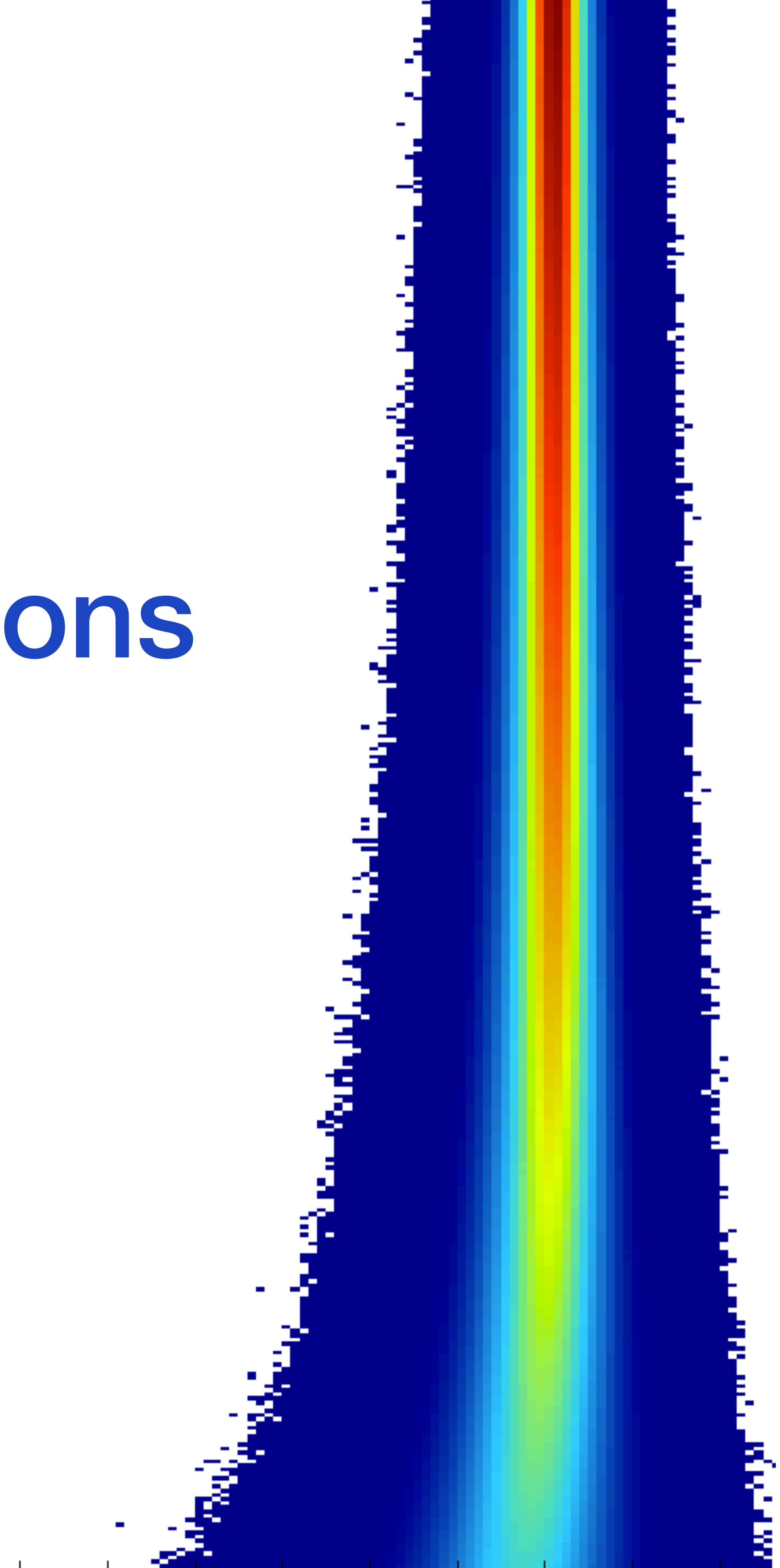
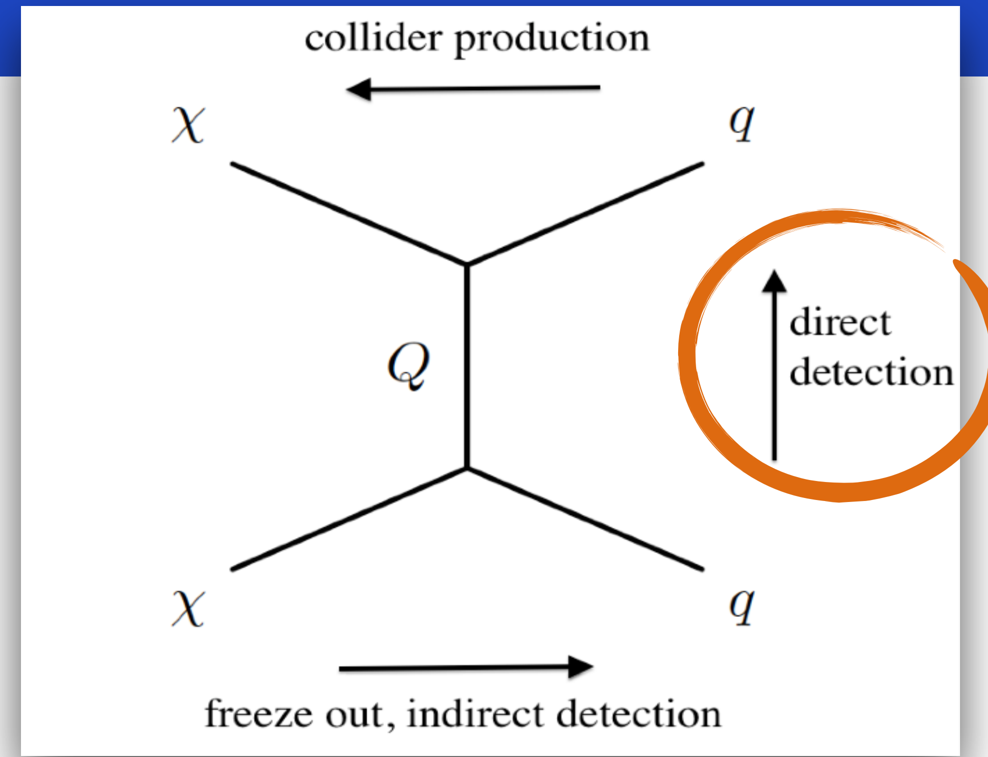
Monte Carlo Simulations in DarkSide

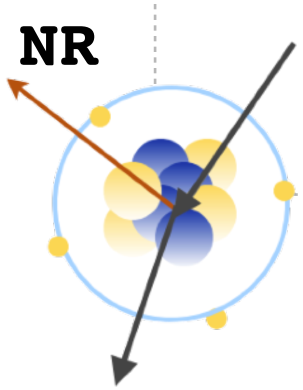
Paolo Agnes
University of Houston

18th April 2018
MC4BSM, IPPP Durham

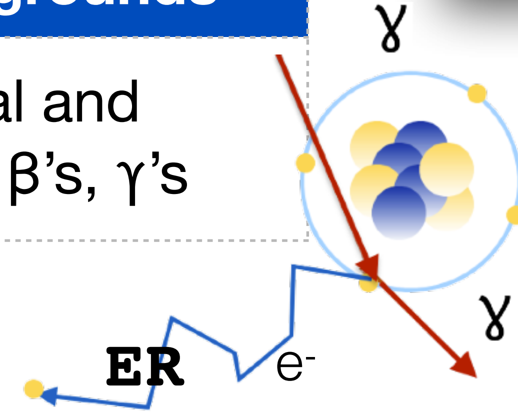




DarkSide: **dual-phase, liquid argon TPC**
for the direct detection of WIMPs



NR signal: ~ 10 keV, ~ 1 ev/t/yr	
NR backgrounds	**ER backgrounds**
neutrons α's	internal and external β's, γ's



Noble liquids are suitable targets:

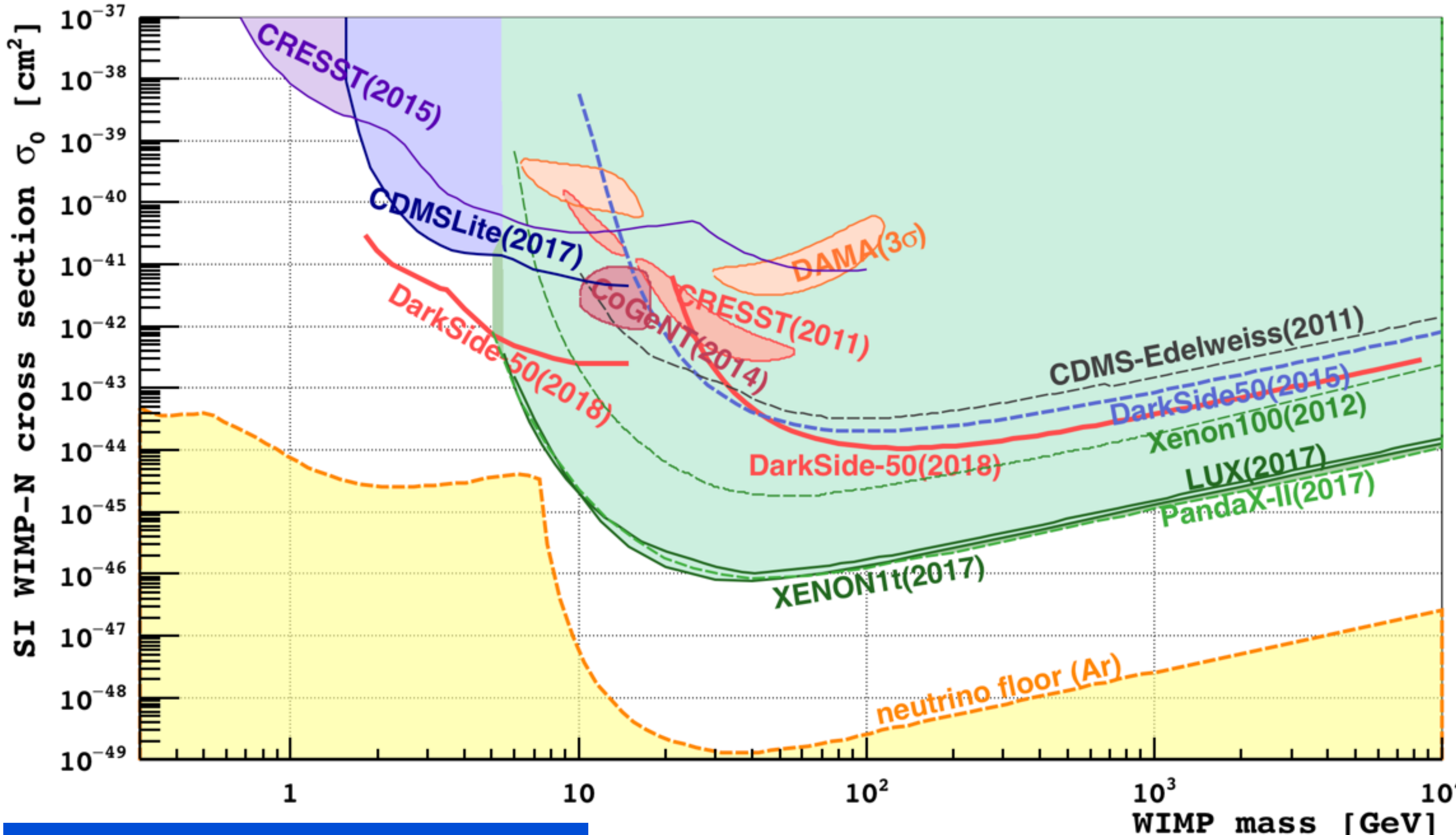
- ☑ dense, inexpensive, easy to purify
- ☑ large ionization/scintillation yields (W~10 eV)
- ☑ ER recoil background discrimination: **10^8 in LAr thanks to Pulse Shape Discrimination (PSD)**

The problem of liquid argon is ^{39}Ar **(1 Bq/kg) in atmospheric argon (AAr)**. Cosmogenically produced, Q = 565 keV, $t_{1/2}$ = 269 yr.

==> **Argon from underground** is depleted!

Direct Detection of dark matter (SI)

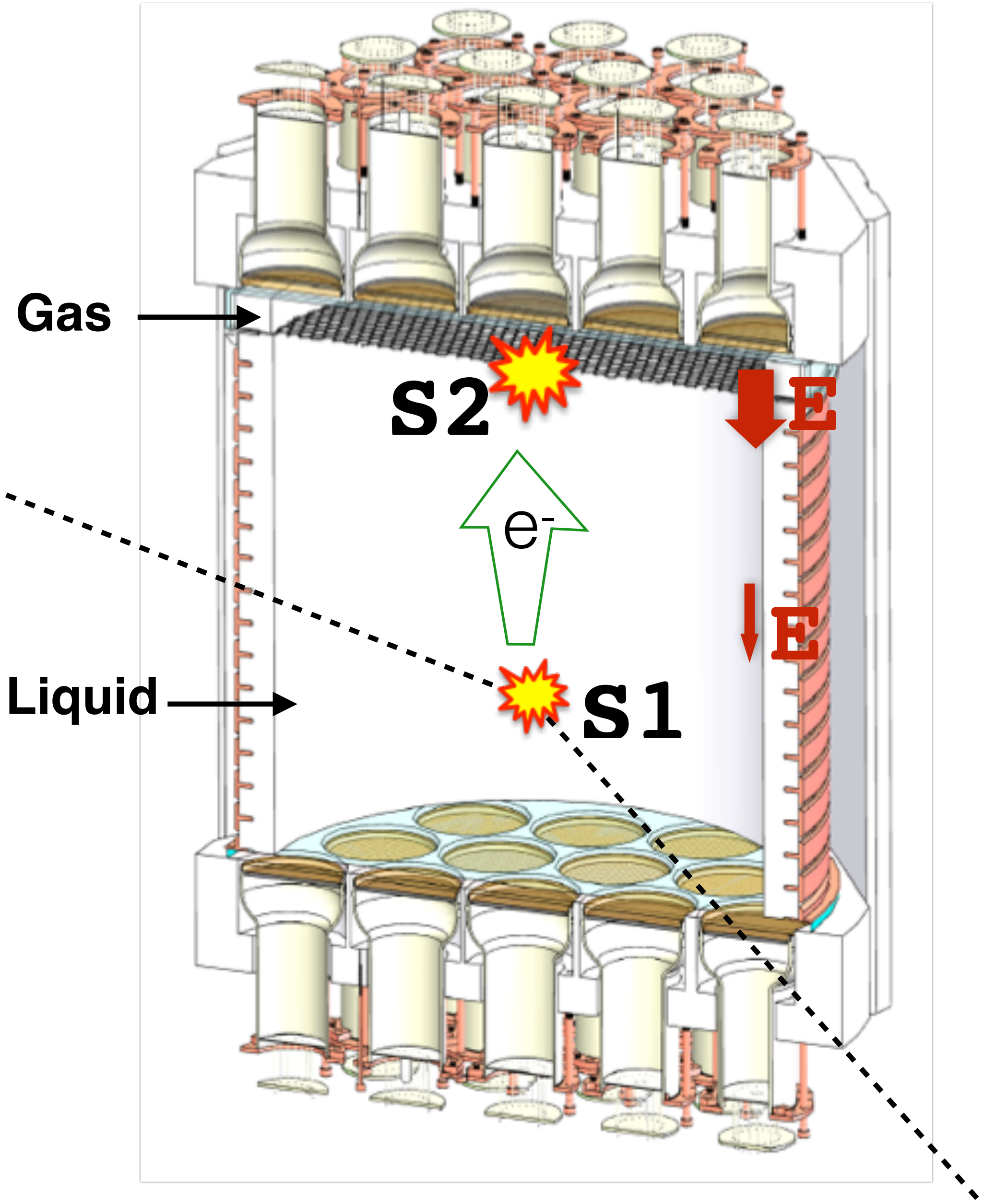
DarkSide is a dual-phase TPC for the direct detection of dark matter in the form of WIMPs

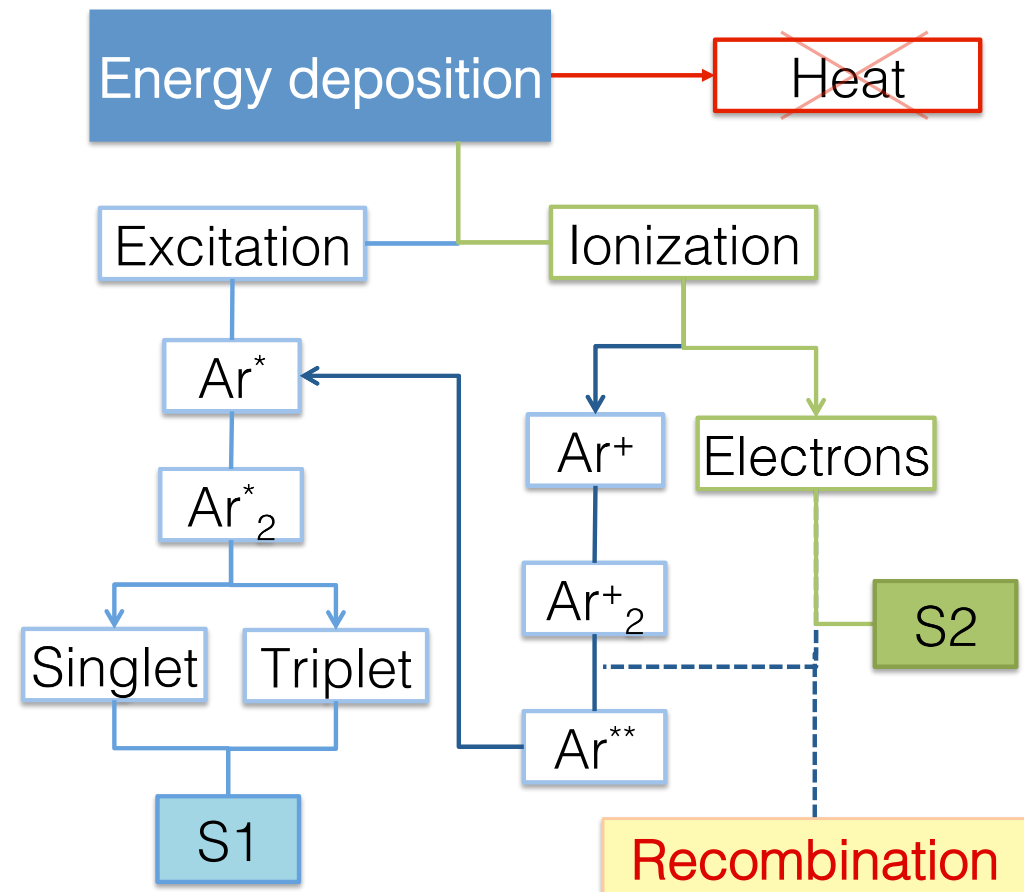


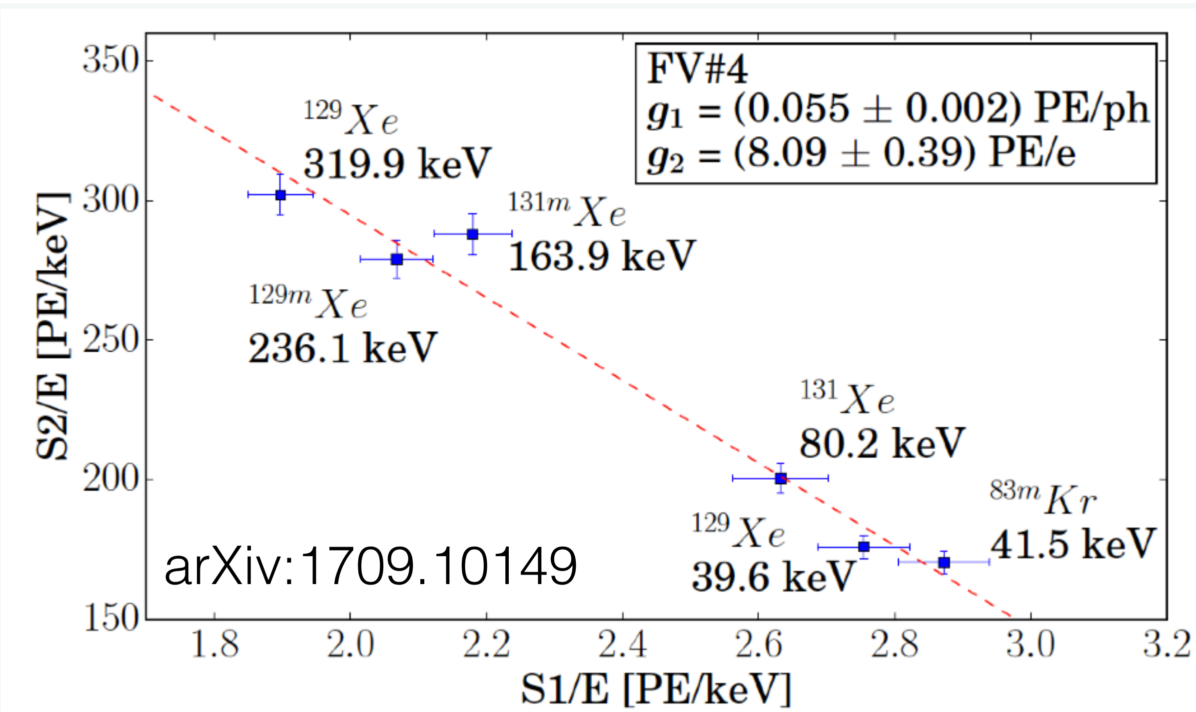
Potential of LAr in low-mass WIMP

Noble liquids will dominate in the high-mass WIMP region

Dual-phase TPC

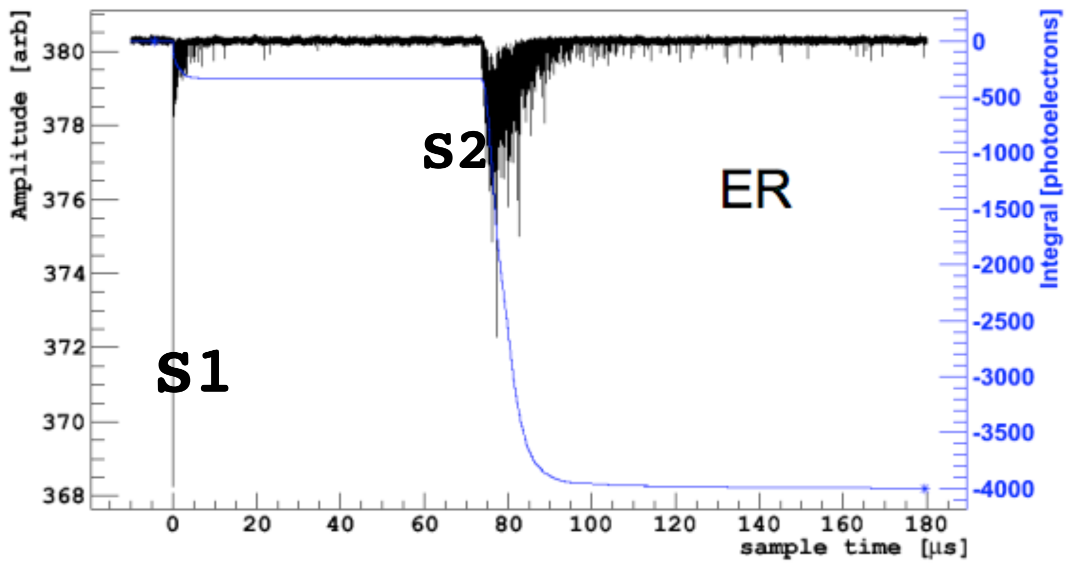


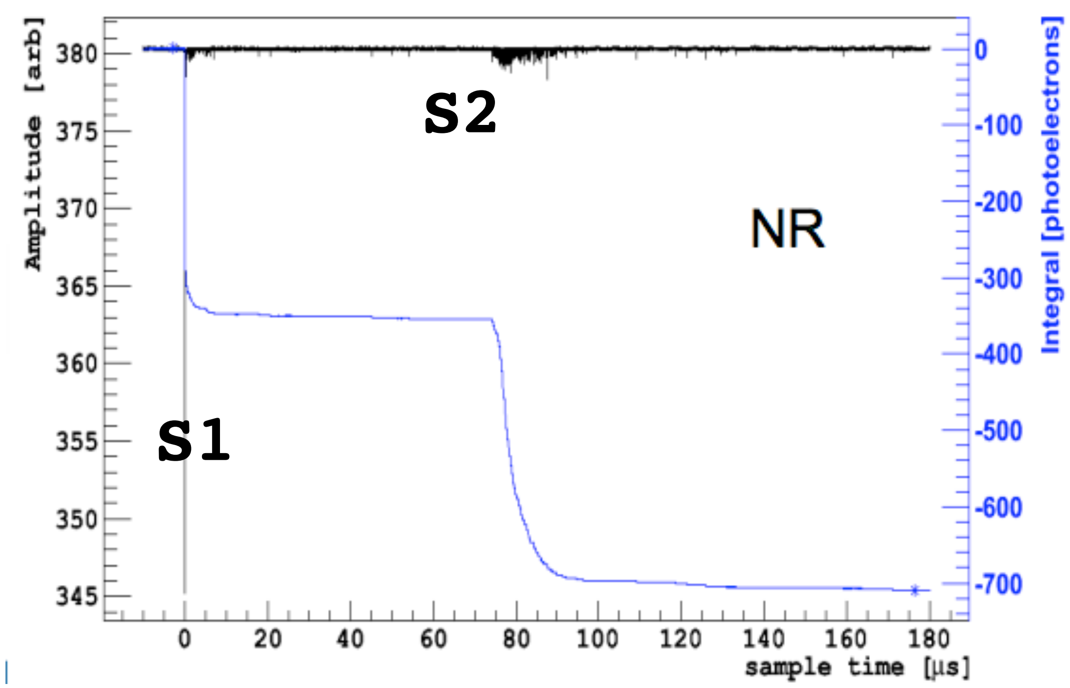


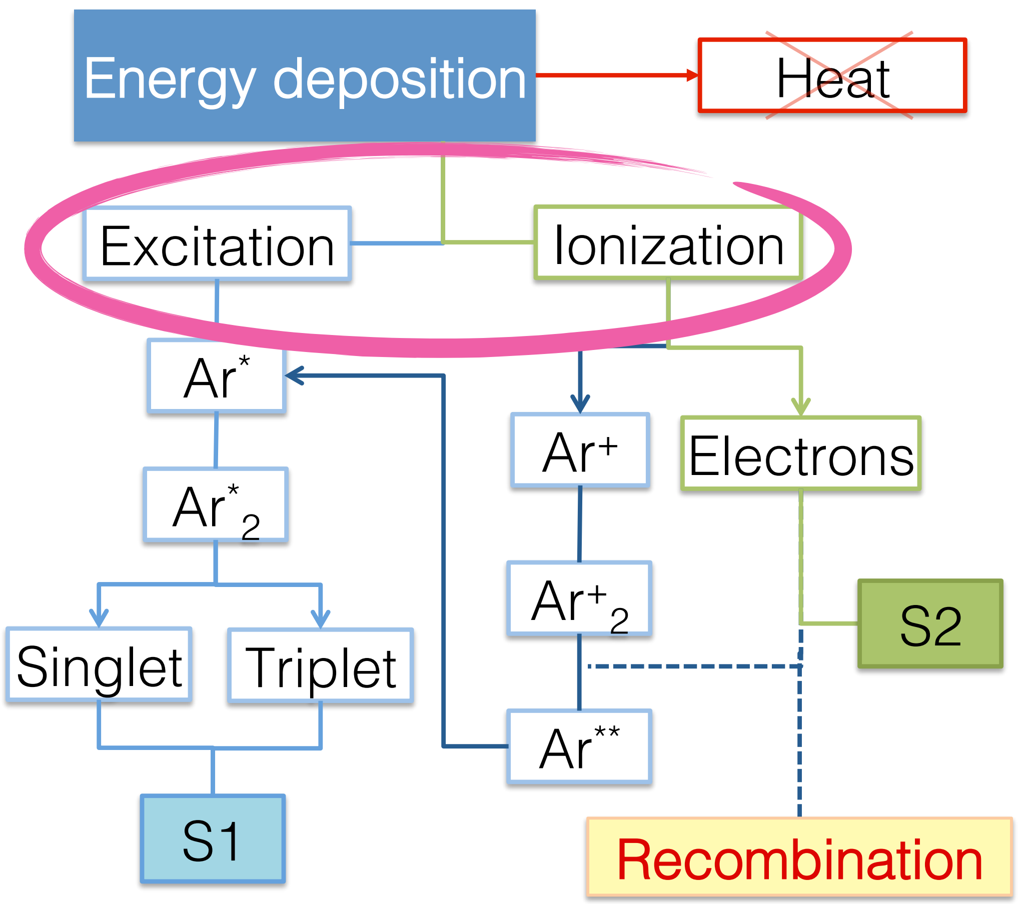


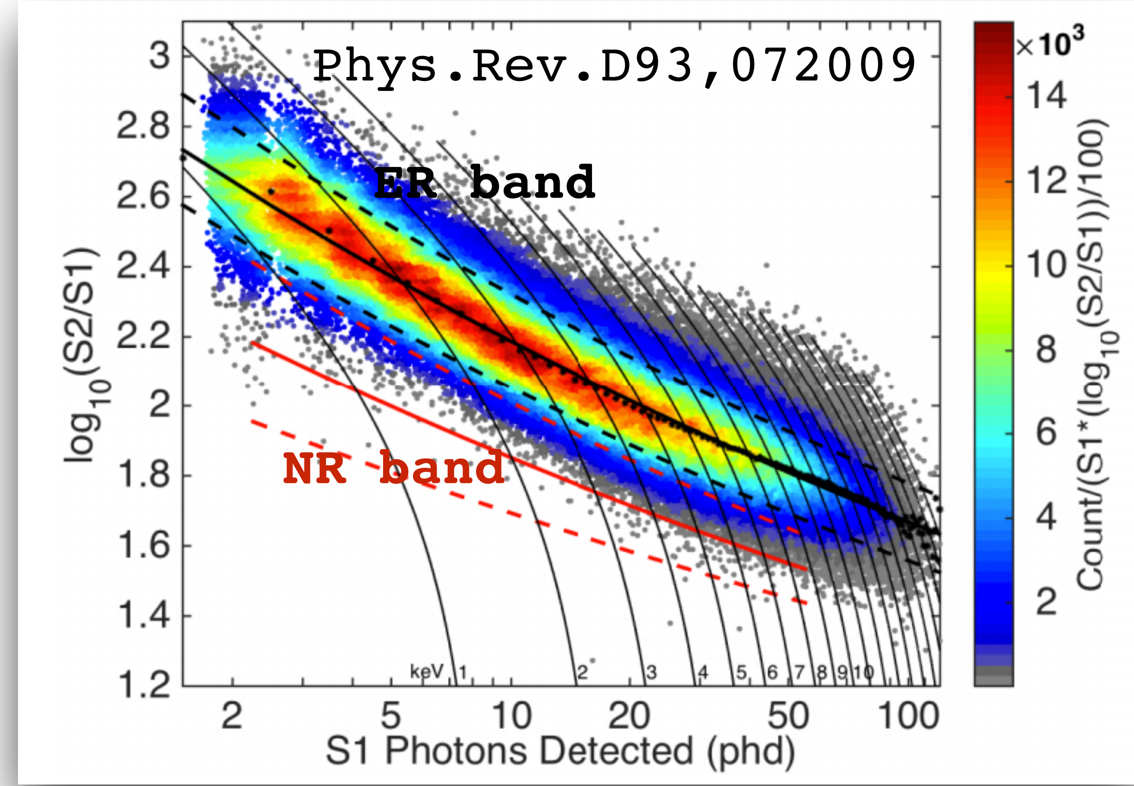
All the excitons produce **scintillation** (S1)
S2 proportional to number of **ionisation** e-
Recombined electron-ion pair contribute to S1

Rejection by Ionization/Scintillation





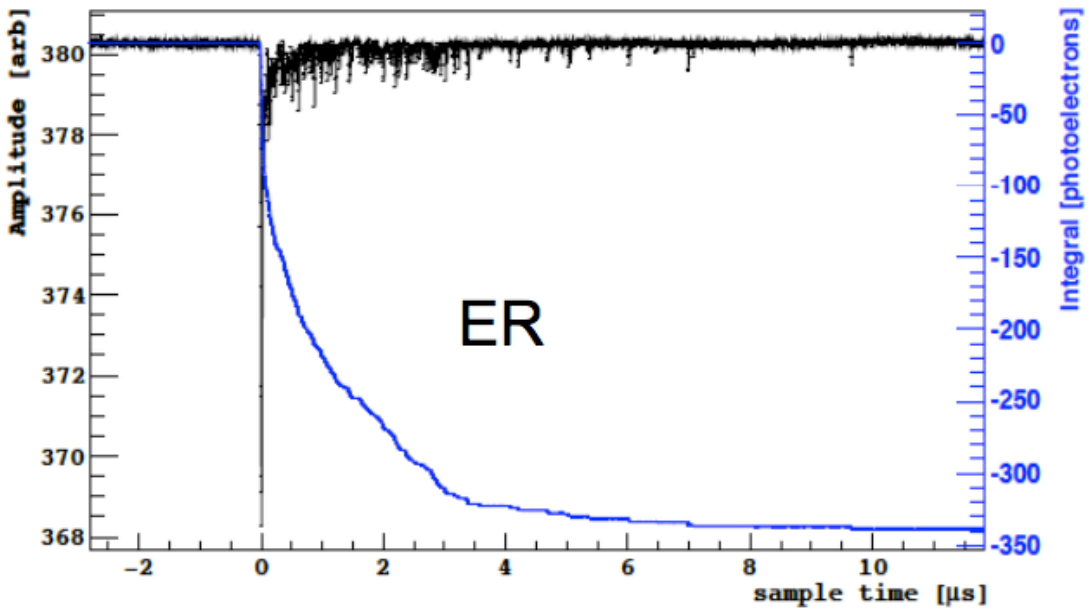


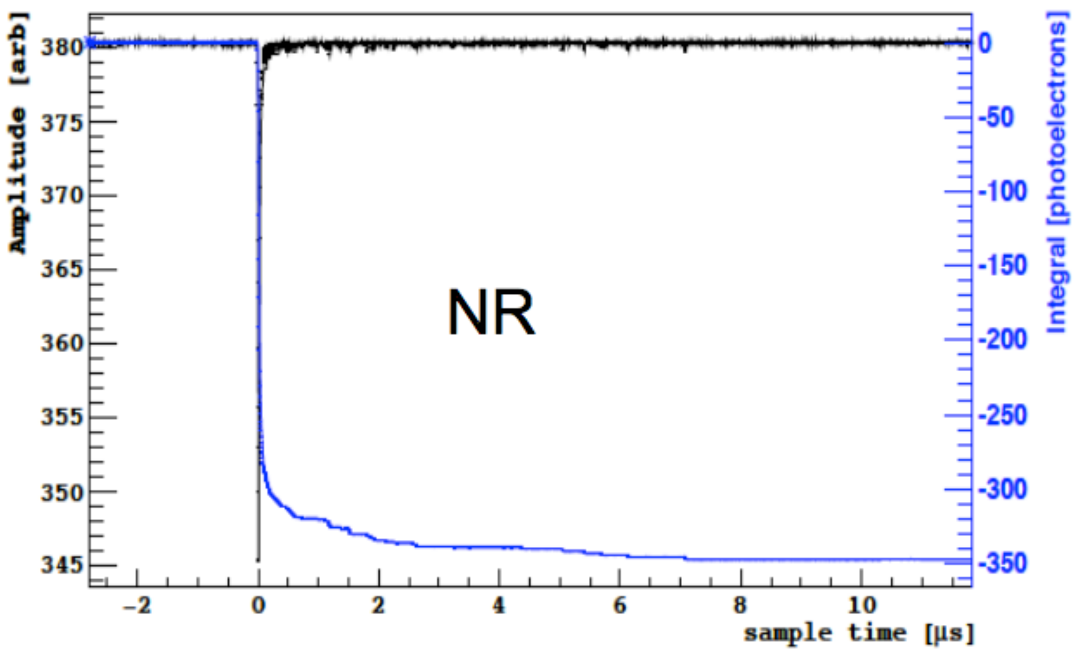


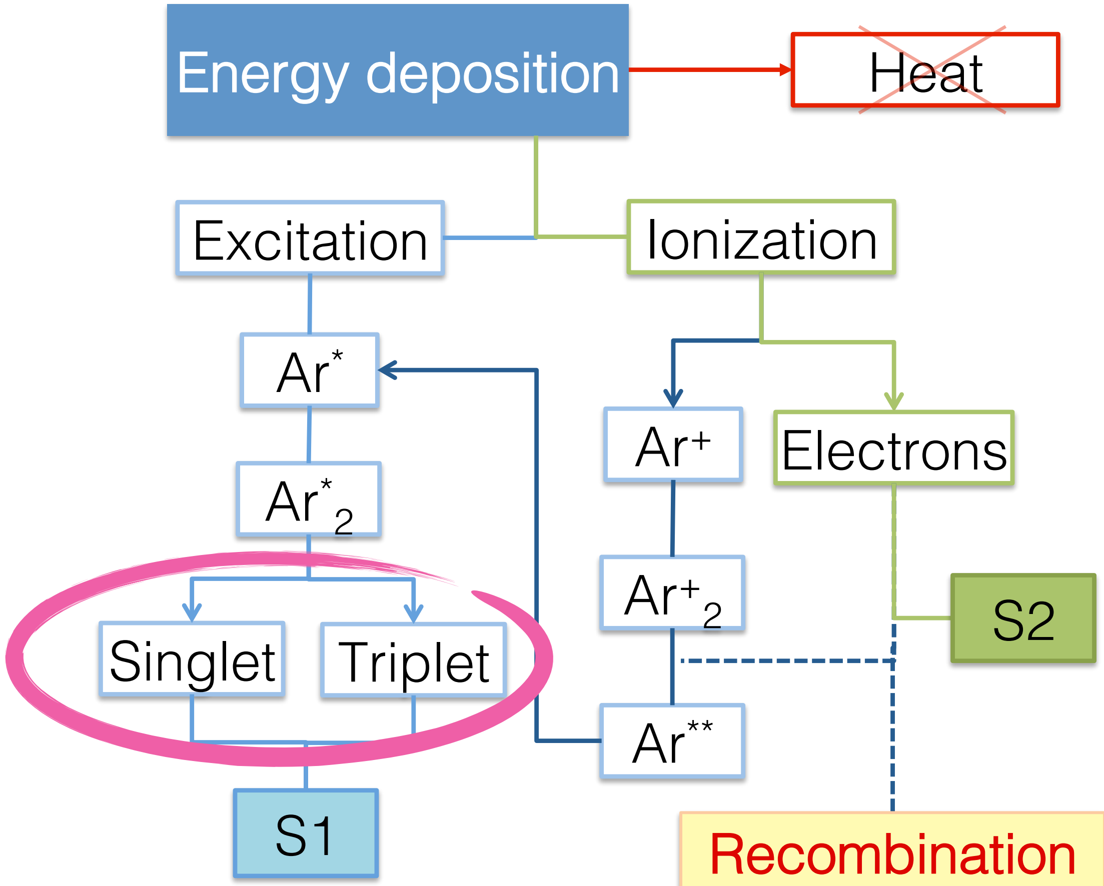
ER Rejection factor: 10^2 - 10^3

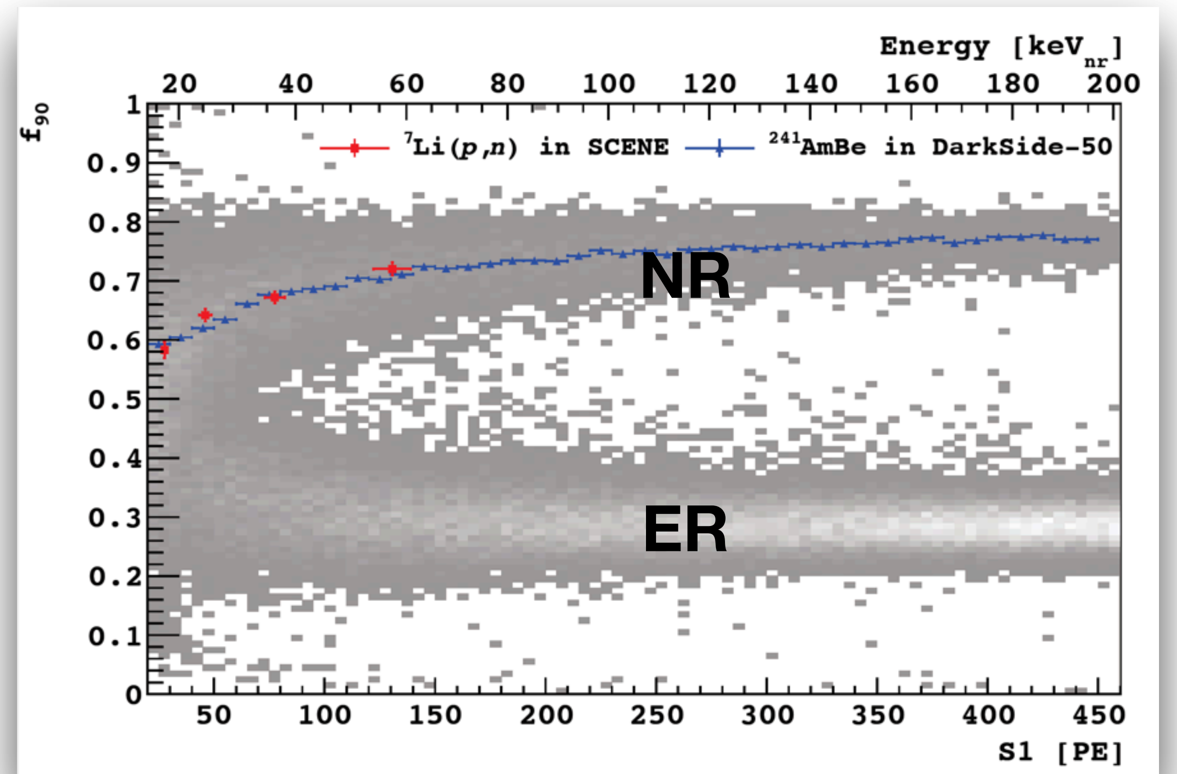
Benetti et al. (ICARUS) 1993;
Benetti et al. (WARP) 2006

Rejection with Pulse Shape Discrimination









ER Rejection factor: ~ 10^8 in LAr

τ_{fast} ~ 6 ns, τ_{slow} ~ 1.6 μs

The DarkSide experiment

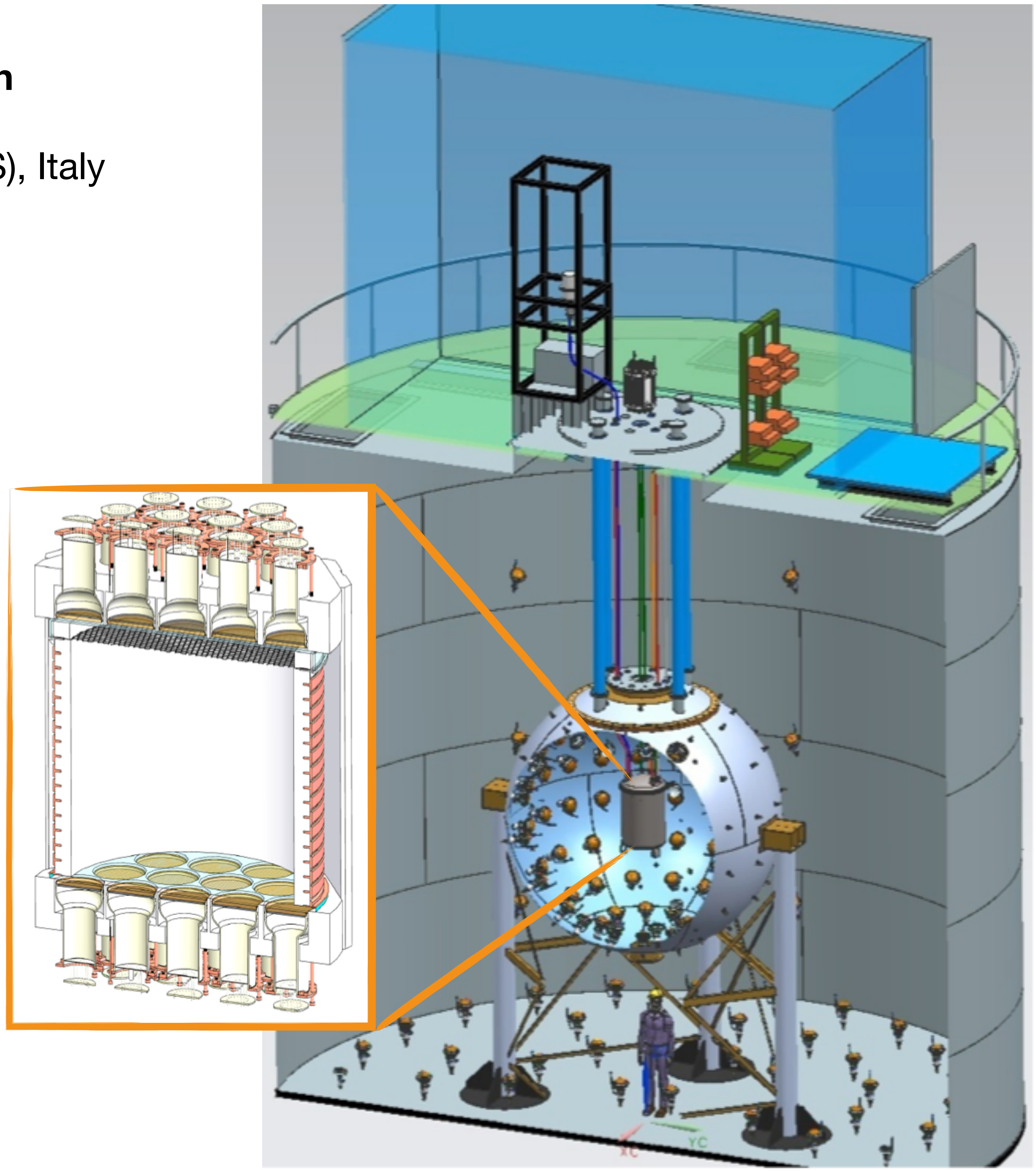
Main goal: a background free WIMP search

At *Laboratori Nazionali del Gran Sasso* (LNGS), Italy
Currently running: **DarkSide-50 (2013-2018)**

Liquid argon TPC
- **50 kg LAr (36.9 kg fiducial mass)**
- **19 + 19 3” PMTs**
- Reflectors and TPB coating

Liquid Scintillator Veto (LSV)
- 30 tons, 2 m radius
- 110 PMTs (LY = 0.5 pe/keV)

Water Cherenkov Detector (WCD)
- 1 kt water, 5.5 m radius
- 80 PMTs



Veto efficiency (99.6%) demonstrated
with AmC/AmBe calibrations

Simulations in DarkSide

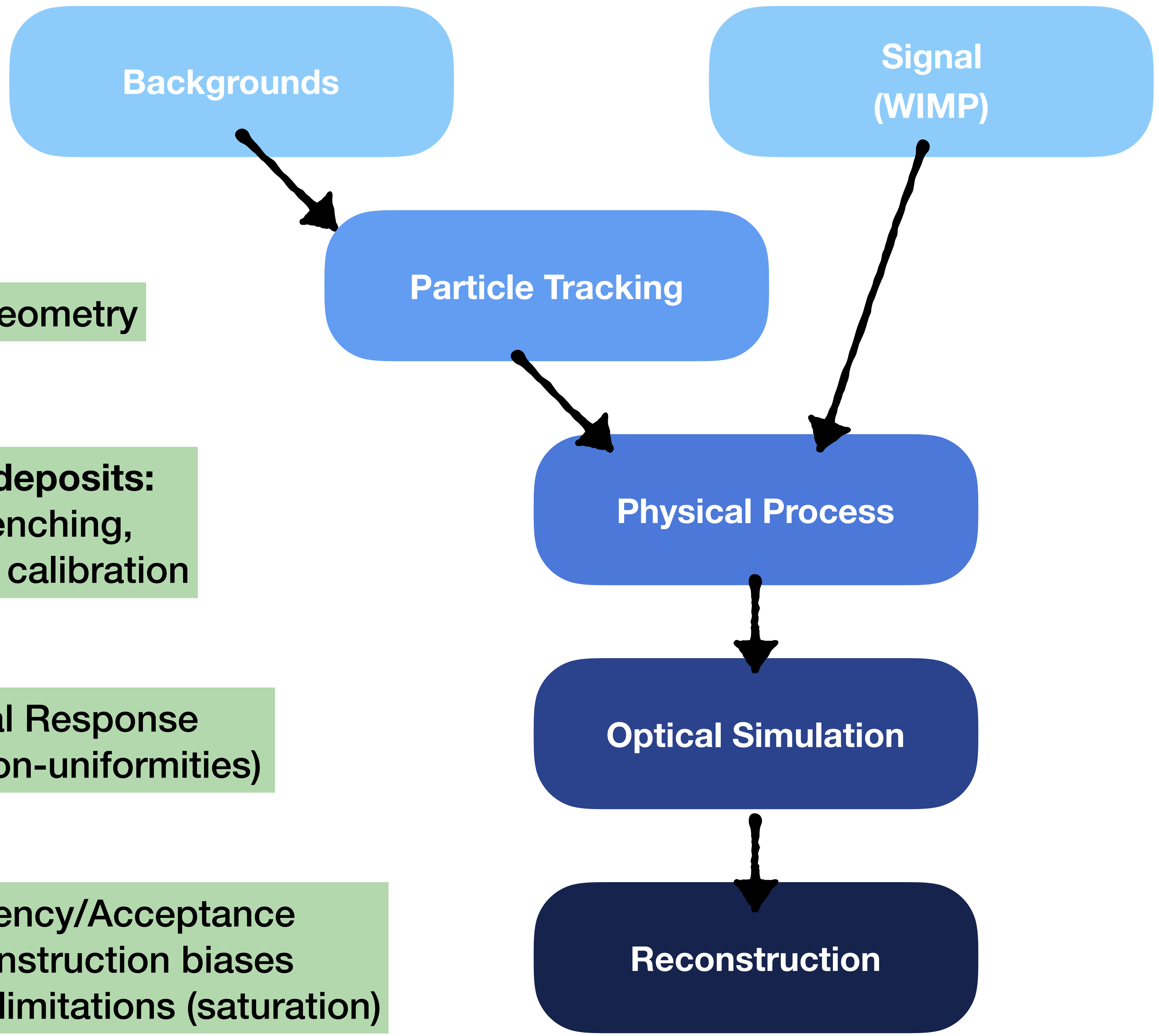
α, β, γ
neutrons

Detailed geometry

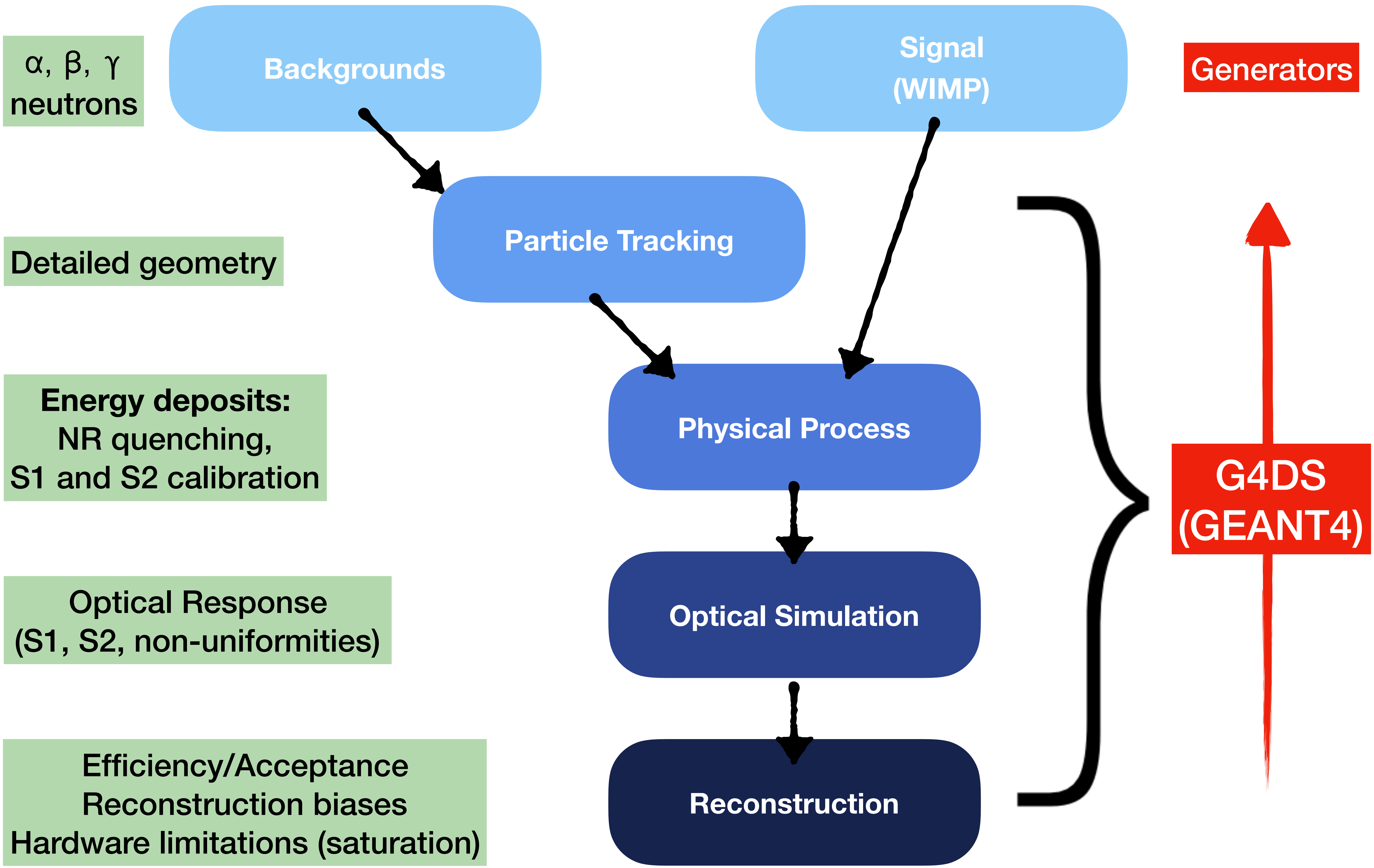
Energy deposits:
NR quenching,
S1 and S2 calibration

Optical Response
(S1, S2, non-uniformities)

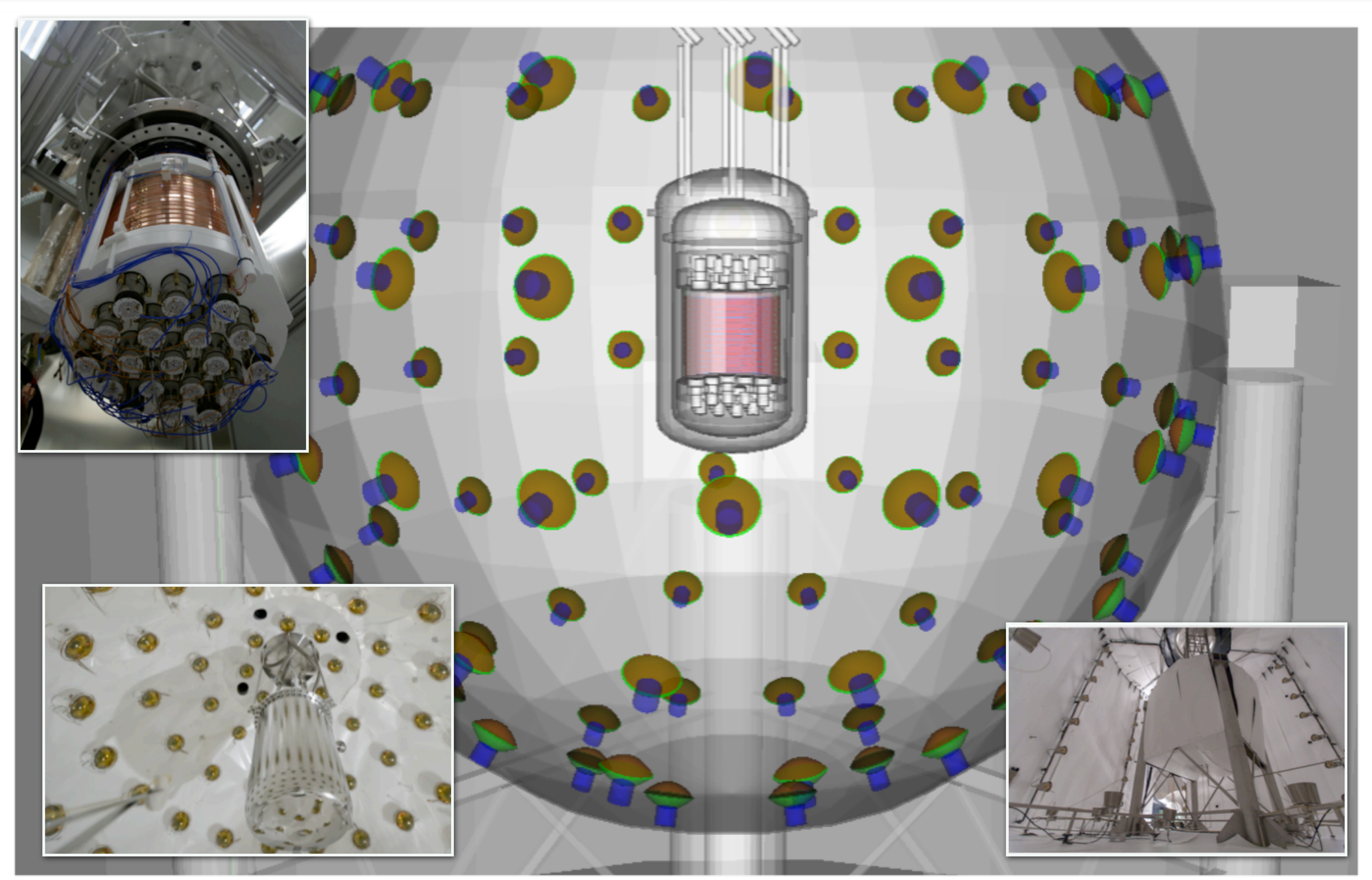
Efficiency/Acceptance
Reconstruction biases
Hardware limitations (saturation)



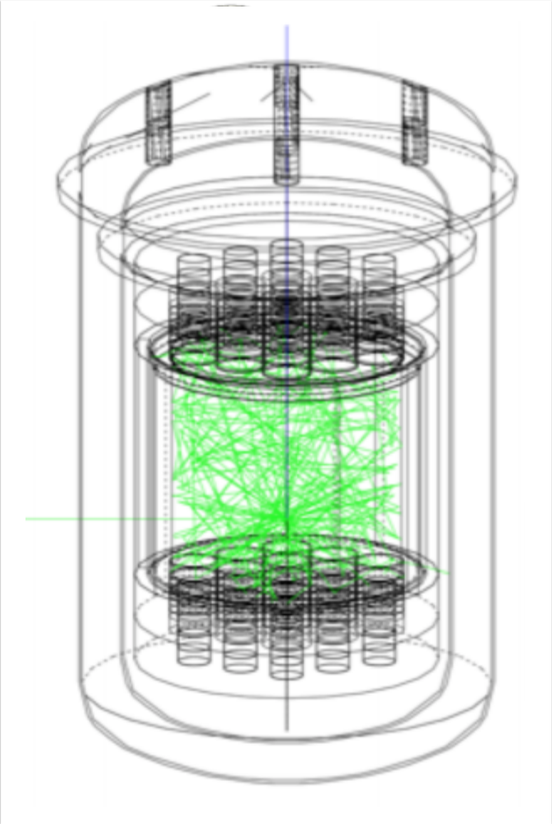
Simulations in DarkSide



G4DS, the DarkSide simulation tool



Optical tuning

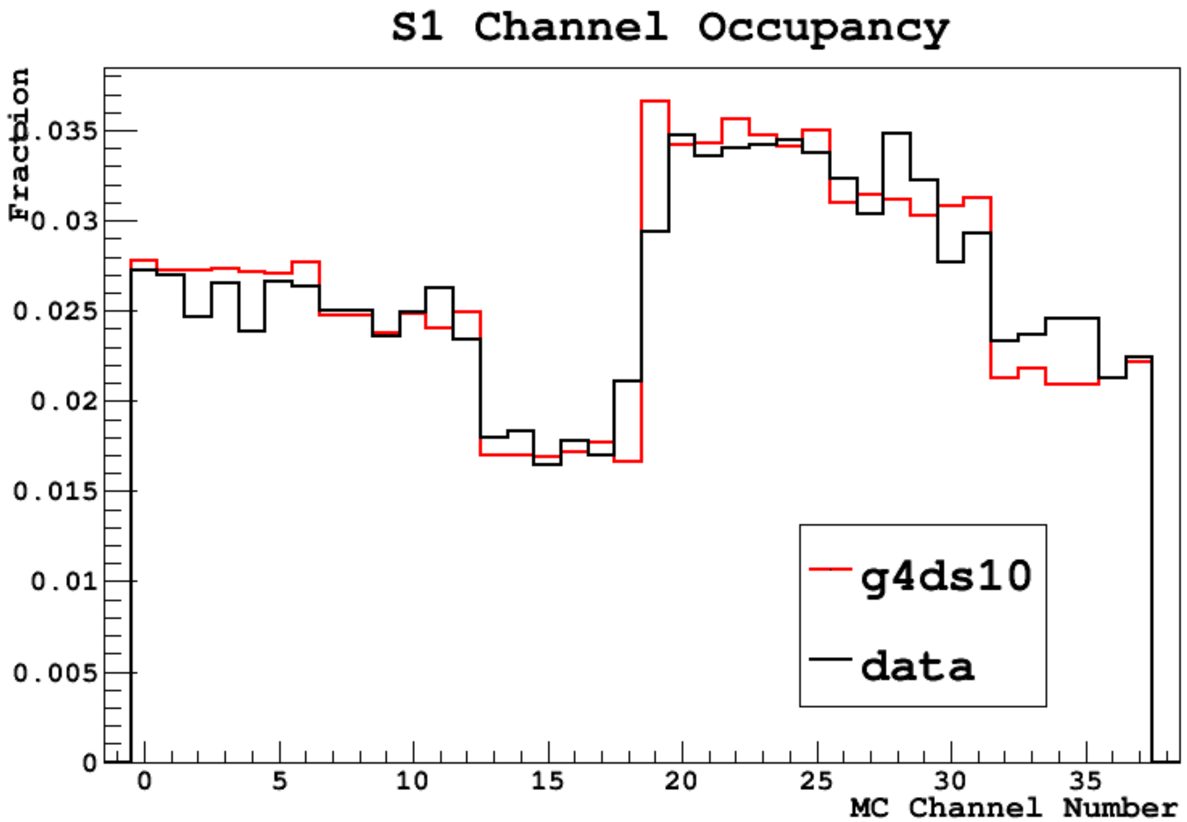


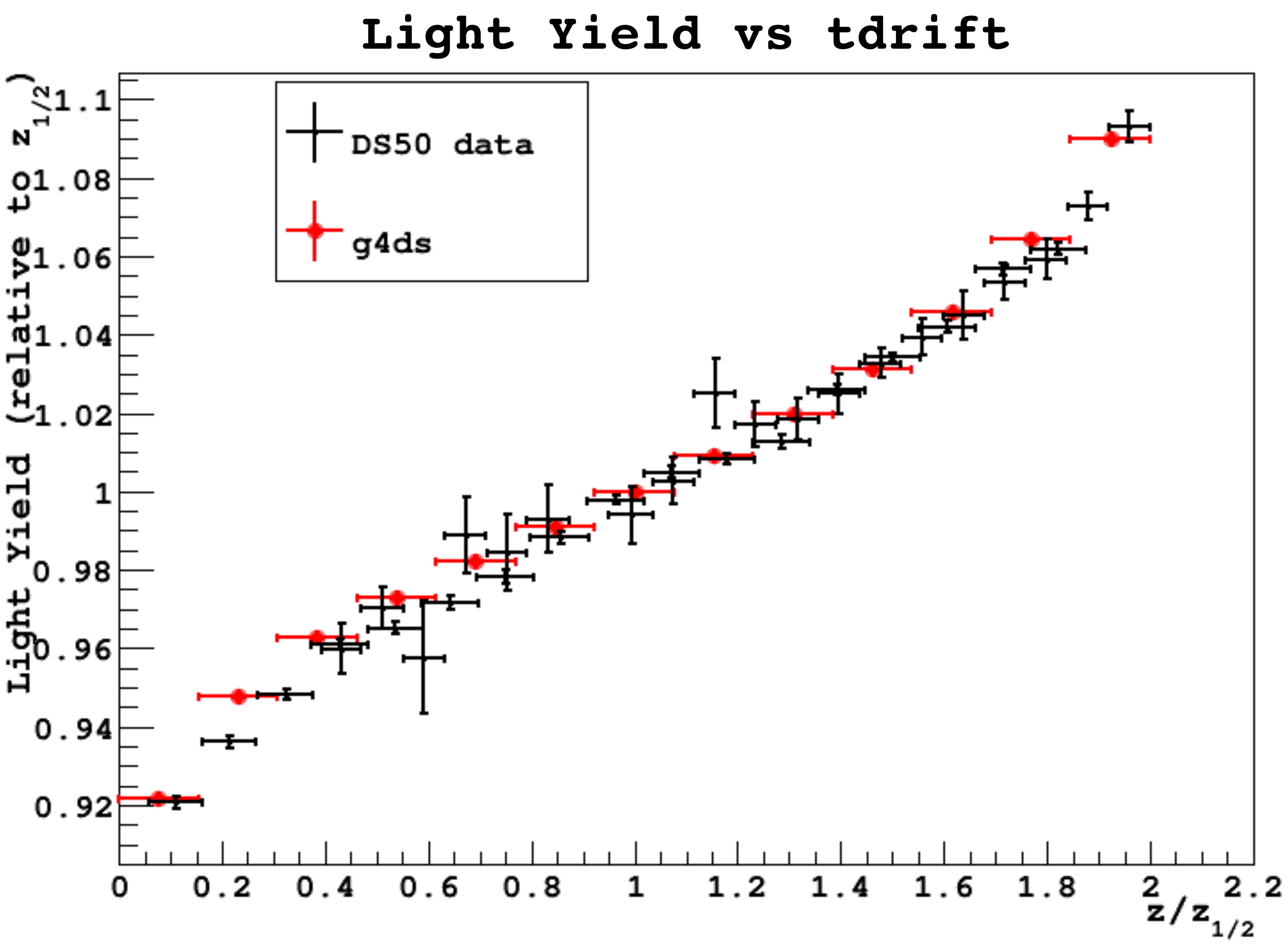
38 PMTs (3 inches) two arrays

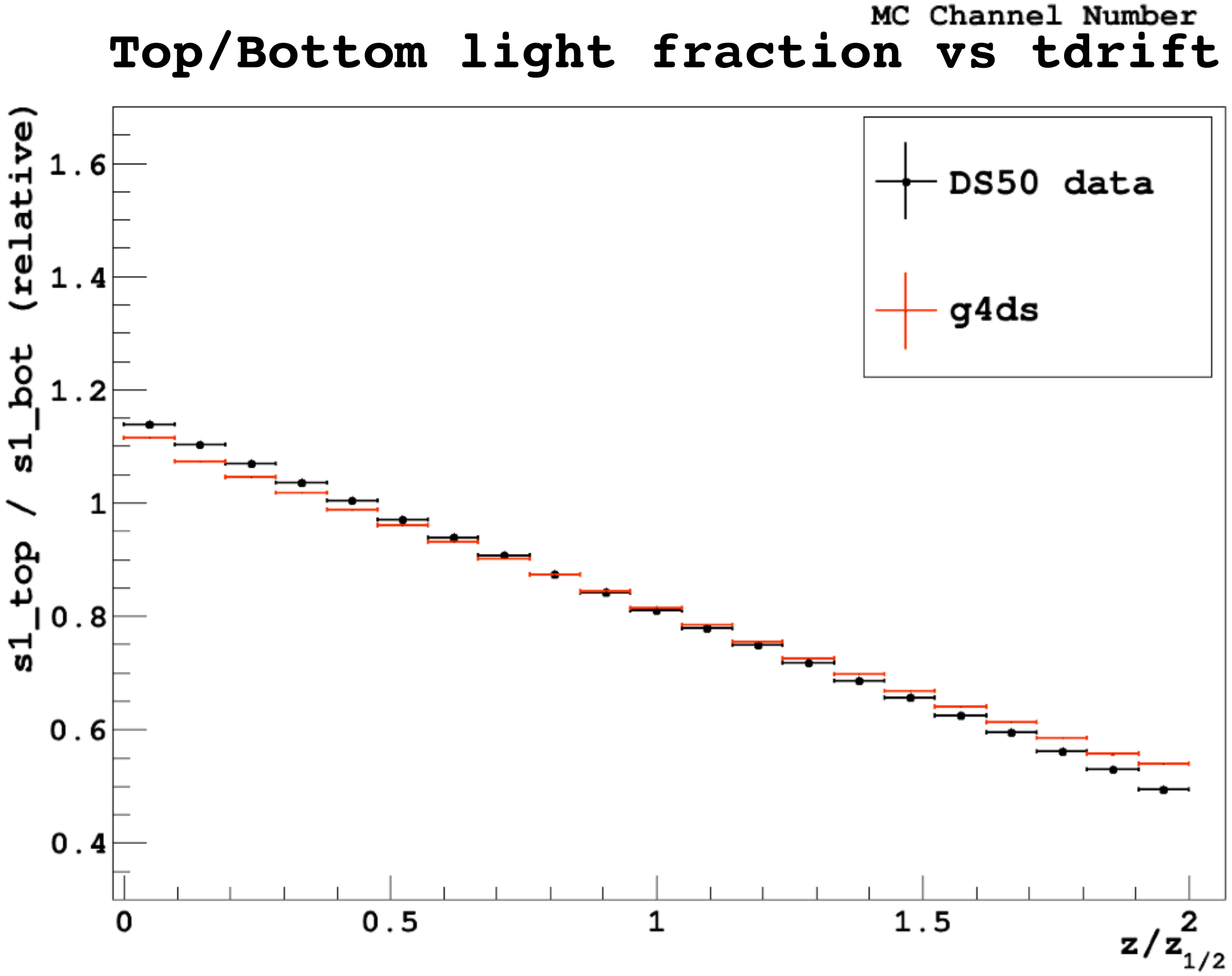
1. Select relative quantities

2. Tuning of ~30 optical parameters

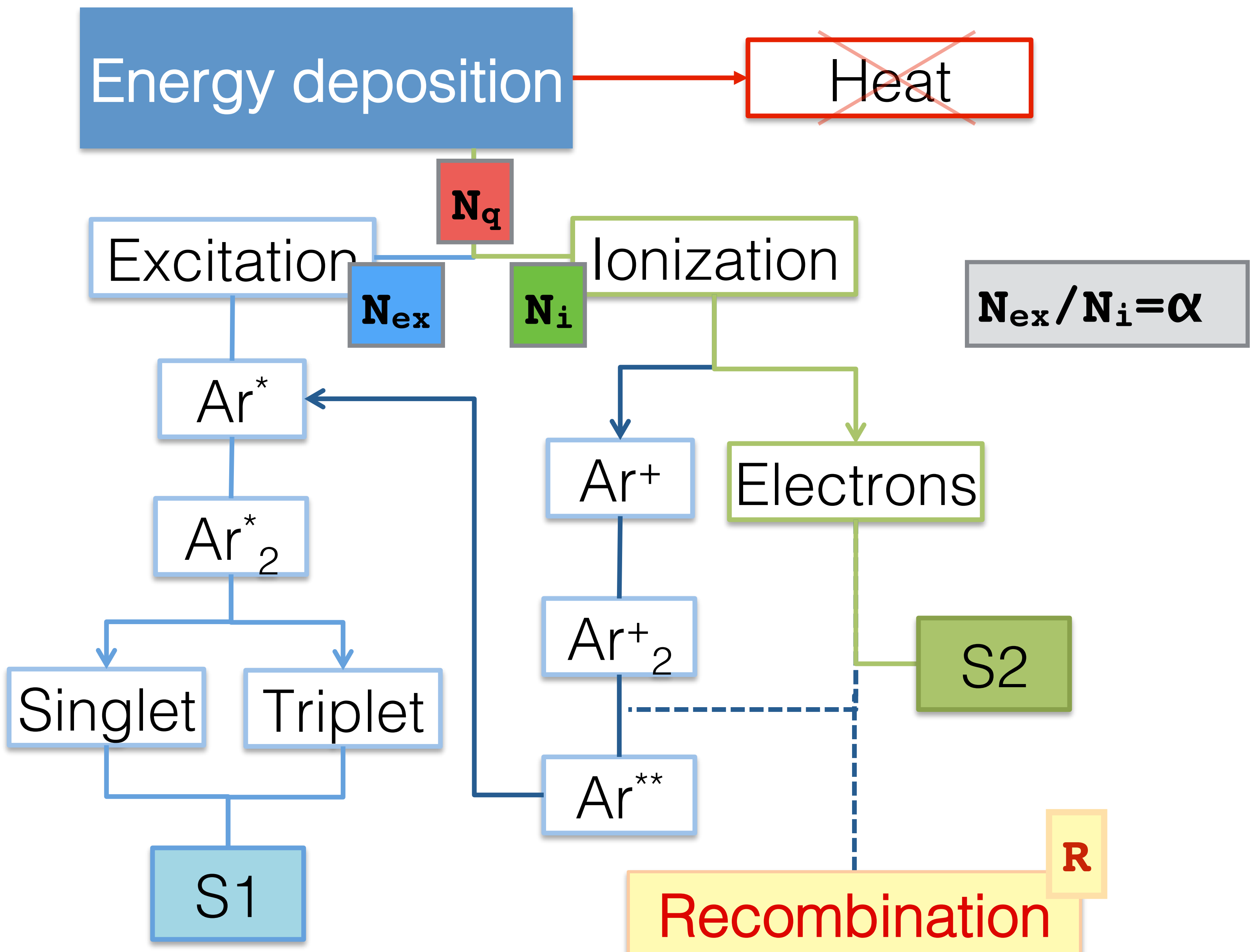
(Ref index, Abs length, WLS…)







Energy scale calibration



$$N_q = E / W$$
$$N_i = N_q / (1+\alpha)$$
$$N_{ex} = N_q - N_i$$

$$N_q^{S1} = N_{ex} + \mathbf{R}N_i$$
$$N_q^{S2} = N_i(1 - \mathbf{R})$$

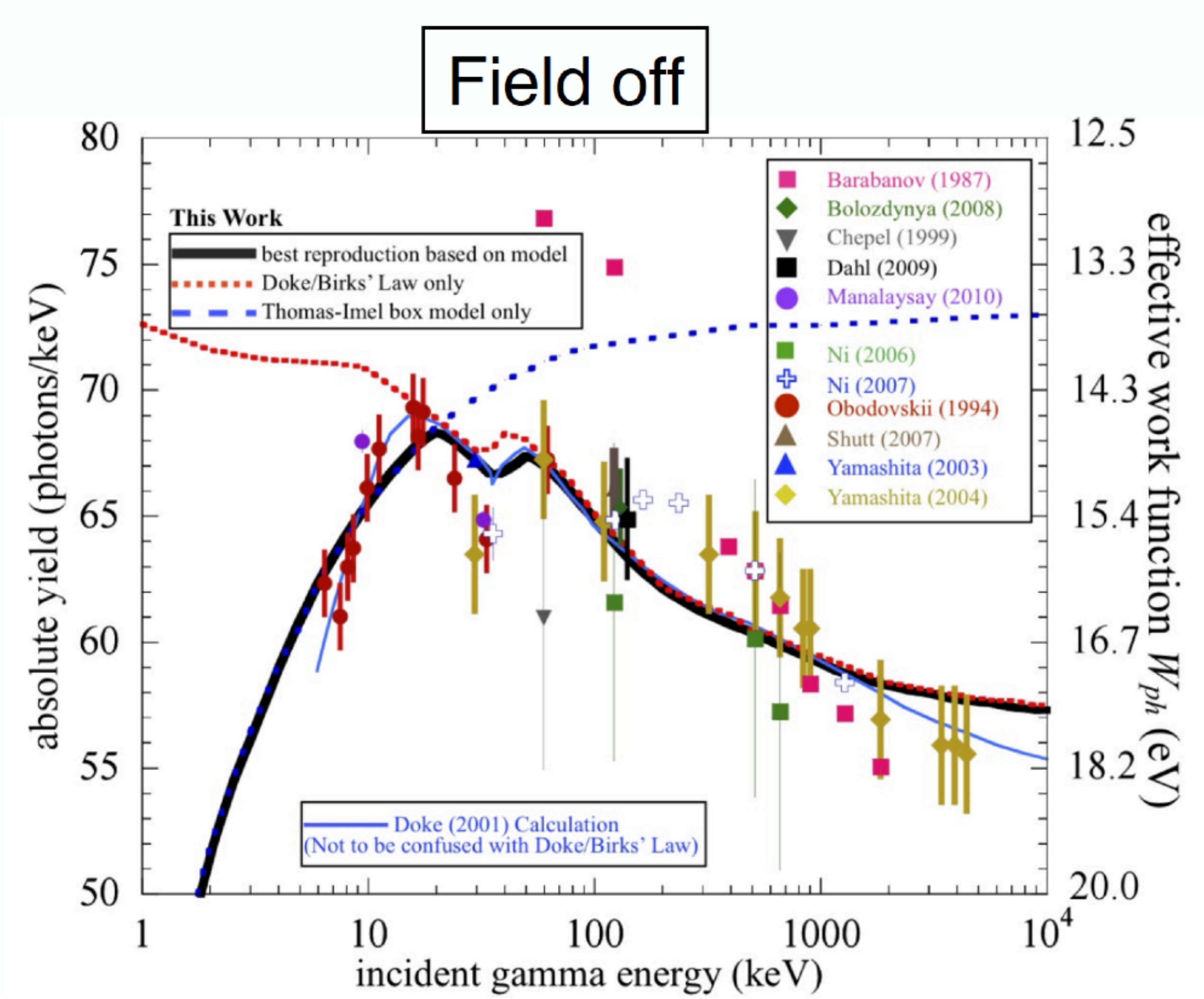
$$S1 = Y_{S1} \; N_q^{S1}$$
$$S2 = Y_{S2} \; N_q^{S2}$$

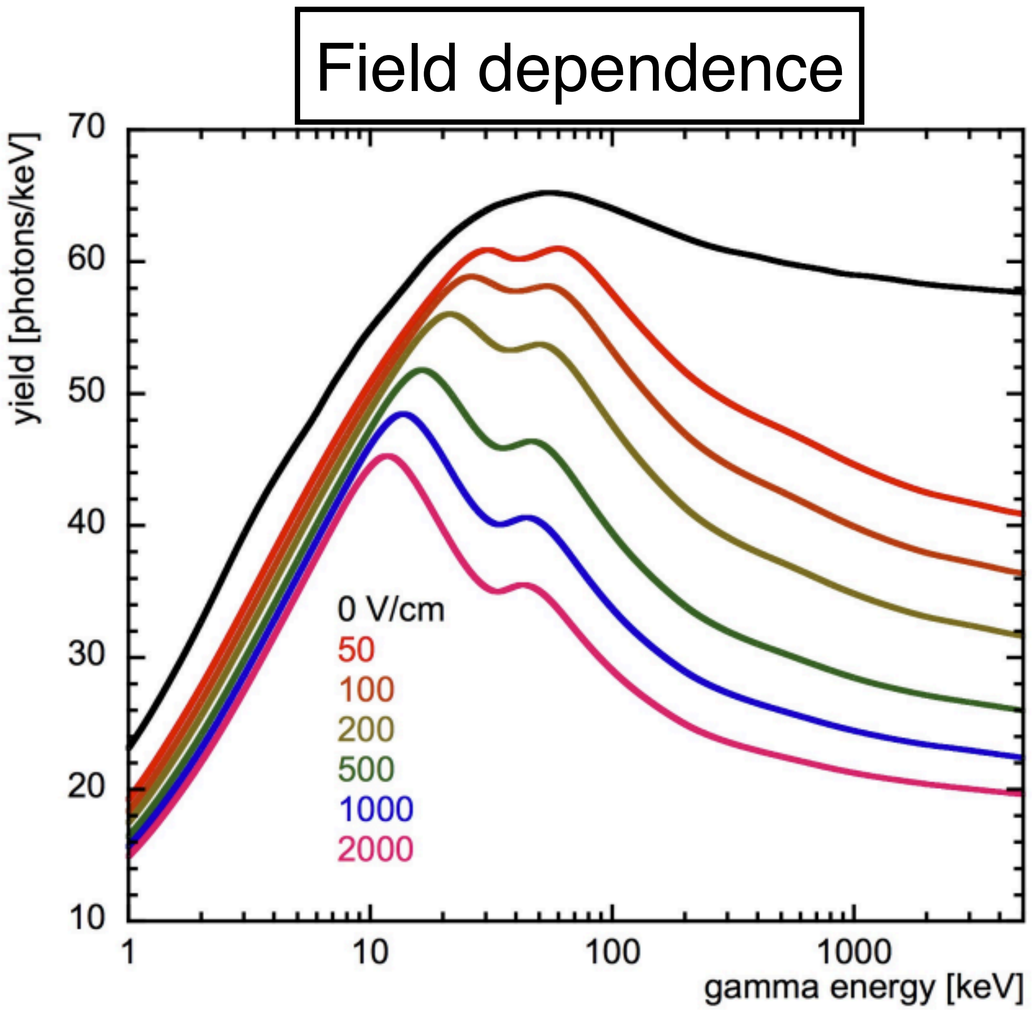
The goal is to model **R**
(the recombination probability)
as a function of the **recoil energy** and **drift field**

Assumptions (ER):
$W = 19.5$ [eV]
$\alpha = 0.21$ (ER)
Constant Y_{S1} and Y_{S2}
(independent on E, field)
For NR:
$\alpha = 1.00$?

In Xenon (NEST)

Doke-Birks and Thomas-Imel joined model, fit parameters to abundant datasets.





Scintillation yield is not constant at null field due to electrons escaping recombination (or running work function).

Less data available for Argon, this approach is not working.

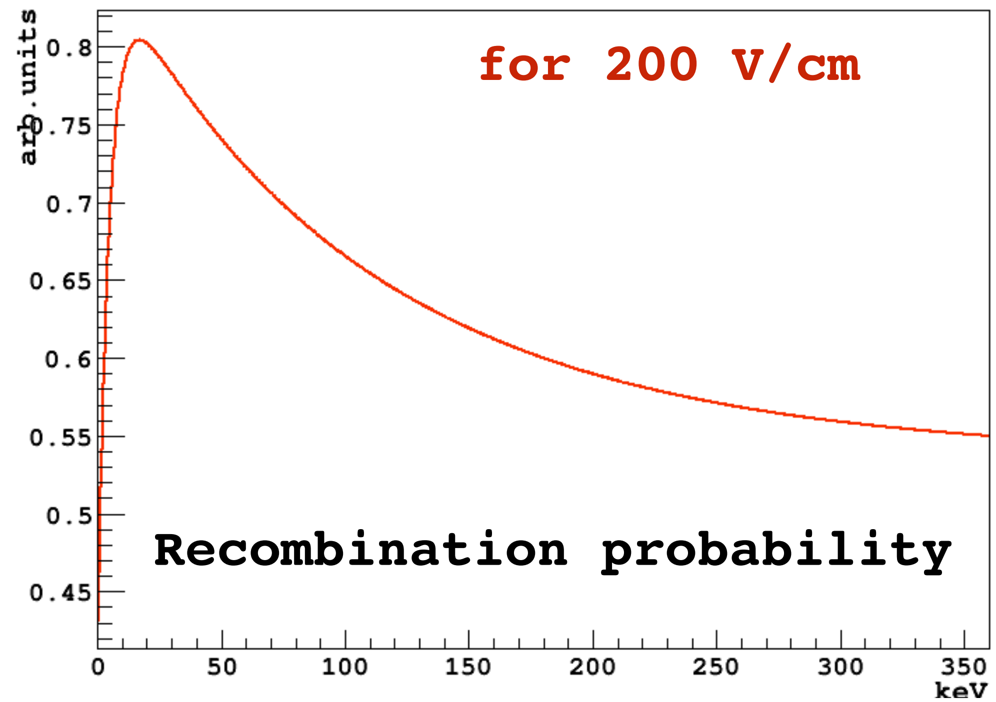
Recombination probability from DS50 data

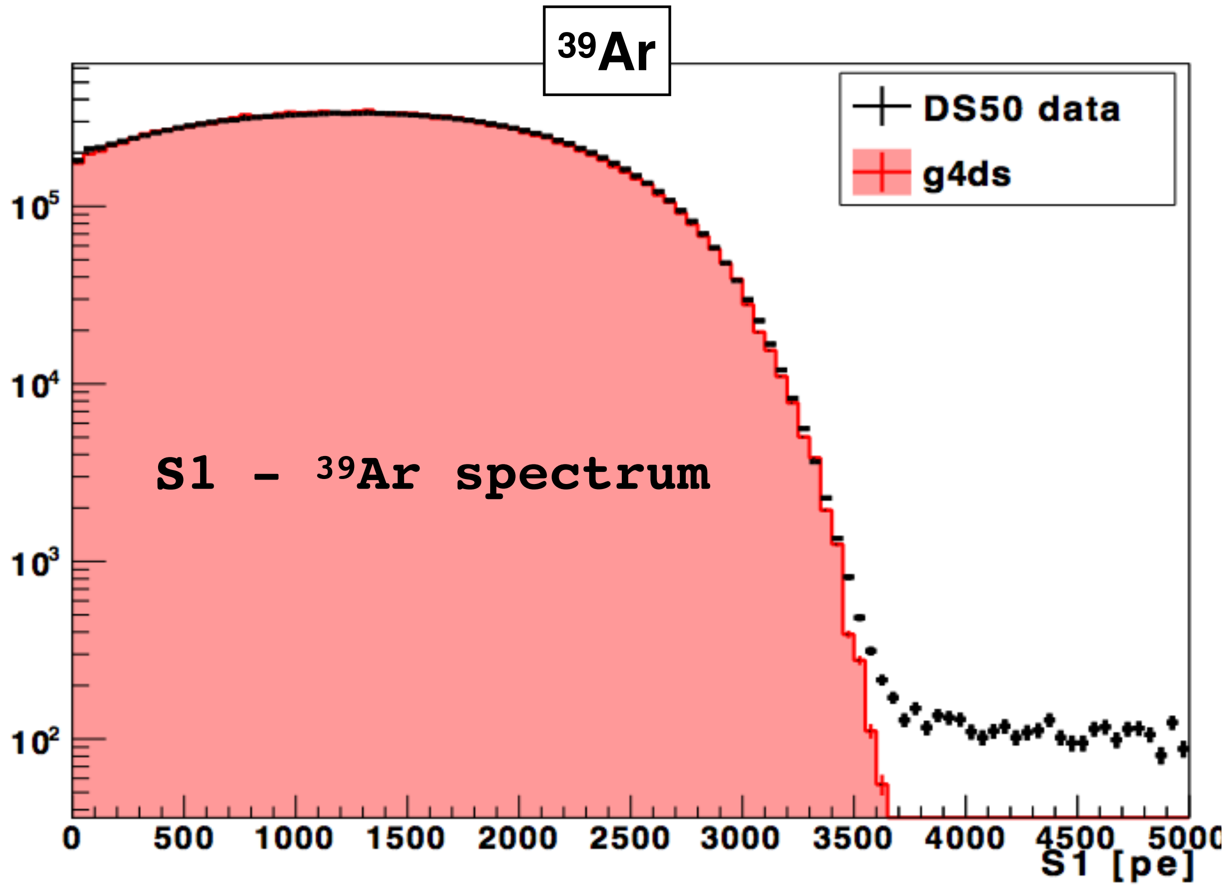
Extraction of the recombination probability from DS50

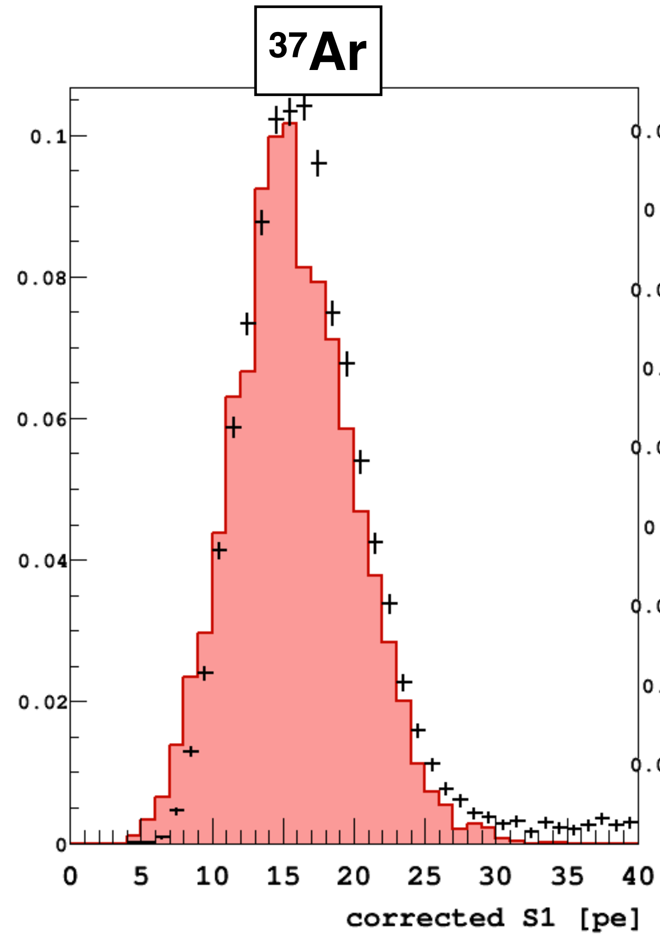
An **effective parameterization** (6 degrees of freedom)

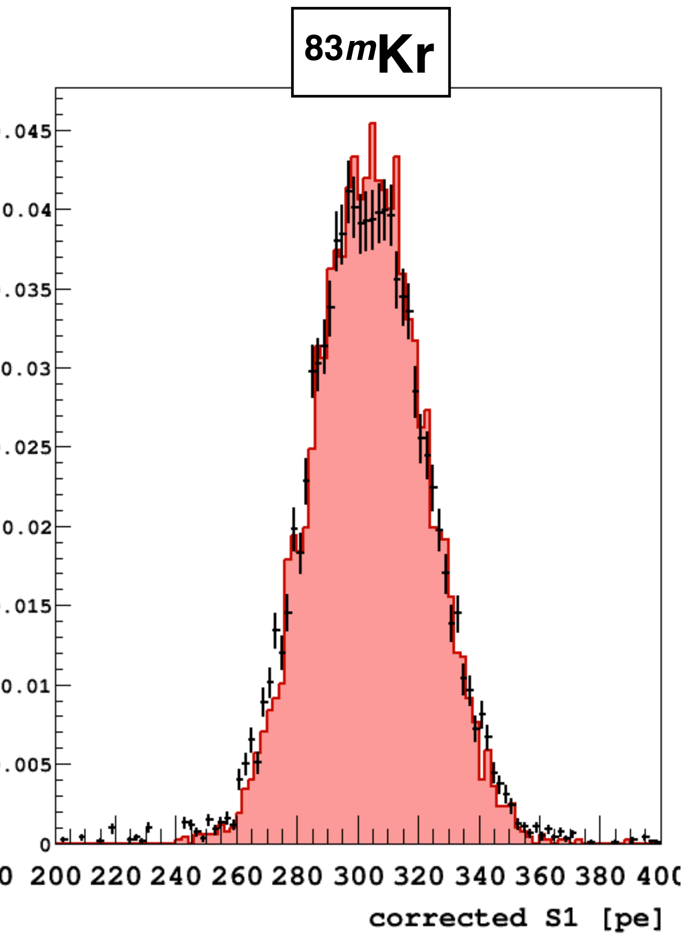
Fit of the
- endpoint of ^{39}**Ar** spectrum (565 keV),
- ^{83m}**Kr** (9.4 keV + 32.1 keV) peak
- ^{37}**Ar** peak (2.7 keV) peak

^{39}Ar beta decay is forbidden (uncertainty at low energy)







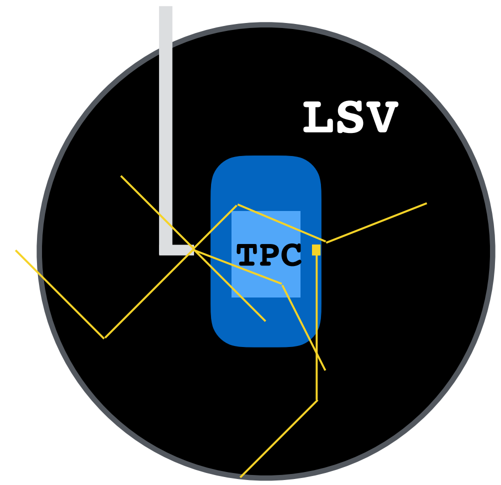


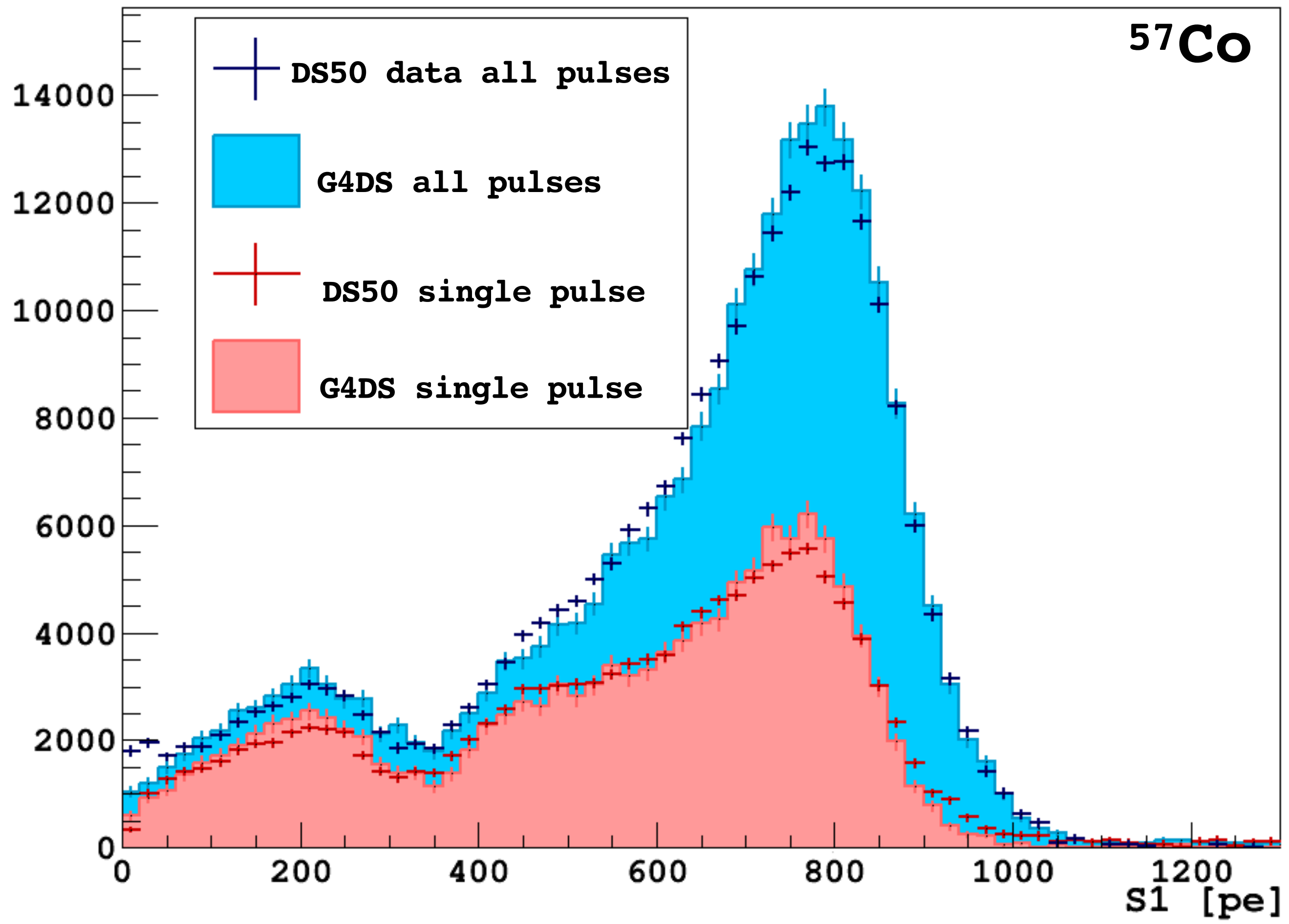
Cross check of ER S1-energy scale

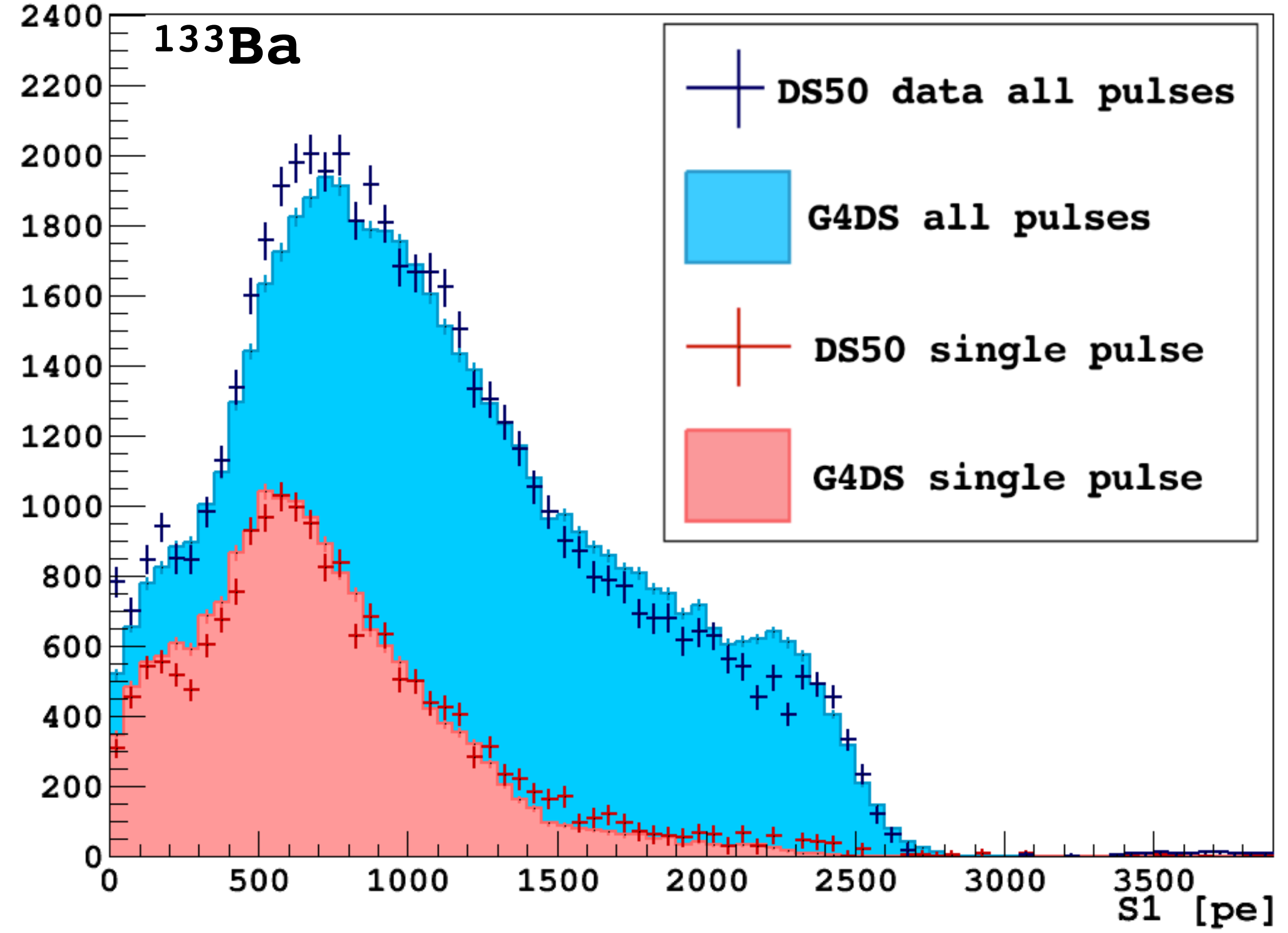
Cross check with **external calibration sources** (^{57}Co and ^{133}Ba)

CALIS (calibration insertion system)

S1 after statistical background (^{39}Ar) subtraction:







Same agreement for number of pulses, tdrift vs x-y distribution…

No additional smearing required!

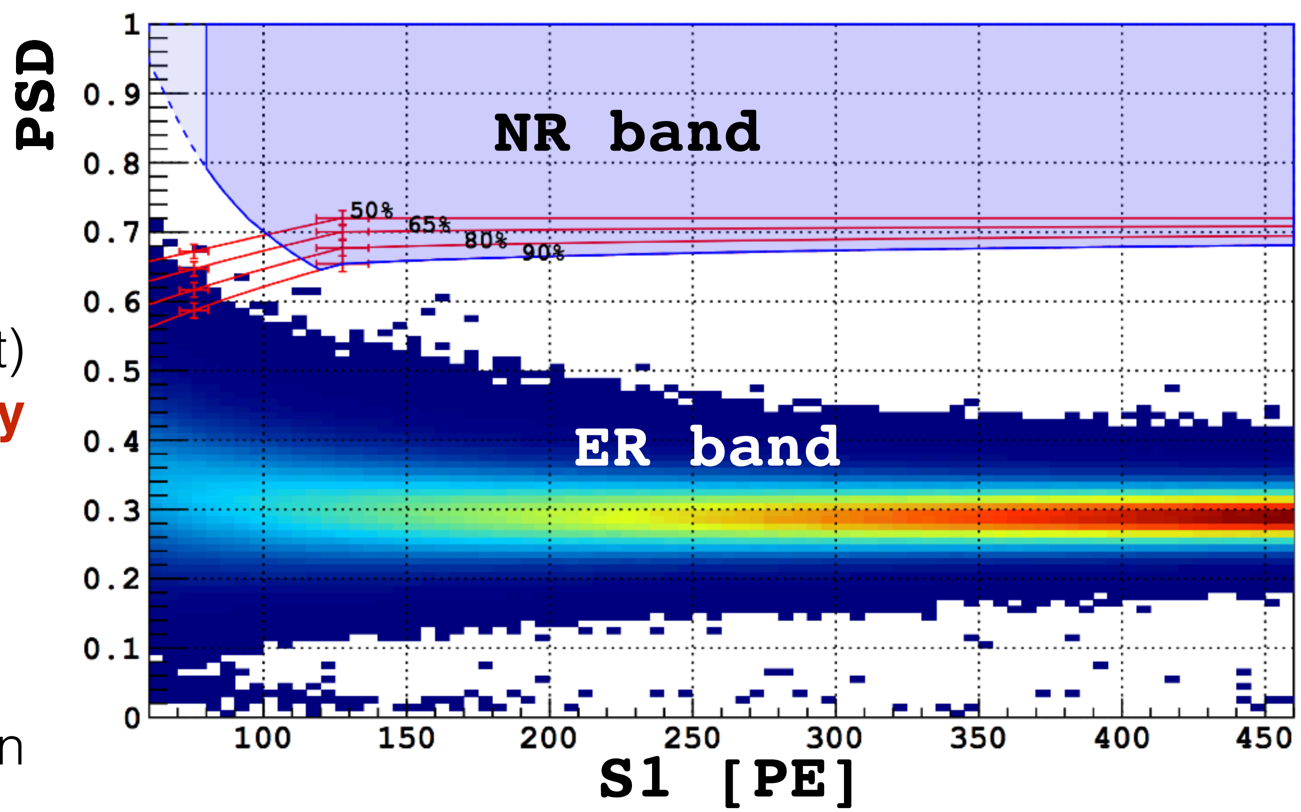
PSD calibration

$$f_{90} = \frac{\int_0^{90\text{ns}} S(t)dt}{\int_0^{7\mu\text{s}} S(t)dt}$$

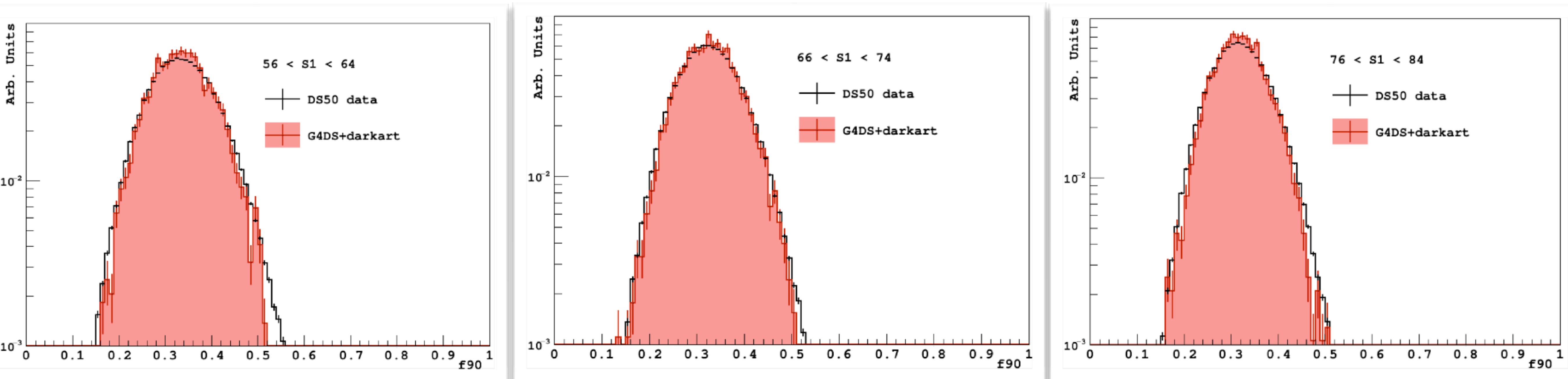
= ~ 0.3 for ER
= ~ 0.7 for NR

The **ratio** between **fast** (singlet) and **slow** (triplet) components of the scintillation pulse is **energy dependent.**

Tuning of G4DS implies a **huge amount of CPU time.**
- Deviations only visible for large statistics samples.
- Counting the PE is not enough (waveform integration —> full reconstruction)



Good agreement in first approximation (**1% deviations**)
ER data compared to simulations with the full optics and reconstruction. The same for NR.



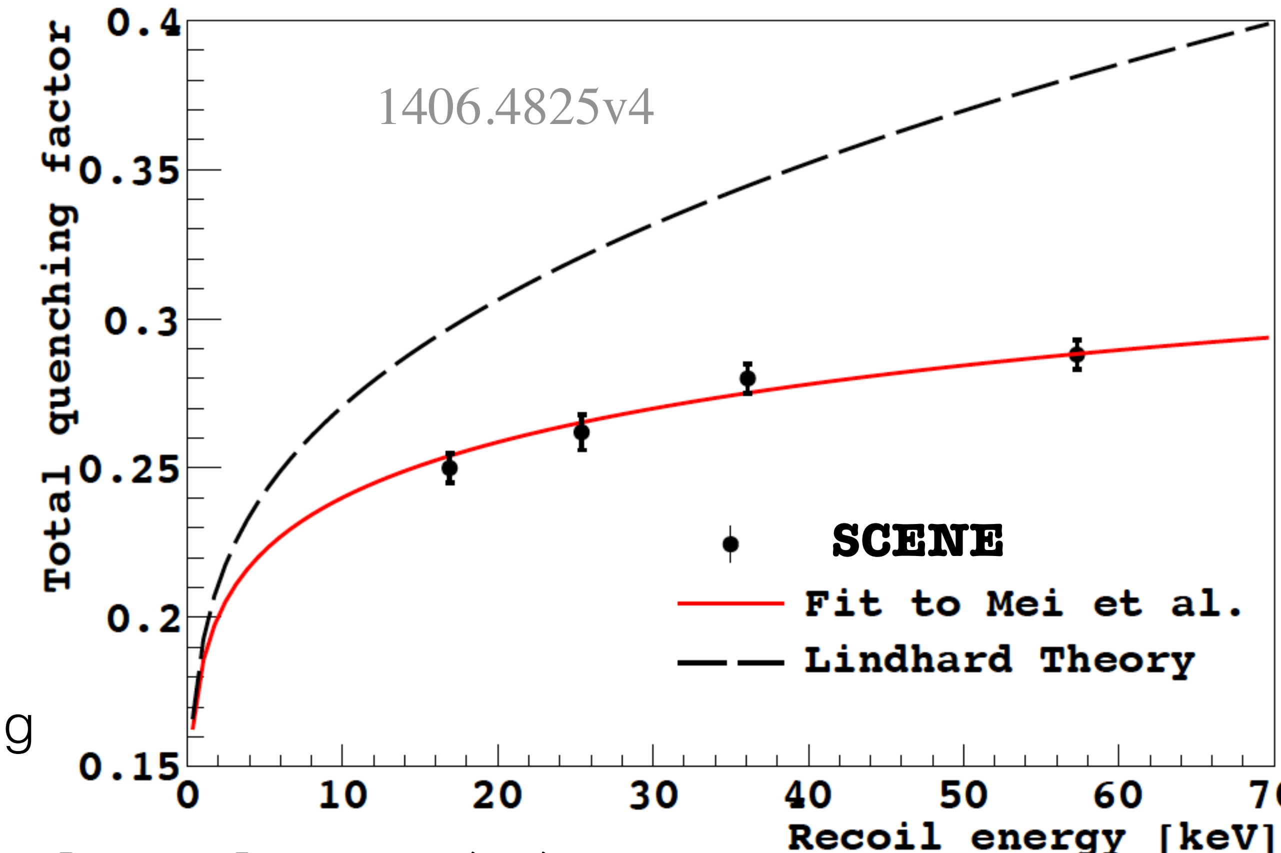
Non-linear quenching for NR

"**Collisional**" quenching

Lindhard theory (electron and ions stopping power)

$$L_{eff}^{L} = \frac{kg(\varepsilon)}{1+kg(\varepsilon)}$$

— kg from theory —



Other "**density**" effects, such as bi-excitonic quenching

Ar* + Ar* –> Ar + Ar$^+$ + e$^-$

(vs standard 2 x (Ar* + Ar –> Ar*$_2$ –> Ar + Ar + γ))

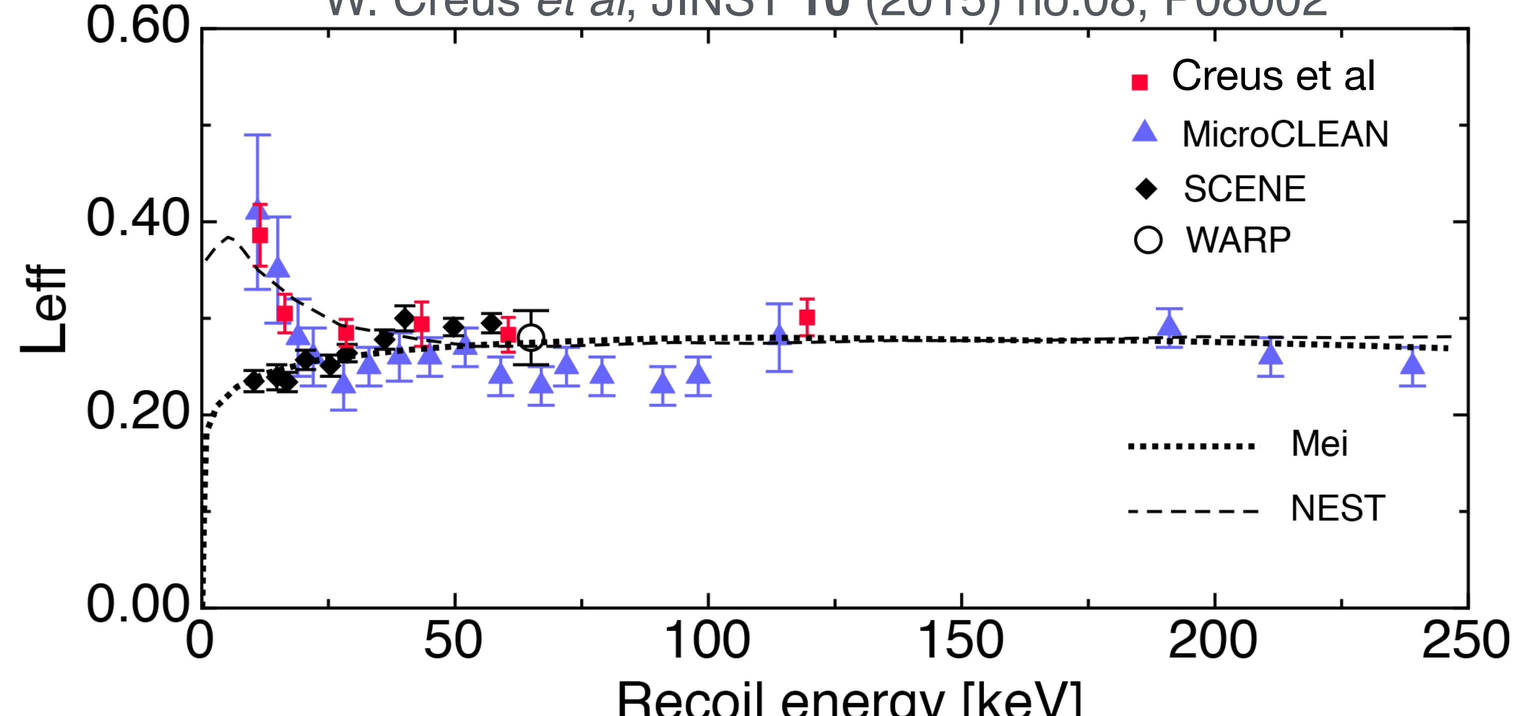
Mei model: arXiv:0712.2470

$$L_{eff}^{M} = L_{eff}^{L} \times \frac{1}{1+k_B \frac{dE}{dx}}$$

$$k_B = 7.4 \times 10^{-4}\ \mathrm{MeV}^{-1}\ \mathrm{g\ cm}^{-2}$$

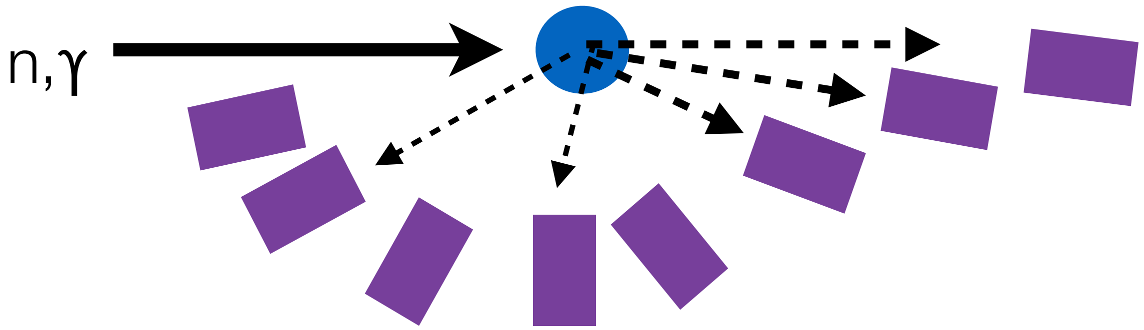
(±30% according to the dataset)

W. Creus *et al*, JINST **10** (2015) no.08, P08002

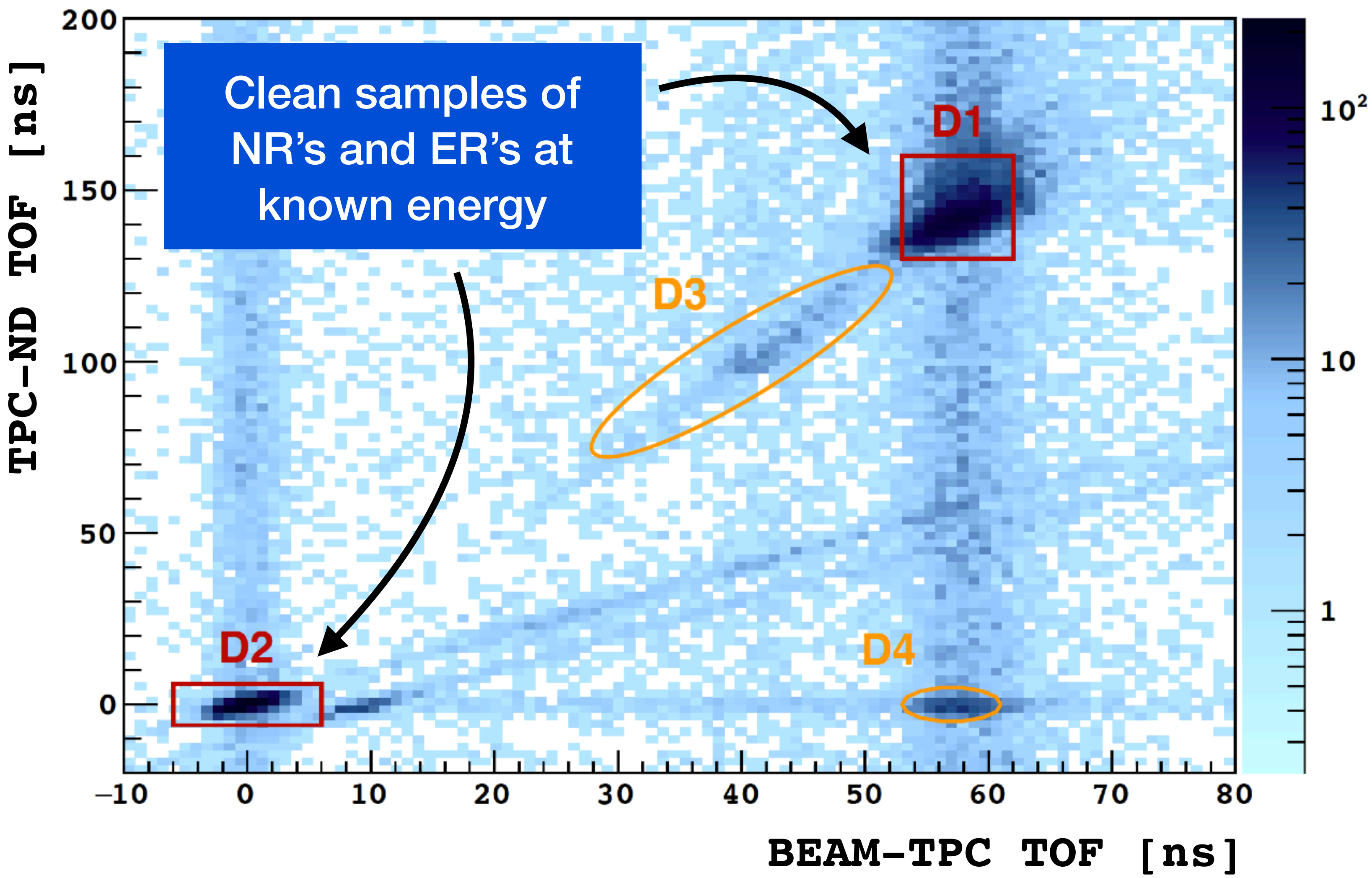


NR calibration: the ARIS experiment

Main goal: L_{eff} at low energy (scintillation efficiency of NR's)



Expose a small scale TPC to a **pulsed**, **collimated**, **mono-chromatic** neutron beam (LICORNE @IPNO), coupled with 8 neutron detectors, to fix NR energy by kinematics.

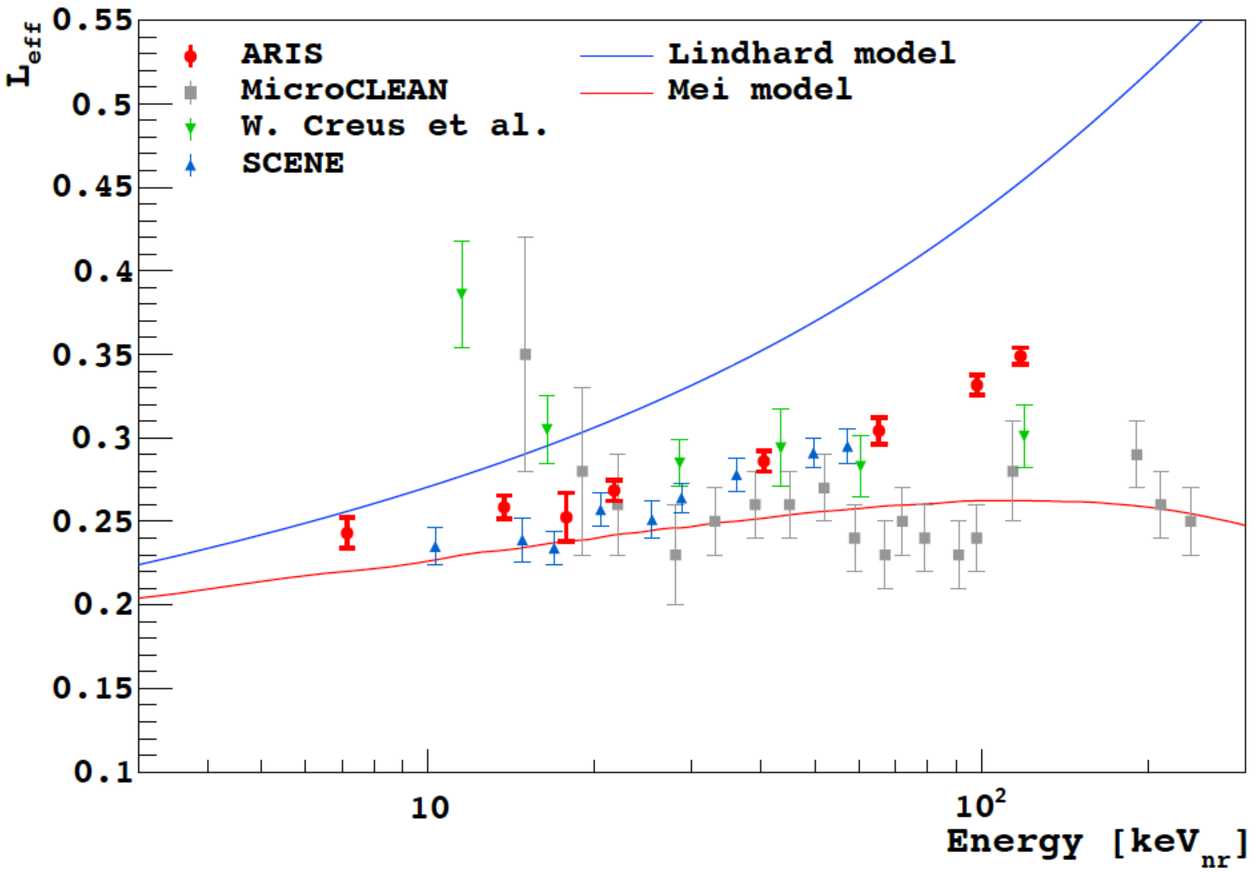


D1 neutrons selected by TOF and ND PSD cuts.

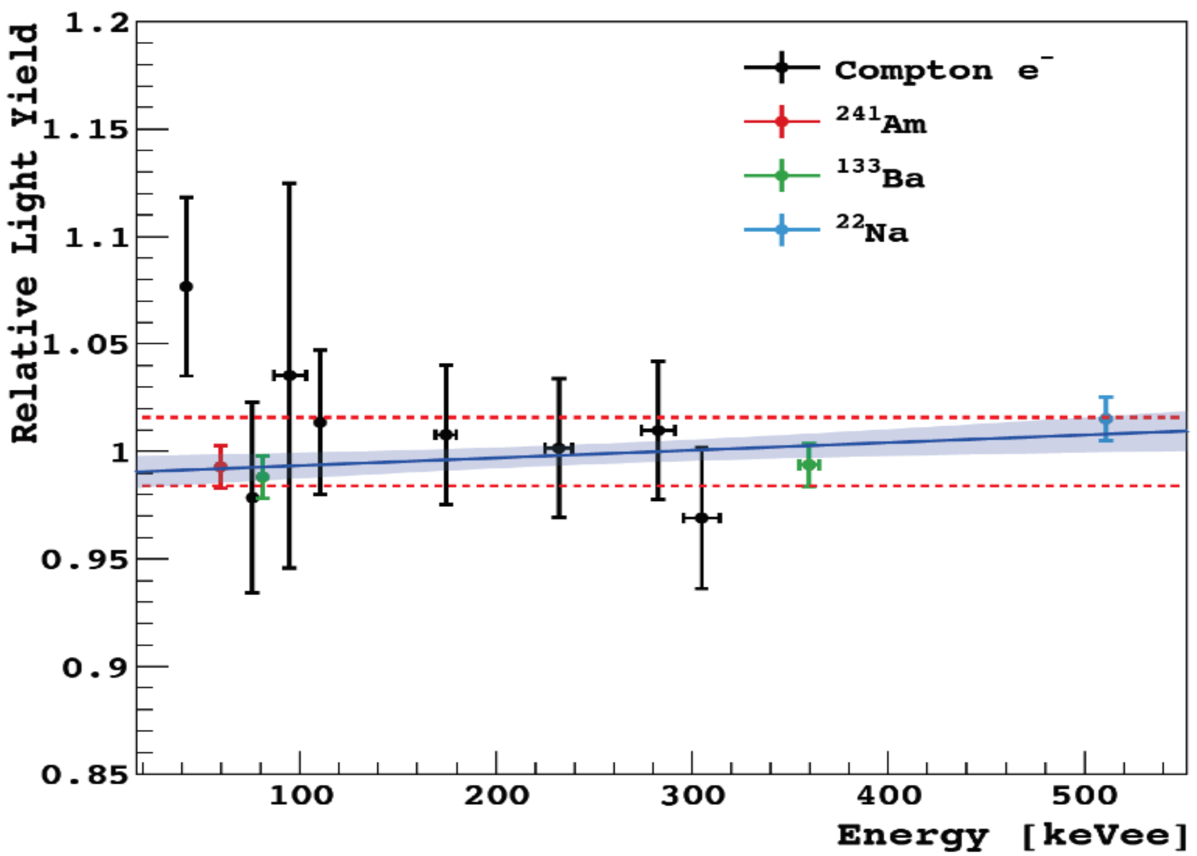
D2 gammas, correlated to the beam.

The ARIS results

Precision L_{eff} at low energy



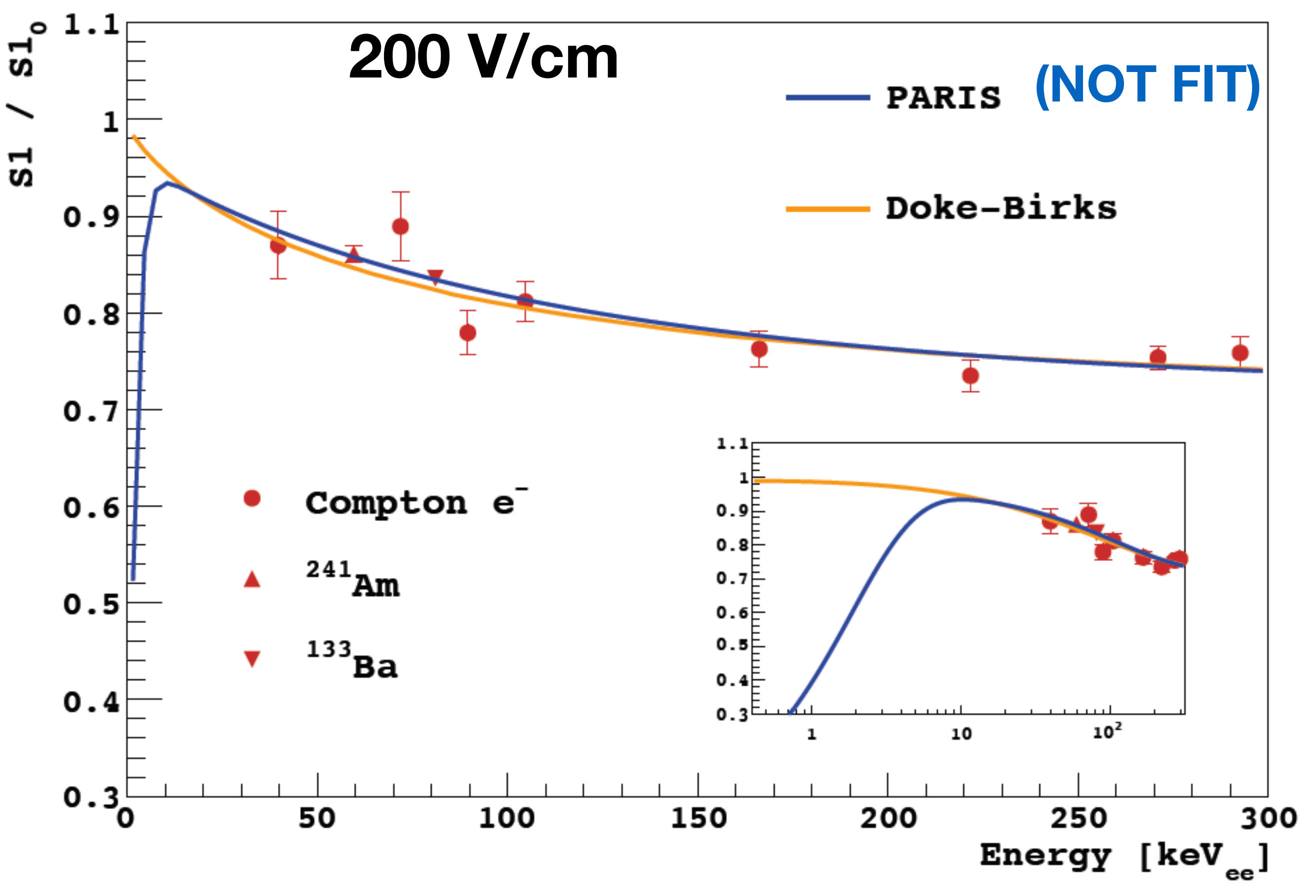
LAr ER linearity

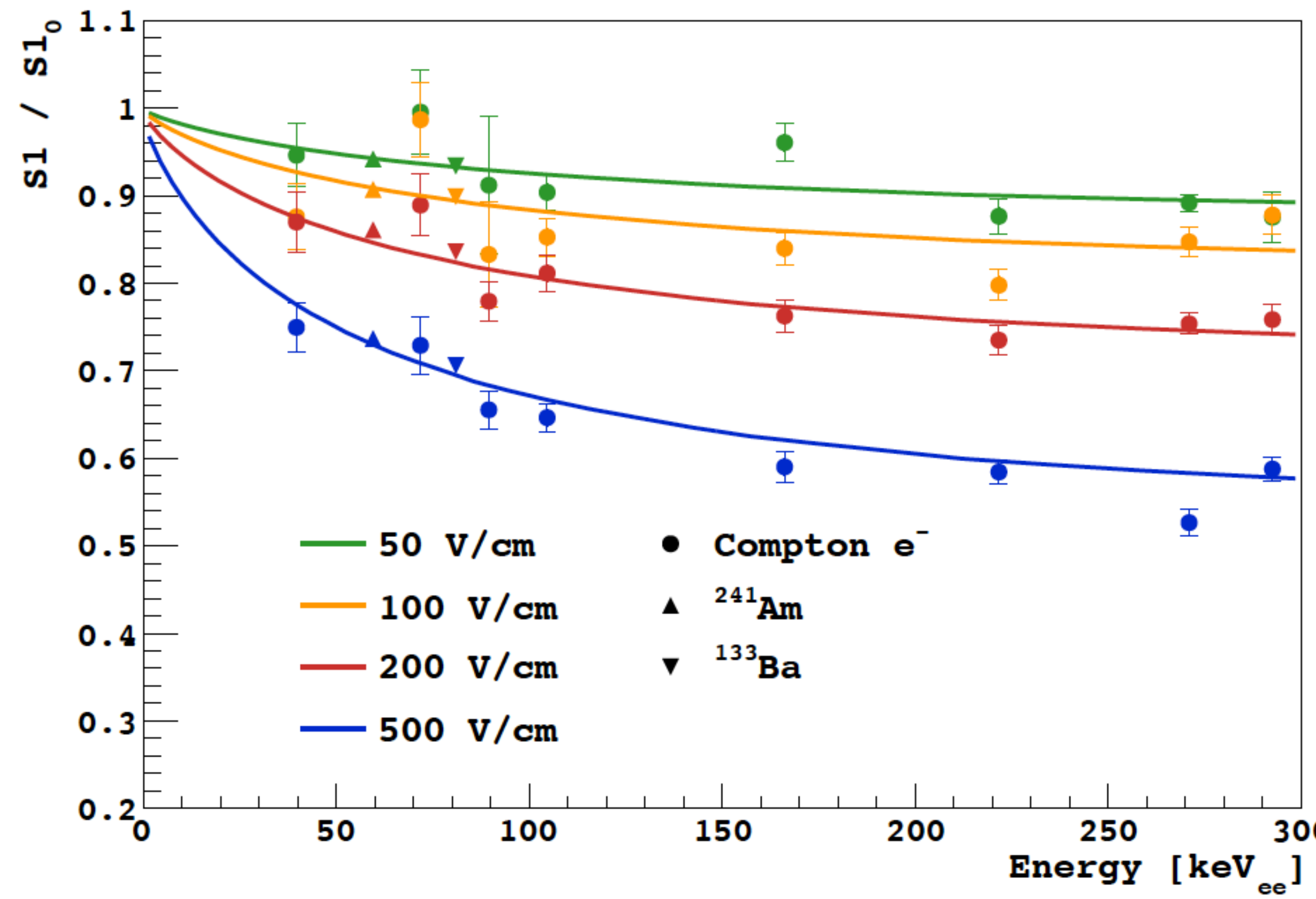


Precise measurement of L_{Eff} parameter down to 7.1 keV_{NR}.

Linearity of LAr response to ER at null field assessed within 1.6% using the Compton induced single ER and external calibration sources

ARIS: Field dependence, ER





$S1^F / S1^0 (E) = (\alpha + R(E)) \; / \; (1 + \alpha)$

Testing the **model** developed for **DarkSide**.

For **E >20 keV, Doke-Birks** model fits well (fails at low E) and describes field dependence.

$$\boxed{R = \frac{A \; dE/dx}{1 + B \; dE/dx} + C e^{-D \times F}}$$

A ~ 2.5E-3 cm/MeV

C ~ 0.77

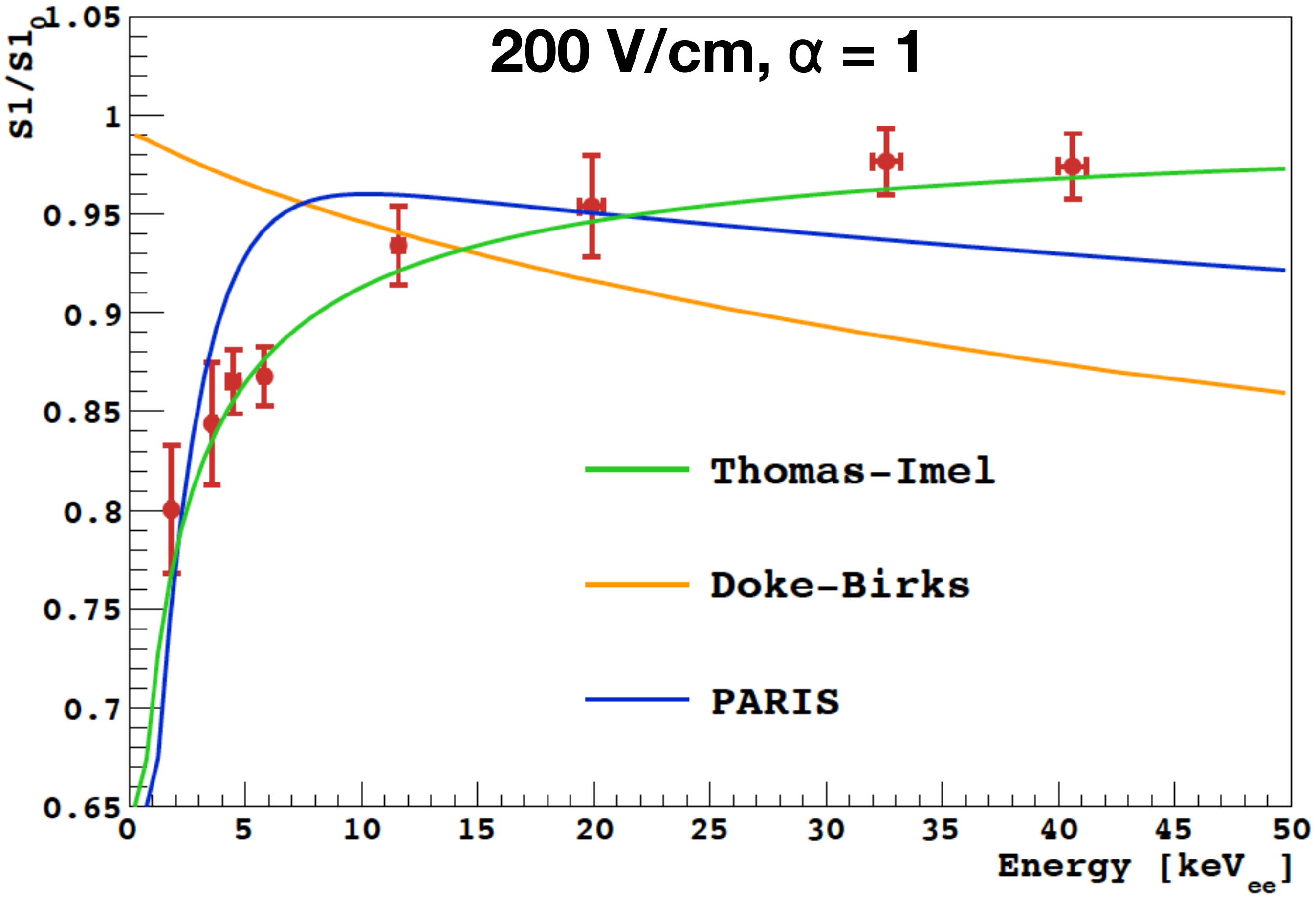
B ~ A/(1-C)

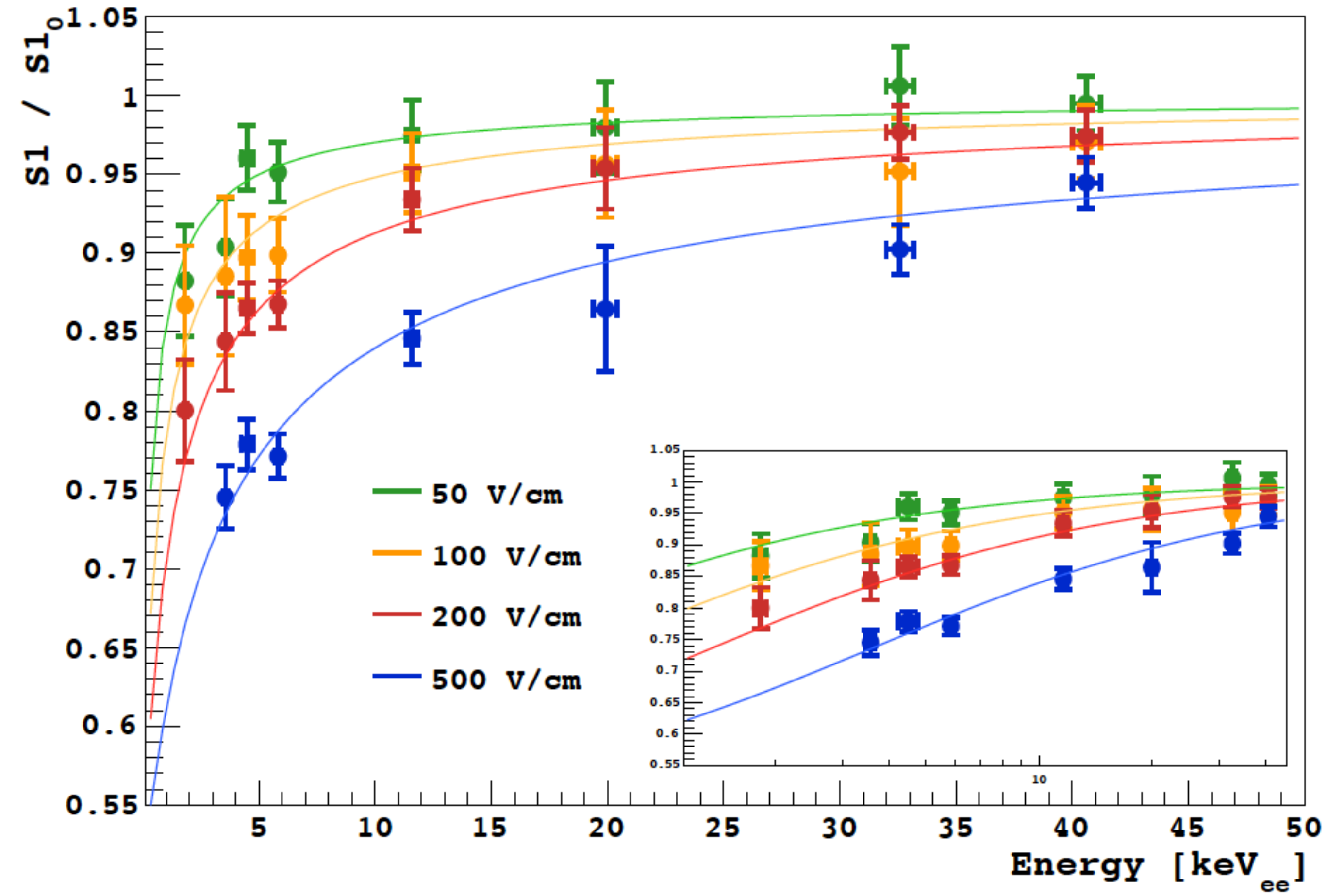
D ~ 3.5E-3 cm/V

dE/dx: e- StP

F: field

ARIS: Field dependence, NR





$$S1^F / S1^0 (E) = (\alpha + R(E)) \; / \; (1 + \alpha)$$

Fixing α = 1 to break the degeneracy between **R** and **α** (do not measure charge).
Under this assumption the Thomas-Imel model is favored (Doke-Birks and PARIS rejected at 5σ)
Thomas-Imel also describes the field induced scintillation quenching with **b ~ 1** and **C ~ 18.5**.
N_i is given by assumptions on W and α.

$$\boxed{R = 1 - \frac{ln(1+\xi)}{\xi}}$$

$$\xi = C_{box} \frac{N_i}{F^\beta}$$

F: field

A comprehensive effective model for the response of LAr to **ER** and **NR** is available in the energy range of interest for **WIMP searches**

Study of the β/γ background in DS50

G4DS features spatial generators. Simulate MC spectra from **radioactivity** in materials.

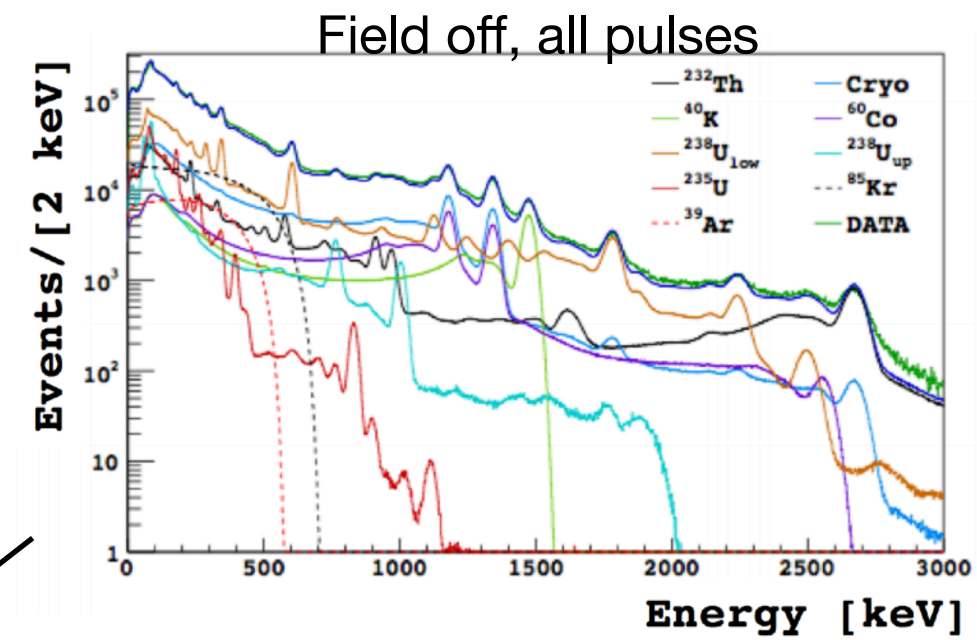
Simultaneously fit **Energy, S1, drift time** variables.

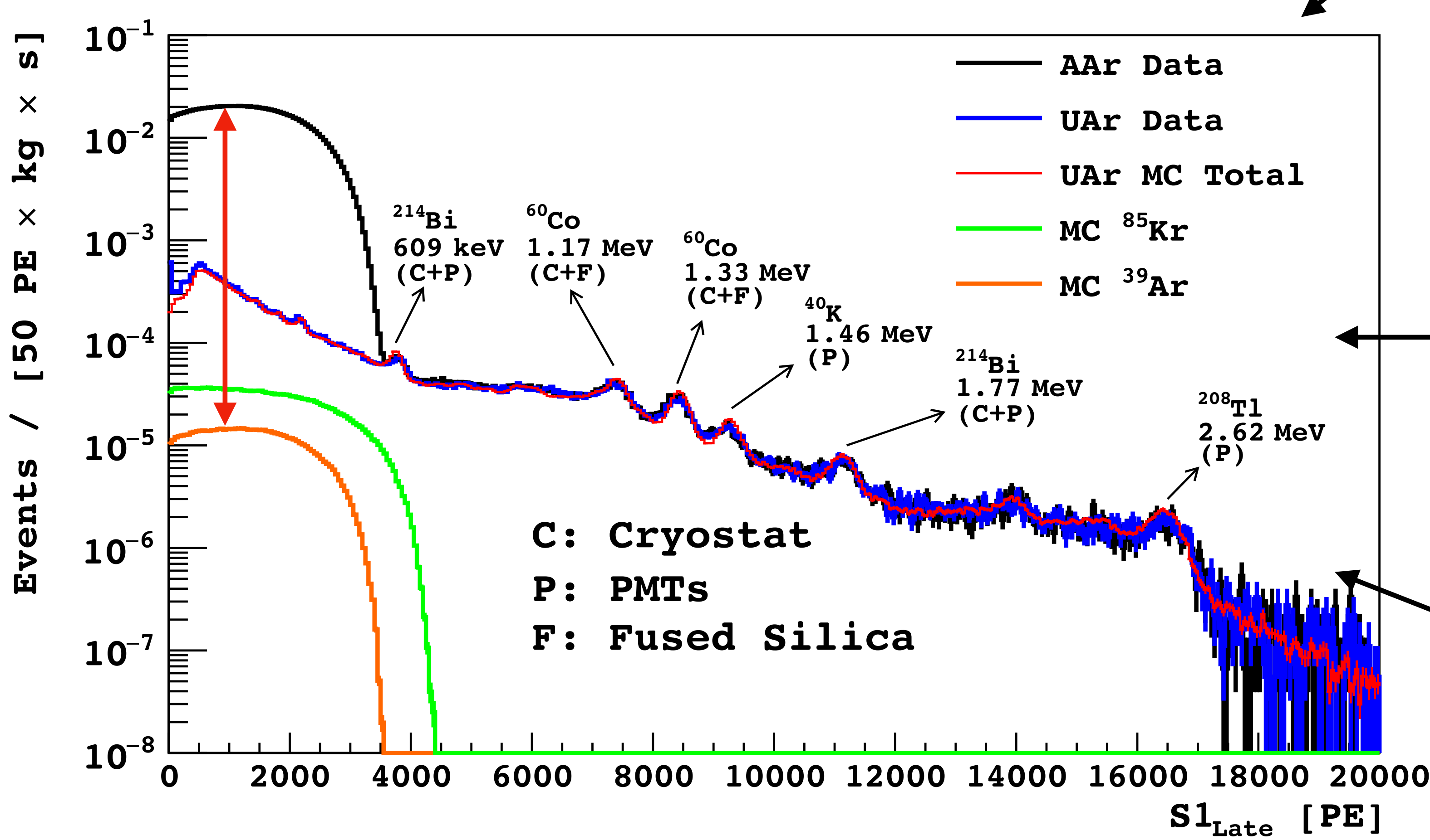
Contamination of ^{85}Kr discovered

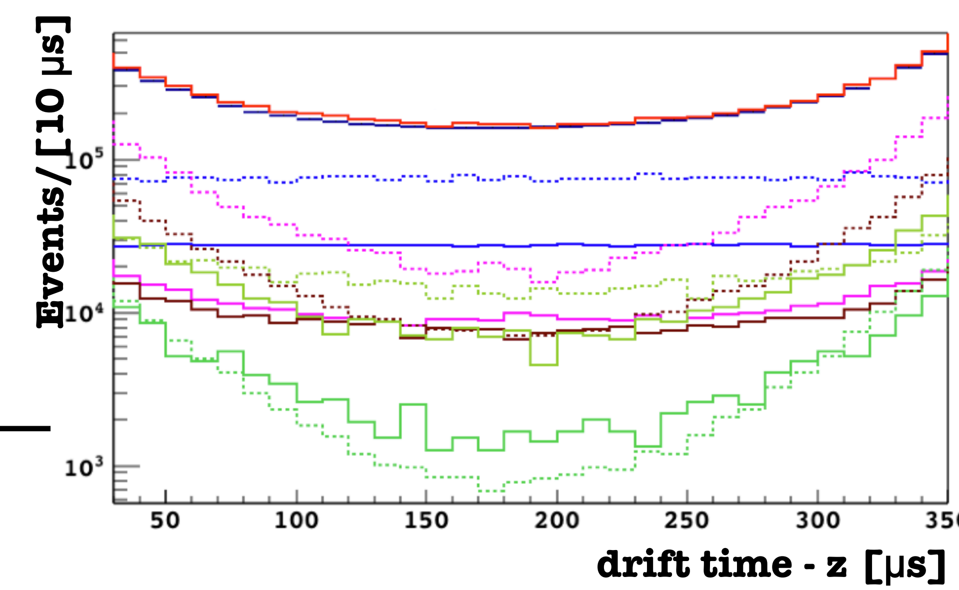
(and confirmed: 0.43% BR with β + 418 keV γ)

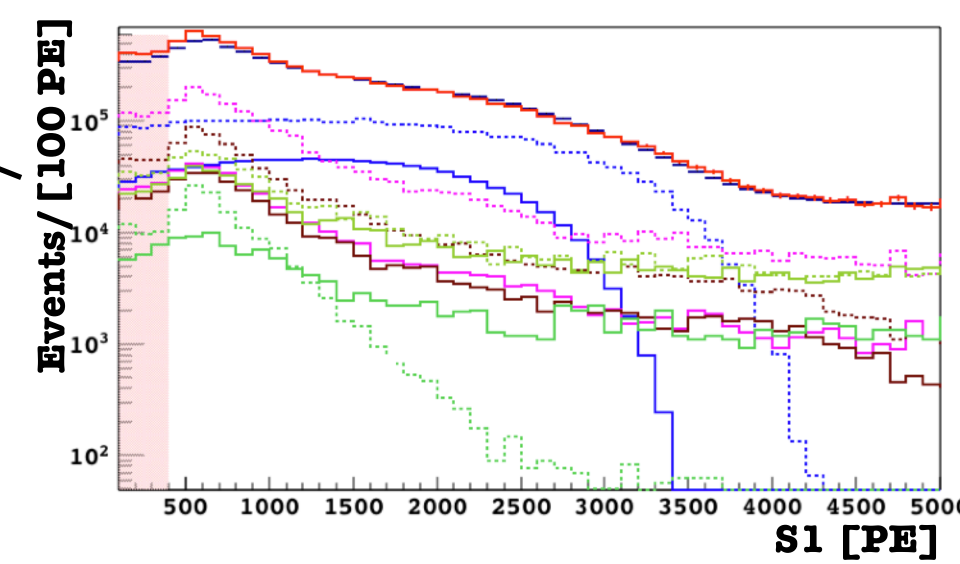
Measurement of ^{39}Ar depletion in UAr:

1400 (0.69±0.09 mBq/kg)









PhysRevD.93.081101

High-mass analysis

532 days exposure

Blind analysis, 60% WIMP acceptance for S1>180

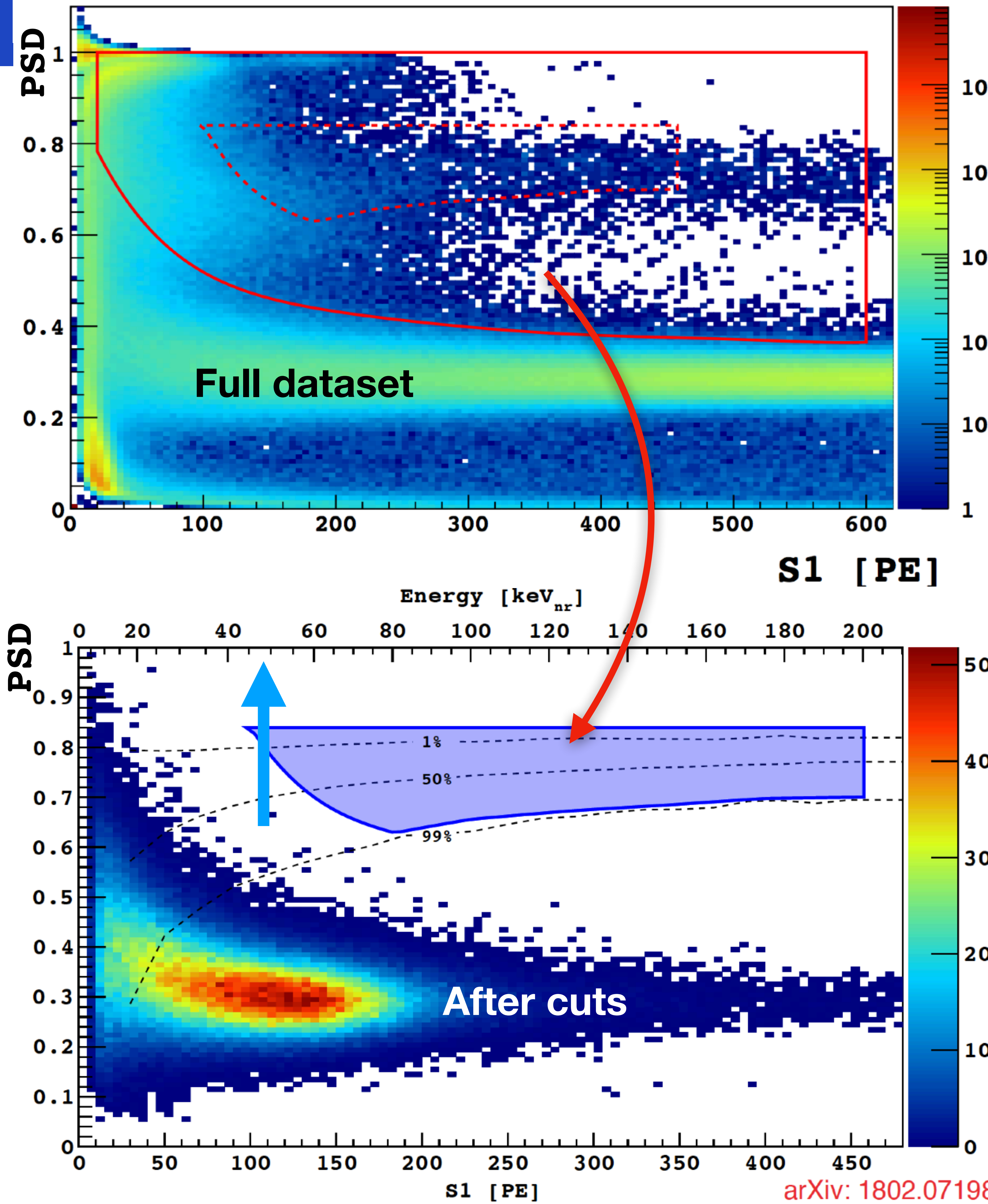
Determine through MC how many ER and NR in the blind search region

- energy scale of NR and ER
- simulation of PSD
- γ-induced Cherenkov included

Draw contours of WIMP search region by requiring 0.1 surviving background events in the full exposure

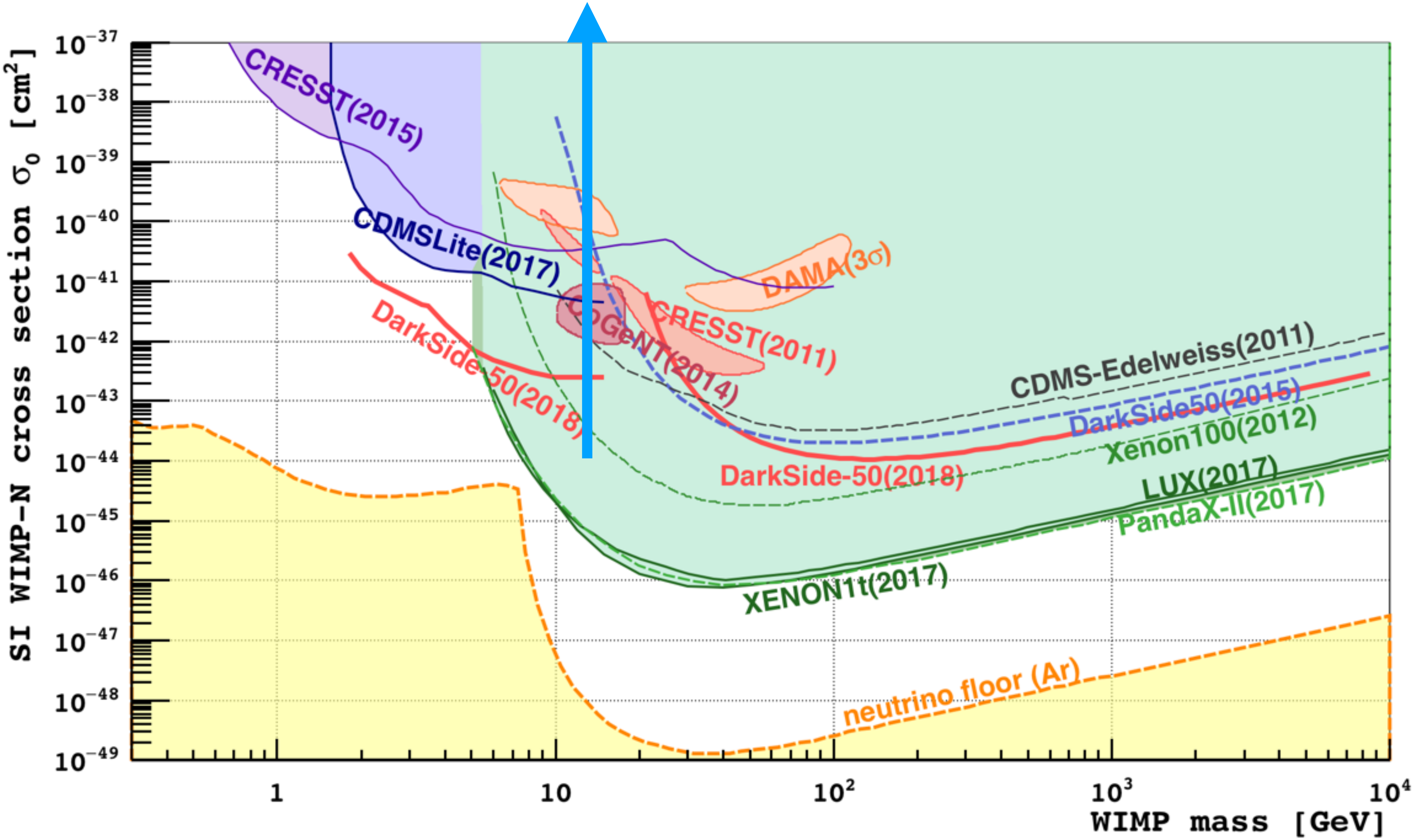
Background-free search

Using S1 (det efficiency ~ 15%)
==> high threshold

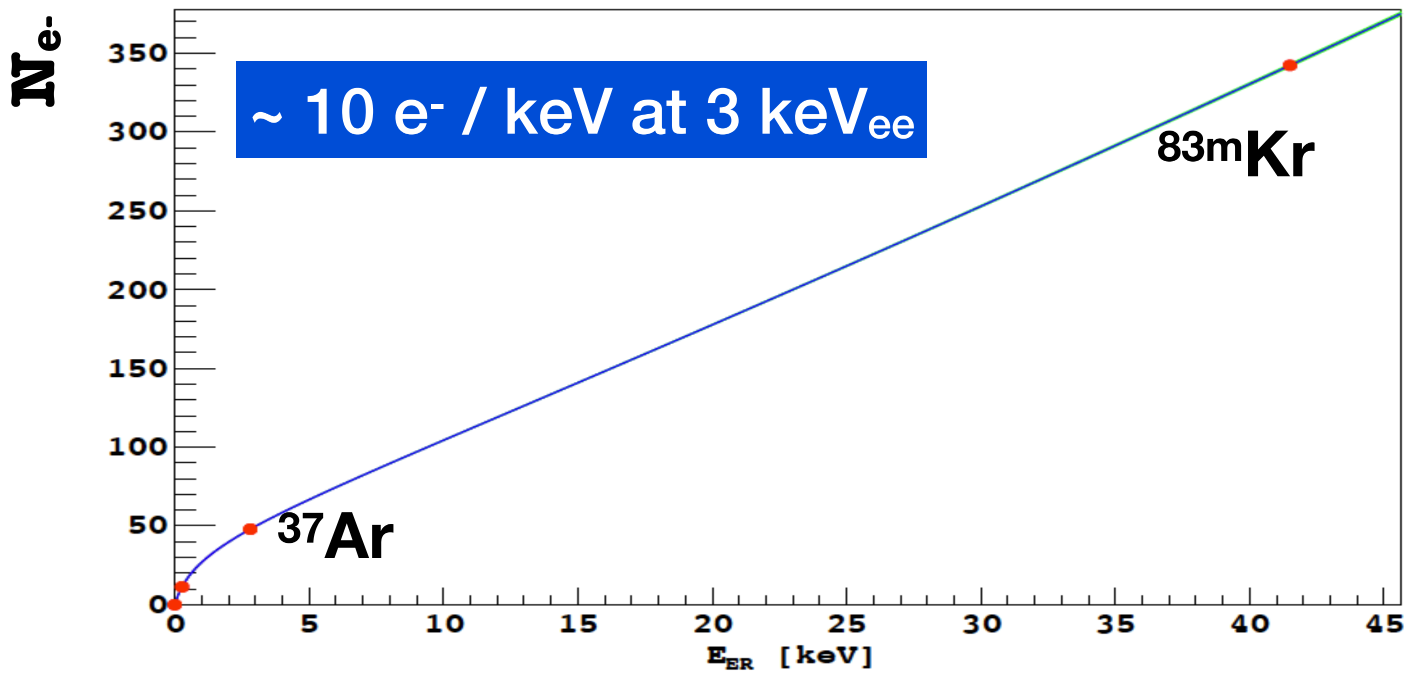


arXiv: 1802.07198

Sensitivity and threshold



Ionization yield, ER

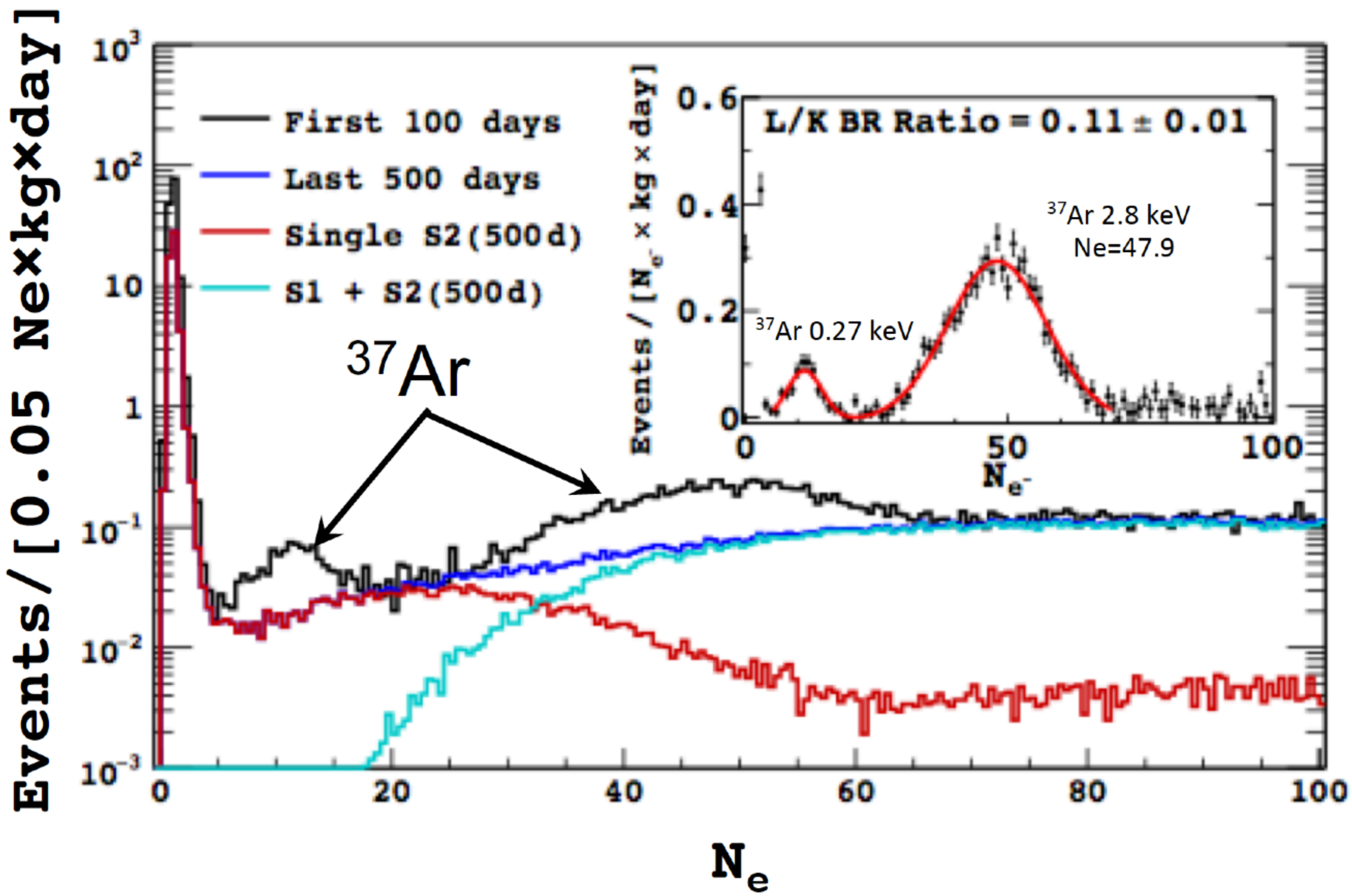


Ionization only spectrum (W_{ion} = 23.5 eV, multiplication in the gas: 23 PE/e^-)

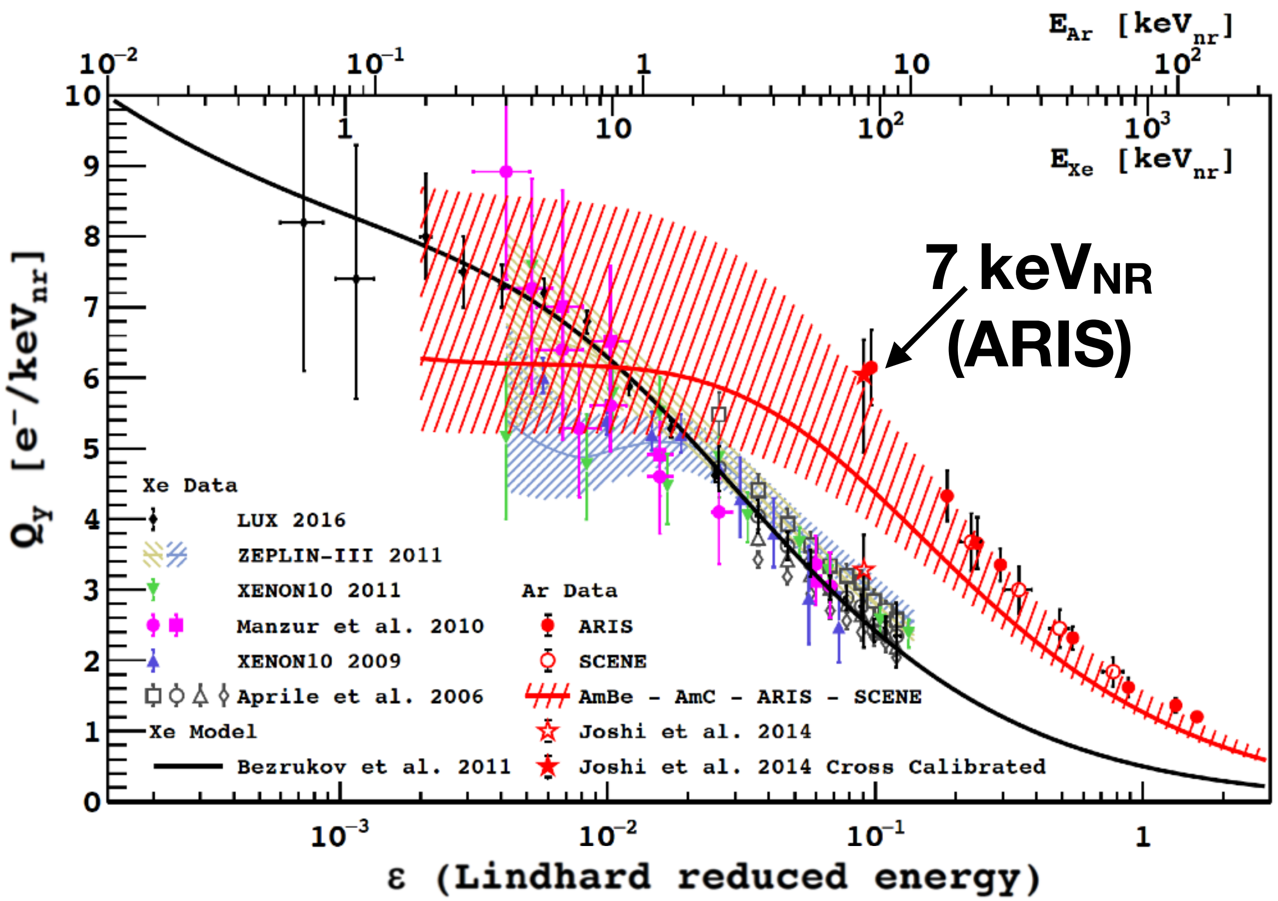
Calibrations:

- ER with ^{37}**Ar** and ^{83m}**Kr**
- NR with **AmC, AmBe** neutron sources

^{37}Ar:	0.27 keV
^{37}Ar:	2.8 keV
^{83m}Kr:	41.5 keV



Ionization yield, NR

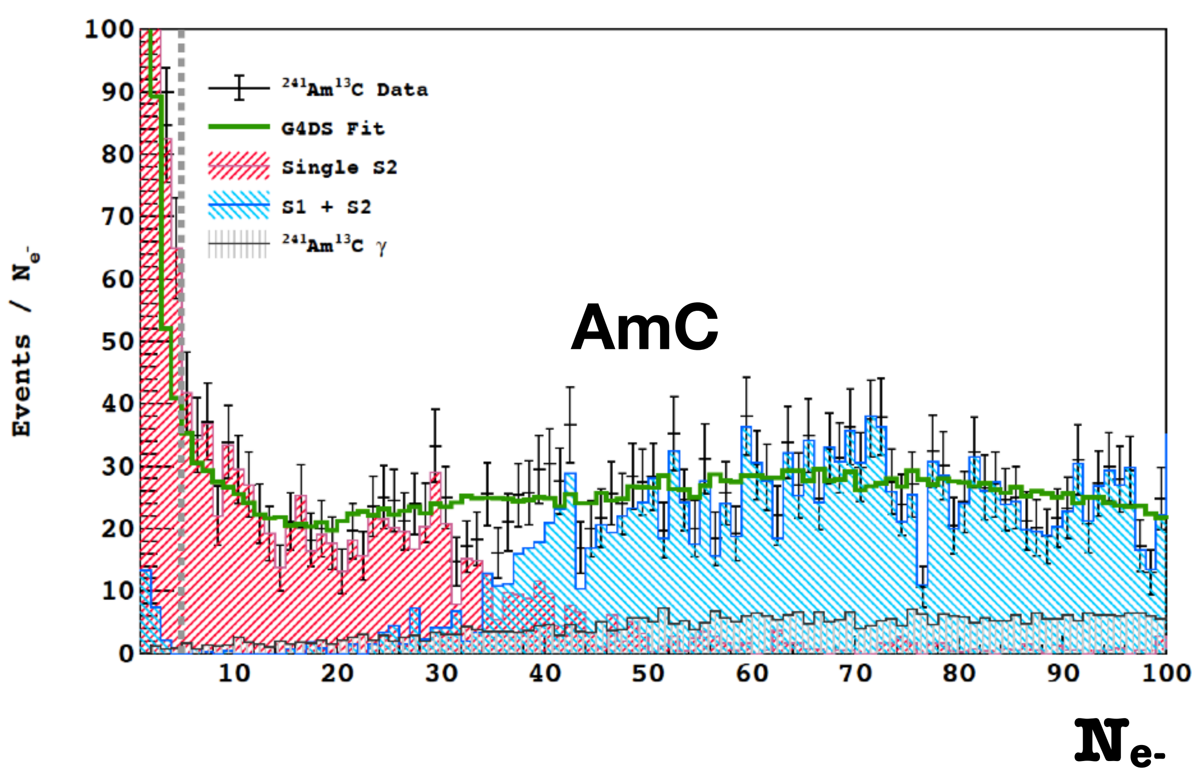


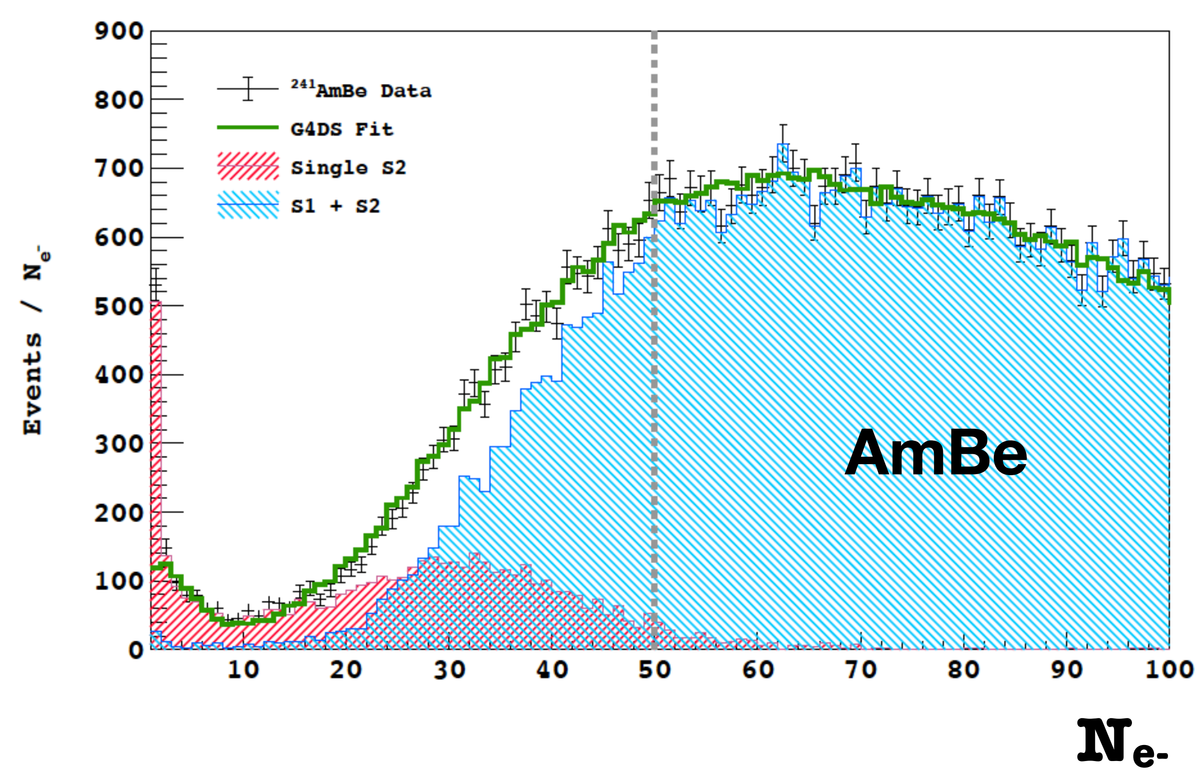
Ionization only spectrum (W_{ion} = 23.5 eV, multiplication in the gas: 23 PE/e^-)

Calibrations:

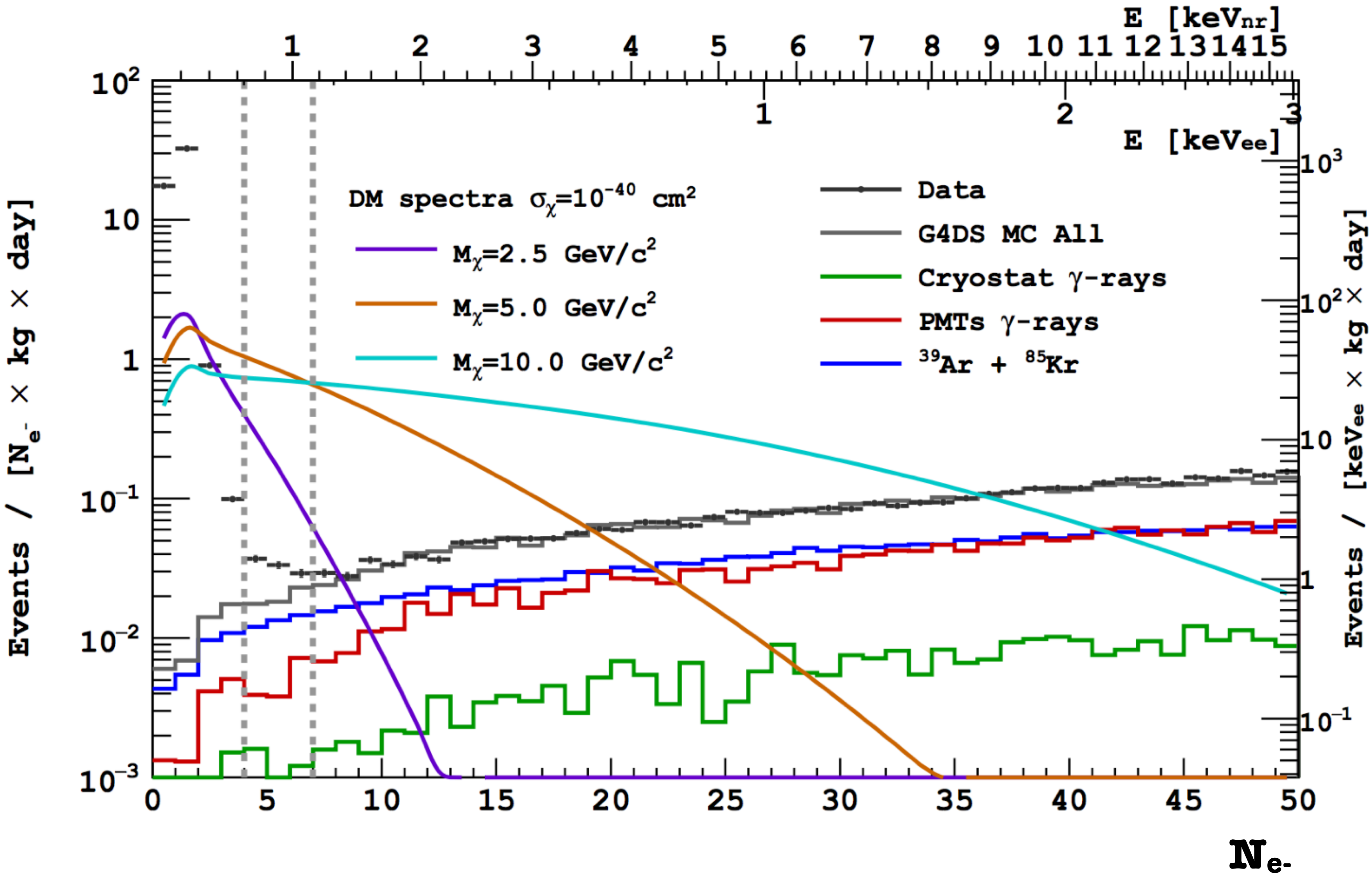
- ER with ^{37}**Ar** and ^{83m}**Kr**
- NR with **AmC, AmBe** neutron sources

- ☑ optical MC: trigger efficiency and fiducialization
- ☑ ^{85}**Kr,** ^{39}**Ar, other γ's** constrained from multivariate MC spectra fit
- ☑ ARIS cross calibration for ionization yield





DarkSide for low-mass WIMPs



MC spectra in the low energy region, converted in N_{e-} (ER). WIMP induced spectra in N_{e-} (NR), PLL analysis

→ **Best limit in [1.8, 6] GeV/c² mass range**

Signal Generators

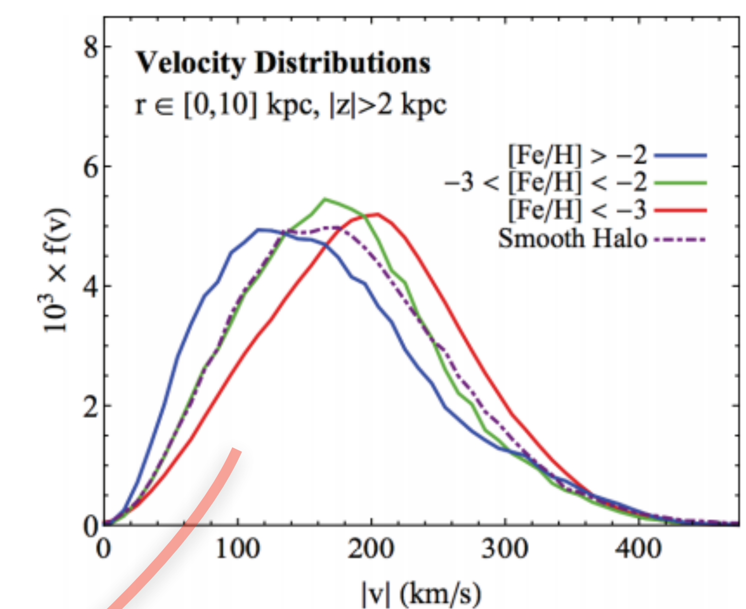
Generators

WIMP spectra and interaction rate:

Astrophysics

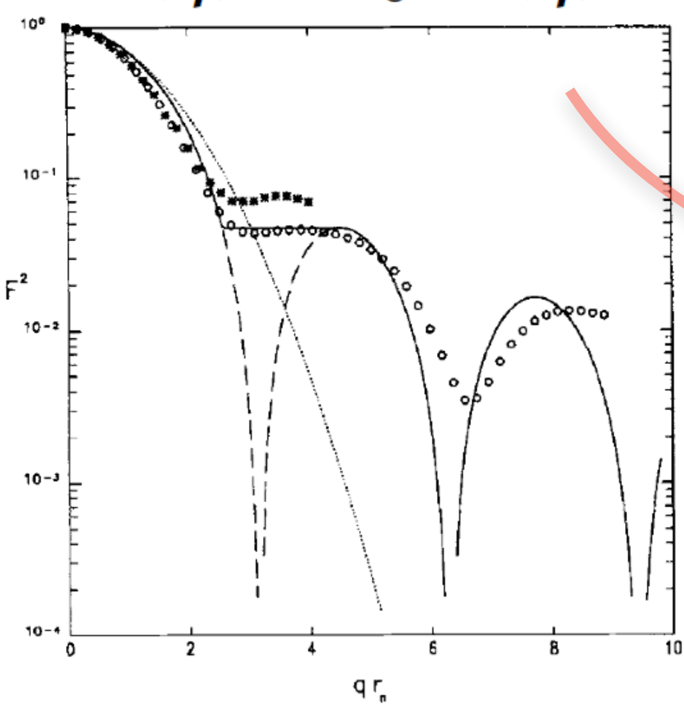
$$\frac{dR}{dE_R} = \frac{N_A}{A}\rho_0\sigma(q)\frac{m_N}{2\mu^2 m_\chi} \times \frac{1}{k}\int_{v_{min}}^{v_{max}} \frac{f(\boldsymbol{v},\boldsymbol{v_E})}{v} d^3v$$

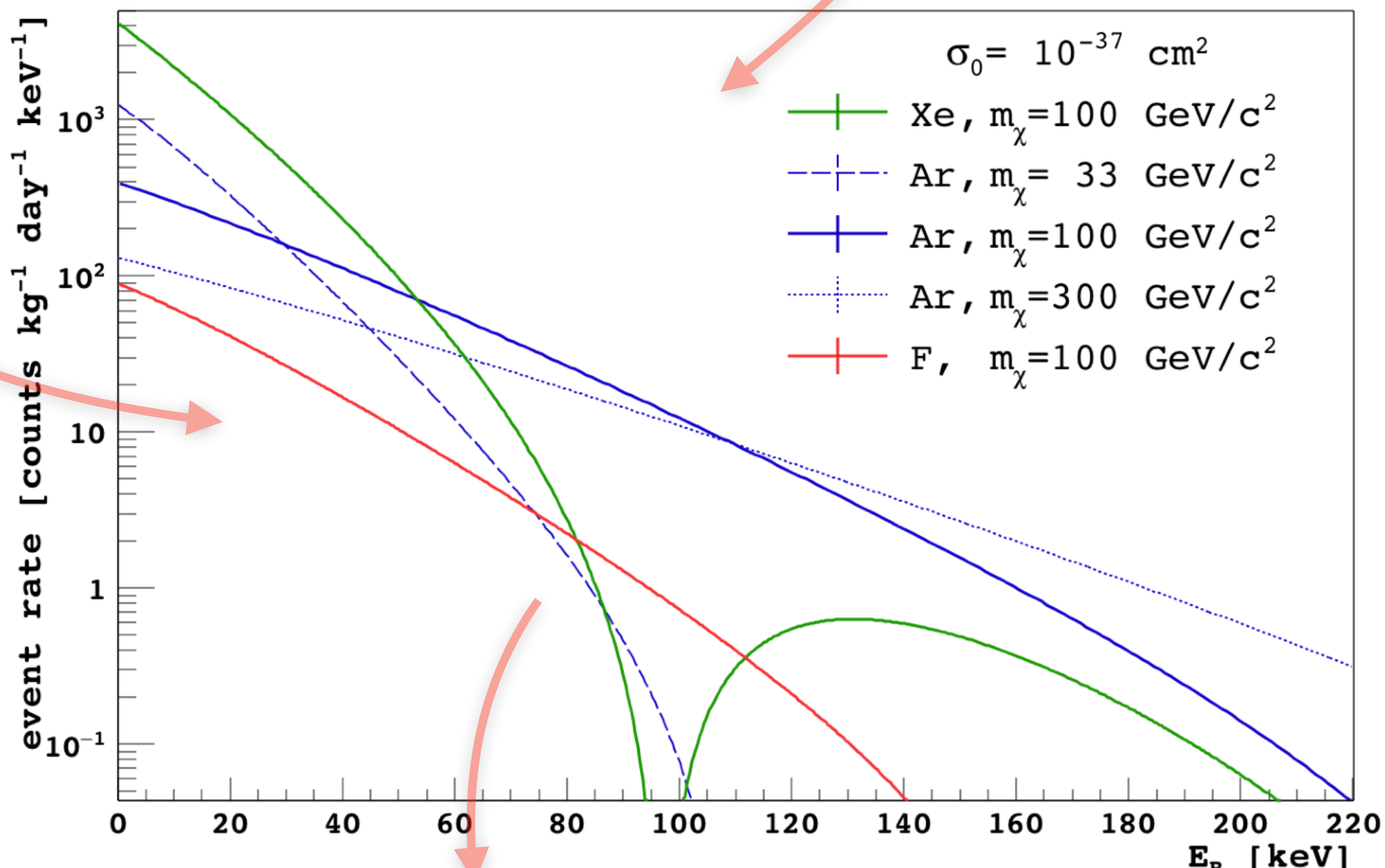
Particle Physics



Nuclear Physics

$$\sigma(q) = \sigma_0 F^2(q)$$

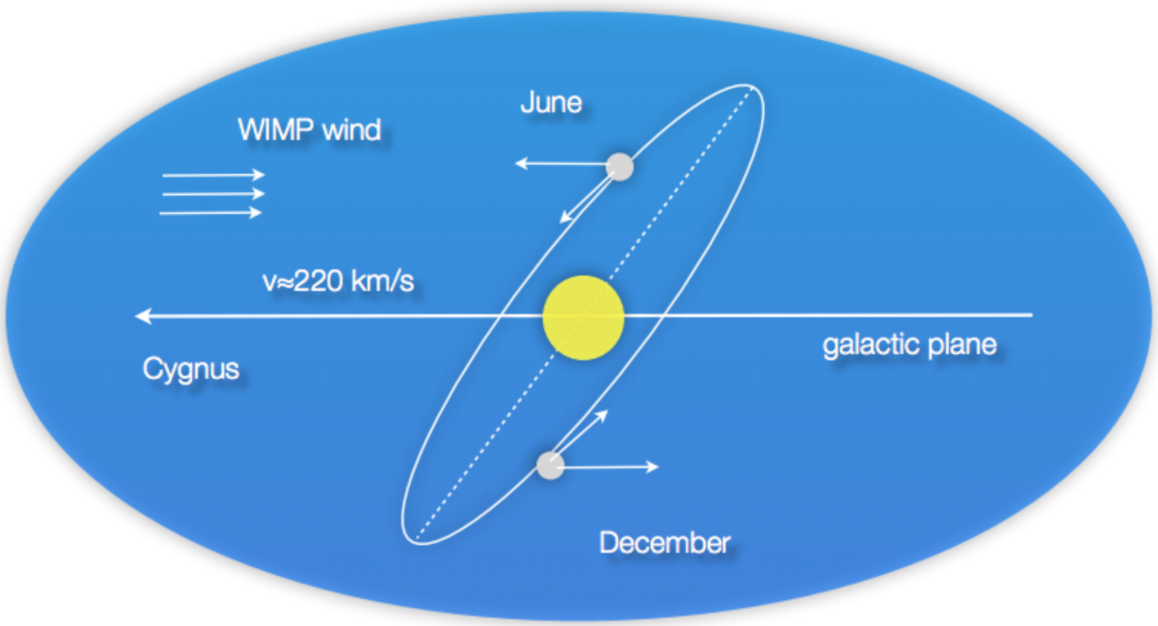




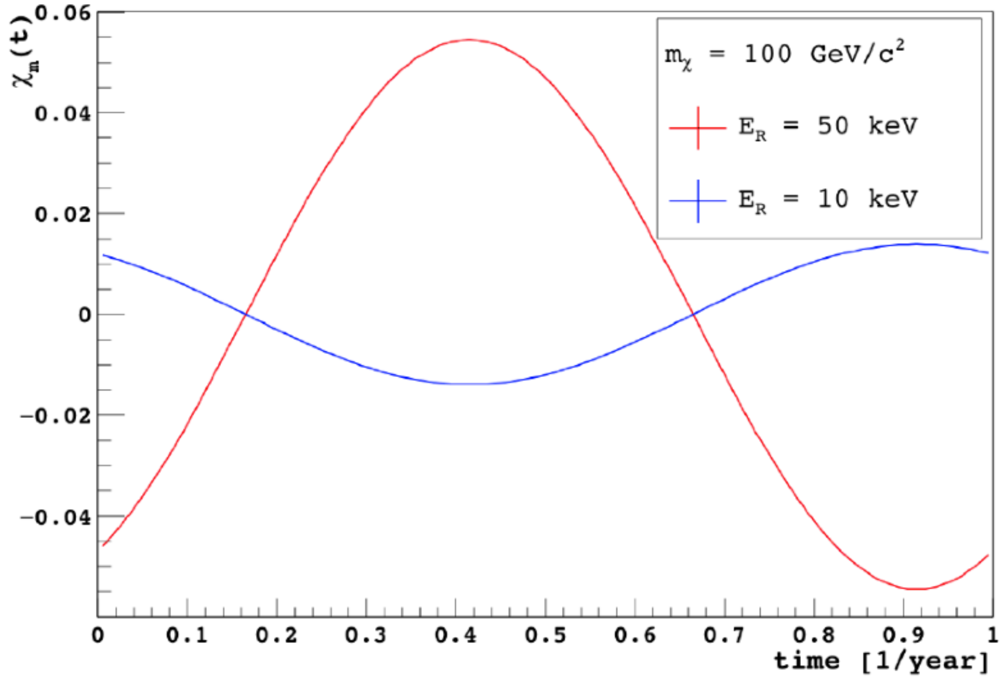
NR spectrum ==> **exclusion limit** (one reference set of assumptions, no full systematics…)

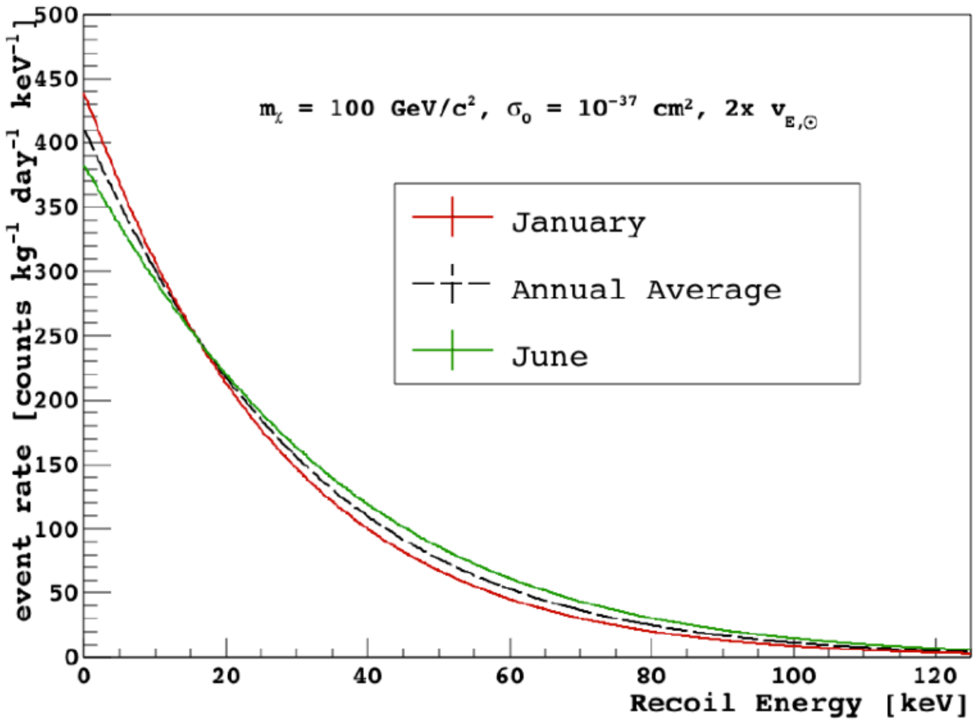
Directionality and modulations

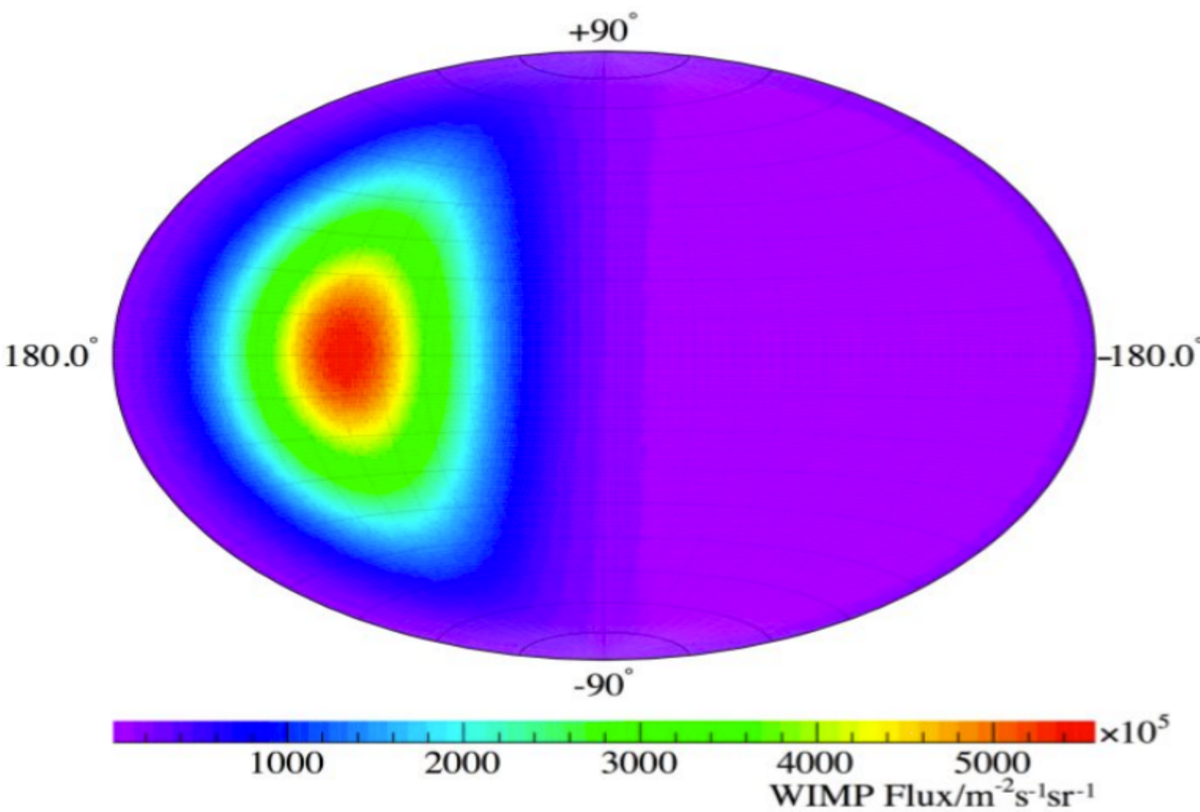
Additional signatures to be considered in case of positive detection



Drukier, Freese, Spergel, PRD 33,1986







Other searches

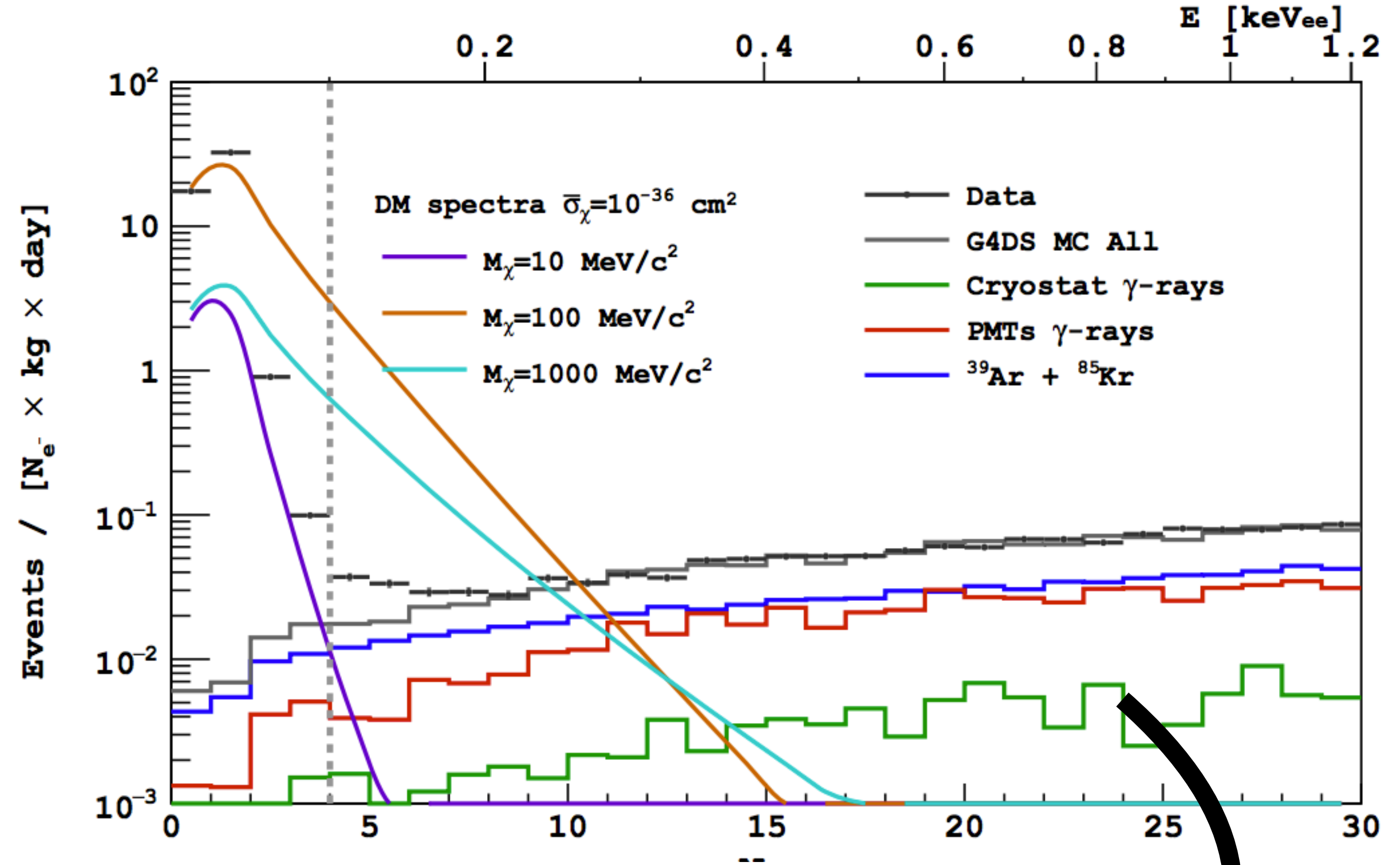
Once your data is understood, many searches are possible

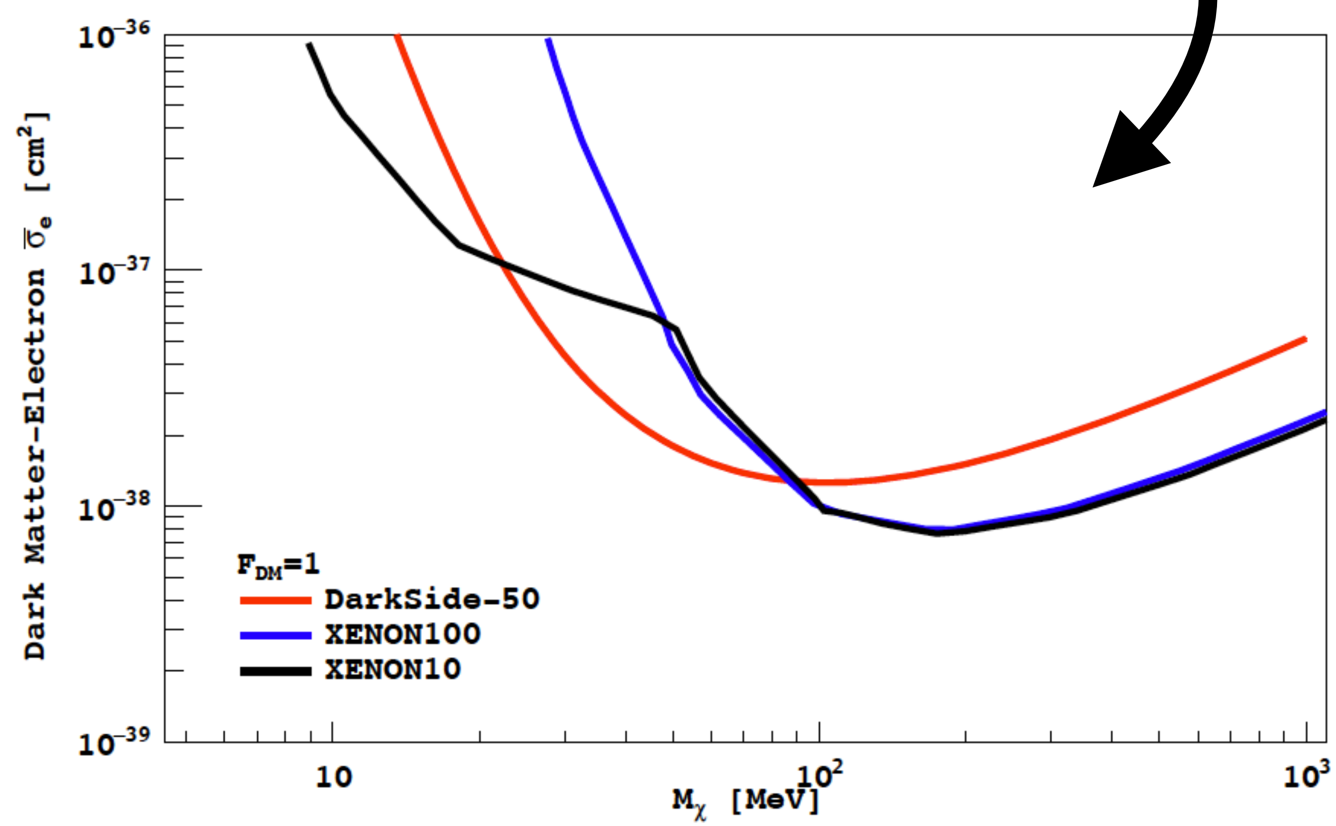
e.g.: WIMP-electron

$$\frac{dR}{d\ln E_{\rm er}} = N_T \frac{\rho_\chi}{m_\chi} \frac{\overline{\sigma}_e}{8\,\mu_{\chi e}^2} \times \sum_{nl} \int dq\, q\, |f_{\rm ion}^{nl}(k', q)|^2\, |F_{\rm DM}(q)|^2\, \eta(v_{\rm min})$$

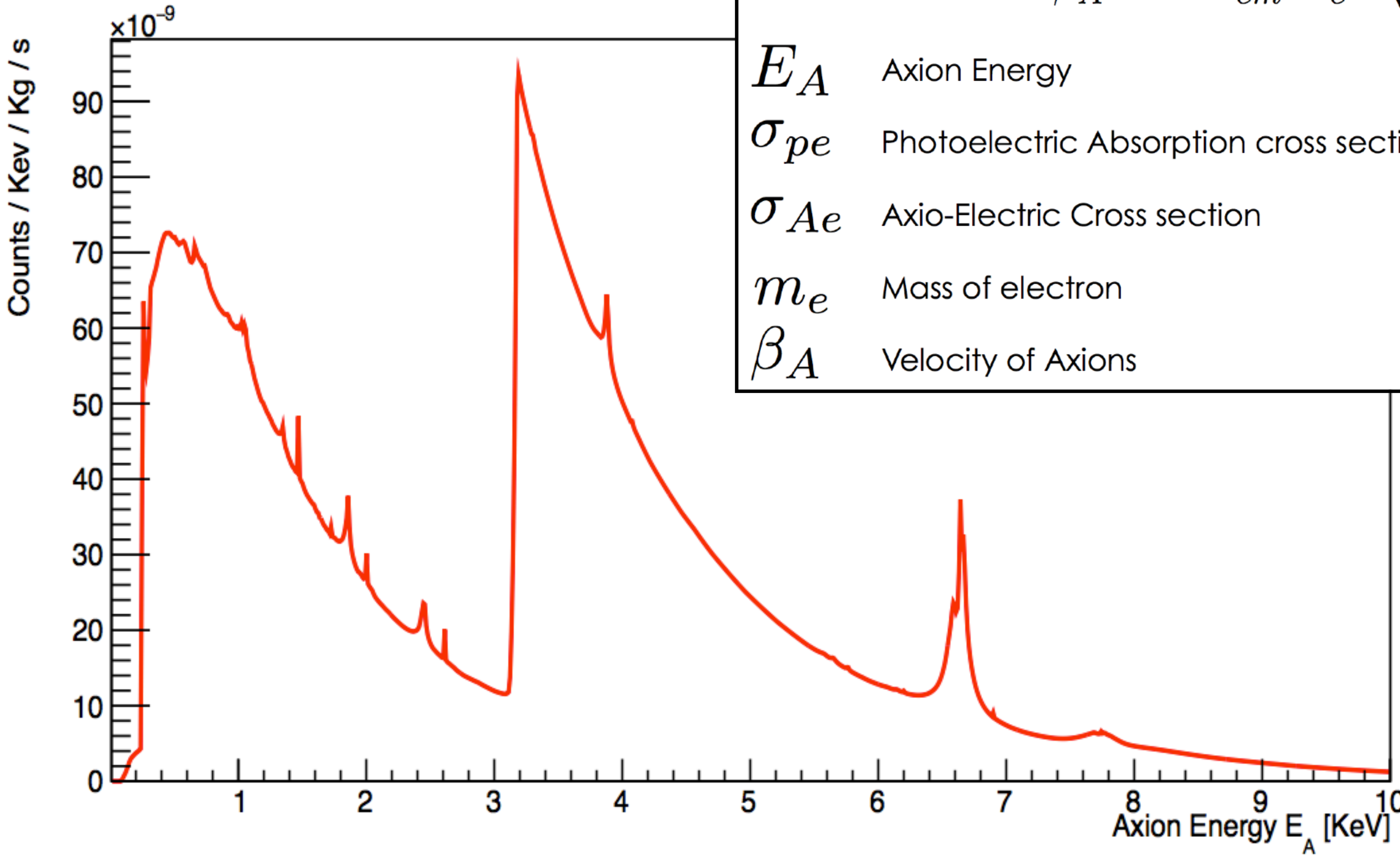
Nuclear form factor ==> electron wave function

$$|F_{\rm DM}(q)|^2 = \begin{cases} 1, & m_{\rm med} \gg \alpha m_e \\ (\alpha m_e/q)^4, & m_{\rm med} \ll \alpha m_e \end{cases}$$





Solar axions



$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{{g_{Ae}}^2}{\beta_A}\frac{3{E_A}^2}{16\pi\,\alpha_{em}\,{m_e}^2}\left(1-\frac{\beta_A^{2/3}}{3}\right)$$

E_A	Axion Energy
σ_{pe}	Photoelectric Absorption cross section
σ_{Ae}	Axio-Electric Cross section
m_e	Mass of electron
β_A	Velocity of Axions

ER spectrum ==> S1/S2 spectrum ==> exclusion limit calculation underway

Conclusions

G4DS, the DarkSide simulation tool, is tuned to reproduce with high accuracy the TPC response

It features a **comprehensive model for the response of LAr** to ER and NR is available in the **energy range of interest for WIMP** searches

==> Ionization and scintillation in LAr

==> NR quenching

==> **can be exported to other setup**

Generators: lacking a general unified framework? Several searches are possible