Photodetectors Summary

Andrey Elagin

for the photodetectors working group

12/10/2019, CPAD Workshop

Photodetector Session

- 52 abstracts were (cross-)referenced as photodetectors
- Accepted all abstracts
- 25 talks in Photodetectors
- ~2.5 talks in Diverse Detectors
- 1 award plenary
- The rest in Quantum and Superconducting, Nobel Liquids, Trigger & DAQ

Sunday

Scintillators:

Water-based, Structural, Plastic, Li-dopped, Opaque, BaF2, LuAG:Ce ceramics, etc

The Scientific Impact of Water-based Liquid Scintillator Hybrid Detectors	*Robert SVOBODA*	
Meeting Rooms K-R, Monona Terrace Convention Center		15:30 - 15:50
Characterization of water-based liquid scintillator	*Prof. Gabriel OREBI GANN et al.*	
Meeting Rooms K-R, Monona Terrace Convention Center		15:50 - 16:10
A low-background structural scintillator for rare event physics experiments	*Dr. Michael FEBBRARO*	
Meeting Rooms K-R, Monona Terrace Convention Center		16:10 - 16:30
Lithium-doped PSD-capable Liquid Scintillator for the PROSPECT Experiment	*Dr. Pieter MUMM*	
Meeting Rooms K-R, Monona Terrace Convention Center		16:30 - 16:50
PSD capable Plastic Scintillators with Li-6 Doping for neutron and reactor antineutrino detection	*Dr. Viacheslav LI*	
LiquidO: A Novel Detector Technique with Opaque Scintillator	*Dr. J. Pedro OCHOA-RICOUX*	
Meeting Rooms K-R, Monona Terrace Convention Center		17:10 - 17:30
The Next Generation Crystal Detectors for future HEP Experiments	*Dr. Ren-Yuan ZHU*	
Meeting Rooms K-R, Monona Terrace Convention Center		17:30 - 17:50
Progress on a photosensor for the readout of the fast scintillation component of BaF2	*Prof. David HITLIN*	

Monday

MCP-based Detectors and Their Applications
Quantum Dots
Photoswitching Molecules

Production of Large Area Picosecond Photo-Detectors – LAPPDTM : Status Update.	*Dr. Alexey LYASHENKO*	
Design of a Dual-Low/Ultra-High Vacuum Facility for Air-Transfer Production of Large-area High-resolution MCP-based Photodetectors at 100 units/week .	*H.J. FRISCH*	
Application of MCP-PMT/LAPPD for EIC Particle Identification	*Junqi XIE*	
Meeting Rooms K-R, Monona Terrace Convention Center		14:10 - 14:30
Precision Time-of-Flight System using Large Area Picosecond Photodetectors at the Fermilab Test Beam Facility	*Evan ANGELICO*	
Advanced Photon Detection in ANNIE for Next Generation Neutrino Experiments	*Dr. Emrah TIRAS*	
Meeting Rooms K-R, Monona Terrace Convention Center		14:50 - 15:10
Development of Long Life Microchannel Plate Photomultiplier Tubes	*Prof. Andrew BRANDT*	
Meeting Rooms K-R, Monona Terrace Convention Center		15:10 - 15:30
NuDot: Fast Photodetectors for Double-Beta Decay with Direction Reconstruction	*Dr. Julieta GRUSZKO*	
Using Switchable Fluorescent Molecules to Image Tracks and Measure Energy in Large Liquid Double Beta Decay Detectors	*Eric SPIEGLAN*	

Tuesday (part 1)

Neutrino detectors
Cosmology

The Physics Potential of Advanced Reactor Neutrino Detectors	*Prof. Bryce LITTLEJOHN*
Meeting Rooms K-R, Monona Terrace Convention Center	09:00 - 09:20
Design and Progress of the JUNO experiment	*Prof. Liangjian WEN*
Meeting Rooms K-R, Monona Terrace Convention Center	09:20 - 09:40
Cosmogenic Background Characterization with the PROSPECT Antineutrino Detector	*Dr. Xianyi ZHANG*
Meeting Rooms K-R, Monona Terrace Convention Center	09:40 - 10:00
Instrumentation for a Post-reionization Intensity Mapping Survey	*paul OCONNOR*
Meeting Rooms K-R, Monona Terrace Convention Center	10:00 - 10:20
Fiber Positioners for Cosmic Surveys	*Dr. H. Thomas DIEHL*
Meeting Rooms K-R, Monona Terrace Convention Center	10:20 - 10:40

Tuesday (part 2)

Calorimetery

SiPMs

Nano-particles

Small-Gap materials

Development of high granularity and dual-readout calorimetry based on the \emph{sipm-on-tile} technique	*Prof. Corrado GATTO*	
Nanoparticle-enhanced photosensors for UV light detection	*Dr. Stephen MAGILL*	
Meeting Rooms K-R, Monona Terrace Convention Center		11:20 - 11:40
Novel Small-Gap Materials as Photodetectors	*Dr. Noah KURINSKY et al.*	
Meeting Rooms K-R, Monona Terrace Convention Center		11:40 - 12:00
Improving the light collection efficiency of silicon photomultipliers through the use of metalenses	*Mr. Alvaro LOYA VILLALPANDO*	

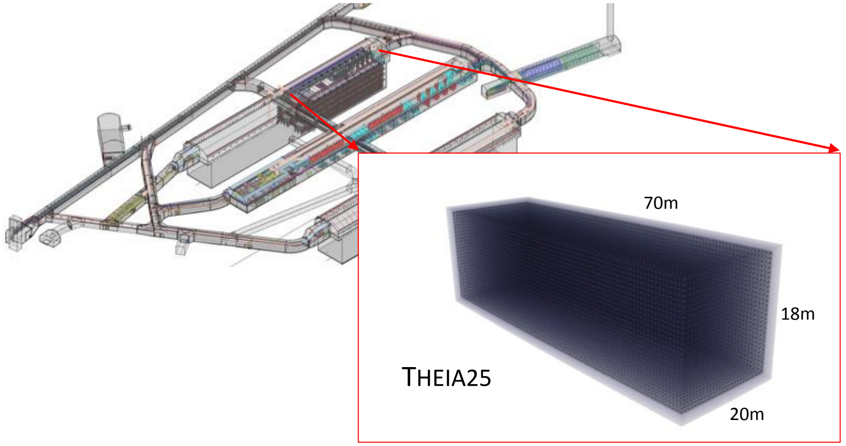
Highlights from the presentations

Disclaimers:

The area/talk (0.3-1 of a slide) in the following reflects only my ability to put slides together from various sources in a single **15-mins** presentation on a very short time scale and has nothing to do with priorities or importance

Apologies for possible omissions or misrepresentations

R.Svoboda

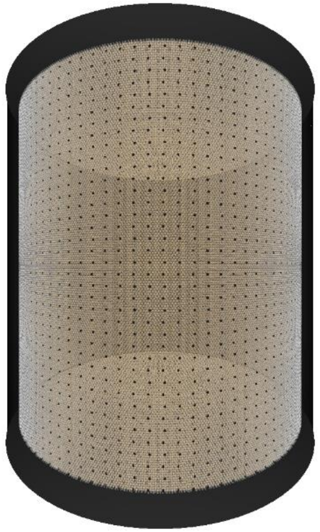


New White Paper on Physics of a hybrid Chereknov/Scintillator detector: arXiv:1911.03501)

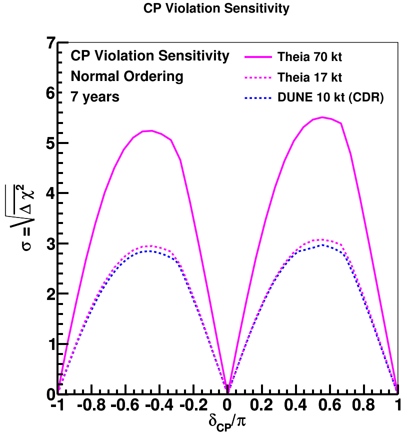
Two versions of the concept for the **LBNF**

Theia25: 25 kTon (total) hybrid detector as the 4th DUNE module

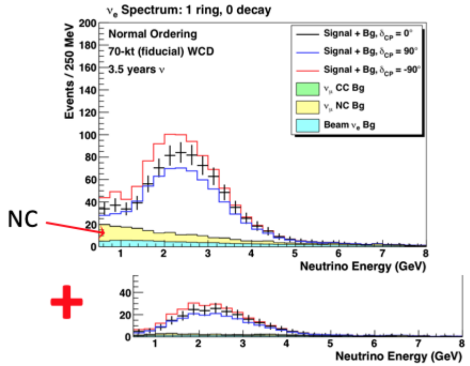
Theia100: 100 kTon (total) hybrid detector as a future stand-alone experiment



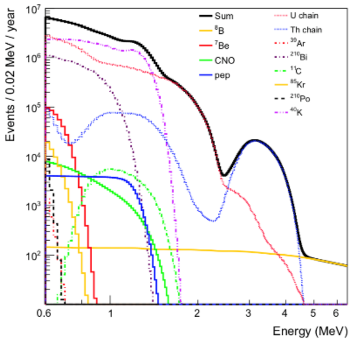
Theia100



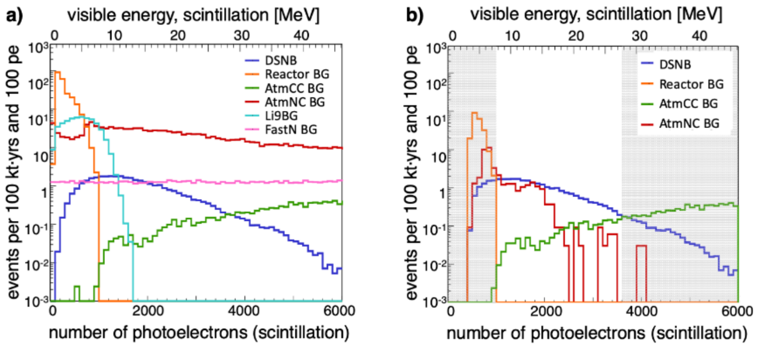
Neutrino CP Violation



Long Baseline Neutrino Physics

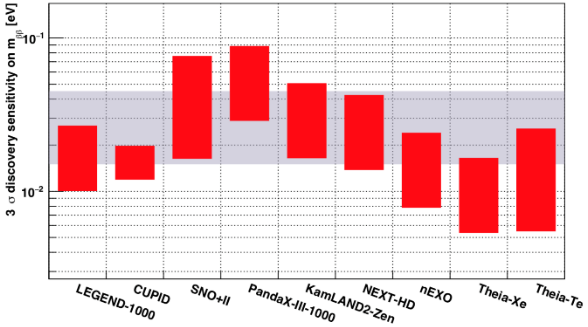


Solar Neutrinos



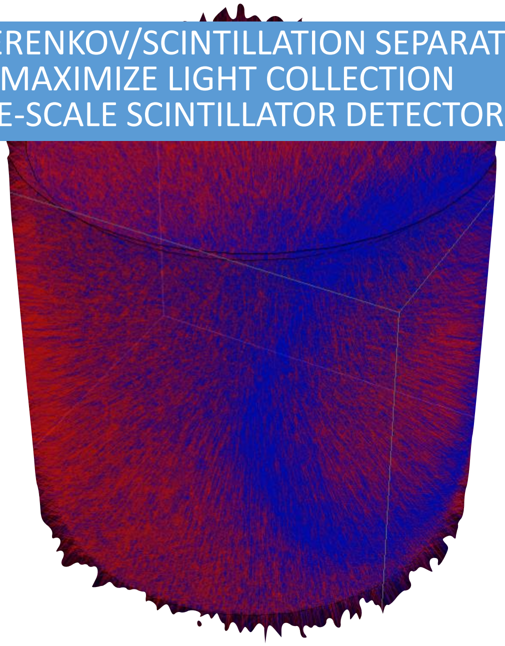
Diffuse SN neutrinos

Majorana Neutrinos



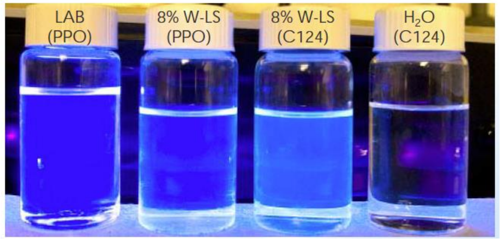
Call for R&D in photosensors and Water-based Liquid Scintillator

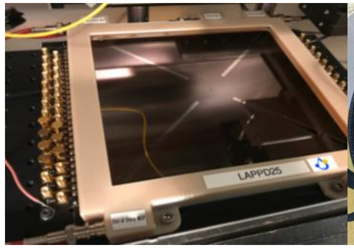
Characterization of water-based liquid scintillator, Javier Caravaca

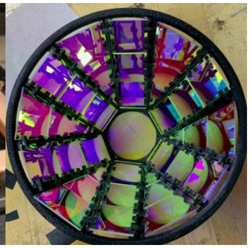


REALIZE CHERENKOV/SCINTILLATION SEPARATION AND MAXIMIZE LIGHT COLLECTION IN LARGE-SCALE SCINTILLATOR DETECTOR

- There exists an international collaboration developing and testing R&D for THEIA
- Water-based liquid scintillator production, optimization and characterization is on-going
- Modern photo-detection techniques with fast timing and sensitive to wavelength being tested
- Cherenkov/scintillation separation has already been realized at small scales using fast timing and wavelength sorting (*)



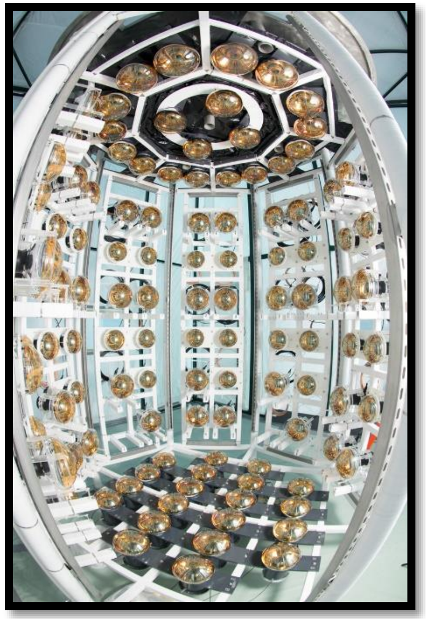




Advanced Photon Detection in ANNIE at Fermilab

Emrah Tiras

annie



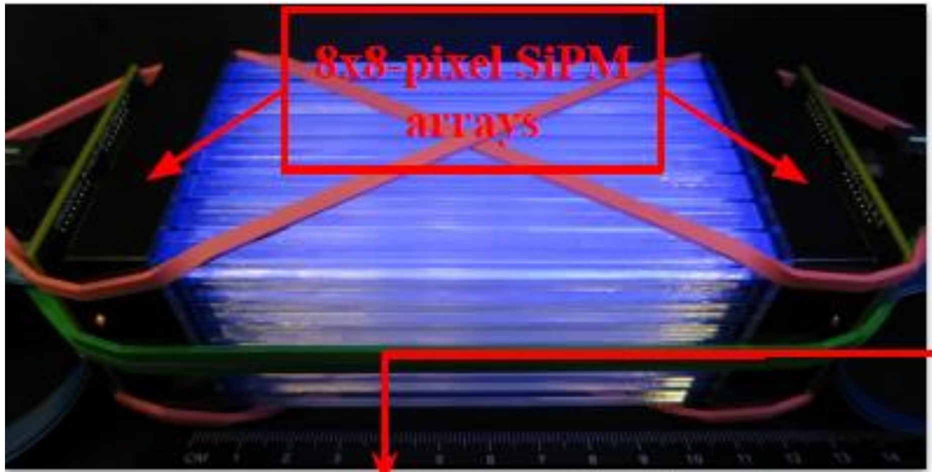
- 26-ton Gadolinium (Gd)-loaded water Cherenkov Detector installed and under commissioning
- Neutrino beam (BNB) data taking to begin in January 2020.
- **ANNIE is pioneering R&D of photodetection technologies:**
  - Neutron tagging in Gd-loaded water
  - **5 LAPPDs characterized at FNAL being readied for installation**
  - **LAPPD coverage can be expanded in-situ** to enable multi-track reconstruction and measurements of more exclusive final states.
  - **Possible addition of WbLS** to combine the tracking capabilities of Cherenkov reconstruction with the energy resolution and expanded sensitivity of scintillation light.

A low-background structural scintillator for rare event physics experiments, Michael Febbraro

- The polyester PEN has been demonstrated as a possible structural active veto scintillator
- Exhibits desirable mechanical properties at room and cryogenic temperatures
  - Good chemical resistance → Can be aggressively clean!
- Fluorescence observed at ~445 nm
  - Well-match with SiPM / PMT
  - Particle discrimination possible
  - Light output ~1/3 of conventional plastic scintillators
- New amorphous PECN (PEN-G) formulations produced at ORNL exhibit enhanced optical clarity during processing of complex or thick geometries
- Low-background PEN components can be prepared for rare-event physics experiments

PSD capable Plastic Scintillators with Li-6 Doping for neutron and reactor antineutrino detection

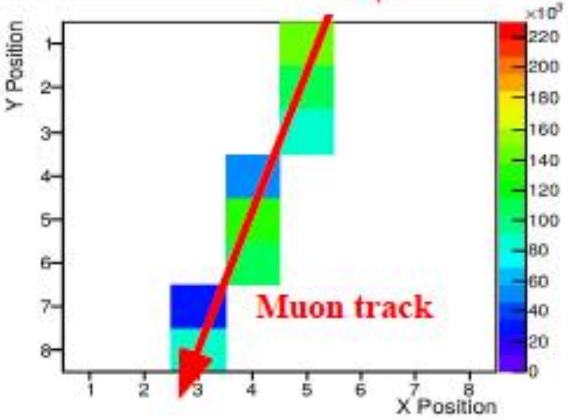
Viacheslav Li

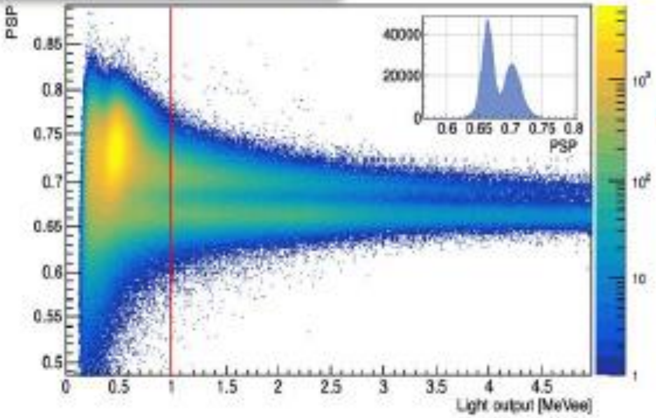


Fine segmentation and pixelization with novel LLNL plastic scintillators allows **particle identification** based on both Pulse-Shape Discrimination and segment multiplicity.

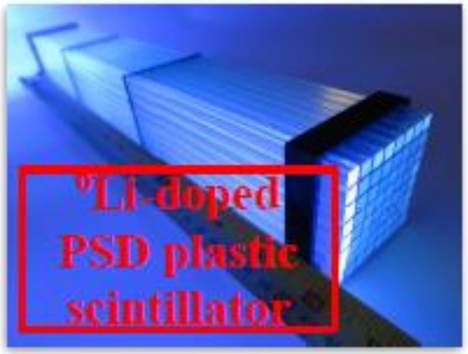
SANDD: A highly-segmented pulse-shape-sensitive plastic scintillator detector incorporating silicon photomultiplier arrays

New opportunities in **Neutrino Physics and beyond.**





- **First PSD** in a **fully-segmented** ^{6}Li-doped plastic scintillator instrumented with **SiPM arrays.**
- Stable and **scalable** ^{6}**Li-doped plastic** scintillator

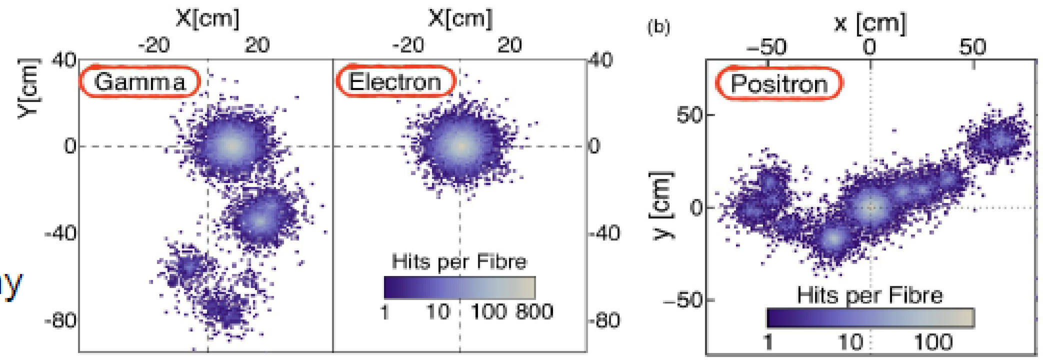


V. Li et al. NIM A942 (2019)

Pedro Ochoa-Ricoux

LiquidO: A new approach

- Work is ongoing on a new approach for neutrino detection called LiquidO
  - **Opaque** scintillator volume traversed by dense array of fibers
- Unprecedented capabilities:
  - Imaging down to the MeV scale
  - Affinity for doping well beyond current limits
- Potential application in many areas of neutrino physics
- See arXiv:1908.02859

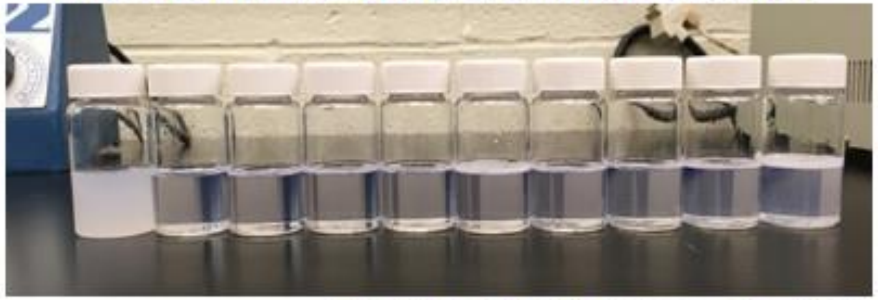


(Gamma and Electron are 2 MeV, positron is 1 MeV)

Lithium-doped PSD-capable Liquid Scintillator for the PROSPECT Experiment, Bryce Littlejohn

- PROSPECT has demonstrated a high-performance Li doped liquid scintillator critical to on-surface background rejection.
- Improvements in raw materials and purification methods have (and will continue to lead to higher performance.
- Better understanding of micelle behavior will allow tuning of micelle size to improve performance.
- Other applications for high light-yield PSD capable liquids

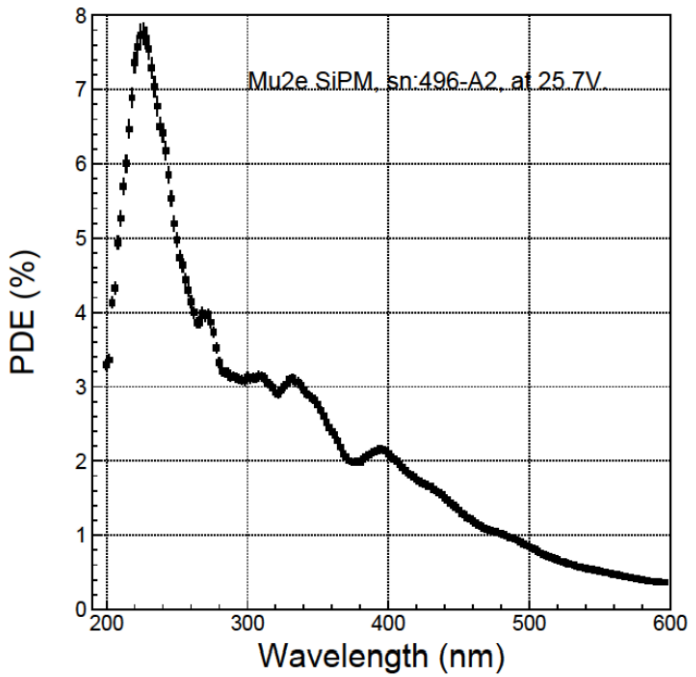
PROSPECT Litihium Doped Scintillator Samples



0.035 to 0.15% ^{6}Li mass fraction

A UV sensitive SiPM for the readout of the fast scintillation, David Hitlin

- Caltech, JPL and FBK are collaborating on a SiPM with good QE at the 220 nm fast component and strong suppression of the 300 nm slow component
- Chips with differing filters and with and without superlattices are being tested for filter performance and PDE Radiation hardness studies and MTF studies
- Best current result (with PDE~8%, due to low overvoltage is extremely encouraging



The Next Generation Crystal Detectors, Ren-Yuan Zhu

* Bright, fast and rad hard LYSO crystals are used at the HL-LHC. LuAG:Ce ceramics may provide an alternative, provided that its slow component is eliminated.

* Ultrafast yttrium doped BaF2 crystals may be used for ultrafast calorimetry to cope with an unprecedented event rate.

* Doped Sapphire crystals with a mass production cost of less than $1/cc may be used for an homogeneous hadron calorimetry, providing unprecedented jet mass resolution by dual readout of both scintillation and Cerenkov light or dual gate .

LAPPD production at Incom Inc., Alexey Lyashenko

I. Baseline GEN I - defined and is being produced
   A. Baseline GEN I LAPPD - Available Today!
      - Present production pace is 4 LAPPDs per month (expandable with demand)
   B. "Typical" performances meet early adopter needs:
      - Gain $>10^6$
      - Mean QE > 20% @ 365nm >80% uniformity
      - Time Resolution < 70 Picoseconds, and mm Spatial Resolution
      - Dark rate $<1000 Hz/cm^2$ @ gain 10^7

II. Baseline GEN II – is being defined
      Prototypes being produced

III. "Early Adopter" programs to make LAPPDs available for test & evaluation.

IV. Smaller format 10cm X 10cm detector is being developed

Air-Transfer High-Volume Production of Large-area MCP-based Photodetectors, Henry Frisch

- **Need for a concerted HEP effort for the development of '4D Precision Measurement' technologies for HEP priorities**
- **Goals are < 500 µm, <5 psec (charged particle) < 25 psec (single photon), low noise, high rate, large-area, affordable**
- **We believe R&D on large-area MCP-PMTs is done; presented a facility for > 100/week, scalable to 10K/yr or more.**
- **Prior obstacles solved: large hermetic seal, air-transfer photocathode, MCP recovery after cesiation, vendor/supply chain established.**
- **Need a mechanism to bridge the gap for volume production- e.g. a dedicated Lab/university/industry consortium 5-year program**

Application of MCP-PMT/LAPPD for EIC Particle Identification, Junqi Xie

Expanding low-cost LAPPD application with optimizations

Ring imaging Cherenkov

The EIC physics program demands excellent particle identification (PID) coverage over a wide range of momenta to achieve the highest precision. Imaging Cherenkov techniques (dRICH, mRICH and HPDIRC) were considered for proposed EIC detector concepts for momentum coverage up to 50 GeV/c.

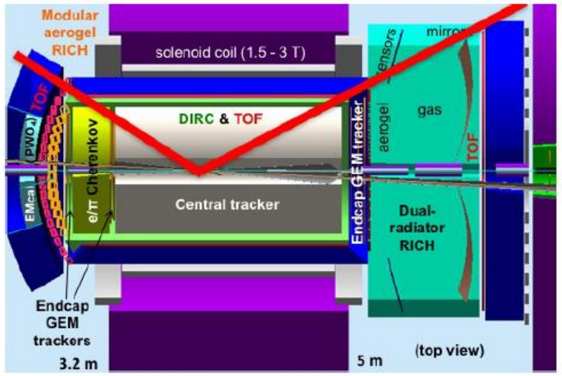
Low-cost, reliable highly-pixelated photodetector with high magnetic field immunity, long lifetime, high rate capability, and radiation hardness is needed for Cherenkov detectors for EIC Particle Identification.

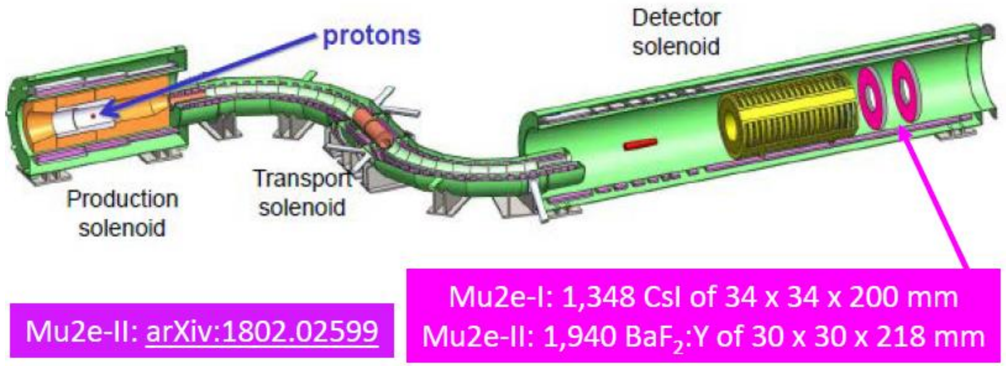
Fast calorimetry

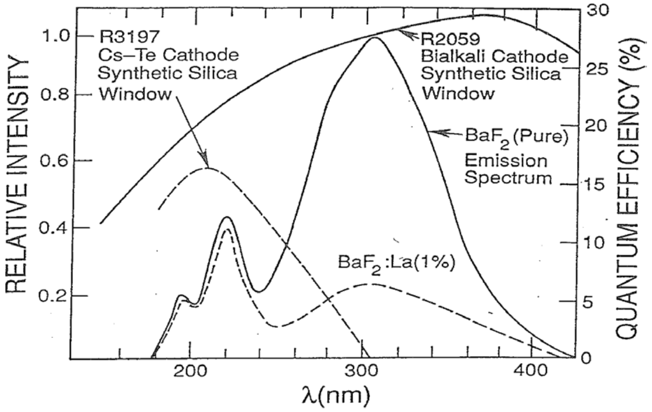
Low-cost LAPPD with solar blind photocathode (Cs-Te) couples with fast scintillator BaF_2:Y to suppress the slow scintillation component of BaF_2:Y, enabling fast colorimetry for Mu2e-II and other projects.

Cryogenic environment

MCP-PMT has shown operational signal at liquid N2 condition, low-cost LAPPD with optimized MCP coating could expand its application into cryogenic environment.



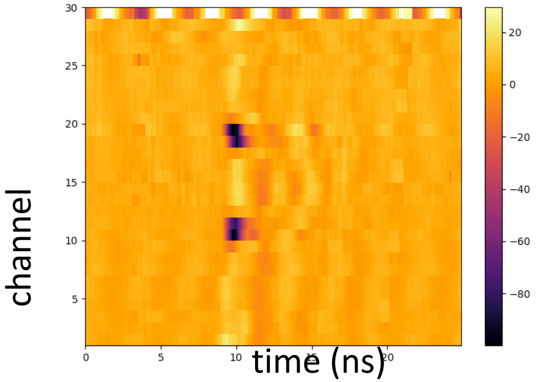


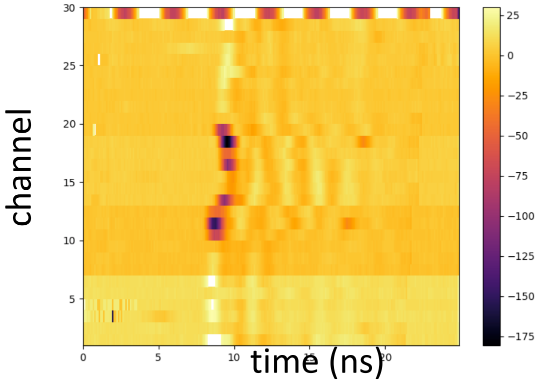


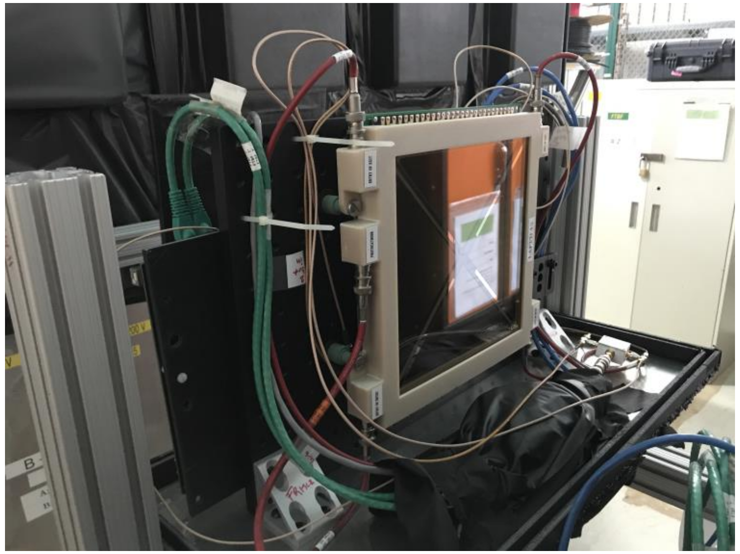
Precision time-of-flight detector in the Fermilab Test Beam Facility (FTBF), Evan Angelico

- 2-LAPPDs have measured charged particles in coincidence with beam at FTBF
- Commercial LAPPDs work out-of-the-box, electronics development will improve ease of operation
- Next step is timing measurements and particle identification with 3-4 LAPPDs in MTest beam enclosure

2-LAPPDs in coincidence with beam







Development of Long Life Microchannel Plate Photomultiplier Tubes, Andrew Brandt

- Developed pixel based lifetime testing method for MCP-PMTs.
- Have started to apply this to LAPPDs.
- Studying afterpulse distribution of different devices. By correlating afterpulse distribution with lifetime, working to develop a non-destructive method for predicting lifetime of specific devices.

NuDot: Fast Photodetectors for Double-Beta Decay with Direction Reconstruction, Julieta Gruszko

- **Cherenkov/scintillation light separation is a key** area of interest in photodetector experiments, and is very promising for both particle ID in liquid scintillators (i.e.cosmogenic and alpha background rejection) and solar neutrino background reduction. We'll need to develop it to move to background-free liquid scintillator experiments.
- **There are a lot of ideas of how to perform that separation.** Many of them share similar challenges as far as DAQ is concerned: timing synchronization, often at the picosecond level, between different types of digitizers (low dead-time slow systems and fast-timing systems), and increasing channel counts overall.
- In **fast-timing detectors**, the increased timing precision often comes paired with fine-grained spatial resolution. In large liquid scintillator experiments, that spatial resolution isn't helpful or necessary. We'd rather trade it for reduced channel counts, so we're thinking about the best way to do that. It may require us to work with industry partners like Incom, in the case of LAPPDs, to make sure they're making flexible read-out schemes that allow for that trade-off.
- **Other developments in chemistry and materials science could help** us with this problem. Options mentioned include quantum dot wavelength shifters, "switchillators," and dichroic reflectors. We should be encouraging/supporting collaboration between physics and chemistry/materials science research groups.

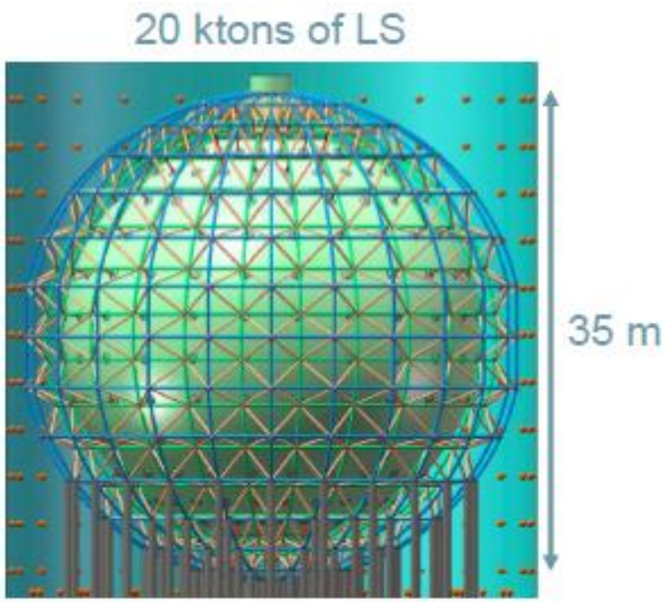
Using Switchable Fluorescent Molecules to Image Tracks and Measure Energy in Large Liquid Double Beta Decay Detectors, Eric Spieglan

* The **switchillator technique** is amethod analogous to organic scintillators in which ionizing particles in a solvent activate the **fluorescence of switchable fluors**
* The switchillator technique **may be useful for photon-scarce low-rate**
* **Potential** benefits of the switchillator technique include the combination of **strong energy resolution and imaging**
* Searching for switchable fluors suitable for the technique

- Advanced short-baseline reactor antineutrino detectors can play a three-pronged role in US science advancement
    - Improve world-leading limits on the sterile oscillation parameter U_{e4}, and untangle reactor antineutrino flux and spectrum anomalies with complimentary data from multiple reactor types.
    - Develop organic scintillator technology and detection techniques broadly valuable for measuring neutrinos and other relevant backgrounds
    - Bridge fundamental and applied physics: use neutrino data to improve nuclear data, and to demonstrate new reactor monitoring technologies
- These efforts can build on recent accomplishments by the PROSPECT experiment
    - First-ever on-surface demonstration of high-signal, low-background reactor antineutrino detection
    - First PRL publications on sterile neutrino and ^{235}U antineutrino energy spectrum results

Design and Progress of the JUNO experiment, Pedro Ochoa-Ricoux

- JUNO is a large multipurpose neutrino observatory with a rich research program in neutrino physics and astrophysics
- JUNO is pushing the limits in liquid scintillator (LS) detection technology
  - Largest and most precise liquid scintillator detector to date (3% energy resolution at 1 MeV)
- Progress is well underway, and expect to complete the construction of the detector by 2021



Cosmogenic Background Characterization with the PROSPECT Antineutrino Detector, Xianyi Zhang

- PROSPECT is able to measure reactor antineutrino spectrum with cosmic neutron background measurement on earth surface, with its PSD+6Li+segmented LS detector.
- PROSPECT's measurement of the near surface cosmogenic neutron can benefit the community by benchmarking cosmic ray models.
- PROSPECT-style detector can also be applied in other P5 experiments to measure cosmogenic and beam generated neutron backgrounds.

Instrumentation for a Post-reionization Intensity Mapping Survey, Paul O'Connor

- 21cm intensity mapping is a new, cost-efficient observational technique that is ***complementary to optical and CMB*** surveys.
- It opens the largely unexplored redshift range $2.5 < z < 6$ where ***beyond-ΛCDM*** physics can be studied - dynamic DE, modified GR, inflationary relic signatures.
- ***Leverages industry advances*** (wireless, AI) and requires no specialized detector environments (cryo, radiation).
- Research needs center on ***DAQ architectures*** (with 2030-era electronics), and on ***calibration methods***.
- The PUMA project is well-matched to HEP expertise and is ***synergistic with many emerging trends in EF and IF DAQ***.

Fiber Positioners for Cosmic Surveys, Thomas Diehl

- A fiber positioner system allows one to economically accumulate many objects spectra in parallel using a telescope.
- There are many types of fiber positioners. Tilting Spines & Twirling Posts are practical robotic options.
- At 5 mm pitch there are advantages/disadvantages of the FP designs (comparing equal pitch) depending on the telescope optics and survey design.
- Twirling Posts size limitations is availability of robust, tiny brushless motors and gears
- Tilting Spines size limitations is less explored and could be significantly smaller.
- On course to engineer, design and build a 5 mm pitch Tilting Spine FP.
- While doing that we will be learning what we need to do to build a minimum-sized design

Nanoparticle-enhanced photosensors for UV light detection, Stephen Magill

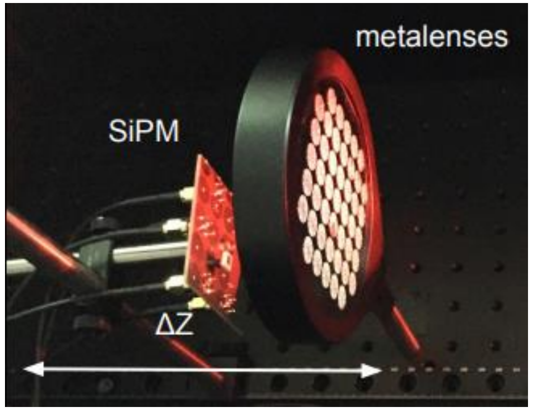
Potential Nanosensors, Applications, Customers

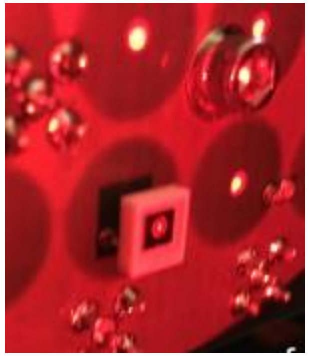
Detector	App	Absorbed λ (nm)	Emitted λ (nm)	Nano Candidates	Customers
Argon	Coating	125	425	CdTe	HEP(DUNE, SBN)
Xenon	Coating	178	425	CdTe	HEP, NP(Dark Matter, $0\nu\beta\beta$)
Water	Coating	125-300	425	CdTe, LaF3:Ce	HEP(ANNIE)
BaF2 Xstal	Cookie, Surface	220	425	LaYO, CuCy, ZnS:Mn, ZnS:Mn-Eu, CdTe	HEP(Mu2e)
PbF2 Xstal	Cookie, Surface	200-300	425	Si, LaYO, LaF3:Ce, CdTe	HEP, NP(g-2, DRCal)
CsI, CeF3, CeBr3, LaCl3, LaBr3 Xstals	Cookie, Surface	300-371	425	LaF3:Ce	Medical
Plastic Lens	Infusion, Coating	300-400	425-550	LaF3:Ce	Night Vision, Defense
Window Glass	Infusion, Coating	300-400	425-550	LaF3:Ce	Homes, Businesses, Greenhouses

Alvaro Loya Villalpando

Metalenses for increasing light collection of SiPMs

- Beneficial to multiple experiments ($0\nu\beta\beta$, dark matter, event neutrino, etc.)
- Low cost, compact and simple fabrication
- 6-7X signal multiplication at ~630 nm - similar expectation at ~430 nm design wavelength
- Outlook: R&D of materials/technologies for VUV range





Novel Small-Gap Materials as Photodetectors, Noah Kurinsky

- Huge computational effort going into identifying new meV-gap semiconductors, and we need R&D to be prepared to take advantage of them as novel, cryogenic photodetectors
- InSb/ZrTe5 could be the pathway to develop key technologies, and use sub-MeV dark matter searches as the science motivation.

Franois Leonard

Quantum Information Science to Design New Types of Photodetectors from the Ground Up

François Léonard, Sandia National Laboratories

- Detecting single photons is critical to many HEP experiments
- Existing detectors are unable to simultaneously achieve high performance across metrics (e.g. efficiency and timing)
- New detector designs are often based on specific new ideas without a general framework to guide design

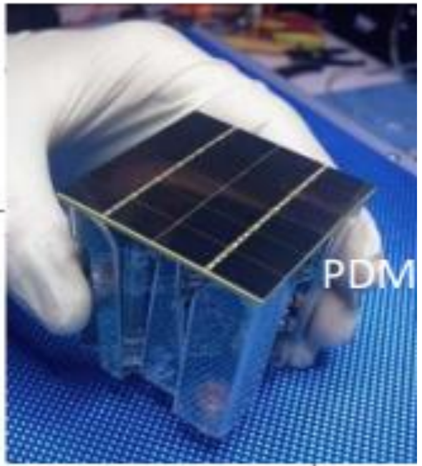
Detecting single photons is inherently a quantum process

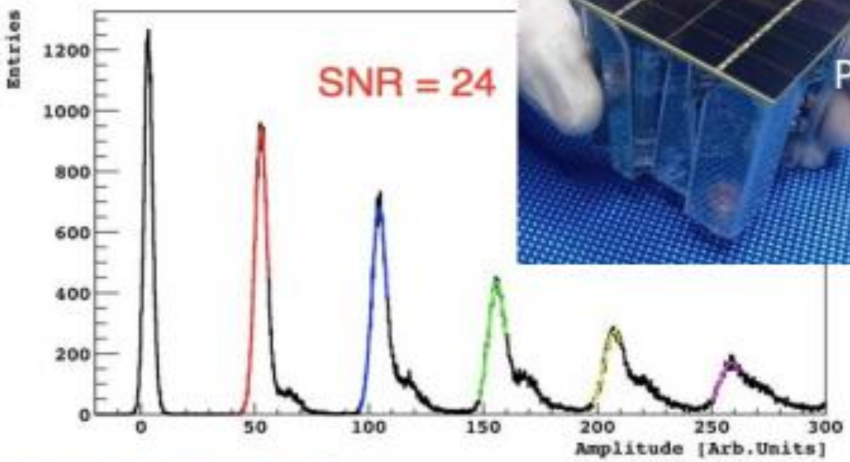
→ Use tools from QIS to design new detectors from basic principles

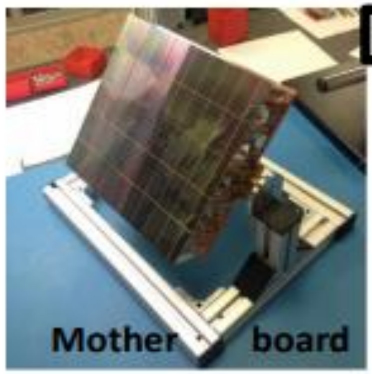
Jelena Maricic

Silicon PhotoMultiplier based
Photon Detector Modules (PDMs) for DarkSide and ARGO

- PDMs: 5×5 cm^2 single-channel modules made of array of 24 SiPMs
- ~5 ns timing resolution
- Photon Detection Efficiency: 50%
- Gain > 10^6
- 0.1 Hz/mm^2 dark count rate (in LAr)
- Single Photoelectron resolution
- Signal/Noise ~ 24
- Power consumption < 100 $\mu W/mm^2$
- Compact and radio-clean
- Mass production under way for DarkSide-20k in Italy (> 10,000 PDMs): dedicated NOA facility (440 m^2 in a a radon suppressed area).







~ 25 cm x 25 cm x 5 cm

25 PDMs with mechanical support structure; base mechanical unit; routing structure for power and signal readout contained

Thank You!