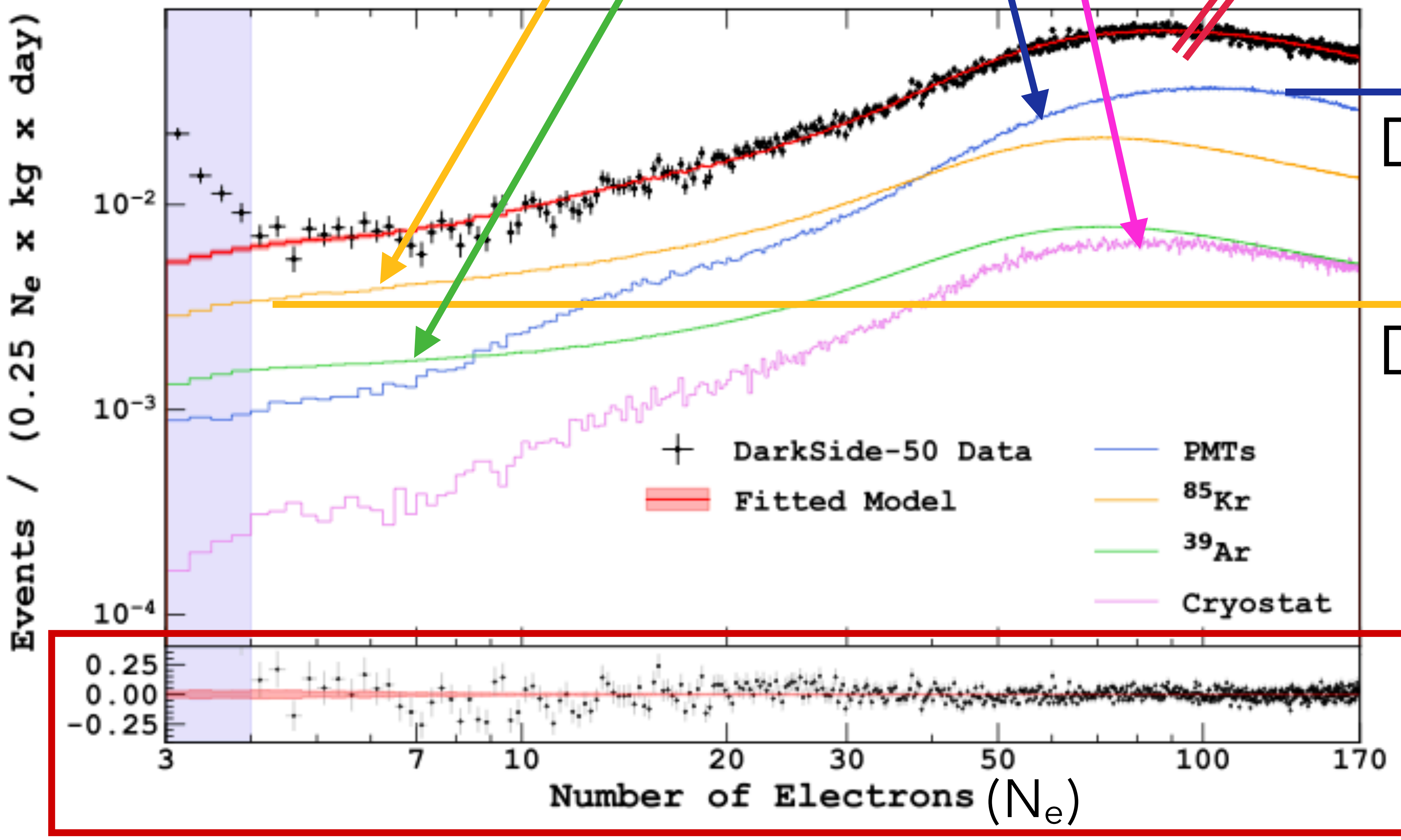


DarkSide-20k

8448 photosensors

Arrays of 24 SiPMs





PMTs

Dominant at high Ne

Use SiPMs

Reduced radio-activity wrt PMTs

^{85}Kr

Dominant at low Ne

URANIA UAr

Extraction facility

→reduced contamination

See talk by R. Stefanizzi

Excellent bkg modelling above 4 N_e

Less ER background → benefitting to the low mass analysis

DarkSide-20k low mass analysis

Pile up

- Expect 80 Hz from β, X and γ backgrounds
- **Select isolated S2**, with other S2 occurring at times greater than one maximum drift time (3.7 ms)

51% of effective livetime

Fiducialization

- **Radial**: 30 cm fiducialization from the walls
- Drift direction: no fiducialization

69% of signal acceptance

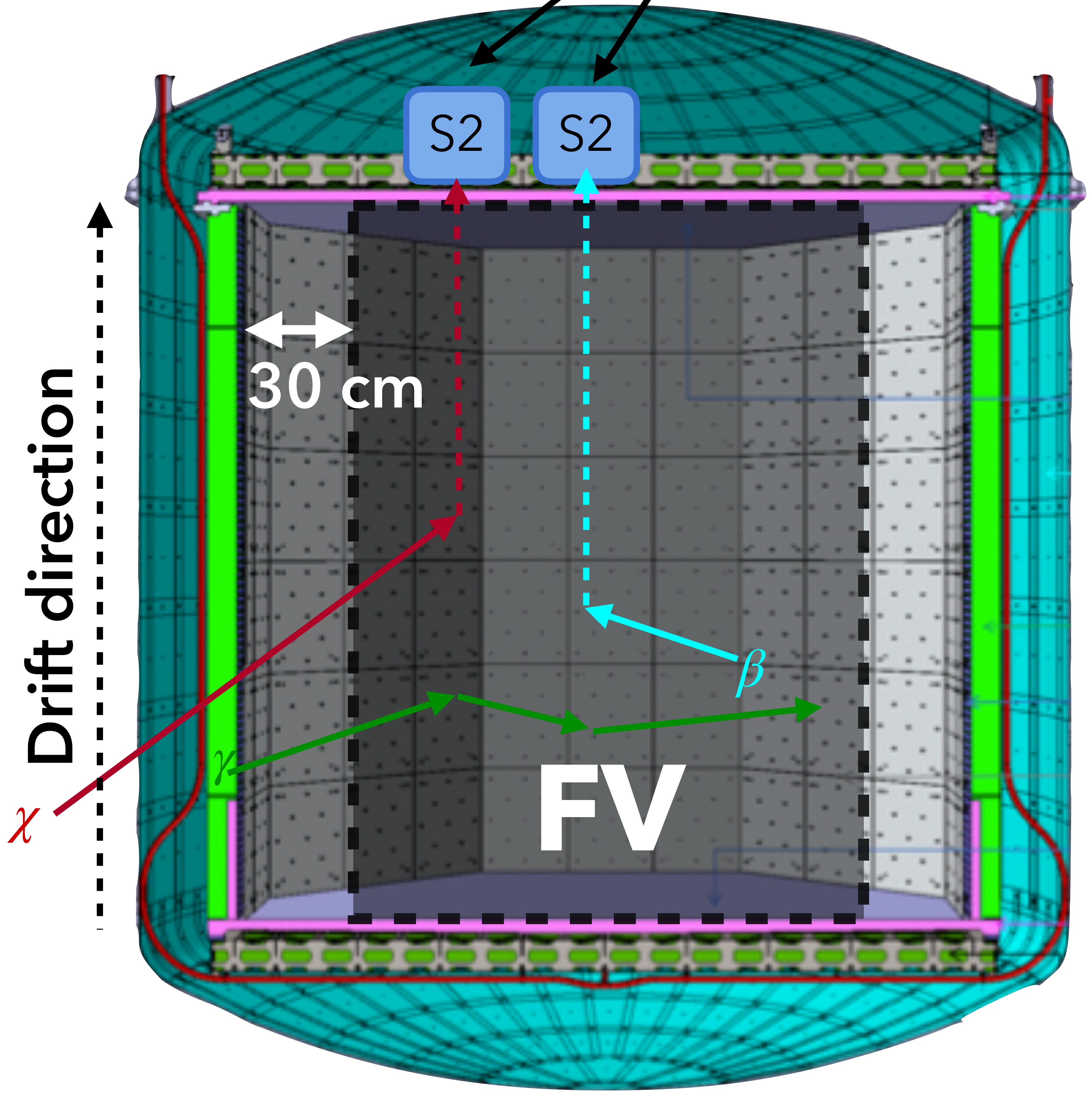
TPC: 49.7 t UAr

x 0.51

x 0.69

Exposure = **17.4 ton.year** for 1 year of data taking

May arrive close in time and look like a multiple scatter



DS-20k inner detector

DarkSide-20k low mass background model

- Uniformly distributed in the fiducial volume
- Include recent calculations of β-decay energy spectra

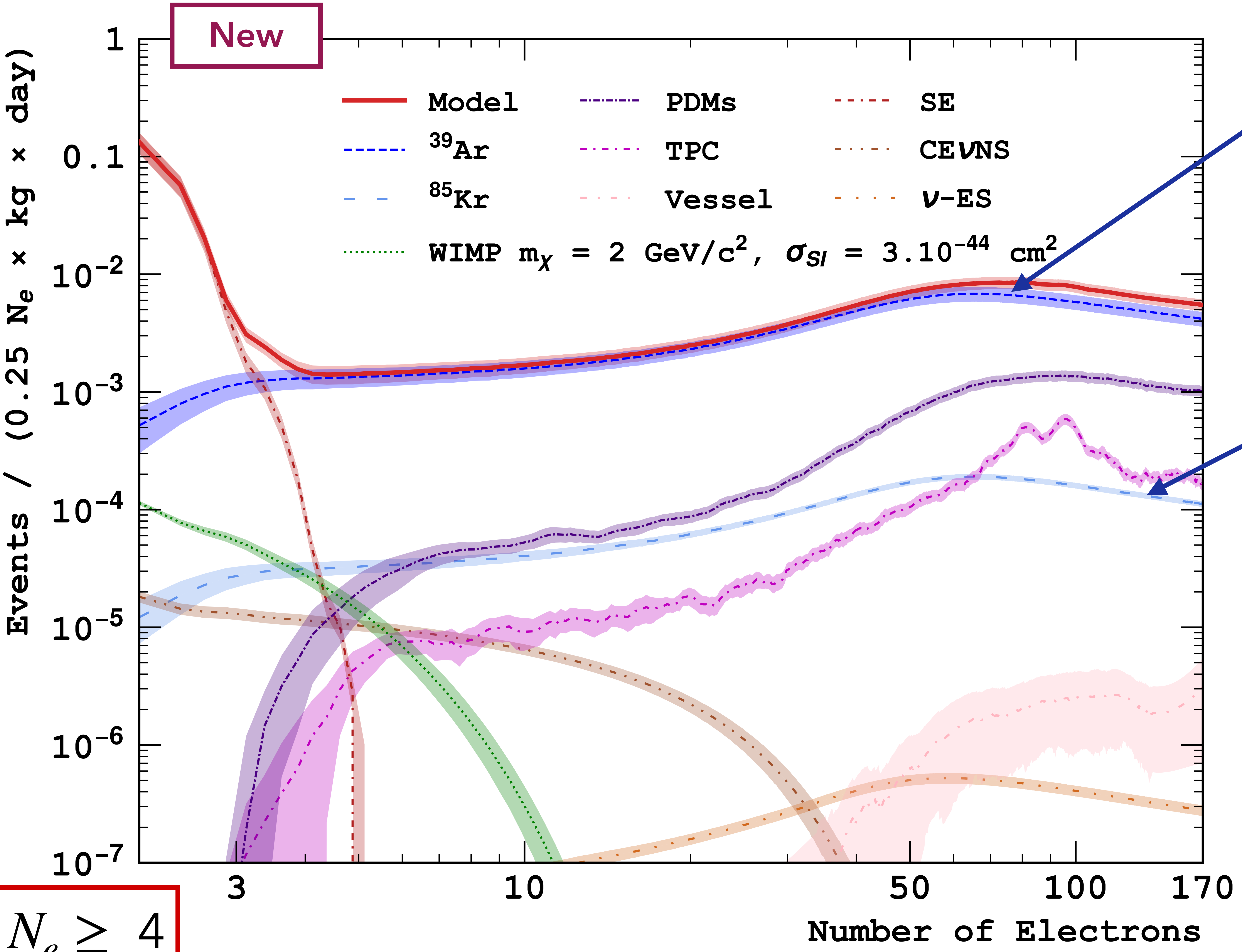
Phys.Rev.A 90 (2014) 012501

Phys.Rev.C 102 (2020) 065501

- Include shape systematics (atomic exchanges, screening effect, Q-value)

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

LAr intrinsic backgrounds (β decays)



^{39}Ar

Same activity as DS-50 (same UAr mine)

A(^{39}Ar) = 0.73 mBq/kg

^{85}Kr

Urania (Colorado, USA): dedicated facility for extraction

Reduced ^{85}Kr activity wrt DS-50

A(^{85}Kr) = 1.9 10^{-2} mBq/kg

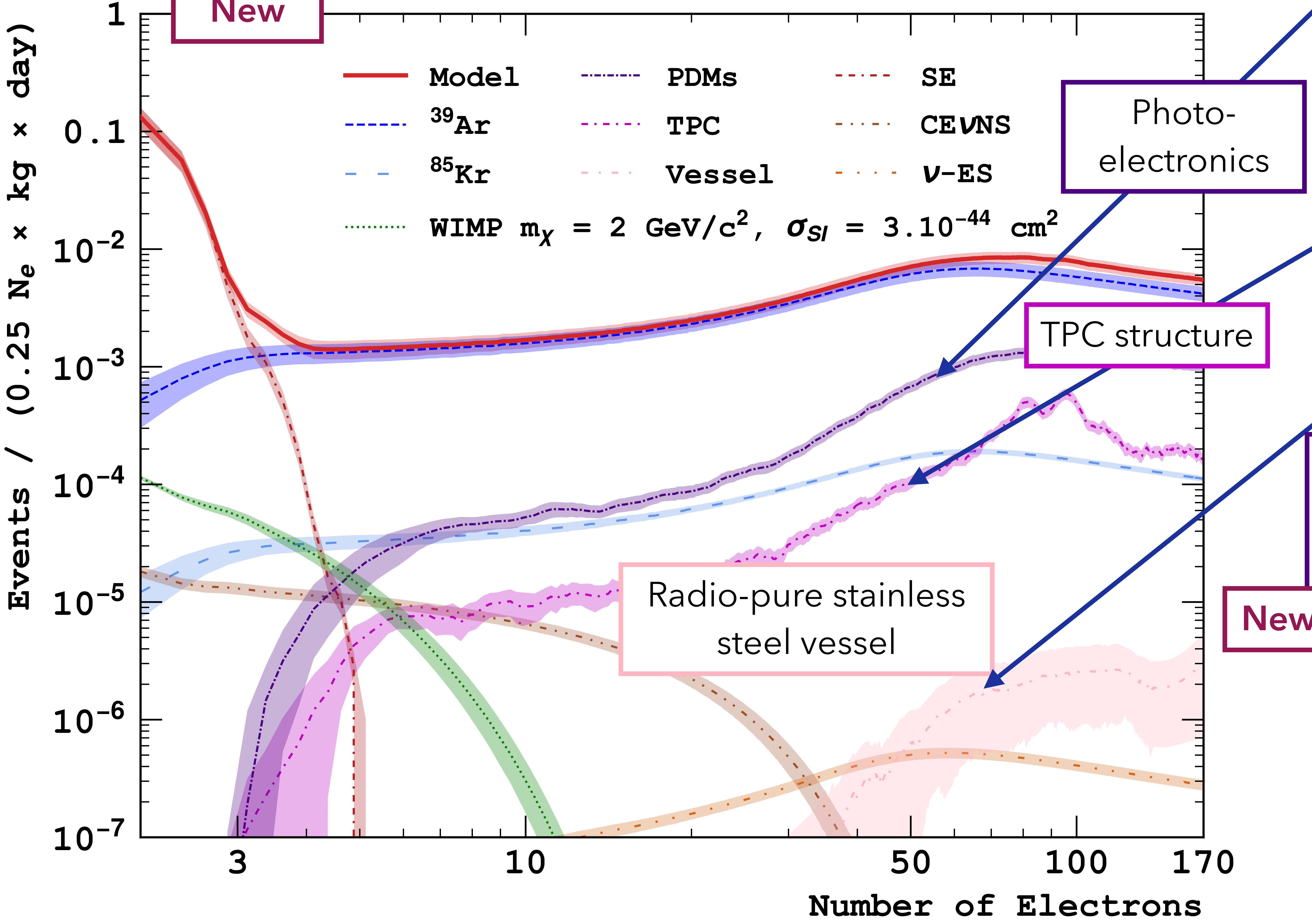
See talk by R. Stefanizzi

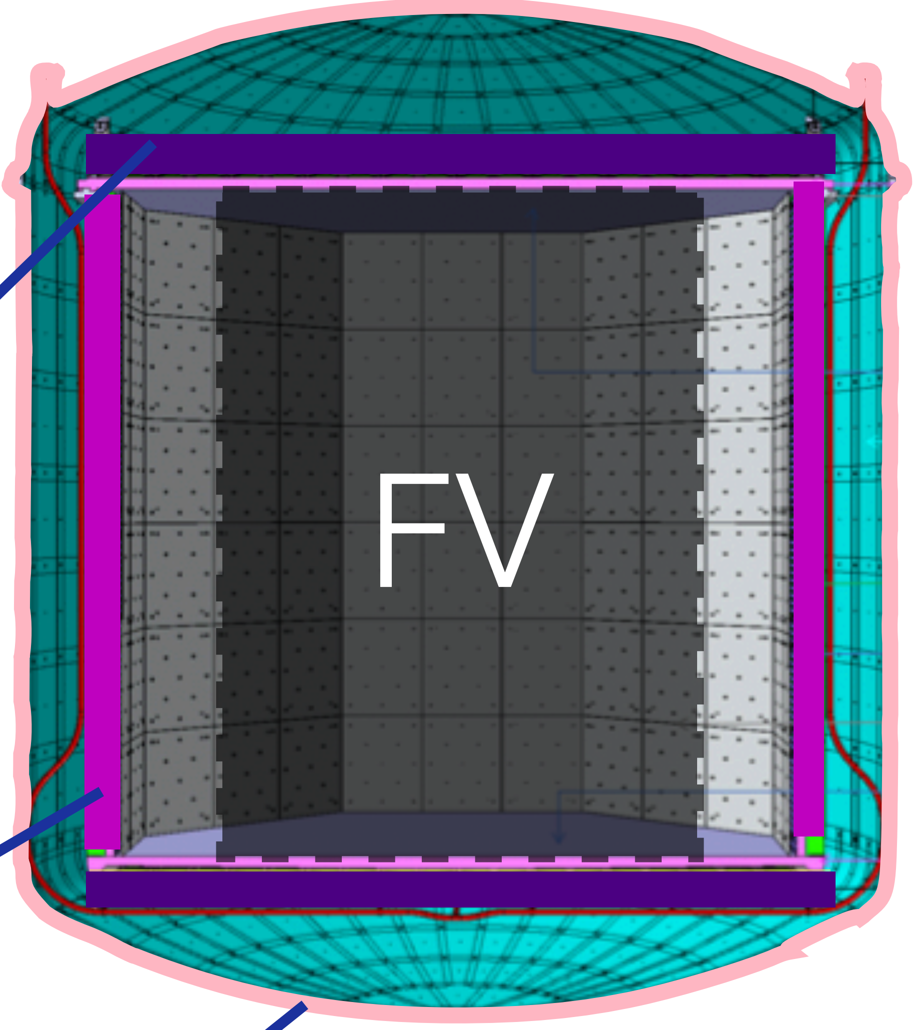
DarkSide-20k low mass background model

- Simulated with a GEANT-4 based simulation tool
- ≈ 2.5x reduced bkg contamination per surface area wrt DS-50

External γ-ray and X-ray backgrounds

New





See talk by R. Santorelli

Radio-contamination estimated from **material assays**

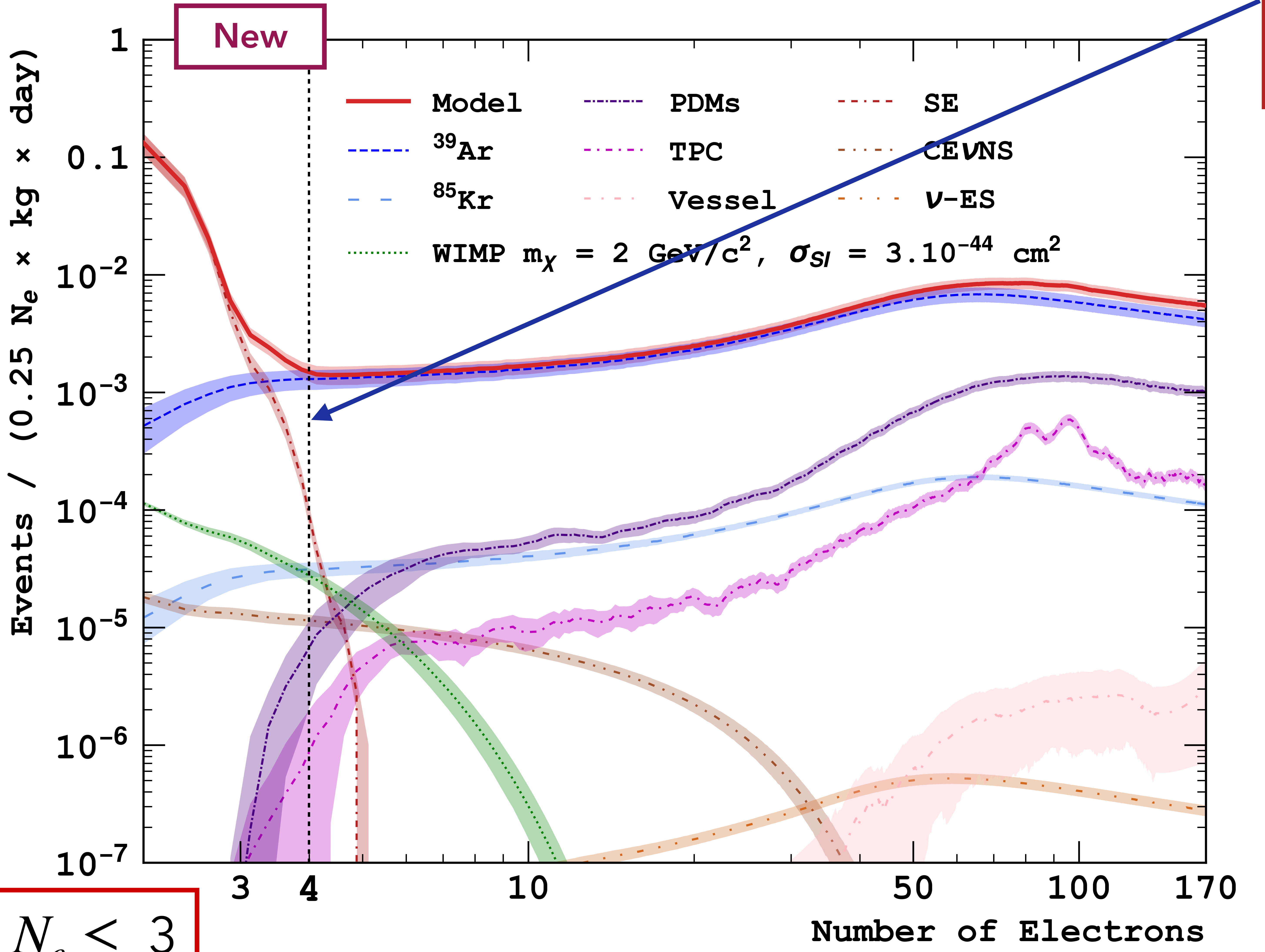
New

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

DarkSide-20k low mass background model

- Observed in DS-50
- Origin might be trapped electrons by impurities and released later
- For DS20k: **Extrapolation from DS-50 data**

Spurious electron (SE) background



SE 18x lower than ^{39}Ar at N_e = 4

SE dominant for $N_e \leq 3$

2 fit scenarii:

- **Conservative** (almost indep. of SE modelling): Fit from N_e = 4 (DS-50 strategy)
- **Ultimate**: Fit from N_e = 2 assuming good control of rate and spectral shape of SE in DS-20k

DarkSide-20k low mass background model

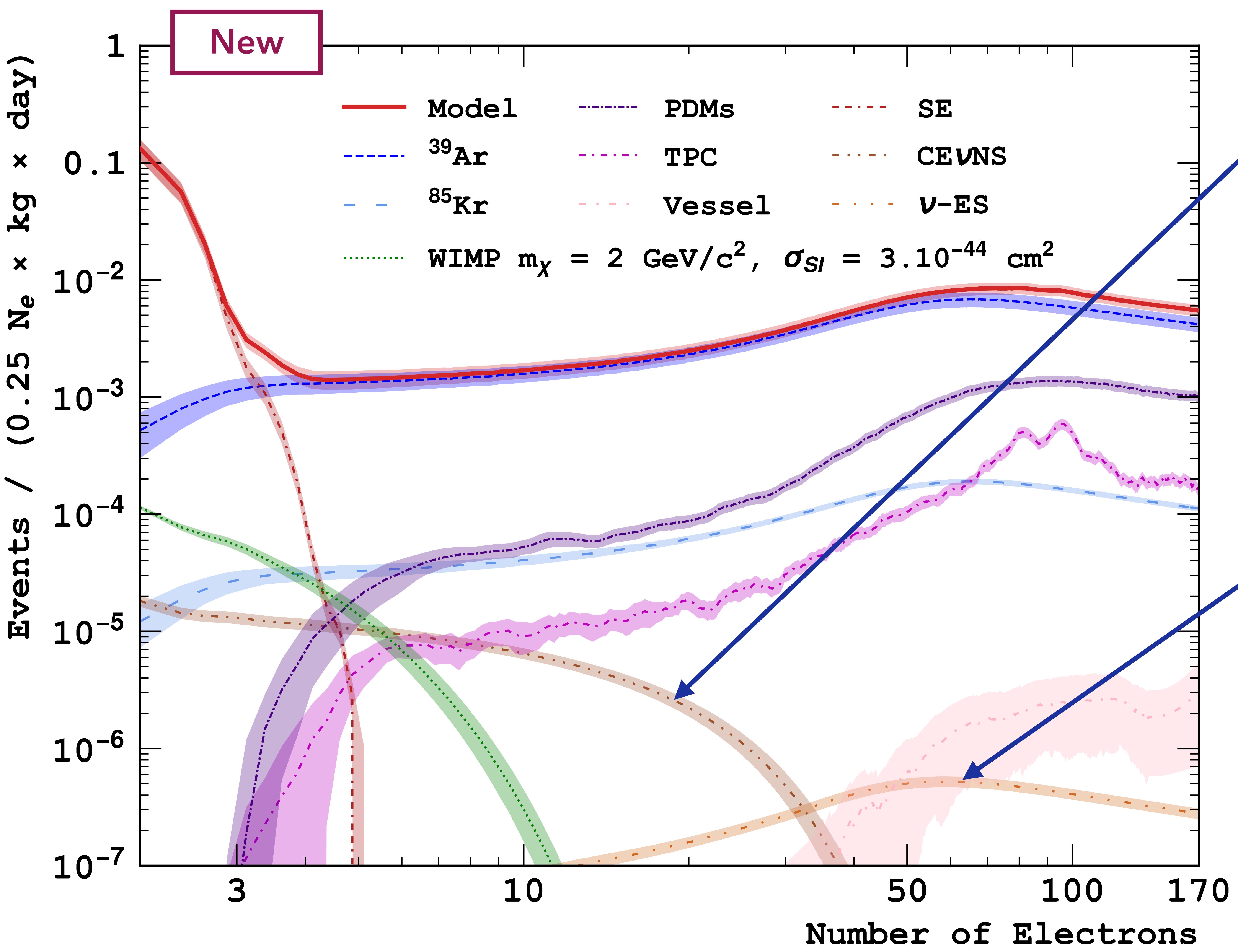
- Mostly from solar neutrinos (^{7}Be, ^{15}O, pep, ^{8}B, hep)
- Include radiative corrections in CEνNS

  JHEP 05, 271

- Include accurate parametrization of the nucleus structure

  Phys.Rev.D 102 (2020) 015030

Neutrino backgrounds



CEνNS

Mainly from solar ^{8}B ν (E_{dep} < 10 keV$_{nr}$)

ν-ES

→ Mainly from pp (+ ^{7}Be) ν (E_{dep} < 20 keV$_{er}$)

→ Dominates over CEνNS at $N_e \gtrsim 30$

Signal models

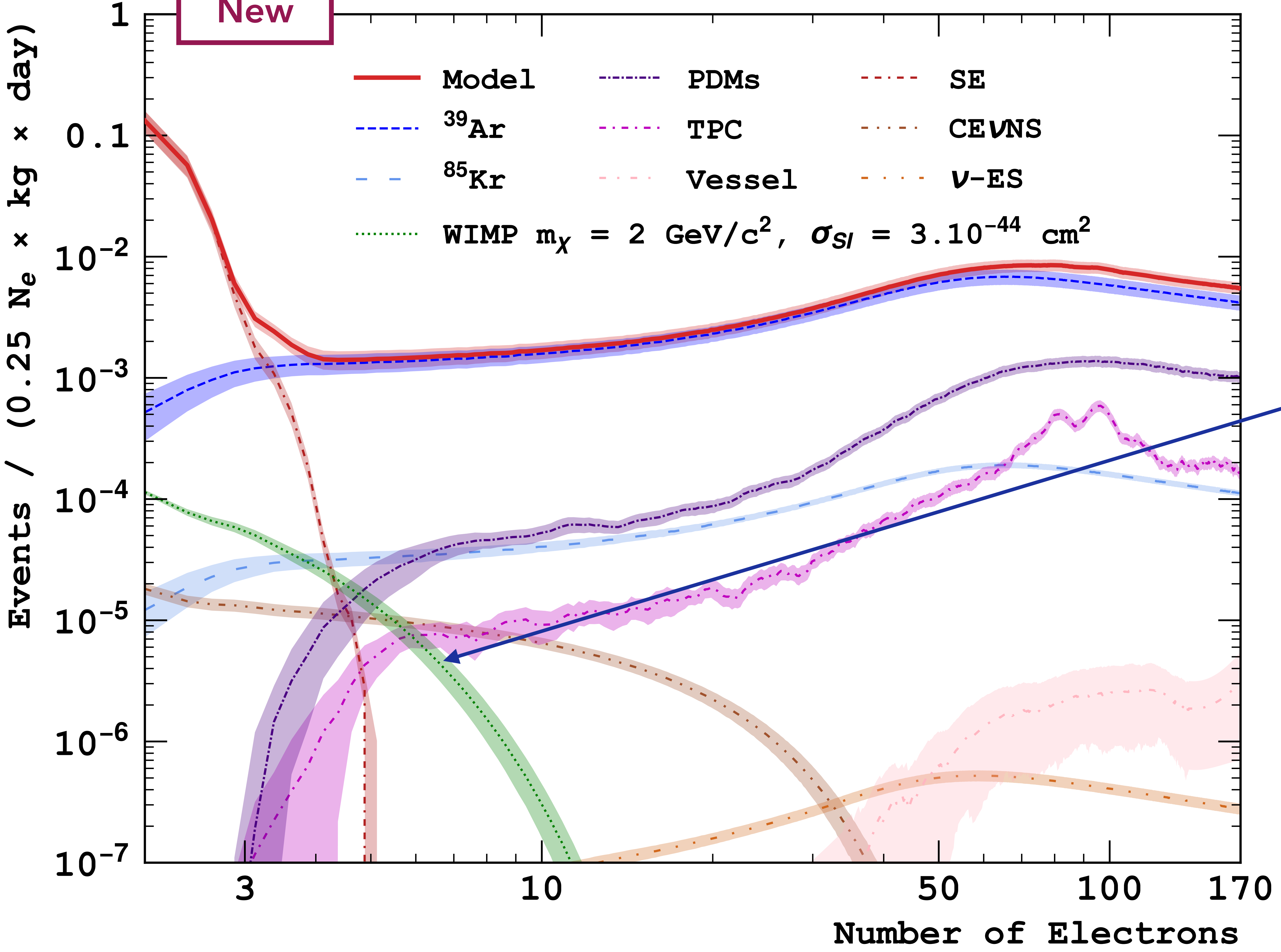
- Assuming Standard Halo Model and recommended conventions

  Eur. Phys. J. C 81 (2021), p. 907

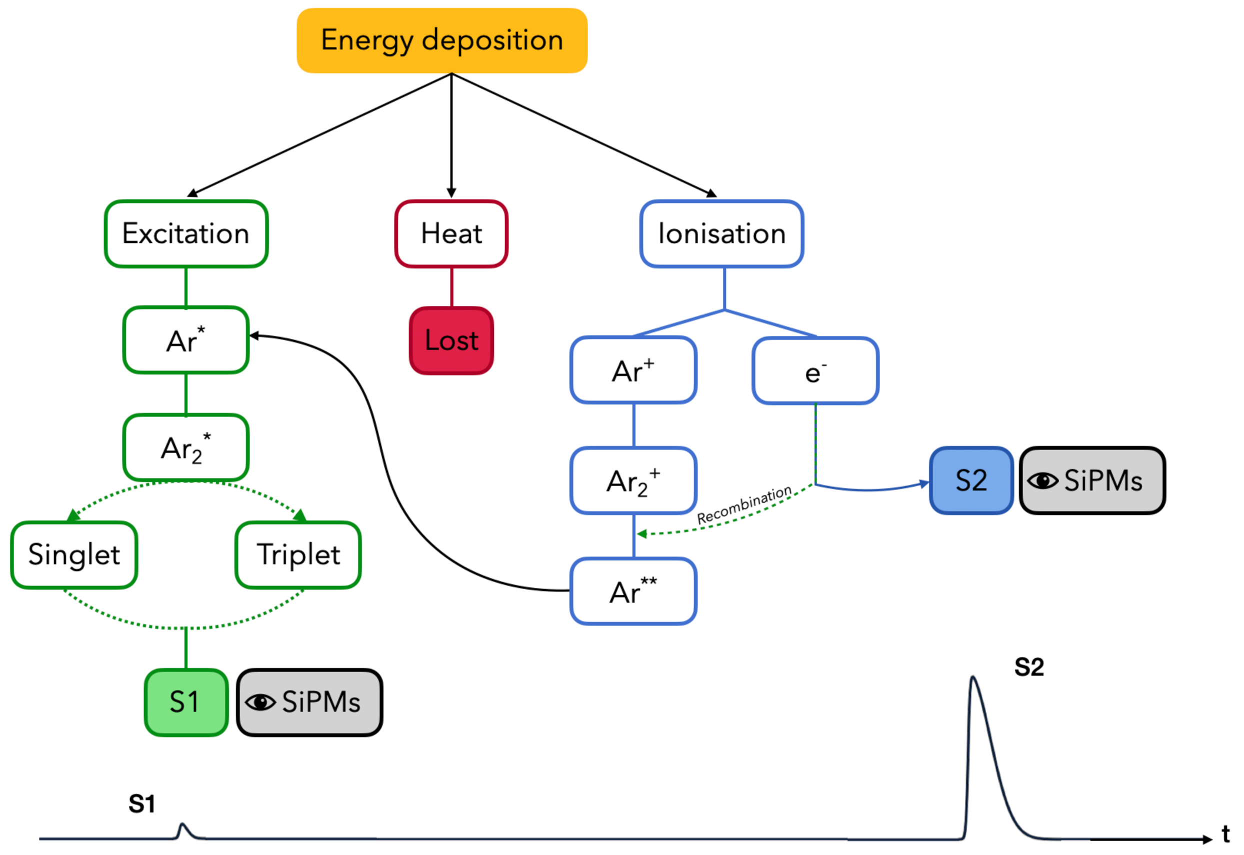
- Localised at low N_e

WIMP (pure NR part)

New



Two ^{40}Ar response models for NR



QF

Assuming **binomial fluctuations** in the fraction of quanta doing quenching

NQ

Assuming no fluctuations

Systematic uncertainties

New

	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

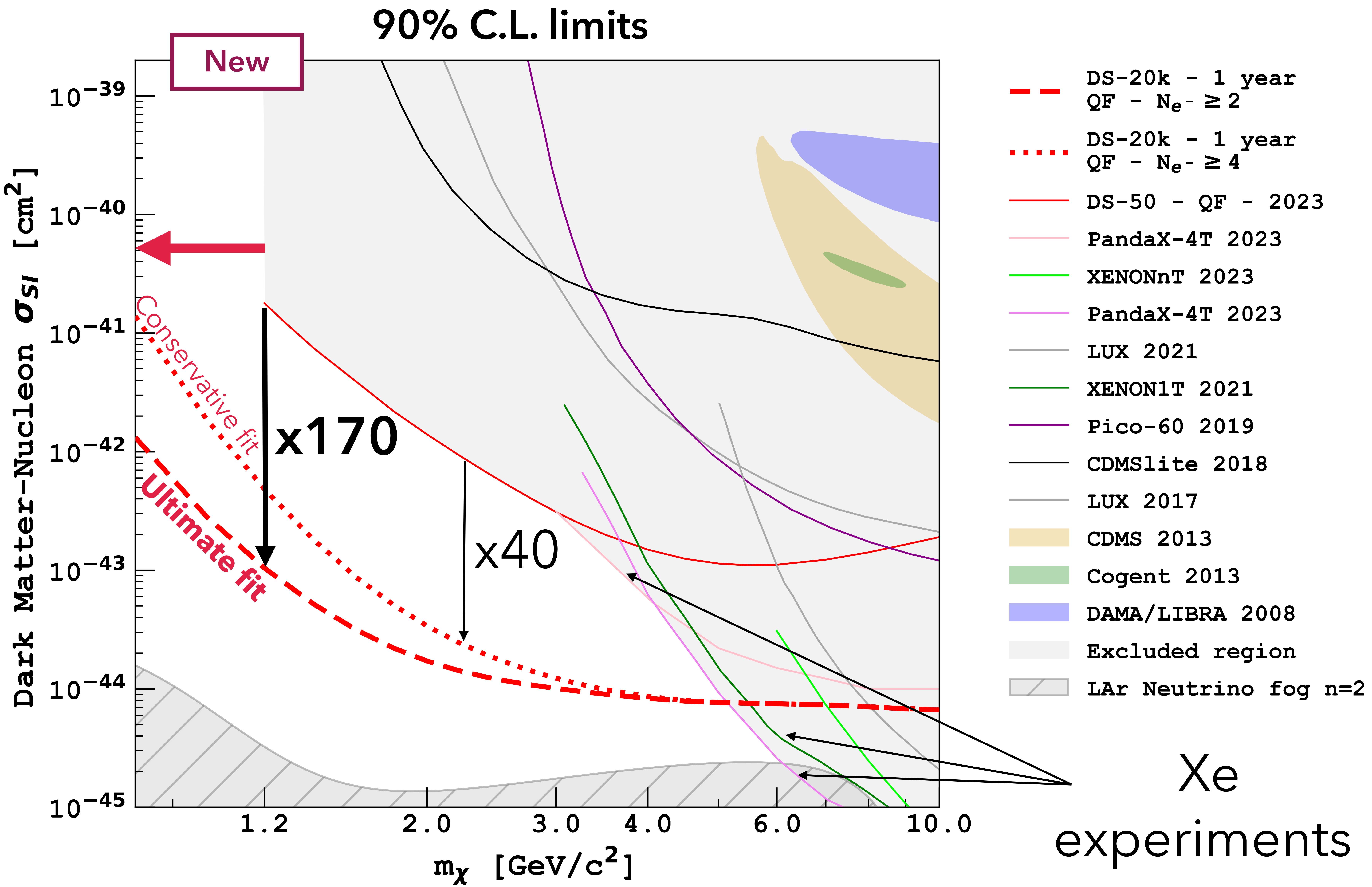
Main bkg components and **ER ionization yield → Dominant systematic uncertainties & constrained by the fit**

DarkSide-20k sensitivity to low mass WIMPs

Assuming 1 year of data taking

- **More than one order of magnitude** of uncharted theory parameter space will be probed
- Stable against detector model assumptions

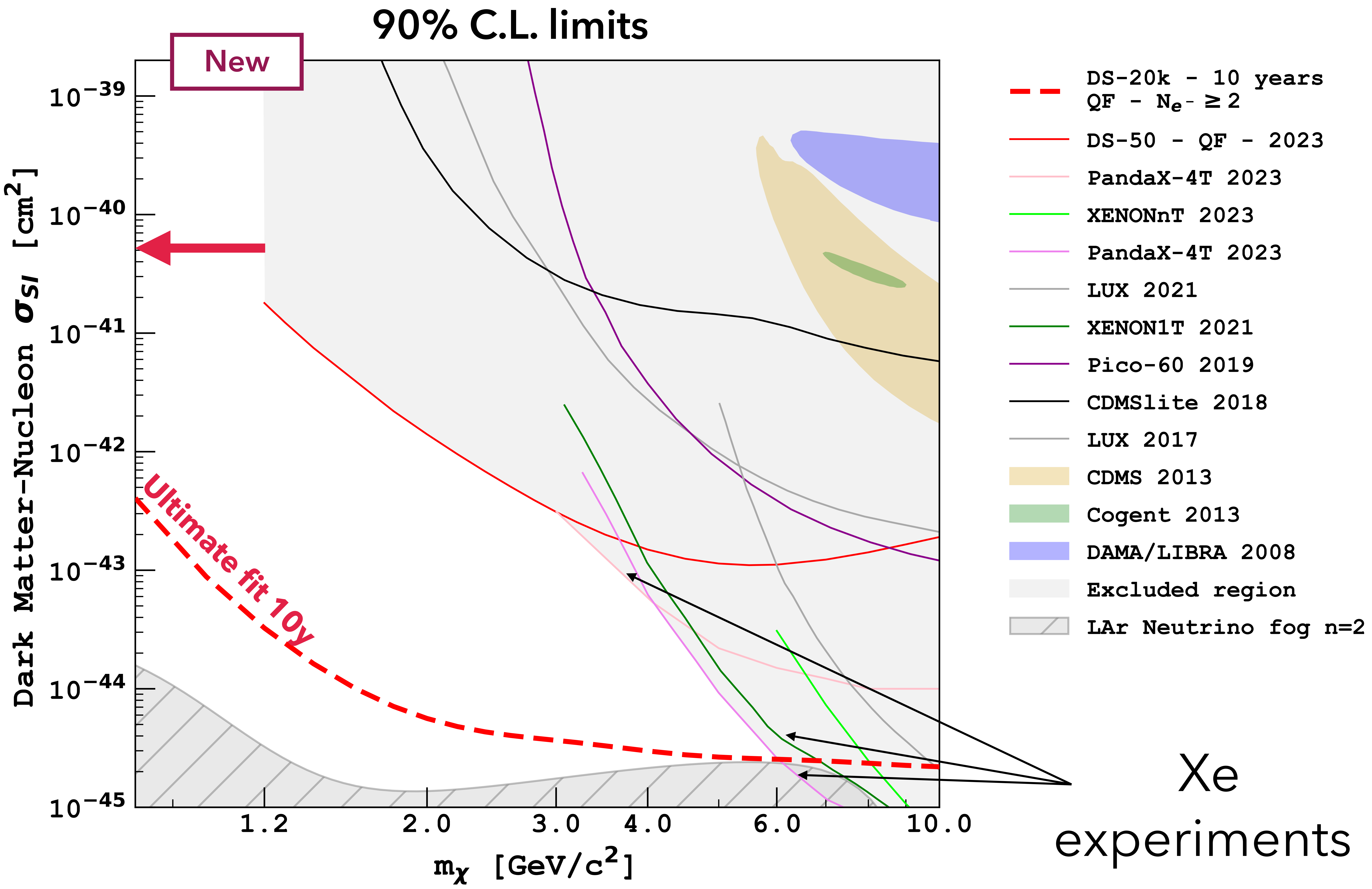
DarkSide-20k will lead the low mass WIMP search below $m_\chi \approx 5$ GeV/c^2 after only one year of data collection



DarkSide-20k sensitivity to low mass WIMPs

Assuming 10 years of data taking

➡ **Scales with $\sqrt{\text{exposure}}$**



DarkSide-20k will reach the neutrino fog around $m_\chi \approx 5$ GeV/c^2 after 10 years of data collection

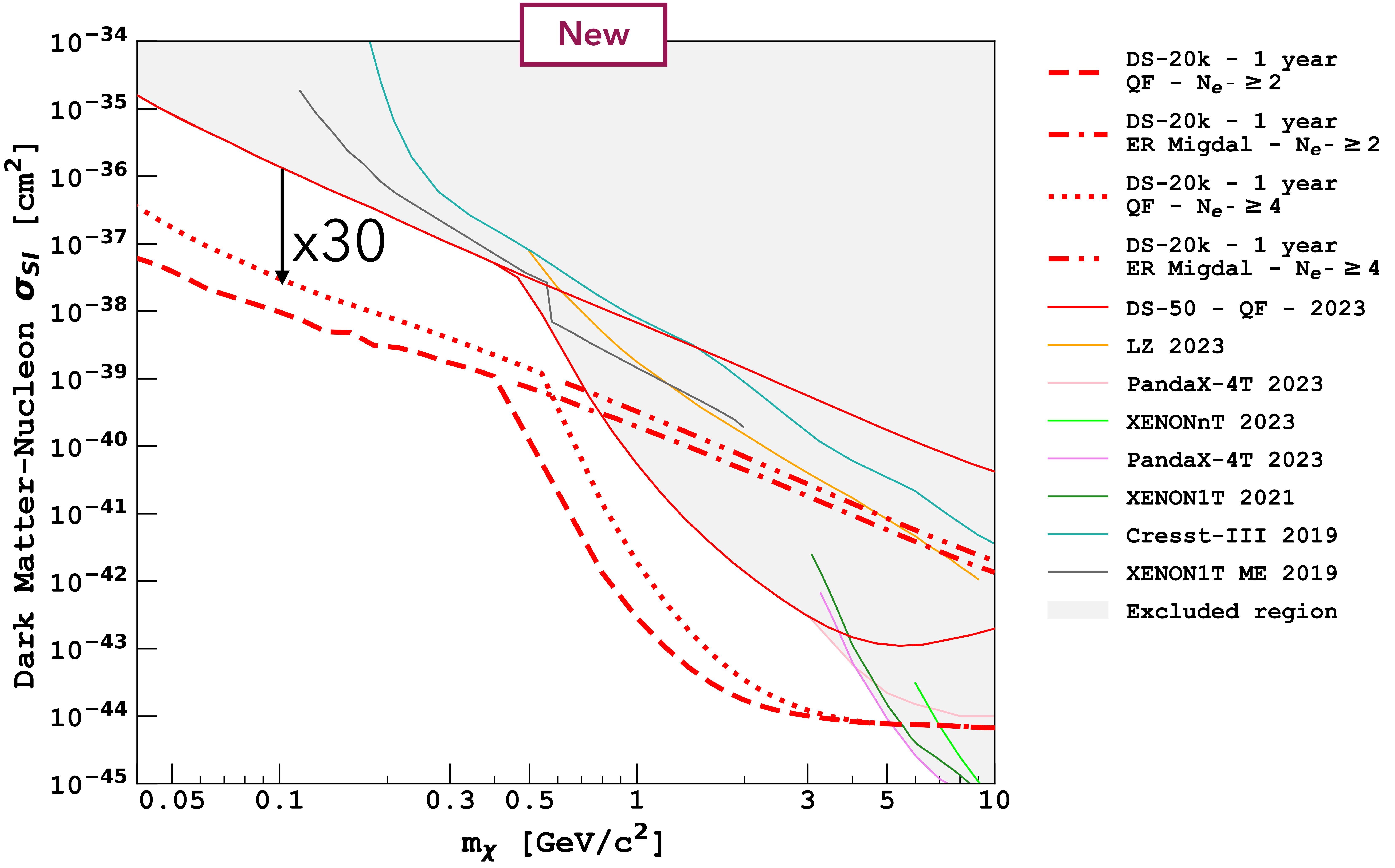
Including Migdal effect

Assuming 1 year of data taking

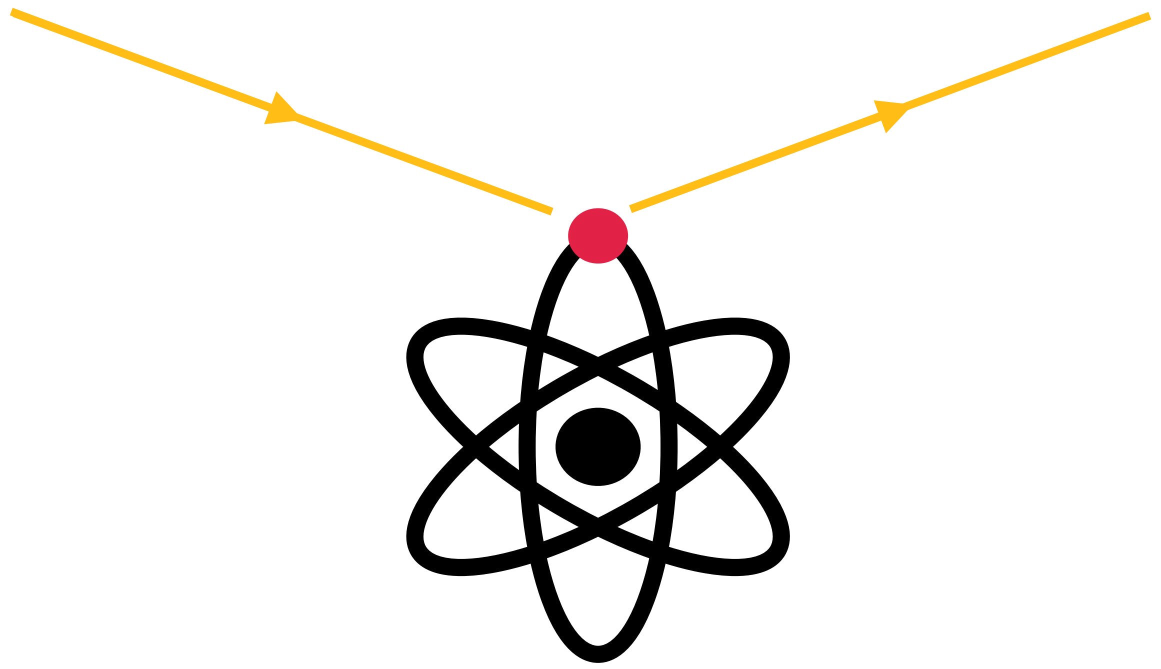
- Migdal effect = possible atomic effect
- Electron released in NR
  - Lower the detection threshold

➡ **With Migdal effect:** best limits from 40 MeV/c² to 5 GeV/c²

➡ Expect **> 1 order of magnitude improvement** wrt to current experiments in **1y** only



Light dark matter (LDM)

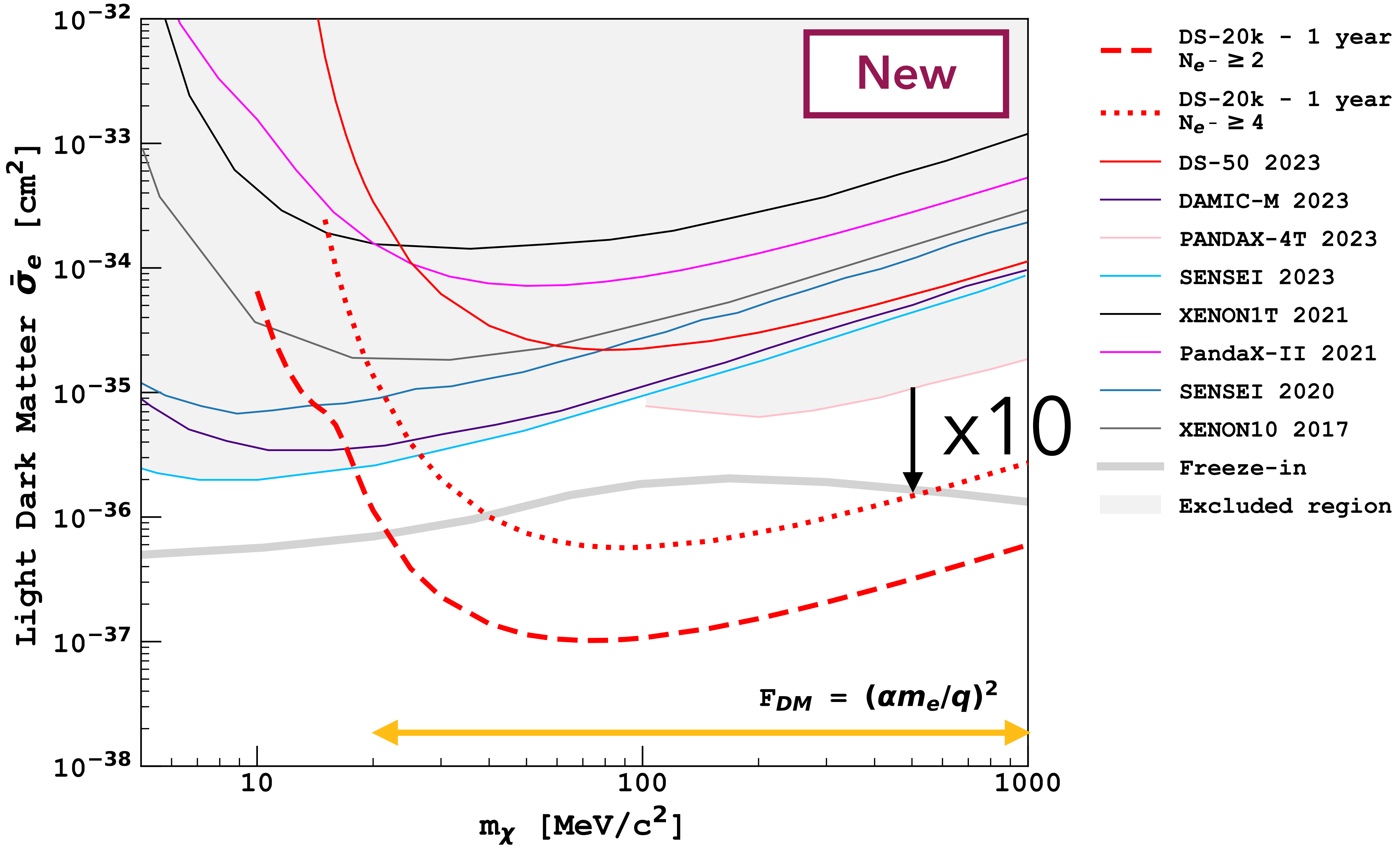


- Elastic scatter of Light Dark Matter (LDM) off bound electrons
- LDM = Sub GeV fermion or scalar boson
- Mediator can be light ($\rightarrow F \sim 1/q^2$) or heavy ($\rightarrow F \sim 1$)

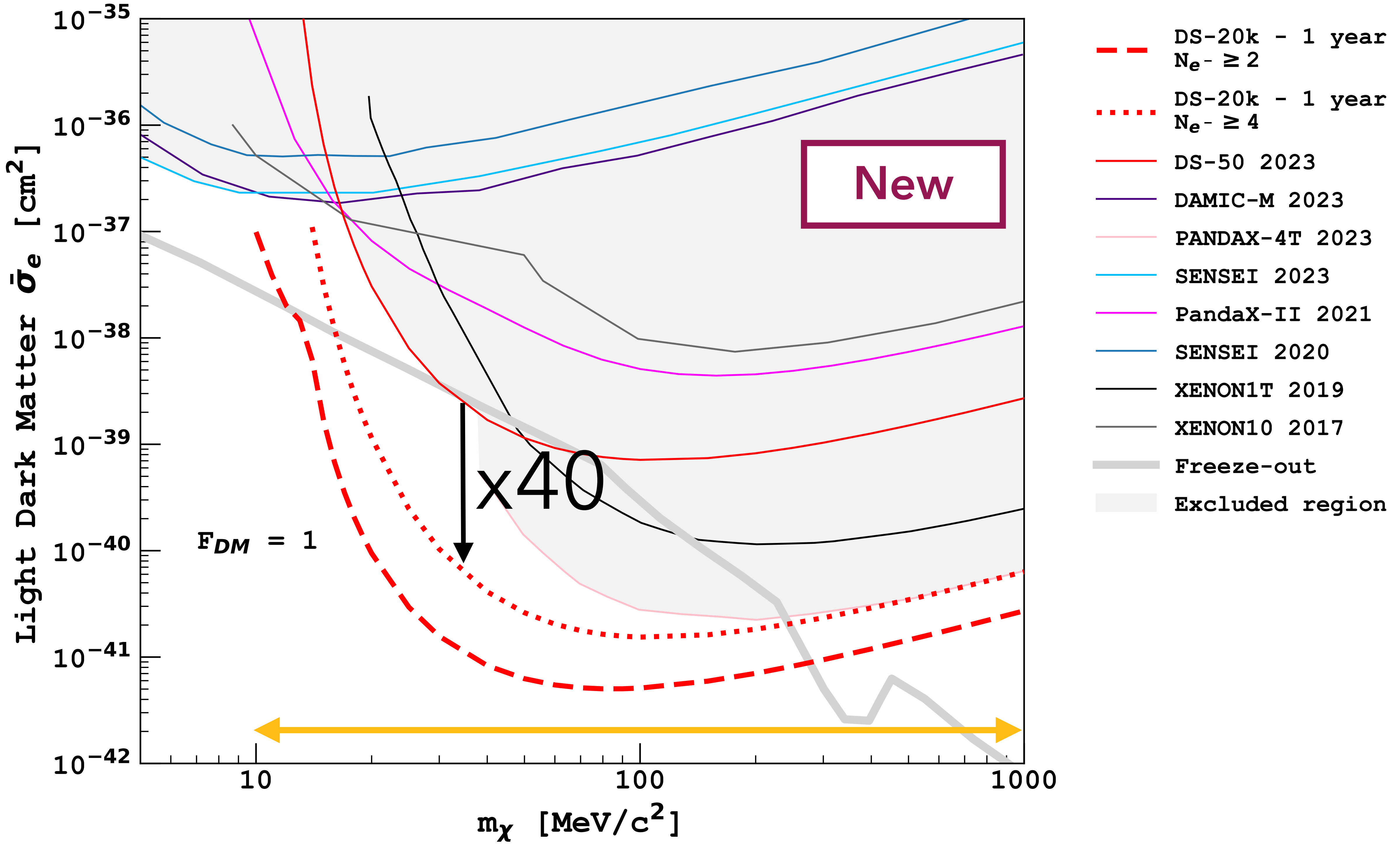
Expect **> 1 order of magnitude improvement** wrt to current experiments in **1y** only

Assuming 1 year of data taking

90% C.L. limits

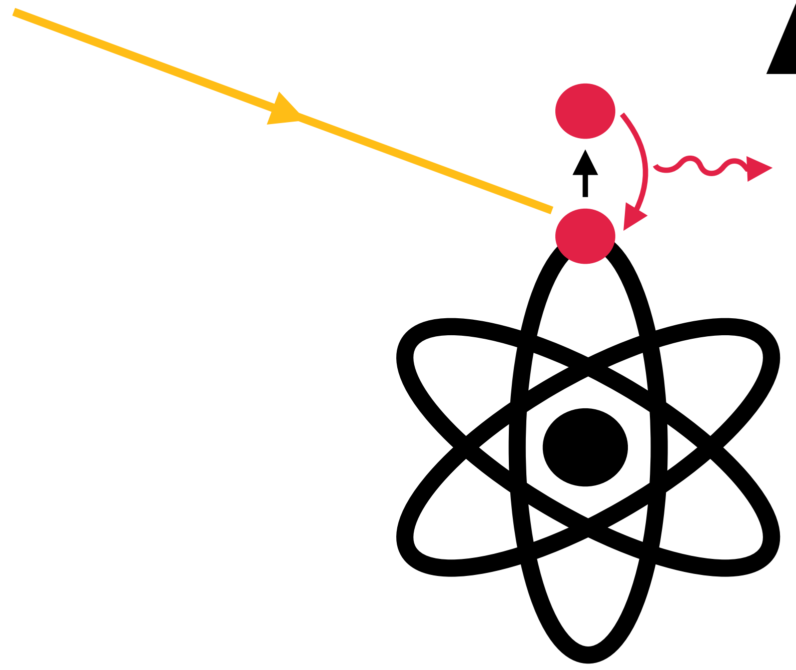


90% C.L. limits



ALP and dark photon (DP)

Expect ≈**5x improvement** wrt to current experiments in **1y** only

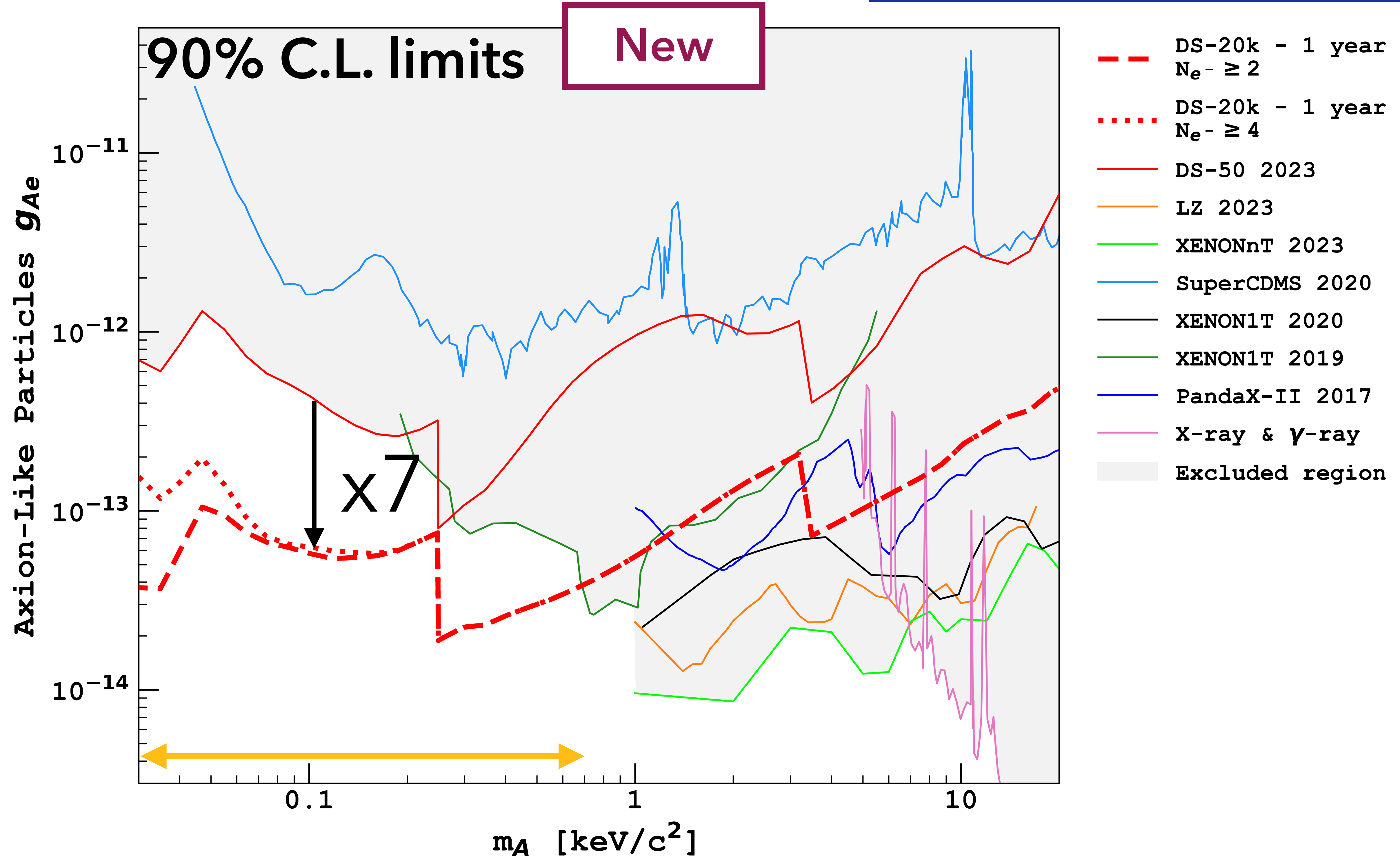


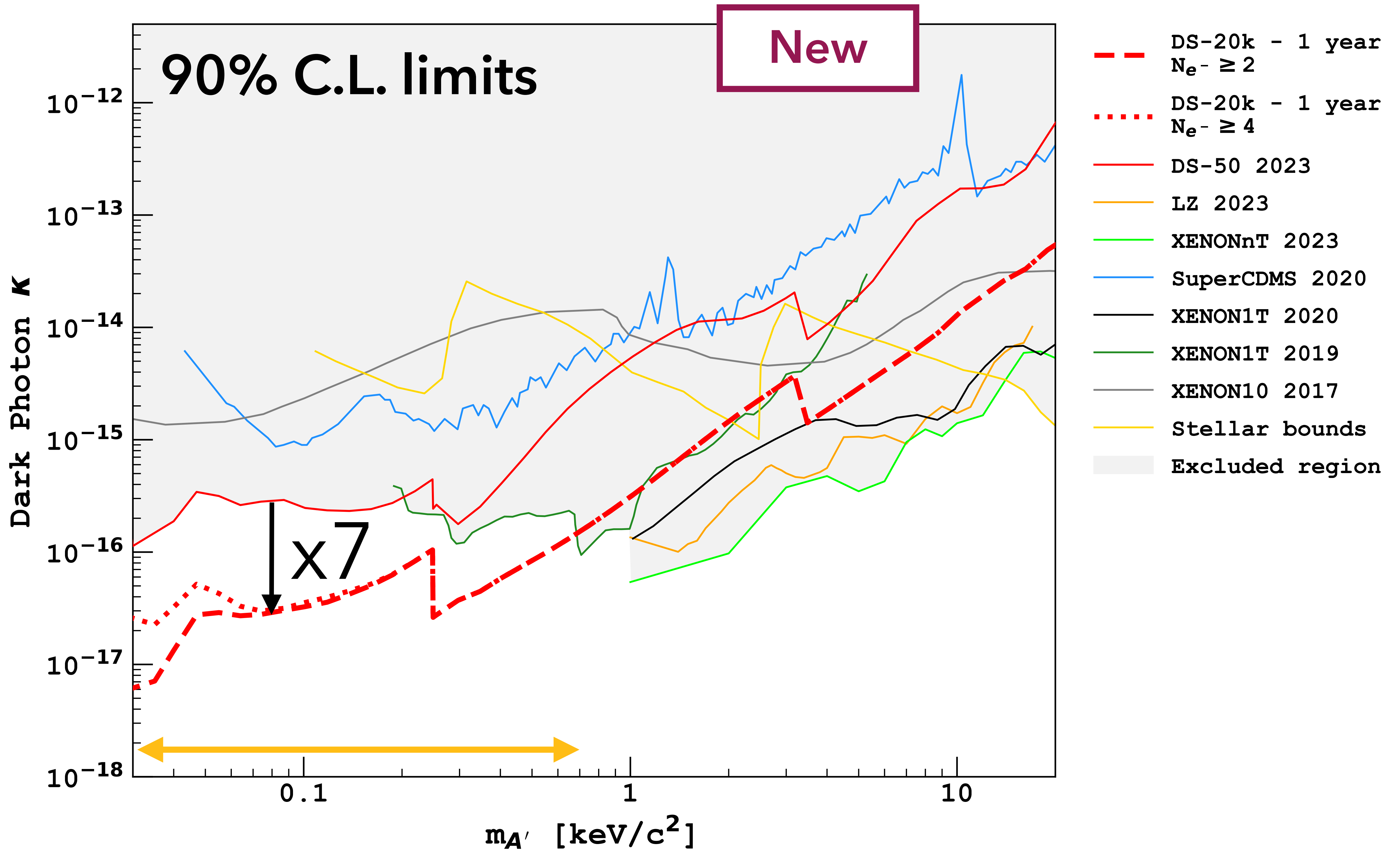
Absorption of ALP/DP by bound electrons → mono-energetic signal

- ALP = pseudo scalar particle
- Coupling ALP - electrons → g_{Ae}

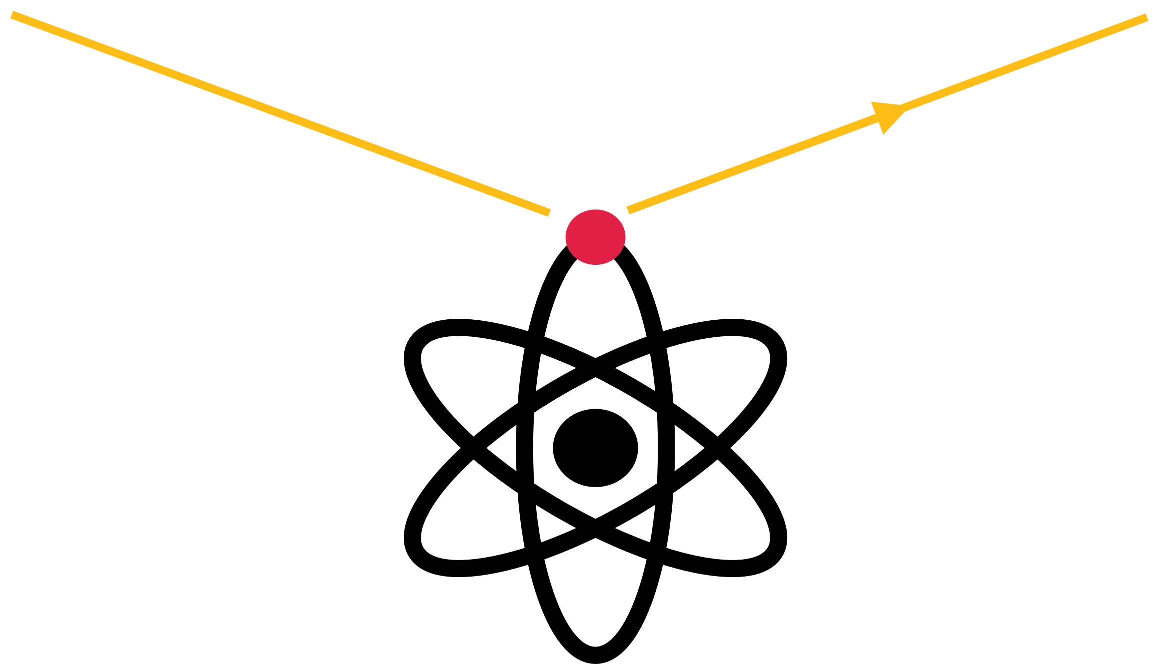
- DP = vector boson particle
- Kinetic mixing between DP and SM photons → strength κ

Assuming 1 year of data taking



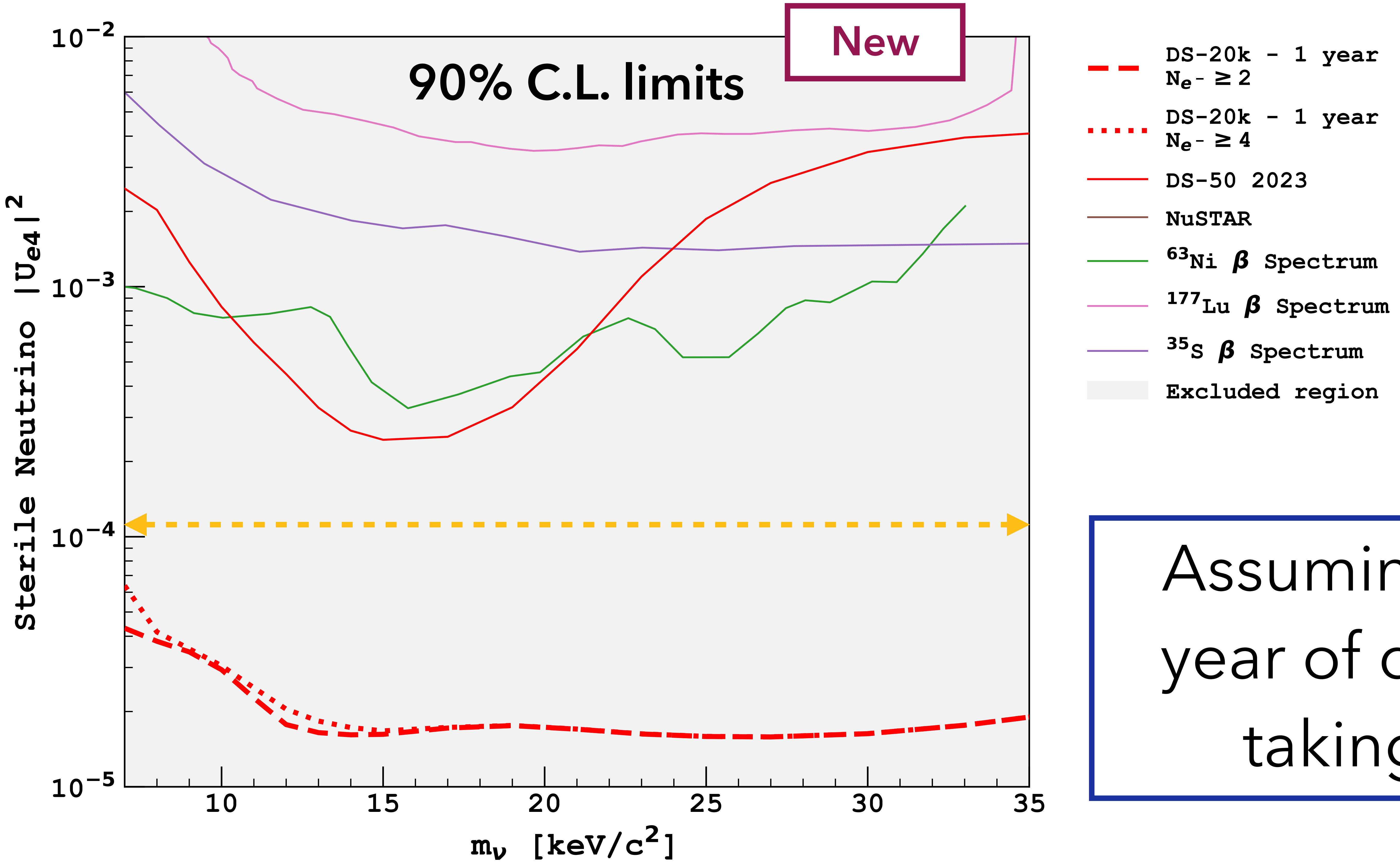


Sterile neutrino ν_s



- Inelastic scatter of sterile ν_s off bound electrons
- Possible mixing with active neutrinos → PMNS-like matrix element $|U_{e4}|^2$

Best direct limits (1 year) but phase space already rejected by NuSTAR indirect measurements



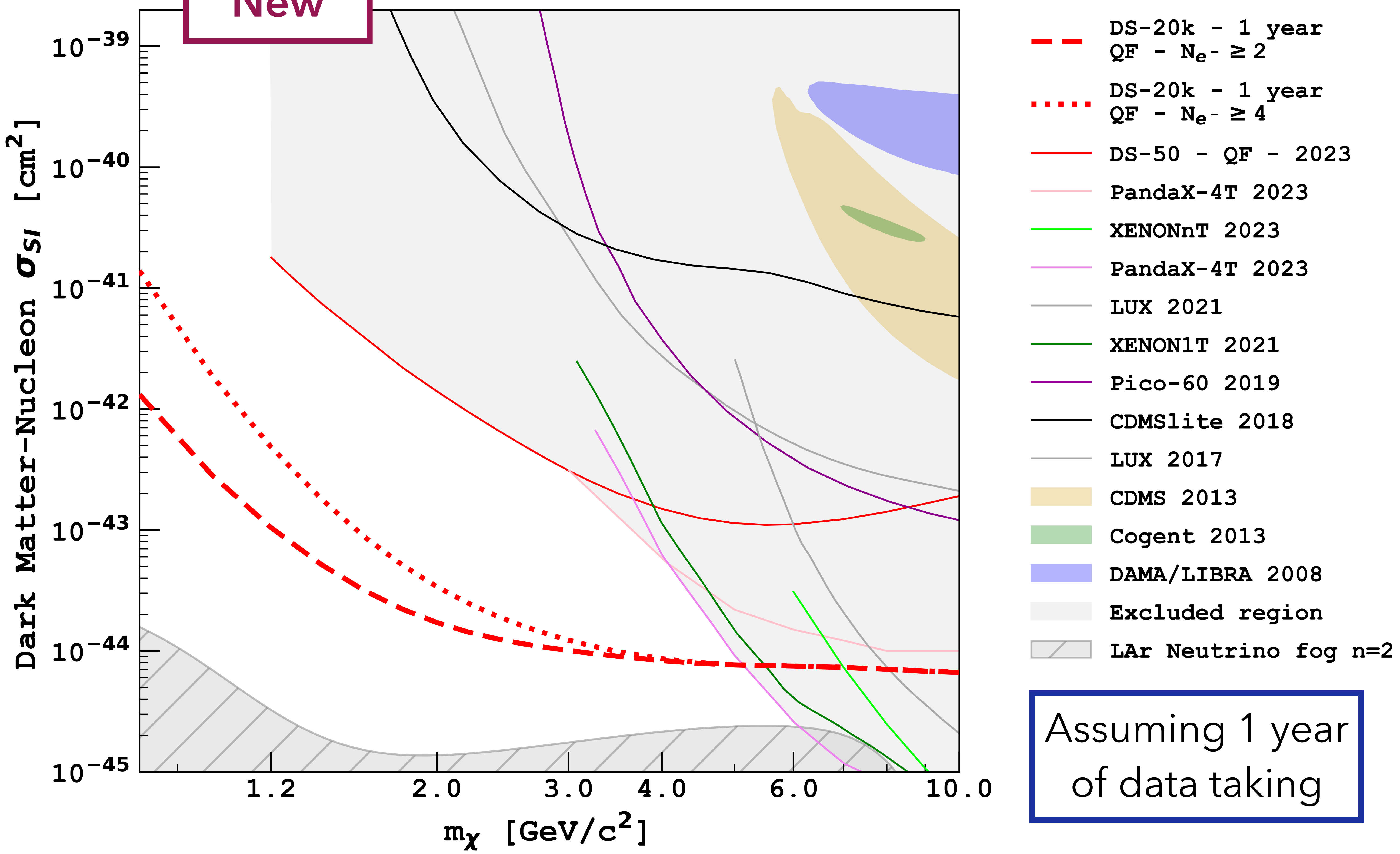
Assuming 1 year of data taking

Conclusions

- First assessment of **DarkSide-20k sensitivity to low mass dark matter particles**
- Further strengthens the physics reach of DarkSide-20k with a leading role below 5 GeV/c²
- Expect to probe > 1 order to magnitude of un-charted theory parameter space **within 1 year only** for a **variety of dark matter particles**
- For WIMPs:
  - Probe $\sigma_{SI} < 10^{-42}$ cm² above m_χ = 800 MeV/c²
  - Reach the neutrino fog at 5 GeV/c² after 10 years

New

90% C.L. limits



Assuming 1 year of data taking

arXiv: 2407.05813

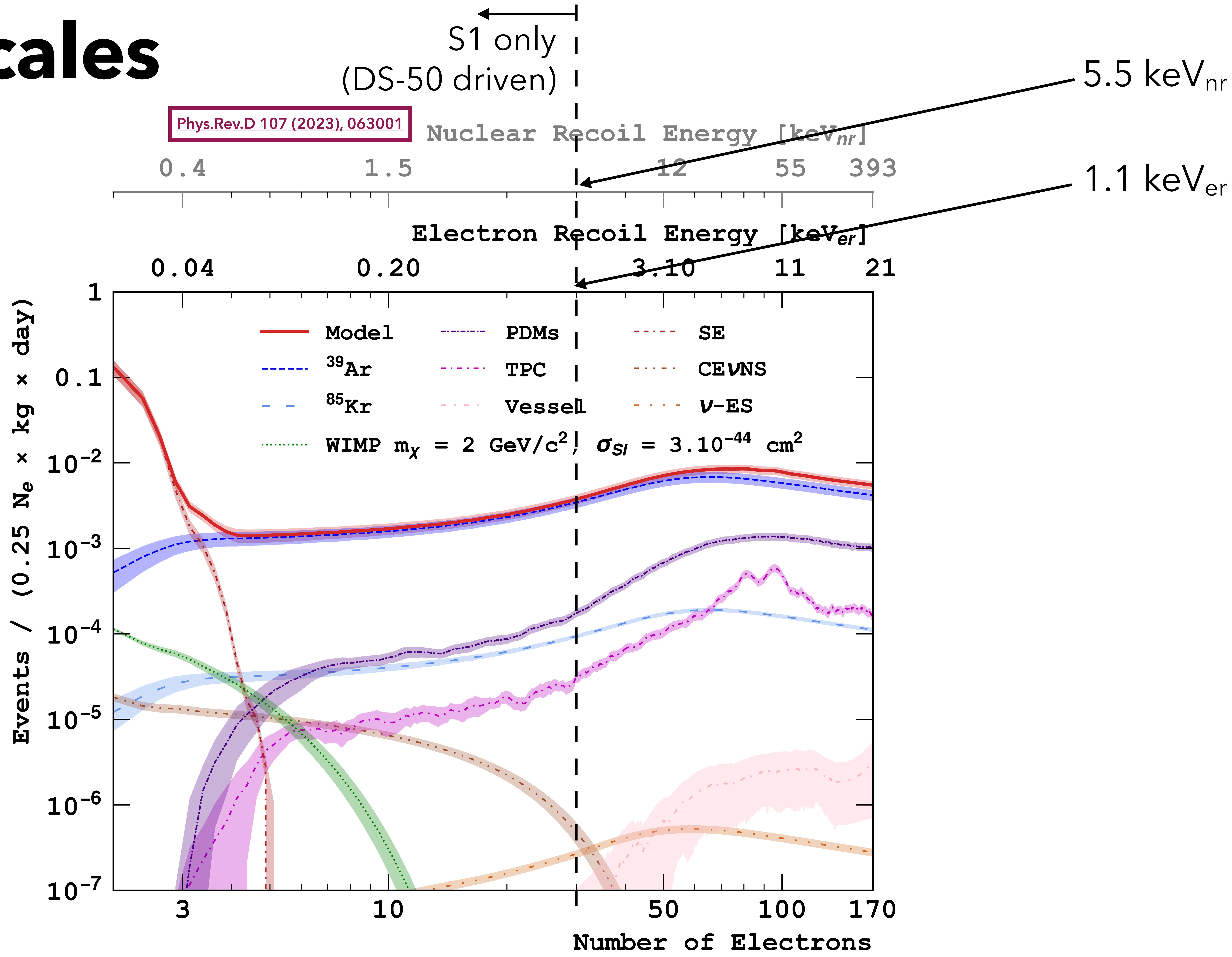
(Submitted to Nature Communications)

Thank you!

Back up

Energy scales

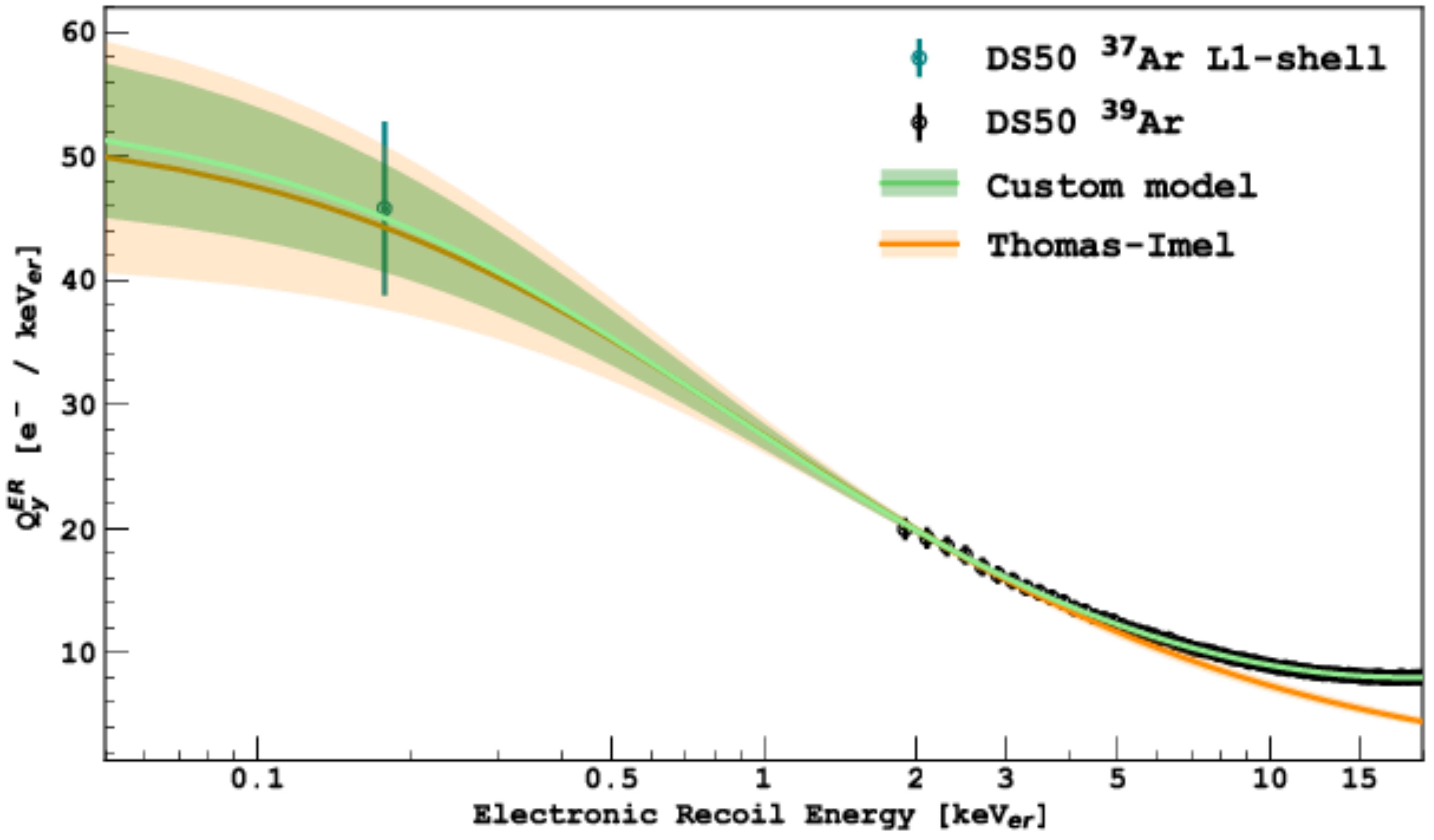
Phys.Rev.D 107 (2023), 063001



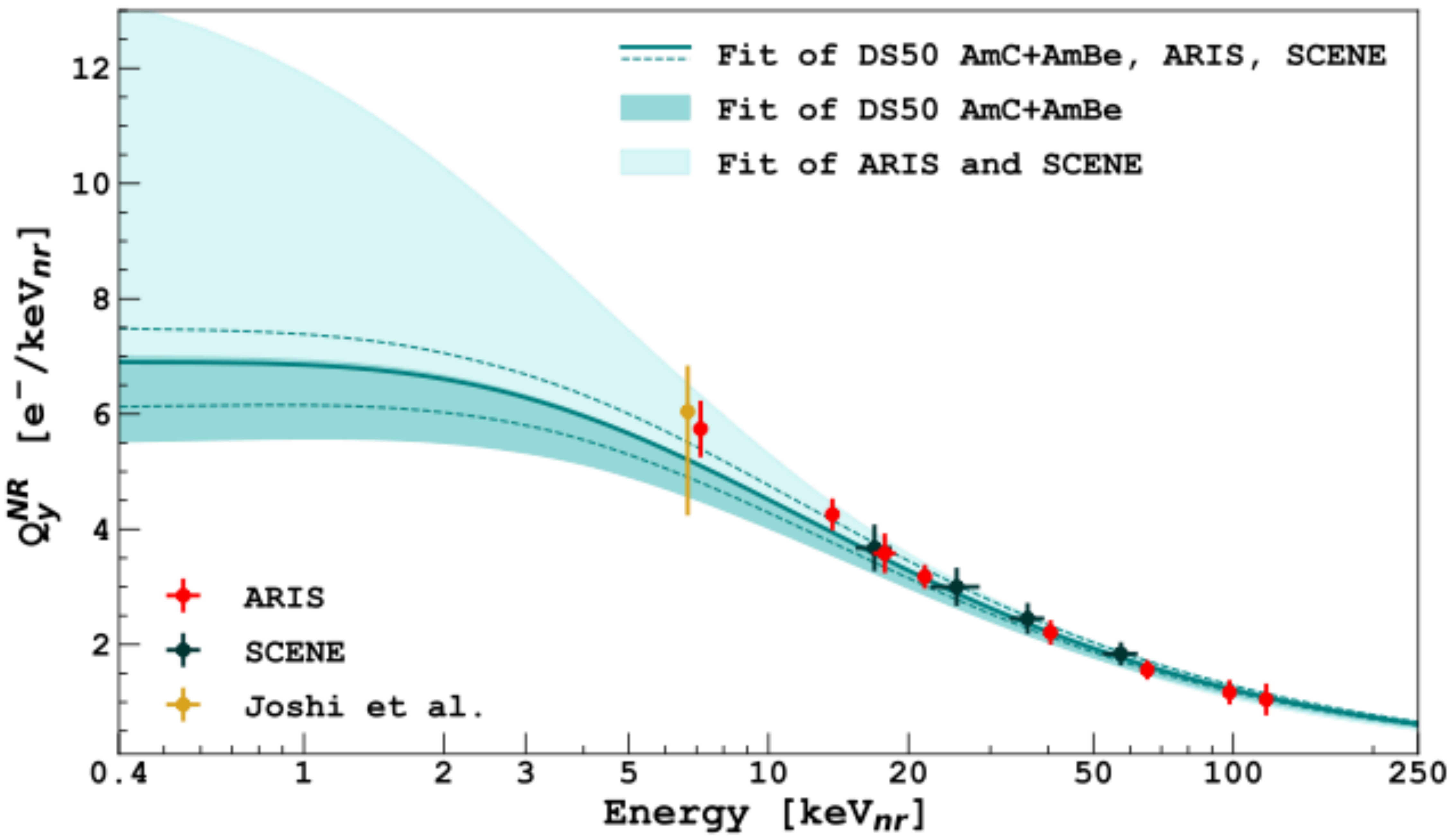
LAr response model

DarkSide-50 calibration

ER ionization yield



NR ionization yield



[Phys.Rev.D 104 (2021), 082005]

See talk by L. Pandola

LAr response model

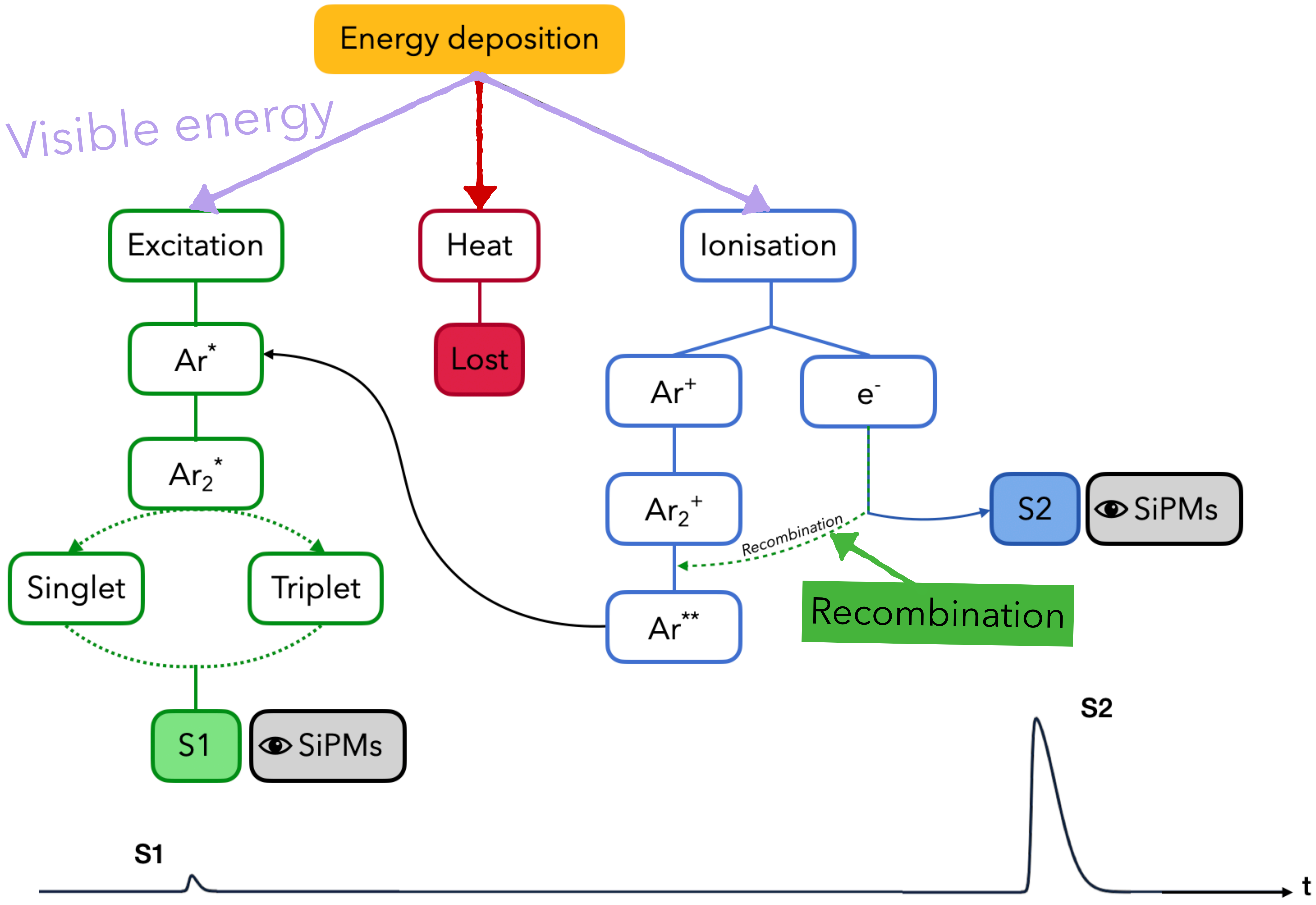
Quenching fluctuations -> no theoretical predictions

NQ model:

Visible energy fixed to its average value. Not physical but conservative.

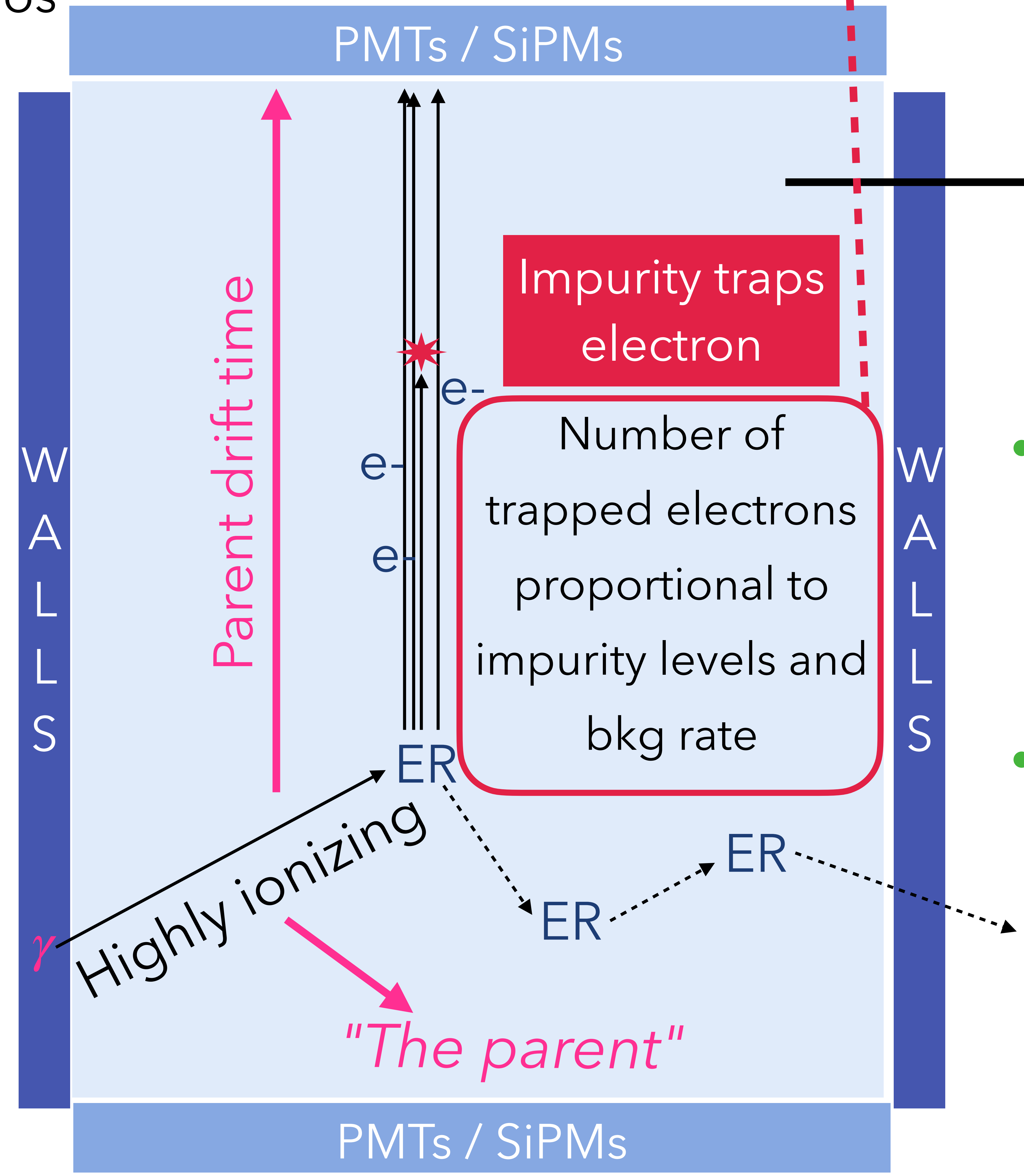
QF model:

binomial quenching fluctuations between detectable and undetectable energy : ensures that the number of produced quanta does not exceed the maximum possible one
+ other fluctuations in recombination process
(nb of electron-ion pair that recombine) and repartition between excitation and ionization quanta



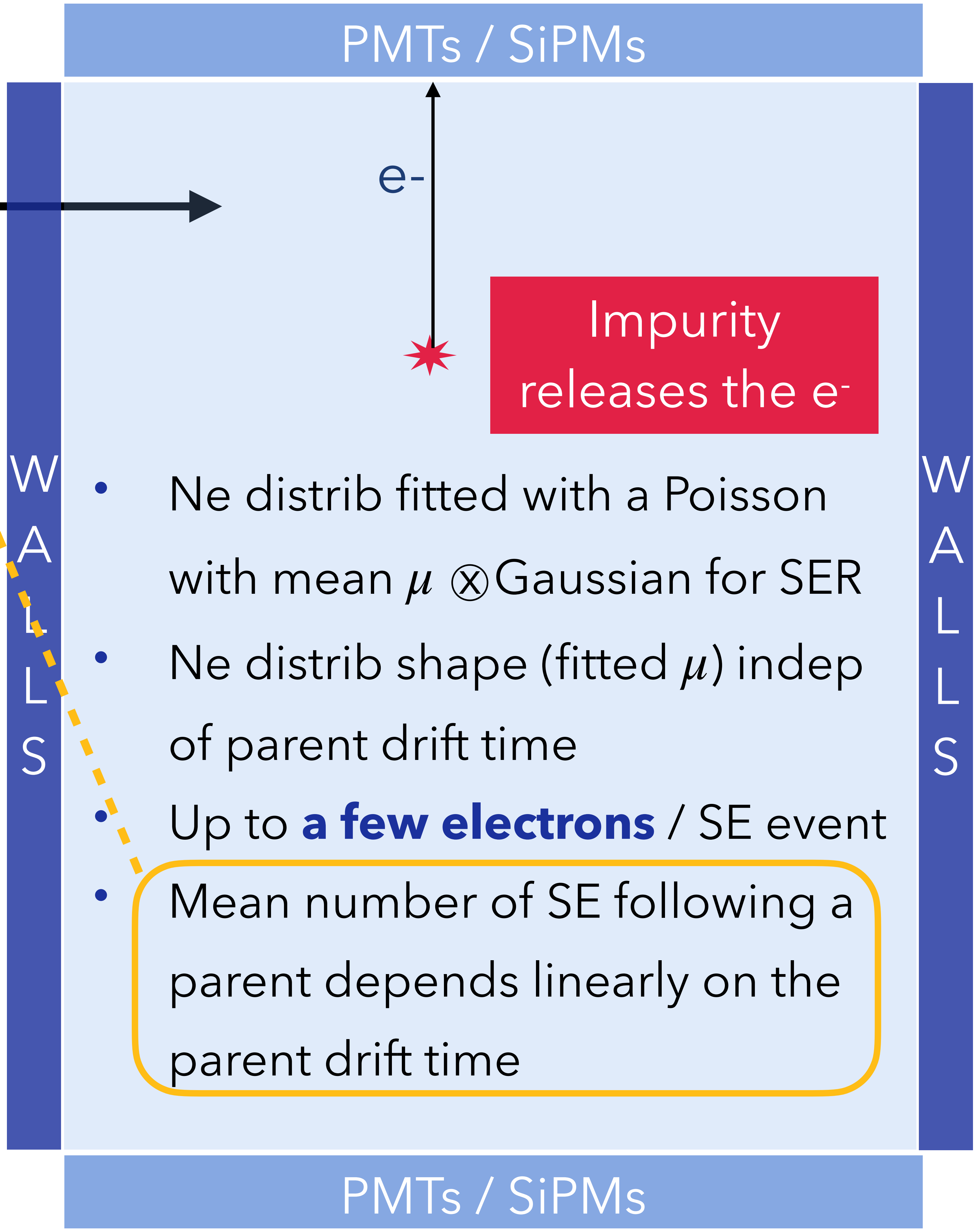
Spurious electron background

- **Extrapolated** from DarkSide-50 data
- **DS20k rate** = DS50 rate scaled with bkg rate and max. drift time ratios
- **DS20k shape (in Ne):** takes into account expected single electron resolution (SER) and electron lifetime



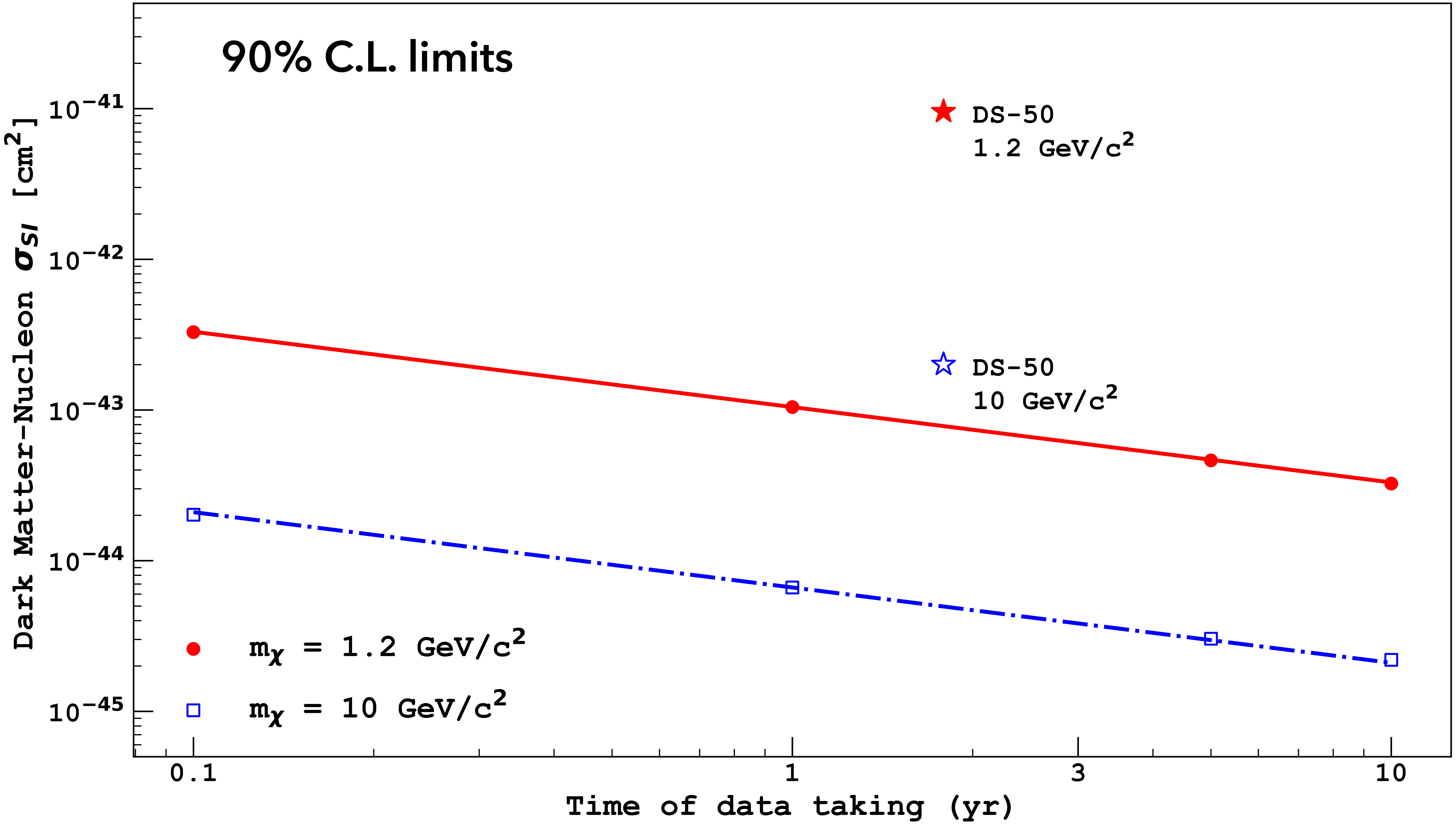
Later

- **Time dependency** (ΔT) with the previous highly ionizing event (the parent)
- ΔT measured to be 3 exponentials (1 uncorrelated component, 1 fast, 1 slow)

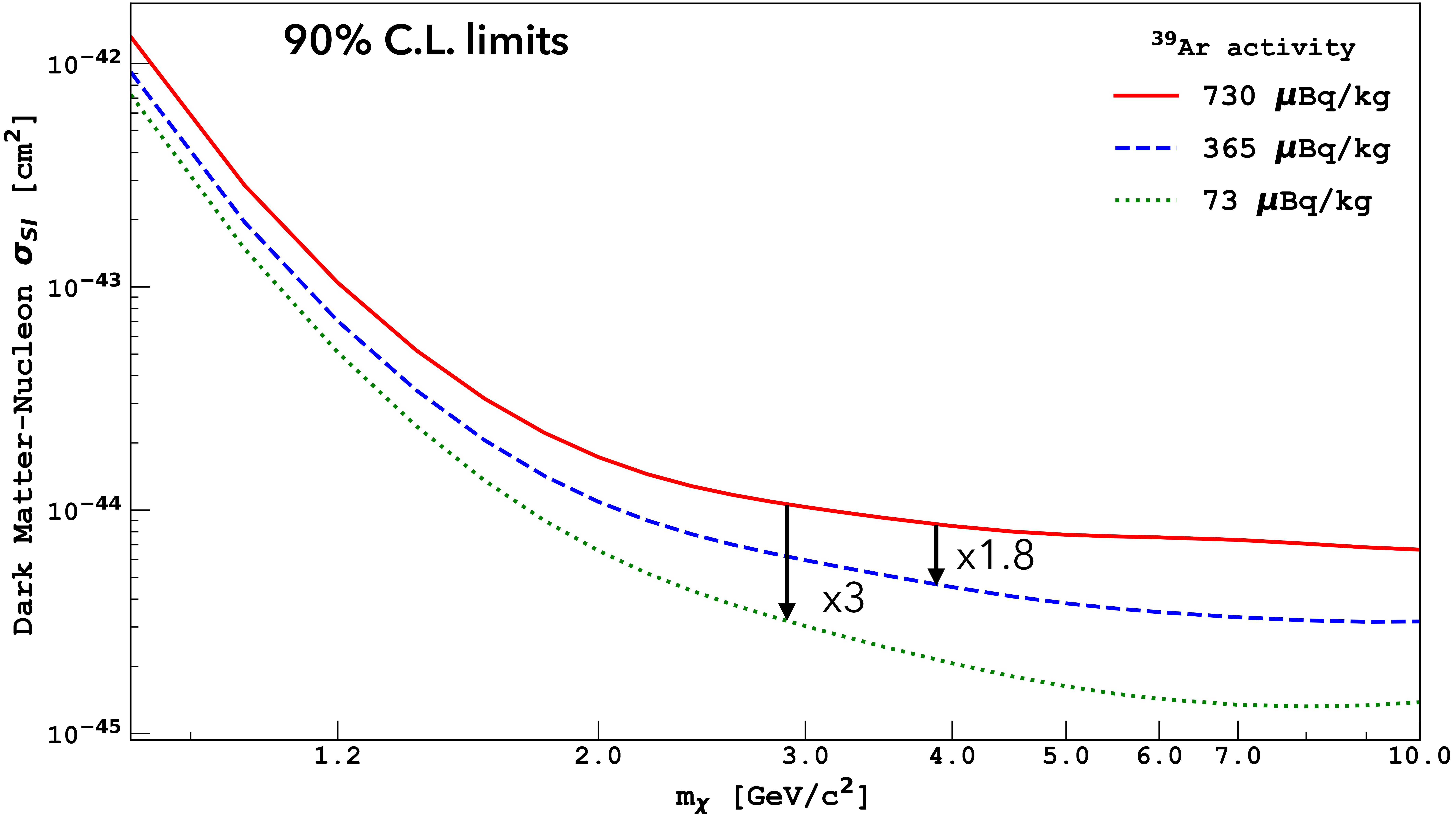


- Ne distrib fitted with a Poisson with mean μ ⊗Gaussian for SER
- Ne distrib shape (fitted μ) indep of parent drift time
- Up to **a few electrons** / SE event
- Mean number of SE following a parent depends linearly on the parent drift time

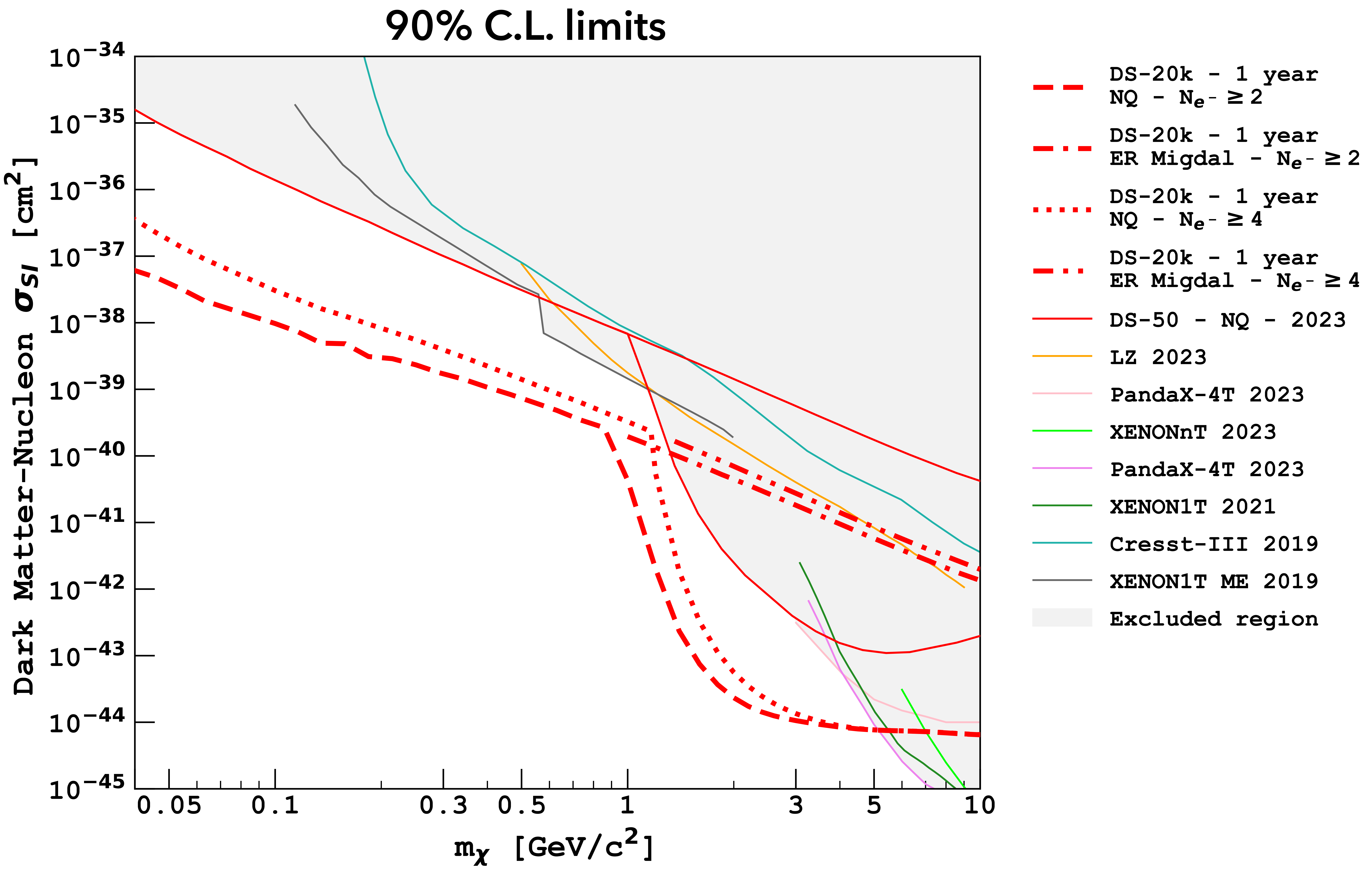
Sensitivity vs exposure



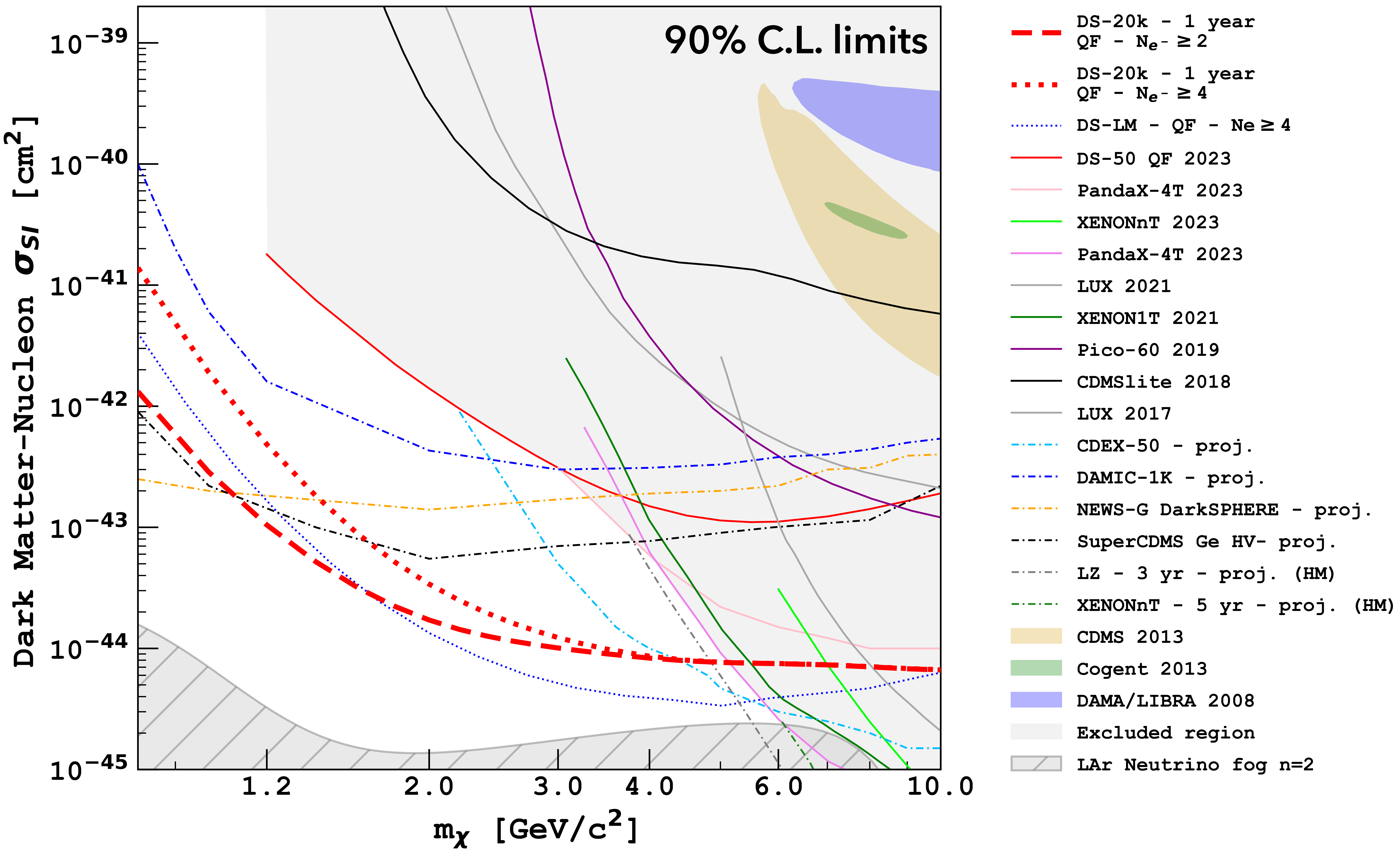
Sensitivity vs argon level



No quenching fluctuations in NR



Prospective experiments



Other signal models

Rates

e⁻ in a given orbital (n, l)

LDM:

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

ALPs:

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

DP:

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

Sterile neutrinos:

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