Direct Searches for Dark Matter with DarkSide: Results and Perspectives

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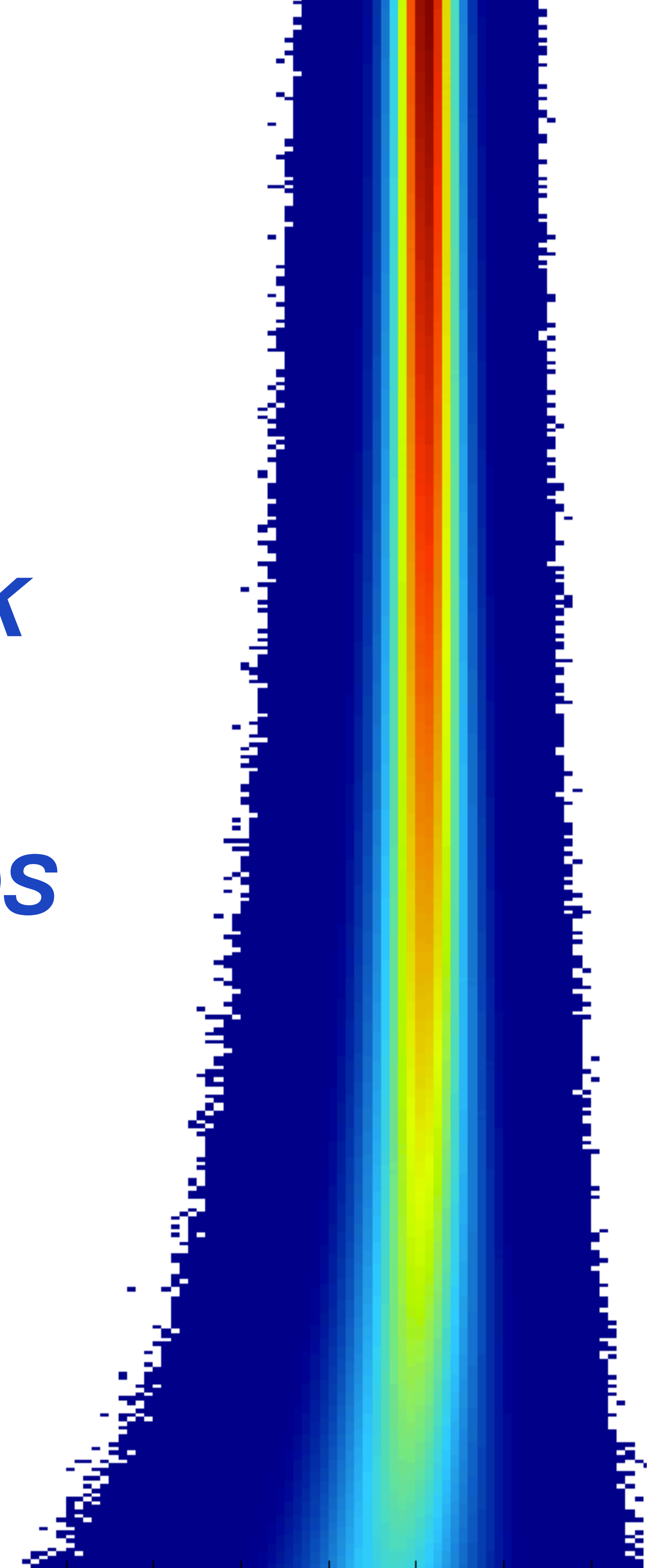
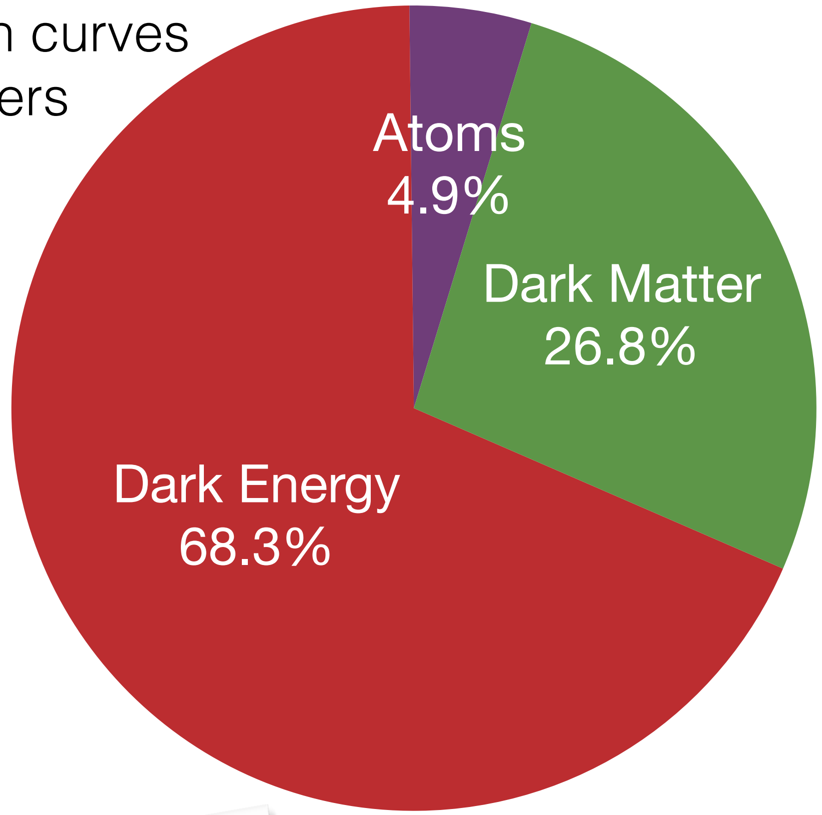
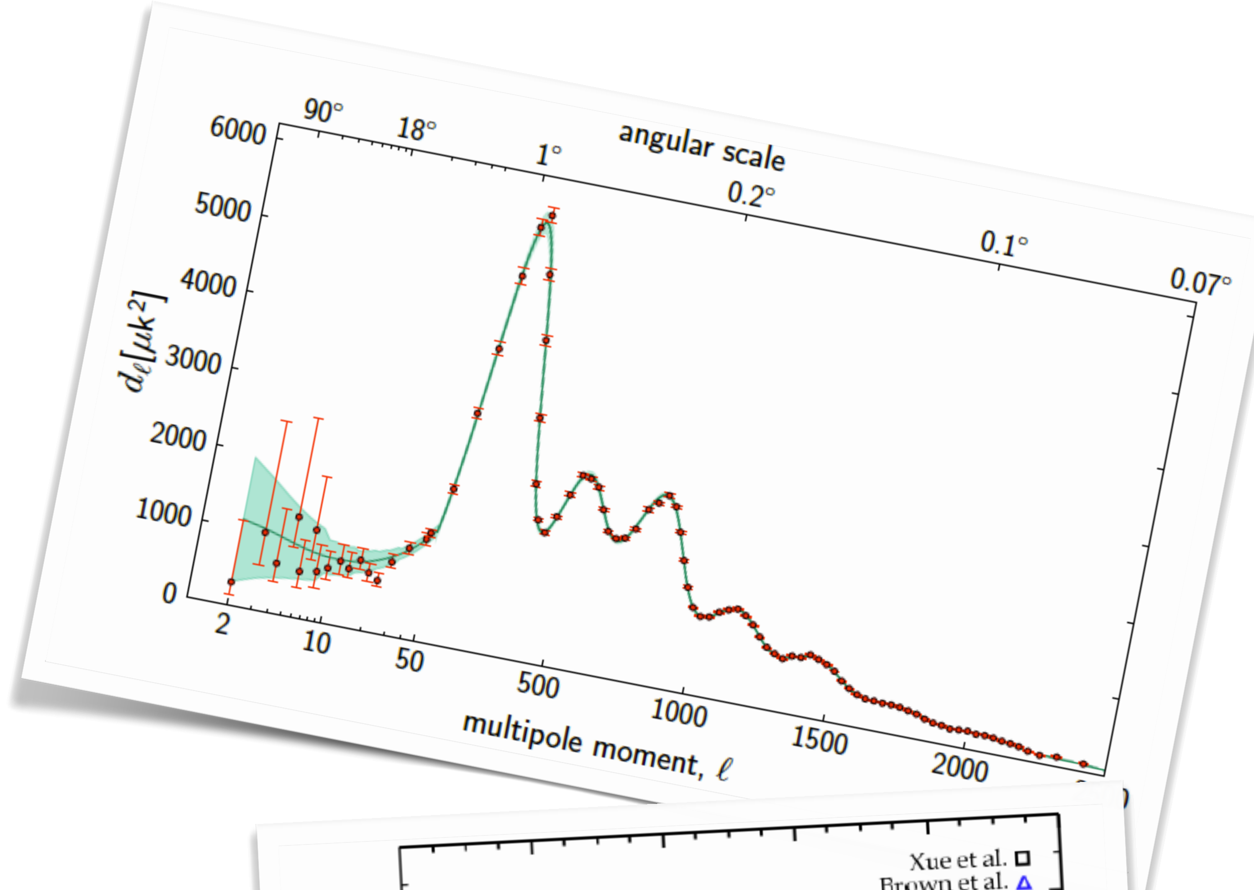
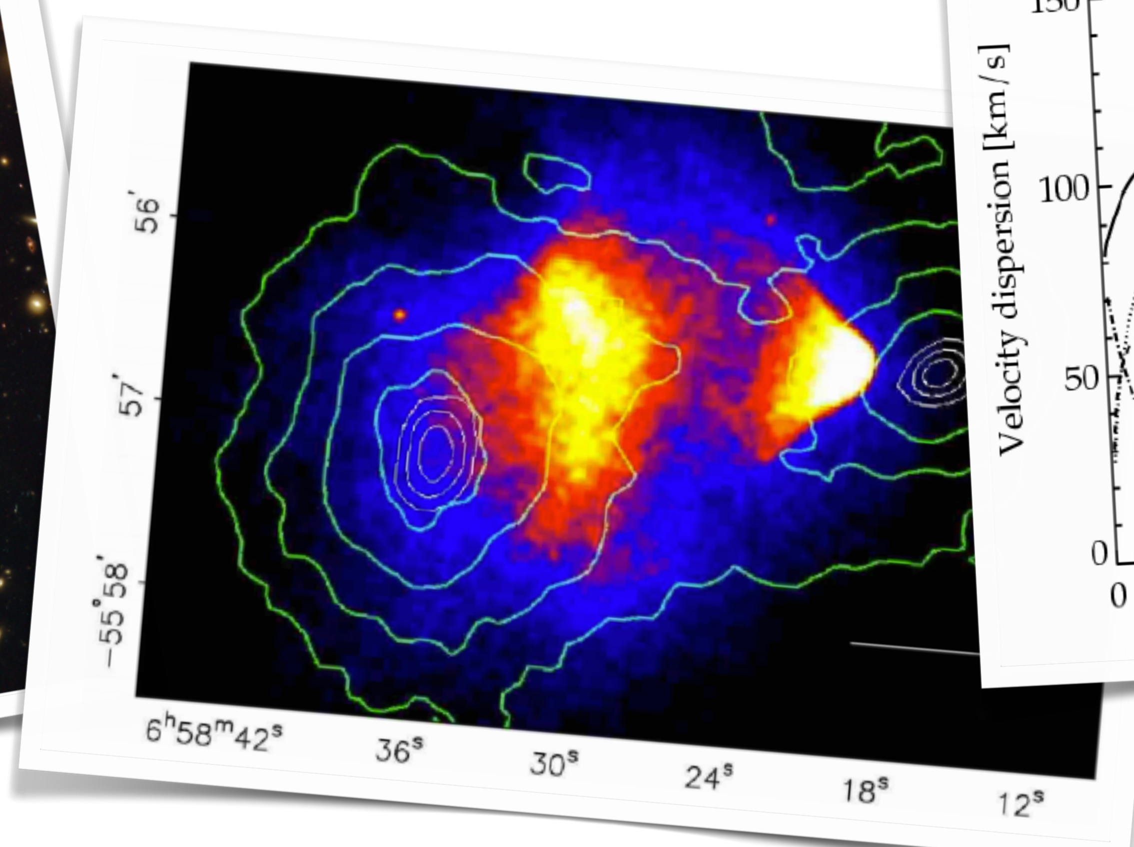


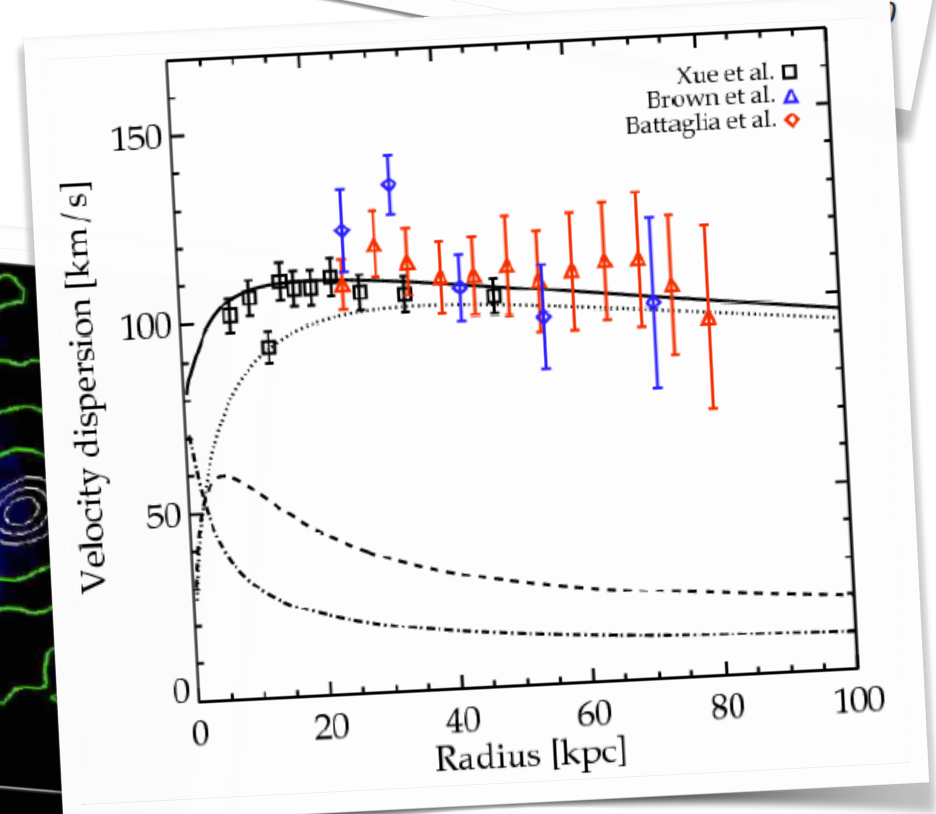
Dark Matter

Several indirect observations:
- Galactic rotation curves
- Hot gas in clusters
- Galaxy clusters
- Strong lensing
- Weak lensing
- Bullet Cluster
- Supernovae
- CMB



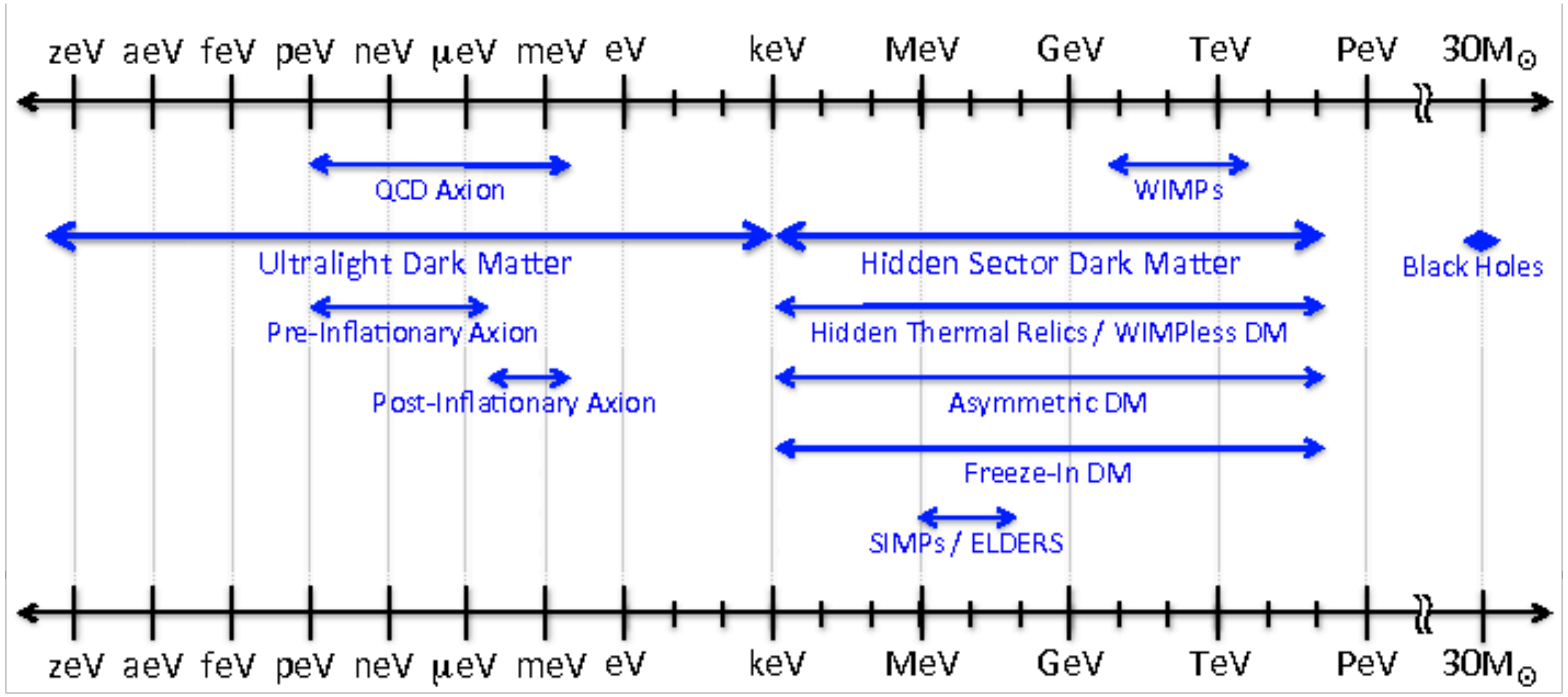






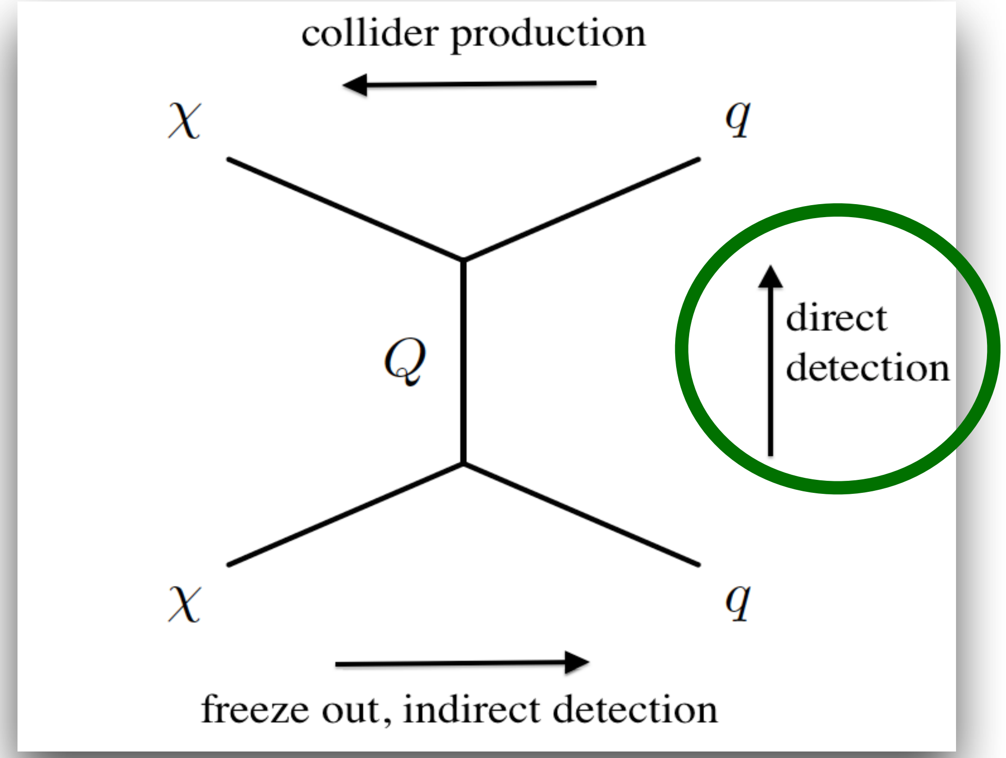
Dark Matter candidates

Dark Matter particles:
- are massive
- are stable
- non relativistic
- interact gravitationally
- electromagnetically neutral



WIMP:
Weakly Interacting Massive Particle

Expected signal for DD: low-energy nuclear recoil

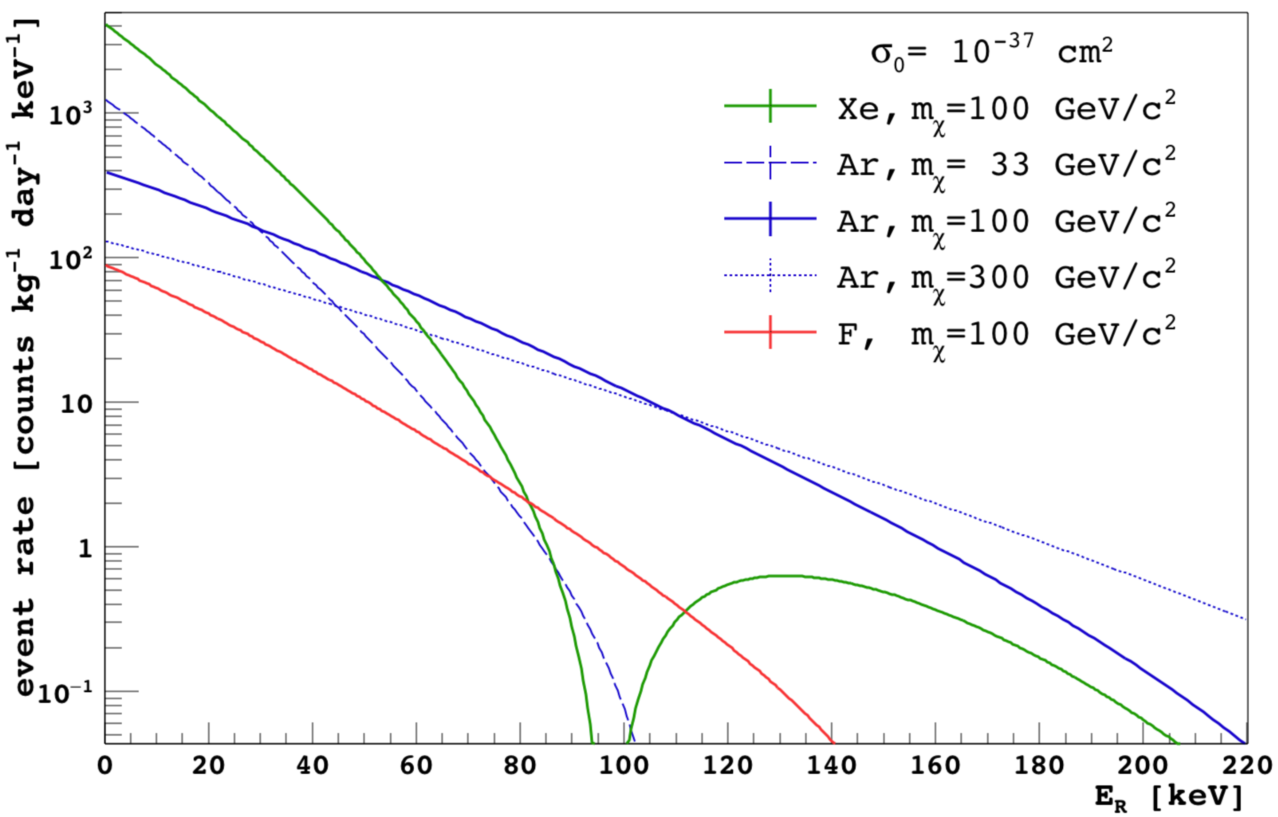


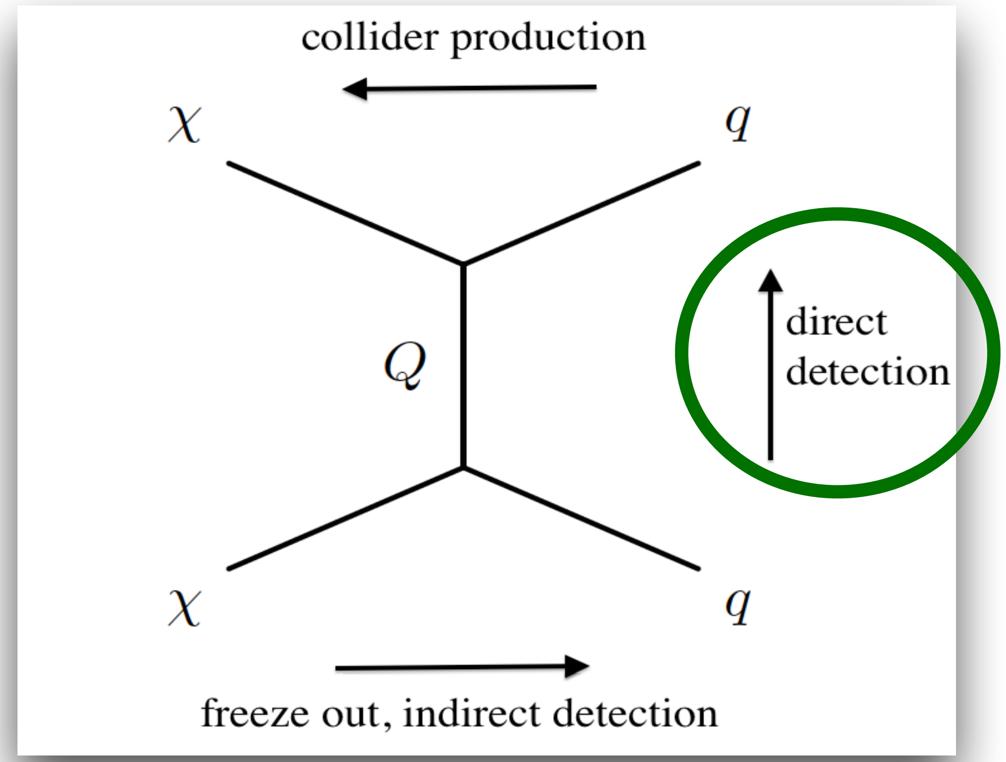
Expected rate in direct detection

Cross section — Nuclear Form Factor — Astrophysics

$$\frac{dR^{NR}}{dE_R} = \sigma_n \frac{\rho_\chi}{M_\chi} \frac{m_A}{2\mu_{n\chi}^2} A^2 F_A(q)^2 \int_{v_{min}(E_R)}^{v_{esc}} d^3v \frac{f(v, v_E)}{v}$$

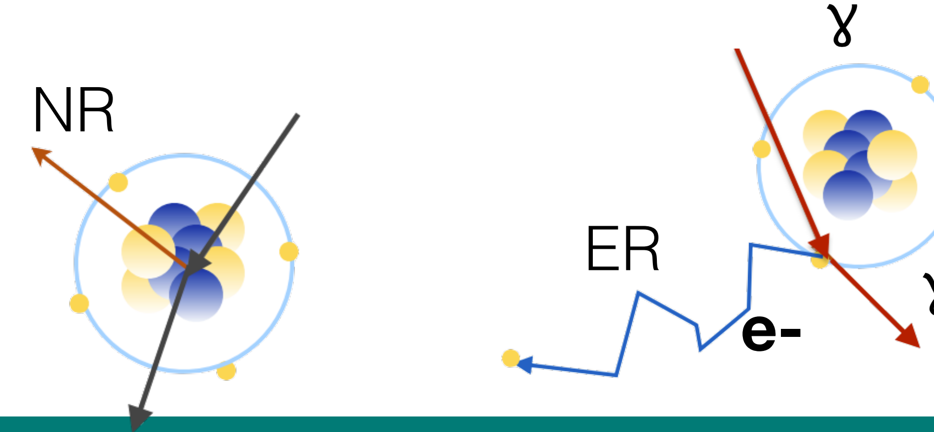
Dark Matter Properties — Target





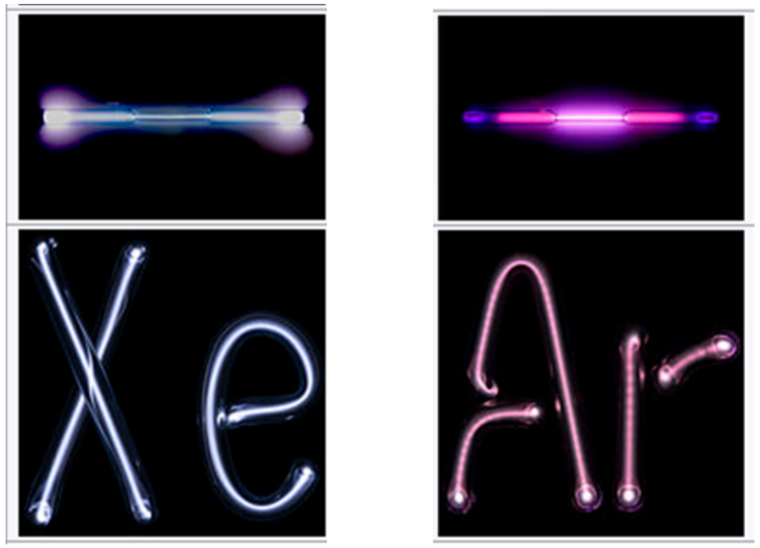
Direct Detection requirements

- Low energy threshold
(E < 100 keV)
- Large mass
(~ 1 event/tonne/yr @ 10-47 cm2 in noble liquids)
- Background suppression
Deep underground
Passive/active shielding
Low intrinsic radioactivity
ER background discrimination



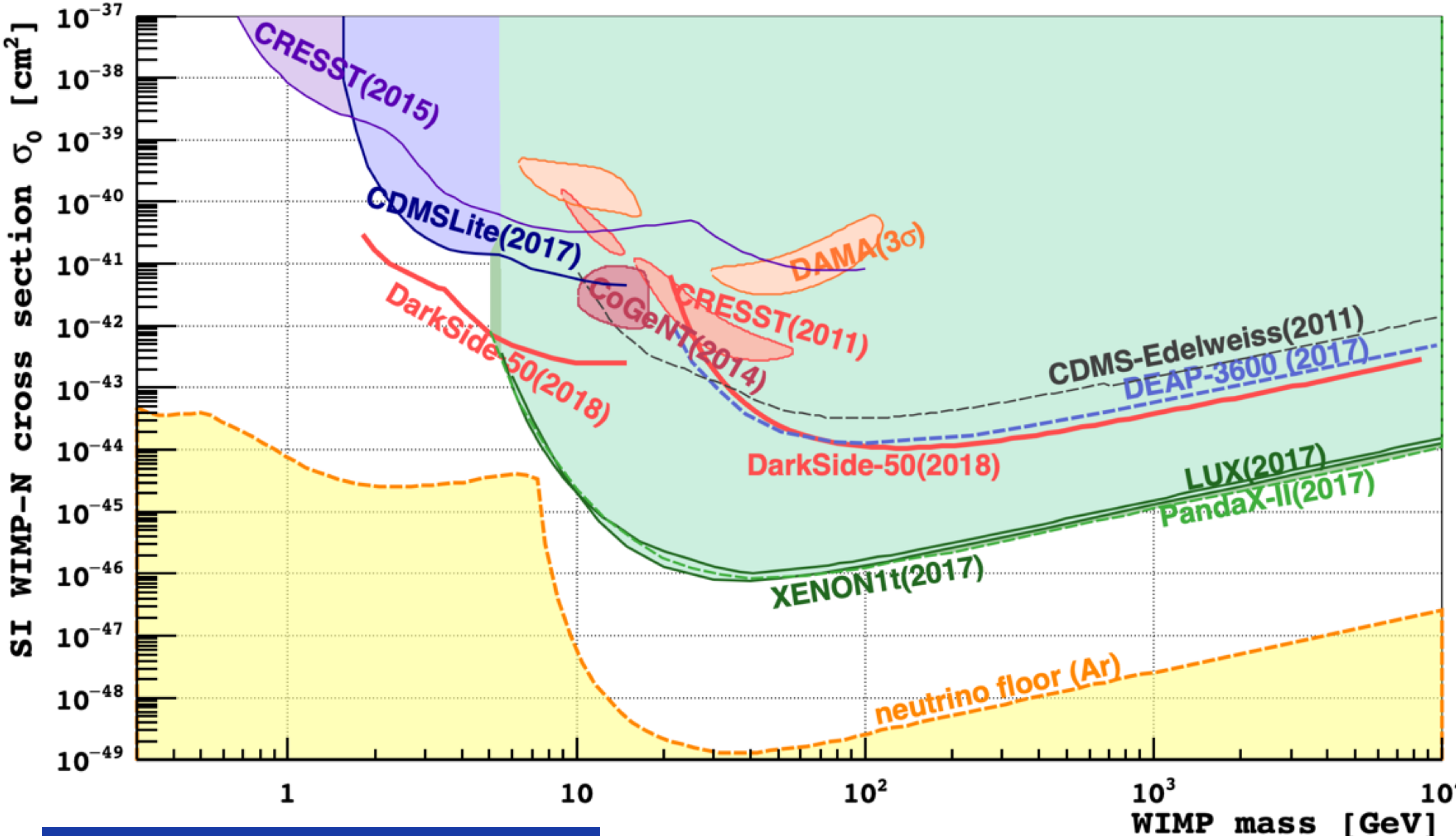
NR backgrounds	ER backgrounds
neutrons α's, ν's	internal and external β's, γ's

Noble liquids are suitable targets:
☑ dense, inexpensive, easy to purify
☑ large ionization/scintillation yields (W~10 eV)
☑ ER recoil background discrimination



Complementarity: great value in case of an excess

Direct detection of dark matter (SI)



Potential of LAr in low-mass WIMP !

Noble liquids will cover the high-mass WIMP region

The DarkSide Program

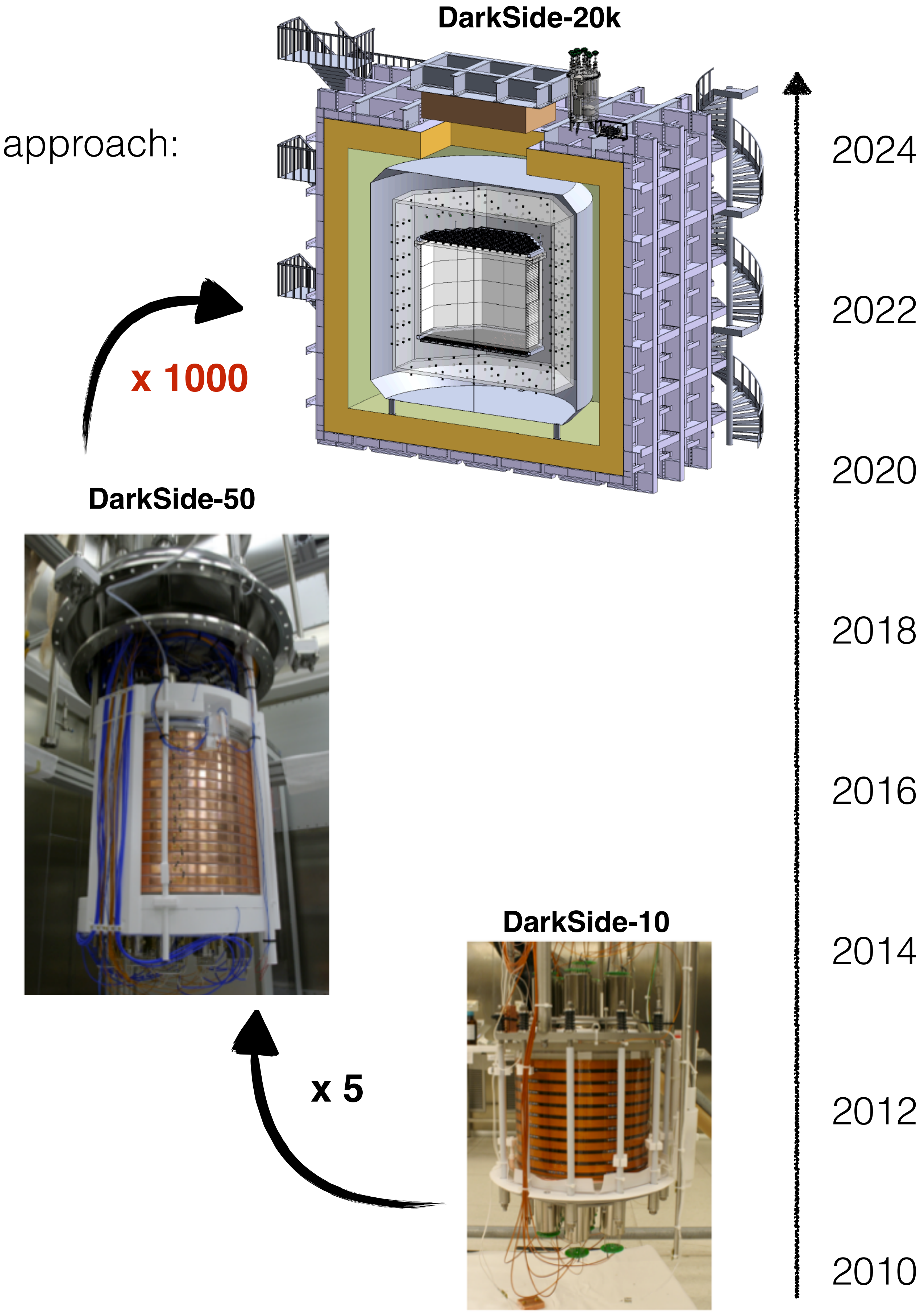
Dual phase liquid argon TPC, through a **staged** approach:

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
- **Active Neutron Veto**
- Water Cherenkov against muons (WCD)

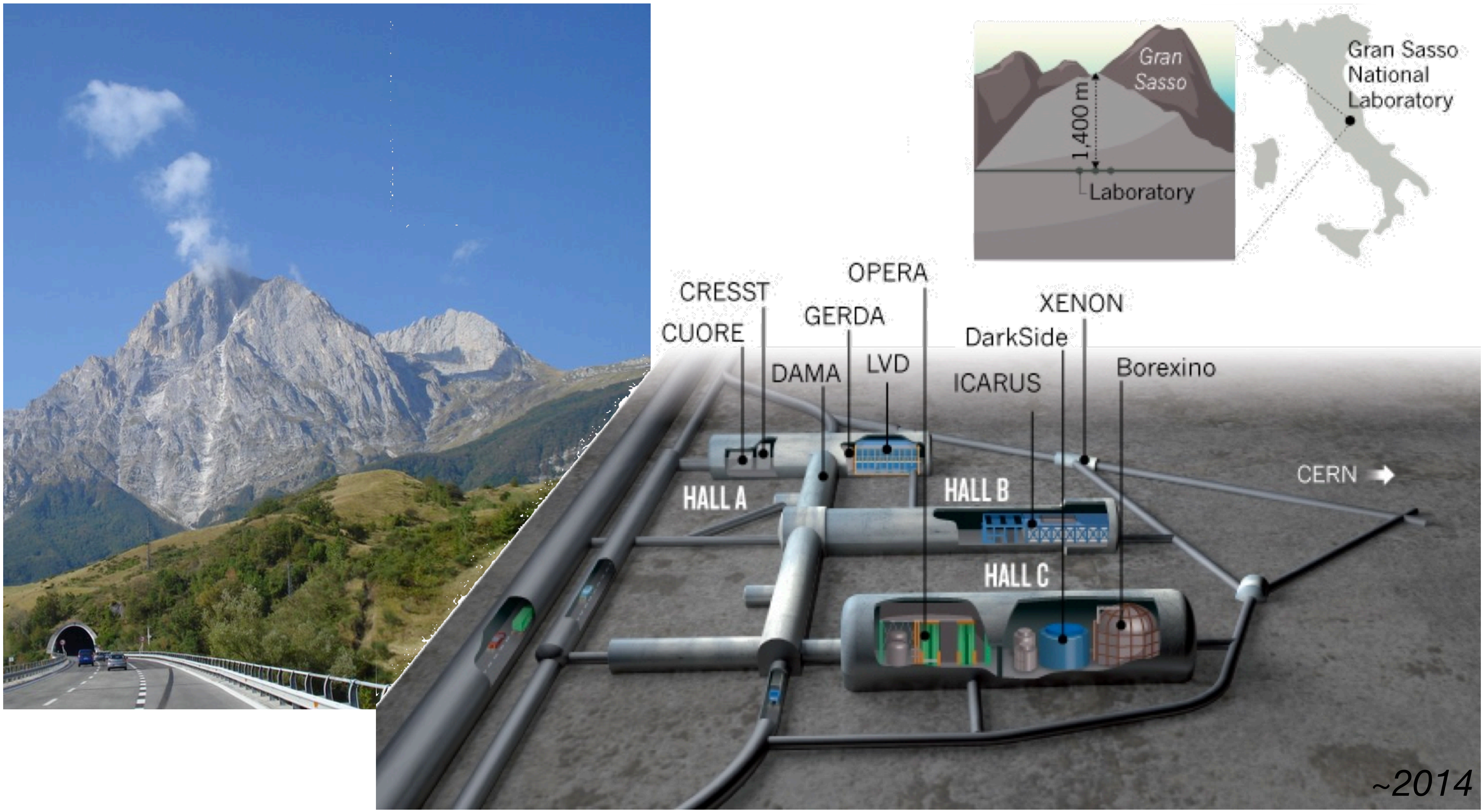
Main goal: collect 200 t yr bg-free exposure



The DarkSide-50 experiment

cosmic μ flux underground ~ 1 / m² / hr

At *Laboratori Nazionali del Gran Sasso* (LNGS), Italy



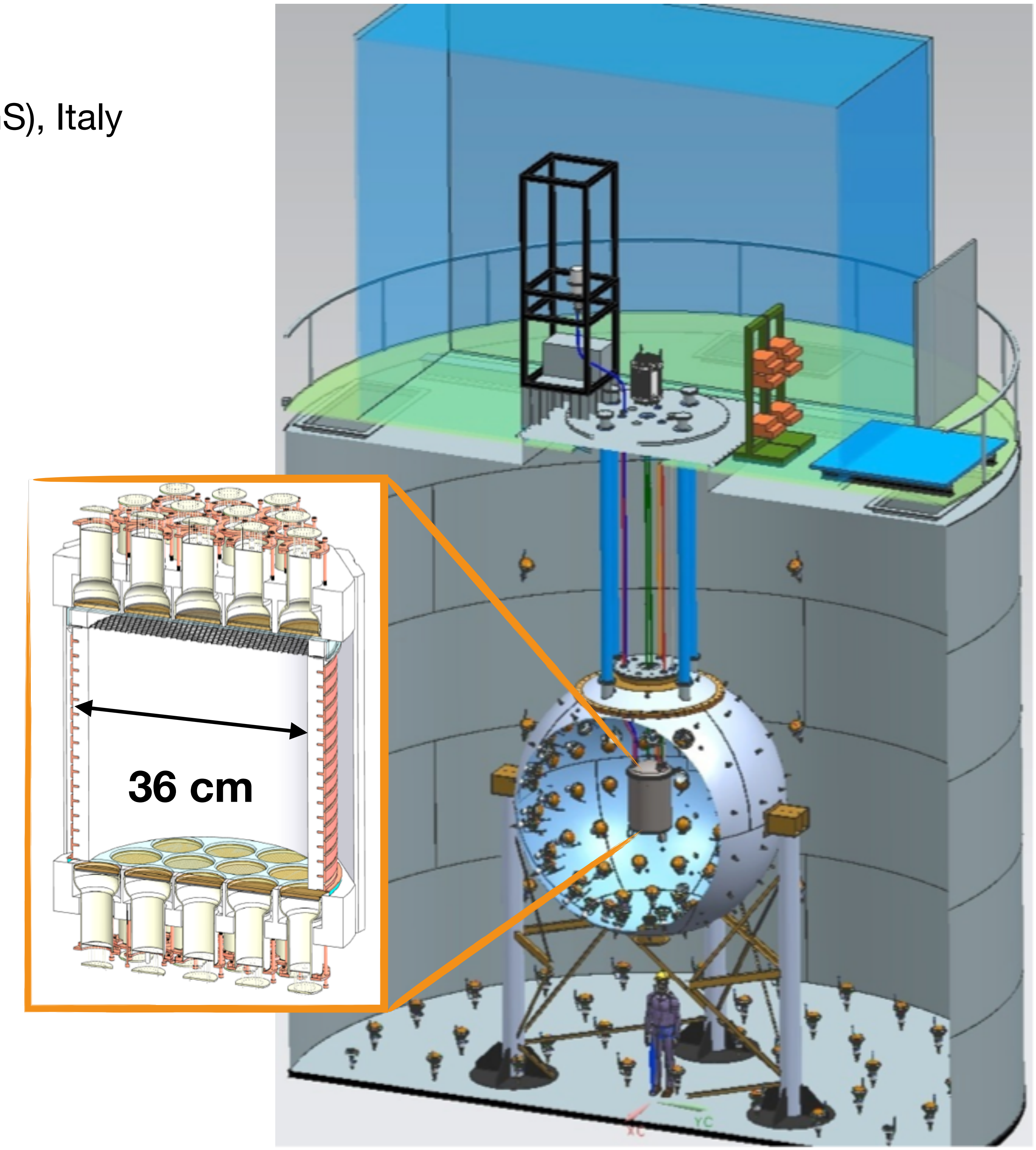
The DarkSide-50 experiment

At *Laboratori Nazionali del Gran Sasso* (LNGS), Italy

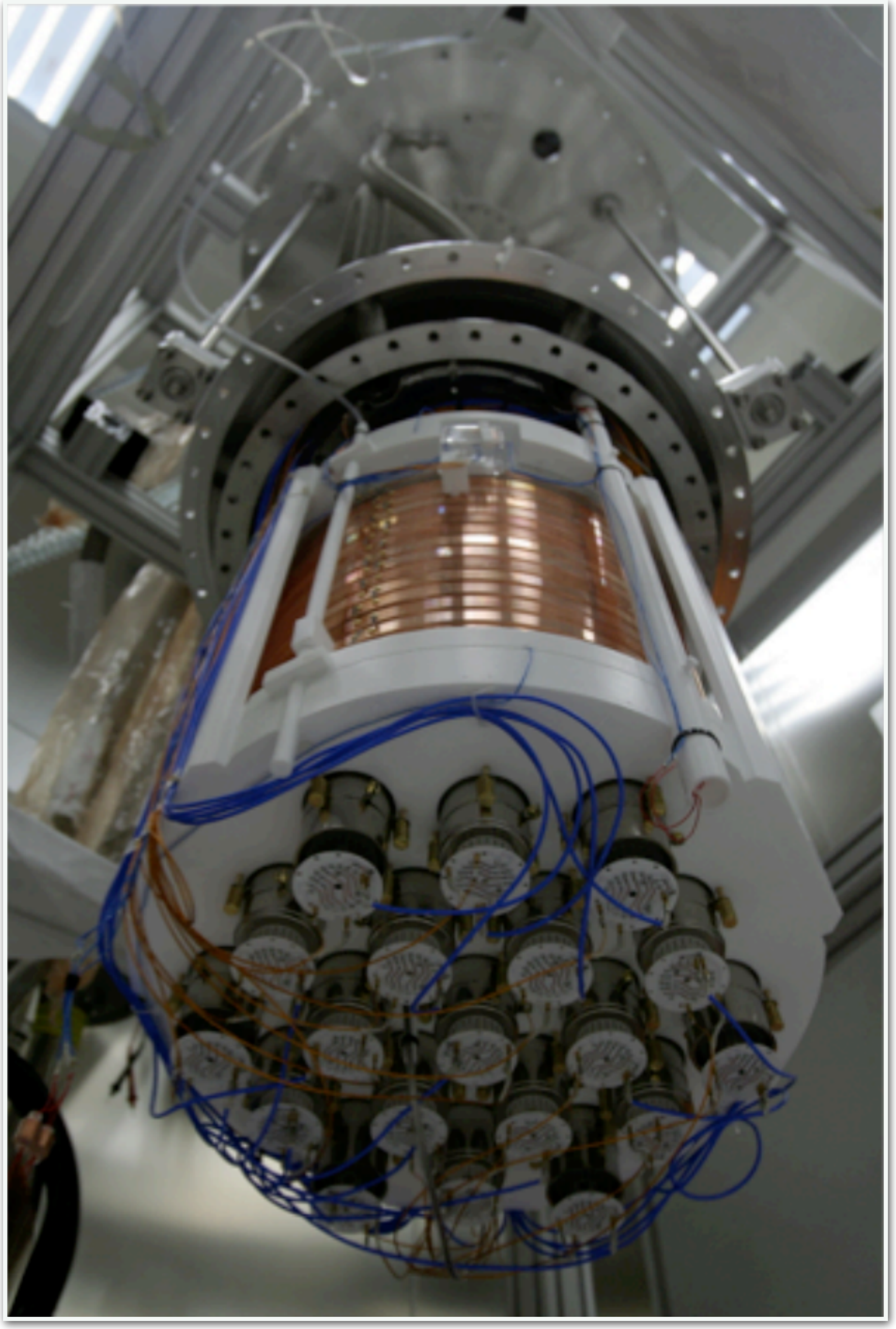
Liquid argon TPC
- **50 kg LAr**
- **19 + 19 3” PMTs**
- Reflectors and TPB coating

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

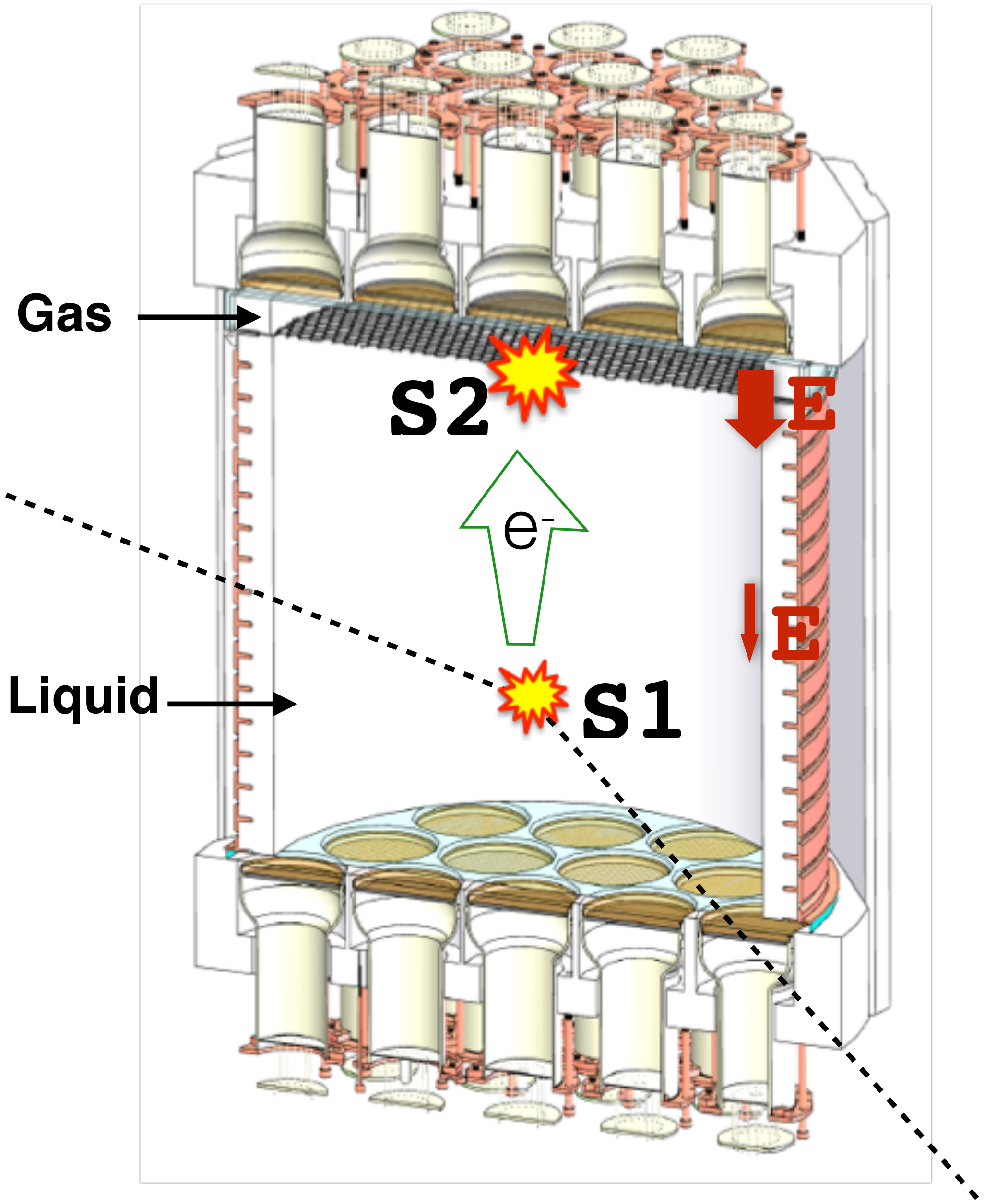
Water Cherenkov Detector (WCD)
- 1 kt water, 5.5 m radius
- 80 PMTs

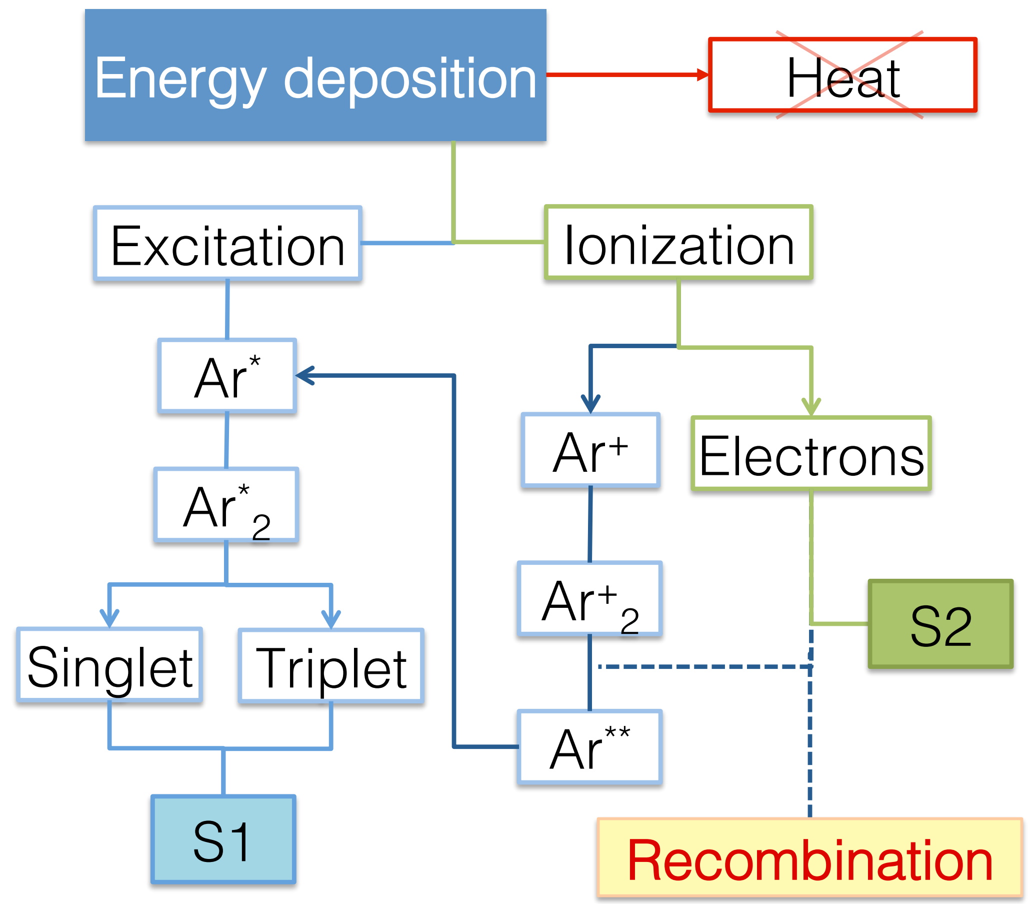


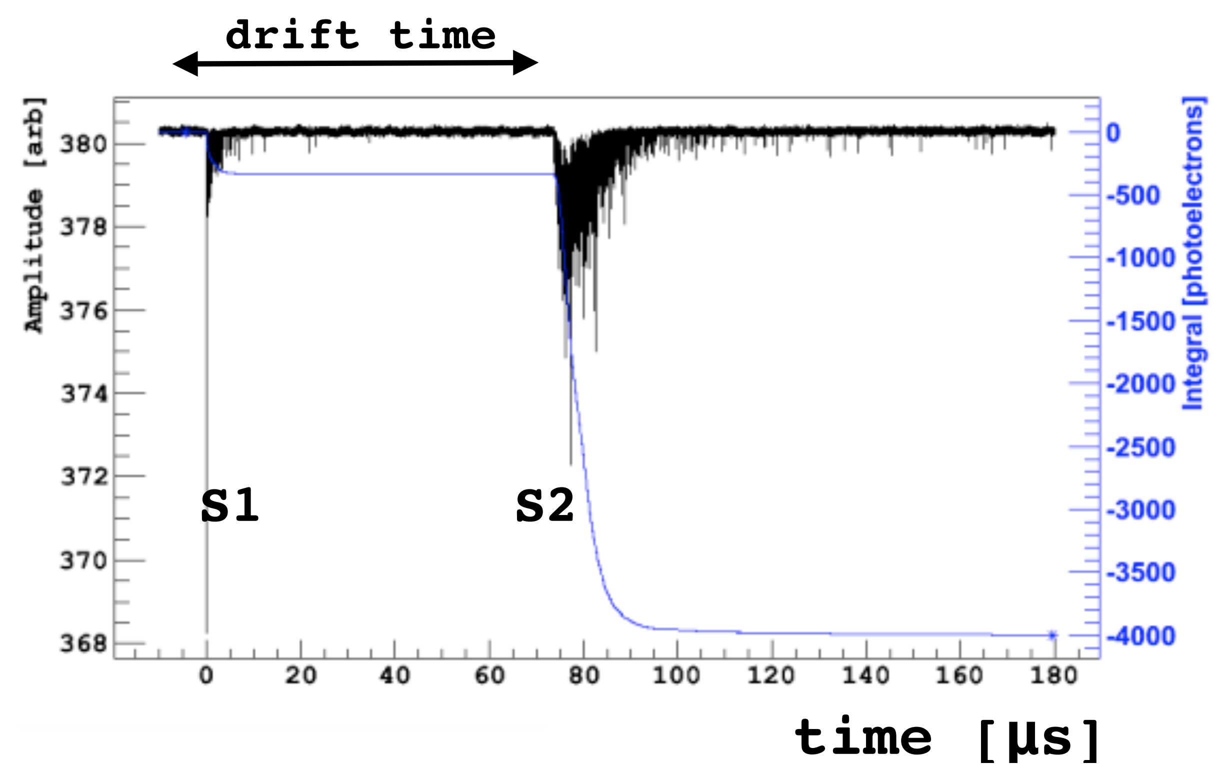
Installation in 2013



Dual-phase TPC

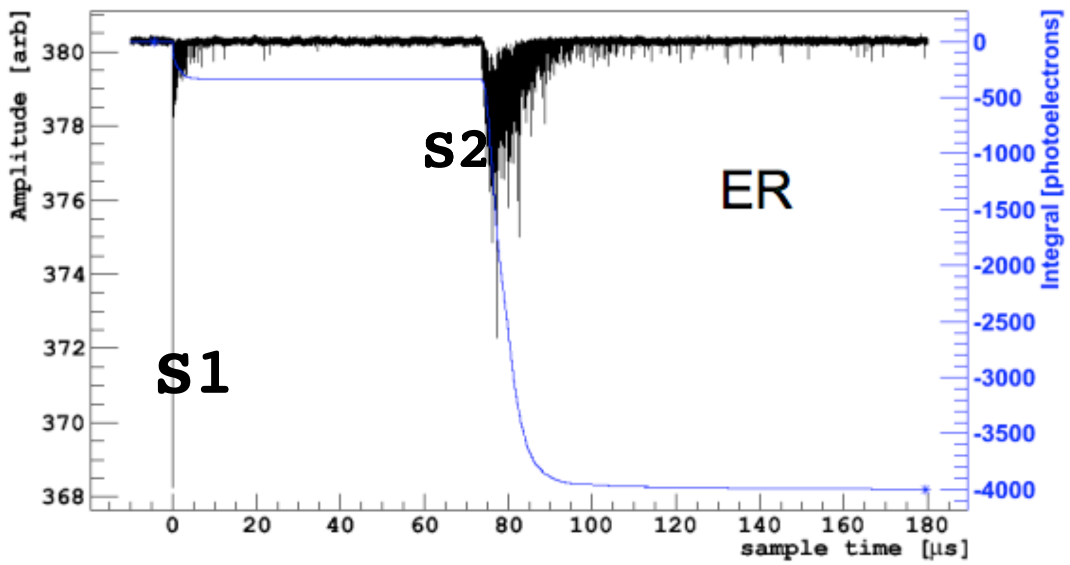


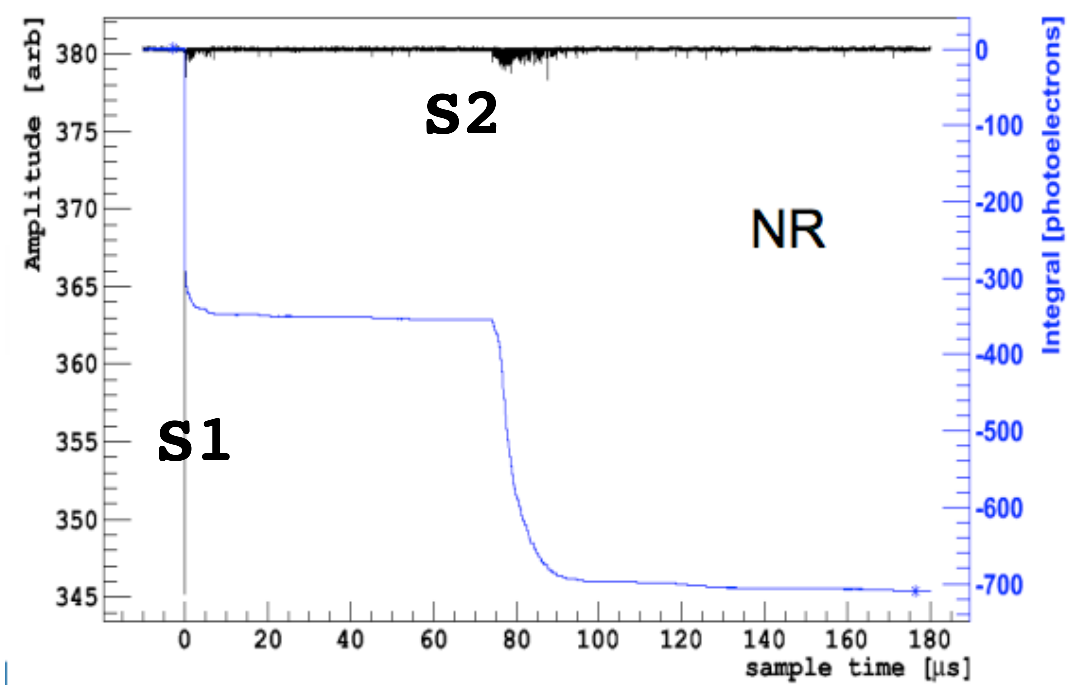


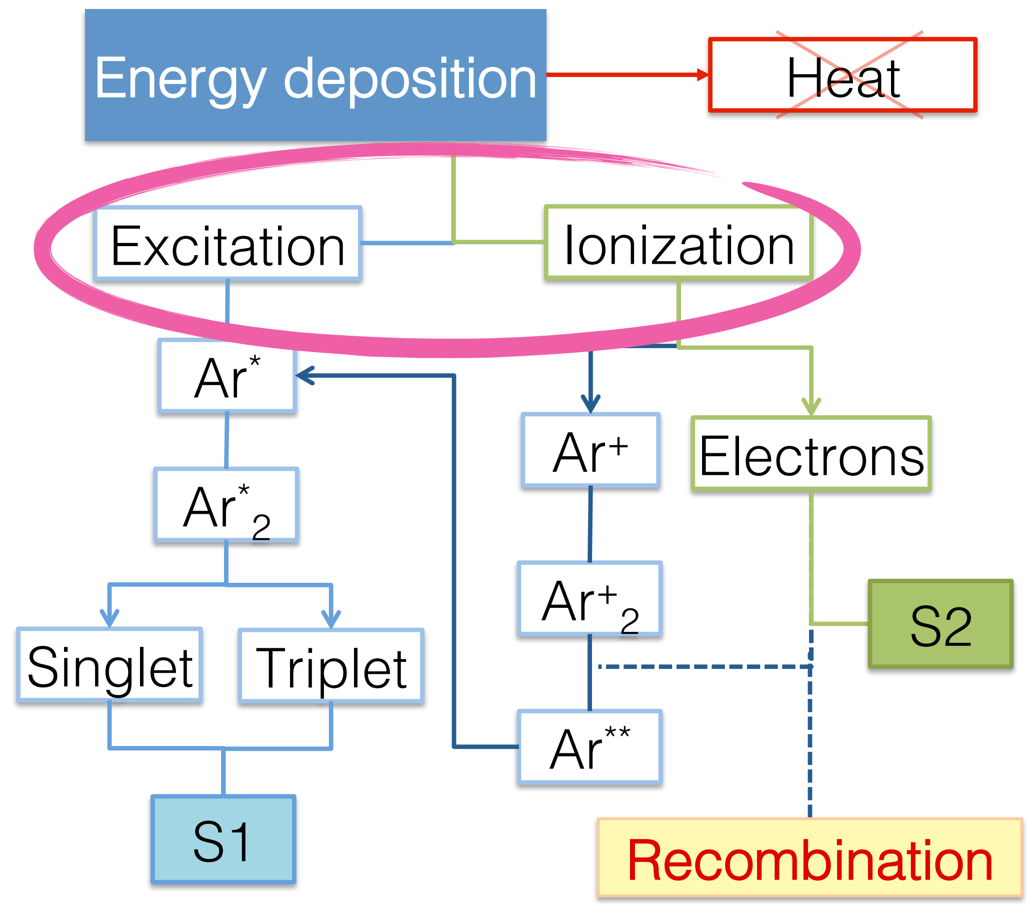


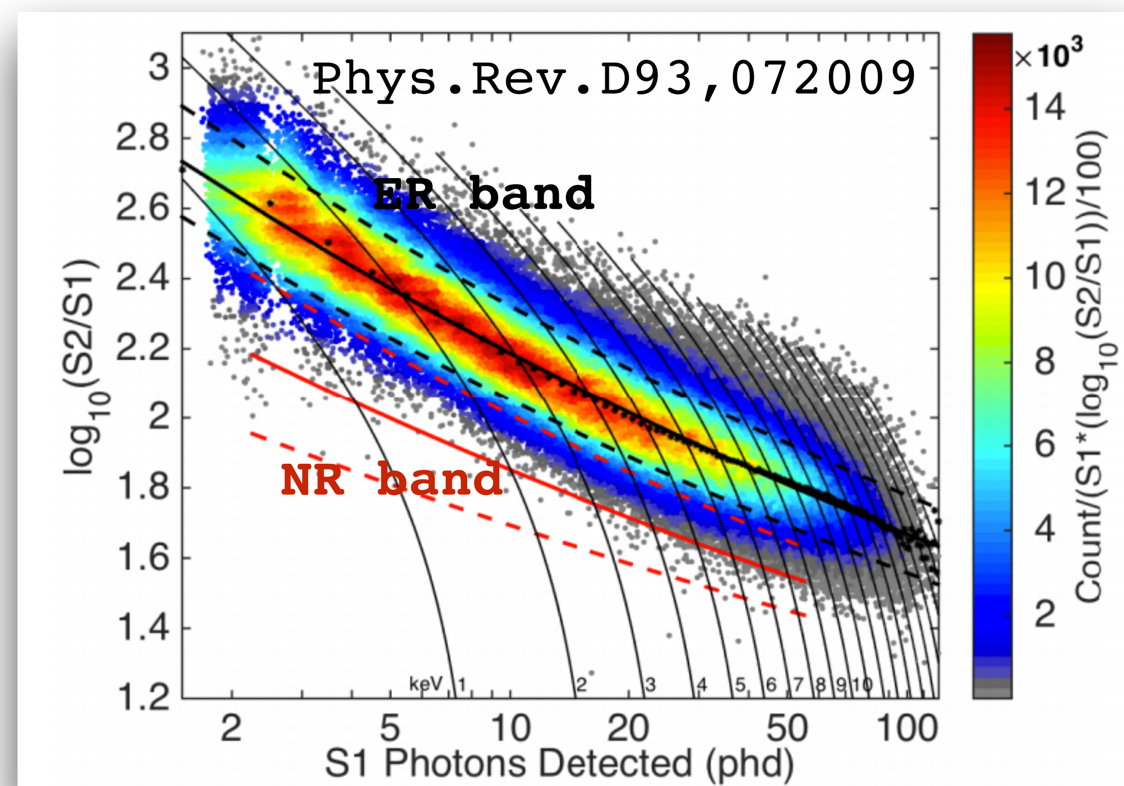
==> 3D vertex reconstruction
(surface events, multi-sited events) !

Rejection by Ionization/Scintillation





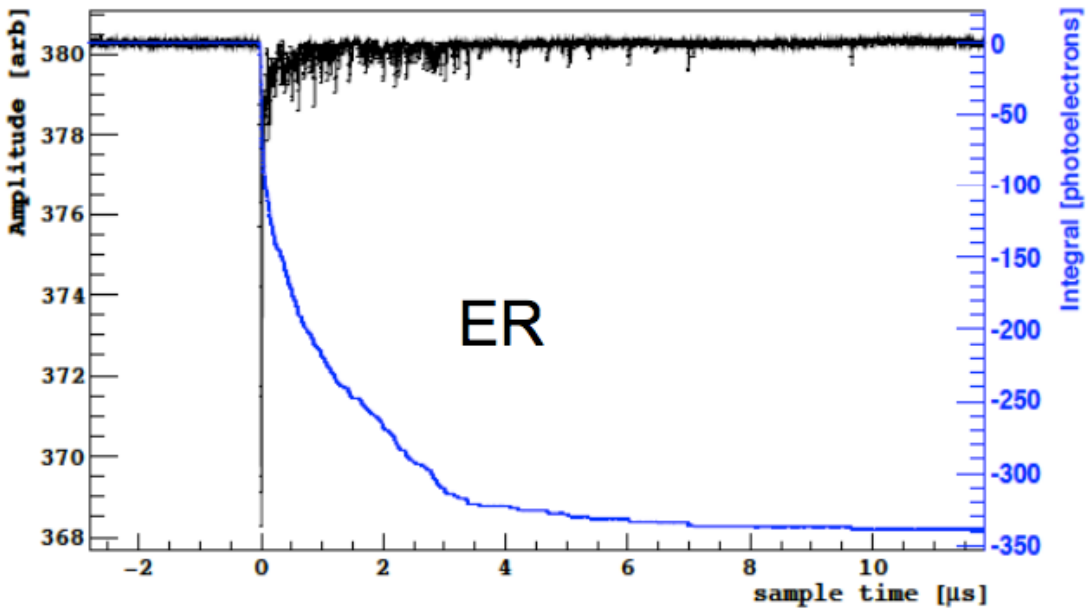


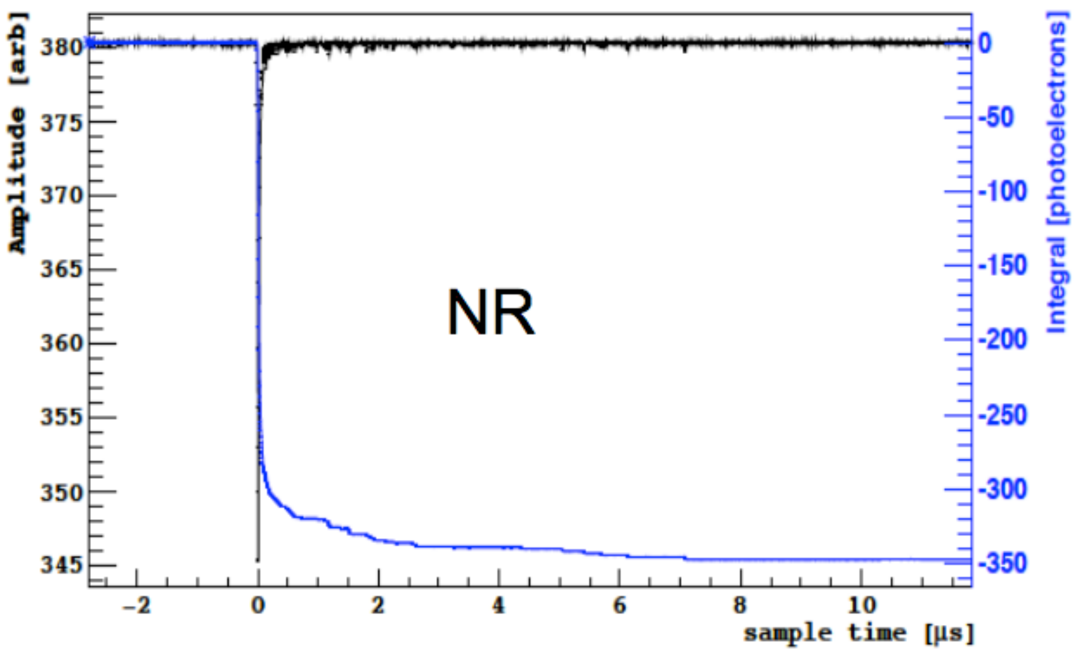


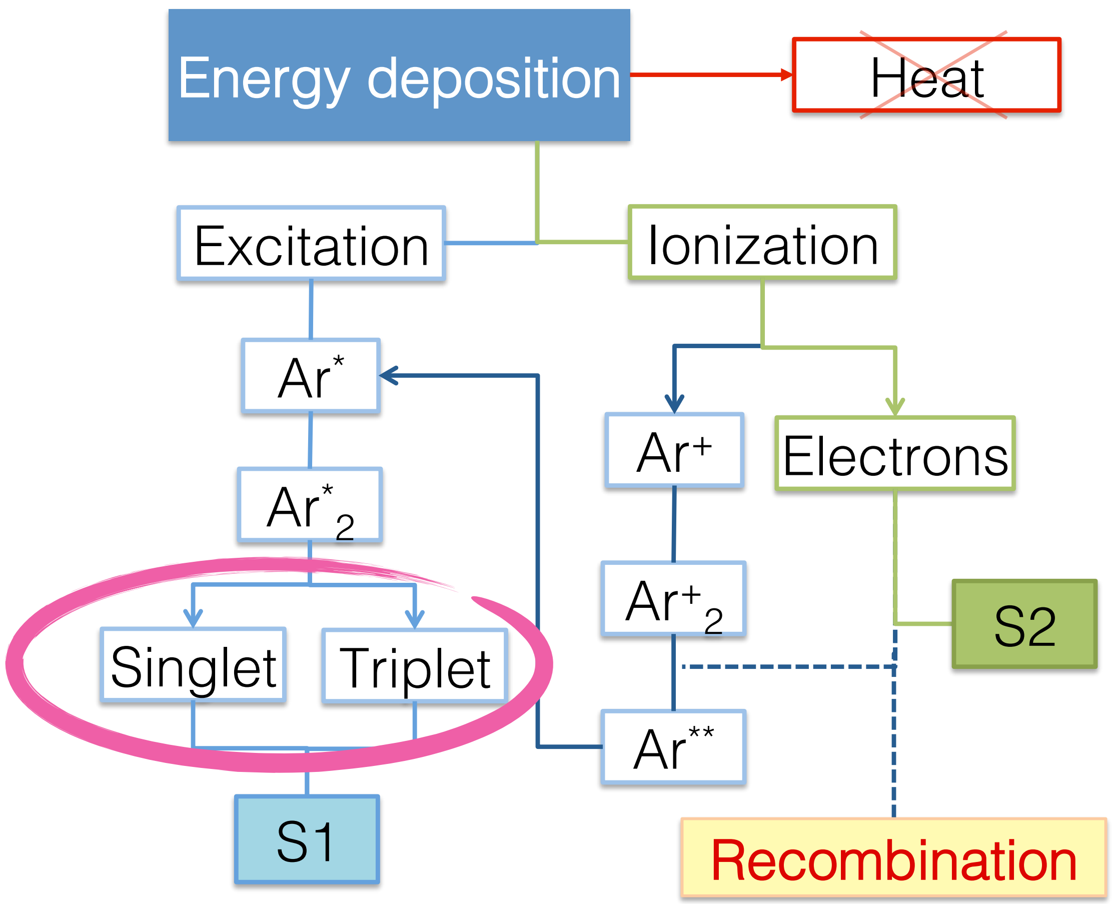
ER Rejection factor: 10^2 - 10^3

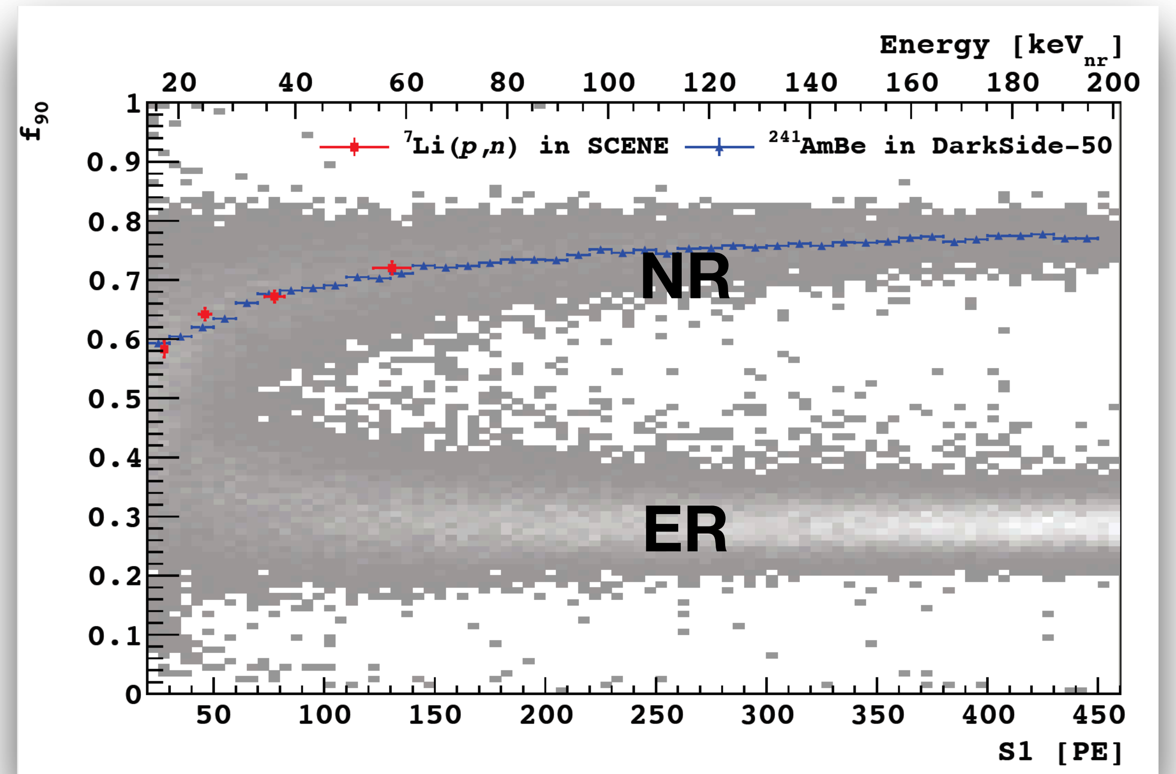
XENON-1t: PRL 121, 111302 (2018)

Rejection with Pulse Shape Discrimination









ER Rejection factor: ~ 10^8 in LAr

τ_{fast} ~ 6 ns, τ_{slow} ~ 1.6 μs

DEAP-3600: Phys. Rev. D 100, 022004

Argon from underground

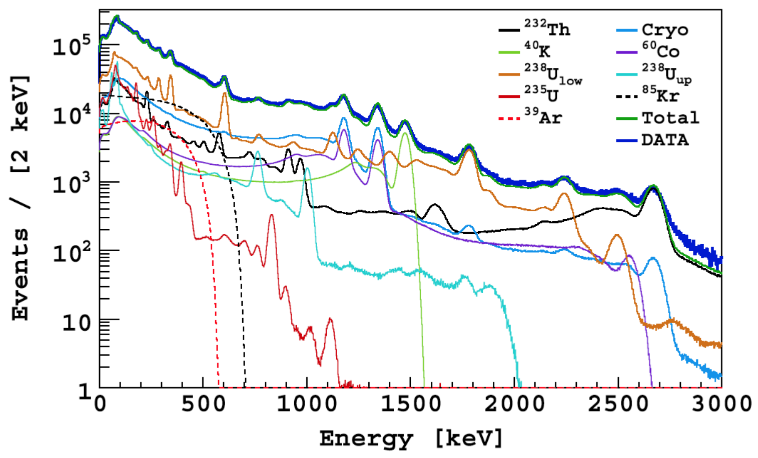
^{39}Ar is produced by cosmic rays in the atmosphere. **β-decay** with **Q = 565 keV**; $\tau_{1/2}$ = 269 yr

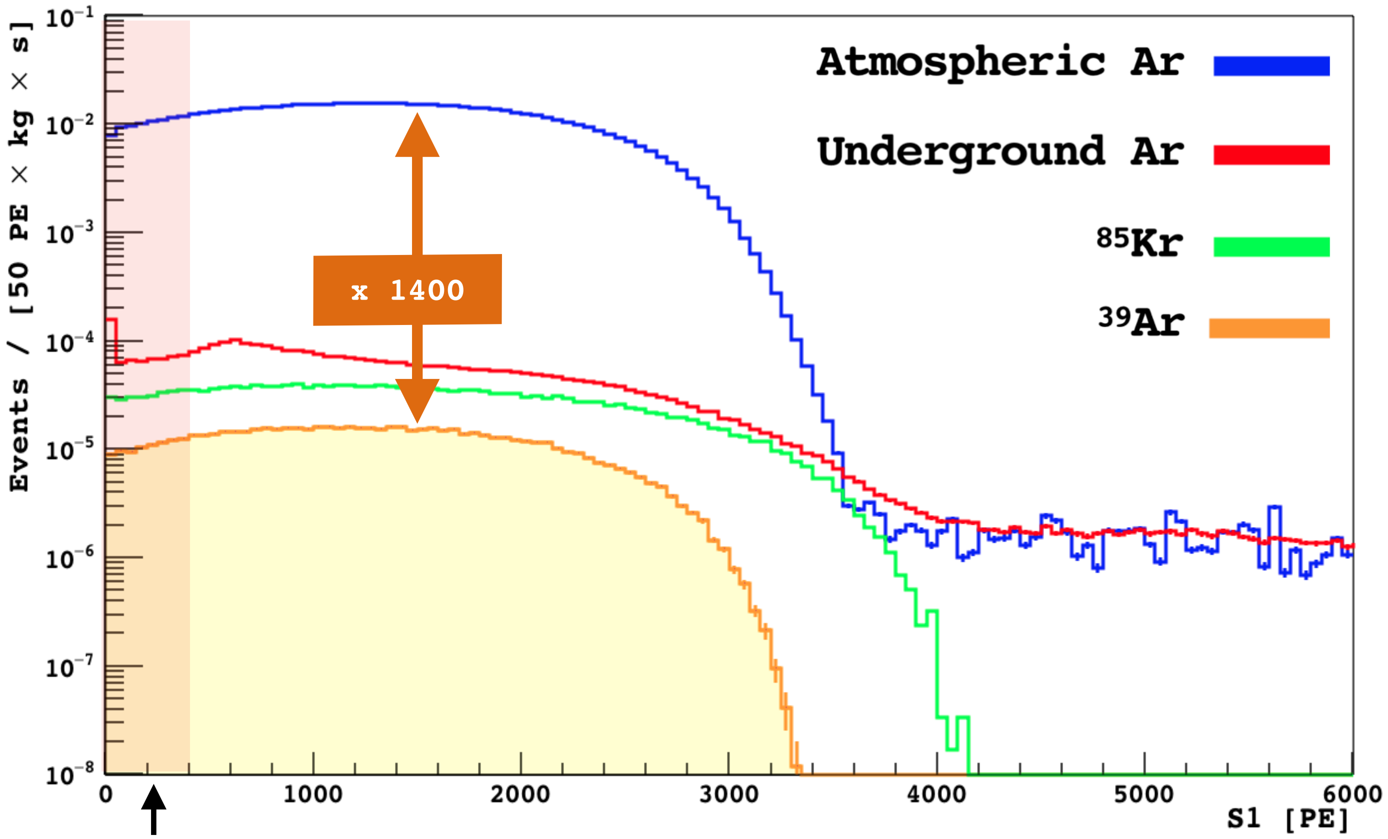
- **^{39}Ar activity in atmospheric argon** (~ 1 Bq/kg): limiting dual-phase target mass

==> extract argon from underground (CO_2 well in Colorado) !

- **^{39}Ar activity in underground argon** (0.73 ± 0.10 mBq/kg)
- Possibly smaller: identification of a ^{85}Kr contamination

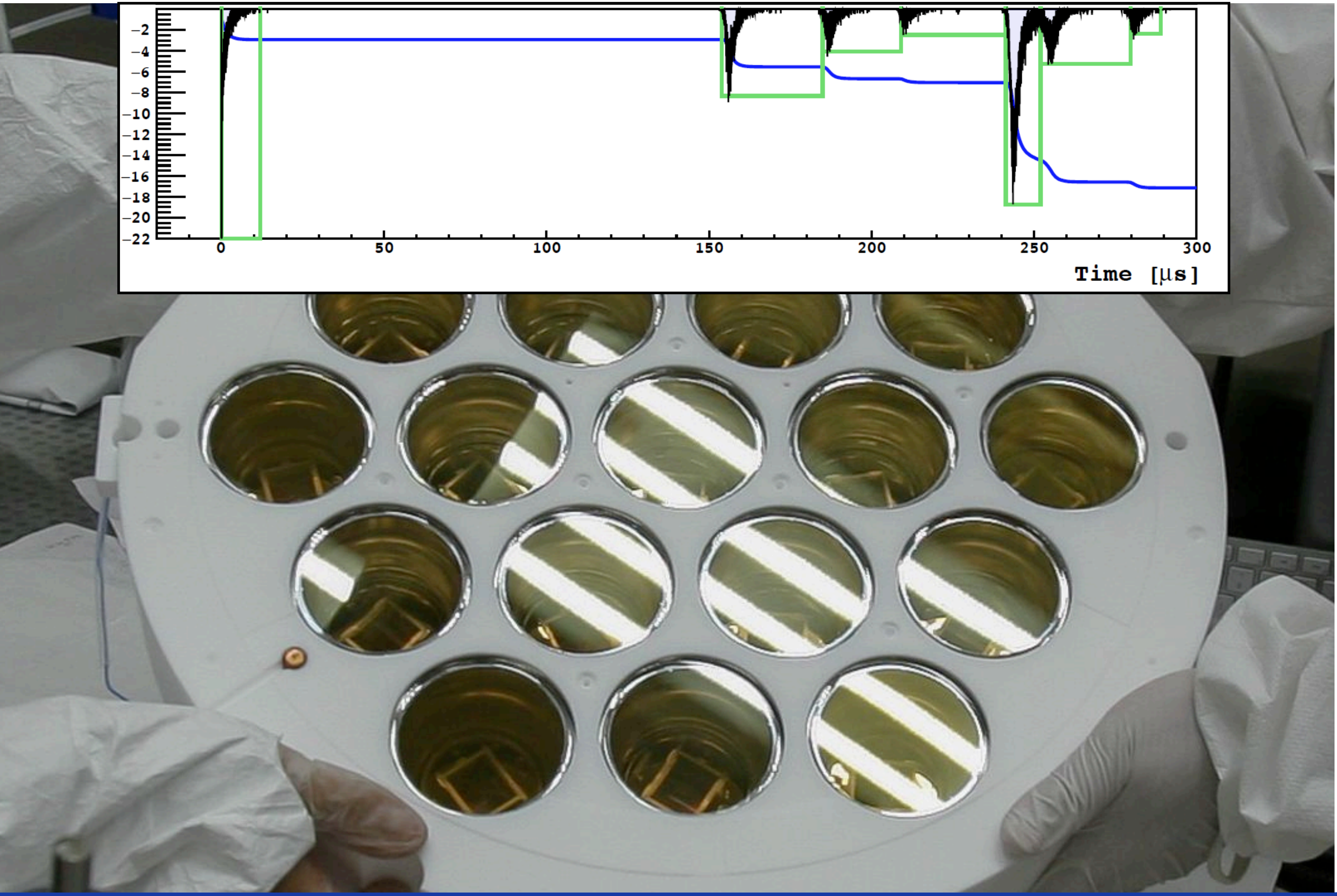
DarkSide-50 running with UAr (since 2015) after first AAr run





dark matter search region (< 50 keV$_{ee}$)

Phys. Rev. D 93, 081101 (2016)

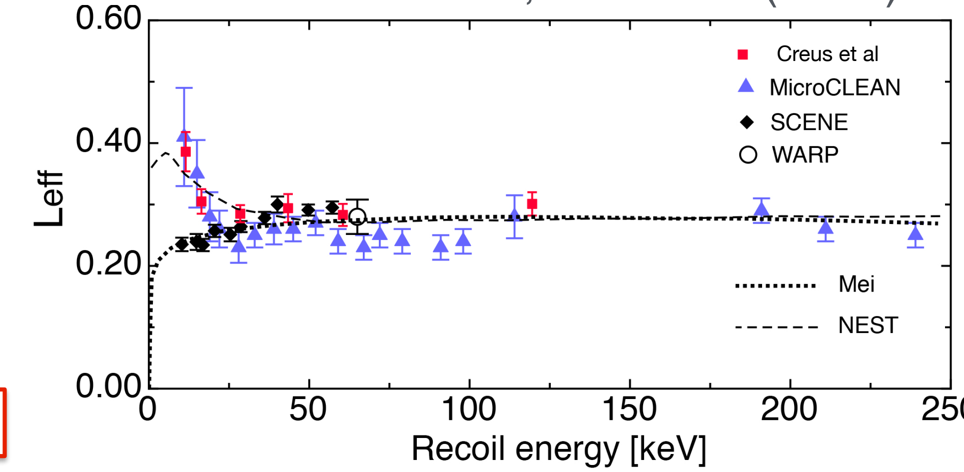

−2
−4
−6
−8
−10
−12
−14
−16
−18
−20
−22
0
50
100
150
200
250
300
Time [μs]

Detector Calibration

Ionisation work function and Nex/Ni are usually assumed, measured only at high energy

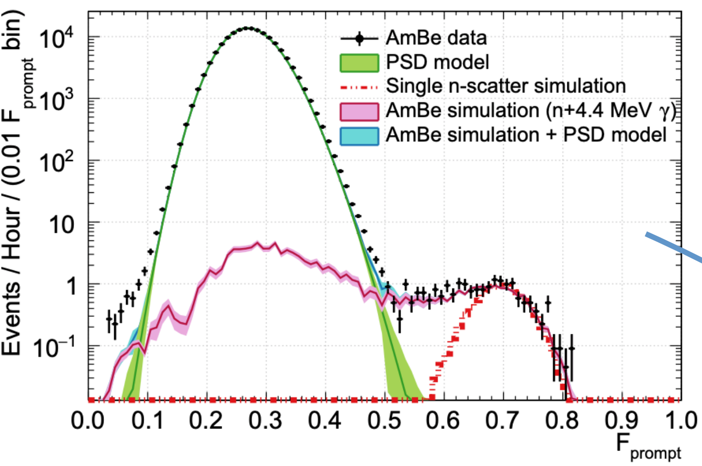
for NR-like only

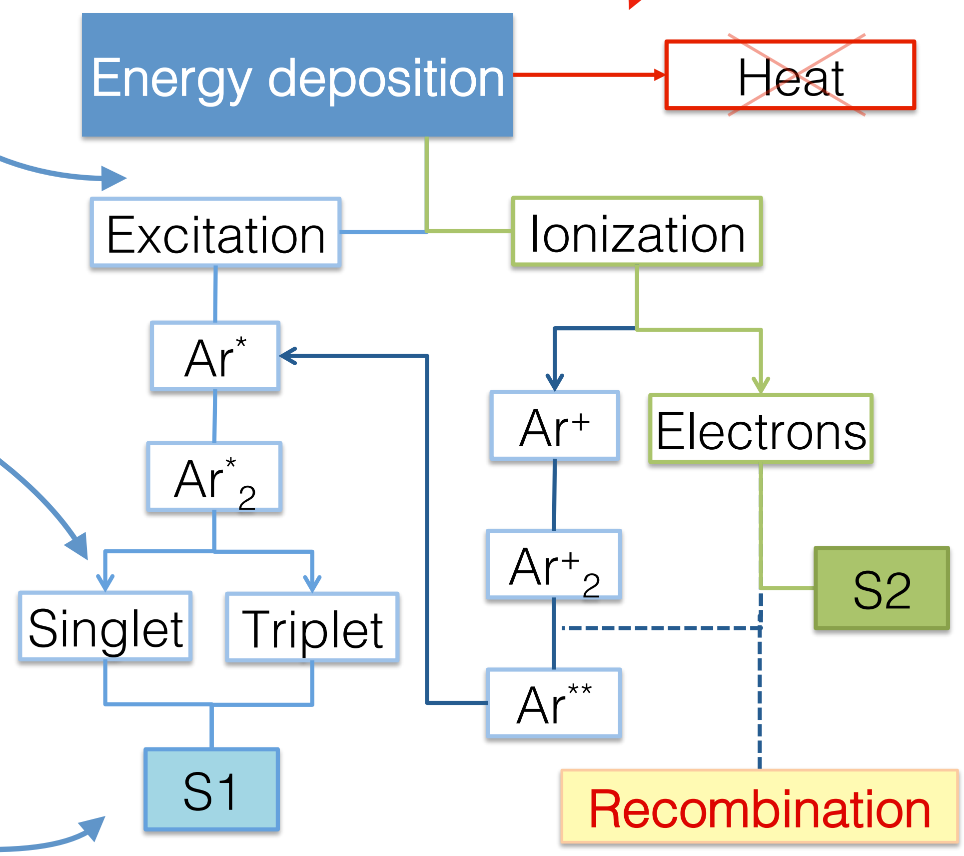
W. Creus *et al*, JINST **10** (2015)



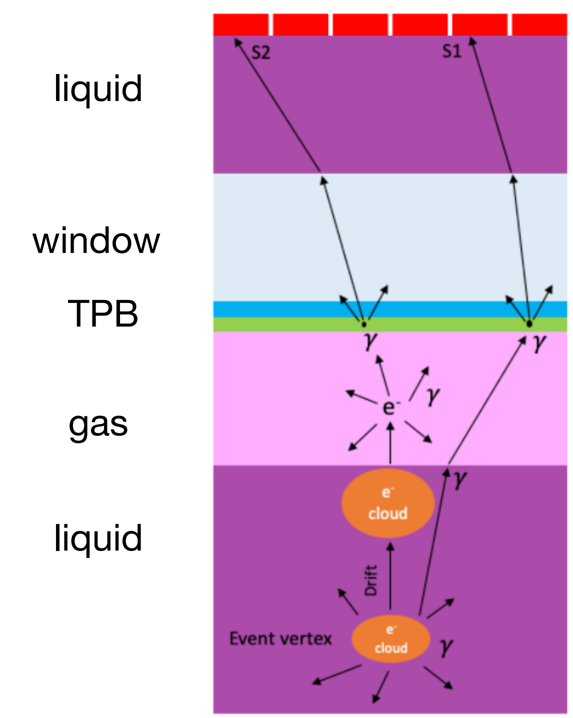
Lindhard theory not accounting for density effects?
Hard in-situ, even with neutron sources

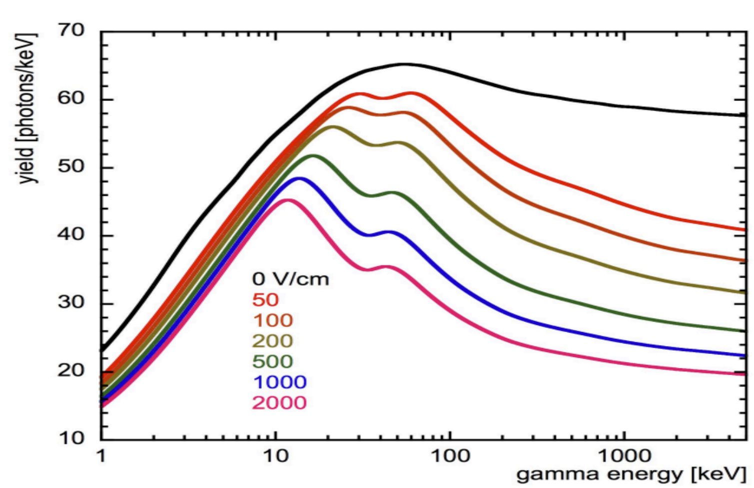
Huge statistics for PSD





Light propagation in the detector and optical simulations





Depends on drift field (and uniformities);
Effective model exist (eg NEST, PARIS)

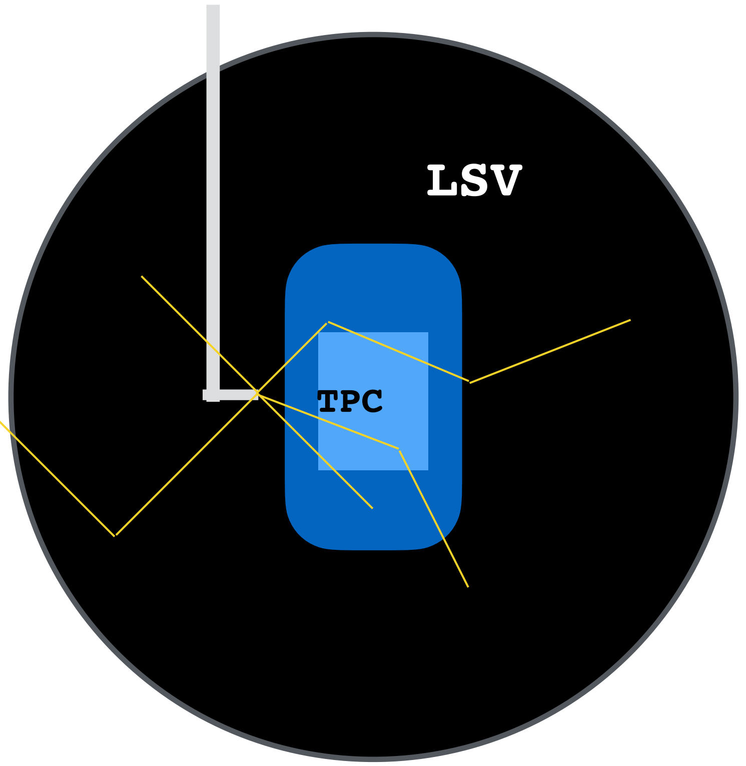
In-situ Calibrations - ER

S1 and S2 Yields:

- S1 Yield ~7.9 pe/keV at null field
- S1 Yield **~7.0 pe/keV** at 200 V/cm
- S2 yield **~23 pe / e-**

Electron lifetime > 5 ms

Maximum drift time: 376 μs

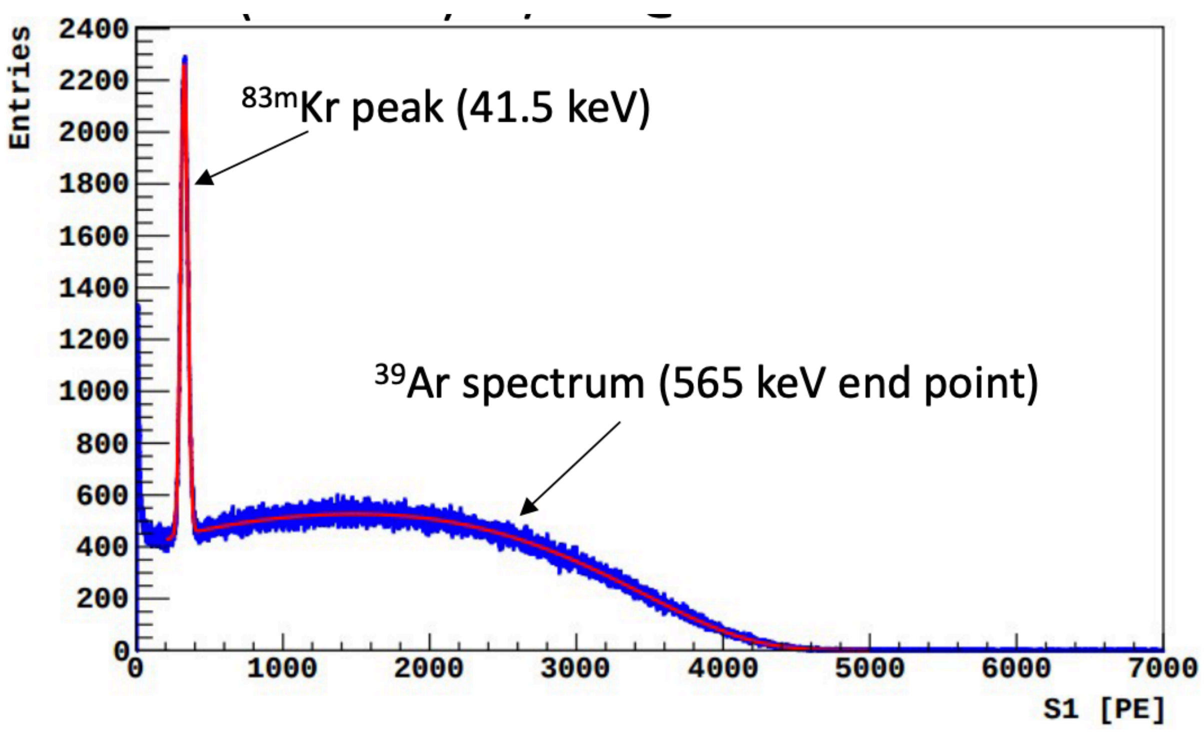


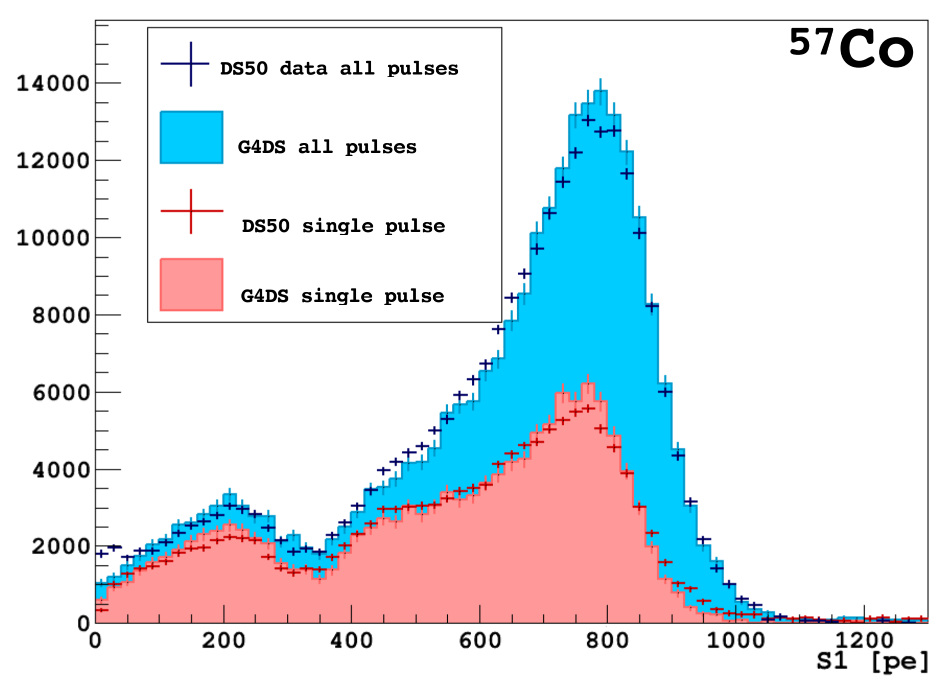
Internal Calibrations:

^{83m}Kr and ^{39}Ar

External Calibrations:

^{57}Co, ^{133}Ba, ^{137}Cs

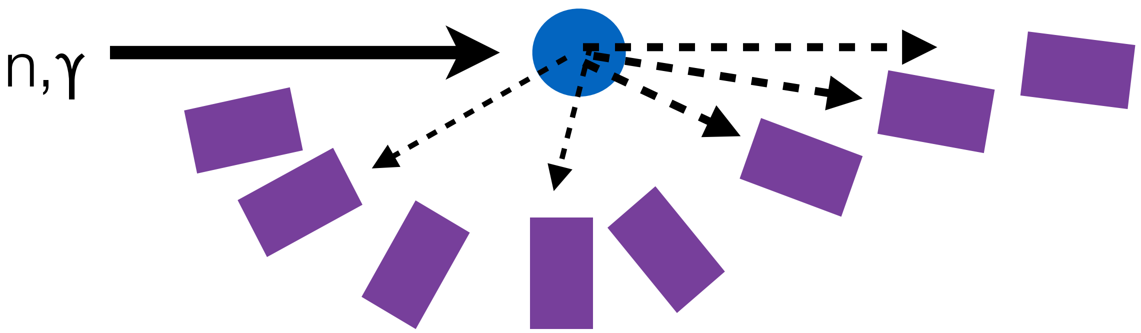




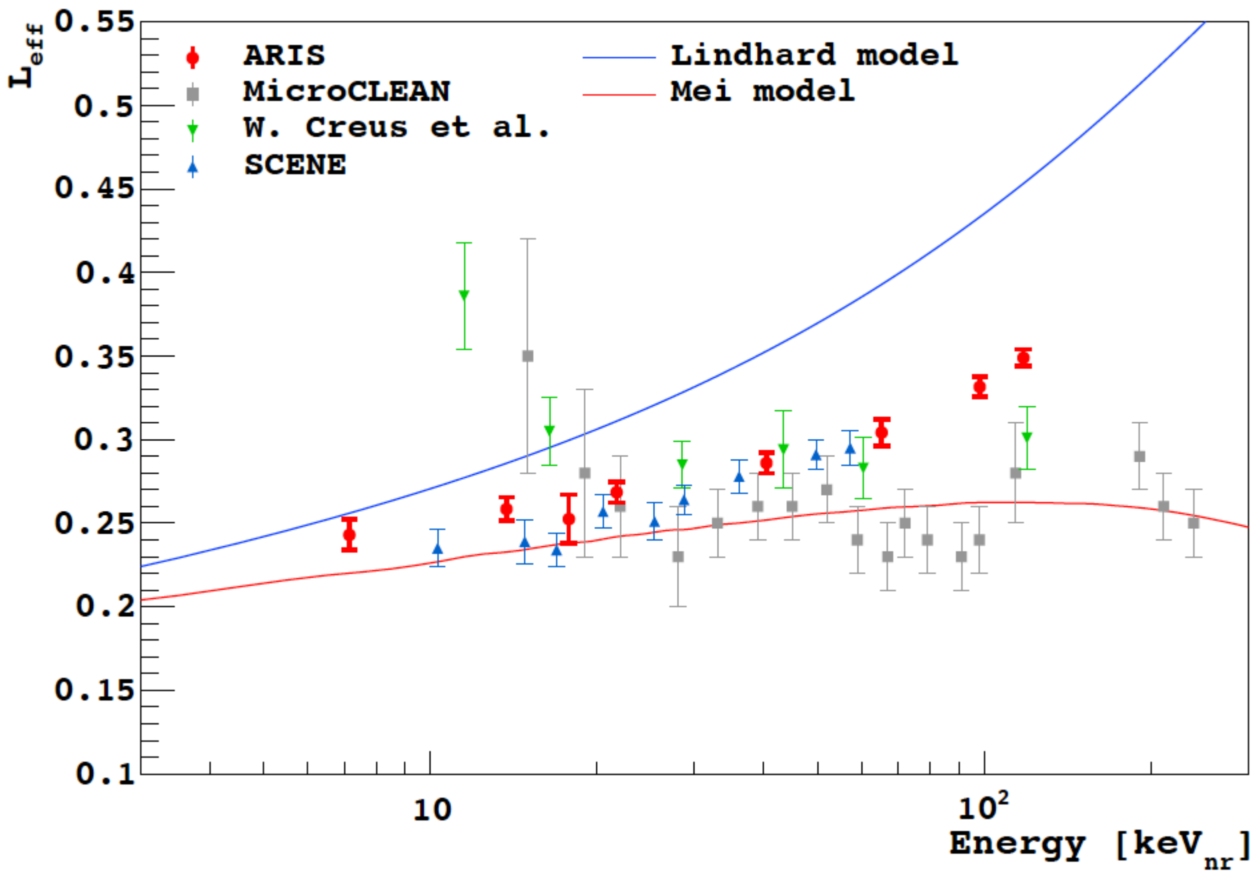
Tune ER energy scale and a full optical modelling (Geant4)

The ARIS experiment: a small scale TPC exposed to a **pulsed**, **collimated**, **monochromatic** neutron beam (LICORNE @IPNO), coupled with 8 neutron detectors, to fix NR energy by kinematics.

==> model response of NR (WIMP-induced interactions)



Precision L_{eff} at low energy

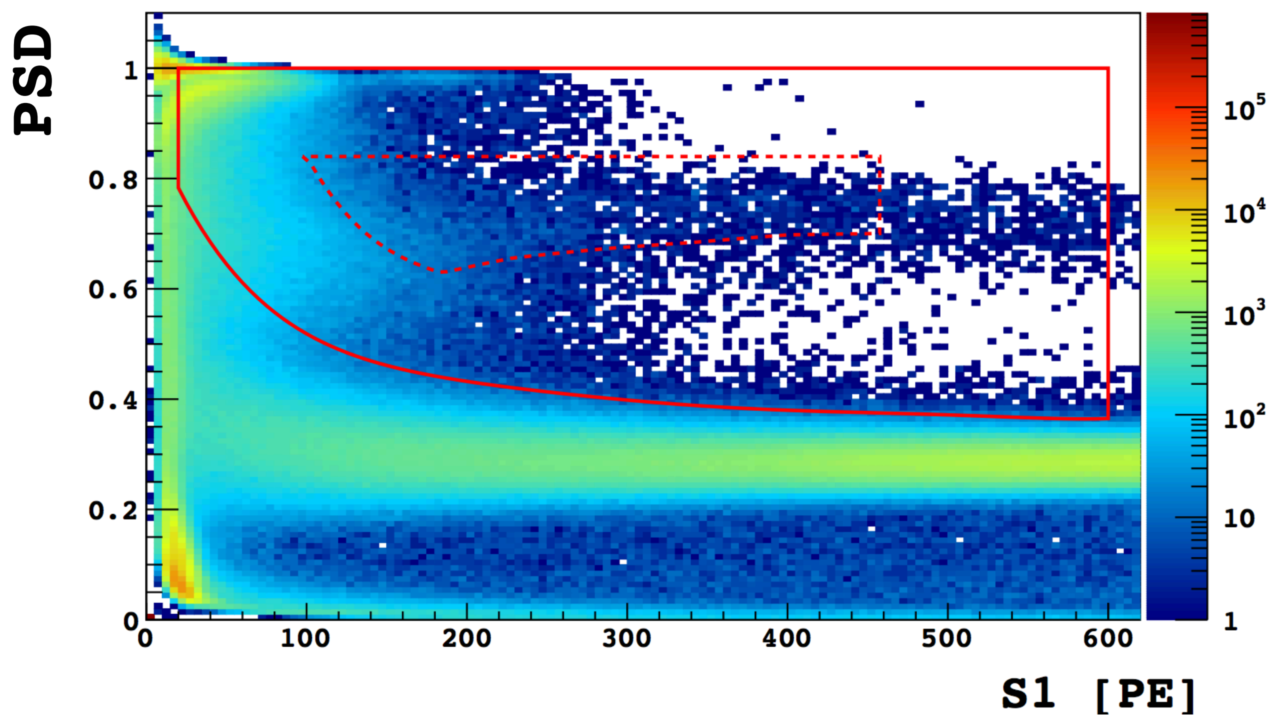


Tune NR energy scale, with ER provides effective model for signal and bg in WIMP ROI

High-mass WIMP results

Blind analysis published in 2018

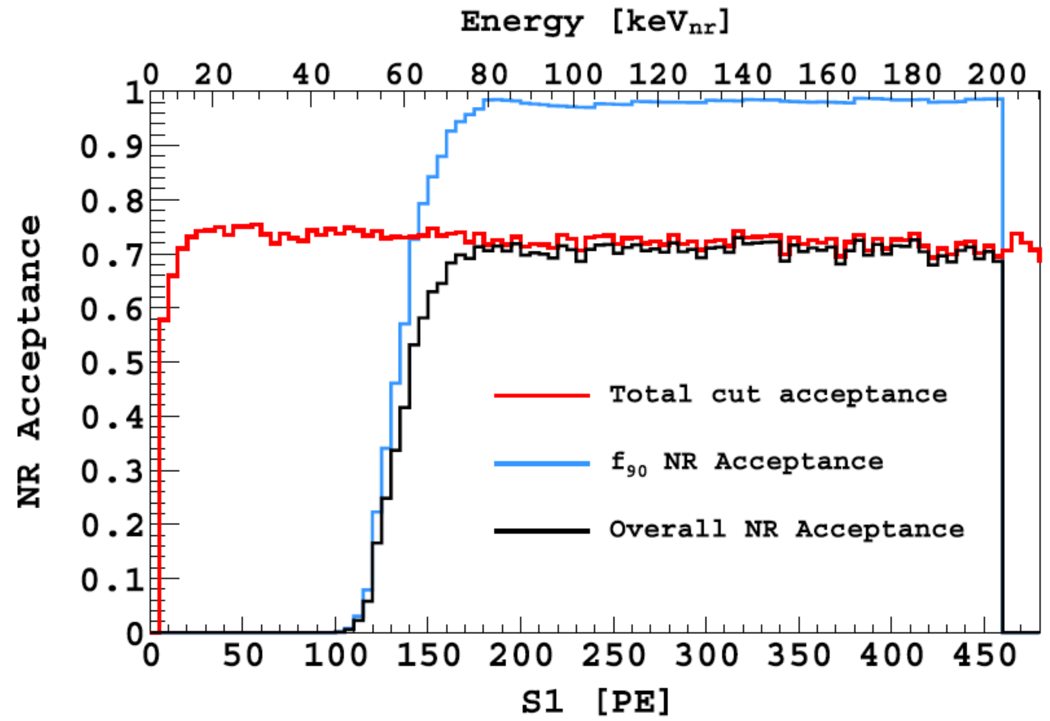
- Use first 70 days of UAr dataset to tune cuts
- Minimise backgrounds while maximising acceptance to NR



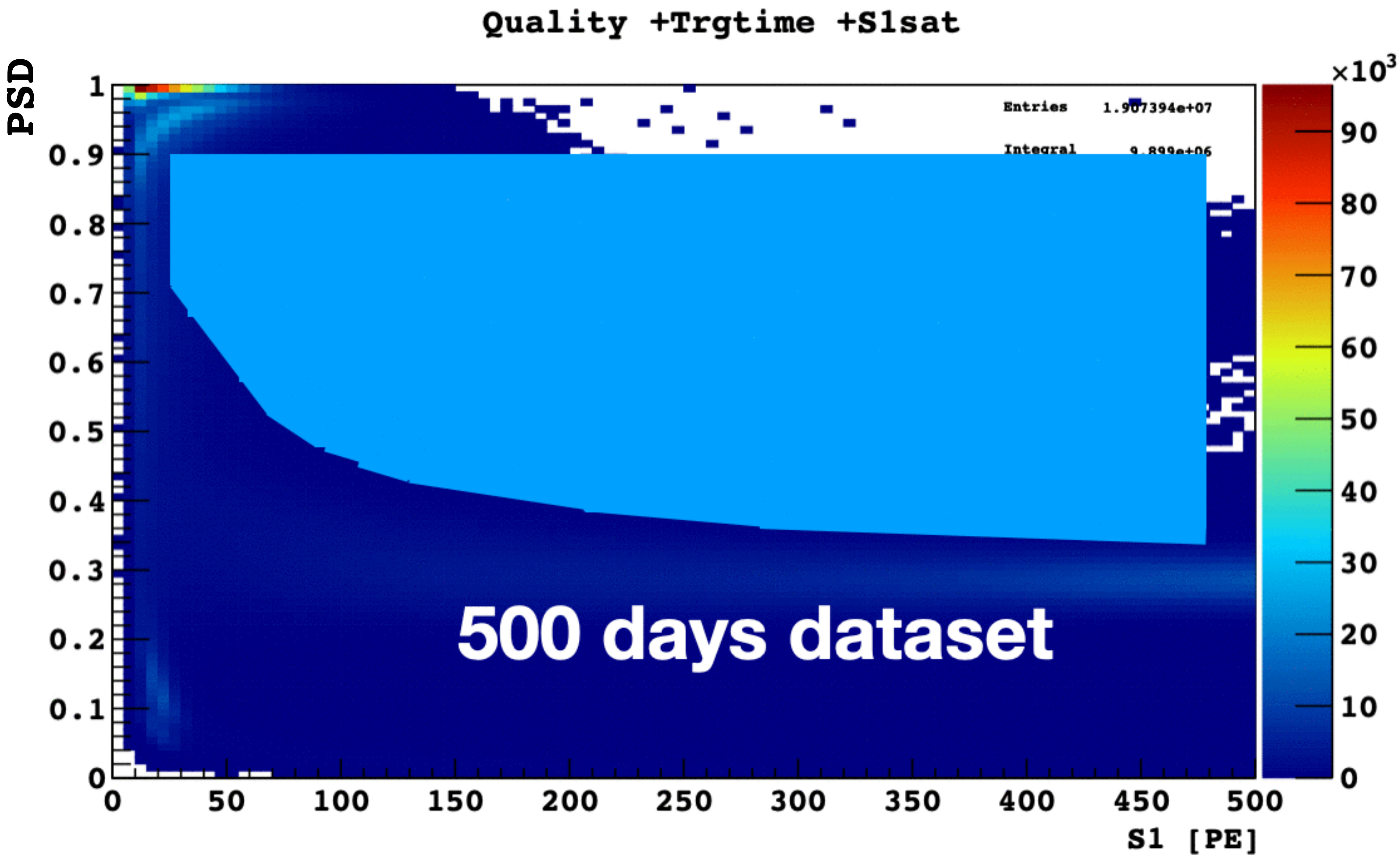
Expected backgrounds in ROI, before opening box

surface alphas	0.001
cosmogenic neutrons	<0.00035
radiogenic neutrons	<0.005
electron recoil	0.08
	0.09±0.04

NR acceptance after all cuts. Threshold driven by PSD:



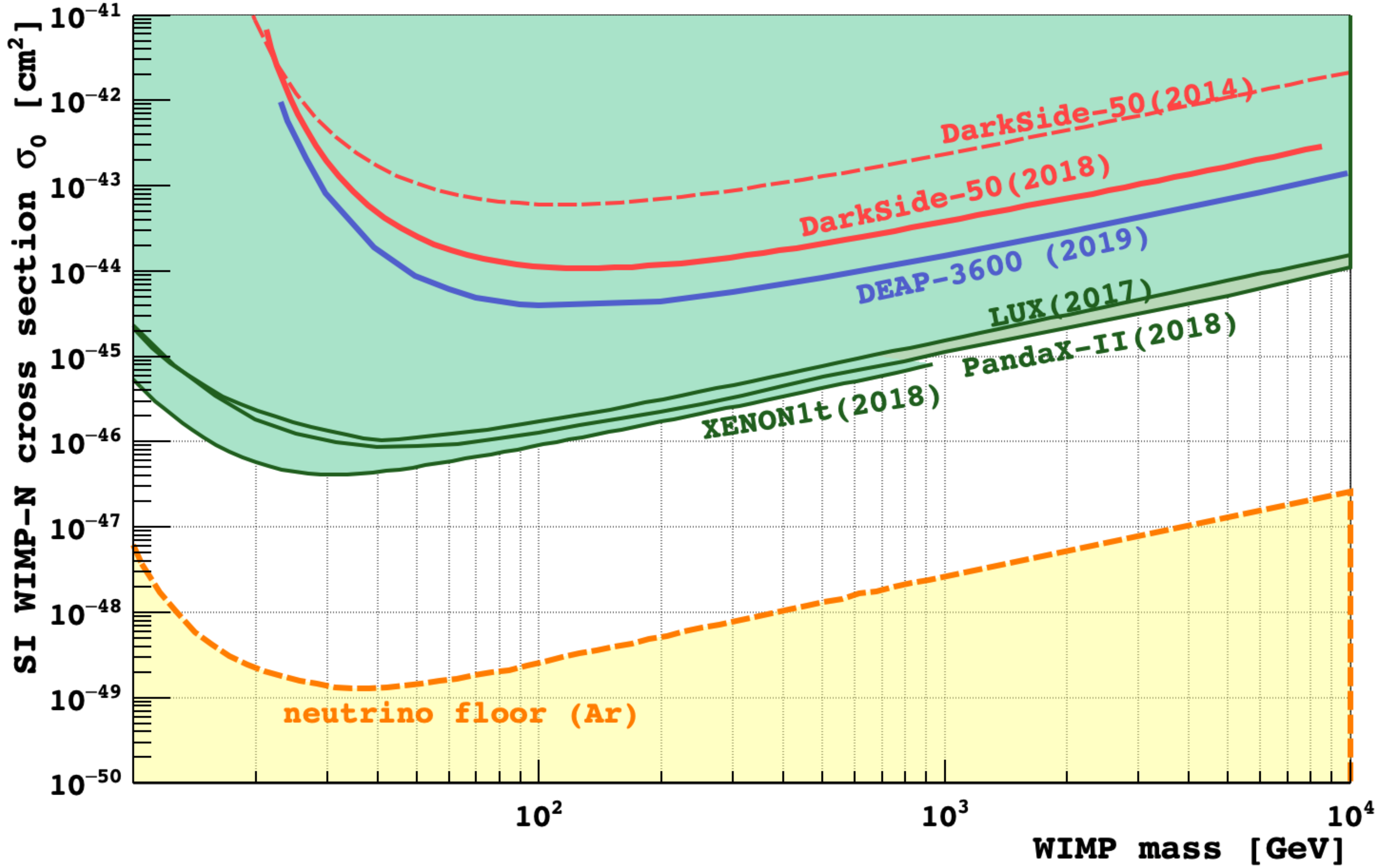
Cut flow



Quality +Trgtime +S1sat
PSD
S1 [PE]
Entries 1.907394e+07
$\times 10^3$
0
10
20
30
40
50
60
70
80
90
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
50
100
150
200
250
300
350
400
450
500
500 days dataset

Background-free search for high-mass WIMPs

90% CL upper limits on spin-independent WIMP-nucleon coupling



DS-50: Phys. Rev. D 98, 102006 (2018)

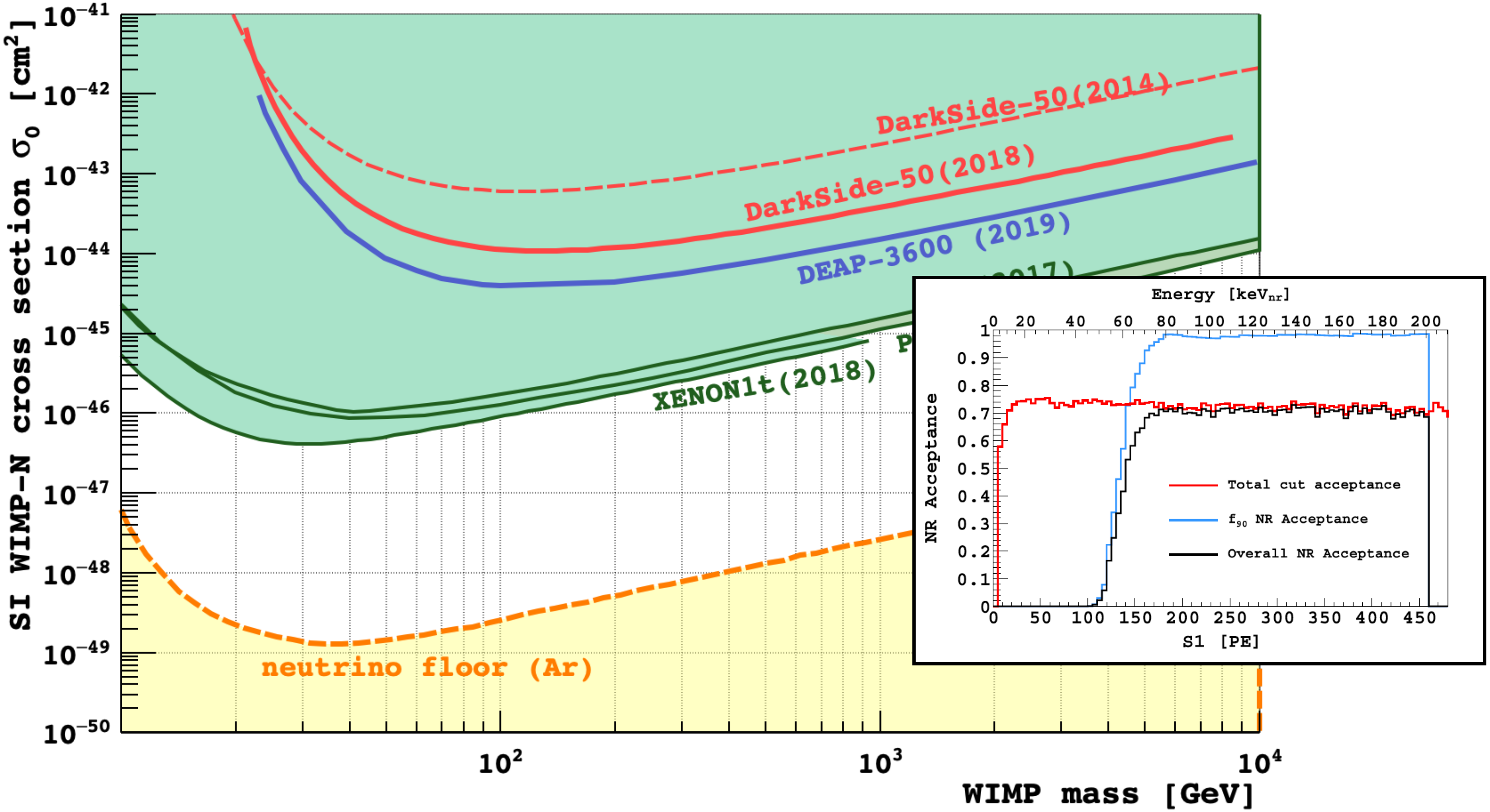
DEAP-3600: Phys. Rev. D 100, 022004

PandaX-II: Phys Lett B 792, 193 (2018)

XENON-1t: PRL 121, 111302 (2018)

Background-free search for high-mass WIMPs

90% CL upper limits on spin-independent WIMP-nucleon coupling. Demonstrates bg-free and UAr



DS-50: Phys. Rev. D 98, 102006 (2018)
DEAP-3600: Phys. Rev. D 100, 022004

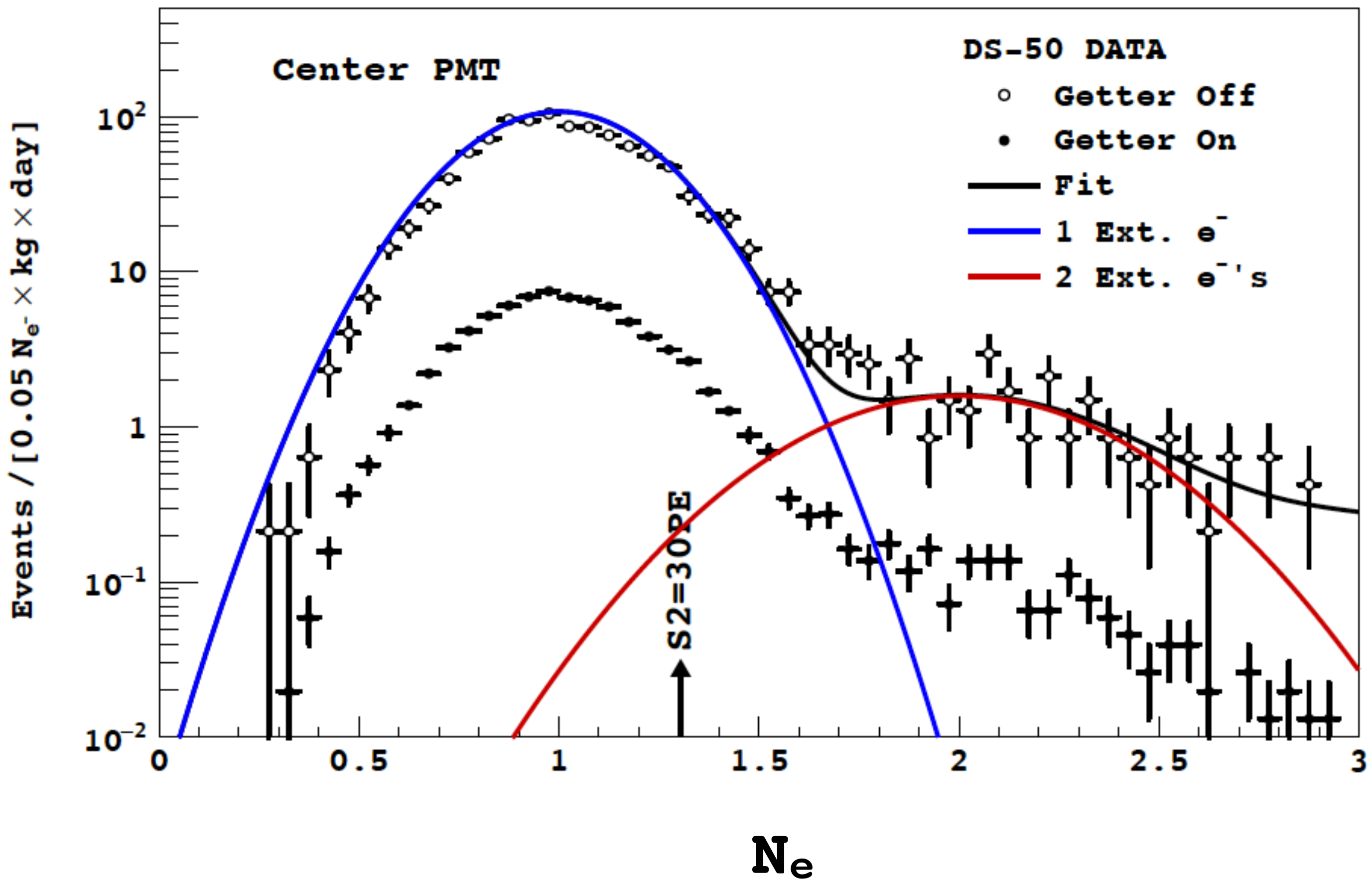
PandaX-II: Phys Lett B 792, 193 (2018)
XENON-1t: PRL 121, 111302 (2018)

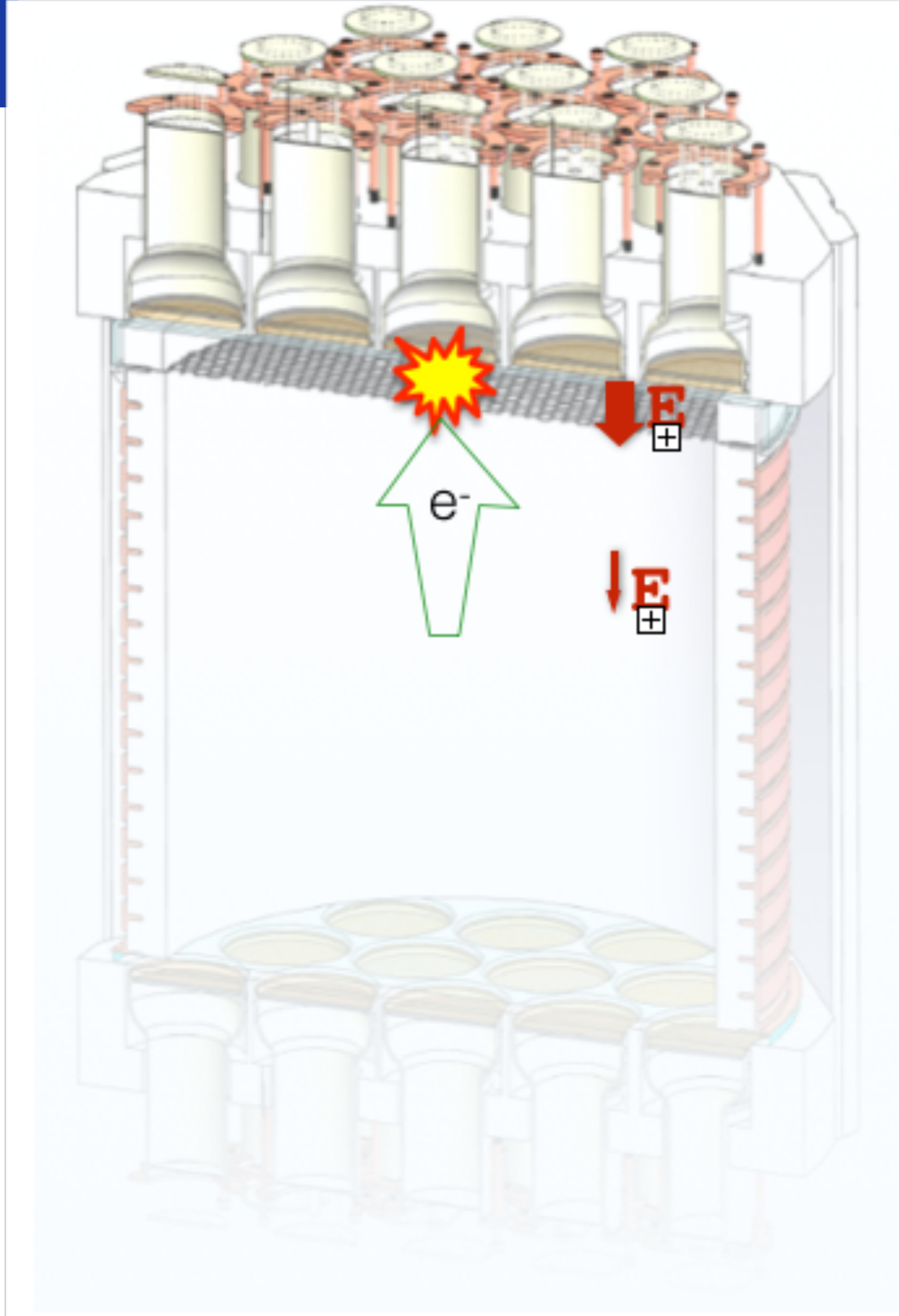
How to lower the threshold?

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

Below 3 keV_{ee}: give up the scintillation signal (too small to trigger the detector), and thus

- **minimal fiducialization** (only radial)
- **no PSD**





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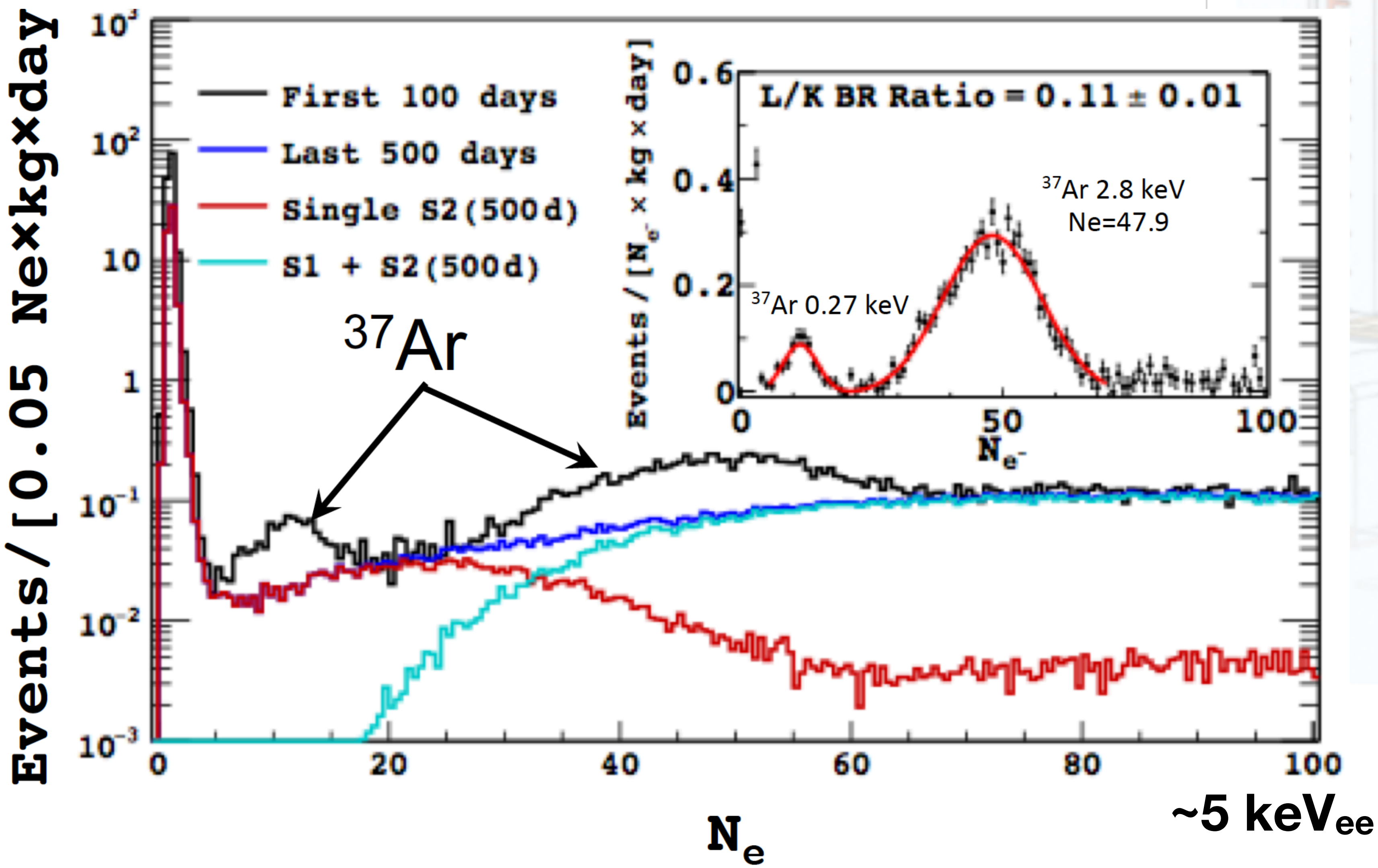
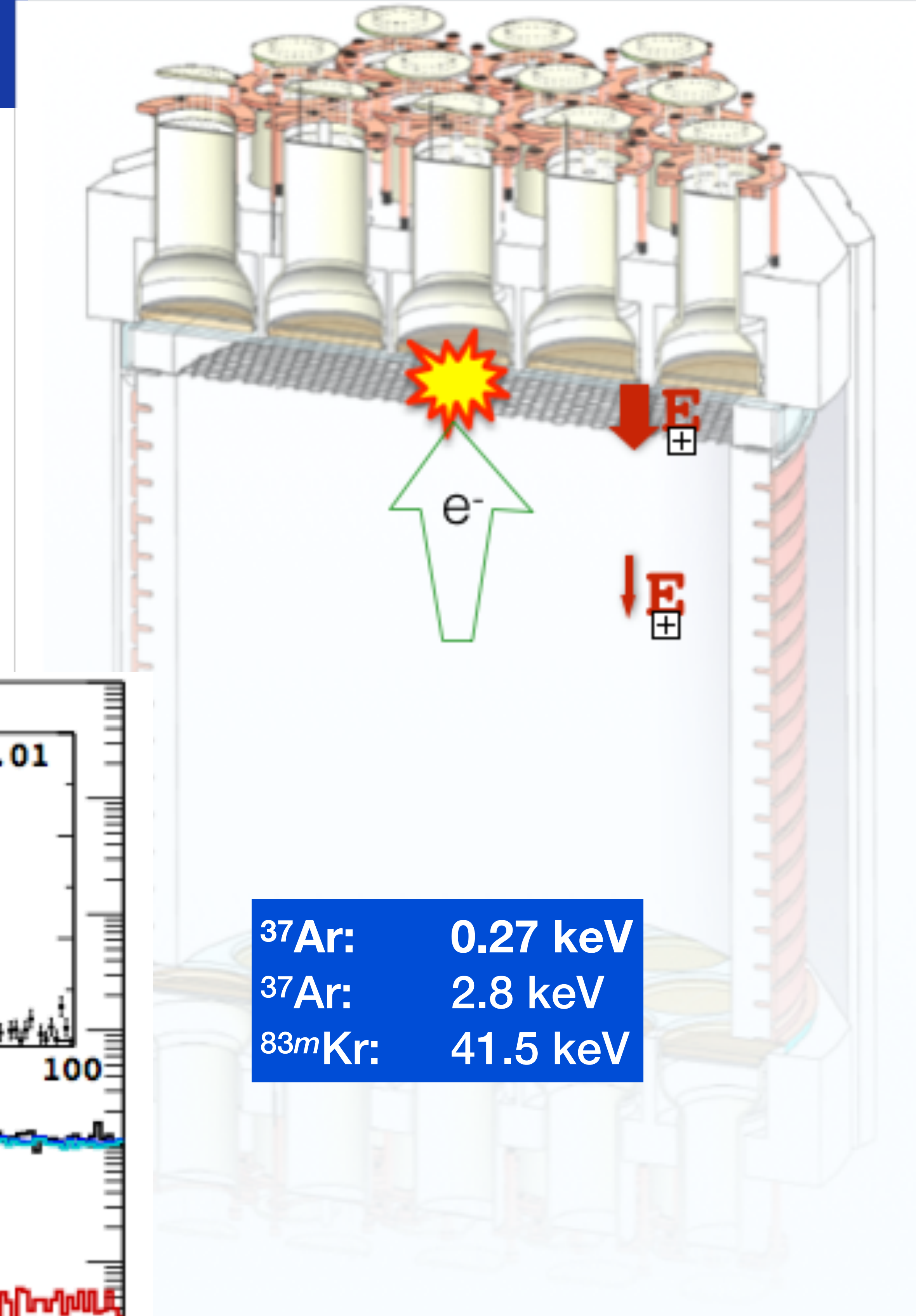
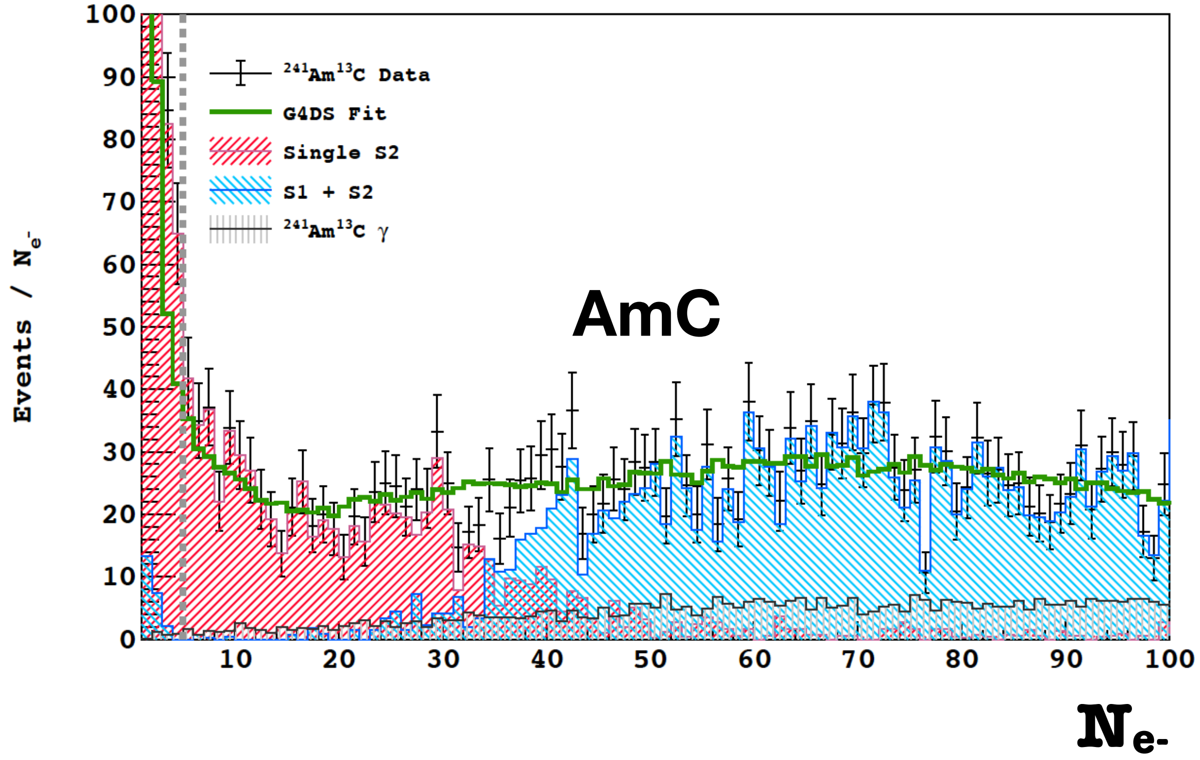
Yet, calibration of ER's with **^{37}Ar** and **^{83m}Kr:**

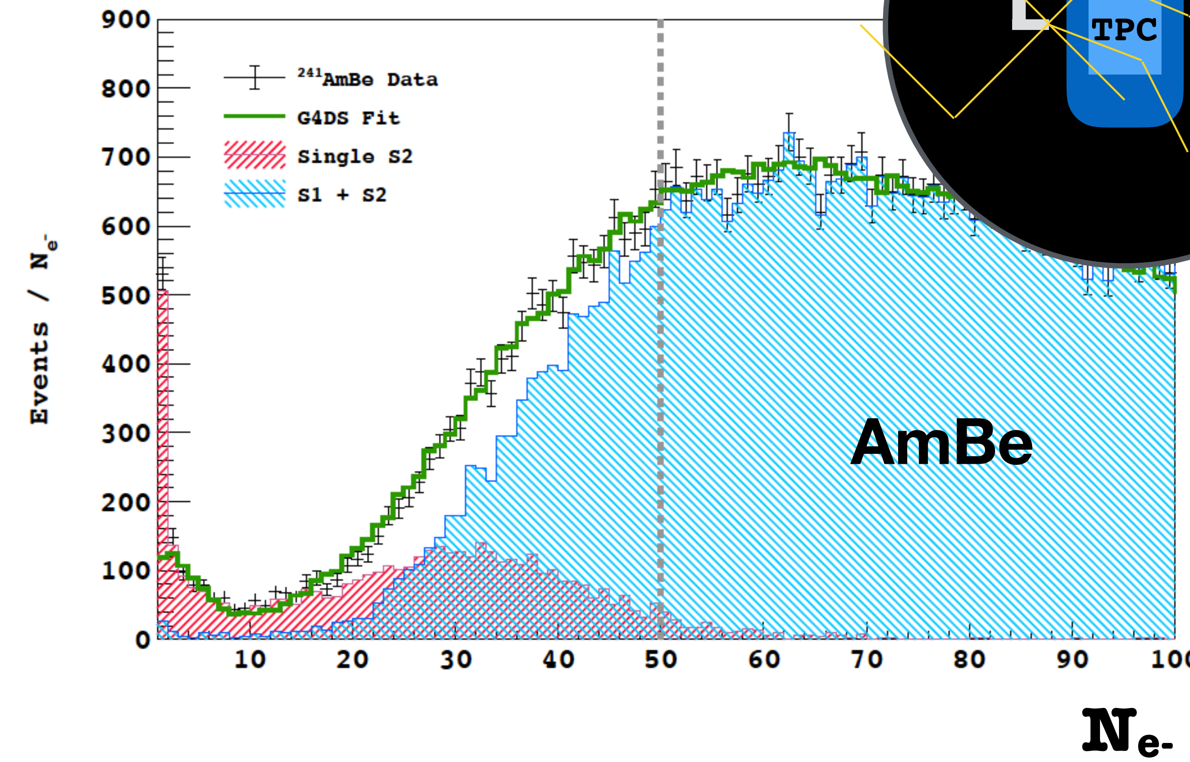


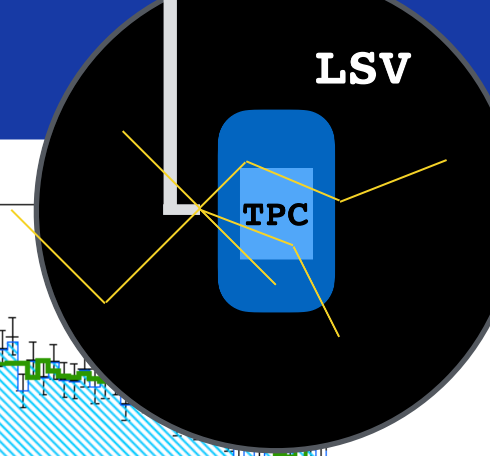


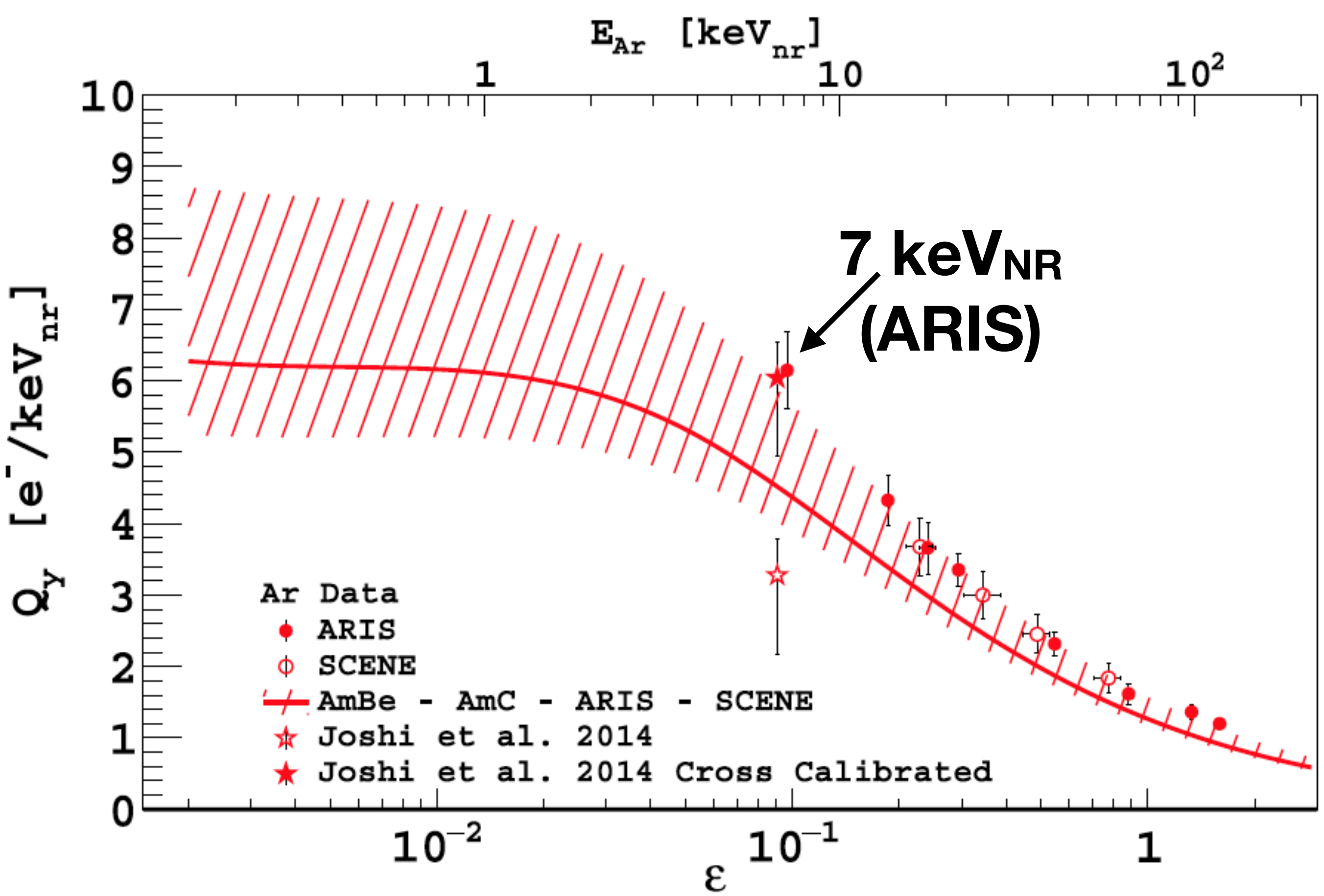
^{37}Ar:	0.27 keV
^{37}Ar:	2.8 keV
^{83m}Kr:	41.5 keV

Ionization yield, NR









Calibrate NR with **AmC, AmBe** neutron sources

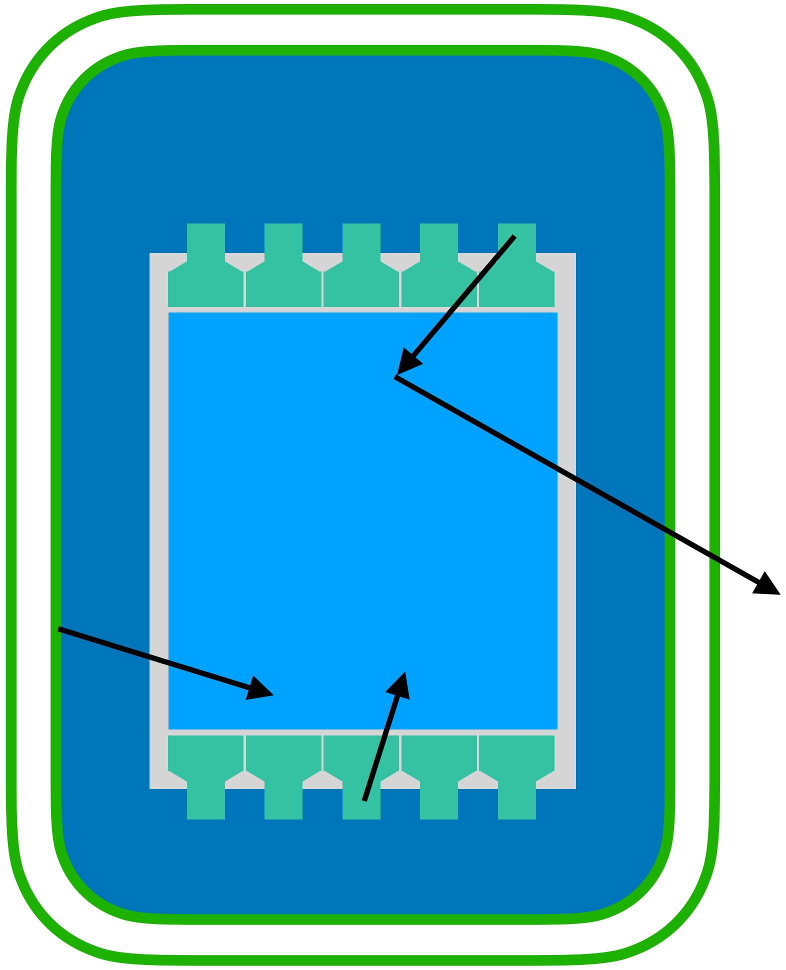
Bezrukov model fit at low energy. Two free parameters to describe quenching and recombination probability of e- / ions.

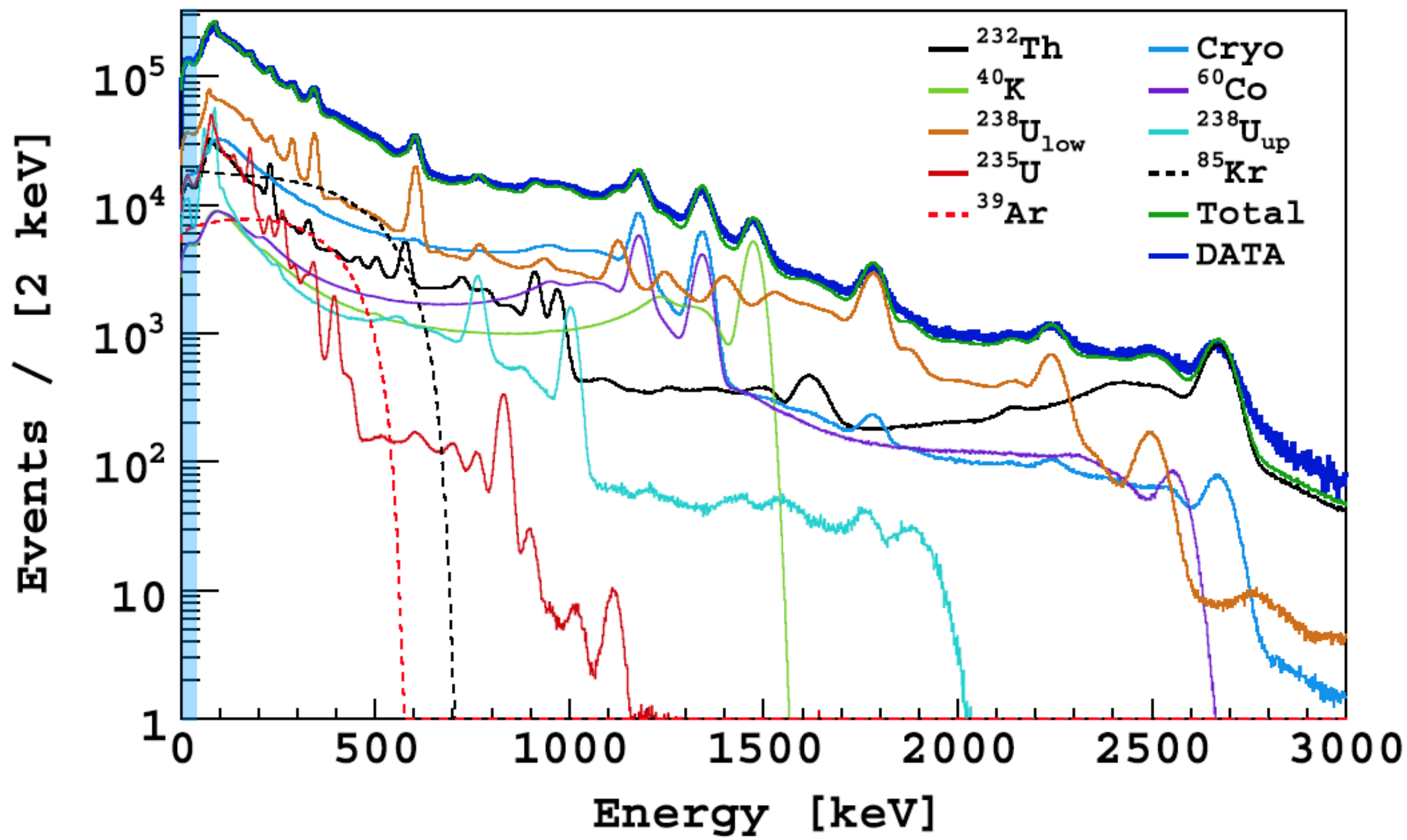
Ref: Astropart. Phys. 35, 119 (2011).

Extrapolation at high energy in agreement with ARIS and other datasets

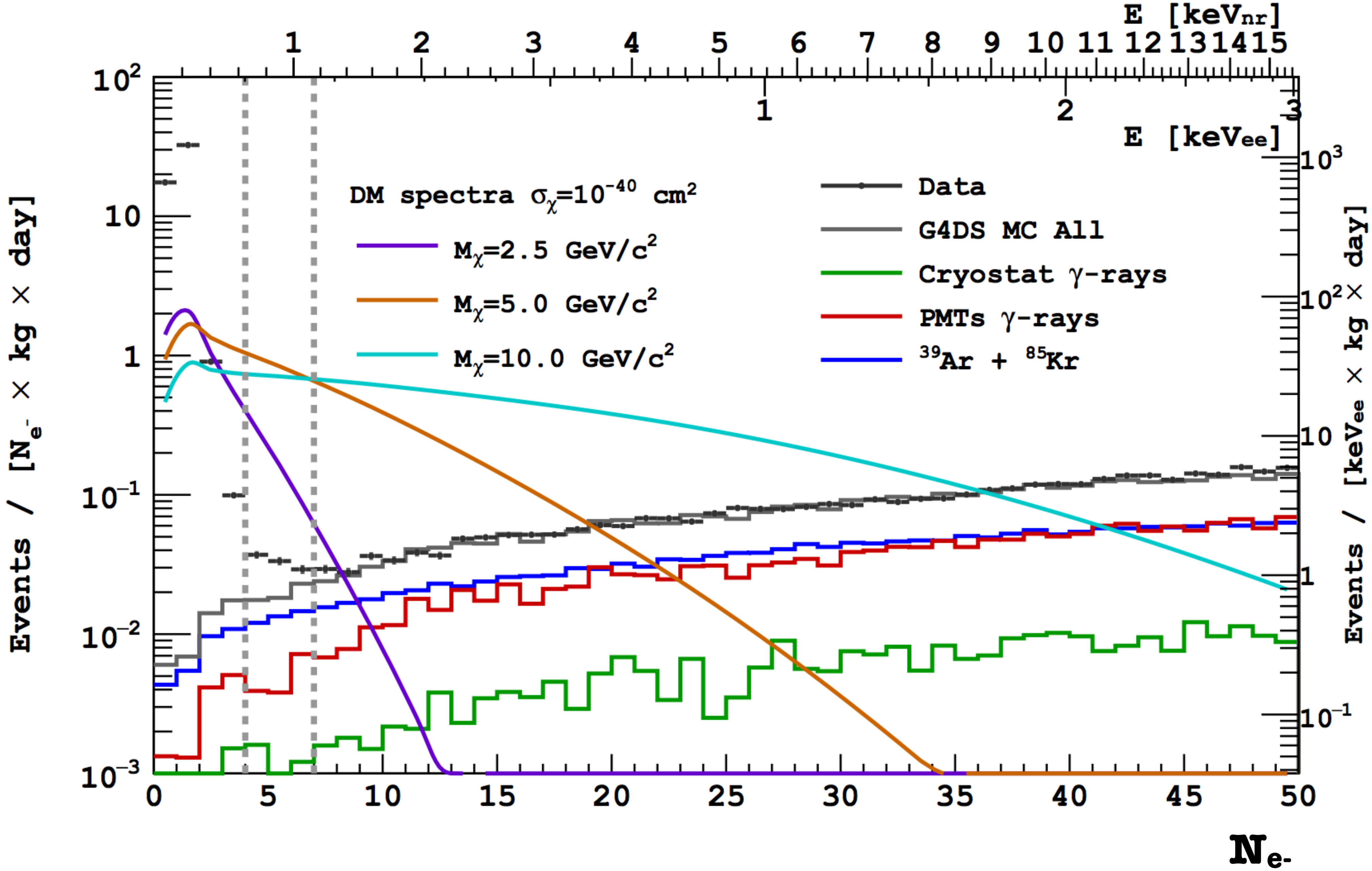
No more background free ==> Background model for DarkSide-50

- Full simulation of **each radioactive component** (^{238}U, ^{232}Th, ^{40}K, ^{60}Co) from detector materials and intrinsic to the target (^{39}Ar and ^{85}Kr).
- **Multivariate fit** based on S1 single scatter, S1 multiple scatter, and drift time
- Covers a wide energy range





DarkSide for low-mass WIMPs

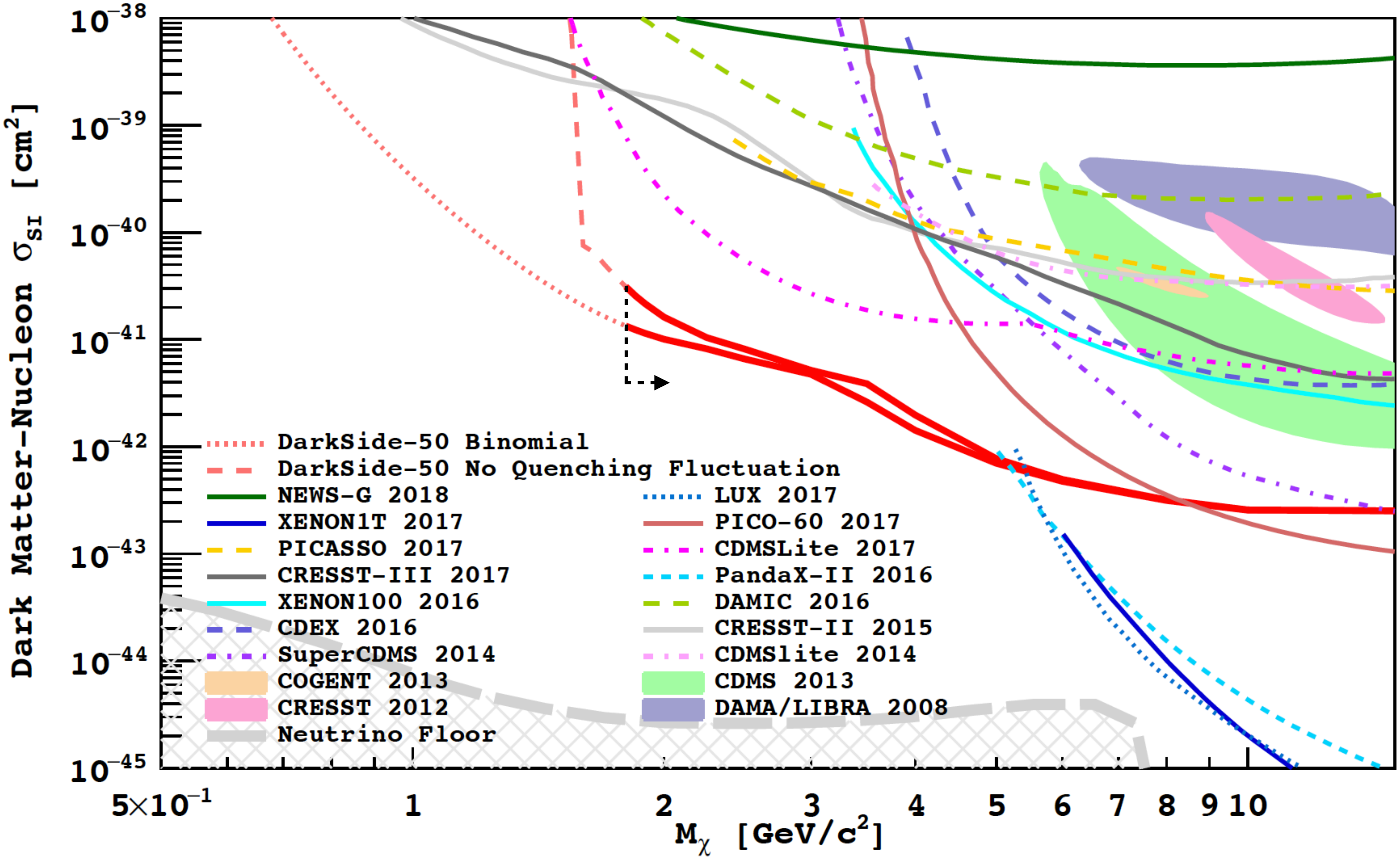


MC spectra in the low energy region, converted in N_{e-} (ER). **Activities constrained to the results of fit at high energy.**

WIMP induced spectra in N_{e-} (NR); PLL analysis.

Un-modeled component(s) below 7 e^-: impurities (+ radiogenic neutrons?)

The extracted limit(s) - 2018



Leading limit in [1.8, 6] GeV/c² mass range

Need a measurement to determine quenching fluctuations

Yet not able to constrain **quenching fluctuation** model, however:

Increased **statistics**: +1.5x the 2018 dataset.

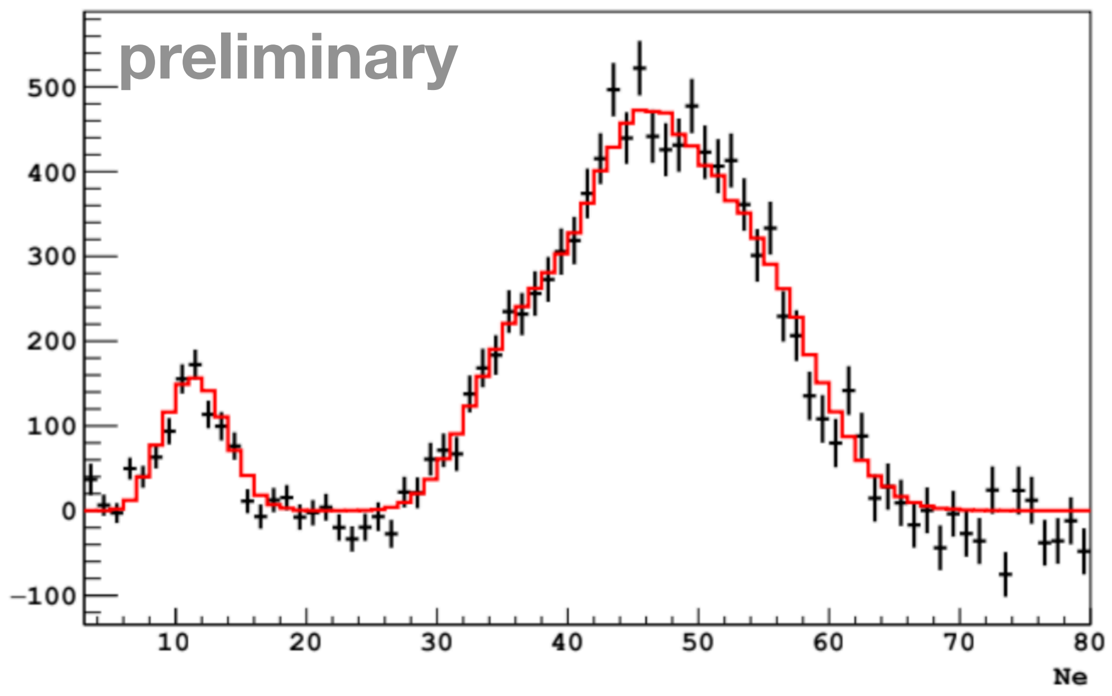
Improved **data selection**

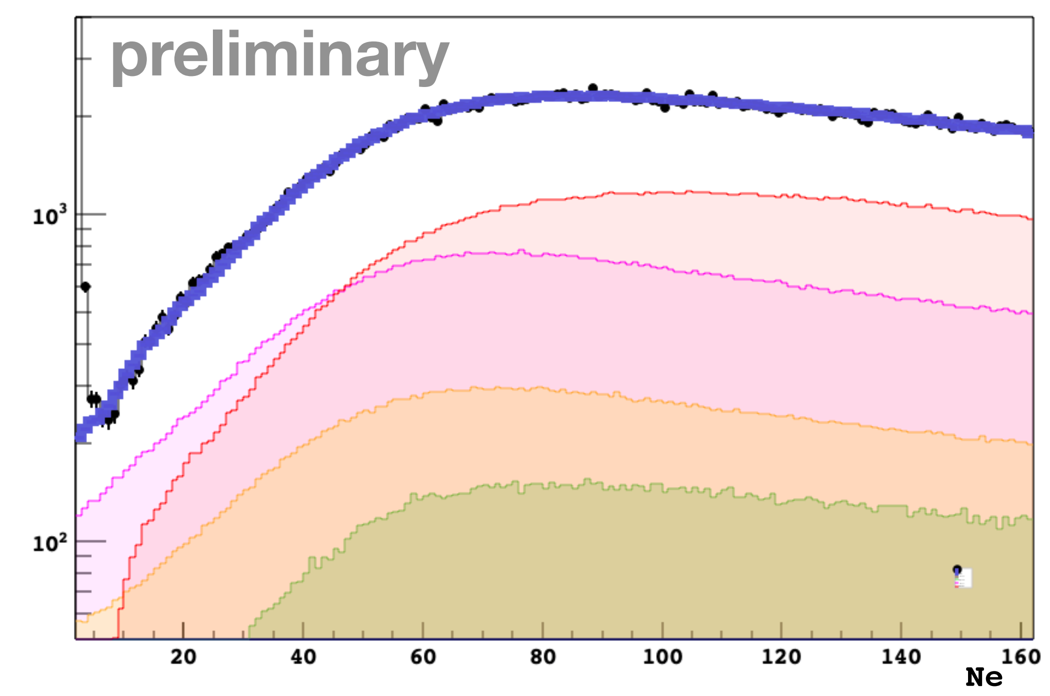
Improved **background model**

Improved **calibrations**: both for NR (signal) and ER (background) responses (optics effect)

Expect improvement on the low-mass dark matter exclusion up to a factor of 10x

ER calibration with 37Ar





Additional searches - DM - electron

Increasing interest for alternative dark matter candidates at low-mass (< 1 GeV/c²)

Cross section

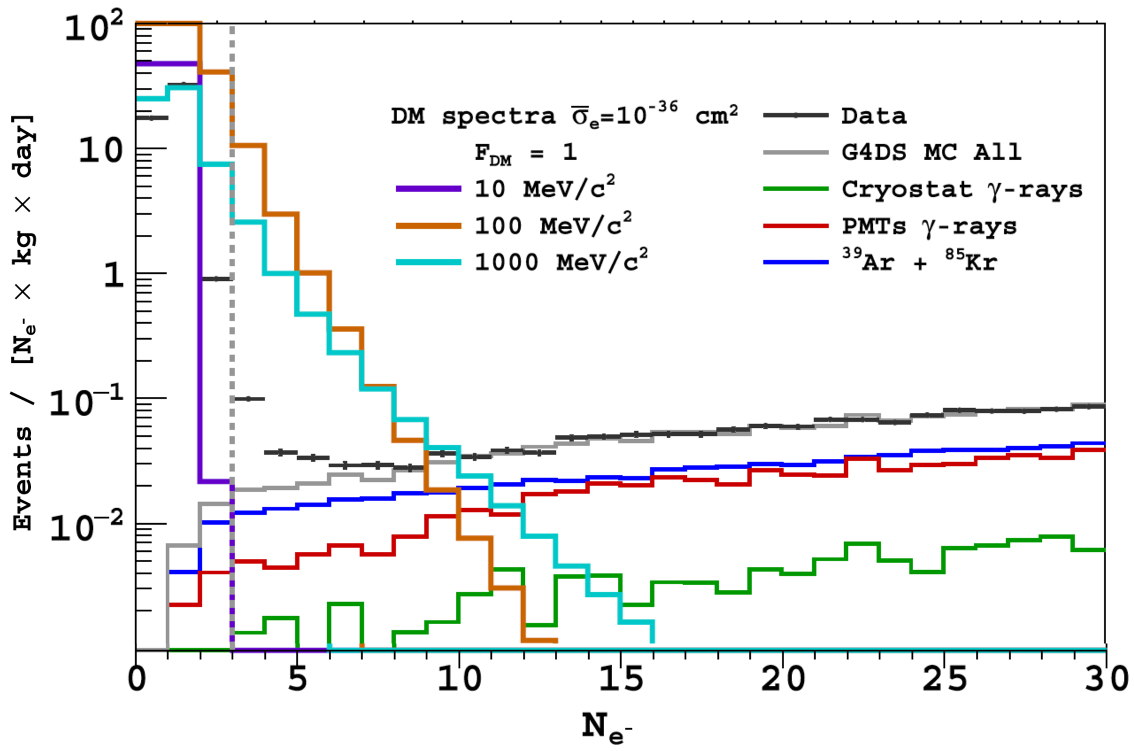
Form Factor (interaction)

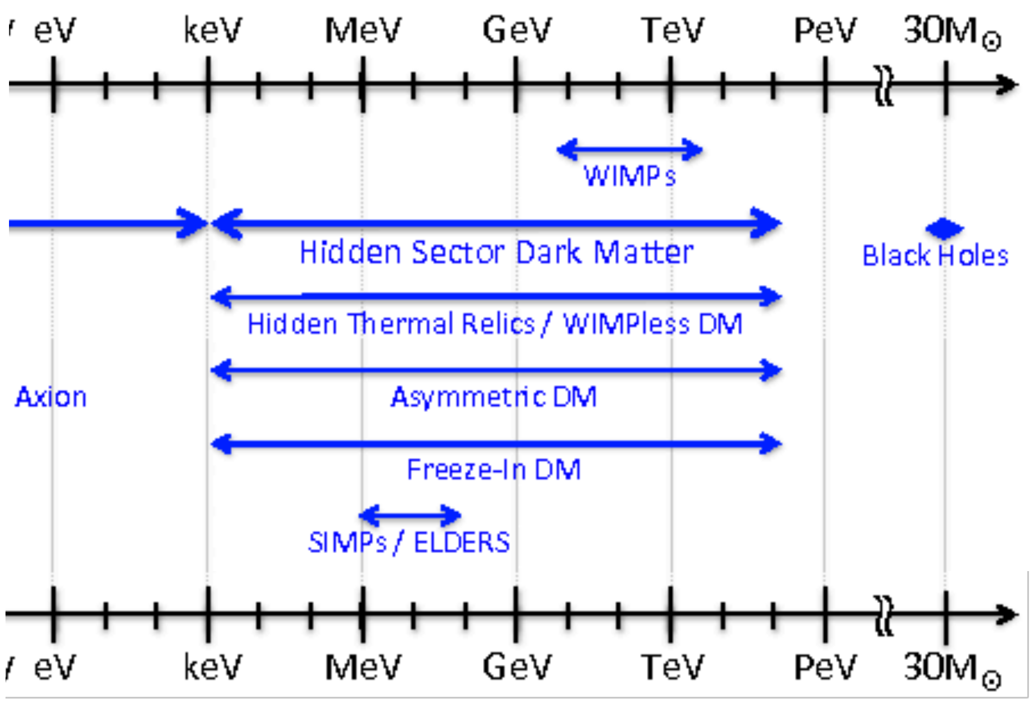
Astrophysics

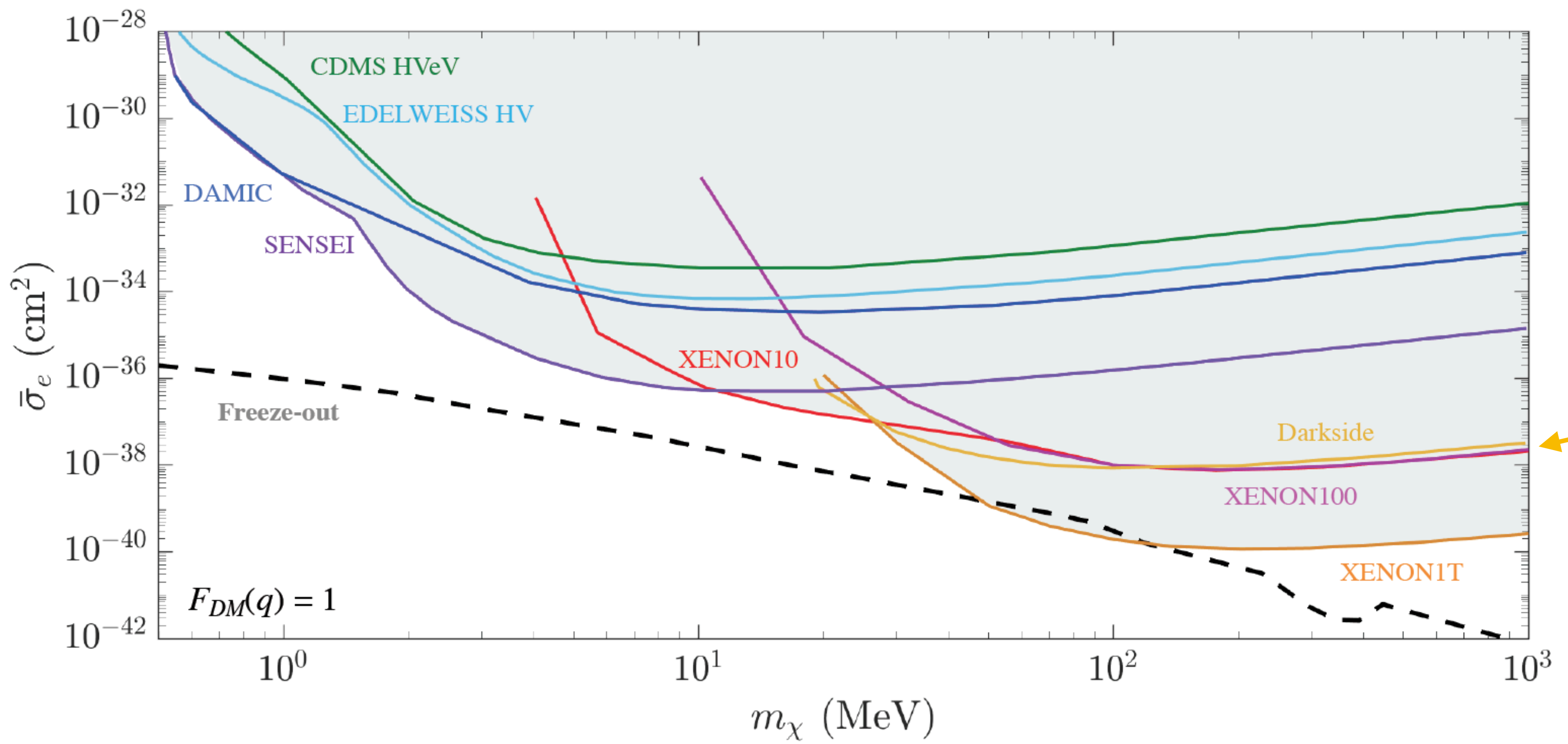
$$\frac{dR^{ER}}{dE_e} = \overline{\sigma}_e \frac{\rho_\chi}{M_\chi} \frac{1}{8\mu_{e\chi}^2} \int q dq |F_{DM}(q)|^2 |f_{n,l}^{ion}(q, E_e)|^2 \eta(v_{min})$$

Electron wave-functions

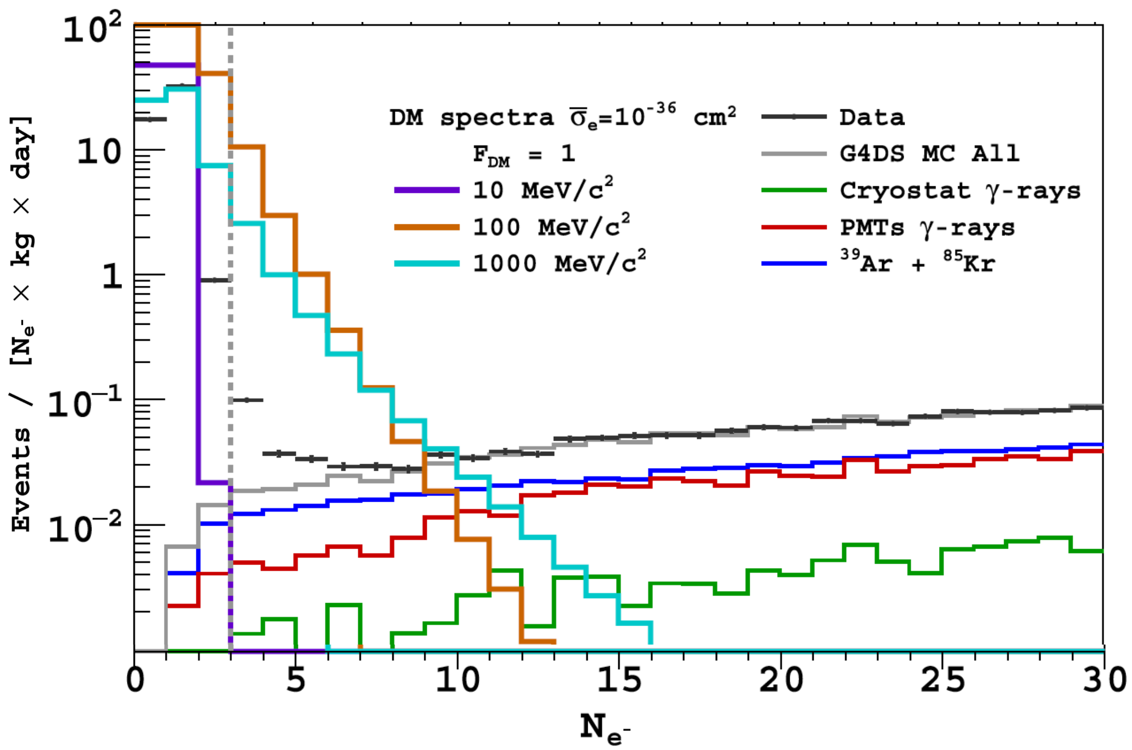
Dark Matter Properties

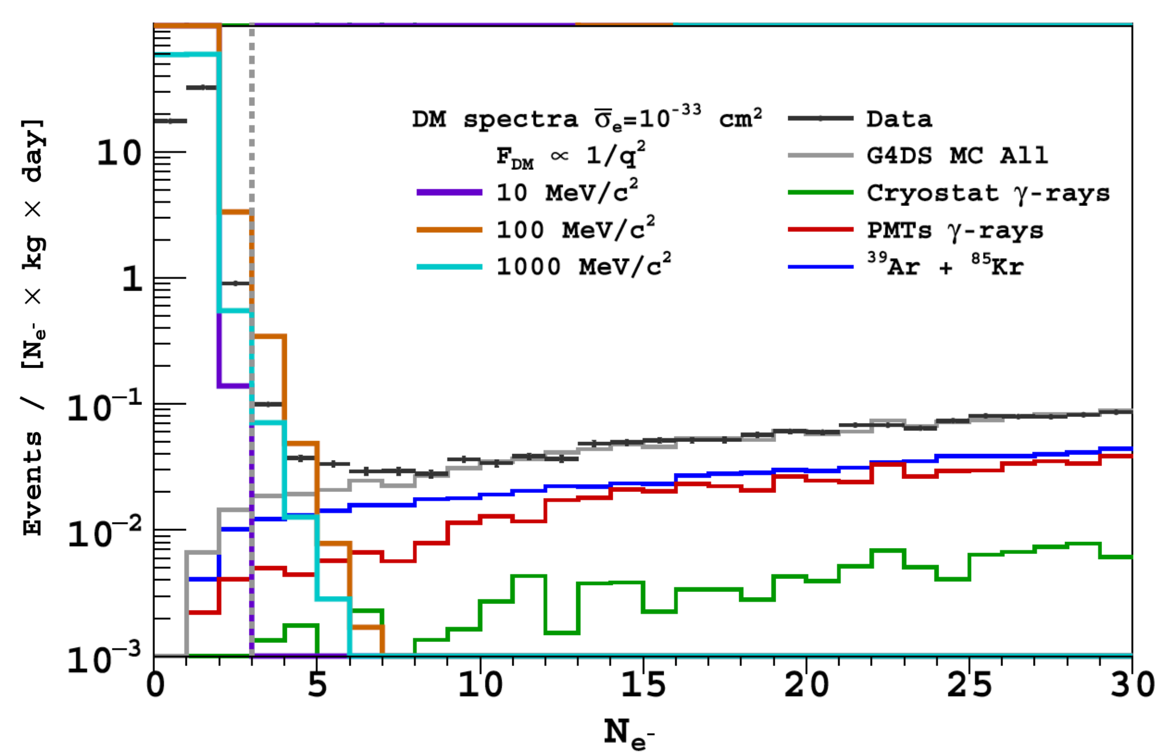






2018 limit,
to be updated

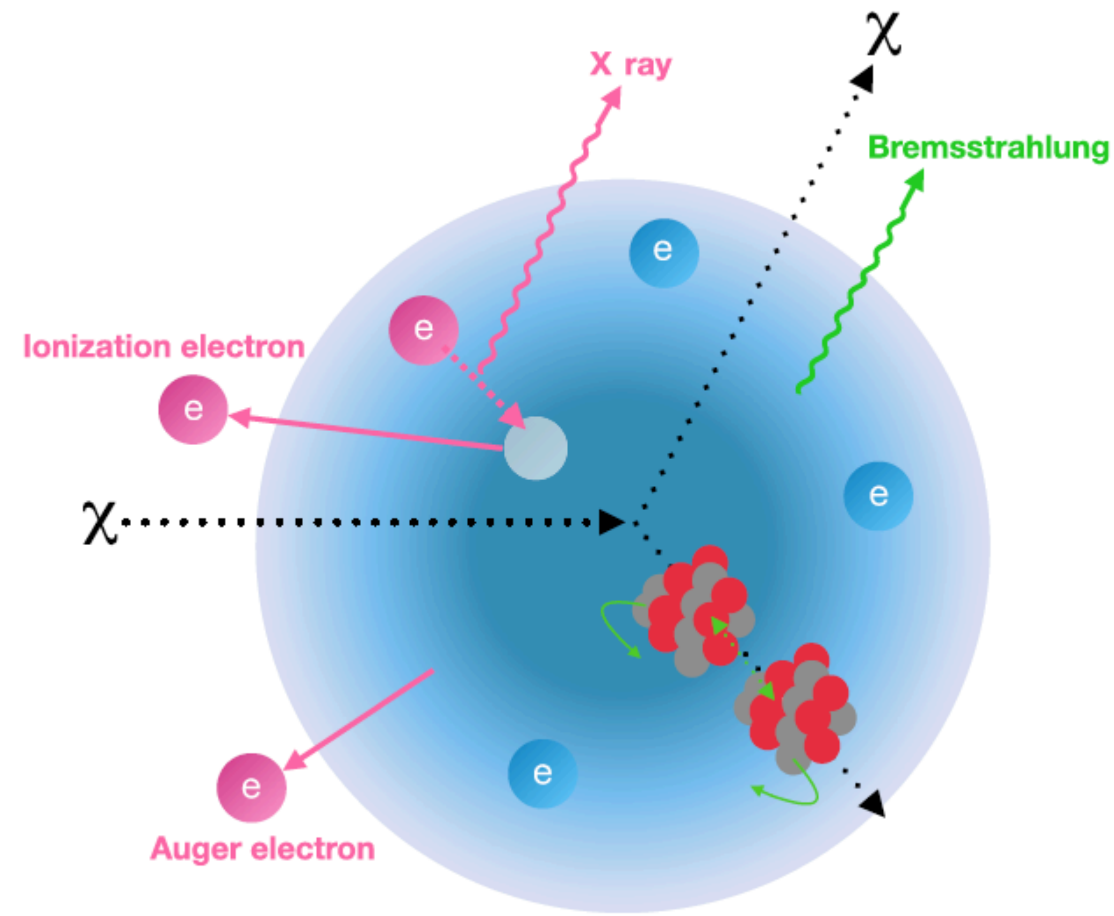




Due to sudden acceleration, the struck atom may **release electron(s)**, total released energies up to keV

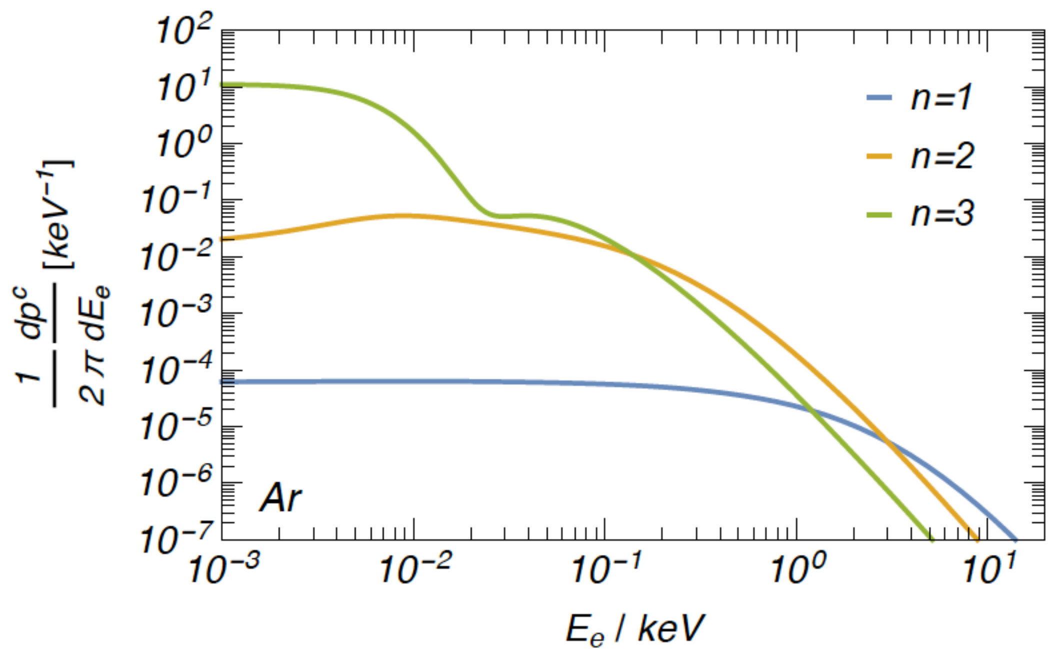
Predicted probability is << 10^{-3} and a function of ***q***, thus:
- only small correction for high-mass WIMPs
- decreases for light DM particles

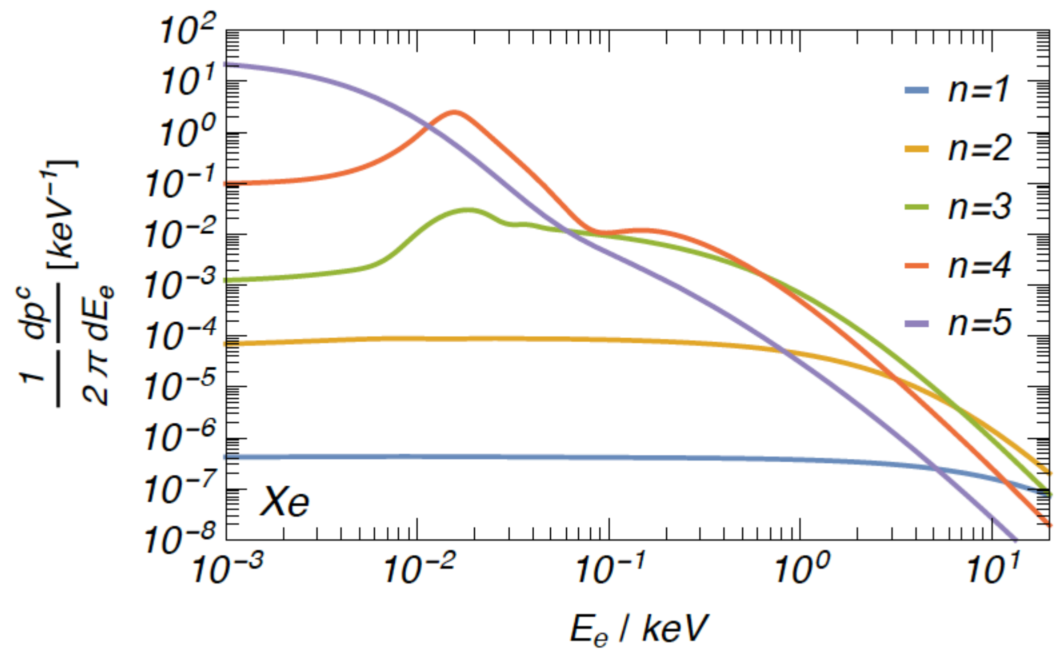
However, the ER channel, as opposed to NR one, is **not quenched** and may enhance sensitivity to low-mass candidates



picture from PRL123, 241803 (2019)

Contributions of different shells:





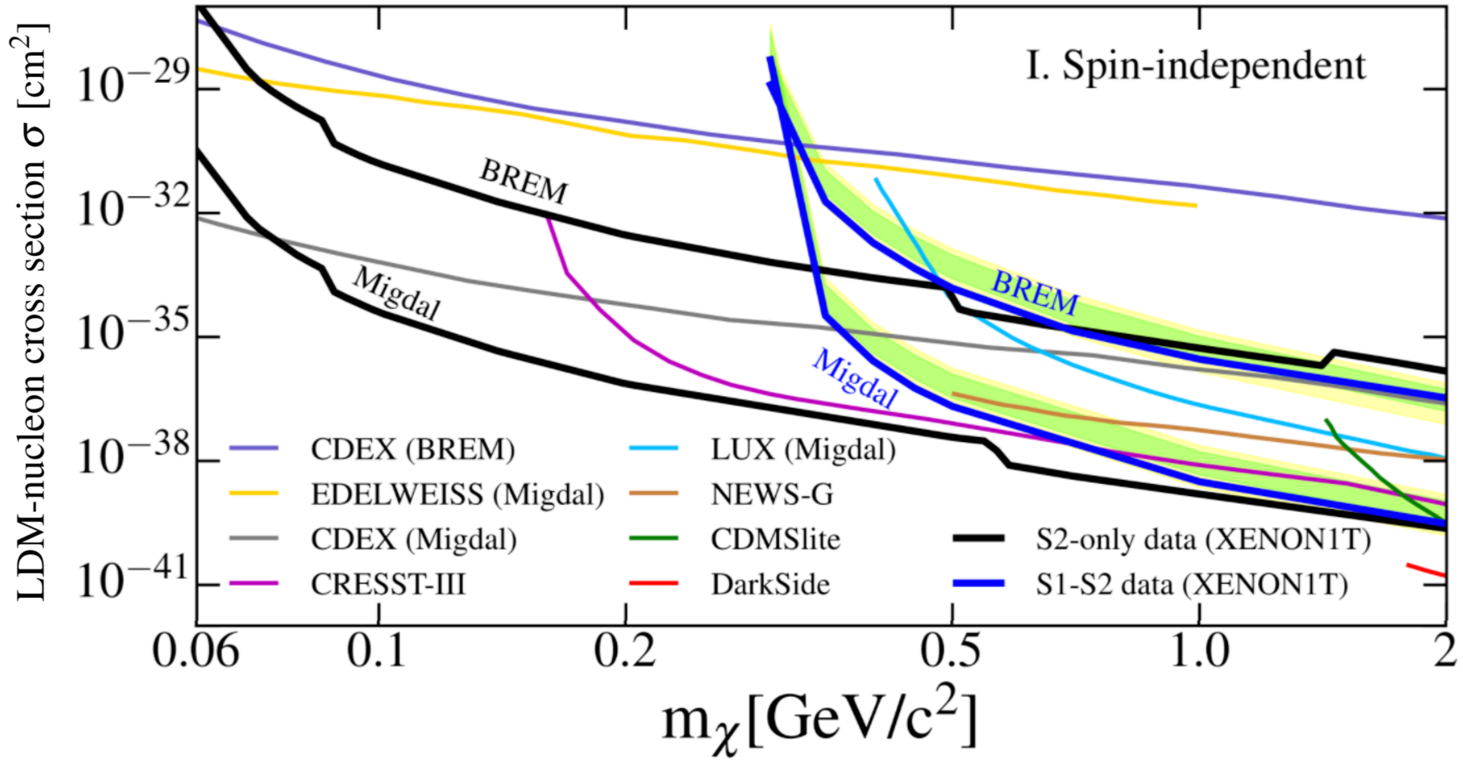
arXiv:1707.07258v2

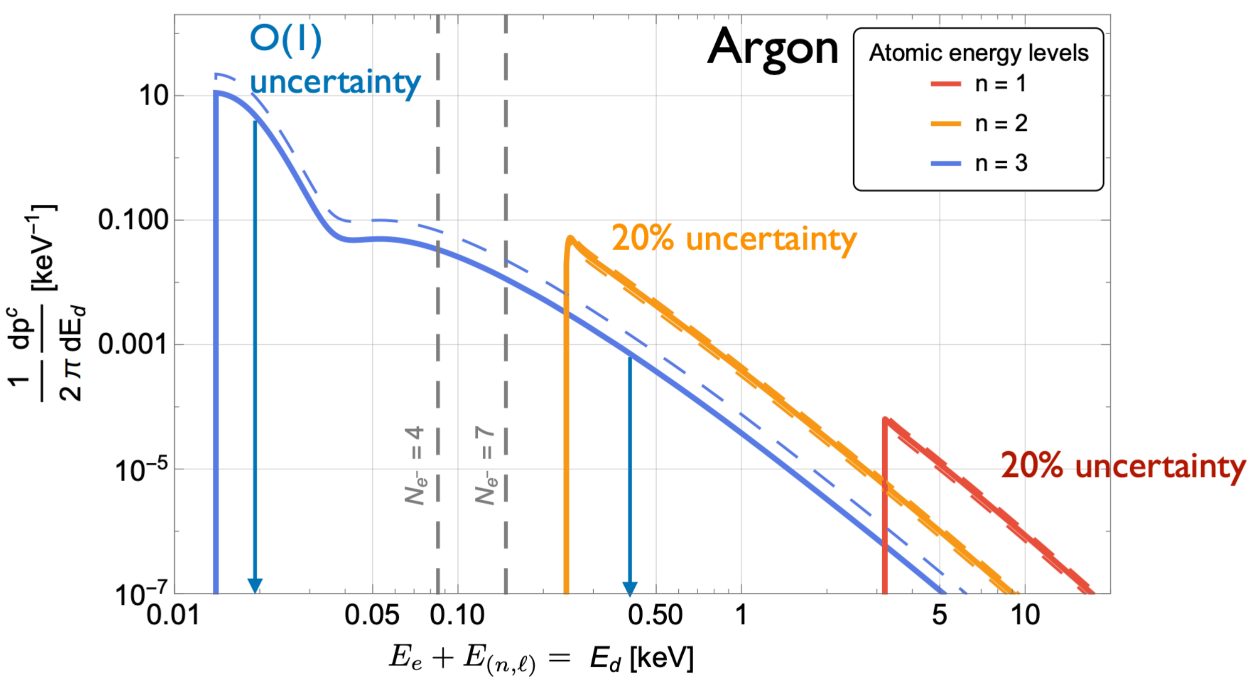
Experimental status

Results with Xenon are leading exclusion. Allow to explore sub-GeV range!

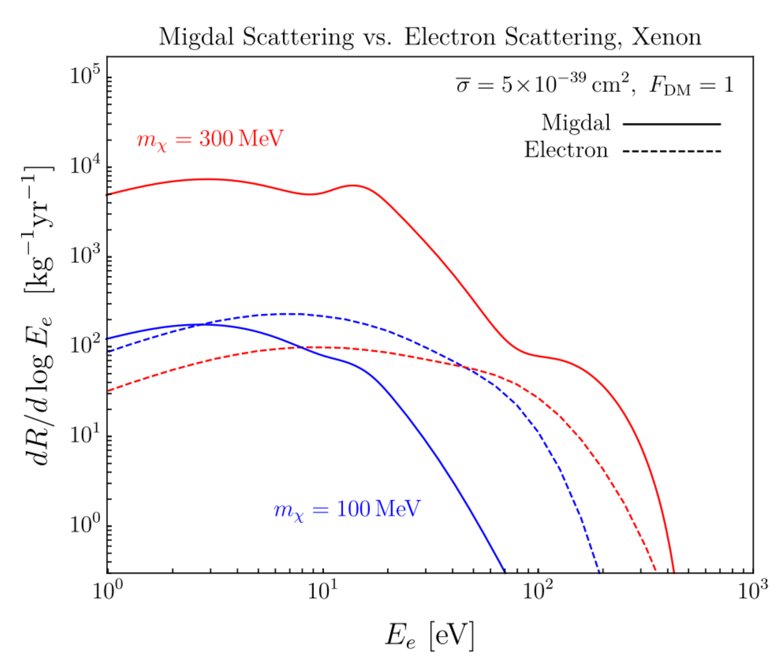
Assume the ER component only

Significant uncertainties in the calculations, yet to be fully characterised experimentally



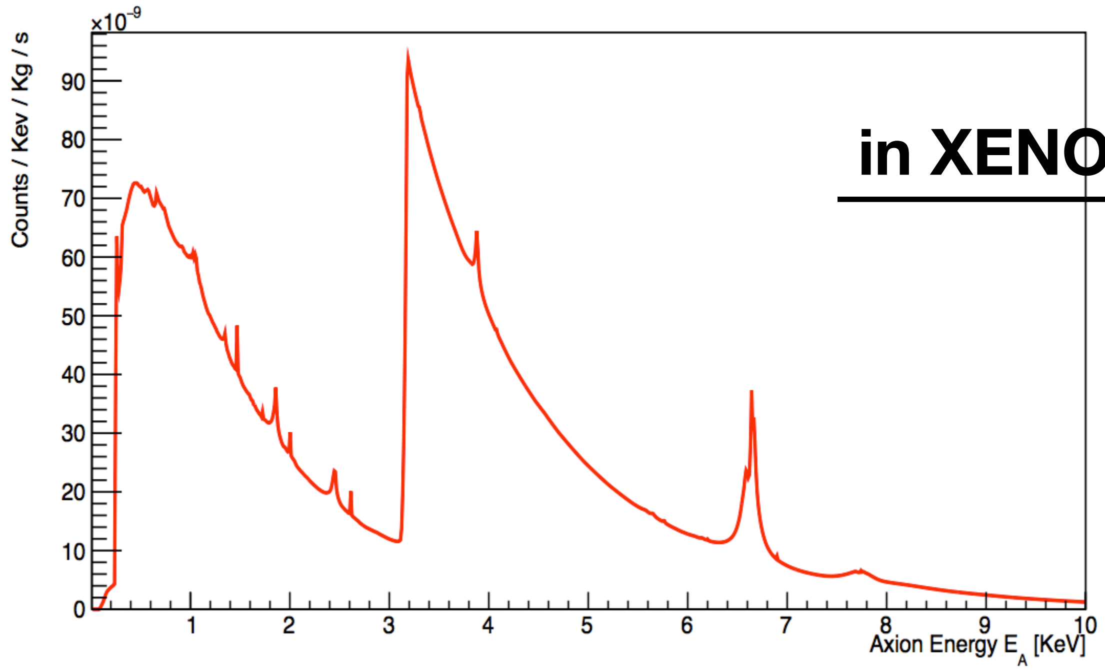


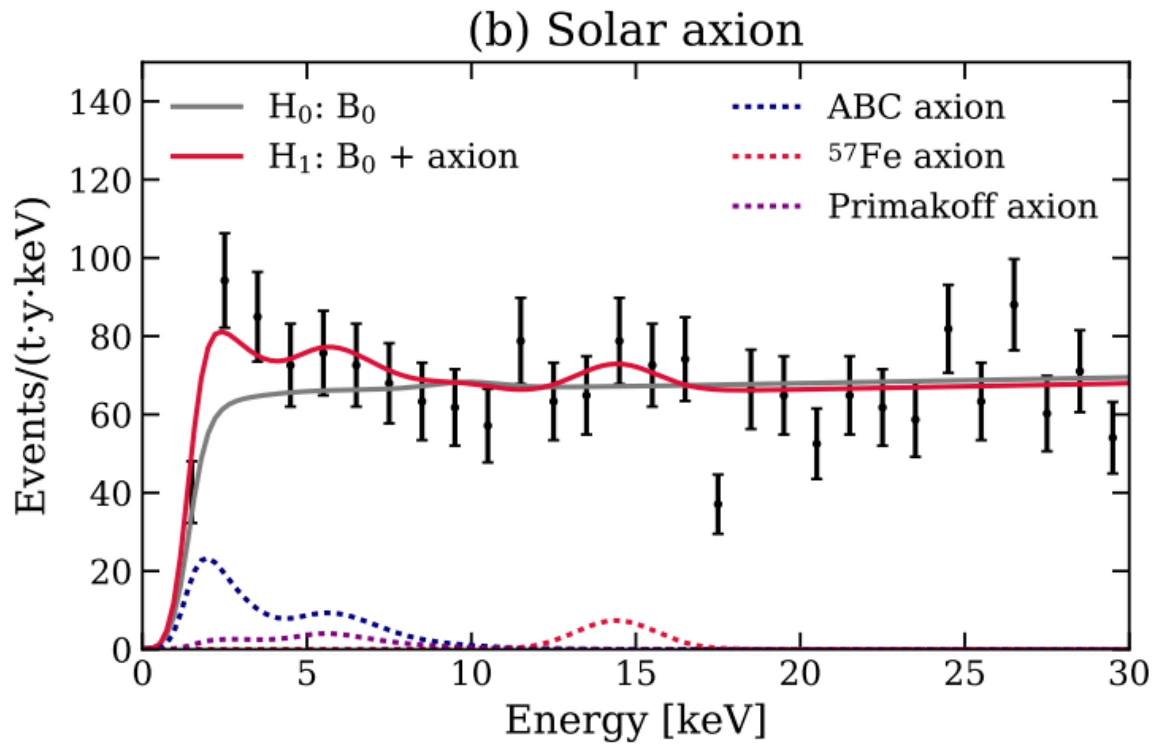
Suggested that experimentally should be even more significant than WIMP-e-
[arXiv:1908.00012]

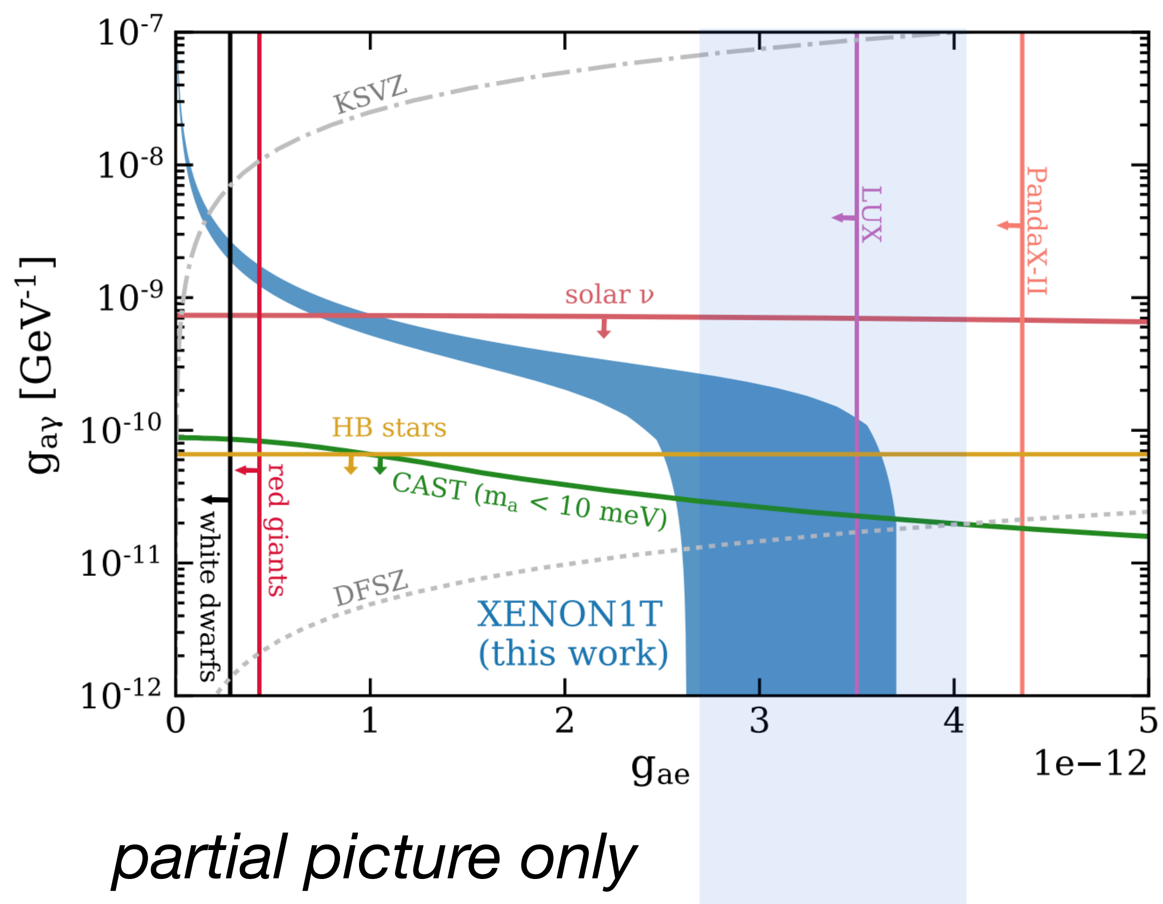


Additional searches - Solar Axions

Phys. Rev. D 102, 072004 (2020)







partial picture only

Axions were introduced to solve the strong CP problem

The Sun could be a source of Axion-like Particles via 3 production mechanisms

Detection via axio-electric effect (photo-electric), constrain coupling strength g_{ae}.

Tritium hypothesis

Towards DarkSide-20k

Global Argon Dark Matter Collaboration (GADMC) is collecting expertise from DarkSide-50, DEAP, ArDM in order to construct a 50 t dual-phase TPC to collect

200 t yr (instrumental) bg free UAr exposure

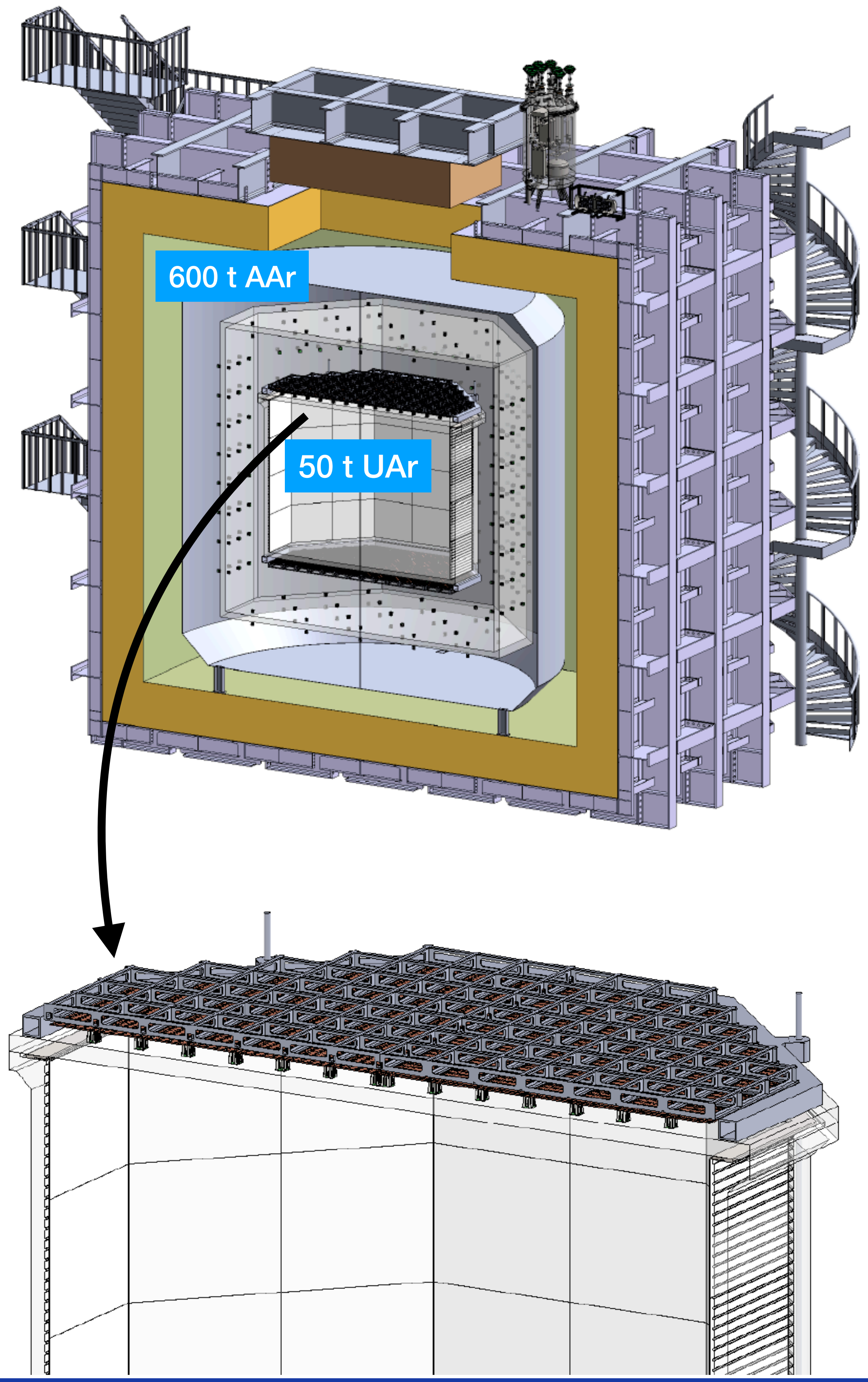
Expected **1.5 ev in 100 t yr** from **neutrinos** (CNNS).

The design is driven by the minimization of the bg.

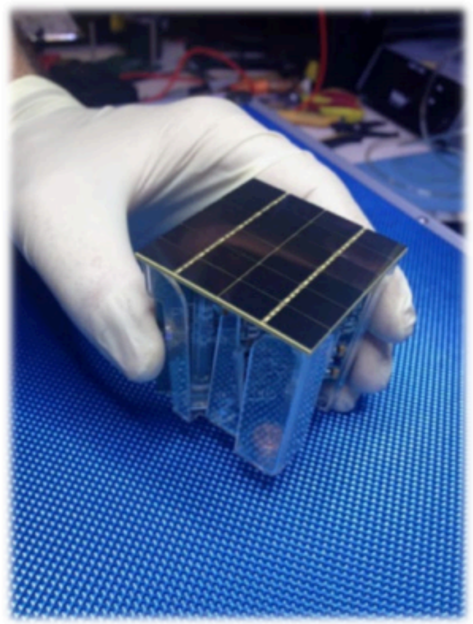
DarkSide-20k will be hosted in a ProtoDUNE cryostat (move material away from the active volume)

Acrylic “thick” walls (DEAP) which also moderate neutrons + Gd-loading for capture (veto for neutrons)

Instead of PMTs: SiPM arrays!



From PMTs to SiPM arrays

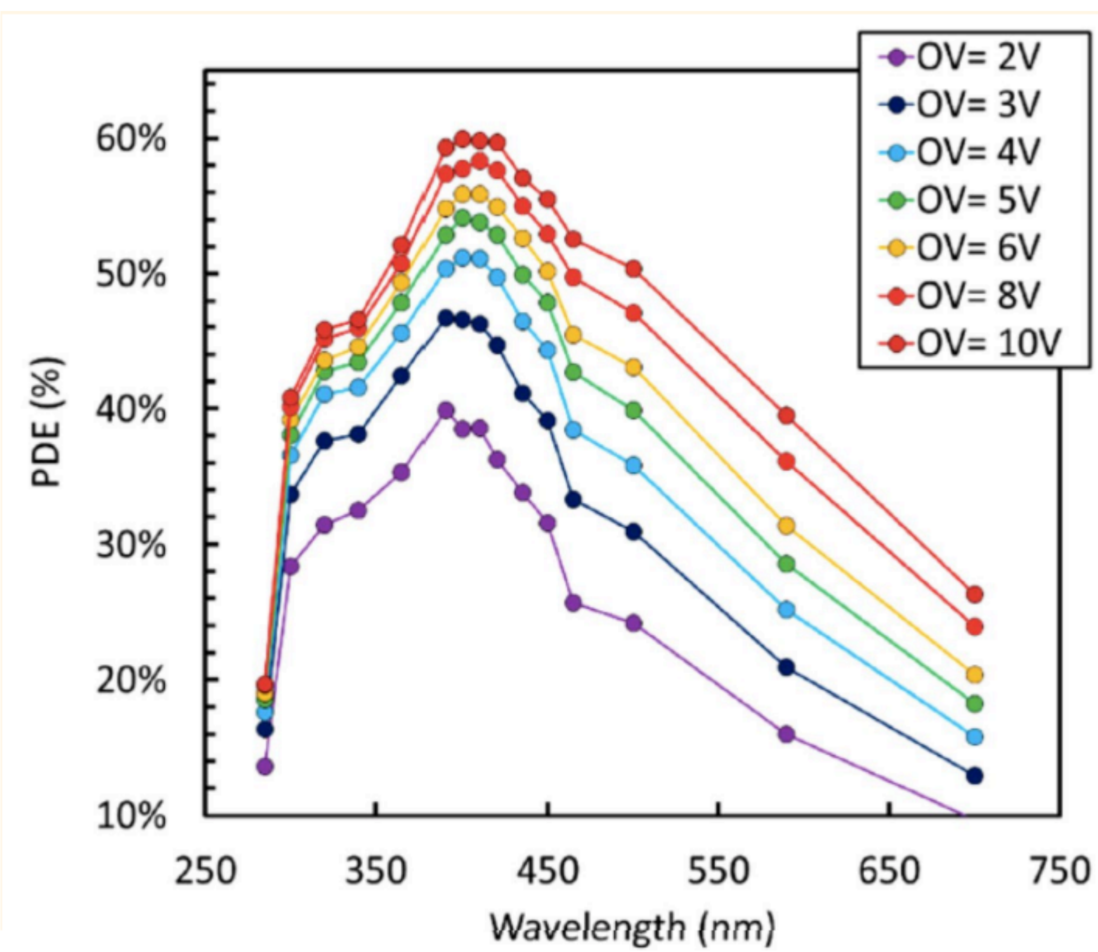


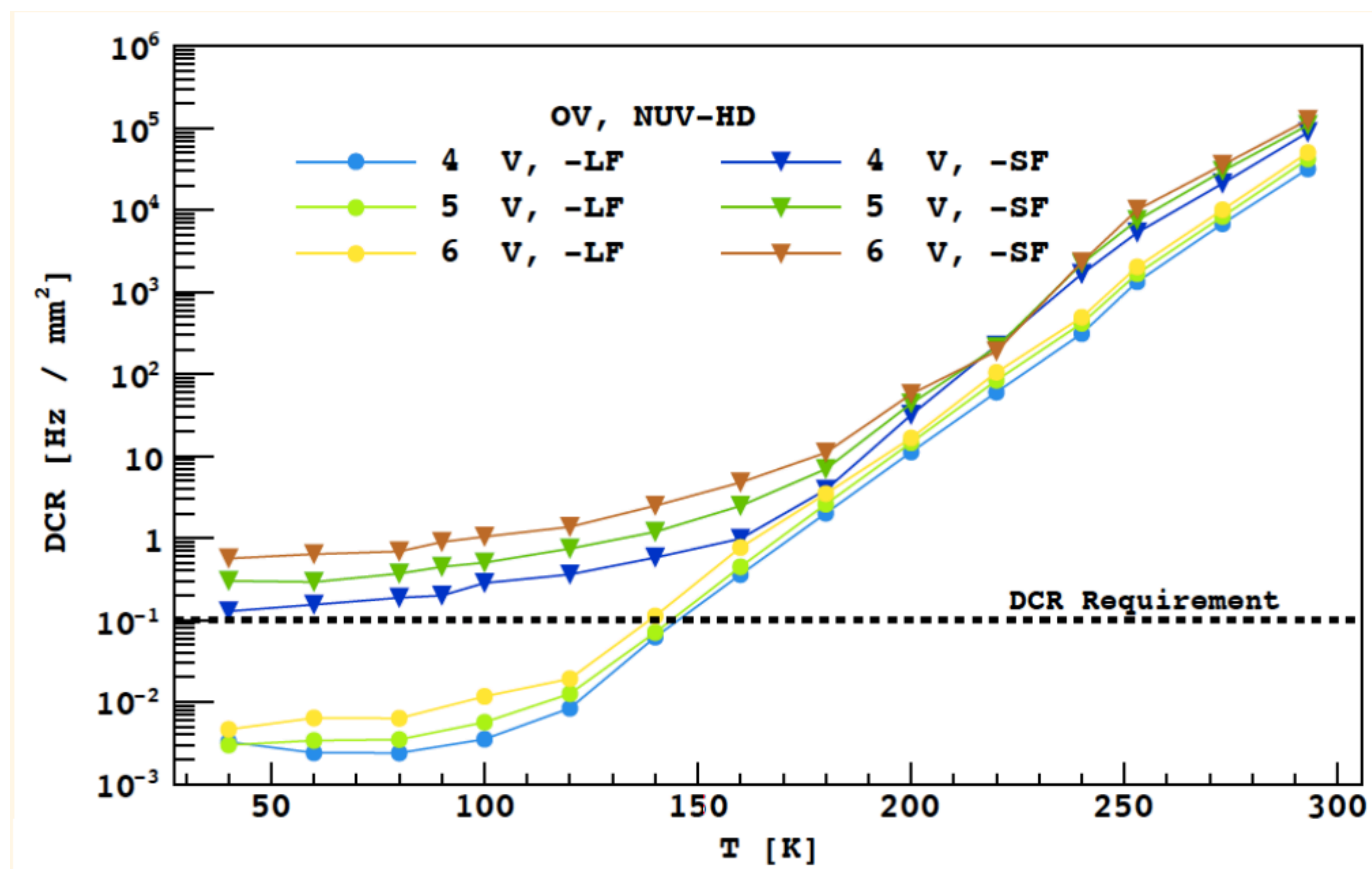
PROS

- Cryogenic temp stability
- Better single photon resolution
- Higher photo-detection efficiency
- Low voltage operation
- Lower background (Si intrinsically radiopure)
- Lower cost

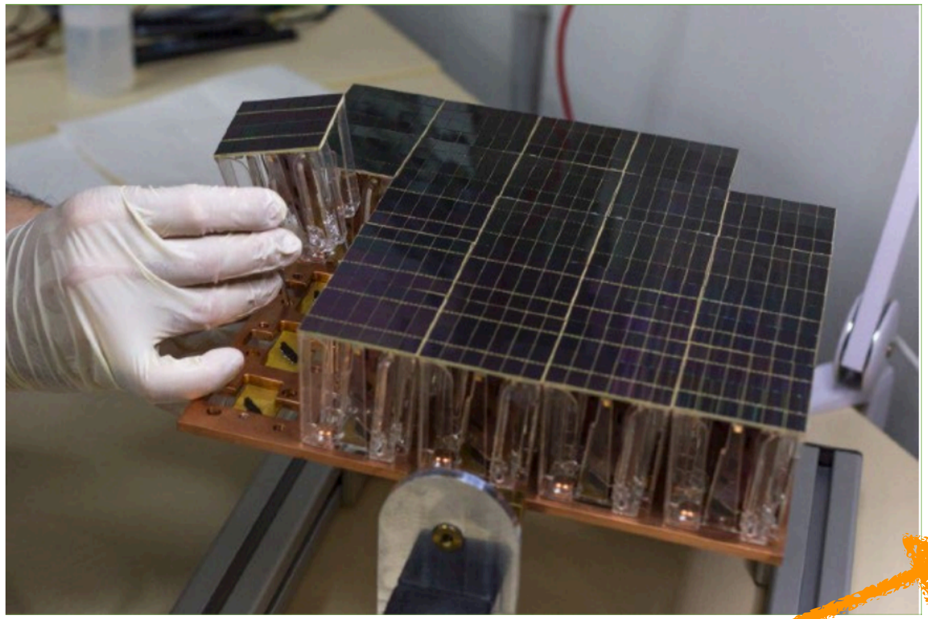
CONS

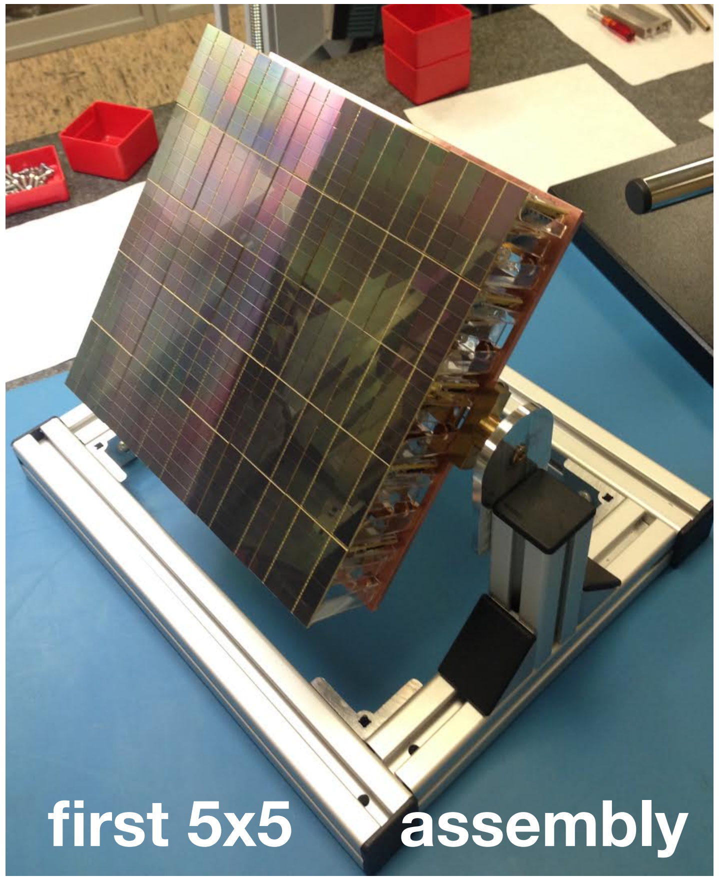
- Small area ≈ cm2 (group them)
- High dark rate (solved, + operated at 87K)
- High output capacitance for large devices (~0.5 us recharge)



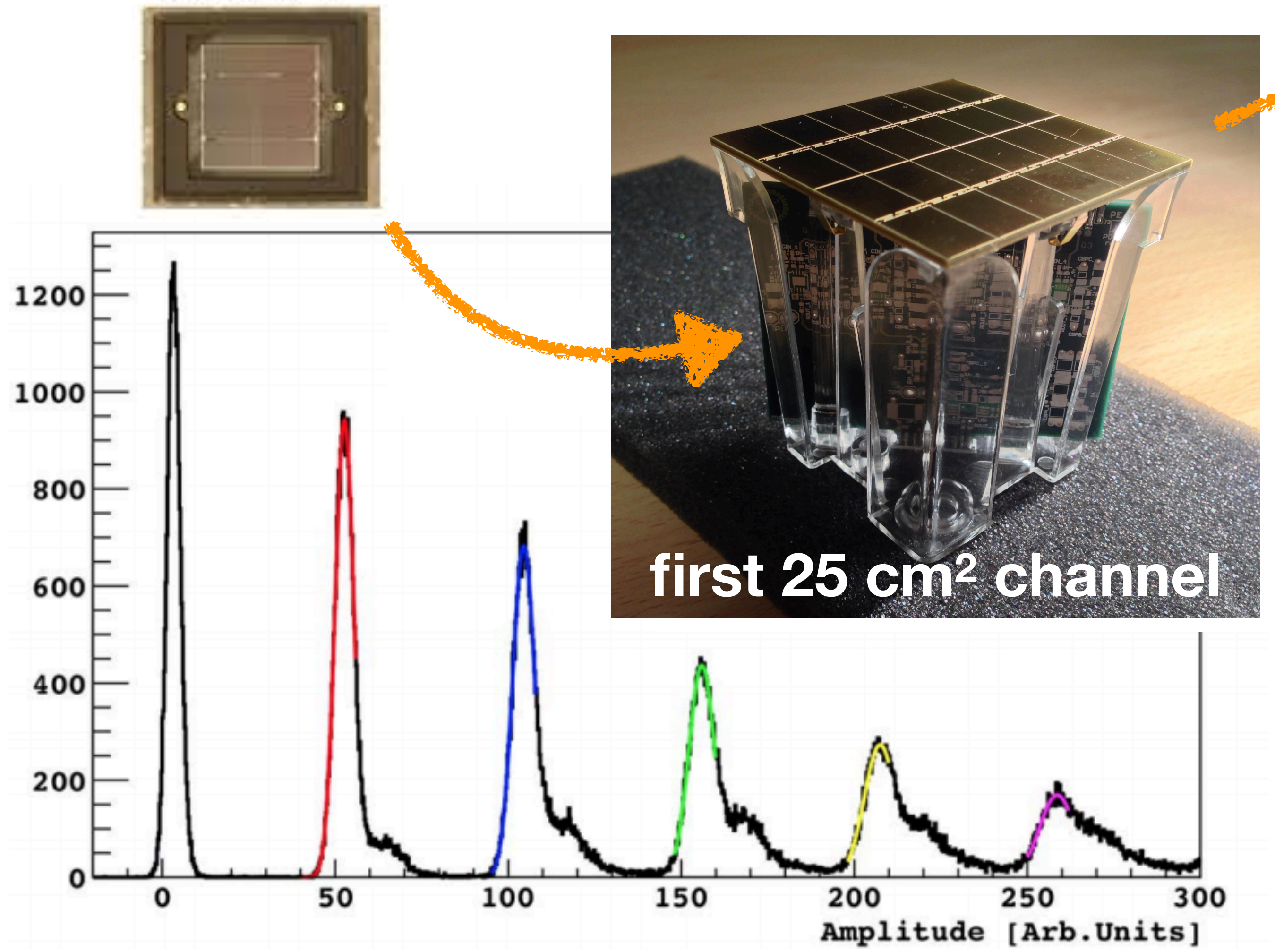


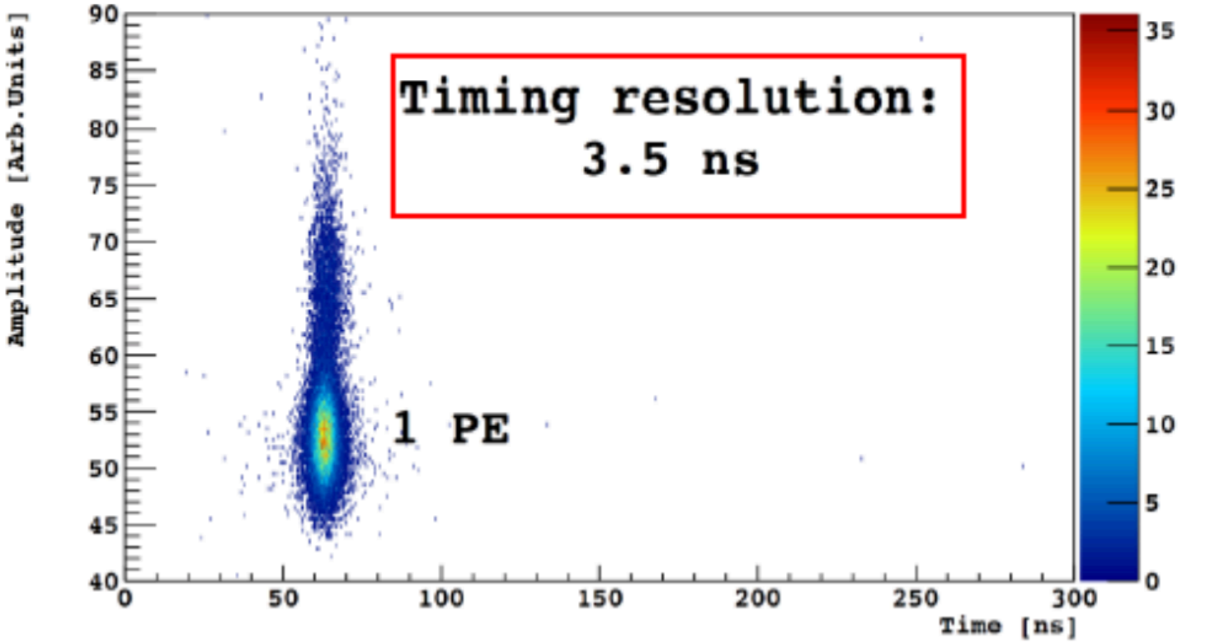
parameter	spec achieved (required)
PDE	> 45% (> 40%)
DCR	< ~20 Hz / PDM (< 250 Hz / PDM)
correlated noise probabilities (afterpulses, cross talk)	(10% + 40%) < 50% + 50%
SiPM gain	> 1E6 (> 1E6)
SNR after ARMA filter	> 20 (> 8)
time resolution	~ 5ns (< 10 ns)





FBK VUV HD-LF

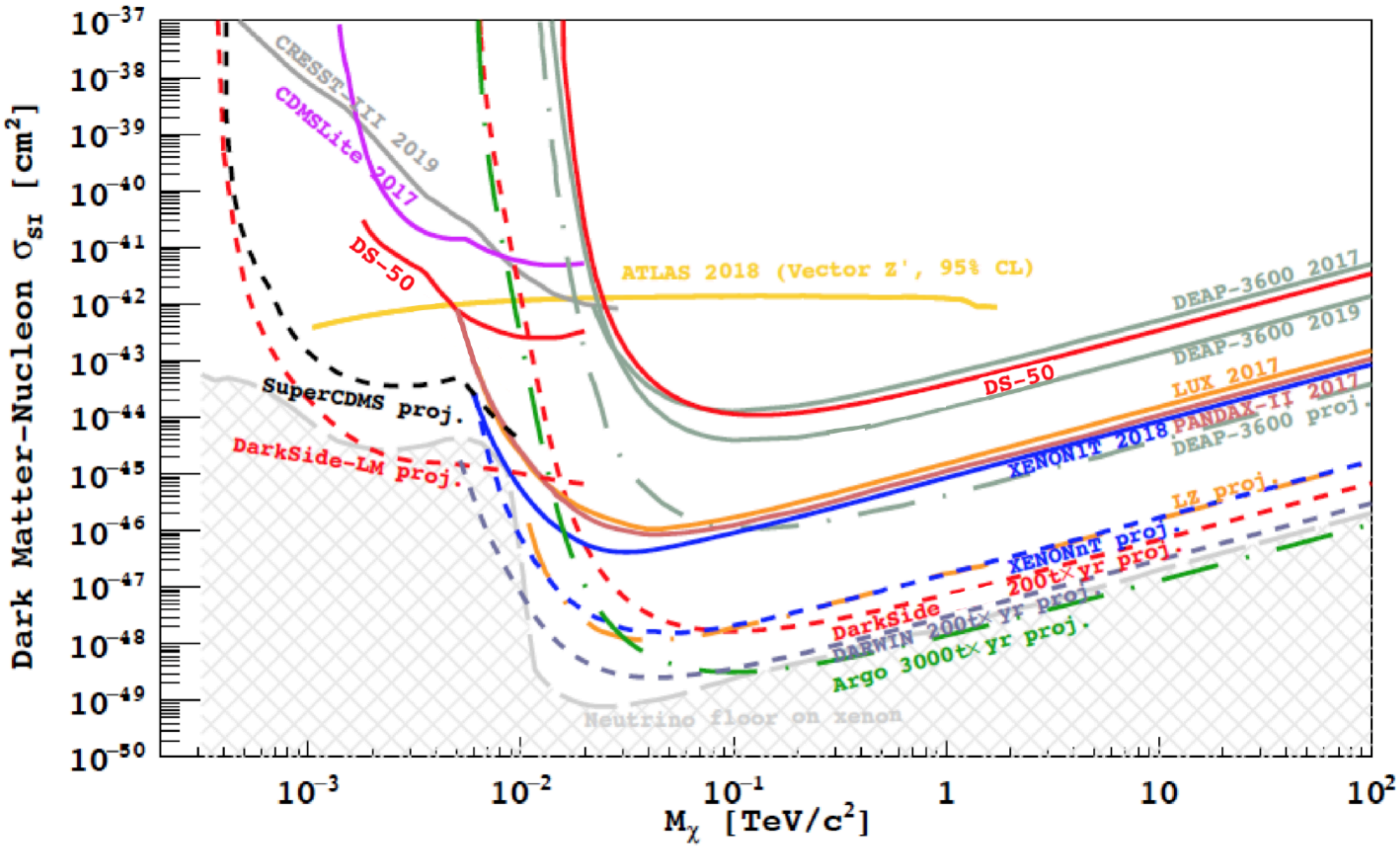




Finalise the DarkSide-50 analysis! Interesting results to come

Low-mass candidates: increasing interest! Experimental efforts to calibrate detectors and target response (e.g. Migdal effect); conceptual design of dedicated experiments (at Boulby?)? Need clean materials, pure target, reduced detector backgrounds

DarkSide-20k (2024?): 50 tonne UAr TPC, at LNGS, contribution in the UK. Focus on high-mass dark matter candidates (**WIMPs**), aiming to collect **200 t.yr exposure free from instrumental backgrounds**. Use of novel large area grouped **SiPM** detector.



Thank you!

paolo.agnes@cern.ch