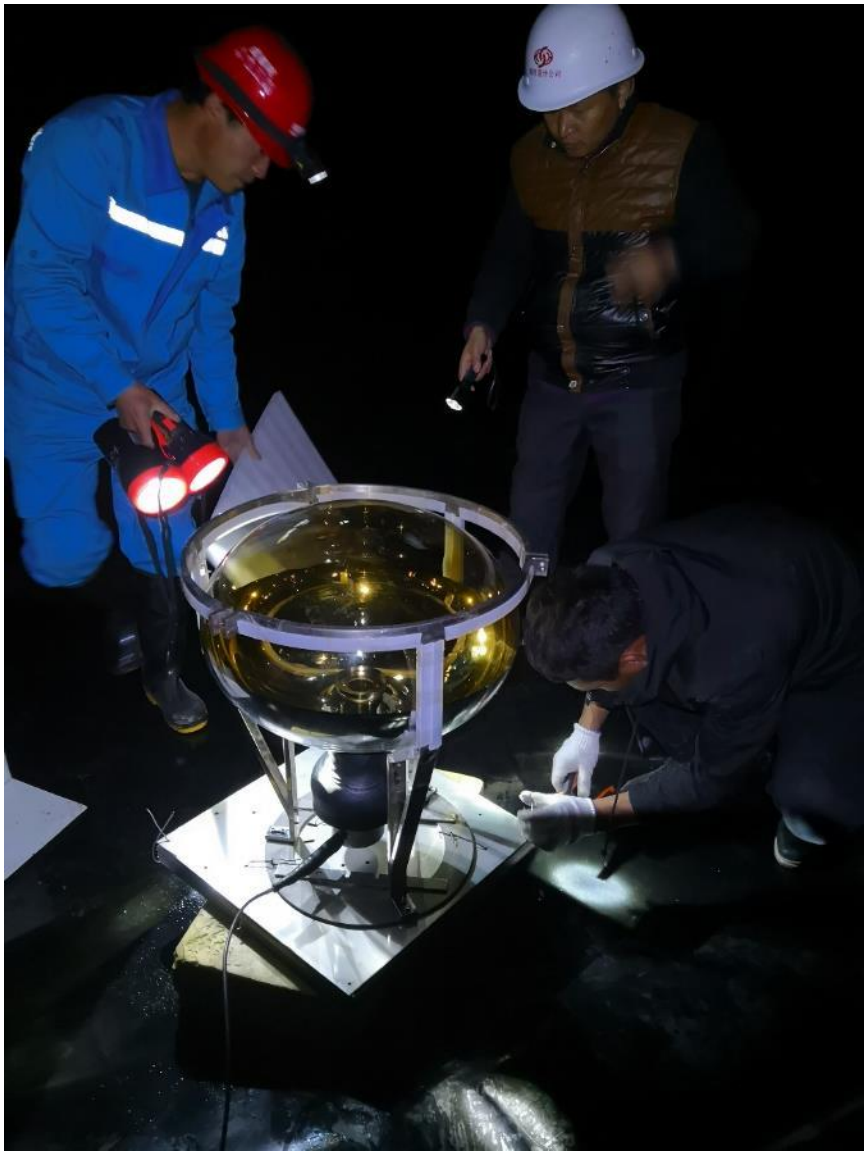
New 20” PMT for LHAASO



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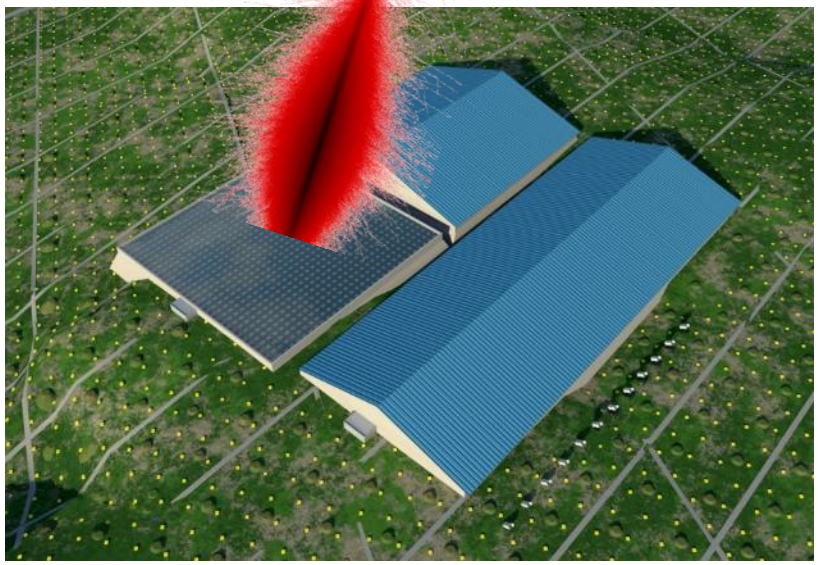
On behalf of WCDA group
2018-9-18, Moscow

9th *Workshop on Air Shower Detection at High Altitudes, 2018*

Content

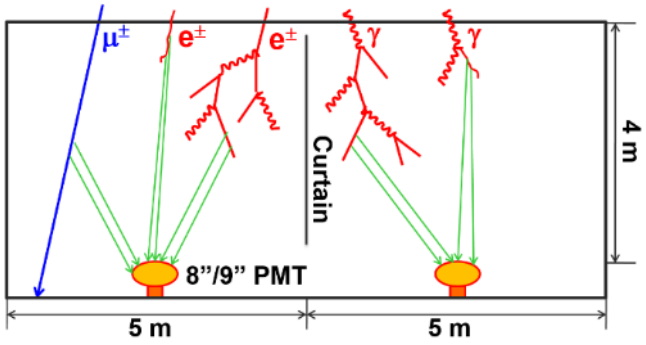
1. Introduction to WCDA
2. Three questions: What, Why & How?
3. Status of WCDA

WCDA - Water Cherenkov Detector Array



3 water ponds:

- 78,000 m^2 in total;
- 4.4 m water depth;
- 3,120 cells, with an 8”PMT in each cell;
- Cells are partitioned with black curtains.

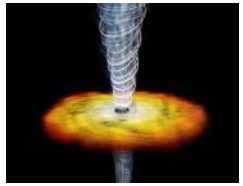


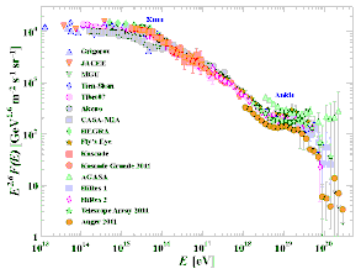
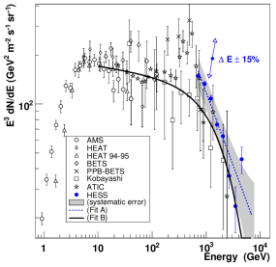
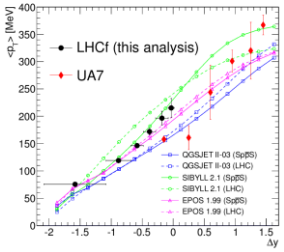
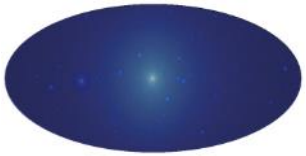
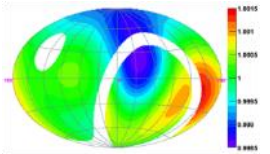
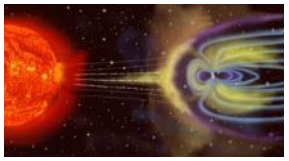
Detect shower secondary particles:

- Electrons/positrons;
- Muons;
- Gammas.

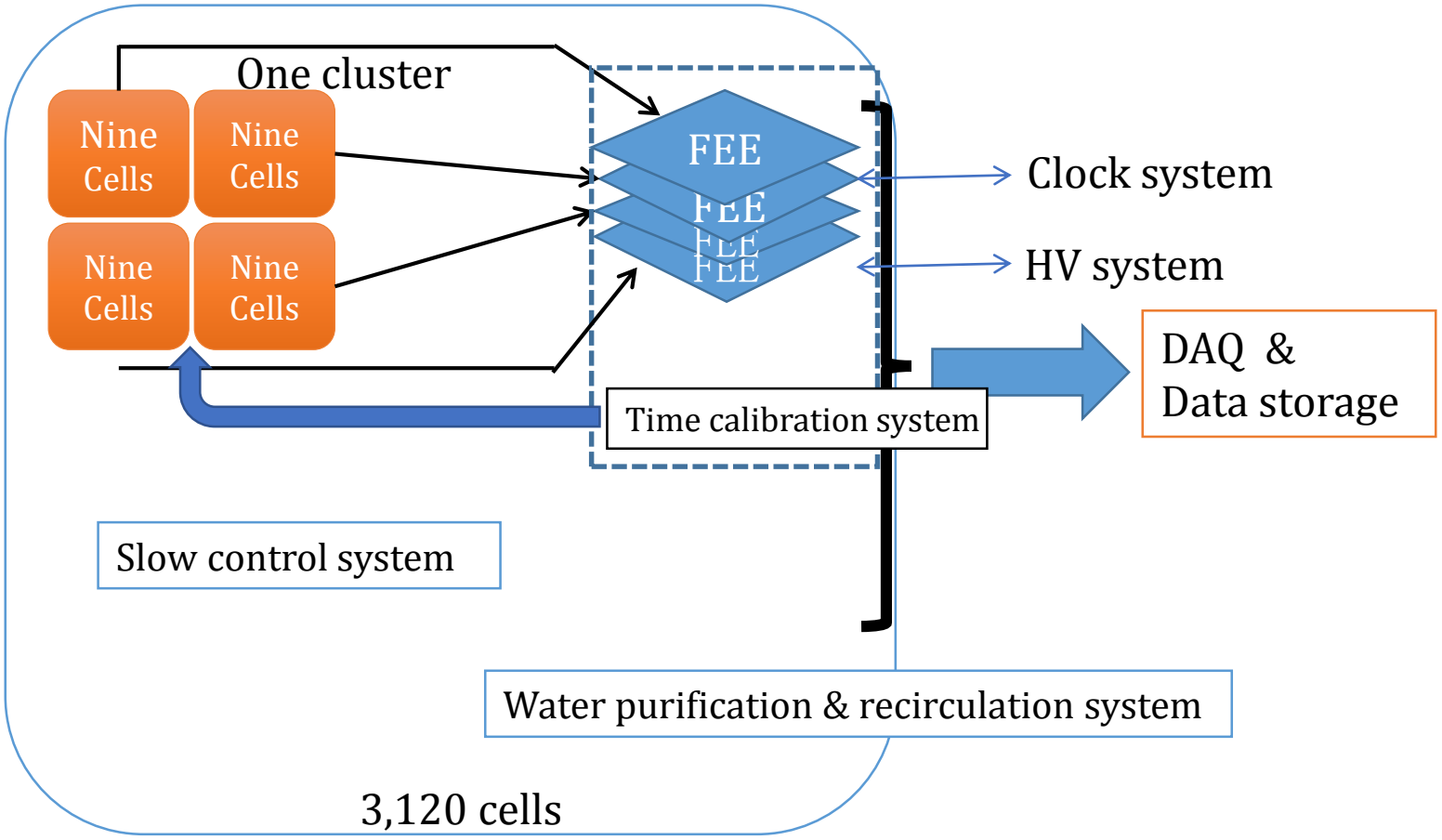
Physics Goals

- **VHE gamma sky survey (100 GeV-30 TeV):**
  - Extragalactic sources & flares;
  - VHE emission from Gamma Ray Bursts;
  - Galactic sources;
  - Diffused Gamma rays.
- **Cosmic Ray physics (1 TeV-10 PeV):**
  - Anisotropy of VHE cosmic rays;
  - Cosmic ray spectrum;
  - Cosmic electrons;
  - Hadronic interaction models.
- Miscellaneous:
  - Gamma rays from dark matter;
  - Sun storm & IMF.

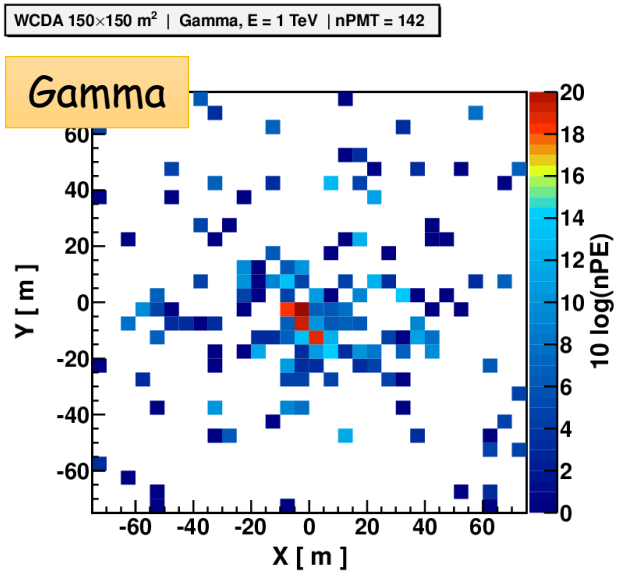
Schematics of WCDA

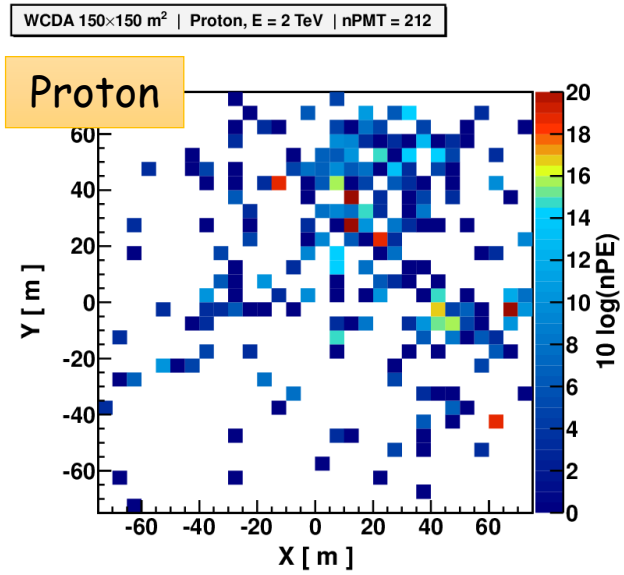


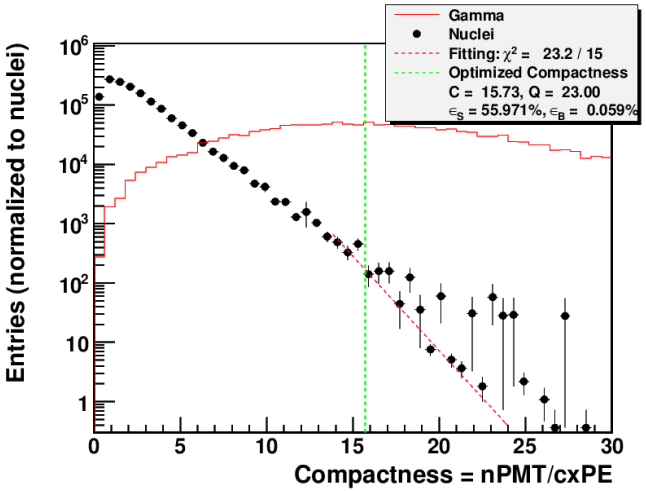
WCDA Specifications

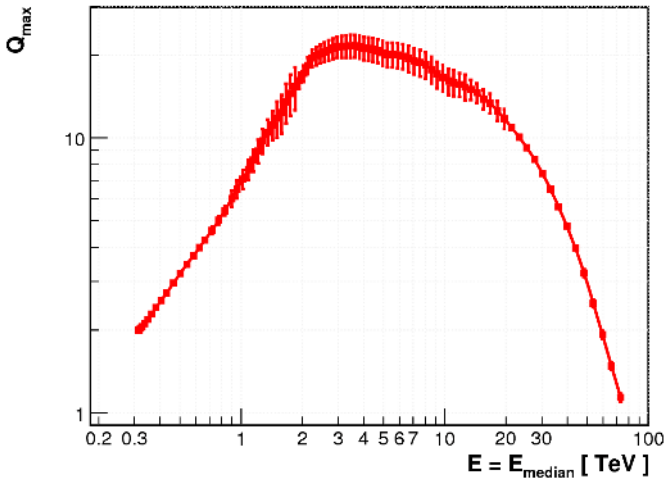
Item	Value
Cell area	25 m^2
Effective water depth	4 m
Water transparency	> 15 m (400 nm)
Precision of time measurement	0.5 ns
Dynamic range	1-4,000 PEs
Time resolution	<2 ns
Charge resolution	50% @ 1 PE 5% @ 4000 PEs
Accuracy of charge calibration	<2%
Accuracy of time calibration	<0.2 ns
Total area	78,000 m^2
Total cells	3,120

Gamma/proton Discrimination



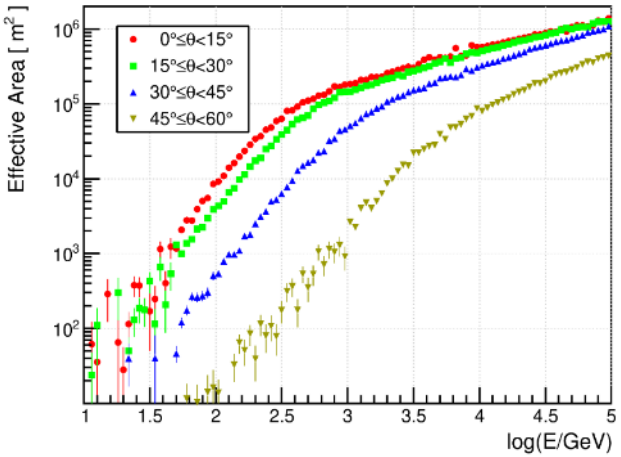






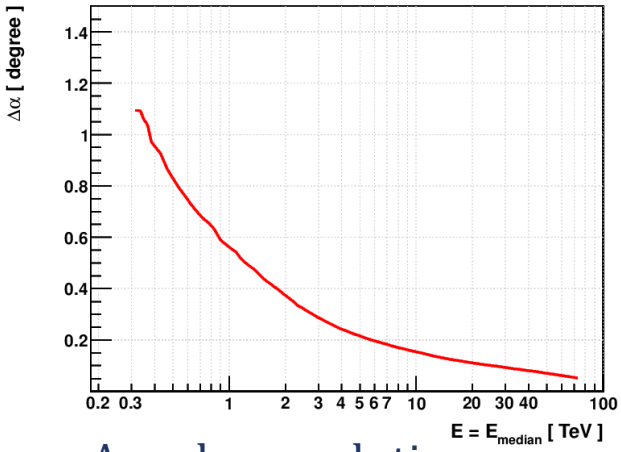
- Brightest "sub-core":
  - Signal of the brightest PMT outside the shower core region (e.g., 45 m);
- "Compactness" can be employed to reject cosmic ray background efficiently.
- Q-factor: ~20 @ 2 TeV

Effective Area & Angular Resolution



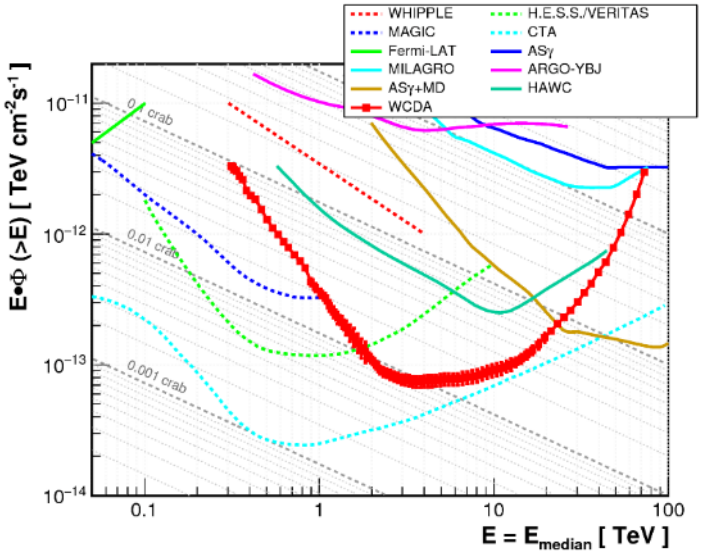
Effective area:

- 2 TeV：~10^5 m^2；100 GeV：~3000 m^2



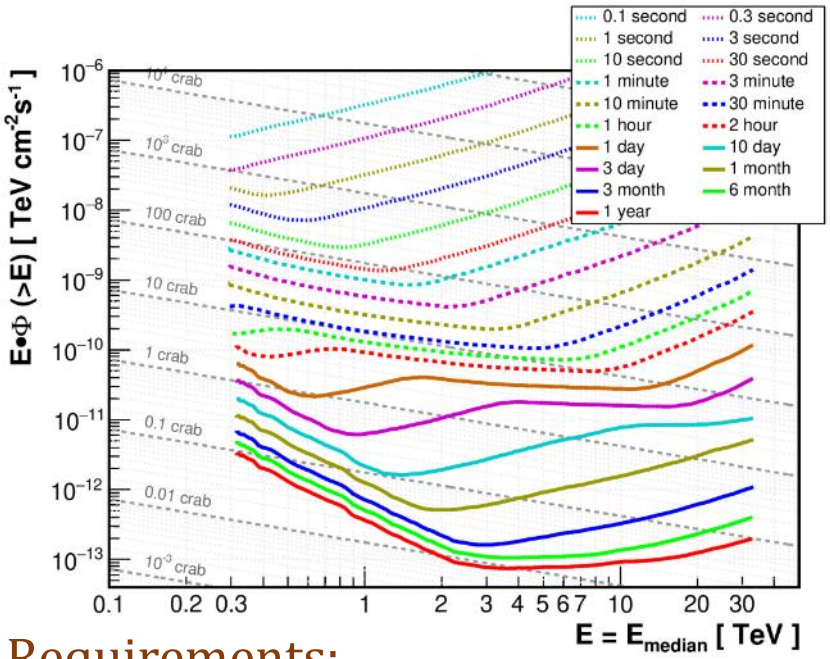
Angular resolution:

- Optimized bin size: 0.4° @ 2TeV



sensitivity ≈ 1% crab@2 TeV

Sensitivity to Flares / GRBs



Requirements:

- 30 events;
- 5 s.d.

Calculation bases on a power law spectrum (λ=-2.62).

Partly limited by statistics;

5σ/day: the detector can be very well calibrated by the Crab.

Duration	Sensitivity (Crab)
1 year	0.0086
6 months	0.012
3 months	0.017
1 month	0.042
10 days	0.11
3 days	0.33
1 day	0.92
2 hours	2.6
1 hour	4.6
30 minutes	10
10 minutes	18
3 minutes	33
1 minute	57
30 seconds	81
10 seconds	140
3 seconds	270
1 second	520
0.3 second	1000
0.1 second	3000

Motivation of 20in MCP-PMT：

1. 20,000 20in PMTs is required by JUNO experiment.

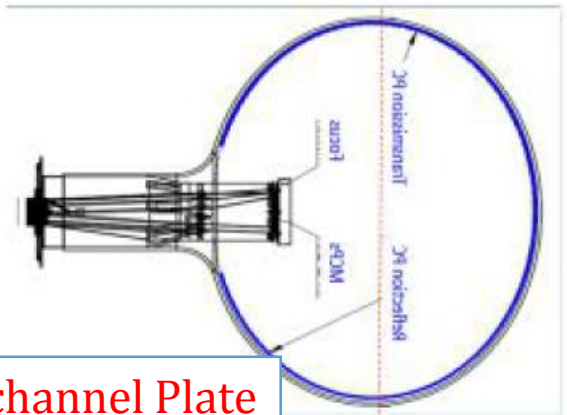
   Japan Hamamatsu : R12860. The initial offer price is 60,000RMB.

   Lower price is critical for JUNO.

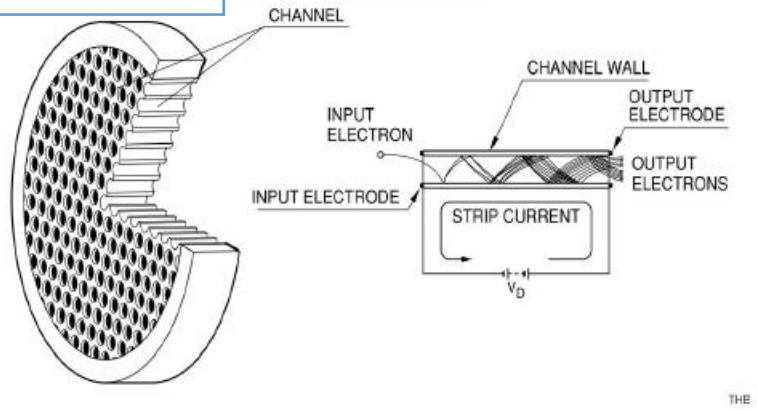
1. Higher detection efficiency for measurement required by JUNO. The traditional dynode PMT only has ~25%.

The development of 20in PMT was led by IHEP, and some other domestic research institutes and manufacturers also involved, such as NNVT, XIOPM, NJU etc.

20 inch Dynode-PMT & MCP-PMT

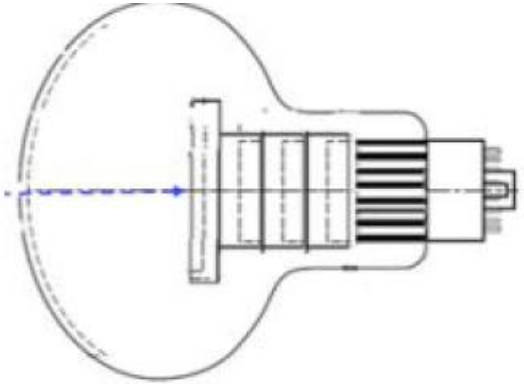


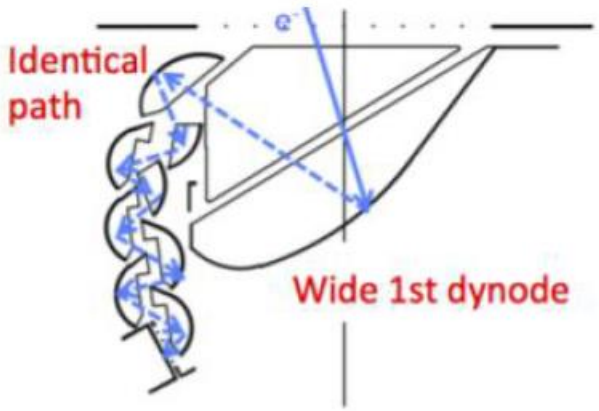
Micro-channel Plate



(a) Schematic structure of an MCP

(b) Principle of multiplication





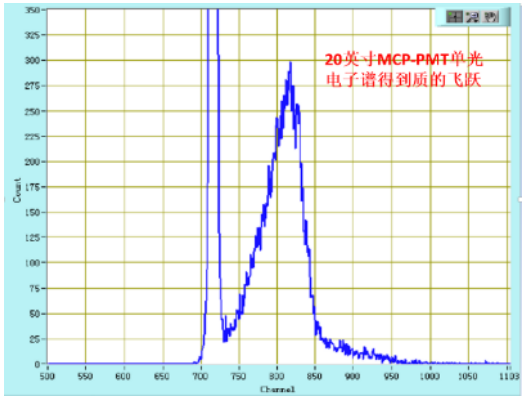
Box & Line

	MCP-PMT	Dynode-PMT	Test Mode
Cathode	Bialkali	Bialkali	pluse
Multiplier	microchannel plate	dynode	current

*By S.Qian

History of 20in MCP-PMT in China

① 2009: Start the design work and establish the collaboration group.
② 2010~2013: Pre-production of 5in & 8in MCP-PMT；
③ 2014~2015: 20in MCP-PMT with high DQE successfully developed；
④ 2016: Ready for mass production；
⑤ 2017: 4000 MCP-PMT delivered to JUNO.



Formally mass production of 20in MCP-PMT

NNVT supplies JUNO: 15,000.
The delivered period ~2.5 years.

Manufacturer supply capacity:
Yield: close to 60%;
Monthly production capacity: 500.

1, high detection efficiency: ~30%
The lower hemisphere has an aluminized reflective film;
There is ALD processing on the MCP.

2, Single photon detection capability:
Use two 50mm diameter MCP stacks;
Make the normal working gain to 10**7.

3, Low cost:
NNVT itself produces MCP.

Discussion on the feasibility of using 20in PMT in WCDA

In No.2 & 3 pool of WCDA：

- Replace the 8in PMT with 20in MCP-PMT.
- Add a 3in PMT to ensure the original dynamic range of the detector .

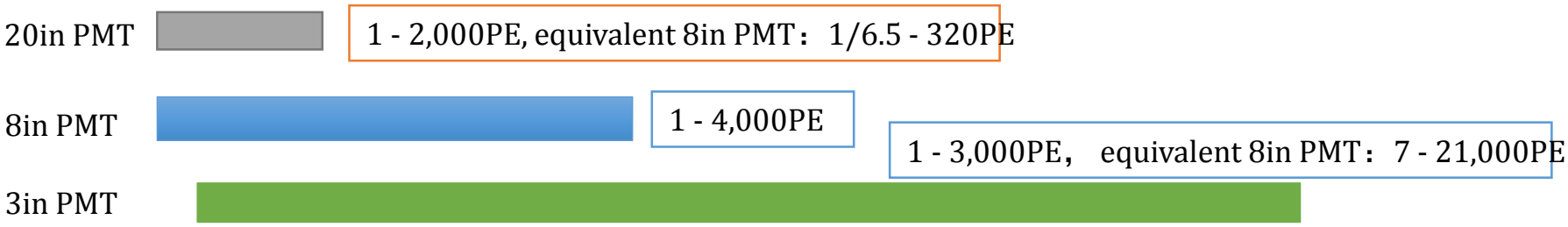
Performance expectation：

- The effective area @50GeV, 7.9X improved.
- Threshold can be reduced from several hundred GeV to 50 Gev.

- For a source with an energy spectrum index of -2.62, the integral significance can be increased by a factor of 1.5.
- The source with a spectral index of -3.62, the integral significance can be increased by a factor of three.

- Obviously improve the detection capability of GRB, etc., and significantly increase the competition with HAWC.

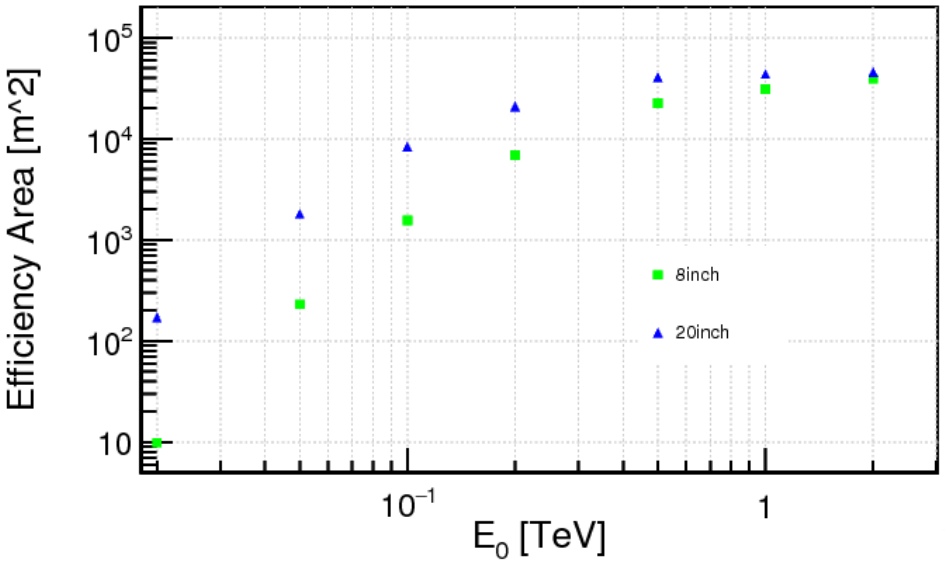
Dynamic range of PMT



1， If only 20in PMT is used, the dynamic range is only about one tenth of the original design’s.

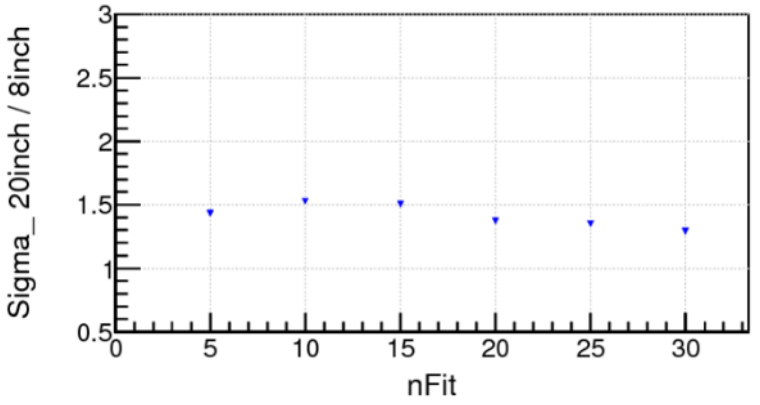
2， Increase the dynamic range by about 5 times with 3in PMT.

Quick Simulation



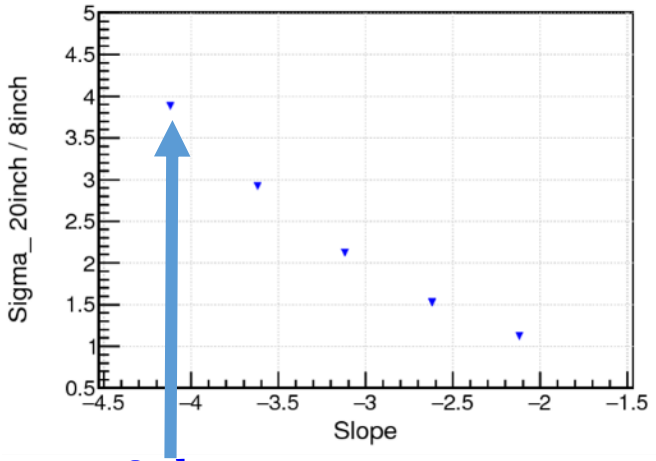
Crab Energy Spectrum($AE^{-2.62}$):

❖ 1.5×improved!



Effective Area

E (GeV)	8inch(m^2)	20inch(m^2)	Ratio(20/8)
20	9.8	171.4	17.5
50	230.2	1807.4	7.9
100	1560.9	8373.6	5.4
200	6847.3	20836.4	3.0
500	22675.8	40588.0	1.8
1000	31109.1	43827.2	1.4
2000	39154.6	45454.4	1.2

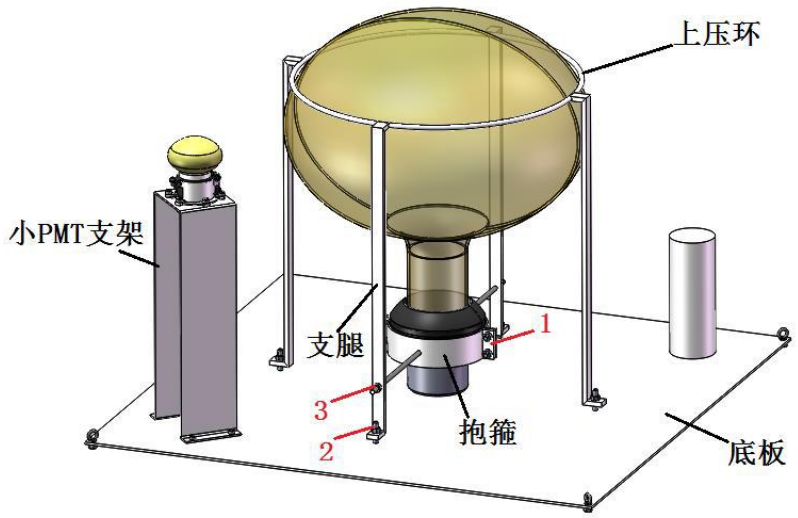


Other spectrum：

❖ Possible 4× improved！

PMT's requirement

- 2,270(20in PMT+3in PMT)
  - 2,220（900+1320）+ 3% spare



	20in PMT （GDB-6203）	**3in PMT （XP72B22）**
TTS	**~6ns**	**~4ns**
CTTD	~2ns	
Rise time	~3ns	~4ns
Linearity	**>=2000PE.**	**>400PE(anode)**
Dark noise rate	**<=10KHz**	**<1KHz**
Gain	**5*10**7**	**3*10**6**
After Pulse ratio	<1%	<5%
Stages	2	10

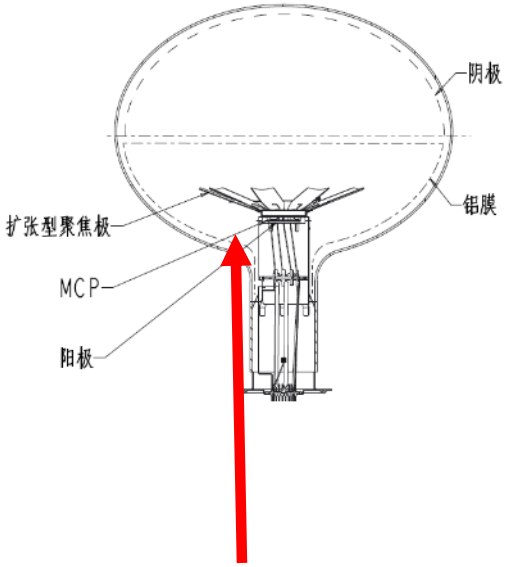
Special improvement for WCDA.

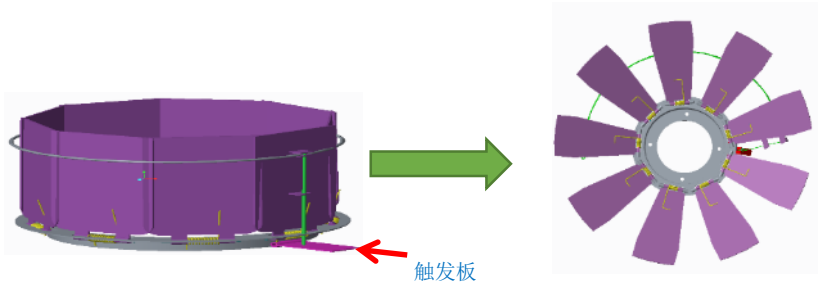
Different from the needs of the JUNO project:

1. High time performance：
   - TTS（<7ns），CTTD（<2ns）

2. Low dark noise rate：
   - <10KHz at <10 degree.

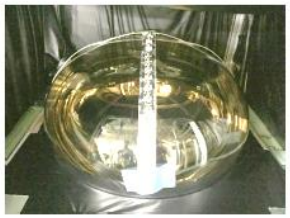
3. Long term stability：
   - Expected exposure is above 50C (JUNO:~5C)
   - Reduce power supply costs: 200uA operating current, reducing body resistance of MCP-PMT.





Structure of the first focusing electrode

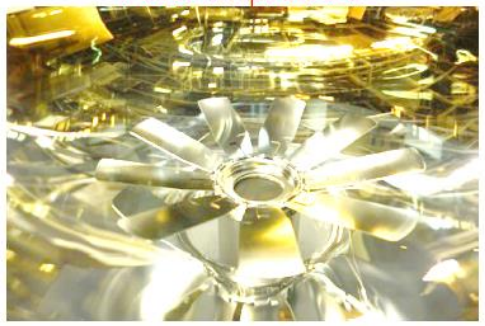
TTS improvement (Measured by Hyper-Kamiokande.)

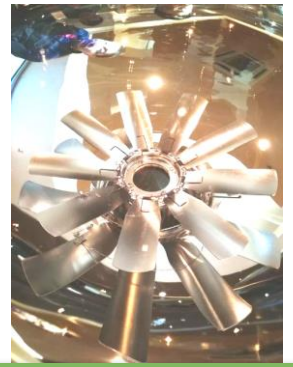


Scanned injected position from center to edge

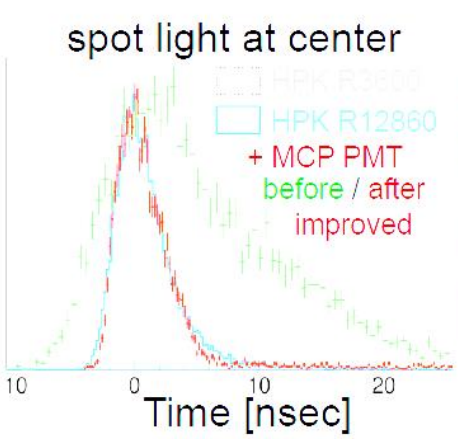
Before improved

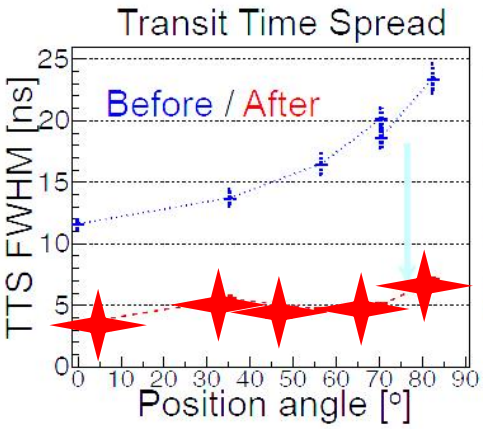
After improved

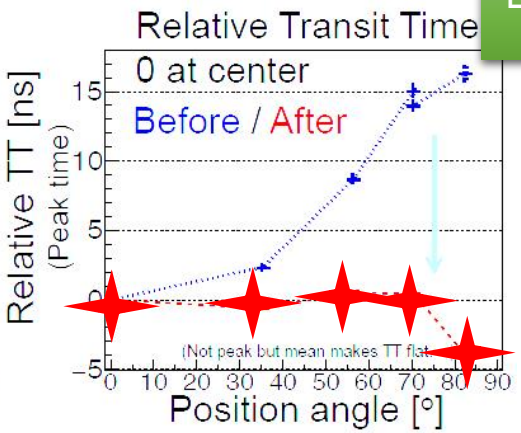




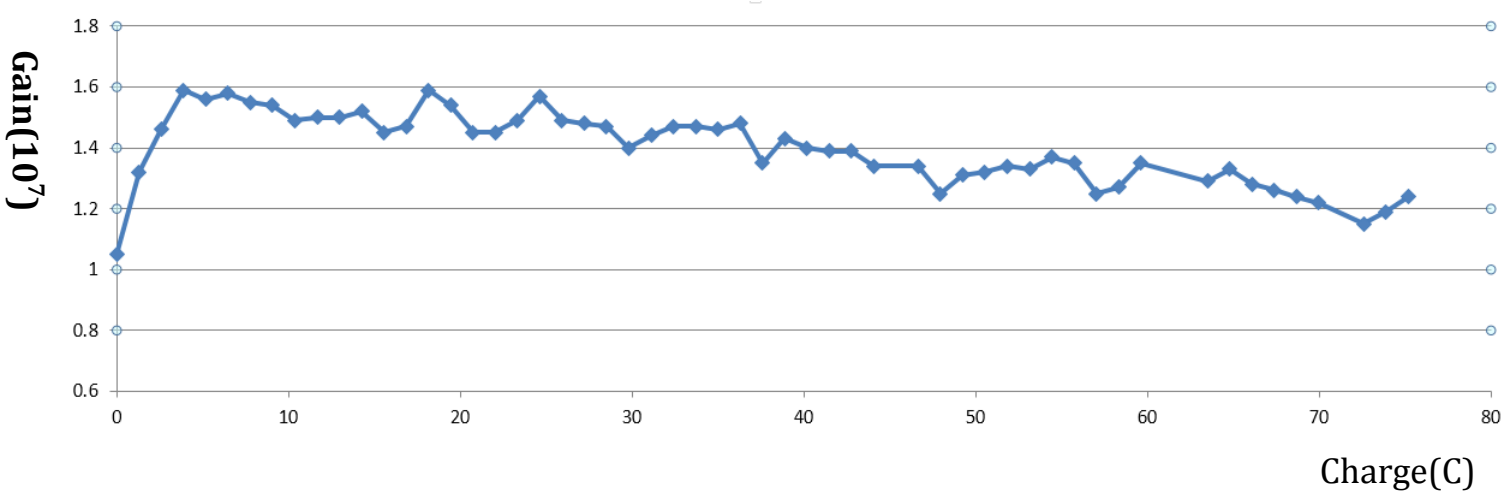
Lotus shape focusing structure







Long term stability



The anode output current is 15uA, a total of 75 C, and the gain is reduced by about 15%.

Ten MCP-PMTs already provided.

- Average performance @Gain5*10**7：
  - TTS：~6.3ns
  - CTTD: <2ns
  - Nonlinearity of anode：>2,900PEs
  - P/V: >2.0
  - Quantum Eff.： ~30%
  - After pulse ratio： ~0.13%
  - Rise time ~1.4ns
  - Dark noise rate：~15KHz@22degree

GDB-6203 微通道板型光电倍增管正样检测报告

	指标	结构	外形尺寸	管脚定义	外观质量	量子效率/%	TTS/ns	上升时间/ns	下降时间/ns	CTTD/ns	暗噪声计数率/kHz	工作电压/V	峰谷比	后脉冲比例/%	趋势10%线性/P.E.	稳定性	寿命	振动	结论
	技术要求	详见《GDB-6203 微通道板型光电倍增管制造与验收技术条件》				≥22% @420nm	≤7ns @5×10⁶	≤3ns	≤30ns	≤5ns @5×10⁶	≤25kHz @1/3PE，22℃，5×10⁶	≤2000V @5×10⁶	≥2 @增益5×10⁶	≤5% @0.1μs-10μs	≥1000 P.E.	详见《GDB-6203 微通道板型光电倍增管制造与验收技术条件》			合格
正样实测	PC1805-2208	√	√	√	√	32.55	6.25	1.37	24.71	0.94	18.41	1947	2.73	0.04	5040	√	-	√	合格
	PC1806-2201A	√	√	√	√	26.09	6.46	1.87	25.50	3.28	9.41	1904	2.65	0.14	5600	√	-	√	合格
	PC1806-2202	√	√	√	√	26.44	6.62	1.44	26.00	1.54	8.03	1844	2.75	0.13	4800	-	-	-	合格
	PC1806-2203	√	√	√	√	28.03	6.21	1.46	22.77	1.46	10.64	1950	2.85	0.04	2900	-	-	-	合格
	PC1806-2204	√	√	√	√	28.23	6.21	1.39	24.15	1.21	10.17	1970	2.33	0.02	3400	-	-	-	合格
	PC1806-2206C	√	√	√	√	34.50	6.80	1.52	21.80	1.01	10.42	1815	2.39	0.09	3500	-	-	-	合格
	PC1806-2207C	√	√	√	√	31.40	6.46	1.22	23.66	1.01	15.78	1918	2.25	0.39	2900	-	-	-	合格
	PC1806-2209C	√	√	√	√	31.55	6.45	1.56	23.51	1.42	22.40	1815	3.98	0.18	3300	-	-	-	合格
	PC1804-2206CC	√	√	√	√	33.86	6.18	1.45	22.29	1.67	24.34	1822	2.37	0.14	4200	-	-	-	合格
	PC1806-2211	√	√	√	√	28.86	6.22	1.37	15.80	2.18	14.90	1880	2.34	0.08	3600	-	-	-	合格

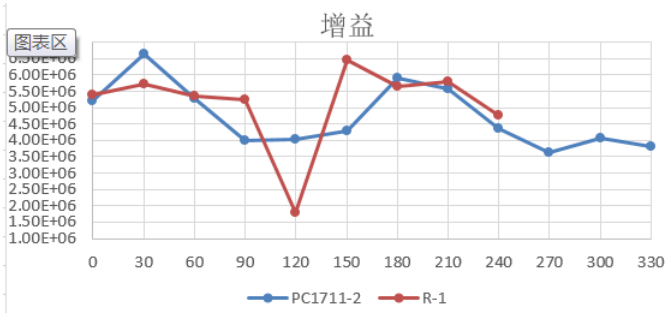
注：寿命具体情况详见寿命检测报告。

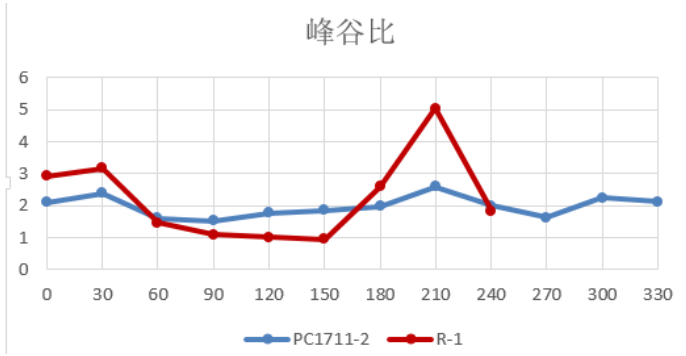
Summary of 20in MCP-PMT's specification

Red line： MCP-PMT
blue line： Hamamatsu PMT

Advantages:

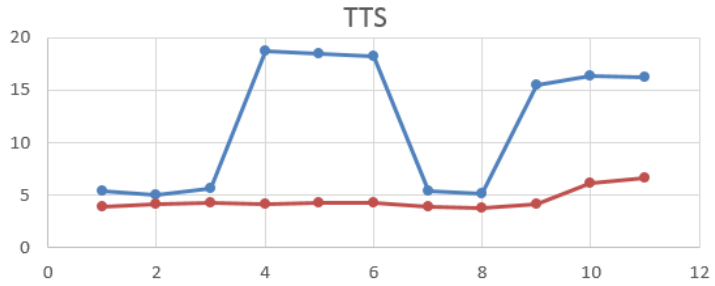
- Small after pulse ratio：<1%;
- Good linearity of anode output：>2,000PE;
- The transit time has a small discrete value, good time characteristics, and a large effective area;
- Low dark noise rate



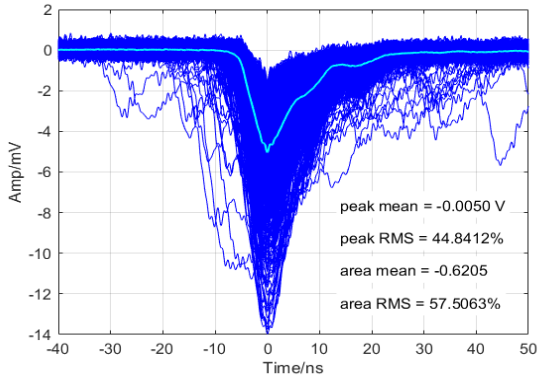


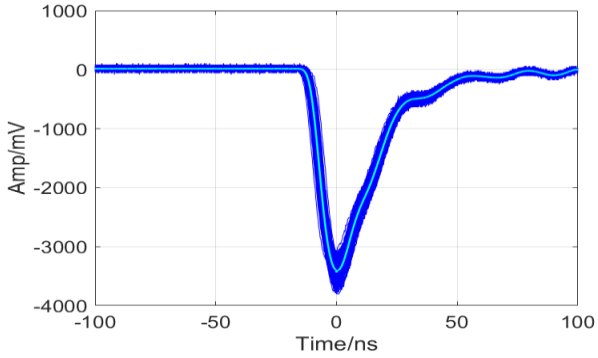
Some disadvantages:

- Affected by geo-magnetic fields largely;
- The high voltage coefficient(beta) is widely distributed;
- Mechanical ability etc.



20in PMT signal



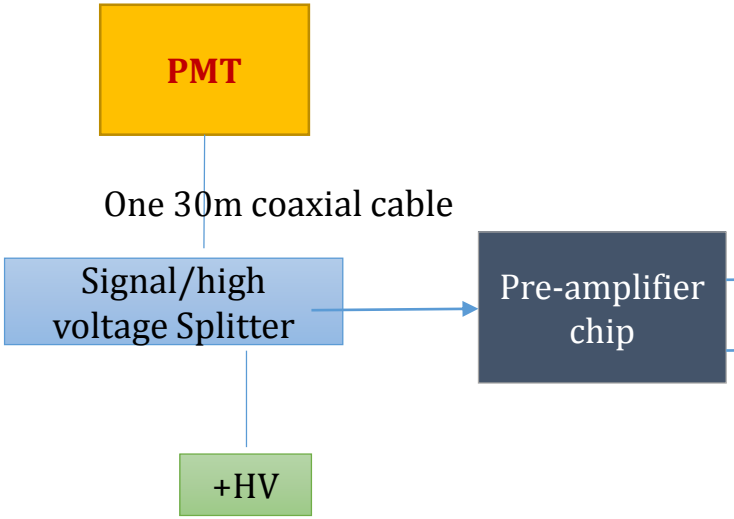


Single P.E：

- Average amplitude：~4.5mV
- Rise time：~4ns，Fall time：~12 ns

2000 P.E.:

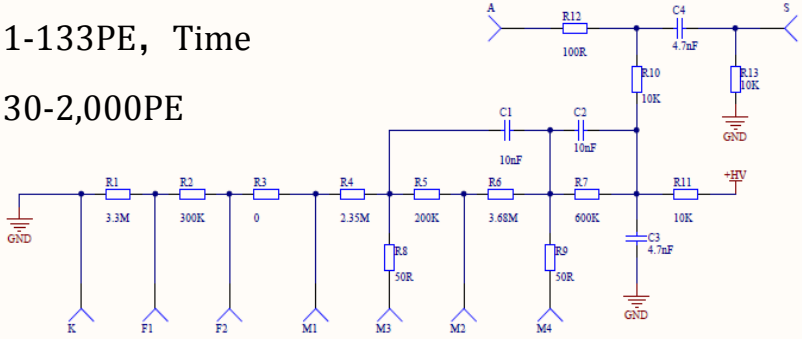
- Average amplitude：~3.5V
- Rise time：~8 ns，Fall time:~35 ns



One high voltage supplies two PMTs simultaneously

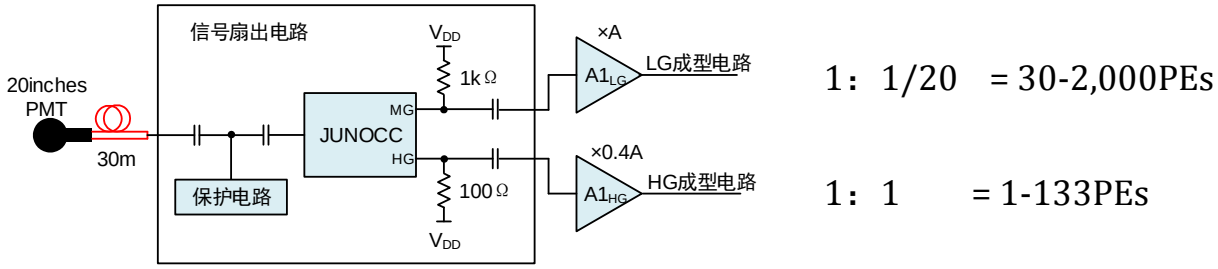
1-133PE，Time

30-2,000PE

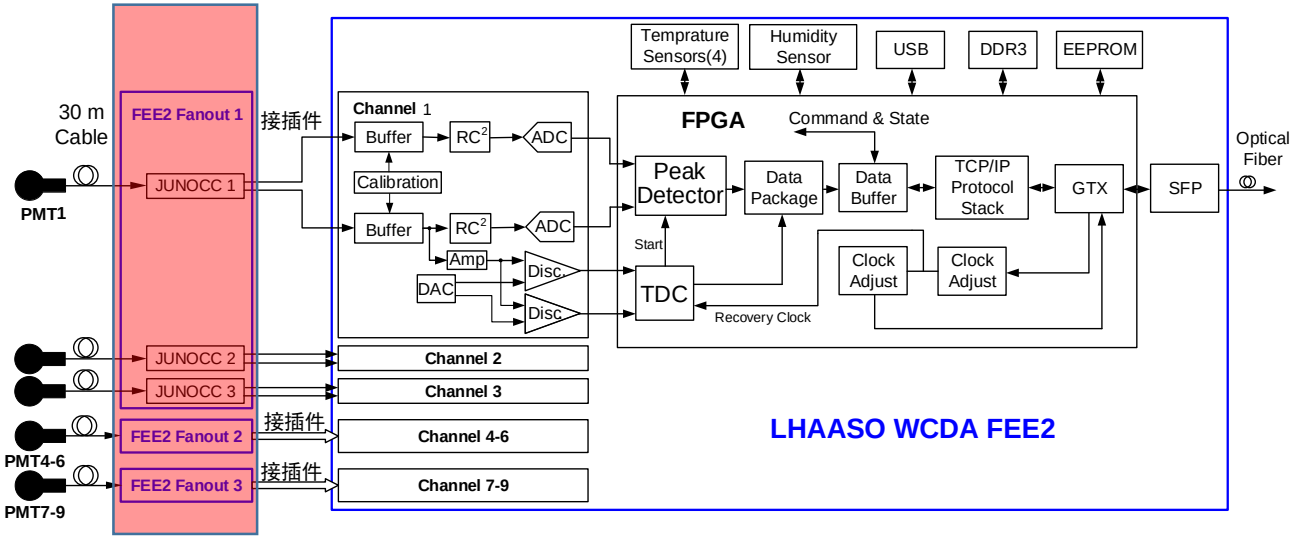


Electronics system of 20in PMT

- Each channel of WCDA electronics board can handle the hits with 200 kHz.



Signal splitting is realized by the fan-out chip **JUNO CC**



One PMT divided into two parts.

3in PMT: HZC XP72B22

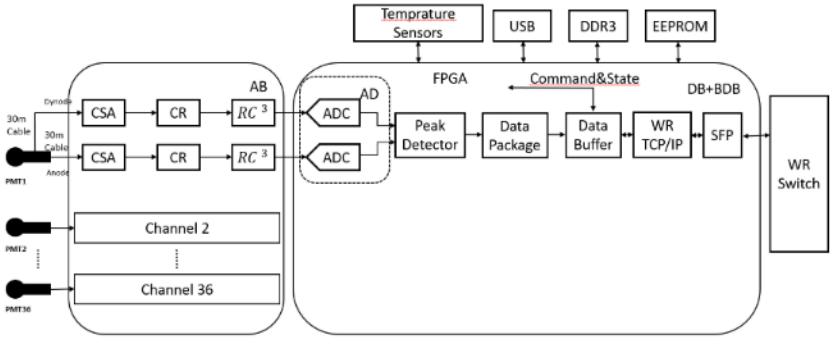
1. P/V>2.0 @Gain 3*10**6;
2. Large dynamic range(0-3,000PEs)

Mass production ability of HZC：1000/month

Bare PMT Testing Summary				
Parameters	**Sampling data req.**	**Vender** (Mass)	**Vender** (Sampling)	**JUNO**
1. Diameter Of Glass Bulb (mm)	78<Dia.<82	✓	✓	✓
2. QEXCE@420nm (%)	>22 (Mean>24)	24.8	24.9	25
3. HV@3X10^{6}gain	900-1300	1097	1094	1098
4. SPE resolution (%)	<45 (Mean<35)	33	32.9	32.8
5. P-V Ratio	>2 (Mean>3)	3.2	3.2	3.2
6. Dark Rate@0.25PE (Hz)	<1.8k (Mean<1k)	489	501	477
7. Dark Rate@3PE (Hz)	<30	7.2	7.4	8.2
8. SPE TTS （FWHM） (ns)	<5			4.9
9. Pre pulse ratio （10-90ns)	<5 (Mean<4.5)			0.4
10 .After pulse ratio （50ns -20μs ）	<15 (Mean<10)			4.8
11. QE non-uniformity (%)	<11			5.2
12. Effective Dia. Of cathode (mm)	>74 (Mean>76)			77.1
13. Spectral response range (%)	QE320>5			13.4
	QE550>5			8.8

Electronics system of 3in PMT

- Gain：3*10**6
- Two outputs：Anode and 8th dynode
- PMT dynamic range：1-3,000PEs
- Data size：1KHz~10Mbps（36 PMTs）

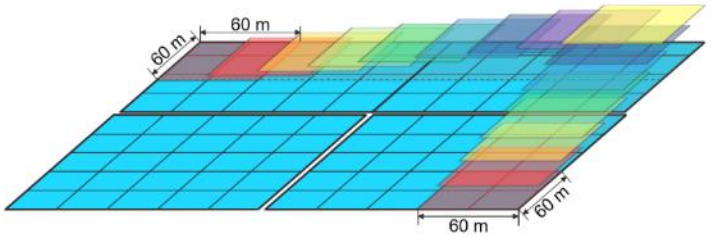


Performance of electronics board

Items	Parameter
Channels	900*2
Charge range	Anode：1.28pC-256pC Dynode：0.64pC-128pC
Charge measurement error	<10%@<12.8pC, <5% @>12.8pC
Charge error	<5% @<12.8pC, <2% @>12.8pC
Stability of baseline	基线温漂<0.2mV/℃
Uniformity of channels	<3%
Time resolution	<20ns
Average event	100Hz
Work temperature	0℃－+60℃

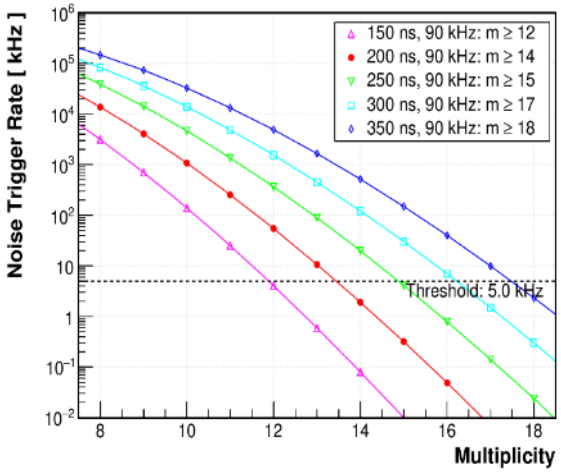
Trigger and data process

- Online trigger mode remains unchanged.



If multiplicity >=14, then the entire array is triggered

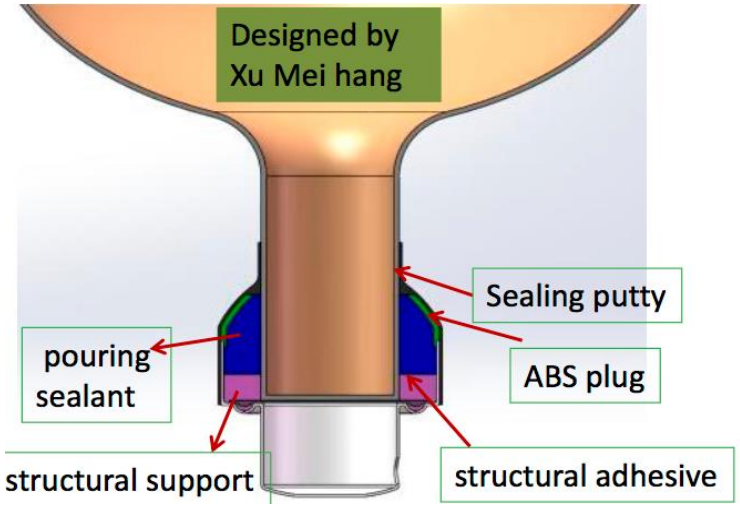
Accidental coincidence noise rate of 20in PMT under different trigger conditions



- 128 bit/hit，Includes header information, channel number, charge, time, identifier, etc. Simple estimation: Raw data ~29.0Gbps, and 115 PB/year data (estimated by single channel 87.5KHz) 。
- After partitioned online triggering, the amount of data that needs to be transferred and stored can be compressed to: 12Gbps.

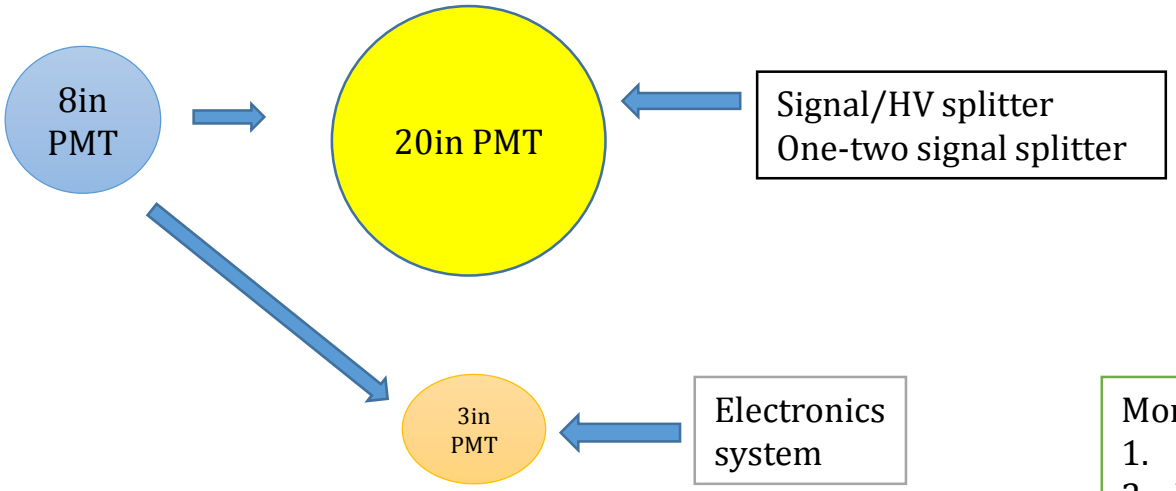
PMT waterproof

- 20in PMT's uses JUNO technical solution
- The manufacturer is responsible for 3in PMT's.



Waterproof work is expected to begin in January 2019.

Summary of 20in PMT optimization design.



More work need to do:

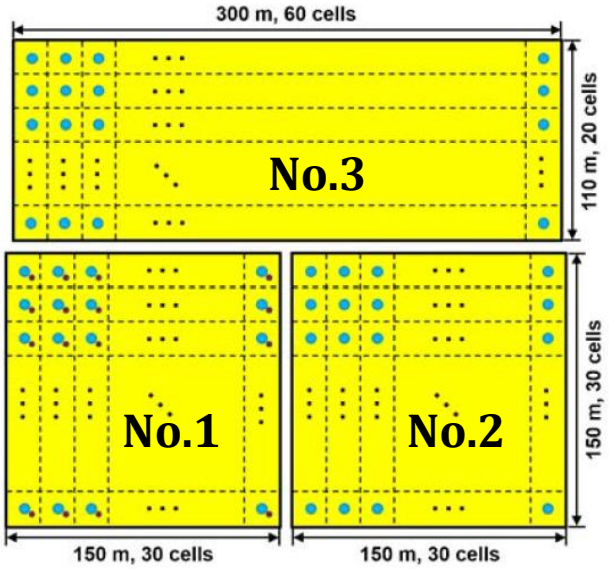
1. PMT waterproof
2. WR switches due to more data
3. PMT cable, HV system
4. Crates for the electronics
5. Installation structure.

Cost control

- . The unforeseen factors of project implementation are well controlled.
  - No.1 pool of WCDA and the other three detectors of the LHAASO project (ED, MD and WFCTA) have completed the bidding and procurement of major equipment

- The budget : about 20 million RMB
  - Mainly caused by 20in PMT, HV system, cable and electronics.

Schedule: PMT



4， December, 2019, Start detector installation of No.3 pool.

3， June,2019, Start detector installation of No.2 pool.

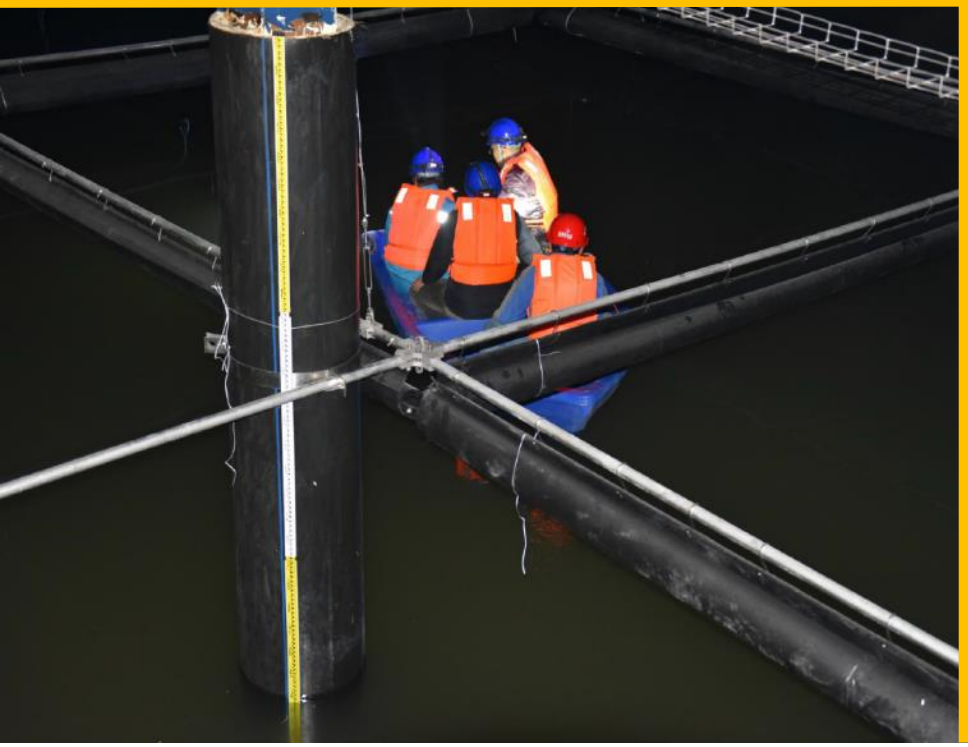
2， May,2019, 950 20in PMTs and 3in PMTs prepared.

1， November 2018, 150 20in PMTs and 3in PMT delivered.

According to this plan, in the beginning of 2021, the detector installation tasks of the 2nd and 3rd pools will be completed.

Status of WCDA

- ✓Infrastructure of No.1 pool is almost finished.
- ✓All of detector parts have been already transported to the site and are ready for installation.
- ✓We will start detector installation soon.



Ready for installation.

Brief Summary

① The successful production of 20in MCP-PMT brings much help for the detectors. For Baikal-GVD?

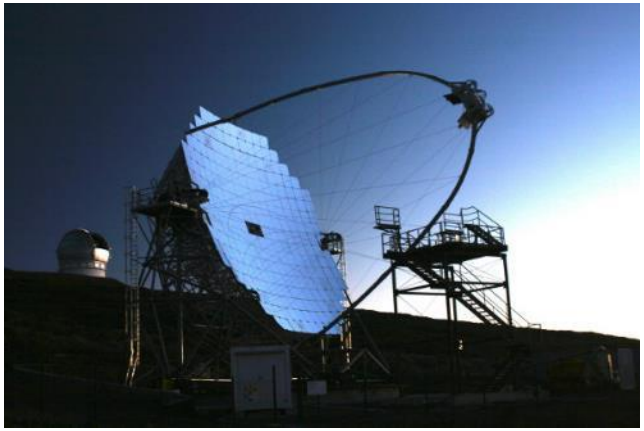
② The performance of WCDA using 20in PMT will be improved lots. The optimization design of 20in PMT for WCDA has no much technical difficulties.

③ This optimization proposal has already internal approved officially. And the project cost and schedule are generally controllable.

④ The 20in PMT will be delivered by NNVT from the next month.

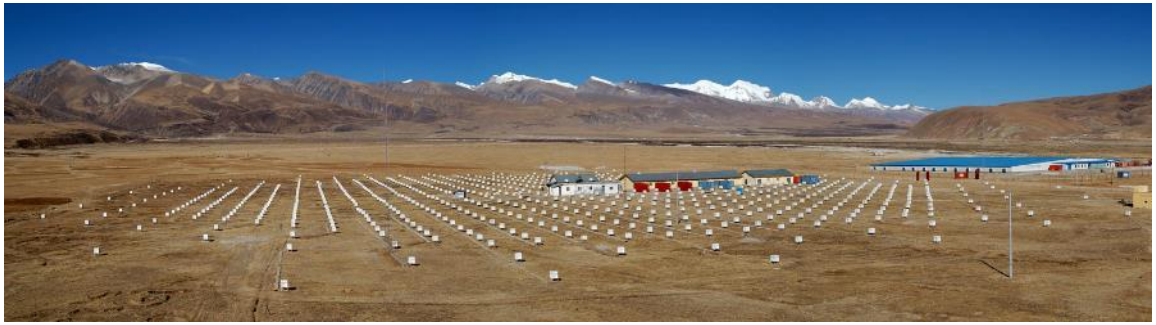
Thanks.

VHE γ-astronomy: Two Techniques



- IACTs: H.E.S.S., VERITAS, MAGIC, …
  - Good angular resolution (~0.1°);
  - Fair background rejection power;
  - Short duty cycle (~10%);
  - Narrow FOV (<5°);
  - Low energy threshold (~100 GeV);

➔ Mainly focused on deep observation.



- Ground particle array: ASγ, ARGO-YBJ, Milagro, HAWC, …
  - Not-so-good angular resolution (~0.5°);
  - Poor background rejection power (but much elaborated in water Cherenkov);
  - Full duty cycle (>95%, ~10× IACT);
  - Wide FOV (>2/3π, ~150× IACT);
  - High energy threshold ➔ improved by construction at high altitude (~1 TeV);

➔ Good at sky survey, extended sources and flares.

Possible methods on optimization

1, Increase detector area：

- High cost： 0.27B ←→ 78000 m^2
- Already surrounded by other detectors, no room for expansion

2, Change detector layout ：

- Reduce water depth while increasing the number of cells: reducing optimal sensitivity （~2 TeV）

3, Using more PMTs：

- Increase PMT and electronics (15%, high cost)

4, Increase the PMT's photocathode area：

- PMT itself (excluding electronics) only accounts for ~8.5% of the total cost, the most cost-effective.
- Candidate : 20in PMT， provided by NNVT & Japan Hamamatsu.

20in PMT的批量测试内容

- 设定工作增益为5*10**6，测量单光电子峰
- 稳定性；
- 相对探测效率
- 高压响应曲线
- 非线性度
- 后脉冲比率
- 暗噪声率
- 中心点的TTS
- 抽样测量：TTS和CTTD的二维扫描

3in PMT批量测试内容

- 3*10**6增益下的单光电子峰；
- 稳定性；
- 高压响应曲线；
- 相对探测效率；
- 非线性度；
- 暗噪声率；
- A/D；
- 后脉冲比率；

- 抽样测量：TTS和CTTD的二维扫描。

DAQ与数据处理部分的预算估计

① DAQ数据传输部分：数据量相对原先的50KHz的单路计数率，总量增加约3倍，即商用交换机增加约3倍。4个--》14个。按7万元计，约增加70万。

② DAQ数据处理部分：按现有估计，约需增加两箱刀片，共计约100万。

③ 计算部分：不改变现有的触发模式下，需增加3箱刀片（512核），每箱90万。

以上增量按200KHz的单路事例率考虑。

另，每1PB硬盘数据的成本为100万（未考虑）。

单路计数率的测量

- 90KHz or 200KHz?
- **解决方案：**
- 计划在年底的1号水池运行前，考虑放置一个20in PMT和8in PMT，进行实际测量。

- 目前：
- JUNO组提供两个封装好的20in PMT。

事例丢失率

1. 电子学板有400ns死时间。

2. 1us dead time, 100KHz, 9.5%
3. 1us dead time, 200KHz, 18%

4. 400ns-200KHz-7%
5. 400ns-100KHz-4%

防水封装

- 1，20in PMT
- JUNO在5月份评审防水封装，约在2019年1月份开始批量制作。
- 2，3in PMT
- JUNO在8月份评审防水封装，约在10月份开始，批量制作。

Clock system： WR交换机增加

- **现有的方案，有三层WR交换机。**
- **原方案：**第三层WR交换机的个数为：65基站*4块板/14=19个 。
- 20in PMT方案:
  - 第三层WR交换机个数：65基站*4块板/10=26个 ；
  - 再增5个WR交换机用于小PMT数据。
- **即第三层WR交换机共增加15个，含三备份。**

其中：一个WR交换机的18个端口中：

- 有10个端口用于输入，
- 6个端口输出（含一个备份），
- 一个用于时钟传输等。