Improved liquid argon ionization response model and impact on DarkSide sensitivity

Timothée Hessel *on behalf of the DarkSide collaboration*

Status of direct dark matter search

Current limits on DM-Nucleon spin-independent interactions
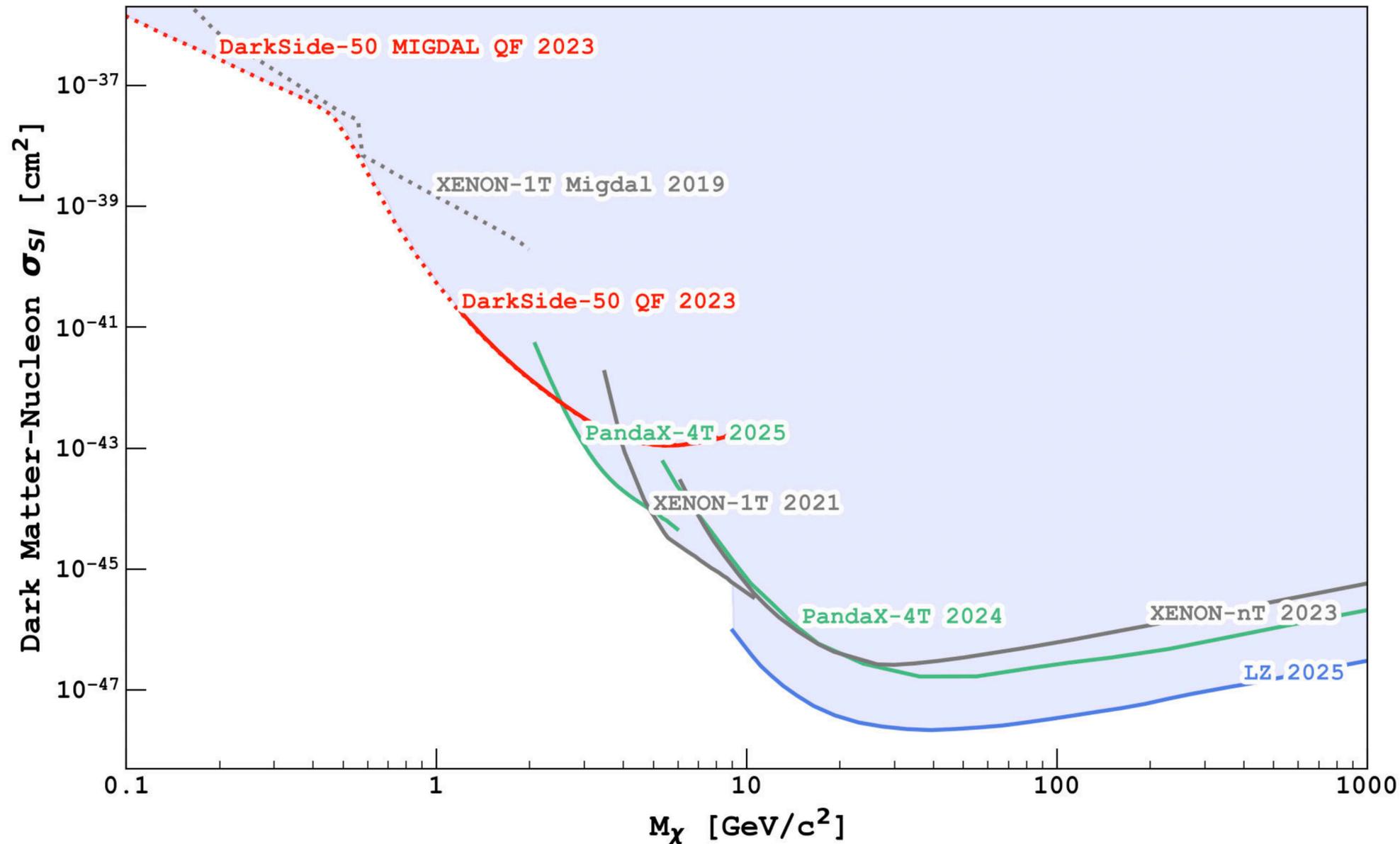
- ‣ Dual-phase TPCs dominate WIMP searches from the sub-GeV scale

- ‣ DarkSide-50, with only 50 kg, is still competitive with respect to multi-ton liquid xenon detectors
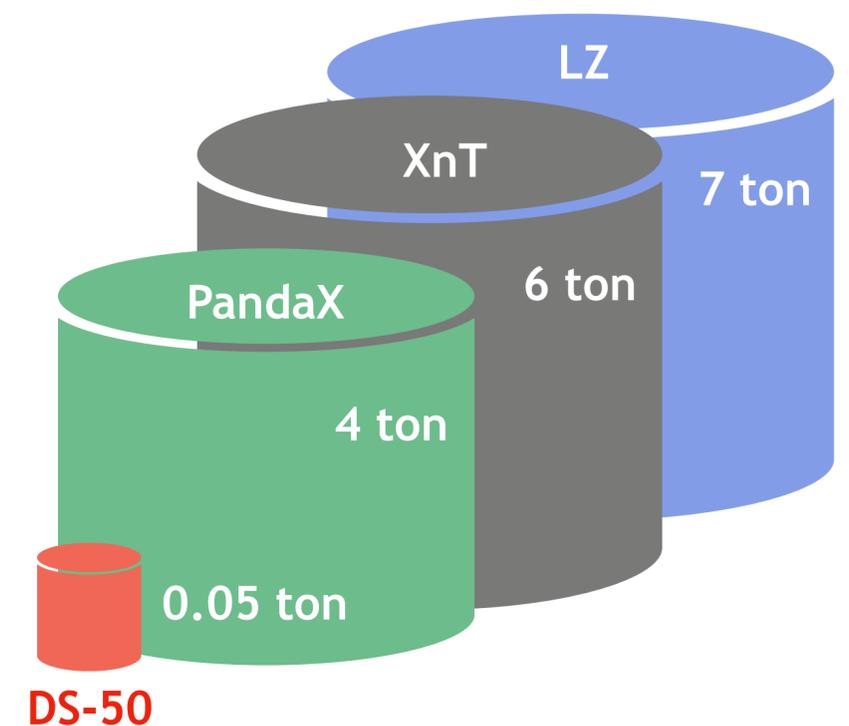
DarkSide-50

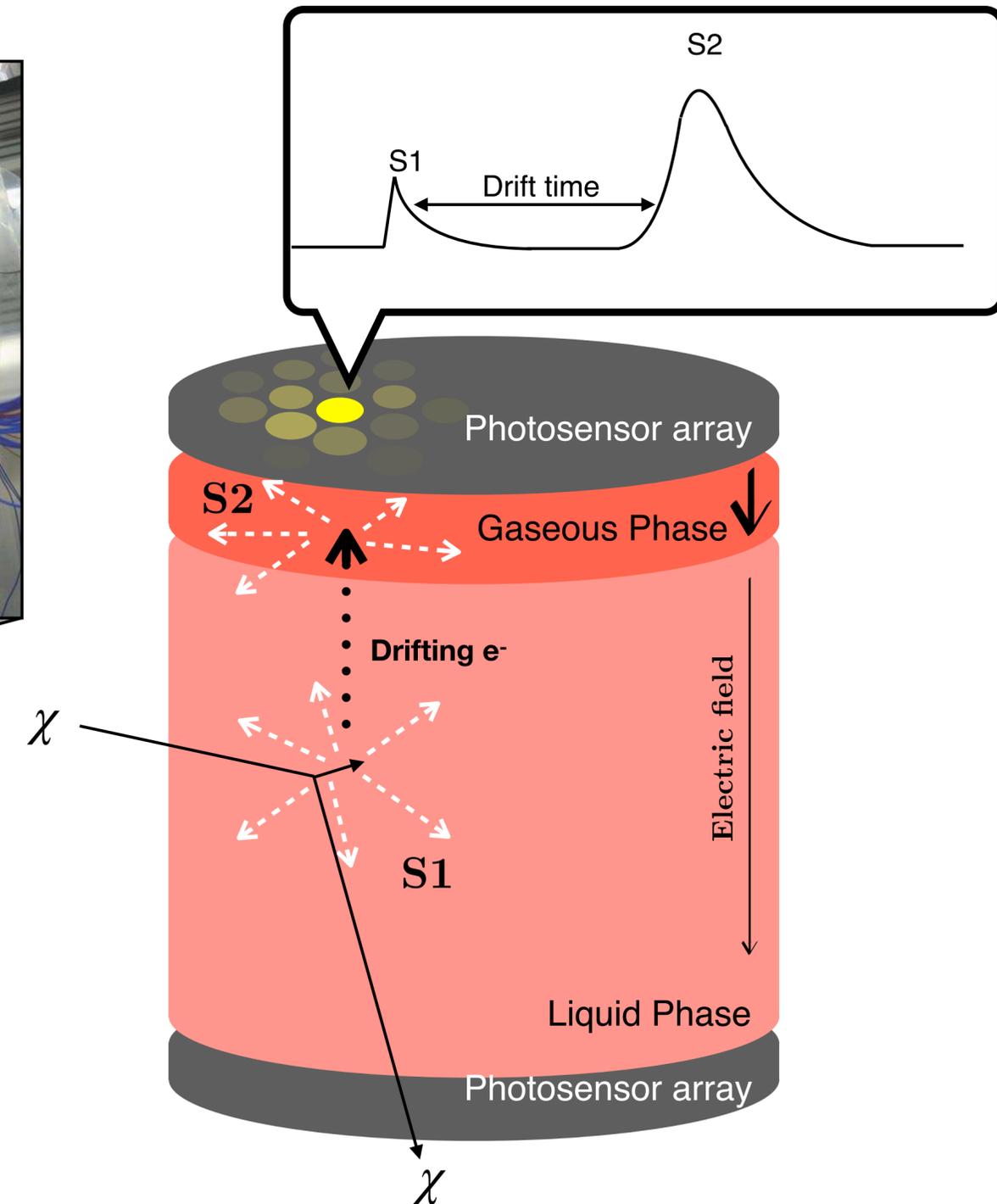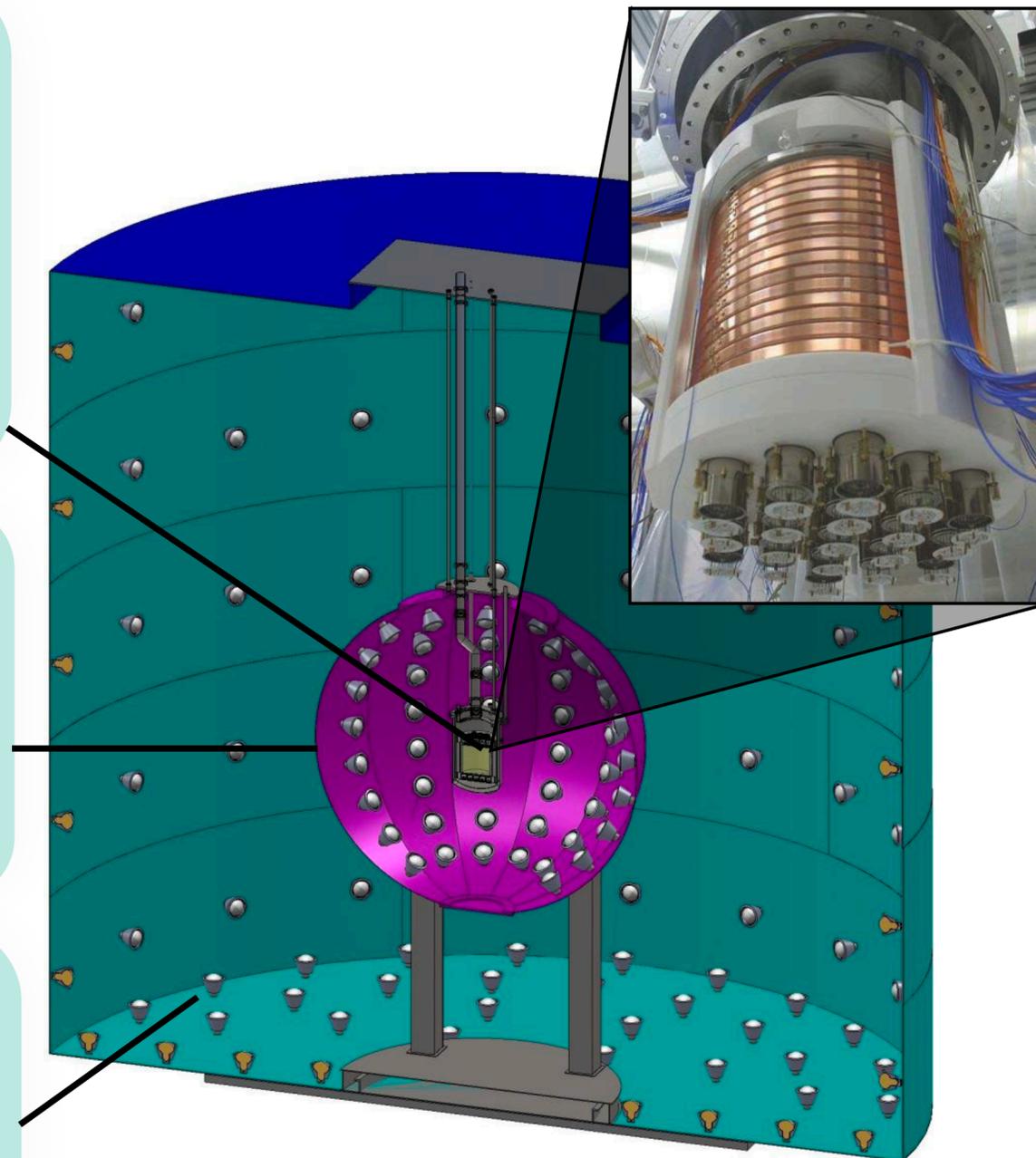## Low-radioactivity liquid argon dual-phase TPC

The Dual-Phase TPC:

▸ 50 kg active mass of UAr

▸ 19 top + 19 bottom 3" PMTs

▸ 36 cm height, 36 cm diameter

Liquid Scintillator Veto against neutrons:

▸ 4 m diameter sphere

▸ 110 8" PMTs

Cherenkov Water Detector:

▸ 11 m diameter x 10 m

▸ 80 PMTs

S1

Drift time

S2

Photosensor array

S2

Gaseous Phase

Drifting e⁻

χ

Electric field

S1

Liquid Phase

Photosensor array
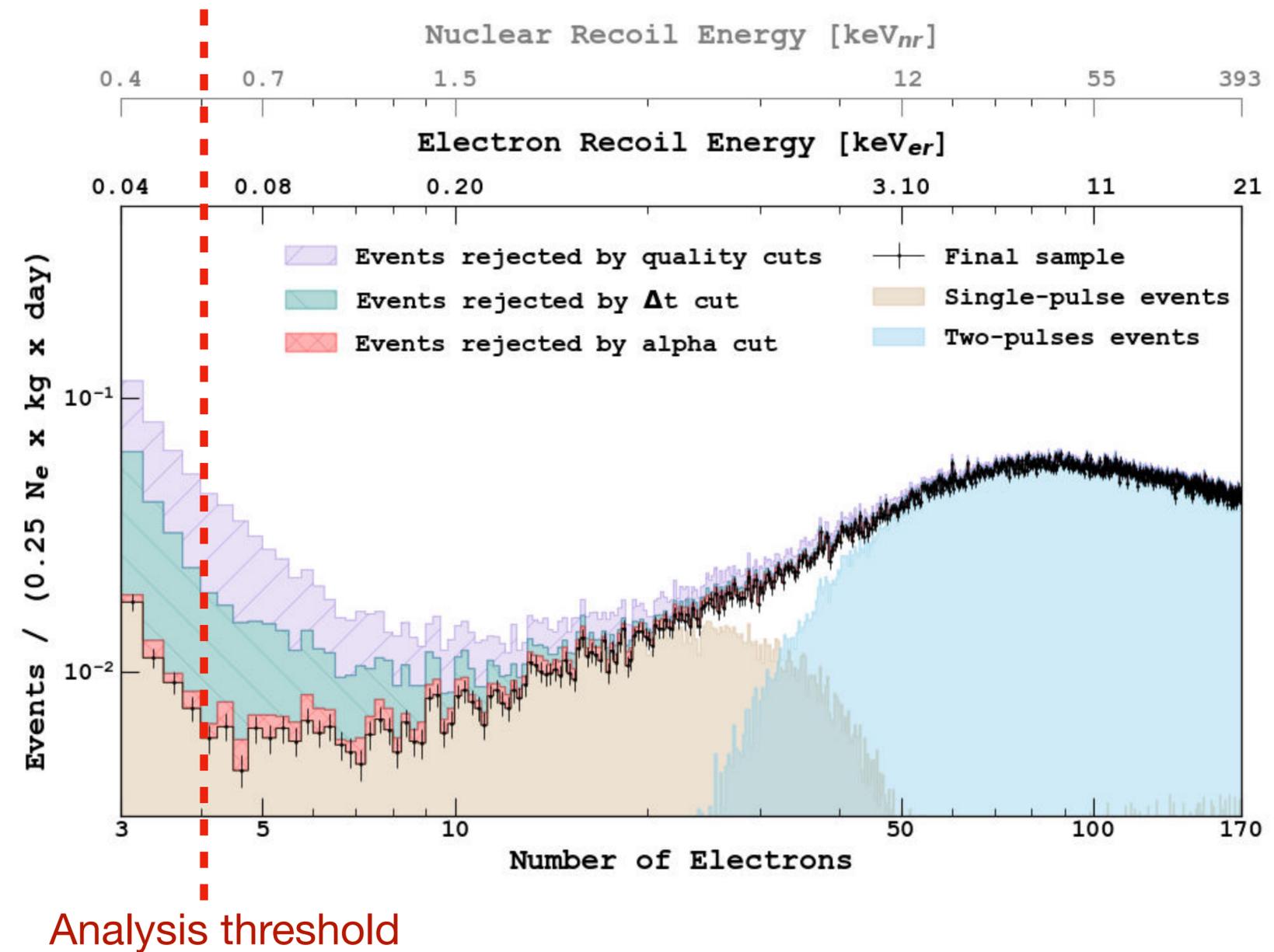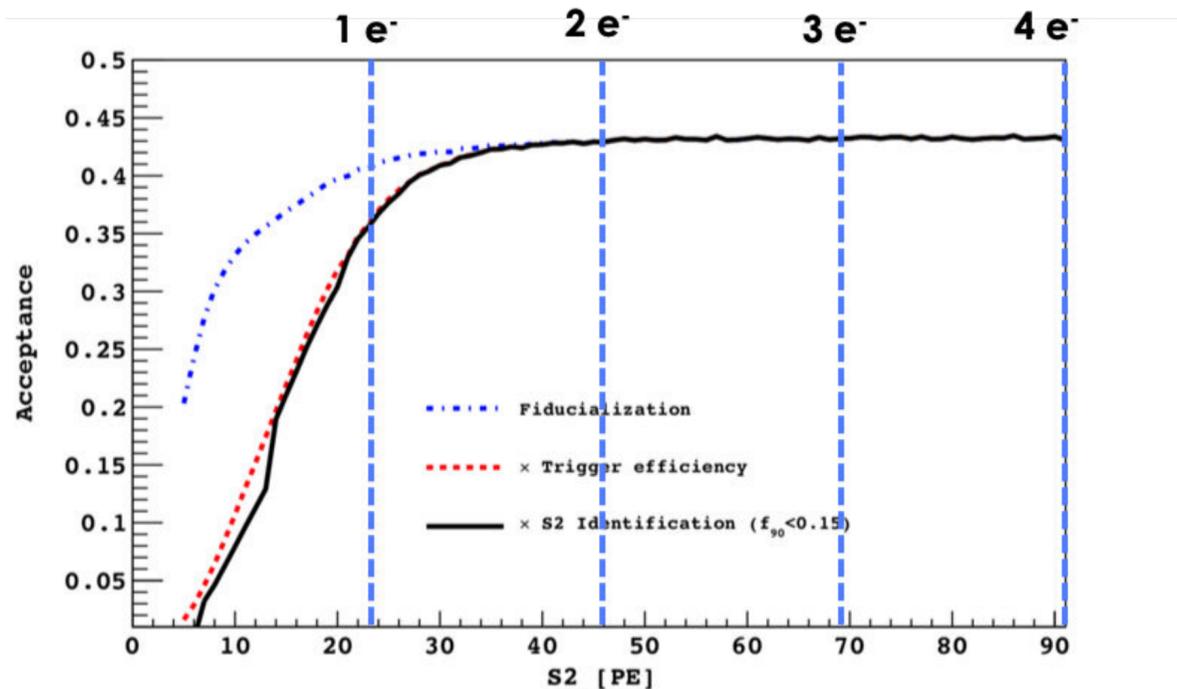
χ

Light DM search in the ionization channel

S2-only analysis

Scintillation (S1):

▸ Detection efficiency (g_1) ~ 16%

Ionization (S2):

▸ Efficiency to extract 1 e- in the gas pocket ~100%

▸ Amplification factor (g_2) ~ 23 pe/e-
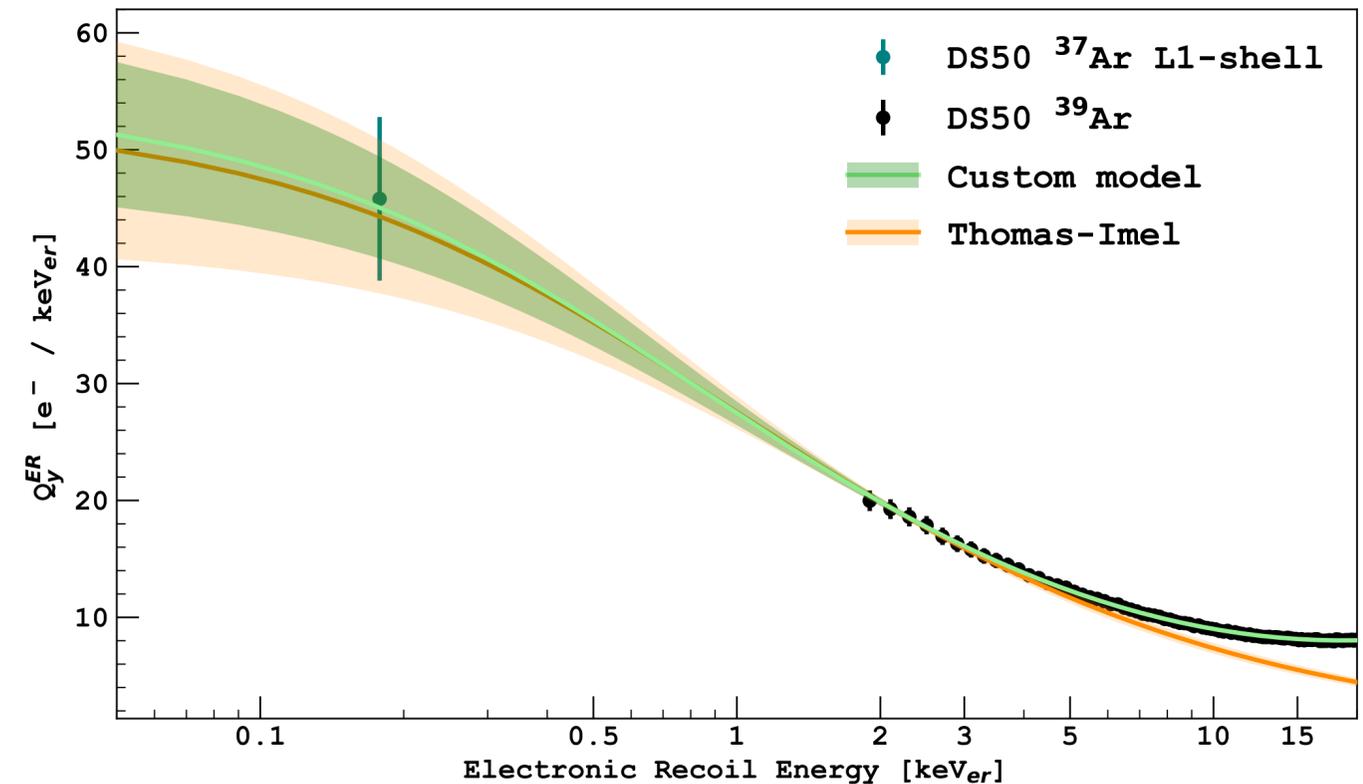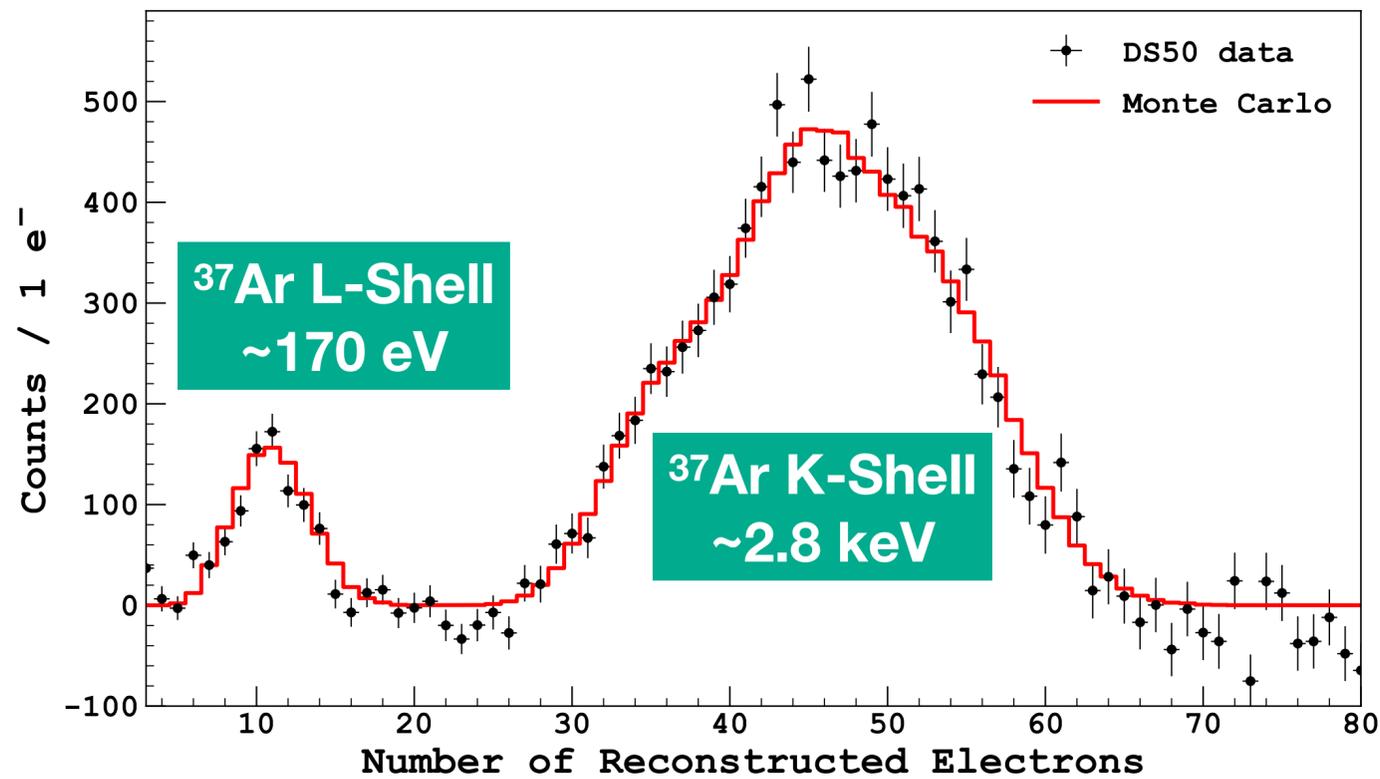

Analysis threshold

Ionization response model

To Electronic Recoils

Thomas-Imel box model

Extended custom model

$$Q_y^{ER} = \left(\frac{1}{\gamma} + p_0 \left(E_{er}/\mathrm{keV}_{er}\right)^{p_1}\right) \frac{\ln(1 + \gamma \rho E_{er})}{E_{er}}$$


^{37}Ar L-Shell ~170 eV

^{37}Ar K-Shell ~2.8 keV

DS50 data
Monte Carlo

Counts / 1 e$^-$
Number of Reconstructed Electrons

DS50 ^{37}Ar L1-shell
DS50 ^{39}Ar
Custom model
Thomas-Imel

Q_y^{ER} [e$^-$ / keV$_{er}$]
Electronic Recoil Energy [keV$_{er}$]

Ionization response model

To Nuclear Recoils

DS-50 AmC

DS-50 AmBe

In 2021, **simultaneous fit** of:

‣ DS-50 calibration data with neutron sources

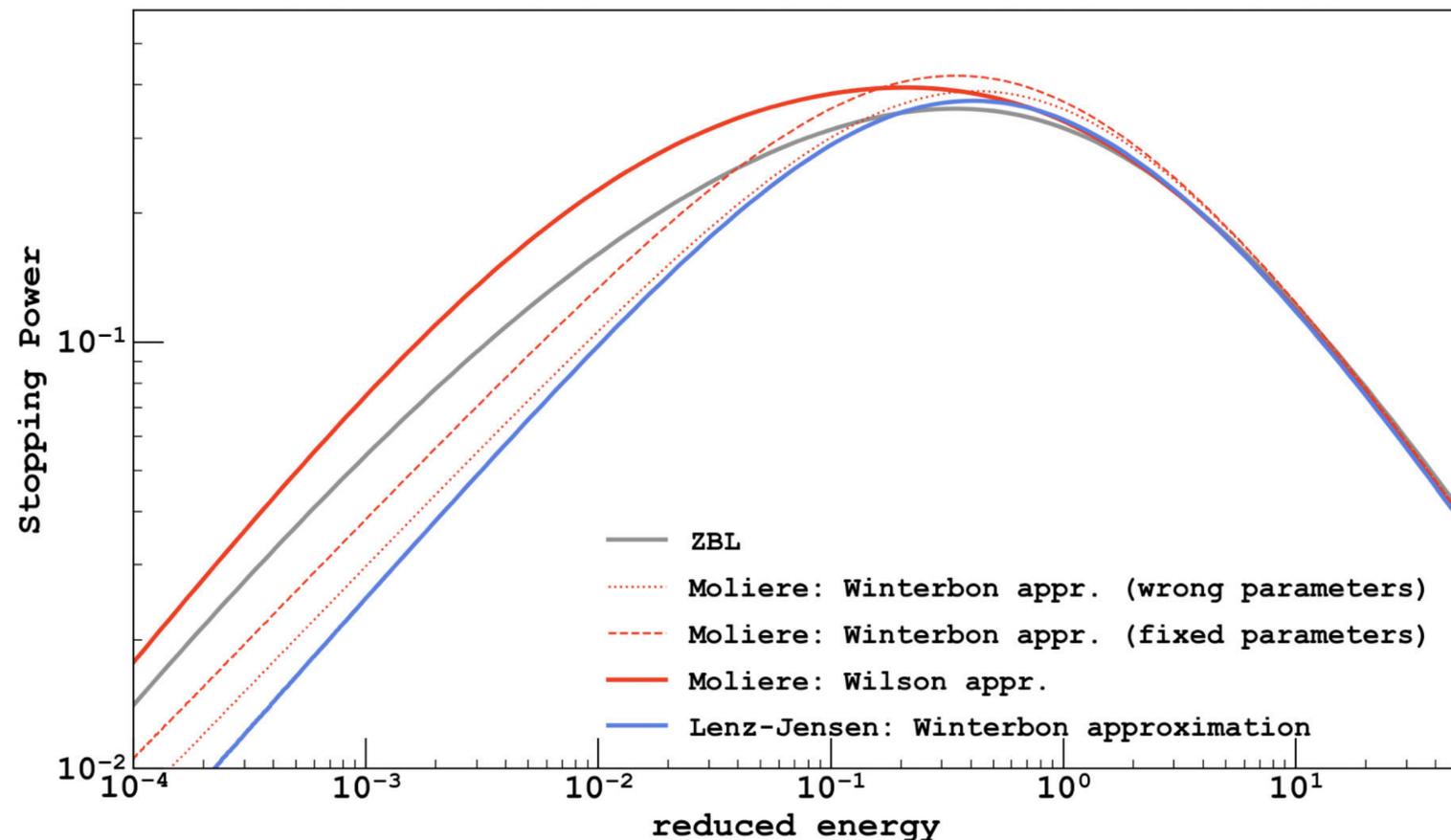‣ External data set (ARIS and SCENE)
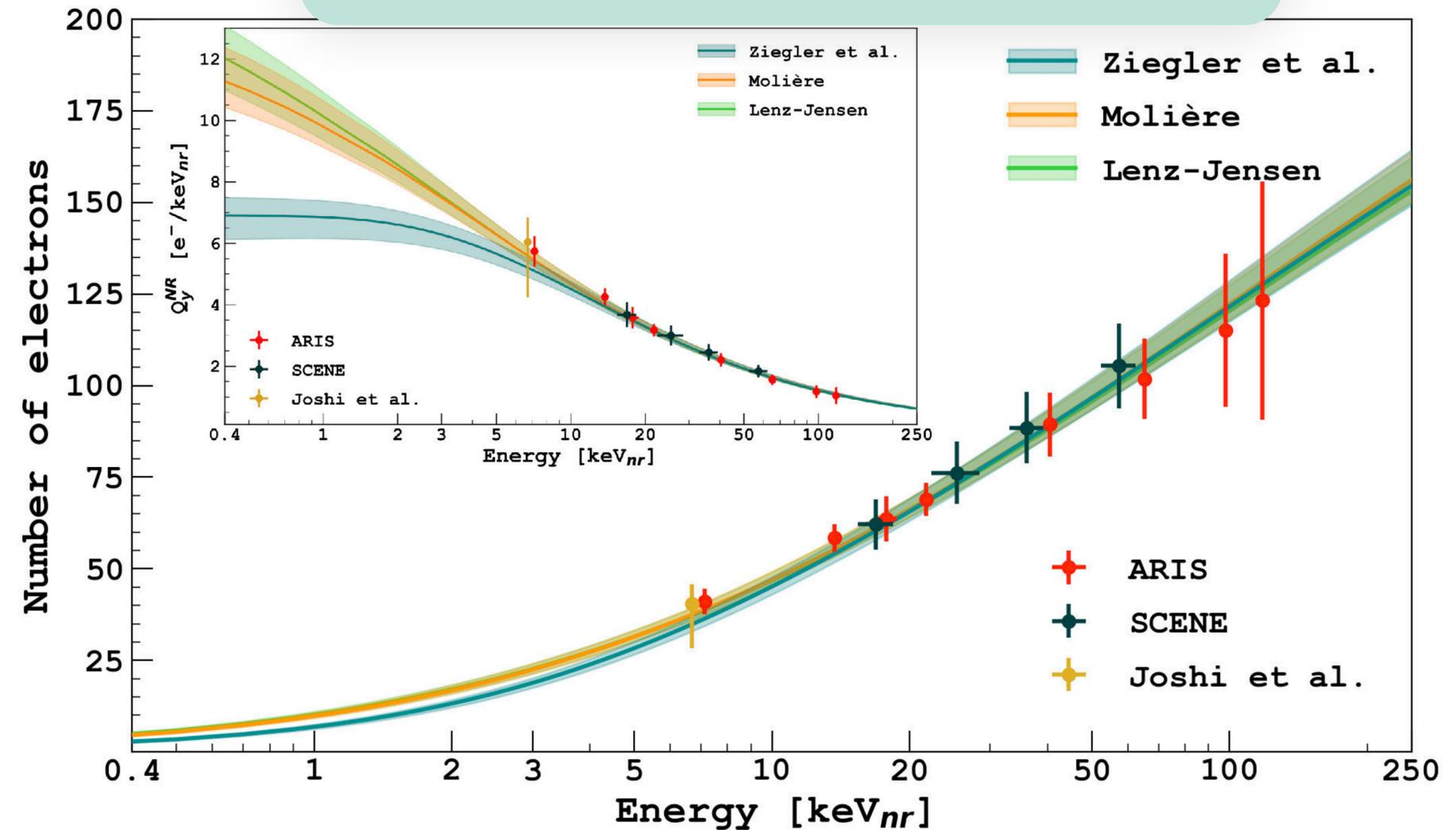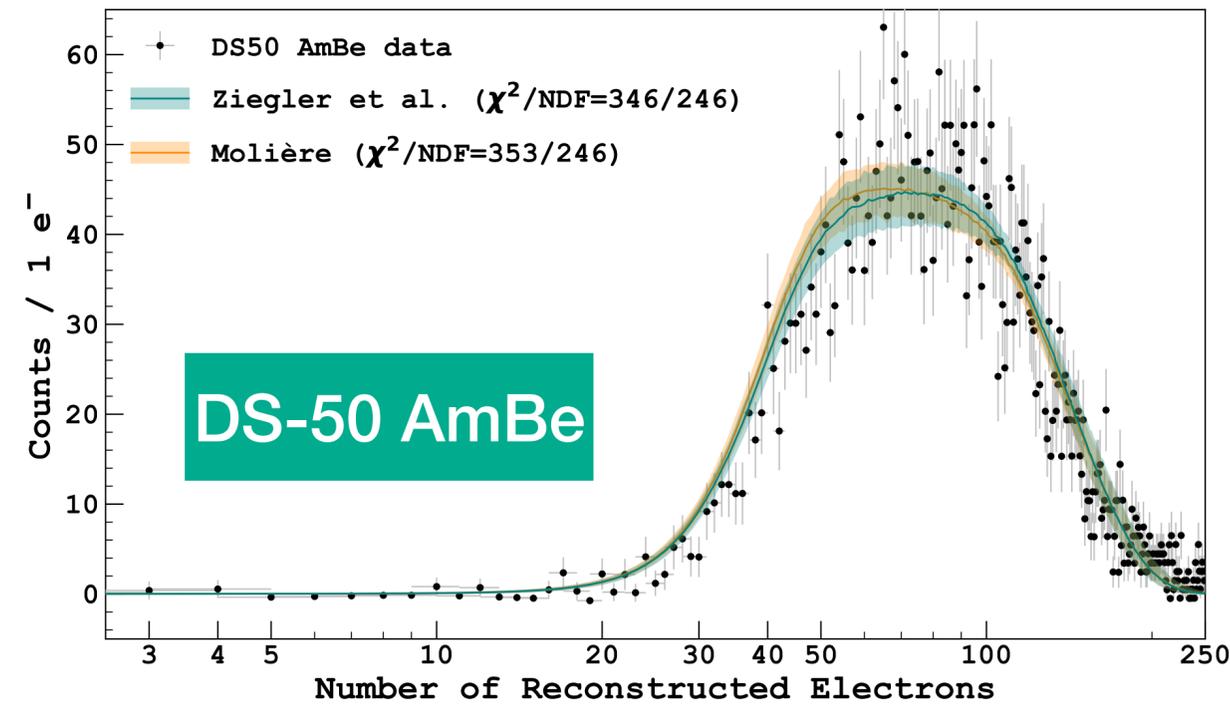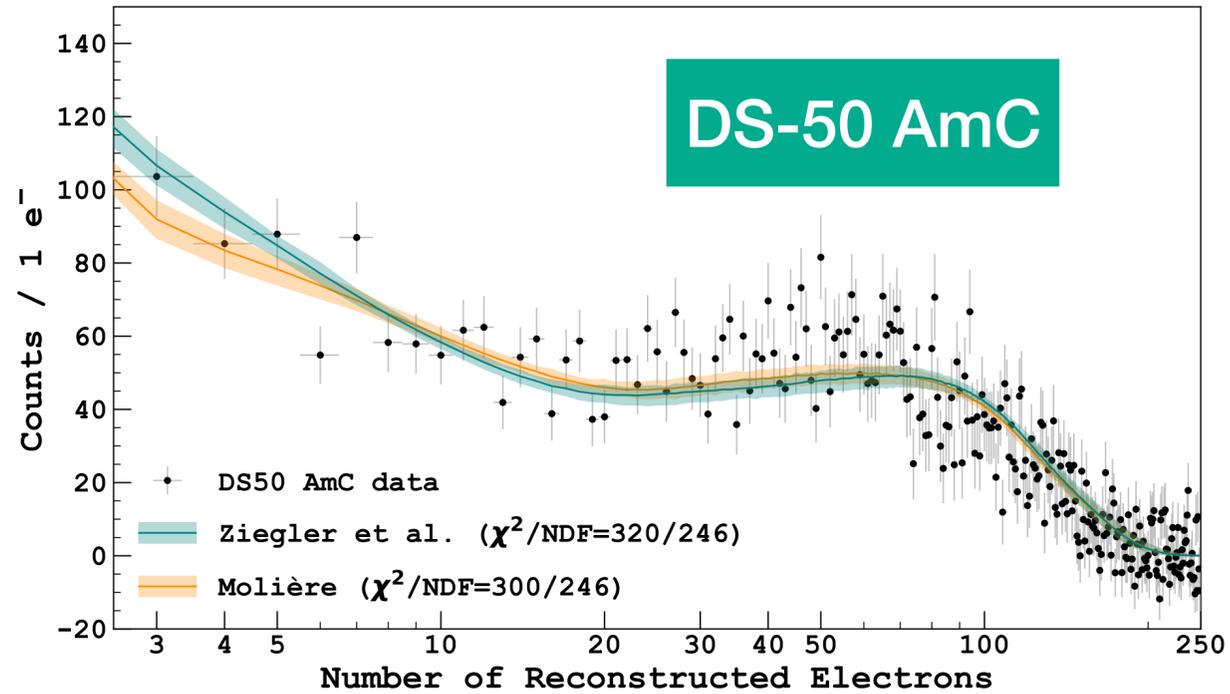
Ziegler used as baseline, because most conservative Q_y.

Screening potential models

Thomas-Imel box model

$$f_q(E_{nr}) = \frac{F}{E_{nr}\, C_{\text{box}}} \ln\left[1 + \frac{C_{\text{box}}}{F} \cdot \beta \cdot \frac{\epsilon(E_{nr})\, s_e(\epsilon)}{s_e(\epsilon) + s_n(\epsilon)} \right]$$

▸ C_{box}, β: free parameters

▸ s_e, s_n: electronic and nuclear stopping powers

Ziegler, Biersack, Littmark (ZBL)

▸ Defined from total energy difference of 2-atom system.

▸ Universal fit over 522 potentials.

Molière:

▸ Analytical approximation of Thomas-Fermi potential.

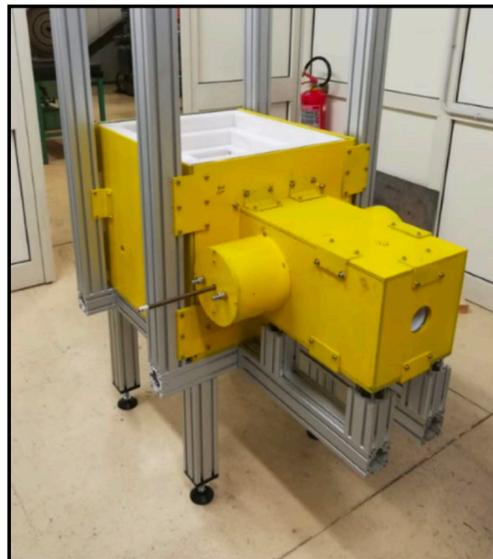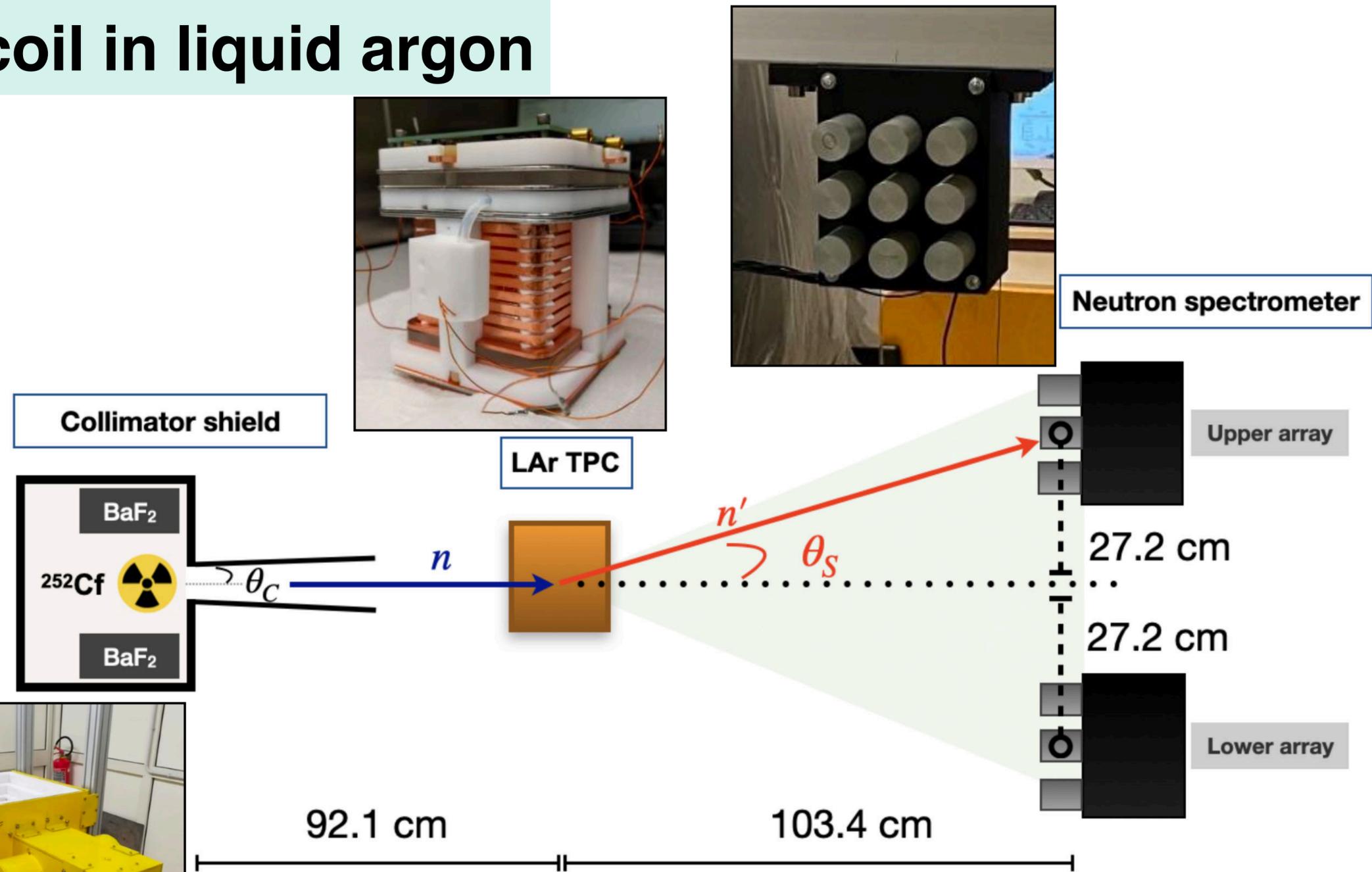▸ Widely used in multiple scattering.

▸ Found a bug in the litterature.

Lenz-Jensen:

▸ Analytical approximation of Thomas-Fermi potential.

▸ Additional shell corrections for improved accuracy at small radii.

Low energy nuclear recoil in liquid argon

- $\mathcal{O}$(2 MeV) neutrons from spontaneous ^{252}Cf fission, tagged from γ with BaF$_2$ scintillator.

- **Nuclear recoil** in small scale LAr TPC.

- Scattered neutron detected in plastic scintillator array with **energies between 2 and 10 keV**.

Neutron spectrometer

Collimator shield

LAr TPC

BaF$_2$

^{252}Cf

θ_C

n

n'

θ_S

Upper array

27.2 cm

27.2 cm

Lower array

92.1 cm

103.4 cm

DARKSIDE

Reconstructing nuclear recoil energy

Event-by-event from two-body kinematics

▸ Trigger on coincidence between γ signal in BaF$_2$ and neutron spectrometer.
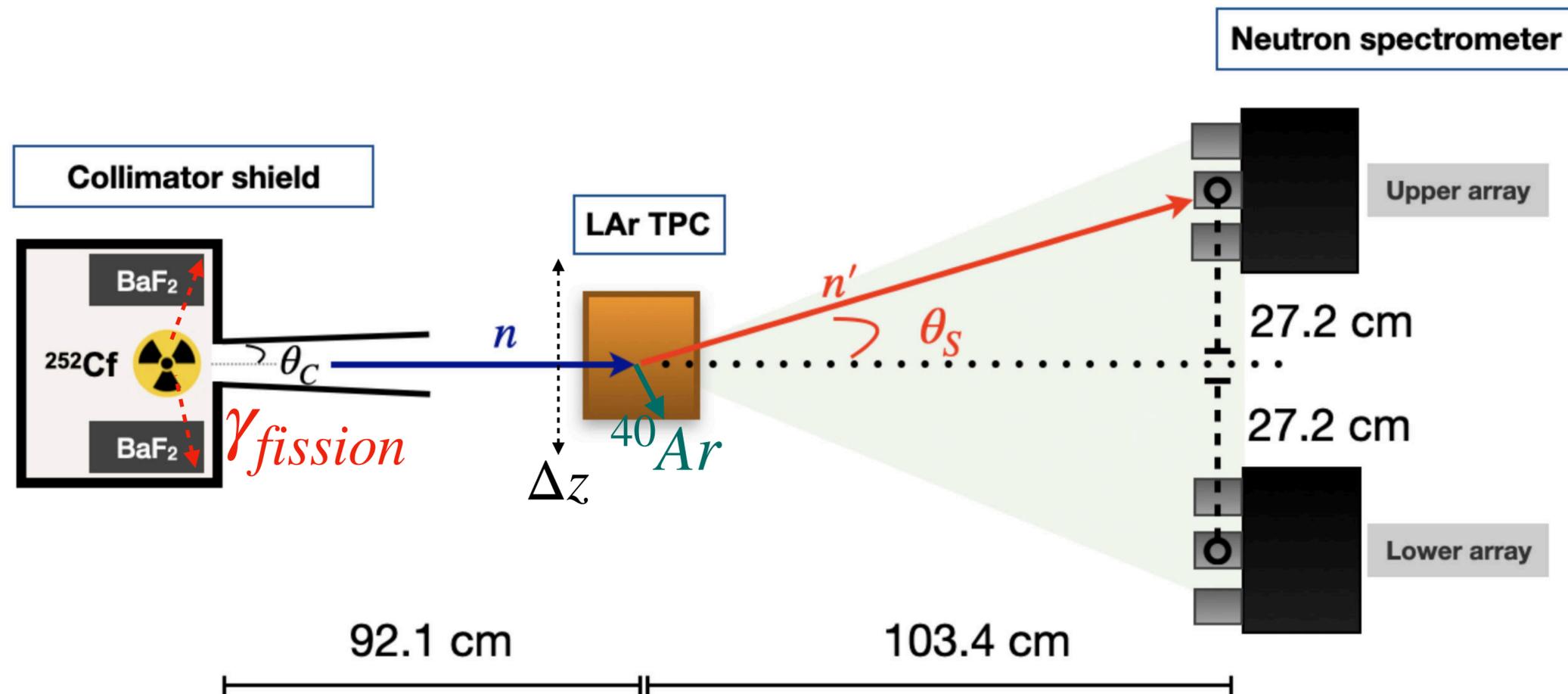
▸ Neutron time of flight = $t_{spectrometer}$ - t_{BaF2}

▸ Scattering angle given by the position of the detecting neutron spectrometer.

▸ Two-body kinematics:

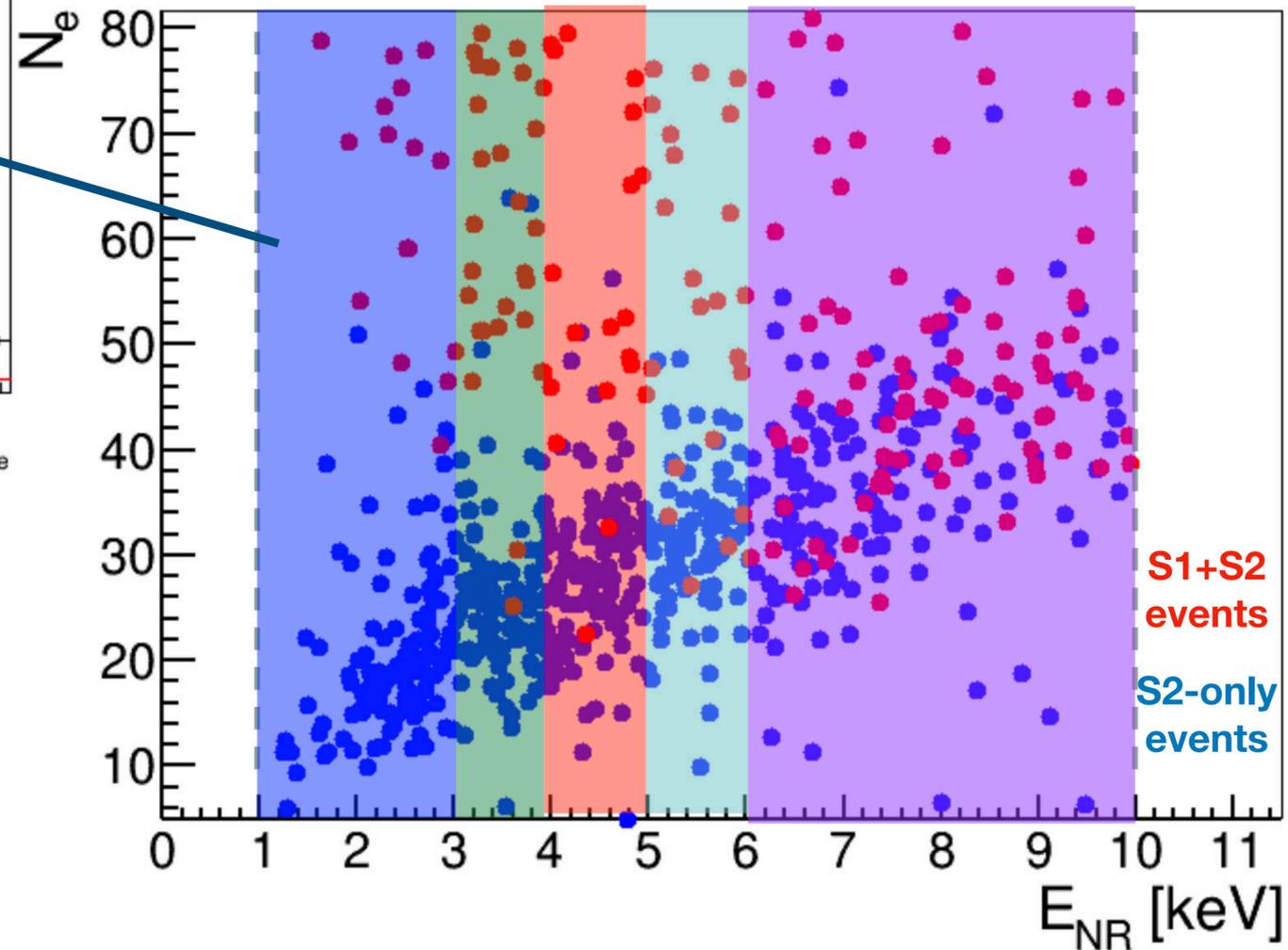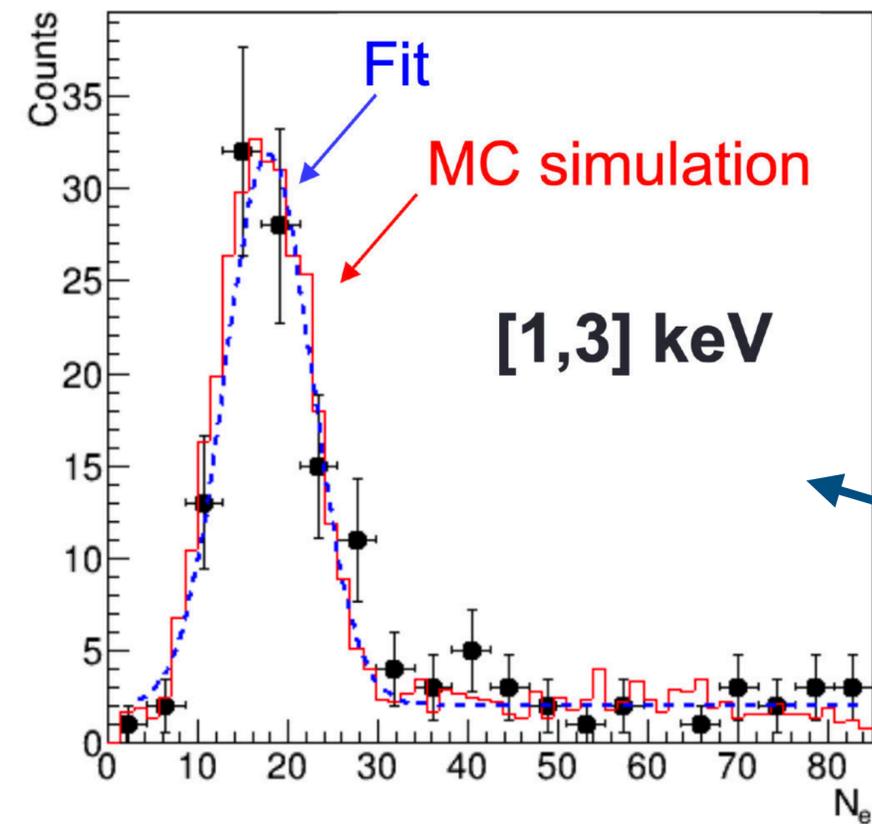$$E_{NR} = 2KE_{neutron}\frac{m_n m_{Ar}}{(m_n + m_{Ar})^2}(1 - \cos\theta_s)$$

▸ **Nuclear recoil energy reconstructed event by event.**

▸ Systematic uncertainty sources:
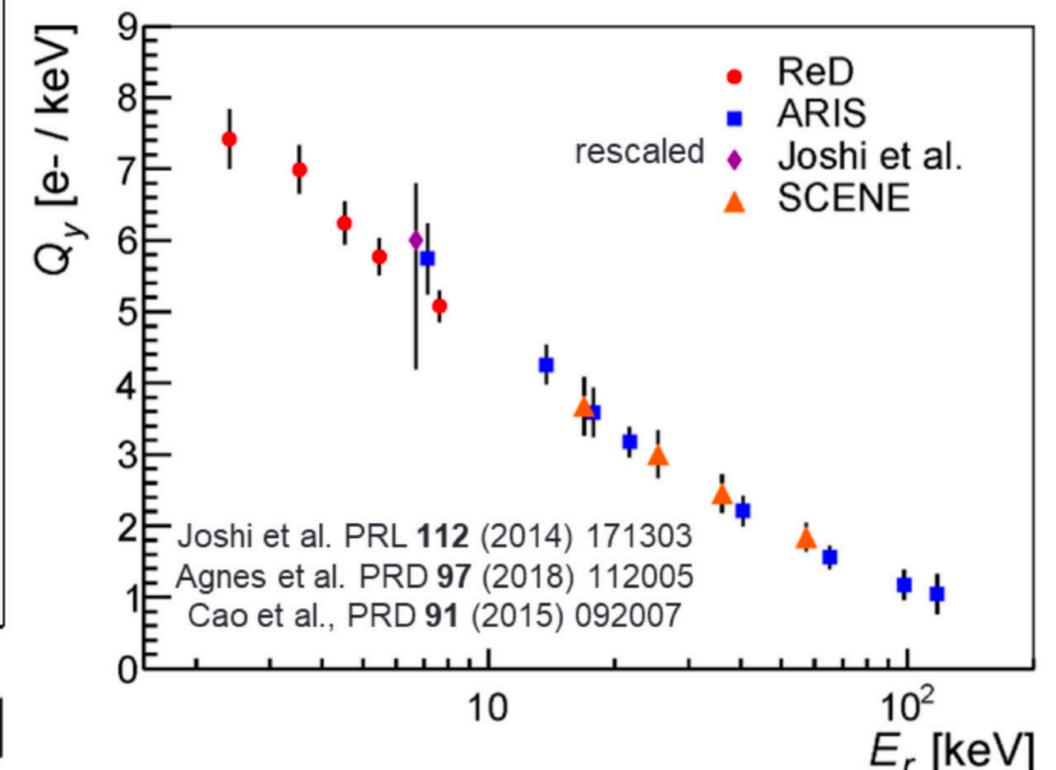 - Ionization amplification factor g_2
  - TPC vertical offset Δz

ReD data

Ionization yield measurement down to 1 keV

Fit

MC simulation

[1,3] keV

S1+S2 events

S2-only events

‣ Dataset split in 5 energy slices.

‣ N_e is fitted with Gaussian + Constant (multiple scattering background).

‣ Strong agreement with MC simulation.

ReD
ARIS
rescaled   Joshi et al.
SCENE

Joshi et al. PRL **112** (2014) 171303
Agnes et al. PRD **97** (2018) 112005
Cao et al., PRD **91** (2015) 092007

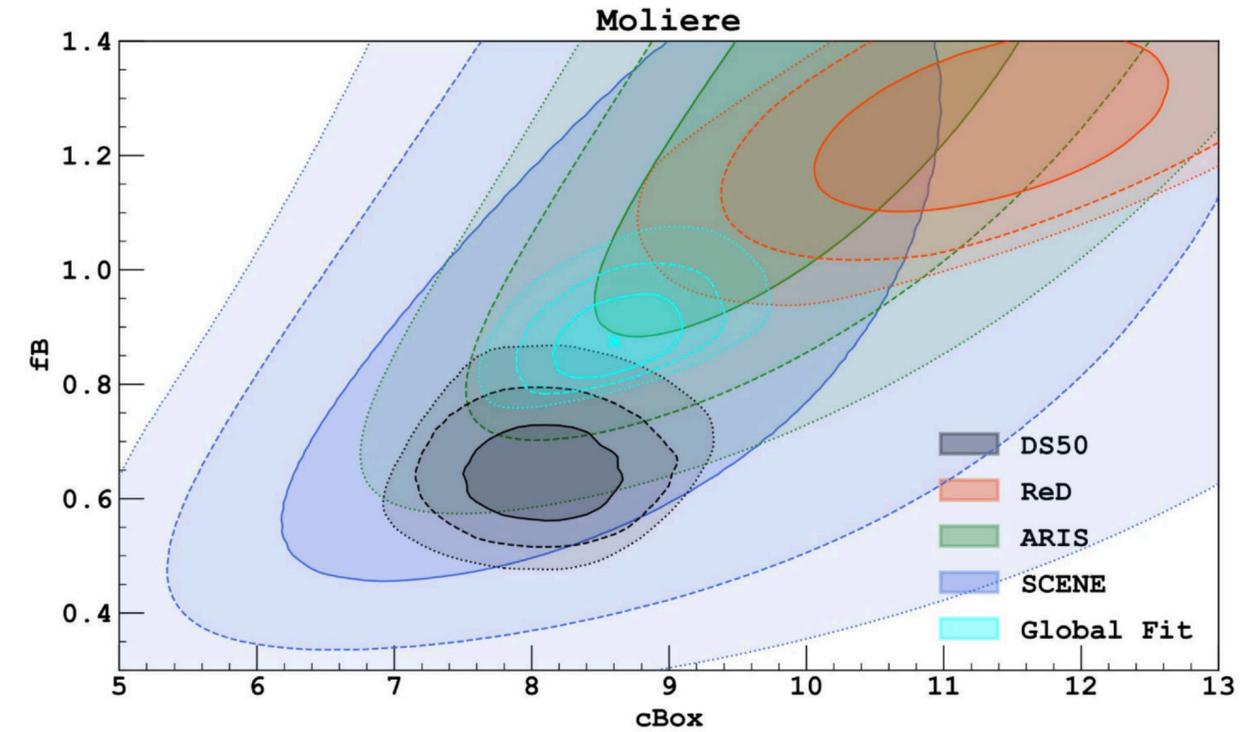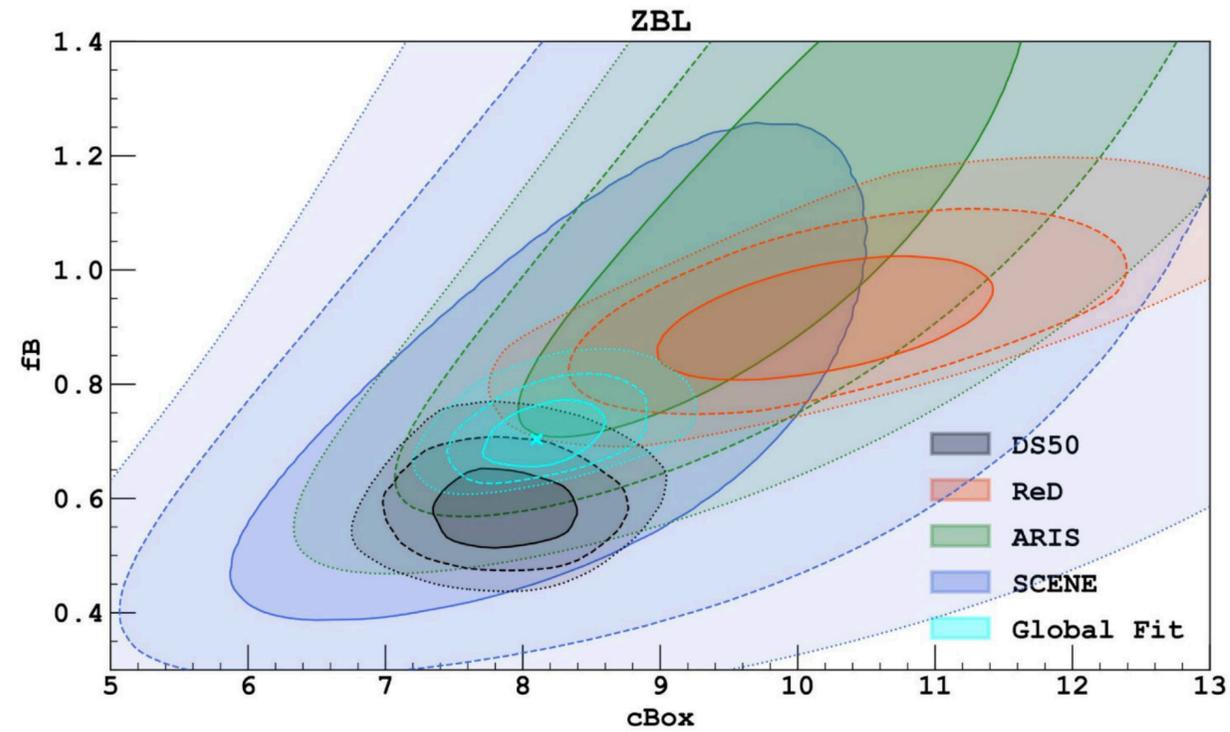# Global fit
Including ReD, DarkSide-50, ARIS, SCENE

$$\chi^2_{\text{tot}}(C_{\text{box}}, \beta) = \chi^2_{\text{ARIS}}(C_{\text{box}}, \beta) + \chi^2_{\text{SCENE}}(C_{\text{box}}, \beta) + \chi^2_{\text{DS50}}(C_{\text{box}}, \beta) + \chi^2_{\text{ReD}}(C_{\text{box}}, \beta; g_2, \Delta z)$$

- ▸ Numerical χ^2 scan over the Thomas-Imel model parameters.

- ▸ ReD systematic uncertainties (g_2, Δz) are marginalised.
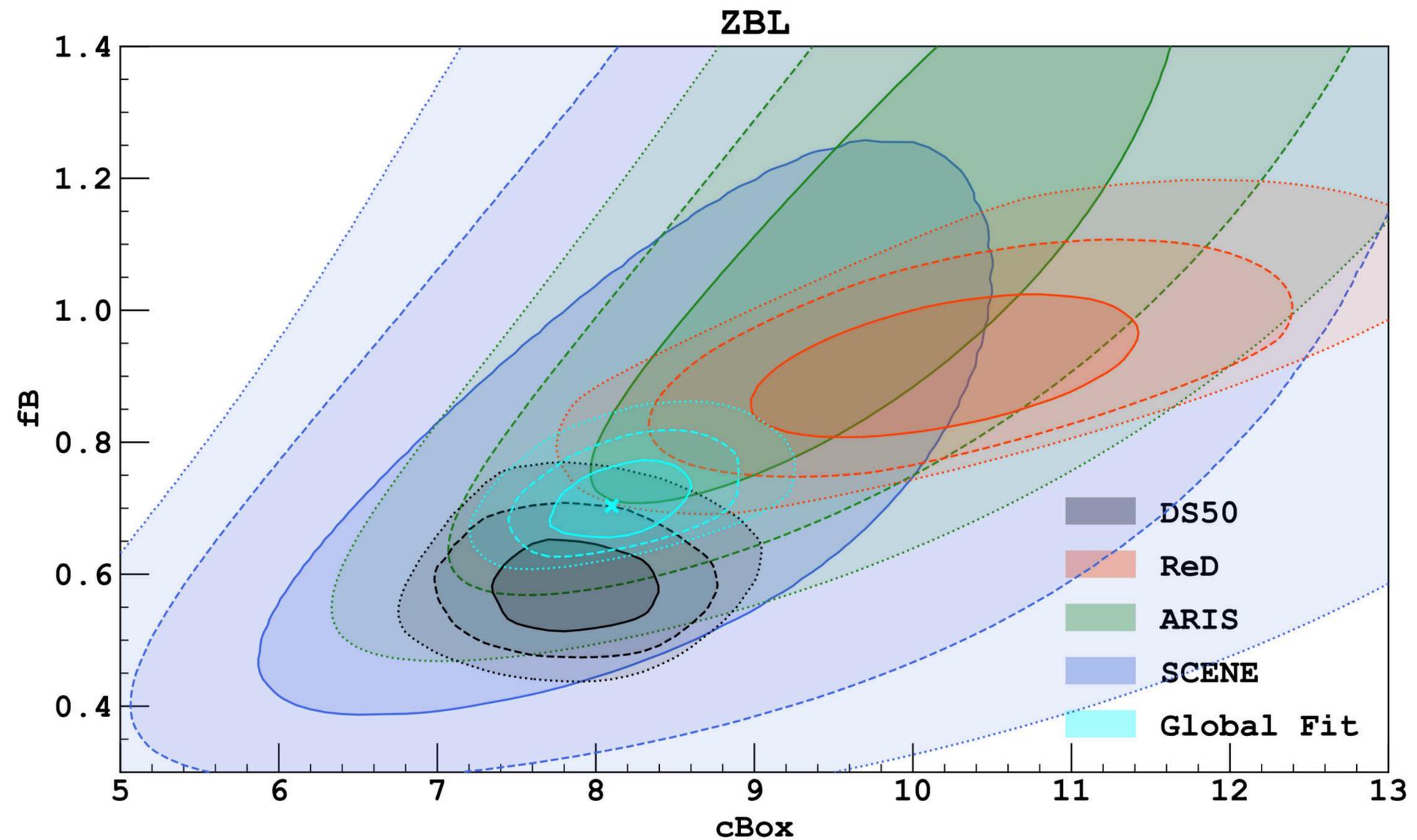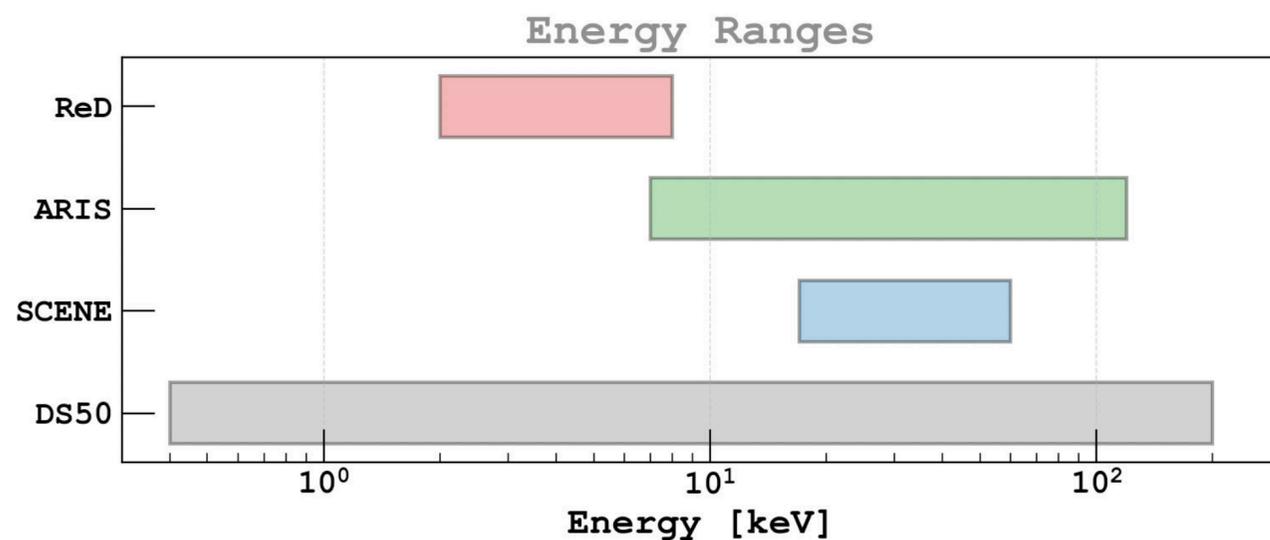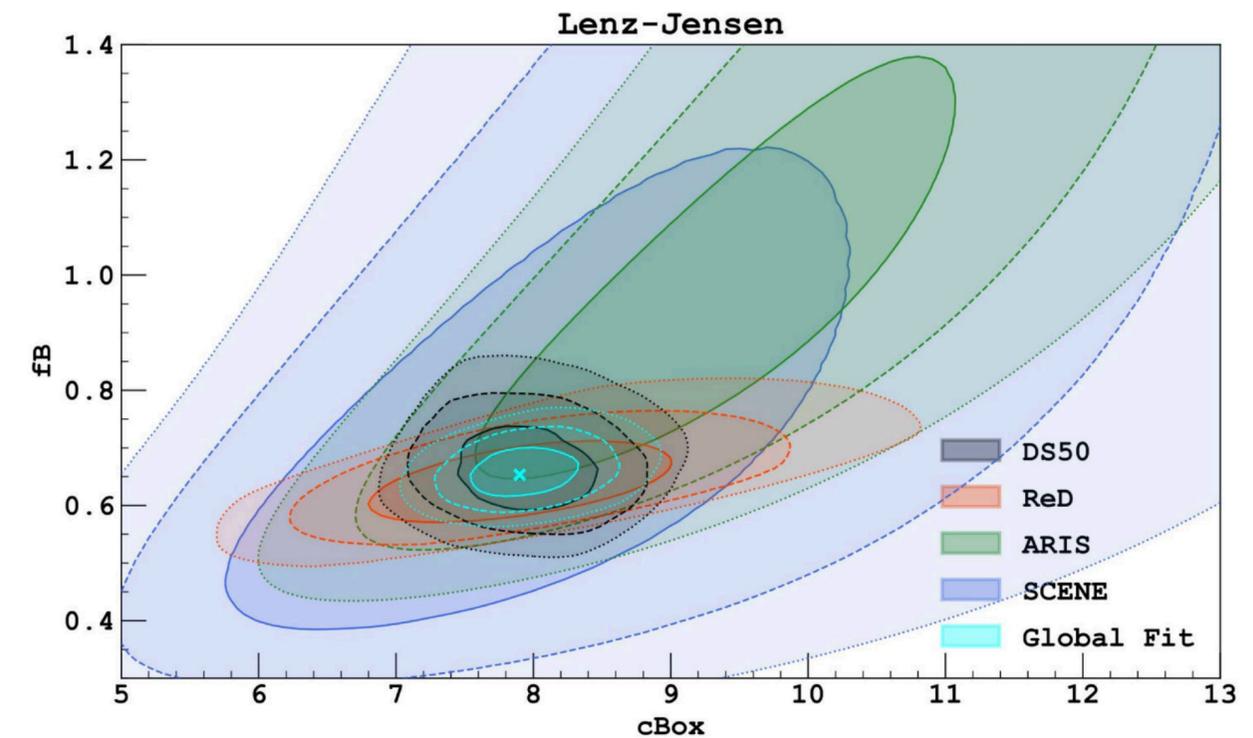
Fitted ionization model parameters
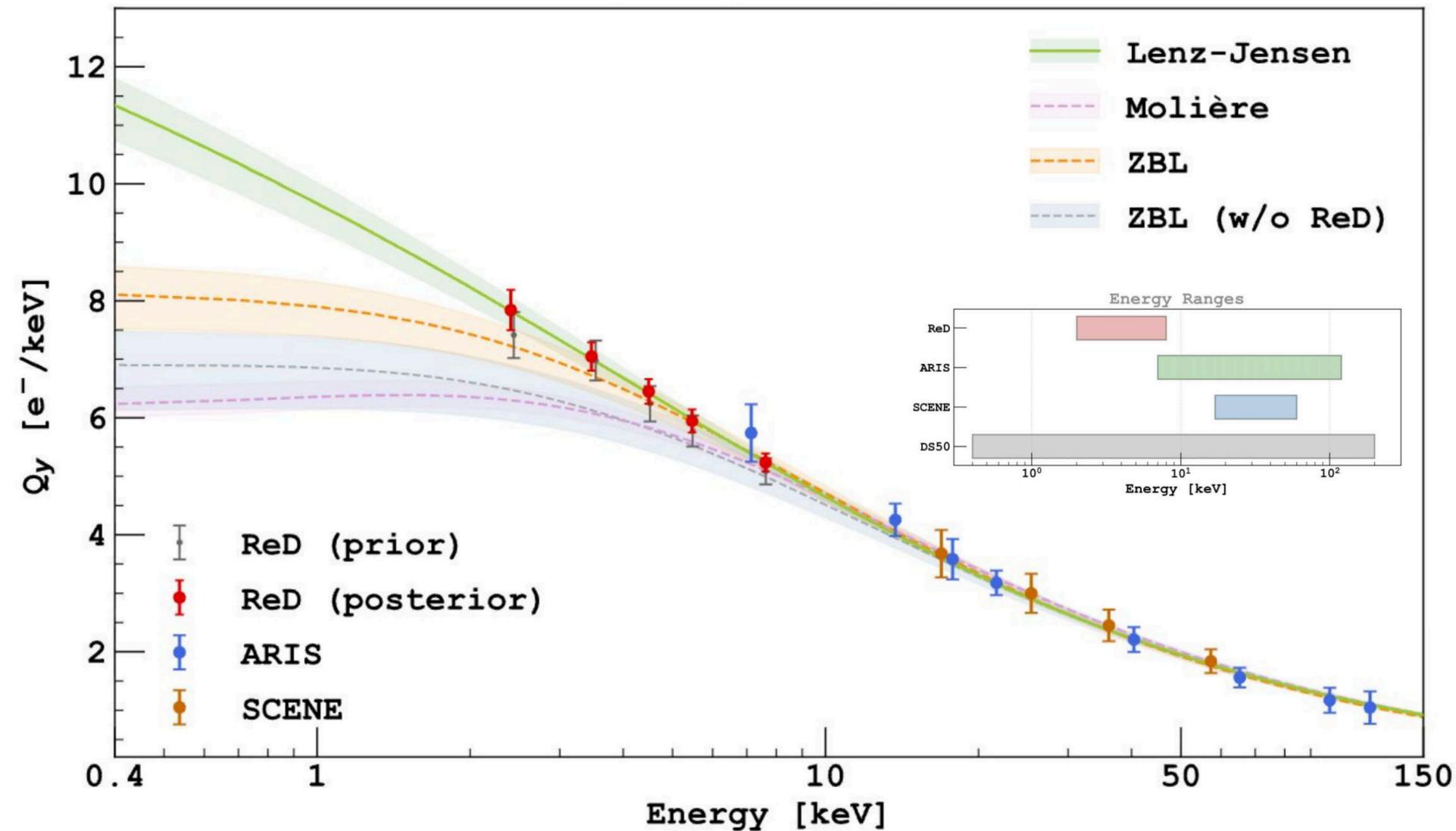
Lenz-Jensen favoured against *Molière* and *ZBL*

Model discrimination with **Bayes Factor**:

▸ **Lenz-Jensen** over **Ziegler** $\rightarrow \log_{10} BF = 3.8 \rightarrow$ Rejected

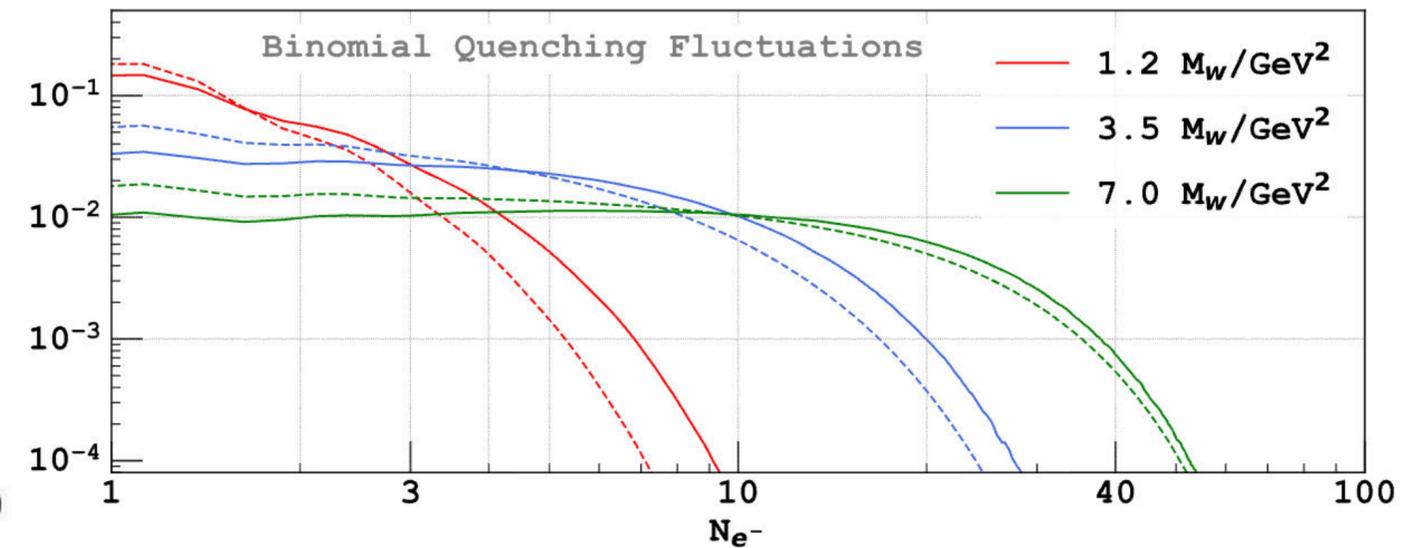▸ **Lenz-Jensen** over **Molière** $\rightarrow \log_{10} BF = 7.2 \rightarrow$ Rejected

Improved ionization response model
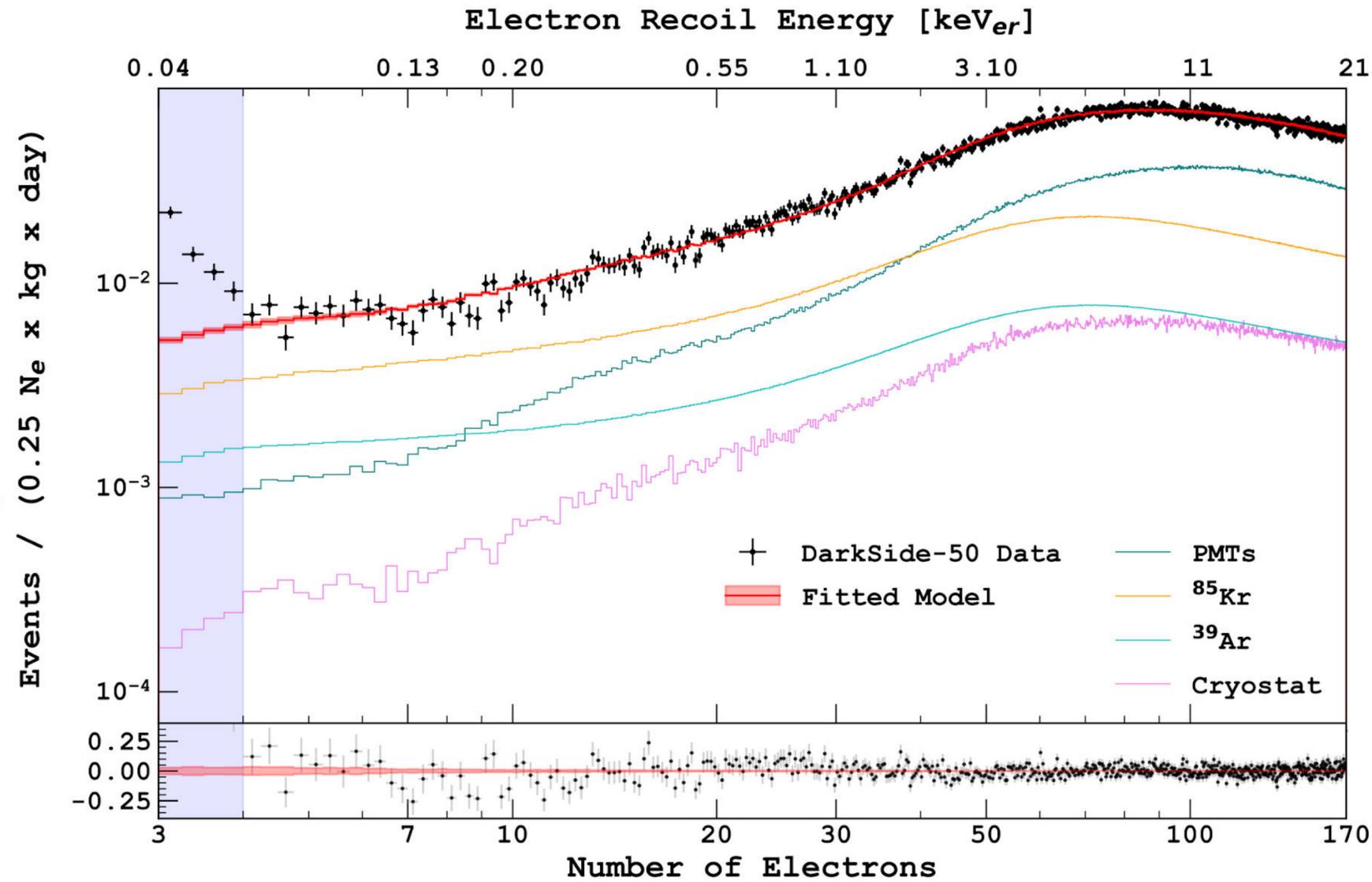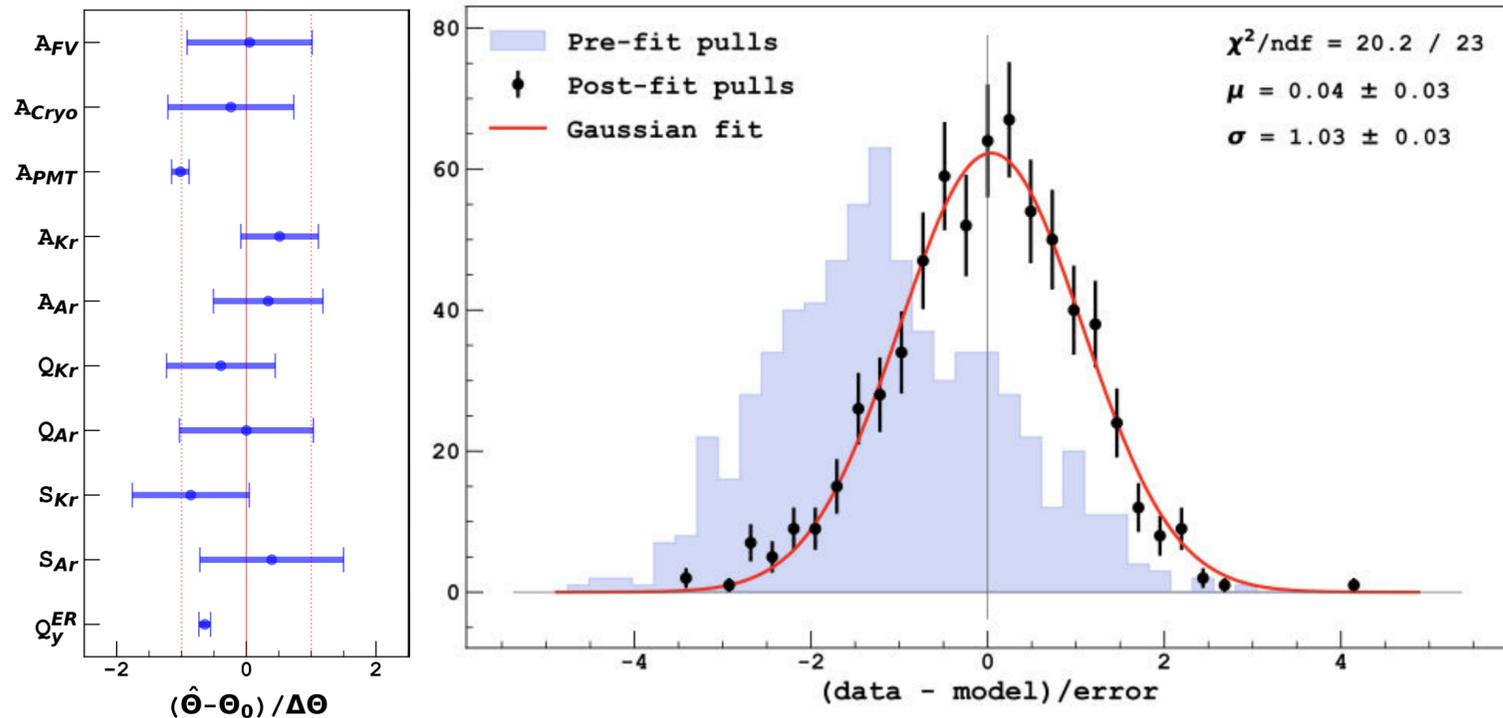
And impact on WIMP spectrum

- ‣ Prior and posteriors on g_2 and Δz are compatible within 1 σ.

- ‣ Using the **Lenz-Jensen** function, the new ionization model predicts stronger signal from WIMPs:
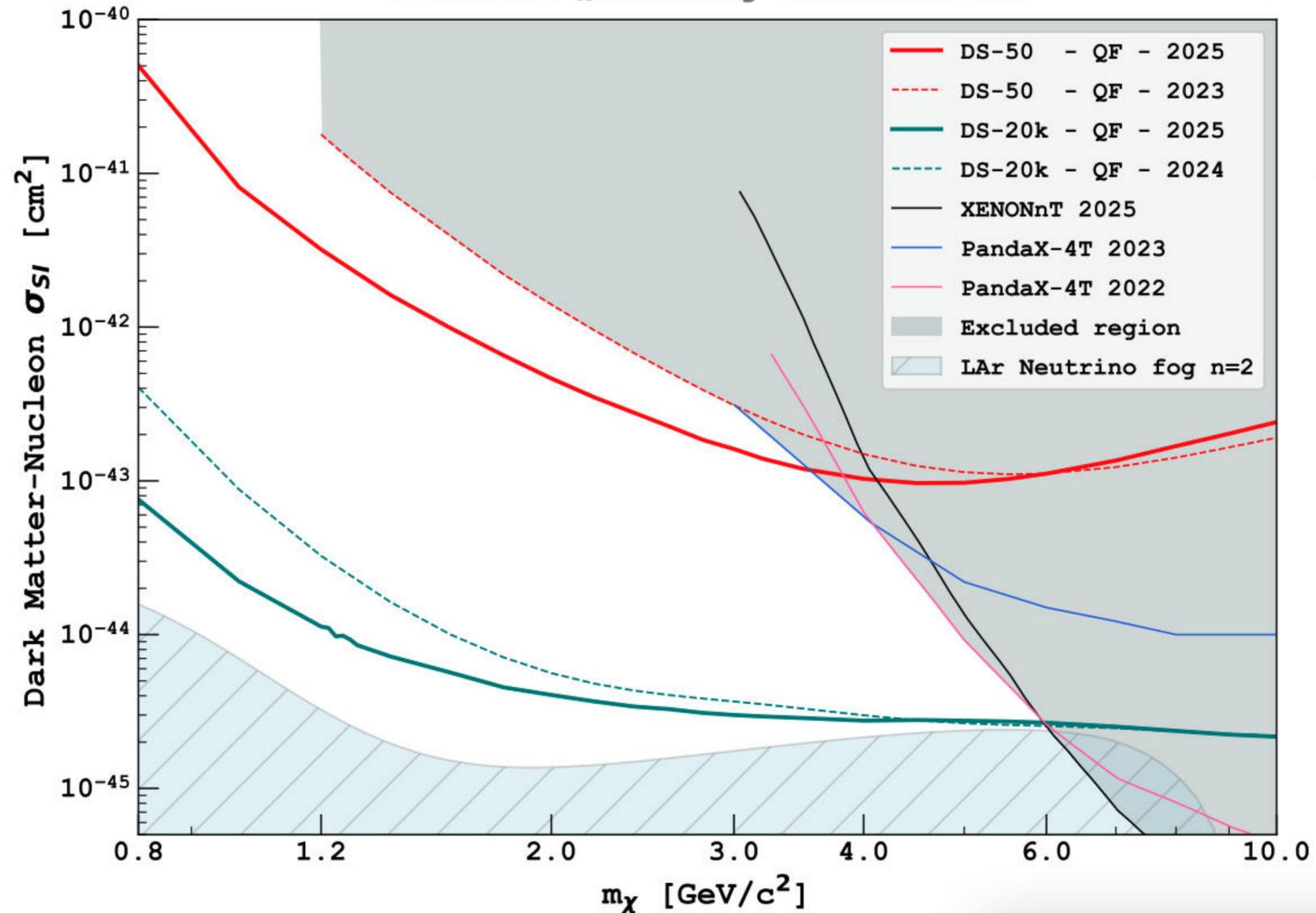
Background-only fit

Improved sensitivity to light dark matter

In DarkSide-50 data and in DarkSide-20k projection


DarkSide-50 $\Rightarrow$ 12 ton-day

**DarkSide-20k** $\Rightarrow$ 34 ton-year

Conclusion

Further improvement of the ionization response

▸ High constraints of NR ionization from 2 to 9 keV with excellent agreement between ReD, DarkSide-50, ARIS, and SCENE.

  ⇒ *Ziegler* and *Molière* screening functions rejected.

  ⇒ Improved limits to light dark matter with DarkSide-50 data.

  ⇒ Improved projected sensitivity of DarkSide-20k.

▸ On-going analysis to assess **sensitivity to quenching fluctuation** from ReD data.

▸ **ReD+:** Replace the ^{252}Cf with a DD generator (mono-energetic 2.4 MeV neutrons)

  ⇒ Cleaner data: higher rate and less background.

  ⇒ Nuclear recoils down to 0.2 keV.

  ⇒ Improved setup TPC, neutron spectrometer, shielding…
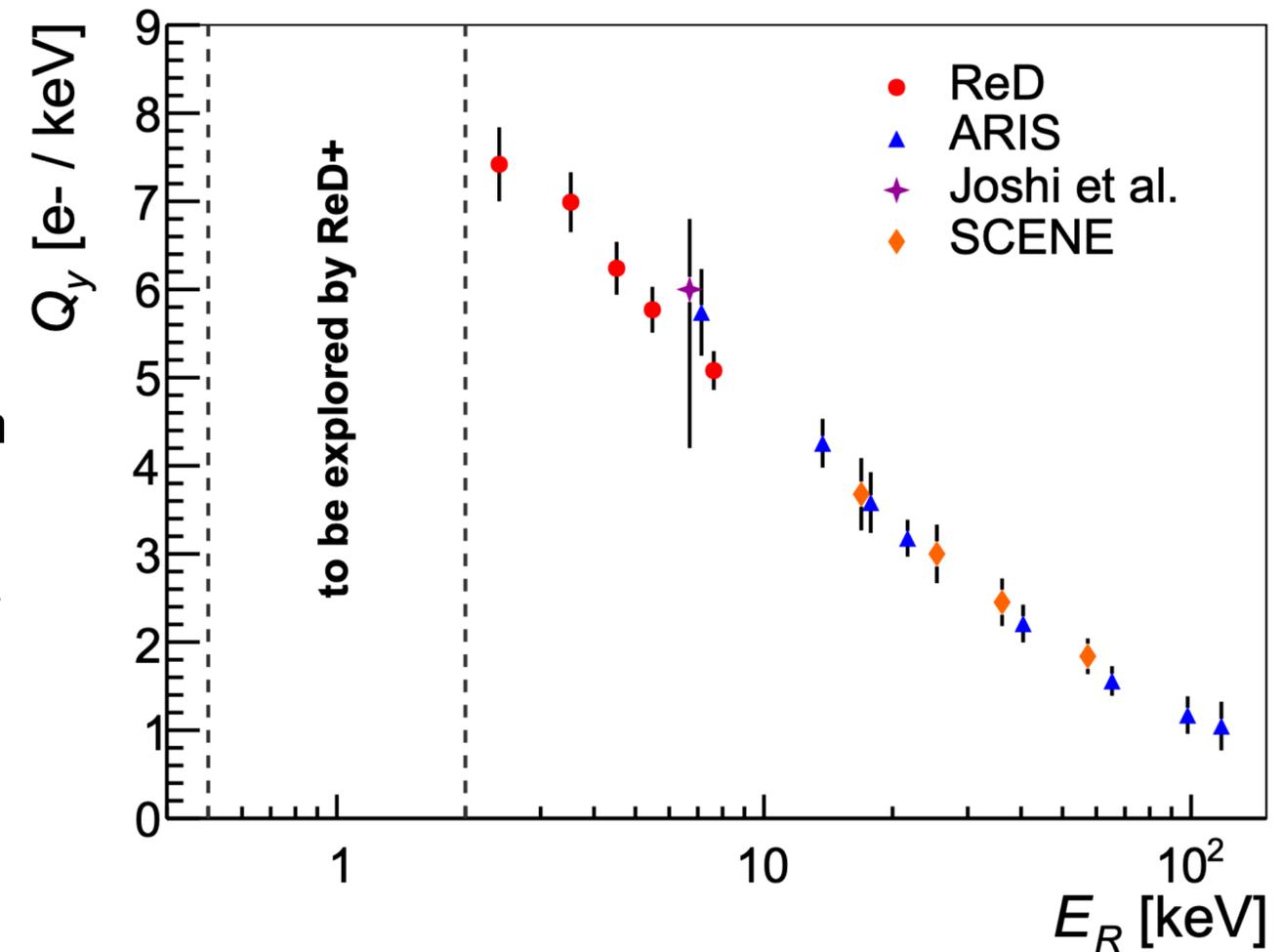
BACK-UP
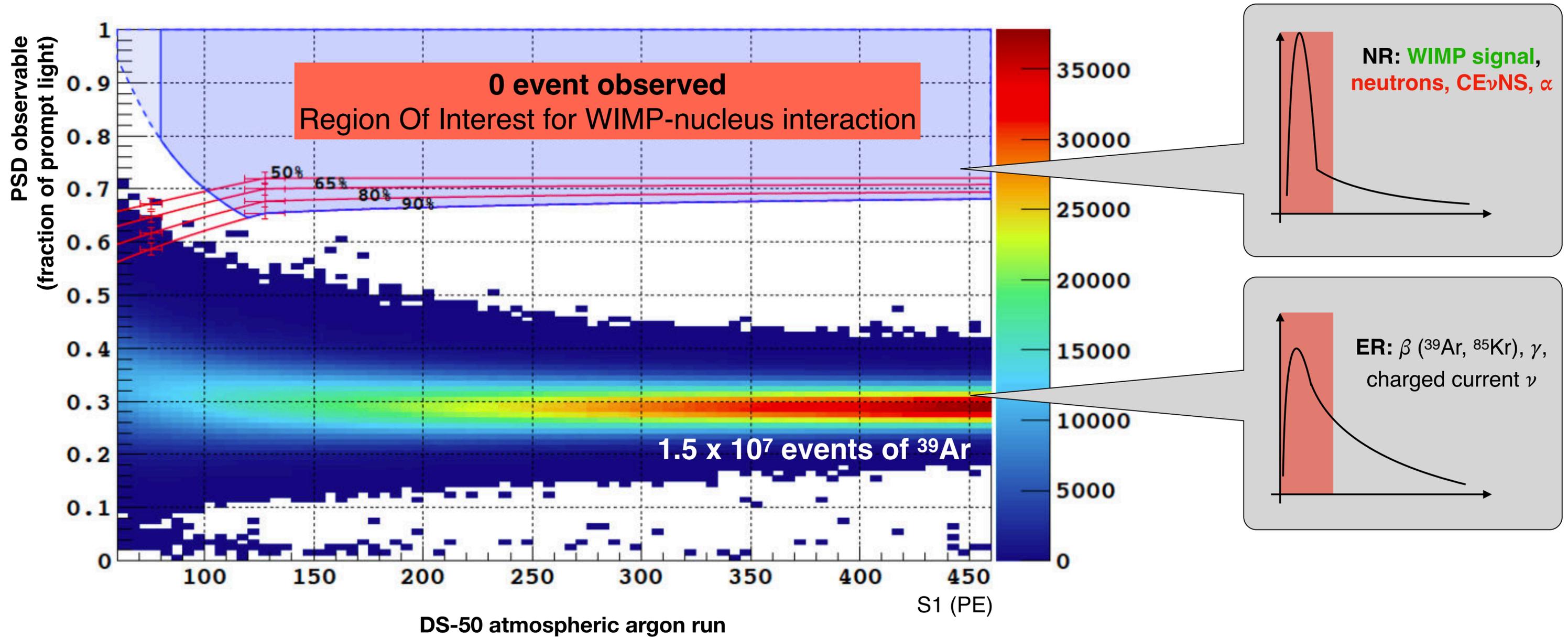
From DarkSide-50 to DarkSide-20k

DarkSide-50
(2013-2019)
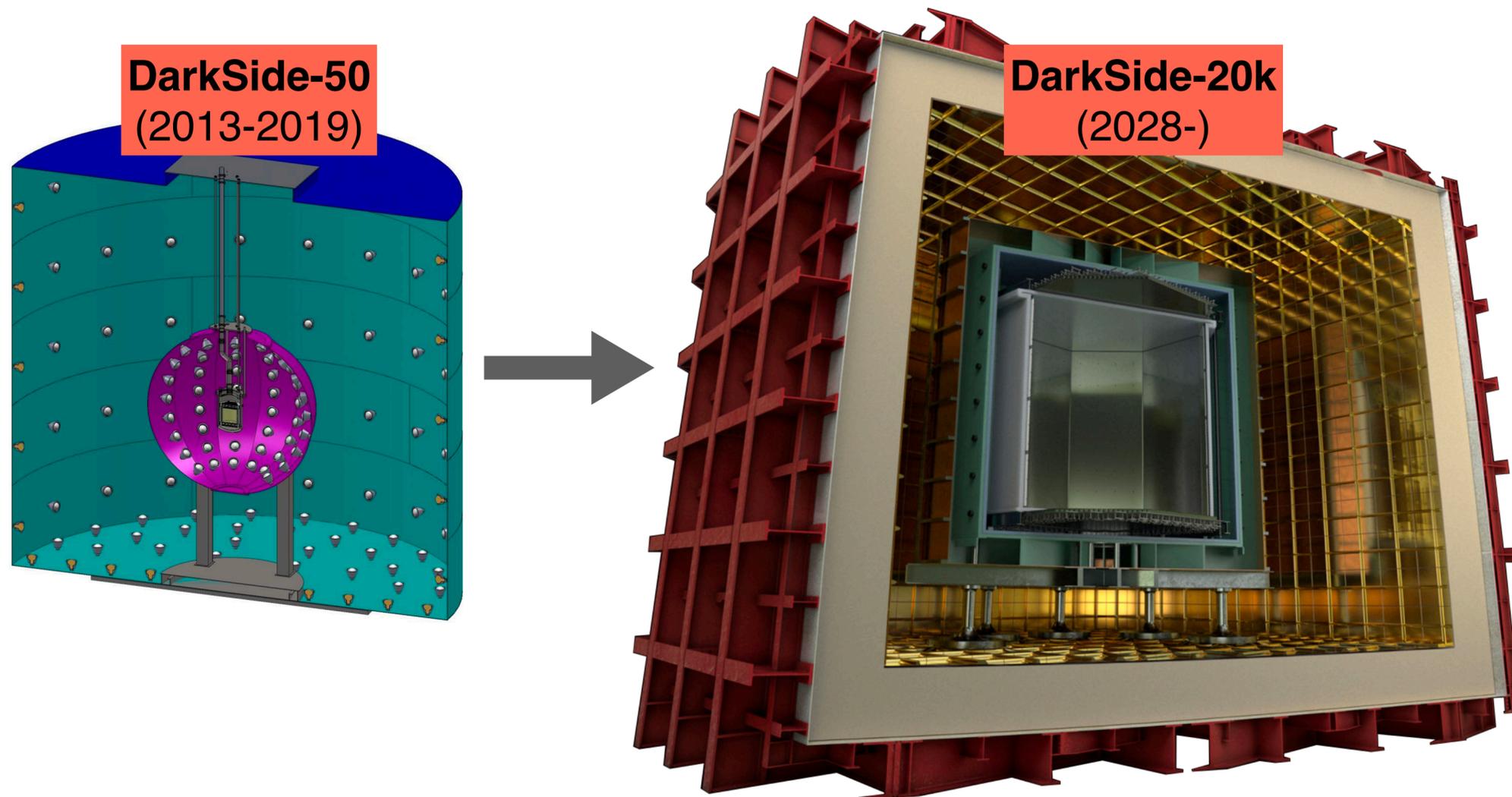
DarkSide-20k
(2028-)

Goal:
Less than 0.1 instrumental background events
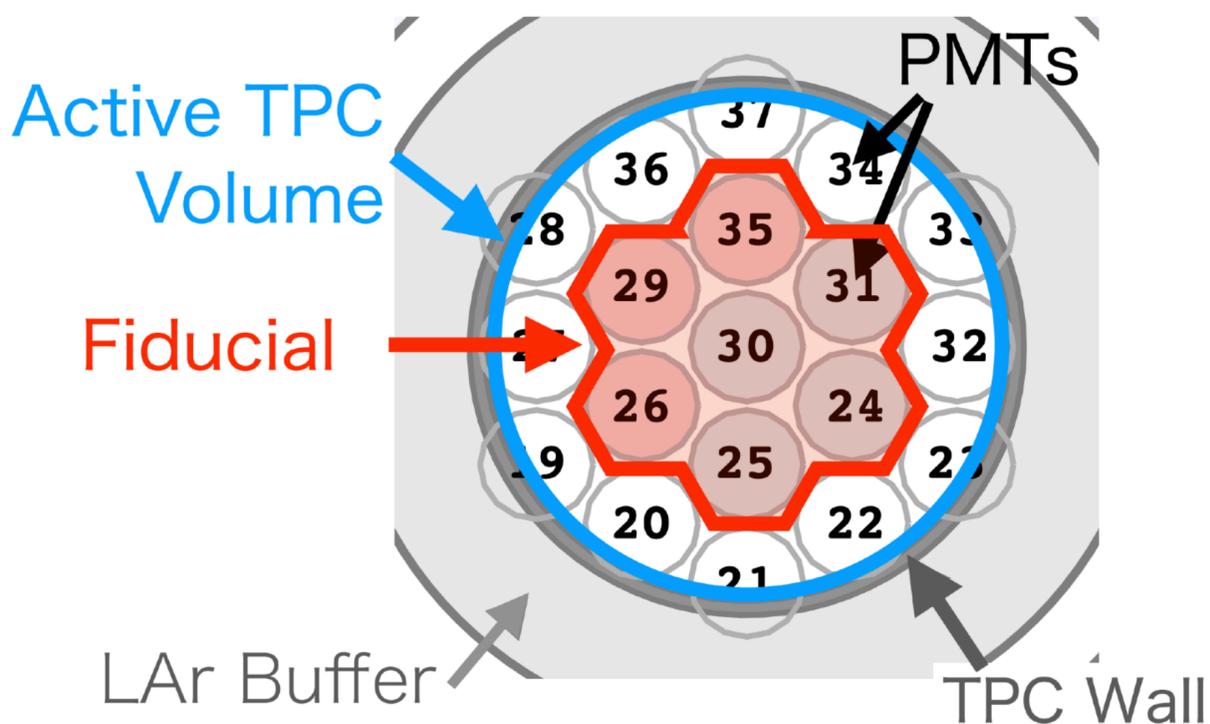
‣ 46.6 kg ⋯➤ 50 tons of UAr.

‣ 38 Photo-multiplier Tubes ⋯➤ **2112 SiPM readout channels in the TPC**.

‣ **1 day of DarkSide-20k** gives the same exposure as **DarkSide-50 full dataset**.

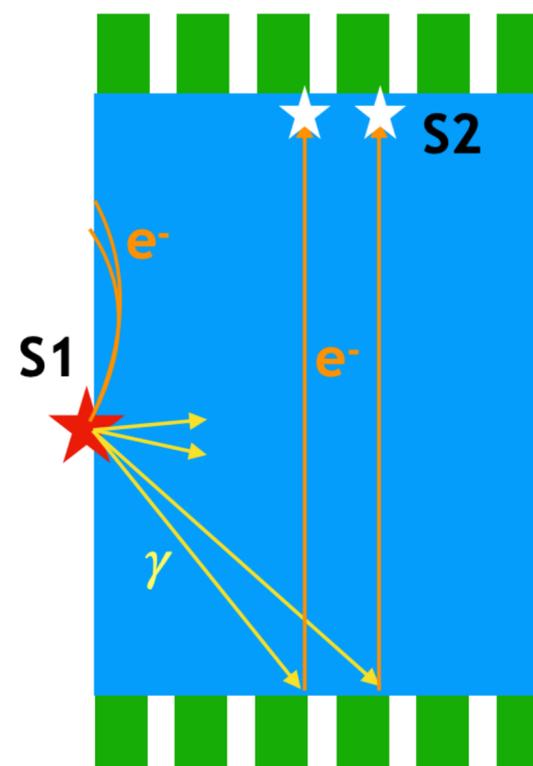# Pulse shape discrimination in liquid argon


19

Low-mass data selection

Fiducialization

Active TPC Volume

Fiducial

LAr Buffer

PMTs

TPC Wall

‣ Select events with max fraction of PEs in one of the 7 central top PMTs

‣ 41% acceptance

Alpha-induced S2 pulses

S2

e⁻

S1

e⁻

γ

‣ Reject anomalous S2/S1 events (tuned on calibration data)

‣ 99% acceptance

Spurious electrons

Normalised to >20 ms dataset livetime

ΔT > 20 ms
ΔT in [0.8, 2] ms
ΔT in [2, 20] ms
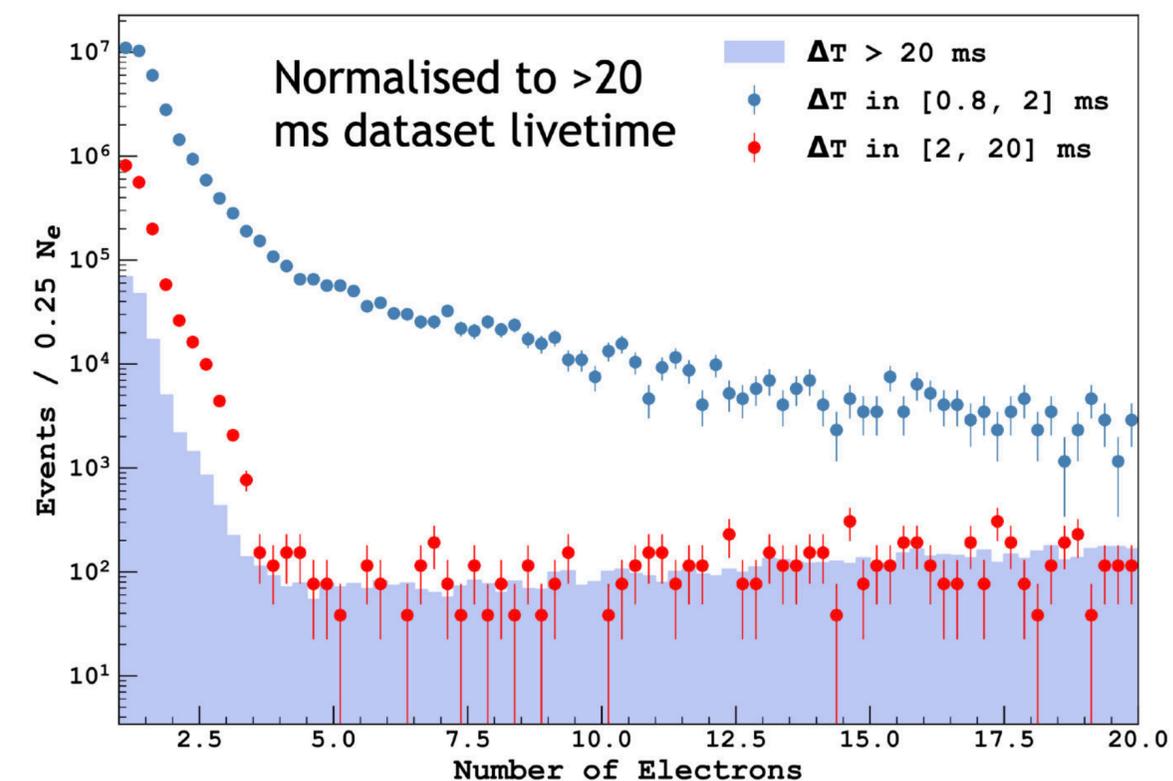
‣ Reject correlated events (< 20 ms from the previous one)

‣ 97% acceptance

Systematic uncertainties

Ionization amplification factor g_2:

▸ From γ calibration, ratio between S2 signal and number of electrons expected (model from DarkSide-50)

▸ Validated on isolated single-electron signals

▸ $g_2 = 18.56 \pm 0.71$ PE/e⁻

Vertical offset in TPC position:

▸ Relative offset with respect to the cryostat center altering angles used in energy reconstruction.

▸ Inducing **asymmetry in the ionization yield between top and bottom** neutron spectrometer arrays

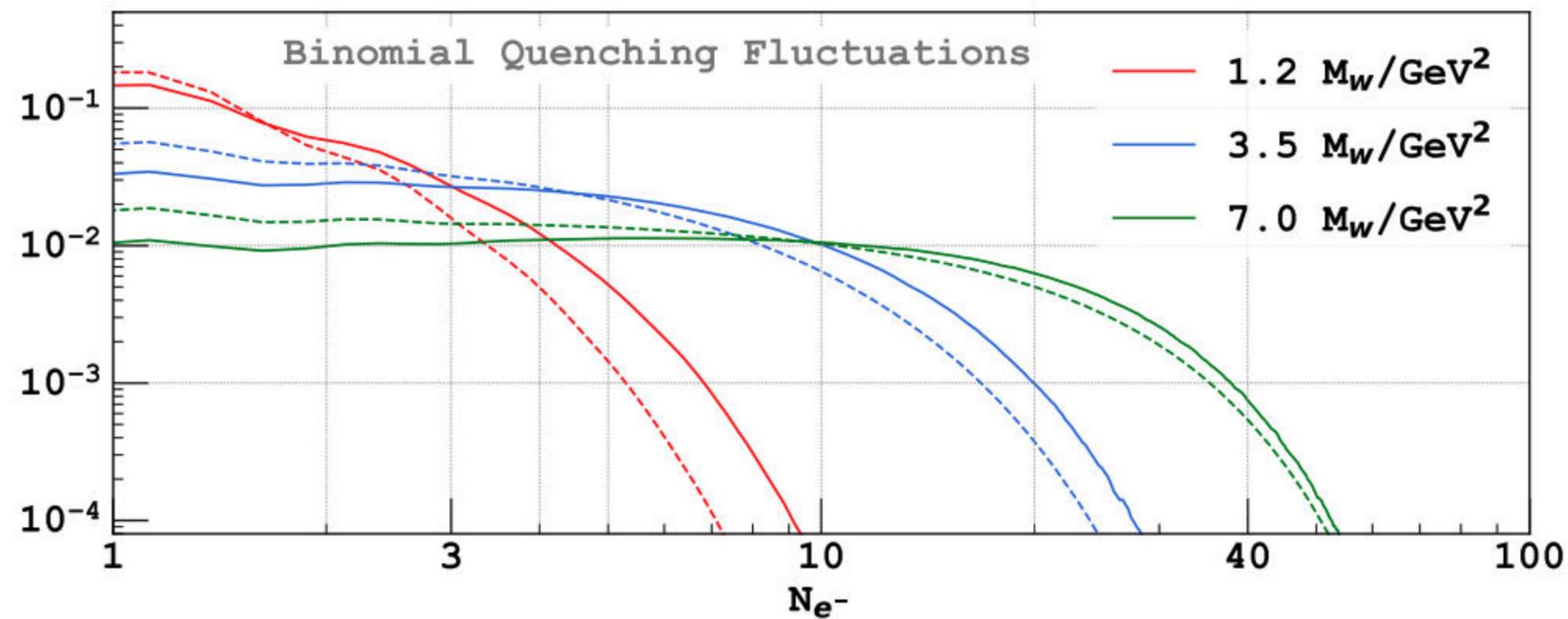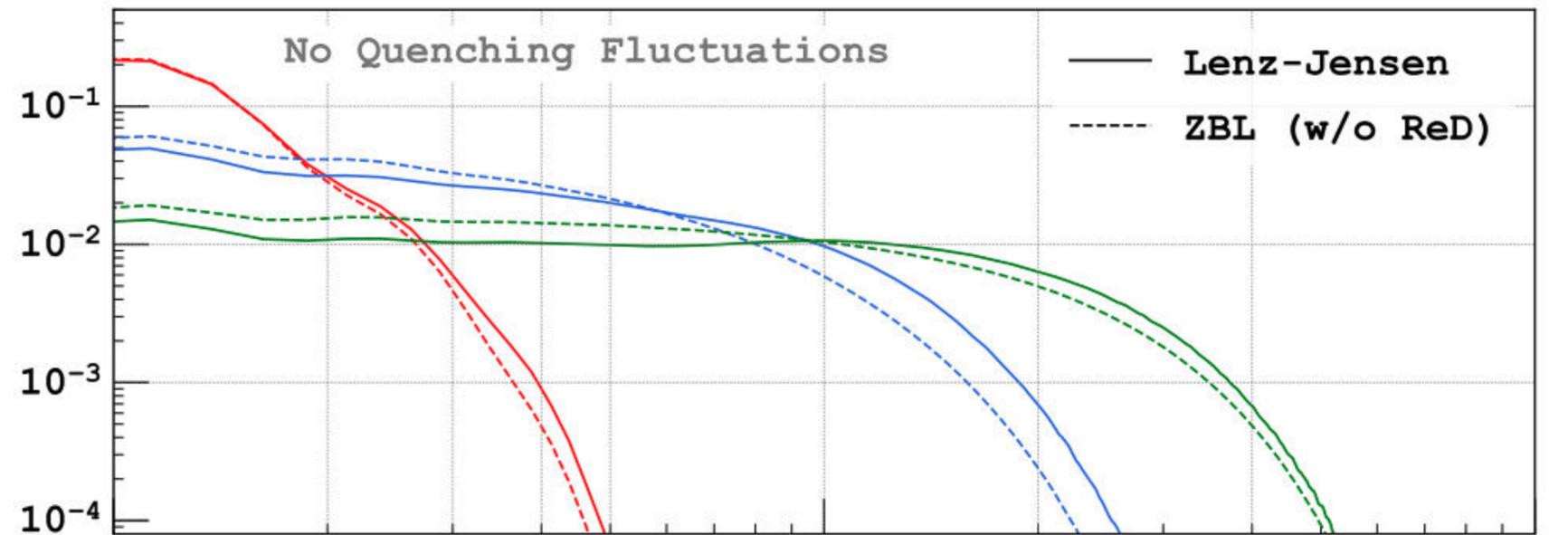▸ From γ calibration, known position of the source used to evaluate Δz from MC simulation.

$\Delta z = (0.23 \pm 0.95)$ cm
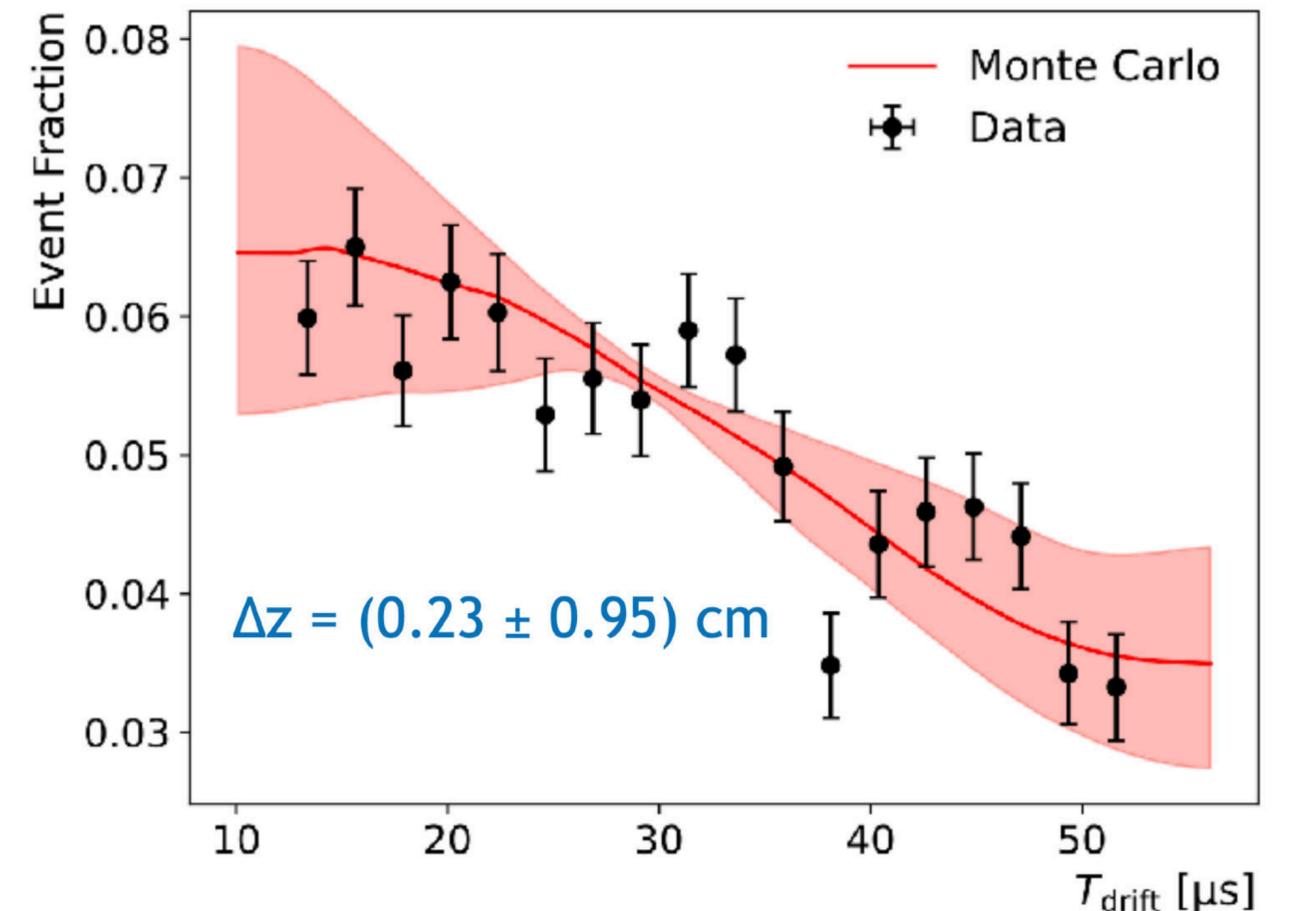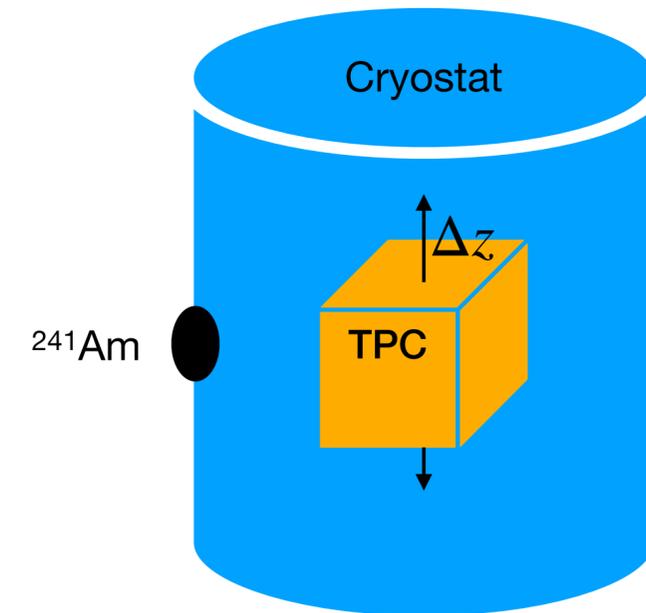
Posterior values on systematics

| SF	C_{box}	β	Δz	g_2
	[V/cm]	[$\times 10^3$]	[cm]	[p.e./e^-]
Ziegler	9.6 ± 0.5	10.0 ± 0.9	$-0.72^{+0.29}_{-0.05}$	$18.3^{+0.4}_{-0.3}$
Molière	8.1 ± 0.04	$7.3^{+0.6}_{-0.5}$	$-0.72^{+0.29}_{-0.05}$	17.8 ± 0.4
Lenz-Jensen	$8.0^{+0.5}_{-0.3}$	$6.9^{+0.7}_{-0.4}$	$-0.72^{+0.29}_{-0.05}$	17.7 ± 0.4
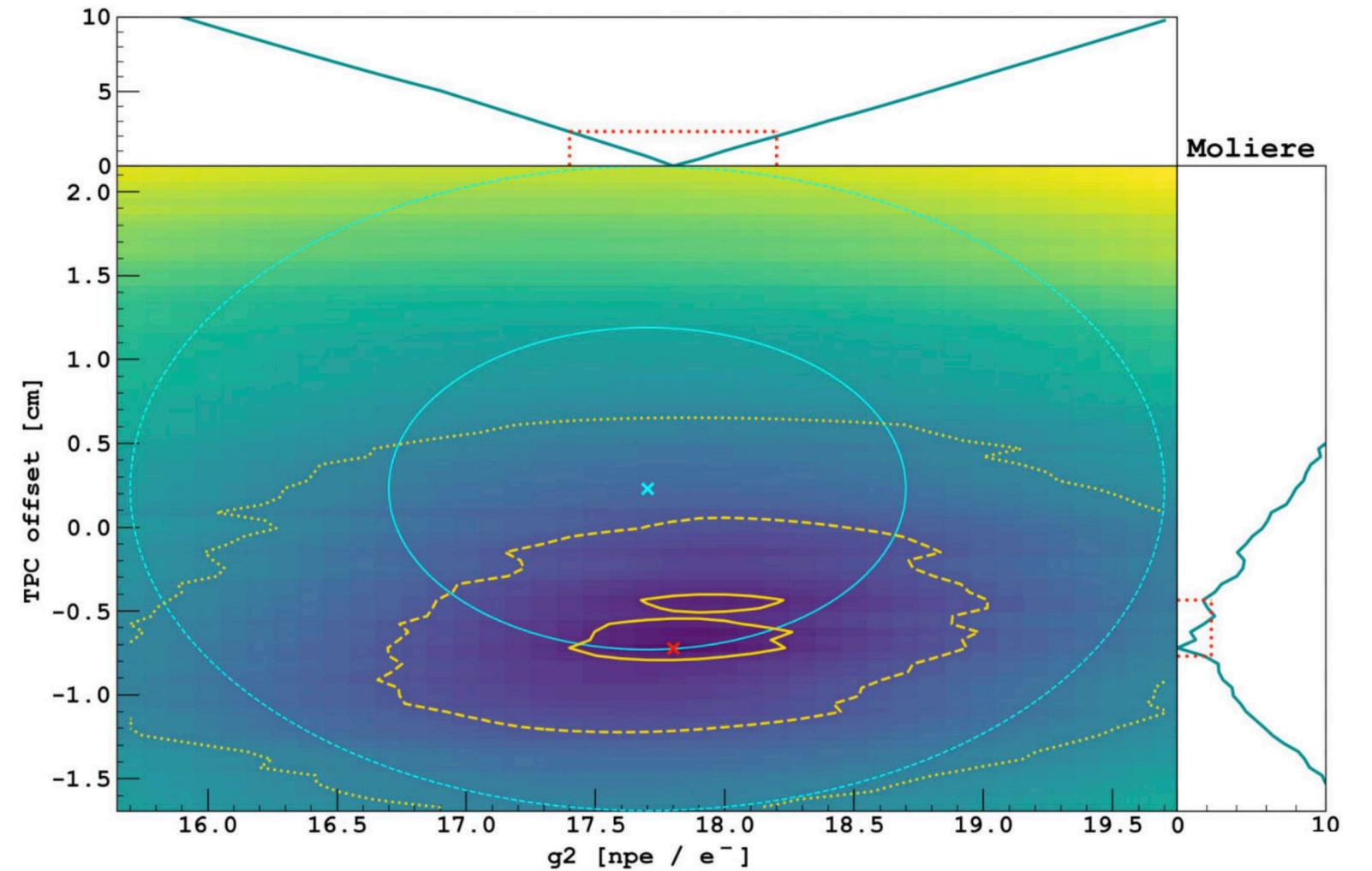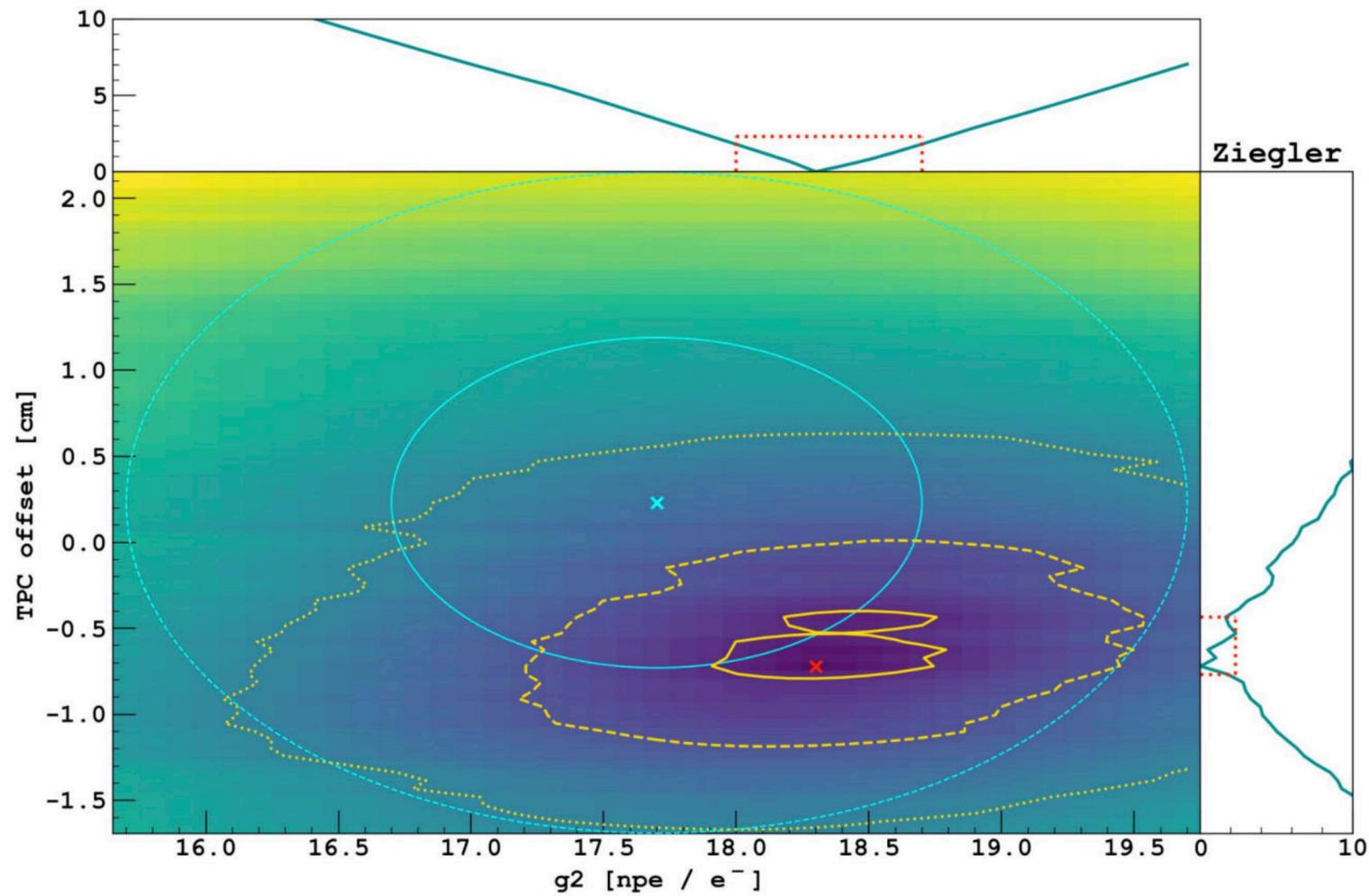
Light WIMP ionization signal spectrum



Unknown nature of the statistical fluctuations of NR quenching
→ 2 scenarios considered:

▸ **No fluctuations** (NQ): deterministic quenching

▸ **Binomial fluctuations** (QF): between visible and invisible channels

▸ Signal spectra for light WIMPs and other light dark matter candidates.

▸ **Background spectrum** from Monte Carlo simulation.

▸ Convoluted with **ionization response** and **detector resolution**.

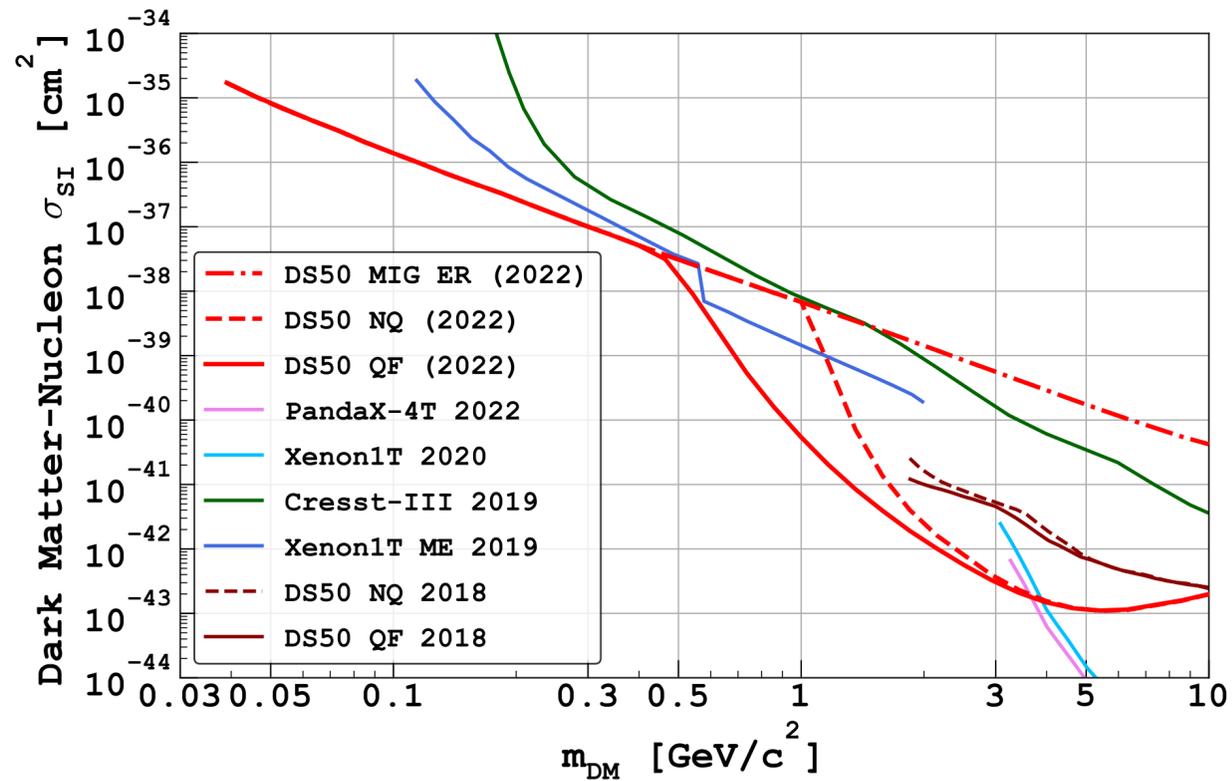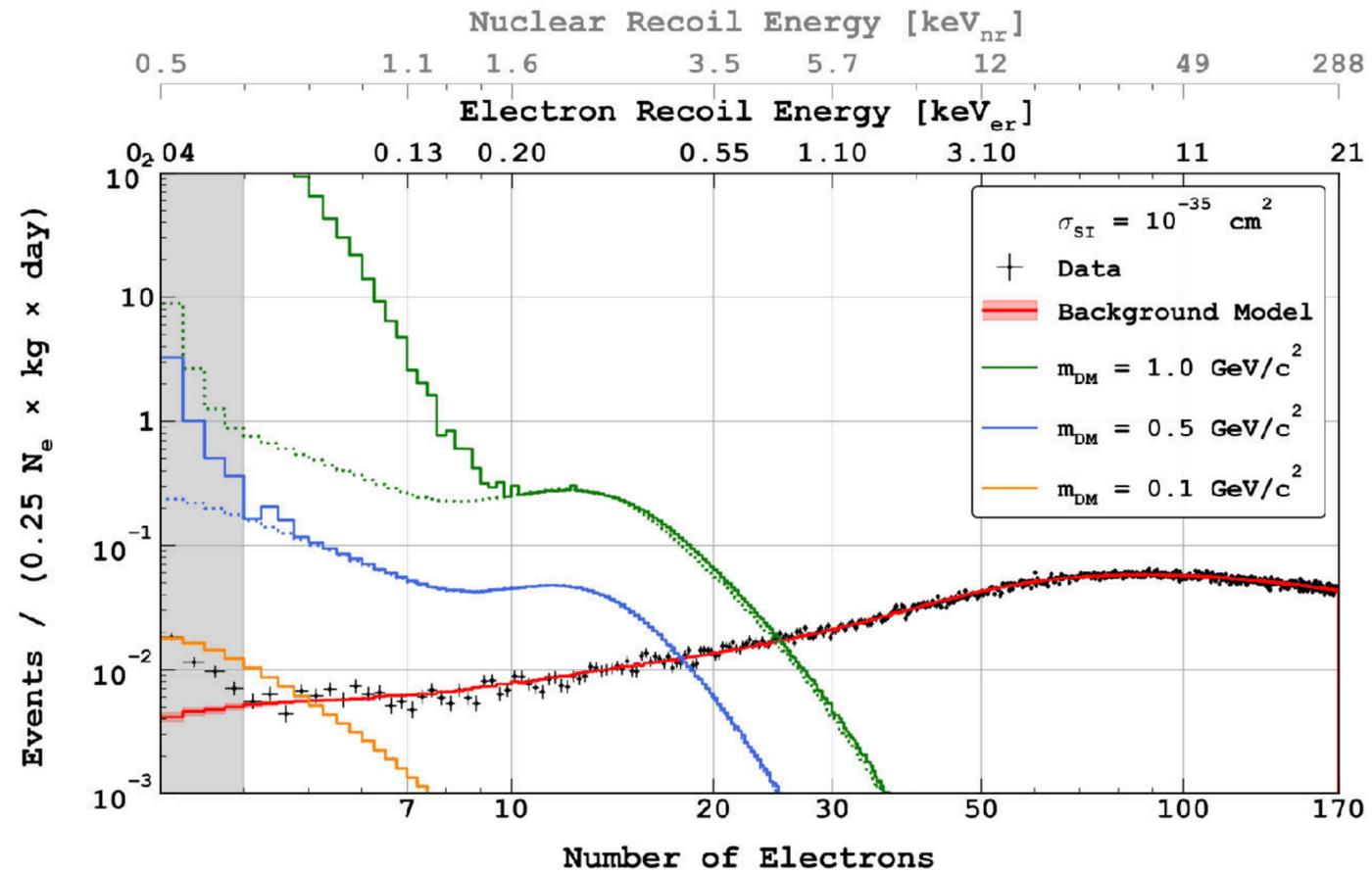Masses between 0.8 GeV/c^2 and 11 GeV/c^2 with $\sigma_{SI} = 10^{-38}$ cm
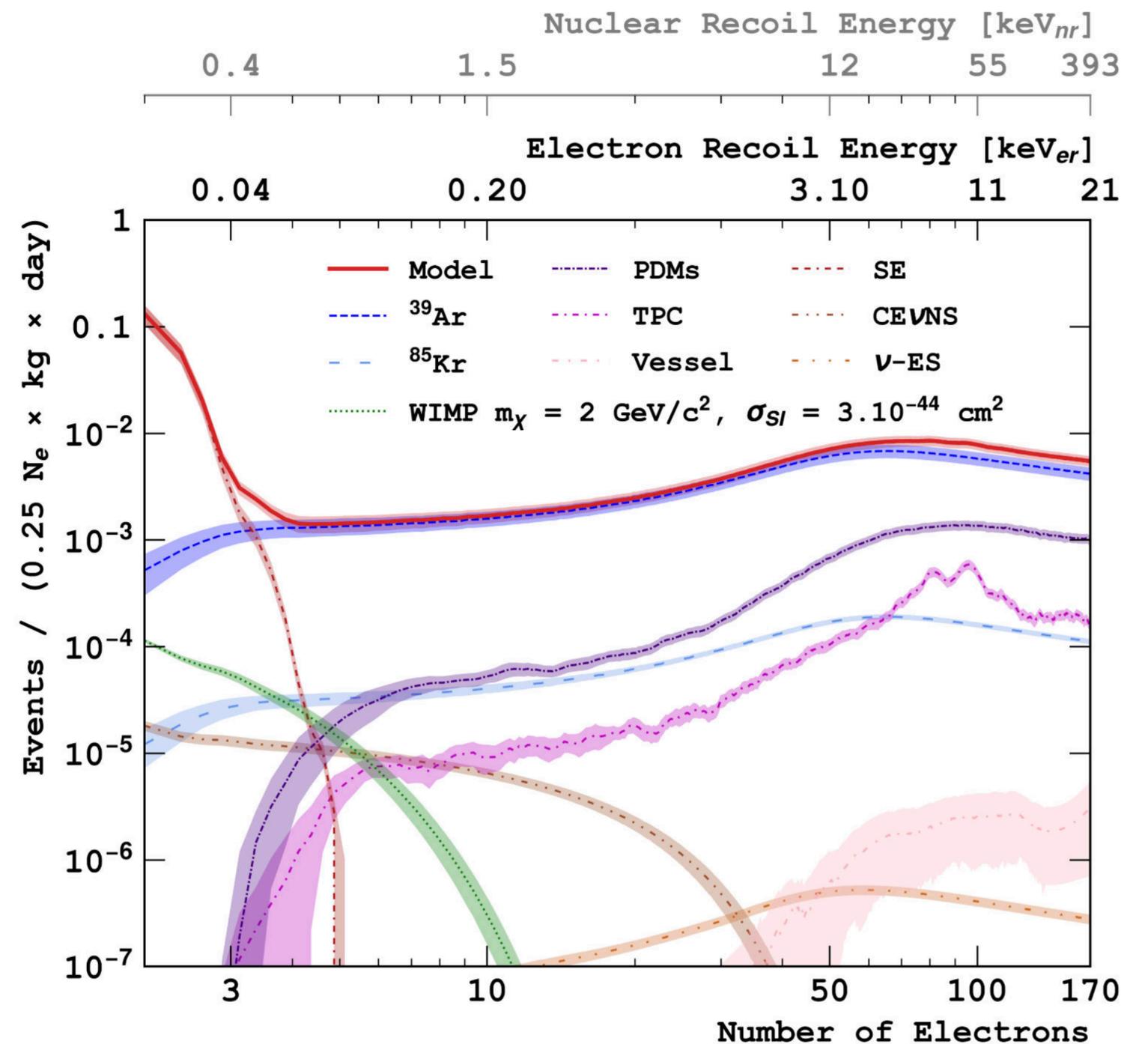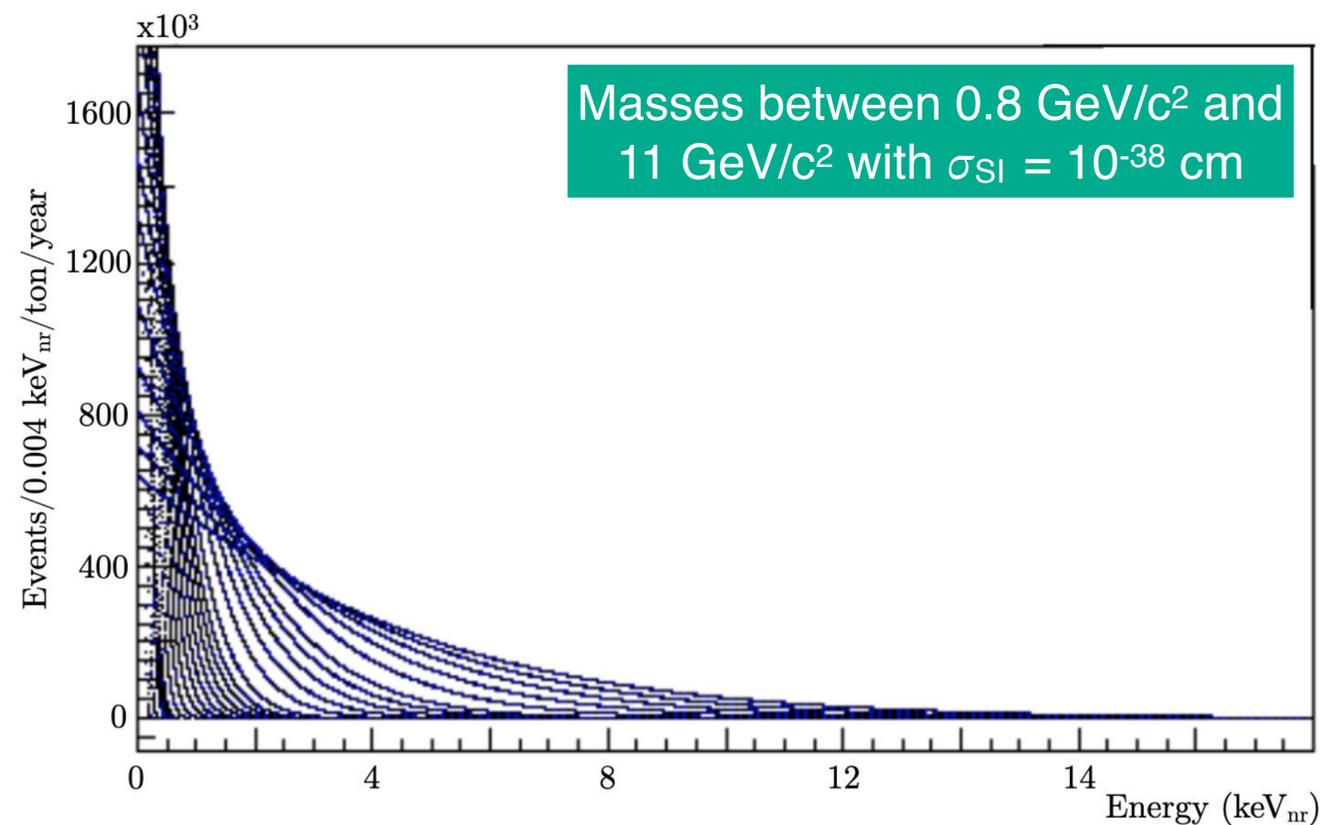
Model discrimination with Bayes factor

‣ Bayes factor allows to compare non-nested models evaluated on the same data.

‣ Integrated over the full parameter space, posterior to fit.

$$BF_{A/B} = \exp(-\frac{1}{2}\left(\chi^2_{min,A} - \chi^2_{min,B}\right) \times \frac{\sum_i \exp(-\frac{1}{2}\left(\chi^2_A(\theta_i) - \chi^2_{min,A}\right)}{\sum_j \exp(-\frac{1}{2}\left(\chi^2_B(\phi_j) - \chi^2_{min,B}\right)}$$

$\log_{10} BF$	< 0.5	0.5 - 1	1 - 2	> 2
Rejection	Neglibigle	Substantial	Strong	Decisive

Migdal effect

First direct observation of Migdal effect