Review of photo-sensors for huge detectors

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NNN18 workshop @ UBC, Nov 1-3, 2018

Review of photo-sensors for huge detectors

14:00	The IceCube Neutrino Observatory: Detector Status and Designs for the Future - John Kelley (University of Madison–Wisconsin)

17:00	Light detection in DUNE - Zelimir Djurcic (Argonne National Lab)

15:00	Spectral Sorting of Photons Using Dichroic Winston Cones - Tanner Kaptanoglu (University of Pennsylvania)
15:15	The MCP-PMT for Neutrino Detector - Sen QIAN (IHEP,CAS)
15:30	--- Coffee break ---
16:00	Review of photo-detectors for huge detectors - Liangjian Wen (Institute of High Energy Physics, Chinese Academy of Sciences)
16:20	Large Area Picosecond Photo-detectors - Alexey Lyashenko (Incom Inc)
16:40	20" PMT development for Hyper-K - Jun Kameda (University of Tokyo)

There are some other talks related with photo-sensors for future detectors.

I would like change the title a bit and talk about something slightly different....

PMT choices for large scale detectors

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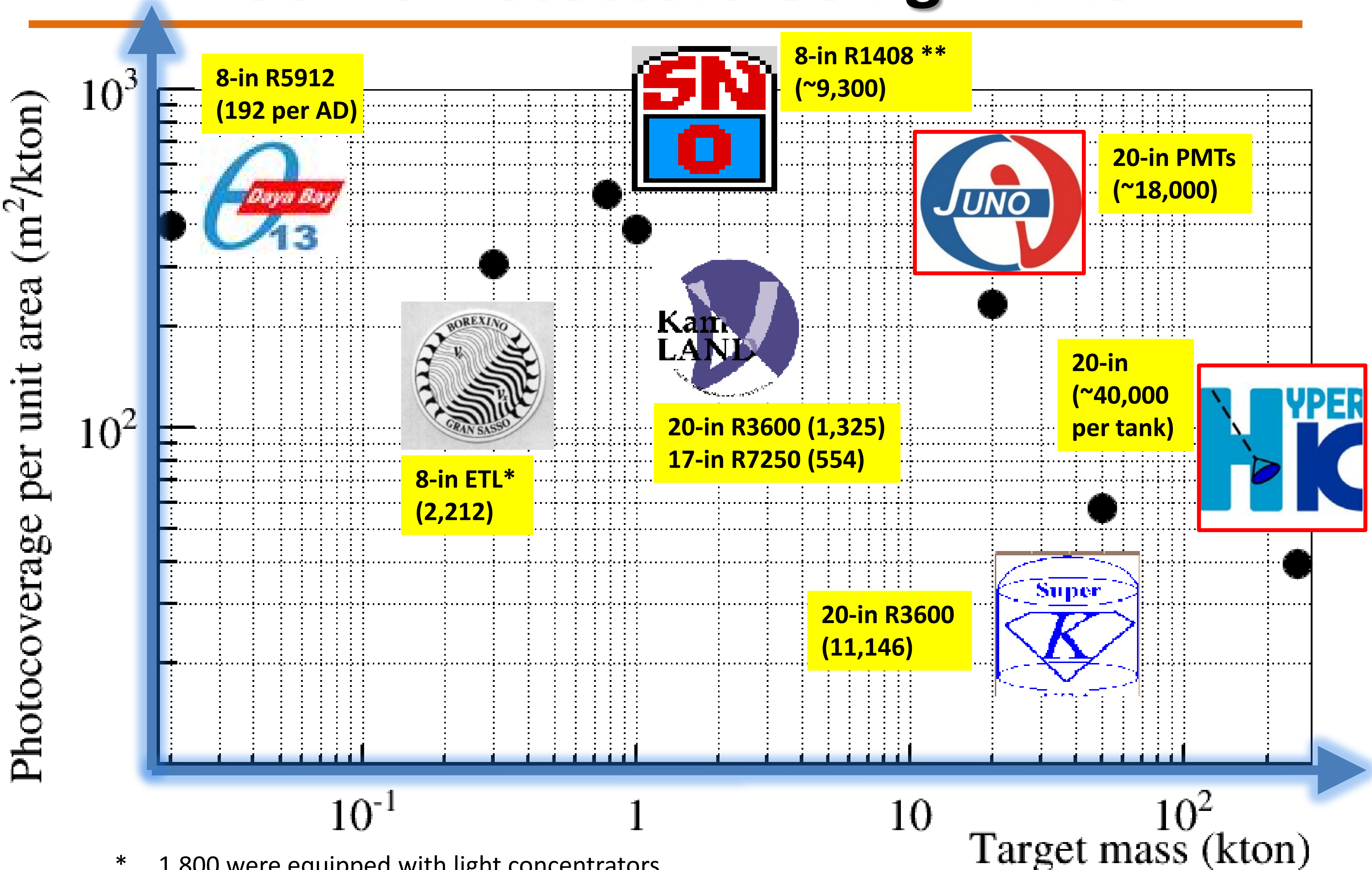
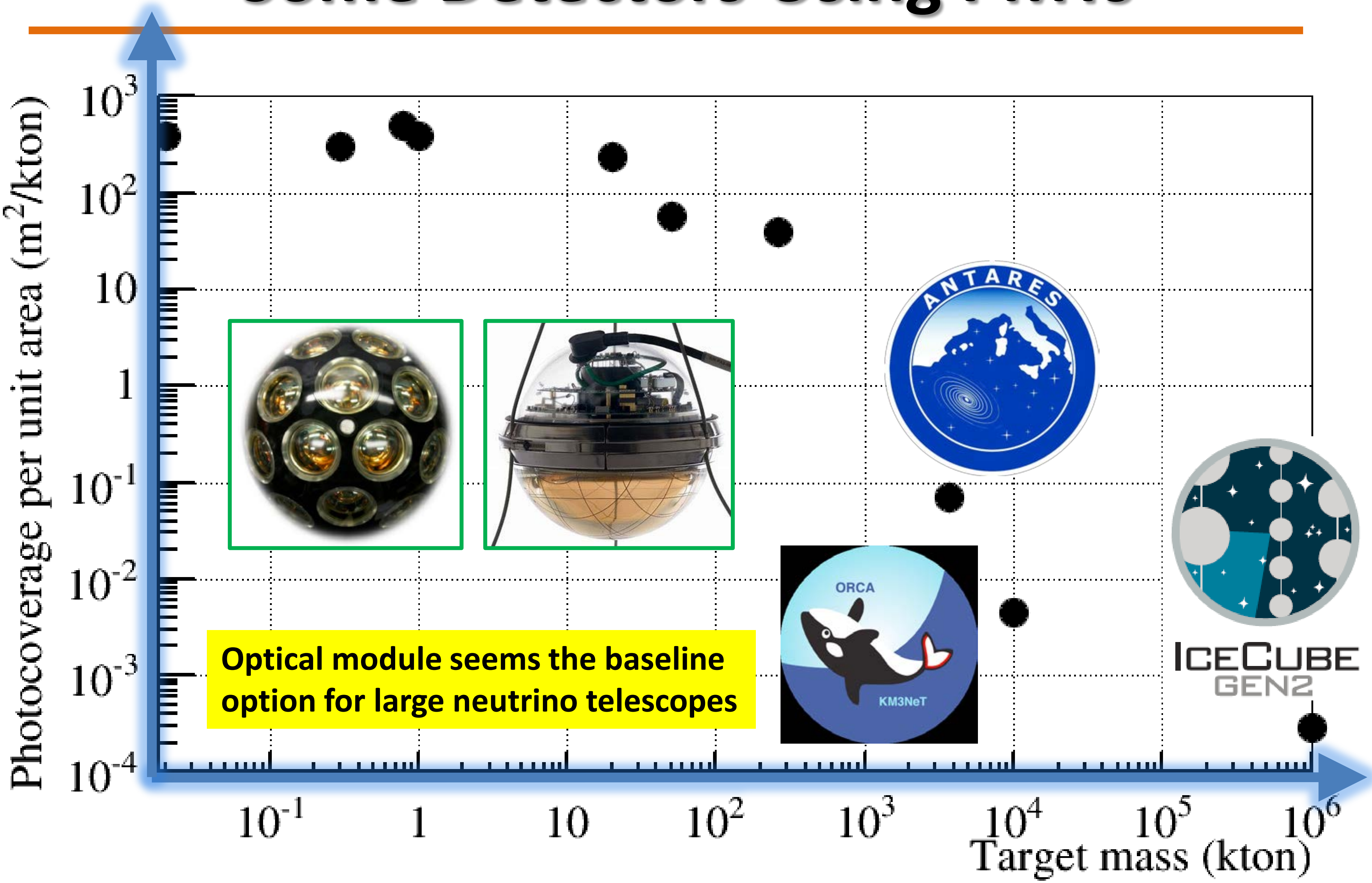
Some Detectors Using PMTs



* 1,800 were equipped with light concentrators

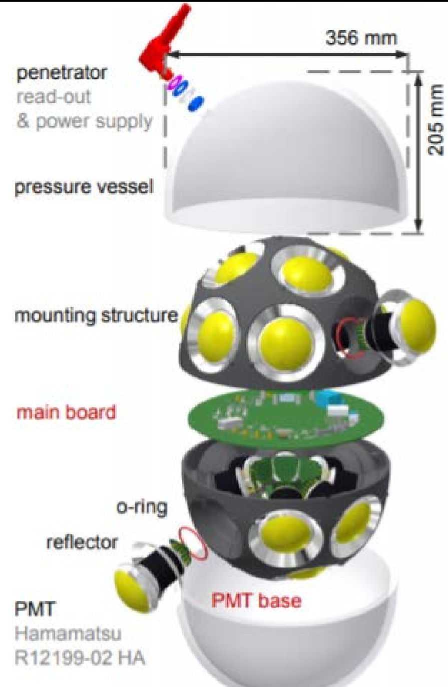
** each PMT was equipped with a 27 cm diameter concentrator

Some Detectors Using PMTs

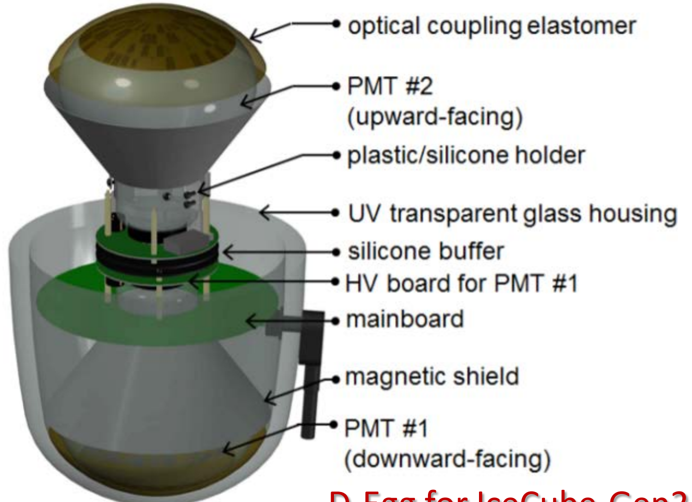


Optical Modules

KM3Net
Digital Optical Module



mDOM for IceCube-Gen2
PoS (ICRC2017)1047



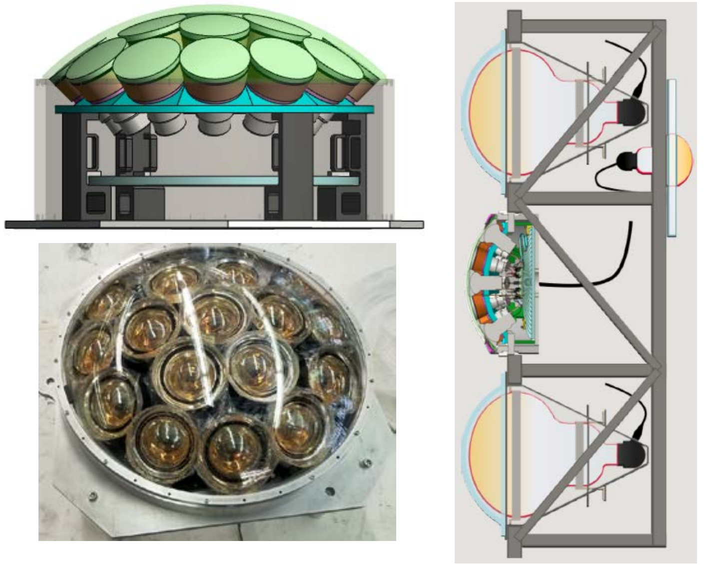
PoS(ICRC2017)1051
D-Egg for IceCube-Gen2

finer granularity,
good timing,
directional sensitivity,
lower dark noise,
less sensitive to Earth
magnetic field, etc

ET
Enterprises

Hamamatsu R12199-02

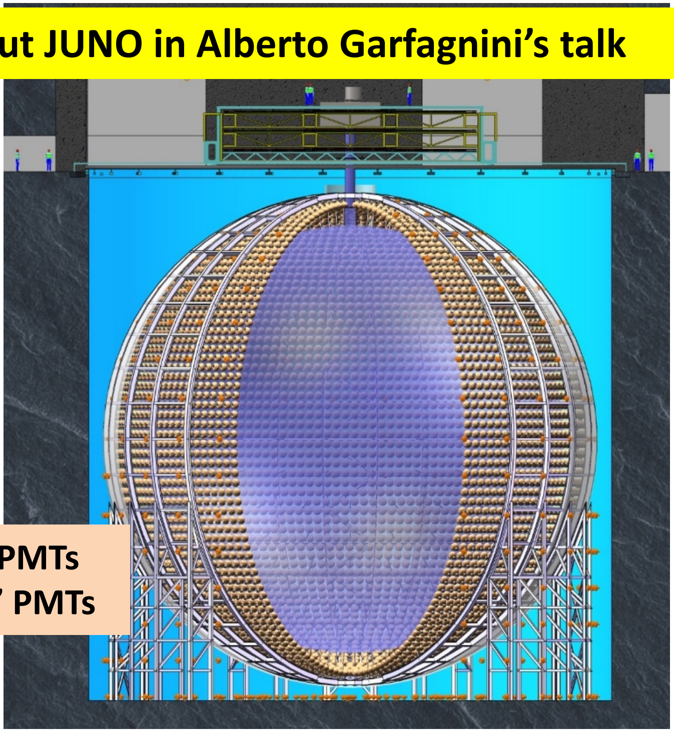
HZC XP82B20



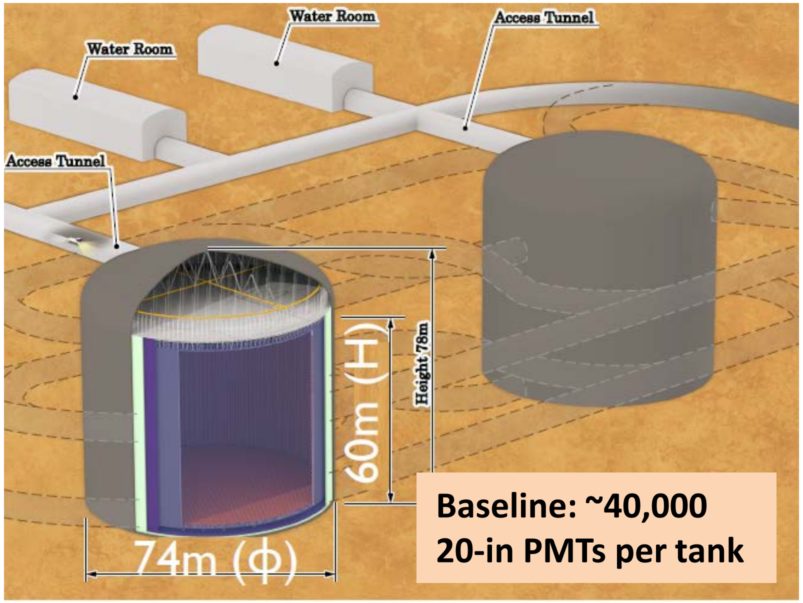
Hyper-K multi-PMT module R&D

JUNO and Hyper-K

More about JUNO in Alberto Garfagnini's talk



~18,000 20" PMTs
+ ~25,000 3" PMTs



Baseline: ~40,000
20-in PMTs per tank

- **JUNO: get max. photons in a 20 kton LS detector, 75% photo-coverage**
  - **High PDE PMT**
  - **High transparent LS:** > 20m A.L @430nm
  - **Pure LS:** (U, Th)< 10^{-15} g/g

- **Hyper-K: 20 times larger than Super-K, 40% photo-coverage**
  - **Better timing resolution**
  - **Low dark rate**
  - **Better PDE: minimum requirement: 16% → 26%**

20-inch PMTs

20-inch MCP-PMT

Produced by NNVT Co.

北方夜视技术股份有限公司
NORTH NIGHT VISION TECHNOLOGY CO.,LTD

More about MCP-PMT developments in Sen Qian's talk

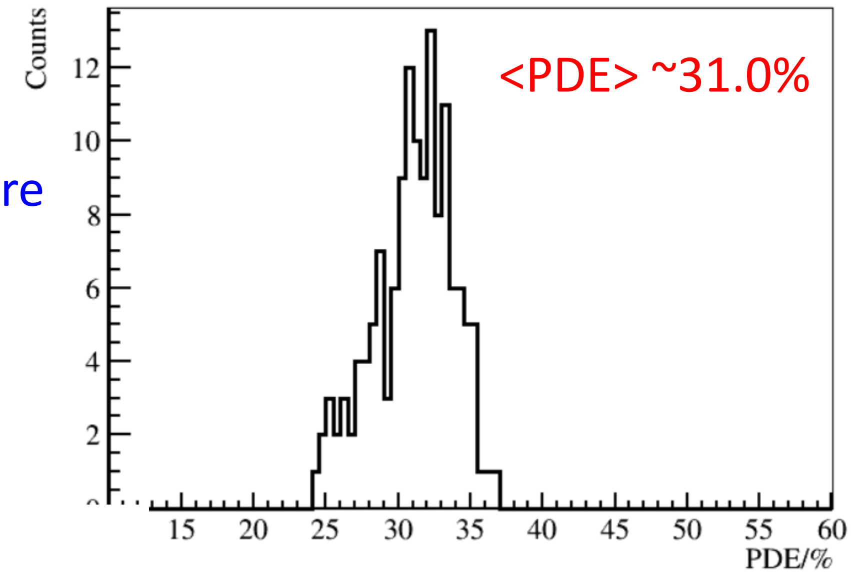
20-inch dynode-PMT or Hybrid PMT

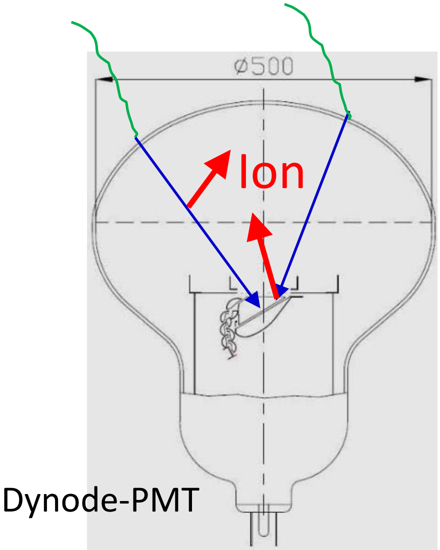
Produced by Hamamatsu Co.

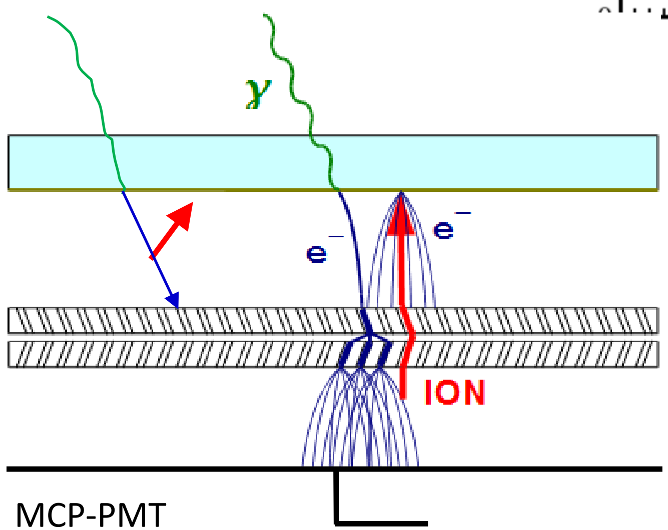
More about Hamamatsu PMT developments in Jun Kameda's talk

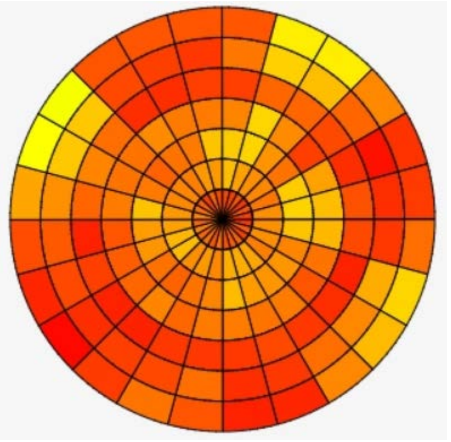
High PDE 20” MCP-PMT

- **High QE tubes for mass production since Jul, 2018**
  - Improved monitoring and control during photocathode fabrication
  - Similar dark noise as before
- Good QE and CE uniformity
  - Symmetric electron focusing structure
- Low radioactivity of PMT glass
- Smaller after-pulse and pre-pulse
  - Smaller Ion feedback

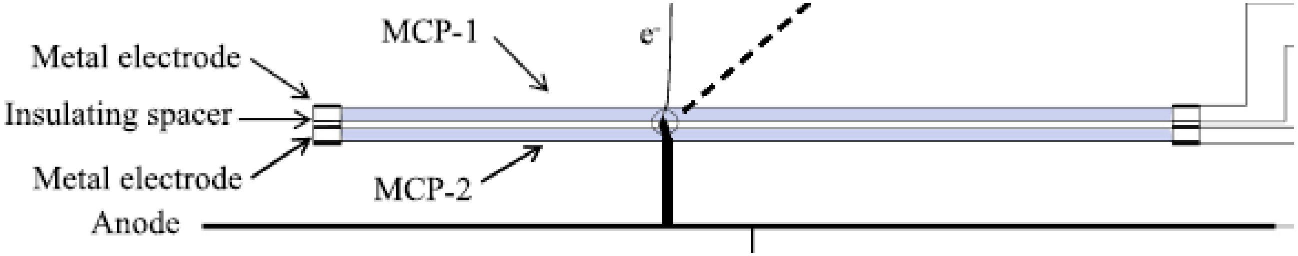


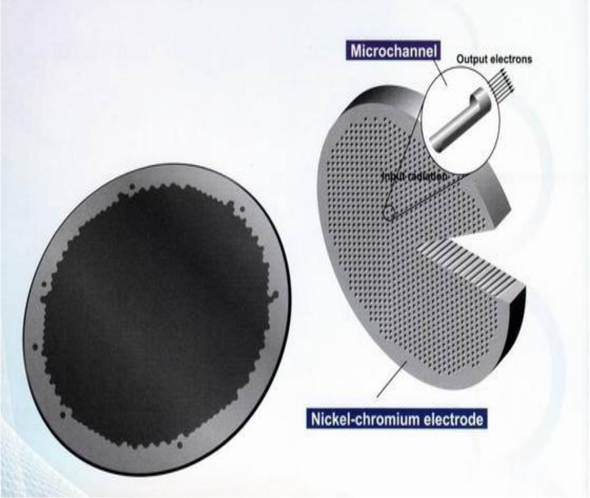




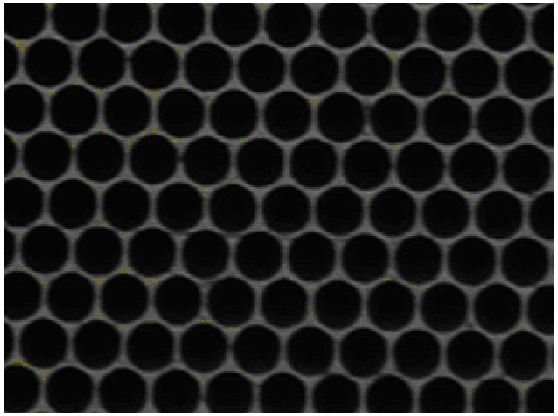


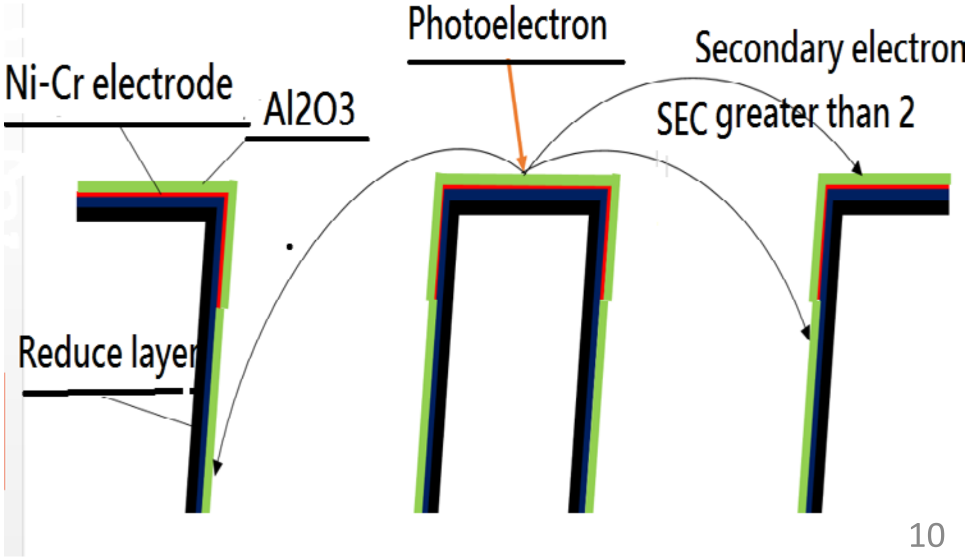
~100% CE in 20" MCP-PMT





- Optimize the MCP
  - Diameter of MCP, size of the hole, inclined angle, open area ratio, etc
  - ALD technology





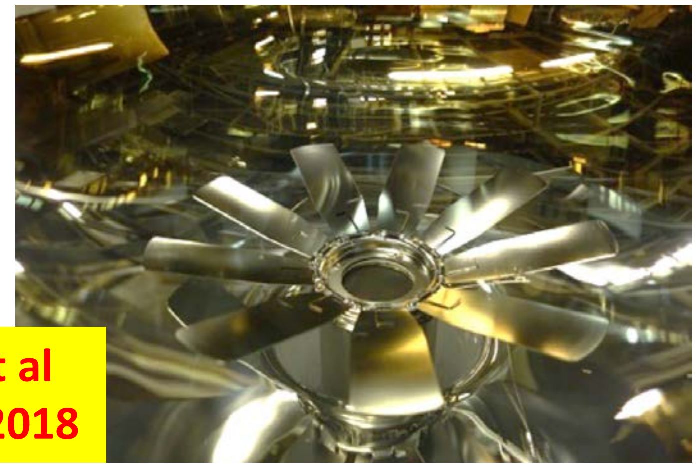
Shulin Liu, Optimal Design of MCP components in 20-inch MCP-PMT for JUNO (Poster)

New 20-inch MCP-PMT for Hyper-K

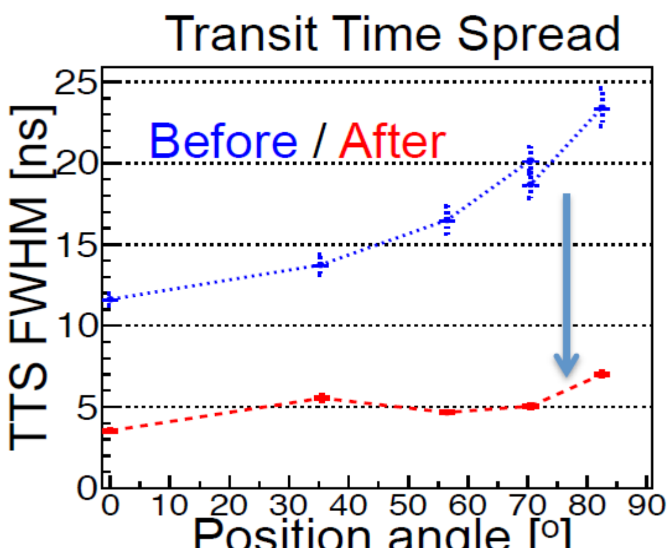
- Hyper-K has different requirements from JUNO, particularly, TTS is more important. A new type of 20-inch MCP-PMT is being developed to have good TTS although a bit worse PDE

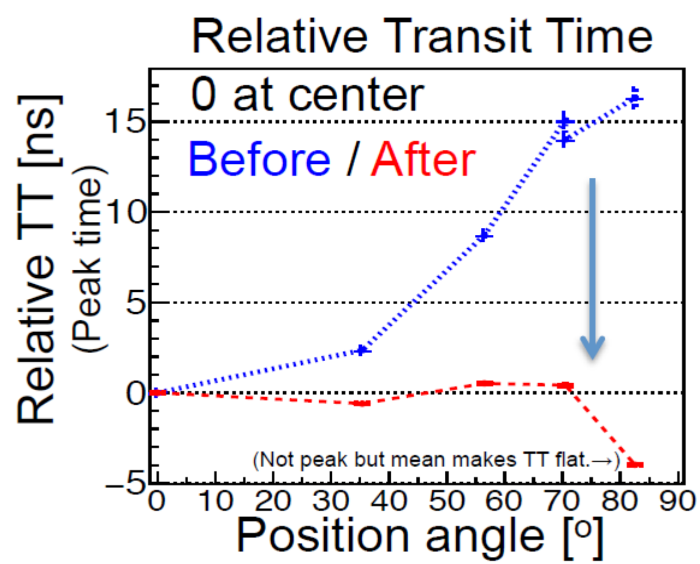
Normal focusing electrode

Lin Ren et al @ ICHEP2018



Flower-like focusing electrode





Comments about PMT choices for huge detectors

- Huge detectors → big science, but also huge cost, risk. The PMT choice is a critical question

- Besides photon detection efficiency, other specifications such as dark rate, transit time spread, radioactive background of glasses, peak-to-valley ratio, etc, will affect the photon detection and hence affect the physics goals.

- Need an approach to quantify the impact of all PMT parameters, including cost and risk, to the physics goals

Take JUNO as an example …

20” PMTs candidates for JUNO in ~2015

Characteristics	unit	MCP-PMT（NNVT）	R12860（Hamamatsu）
Detection Efficiency (QE*CE*area)	%	27%, >24%	27%, >24%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point (FWHM)	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	R~2, F~12	R~5,F~9
Anode Dark Count	Hz	20k, < 30k	10k, < 50k
After Pulse Rate	%	1, <2	10, < 15
Radioactivity of glass	ppb	238U:50 232Th:50 40K: 20	238U:400 232Th:400 40K: 40

- Sensitivity calculation used for JUNO PMT choices

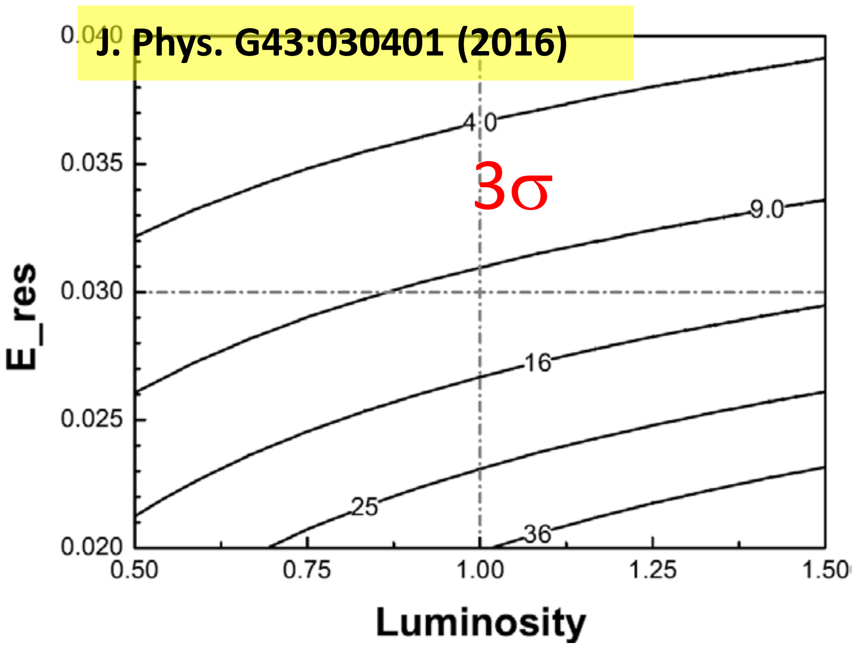
$$\chi^2_{\mathrm{REA}} = \sum_{i=1}^{N_{\mathrm{bin}}} \frac{[M_i - T_i(1 + \sum_k \alpha_{ik}\epsilon_k)]^2}{M_i} + \sum_k \frac{\epsilon_k^2}{\sigma_k^2}$$

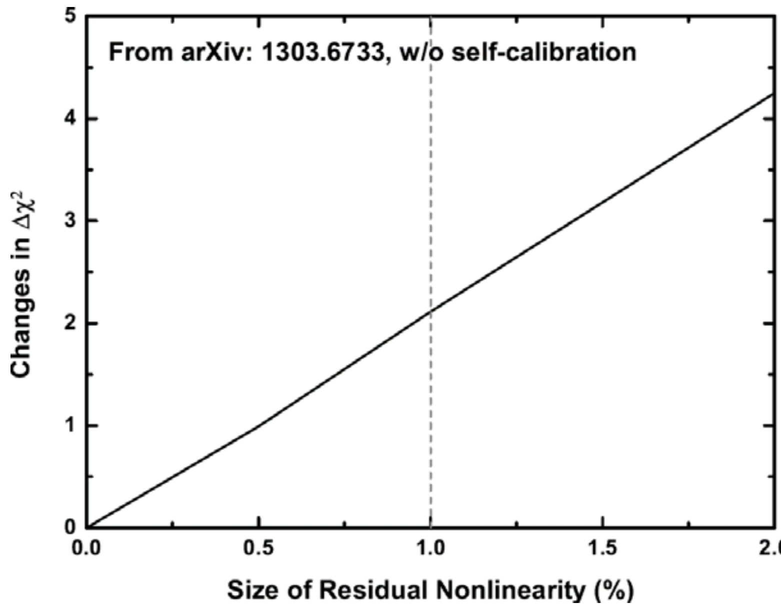
Phys. Rev. D.88.013008

$$\Delta\chi^2_{\mathrm{MH}} = |\chi^2_{\mathrm{min}}(\mathrm{N}) - \chi^2_{\mathrm{min}}(\mathrm{I})|$$

Event type	Rate (per day)
IBD candidates	60
Geo-νs	1.1
Accidental signals	0.9
Fast-n	0.1
^{9}Li-^{8}He	1.6
^{13}C$(\alpha, n)^{16}$O	0.05

Table 2-5: The background summary
in 17.2m volume (18.3 kton)





Merit of PMT physics performance

PDE

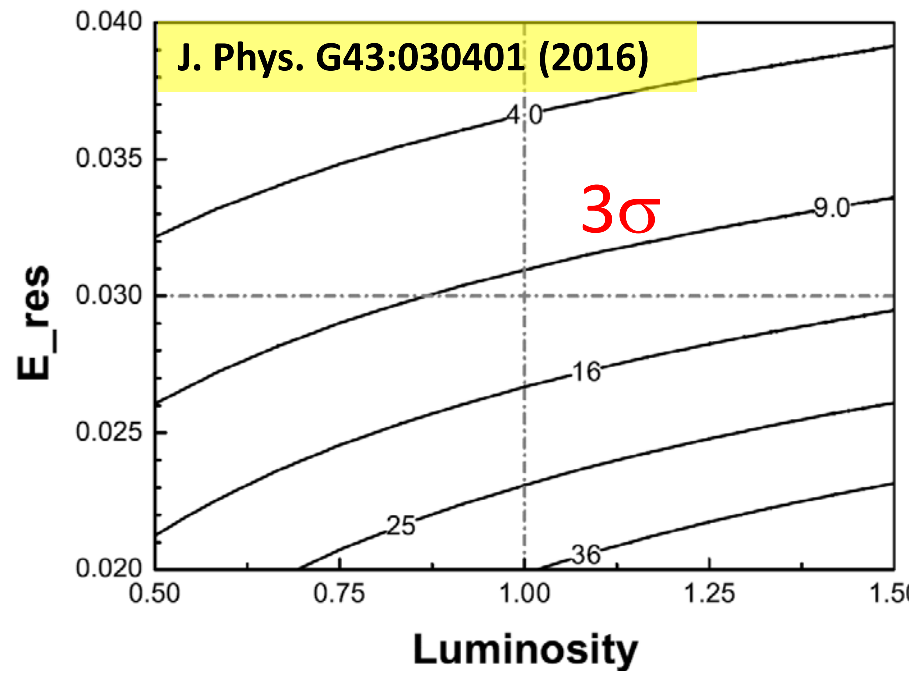
Dark rate

$$\sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2} \simeq \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{1.6\,b}{\sqrt{E}}\right)^2 + \left(\frac{c}{1.6\,\sqrt{E}}\right)^2}$$

Transit time spread (TTS)

→ Resolution of reconstructed vertex

→ Residual uncertainty after non-uniformity correction



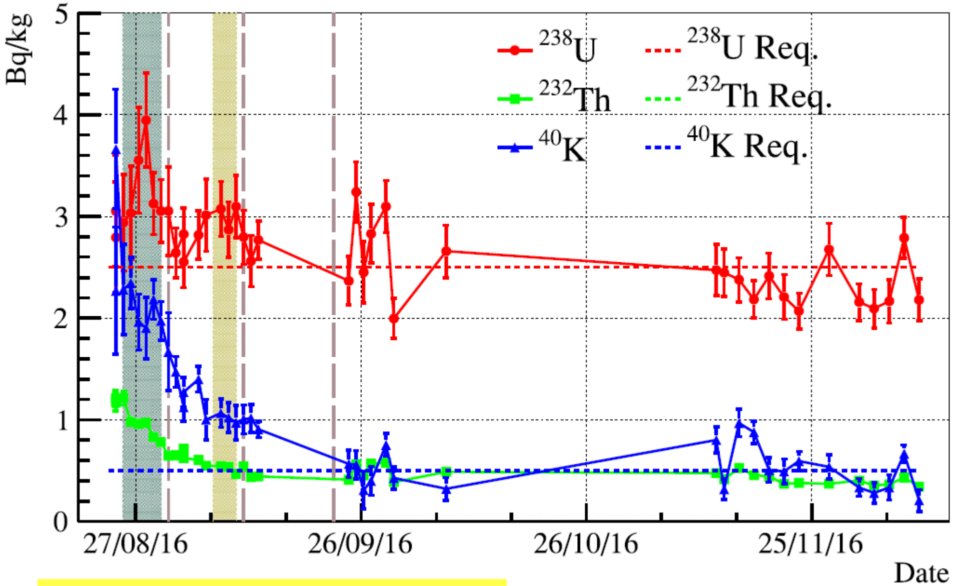
Scale the changes of resolution for LS quantity to reach 3σ @6 years

Corresponding detector costs were considered:
the changes of LS mass, and corresponding acrylic sphere size, number of PMTs, size of stainless steel framework, size of experimental hall

Merit of PMT physics performance

Glass radioactivity specification in ~2015

Bq/kg	^{238}U	^{232}Th	^{40}K
Hamamatsu PMT	4.96	1.62	10.8
MCP-PMT	1.2	0.4	0.3



NIMA 898 (2018) 67–71

- Careful radioactivity control was set and executed for MCP-PMT glass. Yet not practical for dynode PMTs

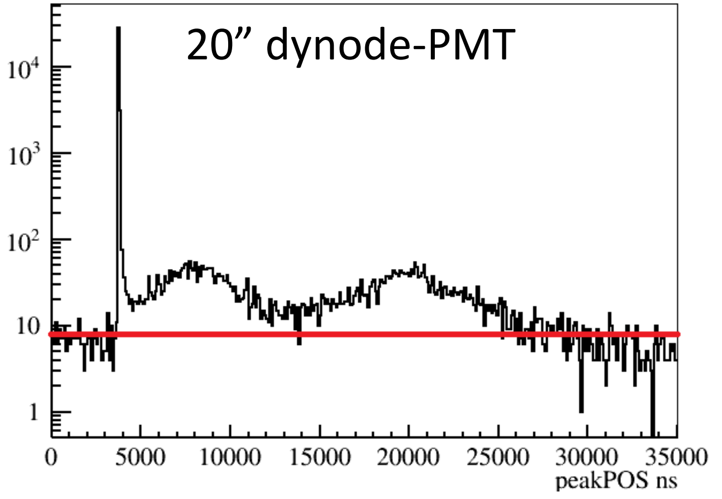
- PMT glass radioactivity affects
  - Thickness of water buffer
  - Accidental background in LS

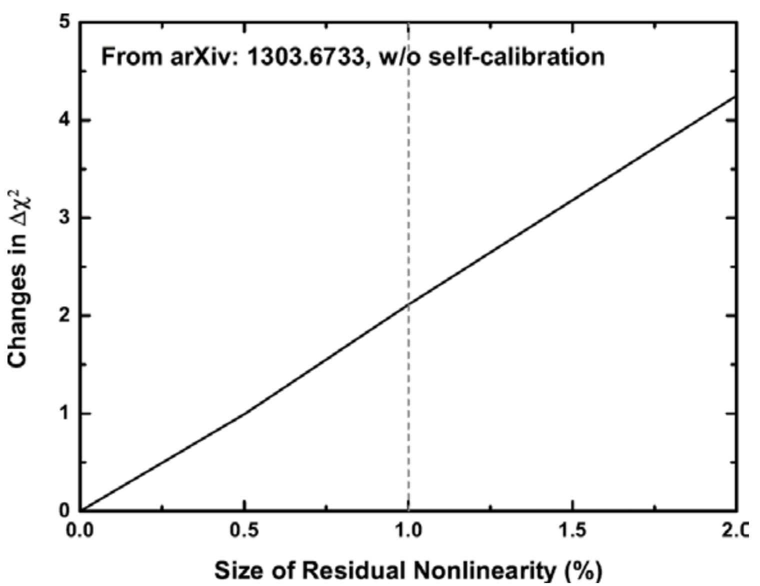
- A simply way: scale LS volume or water buffer to keep same S/B in fiducial volume

- Another: a first order $\Delta\chi^2$ check, only consider the statistical impact

$$\Delta\chi^2_{S+B} \approx \chi^2_S \cdot S/(S+B)$$

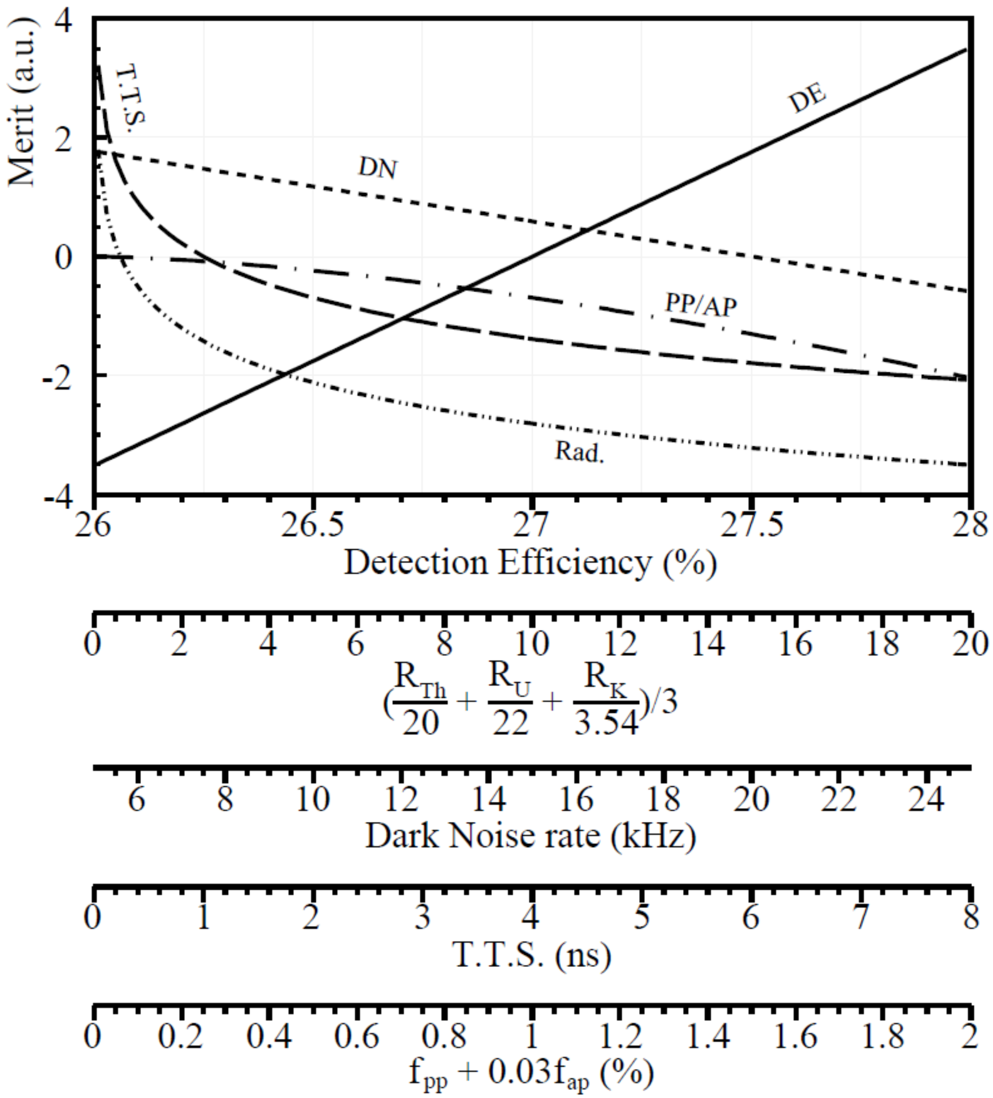
Merit of PMT physics performance





- 20” MCP-PMT has smaller pre-pulse and after-pulse ratio, due to different MCP-based/dynode-based anode structures, and better vacuum in the bulb
- After pulse and pre-pulse effects
  - Energy scale uncertainty
  - For correlated events like Inverse-β, the after-pulse of prompt signal may shift the energy of delayed signal
  - Events after a muon
- The contributions to energy scale uncertainty from pre- and after-pulse were estimated and converted to $\Delta\chi^2$ change

Merit of PMT physics performance



Parametrized merit formula

$$P_{DE} = (\varepsilon - 27) \times 3.518$$

$$P_{DN} = (20 - DN) \times 0.118$$

$$P_{TTS} = -\log(TTS)$$

$$P_{Rad} = -\log\left[\frac{1}{3} \times \left(\frac{R_{Th}}{20} + \frac{R_U}{22} + \frac{R_K}{3.54}\right) \times 1.663\right]$$

$$P_{PA} = -0.693 \cdot (pp + 0.03 \cdot ap)^{1.56}$$

JUNO 20-inch PMTs selection

- The idea that drove the strategy: certain combination of different type of PMTs may be the best
- Each vendor was requested to provide a set of quotations for 20 packages (η = 0.05, 0.1, ..., 1.0). One package has 1000 tubes
- For each package, the performance **merit for physic**, the **price factor** and **safety factor** was calculated based on vendor's specification

Merit of Physics P_i^{spec}

Quantify the impact of each key parameter on physics goals by using the formulas in previous page, and sum them up

Price factor

$P_i^{price} = 30 * (2.5 - M_i)$

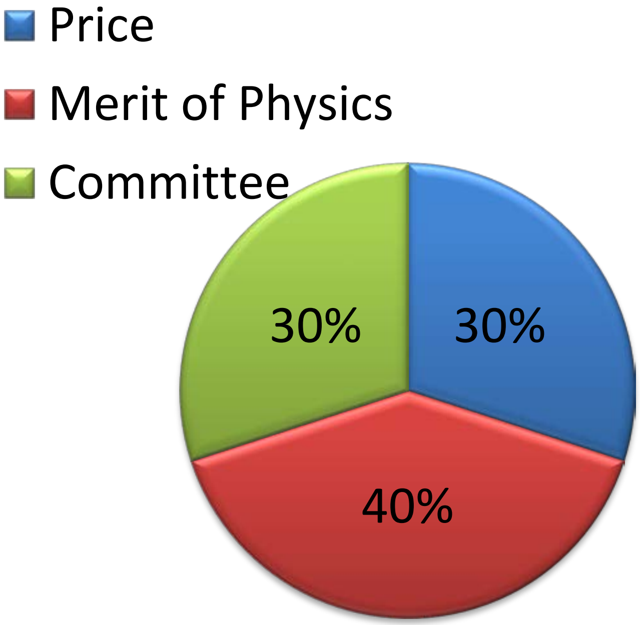
M_i: the quoted average price per PMT for a given award fraction η_i

Safety factor

$S_i = 1 - k_S * \eta_i$

k_S was arbitrarily set to 0.15

JUNO 20-inch PMTs selection



- Multiple vendors: {A, B, C, …}
- Award fractions of certain combination: $\{\eta_A, \eta_B, \eta_C, \ldots\}$, $\Sigma_i \eta_i = 1$
- The best combination of different products was determined by selecting the maximum total score

$$S = \sum_{i \in \{A,B,C,\ldots\}} \left(P_i^{spec} + P_i^{price} + P_i^{committee}\right) \cdot S_i \cdot \eta_i$$

Final Choice in Dec 2015
15k MCP-PMT from NNVT
5k dynode-PMT (R12860-50) from Hamamatsu

Summary

- Briefly reviewed photosensors for future huge neutrino detectors, particularly focus on 20-inch PMTs

- huge detectors → big science, but also huge cost, risk
- **ULTIMATE dream:** use minimum money to buy maximum physics potential
- **REALISTIC approach:** quantify the impact of all PMT parameters, including cost and risk, to the physics goals

- Optimizing the PMT choices to build state-of-the-art neutrino observatories is good for future science