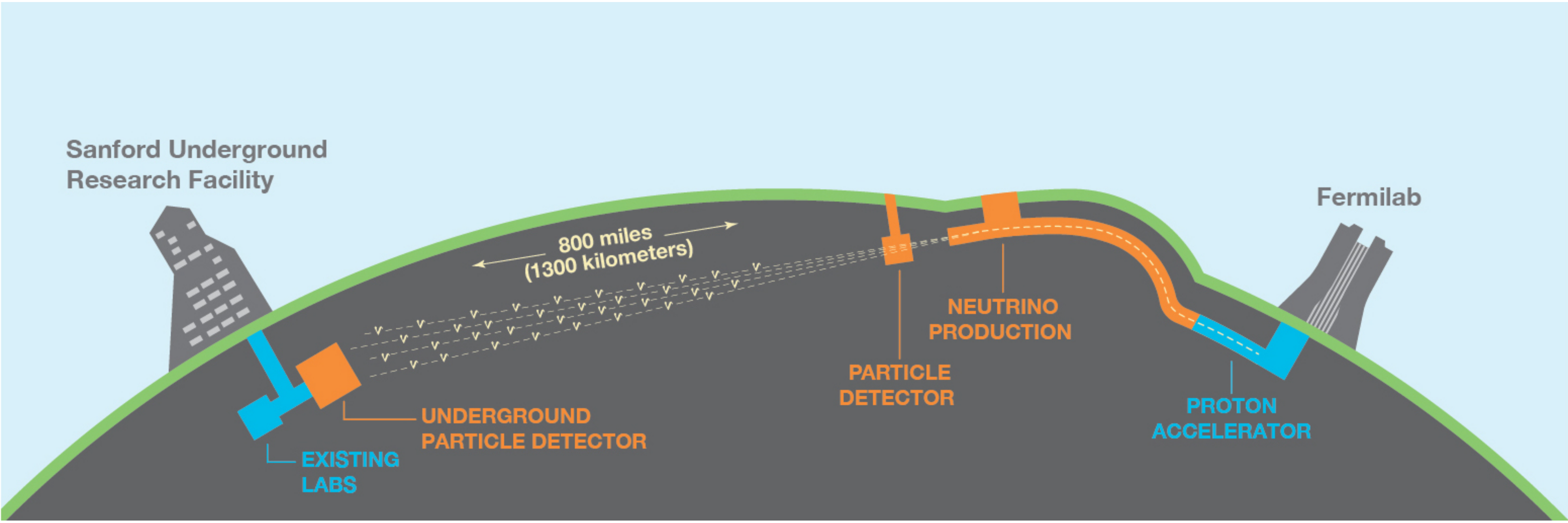

DUNE SP PDS: Photosensors

V. Zutshi, Northern Illinois University
for the Photosensor Working Group
12th November, 2018

DUNE SP PDS Photosensor Team

Has fabricated, commissioned and operated SiPM-based detectors (calorimetry, muon detection, tracking, ….) successfully:

- N. Buchanan[1)], A. Dyshkant[2)], M. Eads[2)], K. Francis[2)], L. Patrizii[3)], F. Terranova[4)], R. Wilson[1)], J. Zalesak[5)], V. Zutshi[2)]
- In collaboration with: G. Cancelo[6)], L. Mualem[7)], D. Warner[1)]

1) Colorado State University

2) Northern Illinois University

3) INFN, Bologna

4) INFN, Milano-Biccoca

5) Institute of Physics, Prague

6) Fermi National Accelerator Laboratory

7) Caltech

Plus numerous students & technicians

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DUNE SP PDS Organization

WBS 2.4 SP PDS
- Ettore Segreto (Lead) / UNICAMP
- David Warner (Tech. Coord.) / CSU
- Leon Mualem (Dy. Tech. Coord.) / Caltech

Physics/Simulation
- Alex Himmel / Fermilab
- Kate Scholberg / Duke
- Andrzej Szelc / Manchester

Photosensors
- Laura Patrizii / Bologna
- Robert Wilson / CSU
- Vishnu Zutshi / NIU

Integration
- Norm Buchanan / CSU
- Ernesto Kemp / UNICAMP
- Yasar Onel / Iowa

Photon Collectors
- Flavio Cavanna / Fermilab
- Ana Machado / UNICAMP
- Denver Whittington / Syracuse

Electronics
- Zelimir Djurcic / ANL
- Deywis Moreno / UAN
- Giovanni Franchi / AGE Sci.

Scope

Photosensors
Patrizii/Wilson/Zutshi

Photosensor Procurement
This task covers all aspects of the selection and evaluation of prototype photosensors, and the procurement and testing of the production photosensors.

Photosensor Quality Assurance Design and Fabrication
This task covers: (1) specifying the requirements for the photosensors, including those required of the manufacturer, (2) determining the parameters to be tested upon receiving the photosensors, (3) designing the test stand for photosensor testing, and (4) fabricating the test stand.

Derived Requirements

- The DUNE Single Phase Photon Detection System requirements are described in doc-db #6422
- The Photosensors must meet the following requirements:
  - It should be possible to gang up to 48 SiPMs per readout channel so as to allow for adequate photon system efficiency for detection and triggering of low energy neutrinos
  - The SiPM characteristics along with the associated FEE should allow for single photoelectron identification for detection of low energy neutrinos interacting close to the CPAs and for reliable calibration and threshold setting.
  - For a given threshold, the SiPM DCR should not dominate the background rate
  - The threshold needed for the above requirement should be less than the one needed to satisfy the overall efficiency requirement of the PD system

Derived Requirements

- The SiPMs should not contribute substantially to the timing resolution of the PDS (requirement: 1 μsec; goal: 0.1 μsec)
- The SiPM should be able to meet the above requirements and function within specifications for at least 10 years in a LAr environment.
- The sensors must survive room-temperature to LAr temperature cycles during the QA/QC phases with no significant impact on the mechanical and electrical characteristics

As these requirements get translated into device specifications there will be trade-offs involved

Device Specifications

- **Quantity**
  - ~ 300 k devices for the 10 kT far detector module
  - The quantity required places constraints on the vendors that can be used
  - The quantity required gives us some customization ability within budgetary constraints
  - The two “vendors” that can handle this scale of production and would be willing to carry out customization R&D: FBK (developer w/ sub-contractors for fabrication) & Hamamatsu
- **Form factor**
  - Driven largely by the mechanical design of photon collector
  - Available 6mm x 6mm devices look most consistent with the current baseline and alternative options

Device Specifications

- **Dynamic range**
  - Does not seem to be a stringent constraint
  - Very small correction with 25-30% occupancy
  - Assuming 20 PE/MeV and a few GeV going into one readout channel, even 100 micron pixel devices would be fine
  - 75 micron pixel size may be optimal
- **Bias & bias dispersion**
  - < 50 V (operating point, cold); considered low voltage
  - Ganging places constraints on operating voltage range
  - Within ± 0.1 V (rms) per batch (2-3k devices) to keep gain variation within a reasonable range and minimize sorting
  - Within ± 1 V for the full production

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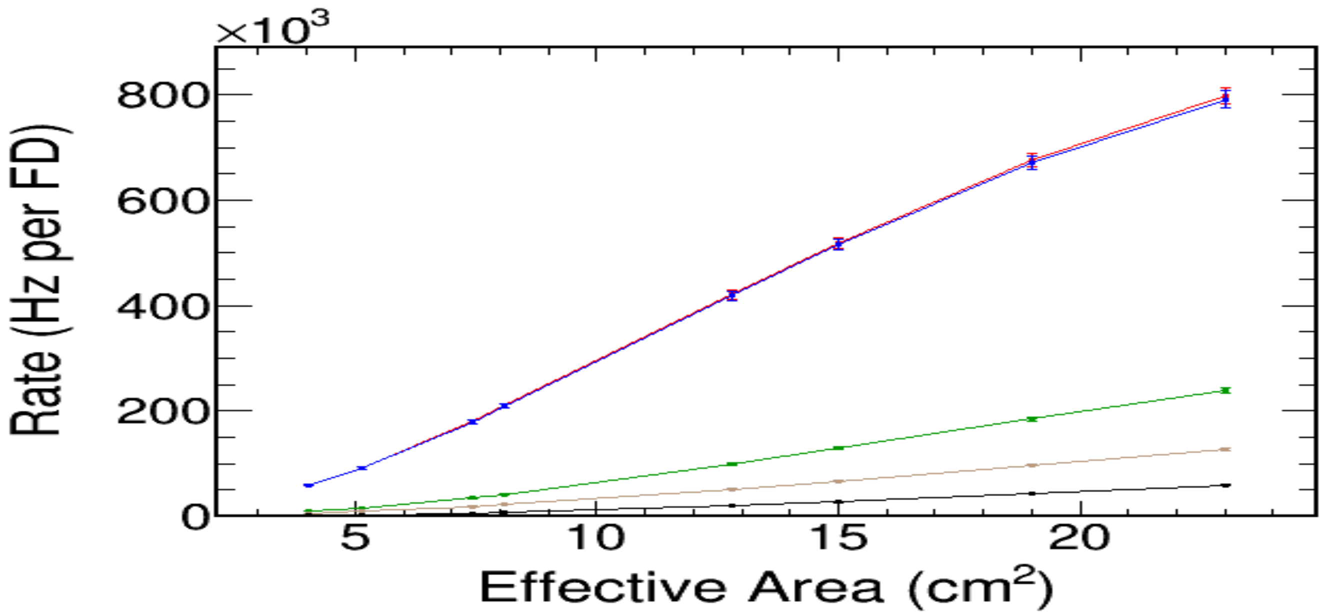
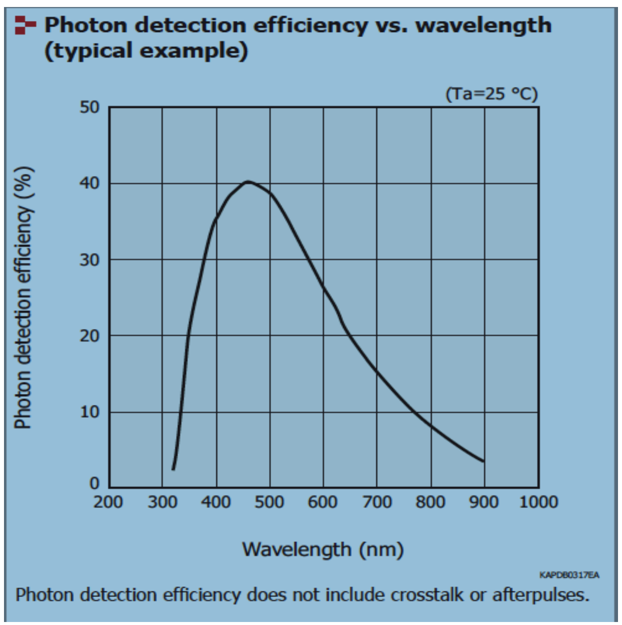
Device Specifications

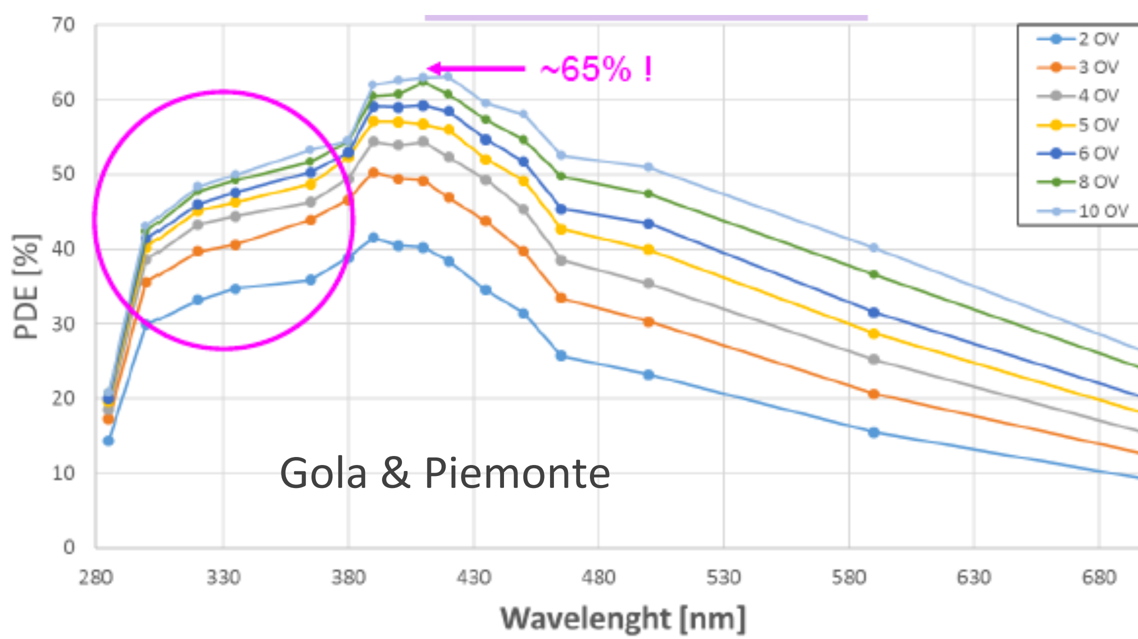
- **DCR**
  - Assuming ~1MHz for a 10kT detector, the background rate (Ar39 abundance) roughly 200 Hz per readout channel
  - Keep ganged SiPM DCR < 100 Hz
  - DCR < 0.06 Hz/mm^2



Device Specifications

- **PDE**
  - > 35% at nominal (+2-3 V) operating voltage
  - Consistent with what is included in the simulation
  - Broad maxima in the 400-520 nm range





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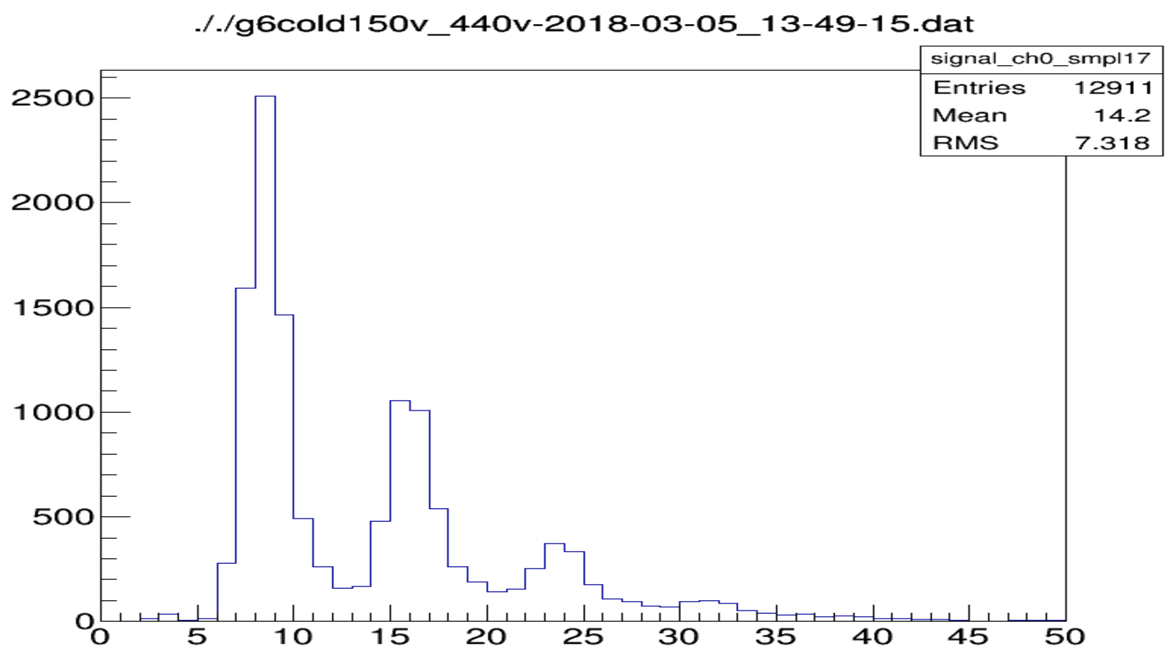
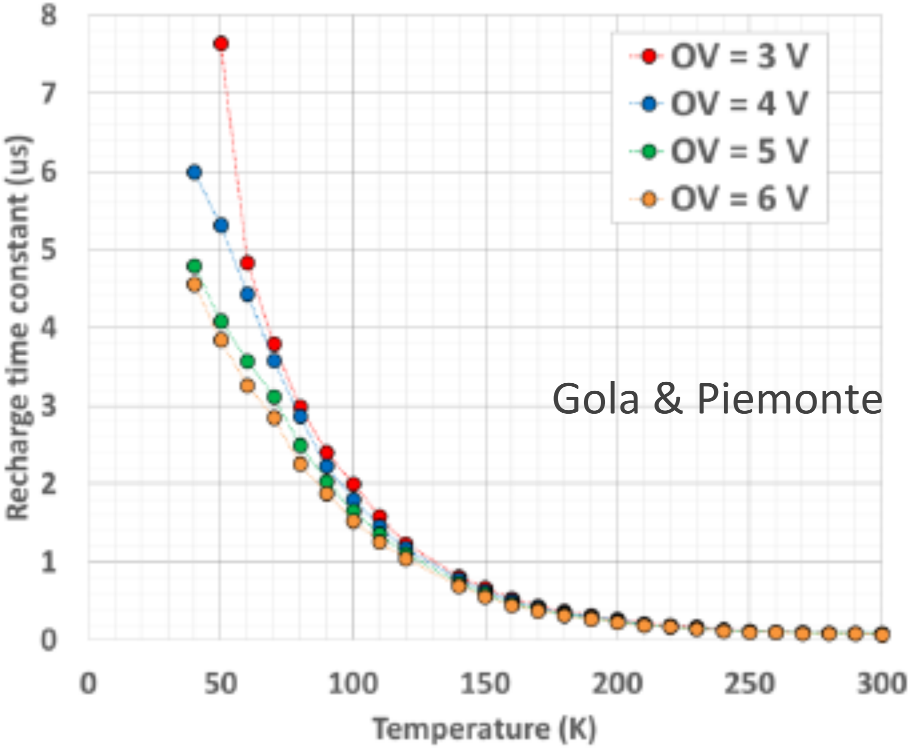
Device Specifications

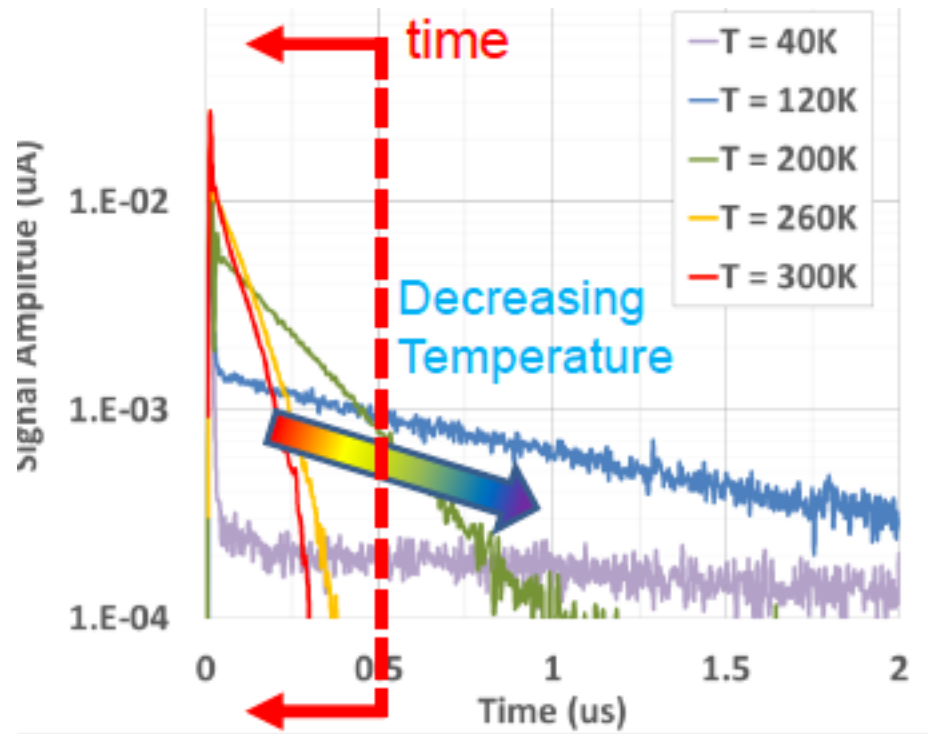
- **Terminal capacitance**
  - ➢ Passive parallel ganging imposes constraints
  - ➢ Currently 6-fold passive ganging being considered (12-fold has also been shown to work)
  - ➢ Requires < 0.03 nF/mm^2 (aiming for S/N ~ 5)



Device Specifications

- **Quenching resistor**
  - Poly-silicone or metal type
  - Value and variation





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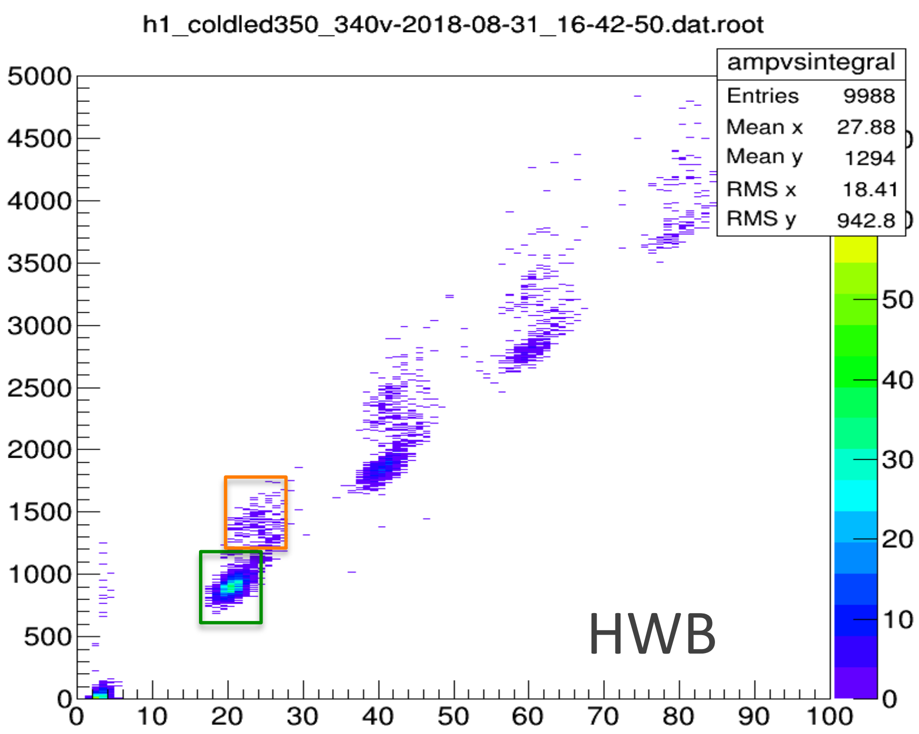
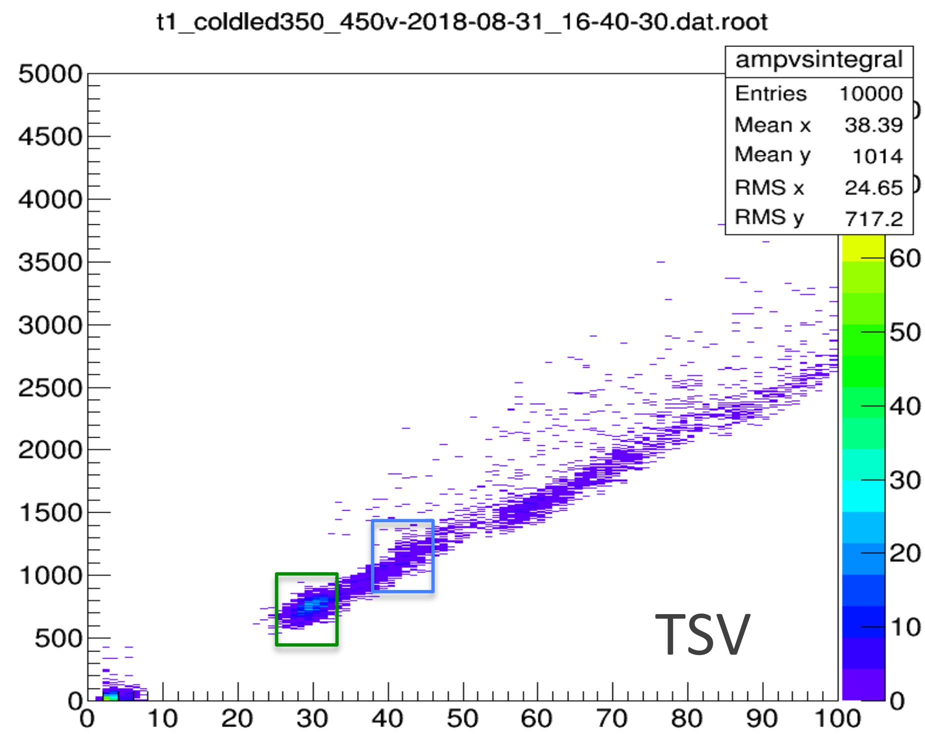
Device Specifications

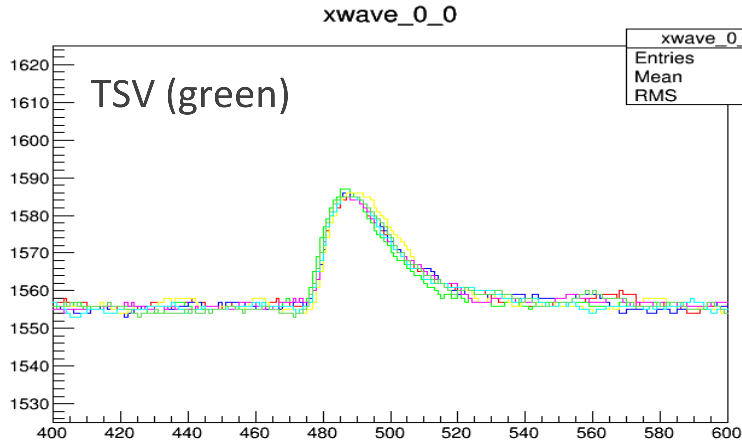
- **X-talk & after-pulsing**
  - Devices with trench technology
  - < 15% at nominal operating voltage

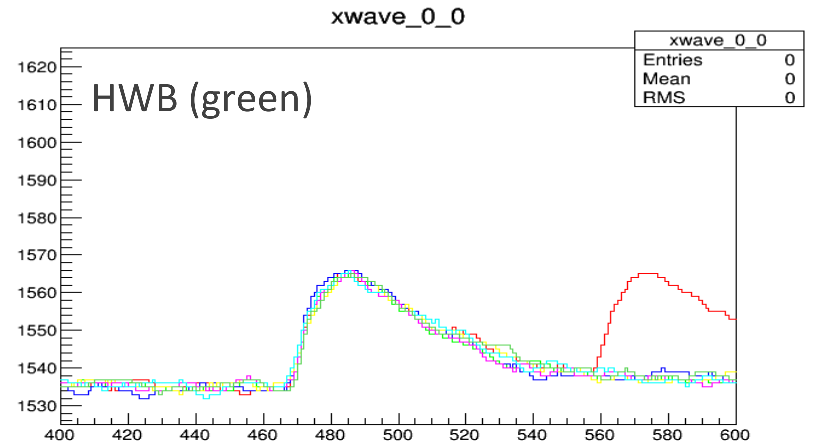


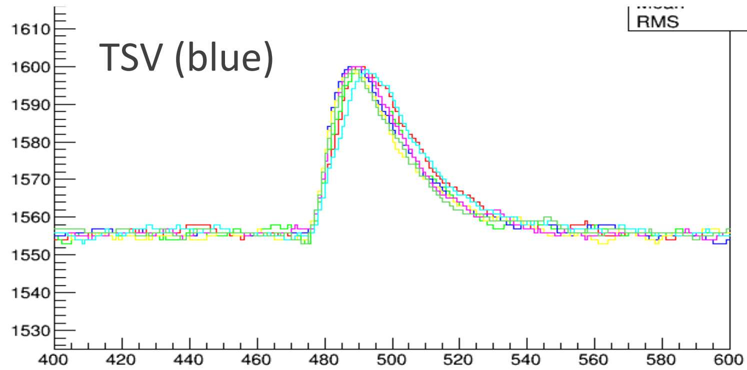


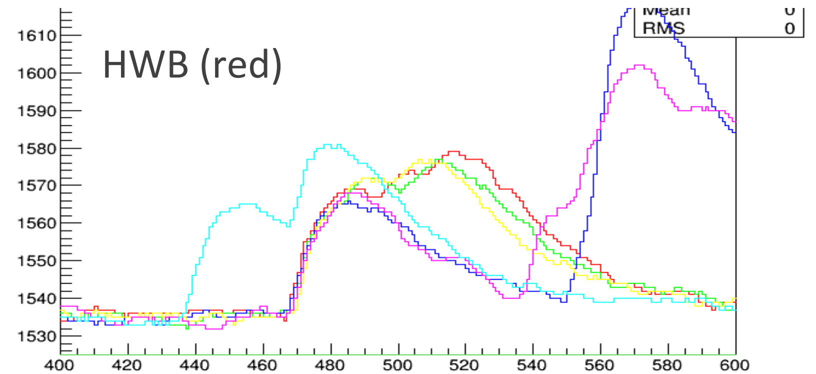
Amplitude vs. Integral

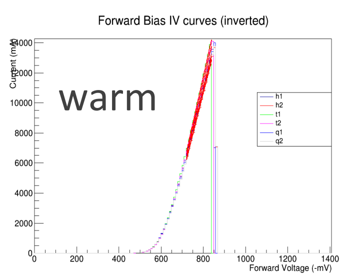
Device Specifications

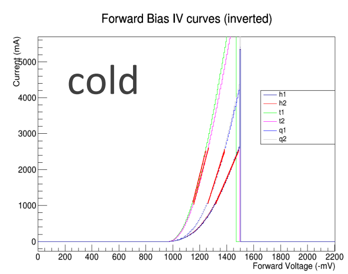












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Preliminary Device Specifications (Summary)

- All values at -186^{o} C at overvoltage of 2.5V:
  1) 6mm x 6mm, 75 µm pixel
  2) Surface-mount, TSV packaging
  3) PDE > 35% (400-520 nm)
  4) Gain ≥ $1.25*10^{6}$
  5) Pulse rise time < 10 nsec
  6) Dark rate < 0.06 Hz/mm^{2} @ 0.5 PE threshold
  7) Terminal capacitance < 0.03 nF/mm^{2}
  8) Bias spread: ±0.1V (within batch); ±1.0V (full sample)
- Will be part of the RFQ and purchase requisition
- Commercial devices in vicinity of these specs with flexibility for customization for enhanced performance

N.B. Starting point, expected to evolve and sharpen

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Ongoing testing

- Testing and characterization of devices, to sharpen specifications and interact with vendors, underway in the US and Europe (Czech Republic and Italy); more experience with Hamamatsu on the US side but now benefitting from INFN experience with FBK
- Key to arriving at an optimal sensor for the experiment
- Includes testing and certification protocol for photosensor packaging for long-term survival in a cryogenic environment
- Studies of ganged SiPMs is essential for determining the overall performance of the system; noise characterization of the summing board, modeling of signals to optimize ganging
- Demonstrated QA/QC plan for prod. quantity sensors

Interfaces

Internal Interfaces	
Interface	Descriptions
Photosensor to Hoverboard	The hoverboards must provide mounting and mechanical alignment for the photosensors. On the electrical side they must provide the bias and signal path for the photosensors.
Photosensor to ARRAPUCA module	The photosensor form factor and the mechanical design of the collector must be consistent with each other including alignment features as needed. The spectral PDE of the photosensor needs to be consistent with the collector photon wavelength distribution.
Photosensor to summing electonics board	The ganged photosensor and summing electronics should provide adequate S/N performance, self-triggering, diagnostic/monitoring measurements abd be robust against device and/or single point failures.
External Interfaces	
Photodetector to LAr	Photosensor must survive long-term in the cryogenic environment without significant deterioration in mechanical and electrical properties.

Interfaces are documented and actively managed

See docdb#s: 6718, 6721,7051, 7123

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SiPMs in Noble Liquids

- Relatively young field
- Some experiments/installations one can hope to learn from:
  - GERDA (LAr veto shield, running)
  - MEG II (commissioning)
  - Darkside, nEXO etc. (at various stages of preparation)
- Observations:
  - have generally worked rather closely with the SiPM vendors (there is an implicit customization)
  - pre-protoDUNE state of mind
  - in principle do not have the accessibility and longevity constraints we have

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Risk Mitigation

- Typically the sensors are rated for operation down to -40 C
- This means that changes in the production process could have unforeseen consequences at LAr or LN_2 temperatures since they are in principle outside the range of applicability of the devices as tested by vendors
- Possible paths:
  - ➢ Reliability engineering
  - ➢ Process control
  - ➢ Vendor and collaboration testing

Intend to employ all three for effective risk mitigation

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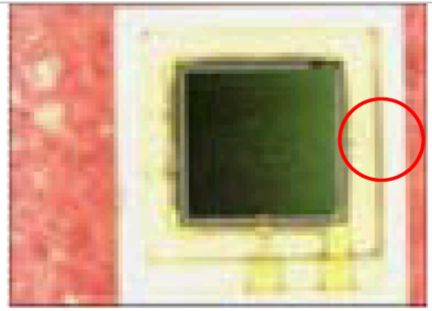
Packaging at Low Temperatures

- Provides protection to the die, a means of connecting electrically and thermally to the die
- Primary issues are changes in material properties and stressed induced due to differential CTEs
- In general:
  - ➢ increased modulus of elasticity for metals and polymers
  - ➢ decreased elongation(brittleness)
  - ➢ phase transitions in metals, particularly solders
- Interfaces of interest to us:
  - ➢ die-to-substrate
  - ➢ substrate-to-potting mold
  - ➢ potting mold-to-encapsulation
  - ➢ solder joints to everything else

Die Attach

Epoxy resin
w/ conductive adhesive glue

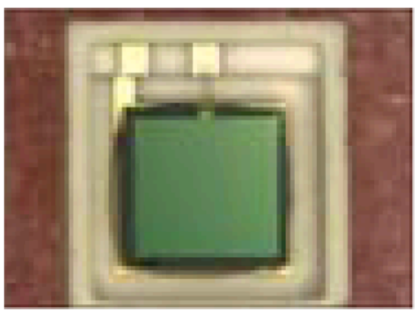
cracked at 1cycle
conductivity: good > 20cycles



Silicone resin
w/ conductive adhesive glue

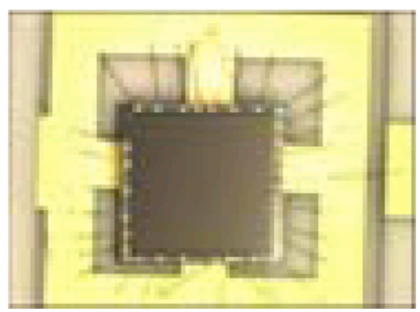
small crack at 10cycles
minor detachment at 20 cycles
conductivity: good > 20cycles

Hamamatsu Study



bare
w/ conductive adhesive glue

no visible damage: at > 20cycles
conductivity: good at > 20cycles



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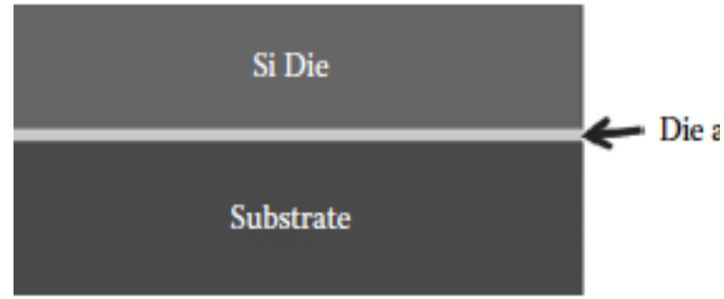

a)

(b)

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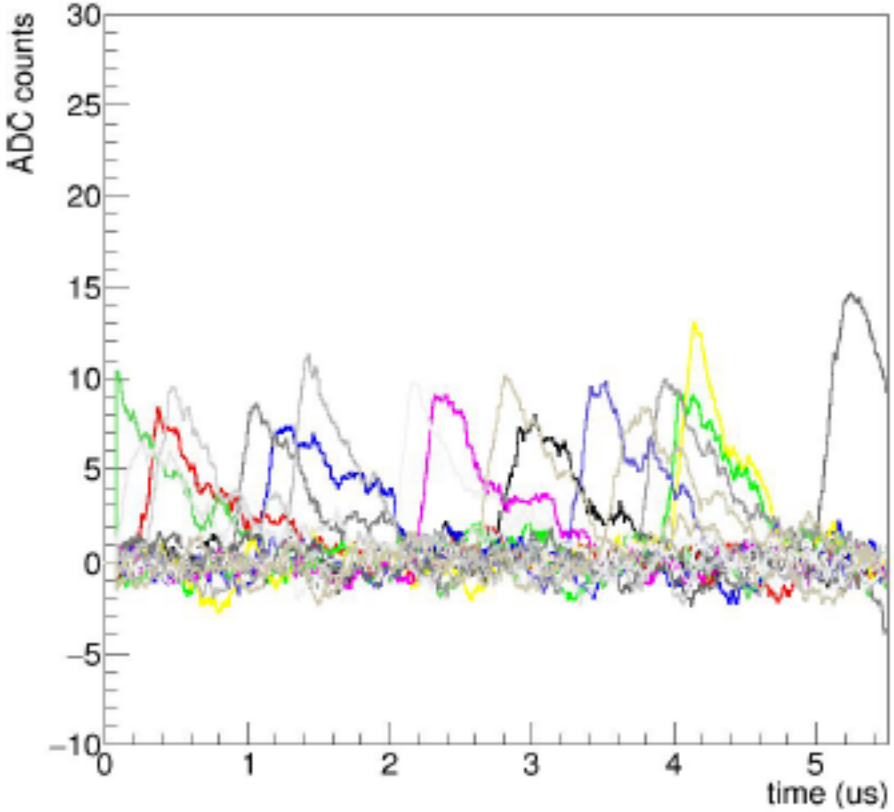
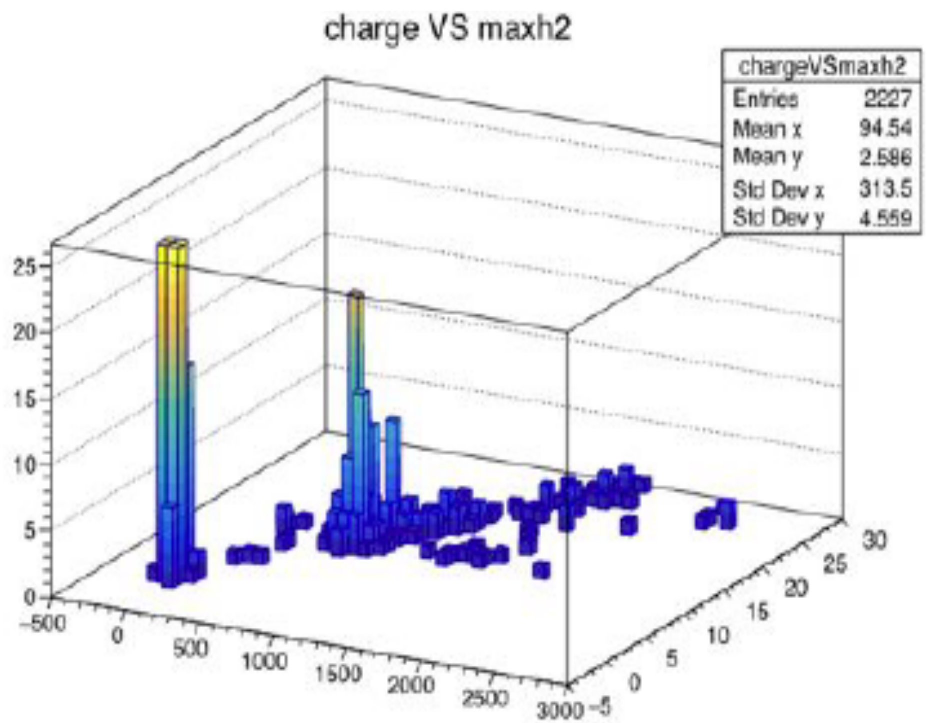
Proto-DUNE Observations

- Months long operation of 100's of photosensors
- All MPPC channels operational; detailed performance studies underway





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Quality Assurance

- Production:
  - ➢ Restrict number of production batches
  - ➢ Communicate desired device and packaging parameters to vendor
- Vendor Testing:
  - ➢ The vendor should be willing to warrant the operation of the device down to LN_2 temperature
  - ➢ Implies performance of in-house qualification tests before shipment of a batch
  - ➢ The "qualification" would of course include thermally stressing the devices and visual and electrical before-after measurements

Quality Control

- Expect to have sensors tested multiple times, at various stages of assembly, before installation in the far detector
- Assuming the sensors will be mounted on the "hover-boards" by the Collaboration; warm and cold testing of unmounted devices
- A small fraction of the devices per batch will undergo stress testing with monitoring of both the mechanical and electrical properties
- Cold testing of all hoverboards prior to assembly in photon collector modules
- A small fraction of the hover-boards will undergo stress testing with monitoring of the electro-mechanical properties

Risks

- Device operation and performance in cryogenic environment (Moderate)
  - Effective mitigation using process control, reliability engineering and testing
  - Long term aging to be informed by proto-DUNE, MEG II, Darkside etc.
- Sole source (Low)
  - Interacting closely with two “vendors”
  - Both have experience with delivering devices for cryogenic experiments
- Custom SiPM (Low)
  - Current testing shows that stock devices would be adequate
  - Reasoned customization may deliver desieable performance enhancement
  - Prior experience indicates that this potential customization should not pose a significant cost or schedule risk

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Environmental, Safety, & Health

- In consultation with safety personnel at home institutions
- SiPM operation
  - SiPM operating voltages vary by vendor (generally within 20 - 80 V)
  - Devices of most interest to us will be in the 20-45 V range
  - Operation of SiPMs will follow Fermilab ES&H Manual (FESHM) standards for electrical equipment operation.
- QC SiPM testing jig
  - Hazards are minimum (Soldering, epoxy, etc.)
- LN_2 handling
  - Standard safety procedures (gloves, safety glasses etc.)
  - Volume of LN_2 in SiPM testing is not big enough for ODH issues

Summary

- Vigorous R&D program underway on both sides of the Atlantic for photosensor characterization, specification and selection
- Baseline photosensor options exist that will deliver adequate (test bench studies, proto-DUNE experience) performance
- Ongoing studies to inform potential customization for superior performance (individually and in the ganged configuration) for evolving physics needs and enhanced reliability in partnership with “vendors”
- Close coordination with the photon collector & electronics WG
- Photosensors on track to demonstrably meeting Photon Detector system physics and technical requirements on the TDR time-scale