DarkSide-50

Characterisation of the LAr ionization response in the keV regime

DARKSIDE

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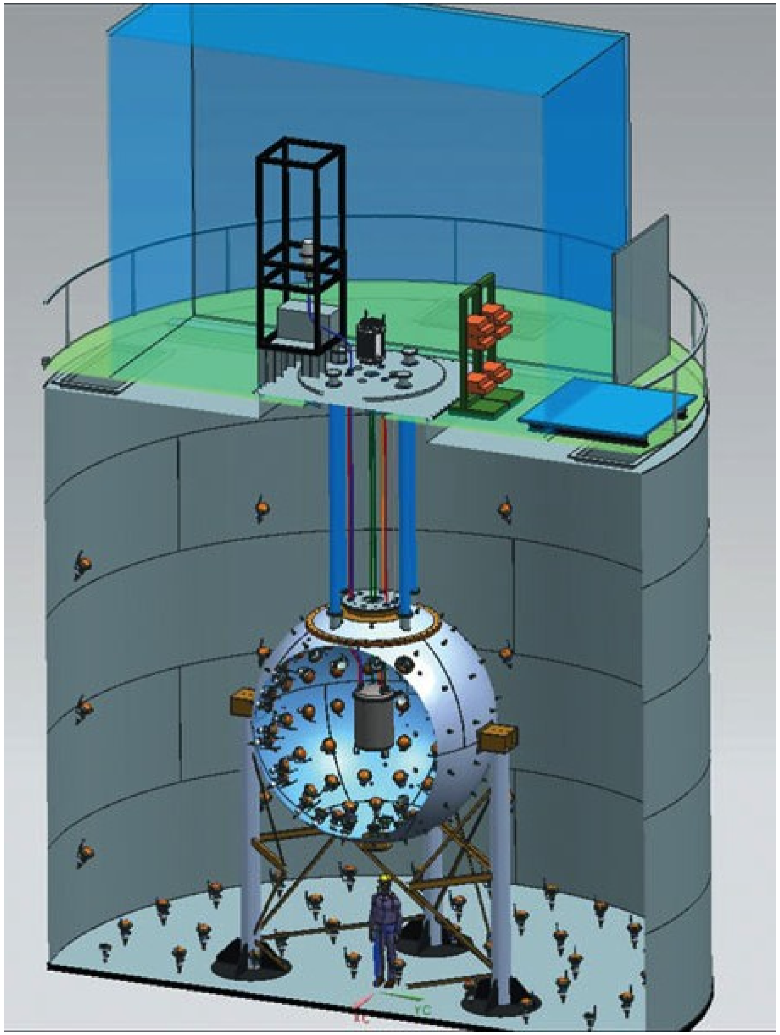
16/02/2022

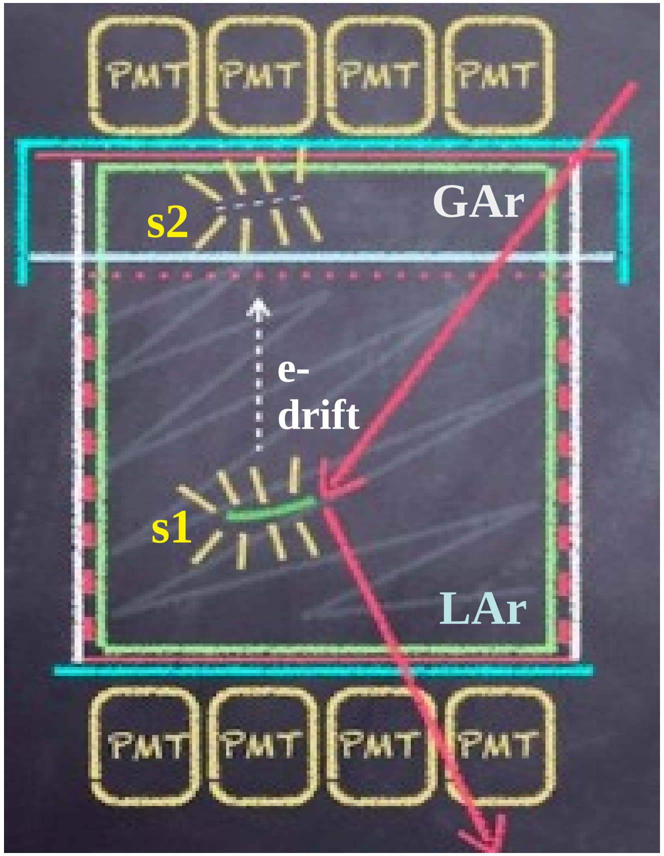
DarkSide-50 experiment

- **50 kg** dual-phase Liquid **Argon** TPC
- Using Underground Argon: **depleted in ^{39}Ar**
- In a **30 tonnes** borated liquid scintillator **neutron veto**
- In a **1000 tonnes Water** Cherenkov Veto
- **Underground** in Gran Sasso National Lab, Italy



DOI:10.1088/1748-0221/12/12/P12011

Dual-phase LAr TPC



http://aris.in2p3.fr/doc/aris.pdf

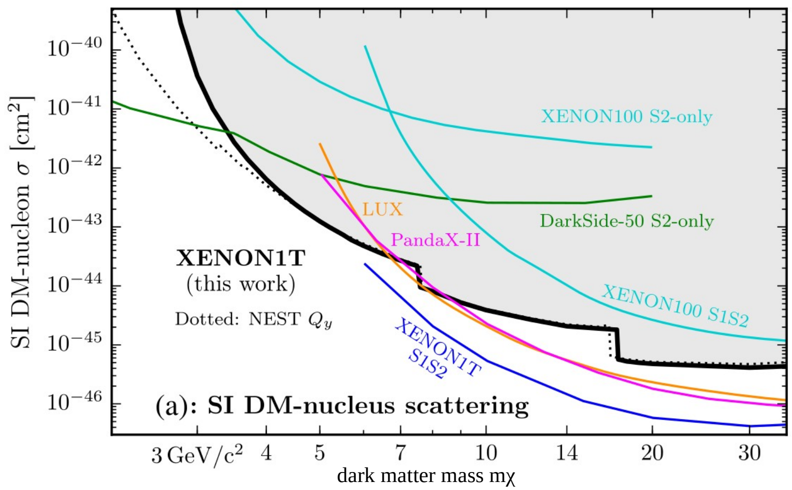
DarkSide-50
- s1 light collection efficiency: 0.16±0.01 → ***low efficiency***
- s2 yield: 23±1 pe/e- → ***amplification***

DOI: 10.1088/1748-0221/12/10/P10015

keV regime accessible using s2 only

Motivation

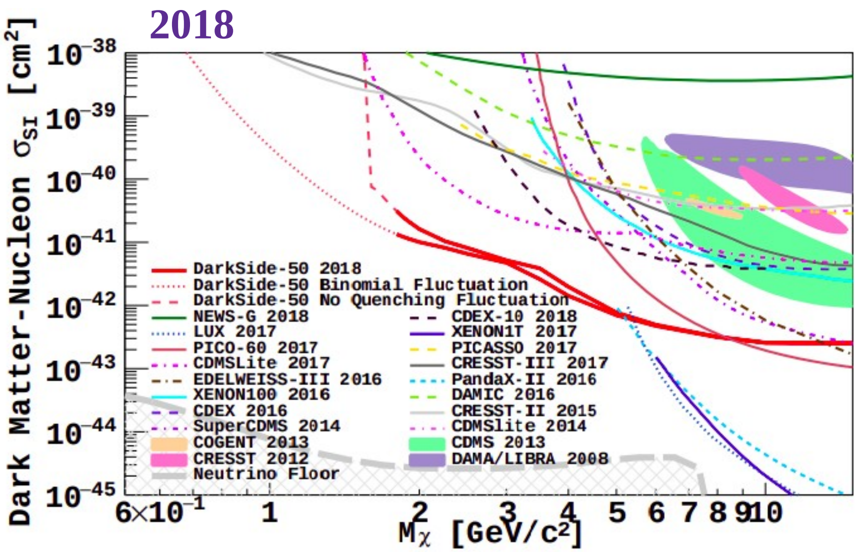
Lower detection threshold, higher sensitivity to light dark matter candidates:
- WIMP-nucleon interaction with/without Migdal effect
- WIMP-electron interaction
- Sterile neutrinos
- Axion-like particles



DOI: 10.1103/PhysRevLett.123.251801

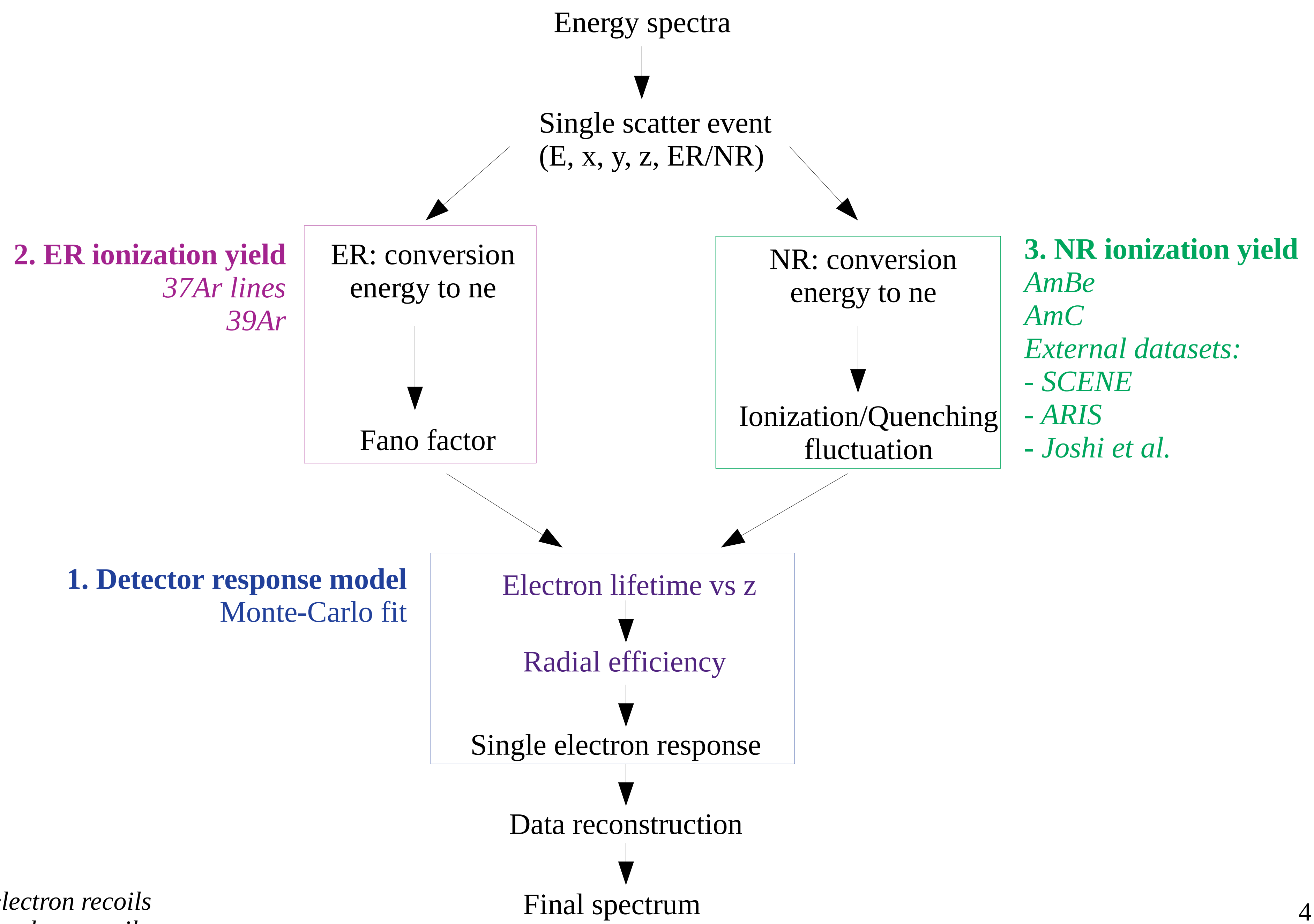
Noble liquid detectors:
- Efficient background discrimination
- Massive target
- High scintillation yield

Liquid argon detectors:
- Massive
- Radiopure
- High scintillation yield
- High ionization yield
- Low electron mobility
- Argon mass << Xenon mass
- Higher recoil energy (transferred momentum) wrt Xe at low energy



DOI:10.1103/PhysRevLett.121.081307

Response model

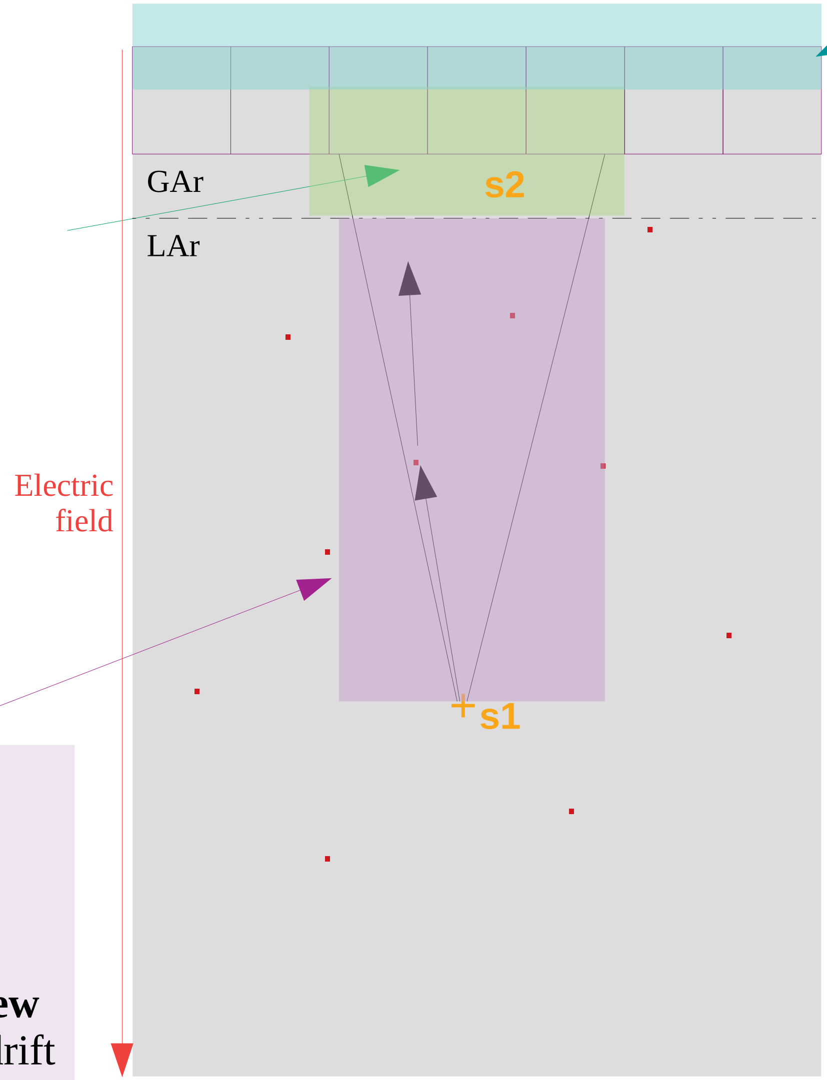


ER: electron recoils
NR: nuclear recoils
ne: number of electrons

Instrumental effects

Monte-Carlo modelling of the detector response in S2

Resolution dominated by:
- Electroluminescence fluctuations
- PMT charge response



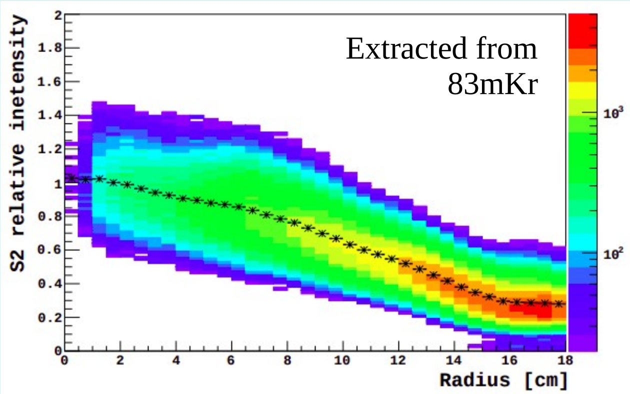
Electron lifetime

- Capture from **impurities** along the drift
- Measured > 10 ms
- Maximal distortion of **a few percent** wrt the maximal tdrift

Radial distortion

Low S2 pulse: XY reconstruction inefficient

XY estimator: top PMT position with max light fraction



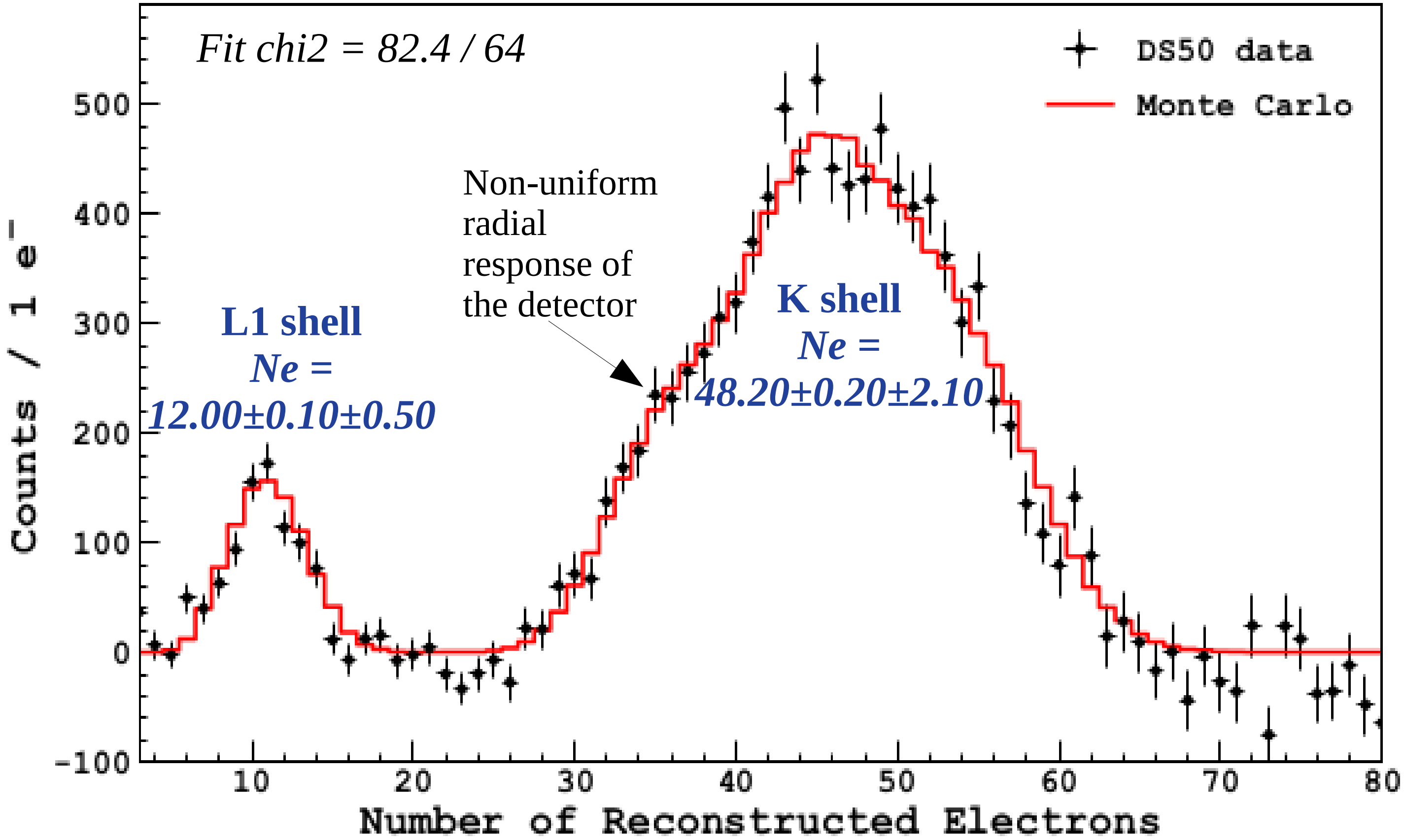
DOI:10.1088/1748-0221/12/10/P10015

37Ar K and L electron capture

Sample selection

→ Subtraction between the first ~ 100 days from the latest ~500 days of the UAr campaign
→ 37Ar almost entirely decayed in the last ~ 500 days
→ Samples normalized by their lifetime

Fit performed with a **chi2 analysis**
→ Free parameters: number of extracted electrons (both lines 37Ar + Fano factor)



L1/K shells ratio:

→ measured = 0.10±0.01
→ expected = 0.103±0.01

DOI: 10.1103/PhysRev.120.2196

0.102±0.01

DOI: 10.1080/14786436208212179

0.098±0.003

DOI: 10.1007/BF01333365

Fitted Fano factor:

→ measured = 0.10±0.03
→ expected = 0.107 (Schockley)
0.116 (Alkhazov)

DOI: 10.1016/0029-554X(76)90292-5

37Ar decay

Single electron capture transition ground state to ground state (half life of 35.01 days)

Evaluation of emitted cascades of electrons, X-rays and UV photons with RELAX software (EADL2017 library of atomic transition data)

- Atomic relaxation spectra of UV photons, X rays, Auger electrons (primaries)
- Primaries from bound state to bound state transitions for a single initial vacancy in the different sub-shells
- Deterministic propagation of the vacancies up to the valence shell and to the neutralization
- Consideration of atomic configurations

using BetaShape code
https://doi.org/10.1016/j.apradiso.2019.108884

Fit: 12.0±0.1(stat.)±0.5(syst.)

	L1–shell EC			K–shell EC	
Branching Ratio	8.4%			90.4%	
Total Released Energy	277			2829	
Mean number of primaries[a]	2.8			3.9	
	⟨N⟩	⟨E⟩[eV]		⟨N⟩	⟨E⟩[eV]
K Auger electrons				0.905	2414
K X-rays				0.095	2634
L Auger electrons	0.9995	179	→ - 1	1.77	179
L X-rays	0.0005	207	→ neglected	8E-4	188
M Auger electrons	0.96	51	→ - (2±1)	0.35	51
UV photons (E>16 eV)	0.86	25	→ - 1	0.77	25
Undetectable via ionization	2.10	13	→ 0	3.26	13

Lack of model: complex event topology → **exclude K shell**

Ionization electrons at 179eV: **8.2±1.3**

Electron Recoil Ionization yield

Ionization yield per unit of ER energy following the custom model:

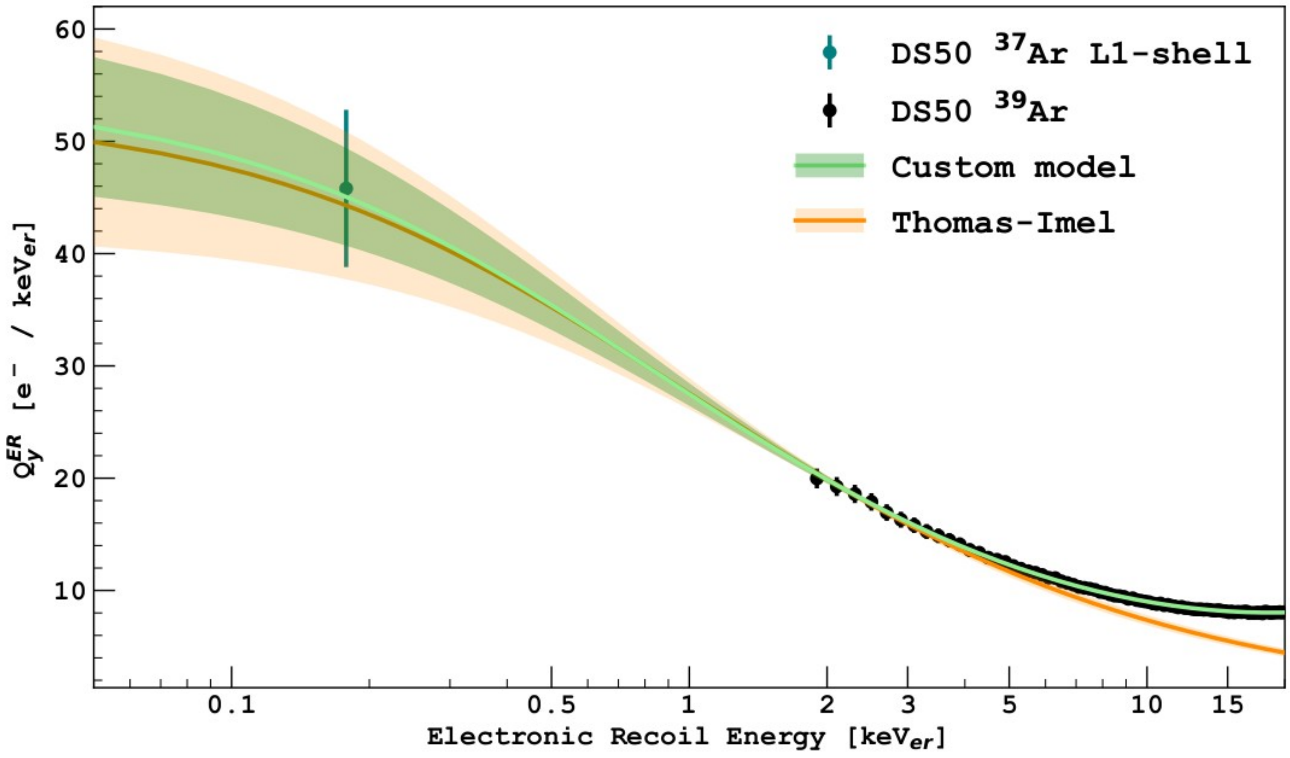
$$Q_y^{ER} = \frac{\ln(1+\gamma\,\rho\,E_{er})}{E_{er}}\left(\frac{1}{\gamma} + p_0\,(E_{er}/\mathrm{keV}_{er})^{p_1}\right)$$

Thomas-Imel model

Custom model: extension above 3keVer

γ = Cbox/F
with F the drift field

→ Assumption of a constant excitation-to-ionization ratio



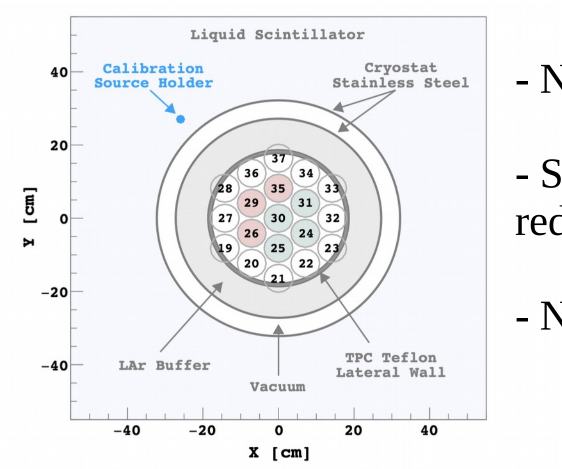
Fit result

Cbox = 9.2±0.9 V/cm
ρ = 54.4±7.3 keVer-1
p0 = 0.11±0.003
P1 = 0.71±0.08

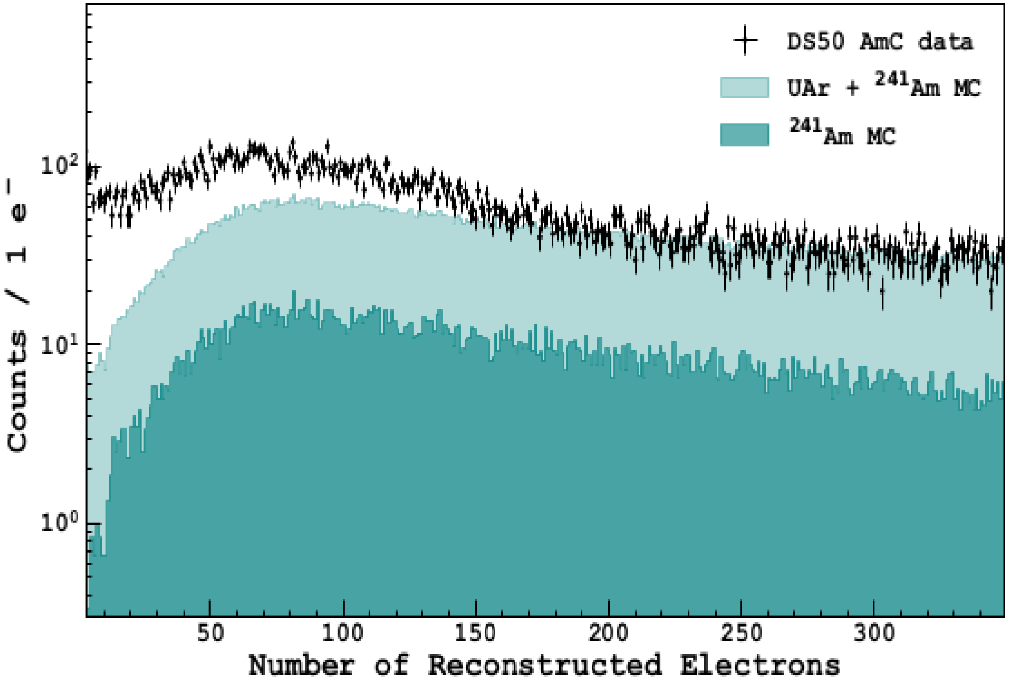
Compatible with Thomas-Imel fit at 1σ up to 3keVer

Nuclear Recoil Ionization Yield

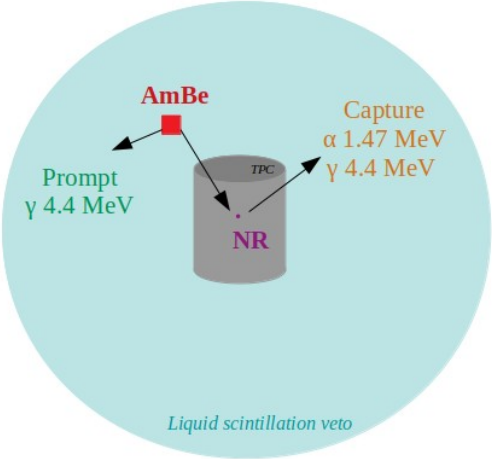
241Am-13C (AmC)



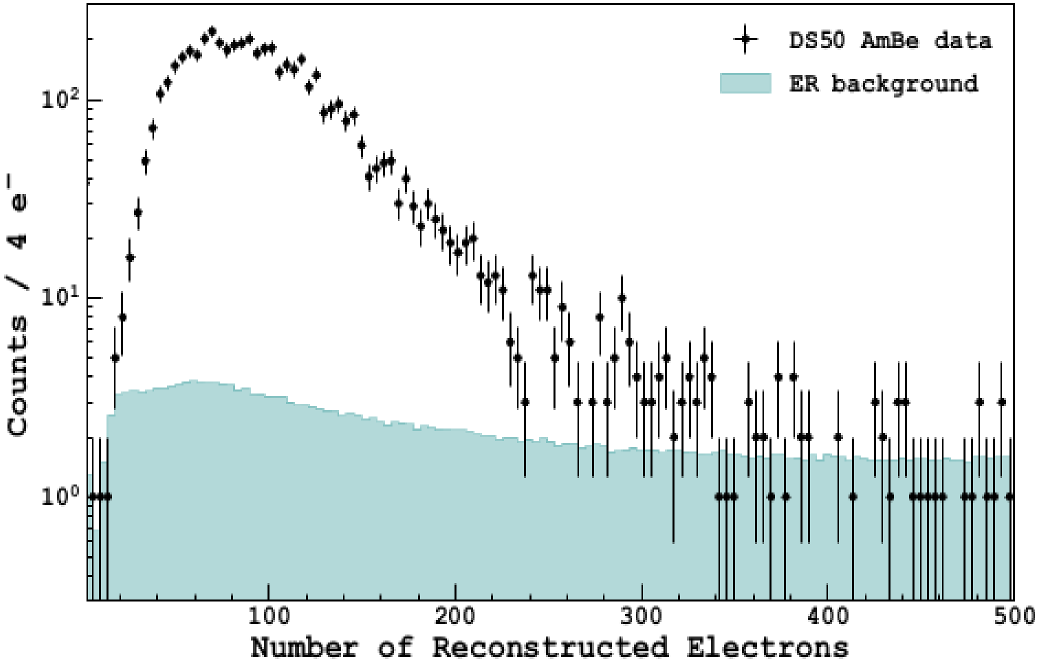
- Non-taggable source
- Stronger data selection to reduce Am γ contamination
- No coincidence with s1



241Am-9Be (AmBe)



- Taggable source
- NR events selected by triple coincidence
- Coincidence with s1



Simultaneous fits of Internal and External Data

External datasets

*** SCENE**

- 4 ionization yields between 16.9 and 57.3keV,
- Drift field: g2=3.1±0.3pe/e-
- Results normalized to DarkSide-50 response by the g2 ratio

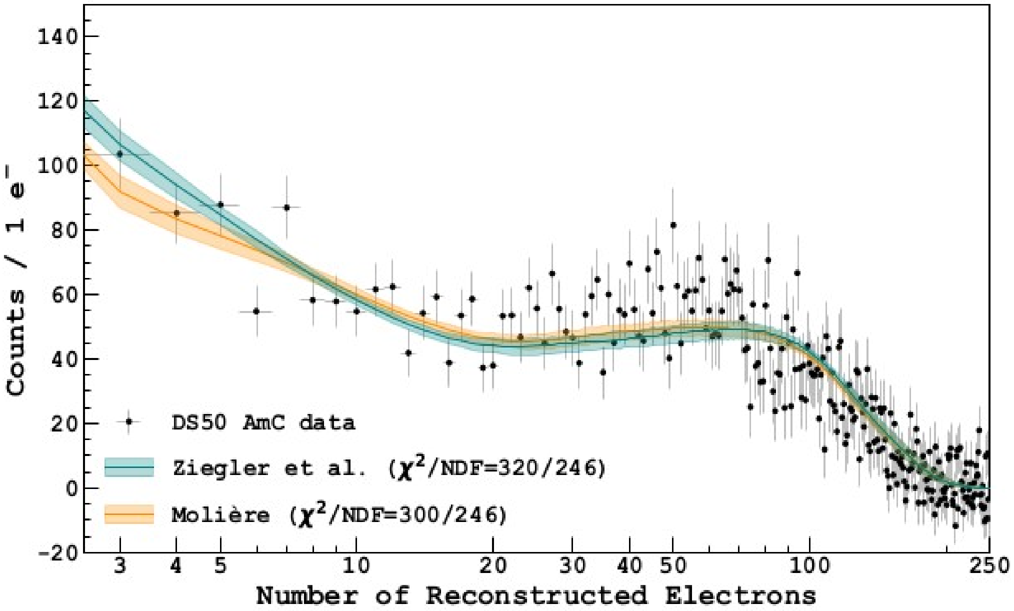
*** ARIS**

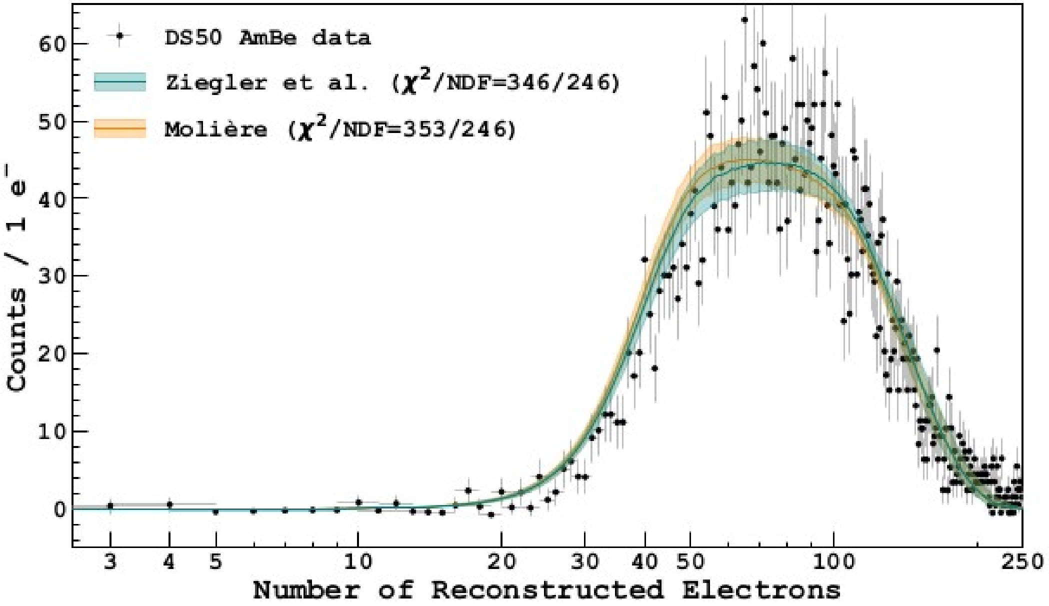
- 8 scintillation responses between 7.1 and 117.8 keVnr
- Same drift field than DarkSide-50
- Results normalized to DarkSide-50 by the ratio between field-off S1 yields
- S2 by the NR S2/S1 ratio within the AmBe dataset (MC simulations)

*** Joshi et al.**

- Ionization yield at 6.7keV
- Correction from the initial publication
- Compared to the final result only

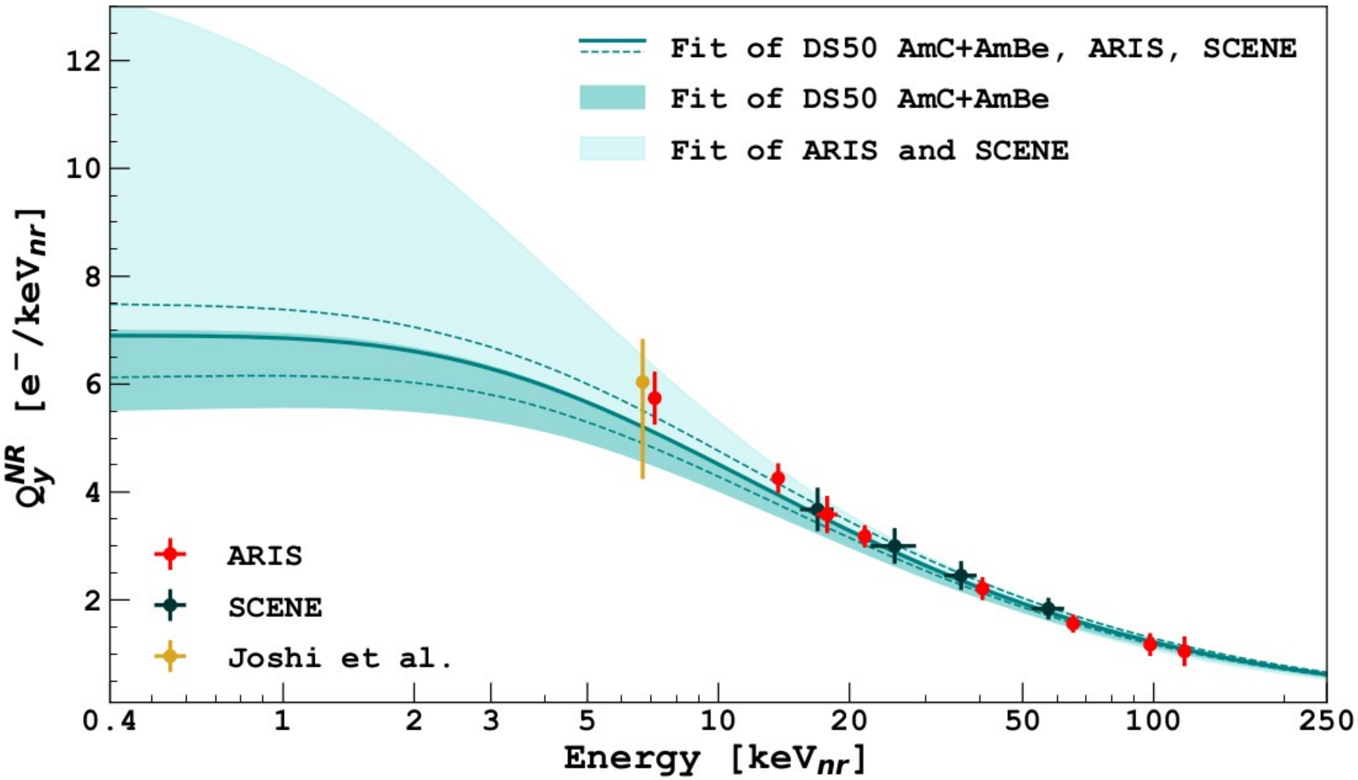
Internal datasets





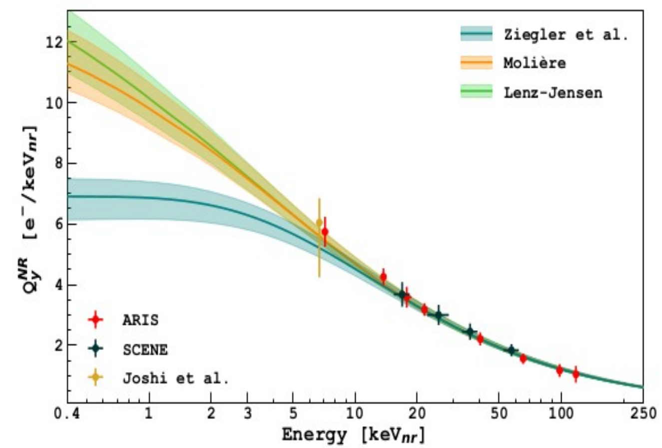
Combined fit

Best parameters:
Cbox = 8.1+0.1-0.2 V/cm
B = 6.8+0.1-0.3 10^3

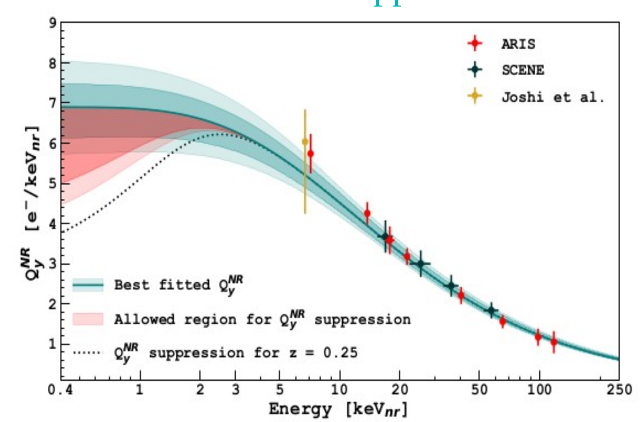


→ Lowest NR threshold in LAr: **3 electrons**
→ Errors from statistical uncertainties and systematics of g2

Dependence of the screening function



Test of the se suppression



See: 10.1103/PhysRevD.104.082005

Conclusion

More details on:
10.1103/PhysRevD.104.082005

Detector response validation

LAr ionization response calibration

ER

Down to ***180eV***$_{er}$
Extrapolated down to
few tens of eV

NR

Down to ***~500eV***$_{nr}$
(model dependant)

New DarkSide-50 lowmass analysis in progress,
stay tuned!

Thank you for your attention!

39Ar

Additional points from rotated energy as:
→ AAr campaign

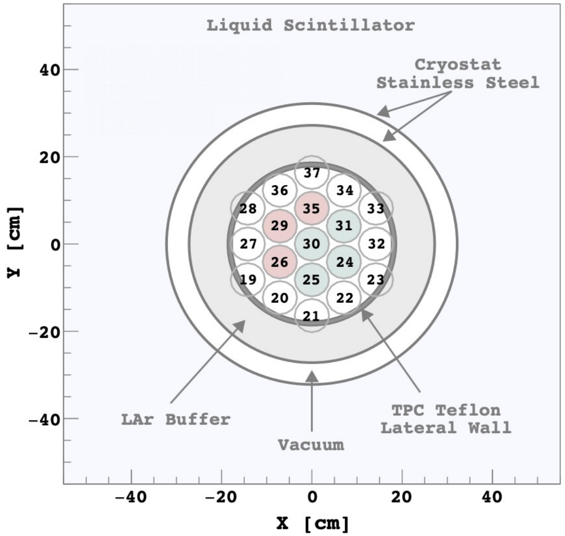
$$E_{er} = w\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$

with w = 19.5±1.0 eV
→ from *doi.org/10.1143/JJAP.41.1538*

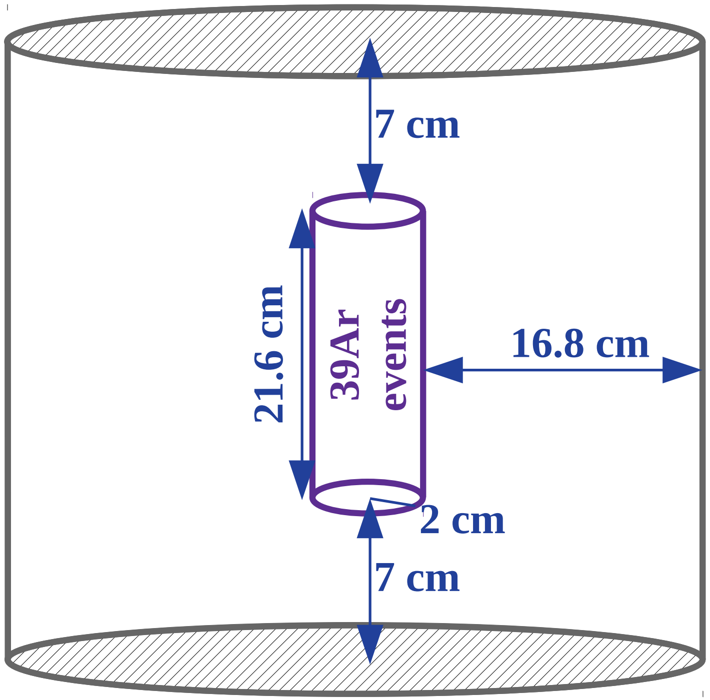
g1 = 0.16±0.01
→ fit of spectral shapes of 133Ba and 57Co [*arXiv:1707.05630v3*]

g2 = 23±1 pe/e- (in central PMTs)
→ from s2 echoes

Event selection:



Fiducialisation of the volume



+ Number of S2 ≤ 1

Nuclear Recoil Ionization Yield

Ionization yield using Thomas-Imel

$$Q_y^{NR} = \frac{N_{i.e.}}{E_{nr}} = \frac{(1-r)N_i}{E_{nr}}$$

Recombination using Thomas-Imel

$$1 - r = \frac{1}{\gamma N_i} \ln(1 + \gamma N_i)$$

with γ = Cbox/F

Numbers of ion as a function of electronic and nuclear stopping power

$$N_i = \beta\, \kappa(\epsilon) = \beta \frac{\epsilon\, s_e(\epsilon)}{s_n(\epsilon) + s_e(\epsilon)}$$

Free parameters of the model

Reduced energy

$$\epsilon = \frac{a}{2e^2 Z^2} E_{nr}/\text{keV} \simeq 0.0135\, E_{nr}/\text{keV}$$

Electronic stopping power

$$s_e(\epsilon) = \frac{0.133\, Z^{2/3}}{A^{1/2}} \sqrt{\epsilon} \simeq 0.145\, \sqrt{\epsilon}$$

Nuclear stopping power based on Universal Screening Function

Other functions tested

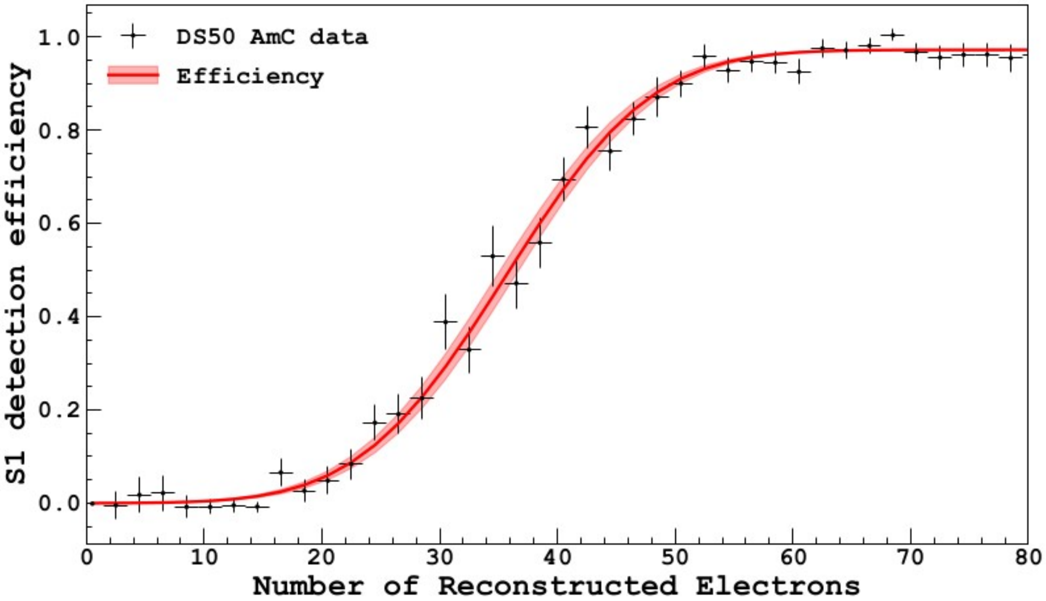
$$s_n(\epsilon) = \frac{\ln(1 + 1.1383 f_Z\, \epsilon)}{2[f_Z\, \epsilon + 0.01321 (f_Z\, \epsilon)^{0.21226} + 0.19593 (f_Z\, \epsilon)^{0.5}]}$$

Test of two extreme models for intrinsic resolution

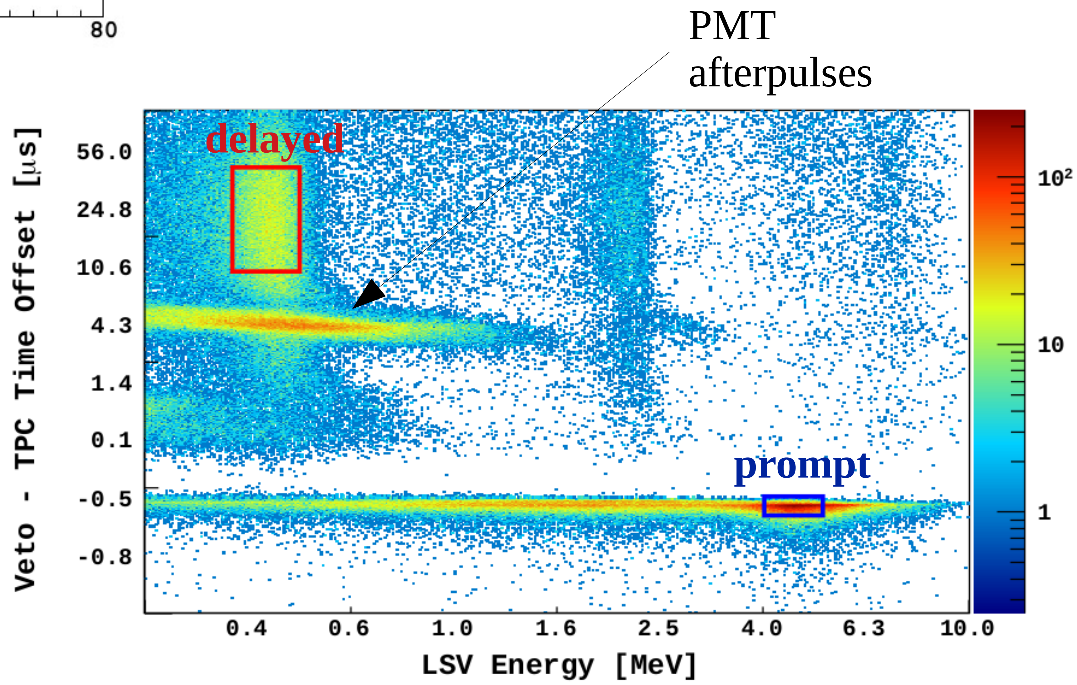
1/ Binomial fluctuations in energy quenching
2/ No fluctuations in energy quenching

→ Negligible difference: use of 2/

Nuclear Recoil Ionization Yield: AmBe



S1 detection efficiency:
- Ratio of ER contamination subtracted to AmC samples for S2only and for S1+S2
- Error function fit

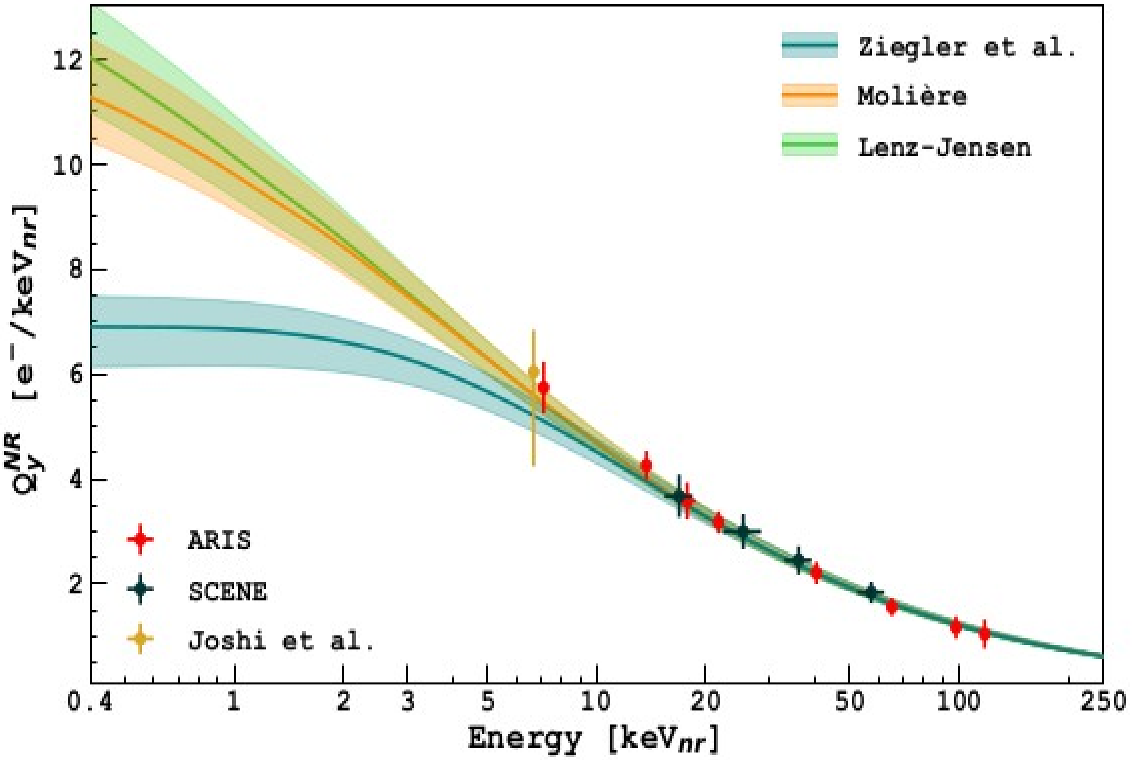


(Detectors difference trigger offset: -550 ns)

Dependence on the screening function

Different nuclear stopping power models

$$s_n(\epsilon) = \frac{1}{\epsilon}\int_0^{\epsilon} f(\eta)\, d\eta \qquad \text{with} \qquad f(\eta) = \frac{\lambda\,\eta^{1-2m}}{\left(1+\left[2\,\lambda\,\eta^{2(1-m)}\right]^{q}\right)^{1/q}}$$



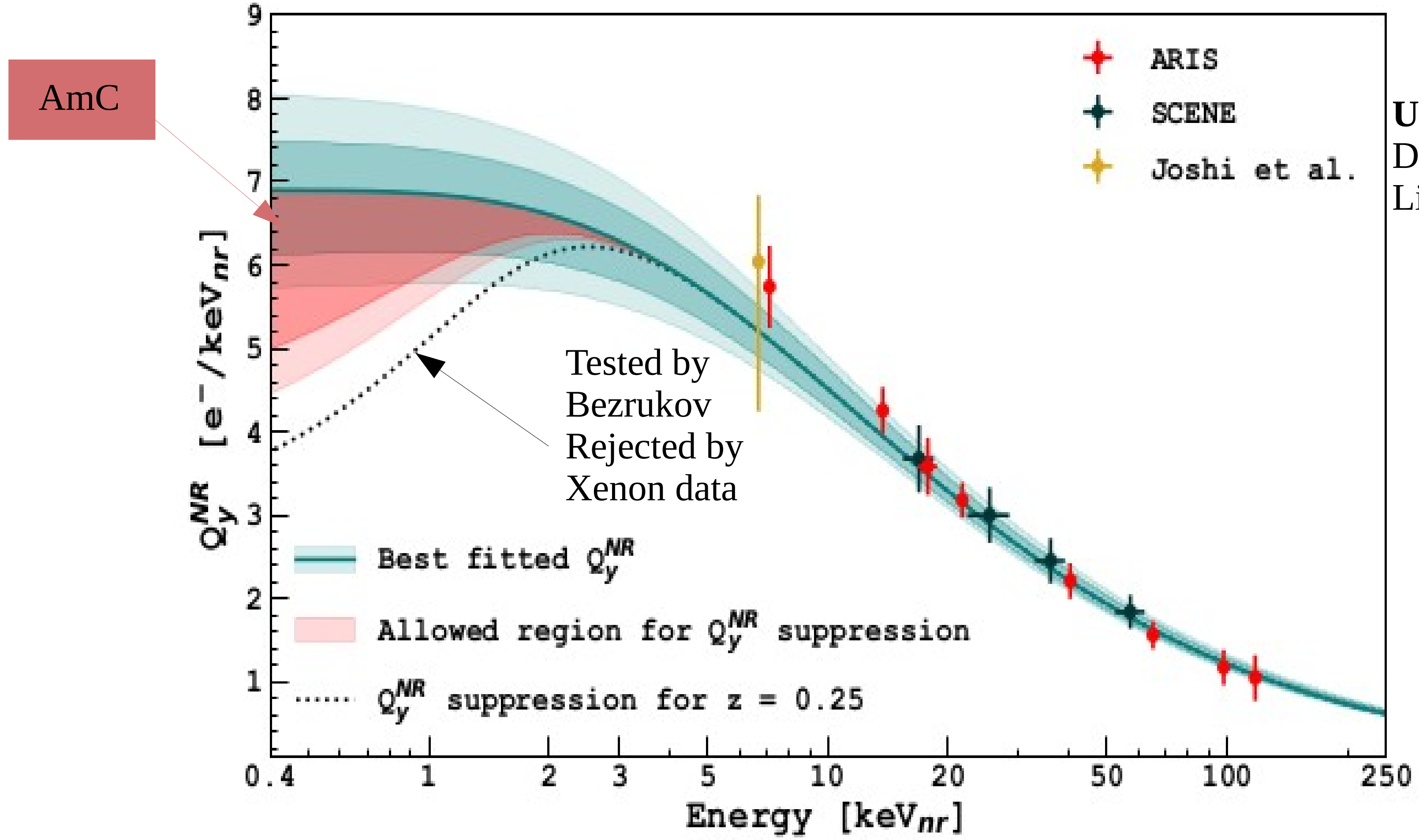
Ziegler et al. yields the **lowest ionization yield** in the WIMP's interest region
→ most conservative result

Se suppression

Impact of low energy se suppression (from arXiv:1011.3990)

$$F(v/v_0) = 1/2\ (1 + \tanh(50\ \epsilon - z)) \quad \text{with} \quad F(v/v_0) \rightarrow 1 \text{ for } z \rightarrow -\infty$$

and z= 0.25: hypothesis of Coulomb effects inside se



Uncertainty bands
Dark area: 1σ
Light area: 2σ

→ Suppression **not compatible** with the LXe (arXiv:1011.3990) and AmC dataset (z>0.04 excluded at 2σ)