Calibration of Hyper-Kamiokande photomultiplier tubes with diffuse light

Polina Sukhova (pasukhova15@gmail.com), Dr. Caio Licciardi, Dr. Xiaoyue Li

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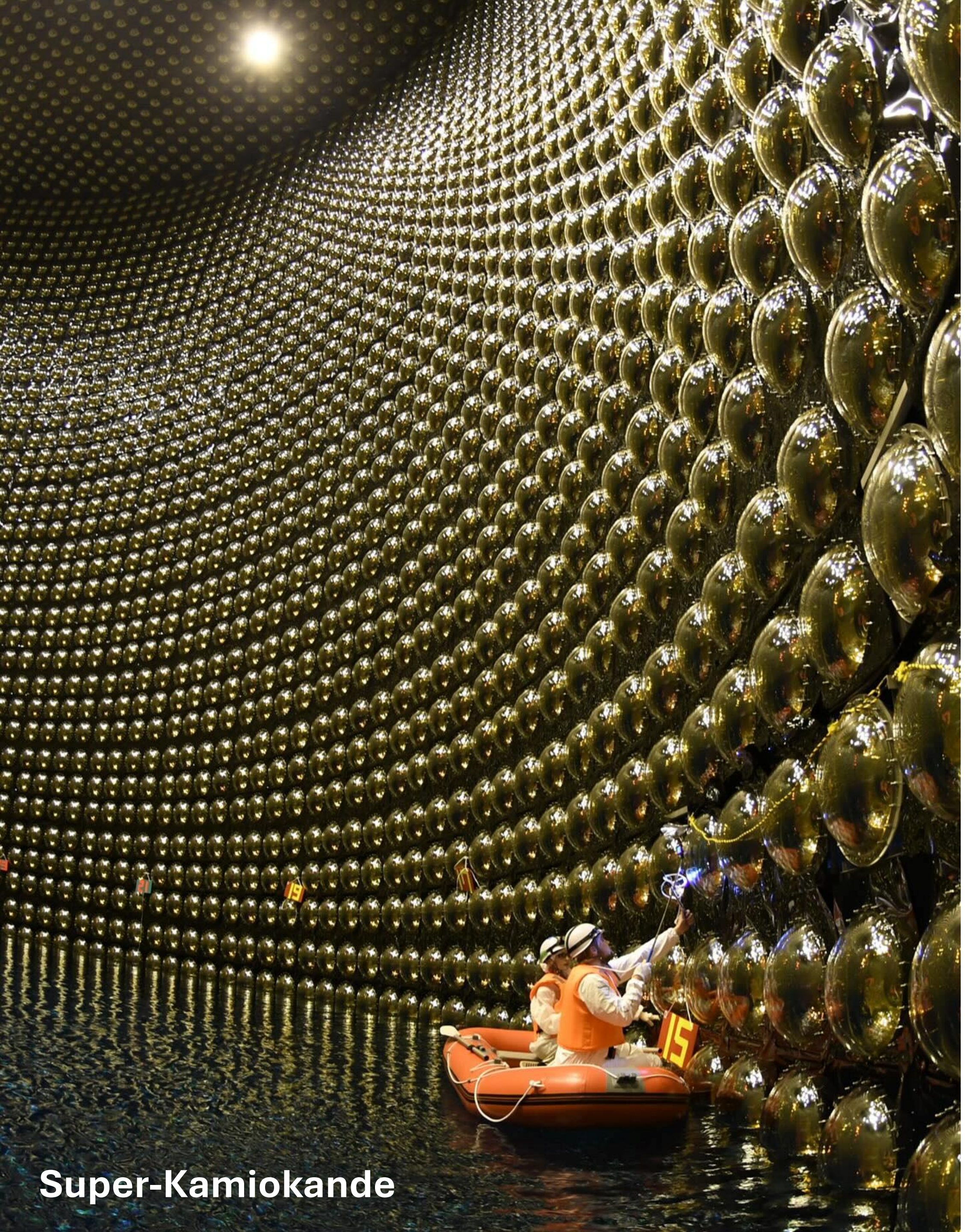


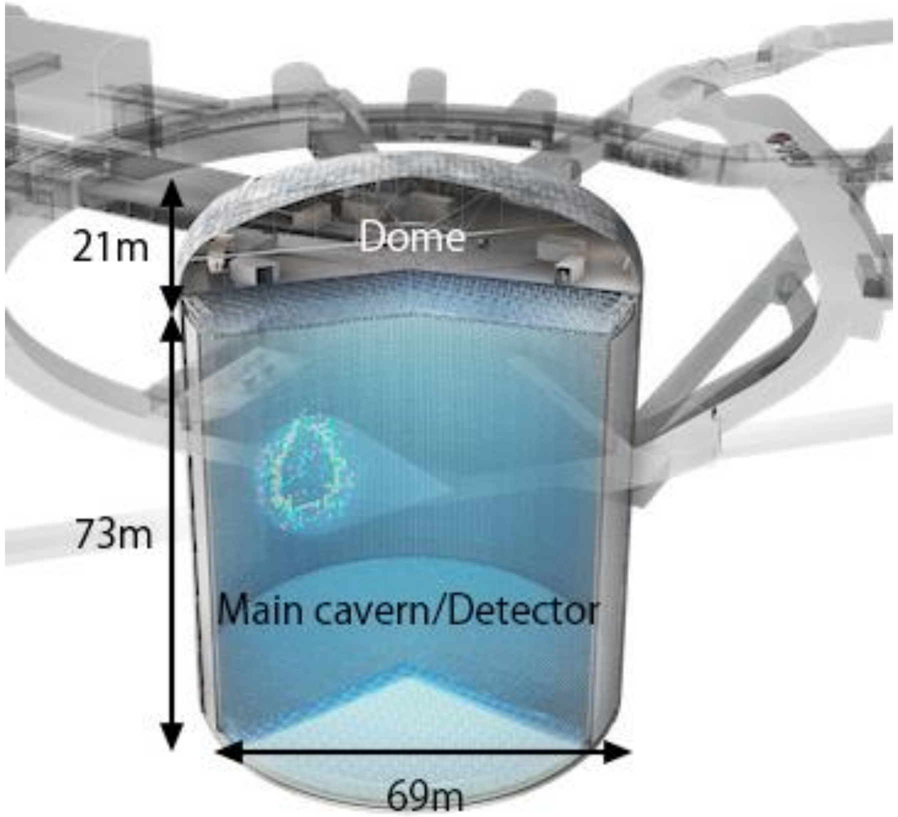
Super-Kamiokande

Outline

- Hyper-Kamiokande experiment,
- Response of photomultiplier tubes,
- Setup for the calibration with diffuse light,
- Iterative optimization.

Hyper-Kamiokande **(A. Fiorentini, T1-8)**

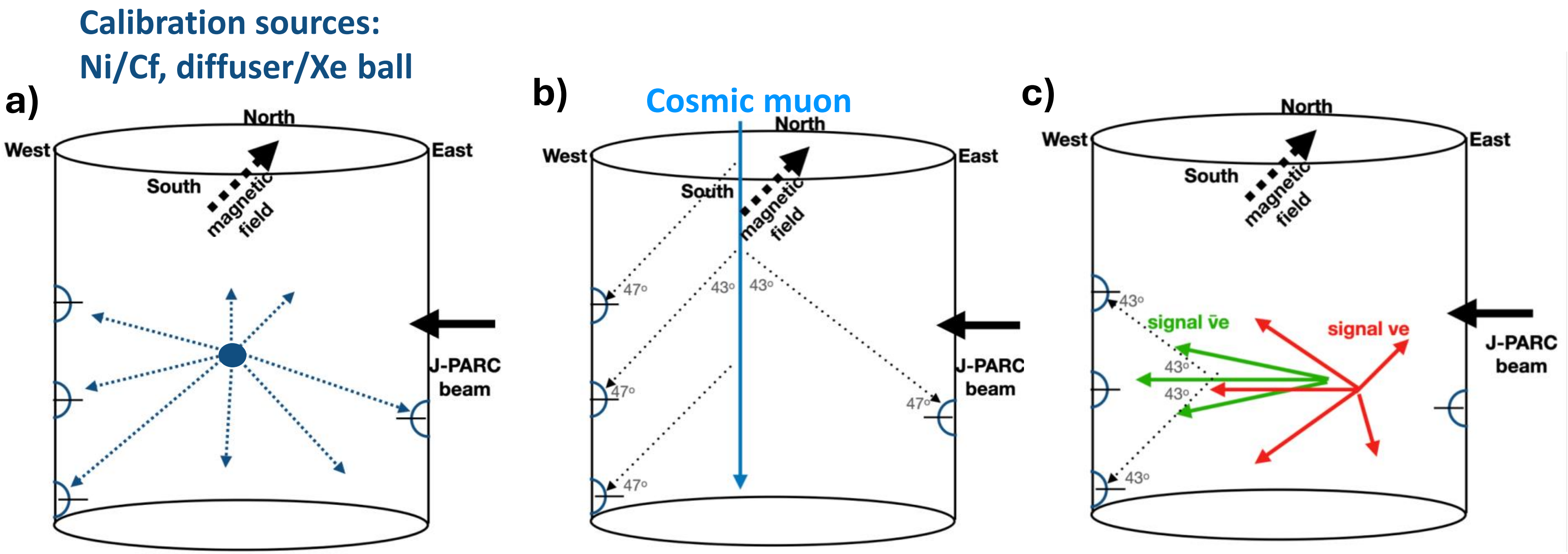
- The measurement of charge-parity violation phase,
- The tank is 71 meters tall,
- 20,000 PMTs are placed uniformly.
- 800 **mPMTs.** **(R. Collister, R2-1)**



Aim is to understand PMT response and determine it more accurately.

Motivation

- 200 LED-mPMTs contain 5 diffusers each.
- A 20-inch PMT receives light from hundreds of sources.
- Other calibration sources can be used in a joint analysis.

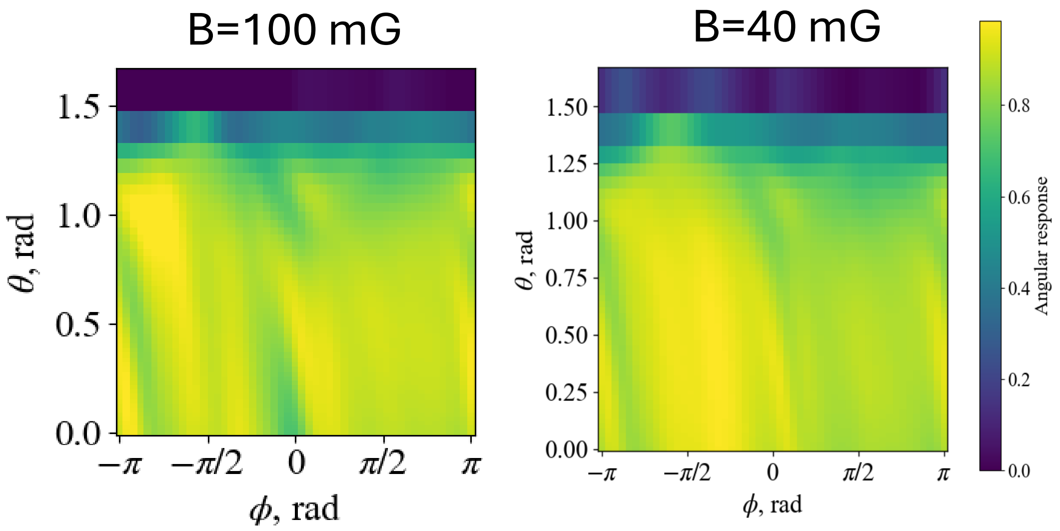


Calibration sources:
Ni/Cf, diffuser/Xe ball

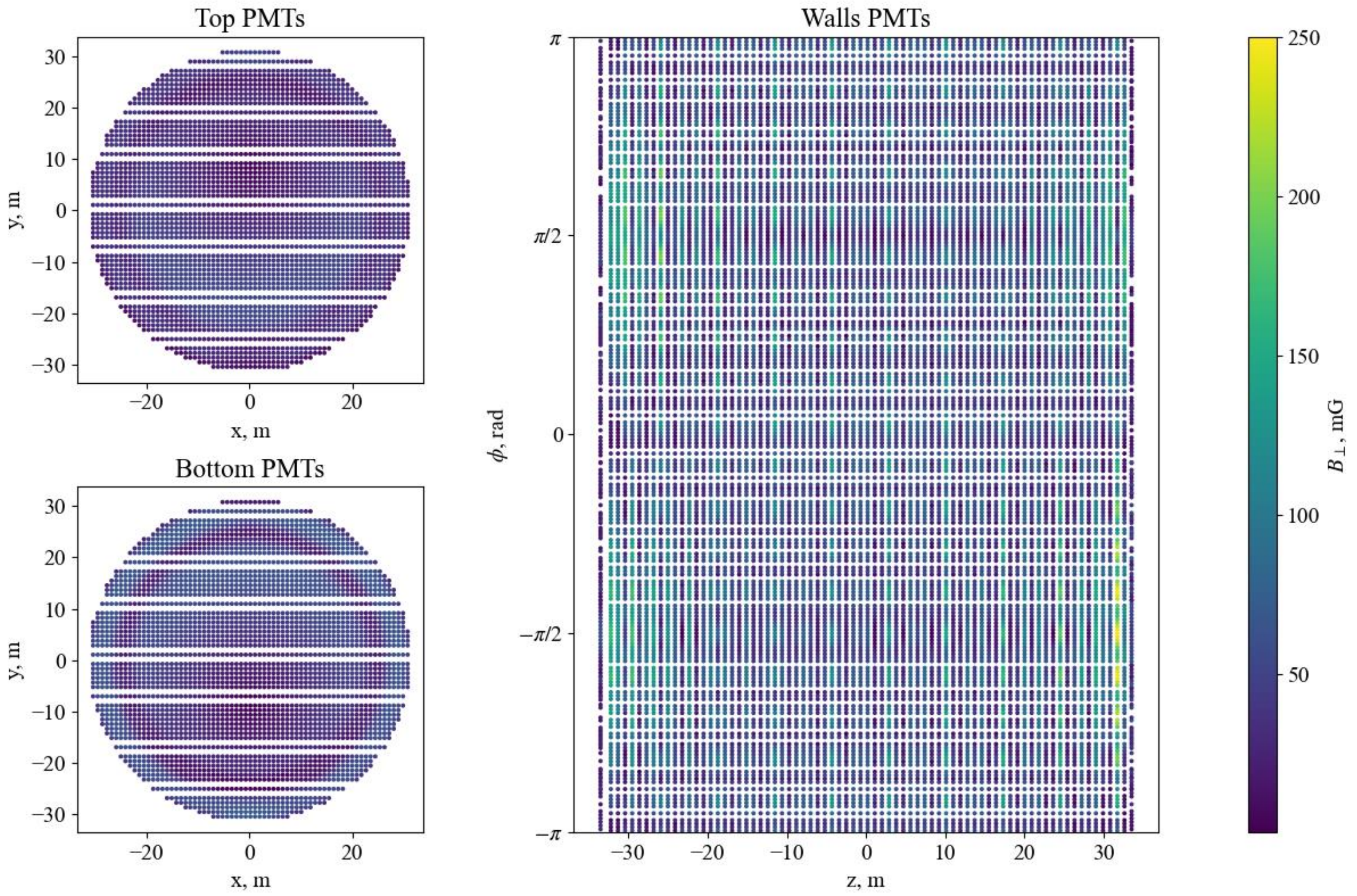
Cosmic muon

PMT placement and magnetic field influence

- Helmholtz coils cancel most of the Earth magnetic field.
- ~8% PMTs have $B > 100$ mG.

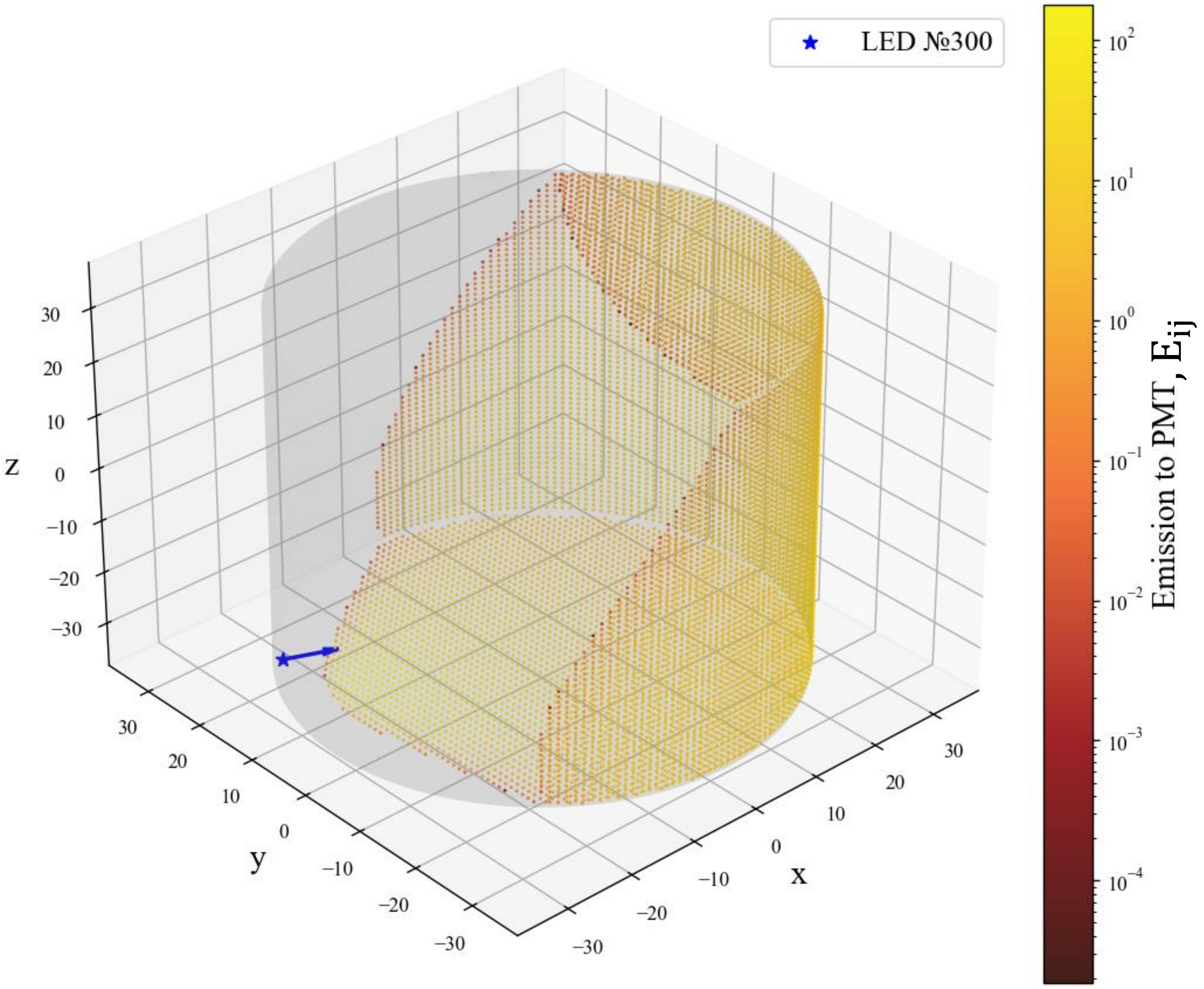


Ex-situ tests on PMT angular response



Residual magnetic field in the tank

Diffuse light sources

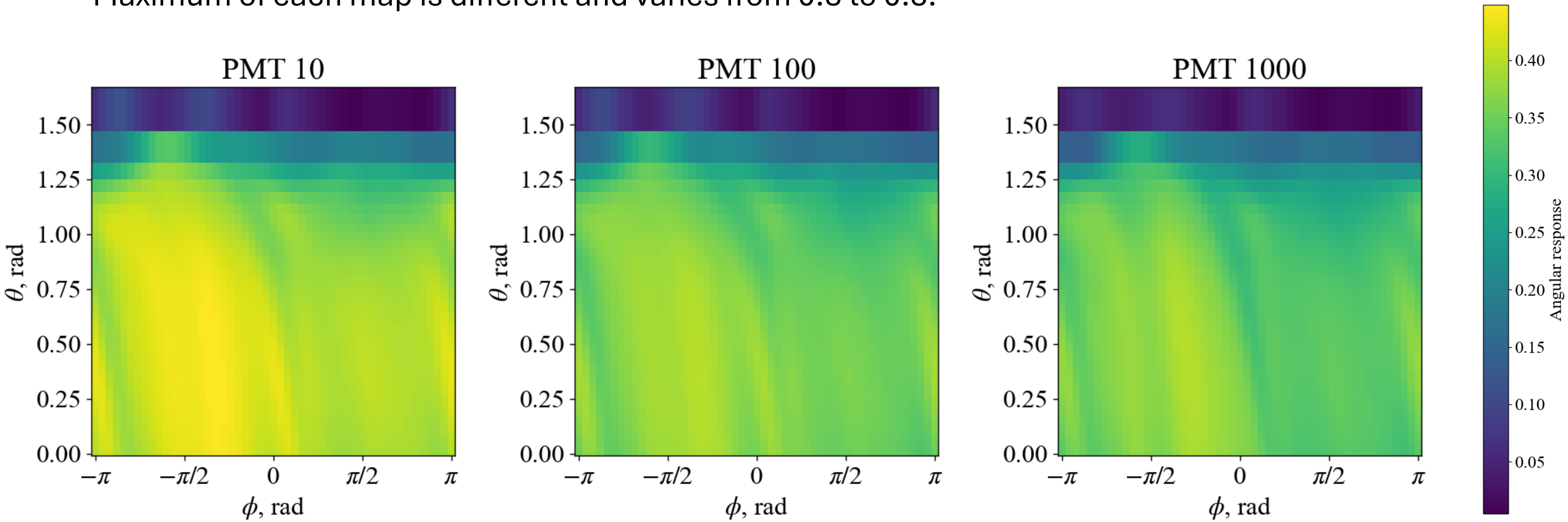


- In 200 mPMTs 5 diffusers.
- Light emission profiles for **all diffusers** have unknown variations.
- Each diffuser has a unique unknown intensity.

LED-mPMT

Angular response maps

- Each PMT has unique 2D angular response map from simulations,
- Pattern of the map depends on the magnetic field direction and magnitude + PMT dynode direction,
- Current map accuracy is ~7° in azimuthal and ~2° in zenith angle,
- Maximum of each map is different and varies from 0.3 to 0.5.



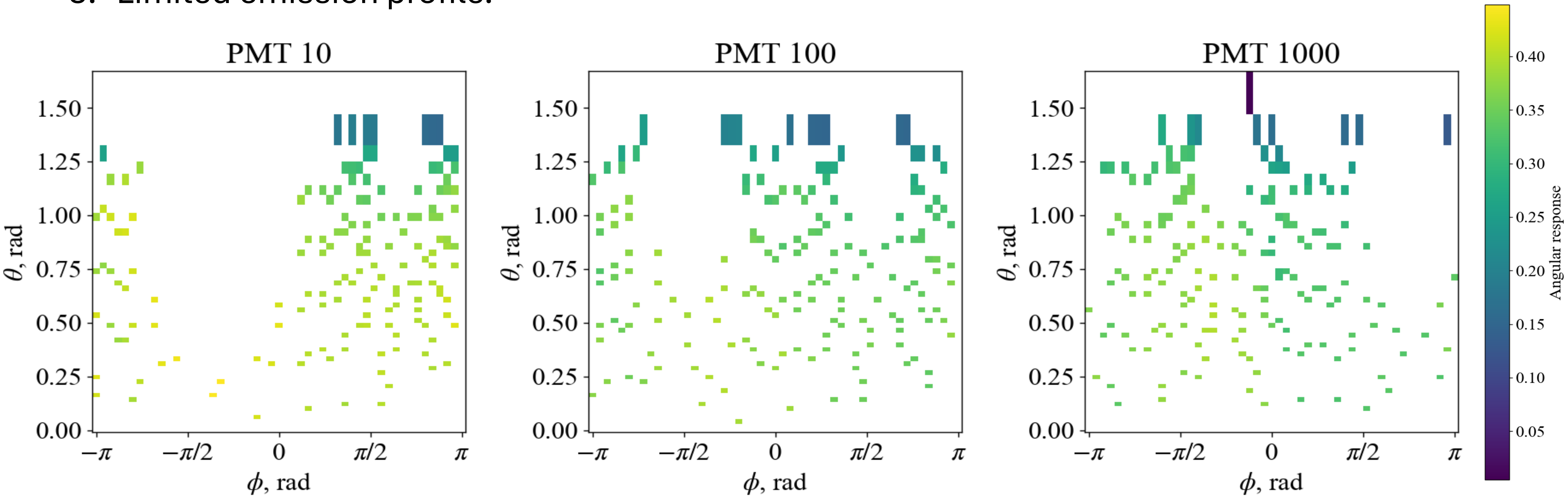
Experimental maps

The number of available pixels from LED/PMT combinations is limited.

Main reasons are:

1. PMT location,
2. Several LED hit the same pixel,
3. Limited emission profile.

Each available pixel is a free parameter.



Model assumptions

- **Number of photoelectrons (p.e.)** that each $\boldsymbol{j}$ PMT detects from each $\boldsymbol{i}$ LED:

$$\boxed{\mu_{ij} = \boldsymbol{n} \cdot E(\Delta\theta_{ij}) \cdot \boldsymbol{I_i} \cdot \boldsymbol{\eta_{ij}} \cdot \boldsymbol{e^{-0.02L_{ij}}}}$$

where E_{ij} – emission that PMT has detected, $\boldsymbol{I_i}$ – intensities, $\boldsymbol{n}$ – number of flashes, $\boldsymbol{\eta_{ij}}$ – angular dependence efficiency, L_{ij} –distance between $\boldsymbol{i}$ LED and $\boldsymbol{j}$ PMT.

- Diffuser will flash ~5,000 times.
- 20M responses per flash!
- **Number of flashes with a non-zero number of p.e. can be measured.**

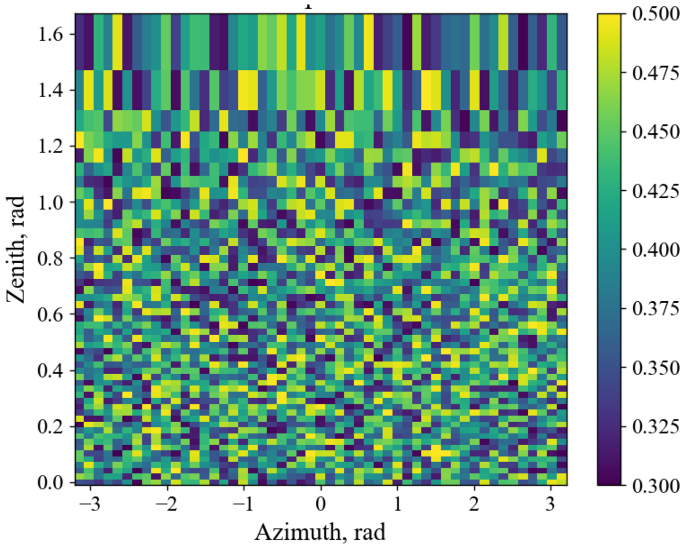
$\boldsymbol{\mu_{ij}^{exp}}$ **can be deduced from number of flashes.**

Iterative optimization

(Using weighted least square method)

Idea is to divide task into two independent steps: **intensity** and **angular response** reconstruction.

Prior map



~1,000 parameters

Find **intensities**. **Data** for each I_i is fitted by a constant.

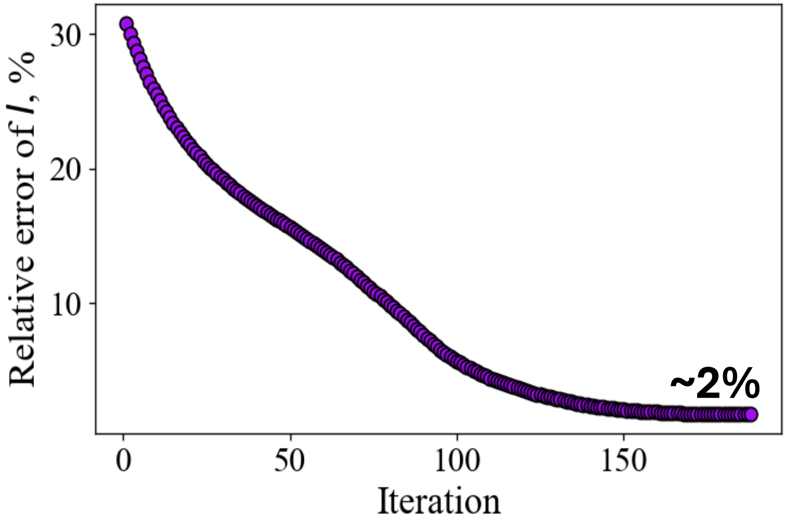
~4M parameters

Find each **available pixel** $\eta_{ij} < 0.5$ on the PMT map and take the average.

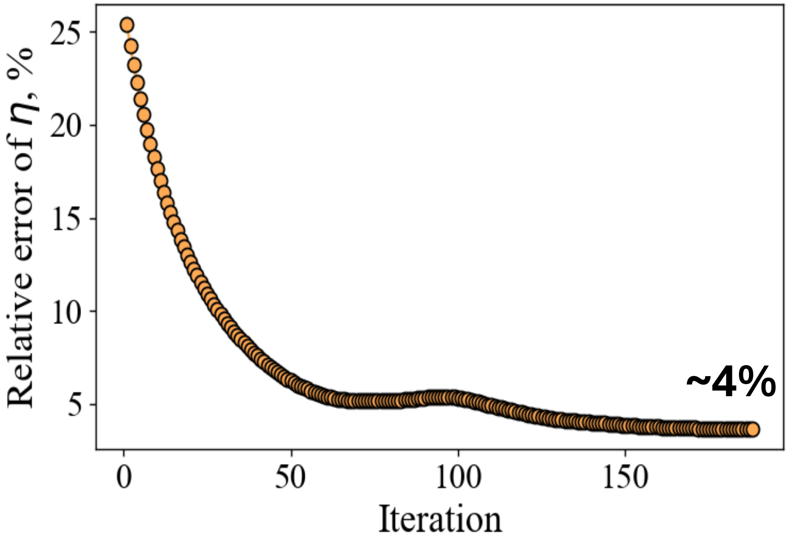
Repeat until algorithm converges.

Optimization results

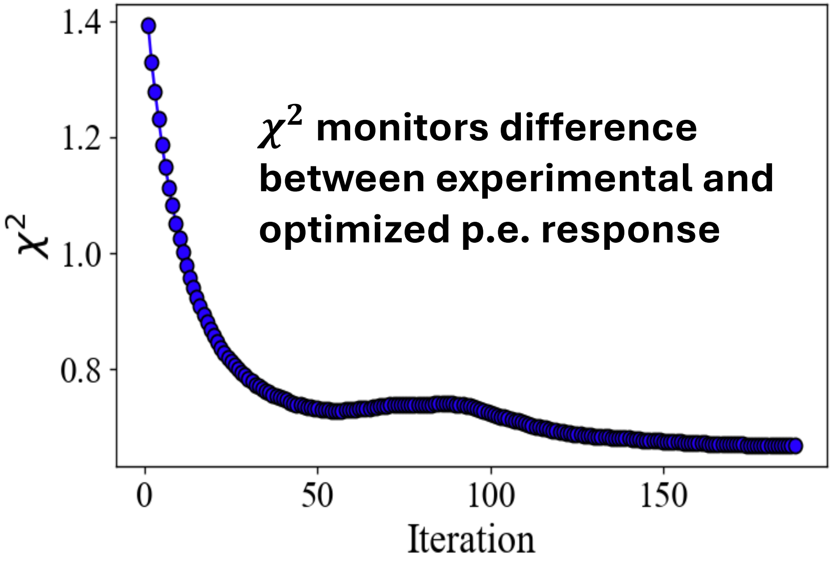
- All monitoring metrics decreases with an iteration step,
- With current assumptions algorithm converges in 189 iterations within 20 minutes,
- The angular response reconstruction error is 4%.



~2%



~4%



χ^2 monitors difference between experimental and optimized p.e. response

Summary

- Hyper-Kamiokande will search for a charge-parity symmetry violation,
  → better understanding of the detector response is necessary.

- Current calibration model allows to measure PMT angular response with 4% error.

- Other calibration techniques will be used in joint analysis!

Hyper-Kamiokande

University of Windsor

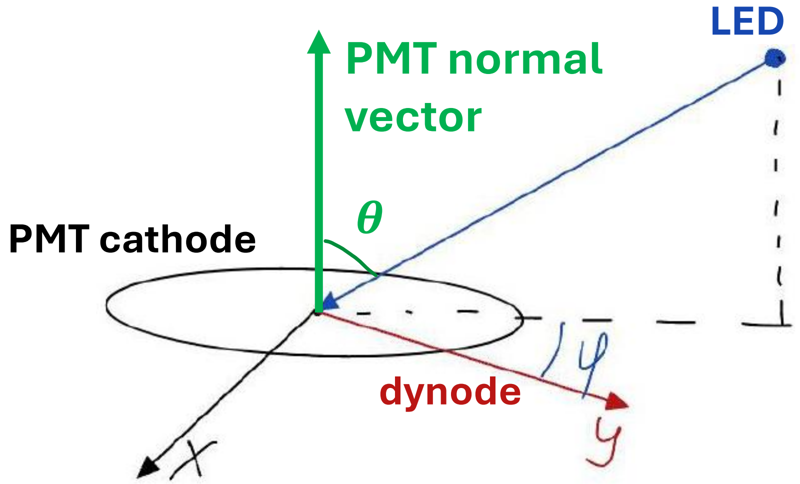
Thank you for your attention!

Backup

Detection angles

Geometry:

- **Dynode** directions were set randomly for each PMT. Condition: dynode direction (Y) is perpendicular to the PMT normal.
- **Azimuthal angle φ** – angle between projection of the light ray from each LED on the **XY plane** (PMT inner coordinate system) and dynode.
- **Zenith angle θ** – angle between PMT normal vector and light ray.



Emission profile of the diffusers

- Experimental emission profile $E_{ij}^{\mathrm{exp}}(\theta,\varphi)$:

$$\boldsymbol{E_{ij}^{\mathrm{exp}}} = \boldsymbol{\alpha_i(\theta_{ij})} \cdot \boldsymbol{\beta(\varphi_{ij})}$$

- Emission profile in the model:

$$\boldsymbol{E_{ij}^{\mathrm{opt}}} = \boldsymbol{\alpha_{\mathrm{PTFE}}(\theta_{ij})} \cdot \mathbf{1}$$

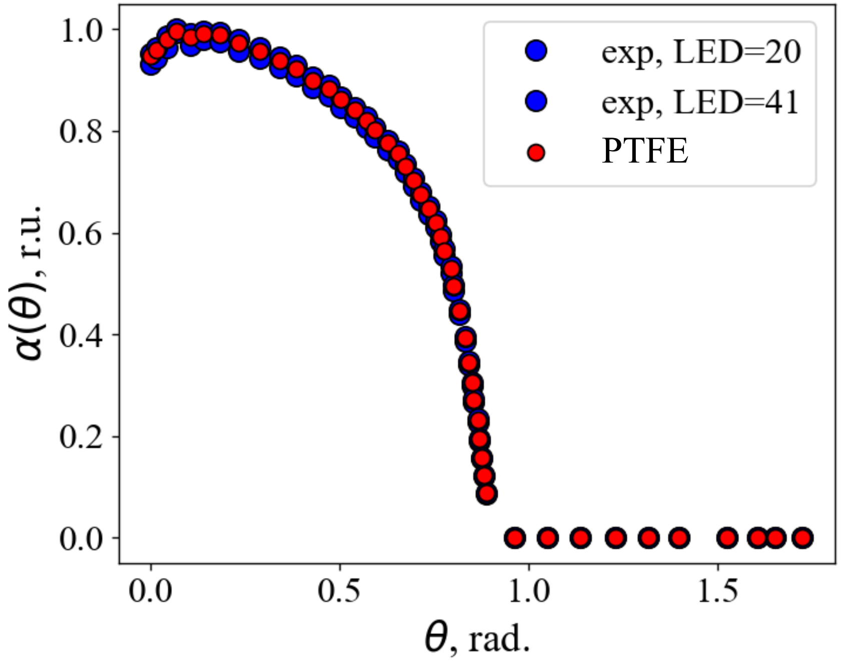
where $\boldsymbol{\alpha_i(\theta_{ij})}$ is the emission profile with variations.

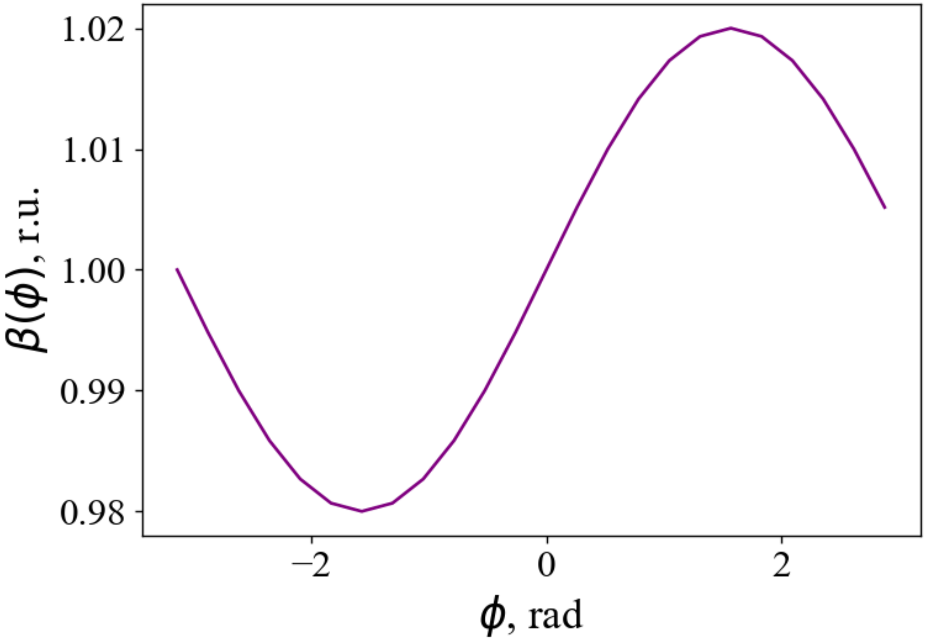
- **Each LED has different amplitude in variations (but less than 2%).**

- And $\boldsymbol{\beta(\varphi_{ij})}$ is an azimuthal emission profile:

$$\boldsymbol{\beta(\varphi_{ij})} = 1 + \mathbf{0.02} \cdot \sin\varphi_{ij} \,,$$

where φ_{ij} – random angle.





Model assumptions

Number of photons is distributed according to Poisson distribution.

Probability to detect more than 0 p.e.

$$\boxed{p_{ij} = 1 - e^{-\mu_{ij}}}$$

Number of flashes with non-zero p.e.

$$\boxed{K_{ij}^{\exp} = \mathrm{Binomial}(\boldsymbol{n}, p_{ij})}$$

Statistical uncertainty $\boldsymbol{\sigma_{ij}}$

$$\boxed{\boldsymbol{\sigma_{ij}} = \sqrt{\boldsymbol{n} \cdot p_{ij} \cdot (1 - p_{ij})}}$$

Target function

- Obtain an approximate number of p.e. from the experimental number of flashes K_{ij}^{exp} :

$$\mu_{ij}^{\text{exp}} = -\ln\left(1 - \frac{K_{ij}^{\text{exp}}}{\boldsymbol{n}}\right) = -\ln(1 \ - P_{ij}),$$

with the related error

$$\sigma_{ij}^{\mu} = \sqrt{\frac{P_{ij}}{\boldsymbol{n}(1 - P_{ij})}}.$$

- Considering that

$$\mu_{ij}^{\text{exp}} = B_{ij}^{\text{exp}} \cdot \boldsymbol{I_i} \cdot \boldsymbol{\eta_{ij}},$$

where $B_{ij}^{\text{exp}} = \boldsymbol{E_{ij}^{\text{exp}}} \cdot e^{-0.02 r_{ij}}$.

Metrics

- $I_i^{\mathrm{opt}}, \eta_{ij}^{\mathrm{opt}},\ \mu_{ij}^{\mathrm{opt}}$ – intensities, angular response and number of p.e. after **189** iterations.

- Relative error of $\boldsymbol{I_i}$:

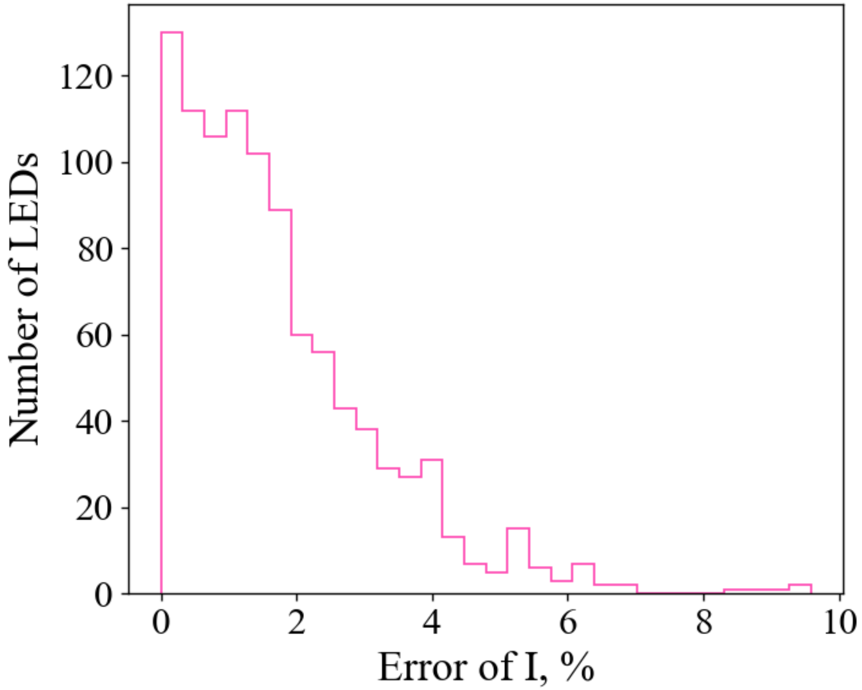
$$100\% \cdot \mathrm{mean}\frac{\left|\boldsymbol{I_i} - I_i^{\mathrm{opt}}\right|}{\boldsymbol{I_i}} \approx 1.8\%,$$

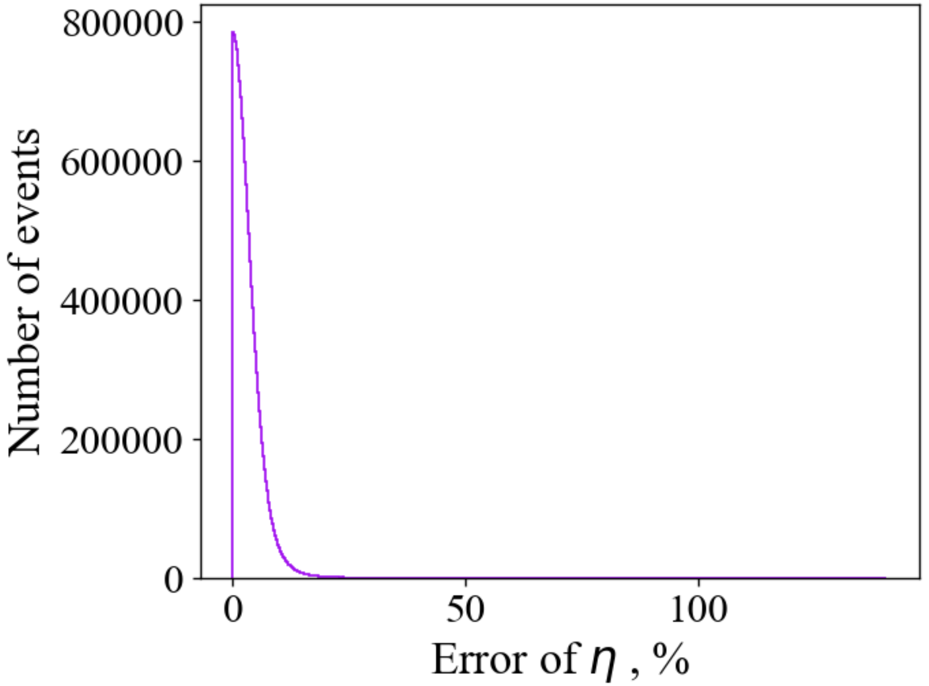
- Relative error of $\boldsymbol{\eta_{ij}}$, if $0 < \theta_{\mathrm{PMT}}^{ij} < \frac{\pi}{2}$:

$$100\% \cdot \mathrm{mean}\frac{\left|\boldsymbol{\eta_{ij}} - \eta_{ij}^{\mathrm{opt}}\right|}{\boldsymbol{\eta_{ij}}} \approx 3.6\%,$$

- **χ^2 for the number of p.e.:**

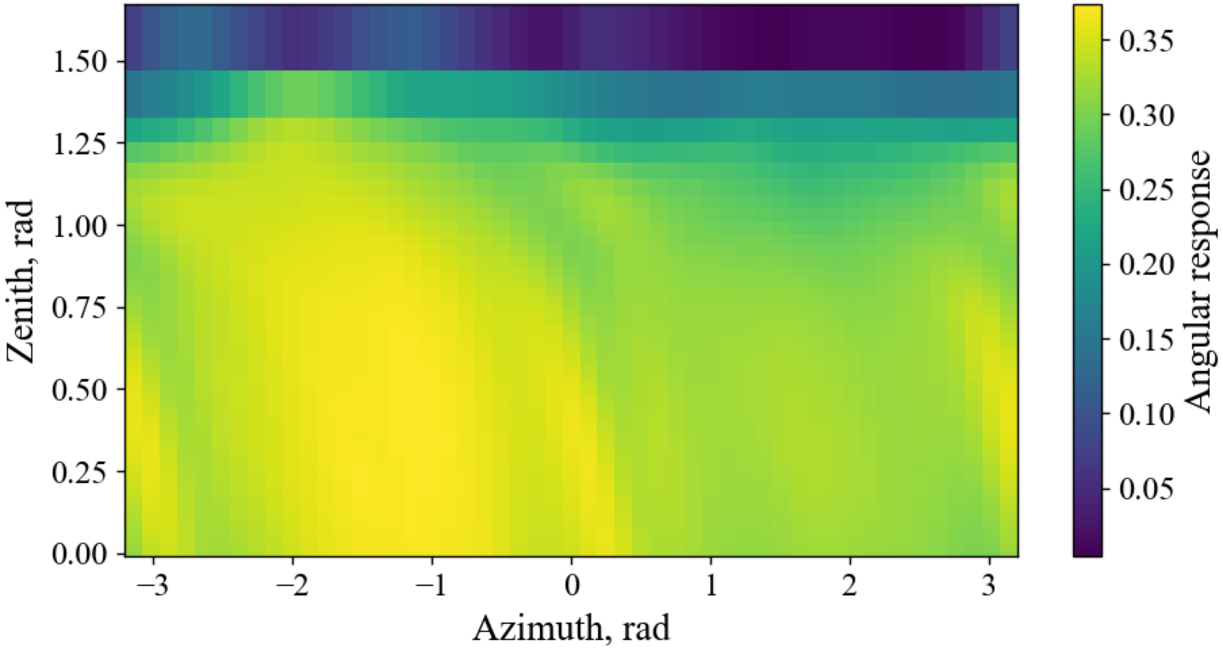
$$\chi^2 = \sum_{i,j}\left(\frac{\mu_{ij}^{exp} - \mu_{ij}^{opt}}{\sigma_{ij}^{\mu}}\right)^2.$$



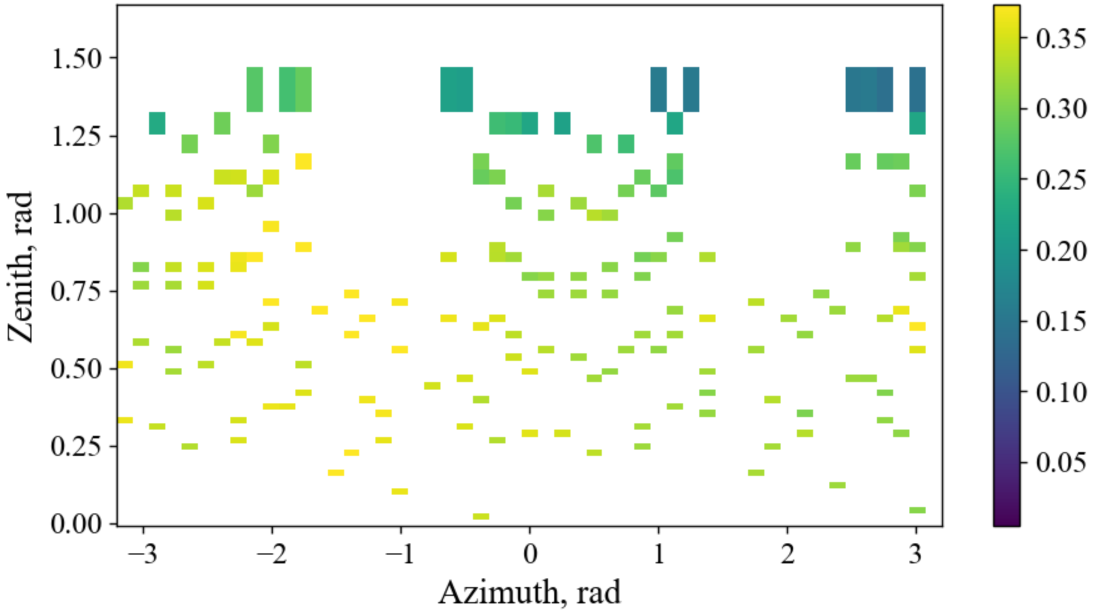


Example of reconstructed map for PMT

Angular response map, PMT 5000
B = (50.89, 18.21, -21.28) mG



Optimised map, PMT 5000



Experimental map, PMT 5000