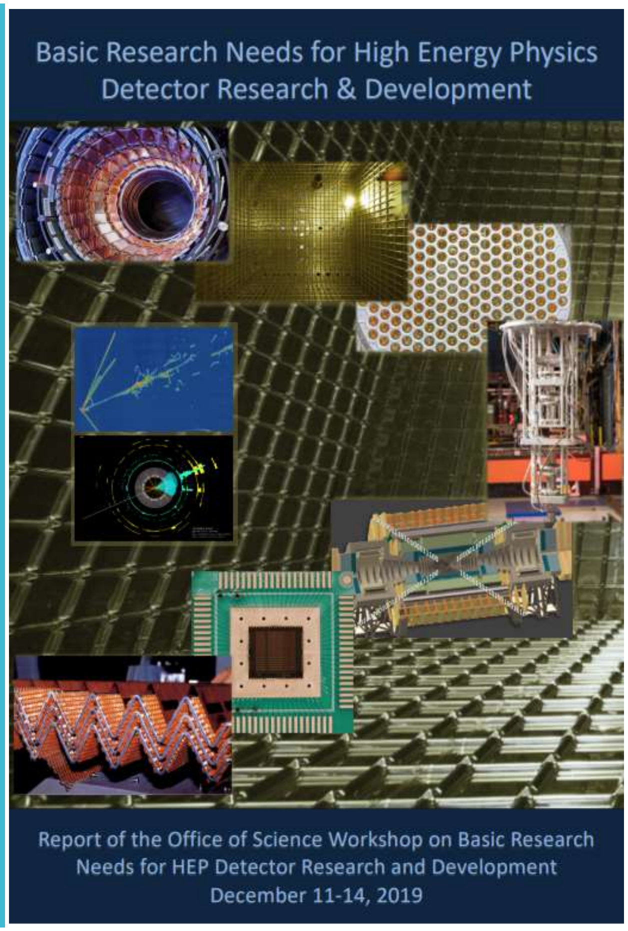
Instrumentation Frontier

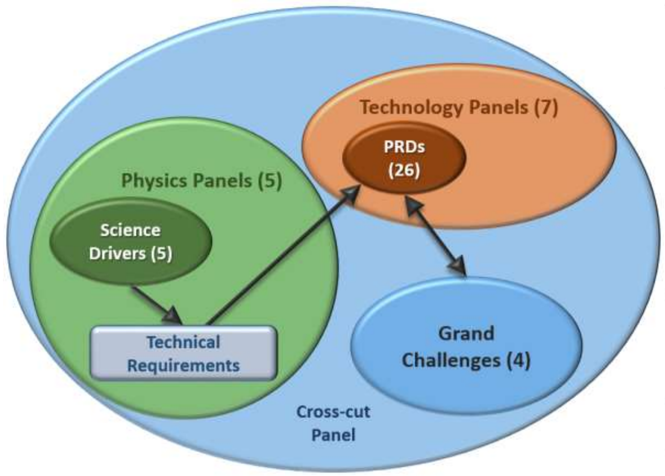
Gabriella Carini

Snowmass 2021

BRN: natural basis for IF



BRN: natural basis for IF



	PRD: Priority Research Direction	Grand Challenge
Calorimetry	PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements	1
	PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments	1,4
	PRD 3: Develop ultrafast media to improve background rejection in calorimeters and particle identification detectors	1,3,4
Nobles	PRD 4: Enhance and combine existing modalities to increase signal-to-noise and reconstruction fidelity	1,2
	PRD 5: Develop new modalities for signal detection	1
	PRD 6: Improve the understanding of detector microphysics and characterization	1
Photodetectors	PRD 7: Extend wavelength range and develop new single-photon counters to enhance photodetector sensitivity	1,3
	PRD 8: Advance high-density spectroscopy and polarimetry to extract all photon properties	2,3
	PRD 9: Adapt photosensors for extreme environments	2,4
	PRD 10: Design new devices and architectures to enable picosecond timing and event separation	1,2,4
	PRD 11: Develop new optical coupling paradigms for enhanced or dynamic light collection	1,2,3
Quantum	PRD 12: Advance quantum devices to meet and surpass the Standard Quantum Limit	1,3
	PRD 13: Enable the use of quantum ensembles and sensor networks for fundamental physics	1,2
	PRD 14: Advance the state of the art in low-threshhold quantum calorimeters	1,3
	PRD 15: Advance enabling technologies for quantum sensing	1,2,3
ASIC	PRD 16: Develop process evaluation and modeling for ASICs in extreme environments	3,4
	PRD 17: Create building blocks for Systems-on-Chip for extreme environments	1,4
SolidState	PRD 18: Develop high spatial resolution pixel detectors with precise high per-pixel time resolution to resolve individual interactions in high-collision-density environments	1,4
	PRD 19: Adapt new materials and fabrication/integration techniques for particle tracking	2,3
	PRD 20: Realize scalable, irreducible-mass trackers	2,3
TDAQ	PRD 21: Achieve on-detector, real-time, continuous data processing and transmission to reach the exascale	2,4
	PRD 22: Develop technologies for autonomous detector systems	2
	PRD 23: Develop timing distribution with picosecond synchronization	1
Xcut	PRD 24: Manipulate detector media to enhance physics reach	1,3
	PRD 25: Advance material purification and assay methods to increase sensitivity	1,2,3,4
	PRD 26: Addressing challenges in scaling technologies	2,3

Instrumentation Frontier conveners and scope

Phil Barbeau	Duke University	psbarbeau[at]phy.duke.edu
Petra Merkel	Fermi National Accelerator Laboratory	petra[at]fnal.gov
Jinlong Zhang	Argonne National Laboratory	zhangjl[at]anl.gov

The Instrumentation Frontier group is geared to discussing detector technologies and R&D needed for future experiments in collider physics, neutrino physics, intensity physics and at the cosmic frontier. It is divided into more or less diagonal sub-groups with some overlap among a few of them. The sub-groups are Calorimetry, Cross Cutting and Systems Integration, Electronics/ASICs, Micro Pattern Gas Detectors, Noble Elements, Photon Detectors, Quantum Sensors, Solid State Detectors and Tracking, and Trigger and DAQ. Synergies between the different sub-groups, as well as with other Frontier groups and research areas outside of HEP will be paid close attention to.

IF topical groups and co-conveners

Topical Group	Co-Conveners			
Quantum Sensors	Thomas Cecil (ANL)	Kent Irwin (SLAC)	Reina Maruyama (Yale)	Matt Pyle (Berkeley)
Photon Detectors	Juan Estrada (FNAL)	Mayly Sanchez (ISU)	Chris Rogan (Kansas)	
Solid State Detectors and Tracking	Tony Affolder (UCSC)	Artur Apresyan (FNAL)	Steve Worm (DESY)	
Trigger and DAQ	Darin Acosta (Florida)	Wes Ketchum (FNAL)	Stephanie Majewski (Oregon)	
Micro Pattern Gas Detectors	Bernd 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)	Roxanne Guenette (Manchester)	Jen Raaf (FNAL)	
Cross Cutting and System Integration	Jim Fast (PNNL)	Maurice Garcia-Sciveres (LBL)	Ian Shipsey (Oxford)	
Radio Detection	Amy Connolly (Ohio State)	Albrecht Karle (Wisconsin)		

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IF Liasions

- Liaisons are providing high-level and bi-directional communication b/w Frontiers
- IF Liaisons:
  - Energy Frontier: Caterina Vernieri (SLAC), Maksym Titov (CEA Saclay)
  - Neutrino Physics Frontier: Mayly Sanchez (ISU)
  - Rare Processes and Precision: Marina Artuso (Syracuse)
  - Cosmic Frontier: Kent Irwin (SLAC), Hugh Lippincott (UCSB)
  - Accelerator Frontier: Andy White (UTA)
  - Computational Frontier: Darin Acosta (Florida)
  - Underground Facilities: Eric Dahl (Northwestern), Maurice Garcia-Sciveres (LBNL)
  - Community Engagement: Farah Fahim (FNAL)

Gearing up after the pause

- Before the pause:
  - Defined possible overlaps and boundaries between topics
  - Engaged community with several topical workshops leading towards the community meeting
  - We had received 343 LOIs and had started to work on white papers
- After the pause:
  - Slightly reorganized topical groups
  - Focus on white papers
  - Kick-off meeting in November

Contributed white papers and path to Snowmass report

- Papers may include documents on specific scientific areas, technical articles presenting new results on relevant physics topics, and reasoned expressions of physics priorities
- Contributed papers will remain part of the permanent record of Snowmass
- LOIs are not required to submit contributed papers
- The 10 IF Topical Groups are organizing solicited White Papers on specific topics based on the received LOIs
- White Papers are due March 15, 2022 to arXiv
    - See https://snowmass21.org/submissions/start for more info also on how to submit
- White Papers will be basis for summaries by Topical Group
- Summaries will go into IF portion of Snowmass report
- Late White Papers will be part of online Snowmass repository, but might not make it into summaries

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Snowmass-IF + CPAD Workshop

- Last Snowmass:
  - CPAD was the Instrumentation Frontier group 6
- Since then:
  - Vibrant, annual instrumentation workshops
  - Cross-cutting Quantum Sensing workshop
  - Workshop reports
  - Instrumentation Awards, Instrumentation Studentships GIRA, SBIR process, …
- **Next Snowmass + CPAD Workshop: February 15-18 @ Stony Brook**
  - Baseline plan is hybrid version, in-person participation highly encouraged
  - Serve as Snowmass Instrumentation Frontier workshop: White Paper readiness
  - Facilitate cross-fertilization with NP/EIC community
  - Early Career plenary

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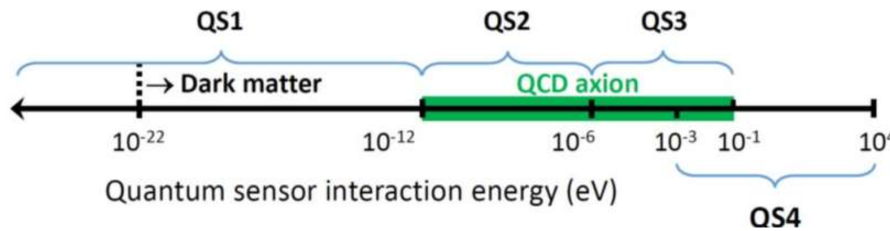
Quantum Sensors

Community papers:
- Superconducting Sensors
- Quantum Calorimeters
- AMO: Spins, NMR, and Defects
- Interferometers, Clocks, and Traps

Tom Cecil, Kent Irwin, Reina Maruyama, Matt Pyle

- **Quantum Sensors and Snowmass science**
  - Ultralight wavelike dark matter (generalized axions, hidden photons, scalars)
  - Scattering / absorption of dark matter particles
  - Electric dipole moment measurements (electron, nuclear, neutron)
  - Gravitational waves
  - Dark energy
  - Violations of fundamental symmetries
  - New forces and particles
- **Quantum sensors instrumentation has close connection with**:
  - IF2: Instrumentation Frontier, photon detectors
  - IF7: Electronics/ASICs subgroup
  - CF1: Cosmic Frontier, Dark Matter particle-like
  - CF2: Cosmic Frontier, Dark Matter wave-like
  - AF5: Accelerator for PBC and Rare Processes
- Important to make sure that interfaces are well defined, and nothing is "dropped in the cracks." This is an emerging technology area - and connections to other frontiers will emerge.



Quantum sensors by interaction energy

- QS1 (0 eV - 1 peV) - wavelike interactions
  - Atomic & molecular spectroscopy, atom interferometers and mechanical sensors, clocks, atomic magnetometers, spins, quantum defects in solids
- QS2 (1 peV - 1 microeV) - wavelike interactions
  - Nuclear, electronic, and other spins, electromagnetic quantum sensors, optical cavities, quantum defects in solids
- QS3 (1 microeV - 0.1 eV) - wavelike interactions
  - Superconducting qubits / sensors, spins, Rydberg atoms, quantum defects in solids
- QS4 (1 meV - 10 keV) - particle-like interactions
  - Low threshold phonon and charge detectors, quantum defects in solids, single-photon counters (SNSPD, APD, ...) - interface to IF2: Photon detectors, depending on application
- See Basic Research Needs for HEP Detectors report for more detail

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Quantum Sensors

Tom Cecil, Kent Irwin, Reina Maruyama, Matt Pyle

Quantum Sensors

Quantum sensors by technology

- Superconducting sensors
  - Operation above and below the Standard Quantum Limit: squeezing, backaction evasion, entanglement, superposition, QND photon counting
  - Qubit-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 searches, 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

Tom Cecil, Kent Irwin, Reina Maruyama, Matt Pyle

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Photon Detectors

	Neutrino Frontier 1	Cosmic Frontier 2	Energy Frontier 3	Rare & Precision 4
Sensors hiE(1)		•		
Sensors UV (2)	•	•		•
Sensors VIS (3)	•	•	•	•
Sensors IR (4)		•		
Sensors μwave/Radio (5)		•		
Large Area (6)	•			•
Low Background (7)				•
Fast Timing (8)	•	•	•	
Light collection (9)	•	•		•
RD facility (10)				

Mayly Sanchez, Chris Rogan, Juan Estrada

Grouped in categories that are technology centered/cross cutting across frontiers

- New sensors visible and IR Development of new photon sensors for visible light.
  - Semiconductor detector (CCD, CMOS, SiPM) for use in the next generation of experiment in all frontiers in HEP.
  - Includes single photon imaging devices, IR semiconductor devices (like Ge imaging detectors), images with integrated processing (3D integration). Also SNSPDs.
- Large area photodetectors and Light collection systems
  - Development of cost efficient solutions covering large areas for photon detection in HEP experiments, cosmic, nuclear physics and radiation therapy.
  - Technology developments for astronomical spectrographs (fiber positioners), light collecting systems and filtering in next generation neutrino detectors.

Photon Detectors

- Detector for microwaves
  - Development of new sensor technologies for microwaves that do not have the focus on quantum techniques on quantum sensing.
  - Sensors that do not fit into the microcalorimeter WP that the IF01 group is organizing. We have moved the radio astronomy detectors to the new IF10 group.
- New sensors high-energy, UV and fast timing
  - Development of novel photosensor technology above UV energies. This focus mainly in Gamma ray instrumentation for space.
  - Development of UV and VUV detectors sensor for noble liquids (light and charge collection), calorimetry and Cherenkov imaging (Particle ID). With some overlap in BES.
    - Could be merged with Large-Area/Light Collection.
  - Focused on the photodetector with fast timing (psec) in colliding experiments, neutrino experiments. LGAD, psec timing in sub-micron CMOS, fast timing in calorimeters.

Mayly Sanchez, Chris Rogan, Juan Estrada

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Solid State Detectors and Tracking

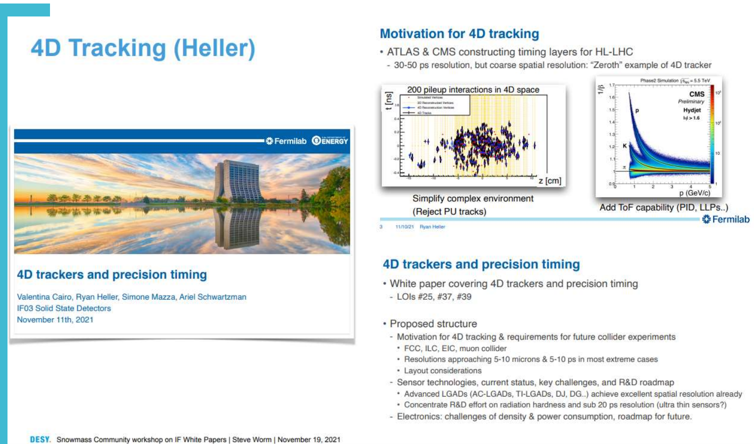
From white papers…

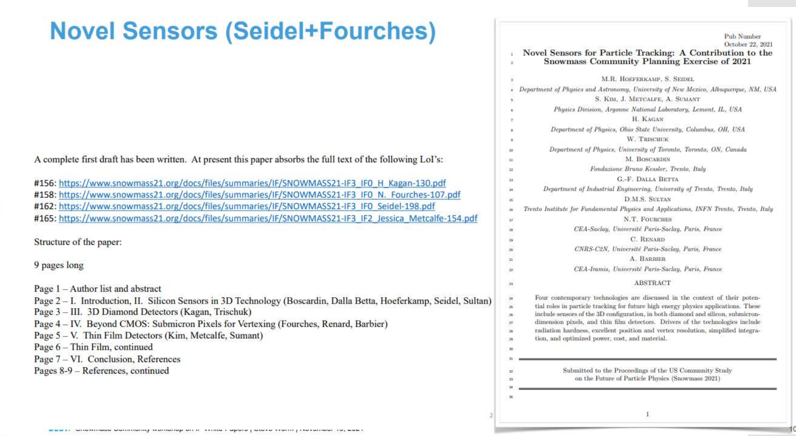
- Physics motivations for requirements of tracking detectors (Requirements)
- 4D trackers, precision time + position; OR precision position + moderately good time (Timing)
- Monolithic integrated silicon detectors, CMOS (MAPs)
- Integration and Packaging (Integration)
- Mechanics, lightweight materials, cooling (Mechanics)
- Novel Sensors for Particle Trackers (Novel)
- Non-silicon trackers: (Non-silicon)
- Simulation Tools for Silicon Detector Developments (Simulation)

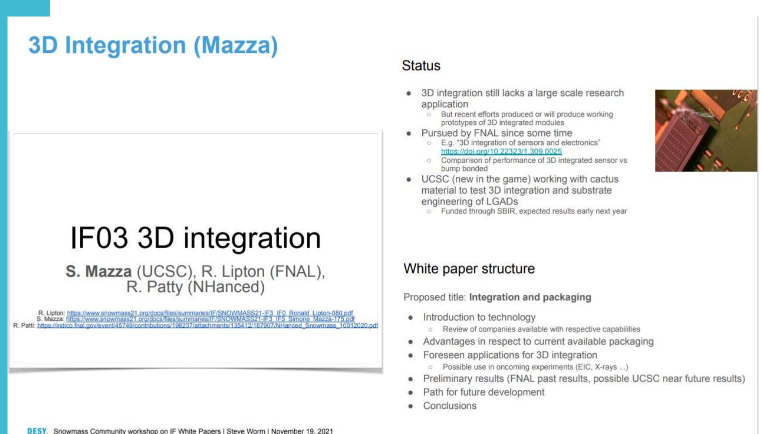
Anthony Affolder, Artur Apresyan, Steven Worm

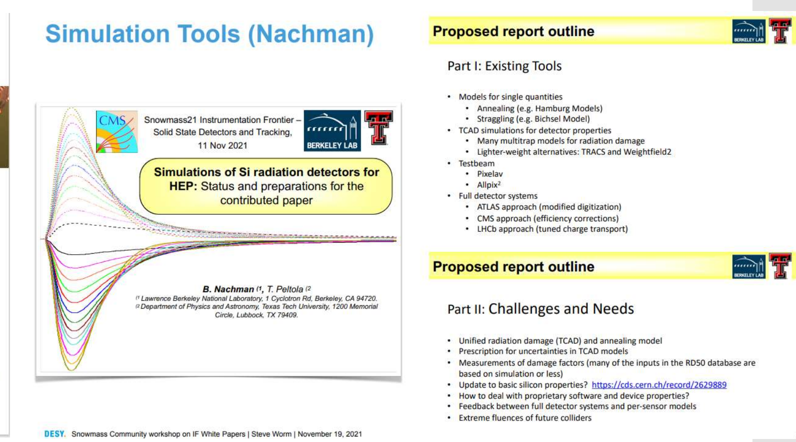
Solid State Detectors and Tracking

…to contribute papers









Anthony Affolder, Artur Apresyan, Steven Worm

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Trigger and DAQ

General trends clearly emerged, which form the basis for possible TDAQ white papers:

- ***Artificial Intelligence and Machine Learning in TDAQ***
- ***General innovations in TDAQ for next generation detectors***
- ***Readout technologies for future detectors***

Proposed Common White Papers, and Associated LOIs:

- "Artificial Intelligence and Machine Learning in Trigger and DAQ"
  - Big and popular topic, so depending on community feedback consider split to two white papers? e.g. "AI/ML at the edge" and "AI/ML in High-level triggers, event-filtering, and detector control"
  - Work closely with IF07 (especially on the former) and computing frontier (especially on the latter)
- "Innovating Trigger and DAQ for the next generation of detectors"
  - Include TDAQ architecture and infrastructure (e.g. streaming DAQ), fast computation on heterogeneous computing, fast timing, trigger-aware ASIC development (work with IF07)
  - Natural place for ideas not specific to AI/ML (e.g. fast tracking triggers, fast spectral analysis), and a way to tie-in needs of future experiments
- "Readout technologies for future detectors"
  - Include wireless readout, rad-hard links, multiplexed high-speed readout (with IF07)

Trigger and DAQ

Other Proposed Common White Papers

- "Innovating Trigger and DAQ for the next generation of detectors"
  - Include TDAQ architecture and infrastructure (e.g. streaming DAQ), fast computation on heterogeneous computing, fast timing, trigger-aware ASIC development (work with IF07)
  - "Self-driving" triggers
  - Natural place for ideas not specific to AI/ML (e.g. fast tracking triggers, fast spectral analysis), and a way to tie-in needs of future experiments General catch-all for innovative ideas.
- "Readout technologies for future detectors"
  - Include wireless readout, rad-hard links, multiplexed high-speed readout (with IF07)

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Micro-Pattern Gas Detectors

Five white papers:

- MPGDs: Recent advances and current R&D
  - Will use RD51 LOI as overall guide, use sections of submission to LHCC for RD51 detailed activities, and topical LOIs
- MPGDs for nuclear physics experiments
  - Facility for Rare Isotope Beams
  - Thomas Jefferson National Laboratory: Current & Future Experiments
  - Electron Ion Collider: Requirements, MPGDs for Tracking, MPGDs for PID (RICH, TRD, TOF)
- Recoil imaging for DM, neutrino, and BSM physics
  - Inter-frontier (Neutrino, Dark Matter, Instrumentation) White Paper on directional nuclear + electron recoil detection w/ dedicated executive summaries for each Snowmass topical group (including MPGD requirements for IF5)

Bernd Surrow, Maxim Titov, Sven Vahsen

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Micro-Pattern Gas Detectors

- Recoil imaging for DM, neutrino, and BSM physics (continued)
  - Current status of recoil imaging, Dark matter, Neutrinos, Beyond-the-SM physics, Other applications that benefit from directionality, Detector Requirements, Blue-sky R&D
- MPGDs for TPCs at future lepton collider (from 4 LOIs)
  - Belle II TPC, Time projection chamber R&D, A time projection chamber using advanced technology for the International Large Detector at the International Linear Collider, A high-gain, low ion-backflow double micro-mesh gaseous structure
- MPGDs for muon detection at future colliders
  - State of the art (MPGDs for tracking and muon detection: progress review and updated R&D), Technologies, Infrastructures and integration aspects

Bernd Surrow, Maxim Titov, Sven Vahsen

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Calorimetry

Five topics divided in six whitepapers for calorimetric instrumentation (AstroCosmic to be included in IF2)

- Collider, Neutrino, Dark Matter, Materials, Astro/Cosmic
    - Particle Flow Calorimetry, Dual Readout Calorimetry for Future Colliders, Precision Timing for Collider Experiment based Calorimetry
    - Neutrino-related Calorimetric Detector WP: LOIs in NF10 are quite comprehensive for calorimetric instrumentation including noble liquids, water, scintillator, emulsion, and radio detection; white paper for the Instrumentation Frontier "IF6/neutrinos" to be coordinated with NF10 to produce a common document for neutrino detectors (with a section on calorimetric techniques)
    - Materials for Future Calorimeters: current and planned projects, key issues and onwards
        - e.g. preferable materials with high density, better optical property, high light-yield and fast/short light pulse (and low cost); novel calorimeter concepts with new materials

Andy White, Minfang Yeh, Rachel Yohay

Electronics / ASICs

- Reviewed IF7 White Paper worthy sub-topics from 2020
- Starting consolidating/coordinating on a few areas:
  - ASIC Workforce/tools/Foundries
  - Calorimetry
  - Photodetectors
  - Silicon Sensors
  - TDAQ
- IF7 - Strong connection established (last year) with:
  - TDAQ/Triggering (IF4)
  - Solid State Detectors /Tracking (IF3)

IF7 related contributions will likely be merged into IF3 and IF4 white papers.

Gabriella Carini, Mitch Newcomer, John Parsons

Electronics / ASICs

From LOIs to White Papers

- Data handling
  - Addressable Readout Techniques for Scalable Readout System
  - Self-driving data trigger, filtering, and acquisition systems for high-throughput physics facilities
  - Real-time adaptive deep-learning with embedded systems for discovery science
  - FPGA Based Artificial Intelligence Inference In Triggered Detectors
- AI/ML
  - Self-driving data trigger, filtering, and acquisition systems for high-throughput physics facilities
  - Real-time adaptive deep-learning with embedded systems for discovery science
  - FPGA Based Artificial Intelligence Inference In Triggered Detectors
  - AI ASICs for front end processing focus on Optimal Implementation
  - ML and AI data inferential reduction

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Electronics / ASICs

From LOIs to White Papers

- Pixelated Liquid Noble readouts
  - Pixelated LAR_TPC ionization current Reconstruction Technique
  - Pixelated LAR_TPC Readout Establish R&D mechanisms
- Monolithic sensor readout
  - Large area CMOS monolithic active pixel sensors for future colliders
  - 28nm CMOS for 4D Tracker Readout Chips
  - 4-Dimensional Trackers
  - BNL & LBL MAPs Tracker development

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Electronics / ASICs

From LOIs to White Papers

- Calorimetry
  - High precision, high dynamic range readout
- Optical links
  - Optical Link HS (extreme radiation environment)
  - Radiation-hard high-speed fiber-optical data links for HEP experiments
- Timing
  - Time of Flight Detector for circular electron positron collider
  - PRECISION TIMING DETECTORS FOR FUTURE COLLIDERS
- Deep cryogenic readout
  - 4K and below Cryo SiGe heterogeneous bipolar
- Design for reliability analytical techniques
  - Quality Control Cryogenic Detector FE Readout
- Photodetector readout
  - Analog Processor with parametric feature Extraction

Gabriella Carini, Mitch Newcomer, John Parsons

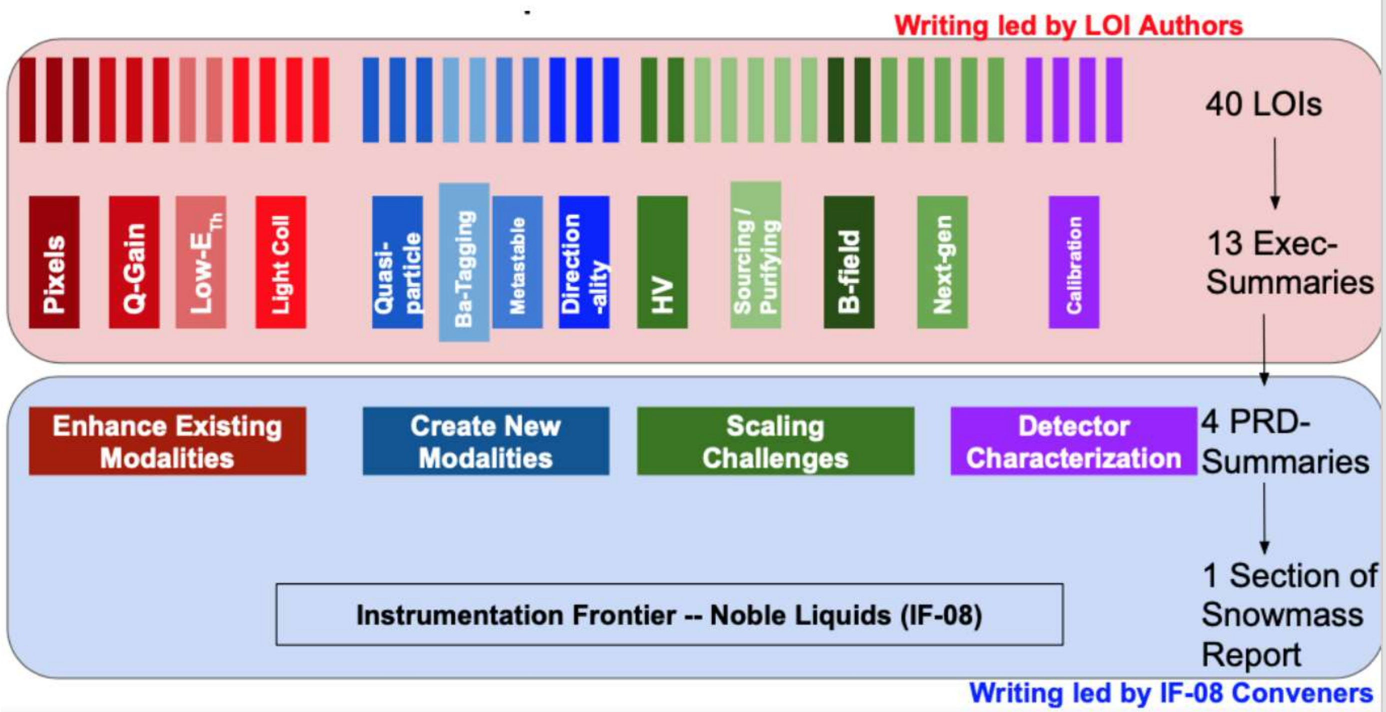
Electronics / ASICs

Related Initiatives

Our CPAD community discussion concluded that there was movement towards direct support for instrumentation and, in fact, two FOA's from DOE appeared in the Spring that included some wording from the 2019 BRN Instrumentation report

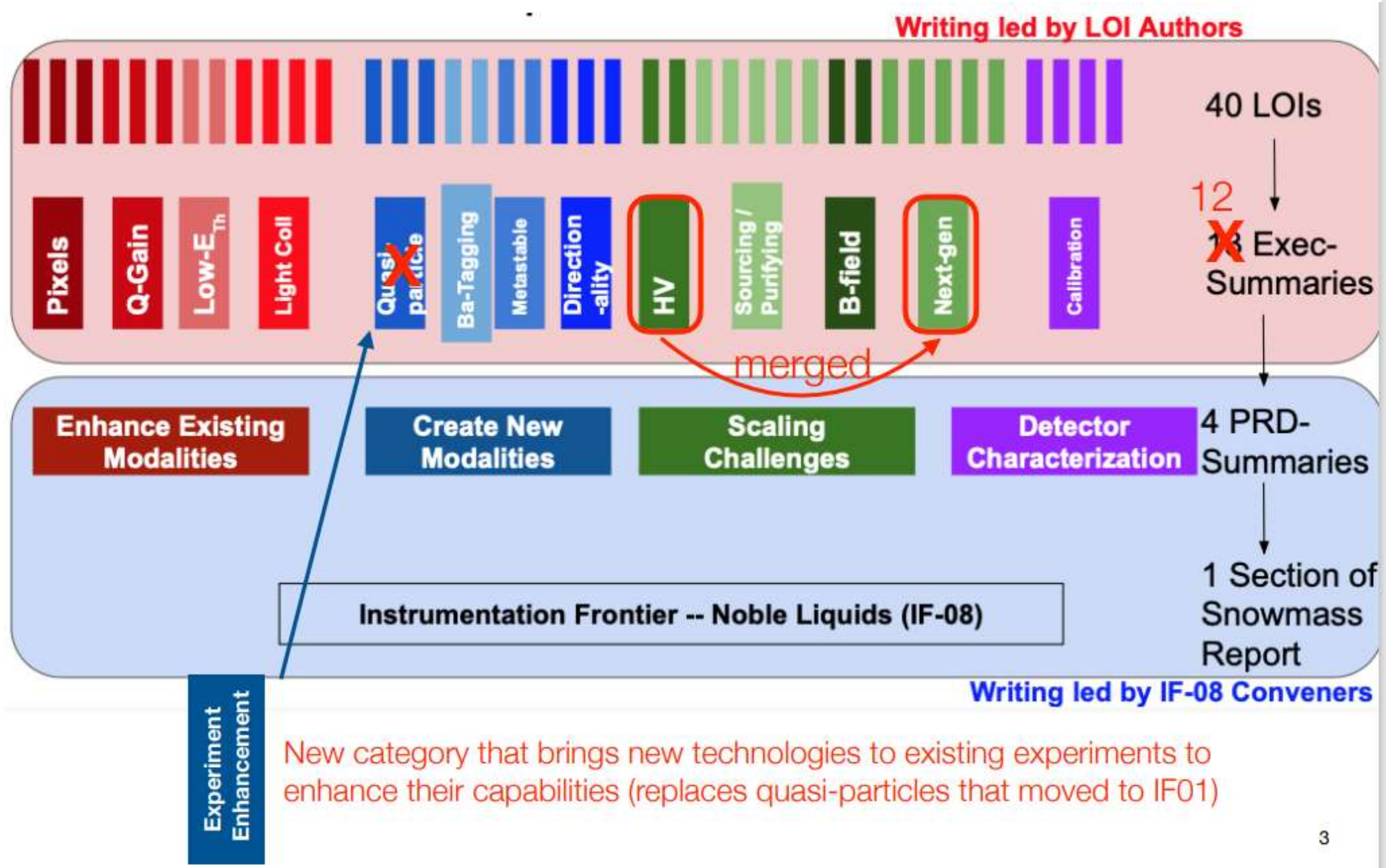
- *Microelectronics Co-Design Research* LAB opportunity
- *Traineeship in High Energy Physics* University Program
- This year we have participated in discussions with ASIC foundry representatives to explore opportunities for multi-party NDA's
  - Notably: *Skywater & TSMC*
- We expect to continue to pursue opportunities through the HEPIC and follow the progress of the 3 funded Traineeship programs.
  - Analog Processor with parametric feature Extraction
- DOE-led effort for EDA tools

Noble Elements



Eric Dahl, Roxanne Guenette, Jen Raaf

Noble Elements



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Cross Cutting and System Integration

- Foundries and foundry access
- Calibration & Test beams and irradiation facilities
- Facilities for unique environments
  - Low environmental noise
  - Cryogenic facilities (LAr to mK)
  - Low-background LOIs will be covered by Underground Facilities working group

Jim Fast, Maurice Garcia-Sciveres, Ian Shipsey

Radio Detection

New topic

- Working on coordination: dark matter, axions, high energy neutrino, etc.

Amy Connelly, Albrecht Karle

Thank you!

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