

Instrumentation Highlights in Nuclear Physics Projects

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U.S. Nuclear Physics Landscape

DOE-NP User Facilities

- **RHIC (Brookhaven, 2000–2026) → EIC (planned):** Transition from heavy-ion collisions studying quark–gluon plasma to electron–ion collisions exploring the quark and gluon structure of matter.
- **FRIB (Michigan State, 2022–present):** Rare-isotope accelerator for nuclear structure and astrophysics.
- **CEBAF (Jefferson Lab, 1995–present):** High-intensity electron accelerator for hadron structure and fundamental symmetries.
- **ATLAS (Argonne, 1985–present):** Heavy-ion accelerator for nuclear structure and astrophysics.

U.S.-based experiments outside DOE-NP user facilities

- **COHERENT (Oak Ridge, 2017–present):** Neutrino–nucleus scattering.
- **Project 8 (University of Washington, R&D ongoing):** Precision tritium beta-decay spectroscopy to measure the absolute neutrino mass.

Major international experiments/facilities with U.S. NP participation

- **LEGEND-1000 (site TBD, planned):** Tonne-scale germanium experiment searching for neutrinoless double-beta decay.
- **ALICE (CERN/LHC, 2010–present; upgrading):** Heavy-ion experiment studying quark–gluon plasma, with major detector upgrades for 2029 and beyond.
- **KATRIN (Germany, 2019–present; upgrading):** Precision tritium beta-decay experiment transitioning to searches for keV-scale sterile neutrinos.
- **FAIR (Germany, under construction):** Accelerator facility for nuclear structure, astrophysics, and strongly interacting matter.
- **RIBF (RIKEN, Japan, 2007–present):** Rare-isotope accelerator facility for nuclear structure and astrophysics.

Yellow = covered in this talk. List above is a sample,
not a comprehensive survey of US NP efforts!

NP & HEP Budgets

Program	FY2026 enacted	FY2027 President's request	Change	FY2027 House proposal
Nuclear Physics	\$866.1M	\$791.4M	-8.6%	\$870M
High Energy Physics	\$1,235M	\$1,120M	-9.3%	\$1,260M
Combined	\$2,101M	\$1,911M	-9.0%	\$2,130M

Note: NP/HEP 2027 requests increase construction funding, hence reducing the rest of the program somewhat more than suggested above (see backup).

Detector R&D

HEP Detector R&D activity	Funding
FY2026 enacted	\$11.075M
FY2027 request	\$10.268M

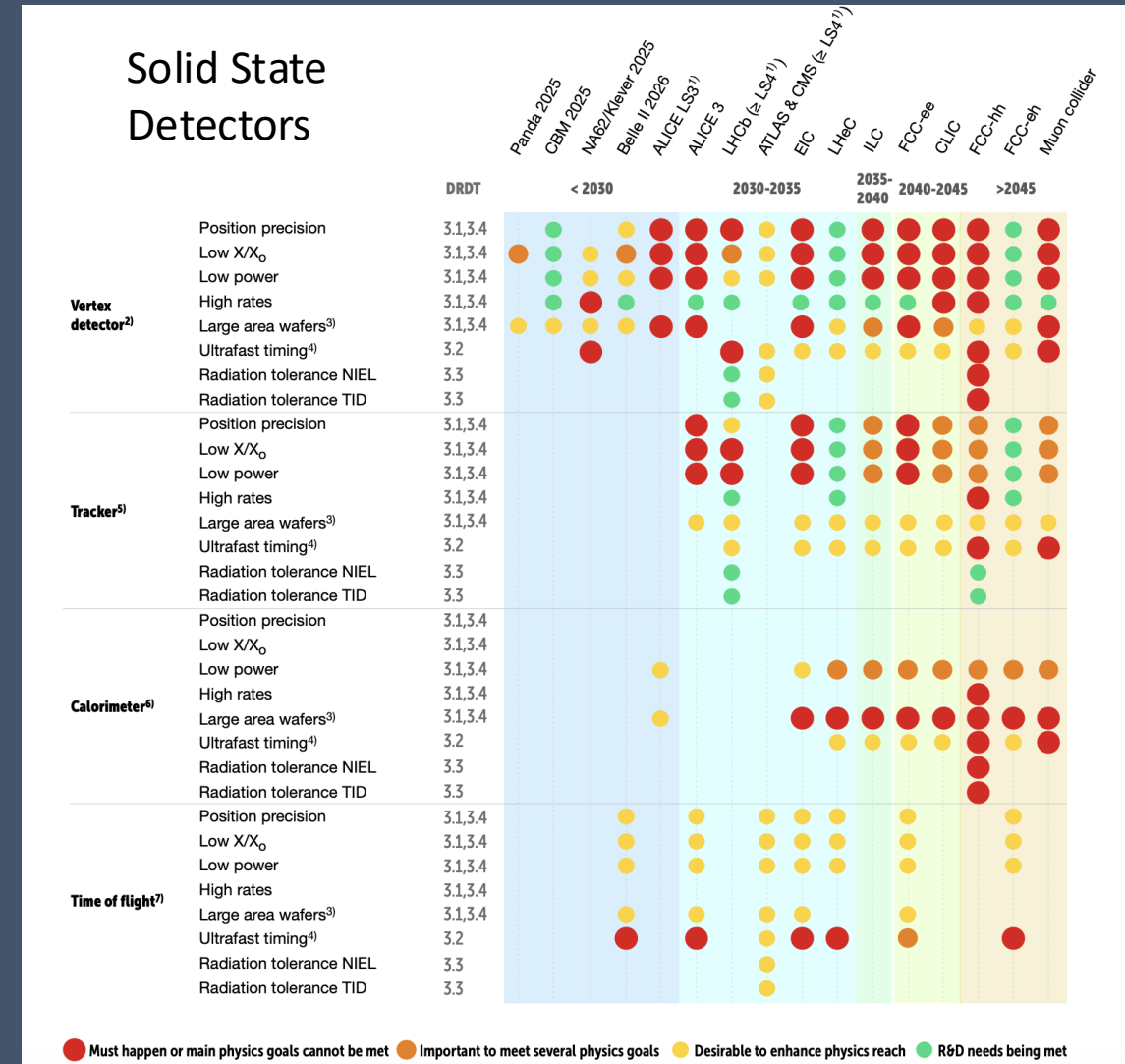
HEP has an explicit program prioritizing generic detector R&D. NP detector R&D has largely been driven by specific experimental needs, with fewer dedicated opportunities for long-term exploratory development. Particularly true for universities.

But see talk by Helmut Marsiske (DOE SC). Effective HEP R&D funding benefits from special initiatives; Microelectronics, AI/ML, QIS, Traineeships, Early Career, US-Japan, EPSCoR, workshops, etc.

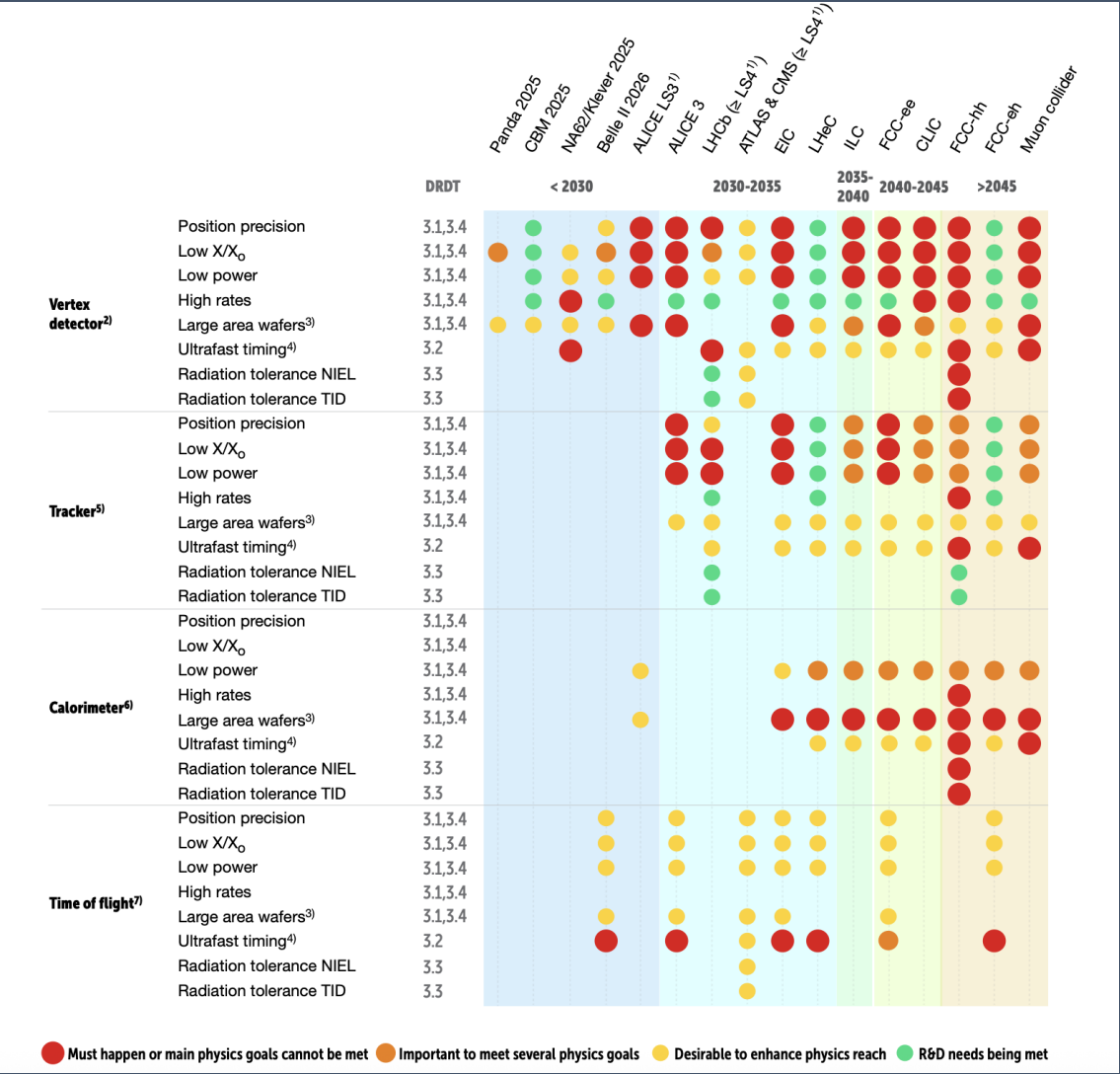
- **Research funding is \$27M, \$22M/\$5M at labs/universities**
- Facilities/test beam operation is \$4M (all at labs)

NP Instrumentation Challenges

- NP is different science from HEP, but there's substantial overlap in instrumentation needs.
- The [ECFA Detector R&D Roadmap](#) is a strategic plan developed by the European Committee for Future Accelerators (ECFA) following the 2020 Update of the European Strategy for Particle Physics.



Vertex Detector R&D Synergies; Quantitatively



"Technical" Start Date of Facility (This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)				< 2030					2030-2035					2035 - 2040	2040-2045		> 2045		
				Panda 2025	CBM 2025	NA62/Kleier 2025	Belle II 2026	ALICE LS3 ¹⁾	ALICE 3	LHCb ($\geq$ LS4) ¹⁾	ATLAS/CMS ($\geq$ LS4) ¹⁾	EIC	LHeC	ILC ²⁾	FCC-ee	CLIC ²⁾	FCC-hh	FCC-eh	Muon Collider
Vertex Detector ³⁾	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.1	Position precision σ_{hit} (μm)		≈ 5		≈ 5	≈ 3	≈ 3	≈ 10	≈ 15	≈ 3	≈ 5	≈ 3	≈ 3	≈ 3	≈ 7	≈ 5	≈ 5
			X/X ₀ (%/layer)	≈ 0.1	≈ 0.5	≈ 0.5	≈ 0.1	≈ 0.05	≈ 0.05	≈ 1		≈ 0.05	≈ 0.1	≈ 0.05	≈ 0.05	≈ 0.2	≈ 1	≈ 0.1	≈ 0.2
			Power (mW/cm ²)		≈ 60			≈ 20	≈ 20		≈ 20			≈ 20	≈ 20	≈ 50			
			Rates (GHz/cm ²)		≈ 0.1	≈ 1	≈ 0.1		≈ 0.1	≈ 6		≈ 0.1	≈ 0.1	≈ 0.05	≈ 0.05	≈ 5	≈ 30	≈ 0.1	
		Wafers area (") ⁴⁾					12	12				12		12		12		12	
		DRDT 3.2	Timing precision σ_t (ns) ⁵⁾	10		≈ 0.05	100		25	≈ 0.05	≈ 0.05	25	25	500	25	≈ 5	≈ 0.02	25	≈ 0.02
DRDT 3.3	Radiation tolerance NIEL (x 10 ¹⁶ neq/cm ²)							≈ 6	≈ 2						$\approx 10^2$				
	Radiation tolerance TID (Grad)							≈ 1	≈ 0.5						≈ 30				
Tracker ⁶⁾	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.1	Position precision σ_{hit} (μm)						≈ 6	≈ 5		≈ 6	≈ 6	≈ 6	≈ 6	≈ 7	≈ 10	≈ 6	
			X/X ₀ (%/layer)							≈ 1	≈ 1		≈ 1	≈ 1	≈ 1	≈ 1	≈ 2	≈ 1	
			Power (mW/cm ²)							≈ 100	≈ 100		≈ 100		≈ 100	≈ 100	≈ 150		
			Rates (GHz/cm ²)								≈ 0.16								
		Wafers area (") ⁴⁾							12			12		12	12	12	12		12
		DRDT 3.2	Timing precision σ_t (ns) ⁵⁾						25	≈ 25		25	25	≈ 0.1	≈ 0.1	≈ 0.1	≈ 0.02	25	≈ 0.02
DRDT 3.3	Radiation tolerance NIEL (x 10 ¹⁶ neq/cm ²)								≈ 0.3						≈ 1				
	Radiation tolerance TID (Grad)								≈ 0.25						≈ 1				
Calorimeter ⁷⁾	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.2	Timing precision σ_t (ns) ⁵⁾										≈ 0.05	≈ 0.05	≈ 0.05	≈ 0.02		≈ 0.02	
		DRDT 3.3	Radiation tolerance NIEL (x 10 ¹⁶ neq/cm ²)														$\approx 10^2$		
				Radiation tolerance TID (Grad)												≈ 50			
Time of Flight ⁸⁾	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.2	Timing precision σ_t (ns) ⁵⁾				≈ 0.02		≈ 0.02		≈ 0.03	≈ 0.02	≈ 0.02		≈ 0.01		≈ 0.01	≈ 0.02	
			Radiation tolerance NIEL (x 10 ¹⁶ neq/cm ²)															$\approx 10^2$	
			Radiation tolerance TID (Grad)													≈ 30			

Values are indicative of performance targets and of operating conditions relevant to R&D. The latter are reported for the regions most exposed to radiation. Empty cells indicate either that projects are not concerned; or that specifications are already met or not yet fully established, for instance power consumption depends strongly on granularity and digital features that would be finally implemented.

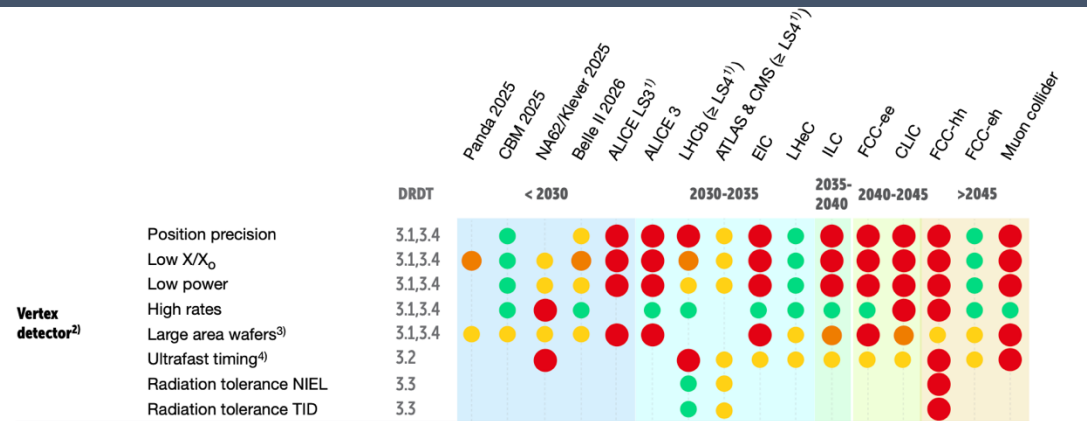
1) LS3/LS4 are scheduled to start in 2025/2031 at the time of this document.

2) Reported rates are within the bunch trains.

3) LHCb/ATLAS/CMS consider Planar/3D sensors at the time of this document for rates and radiation tolerance. Pixelated LGADs could already be considered for NA62/Kleier and for longer term Vertex Detectors for timing precision for high timing precision.

4) The size of wafers achievable can depend on technology (industrial process) with a general trend to benefits from larger areas.

Vertex Detector R&D Synergies; *Quantitatively*



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Vertex Detector ³⁾	MAPS Planar/3D/passive CMOS LGADs	DRDT 3.1 DRDT 3.4	Position precision σ_{hit} (μm)		≈ 5		≈ 5	≈ 3	≈ 3	≈ 10	≈ 15	≈ 3	≈ 5	≈ 3	≈ 3	≈ 3	≈ 7	≈ 5	≈ 5
			X/X ₀ (%/layer)	≈ 0.1	≈ 0.5	≈ 0.5	≈ 0.1	≈ 0.05	≈ 0.05	≈ 1		≈ 0.05	≈ 0.1	≈ 0.0	≈ 0.05	≈ 0.2	≈ 1	≈ 0.1	≈ 0.2
			Power (mW/cm ²)		≈ 60			≈ 20	≈ 20		≈ 20		≈ 20	≈ 20	≈ 20	≈ 50			
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			Wafers area (cm ²) ⁴⁾					12	12			12			12		12		12
		DRDT 3.2	Timing precision σ_t (ns) ⁵⁾	10		≈ 0.05	100		25	≈ 0.05	≈ 0.0	25	25	500	25	≈ 5	≈ 0.02	25	≈ 0.02
		DRDT3.3	Radiation tolerance NIEL (x 10 ¹⁶ neg/cm ²)						≈ 6	≈ 2							$\approx 10^2$		
			Radiation tolerance TID (Grad)						≈ 1	≈ 0.5							≈ 30		
			Position precision σ_{xy}																

- EIC and FCC-ee vertex requirements are remarkably similar
- Only difference in table: x 2 higher rate/unit-area at EIC
- This is just a single example of NP/HEP R&D synergies for collider detectors
- ECFA report is a goldmine of information - contains eight such graphs and summaries...

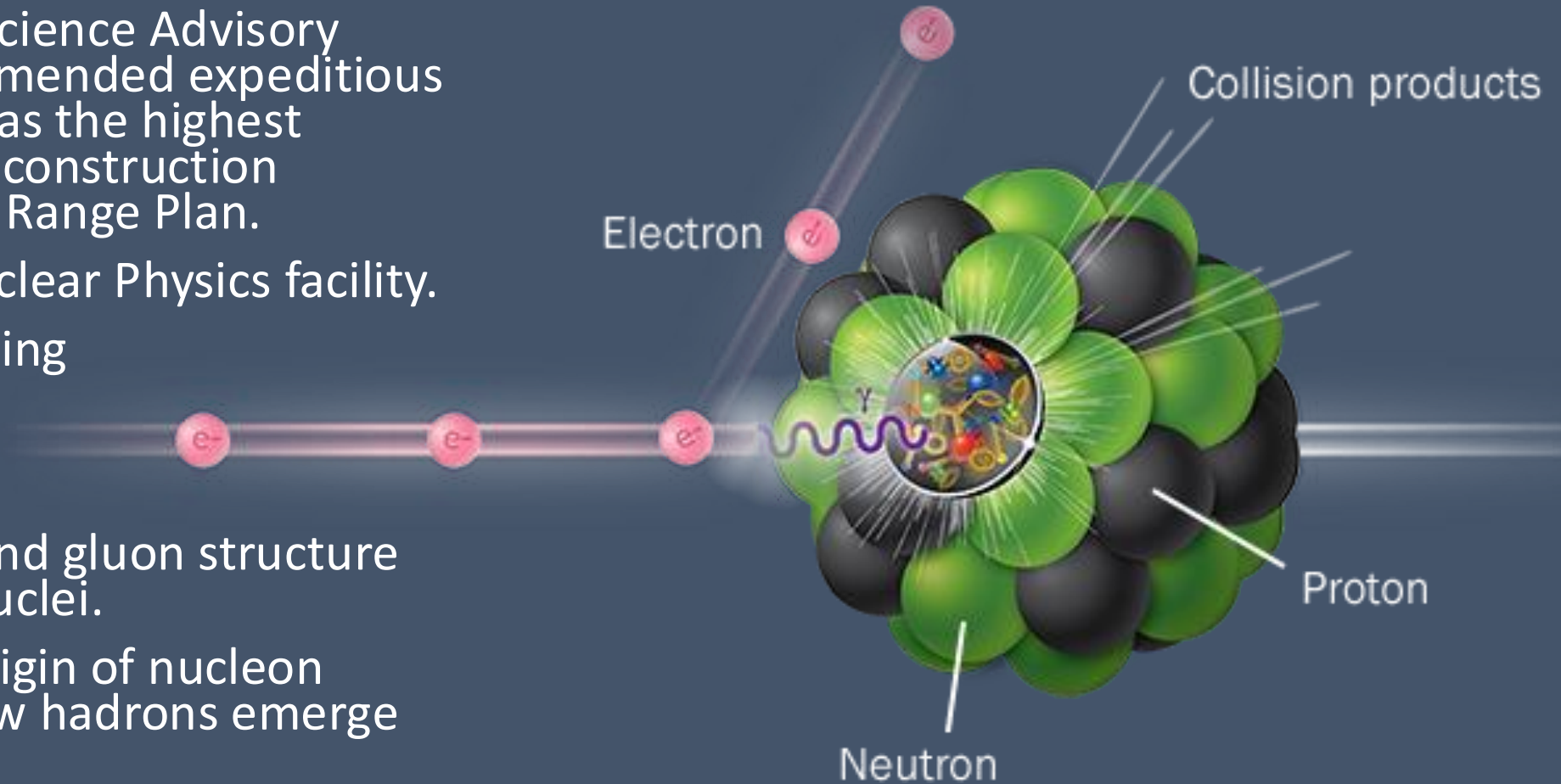
Electron-Ion Collider (EIC): A New Window into QCD

Status

- The U.S. Nuclear Science Advisory Committee recommended expeditious completion of EIC as the highest priority for facility construction in their 2023 Long Range Plan.
- \$2–3B flagship Nuclear Physics facility.
- Construction ongoing

Physics goals

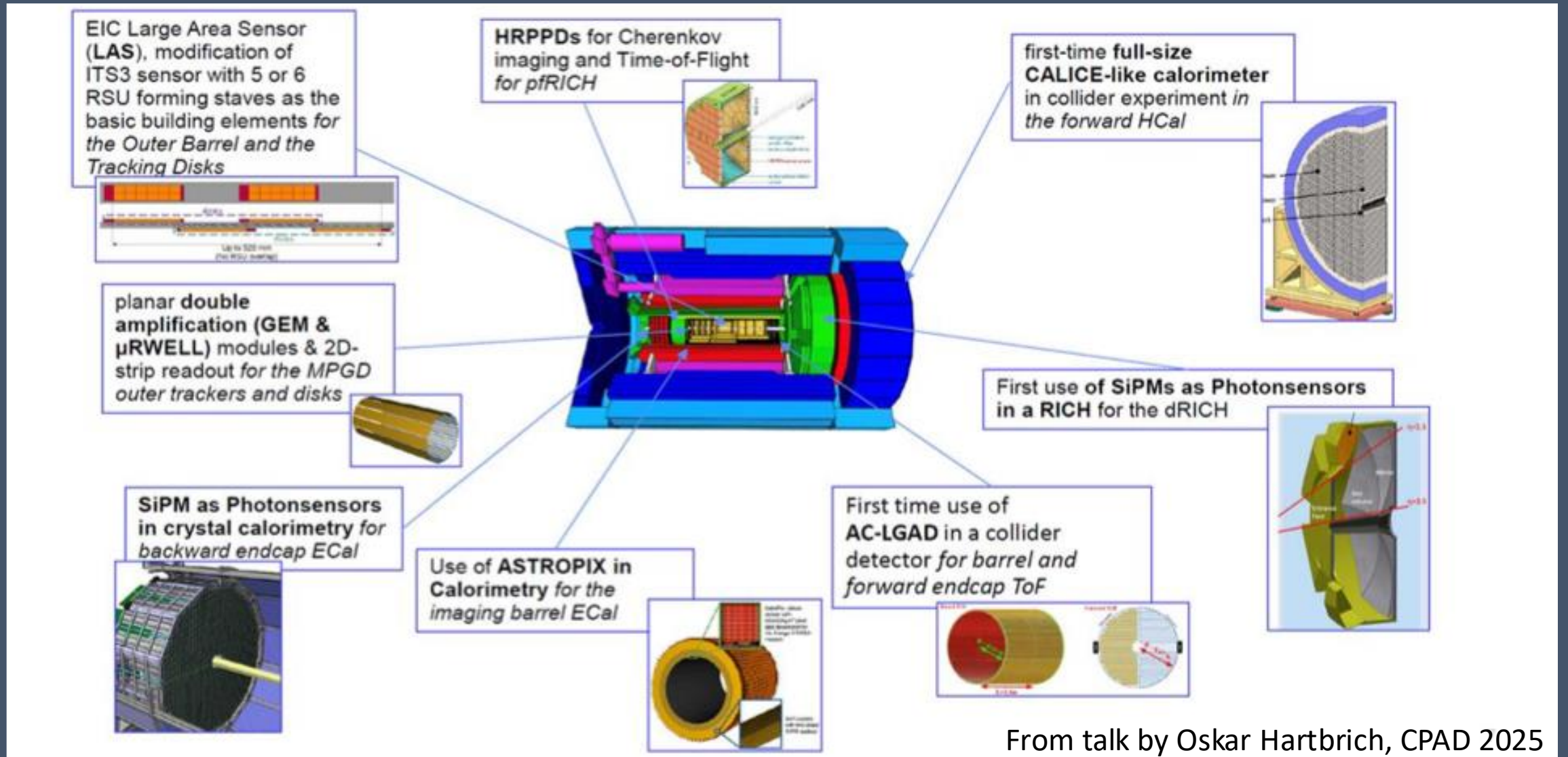
- Image the quark and gluon structure of nucleons and nuclei.
- Understand the origin of nucleon properties and how hadrons emerge from QCD.



Startup expected mid 2030s



ePIC Detector: New Technologies



From talk by Oskar Hartbrich, CPAD 2025

Curved Monolithic Active Pixel Sensors (MAPS)

- **Innovation**

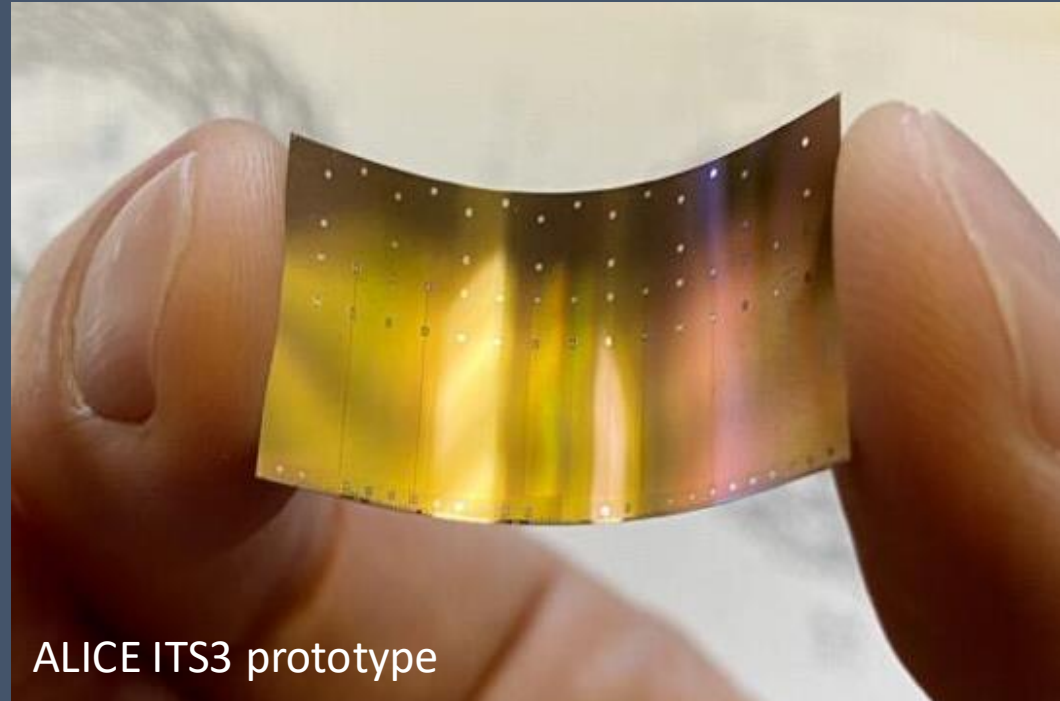
Large area, stitched CMOS pixel sensors, thinned to $\sim 50\text{ }\mu\text{m}$ and bent into cylindrical tracking layers.

- **Detector benefit**

Precision vertexing with exceptionally little material, hence minimal multiple scattering.

- **HEP–NP connection**

Shared technology development with ALICE ITS3; strong potential for future precision HEP experiments such as FCC-ee.

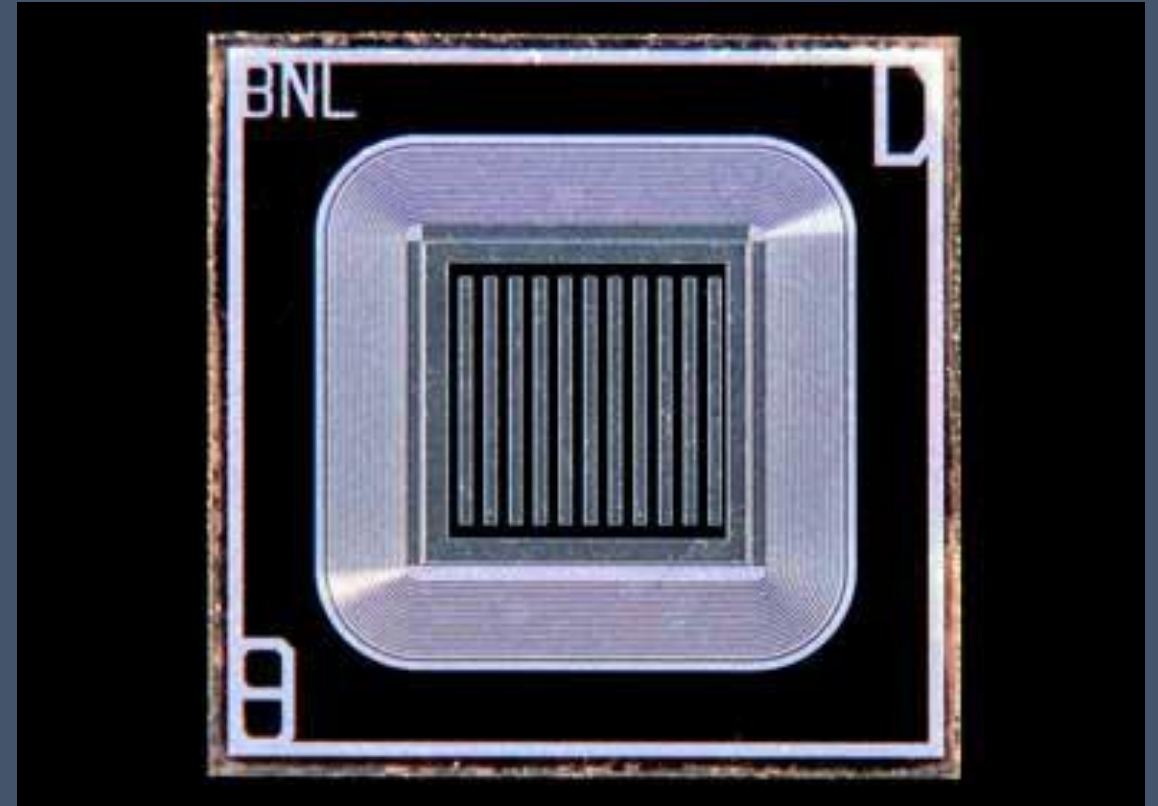


The three innermost ePIC tracking layers use this technology

Design target: approx. 0.07% X_0 per inner barrel layer.

AC-Coupled Low-Gain Avalanche Detectors (AC-LGADs)

- **Innovation**
Internal charge gain combined with AC-coupled, finely segmented electrodes.
- **Detector benefit**
Extends PID (via time-of-flight) over broad momentum range, simultaneous position measurement.
- **HEP–NP connection**
ePIC builds on the LGAD technology developed for HL-LHC timing detectors, extending it to high-precision simultaneous position and time measurements.

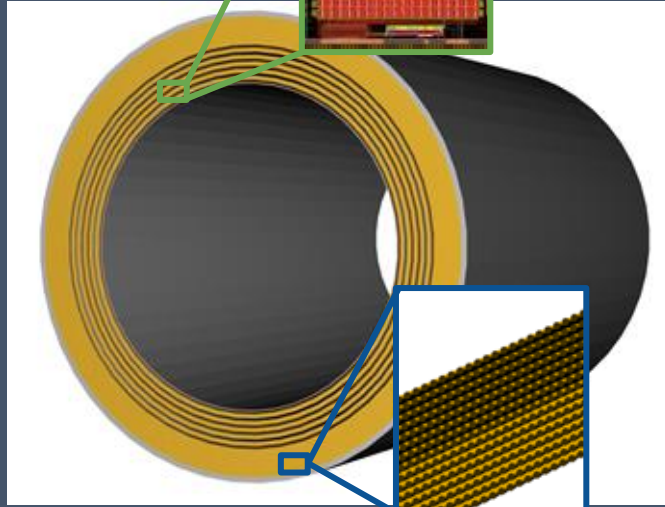


~30 ps timing resolution (design goal)

~10 m² of AC-LGAD sensor area required for ePIC detector; first large-scale application of AC-LGADs

Barrel Imaging Calorimeter with Astropix

AstroPix: silicon sensor with $500 \times 500 \mu\text{m}^2$ pixel size

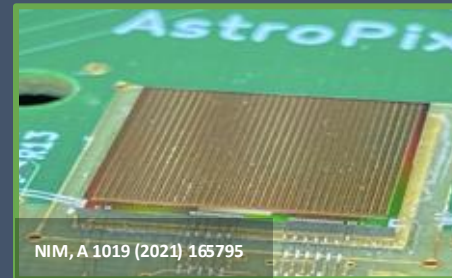


ePIC Simulations: Barrel ECal Geometry Rendering

ScFi Layers with two-sided SiPM readout



NIM, A 896 (2018) 24-42



NIM, A 1019 (2021) 165795



Innovation

Low-power silicon pixel layers embedded *within a sampling calorimeter*.

Detector benefit

Combination of SciFi and Si tracking layers yields unprecedented shower position resolution $\sim 0.1^\circ$.

3D shower imaging enables electron/pion discrimination and separation of overlapping photons from $\pi^0 \rightarrow \gamma\gamma$ decays.

HEP–NP connection

Technology transfer from high-energy *astrophysics* (gamma ray astronomy) to nuclear physics calorimetry; potential applications to future imaging calorimeters.

ePIC: Hybrid GEM- μ RWELL Detectors

- **Innovation**
GEM preamplification combined with resistive μ RWELL amplification and readout.
- **Detector benefit**
Large-area, low-material tracking with high efficiency, spatial precision, and robust operation at high rates.
- **HEP-NP connection**
Shared MPGD technologies developed for collider tracking, neutrino experiments, and rare-event detectors.

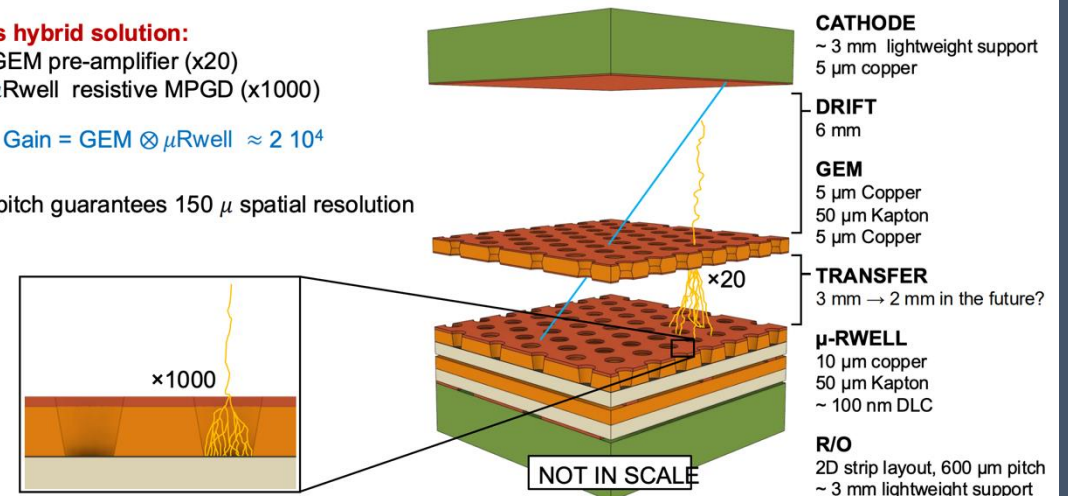
New MPGD Technology: - GEM- μ RWELL Hybrid Detector

Two stages hybrid solution:

- GEM pre-amplifier (x20)
- μ Rwell resistive MPGD (x1000)

$$\text{Total Gas Gain} = \text{GEM} \otimes \mu\text{Rwell} \approx 2 \cdot 10^4$$

- 600 μm pitch guarantees 150 μ spatial resolution



All R&D Studies for EIC disks performed in synergic collaboration with INFN-LNF and JLAB

Spatial resolution $\leq 150 \mu\text{m}$ (design target).

ePIC: Next-Generation Detector Systems

Three examples illustrating innovation **beyond individual sensors**.

Accelerator-integrated forward detectors

- **Innovation:** Detector systems integrated into the accelerator lattice.
- **Benefit:** Access to particles escaping conventional detector acceptance.
- **HEP–NP:** Shared challenges with forward physics at hadron colliders.

AI-assisted detector design

- **Innovation:** Multiobjective optimization of detector geometry and technology.
- **Benefit:** Optimize physics performance, complexity, and cost.
- **HEP–NP:** A general approach to designing future experiments.

Intelligent streaming readout

- **Innovation:** FPGA-based neural-network processing in the dRICH.
- **Benefit:** Real-time noise rejection and reduced data bandwidth.
- **HEP–NP:** Real-time processing for future high-rate experiments.

Facility for Rare Isotope Beams (FRIB)

Operated by a University (Michigan State) — unique feature among DOE Office of Science user facilities.

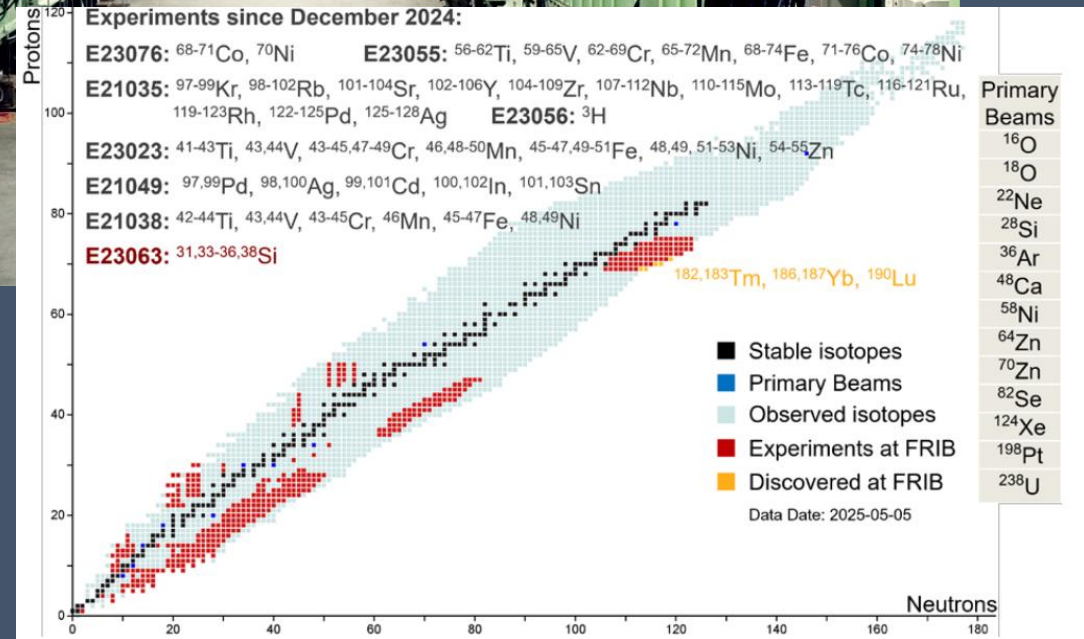
Facility

- Operating since 2022.
- Superconducting heavy-ion accelerator providing access to thousands of rare isotopes, many never previously studied.
- High Rigidity Spectrometer (HRS) under construction, promising up to 100× higher experimental luminosity.



Physics goals

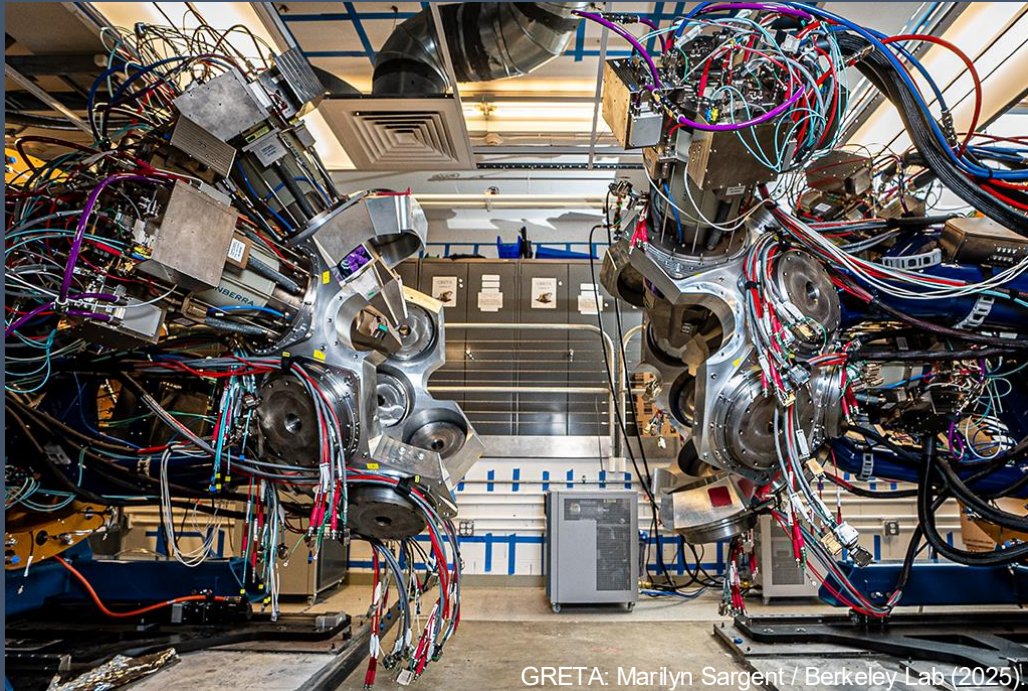
- Explore exotic nuclei and the limits of nuclear existence; measure nuclear reactions and decay properties governing astrophysical nucleosynthesis.



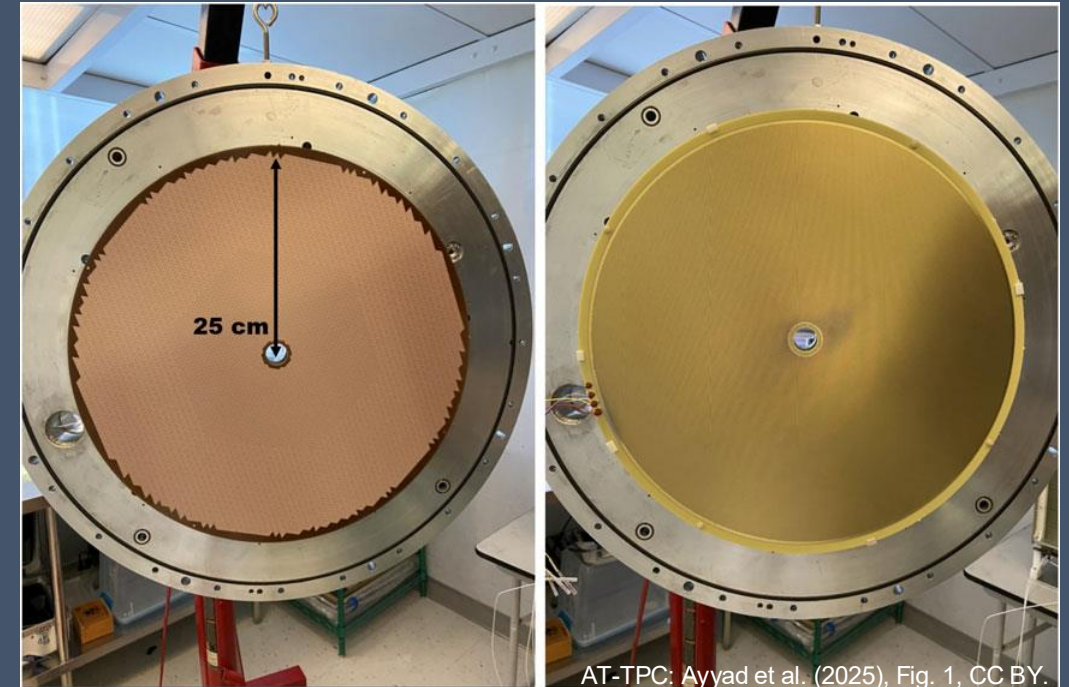
FRIB hosted 2026 DRD1 Summer School on Gaseous Detectors – thank you!

Examples of Operational FRIB Detectors

Gamma-Ray Energy Tracking Array (GRETA)



Active-target TPC (AT-TPC)



- GRETA and AT-TPC provide high-efficiency, nearly hermetic detection of gamma rays and charged particles, respectively, enabling detailed reconstruction of reactions involving rare-isotope beams.
- AT-TPC
 - The gas serves both as the target and detection medium
 - Employs a hybrid multilayer THGEM (M-THGEM) and Micromegas readout, enabling high-gain 3D charged-particle tracking in pure target gases such as H_2 , D_2 , and He, without quenchers
 - Advancement in micro-patterned gaseous detectors (MPGD) by FRIB researchers, highly synergistic with R&D towards future low-energy HEP/NP experiments

Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab (JLab) in Newport News, VA



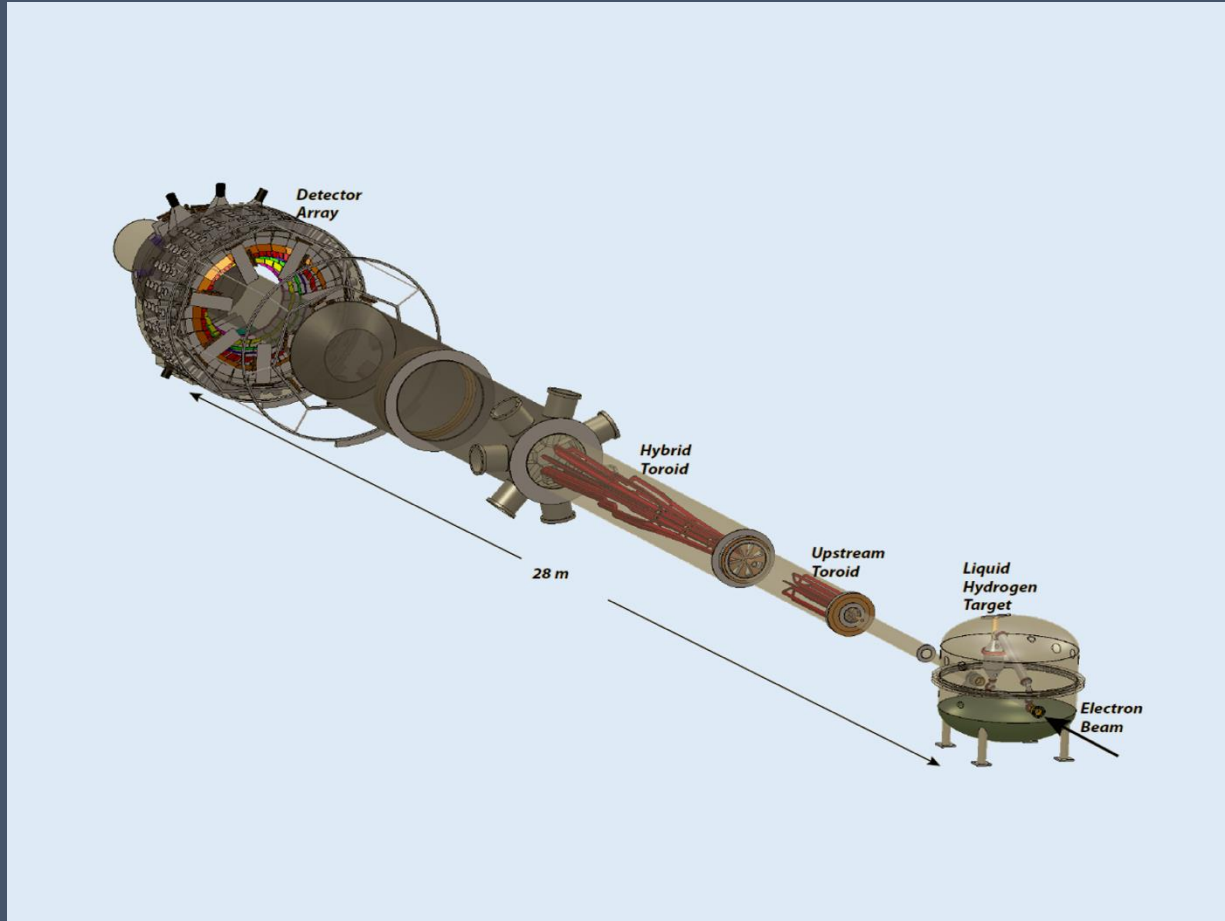
12-GeV “continuous” (high-duty-factor) electron beams

Physics goals

- Explore the quark–gluon structure of hadrons.
- Test the Standard Model through precision electroweak measurements.

MOLLER*: Precision Electroweak Physics at JLab

*Measurement of a Lepton-Lepton Electroweak Reaction.



- **Physics:** Measure parity-violating asymmetry in polarized electron–electron scattering to determine the weak mixing angle and probe BSM physics.
- **Precision:** Tiny asymmetry of **~33 ppb**, measured to 2.4% relative precision.
- **Status:** Under construction and installation; operation in 2027.

HEP/NP instrumentation: MOLLER combines GHz-rate integrating Cherenkov detectors, ultra-low-noise precision electronics, and GEM tracking to measure a ~33 ppb parity-violating asymmetry with sub-ppb precision.

Measuring the Neutrino Mass

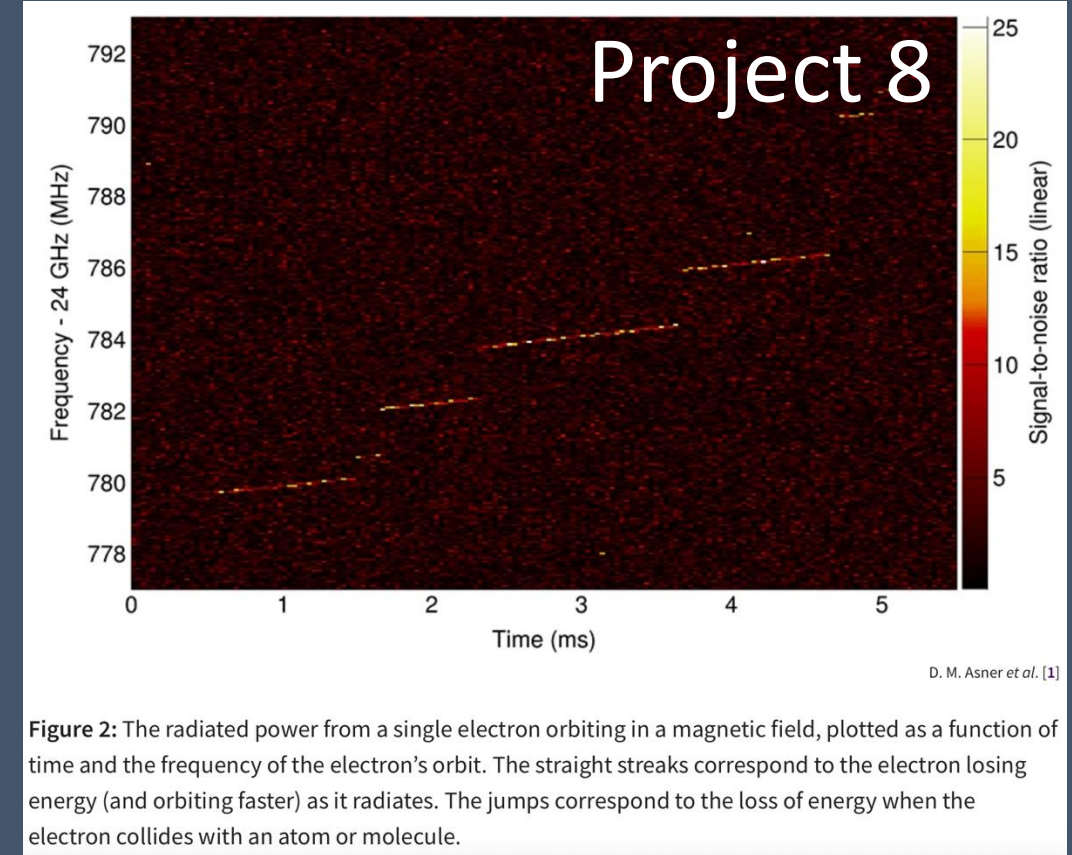
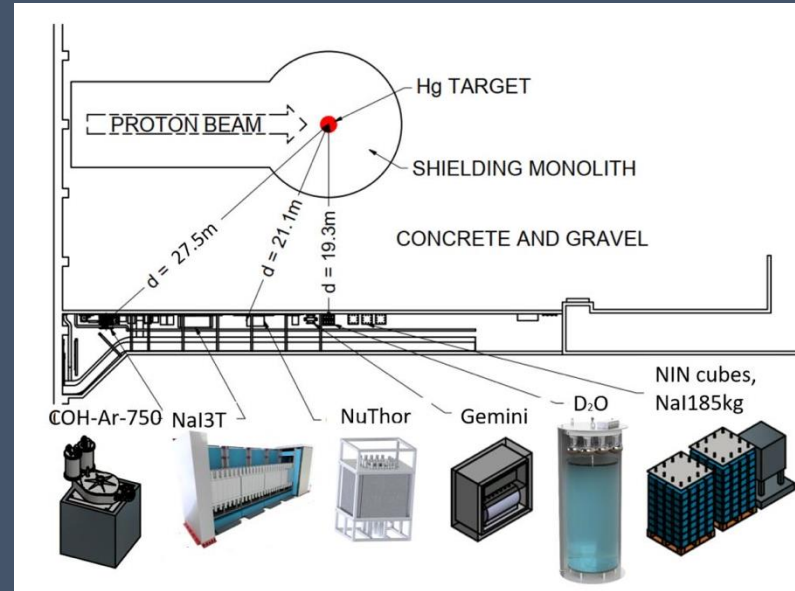


Figure 2: The radiated power from a single electron orbiting in a magnetic field, plotted as a function of time and the frequency of the electron's orbit. The straight streaks correspond to the electron losing energy (and orbiting faster) as it radiates. The jumps correspond to the loss of energy when the electron collides with an atom or molecule.

- **KATRIN:** Direct neutrino-mass measurement using tritium beta decay and an enormous, ultra-high-resolution electrostatic spectrometer. **Result:** $m_\beta < 0.45$ eV (90% CL, 2025); full dataset under analysis, final result expected in 2027.
- **Project 8:** Next-generation approach. Measures individual electron energies from their cyclotron radiation frequencies, pioneering a potentially scalable technique for direct neutrino-mass measurements.
- **Project 8 is an example of pioneering detector R&D in NP. Right here at the University of Washington (CENPA).**

Rare Events

- **COHERENT:** Measuring coherent elastic neutrino-nucleus scattering (CEvNS) at the SNS; low-threshold nuclear-recoil detection. Operational at SNS.
- **LEGEND-1000:** Search for neutrinoless double-beta decay using one tonne of enriched germanium detectors. In design and pre-construction R&D.



HEP/NP synergies: Strong overlap with dark matter searches. COHERENT in low-energy signal detection; LEGEND-1000 in extreme background suppression and argon purification.
Also: new proposal to [perform directional CEvNS measurements at SNS](#). HEP group detector R&D for NP physics at a BES facility.

HEP–NP Instrumentation: Stronger Together

- **Shared challenges:** Detector requirements on precision, sensitivity, and background suppression transcend disciplinary boundaries.
- **Existing synergies:** R&D already crosses these boundaries, making the HEP–NP merger a natural step for our community.
- **R&D investment:** The fraction of total HENP funding going to blue-sky detector R&D is of order 1% (national labs) and 0.2% (universities).
- **Complementary strengths:** Labs and universities each bring unique resources, facilities, and expertise.
- **Looking forward:** How can we make it easier for labs and universities to work together?