

Simulation of liquid argon TPCs

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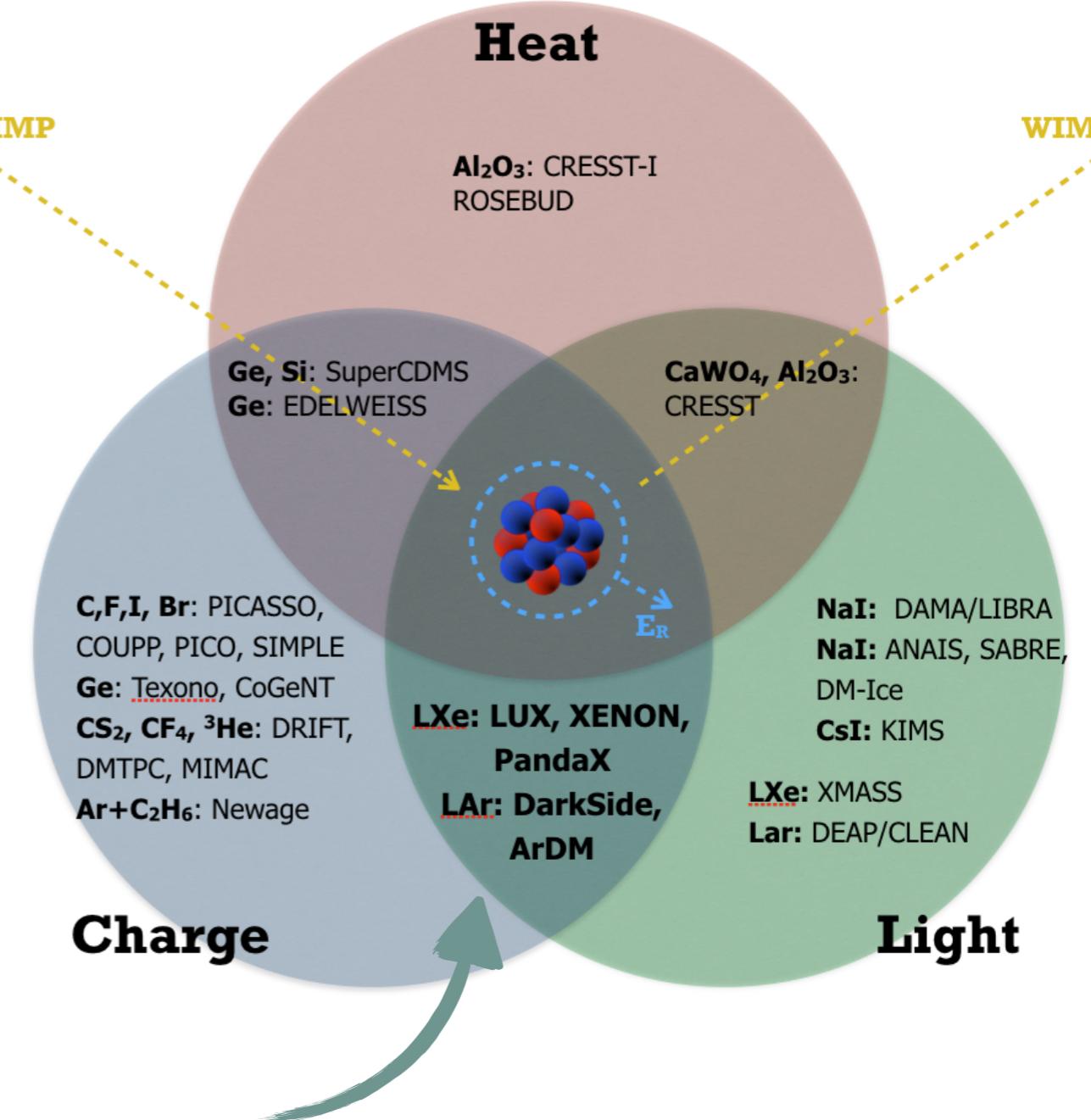
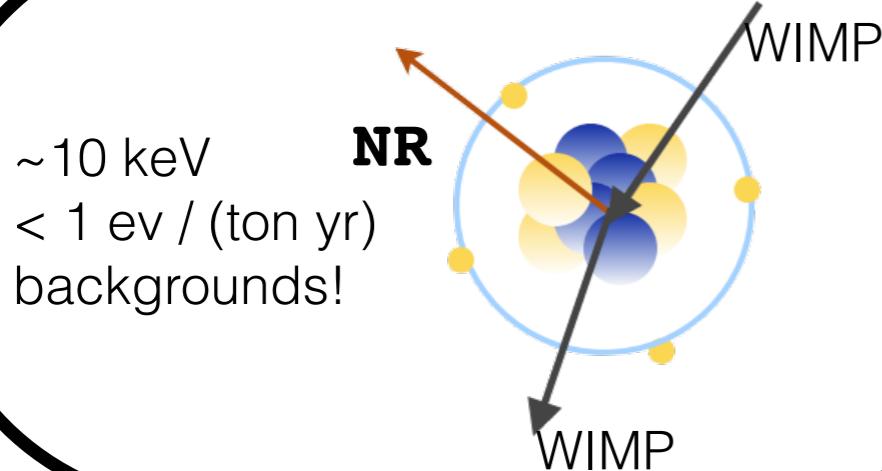
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Instrumentation Days on gaseous detectors 2017



Direct Detection of Dark Matter

Most favored candidate for **Dark Matter**
WIMP
(Weakly Interactive Massive Particles)



Noble liquid experiments, in the **dual-phase TPC** layout

Noble Liquids

Dense, relatively **inexpensive**, easy to **purify**

High **ionisation** yield ($W \sim 10-20$

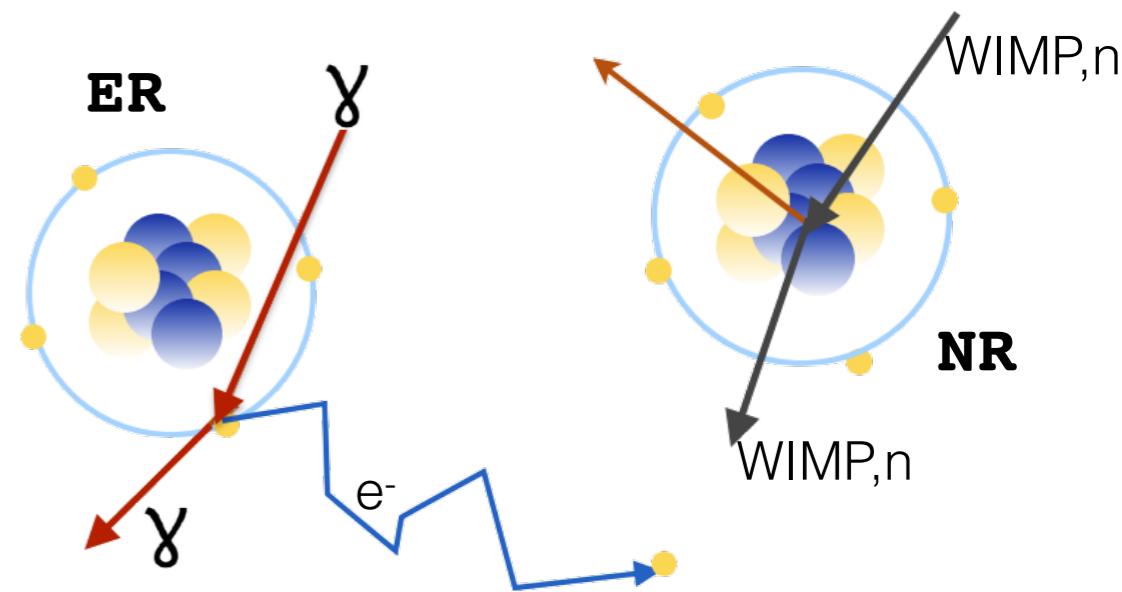
High **scintillation** yield ($> 50,000$ photons/MeV)

Transparent to their own scintillation

High electron mobility and low electron diffusion

Discrimination electron/nuclear recoils (**ER/NR**)

with **ionisation/scintillation**



Liquid Xenon

More dense

High intrinsic radio-purity

Liquid Argon

Better discrimination:

ionisation/scintillation + PSD

Intrinsic contamination from ^{39}Ar

(it can be depleted)

Complementarity

ER Background

internal beta's (^{39}Ar , ^{222}Rn)

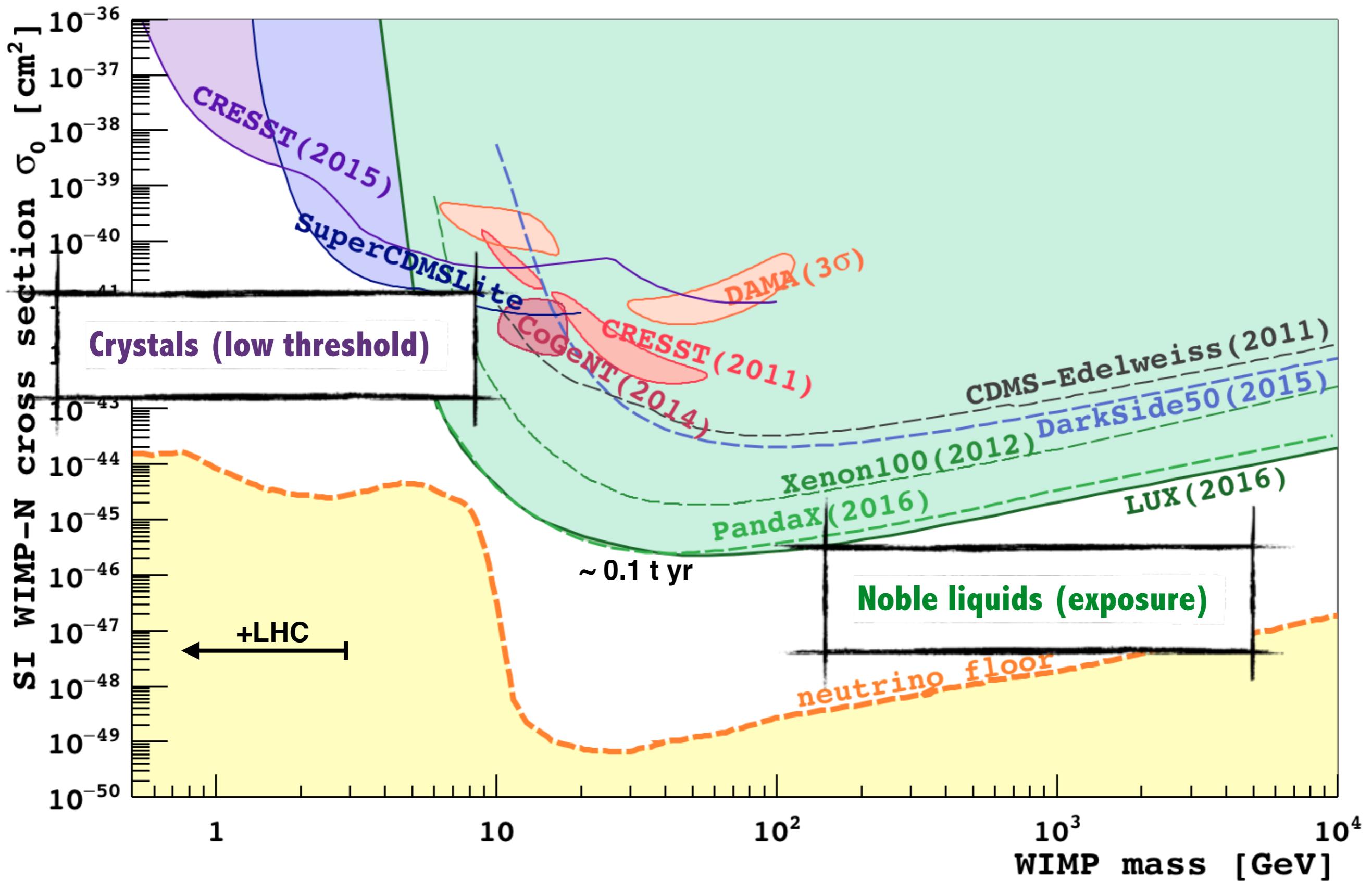
internal/external gammas

NR background

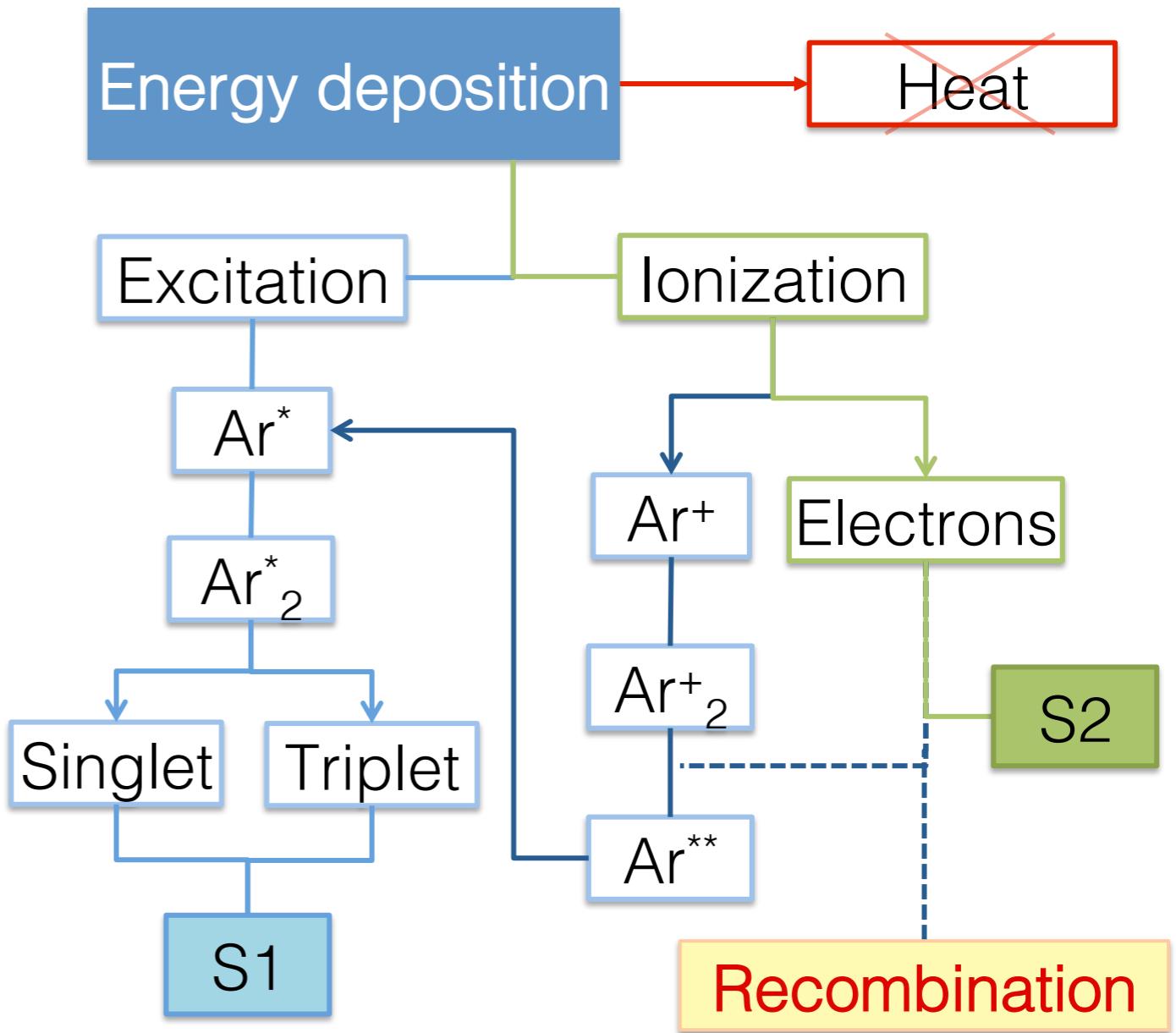
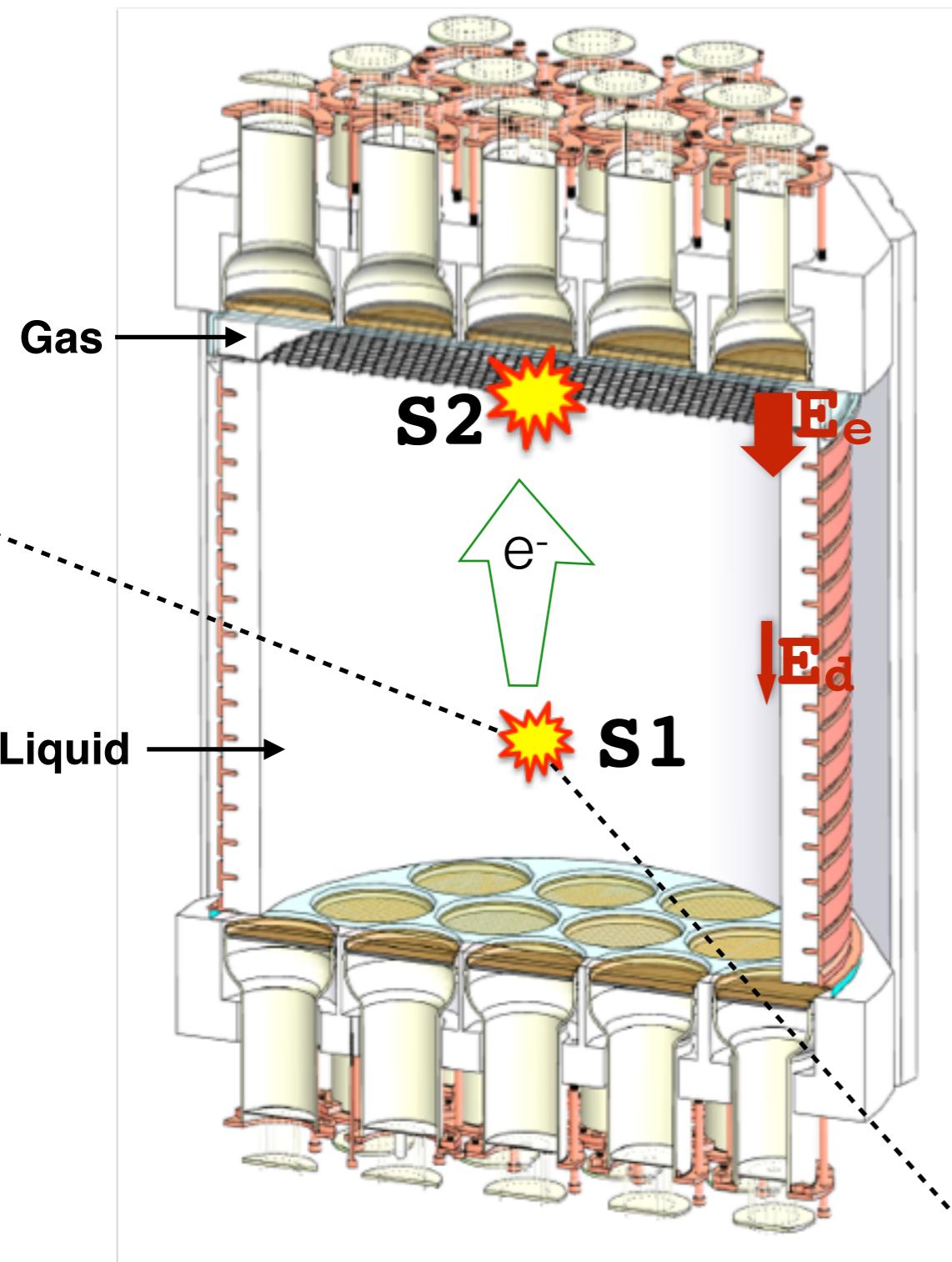
radiogenic neutrons

solar neutrino CNNS (irriducibile)

WIMP-nucleon X-Section Sensitivity

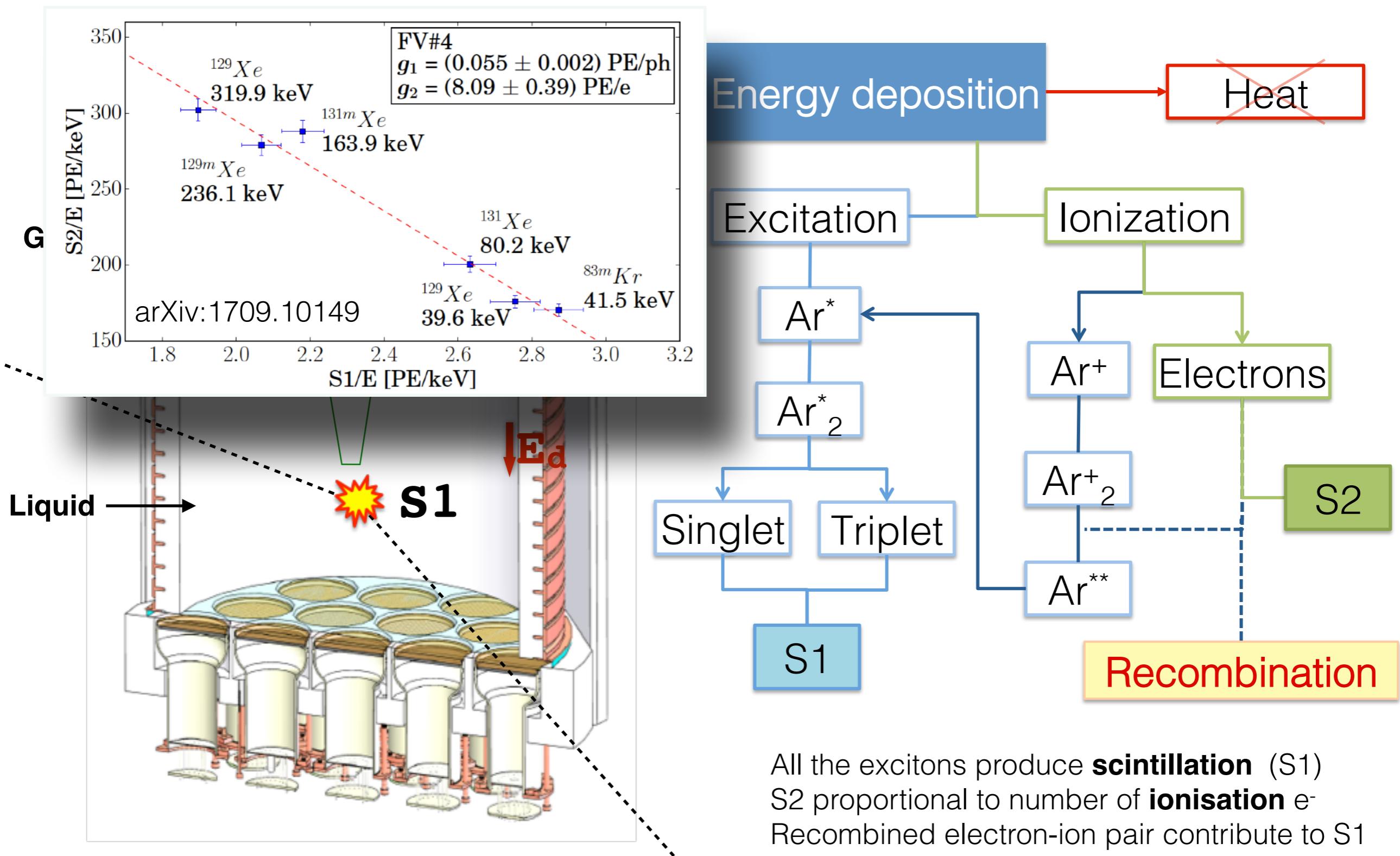


Dual-phase Noble Liquid TPC

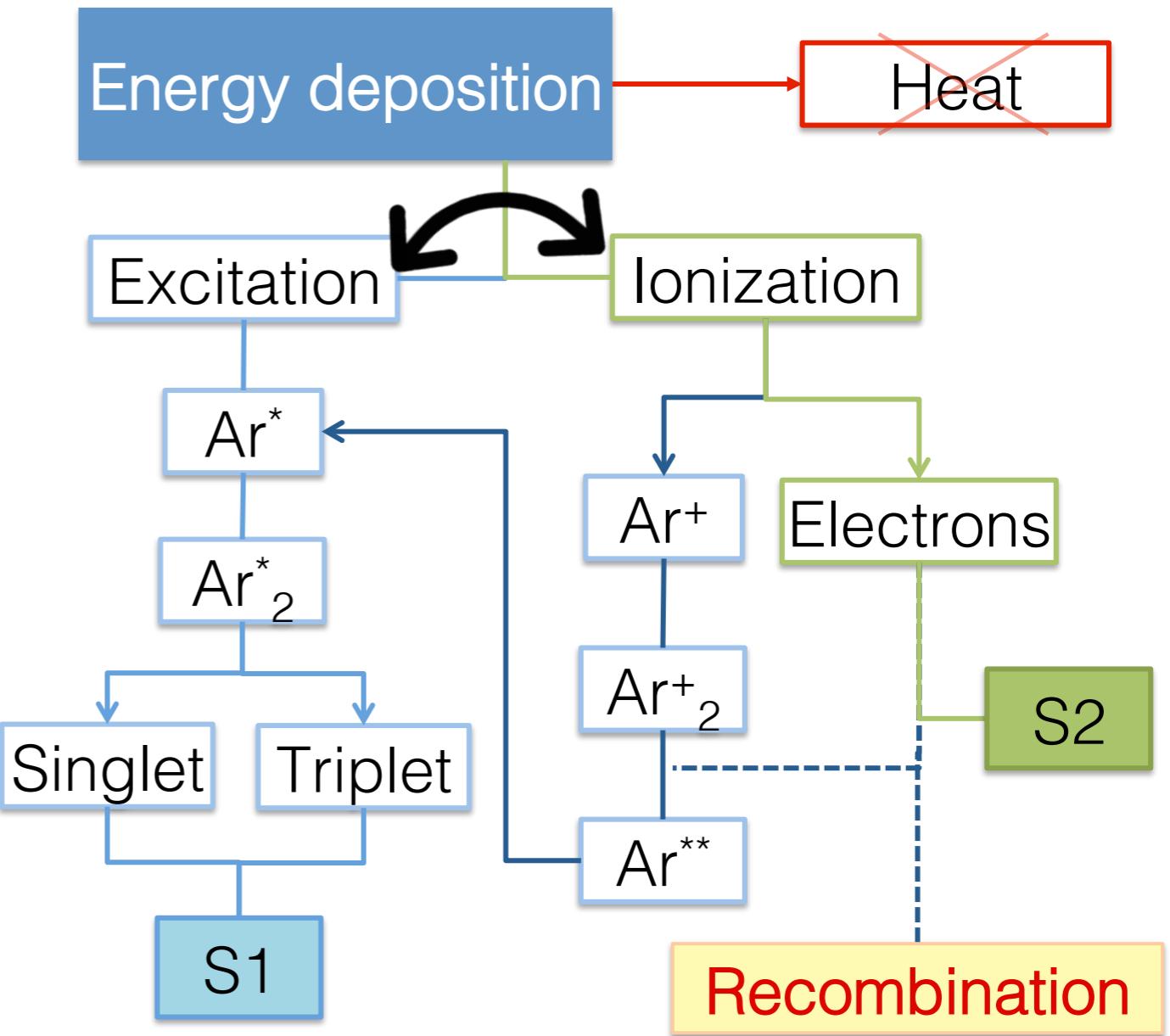
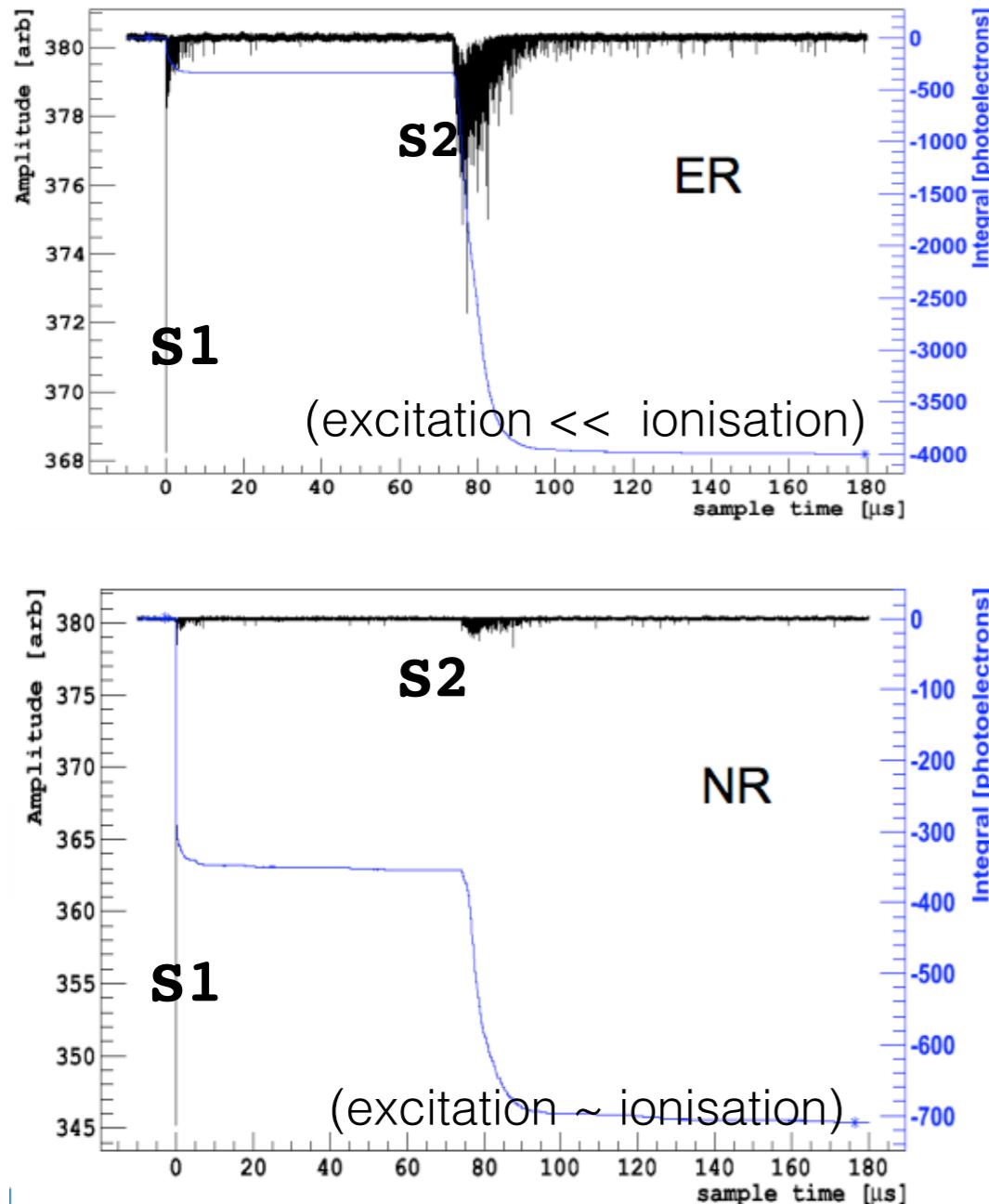


All the excitons produce **scintillation** (S1)
S2 proportional to number of **ionisation** e^-
Recombined electron-ion pair contribute to S1

Dual-phase Noble Liquid TPC



S2/S1 Ratio



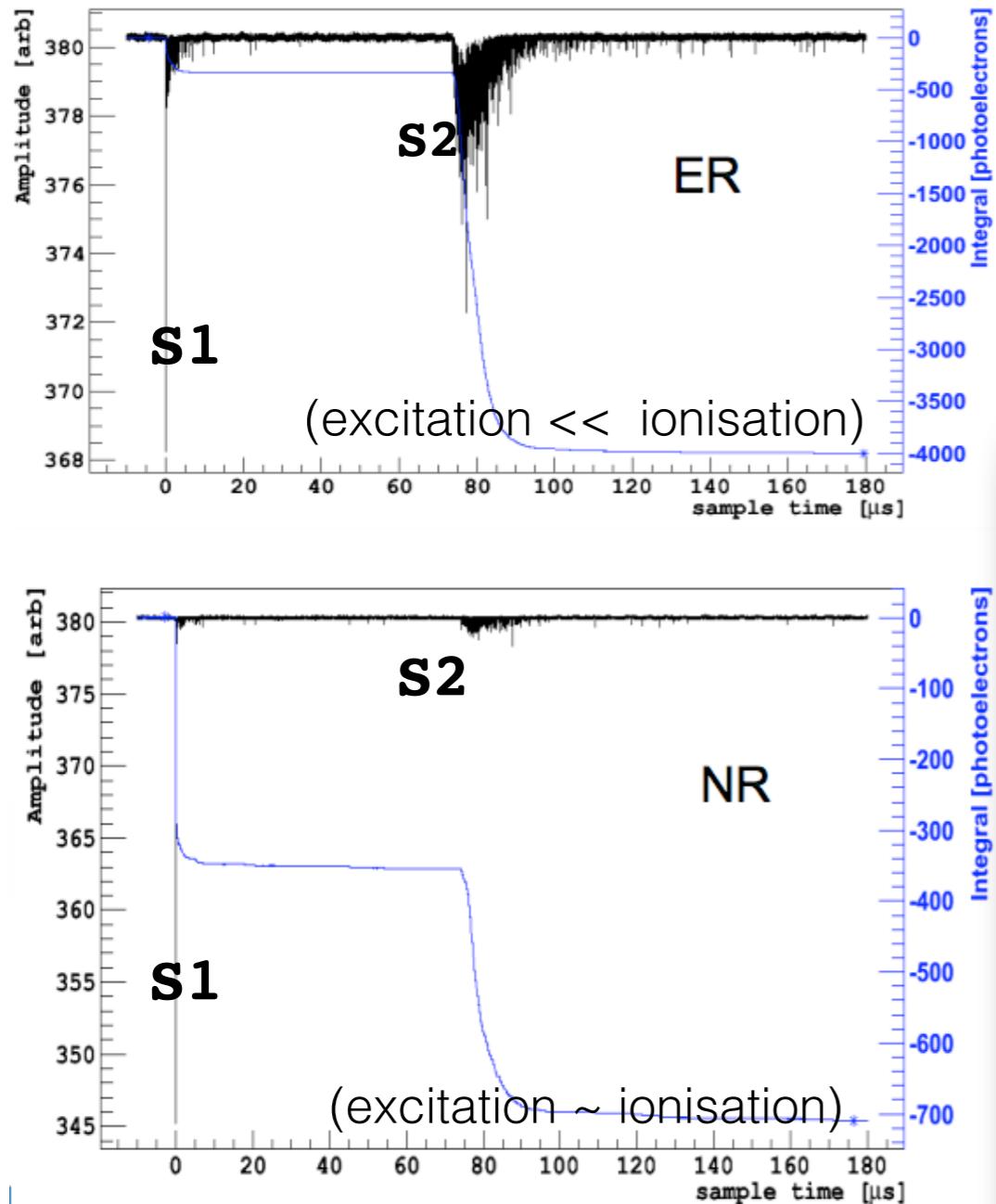
ER Rejection factor: $10^2 - 10^3$

Benetti et al. (ICARUS) 1993;

Benetti et al. (WARP) 2006

Discrimination between
NR (WIMP-induced) and ER (background)

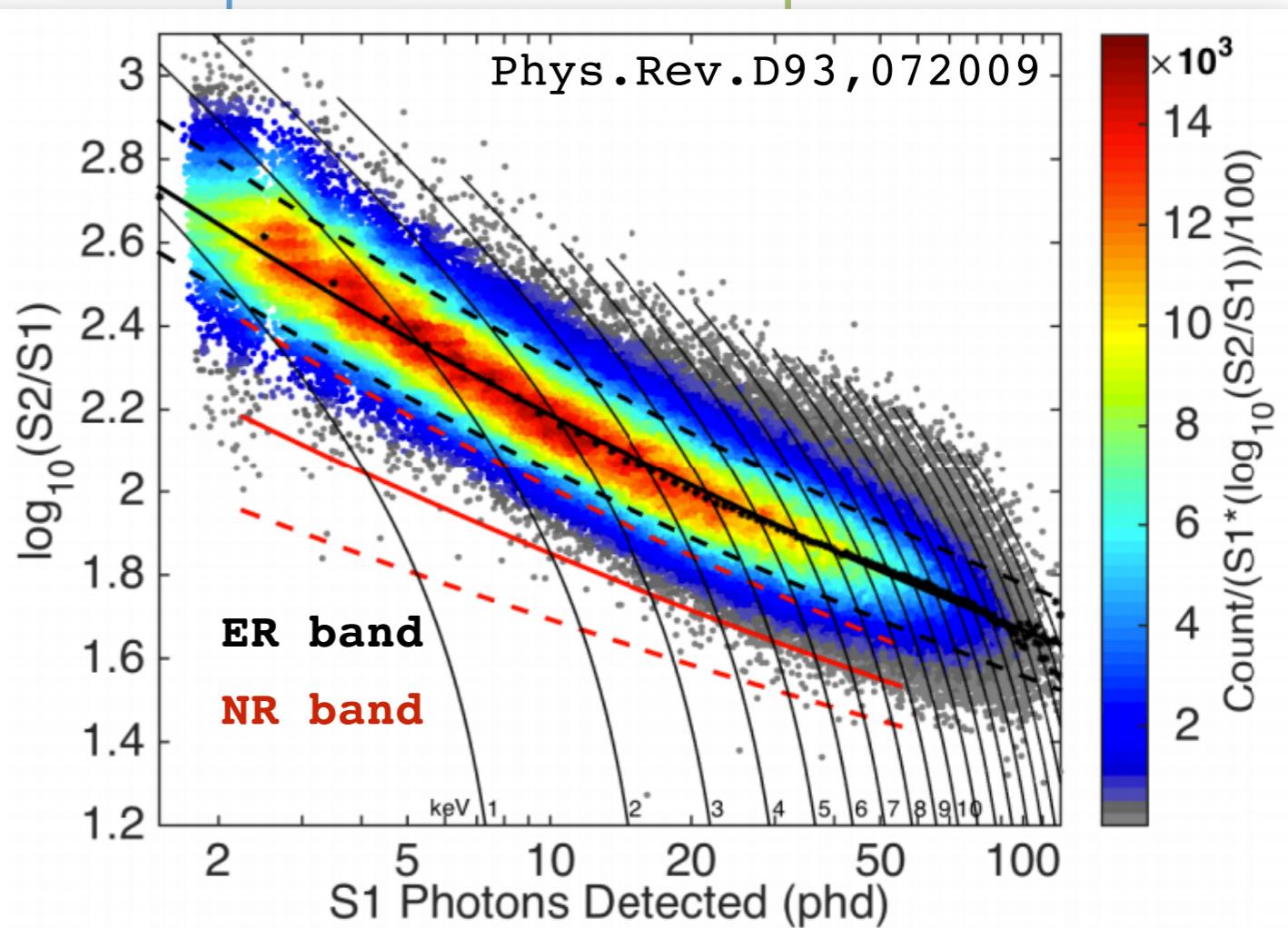
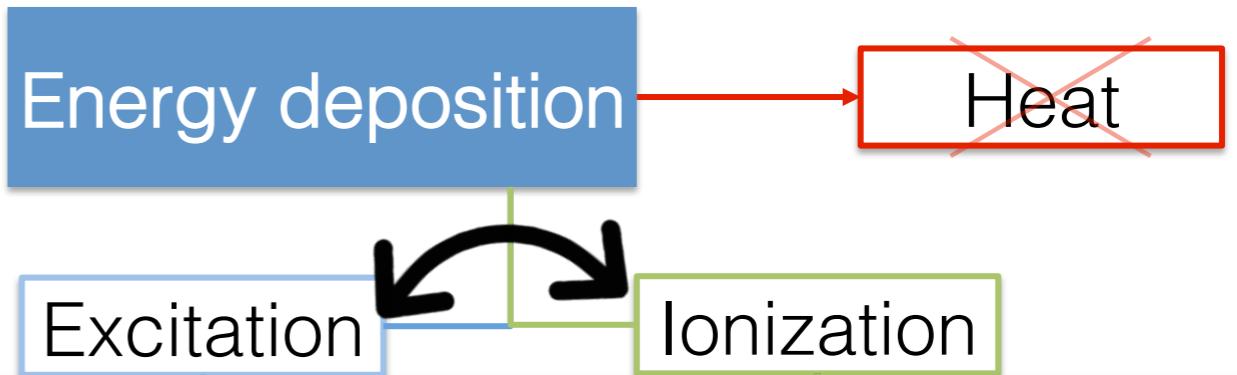
S2/S1 Ratio



ER Rejection factor: $10^2 - 10^3$

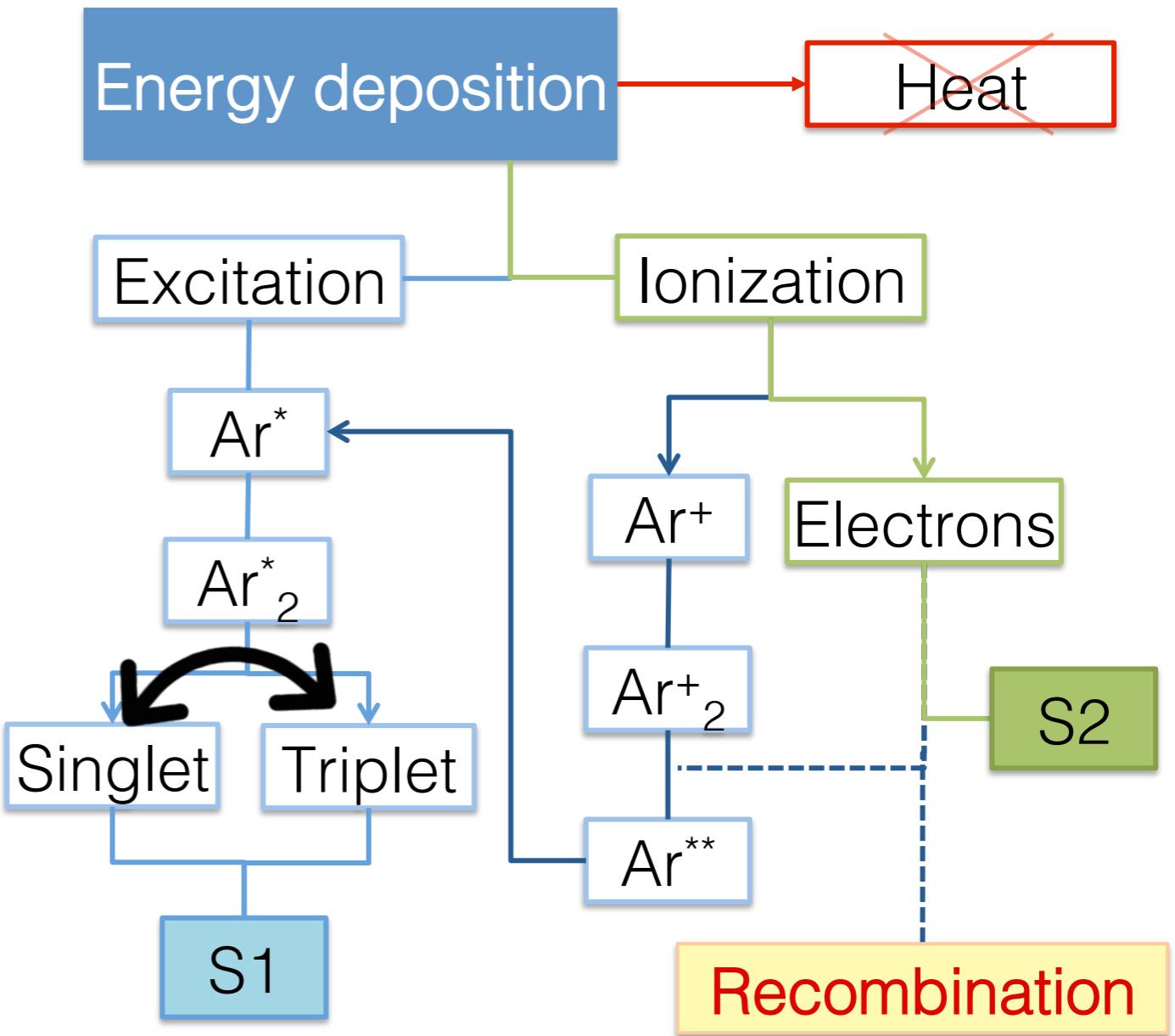
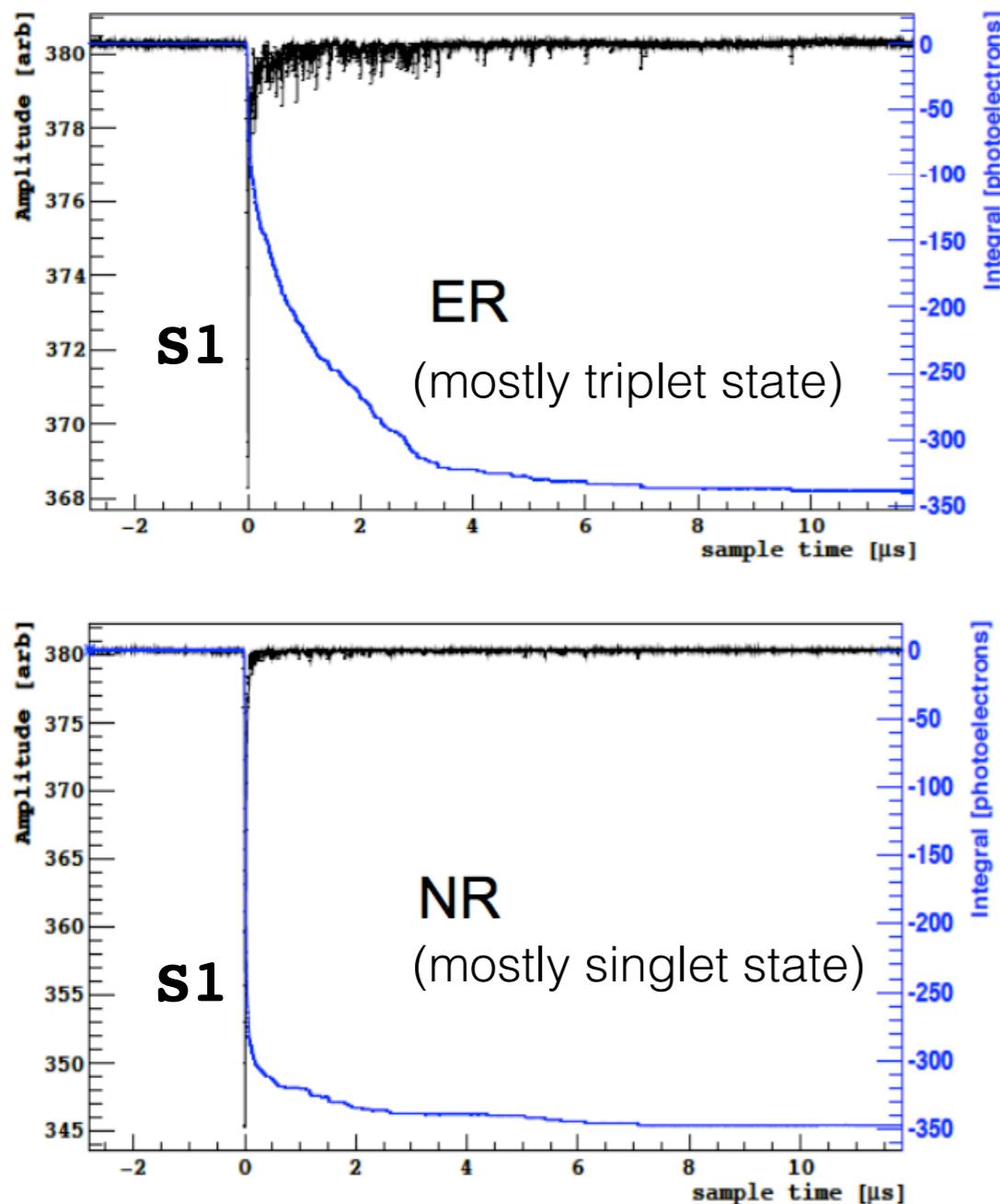
Benetti et al. (ICARUS) 1993;

Benetti et al. (WARP) 2006



Discrimination between
NR (WIMP-induced) and ER (background)

Pulse Shape Discrimination



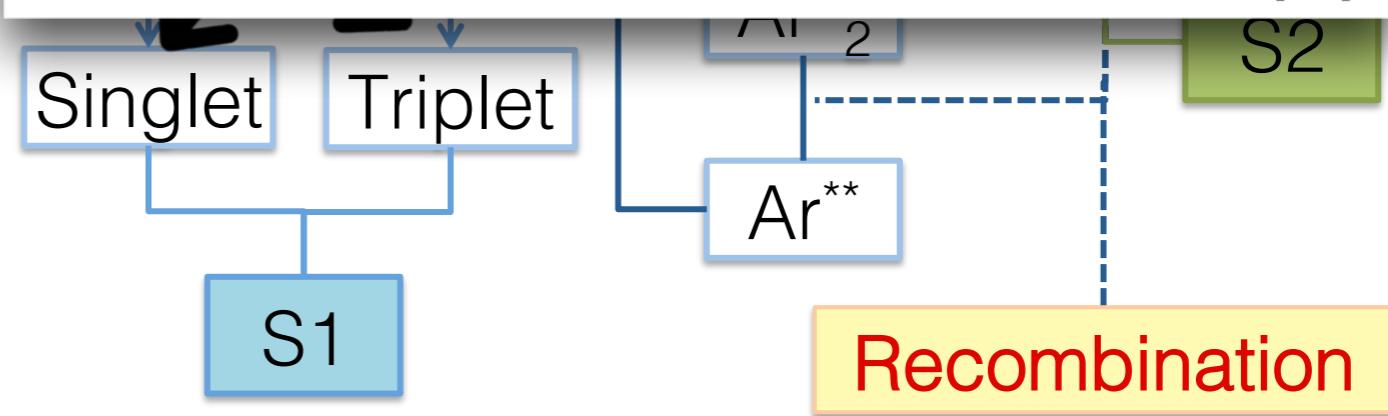
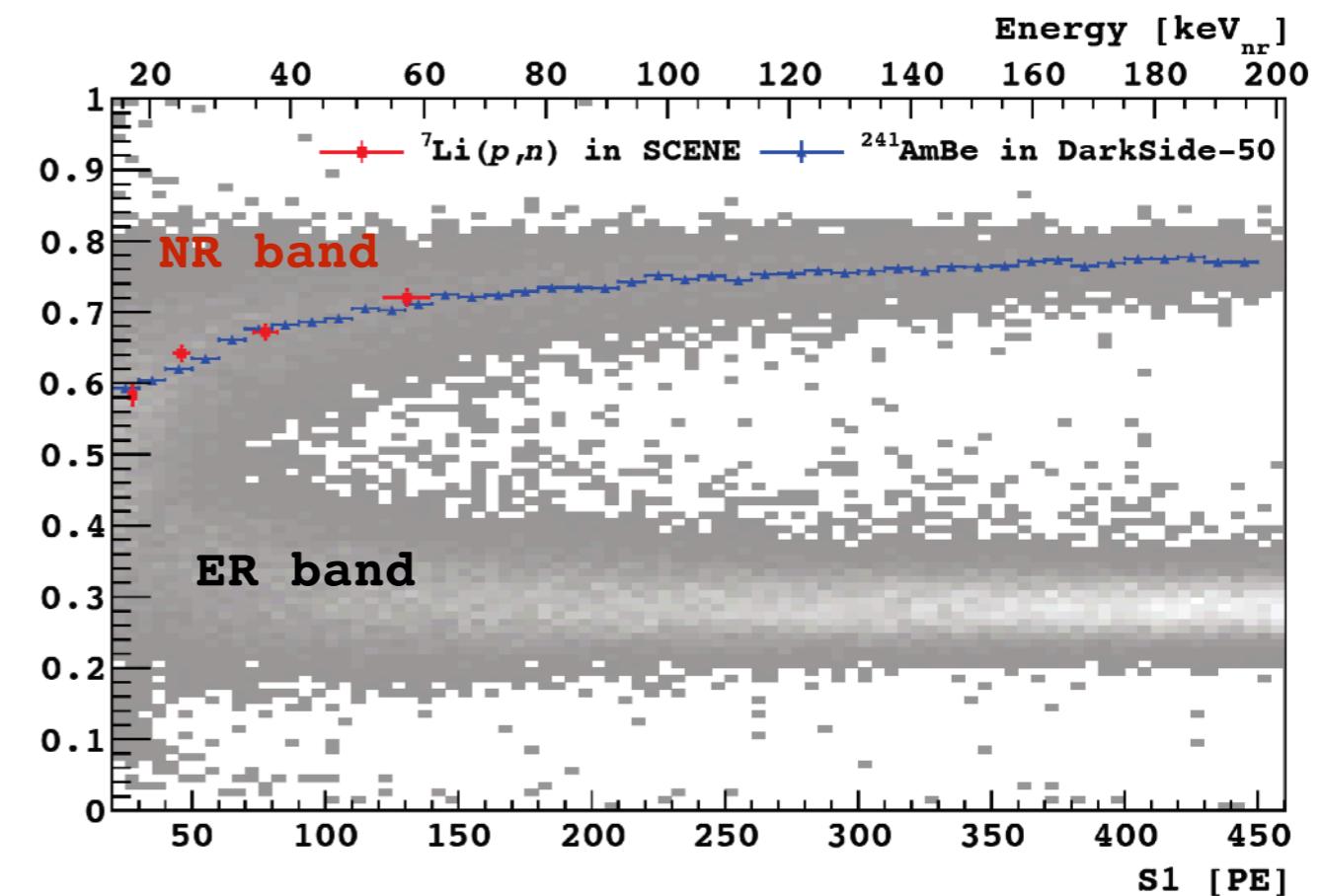
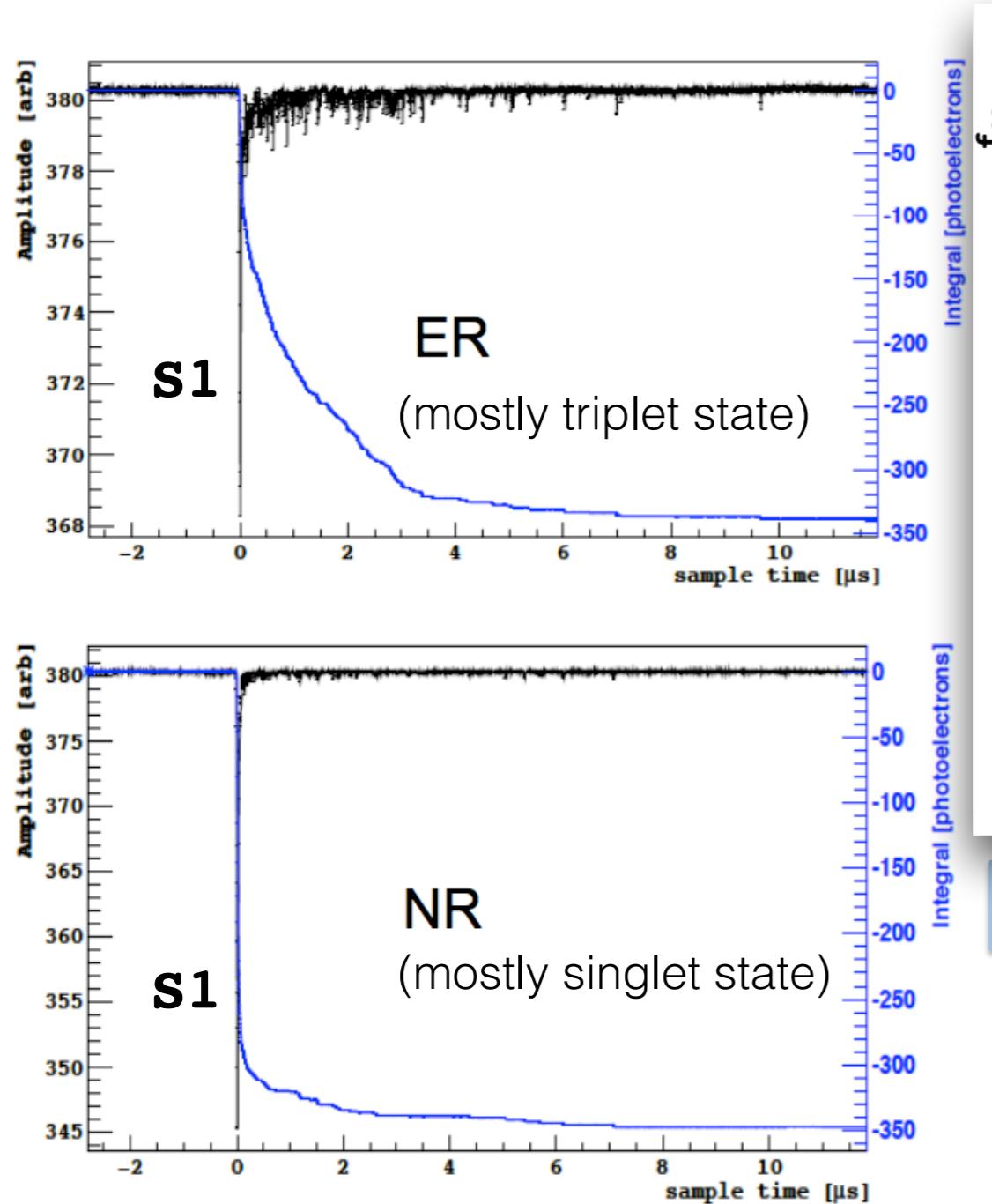
ER Rejection factor: $\sim 10^8$ in LAr

QUOTE DARKSIDE instead of WARP

$$\begin{aligned} \text{LAr } \tau_{\text{singlet}} &= 7 \text{ ns} \\ \text{LAr } \tau_{\text{triplet}} &= 1600 \text{ ns} \end{aligned}$$

PSD: fraction of S1 in the first tens of ns

Pulse Shape Discrimination **in Argon.**



ER Rejection factor: $\sim 10^8$ in LAr

QUOTE DARKSIDE instead of WARP

$$\begin{aligned} \text{LAr } \tau_{\text{singlet}} &= 7 \text{ ns} \\ \text{LAr } \tau_{\text{triplet}} &= 1600 \text{ ns} \end{aligned}$$

PSD: fraction of S1 in the first tens of ns

The DarkSide Program

Dual phase liquid argon TPC, through a **staged** approach:

Main goal: a bg-free experiment, 100 t.yr exposure

Background suppression

- Ultra-low background materials
- **Depleted Liquid Argon**
- Low background photo-detectors
- Low background material components

Background identification

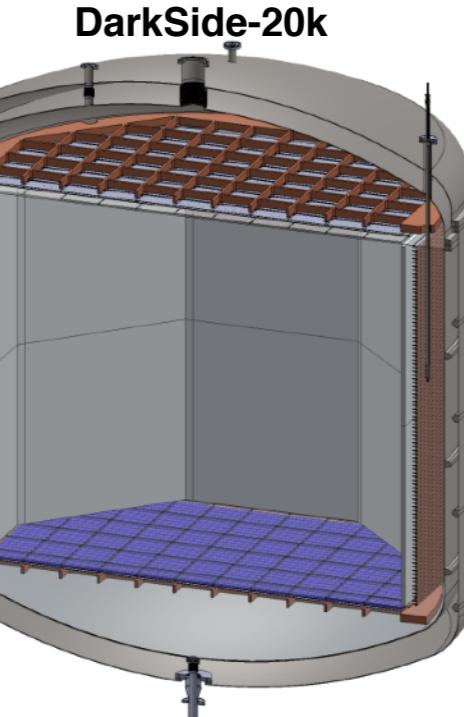
- **Pulse Shape Discrimination** (PSD)
- Ionization/scintillation ratio
- Position reconstruction
(surface events)
- Multiple scatters within the TPC

Active Shielding

- **Liquid Scintillator Veto** (LSV)
- Water Cherenkov against muons (WCD)

x 400

DarkSide-50

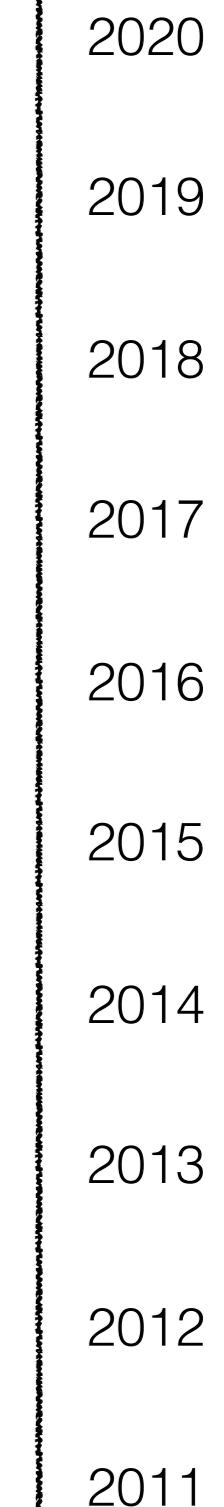


~2000 kg.day

DarkSide-10



x 5



The DarkSide-50 Detector Design

At Laboratori Nazionali del Gran Sasso (LNGS), Italy

Liquid argon TPC

36 cm x 18 cm radius

50 kg LAr (36.9 kg fiducial mass)

19 + 19 3" PMTs

Cold pre-amplifiers

Uniform Electric Field (200 V/cm)

~ 1 cm Gas Pocket

Extraction Electric Field (2.8 kV/cm)

Reflectors and TPB coating

Liquid Scintillator Veto (LSV)

30 tons, 2 m radius

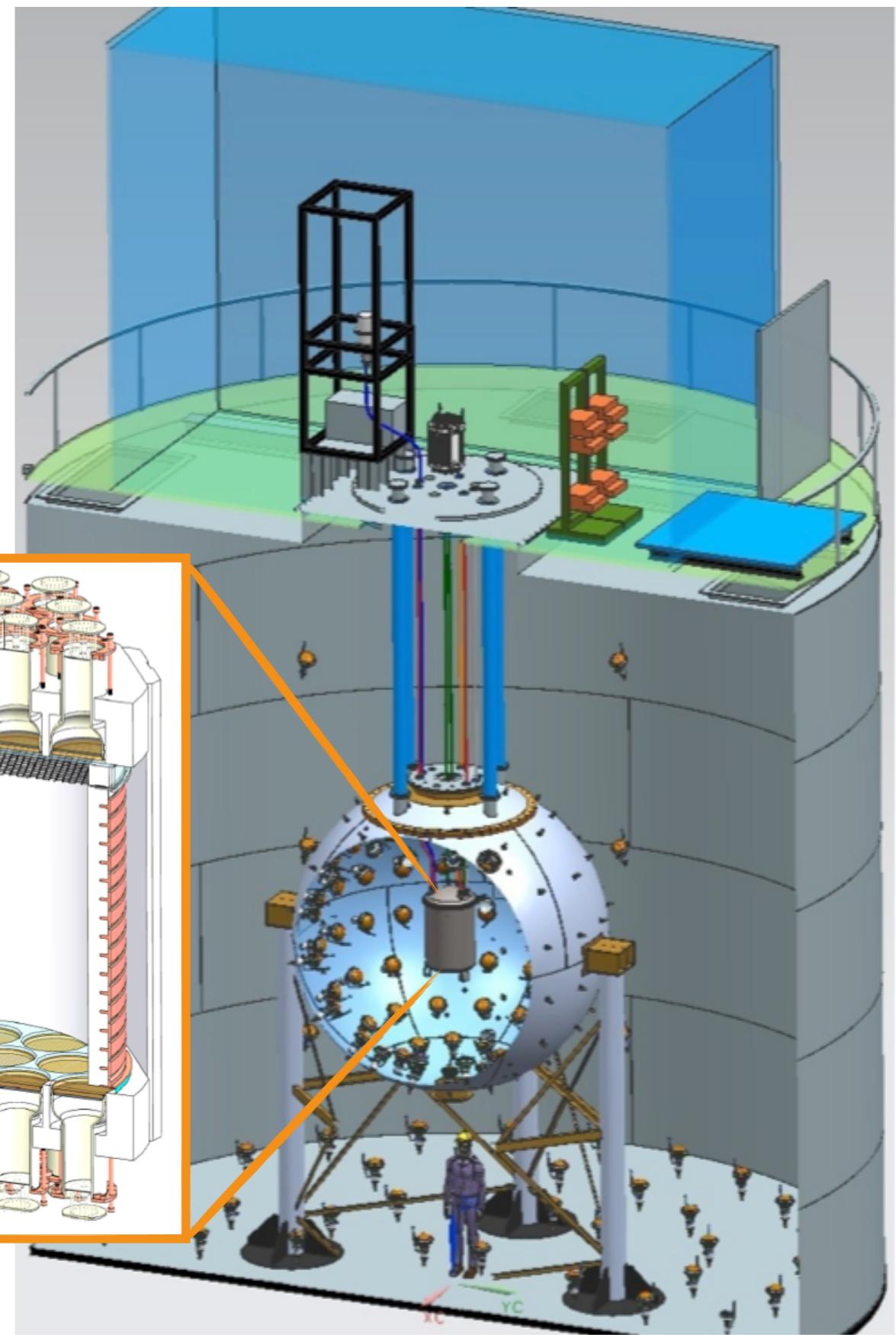
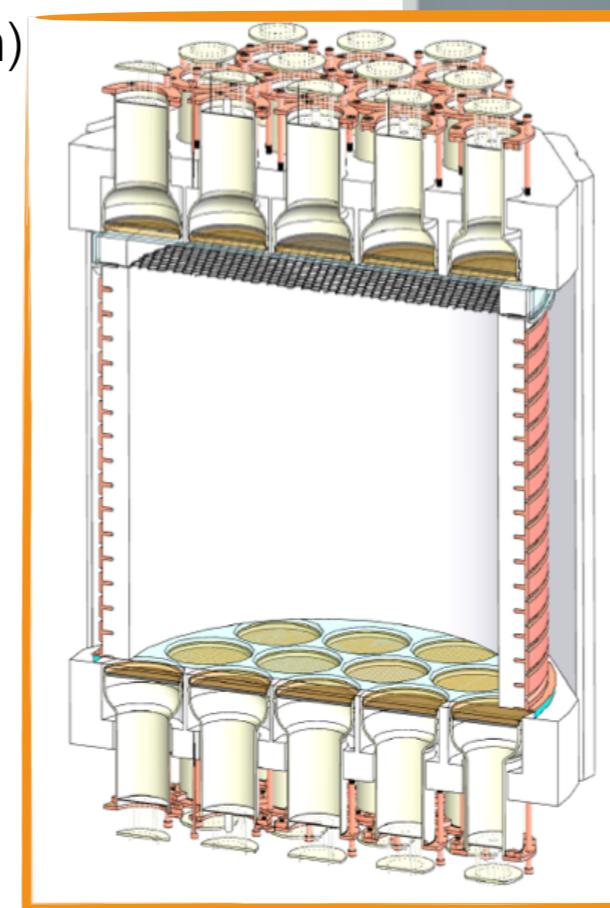
Liquid Scintillator (1:1 TMB + PC)

110 PMTs (LY = 0.5 pe/keV)

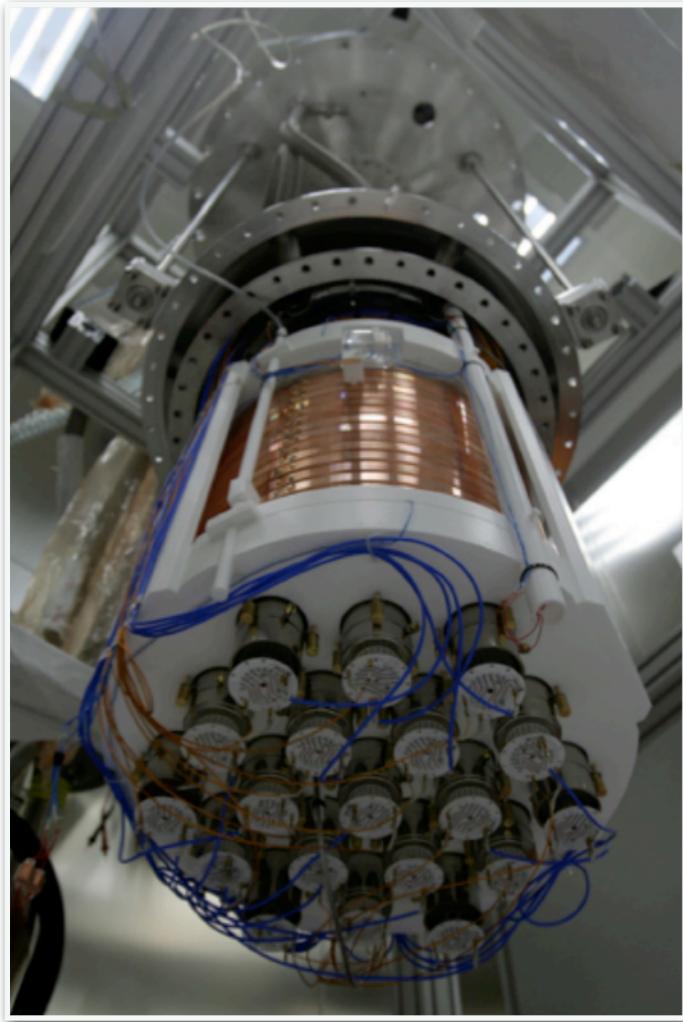
Water Cherenkov Detector (WCD)

1 kt water, 5.5 m radius

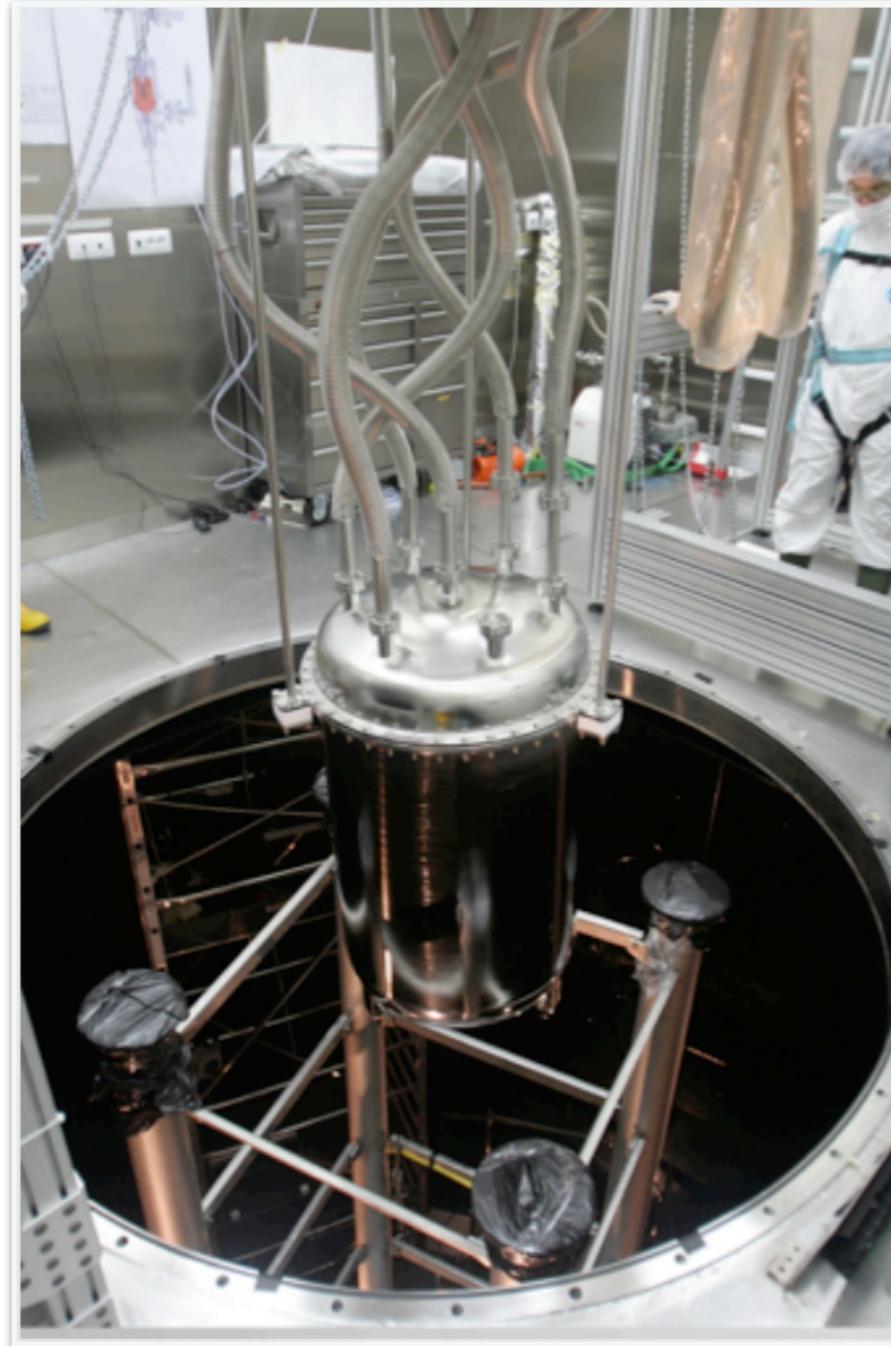
80 PMTs



DarkSide-50 Assembly

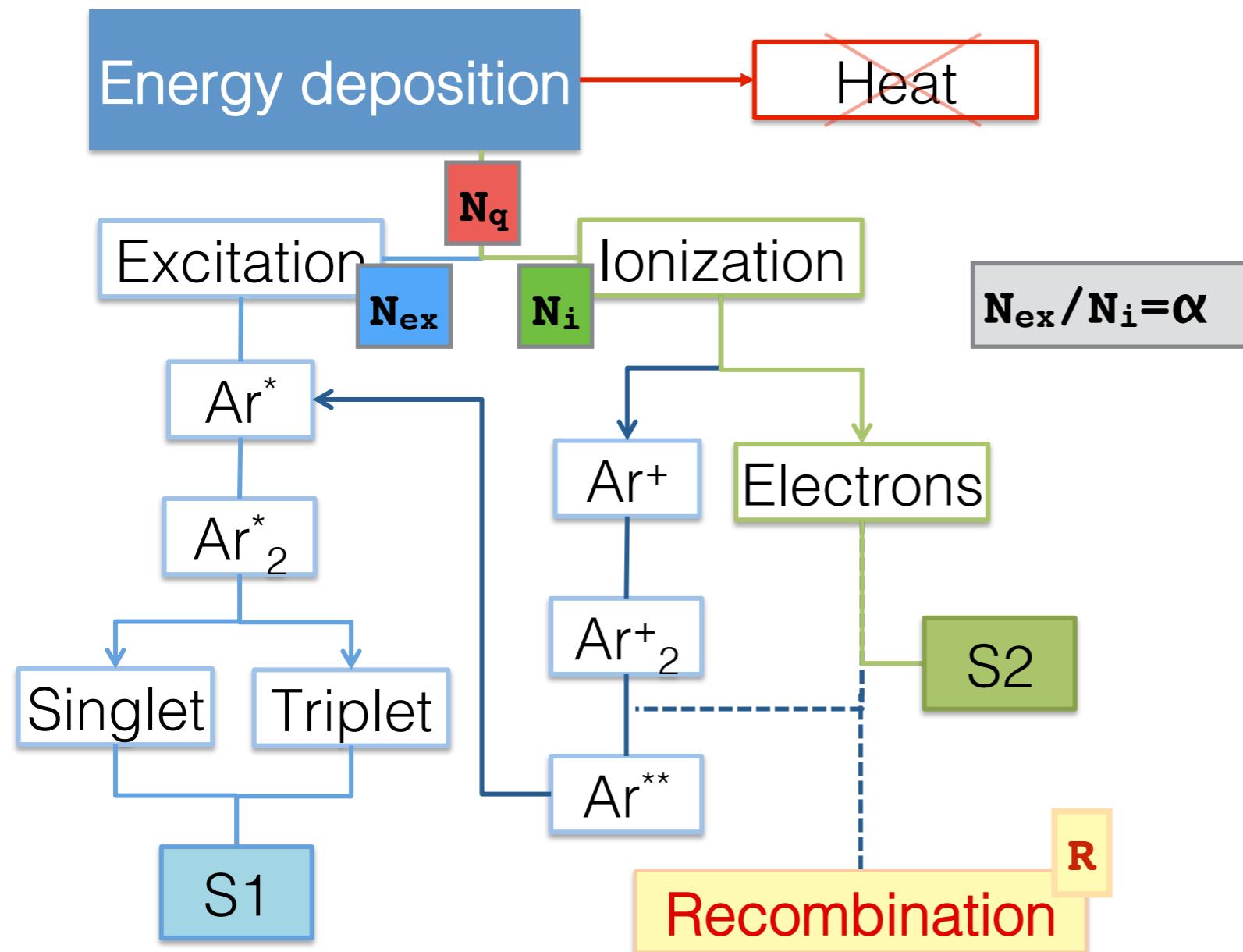


Taking data since
Oct 2013



Physics results: [Phys.Lett.B 743\(456\) \(AAr\)](#), [Phys.Rev.D 93\(2016\)8 \(UAr\)](#)

The Ionization-Scintillation Mechanism



Several models for **Recombination**

Thomas-Imel, Doke-Birks

Detector dependent parameters: light detection efficiency, S2 multiplication factor

Heat fraction is negligible for ER

Mean energy to produce an e^-/ion pair is ~well determined

$$W_i(\text{LAr}) = 23.5 \text{ eV}$$

$$W_i(\text{LXe}) = \sim 14 \text{ eV}$$

For ER:

$$\alpha(\text{LAr}) = 0.21$$

$$\alpha(\text{LXe}) = 0.06(0.20)$$

For NR:

$$\alpha(\text{LAr}) = ?$$

$$\alpha(\text{LXe}) = \sim 1$$

Maximum light output

$$\text{LAr: } (23.5(1+\alpha))^{-1} \rightarrow 51 \gamma/\text{keV}$$

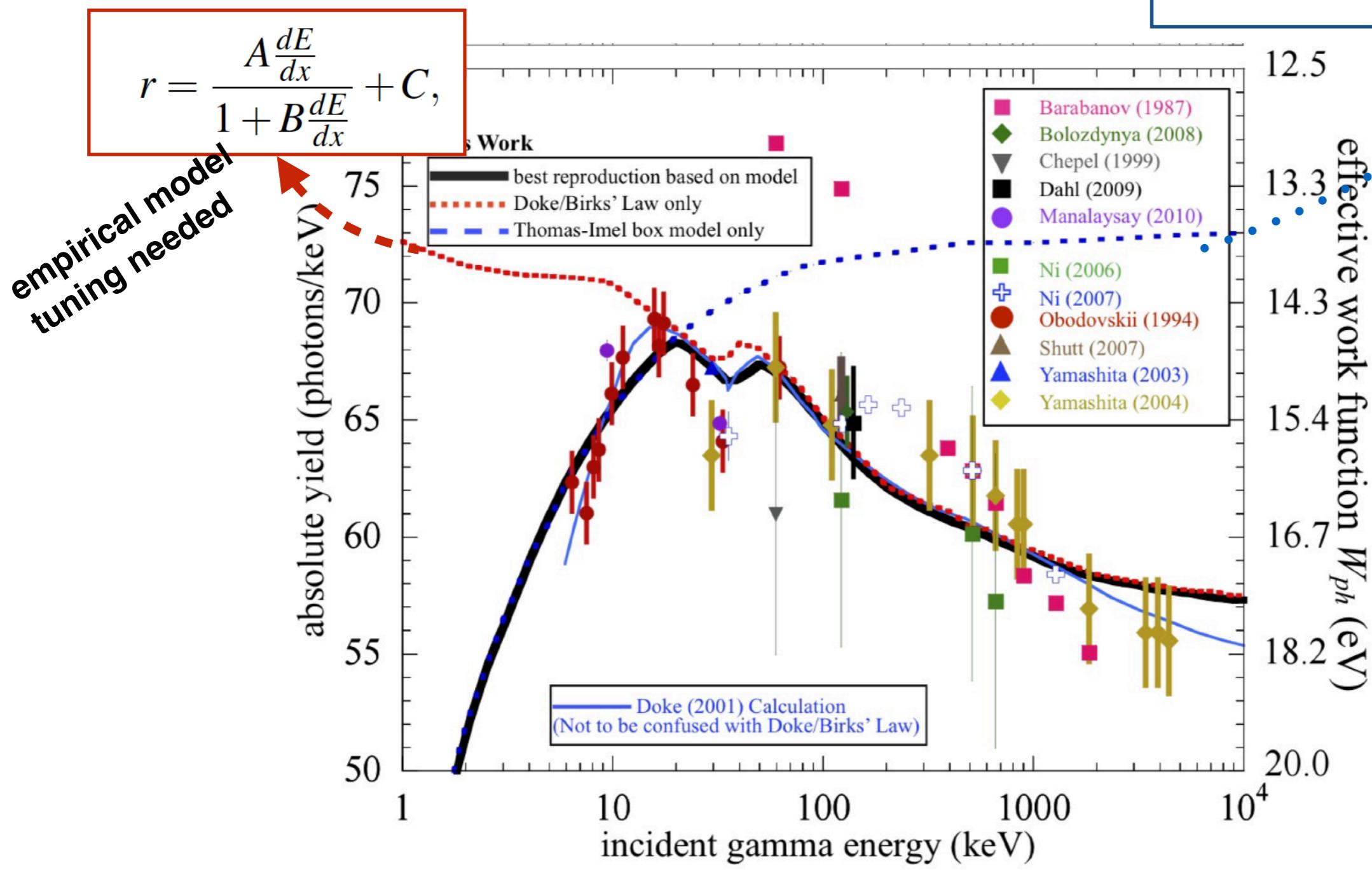
$$\text{LXe} \rightarrow \sim 71 \gamma/\text{keV}$$

NEST for Liquid Xenon

Take into account:

- electrons escaping recombination even at null field ($\sim 10\%$ in LXe?)
- ionization density along the track (dE/dx)
- field dependence (stronger field \rightarrow less recombination)

$$r = 1 - \frac{\ln(1 + \xi)}{\xi}, \quad \xi \equiv \frac{N_i \alpha'}{4a^2 v}$$



JINST 6 P10002

G4DS, the DarkSide Simulation

GEANT-4 based simulation (developed from scratch)

All the detectors included, additional geometries

1. Electronics simulation

2. Full optics description

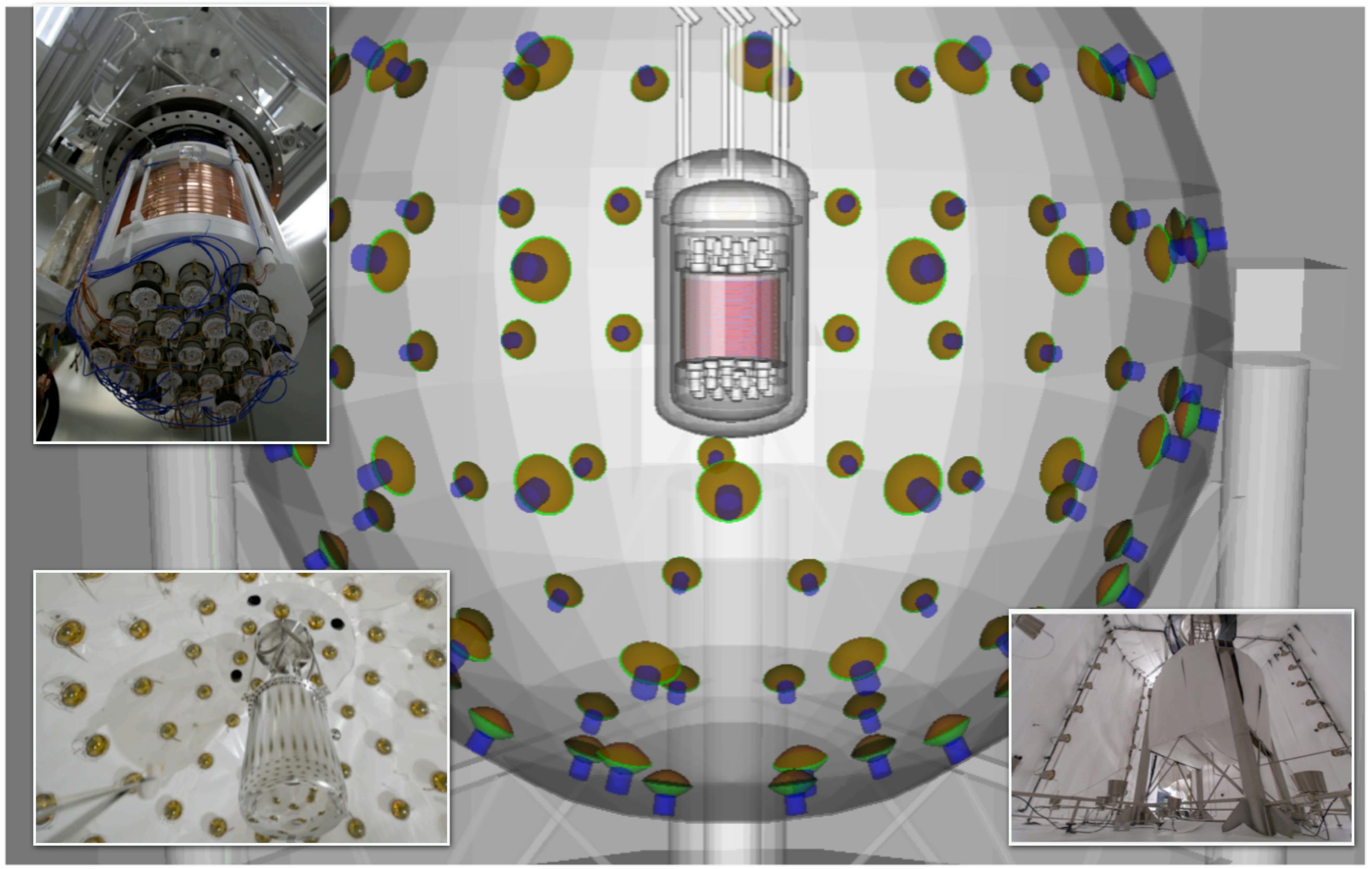
3. TPC energy scale (S1 and S2)

with PARIS (Precision Argon Recoil Ionisation and Scintillation)

4. Calibration of the vetoes

5. Pulse shape discrimination parameter (f90)

DarkSide-50 Geometry



G4DS - Optical Tuning

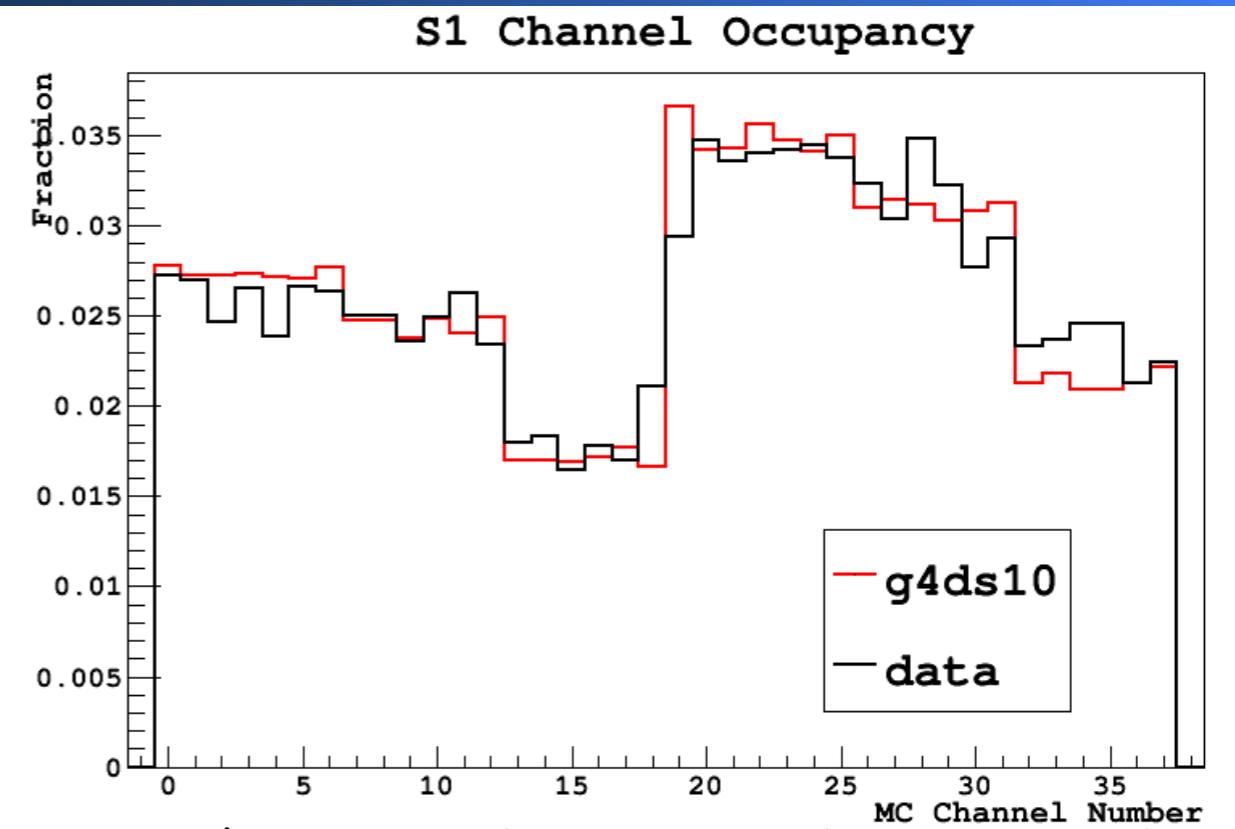
38 PMTs (3 inches), two arrays (top and bottom)

1. Relative quantities: no assumption on energy

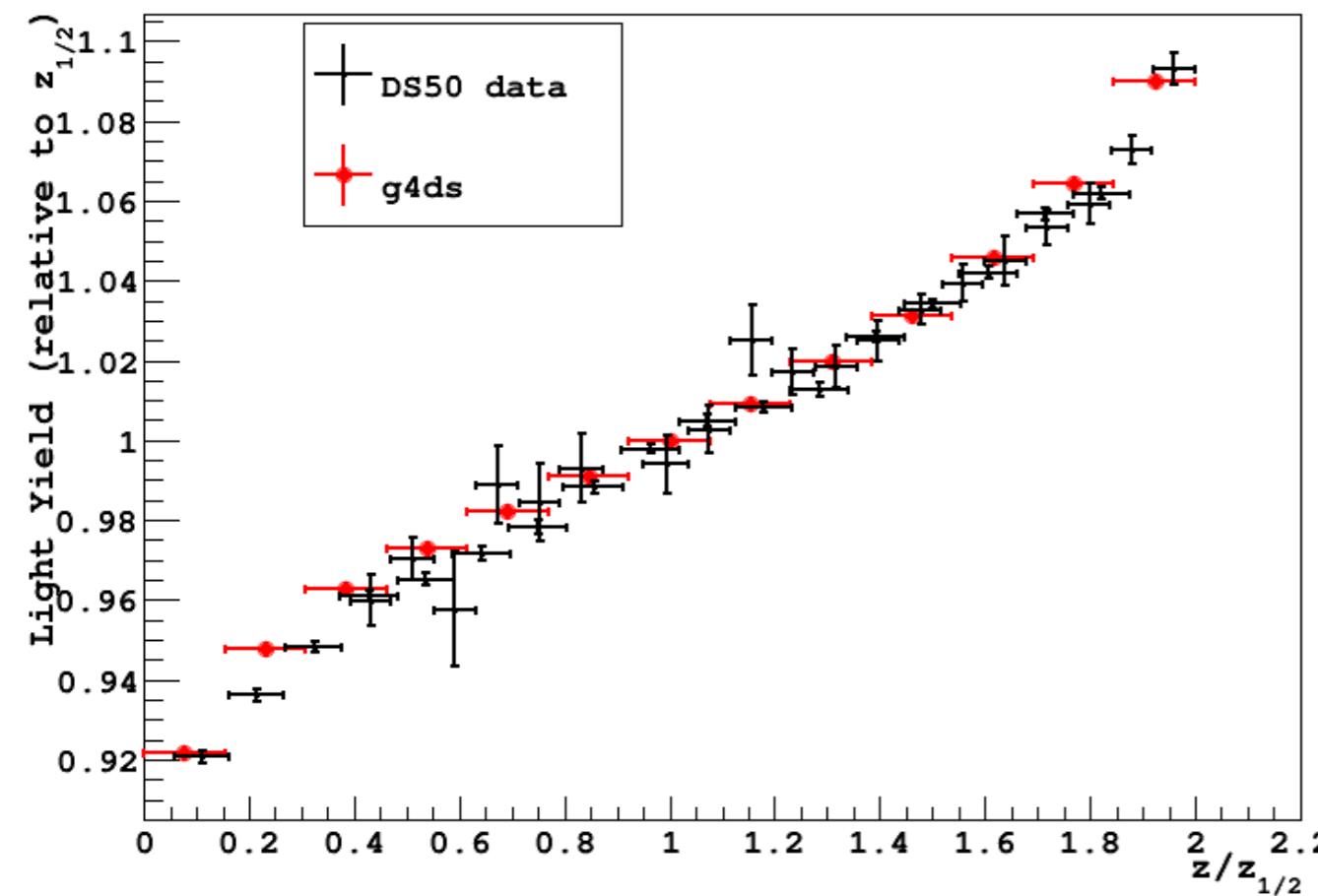
2. Tuning of optical parameters

(refractive indexes, absorption lengths, WLS...)

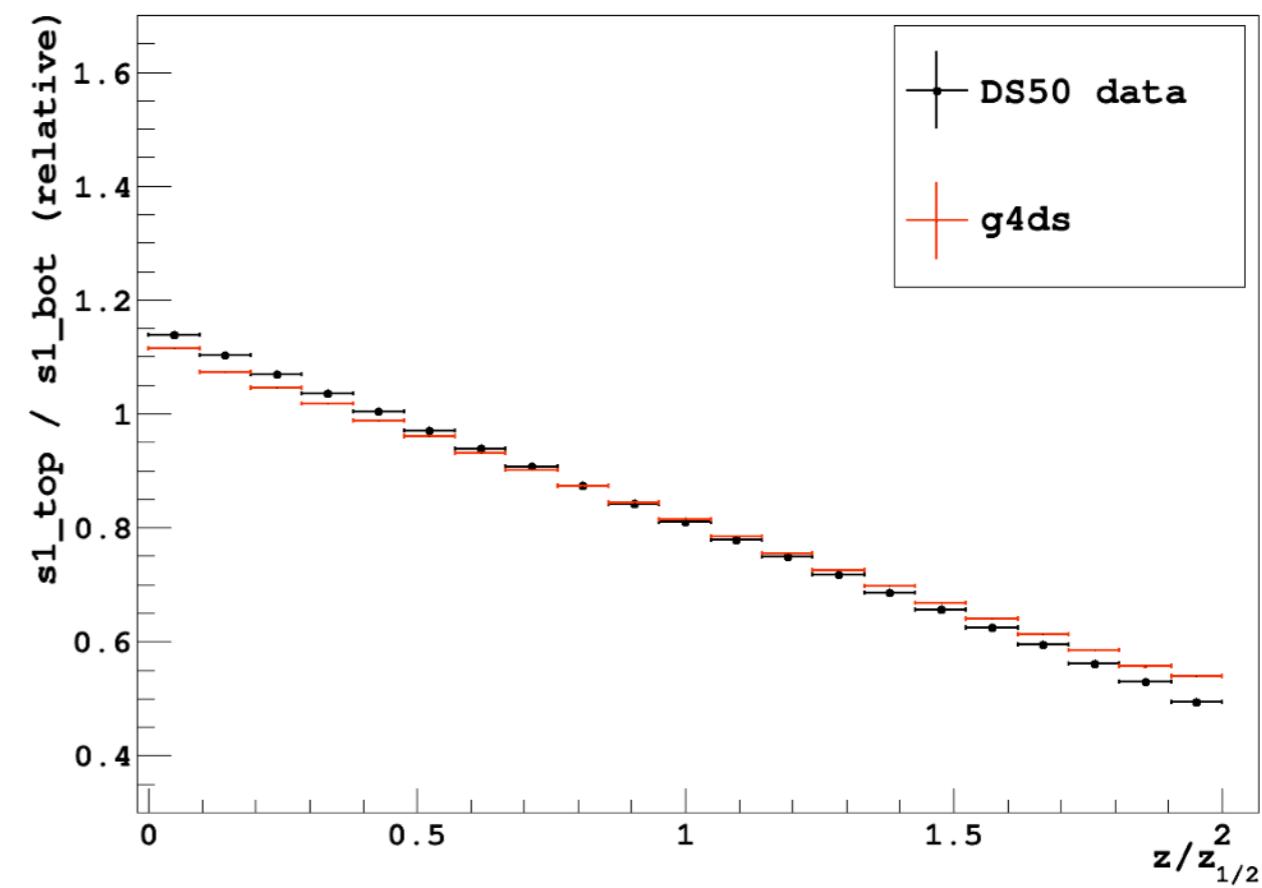
+ condensed Ar layer found/WLS defects



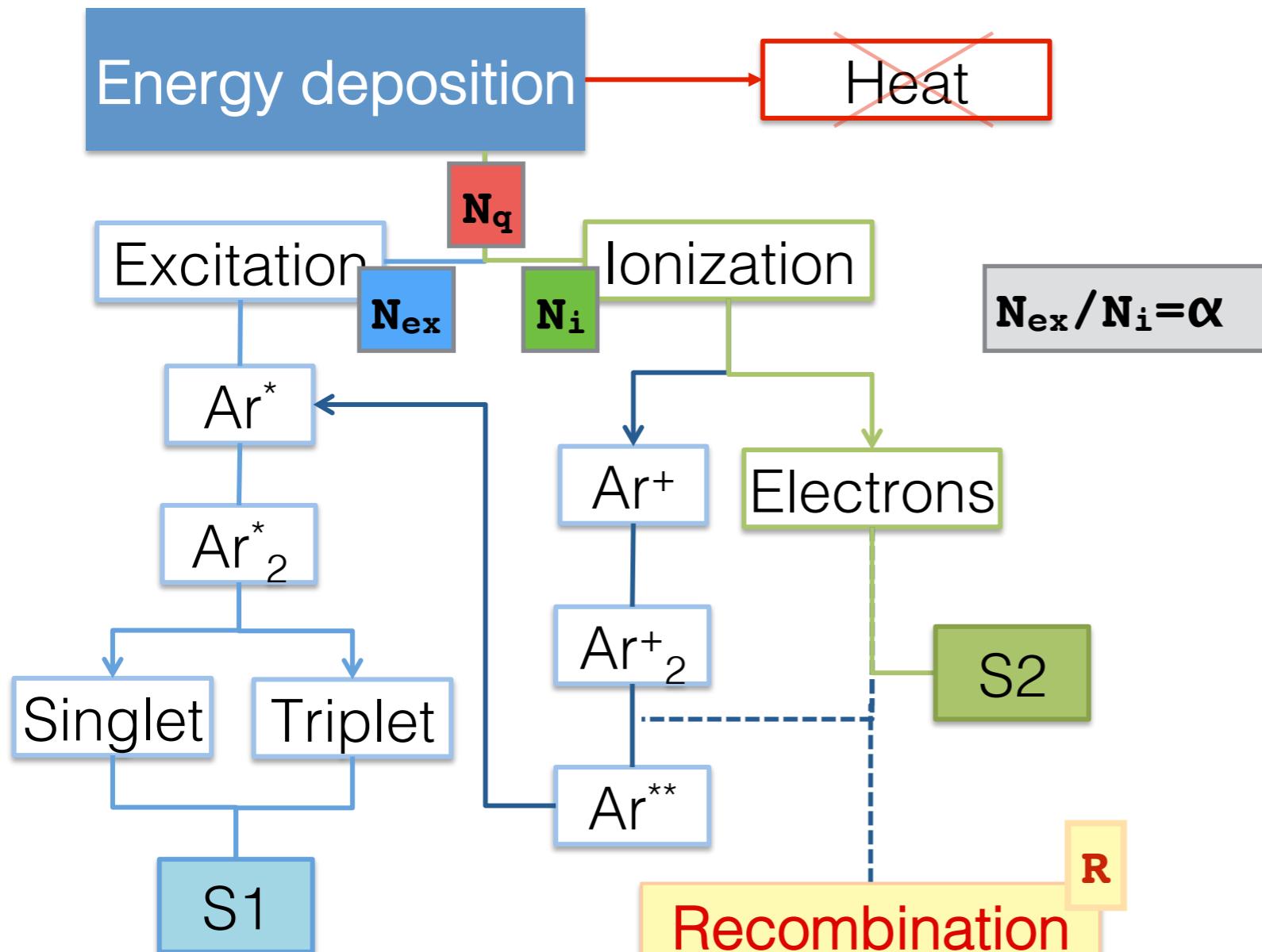
Light Yield vs tdrift



Top/Bottom light fraction vs tdrift



The PARIS Model (ER)



$$N_q = E / W$$

$$N_i = N_q / (1 + \alpha)$$

$$N_{\text{ex}} = N_q - N_i$$

$$N_q^{S1} = N_{\text{ex}} + R N_i$$

$$N_q^{S2} = N_i (1 - R)$$

$$S1 = Y_{S1} N_q^{S1}$$

$$S2 = Y_{S2} N_q^{S2}$$

fluctuations

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:

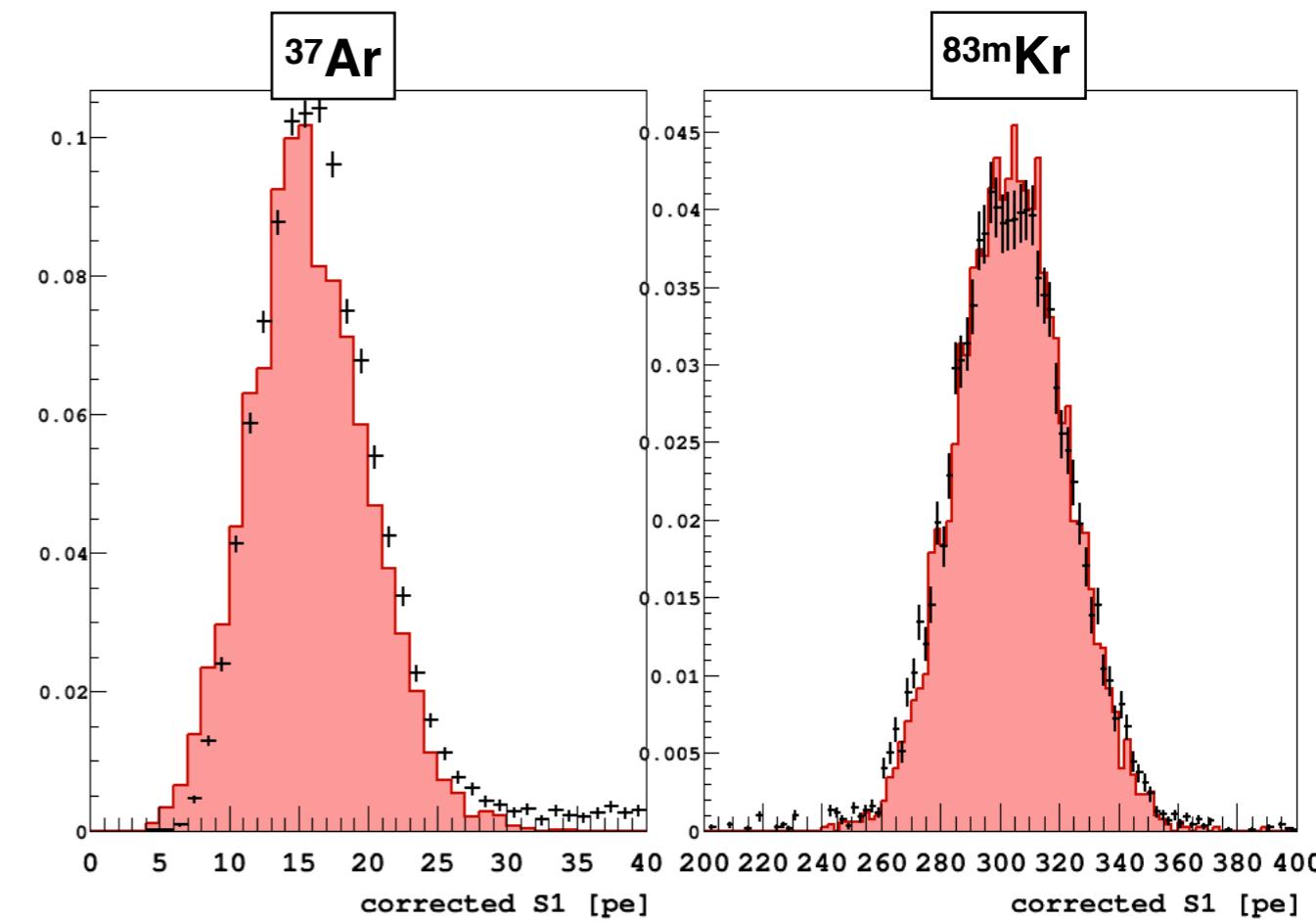
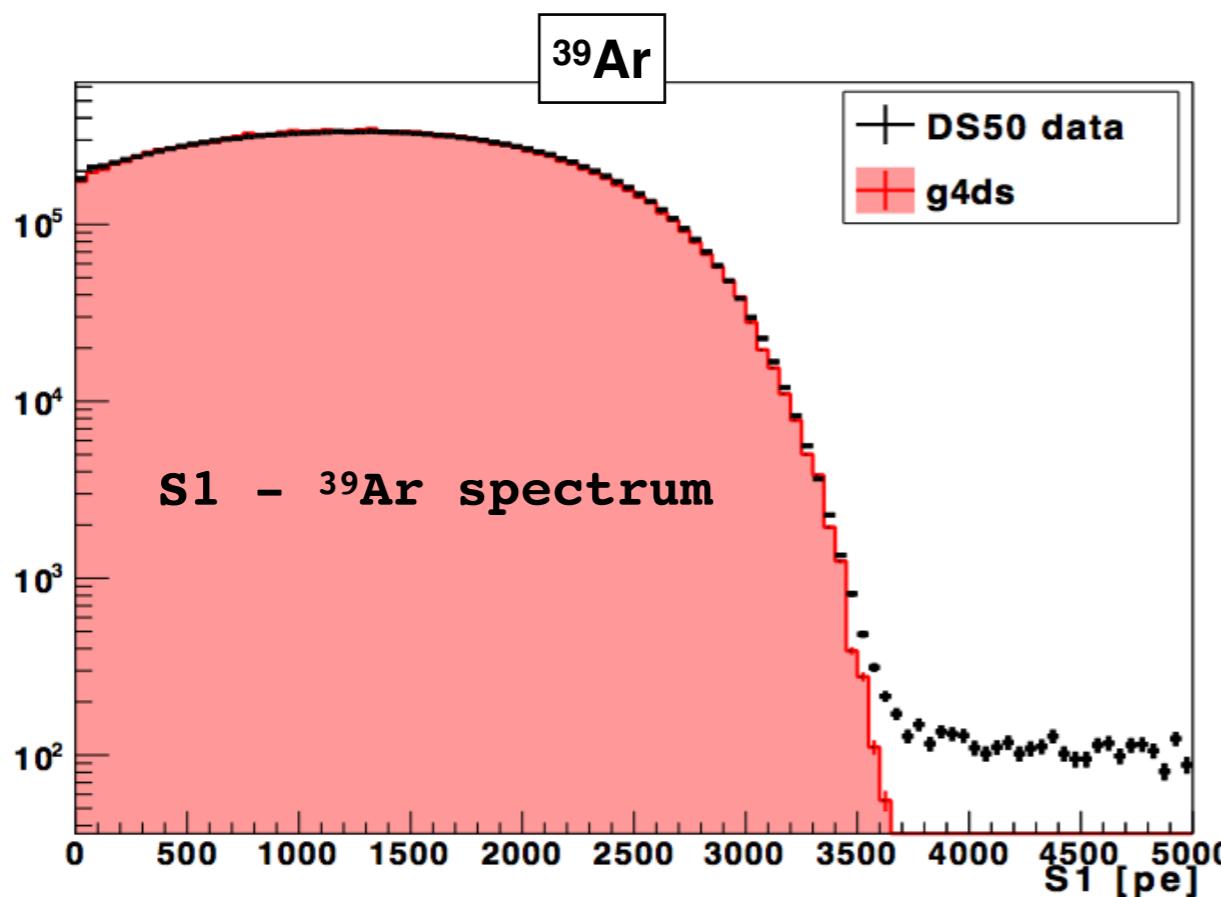
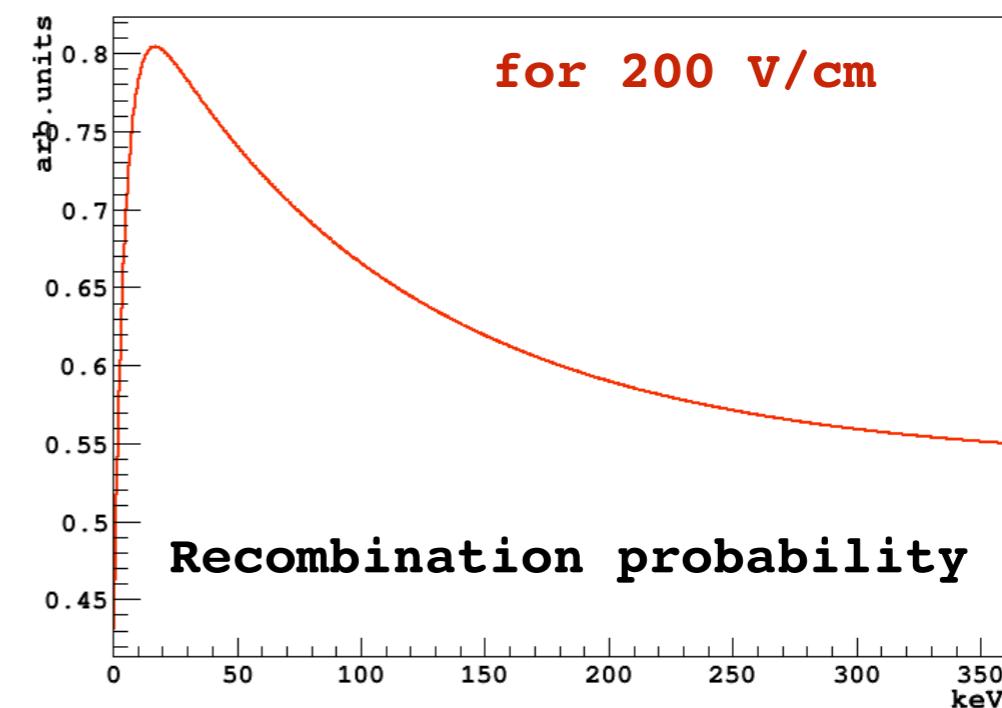
$\alpha = 1.00 ?$

The Recombination Probability

Extraction of the recombination probability from data

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

Fit of the $\left\{ \begin{array}{l} \text{endpoint of } {}^{39}\text{Ar} \text{ spectrum (565 keV),} \\ \text{83mKr (9.4 keV + 32.1 keV) peak} \\ \text{37Ar peak (2.7 keV) peak} \end{array} \right.$

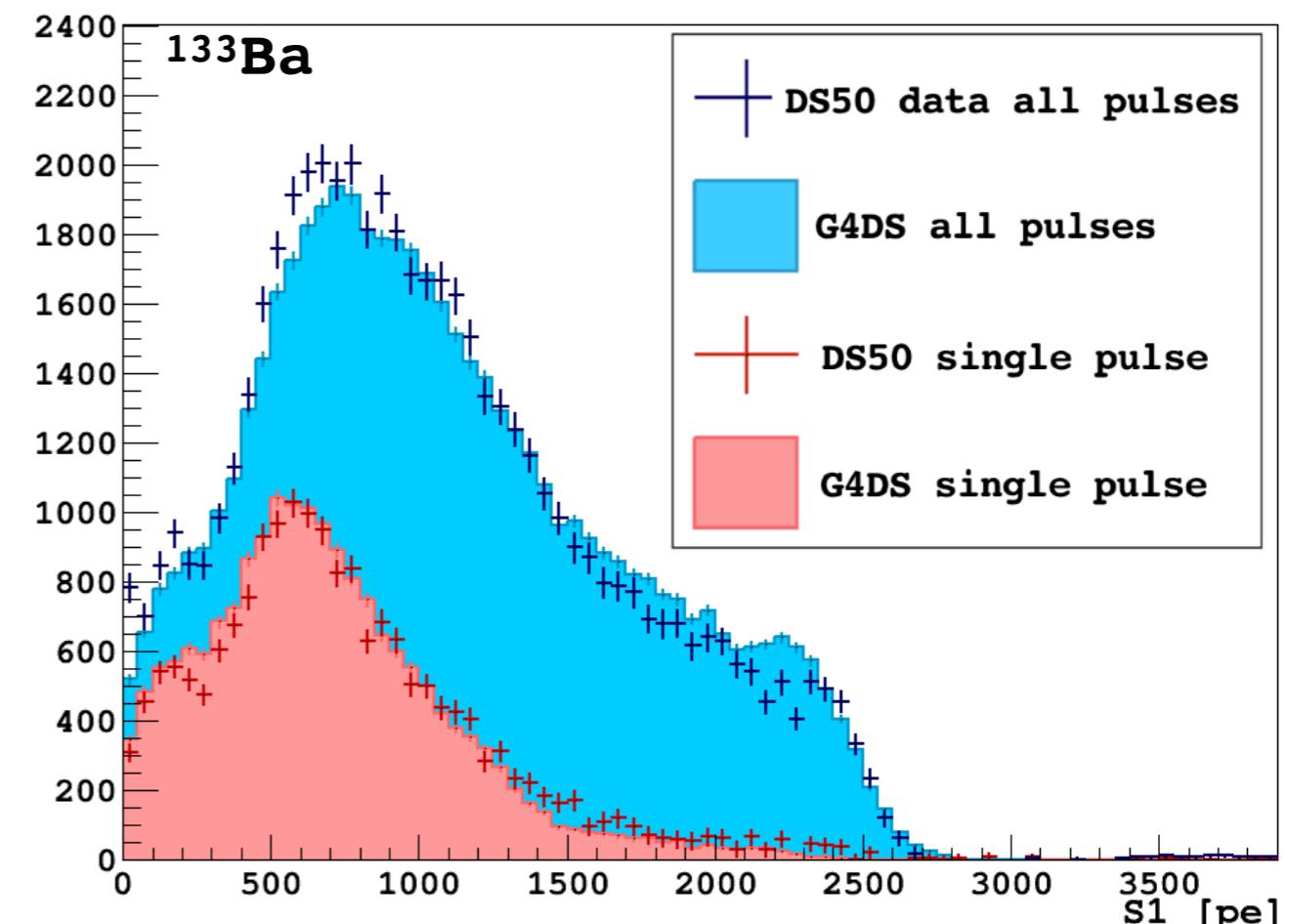
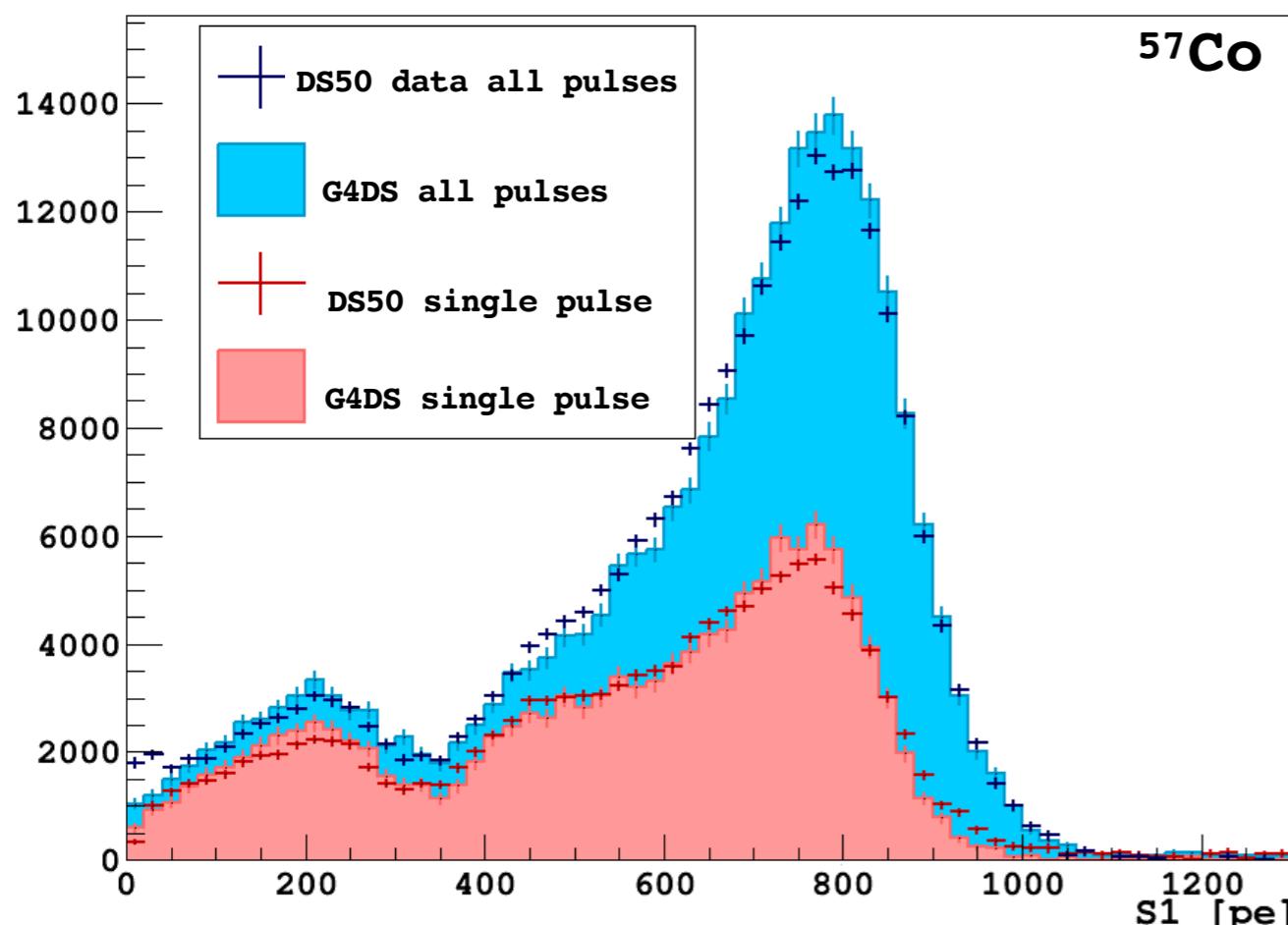
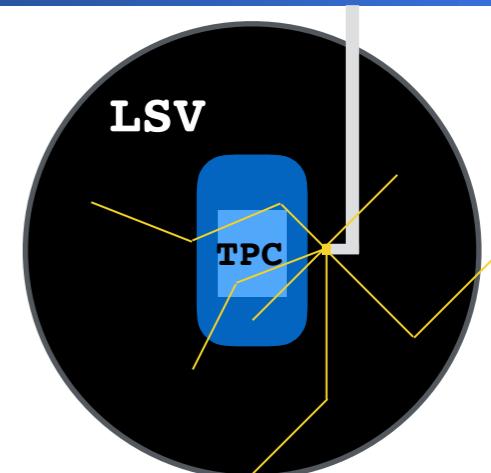


Electronic Recoils: Cross Check

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

CALIS (calibration insertion system)

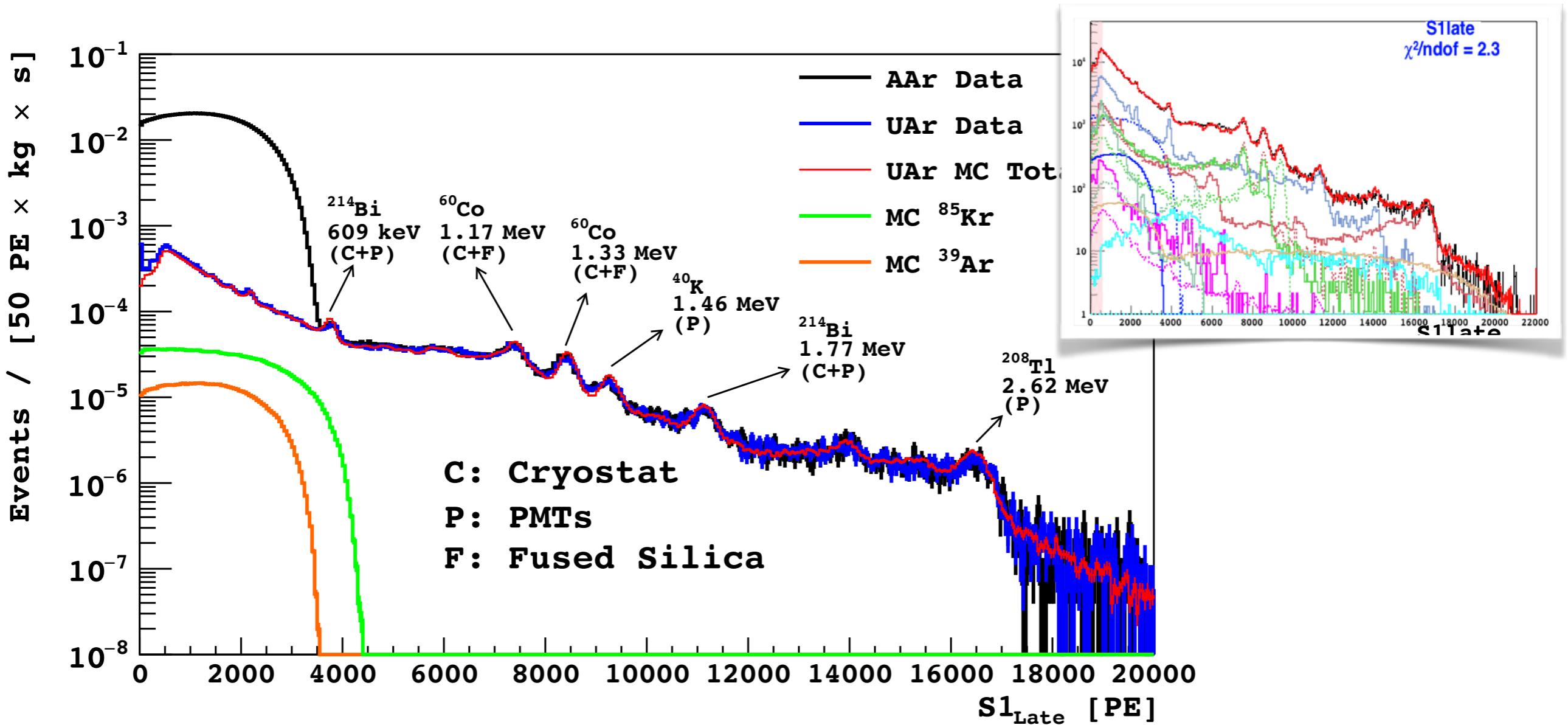
S1 after statistical background (^{39}Ar) subtraction:



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

No additional smearing required!

One application



Produce **MC spectra** of **beta/gammas from all the detector materials and all the radioactive contaminants**

Internal ^{85}Kr , ^{39}Ar , $^{42}\text{Ar}/^{42}\text{K}$, ^{222}Rn

External ^{238}U , ^{235}U , ^{232}Th , ^{60}Co , ^{40}K decays from PMTs, cryostat, anode/cathode windows

A good agreement with the material screening measurement is generally found!

NR Energy Calibration

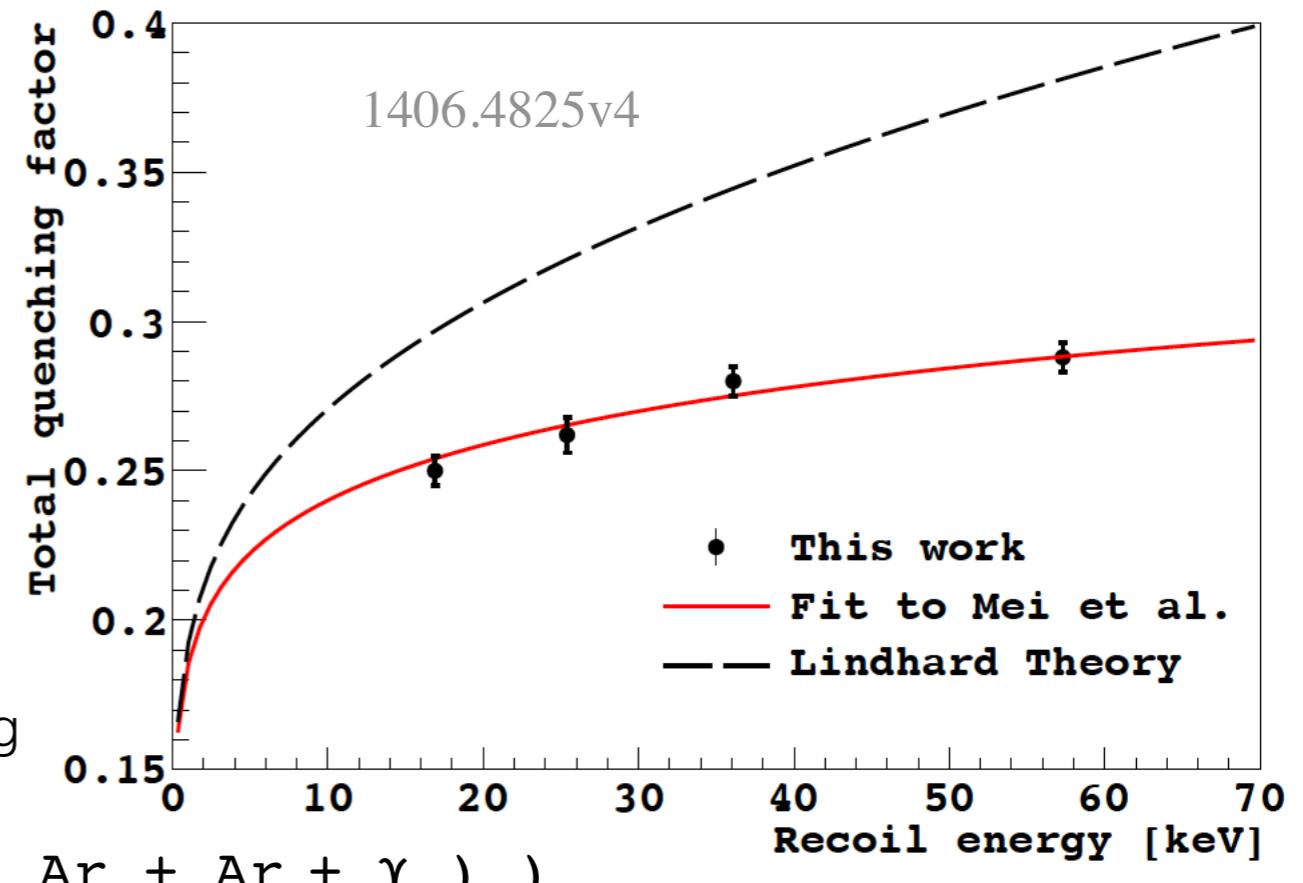
“Collisional” quenching

Lindhard theory (electron and ions stopping power)

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

— kg from theory —

Other “density” effects, such as bi-excitonic quenching

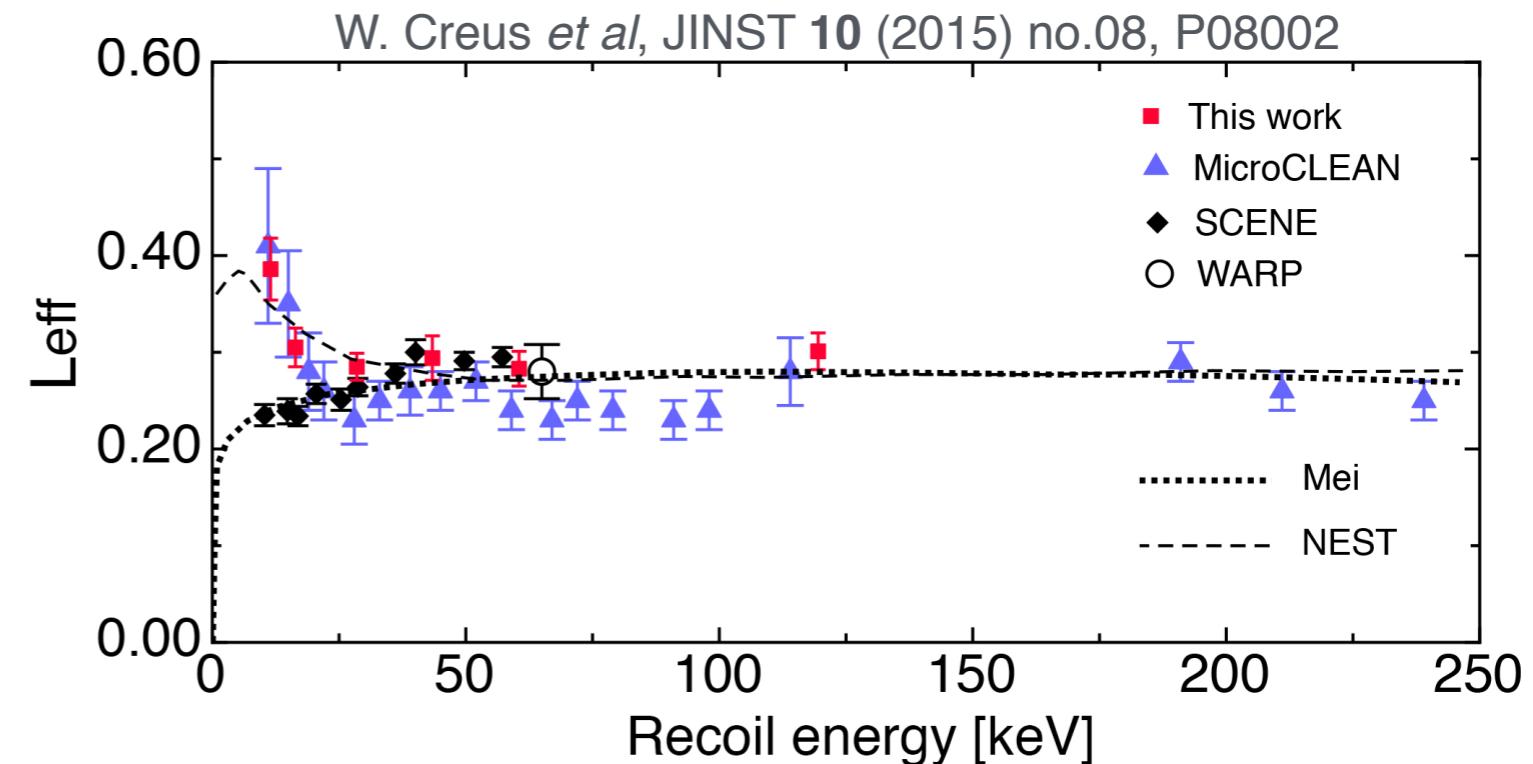


Mei model: arXiv:0712.2470

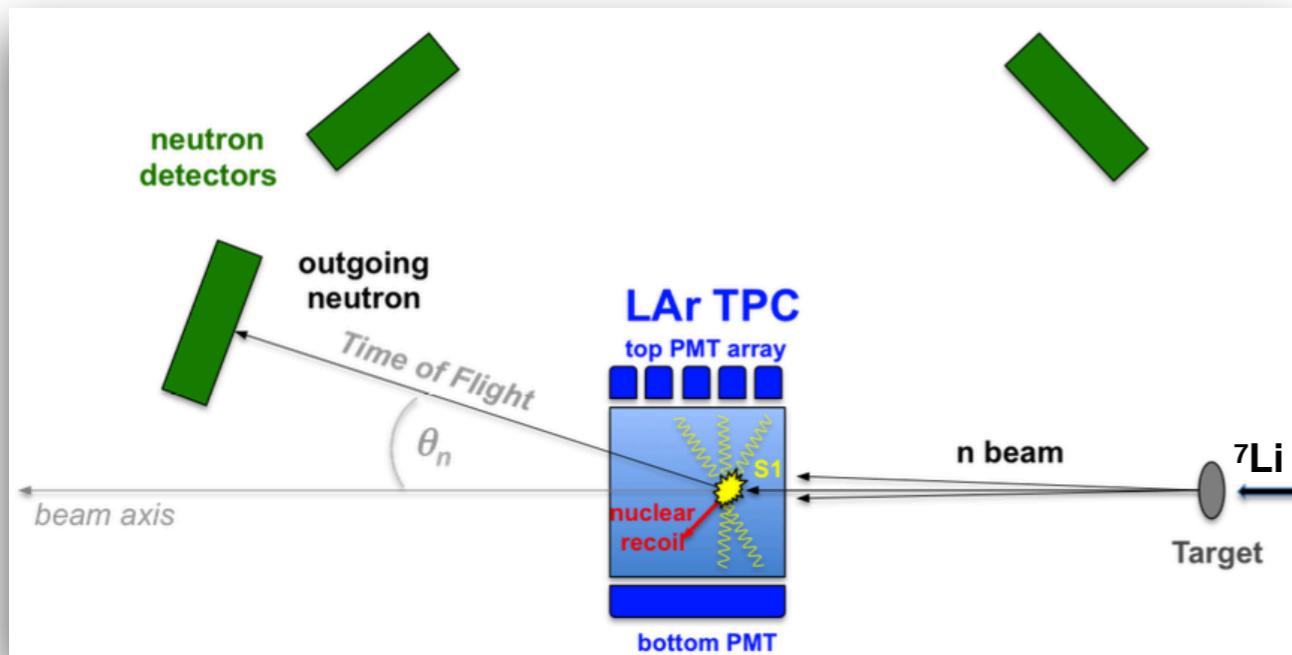
$$L_{eff}^M = L_{eff}^L \times \frac{1}{1 + k_B \frac{dE}{dx}}$$

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

(±30% according to the dataset)



The ARIS calibration experiment

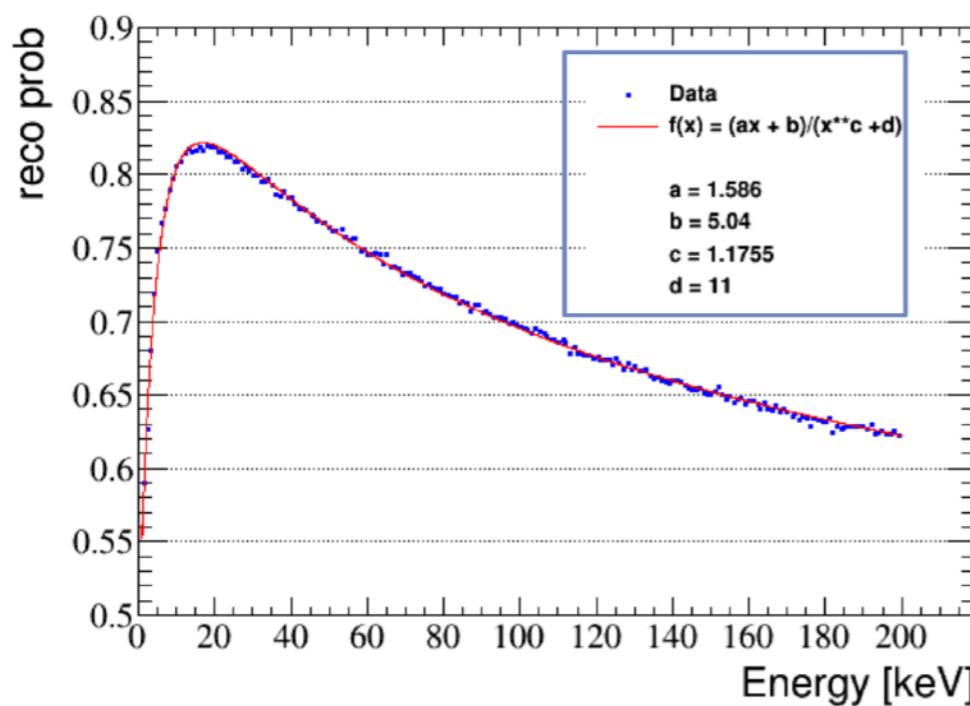


Neutron production: inverse $^{7}\text{Li}(p.n)^{7}\text{Be}$

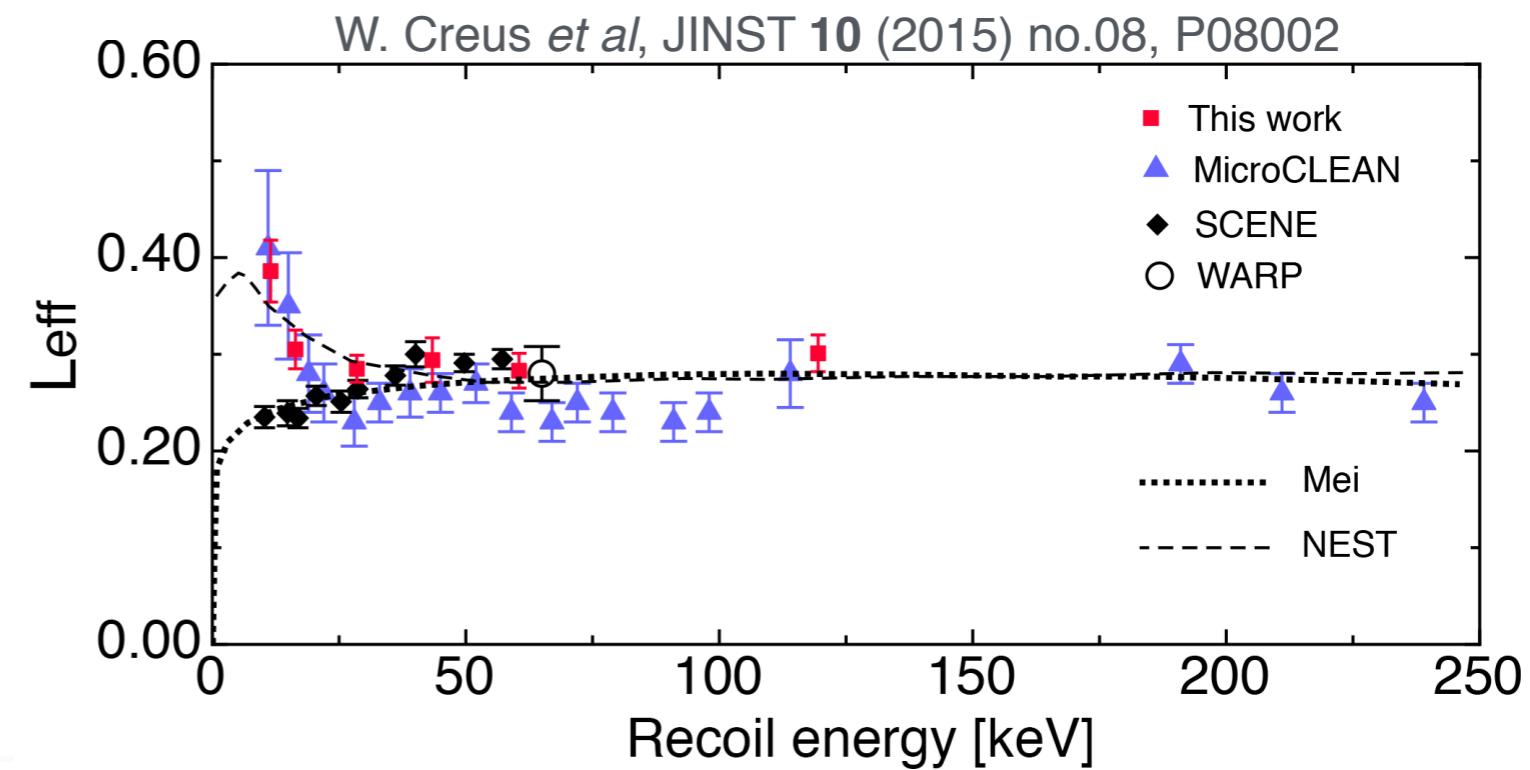
- Monochromatic
- Collimated beam
- Neutron energy ~ 1.47

Single phase detector

Recombination probability



NR quenching



ARIS

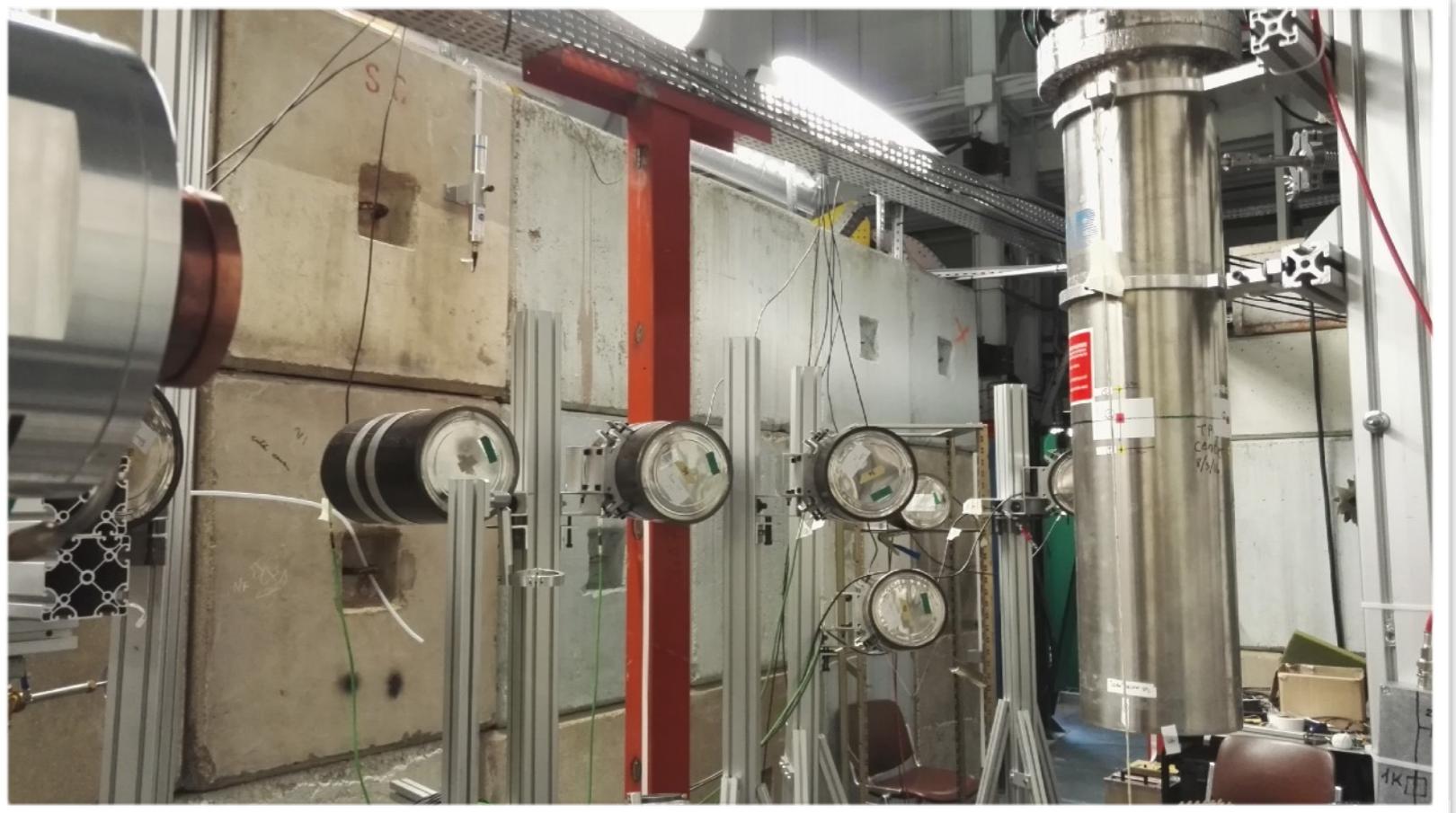
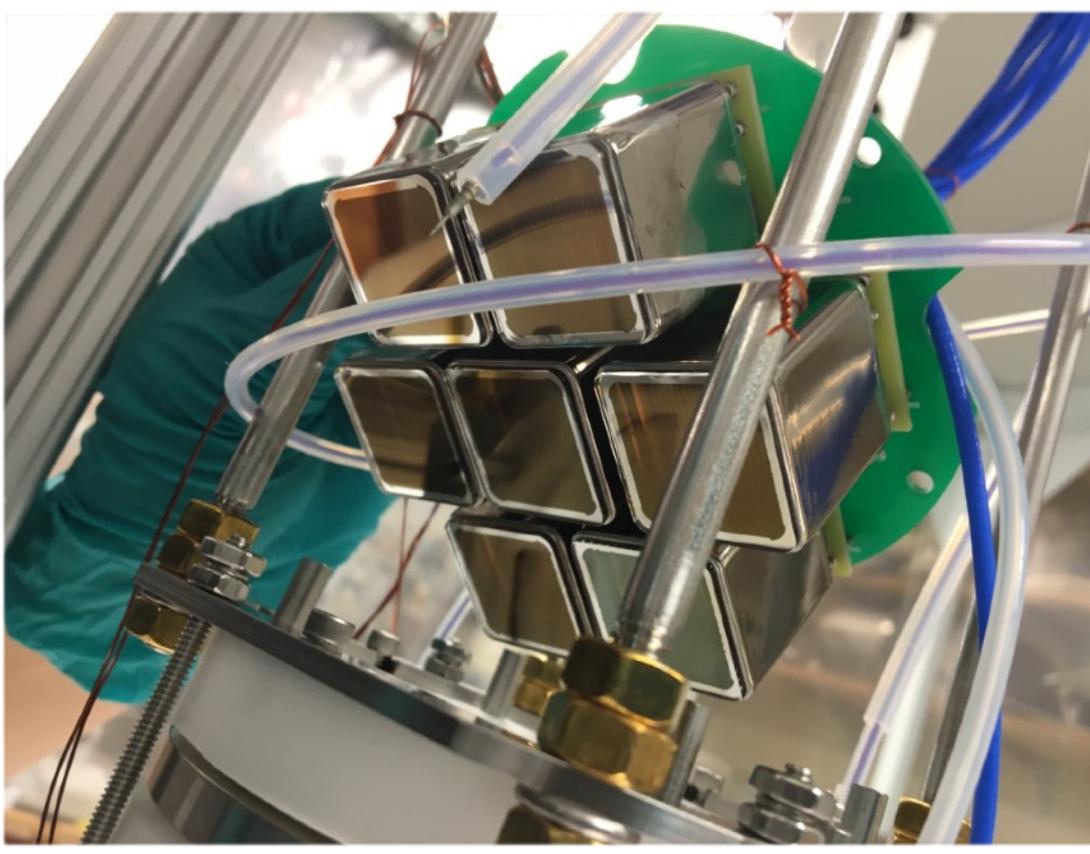
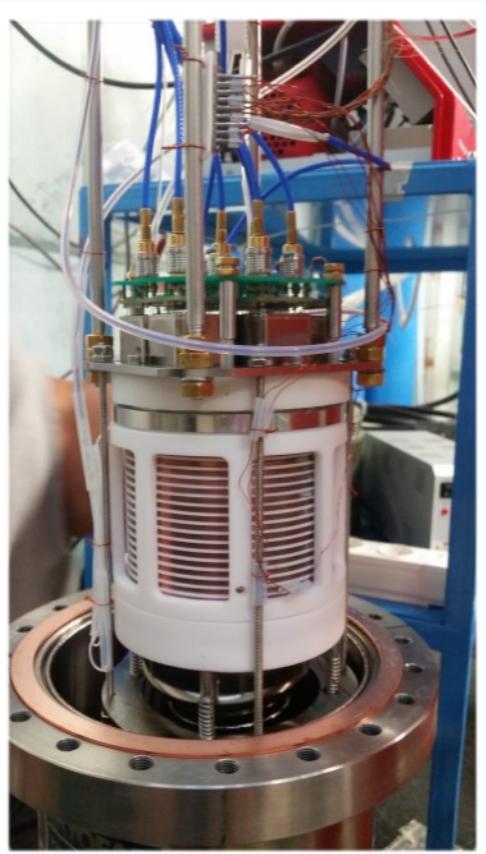
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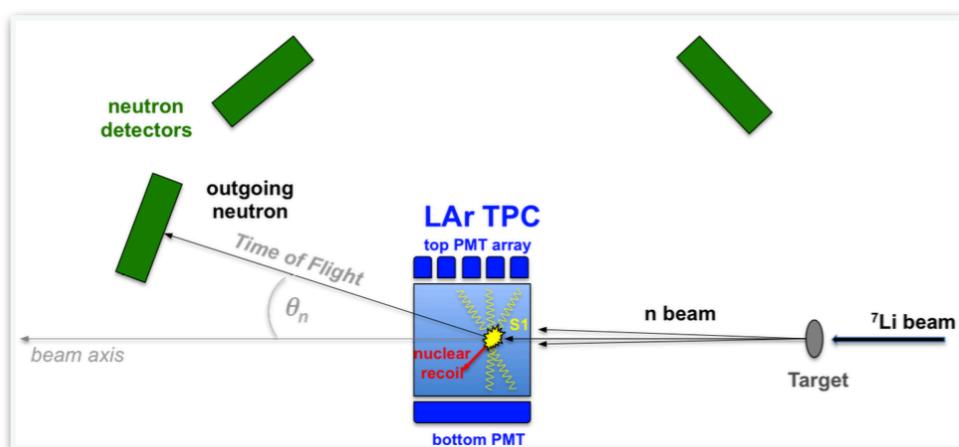
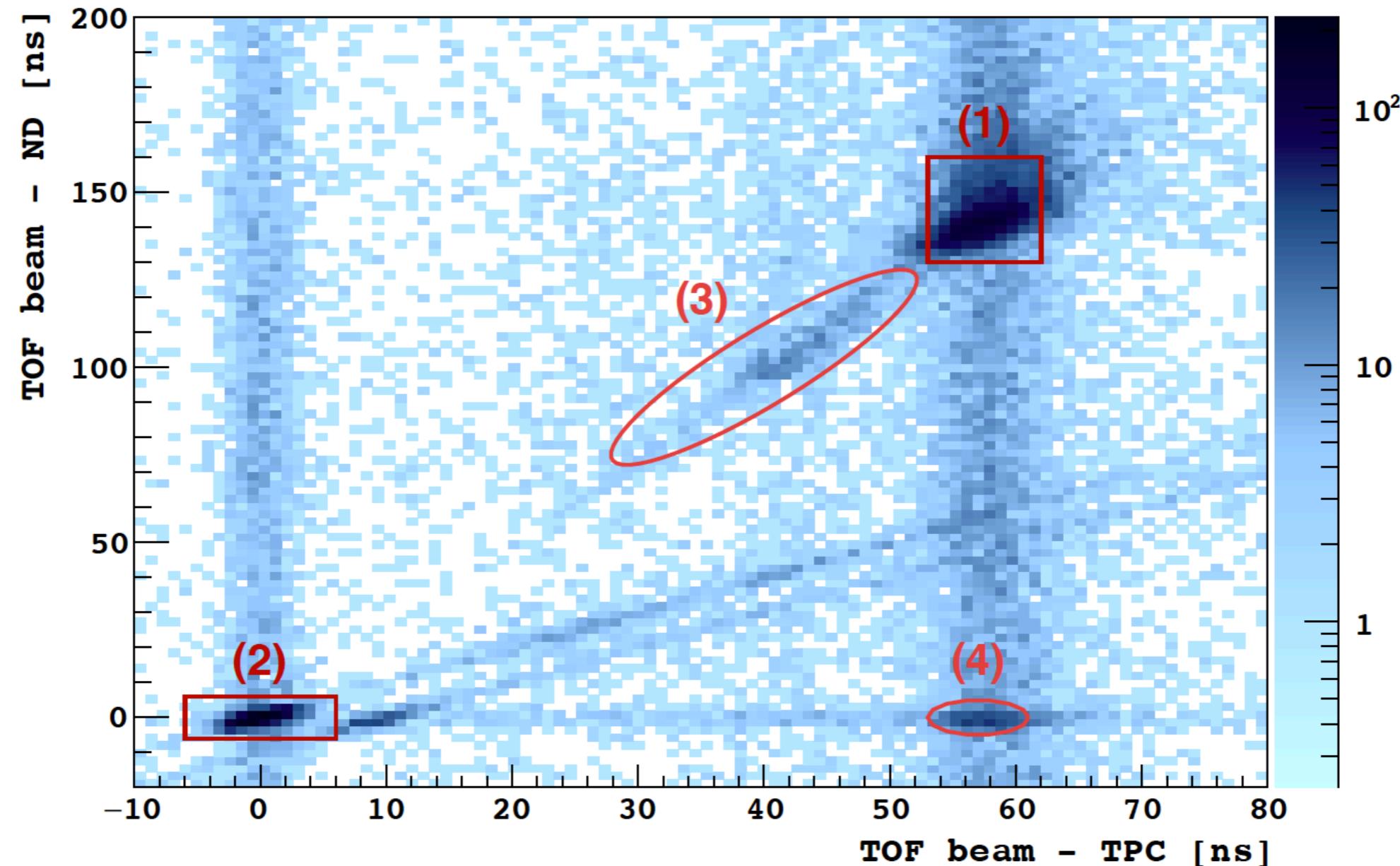
LPNHE
PARIS



G S
S I



TOF based selection cuts



(1) neutrons
(2) Gammas from de-excitation of $^{7}\text{Li}^*$ (478 keV)

ER (Compton peaks) analysis

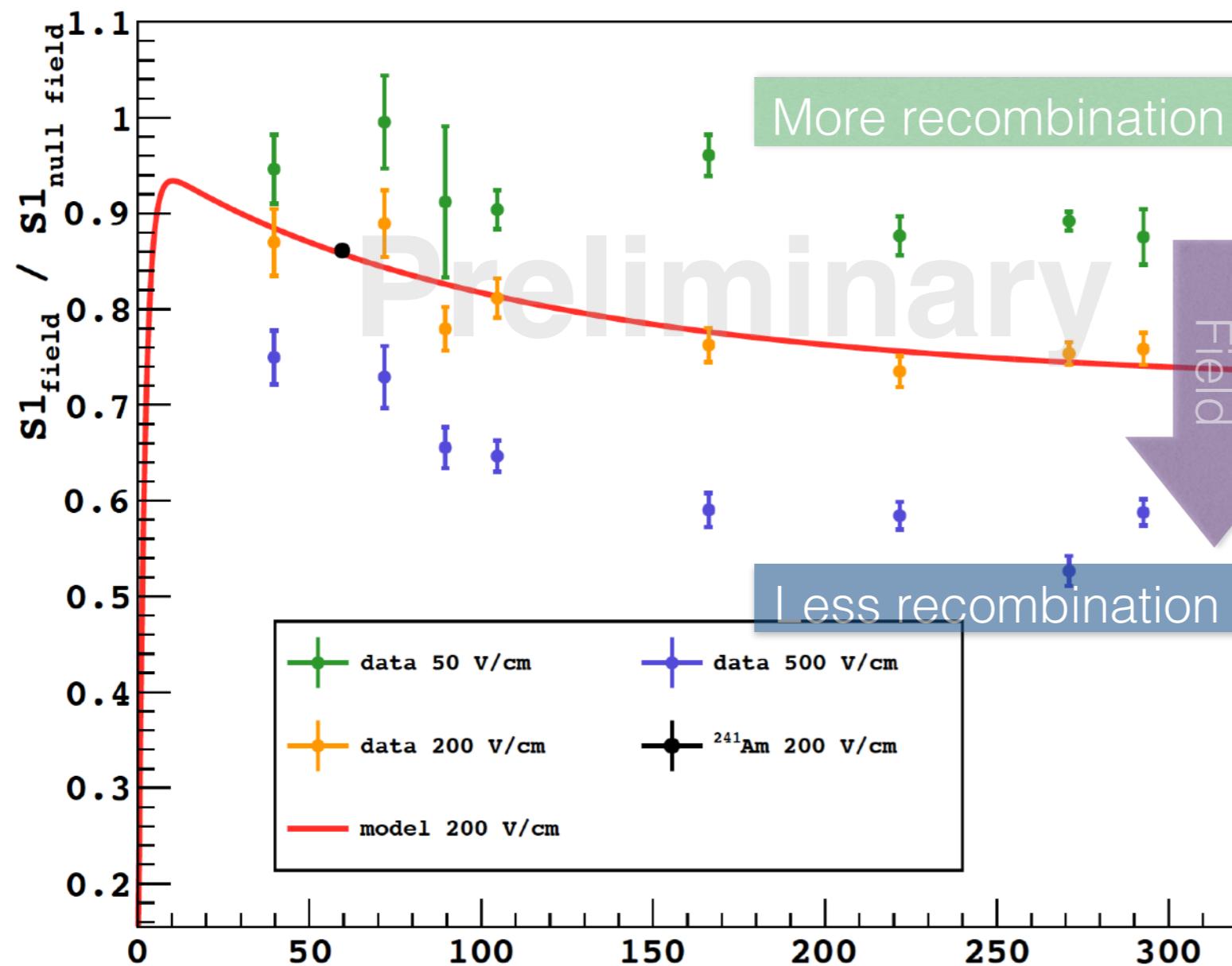
Unique opportunity to study **single ER** in a wide energy range.

Compare with **DarkSide-50 model** at 200 V/cm (no assumption on 0 V/cm!)

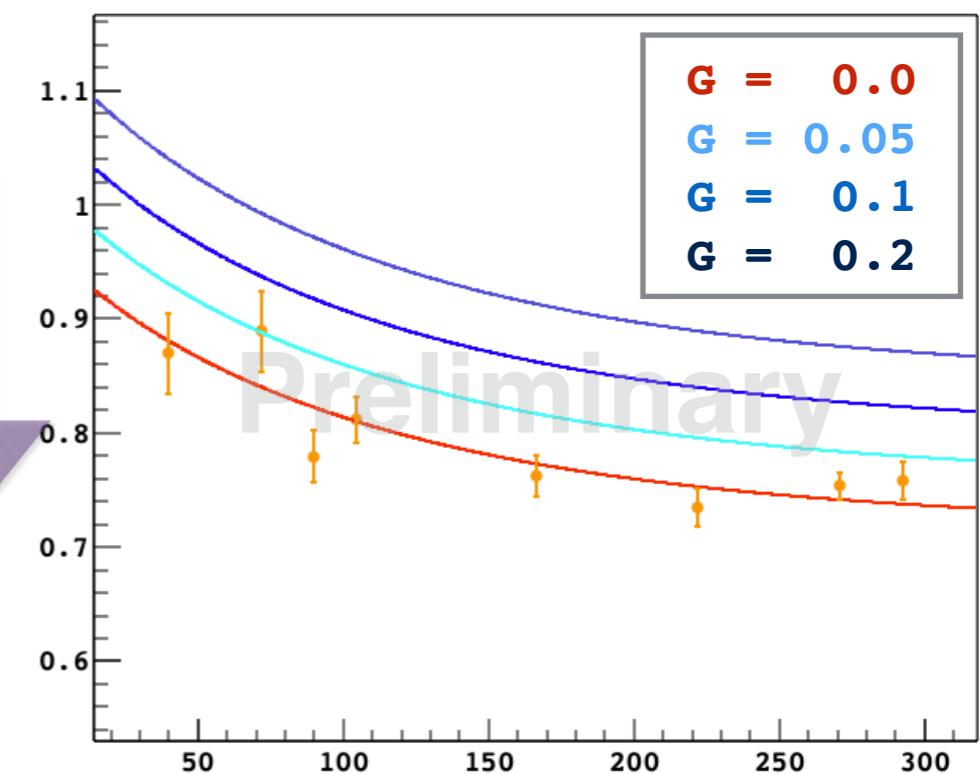
$$\frac{S1_{field}}{S1_{null-field}} = \frac{\alpha + R(E_{dep})}{1 + \alpha}$$

$$S1_{Field} = N_{ex} + \mathbf{R} N_i \\ = \alpha N_i + \mathbf{R} N_i$$

$$S1_{Null\ Field} = N_{ex} + N_i \\ = \alpha N_i + N_i \\ (\text{assuming full recombination})$$



$$(\alpha + R) / ((1 - G) + \alpha)$$



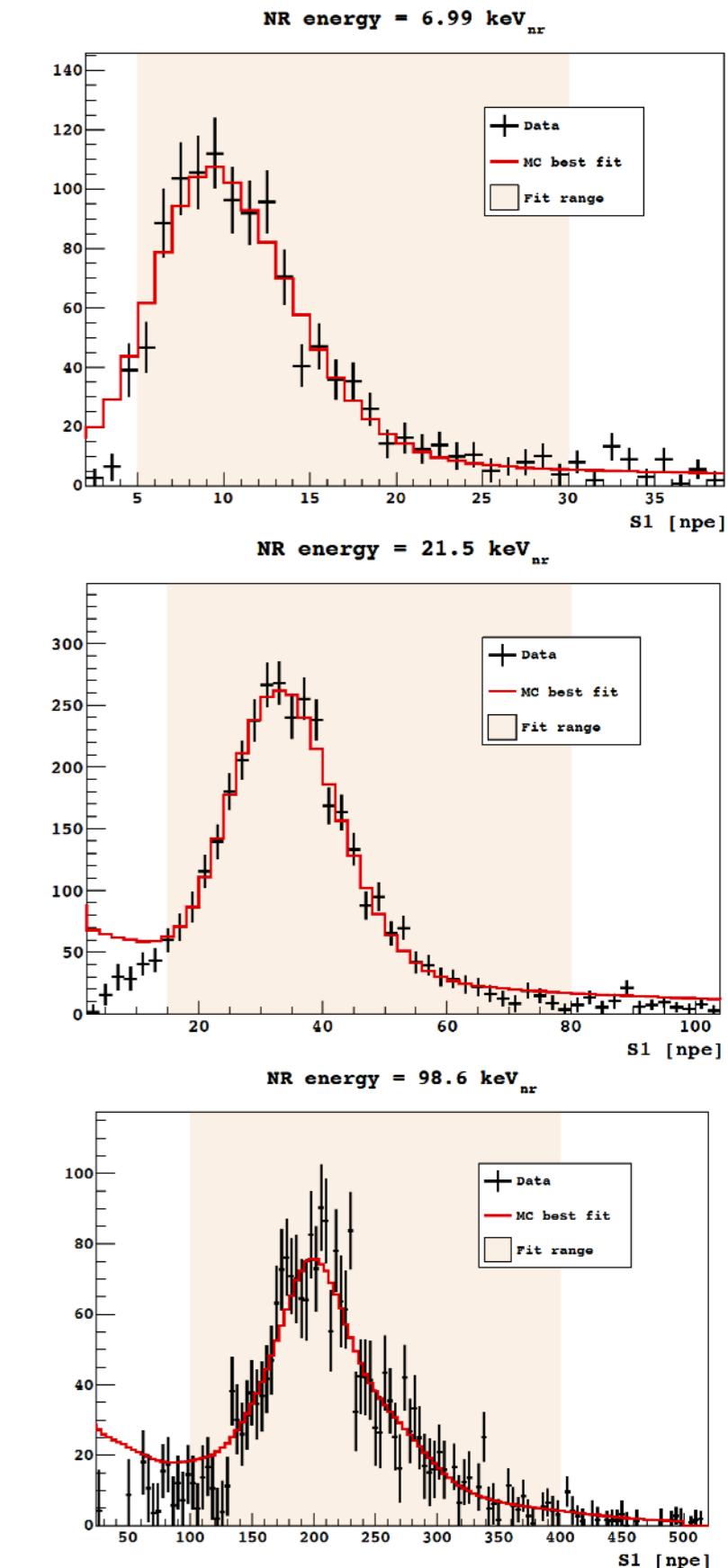
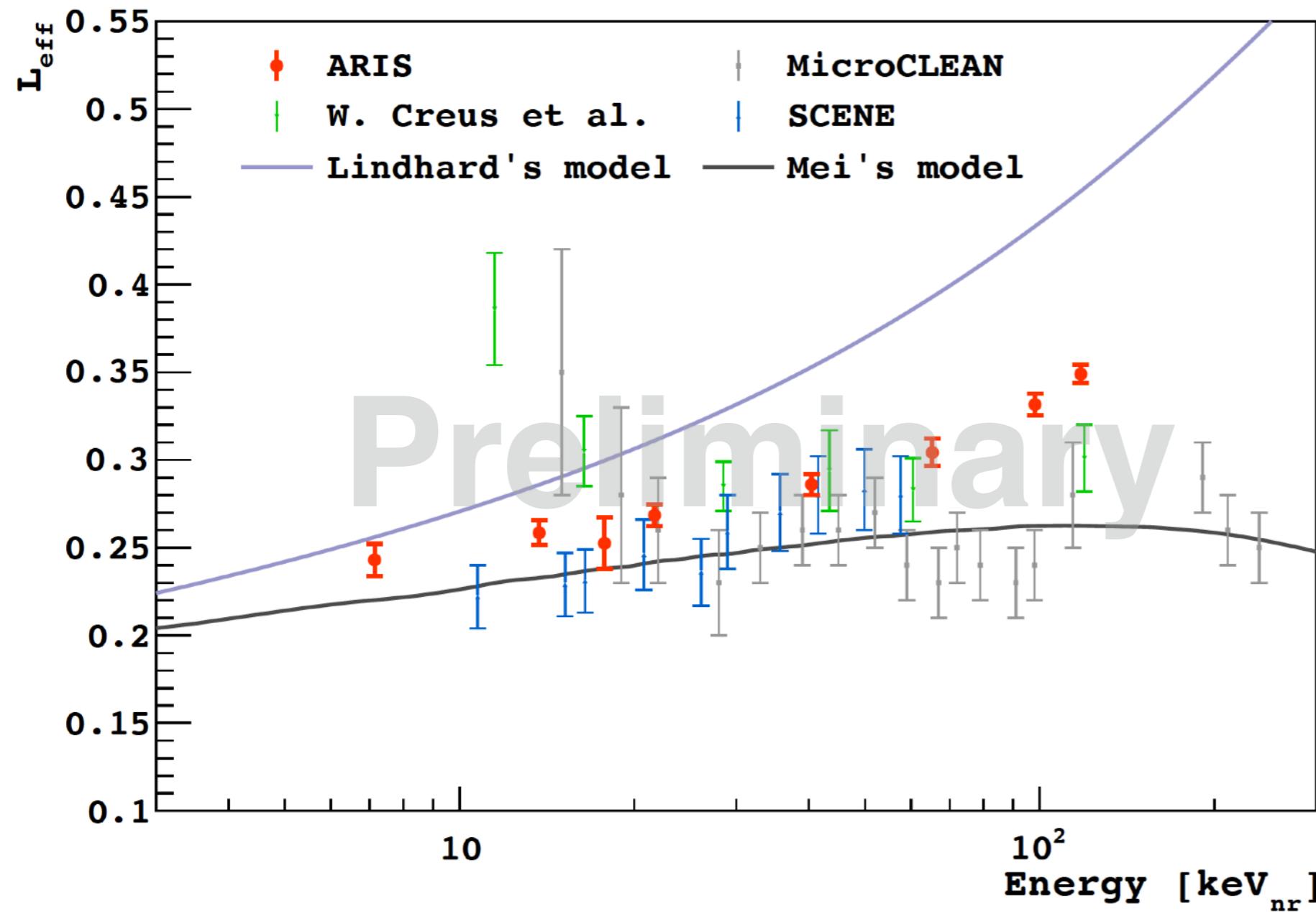
Hints that the recombination
at null field is ~ 1

No assumption on the
recombination at null field in the
PARIS model

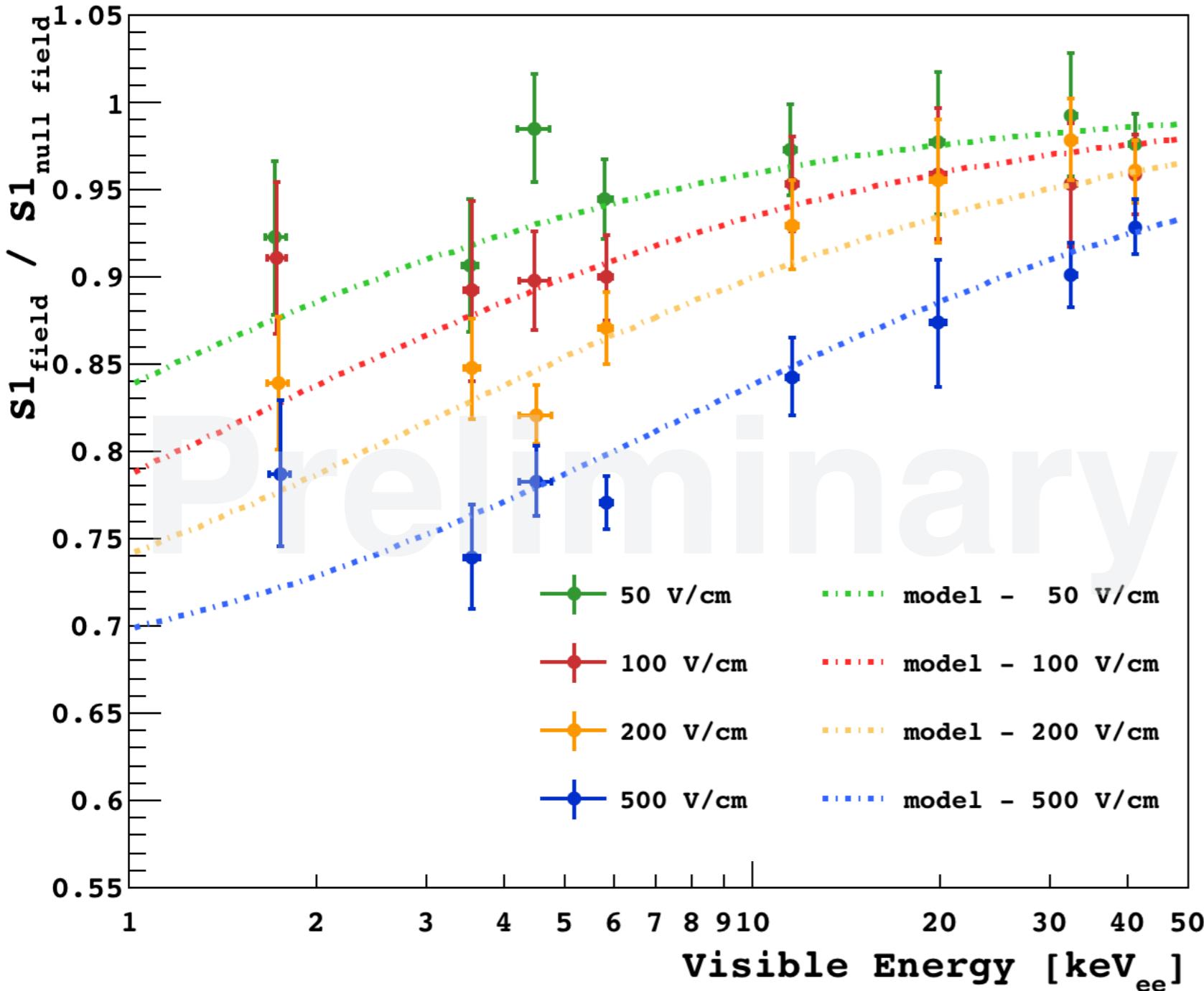
NR analysis: Leff

Field Off data only
Fit with MC spectra

$$S1 = Leff \times E_{true}(\text{MC}) \times LY_{\text{nullField}}(\text{ER})$$



NR recombination



$$\frac{S1_{field}}{S1_{null-field}} = \frac{\alpha + R(E_{dep})}{1 + \alpha}$$

Recombination at null field?

α / R degeneracy
We do not measure the charge

$$r = 1 - \frac{\ln(1 + \xi)}{\xi}, \quad \xi \equiv \frac{N_i \alpha'}{4a^2 v}$$

[a = box size]
[v = mean velocity]
[α' = constant]

equated to
 $C = e^2 / (\delta e k T)$
[e = e- charge]
[k = Boltzmann const]
[T = mean e- T]

Conclusion

Within the **DarkSide Collaboration** we developed a data-driven model for the **ionisation and scintillation** mechanism in liquid argon

Based on an **effective parameterization** of the **recombination probability** as a function of the recoil energy, extracted from 200 V/cm data and **cross checked** with external calibration sources (ER) and the ARIS data.

The **NR calibration** needs some more investigation (data)

A parameterization of **both the field** and **energy dependence** of the recombination is available

More data (charge yield) is needed to break the degeneracy between a and the recombination

The ER current status (completed) and preliminary NR are public at: arXiv:1707:05630

The ARIS data and analyses are coming soon