

AI/ML Tools for Fast Online Analysis and Real-Time Data Processing Workflows

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29 September 2026

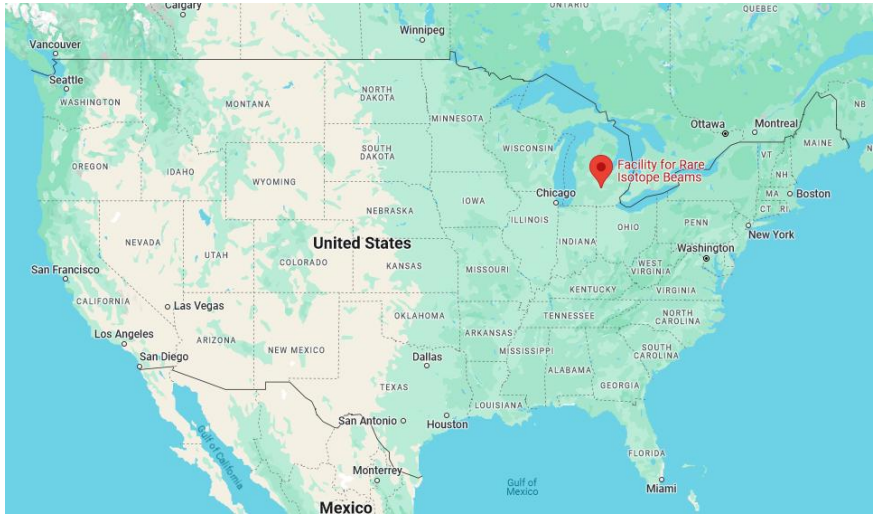




This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.

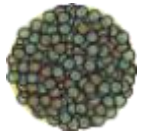
The Facility For Rare Isotope Beams (FRIB)

- FRIB is a scientific user facility funded by the US Department of Energy Office of Science (DOE-SC) Michigan State University, and the State of Michigan
  - User Organization: 1800 members (125 colleges and universities, 13 national labs, 53 countries)
  - Experimental program began in May 2022
- Key feature of FRIB: high-power LINAC, 400 kW at 200 MeV/u for ^{238}U
- Experimental areas for fast, stopped and reaccelerated beams
  - Access to atomic nuclei across the nuclear chart (oxygen to uranium) at a range of energies

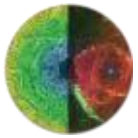




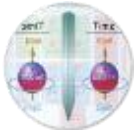
The FRIB Scientific Program



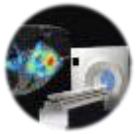
- Nuclear structure
  - Evolution of structure far from stability
  - Limits of nuclear existence



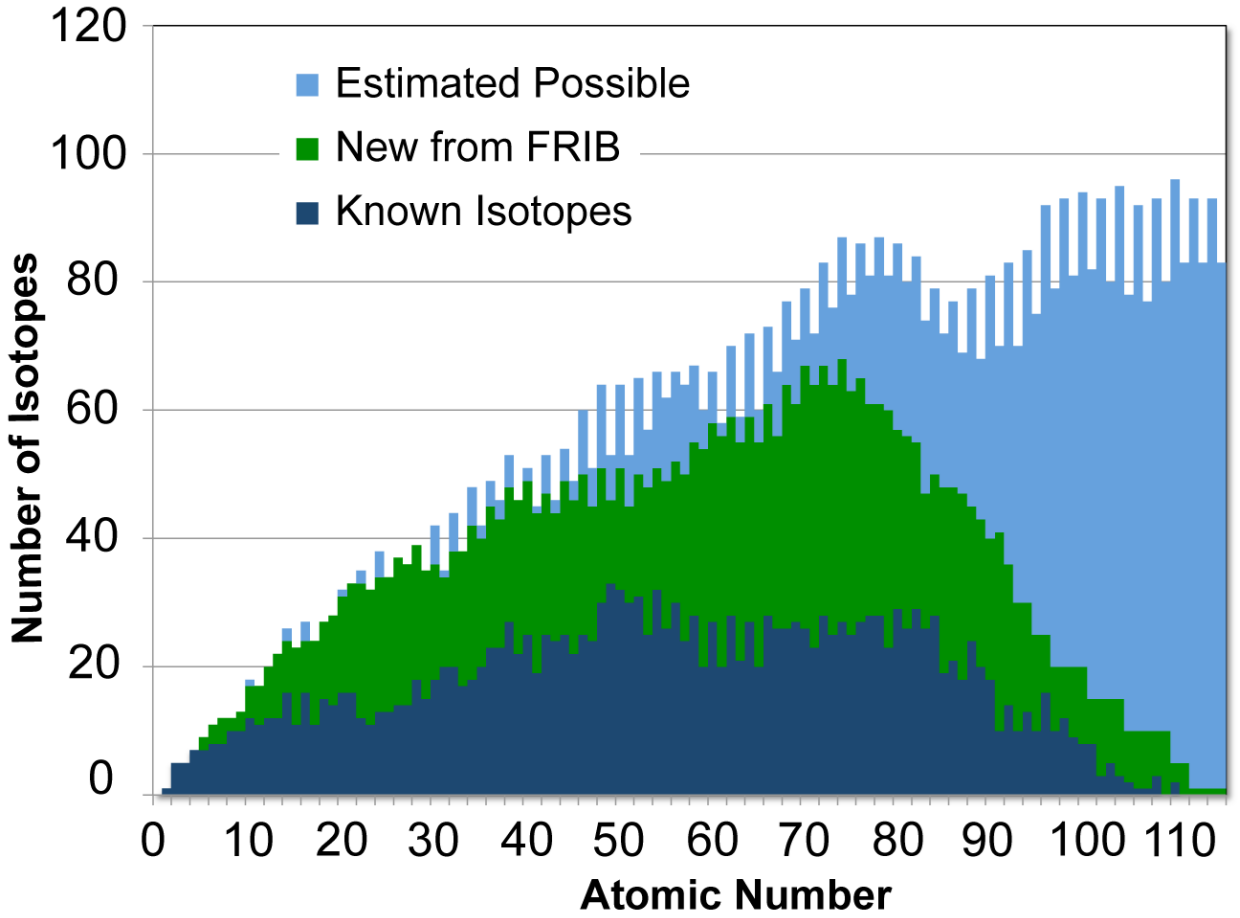
- Nuclear astrophysics
  - Creation of the chemical elements
  - Properties of matter at extreme temperatures and densities



- Fundamental symmetries
  - Matter/antimatter asymmetry
  - Physics beyond the Standard Model



- Societal applications and benefits
  - Medicine, energy, material sciences, environment, workforce development



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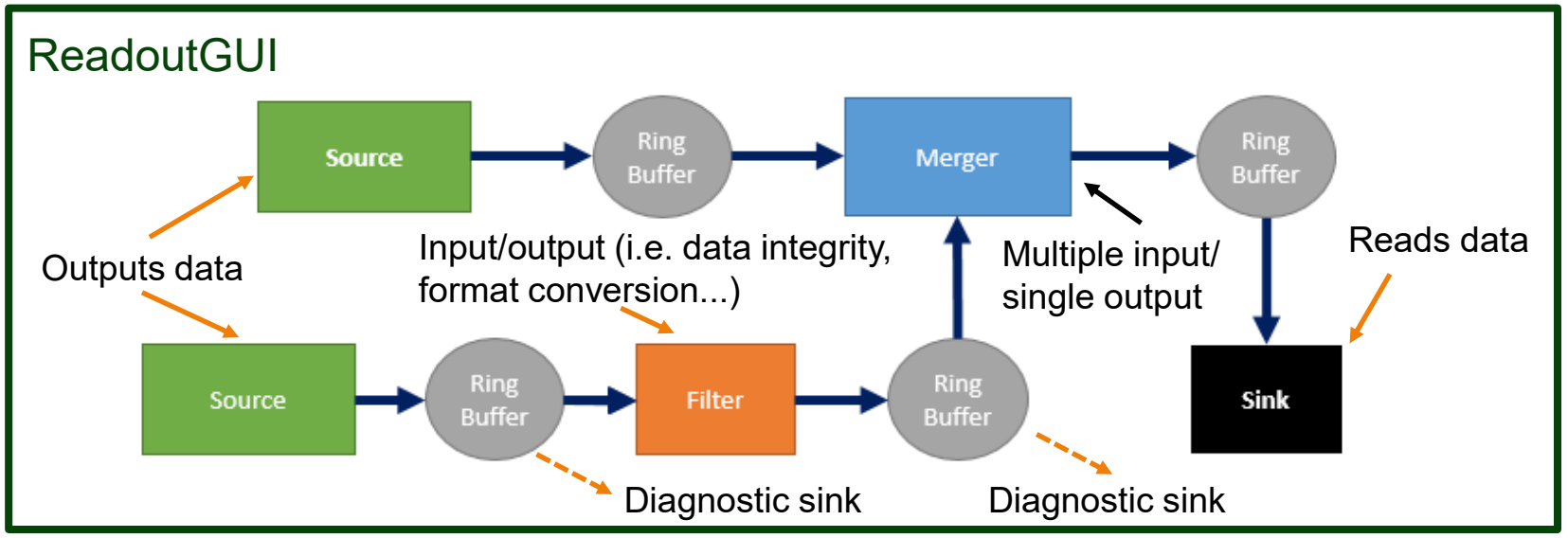
Data Acquisition and Analysis for User Experiments at FRIB

- FRIB supports the user's data acquisition and analysis needs by providing:
  - A stable and portable **containerized environment** that can be used in any Linux OS system
  - **FRIBDAQ:** A scalable DAQ framework which provides solutions for different detectors
  - **SpecTcl:** A flexible data analysis framework for online and offline analysis
    - » ROOT support available
    - » Extensible PyQt5-based histogram viewer for advanced online analysis
- This approach has been adopted by several universities in the US and has been successfully deployed at other laboratories for experiments (SπRIT TPC @ RIKEN)
  - Simplify the integration of non-FRIB auxiliary detectors with FRIB experimental devices
- The software is available on GitHub as releases ready to be installed
  - Possibility to have users as code contributors
  - See https://github.com/FRIBDAQ

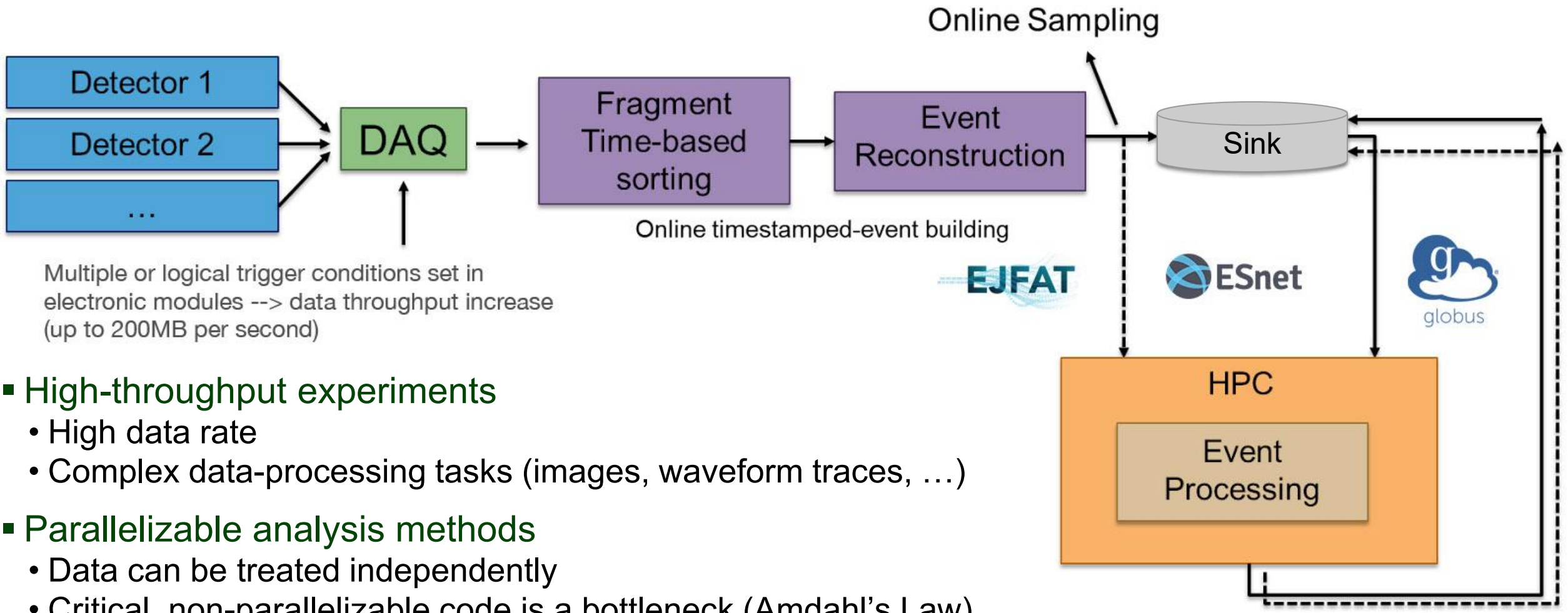
FRIBDAQ Readout Architecture

- Software suite (C++, Tcl – being replaced by PyQt5, Python) that provides a flexible and extensible framework for handling the data flow produced by nuclear physics experiments
- Support for a wide variety of commercial (CAEN, Mesytec, XIA, …) and international collaboration electronics (GET, CERN SRS, AMANEQ, …)
- ReadoutGUI is the “conductor” of the system
  - Pipeline management, data recording, consolidation of data to output, …

Ring buffer: a TCP-based circular-buffer mechanism to make data available to different processes

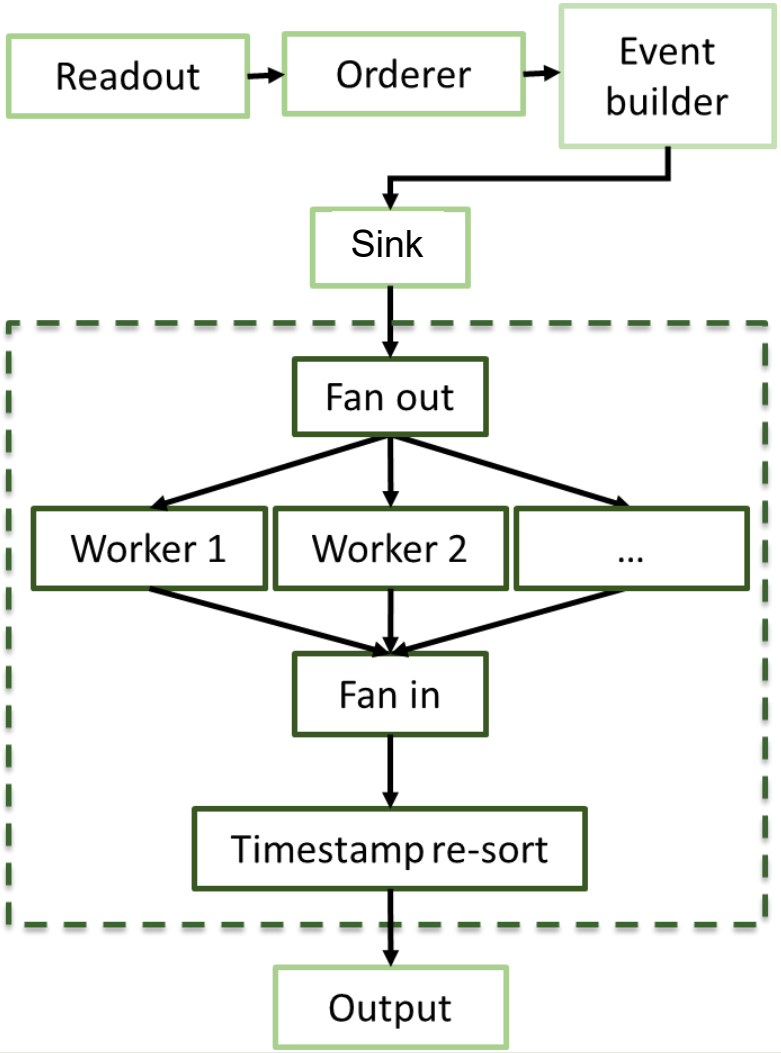


(Nearly) Real-Time Wide-Area Workflows with FRIBDAQ



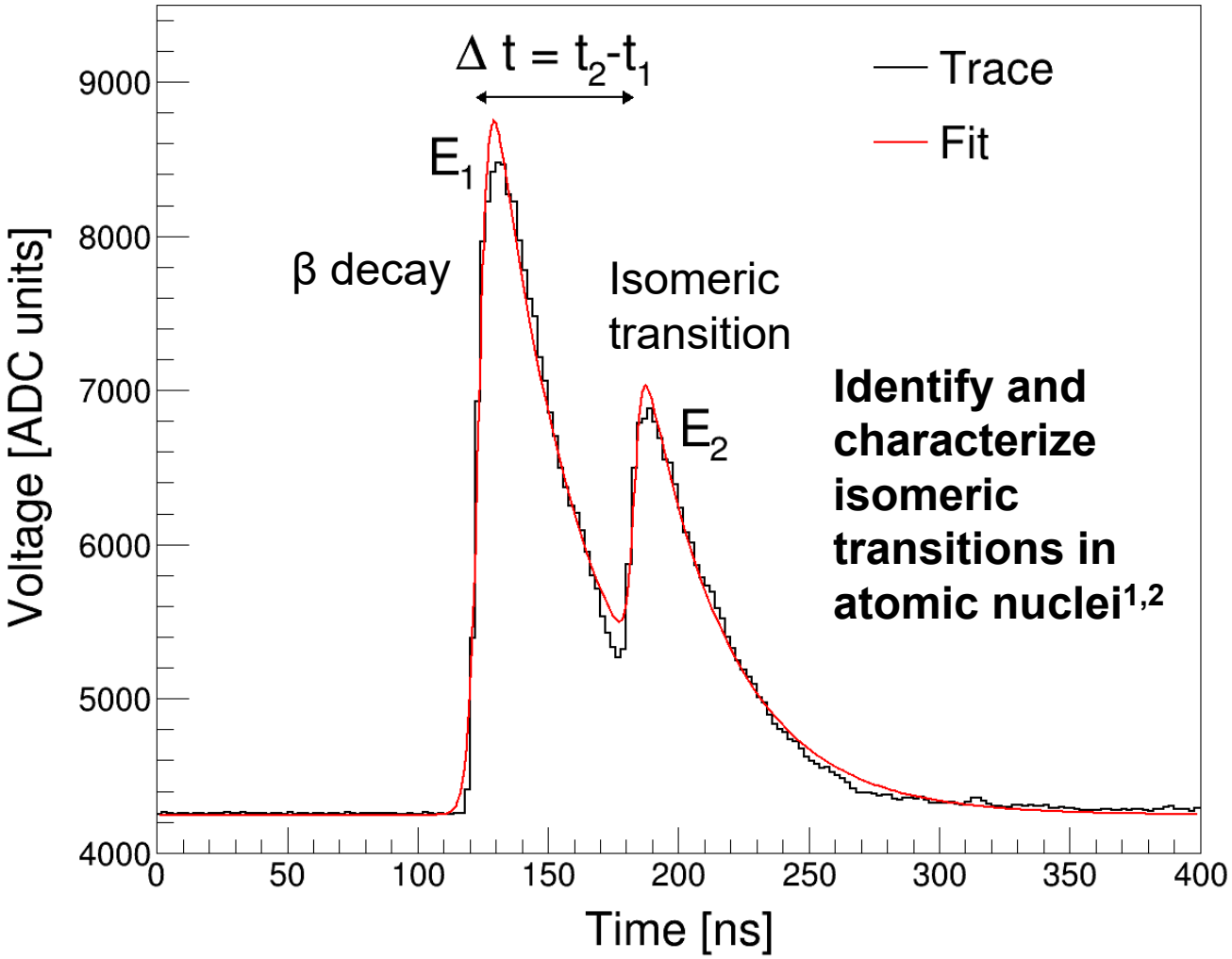
- High-throughput experiments
  - High data rate
  - Complex data-processing tasks (images, waveform traces, …)
- Parallelizable analysis methods
  - Data can be treated independently
  - Critical, non-parallelizable code is a bottleneck (Amdahl's Law)

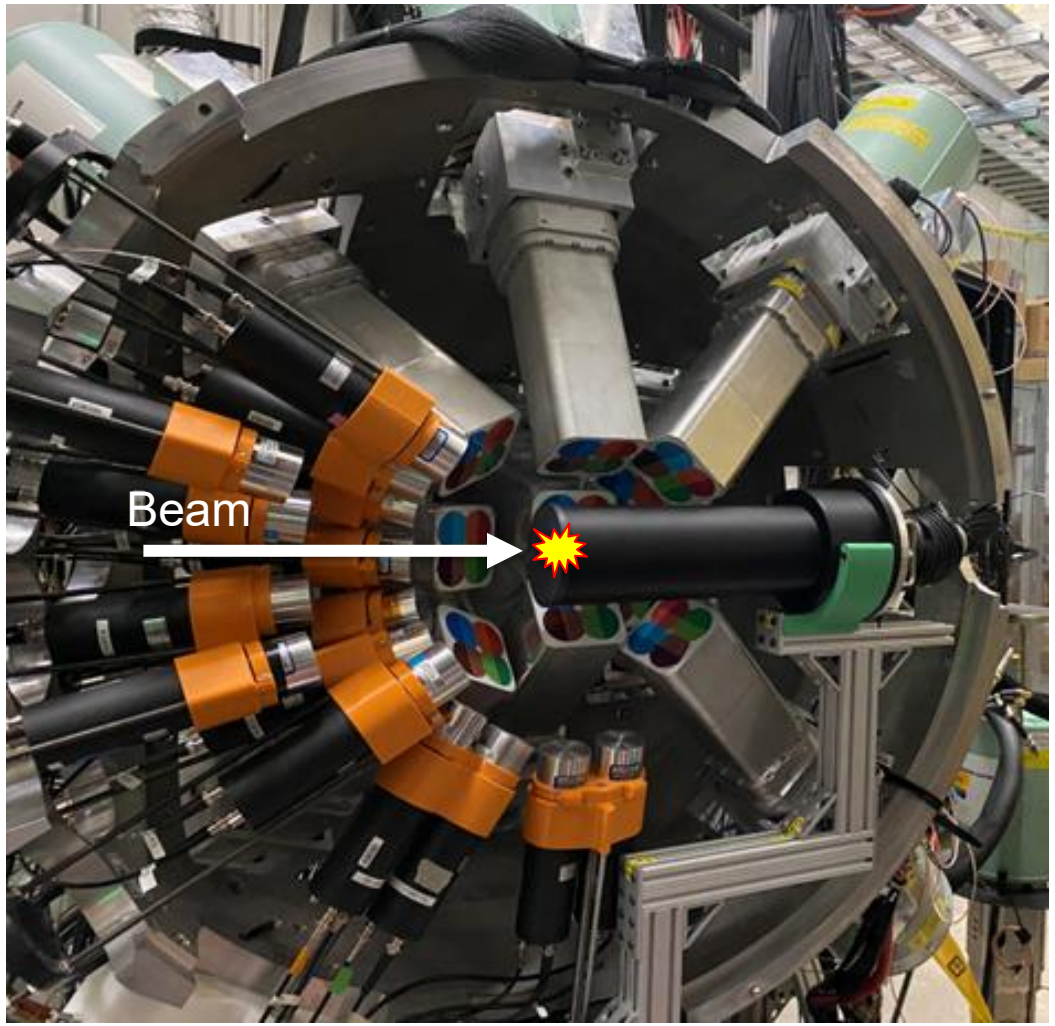
Parallel Event-Editing Software in FRIBDAQ



- Process-level pipeline parallelism for readout
  - Separate readout and timestamp sorting
  - Zero-copy whenever possible
- Parallel analysis framework
  - Common operations implemented via plugins
  - Parallel task distribution via OpenMPI or 0MQ
- Event-editing software:
  - Filters (parallel software trigger)
  - Body editors (add to or modify event data)
- Rate limited by DAQ hardware backplane
  - 80 MB/s VME64
  - 109 MB/s PCIe

Isomer Identification by Pulse-Shape Analysis

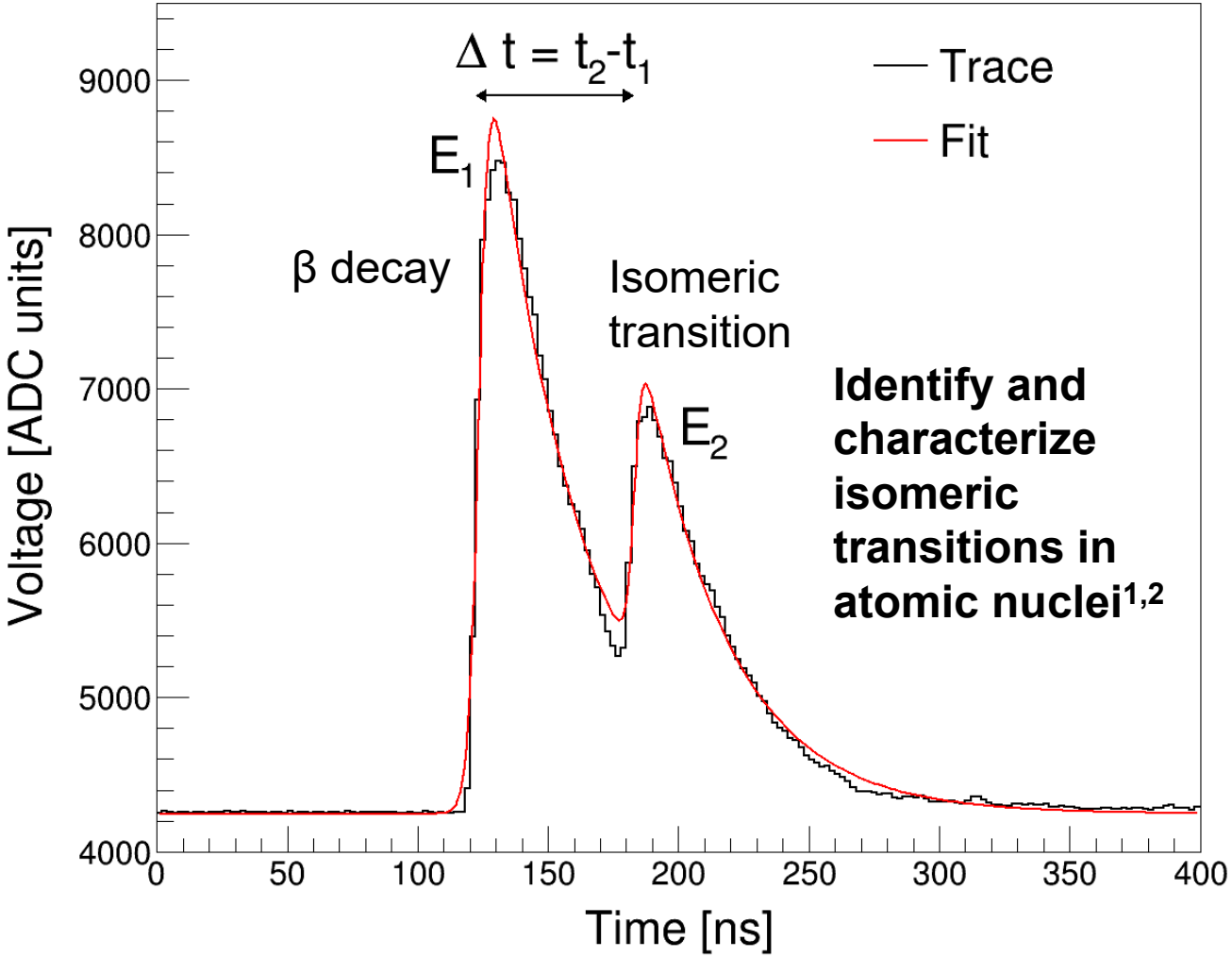


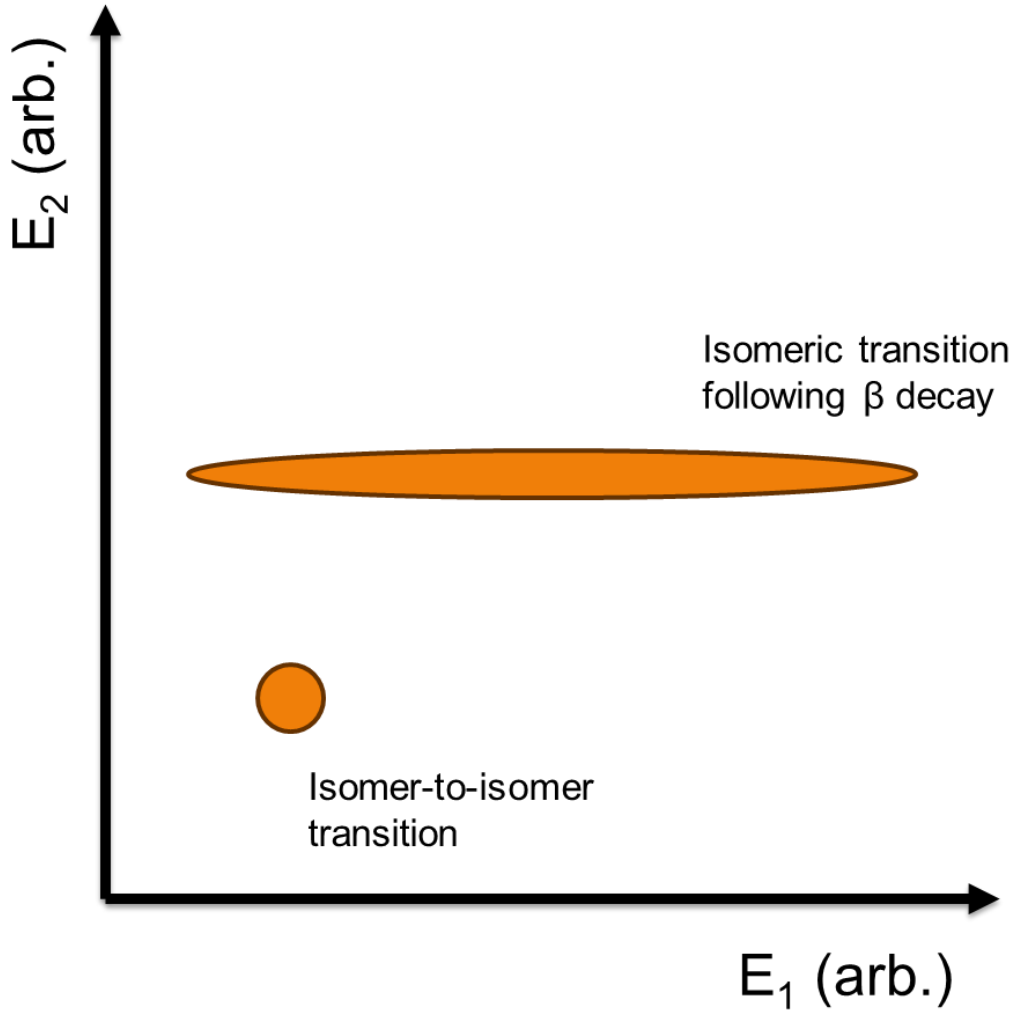


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[1]A. Chester et al., Phys. Rev. C **104** (2021) 054314
[2]A. Chester et al., Phys. Rev. C **105** (2022) 024319

Isomer Signatures in Double-Pulse Energy Spectra



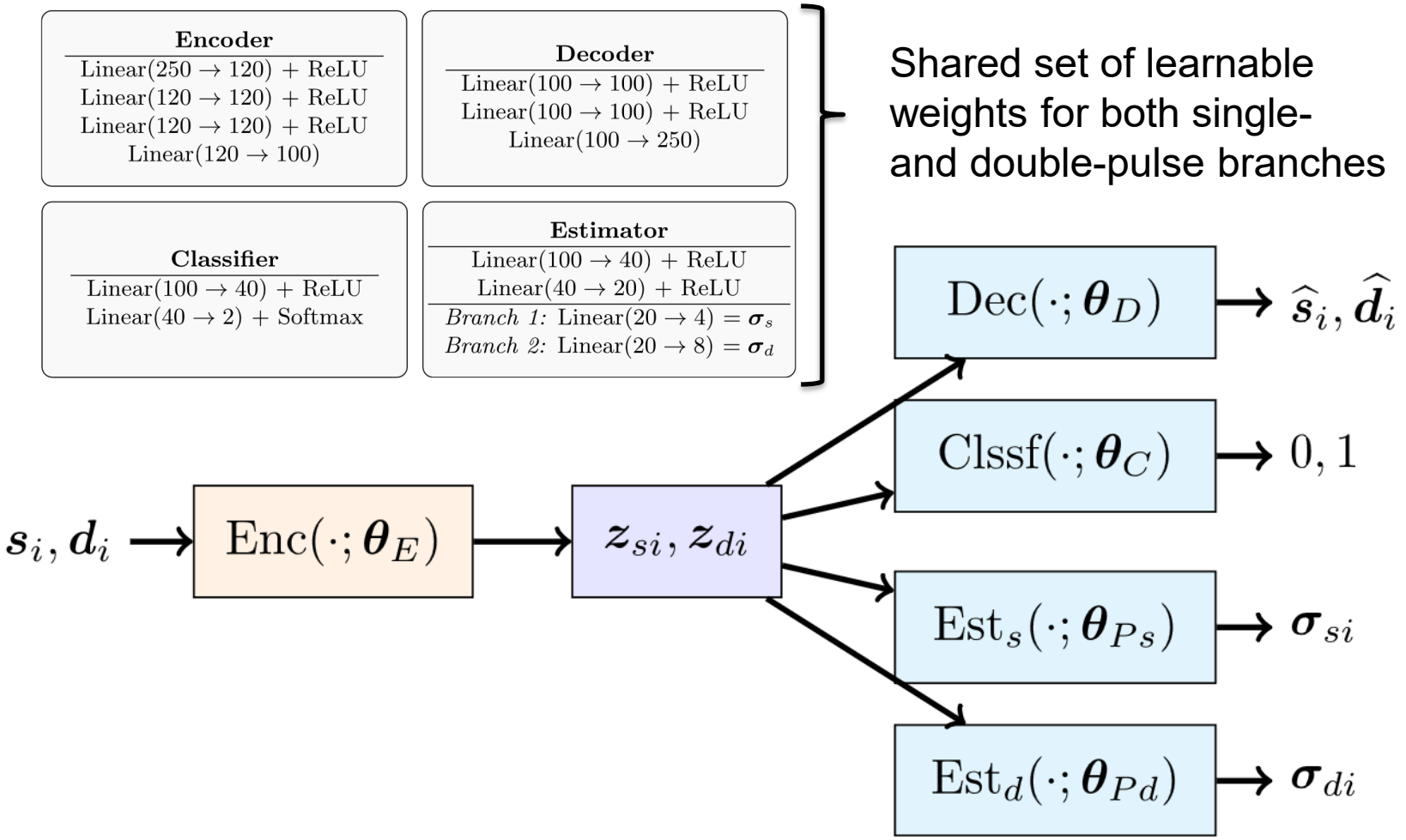


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Pulse-Shape Analysis With Machine-Learning (ML) Inference

- Siamese autoencoder neural network architecture[3]
  - Single autoencoder with shared weights for classification of single- and double-pulse trace data
- 250-sample trace reduced to 100-dimension representation z_{si}, z_{di}
- Simultaneously aim to:
  - Classify events containing one or two pulses
  - Accurately and precisely estimate model parameters
  - Maximize speed, minimize resources required



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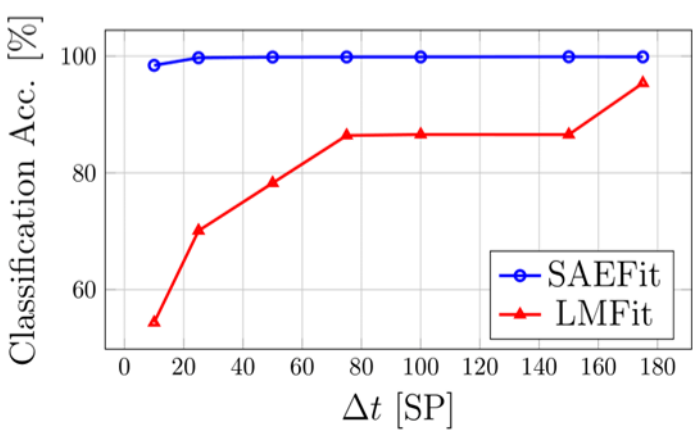
[3]B. Sadeghi et al., Nucl. Inst. Meth. A **1082** (2026) 170971

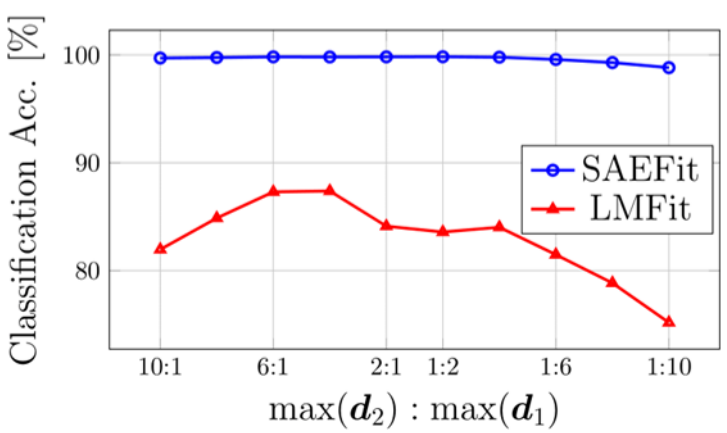
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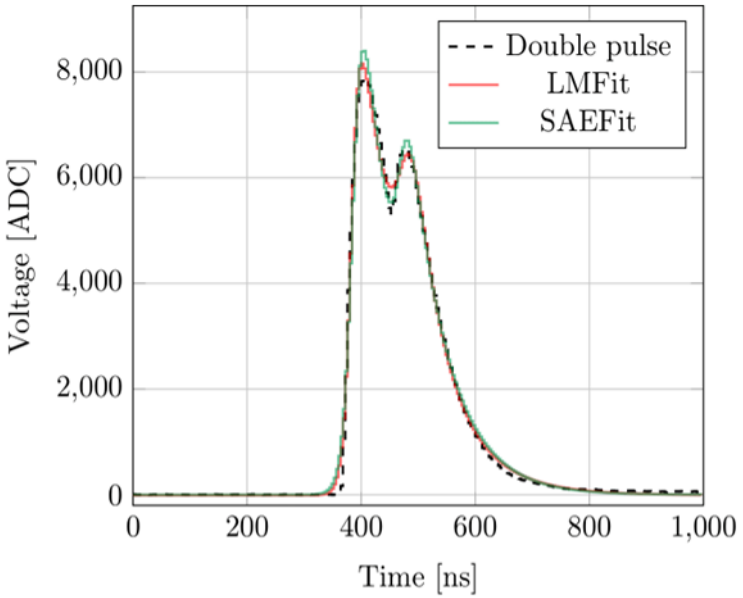
SAEFit: ML-based fit
LMFit: GSL Levenburg-Marquardt iterative fit

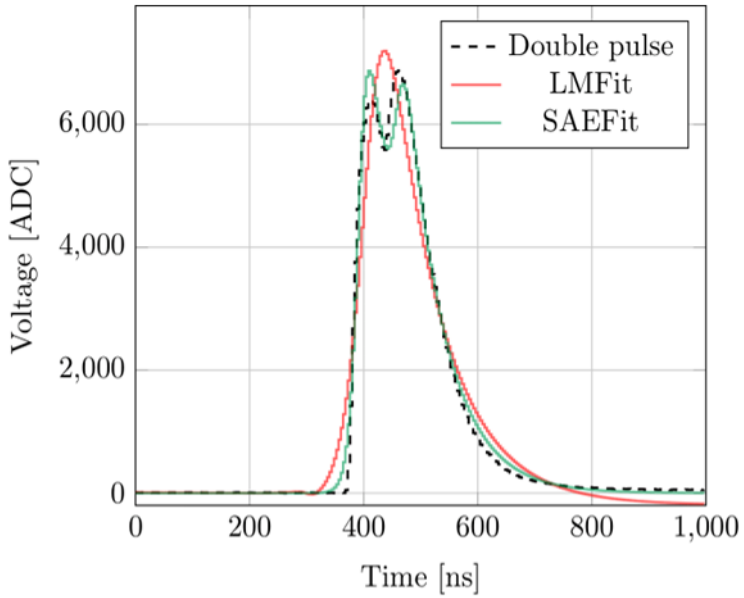
Confusion Matrix	Predicted Single		Predicted Double	
	SAEFit	LMFit	SAEFit	LMFit
Actual Single	**99.69%**	83.72%	**0.31%**	16.28%
Actual Double	**0.44%**	15.09%	**99.56%**	84.91%

- SAEFit improves classification accuracy across a range of time-differences Δt and amplitude ratios $\boldsymbol{d_2}$:$\boldsymbol{d_1}$
- Identification of doubles with small Δt increases statistics and extends the applicability of the method to shorter isomer lifetimes
- Parameter estimation also improved





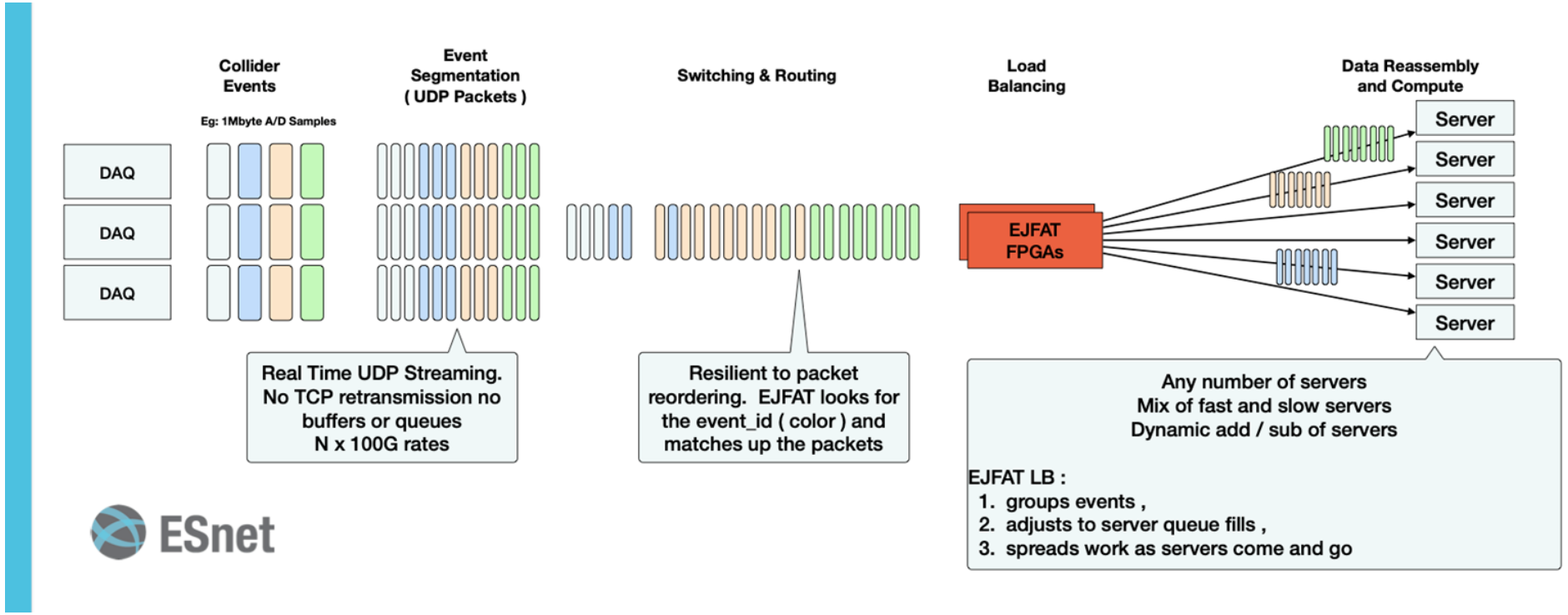




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Integrating EJFAT into Workflows for FRIB Science



- FRIB experiments are reliant on local cluster for computationally intensive data processing
  - Contention for shared resources, no GPUs
- What does EJFAT provide?
  - Low latency streaming architecture, direct connection to real-time resources at HPC centers

EJFAT-Assisted Workflows at FRIB: Current Status

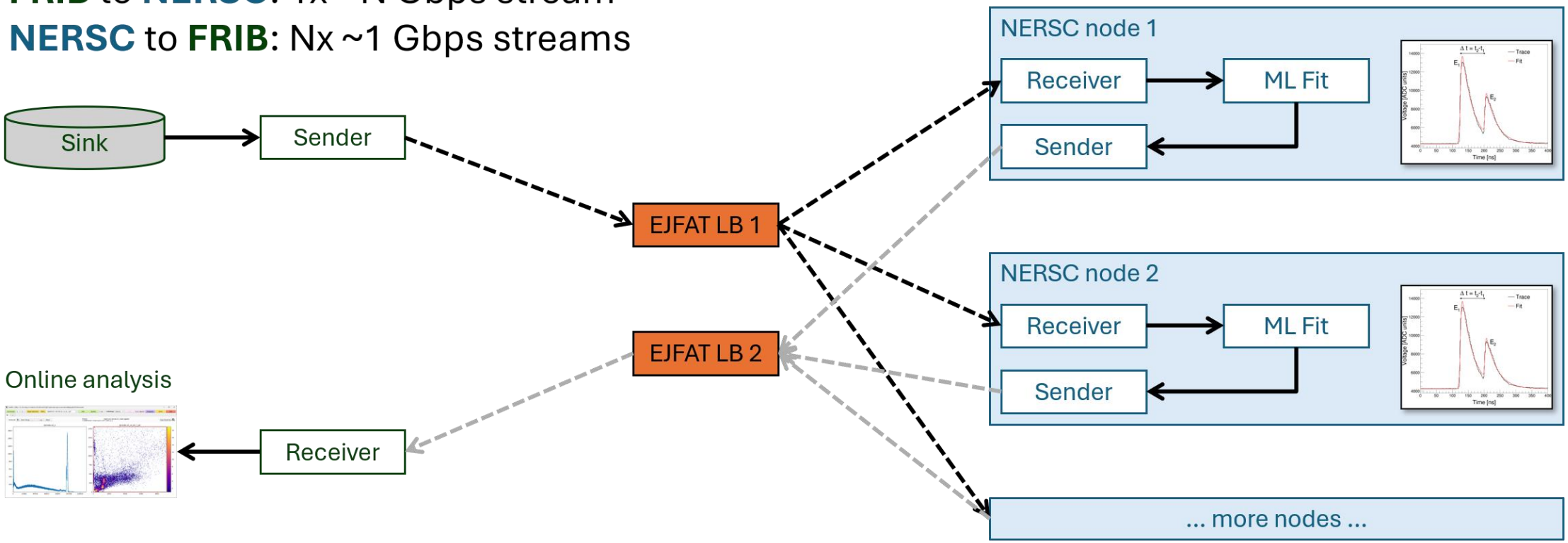


---→ Data transmitted over EJFAT

←--- Load Balancer data plane

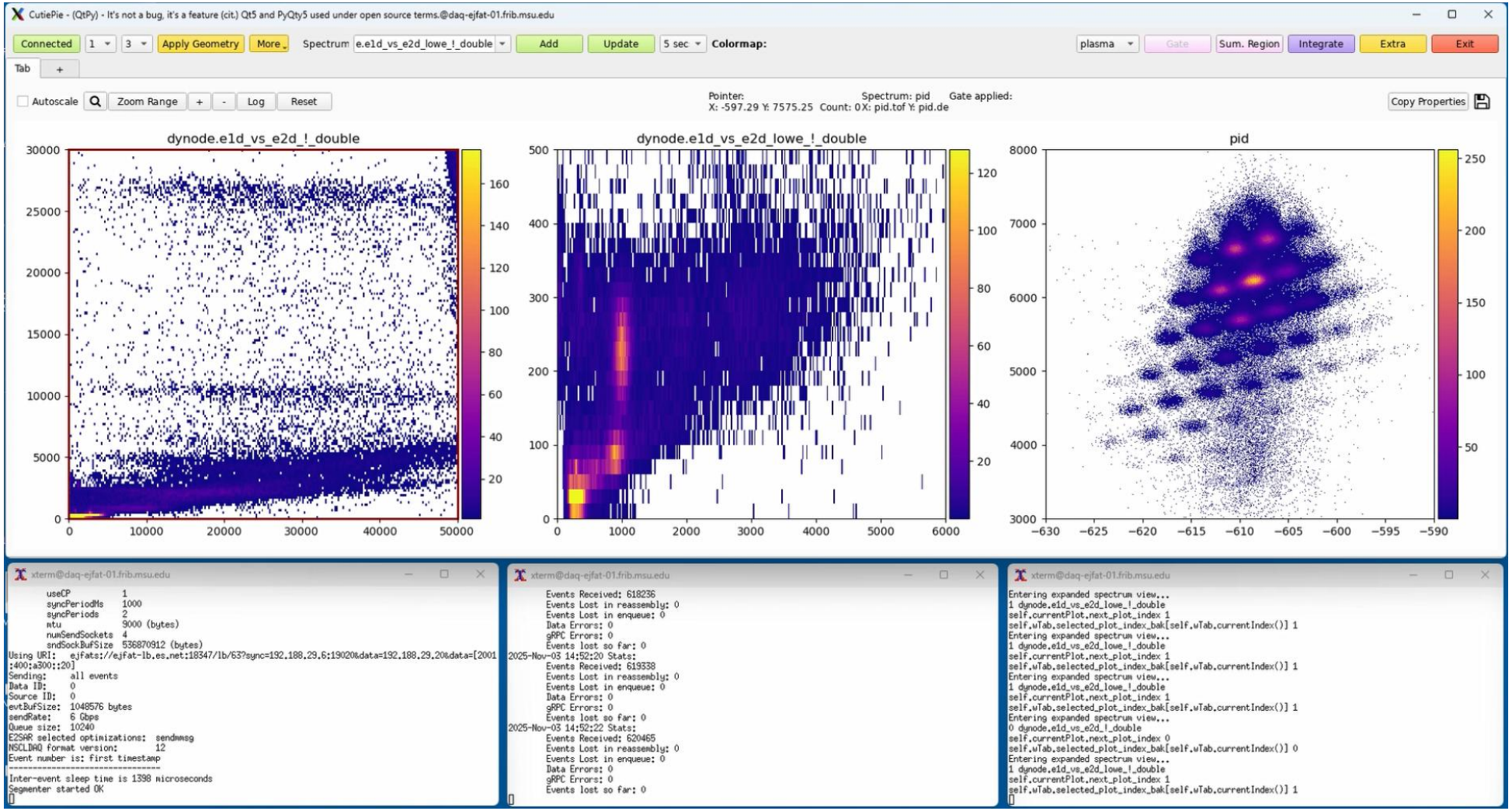
FRIB to **NERSC**: 1x N Gbps stream

NERSC to **FRIB**: Nx ~1 Gbps streams



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FRIB-E2SAR Workflow at SC25



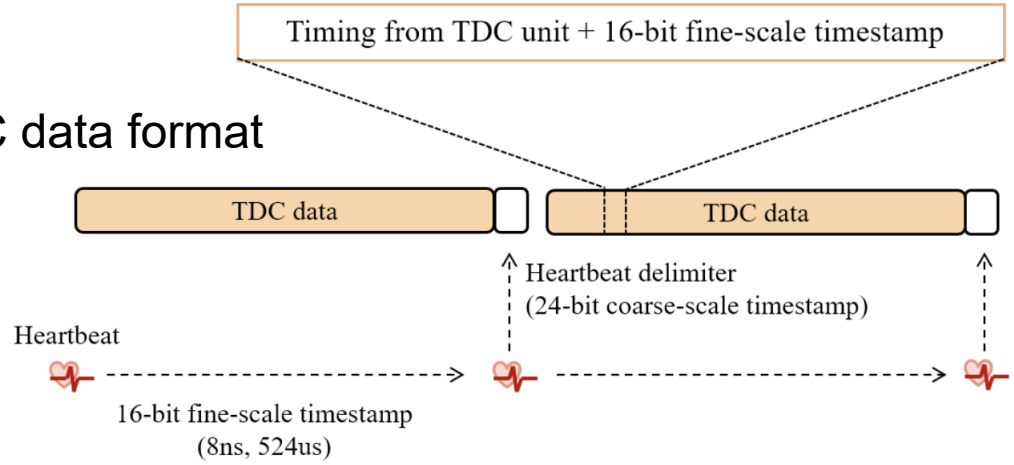
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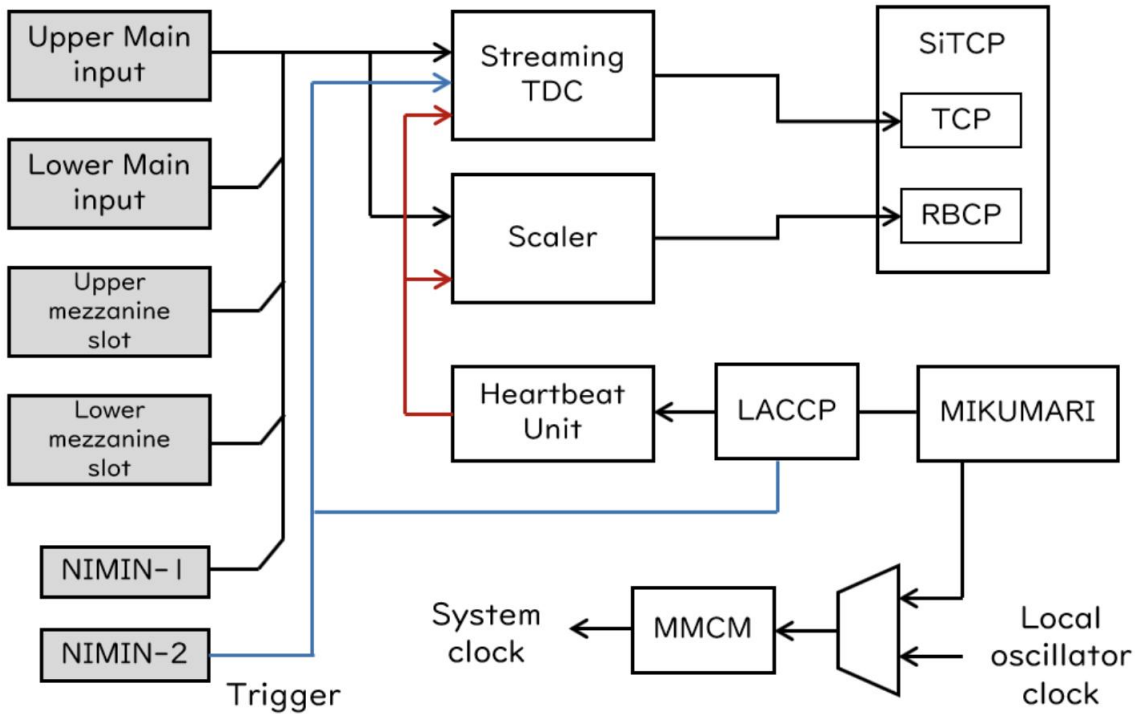
Data from FRIB experiment e23055 (B. Crider, Miss. St. University)

Towards Streaming Readout: MIKUMARI + FRIBDAQ

- Global clock synchronization at FRIB: AMANEQ board + MIKUMARI[4] (earlier talk by R. Honda)
- AMANEQ HR-TDC
  - Continuous read of TDC and scaler blocks
    - » Signal leading and trailing edge measured with 1 ns accuracy, time over threshold calculated internally
  - Data transmission via SiTCP

HR-TDC data format



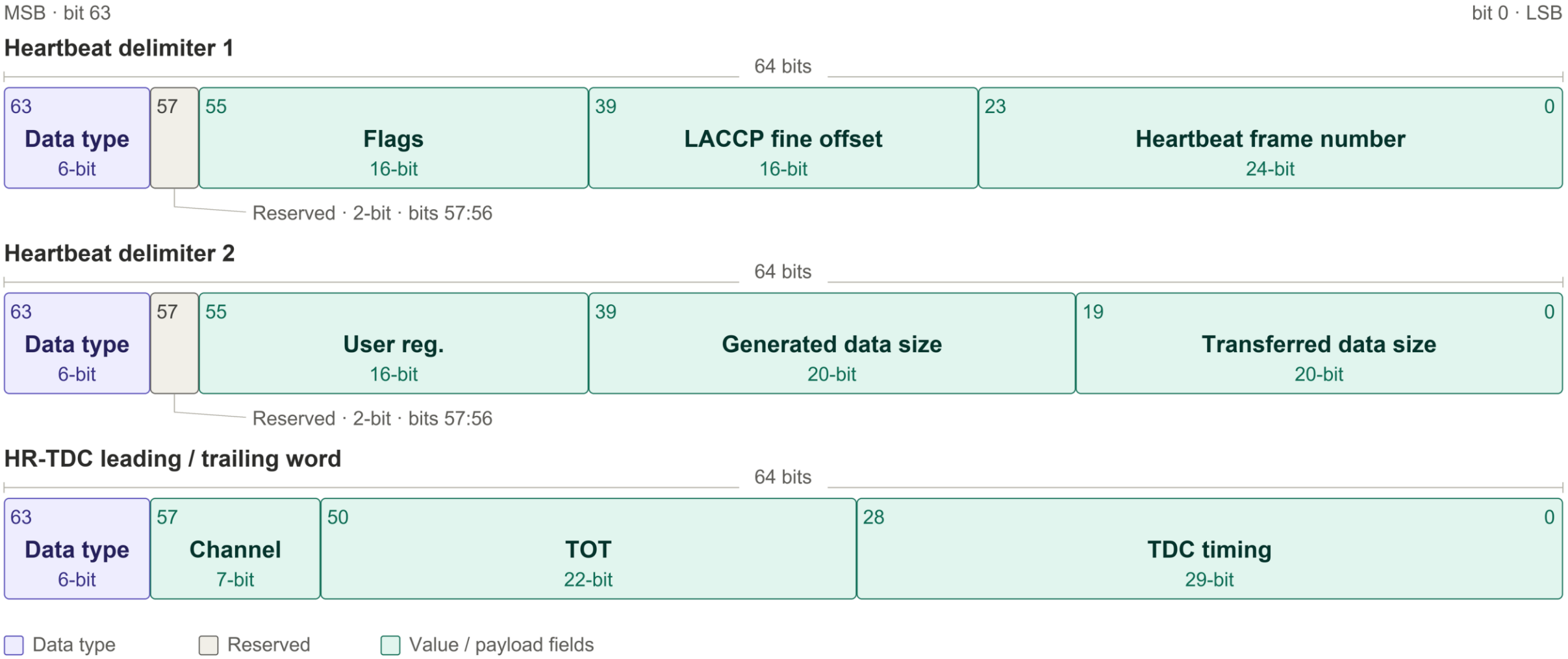


[4]Honda et al., *IEEE Trans. Nucl. Sci.* 72 (2025) 3, 614-622

Towards Streaming Readout: MIKUMARI + FRIBDAQ

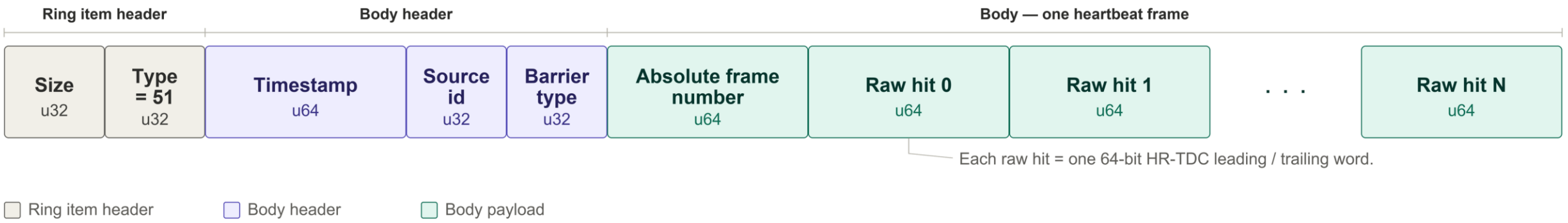
- Goal: Build HR-TDC data into events consisting of all TDC hits which satisfy a user-defined coincidence window
  - Typical event-building coincidence window is 0.1-10 μs, while heartbeat (HB) period is 524 μs
- Employ two-stage data processing
  - Stage 1: Encapsulates all data contained in a single HB, convert HB frame to coarse timestamp
  - Stage 2: Build events consisting of multiple coincident HR-TDC hits
- Built, timestamped HR-TDC data can be integrated into more complex FRIBDAQ data-processing pipelines using standard tools
  - Systems must be on a common clock…

MIKUMARI + FRIB: MIKUMARI Raw Data Format



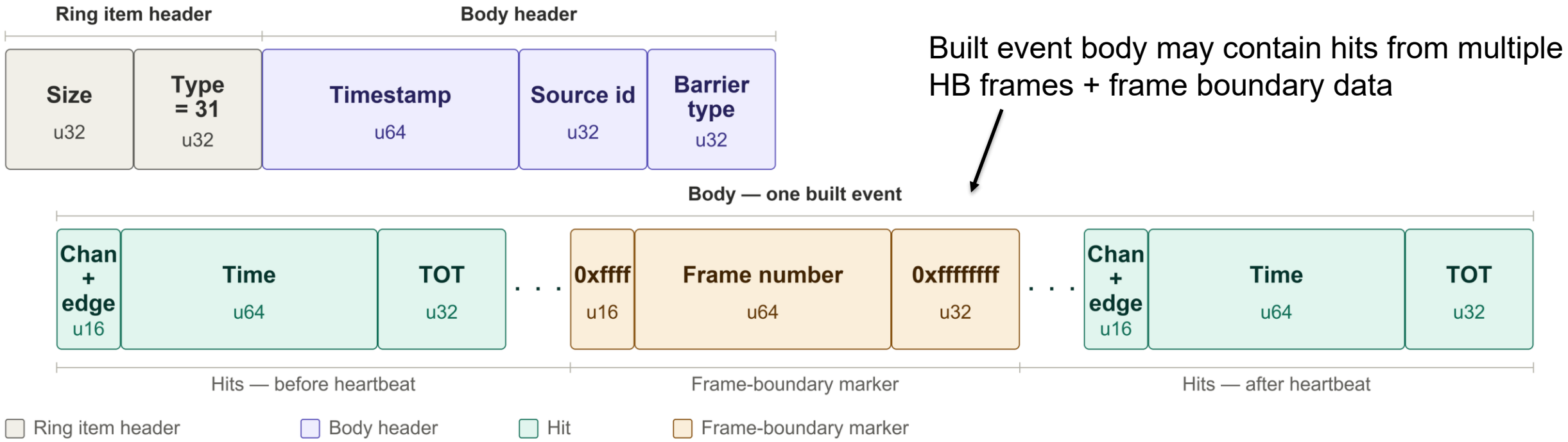
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MIKUMARI + FRIB: Stage 1 Data Format



- New FRIBDAQ data type 51 for MIKUMARI
- Absolute HB frame number increments from 0 at the start of a run
- Body header timestamp = HB frame number * 2^{29} clock ticks/frame
  - Each tick = 1/1024 ns
- Source id configurable by user
- Barrier type = 0

MIKUMARI + FRIB: Stage 2 Data Format



- FRIBDAQ PHYSICS_EVENT type 31
- Body header timestamp: Absolute time (in ticks) of first hit in the built event
- Hit timestamp = t_{HB} + $t_{rel.}$ (in ticks)
  - $t_{rel.}$ = time relative to the start of the hit's HB frame

Summary and Conclusions

- Developed a real-time workflow for distributed analysis of production FRIB experiment data offsite at NERSC
  - Integrated real-time trace fitting into standard FRIBDAQ online analysis tools
- SC25 demo workflow results
  - 615 GB of data: 15 hours of run time during the experiment
  - Total processing time: 20 minutes using 8 Perlmutter nodes
  - Average rate: 525 MB/s (hardware limited on FRIB data-transfer node)
- Successful integration of FRIBDAQ software with EJFAT/E2SAR
  - Attractive option for future SRO systems
  - Excellent support from EJFAT team
  - Very positive user experience
- Investigating data-processing schemes and formats for current and future SRO applications

Acknowledgements

Giordano Cerizza, Sean Liddick, Rebeka Lubna, Paul Reece, Tom Rockwell, Bashir Sadeghi, Jerry Vasquez

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Ben Crider

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