Detecting SN neutrino bursts via CEvNS with DarkSide-20k

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on behalf of the DarkSide-20k Collaboration

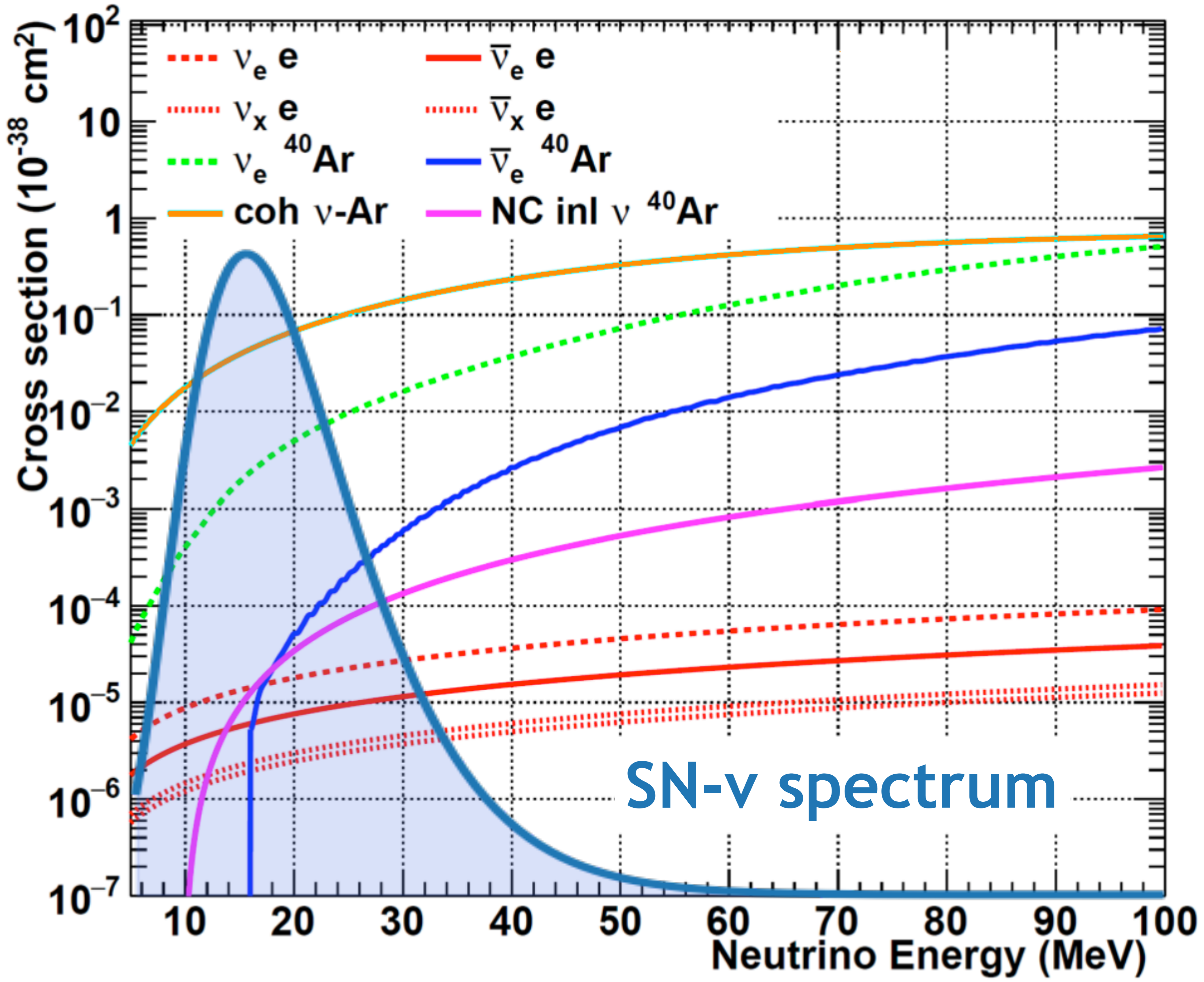
SNvD 2023@LNGS - 29/05/2023

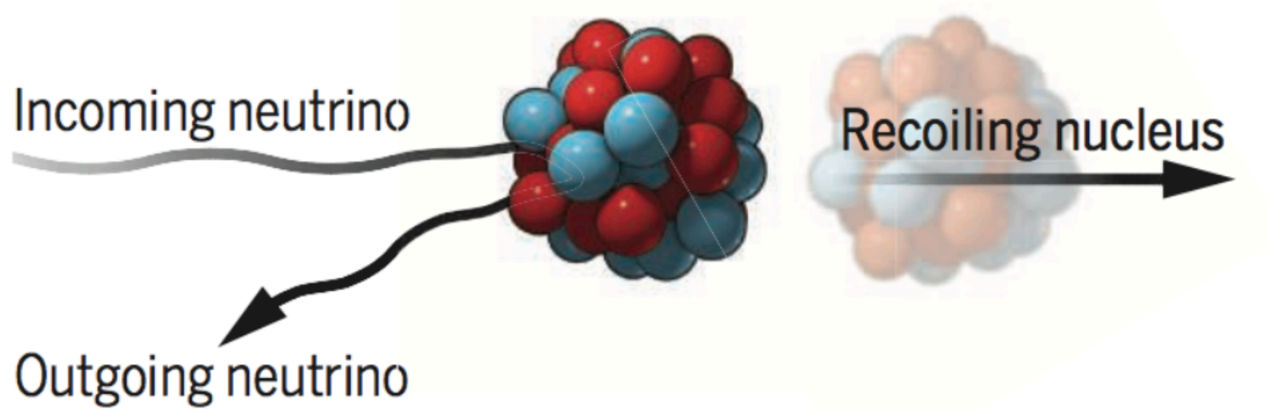
Supernova neutrino detection via CEvNS

CEvNS: Coherent Elastic Neutrino-Nucleus Scattering

measured for the first time with the COHERENT CsI[Na] detector in 2017 (Science 357, 1123, 2017)

$$Q_W^2 = (N-(1-4\sin^2\theta_W)Z)^2 \approx N^2$$





Advantages

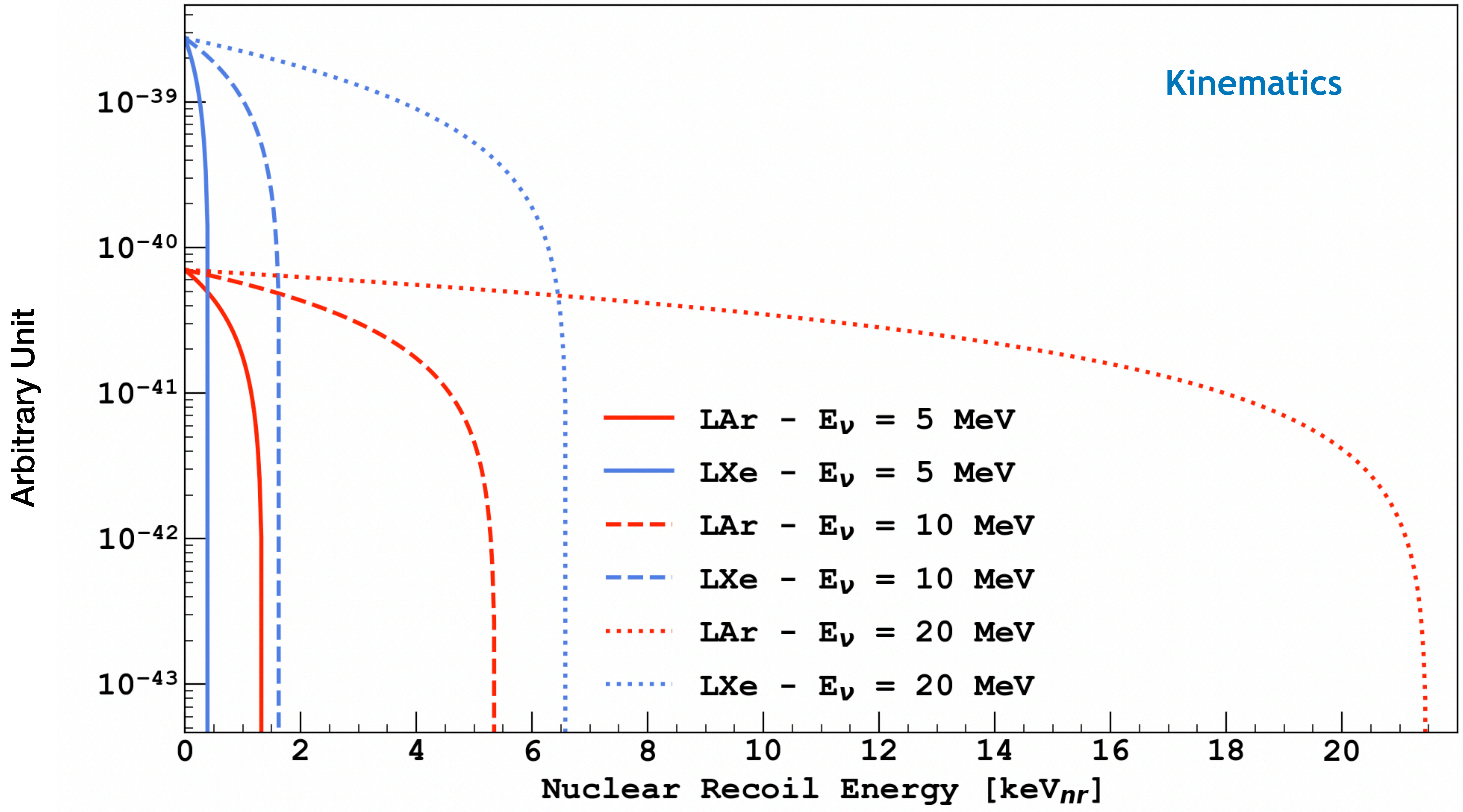
- highest **cross section** in the SN-ν energy range
    - “small” detectors become sensitive to SNs

- **Insensitive** to neutrino flavours
    - Measurement of the entire SN-ν flux
    - Sensitivity to the neutronization burst
    - Complementary to CC and ES from giant detectors

Disadvantages

- **keV / sub-keV** recoils due to:
    - Kinematics
    - Nuclear recoil quenching
    - Electric-field induced quenching

CEvNS Kinematics in Noble Liquids



LAr lower cross section wrt LXe but higher recoil energies: rate depends on threshold and quenching

SN Neutrino Rate

27 M_{sun} at 10 kpc

CC, ES, IBD, NC, …

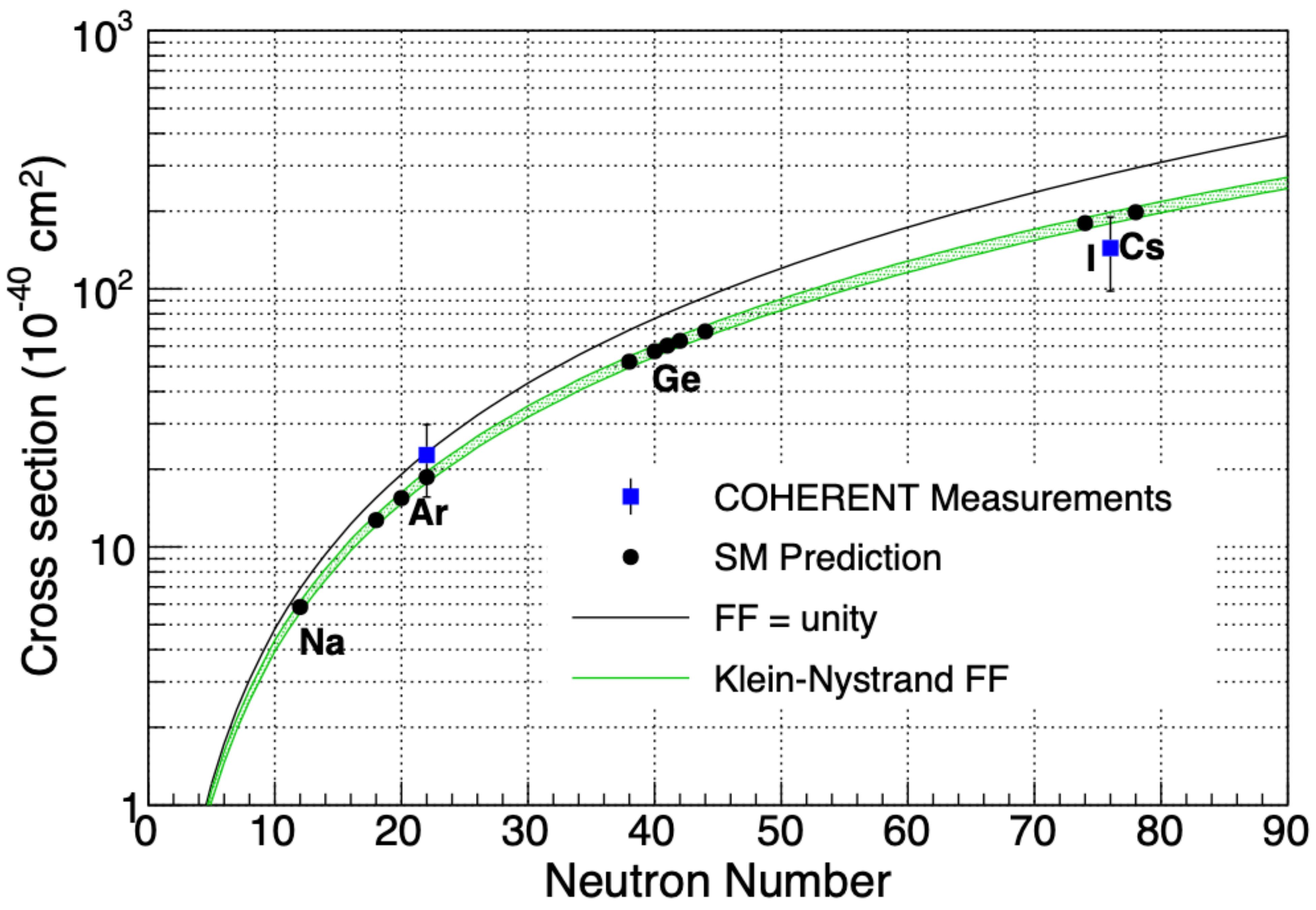
Detector	Type	Mass (kt)	Location	Events	Status
Super-Kamiokande	H_2O	32	Japan	7,000	Running
LVD	C_nH_{2n}	1	Italy	300	Running
KamLAND	C_nH_{2n}	1	Japan	300	Running
Borexino	C_nH_{2n}	0.3	Italy	100	Running
IceCube	Long string	(600)	South Pole	(10^6)	Running
Baksan	C_nH_{2n}	0.33	Russia	50	Running
HALO	Pb	0.08	Canada	30	Running
Daya Bay	C_nH_{2n}	0.33	China	100	Running
NOνA*	C_nH_{2n}	15	USA	4,000	Running
MicroBooNE*	Ar	0.17	USA	17	Running
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
DUNE	Ar	40	USA	3,000	Future
Hyper-Kamiokande	H_2O	374	Japan	75,000	Future
JUNO	C_nH_{2n}	20	China	6000	Future
RENO-50	C_nH_{2n}	18	Korea	5400	Future
PINGU	Long string	(600)	South Pole	(10^6)	Future

From K. Scholberg, J.Phys. G45 (2018) no.1, 014002

CEvNS

7 counts / ton in **LAr** (JCAP 03 (2021) 043)

27 counts / ton in **LXe** (PRD 94 (2016) 10, 103009)



Dual-Phase Noble Liquid TPCs for Dark Matter Search

2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033

ARGO — 400 ton LAr

XLZD — 40 ton LXe

DarkSide-20k — 50 ton LAr

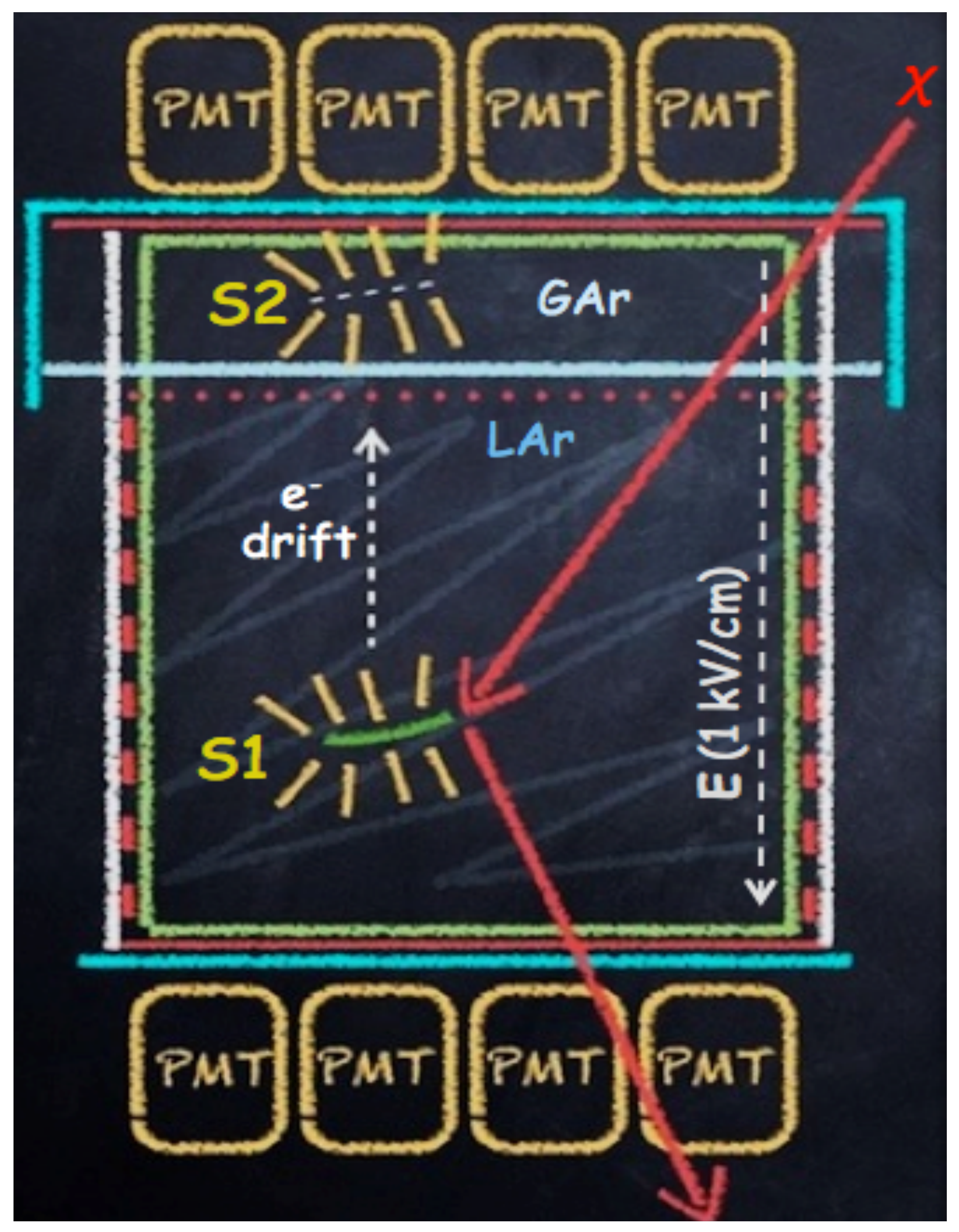
XENON-nT — 6 ton LXe

LZ — 7 ton LXe

PandaX-4T — 4 ton LXe

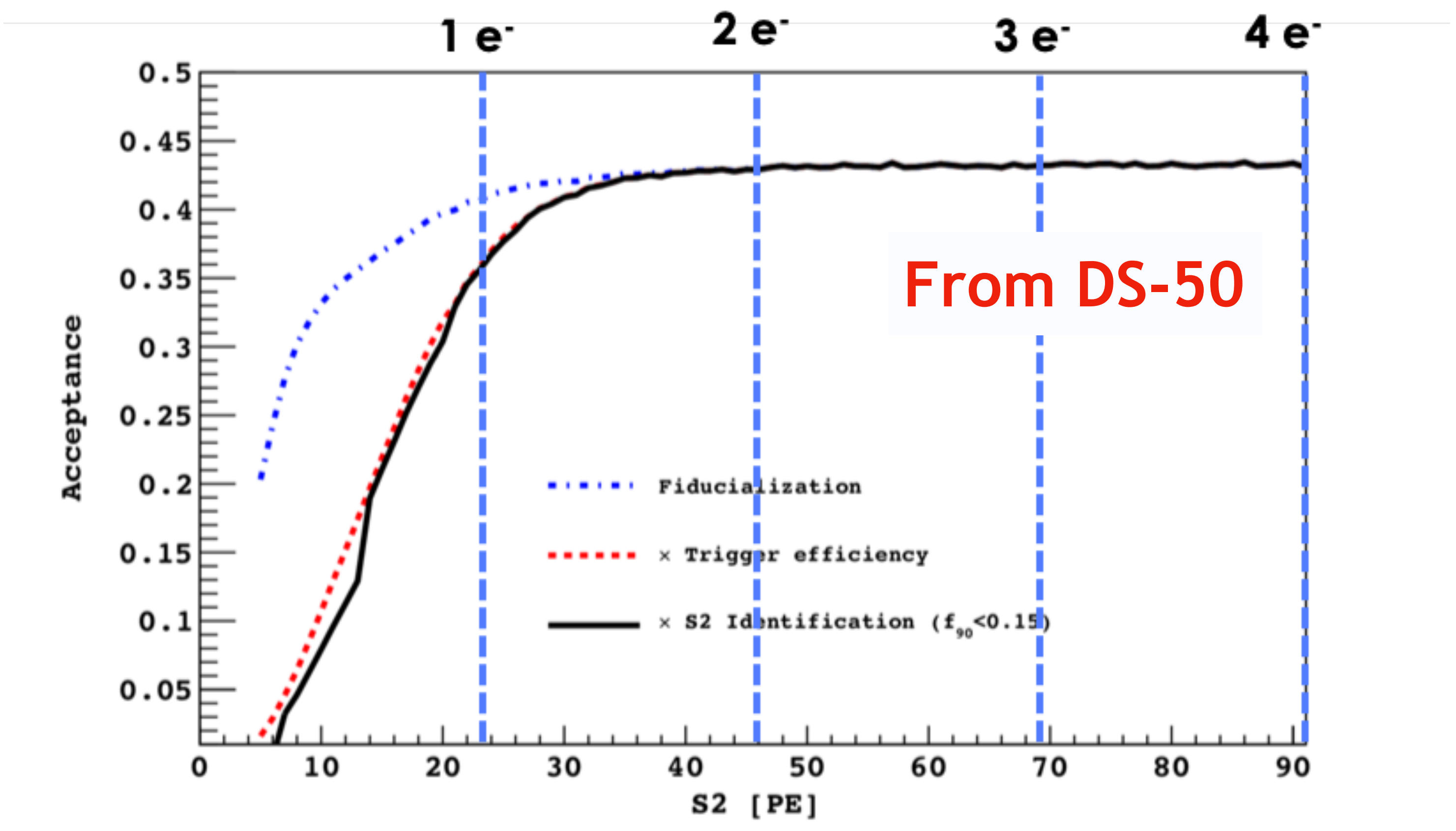
Noble Liquids
- Radiopurity
- Low-energy thresholds
- High scintillation / ionization yields
- Scalability to multi-ton targets

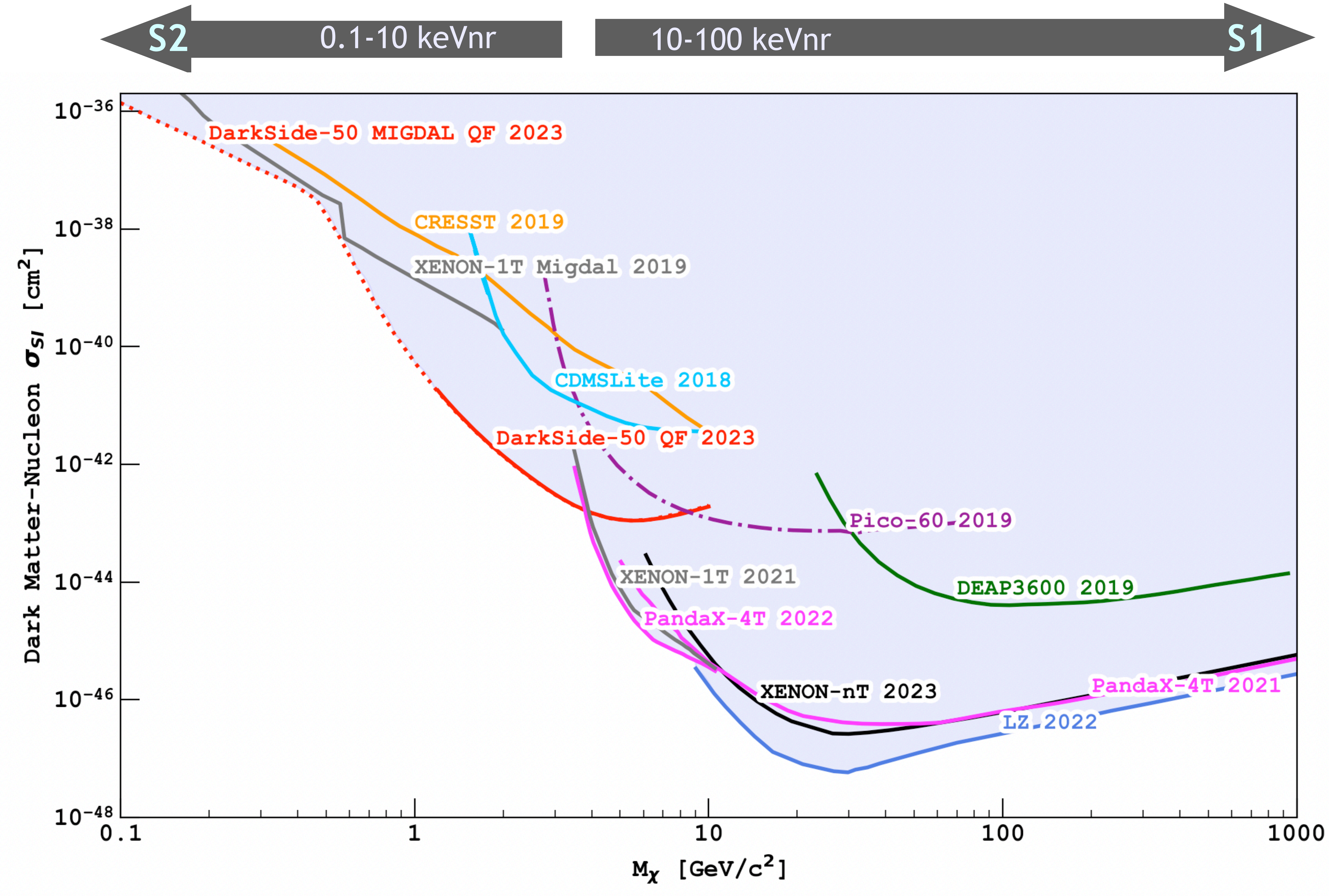
Dual-phase TPC
- High spatial resolution
- Fiducialization
- Multi-scatters rejection
- “Fast” response => active vetoes



Dual-Phase Liquid Argon TPCs for Dark Matter Search

- Scintillation (S1)
  - Detection efficiency (g1) < 20%
- Ionization (S2)
  - Efficiency to extract 1 e- ~ 100%
  - Amplification factor (g2) > 20 pe / e-





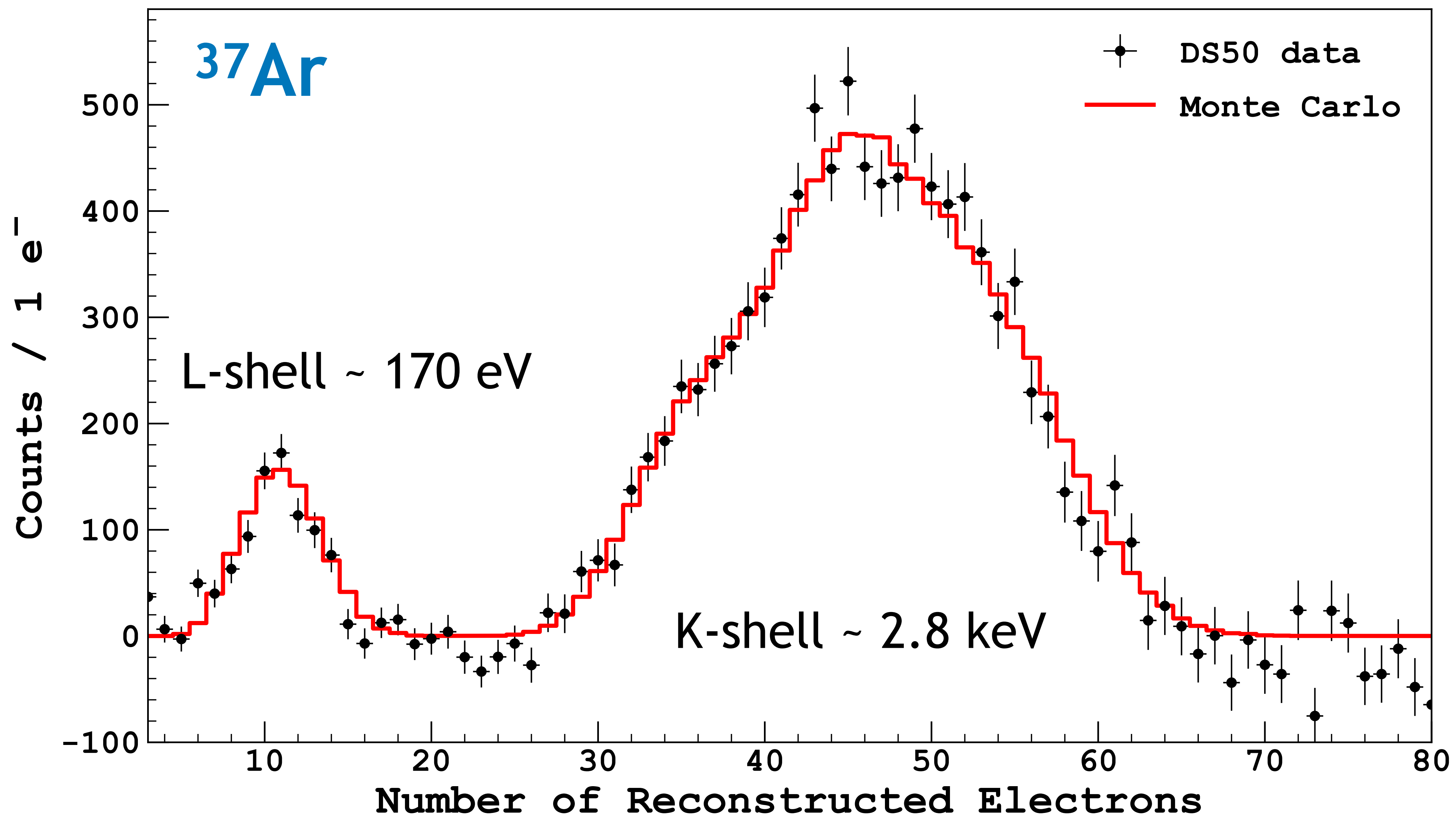
- Low energy threshold (a few tens of eV)
- Loss of scintillation pulse shape discrimination
- Loss of position reconstruction along the electric field

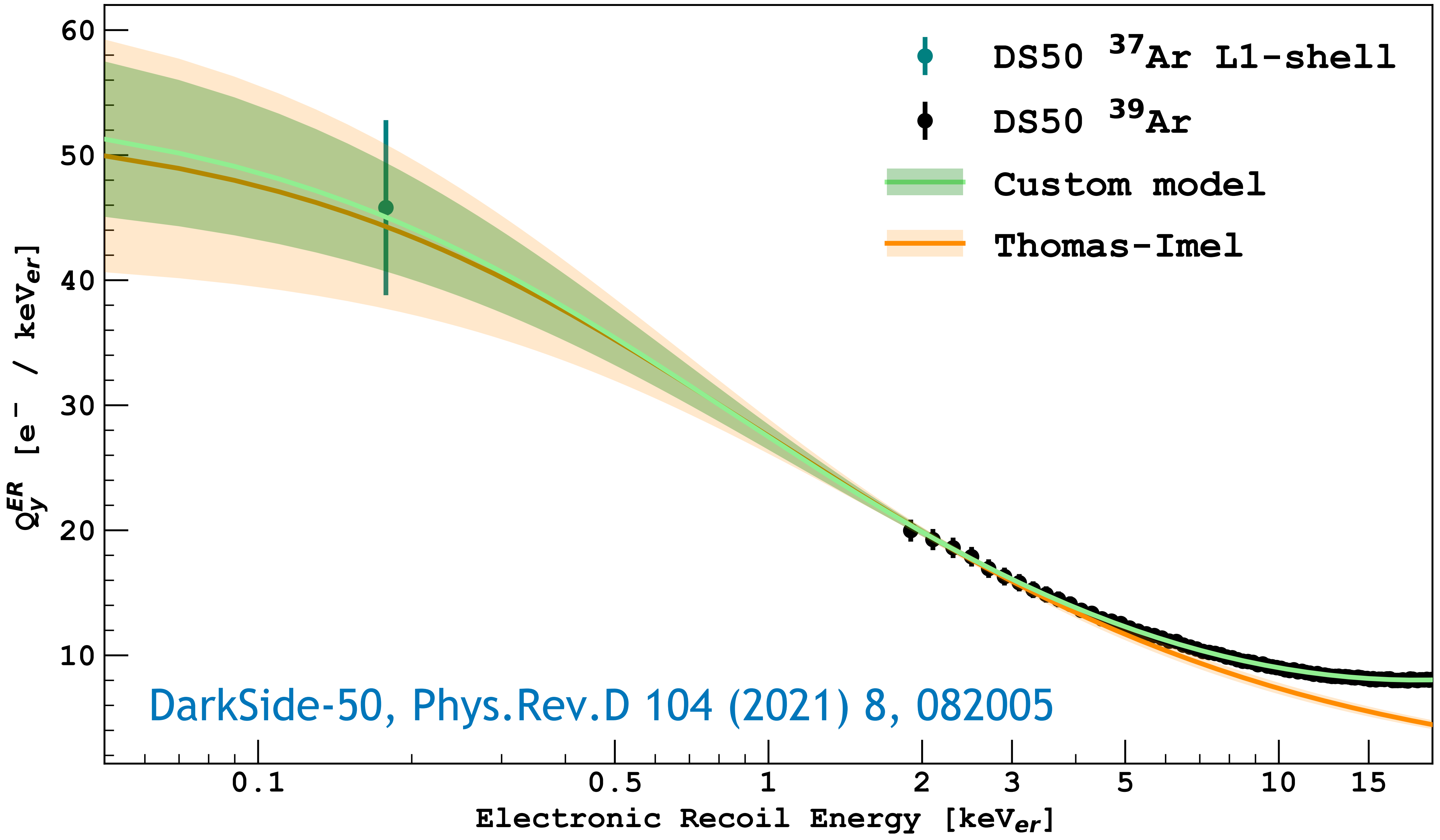
- Efficient particle discrimination
- High accuracy position reconstruction
- High energy threshold (a few keV)

LAr Ionization Response to Electronic Recoils

Thomas-Imel + extended custom model

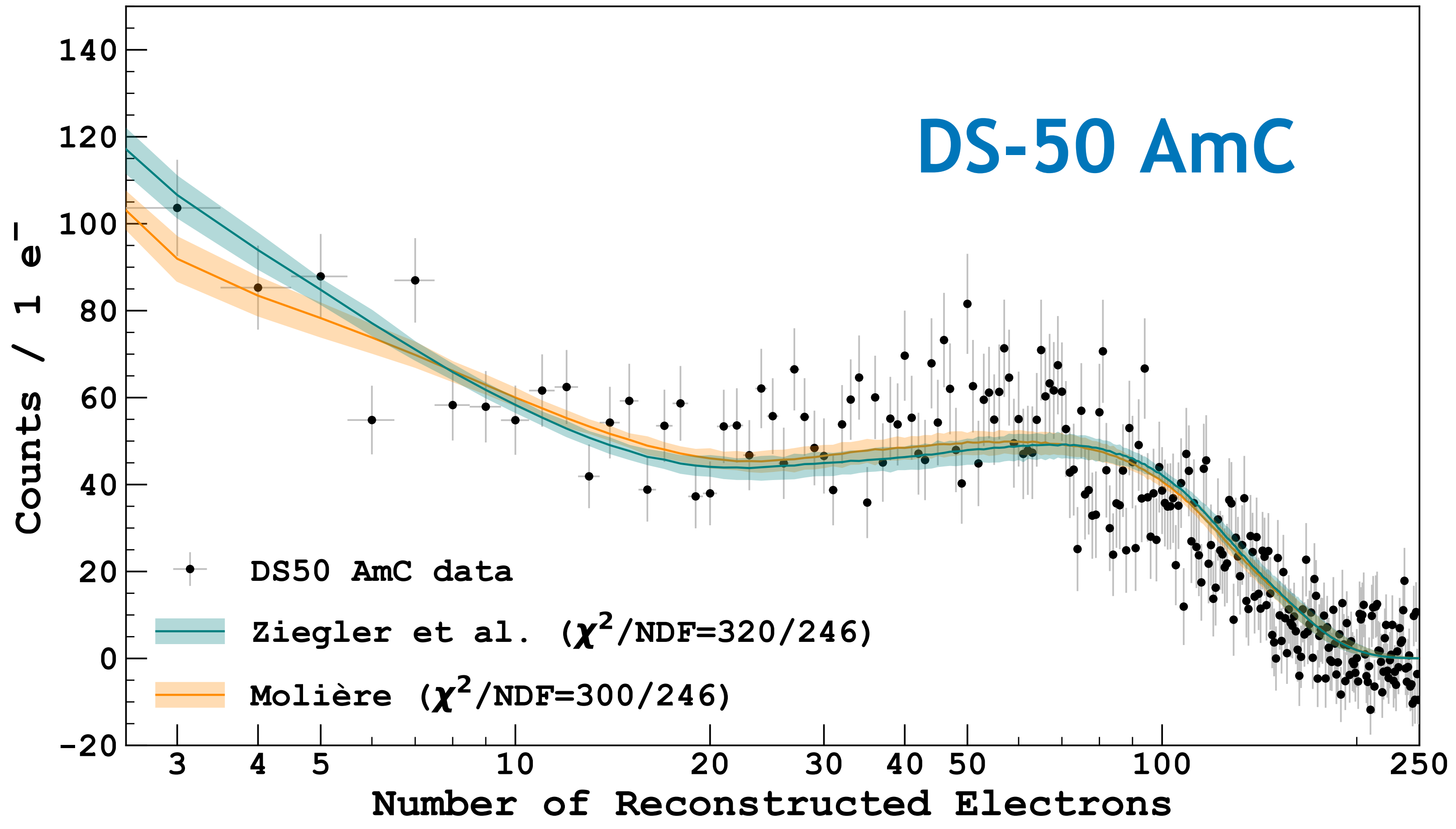
$$Q_y^{ER} = \left(\boxed{\frac{1}{\gamma}} + \boxed{p_0\,(E_{er}/\mathrm{keV}_{er})^{p_1}}\right)\boxed{\frac{\ln(1+\gamma\,\rho\,E_{er})}{E_{er}}}$$

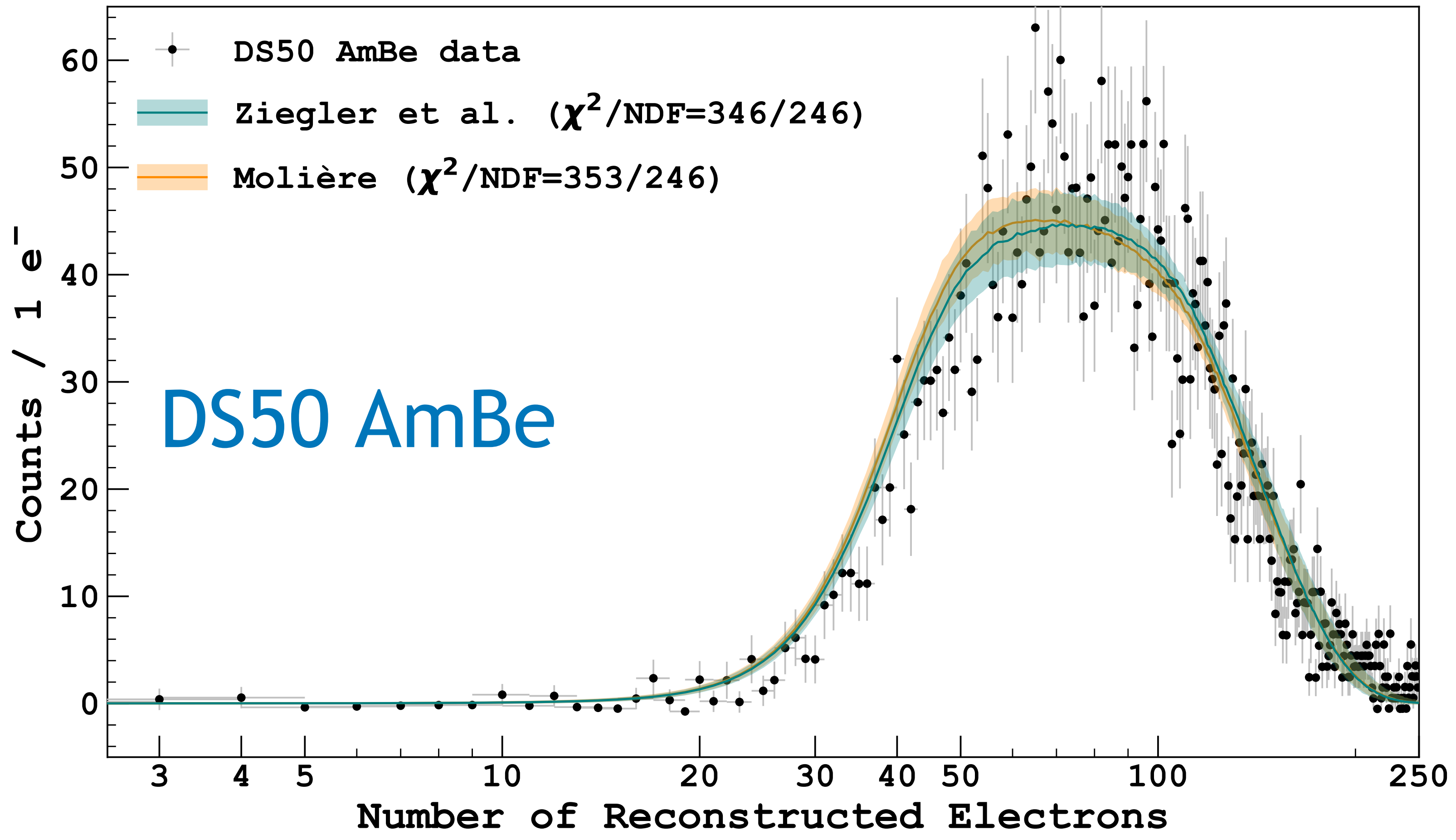


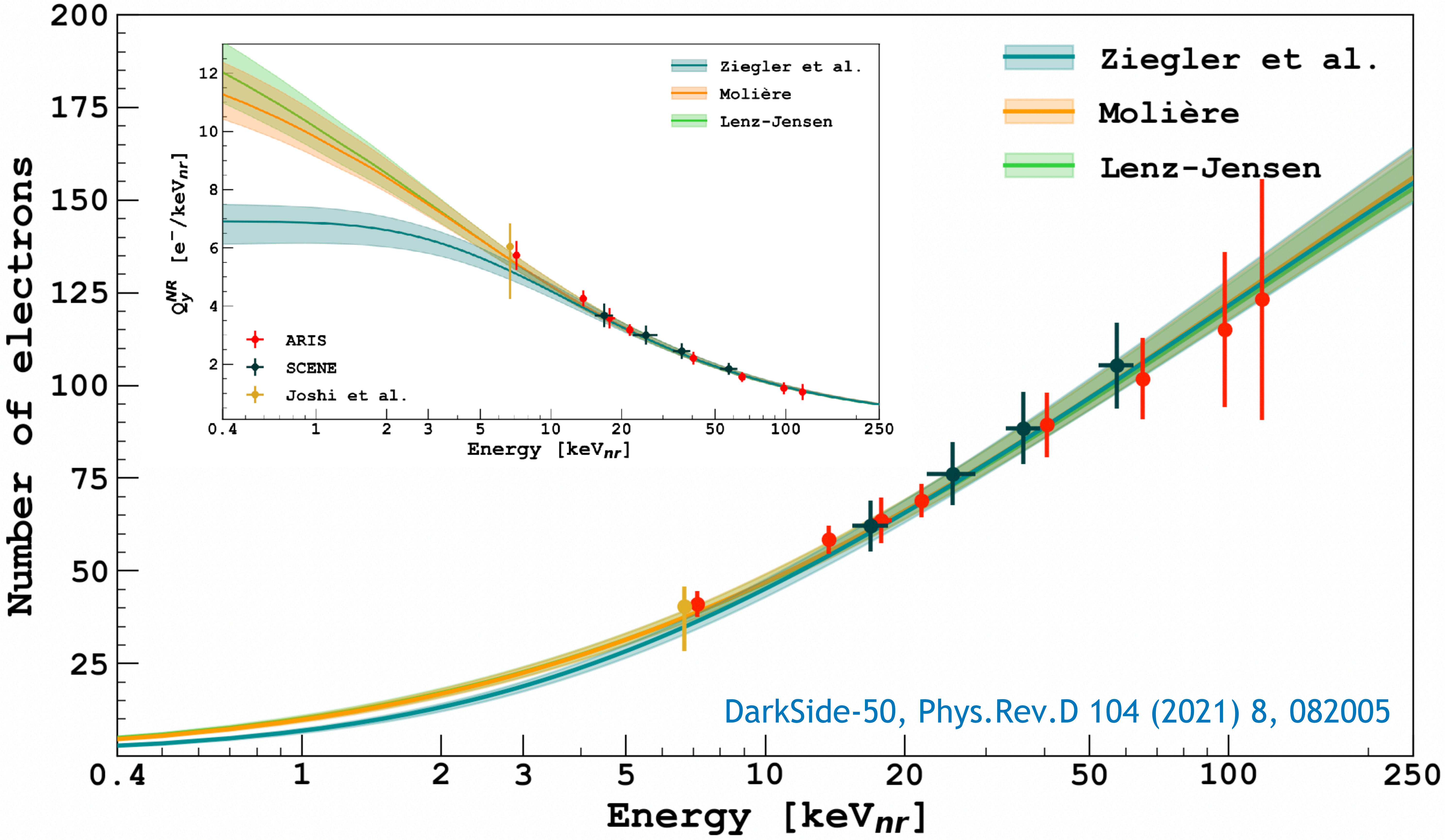


LAr Ionization Response to Nuclear Recoils

Global fit to DS-50 calibration data with neutrons sources + external datasets (ARIS and SCENE)



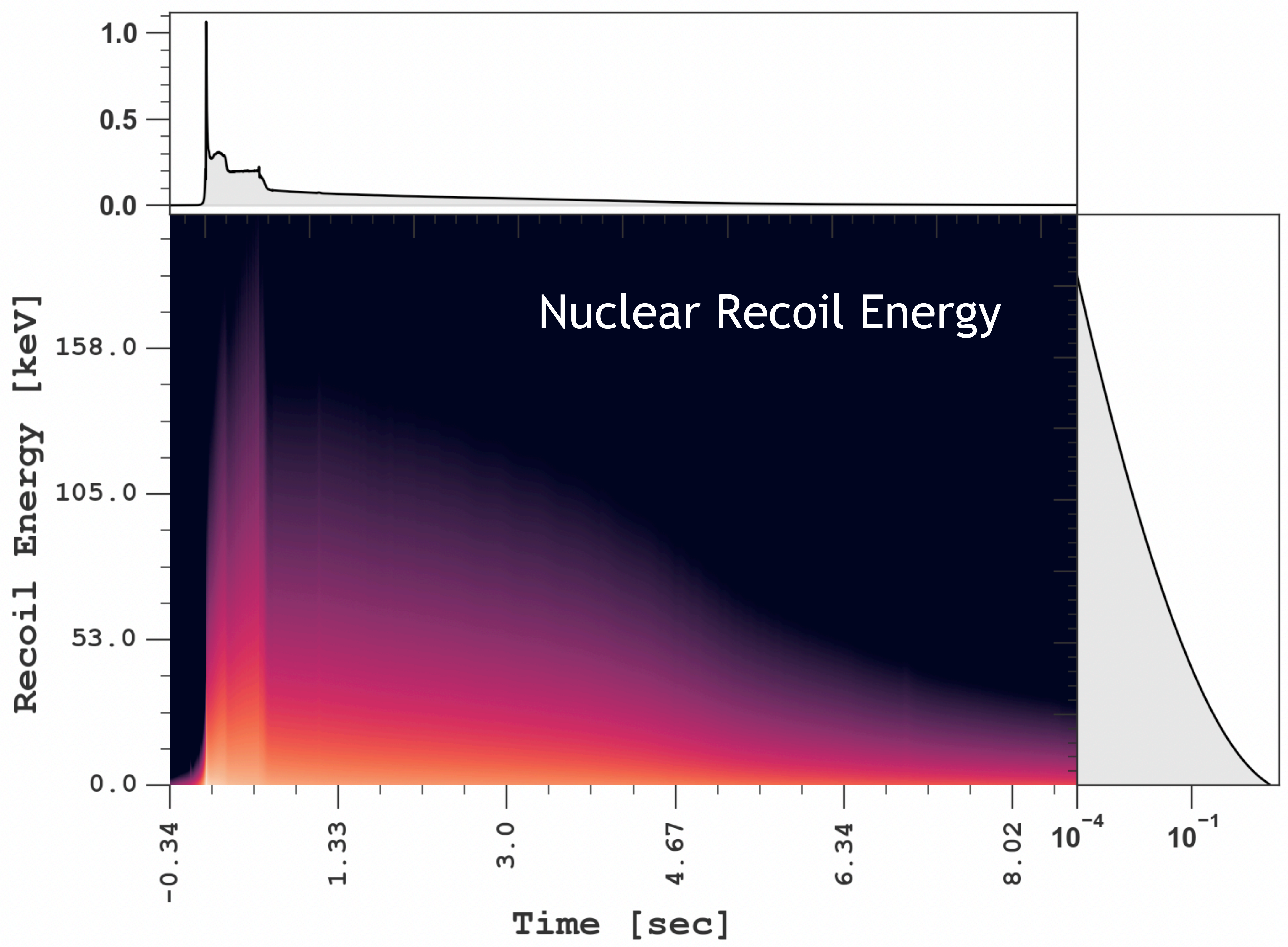


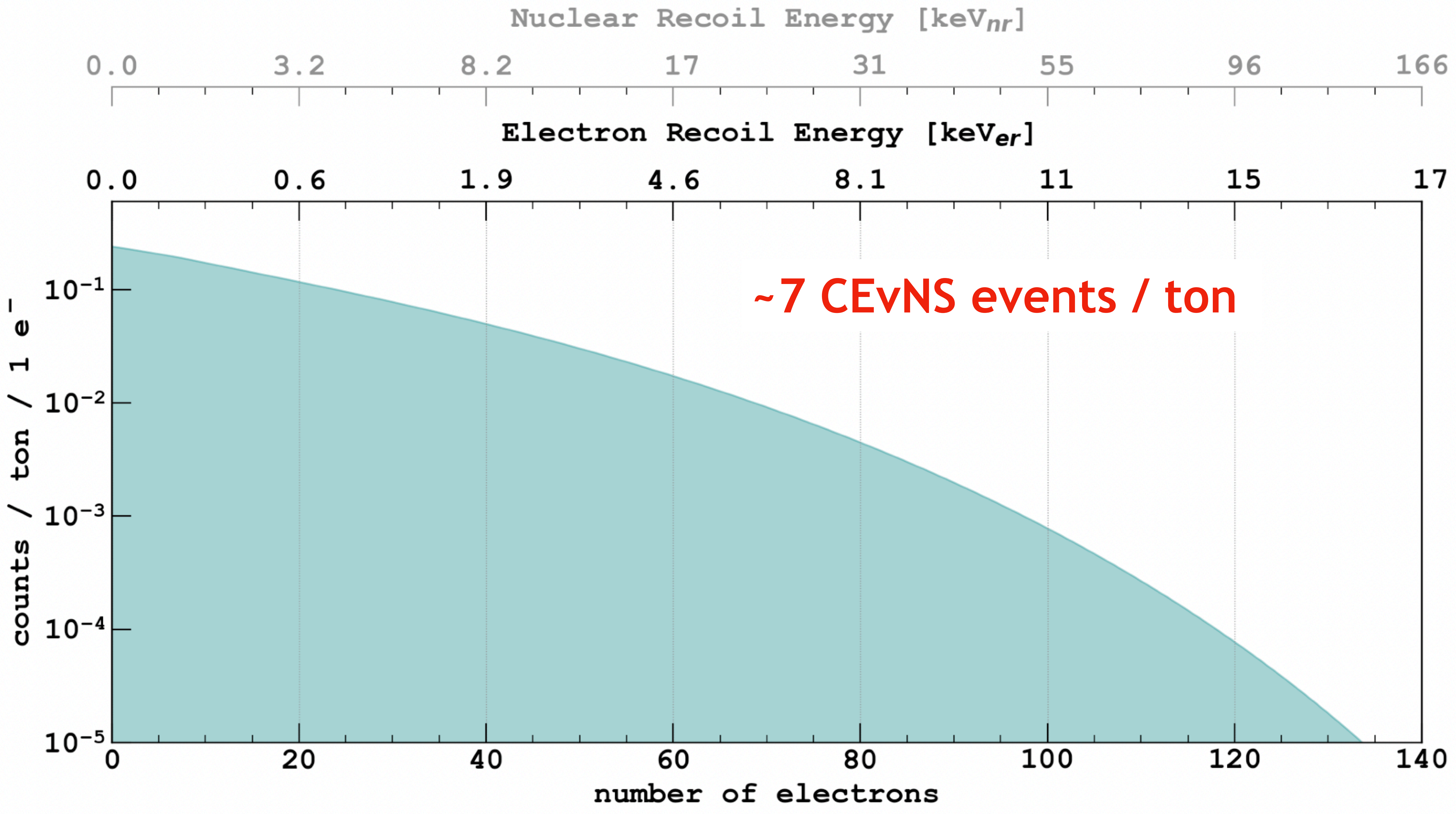


Ziegler's screening function is the baseline for this analysis

The SN-ν CEνNS Signal in LAr

Bollig 2016 / s27.0c model at 10 kpc





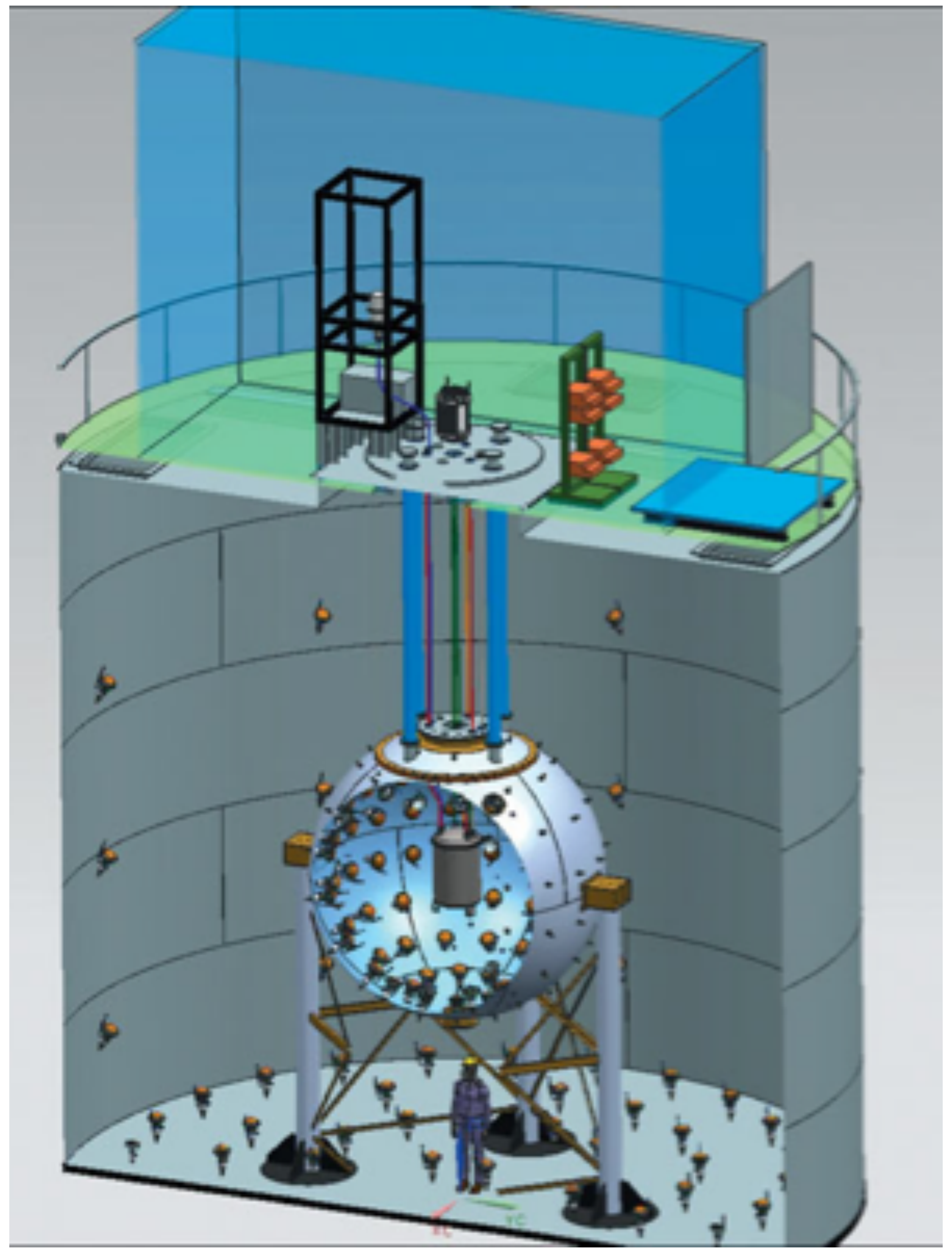
From SNEWPY (and many thanks to S. El Hedri and I. Goos, APC)

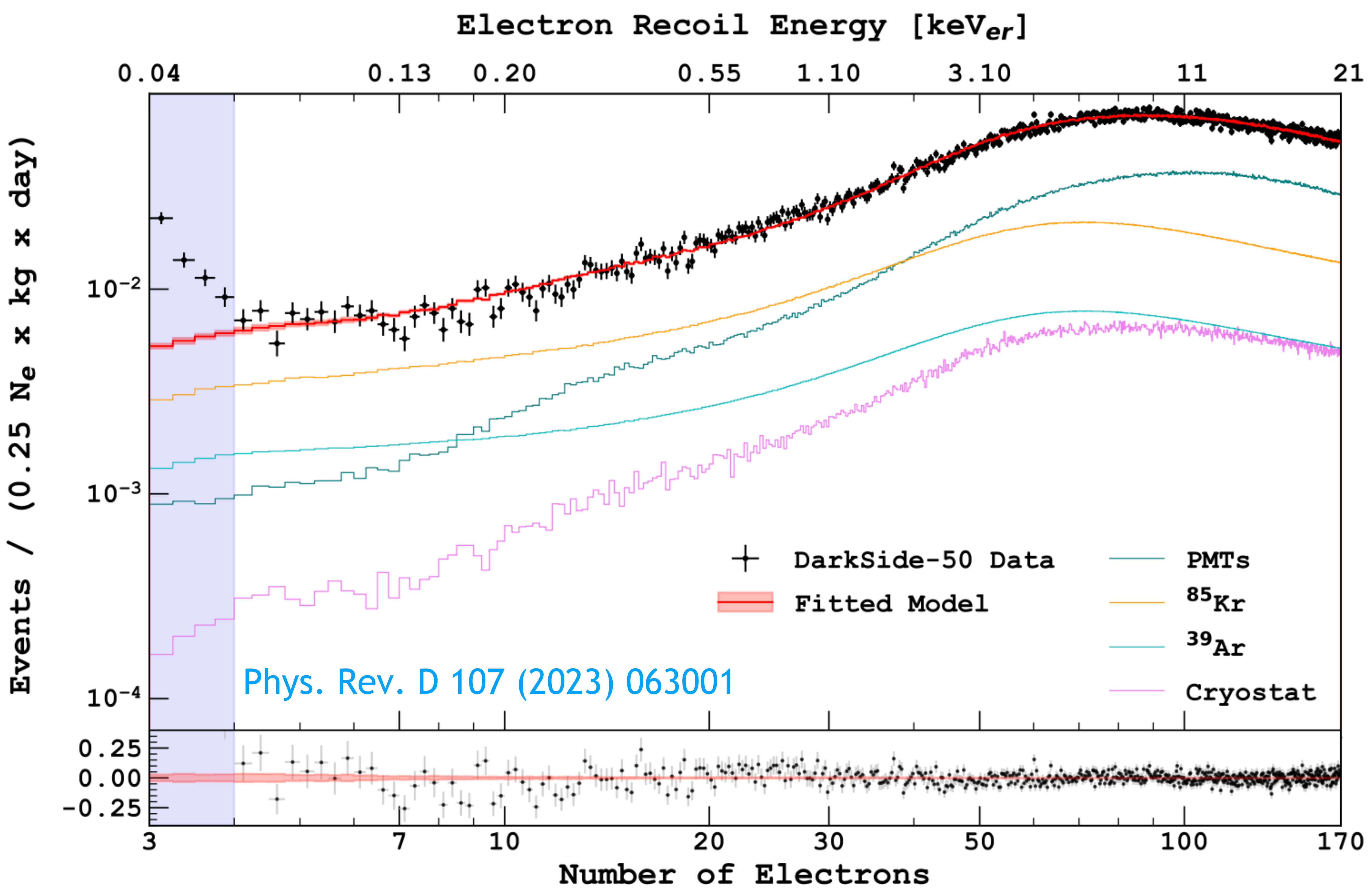
The DarkSide-50 Background

Background rate per unit of target mass scales with surface / volume ratio

The DS-50 TPC

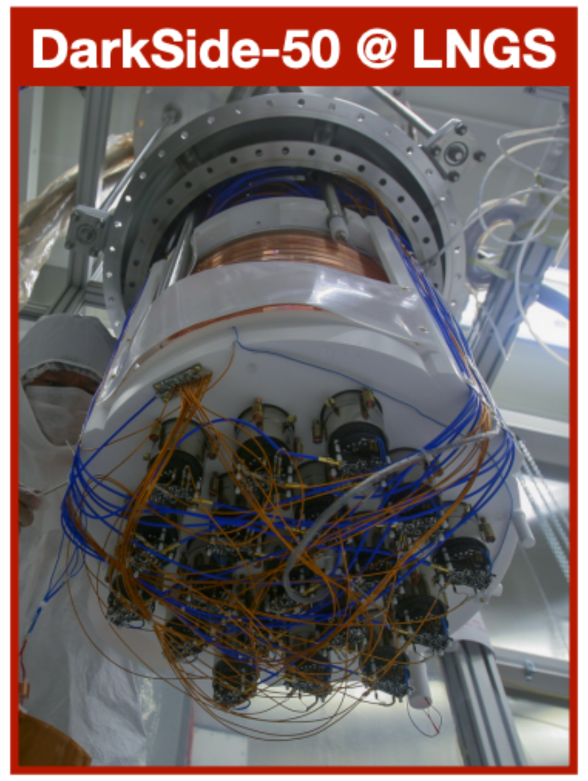
- 50 kg active mass of UAr
- 19 top + 19 bottom R11065 HQE 3’’ PMTs
- 36 cm height, 36 cm diameter
- Low field of 0.2 kV/cm drift





DS-50 event rate in [4, 140] Ne and d_{xy} > 6 cm from the lateral walls: 2.7 / ton / 10 s

The Global Dark Matter Argon Collaboration

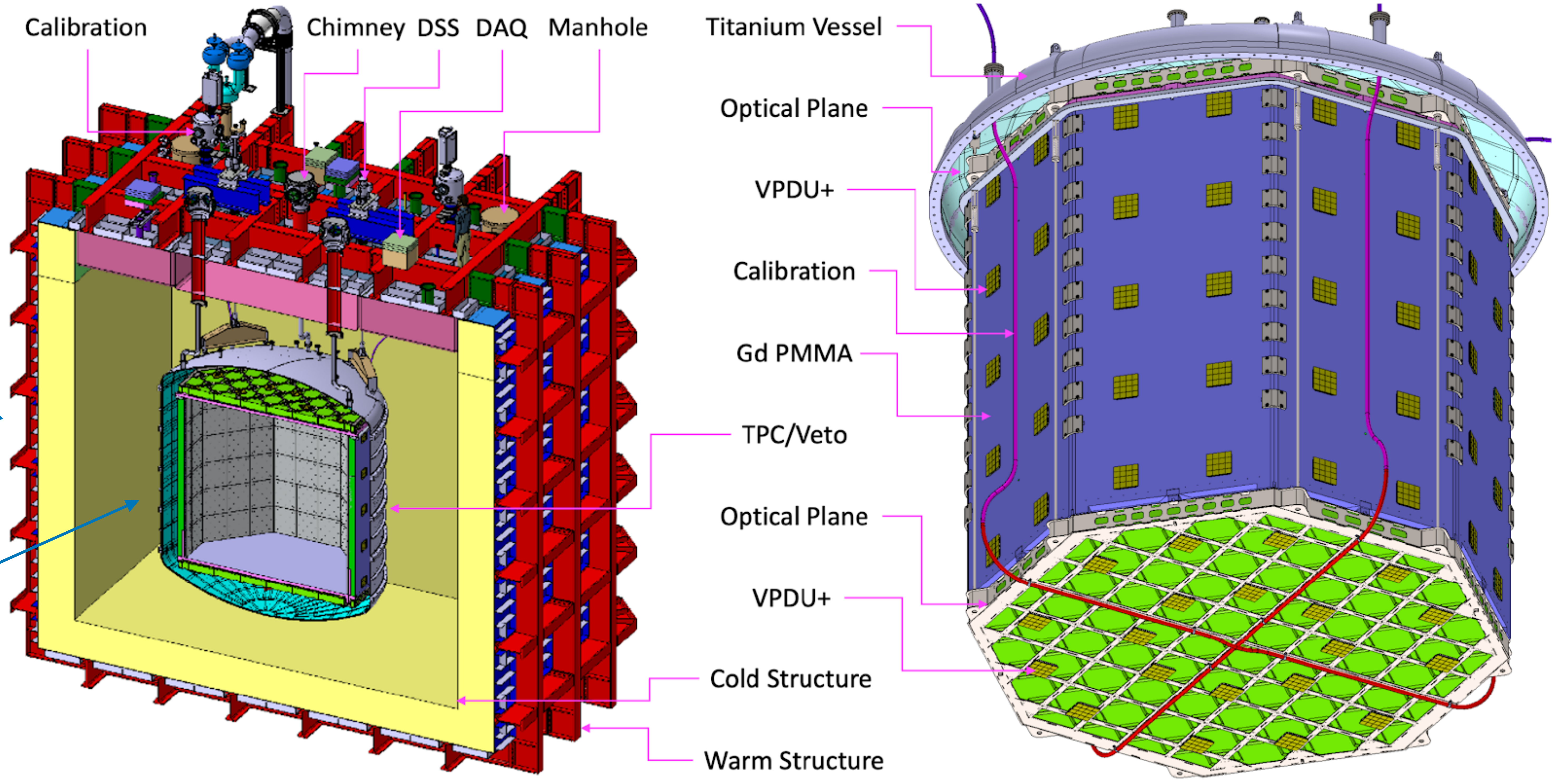


> 500 Collaborators, > 100 institutes distributed across 14 countries

DarkSide-20k @ LNGS

ProtoDUNE-like cryostat (8x8x8m^3)

Ti vessel separating AAr from UAr



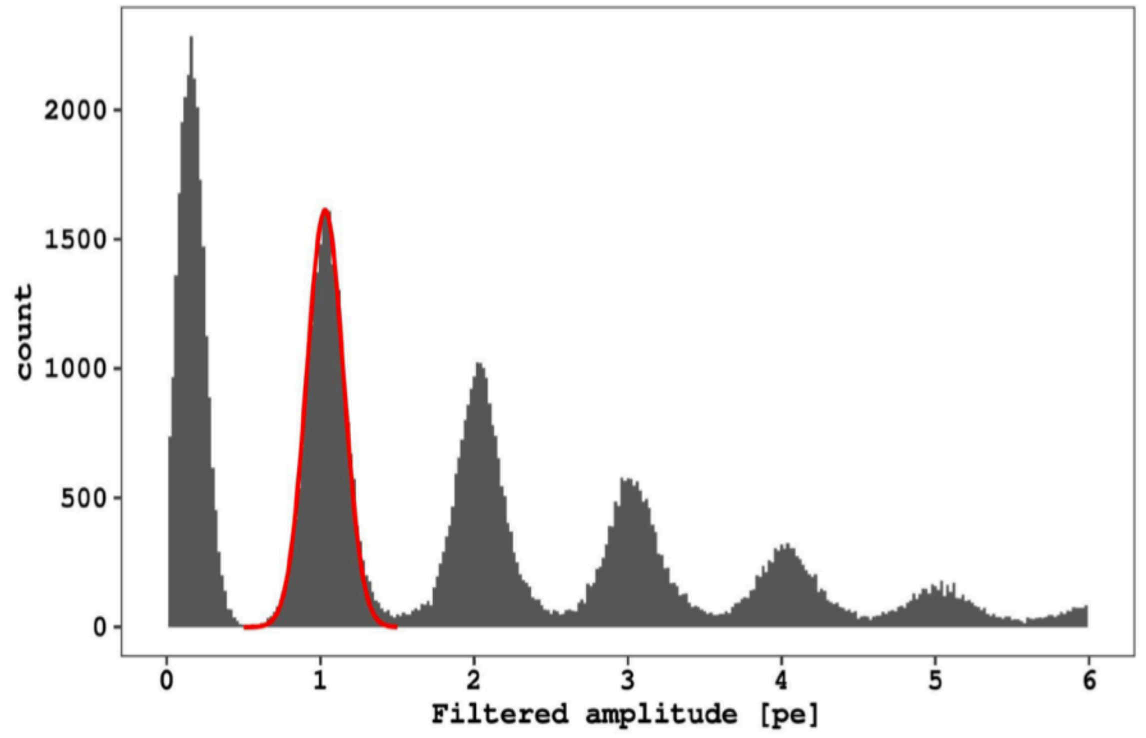
TPC
- 50 ton of underground LAr (dual-phase)
- Gd-loaded acrylic (PMMA) walls
- Walls coated with TPB as WL shifter
- 2112 channels*

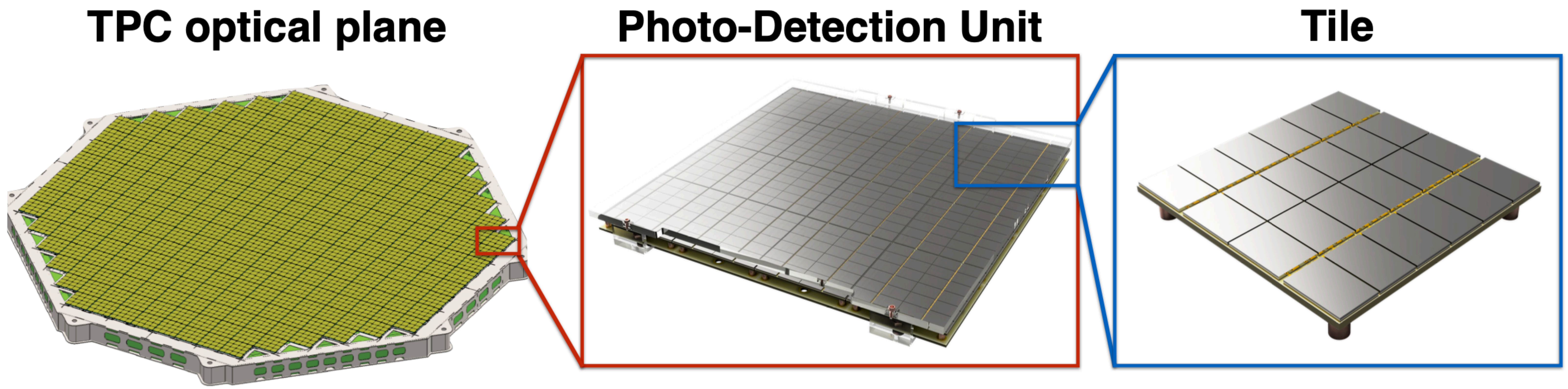
Inner Veto
- 35 ton of underground LAr (single-phase)
- 480 channels*

Outer Veto
- 700 ton of atmospheric LAr (single-phase)
- 128 channels*

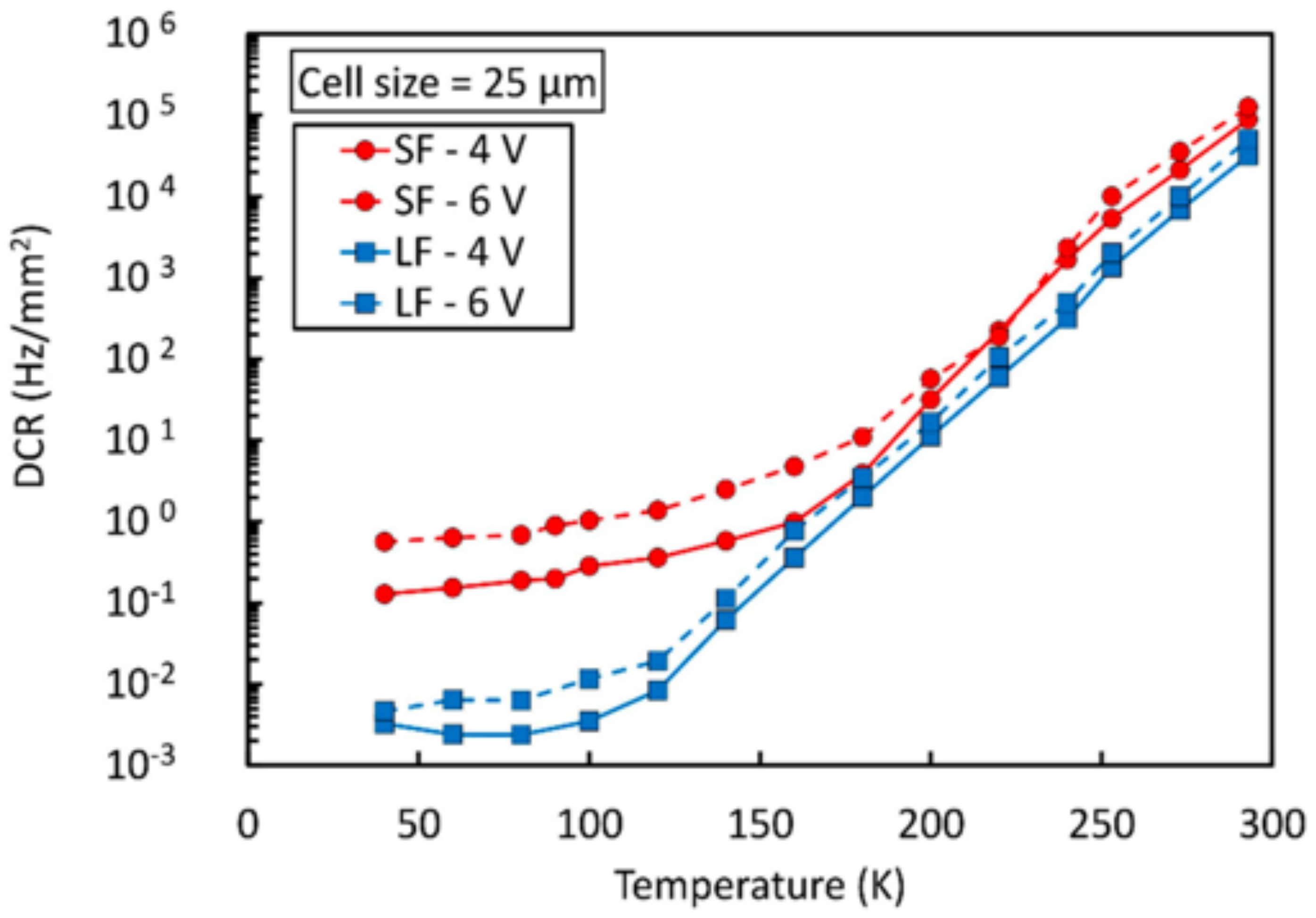
(*) each channel = 96 SiPMs

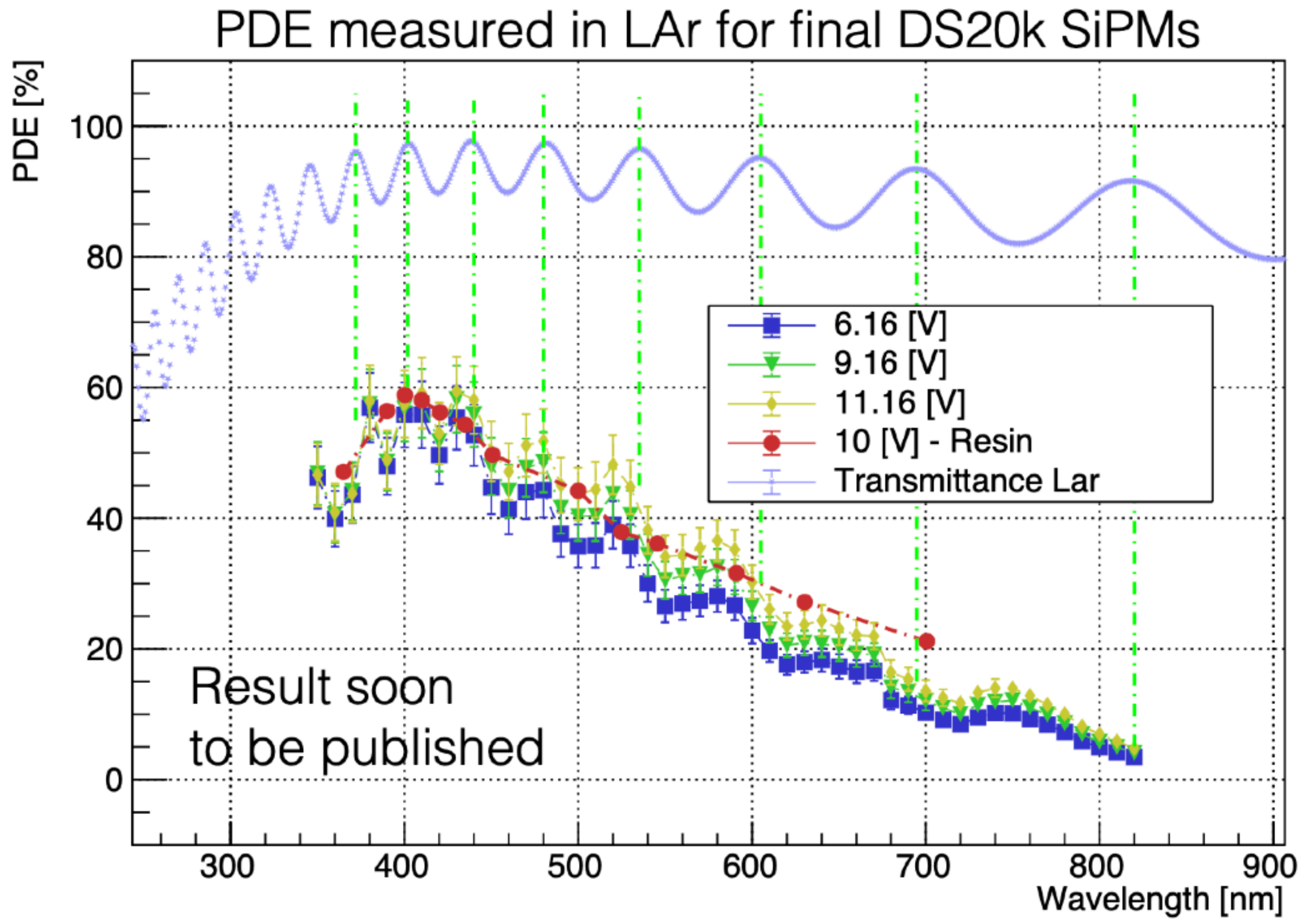
DarkSide-20k Light Readout





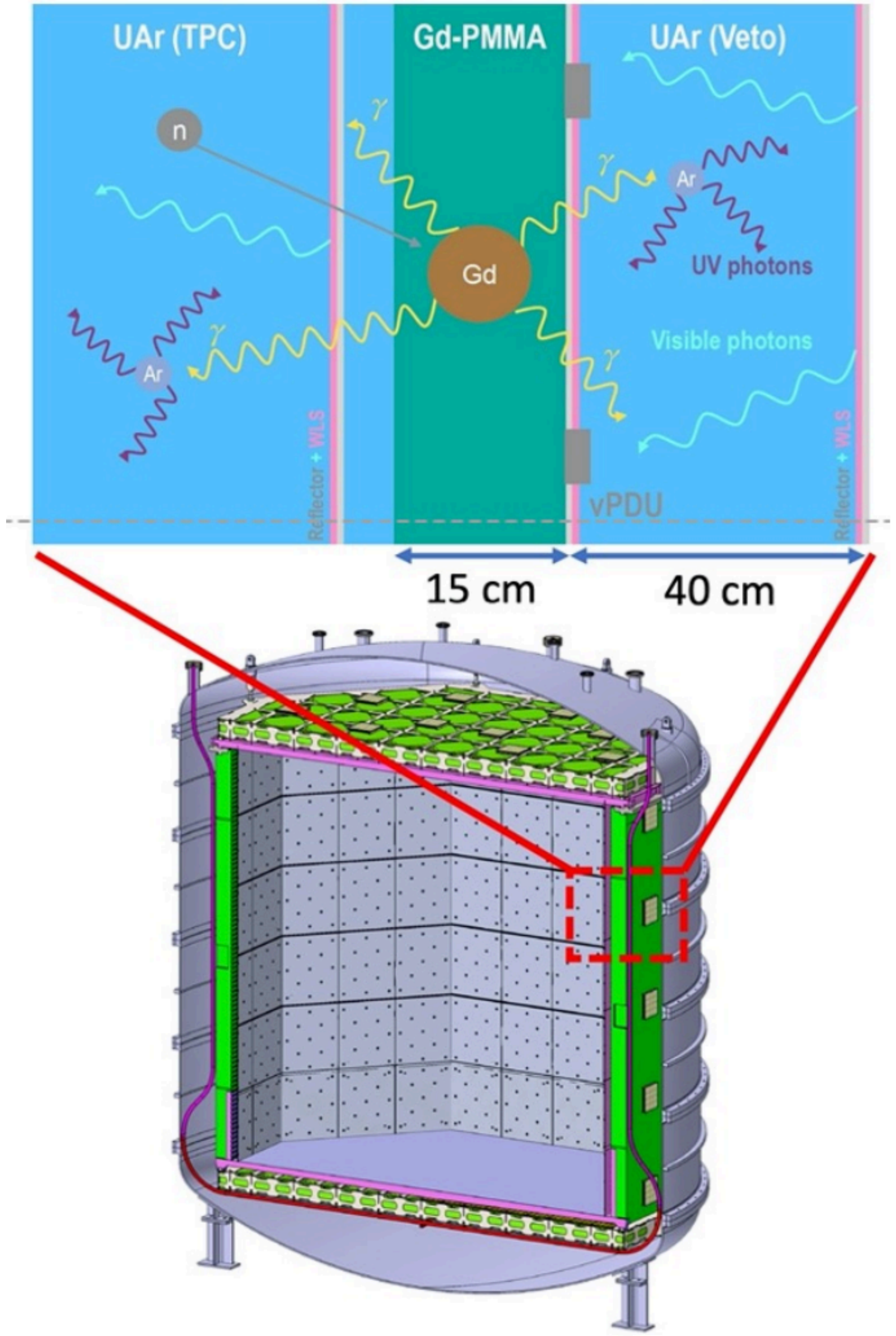
Performances





parameter	spec required	spec achieved
PDE @ 420 nm	> 40%	~50%
DCR (87 K)	250 Hz / tile	~20 Hz / tile
correlated noise probabilities (afterpulses, cross talk)	< 50% + 50%	<10% + 35%
SiPM gain	> 1E6	> 1E6
SNR after ARMA filter	> 8	> 8
time resolution	~ 10 ns	~15 ns

DarkSide-20k Neutron Veto

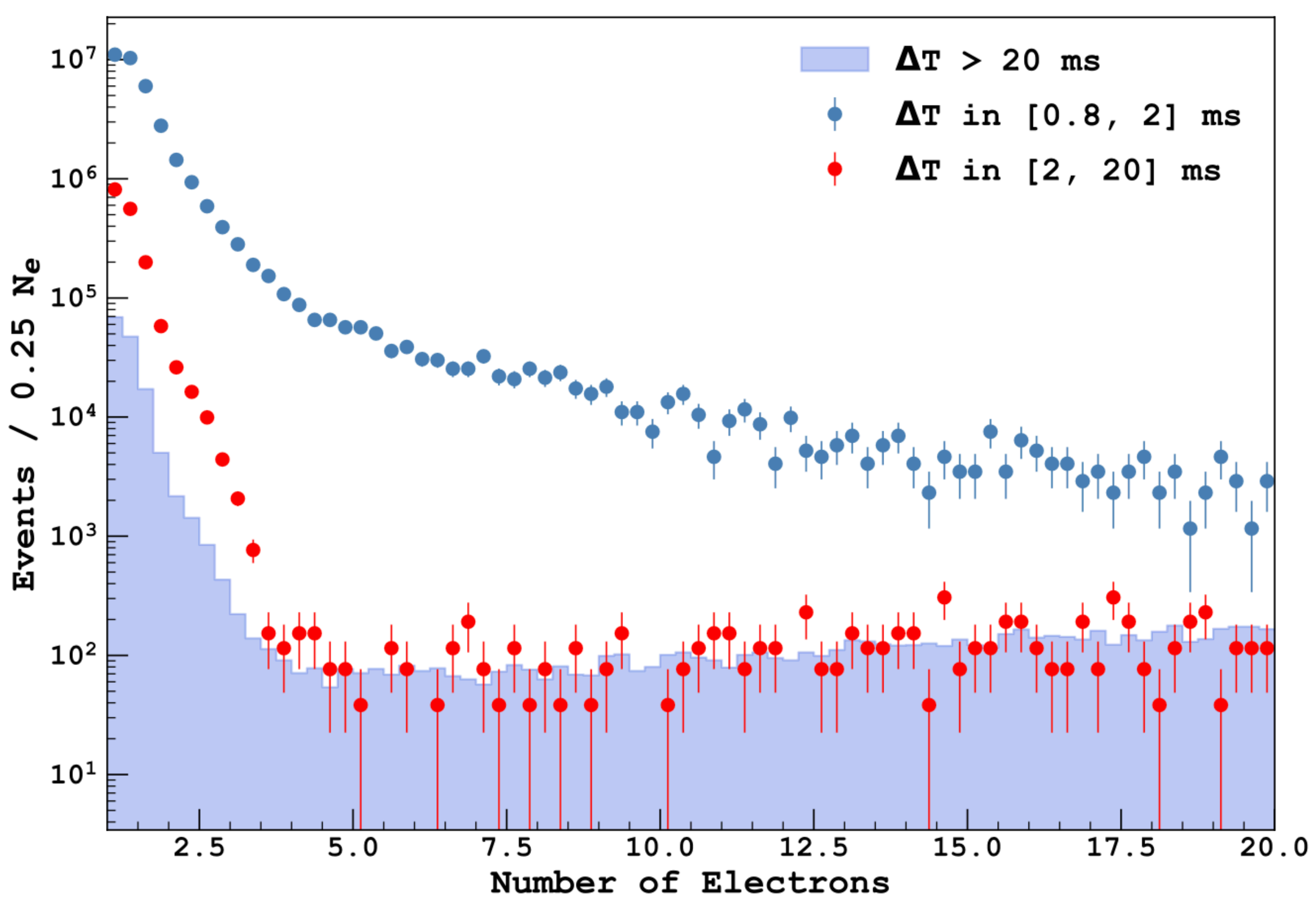


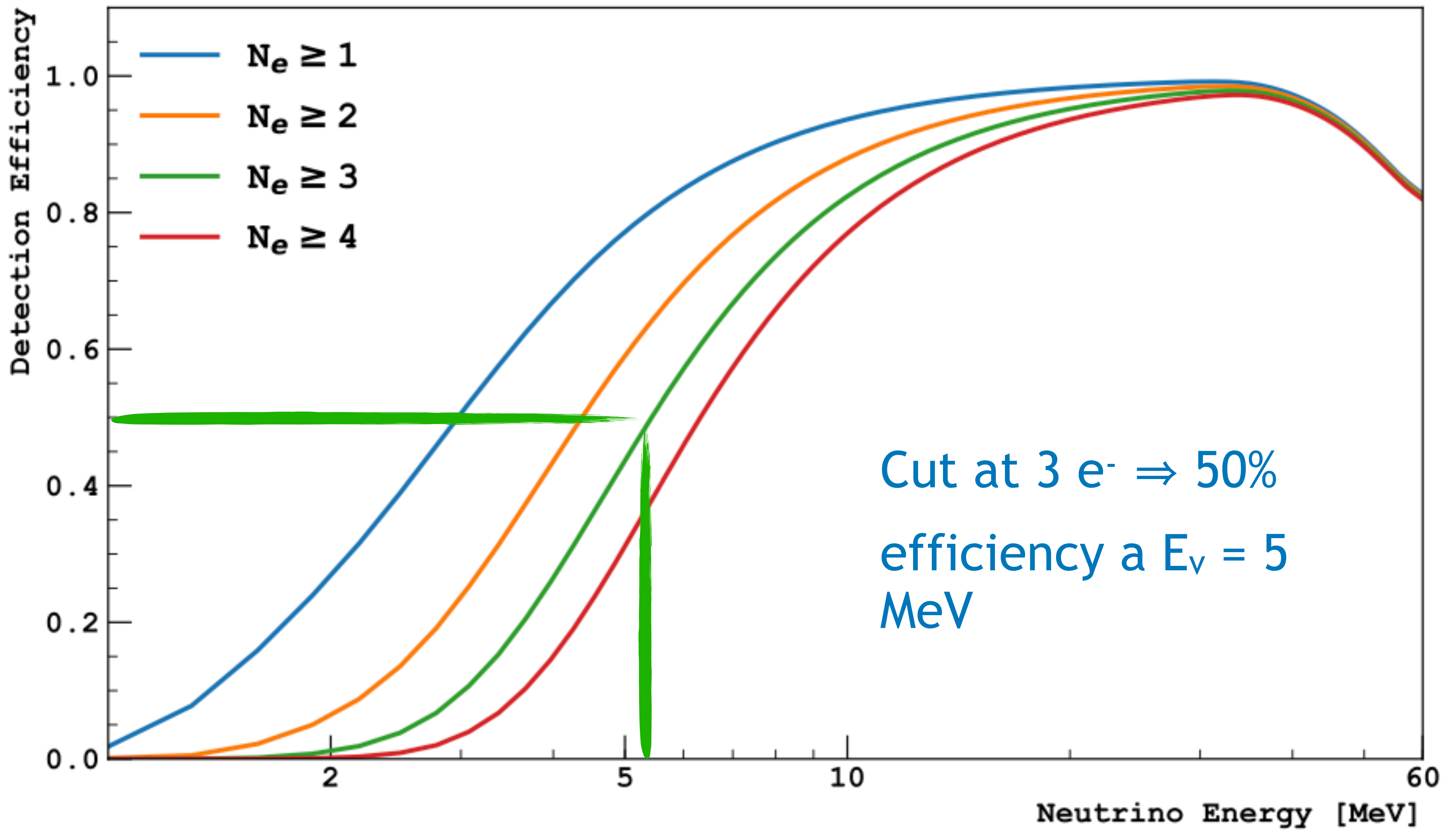
- Neutron thermalisation in acrylic
- Thermal neutron capture on Gd
- TPC and IV detection of gamma ray cascade
- Radioactivity assay satisfactory
- **~90% tagging efficiency** from simulation

$Gd(MAA)_3$ doped acrylic sheet
(5 cm thick)

Spurious Electrons and Analysis Threshold

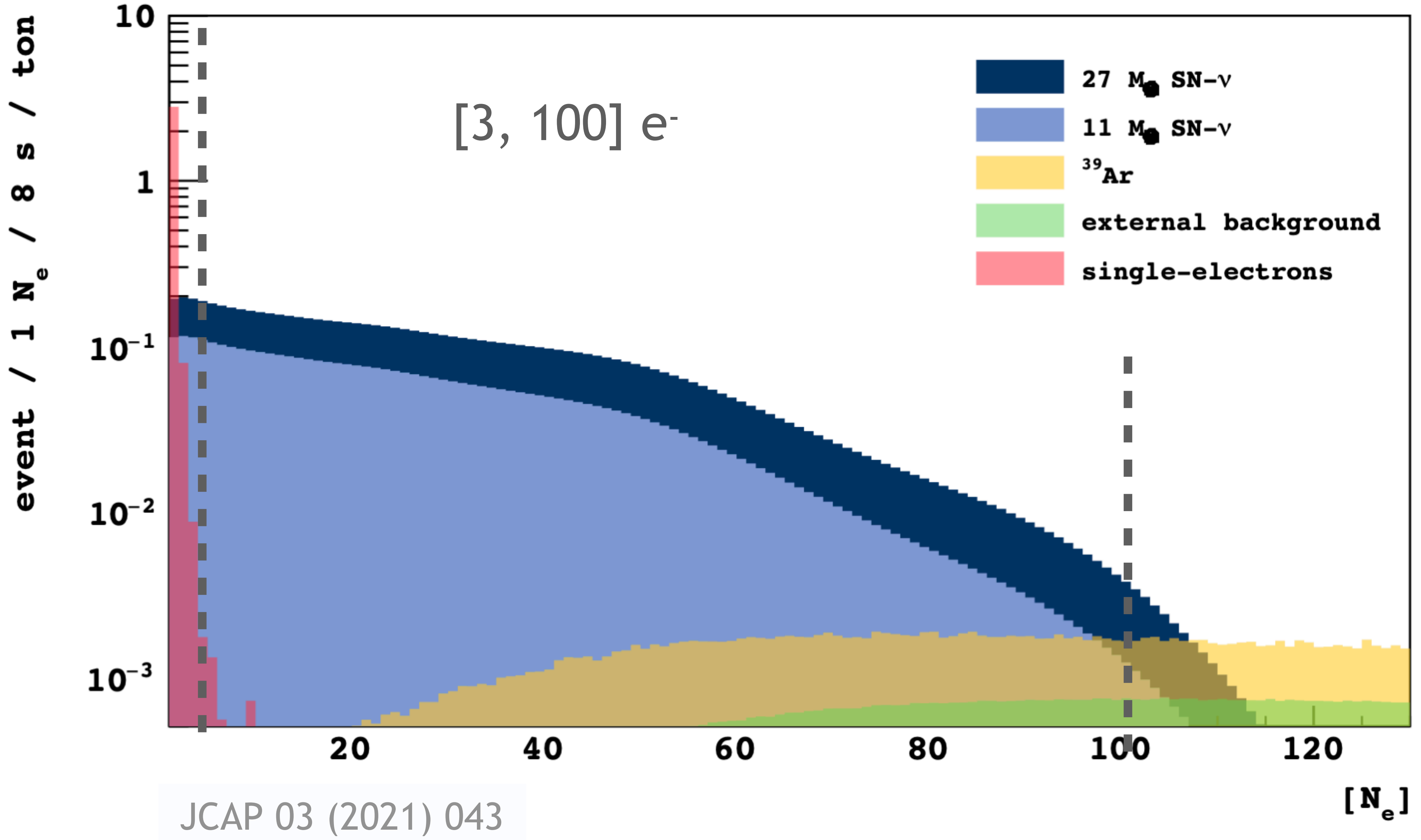
Spurious Electrons





- **Excess** of events observed in DS-50 with E < 4 e- mostly **correlated in time** with preceding events
- Likely due to ionization **electrons captured by impurities** and re-emitted with a certain delay
- A **cut at 3 e-** is applied for the results shown in these slides. Increasing the **cut at 4 e-** does not significantly impact the results

SN @ 10 kpc, Ne in [3, 100] e-	DarkSide-20k
11-$M_\odot$ SN-νs	181.4
27-$M_\odot$ SN-νs	336.5
^{39}Ar	4.3
external background	1.8
single-electrons	0.7



JCAP 03 (2021) 043

Internal background

- ^{39}Ar at 0.7 mBq / kg (as in DS-50)
- 35 Bq in the active mass / 0.5 Bq in [3, 100] e-

External backgrounds

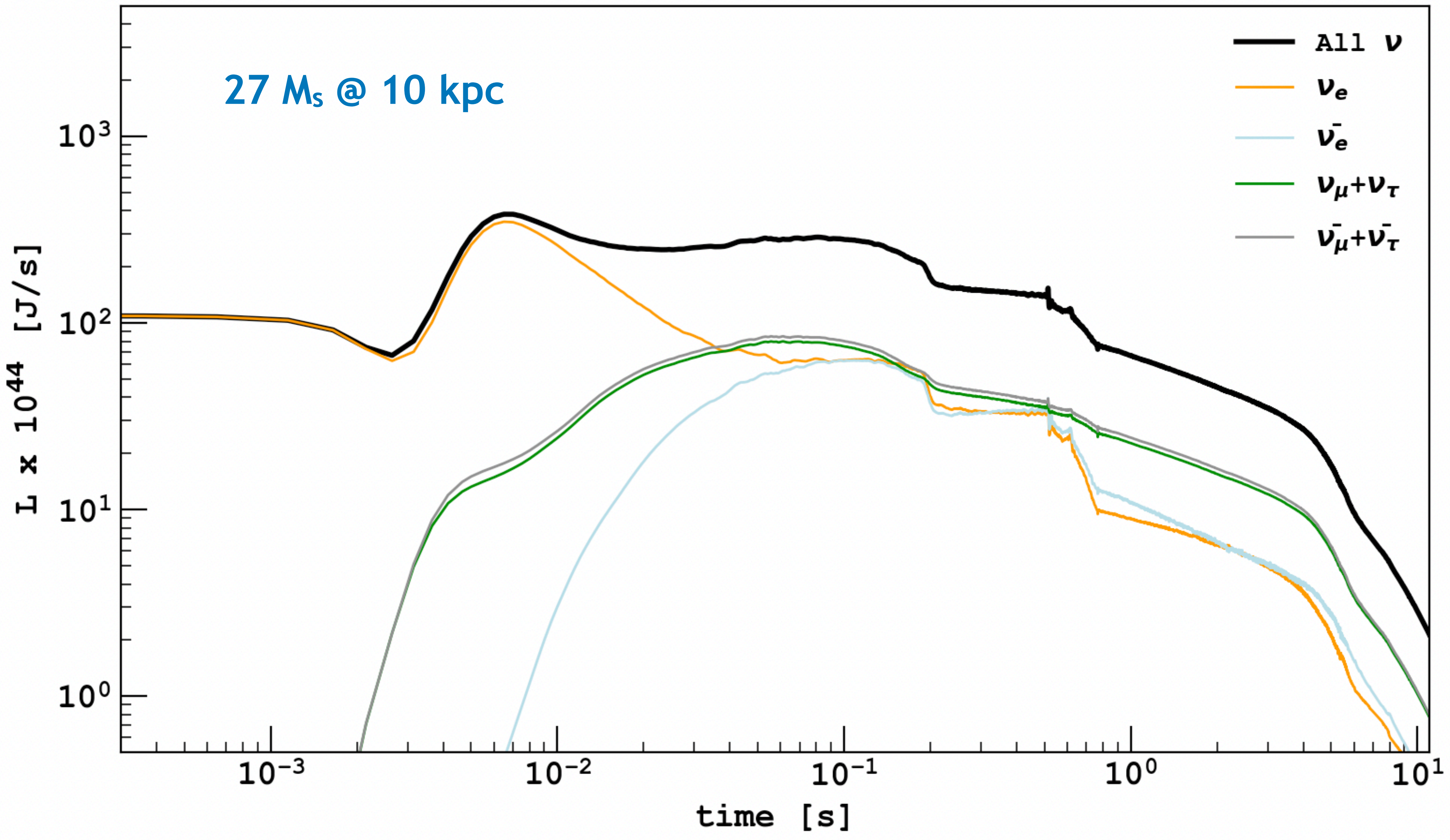
- ^{238}U, ^{235}U, ^{232}Th, ^{137}Cs, ^{53}Mn, ^{40}K, ^{60}Co from early (<2020) material screening measurements
- 75 Bq in the active mass / 0.3 Bq in [3, 100] e-

Almost a factor 2 less external background from recent measurements, material selection, and detector optimization

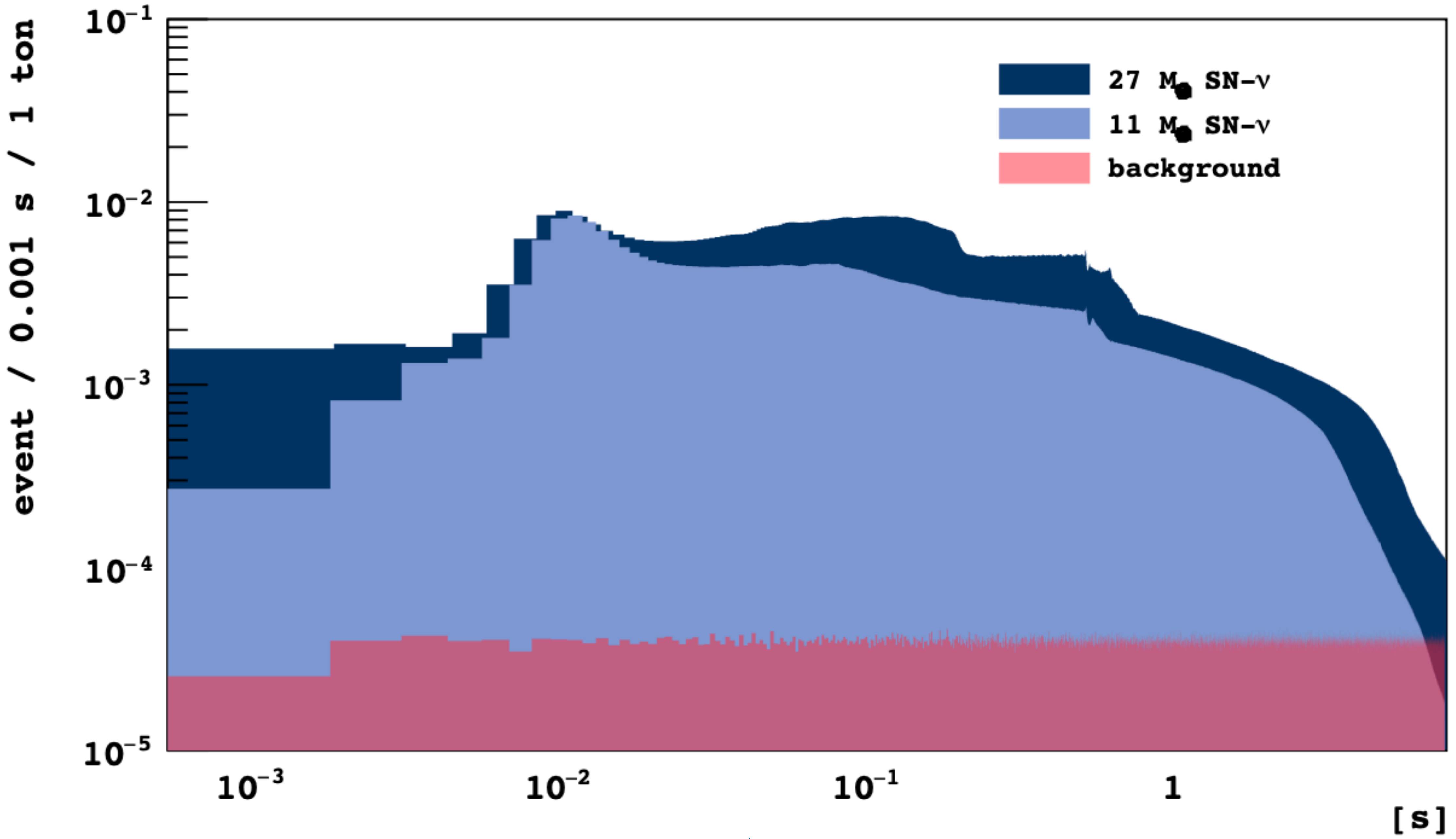
From 2.7 / ton / 10 s in DS50 to 0.16 / ton / 10 s in DS20k (without fiducialization)

SN-ν Time Evolution

SN luminosity



Expected Event Rate Time Evolution in DS20k



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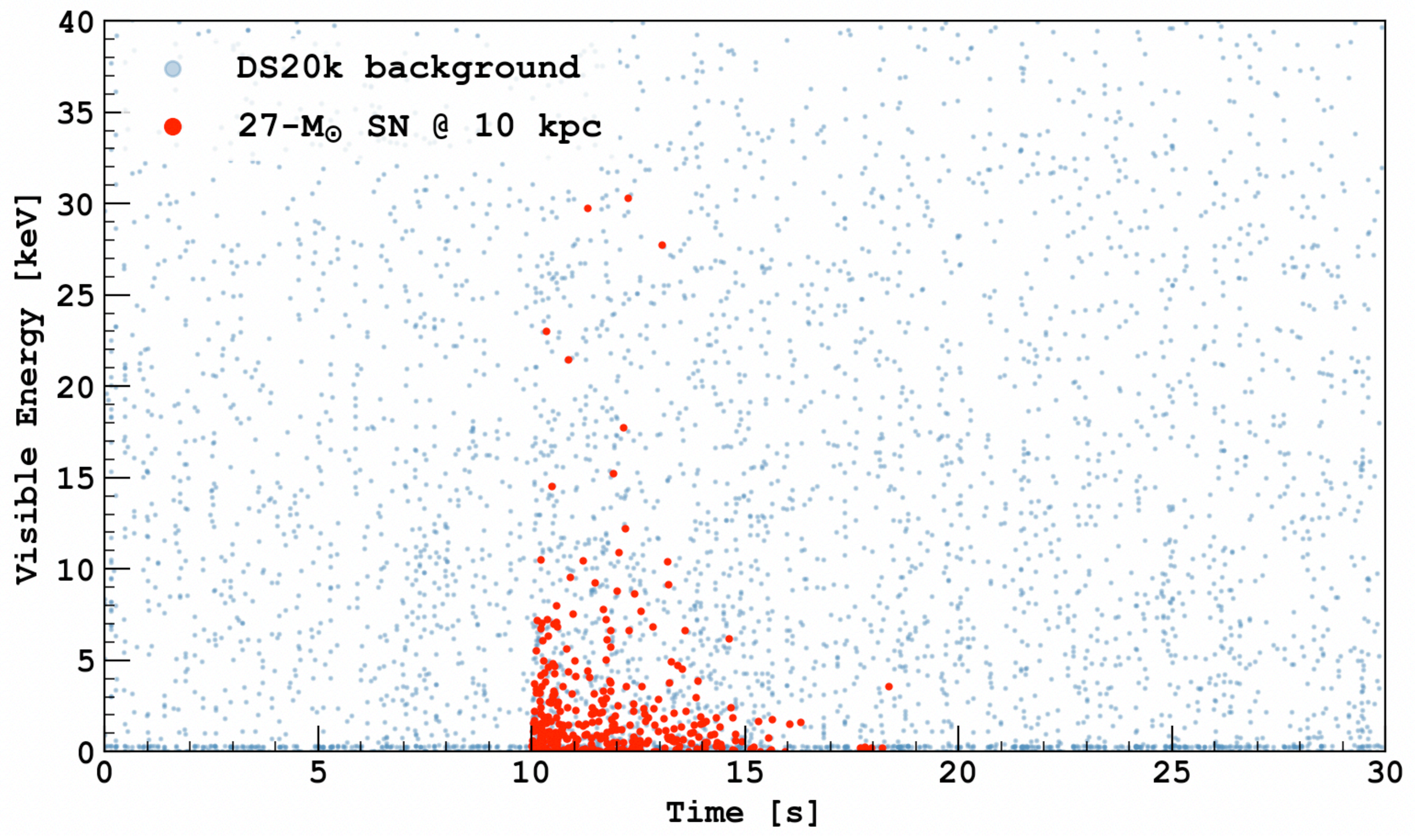
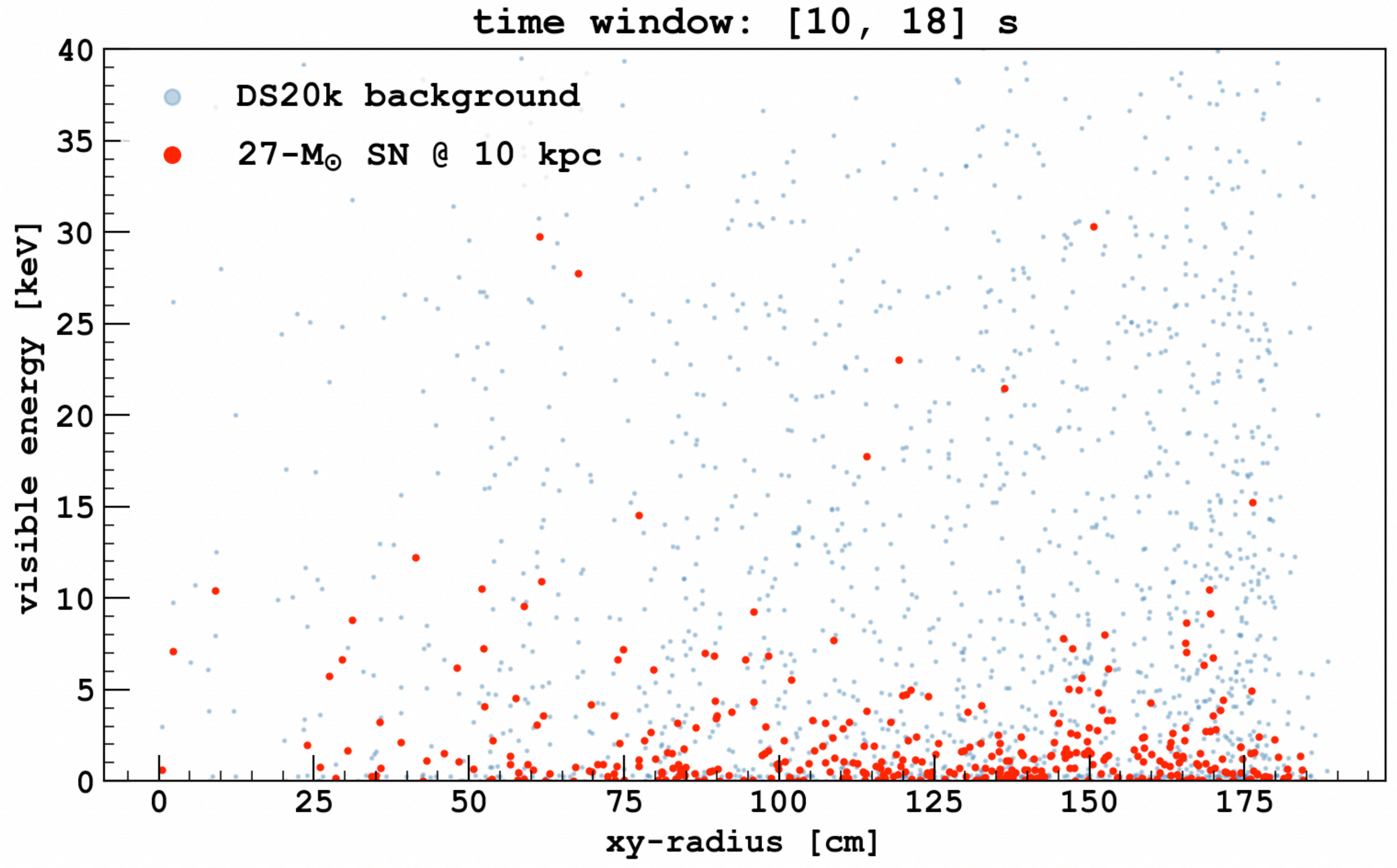
Event time resolution is dominated by the electron drift time (maximum drift time ~ 3.5 ms)

Spatial and time distributions of energy deposits from radioactive background and SN neutrinos





Trigger-less DAQ

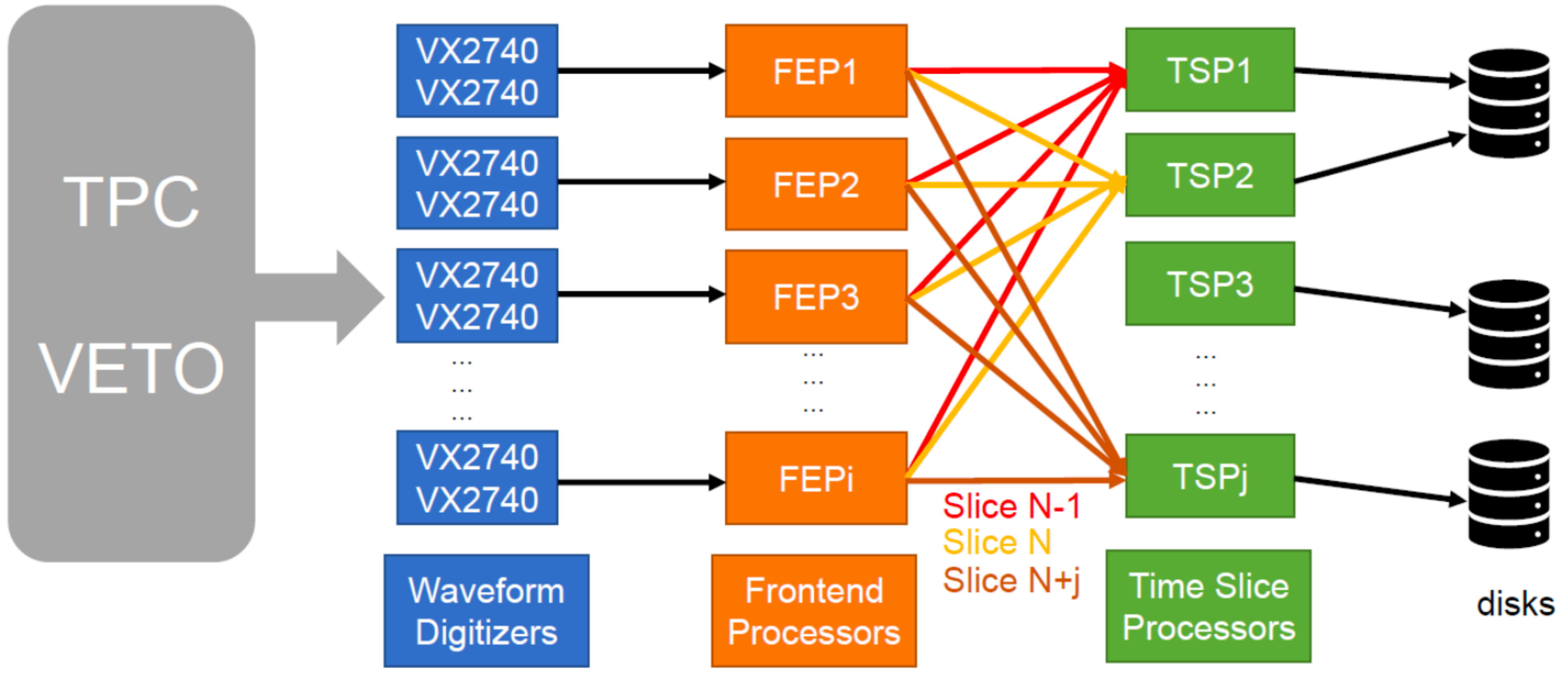
1) Identification of waveform (WF) segments containing a signal

2) WF segments from 64 digitizers are transferred to a Front-End Processor

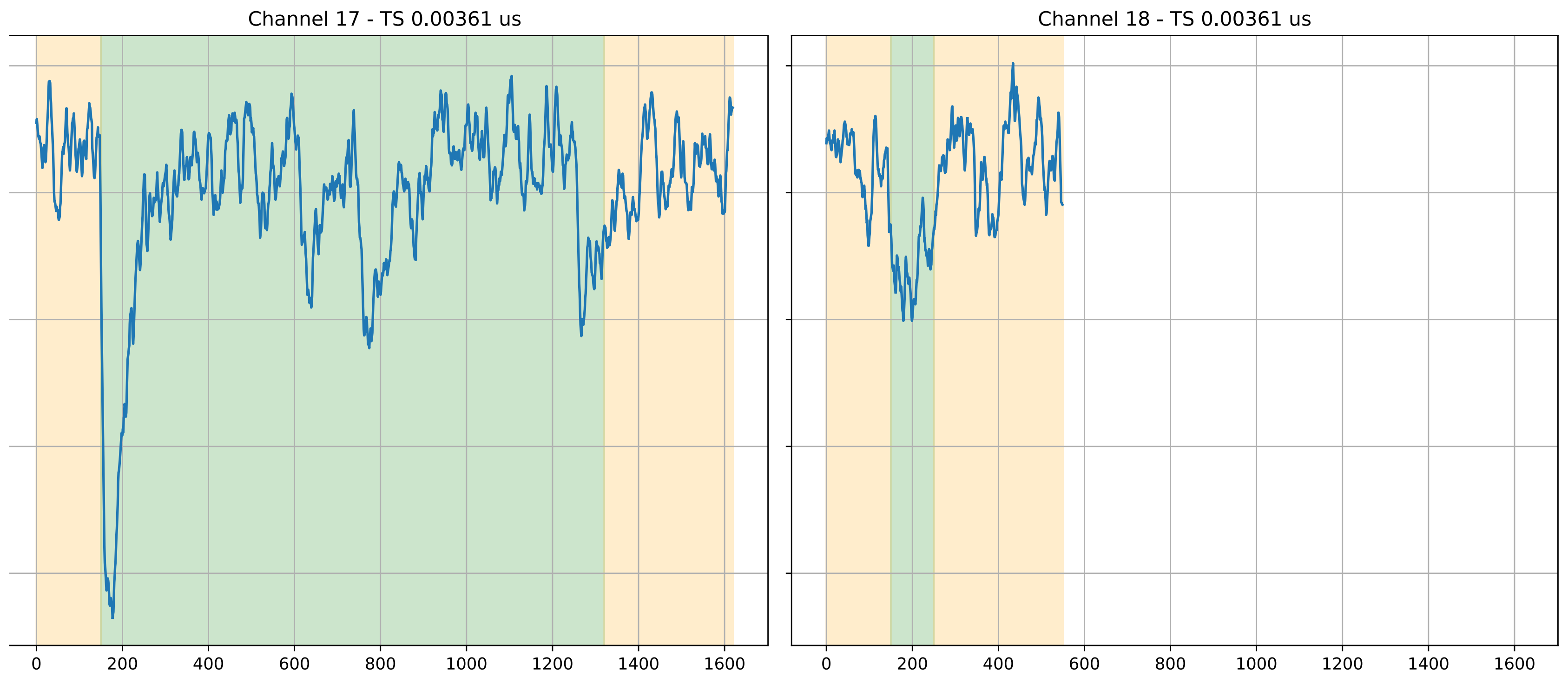
3) WF segments are filtered

4) Hit finder applied to each filtered WF segment

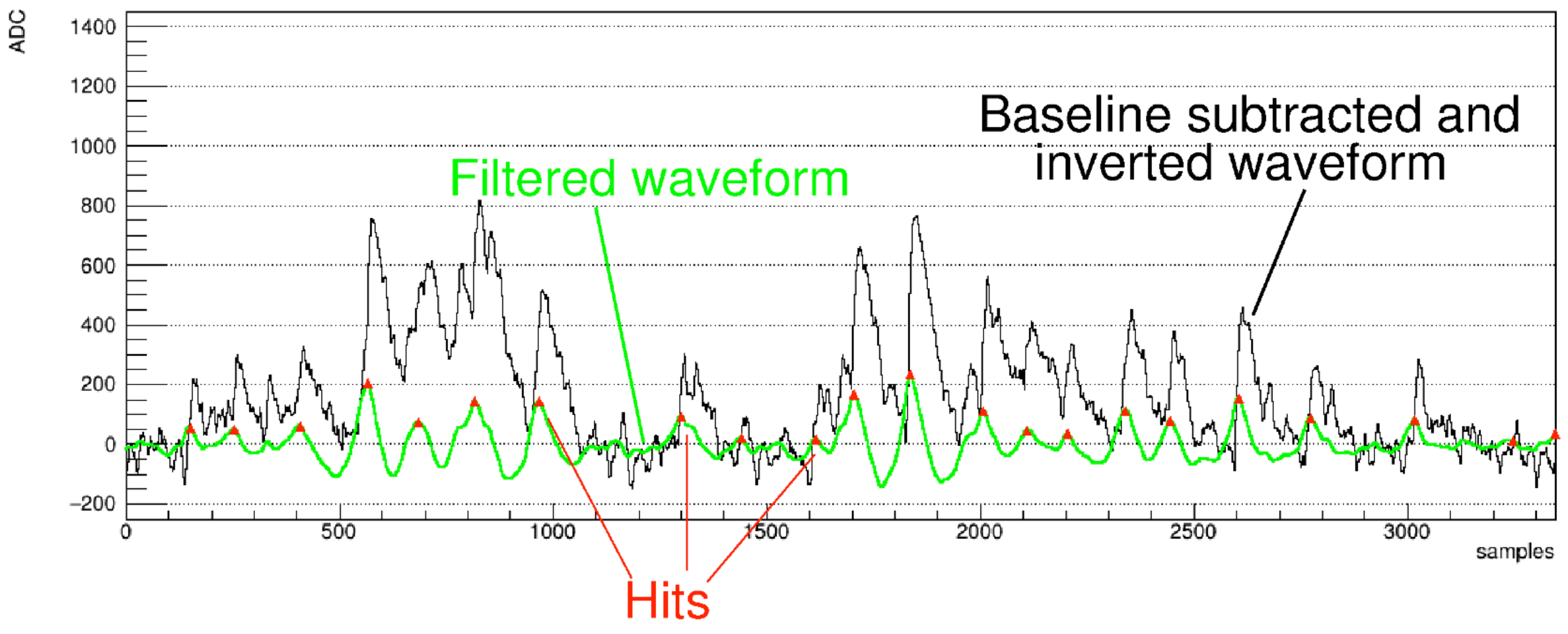
5) Hits are transferred to Time Slice Processors, processed to derive additional variables, and stored



Identification of WF segments

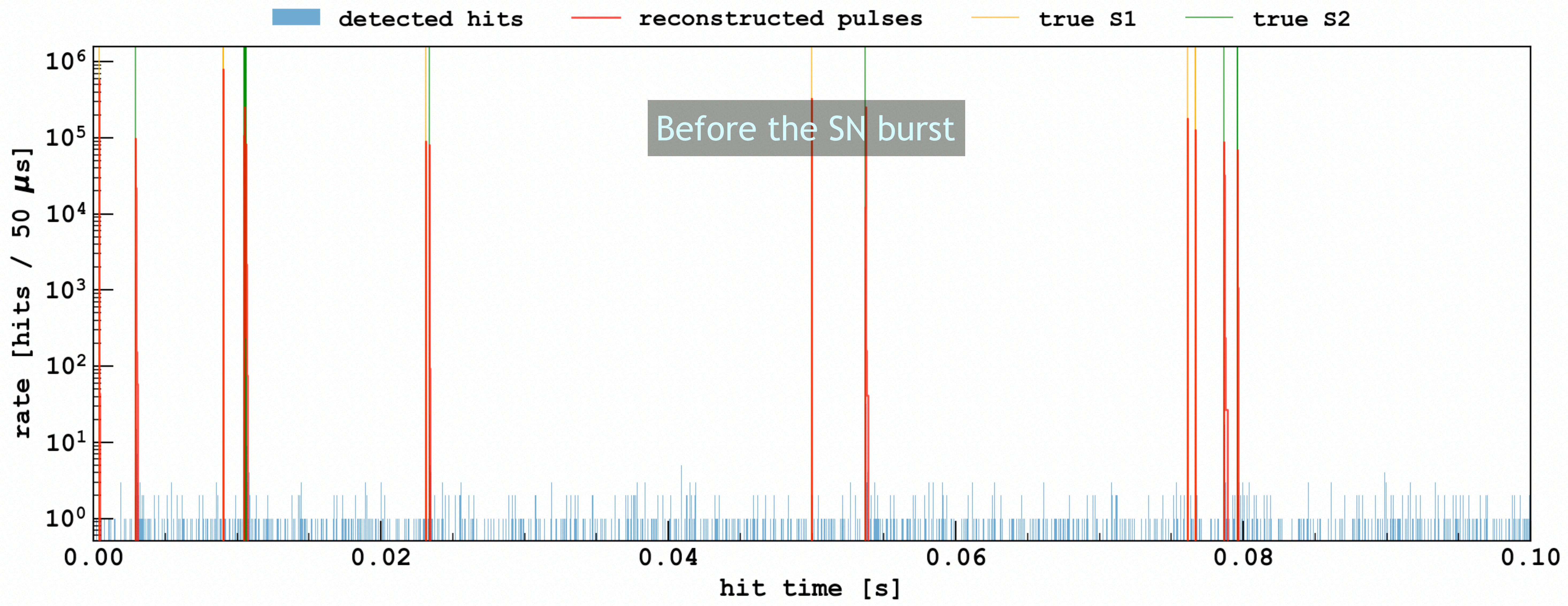


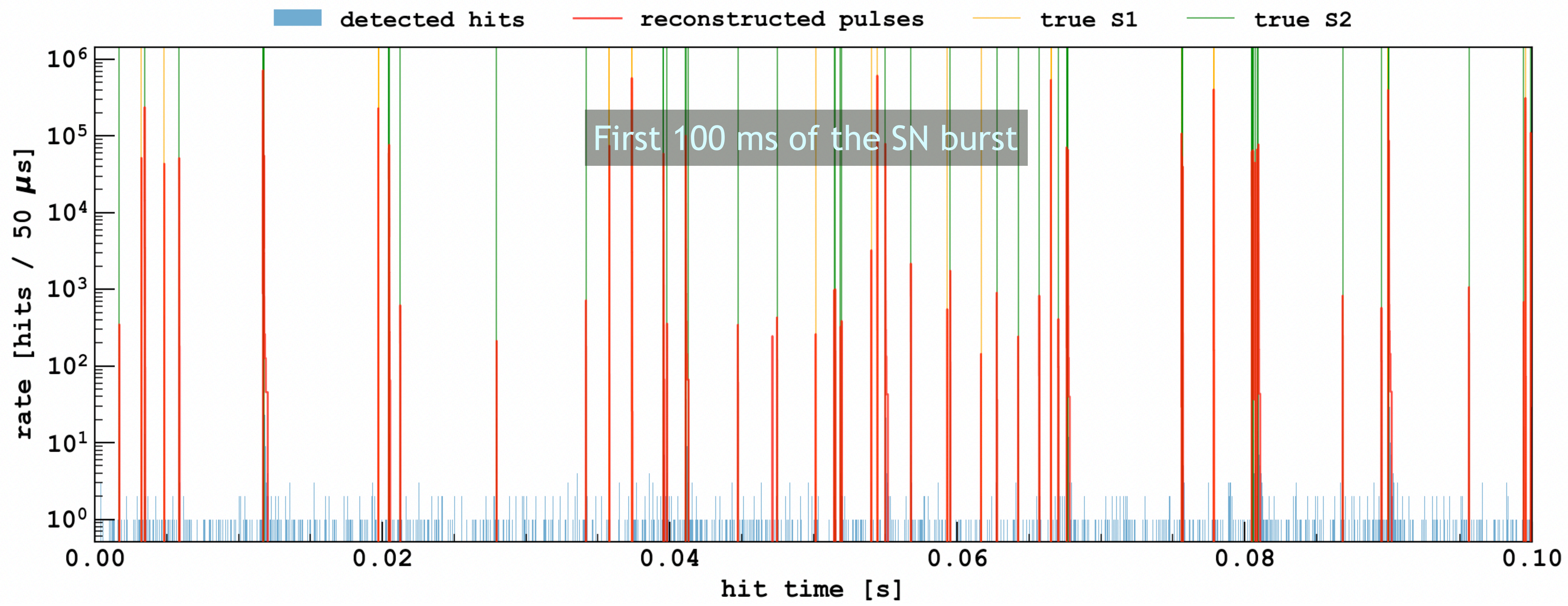
Filtering at hit finder



Reconstructed Pulses

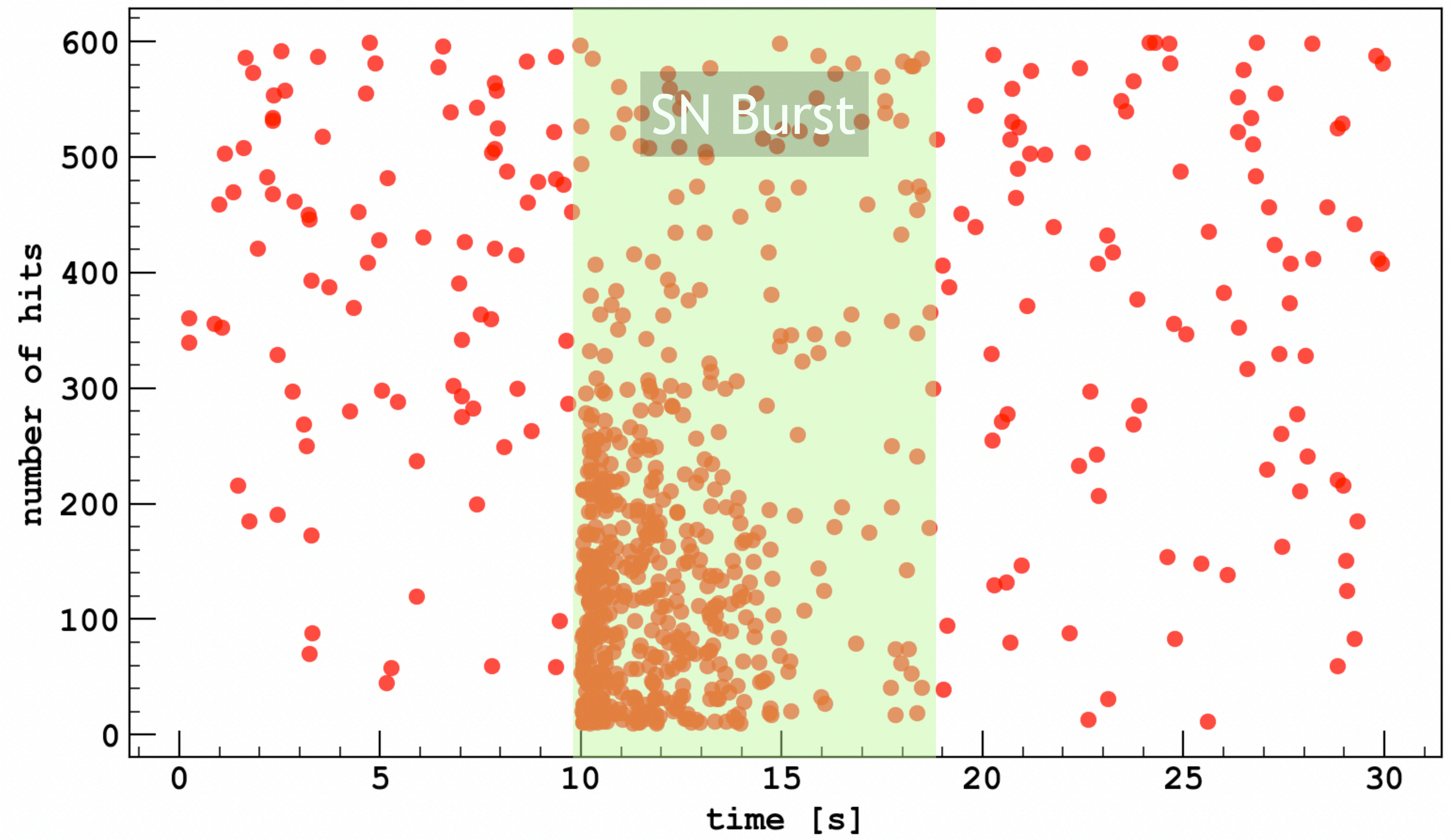
- Full radioactive background simulation from most recent screening material campaign
- Waveform simulation with realistic electronic noise
- Simulation of SiPM dark counts, after-pulses, and cross-talks
- Full DAQ emulation
- S1/S2 pulse finder / reconstruction (98% identification efficiency at 1 ionization electron)





Impact on the DAQ

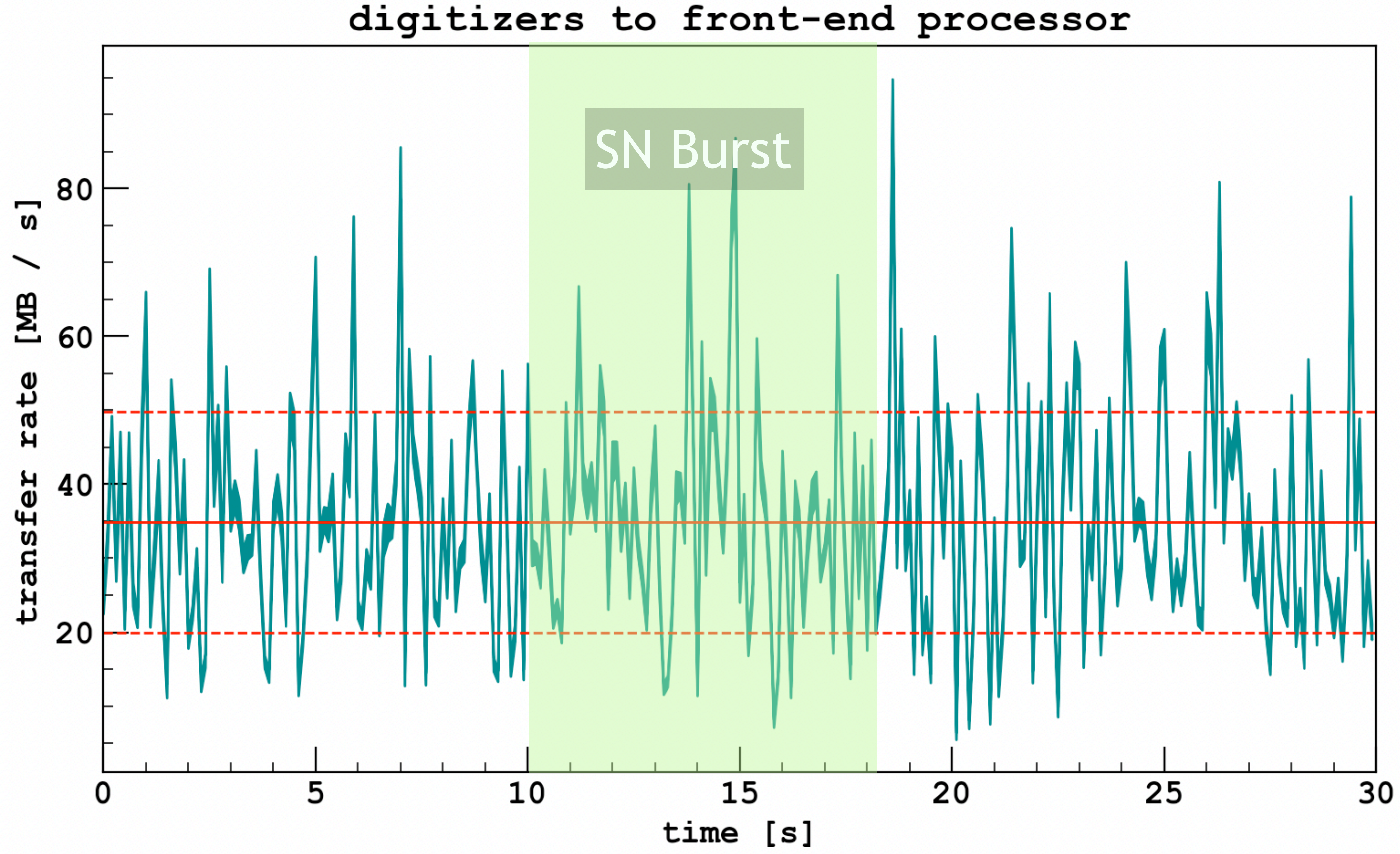
Reconstructed pulses



- Significant increase in the number of S2 pulses with a low number of hits
- Potential signature for the SNEWS alarm

Expected data transfer rate

from WF digitizer board (64 channels) to front-end CPUs



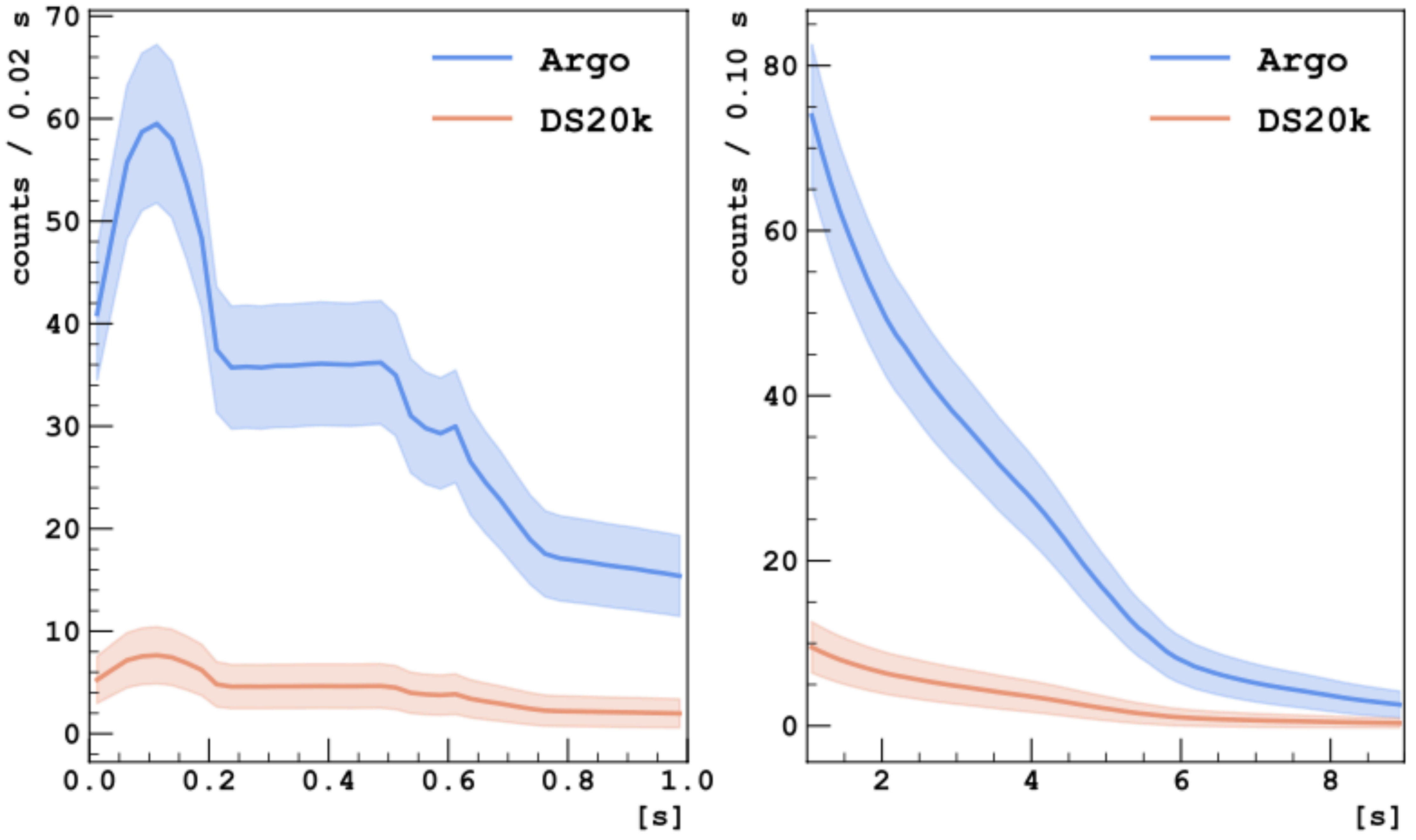
- Non-significant increase in data flow
- DAQ not impacted

ARGO

The GADMC is considering a future single-phase or dual-phase multi-hundred tonne detector after DS-20k likely at SNOLAB

For this work we assume that Argo is a dual-phase TPC with a target mass of 370 t.

	11-M$_\odot$ SN			27-M$_\odot$ SN		
	SN-ν	S/B		SN-ν	S/B	
SN phase	[1/t]	DS20k	ARGO	[1/t]	DS20k	ARGO
Burst	0.08	212	231	0.09	243	264
Accretion	1.83	105	114	3.30	190	207
Cooling	1.96	16	17	3.76	30	33



Reconstructed Mean and Total Energies

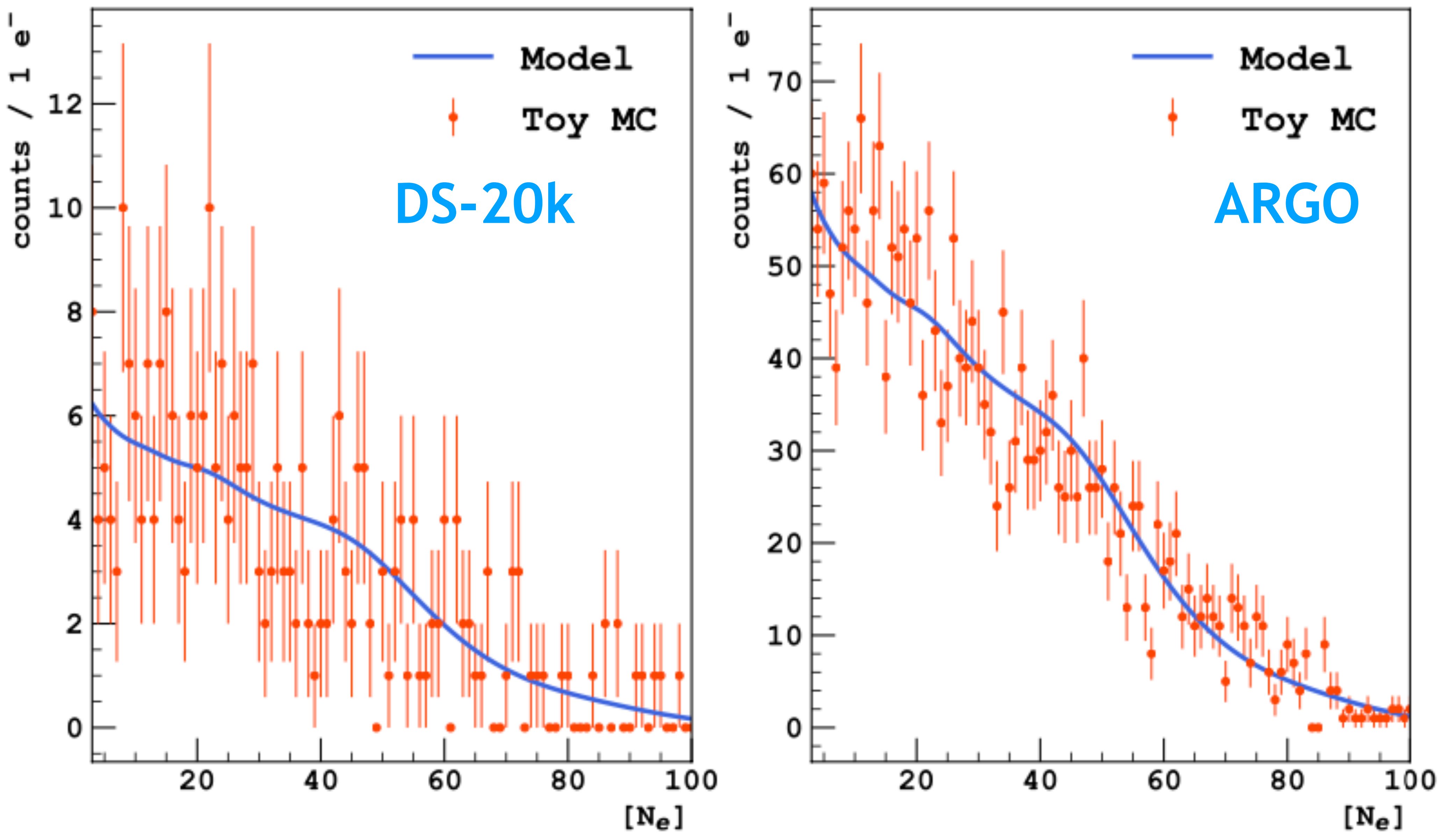
Model = f(E$_\nu$) ⊗ CEvNS(E$_\nu$, E$_{nr}$) ⊗ g(E$_{nr}$, N$_e$)

approximated spectrum — cross section — detector response

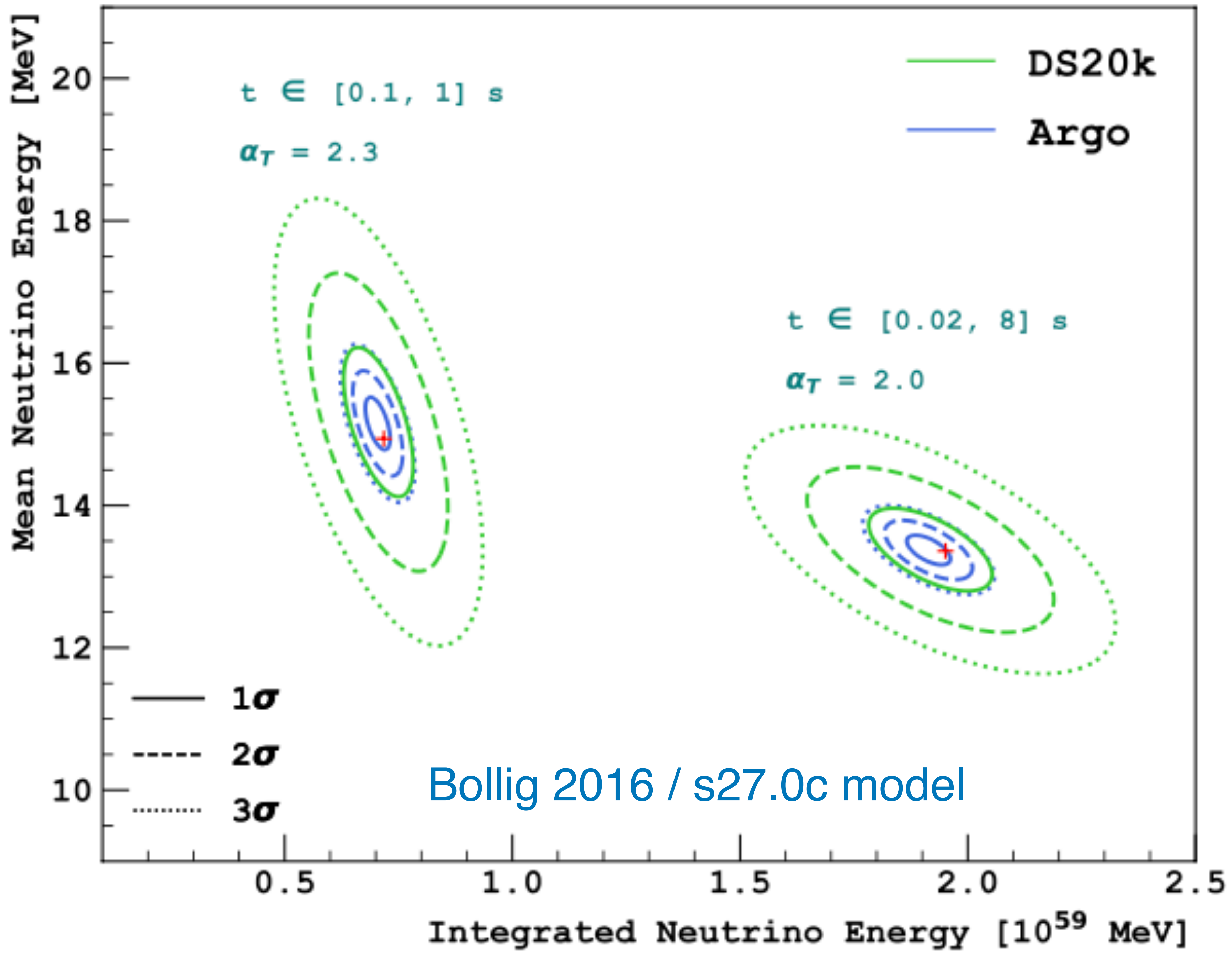
$$f(E_\nu) = \frac{\xi}{4\pi D^2}\frac{(\alpha_T+1)^{\alpha_T+1}E_\nu{}^{\alpha_T}e^{-\frac{E_\nu(\alpha_T+1)}{\langle E_\nu\rangle}}}{\langle E_\nu\rangle^{\alpha_T+1}\Gamma(\alpha_T+1)}$$

D = SN distance
ξ = total neutrino energy
⟨E$_\nu$⟩ = mean neutrino energy
α_T = pinching parameter

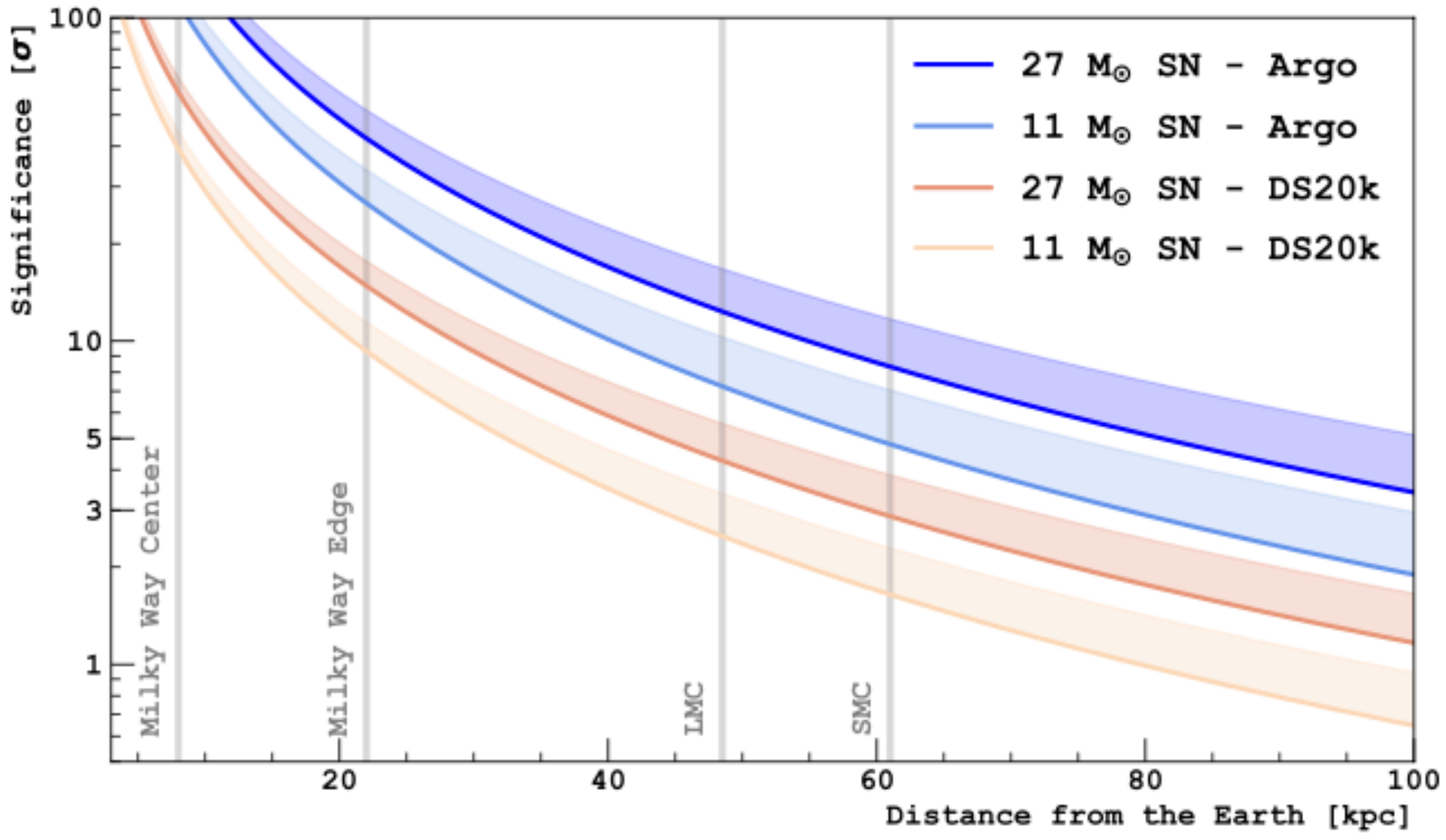
M. T. Keil, G. G. Raffelt and H.-T. Janka, Astrophys. J. 590 (2003) 971



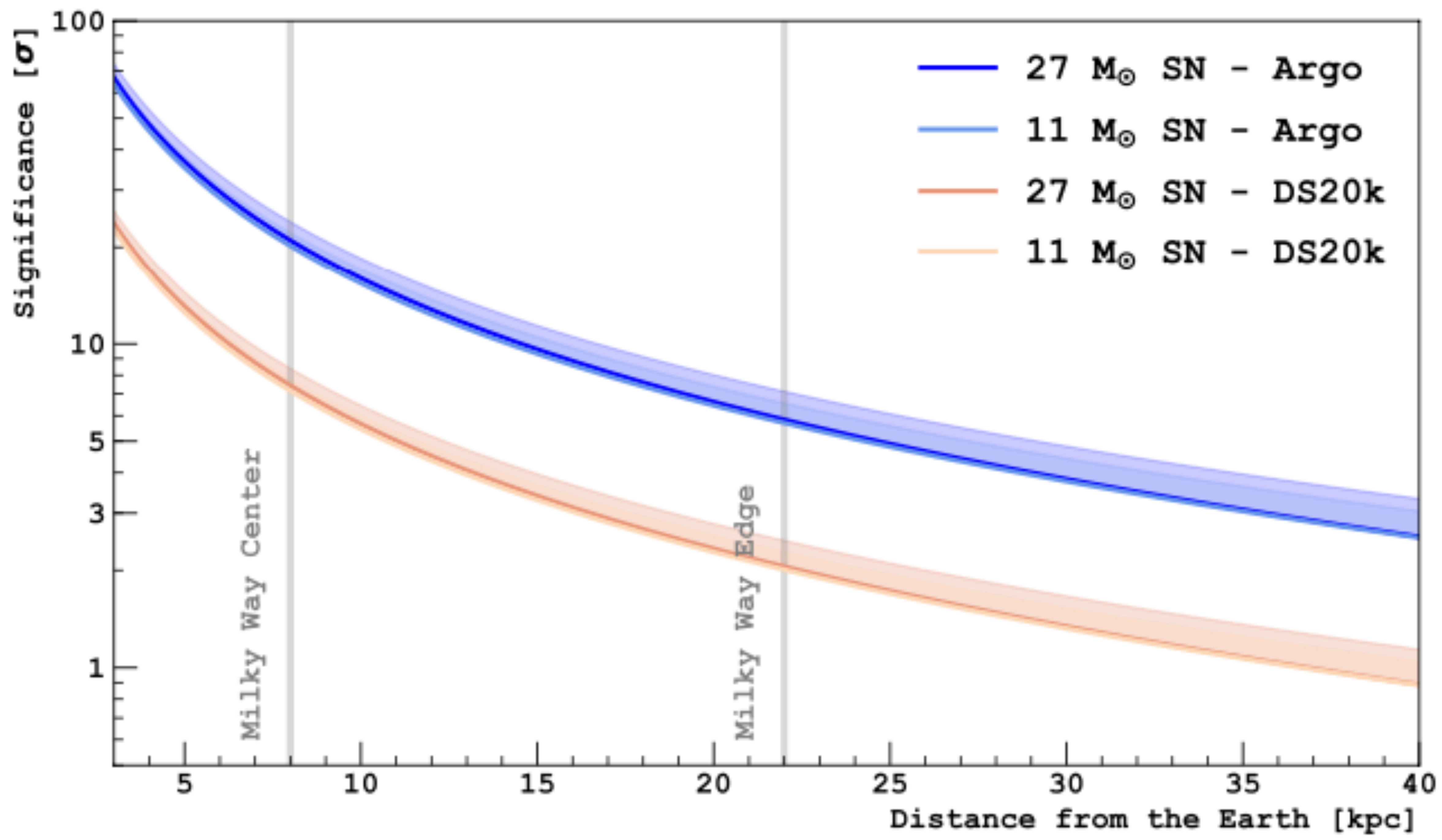
Fitted Toy MC Samples



Core-collapse SN discovery potential



SN neutronization burst discovery potential



Conclusions

DarkSide-20k and SN neutrino physics

- Discovery potential up to the Small Magellanic Cloud
- Sensitivity to neutronization burst up to the Milky Way edge
- Preliminary studies confirm that signals from a 27 M_{sun} SN at 10 kpc can be handled by the foreseen trigger-less DarkSide-20k DAQ system without special data processing.
- Expected ~50 CC ν_e events in the outer veto from 27 M_{sun} SN data at 10 kpc in the veto (evaluation of the trigger threshold ongoing)
- Ongoing exploration on low-energy pulse number-based warning system for SNEWS