The R&D of the Fast MCP-PMTs for High Energy Physics Detectors

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The Institute of High Energy Physics, CAS

第三届地下和空间粒子物理与宇宙物理前沿问题研讨会

Conference on frontiers of underground and space particle physics and cosmophysics

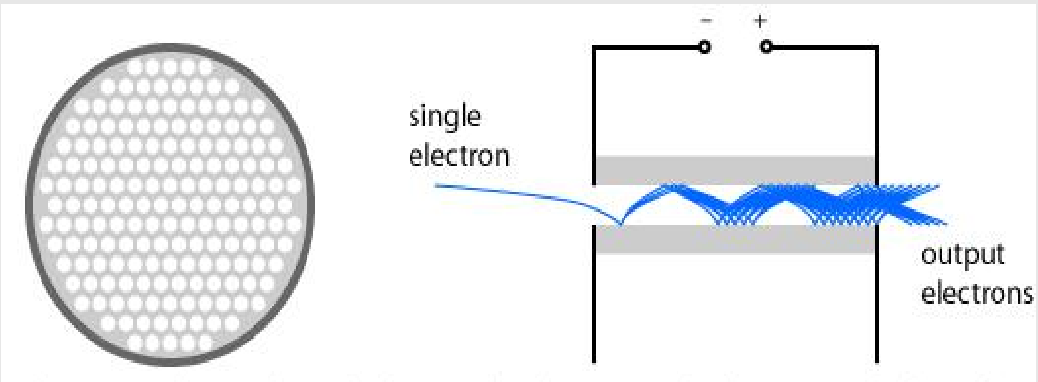
2024年5月7日-11日，四川西昌

Outline

- 1. The Conventional PMTs
- 2. The 20 inch Large MCP-PMT （LPMT)
  - 2.1 The Design of LPMT ;
  - 2.2 The Roadmap for the R&D of LPMT ;
  - 2.3 The Application of the LPMTs ;
- 3. The 2 inch Fast timing MCP-PMT (FPMT)
  - 3.1 The Roadmap for FPMT ;
  - 3.2 The Performance of FPMT ;
  - 3.3 The Beam Test Results ;
  - 3.4 The CTR of FPMTs;
- 4. Summary

1.1 The Conventional -- Small-MCP-PMT

- The Microchannel Plate MCP

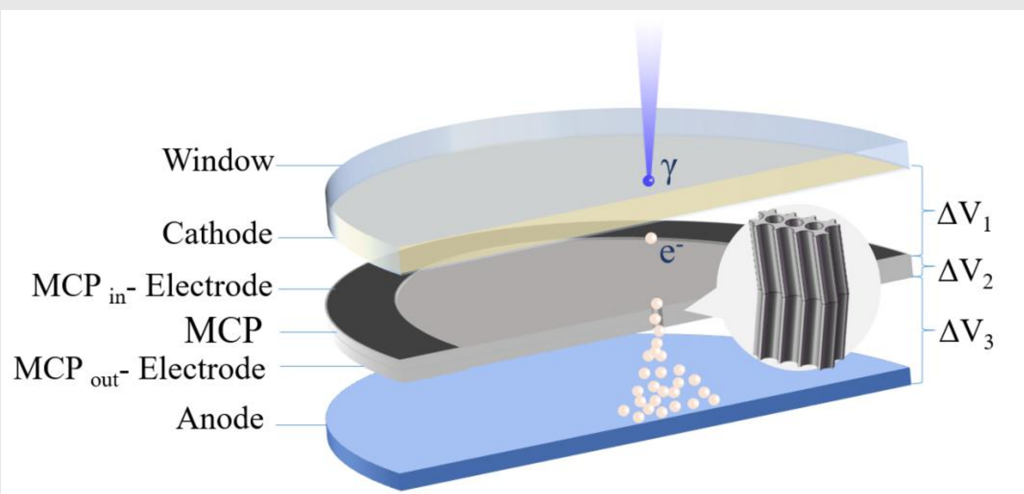


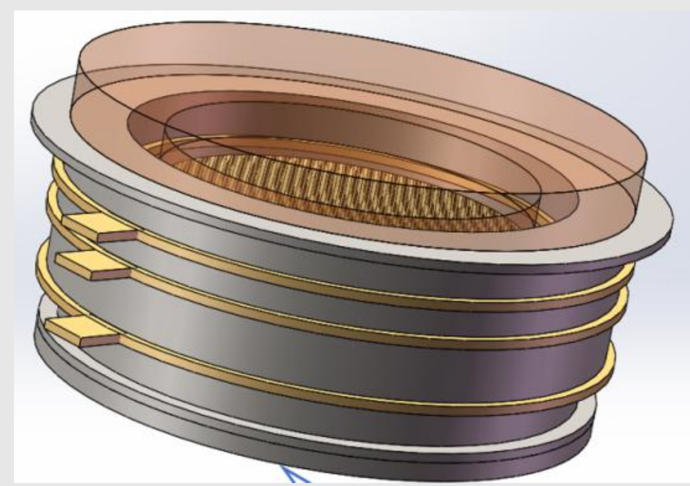
a) front view of microchannel plate   b) electron avalanche in a single channel

performance of the MCP:

- High Gain： $1X10^4$ / 1 pic
- Small Size: Diameter=50mm
- Fast Signal：Rise time < 1ns
- TTS@SPE：~30ps

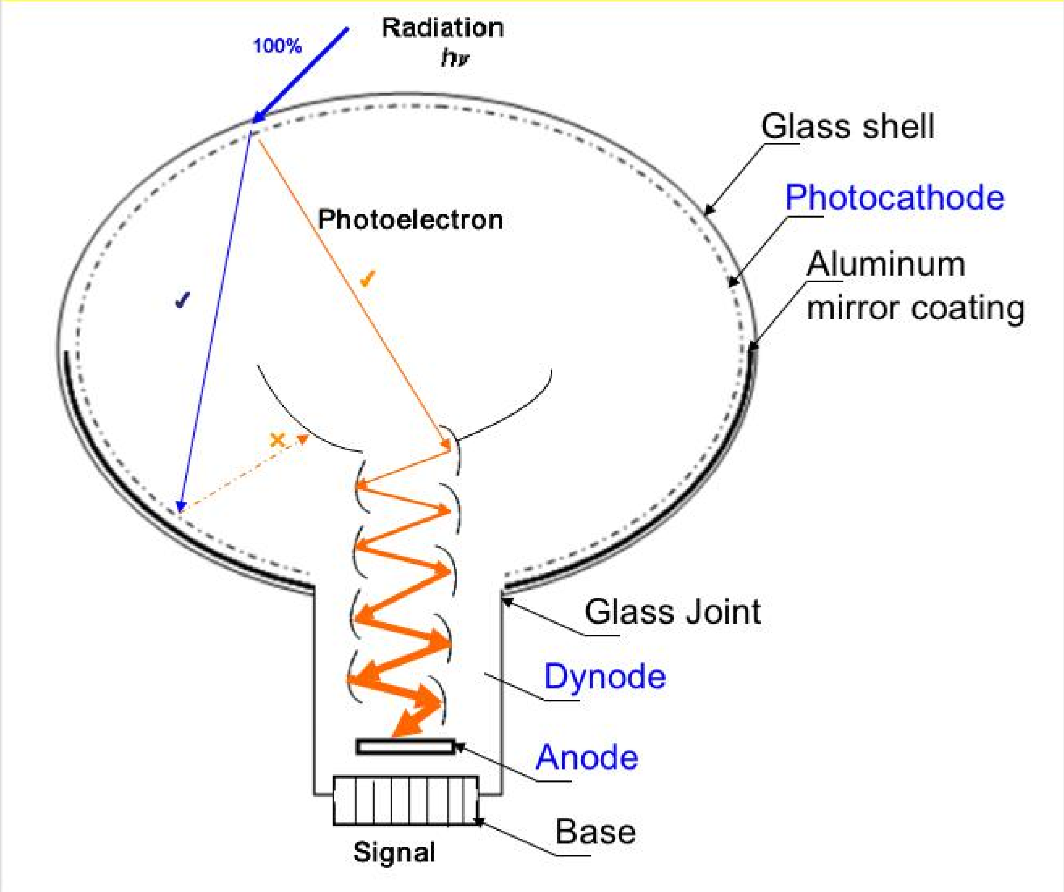
- The Conventional small，fast timing MCP-PMT， FPMT





1.2 The Conventional -- Dyonde-PMT

➢ The 20 inch Dynode PMT



The first PMT in the world in 1933
“Kubetsky’ s tube”

How to improve the PDE of PMT?

Quantum Efficiency (QE) :

20%

Collection Efficiency (CE) of Anode:

70%

Photon Detection Efficiency (PDE)= QE_{Trans} * CE = 20% * 70% = 14%

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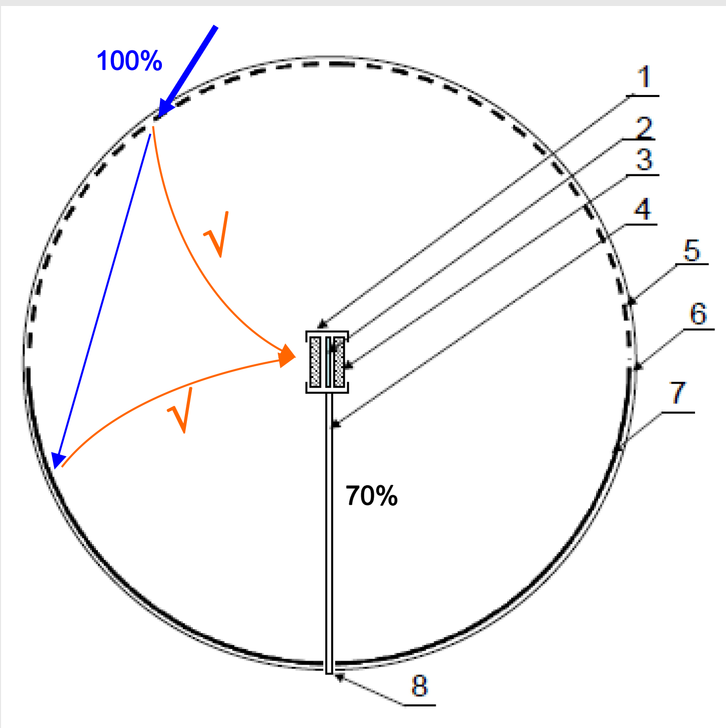
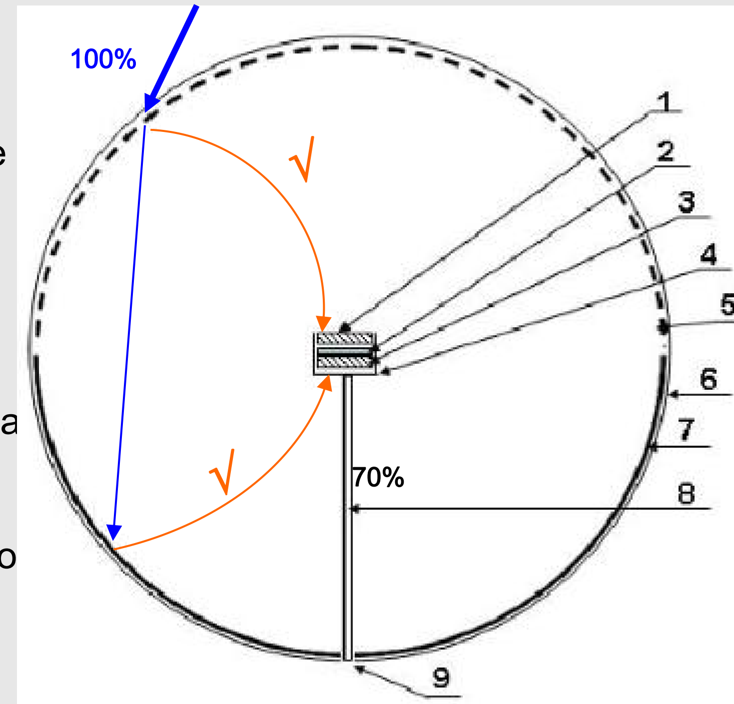
2.1 the design of a Large MCP-PMT (2009)

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



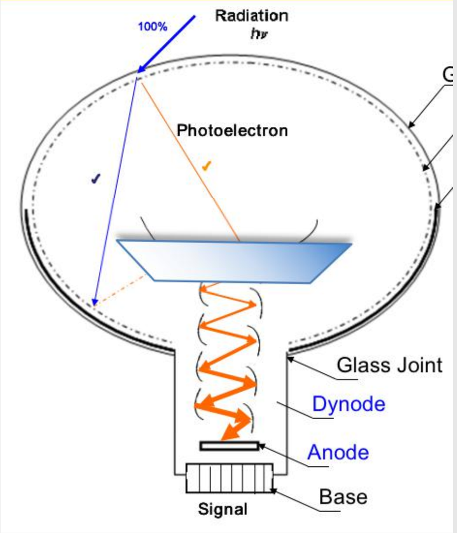
$$PD = QE_{Trans} * CE + TR_{Photo} QE_{Ref} * CE$$

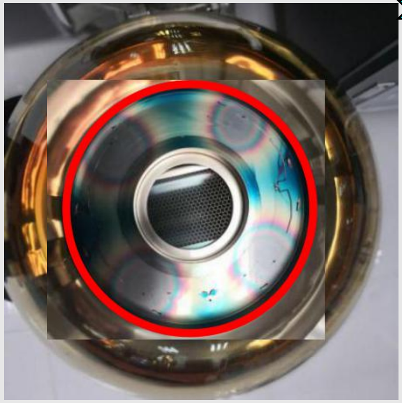
Photon Detection Efficiency: 15% → 30% ； ×~2 at least !

2012 NIMA 695

2.2 The Roadmap -- （1） Technology

- Dynode-PMT





① MCPs for the SPE test

2016 NIMA 824

Quantum Eff.=20%

②QE=30%

2020 NIMA 971

- new tech. for the Photochade

Collection Eff.=70%

③CE=100%

2017 NIMA 868

- ALD coatting for the MCP

Detection Eff.=14%

④DE=30%

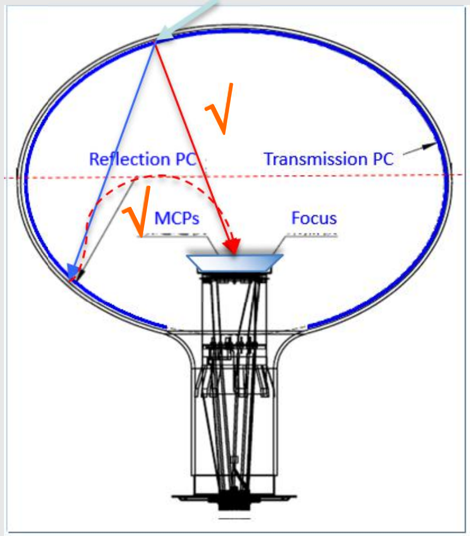
2021 JINST 16 T05007

⑤ Low-Potassium Glass

2018 NIMA 898

⑥ Low cost （3000$, 20KRMB）

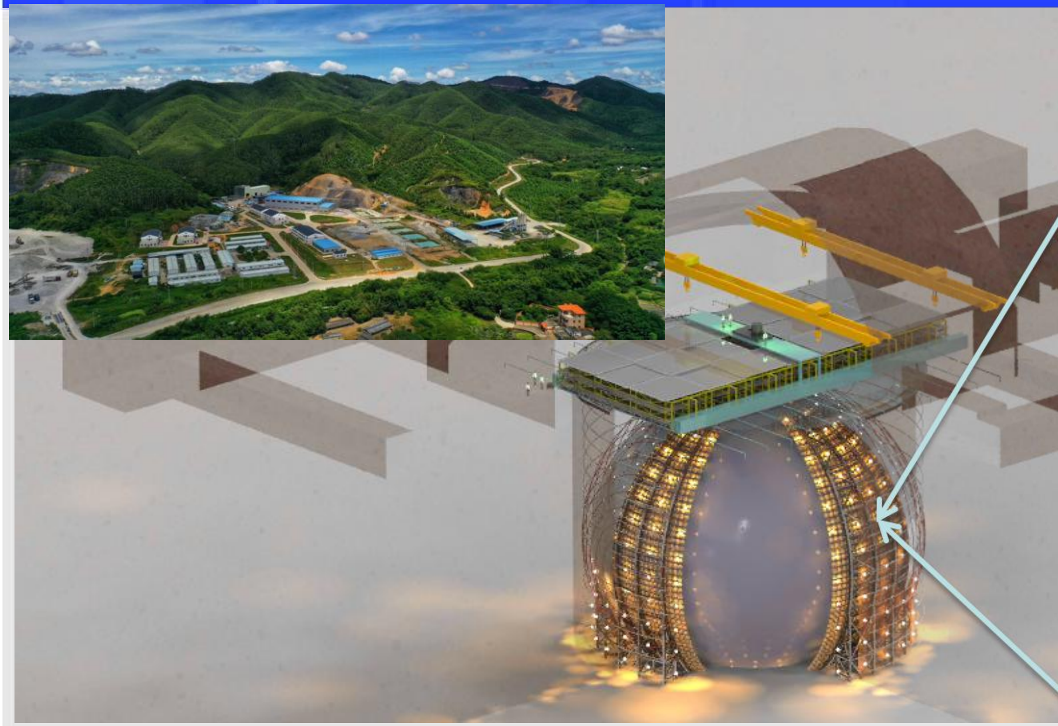
- MCP-PMT



2.2 The Roadmap -- （2） Parameters

Characteristics （20inch）	unit	MCP-PMT Prototype（IHEP）	MCP-PMTs 15K pieces（NNVT）
Electron Multiplier	--	MCP	MCP
Photocathode Mode	--	reflection+ transmission	reflection+ transmission
Quantum Efficiency（400nm）	%	26 (T), 30 (T+R)	32%
Collection Efficiency		~99%	99%
Detection Efficiency（400nm）	**%**	**~ 27%**	**31.5%**
Detection Efficiency（420nm）	**%**	**--**	**28.3%**
P/V of SPE		＞ 5	7.1
TTS on the top point	ns	~15	~ 20
Rise time/ Fall time	ns	R~2 ， F~20	R~1.4 ， F~24
Anode Dark Rate	Hz	~30K	40K
After Pulse Time distribution	us	0.1, 4.5	0.2 , 0.8 , 3 , 4.5, 17
After Pulse Rate	%	2.5%	5.2%
Glass	--	Low-Potassium Glass	Low-Potassium Glass

2.3 The Application of LPMT --(1) JUNO



✓ **The High PDE 20" MCP-PMT for JUNO**

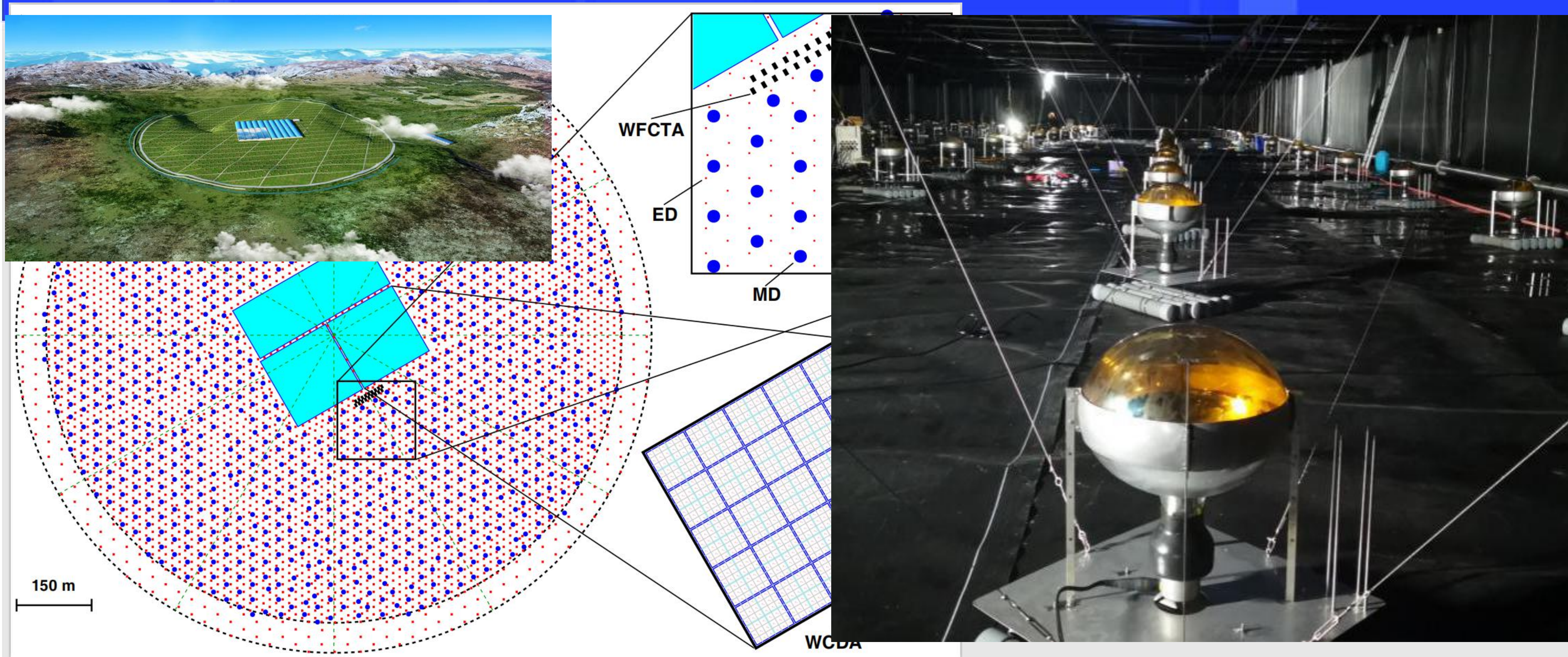
—JUNO（**Jiangmen Underground Neutrino Observatory**), has already supported the MCP-PMT collaboration group to R&D the 20 inch MCP-PMT from 2009 to 2020.

—Yifng Wang in IHEP is our group leader for this type of MCP-PMT development and the the company NNVT is the one to do the mass production work.

Parameters	MCP-PMT	Dynode-PMT
Total number	15000	5000
DE@420nm	28.3%	27.6%
Dark Rate	~ 40KHz	~ 17KHz
P/V	~7	~3

2020 NIMA 952; 2021 JINST 16 C11003

2.3 The Application of LPMT --(2) LHAASO



✓ **The FAST 20" MCP-PMT for LHAASO**

—LHAASO（**Large High Altitude Air Shower Observatory**), has already ordered 2270 pics 20" Flower-like-MCP-PMT.

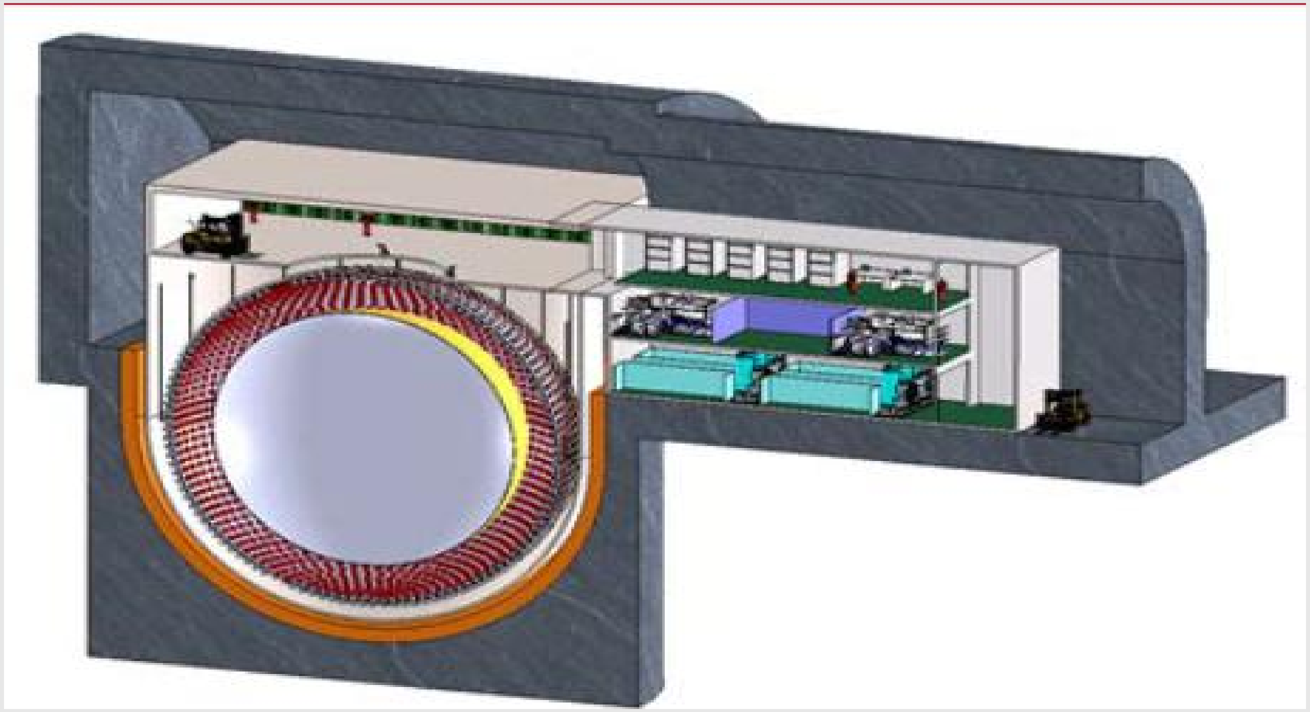
—The 20 inch Prototype with potting has also post to the HyperK PMT Group in Tokyo University for the testing.

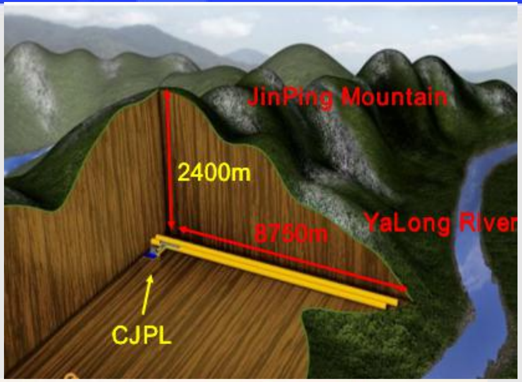
—The performance are different from the tubes for JUNO.

Parameters	JUNO	LHAASO
Total number	15000	2270
DE@400nm	30%	26.8%
Dark Rate	~ 40KHz	~ 20KHz
TTS	~20ns	~5.5ns

2020 NIMA 977;

2.3 The Application of LPMT --(2) JNE





✓ The FAST 8" MCP-PMT for JNE

--The JNE (**Jinping Neutrino Experiment**) under construction is a hundred-ton liquid scintillator detector with Cherenkov and scintillation light readout at CJPL II.

--with 2400m rock overburden, JNE will study for the targeting solar, terrestrial and supernovae neutrinos

Parameters	20-MCP-PMT	8-MCP-PMT
Experiment	LHAASO	JNE
DE@400nm	26.8%	30%
P/V	~ 3	~ 5
TTS	~5ns	~1.5ns

2023NIMA 1055


中国锦屏地下实验室

清华大学
Jinping Neutrino Experiment
One-ton Prototype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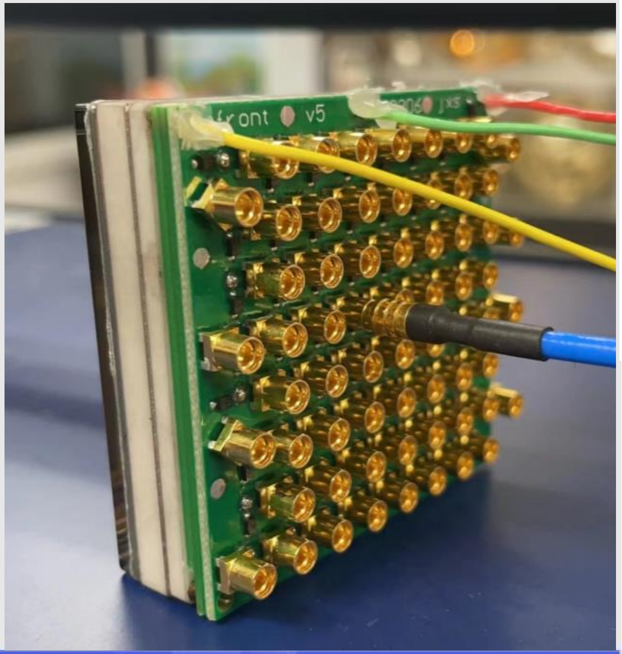
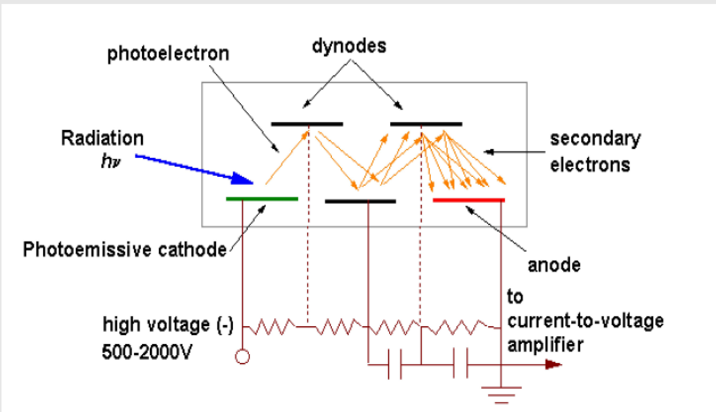
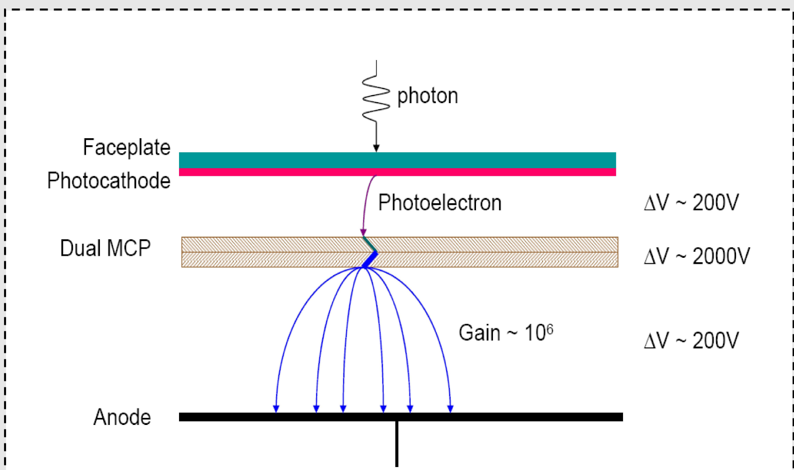
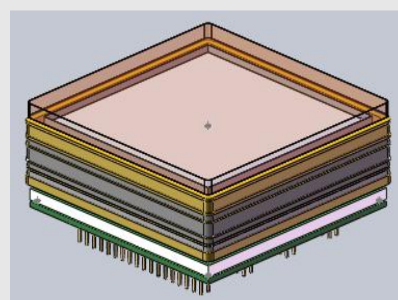


3.1 The Roadmap for FPMT-- （1） Purpose

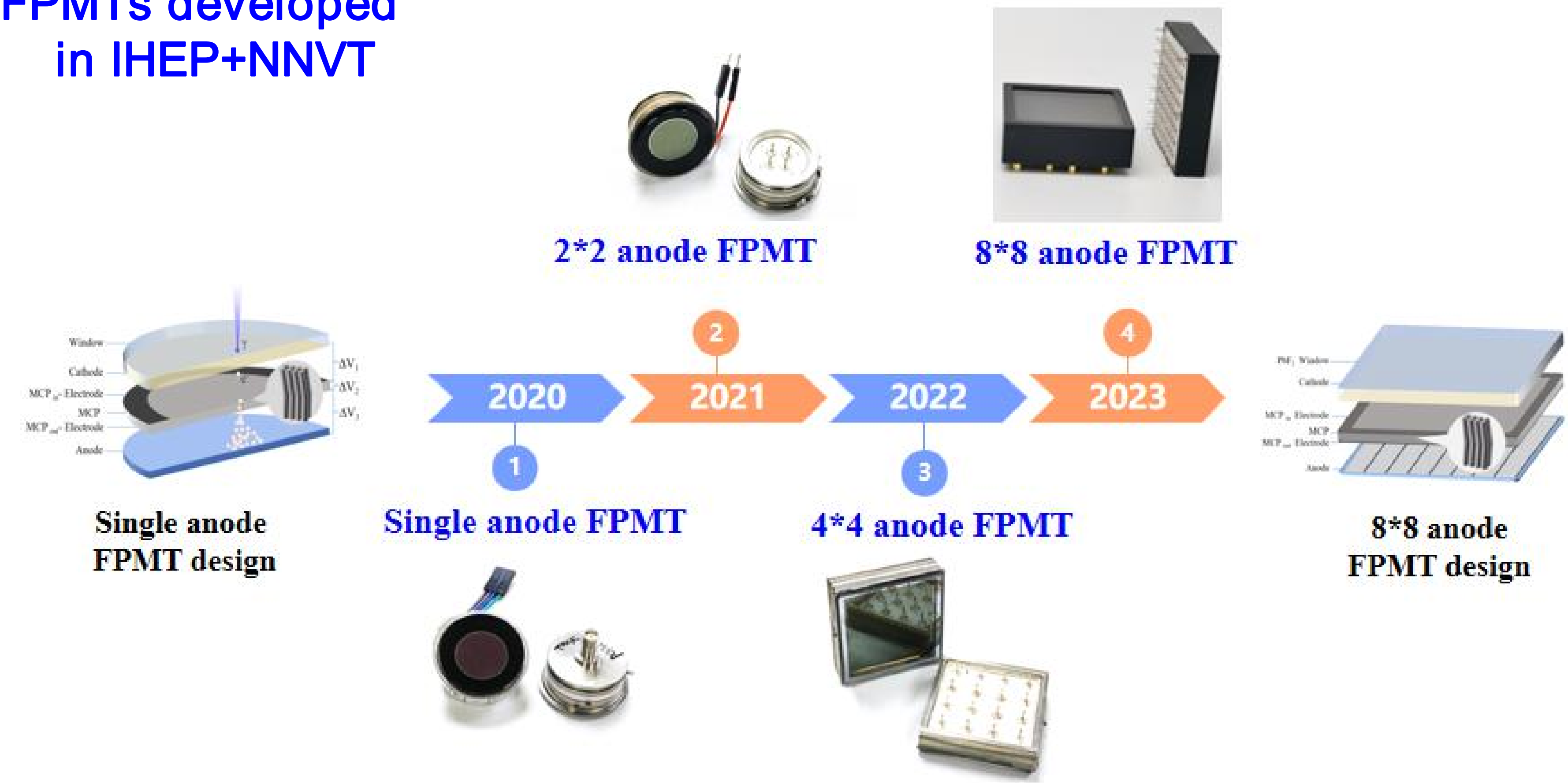
<table>
<tr><th></th><th>Operation Principle</th><th>Small Size
（proximity focusing）</th><th>Large Size
（electrostatic focusing）</th></tr>
<tr><td>Dynode</td><td>
</td><td>2“ Dynode-PMT ✔

</td><td>20“ Dynode-PMT ✔

</td></tr>
<tr><td>MCP</td><td>
</td><td>2“ MCP-PMT ?
</td><td>20“ MCP-PMT ✔
</td></tr>
</table>

3.1 The Roadmap for FPMT -- （3）Prototypes

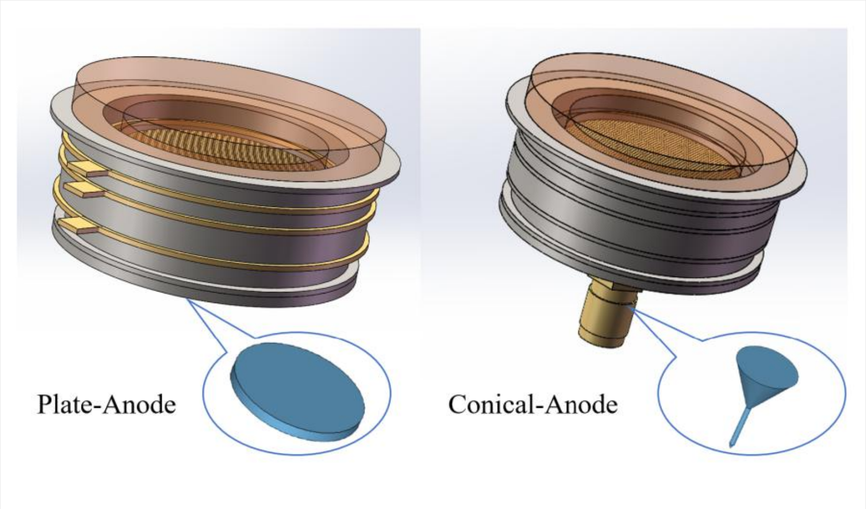
FPMTs developed in IHEP+NNVT



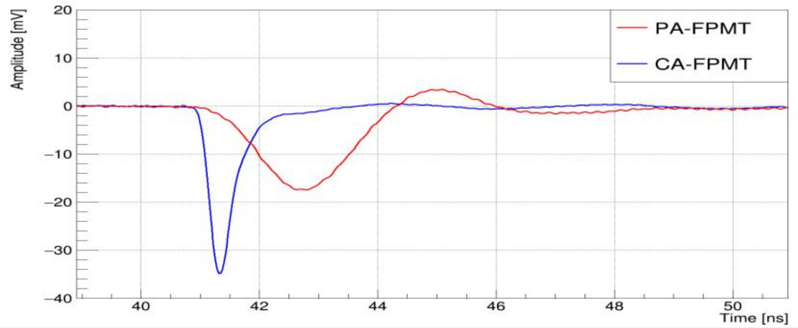
Since 2020, our team has successfully developed FPMT from single anode to multi-anodes, more optimization to single anode FPMT and 8x8 anodes FPMT.

3.2 The Performance -- （1） Single Anode FPMT

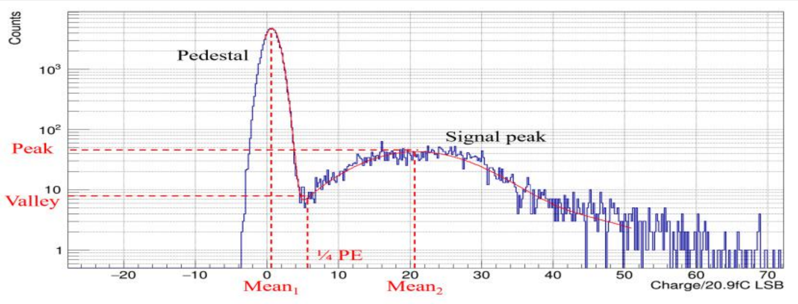
➢ Anode Optimization



➢ Waveform comparison



➢ SPE Spectrum



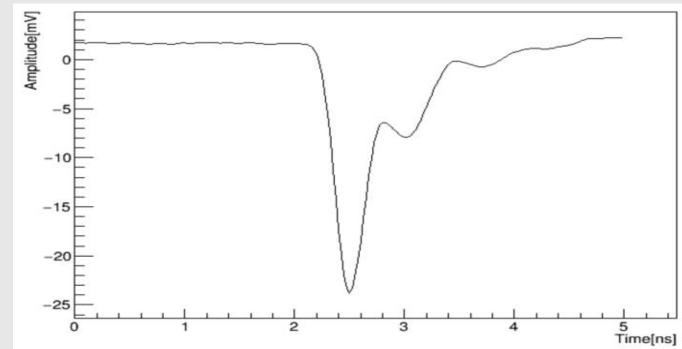
	HV/V	Gain	P/V	Amp(SPE)	RT	FT	Width	TTS@SPE	TTS@MPE
Photek 210	-4700	2.9E6	2.0	93 mV	96 ps	350 ps	190ps	45 ps	10 ps
Plate-Anode	-2000	1.9E6	28.8	7 mV	1.4 ns	1.4 ns	1.8 ns	70 ps	25 ps
Conical-Anode	-3181	2.6E6	6.3	53 mV	150 ps	420 ps	330 ps	27 ps	5 ps

Ref. Sensor Actuat. A-Phys 318 (2021)， NIMA 1041 (2022) 167333,

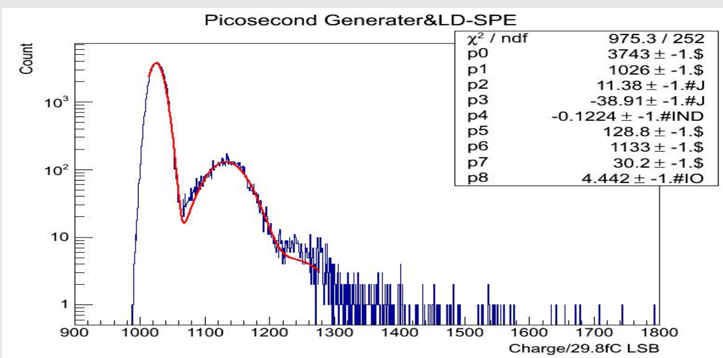
3.2 The Performance -- （2）2X2 Anode FPMT

➢ 2*2 Anodes FPMT

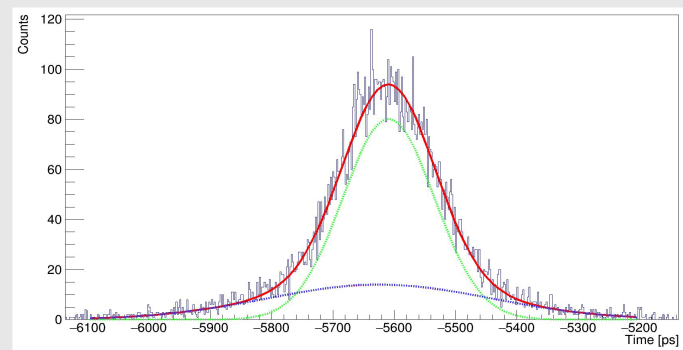
➢ Average waveform of SPE



➢ SPE Spectrum

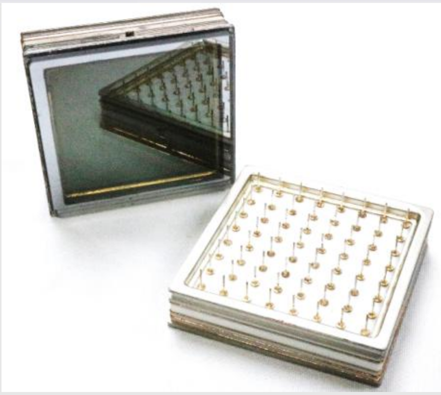


➢ SPE-TTS Spectrum

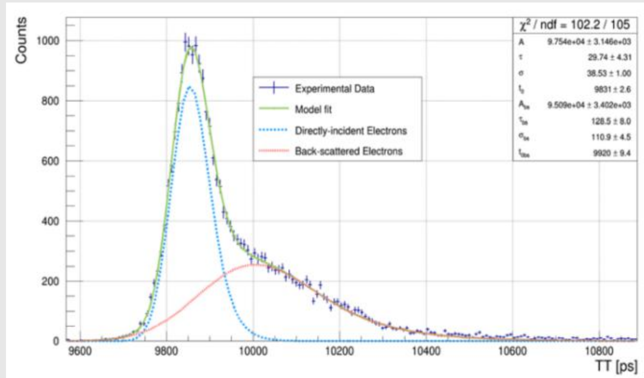


	HV/V	Gain	P/V	Amp(SPE)	RT	FT	Width	TTS@SPE	TTS@MPE
Photek 210	-4700	2.9E6	2.0	93 mV	**96 ps**	350 ps	190 ps	**45 ps**	10 ps
2X2-Anode	-2500	1.9E6	6.5	34 mV	243 ps	516 ps	378 ps	**67 ps**	17 ps

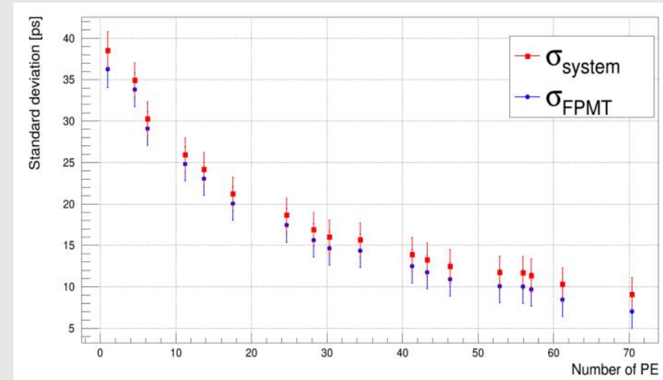
3.2 The Performance -- （3） 8X8 Anode FPMT



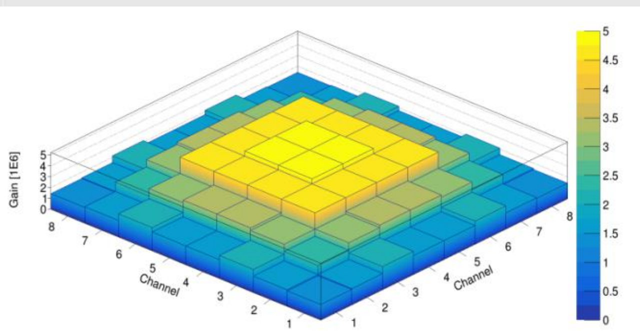
➢ TTS Spectrum



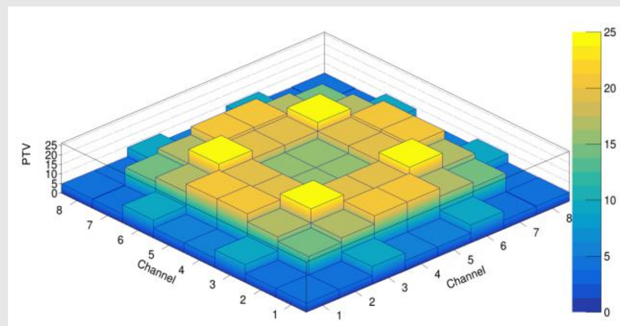
➢ TTS Variation with light intensity



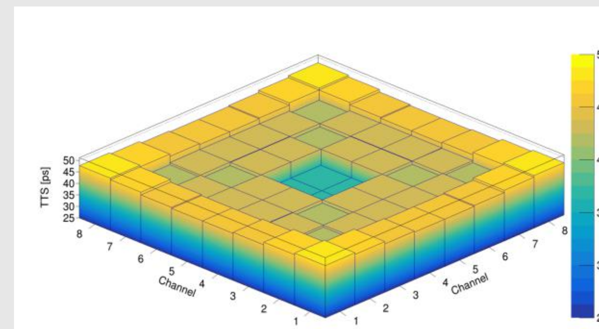
➢ Uniformity of Gain



➢ Uniformity of P/V



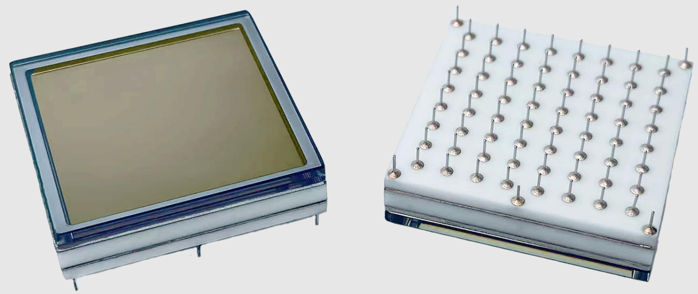
➢ Uniformity of TTS

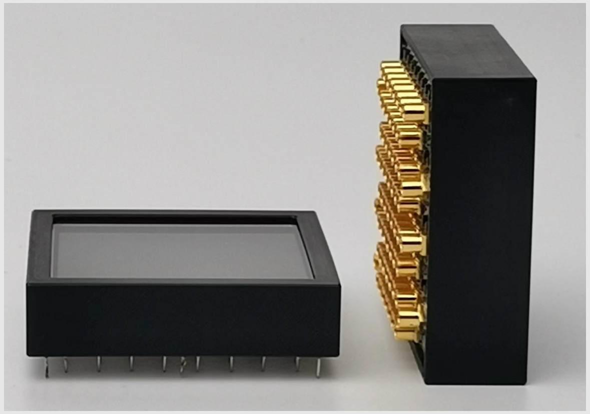


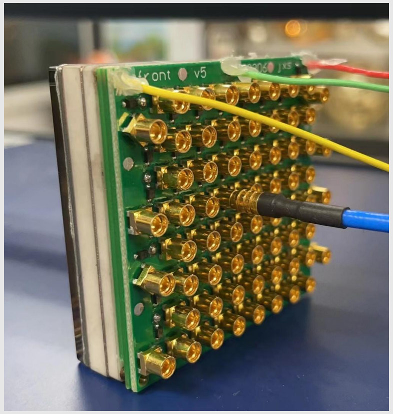
	HV/V	Gain	P/V	Amp(SPE)	RT	FT	Width	TTS@SPE	TTS@MPE
Photek-253	-2600	1.2E7	11.2	113 mV	490 ps	1.1 ns	~1ns	45 ps	16 ps
8*8 Anodes	-1500	3.9E6	18.6	45 mV	334 ps	660 ps	~900ps	40 ps	10 ps

Ref. JINST 17 (2022) T04002, JINST 18 (2023) C12020 ,

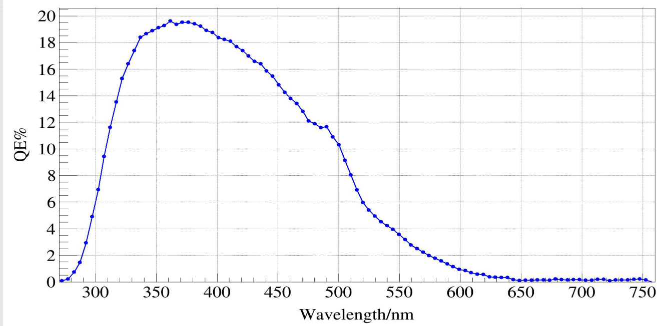
3.2 The Performance -- （4） CRW-FPMT



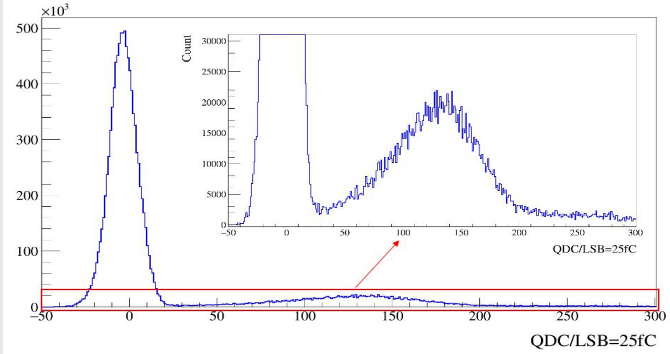




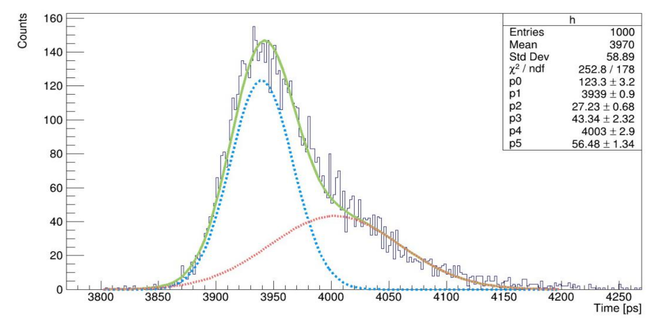
- QE @400nm ~20%



- P/V @SPE >4



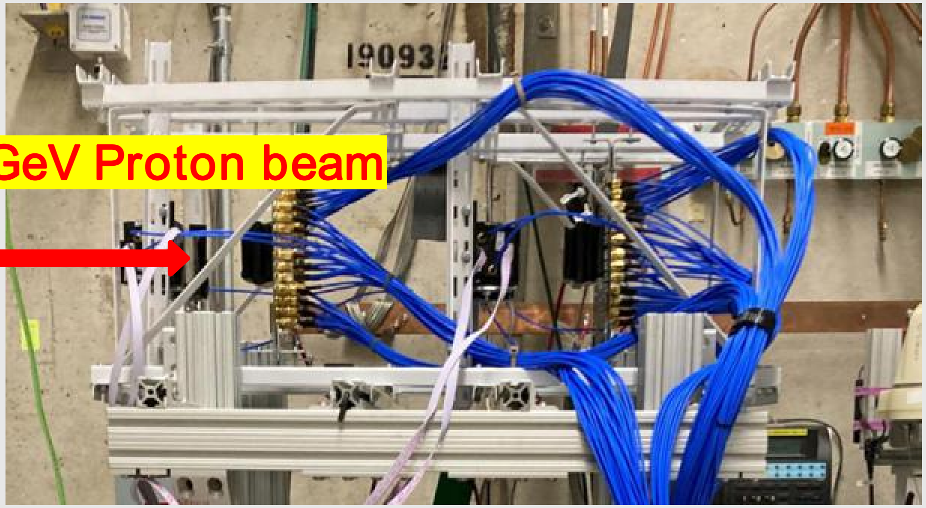
- TTS @SPE < 30ps



Ref. NIMA 1062 (2024) 169173

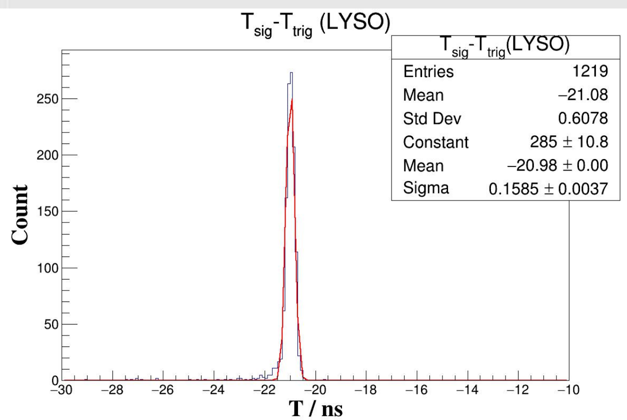
	HV/V	Gain	P/V	Amp(SPE)	RT	FT	Width	TTS@SPE	TTS@MPE
8*8 Anodes	-1500	6E6	4	100 mV	250 ps	400ps	~500ps	30 ps	10 ps

3.3 The Beam Test -- （1）Proton in Fermi

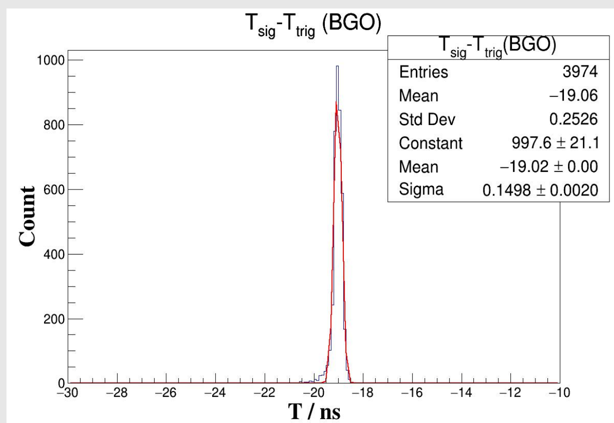


- Beam：120GeV Proton (Fermi)
- Crystal：LYSO & BGO
- PMT： 8*8 FPMT
- DAQ：CAEN V1742~50ps；
- Carried out by Zhenyu Ye (UIC)

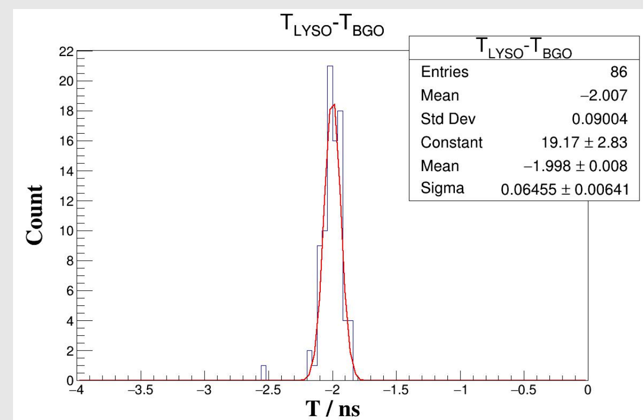
  Zhihong Ye (THU)



- LYSO single channel Time Resolution
  Sigma：158.5 ps

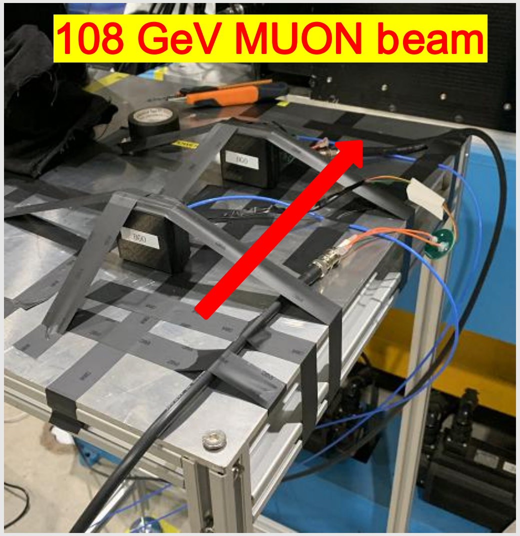


- BGO single channel Time Resolution
  Sigma：149.8 ps



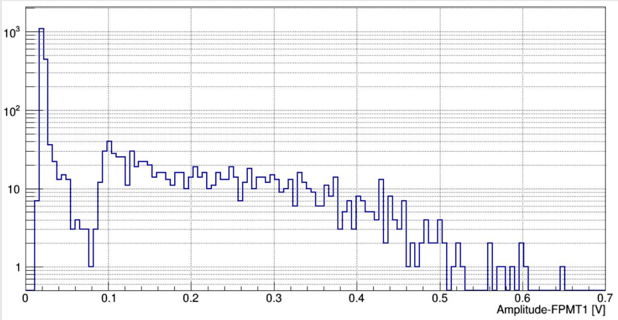
- LYSO & BGO
  Coincidence Time jitter~64 ps
  Single tube Time jitter ~45ps

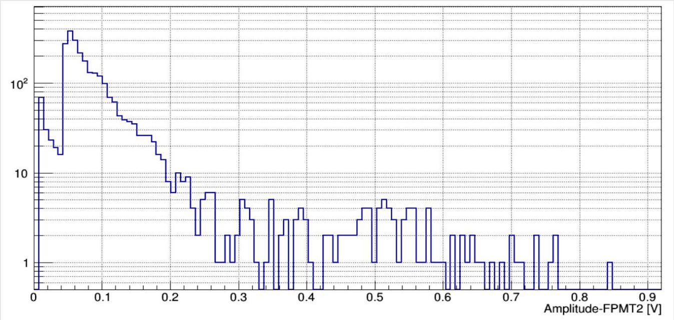
3.3 The Beam Test -- （2）Muon in CERN



- **Beam：** (CERN)
  108GeV Muon
- **Scintillator：**
  Quartz Glass;
- **PMT：** 8*8 FPMT
  TTS = 50ps@SPE;
- **DAQ：** 15 GSa/s ~ 25ps

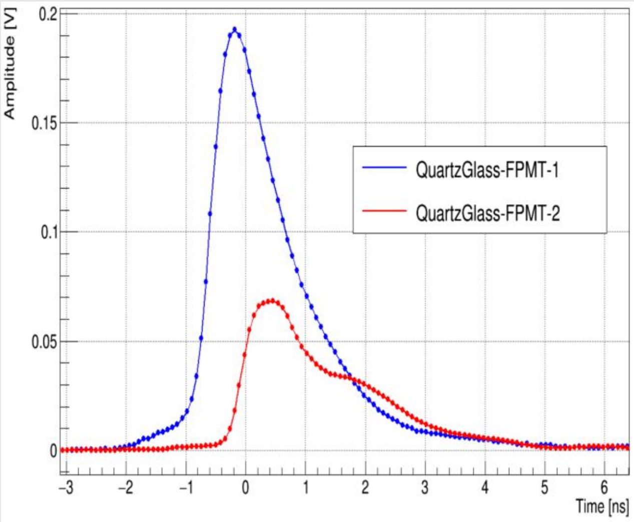
➢ Quartz Glass + FPMT

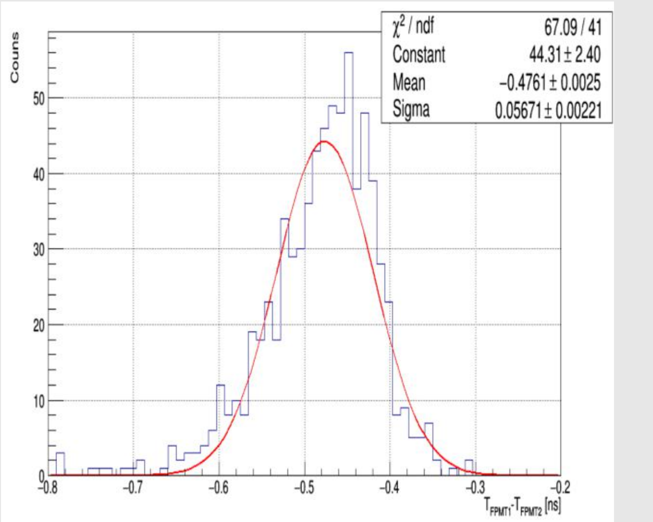




Coincidence time jitter~ 56ps

Single tube Time jitter ~**40ps**

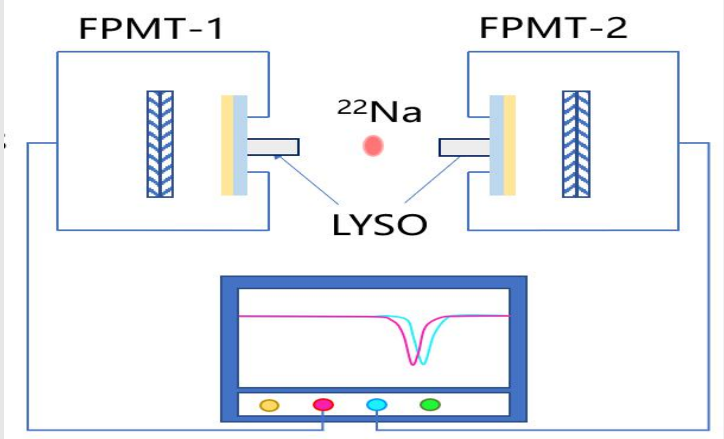




Ref. NIMA 1064 (2024) 169373

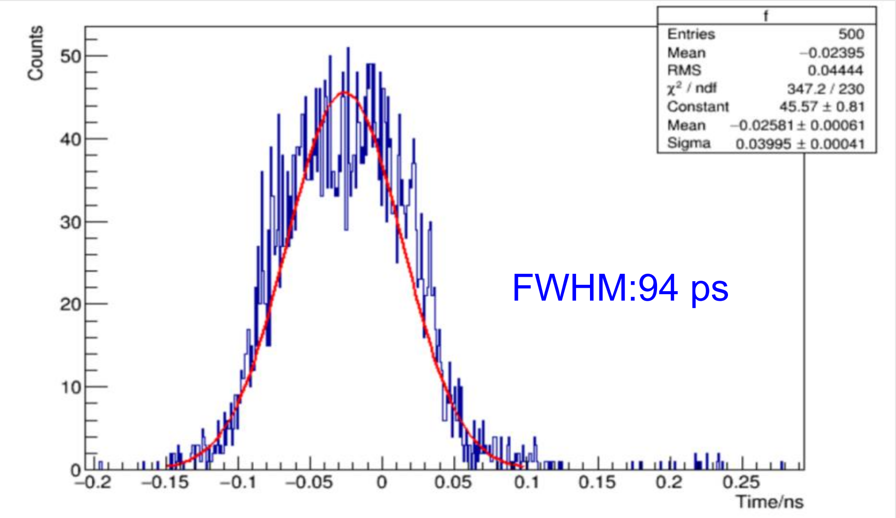
3.4 The Timing -- （1） FPMT-CTR test

- ✓ **Radioactive sources:** Sodium（^{22}Na），
- ✓ **Crystal:** LYSO / Lead Fluoride（PbF_2）
- ✓ **DAQ:** Oscilloscope~25ps
- ✓ **FPMT:** 1CH- Anodes FPMT*2

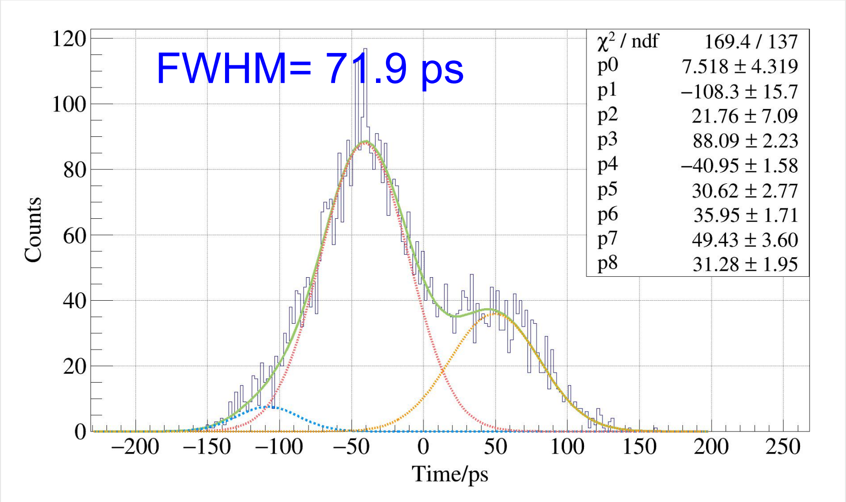


The Best **Coincidence Time Resolution:**

➢ **CTR :FPMT+LYSO**（3*3*5mm³）



➢ **CTR: FPMT+PbF_2**（ 3*3*5mm³ ）

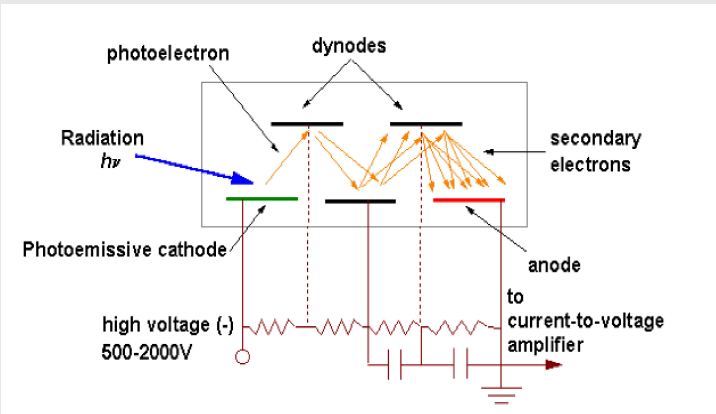


Ref. *2022 J. Phys.: Conf. Ser. 2374 012132*

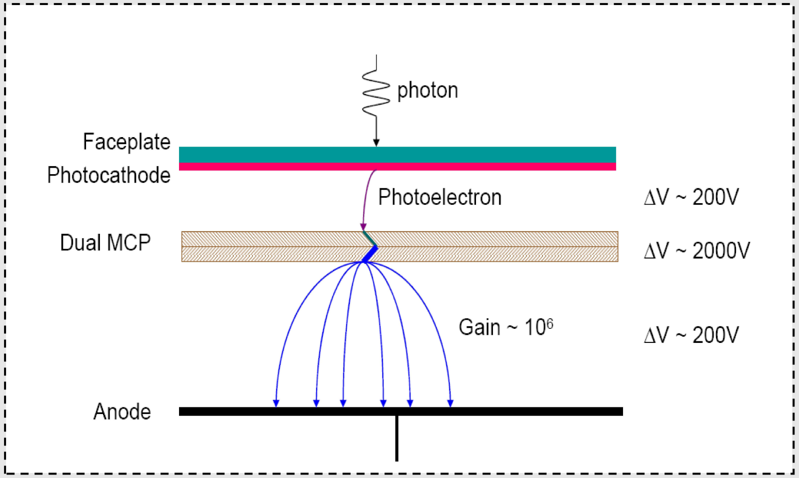
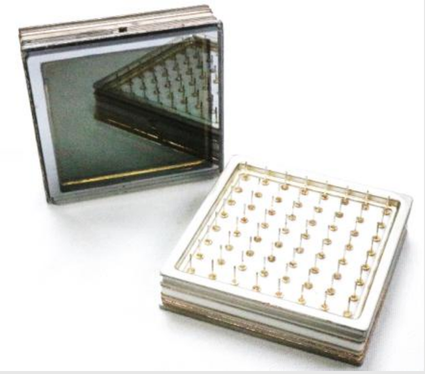
Outline

- 1. The Conventional PMTs
- 2. The 20 inch MCP-PMT （LPMT)
  - 2.1 The Design of LPMT；
  - 2.2 The Roadmap for the R&D of LPMT；
  - 2.3 The HPD LPMT for JUNO；
  - 2.4 The Fast LPMT for LHAASO;
- 3. The Fast timing MCP-PMT (FPMT)
  - 3.1 The Roadmap for FPMT；
  - 3.2 The Performance of FPMT；
  - 3.3 The CTR of FPMTs;
  - 3.4 The Proton Beam Test；
- 4. Summary

4. Summary-- （1） The PMTs

<table>
<tr><th></th><th>Operation Principle</th><th>Small Size
（proximity focusing）</th><th>Large Size
（electrostatic focusing）</th></tr>
<tr><td>Dynode</td><td>
</td><td>2“ Dynode-PMT ✓

</td><td>20“ Dynode-PMT ✓

</td></tr>
<tr><td>MCP</td><td>
</td><td>2“ MCP-PMT ✓
</td><td>20“ MCP-PMT ✓
</td></tr>
</table>

4. Summary-- （2）The Group

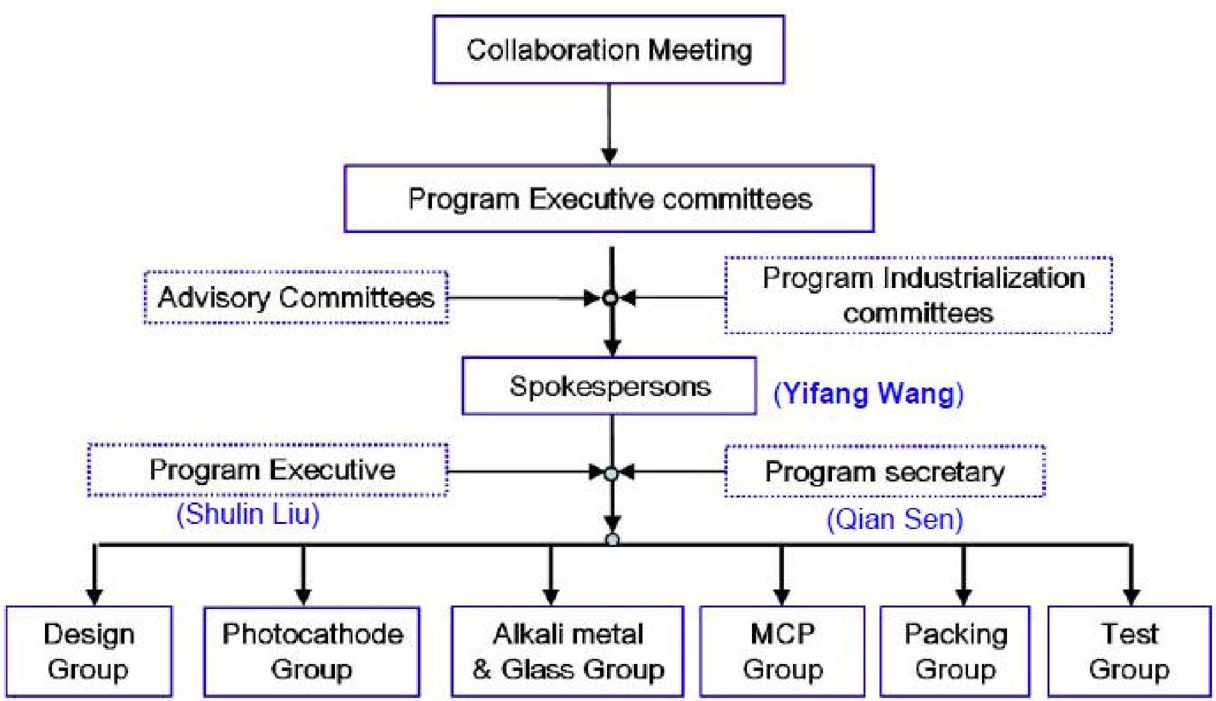
中国科学院高能物理研究所

Institute of High Energy Physics Chinese Academy of Sciences

Institute of High Energy Physics,　CAS

effort by **Yifang Wang**

Microchannel-Plate-Based Large Area Photomultiplier Collaboration (MLAPC)



北方夜视技术股份有限公司

NORTH NIGHT VISION TECHNOLOGY CO.,LTD

中国科学院西安光学精密机械研究所

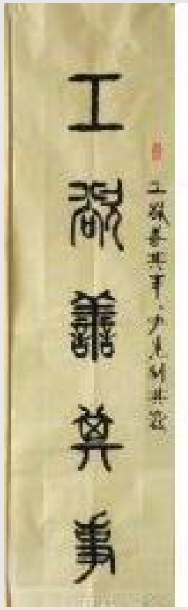
XIAN INSTITUTE OF OPTICS AND PRECISION MECHANICS OF CAS

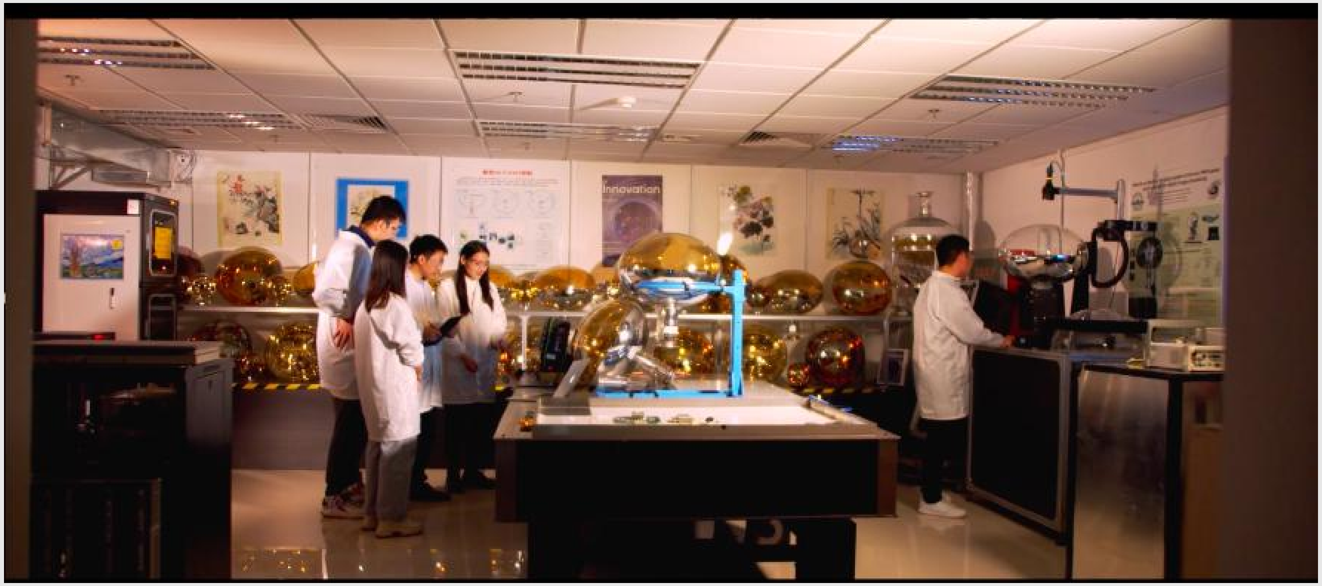
中核（北京）核仪器厂

CNNC Beijing Nuclear Instrument Factory

南京大学

4. Summary--(3) The Photodetector Lab in IHEP





中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences
中国科学院空间应用工程与技术中心
Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences

中国科学院可靠性保障中心

光电器件性能标定实验室

CMA
240020349767

中国检验检测机构资质认定(CMA)认可实验室

中国科学院高能物理研究所测试中心

光电探测器件检测室

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Chinese Academy of Sciences
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光电探测联合实验室

Joint Laboratory of Photoelectric Detection

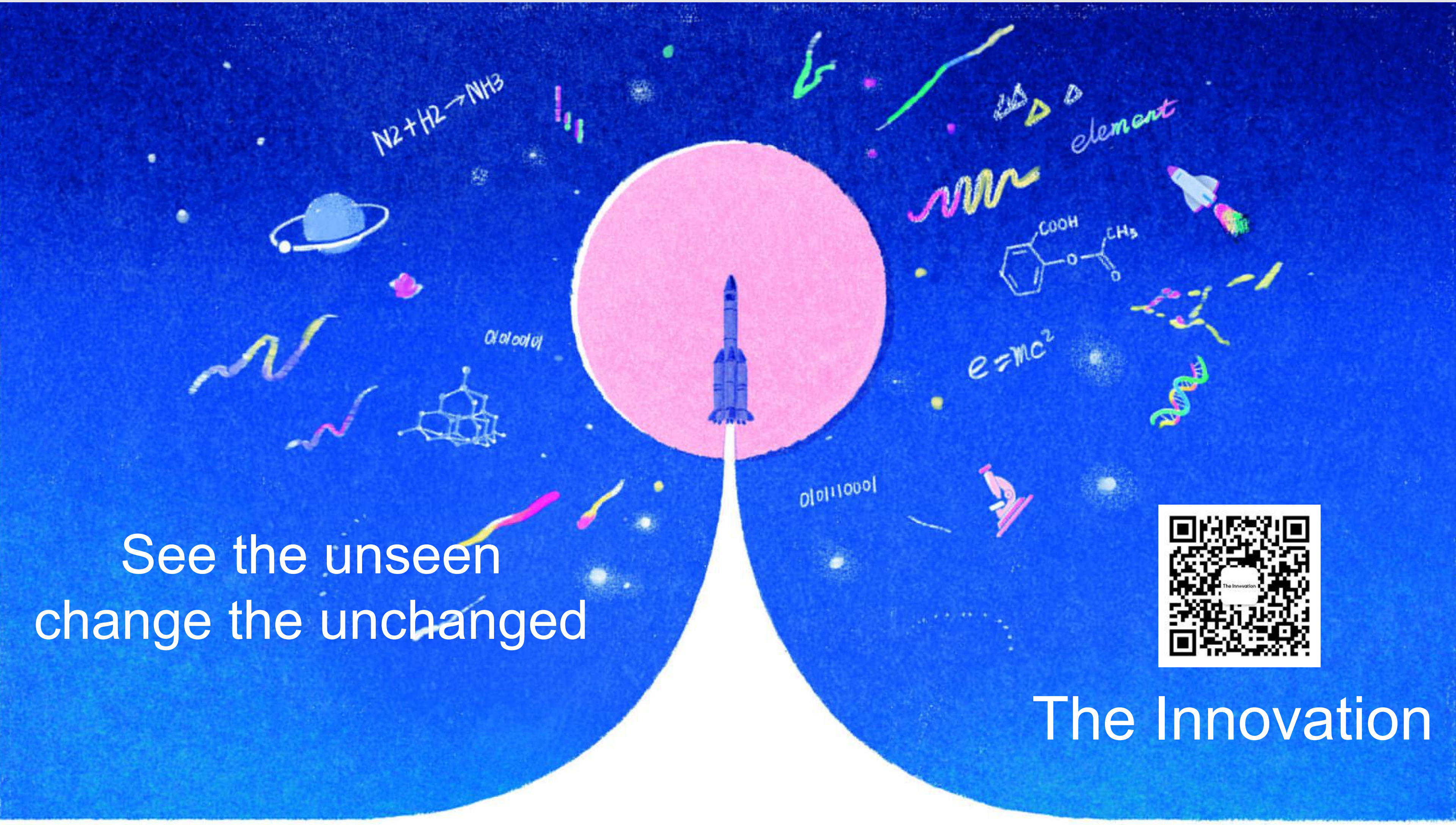
谢谢！

Thanks for your attention!

Any Comment & Suggestion are welcomed!

The PMT Family in NNVT in China

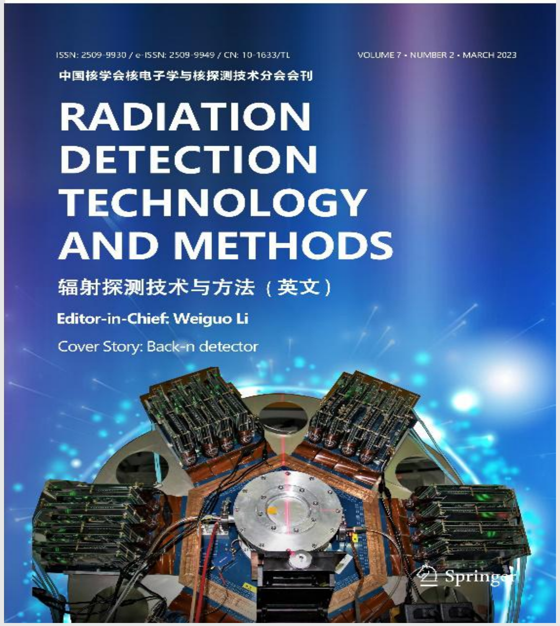
THANKS

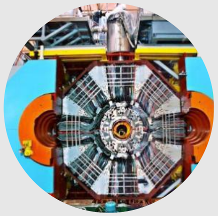


See the unseen
change the unchanged

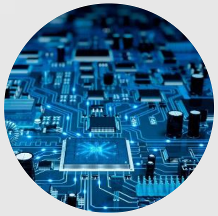
The Innovation

核电子学与核探测技术 & Radiation Detection Technology and Methods

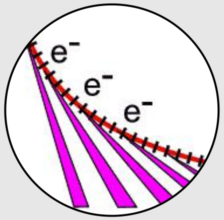




核探测
技术



核电子学
技术



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