How We Hunt for Rare Processes: Overview of the XENONnT Analysis Workflow

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On behalf of the XENON collaboration

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GDR DUPhy - Lyon

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Context

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Success is a journey, not only a destination

~O(100) Analysts → Data Analysis, Detector Calibration, MC Simulation, Inference, etc…

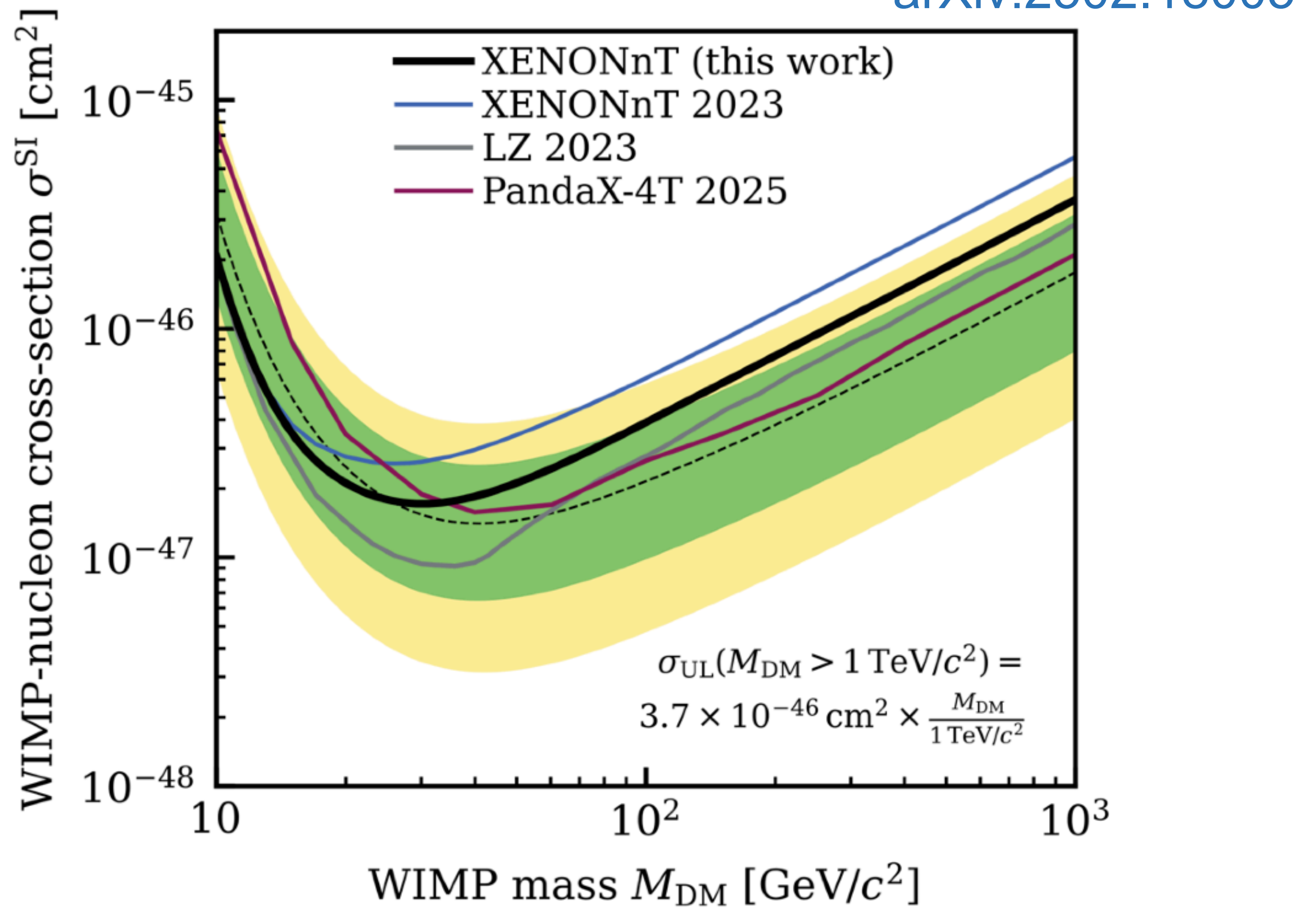
📖 **XENONnT analysis: Signal reconstruction, calibration, and event selection**

📖 **XENONnT WIMP search: Signal and background modeling and statistical inference**

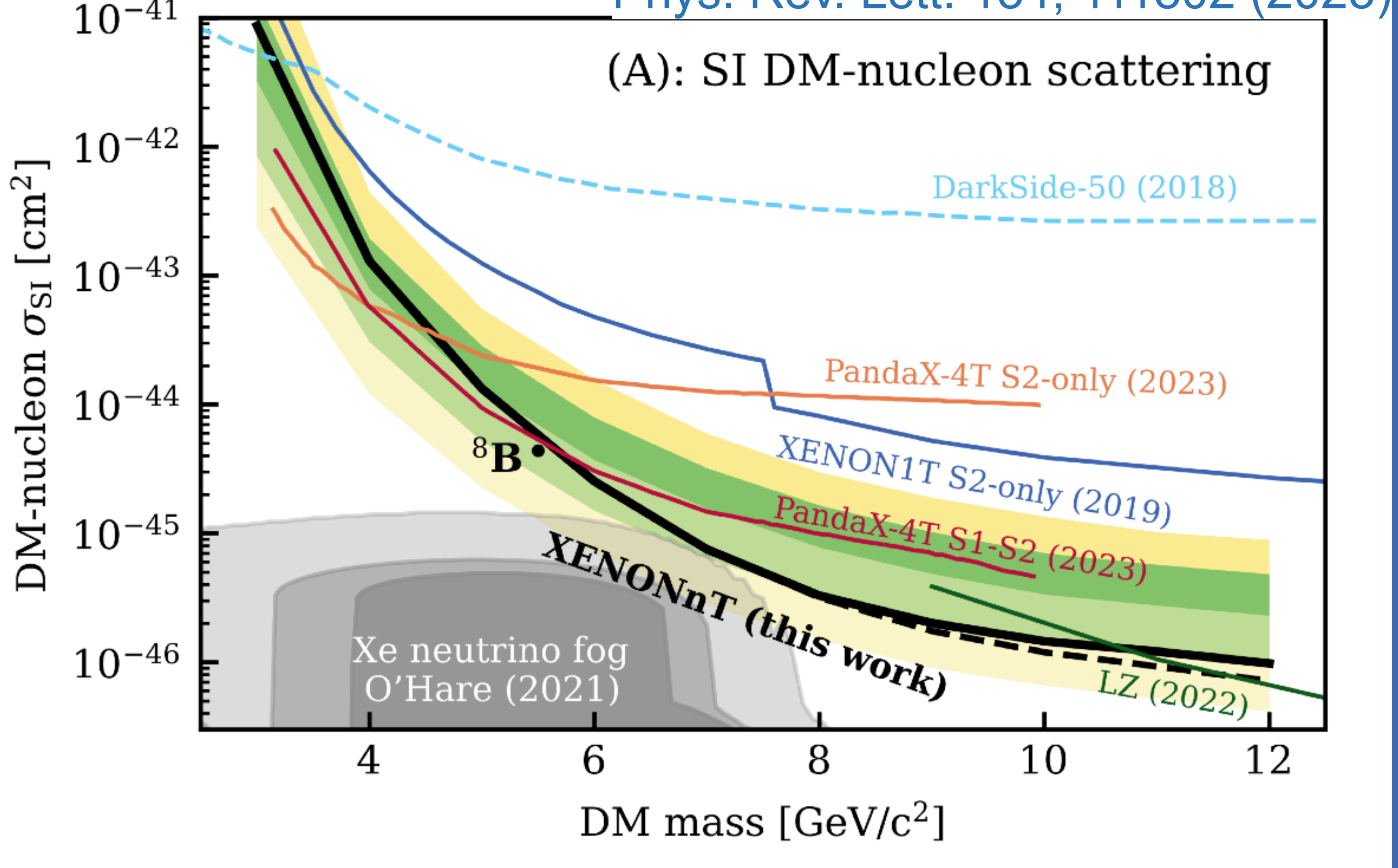
Start

Destination

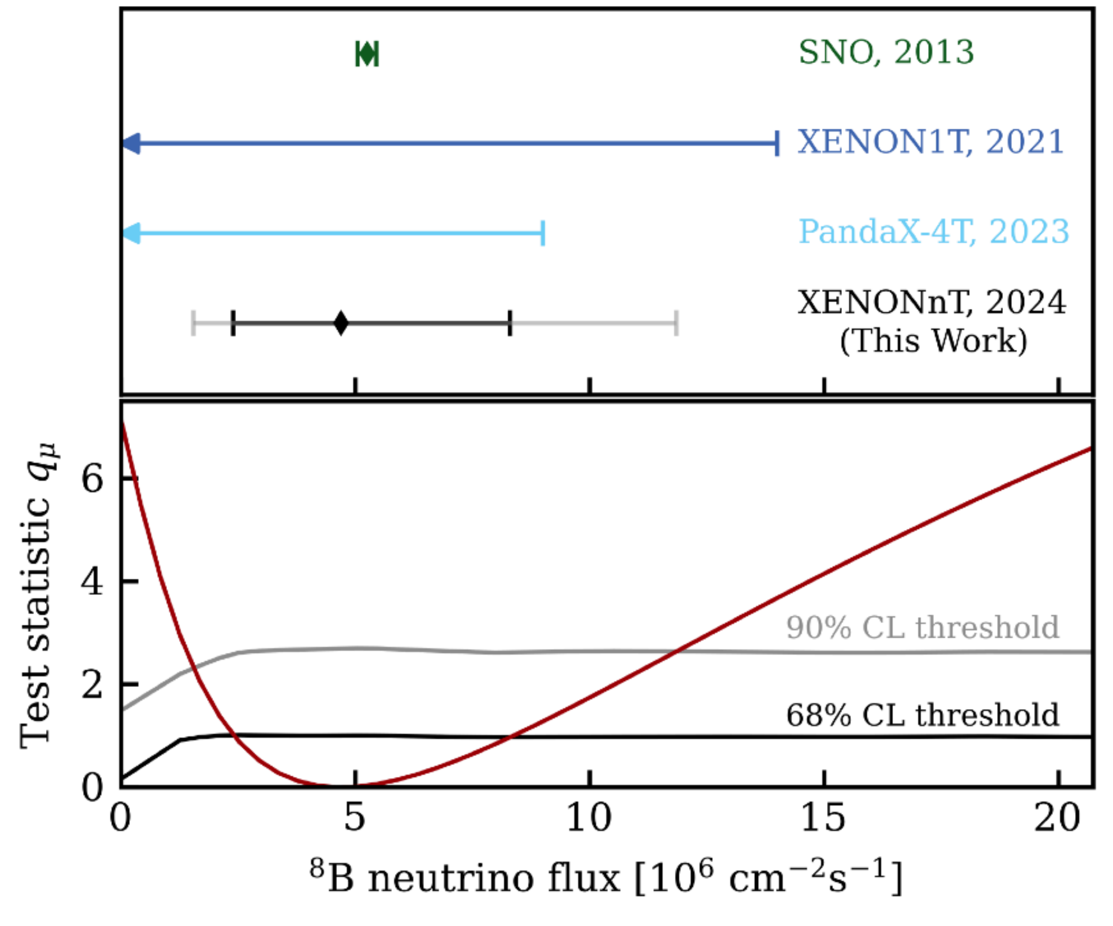
arXiv:2502.18005



Phys. Rev. Lett. 134, 111802 (2025)



Phys. Rev. Lett. 133, 191002 (2024)



XENON TPC in a nutshell

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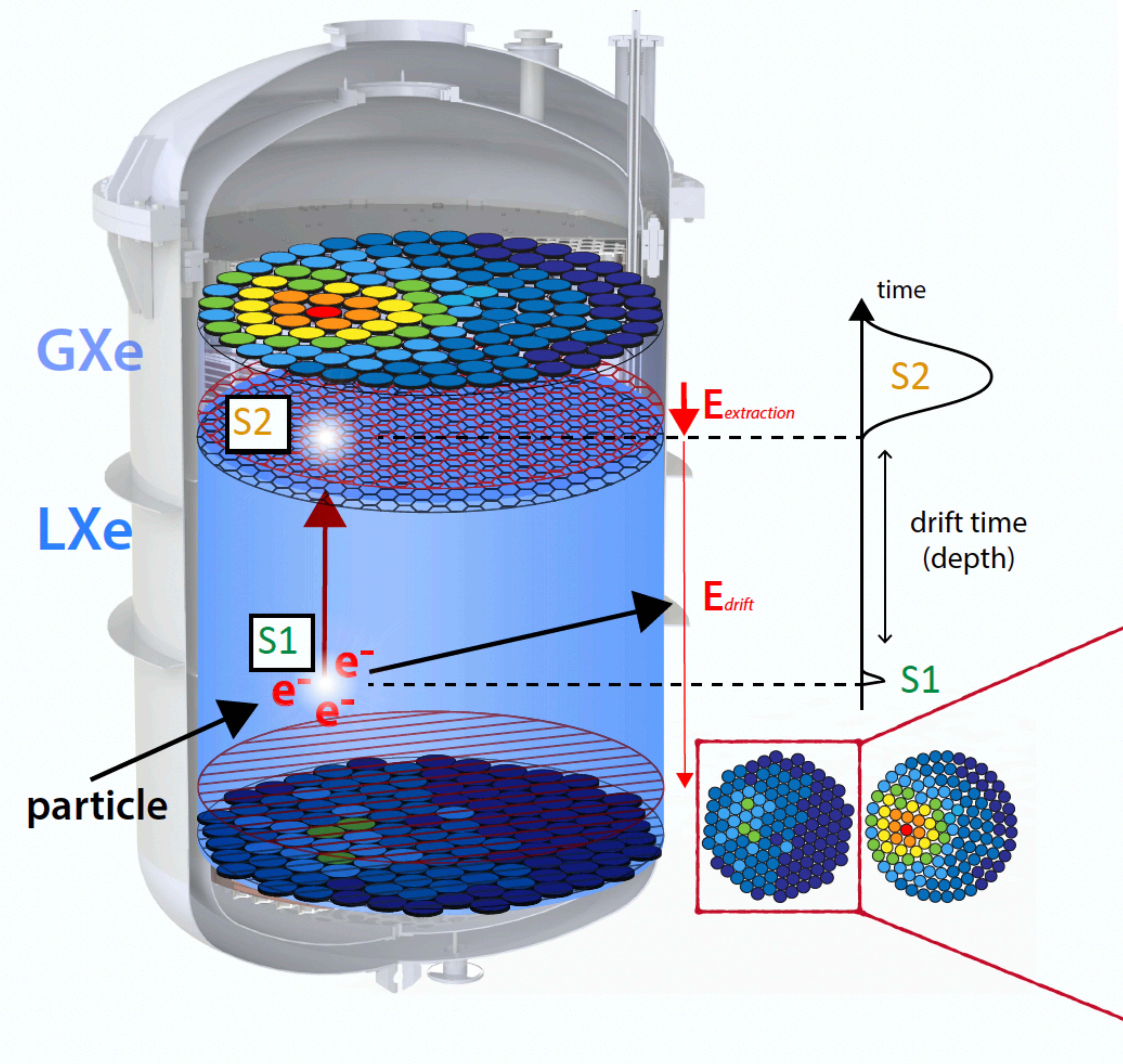

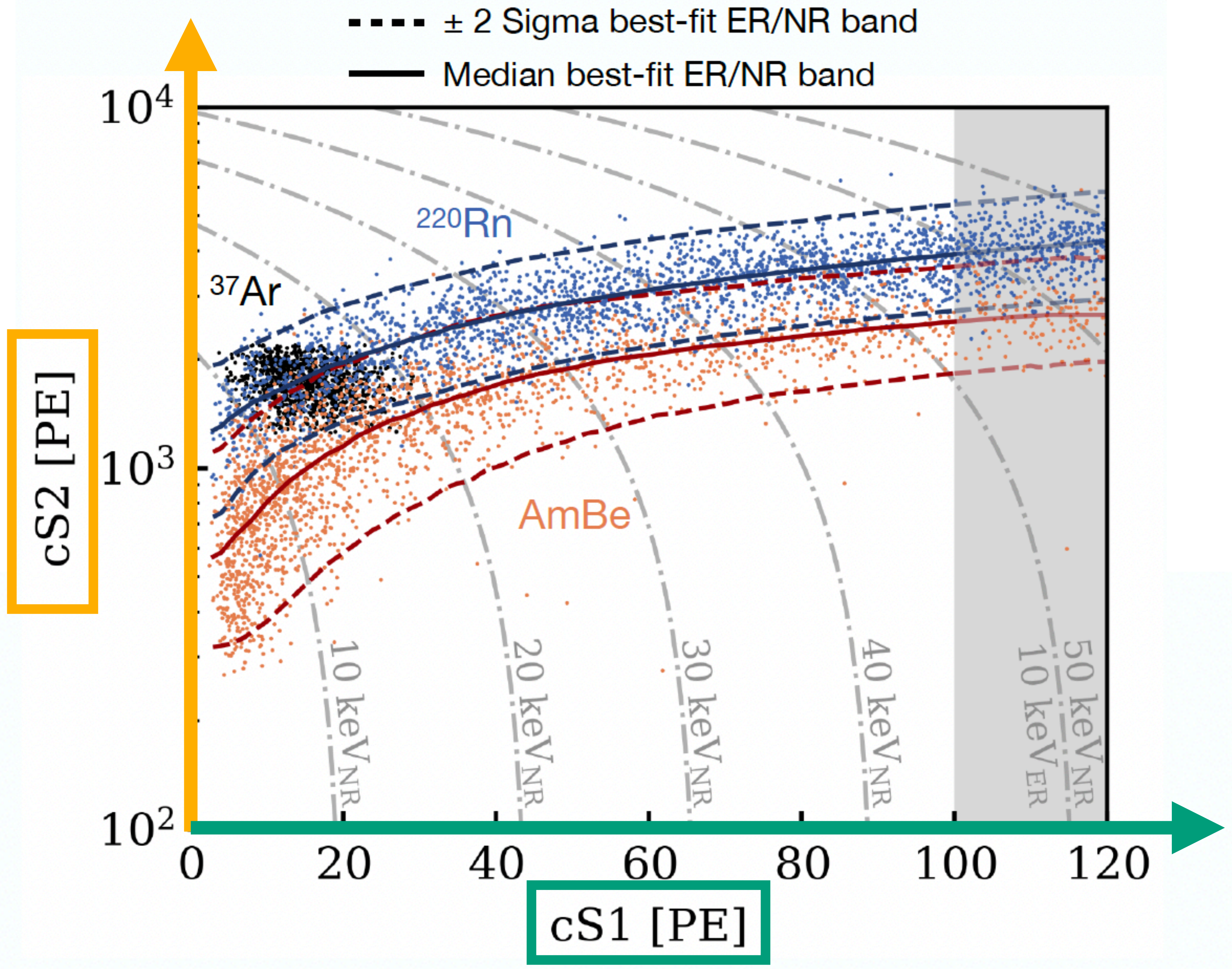

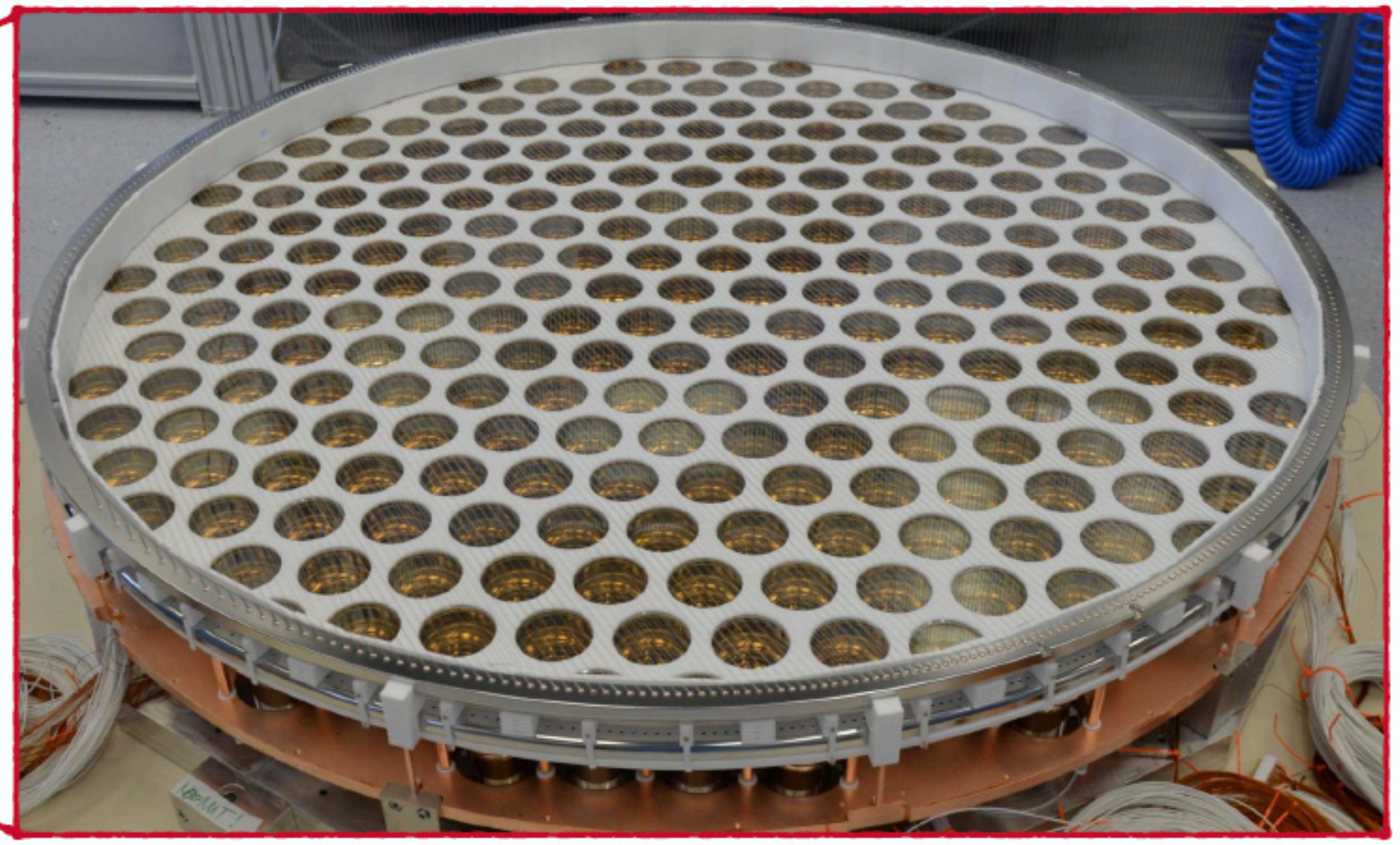

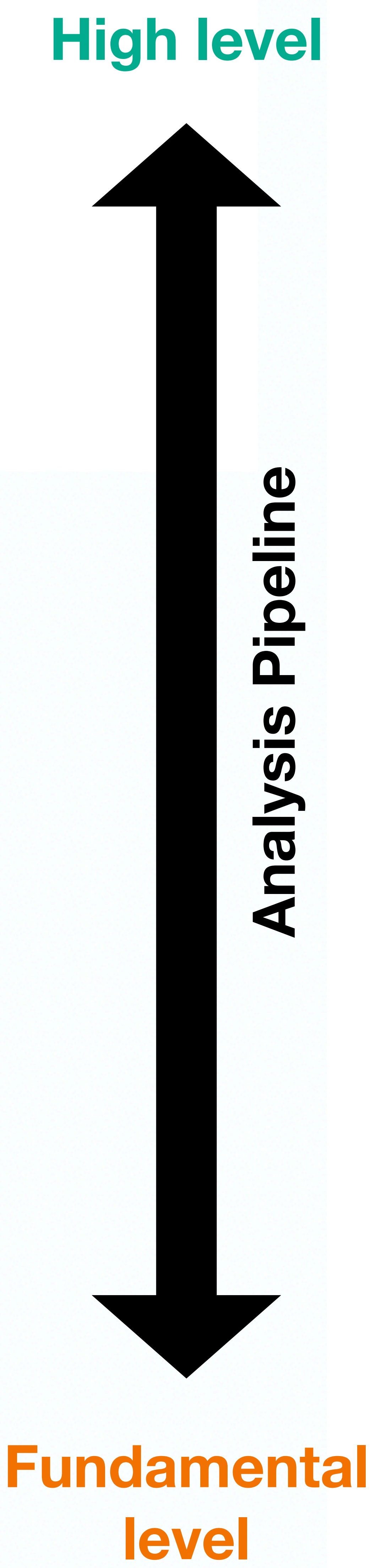

XENON Physics Program

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Primary goal → DM direct detection at low-energy recoil in our xenon target

Lower background level → open new physics channel…

XENON Physics Program

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- Supernova neutrinos

- Solar ^{8}B CEvNS
- Solar pp neutrinos
- Solar axions

Double Weak Decay

- ^{124}Xe 2νECEC capture
- ^{136}Xe $0\nu\beta\beta$ decay
- ^{124}Xe $2/0\nu(EC,\beta^{+})$ decay
- $^{136/4}$Xe $2/0\nu\beta\beta$ decay

WIMPs DM candidate

- Spin-independent
- Spin-dependent
- Sub-GeV

Other DM candidate

- Light DM
- Heavy DM
- Bosonic DM

Primary goal → DM direct detection at low-energy recoil in our xenon target

Lower background level → open new physics channel…

Broad physics program → Flexible/versatile Analysis Pipeline

JINST 18 P07054

Able to handle the new detector and improve physics potential!

XENON1T	XENONnT
TPC: 248 PMTs MV: 84 PMTs	TPC: **494** PMTs **NV: 120 PMTs** MV: 84 PMTs
Triggering software running live to keep only specific events	**Save all data above per-channel digitization threshold and post-pone the event logic at a later stage**

Facilitate the measurement and study of isolated signals that can be a signal or background source for low-energy interaction

XENON Triggerless DAQ

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Facilitate the measurement and study of isolated signals that can be a signal or background source for low-energy interaction

Why?

Energy threshold definition

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Energy Scale:

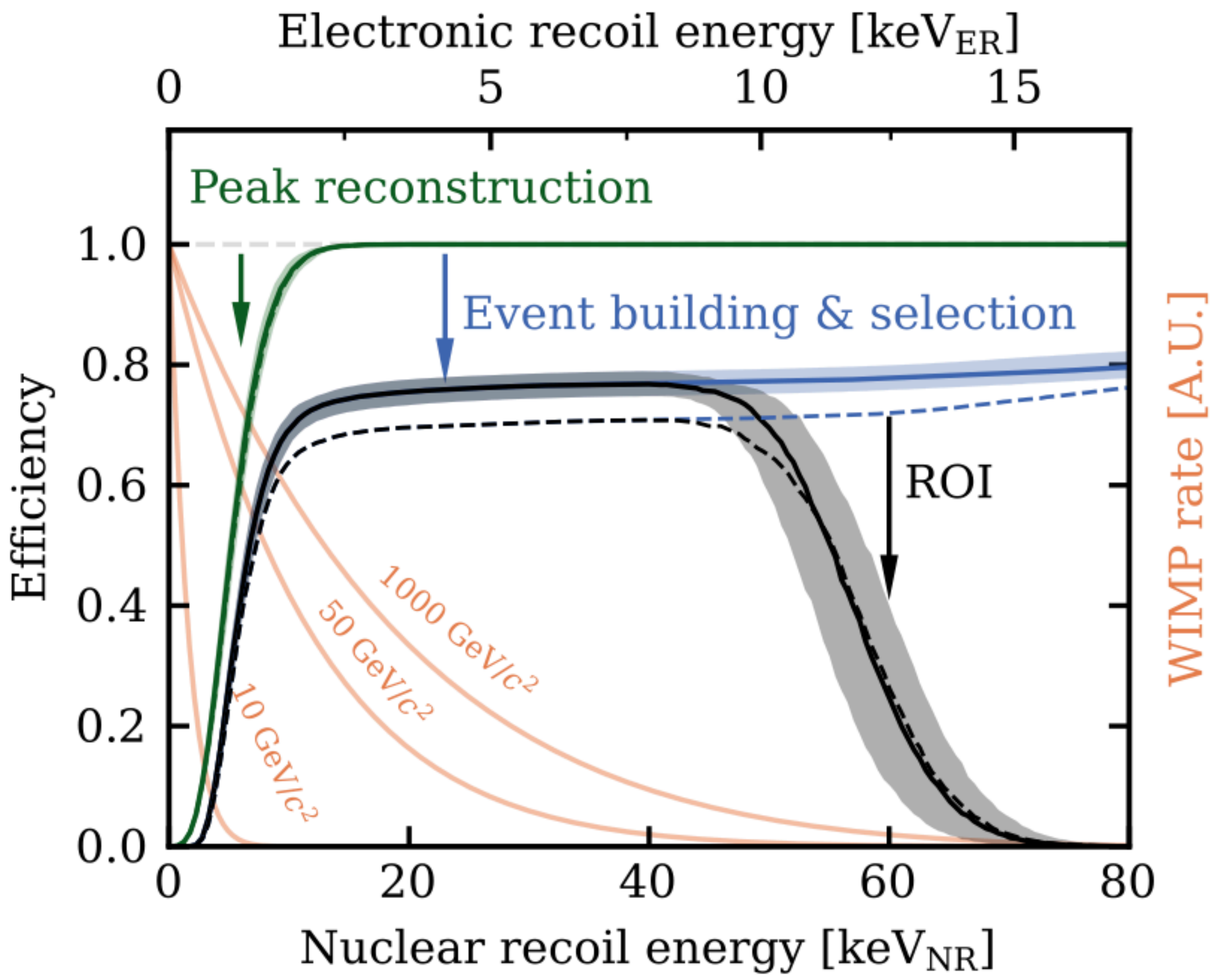
- g1: photon detection efficiency.
- g2: charge amplification factor.

$$E = W \times (n_{ph} + n_e) = W \times \left(\frac{S1}{g1} + \frac{S2}{g2} \right)$$

Energy threshold:

	S1-S2		S2-Only
DM mass	> $\mathcal{O}$(10) GeV	$\mathcal{O}$(1) GeV	< $\mathcal{O}$(1) GeV
S1			
S2	13 e$^-$	8 e$^-$	1 e$^-$
E_{th}*	ER: 0.6 keV NR: 3.8 keV	- NR: 0.5 keV	ER: 13.7 eV -

*>10% efficiency



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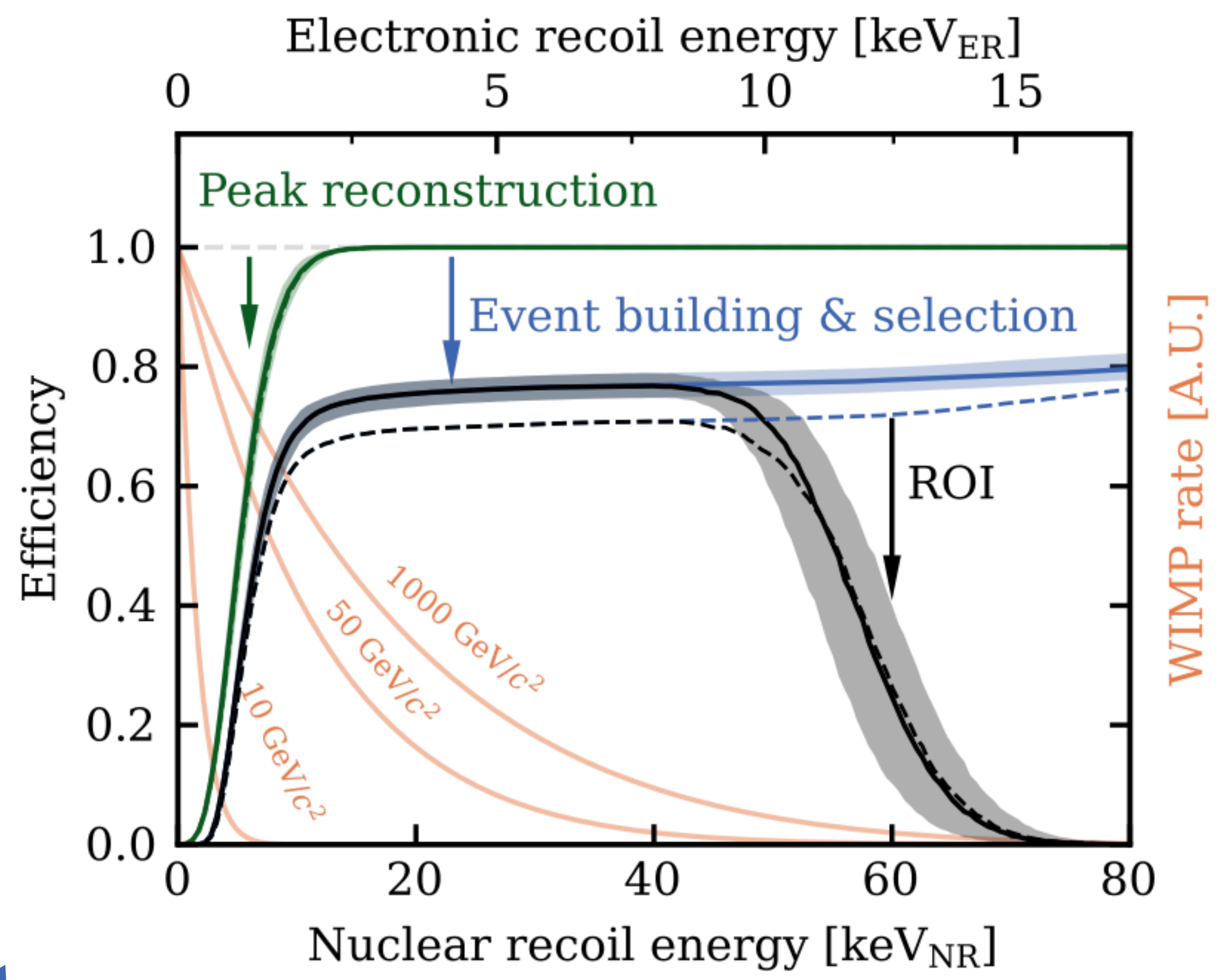

New Results with S2-only analysis searching for DM-electron interaction: Phys. Rev. Lett. 134, 161004 (2025)

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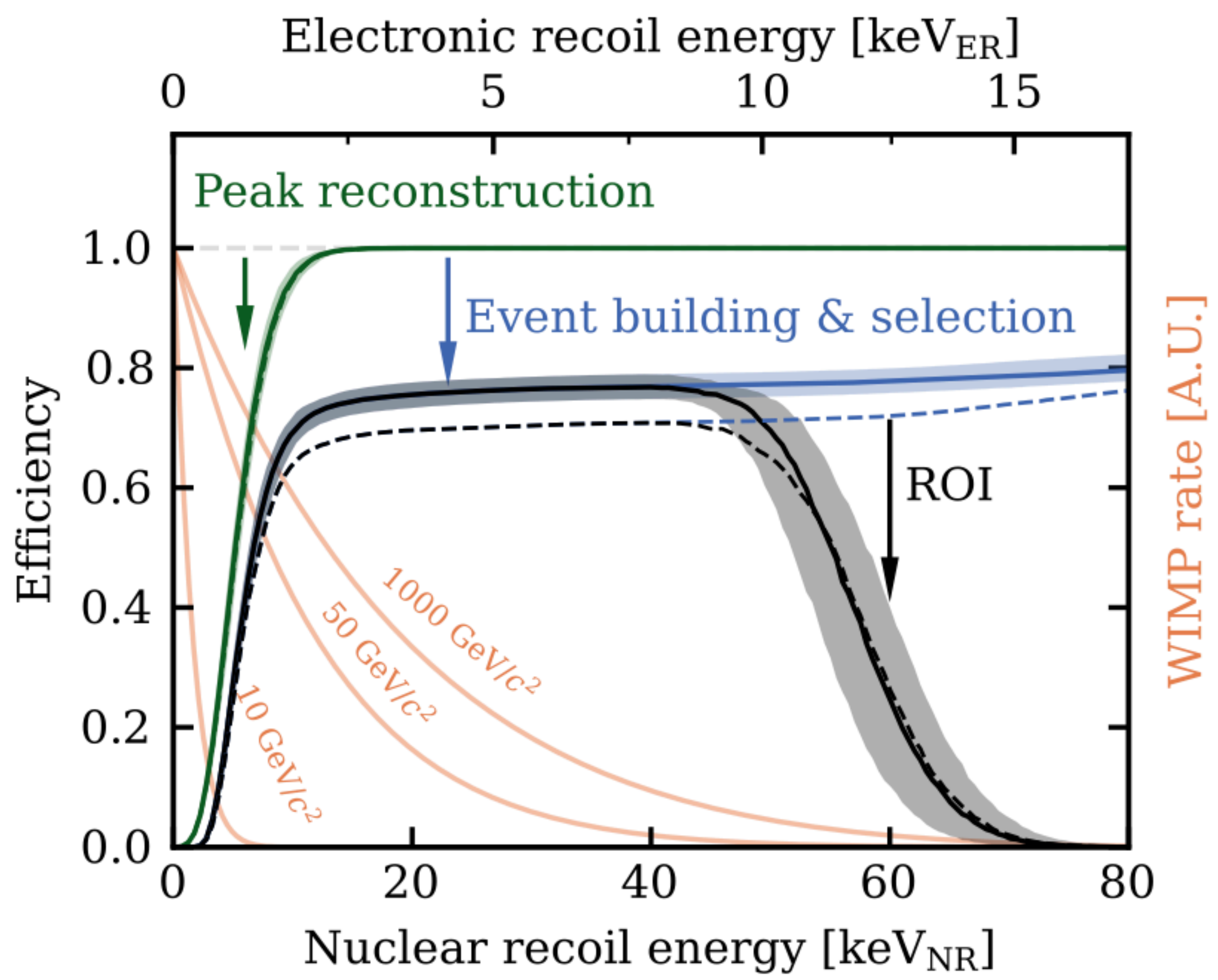

But how do we reconstruct an event interaction and derive its properties?

Signal Reconstruction

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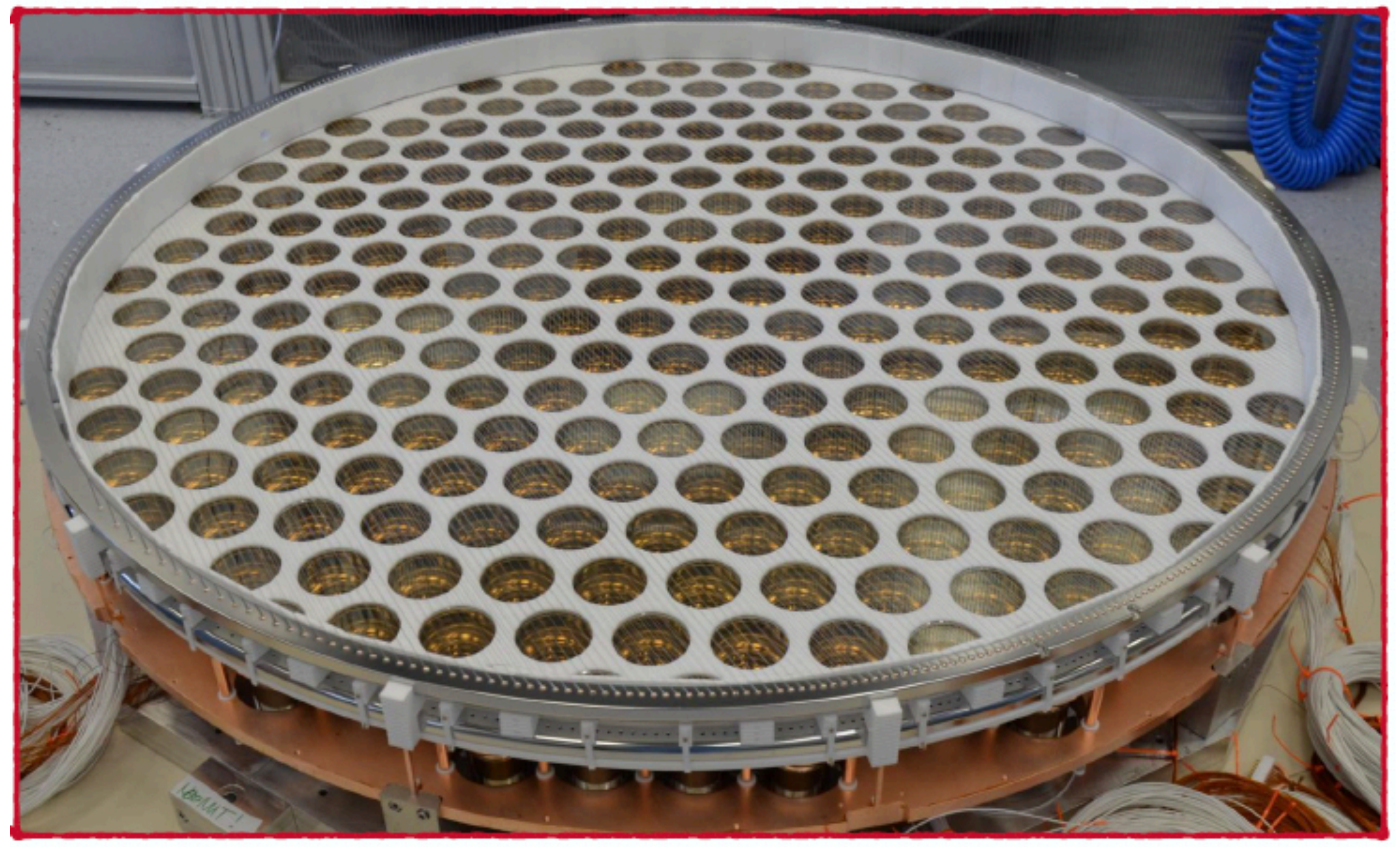
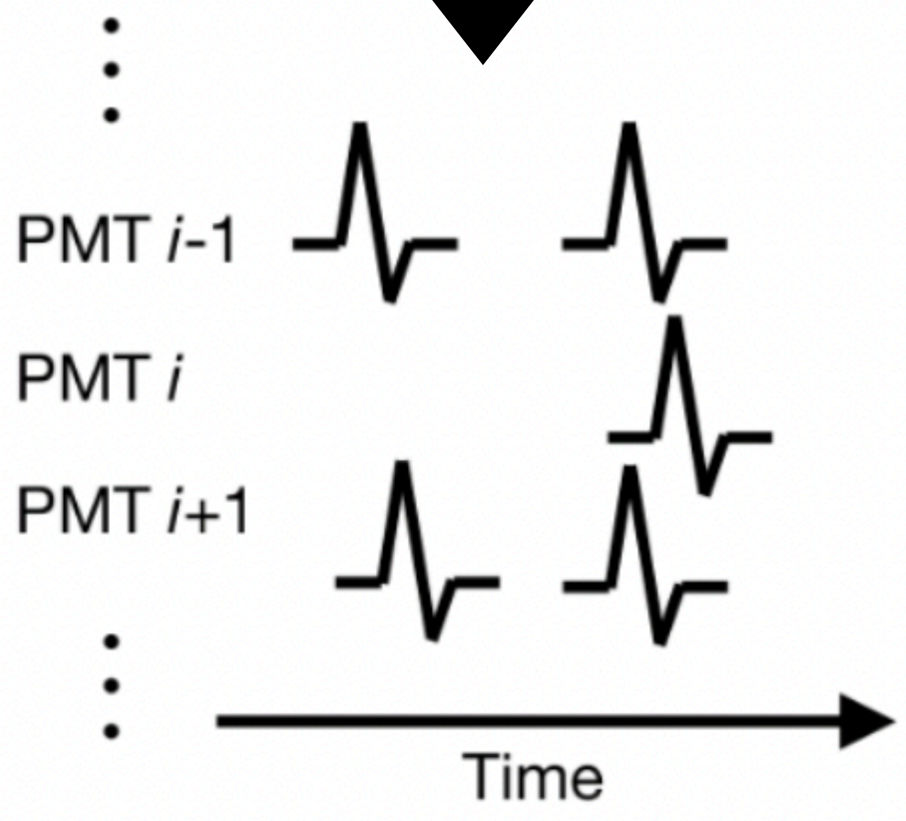
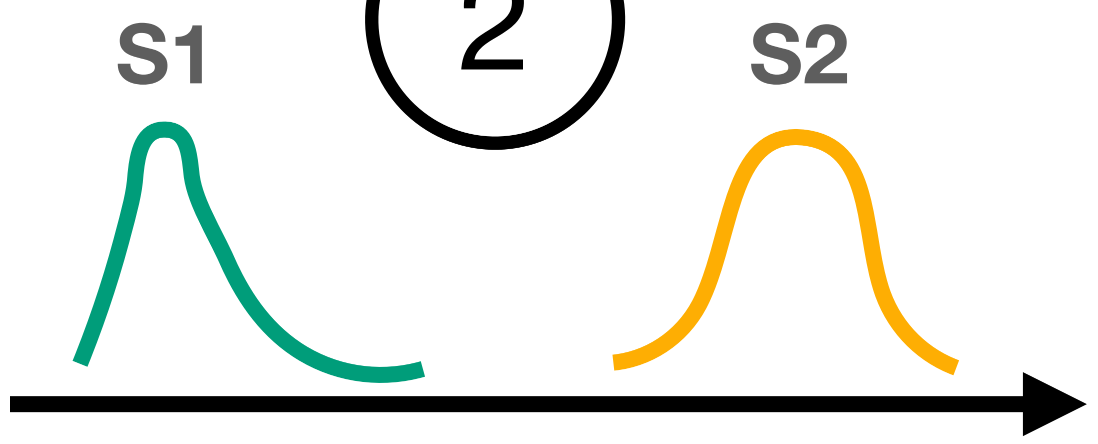


1. Reconstruct physicals signals seen by PMTs as Peaks
2. Classify Peaks corresponding to the prompt scintillation (S1) or the delayed charge (S2) signals
3. Build events based on S2s peaks > 100 PE
4. Apply correction to this events



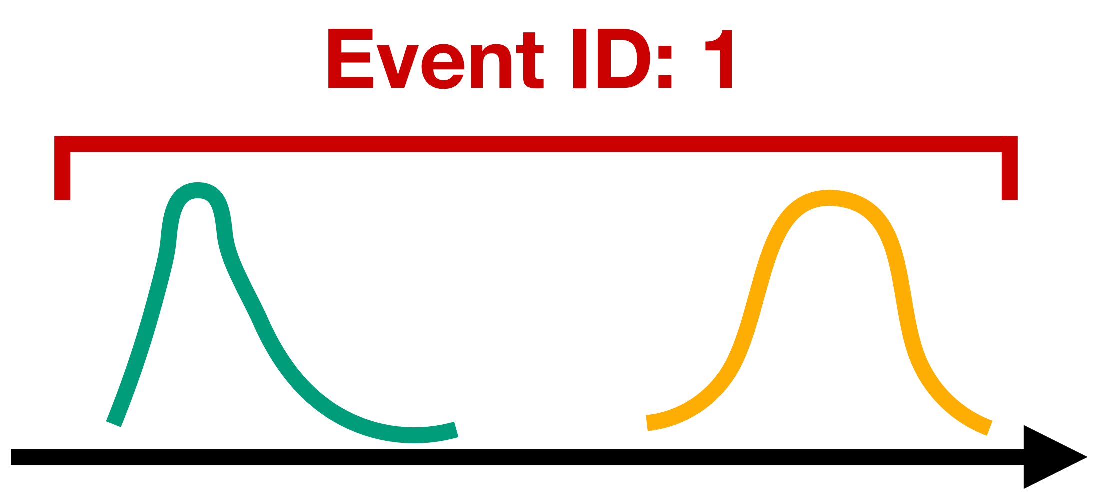
PMTs pulses

1



Peaks

3



Events 4

Signal Reconstruction with strax

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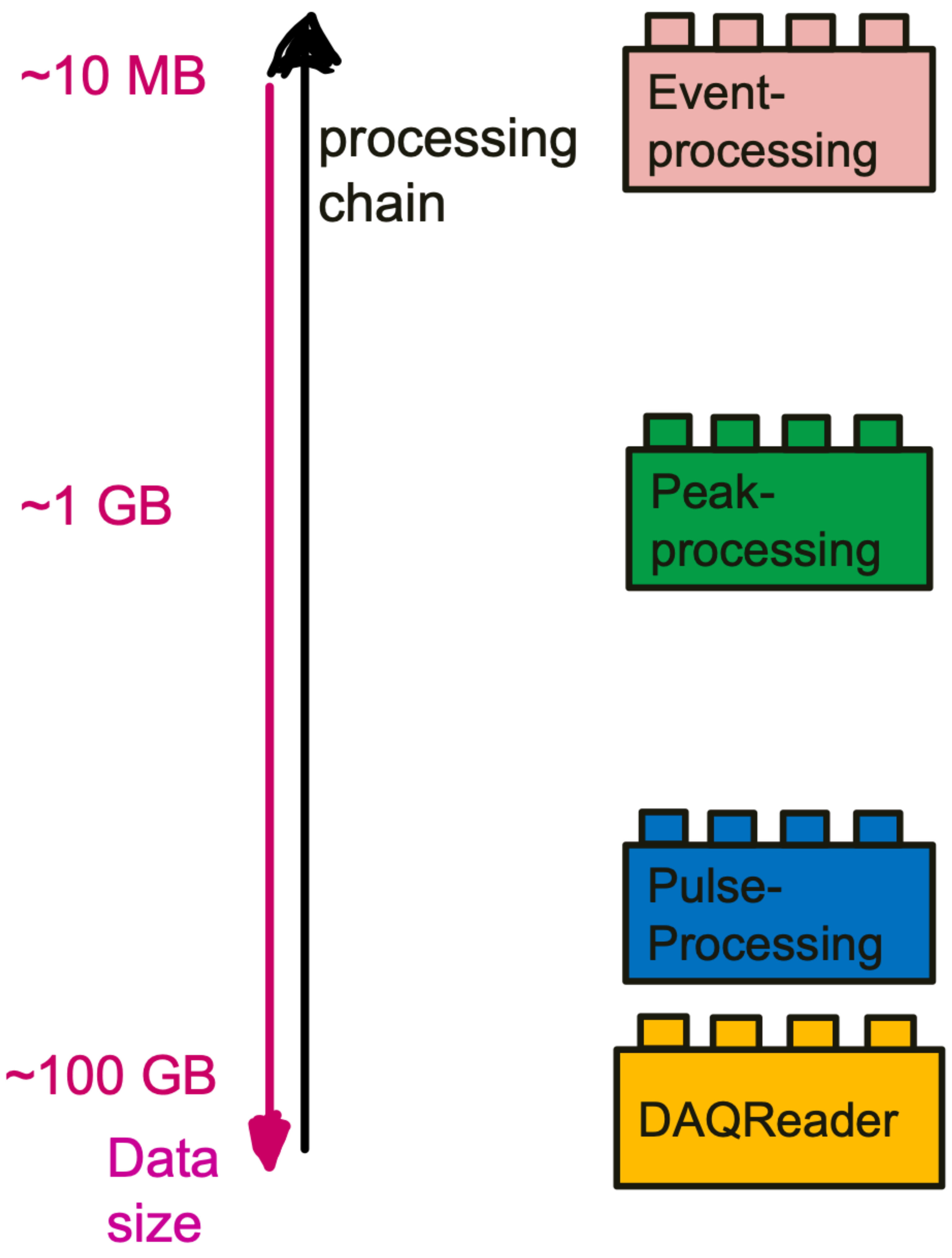
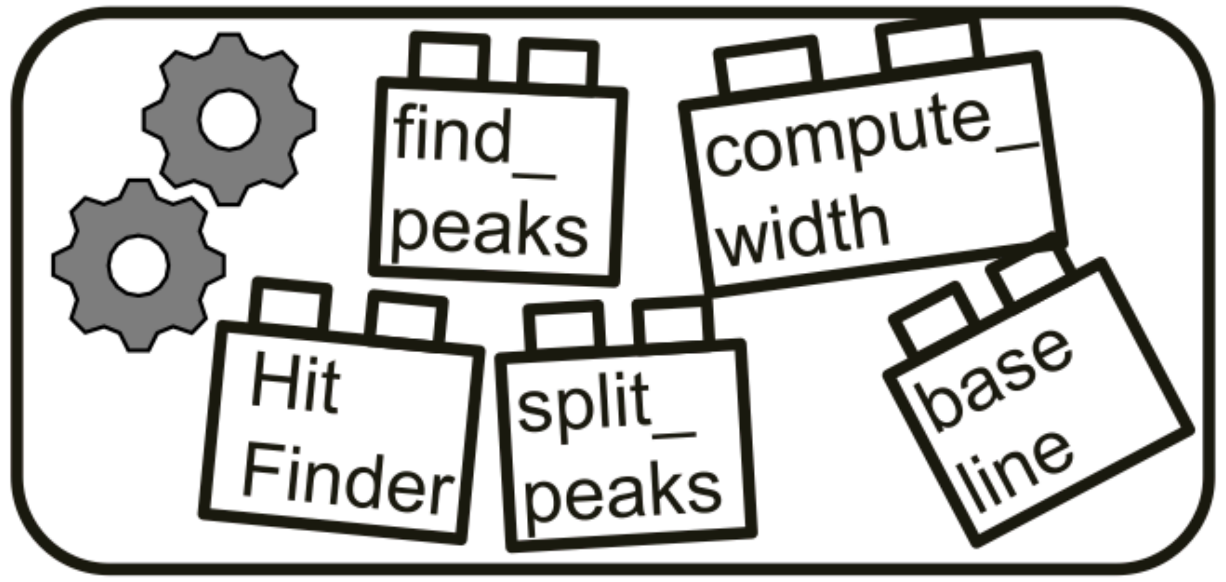
Modular TPC Signal Processing

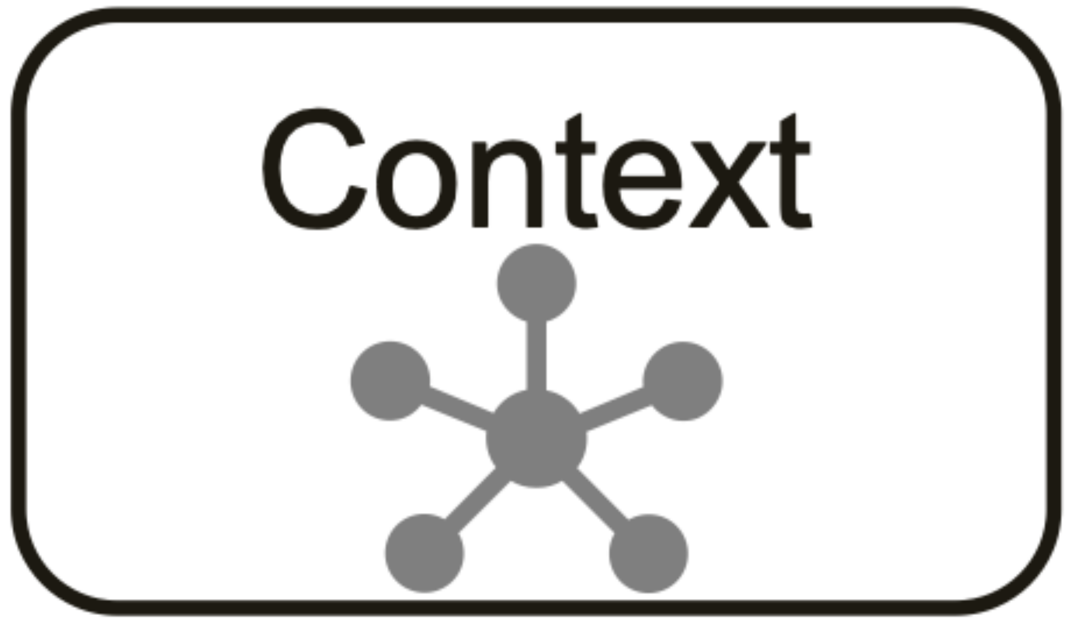
strax(en)



- Python based… but fast (numba, tabular format → autovectorisation)
  - ➡ ~60 MB/s/core
- Modular approach to allow development of specific aspect of the reprocessing (data-type, data-kind, plugins)
  - ➡ Allow partial (re)processing of only impacted part of the data flow
  - ➡ Lineage hash used (plugin version and option) to keep track of the data processing version
- Allow to process TPC data but also data from our vetos system.

Strax - utilities





Storage
Processing version
Correction version

Credit: D. Wenz, J. Angevaare

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Detector effects impacting the signal measurements needs to be corrected

- Spatial-Dependent Effect
  - Electric Field Distortion
  - Light Collection Efficiency
- Time Dependent Effect
  - Relative Light Yield
  - Single Electron Gain and Extraction Efficiency
  - Electron Lifetime

Signal Correction

French Contribution
Ananthu, Federica, Yongyu

Maxime Pierre
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Spatial-Dependent Effect

Electric Field Distortion

Light Collection Efficiency

Time Dependent Effect

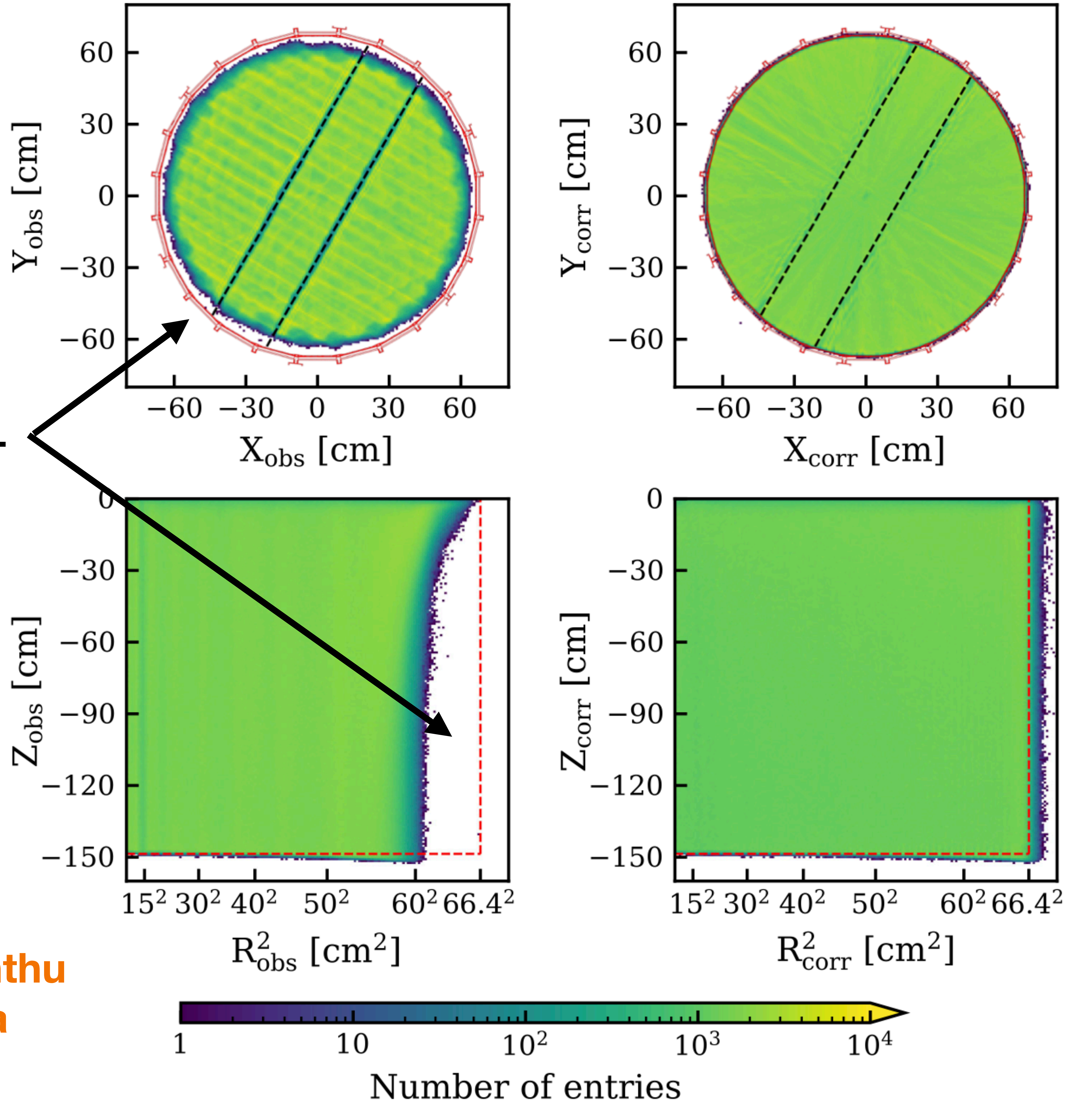
Relative Light Yield

Single Electron Gain and Extraction Efficiency

Electron Lifetime

Inward push of electrons in LXe bulk due to charge-up effect on PTFE walls

Use homogeneously distributed calibration source (Kr-83m) to correct the observed position of events.



Contribution from Ananthu Ravindran and Federica Pompa (Subatech)

Signal Correction

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Spatial Dependent Effect

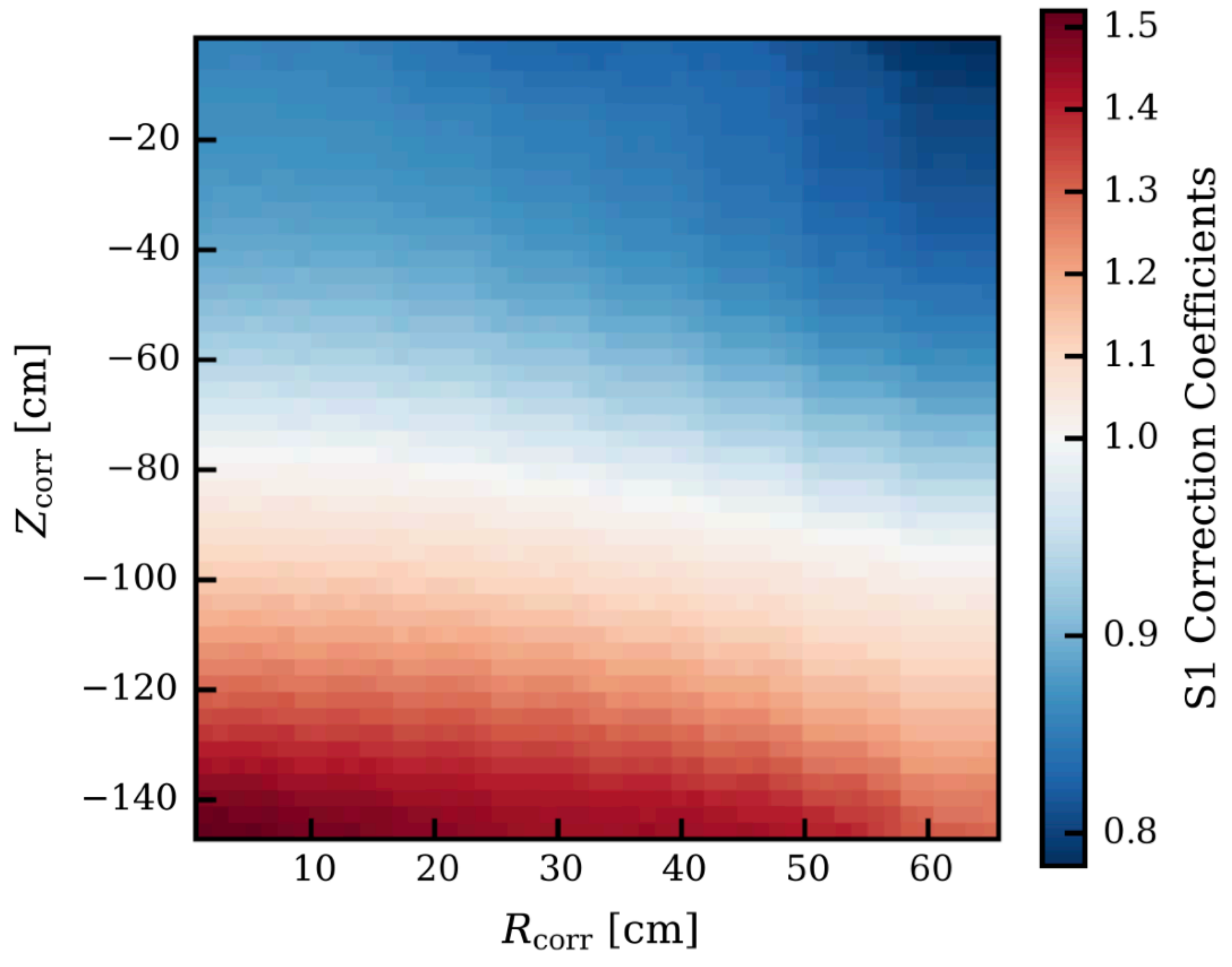
- Electric Field Distortion
- Light Collection Efficiency

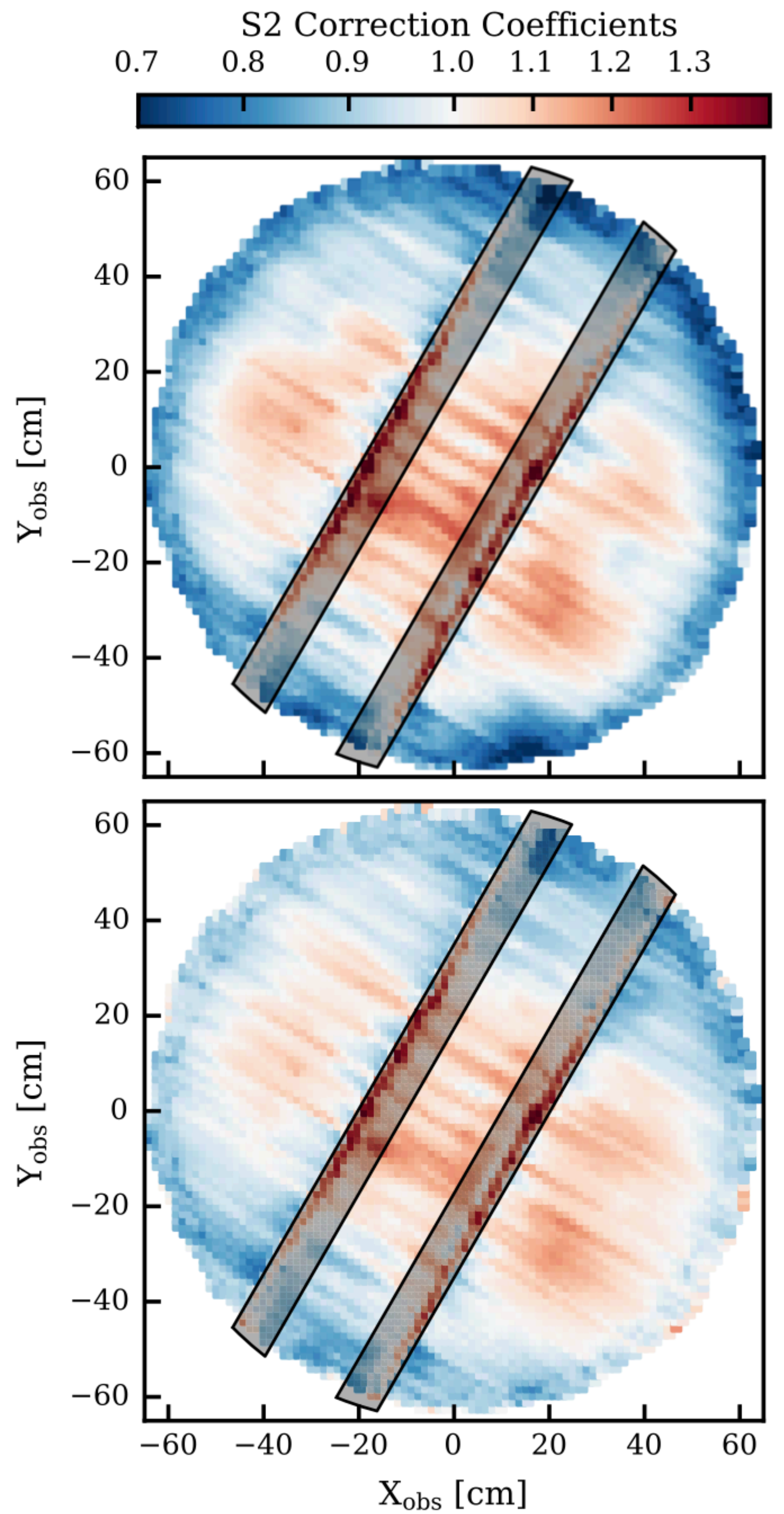
Time Dependent Effect

- Relative Light Yield
- Single Electron Gain and Extraction Efficiency
- Electron Lifetime

We do not collect 100 % of the photons from both S1 and S2 signals.

- Photon absorption, different travelling and reflectivity paths (3D correction)
- Also true for S2s but they are produce in a thing gas layer (2D correction)





Signal Correction

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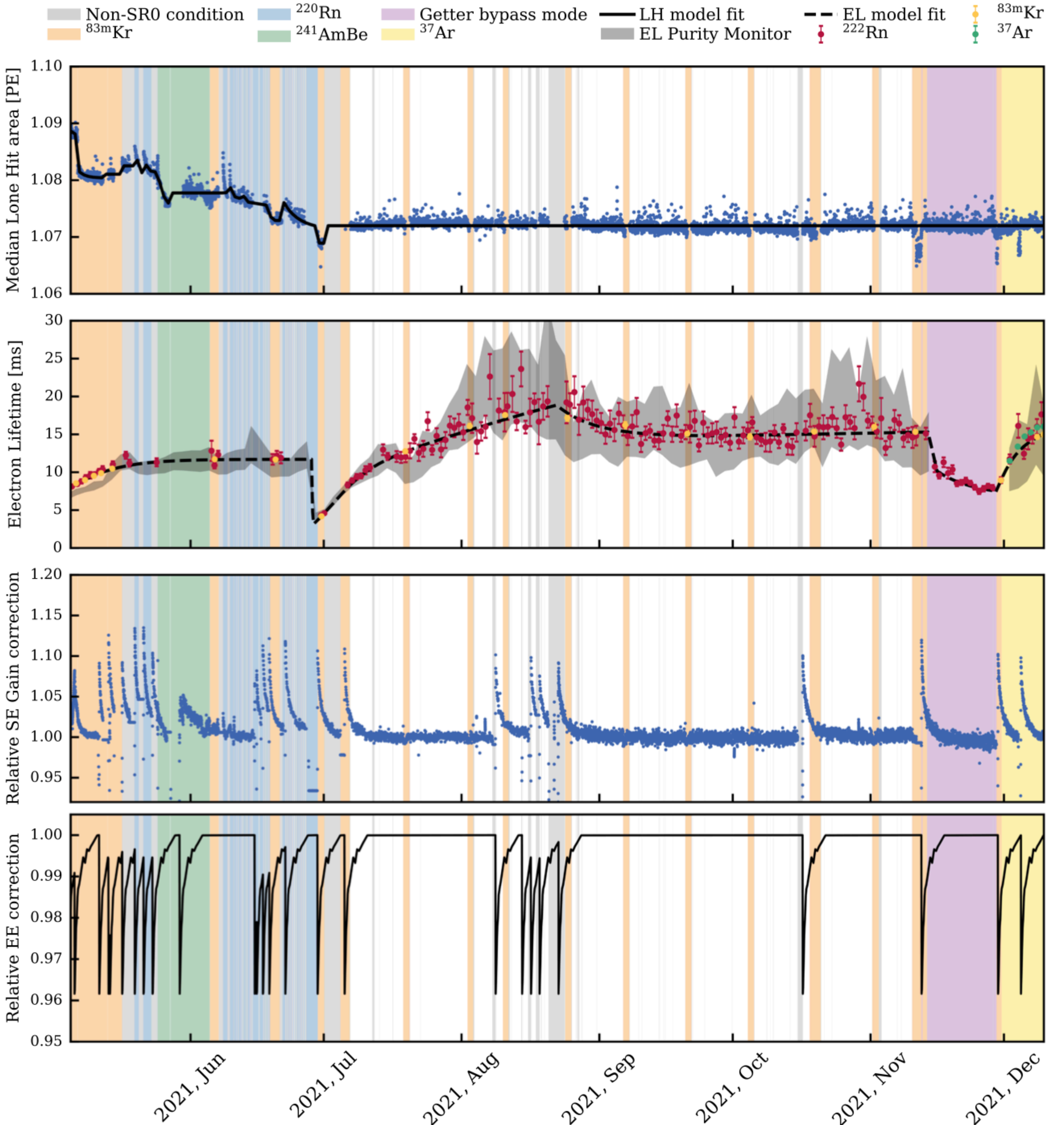
- When we have localised strong emissions of charge signals we ramp down the anode. After cycling the anode we correct for local field instability near perpendicular wires.
- Electron lifetime (xenon purity) > 10 ms during science data taking, modelled over time with different calibration sources.
- Relative LY is also corrected over time for potential variation of impurity level.

Time Dependent Effect

Relative Light Yield

Single Electron Gain and Extraction Efficiency

Electron Lifetime



Signal Correction

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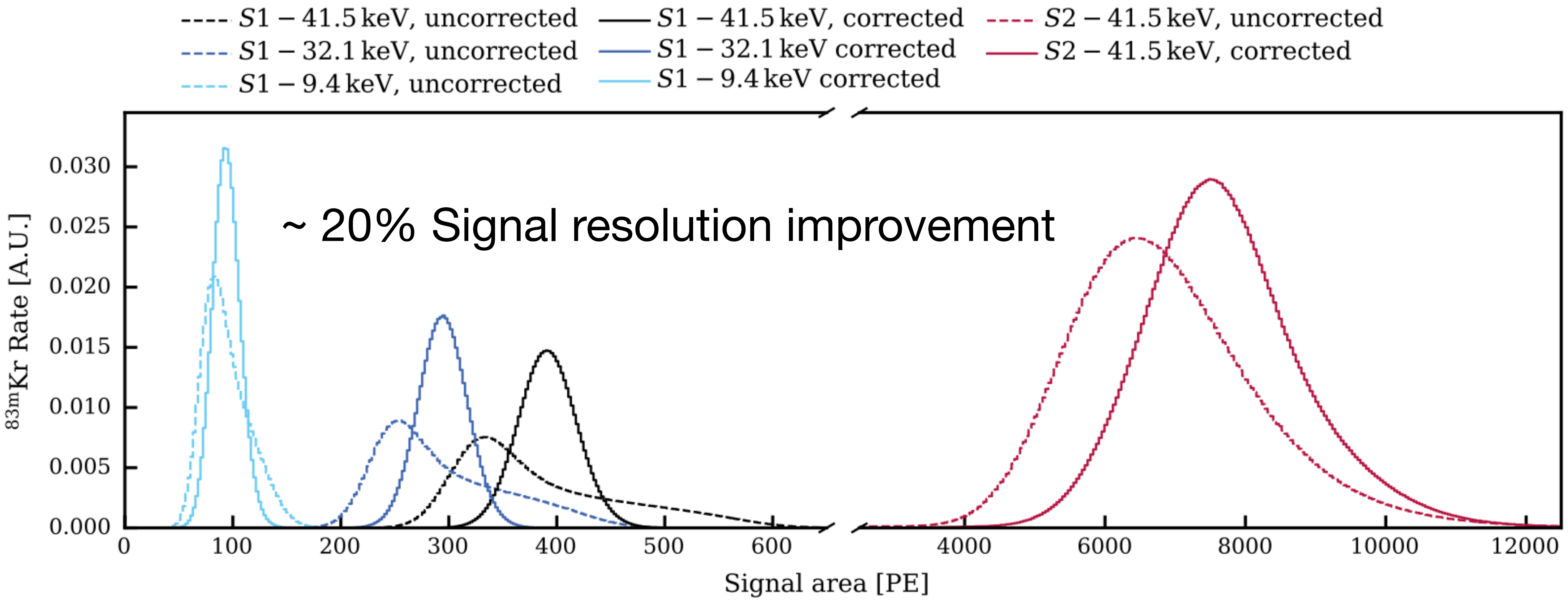
Spatial Dependent Effect

- **Electric Field Distortion**
- **Light Collection Efficiency**

Time Dependent Effect

- **Relative Light Yield**
- **Single Electron Gain and Extraction Efficiency**
- **Electron Lifetime**



xedocs

Contribution from Ananthu Ravindran (Subatech)

- Handle versioning of correction schema to be updated to database and used in the context of data (re-)processing.
- Prevent overwriting correction from the past version in case improved version is released (reproducibility of results)

Full Chain Simulation - G4 + fuse

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XENONnT Full chain simulation framework

fuse

- Produce MC simulation in a data-like format, up to the waveform level
- Plug and Play with our data processing framework

fuse: Micro Physics → Detector Physics → PMTs and Electronics

straxen: Processing

Geant4 MC → Micro Physics → Detector Physics → PMTs and Electronics → Processing

Yields models (NEST, Custom)
Energy deposition clustering

Quanta propagation
Detector effect modeling

Afterpulses, Noise
Hit timing and PMT response

Optical simulation
S2 Width modeling

Contribution from Bernard Andrieu and Yongyu Pan (LPNHE)

Analysis Computing Infrastructure

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Remaining part of the journey

- We can now harness the highest level part of an analysis:
  - ➡ Cut selection
  - ➡ Background modeling
  - ➡ Inference framework
- Understanding the performances of the detector performances but also all the different sub-system is critical!
  - ➡ Impact on data quality
  - ➡ Connection between analysts and hardware expert.

Many aspects not covered!

appletree

Simulation and fit of xenon response

axidence
saltax

Data/MC salting framework (study ambiance condition)

alea

Statistical Inference Framework

admix
utilix

Data management/Analysis tools

XOM

Data Quality monitoring

Contribution from Luca Scotto, Romain Gaior (LPNHE)

Conclusion & Outlooks

Production of new physics results is a collaborative work relying on contribution and commitment of numerous people and the development of an elaborate analysis framework!

Many analysis still ongoing with the first two science runs with very interesting results to come!

XENONnT completed a third science run (SR2), so we have more data to analyse.

Various and strong contribution from French group to the analysis effort… Looking forward to deliver the next new results!

Back-Up

XENON

Signal Reconstruction with strax

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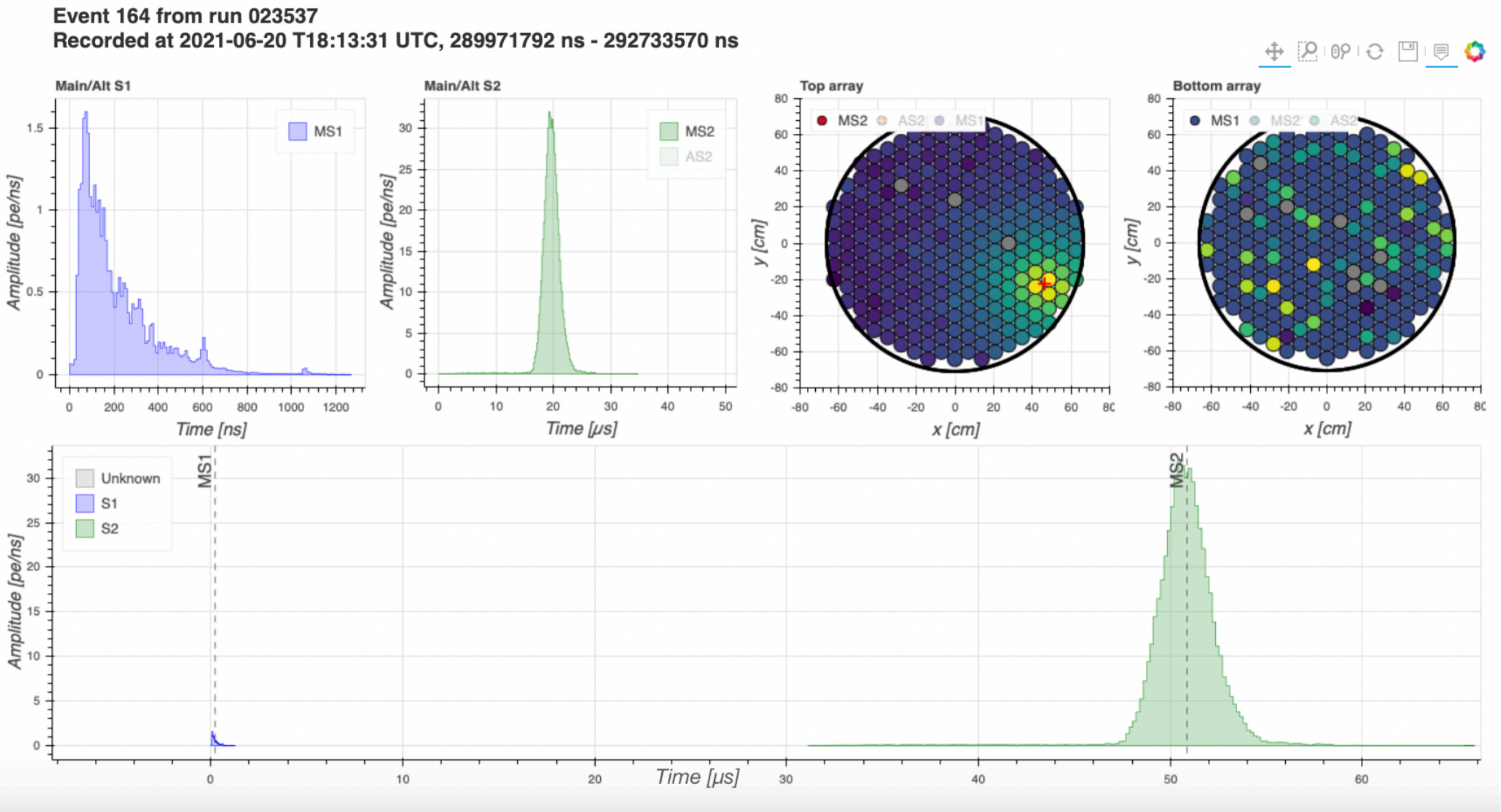

Full Chain Simulation - G4 + fuse

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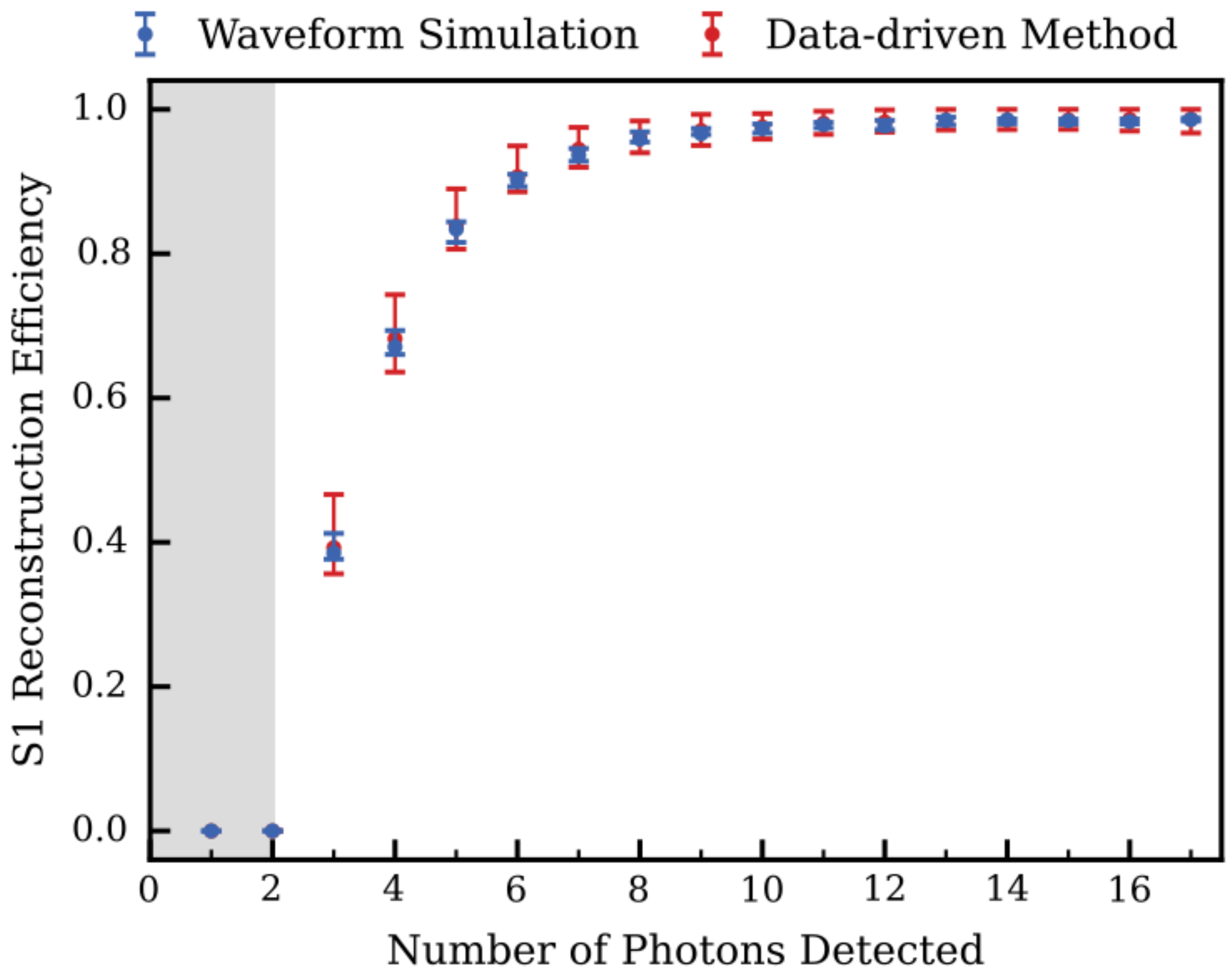
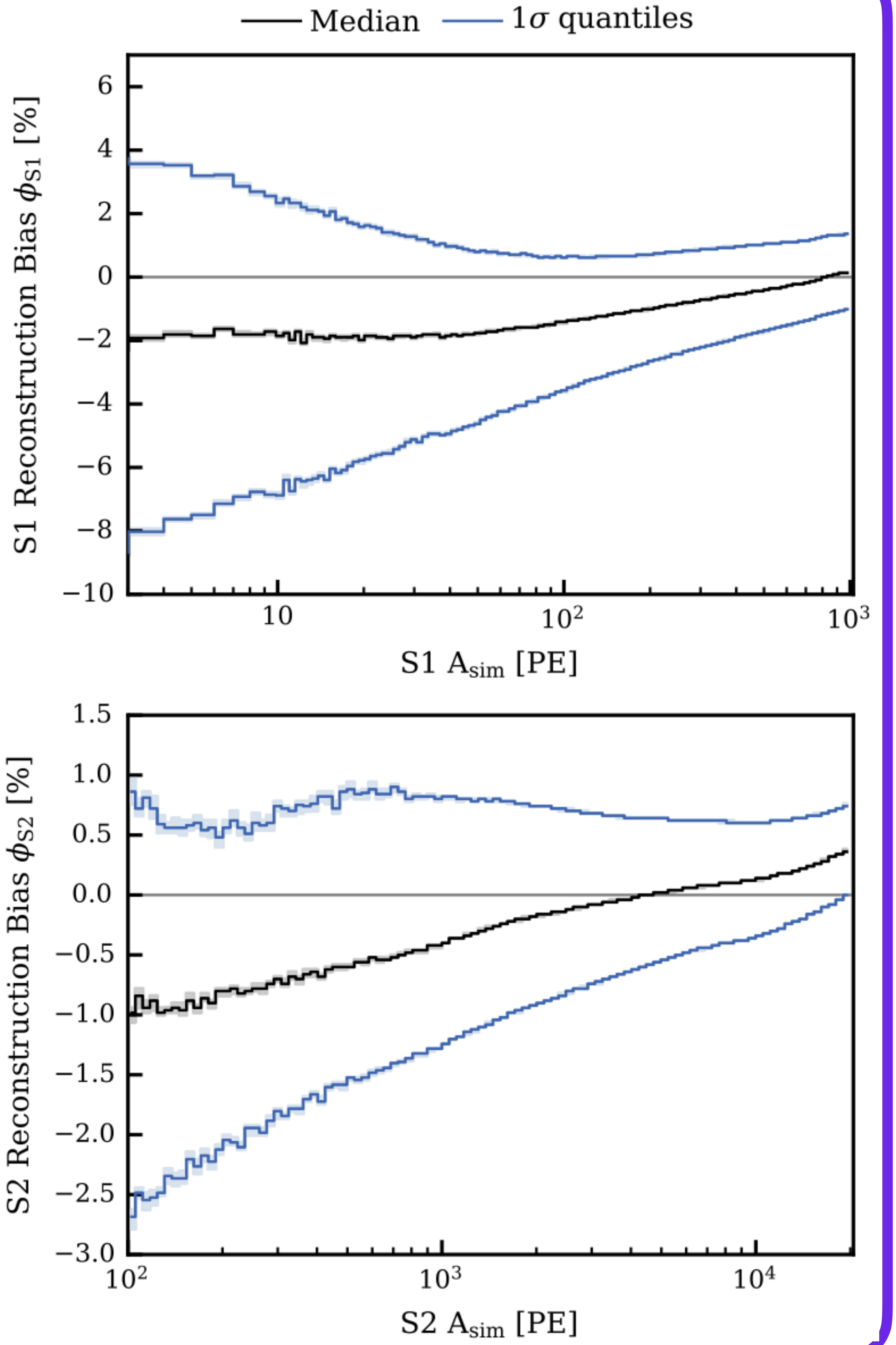
Use case example

Study S1 reconstruction efficiency



Study signal bias

- ➡Per-PMT Digitisation threshold
- ➡SPE response
- ➡Afterpulses
- ➡Noise



From XENON1T to XENONnT

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UPGRADE

x3 larger TPC 8.5 t LXe 494 PMTs	**Xenon handling** New purification & ER bkg. reduction New recovery/storage	**Water Cherenkov Neutron Veto** Gd-doping ongoing

Goal →

More target mass
Reduced background level