Sensitivity to low-mass WIMPs in the DarkSide programme with an improved liquid argon ionization response model

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on behalf of the DarkSide-50 and DarkSide-20k Collaborations

LIDINE 2025

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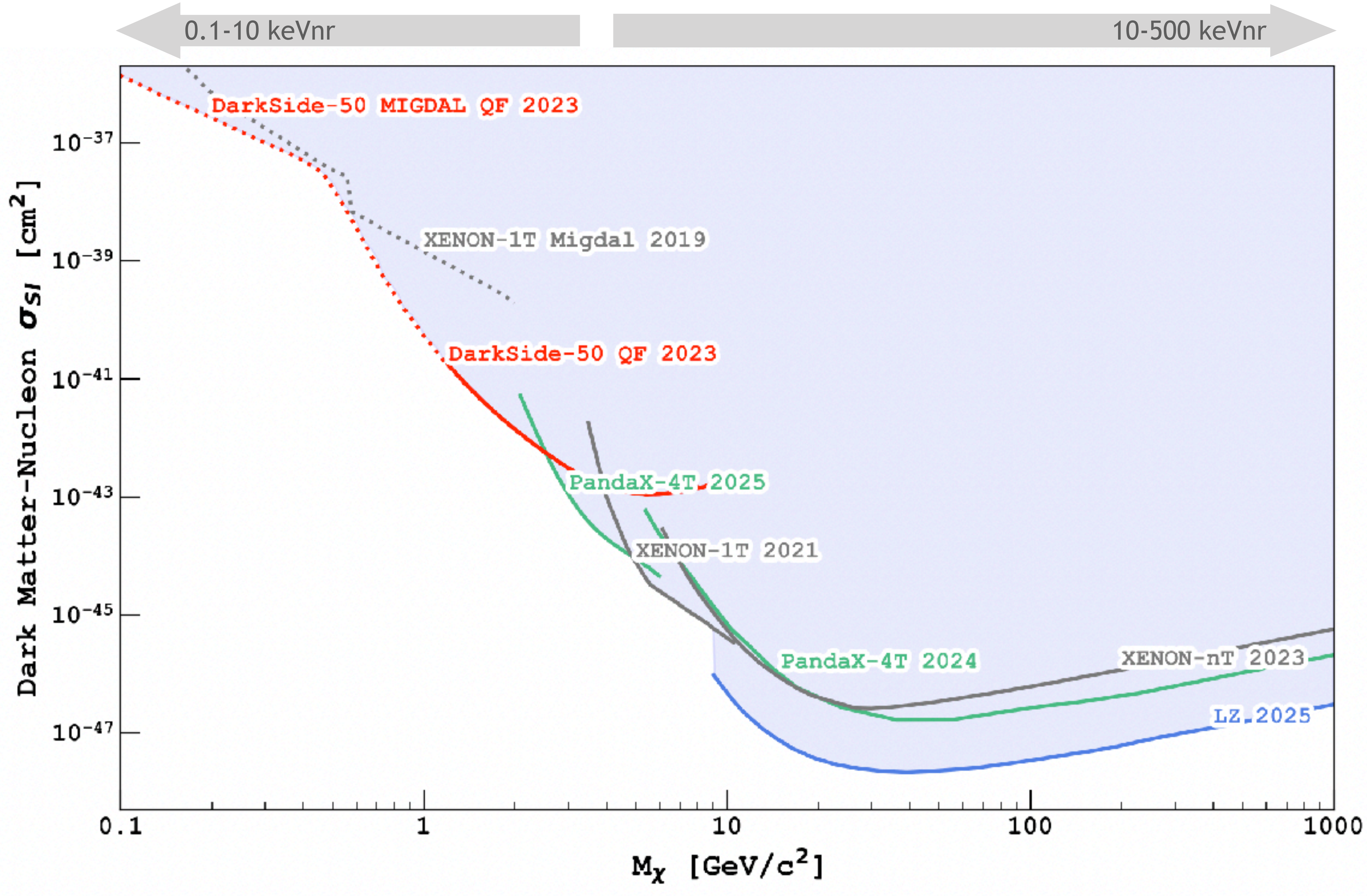
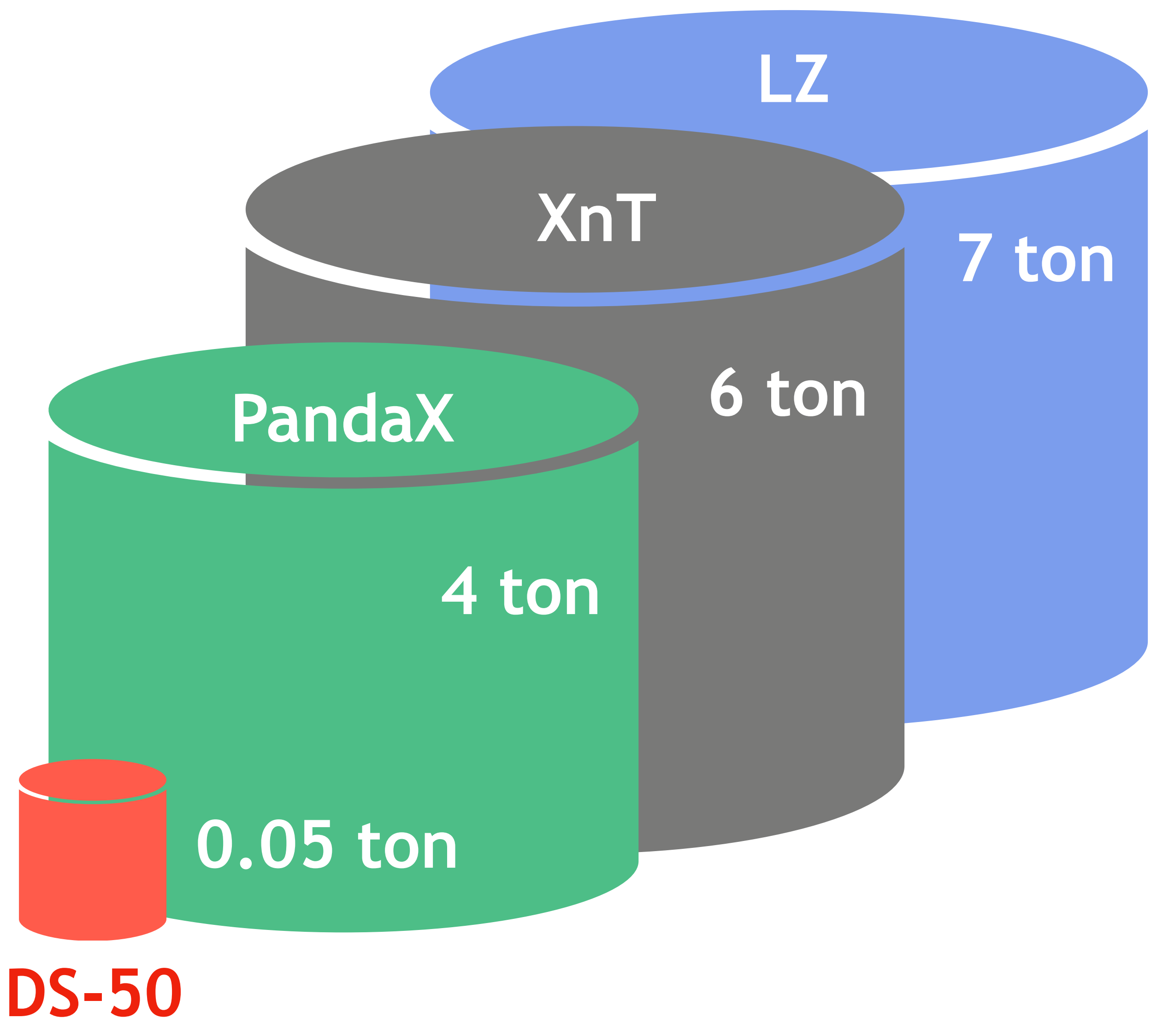
Current limits on DM-Nucleon SI interactions



- **Dual-phase TPCs** dominate WIMP searches from the sub-GeV scale
- **DarkSide-50**, with only 50 kg of LAr, **competitive** with respect to multi-ton LXe detectors.



DS-50: so sensitive despite its size…

The Dual-Phase TPC

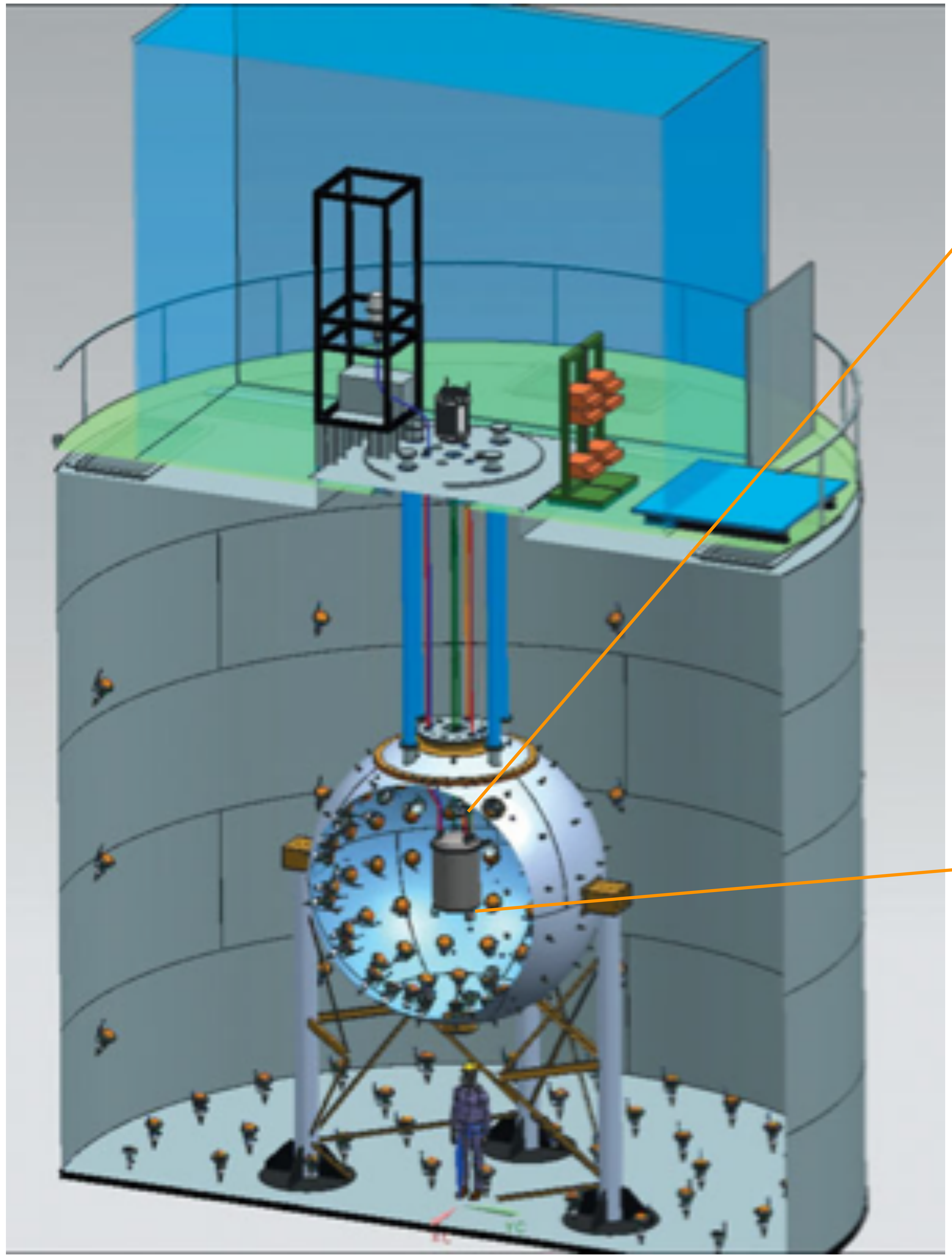
- 50 kg active mass of UAr
- 19 top + 19 bottom R11065 HQE 3'' PMTs
- 36 cm height, 36 cm diameter
- Low field of 0.2 kV/cm drift

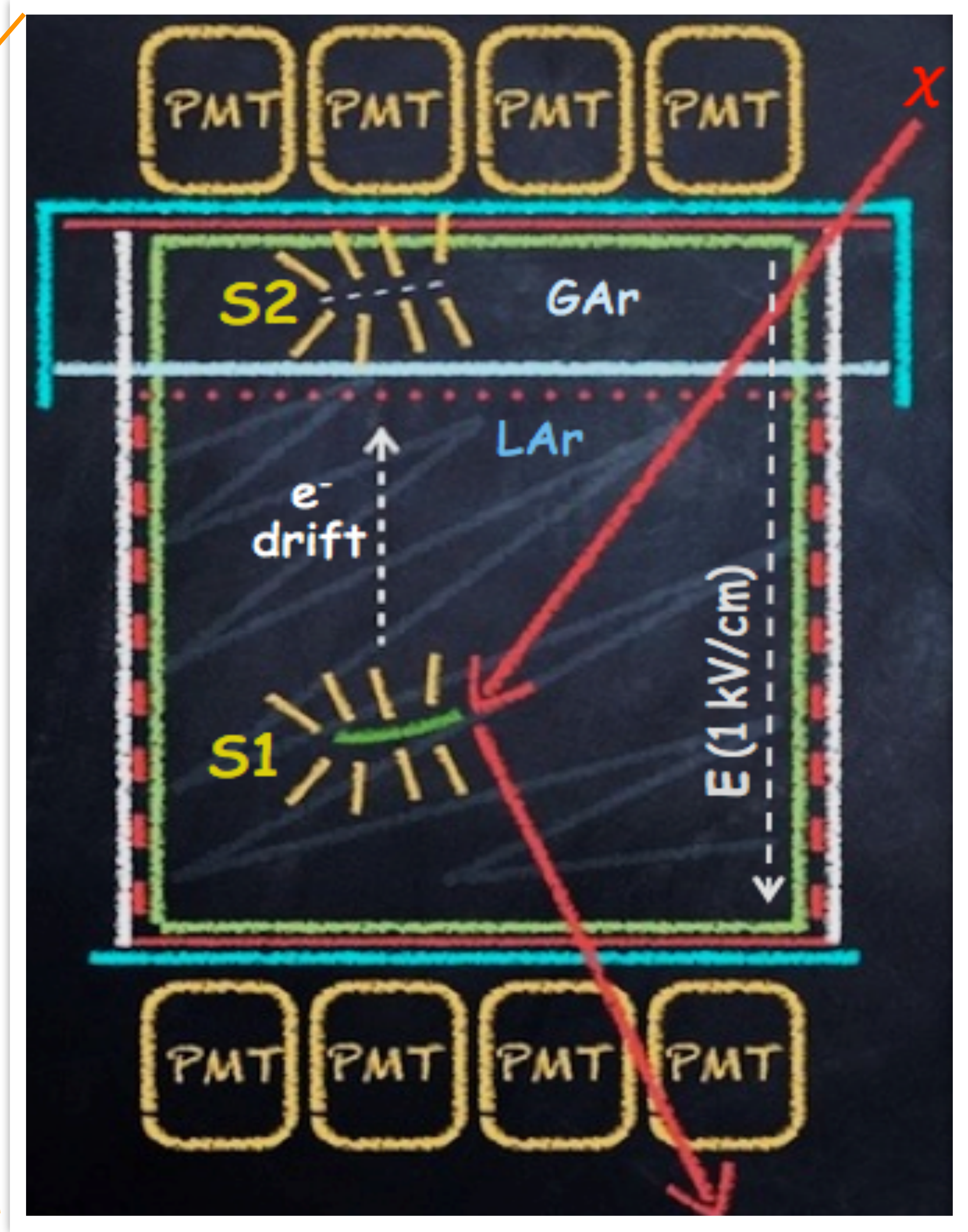
Liquid Scintillator Veto against neutrons

- 4 m diameter sphere
- Boron-loaded: 1:1 PC and TMB
- 110 8'' PMTs
- LY ~ 500 pe/MeV

Cherenkov Water Detector

- 11 m diam. x 10 m
- 80 PMTs

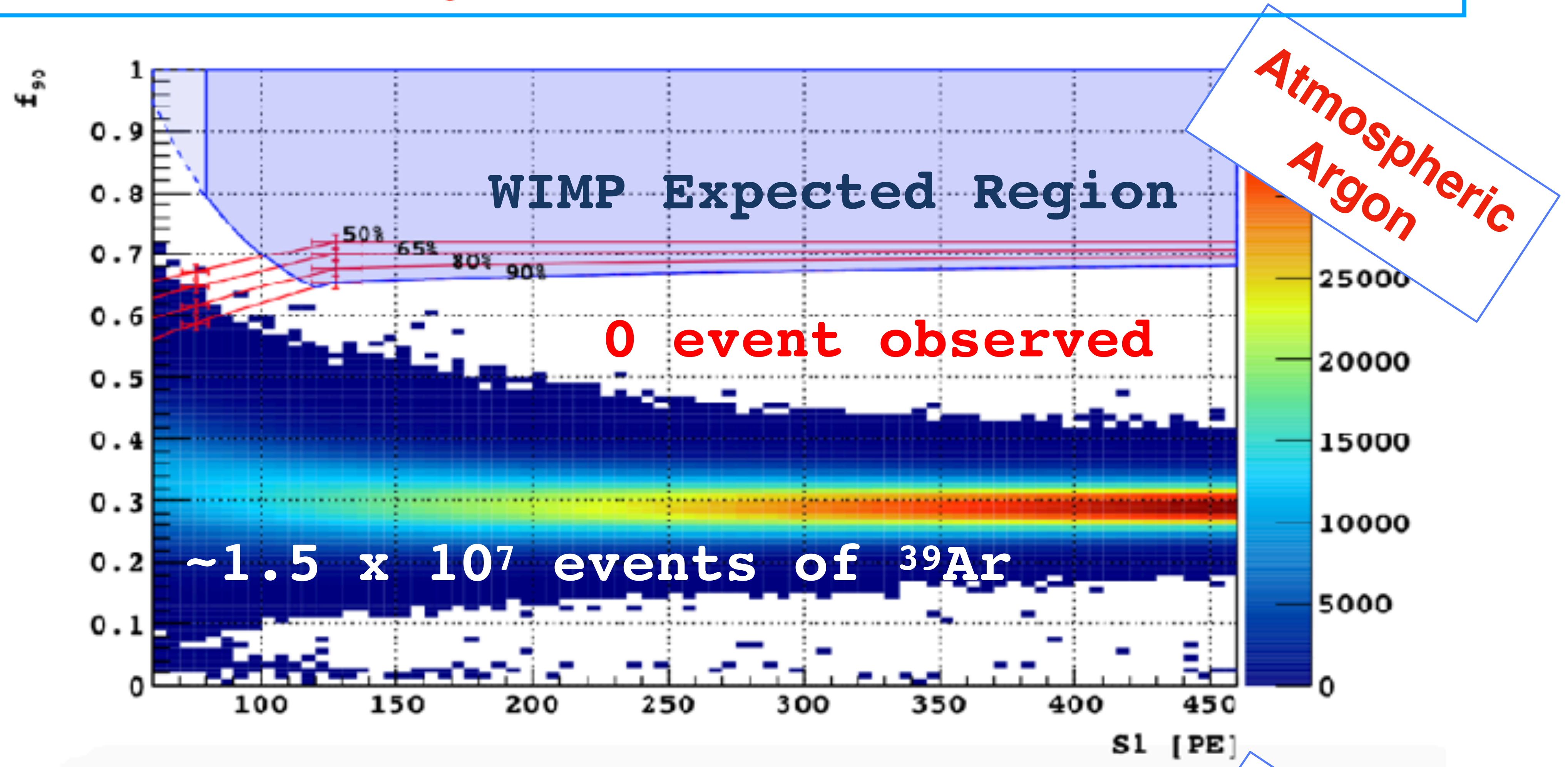


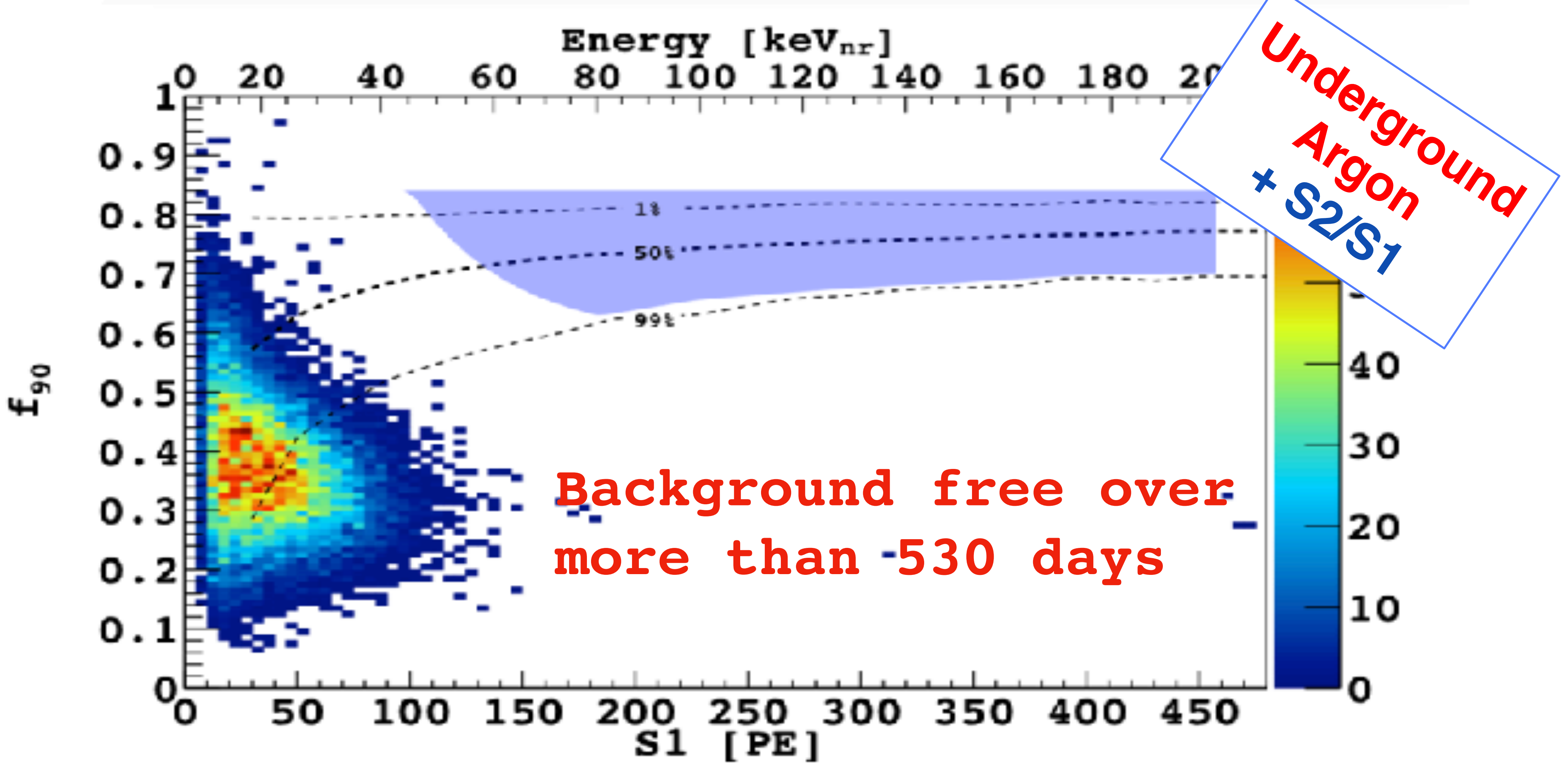


The DS-50 WIMP Search

Pulse Shape Discrimination

“high-mass” WIMP search



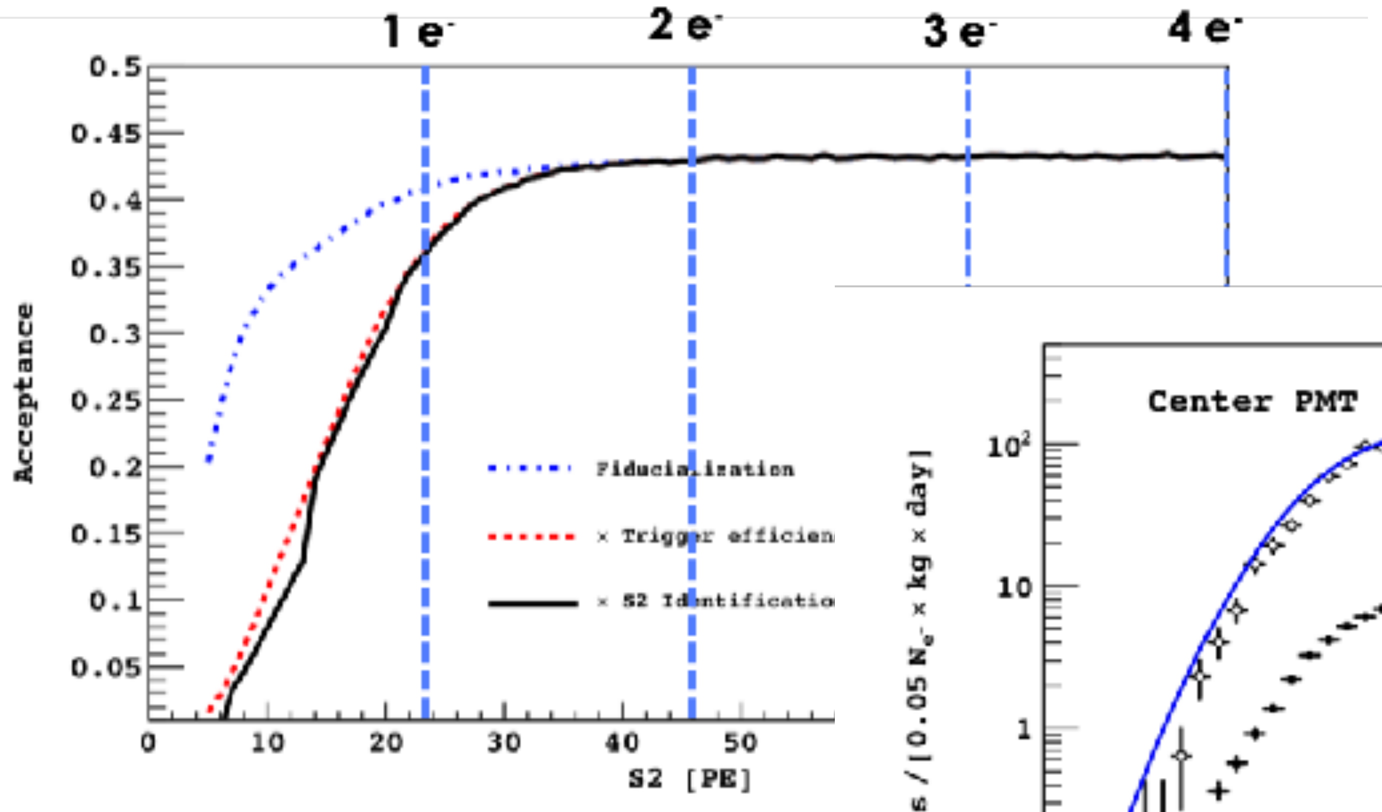


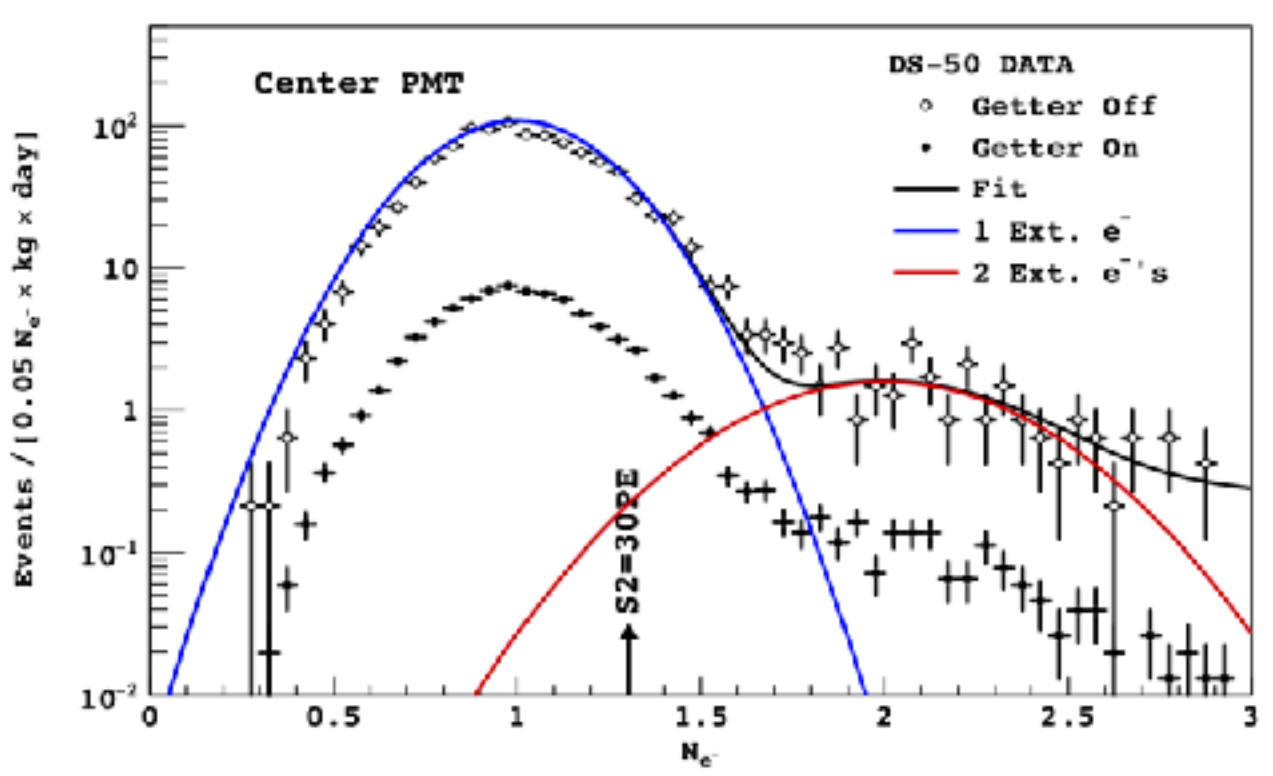
[Phys. Rev. D 98 (2018) 102006]

Ionization Only

“low-mass” WIMP search

- Scintillation (S1)
  - Detection efficiency (g1) ~ 16%
- Ionization (S2)
  - Efficiency to extract 1 e- in the gas pocket ~ 100%
  - Amplification factor (g2) = ~23 pe / e-

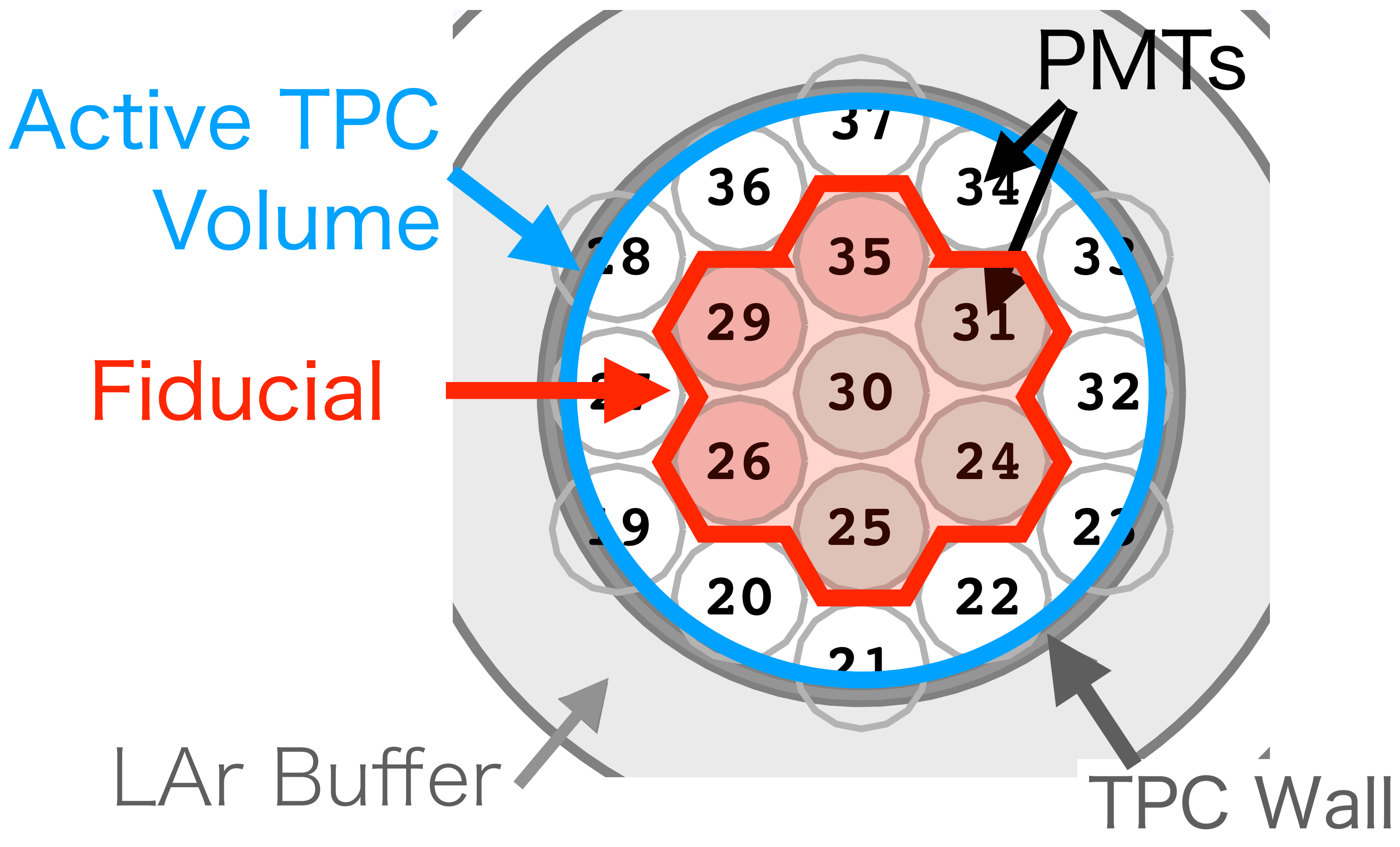




[Phys. Rev. Lett. 121 (2018) 081307]

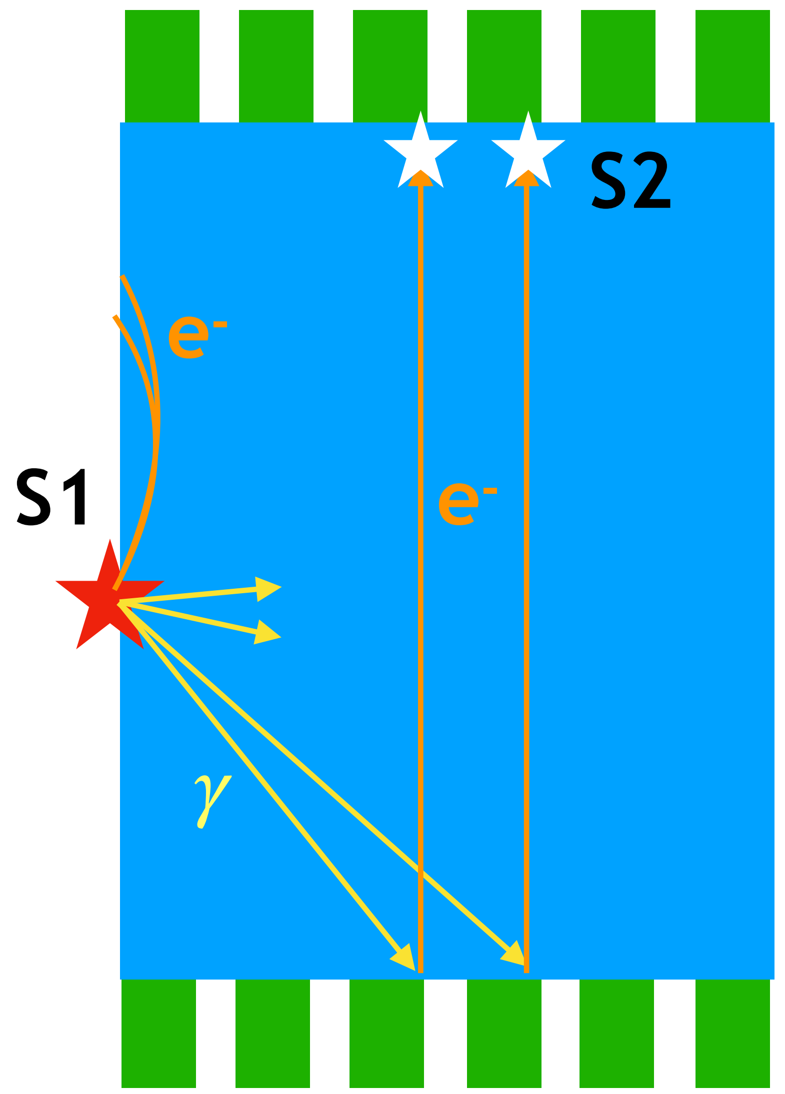
Low-Mass Data Selection

Fiducialization



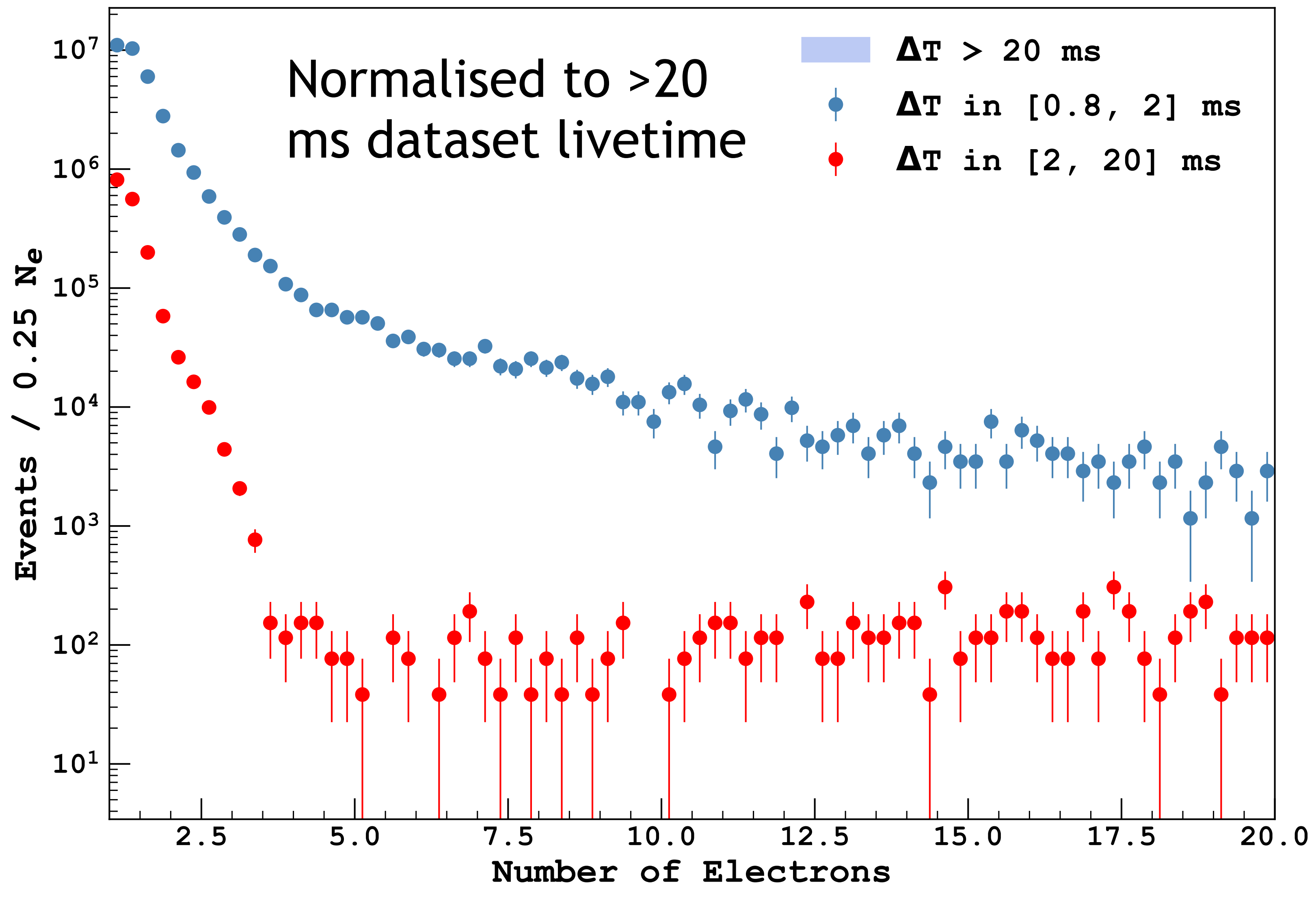
- Select events with max fraction of pes in one of the 7 central top PMTs
- Acceptance ~ 41%

Alpha-induced S2 pulses



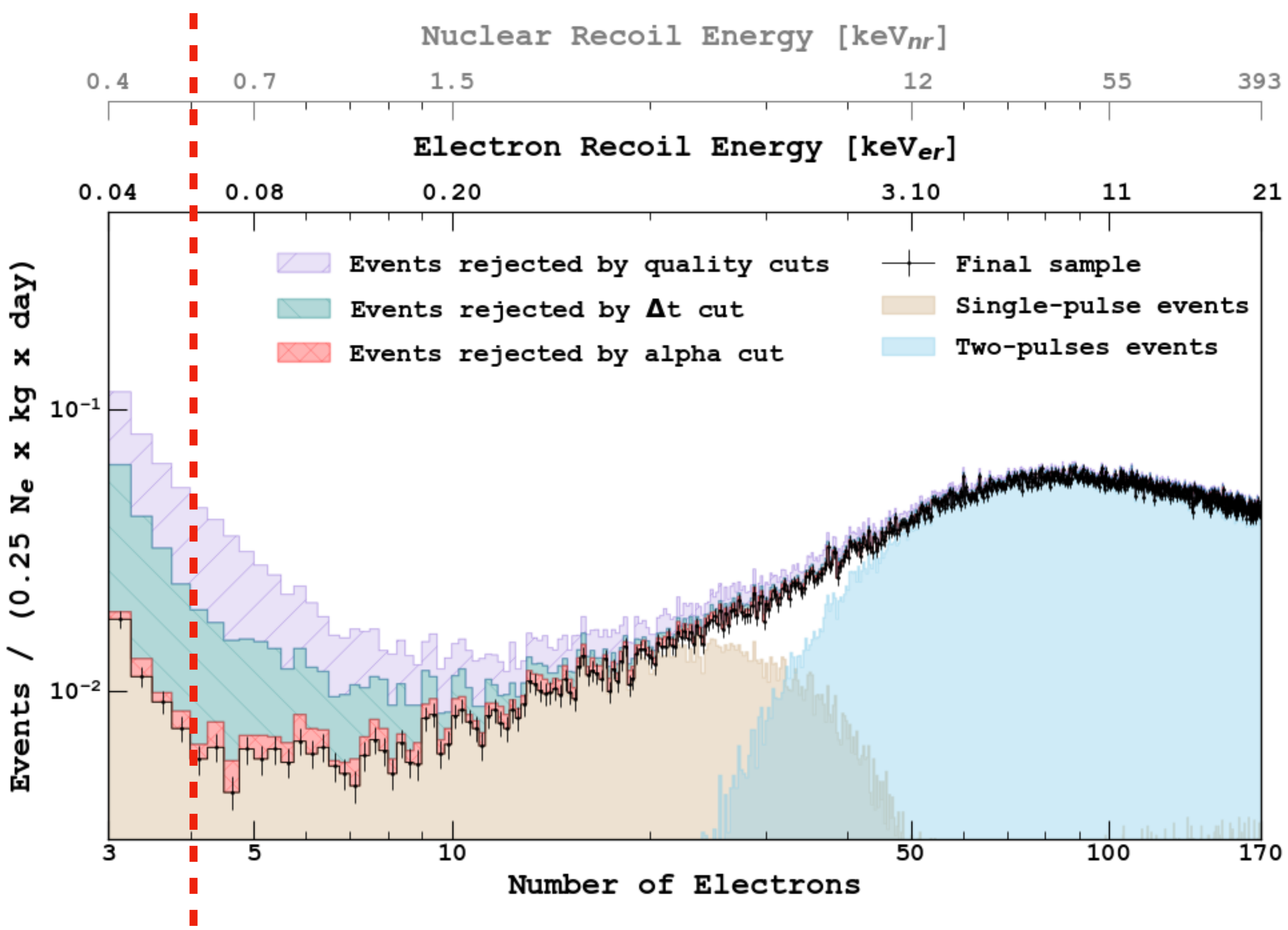
- Reject events with “anomalous” S2/S1
- Cut tuned on calibration data
- Acceptance ~ 99%

Spurious Electrons



- Reject correlated events (if within 20 ms from the previous one)
- Acceptance ~ 97%

Low-Mass Data Selection



Analysis threshold

Exposure

- 650 live-days or 12 ton-day

Data Selection

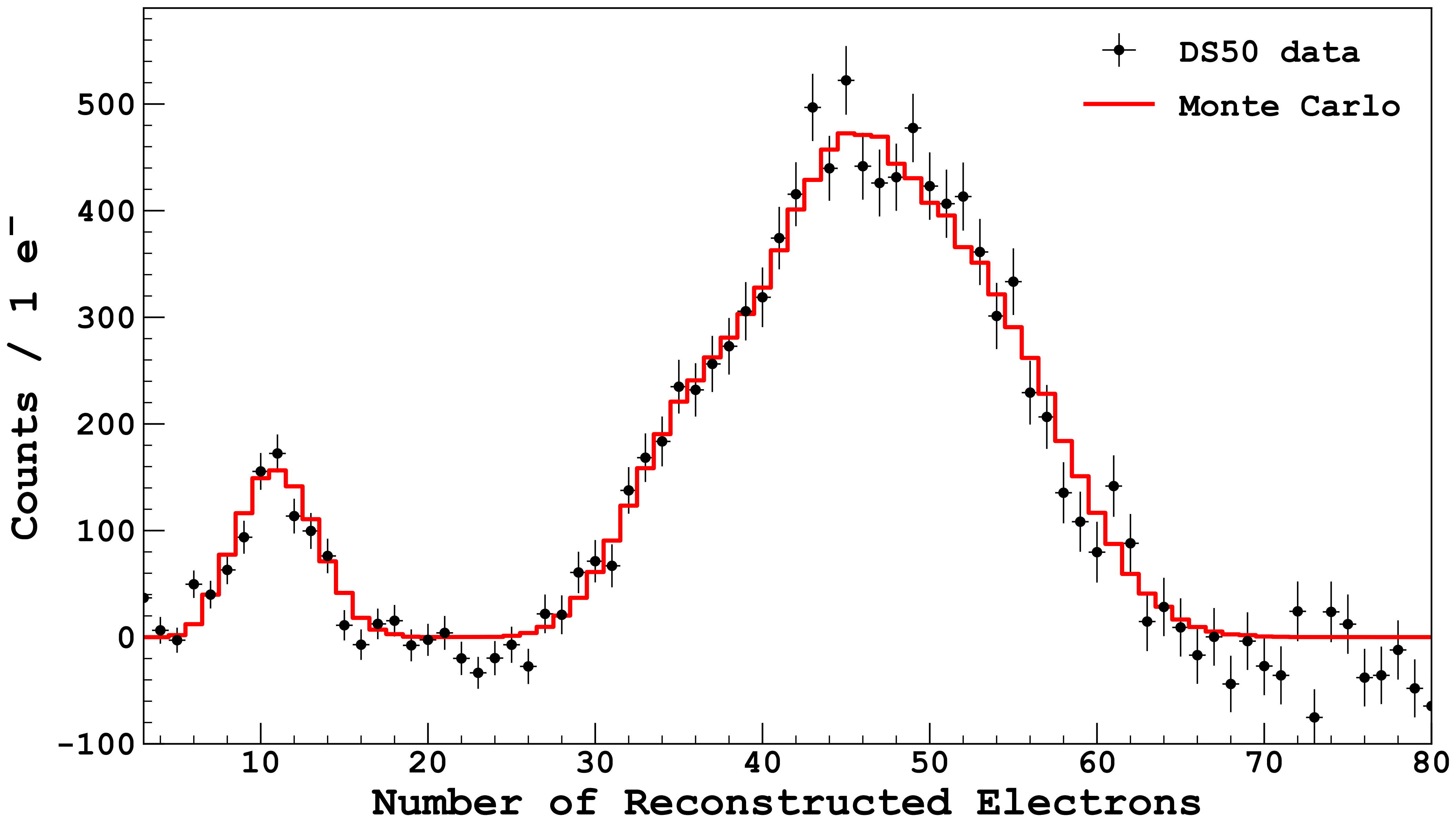
- Quality cuts
  - pile-up of multiple pulses (95% @ 4 Ne / 99% @ 15 Ne)
- Selection cuts
  - Fiducialization against external bg (41%)
  - S2/S1 against S2's from alphas on the walls (99%)
  - Time veto agains spurious (or "single") electrons (97%)

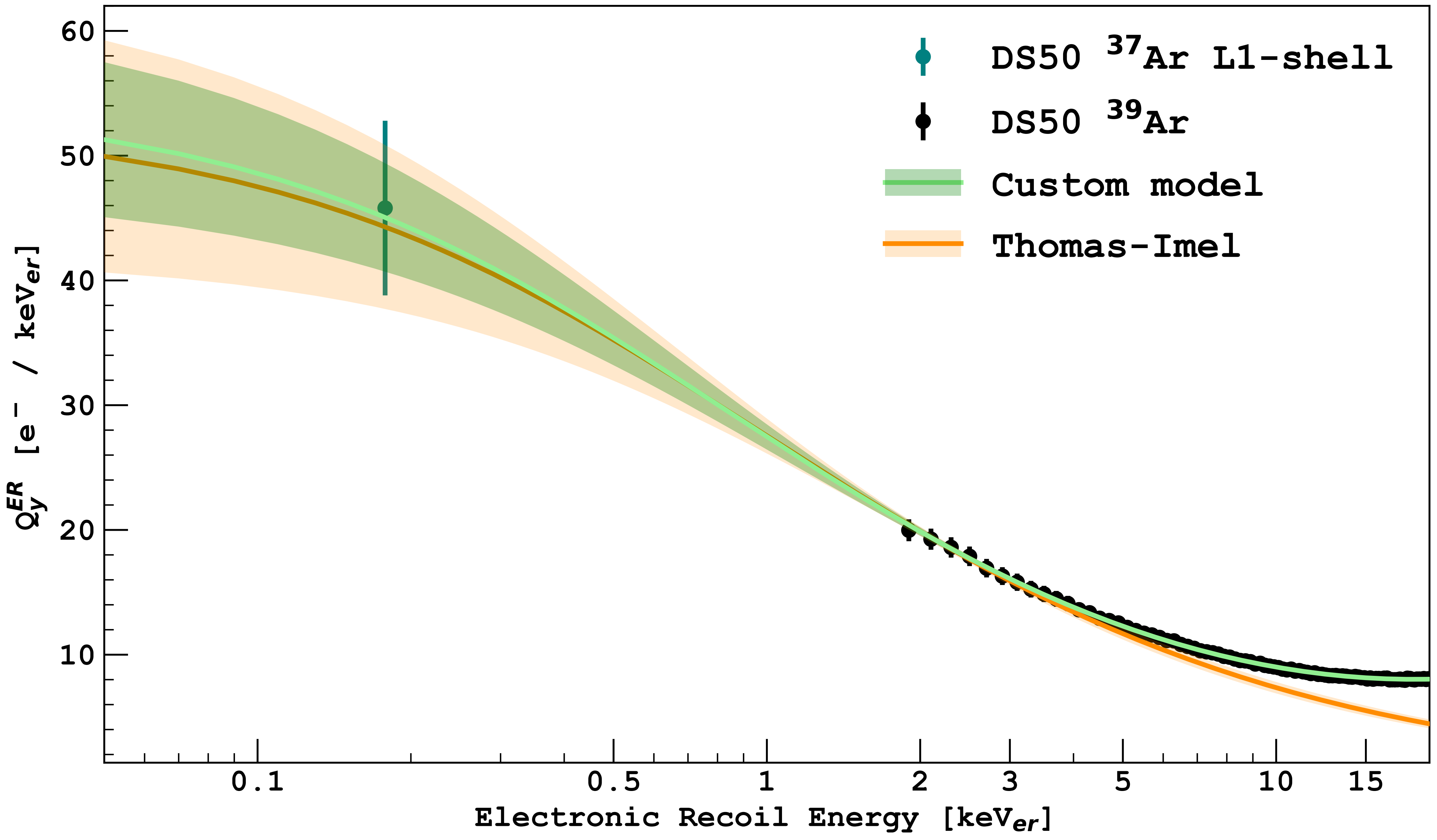
Phys. Rev. D 107 (2023) 063001

Ionization Response to Electronic Recoils

Thomas-Imel + extended custom model

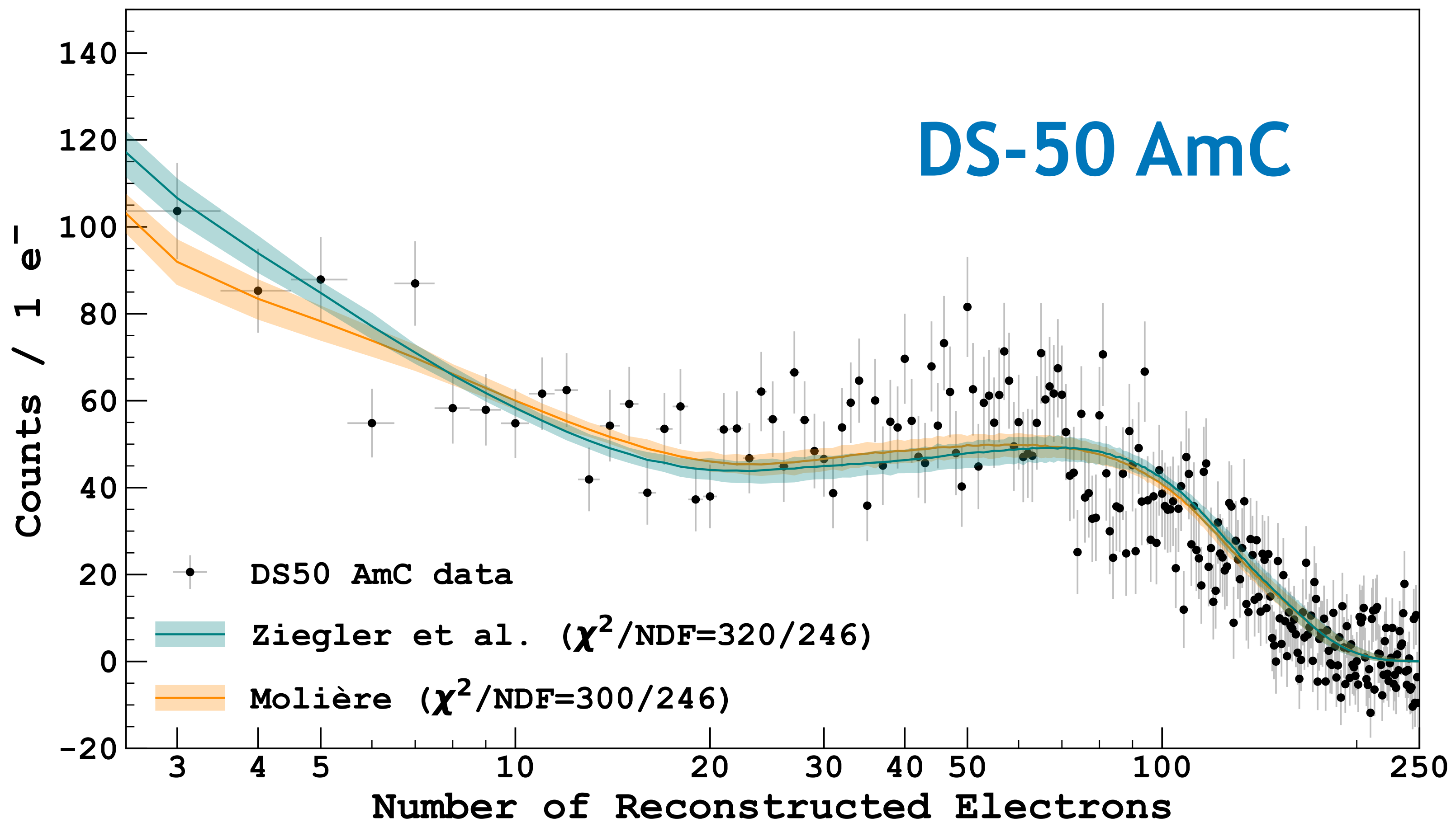
$$Q_y^{ER} = \left(\boxed{\frac{1}{\gamma}} + \boxed{p_0\,(E_{er}/\mathrm{keV}_{er})^{p_1}} \right) \boxed{\frac{\ln(1+\gamma\,\rho\,E_{er})}{E_{er}}}$$

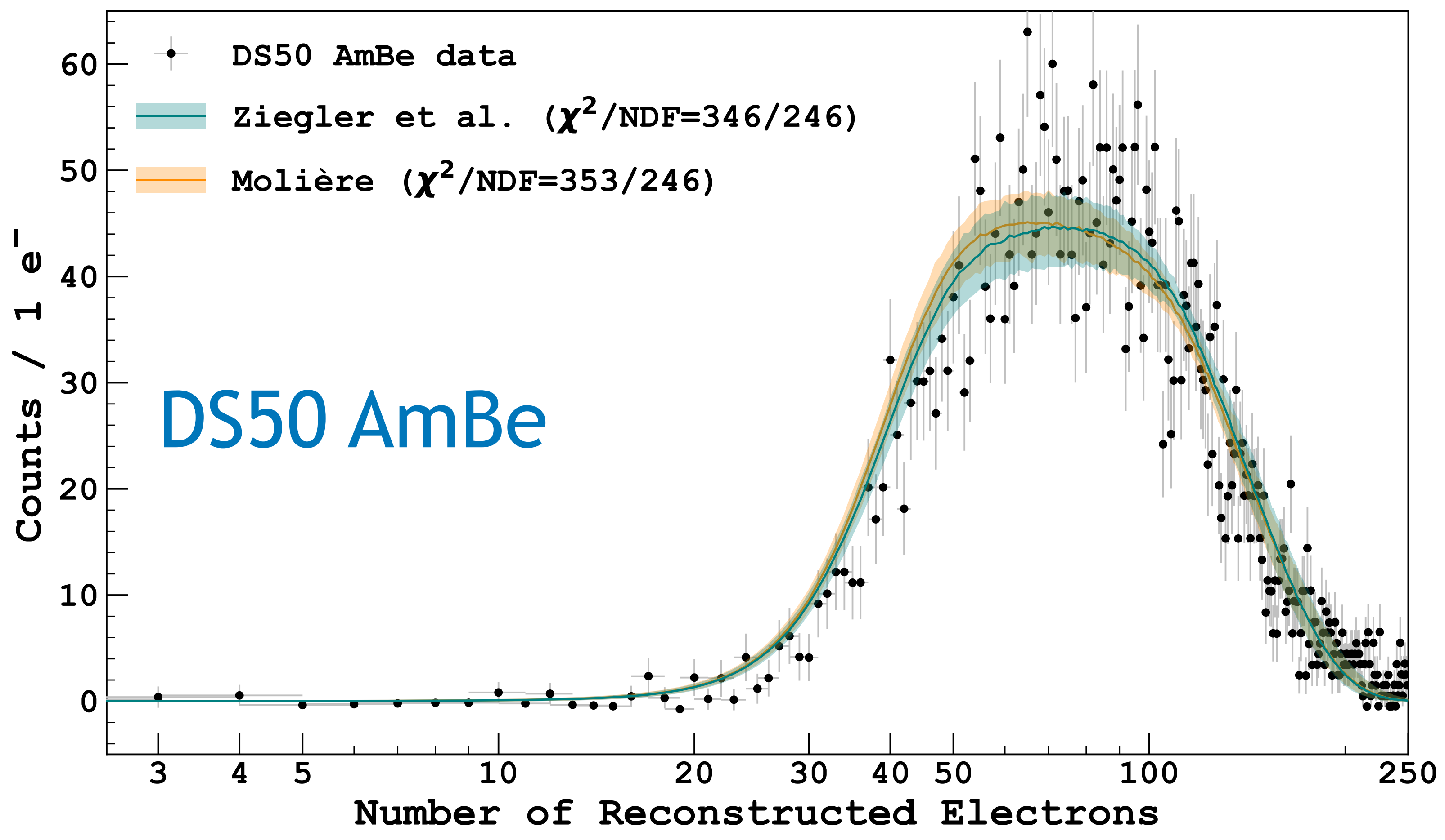


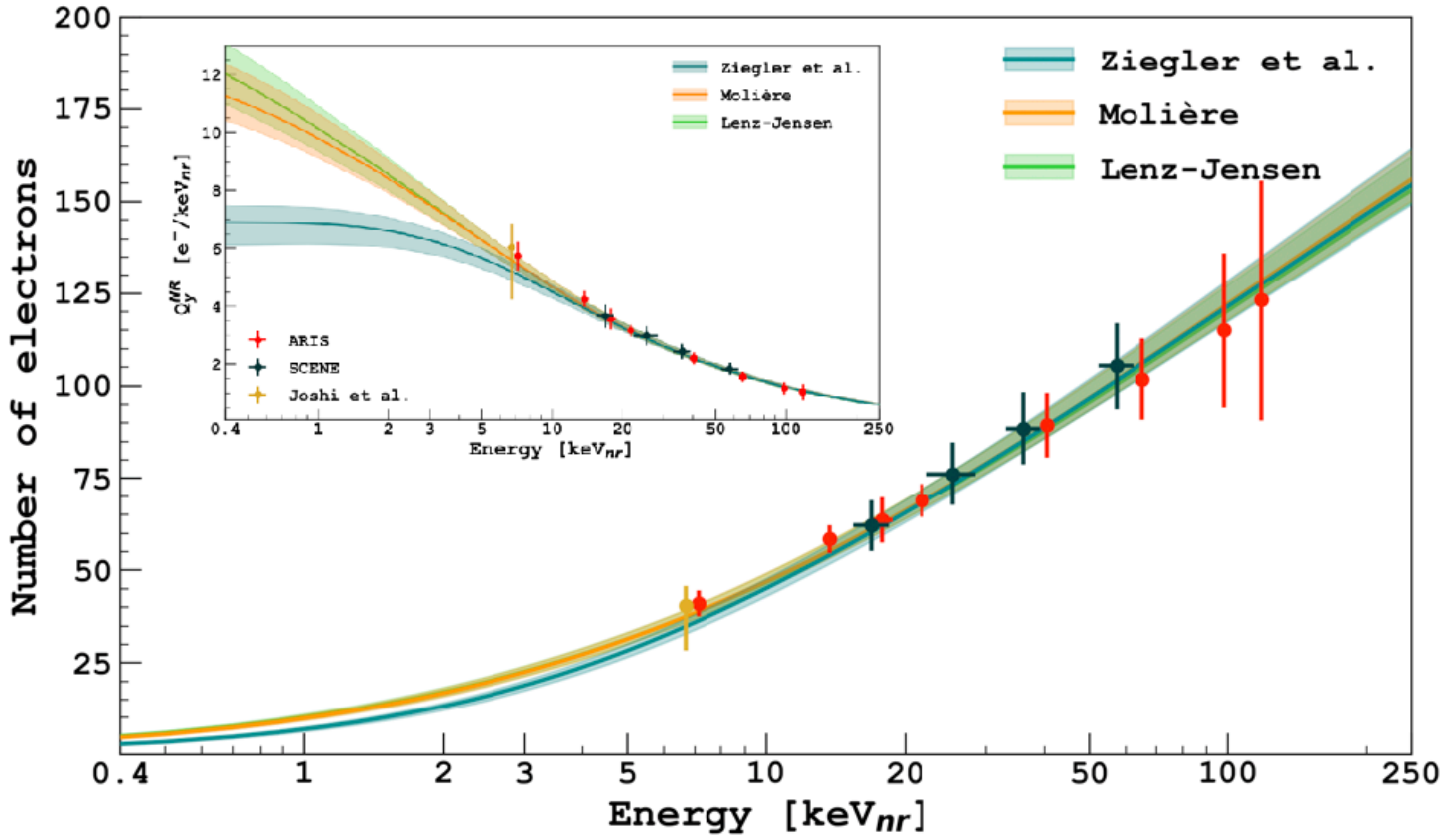


Phys.Rev.D 104 (2021) 8, 082005

Global fit to **DS-50 calibration data** with neutrons sources + **external datasets** (ARIS and SCENE)







In 2023, Ziegler's screening function chosen for sensitivity studies

[Phys.Rev.D 104 (2021) 8, 082005]

Screening Potential Models

Thomas-Imel Box Model

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

- (C_{box}, β): free parameters
- s_e, s_n: electronic and **nuclear** stopping powers

Screening Potential Models

- **ZBL** (Ziegler, Biersack, Littmark)
  - Defined from total energy difference of 2-atom system
  - Universal fit (522 potentials) → basis of SRIM
- **Molière**
  - Analytical approximation of Thomas-Fermi potential
  - Widely used in multiple scattering
- **Lenz-Jensen**
  - Modified Thomas-Fermi model with shell corrections
  - Improved accuracy at small radii

The Molière "Problem"

- **Bezrukov** et al. (Astropart. Phys. 35, 119-127, 2011): used **Sigmund** (2006) ⇒ coefficients **miscopied** from **Winterbon** (Radiation Effects, 13, 215-226 1972)
- **Winterbon** approximation: **good** for Lenz-Jensen, **not valid for Molière**
- **Wilson** approximation: reproduces Molière **at percent level**

Thomas-Imel Box Model

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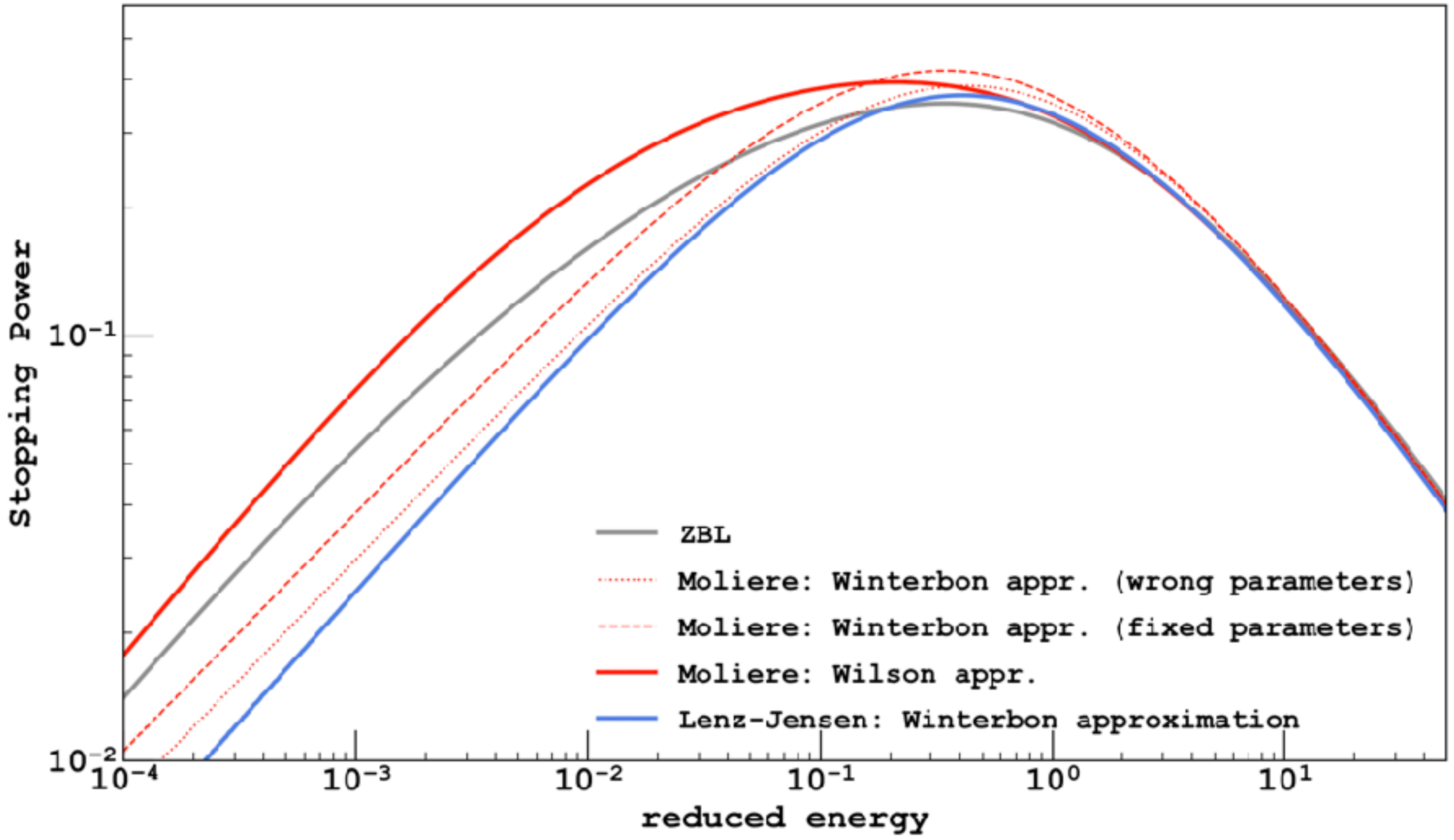
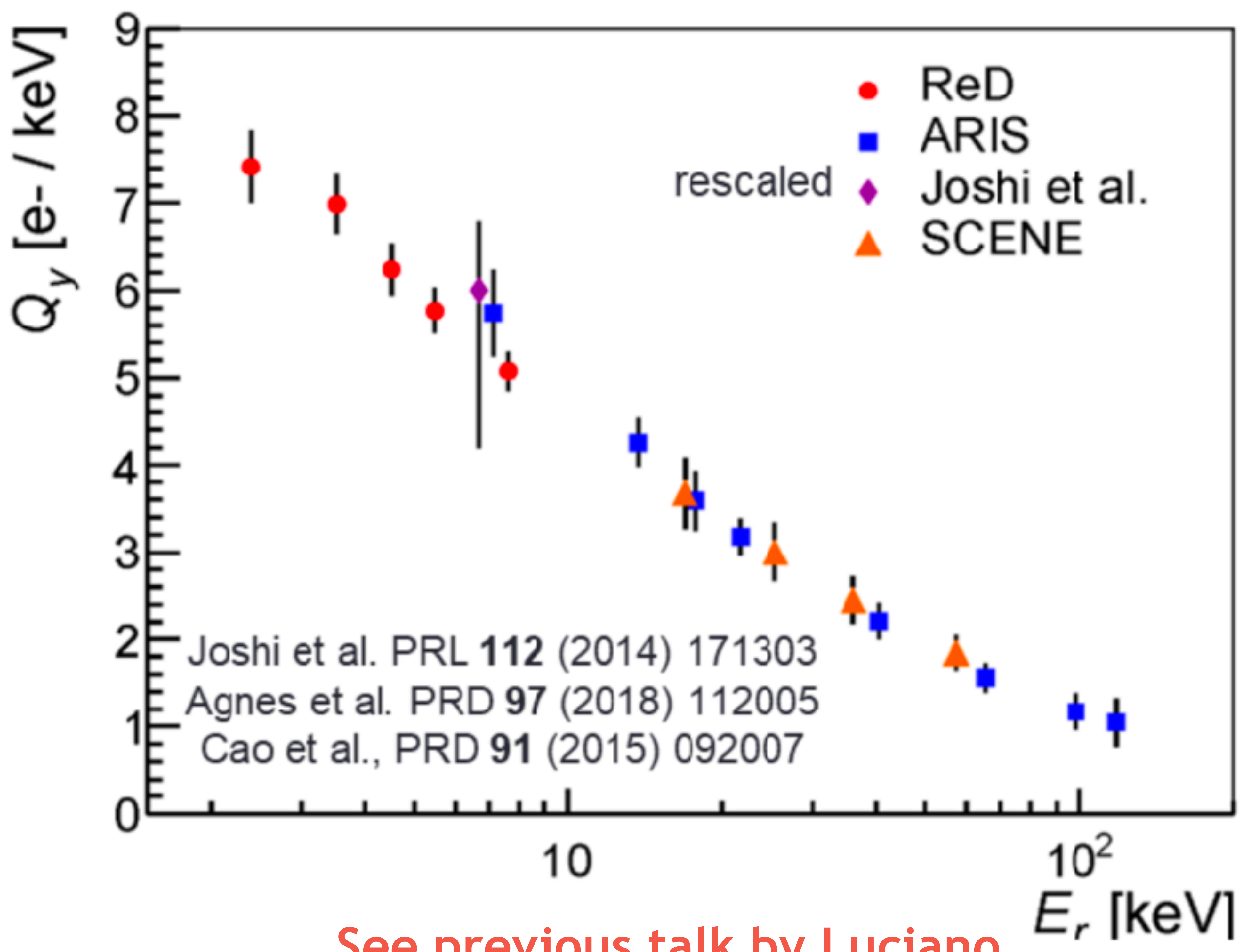


Including ReD data

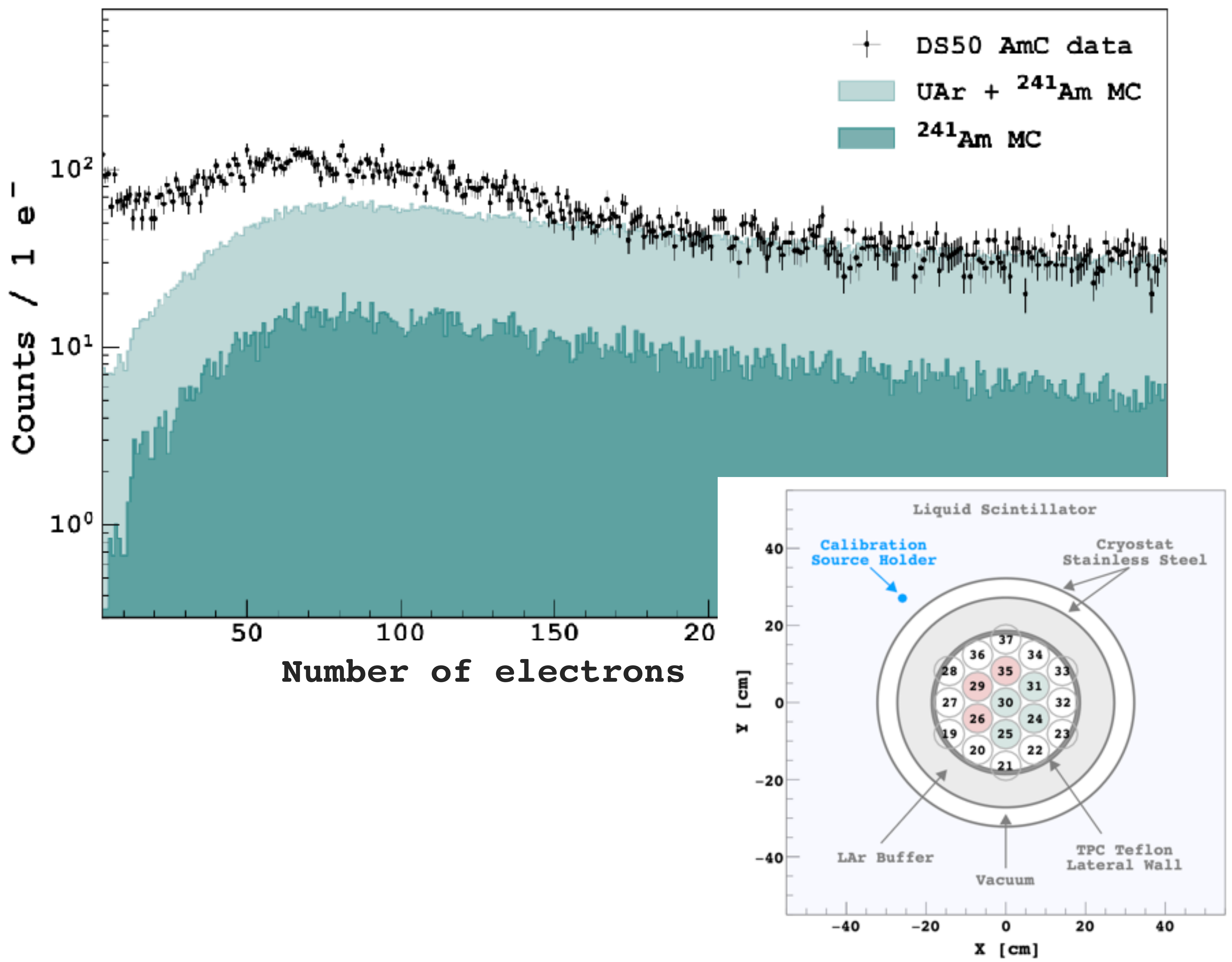
Combined fit of

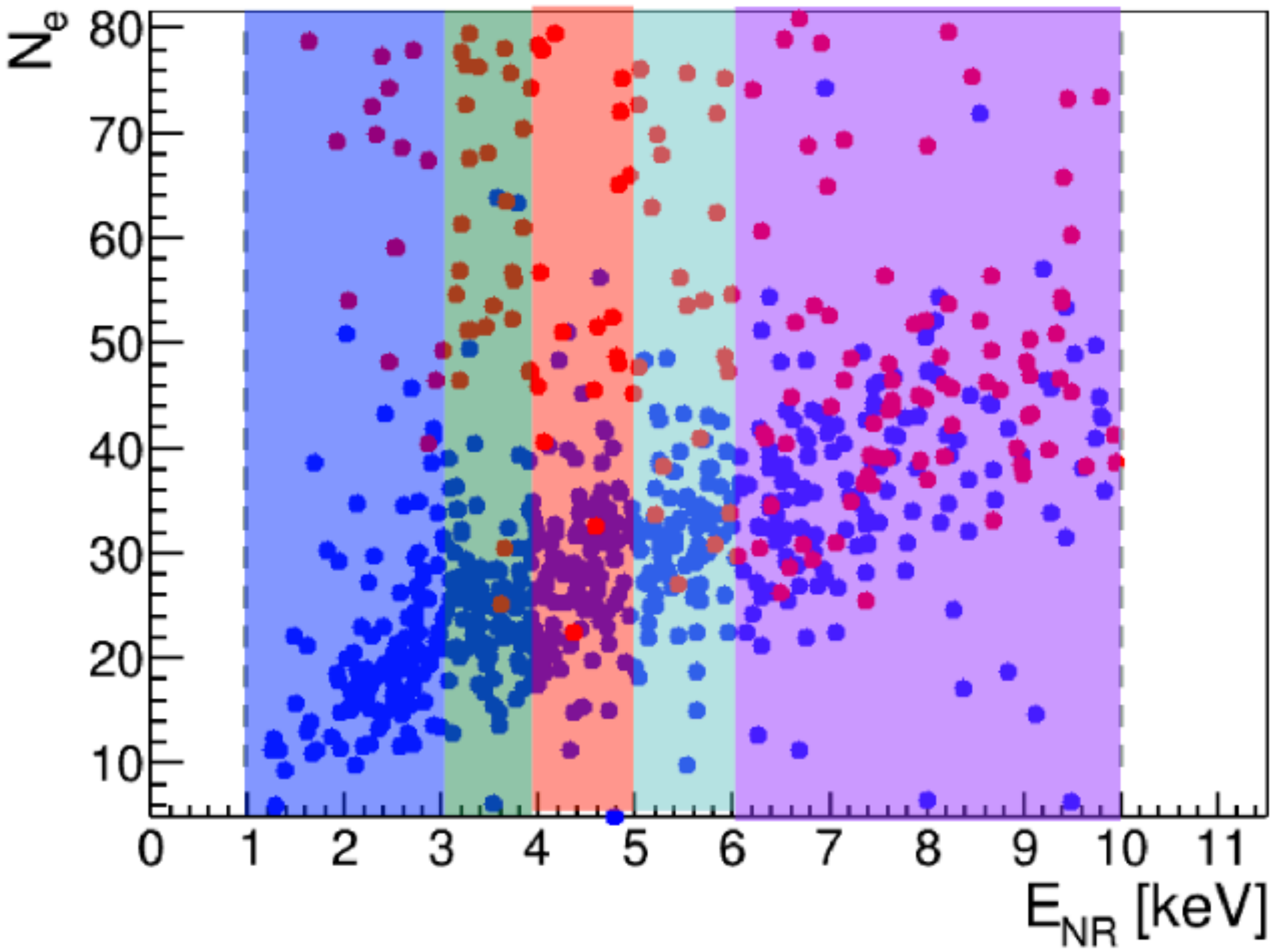
ionization yields from ARIS, SCENE and ReD

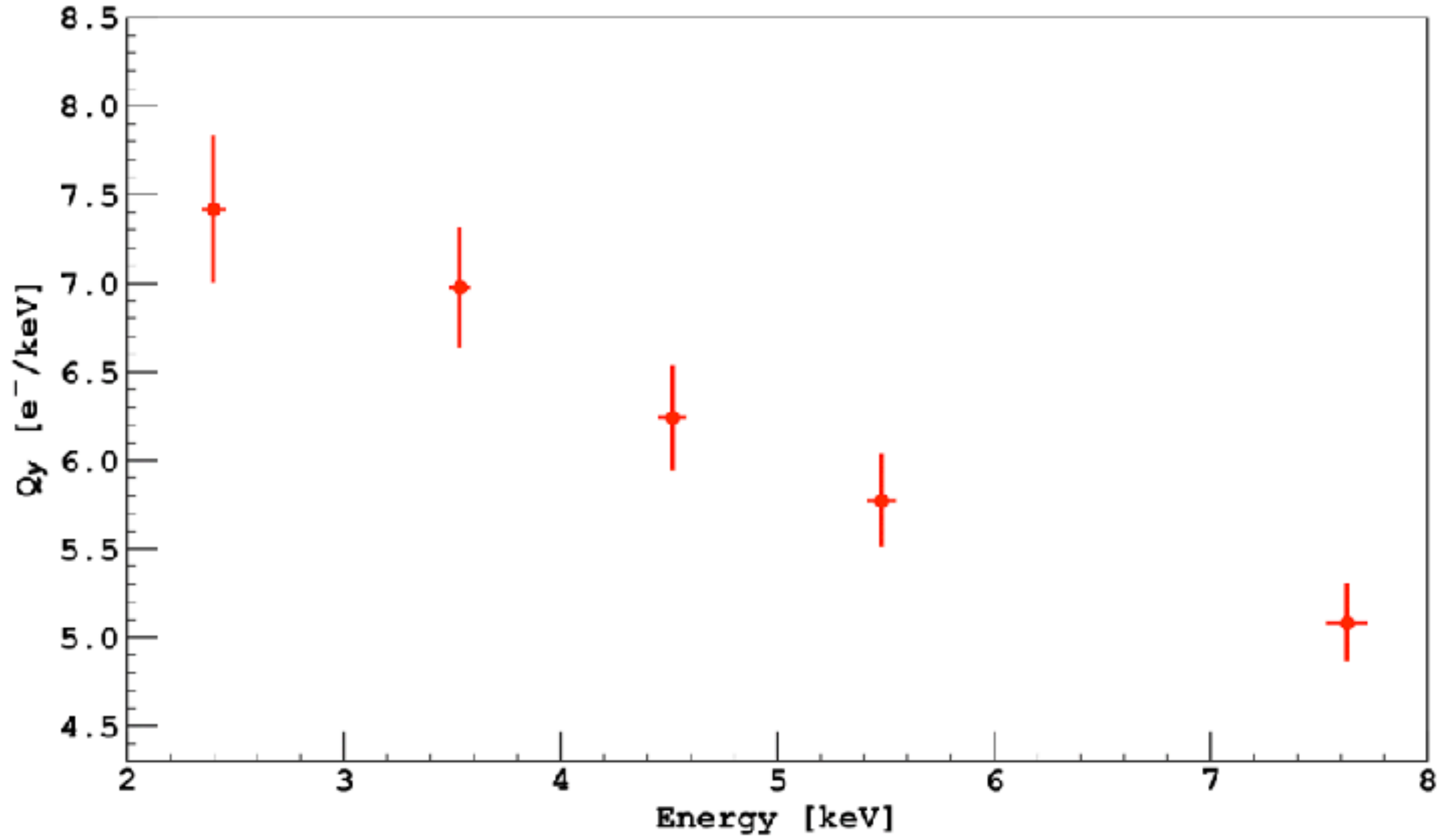


See previous talk by Luciano

spectrum of nuclear recoils from AmC neutron source in DarkSide-50



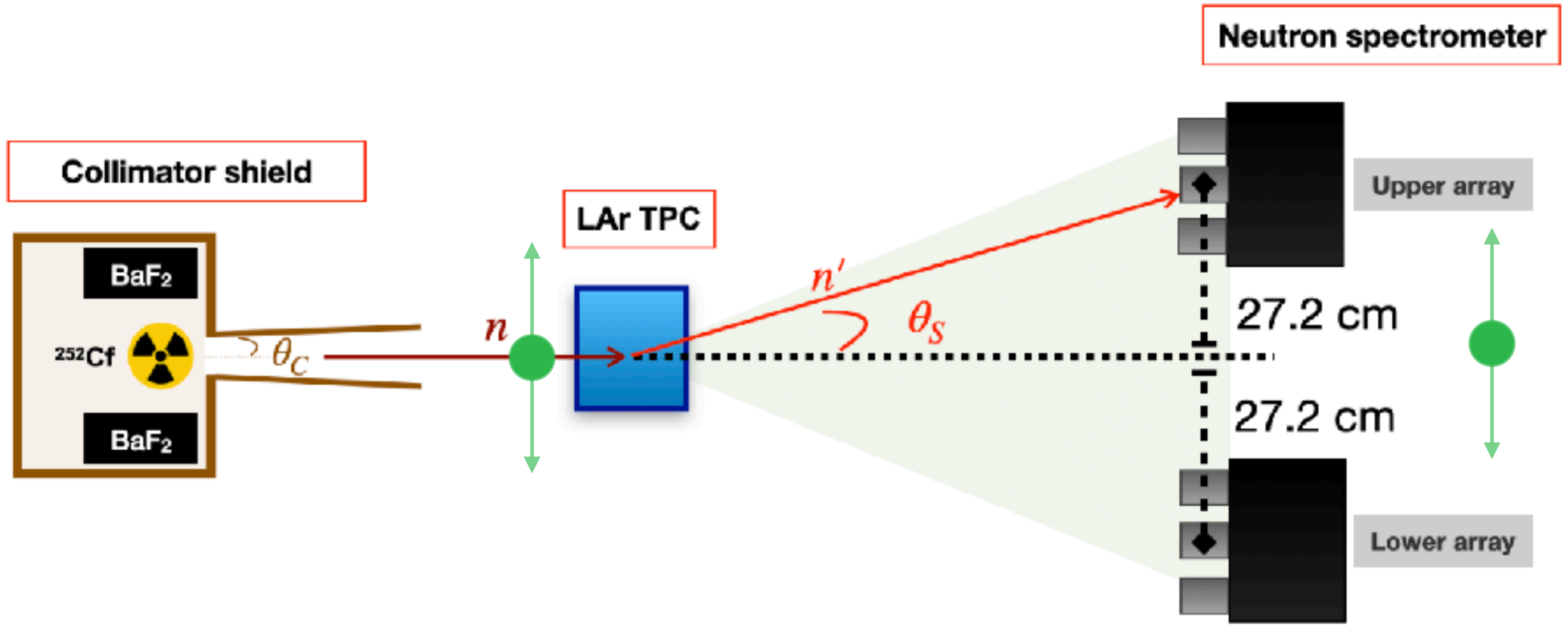




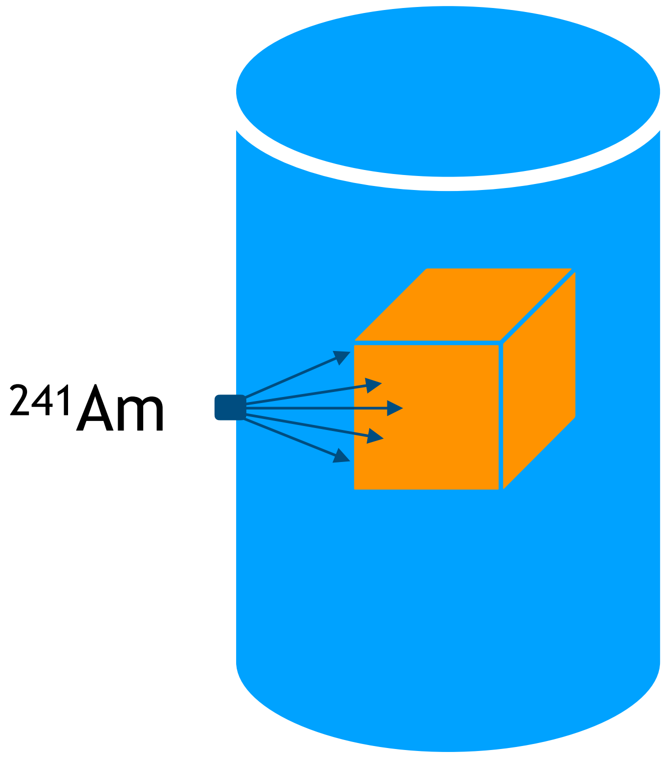
$$g_2 = (18.56 \pm 0.71)\ \text{PE/e-}$$

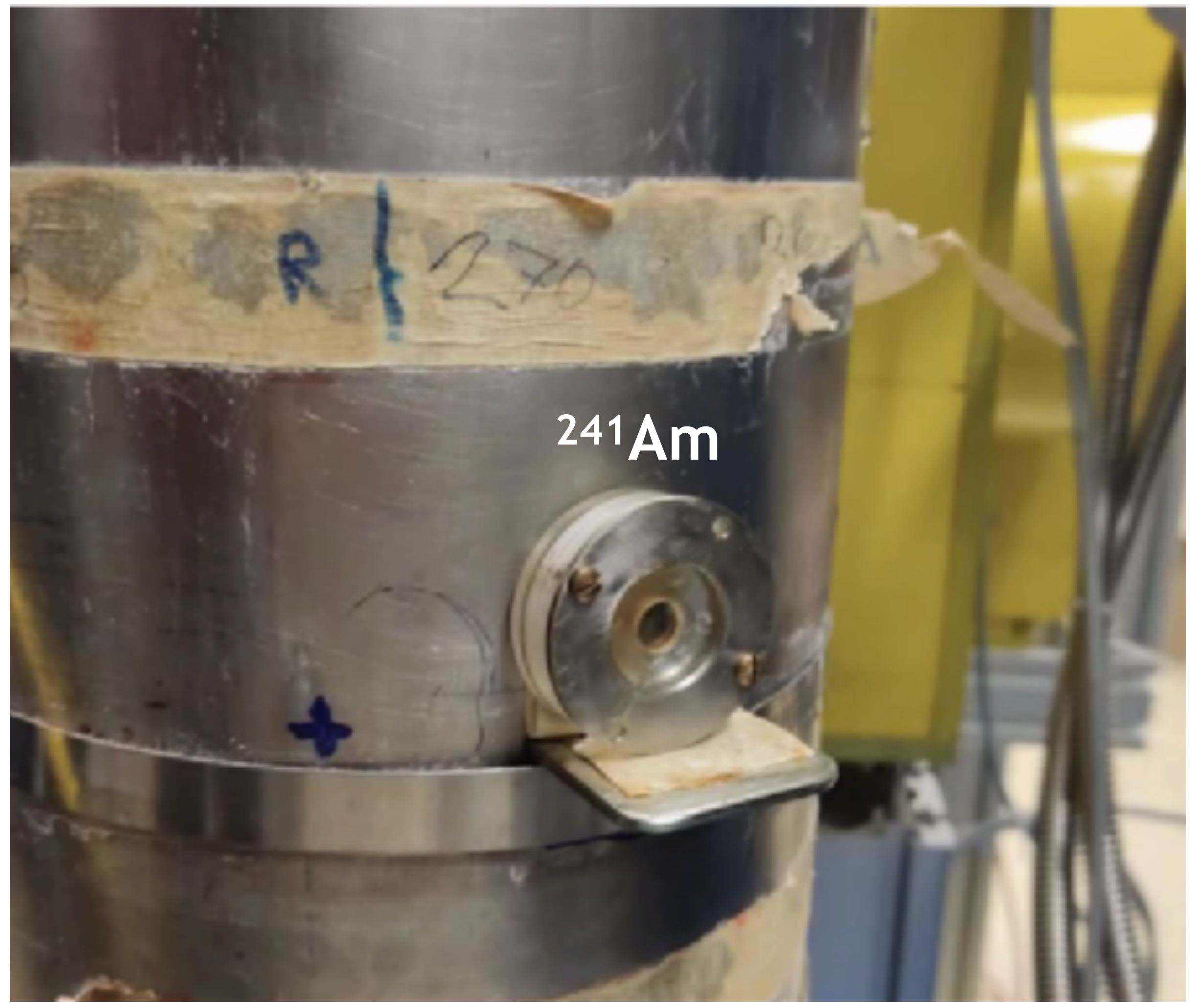
- Obtained from the **ratio of S2 signals** from a ^{241}Am γ source in ReD to the expected **number of electrons** (model from DarkSide-50 data)
- Cross-checked using **isolated single-electron** signals in the S2 tails

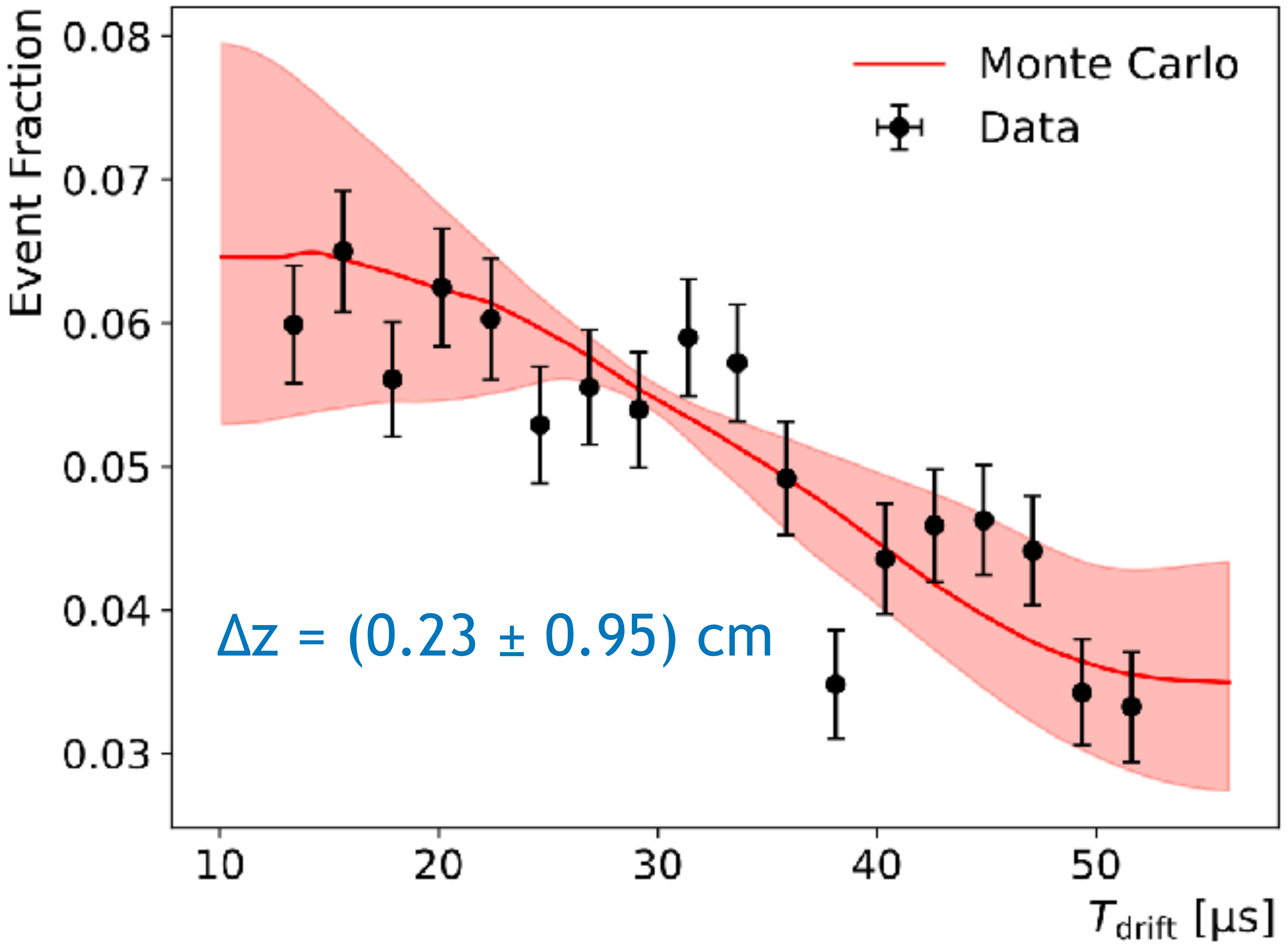
ReD systematics: TPC offset



- Relative **offset** of the TPC with respect to the cryostat center
- Alters the **angles** used in the kinematic energy reconstruction
- May lead to a **Qy asymmetry** between top / bottom arrays



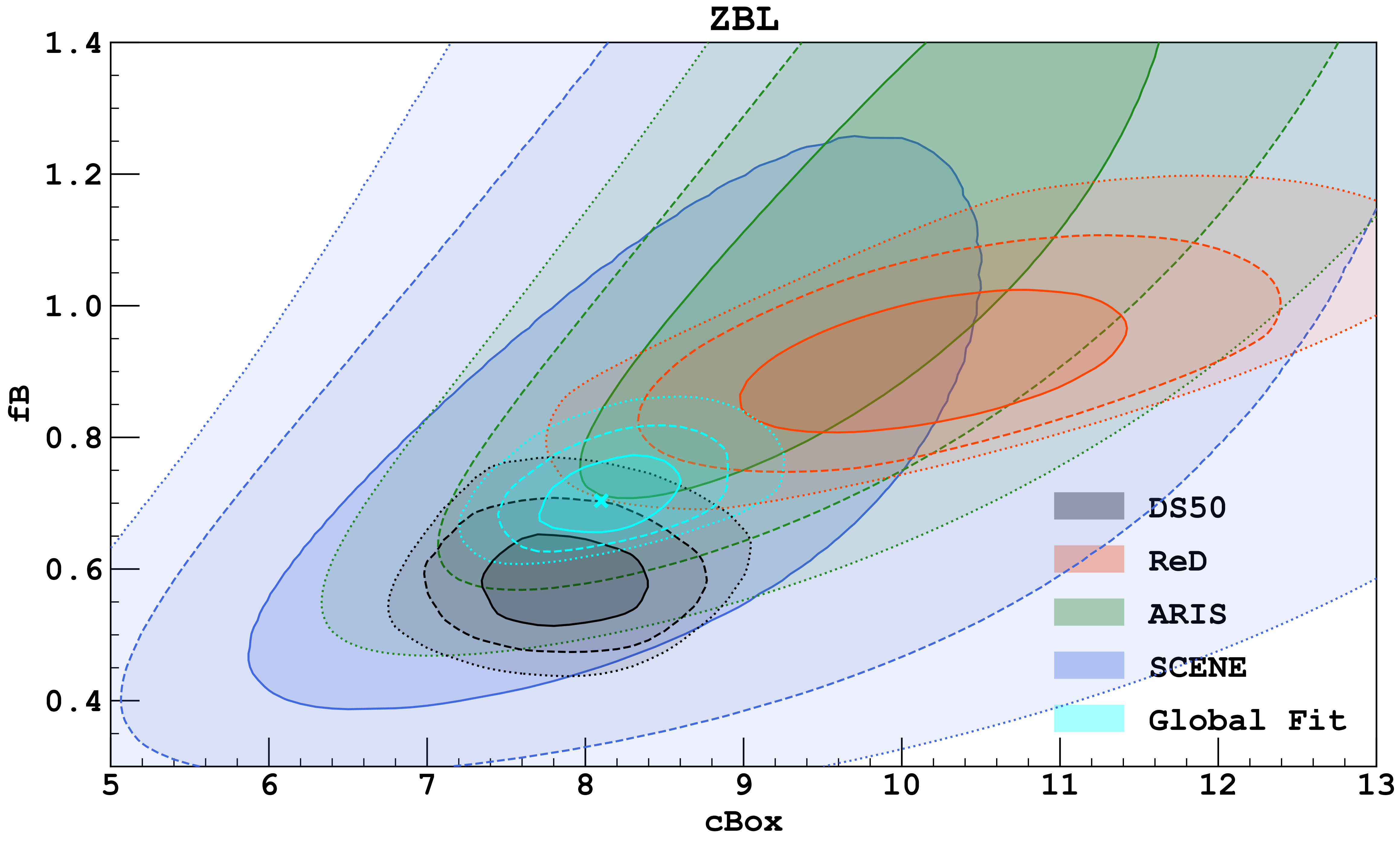


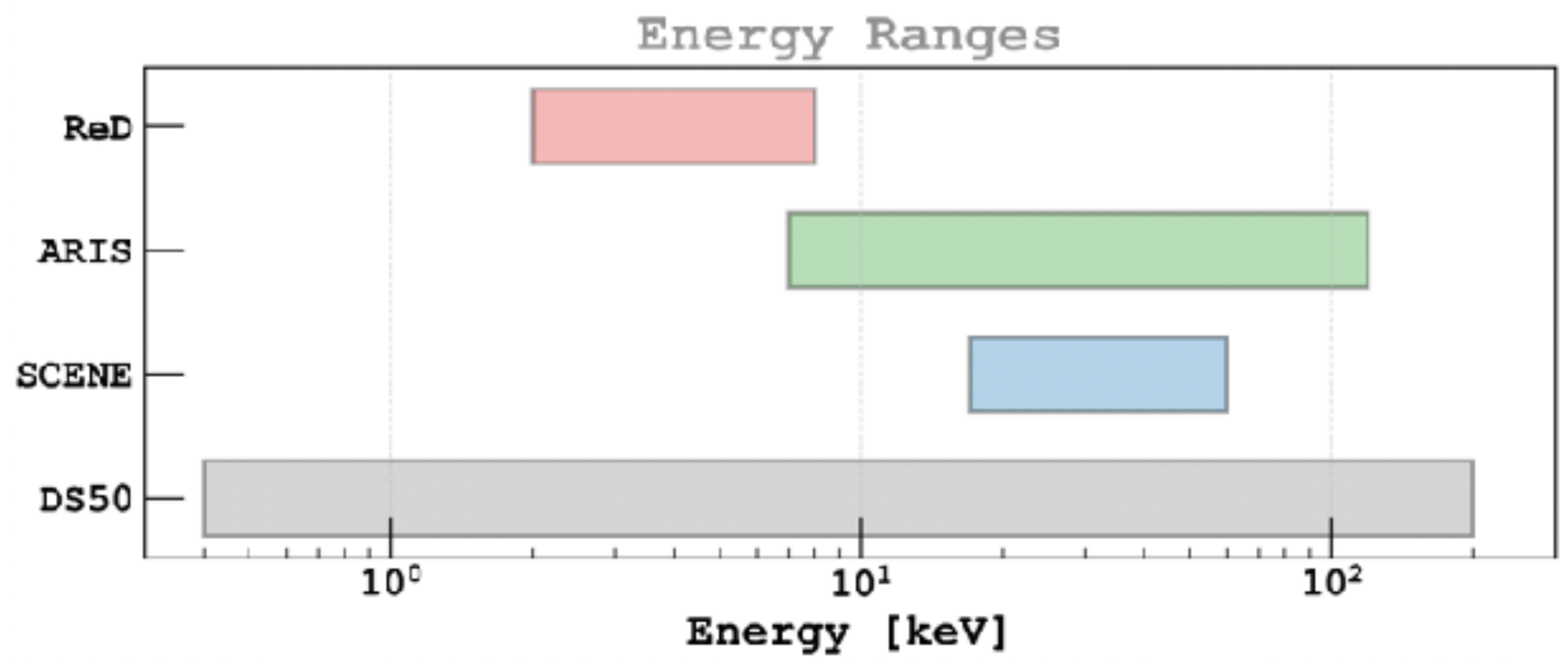


Numerical scan of the (C_{box}, β) parameter space

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

$$\chi^2_{\text{ReD}} = \min_{g_2,\delta z}\left[\chi^2_{\text{data-mod}} + \left(\frac{g_2-\hat{g}_2}{\sigma_{g_2}}\right)^2 + \left(\frac{\delta z-\hat{\delta z}}{\sigma_{\delta z}}\right)^2\right]$$





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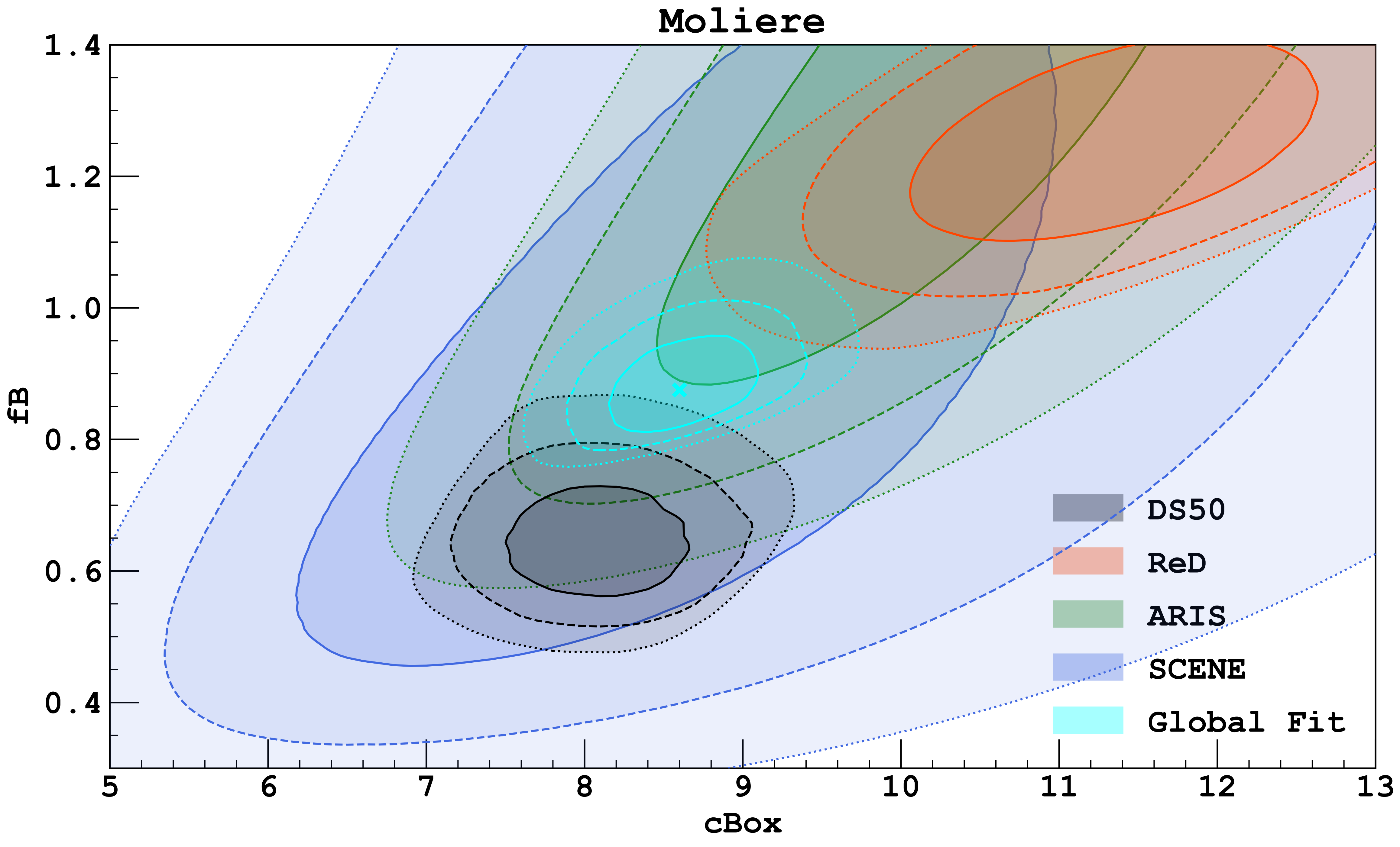

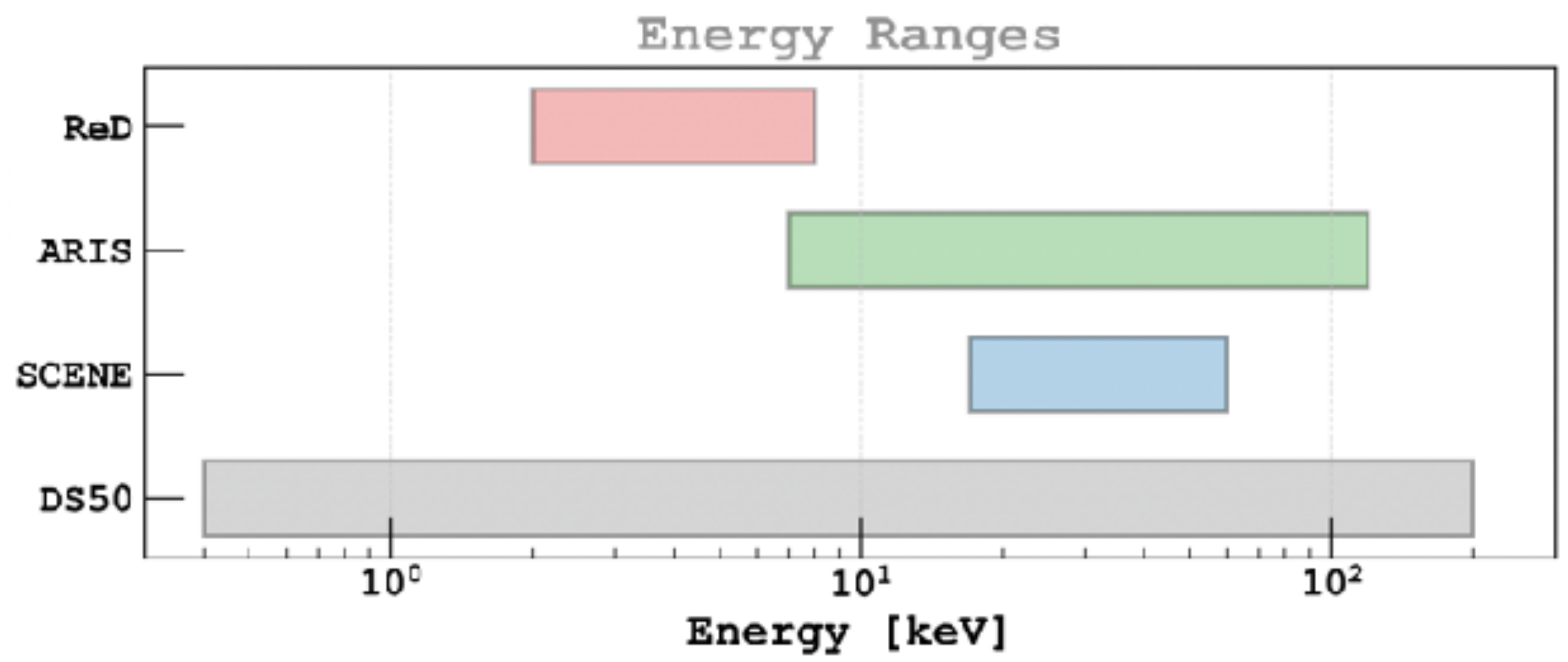

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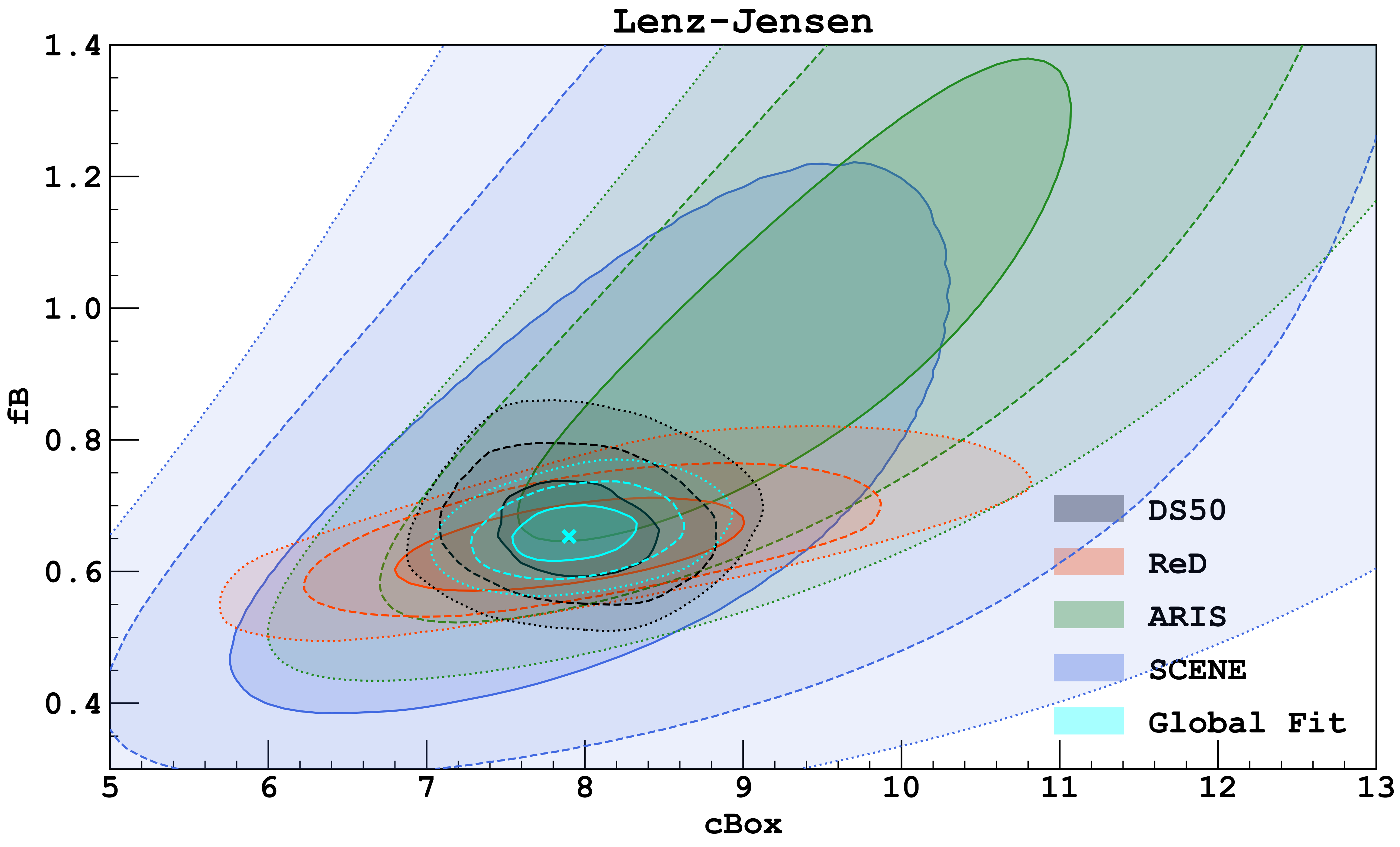
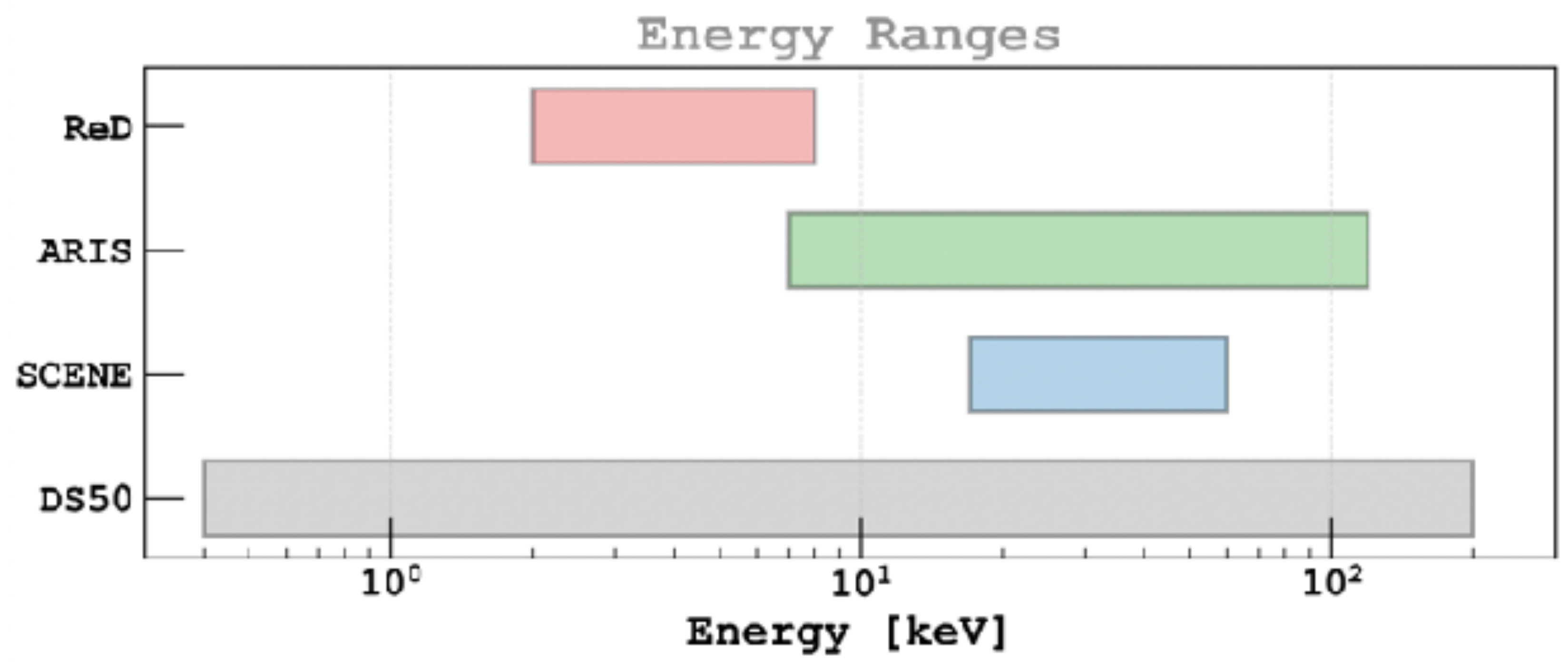
$$\chi^2_{\text{ReD}} = \min_{g_2, \delta z} \left[\chi^2_{\text{data-mod}} + \left(\frac{g_2 - \hat{g}_2}{\sigma_{g_2}}\right)^2 + \left(\frac{\delta z - \hat{\delta z}}{\sigma_{\delta z}}\right)^2 \right]$$





Applying the Bayes factor for non-nested but "comparable" models

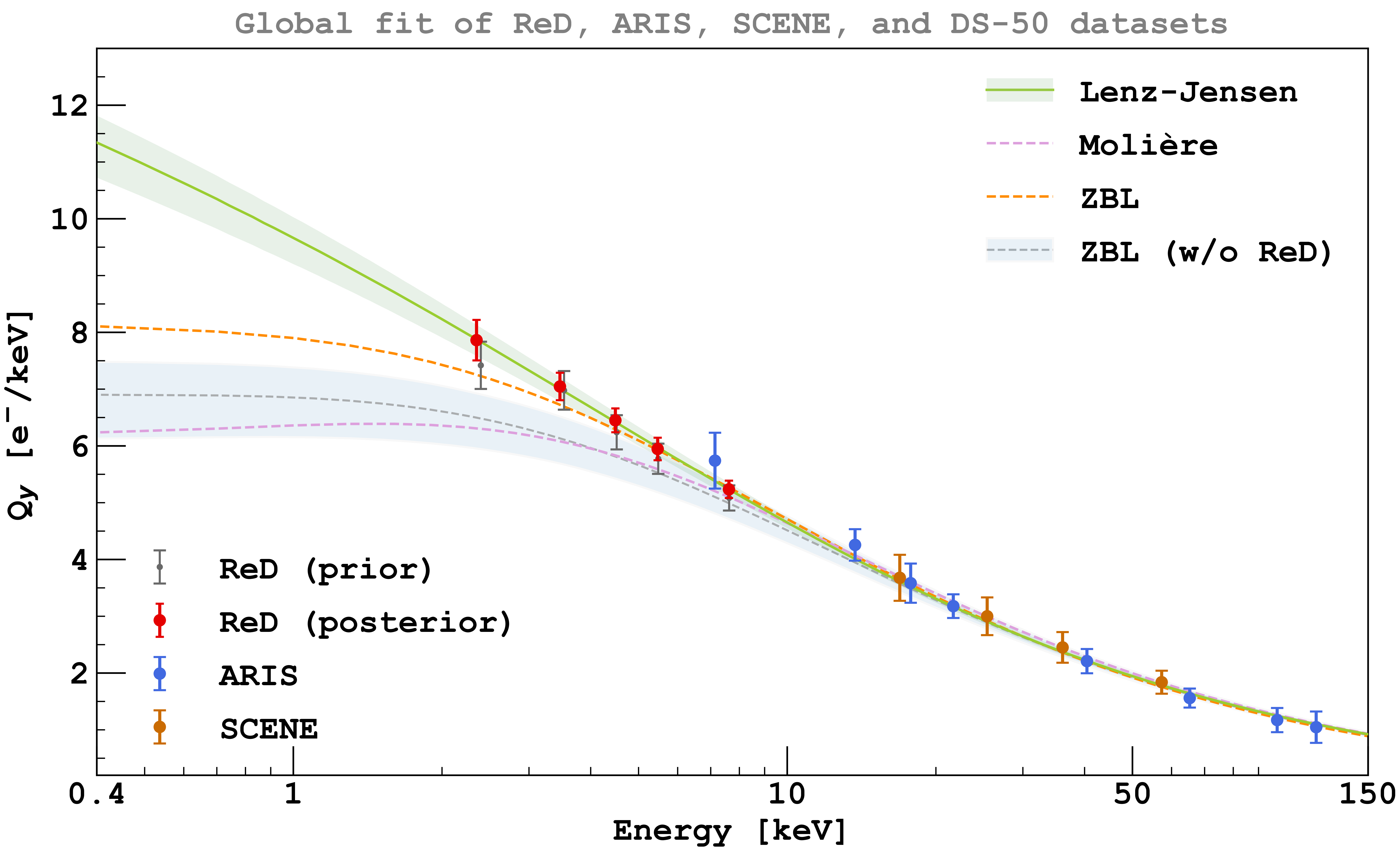
$$B_{A/B} = \exp\left(-\frac{1}{2}({\chi^2_{\min}}^A - {\chi^2_{\min}}^B)\right) \times \frac{\sum_i \exp\left(-\frac{1}{2}(\chi^2_A(\theta_i) - {\chi^2_{\min}}^A)\right)}{\sum_j \exp\left(-\frac{1}{2}(\chi^2_B(\phi_j) - {\chi^2_{\min}}^B)\right)}$$

- Lenz-Jensen over ZBL: $\log_{10}$ BF = 3.8
- Lenz-Jensen over Molière: $\log_{10}$ BF = 7.2

ZBL and Molière: rejected

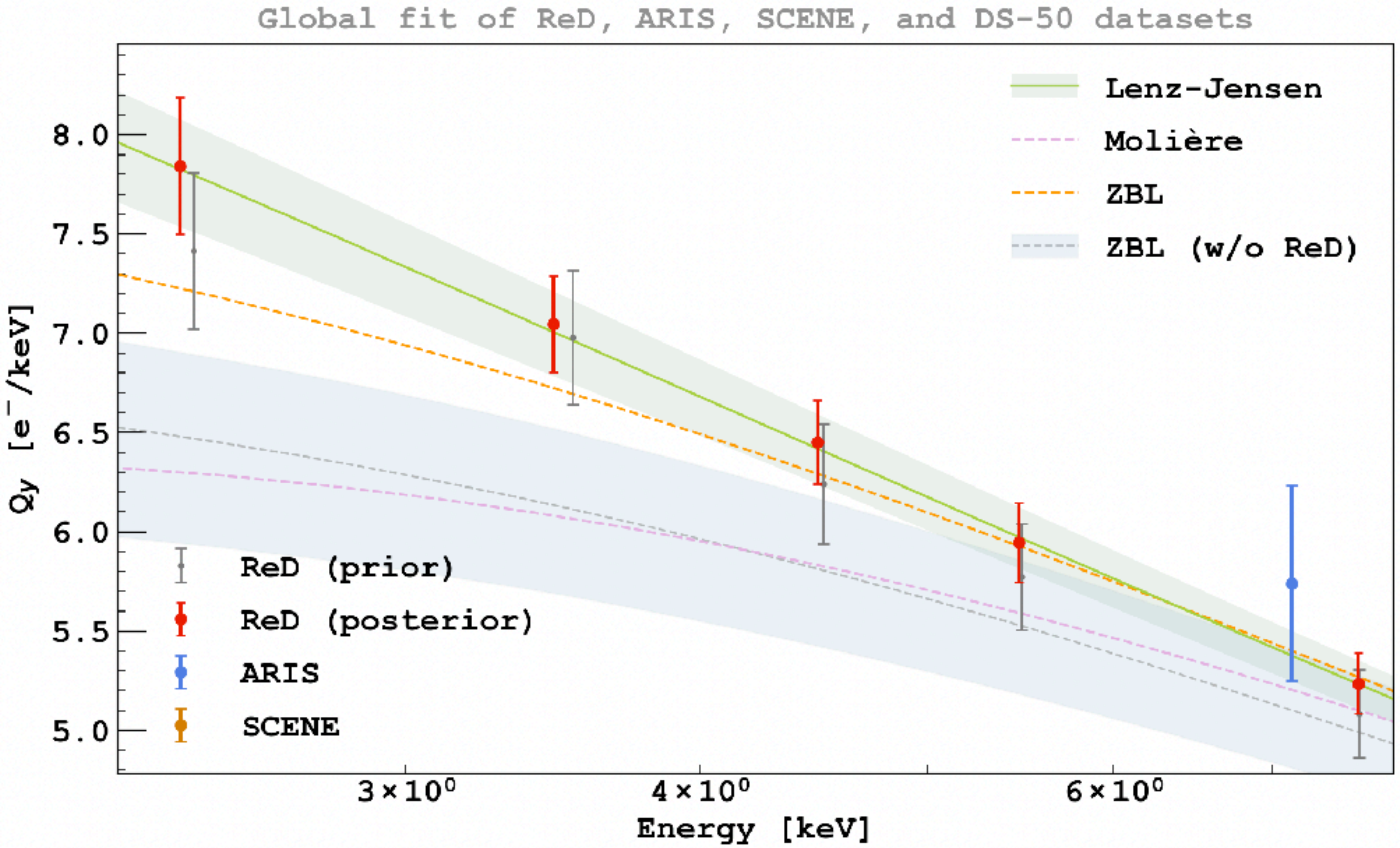
$\log_{10}$BF	Jeffrey (1961)	Kass & Raftery (1995)
Negligible	<0.5	<0.5
Substantial	0.5-1	0.5-1.3
Strong	1-2	1.3-2.2
Decisive	>2	>2.2

The fitted Q_y



The fitted Q_y

Zoom in the ReD range



Fitted parameters

Parameter	ZBL	Lenz–Jensen	Molière
C_{box} [V/cm]	$8.1^{+0.1}_{-0.2}$	$7.9^{+0.2}_{-0.2}$	$8.6^{+0.3}_{-0.2}$
β [$\times 10^3$]	$7.0^{+0.3}_{-0.2}$	$6.5^{+0.1}_{-0.3}$	$8.8^{+0.4}_{-0.5}$

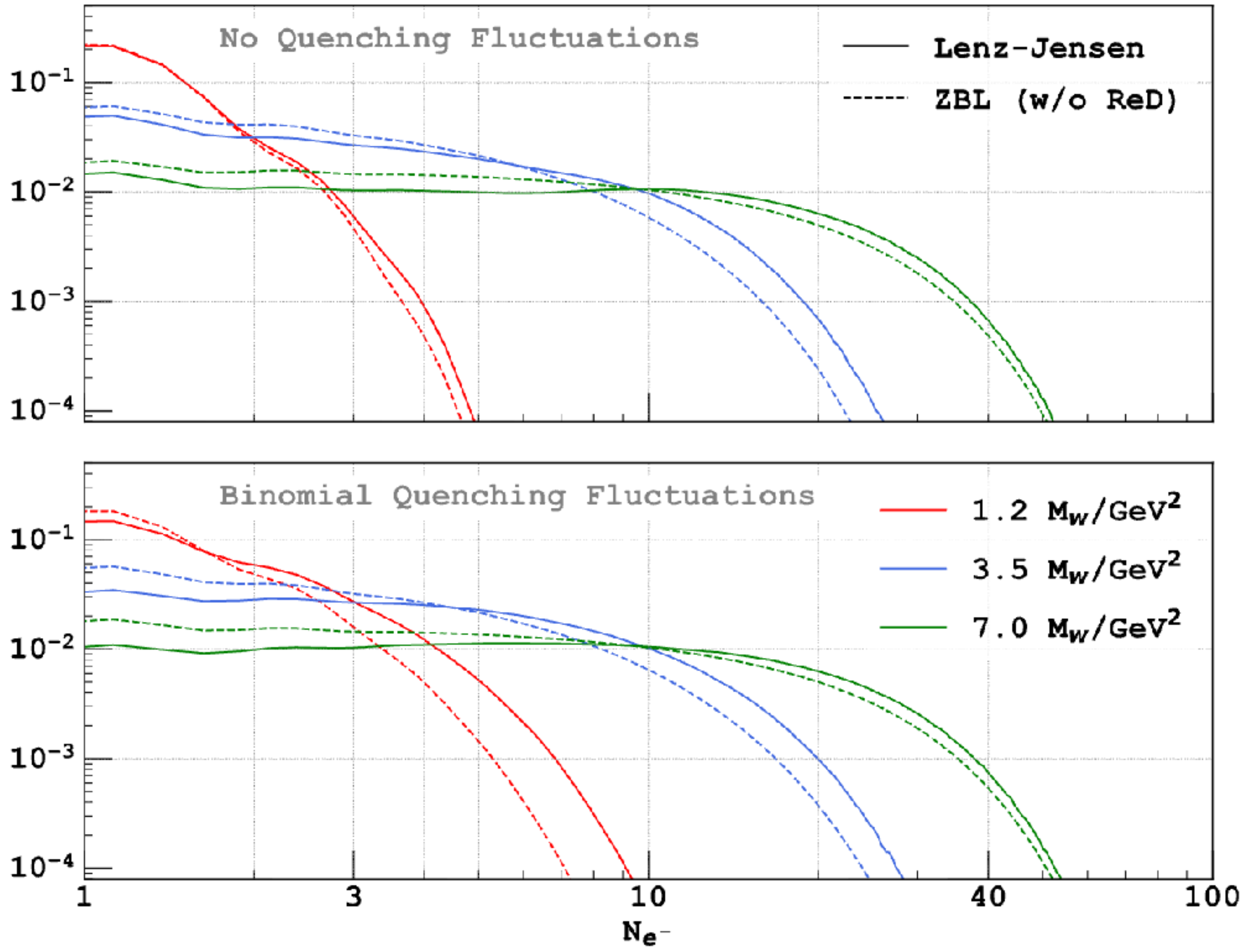
Post-fitted nuisance parameters

$$g_2 = 18.8 \pm 0.4\ \mathrm{pe/e^-} \qquad \Delta z = -0.58^{+0.05}_{-0.14}\ \mathrm{cm}$$

(assuming Lenz-Jensen)

within 1-sigma agreement with priors

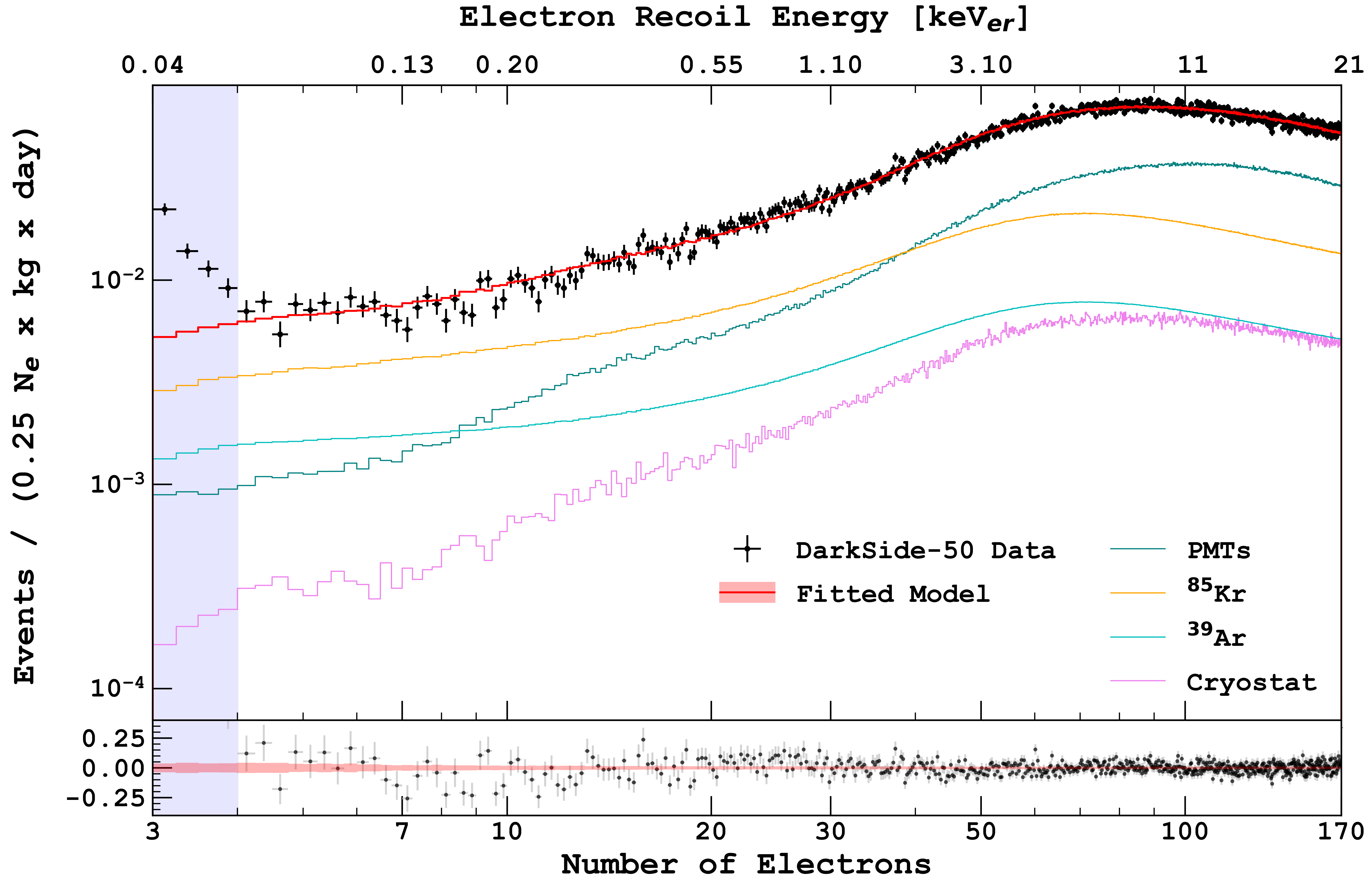
Q_y impact on WIMP spectra



Reminder: Quenching Fluctuations

- The statistical nature of nuclear recoil quenching is **unknown**
- Fluctuations can push signal **above the analysis threshold**
- Two scenarios considered:
  - **No fluctuations** – deterministic quenching (unphysical, but limiting case)
  - **Binomial model** – energy stochastically partitioned between *visible* and *invisible* channels

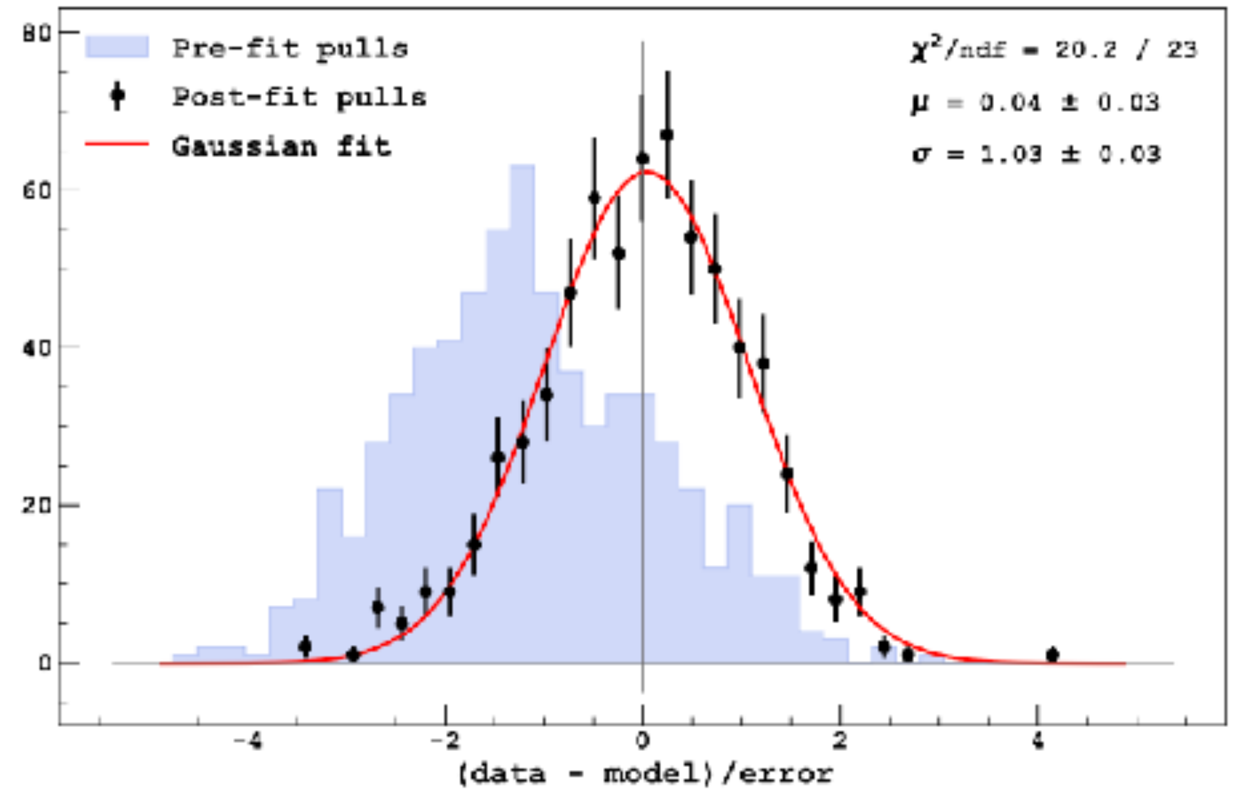
Background Model



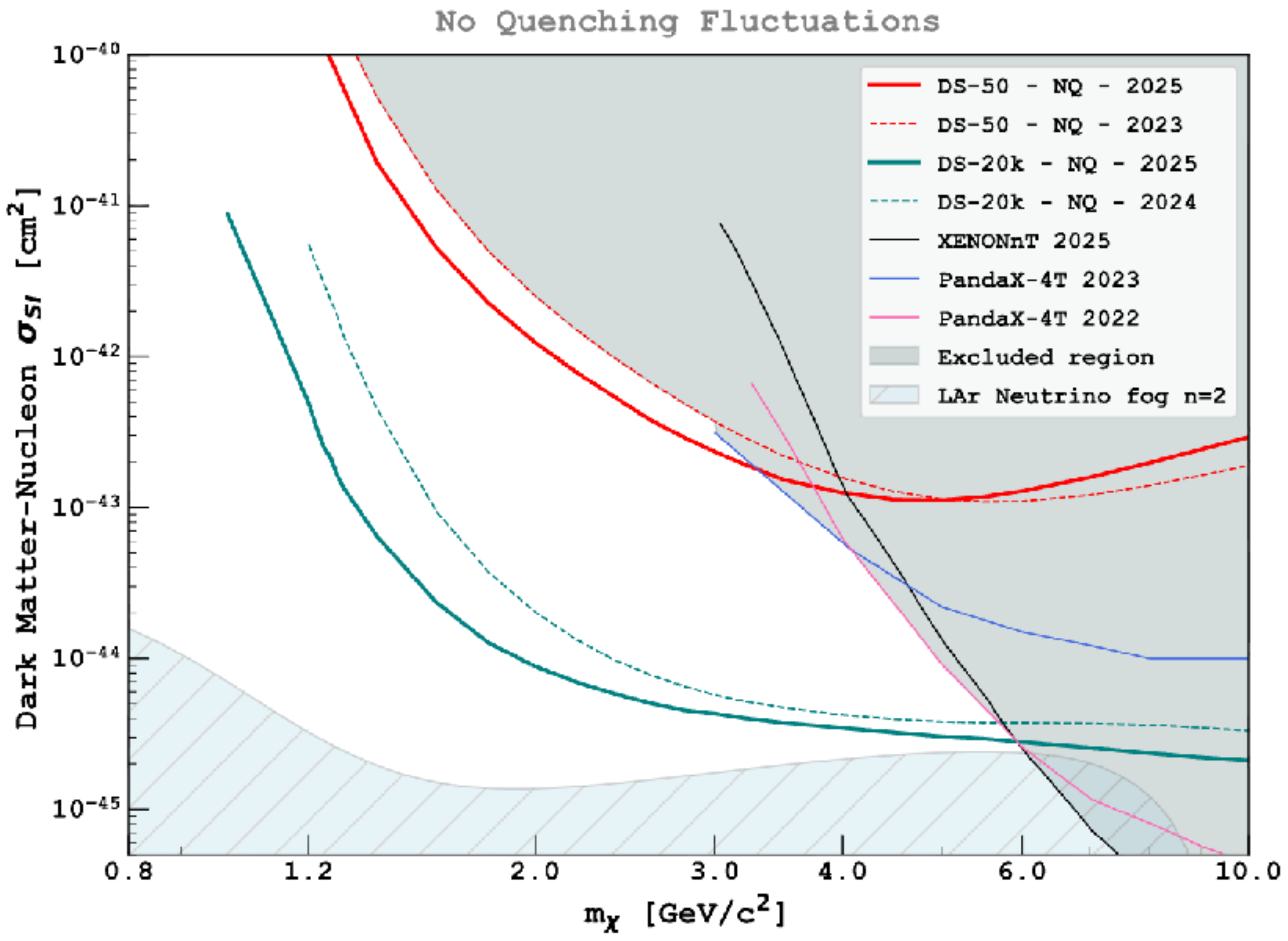
Nuisance parameters

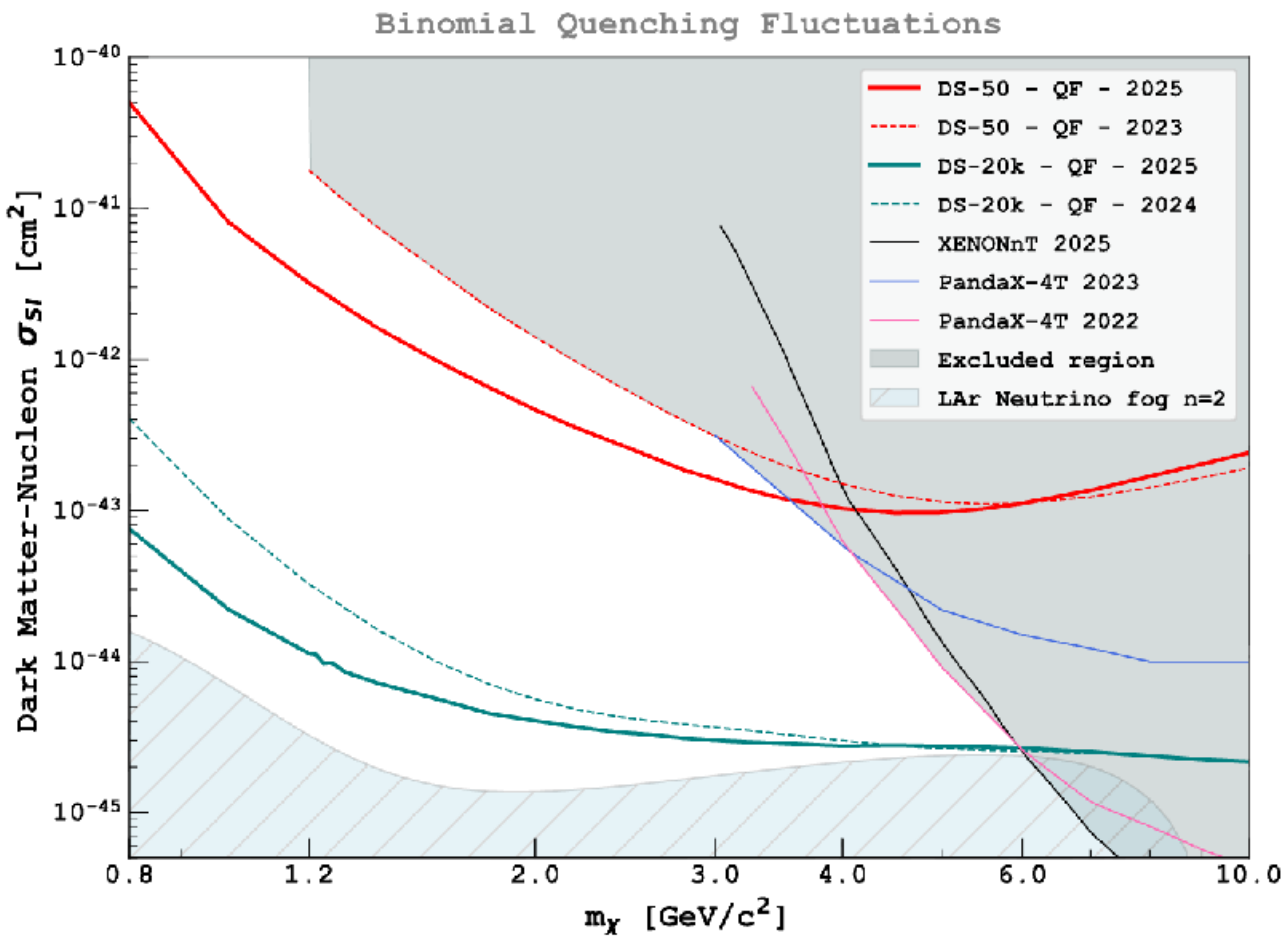
	Name	Source
Amplitude	A_{FV}	uncertainty on the fiducial volume
	A_{Ar}	14.0% uncertainty on ^{39}Ar activity
	A_{Kr}	4.7% uncertainty on ^{85}Kr activity
	A_{pmt}	11.5% uncertainty on activity from PMTs
	A_{cryo}	6.6% uncertainty on activity from the cryostat
Shape	Q_{Kr}	0.4% uncertainty on the ^{85}Kr-decay Q-value
	Q_{Ar}	1% uncertainty on the ^{39}Ar-decay Q-value
	S_{kr}	spectral shape uncertainty on atomic exchange and screening effects
	S_{Ar}	spectral shape uncertainty on atomic exchange and screening effects
	Q_y^{er}	spectral shape systematics from ER ionization response uncertainty
	Q_y^{nr}	spectral shape systematics from NR ionization response uncertainty

Background-only fit



Recasting the DarkSide-50 and DarkSide-20k sensitivities





Conclusions

- **Excellent agreement** between multiple datasets with **Lenz-Jensen** screening potential
- **Molière** and **ZBL** screening functions **rejected**
- Recasting DarkSide-50: new **best-limit** below 3.5 GeV / c2
- Enhanced potential of DarkSide-20k in the low-mass range

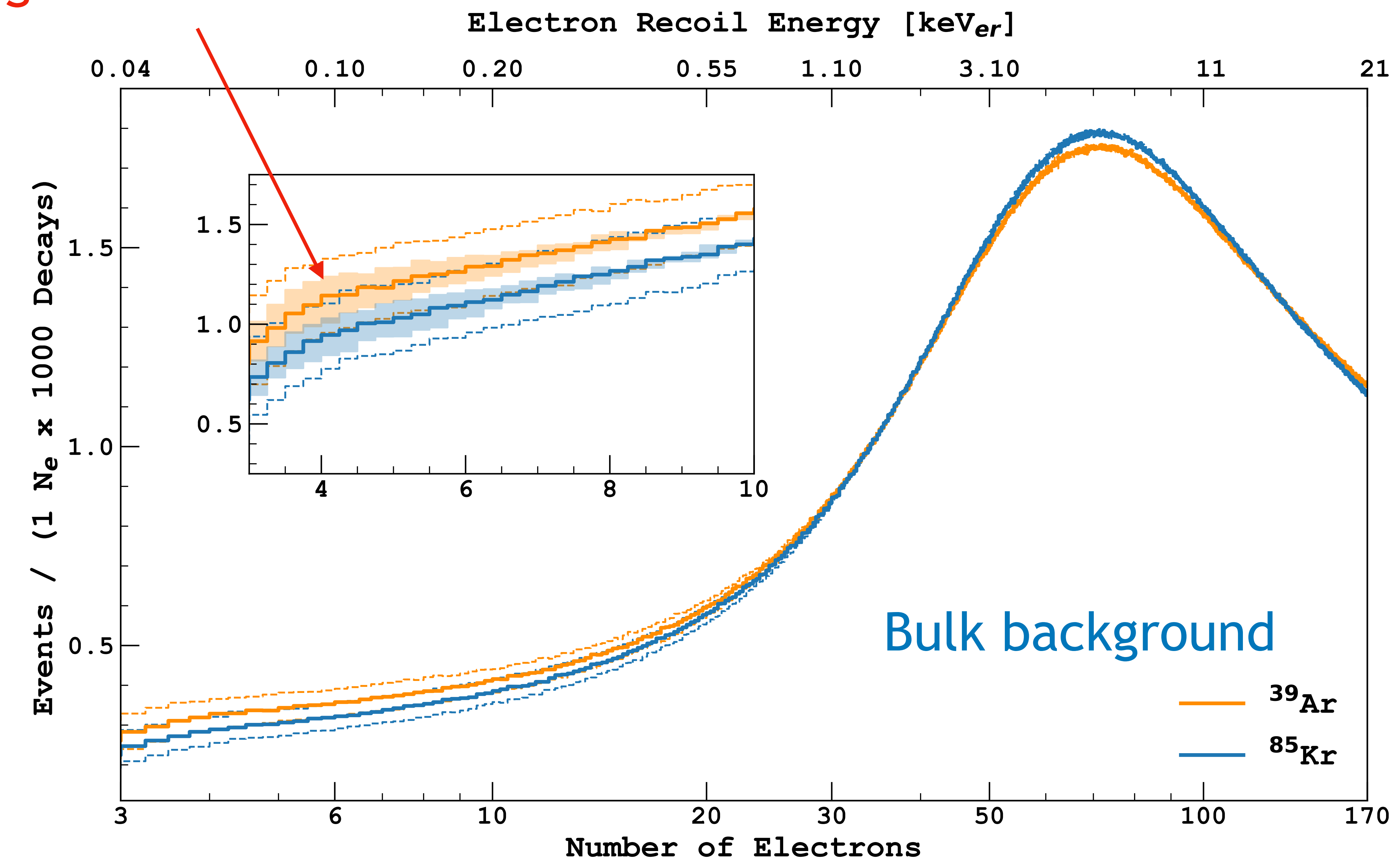
What Next?

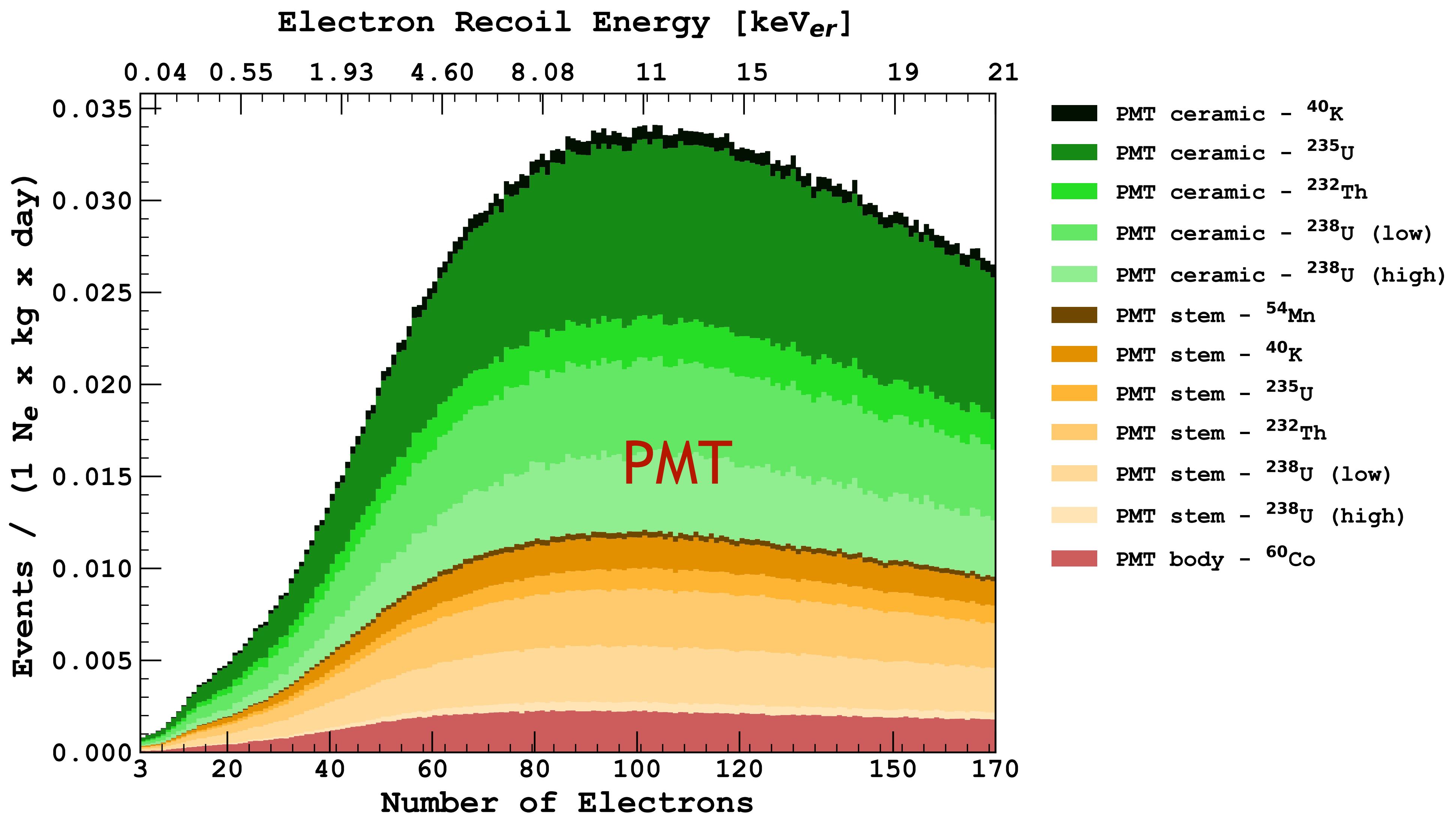
- Including **spurious electron** model in the DarkSide-50 background model
- Solving the long-standing issue of **quenching fluctuations** with **ReD**/**ReD+**
- Extend coverage down to 0.2 keV NRs with **ReD+**

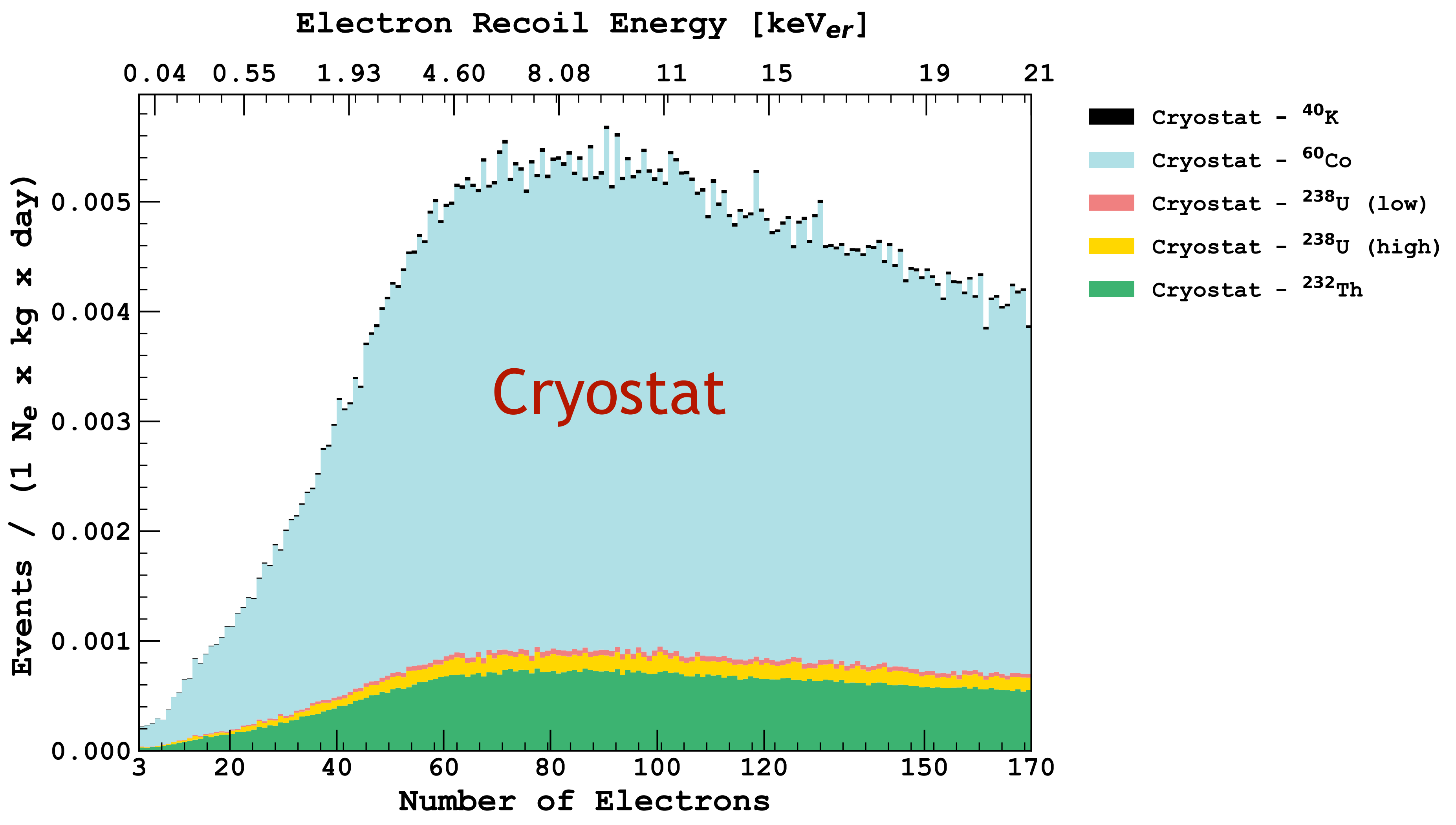
BACK UP

Background Model

Uncertainty from atomic exchange and screening effects







- ^{39}Ar activity: **0.7 ± 0.1 mBq/kg**
- ^{85}Kr activity: **1.8 ± 0.1 mBq/kg**
- **PMT** and **cryostat** components from material screening measurements