DarkSide-50

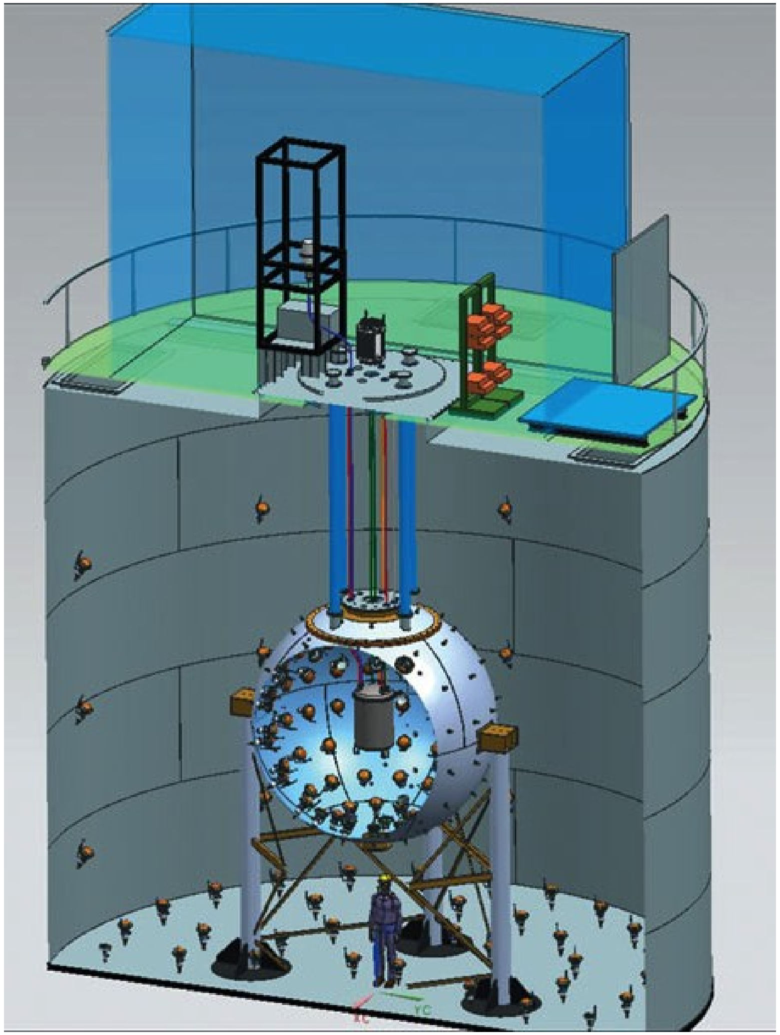
Characterisation of the LAr ionization response in the keV regime

Julie Rode on behalf of the DarkSide IN2P3

01/12/2021

DarkSide-50 experiment

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



S1 Yields:

- S1 Yield ~7.9 pe/keV at null field
- S1 Yield **~7.0 pe/keV** at 200 V/cm at 41 keV_e
- Ionization Work Function ~ 23.4 eV

Electron lifetime > 10 ms

Maximum drift time: 376 ms at 200 V/cm

Drift velocity: 0.93 mm /ms

Position reconstruction:

- Resolution in Z **~1 mm**
- Resolution in XY **<1 cm**

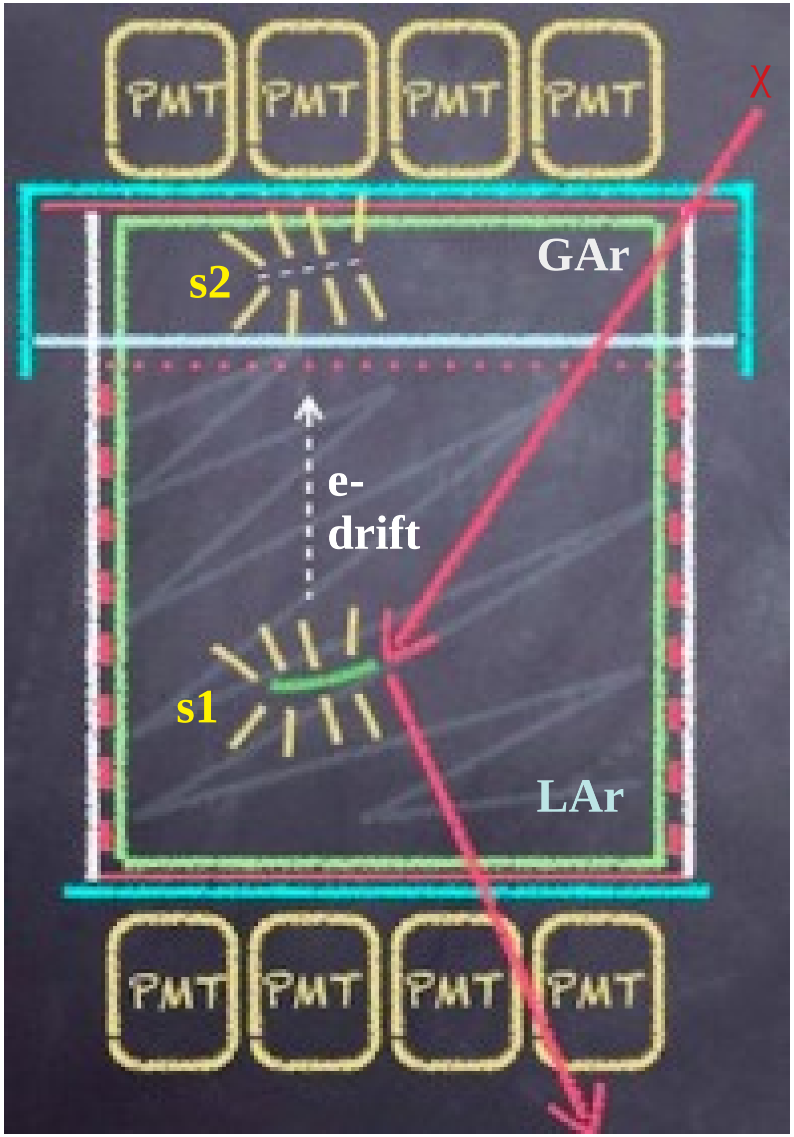
^{39}Ar depletion factor in UAr ~**1400** (~0.7 mBq/kg)

Full characterization of the detector response with **Monte Carlo** (JINST 12 (2017) P10015)

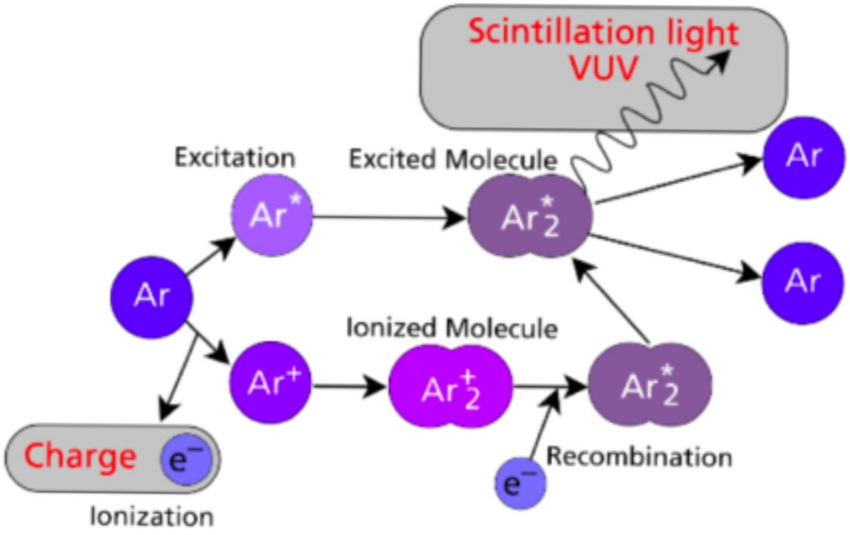
38 PMTs

DarkSide-50 experiment

Dual-phase LAr TPC



Argon scintillation and ionisation mechanisms



DarkSide-50
- S1 light collection efficiency: 0.16±0.01 → ***low efficiency***
- S2 yield: 23±1 pe/e- → ***amplification***

10.1103/PhysRevLett.121.081307

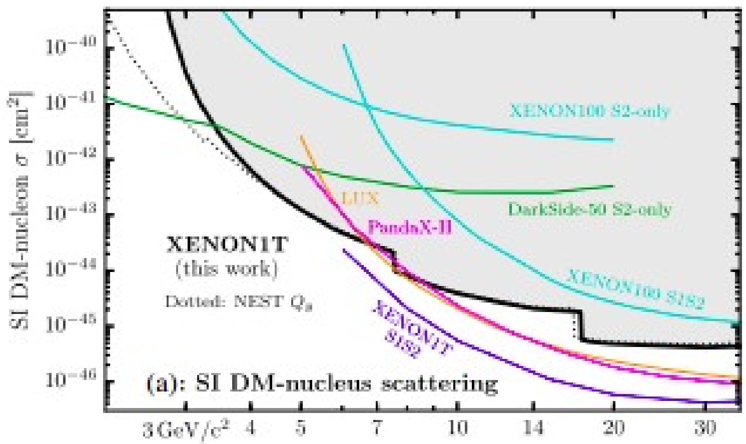
keV regime accessible using s2 only

Right figure: http://darkmatter.ethz.ch/

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

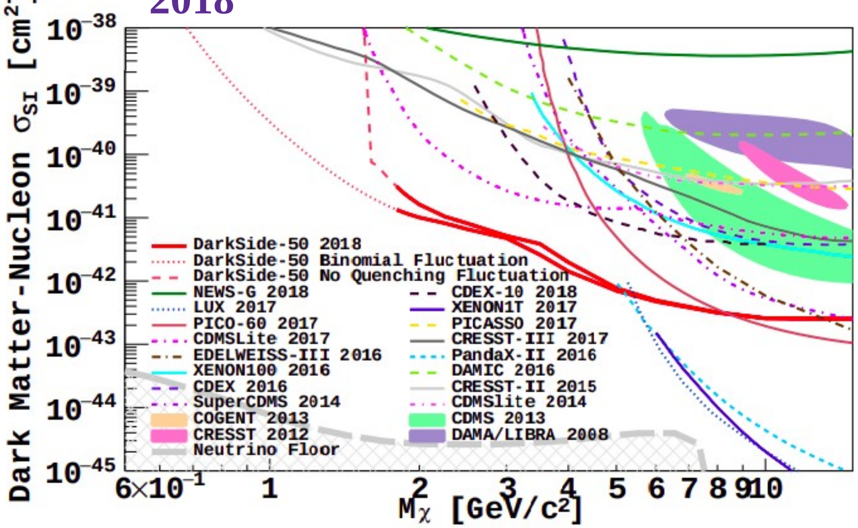
Noble liquid detectors:

- 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

2018



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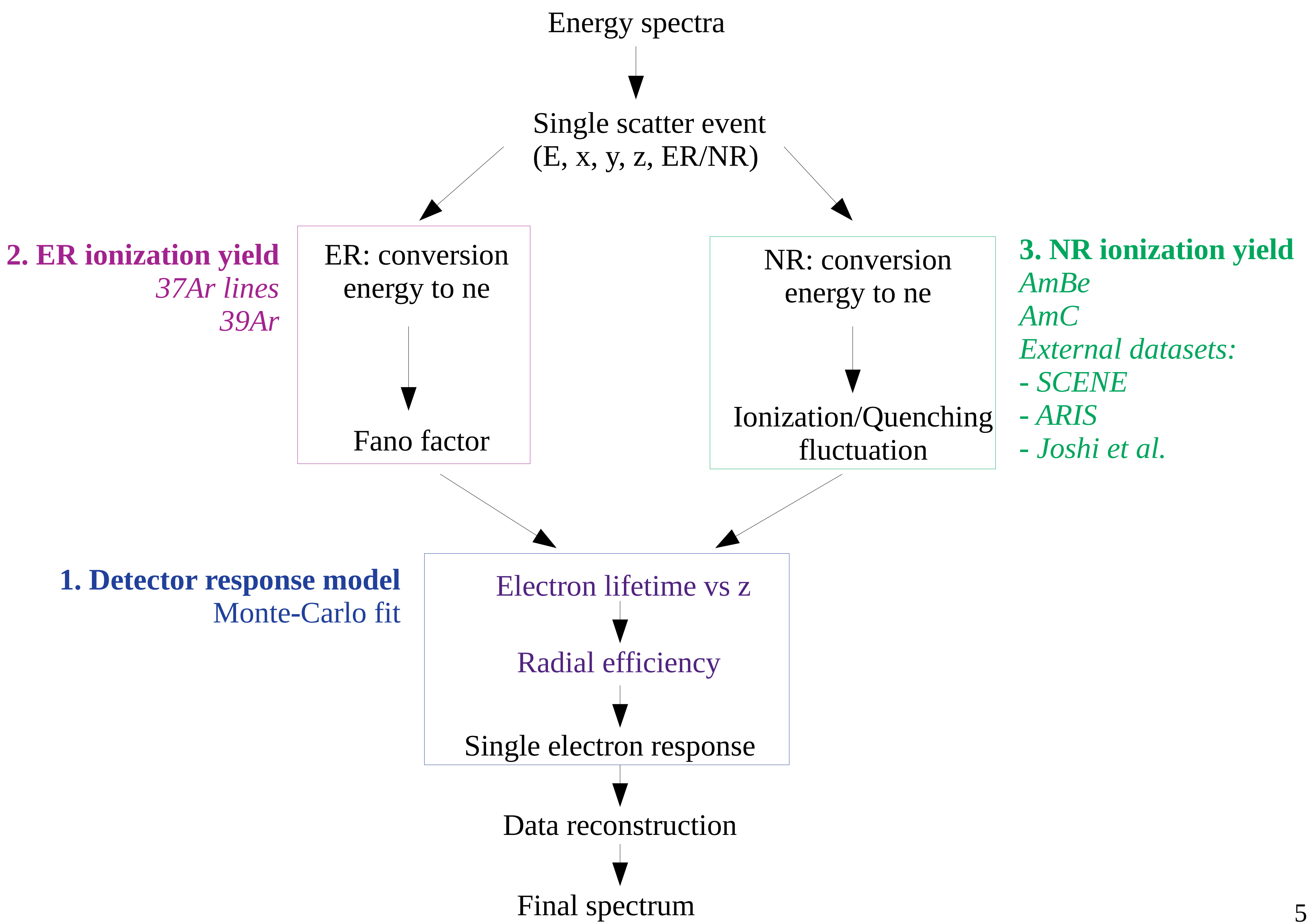
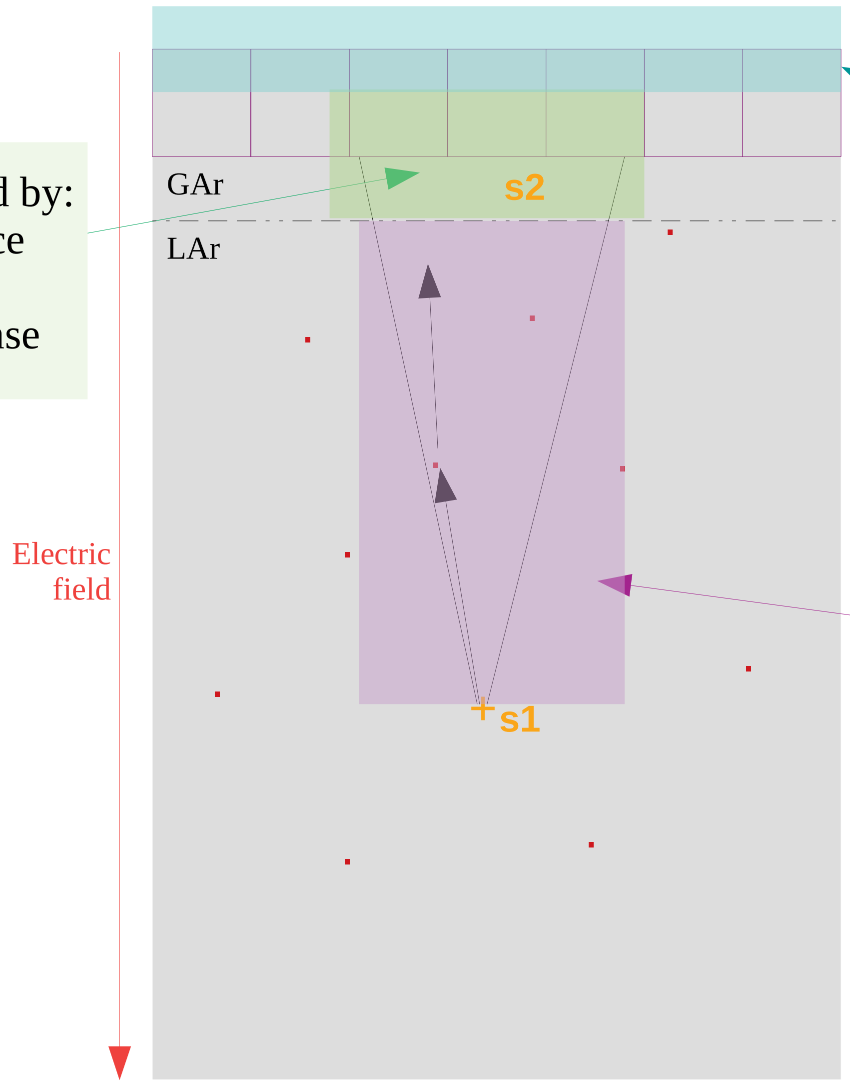
Response model



Instrumental effects

Monte-Carlo modelling of the detector response in S2

Resolution dominated by:
- Electroluminescence fluctuations
- PMT charge response



Radial distortion

Electron lifetime

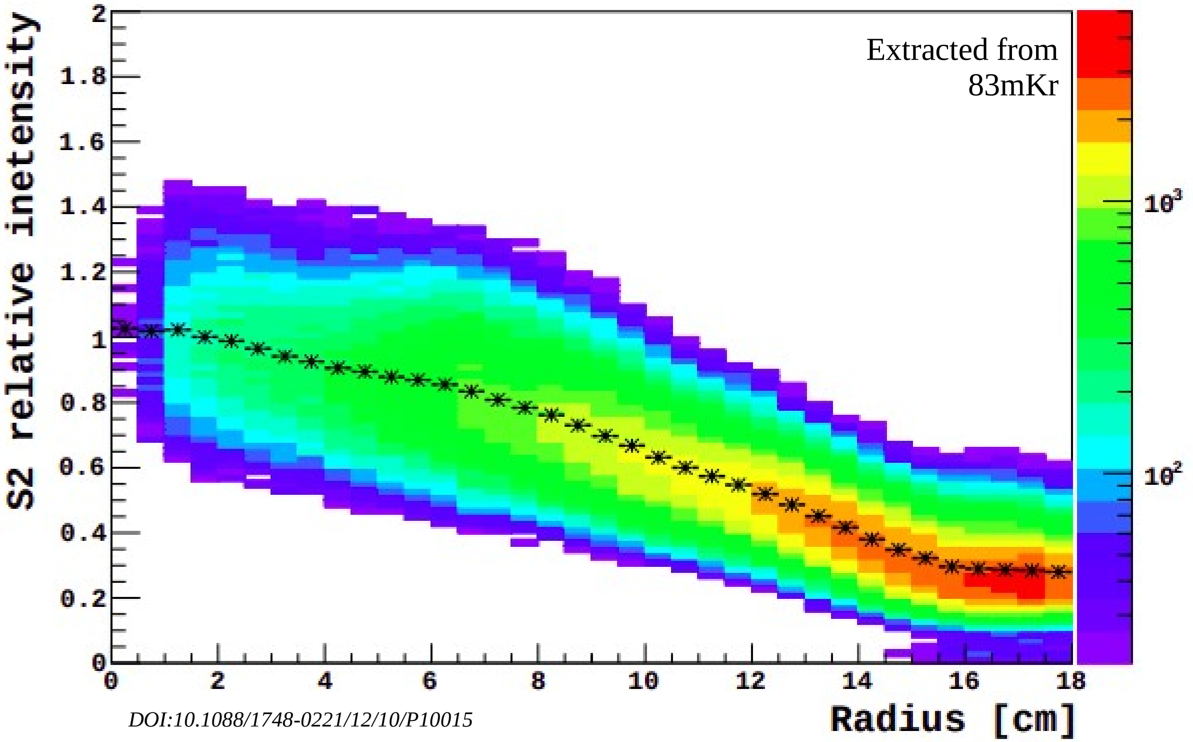
- Capture from **impurities** along the drift
- Measured > 10 ms
- Maximal distortion of **a few percent** wrt the maximal tdrift

Radial distortion and correction

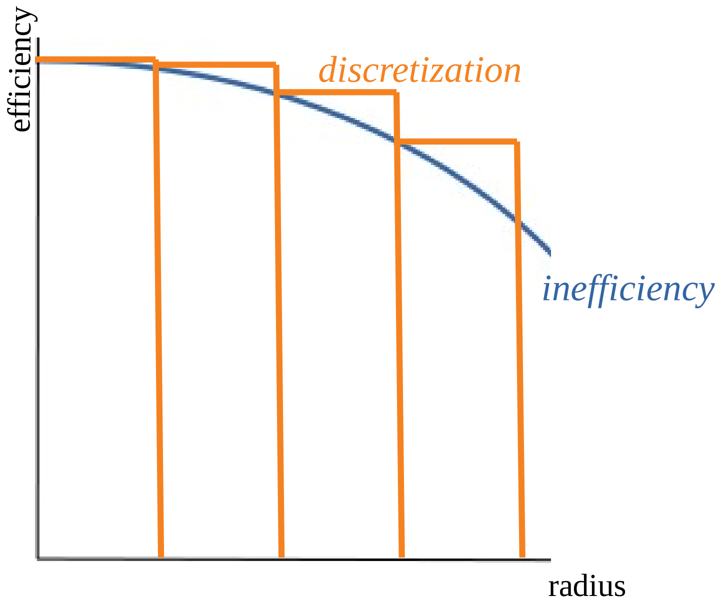
Low S2 pulse: XY reconstruction inefficient

⇩

XY estimator: top PMT position with max light fraction



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



Distortion induced by either

→ non uniformity of the TPB thickness on the top fused silica window

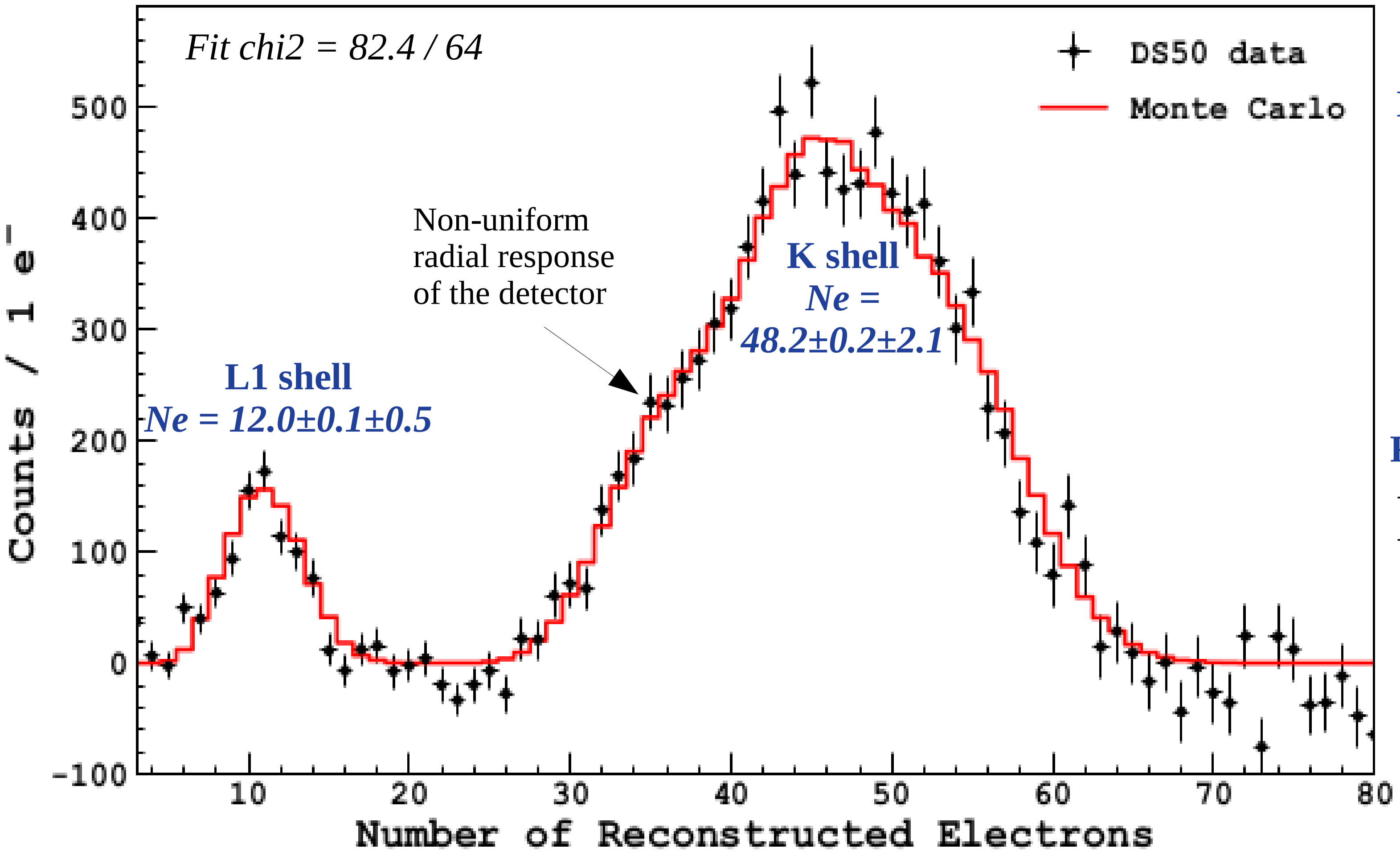
→ sagging of the window causing a variation in the GP thickness

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**

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*

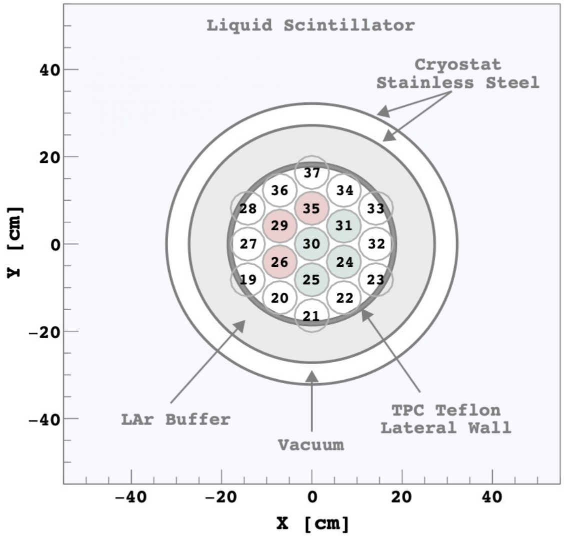
g1 = 0.16±0.01

→ fit of spectral shapes of 133Ba and 57Co [*arXiv:1707.05630v3*]

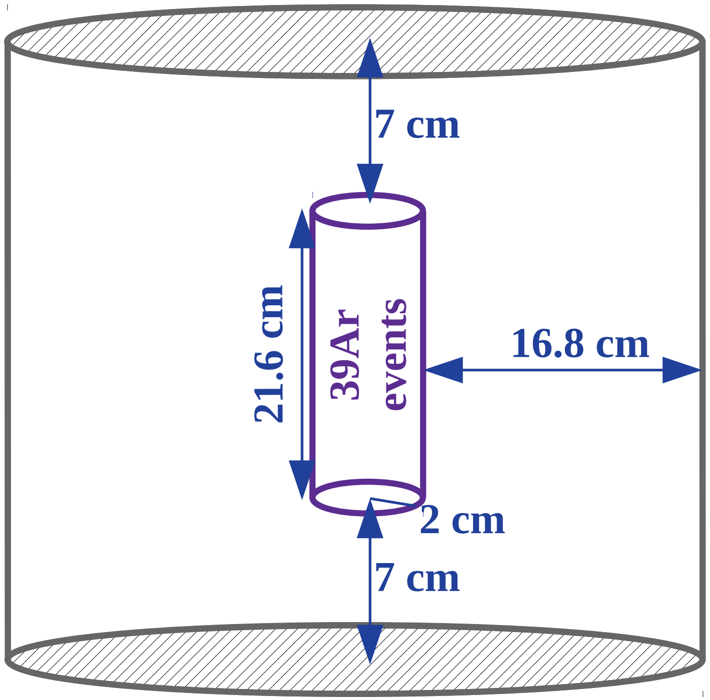
g2 = 23±1 pe/e- (in central PMTs)

→ from s2 echoes

Event selection:



Fiducialisation of the volume



+ Number of S2 ≤ 1

Electron Recoil Ionization yield

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

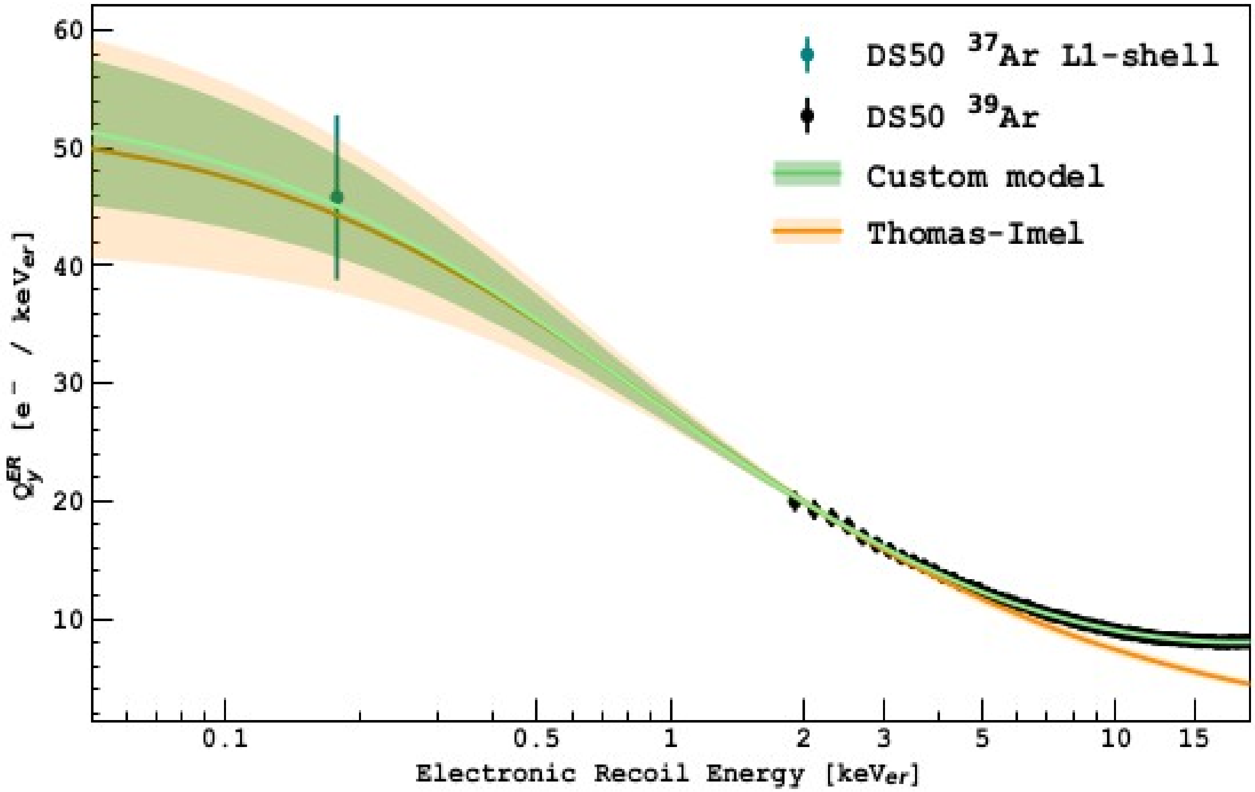
$$Q_y^{ER} = \frac{\ln(1 + \gamma\,\rho\,E_{er})}{E_{er}} \left(\frac{1}{\gamma} + p_0\,(E_{er}/\mathrm{keV}_{er})^{p_1} \right)$$

γ = Cbox/F
with F the drift field

Thomas-Imel model

Custom model:
extension above 3keVer

→ 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

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

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

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

241Am-13C (AmC)

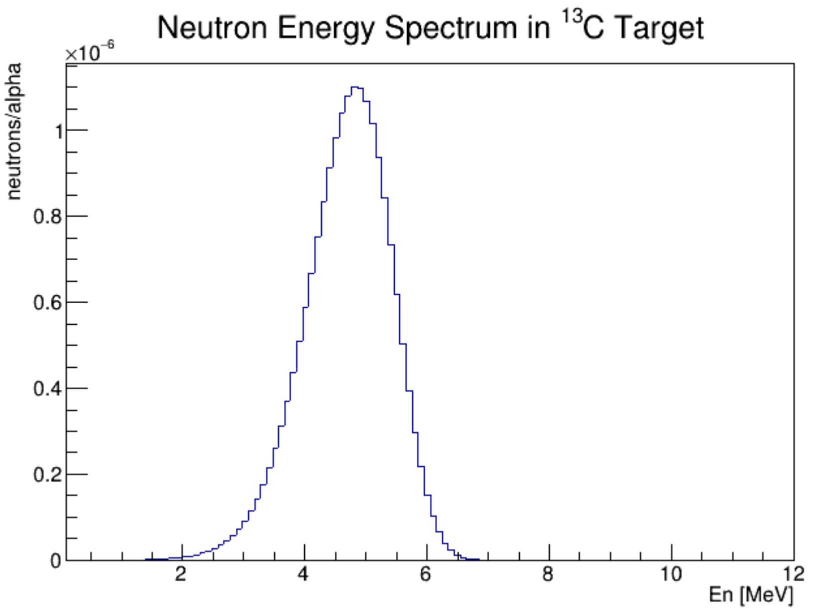
- Neutron source via (α, n) on 13C
- Almost monochromatic
- No γ coincidence
- High rate of low energy γ from AmC

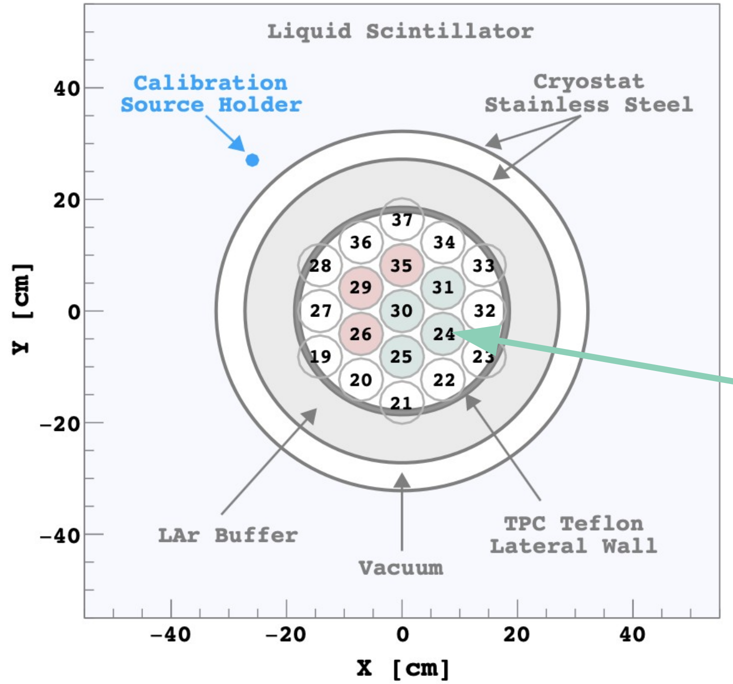
241Am activity ~ 3.6 Mbq

→ pile-up X-rays

→ γ's able to contaminate the active volume

  - γ's at 59.5keV, BR=35.9 : absorbed in the LAr buffer
  - γ's > 99keV, BR=10-9 : MC simulation





AmC dataset: 19.97 days

4 central PMTs: 30, 31, 24, 25

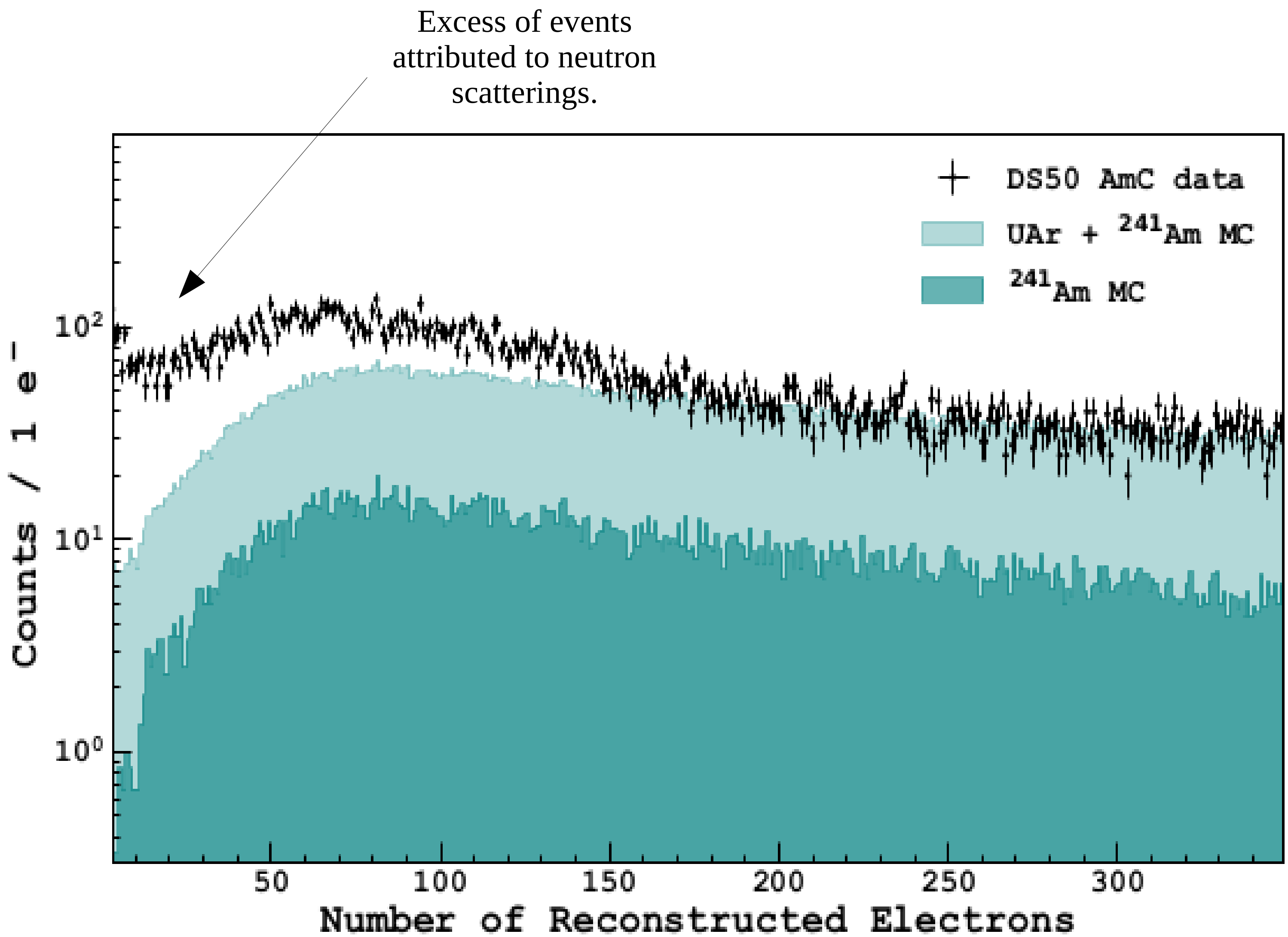
UAr normalized by the lifetime

Am γ contamination reduced

(5.2% - MC simulation)

Nuclear Recoil Ionization Yield

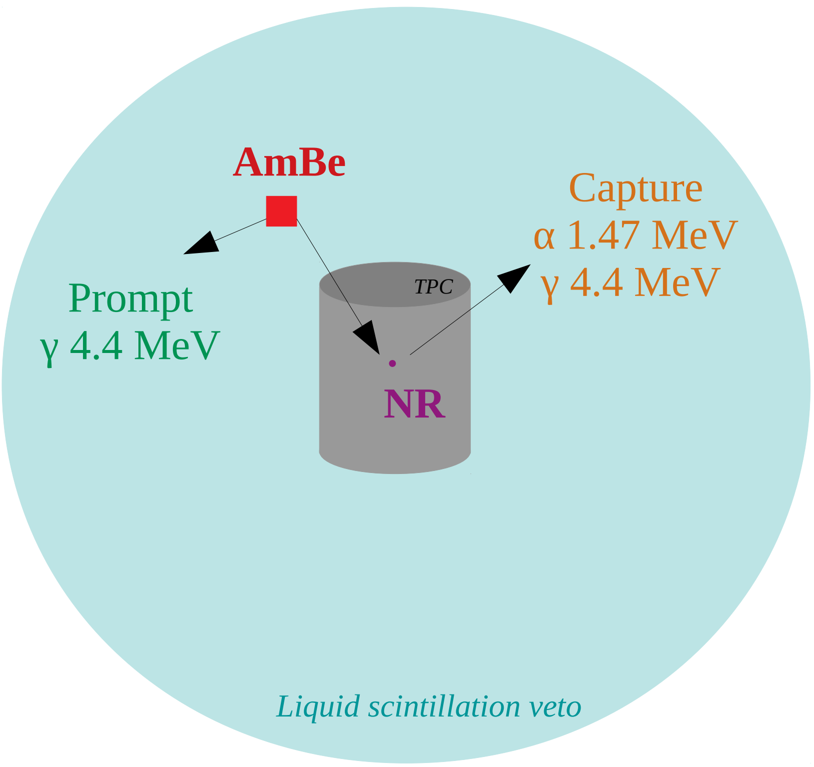
→ Spectrum of uncorrelated events from G4DS MC simulations
→ Uncorrelated events are subtracted to the data
→ Not dependant on s1 efficiency

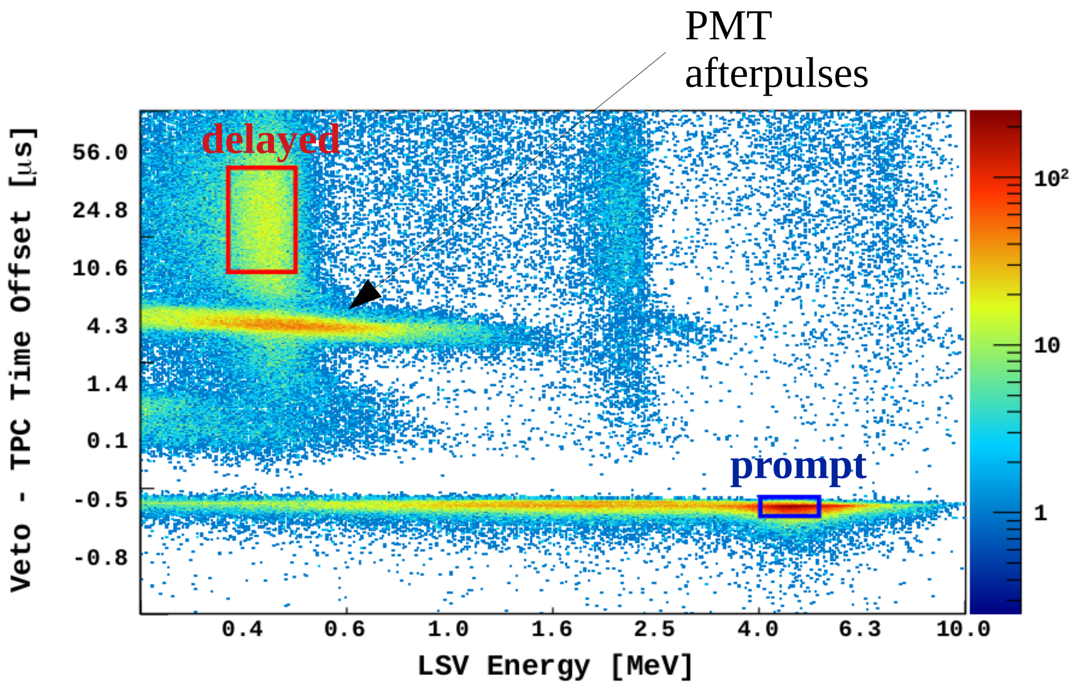


Nuclear Recoil Ionization Yield

241Am-9Be (AmBe)

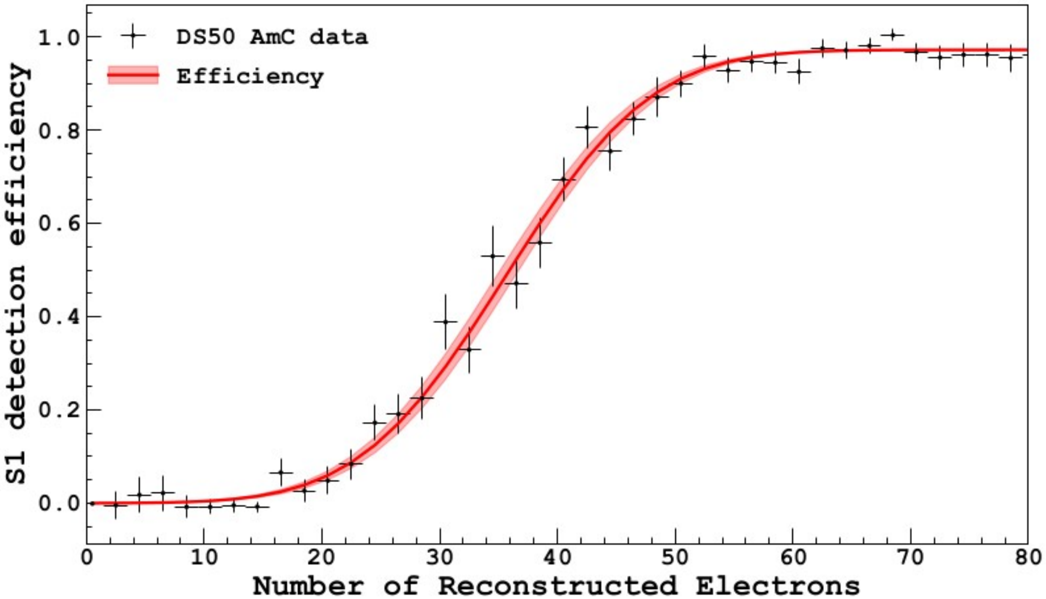
→ Neutron and γ source
→ Taggable source
→ Non monochromatic
→ NR events selected by **triple coincidence** in the TPC
→ Coincidence with s1: inefficient when s1 not detected





(Detectors difference trigger offset: -550 ns)

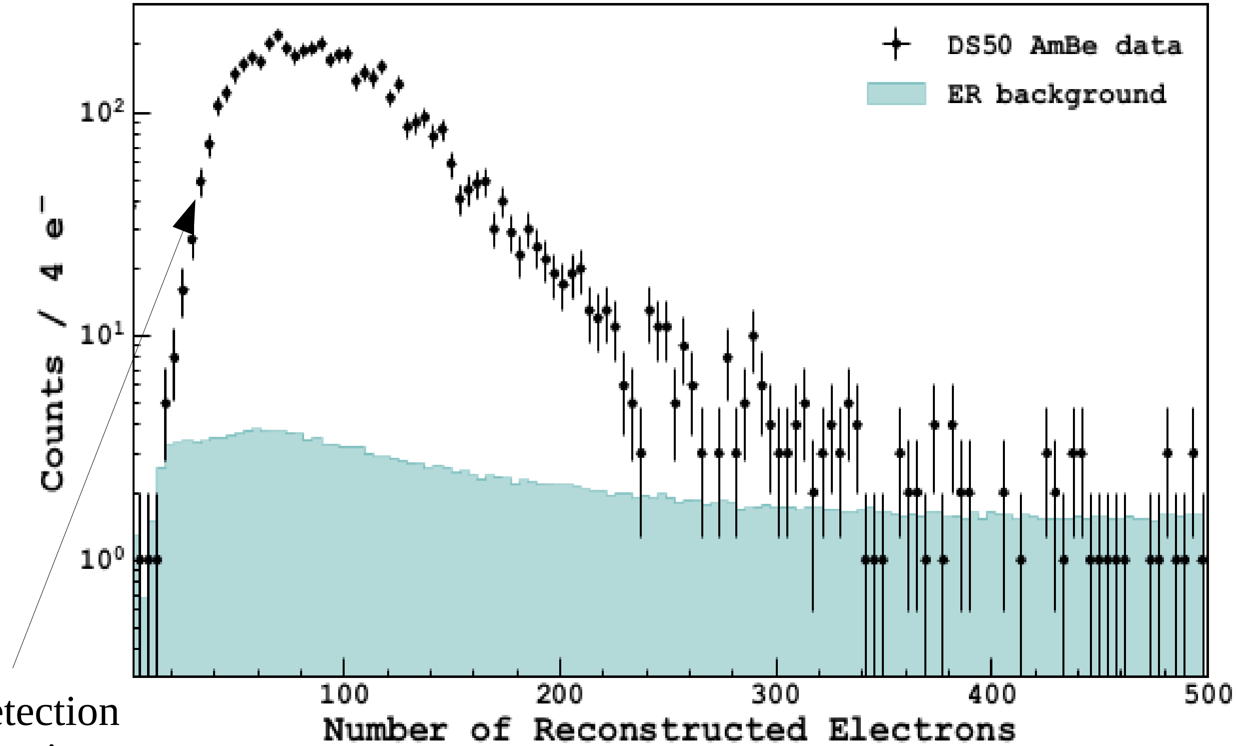
Nuclear Recoil Ionization Yield



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

→ Electron recoil background assessed using a control region where no NR events are expected

→ UAr spectra normalized and retrieve from the AmBe one



S1 detection efficiency impact

Nuclear Recoil Ionization Yield

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**

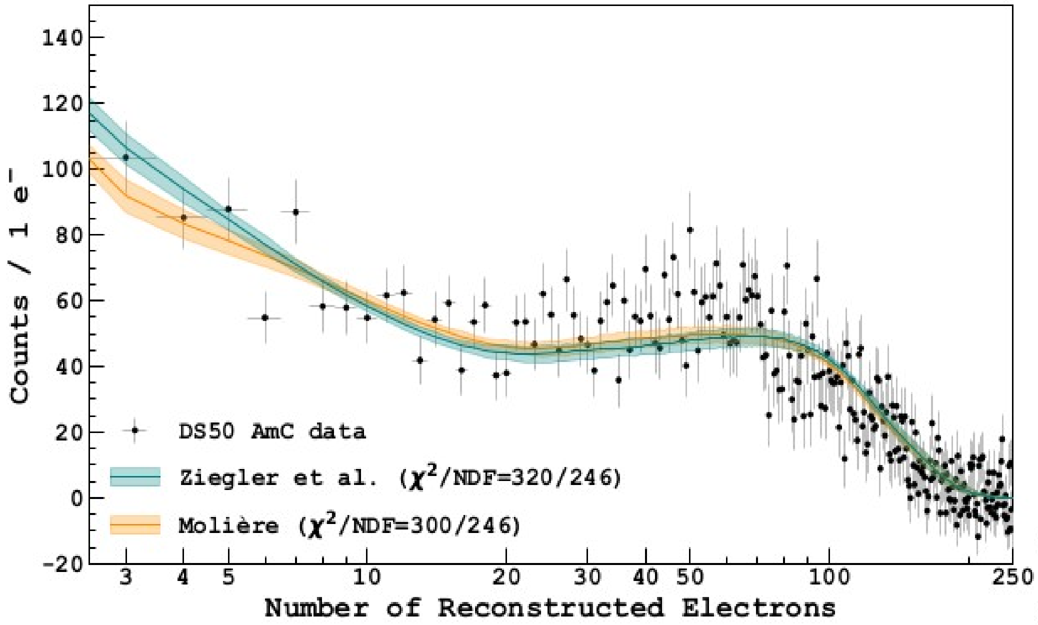
- 8 scintillation response between 7.1 and 117.8 keVnr
- Same drift field than DarkSide-50
- Results normalized to DarkSide-50 by the ratio between field-off S1 yields
- S2 by the NR S2/S1 ratio within the AmBe dataset (MC simulations)

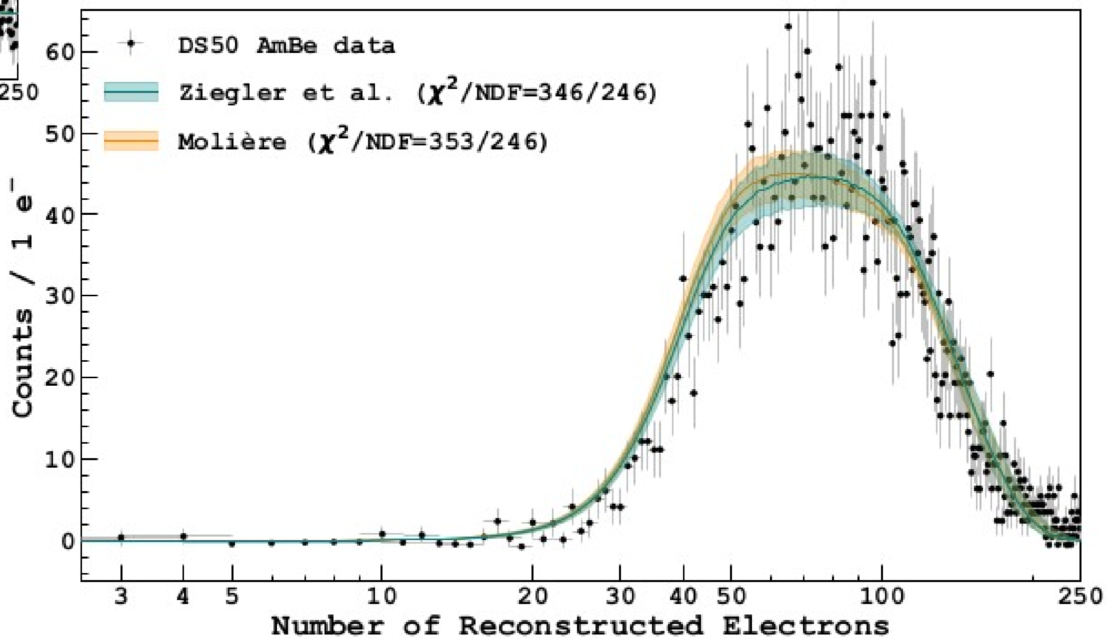
*** Joshi et al.**

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

Nuclear Recoil Ionization Yield

Simultaneous fit of DS-50 AmC , DS-50 AmBe, ARIS, SCENE

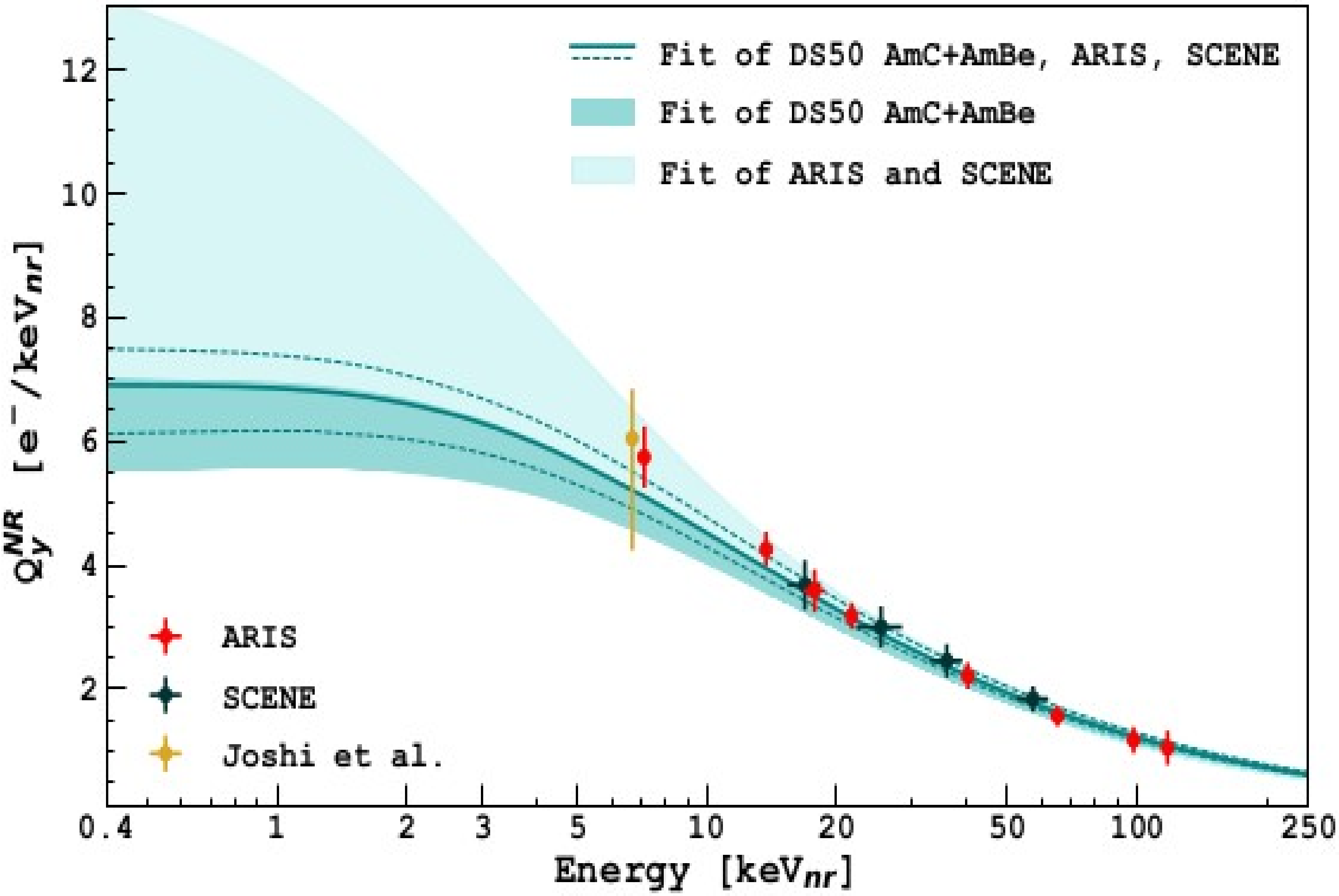




1σ uncertainty bands

Nuclear Recoil Ionization Yield

Combined fit



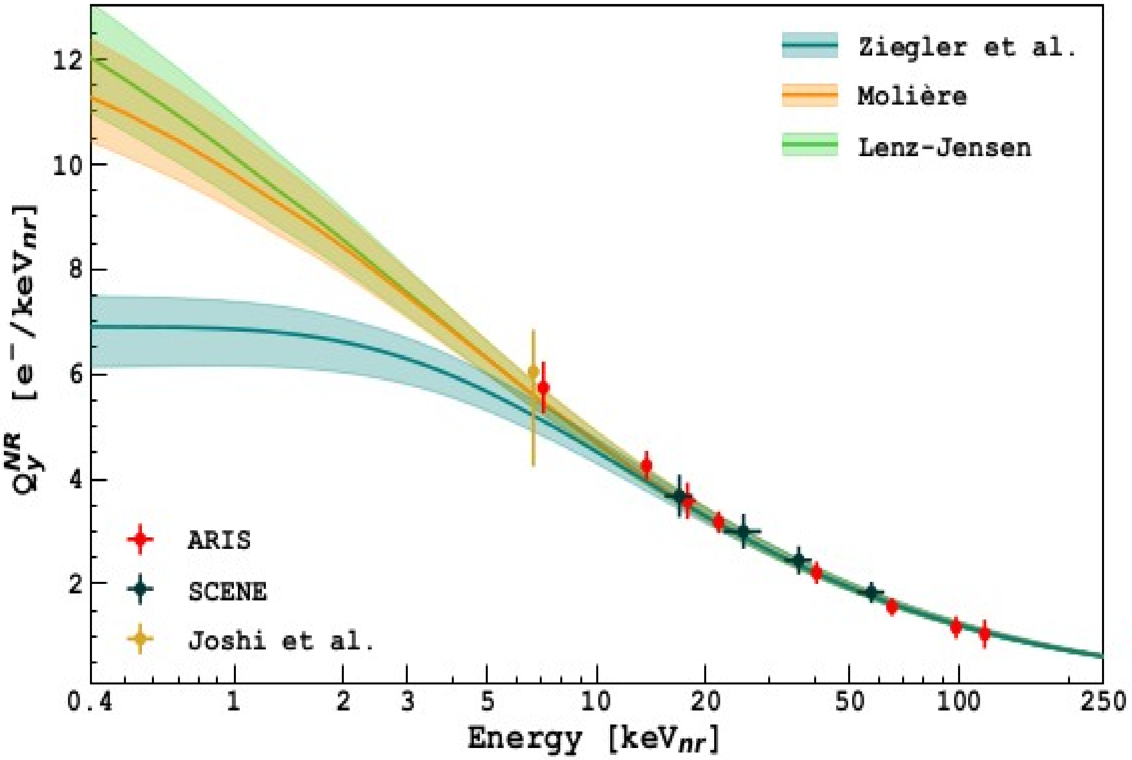
Best parameters:
Cbox = 8.1+0.1-0.2 V/cm
B = 6.8+0.1-0.3 10^3

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

Dependence on the screening function

Different nuclear stopping power models

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



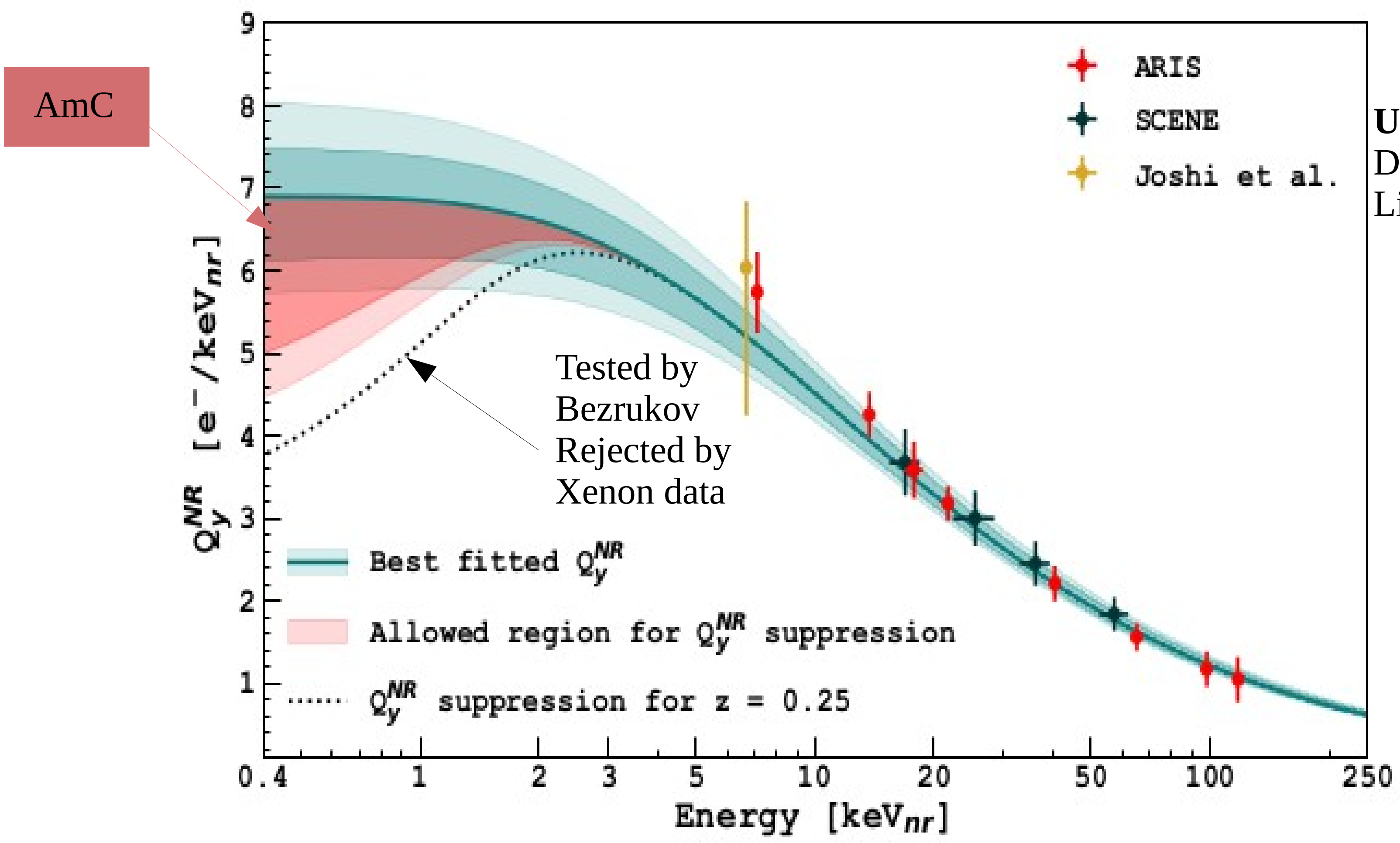
Ziegler et al. yields the **lowest ionization yield** in the WIMP's interest region
→ most conservative result

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)

Conclusion

- IN2P3 leadership in low mass WIMP search

Published paper: 10.1103/ PhysRevD.104.082005

- Validation of the detector response

- Characterisation of the **ER** LAr ionization response calibration **down to 180eV**$_{er}$, extrapolated **down to few tens of eV**

- Characterisation of the **NR** LAr ionization response calibration **down to ~500eV**$_{nr}$ (model dependant)

- Improvement of the DarkSide-50 low-mass sensitivity

- Bases for further liquid argon experiments

- Exploit this calibration expertize for DS20k and further extend it with hardware contributions *(see Pascal talk on Monday)*

- Further improvement thanks to measurement with neutron beams

Thank you for your attention!