江门中微子实验小PMT系统
The SPMT systems in JUNO experiment

徐吉磊
xujl@ihep.ac.cn

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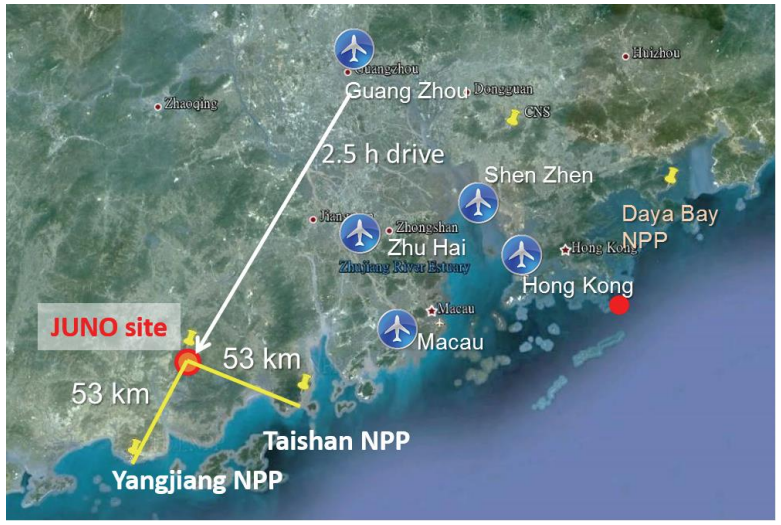
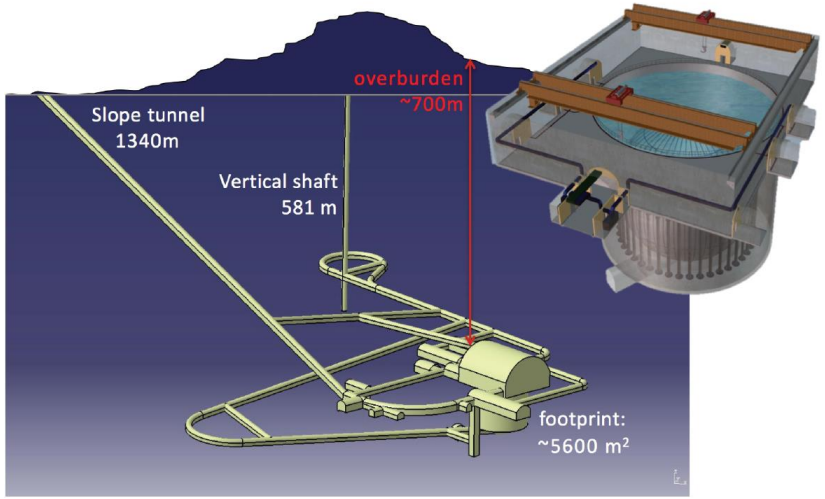
大纲

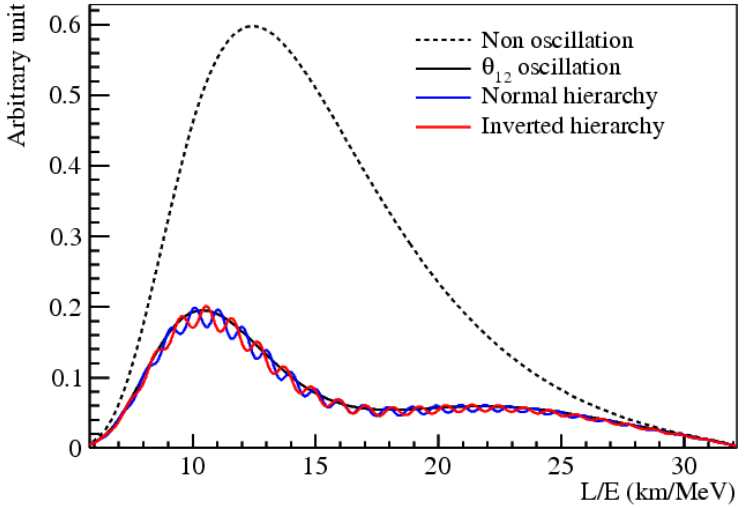
- 江门中微子实验及探测器简介
- 大PMT系统进展
- 小PMT系统的物理潜力
- 小PMT系统和进展
- 总结展望

江门中微子实验（JUNO）

- 位于广东省江门市的大型地下中微子实验，山体覆盖~700米。
- 丰富的物理目标：
  - 确定中微子质量顺序
  - 精确测量中微子振荡参数
  - 研究太阳、超新星、大气、地球中微子等
- 2万吨液体闪烁体（LS），能量分辨率 3% @ 1 MeV，能量精度 1%
- 探测器要求：靶体积大，LS透明且光产额高，PMT光学覆盖率高，放射性本底低等
- JUNO探测器是目前世界上最具挑战的大型液闪探测器







JUNO 探测器

刻度间

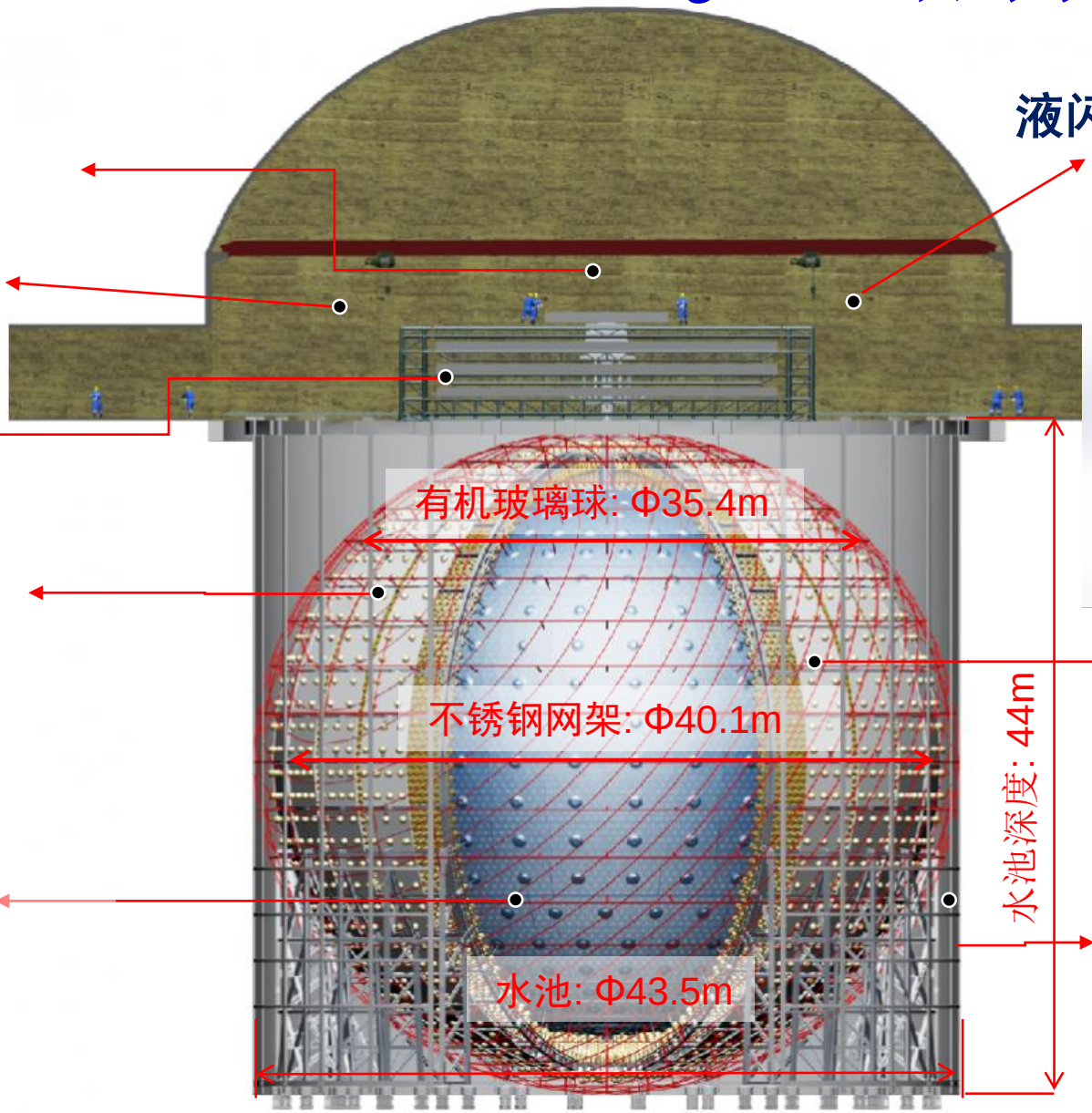
纯水间

顶部径迹探测器

中心探测器
不锈钢网架
有机玻璃球

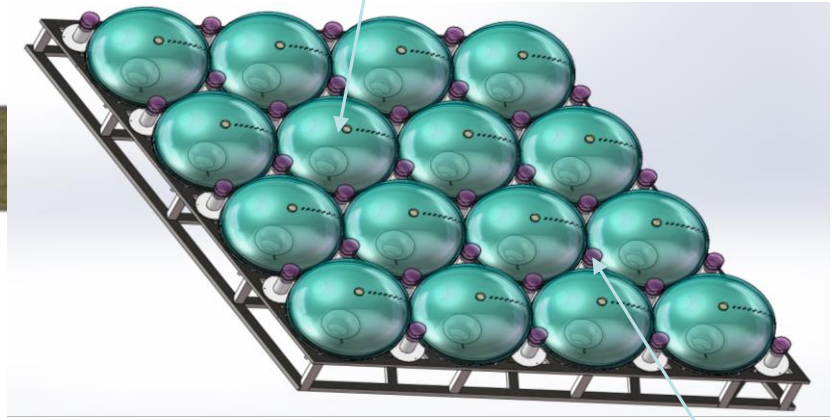
液闪
2 万吨

~700m 地下



液闪灌装间

20” PMT (~18K)
MCP-PMT (~13K from NNVT)
Dynode PMT (~5K from Hamamatsu)



PMT
17612 20” PMTs +
25600 3” PMTs:
覆盖率 75.2% + 2.7%

3” PMT(~25K)
Dynode PMT from
HZC Photonics

水切伦科夫探测器
3.5 万吨纯水
2500 20” veto PMTs

JUNO探测性能要求及特点

要求：能量分辨率 3% @ 1 MeV，能量精度1%

$$\frac{\sigma_{E_{\rm vis}}}{E_{\rm vis}} = \sqrt{\left(\frac{a}{\sqrt{E_{\rm vis}}}\right)^2 + b^2 + \left(\frac{c}{E_{\rm vis}}\right)^2}$$

Stochastic term~1345 p.e./MeV (Light yield, Transparency, Photo-coverage, QE…)

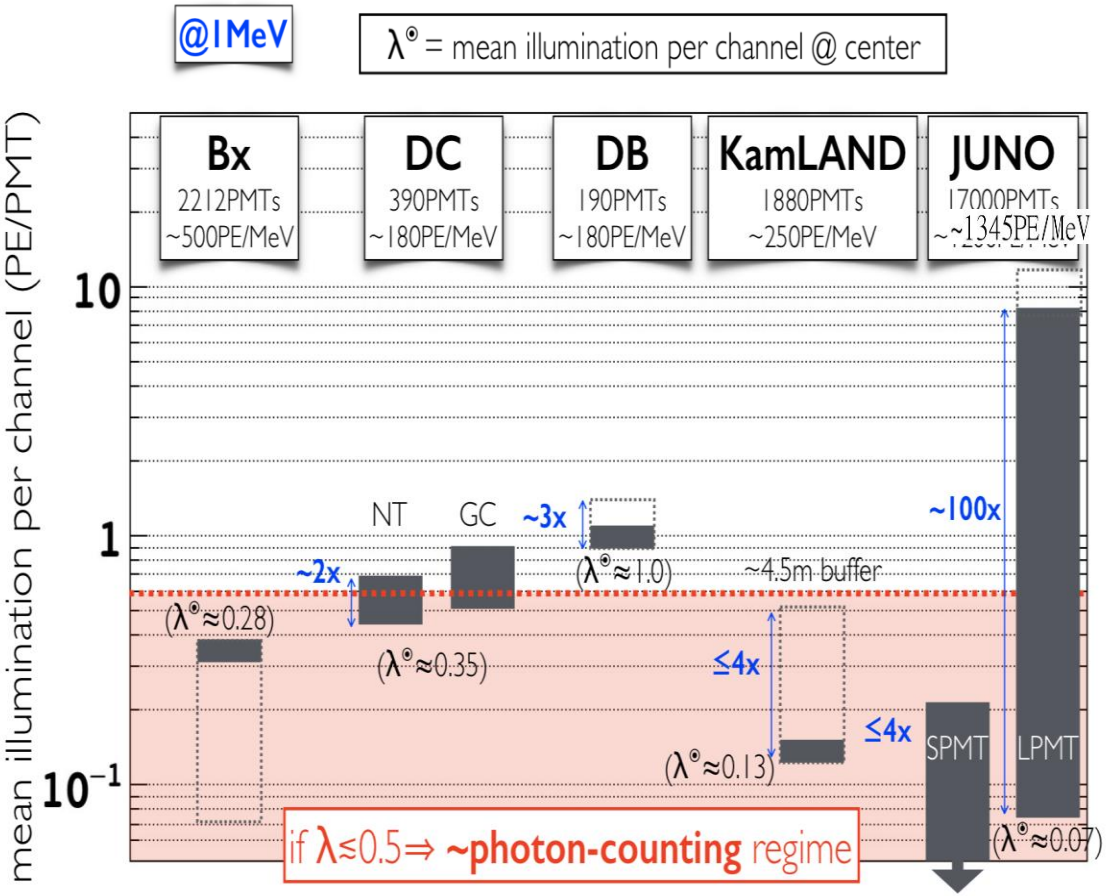
Non stochastic terms (Non-uniformity, background noise)

LPMT（20 英寸）：

- 密排，光阴极覆盖率高
- 光子统计量大，可减小统计项

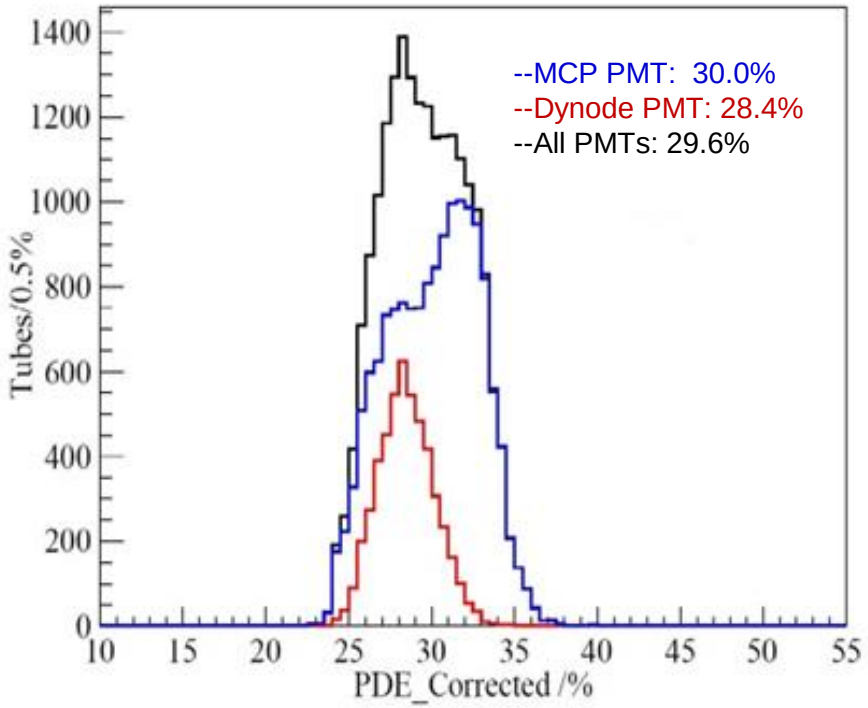
SPMT（3 英寸）：

- 对于IBD事例，工作在单光子计数模式
- 可直接数光子数（1 hit = 1 p.e.）
- 控制系统误差，减小非统计项

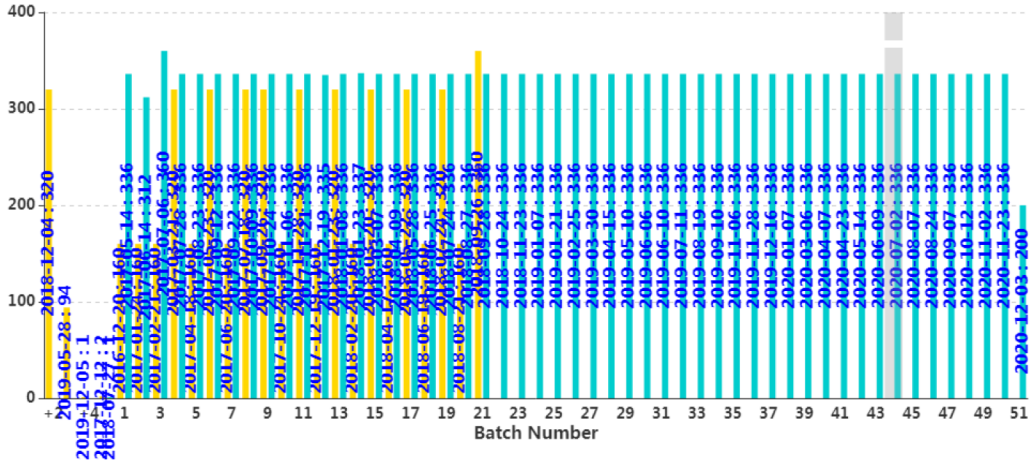


20吋PMT

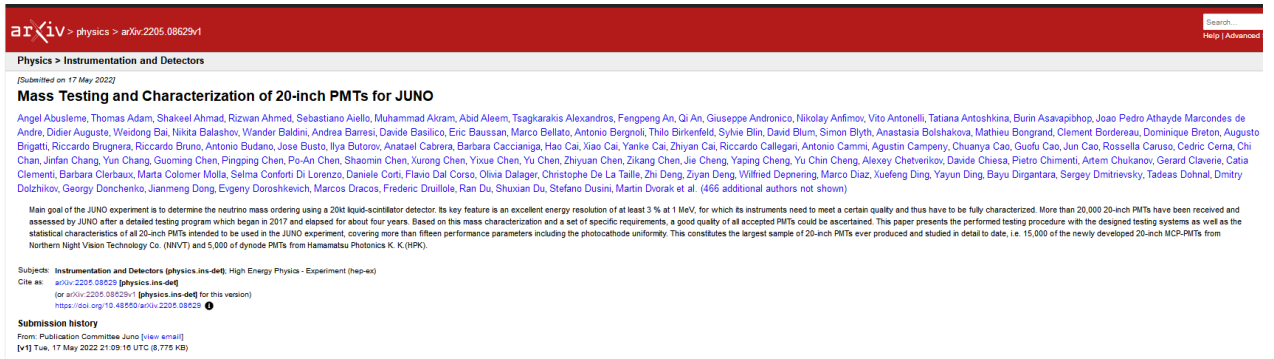
- **PMT delivering & testing: finished all**
  - All 20012 PMTs delivered and tested, in which 15012 are MCP-PMTs and 5000 dynode PMTs
  - Average PDE of all PMTs reached 29.6% (**30.0% for MCP-PMTs， 28.4% for dynode PMTs**), after a correction of aging effects of the testing system
  - More than 15 parameters are tested with the most 20” PMT numbers



PDE of PMTs



https://arxiv.org/abs/2205.08629v1



Physics > Instrumentation and Detectors

[Submitted on 17 May 2022]

Mass Testing and Characterization of 20-inch PMTs for JUNO

Angel Abusleme, Thomas Adam, Shakeel Ahmad, Rizwan Ahmed, Sebastiano Aiello, Muhammad Akram, Abid Aleem, Tsagkarakis Alexandros, Fengpeng An, Qi An, Giuseppe Andronico, Nikolay Anfimov, Vito Antonelli, Tatiana Antoshkina, Burin Asavapibhop, Joao Pedro Athayde Marcondes de Andre, Didier Auguste, Weidong Bai, Nikita Balashov, Wander Baldini, Andrea Barresi, Davide Basilico, Eric Baussan, Marco Bellato, Antonio Bergnoli, Thilo Birkenfeld, Sylvie Blin, David Blum, Simon Blyth, Anastasia Bolshakova, Mathieu Bongrand, Clement Bordereau, Dominique Breton, Augusto Brigatti, Riccardo Brugnera, Riccardo Bruno, Antonio Budano, Jose Busto, Ilya Butorov, Anatael Cabrera, Barbara Caccianiga, Hao Cai, Xiao Cai, Yanke Cai, Zhiyan Cai, Riccardo Callegari, Antonio Cammi, Agustin Campeny, Chuanya Cao, Guofu Cao, Jun Cao, Rossella Caruso, Cedric Cerna, Chi Chan, Jinfan Chang, Yun Chang, Guoming Chen, Pingping Chen, Po-An Chen, Shaomin Chen, Xurong Chen, Yixue Chen, Yu Chen, Zhiyuan Chen, Zikang Chen, Jie Cheng, Yaping Cheng, Yu Chin Cheng, Alexey Chetverikov, Davide Chiesa, Pietro Chimenti, Artem Chukanov, Gerard Claverie, Catia Clementi, Barbara Clerbaux, Marta Colomer Molla, Selma Conforti Di Lorenzo, Daniele Corti, Flavio Dal Corso, Olivia Dalager, Christophe De La Taille, Zhi Deng, Ziyan Deng, Wilfried Depnering, Marco Diaz, Xuefeng Ding, Yayun Ding, Bayu Dirgantara, Sergey Dmitrievsky, Tadeas Dohnal, Dmitry Dolzhikov, Georgy Donchenko, Jianmeng Dong, Evgeny Doroshkevich, Marcos Dracos, Frederic Druillole, Ran Du, Shuxian Du, Stefano Dusini, Martin Dvorak et al. (466 additional authors not shown)

Main goal of the JUNO experiment is to determine the neutrino mass ordering using a 20kt liquid-scintillator detector. Its key feature is an excellent energy resolution of at least 3 % at 1 MeV, for which its instruments need to meet a certain quality and thus have to be fully characterized. More than 20,000 20-inch PMTs have been received and assessed by JUNO after a detailed testing program which began in 2017 and elapsed for about four years. Based on this mass characterization and a set of specific requirements, a good quality of all accepted PMTs could be ascertained. This paper presents the performed testing procedure with the designed testing systems as well as the statistical characteristics of all 20-inch PMTs intended to be used in the JUNO experiment, covering more than fifteen performance parameters including the photocathode uniformity. This constitutes the largest sample of 20-inch PMTs ever produced and studied in detail to date, i.e. 15,000 of the newly developed 20-inch MCP-PMTs from Northern Night Vision Technology Co. (NNVT) and 5,000 of dynode PMTs from Hamamatsu Photonics K. K.(HPK).

Subjects: Instrumentation and Detectors (physics.ins-det); High Energy Physics - Experiment (hep-ex)
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[v1] Tue, 17 May 2022 21:09:16 UTC (8,775 KB)

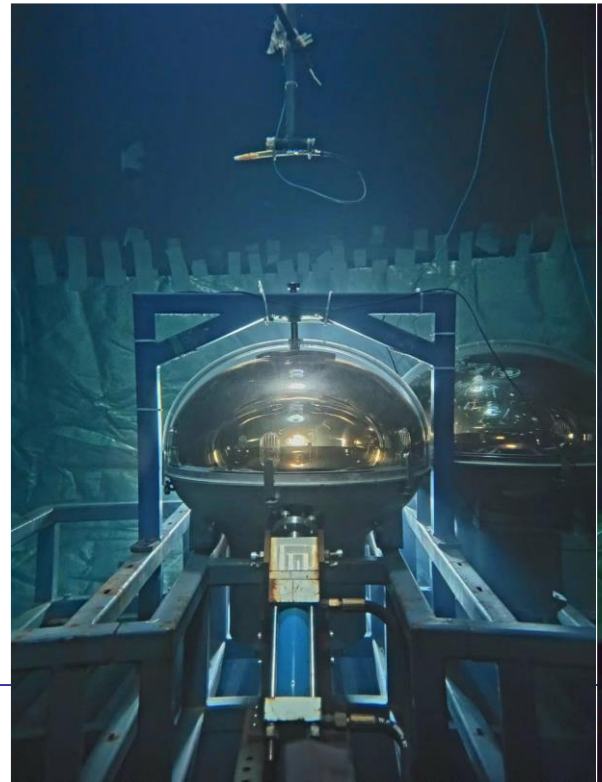
20吋PMT

- **PMT Potting & protecting**
  - All 20012 JUNO PMTs potted for waterproof, no leaks found
  - More than 10,000 acrylic covers for implosion protection has been delivered
  - Bottom SS cover passed the review.

    Production just started.
  - Cover installation and testing in water is under way.

PMT potting

Acrylic covers



Validation of mass produced acrylic and SS covers, with the final connection structure

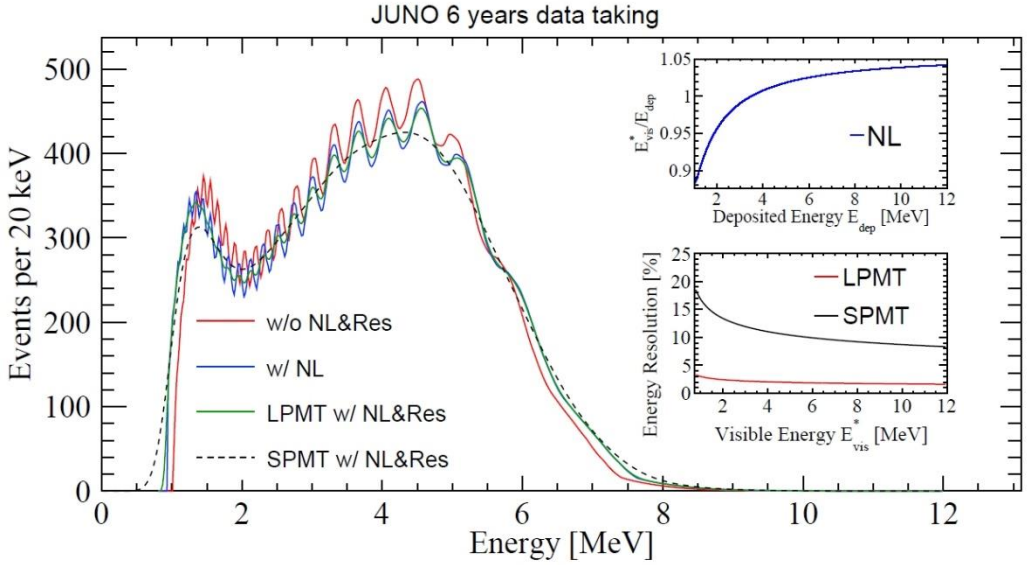
小PMT系统的物理潜力

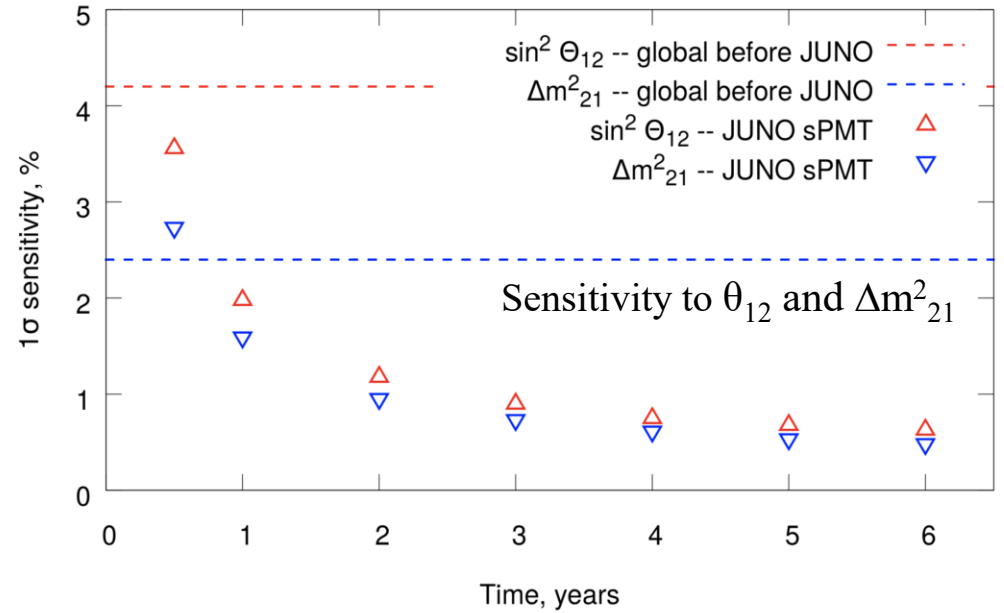
提供独立的测量，与LPMT系统构成双量能器系统

- 轻微提高JUNO光产额（~3%）
- 精确刻度大PMT的电荷重建非线性，控制残余非均匀性
- 提高能标精度

其他物理研究

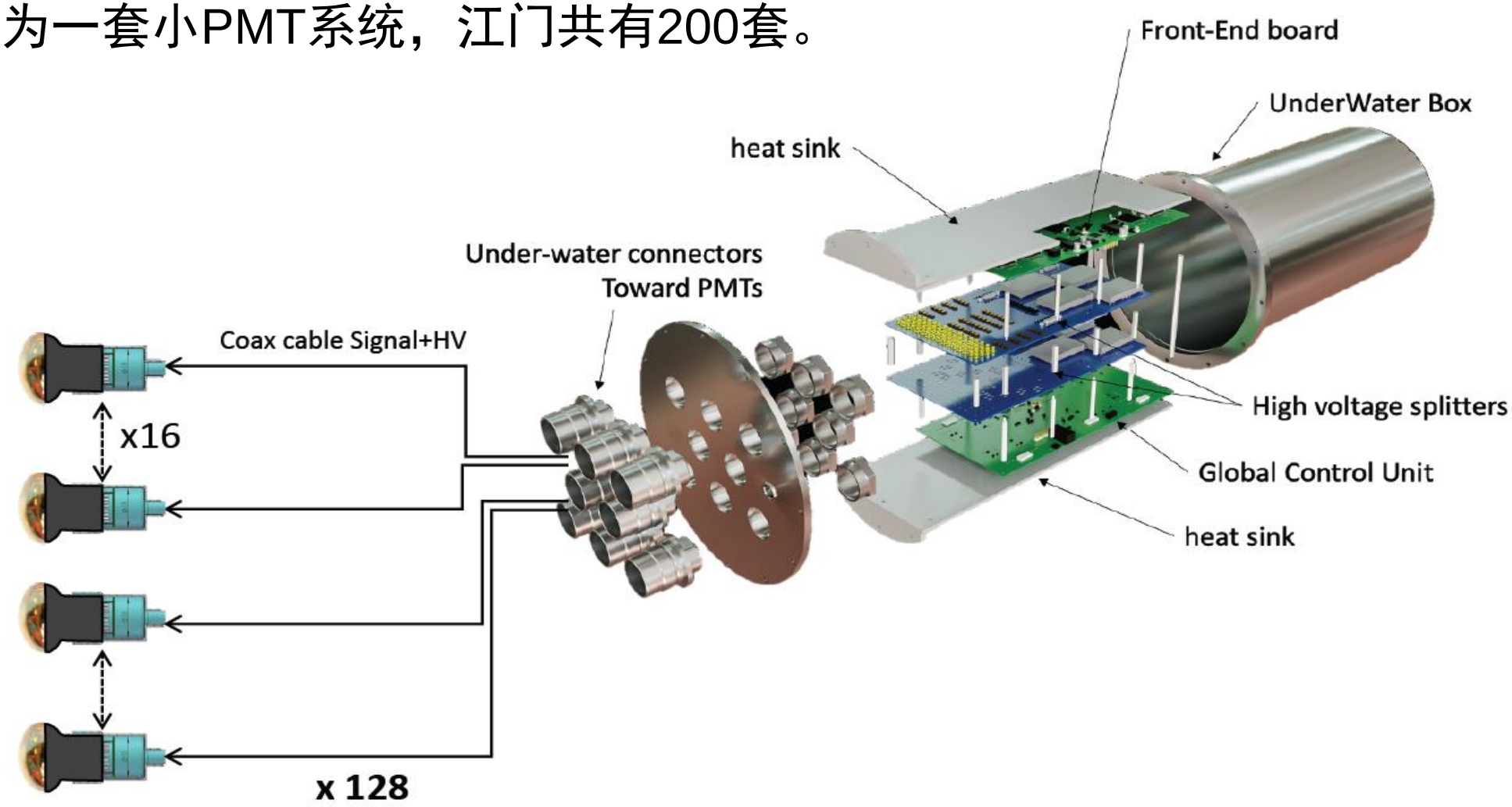
- 独立的太阳中微子振荡参数测量（θ_{12} and Δm^2_{21}）
- 高能量物理事例的重建（大气中微子，muon）
- 超新星中微子（小PMT系统支持高事例率的触发及传输）



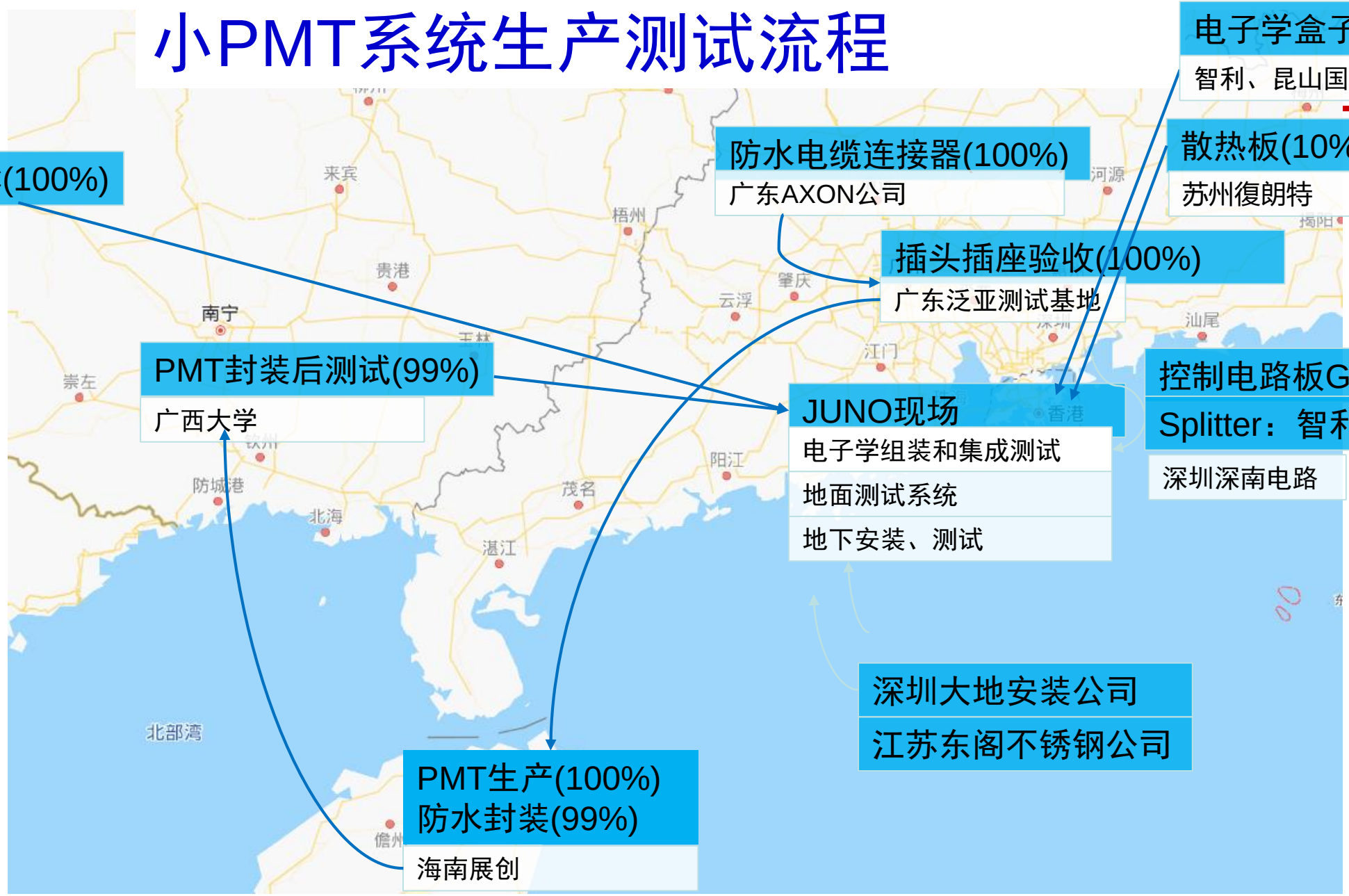


SPMT系统的组成

这里为一套小PMT系统，江门共有200套。



小PMT系统生产测试流程



电路板ABC(100%)

法国

防水电缆连接器(100%)

广东AXON公司

插头插座验收(100%)

广东泛亚测试基地

电子学盒子生产(2%)

智利、昆山国力

散热板(10%)

苏州復朗特

PMT封装后测试(99%)

广西大学

JUNO现场

电子学组装和集成测试

地面测试系统

地下安装、测试

控制电路板GCU(100%)

Splitter：智利、深圳(2%)

深圳深南电路

深圳大地安装公司

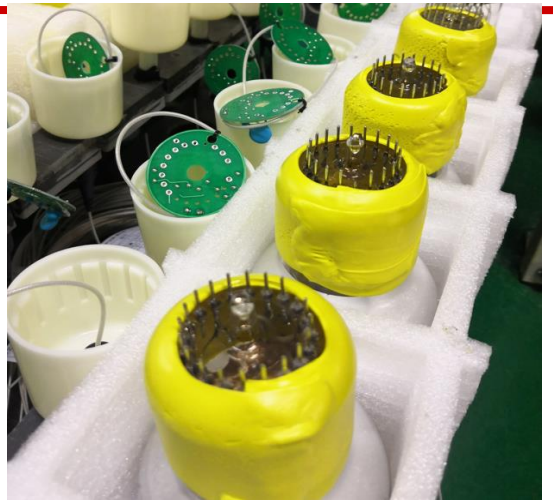
江苏东阁不锈钢公司

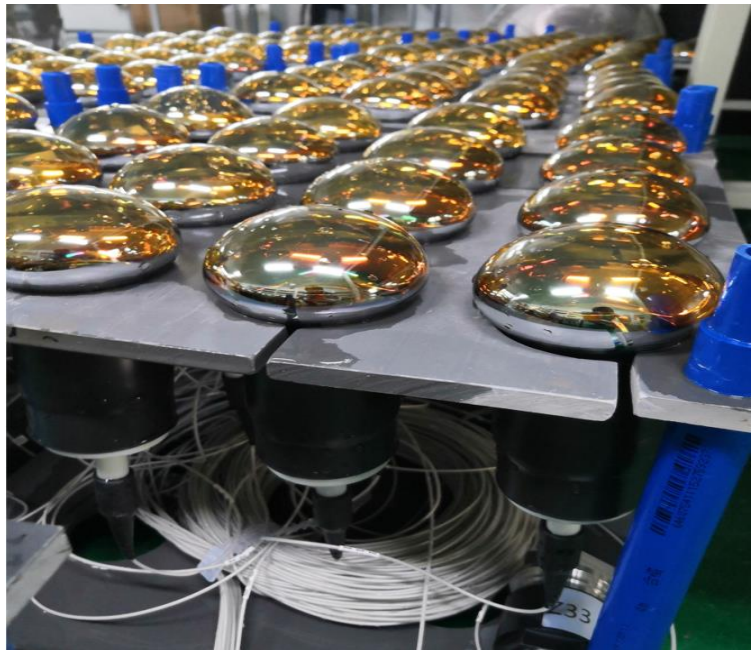
PMT生产(100%)
防水封装(99%)

海南展创

小PMT的生产和防水封装

- 2017-2020年完成了26,000支小PMT的生产
  - 是目前同类型PMT在一个实验上的数量最大的集合。
  - 文章对国际上其他的大型实验有参考价值（hyper-K等）
- 2020-2022年基本完成了所有PMT的防水封装





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Mass production and characterization of 3-inch PMTs for the JUNO experiment

Chuanya Cao [a,b], Jilei Xu [a,*], Miao He [a,*], Angel Abusleme [c], Mathieu Bongrand [d], Clément Bordereau [e,f], Dominique Breton [g], Anatael Cabrera [g,h], Agustin Campeny [c], Cédric Cerna [e], Haoqiang Chen [i,1], Po-An Chen [f], Gérard Claverie [e], Selma Conforti Di Lorenzo [j], Christophe De La Taille [j], Frédéric Druillole [e], Amélie Fournier [e], Marco Grassi [g,h], Xiaofei Gu [i], Michael Haacke [c], Yang Han [g,h], Patrick Hellmuth [e], Yuekun Heng [a], Rafael Herrera [c], Yee Hsiung [f], Bei-Zhen Hu [f], Yongbo Huang [k], Cédric Huss [e], Ignacio Jeria [c], Xiaoping Jing [a], Cécile Jollet [e], Victor Lebrin [d], Frédéric Lefèvre [d], Hongwei Li [l], Nan Li [a,2], Hongbang Liu [k], Xiwen Liu [k], Shuxiang Lu [l], Bayarto Lubsandorzhiev [m], Sultim Lubsandorzhiev [m], Arslan Lukanov [m], Jihane Maalmi [g], Anselmo Meregaglia [e], Diana Navas-Nicolás [g], Juan Pedro Ochoa-Ricoux [n,c], Frédéric Perrot [e], Rebin Karaparambil Rajan [d], Abdel Rebii [e], Bedřich Roskovec [n], Cayetano Santos [b], Mariangela Settimo [d], Andrey Sidorenkov [m], Igor Tkachev [m], Giancarlo Troni [c], Nikita Ushakov [m], Guillaume Vanroyen [d], Benoit Viaud [d], Dmitriy Voronin [m], Pablo Walker [c], Chung-Hsiang Wang [o], Zhimin Wang [a], Diru Wu [a,b], Hangkun Xu [a,b], Meihang Xu [a], Chengfeng Yang [k], Jie Yang [i], Frédéric Yermia [d], Xuantong Zhang [a]

PMT系统前端测试研究

- 对前端PMT匹配的base进行了优化设计
- 长电缆的信号衰减、连接器的反射等进行了详细研究和测试。
- 在江门的3米模型实验里，验证了大小PMT联合工作的状态。
- 文章已接收，将发表在RDTM。

Study of the front-end signal for the 3-inch PMTs instrumentation in JUNO

Diru Wu[1,2], Jilei Xu[1*], Miao He[1], Zhimin Wang[1] and Ziliang Chu[1,2]

[1]Institute of High Energy Physics, Beijing, 100049, China.
[2]University of Chinese Academy of Sciences, Beijing, 100049, China.

Abstract

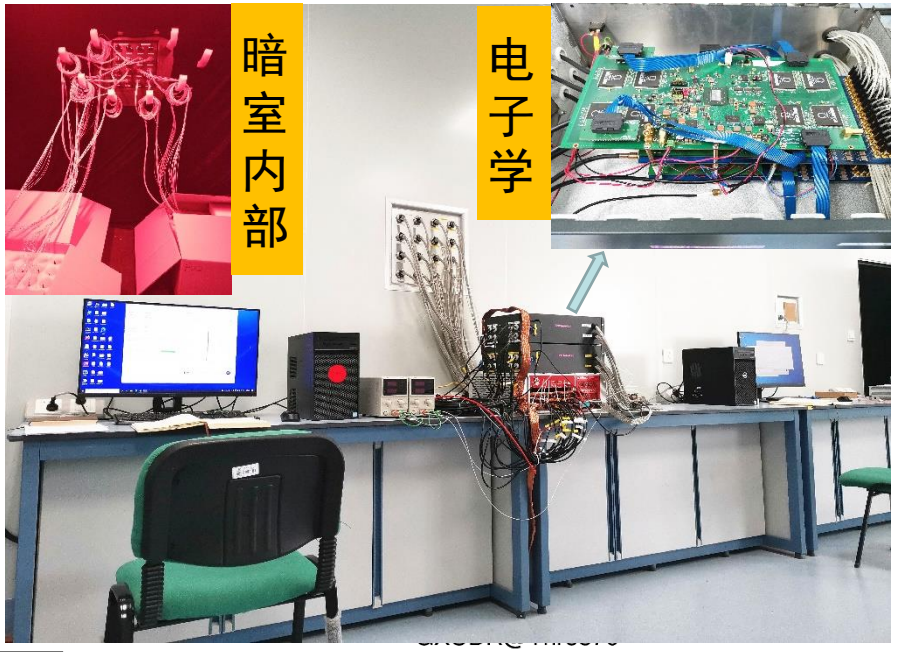
25,600 3-inch PMTs will be installed in Jiangmen Underground Neutrino Observatory (JUNO) to achieve more precise energy calibration and to extend the physics detection potential. Performances of all bare PMTs have been characterized and these PMTs are being instrumented with the high voltage divider, underwater front-end cable, and connector. In this paper, we present a dedicated study on signal quality at different stages of the instrumentation. An optimized high voltage ratio was confirmed and finalized which improved the PMT transit time spread by 25%. The signal charge was attenuated by 22.5% (13.0%) in the 10 m (5 m) cable and it required the addition of 45 V (23 V) to compensate for the loss of PMT gain. There was a 1% overshoot following the PMT signal and no sign of reflection in the connector. A group of 16 3-inch PMTs with the full instrumentation was installed in the JUNO prototype detector together with a few 8-inch and 20-inch PMTs, which showed good stability and demonstrated a photon detection system with multiple types of PMTs.

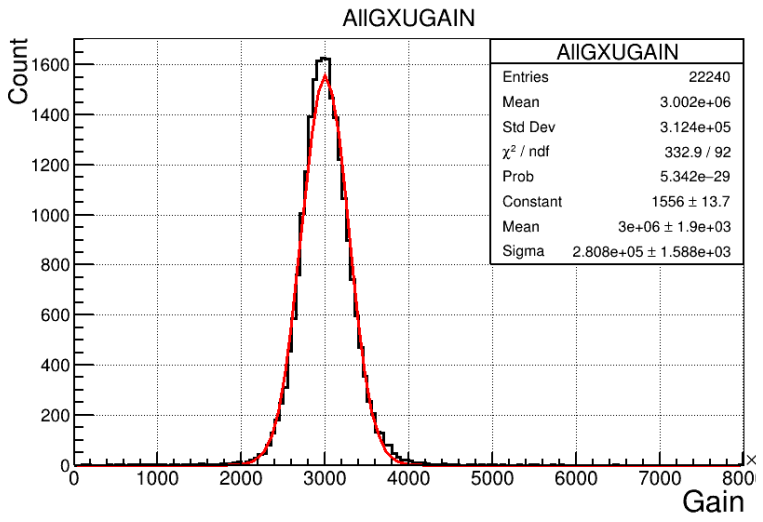
防水电缆和防水连接器生产完成

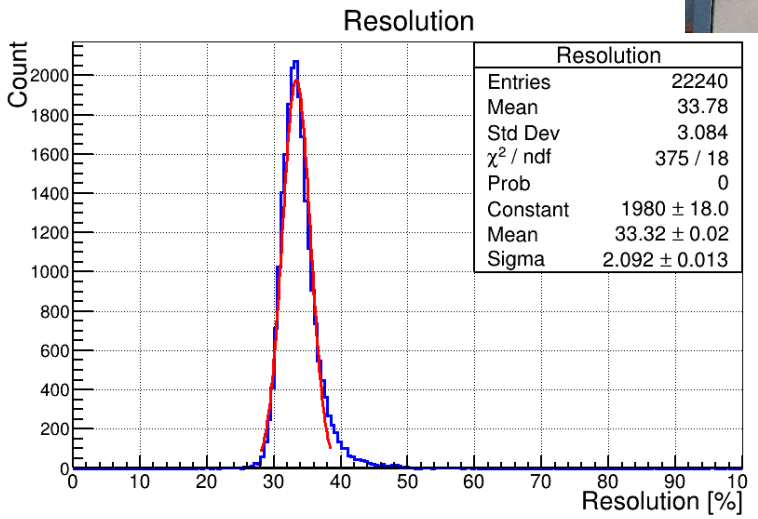
- 2020.5-2022.1完成了所有防水电缆和连接器生产和验收。
- 通过了耐电压和水压测试、可靠性试验、兼容性试验、老化试验等。

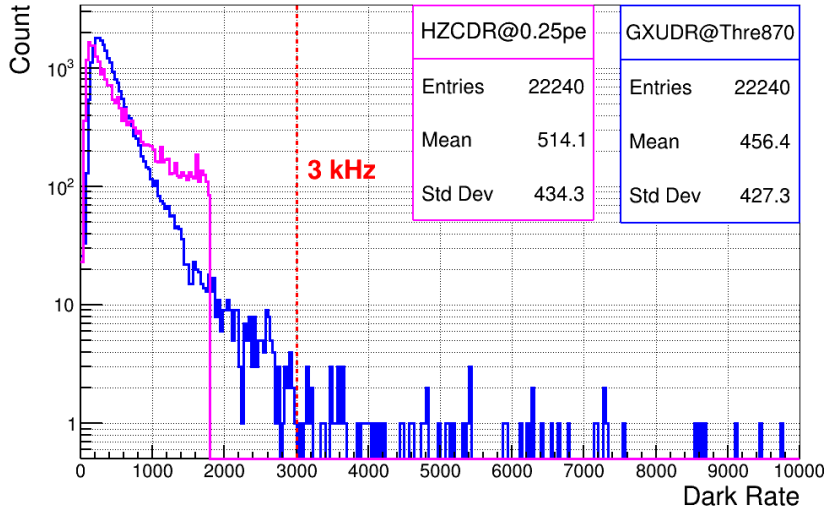
防水封装后测试@广西大学

- Have tested almost all the PMTs (99%).
- Totally, 0.67% (149/22240) unqualified PMTs inside 22240 tested PMTs, since:
  - Low gain.
  - High dark counting rate
  - High resolution

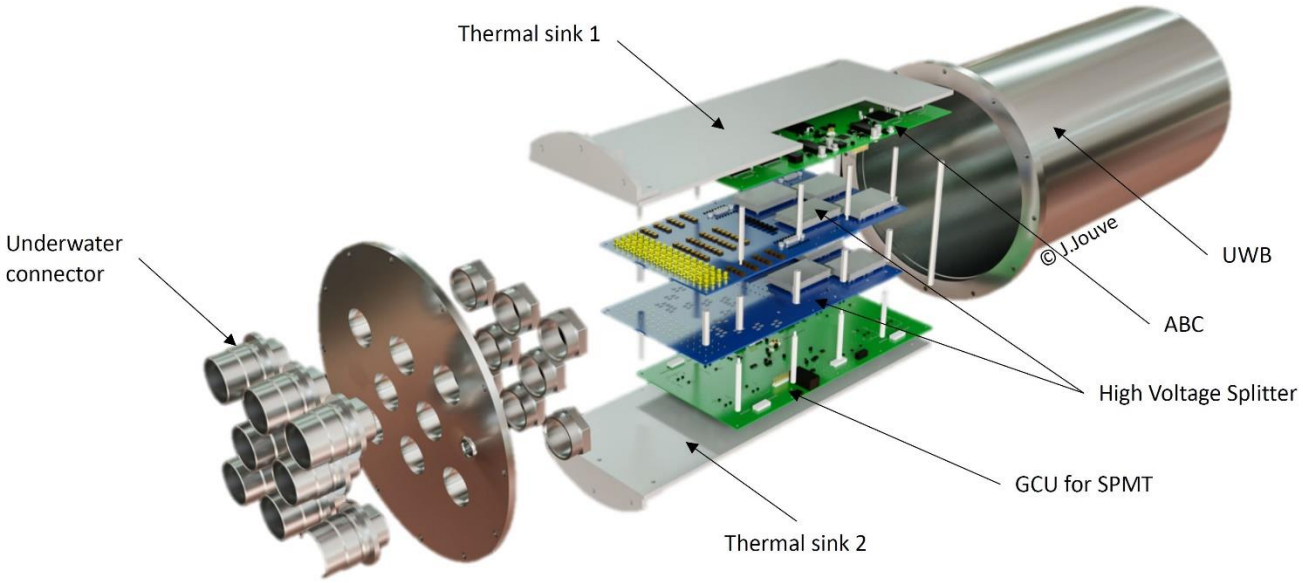


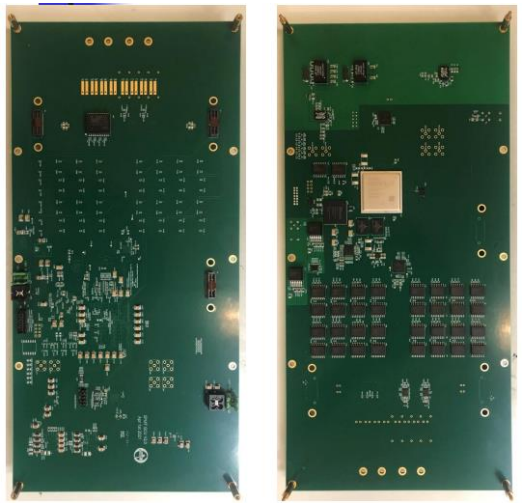






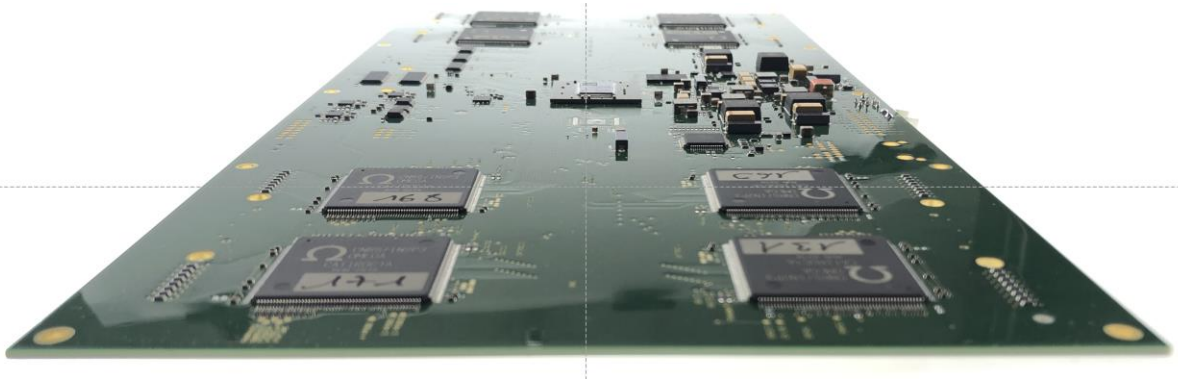
SPMT系统的电子学(都在水下)





- Global Control Unit

- 2 HV splitter boards to split HV and signal

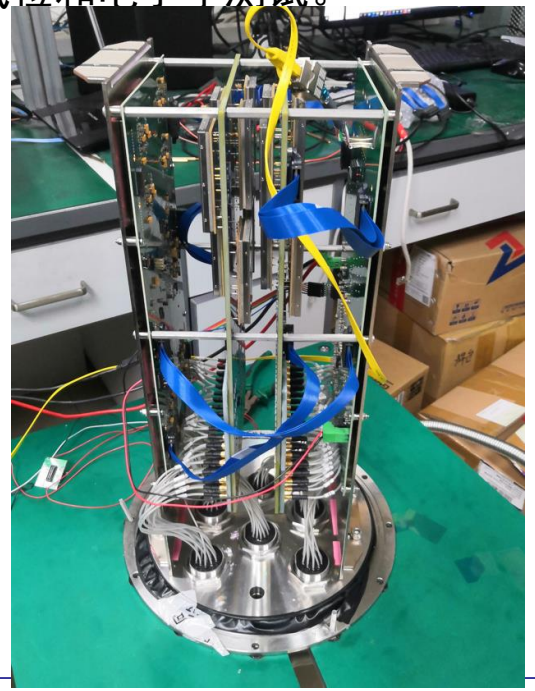


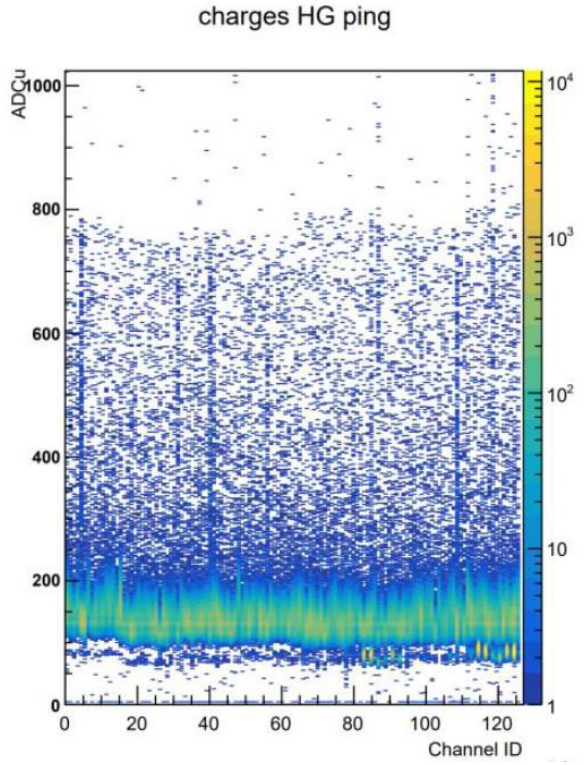
- ABC (ASIC Battery Card): Eight 16-channels CATIROC (Charge And Time Integrated Read Out Chip) from Omega Lab, Kintex-7 Field Programmable Gate Array (FPGA)

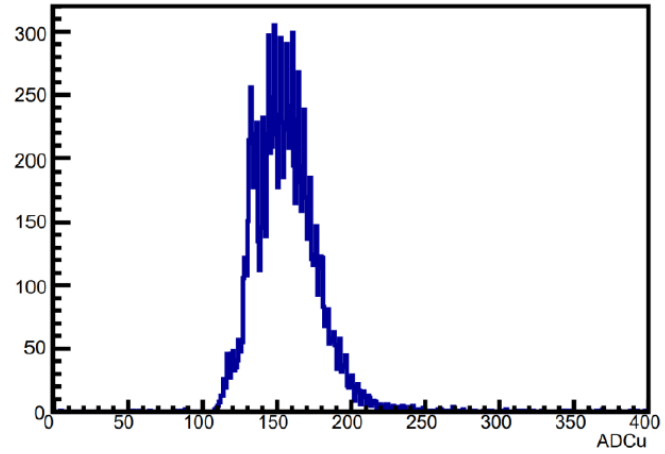
电子学组装和测试@江门现场

- 在高能所完成头3套电子学装配，积累经验。
  - 抽真空，负压法氦检通过。
  - 验证了由负压氦检到正压SF6检测的可行性。
  - 第一次正式的PMT+电子学测试通过。
- 在江门现场地面洁净间完成2套电子学装配，工作正常。
  - 完成了现场测试条件的搭建：暗室、场地、气检系统等搭建。
  - 完成了气检和电子学测试。

Heat sink installation

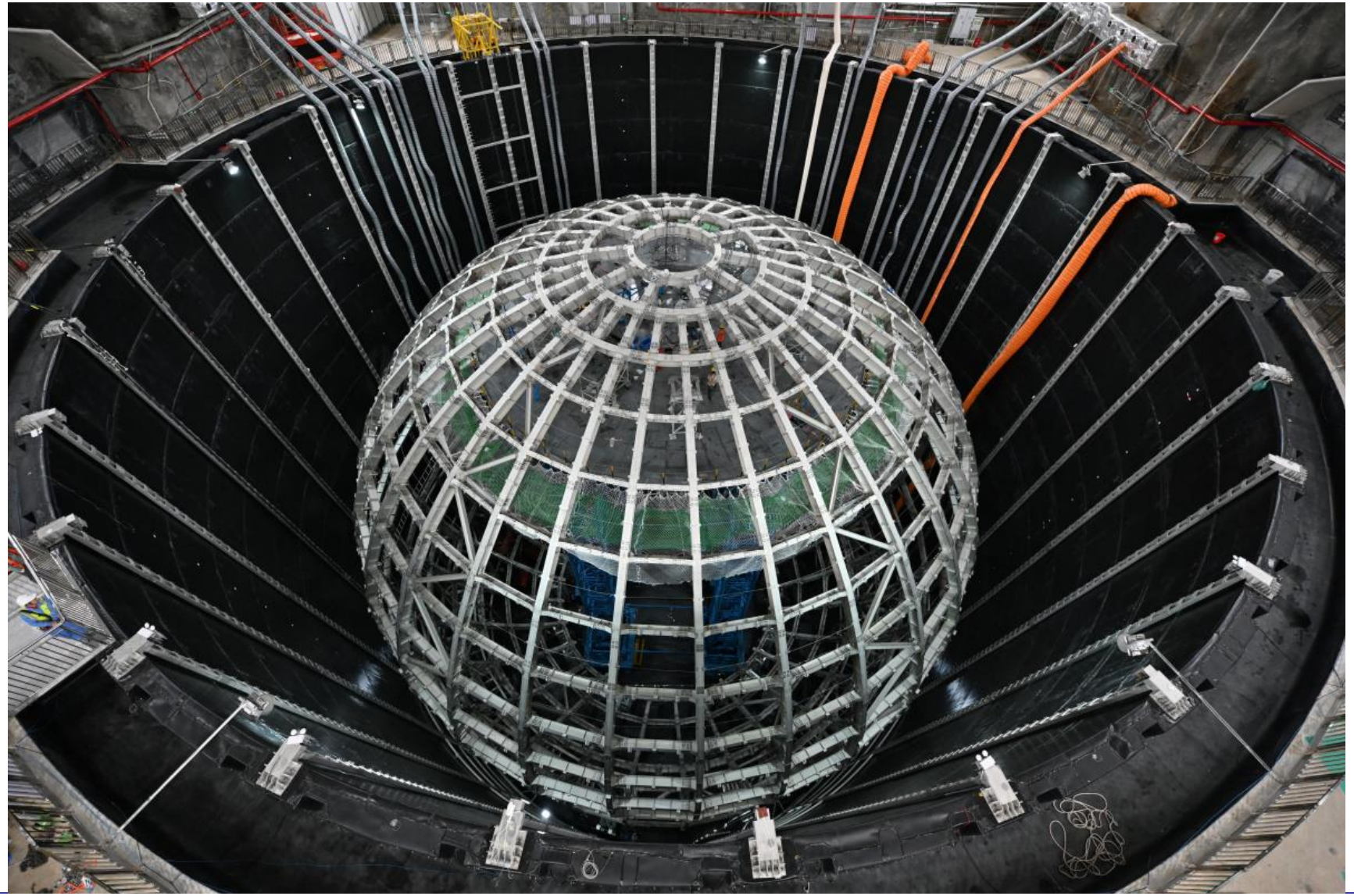






SPE spectrum of Chn0

目前地下探测器状态

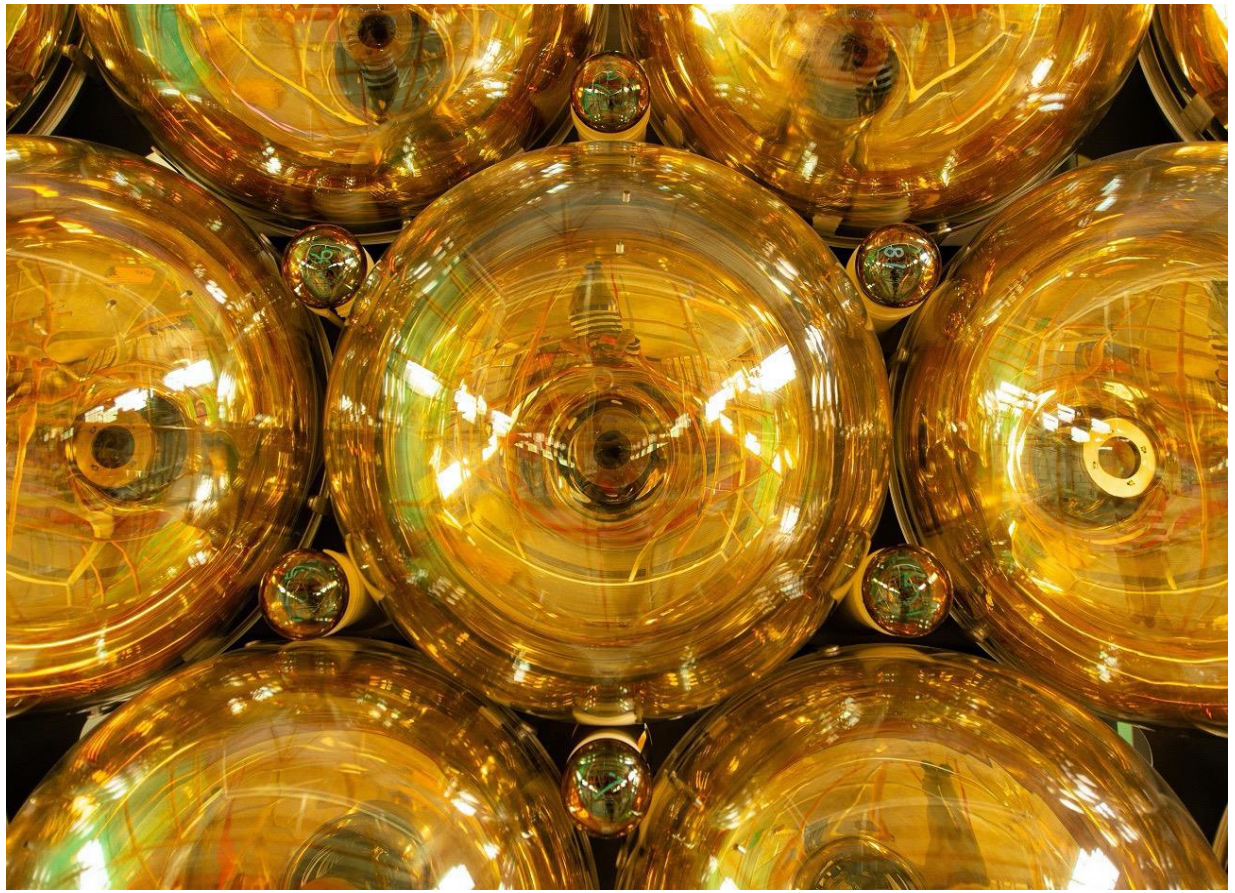


- 不锈钢网壳封顶
- 正在拼接有机玻璃球
- 地面洁净间的PMT检测系统已搭建好，为地下安装做好了准备
- 预计今年第四季度安装PMT

总结展望

- 小PMT系统可以提供独立的测量，与 LPMT 系统构成双量能器系统
  - 可用于精确刻度LPMT 的电荷重建非线性，控制残余非均匀性
  - 有利于改善能标精度和能量分辨率
- 大PMT系统进展顺利
  - 已经完成2万支的20英寸PMT生产和防水封装，合作组文章已放到ArXiv
  - 其他各方面进展顺利
- 小PMT系统进展顺利
  - 已完成2.6万只3英寸PMT的裸管生产和防水封装
  - 已完成99%的防水封装后的PMT测试，其他各部分进展顺利，正逐渐汇聚到江门现场，进行电子学组装和测试
- 已为第四季度安装大小PMT做好了准备。

Thank you for your attention!



Back up

A Multipurpose Neutrino Observatory

Supernova ν's
~10^4 in 10 s
for 10 kpc

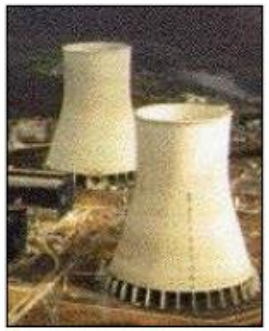
Atmospheric ν's
several/day

Solar ν's
(10-1000)/day

700 m

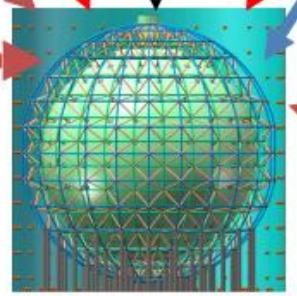
Cosmic muons
~ 250k/day

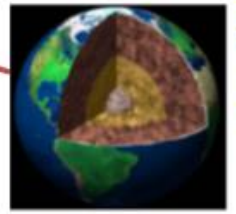
0.003 Hz/m^2, 215 GeV
10% multiple-muon



reactor ν's
~ 80/day

36 GWth, 53 km





Geo-ν's
1-2/day

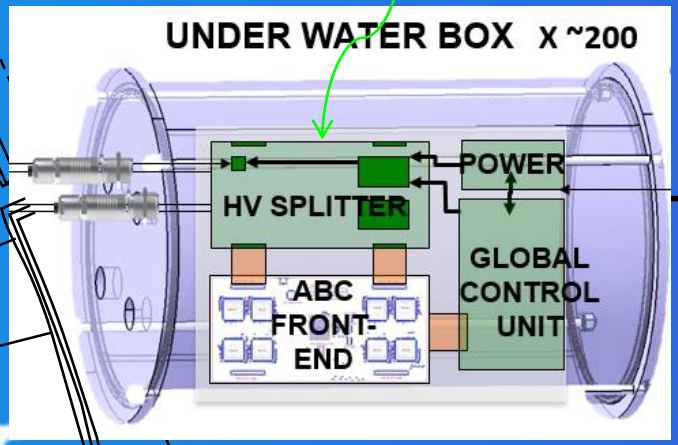
LPMT + SPMT 系统

MAIN DAQ

SURFACE

MAIN DAQ

SPMT Under Water Box
- 128 ch. Photomultipliers
- High Voltage
- Decoupling HV/Signal
- Frond-End + digitalization Electronics
- Global Control Unit (GCU)



≈100m

LPMT Under Water Box
- 3 ch. Photomultipliers
- High Voltage
- Decoupling HV/Signal
- Frond-End + digitalization Electronics
- Global Control Unit

LPMT

≈20m

Zoom in