赵忠尧博士后面试

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工作单位： 高能物理研究所

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个人介绍

➢基本信息

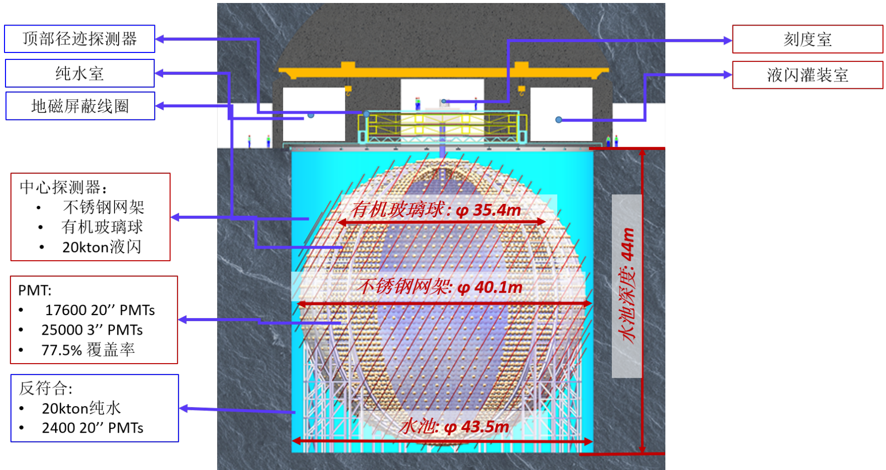
- 姓名：王耀光
- 籍贯：河南省滑县
- 出生日期：1992.06

➢教育经历

- 2010.09~2014.06: 中山大学，物理学专业
- 2014.09~2019.12: 武汉大学，理论物理专业，导师：贾俊基 副教授
- 2015.08~2019.01: 高能物理研究所联合培养，导师：温良剑 研究员
- 2020.07至今: 高能物理研究所，博士后，合作导师：温良剑 研究员

➢科研工作

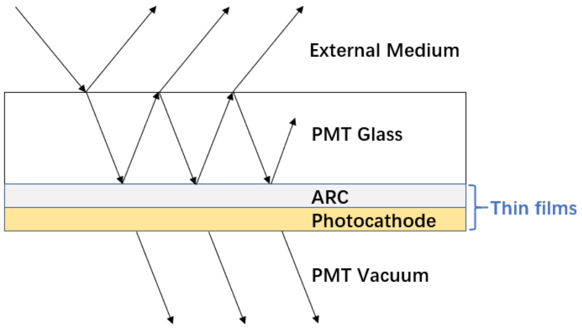
- 参与江门中微子实验 (JUNO)
- 光电倍增管(PMT)模拟、实验研究
- 超新星中微子唯象研究



PMT光学模型

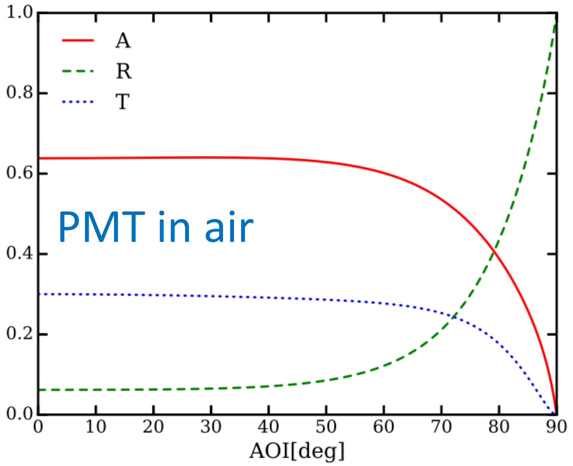
➢目标：实现PMT角度响应的精确模拟

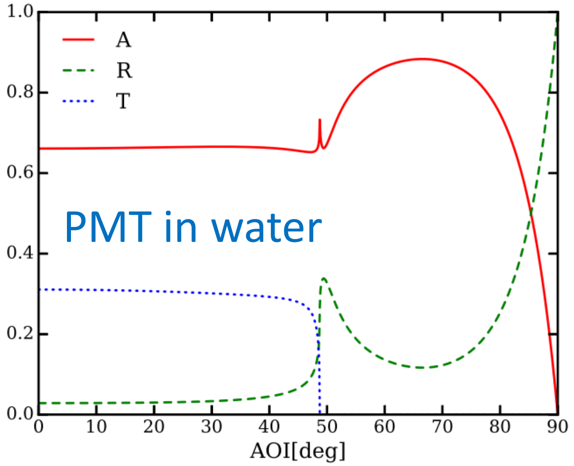
- PMT玻壳的多层结构：外部介质-玻璃-增透膜-光阴极-真空
- PMT内部的多次反射

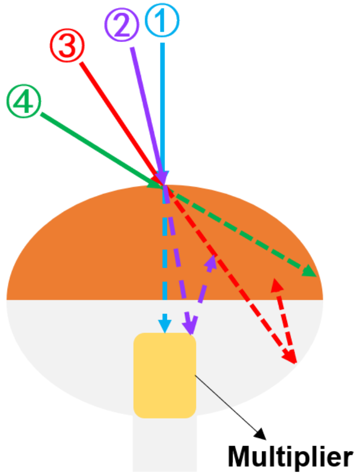


➢研究方法

- 理论计算：基于Transfer Matrix Method，计算光在介质中的**反射**、**透过**和**吸收**
- 实验测量：通过PMT玻壳的反射谱获取增透膜以及光阴极光学参数
- Geant4模拟：结合理论计算与实验测量，并在Geant4中添加相关功能，实现对PMT的精确模拟

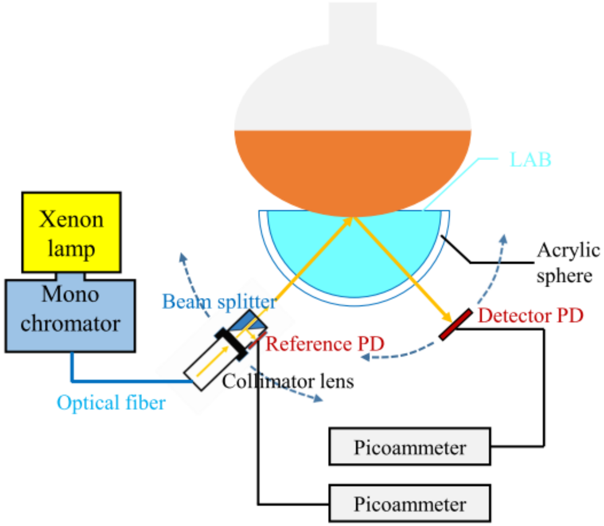


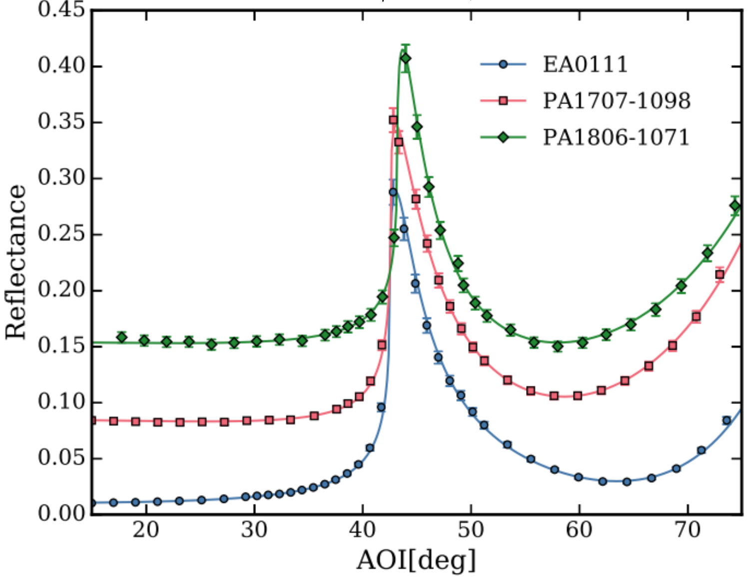




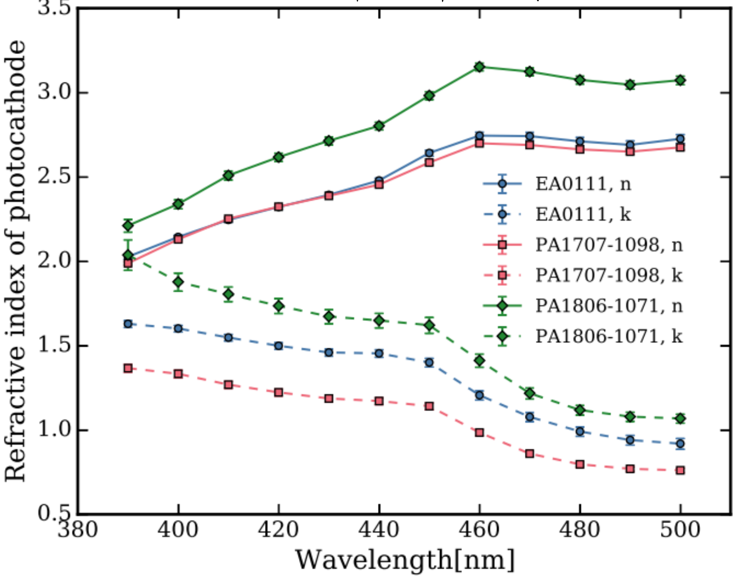
实验测量

- ➢ **完成了3只20英寸PMT的反射率测量以及量子效率测量**
  - 波长：390 ~ 500nm
  - 入射角：0 ~ 75度
- ➢ **拟合得到增透膜及光阴极的光学参数**
- ➢ **估计PMT内部结构反射的影响**





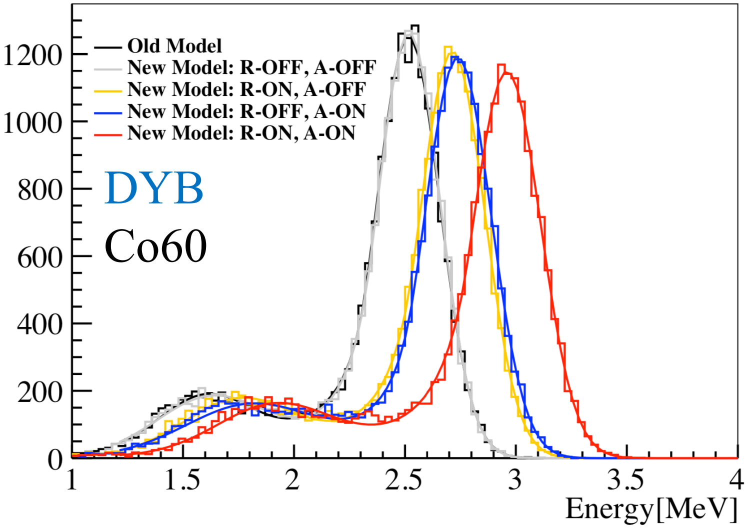
反射率拟合

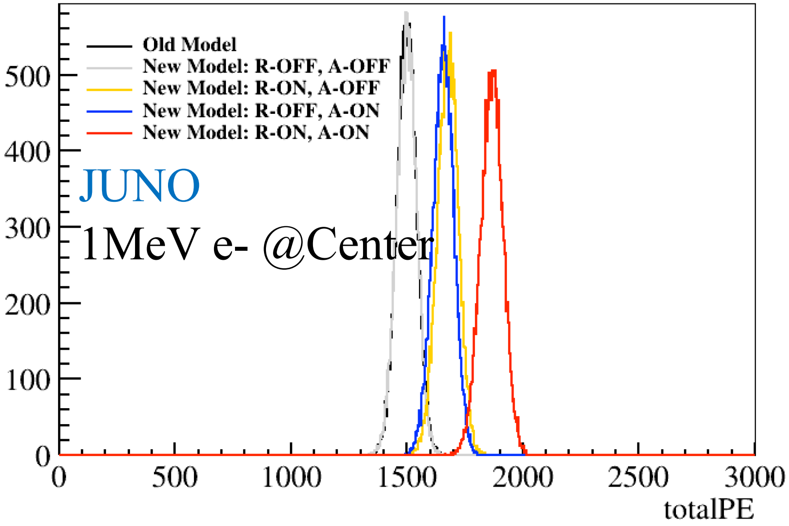


光阴极折射率结果

对JUNO探测器的影响

- ➢**结合新的PMT光学模型，更新了Daya Bay和JUNO探测器模拟，更加合理地预估JUNO的PE数**
- ➢**结果表明，JUNO的预期PE数会提高8.3%**





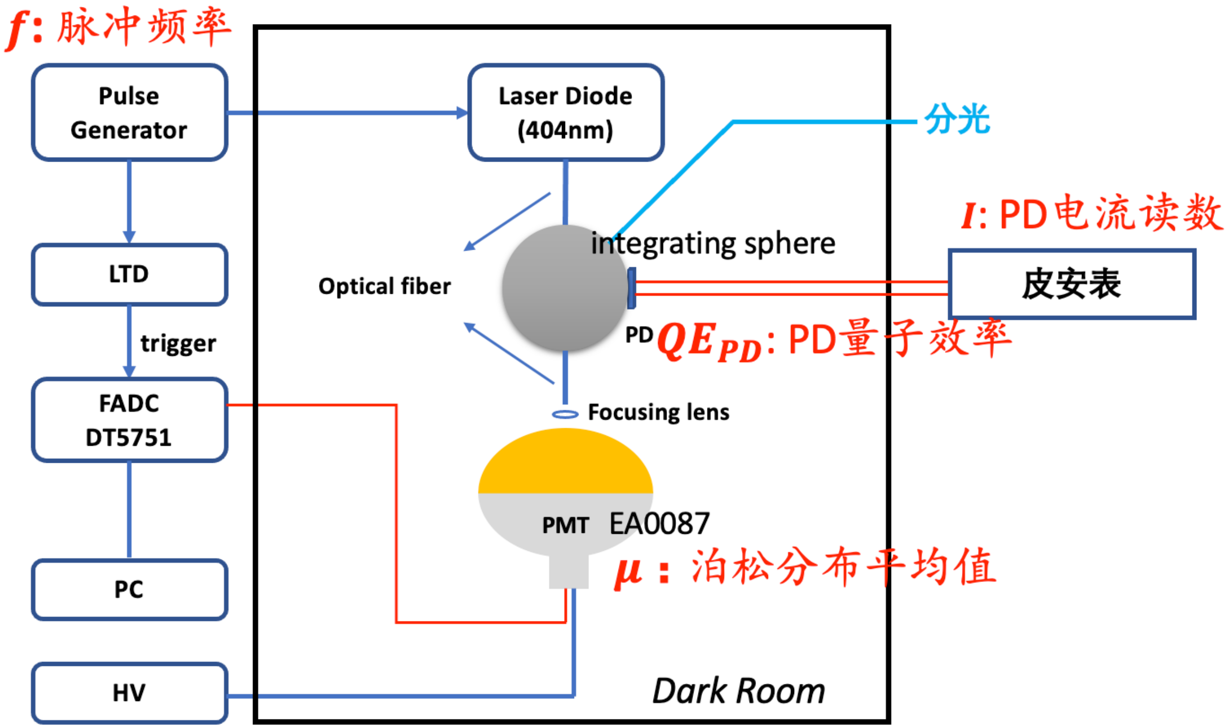
- 该结果被JUNO质量顺序文章采用，显著提高JUNO对中微子质量顺序的鉴别能力
- 合理解释国际上大多数中微子实验中，实际观测光子数总是大于预期值的现象
- 2021年JUNO国际科学顾问委员会亮点工作

PMT绝对探测效率测量

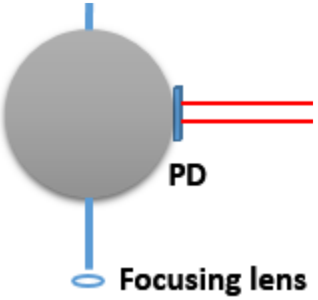
- 绝对探测效率测量难点在于如何获得**入射光子数**，过去的探测效率数据依赖于模拟结果

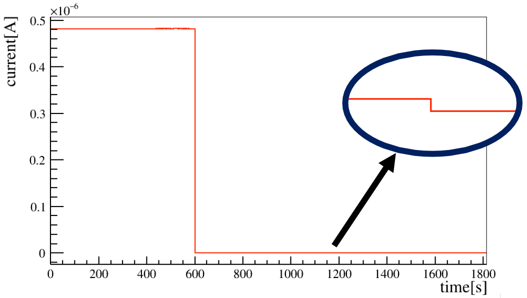
$$\mathrm{DE} = \frac{\text{信号数目}}{\text{入射光子数}}$$

- 测量方案



- 分光比测量

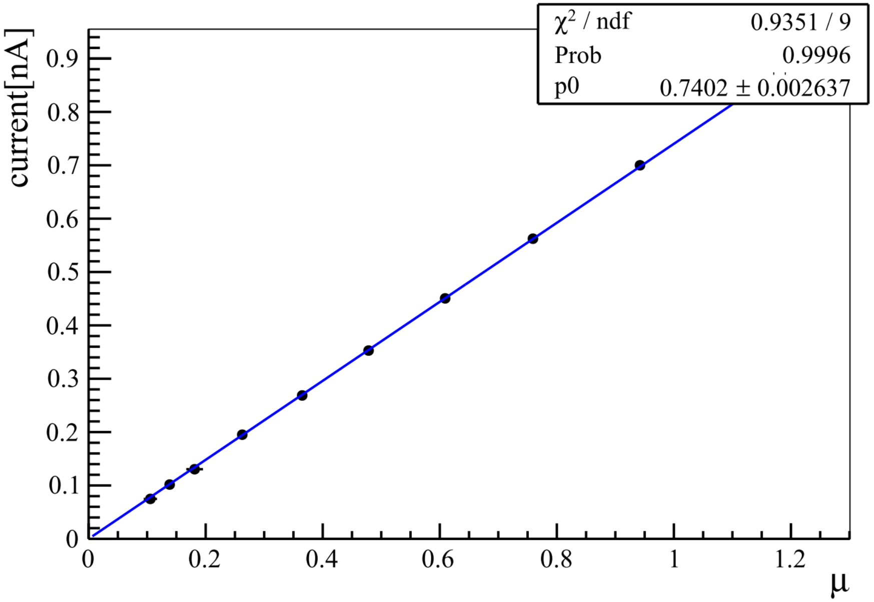


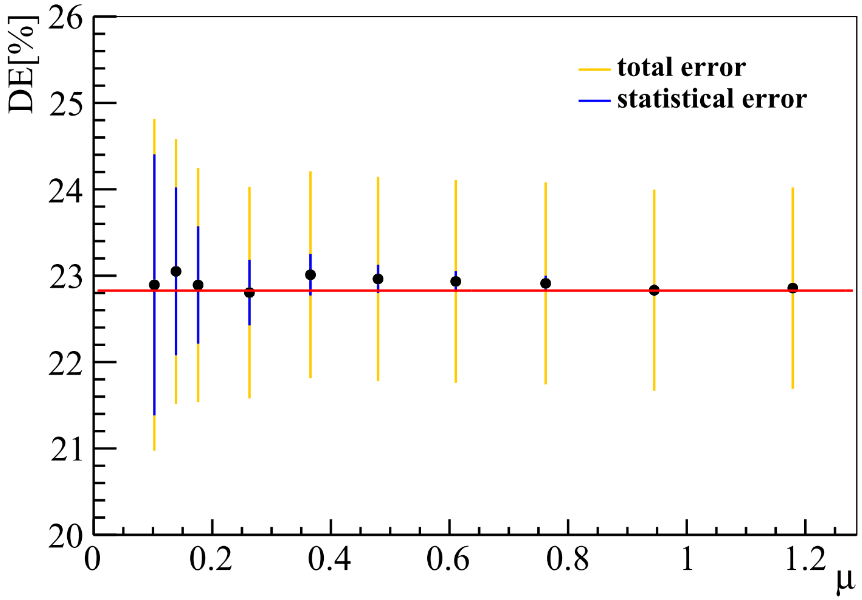


$$R = \frac{I_2 - I_0}{I_1 - I_0} = 1663 \pm 10$$

测量结果

- 分别在10组不同光强下进行探测效率测量
- 左图为分光系统的线性测试，即$\boldsymbol{\mu - I}$关系
- 右图为10组光强下探测效率的拟合结果





$$\chi^2=\sum_{n=1}^{10}\left(\frac{\mathrm{DE}[n]-\mathrm{DE}_{exp}-\xi_R c_R-\xi_{QE}c_{QE}}{u_n}\right)^2+\xi_R^2+\xi_{QE}^2 \xrightarrow{\text{极小化}} \mathrm{DE}=(22.9\pm1.2)\,\%$$

$\mathrm{DE}[n]$: 10 measurements of DE

$\mathrm{DE}_{\mathrm{exp}}$: expected DE value, to be fitted

c_R, c_{QE}: $1\sigma_R$ or $1\sigma_{QE}$ induced DE shift

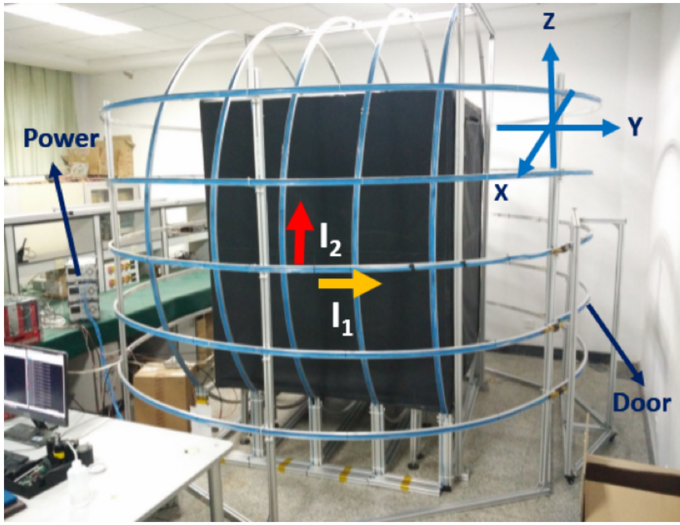
ξ_R, ξ_{QE}: nuisance parameters

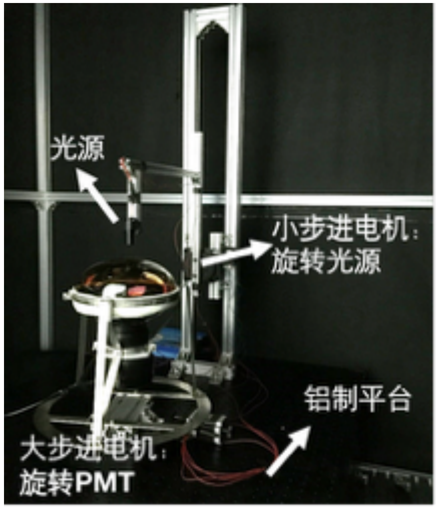
u_n: uncorrelated error

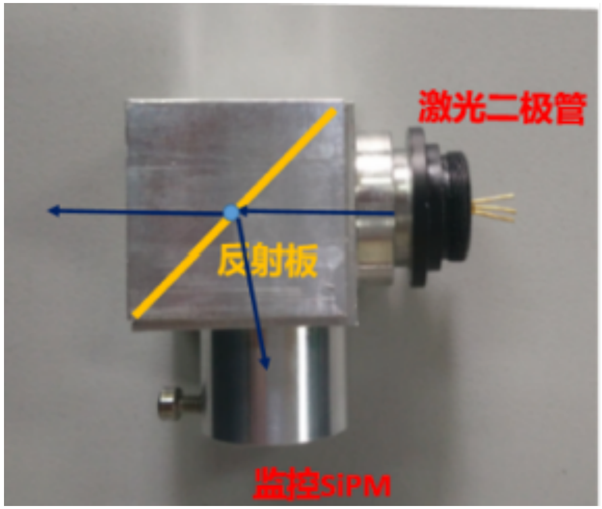
DE	**QE**	**CE**
22.9 ± 1.2	26.7 ± 1.4	85.7 ± 1.6

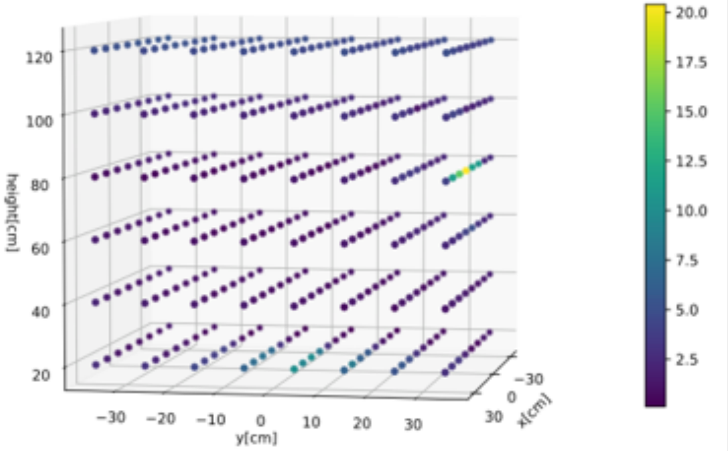
磁场对PMT探测效率的影响

- 搭建了地磁屏蔽系统，中心区域残余地磁场小于~5%
- 步进电机控制PMT及光源旋转
- 对PMT表面不同位置，在不同磁场强度、磁场方向下的效率变化进行了详细研究
- 总结出了磁场对PMT效率影响的规律





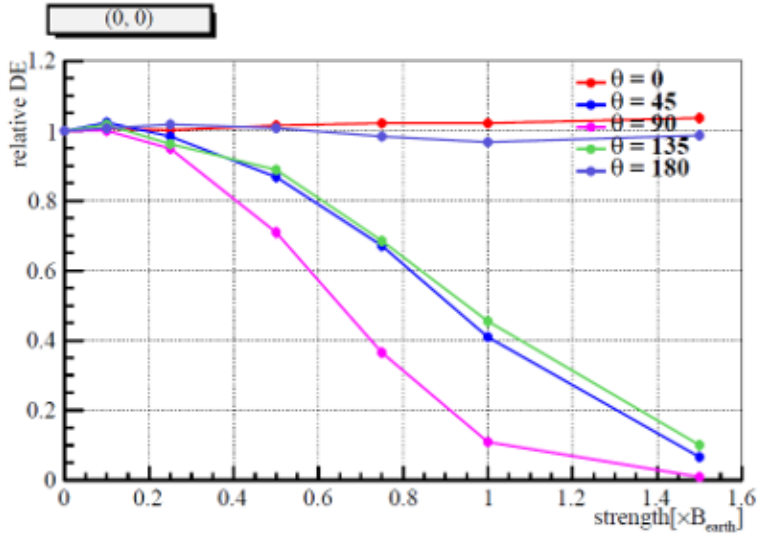


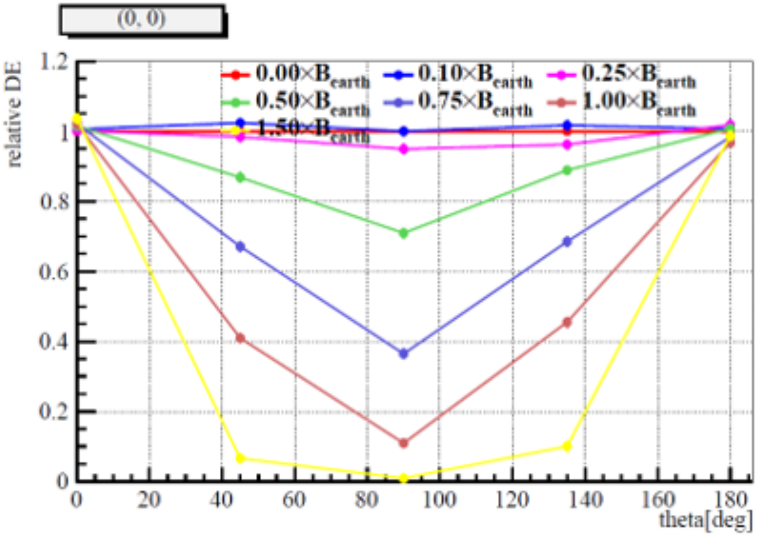


- 主动屏蔽
- 使用两组线圈补偿地磁场的水平和竖直分量

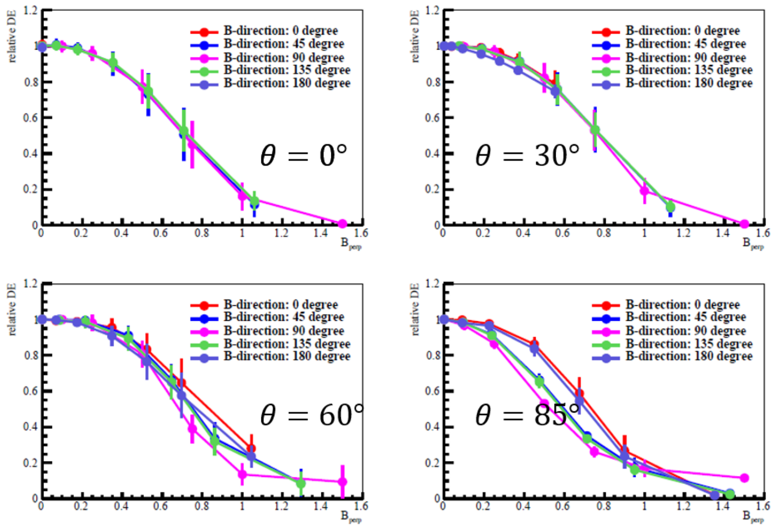
测量结果

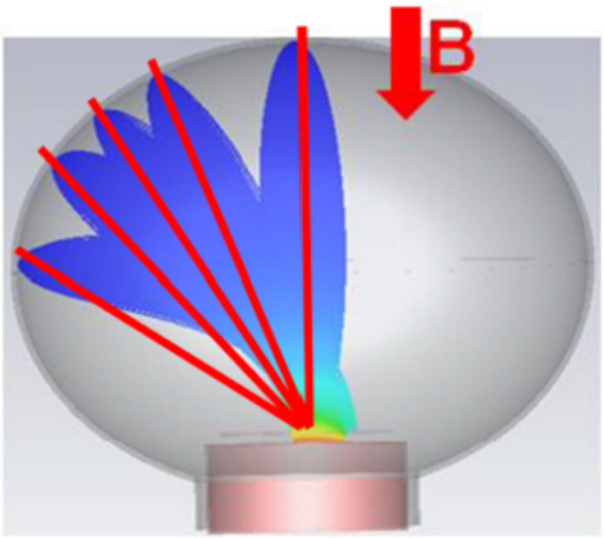
- **顶点**



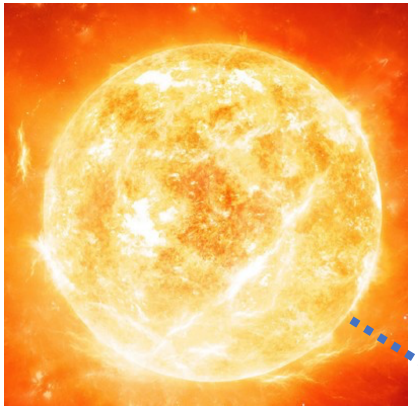


- **与磁场垂直分量之间的关系**





超新星中微子鉴别质量顺序研究



中微子味转换：

- MSW效应
- 集体振荡效应

$$\mathrm{Prob}(\,|\nu_e\rangle \rightarrow |\nu_i\rangle, E) \equiv P_{ei}$$

超新星中微子能谱：

$$n_{\nu_e}(t,E) = \frac{L(t)}{\langle E(t)\rangle}\frac{E^{\alpha}}{\Gamma(\alpha+1)}\left(\frac{\alpha+1}{\langle E(t)\rangle}\right)^{\alpha+1}\exp\left(-\frac{(\alpha+1)E}{\langle E(t)\rangle}\right)$$

超新星表面质量本征态的数密度：

$$n_{\nu_i}(t,E) = n_{\nu_e}(t,E)P_{ei}(E)$$

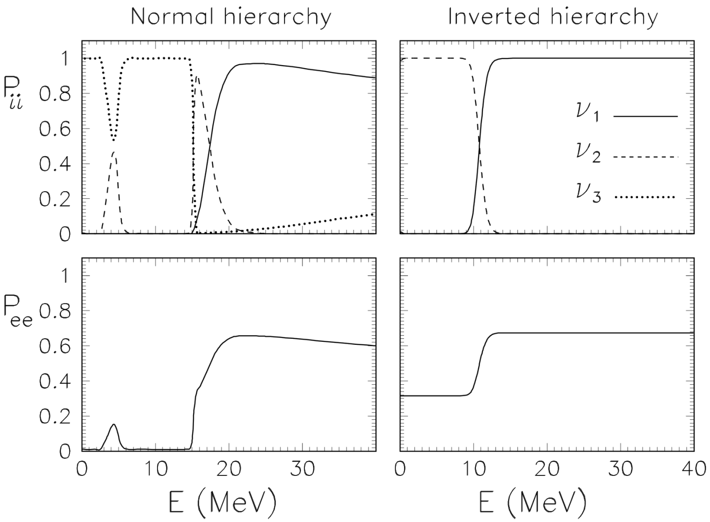
不同质量本征态中微子飞行时间差：

$$\boldsymbol{\Delta t_{ij} = 5.15}\mathrm{ms}\cdot\frac{\boldsymbol{\Delta m_{ij}^2/eV^2}}{\boldsymbol{(\langle E\rangle/10MeV)^2}}\cdot\frac{\boldsymbol{D}}{\boldsymbol{10kpc}}$$

地球接收的中微子谱：

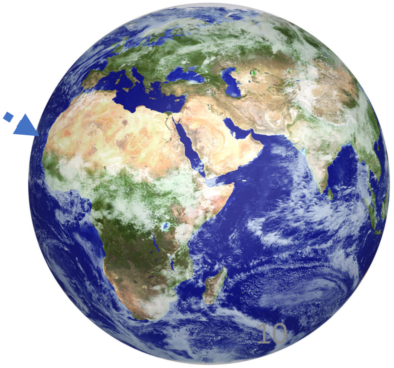
$$F_{\nu_i}(t_d,E) = \frac{1}{4\pi D^2}n_{\nu_e}(t_d-\Delta t_{i1},E)P_{ei}(E)$$

情形A：



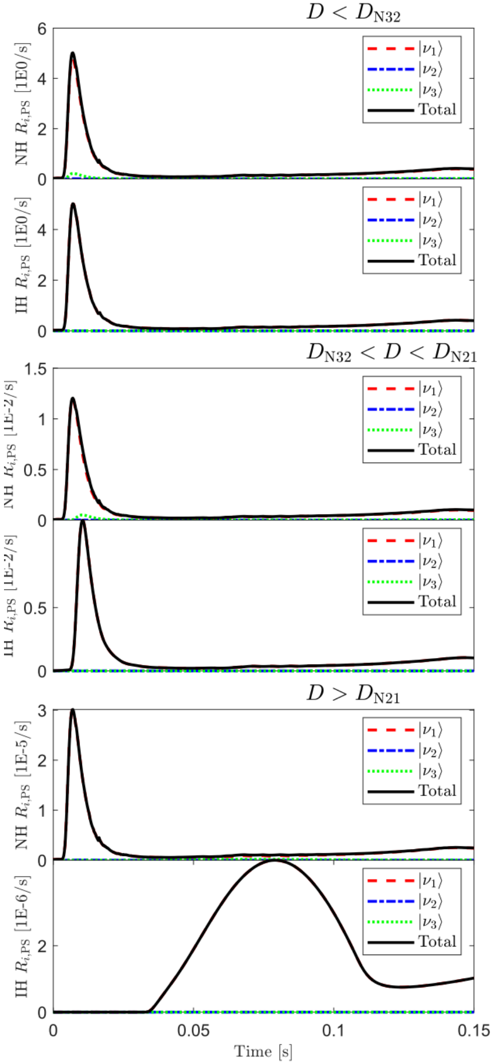
情形B：

$$P_{e1} = \frac{1}{6}, P_{e2} = \frac{1}{3}, P_{e3} = \frac{1}{2}$$

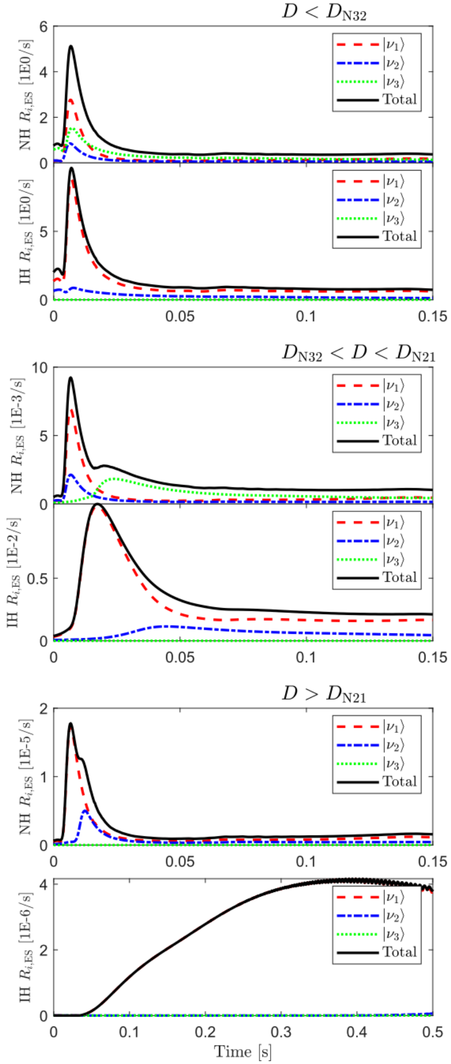


中子化与黑洞形成过程

中子化过程

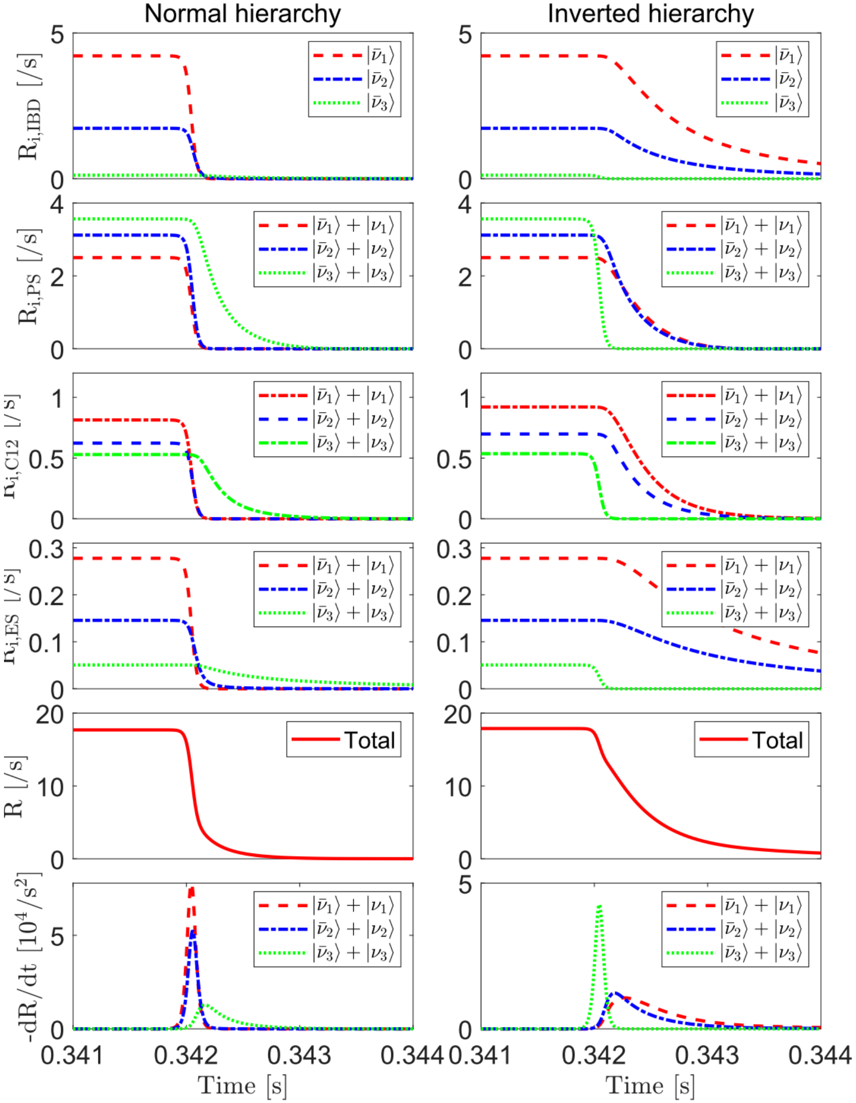


中微子-质子



中微子-电子

黑洞形成过程



尚无法应用于当前中微子实验

工作总结

➢PMT光学模型

- 结合理论计算、实验测量和Geant4模拟，建立了完整的PMT光学模型
- 利用新的PMT光学模型，更加合理地预期了JUNO的光电子数
- 开发了多层介质系统反射率、透过率和吸收率计算的Python包，并完善了TMM理论
- 可以对未来PMT的设计、生产提供优化方向

➢PMT效率研究

- 搭建了屏蔽效果好于～95%的地磁屏蔽间
- 设计积分球分光方法，对PMT的绝对探测效率进行精确标定
- 详细研究了磁场对PMT探测效率的影响，并总结出了一般规律

➢超新星中微子唯象研究

- 尝试利用中子化和黑洞形成过程短时间特征鉴别中微子质量顺序
- 距离与事例率之间的矛盾导致无法用于当前中微子实验之中

文章发表及获奖情况

文章发表

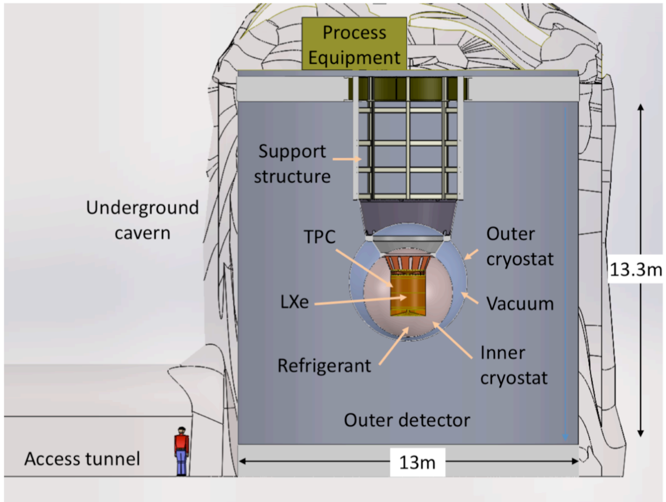
- Junji Jia, **Yaoguang Wang** and Shun Zhou. On the possibility to determine neutrino mass hierarchy via supernova neutrinos with short-time characteristics. Chin. Phys. C 43(9):095102 2019.
- **Yaoguang Wang**, Xionghui Liu, Nan Yang et al. Escape, bound and capture geodesics in local static coordinates in Schwarzschild spacetime. Gen Relativ Gravit 52, 16 (2020)
- **Yaoguang Wang**, Guofu Cao, Liangjian Wen et al. Optical model for larger area PMTs. To be submitted
- **Yaoguang Wang**, Guofu Cao, Liangjian Wen et al. Total internal reflection in a multilayer optical system. To be submitted
- **Yaoguang Wang**, Guofu Cao, Liangjian Wen et al. Magnetic field effects on detection efficiency of PMT. To be submitted

获奖情况

- PANIC 2017 Best Poster Prize

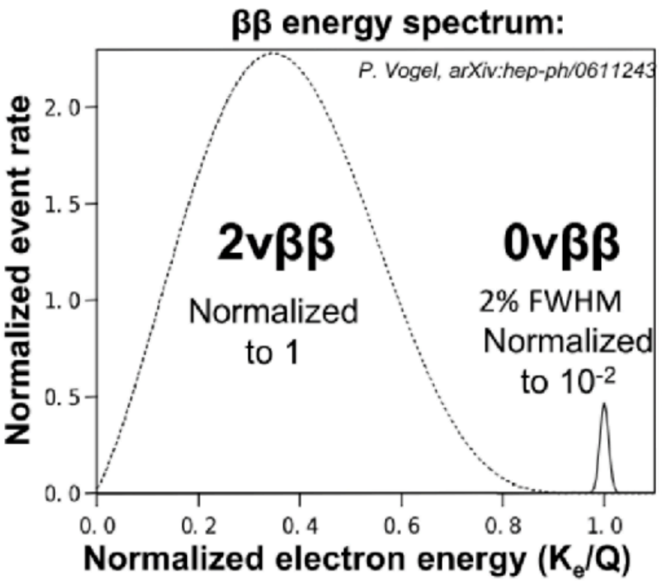
未来工作计划

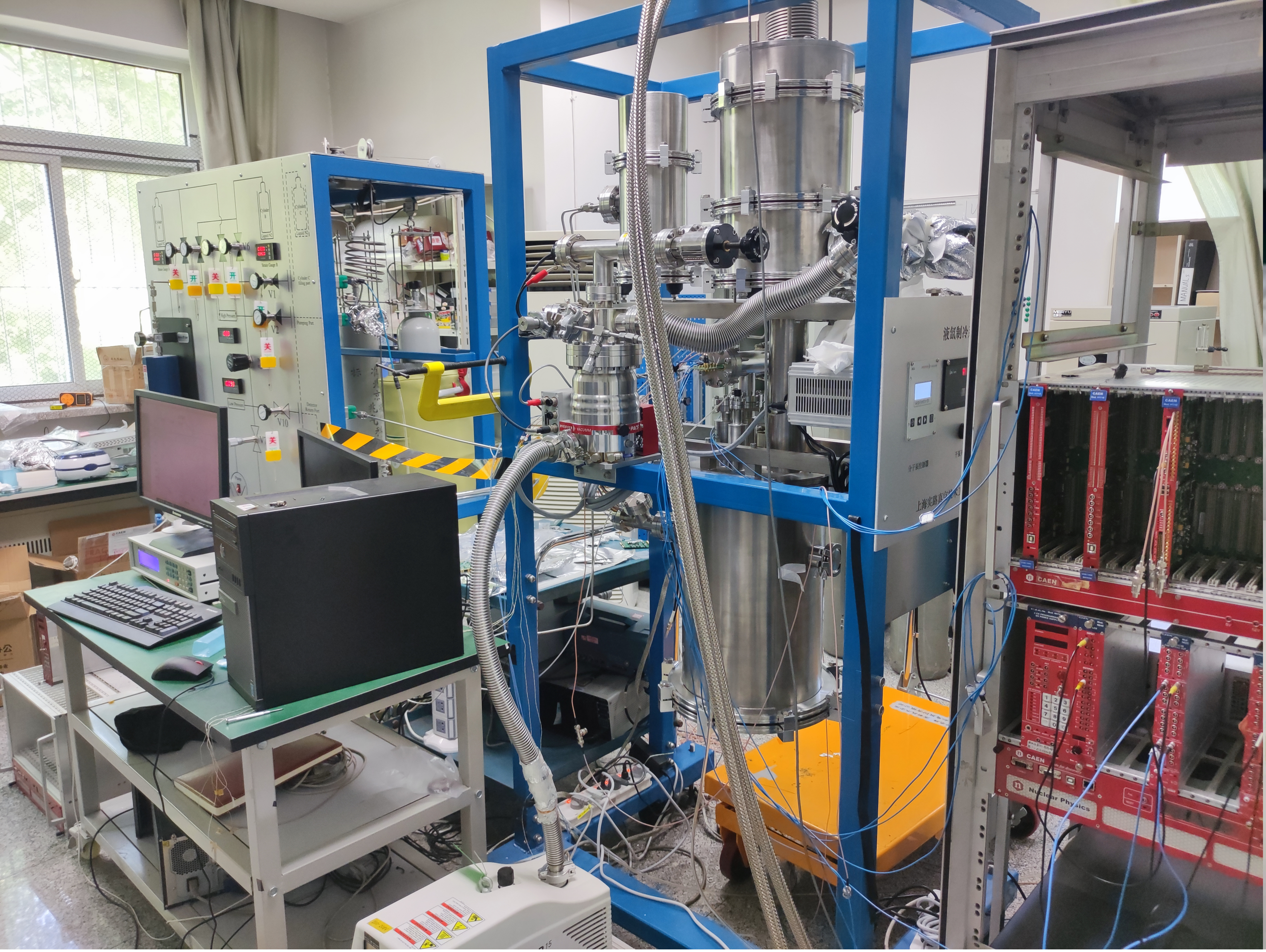
- Next Enriched Xenon Observatory (**nEXO**)
  - 利用LXe寻找无中微子双贝塔衰变($0\nu\beta\beta$)
  - TPC能量分辨率 ~ 1%
  - 关键技术：**电荷读出与SiPM技术**

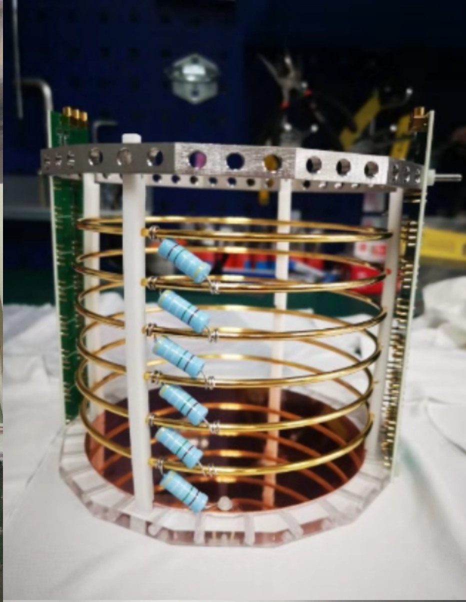


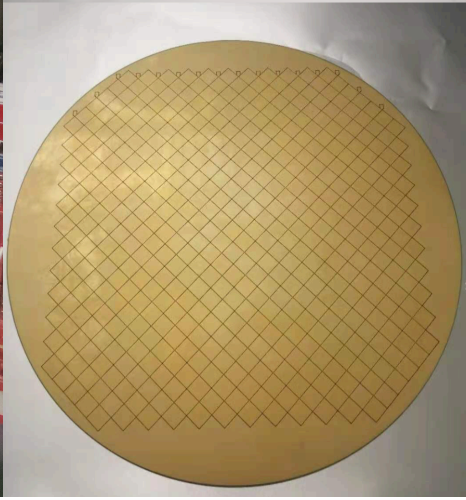
- miniTPC@IHEP
  - **Charge tile**及其**芯片**的设计和性能测试
  - **SiPM**低温性能测试
  - **能量分辨率**验证测试

miniTPC运行调试中……







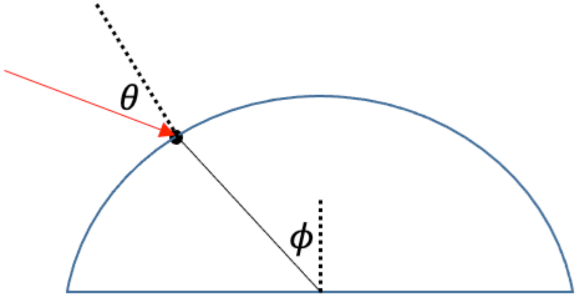


谢谢！

Backup

Basic Idea: DE

➢DE at one **POINT**



$$DE(\lambda,\theta,\phi) = QE(\lambda,\theta)\cdot CE(\phi)$$

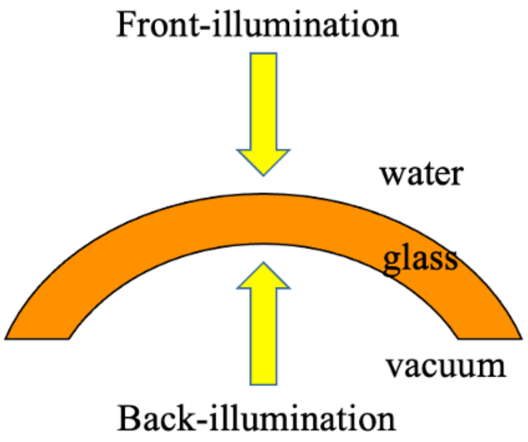
$$= A(\lambda,\theta)\cdot\rho(\lambda)\cdot CE(\phi)$$

absorption

escape factor: escape probability of p.e. from p.c.

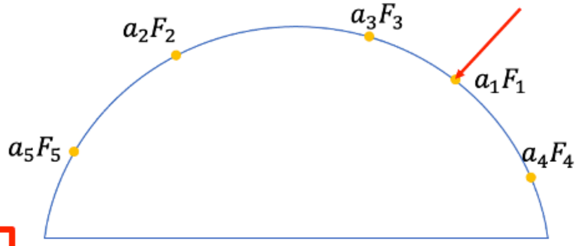
➢DE for one **LIGHT BEAM**

- For an arbitrary incident light, DE is contributed by **Front-illumination** and **Back-illumination** due to multiple reflection inside PMT



$$DE = \sum_i a_i\cdot\boxed{\rho_i\cdot CE_i} = \sum_i a_i\cdot\boxed{F_i}$$

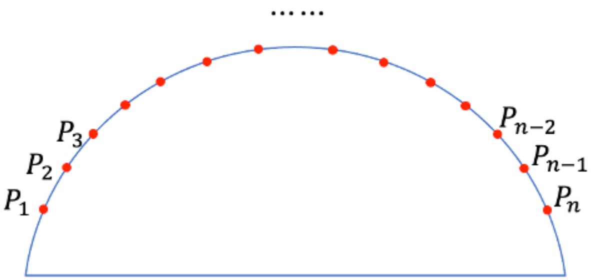
- ◆ *DE for one light beam is contributed by several POINTs*
- ◆ *a_i: absorption ratio at each POINT, from simulation*
- ◆ *F_i: independent of angle of incidence (AOI)*



How to get **F-factor distribution**?--**Based on DE data!**

Basic Idea: F-factor

- Suppose we have measured n points along two opposite longitudes



- For P_i, its DE is contributed by j points:

$$DE_i = \sum_j a_{ij} F_j{}'$$

- $F_j{}'$ can be denoted as weighted mean of $F_1 \sim F_n$:

$$F_j' = \sum_{k=1}^{n} \beta_{jk} F_k$$

- So,

$$DE_i = \sum_j a_{ij} \sum_{k=1}^{n} \beta_{jk} F_k = \sum_j \sum_{k=1}^{n} a_{ij} \beta_{jk} F_k = \sum_{k=1}^{n} \boxed{\sum_j a_{ij} \beta_{jk}} F_k = \sum_{k=1}^{n} \boxed{A_{ik}} F_k$$

- In matrix form:

from simulation

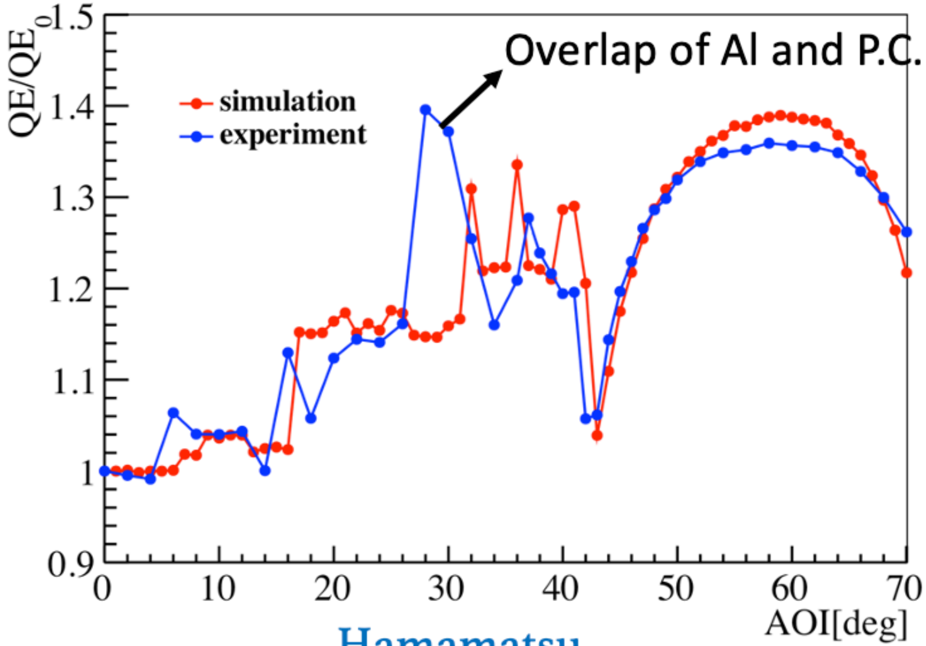
from experiment

$$\boxed{\begin{pmatrix} DE_1 \\ DE_2 \\ \vdots \\ DE_n \end{pmatrix}} = \boxed{\begin{pmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nn} \end{pmatrix}} \begin{pmatrix} F_1 \\ F_2 \\ \vdots \\ F_n \end{pmatrix}$$

- ◆ *Then, **F** distribution can be solved*
- ◆ *To obtain A matrix, we need to know the **absorption** of photocathode -- **multilayer thin film theory***

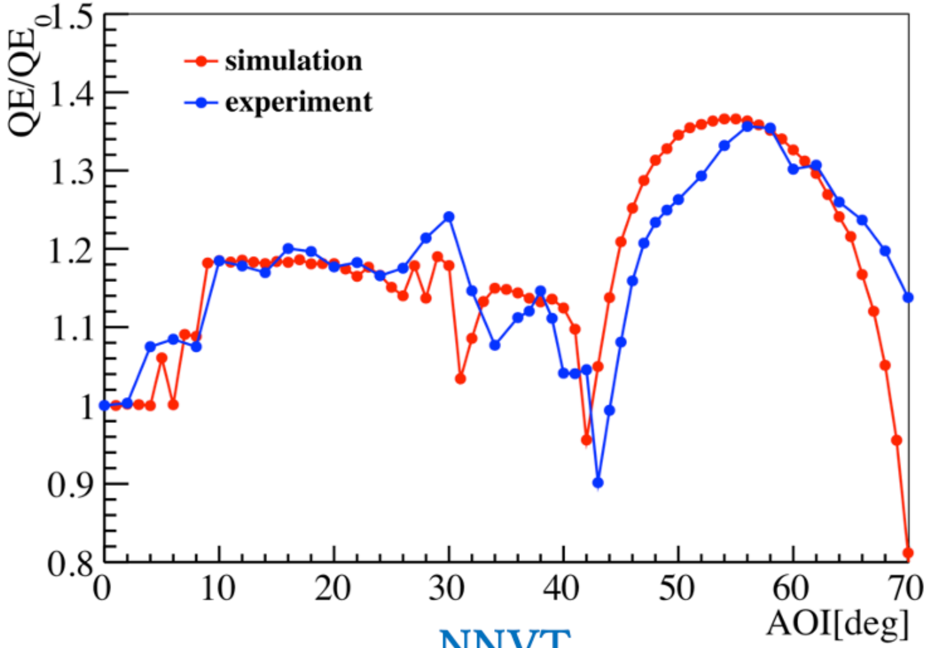
QE vs AOI

- After taking into consideration the optical processes inside PMT, the QE curve can be well simulated



Overlap of Al and P.C.

Hamamatsu

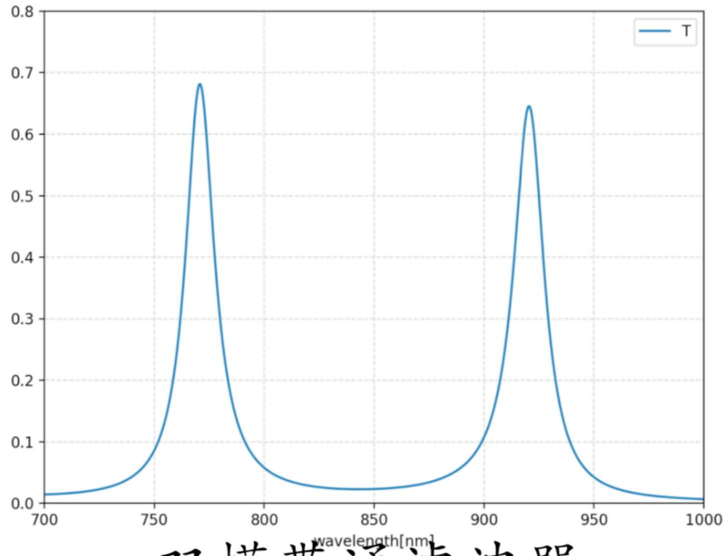


NNVT

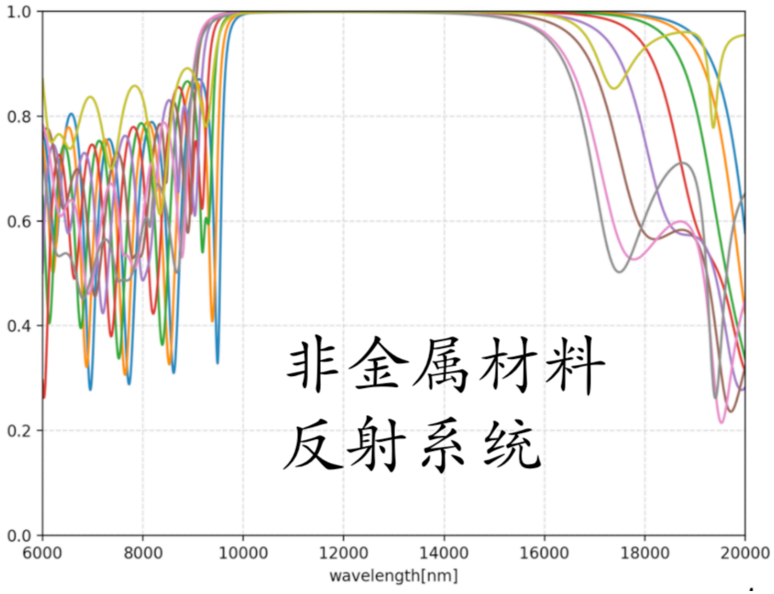
- *Compared with NNVT PMT, the inner structures of Hamamatsu PMT is more complicated*
- *Fine structures of the metal tube may lead to fluctuations of QE curve*
- *Overlap of photocathode and Al film below the PMT equator is not considered in simulation*

多层膜计算Python包

- 吸收率、反射率和透过率计算（ART）
  - 数据库包含280多种常用材料
  - 任意层数
  - 厚、薄介质任意排列
  - 角度扫描
  - 波长扫描



双模带通滤波器



非金属材料
反射系统