中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Overview of new detector technologies for neutrino experiments

Zhimin Wang (王志民)

IHEP, CAS, China

The 21st International Workshop on Neutrinos from Accelerators (NUFACT2019)
Daegu, Korea

Aug. 29, 2019

Summary of the Detector Parallel session, NNN18
arXiv:1907.08311v2 [hep-ph] 24 Jul 2019
arXiv:1908.00194v2 [physics.ins-det] 10 Aug 2019
SENSE-brochure

Email. nufact2019@gmail.com
Website. https://nufact2019.knu.ac.kr
Mt. Biseul, photo provided by Daegu Metropolitan City

Contents

Energy Frontier
Intensity Frontier
Cosmic Frontier

Face to the Challenges

Neutrino
&
Neutrino BSM

Neutrino mass ordering

Neutrinoless-double-beta-decay (NLDBD)

Neutrino Mass

CP violation phase

Testing the three-favor paradigm

Precision measurements of mixing parameters

Neutrino-nucleus interactions over a wide range of energies

Energy Frontier
Intensity Frontier
Cosmic Frontier

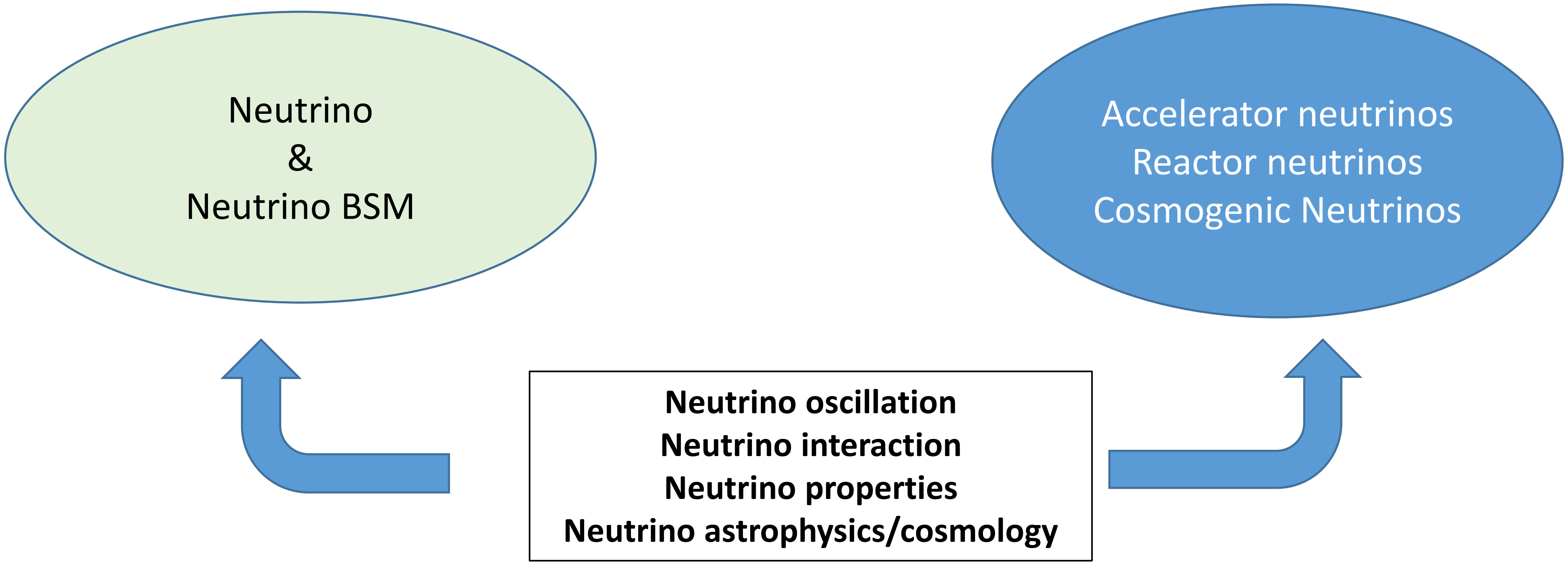
Face to the Challenges

Neutrino
&
Neutrino BSM

Sterile Neutrinos
Non-Standard Neutrino Interactions
Non-Standard Neutrino Interactions with Dark Matter
Neutrino Tridents
Non-Unitarity
Lorentz Violation
Neutrino Decays
Heavy Neutral Leptons
Ultra-light dark matter
Large Extra-Dimensions
Neutrino Dipole Operators
BSM Physics with Tau Neutrinos

Face to the Challenges

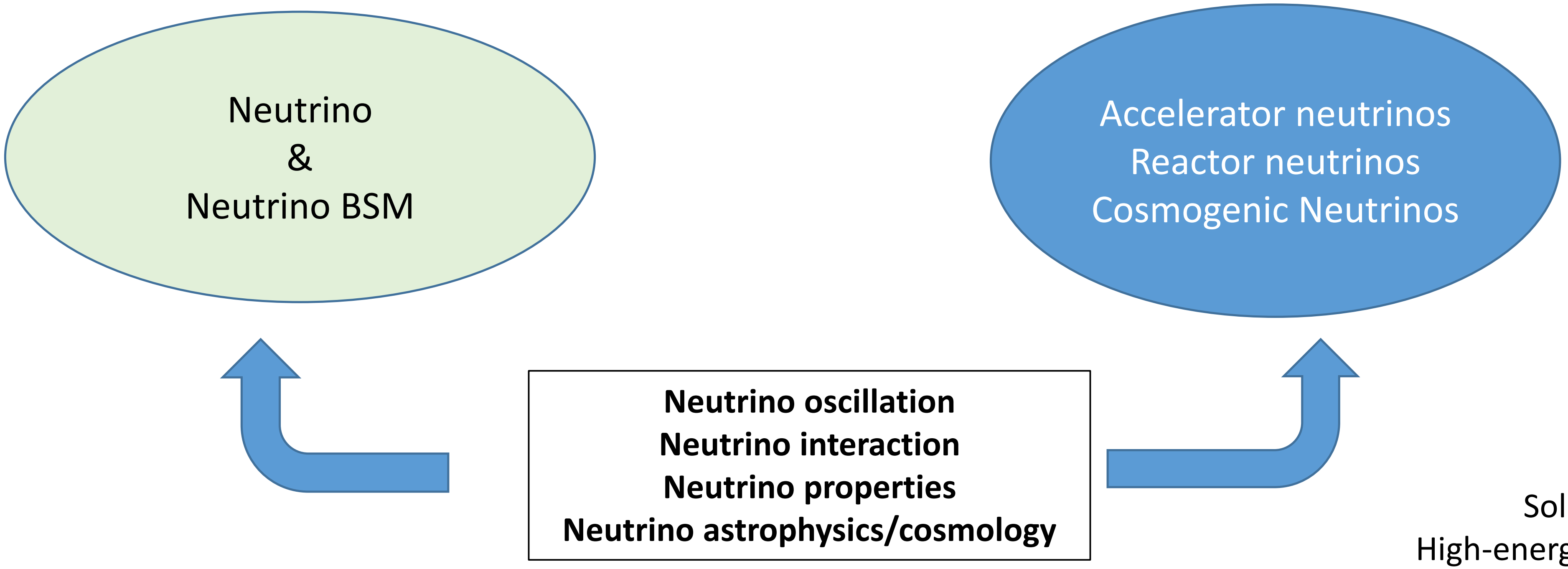
Energy Frontier
Intensity Frontier
Cosmic Frontier



Face to the Challenges

Energy Frontier
Intensity Frontier
Cosmic Frontier

Pion decay-in-flight
Muon decay-in-flight
Pion decay-at-rest
Isotope decay-at-rest



Geo
Solar
Big Bang
Supernovae
Atmospheric
Solar Atmospheric
High-energy astrophysical
……

Face to the Challenges

Energy Frontier
Intensity Frontier
Cosmic Frontier

Neutrino-nucleus interactions over a wide range of energies
Precision measurements of mixing parameters
Testing the three-favor paradigm
Neutrino mass ordering

Pion decay-in-flight
Muon decay-in-flight
Pion decay-at-rest
Isotope decay-at-rest

Neutrinoless-double-beta-decay (NLDBD)
CP violation phase
Neutrino Mass
Coherent neutrino

Neutrino
&
Neutrino BSM

Accelerator neutrinos
Reactor neutrinos
Cosmogenic Neutrinos

Sterile Neutrinos
Neutrino Tridents
Non-Unitarity
Lorentz Violation
Neutrino Decays
Heavy Neutral Leptons
Ultra-light dark matter
Large Extra-Dimensions
Neutrino Dipole Operators
BSM Physics with Tau Neutrinos
Non-Standard Neutrino Interactions
Non-Standard Neutrino Interactions with Dark Matter

Neutrino oscillation
Neutrino interaction
Neutrino properties
Neutrino astrophysics/cosmology

Geo
Solar
Big Bang
Supernovae
Atmospheric
Solar Atmospheric
High-energy astrophysical
……

Face to the Challenges

Few MeV neutrinos from reactors
Few 100MeV to a few GeV in long-baseline experiments
UHE cosmogenic neutrinos...

Accelerator neutrinos
Reactor neutrinos
Cosmogenic Neutrinos

Face to the Challenges

Scintillator Detectors
Noble Liquid Detectors
Water Cherenkov Detectors
Ice Detectors
Photodetectors
Calorimetry
Gas Detectors
Silicon/Germanium Detectors
Superconducting Detectors
Quantum Sensors

Accelerator neutrinos
Reactor neutrinos
Cosmogenic Neutrinos

Face to the Challenges

Scintillator Detectors Noble Liquid Detectors Water Cherenkov Detectors Ice Detectors Photodetectors Calorimetry Gas Detectors Silicon/Germanium Detectors Superconducting Detectors Quantum Sensors

Low energy threshold
Low background
Large mass

High efficiency
Better Reconstruction
Fast timing
PID

High voltage delivery
Cold electronics design

Beam-generated Fluxes

Directional detectors for low-energy neutrinos
Precise measurement of vertex substructure in neutrino scattering

Face to the Challenges

Scintillator Detectors
Noble Liquid Detectors
Water Cherenkov Detectors
Ice Detectors
Photodetectors
Calorimetry
Gas Detectors
Silicon/Germanium Detectors
Superconducting Detectors
Quantum Sensors

(Micro-)electronics
Calibration systems
Trigger and Data Acquisition
(Automated) event reconstruction
Computing and Machine Learning

Face to the Challenges

Few MeV neutrinos from reactors
Few 100MeV to a few GeV in long-baseline experiments
UHE cosmogenic neutrinos...

Scintillator Detectors
Noble Liquid Detectors
Water Cherenkov Detectors
Ice Detectors
Photodetectors
Calorimetry
Gas Detectors
Silicon/Germanium Detectors
Superconducting Detectors
Quantum Sensors

Low energy threshold
Low background
Large mass

High voltage delivery
Cold electronics design

High efficiency
Better Reconstruction
Fast timing
PID

Accelerator neutrinos
Reactor neutrinos
Cosmogenic Neutrinos

Beam-generated Fluxes
Directional detectors for low-energy neutrinos
Precise measurement of vertex substructure in neutrino scattering

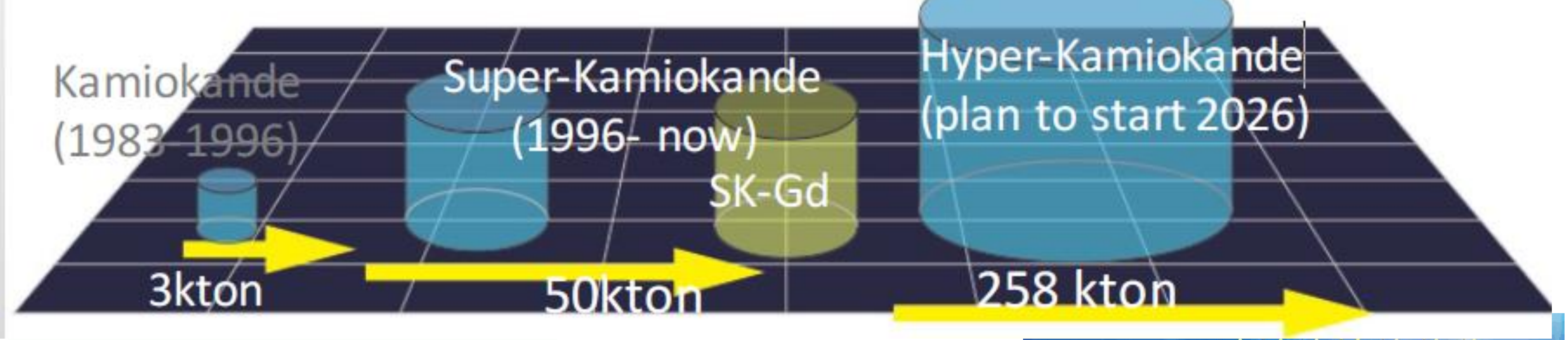
(Micro-)electronics
Calibration systems
Trigger and Data Acquisition
(Automated) event reconstruction
Computing and Machine Learning

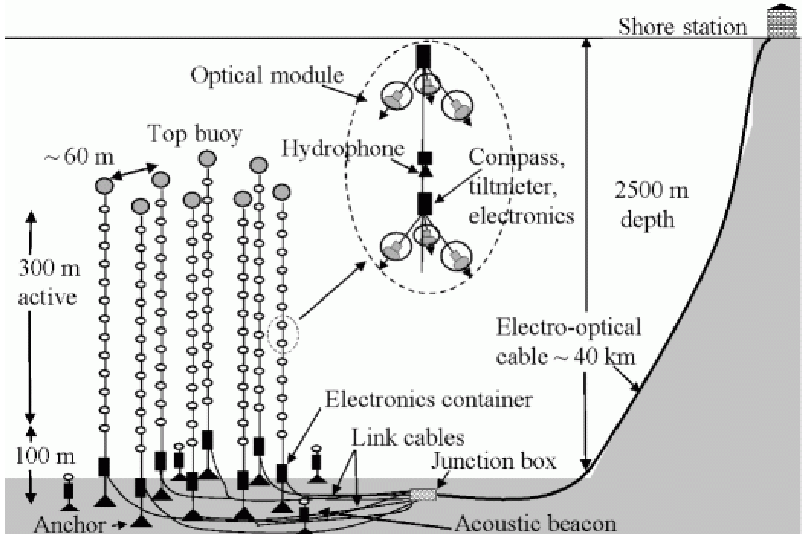
Cherenkov light

Water detectors

Large mass
Direction

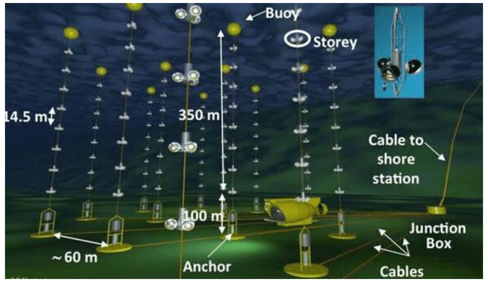
A few MeV to over 100GeV interactions

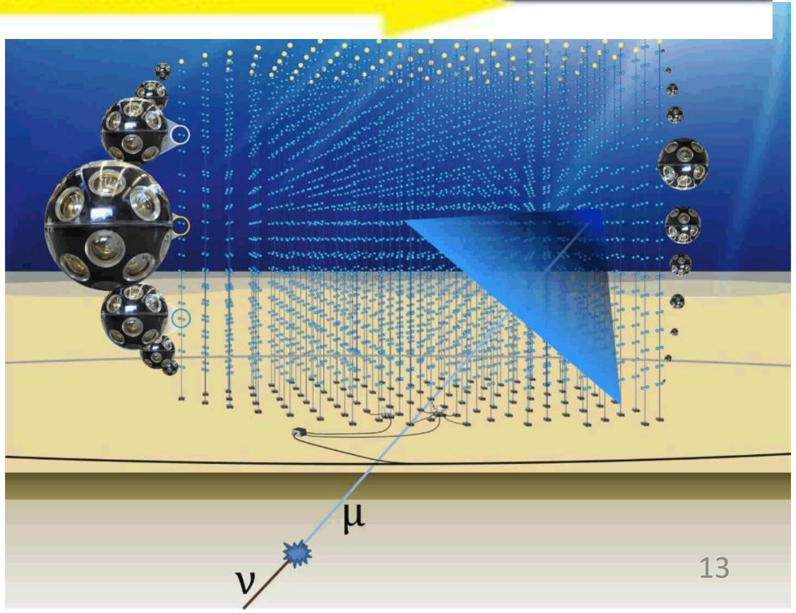




ANTARES
KM3NeT-ORCA
KM3NeT-ARCA

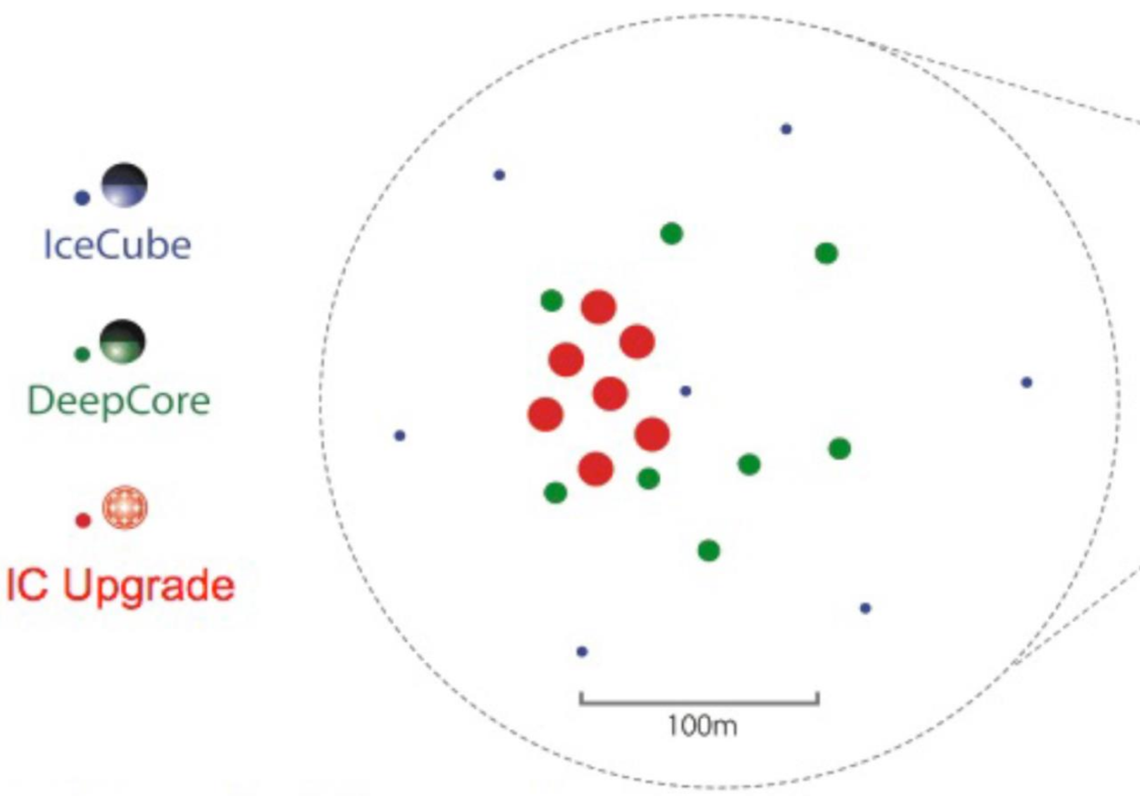
Over GeVs interactions

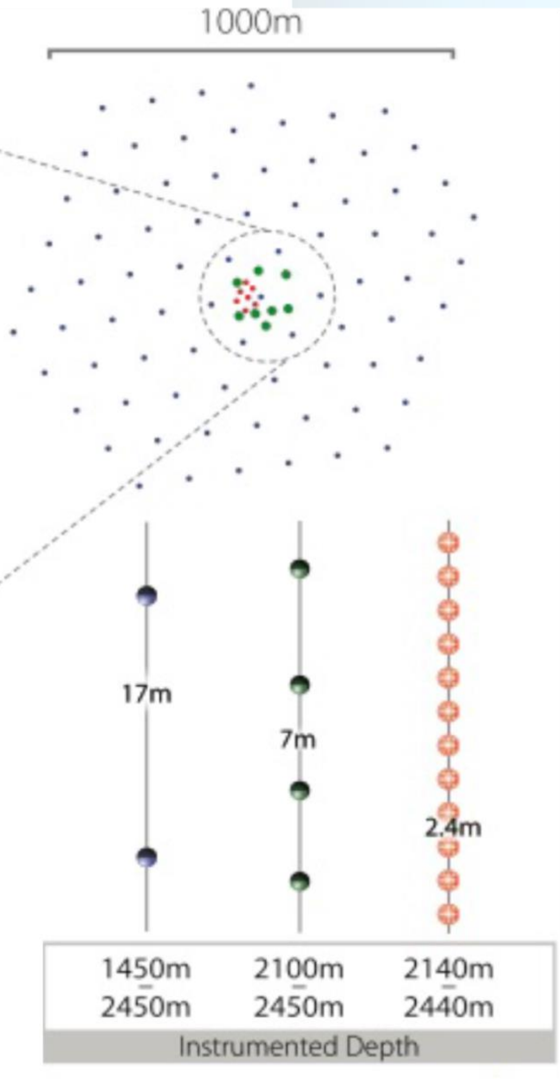




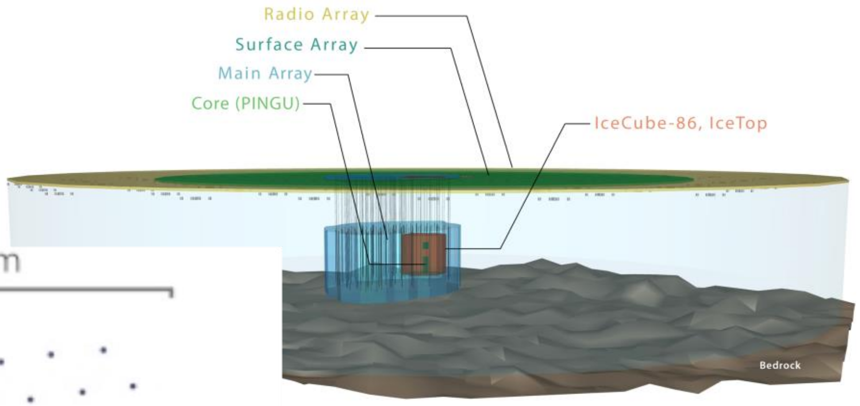
Ice detectors

Multi-component MeV to EeV neutrino detection

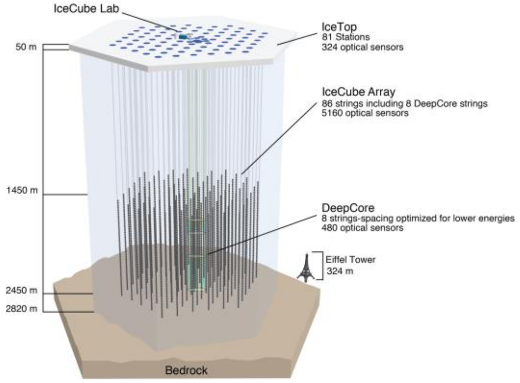


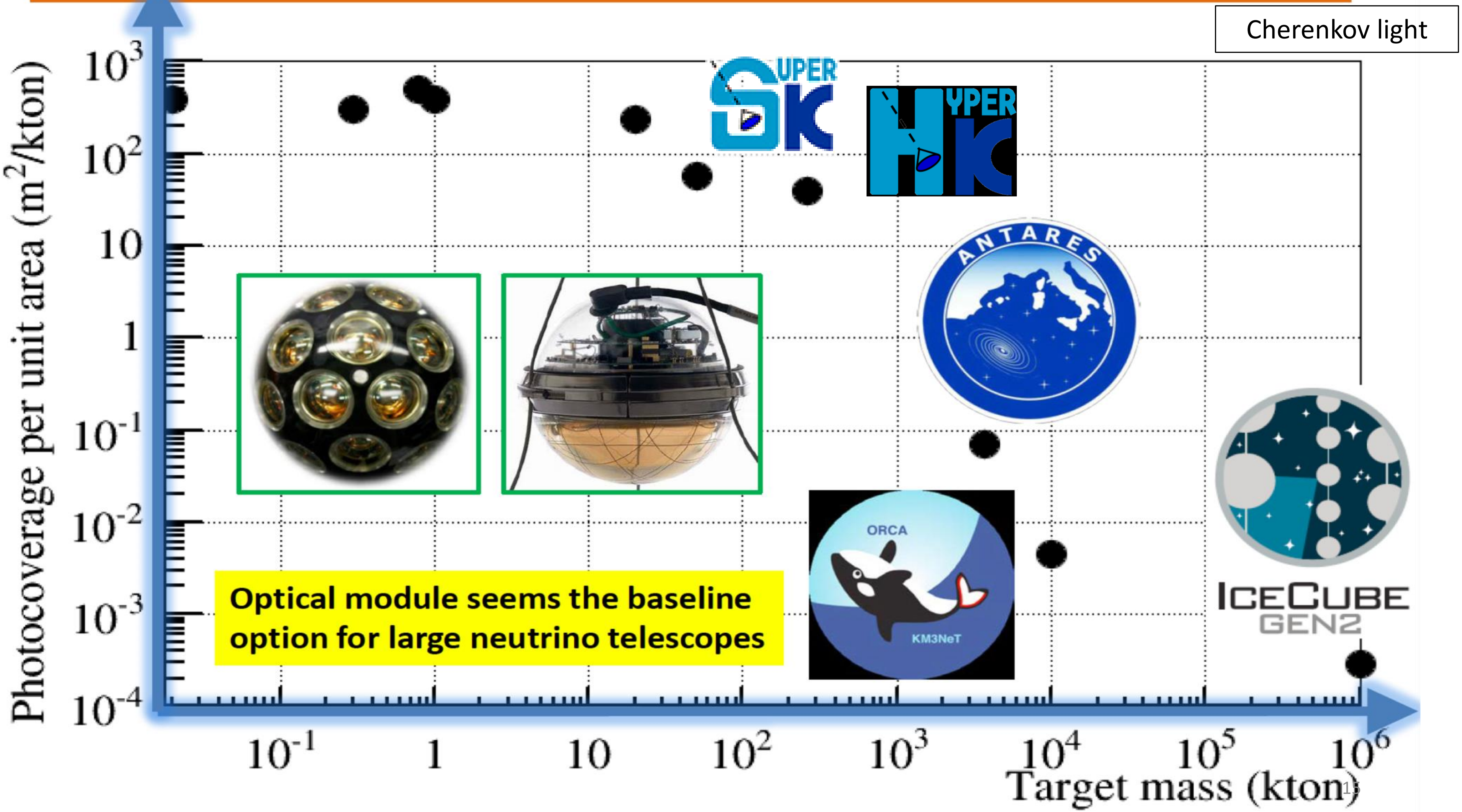


- seven strings, exact geometry still under optimization
- ~120 modules/string, 2–3m vertical spacing in deep ice
- precision calibration and GeV-scale neutrino physics
- funded, deployment in 2022–23



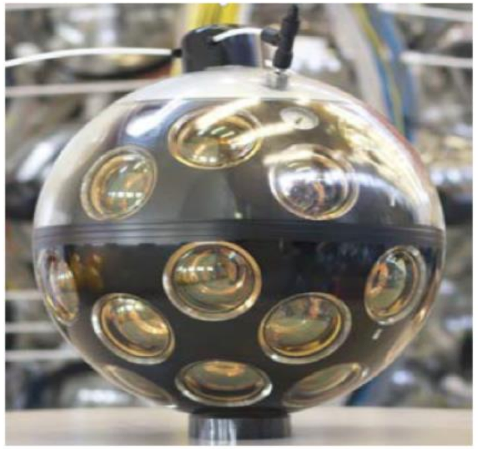
Large mass
Direction



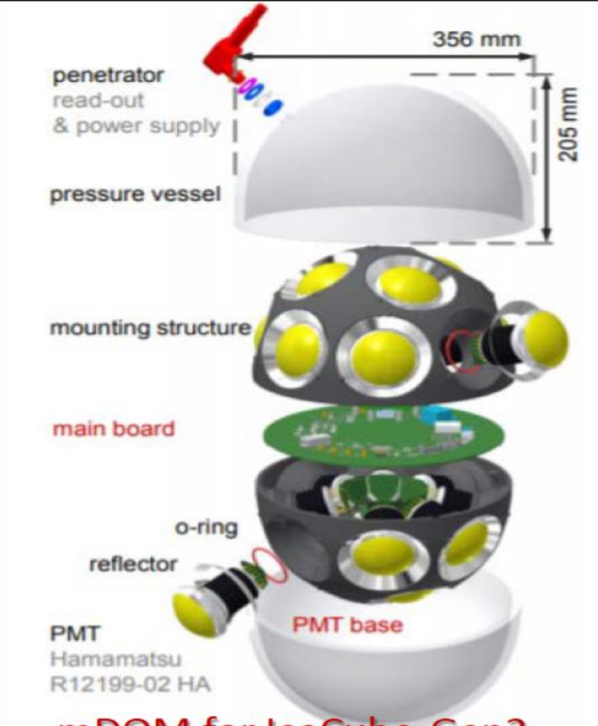


Cherenkov light
Photocoverage per unit area (m²/kton)
10³
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻¹
1
10
10²
10³
10⁴
10⁵
10⁶
Target mass (kton)
SUPER K
HYPER K
ANTARES
ORCA
KM3NeT
ICECUBE GEN2
Optical module seems the baseline option for large neutrino telescopes

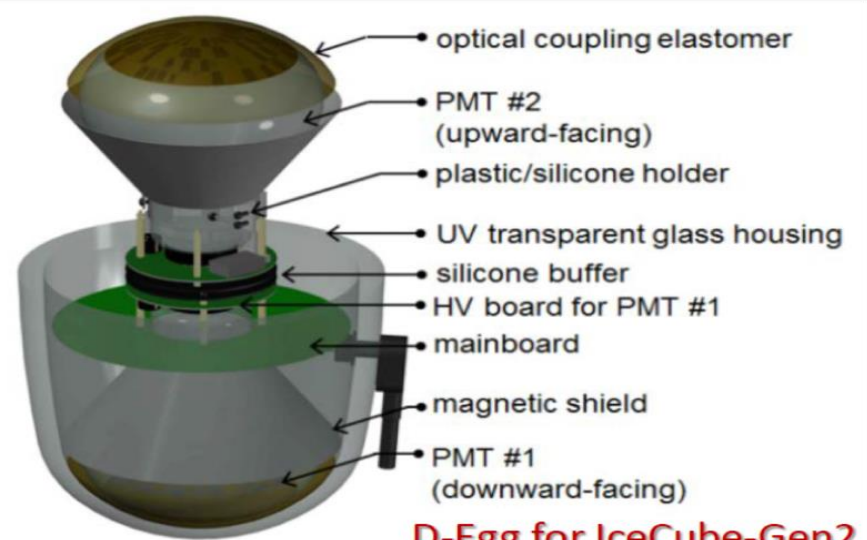
Optical Modules



KM3Net
Digital Optical Module

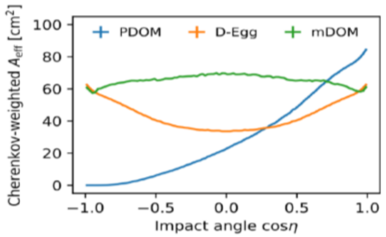


mDOM for IceCube-Gen2
PoS (ICRC2017)1047



PoS(ICRC2017)1051
D-Egg for IceCube-Gen2

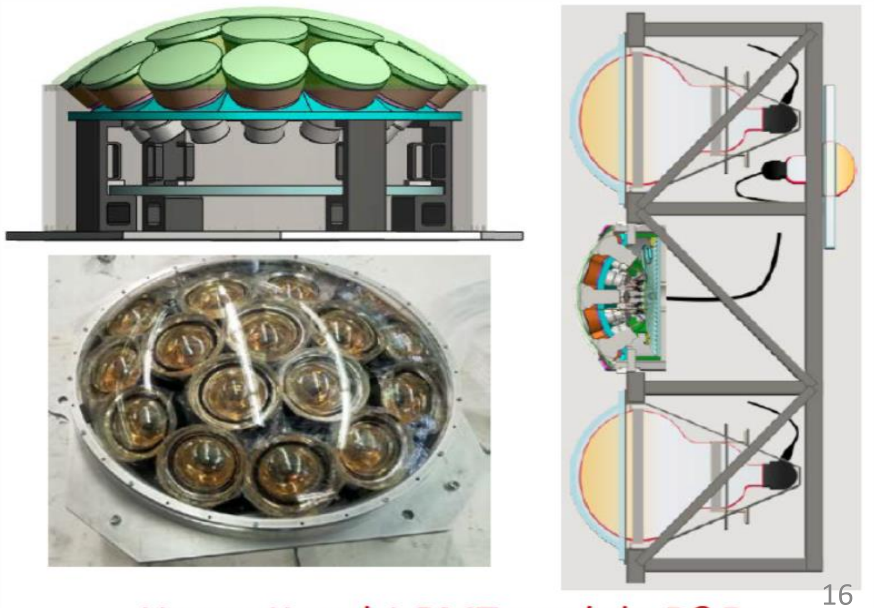
finer granularity,
good timing,
directional sensitivity,
lower dark noise,
less sensitive to Earth
magnetic field, etc



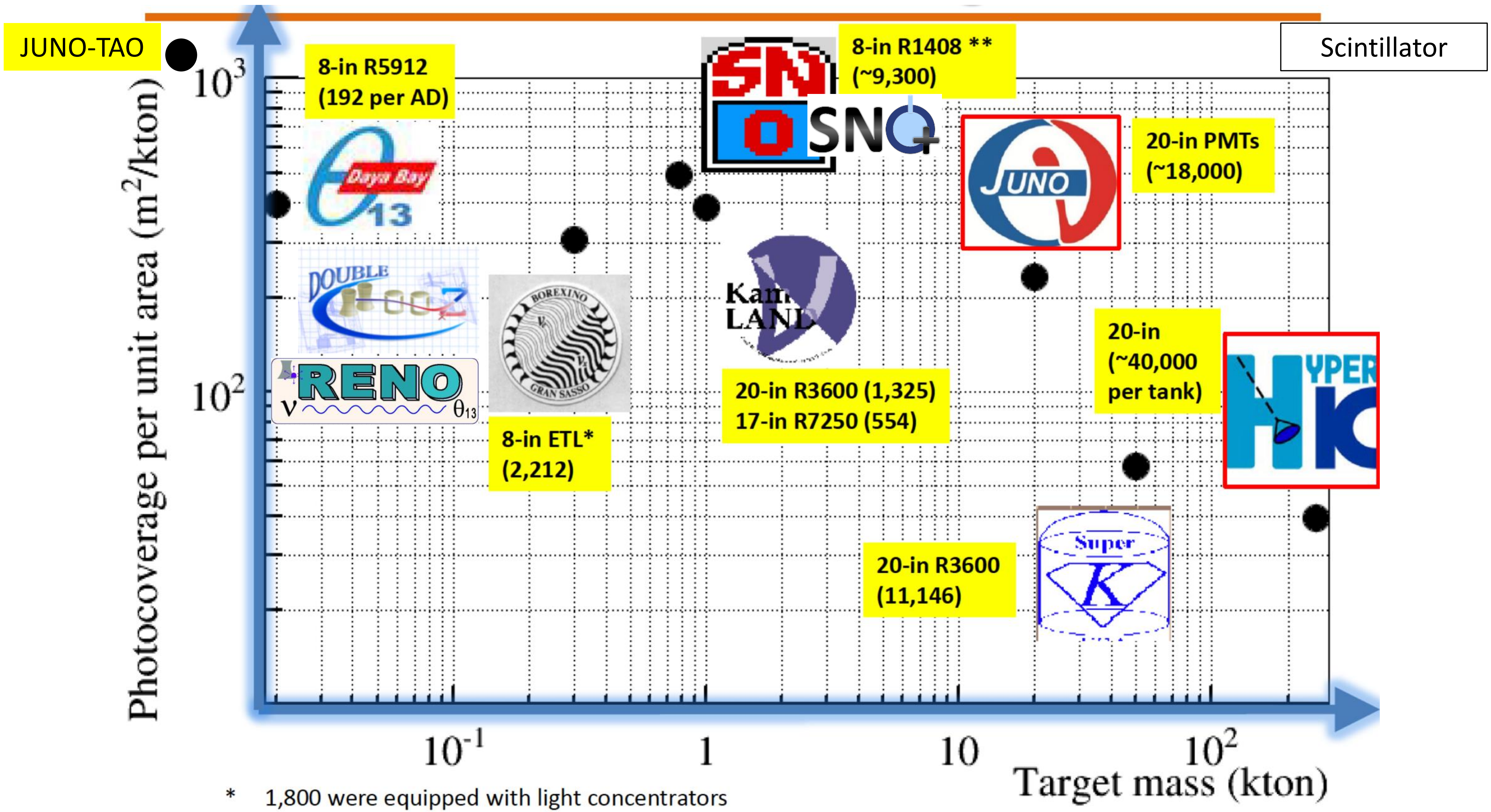
Hamamatsu R12199-02

ET Enterprises

HZC XP82B20



Hyper-K multi-PMT module R&D

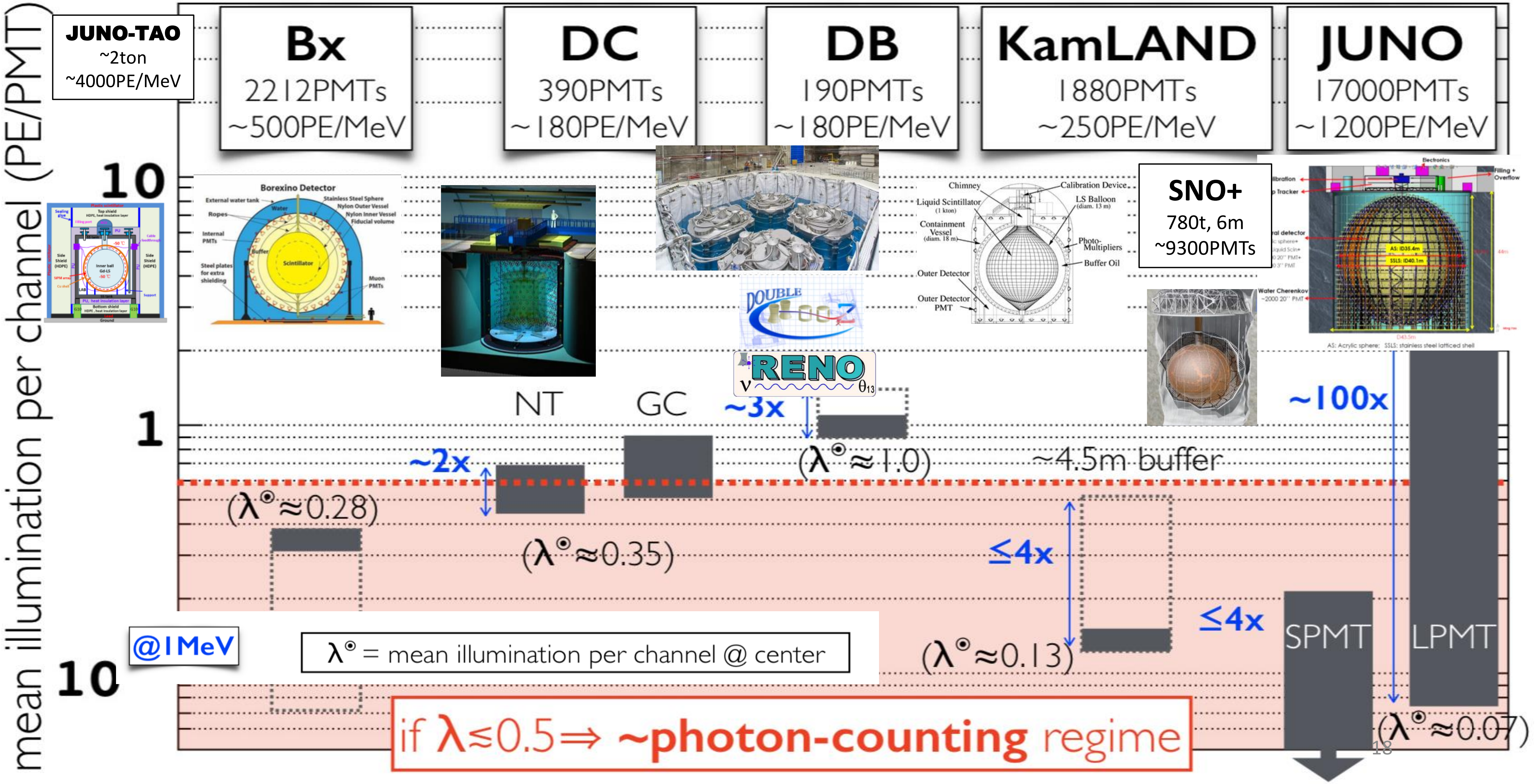


* 1,800 were equipped with light concentrators

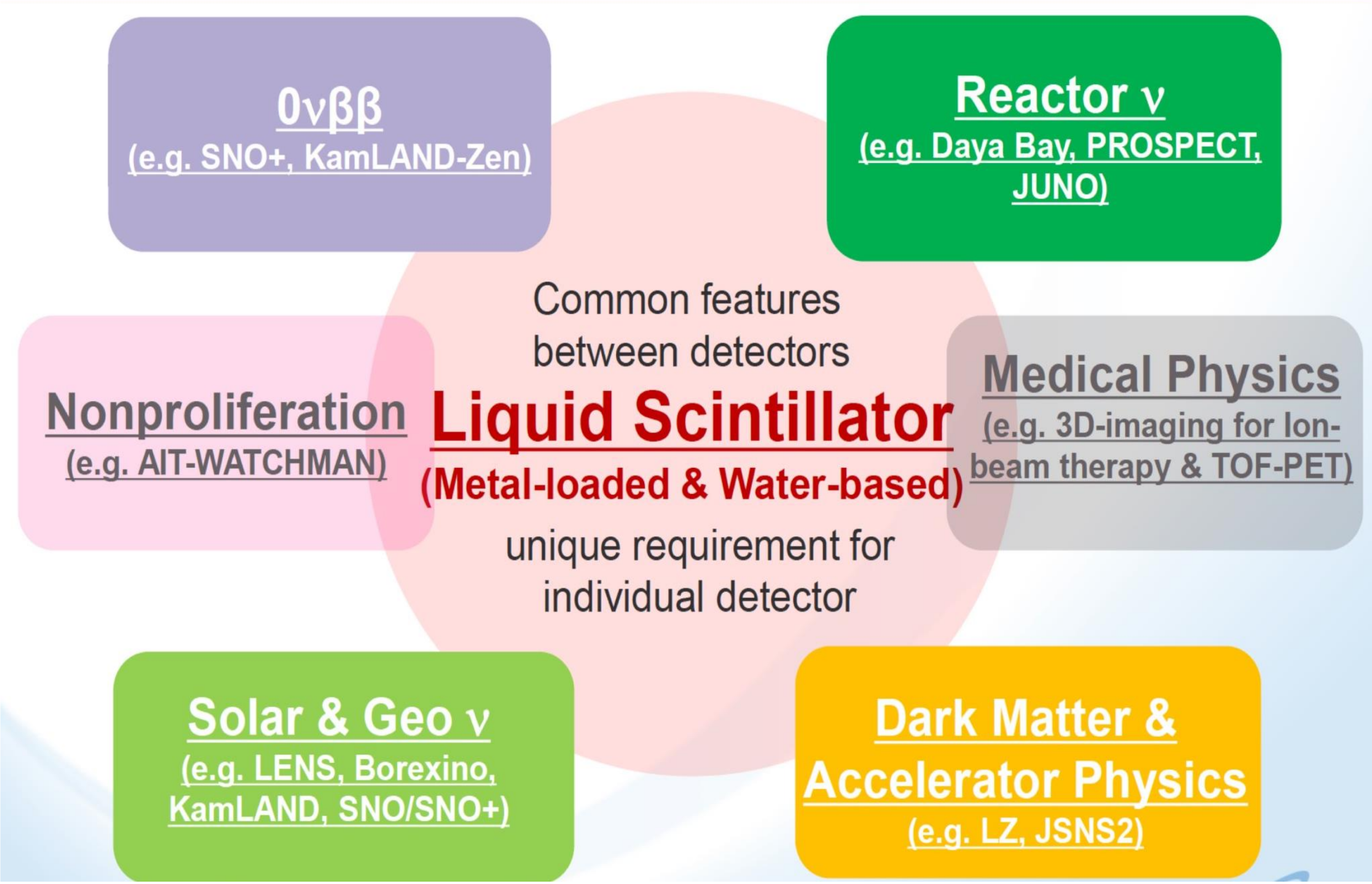
** each PMT was equipped with a 27 cm diameter concentrator

LS detectors

(1 ~20k ton; <MeV~ 10s MeV)



Scintillator Physics



From Mingfang

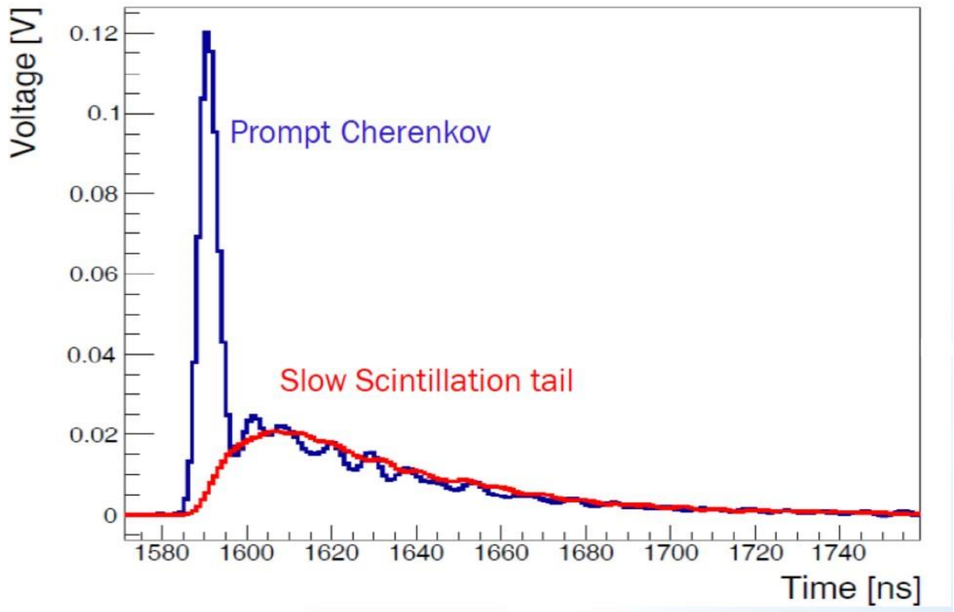
Achieve both a high light yield and direction reconstruction

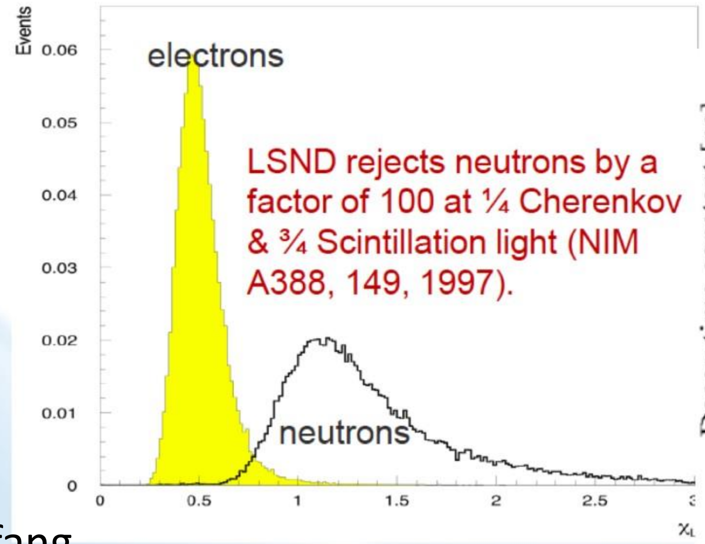
- Search for new scintillation medium with Scalability, Stability, Compatibility and Photon-yield
- Cleaner and Brighter (Purification)
- Metallic-ion loadable (M-doped LS)
- Pulse-shape discrimination
- Directionality
    - PID and background rejection
    - Water-based Liquid Scintillator (WbLS) and Slow liquid scintillator

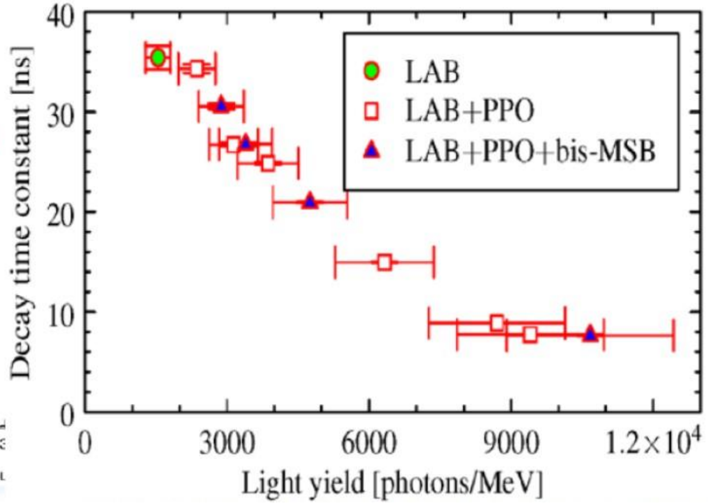
Directional Liquid Scintillator

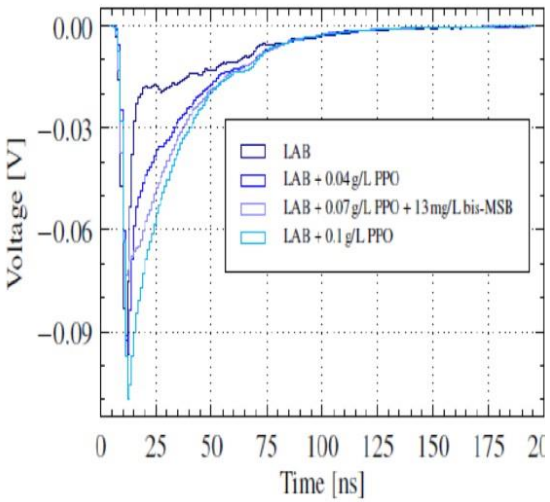
*A Cherenkov-visible Scintillation Liquid is the **key** to future LS detectors:*

- *Oil-based scintillator: **reducing** scintillation light or **slowing** scintillation decay-time to allow Cherenkov imaging*
- ***Water-based Liquid Scintillator (WbLS)***
- *Fast photosensors/electronics (LAPPD)*
- *Liquid Scintillator Imaging*







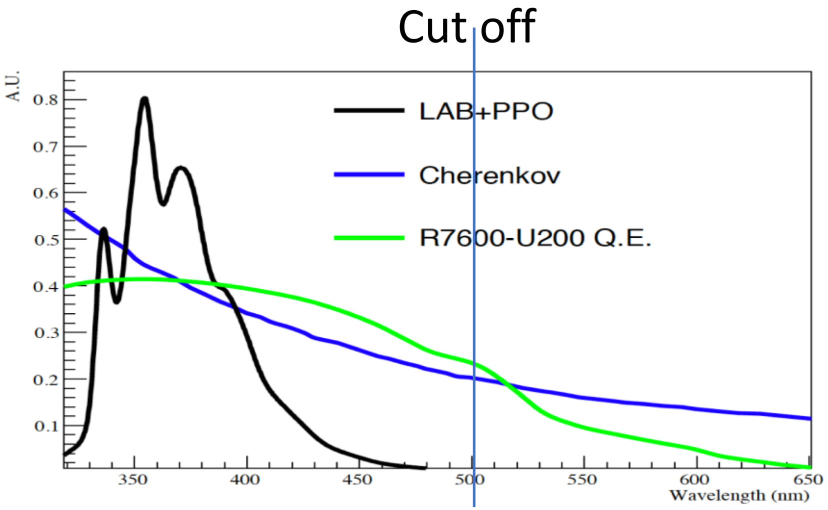


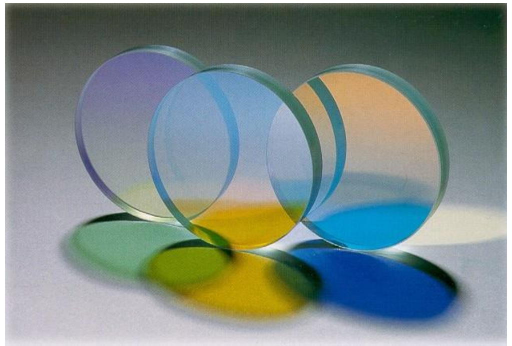
From Mingfang

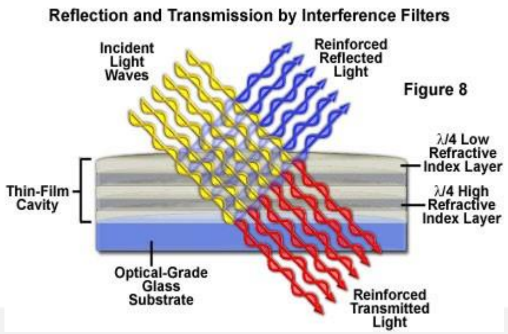
Directional detector

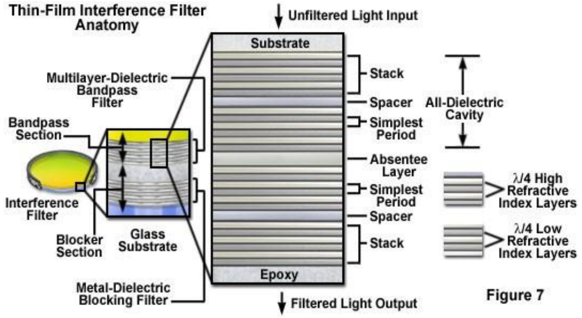
Interference filters

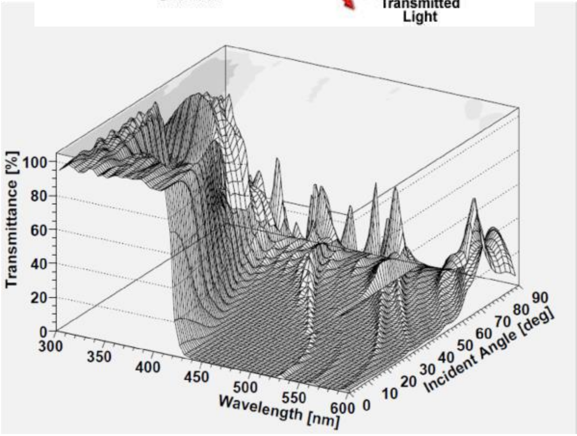
Cerenkov/scintillation separation by wavelength sorting

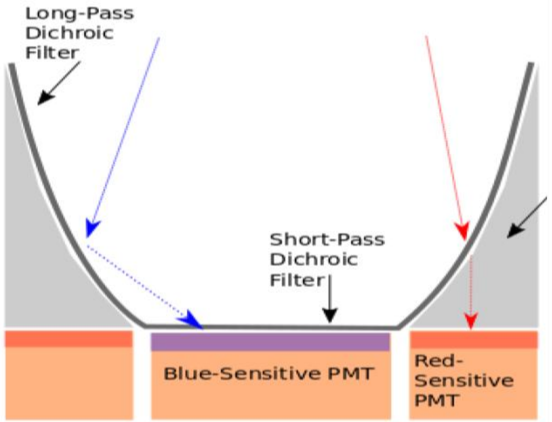


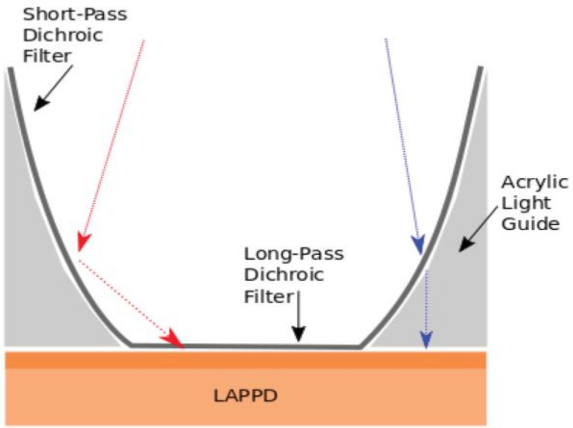






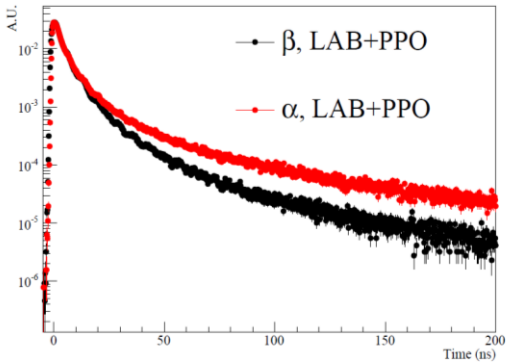






506 nm Long-Pass: LAB+PPO Transmitted Light

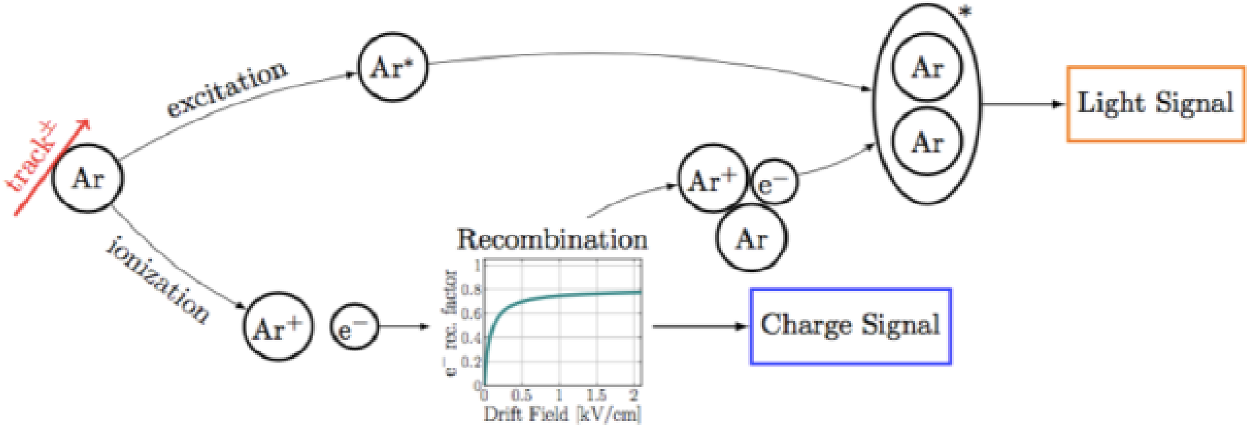
beta source, LAB+PPO target, transmitted light shows clearly separated Cherenkov peak!



Liquid Argon Scintillation Light

- LAr is a scintillator that emits about 40,000 ph/MeV (E = 0) when excited by MIP
  -at nominal DUNE SP E = 500 V/cm the yield is approximately 24,000 ph/MeV
  (reduced due to recombination)

Higher light yield
Photon and charge
PID
Cleaner

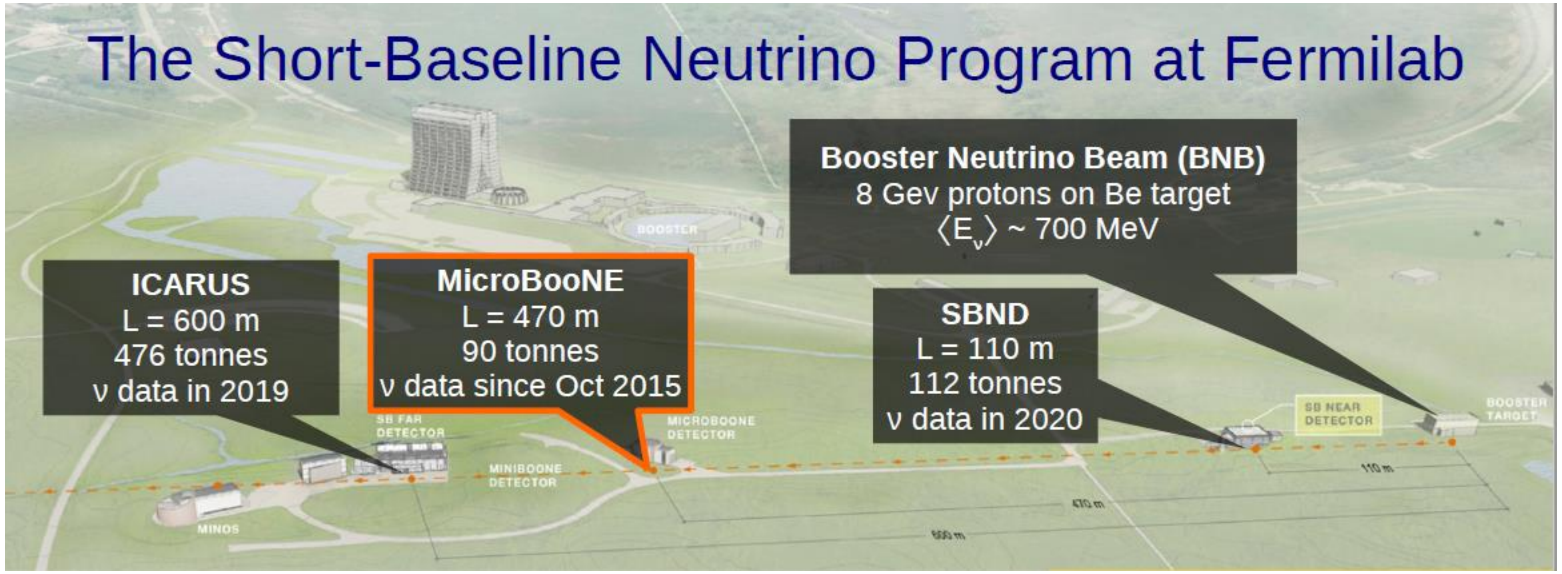


Light collection (VUV region)
Charge collection

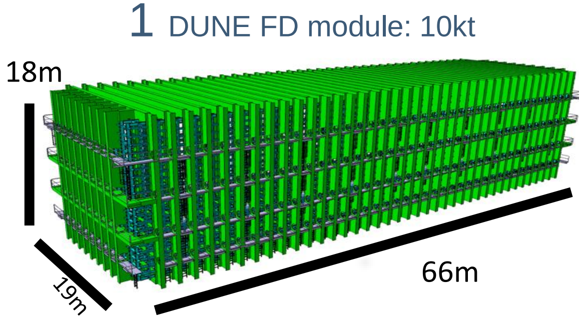
- Ionization radiation in LAr results in formation of excited dimer Ar_2^*
  -photon emission follows through de-excitation of singlet $^1\Sigma$ and triplet $^3\Sigma$ states
  -photons emitted in a narrow band around 128 nm (VUV region)
  -de-excitation from $^1\Sigma$ is fast with $\tau_{fast} \approx 6$ ns
  -de-excitation from $^3\Sigma$ is slow with $\tau_{slow} \approx 1.3$ μs
  -ratio of fast and slow components dependent on the ionizing particle through ionization density of LAr (0.3 for e^-; 1.3 for α; 3 for n)
  => basis for PID capability

Noble Element Detectors

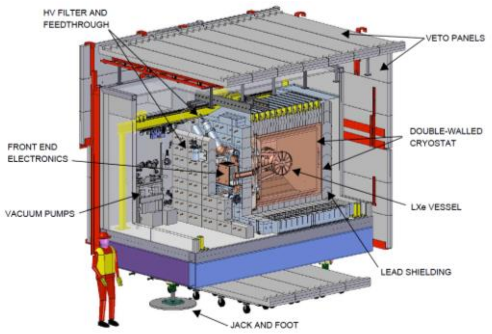
Sub-KeV to few GeV, kg to few 10 kt



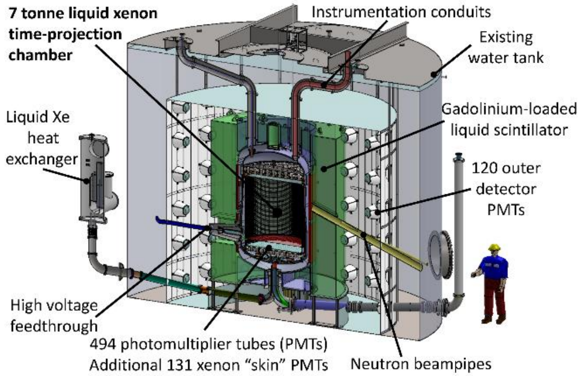
DUNE



EXO-200



LZ



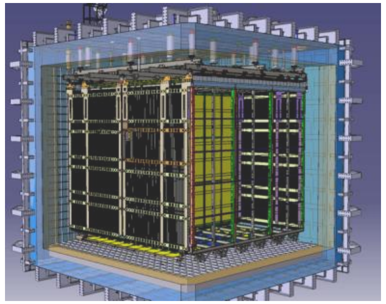
Dark matter

- Noble Element Detectors for Accelerator Neutrino Physics
  - Optimally Granular Charge Collection and Electronics
  - Efficient and High-Quality VUV Light Detection
  - Delivery of Very High Voltage
  - Calibration of a large detector system.
- Noble Detectors for Neutrinoless Double Beta Decay Searches
  - Energy Resolution
  - Material Screening and Radio purity
  - Topology
  - Daughter Tagging
  - High Voltages and Long Drift Lengths
  - Calibration
  - Isotope Enrichment

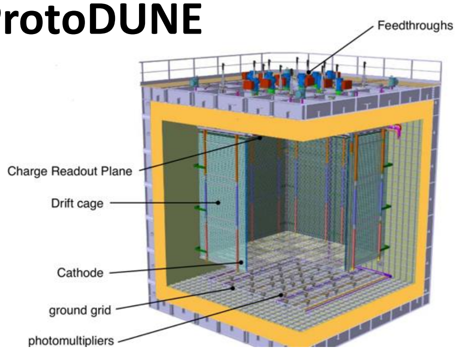
DUNE Challenges

- So far largest LAr TPC operated ICARUS 2 x 235t (active) → 1 DUNE FD module will be ~10kt
- Several **new challenges** to scale to DUNE. Need **prototypes** to develop solutions **scalable** for DUNE
- Engineering aspects
  - Test full scale detector elements used in DUNE, for SP
  - Installation sequence and test procedures
  - Long term operation stability
- Physics aspects
  - Benchmark reconstruction performance
  - dQ/dx recombination
  - calibration techniques
  - Characterize hadron – argon interactions

ProtoDUNE



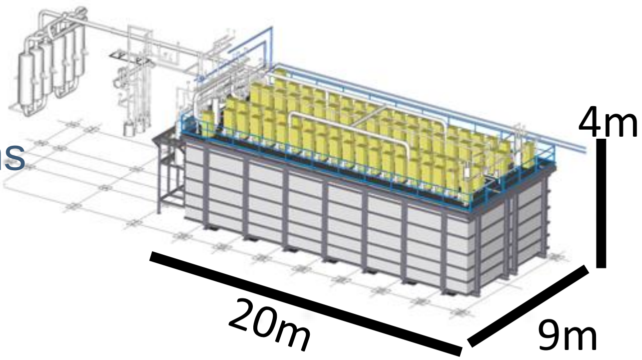
3D model of SP



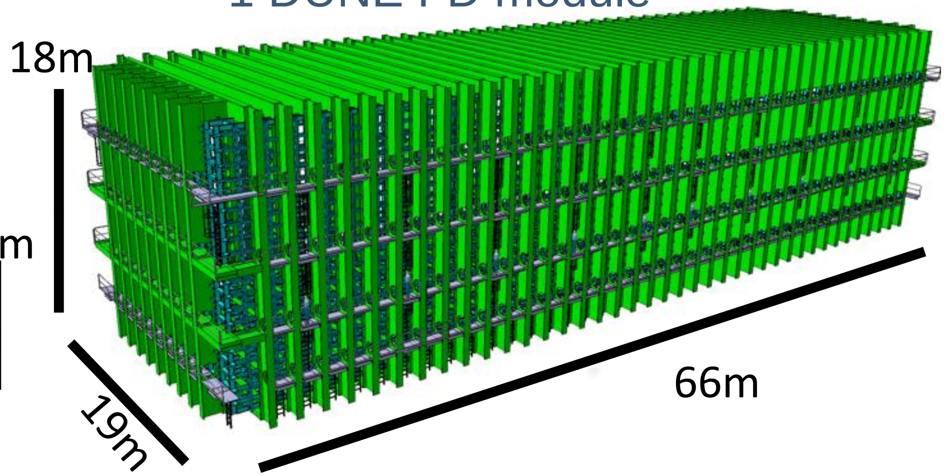
3D model of DP

The biggest small prototype (1/20 of one DUNE module)
2 11x11x11 m^3 cryostats
2 LAr TPC technologies, SP and DP
750t of LAr → 420t active TPC

ICARUS



1 DUNE FD module



ArgonCube Modules

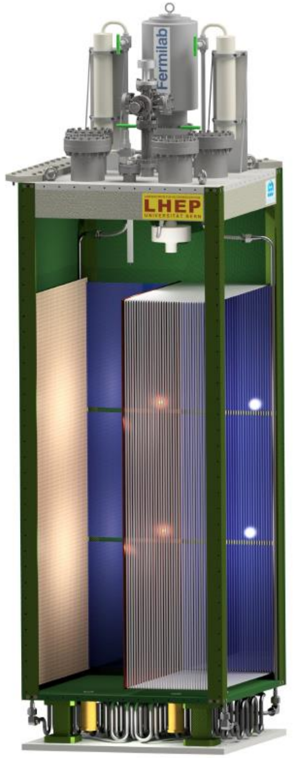
Opaque dielectric G10 structure (200 kV/cm @ 1 cm)
Transparent to tracks:

	LAr	G10
Rad. Lenght (cm)	14.0	19.4
Had. Int. Length (cm)	83.7	53.1

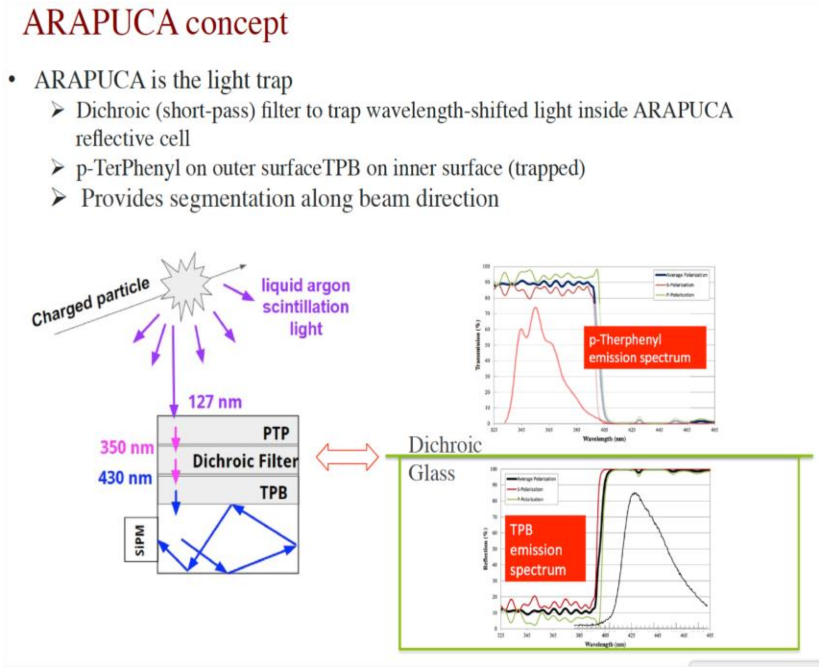
Maximise active volume. Minimise dead material.

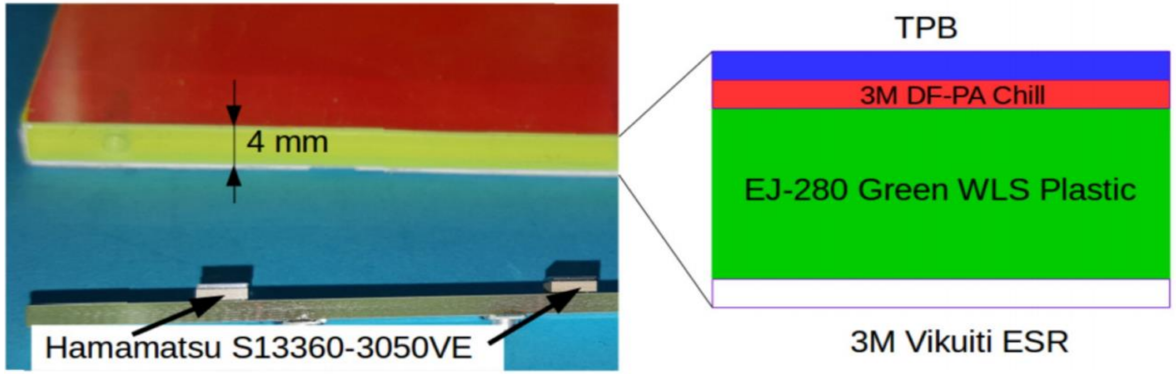
Charge readout:
Compact, mechanically robust, and unambiguous

Light readout:
Compact, dielectric, and large area coverage



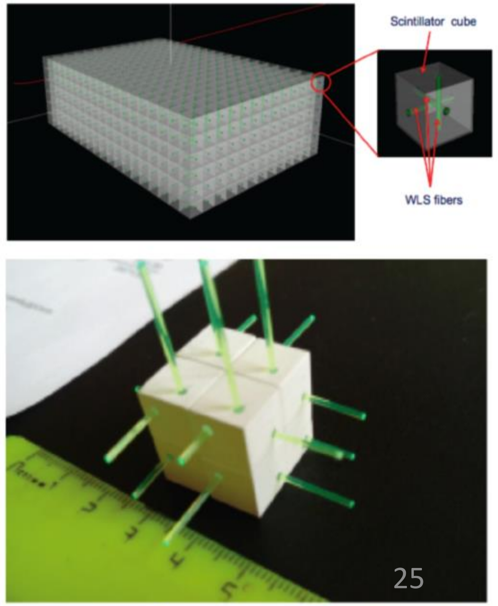
Cut-away illustration of an ArgonCube module[4]





ArCLight cross-section

ND280:
SuperFGD

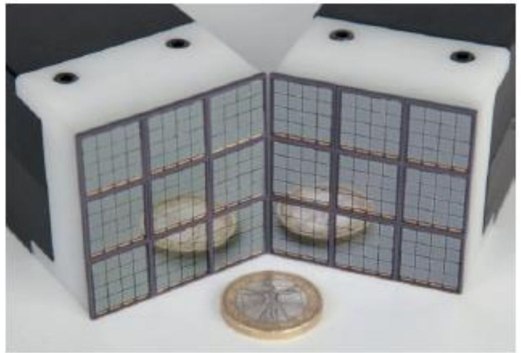


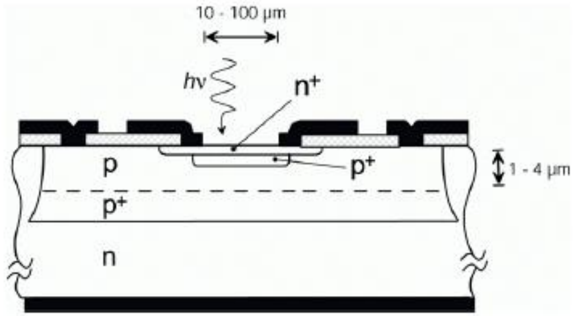
Photodetectors

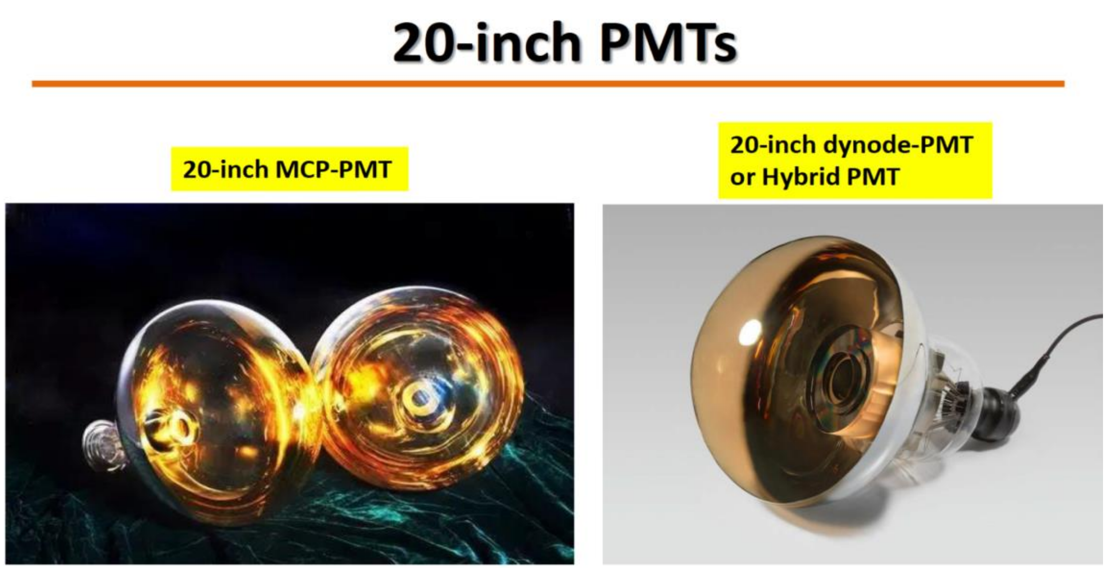
Photons detection is fundamental to particles' detection at ranging from liquid nitrogen up to room temperature.

- **PMT:** low noise, detection of single photons with nanosecond timing
- **LAPPD** (Large Area Picosecond Photodetector) : timing to <100 ps and more immune to magnetic fields
- Silicon Photomultipliers (SiPMs) : solid
    - Small but economical, and when cooled, have dark noise levels competitive to PMTs.
    - Sensitive in VUV, release the limiting needs for secondary wavelength shifters.
    - Lower high voltage, Low power consumption
    - Not affected by magnetic fields, Robust, Negligible aging effects, Mass production
    - Cross-talk, After-pulsing.
- Superconducting transition edge sensors (TES)
    - Fast and high efficiency
    - Challenges : to build larger arrays and readout technology

SiPM



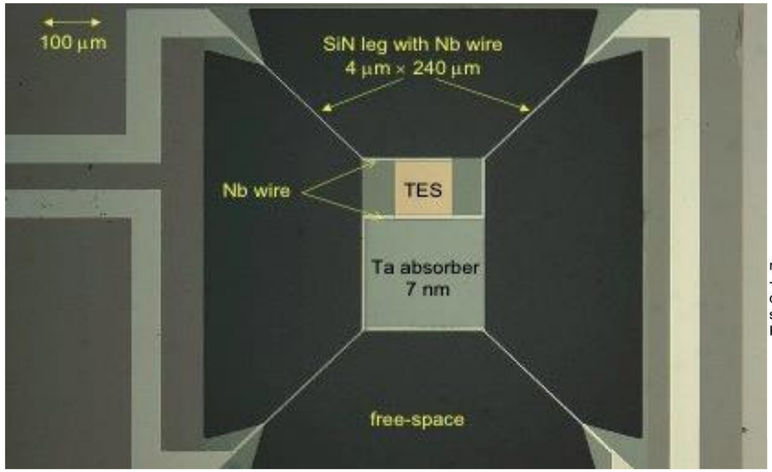




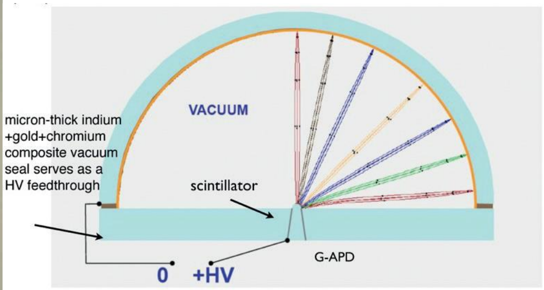
Produced by NNVT Co.

Produced by Hamamatsu Co.

TES

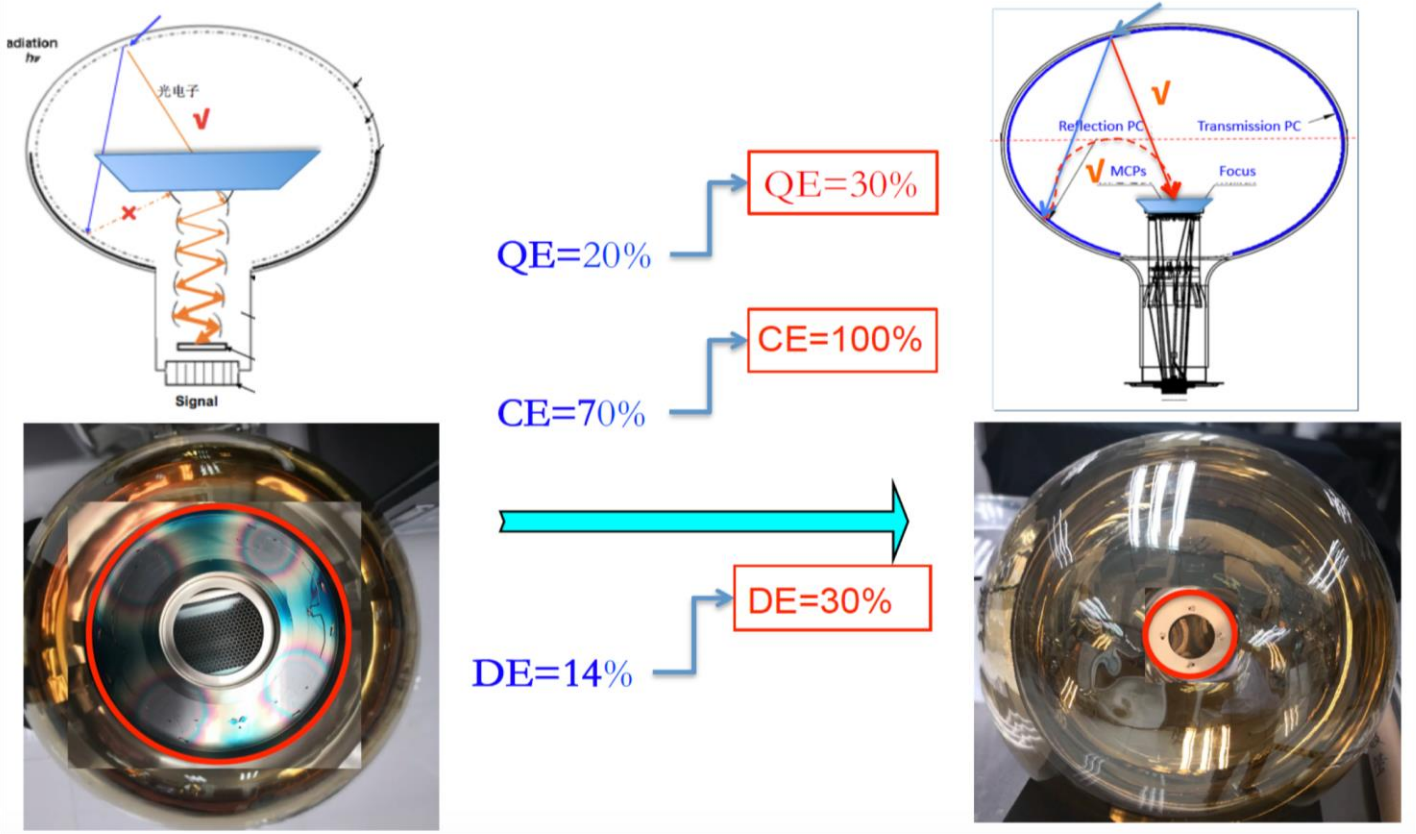


Abalone concept

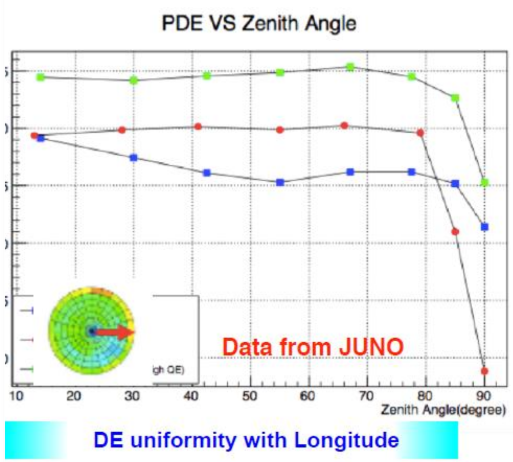


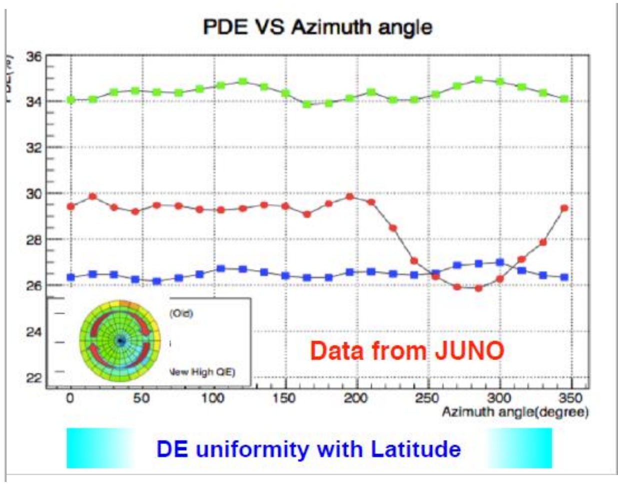
HQE NNVT 20”MCP PMT

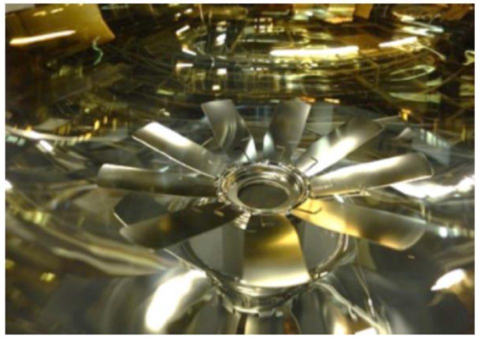
In 2015, the MCP-PMT work group did the best to improve the CE of the MCP modules, and finally, the CE of the MCP-PMTs was improved from 70% to 100%.

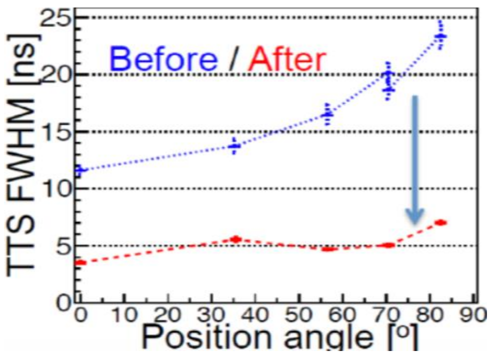


Uniformity



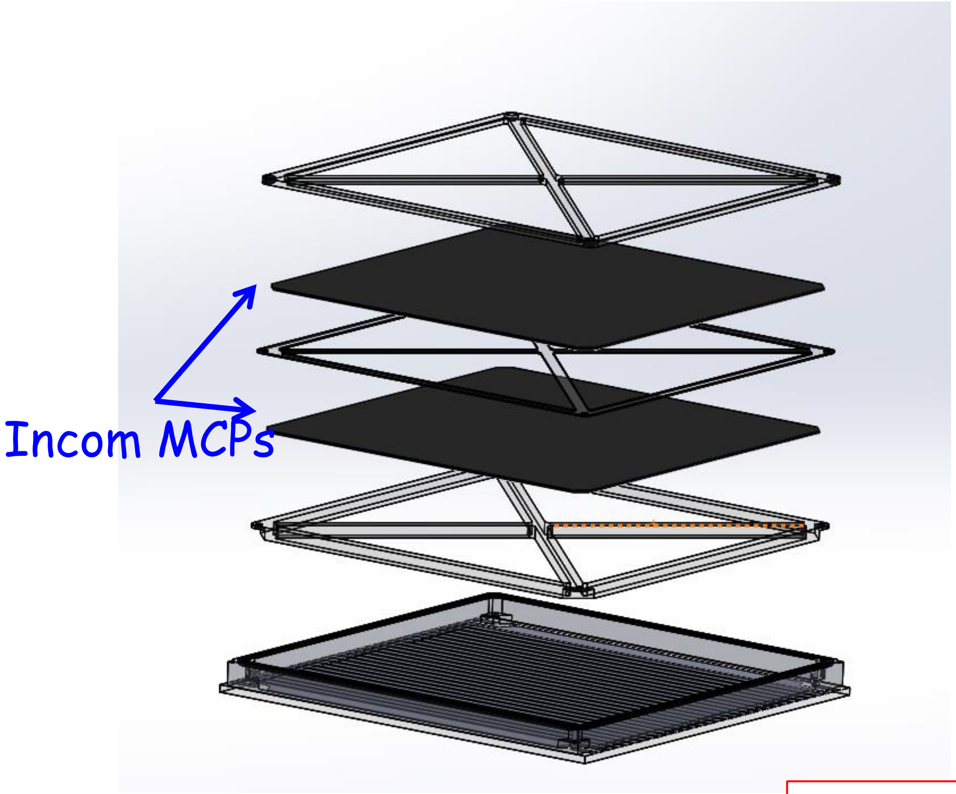






Better TTS R&D

LAPPD features



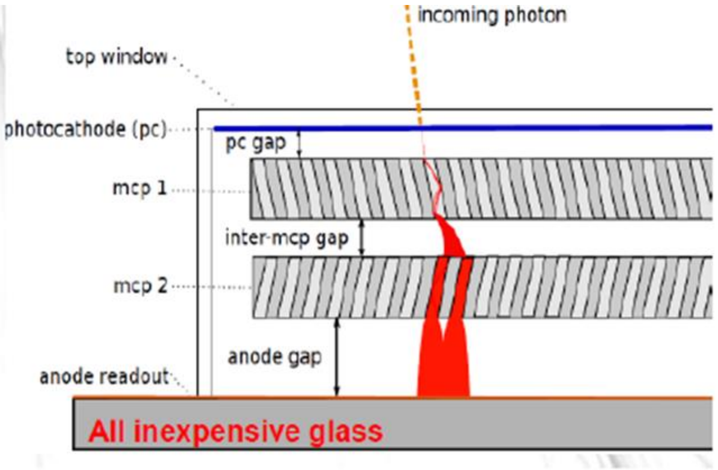
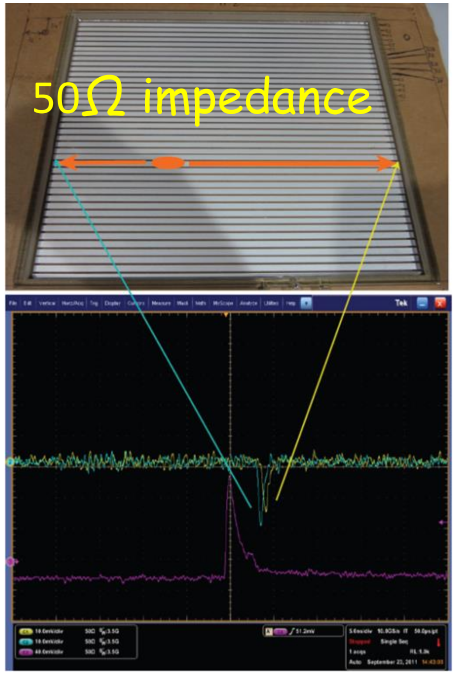
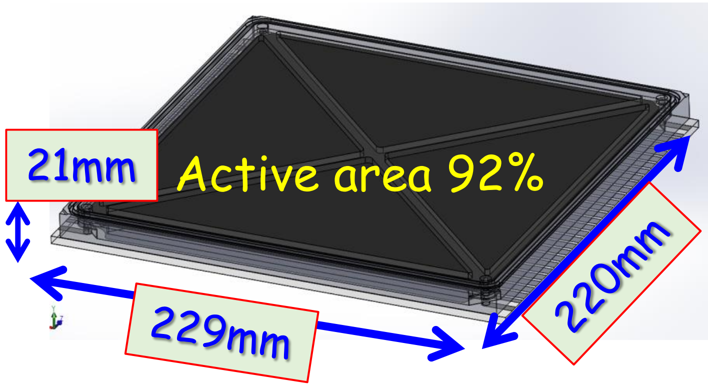
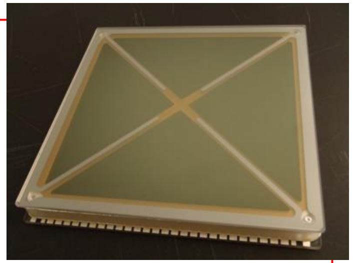


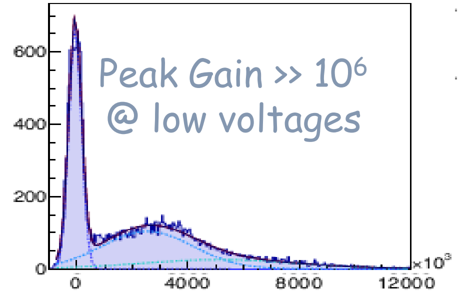
Illustration provided by Univ. of Chicago

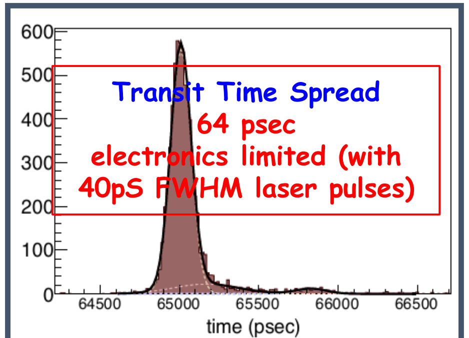




- Glass/ceramic body
- Large Active Area: 195 x 195 mm^2
- Picosecond timing resolution
- mm spatial resolution
- QE >20% w/bi-alkali photocathode
- Fused Silica/Borosilicate window
- Flat square geometry, high filling factor
- Lower Cost per Unit Area



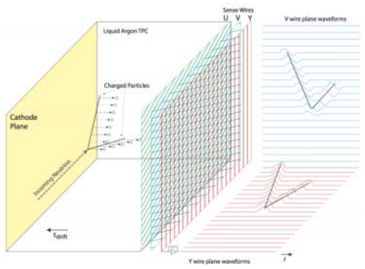


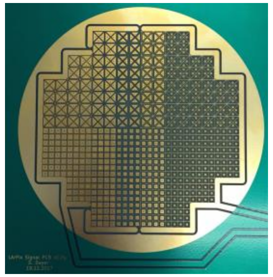


At optimal operation conditions @ 50V extraction voltage, 875V-900V MCP voltage with

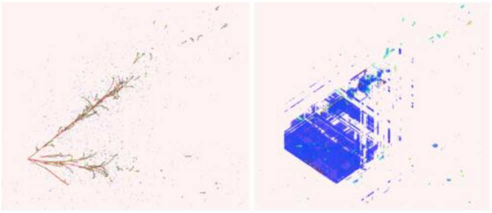
Dark count rate 30-60 Hz/cm^2

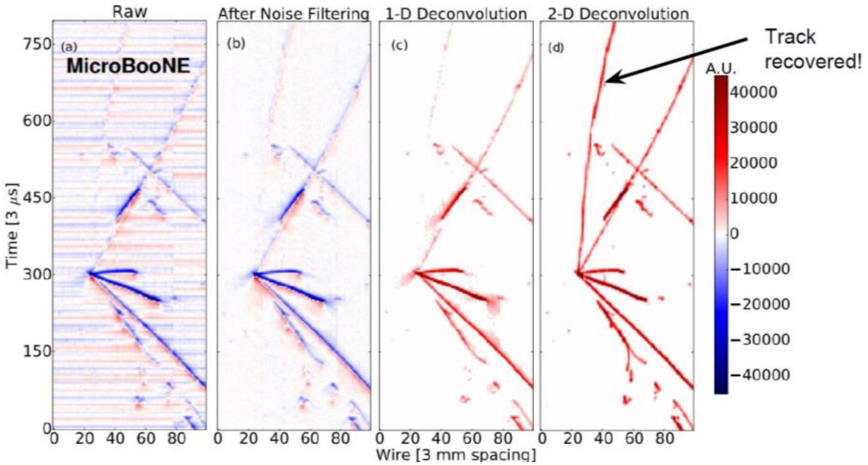
- Electronics
- Trigger and Data Acquisition
  - Extract the data at high bandwidth from the tracking detectors without adding a prohibitive burden of material due to the large number of drivers and the power and cooling
  - Data volume to be produced will be at PB scale, which will require significant DAQ infrastructure and computation resource.
- Computing and Machine Learning
  - Overtaken more traditional approaches based on expert hand-tuning and found natural applications in a variety of areas in particle physics
    - Deep Learning for Detector Reconstruction, Data Reconstruction using Deep Neural Networks for LArTPCs, End-to-end Deep Learning for Particle and Event Identification, Identification of Double-beta Decay Events, Computational and Real-time Inference Challenges
    - Deep Learning on FPGAs for CMS Level-1 Trigger and DAQ, Track Reconstruction in High-pileup Collider Environment, Integrated Research Software Training in HEP



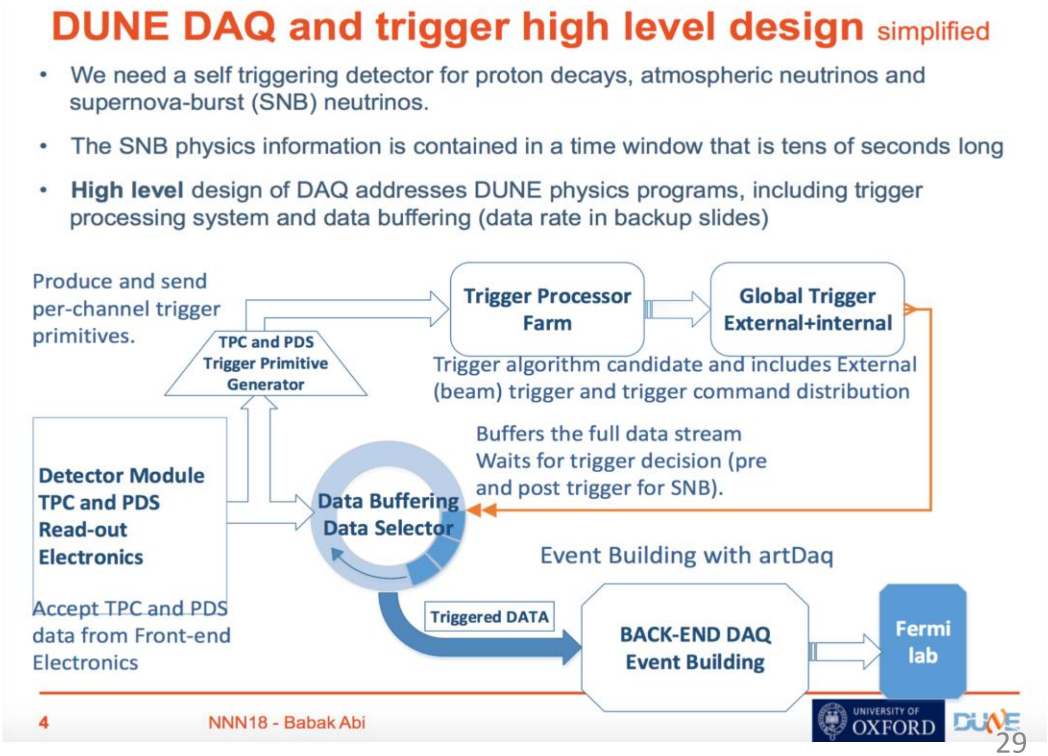


LArPix
DUNE Near Detector





MicroBooNE tracks



Summary

- Facing to the challenges on neutrino detection
  - Large mass
  - Low background
  - Low energy threshold
  - Directional detectors
- Interesting technologies developing and needed for better detectors
- Interesting Precise detectors for short baseline
- Neutrino BSM & Neutrino Detector


Thank you for your attention!

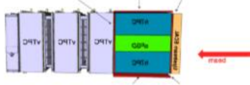
Backup

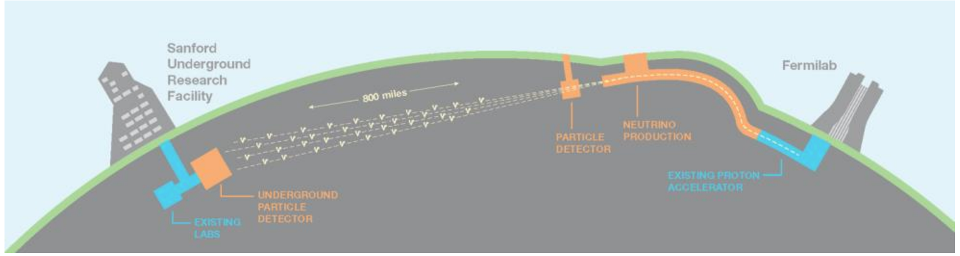
DUNE

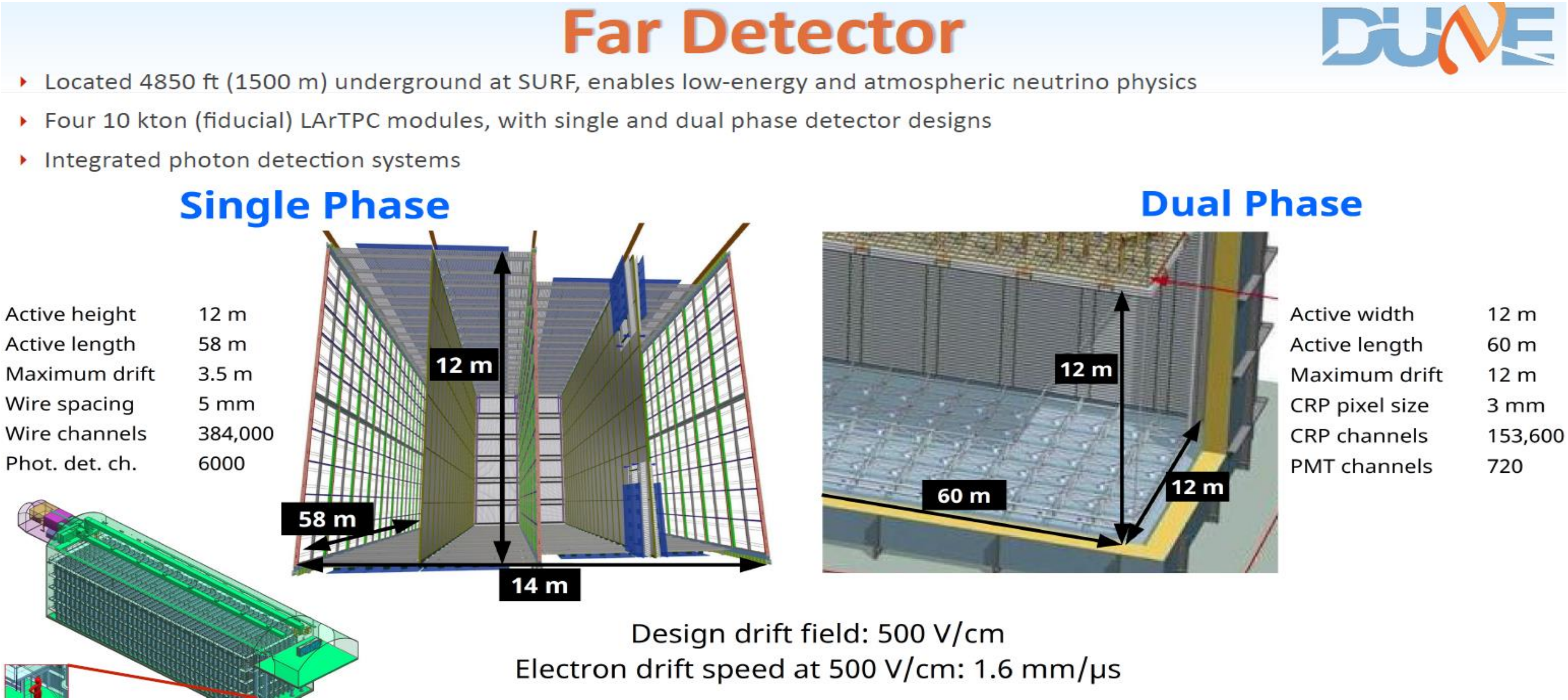
- Precise measurement of neutrino oscillations parameters, particularly δ_{CP} violation phase and determination of mass hierarchy
- Detection of galactic-core supernovae neutrinos
- Nucleon decay
- Search for NSI (Non Standard Interactions)

ND280

Near Detector (ND)
Hosted at Fermilab

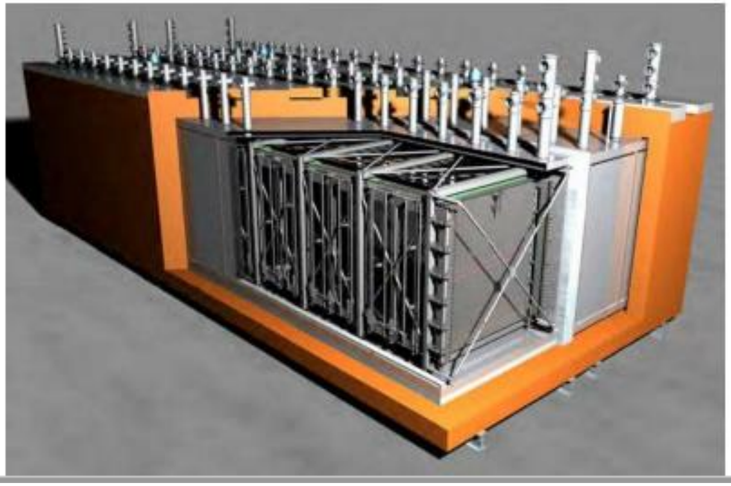


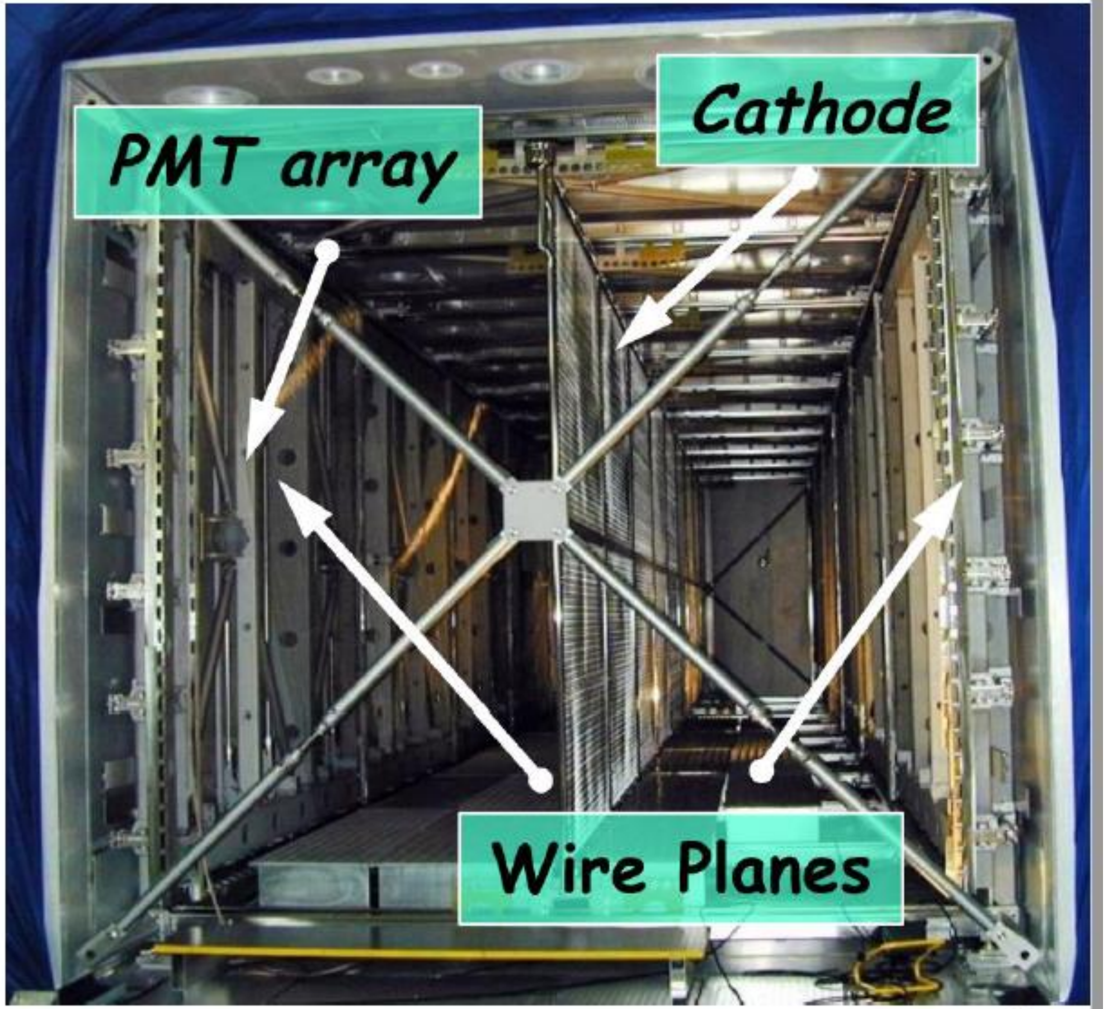




ICARUS T600 Detector

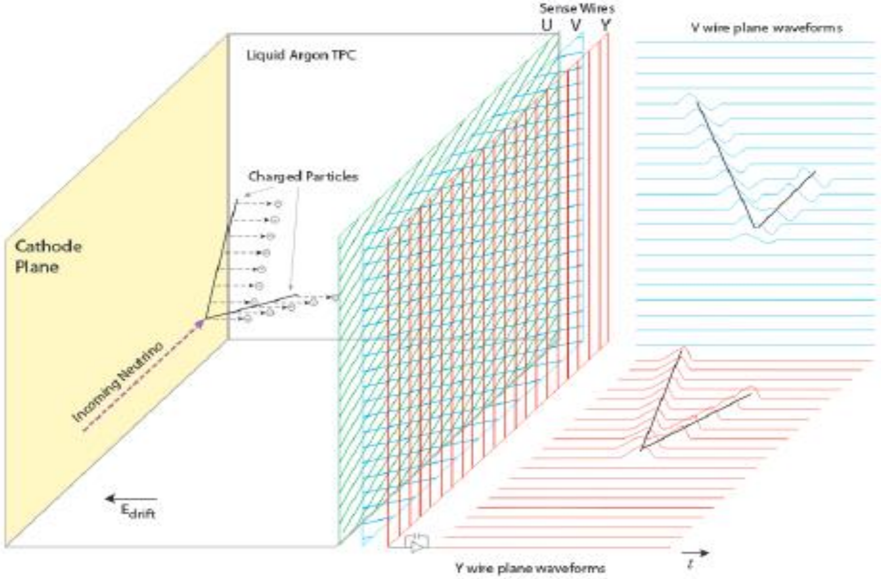
- Two identical LArTPC modules
  - 476 tonnes total fiducial mass
  - Two drift modules per module sharing central cathode
  - 1.5 m drift length
  - ~ 500 V/cm drift field (~1.6 mm/μs drift velocity)
- Three wire planes with 3 mm pitch (0°, ±60° wrt horizontal)
  - Two induction and one collection (last plane)
  - ~54,000 total wires
  - 400 ns sampling time
- VUV scintillation light read out by PMTs coated in wavelength shifter



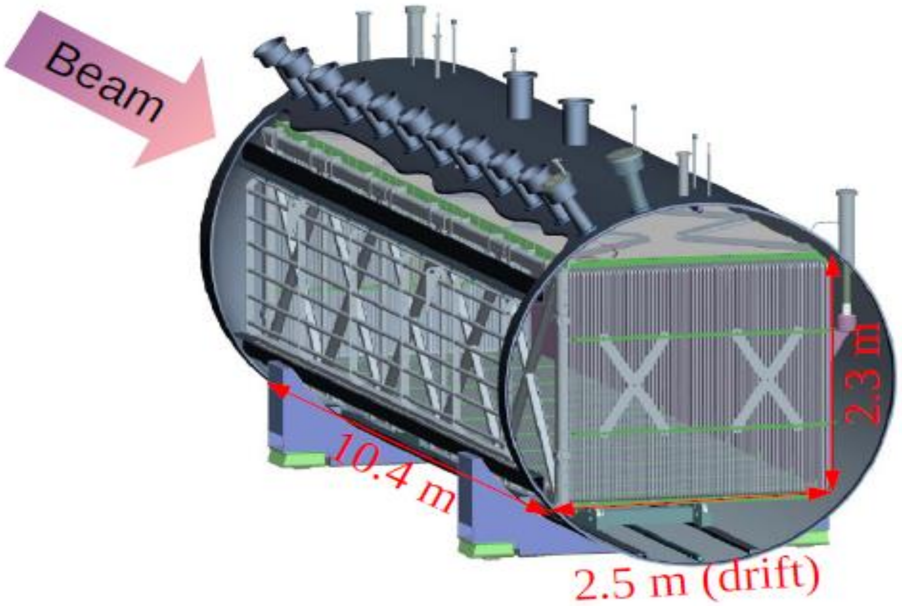


8

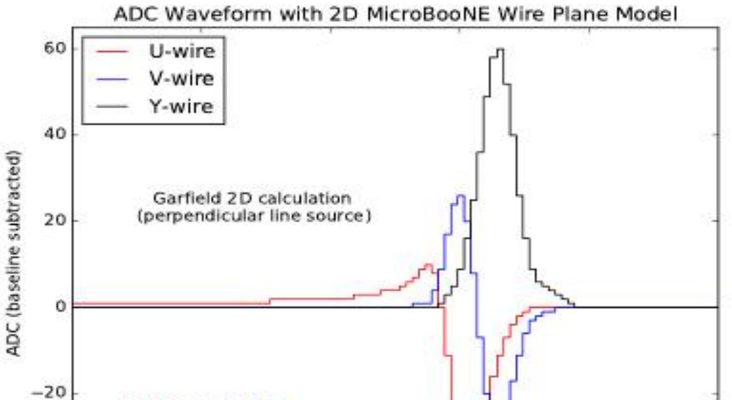
MicroBooNE TPC



JINST 12 P02017 (2017)

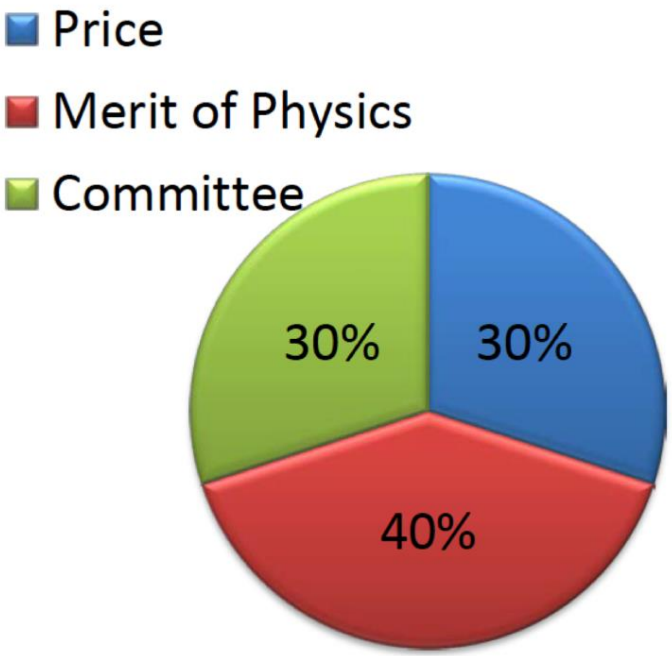


- 170 tonnes of liquid argon (**90 tonnes active**).
- Cathode at -70 kV. E_{drift} ~ 273 V/cm.
- **Maximum drift length: 2.5 m.** Drift time: 2.3 ms.
- Three wire planes to reconstruct 3D interaction. 3 mm wire pitch. **8256 channels.**
- Two induction planes with 2400 wires each at ± 60º from vertical. One collection plane with 3456 vertical wires.
- Cold front-end electronics.
- 2 MHz digitization with warm electronics.



JINST 12 P08003 (2017)

JUNO 20-inch PMTs selection



- Multiple vendors: {A, B, C, …}
- Award fractions of certain combination: $\{\eta_A, \eta_B, \eta_C, \ldots\}$, $\Sigma_i\, \eta_i = 1$
- The best combination of different products was determined by selecting the maximum total score

$$S = \sum_{i \in \{A,B,C,\ldots\}} \left(P_i^{spec} + P_i^{price} + P_i^{committee}\right) \cdot S_i \cdot \eta_i$$

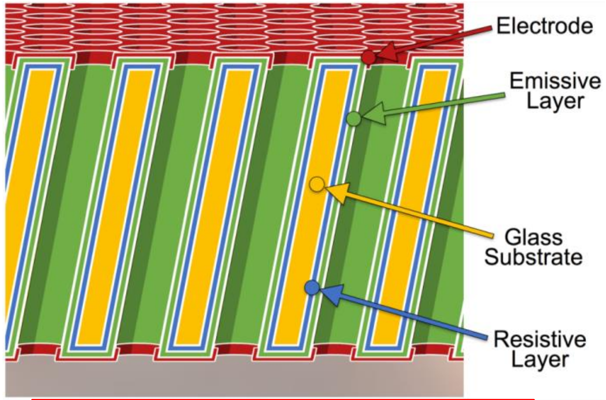
Final Choice in Dec 2015

15k MCP-PMT from NNVT

5k dynode-PMT (R12860-50) from Hamamatsu

Incom MCPs

Glass capillary arrays functionalized in-house with ALD



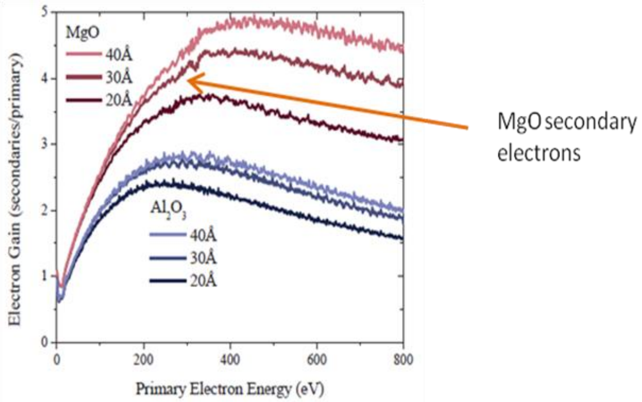
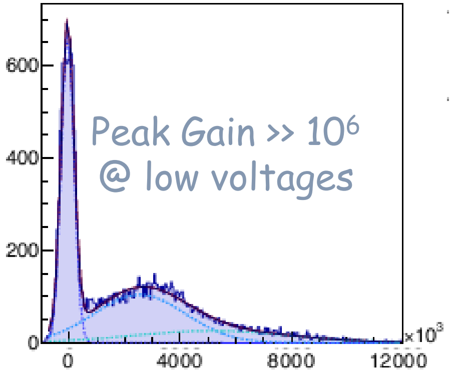
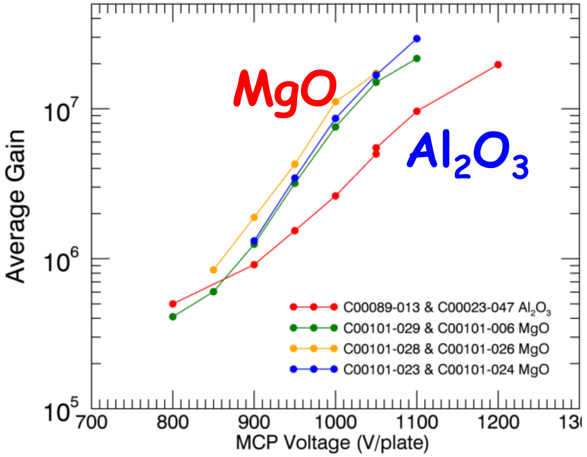


Figure 2. Secondary electron yield from select thicknesses of ALD MgO and Al_2O_3. See Figure 3 for the entire data set.



Gain >10^7



Gain Uniformity in 203mm X 203mm MCP

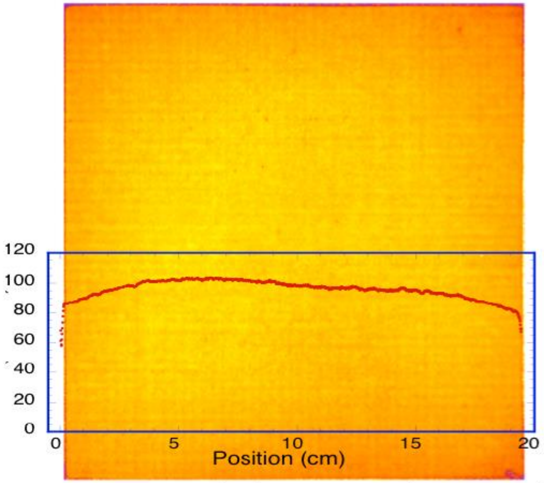


Fig. 8: Average gain image "map" (<15% overall variation). 8" MCP pair 20μm pore, 60:1 L/D ALD-MCP pair. ~7 × 10^6 gain, 0.7mm inter-MCP gap/200V.

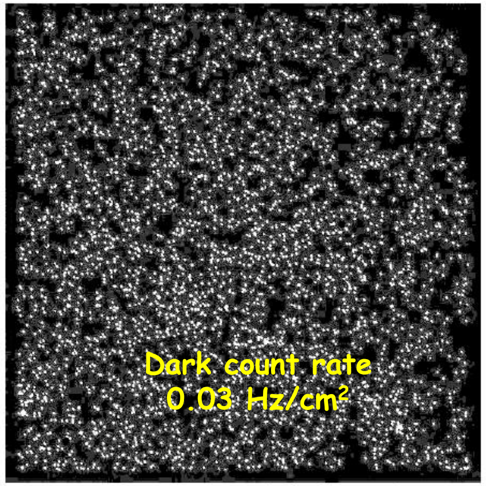
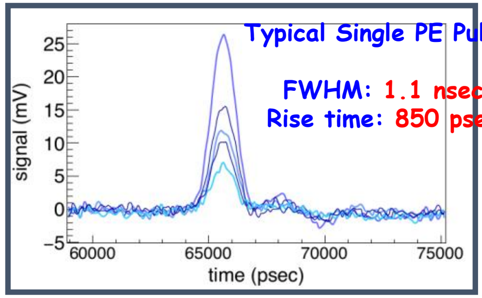
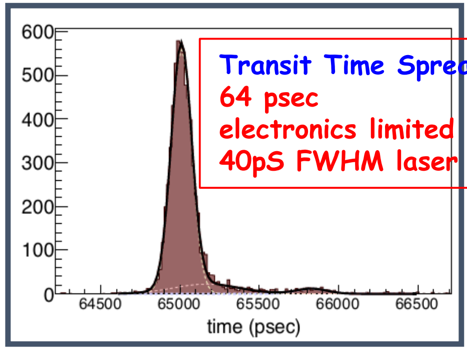
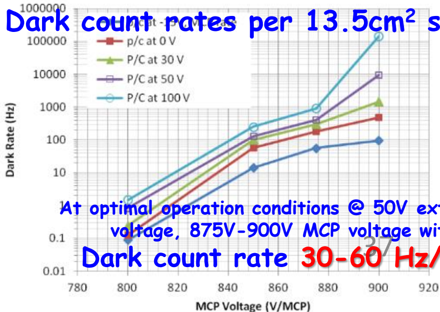


Fig. 9: 20 cm ALD MCP pair background, 500 sec, 0.03 events/cm²/sec[1]. Overall background ~8× better than standard glass MCPs (less K^{40}),





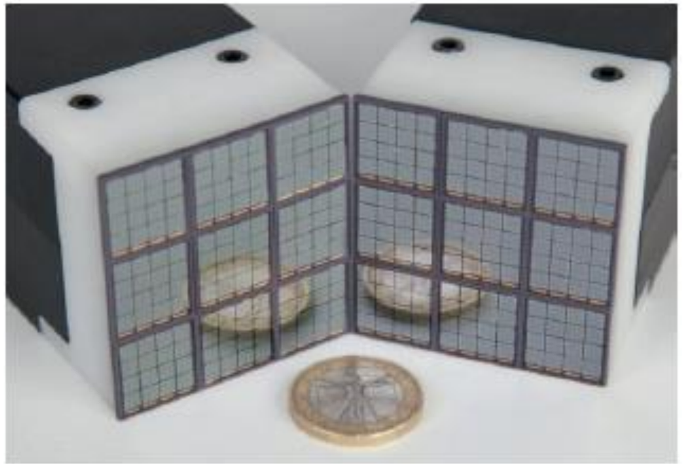
Dark count rates per 13.5cm² strip

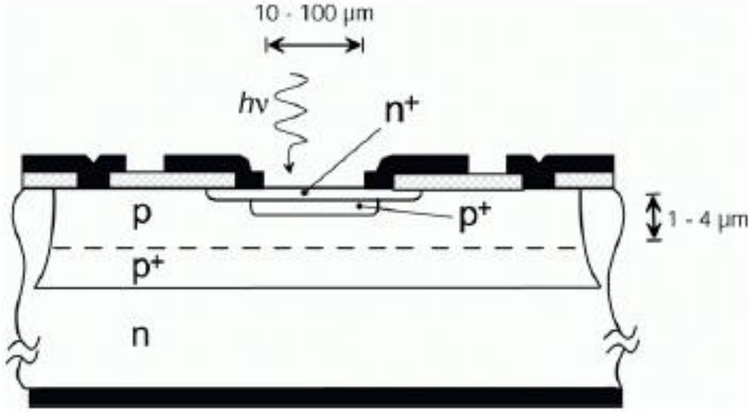


At optimal operation conditions @ 50V extraction voltage, 875V-900V MCP voltage with Dark count rate 30-60 Hz/cm²

MCPs are a separate product line.
Standard dimensions DIA33mm, SQ53mm, SQ60mm, SQ127mm, SQ200mm. Curved MCPs.

SiPM

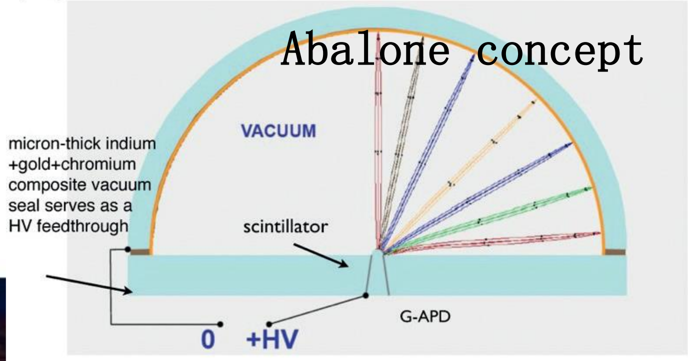


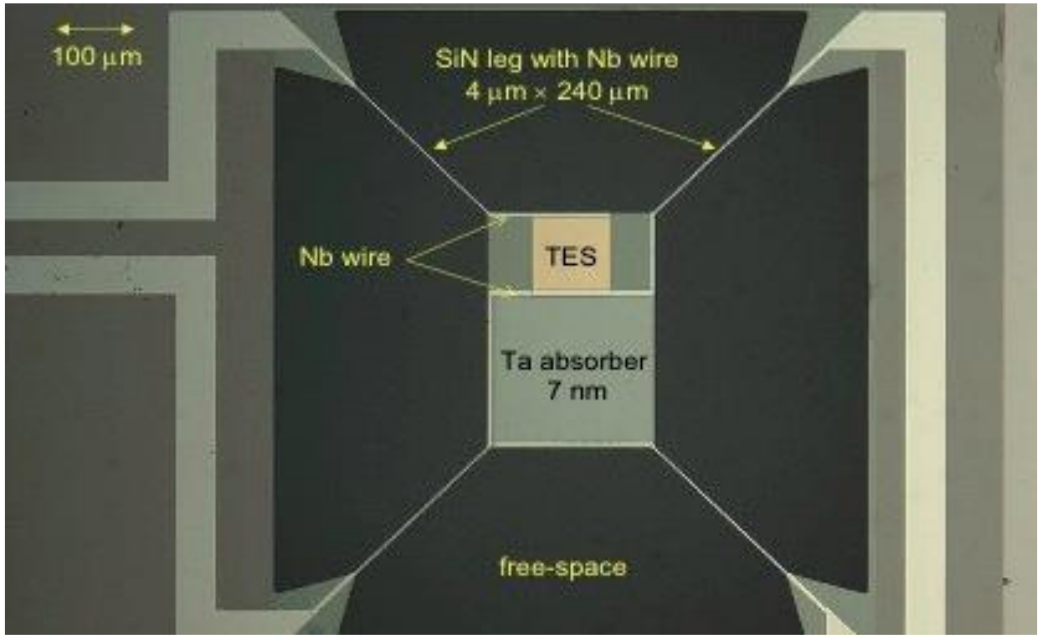


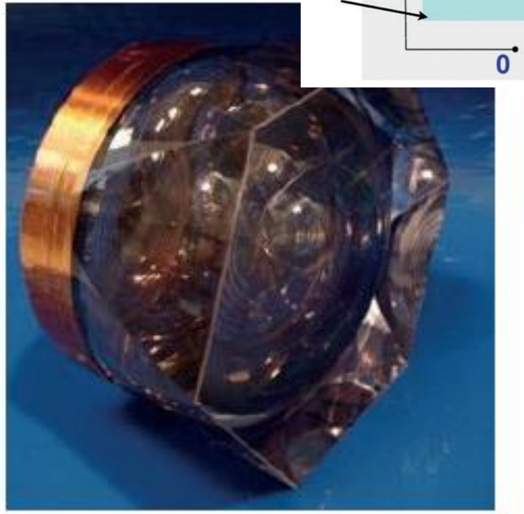
- SiPM are matrices of avalanche photo diodes with a common cathode that are operated in Geiger mode.
  - Operates under a substantially **lower high voltage** than the PMT
  - **Low power consumption**
  - **Not affected by magnetic fields**
  - **Robust**, since it is not affected by light as much as PMTs
  - **Negligible aging effects**, on the contrary to what happens to PMTs
  - **Mass producible** and their **price is fastly decreasing**.
  - **Cross-talk between neighboring photo-cells**
  - **After-pulsing**.

Superconducting transition edge sensors (TES)

- A transition-edge sensor is a thermometer made from a superconducting film operated near its transition temperature.
- It allows to push measurement to the point that quantum effects become the dominant effect limiting the sensitivity of the technique.
  - One design allows the device to obtain low timing jitter, 18.4 ps, and high absorption efficiency 99.9% at 775 nm.
  - **Challenges : to build larger arrays** (tens of thousands of pixels) **while striving for an energy resolution** allowing for the detection of individual photons
  - Superconducting detector readout technology

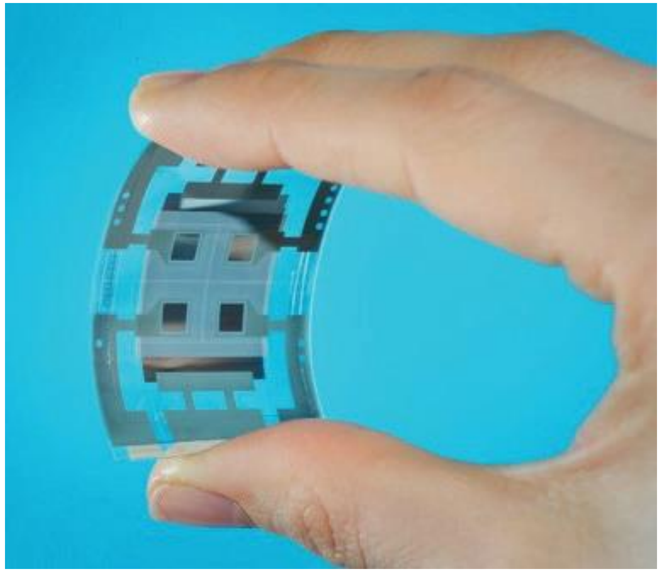


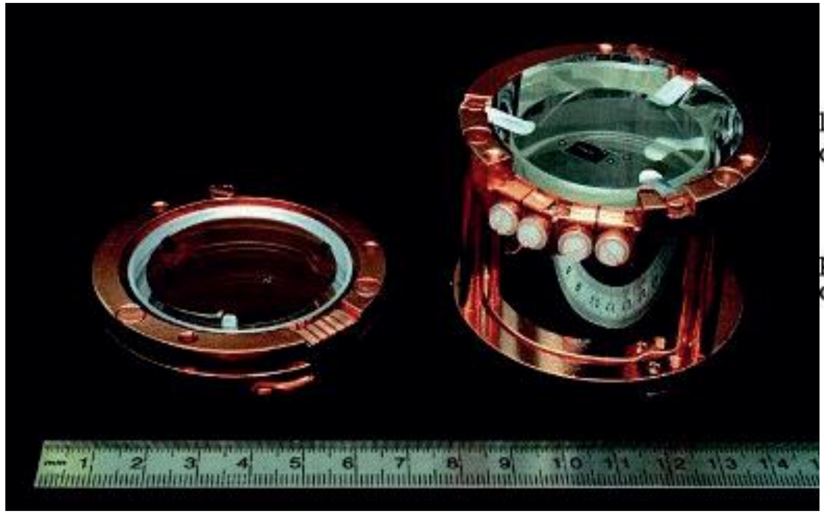




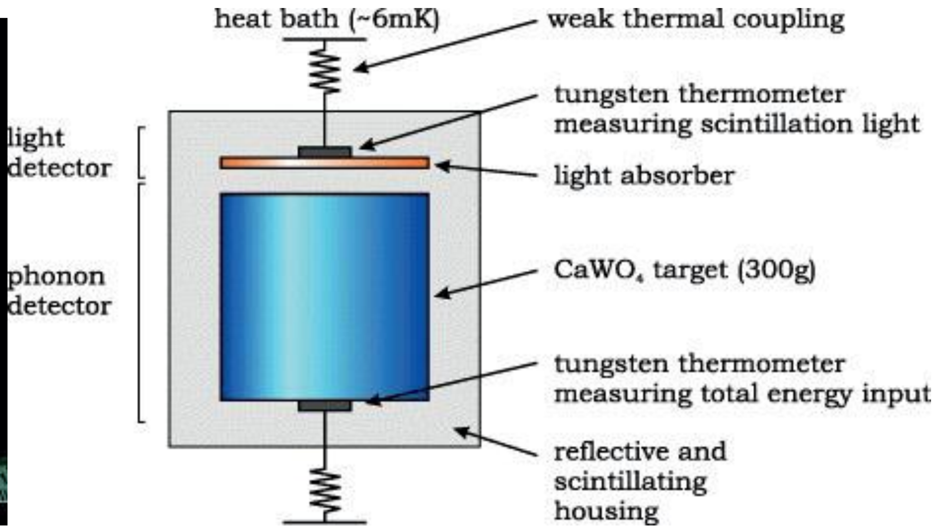
Organic sensors

- These ultra-thin organic sensors – with carbon instead of silicon as material converting light into electrical signals – can be applied to CMOS chips over large and small surfaces, as well as to glass or flexible plastic films.
  - **more sensitive to light** than the conventional silicon versions, with the advantage of **simple and cheap to produce**.





Neganov-Luke light devices



- Calorimetry
  - Imaging Calorimeters
  - Crystal and Homogenous Calorimetry
  - Precision Timing for Calorimeters
    - Picosecond time resolution.
    - Modern image processing technology,
    - Low-cost, high-light-yield, fast and radiation-tolerant organic and inorganic scintillators.
    - Further advances in Silicon Photomultiplier (SiPM) technology
    - Low-cost radiation-tolerant electro-optical transceivers,
    - Continued development of GEANT to match the new information being used in calorimeters

- Micro-Pattern Gas Detectors
  - MPGD Applications
    - Gas Electron Multiplier (GEM), Micro-Mesh Gaseous Structure (MicroMegas,MM), THick GEMs (THGEM), also referred to in the literature as Large Electron Multi-pliers (LEM), GEM-derived architecture (-RWELL), Micro-Pixel Gas Chamber (-PIC),and integrated pixel readout (InGrid) are being optimized for a broad range of applications.
- Silicon Detectors
  - Silicon-based Detectors in Cosmology
    - Astronomical CCD cameras
  - Silicon-based Detectors for Dark Matter Detection
    - CCD arrays to directly search for dark matter
    - Germanium CCDs
    - Si(Li) detectors to indirectly search for dark matter
  - Ionization pixel detectors with integrated-circuit readout
  - Silicon Detectors for Collider Experiments
    - Development of fast timing sensors based on LGADs
    - Monolithic Silicon Pixel detectors (MAPS)
  - 3D Si sensors
  - Substrate engineering
  - 3D integrated IC and small pixel sensors
  - Direct access to industrial vendors and foundry processes