APS Division of Nuclear Physics DNP

APS Division of Particles & Fields DPF

Physics in a Flash

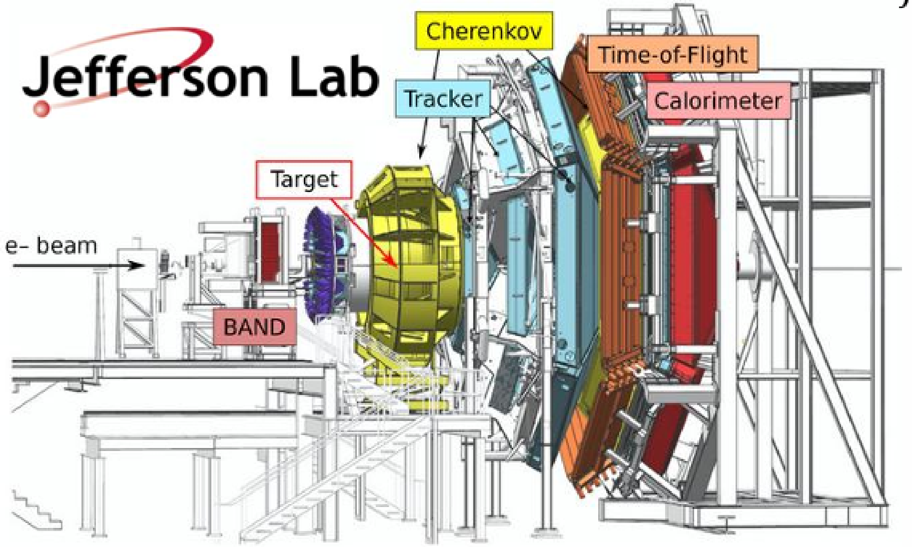
Nuclear Physics Data to Empower World-Leading Neutrino High-Energy Physics

Vector (V) EM interaction

$$j_\mu^{EM} = \bar{u}\gamma^\mu u$$

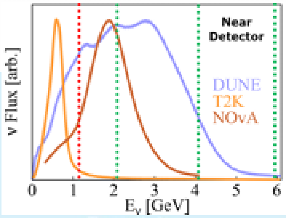
Vector minus axial vector ($V - A$)
EW CC interaction

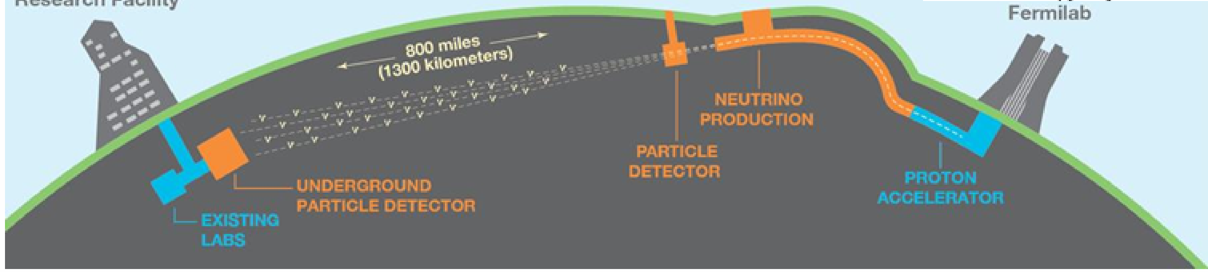
$$j_\mu^{EW\pm} = \bar{u}\frac{-ig_W}{2\sqrt{2}}(\gamma^\mu - \gamma^\mu\gamma^5)u$$



Almost identical FSI and nuclear effects between interaction types!

No pesky axial form factor issues!





- $e4\nu$: a collaboration of NP & HE scientists
- Data taking data at NP lab (Jefferson)
- **Main purpose**:
  - **Provide detailed measurements of the vector EM production of hadronic final states**
  - **Empower ν-nucleus simulations for ν oscillation experiments**

- Leading collaborators from Israel, US, Spain, and UK
- **10's of millions of events for ^{40}Ar**, and more—ready for analysis!
- Beam energies relevant to DUNE + NOvA—**empowering US ν program!**
- Filling the gap: very little existing data for hadronic final states (e.g. w/ πs)
- Analyses for (e, e') underway—also for many other possible final states: $\{(e, e'p), (e, e'\pi^\pm), (e, e'p\pi^\pm), (e, e'pp), \ldots$ with future prospects for ns!$\}$
- Other final states open to new collaborators—consider joining!

Support Letters

$e4\nu$ — Electrons for Neutrinos Webpage
Adapted from S. Dytman, A. Ashkenazi, J. Tena-Vidal, L. Weinstein, A. Papadopoulou, O. Hen *et al.*
New: Proton transparency and neutrino physics: New methods and modeling | Phys. Rev. D
See also Nature 599, 565–570 (2021), Neutrino 2024 | e4nu | J. Tena-Vidal

The Beam Dump eXperiment - BDX

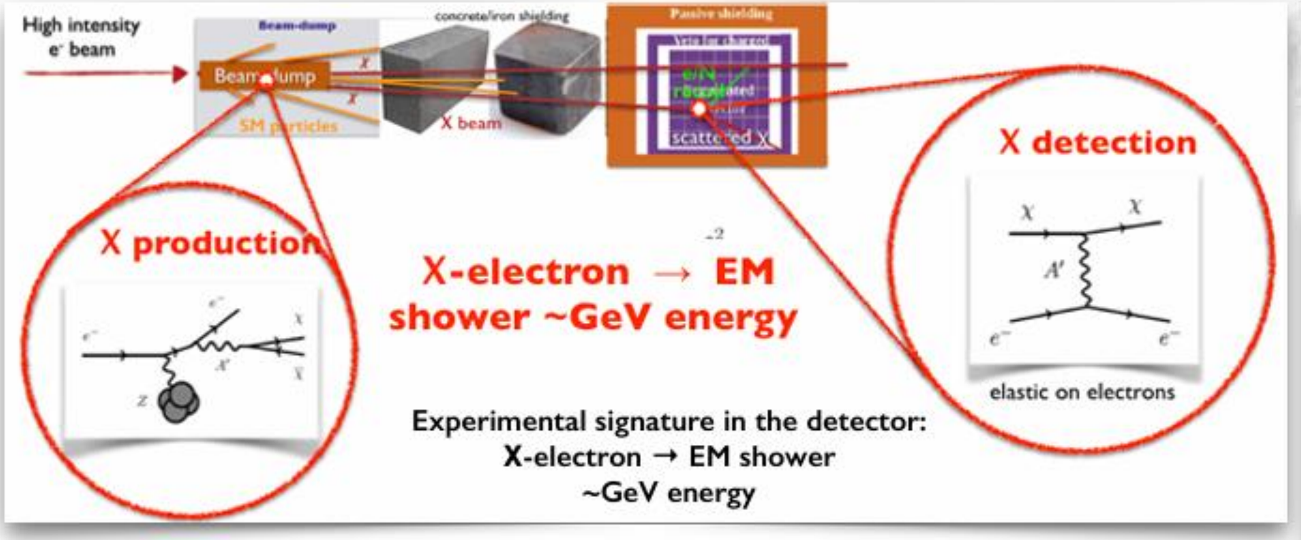
Spokespersons:
M.Battaglieri (INFN), M.Bondi (INFN), A.Celentano (INFN), M.DeNapoli (INFN), R.DeVita (JLab), G.Krnjaic (FNAL)

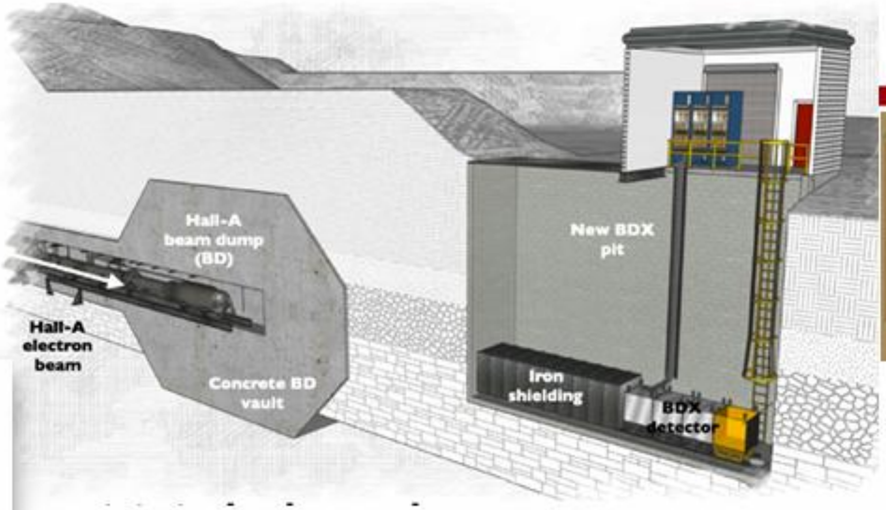
★ Unique experiment able to **PRODUCE** and **DETECT** Light Dark Matter

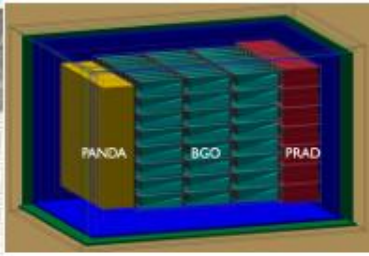
Two-step process:

I) An electron radiates an A' and the A' promptly decays to a χ (DM) pair

II) The χ (in-)elastically scatters on an e⁻/nucleon in the detector producing a visible recoil (GeV)





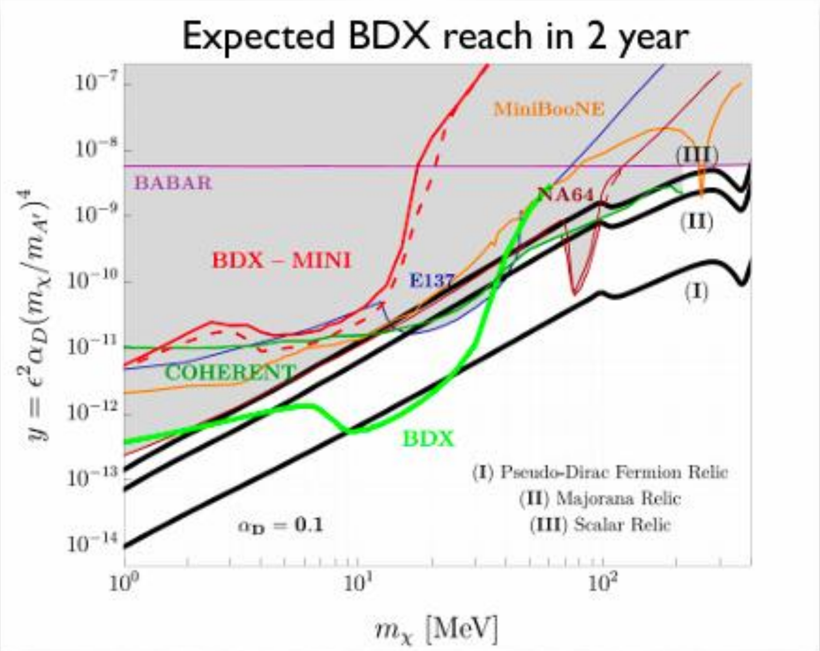


BDX detector: E.M. Calorimeter + 3 veto's layers

- 3 tons of active target (crystals)
- 480 BGO + 1200 PbWO + 800 PbWO
- 6x6 mm² Hamamatsu SiPM readout
- 2 Plastic scintillator veto's + WLS fibres + SiPMs
- Detector Size (L x H x W) : 1.6 x 1.2 x 1.1 m3

★ JLab offers the best condition for BDX:

- A high energy beam: 11 GeV
- The highest available electron beam current: ~65 uA
- The highest integrated charge: 10^{22} EOT (41 weeks)
- Fully opportunistic wrt Hall-A physics program (Moeller experiment)
- Calorimetry + Skipper-CCD technologies



Accumulating 10^{22} EOT in ~2y BDX sensitivity is 10-100 times better than existing limits on LDM

★ BDX Collaboration: more than 100 researchers from 18 institutions (US, Italy, Germany, UK, Korea) signed the BDX proposal

LEGEND

LEGEND aims to improve the half-life discovery sensitivity for ^{76}Ge $0\nu\beta\beta$ by two orders of magnitude, targeting the inverted ordering and beyond

- 90%-enriched HPGe detectors deployed in LAr scintillator at LNGS
- LEGEND-200 running now – first results in [PRL **136**, 022701 (2026)]
- LEGEND-1000 to start in the early 2030's: successful CD-1 IPR in'26, planning for NSF MREFC FDR in '27

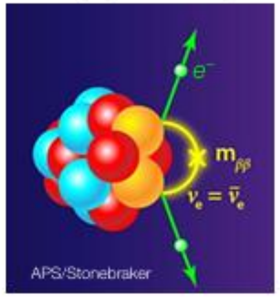
Scientific Synergies

- LNV and ν properties
- DM and other rare event searches
- Tests of QM and fundamental principles(wavefunction collapse, Pauli Exclusion Principle, charge conservation…)
- SN watch, cosmogenic/n-induced background measurements, …

Technological Synergies

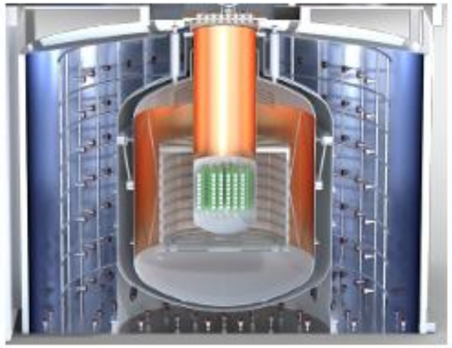
- Novel semiconductor detector technologies, cryogenic ASIC readout
- Ultralow activity materials and advanced manufacturing: electroformed Cu, scintillating plastics (fibers and bulk materials like PEN), cables and connectors
- LAr handling, instrumentation, modeling, reconstruction
- DAQ and analysis tools, statistical analysis (e.g. BAT), AI/ML methods (analysis, data cleaning and monitoring, triggering, detector design…)
- Beyond HEP: large-scale Ge enrichment (^{73}Ge-depleted Ge for high-fidelity qubits, ^{73}Ge-enriched Ge for solid-state MRI), microelectronics (graphene FET R&D), gamma spectroscopy, …

$0\nu\beta\beta$ decay

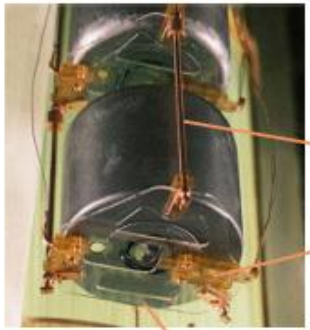


L200 Array

LEGEND-1000



HPGe mount



EFCu support

low-mass electronics

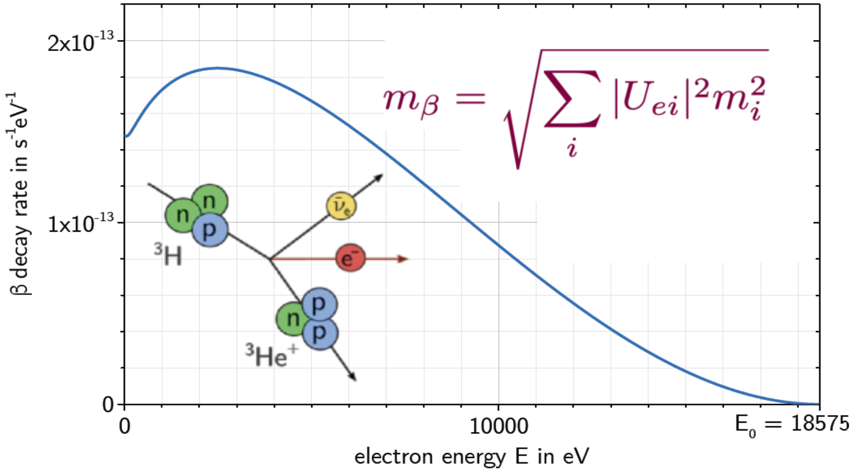
PEN plate

L1000 fiber curtain prototype

MJD EFCu cryostat at DAMIC-M

The Project 8 Neutrino Mass Experiment

J.A. Formaggio (MIT), on behalf of the Project 8 Collaboration



⊙ **Project 8** aims to measure the absolute scale of neutrino masses

One of the fundamental parameters of the Standard Model

⊙ Uses the beta decay spectrum of **atomic tritium** to measure m_β.

Sensitive to neutrino masses, independent of whether neutrinos are Majorana

⊙ Uses **C**yclotron **R**adiation **E**mission **S**pectroscopy (or **CRES**)

Measures single electron energies non-destructively using frequency

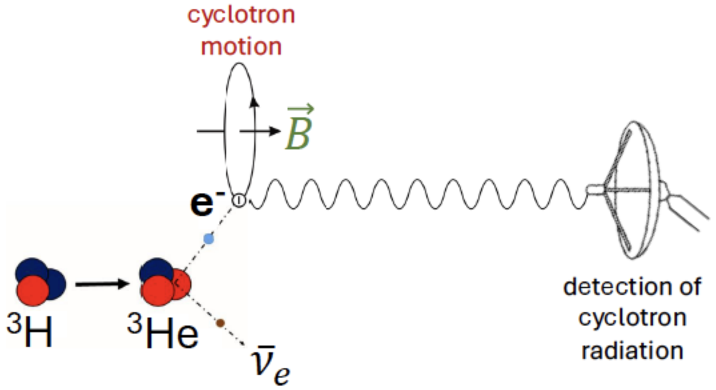
Connections with High Energy Physics

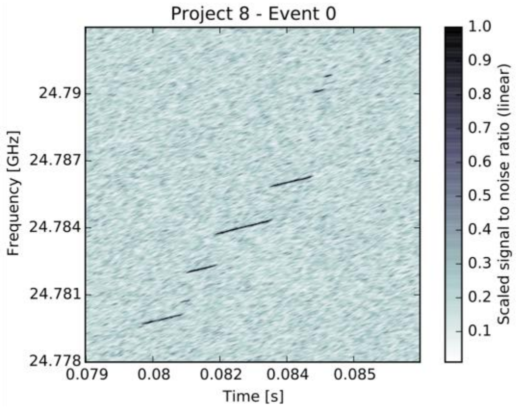
PROJECT 8

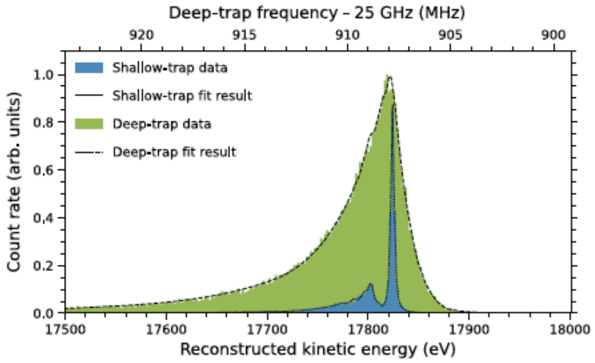
⊙ Measures the scale of neutrino masses *directly*

⊙ Has sensitivity to low mass (eV and keV) sterile neutrinos and other BSM physics

⊙ Microwave detection inherent in CRES technique is open to other physics (i.e. axions)







Connections with Other Fields

⊙ *Cosmology:* The neutrino mass scale impacts interpretation.

⊙ *Quantum*: CRES as a quantum-limited technique for electron detection.

⊙ *Fusion:* Atomic tritium source shares technology with fusion R&D

⊙ *Magnet Technology:* Novel configurations for atom & electron confinement

Sub-100-MeV ν interaction modeling

Low-energy astrophysical neutrinos of interest to current and near-future experiments

Signal (supernovae, solar fusion, …) and background (exotic physics)

Interaction simulations sensitive to many nuclear structure details

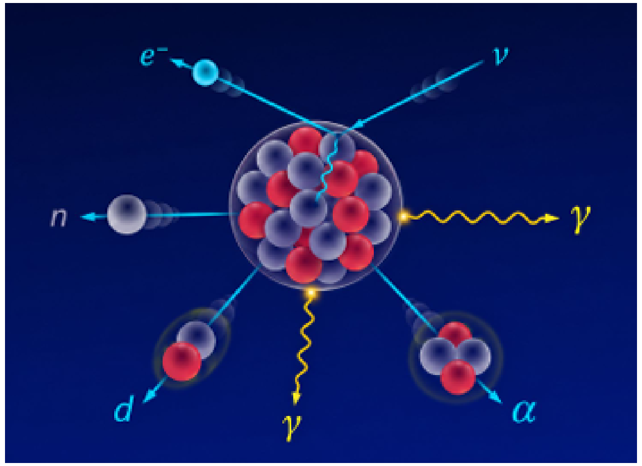
- Gamow-Teller strengths, **optical potentials**, level densities, …
- Need well-quantified uncertainties

UQ effort in NP well underway, directly relevant

- Engage with ν HEP = expand impact of UQ work

2025 ECA supporting me to work on this topic for DUNE

- Please contact me to explore synergies further

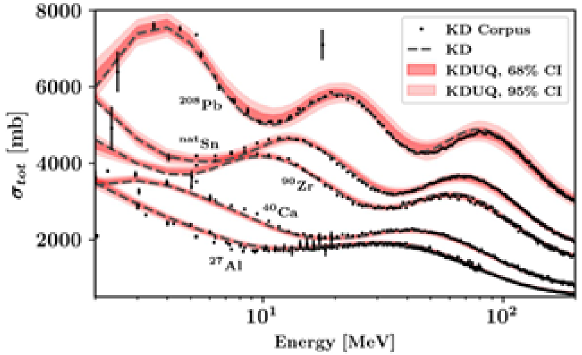


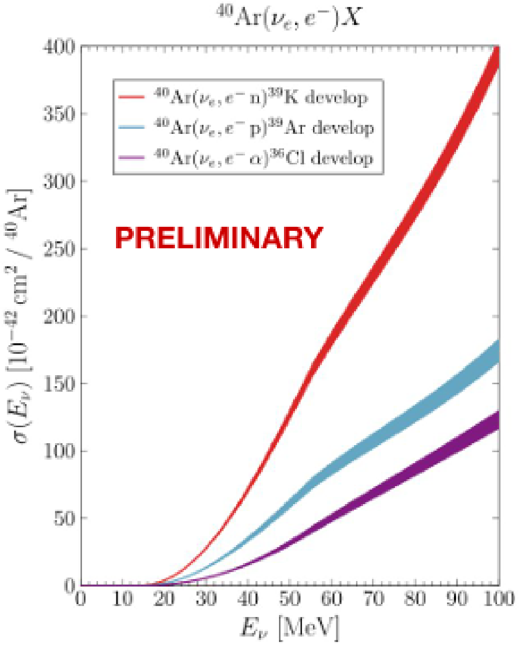
MARLEY ν event generator

Phys. Rev. C 103, 044604 (2021)

arXiv:2604.26801

Phys. Rev. C 107, 014602 (2023)

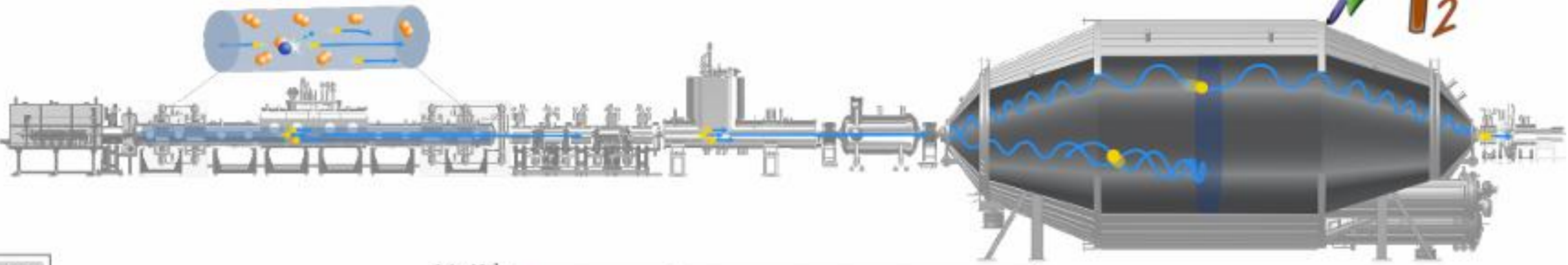




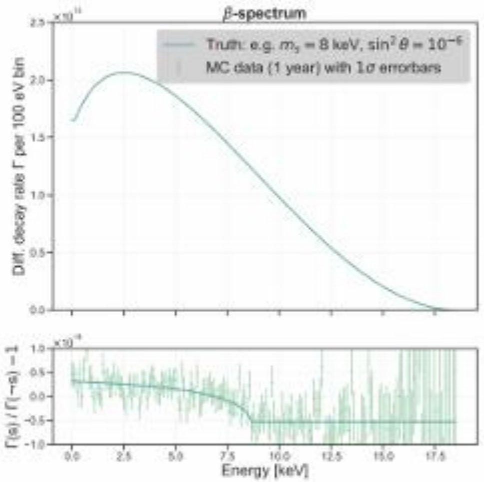
KDUQ optical model uncertainties propagated into ν-Ar cross sections

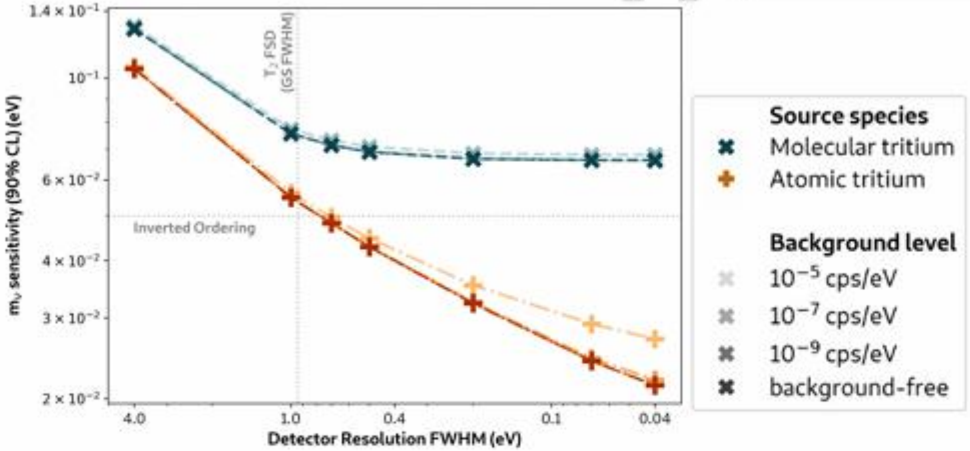
Steven Gardiner, Fermilab (gardiner@fnal.gov)

Synergies with KATRIN's Next Science Goals



After 1000 days of neutrino mass data taking KATRIN aims towards





searching for new heavy neutrinos
high statistics

- Machine-learning-accelerated simulation, model evaluation, and parameter extraction

probing the inverted hierarchy
high precision

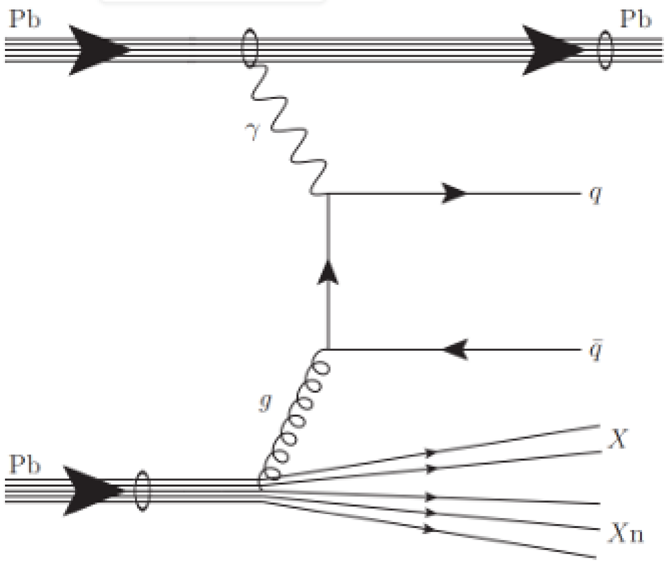
- Large area cryogenic detectors
- Low-noise amplifier technologies
- Atomic tritium pathfinder collaboration

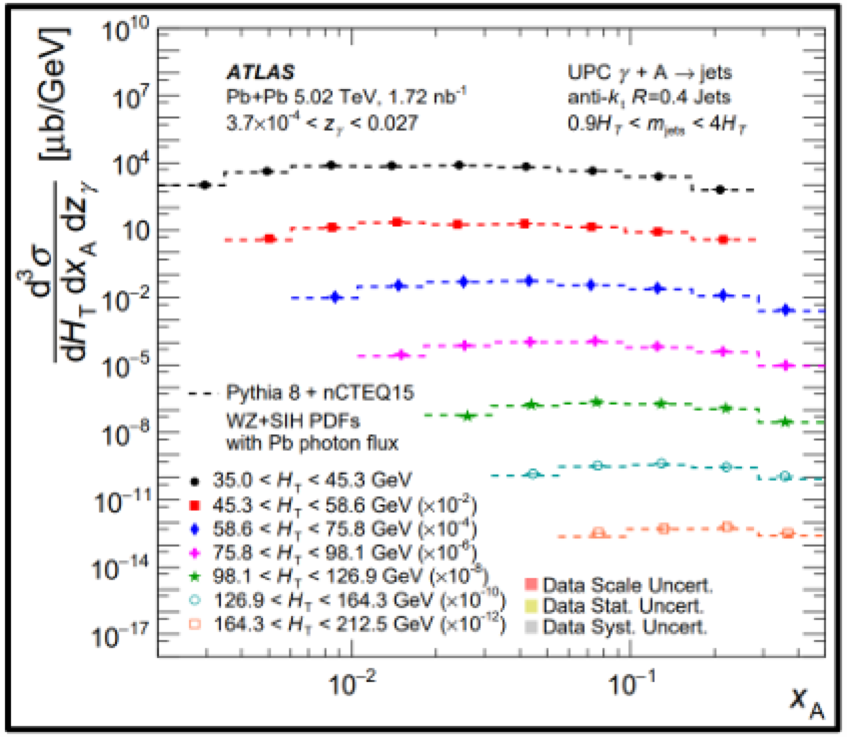
Jet Photoproduction in Heavy Ion Collisions with ATLAS at the LHC

Ben Gilbert, Lawrence Livermore National Laboratory [ATLAS]

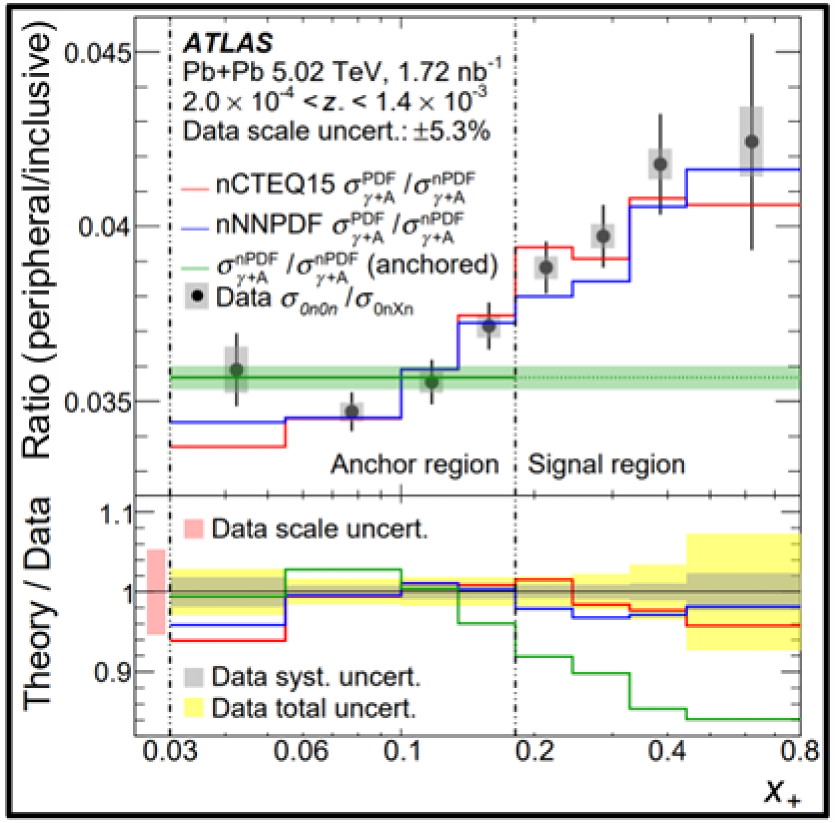
PRD 111 (2025) 5, 052006
arXiv:2604.20559
arXiv:2604.24435

In ultra-peripheral heavy ion collisions, one nucleus may emit photons which strike the other, producing jets.





Jet cross-sections constrain nuclear parton distributions with a clean EM probe.



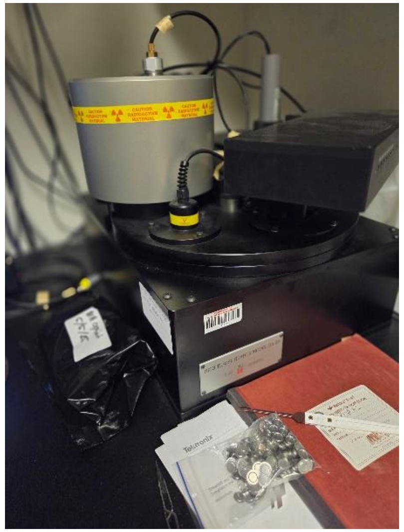
Recent measurements constrain the dependence of nPDFs on impact parameter for the first time!

Efforts are ongoing to expand these measurements to include heavy flavor tagging using Run 3 data. A huge range range of possibilities exist in nuclear physics, jet physics, and more! We are starting the EIC physics program right now in UPCs at the LHC.

This work is supported by DOE-SC/HENP under LLNL Contract DE-AC52-07NA27344

Passive Nuclear Forensics Using Ubiquitous Materials

NC STATE UNIVERSITY

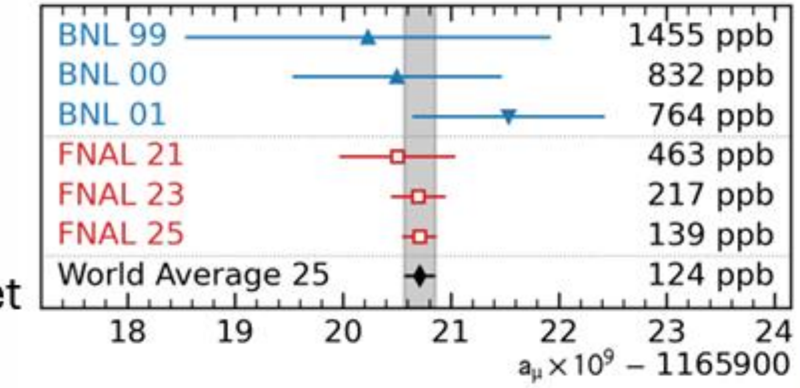


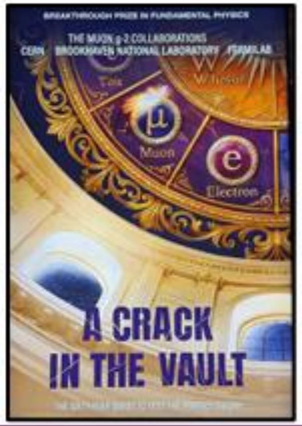
1) Aras, E.M., & Hayes, R.B. (2022, June). A Novel Approach for Detection of Illicit Nuclear Activities Using Optically Stimulated Dosimetry. *ESARDA Bulletin - The International Journal of Nuclear Safeguards and Non-proliferation*, 64(1), 64-74.
2) Kanies B, Hayes R, Yang G. Thermoluminescence and optically stimulated luminescence response of Al2O3 coatings deposited by mist-chemical vapor deposition. *Radiat. Phys. Chem*. **191**, 2022, 109860, ISSN 0969-806X, doi.org/10.1016/j.radphyschem.2021.109860.
3) Tchouaso MT. Coon N, Hayes RB. A Nondestructive Method for Accidental Dose Assessment from Electronic Devices *Radiat. Meas*. **148**, 106648, 2021
4) Hayes RB. (2019) Retrospective uranium enrichment potential using solid state dosimetry techniques on ubiquitous building materials *J Nuc Mat Mgmt*. **47**(2), 4-12.
5) Hayes RB, O'Mara RP. (2019) Retrospective dosimetry at the natural background level with commercial surface mount resistors. *Radiat. Meas*. **121**, 42-48. doi:10.1016/j.radmeas.2018.12.007
6) O'Mara RB, Hayes RB. (2018) Dose deposition profiles in untreated brick material. *Health Phys*. **114**(4), 414-420.

Department of NUCLEAR ENGINEERING

Precision Physics: A natural NP-HEP overlap area

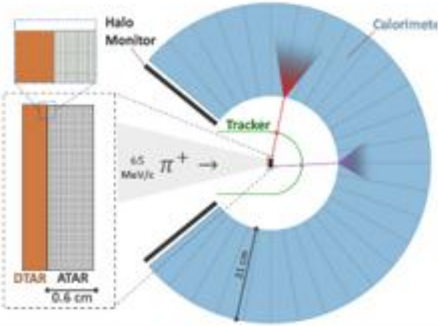
- Example 1: Proven experience: **Muon g-2**
  - 7 groups from DOE-NP and NSF NP
  - 7 groups from DOE-HEP: 3 @ labs; 4 @ universities
  - Many international groups & from other communities
  - NP+HEP synergy delivered the required diverse skillset
  - The results have been evidently very successful





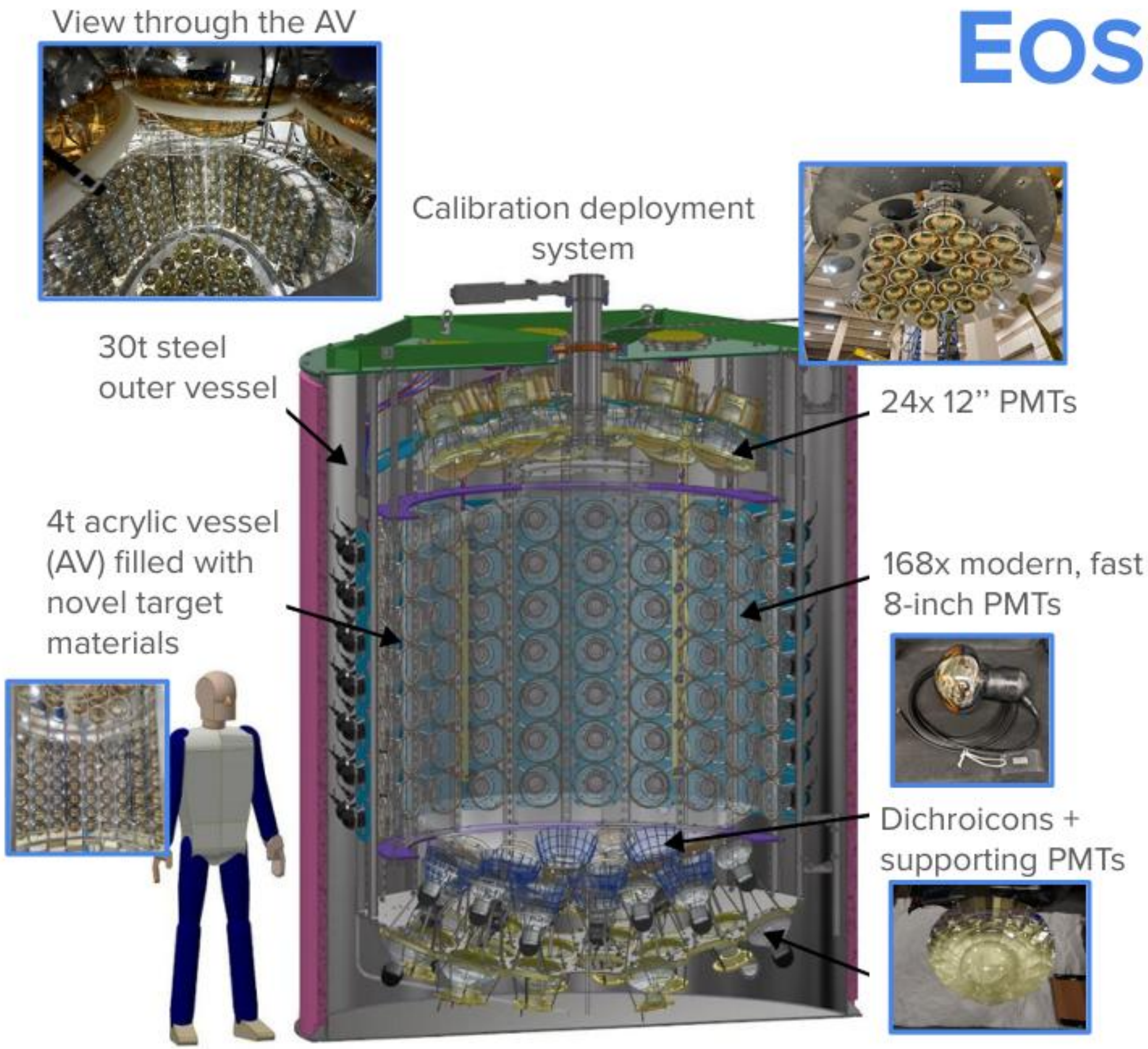
Breakthrough Prize in Fundamental Physics

- Example 2: A similar test of SM to high precision: **PIONEER rare pion decays**
  - Physics I: Lepton Flavor Universality: e/μ to10^{-4}; 10's to 100's of TeV reach for BSM
  - Physics II: V_{ud} from Pion beta decay: $\pi^+ \rightarrow \nu_e e^+ \pi^0$; CKM unitarity key element
  - Technologies from both communities needed and overlap:
    - First-ever 5D tracking system; we use LGADs with AI driven reconstruction (HEP/NP co-development)
    - 300 tapered LYSO crystal calorimeter for 0 – 70 MeV e+ range; NP development; low energies, high resolution
    - APOLLO-based (CMS) fast triggering based DAQ coupled to MIDAS (HEP → NP)
    - Digital Twin based pion beam line tuning program (GENESIS proposal, NP, HEP, CS, industry)



We need **opportunities to seek funding** for these unique and strategic experimental concepts
PIONEER is approved at PSI with high priority, but needs to establish a funding stream soon

Eos@SNS



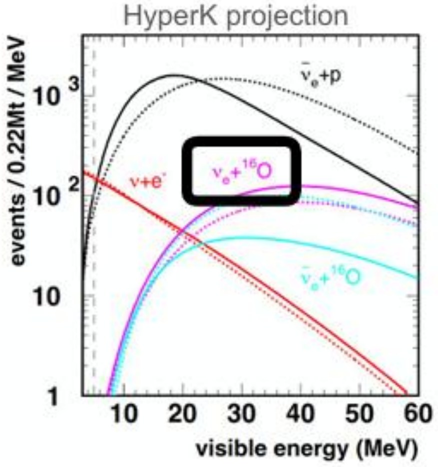
Eos is an existing detector built @ UC Berkeley that utilizes next-generation "hybrid" detector technology to enable Cherenkov/scintillation separation for advanced neutrino detection.

For more information, see: JINST 18 (2023) 02, P02009

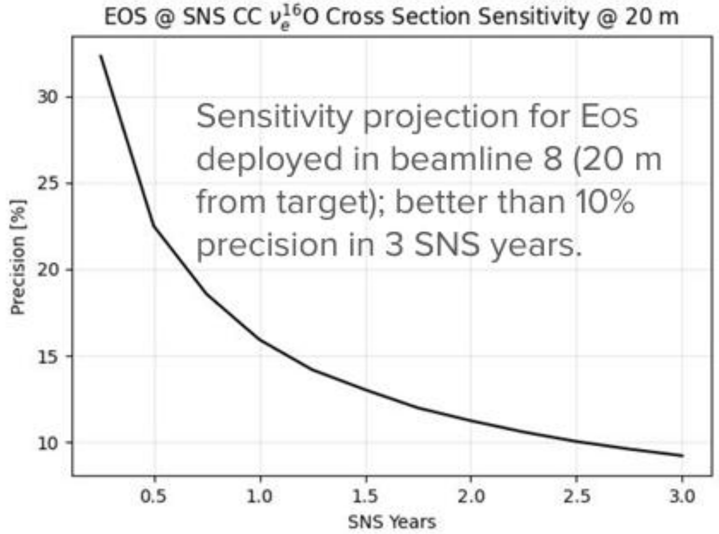
Plan to move Eos to the spallation neutron source (SNS) at Oak Ridge National Lab.

Beamline 8

$\nu_e + {}^{16}O$ (CC)



Astrophys.J. 916 (2021) 15



Plan to deploy other target materials. Tellurium is of interest for relevant x-sec measurement for future 0νββ with large liquid scintillation detector (THEIA).

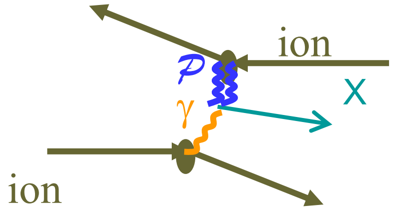
Eos@SNS provides a platform connecting nuclear physics (0νββ), neutrino physics ($\nu_e + {}^{16}O$), and next-generation instrumentation.

National Nuclear Security Administration

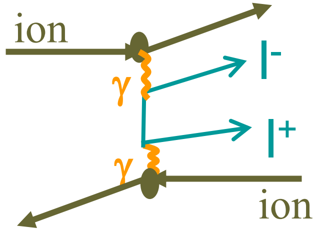
U.S. DEPARTMENT of ENERGY

Ultra-peripheral collisions: HEP/NP synergy

Spencer Klein, *LBNL*



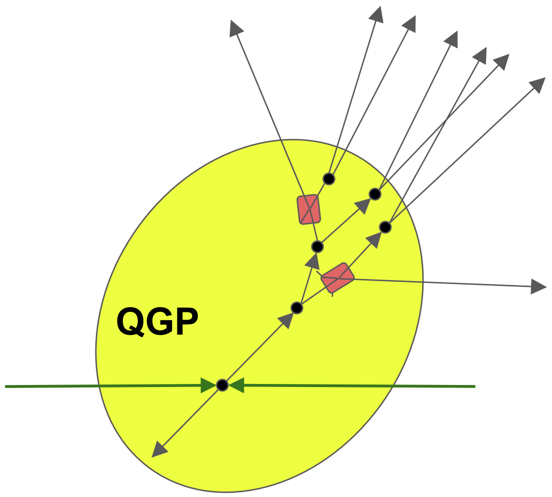
- Diverse electromagnetic interactions
  - Usually exclude events with hadronic interactions
- The LHC is the energy frontier for photon physics
- Photonuclear interactions probe the partonic structure of nuclei
  - Protons: $W_{\gamma p}$ up to 5.4 TeV probe Bjorken-x below 10^{-6}
  - Heavy Ions: $W_{\gamma p}$ up to 700 GeV probe Bjorken-x below 10^{-5}
  - Coherent photoproduction probe parton transverse spatial distributions
  - Incoherent photoproduction may access partonic fluctuations
- Two ions-> 2 slit interferometer -> Studies of quantum mechanics
- Two-photon interactions reach $W_{\gamma\gamma}$ up to 4 TeV
  - Light-by-light scattering: BSM particles and axions
  - $\tau^{\pm}$ anomalous magnetic moment
  - Antihydrogen production and LHC ion luminosity limits
    - Via bound-free pair production



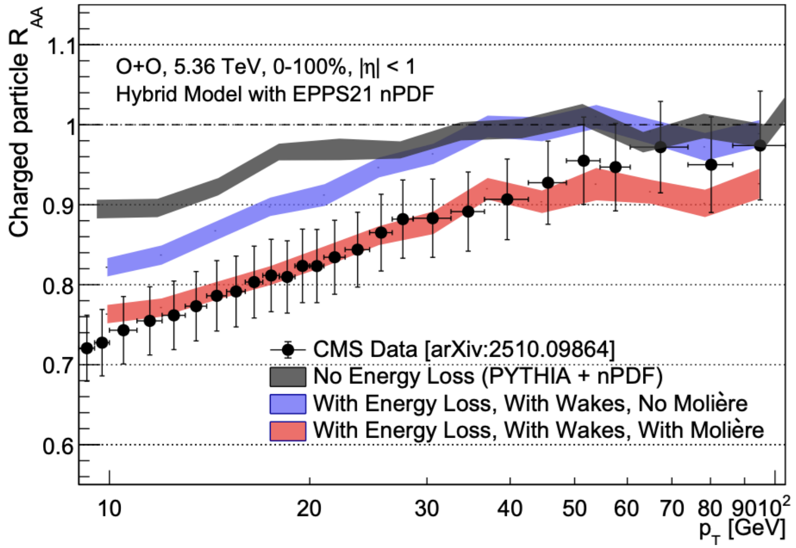
Revealing the Short-Distance Structure of QGP using Jets

Arjun Kudinoor (MIT)

[1808.03250] [D'Eramo et al.]
[2603.08776] [Hulcher et al.]
[2603.23596] [Kudinoor et al.]

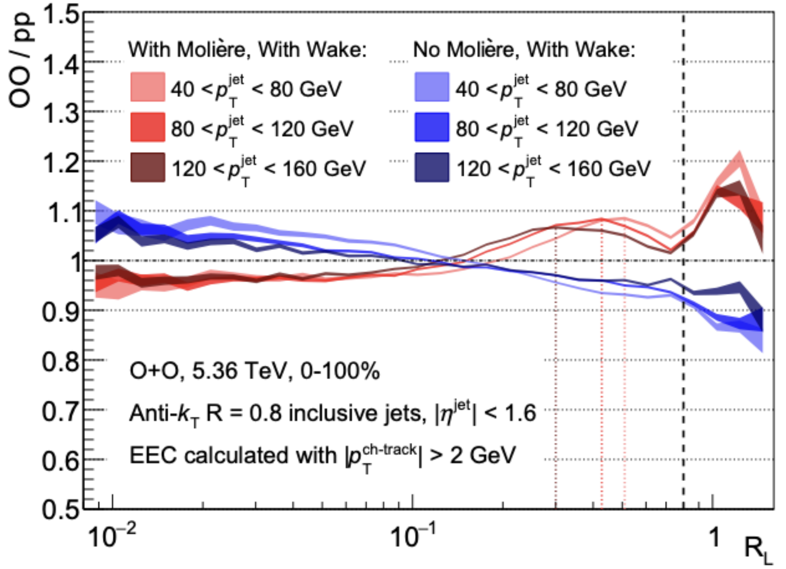


At length scales O(1/T) and longer, QGP is a liquid. Since QCD is asymptotically free, QGP must be particulate at short-distance scales. Currently, no unambiguous experimental evidence for this. Quasiparticles in QGP can be revealed by large-angle scatterings between jet partons and the medium.



- [2603.23596] **Jet substructure measurements in oxygen-oxygen collisions at the LHC:** Large-angle 2 → 2 scatterings can be a dominant effect (relative to energy loss) in selected observables
  - EECs
  - Soft Drop R_g

- **An opportunity to reveal the microscopic structure of QGP and to develop and test theoretical descriptions of it** (analogous to PDFs in DIS)

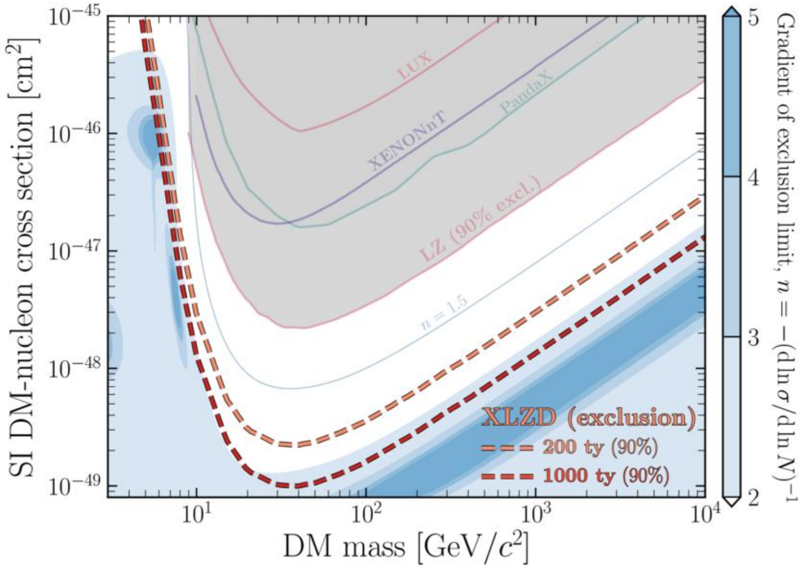


XLZD: the definitive detector for low-background physics with liquid xenon

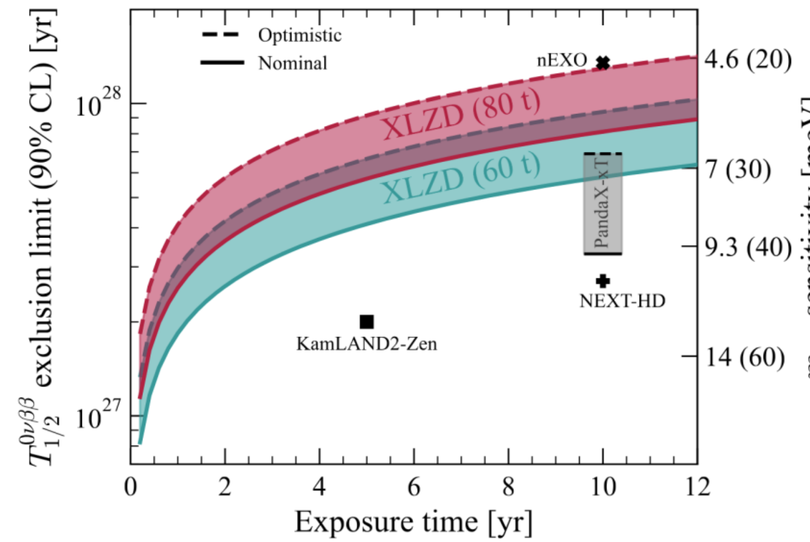
Designed for 60t ${}^{nat}Xe$ target

80t possible with favorable Xe market

Definitive "G3" search for WIMP dark matter



Opportunity for "ton-scale" 0νββ search in ${}^{136}Xe$



Single experiment can address key science targets recommended by **both** P5 and 2023 Long Range Plan for Nuclear Science

See publications:

XLZD design book: J. Aalbers et al., Eur. Phys. J. C 85 (2025) arXiv:2410.17137

0νββ sensitivity: J. Aalbers et al., J. Phys. G 52 (2025) arXiv:2410.19016

Radio-Frequency Technology Synergies

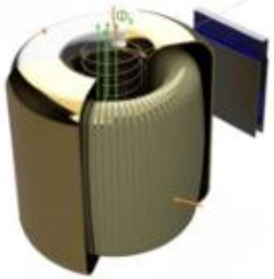
between wavelike dark matter searches and neutrino-mass measurements

Cavities

- Optimization for relevant physics
- Detection of extremely weak signals
- Mode selection
- Tuning

BREAD

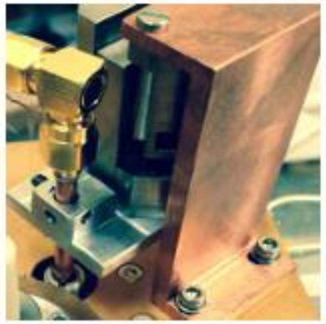
ADMX



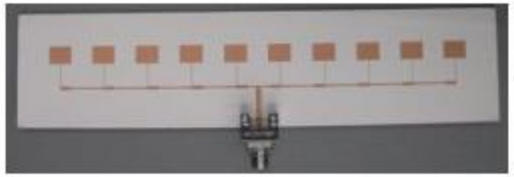
DMRadio

Antennas

- Detecting or injecting microwave radiation
- Geometry
- Mode coupling



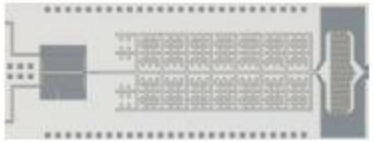
ADMX



Project 8

Quantum Techniques

- Noise reduction and signal amplification
- Mode squeezing
- Single-photon counting
- Quantum-limited amplifiers

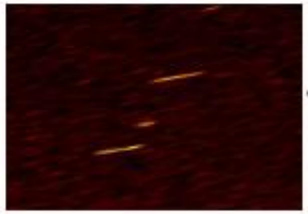


ADMX

Signal Processing

- Use of modern technology and techniques
- RF System-on-Chip
- AI-enabled hardware
- Signal reconstruction

AMD

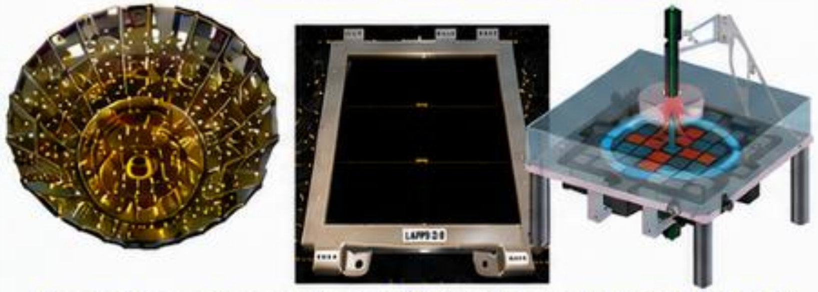


Project 8

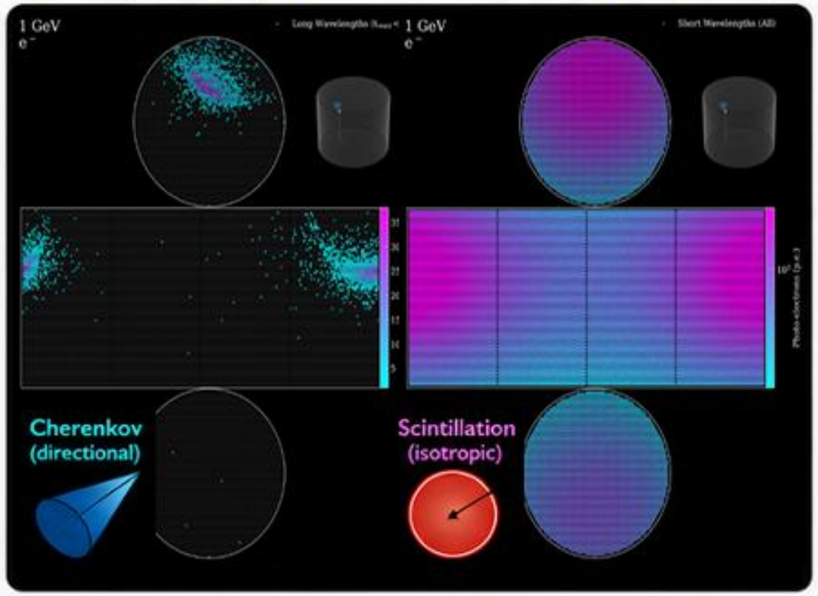
THEIA: Pushing the Boundaries of Neutrino Physics

NOVEL TECHNOLOGY

Hybrid Cherenkov/scintillation detection

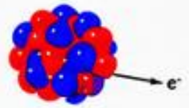


Event-by-event separation of Cherenkov and scintillation light



PHYSICS REACH

0νββ



$^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^{-}$

Neutrinoless double-beta decay

Search for lepton number violation with sensitivity into the normal ordering region

DUNE
LBNF

Long-baseline oscillation physics

Precision measurements with the LBNF beam at SURF
Mass ordering, CP violation, and precision oscillation parameters

Supernova neutrinos + Diffuse Supernova Neutrino Background (DSNB)

Real-time detection of core-collapse events and sensitivity to the DSNB

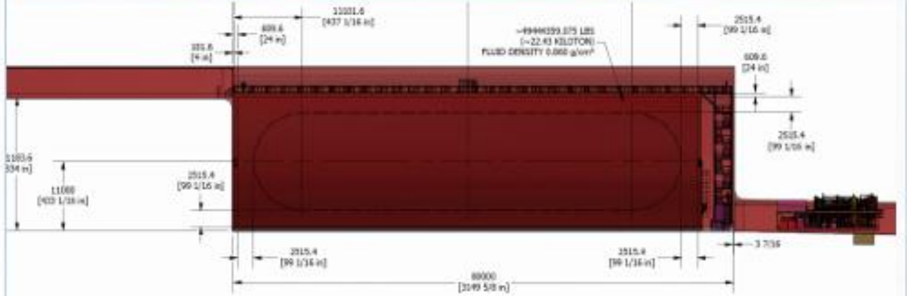
Solar neutrinos

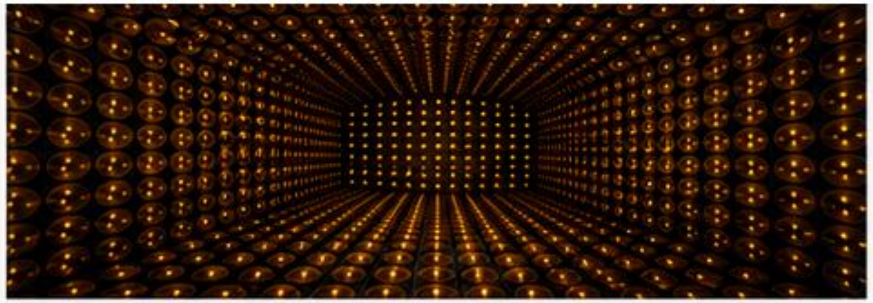
Precision measurements across a wide energy range

Geoneutrinos

Probing Earth's radiogenic heat production

LARGE-SCALE DEPLOYMENT





ENDORSED BY THE U.S. COMMUNITY:

Particle Physics Project Prioritization Panel (P5)
Called for novel detector technologies and a broad physics program with the LBNF beam.

&

Nuclear Physics Long Range Plan (NP LRP)
Identified Theia as one of a small number of technologies capable of scaling beyond tonne-scale.

Strong community support across HEP and NP

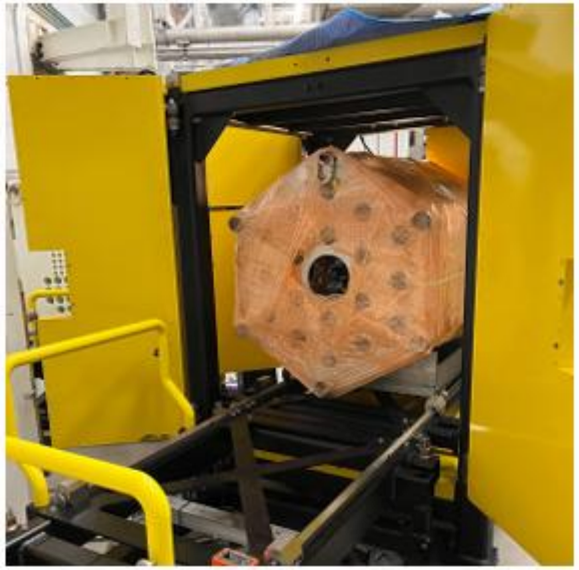
A common detector platform spanning nuclear and high-energy physics

Precise $\bar{\nu}$-Energy Spectra from Complete β-γ Spectroscopy

High Efficiency Leads to High Precision Results

MTAS

1 ton of NaI and 12+Tons Shielding

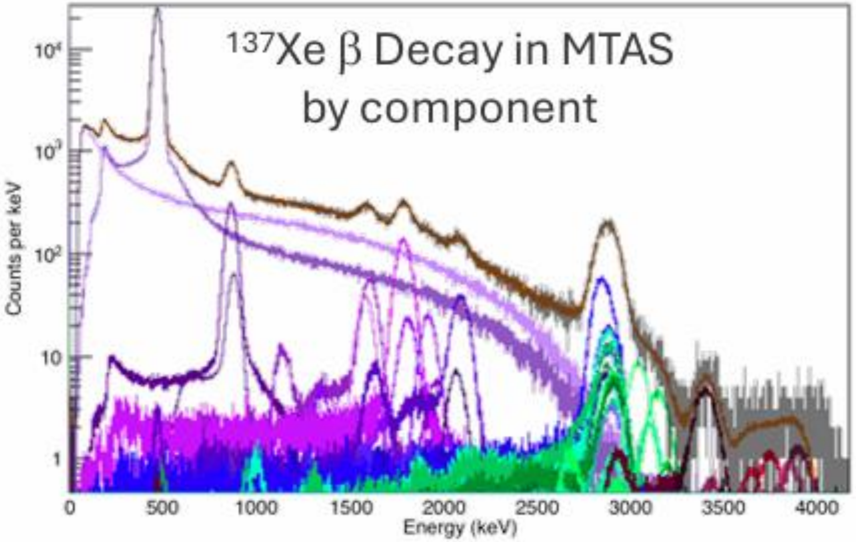


MTAS Near 99% γ-Ray Efficiency (0.2-6 MeV)

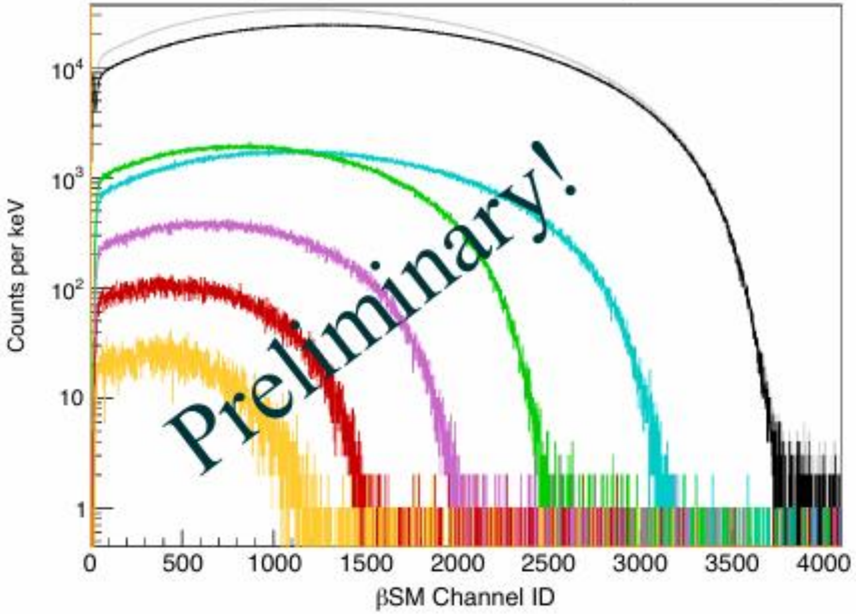
Accurately Measure Complex β-Decay Feeding Patterns

Reactor Neutrino and Decay Heat Calculations

Measure Background Spectra Important for Other Experiments



Isolated Individual β-Decay Energy Spectra in ^{106}Rh β Decay



β-Spectrum Module (βSM): Near 99% Electron Efficiency

Isolate Individual β Transition Energy Spectra in Complex β Decay

Measurement of Decay and Detector Bremsstrahlung

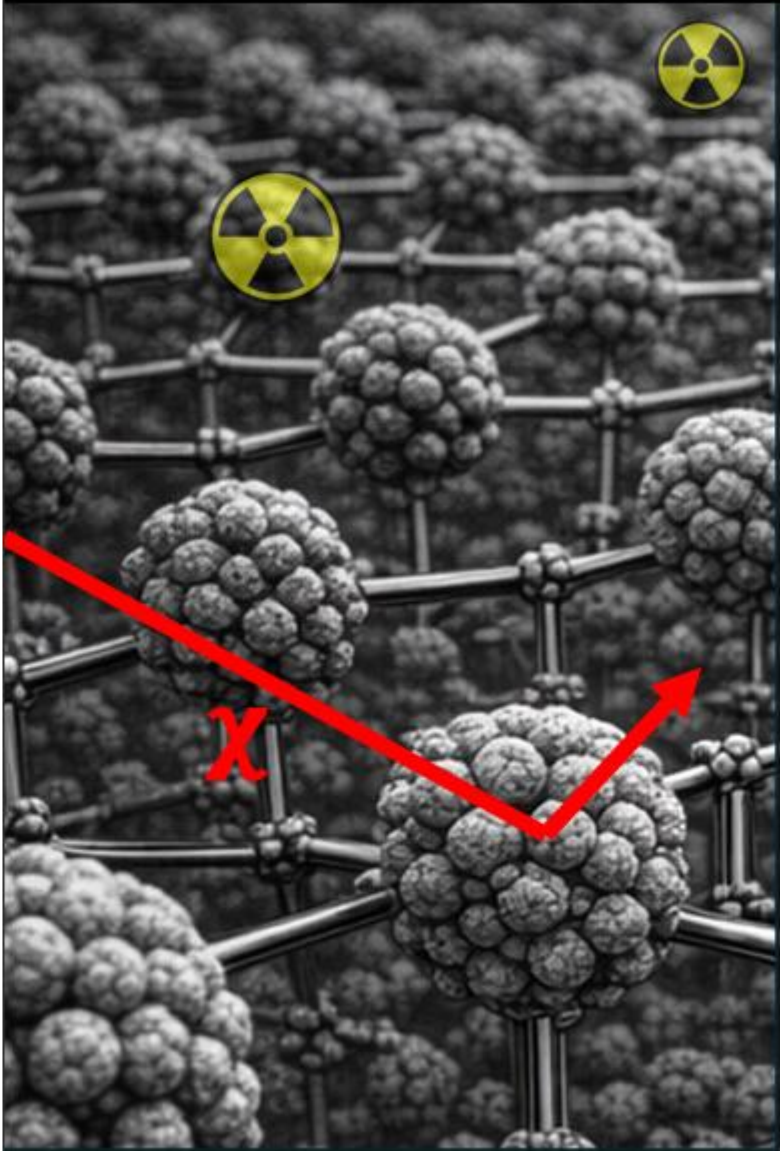
Allows Precise Experimentally Based Neutrino Spectra Predictions

OAK RIDGE National Laboratory

This work is supported by the Nuclear Data Inter Agency Working Group (NDIAWG) FOA-0002440 and by the US DOE by award no. DE-FG02-96ER40978 by the US DOE, Office of Nuclear Physics

rascobc@ornl.gov

Low radioactivity synergies between particle dark matter and neutrinoless double beta decay searches

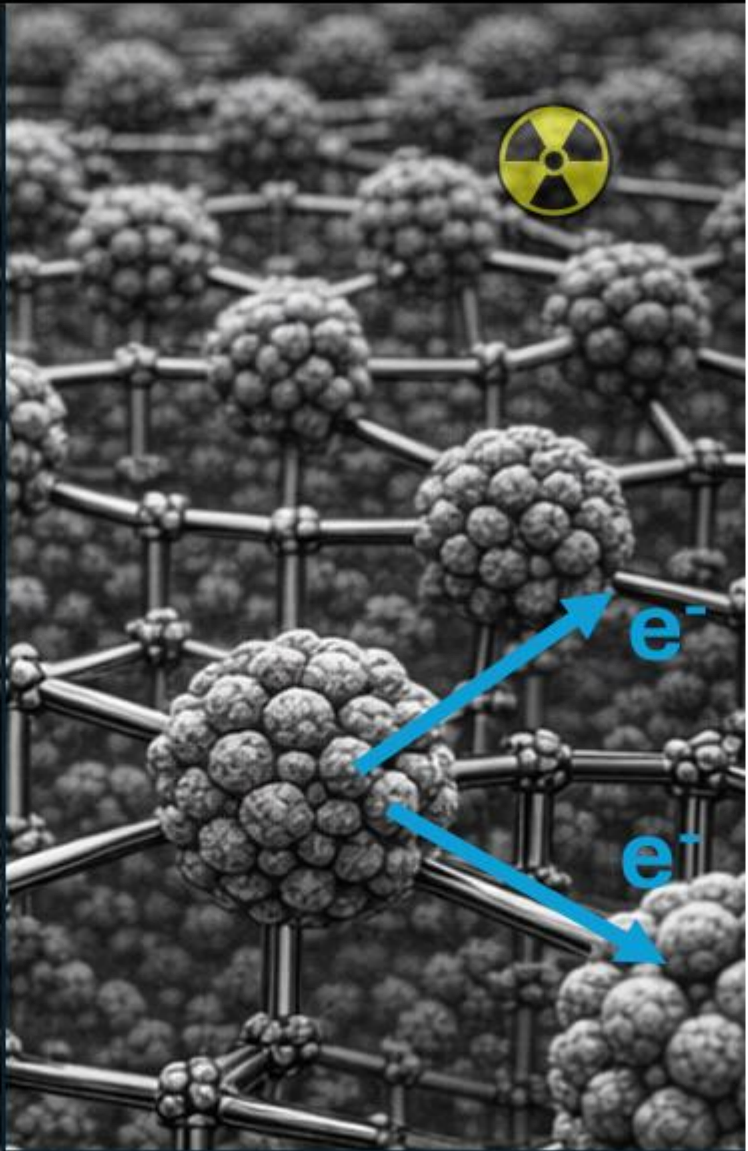


Development of Low Background Materials
- Structural materials (SS, Ti, Ni, Cu alloys)
- Insulators (PTFE, Sapphire)
- Scintillators and wavelength shifters (PEN, fibers, vapor deposited films)

Low Radioactivity Sensors and Electronics
- Photosensors
- Capacitors
- Resistors
- Cables

Novel Assay Techniques
- < 50 uBq/kg ^{226}Ra
- < 10 mBq/kg ^{39}Ar
- < 50 uBq/kg ^{42}Ar

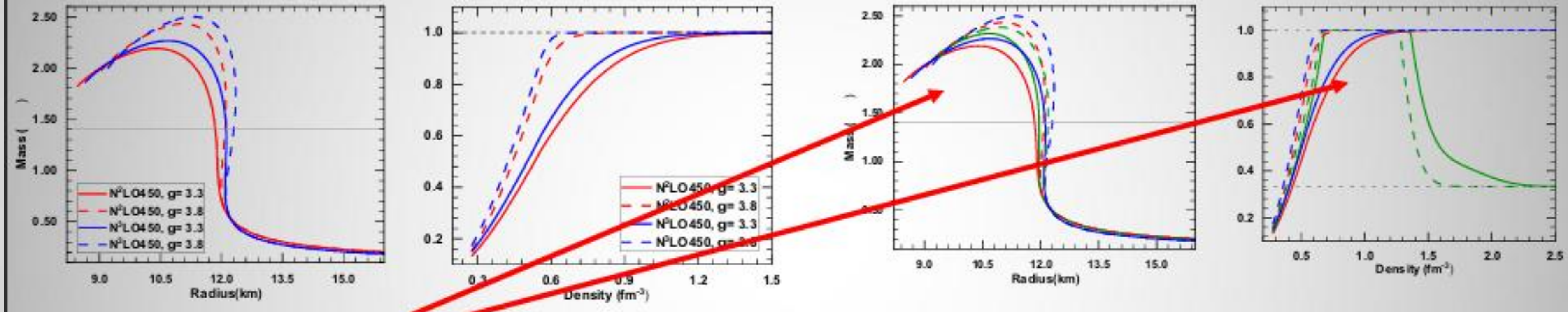
Community Assay Facilities
- < 1 mBq/kg HPGe gamma counting
- < 1 ppt ICP-MS, NAA
- Radon emanation, alpha counting, etc.



Richard Saldanha, PNNL

Can we open a window into the most exotic state of matter through hard theoretical constraints from QCD?

- Ongoing partnership between nuclear physics and astrophysics:
  - **Maximum-mass constraint moving to higher values, together with the causality requirement at any central density, poses significant restrictions on the high-density continuation of the EoS. ****



Enforcing drastic variations of SoS at very large density to implement the conformal limit of 1/3 for $(v_s/c)^2$ predicted by QCD calculations in the asymptotic freedom regime is incompatible with recent maximum-mass constraints if the speed of sound in stellar matter is a monotone function up to super-high densities.

- **Proposed synergy:**

A closer interaction between theorists who work with the neutron star equation of state and the QCD and Lattice QCD communities to seek robust theoretical constraints. Let's talk more to one another!

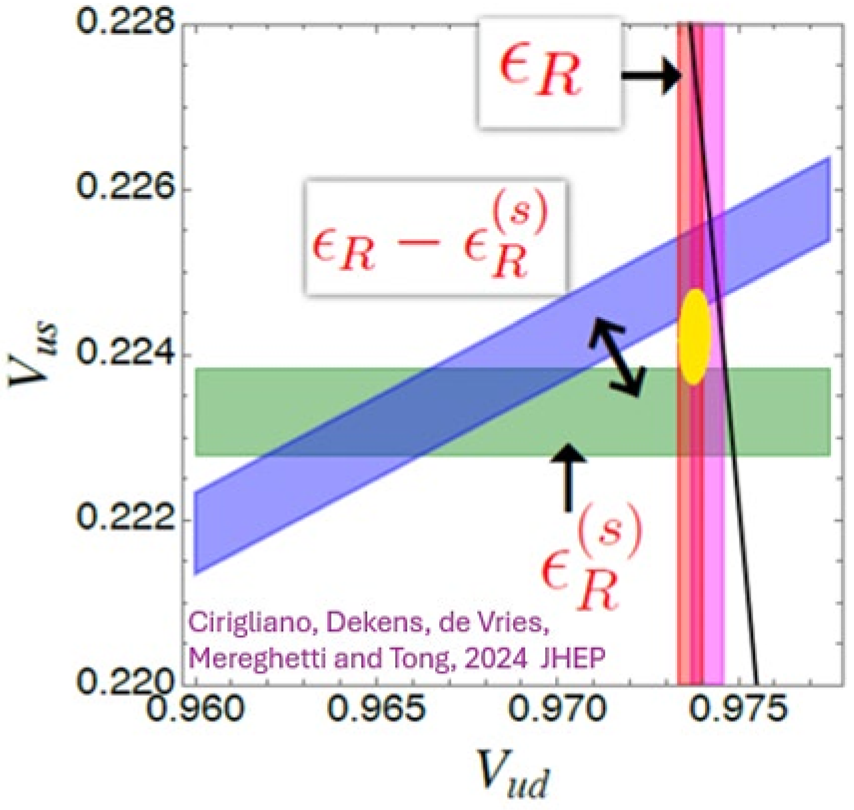
SoS monotonic and subluminar ✓
monotonic and subconformal ✗
non-monotonic & conformal at infinity ✓

Trace anomaly in strongly coupled matter?
Conformal limit approached from above?

**F.S. & T. Ajagbonna, Front. Astron. Space Sci. 12 (2025) 1554123
F.S. & P. Thapa, arXiv: 2512.00354

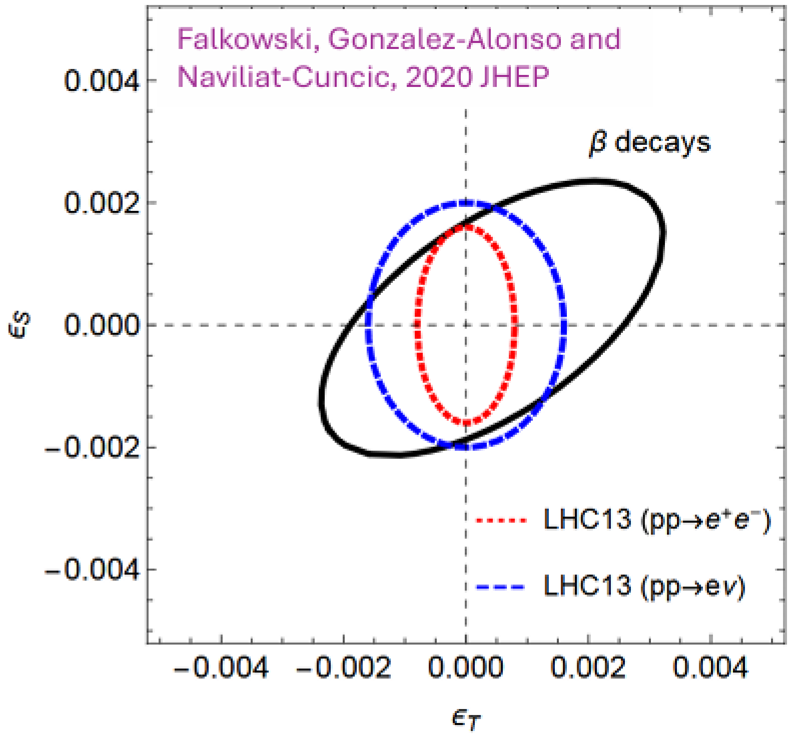
Discovering BSM physics with data from MeV to TeV scale

Chien Yeah Seng
University of Tennessee

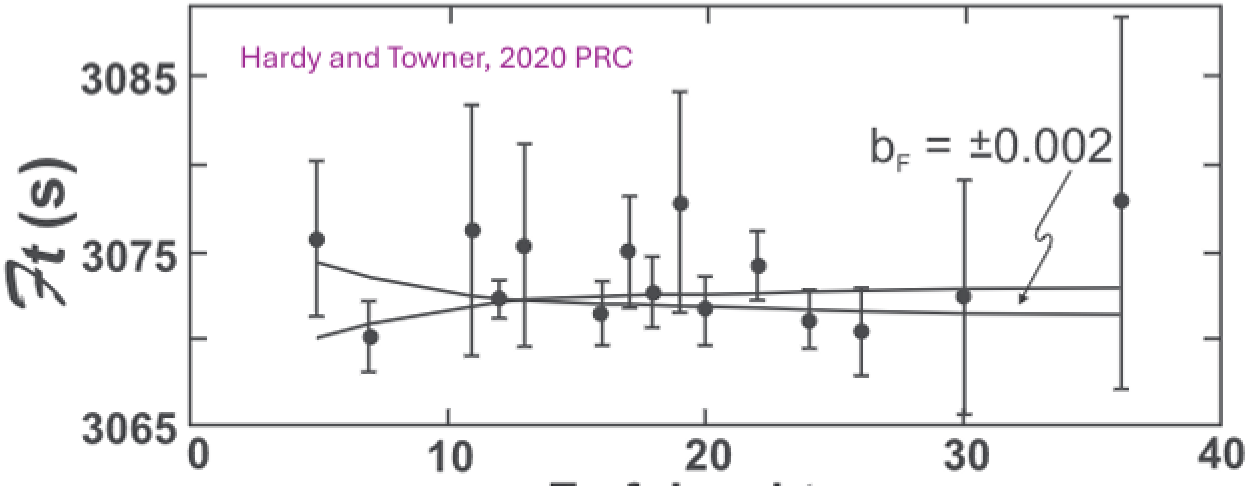


Cabibbo angle anomaly and right-handed quark interaction

Synergy:
HE + NP experiments + Theory (SM + BSM EFT, lattice, nuclear ab-initio, data-driven...); AI opportunities



Constrain scalar and tensor currents from LHC + β decays



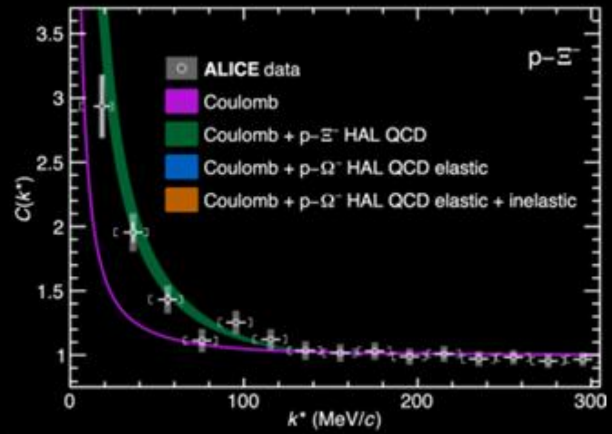
Fierz term from superallowed β decay rate

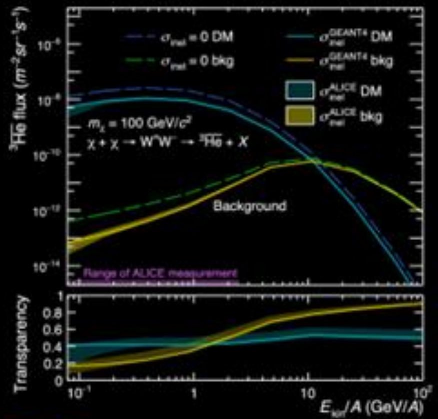
Quarks to the Cosmos with ALICE

- Would you like to…
  - ✓ Investigate how rare hadron-interactions unravel the properties of **neutron stars**?
  - ✓ Examine how anti-nuclei production reveals **dark matter** in the galaxy?
  - ✓ Understand why the universe thermalized so early after the **Big Bang** from little ones?

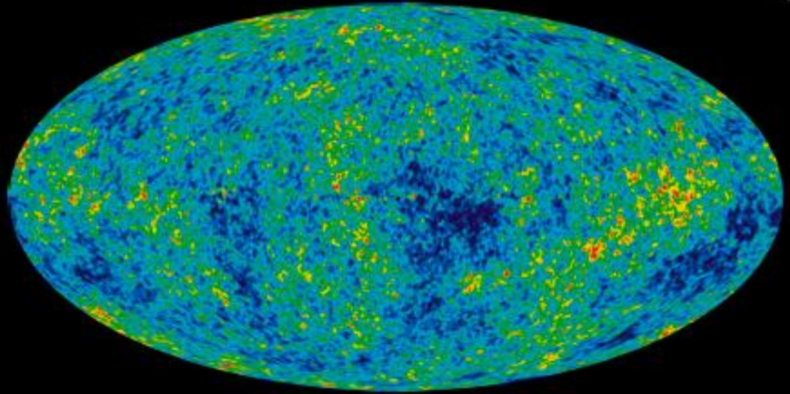
- **Join <u>ALICE on a journey through QCD</u>!**
  - ✓ Capitalize on DOE and NSF NP investments in ALICE, and DOE-HEP in the HL-LHC
  - ✓ Pave the way for the next generation detectors at LHC, EIC, and FC-ee…

Nature 588 (2020) 232-238





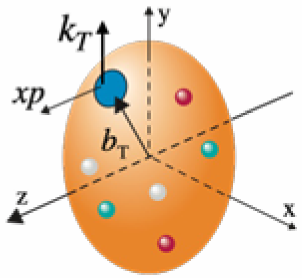
Nature Phys. 19 (2023) 61-71

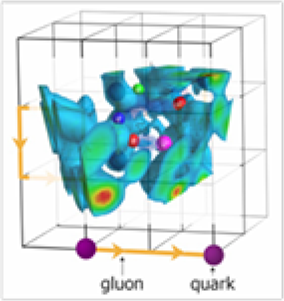


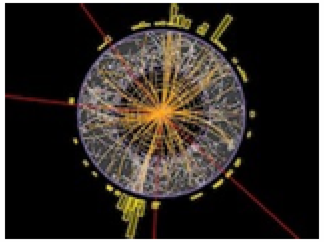
ALICE 3 Letter of Intent

Precision Lattice QCD for Nucleon Imaging and the Energy Frontier

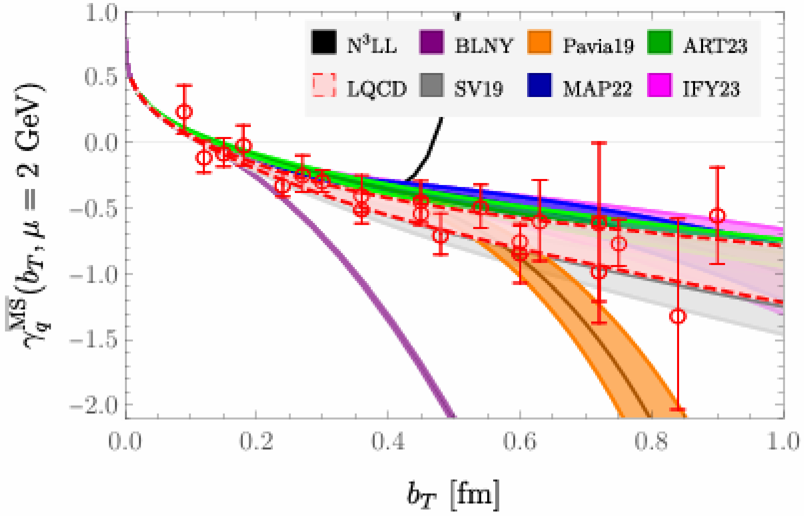
Yong Zhao, Physics Division, Argonne National Laboratory





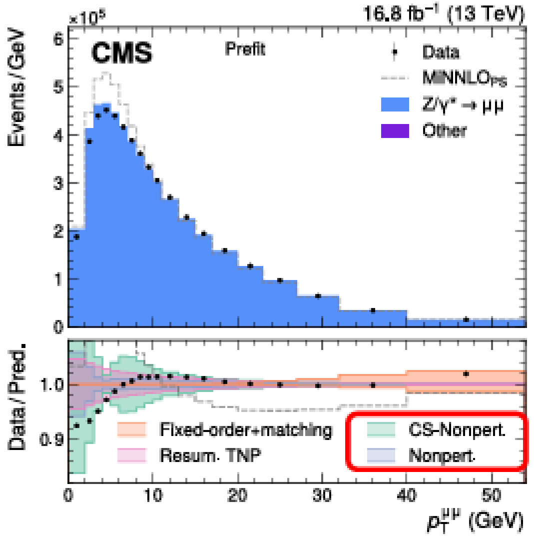


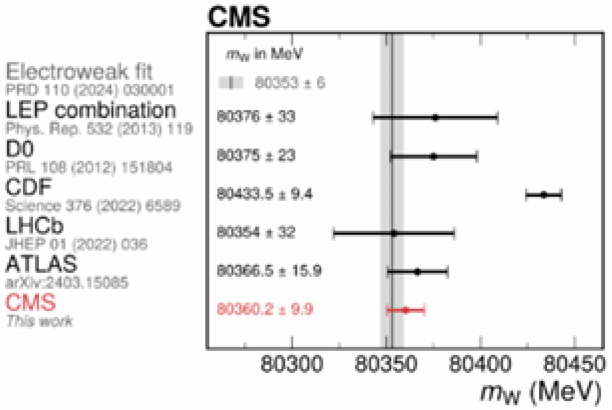
Nonperturbative Collin-Soper (CS) kernel for the evolution of transverse-momentum distributions



Avkhadiev, Shanahan, Wagman and YZ, **PRL** 132 (2024).

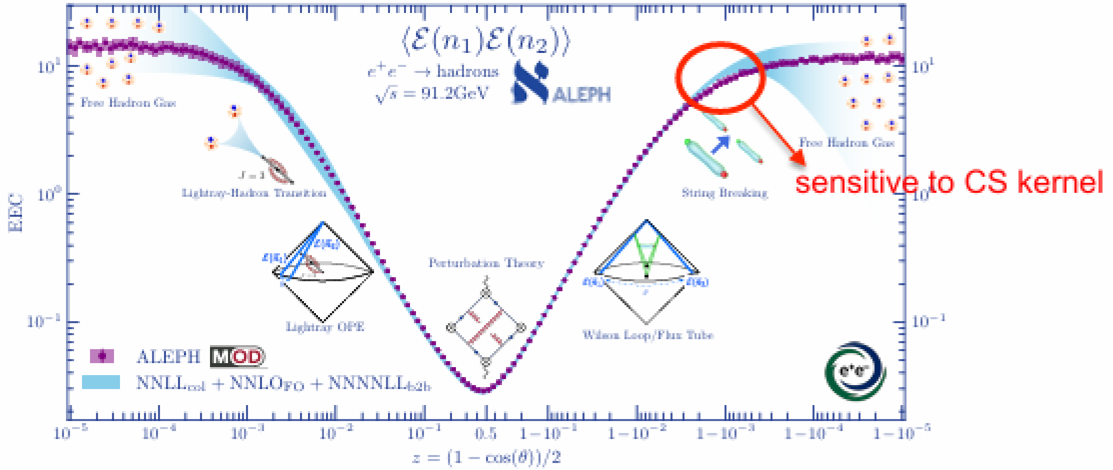
✦ **Precision electro-weak measurements, e.g., *W* boson mass**





CDF Collaboration, **Science** 376 (2022);
CMS Collaboration, **Nature** 652 (2026);
Billis, Michel and Tackmann, **JHEP** 02 (2025).

✦ **Precision measurements with energy correlators**

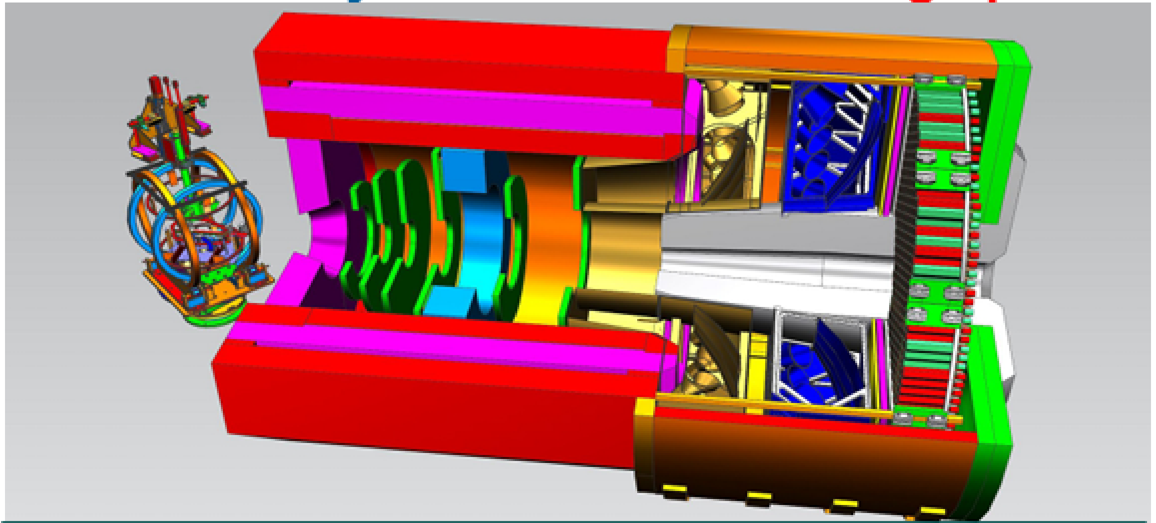


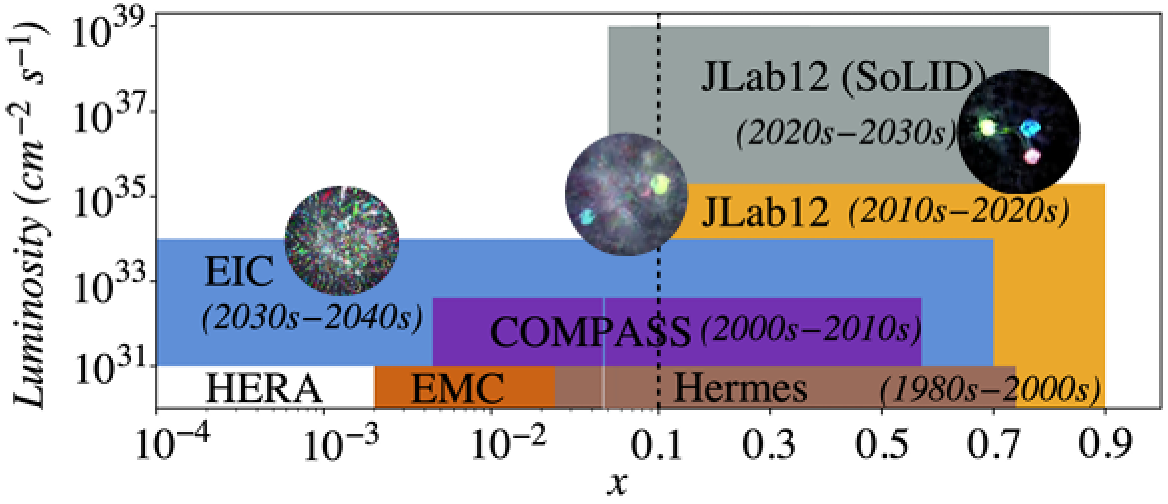
Electron-Positron Alliance, 2511.00149;
Jaarsma, Li, Moult, Waalewijn, and Zhu, 2512.11950.

✦ **Relation to confinement in formal theory**

SoLID @ Jefferson Lab: QCD Intensity Frontier

Nucleon spin, mass and BSM search experiments. Precision measurements of small cross sections and asymmetries. Critical: high polarized luminosity (10^{37}-10^{39} $cm^{-2}s^{-1}$) + large acceptance





Solenoidal Large Intensity Device (SoLID)

Science pillars successfully reviewed by DOE NP panel + JLab PAC

- Precision 3D imaging of the nucleon in the valence region (GPDs, TMDs). Unique, critical to NP science mission but complementary to EIC.
- Exploring the origin of the proton mass and confining color forces. Mass and scalar energy distributions in the proton. Unique, critical to NP science, but complementary to EIC.
- Search beyond the Standard Model of Particle Physics. Unique and complementary to MOLLER @ JLab

Luminosity Frontier in the Valence Region

Multiple JLab Director's Reviews in the last 10 years

- DOE/JLab supported pre-R&D activities on cutting-edge technologies.
- Enhanced credibility of the design with greatly reduced cost/schedule risks
- Scientific excellence and students training ground with a growing impactful science portfolio

J.Phys.G 50 (2023) 11, 110501

2015 and 2023 NSAC LRP