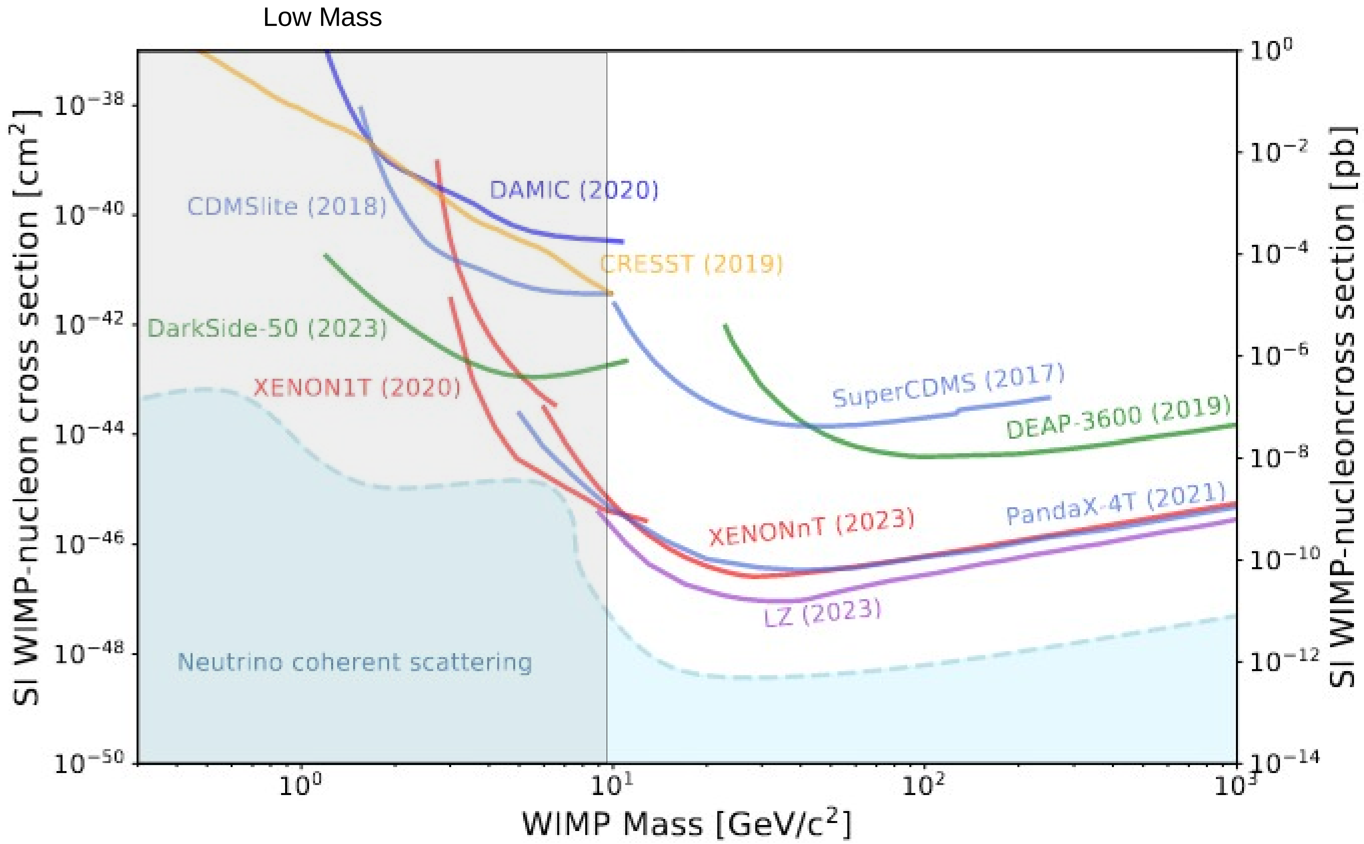
The ReD experiment: current status and prospects

M. Ave (GSSI), on behalf of the ReD working group

Limits in SI DM-Nuclear Cross sections



Particle Data Group 2024

Experiment	Target	Fiducial mass [kg]	Cross section [cm^2]	DM mass [GeV]	Ref.
Spin independent low mass (<5 GeV)					
LUX (Migdal)	Xe	118	6.9×10^{-38}	2	
XENON1T (Migdal)	Xe	1042	3×10^{-40}	2	
XENON1T (ionisation only)	Xe	1042	3.6×10^{-41}	3	
DarkSide-50 (ionisation only)	Ar	20	1.4×10^{-42}	2	
SuperCDMS (CDMSlite)	Ge	0.6	2×10^{-40}	2	
SuperCDMS (CDMSlite, Migdal)	Ge	0.6	6×10^{-38}	2	
CRESST	$CaWO_4$ - O	0.024	1×10^{-39}	2	
CRESST	Si	0.0035	4.5×10^{-32}	0.15	
DAMIC	Si	0.3	1×10^{-40}	4	
NEWS-G	Ne	0.3	1×10^{-38}	2	

Low Energy Excess is limiting the sensitivity of several experiments.

Recent results of Xenon experiments not shown, but they improve upon the ones shown in the graph.

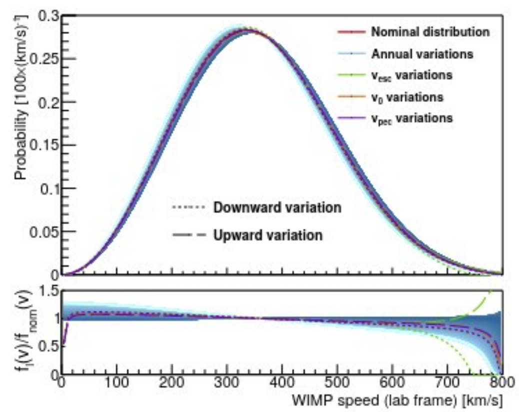
Direct detection: Nuclear Scattering

$$\frac{dR(E_R,t)}{dE_R} = N_T \frac{\rho_0}{m_{\rm DM}} \int_{v>v_{min}} v f(\vec{v}+\vec{v}_E(t)) \frac{d\sigma(E_R,v)}{dE_R} d^3v,$$

Astrophysics (WIMP density)

0.2-0.6 GeV/cm^3

Astrophysics (WIMP velocity distribution)

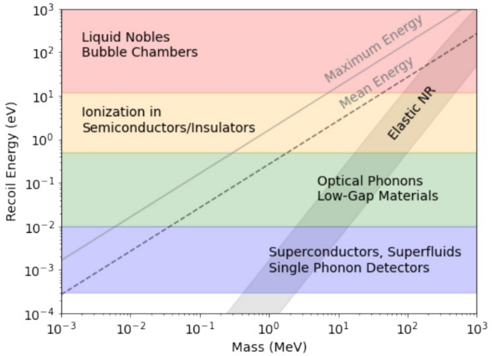


D. Baxter et al, The European Physical Journal C 81, 907 (2021)

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-\frac{E_R}{E_0 r}} \qquad < E_R > = E_0 r = \left(\frac{1}{2} m_\chi v^2\right)\left(\frac{4 m_\chi m_N}{(m_\chi + m_N)^2}\right)$$

For m_χ = 1.5 GeV

Target	***<E$_R$> [eV]***
Xenon	30
Germanium	60
Argon	100
Silicon	144
Neon	200
Oxygen	235



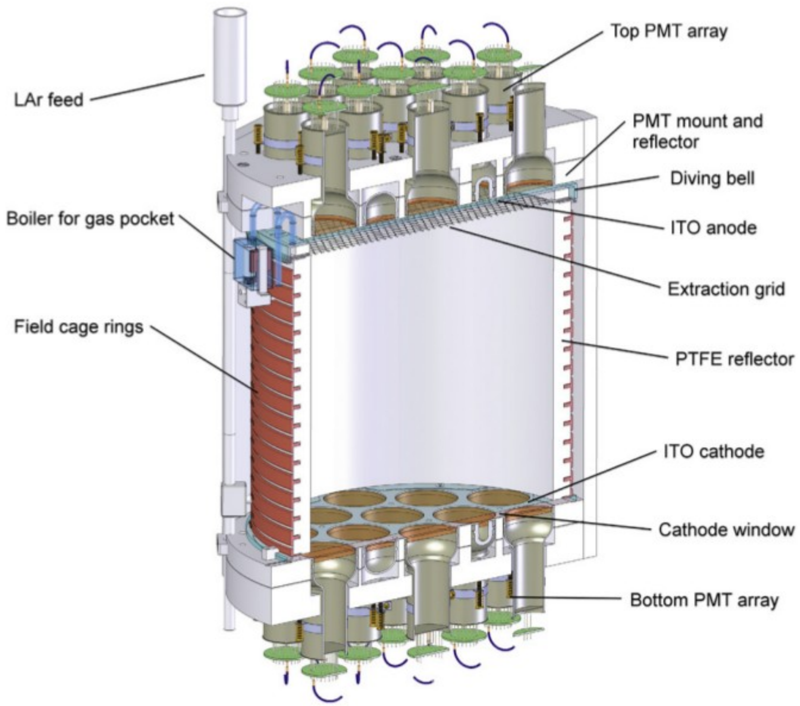
Particle Physics

$$\frac{d\sigma(E_R,v)}{dE_R} = \frac{m_N}{2 m_r^2 v^2}\left(\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R)\right),$$

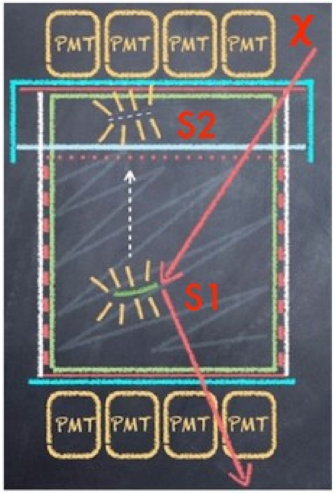
Cross section enhancement A^2 due to coherent interaction.

LAr TPCs: DS-50

AAr: 1 [Bq/kg] of ^{39}Ar
UAr: 0.73 [mBq/kg] of ^{39}Ar



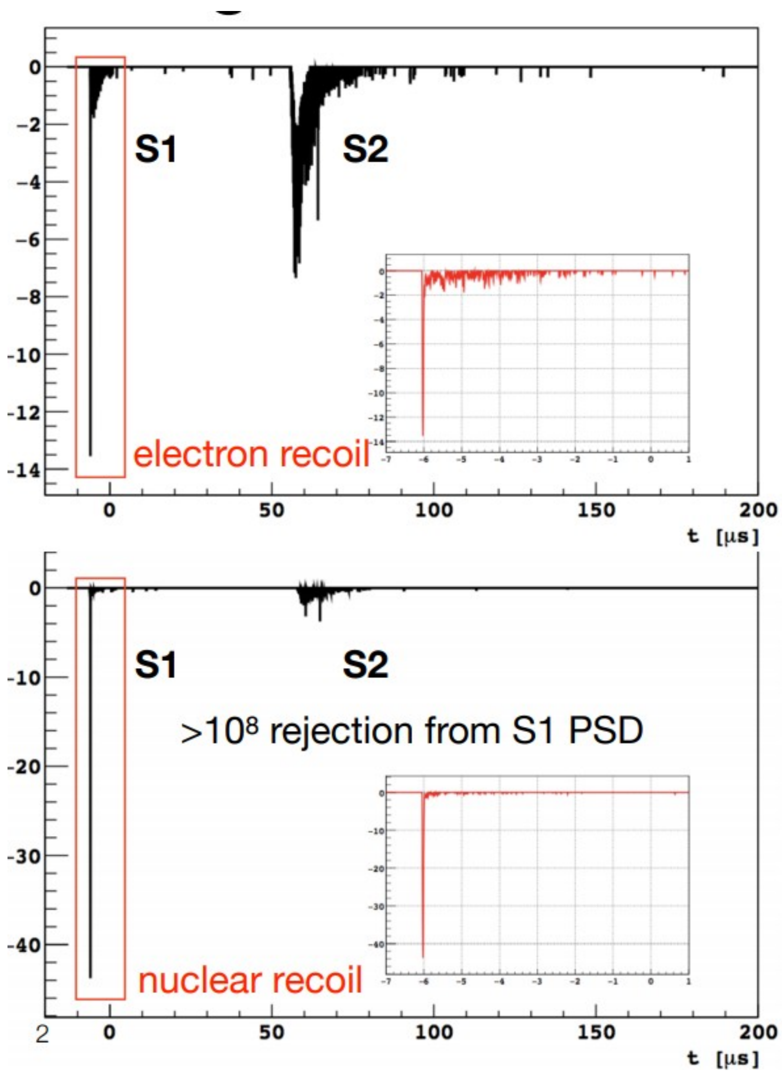
46.4 kg total mass



Powerfull PID above 15 keV

S1 → Scintillation signal
Prompt light Fraction: ER/NR discrimination

S2 → Ionization signal
S2/S1 : ER/NR discrimination

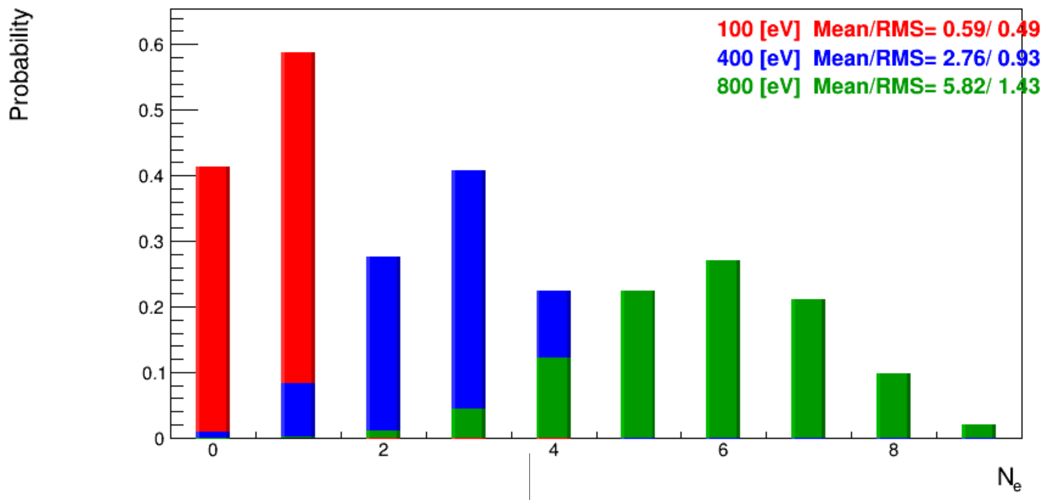


Powerfull Fiducialization

- Z position: S1/S2 time difference
- XY position: Fraction of light in each PMT in S2 pulse.

Challenge I (Seed functions)

N_e spectra for mono-chromatic Nuclear Recoils

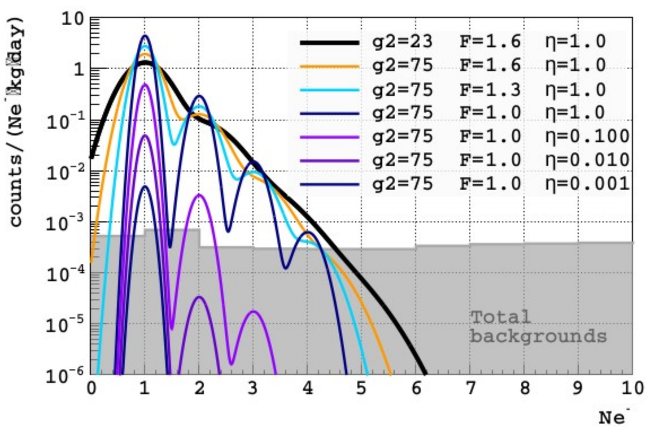


Just for illustration, simple model (not actually measured)
It is likely that 60% of the times a 100 [eV] recoil leaves a measurable signal in a Argon detector.

To predict the WIMP spectrum we need to measure these seed functions accurately.

Needs to be convolved with the experimental resolution.
This depends critically on g2 (Number of PE per extracted electron).

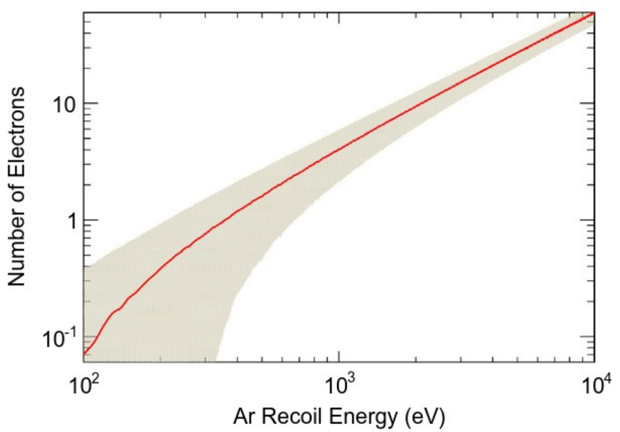
g2=23 [pe/e-] in DS-50, it can be improved tuning the Amplification field or the Gas Pocket Height.



GADMC Collaboration, Phys. Rev. D 107, 112006 (2023)

Nuclear recoils with energies 20-100 [eV] might have a finite probability to leave a signal in the detector.

Since ionization threshold is ~20 [eV], the detectability of the signal depends on the fluctuations, i.e. the competition between Nuclear and Electronic scatterings.

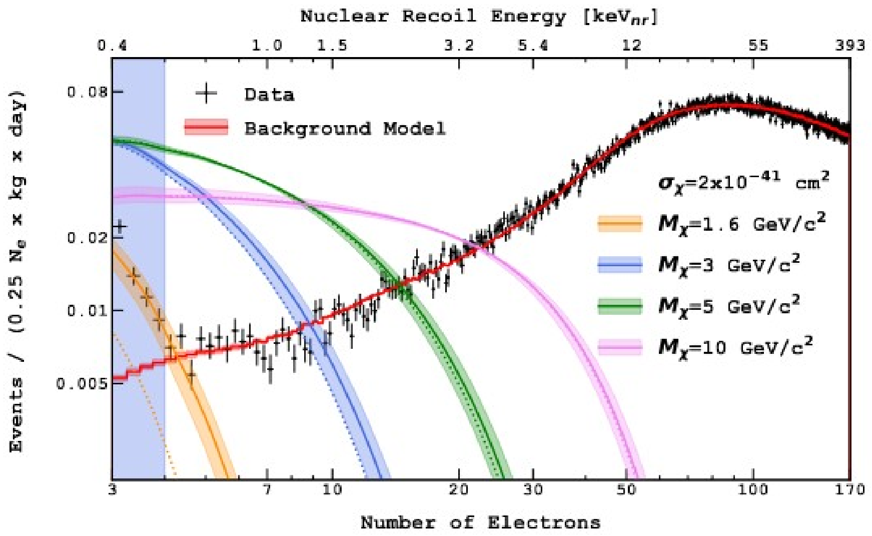


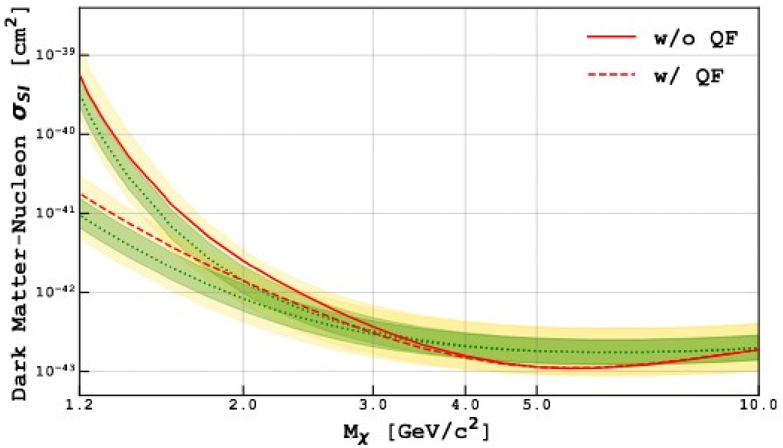
M. Foxe et al, Astroparticle Physics 69, (2015), p 24-29

Atomistic Monte Carlo to model the number of ionizations and its fluctuations

SEED FUNCTIONS: same Mean, different shape.

DS-50 Collaboration, Physical Review D, 107 (2023) 6: 063001





Solid/Dashed lines correspond to two extreme models of fluctuations.
Differences for M_{WIMP}=1.6 [GeV] are noticable.

>x10 uncertainty at 1.2 GeV

With the current threshold of N_e=4 and for M_{WIMP}<2 GeV, we have systematics due to the shape of the seed functions.

The ReD experiment

ReD is a subgroup of the GADM collaboration formed with the initial goal to investigate the directionality sensitivity of the Argon target for High Masses.
The current goal is Low Energy NR characterization.

DS-20k Collaboration
Eur. Phys. J. C 84:24 (2024)

1) Phase I : measure seed functions in the 1-10 [keV] range.

Agnes P., Eur. Phys. J. C 86:220 (2026)

Data already published for the ionization yield. Ongoing analysis for fluctuations and S1

.

2) Phase II : measure the seed functions in the 0.4-1 [keV] range

Ongoing Pilot campaign at INFN-LNS with small TPC.
Final measurements with a larger TPC and a NaI tagger
Test new neutron sources, DD generator.

3) Phase III: measure (S1,S2) for ER using Compton electrons

Additionally:

- Feasibility studies to measure the Migdal effect in Argon
- Apply calibration methodology to other targets: e.g. NaI
- R&D in the abatement of the Spurious Electron Background.

Sub-keV NR energy calibrations are actively pursued by other collaborations. Some of the methods could be adopted for Argon.

Mean of the seed functions: status before ReD

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

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

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

r :recombination probability
N_i : Number of ionizations
$\kappa(\varepsilon)$ **:** fraction of energy lost in electronic w.r.t nuclear

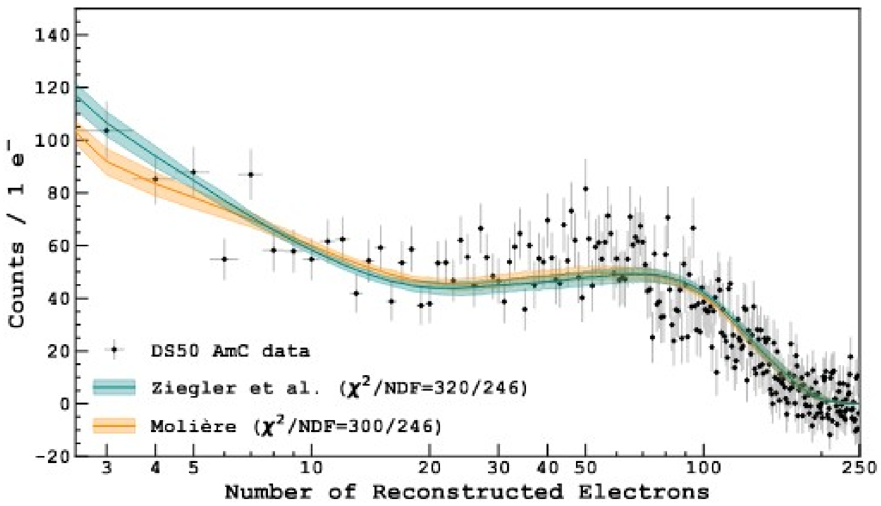
<u>The average number of electrons</u> produced depends critically on:

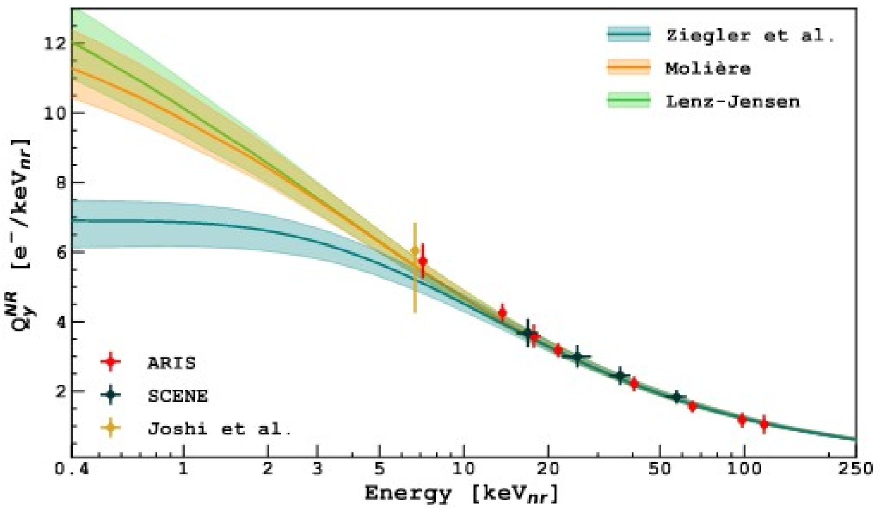
- The average energy required to produce a quantum: 19.5 [eV] for Argon , 3.8 [eV] for Silicon.
- The fraction of energy lost in electronic w.r.t nuclear collisions

<u>The fluctuations in the number of electrons depend critically on:</u>

- The fluctuations in the energy lost in electronic w.r.t nuclear

DS-50 Collaboration, Phys. Rev. D 104, 082005 (2021)





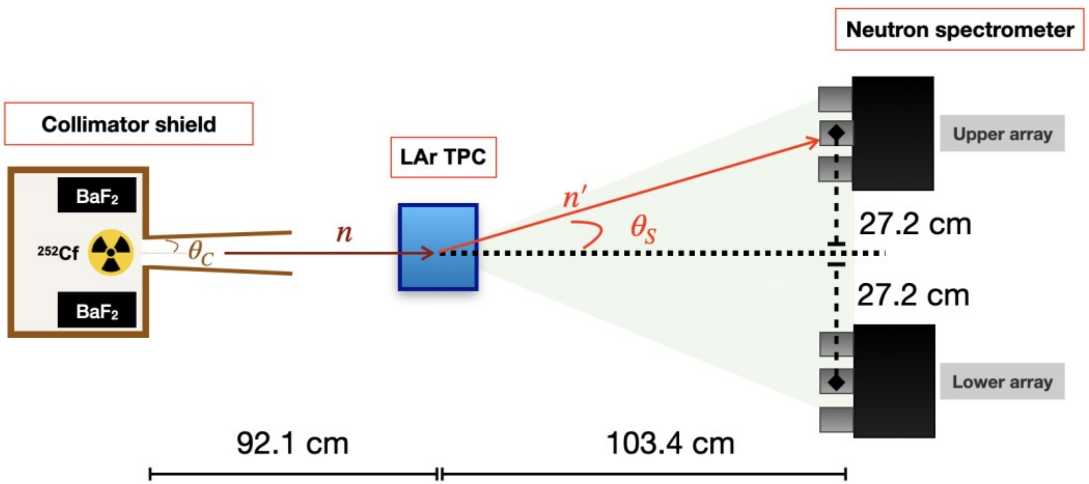
The model used in DS-50 (before ReD) comes from a fit of the AmC spectrum+External Data sets. (β,γ) free parameters.

<u>Issues:</u>

- $\kappa(\varepsilon)$ is fixed to Ziegler et al, other $s_n(\varepsilon)$ reproduce the data as well.
- Data is insensitive to the fluctuations of the number of quanta

The current approach to overcome the second issue is to adopt two extreme models of fluctuations.

Phase I *(at INFN Sezione di Catania, Italy)*



$$E_{NR} = 2KE_{neutron}\frac{m_n m_{Ar}}{(m_n + m_{Ar})^2}(1 - cos\theta_{scatt})$$

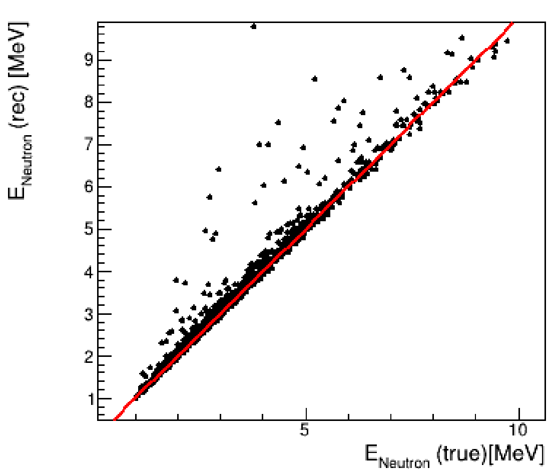
Time of flight

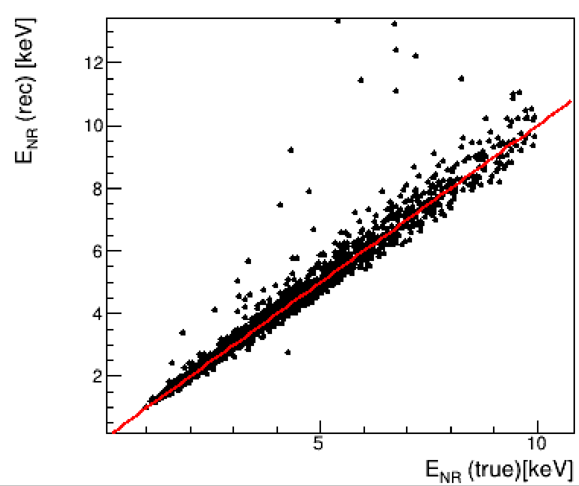
Fixed by geometry

Time of Flight	→	Neutron Energy		
Vertex reconstruction	→	Scattering Angle	→	E_{NR}

Design settings:
- ^{252}Cf source : 26 [kBq] SF
- Scattering angle of 15.25 [deg]
- 1 [cm] accuracy in TPC position reconstruction
- 1 [cm] accuracy in placement of the different detectors
- <1 [ns] accuracy in Psci/Tagger TOF

Full MC simulations (Geant4+Detector Response+Reconstruction)

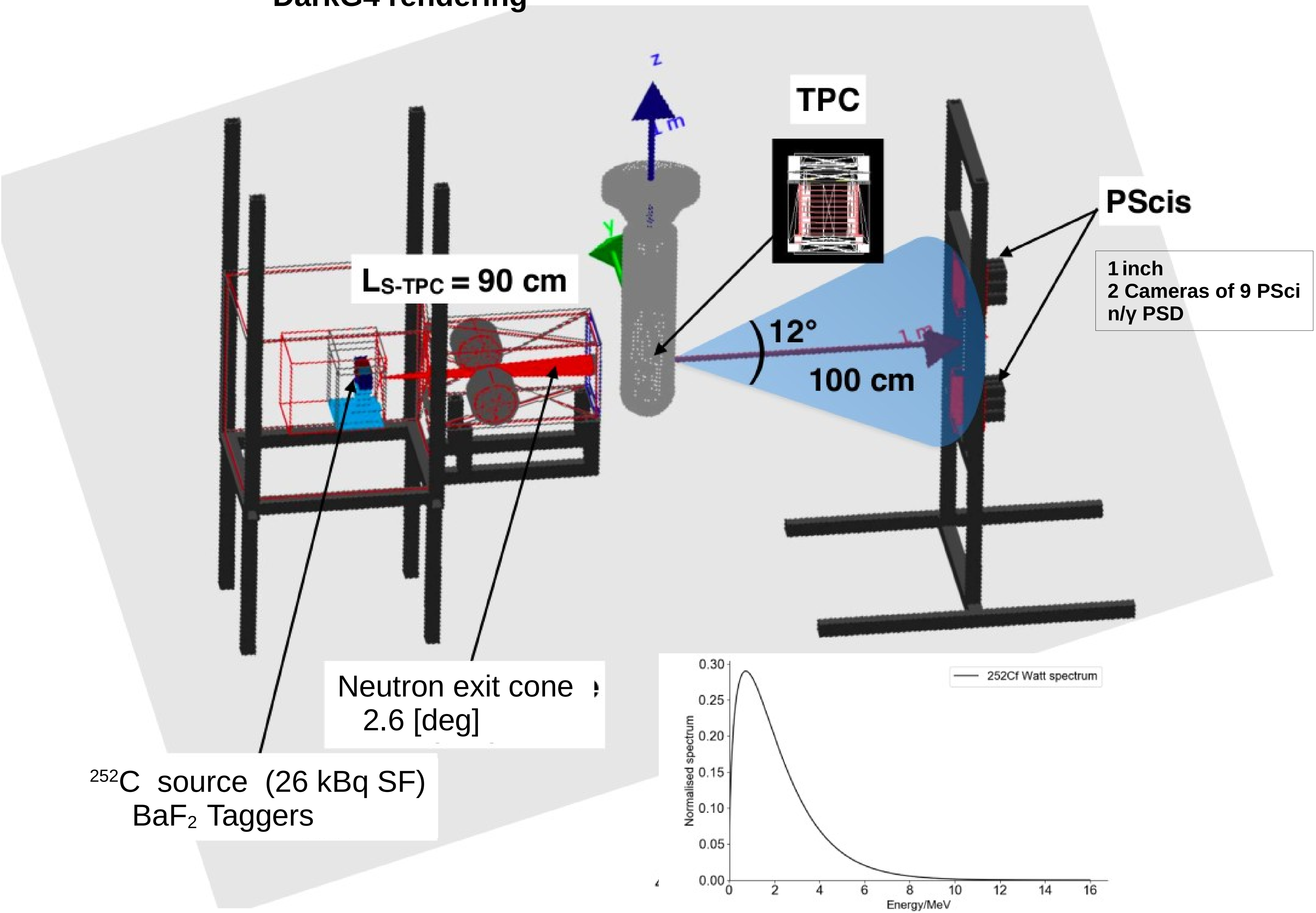




Only good topology events.
BaF0 && PSci coincidences.

~6% accuracy in $E_{neutron}$
~7% accuracy in E_{NR} reconstruction.

DarkG4 rendering

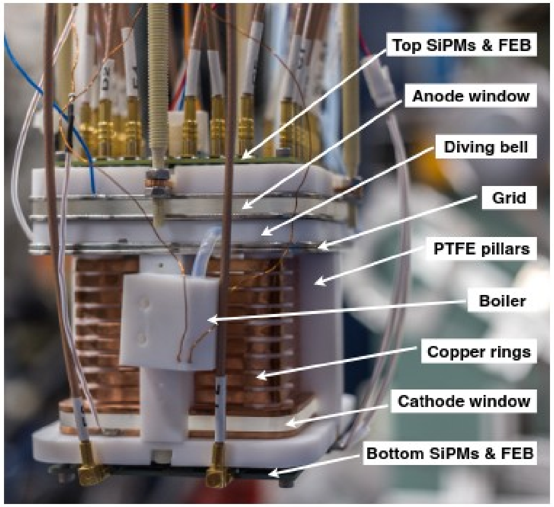


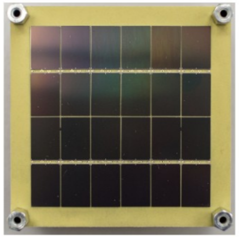
The components

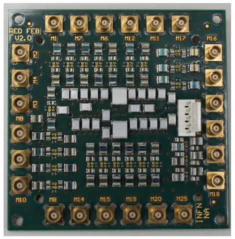
The shield/collimator made of Boron Loaded HDPE and Lead. The collimator is conical with 2.6 [deg] aperture.

- ^{252}Cf source : 26 kBq Fission
- Two BaF taggers: fast detectors that providing the **start tag:**
  - Trigger Logic: OR with ~100-200 [keV] threshold. ~40% SF tagging efficiency.
  - Trigger rate for each BaF ~10 [kHz]

Two cameras with 9 1" Plastic Scintillator.
EJ-276: good PSD and <0.5 [ns] Time Resolution
~10 [Hz] trigger rate each







5x5x5 cm TPC

24 Top SiPM
4 Bottom SiPM
NUV-HD-Cryo from FBK

Gas pocket: 7 mm thick

E_{drift} =200 [V/cm] t_{drift} =54 [us]

E_{EL} = 5.79 [kV/cm] g2=18.56 PE/e^-

TPB coating

Acrylic Windows

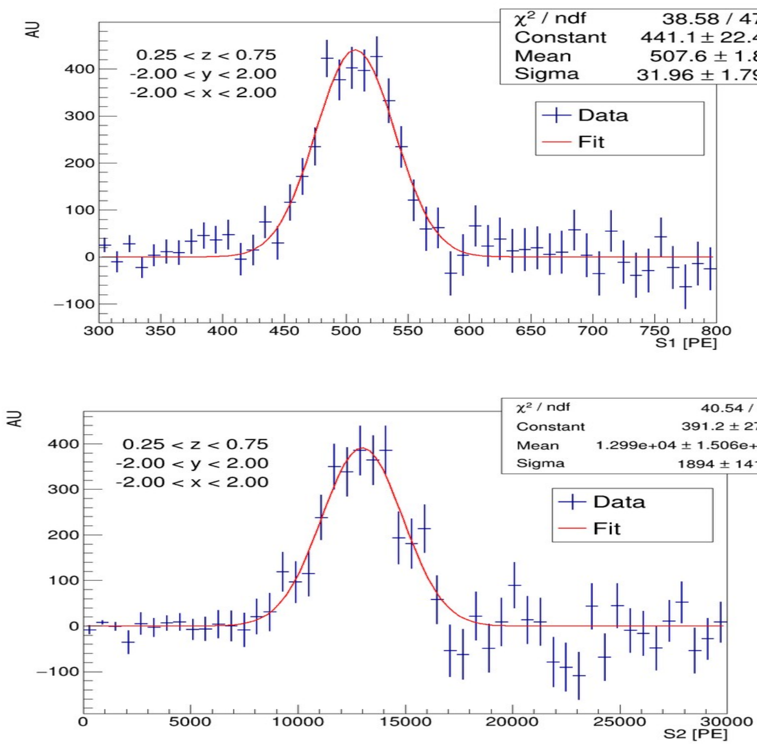
eLifetime > 1 ms

Trigger logic:
Any BaF && Any Psci
~[Hz] rate

The TPC: High Level Calibration and analysis

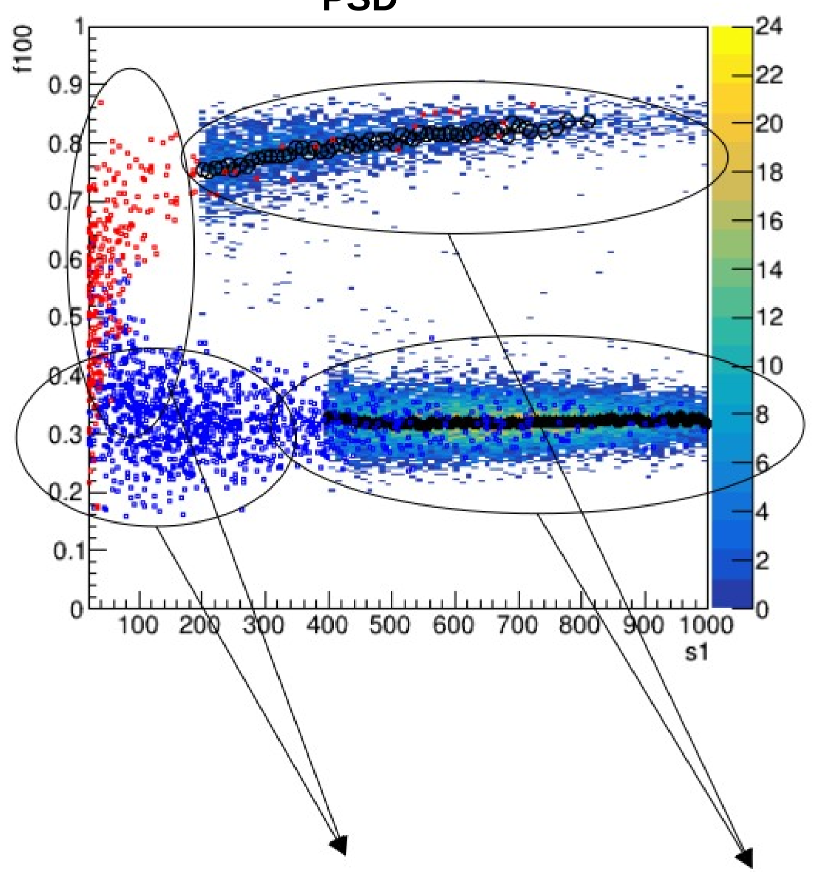
Charge Resolution

Am241 Peak Width: 6% (S1) 14%(S2) From R. Ravona



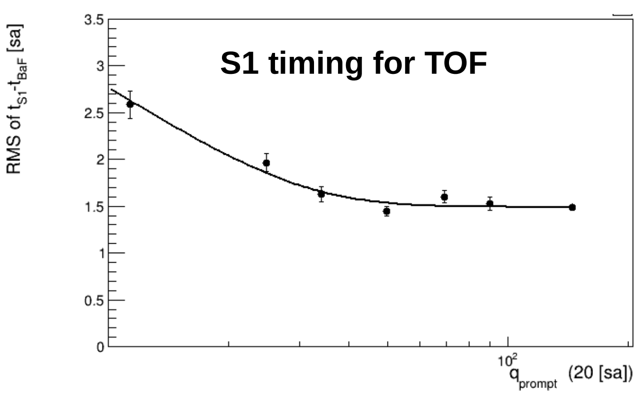
Non-Linearity induced by the method ~1%

PSD



BaF&PSci runs
Pure neutrons/gammas selected by TOF and Psci PSD

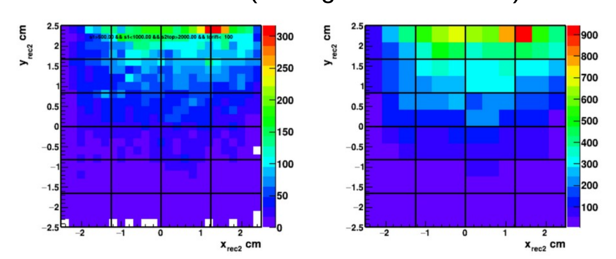
BaF&TPC runs
Neutrons/gammas selected by f100>0.5



Using the Gamma Flash of Cf252, we measured the S1 time accuracy to be 3-5 [ns]

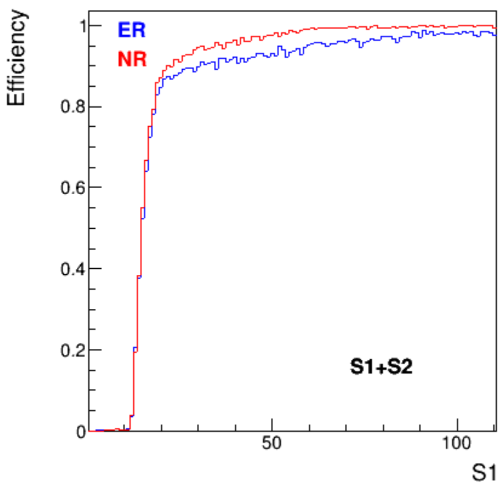
XY reconstruction

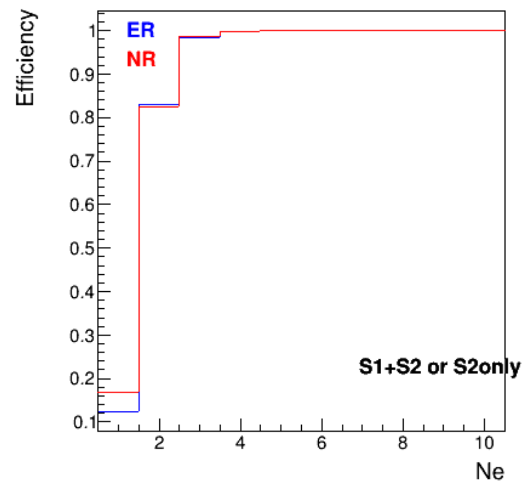
Run 1230 (Strong Am241 source)



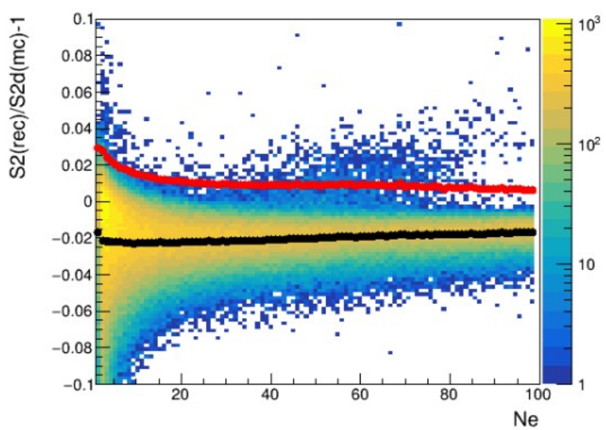
Pulse Finder Efficiency

G2~15 [pe/e-]





S2 charge reconstruction accuracy

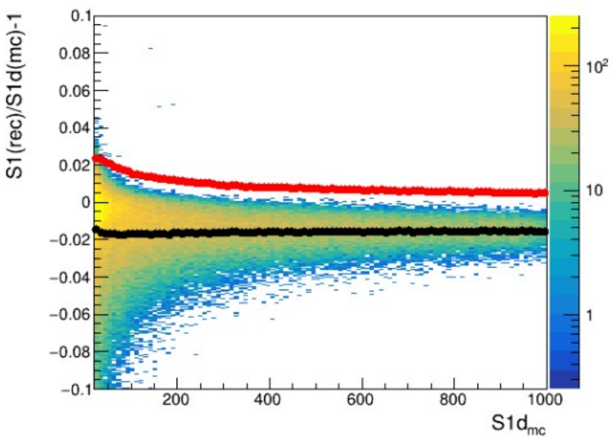


t_{drift} >20 us

Black : mean

Red : rms

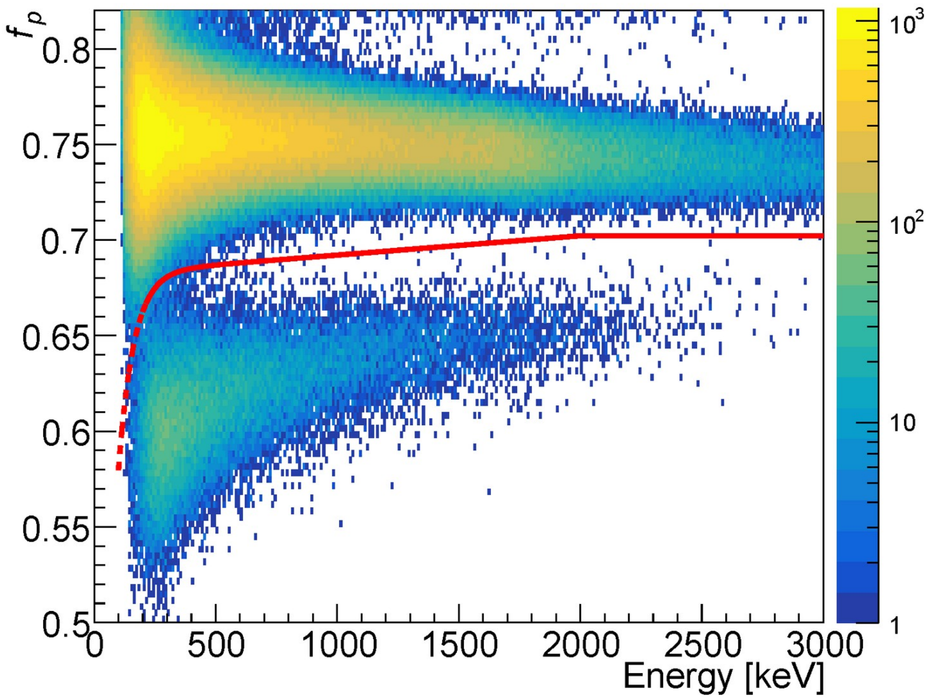
S1 charge reconstruction accuracy



The PSci: PSD and Nuclear Quenching

PSD

f_p = I(30 ns)/I(500 ns)
Short gate optimized on data

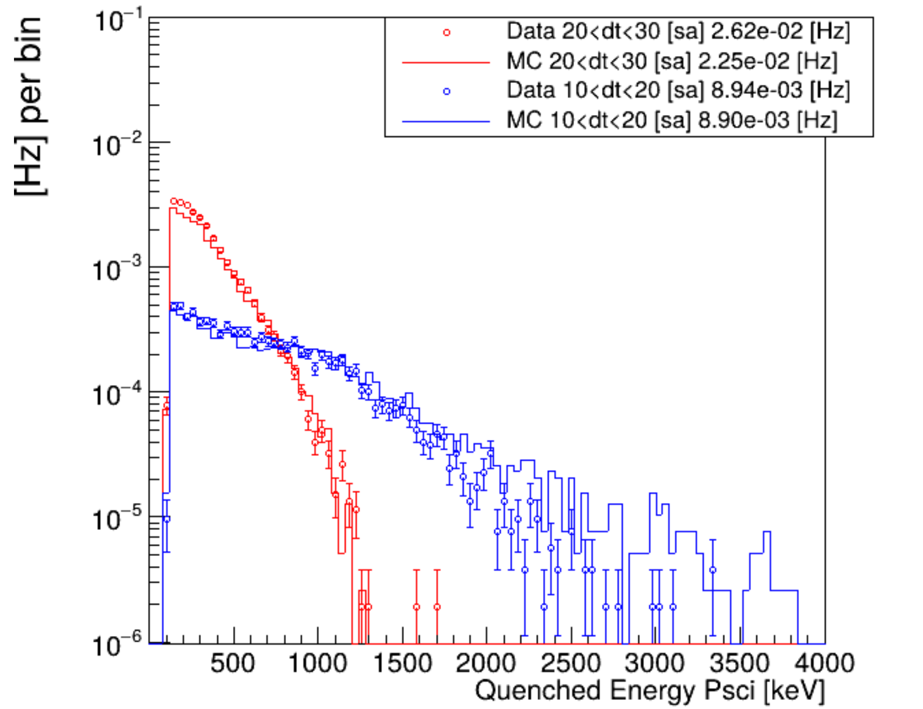


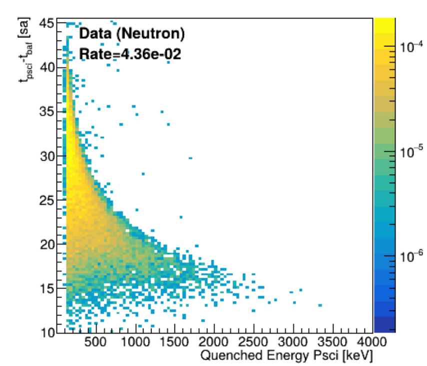
E_{th} ~200 [keV]
1% contamination cut

(i.e. less than 1% of the classified neutron population is a gamma)

Nuclear Quenching

Measured in a dedicated run with PSci in the neutron beam

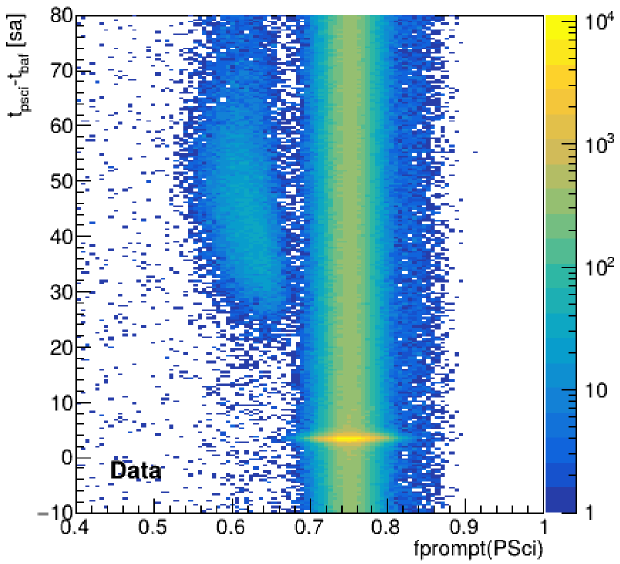


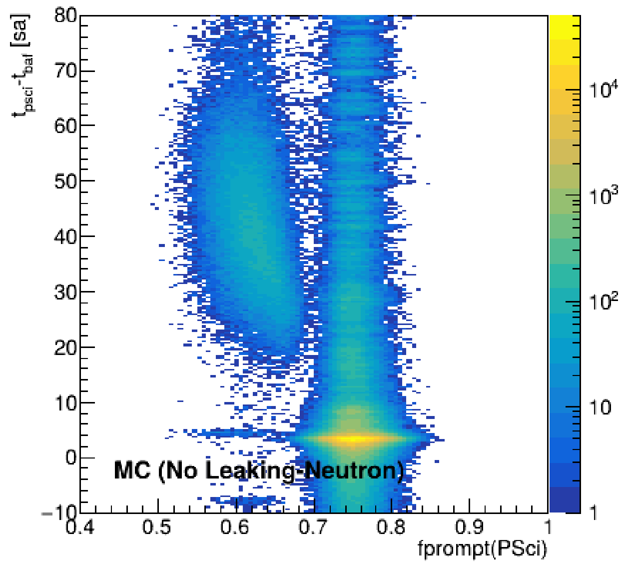


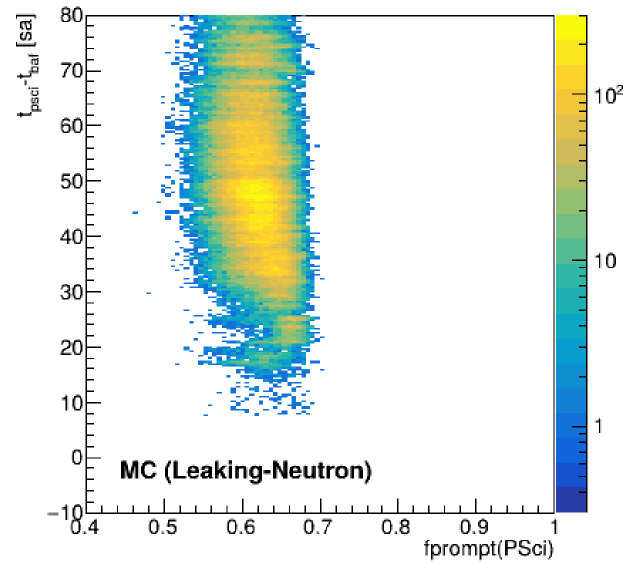
Psci energy is calibrated with Am241 source. An ER recoil quenching is applied, it was measured in a dedicated experiment.

WARNING:
MC ^{252}Cf spectrum uses FREYA model in these plots, Mannhart et al is what we used for the MC with only neutrons (publication)

BaF0-Psci coincidences

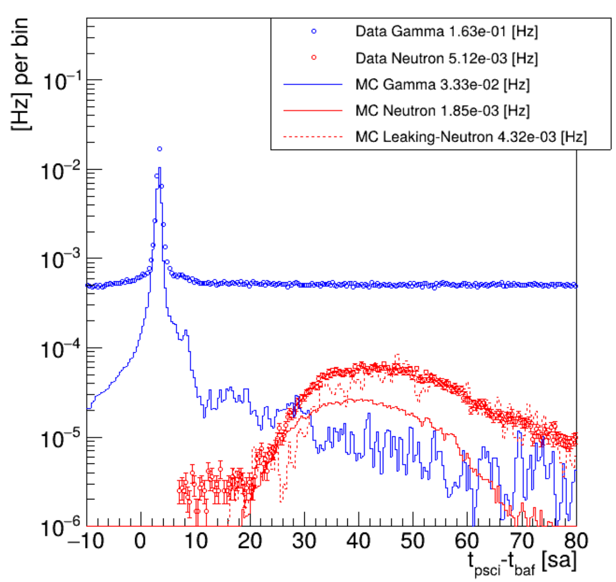






Leaking neutrons refer to neutrons that exit the shield from the front without going through the TPC. The shield was reinforced after these measurements.

- **Gamma Flash:** rate well reproduced and TOF resolution ~0.7 [ns] (6% $E_{neutron}$, slide 11)
- **Accidental Gammas** missing in the simulations.
- **Leaking neutrons** are the dominant population for tof>40 [sa] . When TPC coincidence is required, they disappear.



BaF-Psci coincidences with TPC signal

Agnes P., Eur. Phys. J. C 86:220 (2026)

TPC cuts

- S1+S2 → (f100>0.5 || S1<100) && $|t_{TPC} - t_{TPC}^{expected}|$<15 [ns]
  S2 : 5-65 [us] after BaF_2
- BG before 1st pulse and after last pulse < 0.5 [spe/us]
- (x,y) in the central 4x4 cm region

BaF cuts: E_{baf0} > 100 [keV] E_{baf1} > 200 [keV]

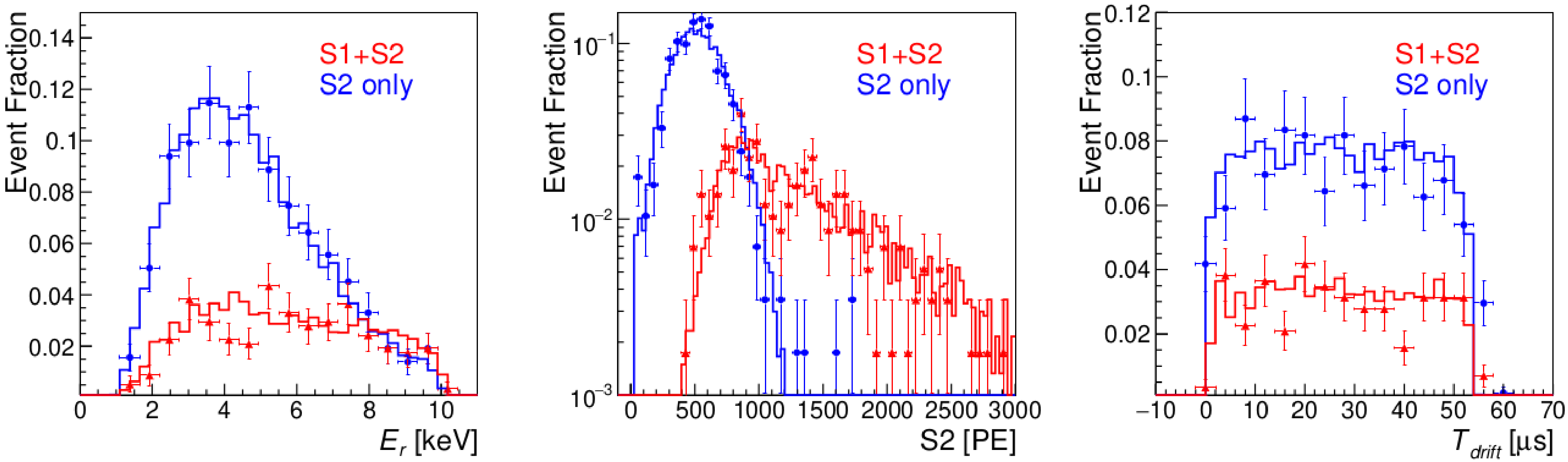
PSci cuts: 1% contamination line , E>200 [keV]

Total number of events (S2 or S1+S2) : 2258
(~7% of neutrons Tagged)

Total selected : 575 (S2 only) 231 (S1+S2)

Data taking: From Jan 10th to Mar 16th, 2023
~2.5 Hz, 80 µs waveforms (600 GB/day)

1045 [hours] 2.1 (0.77) [evt/h]



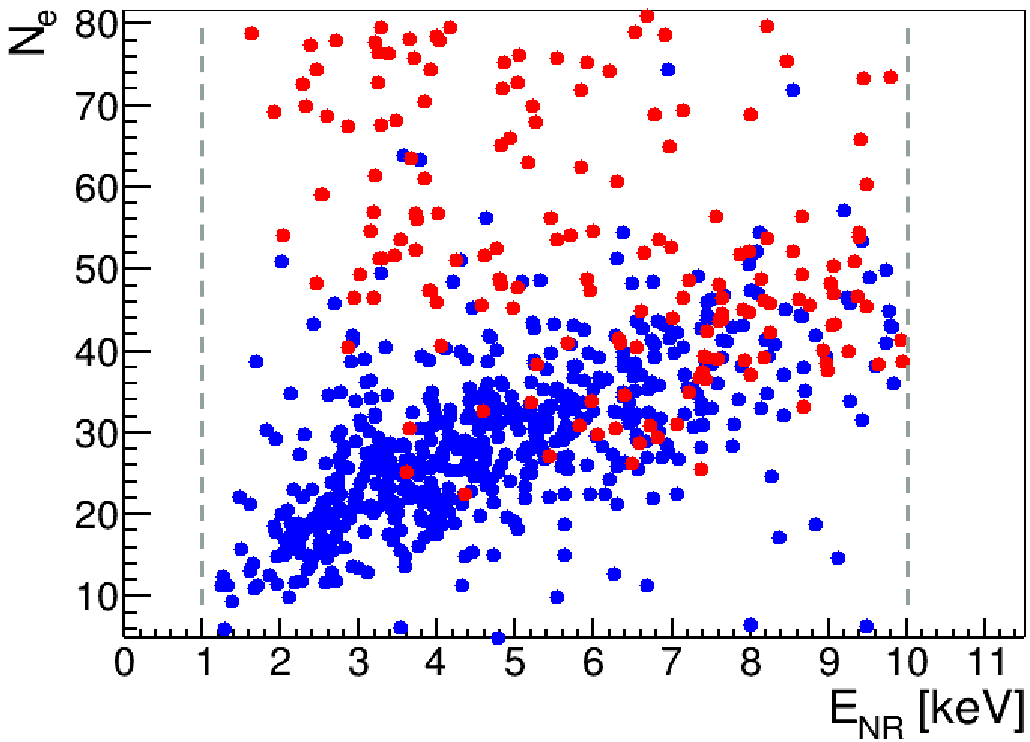
Detailed end-to-end **MC simulation** available
Produce synthetic data, same analysis flow than real data.
Validated on calibration, use to check reconstruction algorithms!

S2 is converted to N_e using a cross-calibration procedure with DS-50.
(back up slides)

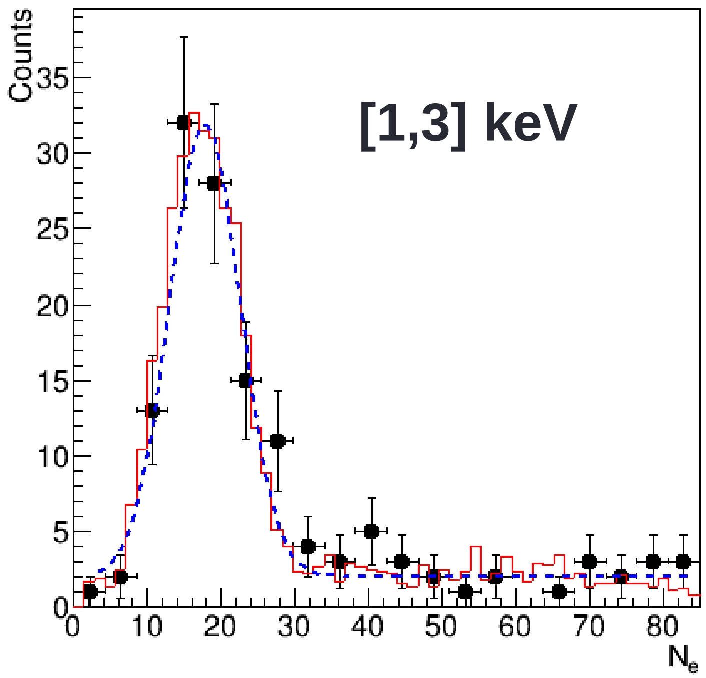
$$g_2 = (18.56 \pm 0.71)\ \text{PE/e-},$$

TPC z position w.r.t. neutron beam height adjusted using t_{drift} distributions of Am241 runs (back up slides)

$\Delta z = (0.23 \pm 0.95)$ cm



Agnes P., Eur. Phys. J. C 86:220 (2026)

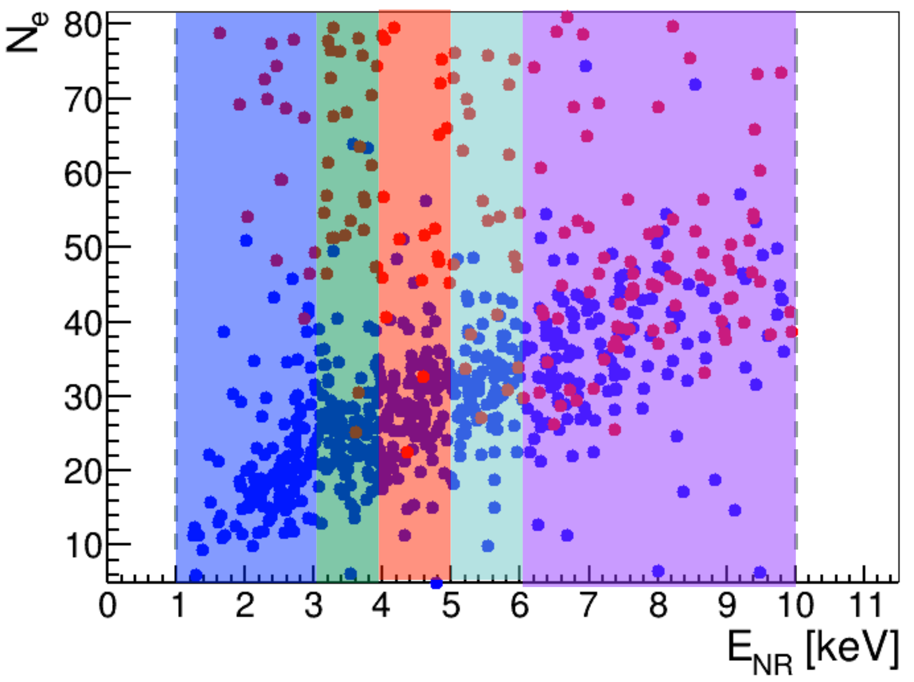


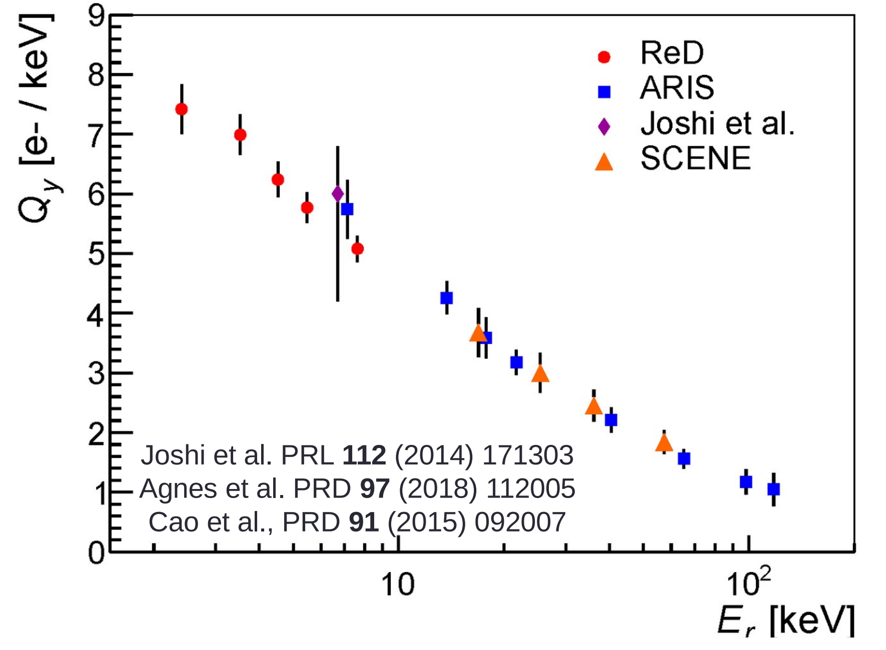
Black: Data
Red : Full MC
Blue : Unbinned Likelihood fit to gaussian+cte BG

Constant BG is mostly due to Passive+TPC Scattering
Procedure tested with synthetic data.

Total Q_y uncertainty 4.5% - 6%

Agnes P., Eur. Phys. J. C 86:220 (2026)





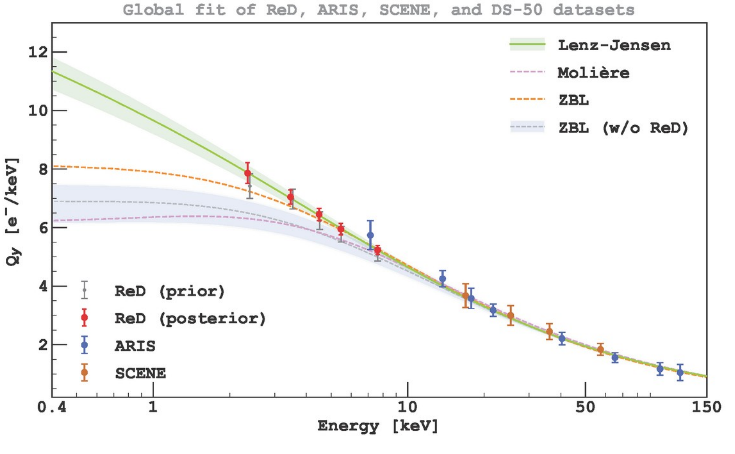
Repeat the **global fit** with DS-50, ARIS and SCENE, **w/ the ReD data points**

- Ziegler, Lenz-Jensen and (*correct*) Moliere screening functions

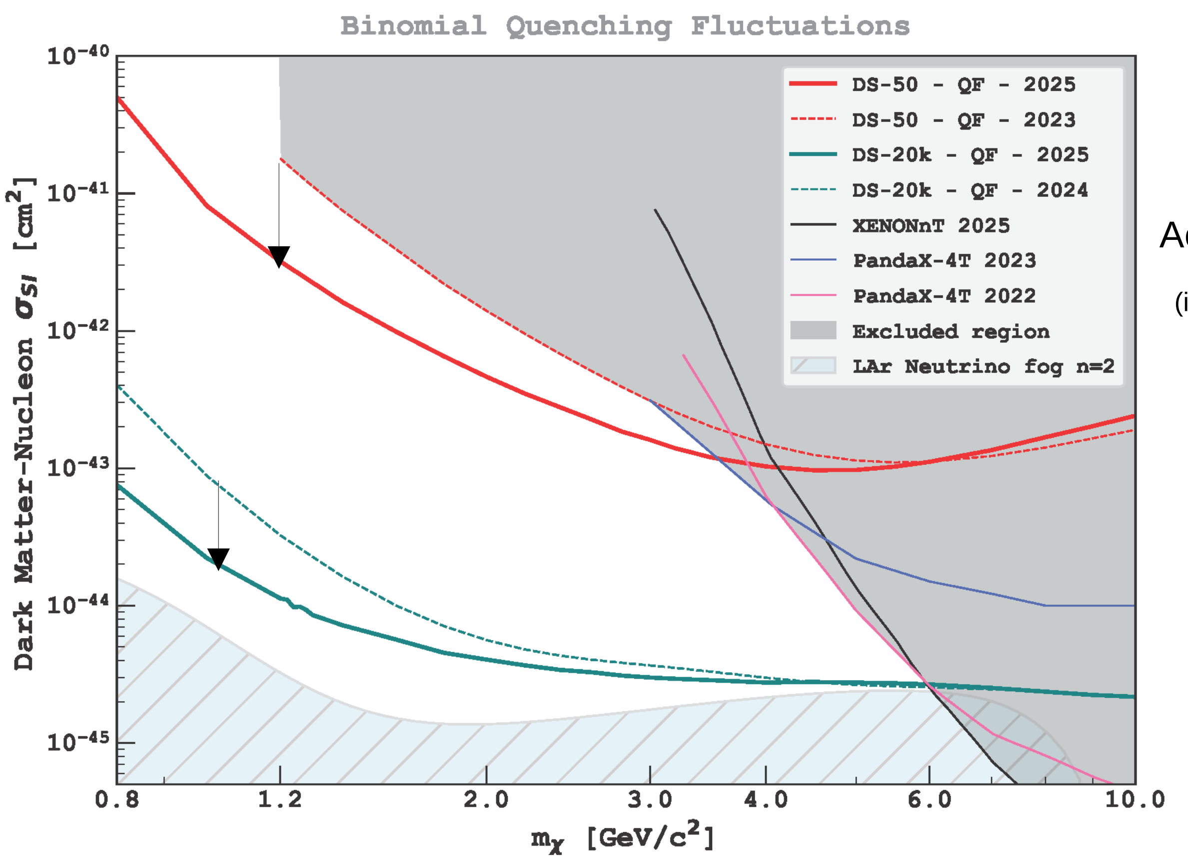
Bonus: marginalization on g_2 and Δz for ReD data

Q_y uncertainty 3.0% - 4.5%

Lenz-Jensen looks **best**



Impact on DS-50 Limits



Acerbi F. et al, arXiv:2511.13629

(in press PRD)

- **Study of the fluctuations is ongoing:** there is sensitivity to constrain the two extreme models
- **S1(E) studies ongoing:** by using a time coincidence window we can go well below the Pulse Finder threshold.

Conclusions

- Argon is an attractive target for direct DM searches in the 1.5-5 [GeV] mass range.
- Very few measurements of the ionization yield response functions. ReD performed the first (based on Kinematics) in the 1-5 [keV] range.
- Phase I : published, very good prospects to constrain the fluctuations of the ionization yield.
- Phase II : a pilot campaign targeting the 0.4-1 [keV] region is on going
- Phase II : a NaI segmented tagger should boost by a factor 2 the rate of the pilot campaign.
- Phase III: very good prospects to characterize the Electron Recoil response in a wide energy range using Compton electrons.
- Abatement of Spurious Electron Background is possible through R&D but not planned yet.
- Measurement of the Migdal effect is feasible.

Back Up slides

The ReD TPC Analysis flowchart

Calibration
Using laser runs (2 [ksa] 4 [us]) derive:
- SPE average shape
- SER : [adc] to [spe]
- DiCT: P_{vino}
- DeCT+AP
- DCR

Red Level Analysis

- FADC Trace Deconvolution: FFT method
- Peak Finder and Charge Integration

Output: TTree of packets
in the low occupancy regime 1 packet is 1 SPE

Blue Level Analysis

- Pulse Finder: S1 and S2 clusters and related variables.
- XY reconstruction
- XYZ corrections of S1 and S2
- S1 and S2 pulse shape fits
- SER charge distributions (Calibration cross check)
- S1 time variable for TOF (weighted average of first SPE of all channels within the tile, within a 20 [sa] window)

Output: TTree of Clusters and Pulse Shape fits

User analysis
- Echo Probability and time distribution
- External Cross Talk from S1 tails
- Delayed Electron Probability from S2 tail fluctuations

Geant4
DarkG4: a local project
- DarkEvent TTree : collection of deposits
- BlueMC TTree : collection of physical clusters

MCGenerator
Given (E_{dep} , t , type) of Physical Clusters generate Raw FADC traces:

- Using ER/NR model → time collection of photon
- Photon share among SiPM: using XYZ corrections for S1 and S2 inferred from data.
- Using calibration : time collection of SPE (DiCT+DeCT+AP and DCR)
- Using user analysis: xCT and Delayed Electrons.
- Using user analysis: Echo (S3) generation

FADC generation: SPE shape of each SiPM + Baseline Fluctuations

Trigger Logic implemented by Masato

69 TB (FADC traces)

1 TB (Packet collection)

~2.4 [evt/s/CPU]
1 evt → 28 FADC traces 40 [ksa]

ONLY ONCE

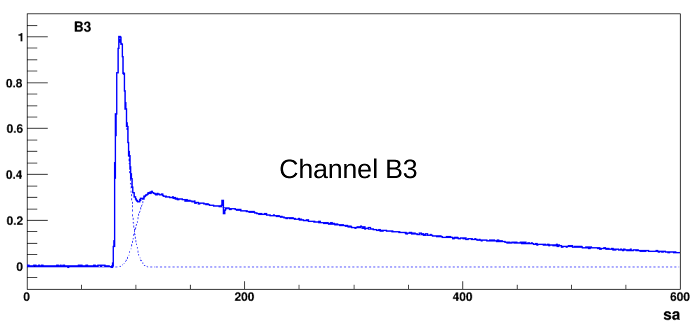
All data can be reanalyzed overnight

ER/NR Model
- S1(E) S2(E) and fluctuations
- S1 pulse shape
- S2 pulse shape (with xyz dependence)

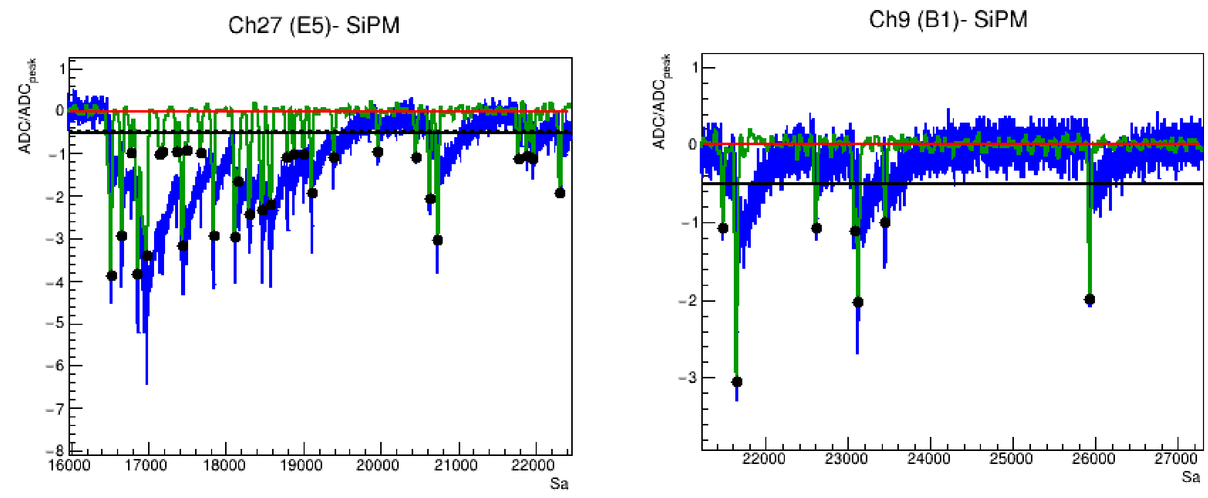
g1 from Am241
g2 from Echo

The framework has been upgraded to read native MIDAS files (ReD+ DAQ based on MIDAS).
Appliable to Proto-0 given manpower is available.

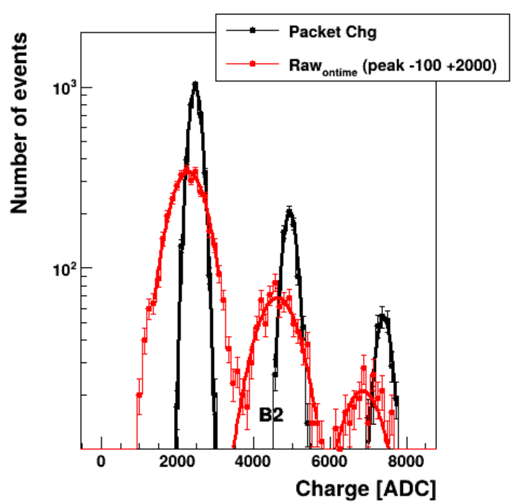
The TPC: Low Level Calibration



SPE time profile from Laser Runs



Raw trace
Deconv trace 30 [ns]
Black points: packets



SPE charge

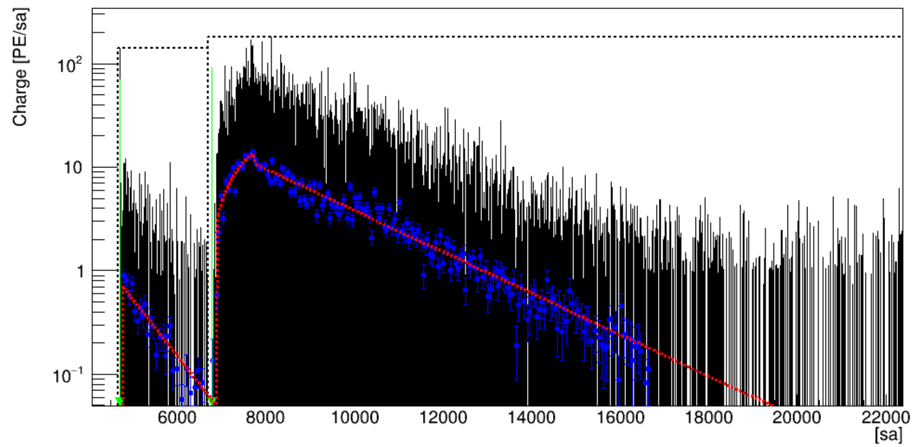
Red Files contain:

All maximum of the deconvoluted trace above 0.5 [spe_{peak}]. Each maximum is assigned:

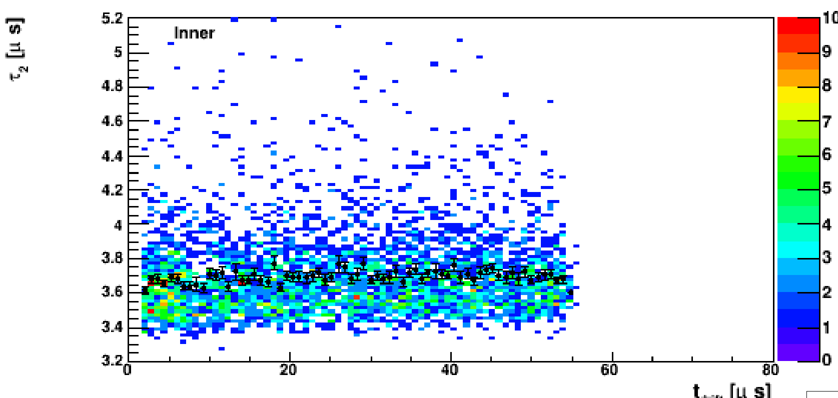
- <u>Time:</u> interpolated with a 2^{nd} degree polynomial
- <u>Charge:</u> integrated in between valleys. If possible the integration range is extended to +-N_{user} [sa].

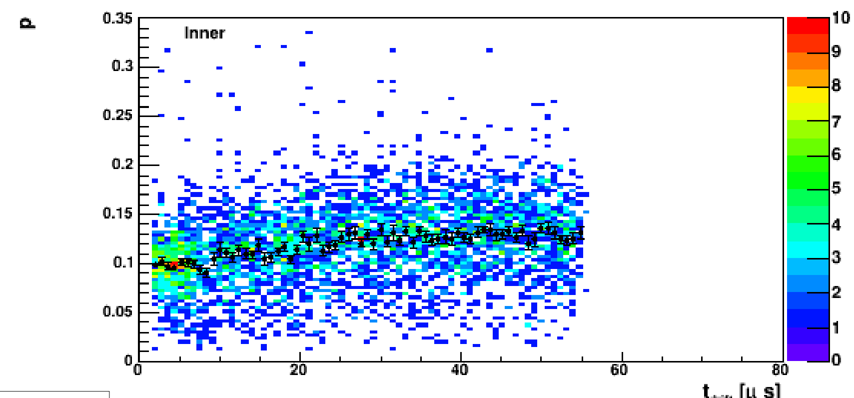
This method preserves charge. No distortion of the time information available.

S2 Pulse Shape Fits (event by event)



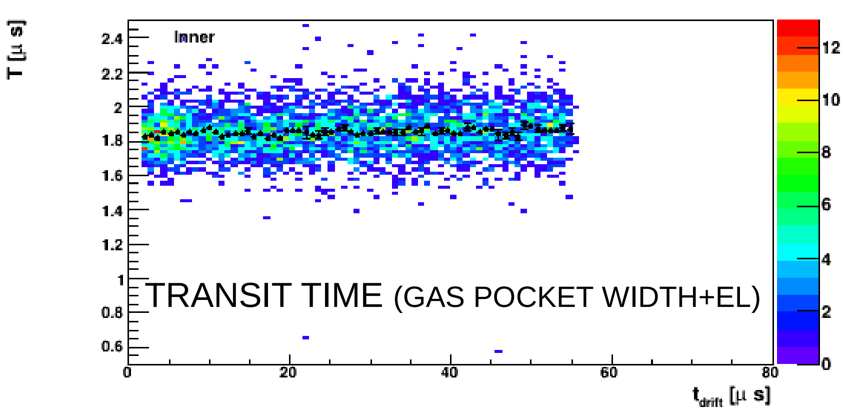
One event

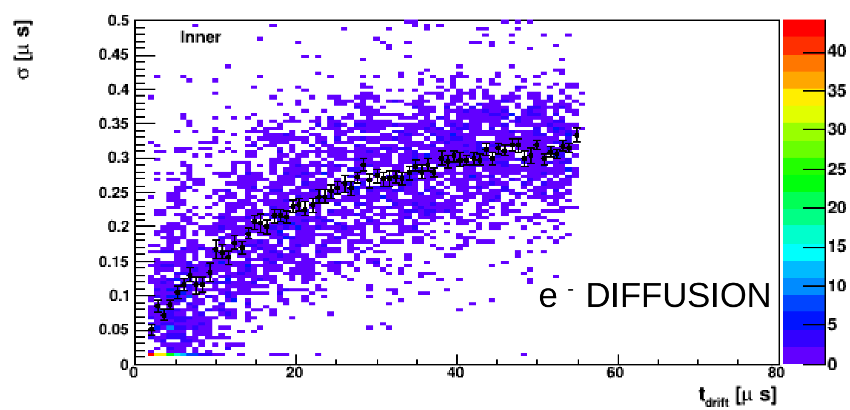




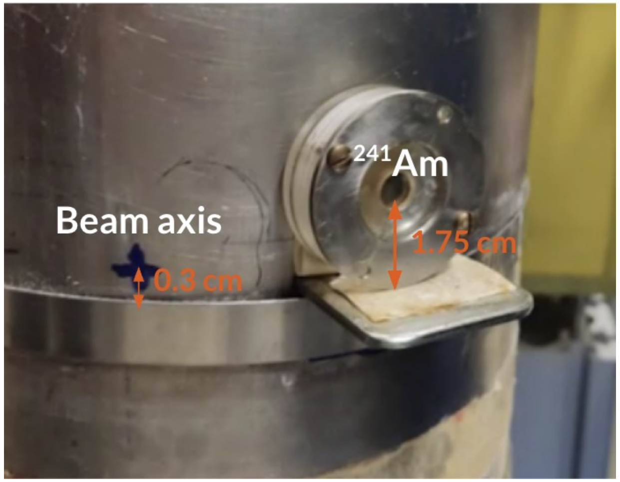
Many events

Run 2299 Cf252+Am241 (Inner Pixels)





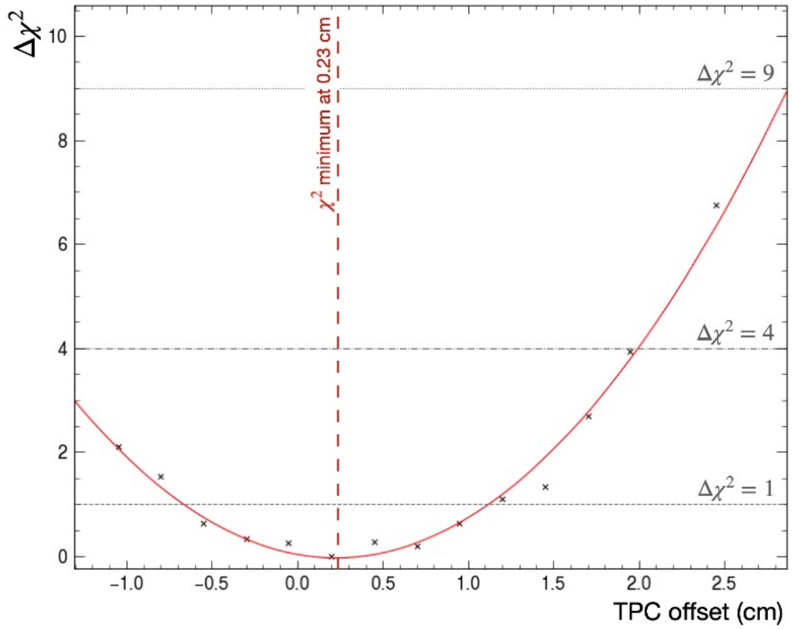
TPC Δz vertical alignment

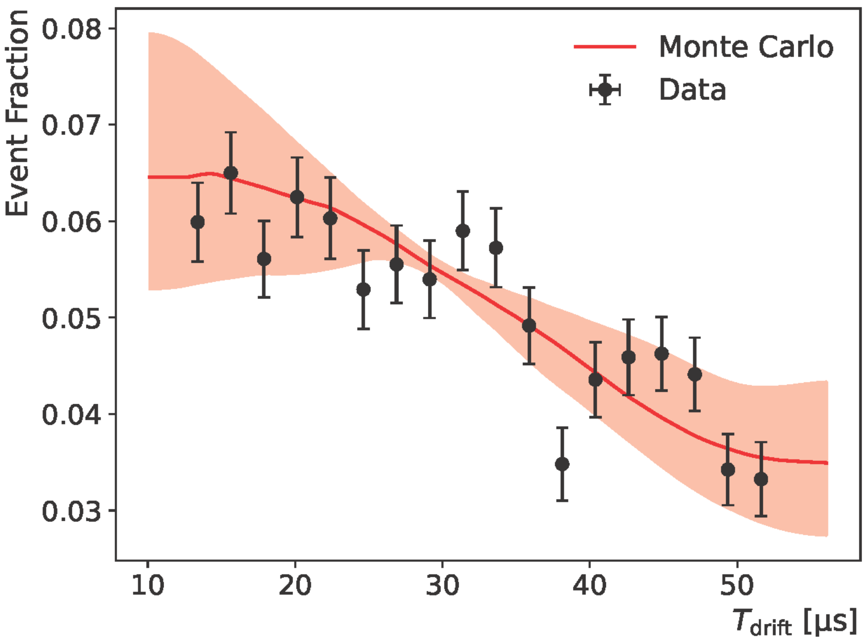


Source and spectrometer aligned **within a few mm** using laser beams.

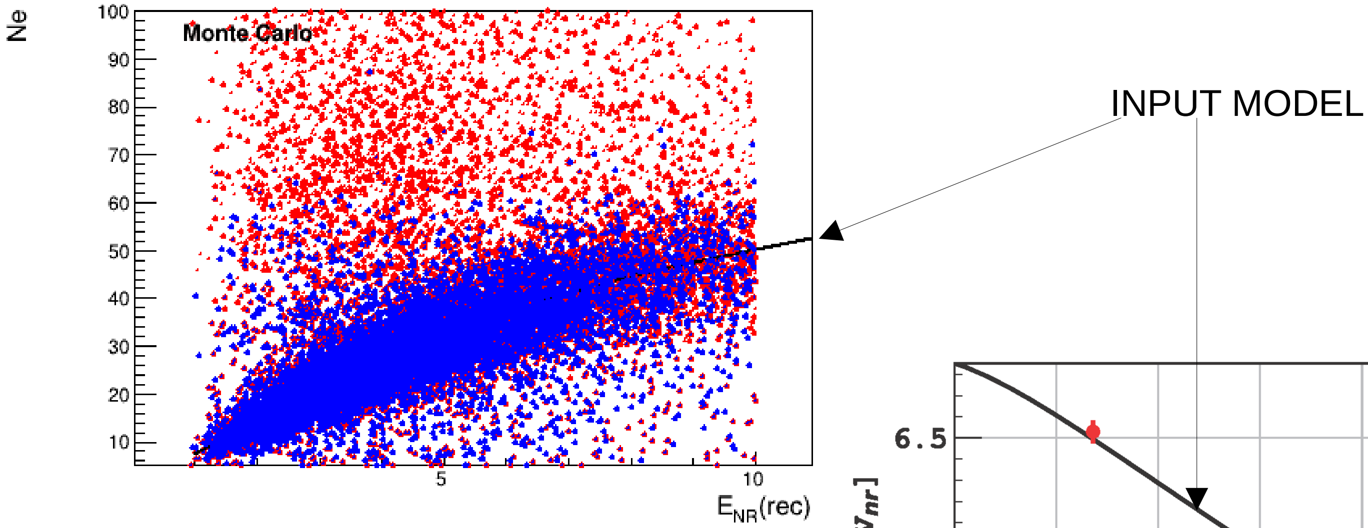
More difficult to do with the TPC, as the object is in the cryostat and there is thermal shrinking at cold.

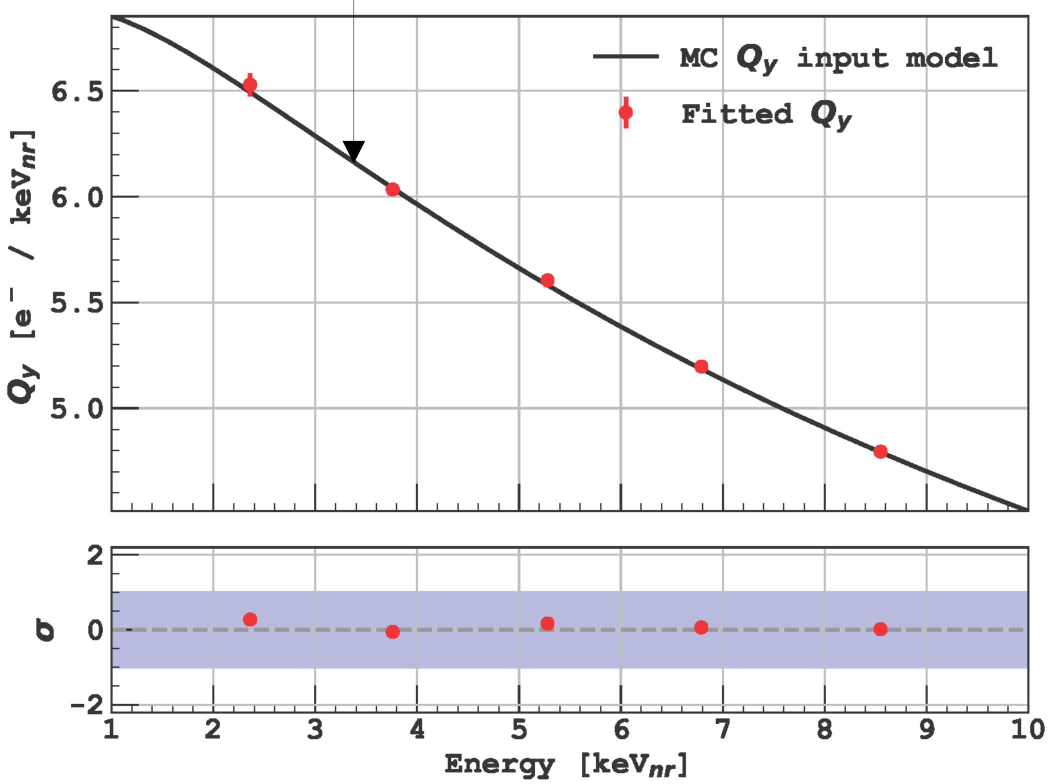
Constrain using **^{241}Am calibration data**
<u>Best fit</u>: **(0.23 ± 0.95) cm**





Unbinned Likelihood validation





The analysis **reproduces** the model which was **fed in input**

S1+S2 events must be included (if not: bias)

From S2 to N_e

- Ionization gain $\mathbf{g_2}$ (PE/e-)

Detector property: must be measured by the ReD data

- Two different approaches

(1) Calibration with ^{241}Am (60 keV γ-ray)

S2 value from ^{241}Am data

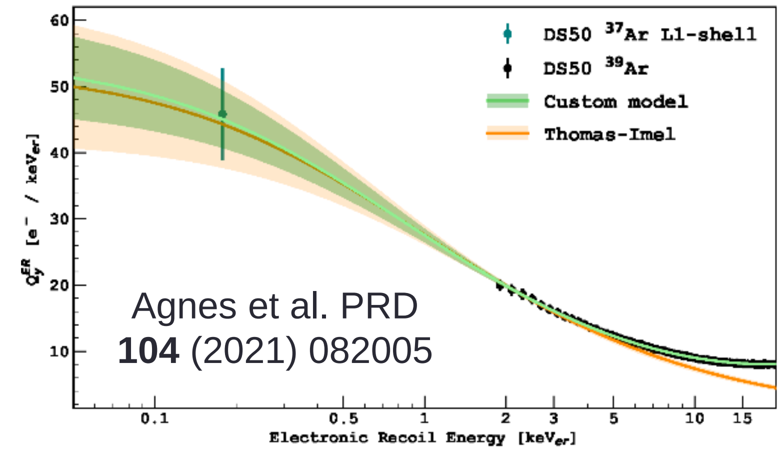
Expected Ne calculated by MC, using the Qy(ER) model from DS50

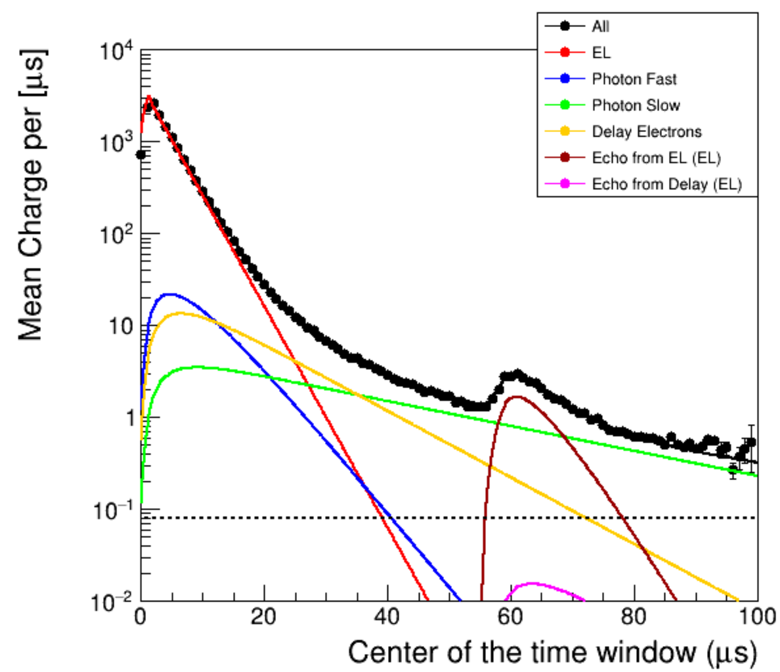
(2) «Echo» events (S3): photoionization of the cathode from the S2 pulse Delay of 54 µs with respect to S2

A-few electron signal

Required the development of a full integrated shape model

Consistent results: 18.6 PE/e-





Phase II

Physics goal: Nuclear Recoil Energies 0.4-1 [keV]

$\Theta_{scattering}$ =6.5 [deg] $D_{source\text{-}spectrometer}$ =260.4 [cm] $D_{source\text{-}TPC}$=114.6

Ingredients:

- Neutron source : ^{252}Cf with higher activity (100 kBq [SF]) and new taggers (NaI Segmented, Higher Eff)
- New TPC : larger, less passive materials, better field configuration and larger g2.
- Spectrometer : 36 PSci (x2) with better camera design (avoid neutron reflections)
- Shield : : reinforced to avoid leaking neutrons
- DAQ : new DAQ that allows triggering on Single Electrons using top multiplicity
  125 [Mhz] 64 ch VX2745 8 [ns] FADC width

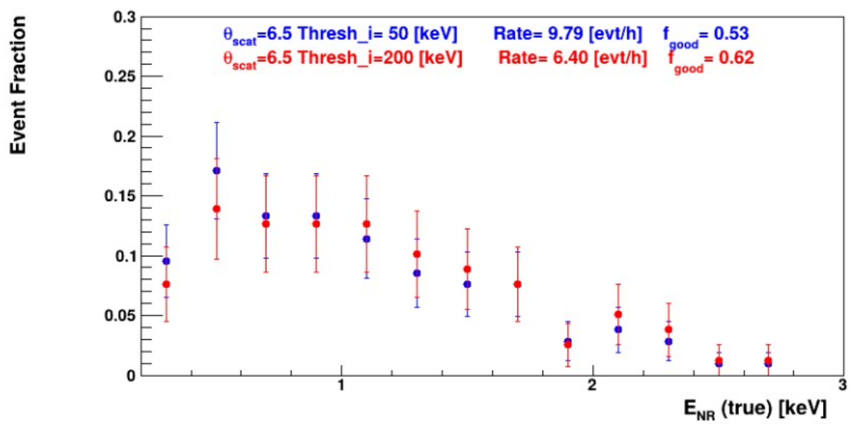
Technical goals:

- Boost signal rate by a factor 10 (x4 source x2 Taggers) 20 [evt/h]
- Decrease bad topologies by a factor of 2

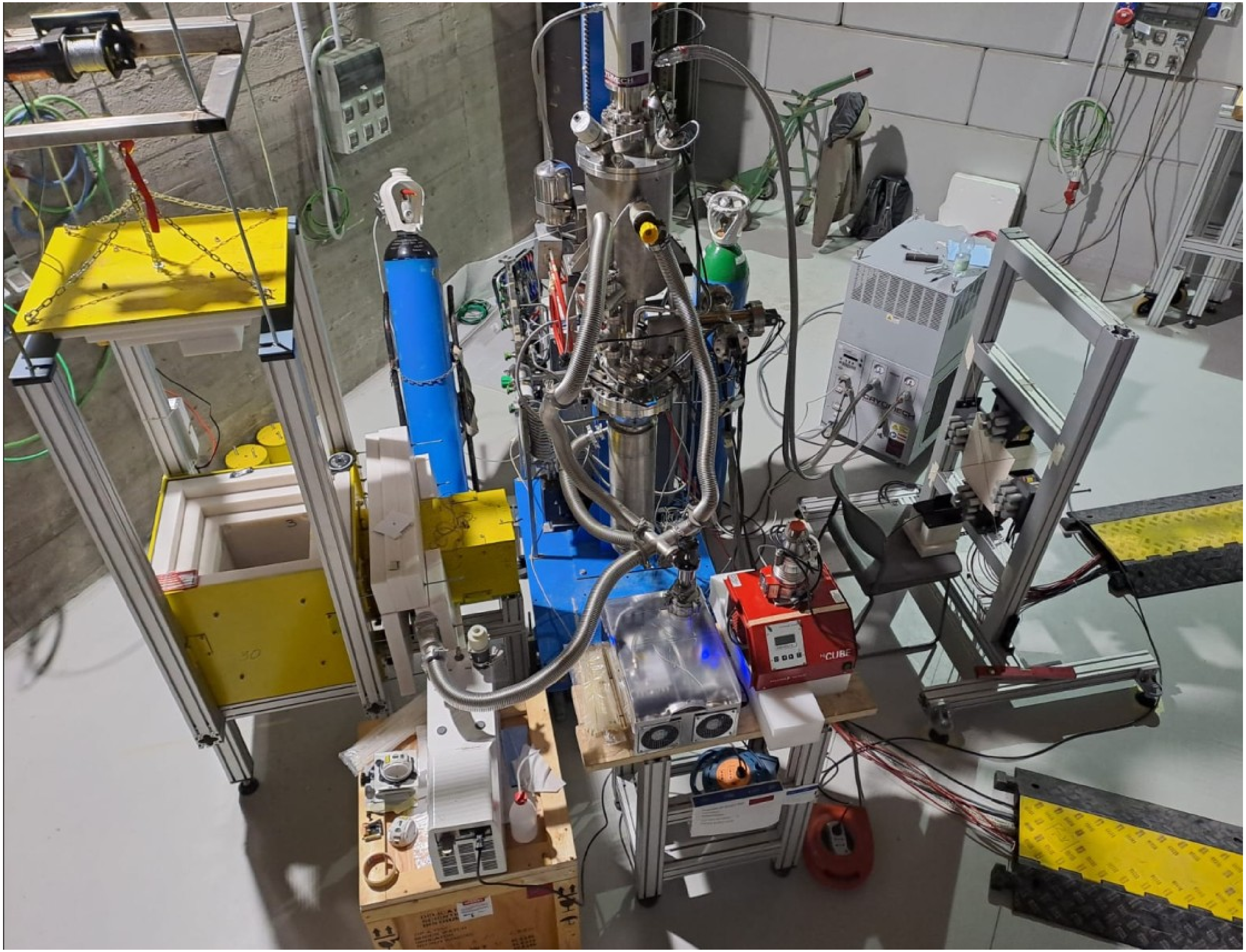
The Pilot Run has the above configuration except:

- Old TPC.
- Taggers: 2 PSci very close to the source (similar efficiency)

  Overall, we expect 8 (3) [evt/h]



TPC, Psci and Taggers ready and calibrated. Taking data



Future: Testing new portable neutron sources

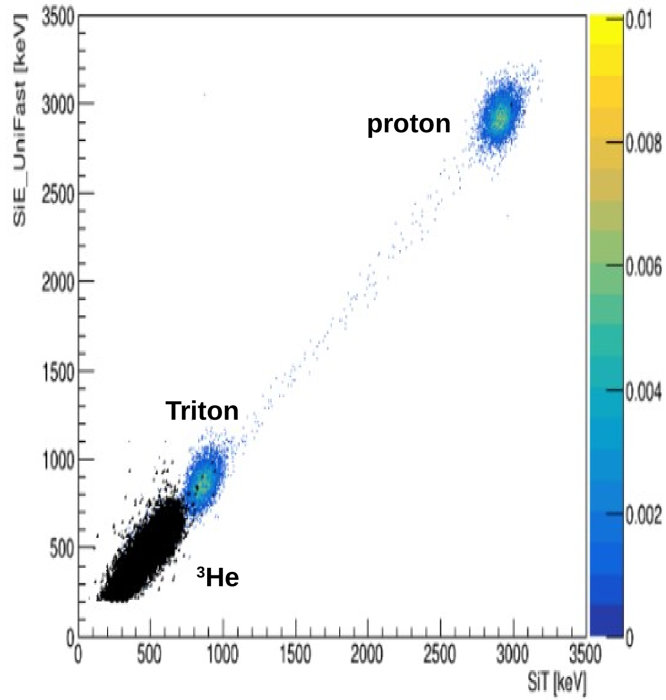
Why a DD Generator?

- *Large flux:* adjustable 3e5-1e7 n/s
- *Mono-energetic neutrons*

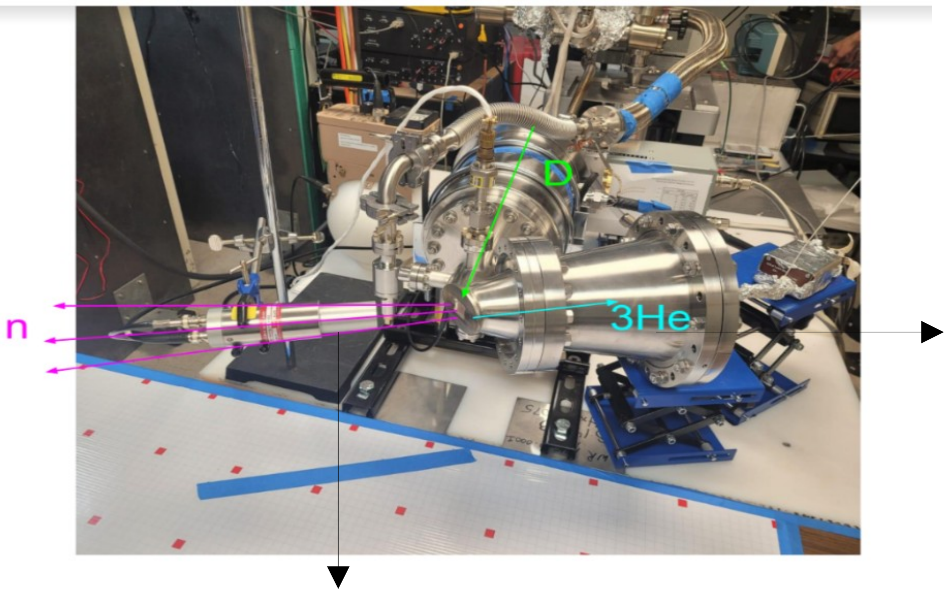
Generator: Adelphi DD-107 API with a home made conical flange that host a Silicon Detector to detect ^{3}He

Requirements

- Low X-ray flux
- Efficient Trigger on ^{3}He with the SiDet.
- Good timing accuracy of SiDet (TOF measurements).
- Narrow neutron cone beam formed when triggering in the SiDet
- SiDet can be operated in long campaigns (radiation damage).

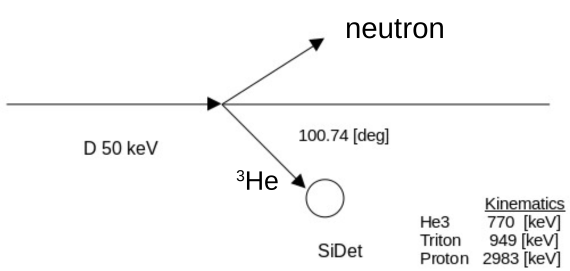


SiDet energy measured with pre-amp (timing) and amp (energy) outputs
Color Histogram: one run with SiDet trigger
Black dots: PSci-SiDet time coincidences in all runs with PSci trigger.



Home made Conical flange hosting the SiDet

1" PSci



Phase III

A model of (S1,S2) for Electrons and Argon recoils 1 [keV]-300 [keV]

$$\frac{S_1}{\epsilon_1} = \frac{E}{W} f_Q(E)\ (r(E)+f)\ f_V(E)$$

$$\frac{S_2}{\epsilon_2} = \frac{E}{W} (1-r(E))\ f_V(E)$$

Doc-DB 1841-v1

- **r(E)** : recombination probability
- **f_v** : visible energy. For ER f_v=1.
- **W** : average energy spent in an electron-ion pair.
- **f** : ratio of primary excitations to ionizations
- **(ϵ_1, ϵ_2)** : pe/photon , pe/extracted electron , that can be experimentally measured
- **f_q** : excimer quenching, not really clear if it is needed.

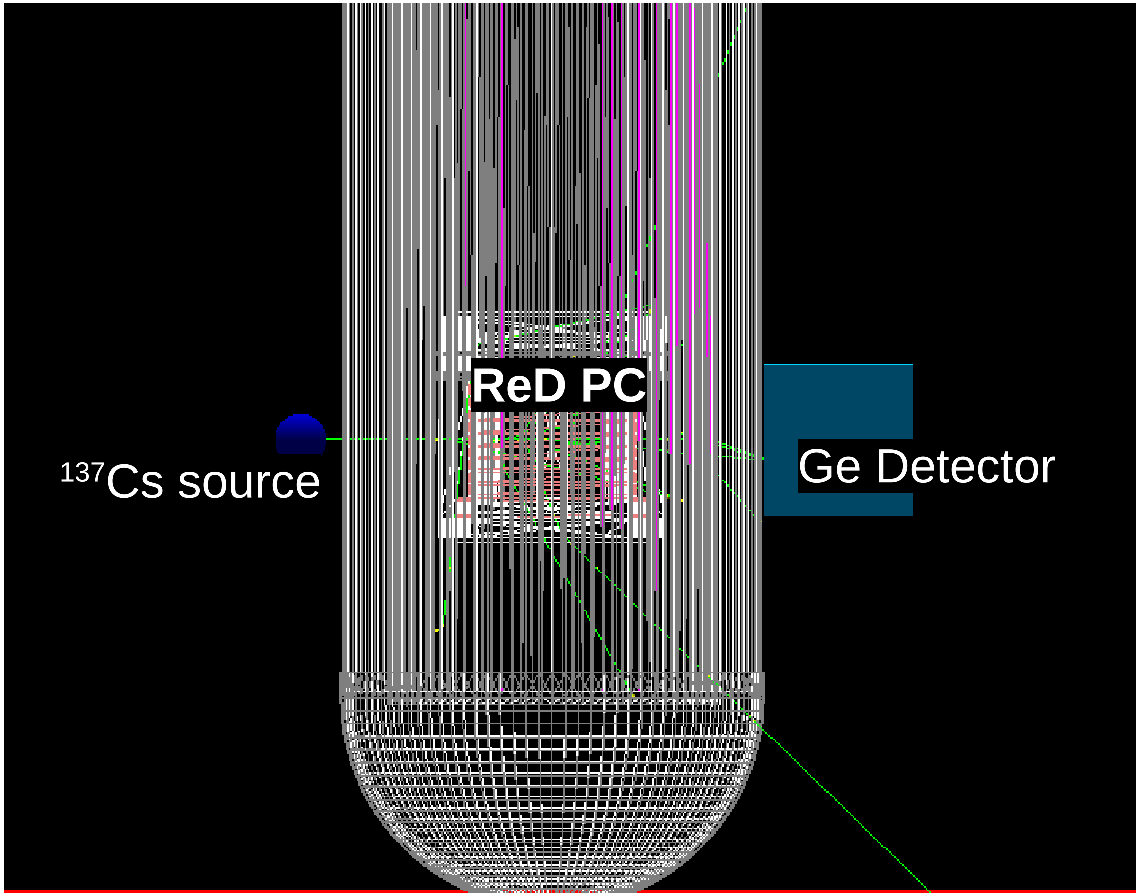
S1 from excitations

$e^- + R \rightarrow R^* + e^-$	*impact excitation*
$R^* + R \rightarrow R_2^{*,v}$	*excimer formation*
$R_2^{*,v} + R \rightarrow R_2^* + R$	*relaxation*
$R_2^* \rightarrow R + R + h\nu$	*VUV emission*

S1 from recombined electrons

$e^- + R \rightarrow R^+ + 2e^-$	*ionization*
$R^+ + R + R \rightarrow R_2^+ + R$	
$e^- + R_2^+ \rightarrow R^{**} + R$	*recombination*
$R^{**} + R \rightarrow R^* + R + \text{heat}$	
$R^* + R + R \rightarrow R_2^* + R + \text{heat}$	
$R_2^* \rightarrow R + R + h\nu$	*VUV emission*

Compton Electrons from a ^{137}Cs source



Trigger in coincidence
TPC+Ge

Use a source with known energy
^{137}Cs 662 keV

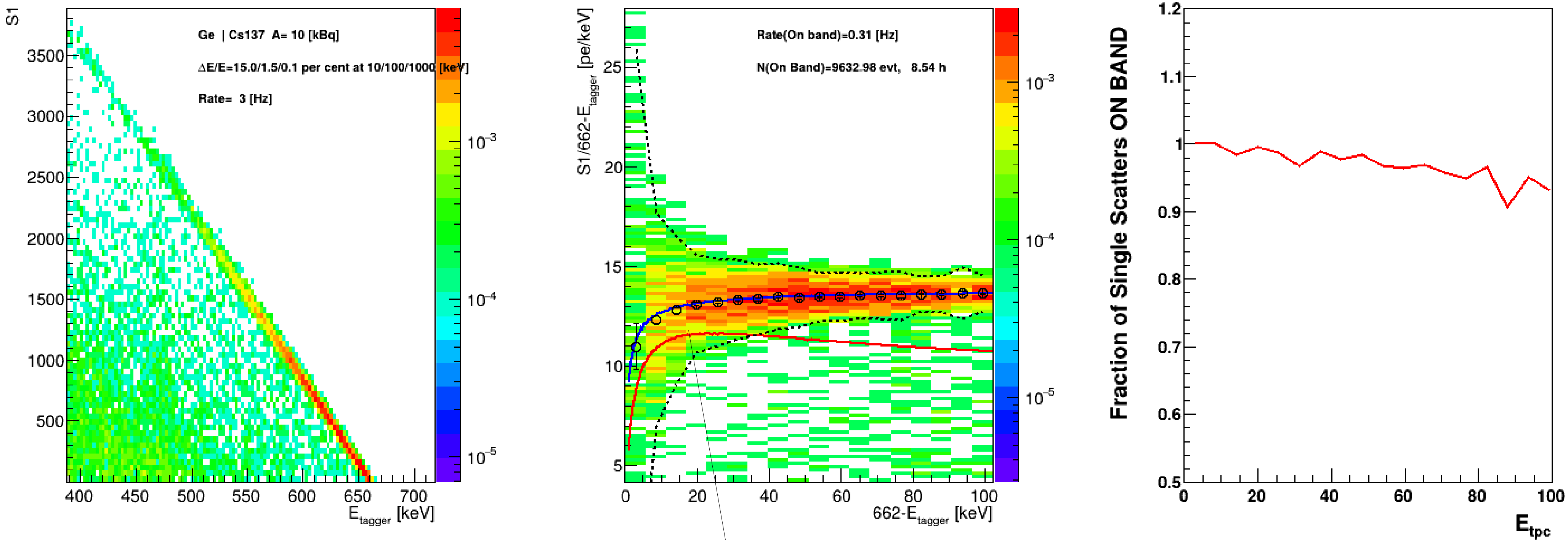
So, E_{tpc} = 662 [keV] - $E_{germanium}$

Procedure already used for calibration of the ER quenching of the PSci.
Energy resolution of Ge detector is fundamental.

For a ^{137}Cs source 10 [kBq]   (100 [Hz] in TPC)

A Ge detector with 0.2% FWHM at 662 keV

0.3 [Hz] of electron recoils tagged with true energy reconstructed with ~1 keV accuracy



200 V/cm Field Model
Null Field Model

~95% Single Scatters

It is better for 200 V/cm since we can distinguish SS/MS with tdrift