Photo-detector R&D for next generation NNN detectors

F. Retière

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Non-exhaustive list of neutrino experiments being planned

Experiment	Photo-detector#	Phot. Det. area (cm^2)	Sensitive area (m^2)	Construction time scale	Type
LBNE (collector)	4,800	4.84 (1760)	0.06 (22)	?	Liquid Ar.
EXO-200 / nEXO	468/10,000	2 / 1-2	0.1 / 1-2	Done/2018-2021	Liquid Xe.
SNO+	10,000	330 (8”)	320	2011-2016	Liquid Scint.
Daya Bay 2	15,000	2040 (20”)	3,000	2016-2020	Liquid Scint.
RENO-50	3,000	510 (10”)	150	?	Liquid Scint.
Super-K	11,146	2040 (20”)	2,260	Operating	Water Ce.
LBNE Ce.	~38,000	735 (12”)	2,800	Defunct	Water Ce.
Hyper-K	99,000	2040 (20”)	20,000	2016-2024	Water Ce.
MICA-KM3NET	450,000	46 (3”)	2,050	2018-2024	Water Ce.
LENA	45,000	330 (8”)	1,460	?	Water Ce.

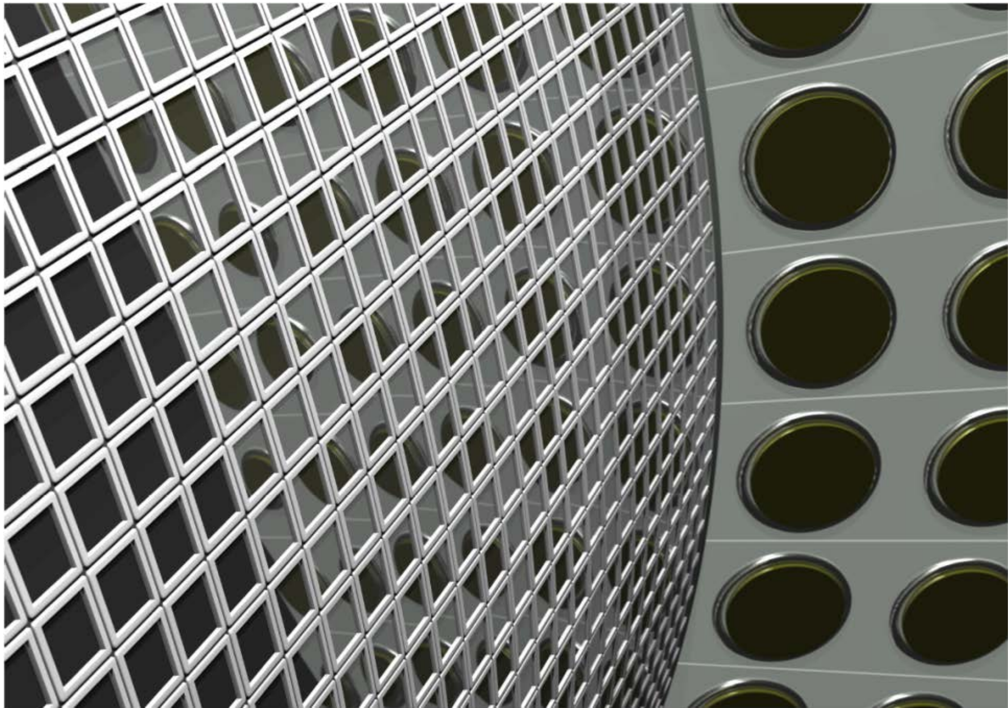
Large area Photo-Multipliers main cost driver of most experiments

Lets get the PPDs out of the way

- Dark noise kills any application requiring large area and low dark noise
- Not an issue in LXe & LAr
  - Pros (compare to PMTs):
    - Higher efficiency
    - Low gain fluctuation
    - Lower radioactivity
    - Better timing resolution
  - Cons:
    - Cost currently ~100$/cm^2 vs 10$/cm^2 for PMT
    - High capacitance

- Pixelated Geiger-ode avalanche Photo-Diode = silicon photo-multiplier

MEG at PSI, 1.2x1.2 cm^2 Hamamatsu MPPC



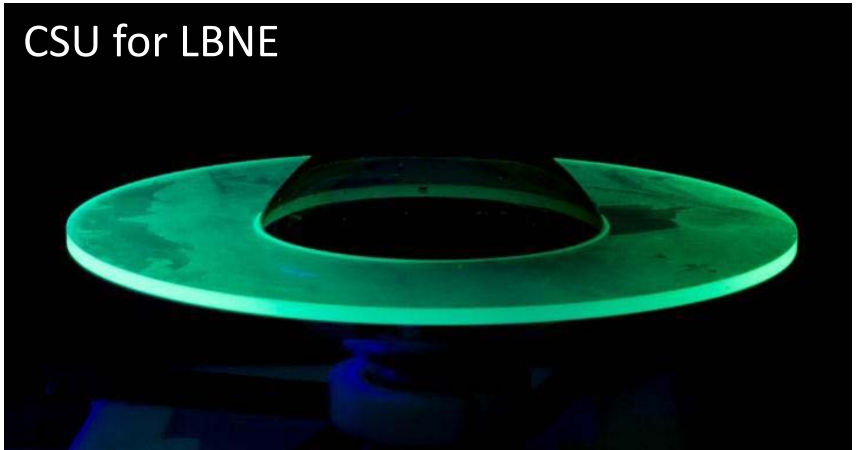
Requirements and outline of solutions

- Low cost → photo-coverage
  - Cheap solution for enhanced photon collection
  - Bring competition to market (Texas PMT, use small PMTs)
  - Develop easier to make PMTs
- Enhanced photo-detection efficiency
  - Hamamatsu HQE and better index of refraction matching
- Good timing resolution
  - Large area MCPs
  - Focusing MCPs
  - Box&line dynodes
- Photon counting capabilities
  - Low electronics noise, easy to get with high gain PMT
  - Low gain fluctuations with hybrid Photo-detector

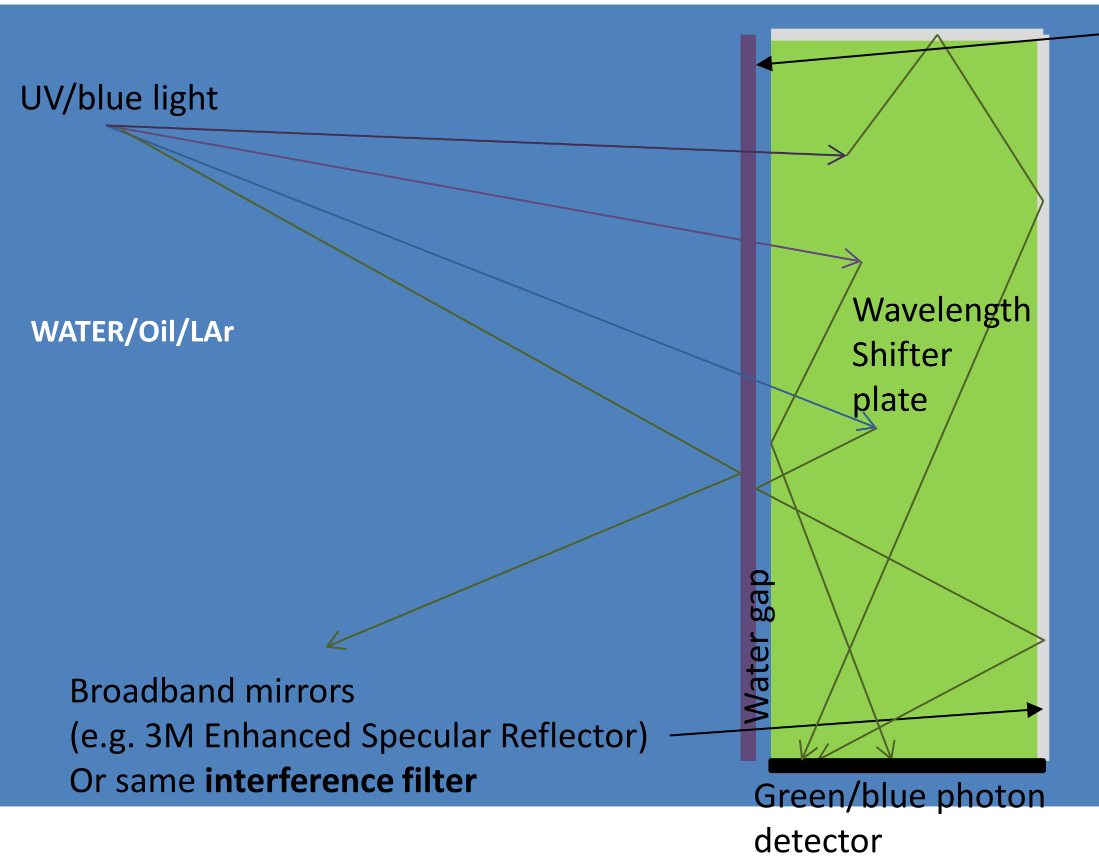
Reducing photo-cathode coverage by enhancing photon collection

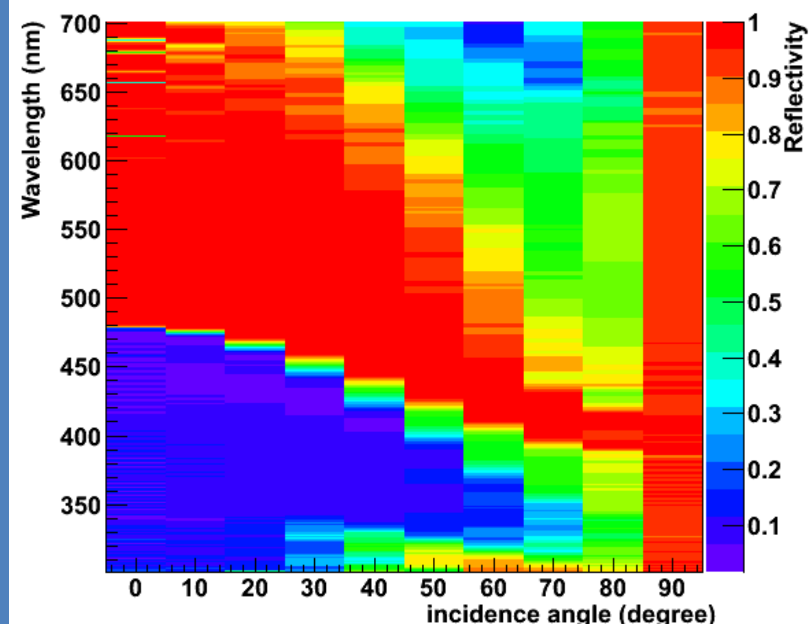
- Cone
  - Increase light collection by up to 50%
  - Decrease fiducial volume

- Wavelength shifter
  - May increase light collection by >x2
  - Cons:
    - worsen timing resolution
    - Some background reemitted light



Trapping reemitted light either by total internal reflection or mirrors





Dichroic mirror by Iridian. Inc
Ottawa, Canada

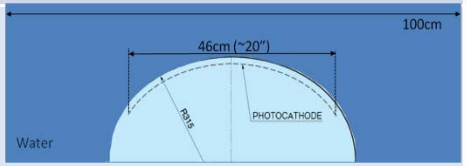
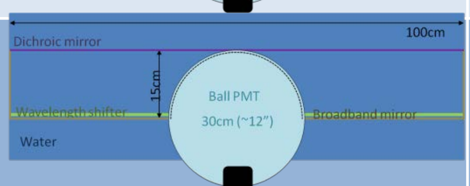
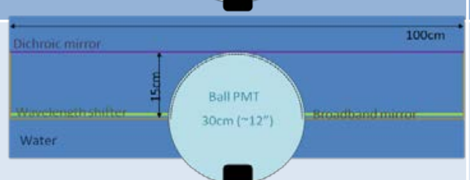
Trapping efficiency:

- ~30% with total internal reflection independently of number of bounces
- $98.5\%^{\mathrm{nbounce}}$ with mirrors
- Can combine both

![TRIUMF]

Geant4 simulations

Photon Collection Performance 100 cm Traps

Configuration		Primary	Internal	External	Ext/Int	Total
20” PMT		1*	0	0	N/A	**1**
12” PMT + 3cm WLS + side mirrors		0.43	0.38	0	N/A	**0.80**
12” PMT + 3cm WLS + side & back mirrors + WLS dichroic mirror		0.42	0.43	0.13	0.30	**0.98**
12” PMT + 15cm WLS + side & back mirrors + dichroic mirror		0.34	0.56	0.47	0.85	**1.37**
12” PMT + 3cm WLS + side & back mirrors + dichroic mirror		0.34	0.44	0.35	0.79	**1.14**
12” PMT + 5mm WLS + side & back mirrors + dichroic mirror		0.35	0.21	0.41	2.00	**0.96**

F Nurozler et al. (TRIUMF)

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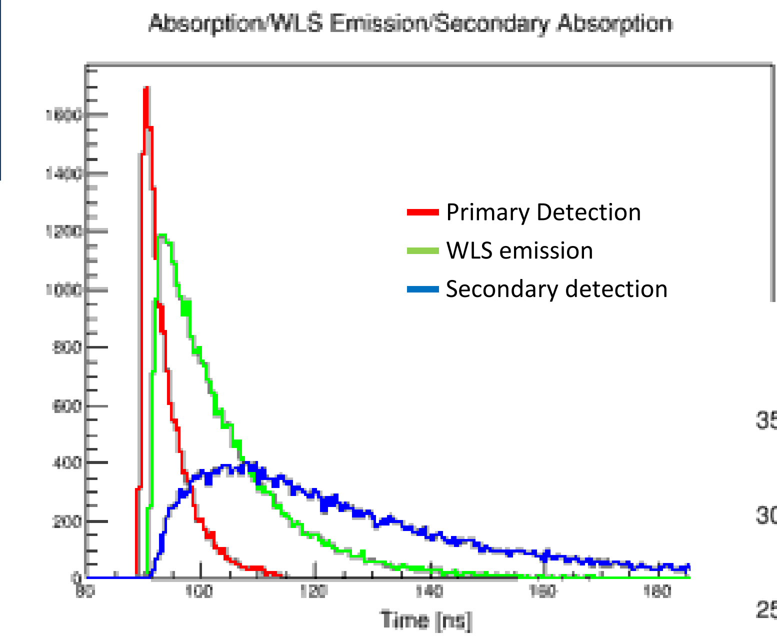
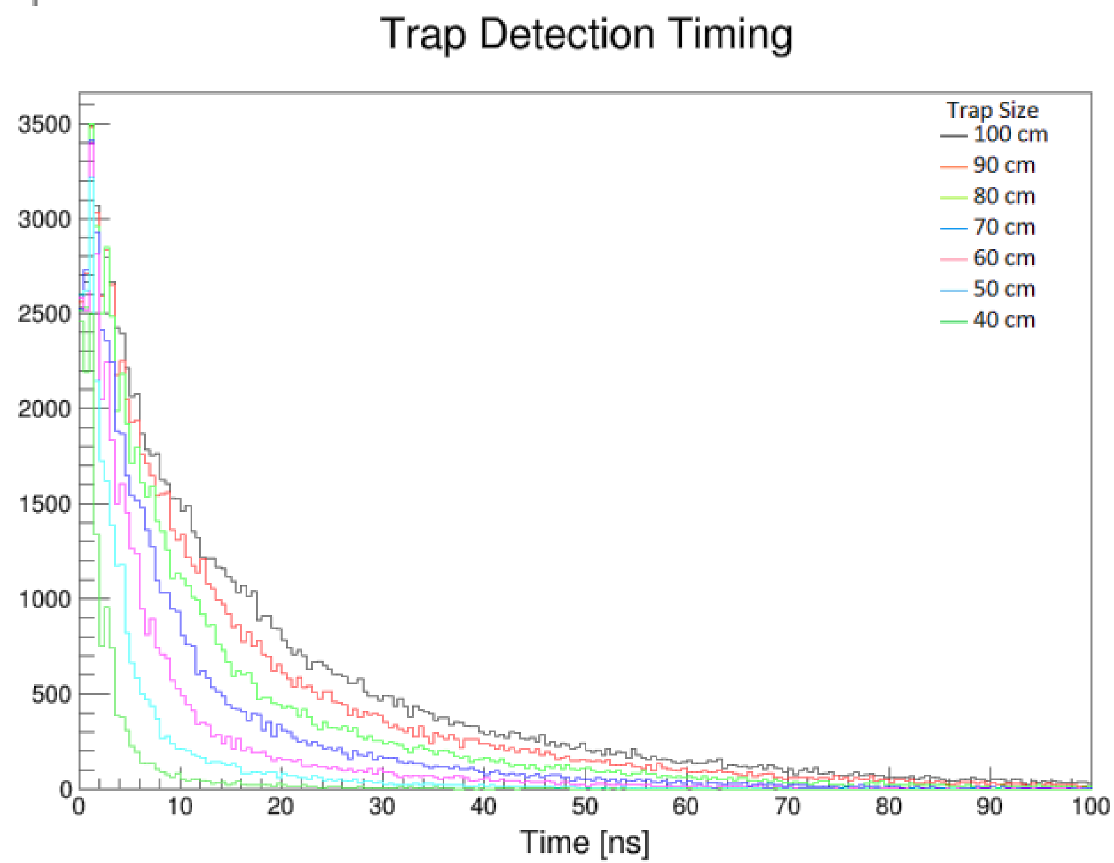
Detection time of trapped photons is rather long

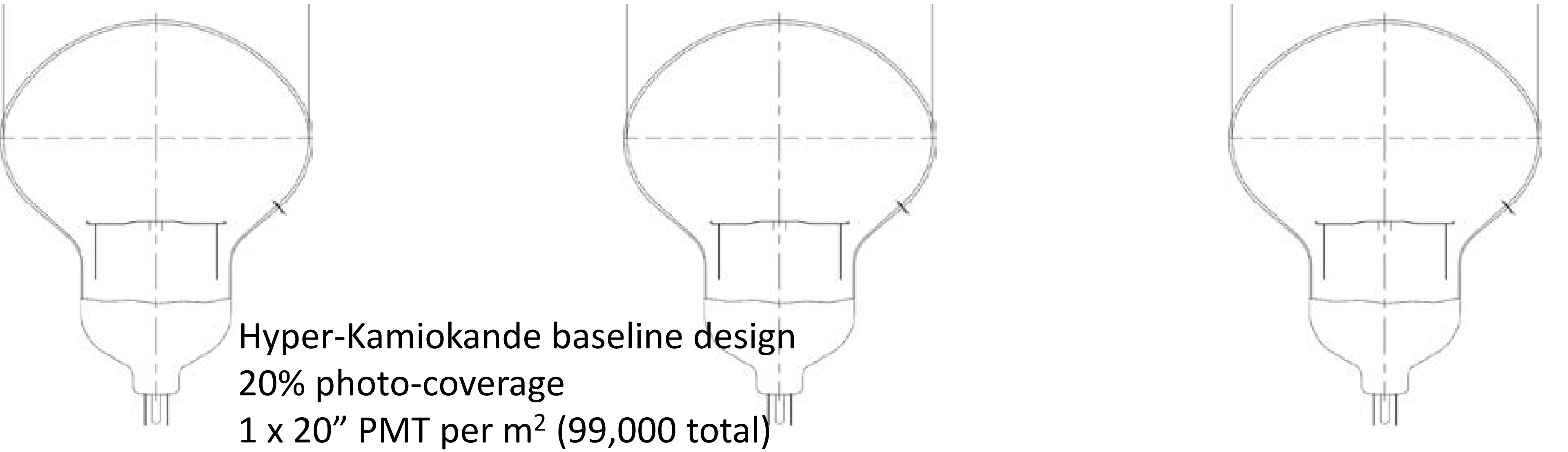


WLS size [cm]	Mean [ns]	RMS
100	19.3	19.9
90	17.0	18.5
80	14.5	16.8
70	11.8	14.6
60	9.1	12.6
50	6.2	9.7
40	3.6	6.5

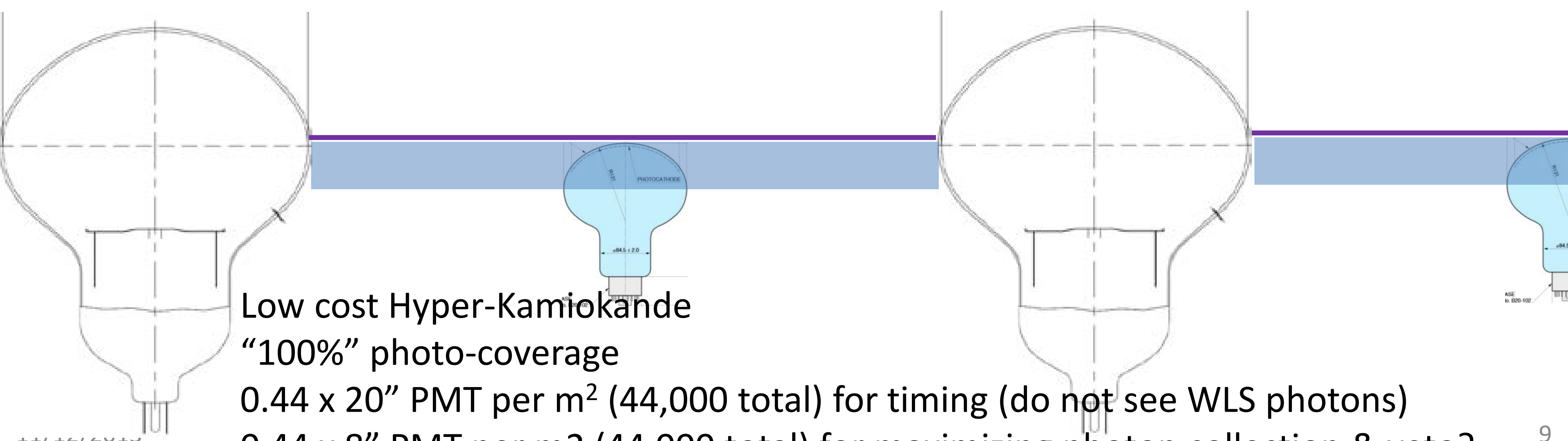


F.Nurozler et al. (TRIUMF)

Direct & WLS combo

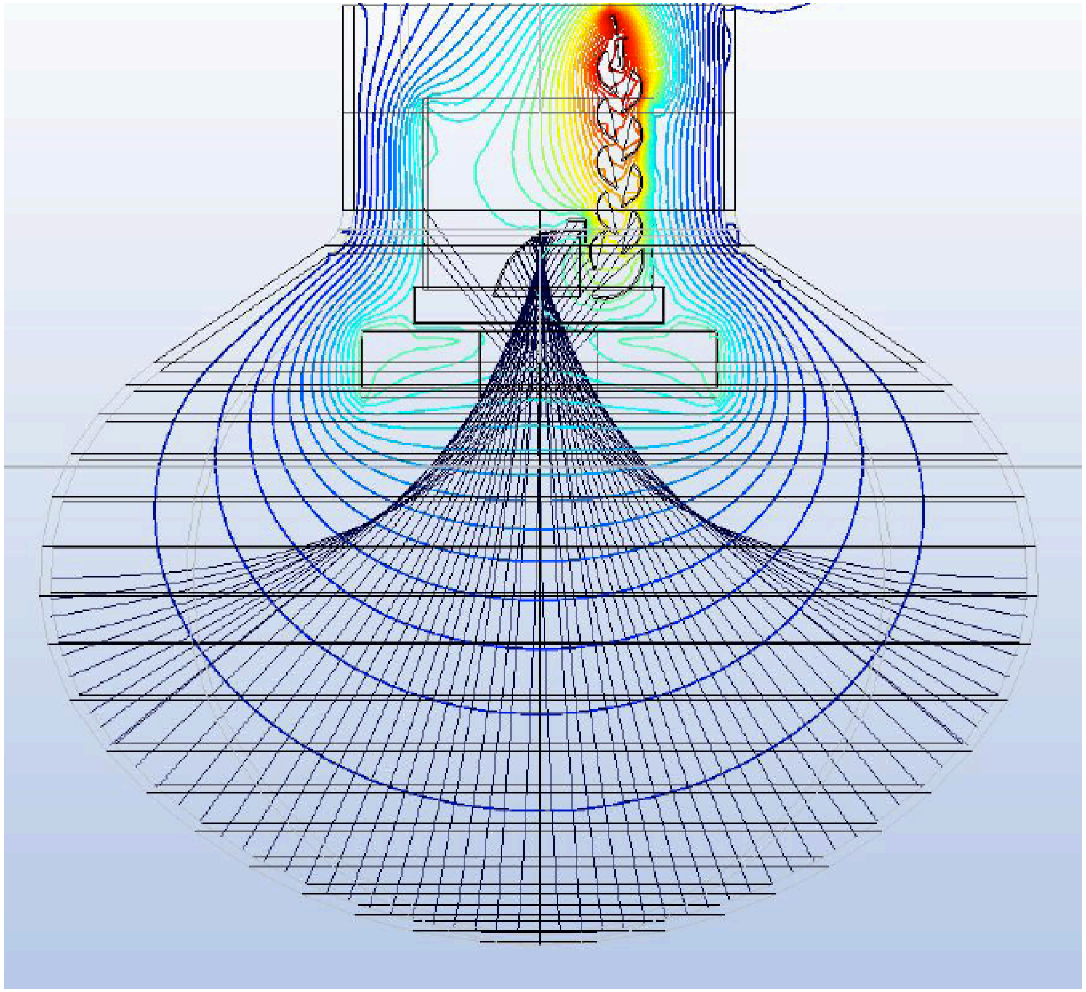


Hyper-Kamiokande baseline design
20% photo-coverage
1 x 20” PMT per m^2 (99,000 total)



Low cost Hyper-Kamiokande
“100%” photo-coverage
0.44 x 20” PMT per m^2 (44,000 total) for timing (do not see WLS photons)
0.44 x 8” PMT per m2 (44,000 total) for maximizing photon collection & veto?

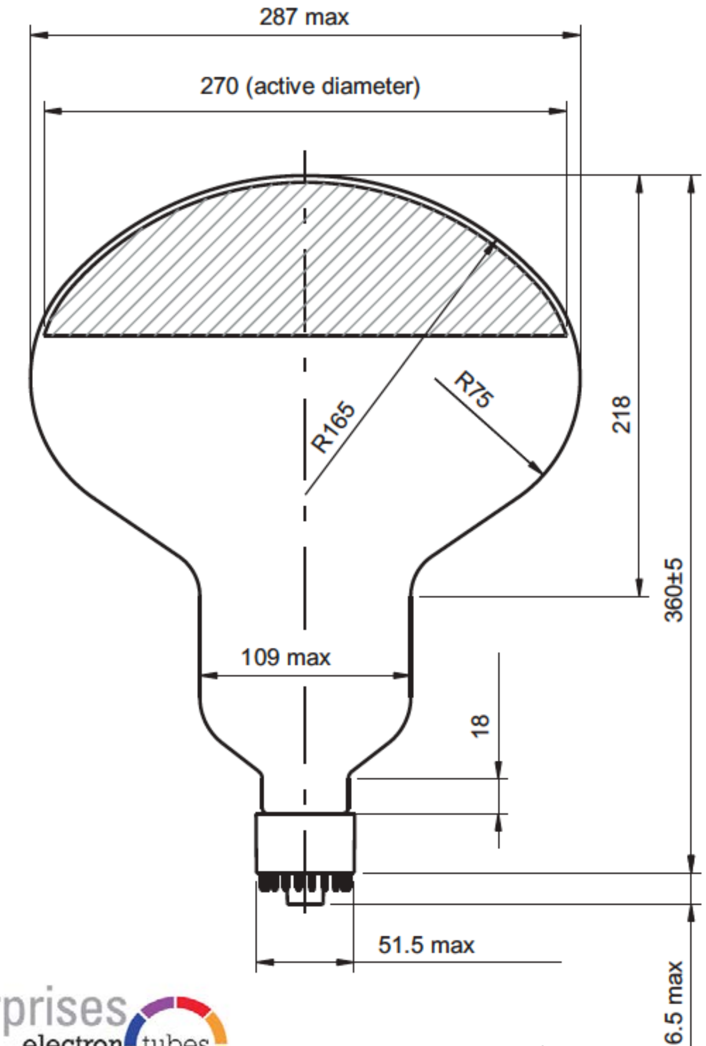
Texas PMT to make the market more competitive



- Develop capabilities of ADIT/ETL companies from Sweetwater Texas
  - Supported by NSF
  - Goal is the development of a US based manufacturer of large area PMTs
- Plan
  - 11” PMTs that could be used for HK veto
  - First prototypes summer 2014
  - Complete tests at Davis, Penn, Drexel by mid 2015

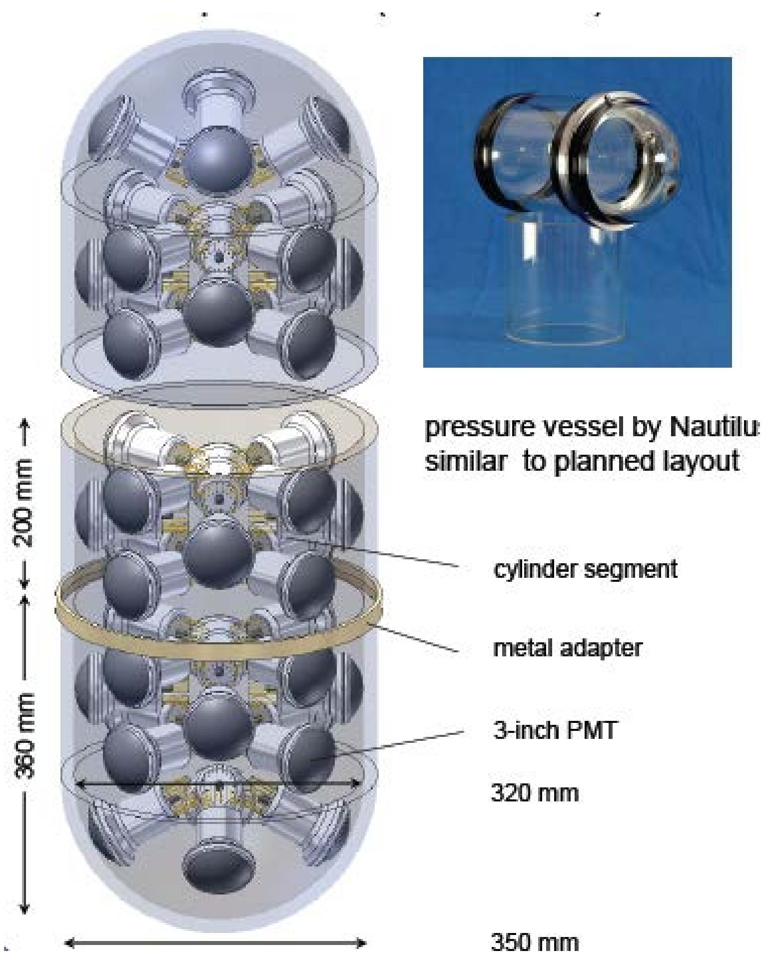
11” PMT provisional data sheet

	unit	min	typ	max
photocathode: bialkali				
active diameter	mm		270	
active surface area	cm^2		800	
quantum efficiency at peak	%		30	
luminous sensitivity	µA/lm		70	
with CB filter		8	12	
with CR filter			1	
dynodes: 12LFSbCs				
anode sensitivity in divider A:				
nominal anode sensitivity	A/lm		500	
max. rated anode sensitivity	A/lm		2000	
overall V for nominal A/lm	V		1400	1800
overall V for max. rated A/lm	V		1550	
gain at nominal A/lm	$\times 10^6$		7	
dark current at 20 °C:				
dc at nominal A/lm	nA		20	200
dc at max. rated A/lm	nA		80	
dark count rate	s^{-1}		20000	
pulsed linearity (-5% deviation):				
divider A	mA		30	
divider B	mA		100	
pulse height resolution:				
single electron peak to valley	ratio		2	
rate effect (I_a for $\Delta g/g$=1%):	µA		20	
temperature coefficient:	% $°C^{-1}$		± 0.5	
timing:				
single electron rise time	ns		5	
single electron fwhm	ns		6	
single electron jitter (fwhm)	ns		3	
transit time	ns		62	
weight:	g		2600	
maximum ratings:				
anode current	µA			100
cathode current	nA			2000
gain	$\times 10^6$			30
sensitivity	A/lm			2000
temperature	°C	-30		60
V (k-a)(1)	V			2350
V (k-d1)	V			750
V (d-d)(2)	V			300
ambient pressure (absolute)	kPa			808



ET Enterprises electron tubes

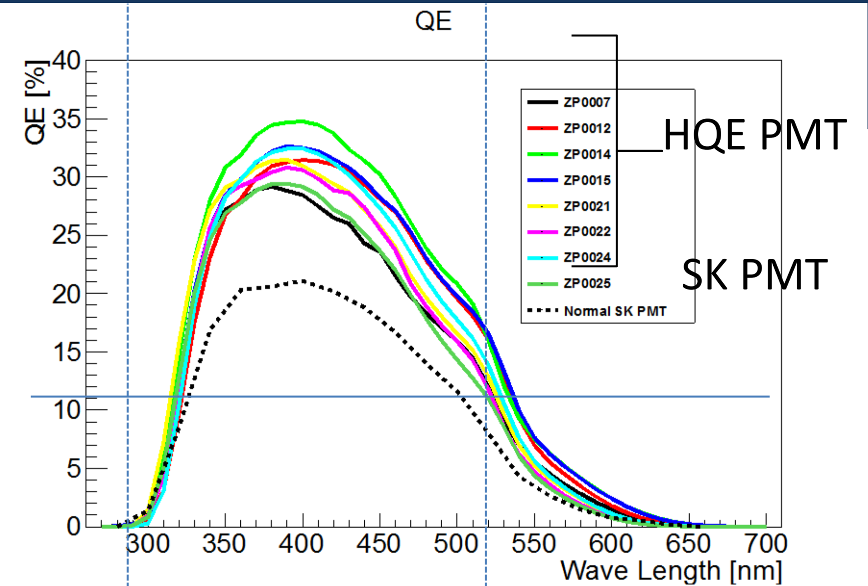
Alternate option pursued by KM3Net and possibly MICA

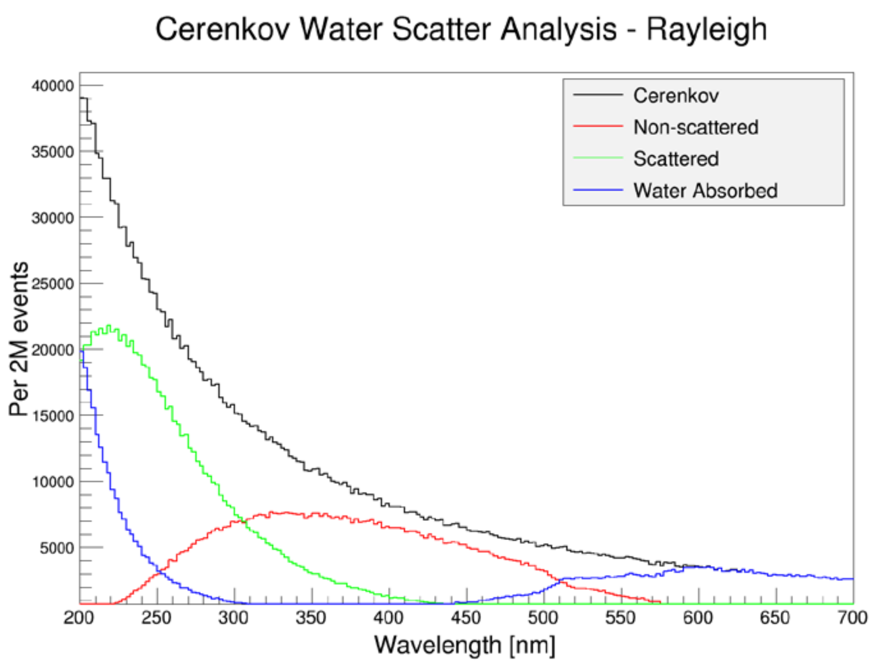


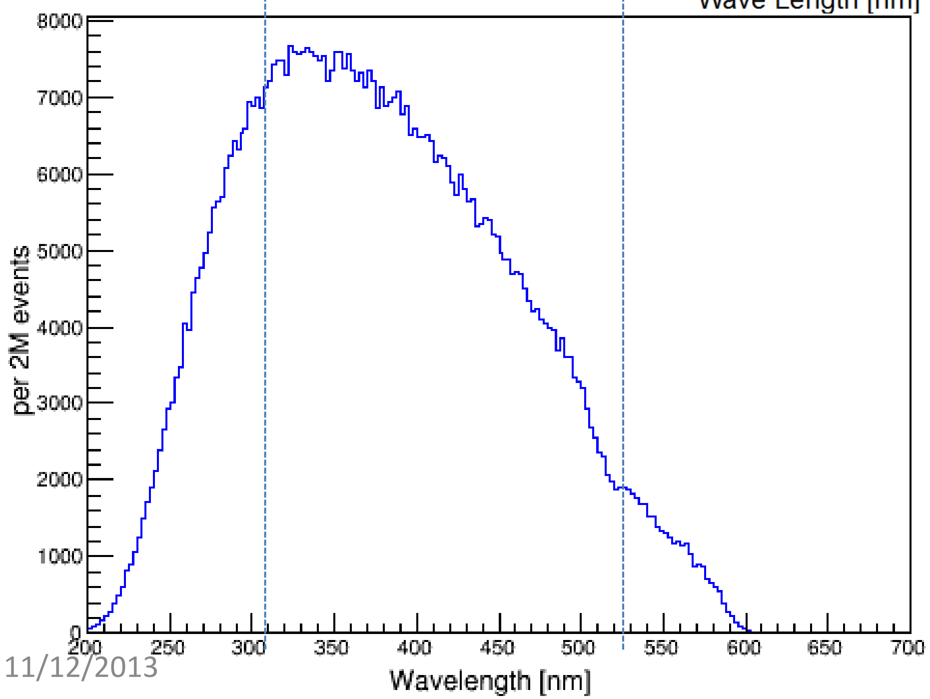
- Use small PMTs
  - High granularity required for background rejection in KM3Net
  - Several manufacturer of small PMTs
- Photon trap could be used in this configuration
  - Cover the inner side of the glass with dichroic mirrors
  - Add wavelength shifter sheets with mirror backing between PMTs

Increasing photo-detection efficiency

- Hamamatsu High quantum efficiency
  - PDE increased from 20 to 30%
  - Also better matching index of refraction matching using BeO?
    - Reduce Fresnel reflection
- Matching to SK water property off by 50 nm







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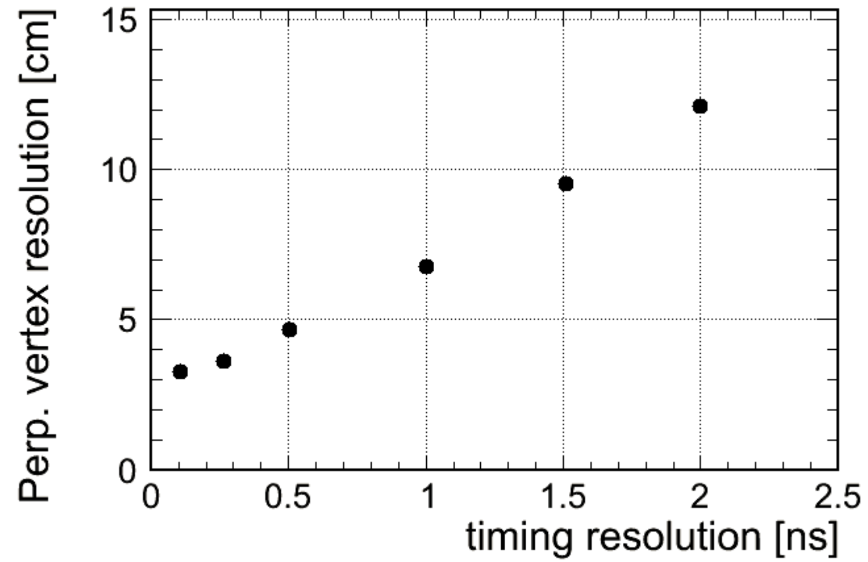
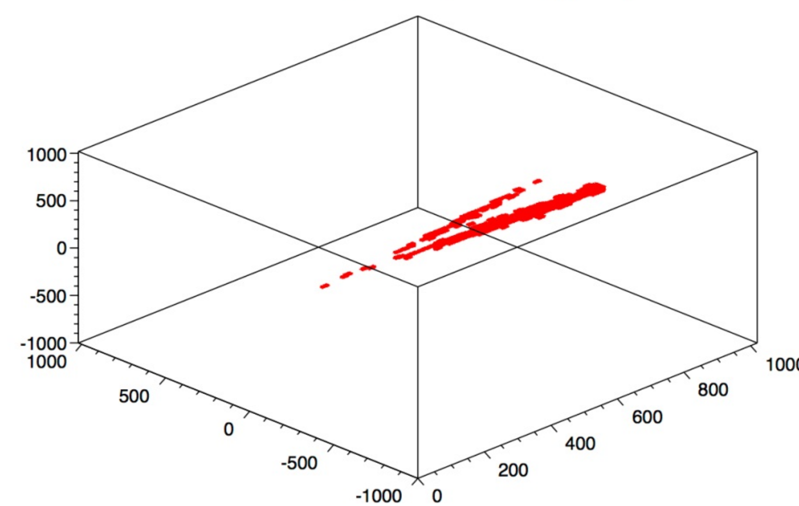
Improving timing resolution

- Currently limited by PMT transit time spread to 2-5ns (per photons)
- LAPPD collaboration has shown the benefit of sub-ns resolution
  - Improved vertex resolution
  - Improved pattern recognition



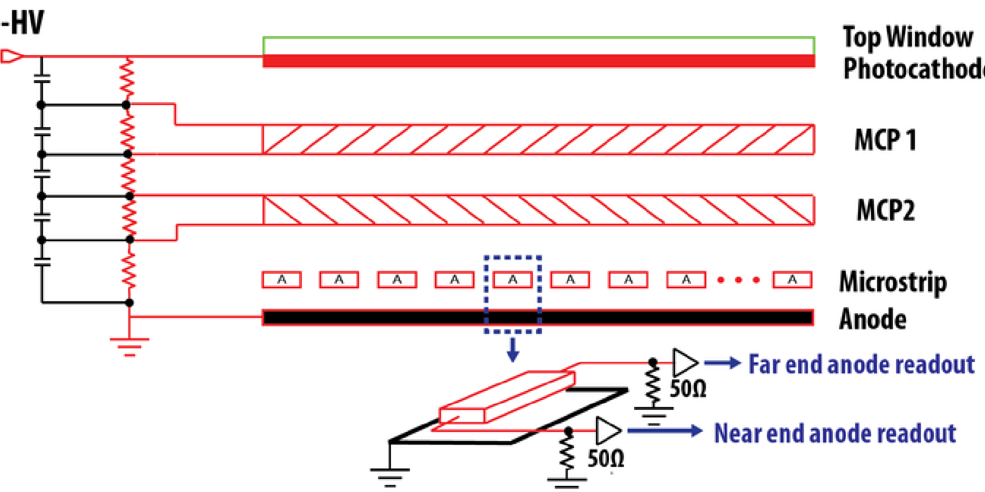
Reconstructed 1.5 GeV Pi0 (geant)

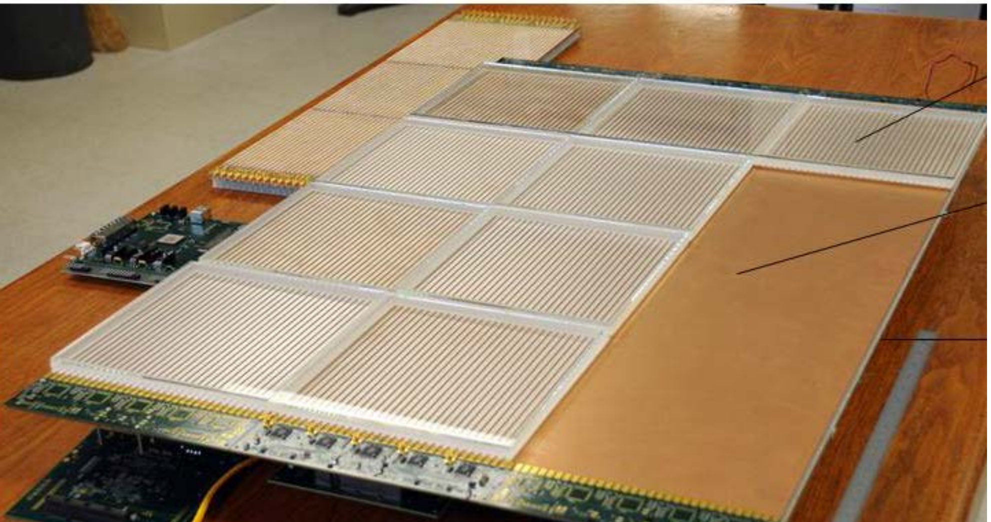


T. Xin, I Anghel, M. Wetstein, M. Sanchez

Large Area Pico-second Photon Detector

LAPPD collaboration





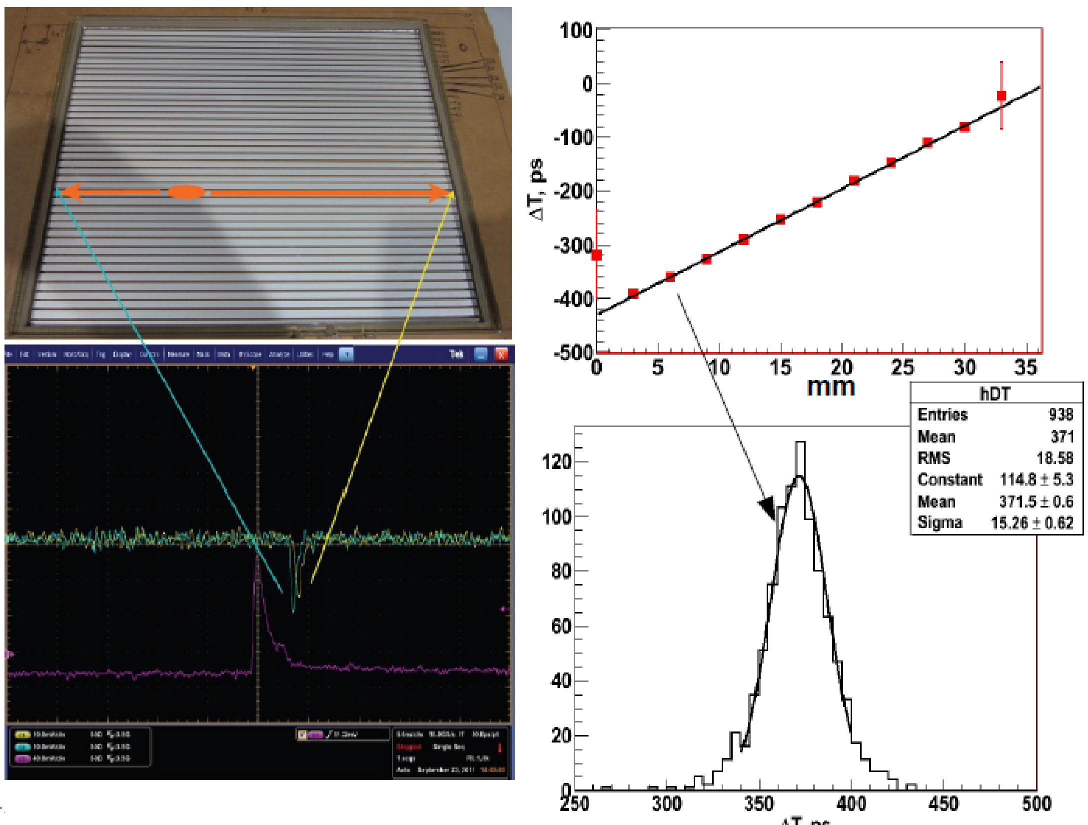
Large Area Picosecond Photo-Detector Project

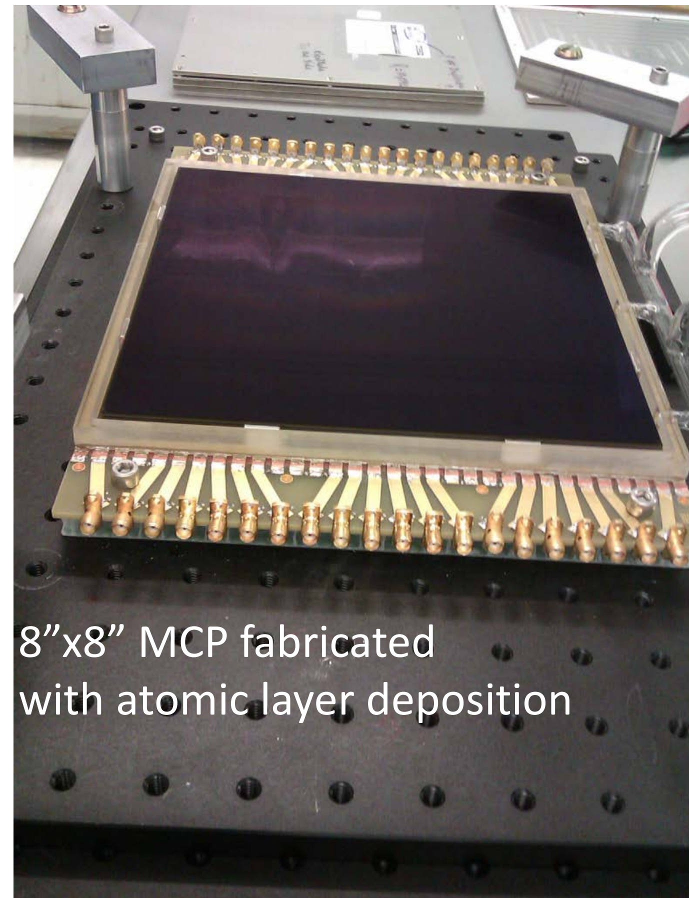
- Goals
  - Single photon timing resolution<100ps
  - Large scale manufacturing
- Solution
  - “Standard” photo-cathode
  - Micro-channel plates
  - Modular tileable solution
    - Expected to be fairly cheap
    - Tile unit 8”x8”
  - High speed electronics
    - With transmission line

LAPPD status

Pictures cropped out of a talk by A. Elagin (U. Chicago)

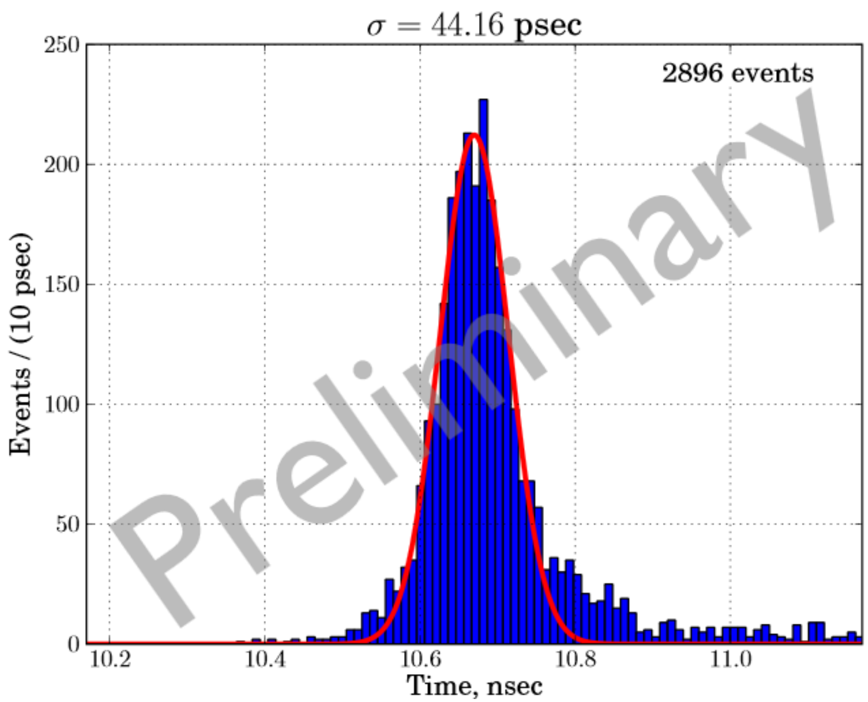
- Managing construction + assembly steps

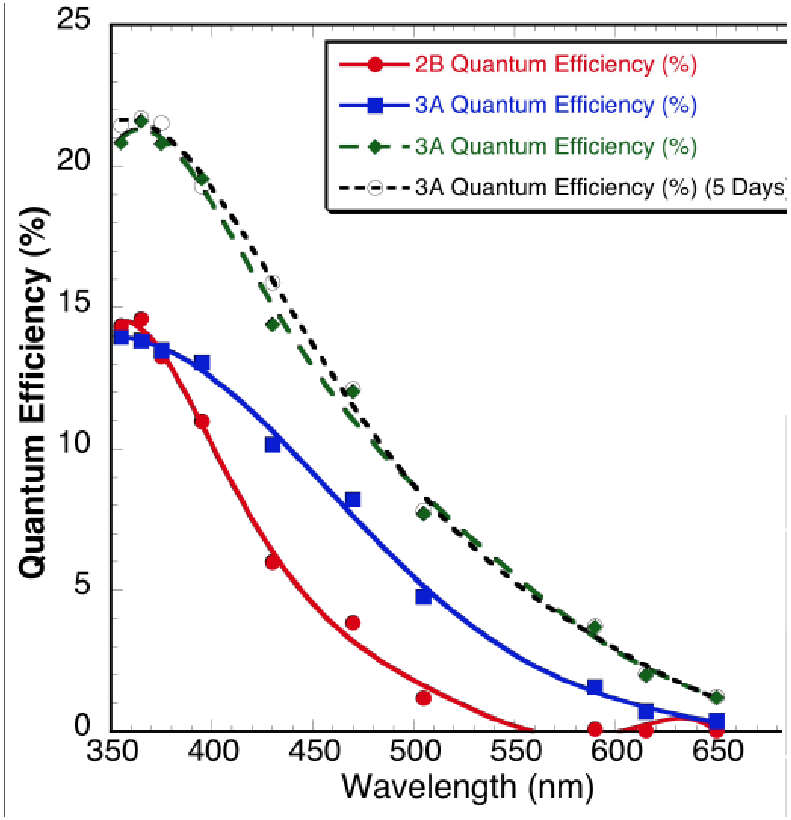




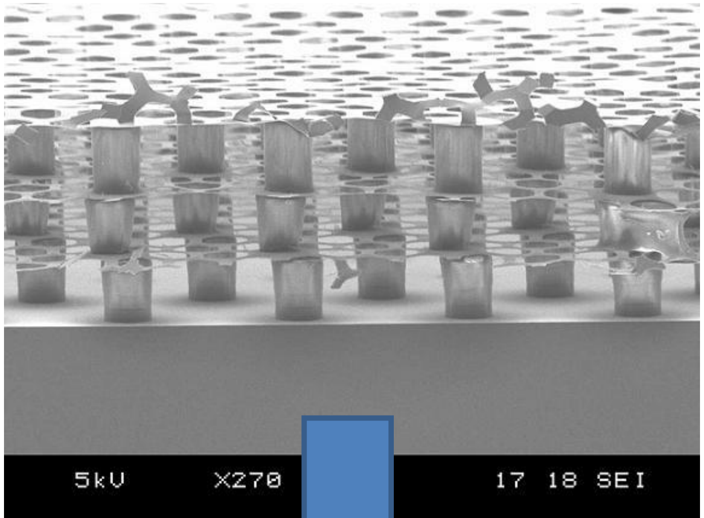
LAPPD status 2

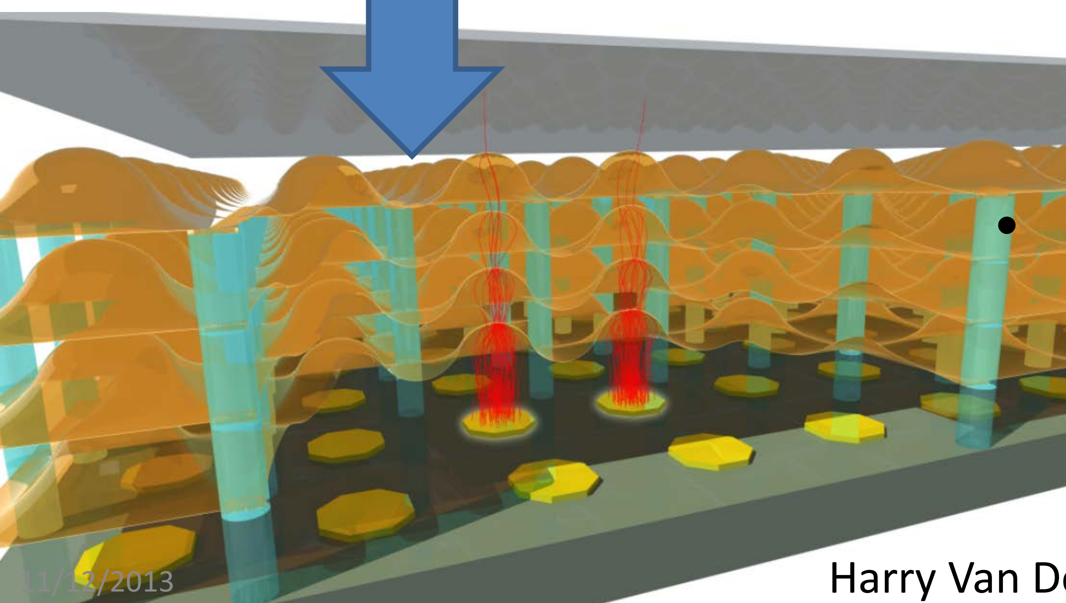
- Excellent single photon timing resolution
- Good photo-detection efficiency





Alternative to MCP: transmission dynodes





- Inspired for gaseous photo-detector
  - Micromegas + timepix
  - Use MEMs technology to build membranes supported by pilars
  - Photo-cathode technology unchanged
- Time Photon Counter (Tipsy)
  - High gain from amplification through membrane + low noise pixel electronics
- Main challenge is to achieve sufficient secondary emission
  - Then mechanical stability will be an issue!

Harry Van Der Graff et al. (Delft/Nikhef)

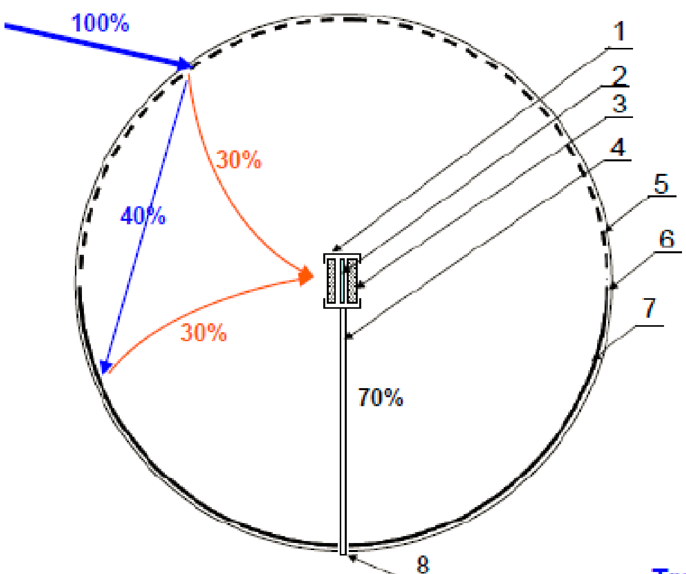
Focus MCP PMT for Data Bay 2

Slides copied from S. Qian (IHEP) IEEE NSS talk

High photon detection efficiency + Single photoelectron Detection + Low cost

1) Using two sets of Microchannel plates (MCPs) to replace the dynode chain

2) Using transmission photocathode (front hemisphere) and reflection photocathode (back hemisphere) } **~ 4π viewing angle!**



1.Insulated trestle table

2.Anode

3.MCP dodule

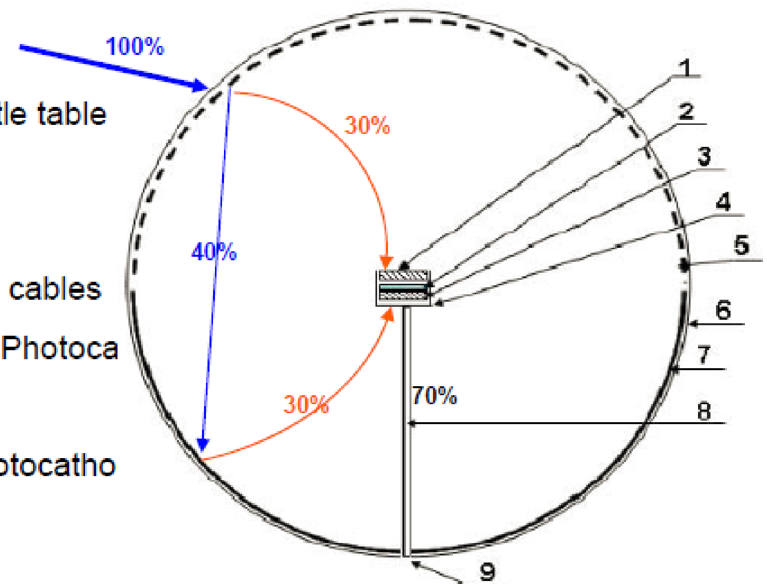
4.Bracket of the cables

5.Transmission Photoca

6.Glass shell

7.Reflection Photocatho

8.Glass joint



Transmission rate of the glass: 40%

Quantum Efficiency (QE) : of Transmission Photocathode 30% ; of Reflection Photocathode 30% ;

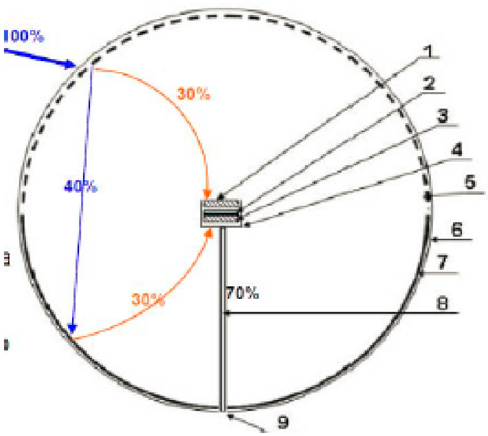
Collection Efficiency (CE) of MCP : 70%;

$$PD = QE_{Trans}{}^{*}CE + TR_{Photo}QE_{Ref}{}^{*}CE = 30\%{*}70\% + 40\%{*}30\%{*}70\% = 30\%$$

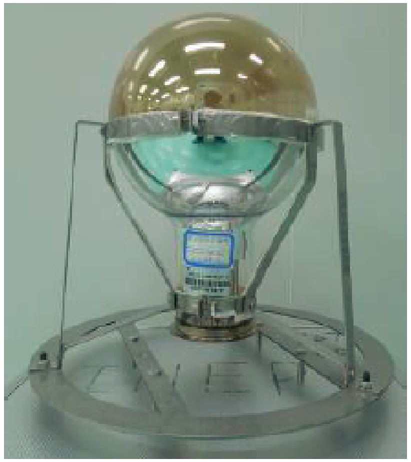
Photon Detection Efficiency: 15% → 30% ; ×~2 at least !

Horizontal configuration results

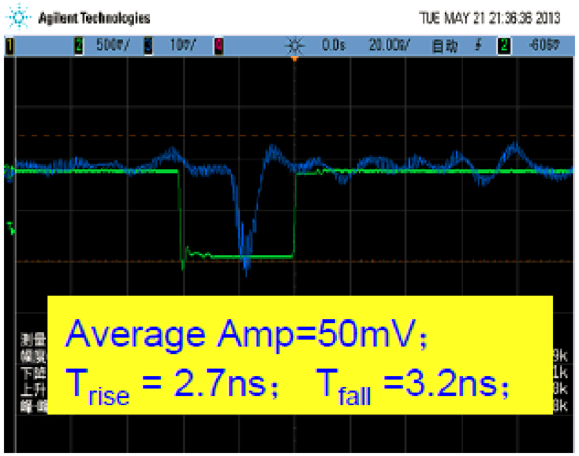
Slides copied from S. Qian (IHEP) IEEE NSS talk



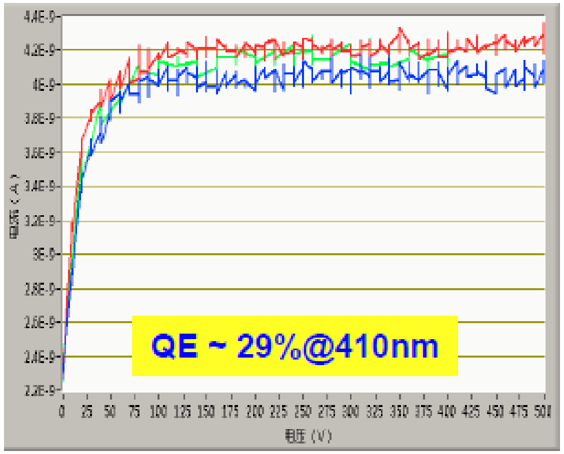
The Design MCP-PMT



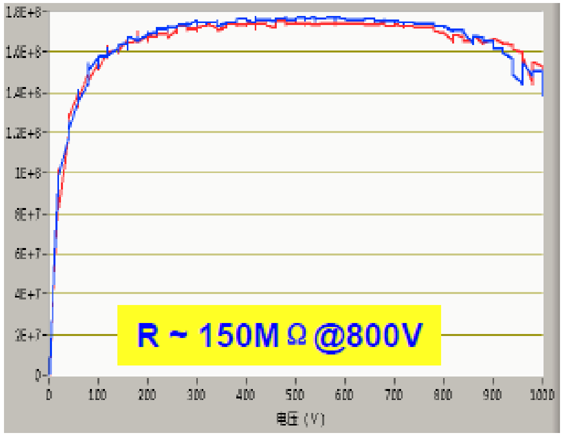
The Prototype



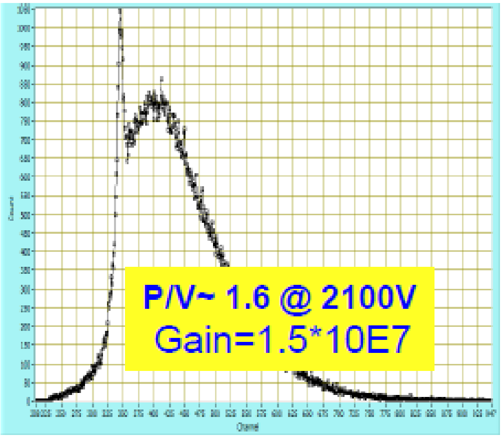
The signal of the 8 inch PMT



The I-V curve of the PC



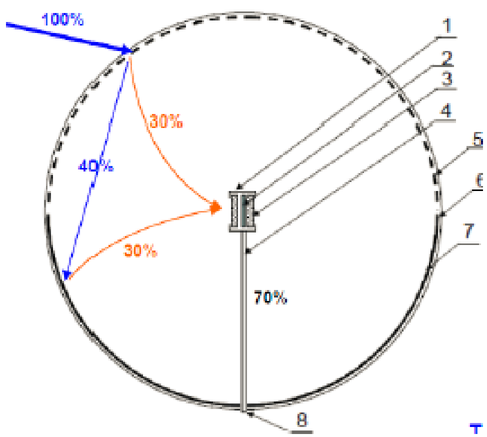
The body resistance of the MCP



The SPE of the PMT

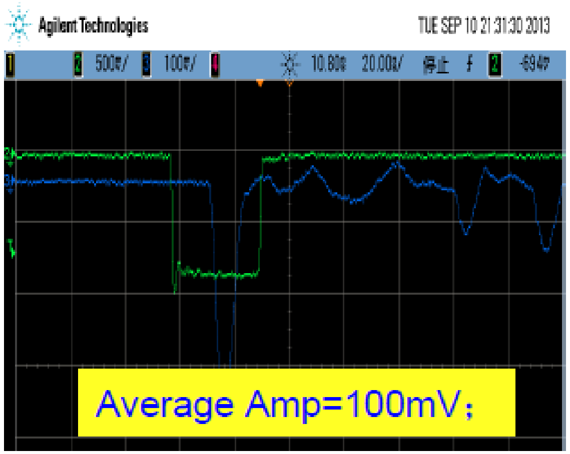
Vertical configuration results

Slides copied from S. Qian (IHEP) IEEE NSS talk

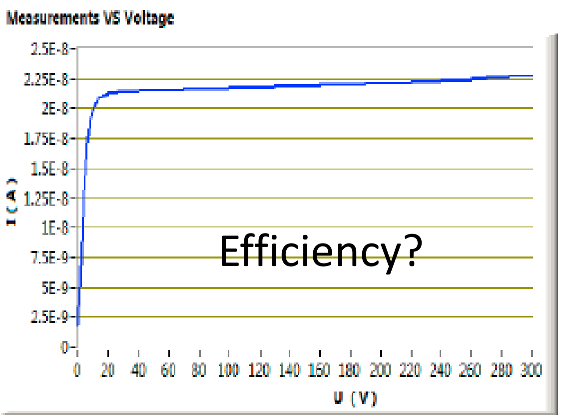


The Design MCP-PMT

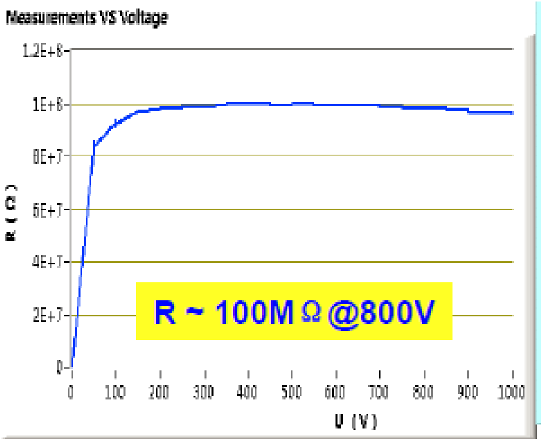
The Prototype



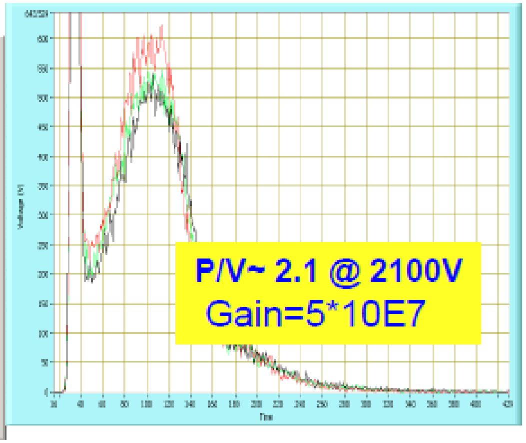
The signal of the 8 inch PMT



The I-V curve of the PC



The body resistance of the MCP

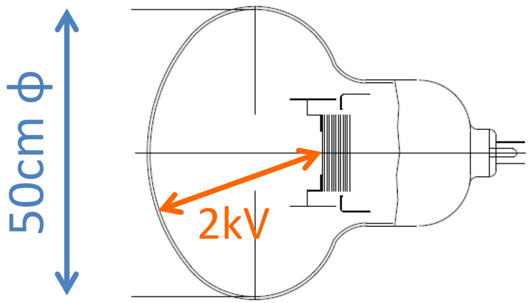


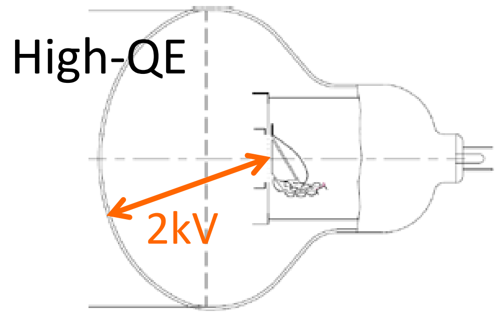
The SPE of the PMT

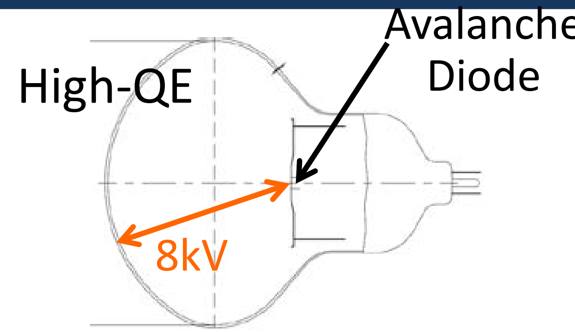
TRIUMF

Hyper-K R&D approach

Y. Hayato[1], S. Hirota[2], I. Kametani[1], M. Nakahata[1], T. Nakaya[2], S. Nakayama[1], Y. Nishimura[1], M. Shiozawa[1], Y. Suda[3], H. Tanaka[1], K. Tateishi[2], M. Yokoyama[3]
[1]Institute for Cosmic Ray Research, The University of Tokyo
[2]Department of Physics, The Kyoto University
[3]Department of Physics, The University of Tokyo







20″ PMT
(Venetian-Blind dynode)

- Super-K ID PMTs
- Used for ~20 years
  → Guaranteed
- Complex production
  → Expensive

20″ Improved PMT
(Box&Line dynode)

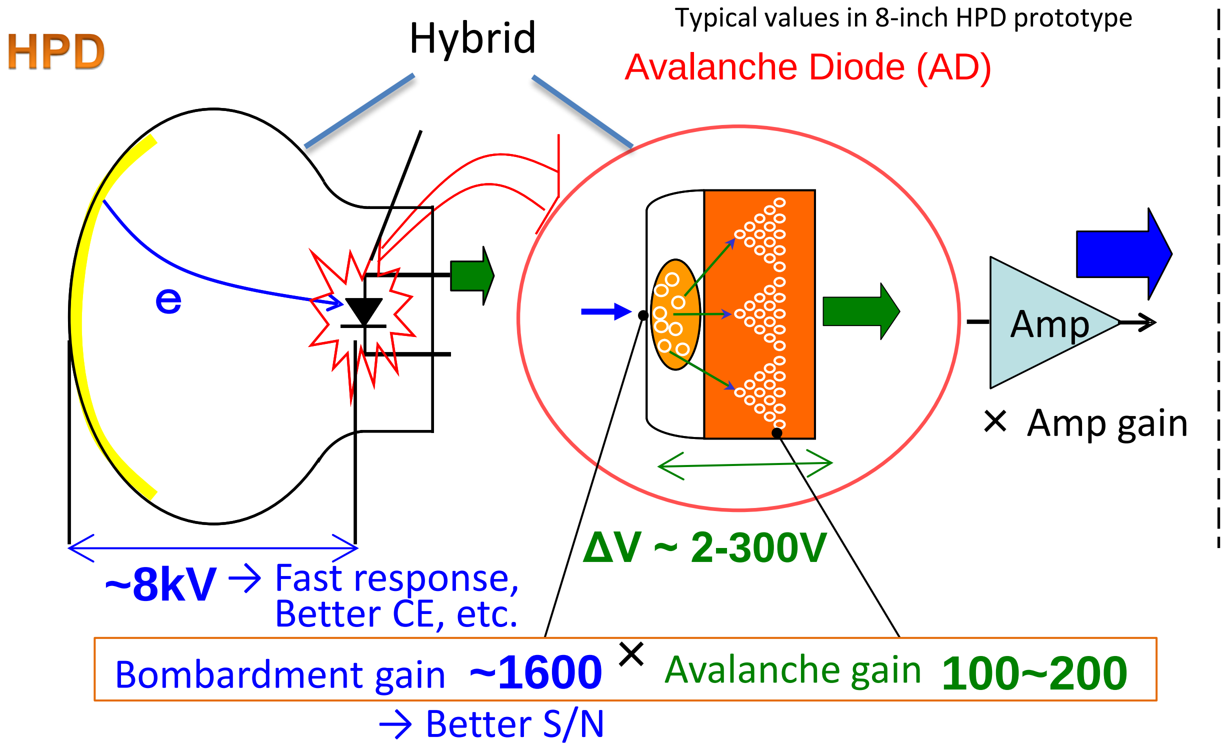
- Under development
- Better performance
- Same technology
  → Lower risk

20″ HPD
(Hybrid Photodetector)

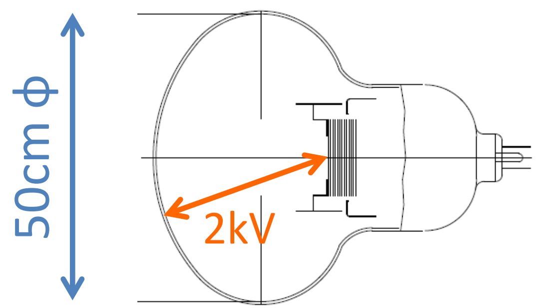
- Under development
- Far better performance
- Simple structure
  → Lower cost
- New technology
  → Higher risk

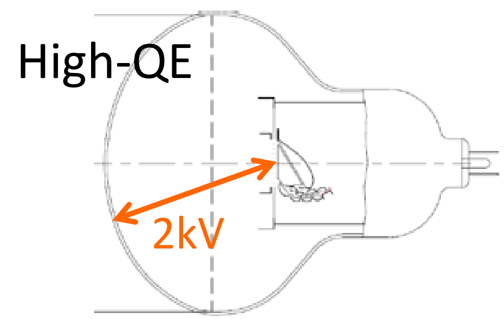
Lower Risk ⟵ ⟶ Higher Performance

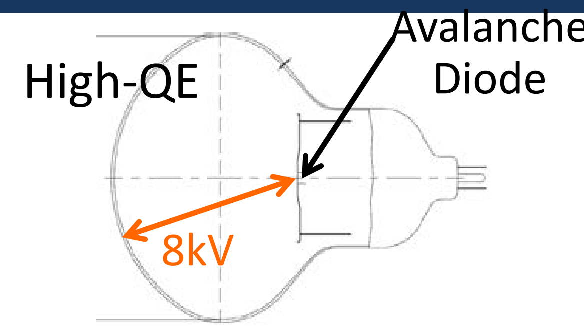
HPD concept


HPD
Hybrid
Typical values in 8-inch HPD prototype
Avalanche Diode (AD)
e
Amp
× Amp gain
ΔV ~ 2-300V
~8kV → Fast response, Better CE, etc.
Bombardment gain ~1600 × Avalanche gain 100~200
→ Better S/N

Hyper-K photodetector candidates







20″ PMT
(Venetian-Blind dynode)

20″ Improved PMT
(Box&Line dynode)

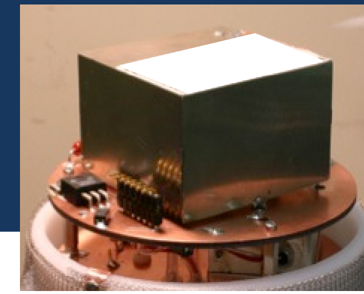
20″ HPD
(Hybrid Photodetector)

	20″ PMT	New 20″ PMT	20″ HPD
Gain	1×10^7	1×10^7	$10^4 \sim 10^5$*
C.E.	80%	93%	95%
T.T.S. (FWHM)	5.5ns	2.7ns	0.75ns*
P/V ratio@1p.e.	1.7	≥2.5	>3

* w/o Preamp

Estimated values

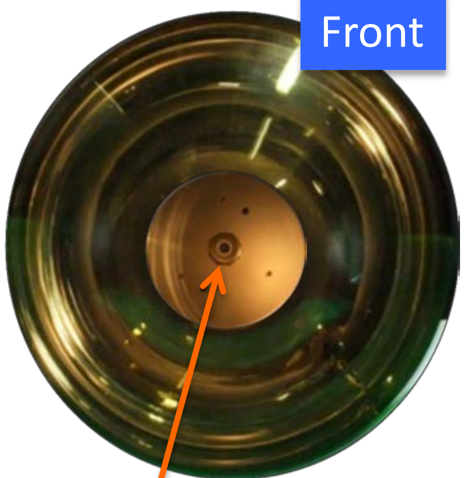
8" HPD prototype

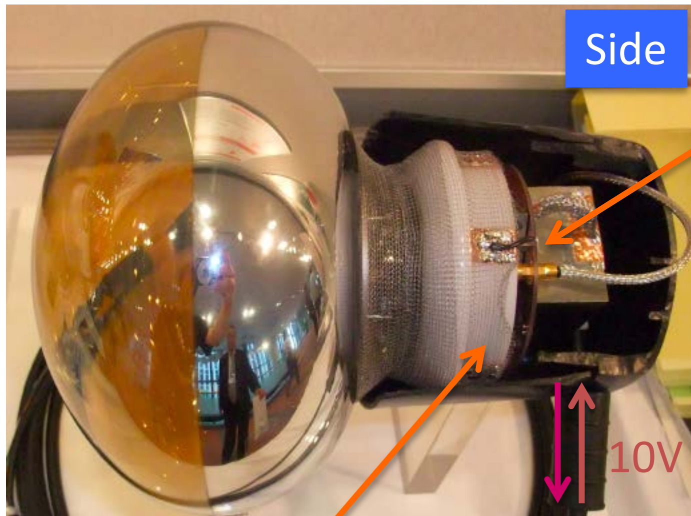


High voltage module
(2ch 10kV/500V Max.)

30cm

20cm





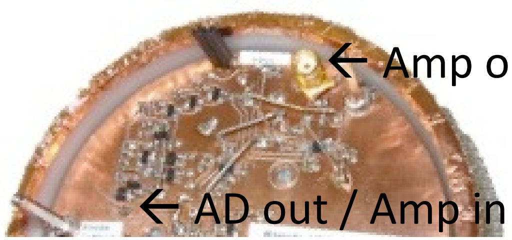
HV module and preamplifier are packed and waterproofed

→ No HV line in water

Signal

5mmϕ AD

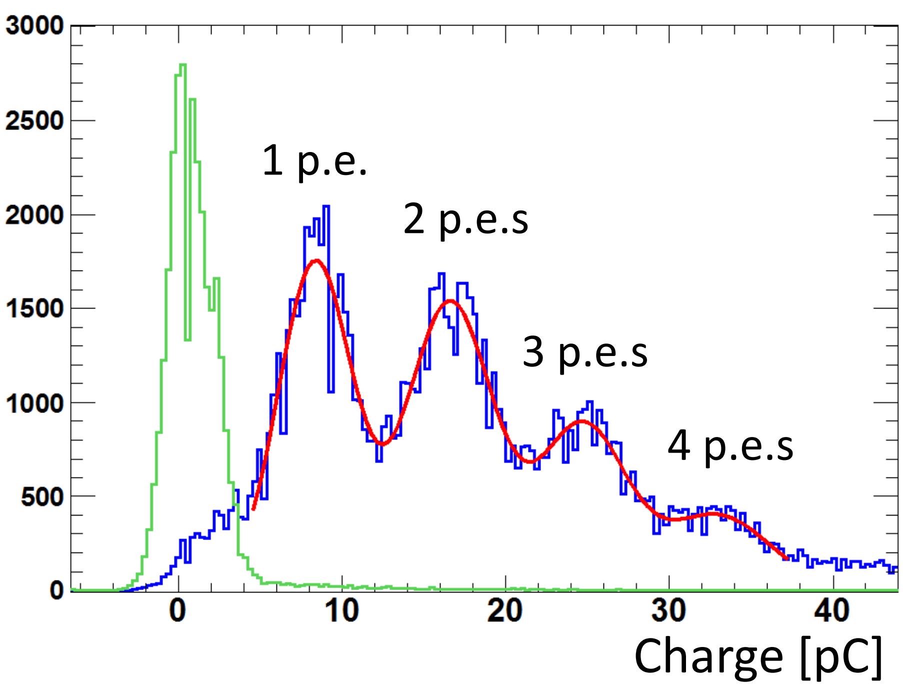
Preamp board

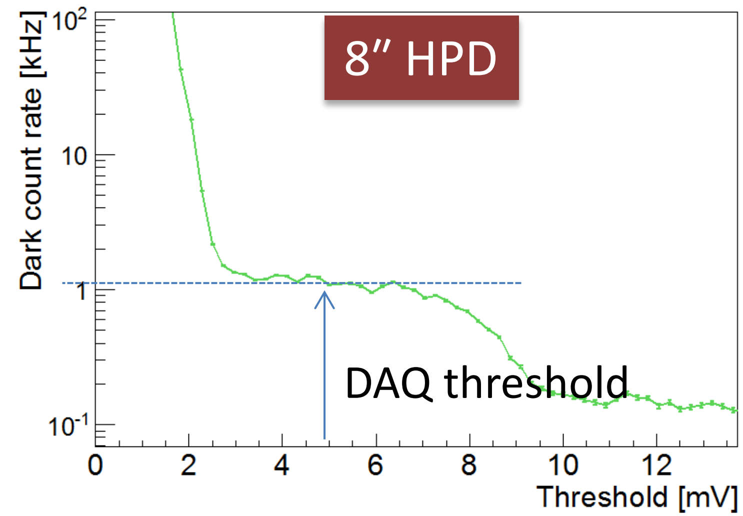


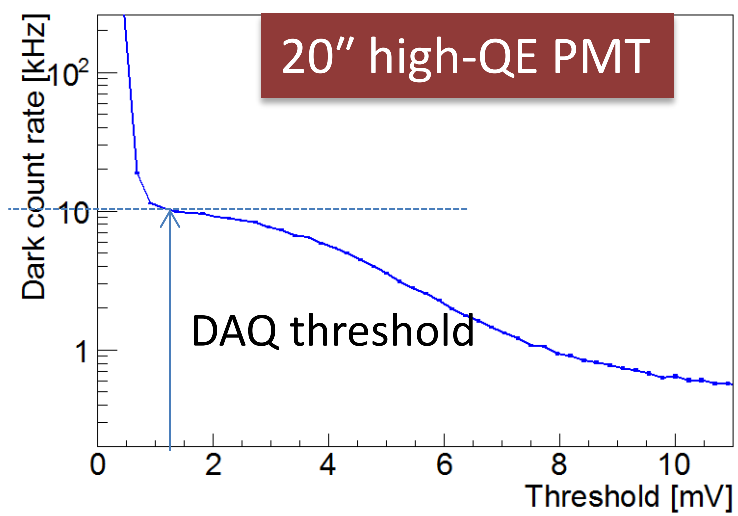
Spectral response		300 - 650 (420 max.) nm
Photocathode		Bialkali
Window material		Borosilicate glass
Gain		4 - 9 $\times 10^4$
Time	Rise	1.7 ns
	Fall	2.7 ns
	T.T.S.	0.62 ns (σ)
Dynamic range		100 pC (1.5×10^4 p.e.)

Ten 8" HPDs were made for long-term testing

HPD measured performances







- Single PE identification
  - Remain for 20" ($20mm^2$ APD)?
- Dark noise / unit area comparable to PMT

New 20” photodetector development status

- Hamamatsu Photonics K.K. is making prototypes of
  - New 20” PMT (Box&Line dynode)
  - 20” HPD
  - Both with high-QE photocathode

- Planning to start a testing in this year

TRIUMF

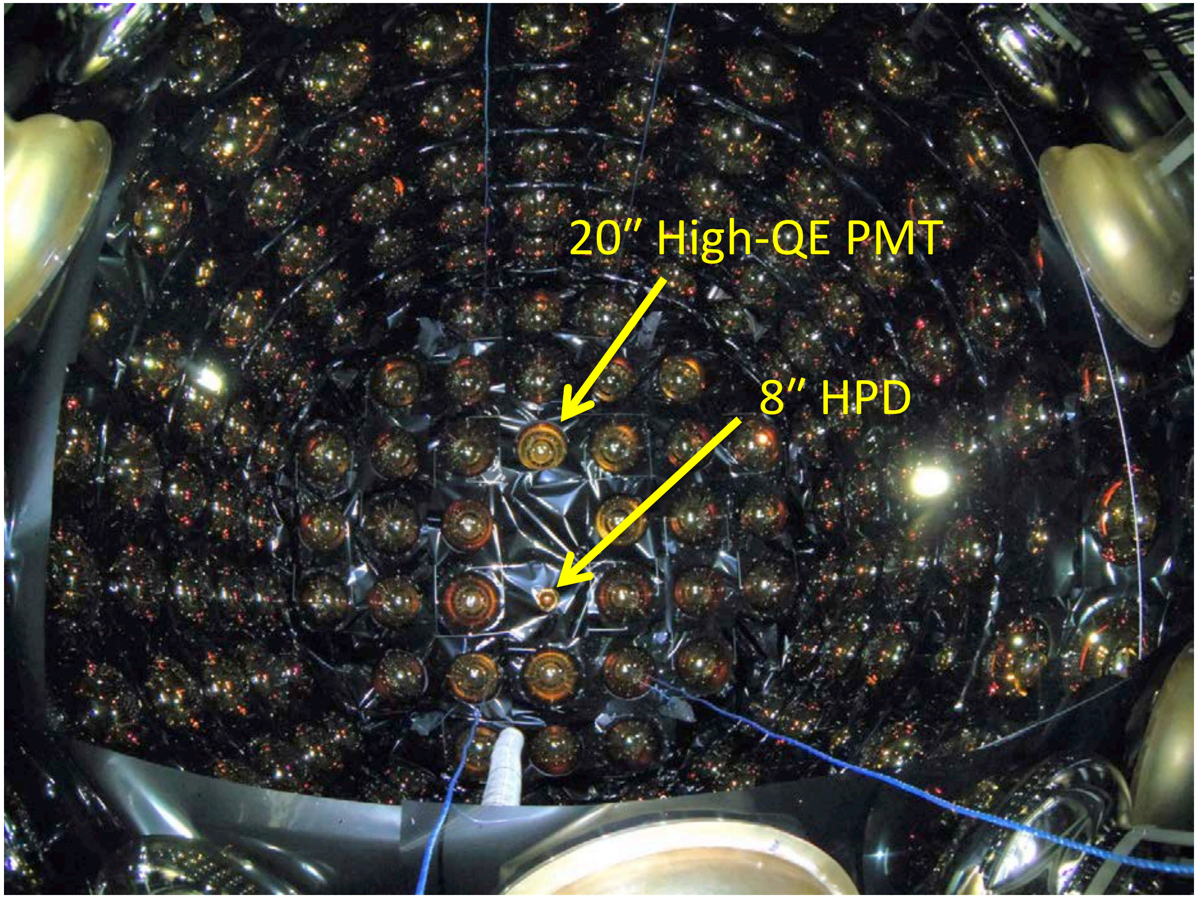
Future photo-detectors for NNN

- Incremental improvement
  - Texas PMT for market diversity
  - Box&line dynode for improved timing
  - Improved photo-detection efficiency
  - Innovative photon collection solution
    - Using WLS + dichroic mirror
  - My guess: pre 2020 detectors
- Game changing solutions
  - <100ps timing resolution with LAPPD (MCP), TYPSI, and cold PPDs (SiPMs)
  - Single photon charge resolution with HPDs & cold PPDs (SiPMs)
  - Need new optimum reconstruction (ala fitQun)
  - My guess: post 2020 detectors
    - If you are not too conservative
    - Is HK pre or post 2020?

Thank you

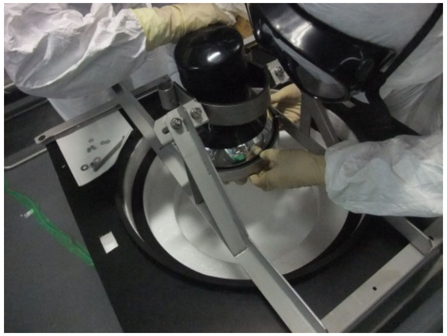
Photodetector installation to EGADS

All 240 photodetectors were installed in July-August



Active work by young students

HPD with supporting frame



Water-proof cable connection

Cable connection in the tank

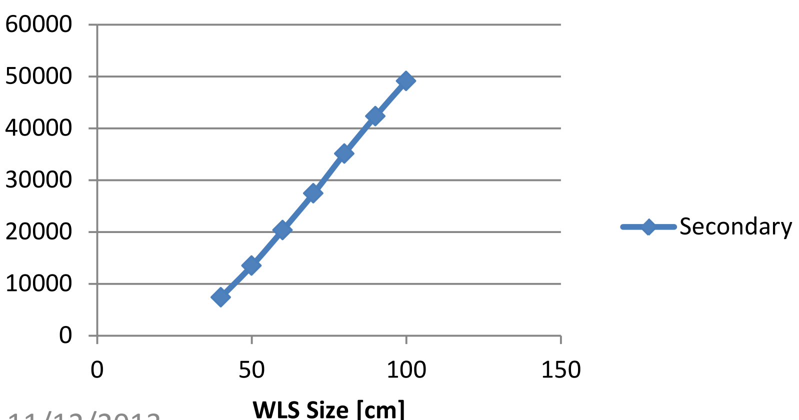
TRIUMF

Trap Size Analysis: WLS Trap

WLS size [cm]	Primary	Secondary	Total	Mean [ns]	RMS
100	0.43	0.38	0.80	16.3	17.9
90	0.43	0.32	0.75	14.1	16.3
80	0.43	0.27	0.69	12.0	14.8
70	0.43	0.21	0.64	9.6	13.0
60	0.43	0.16	0.58	7.4	11.0
50	0.43	0.10	0.53	5.1	8.8
40	0.43	0.06	0.48	2.9	6.3

Details

- Detection numbers are normalized to what a 20” PMT would detect.
- WLS trap: Including a 3cm thick WLS surrounded by side mirrors to support internal reflection.
- Mean and RMS: of time difference between PMT detection and WLS emission.



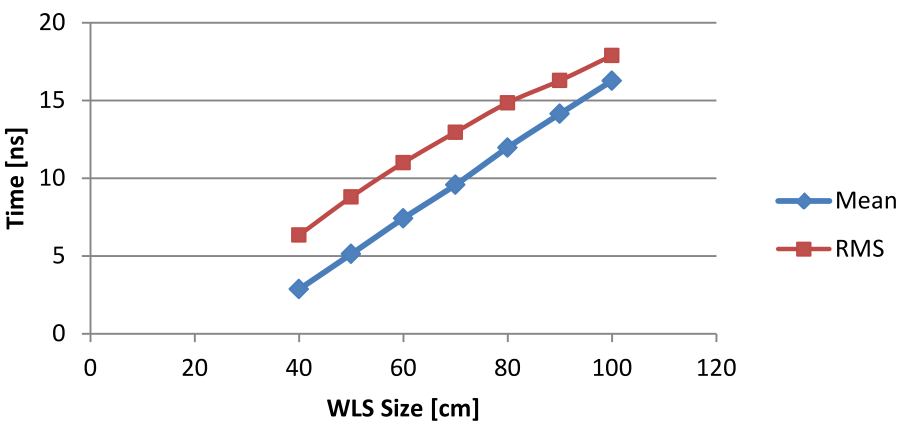
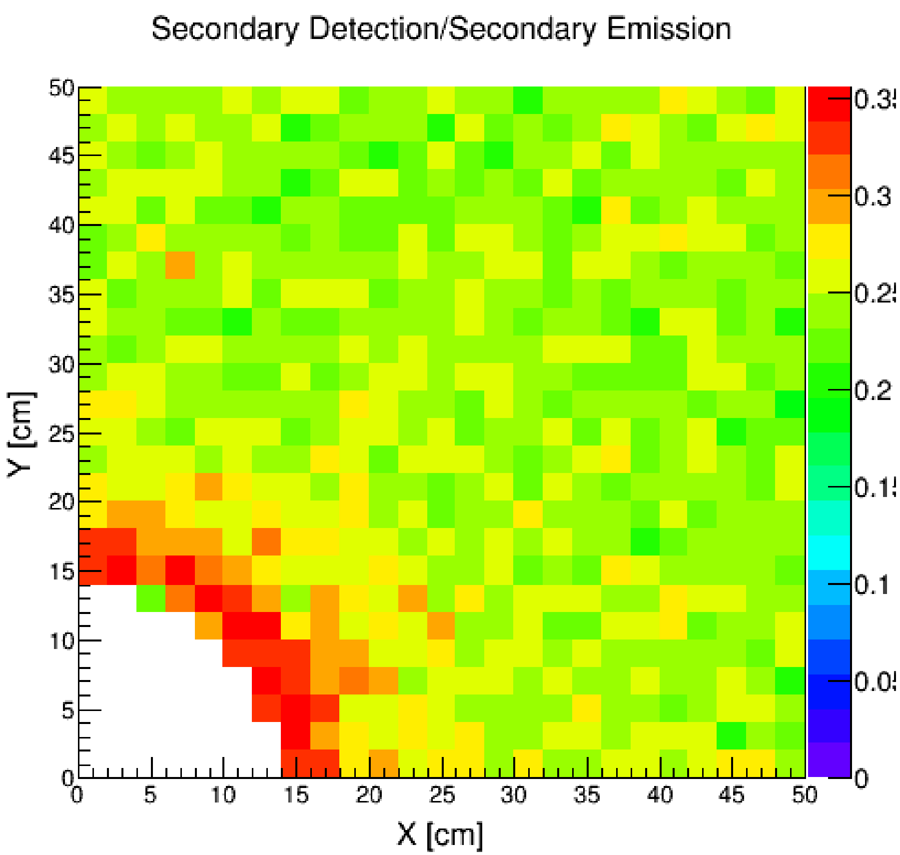


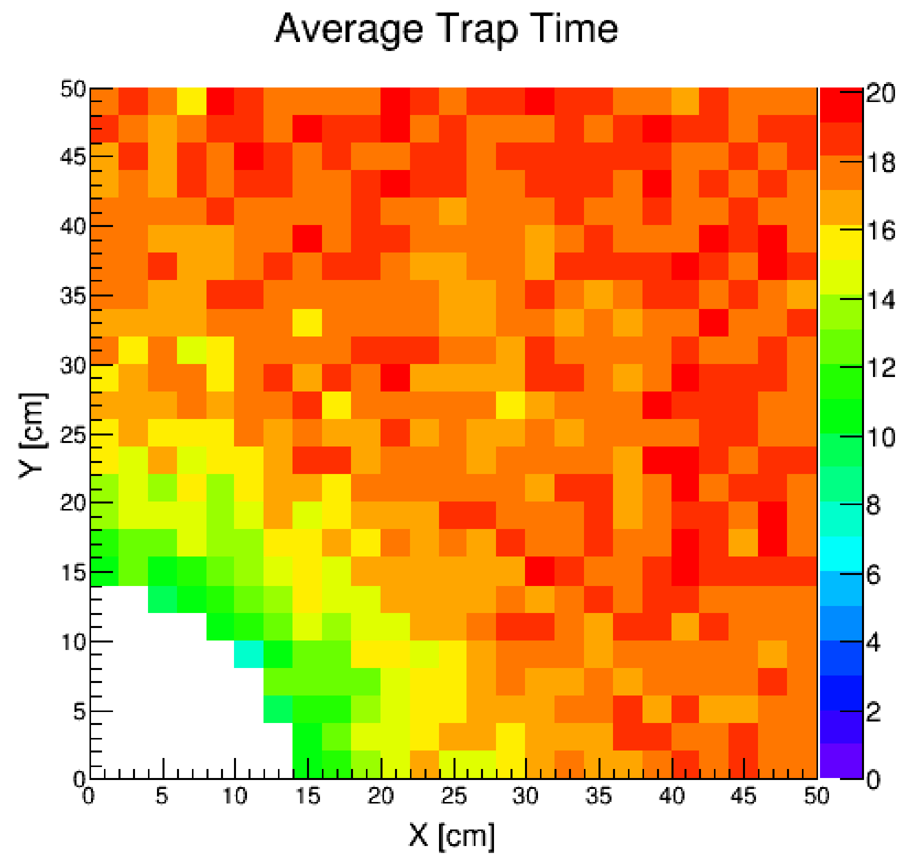
Photo-detector

	Pros	Cons
PMT	Low dark noise Very high gain Low capacitance (low elec. Noise)	-Cost -Fragile -Large gain fluctuations -Max efficiency ~35% -Radioactivity -High voltage
HPD (APD based)	Low dark noise (in principle) Lower cost than PMT (...?) Low gain fluctuations (SPE id)	-Low gain and high capacitance → challenge for electronics -Max efficiency ~35% -Very high voltage
SiPM	-Low dark noise below -100°C -Max efficiency 55% (going up) -Low cost (mass production) -Low radioactivity -Low operating voltage -High gain and low fluctuations	-Huge dark noise at room temp. → non-starter for water Cerenkov -Large capacitance → large area may be challenging for electronics (need R&D)

Other solutions: Micro-Channel Plates, MCP-based HPD, CsI gas detectors

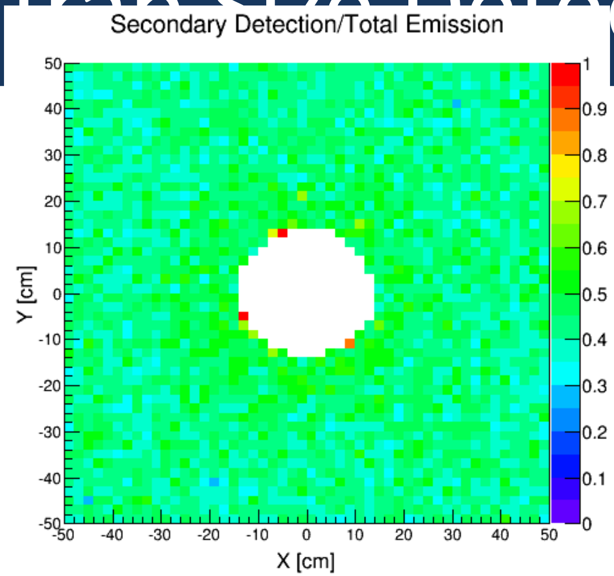
Detection Efficiency: WLS Trap



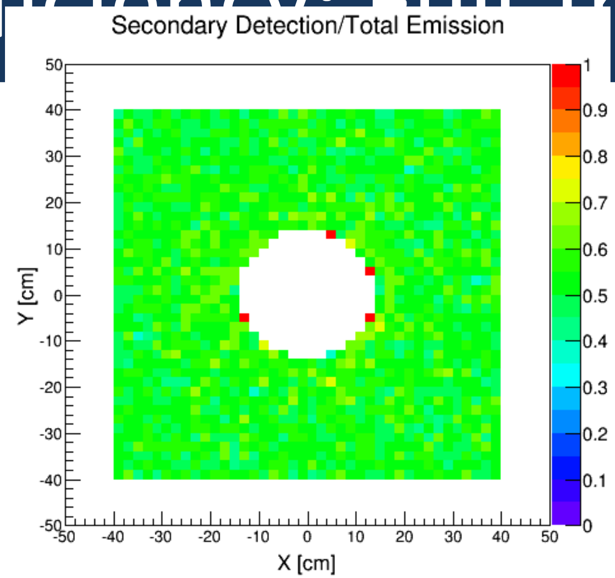


40 times more statistics in these 100 cm WLS traps.

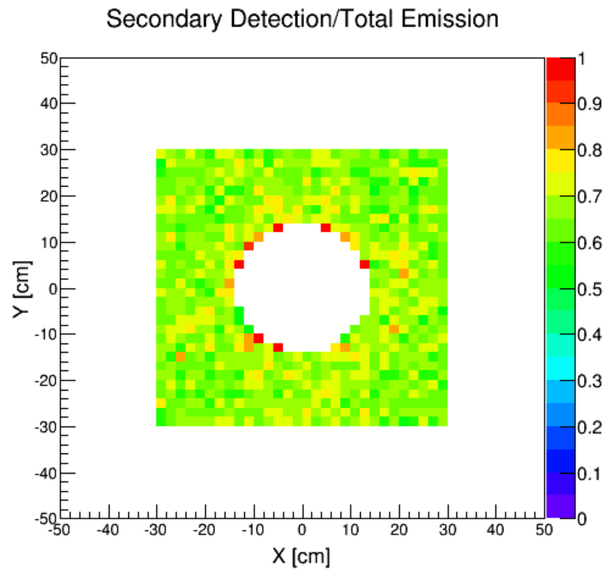
Trap Size Detection Efficiency: Full Trap



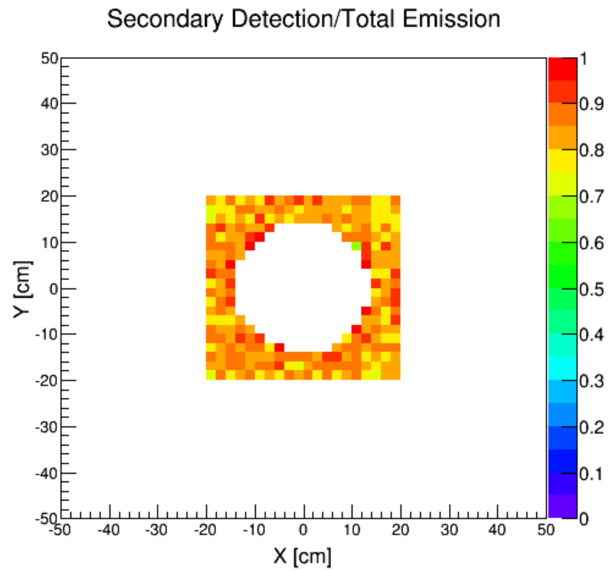
100 cm



80 cm



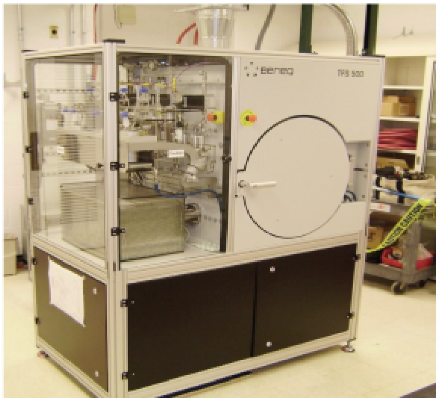
60 cm



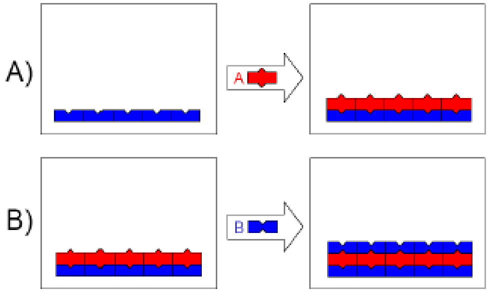
40 cm

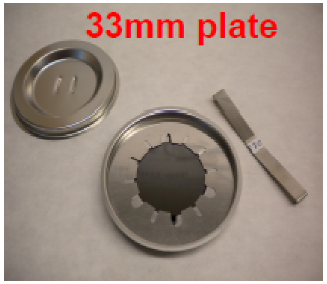
MCP by Atomic Layer Deposition (ALD)

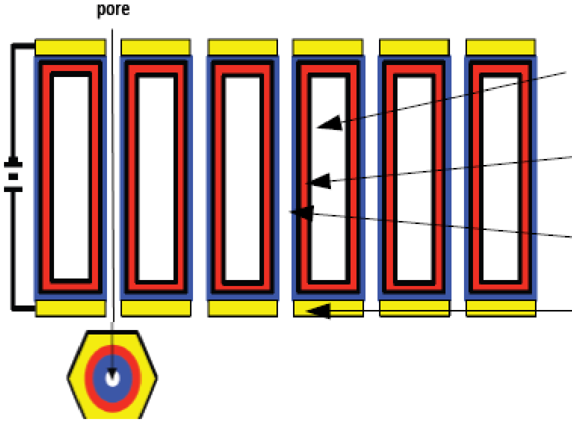
Beneq reactor for ALD @Argonne National Laboratory



ALD Process for MCP Coating Developed by A.Mane, J.Elam







Porous glass

Resistive coating ~100nm (ALD)

Emissive coating ~ 20nm (ALD)

Conductive coating
(thermal evaporation or sputtering)