Highlights from the Snowmass Instrumentation Frontier

PETRA MERKEL, FERMILAB
2022 CPAD WORKSHOP – STONY BROOK UNIVERSITY

NOVEMBER 29, 2022

Outline

IF Organization

Detectors for Collider Experiments

Detectors for Neutrino Experiments

Detectors for Rare and Precision Experiments

Detectors for Cosmic Experiments

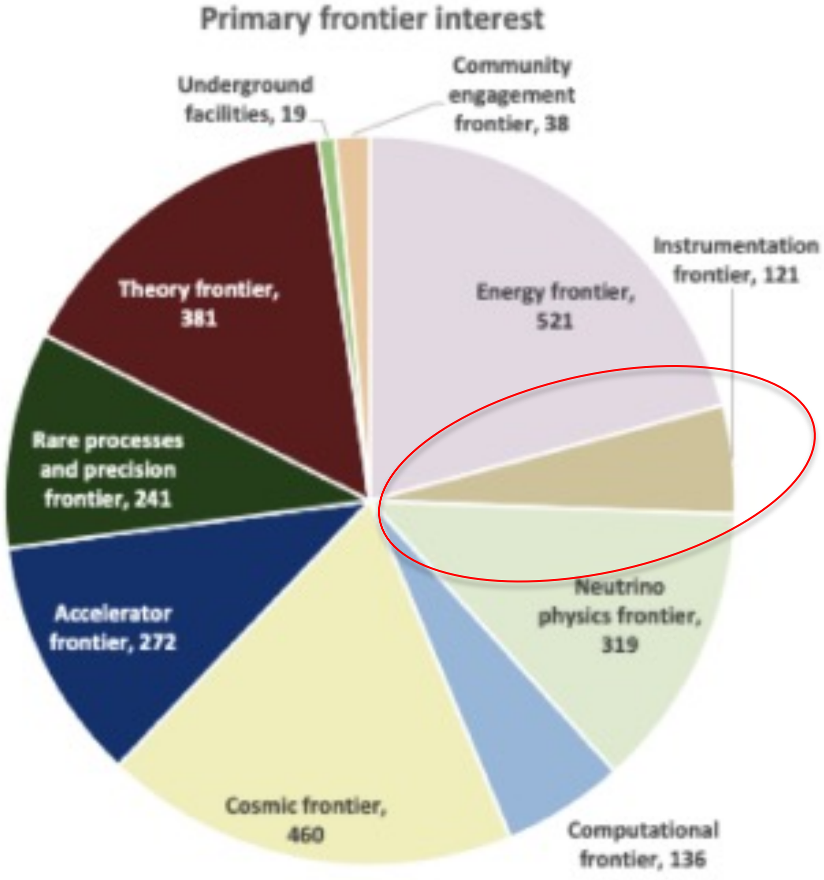
IF Recommendations

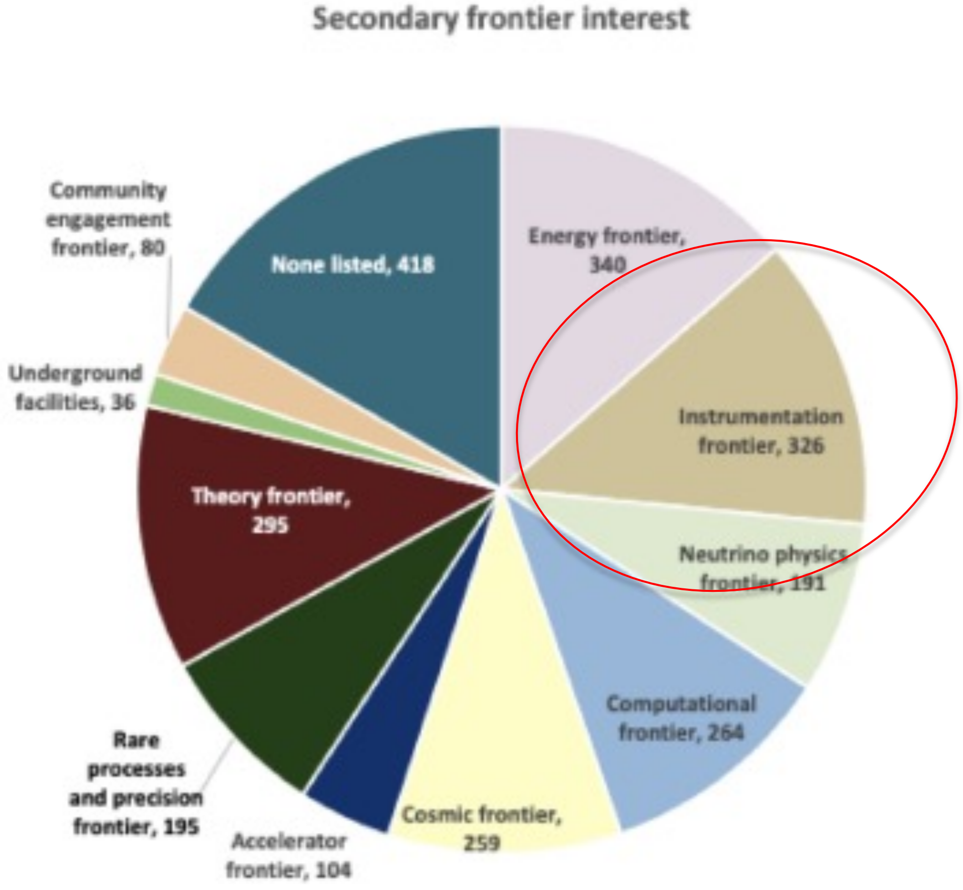
Summary

Many thanks to the IF plenary speakers at the Seattle meeting:
Andy White, Wes Ketchum, Reina Maruyama, Jim Fast

IF is geared to discuss detector technologies and R&D needs for future experiments in collider physics, neutrino physics, intensity physics and at the cosmic frontier, paying close attention to synergies between the different Topical Groups, and with other Frontiers and research areas outside HEP

From the 2021 Snowmass community workshop survey





Organization

IF conveners:
Phil Barbeau (Duke), Petra Merkel (FNAL), Jinlong Zhang (ANL)

Topical Group	Co-Conveners			
Quantum Sensors	Thomas Cecil (ANL)	Kent Irwin (SLAC)	Reina Maruyama (Yale)	Matt Pyle (Berkeley)
Photon Detectors	Chris Rogan (KU)	Juan Estrada (FNAL)	Carlos Escobar (FNAL)	
Solid State Detectors and Tracking	Tony Affolder (UCSC)	Artur Apresyan (FNAL)	Steve Worm (DESY/Humboldt)	
Trigger and DAQ	Darin Acosta (Rice)	Wes Ketchum (FNAL)	Stephanie Majewski (Oregon)	
Micro Pattern Gas Detectors	Bern Surrow (Temple)	Maxim Titov (Saclay)	Sven Vahsen (Hawaii)	
Calorimetry	Andy White (UTA)	Minfang Yeh (BNL)	Rachel Yohay (FSU)	
Electronics/ASICs	Gabriella Carini (BNL)	Mitch Newcomer (Penn)	John Parsons (Columbia)	
Noble Elements	Eric Dahl (Northwestern/FNAL)	Roxanne Guenette (Harvard)	Jen Raaf (FNAL)	
Cross Cutting and System Integration	Jim Fast (JLab)	Maurice Garcia-Sciveres (LBNL)	Ian Shipsey (Oxford)	
Radio Detection	Amy Connolly (OSU)	Albrecht Karle (Wisconsin)		

Frontier	Liaison		
Energy	Caterina Vernieri (SLAC)	Maxim Titov (CEA Saclay)	
Neutrino	Mayly Sanchez (ISU)		
Rare	Marina Artuso (Syracuse)		
Cosmic	Hugh Lippincott (UCSB)		
Acceler.	Andy White (UTA)		
Comput.	Darin Acosta (Rice)		
Undergr.	Eric Dahl (Northwestern)	Maurice Garcia -Sciveres (LBNL)	
Commun.	Farah Fahim (FNAL)		
Early Career	S.Butalla (FIT)	K.Dunne (Stockholm)	J.Zettlemoyer (FNAL)

Snowmass IF webpage: [IF wiki]

Detectors for Collider Experiments

Tracking

Push 4D resolution, low mass and radiation hardness:

- Development of sensor technologies
  - Achieve 4D-capability from timing sensors with fine segmentation and able to cope with high occupancies and radiation tolerance
  - Large area sensors with improved uniformity, e.g. traditional sensors, LGADs, and wafer-scale MAPS
  - Sensors that deliver tracklet 4-vectors instead of hit data
  - Major advances in ASIC development and approaches: bandwidth optimization, low noise, small area and low power dissipation
  - New materials for sensor and electronics: unified design of full systems
- Advanced packaging and edge-computing paradigms
  - Vertical integration of multi-tier processing electronics and sensors, optimization of detector thickness
  - Industry partnerships and adoption of new technologies
- Radiation hard technologies and more effective cooling
- Cohesive set of simulation tools

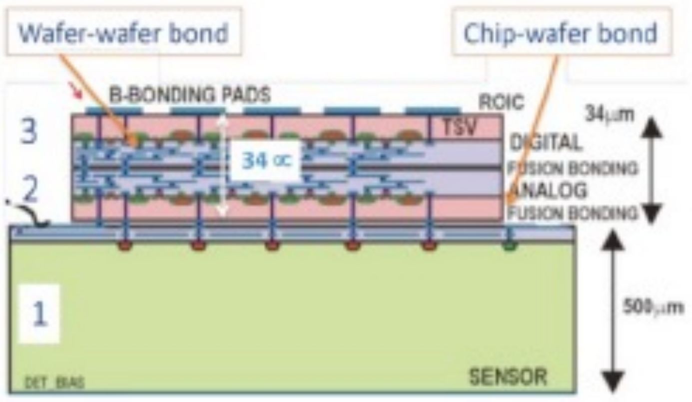
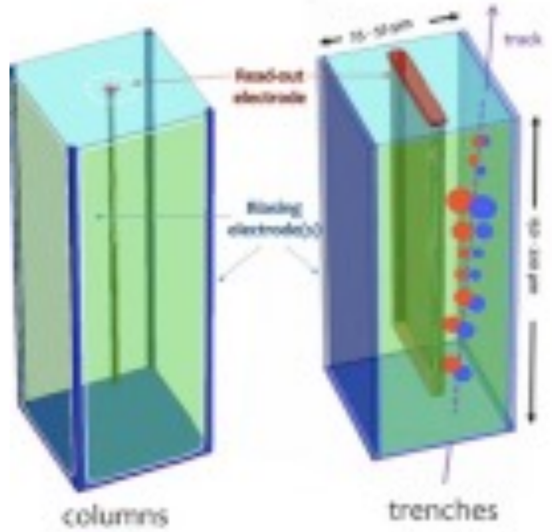
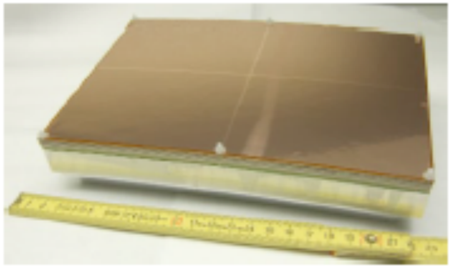


Figure 1: Example of 3D integration of sensor and readout chip.

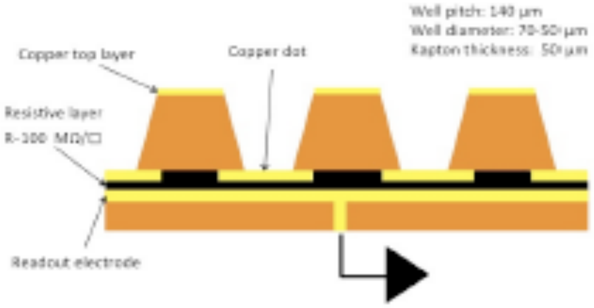


Tracking with Micro Pattern Gas Detectors

- MPGDs have major roles in TPCs and large area muon detection systems. Essential features – large area, low material budget
- TPCs – ILD/ILC, potential Belle II wire chamber replacement, for a detector at CEPC
  - MPGD readout: GEM, GridPix, ...
  - Synergy with Si ASIC development – wafer post-processing, gas amplification on top of pixelized r/o chip
- Muon detection systems
  - Precise muon tracking, trigger and tagger for collider detectors
  - Instrument large areas, high efficiency, in high-background, high-radiation environment
- Challenges:
  - Discharge protection (e.g. micro R-well), miniaturization of readout elements
  - FCC-hh very forward endcap regions
  - Multi-TeV Muon Collider: Fast Timing MPGD, use timing to mitigate beam-induced background
- **Note: there is ongoing discussion about the need for a MPGD facility in the US**



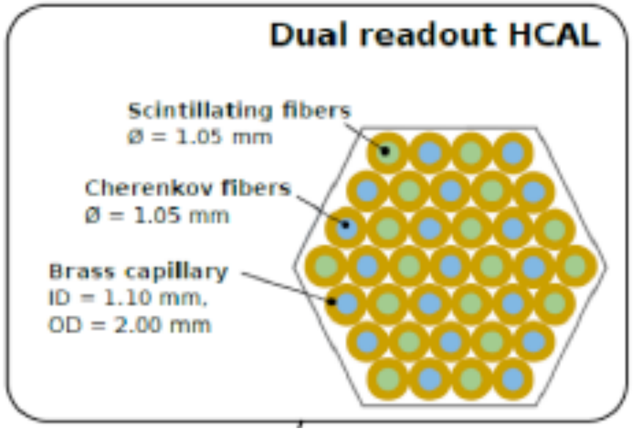
Triple-GEM r/o module for LCTPC

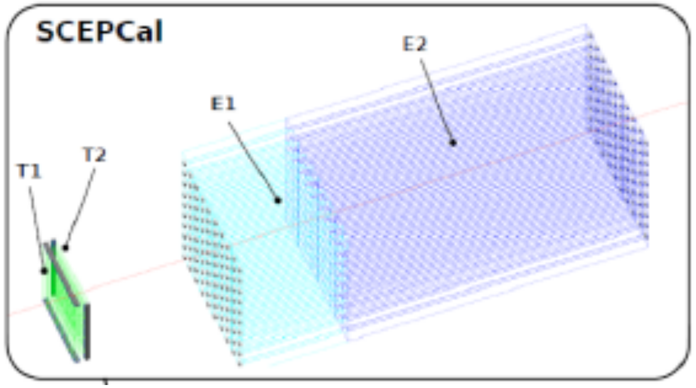


Micro R-well

Calorimetry

- **Two major approaches: particle flow (PF) and dual readout (DR)**
- Recent addition of fast timing information
- Development of new, radiation-hard active materials
- Challenges remain:
  - Mechanics, integration, costing of a realistic spaghetti calorimeter
  - Red-sensitive SiPMs and novel optical materials to boost the Cherenkov signal/noise in homogeneous crystal setups
  - Scaling to 10-100M channels at reasonable cost
  - Thermal and power management of front-end ASICs
  - Compact design (minimizing gaps between sampling layers)

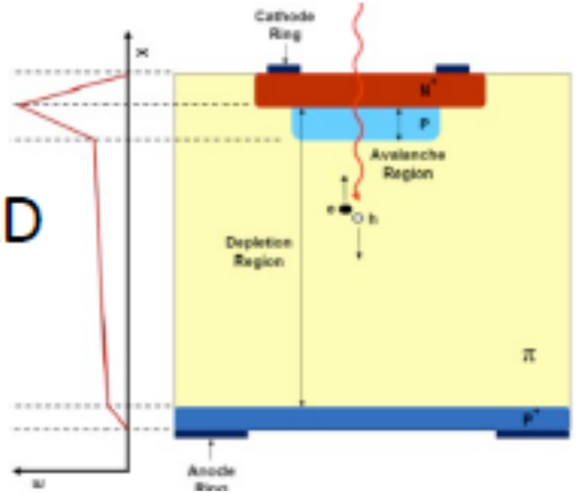


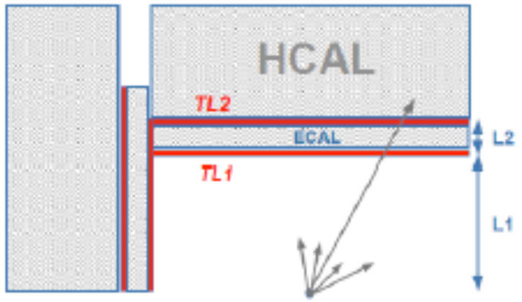


Picosecond Timing

- Timing layers
  - Low-gain Avalanche Detectors (LGADs): ~30ps time and 1mm spatial resolution
  - Ultra-fast silicon monolithic sensors with integrated readout (CMOS): 10-20ps
  - Micro-channel plate (MCP) detectors for single ionizing particles: ~few ps
  - 2-stage Micromegas + Cherenkov radiator equipped with photocathode: <100ps
  - LYSO crystals + SiPM: few 10s ps
  - Deep-diffused avalanche photodiodes: ~40ps
  - Coherent microwave Cherenkov detectors: ~0.3 – 3ps
- Volume timing:
  - Silicon tiles, e.g. LGADs: few 10s ps
  - Plastic scintillator tiles or strips with SiPM readout: sub-ns - few 10s ps
  - Multi-gap RPCs: sub-100ps
  - Highly-granular crystal-based detectors, using a highly-segmented readout
- **R&D needed on electronics to support timing resolution satisfying the constraints on power consumption associated with highly-integrated systems with extreme channel counts**

LGAD





Technology Access

- Ensure institutional retention of >3 decades of collider detector instrumentation design and development experience:
  - System design → moving towards co-design/co-simulation
  - Hierarchical approach to design and simulation of high-channel detector sub-systems
  - Integrated sensors and readout on single/multiple parallel substrates (e.g. MAPS)
  - Engage designers in building radiation tolerant ASIC blocks for future Systems-on-a-Chip (SoC) → to maintain state of art readiness (front-end readout, local memory, on-chip supply conversion DC-DC and LDOs)
- Maintain HEP-specific ASIC web resources for tutorials, examples, references (rad-tolerant/cryo)
- Future designs will require broad, multi-institutional access to:
  - Advanced technology nodes for ASIC fabrication
  - CAD design and design management tools and training
  - Hierarchical system simulation tools

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Detectors for Neutrino Experiments

Noble Element Detectors

- Near-term goals
  - Improve event reconstruction and lower detection thresholds through pixelated charge and light readout
  - Improve sensitivity and energy resolution into VUV scintillation photons through dopants or WLS surfaces and improved sensors
  - Or with photo-ionizing dopants that convert light to charge
  - Further development of optical TPCs and high-pressure gas TPCs
- Technology challenges:
  - Scaled-up target procurement and purification
  - Large-area charge- and photo-sensor development
  - High voltage and large electric fields
  - Reduction techniques for low-energy backgrounds
  - Automated operation and in-situ calibration

QPix Dual Charge+Light Readout

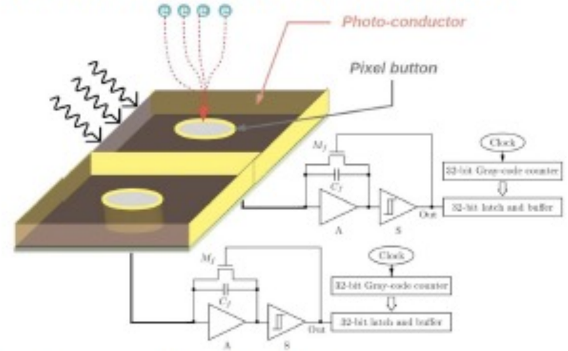
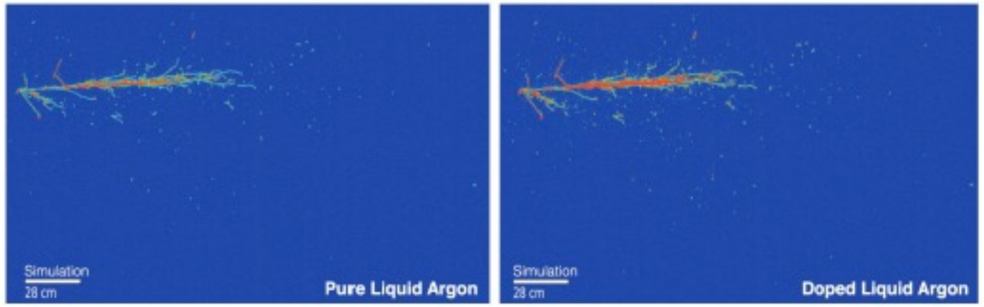


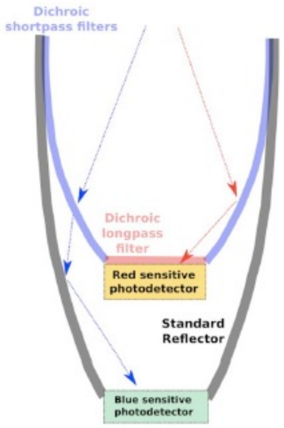
Photo-ionizing dopants in LArTPCs

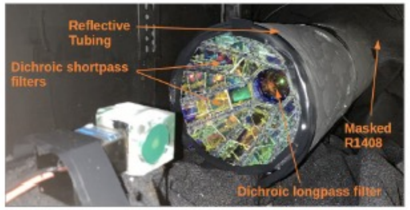


New ideas, materials and sensors

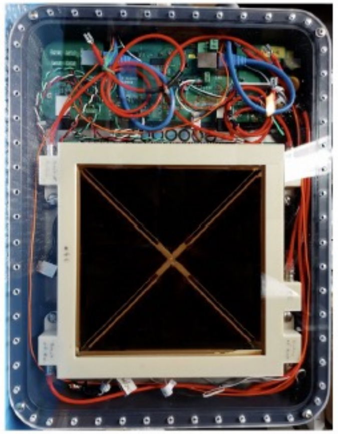
- New modalities in noble detectors (synergies with DM searches)
  - Ion detection and micron-scale track reconstruction for low-energy interactions and directional DM detection
  - Metastable fluids, e.g. scintillating bubble chambers with super-heated noble liquids
  - Enhance existing noble element detectors: e.g. KAMLAND-Zen, and dissolving H or LXe in LZ for light DM sensitivity and enhanced background tagging
- Hybrid detectors: extend capabilities of Cherenkov detectors with technologies that allow separation and detection of scintillation light
  - Separate temporally through fast/precise-timing detectors or slow-fluors
  - Separate spectrally through filters or narrow-band fluors
- All should be coupled with improved performance of existing technologies, e.g. in terms of quantum efficiency and timing, especially for VUV

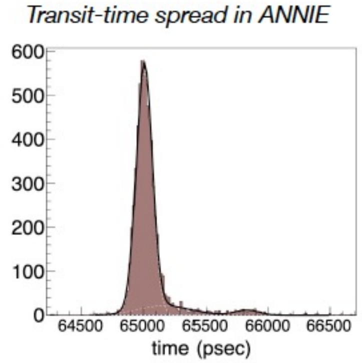
Dichroic filter design





Fast timing with LAPPDs

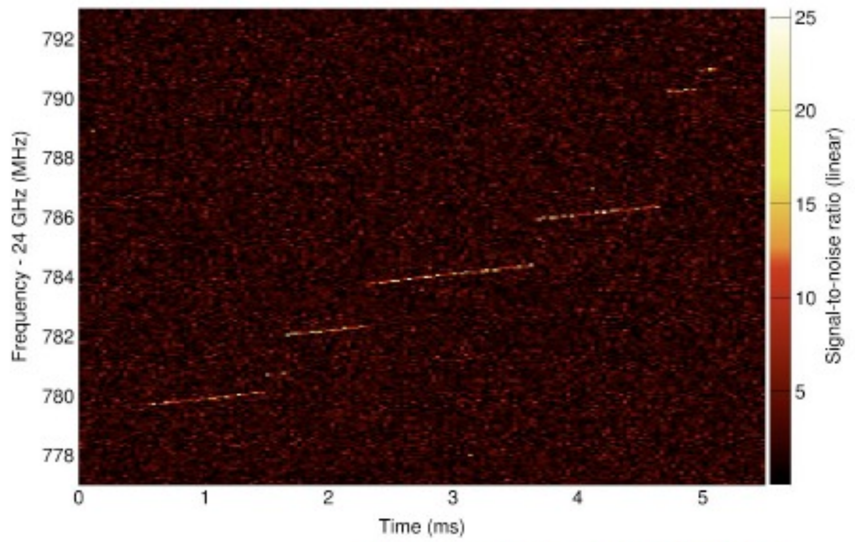




Direct detection of neutrino mass

- Calorimetric:
  - HOLMES: embed 136Ho in sensor and detect phonos from captured β
  - Requires scaling up of detectors using TES arrays through SQUID multiplexing
- Cyclotron radiation emission spectroscopy (CRES)
  - Project 8: measure cyclotron radiation from atomic tritium β in ~1T magnetic field
  - Exploring scaling technologies via high-frequency antenna arrays and cavity resonators

Demonstration of CRES Method from Project8



https://arxiv.org/abs/2203.07349

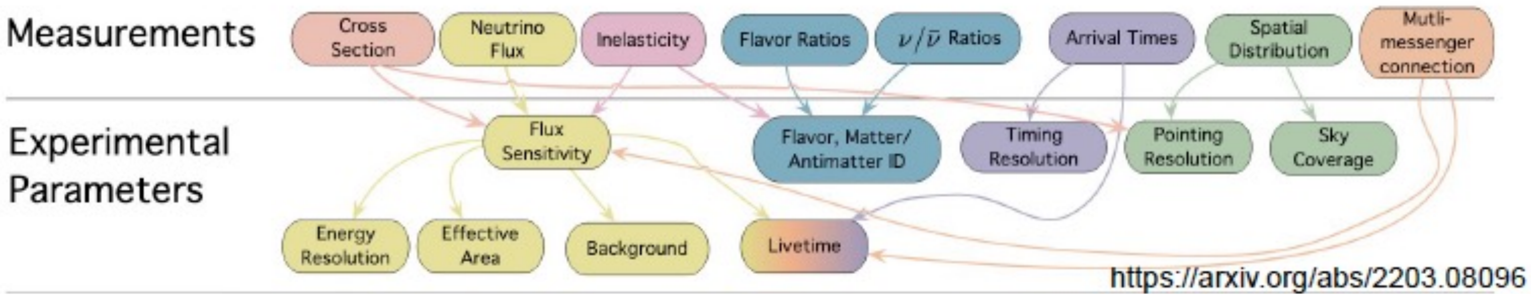
Expanding the energy reach

Pushing to the lowest energies

- Breakthroughs in measuring nuclear recoils enable new neutrino probes through CEvNS detection and extend DM capabilities
  - Variety of technologies: phonon detectors, CCDs, MPGDs, noble liquids and bubble chambers
- Next challenges largely common across detector technologies
  - Improved sensitivity, optimization and multiplexing of readout sensors
  - Reduce backgrounds and understand low-energy response via in-situ calibration

Pushing to the highest energies

- Exploring high- and ultra-high-energy neutrinos (TeV to EeV)
- Techniques include optical Cherenkov detection, radio detection (in ice and air showers) and air-shower imaging via Cherenkov and fluorescent light
  - Commonly require good siting, large exposures, good energy/pointing/timing resolution
  - Improvements in remote power and communication (and timing synchronization) for very large extended arrays
  - Optimizations in electronics, e.g. improving power consumption for RFSoC



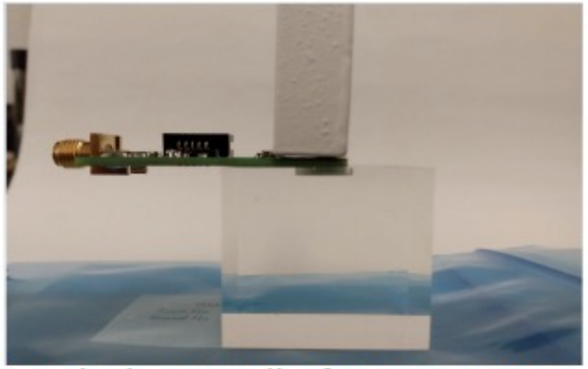
https://arxiv.org/abs/2203.08096

Detectors for
Rare and Precision Experiments

Common and Specific Detector Needs

- Large scientific and experimental diversity
- SM particles as a gateway to understanding the origins of flavor and generations, and fundamental symmetries
- Search for the dark sector through deviations from the SM
- **Detector needs for rare processes sometimes overlap with those of other frontiers, but have some specific needs**
  - Common needs: tracking and calorimetry with both excellent timing and position resolution
    - Thin Si LGADs for tracking
    - 5D calorimetry
    - Fast triggering to suppress large backgrounds
  - Specific needs: e.g. Mu2e-II
    - Ultra-thin straw tracker to reduce multiple scattering
    - New calorimeter materials (e.g. doped BaF2 crystals)

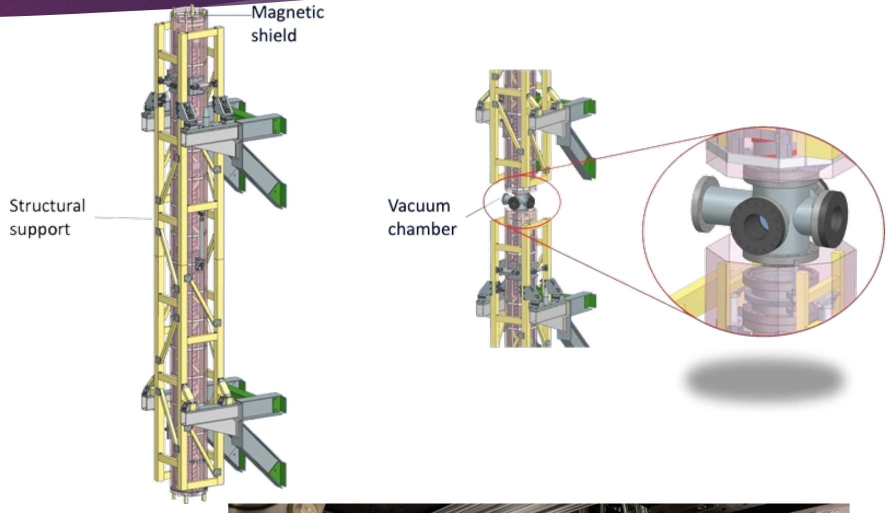
PIONEER Tracker design

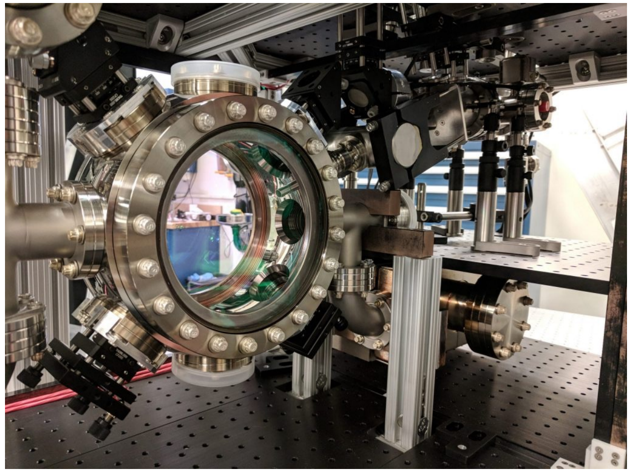


ARIADNO2 Calorimeter tile for REDTOP

Quantum Sensors

- Quantum sensors are a key component of electric and magnetic dipole moment measurements and precision tests of gravity
- Atomic interferometers, optomechanical sensors, optical clocks and spin-dependent sensors
- Key avenue for improvement includes improved techniques on back-evasion and squeezing to push beyond standard quantum limit (SQL)
- Need strong Theory support to address issues of materials and measurement methods

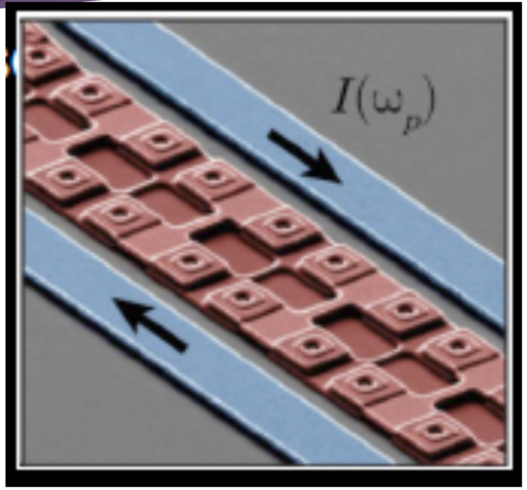


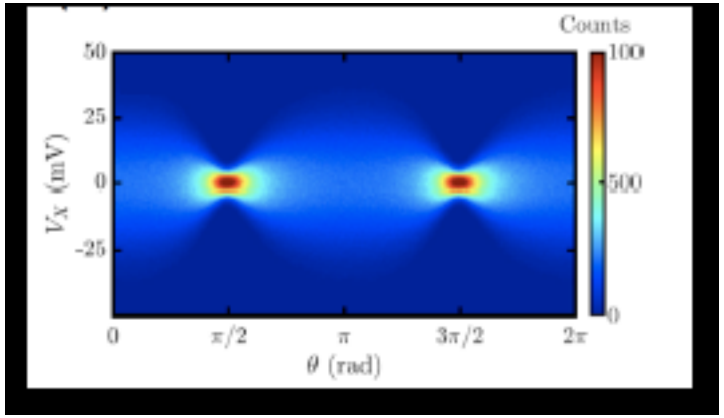


Detectors for Cosmic Experiments

Quantum Sensors (again)

- Superconducting sensors:
  - Operation above and below the SQL: squeezing, backaction evasion, entanglement, superposition, QND photon counting
  - Qbit-based, quantum upconverters, parametric amplifiers, pair-breaking photon counters
- Quantum ensembles:
  - Operation above and below the SQL: superposition, entanglement, squeezing
  - NMR of spin-based sensors, atomic clocks and interferometers, electric dipole moment sensors, Rydberg atoms
- Low-threshold quantum calorimeters:
  - Detection of low-energy scattering events in ionization, phonons, scintillation
  - Transition-edge sensors, MKIDs, liquid helium, quantum defects
- Related technology, facilities, infrastructure:
  - High-Q cavities, magnets, cryogenics, electronics, computing

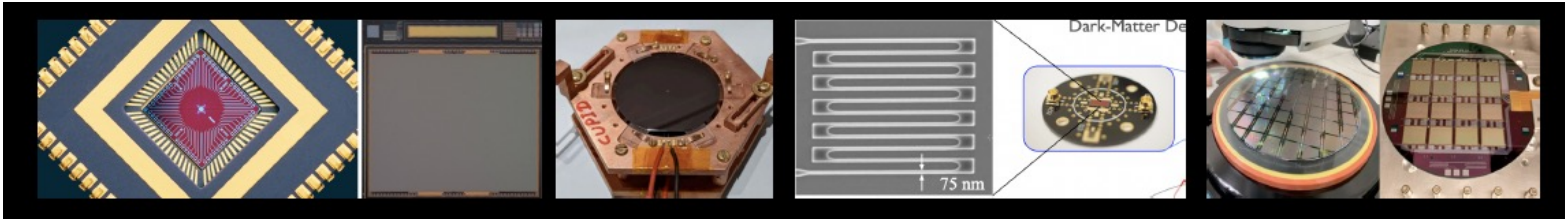




Photon Detectors

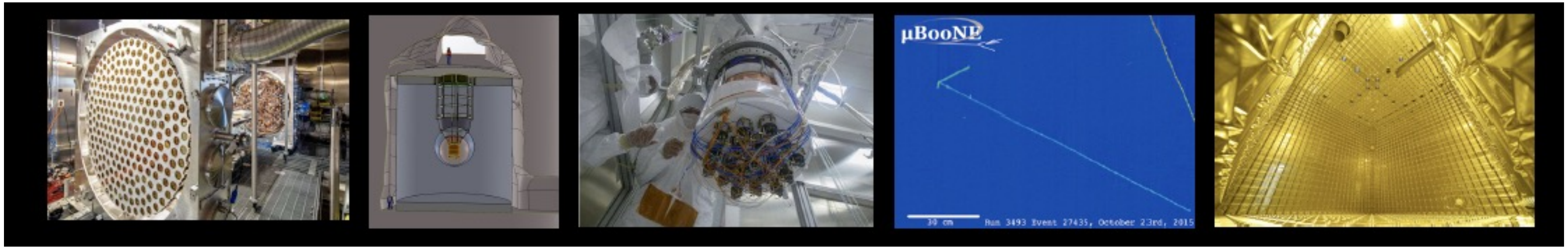
- Wide-field multi-object spectroscopy
- Superconducting sensors, e.g. MKIDs, SNSPDs, TES
- Semiconducting sensors, e.g. skipper-CCDs, also in CMOS, photon-to-digital converter
- Extending wavelength coverage, e.g. visible, IT, UV

- Main challenges now lie in:
  - lower cost
  - increase channel count
  - faster readout



Noble Element Detectors (again)

- Synergies between DM and neutrino physics
- Need better signal-to-noise and reconstruction fidelity
- New signal detection, including methods based on ion drift, metastable fluids, solid-phase detectors and dissolved targets
- Improve understanding of detector microphysics and calibration
- Scaling: material purification, background mitigation, large-area readout and magnetization
- **Train next generation of researchers, using fast-turnaround instrumentation projects to provide the design-through-result training that is no longer possible in very-large-scale experiments**



Cross Cutting Topics

Collaborations, Partnerships, Facilities

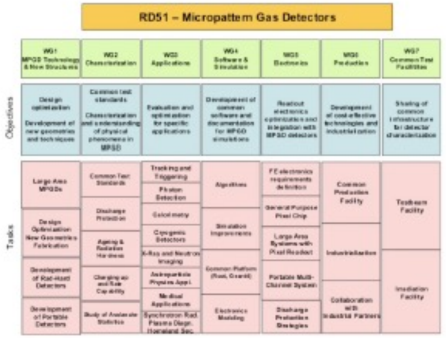
Detector Development takes a village – Collaborations, Partnerships and Stewards

Detector R&D Consortia

New R&D frameworks could enhance U.S. leadership in detector technology

- CERN RD Collaboration Model
  - Topical collaborations around specific technology developments
  - Originated in 1990 with RD-1, now at RD-53
  - ECFA Detector Roadmap (2021)recommended creation of new ones in Calorimetry, Photo Sensors & PID, Liquid Detectors and Quantum Sensing. These RD Collaborations are proposed to be global in extent. **The US HEP community should engage broadly and early to help shape these new RD collaborations**

- NNSA Office of Defense Nuclear Nonproliferation (NA-20) Consortia
  - Topical collaborations around specific thrust areas in nonproliferation
  - Based out of Universities
  - Laboratories participate via existing funding streams from NA-22 and benefit from students and pipeline for career scientists in the field
  - **Strong focus on workforce development**



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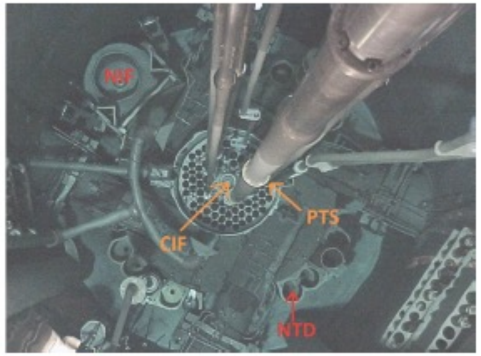
Need to maintain & enhance our facilities

Facilities/Capabilities are a vital element of detector technology development

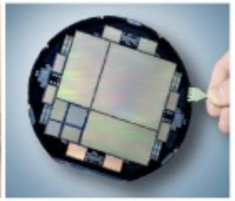
- Test Beams
  - Hadrons at FNAL, LANL, CERN, KEK
  - Electrons at SLAC, Mainz, JLab
- Calibration Facilities
  - Low energy beams, especially neutrons
- Irradiation Facilities
  - BNL, FNAL, PNNL, Sandia
- Dedicated detector development labs
  - SiDet and NLTF at FNAL
  - MSL at LBNL
- Ultra-low background materials and radioassay
  - PNNL, SURF, LBNL
- Ultra-low-background radiochemical analysis and mass-spectrometry
  - PNNL (ICPMS), ANL (AMS)
- Microelectronics, sensor and imager design
  - BNL, FNAL, LBNL, SLAC, Sandia
  - Penn, Northwestern, SMU, Stony Brook University, Washington University, UIC, UIUC, Purdue, UW, Columbia, Stanford etc.



Lithography

Etching

Film Deposition



CCD Wafer

Training the Instrumentation Workforce

- Fundamental to the success of HEP
  - Exciting physics + instrumentation = opportunity to attract and train students from diverse backgrounds
- Build on current success:
  - Dissertation awards, fellowships, traineeship awards
  - Student and postdoc placement and retention
  - Investment for University, National Lab and Industry workforce

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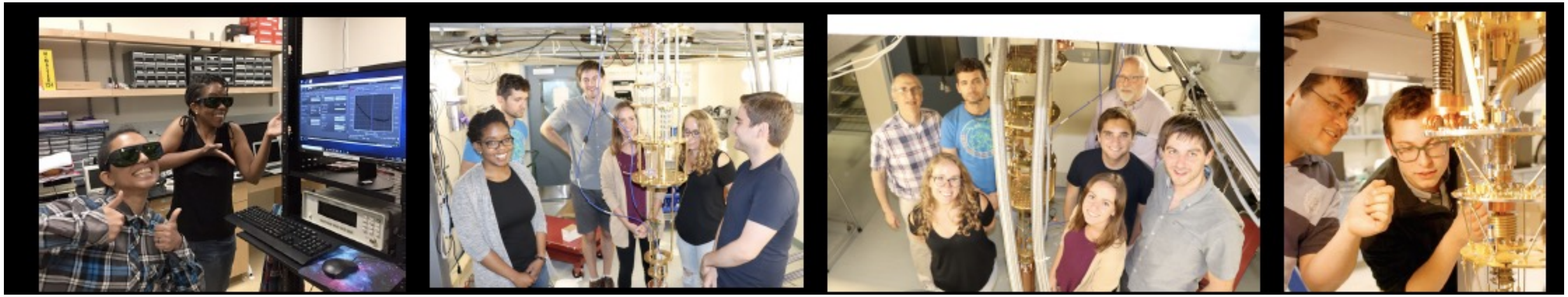

Key Messages

Snowmass IF Report: https://arxiv.org/abs/2209.14111

IF-1 Advance performance limits of existing technologies and develop new techniques and materials, nurture enabling technologies for new physics, and scale new sensors and readout electronics to large, integrated systems using co-design methods.

IF-2 Develop and maintain the critical and diverse technical workforce, and enable careers for technicians, engineers and scientists across disciplines working in HEP instrumentation, at laboratories and universities.

IF-3 Double the US Detector R&D budget over the next five years, and modify existing funding models to enable R&D consortia along critical key technologies for the planned long term science projects, sustaining the support for such collaborations for the needed duration and scale.

IF-4 Expand and sustain support for blue-sky R&D, small-scale R&D, and seed funding. Establish a separate agency review process for such pathfinder R&D, independently from other research reviews.

IF-5 Develop and maintain critical facilities, centers and capabilities for the sharing of common knowledge and tools, as well as develop and maintain close connections with international technology roadmaps, other disciplines and industry.

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Key Messages

Snowmass IF Report: https://arxiv.org/abs/2209.14111

IF-1 Advance performance limits of existing technologies and develop new techniques and materials, nurture enabling technologies for new physics, and scale new sensors and readout electronics to large, integrated systems using co-design methods.

IF-2 Develop and maintain the critical and diverse technical workforce, and enable careers for technicians, engineers and scientists across disciplines working in HEP instrumentation, at laboratories and universities.

IF-3 Double the US Detector R&D budget over the next five years, and modify existing funding models to enable R&D consortia along critical key technologies for the planned long term science projects, sustaining the support for such collaborations for the needed duration and scale.

IF-4 Expand and sustain support for blue-sky R&D, small-scale R&D, and seed funding. Establish a separate agency review process for such pathfinder R&D, independently from other research reviews.

IF-5 Develop and maintain critical facilities, centers and capabilities for the sharing of common knowledge and tools, as well as develop and maintain close connections with international technology roadmaps, other disciplines and industry.