Low Mass WIMP search with DarkSide-50, a liquid argon dual phase TPC experiment

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0- Short Preamble
1- Dark Matter WIMP Search
2- Low Mass WIMP Search with DarkSide-50
3- Status / prospects with DarkSide-20k
4- Conclusions

Preamble (1/2)

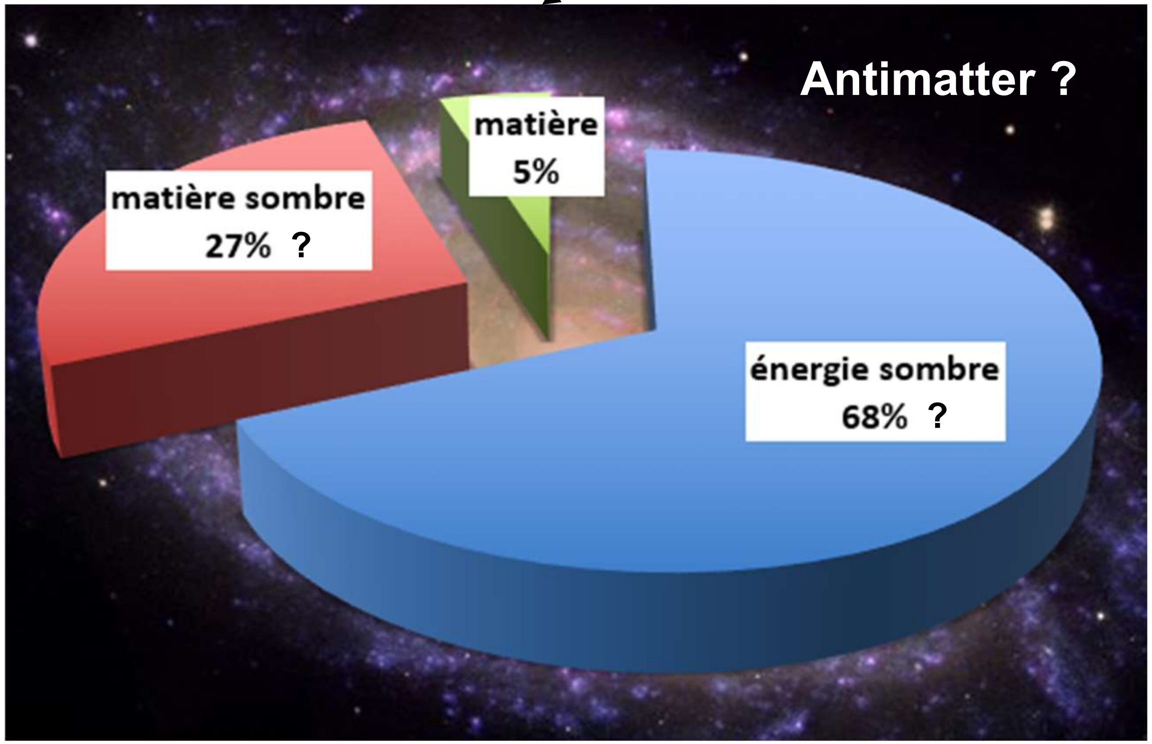
- In XXth century, problems solved by postulating a new particle

– QM and Special Relativity:	Antimatter
– Nuclear spectra:	Neutron
– Continuous spectrum in β decay:	Neutrino
– Nucleon-nucleon interactions:	Pion
– Absence of lepton number violation:	Second neutrino
– Flavour SU(3):	Ω^-
– Flavour SU(3):	Quarks
– FCNC:	Charm
– CP violation:	Third generation
– Strong dynamics:	Gluons
– Weak interactions:	$W^\pm$, Z^0
– Renormalizability:	H

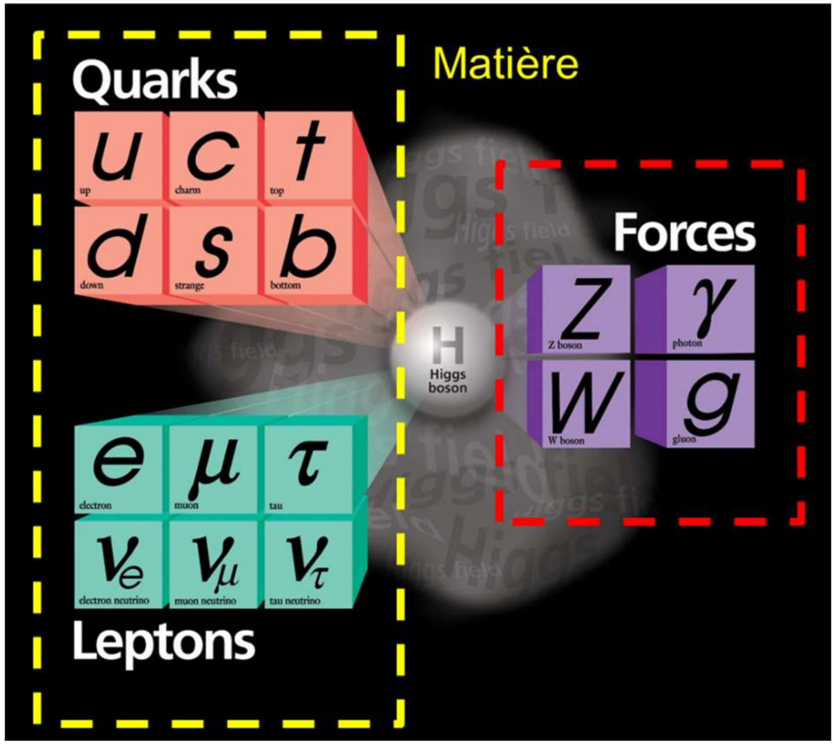
Courtesy of J. Ellis

Preamble (2/2)

- In XXI[th] century, problems from observational cosmology



Standard Model (SM) of Particle Physics

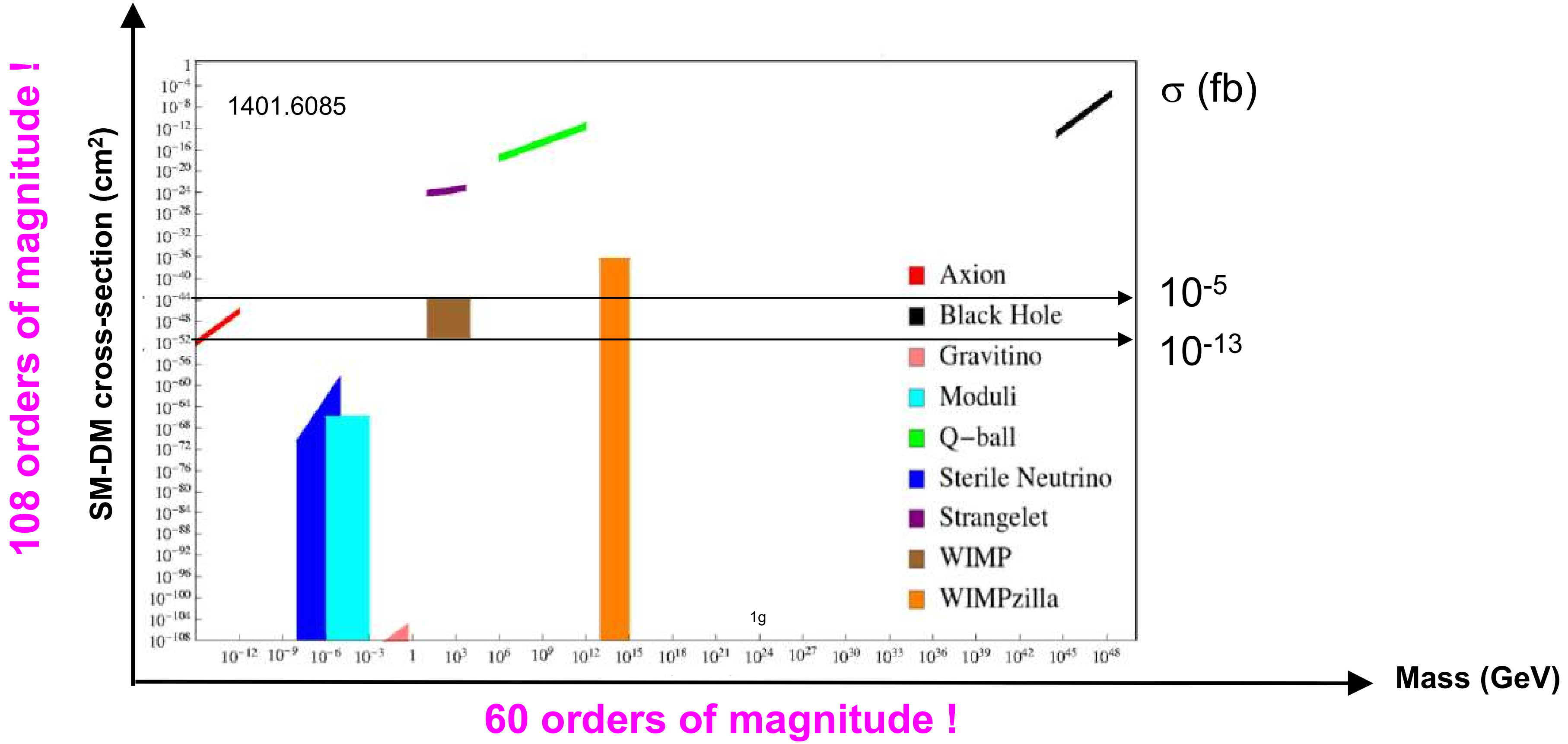


No particle in SM has the required properties to be Dark Matter *(stable, non-relativistic, very feebly interacting)* → all candidates come from Beyond SM theories

→ Dark Matter = puzzle of fundamental physics … that calls for new physics

Dark Matter (DM) Search

❑ **Many dark matter candidates in a gigantic phase space**

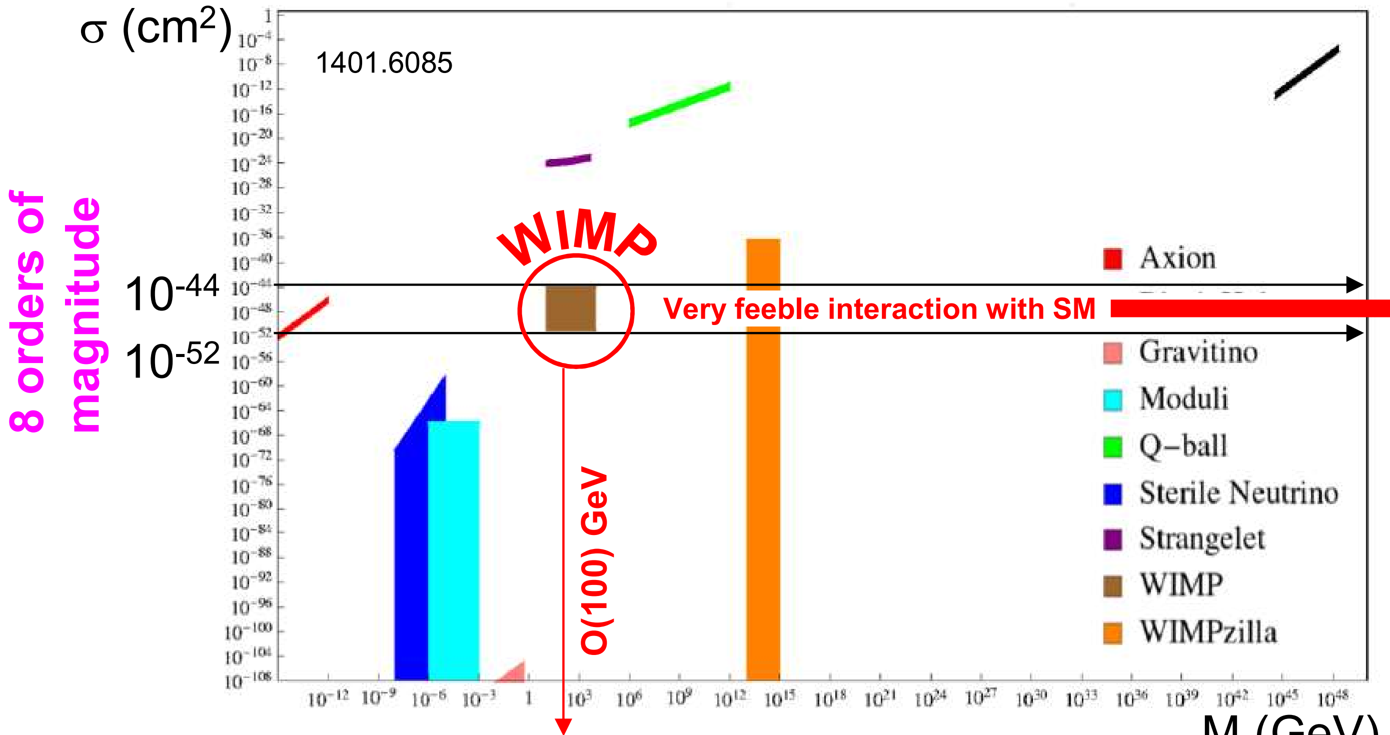


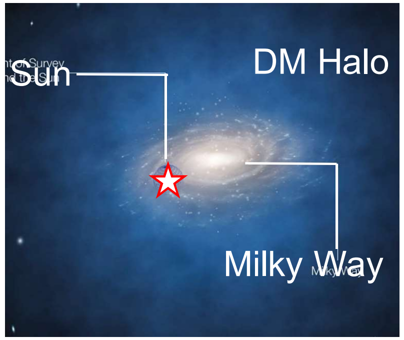
Only a few of them are **also strongly motivated by particle physics**, i.e. solving current theoretical SM problems → **WIMP** *(gauge hierarchy pb)*, **Axion** *(~no CP violation in strong interaction)*, **Sterile neutrino** *(neutrino mass and mixing)*

DM WIMP Search (1/4)

❑ Experimental challenges in the direct search for WIMP dark matter

- WIMP = Weakly Interactive Massive Particle*





… balanced by the abundance of DM particles** stream from our galaxy halo → O(0.1) GeV/cm³ moving at v=230 km/s wrt earth

**produced in very early Universe, but directionless

4 orders of magnitude

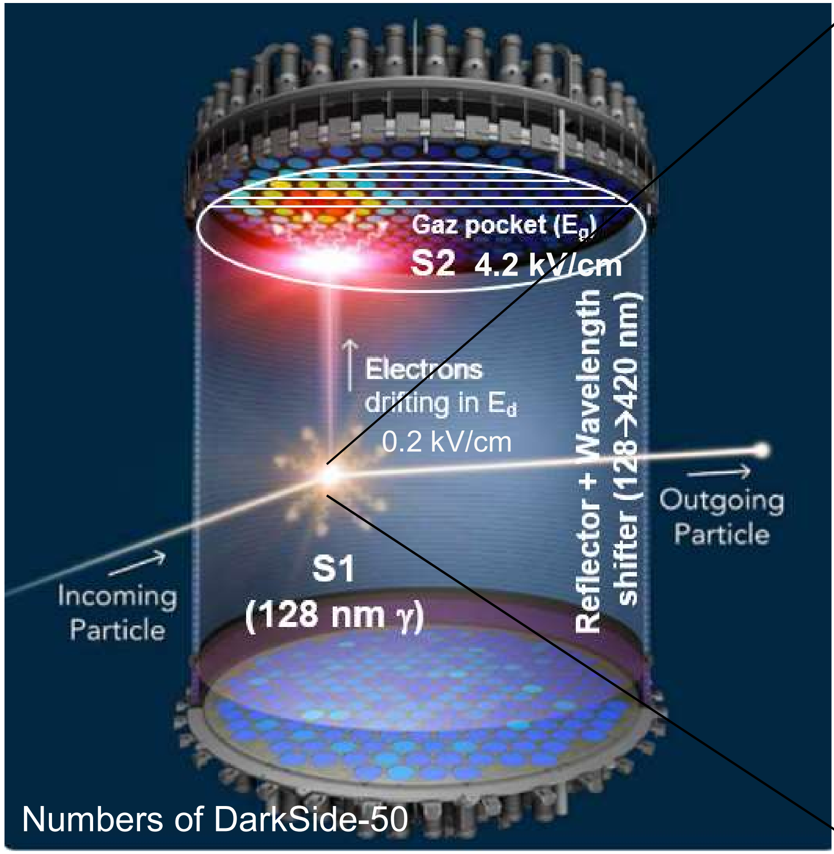
- O(10^3)/m³ → **Very Low occupancy** given low σ
- High mass → visible signal provided the **bkg is under control**

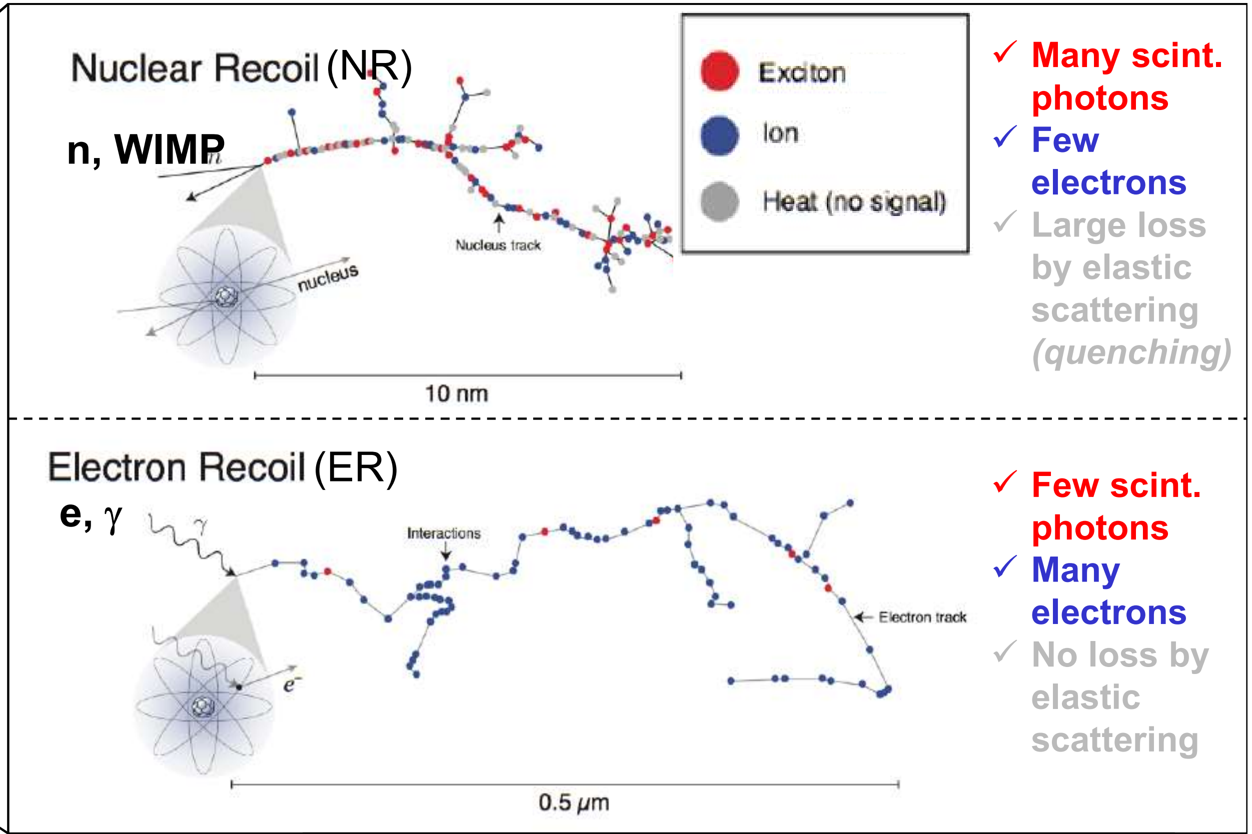
* Lots of attention in the community since 80's : Supersymmetry (SUSY) provides a very nice candidate for WIMP, the lightest SUSY particle χ

2 experimental challenges : **very large volume + very low background**

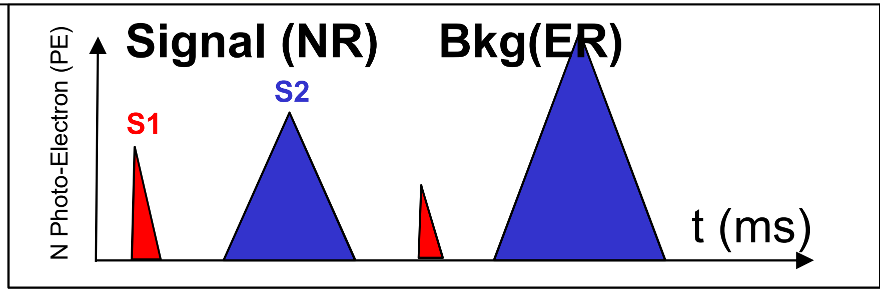
DM WIMP Search (2/4)

❑ **Dual Phase TPC** *(Time Projection Chamber)* **filled with noble liquid** *(Xe, Ar)* …



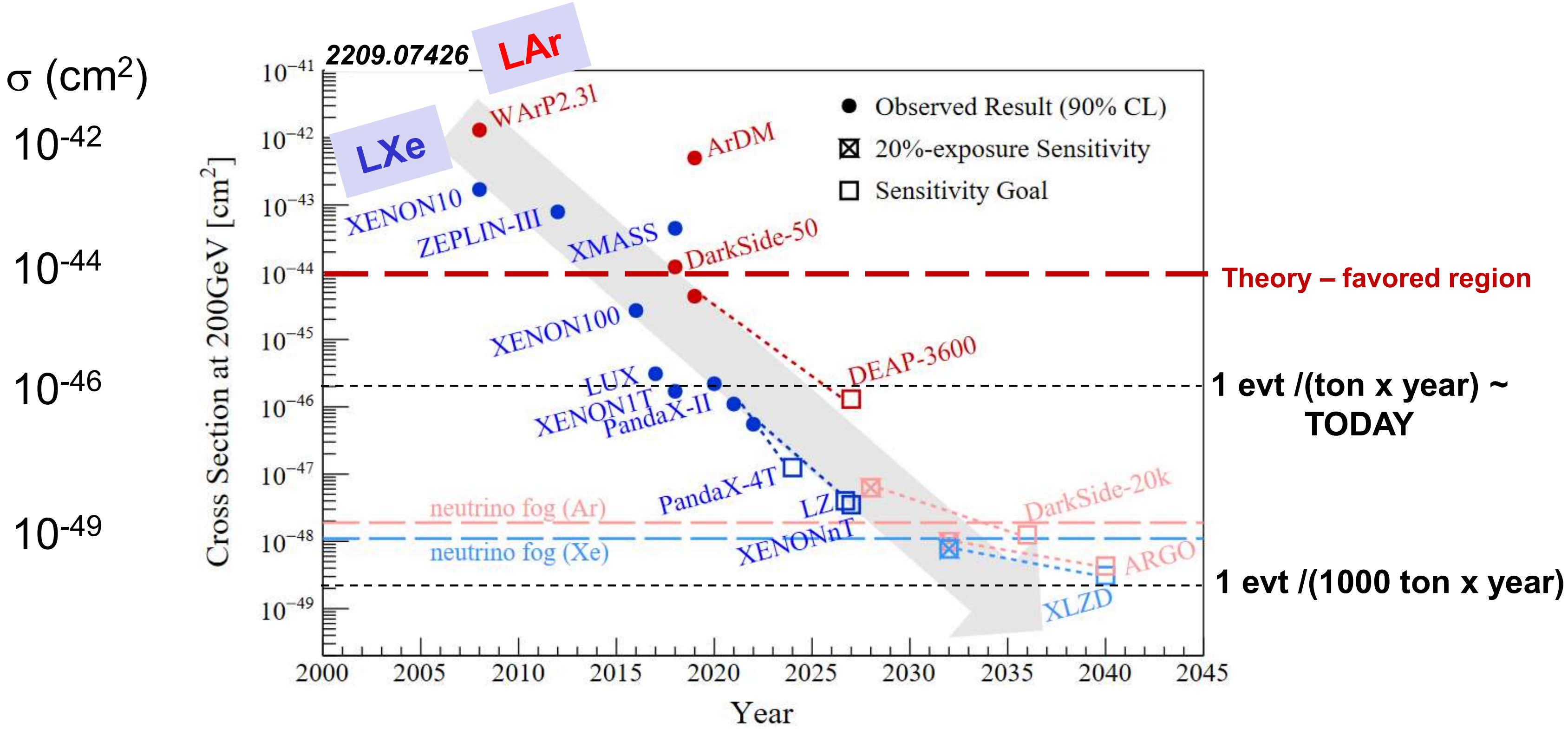


- Combine **scintillation** (S1) and **ionization** (S2)
- Remove very efficiently the ER (e, γ) background
- Reconstruct (E, x, y, z) of the recoil



DM WIMP Search (3/4)

❑ … very sensitive to WIMP dark matter *(e.g. m_χ = 200 GeV)*

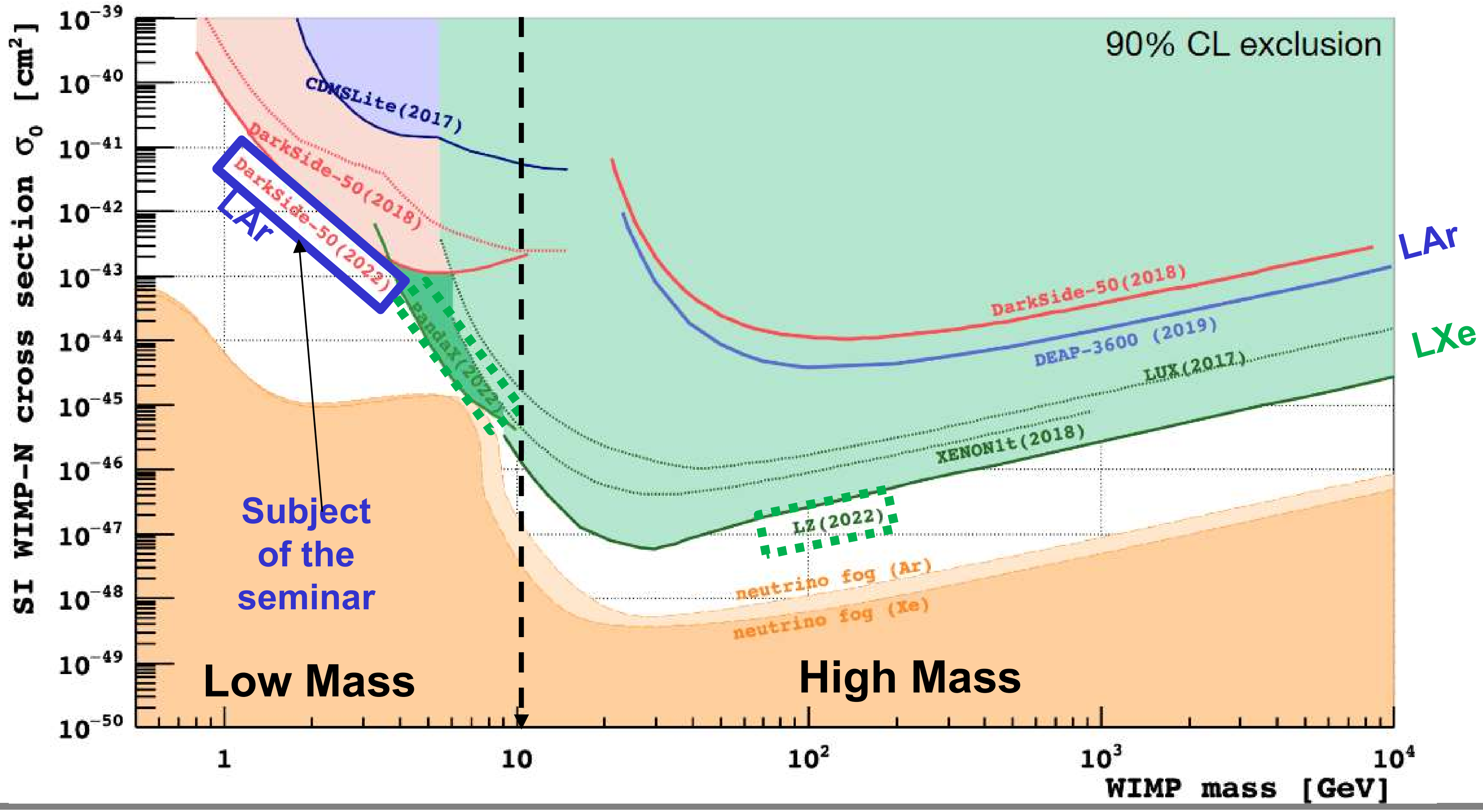


- ✓ Very large volume ➔ **scalable** technology *(from kg to multi-ton)*
- ✓ Very low background ➔ **"shielded" / underground** expt + low **noise** electronics

LXe / LAr dual phase TPC are leading the race !

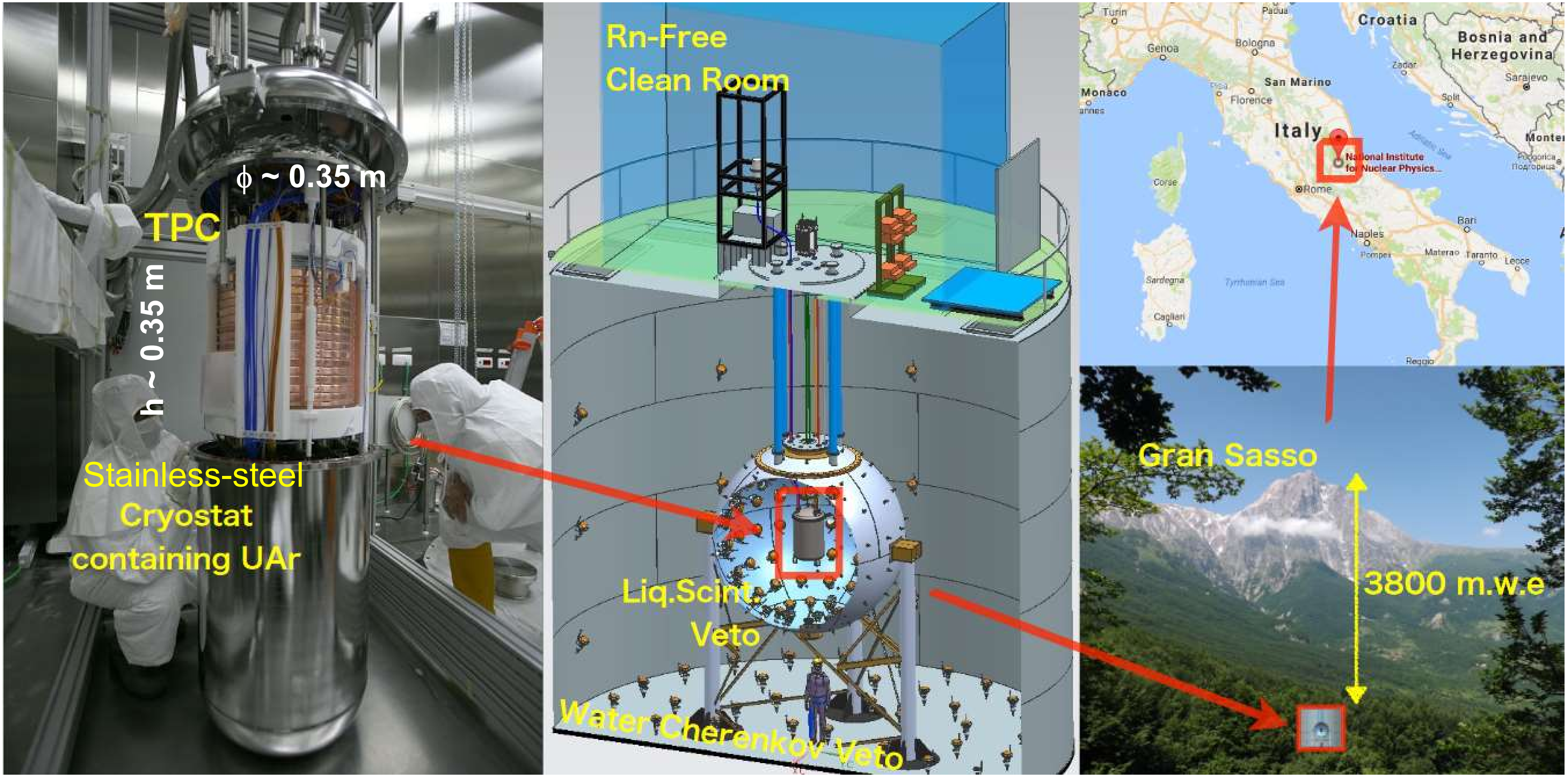
DM WIMP Search (4/4)

- **Very hectic competition between the Dual Phase TPC experiments**
  - One order of magnitude improvment in 1 GeV -- 10 TeV since one year !



DarkSide-50 experiment

❑ **First generation liquid argon TPC (2015-2018)**



- 50 kg of purified liquid argon (UAr)
- 38 PMTs sensitive to 1 PE

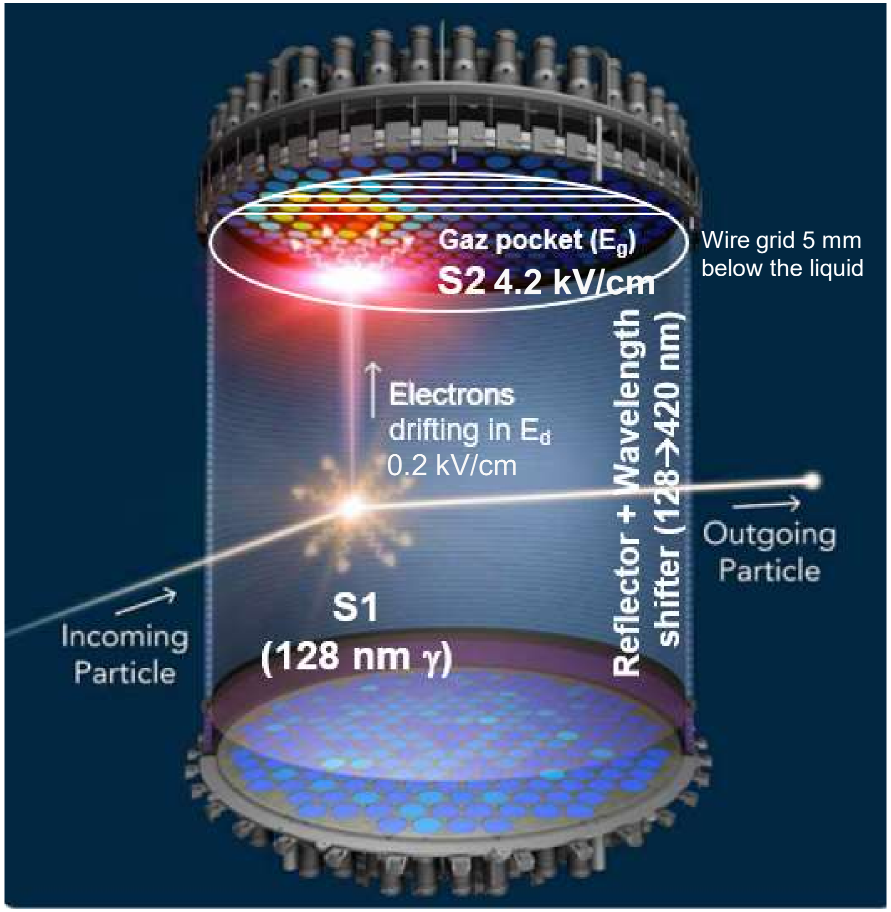
Muon and neutron veto :
Water (1000 t) + Scint. (30 t)

1400 m underground

Low Mass WIMP search

❑ S2-only events

- Recoil energy O(1) keV giving O(1) photo-electron (PE) → **S1 very low**
- But in the 1cm gaz pocket, 1 electron gives **23±1 PE → S2 visible !** PRL **121** (2018) 081307
- Better than Xenon detector a priori *(Ar atom lighter than Xe)*



- Complication because of no S1

- No ER (bkg) / NR (signal) discrimination
- No vertical information → no fiducialisation in z

+ DS-50 is a small detector

- Electron drift time < 376 μs
- Electron lifetime >10ms *(high LAr purity)*

➔ ~All electrons reach the gas pocket

DS-50 very favorable to search for low mass WIMP by counting Nb of electrons
(provided you understand the bkg !)

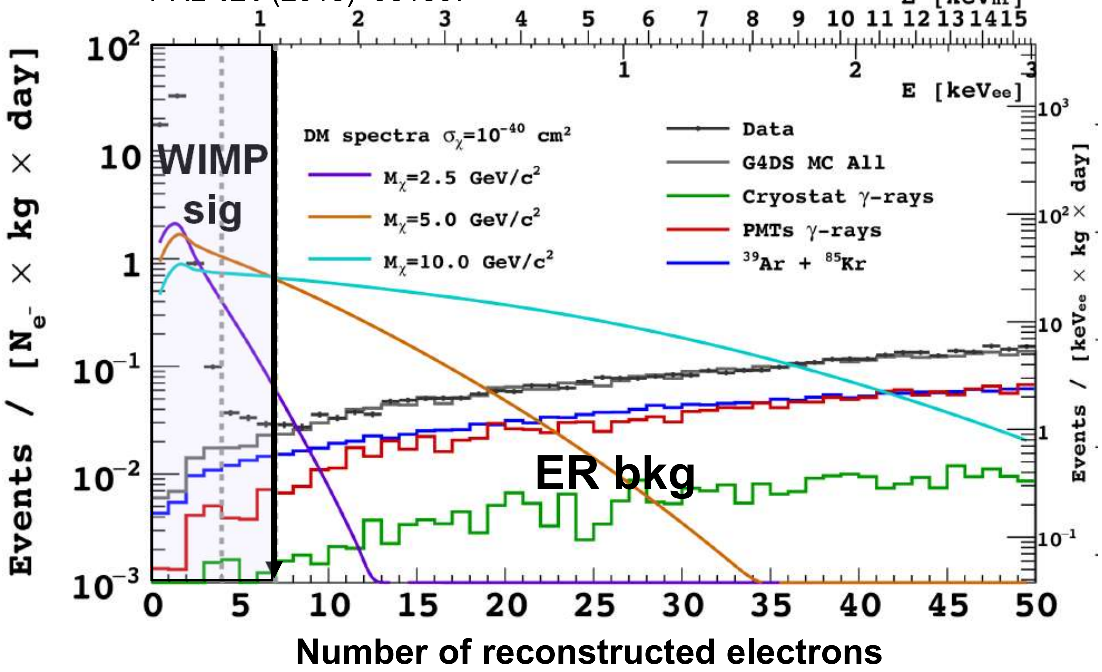
Low Mass WIMP 2018

Improvement 2018→2022

CPPM contributions

- **DS-50 very sensitive to low mass (1-5 GeV) WIMP**
  - Using N_e, very good signal / background separation *(intrinsically)*
  - Fair background description for $\mathbf{N_e \geq 7}$ *(but not $4 \leq N_e \leq 7$!)*
  - 2018 world leader in the 1.8 - 5 GeV mass range

PRL **121** (2018) 081307



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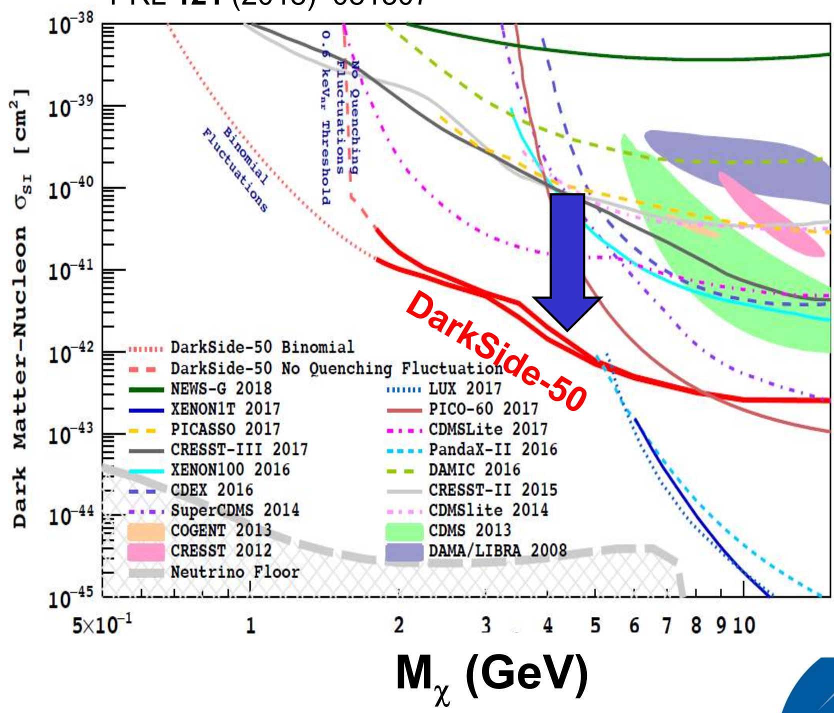


Possible to further increase the sensitivity → Improved analysis in 2022

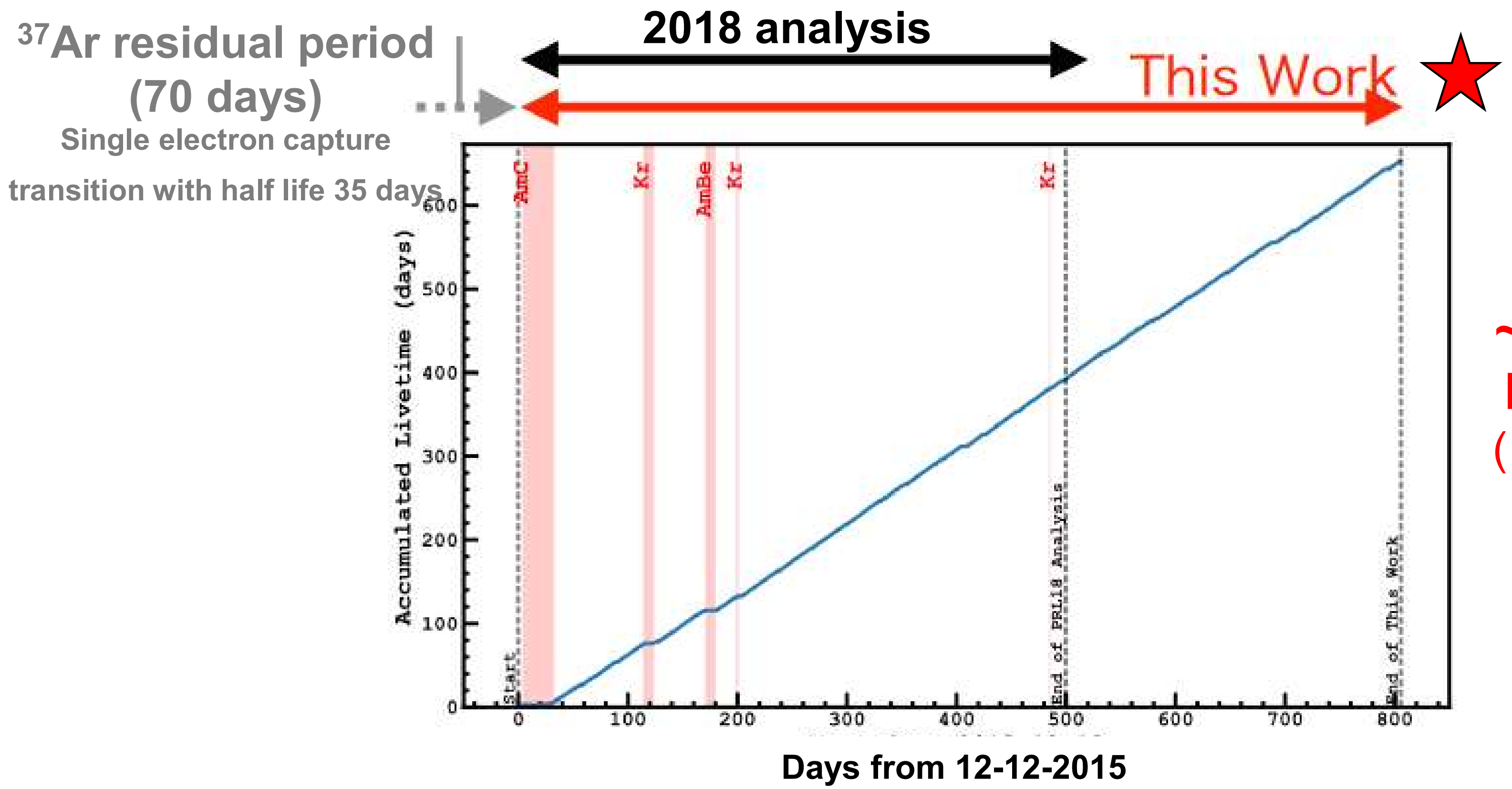
(Ne ≥ 4 instead ≥ 7 !)

3 papers : 2207.11966, 2207.11967, 2207.11968

Low Mass WIMP 2022

1- More data

- No significant break with calibration campaign
- Argon very stable in temperature (+/-0.02 K) and pression (+/-0.005 psi)



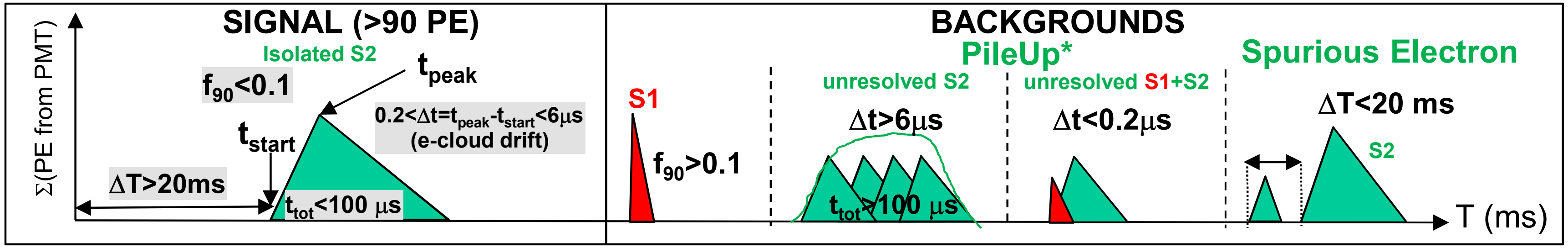
~ 650 live-days of high data quality
(12/2015 → 02/2018)

Increase data by 80% wrt 2018

Low Mass WIMP 2022

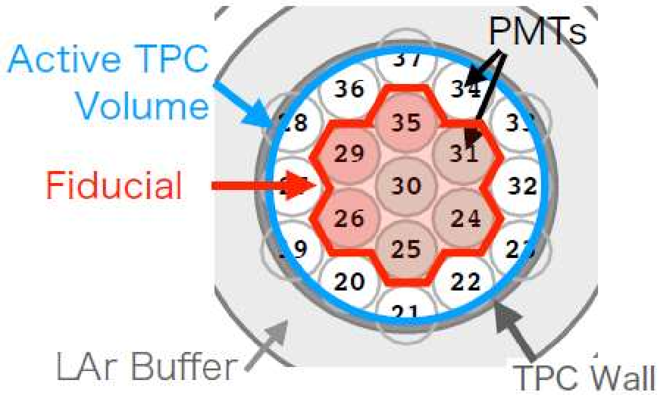
2- Improve selection of one and only one isolated S2

- Remove background coming by the TPC walls using fiducialisation *(as in 2018)*
- Remove S1 with fraction of PE in the first 90 ns (**f_{90}<0.1**, *100% efficient to remove S1)*
- Remove pile-up (**Δt, t_{tot}**), spurious electrons (**ΔT**), surface α (**S2/S1**)



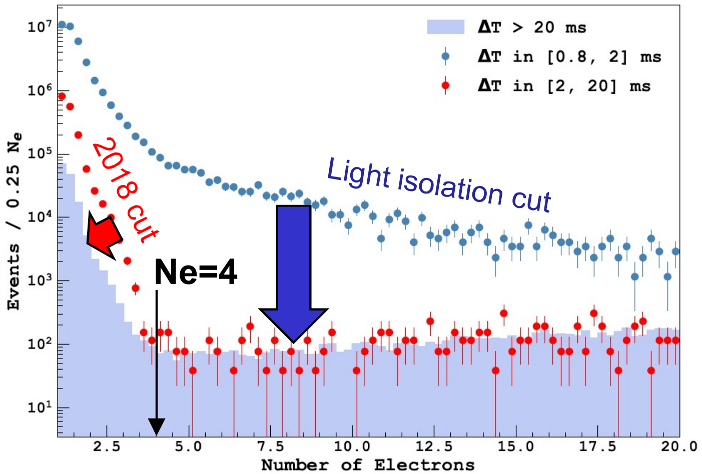
*Pulse finder cannot distinguish two pulses 2 μs apart

Fiducialisation



- Take the central top 7 PMTs
  - Signal acceptance : 41%

Spurious electrons (SE)



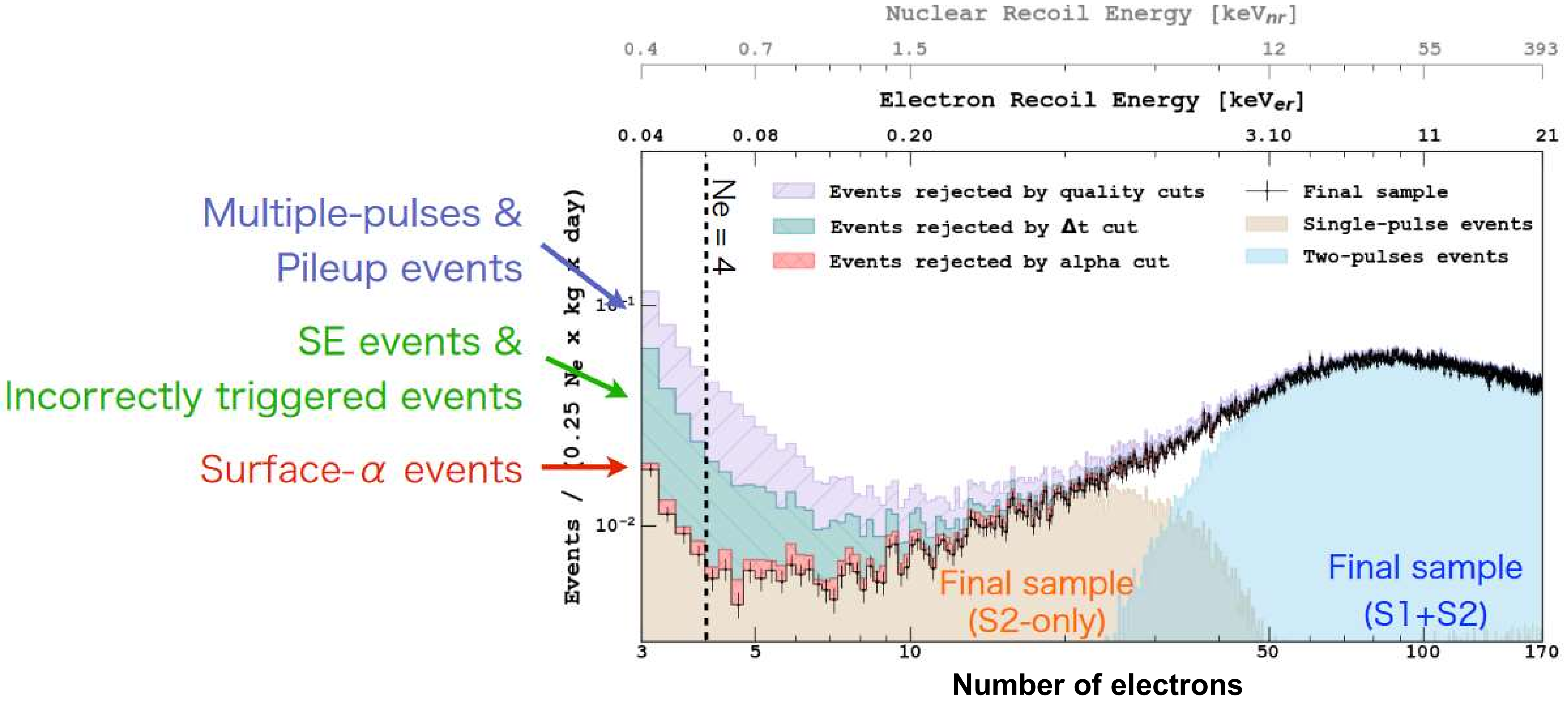
All Normalised to ΔT>20 ms dataset livetime in RoI

- SE from liquid surface or impurities
  - Signal acceptance : 97%

Low Mass WIMP 2022

2- Improve selection of one and only one isolated S2

- Low N_e region cleaned by quality cuts → Natural cut-off N_e=4 ★
- If S1 is present before S2, keep the event → extend to N_e=170 *(was 50 in 2018)* ★



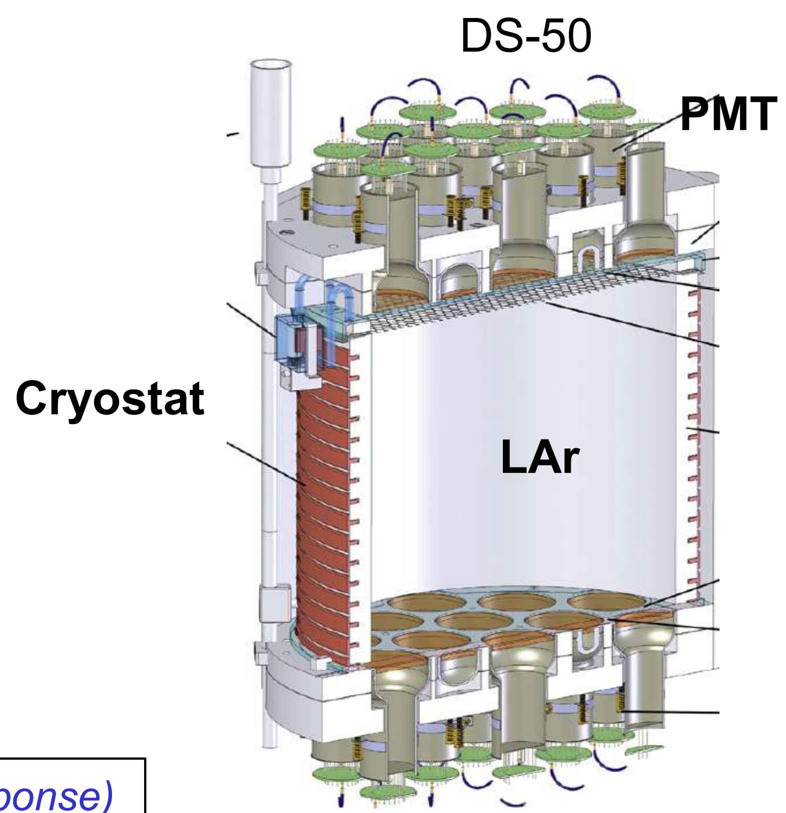
40% signal efficiency in RoI 4 ≤ Ne ≤ 170 and 350 k data evts

12 kton.day

Low Mass WIMP 2022

3- Improve the background model (ER)

- Identify all ER sources in LAr, cryo, PMT



- ❑ Estimate **activity of** radio-active components …
  - ❑ … and their **energy spectrum**

↓

Require **single scatter event** (E_{recoil}=E_{er}, x, y, z)

↓

Convert E_{recoil} to **Number of Electrons (N_e)**

↓

Fano Factor

↓

Correct for **electron lifetime** vs vertical position *(small)*

↓

Model the **PMT response** *(radial efficiency + Single Electron Response)*

↓

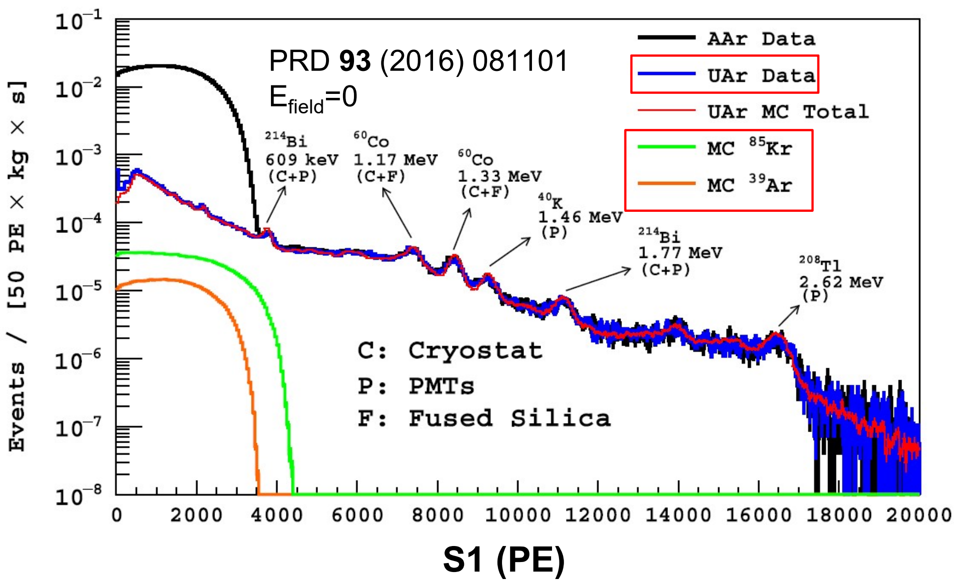
Final N_e spectrum for the background

Background Model (1/4)

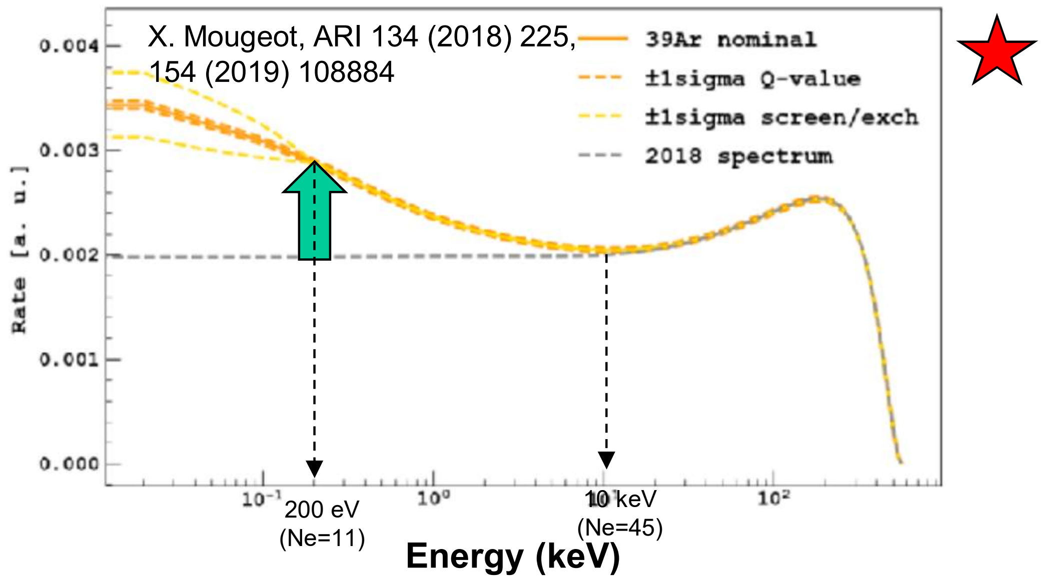
3a- Evaluate more finely β^- decays of ^{39}Ar and ^{85}Kr in LAr

- ❑ Estimate **activity** (mBq) …
- ❑ … and **energy spectrum** analytically (assume uniform spatial distribution in TPC)

Activity measured by fitting the data of high E S1 spectrum 35±5 and 84±4 mBq
(^{39}Ar @ 14%) (^{85}Kr @ 5%)



Energy spectrum shape with up-to-date atomic exchange and screening effects inc. uncertainties

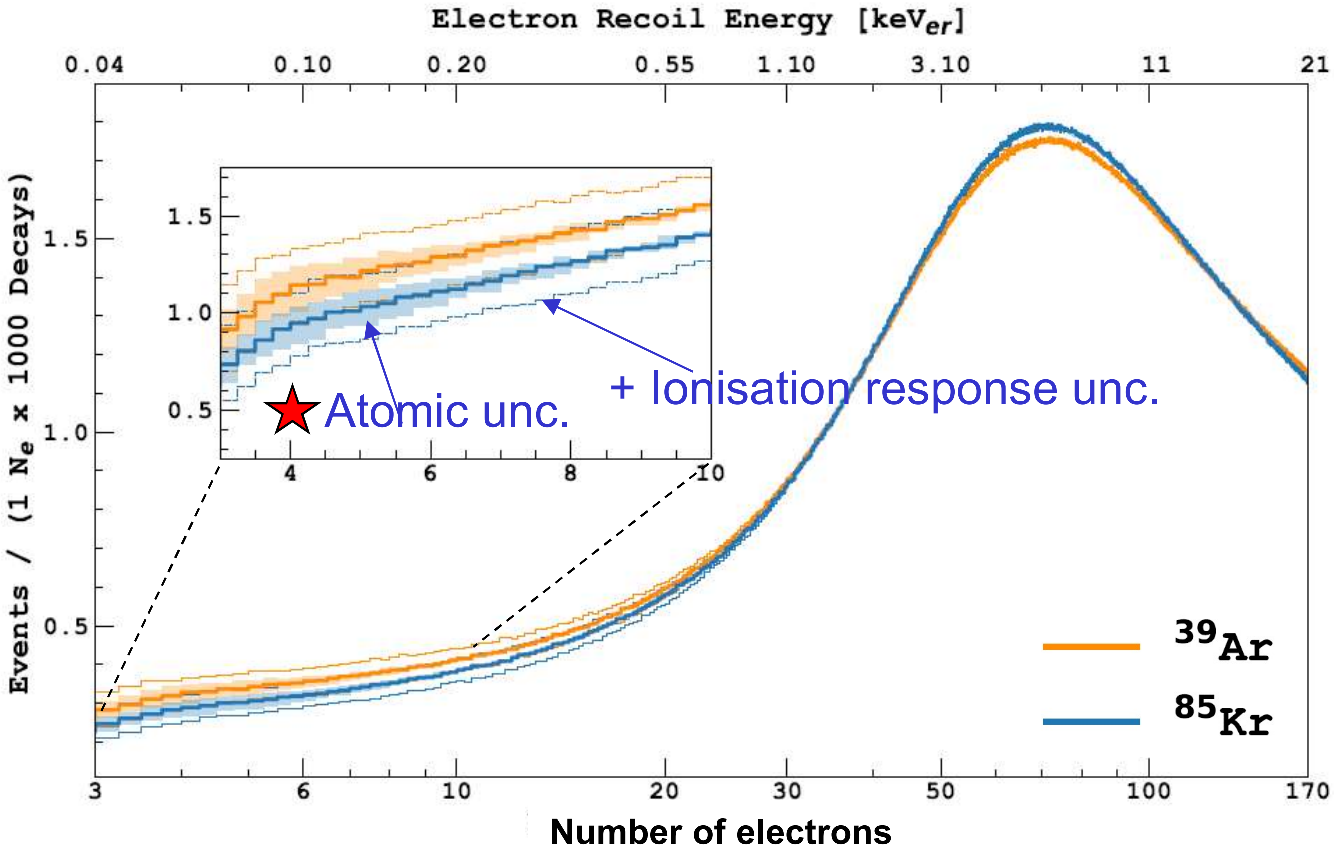


In RoI, predicted event rates are 0.7 ± 0.1 and 1.7 ± 0.1 mHz
(^{39}Ar @14%) (^{85}Kr @5%)

Background Model (1/4)

3a- Evaluate more finely β^- decays of ^{39}Ar and ^{85}Kr in LAr

- New expected Ne shape for background model



Add new uncertainties on energy spectrum shape *(±10% at low energy)*

Background Model (2/4)

3b- Evaluate more finely cryostat and PMT component contributions

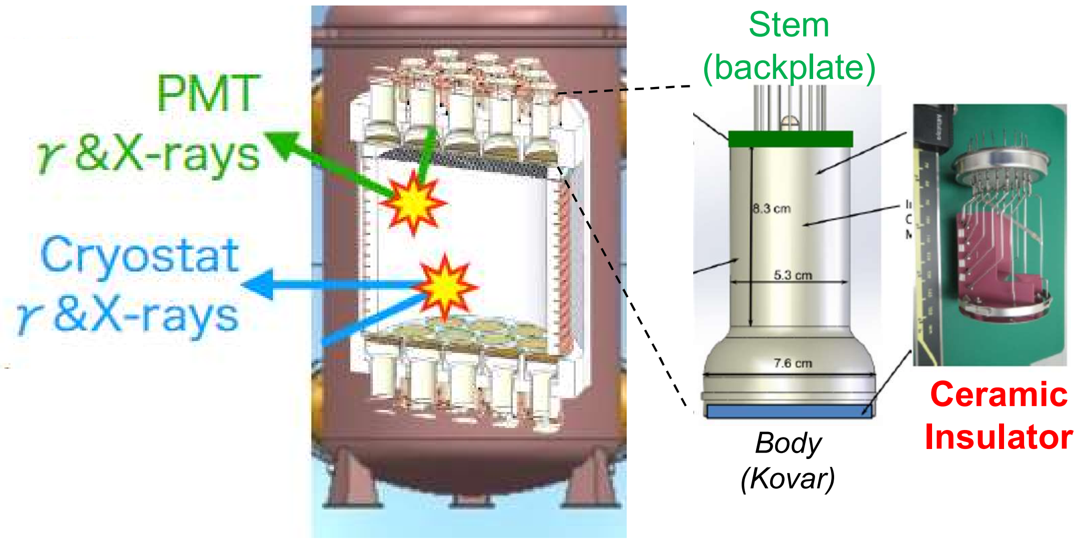
- ❑ Estimate **activity** (Bq) …
- ❑ … and **energy spectrum** using DS50 Geant4 description

★ Radioactive isotope activity measured in extensive material assay campaign
(@ 10-20%)

Location and source		Activity [Bq]
Cryostat	^{232}Th	0.19 ± 0.04
	^{238}U up	$1.30^{+0.2}_{-0.2}$
	^{238}U low	$0.38^{+0.04}_{-0.19}$
	^{235}U	$0.045^{+0.01}_{-0.02}$
	^{60}Co	1.38 ± 0.1
	^{40}K	$0.16^{+0.02}_{-0.05}$

Location and source			Activity [Bq]
PMT	Stems	^{232}Th	0.16 ± 0.03
		^{238}U up	1.06 ± 0.22
		^{238}U low	0.34 ± 0.03
		^{235}U	0.05 ± 0.01
		^{40}K	2.39 ± 0.32
		^{54}Mn	0.05 ± 0.02
	Ceramic	^{232}Th	0.07 ± 0.01
		^{238}U up	4.22 ± 0.88
		^{238}U low	0.34 ± 0.03
		^{235}U	0.21 ± 0.03
		^{40}K	0.61 ± 0.08
	Body	^{60}Co	0.17 ± 0.02

Each isotope is simulated uniformly in the material and decaying particles are tracked over all DS-50 geometry with Geant 4



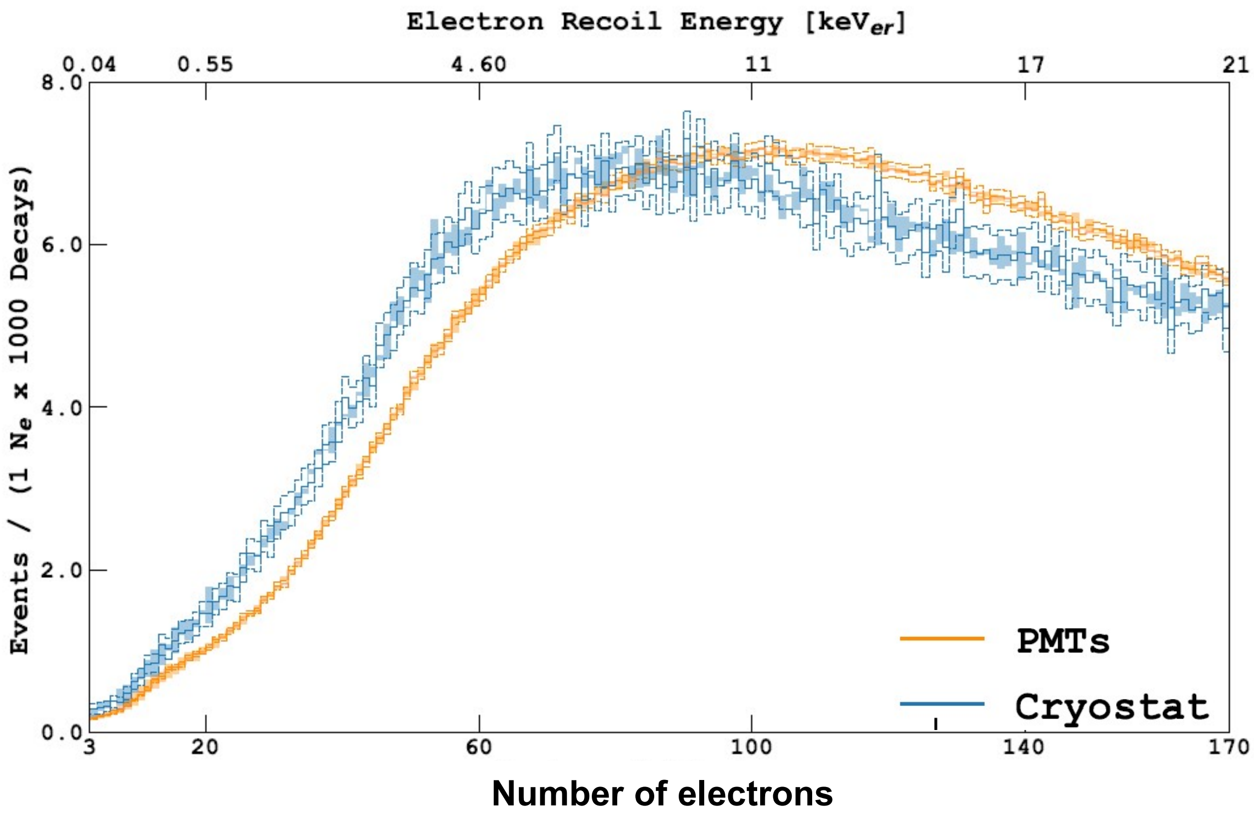
In RoI, predicted event rates are 0.57 ± 0.04 and 3.5 ± 0.4 mHz

(cryo @7%) (PMT @12%)

Background Model (2/4)

3b- Evaluate more finely cryostat and PMT component contributions

- Summing all contributions → New expected N_e shape for the background model



Add uncertainties from MC statistics and ìonisation response

Background Model (3/4)

3c- Better calibration of the ionisation yield (Q, Ne / keV) at very low E

Convert E to **Number of Electrons (Ne)**

PR A36 (1987) 614

Ar^+-e^- **recombination** (r) with Thomas-Imel model (C_{box})

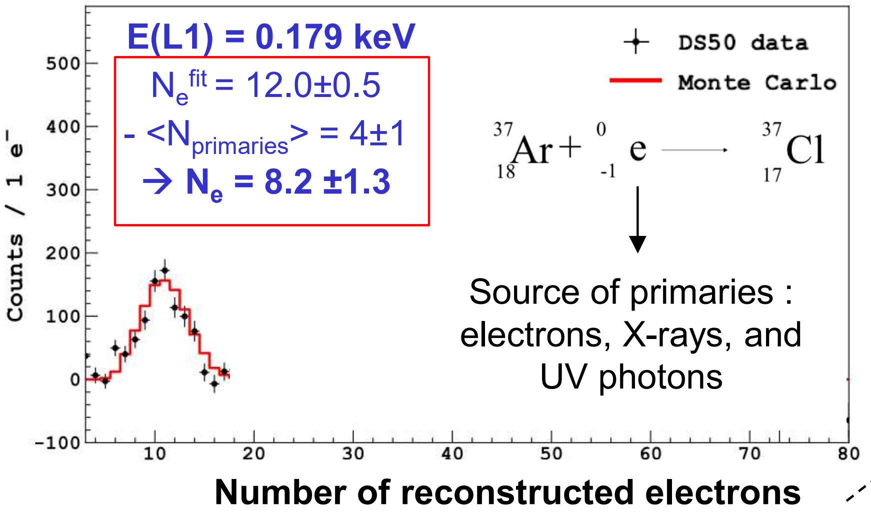
$\rho = N_i / E$

Electron drifting field (V/cm)

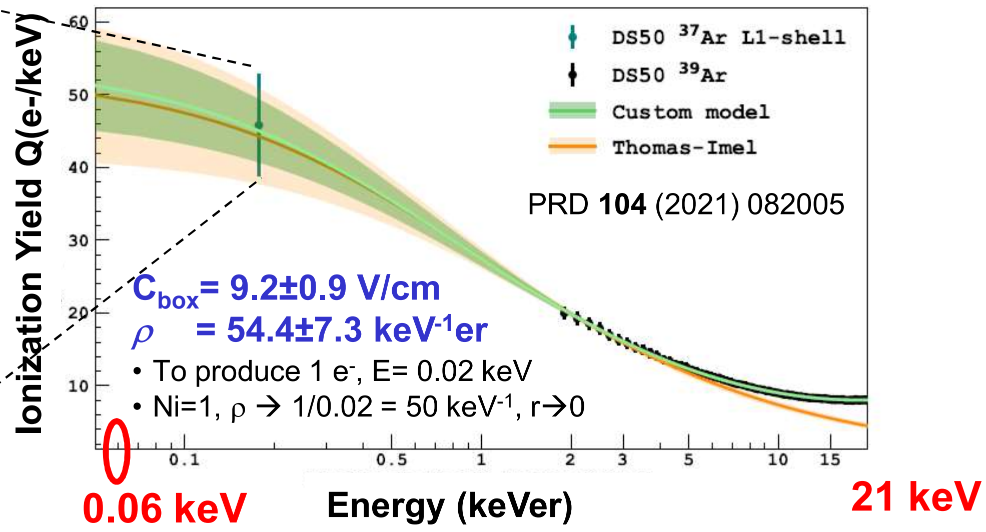
$$Q = \frac{(1-r)N_i}{E} = \frac{200\ln(1+\rho E C_{box}/200)}{E C_{box}}$$

→ Model with 2 free parameters (C_{box} and ρ) ★

^{37}Ar L1-shell → Q = 45.7+/-7.0 e^-/keV



ER: ^{37}Ar and ^{39}Ar



Have a model to extrapolate Q down to O (0.1 keV) *(Ne=3)*

Background Model (4/4)

3d- Validate the PMT response model with ^{37}Ar

Fano Factor

↓

Correct for **electron lifetime** vs vertical position (small)

↓

Model the **PMT response** (radial efficiency + Single Electron Response) ★

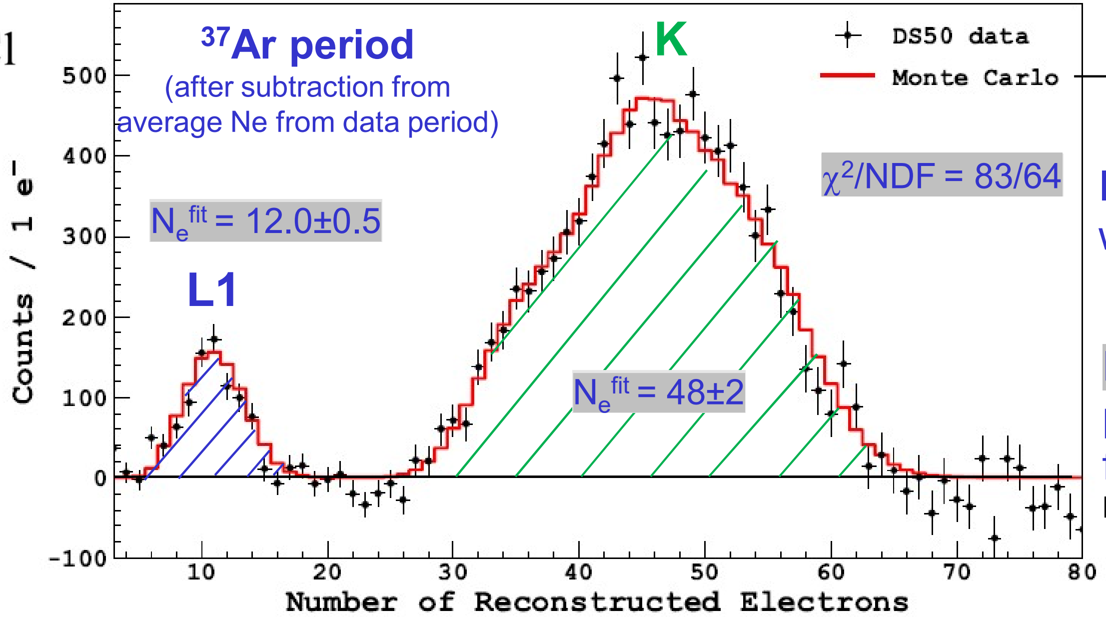
$${}^{37}_{18}Ar + {}^{0}_{-1}e \longrightarrow {}^{37}_{17}Cl$$

↓

from L1 (**0.28 keV**, 8%) or K (**2.83 keV**, 90%) shells

↓

Source of primaries : electrons, X-rays, and UV photons



→ **with all effects describe above**

Int(L1) / Int (K) = 0.10±0.01 agrees with predictions 0.100±0.005

Fano ^{fit} = 0.10±0.03 agrees with predictions on the LAr ionization fluct.. 0.112±0.05
NIM 134 (1976) 353

Very good agreement between prediction and data *(amplitude + shape)*

Signal Model (1/2)

4- Improve the signal model (NR)

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

- WIMP spectrum from Standard Halo Model (SHM)
  - v_{esc} =544 km/s, v_0 =238 km/s,
  - v_{Earth} =232 km/s, and ρ_{DM} =0.3 GeV/c²/cm³

Require **single scatter event** (E_{recoil}=E_{nr}, x, y, z)

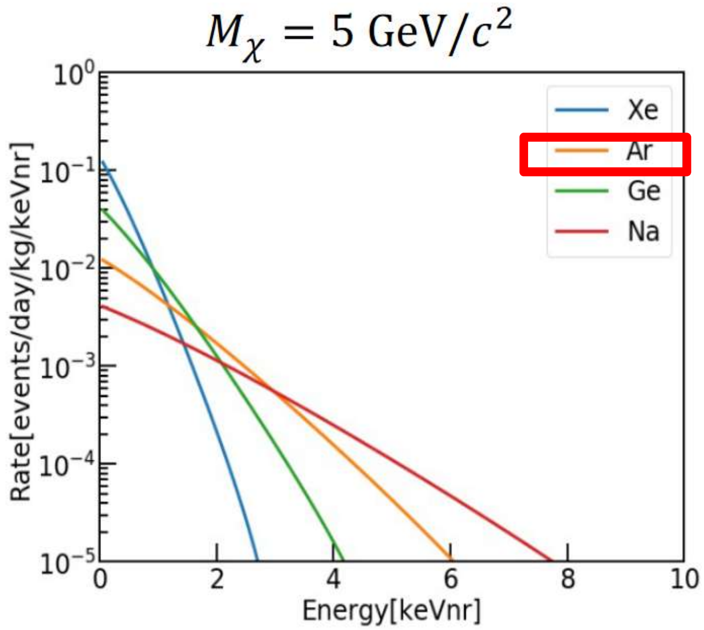
★ Convert E_{nr} to **Number of Electrons (Ne)**

Quenching fluctuations

Correct for **electron lifetime** vs vertical position *(small)*

Model the **PMT response** *(radial efficiency + Single Electron Response)*

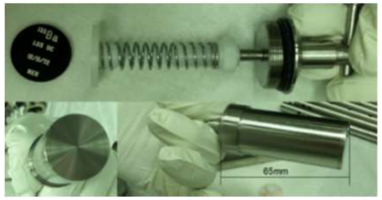
Final Ne spectrum for the signal



Signal Model (2/2)

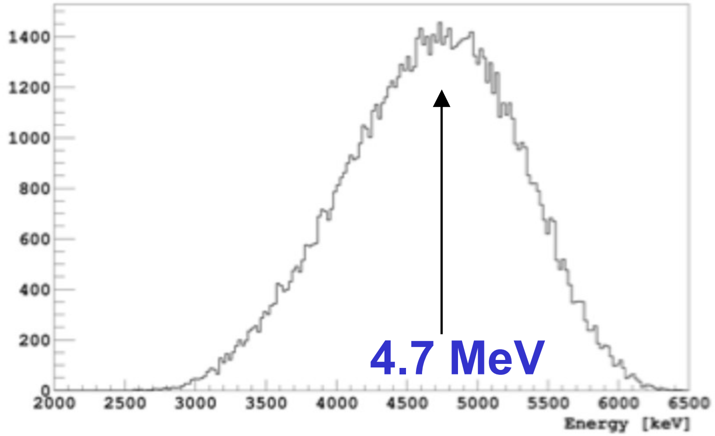
4a- Better calibration of the ionisation yield (Q, Ne / keV) at very low E

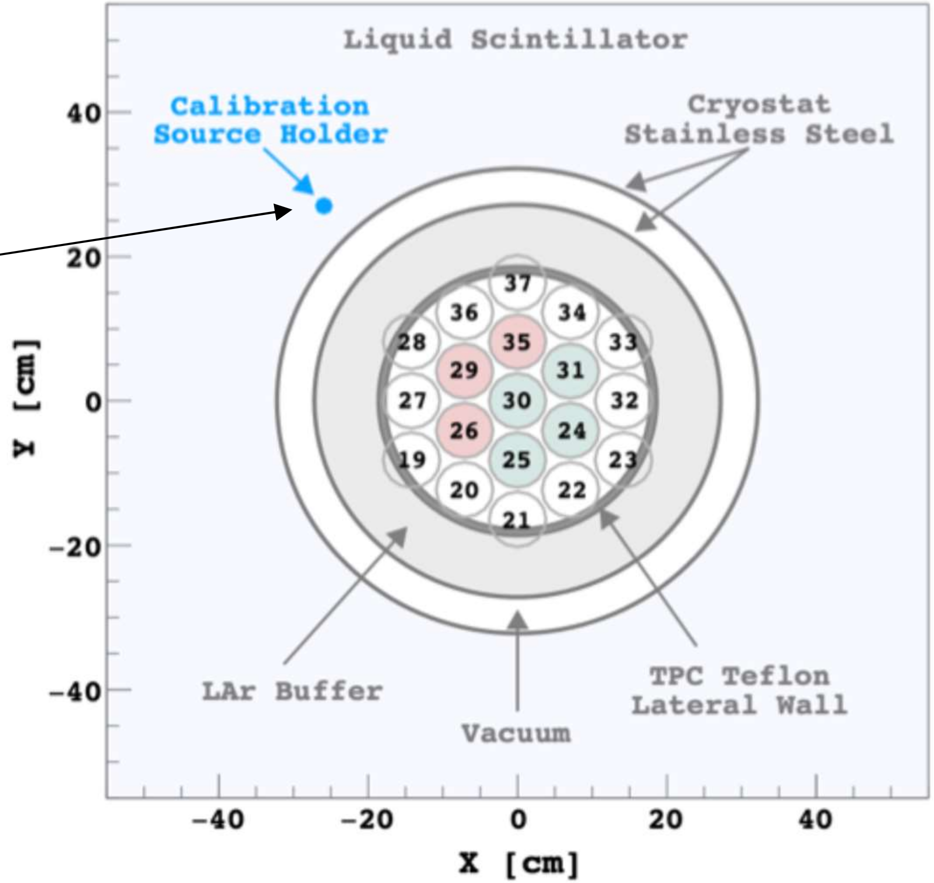
AmC source



shielded with 2mm thick lead
to stop 59.5 keV gammas

AmC → neutrons





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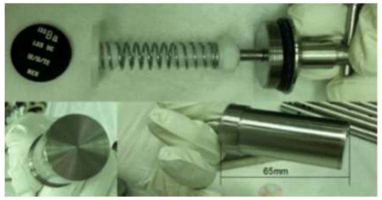

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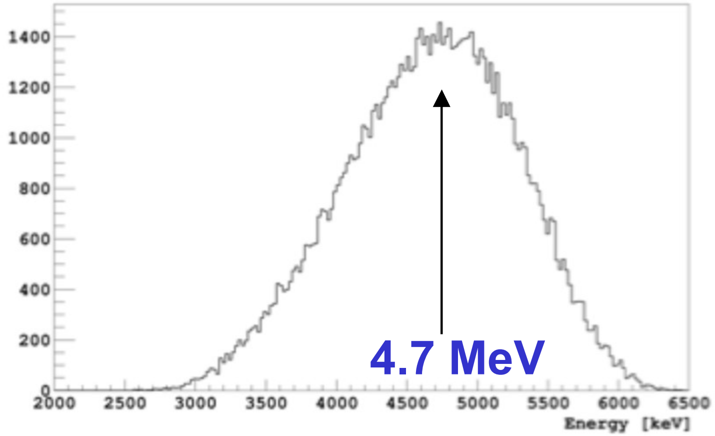
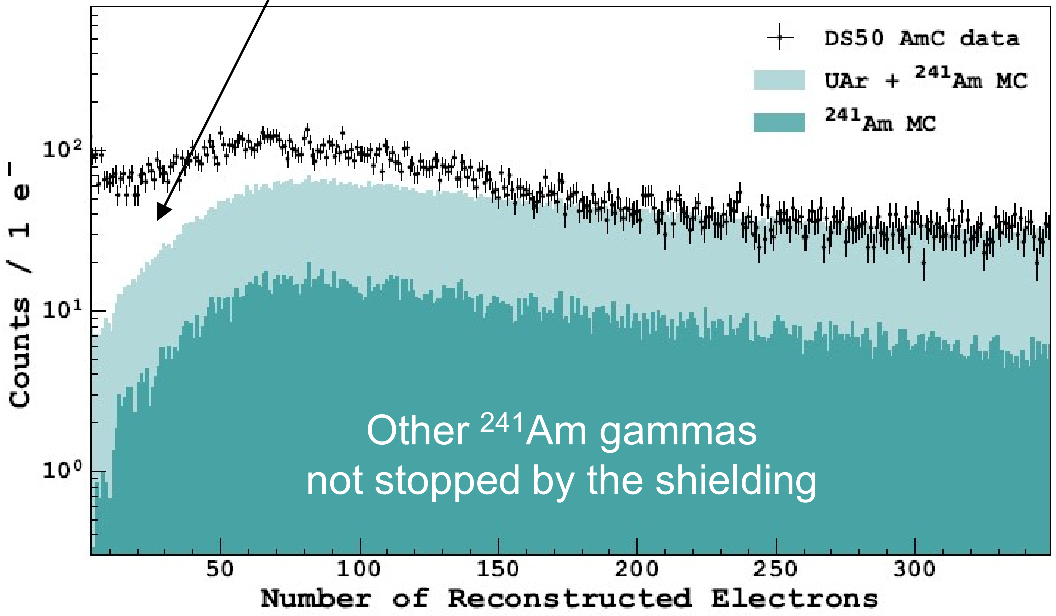


Pure sample of low energy single scatter neutrons



Large sample of low E neutrons used to calibrate the ionization yield

Signal Model (2/2)

4a- Better calibration of the ionisation yield (Q, Ne / keV) at very low E

PR A36 (1987) 614

Ar^+-e^- **recombination** (r) with Thomas-Imel model (C_{box})

AP 35 (2011) 119

$\varepsilon \sim 0.01\, E_{nr}$ / keV, κ dimensionless

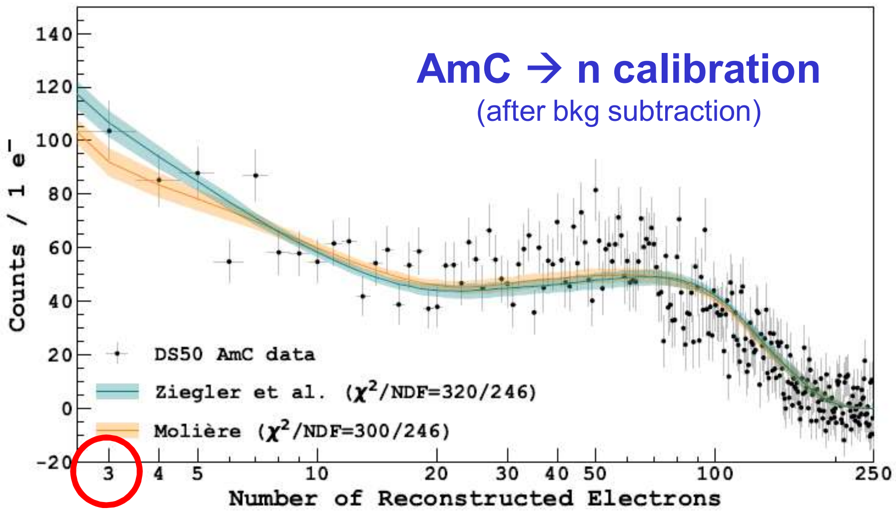
$$N_i = \beta\,\kappa(\epsilon) = \beta\,\frac{\epsilon\, s_e(\epsilon)}{s_n(\epsilon)+s_e(\epsilon)}$$

- $s_e \sim 0.145\sqrt{\varepsilon}$: visible **rate** (S1+S2)
- s_n : "invisible" (**quenching**) rate estimated with '85 Ziegler model

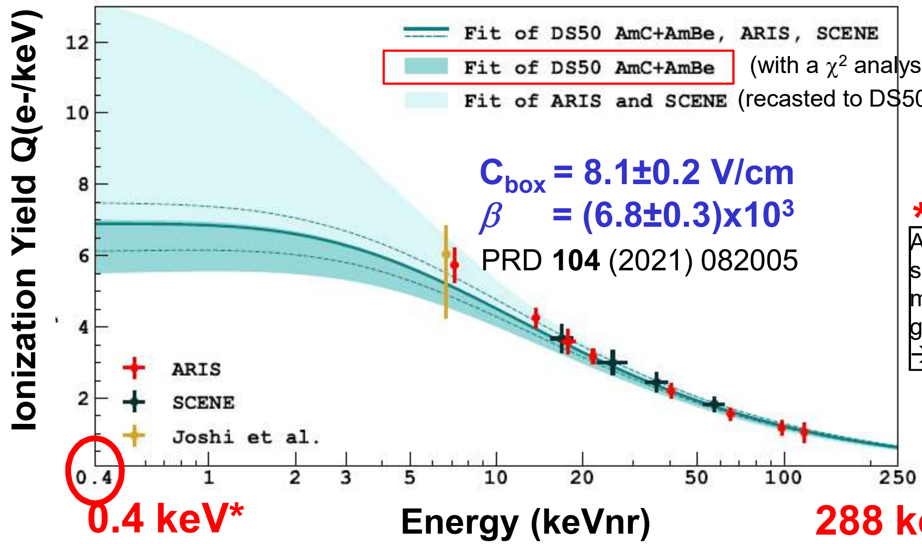
$$Q = \frac{(1-r)N_i}{E} = \frac{200\ln(1+\beta\kappa\,.\,C_{box}/200)}{E\,C_{box}}$$

→ Model with 2 free parameters (**C_{box}** and β)★

NR : AmC and AmBe



Ne=3



0.4 keV* 288 keV

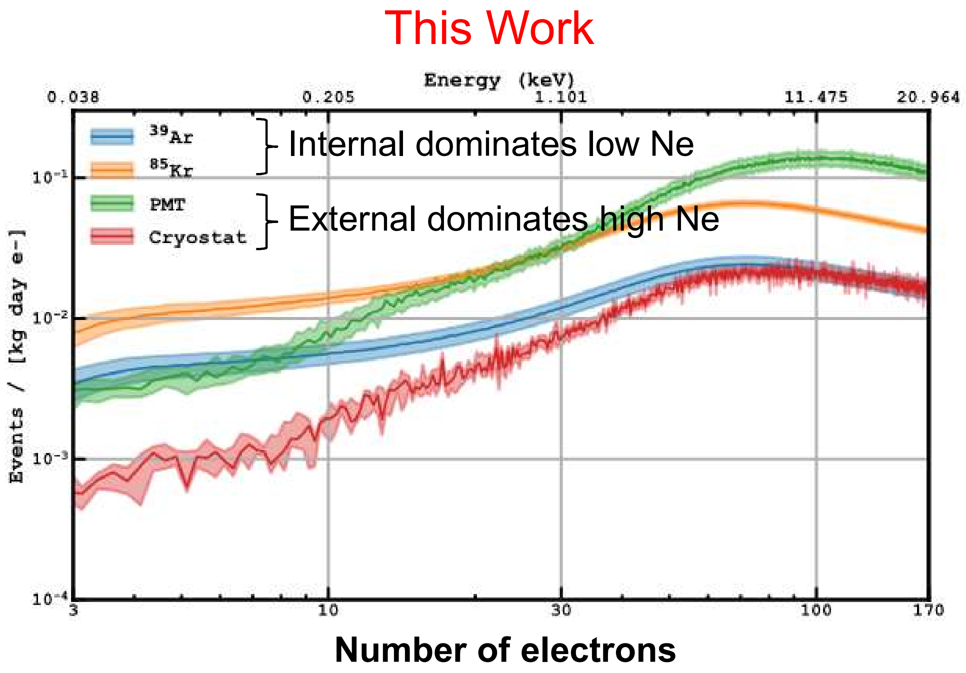
* At E=0.4 keV (ε=4e-3) s_n>>s_e, s_n/s_e = 0.1 meaning that 10 % of E goes into electrons →Ni = 7e3x4e-3x0.1 ~ 3

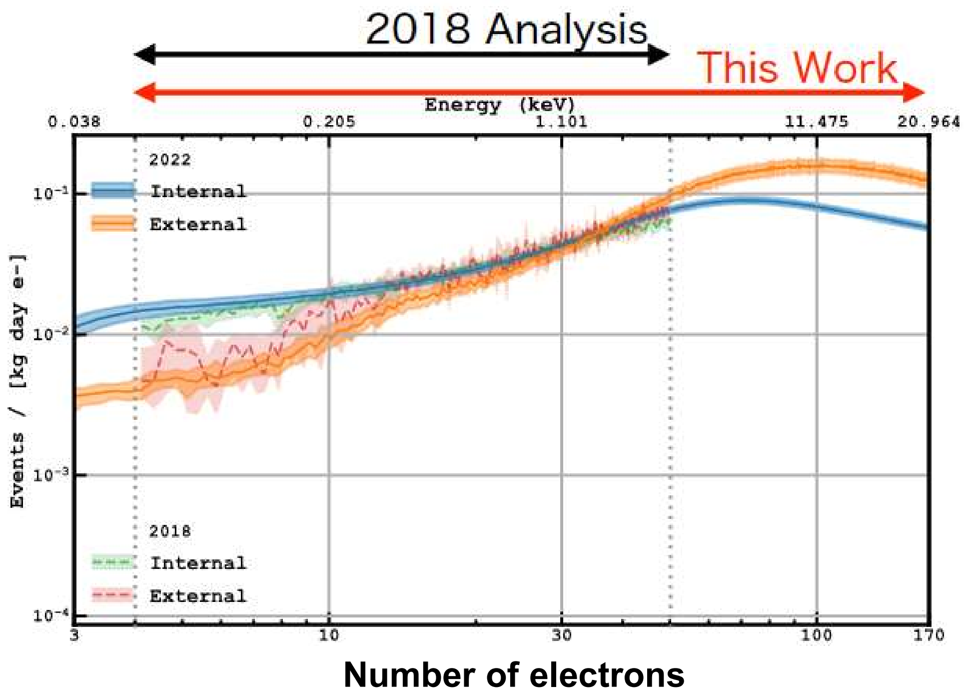
Measured Q down to O (0.5 keV) using calib. data *(lowest energy ever calibrated in LAr)*

(Ne=3)

Fit (1/5)

❑ Pre-fit distributions for each background





Background model more robust and extended to N_e=170 wrt 2018

Fit (2/5)

- Likelihood function with 10 (11) nuisance parameters

$$\mathcal{L} = \prod_{i\,\epsilon\,\text{bins}} \mathcal{P}\left(n_i | m_i(\mu_s, \Theta)\right) \times \prod_{\theta_i\,\epsilon\,\Theta} \mathcal{G}(\theta_i^0 | \theta_i, \Delta\theta_i) \times \prod_{i\,\epsilon\,\text{bins}} \mathcal{G}\left(m_i^0 | m_i(\Theta), \delta m_i(\Theta)\right)$$

Poisson probability of observing n_i events in the i^{th}-bin with respect to the expected ones, $m_i(\mu_s,\Theta)$, with μ_s the signal strength

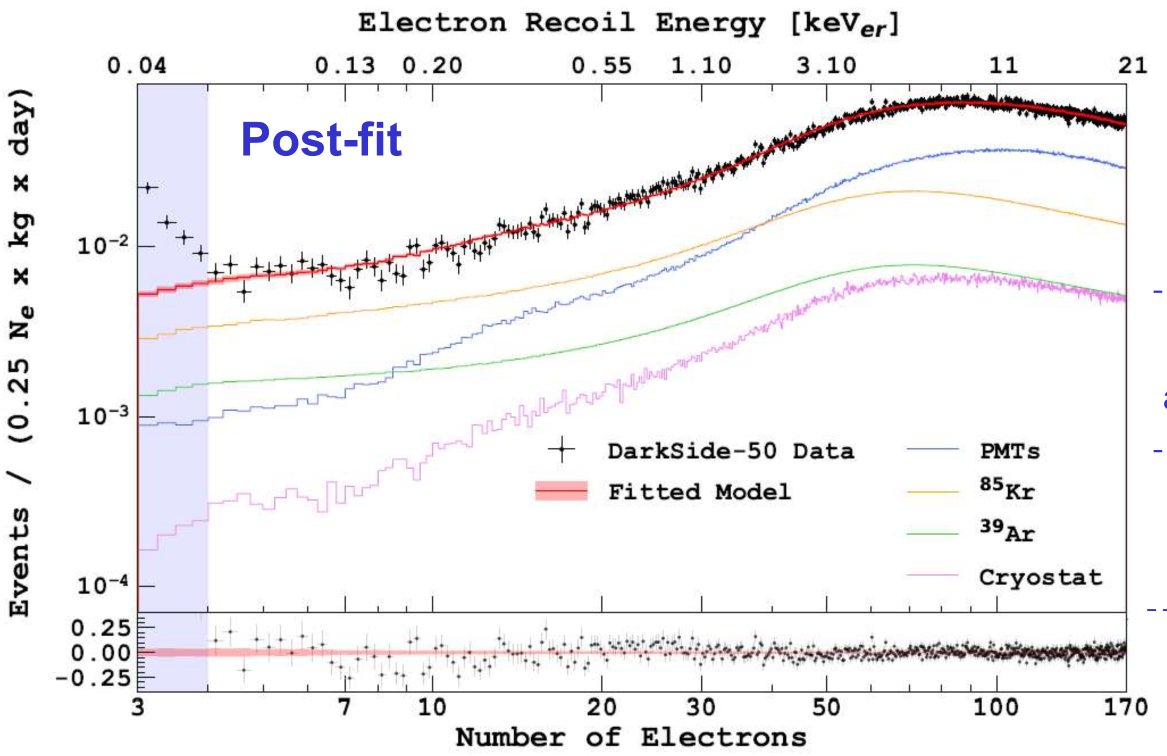
Gaussian penalties to account for the **nuisance parameters** (θ_0 and $\Delta\theta$ are the nominal central values and uncertainties)

Statistical uncertainties of the **simulated** sample

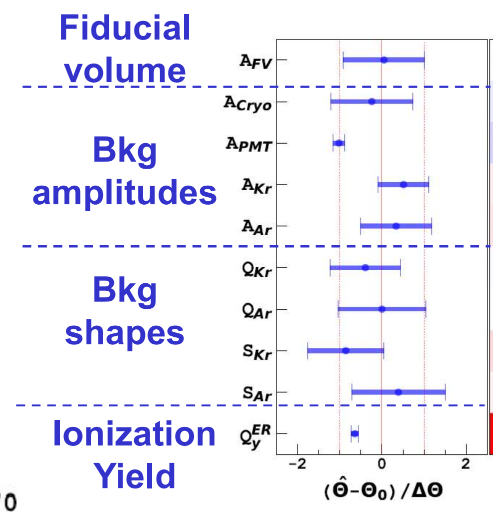
	Name	Source	Affected components
Amplitude	A_{FV}	uncertainty on the fiducial volume	WIMP, ^{39}Ar, ^{85}Kr, PMTs, Cryostat
	A_{Ar}	14.0% uncertainty on ^{39}Ar activity	^{39}Ar
	A_{Kr}	4.7% uncertainty on ^{85}Kr activity	^{85}Kr
	A_{pmt}	11.5% uncertainty on activity from PMTs	PMT
	A_{cryo}	6.6% uncertainty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

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

❑ Putting all together … and fitting the bkg



10 Nuisance Parameters

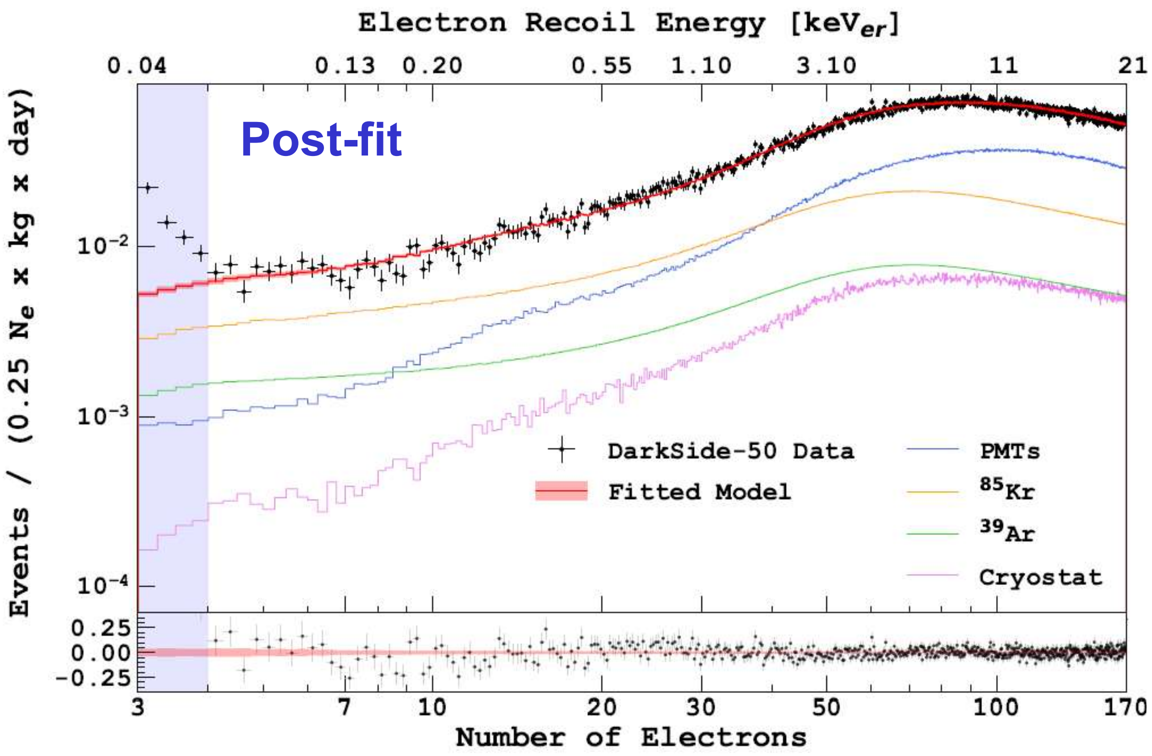


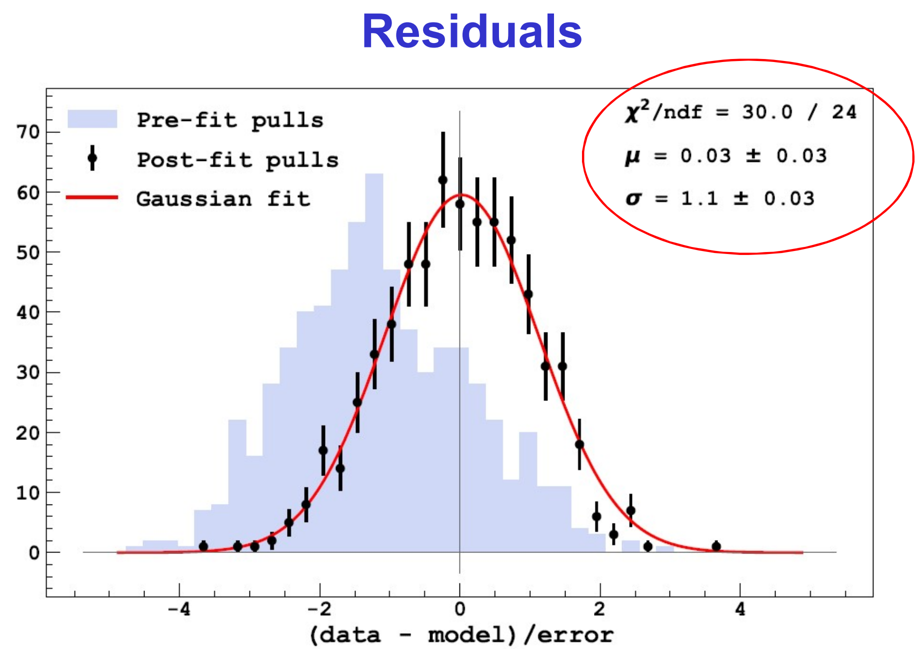
	Q_y^{ER}	S_{Ar}	S_{Kr}	Q_{Ar}	Q_{Kr}	A_{Ar}	A_{Kr}	A_{PMT}	A_{Cryo}	A_{FV}
A_{FV}	0.01	0.00	0.00	0.01	0.01	-0.13	-0.32	-0.66	-0.04	1.00
A_{Cryo}	-0.08	0.01	0.06	0.00	0.01	-0.04	-0.15	-0.35	1.00	-0.04
A_{PMT}	-0.16	0.01	0.06	-0.00	0.01	0.04	0.05	1.00	-0.35	-0.66
A_{Kr}	0.07	-0.03	-0.03	0.05	-0.05	-0.77	1.00	0.05	-0.15	-0.32
A_{Ar}	0.10	0.02	-0.04	0.03	0.11	1.00	-0.77	0.04	-0.04	-0.13
Q_{Kr}	-0.01	0.02	-0.01	-0.01	1.00	0.11	-0.05	0.01	0.01	0.01
Q_{Ar}	-0.00	0.00	-0.00	1.00	-0.01	0.03	0.05	-0.00	0.00	0.01
S_{Kr}	0.15	-0.19	1.00	-0.00	-0.01	-0.04	-0.03	0.06	0.06	0.00
S_{Ar}	0.05	1.00	-0.19	0.00	0.02	0.02	-0.03	0.01	0.01	0.00
Q_y^{ER}	1.00	0.05	0.15	-0.00	-0.01	0.10	0.07	-0.16	-0.08	0.01

All nuisance parameters within +/- 1 σ and correlations understood

Fit (4/5)

❑ Putting all together … and fitting the bkg

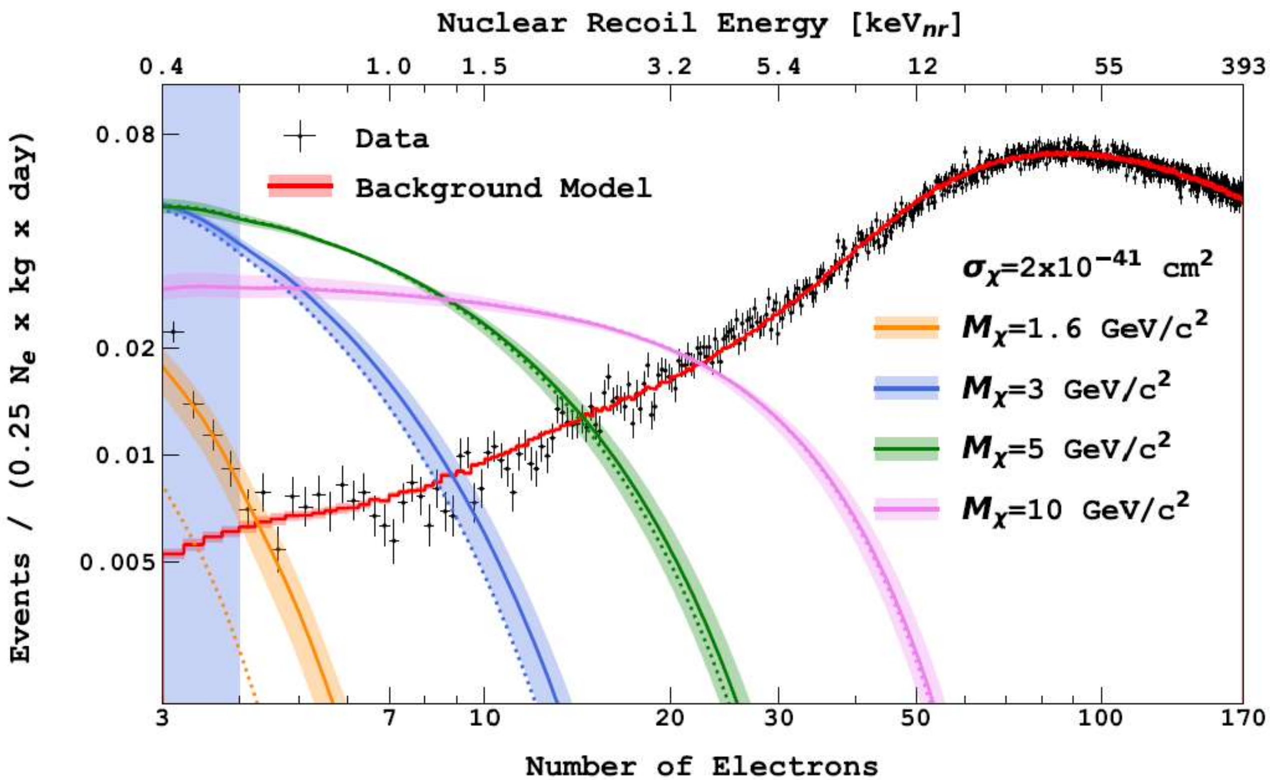




Background model describes very well the data in 4 ≤ Ne ≤ 170 after the fit !

Fit (5/5)

- **… and superimposing the low mass WIMP signal**
  - No model for quenching fluctuations → Show without (NQ) or with (QF)
  - Impact at low N_e



-------- NQ

——— QF

- Binomial fluctuations for Ne with
  n= nQuanta = E(visible keVnr) / 0.02
  p=0.5
- E=0.02 keV to produce 1 quanta

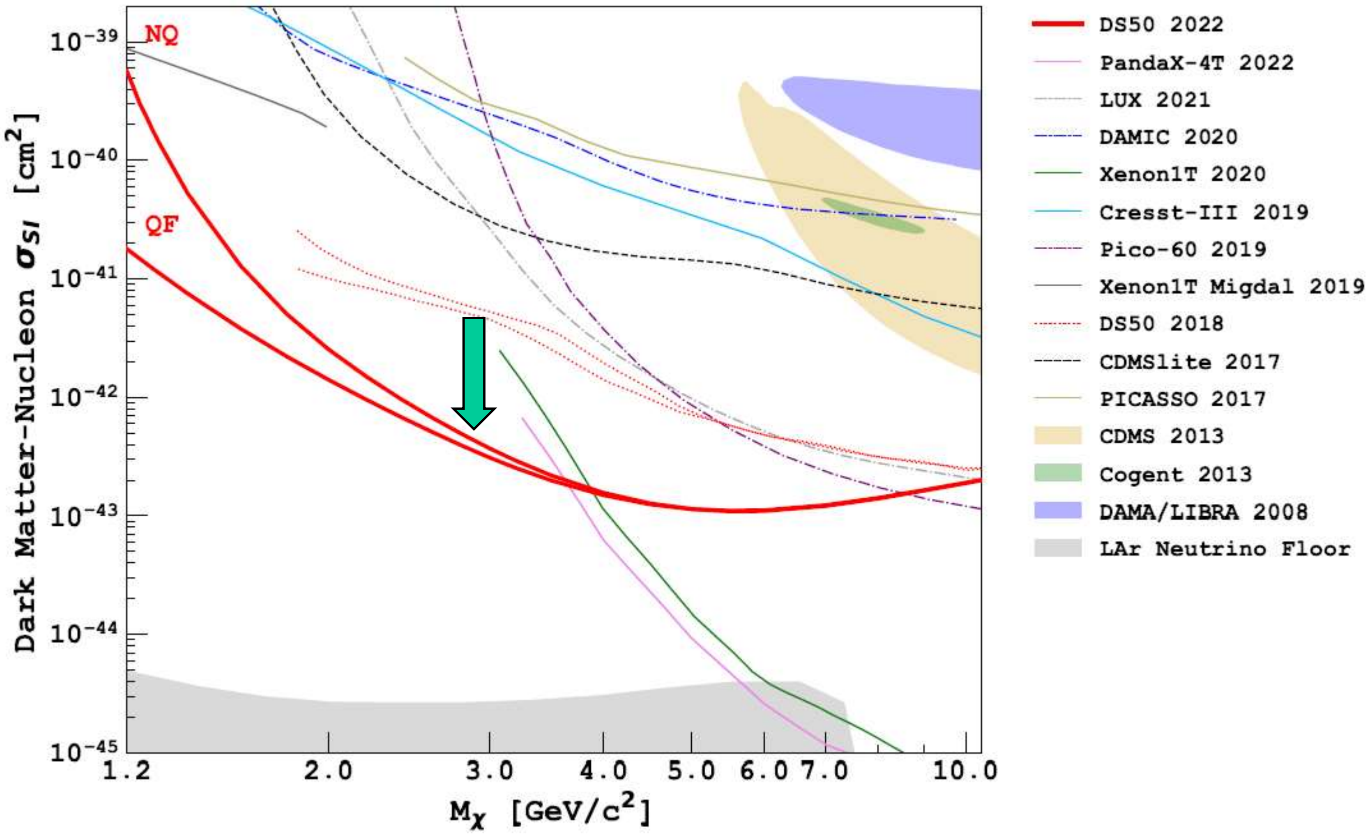
Very different shape between signal and background

New limits (1/4)

❑ WIMP – Nucleus

- Gain one order of magnitude over 2018 (e.g. at 3 GeV)

2207.11966

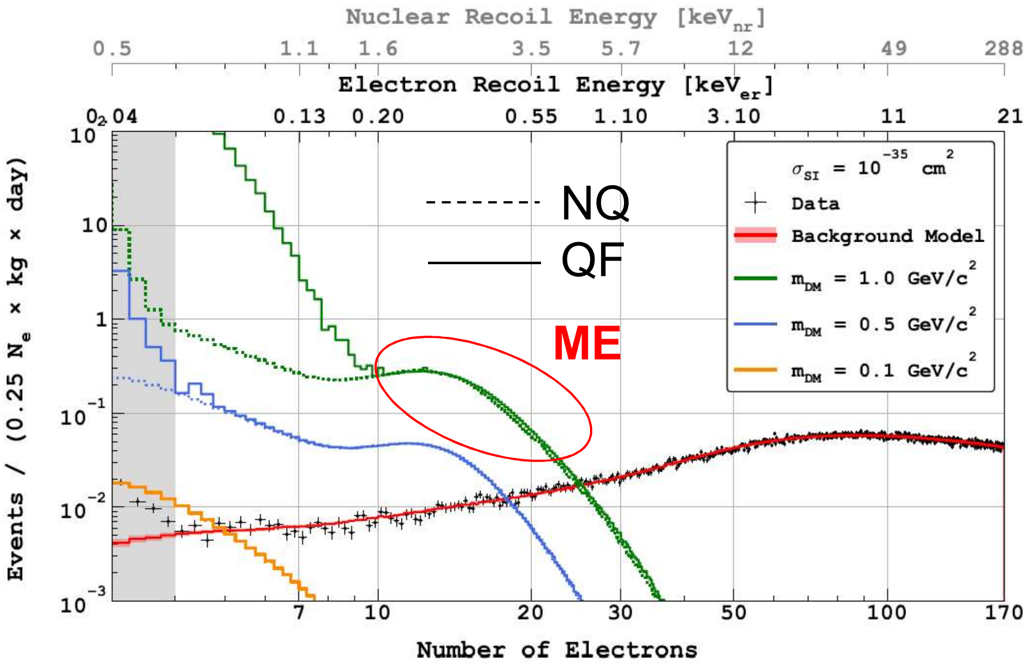


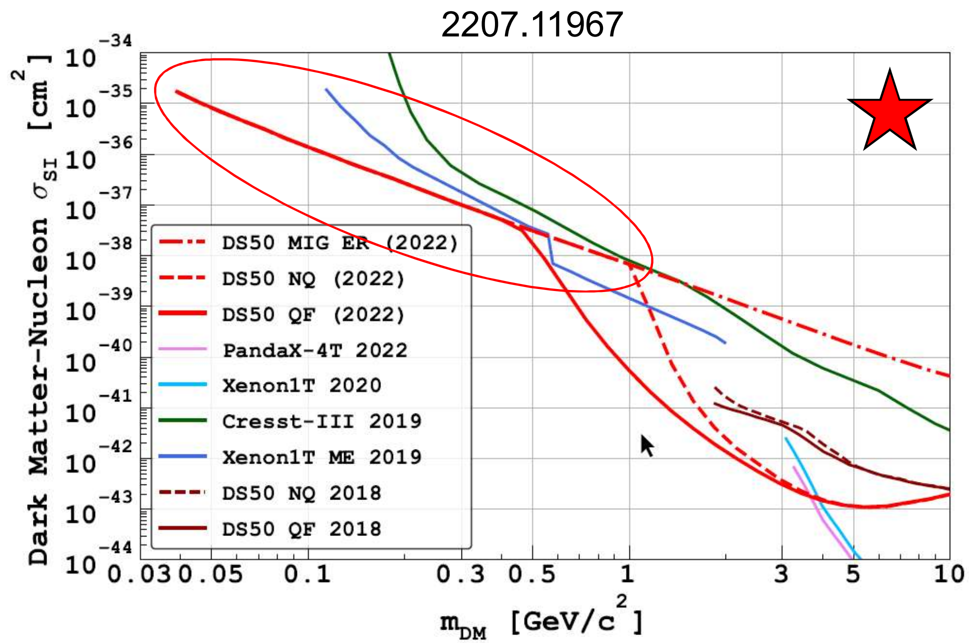
Most stringent limits on WIMP in [1.2 – 3.6] GeV mass range

New limits (2/4)

❑ WIMP – Nucleus + Migdal

- Migdal effect (ME) : additional ionization of the Ar atom following the WIMP scat.
  - ✓ This is still a theoretical prediction pending experimental evidence !
- Allows to extend the limit at very low mass *(was not done in 2018)*

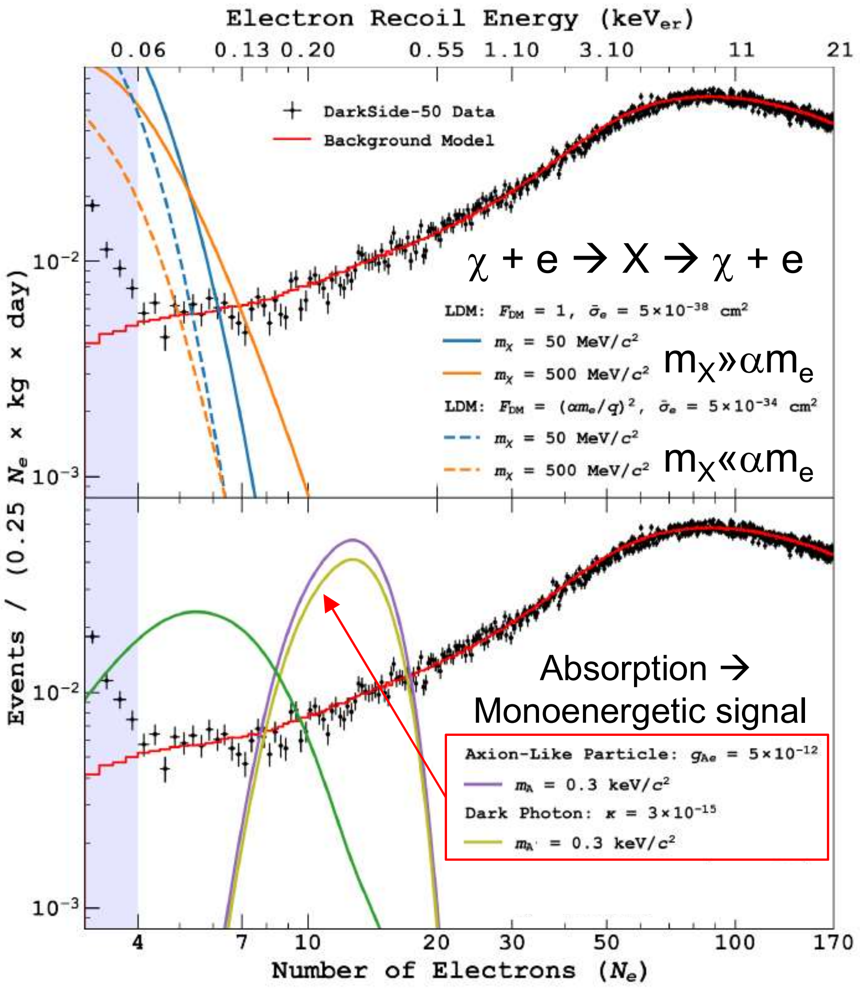




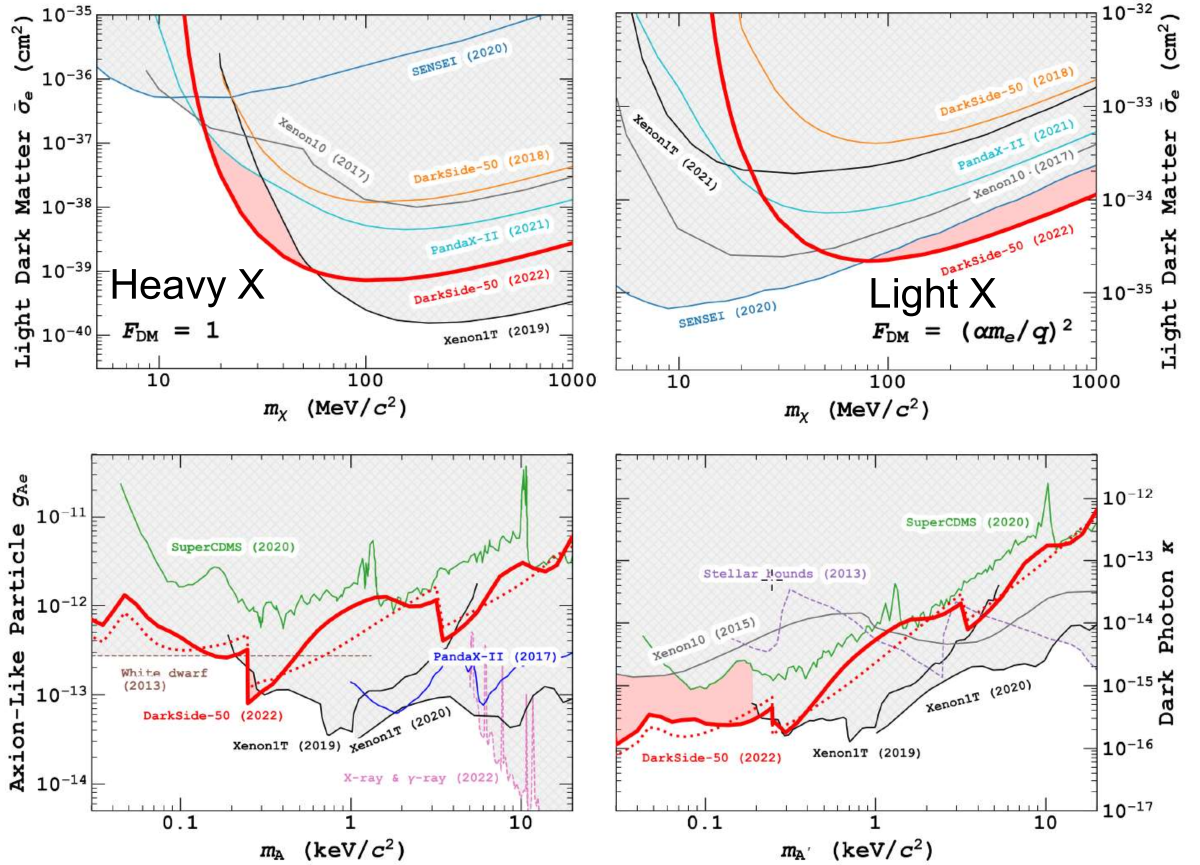
Most stringent limits on WIMP+Migdal in [0.04 – 4] GeV mass range

New limits (3/4)

- **Light Dark Matter, ALP, Dark Photon – electron**
  - Can constraint models in 2D plane electron coupling – M(new particles)



2207.11968

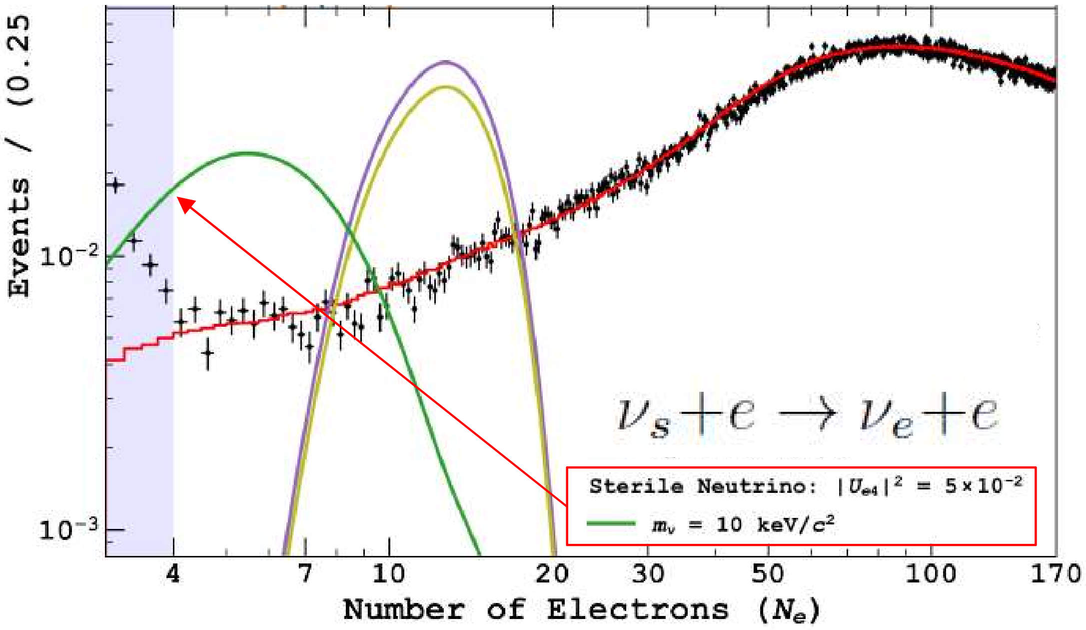


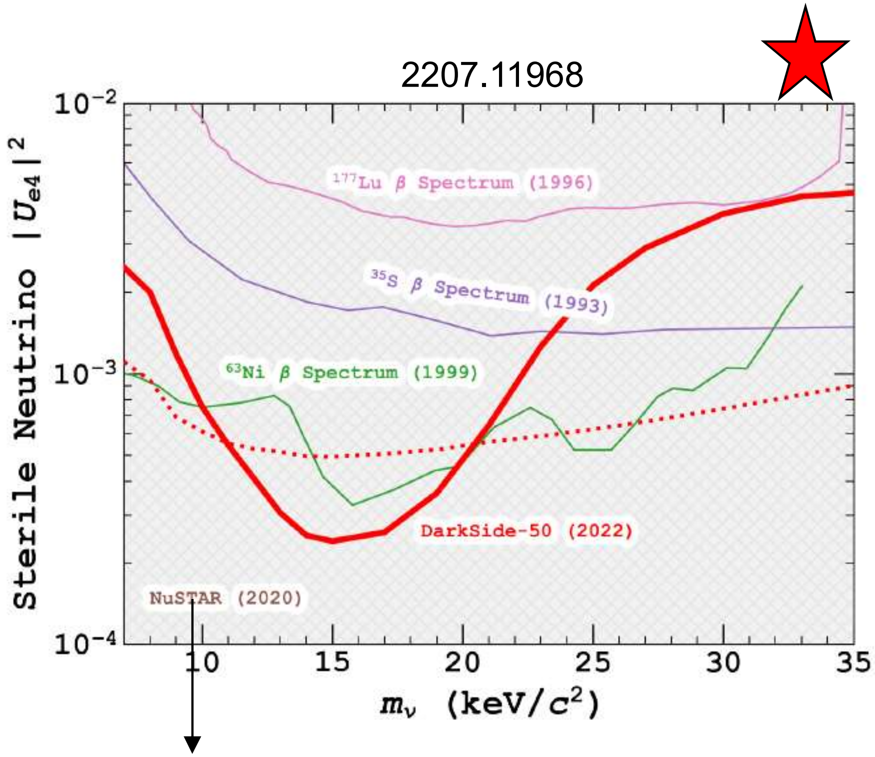
Most stringent limits on Light Dark Matter, ALP and dark photon at few places

New limits (4/4)

❑ Sterile ν – electron

- ν_s mix with an active state via angle $|U_{e4}|^2$
- Inelastically scatter on electron





extend down to 10^{-13} !

First DM direct detection expt to set limit on sterile ν *(much above indirect limit though)*

Next step : DS-20k

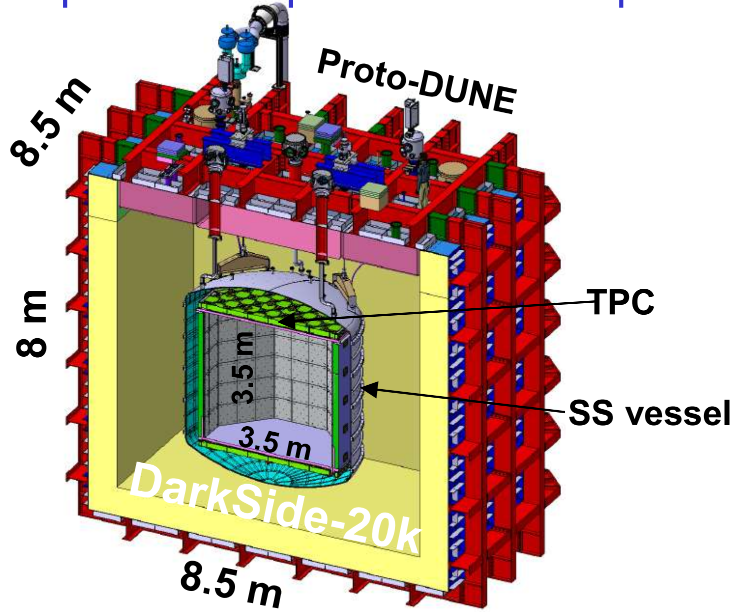
❑ LAr dual phase TPC technology is demonstrated

- Only one global collaboration (GADMC, >350 people) to profit from previous developments

ϕ ~ 0.35 m

h ~ 0.35 m

ϕ ~ 2 m

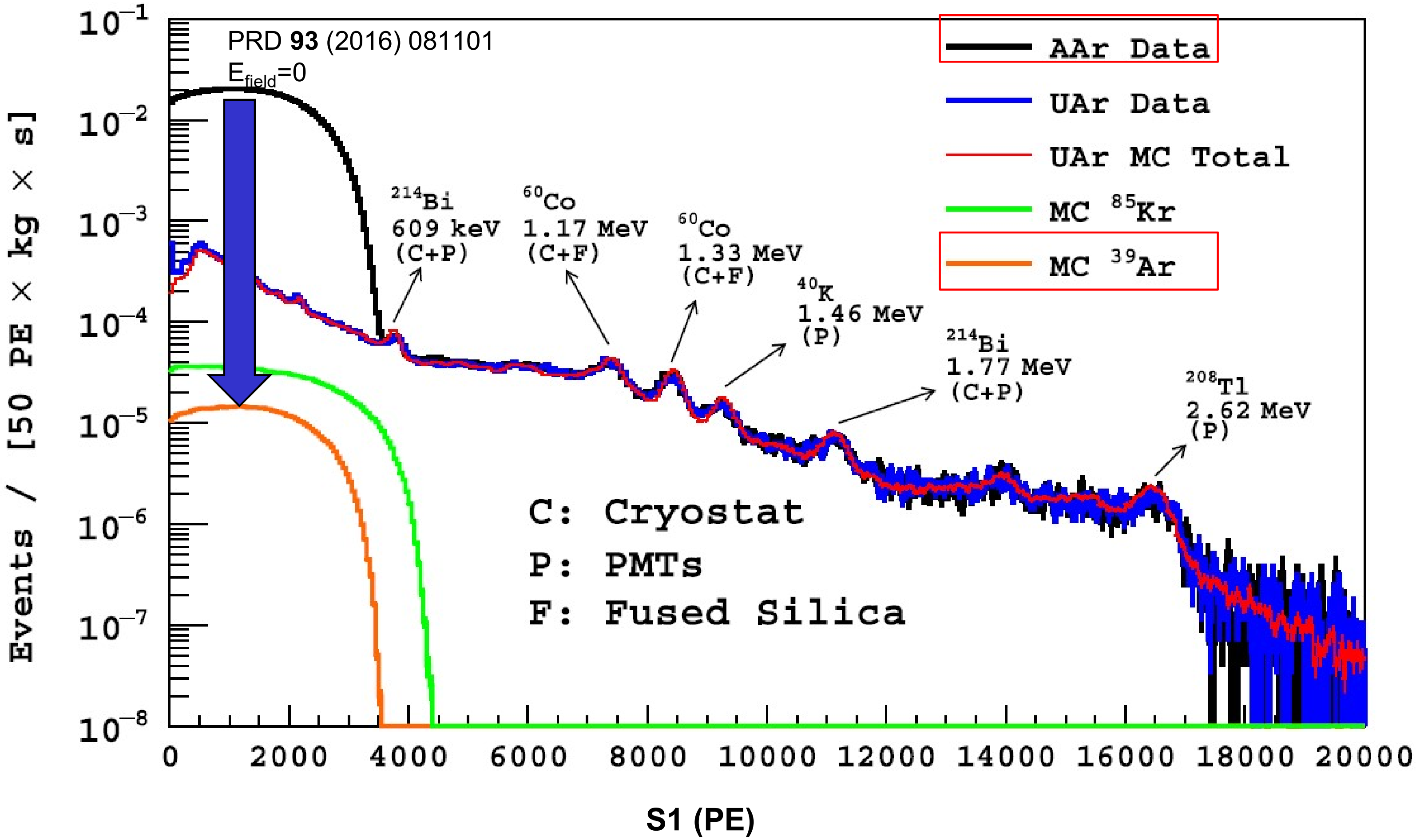


Lab (fid. data)	LNGS (0.04 t.yr)		SNOLab (3 t.yr)		LNGS (200 t.yr)
TPC target	50kg Purified Ar	x70 →	3.6 t *Atmosph. Ar*	x14 →	50 t Purified Ar
TPC wall	*Stainless Steel*		Acrylic		Acrylic
TPC nb ch.	*38 PMT*	x7 →	*255 PMT*	x8 →	~200k SiPM → ~2000 channels
TPC techno	Dual Phase		*Single Phase*		Dual Phase
Veto	*Scint (30 t) + Water (1000 t)* [inner] [outer]		*Water (250 t)*		Ar in vessel (30 t) + ProtoDUNE (700 t) [inner] [outer]

Will be the largest TPC ever build for Dark Matter searches !

DS-20k Purified Argon

- **Argon depleted in ^{39}Ar (UAr) extracted from a deep mine in USA**
  - ^{39}Ar produced by cosmic rays on ^{39}K ($T_{1/2}$=269 yr) : O(1) Bq/kg → Reduce to O(1) mBq/kg



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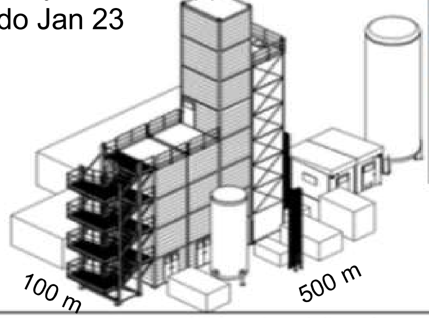
Plant ready will be shipped to Colorado Jan 23

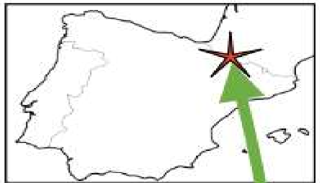


JINST 15 P02024 (2020)

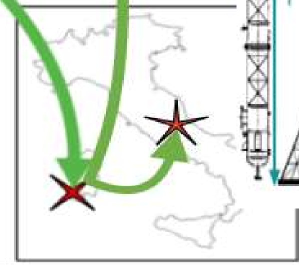
1 liter TPC in 1 ton ArDM cryostat (veto)

Characterise UAr with 10% precision

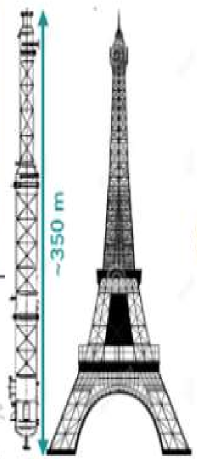
Characterisation: DArT
Measurement of the ^{39}Ar depletion factor



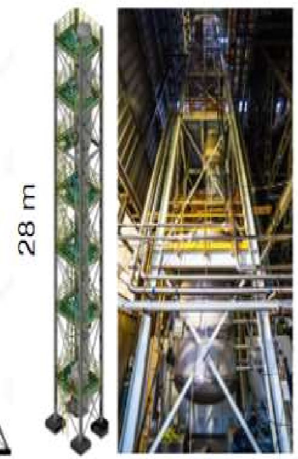
Boat
6-12 ton/trip
2.5 month/trip



Full scale



EPJC 81, 359 (2021)
Demonstrator



Production: Urania
- Commercial-scale plant to extract UAr
- Located in Southwestern Colorado
- UAr extracted from CO_2 well gas at the tonne scale

Extract highly pure 0.3 ton / day *(90 ton/yr)*

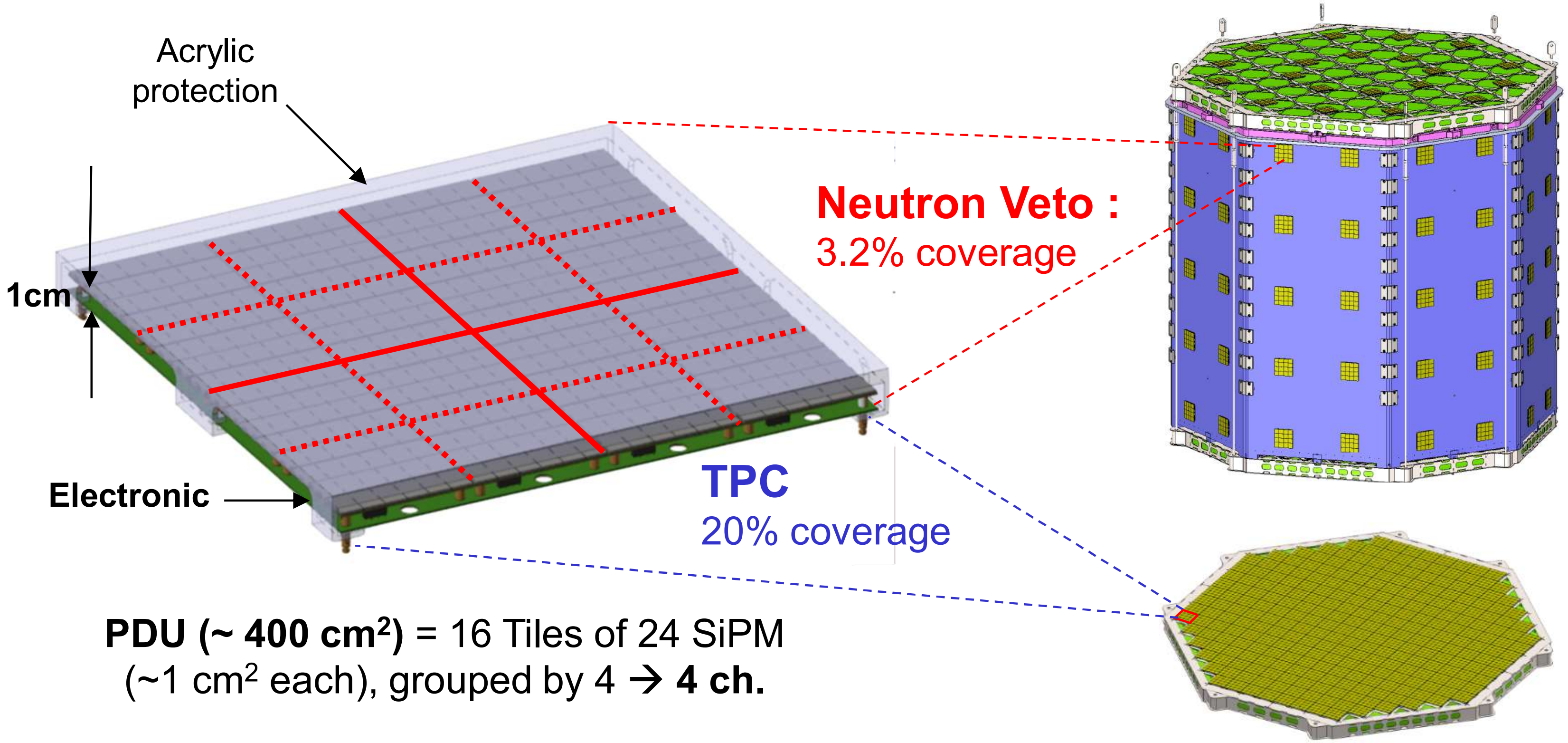
Purification: Aria
- 350 m tall cryogenic distillation column to purify UAr and isotopically separate argon and other elements
- Located in refurbished carbon mine shaft in Sardinia, Italy

Purify 1 ton / day

DS-20k PhotoSensors

❑ 250 000 Silicon Photo Multipliers (SiPMs)

- Custom cryo. SiPMs : 10^6 gain, PDE (420 nm) >42%, DCR < 20 Hz/Tile, σ_t =15 ns, SNR>15
- PDU installation at top/bottom inside the TPC and outside for inner neutron veto*



PDU (~ 400 cm²) = 16 Tiles of 24 SiPM (~1 cm² each), grouped by 4 → **4 ch.**

TPC + Veto =
~8500 + 2500 Tiles
(~20 + 5 m²)
~2100 + 600 ch.

* Outer Veto : 8 arrays lowered from the proto-DUNE flanges *(0.5% coverage, 1 /MeV)*

DS-20k PhotoSensors

- **250 000 Silicon Photo Multipliers (SiPMs)**
  - Custom cryo. SiPMs : 10^6 gain, PDE (420 nm) >42%, DCR < 20 Hz/Tile, σ_t =15 ns, SNR>15
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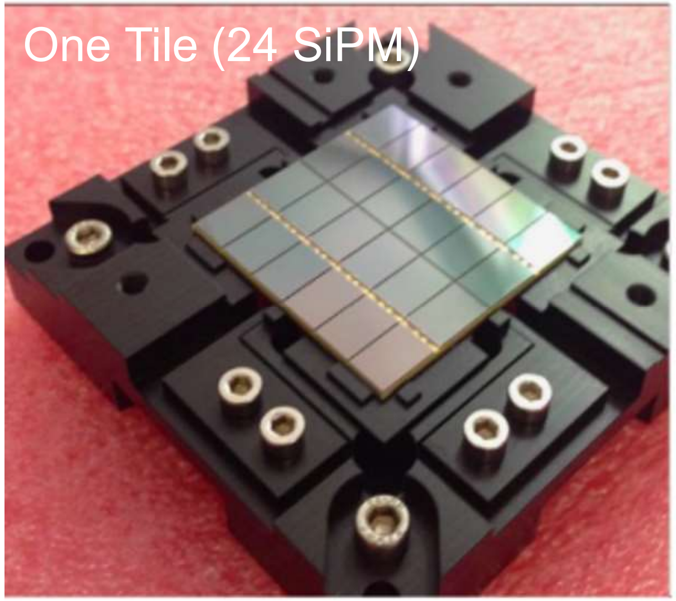
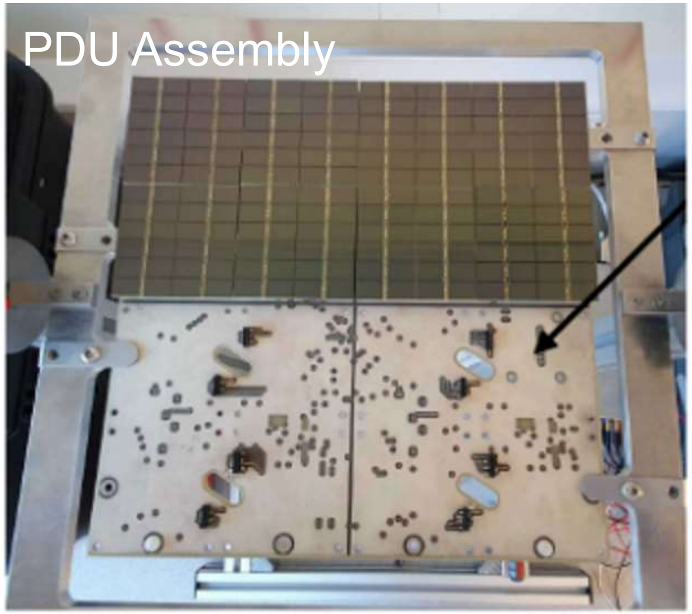
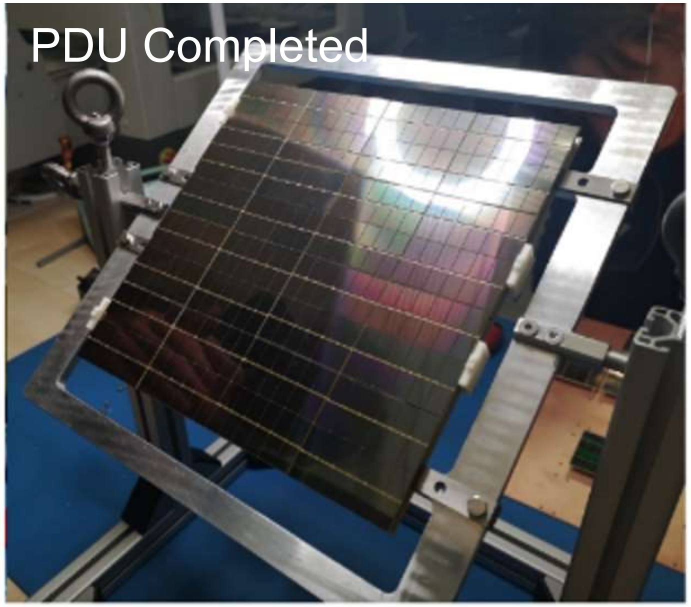


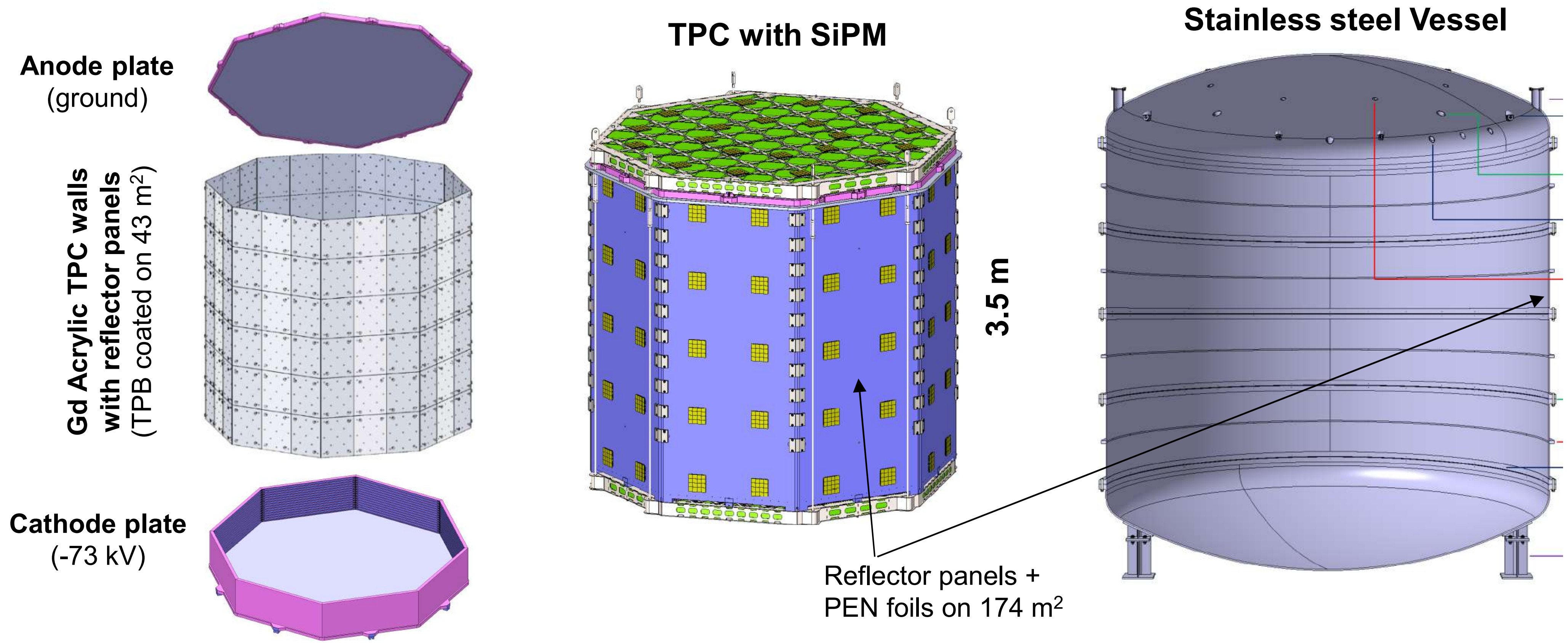




SiPM delivered and PDU electronic design frozen

DS-20k Inner Detector

- **Inner detector** *(TPC + neutron veto)* **compact and simple**
  - High degree of integration in the TPC
    - ✓ TPC walls also serve as overall mechanical structure, Faraday cage, grounding, neutron moderator
    - ✓ Minimize type and amount of passive material to lower the background
  - TPC – vessel gap used for the neutron veto : instrumented with SiPMs



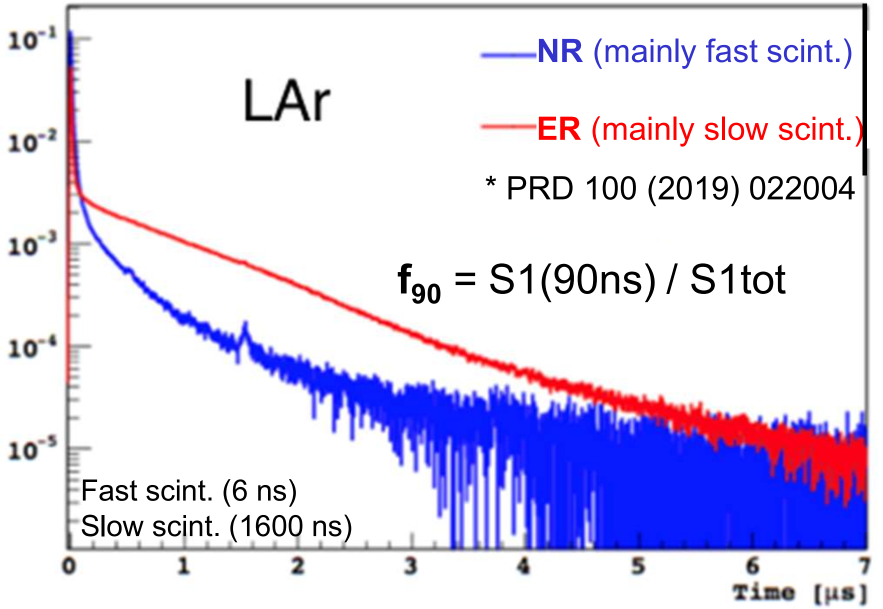
High Mass WIMP (1/2)

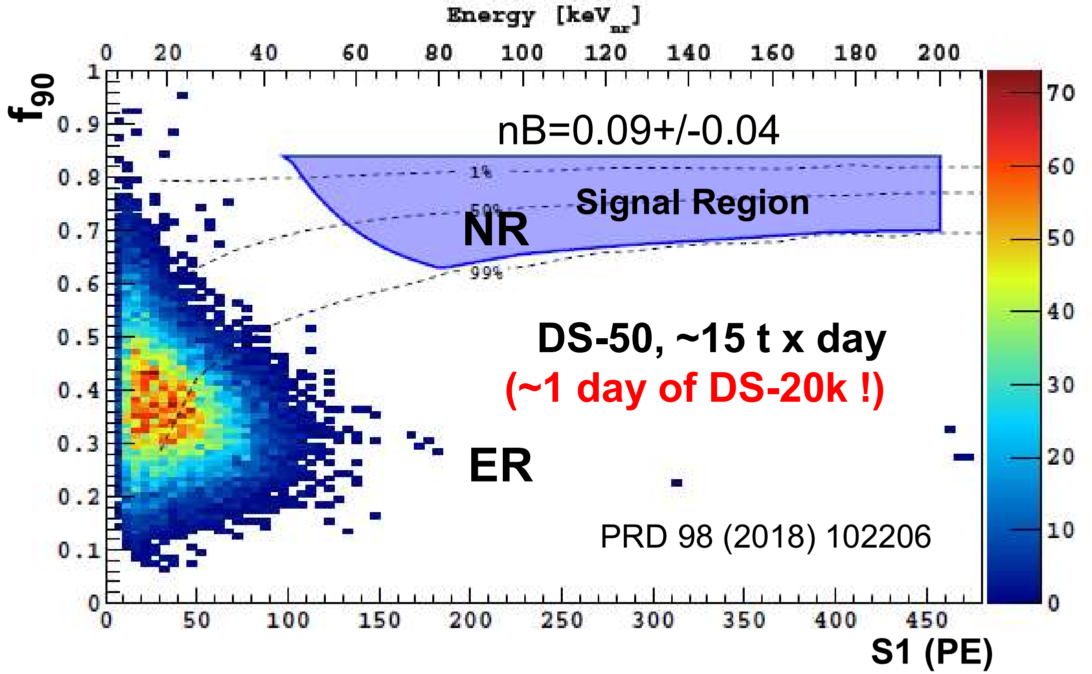
❑ DS-20k optimized to be background free

- Fiducial volume: 70 (30) cm away in z (r) from the TPC walls → **20 t LAr, single scatter**
- ER background: purified argon, S2/S1, S1 PSD → **negligible**
- NR background: LNGS, material selection + cleaning+assay, neutron veto → **suppressed**

<mBq/kg ^{238}U, ^{235}U, ^{232}Th activity → O(10^{-7}) n / decay, E ~ MeV | ^{222}Rn daughters | O(500) | Neutron moderated by Acrylic captured by Gd → ≤ 8 MeV γ

S1 Pulse Shape Discrimination (R_{ER}>10^8)*





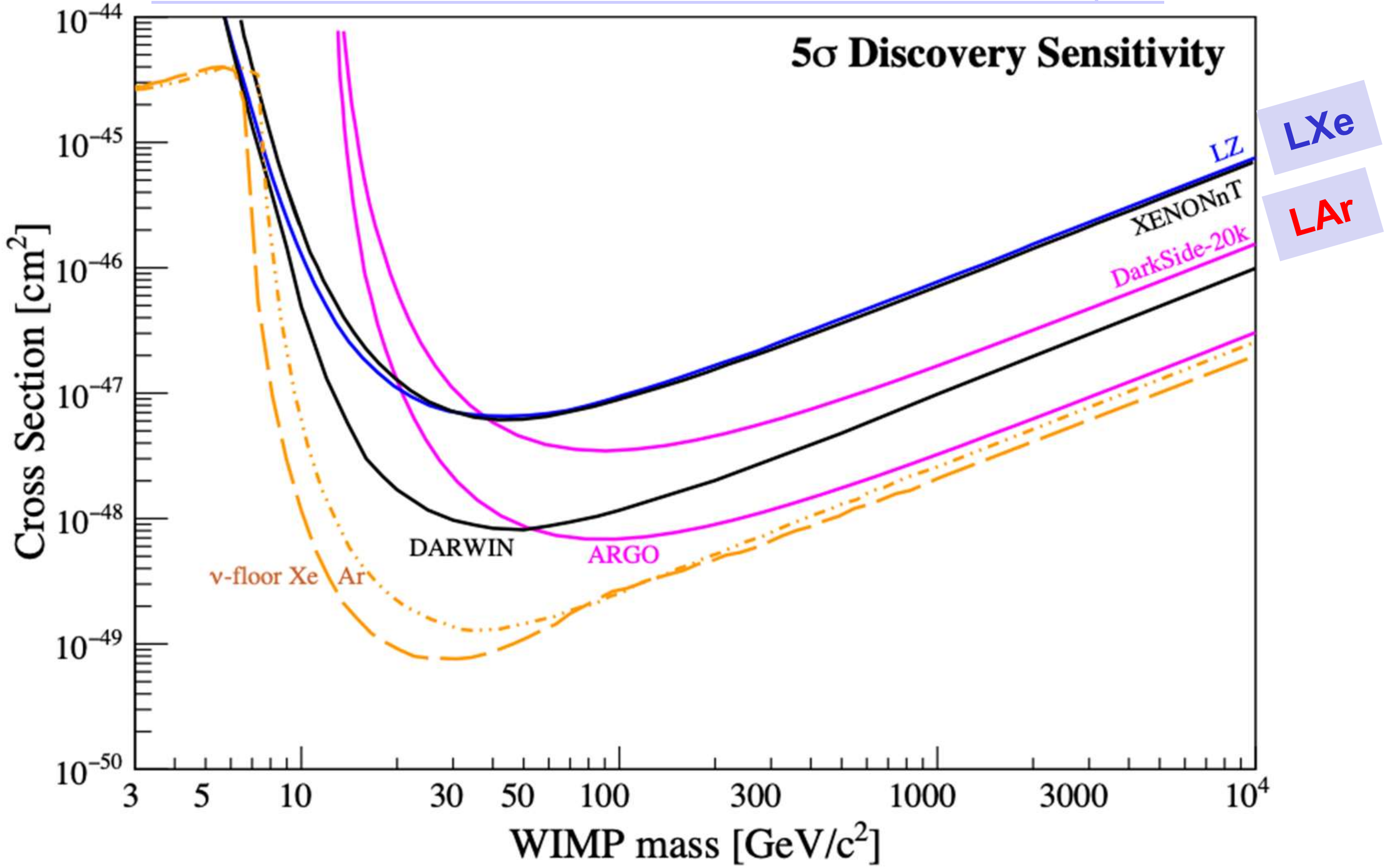
Expect ~0.1 bkg event in 10 years of running (200 ton.year)*

** Note: expect ~3 irreducible evts from ν NR*

High Mass WIMP (2/2)

- **Good discovery potential for high mass WIMP**

Direct Detection of Dark Matter – APPEC Committee Report

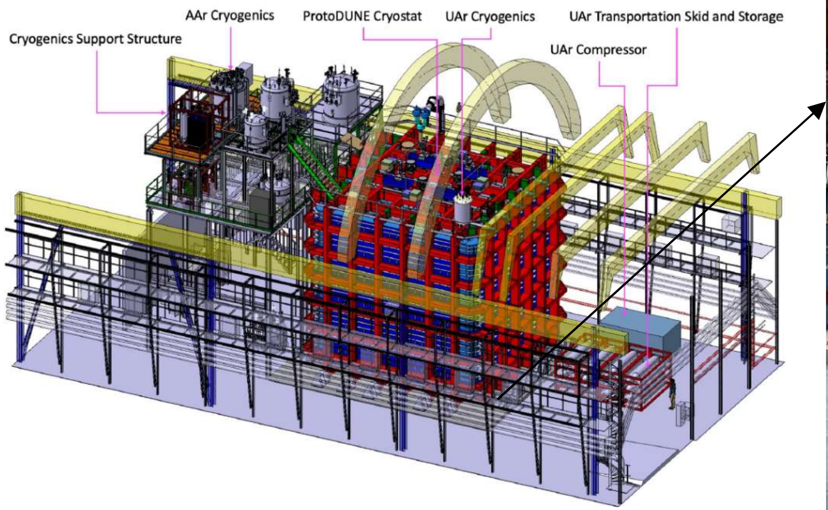


DarkSide-20k and Xenon expts complementary for high mass WIMPs

Status of DarkSide-20k

- **TDR to LNGS December 2021**
  - Installation: started in September 2022 and planned to be completed by end 2026
  - Physics: first run in 2027. Run during 10 years (→ 200 t.yr)

Hall C in LNGS



Conclusions

- **Dark matter WIMP search is in a very exciting period**
  - Recently explore one order of magnitude from 1 GeV to 10 TeV !
  - Still no sign of WIMPs

- **First generation Liquid Argon dual phase TPC** *(DS-50, 2015-18)*
  - Demonstrated feasibility of the technology *(**50 kg** purified LAr)*
  - **Background free** at high WIMP mass
  - Very sensitive to low mass WIMP with final analysis
    - ✓ Model electron (nuclear) recoil ionization yield down to 0.06 (0.4) keV
    - ✓ Accurate background modelling down to Ne = 4
    - ✓ World best limit at in **1 - 4 GeV**
    - ✓ If Migdal effect, can go down to 0.04 GeV

- **Next generation Liquid Argon dual phase TPC** *(DS-20k, 2027-37)*
  - Largest Dark matter TPC ever build *(**50 tons** of purified LAr, x1000 DS-50)*
  - Starting now installation in Gran Sasso → first physics in 2027
  - Optimised to be **background free** at high WIMP mass: High discovery potential
  - Low WIMP mass search potential … to be evaluated

Conclusions

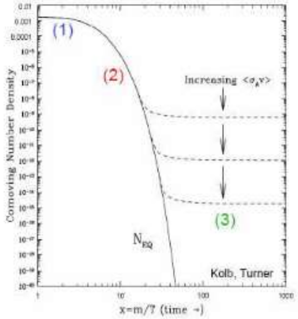
CPPM

CPPM

Back-up

DM WIMP: Miracle

- WIMPs decouple from thermal equilibrium
- freeze–out when $\Gamma \lesssim H$



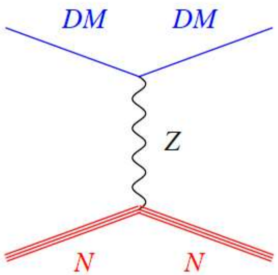
WIMP relic abundance

$$\Omega h^2 \simeq \frac{1}{\left\langle \left(\frac{\sigma_{\rm ann}}{10^{-38}{\rm cm}^2}\right)\left(\frac{v/c}{0.1}\right)\right\rangle} \qquad x_f = \frac{T}{m_\chi} \approx \frac{1}{24}$$

$\sigma_{\rm ann}$ – c.s. for WIMP pair–annihilation in the early Universe

v – their relative velocity, $\langle \ldots \rangle$– thermal average

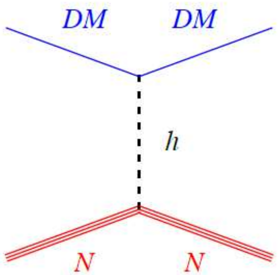
$$\sigma_{\rm ann} \sim \sigma_{\rm weak} \sim 10^{-38}\,{\rm cm}^2 = 10^{-2}\,{\rm pb} \;\Rightarrow\; \Omega h^2 \sim 1$$



10^{-38} cm^2

tree, vector

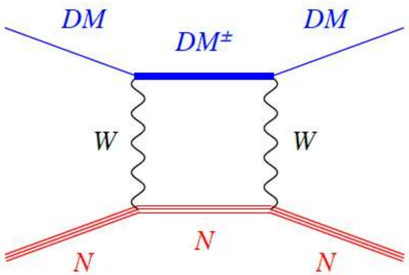
$$\sigma_{\rm SI} \approx \frac{\alpha^2\, m_N^2}{M_Z^4}$$



10^{-43} cm^2

tree, scalar

$$\sigma_{\rm SI} \approx \frac{\alpha^2\, m_N^4}{M_h^6}$$



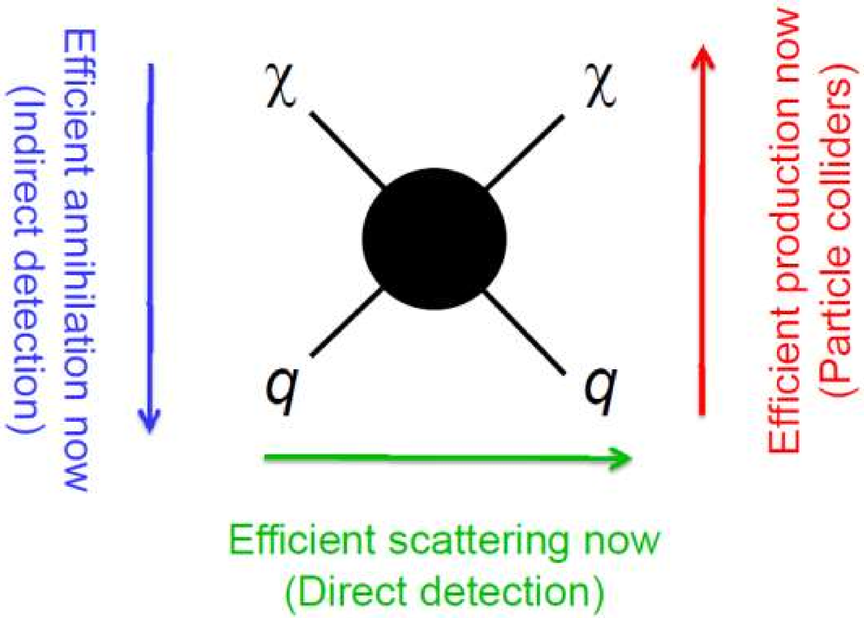
10^{-48} cm^2

loop

$$\sigma_{\rm SI} \approx \frac{\alpha^4\, m_N^4}{M_W^6}$$

DM WIMP: Search

in astrophysical objects, e.g. with KM3NeT, CTA, …



pp → Higgs → invisible, E_T^{miss}+X *(and other SUSY searches)*

with galaxy halo WIMPs on SM particles

Radio active background (1/4)

37-Ar

(τ=35 days)

Produced by solar

$\nu + ^{37}Cl \rightarrow ^{37}Ar + e$

$$^{37}_{18}Ar + ^{0}_{-1}e \longrightarrow ^{37}_{17}Cl$$

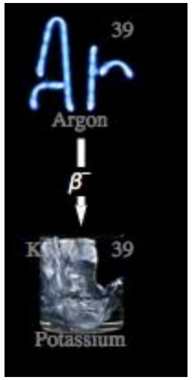
from L1 (0.28 keV, 8%)
or K (2.77 keV, 90%)
shells

Source of primaries :
electrons, X-rays, and
UV photons

39-Ar

(τ =269 yr)

Produced by cosmic rays on ^{40}Ar



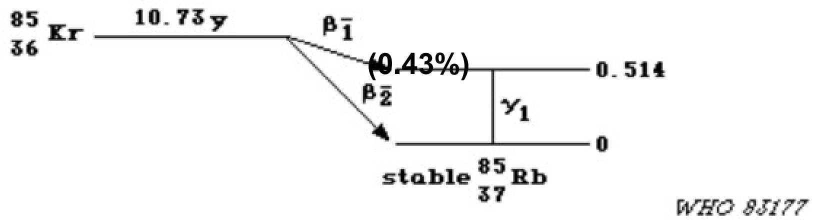
(100%)

Endpoint =565 keV
Mean = 220 keV

85-Kr

(τ =10.8 yr)

Produced by cosmic rays on ^{84}Kr + nuclear fission. It was unexpected to found it underground at such a level. This could have been produced by natural fission or atmospheric leaks (PRD 93 (2016) 081101). Improvements to the UAr extraction facility are expected to completely remove ^{85}Kr



Endpoint = 687 keV
Mean = 251 keV

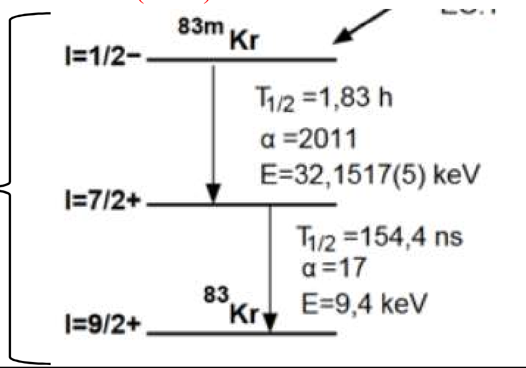
83m-Kr

(τ =1.83 hr)

Injected in the LAr for calibration

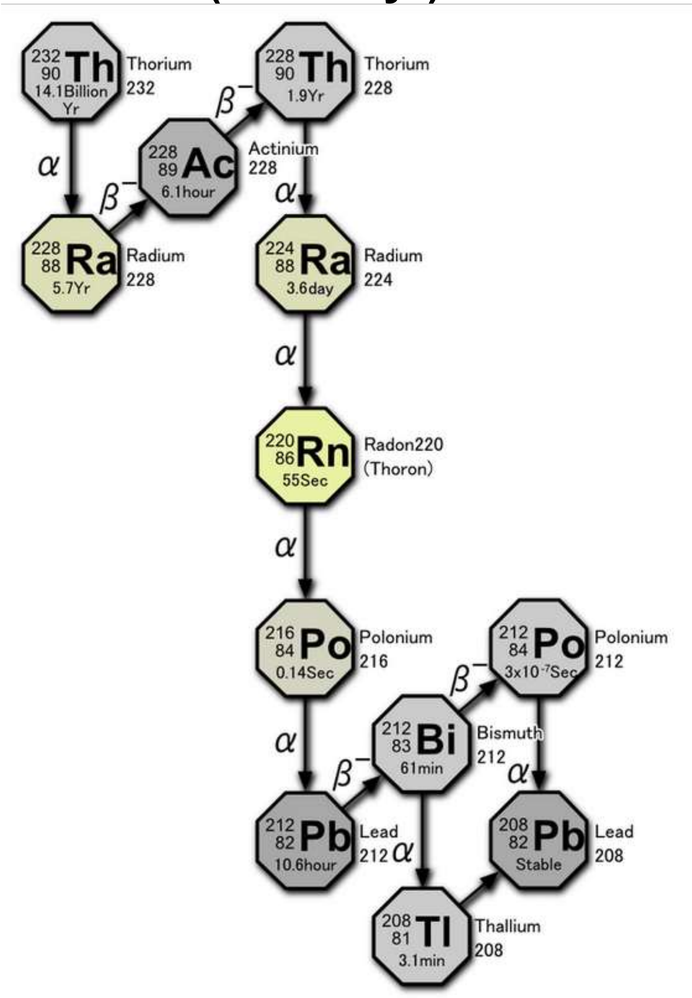
PRC 81 (2010) 045803

Internal conversion → electron + X-ray of 41 .5 keV

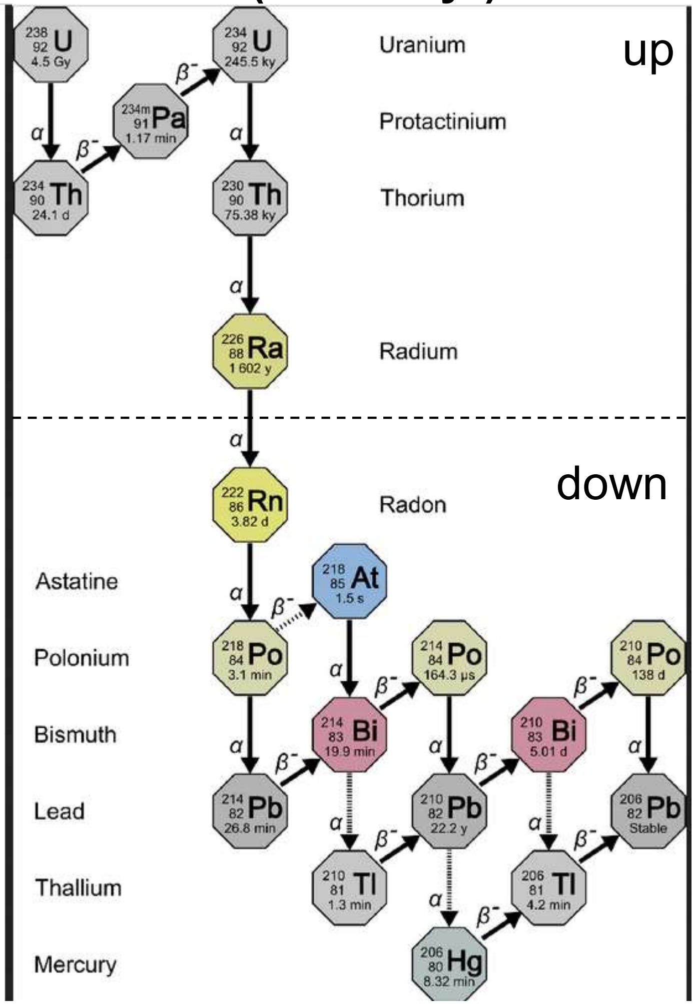


Radio active background (2/4)

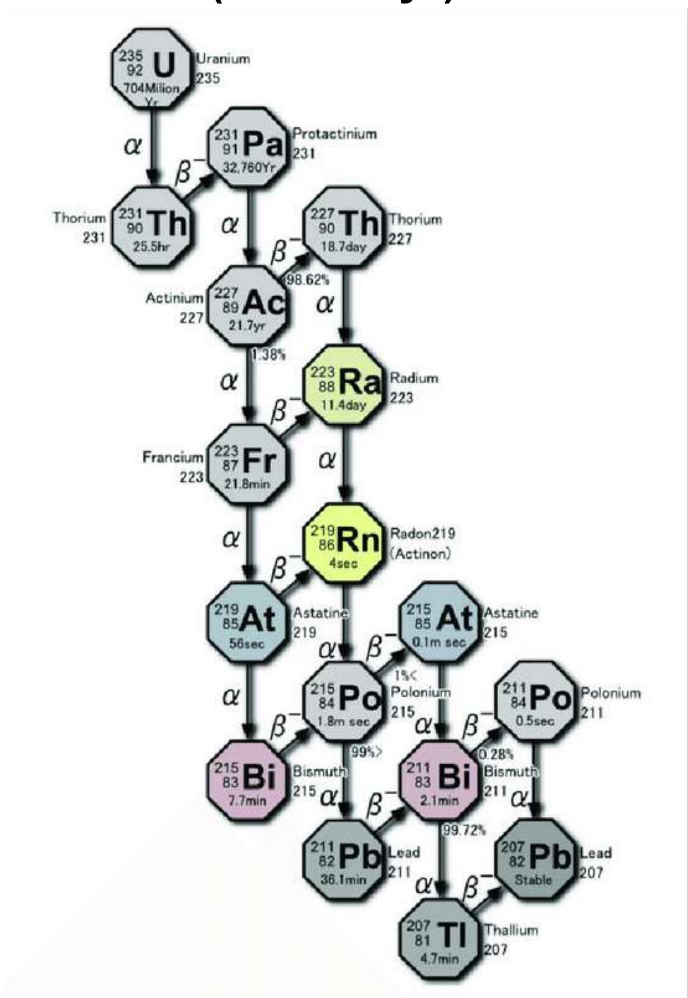
232-Th
(τ =14 Gyr)



238-U
(τ =4.5 Gyr)

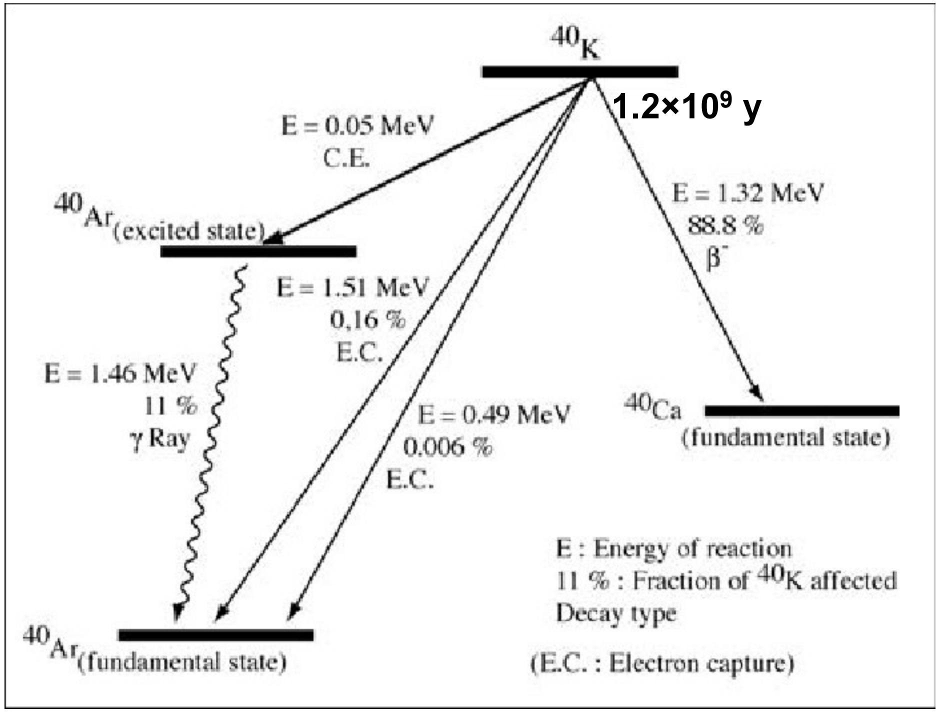


235-U
(τ =0.7 Gyr)

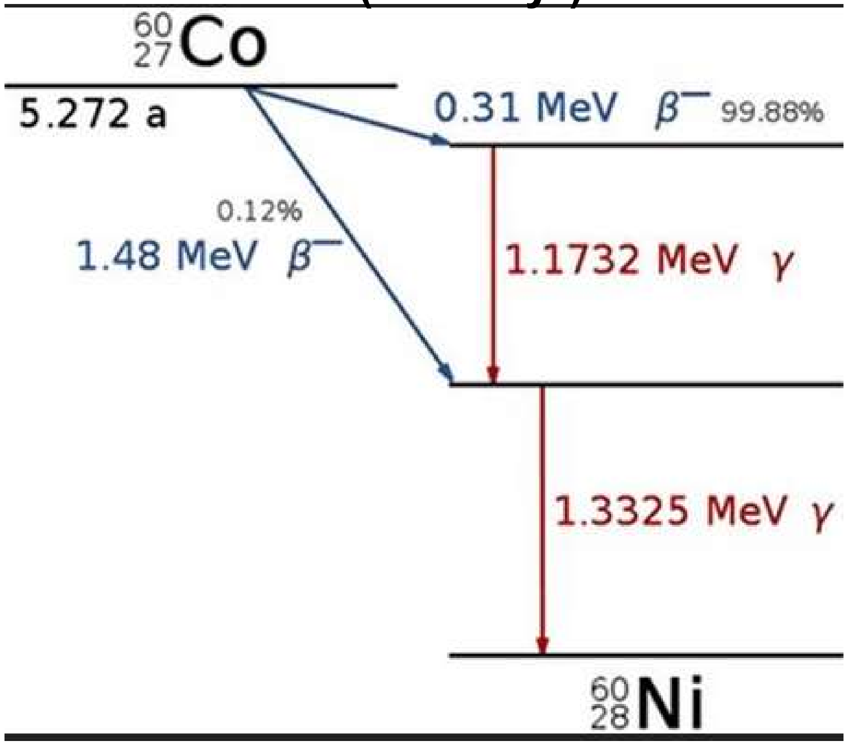


Radio active background (3/4)

40-K
(τ = 1.2 Gyr)

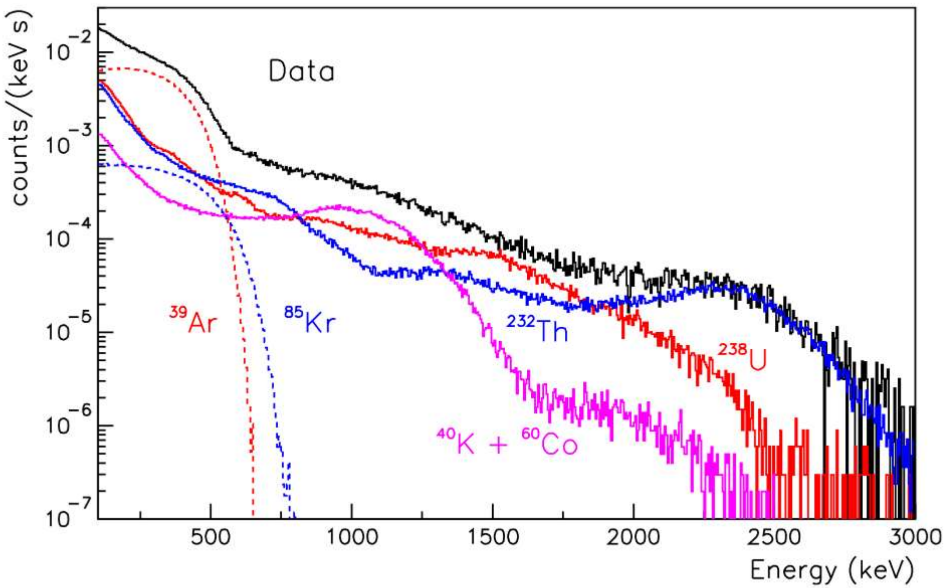


60-Co
(τ = 5.2 yr)

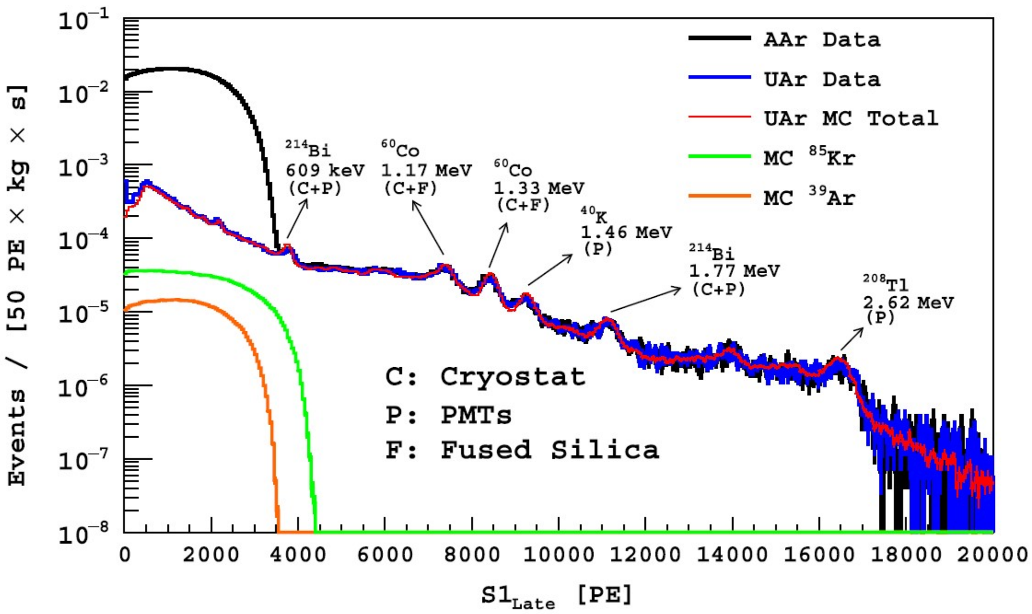


Radio active background (4/4)

WARP, astro-ph/0603131

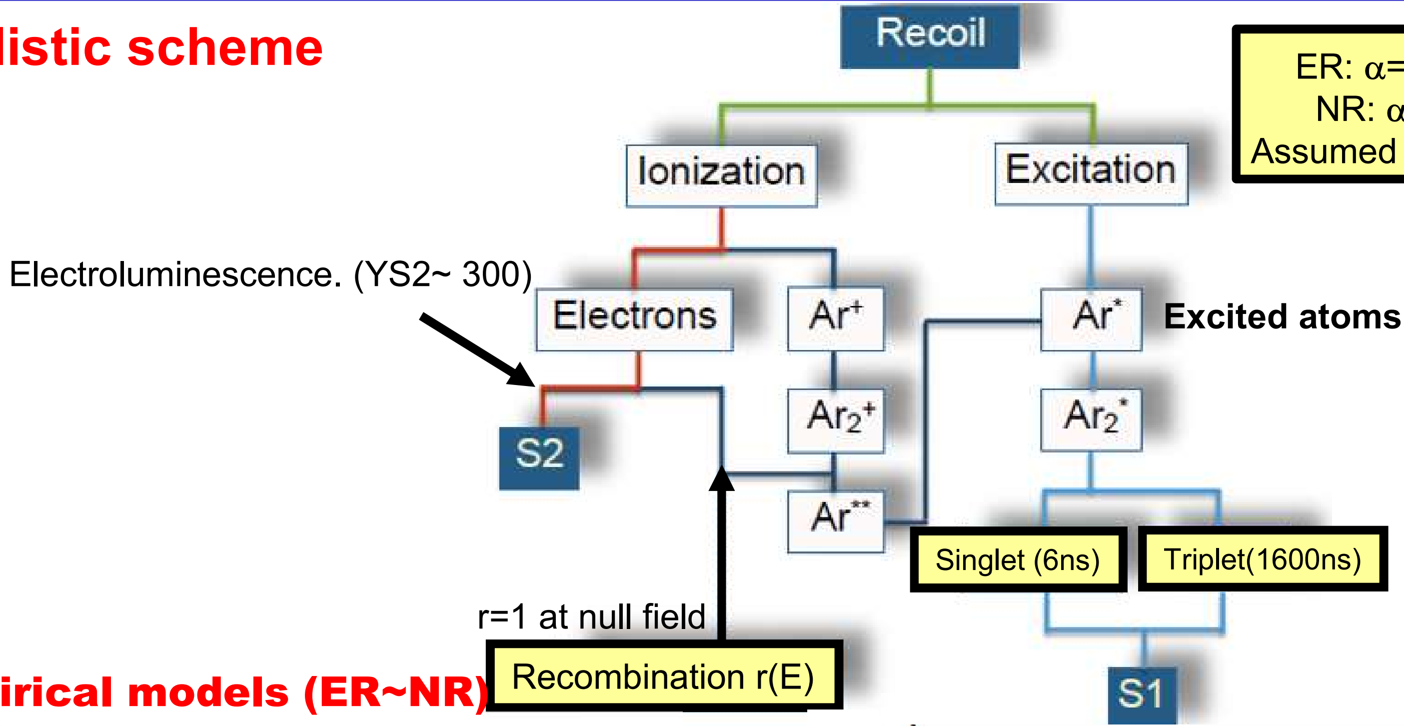


DS-50, PRD **93** (2016) 081101



DS-20k simulation (1/2)

❑ Realistic scheme

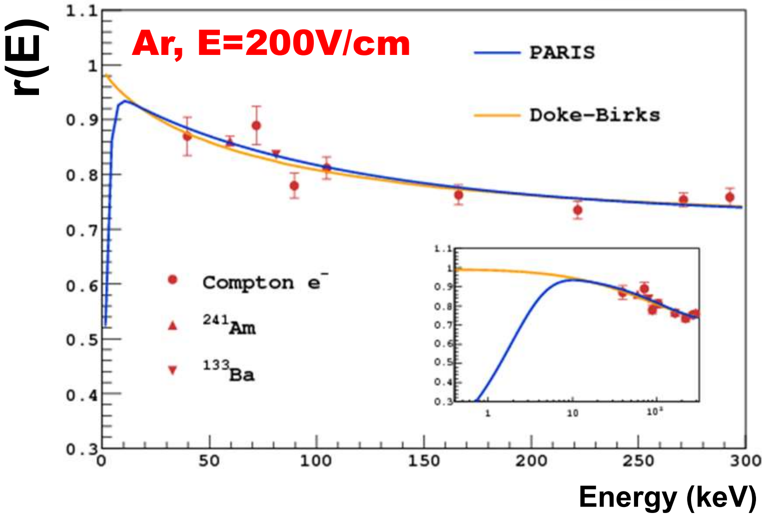


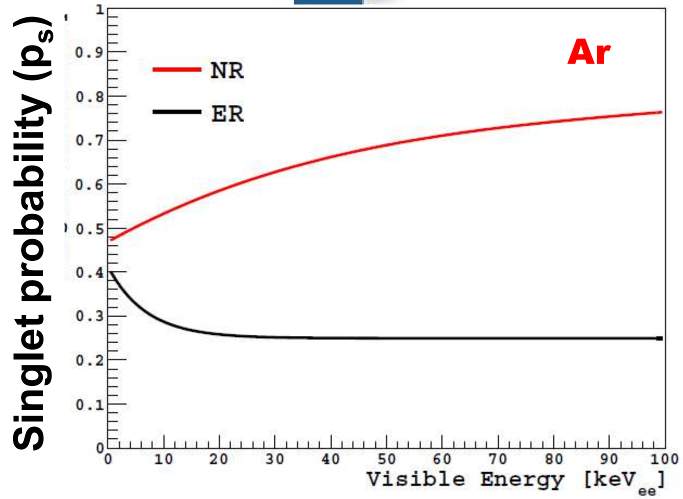
ER: $\alpha=N_{ex}/N_{ion}$~ **0.21**
NR: $\alpha=N_{ex}/N_{ion}$ ~ **1**
Assumed independent of E

[based on 70s/80s measurements]

NIM A269 (1988) 291
PhysRev A9 (1974) 1438
PhysRev B13 (1976) 1649

Empirical models (ER~NR)



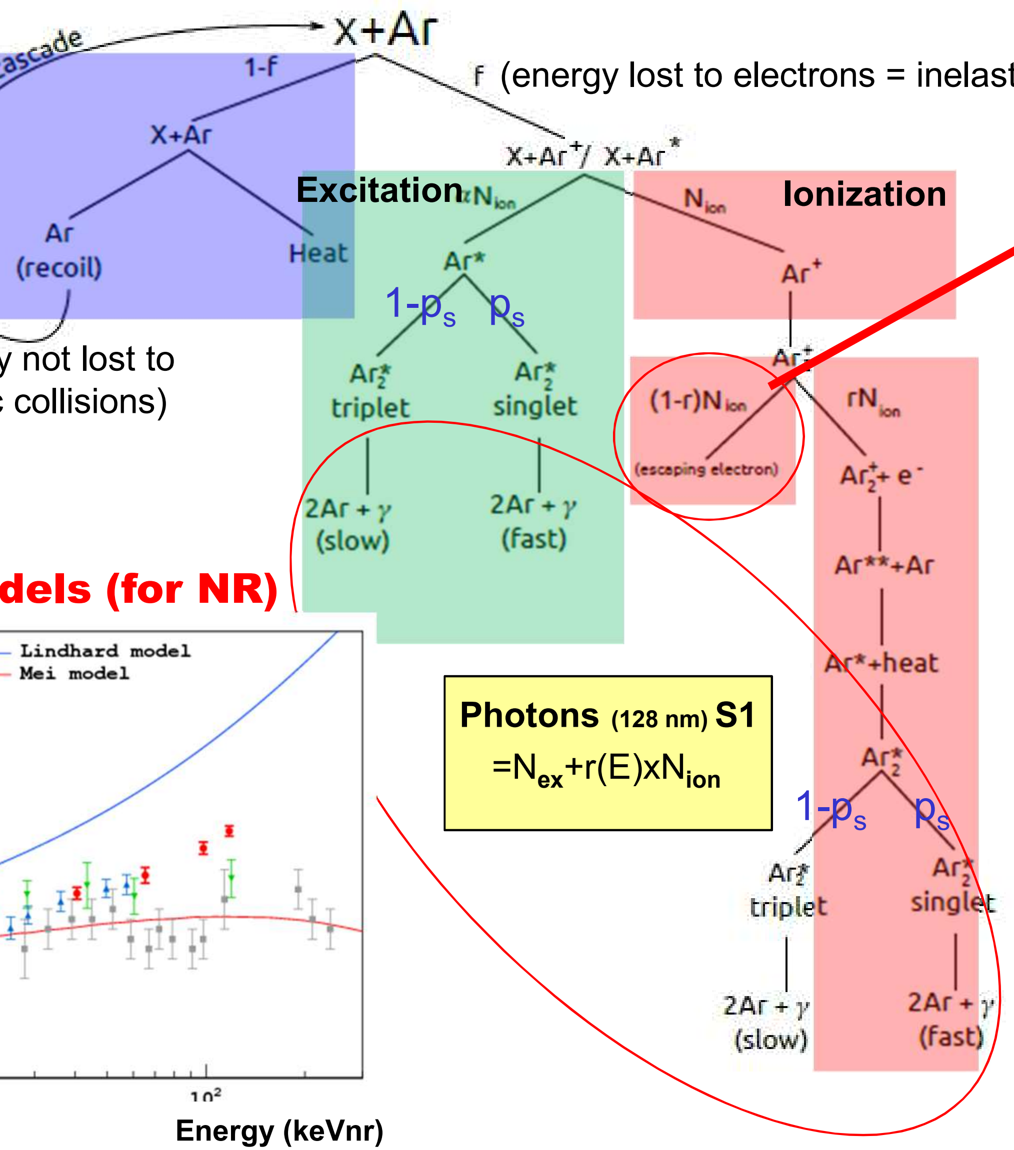


NR=mainly singlet
→ peaky signal

ER=mainly triplet
→ scattered signal

DS-20k simulation (2/2)

❑ Complete scheme

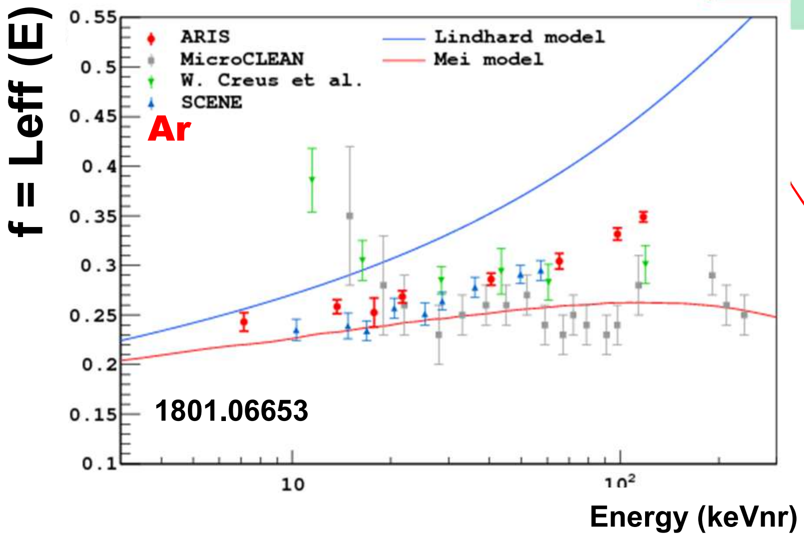


Electrons S2 $= N_{ion}-r(E)N_{ion}$
(photons [128 nm] → x
Y_{S2}=electroluminescence yield)

Quenching (energy not lost to electrons = elastic collisions)

ER: 1-f=0
NR : 1-f ≥ 0.5

Empirical models (for NR)



Photons (128 nm) **S1**
$=N_{ex}+r(E)xN_{ion}$

Summary ER:

W = effective work to extract one quantum (ex or ion) = **19.5 eV**

NIM A269 (1988) 291

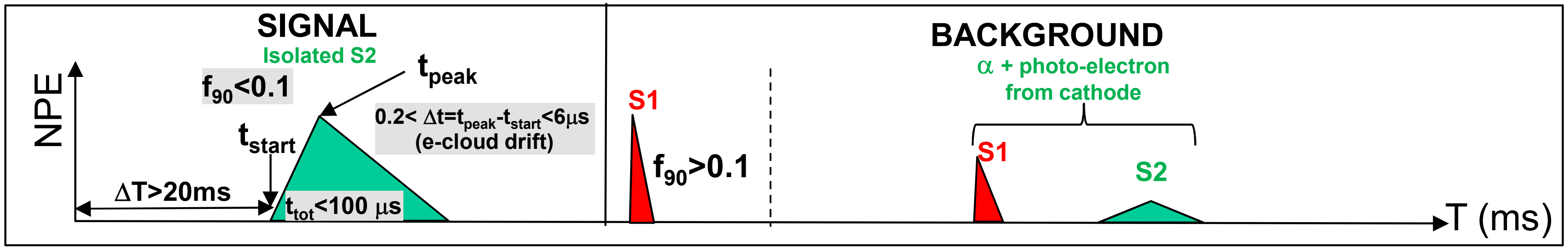
$E_{dep}=W(N_{ex}+N_{ion})$

$W(N_{ex}+r(E)N_{ion})$ → S1

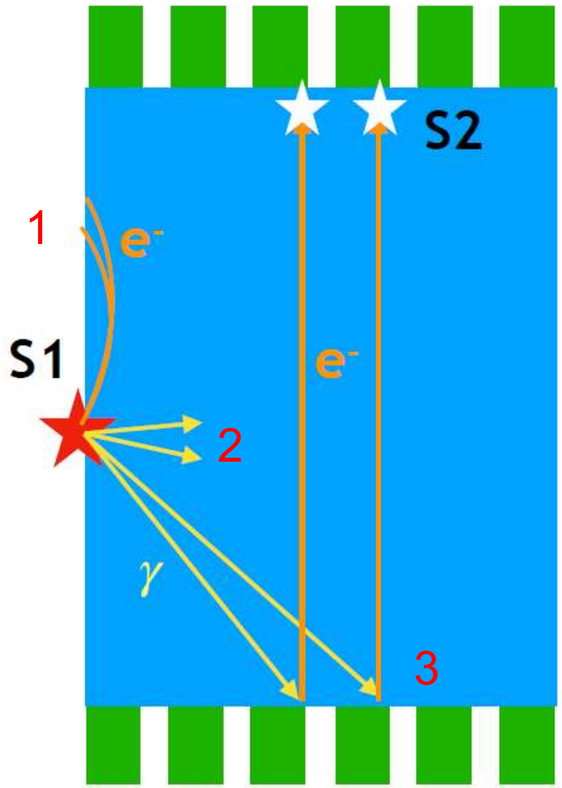
$WxY_{S2}[1-r(E)]N_{ion}$ → S2

[Compton scaterring and photo-electric effect for photons / (in)elastic scaterring and capture for neutrons]

Background: α surface



Note: pulse finder cannot distinguish two pulses 2 μs apart

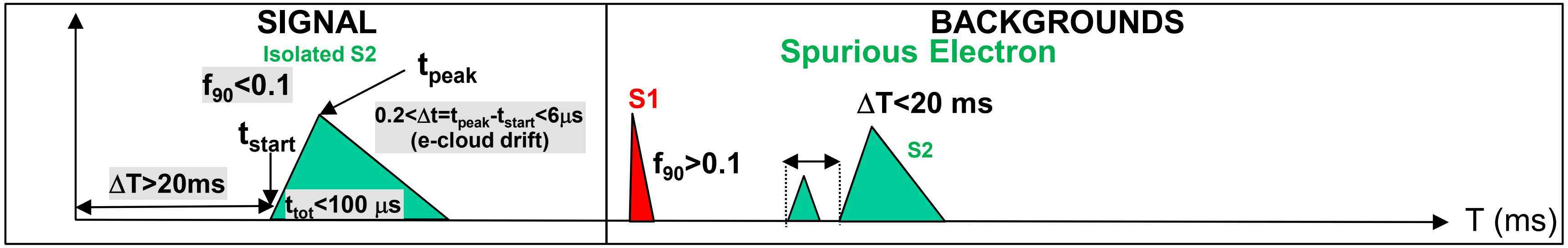


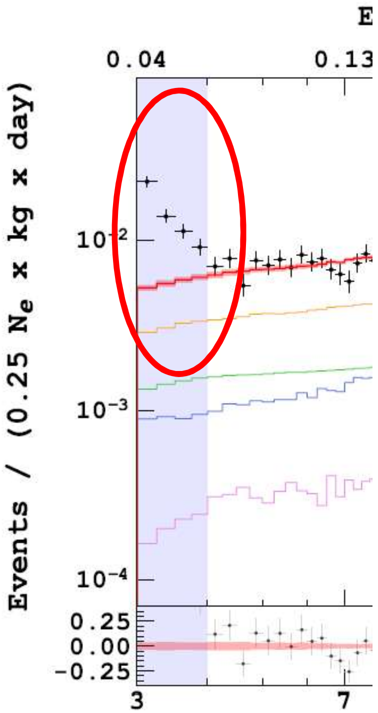
α decays very close (or in) the TPC walls

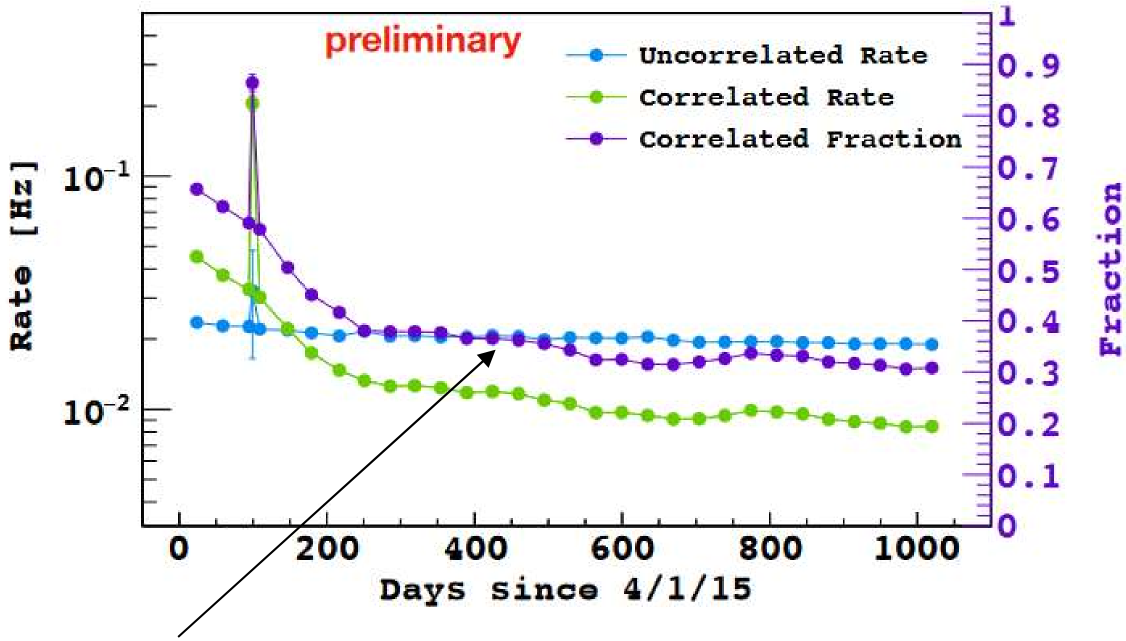
1. Electrons are "reabsorbed" by the wall
2. Large number of photons emitted ➔ Large S1
3. Some photons may create one or two electrons on the cathode
4. These one or two electrons are drifting up ➔ low S2

➔ **Abnormally large value for S1/S2.** Rejected by cutting on S1/S2 – the cut has been adjusted with calibration data (^{83m}Kr)

Background: spurious electron

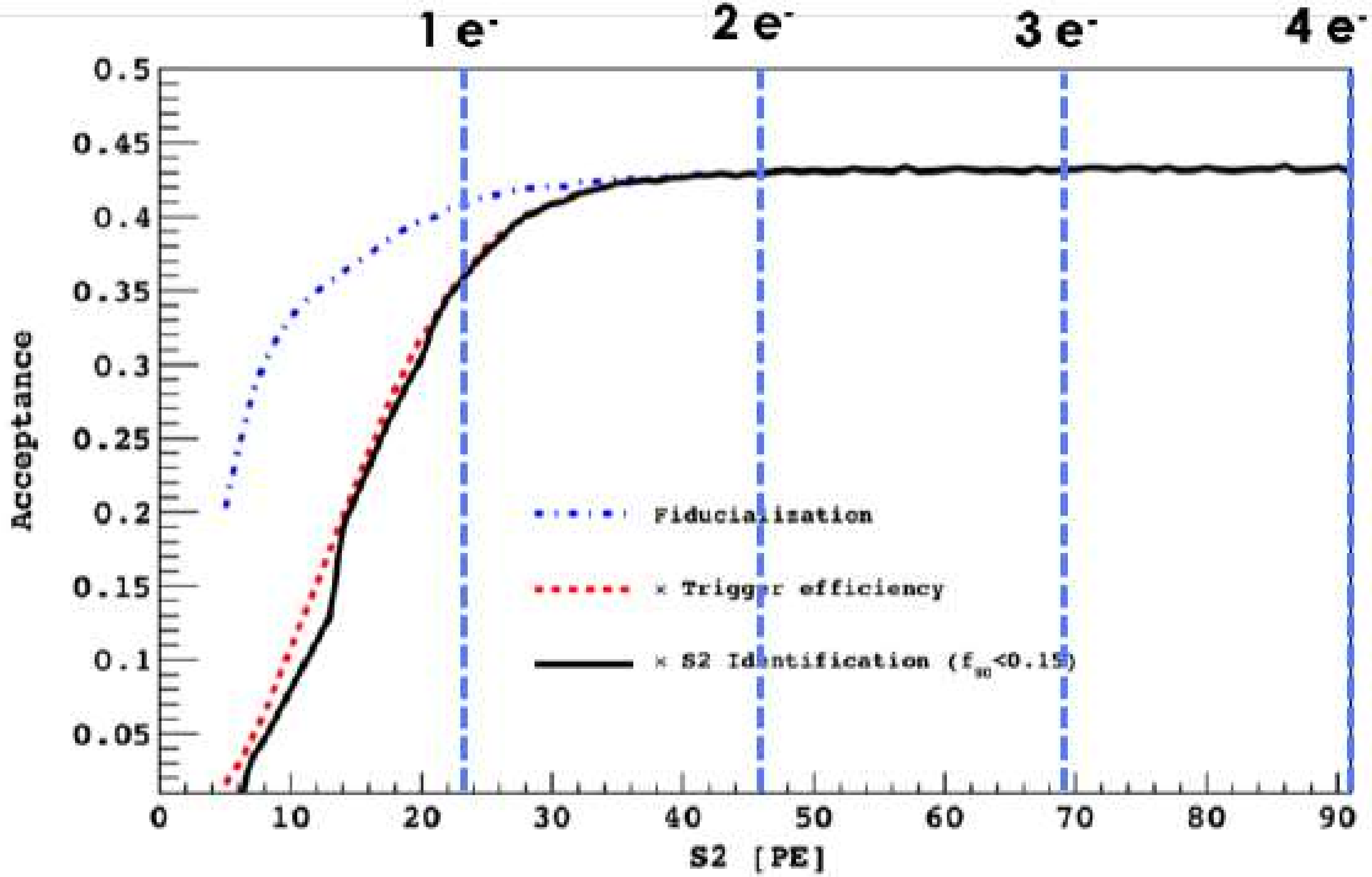






30-70% of Spurious electrons can be explained by the presence of a parent event (large S1 with >1000 PE)

Signal acceptance



Background: PMT and Cryostat

The **PMT** and the **cryostat** components are the combination of

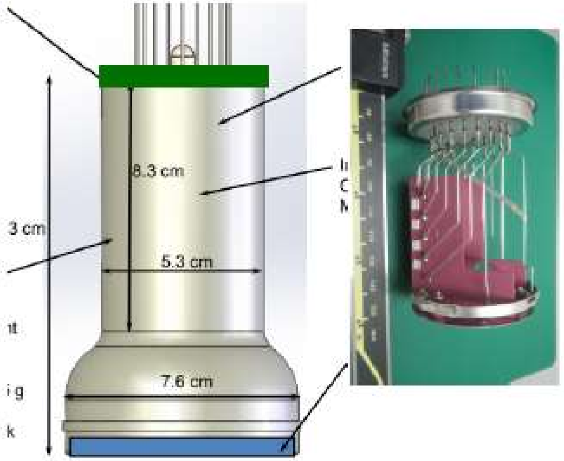
- 238U
- 232Th
- 235U
- 60Co
- 40K
- 54Mn (PMT)

G4DS has spatial generators and an accurate description of the detector geometry and materials

The predicted event rate in the TPC is obtained by using the screening measurement results.

1) correct the 60Co rate for the time elapsed between the measurement and the avg dataset date

2) break the contribution of the PMT in 3 subcomponents (body - stem - ceramic)

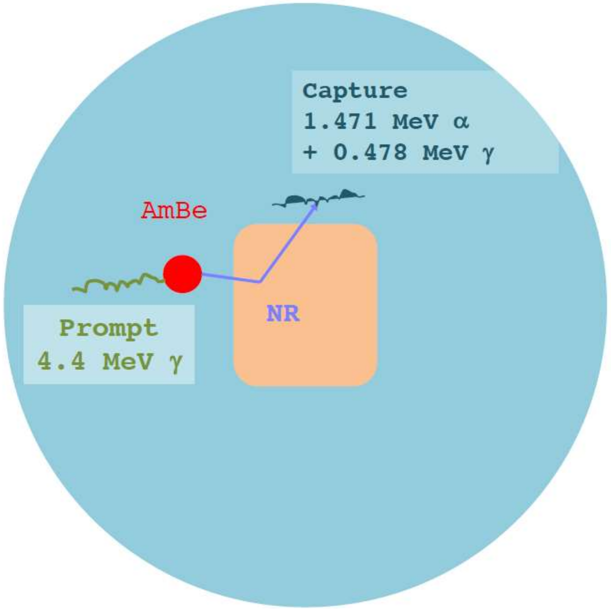


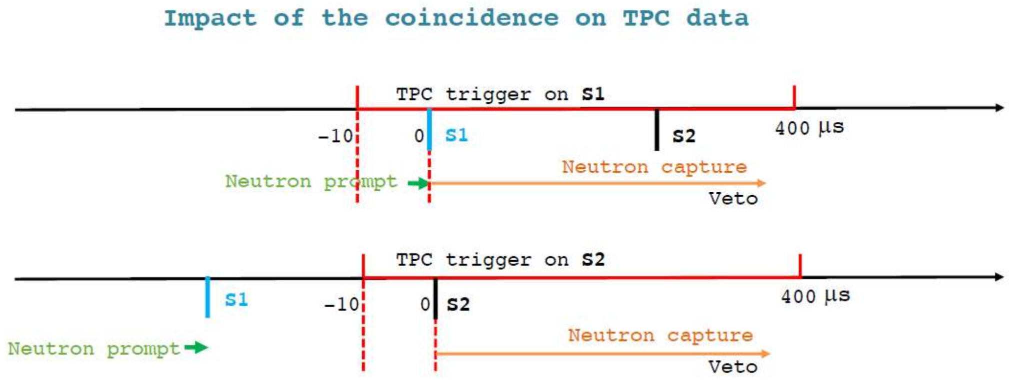
	Ceramic	Stem	Kovar		Ceramic	Stem	Kovar
^{60}Co	0	0	1	^{235}U	0.8	0.2	0
^{40}K	0.2	0.8	0	$^{238}U_{upper}$	0.8	0.2	0
^{232}Th	0.3	0.7	0	$^{238}U_{lower}$	0.5	0.5	0

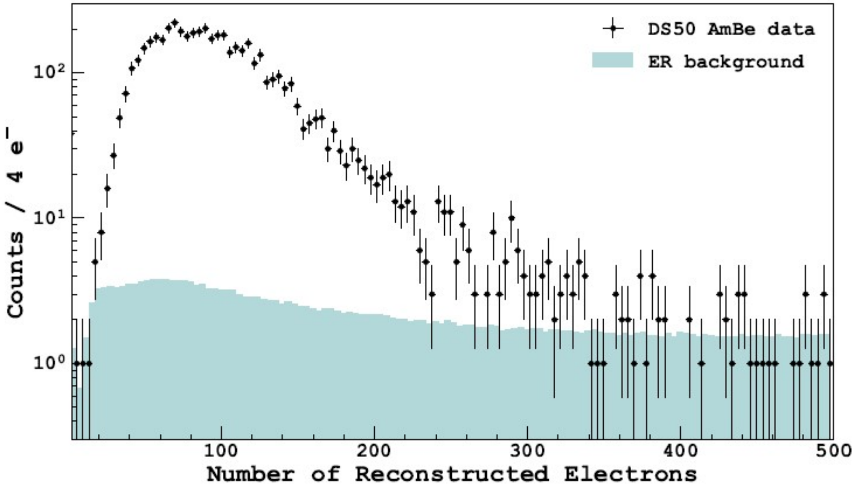
G. Koh's thesis

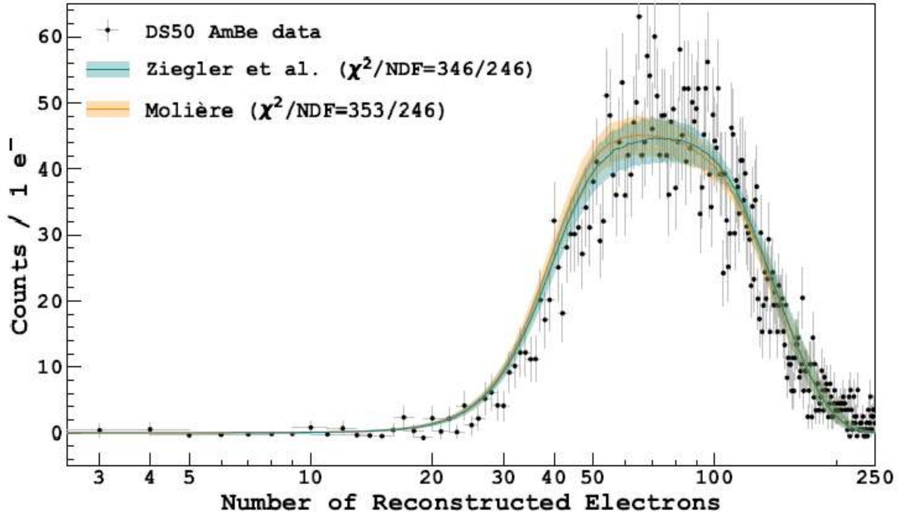
Calibration: AmBe Neutron

NRs from AmBe selected with a three-fold coincidence









Calibration: ^{37}Ar

PRL **121** (2018) 081307

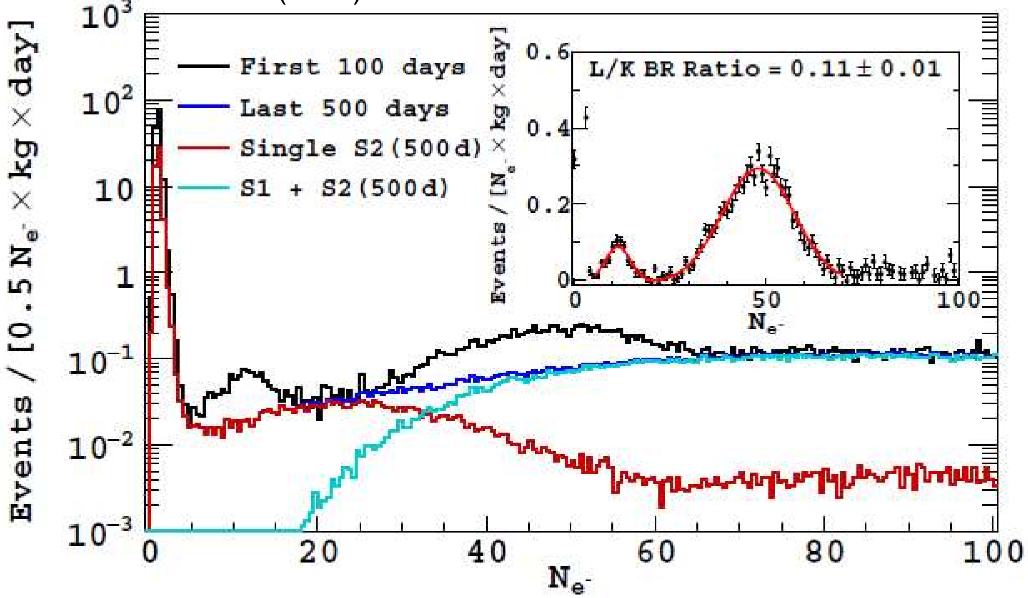
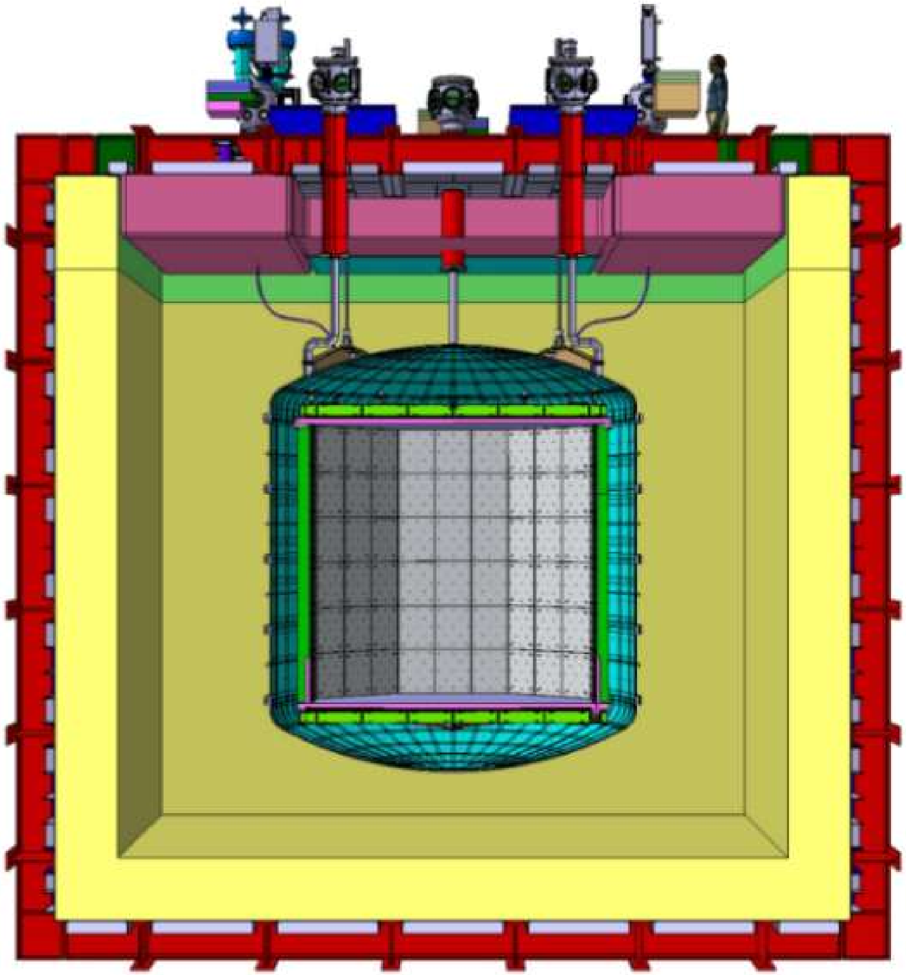


FIG. 3. Spectrum showing cosmogenic ^{37}Ar contributions and their decay as discussed in the text. Black: first 100 days of present exposure. Dark blue: last 500 days. Red and cyan show respectively the contributions to the dark blue spectrum from events with only an S2 pulse and from events with a single S1 and a single S2 pulse. Inset: normalized difference of black minus dark blue, showing the two peaks from ^{37}Ar decay.

DS-20k : Next project of GADMC

DarkSide-20k

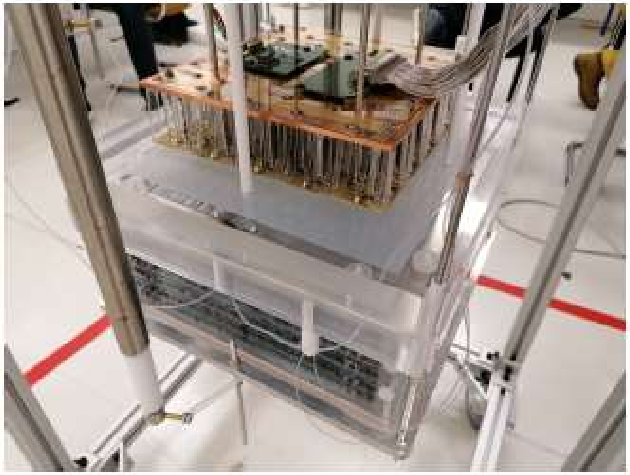
by the Global Dark Matter Argon Collaboration



DS-20k: prototypes

- **Prototyping**
  - Validate technological choices (e.g. integrated TPC)
  - Test the cryogenic system for the TPC (at CERN → LNGS)
  - Measure on-site performance of the SiPM → input for simulation

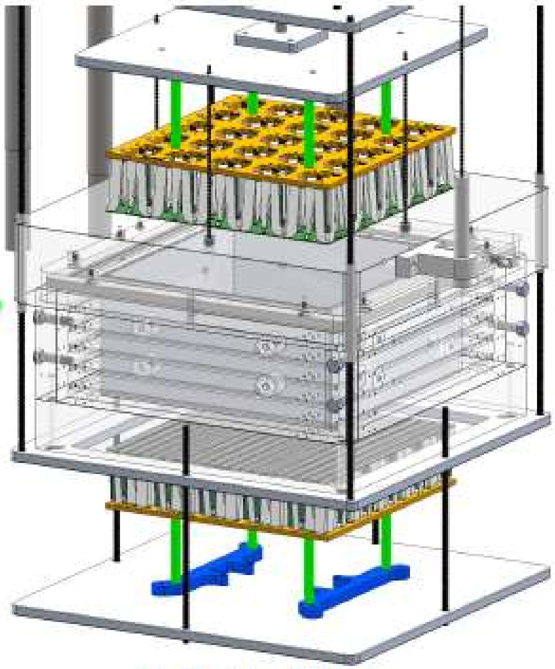
October 2019



Proto-0 at CERN

25x25x10 cm²
1 PDU

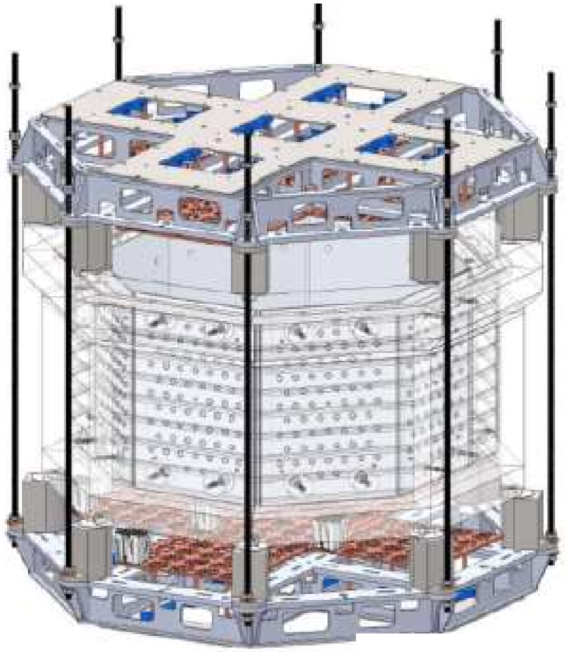
Spring 2023



Proto-0 at Naples

25x25x10 cm²
2 PDUs

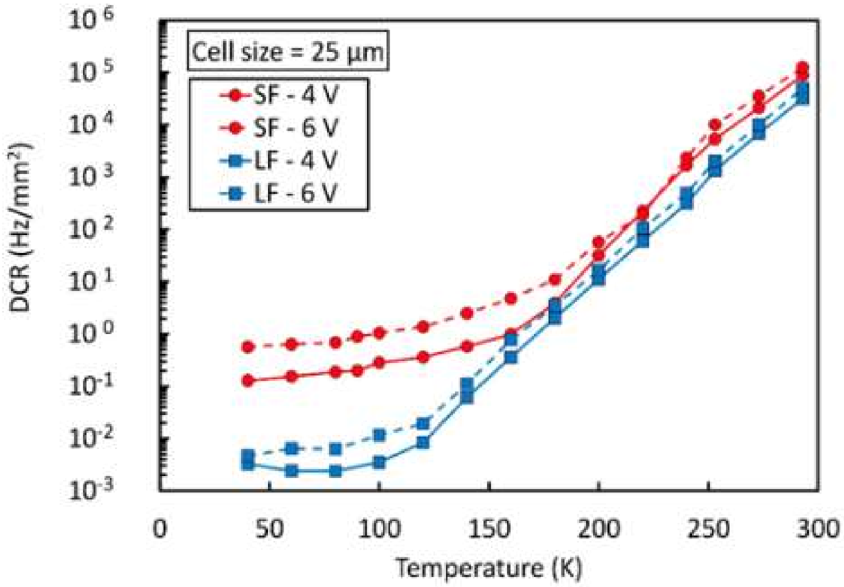
End 2023

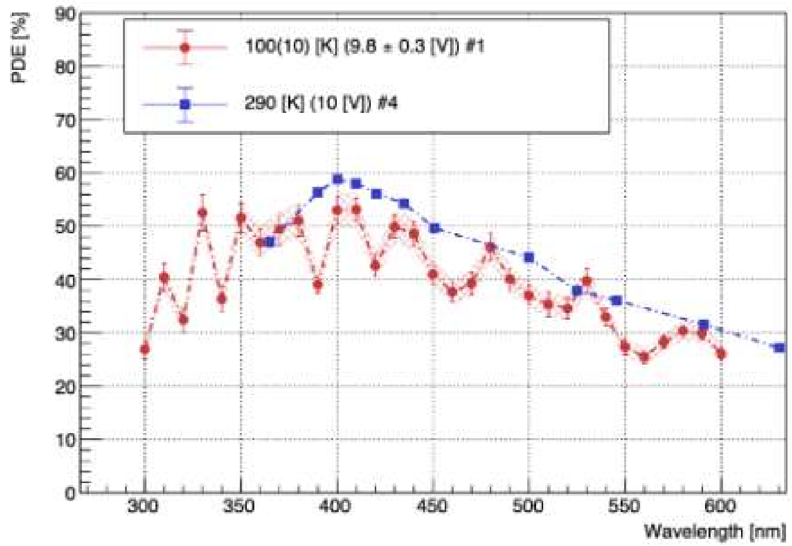


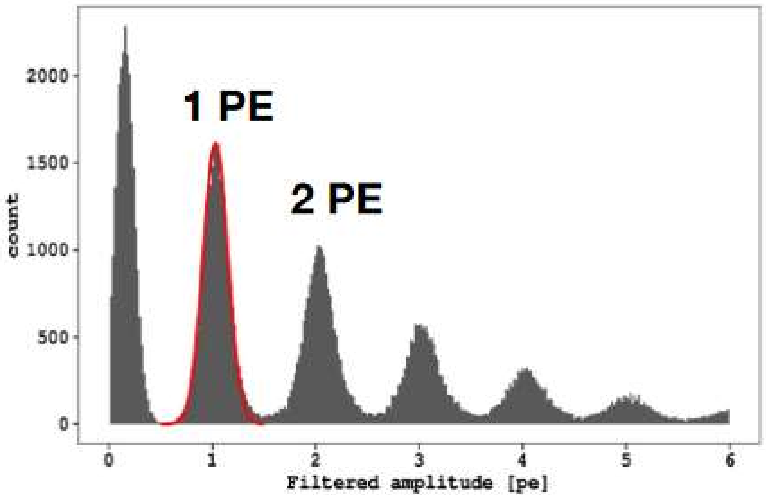
Proto-1T at LNGS

60x60x40 cm²
10 PDUs

DS-20k: SiPM Performance







parameter	spec required	spec achieved
PDE @ 420 nm	> 40%	> 42%
DCR (87 K)	250 Hz / tile	~ 20 Hz / tile
correlated noise probabilities (afterpulses, cross talk)	< 50% + 50%	<10% + 35%
SiPM gain	> 1E6	> 1E6
SNR after ARMA filter	> 8	> 15
time resolution	~ 10 ns	~15 ns

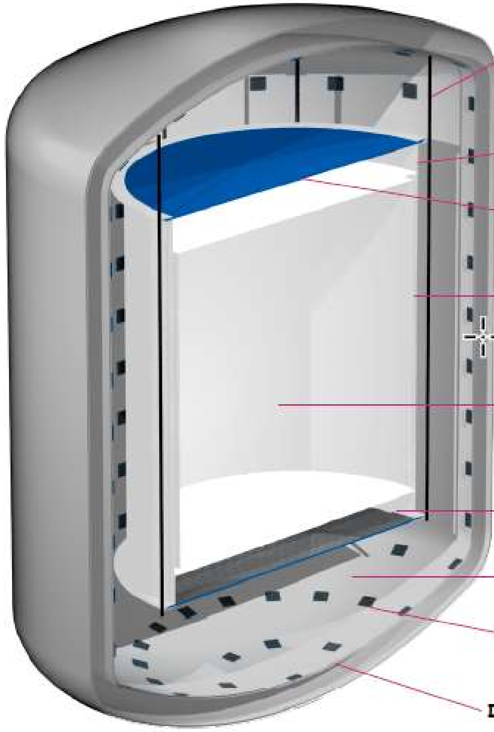
Low Mass detector project

❑ Building on the success of DS-50

- Optimized for a low-electron counting experiment

TABLE I. Conceptual detector design parameters.

Parameter	Value
TPC active LAr mass	1.5 t
TPC fiducial LAr mass	1 t
TPC fiducial cylindrical radius	45 cm
TPC height	111 cm
TPC diameter	110 cm
TPC PDM number	864
TPC PDM peak efficiency	40 %
TPC gas pocket thickness	1 cm
TPC electroluminescence field	6.5 kV/cm
TPC drift field	200 V/cm
Acrylic vessel mass	0.144 t
PDM dimensions	$5 \times 5\,\mathrm{cm}^2$
PDM buffer veto thickness	10 cm
PDM buffer veto total mass	0.3 t
Bath veto UAr mass	4.5 t
Bath veto minimum thickness	28 cm
Cryostat inner height	215 cm
Cryostat inner diameter	170 cm
Cryostat wall thickness	0.5 cm
Ti support structure total mass	0.1 t

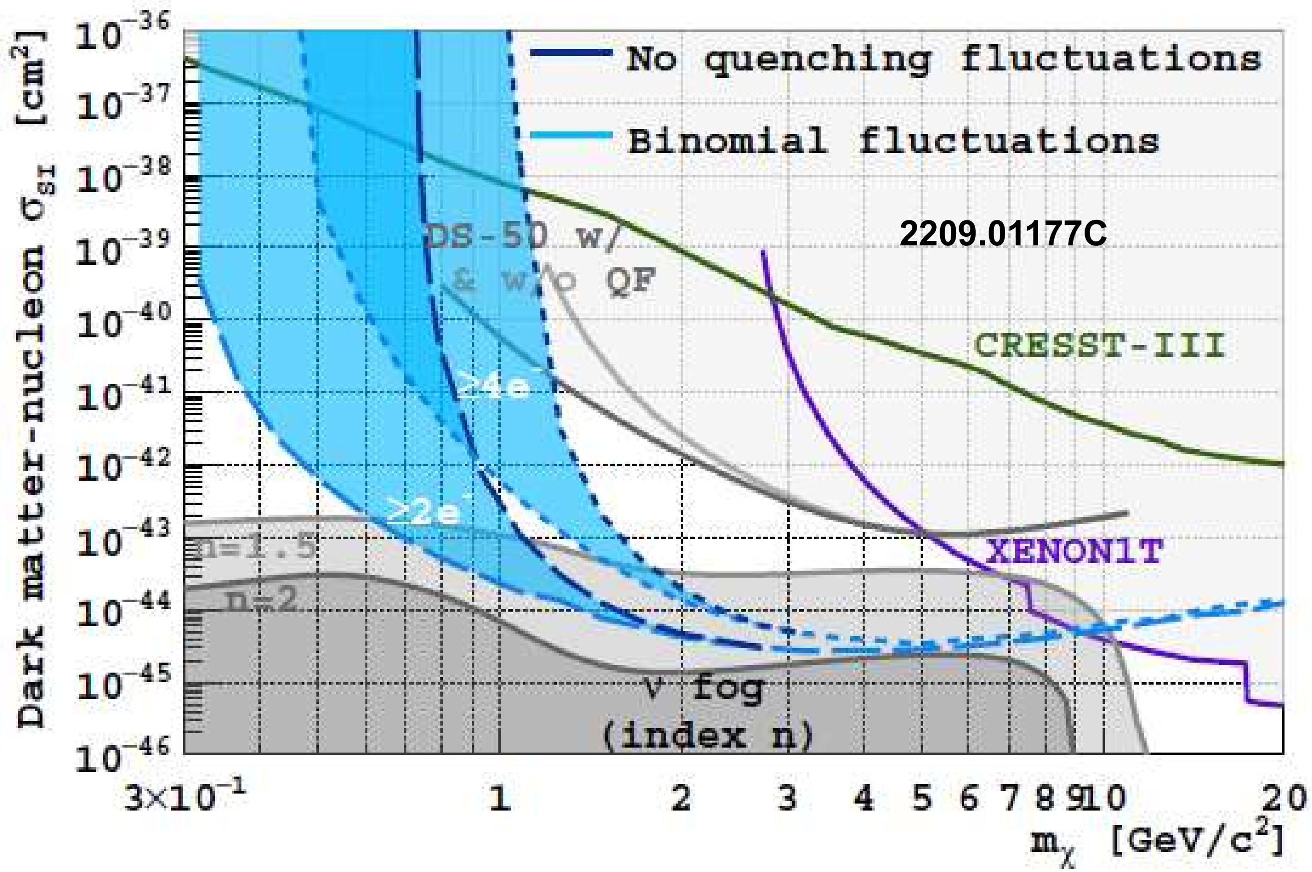


Time scale and location not known

Low Mass detector project

❑ Physics reach

- Sensitivity strongly connected to spurious electron background understanding



Could reach the neutrino floor between 1 and 10 GeV

Comparison with Xenon

- **S2-only analysis**
  - Very complicated to compare
  - Xenon background not under control in low energy region (5 < Ne < 10) because of ^{8}B solar neutrino scattering (largely unknown)