Photon Detection

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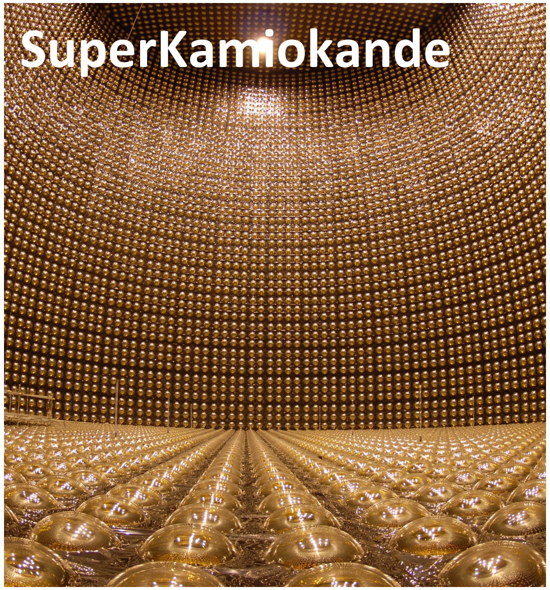
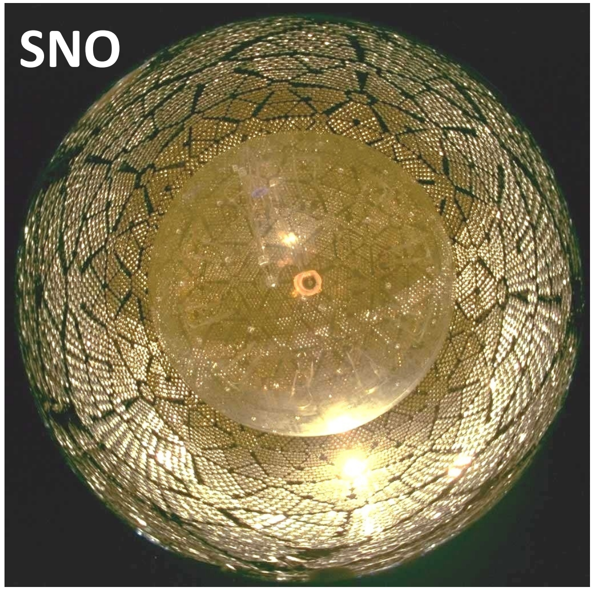
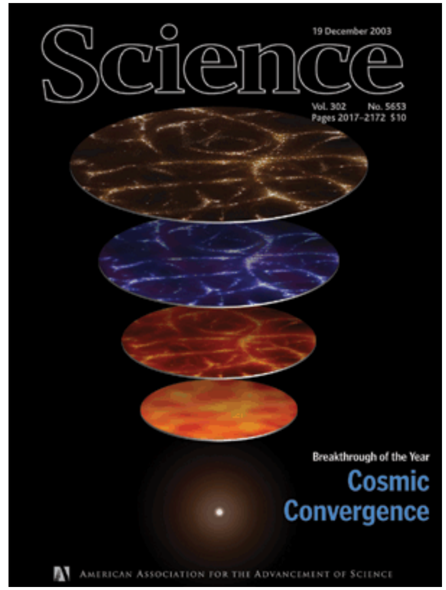
Technology In Particle Physics 2017
Beijing, May 22 – 26, 2017

Photon Detection: Cornerstone of Particle Physics



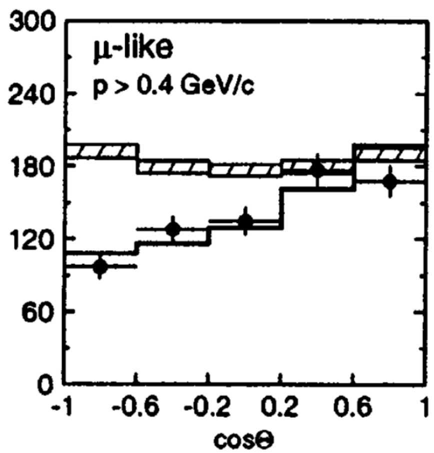




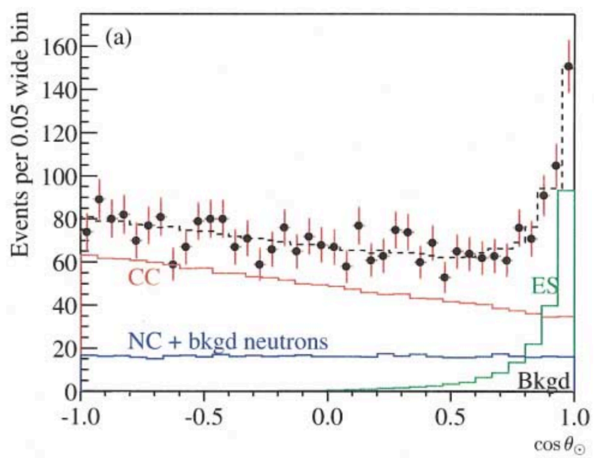
Discovery of neutrino oscillations, SuperK. exp.

Discovery of neutrino oscillations, SNO experiment

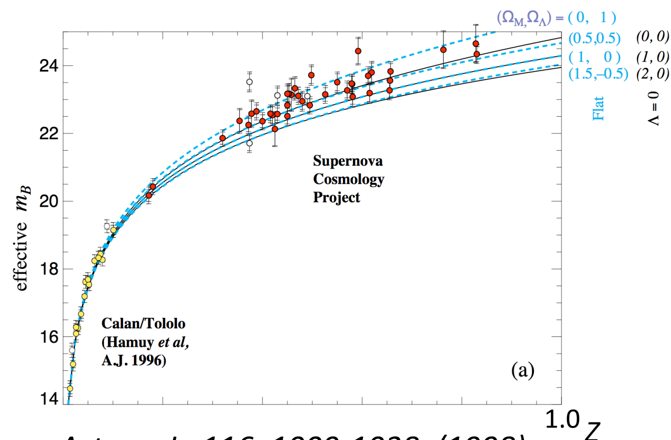
Discovery of the acceleration of the expansion of the universe



Phys. Rev. Lett. 81, 1562 (1998)

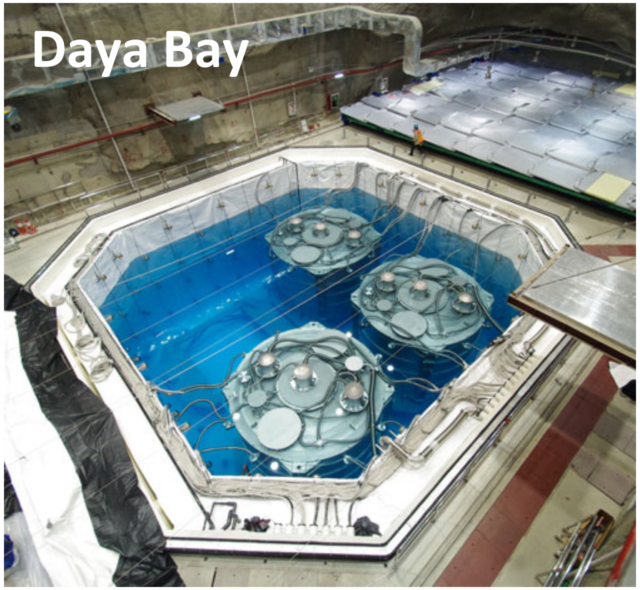


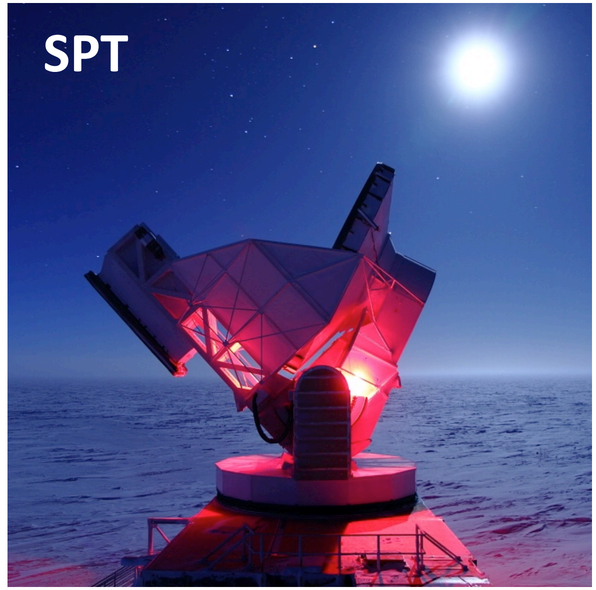
Phys. Rev. Lett. 89, 011301 (2002)



Astron. J., 116, 1009-1038, (1998)
Astrophys. J., 517, 565-586, (1999)

Photon Detection: Cornerstone of Particle Physics

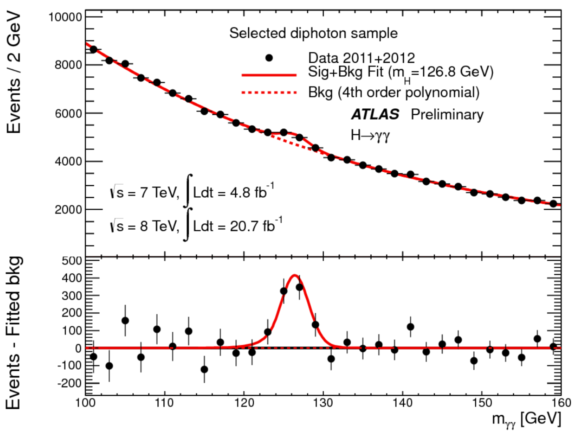


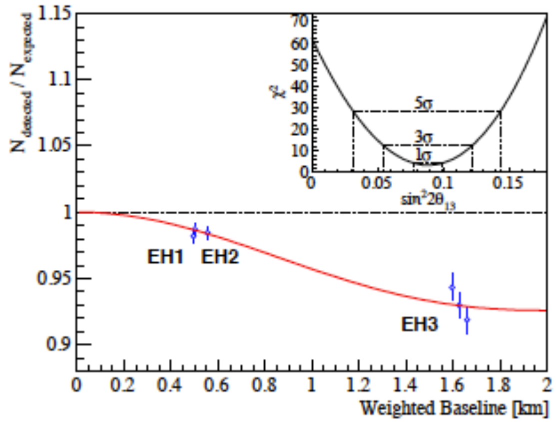


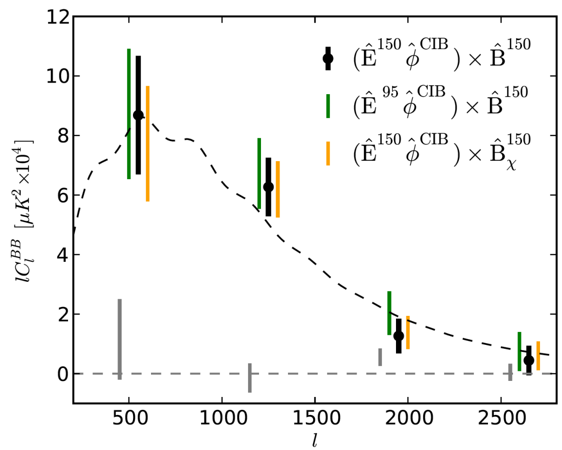
Two experiments at the LHC at CERN observed the Higgs boson

The Daya Bay reactor neutrino expt. measured the ν oscillation parameter $\sin^2\theta_{13} = 0.089 \pm 0.01 \pm 0.005$

The SPT CMB experiment observed B-mode polarization due to gravitational lensing





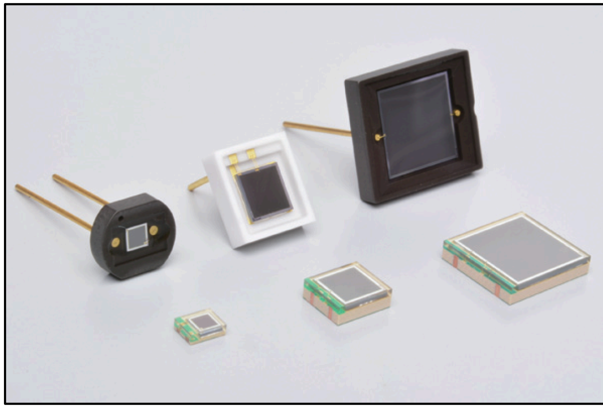


Phys. Rev. Lett. 111, 141301 (2013)

Types of Photodetectors

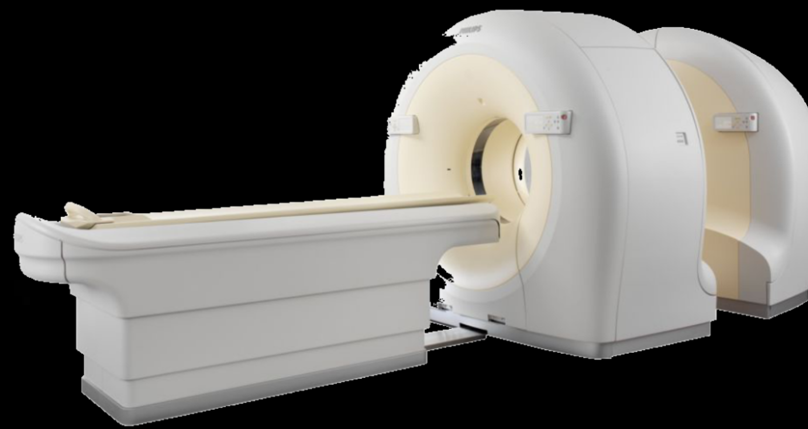
- There are various technologies for photodetectors, with a plethora of types within each technology.

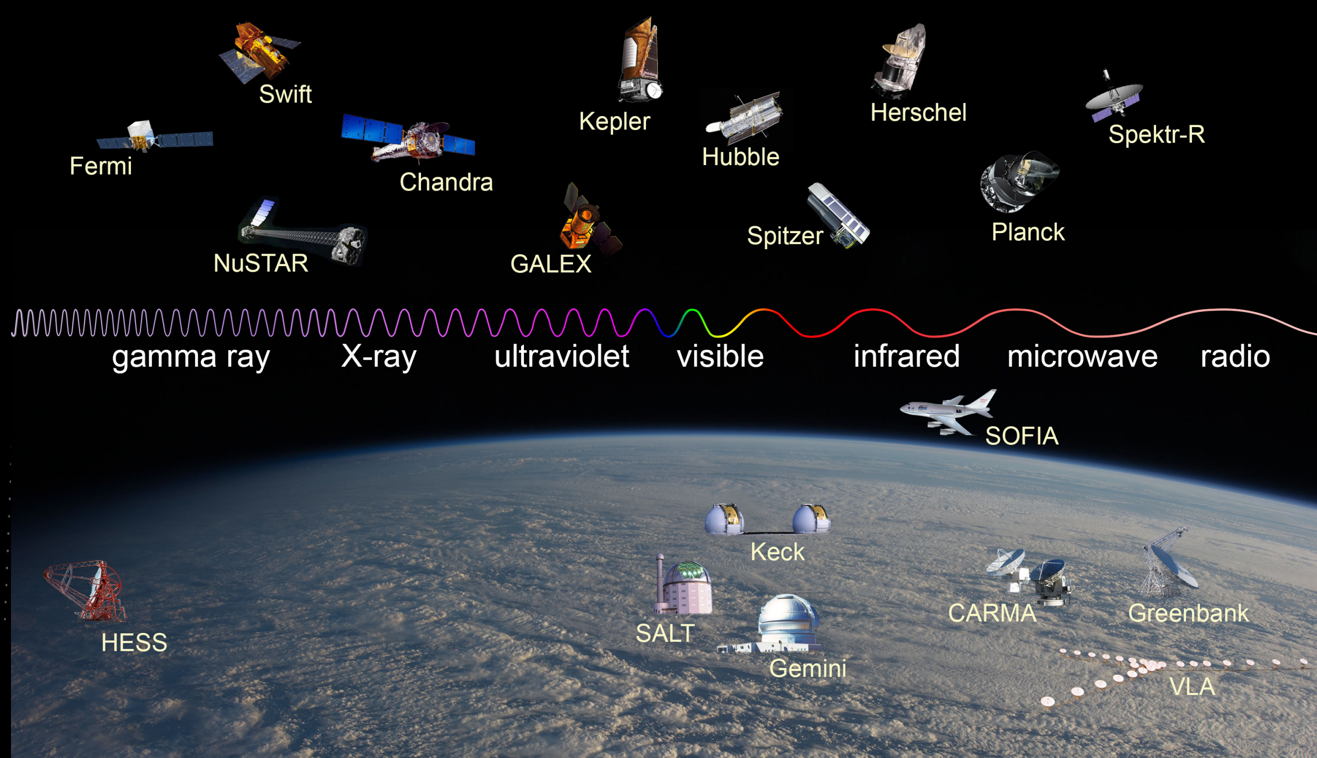
- **Vacuum Photon Detectors**
  - Photo Multiplier Tubes
  - MCP-PMT
  - Hybrid Tubes
- **Solid State Photon Detectors**
  - Silicon-based (MPPC, CCD)
- **Gas-based Photon Detectors**
  - Micro-pattern Detectors
- **Superconducting Photon Detectors**
  - Transition Edge Detectors
  - Kinetic Inductance detectors

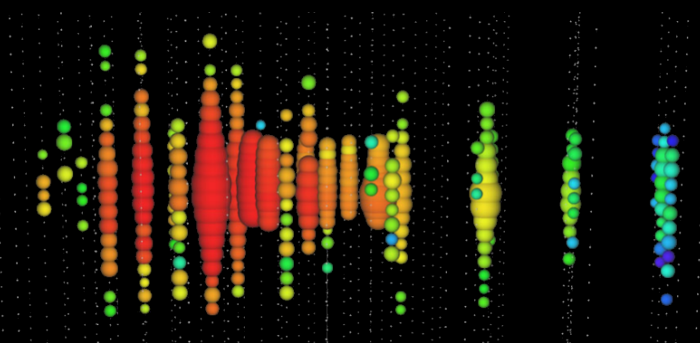


Wide Range of Applications

- Astrophysics
- Astronomy
- Medical Imaging
- Life Science
- Defense
- Fusion
- Process Control
- Oil exploration
- ……





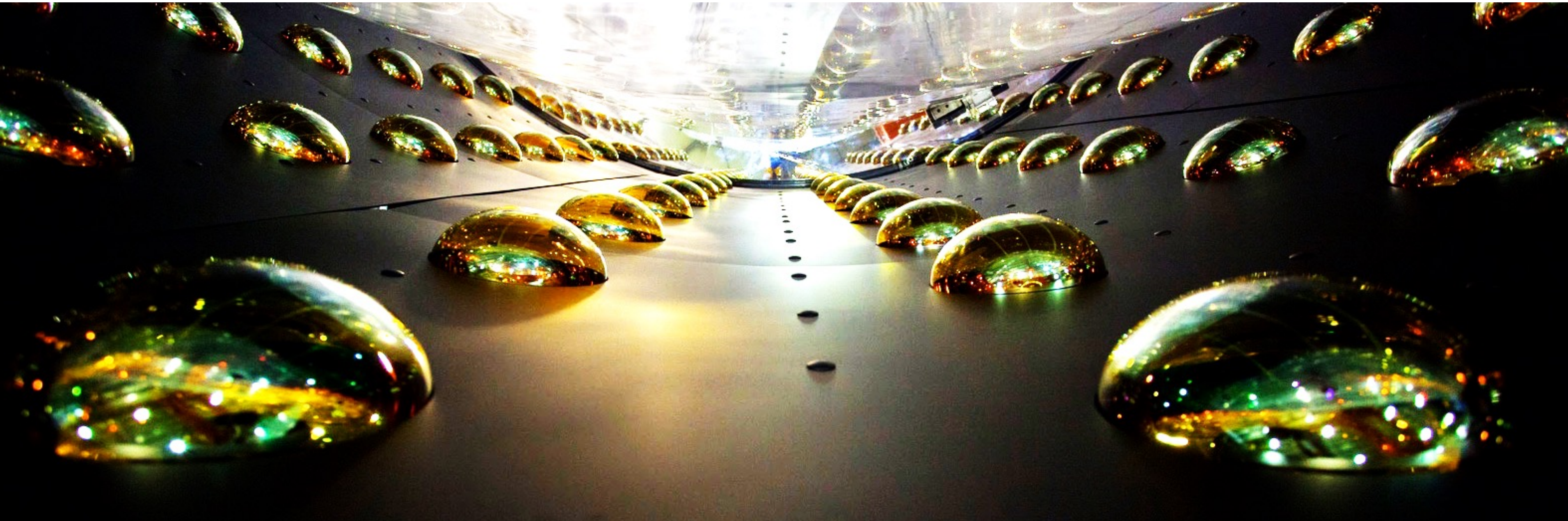


Outline and Disclaimer

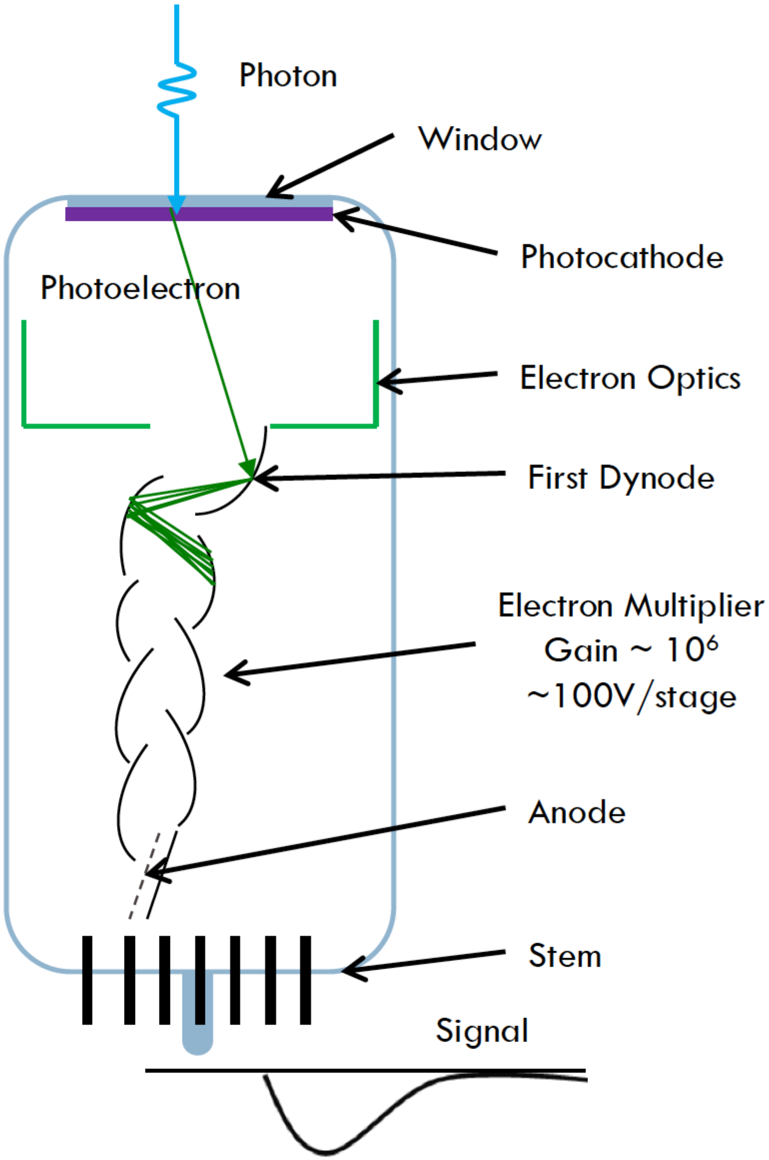
- Vacuum Photon Detectors
  - Discrete Electron Multipliers
  - Continuous Electron Multipliers
  - Hybrid Photon Detectors
- Solid State Photon Detectors
- Gas-based Photon Detectors
- Superconducting Photon Detectors
- Outlook and Conclusions

- This short presentation cannot do justice to the enormous amount of work being carried out in the area of photodetector development.
  The talk reflects mainly the speaker's experience and taste.
  Apologies for all experiments, projects and technologies not mentioned.

Vacuum Photon Detectors

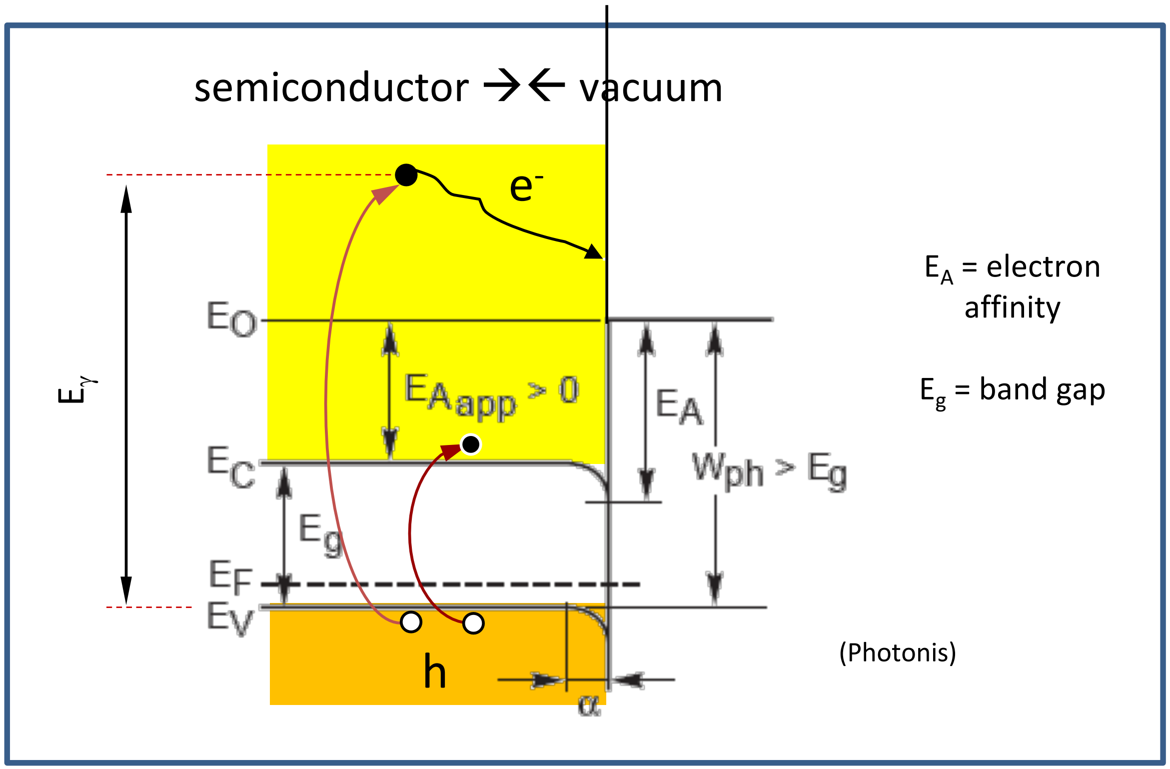


Anatomy Traditional Vacuum PMT



- Traditionally glass vacuum envelope, alternatively metal or metal/ceramic
- Typically the photocathode is processed in-situ
- Vacuum sealed using a glass or copper sealing after processing
- Wide variety of electron optics and discrete dynode structures, often optimized for specific applications
- Relatively low cost of production

Photon Detection Model

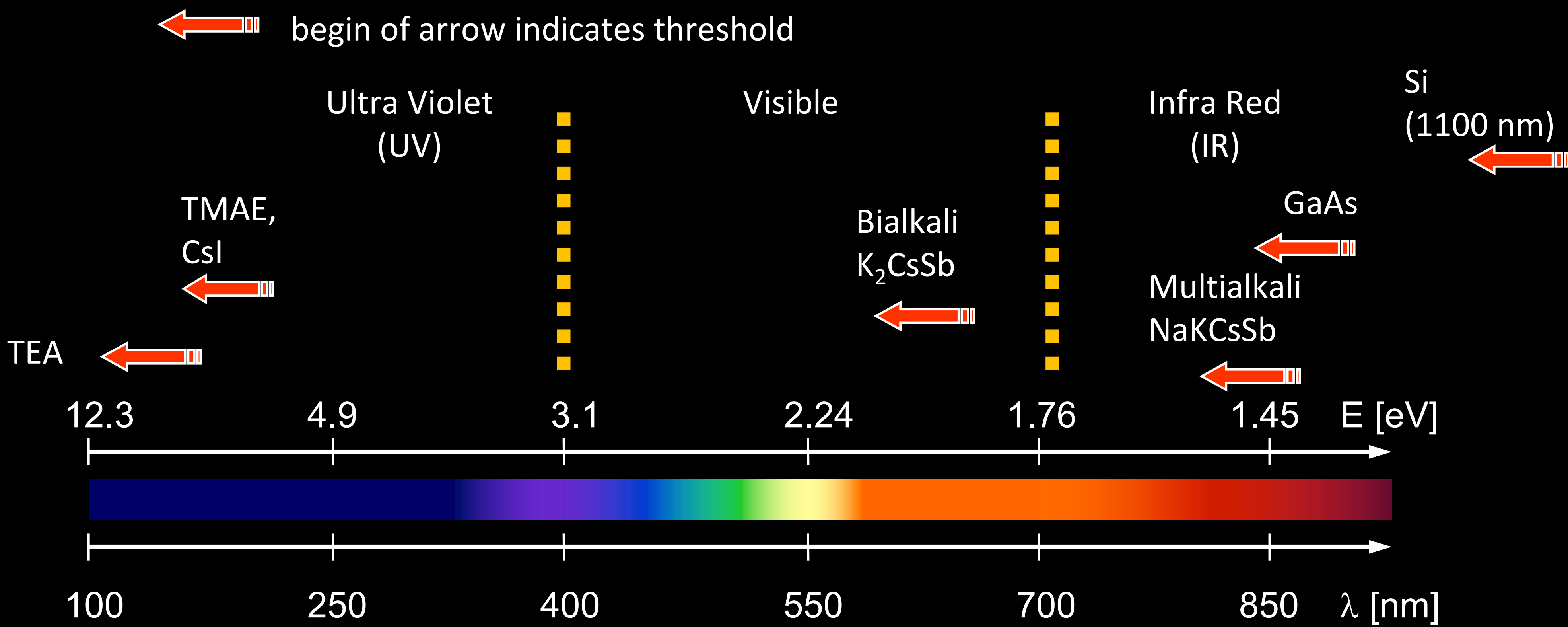


Three-step Spicer model

1. **Excitation**
   - Reflection, Transmission, Interference
   - Energy distribution of excited e^-
2. **Transport to Surface**
   - e^- lattice scattering
   - Mean free path ~100 Å
   - Random Walk
3. **Escape surface**
   - Overcome Electron Affinity

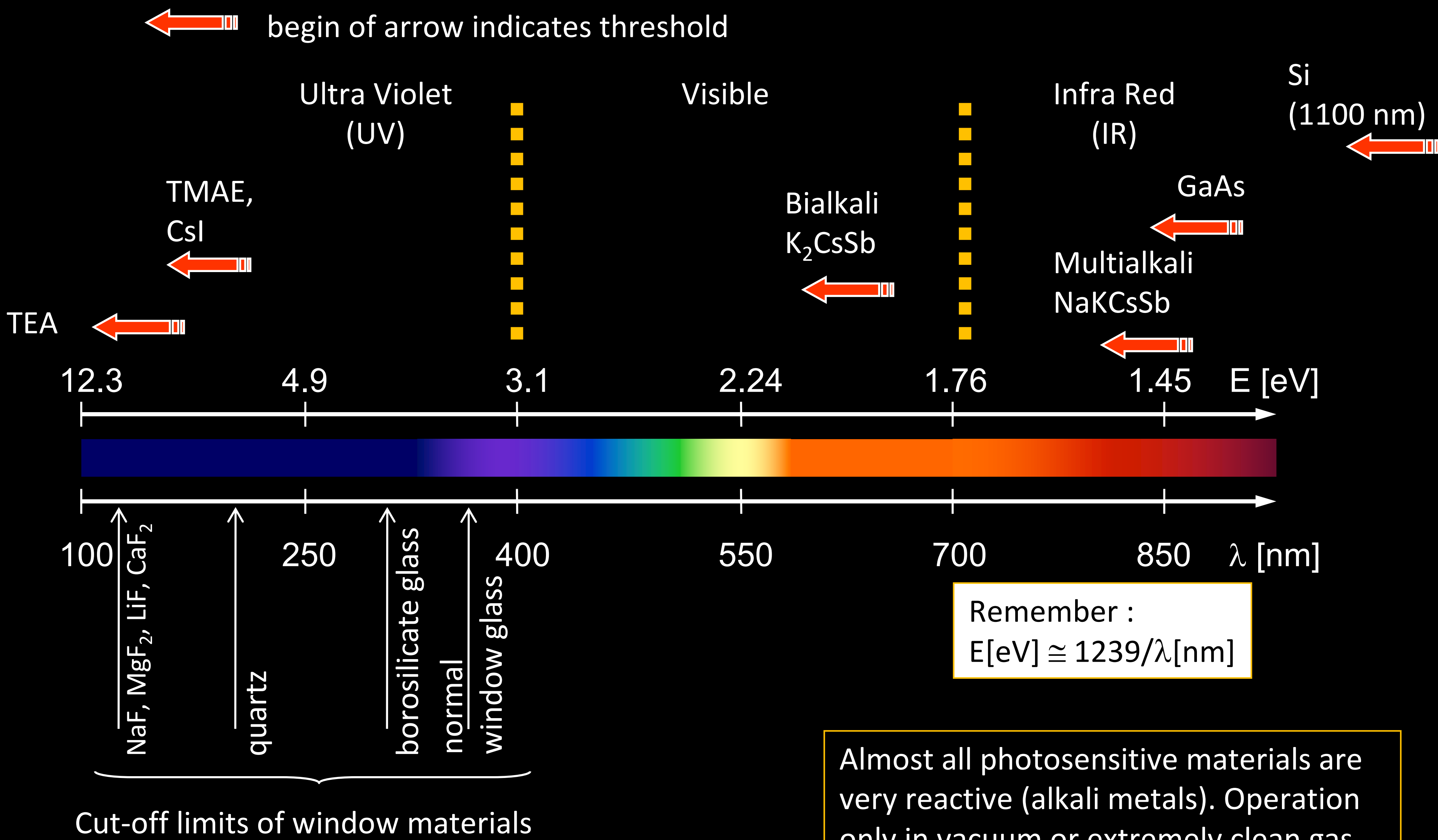
- In a Si-photodiode or a CCD, the electrons create a photo-charge or photo-current internal to the medium and only the first step applies (”Internal Photo-effect”)
- For the ”External Photo-effect”, extraction of the electrons required

Photo-sensitive Materials



Edit School 2011: https://edit2011.web.cern.ch/edit2011/

Photo-sensitive Materials

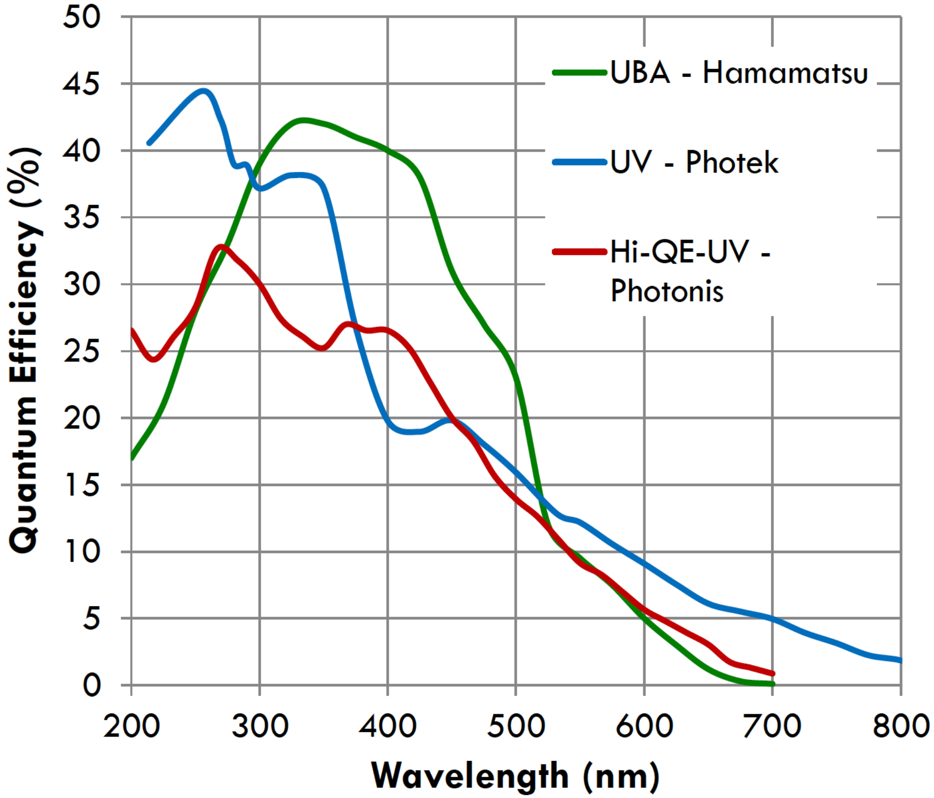


Almost all photosensitive materials are very reactive (alkali metals). Operation only in vacuum or extremely clean gas. Exception: Silicon, CsI.

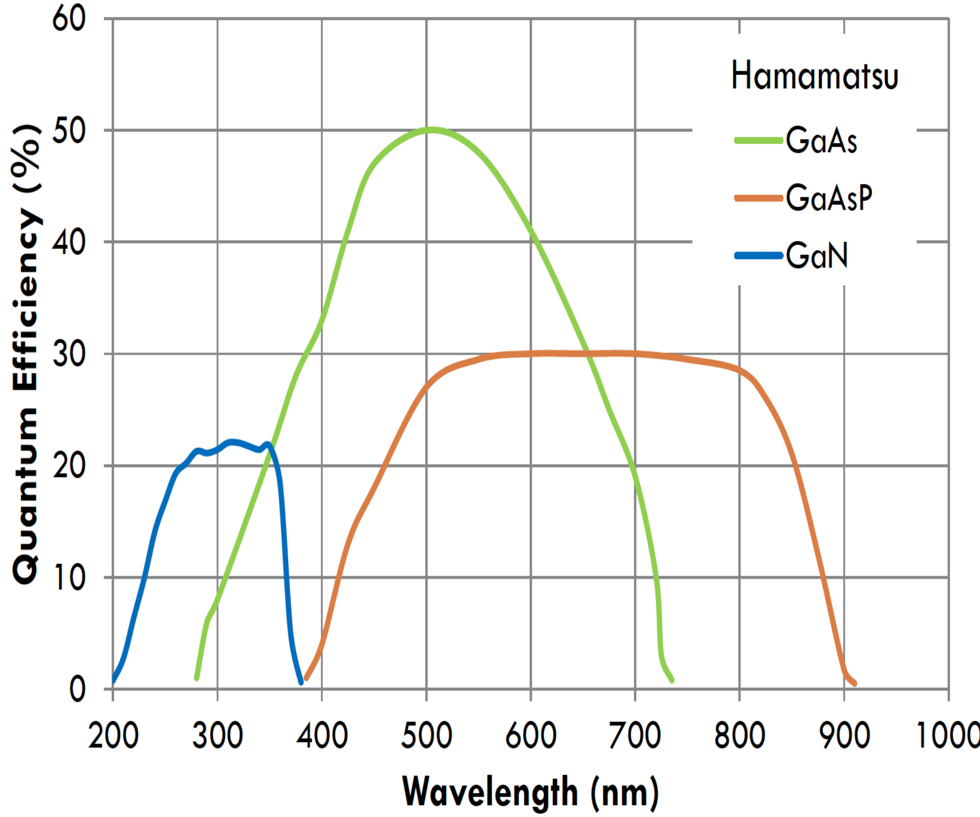
Edit School 2011: https://edit2011.web.cern.ch/edit2011/

Status Photocathodes

UV/Blue Alkali-Antimonide Transmission Photocathodes



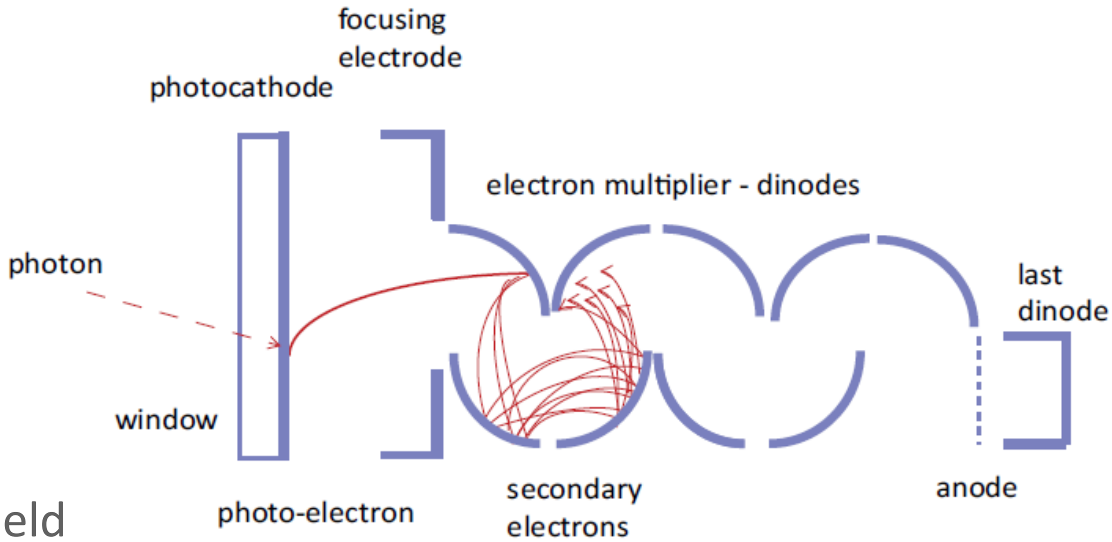
UV/Blue III-V Transmission Photocathodes



- Alkali Antimonides:
  - Cs_3Sb
  - K_2CsSb
  - Na_2KSb
  - Rb_2CsSb
  - $Na_2KSb:Cs$
- III-V Semiconductors:
  - GaAs – VIS/NIR
  - InP/InGaAs – NIR/SWIR
  - GaAsP – VIS
  - GaN – UV

Discrete Dynodes

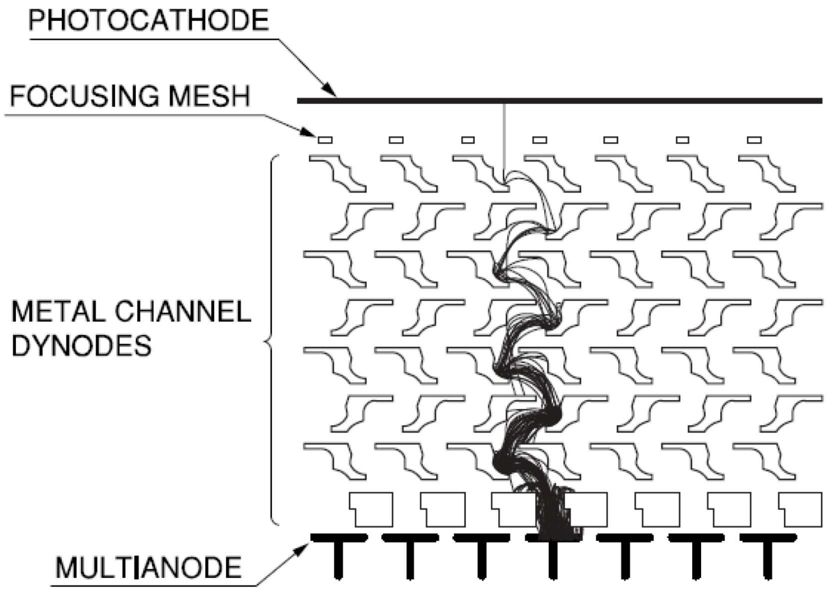
- Dynodes form the amplification stage of the PMT
- Many different types of discrete dynodes:
  - Circular-cage; Box-and-grid; Linear-focused; Venetian blind; Mesh; Metal channel
- The metal dynodes are processed to have high secondary electron yield
  - Alkali antimonide, BeO, GaP, Diamond
  - First dynode often processed for higher SEY, for better detection efficiency and SNR

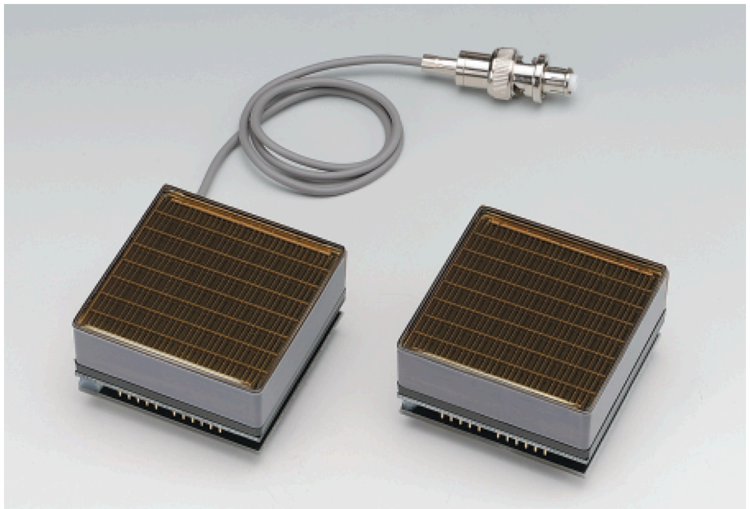


Dynode Type	Rise Time (ns)	Fall Time (ns)	Pulse Width (ns)	Electron Transit Time (ns)
Linear-focused	0.7 to 3	1 to 10	1.3 to 5	16 to 50
Circular-cage	3.4	10	7	31
Box-and-grid	to 7	25	13 to 20	57 to 70
Venetian blind	to 7	25	25	60
Fine mesh	2.5 to 2.7	4 to 6	5	15
Metal channel	0.65 to 1.5	1 to 3	1.5 to 3	4.7 to 8.8

http://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE.pdf

Discrete Dynodes





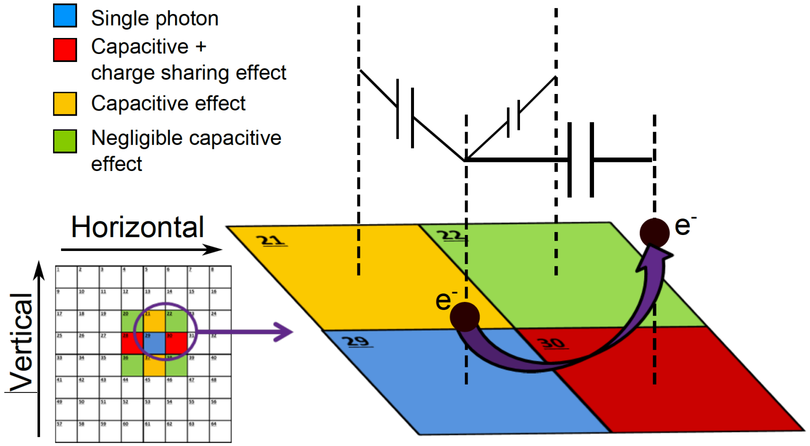
Metal Channel

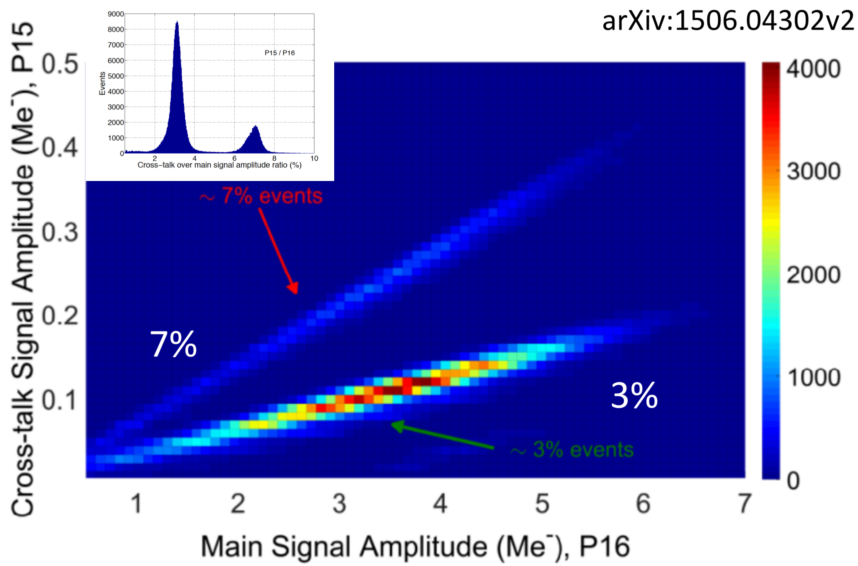
- Compact form factor
- Square format enables close packing
- Segmented readout: multi-anode options at few mm scale
- Good timing characteristics

Hamamatsu: PMT 12700

- 52 x 52mm^2, 87% effective coverage
- 64 (8x8) channels
- pixel size 6 x 6 mm^2
- 10 dynodes, metal foil type
- Bialkali cathode, max 33% quantum efficiency @ 350nm

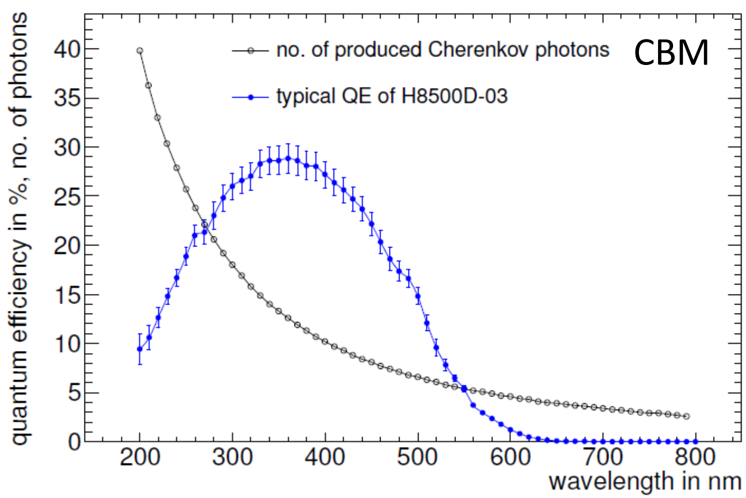
Metal Channel Multi-Anode PMT

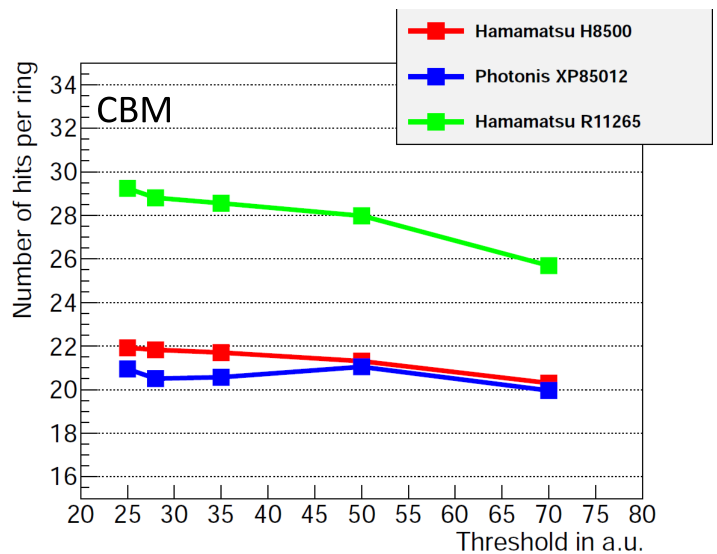




- Many characteristics to evaluate for specific application: charge sharing and capacitive coupling; overall efficiency

CBM RICH:
CO_2 gas, length 1.7 m
n = 1.00045 at 600 nm,
γ_{thr} = 33.3, p_{thr} =4.65 GeV/c

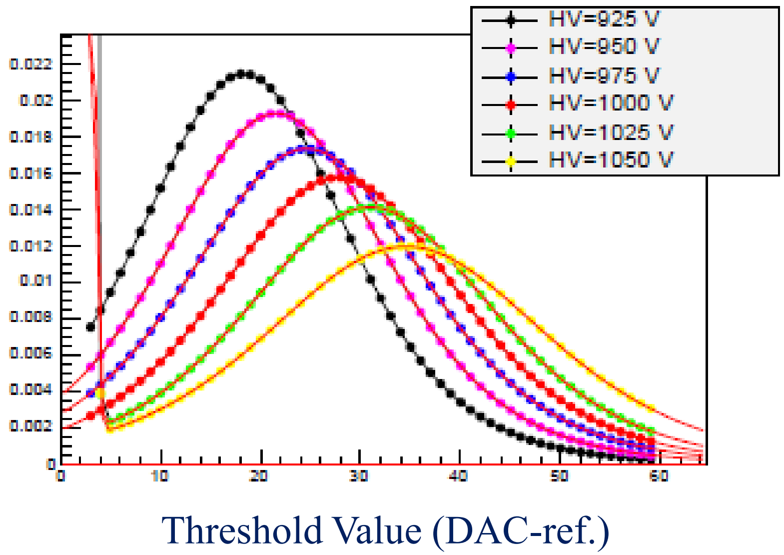


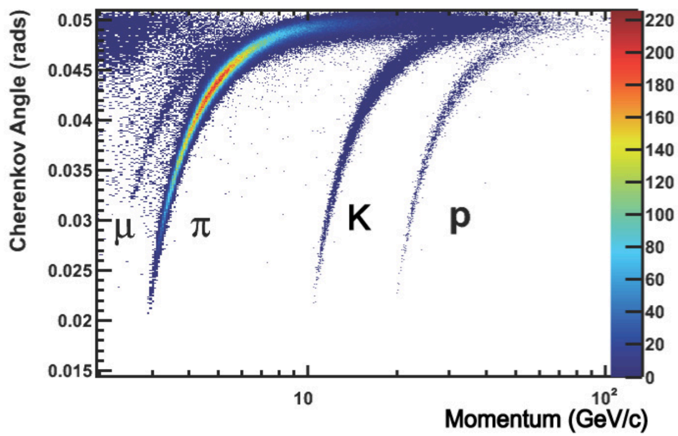


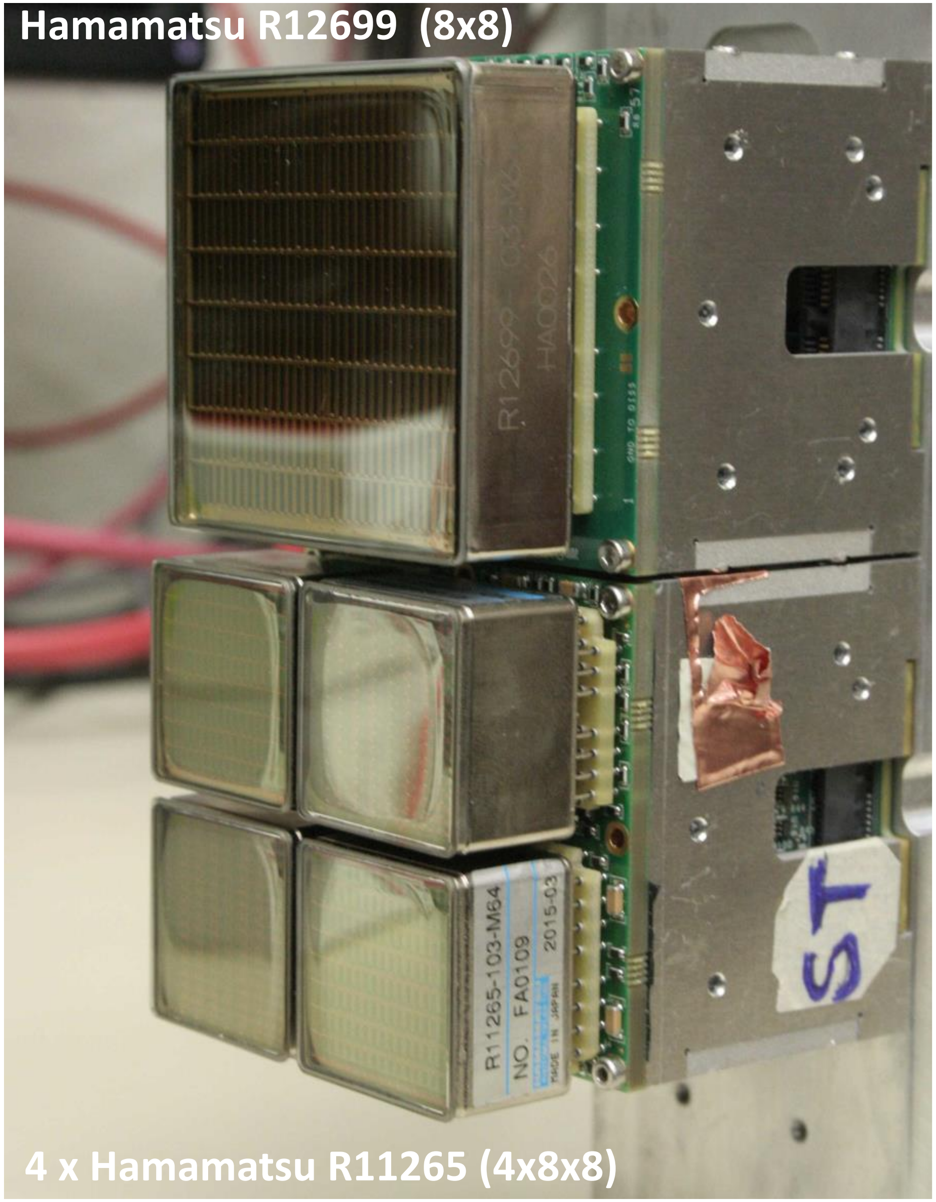
https://indico.gsi.de/getFile.py/access?contribId=4&sessionId=1&resId=0&materialId=slides&confId=2632

LHCb Upgraded RICH

- Upgrade of the LHCb Rich Imaging Cherenkov detector employs MA-PMTs



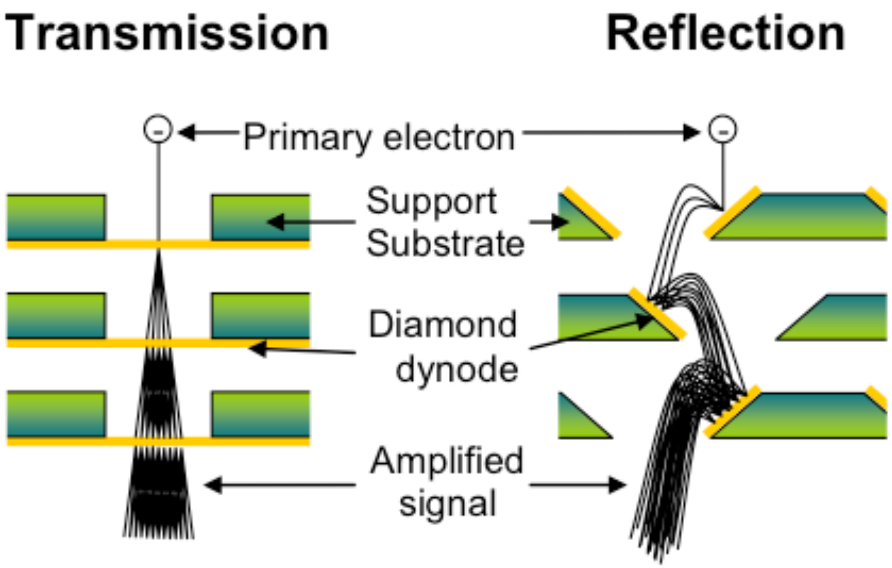


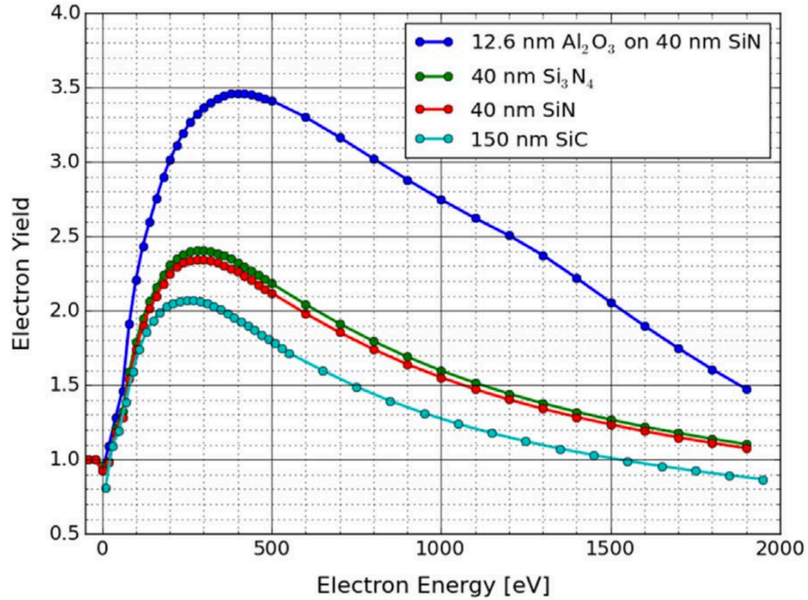


PoS(ICHEP2016)298

Novel Discrete Dynodes

- With the advent of new materials science techniques and IC integration technologies, intriguing new designs can and are being pursued

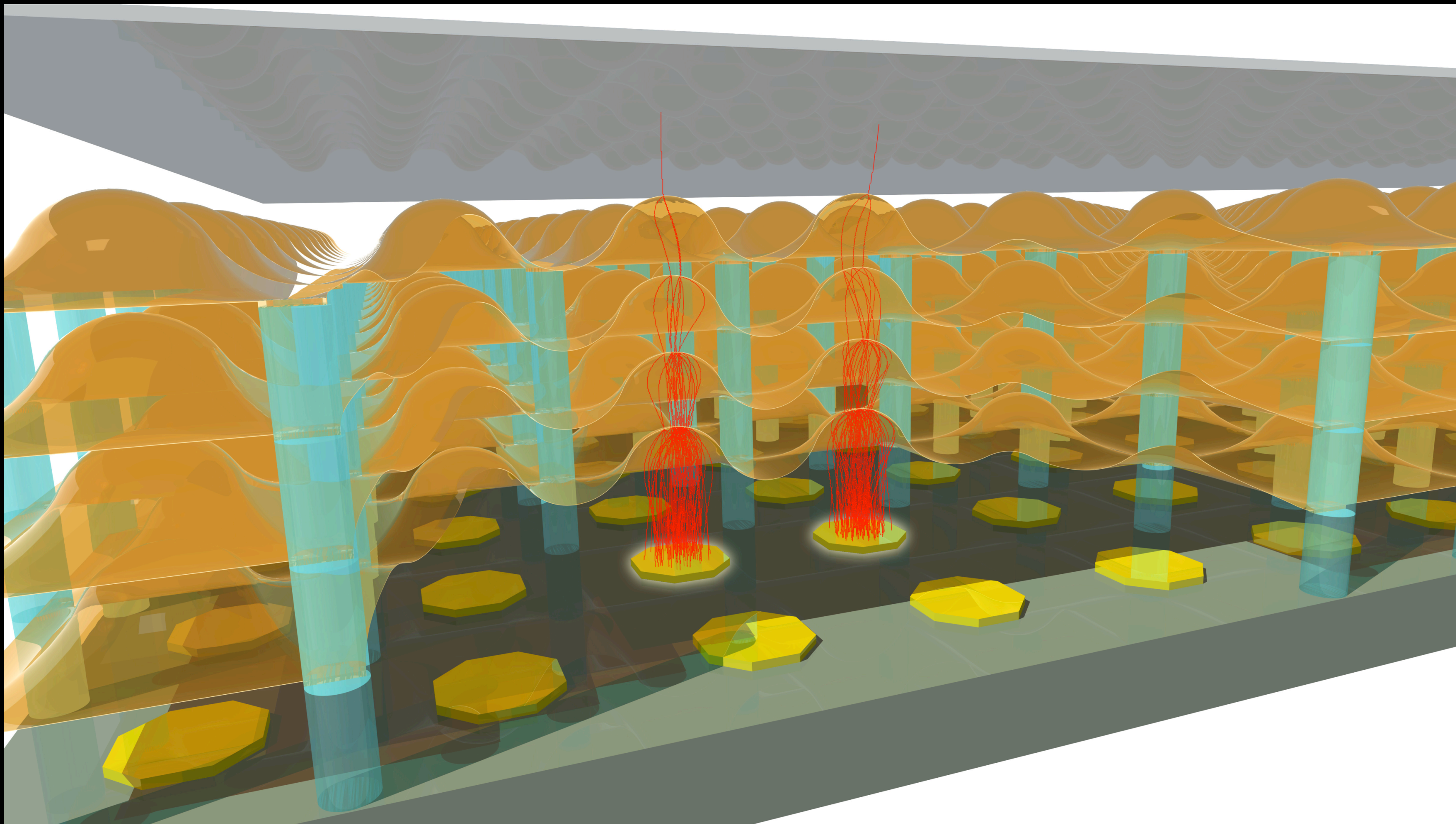




NIM A, (847), 1 March 2017, Pages 148–161

- Transmission dynode (Tynode) of various materials (Si_3N_4, SiC, Al_2O_3,SiN)
- Possibility for fewer (t)dynodes, very fast time response, low dark count, better radiation hardness
- Spatial resolution determined by CMOS pixel granularity (55 µm x 55 µm)
- Strong electric field between dynodes, however

Timed Photon Counter (TIPC)

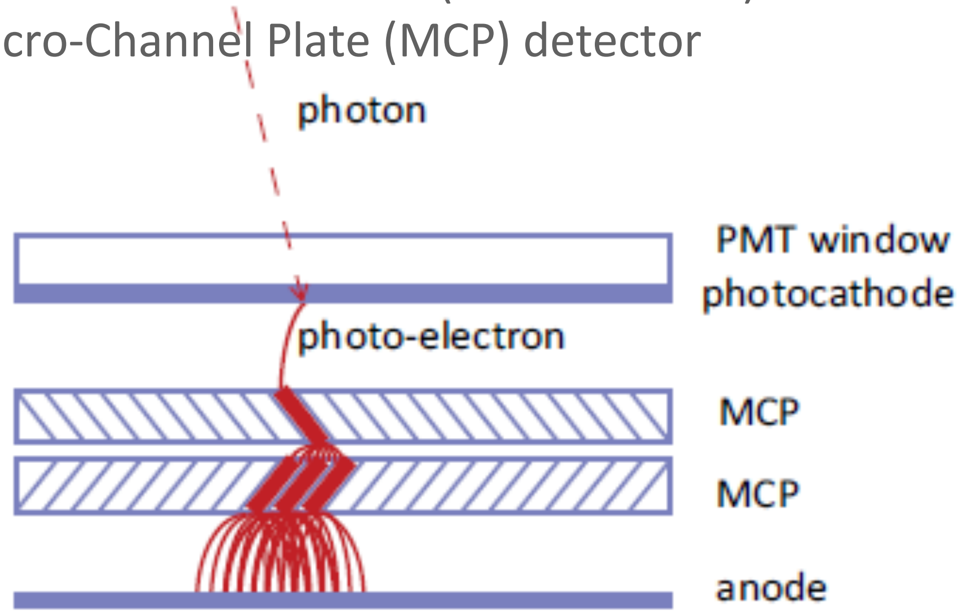


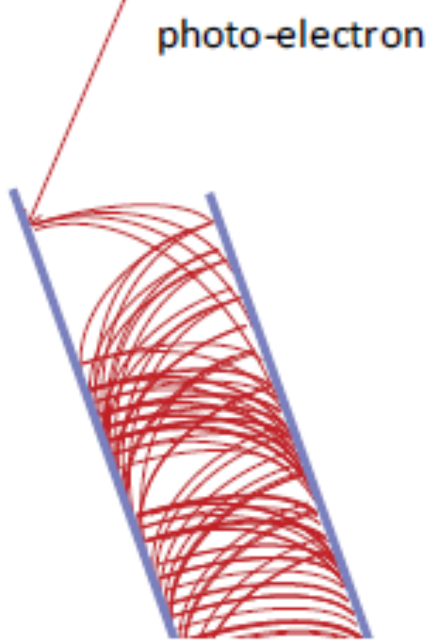
- Combination of MEMS technology for membrane fabrication, materials science techniques for dynode fabrication and IC integration technology to integrate the front-end readout circuit.

Harry van der Graaf, this conference

Channel Electron Multiplier Photodetector

- Most common channel (or continuous) electron multiplier photodetector is the Micro-Channel Plate (MCP) detector





- Conventional MCP based on **lead-glass**:
  - Glass is chemically etched leaving a glass capillary array (GCA)
  - The CGA is hydrogen fired to produce a PbO resistive surface layer
  - Further processing provides alkali rich silica emissive layer with SEY of 2 – 3
  - Diameter/pitch of pores ranges from 2/3 – 25/32µm, typically 10/12µm
  - Length to Diameter ratio (L:D) of pores from 40 – 120, typically 60:1 for 10 µm pores
  - Transit time decreases with decreasing pore size – smaller pores have better timing

Channel Electron Multiplier Photodetector

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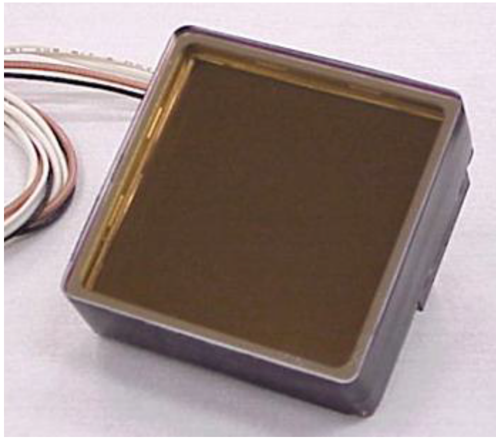
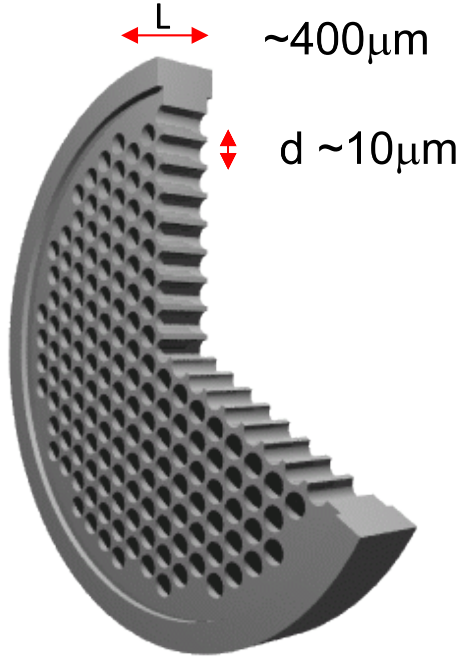


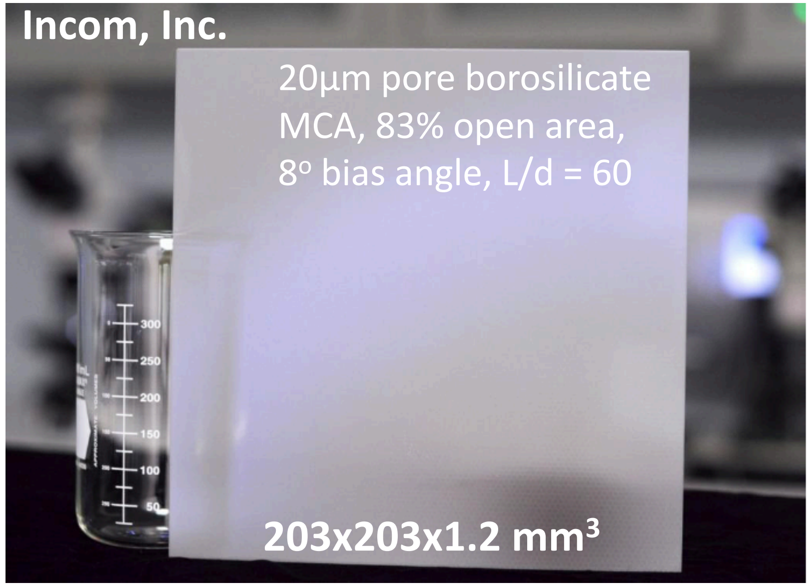
Photonis Planacon
53mm x 53mm, 8x8
25 μm pore, L/d = 40



- Conventional MCP-PMT:
  - Very good time resolution
  - Lifetime limitations due to ion feedback and poisoning of photocathode
  - Relatively expensive
  - Multiple functionalities all incorporated in substrate
- **Considerable developments due to new available techniques**

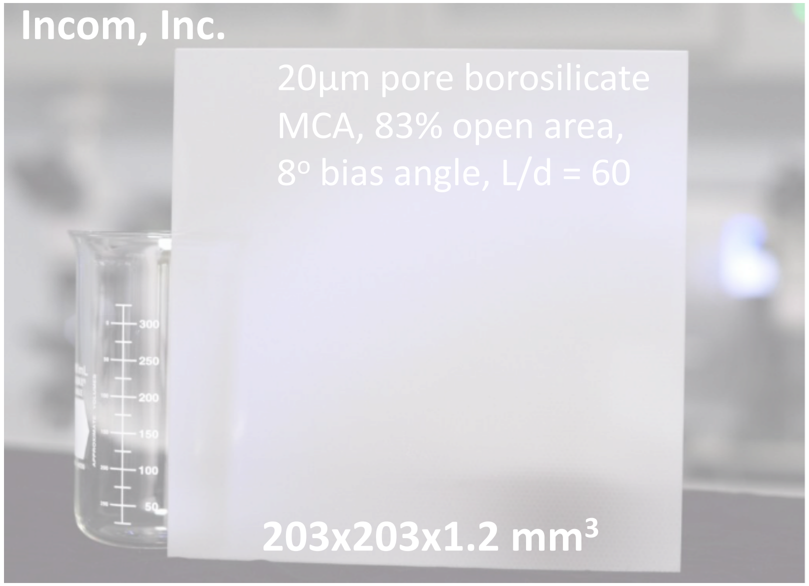
CEM Photodetector Developments

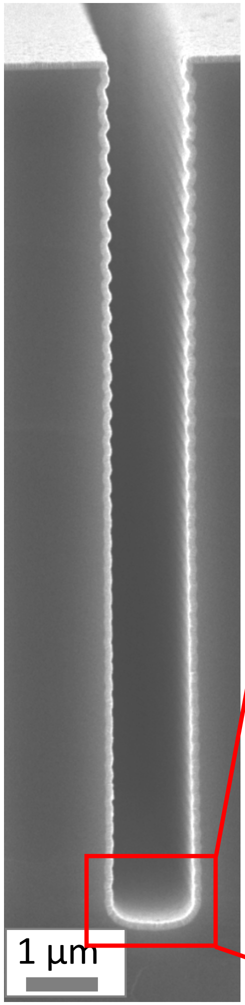
- Replacement of lead-glass with fused borofloat glass capillary arrays (GCA)
  - More cost-effective
  - Enables large areas

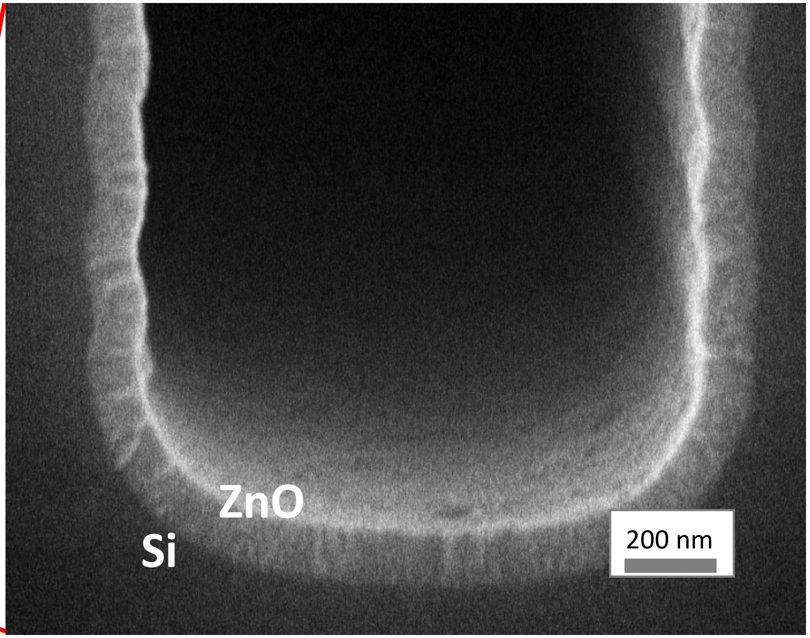


CEM Photodetector Developments

- Replacement of lead-glass with fused borofloat glass capillary arrays (GCA)
  - More cost-effective
  - Enables large areas
- Application of Atomic Layer Deposition (ALD) Process: *a sequential saturated self-limiting surface reaction, which enables growth atomic layer by atomic layer*
  - Low Temperature Fabrication
  - No Line-of-Sight Dependence
  - In principle, full control over MCP parameters



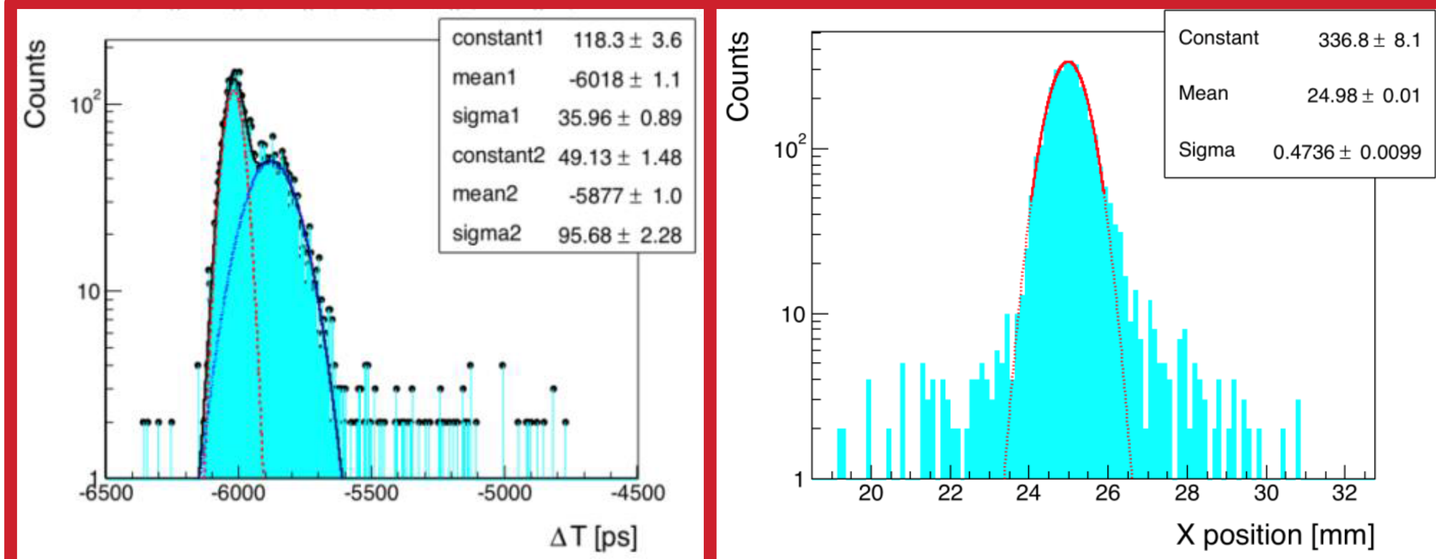




6-cm MCP-based Photon Detectors

- Small form-factor (6cmx6cm) MCP-based photo detector development at Argonne with stripline readout
- Glass capillary arrays undergoing ALD process in-house
- 20 μm pores, L/D = 60, MCP thickness 1.2mm, 8-degree bias angle

Timing and Position Resolution



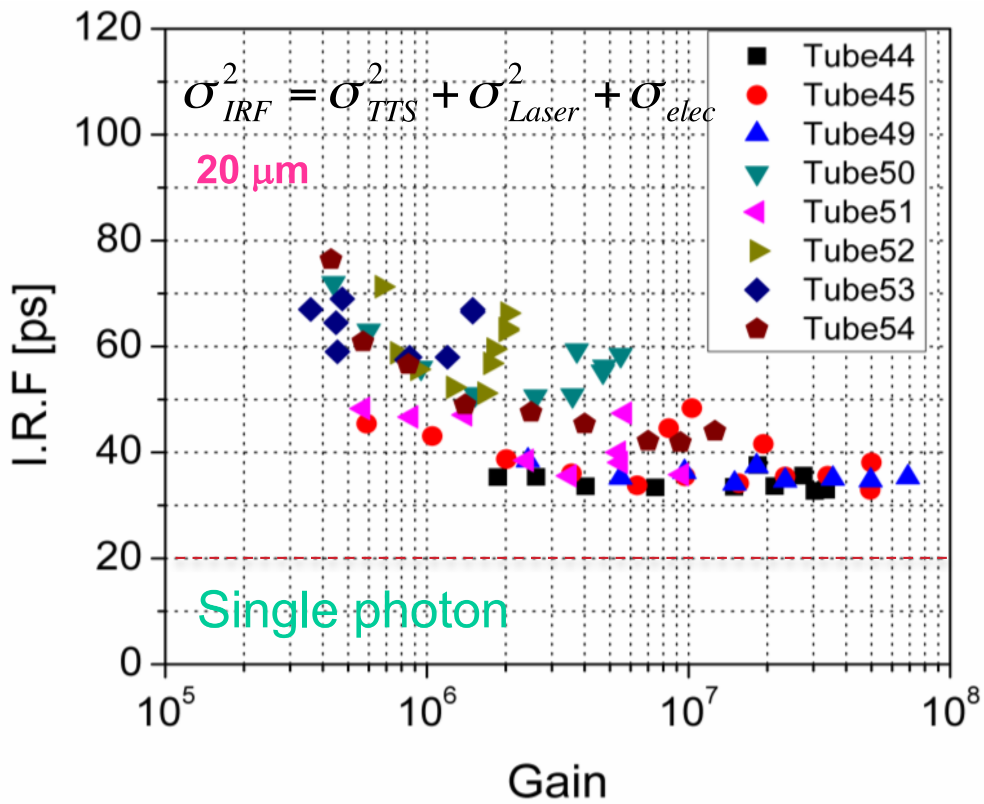
σ_{IRF}~35 ps (SPE)

σ < 1 mm (SPE)
σ_{TTS} ~ 20 ps

Junqi Xie, this conference

IRF = Instrument Response Function
TTS = Transition Time Spread

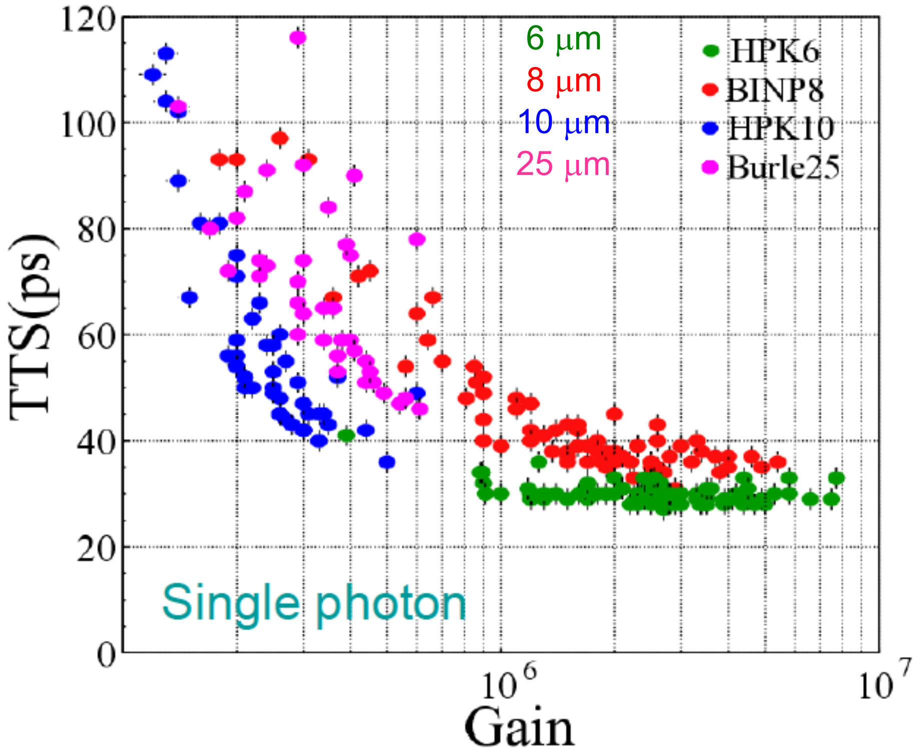
6-cm MCP-based Photon Detectors



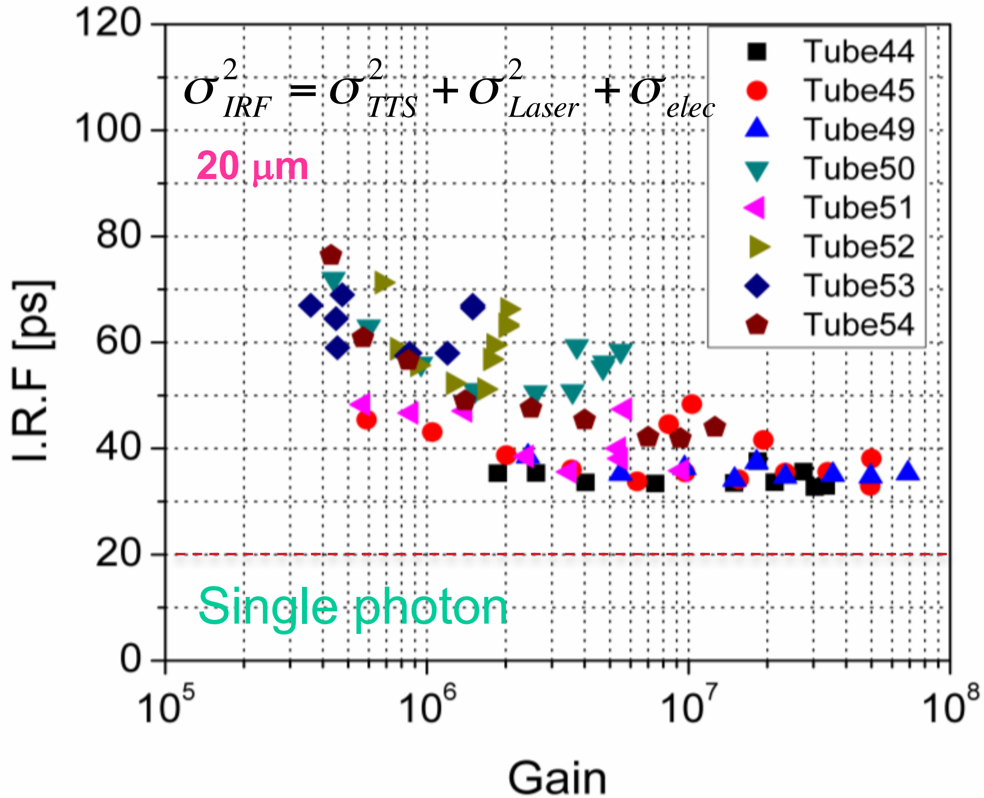
Performance of non-optimized tube

- **Significant room for improvement through optimization of geometry**

6-cm MCP-based Photon Detectors



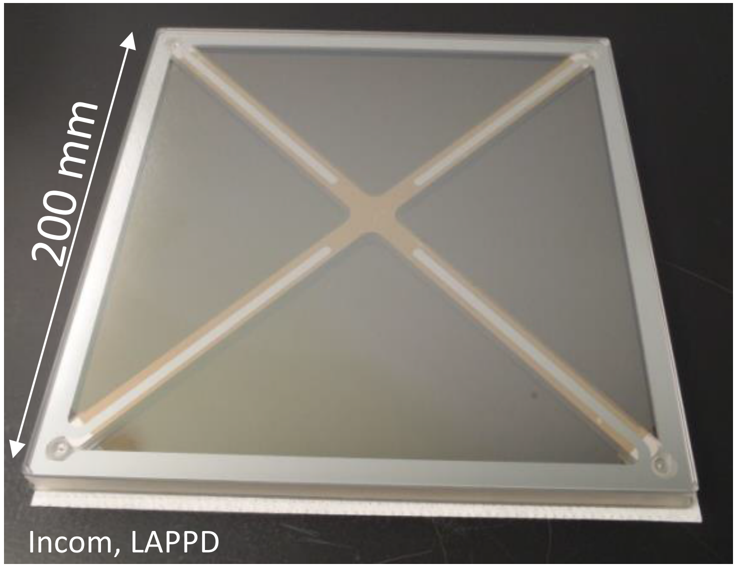
As measured by the Nagoya group



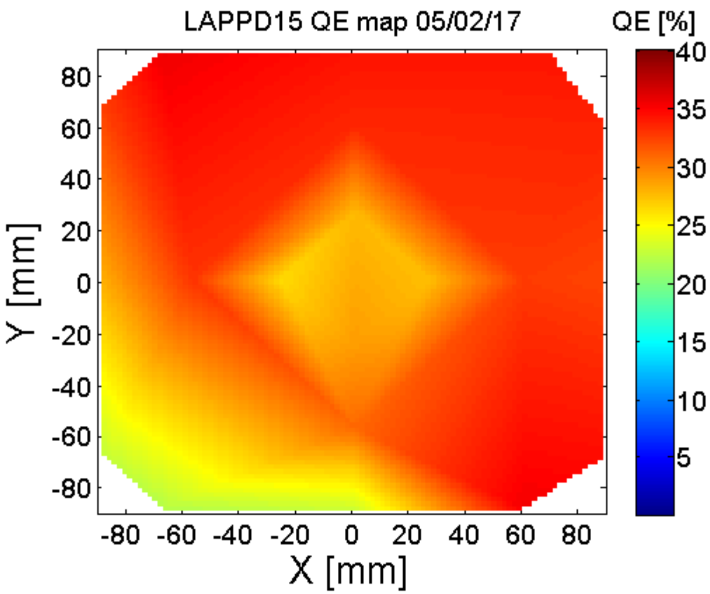
Performance of non-optimized tube

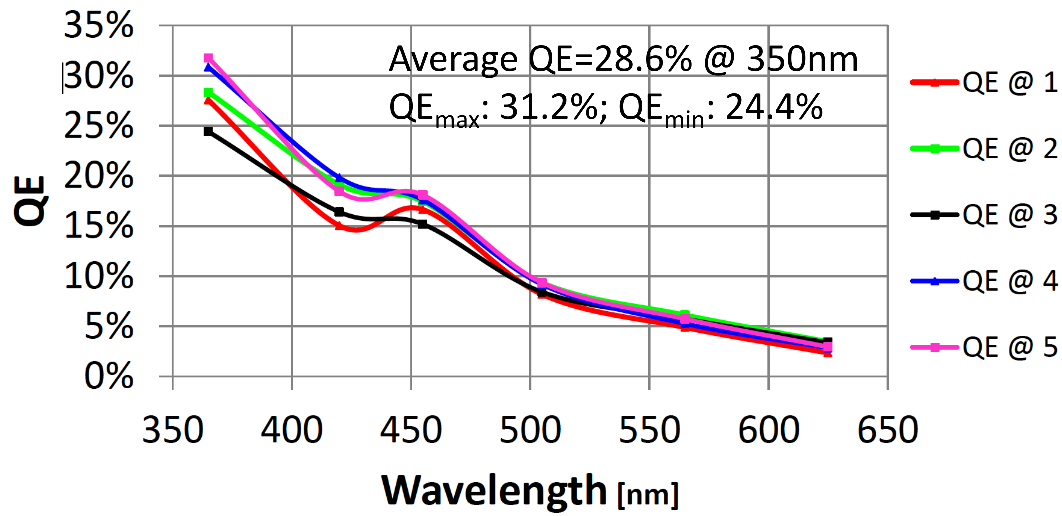
- **Significant room for improvement through optimization of geometry**

Large-Area Picosecond Photodetector



- Gain ~10^7 at 1000V/plate
- Uniformity better than 10% over 400 cm^2 area
- Dark count rate: 1 ct/s/cm^2
- Position determination through stripline readout over whole area
- Produced by Incom

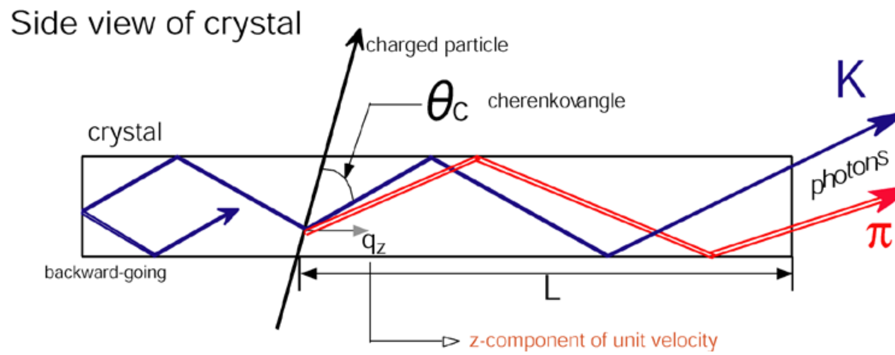




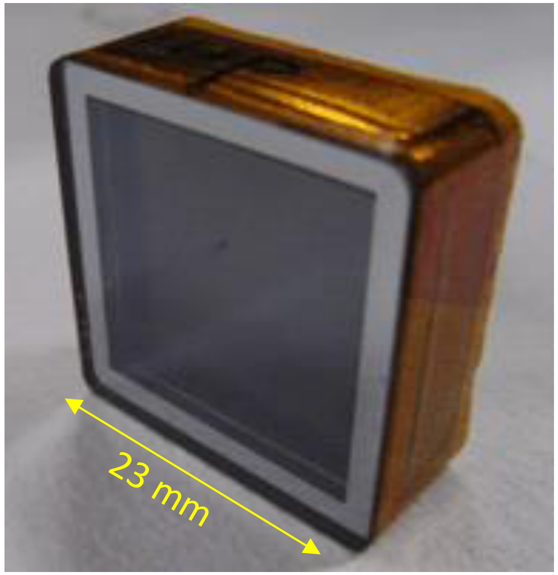
Chris Craven, Incom, this conference

Belle-II Time Of Propagation Detector

- Particle identification in Belle-II through Time of Propagation detector; stringent requirements on photodetectors
- Integrated charge
  - ~8 C/cm^2/50 ab^{-1} (5x10^5 gain)
  - Over lifetime: 0.8xQE
  - Enhanced multi-alkali (>28% QE at peak)
- MCP
  - Channel ϕ 10μm, thickness 400μm
  - bias angle 13°, two layers
  - Al protection layer on 2nd MCP + sealing + ALD
  - Anode 4x4 channels
  - Sensitive region 64%
  - HV: ~2500 – 3500 V
- TTS (Transit Time Spread) less than 50 ps for single photon
- Work in a magnetic field of 1.5 T
- Readout: waveform sampling (IRS chip)



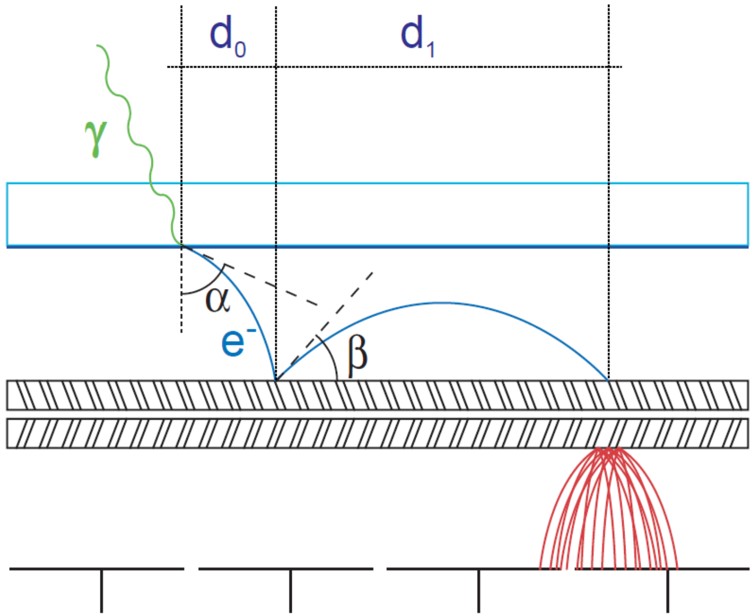
Different opening angle for the same momentum gives different propagation length, thus time.



K. Matsuoka, this conference

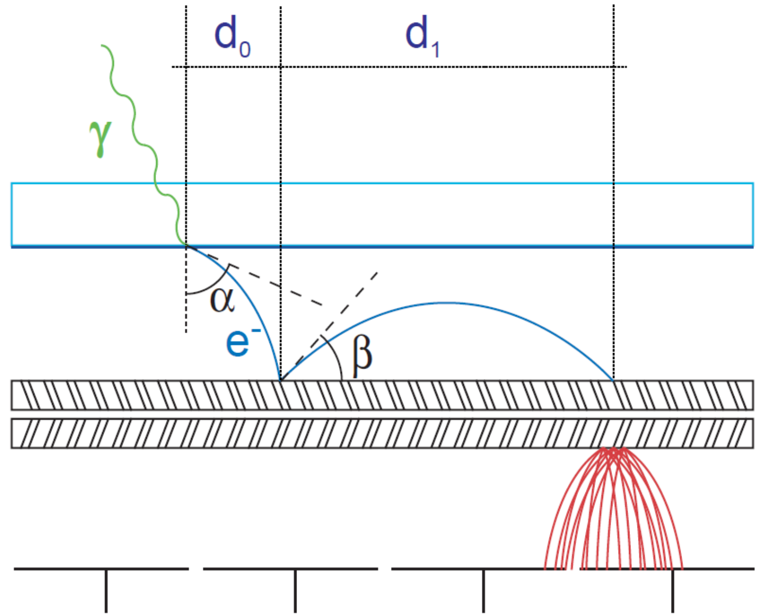
Meeting Requirements

- Back-scattered electrons introduce tails both in timing and spatial distribution
  - Spatially:
    - Worst case: elastic scattering @ 45°
    - Range twice PC/MCPin gap
  - Timing:
    - Worst case: elastic scattering @ 90°
    - Range twice transit time PC/MCPin

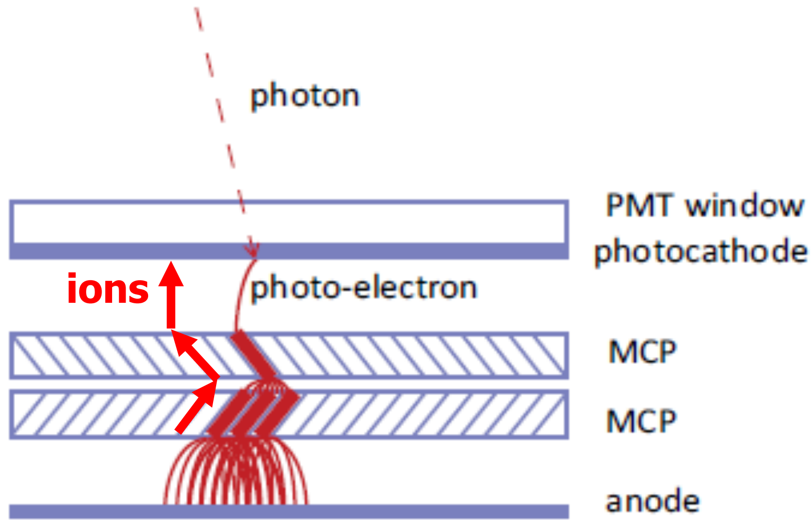


Meeting Requirements

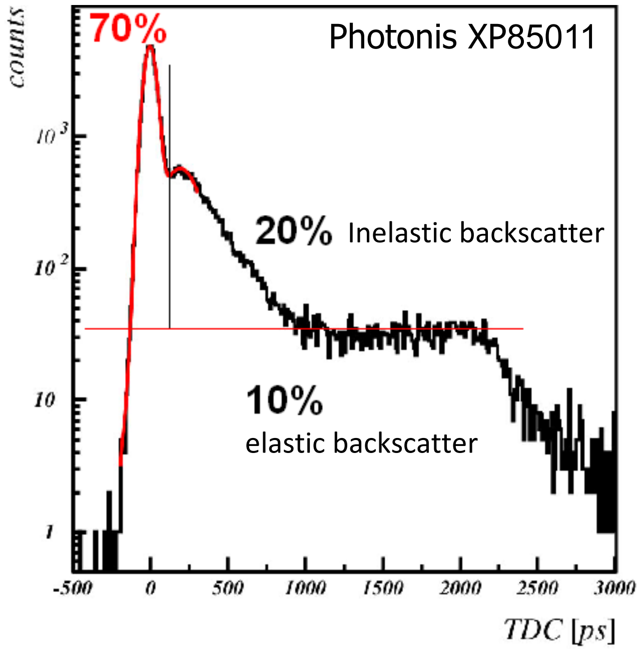
- Back-scattered electrons introduce tails both in timing and spatial distribution
  - Spatially:
    - Worst case: elastic scattering @ 45°
    - Range twice PC/MCPin gap
  - Timing:
    - Worst case: elastic scattering @ 90°
    - Range twice transit time PC/MCPin



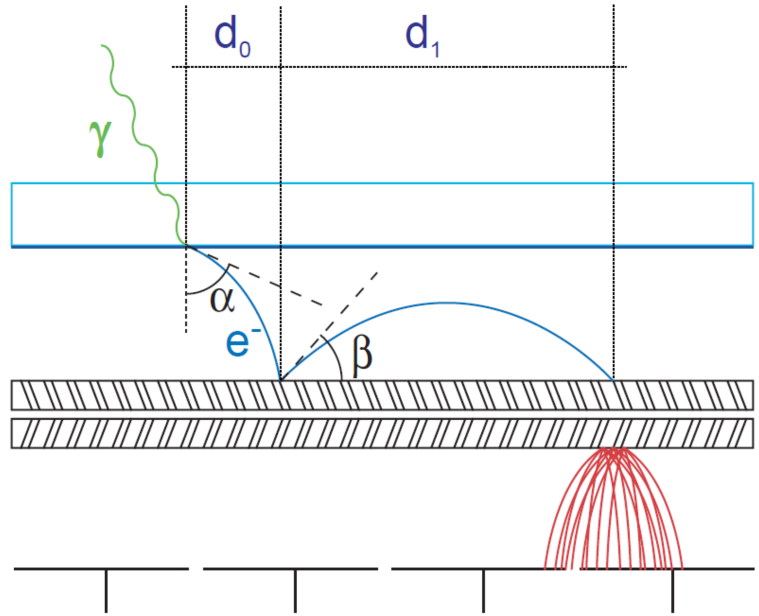
- Ion backflow can destroy photocathode and may reduce gain
  - Implement aluminum ion barrier film
  - Coat channel tubes 5-10nm Al_2O_3

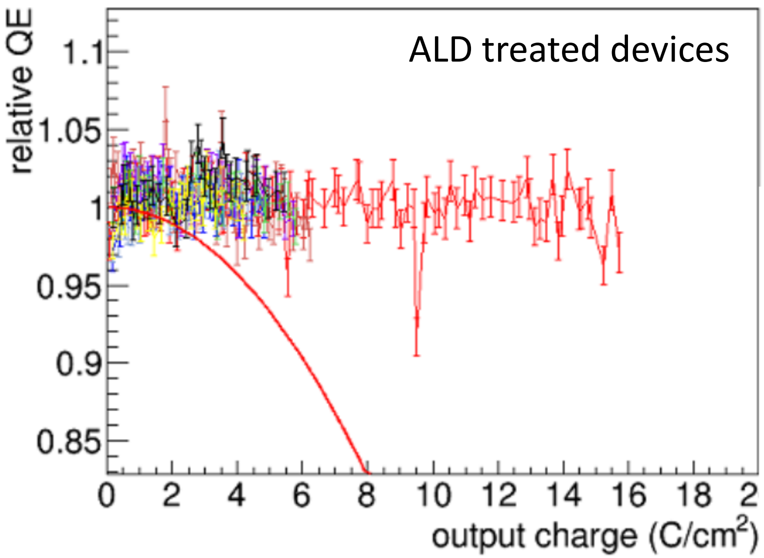


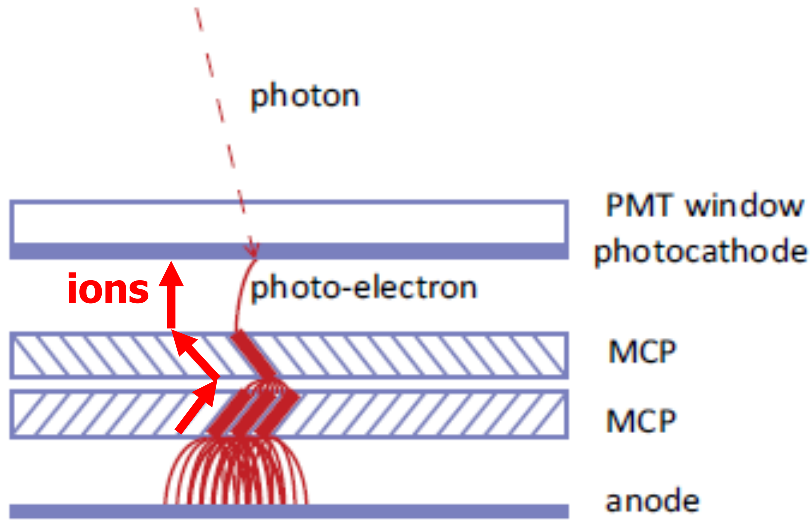
Meeting Requirements



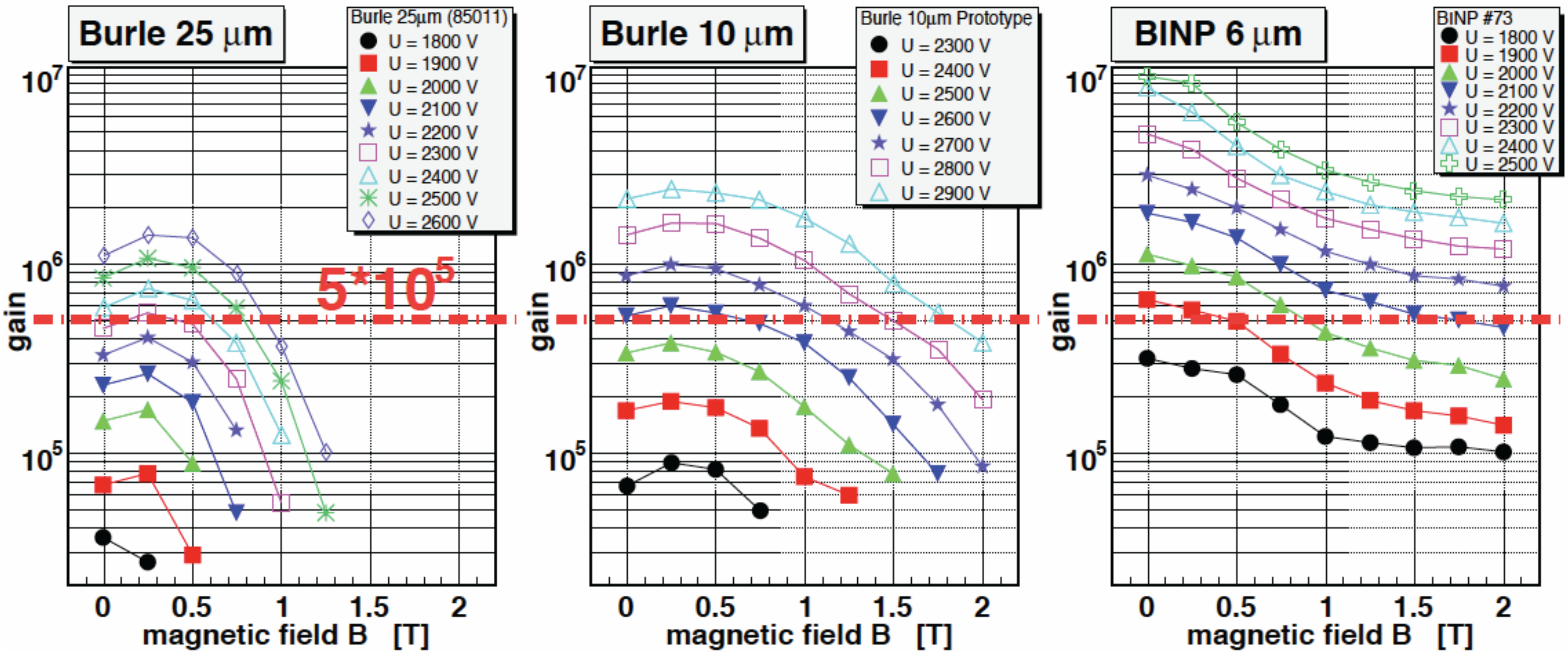
NIMA 595 (2008) 169
JINST 4 (2009) P11017







MCP Magnetic Field Sensitivity

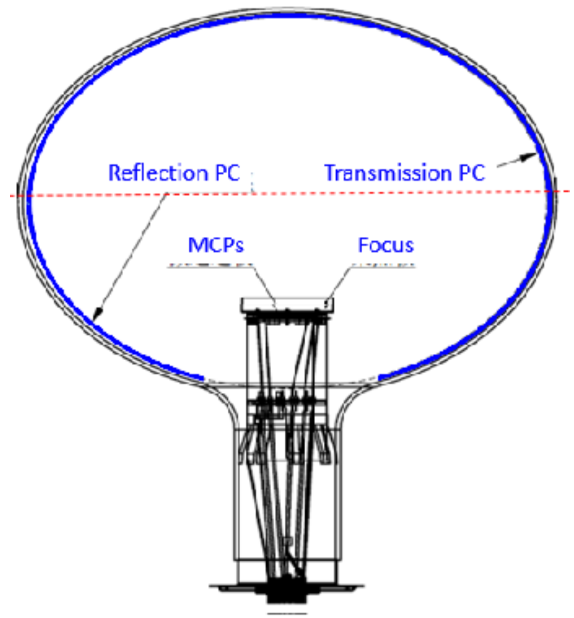


A. Lehmann, NIMA 595 (2008) 173

- Gain drop with increasing B-field possibly caused by the avalanche electrons with lower energies curling inside the pores (Larmor radius of a 50 eV electron is only 24 μm; the gain for a tube with 25 μm pores collapses almost completely at around 1 Tesla).

4π MCP-based Photon Detector

- Using both a transmission and reflection photocathode, 20" MCP-based PMT for JUNO
- Equatorial transition for photo-collection
- Good performance compared to 'Line and Box' 20" HPK R12860 PMT.
- TTS distribution is quite broad (and shows multiple peaks) due to the geometry of the device

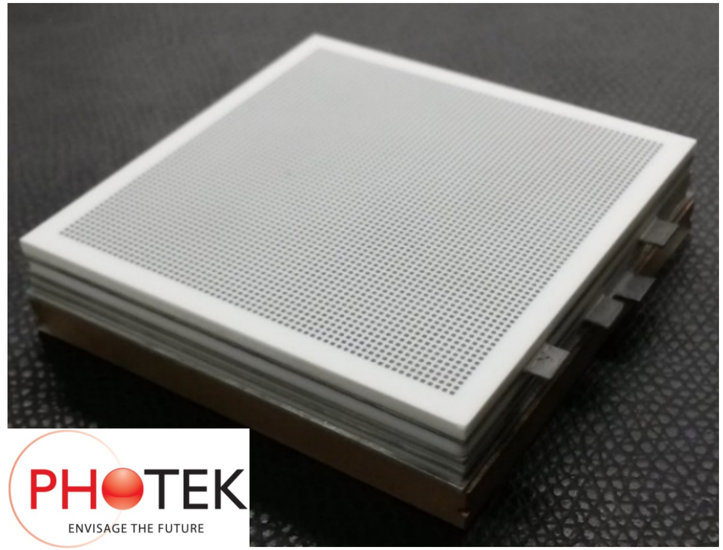


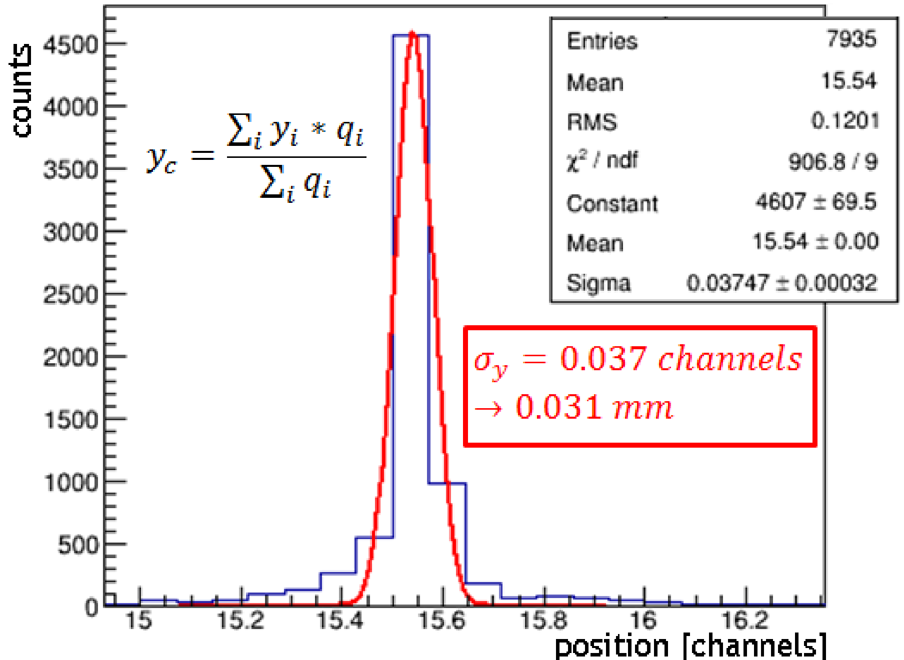
	R12860	IHEP-JUNO
QE@410nm	~30%	~26%
Risetime (ns)	~6.7	~2.2
SPE P/V	~3.7	~5.6
TTS (ns)	~2.8	~12
Dark rate @ 0.25PE	~25 kHz	~30 kHz

Qian Sen, this conference

High-Granularity MCP-PMT

- Development of high-granularity MCP-PMT for the TORCH (Timing Of internally Reflected Cherenkov) detector for LHCb
  - Format 53 mm x 53 mm
  - 64 x 64 channels
  - Pad width 0.73 mm, pitch 0.83 mm



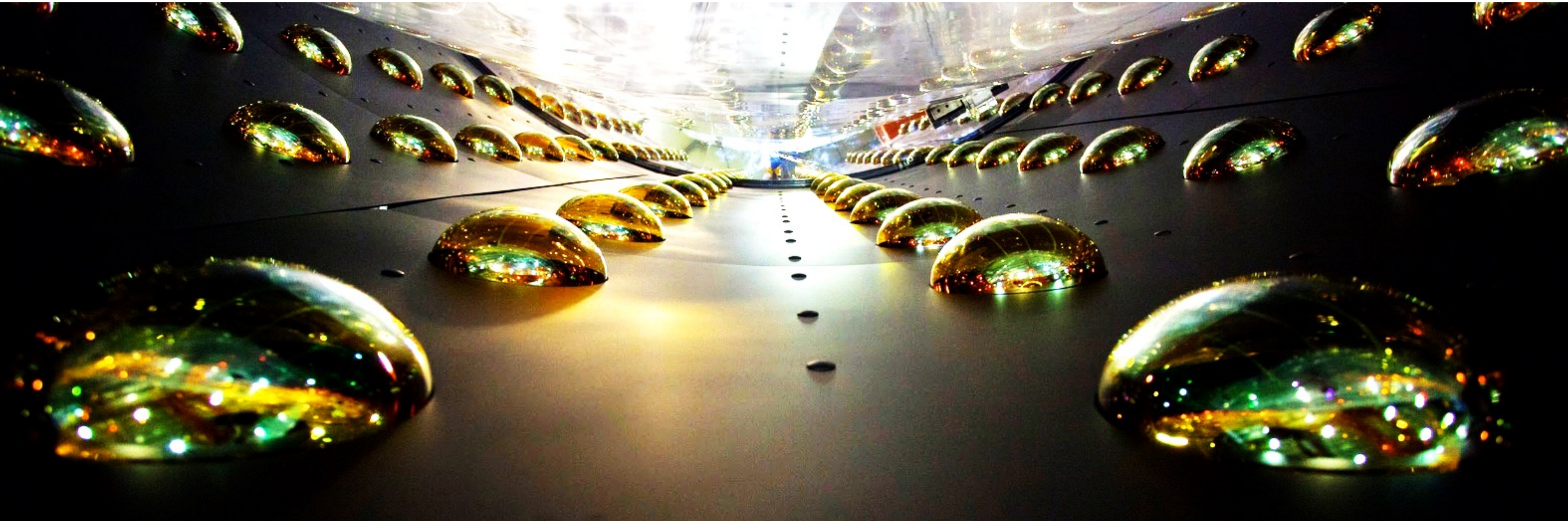


JINST 11 C05022 (2016)

- Position resolution using various methods:
  - σ = 0.031 – 0.096 mm
  - TORCH target σ = 0.12 mm

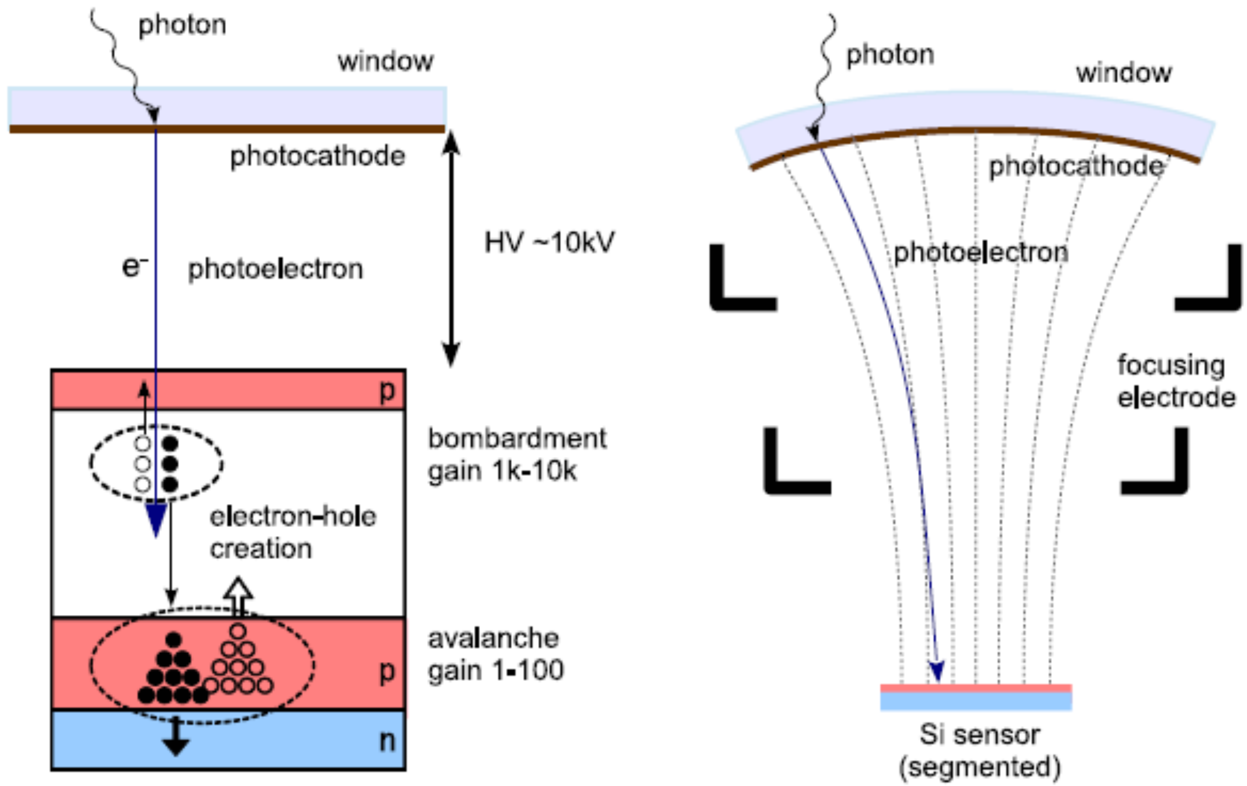
James Milnes, this conference

Hybrid Photon Detectors



Hybrid Photodetectors

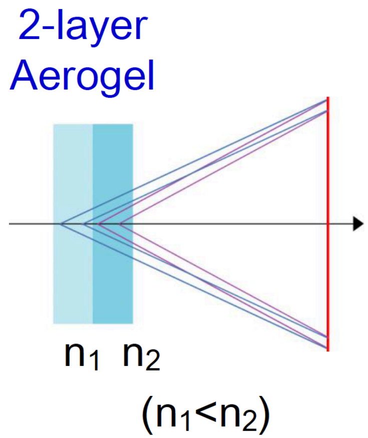
- Combination of vacuum photon detector with solid-state detector
- Input: collection lens, (active) optical window, photo-cathode

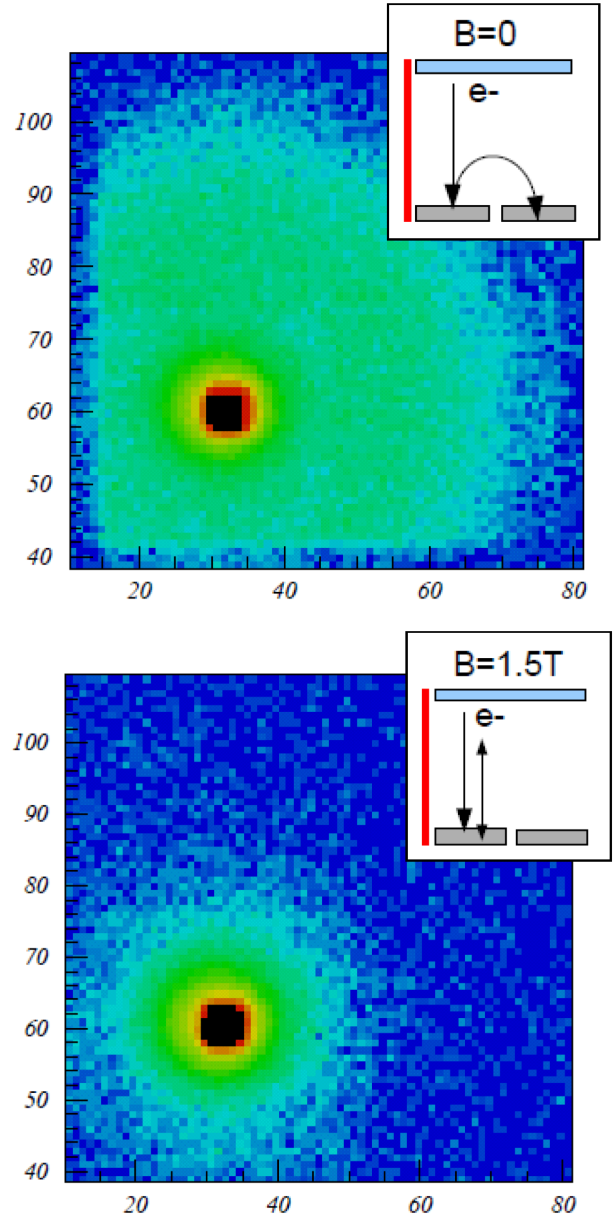


- Gain is achieved in one step by energy dissipation of keV pe's in solid-state detector anode, resulting in low gain fluctuations;
- Encapsulation in the tube requires compatibility with high vacuum technology

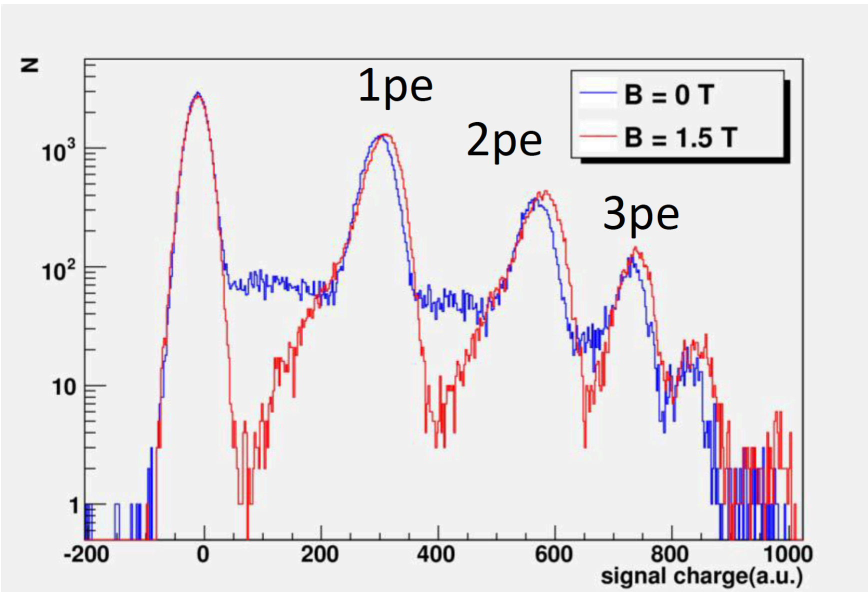
Belle-II RICH

- Belle-II forward particle identification with aerogel Ring Imaging Cherenkov using 420 HAPD photodetectors
- Each HAPD 144 pixels
  - 63mm x 63mm active area
  - 4.8mm square pixels
  - Average QE = 31.6%
  - Avalanche diode gain of ~7x10^4
  - Operates in 1.5T magnetic field
- Magnetic field reduces p.e. back-scattering cross-talk





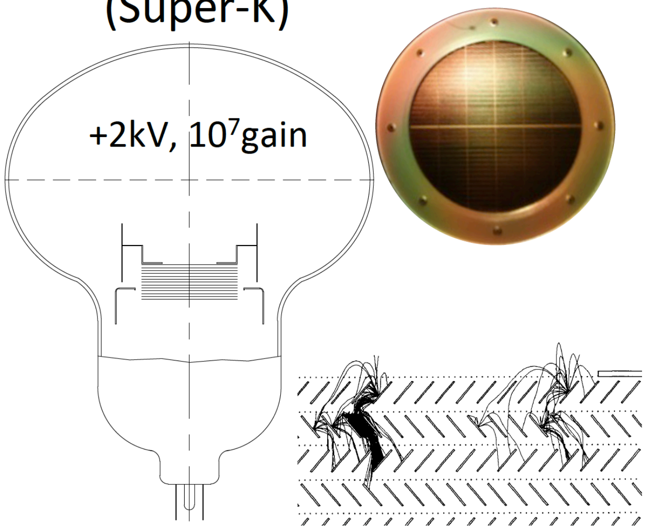
Tomoyuki Konno, this conference



50-cm Photon Detectors

Venetian blind dynode

(Super-K)

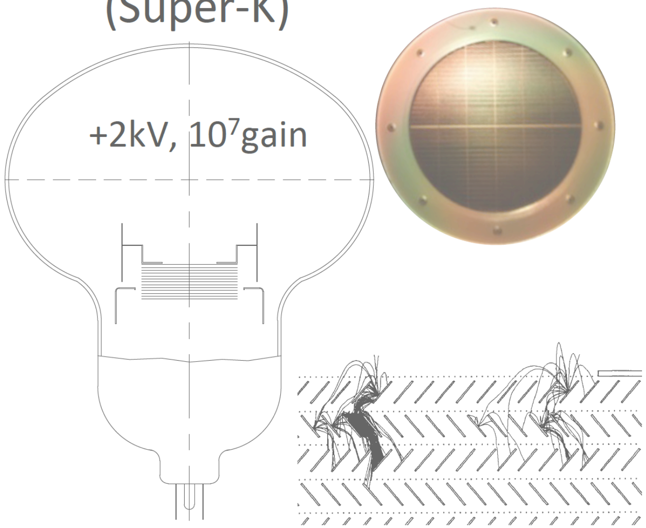


- HPK R3600, Venetian blind dynode (11,000 PMTs)
- Modest electron collection efficiency
- Modest charge and time response

50-cm Photon Detectors

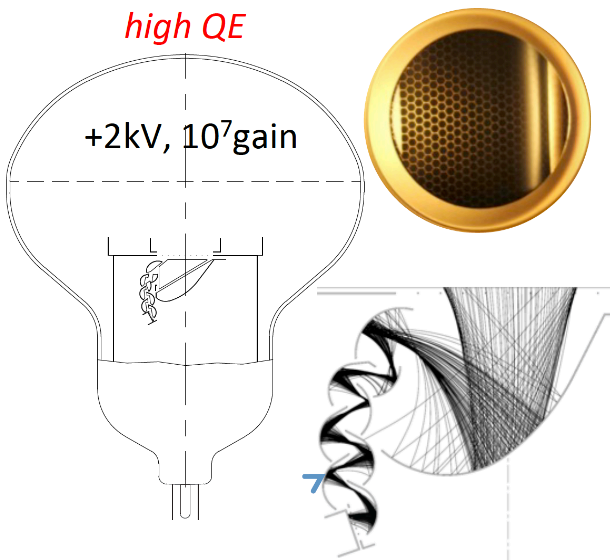
Venetian blind dynode

(Super-K)



Box & Line dynode

high QE



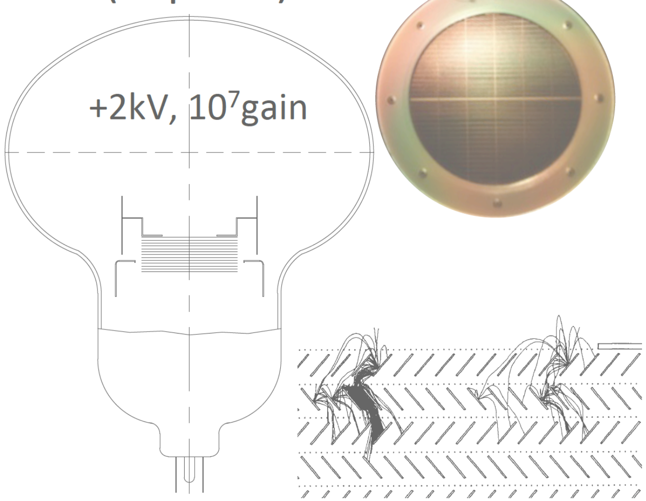
- HPK R3600, Venetian blind dynode (11,000 PMTs)
- Modest electron collection efficiency
- Modest charge and time response

- Box and Line dynode is **baseline** design for Hyper-K (40,000 PMTs)
- High collection efficiency due to uniform drift path
- Good charge and time resolutions

50-cm Photon Detectors

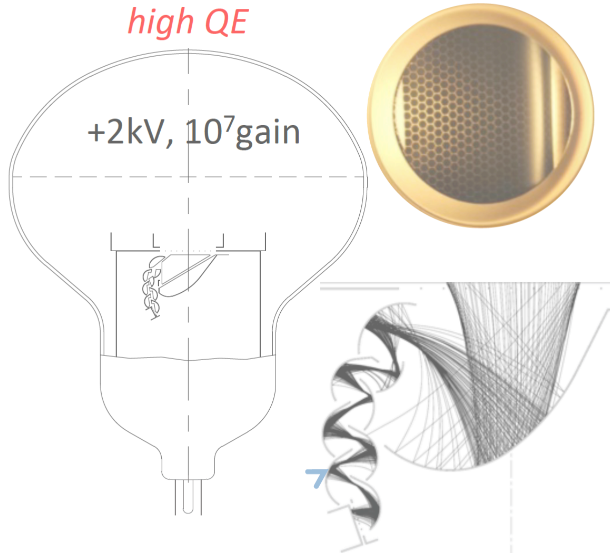
Venetian blind dynode

(Super-K)



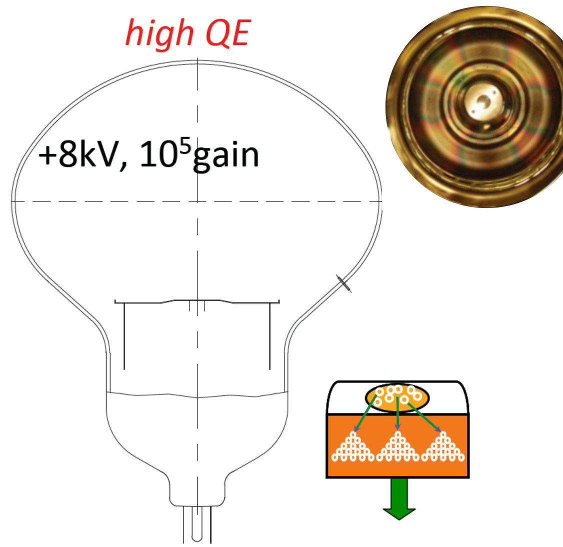
Box & Line dynode

high QE



Avalanche diode (AD)

high QE



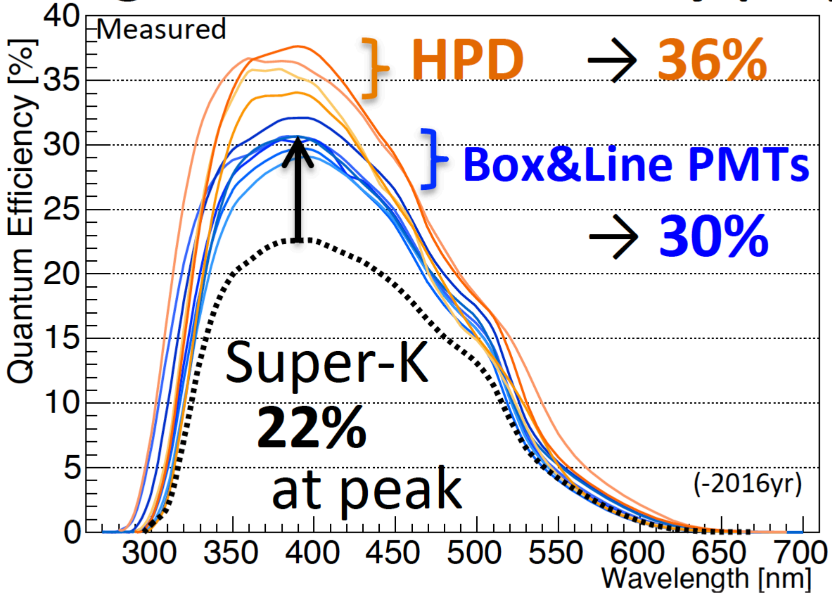
- HPK R3600, Venetian blind dynode (11,000 PMTs)
- Modest electron collection efficiency
- Modest charge and time response

- Box and Line dynode is **baseline** design for Hyper-K (40,000 PMTs)
- High collection efficiency due to uniform drift path
- Good charge and time resolutions

- **Possible alternative**
- **Lower cost; 1-channel avalanche diode**
- **Built-in preamplifier**
- **Aimed at better overall performance**

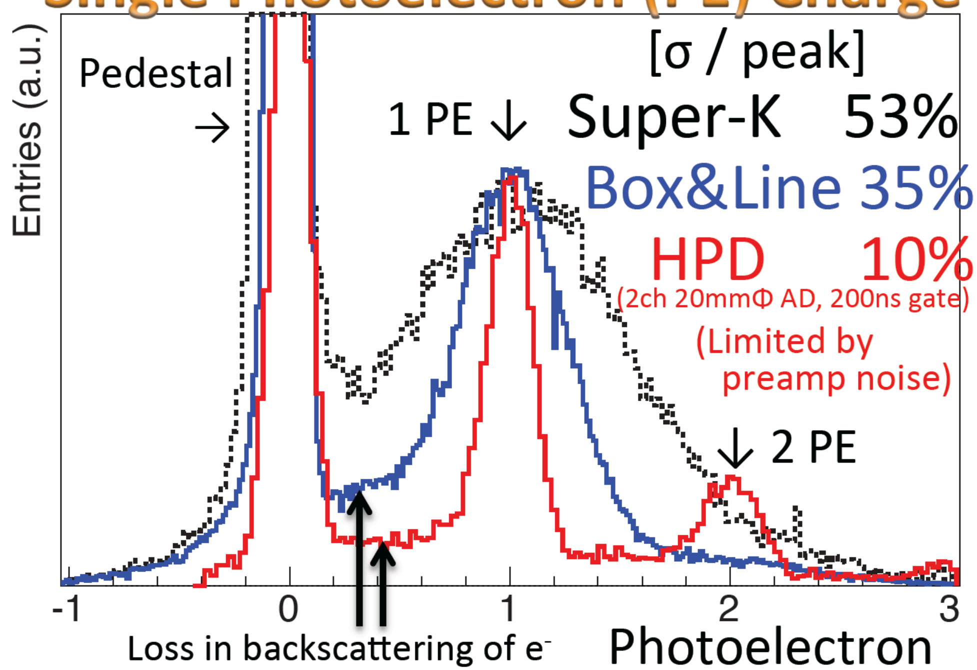
Hyper-Kamiokande Photodetectors

High Quantum Efficiency (QE)



- Significant improvements obtained over Super-K PMTs with baseline 'Box and Line' design.

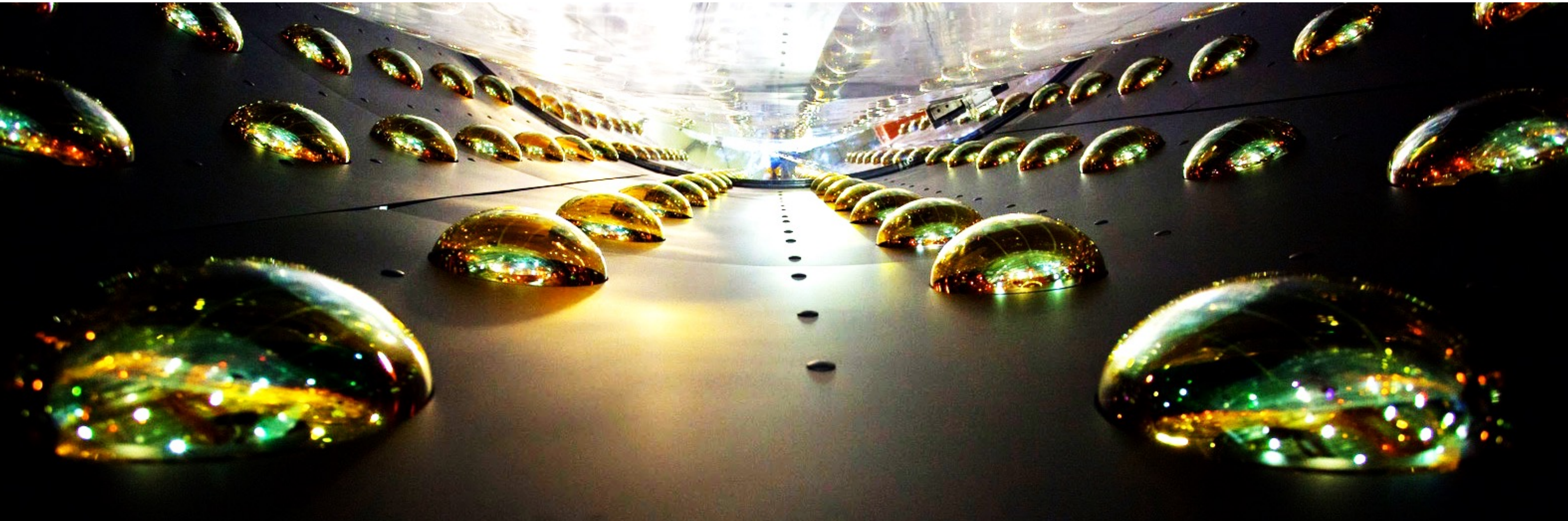
Single Photoelectron (PE) Charge



- HPD option promises continued improvements.

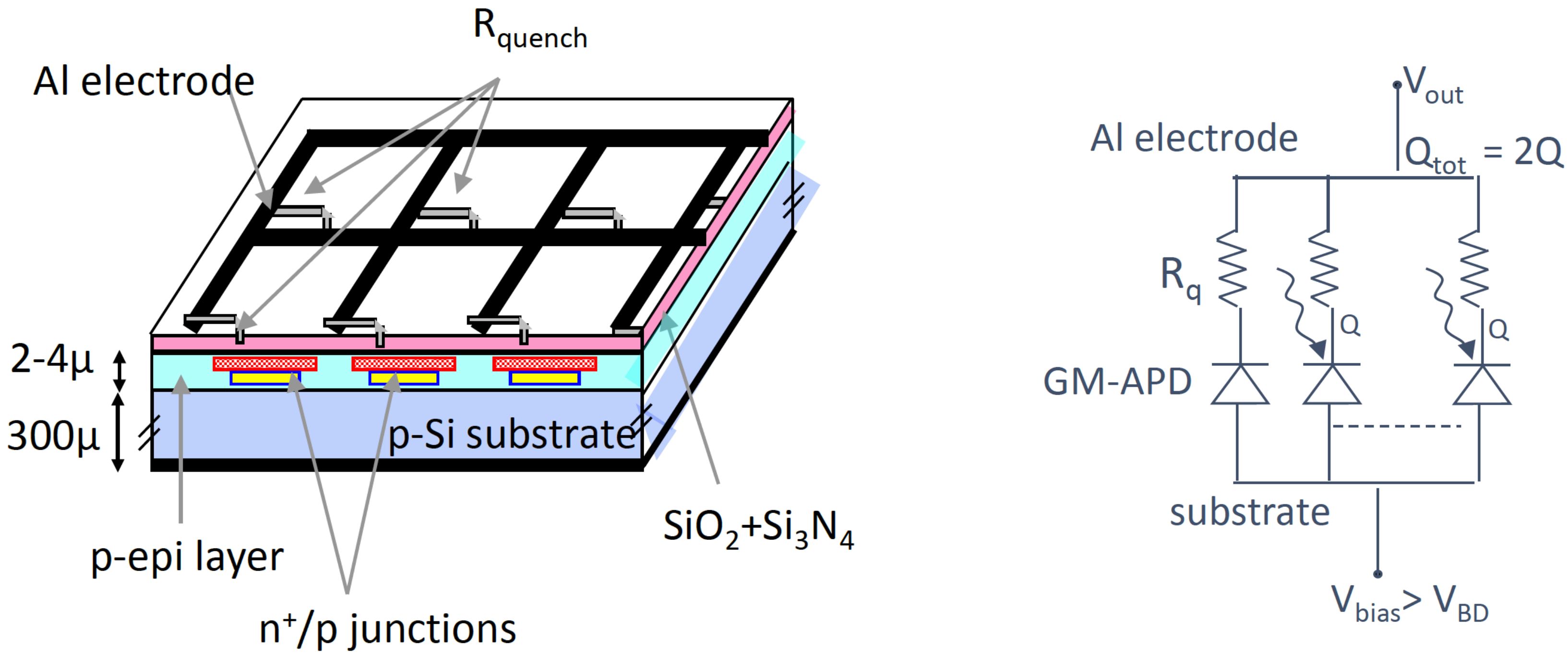
Y.Nishimura, ICHEP 2016

Solid State Photon Detectors



Multi-Pixel Photon Counter (SiPM)

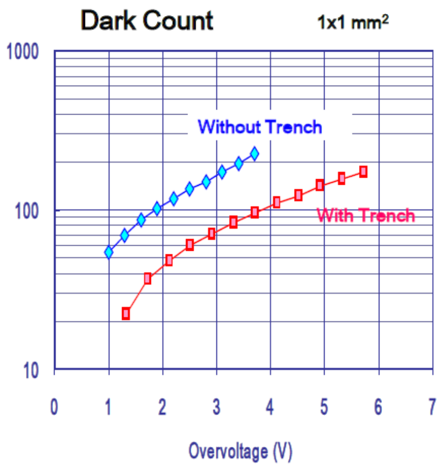
- Most recent, and arguably most popular, solid state photon detector is the SiPM



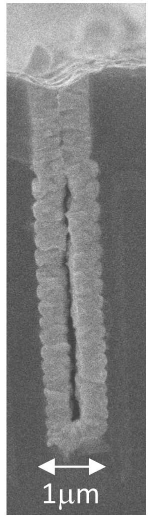
- *SiPM is an array of small cells (GM-APDs) connected in parallel on a common substrate*
  - *Each cell has its own quenching resistor (from 100kΩto several MΩ)*
  - *Common bias is applied to all cells (~10-20% over breakdown voltage)*
- *Cells fire independently; output signal is a sum of signals produced by individual cells*
- *For small light pulses (N_γ<<N_{pixels}) SiPM works as an analog photon detector*

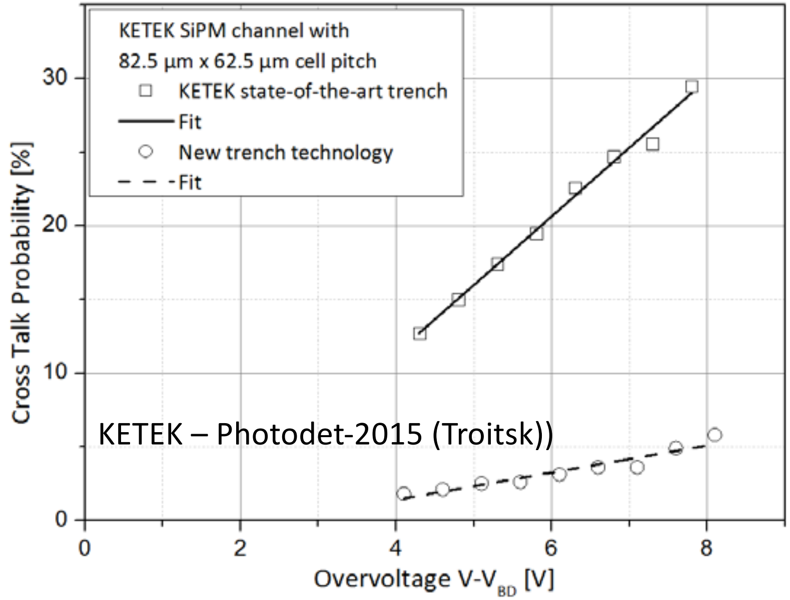
SiPM Performance Improvements

- Cross-talk reduction: metal filled trench

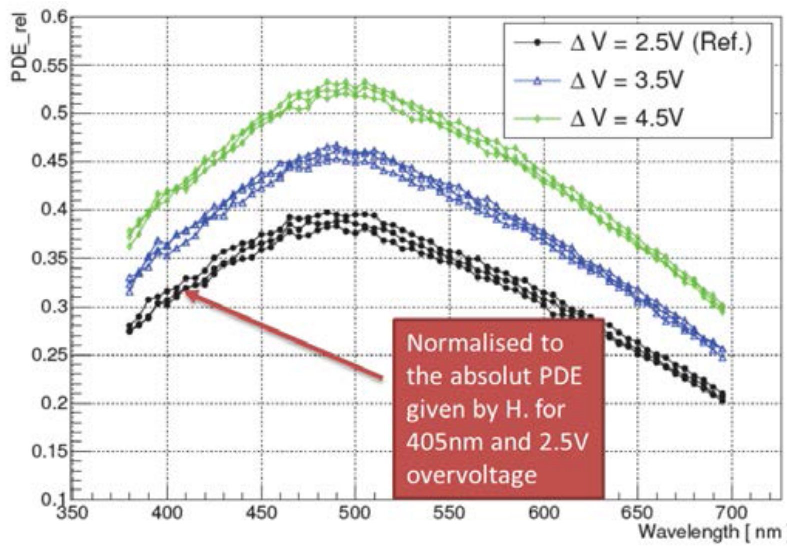


HPK: 2nd SiPM Advanced Workshop, March 2014)

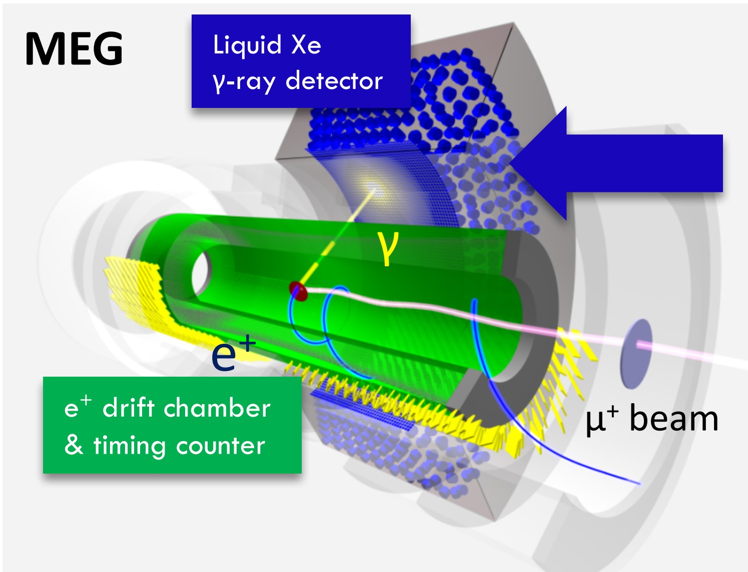




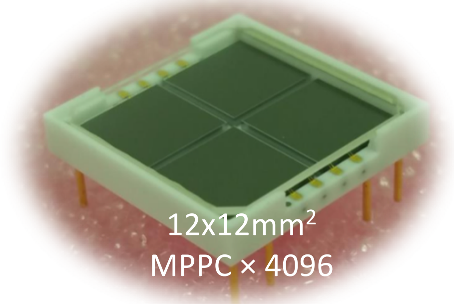
- Photon Detection Efficience (PDE) Increase
  - Small X-talk and after-pulsing allow SiPM operation at high over-voltages.
  - Increase in maximum PDE (SiPMs with 43÷50 μm cell pitch).



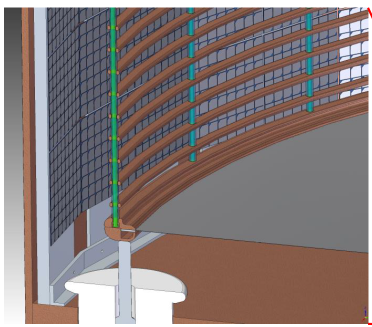
VUV Sensitive Silicon Photomultipliers



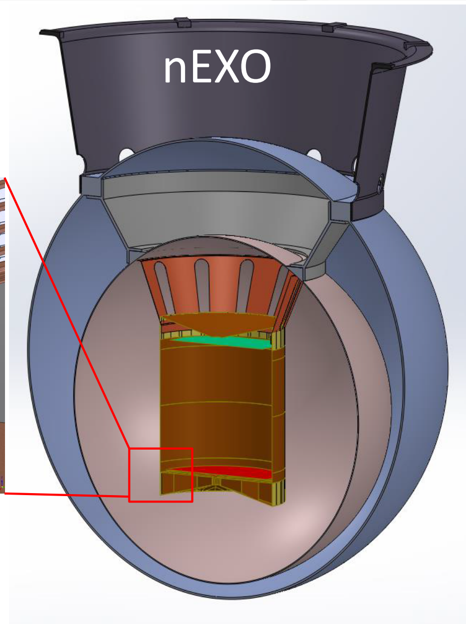
- Recently developed SiPM sensitive to VUV light for noble liquid detectors
  (LAr: λ = ~128 nm, LXe: λ = ~178 nm).
- MEG experiment to replace existing 2” PMTs with VUV SiPMs
  - Gain: 8×10^5
  - PDE: 16~25%
  - 50 μm pixel pitch

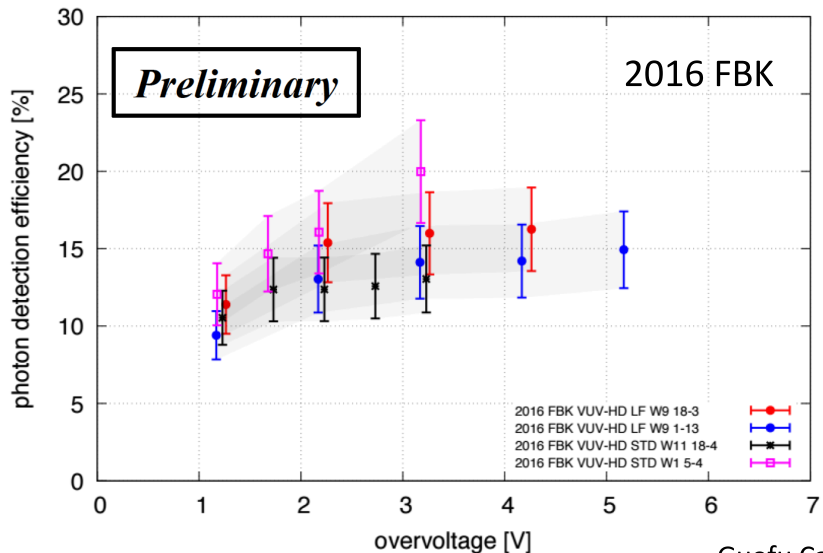


Hamamatsu S10943-3186(X)



4 m^2 panels of VUV SiPMs

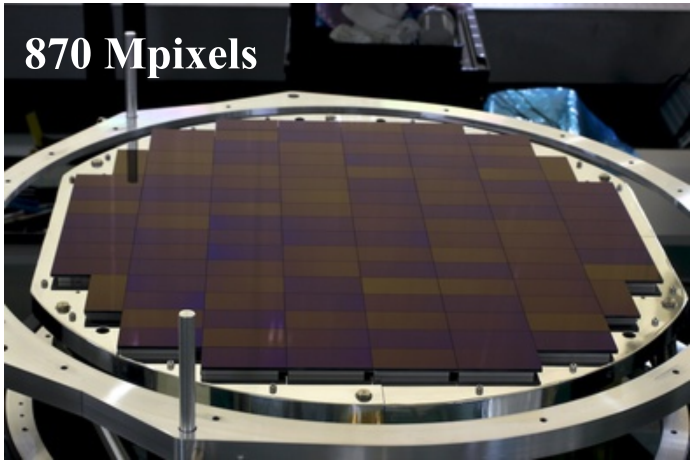




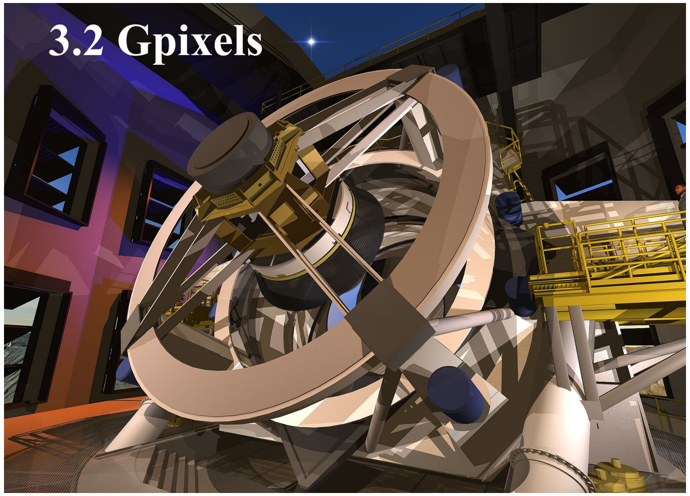
Guofu Cao, this conference

arXiv:1502.07837v2

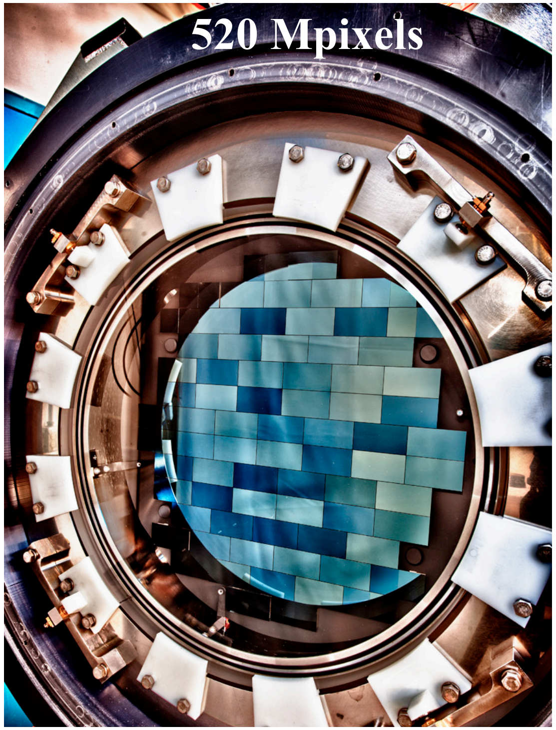
Cosmological Surveys



HyperSuprimeCam
116 2k x 4k, $(15\ \mu m)^2$-pixel CCDs
CCDs from Hamamatsu Corporation
Subaru 8-m Telescope

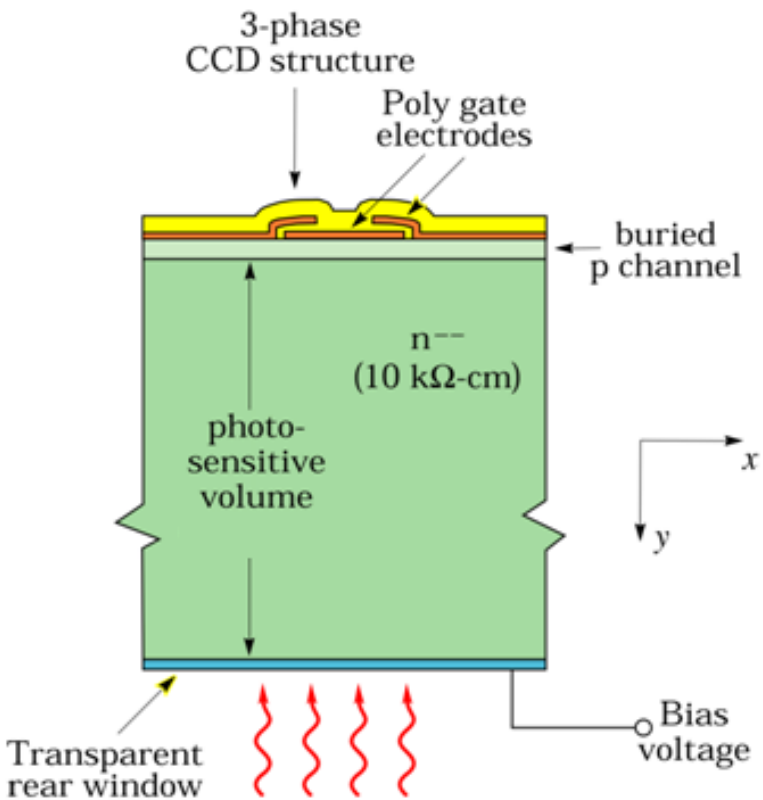


Large Synoptic Survey Telescope
189 4k x 4k, $(10\ \mu m)^2$-pixel CCDs
CCDs from E2v, ITL
Cerro Pachón

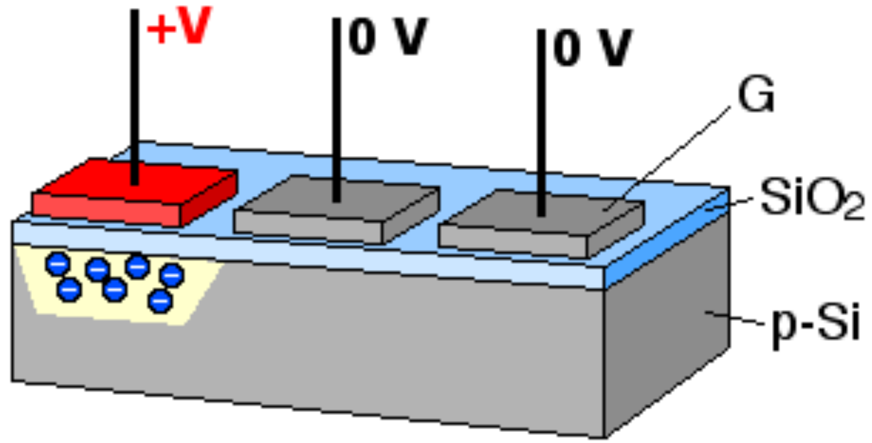


Dark Energy Survey Camera
62 2k x 4k, $(15\ \mu m)^2$-pixel CCDs
CCDs from DALSA Semicon / LBNL
NOAO Cerro Tololo
Blanco 4-m Telescope

Charge-Coupled Device (CCD)



LBNL back-illuminated CCD



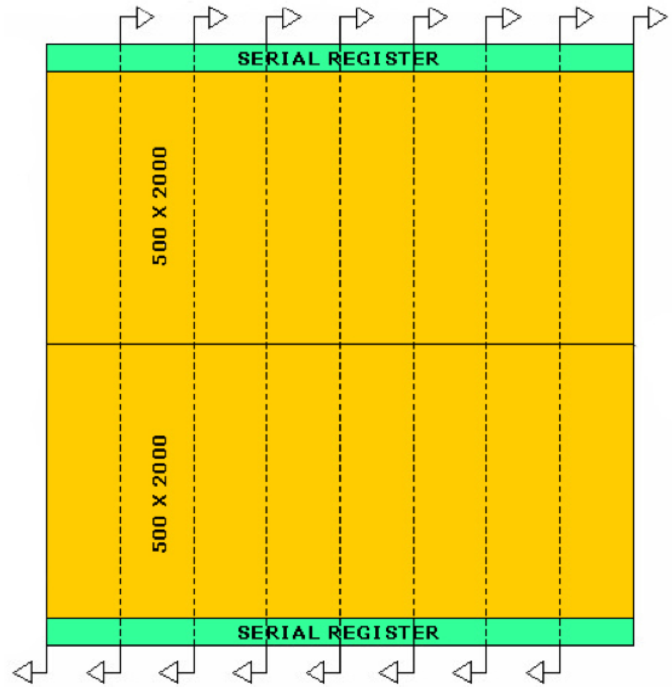
- Photons create electron-hole pairs and charge collected in buried well; transferred to periphery for readout
- Back-illuminated CCD: standard CCD fabricated on a high-resistivity silicon substrate that is fully depleted by the application of a substrate bias voltage
- Merging of CCD / p-i-n detector
- Typical thickness: 200 – 250 µm,
  500 – 650 µm in some cases
- Typical Vsub ~ 40 – 100V

Charge-Coupled Device

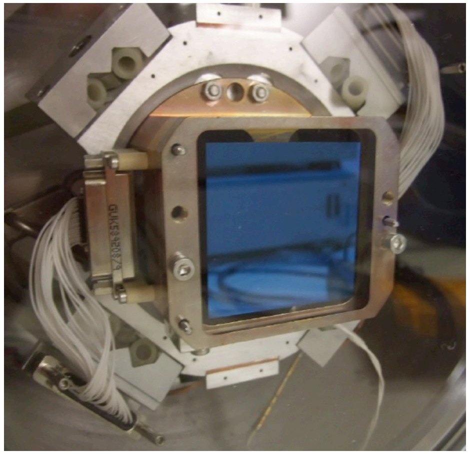
- 4k x 4k array = 16 Mpixels per CCD
  - 10x10 μm^2 pixels
- 2 second readout time
  - 16 amplifiers / 16 Mpix CCD

LSST:

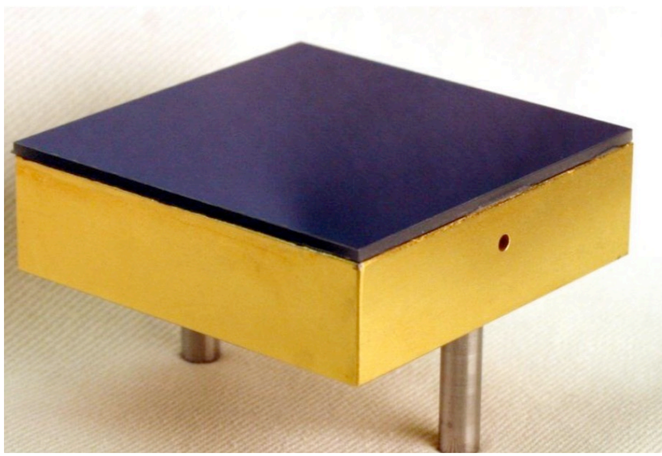
- Noise 8 e^-, based on anticipated sky noise
- Pixel read rate is 550 Kpix/s
- Si thickness 100 micron → Enhanced IR response



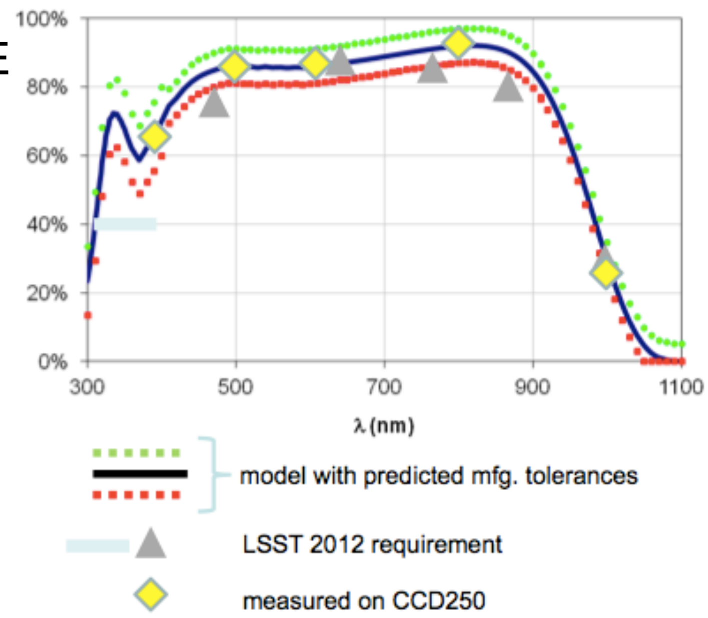
e2v CCD250



ITL STA3800

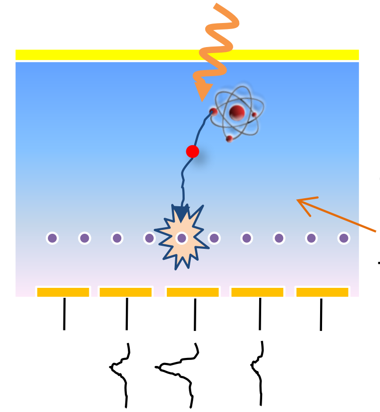


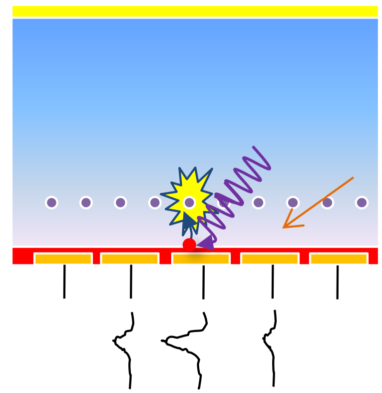
QE

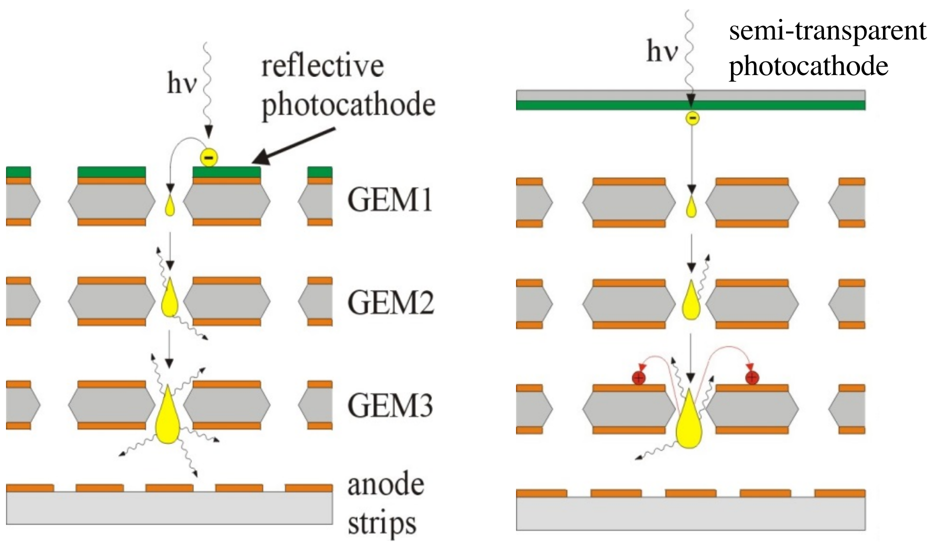


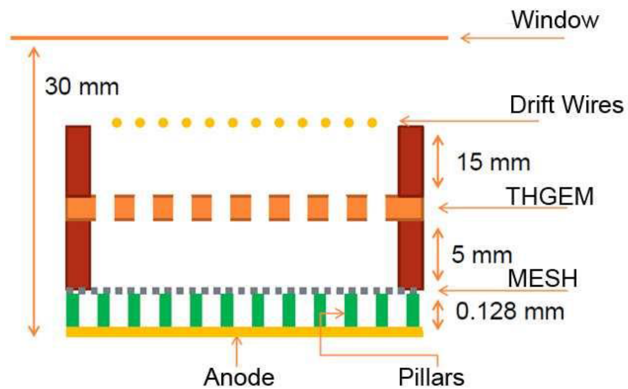
Gas-based Photodetectors

- Two main detection methods:
  - Ionize photosensitive molecules, admixed to the counter gas (TMAE, TEA);
  - Release photoelectron from a solid photocathode (CsI, bialkali...); use free p.e. to trigger an avalanche
- Gaseous photon detectors are the most effective approach to instrument large surfaces at affordable costs
- MPGD-based photon detectors allow to overcome the limitations of open geometry gaseous photon detectors
  - Recovery time after trip; Ion feedback; Aging





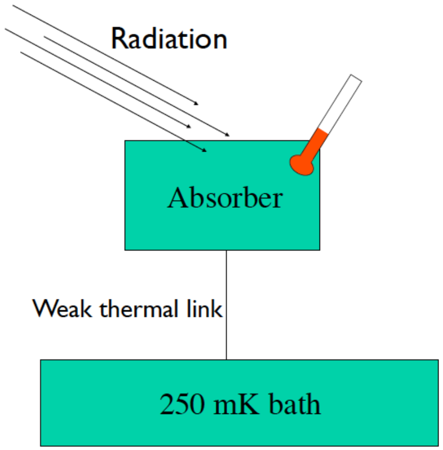


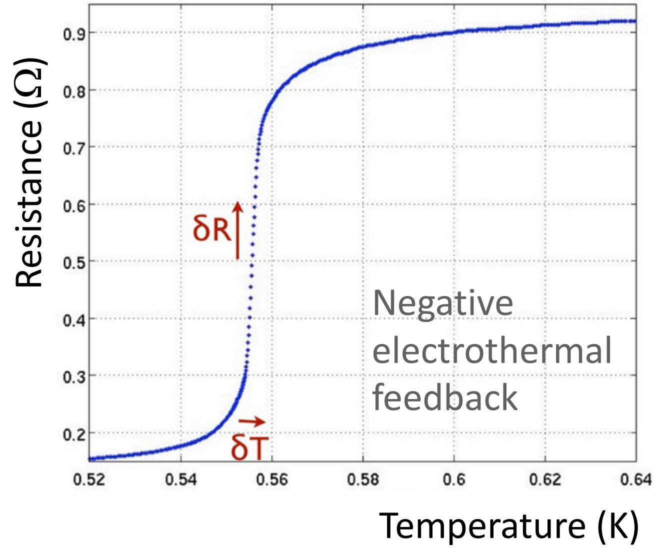


See Shikma BRESSLER, this conference

Superconducting Photon Detectors

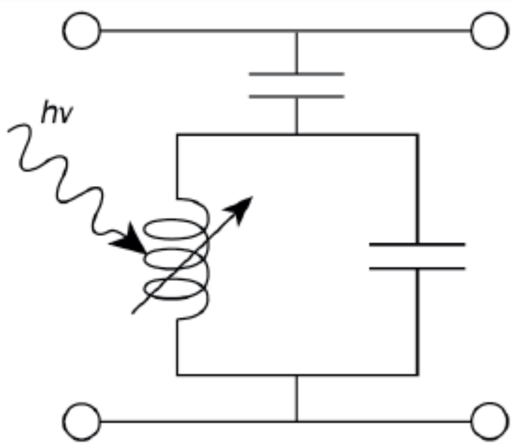
Transition Edge Sensors

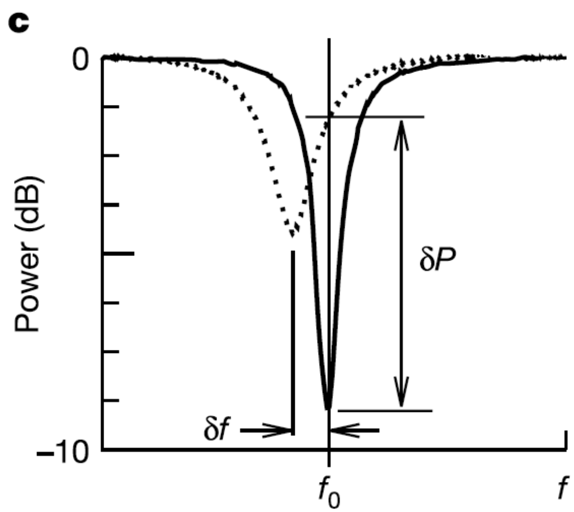




- Thermometer; held at transition between normal and superconducting
- Measures pW incident power

Kinetic Inductance Detectors

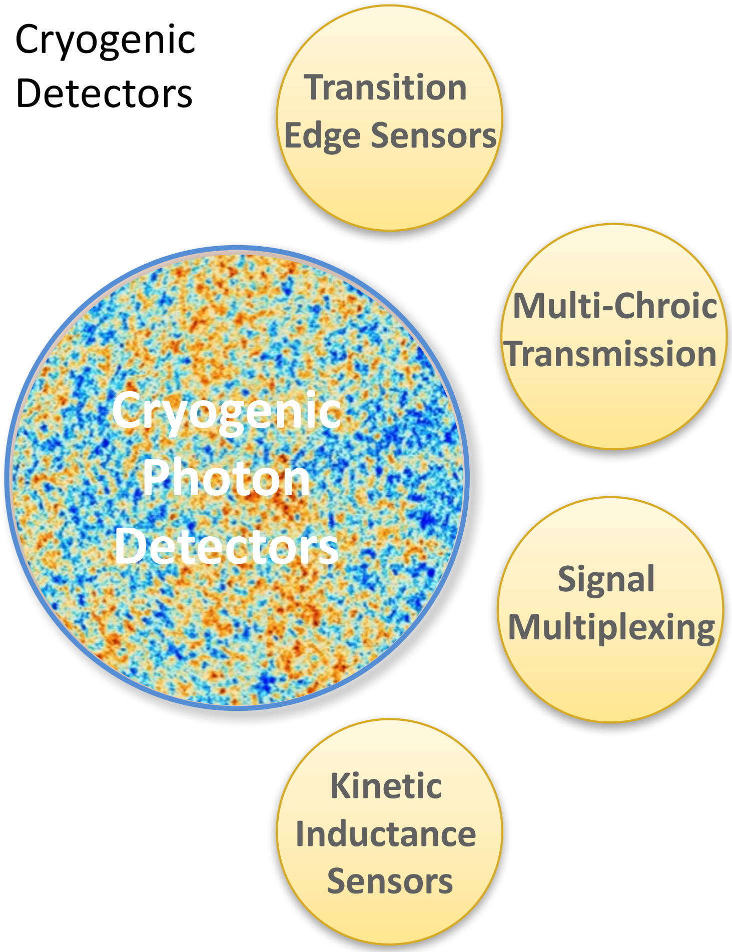


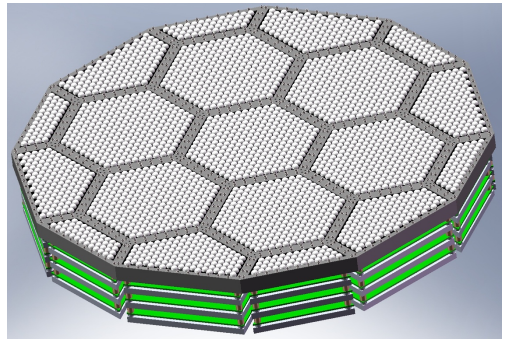


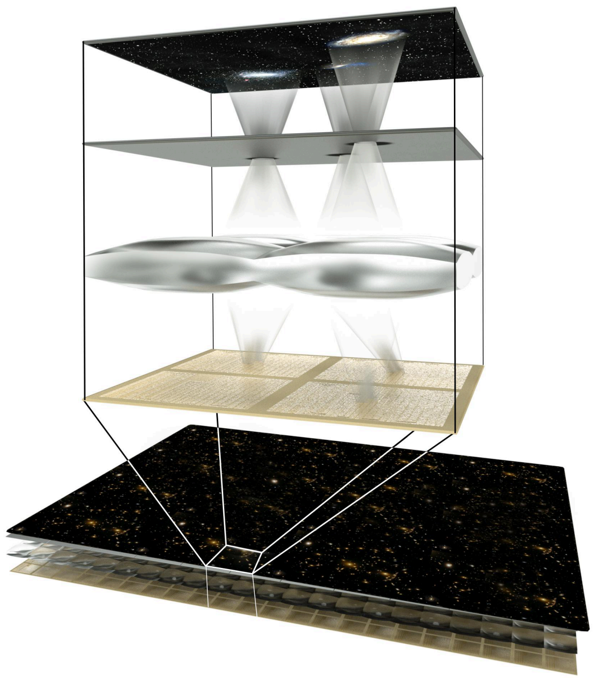
- Superconducting resonator
- Breakup of Cooper pairs changes inductance and resonant frequency

Cryogenic Photon Detectors

Cryogenic Detectors







Science Reach:

- Effective number of neutrinos
- Σm_ν
- Dark Energy, w
- Inflation & GUT scale physics
- $0\nu\beta\beta$-decay
- Relic neutrinos
- Spectroscopic galaxy information

Cosmic Microwave Background Radiation

Summary and Outlook

- Photon detection has been a cornerstone in particle physics.
- Traditional photo-detectors are based on a mature, time-honored technology that has seen incremental improvements over time.
- Recent years, however, have seen a rapid increase in new developments – witness the SiPM.

- The research in new materials and technologies has just started
- Very healthy set of producers are engaged in the development
- The future of photon detector development is very bright.

References and Acknowledgements

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