This is our first draft of broad recommendations:

IR Sensitivity: The redshift range of surveys is limited by the wavelength range. There may be synergies with particle detectors that could move to longer wavelengths or the making of the devices into particle detectors themselves.

UV Sensitivity: Scintillators included liquid noble gases scintillate primarily in the UV.

Radiation Hardness: This is a requirement that naturally comes from the next generation of colliders.

Timing: The study of ~50ps timing has lead to interesting new detector concepts. As both SiPMs and LAPPDs achieve this timing what would be possible with <20ps timing, or even 5ps timing, and in many fine pixels.

Improved low light level detection performance: particularlly important in single photon detection for particle ID detectors.

This is our first draft of technology recommendations:

SiPMs: Develop radiation hard devices, reduce the optical cross-talk, improve the UV/VUV sensitivity. Further reduce the impact of dark counts on single photon detection by light collection features.

LAPPD: Continue to pursue the development of the LAPPD for both its possible advanced timing characteristics and its ability to outperform PMTs in certain environments.

Germanium CCDs: This seems to be the most feasible technology to meet the needs of the next generation of surveys. An organized effort to build this expertise and facilities is needed.

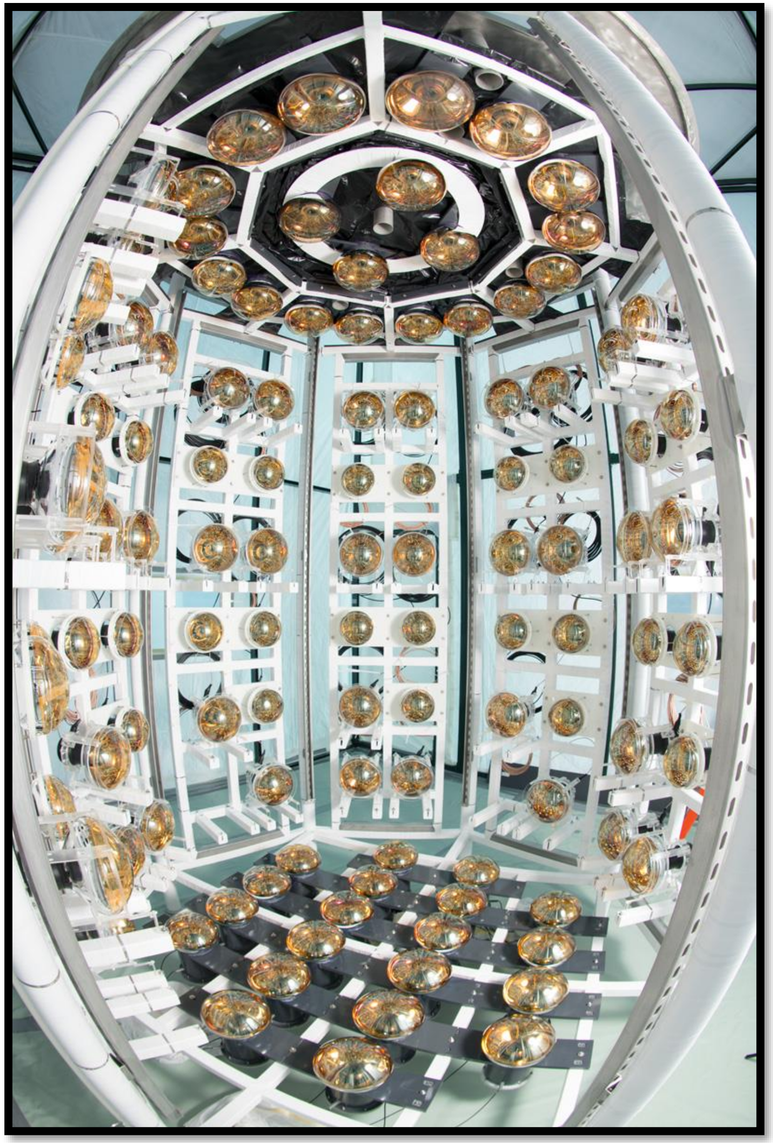
Accessories: Filters, Waveguides, and Fiber Positioners are critical for extracting the most information from the detectors and their development should continue in parallel to the sensor development.

These are our general recommendations:

Cost Reduction: Whether it is CCDs in a telescope or LAPPDs in a neutrino detector, our ability to dream is limited by the cost of the new technology.

Explore New Technologies: New technologies are constantly emerging especially on the border with quantum sensors. These should be pursued and may lead us to interesting new science.

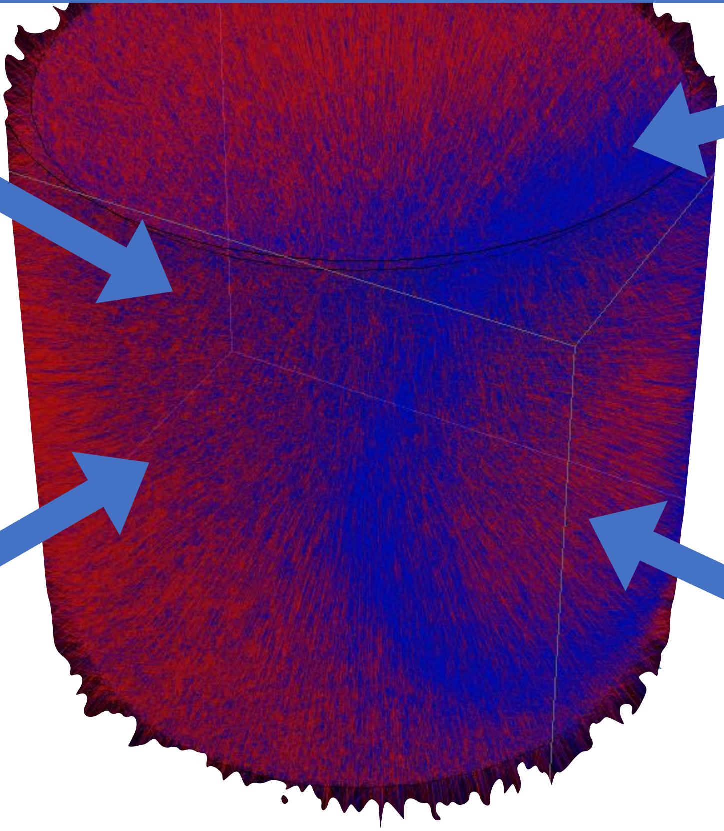
Advanced Photodetection in ANNIE for Future Neutrino Experiments



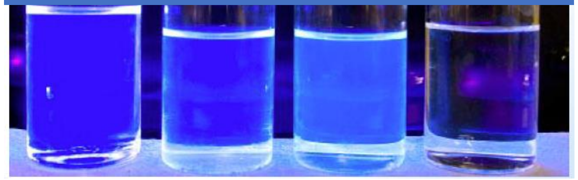
- 26-ton **Gadolinium (Gd)-loaded water Cherenkov Detector** on the Booster Neutrino Beam (BNB) at Fermilab
- Physics Phase detector installed and under commissioning
- ANNIE will measure the beam induced final state neutron multiplicity & CC inclusive cross section on water
- ANNIE is pioneering R&D of photodetection technologies/techniques:
  - 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.
- Neutrino beam data taking to begin in January 2020.

Towards the THEIA detector challenge: R&D overview

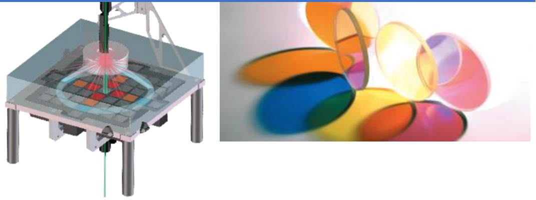
REALIZE CHERENKOV/SCINTILLATION SEPARATION AND MAXIMIZE LIGHT COLLECTION IN LARGE-SCALE SCINTILLATOR DETECTOR



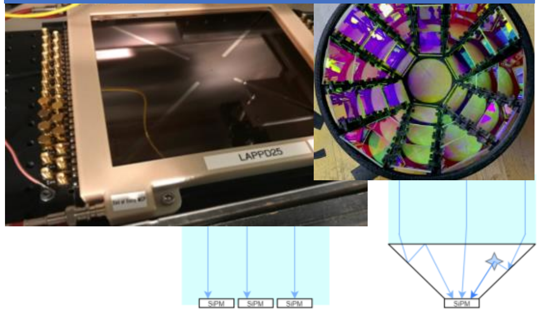
NOVEL LIQUID SCINTILLATOR MEDIUM:
WATER-BASED LIQUID SCINTILLATOR



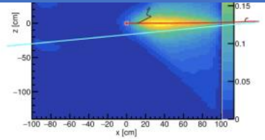
SMALL SCALE REALIZATION OF CHERENKOV/SCINTILLATION SEPARATION:
CHESS, DICHROIC FILTERS



MODERN PHOTOSENSORS:
LAPPD, DICHROICONS, SIPM ARRAYS



NEW RECONSTRUCTION ALGORITHMS:
TOPOLOGICAL RECO., NEURAL NETS.



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

Example with Andrey Elagin, U. Chicago:

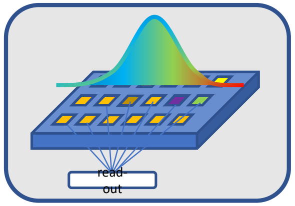
High Efficiency, Low Jitter, and Energy Resolution in the same single photon detector

(e.g. to reconstruct trajectories in liquid scintillators; <10ps timing resolution and <10nm wavelength resolution)

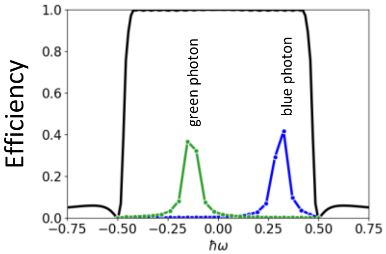
QIS tools

$$\dot{\rho}(t)=v_{sys}+v_{l-m}+v_{amp}$$

new design



performance projections



-100% efficiency
-Jitter only determined by pulse width
-Energy resolution

Potential Nanosensors, Applications, Customers

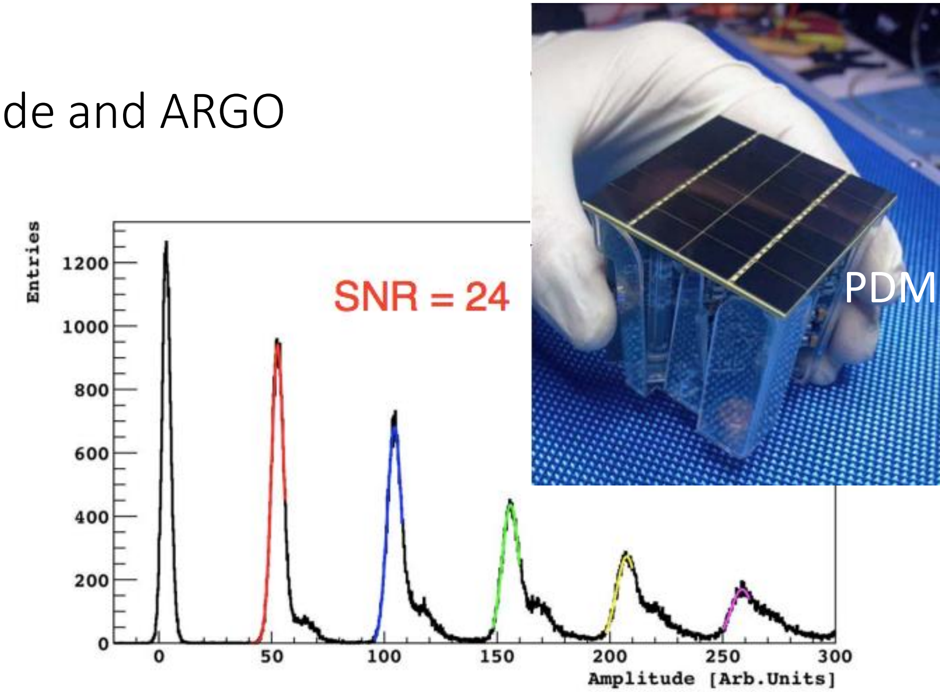
Detector	App	Absorbed λ (nm)	Emitted λ (nm)	Nano Candidates	Customers
Argon	Coating	125	425	CdTe	HEP(DUNE, SBN)
Xenon	Coating	178	425	CdTe	HEP, NP(Dark Matter, 0νββ)
Water	Coating	125-300	425	CdTe, LaF3:Ce	HEP(ANNIE)
BaF2 Xstal	Cookie, Surface	220	425	LaYO, CuCy, ZnS:Mn, ZnS:Mn-Eu, CdTe	HEP(Mu2e)
PbF2 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

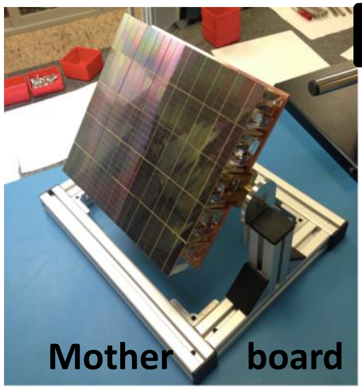
Tested candidates at desired wavelength range (green highlight)

Published results (blue candidates)

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