The Detectors based on PMTs

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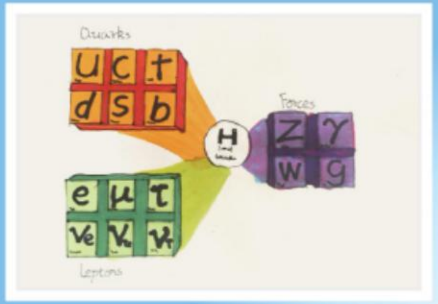
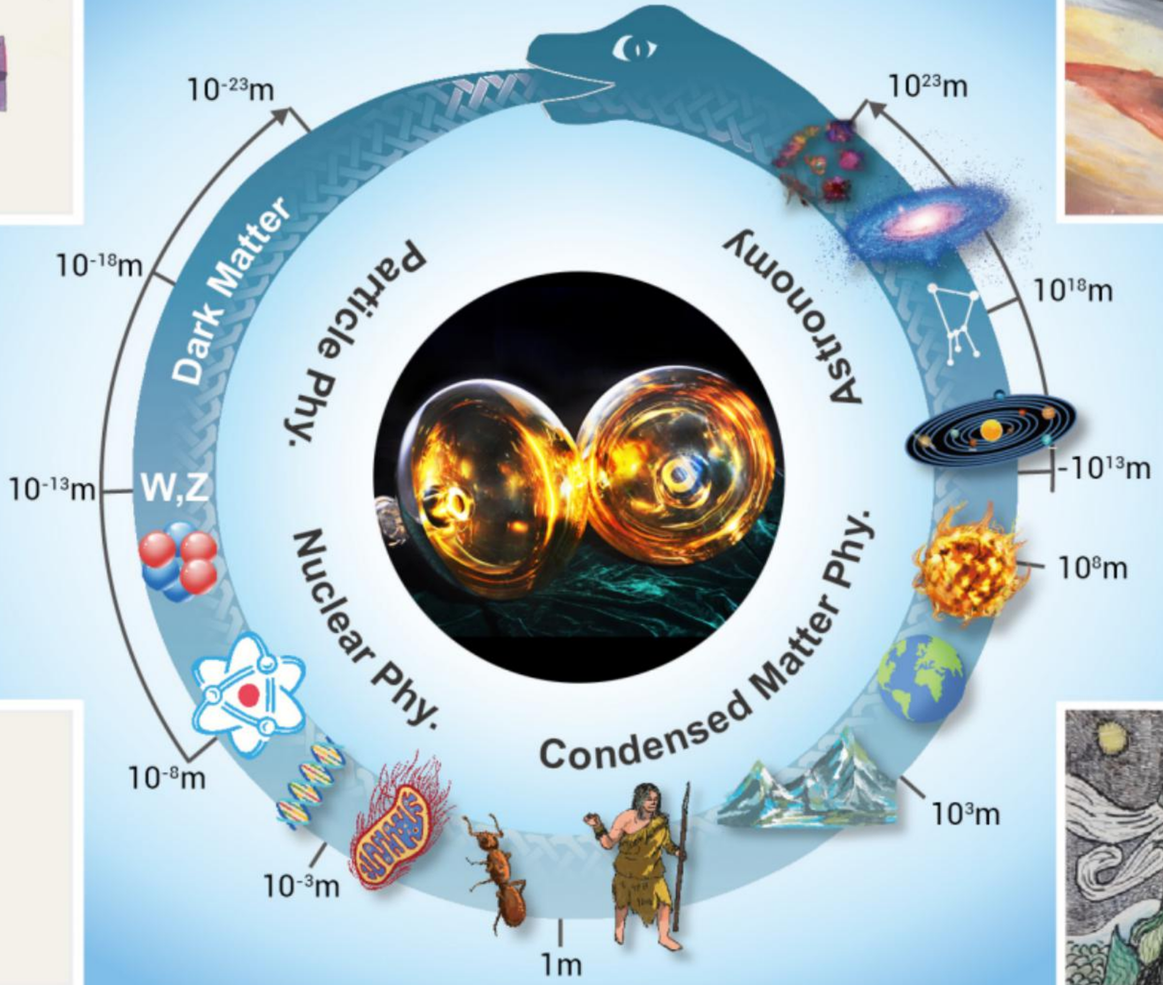
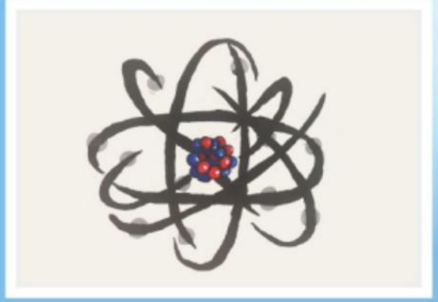
The PMTs in the Physics World

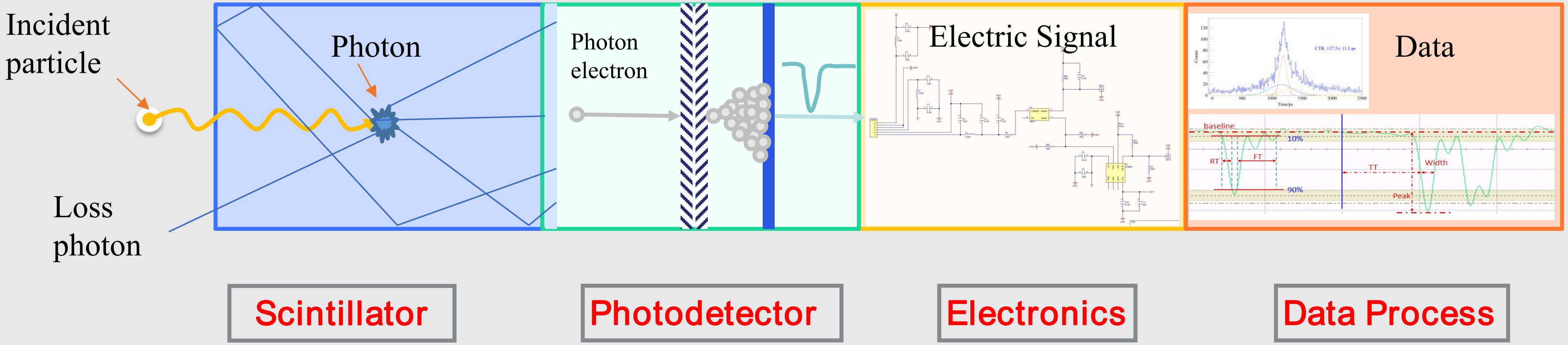






- 1. The Introduction of PMTs
- 2. The Application of PMTs in Fundamental Physics
- 3. The Application of PMTs in Medical Imaging
- 4. The Application of PMTs in Analytical Instruments
- 5. The Future of the PMTs

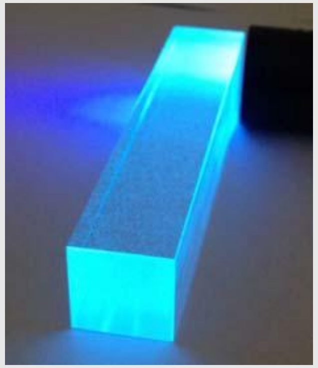
1.1 The Key technology of Scintillator Detector



- ✓ The photoelectric device and scintillation material promote each other. A good combination!
- ✓ The Max. QE of PMT @ **400**nm----> Transparent scintillator with optical wavelength, like BGO crystal;
- ✓ Large-area liquid scintillator， plastic scintillator----> R&D of large-area PMT (20 inch PMT);
- ✓ Development of the SiPM， PDE plateau （300-600 nm） ----> all kinds of high light yield scintillator, like GAGG crystal;
- ✓ Development of low-cost SiPM, PD, PMT----> large-area scintillator with low-cost, like **Glass Scintillator** (GS);
- ✓ …………So！ What about the progress of PMTs?

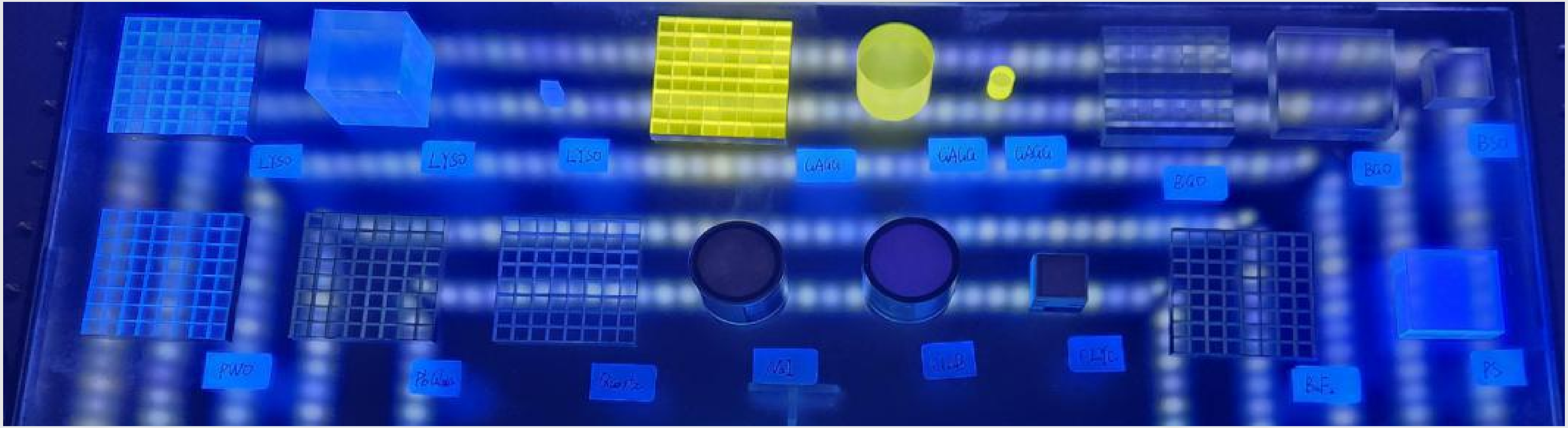
What is the Glass Scintillator？

Plastic Scintillator



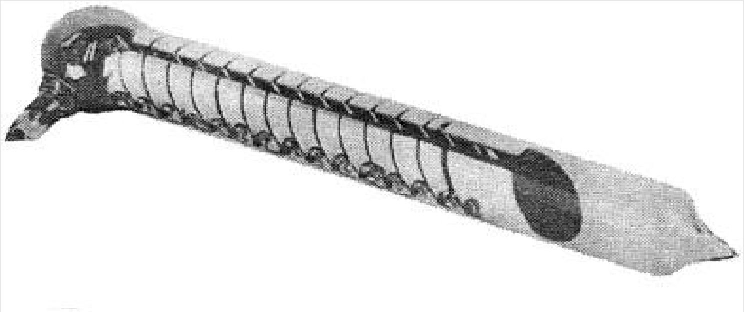
Glass Scintillator

Crystal Scintillator



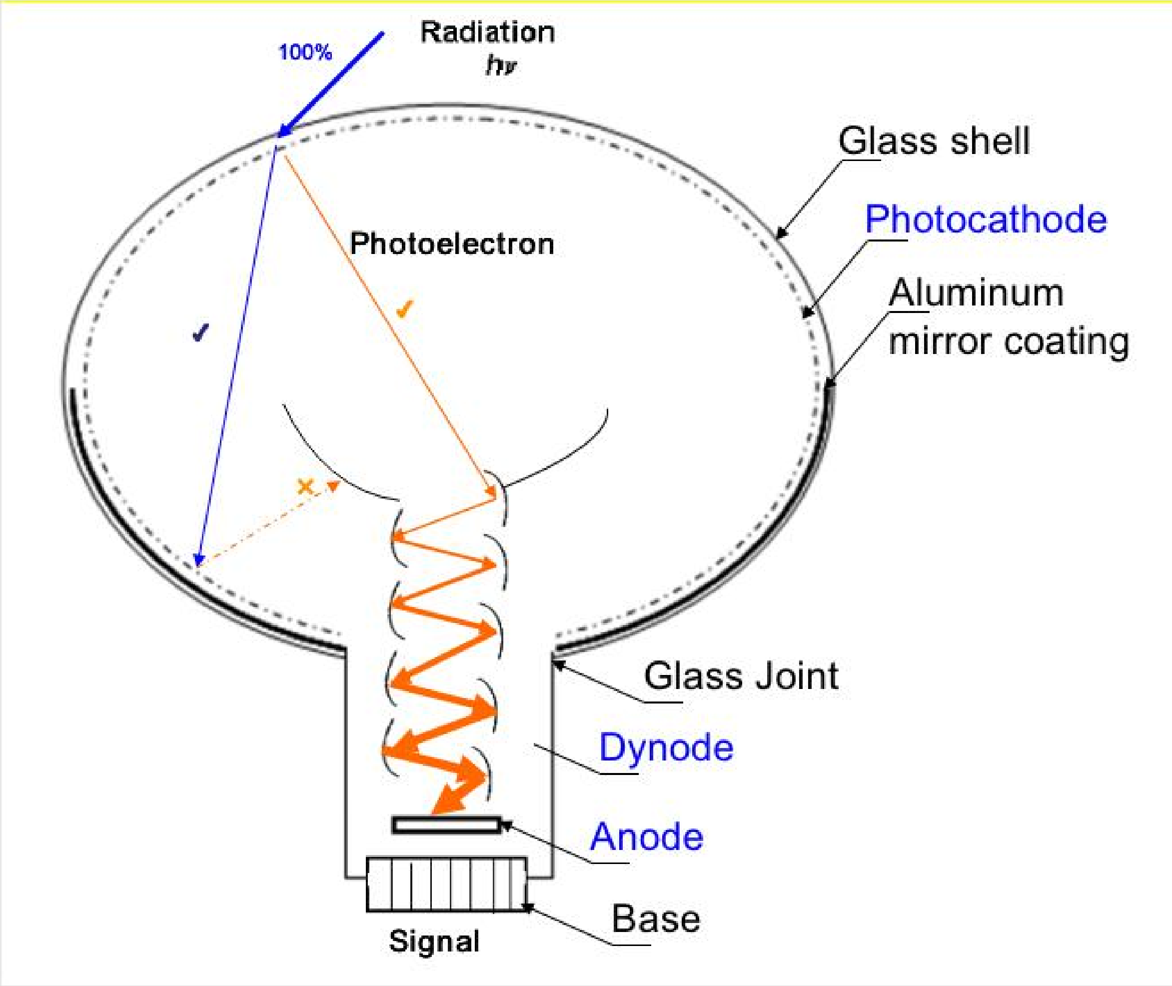
What is the photomultiplier Tube (PMT)?

1.2 The Structure of PMTs



- The first photomultiplier in the world:
  - "Kubetsky's tube"

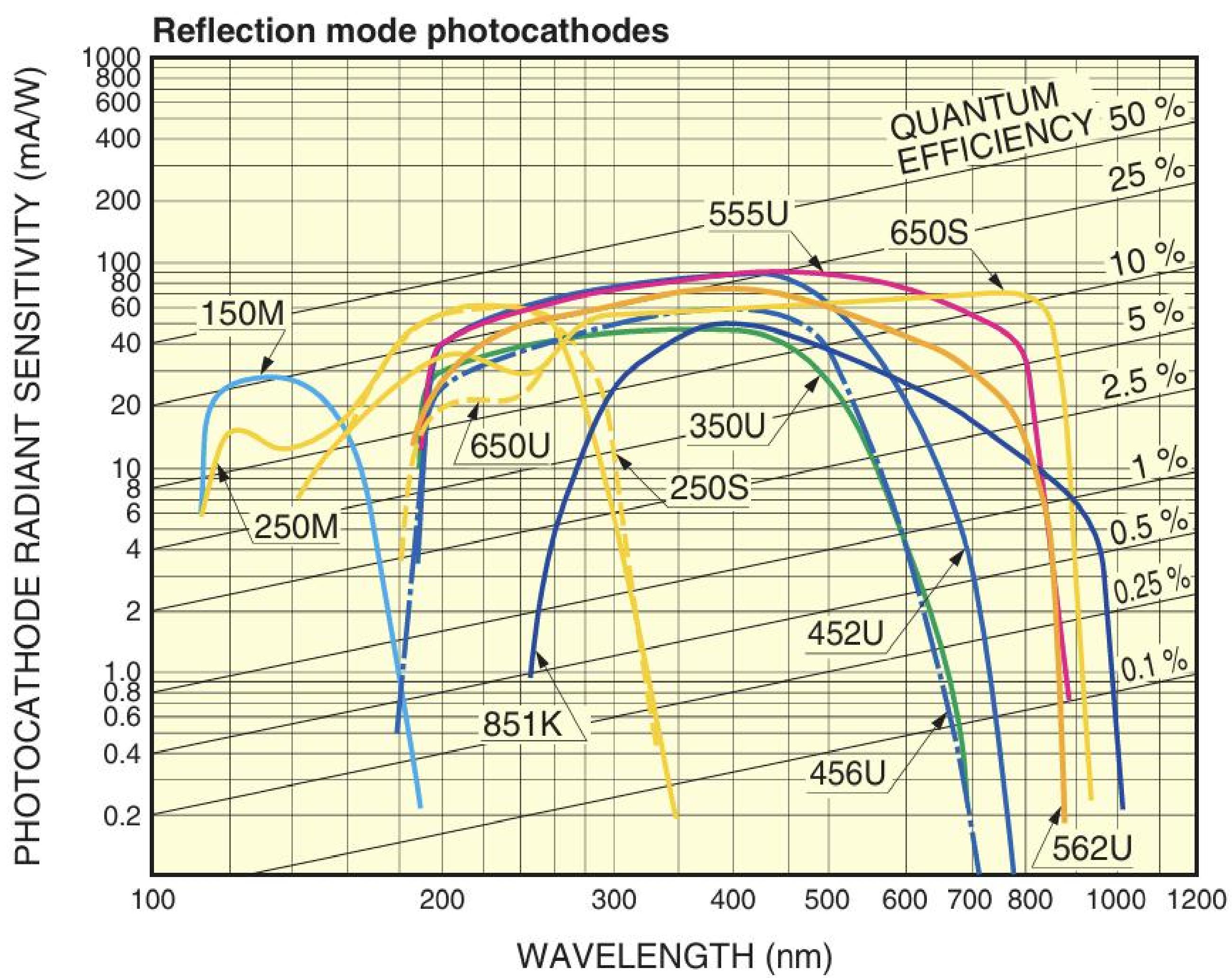
- A typical PMT contains a **photoncathode**, several **dynodes**, and an **anode** in a sealed glass envelope with a high vacuum inside.
- PMTs are widely used in various fields, such as fundamental physics, medical imaging, analytical instruments et al. Different types of PMTs have been developed to meet different requirements.



- The Structure of the large PMT

Ref：NIMA 567 (2006) 236–238

(1) Photocathode



- Photocathodes are generally made of compound alkali metals, or semiconductors activated with alkali
- Cs-I and Cs-Te are used for **ultraviolet light (UV)**
- Bialkali (Sb-Rb-Cs, Sb-K-Cs) and multialkali (Sb-Na-K-Cs) photocathodes are sensitive to the photons of **visible light**
- Semiconductors, such as GaAsP, GaAs, and InGaAs activated with alkali (Cs) are used to extend sensitivity further to about 1000 nm (**infrared ray**)

Ref：Sergey V. Polyakov, Experimental Methods in the Physical Sciences, Chapter 3 - Photomultiplier Tubes

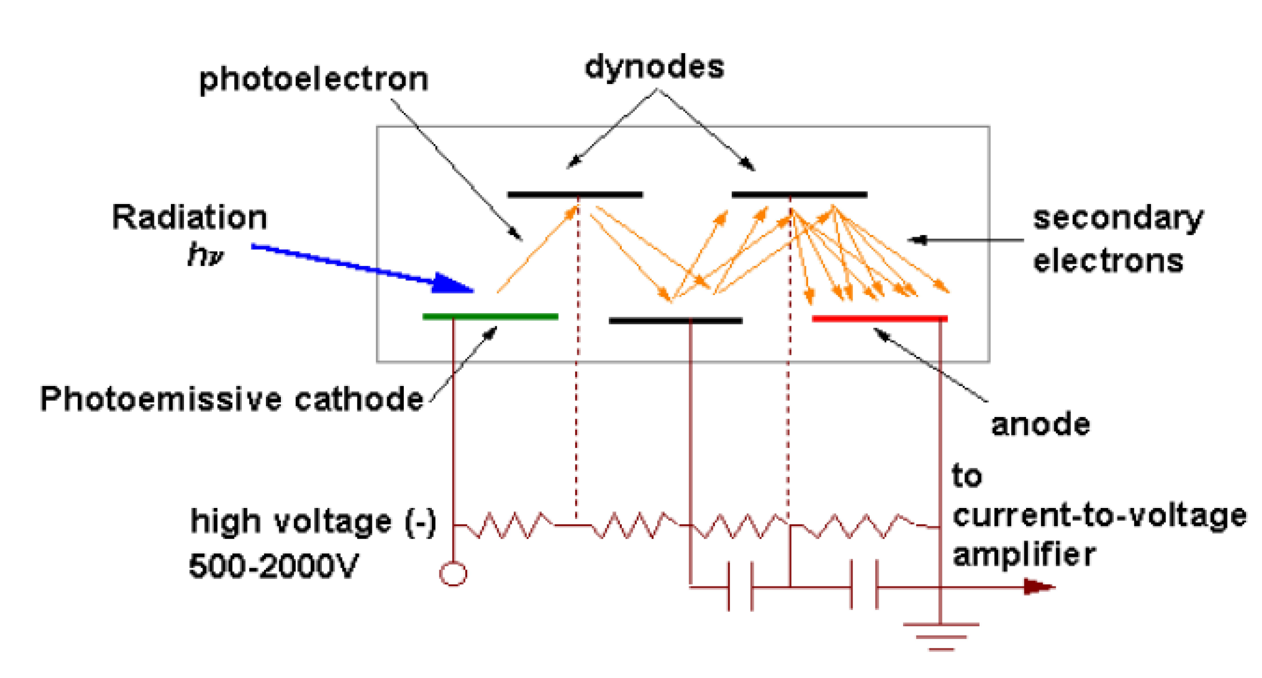
- Different material photocathode in the vacuum tube could detected different wavelength light

Photocathode Material	Reflection Mode Spectral Range, (nm)	Reflection Mode Peak Quantum Efficiency (%)	Transmission Mode Spectral Range, (nm)	Transmission Mode Peak Quantum Efficiency (%
Cs-I	115 to 200	26 @ 125 nm	115 to 200	13 @ 130 nm
Cs-Te	115 to 320	37 @ 210 nm	115 to 320	14 @ 210 nm
Sb-Cs	185 to 750	25 @ 280 nm	–	–
Bialkali	185 to 750	30 @ 260 nm	160 to 650	27 @ 390 nm
Multialkali	185 to 900	30 @ 260 nm	160 to 850	25 @ 280 nm
Ag-O-Cs	–	–	400 to 1200	0.36 @ 740 nm
GaAs(Cs)	185 to 930	23 @ 300 nm	380 to 890	14 @ 760 nm
InGaAs(Cs)	300 to 1040	16 @ 370 nm	–	–
InP/InGaAs(Cs)	300 to 1700	1 @ 1200 nm	950 to 1700	2 @ 1550 nm

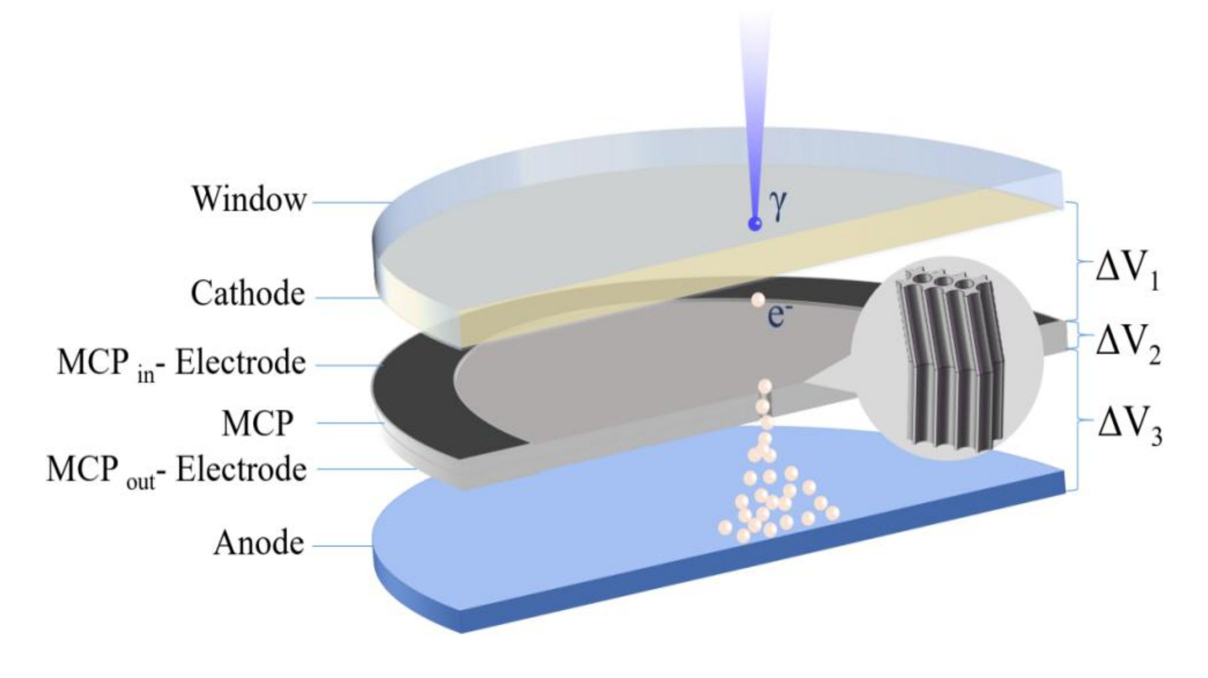
Ref： Sergey V. Polyakov, Experimental Methods in the Physical Sciences, Chapter 3 - Photomultiplier Tubes

(2) Electron Multiplier

- For traditional dynode PMT, the number of photoelectrons is multiplied via the secondary-electron emission effect on each of the dynodes in the device.
- For MCP-PMT, when a primary electron impinges on the inner wall of a channel, secondary electrons are emitted.

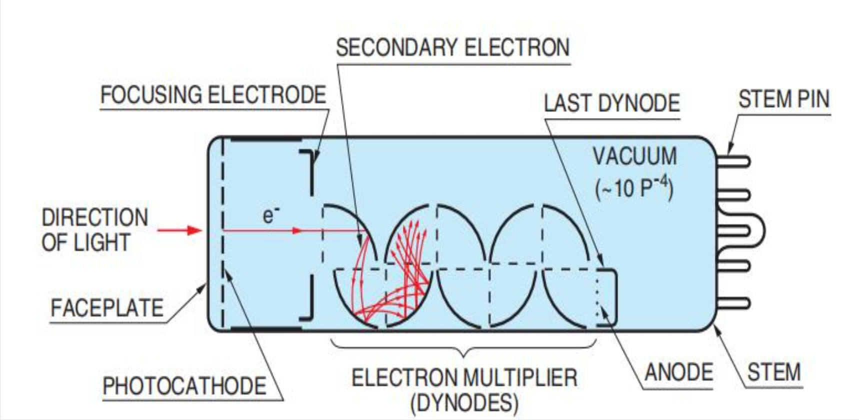


➢ The Typical Dynode part for PMTs

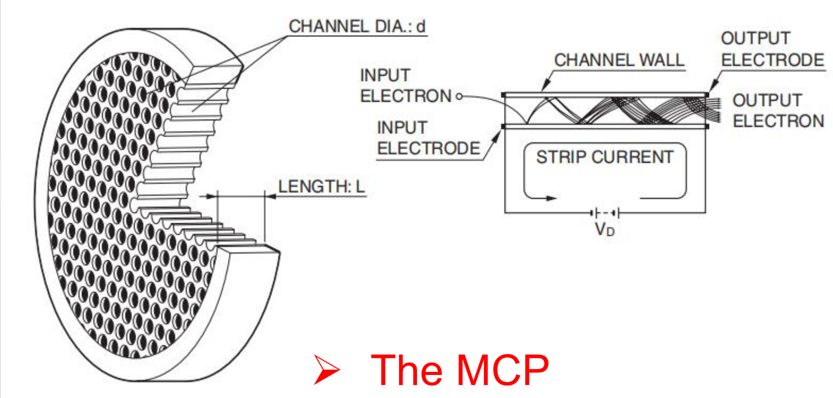


➢ The Typical MCP part for PMTs

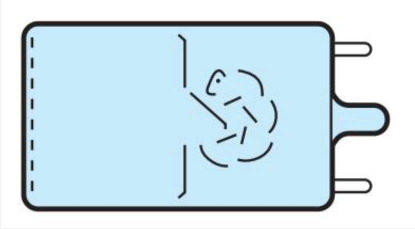
- The Dynode part and MCP part are the most usefull and common electron multiplier in the vacuum tube.



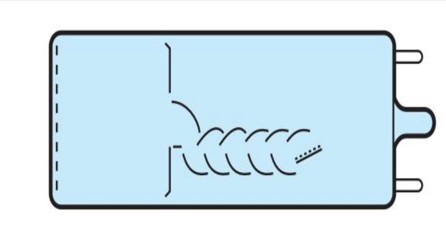
➢ The dynode



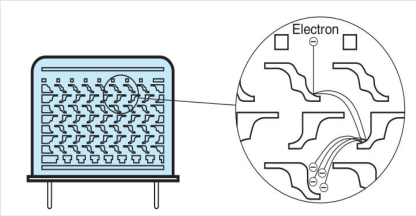
➢ The MCP



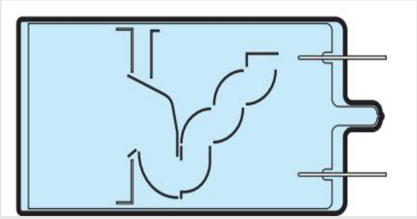
➢ Circular-cage type



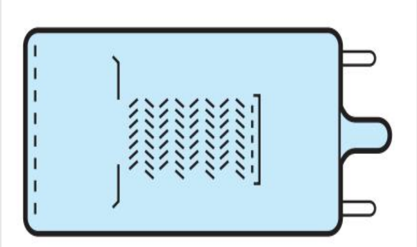
➢ Linear-focused type



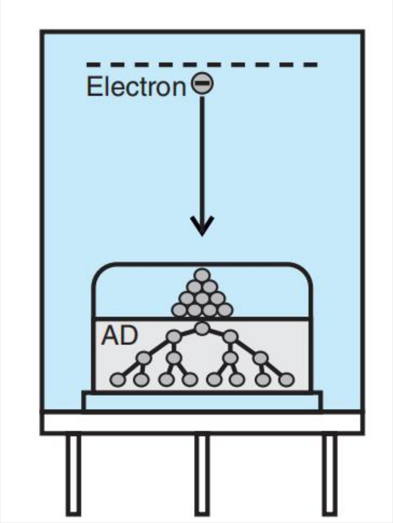
➢ Metal channel type



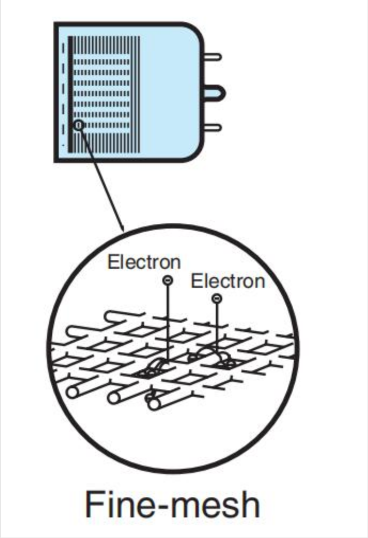
➢ Box-and-line type



➢ Venetian blind type



➢ Eelectron bombadment type

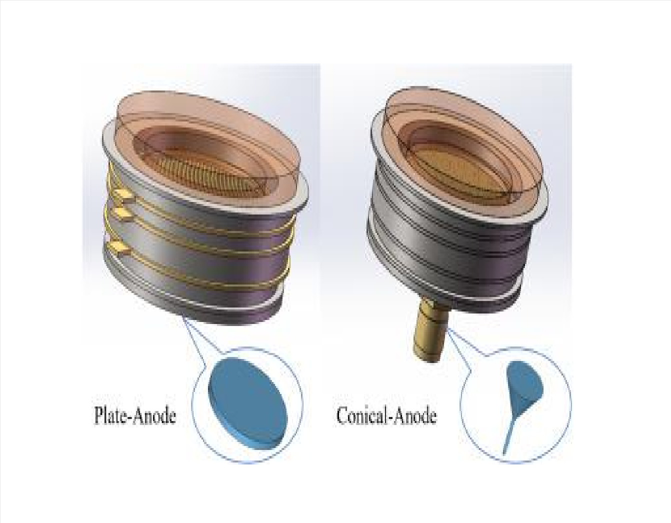


➢ Mesh type

Ref：Photonmultiplier Tubes Basics and Applications, Hamamatsu

(3) The Anode

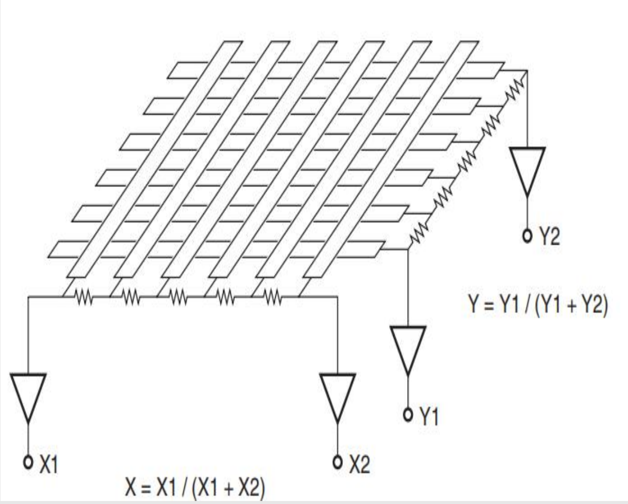
- Compared to the plate anode, a conical anode can significantly improve the **timing performance** .
- Multianode PMTs are used to achieve **position-sensitive** and can be roughly classified into two types or namely a matrix type and a linear type.
- Using cross-plate anodes is another method to achieve position-sensitive.



➢ Single Anode for PMT

Type	Multianode photomultiplier tubes						
	Matrix				Linear		
	M4	M16	M64	M256	L8	L16	L32
Anode shape							
Number of anodes	4	16	64	256	8	16	32

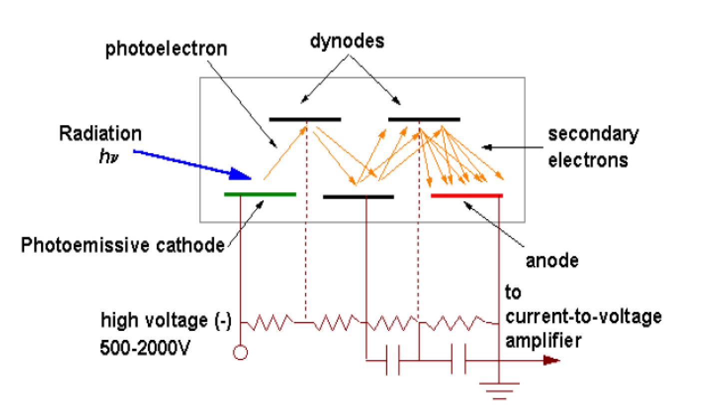
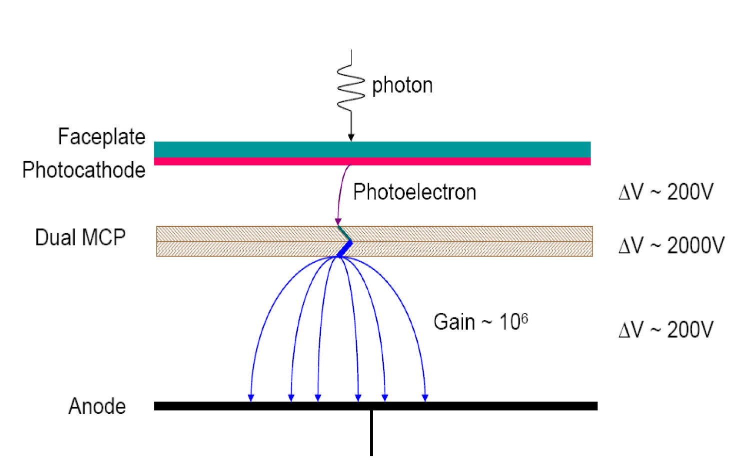
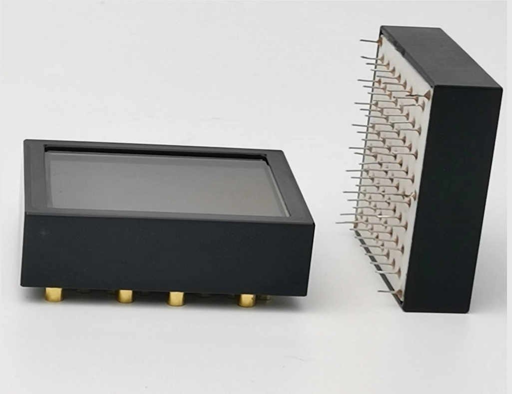
➢ DIfferent types of the position-sensitive anode



➢ cross-plate anodes

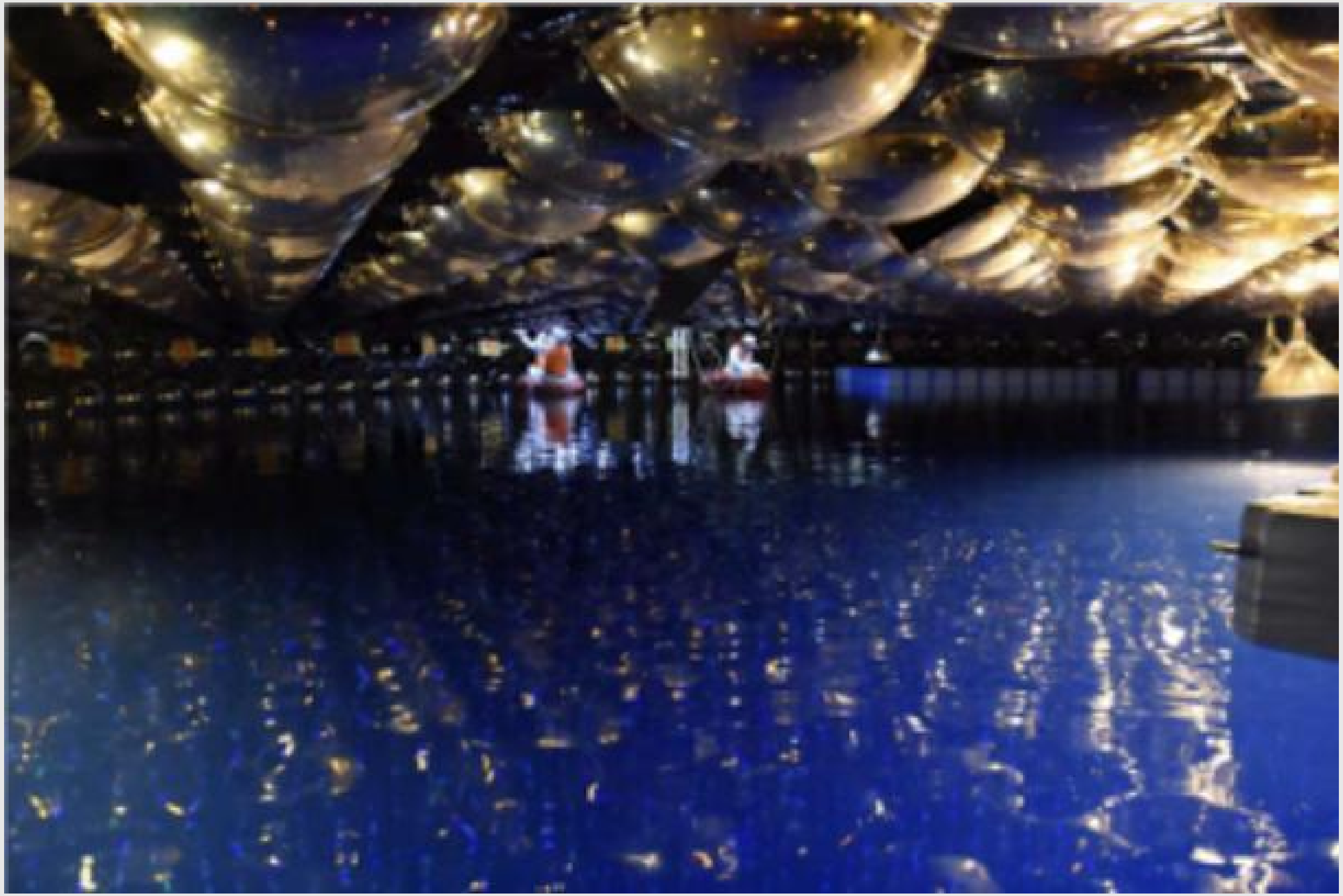
Ref：NIMA 1041 (2022) 167333; Photonmultiplier Tubes Basics and Applications, Hamamatsu

1.3 The Size and shape of the PMTs

	Operation Principle	Small Size (proximity focusing)	Large Size (electrostatic focusing)
Dynode		2" Dynode-PMT H8500 	20" Dynode-PMT R12860 
MCP		2" MCP-PMT 	20" MCP-PMT 

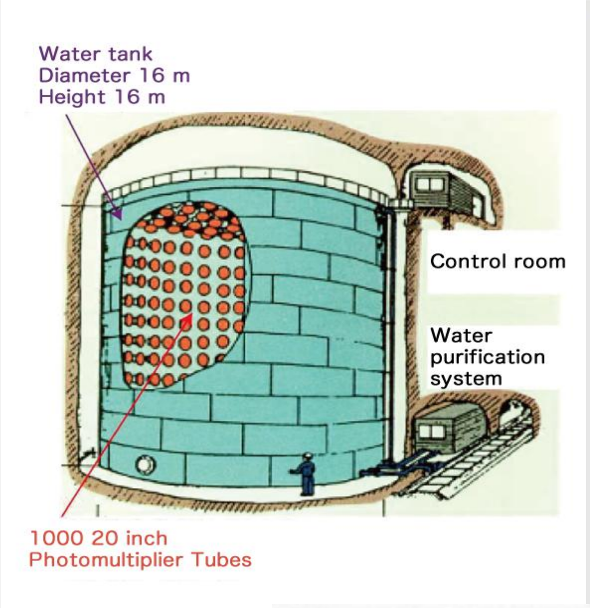
- 1. The Introduction of PMTs
- **2. The Application of PMTs in Fundamental Physics**
  - 2.1. The Detector for Neutrino/Cosmic Rays
    - 2.1.1 the 20inch Dynode-PMT for Neutrino detection
    - 2.1.2 the 8inch Dynode-PMT for Neutrino detection
    - 2.1.3 the large size of MCP-PMT for High Energy Physics
    - 2.1.4 the large DOM with small PMTs for Neutrino detection
  - 2.2. The Detector for Special Detection
- 3. The Application of PMTs in Medical Imaging
- 4. The Application of PMTs in Analytical Instruments
- 5. The Future of the PMTs

2.1.1 20-inch Dynode-PMT for Neutrino detection



➢ The Neutrino Detector of Super-K experiment

(1) Kamiokande

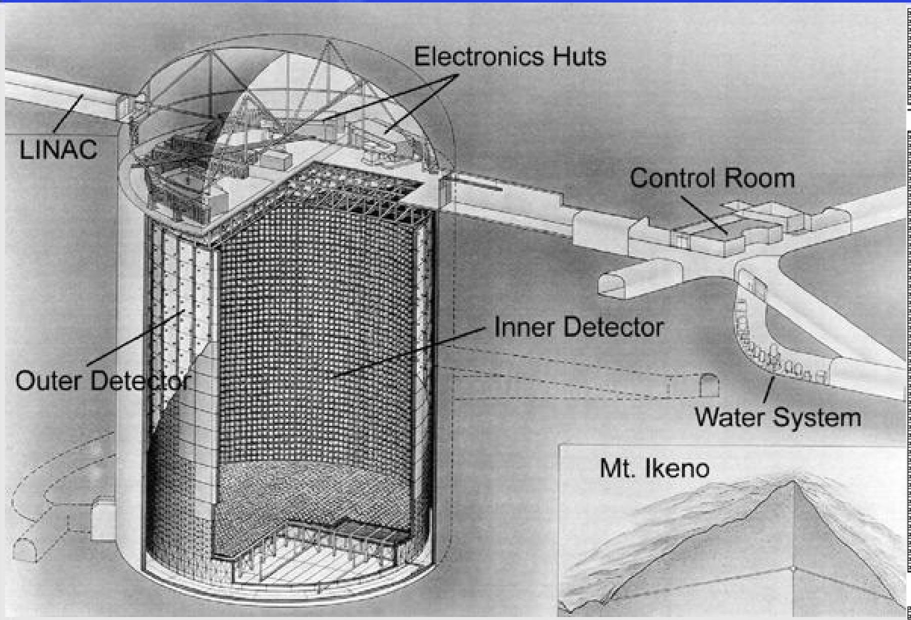


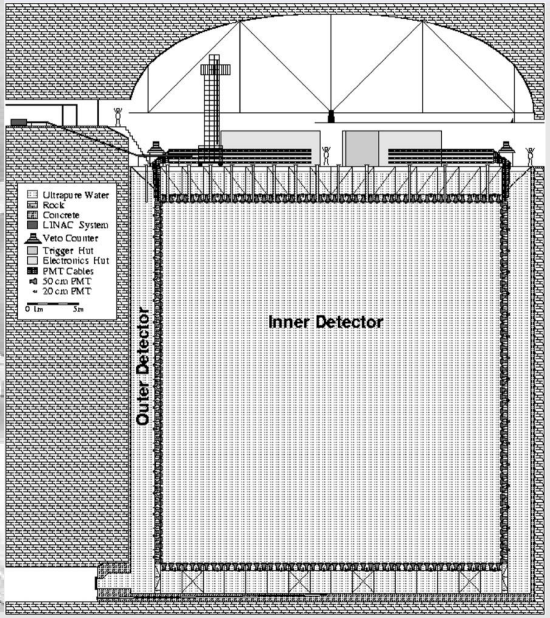
- The KAMIOKA Nucleon Decay Experiment (Kamiokande) was started to verify the Grand Unified Theory of particle physics by searching neutrino.
- The detector was a cylindrical water tank (16 m in diameter and height) with **1000** of the 20-inch dynode-PMTs.

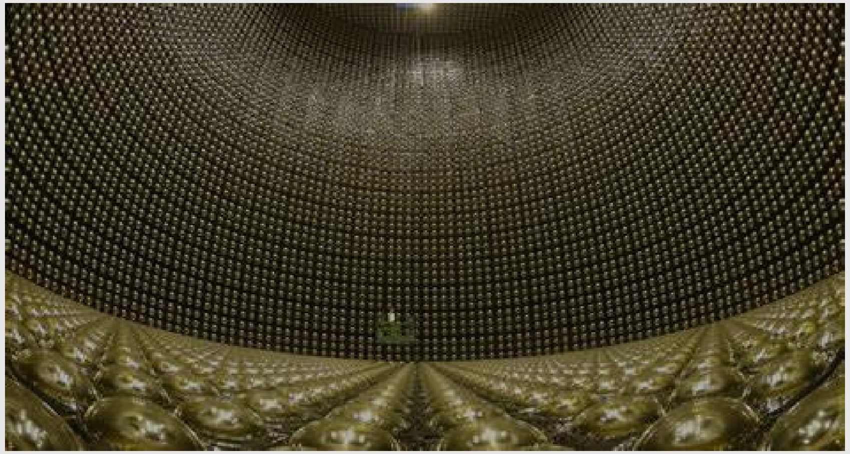
PMT	HamamatsuR1449
QE	~ 20%
CE	40%-50%
Dark rate@0.25PE	8kHz
Gain	10^7
HV	2000V
TTS@SPE	10.4ns

Ref：Suzuki, A. (1994). Kamiokande: Historical Account.

(2) Super-Kamiokande





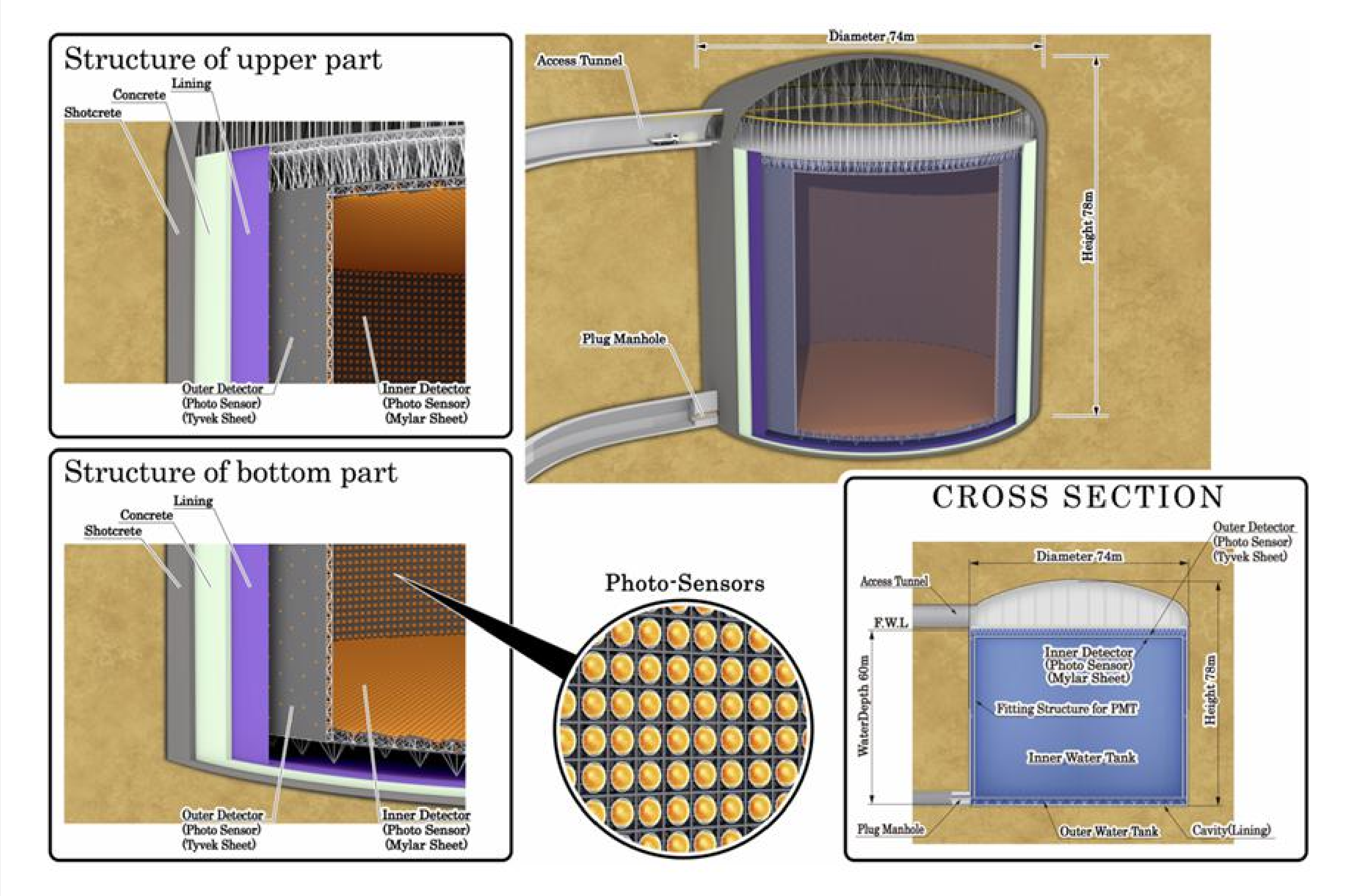


- **Inner detector**: contains 32 ktons of water and was viewed by **11146** inward-facing 20-inch PMTs (Hamamatsu R3600)
- **Outer detector**: instrumented with 1885 outward-facing 8-inch PMTs (Hamamatsu R1408, recycled from the IMB experiment)

PMT	Hamamatsu R3600
QE	21%
CE	70%
Dark rate@0.25PE	3kHz
Gain	10^7
HV	1700 - 2000V
TTS@SPE	2.2ns

Ref: NIMA 501 (2003) 418–462

（3） Hyper-Kamiokande



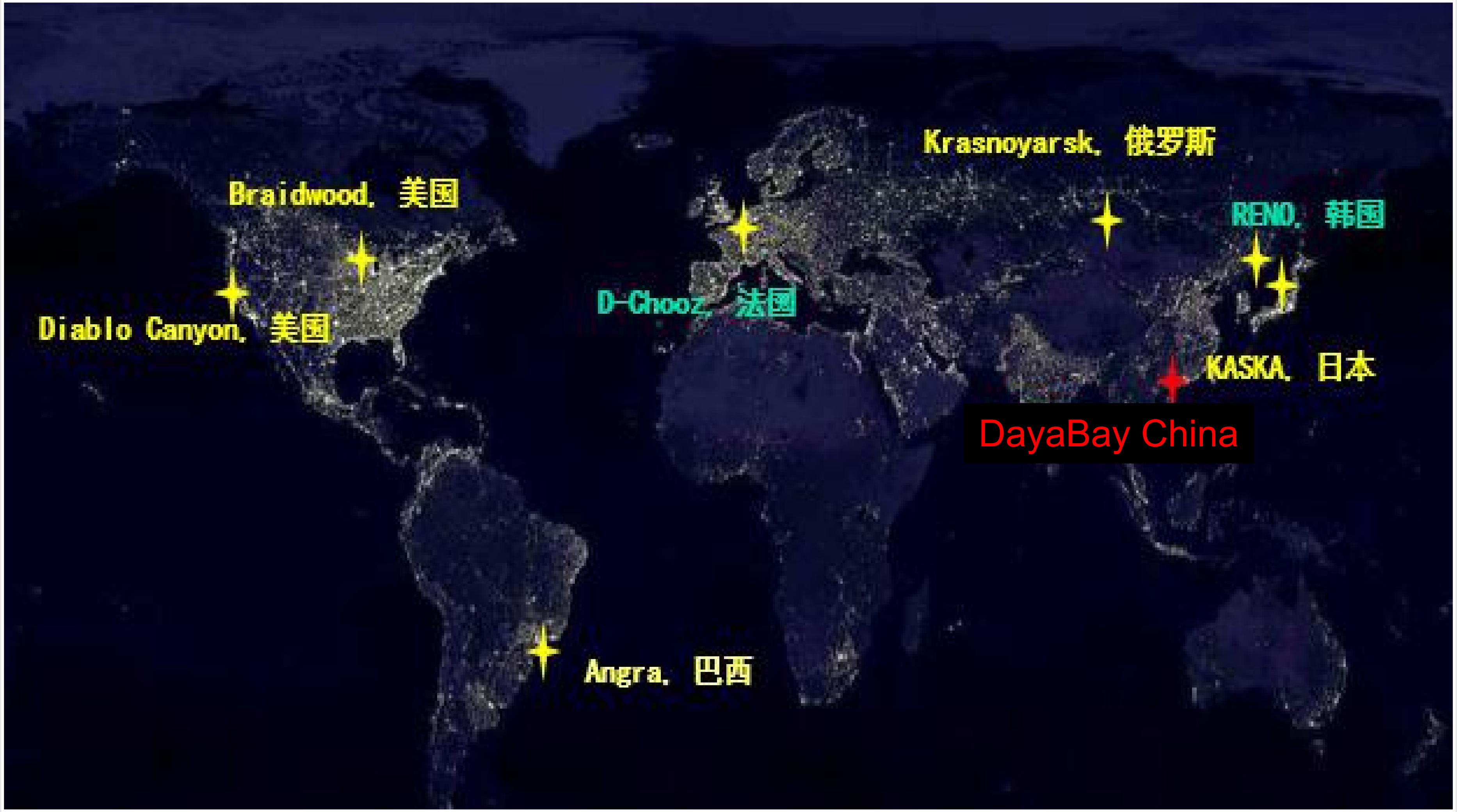
- The detector fiducial volume of Hyper-K is 10 times larger than that of Super-Kamiokande.
- The Inner Detector is the main detector, with 40,000 20-inch ultrasensitive PMTs (Hamamatsu R12860) installed on its walls.

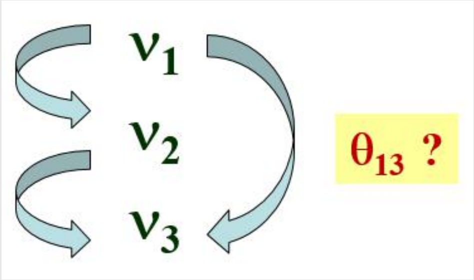
PMT	Hamamatsu R12680
QE	27%
CE	90%
Dark rate@0.25PE	20kHz
Gain	10^7
HV	1800V
TTS@SPE	1.3ns

Ref： C Bronner et al 2020 J. Phys.: Conf. Ser. 1468 012237

	Kamiokande	Super-K	Hyper-K
PMT Type	Hamamatsu R1449	Hamamatsu R3600	Hamamatsu R12860
Structure			
Size	20 inch	20 inch	20 inch
QE	20%	21%	30%
CE	40%-50%	70%	90%
Dark rate@0.25PE	8kHz	3kHz	20kHz
Gain	10^7	10^7	10^7
HV	~2000V	~2000V	~1800V
TTS@SPE	10.4ns	2.2ns	1.3ns

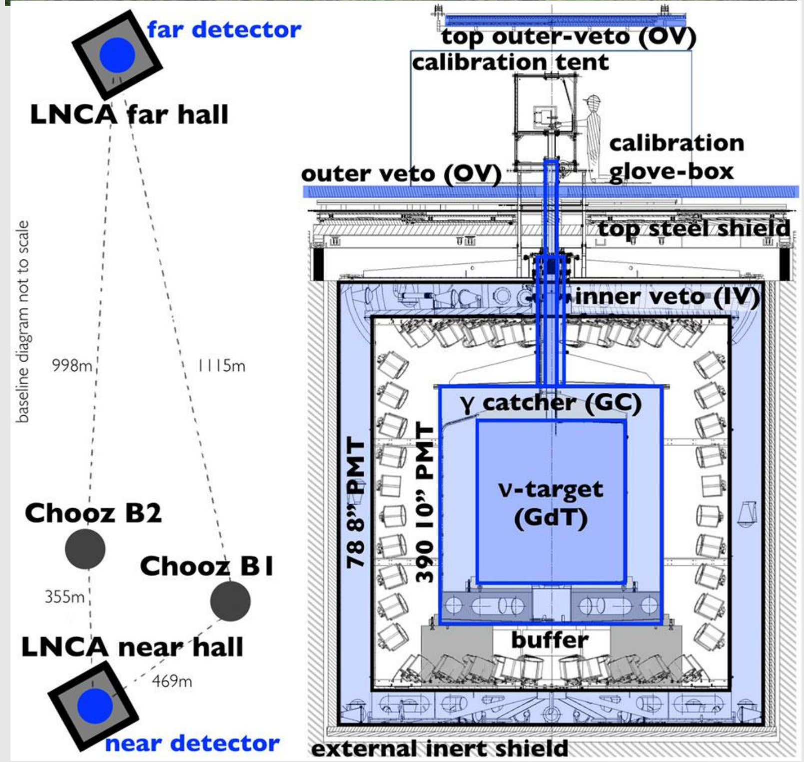
2.1.2 8-inch Dynode-PMT for Neutrino detection





➢ The Neutrino Detector to measure the mixing angle θ13

（1） Double Chooz

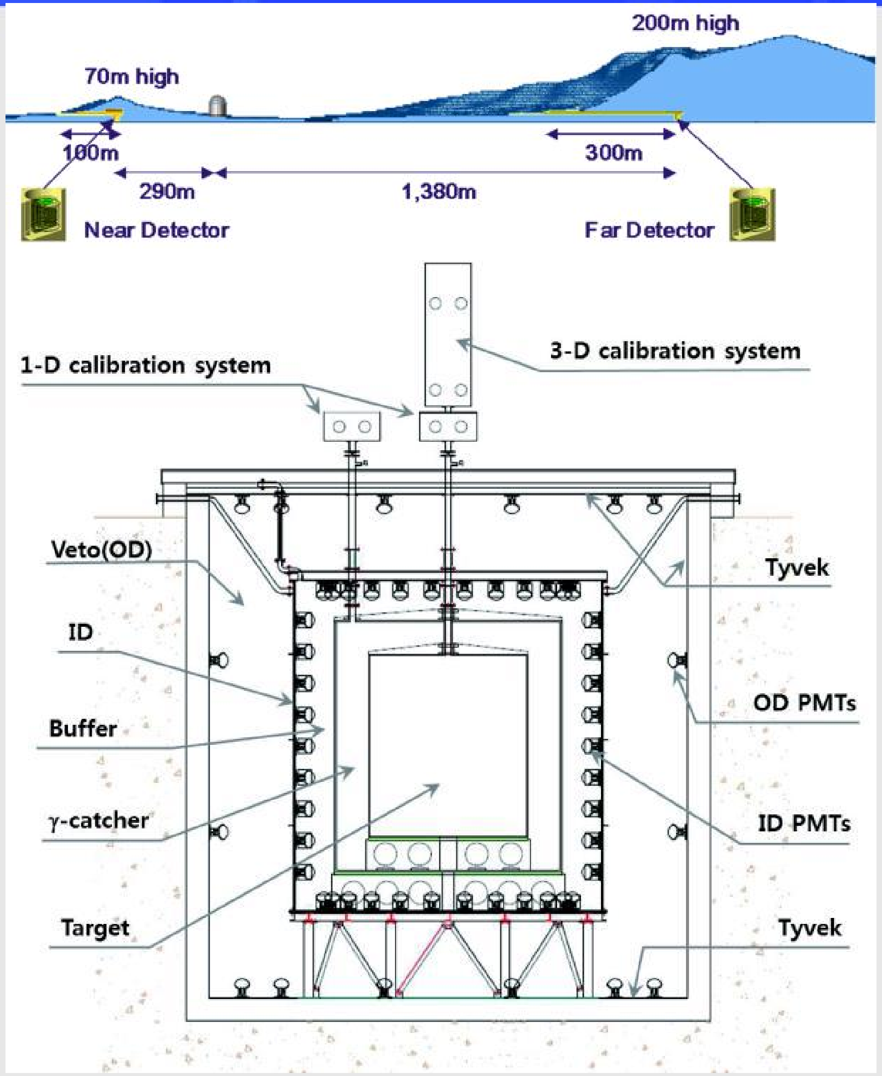


- The inner PMT system was one of the core parts of the Double Chooz detector, which detected the scintillation light and gave information about **the energy and timing** of the signals.
- Each detector used 390 low-background 10-inch PMTs (Hamamatsu R7081), uniformly arranged around the interior of the cylindrical Buffer oil tank.

PMT	Hamamatsu R7081
Supply voltage	1500 V
Gain	1×10^7
QE	25%
Peak sensitivity wavelength	420nm
Minimum effective area	Φ 220 mm
TTS	3.4ns
size	10 inch

Ref：Eur. Phys. J. C (2022) 82:804

（2） RENO

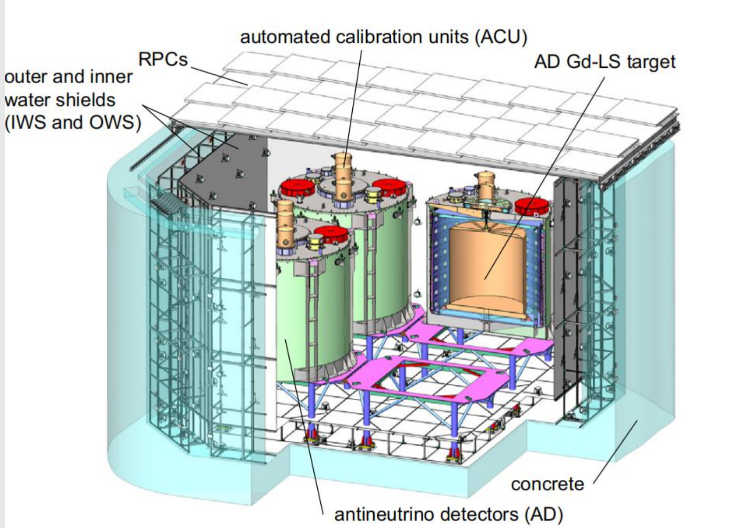


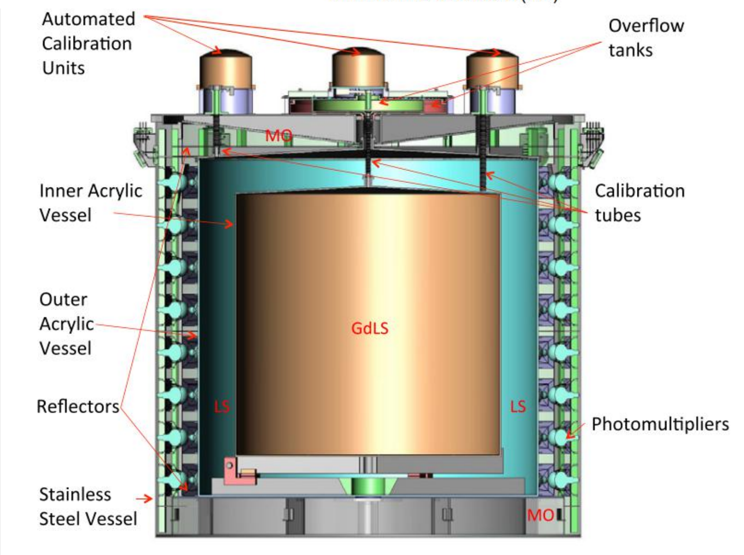
- **Inner detector：** 354 10-inch PMTs (Hamamatsu R7081) are mounted on the inner wall of the stainless steel container, providing 14% surface coverage.
- **Outer detector：** 67 10-inch R7081 water-proof PMTs mounted on the wall of the veto vessel.

PMT	Hamamatsu R7081
Supply voltage	1500 V
Gain	1×10^7
QE	25%
Peak sensitivity wavelength	420nm
Minimum effective area	Φ 220 mm
TTS	3.4ns
size	10 inch

Ref： Nuclear Physics B (Proc. Suppl.) 235–236 (2013) 24–29

(3) Daya Bay





- The Daya Bay Neutrino Experiment is a neutrino-oscillation experiment designed to measure the mixing angle θ13 using anti-neutrinos produced by the reactors of the Daya Bay Nuclear Power Plant (NPP) and the Ling Ao NPP
- **Antineutrino detector:**192 8-inch PMTs (Hamamatsu R5912) installed in the mineral oil volume and around the circumference of the stainless steel vessel.

PMT	Hamamatsu R5912
Supply voltage	1500 V
Gain	1×10^7
QE	25%
Peak sensitivity wavelength	420 nm
Minimum effective area	Φ 190 mm
TTS	2.4ns
size	8 inch

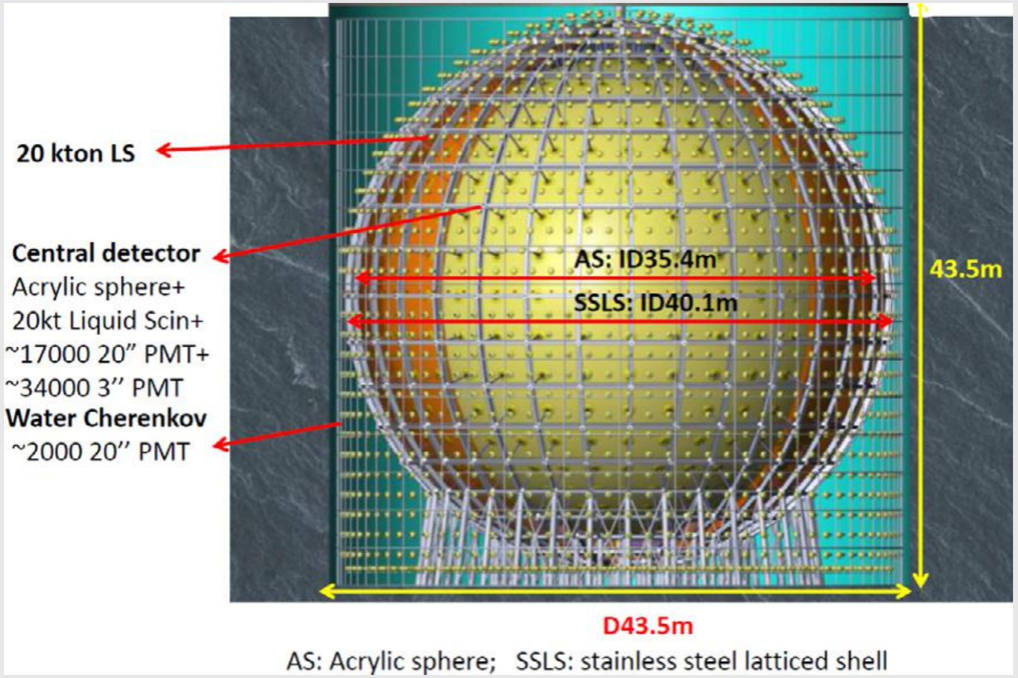
Ref：NIMA 811 (2016) 133–161; Junqueira de Castro Bezerra, T. (2015).

	Double Chooz	RENO	Daya Bay
PMT Type	Hamamatsu R7081	Hamamatsu R7081	Hamamatsu R5912
Structure			
Supply voltage	1500 V	1500 V	1500 V
Gain	1×10^7	1×10^7	1×10^7
QE	**25%**	**25%**	**25%**
Peak sensitivity wavelength	**420nm**	**420nm**	**420 nm**
Minimum effective area	Φ 220 mm	Φ 220 mm	Φ 190 mm
TTS	3.4ns	3.4ns	2.4ns
size	10 inch	10 inch	8 inch

2.1.3 Large size MCP-PMT for High Energy Physics

➢ two types of 20-inch MCP-PMTs produced by NNVT in CHina for JUNO and LHAASO

（1） JUNO

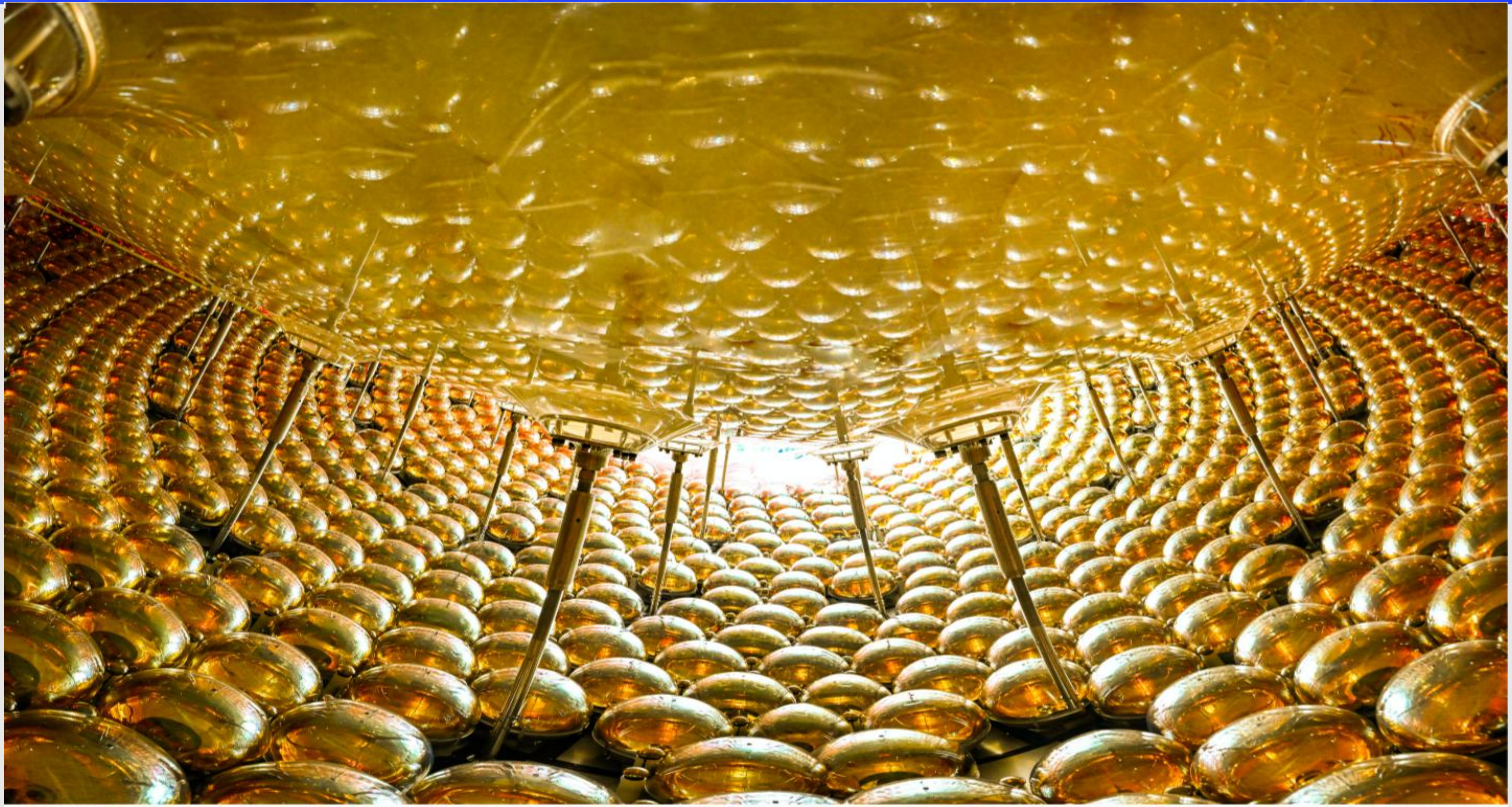


AS: Acrylic sphere; SSLS: stainless steel latticed shell

- **JUNO（Jiangmen Underground Neutrino Observatory).**
- **Central detector**: 20kton liquid scintillator, 18000 20-inch PMTs (both MCP and Dynode) + 25000 3-inch dynode-PMTs;
- **VETO detector**: a top tracker of plastic scintillator walls , a water Cherenkov detector of 35kton ultra-pure water and 2000 20" PMTs;

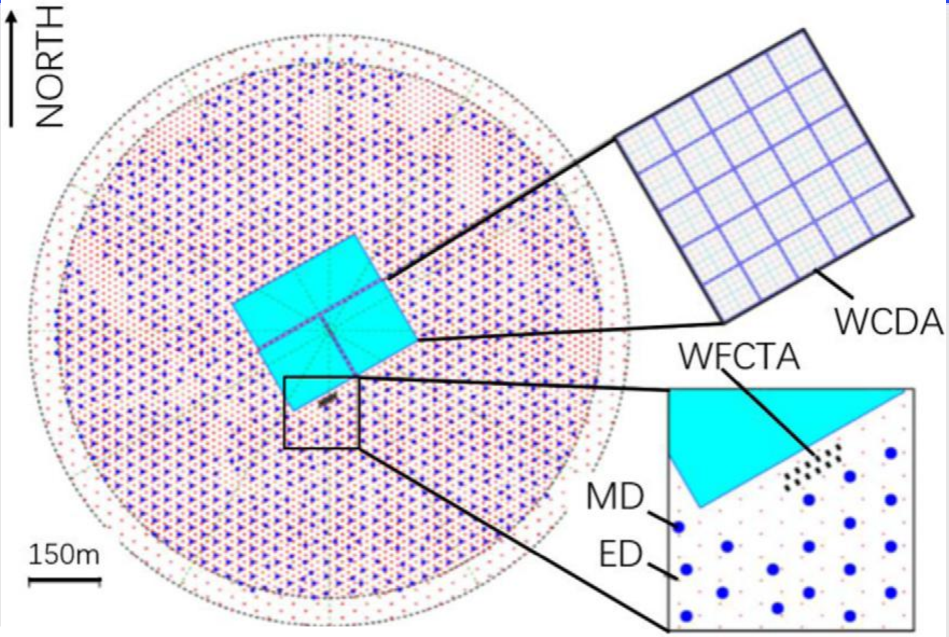
PMT	NNVT GDB-6203	Hamamatsu R12860
QE	30%	30%
CE	100%	90%
DE	30%	27%
Dark rate@0.25PE	49.3kHz	20kHz
HV@10^7	1748V	1800V
P/V	3.9	3
size	20 inch	20 inch
TTS@SPE	7.0ns	2.2ns

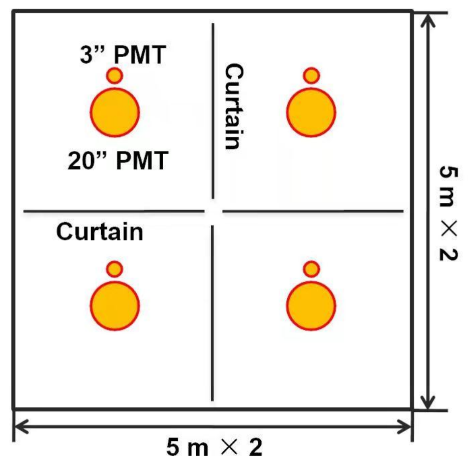
Ref：Progress in Particle and Nuclear Physics 123 (2022) 103927；NIMA 952 (2020) 162002

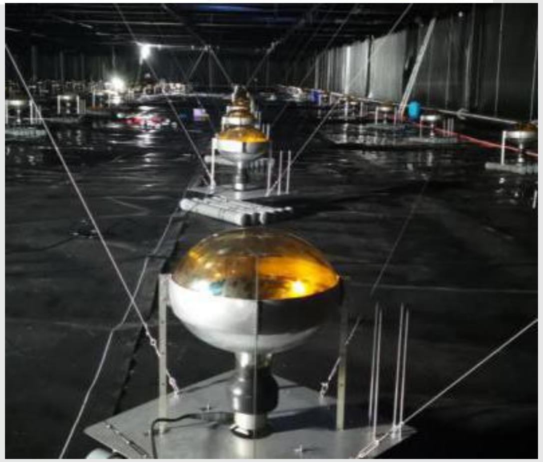


- The JUNO just finished the installation of the CD and PMTs on 19th.Nov 2024

(2) LHAASO WCDA





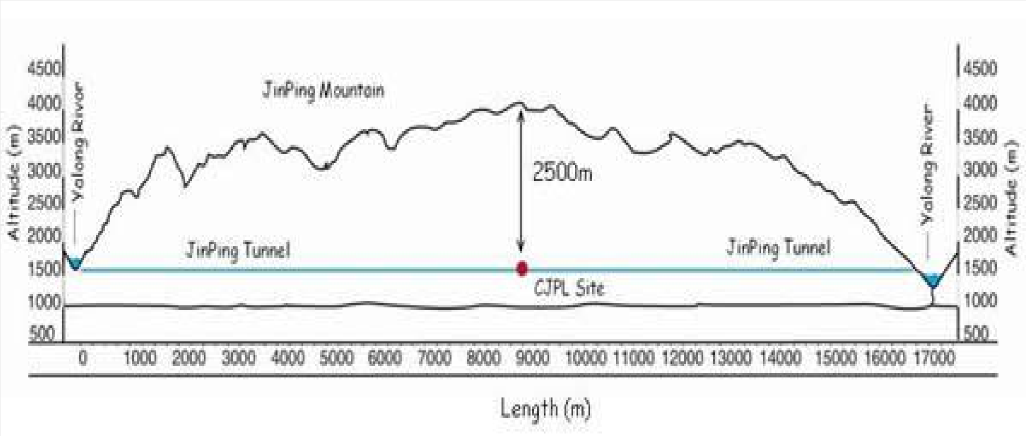


- In the Large High Altitude Air Shower Observatory (LHAASO), the main physics objective of the water Cherenkov detector array (WCDA) is to survey the sky for gamma-ray sources in the energy range of 100GeV to 30 TeV.
- a pair of 20-inch MCP-PMT and 3-dynode-PMTs in each unit of WCDA-2 and WCDA-3

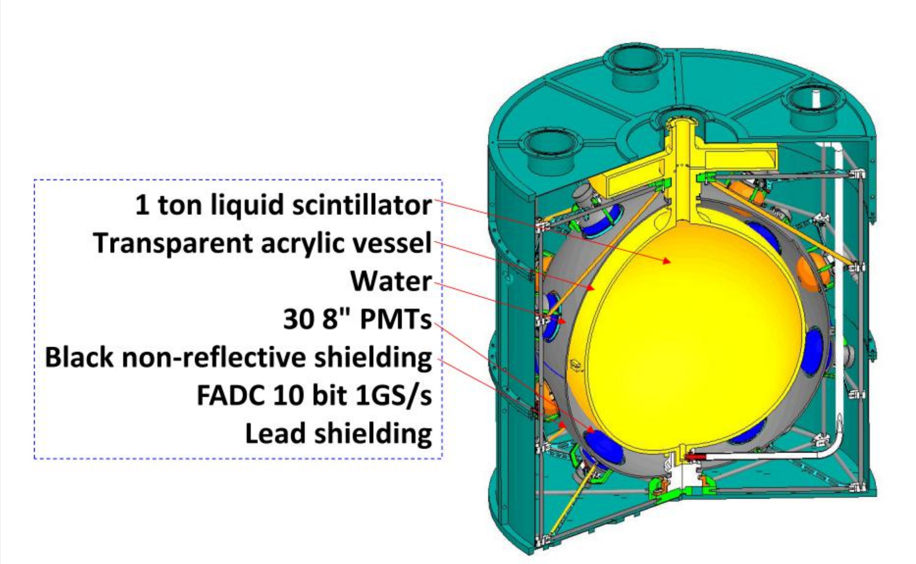
PMT	NNVT
QE	30%
CE	90%
DE	27%
Dark rate@0.25PE	15kHz
HV@10^7	1777V
P/V	3.5
size	20 inch
TTS@SPE	5.5ns
RT	1.4ns

Ref：X. You et al ICRC2021

(3) JNE



- The Jinping Neutrino Experiment (JNE) under construction is a hundred-ton liquid scintillator detector with Cherenkov and scintillation light readout at CJPL II.
- JNE use a new type of 8-inch MCP-PMT with high photon detection efficiency for MeV-scale neutrino measurements



PMT	NNVT GDB-6082
Detection Efficiency	30%
Dark rate@0.25PE	5.8kHz
HV@10^7	1697V
P/V	3.5
size	8 inch
TTS@SPE	1.65ns
RT	3.82ns

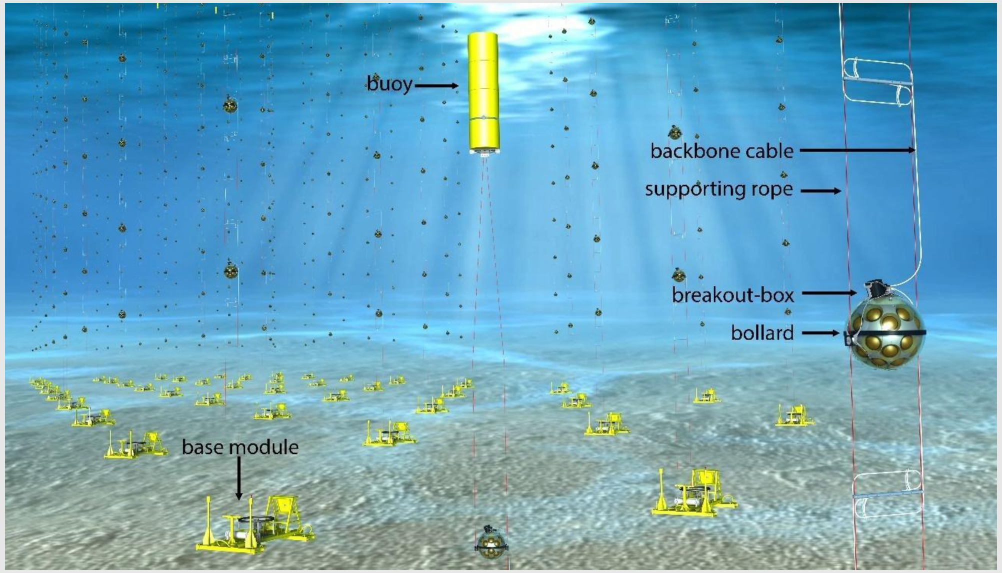
Ref：NIMA 1055 (2023) 168506; Benda Xu 2020 J. Phys.: Conf. Ser. 1468 012212

	JUNO		LHAASO	JNE
Structure				
PMT	NNVT GDB-6203	Hamamatsu R12860	NNVT	NNVT GDB-6082
PMT Size	20 inch	20 inch	20 inch	8 inch
DE	**30%**	**27%**	**27%**	**30%**
QE	30%	30%	30%	30%
High Voltage，HV	1748V	1800V	1777V	1697V
DCR	50kHz	20kHz	15kHz	5.8kHz
P/V	3.9	2.8	5	9.68
RT	4.9ns	6.0ns	1.4ns	3.82ns
TTS	7.0ns	2.7ns	5.5ns	1.65ns

2.1.4 Large DOM with small PMTs for Neutrino Detection

- The Digital Optical Modules (DOM) for IceCube neutrino detection

（1） KM3NeT

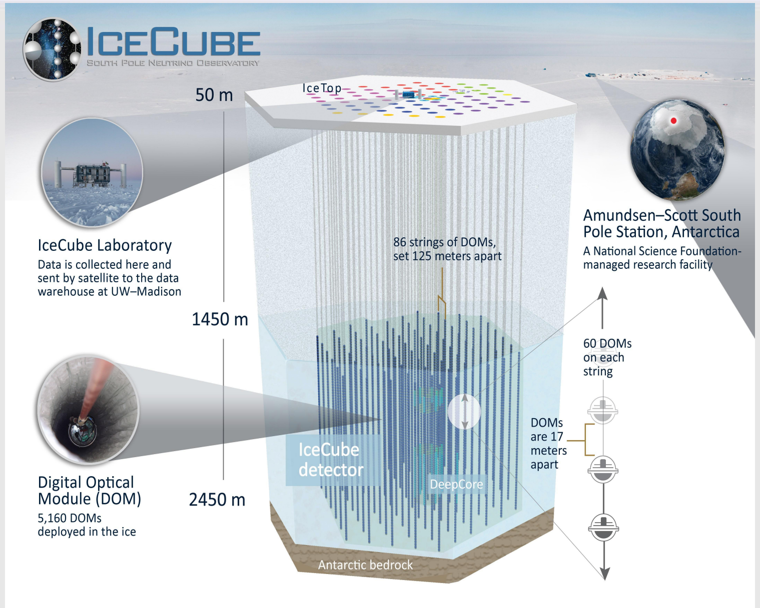


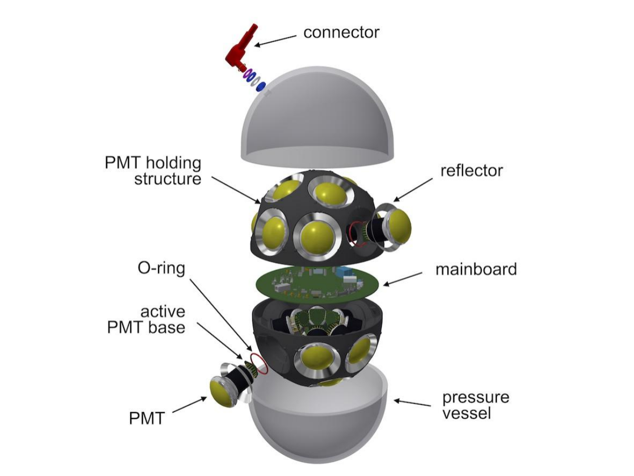
- KM3NeT is a European deep-sea research infrastructure hosting new generation neutrino detectors located at the bottom of the deep seas of the Mediterranean.
- In the design of the KM3NeT **optical module**, the glass sphere is equipped with a set of 31 3-inch PMTs — with approximately the same photocathode area as three 10 inch PMTs — of which the signals are individually processed.

PMT	Hamamatsu R14374
Supply voltage	1500 V
Gain	1×10^7
QE	27.5%
Dark current	50nA
TTS	1.3ns
size	3 inch

Ref：S. Aiello et al 2022 JINST 17 P07038

（2） IceCube



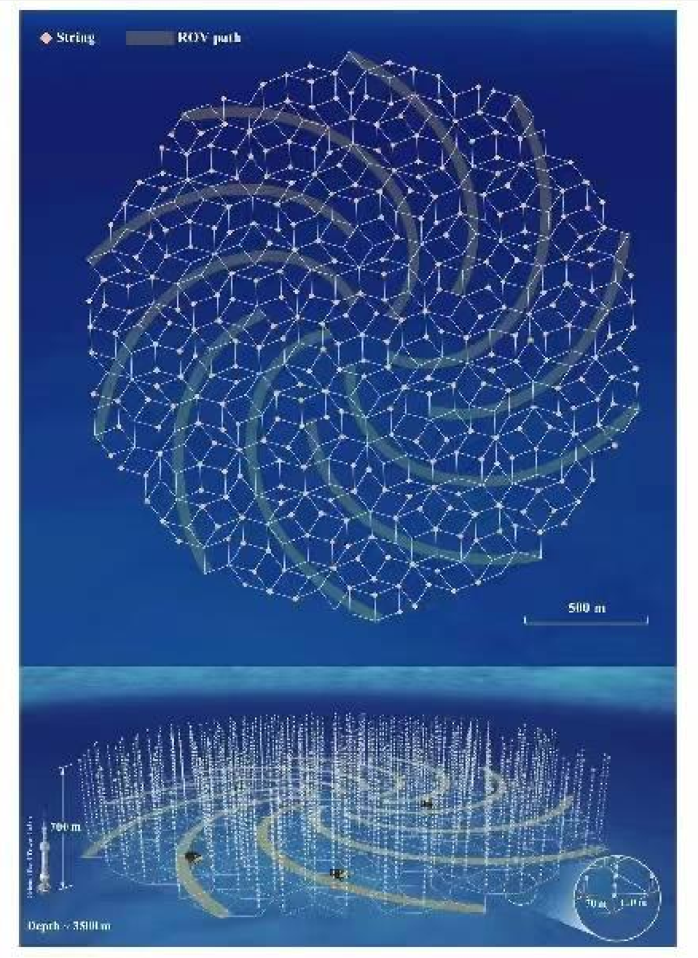


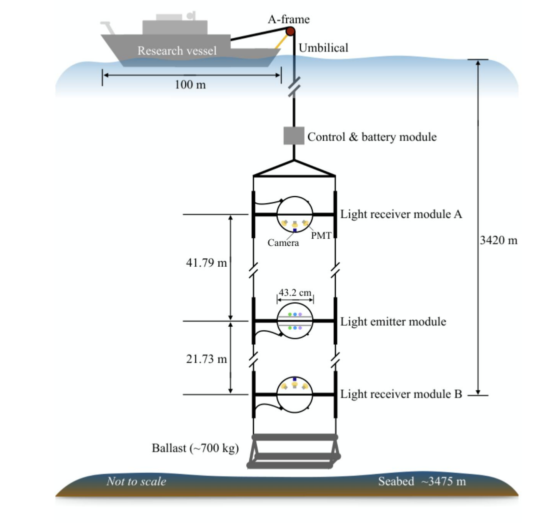
- IceCube uses the 2800m thick glacial ice sheet as a Cherenkov radiator for charged particles.
- Novel optical sensors will play a key role in the expected performance enhancements of the IceCube Upgrade.
- A large fraction will be so-called multi-PMT Digital Optical Modules (mDOMs) featuring **24** relatively small **3-inch PMTs**

	IceCube	IceCube Upgrade
PMT	Hamamatsu R7081-02	Hamamatsu R15458-02
Supply voltage	1500 V	1500V
Gain	1×10^7	5×10^6
QE	25%	25%
Dark rate	500Hz	-
TTS	3.4ns	4.5ns
size	10 inch	3 inch

Ref： NIMA 618 (2010) 139–152; The IceCube Collaboration, ICRC2019

（3） TRIDENT





- The Tropical Deep-sea Neutrino Telescope (TRIDENT), nicknamed Hai-Ling in Chinese (‘ocean bell’).
- aims to rapidly discover multiple high-energy astrophysical neutrino sources and greatly boost the measurement of cosmic neutrino events of all flavours.
- This experiment has already booked the 3-inch dynode-PMTs from different company for the test.

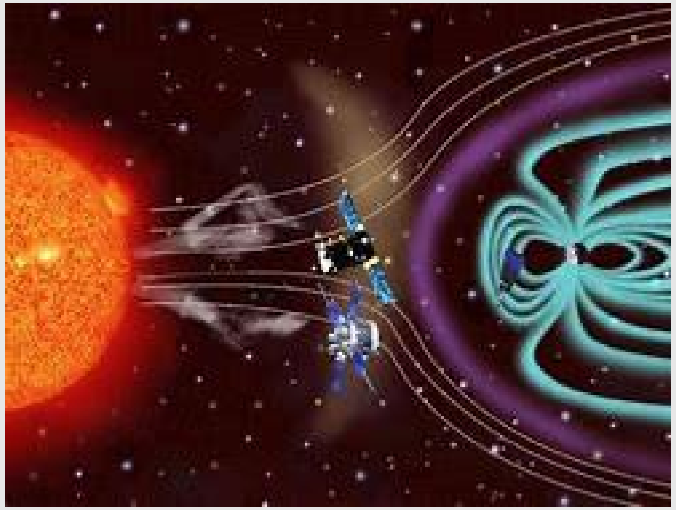
PMT	HZC XP72B20
Supply voltage	1400
Gain	10^7
QE	27%
Dark rate	500Hz
TTS	5ns
size	3 inch

Ref： Fan Hu et al ICRC2021

	KM3NeT	IceCube	IceCube Upgrade	TRIDENT
Structure				
PMT	Hamamatsu R14374	Hamamatsu R7081-02	Hamamatsu R15458-02	HZC XP72B20
PMT Size	**3 inch**	**10 inch**	**3 inch**	**3 inch**
QE	27.5%	25%	25%	27%
High Voltage，HV	1500V	1500V	1500V	1400V
Gain	1×10^7	1×10^7	5×10^6	1×10^7
DCR	-	500Hz	-	474Hz
RT	2.9ns	3.8ns	3.6ns	-
TTS	1.3ns	3.4ns	4.5ns	5ns

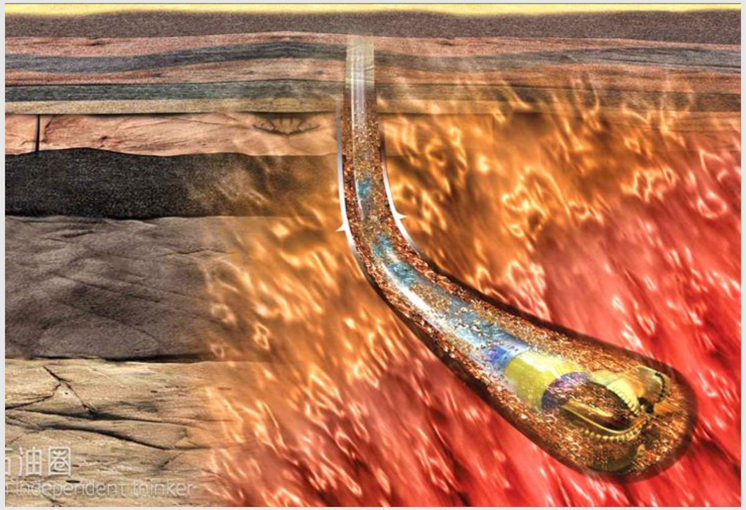
2.2 The Detector for Special Detection

- In Space Radiation Rays

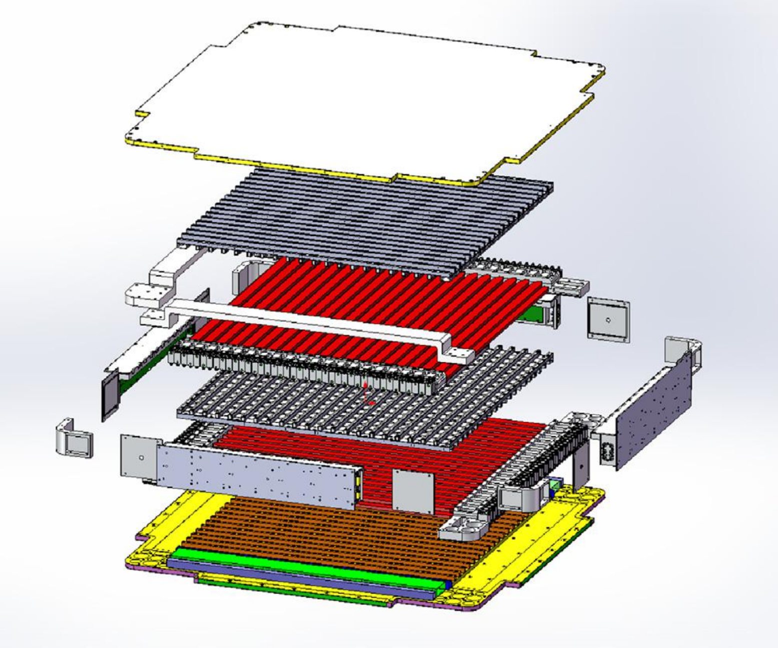


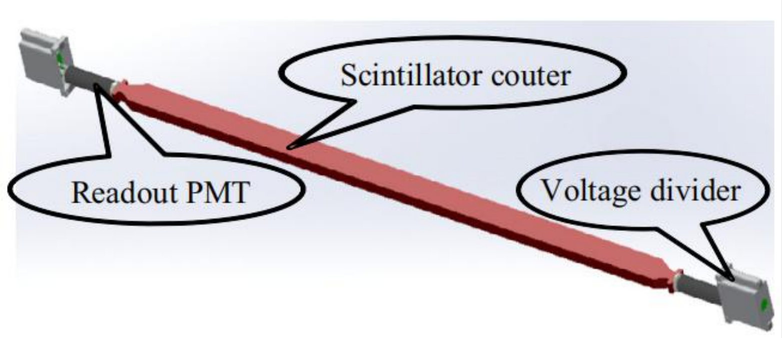
- In Low Temperature

- In High Temperature



（1）In Space Radiation Rays: PSD for DAMPE



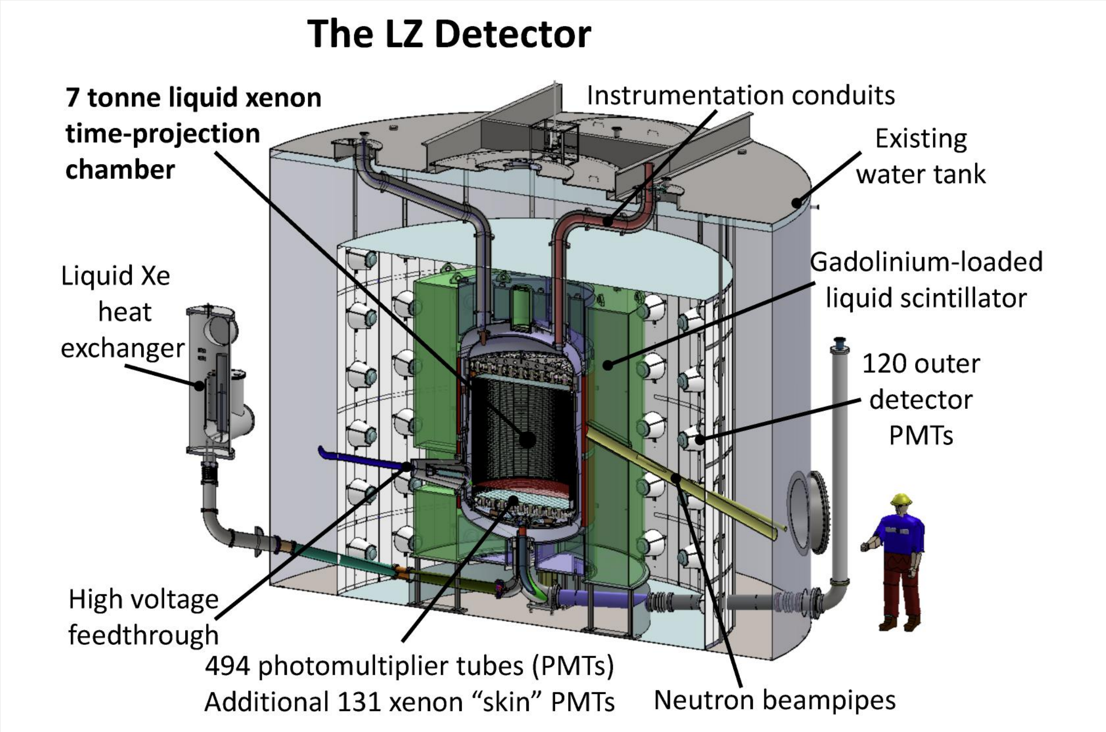


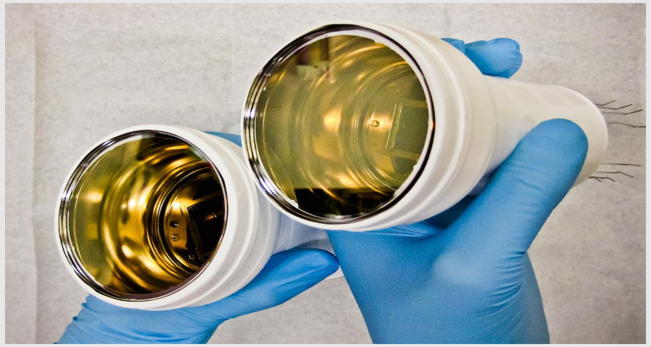
- The Plastic Scintillator Detector (PSD) of the DArk Matter Particle Explore (DAMPE) has a double layer configuration with 82 detector modules in total.
- Each detector module has a long plastic scintillator bar.
- The signals are readout by two **0.5-inch PMTs** coupled to the ends of the plastic scintillator bar.

PMT	Hamamatsu R4443
Supply voltage	1250 V
Gain	2×10^6
QE	16% - 23%
Peak sensitivity wavelength	490 nm
minimum effective area	Φ 10 mm

Ref： Astroparticle Physics 94 (2017) 1–10

(2) in low temperature--Dark mater detection



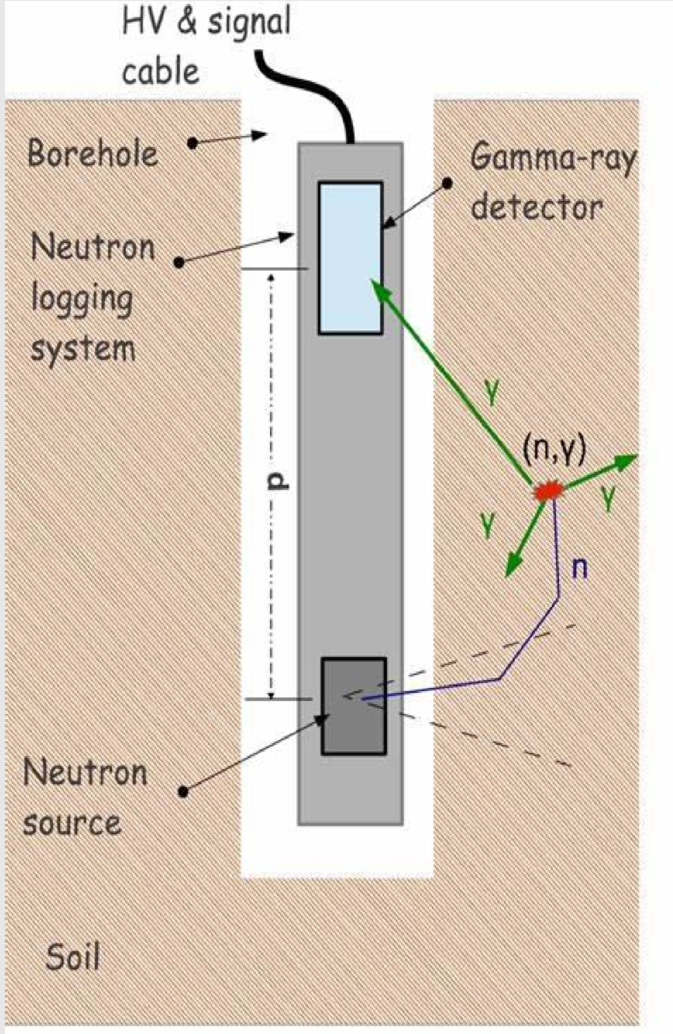


- The LUX dark matter direct detection experiment uses 350 kg of **liquid xenon** for the detection of recoils resulting from the scattering of Weakly Interacting Massive Particles (WIMPs).
- The experiment uses 122 Hamamatsu R8778 PMTs directly above and below the active region to detect scintillation light from xenon nuclear recoils.

PMT	Hamamatsu R8778
Size	3 inch
Supply voltage	1750 V
Gain	5×10^6
Spectral response	160 nm to 650 nm
Operating ambient temperature	-30 ° C to +50 ° C

Ref：NIMA 703 (2013) 1–6

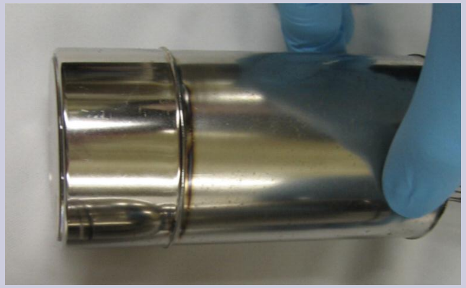
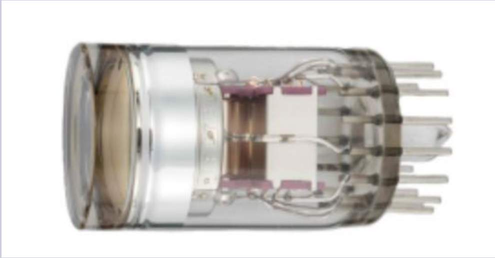
（3） in high temperature



- For **oilfield applications**, gamma ray detectors require reliable and stable performance during hundreds of hours of operation in the harsh well-logging environment (high shock levels and high temperature).

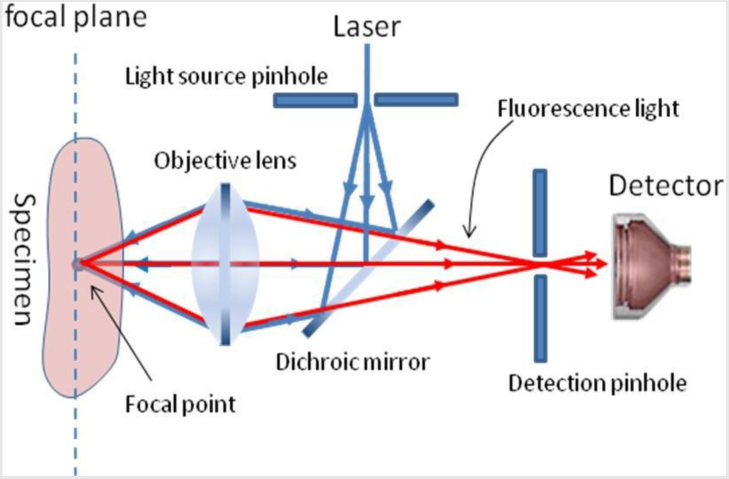
PMT	Hamamatsu R1288
Size	1 inch
Supply voltage	1800V
Gain	5 × 10^5
Operating ambient temperature	175℃

Ref：Procedia Engineering 7 (2010) 223–228

Application	Space detection	Dark matter	Oilfield logging
Special Environment	radiation rays	low temperature	high temperature
Structure			
PMT	Hamamatsu R4443	Hamamatsu R11410	Hamamatsu R1288
PMT Size	0.5 inch	3 inch	1 inch
HV	1250V	1750 V	1800V
Gain	2×10^6	5×10^6	5×10^5
Unique advantage	a ruggedized type for spaceborne experiment	low radioactivity； high QE to xenon VUV light； operate at liquid xenon temperatures	operating ambient temperature of -30~175℃

- 1. The Introduction of PMTs
- 2. The Application of PMTs in Fundamental Physics
- **3. The Application of PMTs in Medical Imaging**
  - 3.1 Development of Microscopic Imaging Technology
  - 3.2 PET / TOF-PET Imaging with PMTs
- 4. The Application of PMTs in Analytical Instruments
- 5. The Future of the PMTs

3.1 Microscopic imaging -- confocal microscopy



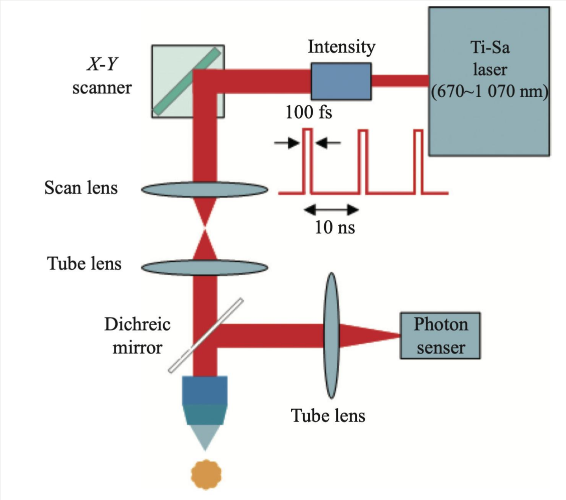
Principle of confocal microscope

LEICA TCS SPE

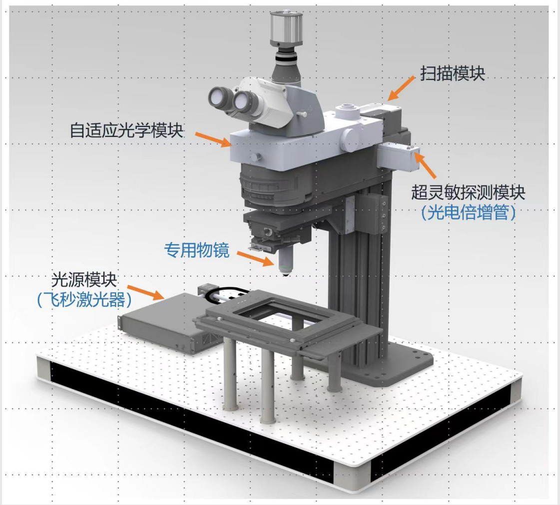
- The optical path diagram of **laser scanning confocal microscopy** uses a laser beam as the light source. The laser beam is illuminated by a pinhole, reflected by a beam splitter to the objective lens, and focused on the sample, rapidly scanning and imaging the focal plane of the specimen point by point, line by line, and face by face.
- The traditional confocal microscope uses PMT as the detector, and SiPM has been used in recent years.

PMT	HAMAMATSU R928P
Wavelength	185 - 900nm
Cathode sensitivity	74 mA/W
Number of stages	9
TTS	1.2ns
QE@260 nm	25.4%
Dark current (max)	50nA

3.1 Microscopic imaging - two-photon microscopy



Principle of two-photonc microscope

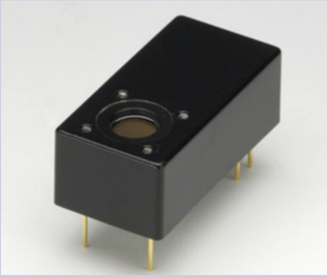


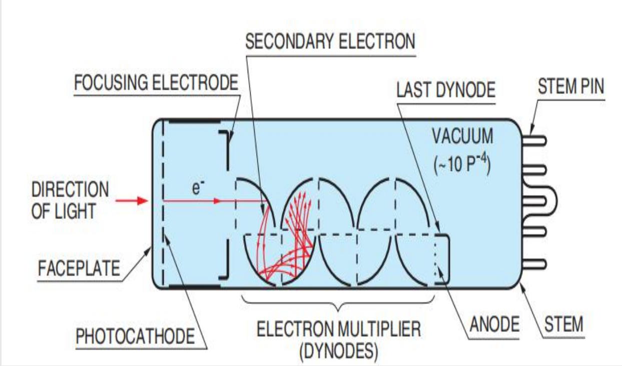
Structure of two-photonc microscope

- The **two-photon microscope** is based on the principle of two-photon absorption, in which two photons are absorbed by the sample at the same time, releasing an ionized electron and a hole, resulting in a random charge distribution.
- By measuring the influence of the electric field on the photon absorption, the image of the sample can be obtained.

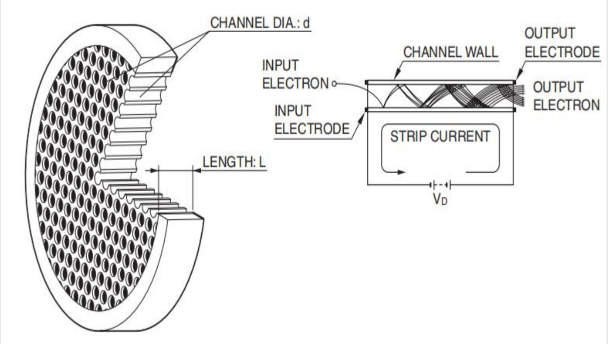
PMT	HAMAMATSU H10720
Wavelength	185-700 nm
Cathode sensitivity	110 mA/W
RT	0.57 ns
TTS	-
QE@260 nm	-
Dark current (max)	10 nA

3.1 Microscopic imaging – Summary

PMT parameter	confocal microscope-R928P	two-photon microscope-H10720
Structure		
PMT size	28 mm side-on	8 mm pin out-put
Detection Efficiency, %	-	-
Quantum Efficiency, %	25.4	-
High Voltage, V	1000	+2.8 ~ +5.5V
Dark Count Rate, kHz	0.5	0.05
After Pulse, %	-	-
Peak/Valley, P/V	-	-
Rise Time, ns	2.2	0.57
Transit Time Spread, ns	1.2	-



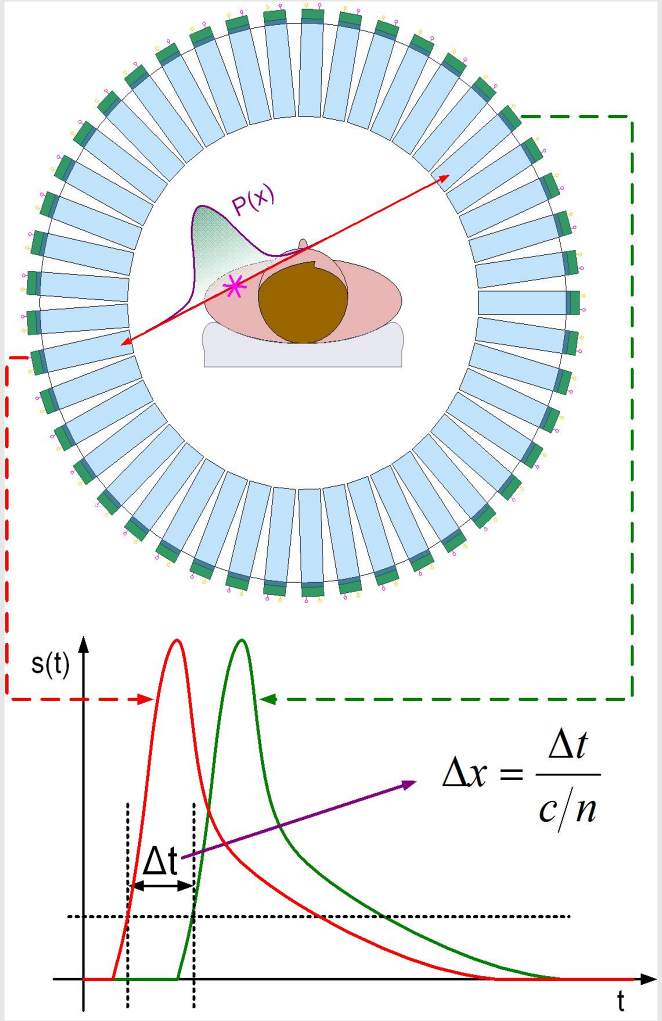
For Better Time Resolution



3.2 PET / TOF-PET Imaging with PMTs

- 2020, the TOF-PET with 214ps time resolution, with the name" Biograph Vision" from Siemens,

(1) Commercial TOF-PET

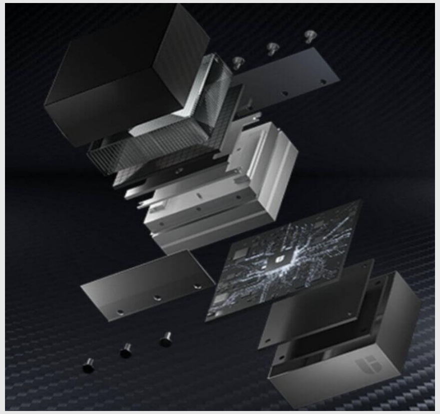


Principle of TOF-PET

- TOF-PET usually uses crystal and PMT as the detection unit, and the core parameters are coherent and time-resolved.
- With the development of SiPM technology, several representative TOF-PET companies have begun to use crystal array and SiPM array as the detection unit.
- Siemens uses PMT for individual PET models, and SIPM for the latest TOF-PET, achieving 178 ps time resolution. United Imaging uses LYSO crystal and SiPM to achieve 196 ps coincidence time resolution（CTR）.

Siemens PMT

Siemens SiPM



United Imaging
LYSO + SiPM

（2）PET for better position resolution

Single-anode PMT

Resolution:

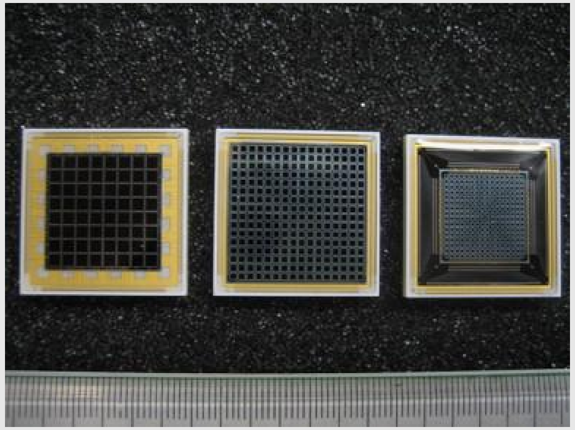
1.3-5mm

Multi-anode PMT

Resolution:

0.5-2mm

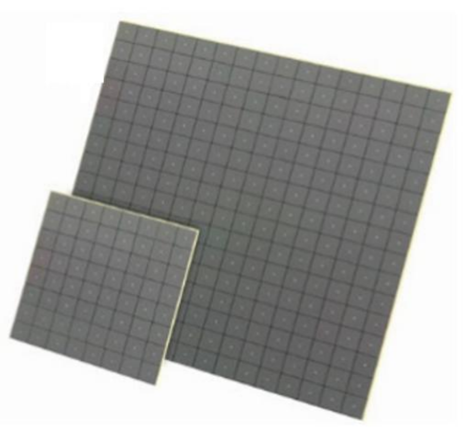
PSAPD



Resolution:

0.5-2mm

SiPM



Resolution:

0.2-2mm

Various digital PET-CT technical parameters comparison.

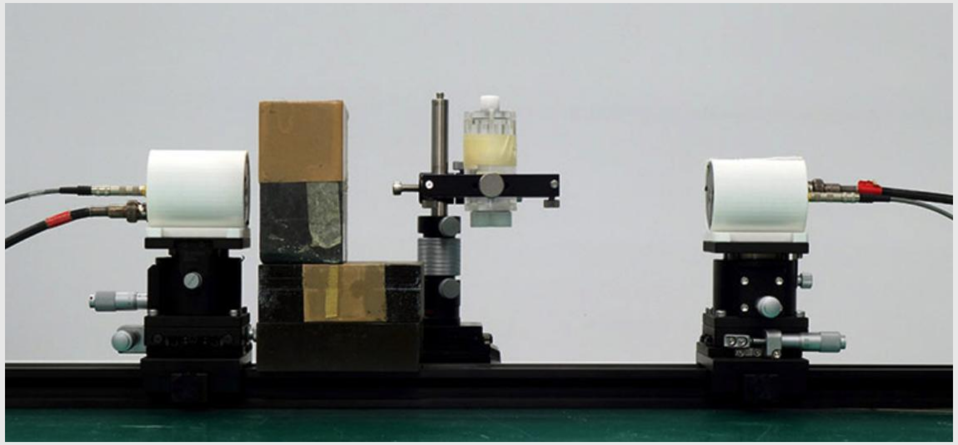
Manufacturer	PETCT Model	sensitivity (cps/KBq)	AFOV (cm)	TOF Resolution ps	Crystal	Photodetector	Crystal dimension (mm)	CT model (slices)	CT detector width (mm)
GE	Discovery MI 3-Ring	7.5	15	385	LBS	SiPM	4 × 4 × 25	128	40
	Discovery MI 4-Ring	13.5	20	385	LBS	SiPM	4 × 4 × 25	128	40
	Discovery MI 5-Ring	21	25	385	LBS	SiPM	4 × 4 × 25	128	40
	Discovery MI 6-Ring	30	30	385	LBS	SiPM	4 × 4 × 25	128	40
	Discovery Omni Legend	45	32	NA	BGO	SiPM	4 × 4 × 30	128	40
Siemens	Biograph Vision 450	13.5	20	214	LSO	SiPM	3.2 × 3.2 × 20	128	38
	Biograph Vision 600	16	26.3	214	LSO	SiPM	3.2 × 3.2 × 20	128	38
	Biograph Vision Quadra	171	104	214	LSO	SiPM	3.2 × 3.2 × 20	128	38
Philips	Vereos	5.6	16.4	325	LYSO	DPC-SiPM	4 × 4 × 20	128	40
Canon	Cartesion Prime	13.5	27	260	LYSO	SiPM	4 × 4 × 20	128	40
United Imaging	uMI550	11	24	385	LYSO	SiPM	2.76 × 2.76 × 16	80	22
	uMI780	16	30	450	LYSO	SiPM	2.76 × 2.76 × 16	160	40
	uMI Vista	11	24	385	LYSO	SiPM	2.76 × 2.76 × 16	160	40
	uExplorer	225	194	450	LYSO	SiPM	2.76 × 2.76 × 16	160	40
Minfound	720E	10	20	380	LYSO	SiPM	4 × 4 × 20	32	20
	730T	23.5	40	380	LYSO	SiPM	4 × 4 × 20	128	40
Prototype	PennExplorer[80]	55	64	256	LYSO	DPC-SiPM	3.86 × 3.86 × 19	NA	NA

Note: The technical data was obtained from the brochure, datasheet, website, and manuals of different manufacturers and literature.[14–19]

All commercial TOF-PET uses SiPM as the core detection for better position-sensitive detection now.

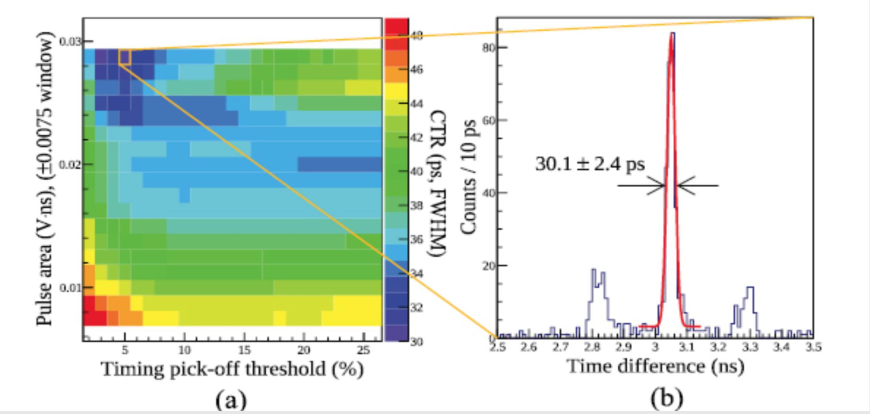
https://doi.org/10.1016/j.radi.2023.10.004

（3）new research status--Hamamtsu



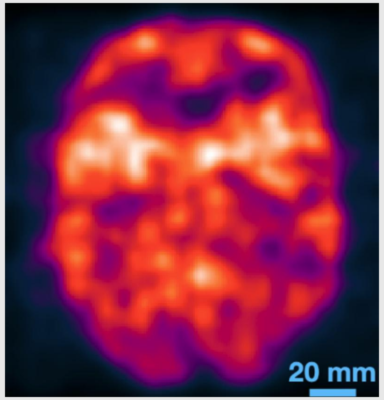
Hamamtsu uses a single anode lead glass window for MCP-PMT

- Hamamatsu proposed in 2019 to use lead glass directly as the light window for MCP-PMT, and achieved a 30 ps time resolution with a **single anode MCP-PMT using this lead glass light window**.
- At the same time, the concept of reconstruction free imaging was proposed, which is expected to realize the implementation of PET imaging.



CTR：**30.1 ± 2.4 ps** FWHM

(R Ota et al 2019 Phys. Med. Biol. 64 07LT01)

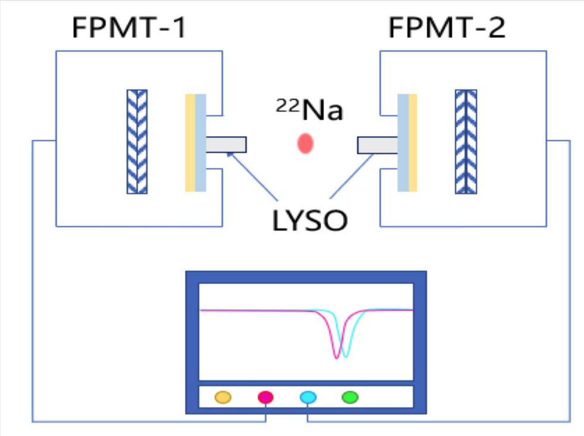


reconstruction-free imaging

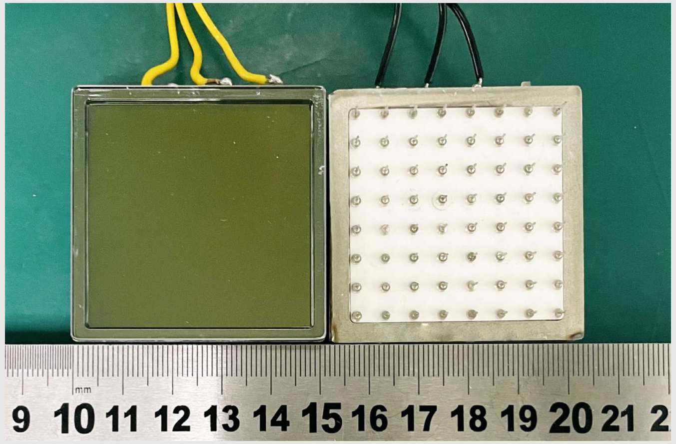
（Sun Il Kwon，Nature Photonics，15, 914–918 (2021)）

PMT	Hamamatsu
Wavelength	UV
Cathode sensitivity	-
RT	<0.2 ns
TTS	<10 ps(RMS)
CTR	30.1 ps
Dark count rate	721 cps

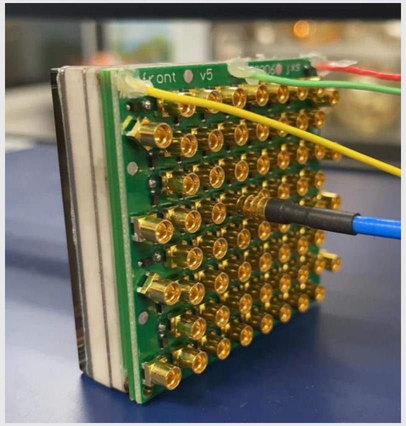
（3） new research status--IHEP



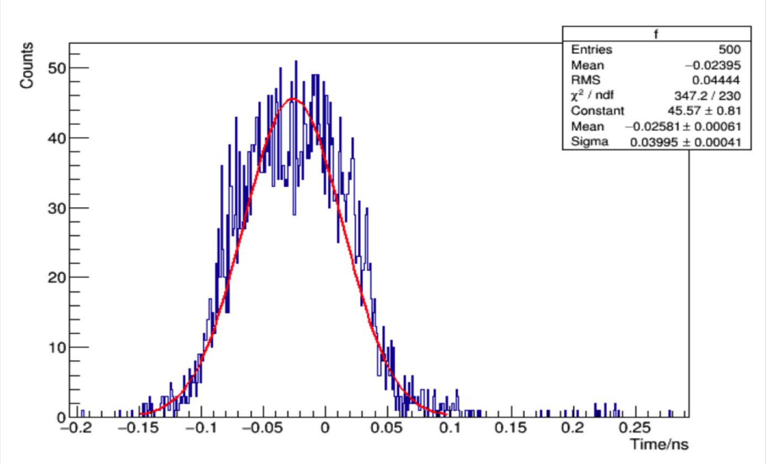
Phtek210+PbF$_2$



V4.0 CRW-FPMT



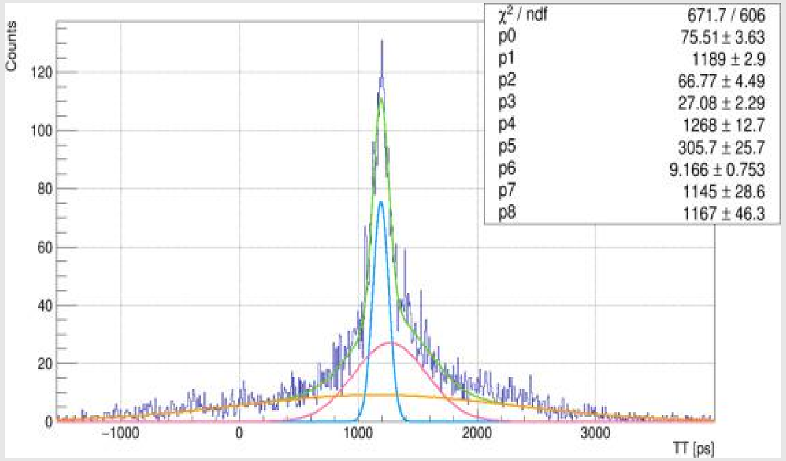
V6.0 CRW-FPMT



Phtek210+PbF$_2$

CTR：93.9 ± 0.1 ps FWHM

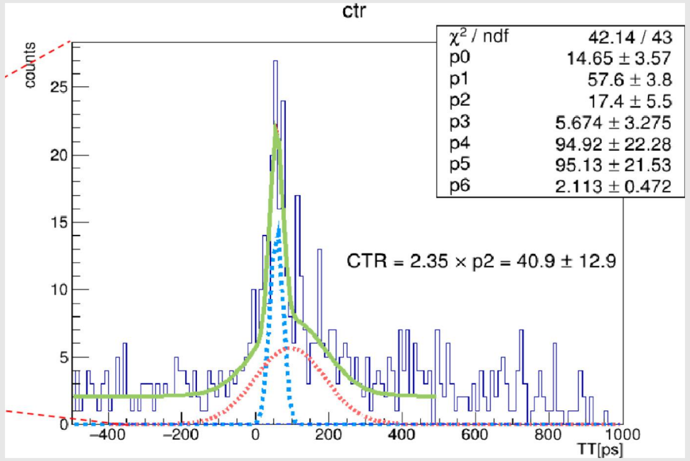
（Lishuang Ma，2022 JPCS. 2374 012132）



V4.0 CRW-FPMT

CTR：156.7 ± 10.6 ps FWHM

(Lishuang MA, NIMA,2023,168089)

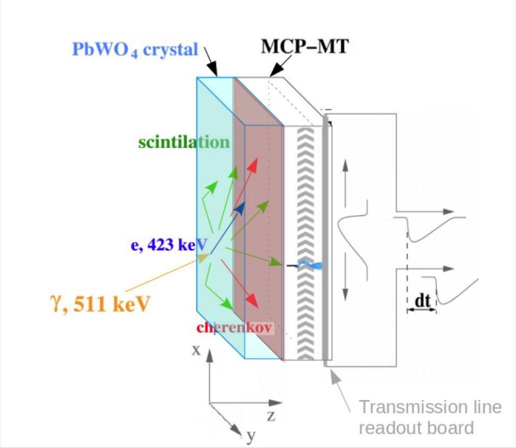


V6.0 CRW-FPMT

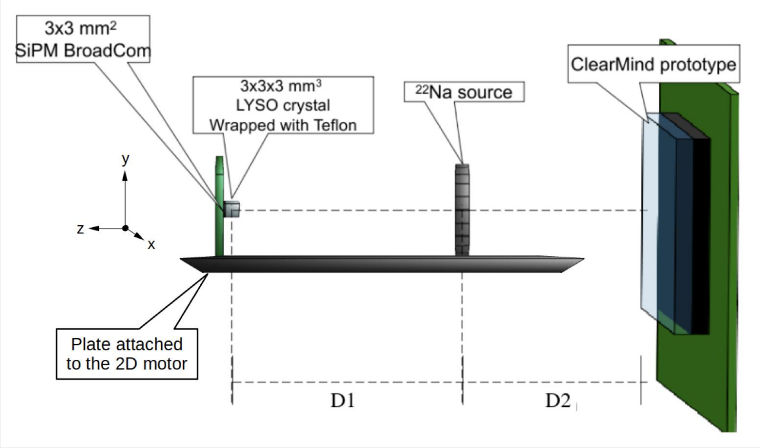
CTR：40.9 ± 12.9 ps FWHM

(Lingyue Chen, NIMA,2024,169173)

（3） new research status--Clearmind

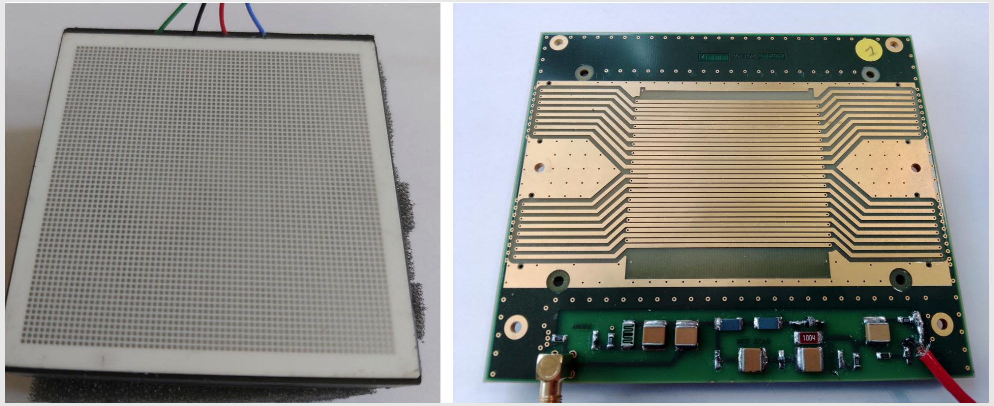


Clearmind detector module



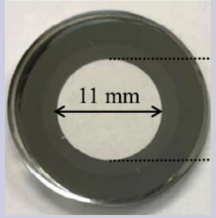
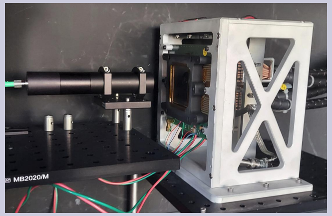
Coincidence time resolution testing device

- The ClearMind project aims to develop an optimized TOF-PET position sensitive detection module. The project uses a 59 * 59 * 4mm^2 $PbWO_4$ crystal, packaged in a commercial microchannel plate photomultiplier tube MAPMT253, and deposited a double alkali photocathode on the crystal. The initial test CTR can reach 350 ps.



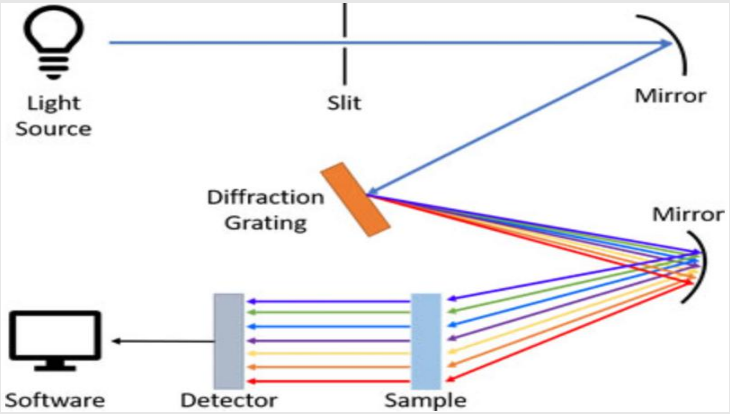
Clearmind Anode and readout electronics design

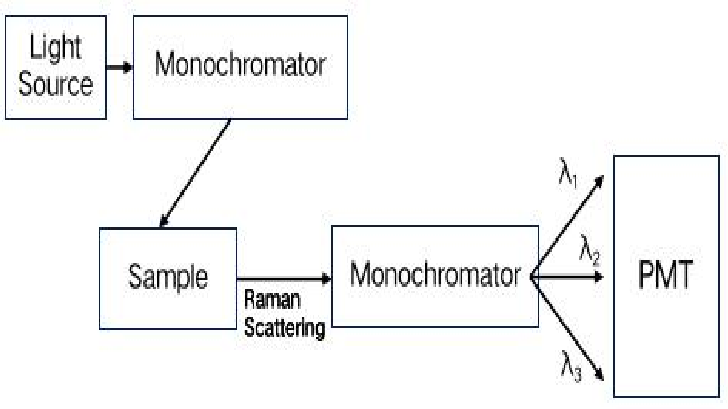
PMT	Clearmind-Photek
Wavelength	300-650nm
Cathode sensitivity	-
RT	-
TTS	29.8 ps
QE@400 nm	~18%
Gain	-

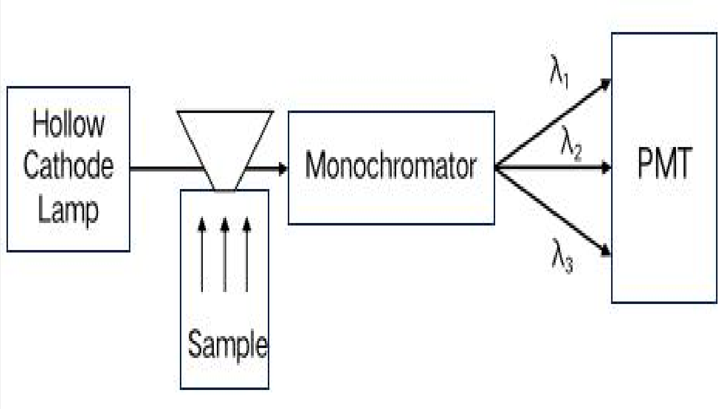
PMT parameter	Hamamatsu	IHEP-NNVT	Clearmind
Structure			
PMT type	Pb glass window	Pb glass Window	Photek-253-PbWO4-window
Sensitive area / mm	11	51×51	53×53
Gain	>1.0 x 106	5.0 x 106	-
Quantum Efficiency	~20%@?	21%@410nm	~18%@410nm
TTS@SPE, ps	<10(RMS)	<30(RMS)	~29.8(RMS)
Rise Time, ns	<0.2	<0.3	-
Pulse width, ns	<0.3	<0.4	-
Readout channel	1	8×8	64*64
Coincidence time resolution, ps	30.1 ps	40.9 ps	350 ps

- 1. The Introduction of PMTs
- 2. The Application of PMTs in Fundamental Physics
- 3. The Application of PMTs in Medical Imaging
- **4. The Application of PMTs in Analytical Instruments**
- 5. The Future of the PMTs

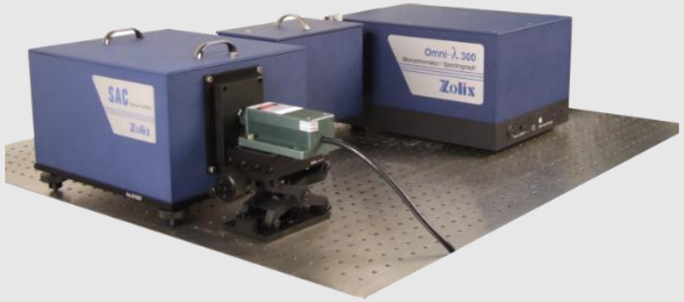
4. The Application of PMTs in Analytical Instruments





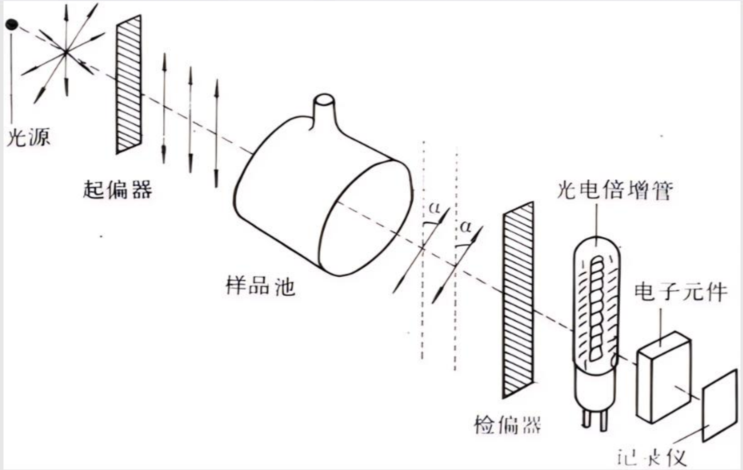


- Fluorescence spectrometer
- Raman spectroscopy
- Atomic absorption spectrometer

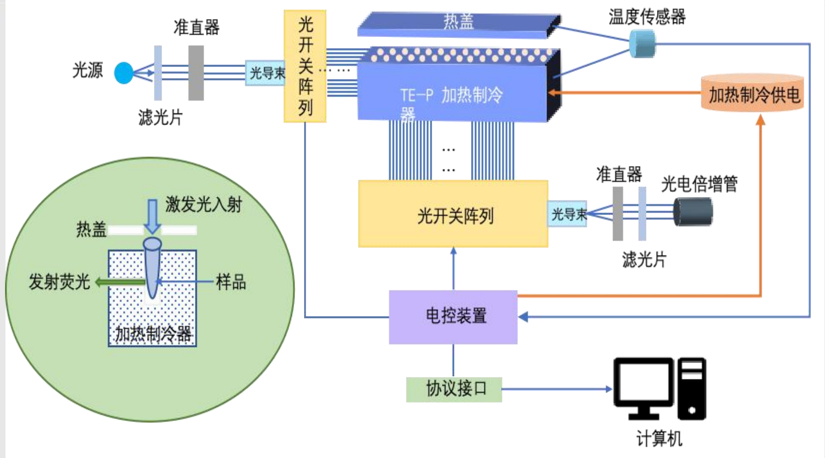


- HORIBA FluoroMax
- ZOLIX OmniRS-532
- Thermo Scientific™ ICE3400

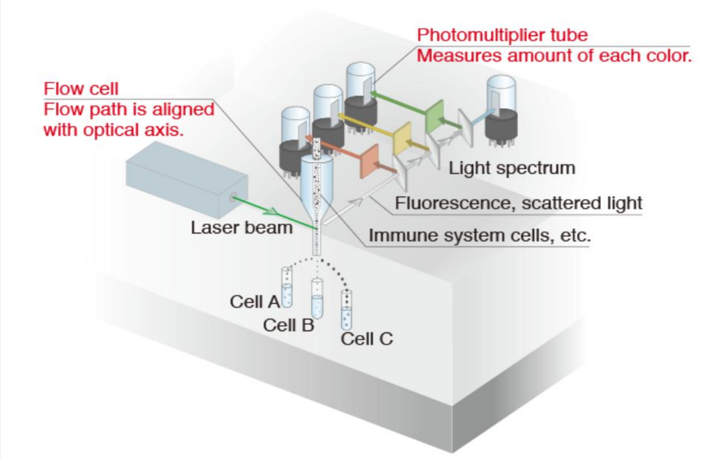
The Medical analysis equipment with PMTs



- Principle of Polarimeter



- Principle of PCR



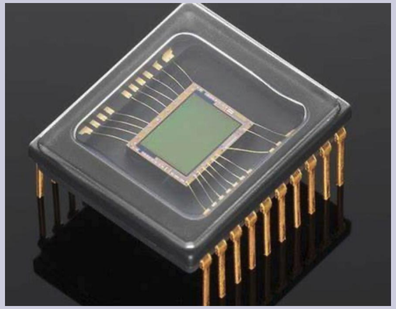
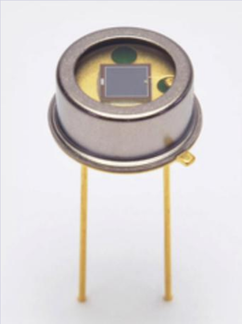
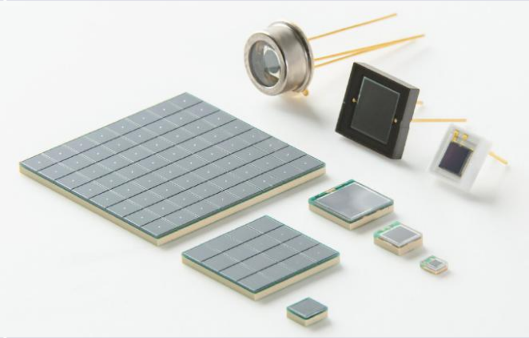
- Principle of Flow cytometer

JASCO P-2000

Archimed 384

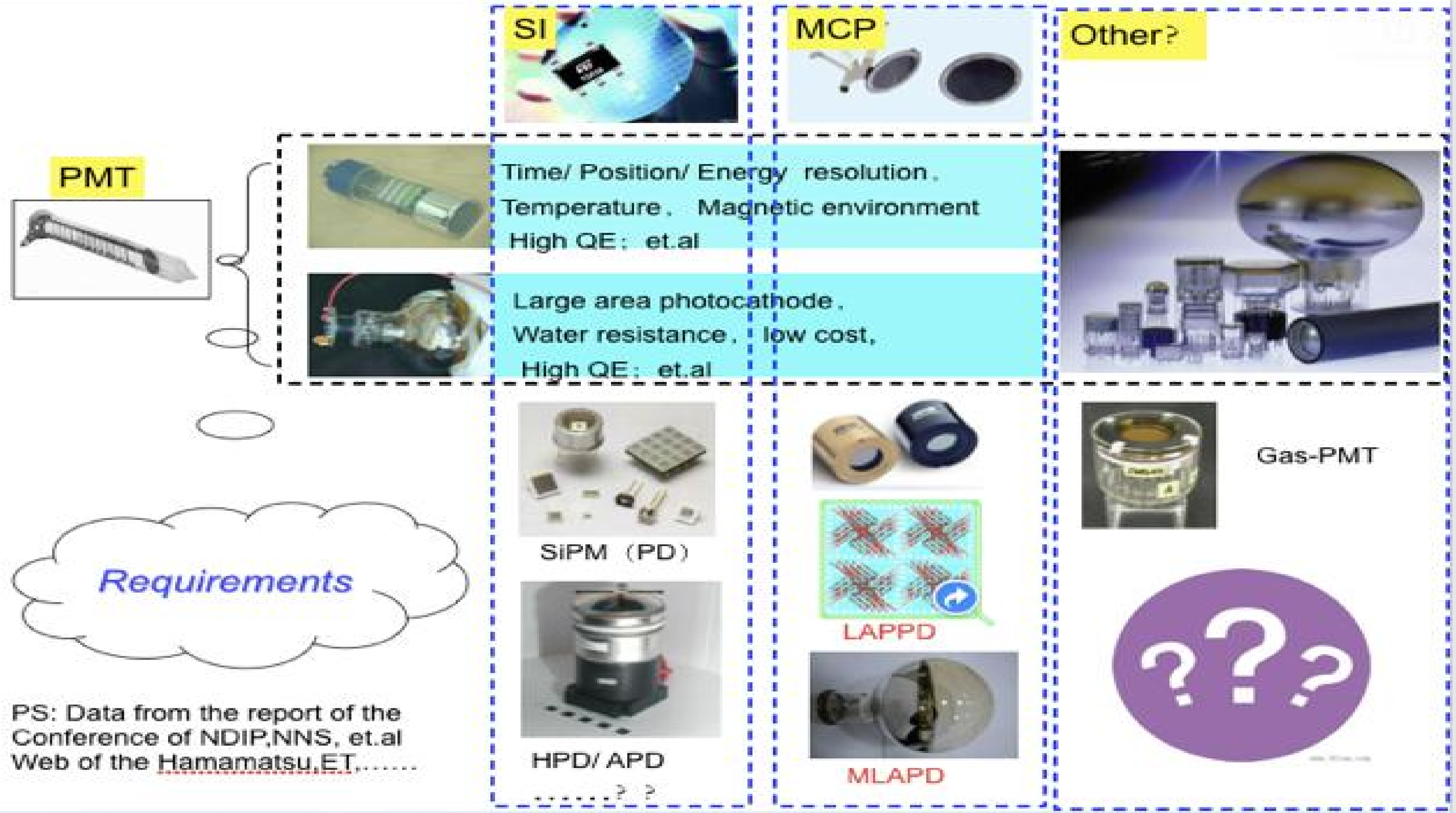
Thermo Scientific™ Attune NxT

PMT parameter	HORIBA FluoroMax	ZOLIX OmniRS-532	Thermo Scientific ICE3400
Structure			
PMT type	R928P	R1527P	R955P
PMT size	φ 28mm	φ 28mm	φ 28mm
Quantum Efficiency, %	25.4	19	29
High Voltage, V	1250	1250	1250
Dark Count Rate, kHz	0.5	0.01	0.5
Rise Time, ns	2.2	2.2	2.2
Transit Time Spread, ns	1.2	1.2	1.2

	PMT	CDD	APD	SiPM
				
Advantage	High-SNR low noise wide detection spectrum	Multiple photos can be taken of the layout in the same loop	low cost small size	low cost small size High sensitivity
Disadvantage	high cost	Edge effect Low sensitivity	Low sensitivity Low SNR	High noise
Application	PCR, Flow cytometer	PCR	PCR, Flow cytometer	PCR

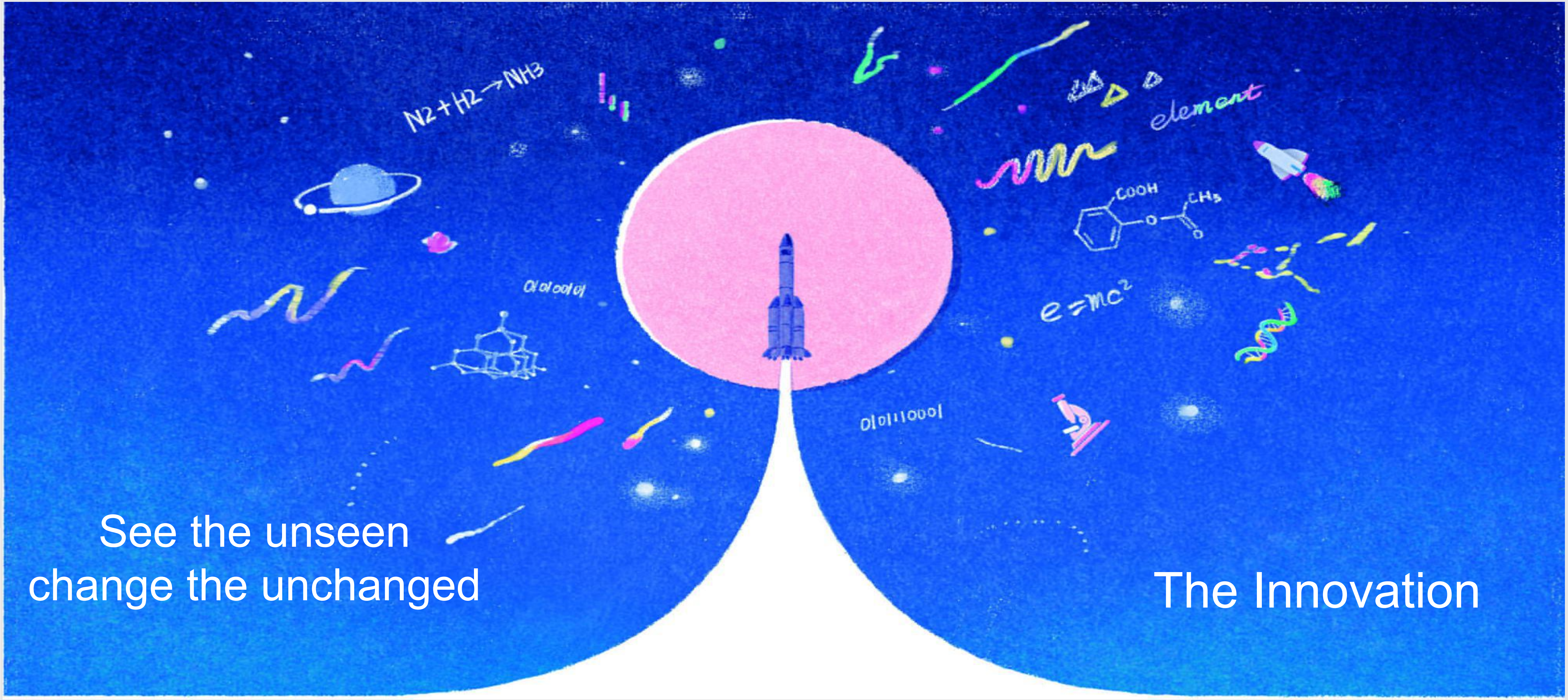
In recent years, the detectors used in biological detection instruments have gradually been replaced by APD and SiPM.

5. The Future of the PMTs



PS: Data from the report of the Conference of NDIP,NNS, et.al
Web of the Hamamatsu,ET,……

THANKS



See the unseen
change the unchanged

The Innovation