Geant4-based DarkSide Monte Carlo Simulation Toolkit - G4DS

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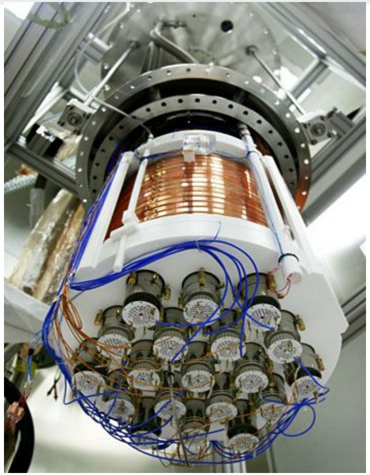
On behalf of the GADMC & DarkSide-20k Collaboration

VIEnna Workshop on Simulations 2024 (VIEWS24), Vienna, Austria.

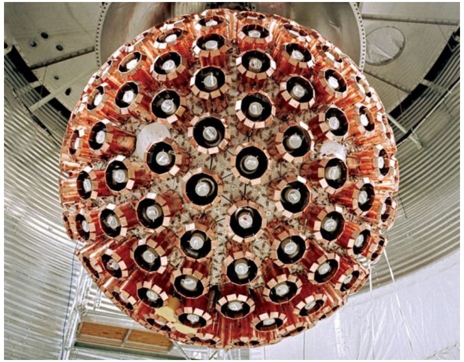
Overview:

- GADMC and DarkSide Program.
- Simulations in G4DS: Standalone and Complementarity
    - Accurate Physics Lists
    - Custom Generators
- DarkSide-50 and the PARIS Model
- Recombination in case of NR: ARIS data
- Results from DS-50.
- Context of DS-20k:
    - External neutrons and (α,n) induced backgrounds
    - Tagging of n-background: Gd-gamma Cascade
    - Problem of Neutron Cross-section in LAr
- Conclusion and Forward

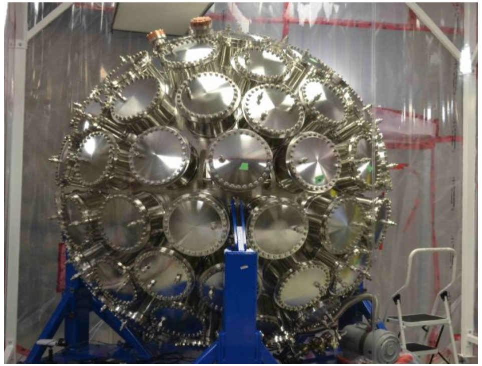
Global Argon Dark Matter Collaboration (GADMC):



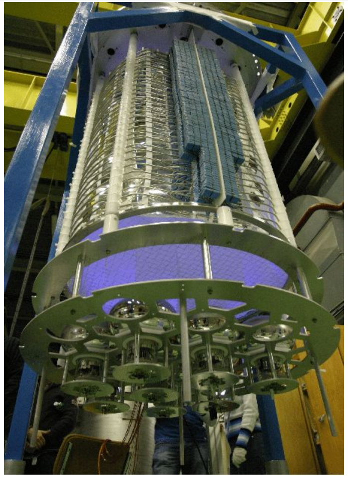
DS50 @ LNGS



DEAP 3600 @ SNOLAB



MiniCLEAN @ SNOLAB



ArDM @ Canfranc

<u>GADMC:</u>

We are ~ 100 institutions and > 400 collaborators from all the above experiments sharing knowledge and experience for the next step of direct DM search with LAr.

DarkSide-20k

- ~ 20 t fiducial mass dual phase TPC
- ~ 50 t mass active + Neutron Veto
- ~ 700 t LAr External Muon Veto
- Under construction @ Hall C LNGS
- Commissioning foreseen in 2026.

ARGO

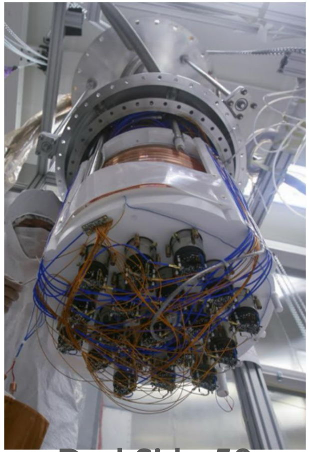
- Future LAr DM detector ~ 203X and beyond
- 300 t fiducial volume
- Explore Heavy WIMPs to the neutrino floor

DarkSide Program

- Direct detection of WIMP dark matter signal in form of Nuclear Recoils (NRs).
- Based on a two-phase **argon** time projection chamber (TPC)
- Design philosophy based on having very low background levels that can be further reduced through active suppression, for **background-free** operation from both neutrons and β/γ's

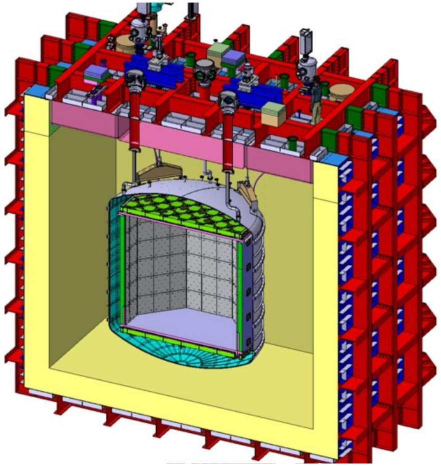
DarkSide-10

T. Alexander et al., Astropart. Phys. 49 (2013) 44 [arXiv:1204.6218]



DarkSide-50

P. Agnes et al., Phys. Rev. D 93 (2016) 081101 [arXiv:1410.0653]



DarkSide-20k

Simulations using G4DS

- **G4DS is a modular package based on Geant4** developed by the DarkSide collaboration and used to perform simulations for a number of related experiments under the DarkSide program.
- G4DS has the primary dependence on the Geant4 libraries and optical photon propagation.
  - *G4EmLivermore* → For electromagnetic physics accurate down to 250 eV.
  - *High Precision Neutron (HP)* → Custom made physics list for hadronic processes for neutrons upto 20 MeV.
  - For the new update to Geant4-11 → using recommended QGSP_BIC_HP
- **Radioactive Decay Manager (RDM) generator:**
  - Handles the background generation from materials, radioactive decay chains → used with virtual spatial generators of Geant4
  - *Special Cross Section (SCS)* generators are employed → for ^{37}Ar, ^{39}Ar, ^{85}Kr

Inputs generated with

BetaShape

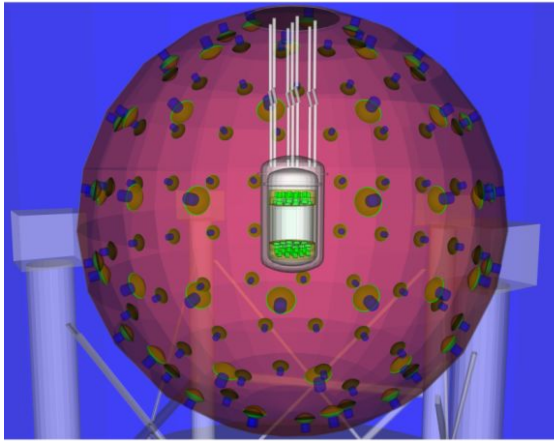
X. Mougeot, Applied Radiation and Isotopes 154, 108884 (2019)

- **Neutron Background Simulation:**
  - *ad hoc* FLUKA[1] for cosmogenic neutrons
  - Yield calculated using SaG4n[3] ← Fully based on Geant4.

1. *A. Ferrari, P.R. Sala, A. Fasso and J. Ranft, FLUKA: A multi-particle transport code, CERN-2005-010, SLAC-R-773, INFN-TC-05-11.*
2. *E. Mendoza et al., Nucl. Instrum. Methods A 960, 163659 (2020). [arXiv:1906.03903]*

DarkSide-50 and the PARIS Model[1]

1. P. Agnes, et, al., JINST12,10(P10015) (2017). [arXiv:1707.05630]



- Cylindrical **dual-phase TPC,** LAr mass ~ 46 kg
- Two 19 3-in PMT arrays
- Drift field = 200 V/cm
- > 99.9% extraction of electrons @ 2.8 kV/cm
- Wavelength shifter used **tetraphenyl butadiene (TPB)**

Operated inside:

- ~ 30 tonne liquid scintillation veto
- ~ 1 kt ultra-pure water Cherenkov detector

For the Scintillation in LAr, please refer to talk by Clea Sunny:
The effect of contamination on the S1 triplet component in DarkSide-50 dark matter experiment.

- Fundamental degeneracy in scintillation detectors:
  - Non-linearity of LAr response in presence of electric fields
  - Non-uniformity in light collection efficiency over the detector volume.
- Towards the decoupling: fine tune the optical properties relying only on the production and propagation of optical photons in LAr and gasAr.
- Next is to model the full energy response taking into account the ionization and effect of electric field.

Precision Argon Response Ionization and Scintillation (PARIS) model ← Relies on effective description of e^- ion recombination

Simulation in DarkSide-50

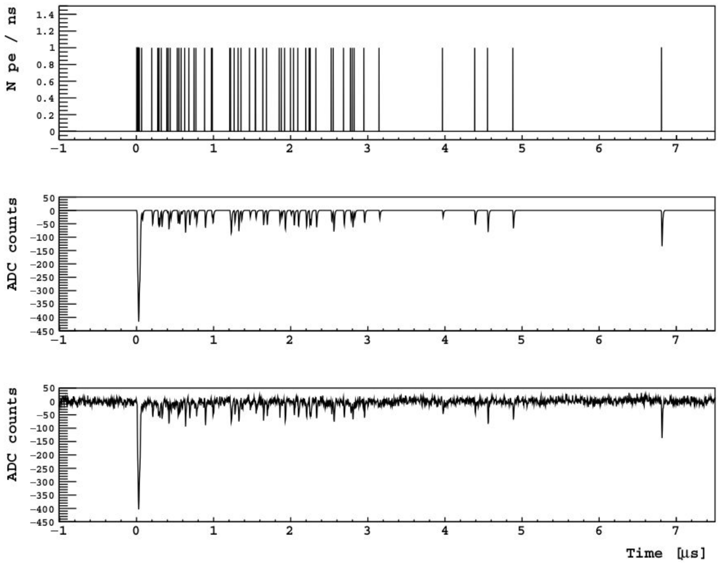
Full Simulation Mode using DarkArt[1]

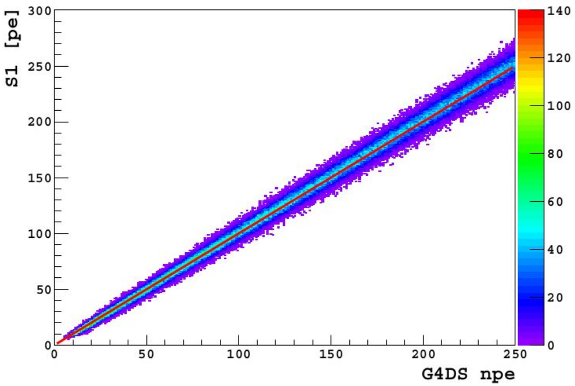
1. *C. Green, J. Kowalkowski, M. Paterno, M. Fischler, L. Garren and Q. Lu, The Art Framework, J. Phys. Conf. Ser. 396 (2012) 022020.*

Production & propagation of optical photons to PMTs and conversion to PEs

Convolution of SER and electronic noise using *DarkArt*

Passed through reconstruction





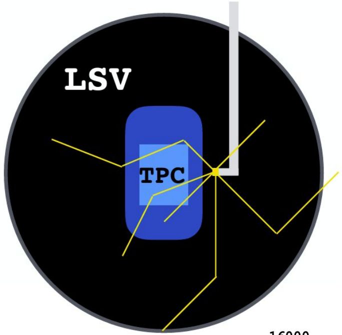
Difference between the reconstructed S1 PE after the full chain and true PE generated by G4DS is ~ 1.1%

The smearing resulted from the full chain after electronics and reconstruction is ~ 5.3%

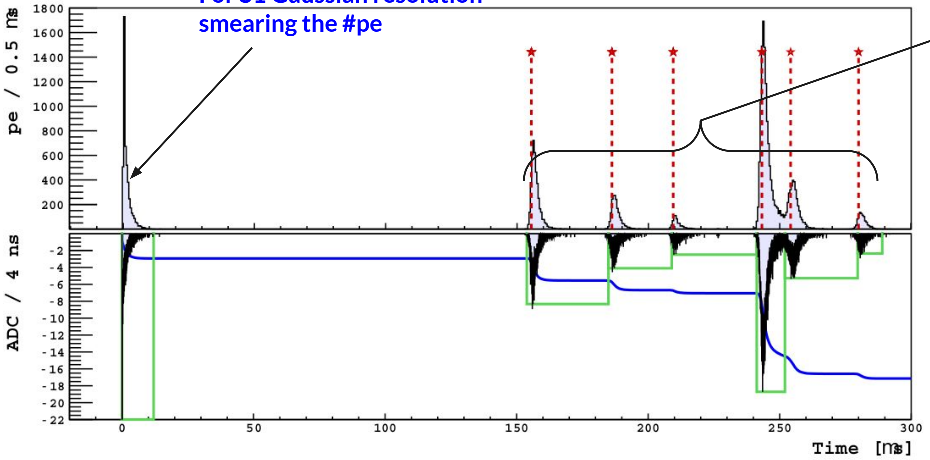
Simulation in DarkSide-50

Fast Mode Approach bypassing DarkArt

To reduce the processing time FMA was used

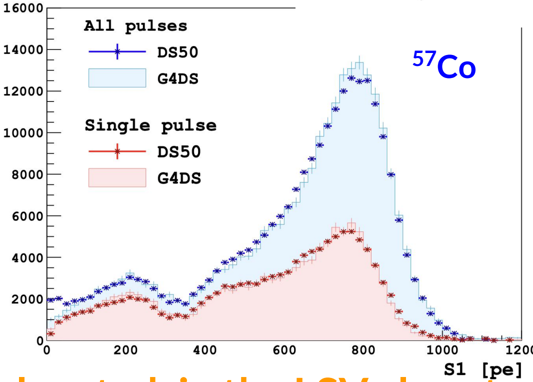


For S1 Gaussian resolution smearing the #pe



For S2 pulses of multiple scattering events, a clustering algorithm is used.

Important parameter to tune was the cluster resolution/size Δz_{min}



Full simulation chain

Using the same algorithm for ^{133}Ba (356 keV) and ^{57}Co (122 keV) and performing a simultaneous fit of data and simulation

Δz_{min} = 3.5 mm $\Rightarrow$ Δt_{min} = 3.8 μs

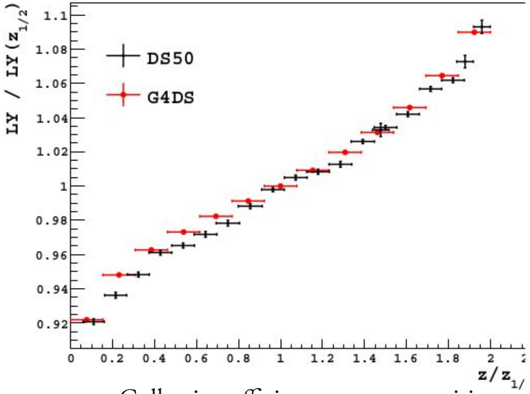
Sources were located: in the LSV close to the cryostat.

Simulation in DarkSide-50

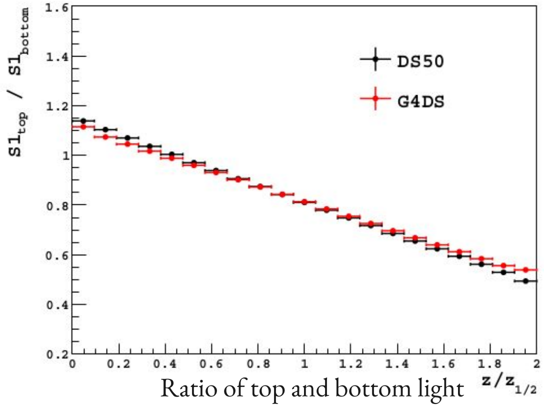
Decoupling the Optical Properties from Ionisation Response

Primarily 4 parameters can be considered to achieve this:

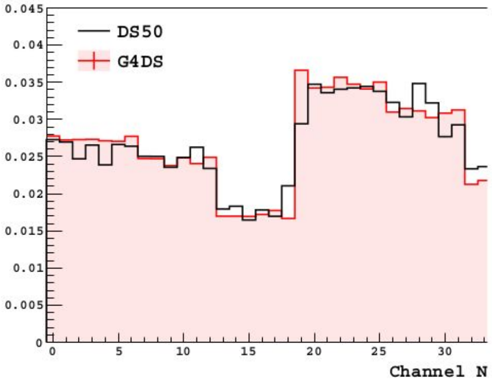
- photon collection efficiency as a function of the event position (collection efficiency);
- ratio of light collected on the top and on the bottom PMTs v/s vertex position;
- fraction of S1 light observed by each PMT (S1 channel occupancy);
- fraction of S2 light observed by each PMT (S2 channel occupancy).



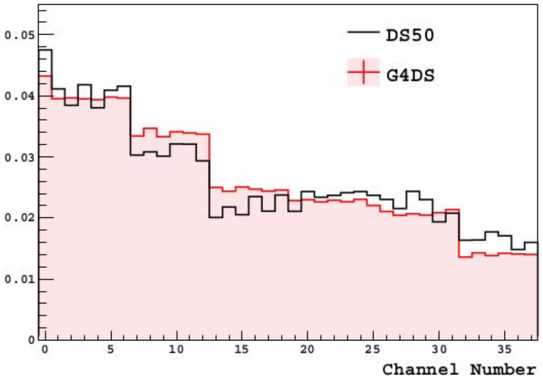
Collection efficiency vs event position



Ratio of top and bottom light vs vertex position



S1 occupancy vs channel numbers



S2 occupancy vs channel numbers

Reference sources used are:

- $^{39}Ar \rightarrow$ (565 keV , 269 y) intrinsic in LAr; and
- $^{83m}Kr \rightarrow$ (32.1 & 9.1 keV, 1.83h) injected gas.

Simulation in DarkSide-50

Decoupling the Optical Properties from Ionisation Response

Optical Components tuned:

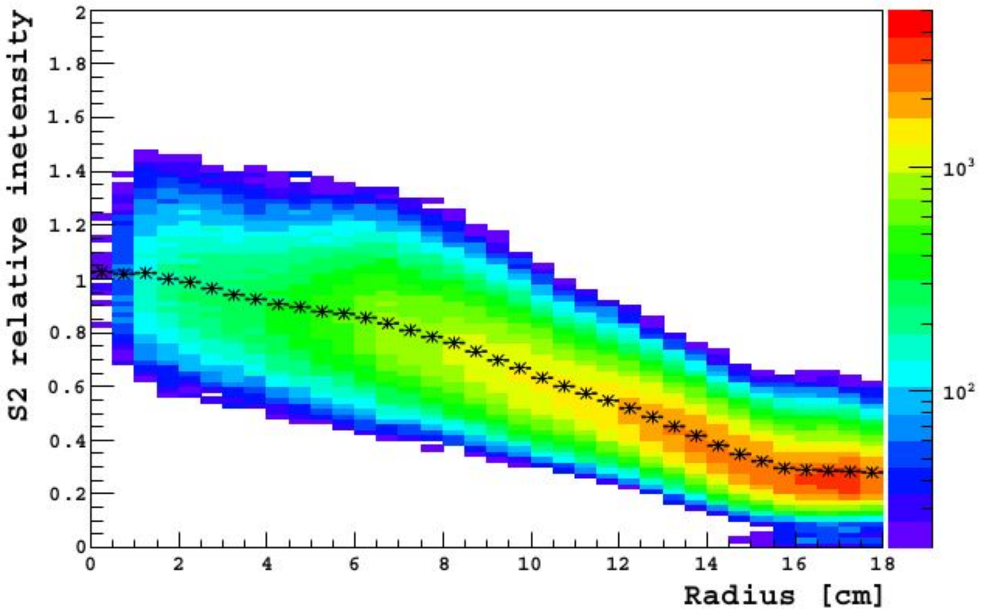
- Most of materials as dielectrics
- Grid → optical surface with transmission (θ)
- ITO → modeled as a thin film with imaginary rindex
- PTFE → modeled with Lambertian reflectivity (λ)
- Custom condensed Ar layer/non-uniform TPB thickness
- LAr Absorption length = 1.6 m for visible
- Rayleigh Scatt. Length = 46±11 cm for VUV

Reference sources used are:

- ^{39}Ar → (565 keV , 269 y) intrinsic in LAr; and
- ^{83m}Kr → (32.1 & 9.1 keV, 1.83h) injected gas.

Evaluation of one of the dominant instrumental effect.

S2 dependence on radial position of event varies by a factor ~ 4 between centre and edge of TPC



⇒ Sagging of the window resulting non-uniform gas pocket thickness

DarkSide-50 and the PARIS Model

The PARIS Model

Deposited Energy → Excitation, Ionization → Interdependent because of recombination

Deposited Energy ⇢ A fraction is lost in "Quenching"

S1 = de-excitation + de-excitation after recombination
S2 = free electrons after recombination

$$S1 = g_1(N_{\rm ex} + r(E) \times N_i)$$
$$S2 = g_2\, Y_{S2} \times (1 - r(E)) \times N_i$$

Dominant only for NRs. **Can reduce the visible energy of NRs by a factor 3-5.**

Assumed to be zero for ERs.

Effective work-function modelling:

$$E_{\rm dep} = W(N_i + N_{\rm ex})$$

where,

$$W = \frac{\alpha_k W_{\rm ex} + W_i}{1 + \alpha_k}$$ with, $\alpha_k = N_{ex}/N_i$, $k = \{\text{ER,NR}\}$

The essence of PARIS model approach is, an empirical parametrization of the recombination probability,

$$r(E) = \text{erf}(E/p_1)(p_2 \times e^{-E/p_3} + p_4)$$

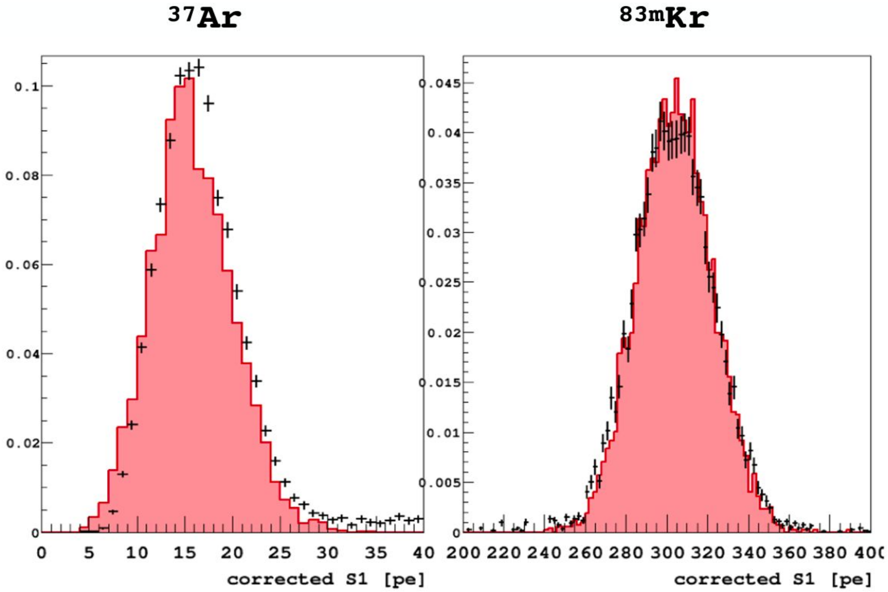
where,
r(E) → the recombination probability as a function of energy.
erf → the error function

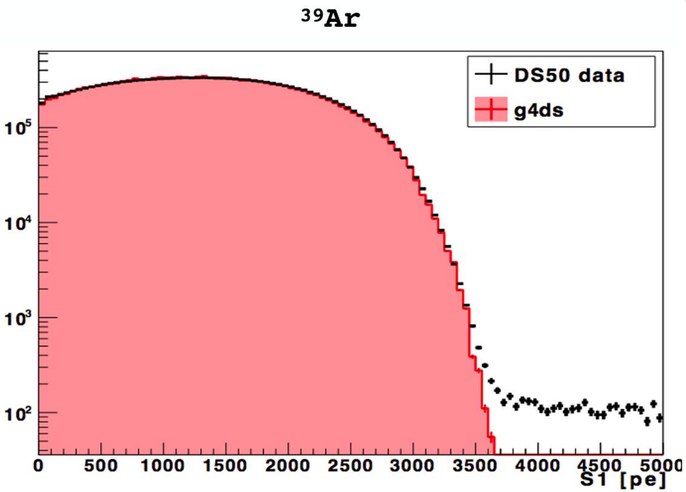
The work function and α_k are fixed based on work T. Doke,
W = 19.5 eV
α_{ER} = 0.21
α_{NR} = 1

DarkSide-50 and the PARIS Model

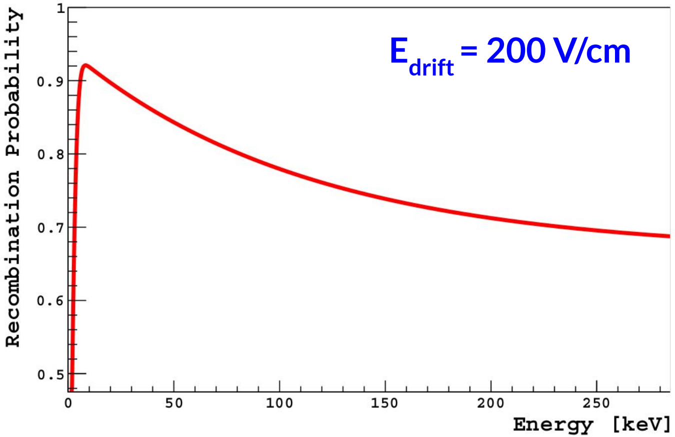
Validation of Model with Data and Parameter Extraction

The parametrized r(E) is fitted with 3 source data.





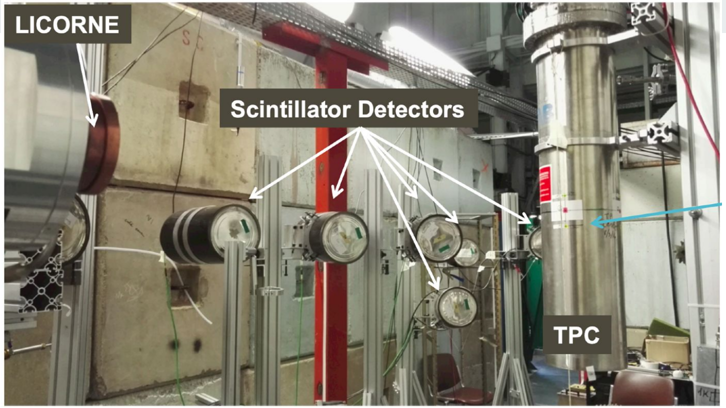
With the obtained r(E), simulation-data comparison for ^{57}Co and ^{133}Ba showed good agreement.

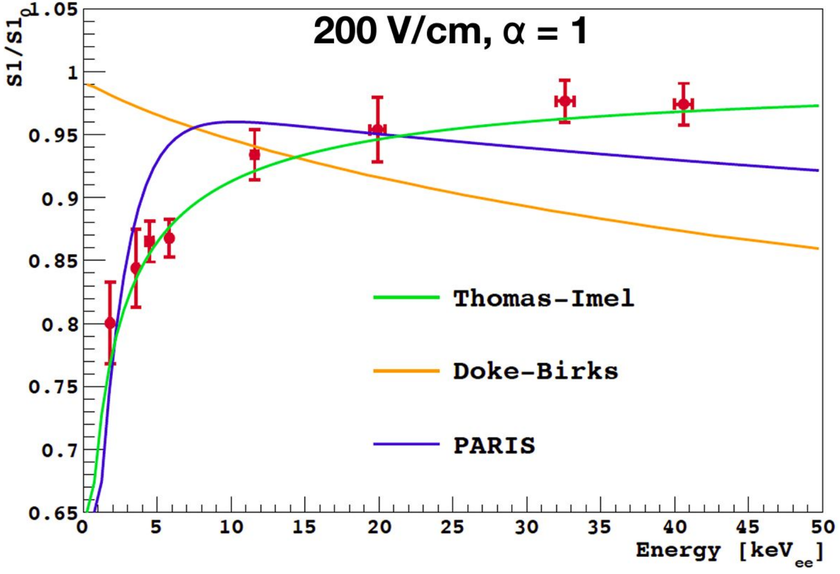


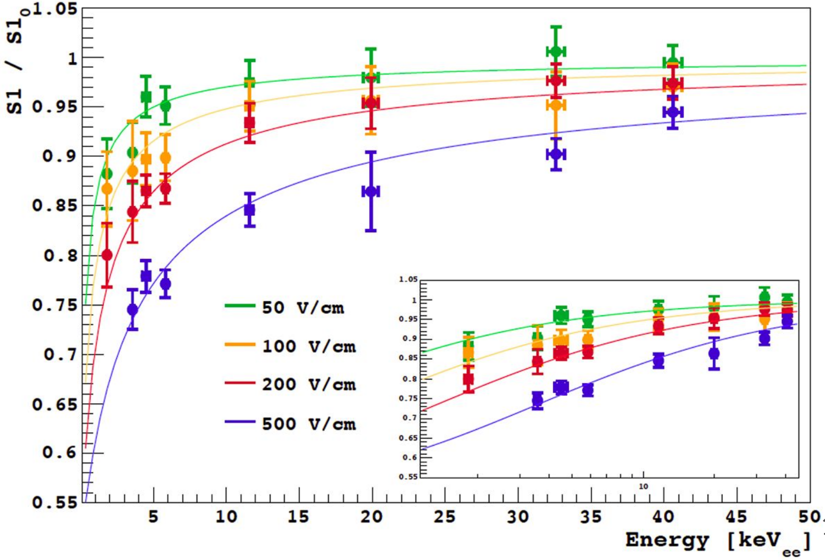
NR Recombinations: ARIS Results[1]

1. P. Agnes et al. (ARIS Collaboration), Phys. Rev. D97 (2018) 11 112005

ARIS is a small TPC exposed to a **pulsed, collimated, monochromatic** (7Li(p,n)7Be) neutron beam (LICORNE@IPNO, Paris), coupled with 8 neutron detectors







Fixing **a = 1** to break the degeneracy between R and a (do not measure charge).

The Thomas-Imel model is favored

Full ER Background in DS-50[1]

1. *P. Agnes et al. (DarkSide-50 Collaboration) Phys. Rev. D 98, 102006 (2018) [arXiv:1802.07198]*

Excellent agreement between the simulated background model and both AAr and UAr data taken.

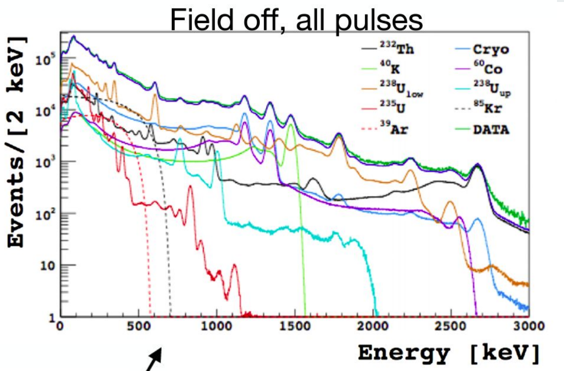
⇒ Demonstrating the ability of G4DS on both deposition and optical sides.

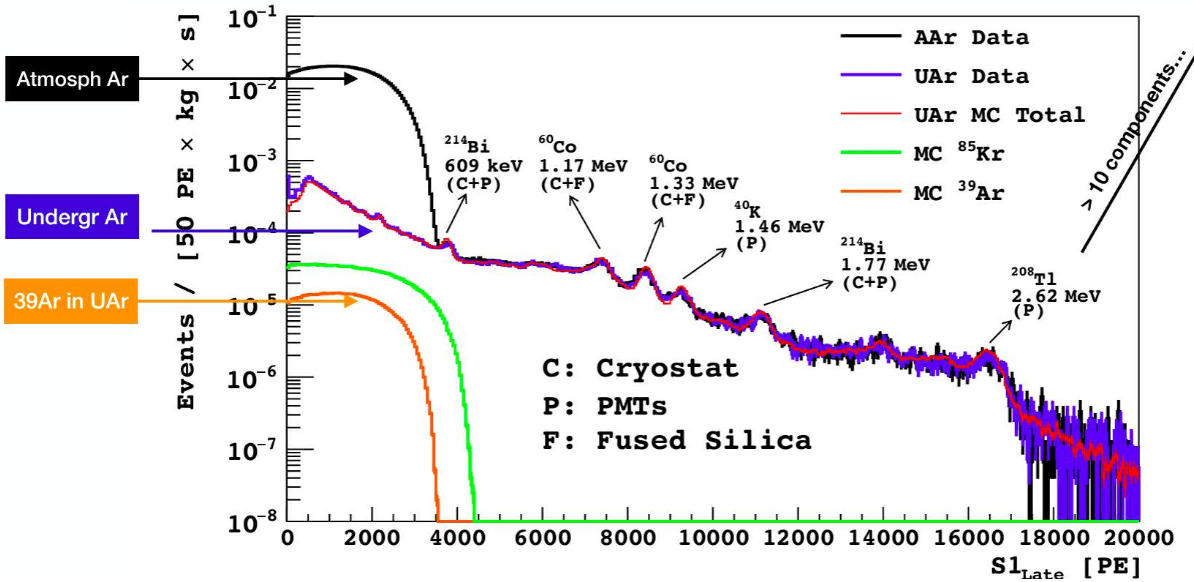
Contamination of ^{85}Kr discovered:

(and confirmed: 0.43% BR with β + 418 keV γ)

Measurement of ^{39}Ar depletion in UAr:

1400 (0.69±0.09 mBq/kg)





DS50 Detector for Low-mass Searches[1]

- Understanding of the DS-50 detector
  - ⇒ calibration down to very low energies for both ER and NR
  - ⇒ enabled world-leading physics results for low mass WIMPs

S2 Only Analysis

M_{WIMP} = 1.8–6 GeV/c^2

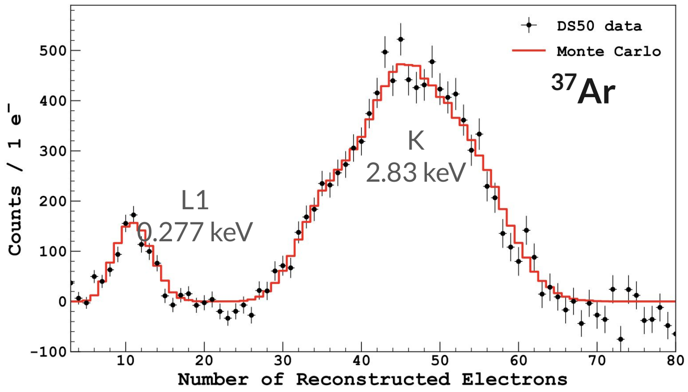
Analysis Thrs. = 0.6 keV_{nr} or 0.1 keV_{ee}

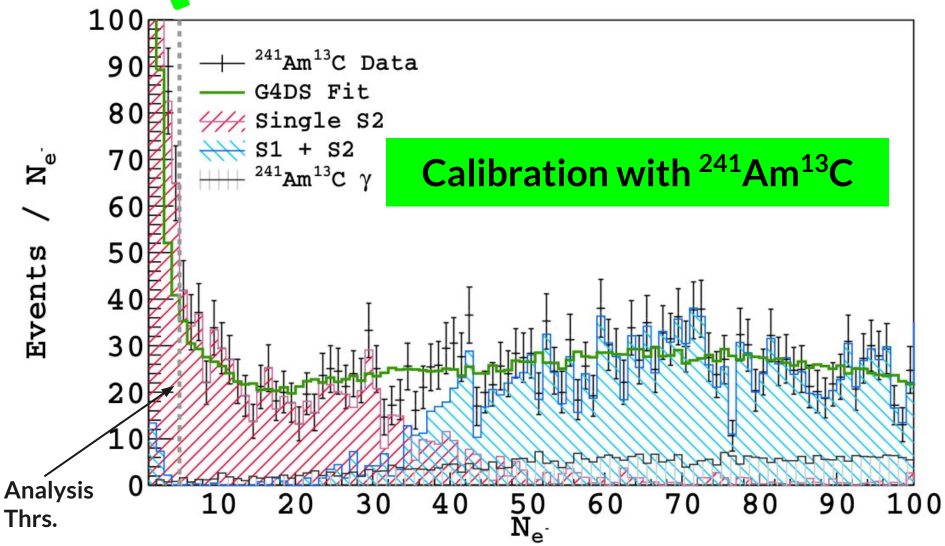
Recoil Energy < 10 keV_{nr}

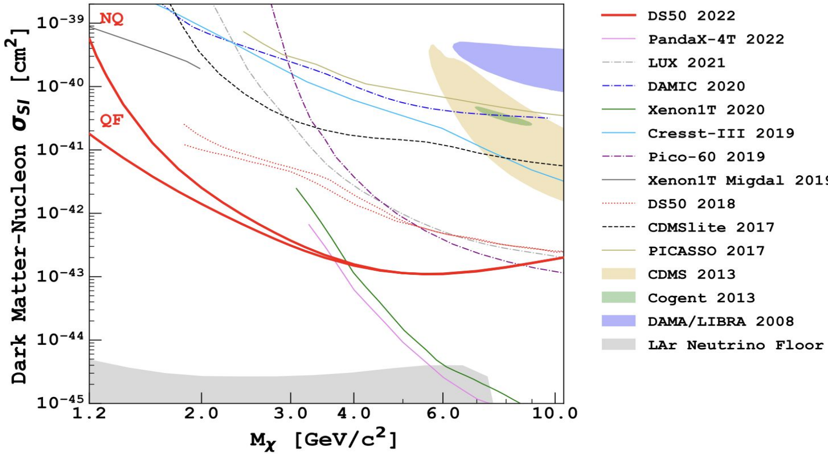
Background Agreement from G4DS

N_{e-} > 7 e^- (~ 1 keV_{nr})

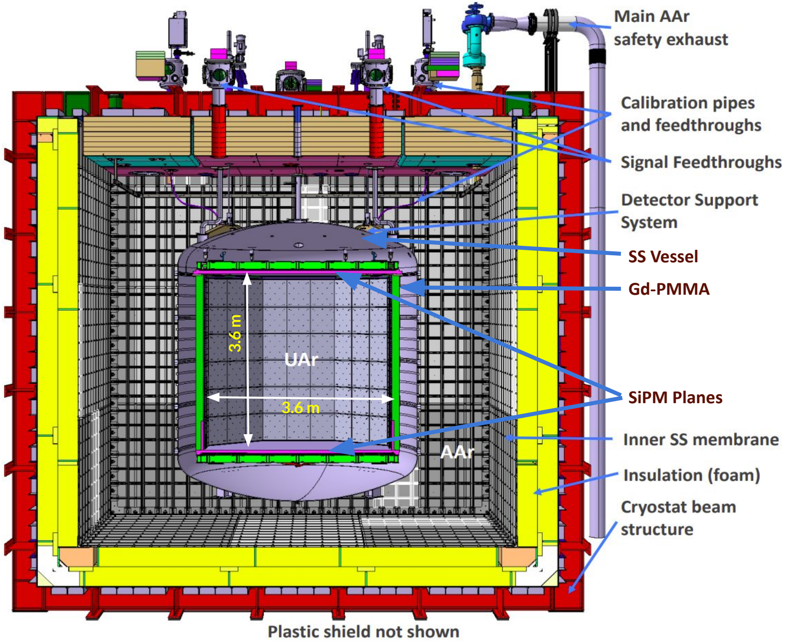
1. P. Agnes et al., (DarkSide Collaboration) Phys. Rev. Lett. 121, 081307 (2018) [arXiv:1802.06994]







DarkSide-20k Detector and Sensitivity:



Inner Detector:

- Octagonal shape dual phase argon TPC;
- Active UAr mass ~ 49.7 tonnes;
- Fiducial UAr mass ~ 20.2 tonnes;
- Inner Neutron veto ⇒ Active UAr mass ~32 tonnes.

Instrumental Background:

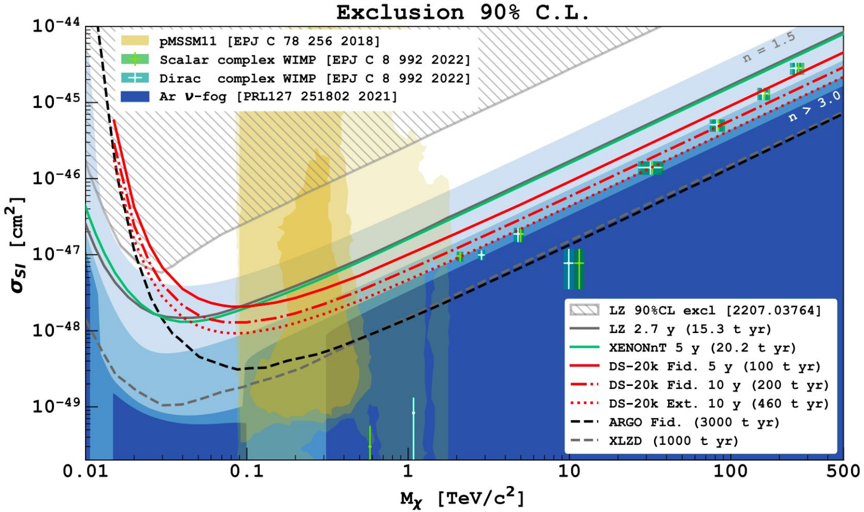
- 0.1 background events over 200 t-y in the ROI (30-200 keVnr).
- Sensitivity to neutrino induced coherent scattering (CEvNS): 3.2 events

Exposure 200 t-y:

- 20 t fiducial volume with nominal 10 year run time
- 5 σ discovery: 2.1 x 10-47 cm2 @1 TeV/c2
- 90% C.L. exclusion: 6.3 x 10-48 cm2 @1 TeV/c2

Nested detectors structure:

- ProtoDUNE-like cryostat (12x12x12 m^3 external)
- ~ 700 tonne LAAr cryostat as muon veto.
- SS vessel separating AAr from underground UAr.
- Integrated neutron and γ veto (Gd-PMMA)
- ~5-10 cm plastic shielding around SS vessel, moderation of neutrons from cryostat insulation, LNGS Hall C (not in the drawing)

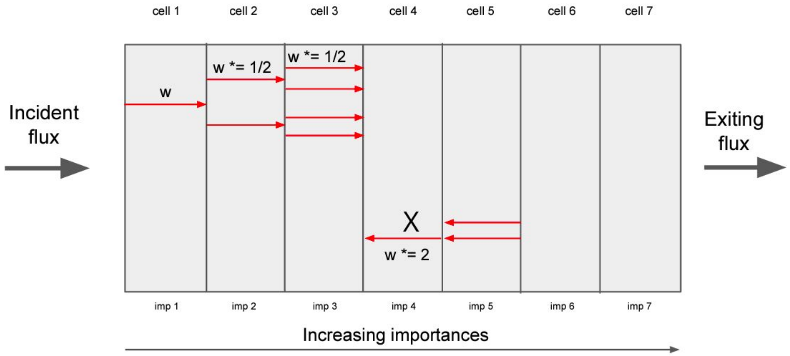


Neutron Background for DS-20k

External Neutrons

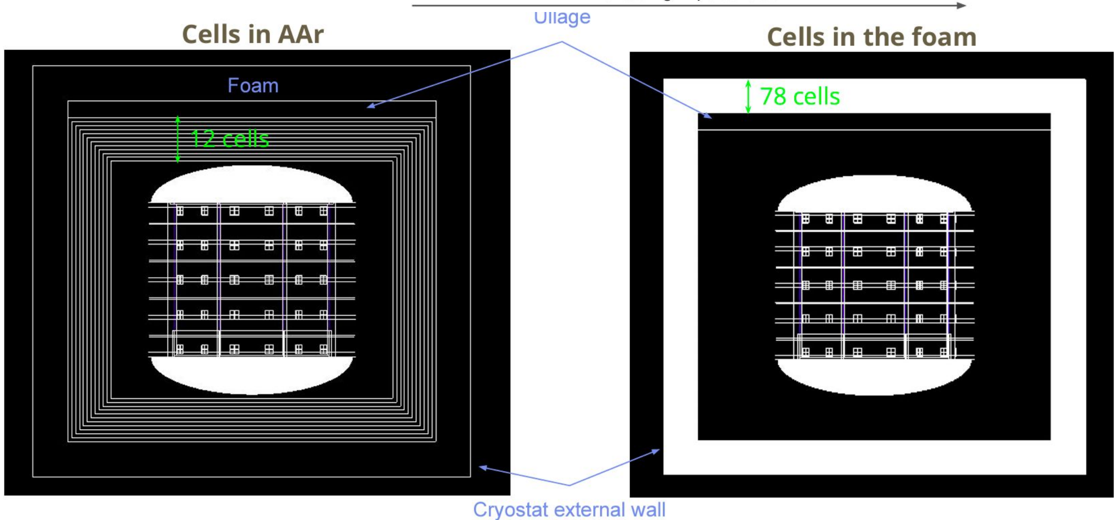
Neutrons pose the **primary background** in the region of interest for an experiment like DS-20k.

- Generation of neutron is done using:
  - **SaG4n** → for neutrons from cryostat
  - FLUKA → For cosmogenic neutrons
- Biasing techniques are applied to reduce the space and time required by simulations.
- Geometrical importance sampling (non-physical biasing) technique is being implemented.



Birgit Zatschler's talk from yesterday:

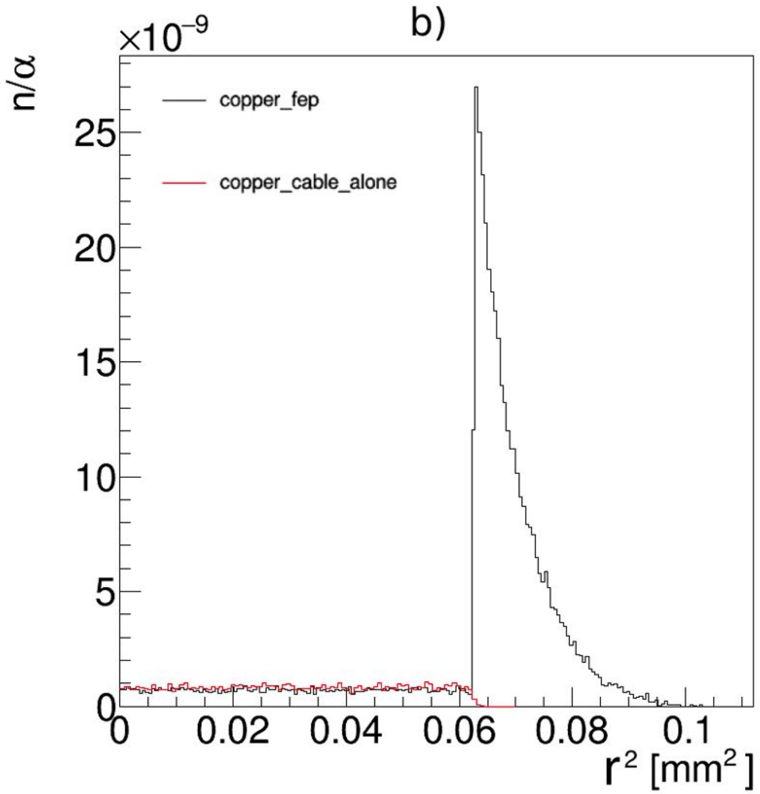
Application of GEANT4's Importance Biasing in radiogenic background simulations



Neutron Background for DS-20k

(α,n) Neutrons: SaG4n

- Developed and maintained by our collaborators at CIEMAT, Madrid.
- Code based on Geant4 for the calculation of neutron production from α of actinides.
- SaG4n can use any library, specifically experimental measures.
- SaG4n uses biasing techniques to artificially increase an effective section and then compensate for the induced effect by assigning weights.
- **Direct calculations do not take into account geometric effects.**
    - Each component considered isolated. Components with high contamination and low n-yield next to materials with high n-yield are not properly quantified.

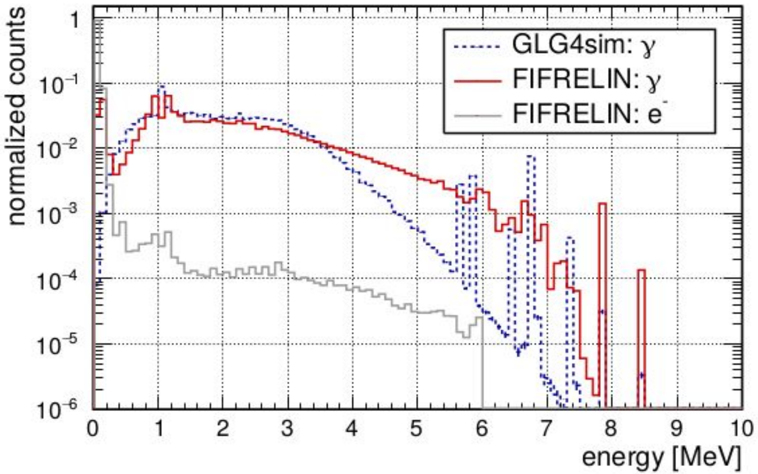


Tagging Neutrons: Gd capture and gamma-cascades

To estimate the neutrons in the final ROI, it is important to simulate the proper tagging in the Gd-PMMA in the inner detector acting as a neutron veto.

- We have used G4GLsim in the past
- We are currently using default G4 class with option to read FIFRELIN[1]

1. *H. Almazán, et al., Argon, Eur. Phys. J. A (2019) 55: 183.*



In the FIFRELIN simulations, both gammas and conversion electrons are generated as the cascade de-excitation products

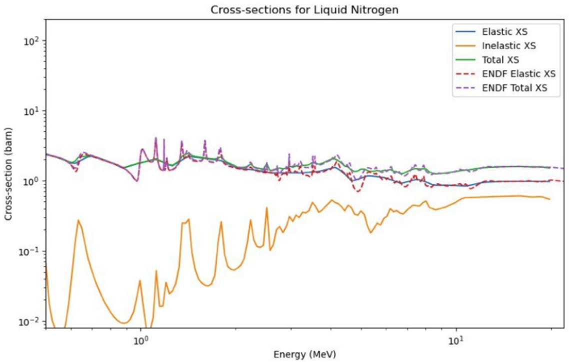
Isotope	Abundance [%]	Cross-section [b]
^{152}Gd	0.200	735
^{154}Gd	2.18	85
^{155}Gd	14.80	60900
^{156}Gd	20.47	1.8
^{157}Gd	15.65	254000
^{158}Gd	24.84	2.2
^{160}Gd	21.86	1.4

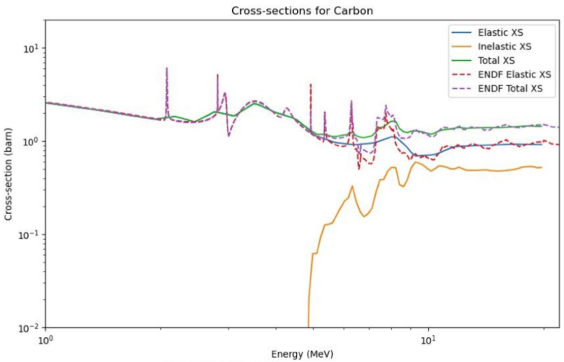
List of isotopic abundances of Gd and the respective thermal neutron capture cross-sections

Issue of n-cross section in LAr

It was noticed that there is an existing discrepancy for the neutron cross section in LAr while upgrading the G4DS-10 to G4DS-11 because of the change on G4NDL library version.

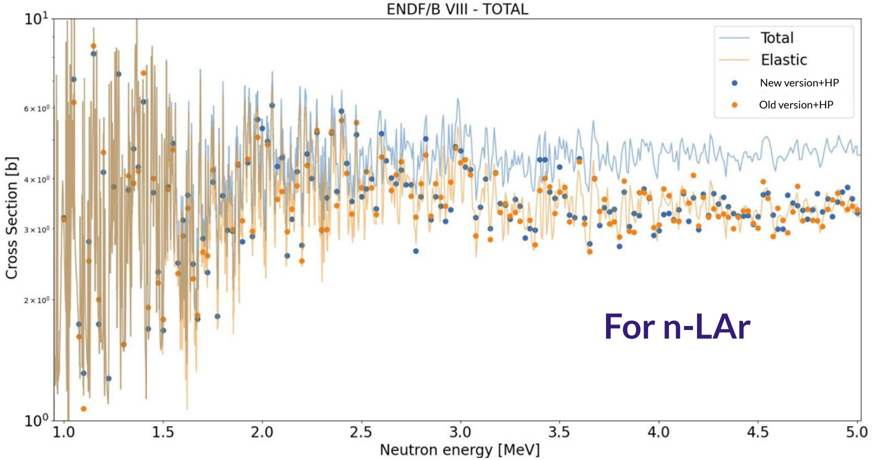
It seems that the discrepancy exists only for LAr.





We have discussed it with the Geant4 Collaboration already and we have been notified that there would be a patched version of the current Geant4 neutron dataset.

Recommended to use ENDF-VIII instead of G4NDL

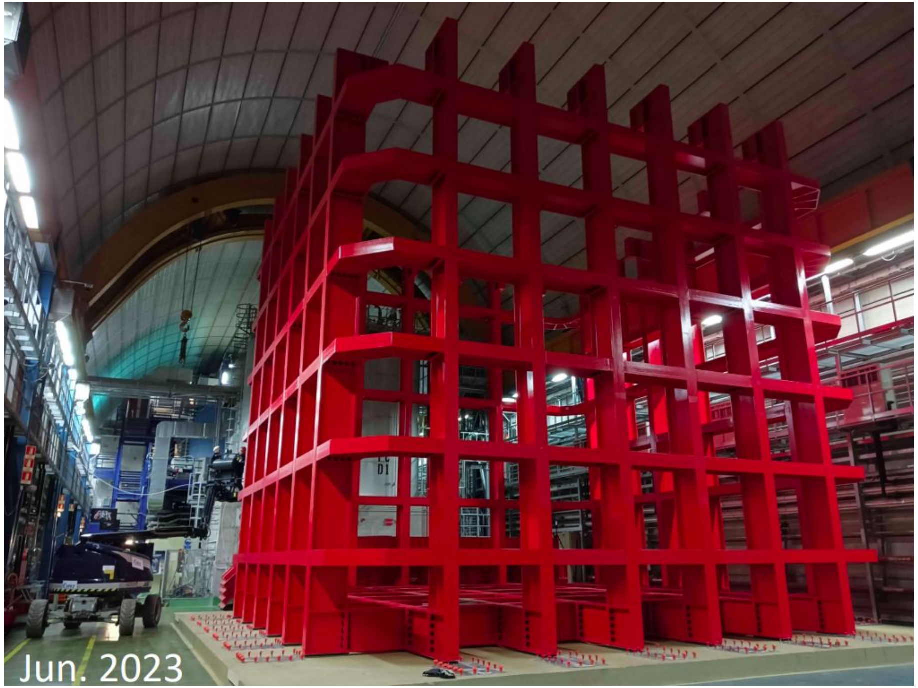


Conclusion and Forward:

- G4DS is a comprehensive toolkit encapsulating the abilities of Geant4 with LAr energy response to both electronic and nuclear recoils.
- The performance of the toolkit is enhanced by inputs from various other codes.
- Many parameters have been tuned with DS-50 data.
- The ability of the toolkit is well proven for the direct WIMP search ROI for both high and low mass.

- G4DS is being actively used for the DS-20k background simulations, both ER and NR.
- Careful considerations are being done for the neutron background and tagging efficiency.
- Large size of detector
  - need for a more efficient full simulation chain
  - **dominance of optical effects**
  - **change in light detectors modelling**
- Development of precise light maps → better position reconstruction
- Low energy ER and NR backgrounds (< 10 keV)
- Improvement of S2 modelling:
  - electron yield and fluctuations
  - relevant for low-energy searches

The voyage has begun….



Collaboration Meeting @ June,2023

Thank You for Your Attention

Backup