**ALPACA Experiment**

Andes Large area PArticle detector for Cosmic ray physics and Astronomy

# ALPACA実験用光電子増倍管のダイナミックレンジの拡張

# Expanding the dynamic range of photomultiplier tube for ALPACA experiment


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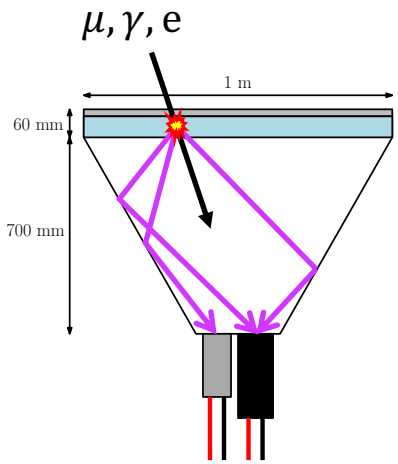
# ALPACA experiment

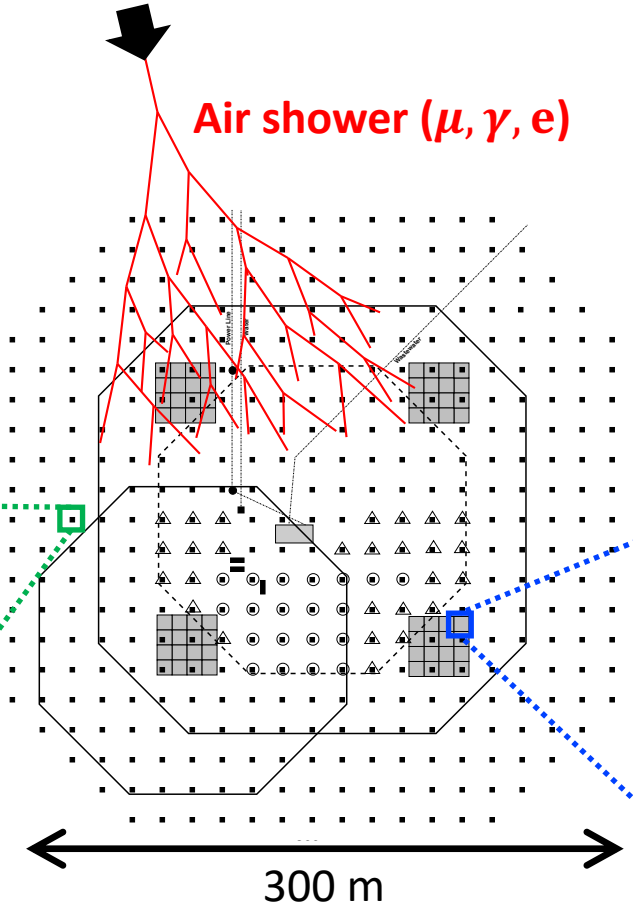
✓ **Goal: Gamma-ray observation from <u>TeV to PeV energies</u> in the southern sky**

**Gamma ray or BG cosmic ray**

**<u>Air Shower Array (Coverage: 83,000 m²)</u>**

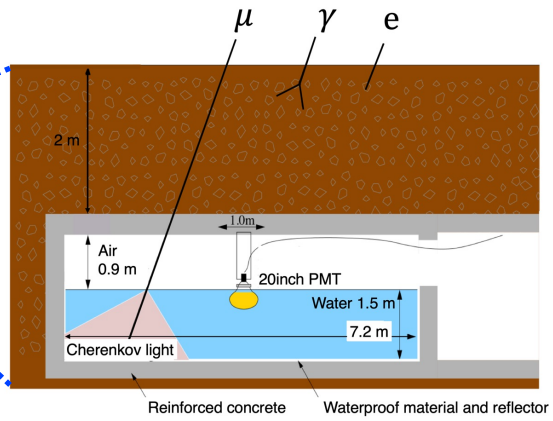
- 1 m² Scintillation detector (× 401)
- **<u>A 2-inch PMT</u>** is installed on each detector
- Determine the primary energy and its arrival direction



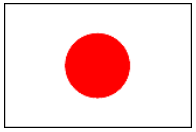




**<u>Underground Muon Detector Array (Total area: 3,700 m²)</u>**

- 58 m² / cells × 64 cells
- A 20-inch PMT is installed each cell
- Discriminate between gamma rays and cosmic rays by the number of muon in showers



# The ALPACA Collaboration

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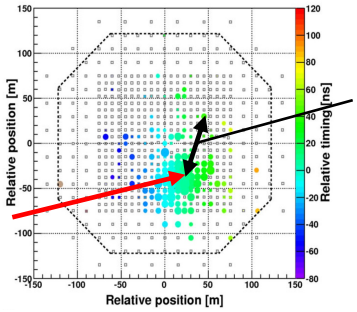
# Required dynamic range of scintillation detector

## Air shower simulation

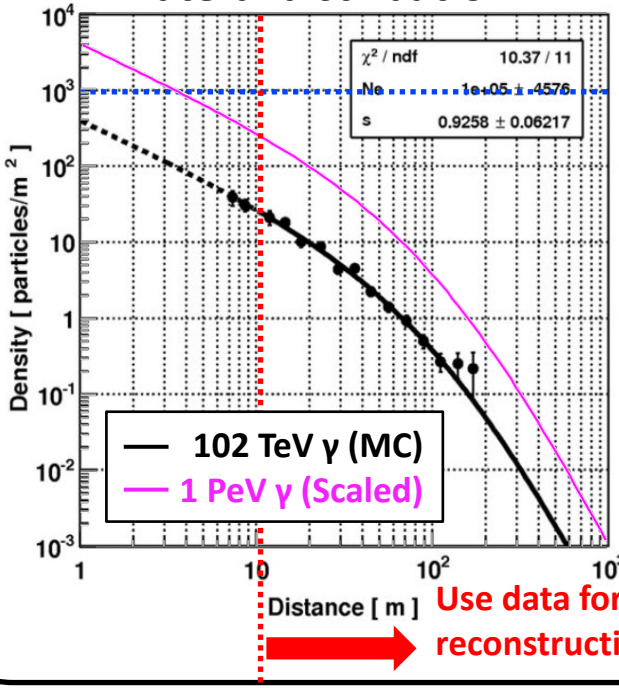
K. Kawata, et al., Experimental Astronomy (2017) 441-9




Distance

Core position

Lateral distribution

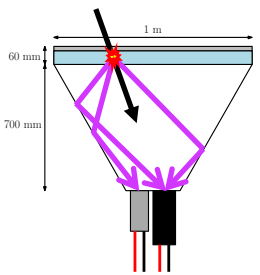



1,000 particles

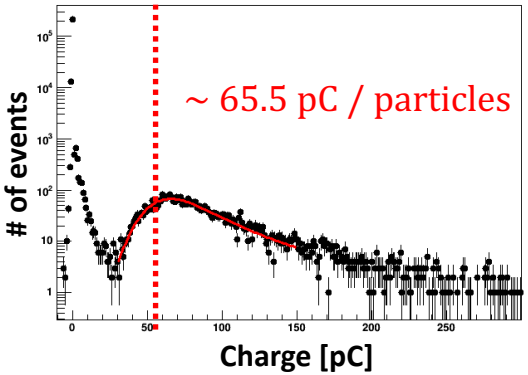
Use data for air shower reconstruction

❑ Definition of 1 particle

$\mu, \gamma, e$



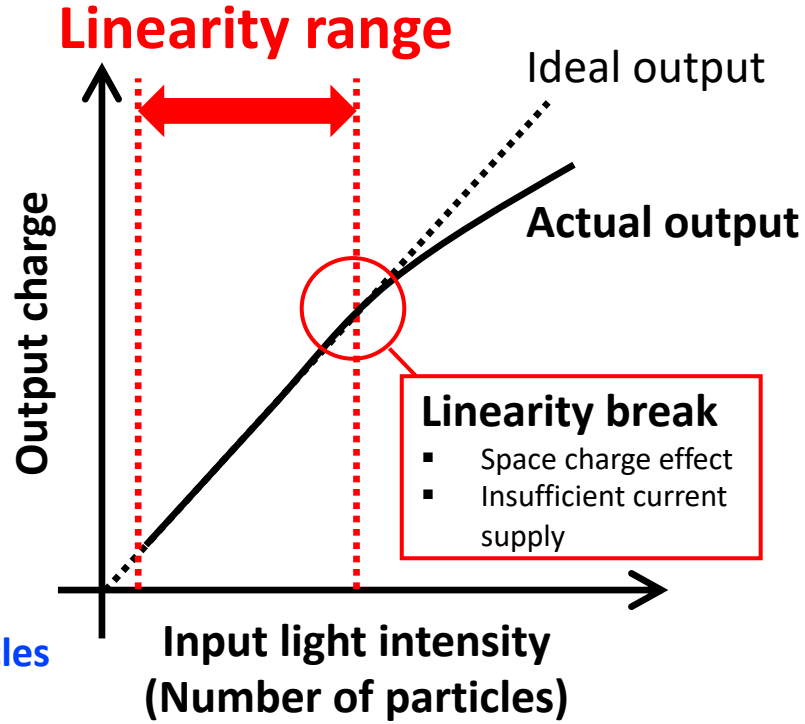

Charge distribution of 2inch-PMT (Data)



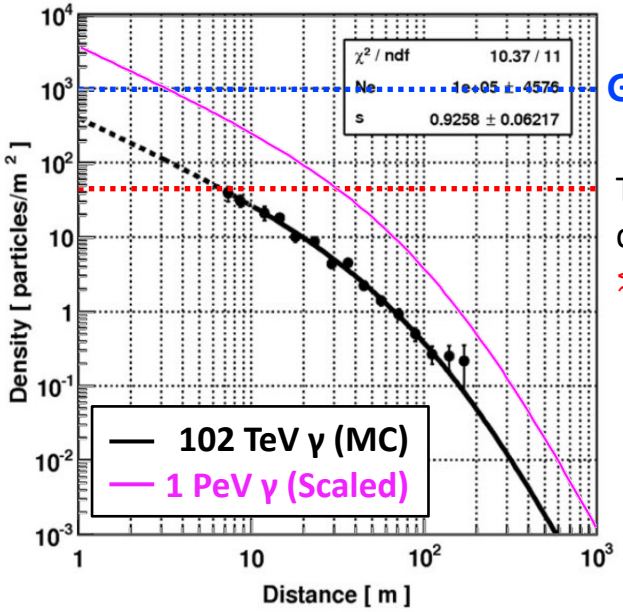

✓ Gamma-ray observation up to **PeV energies** requires accurate observation up to **1,000 particles / detector**.

# PMT linearity range

- ✓ **Required performance of scintillation detectors**
  - One-particle measurement
  - Good timing resolution (~1 ns)
- ➢ Set **2inch-PMT gain higher**
  - → Typical linearity range: Up to **several tens of particles**




**Lateral distribution**




**Goal: 1,000 particles**

The number of particles detectable by 2-inch PMT:
≲ **several tens of particles**

✓ Need to extend linearity range up to **~1,000 particles**

# Conventional method to extend PMT linearity range

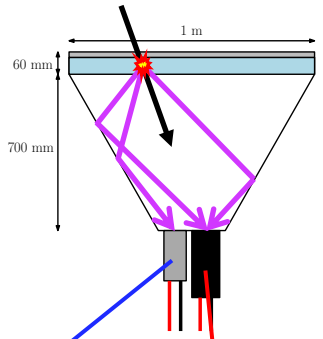
**Use two PMTs with different gains (Tibet ASγ)**

**Calibration between two signals**

① Derive the gain ratio $a$:

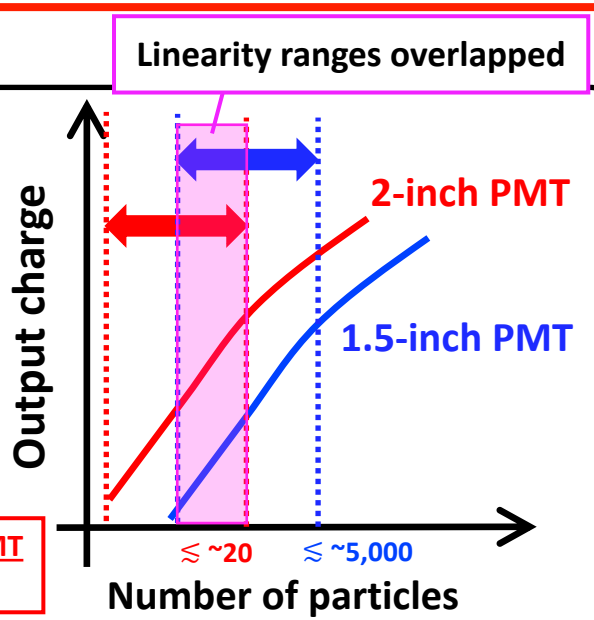
2-inch PMT / 1.5-inch PMT

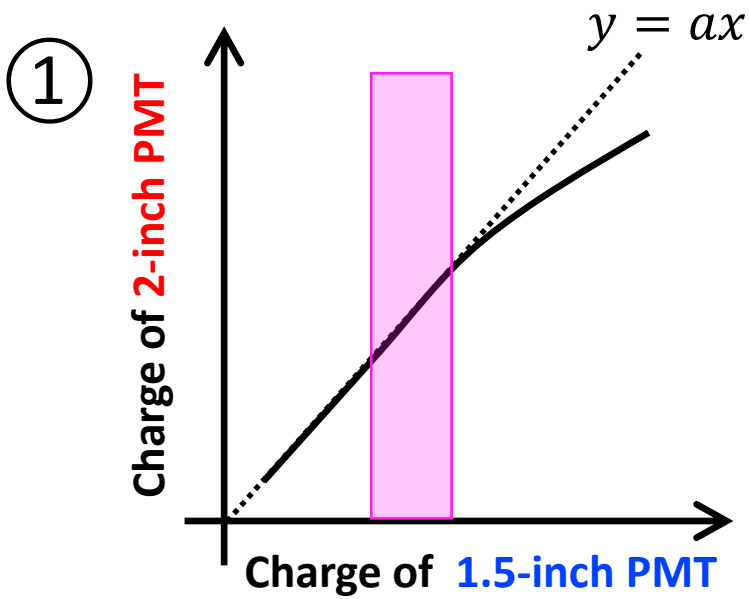
② Convert the charge of 1.5-inch PMT into 2-inch PMT

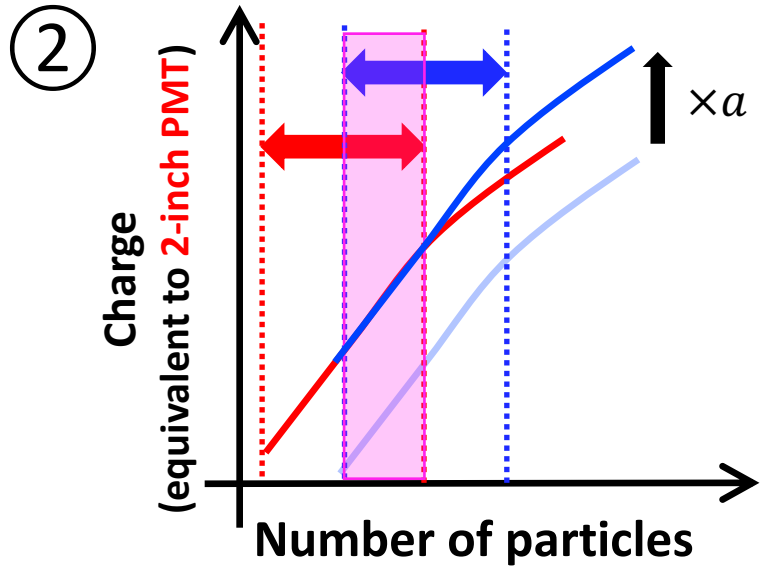



**1.5-inch (Low-gain) PMT**
Range: ≲ ~5,000 ptcls

**2-inch (High-gain) PMT**
Range: ≲ ~20 ptcls



# Motivation of my research

✓**To enable measurement up to 1,000 particles <u>using only 2-inch PMTs</u>**

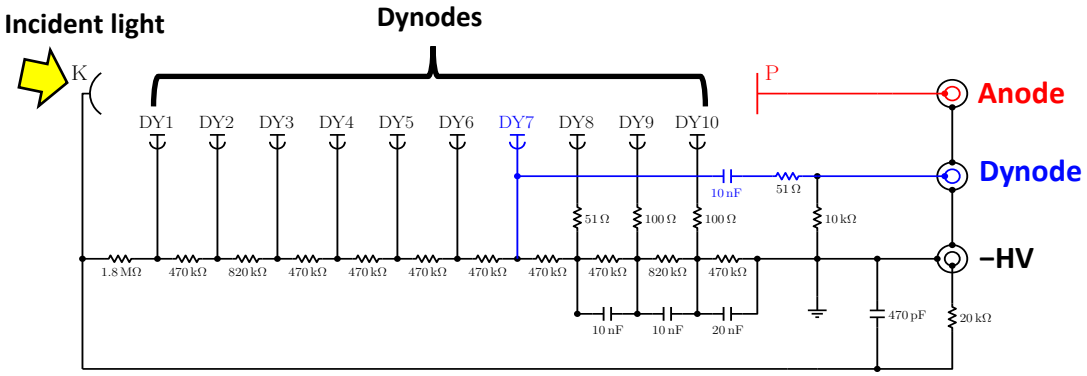
Aiming to avoid the costs of using 1.5-inch PMTs

❑**<u>Dynode readout of 2-inch PMT</u>**

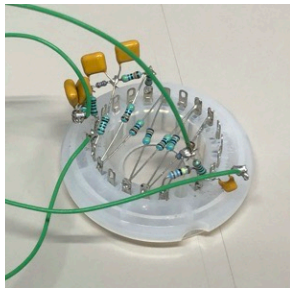
Read out signals from the **<u>dynode</u>** in the middle of amplification

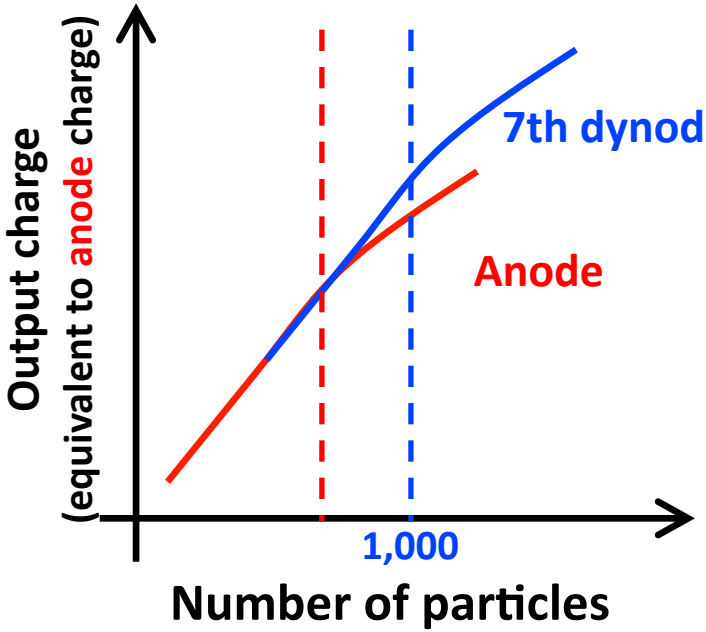
➢ Linearity break can be avoided.

**<u>2-inch PMT (R7724: Hmamatsu made)</u>**

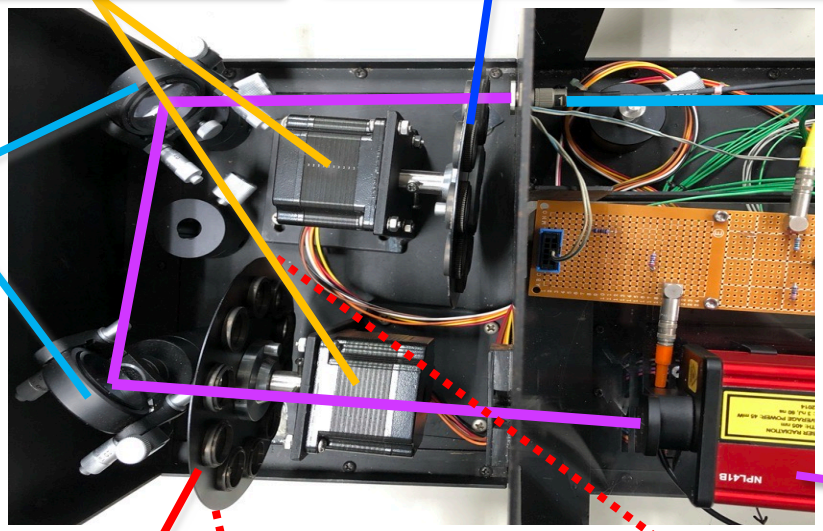



- Voltage distribution ratio: as catalog (normal divider)
- High voltage: −1750 V
- Readout from **<u>seventh dynode</u>**





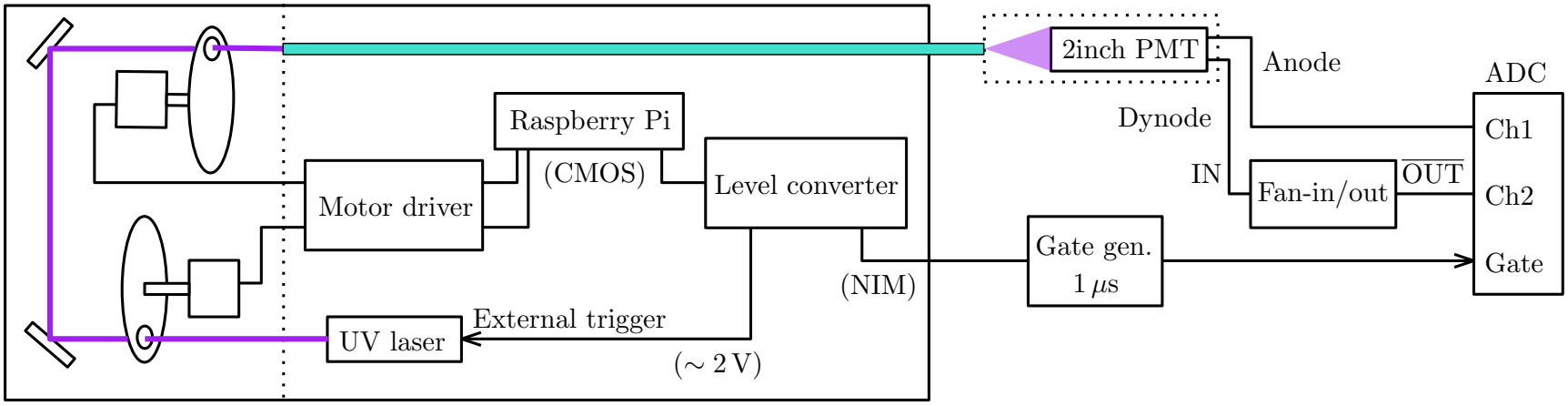
# Linearity measurement: **UV laser calibration system (1)**




1. Set the desired filters (transmittance) by rotating the stepping motors
2. Generates UV light of any desired intensity

# Linearity measurement: **UV laser calibration system (2)**

## UV laser calibration system




## Filter transmittance

| First filters | | Second filters | |
|---|---|---|---|
| Catalog value | Measured value | Catalog value | Measured value |
| 1 | 1 | 1 | 1 |
| $10^{-1}$ | Unmeasured | 0.9 | 0.906 |
| $10^{-2}$ | | 0.8 | 0.836 |
| $10^{-3}$ | | 0.7 | 0.846 |
| $10^{-4}$ | | 0.6 | 0.658 |
| $10^{-5}$ | | 0.5 | 0.569 |
| $10^{-6}$ | | 0.4 | 0.475 |
| $10^{-7}$ | | 0.3 | 0.337 |
| | | 0.2 | 0.258 |
| | | 0.1 | 0.139 |

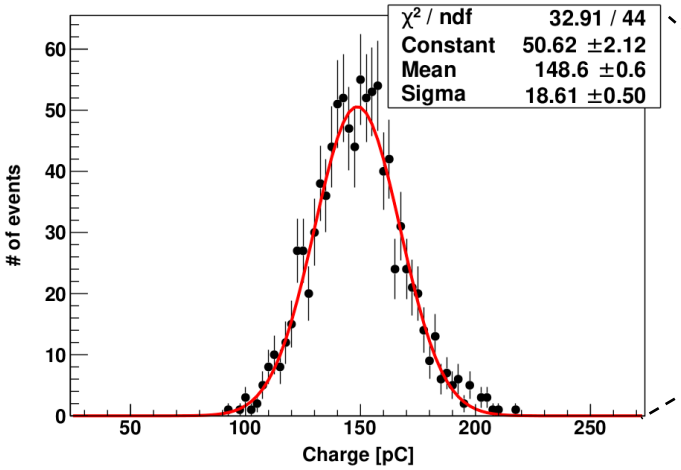
Digit adjustment

Adjustment by ~10% each

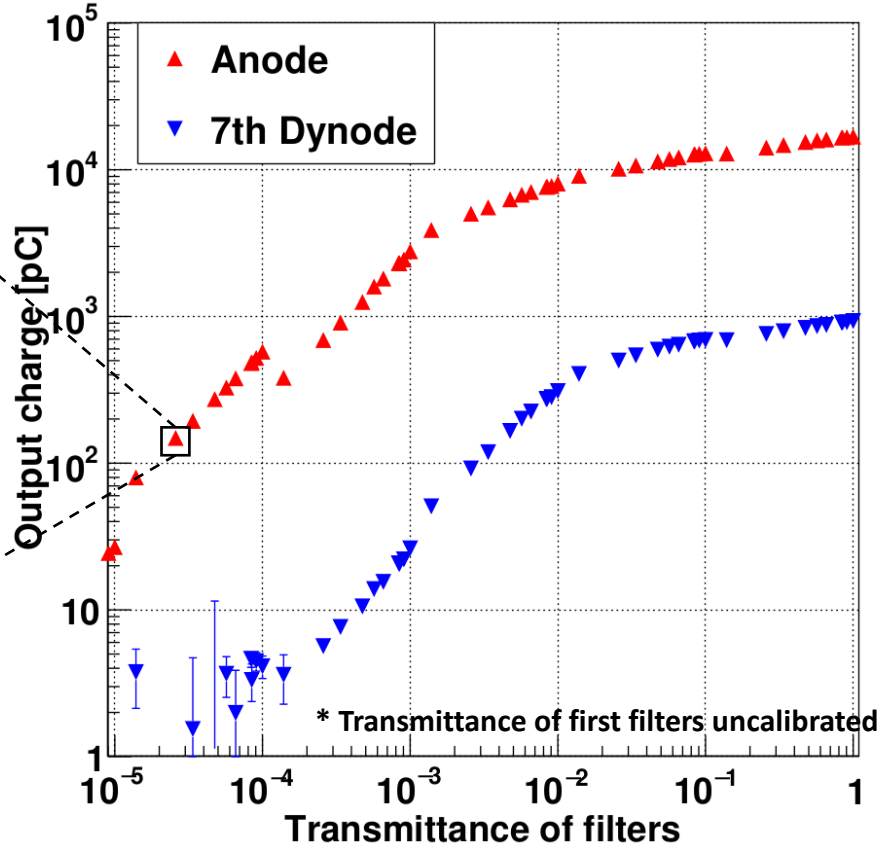
✓ Various filter combinations yielded ADC data for 1,000 events each.

# Result (1): **Linearity plots**

**Charge distribution of anode**
**(First filter: $10^{-4}$, Second filter: 0.2)**




Gaussian peak: 148.6 ± 0.6 pC



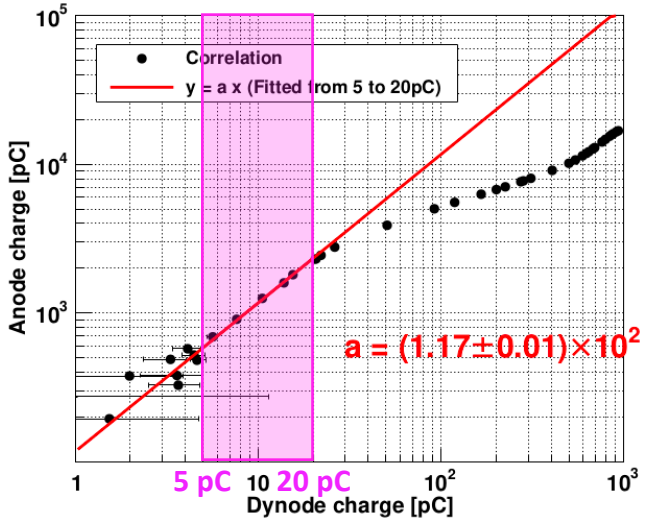
# Result (2): **Calibration between anode and dynode**

① Derive the gain ratio $a$: anode / dynode

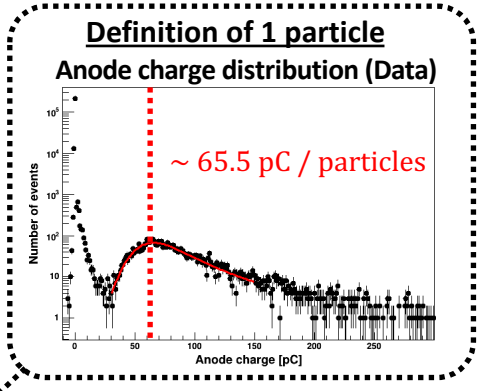
② Convert dynode signals into anode signals

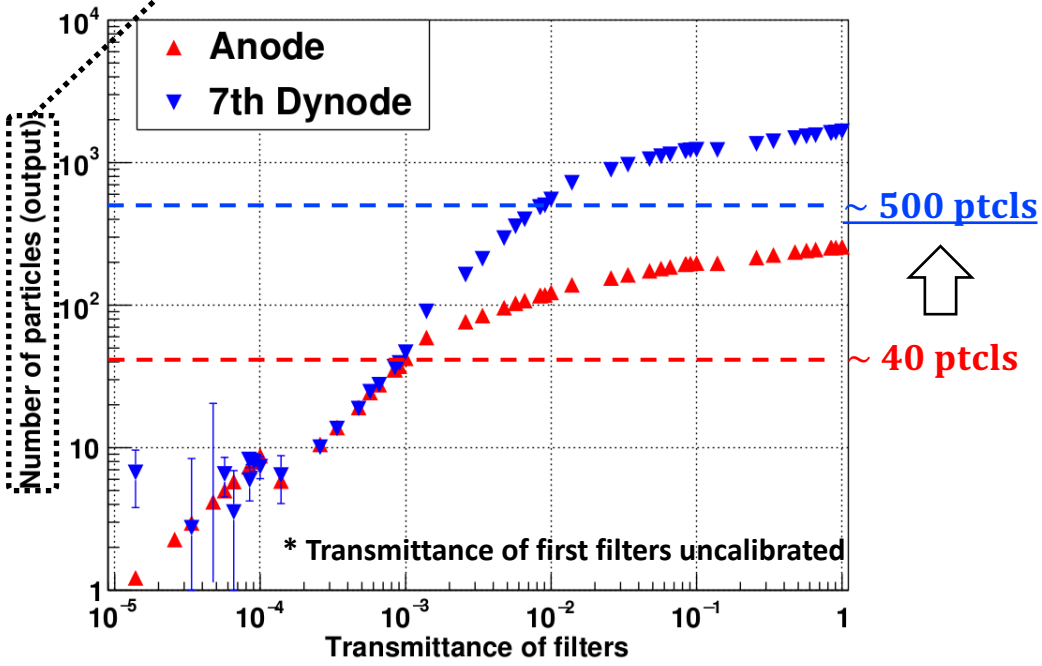
①

**Correlation between anode and dynode charges**




②




✓ Linearity range has been extended from ~ 40 to **~ 500 particles.**

# Summary & Next step

## ❑Summary

1. **Linearity range up to 1,000 particles/detector** required for ALPACA.
2. **Readout at seventh dynode** has been studied for extension of 2inch-PMT linearity range.
3. **UV laser calibration system** for PMT linearity measurement has been set up.
4. Linearity range of 2-inch PMT has been extended from ~40 to **~500 particles**.

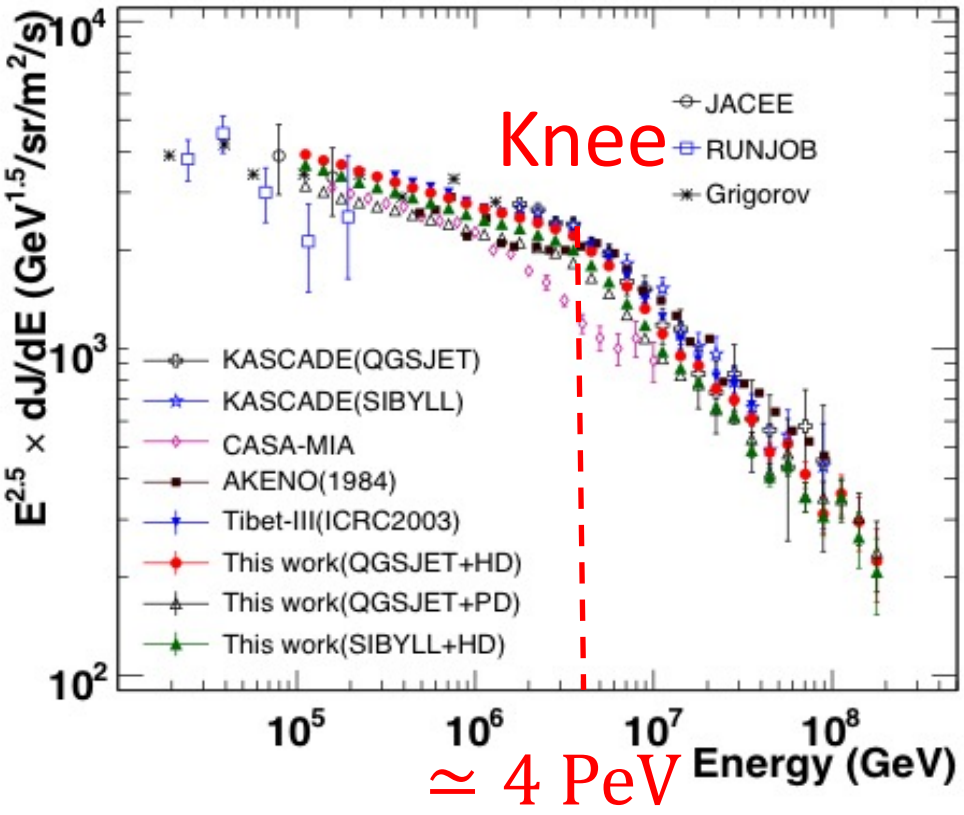
## ❑Next step

1. To extend linearity range up to 1,000 particles
   - Dynode readout at **earlier stages (6th, 5th, …)**
   - Try another voltage distribution ratio **(tapered divider)**
2. For more accurate measurements of linearities
   - Measurement of filter transmittances **with UV laser (wavelength: 405 nm)**

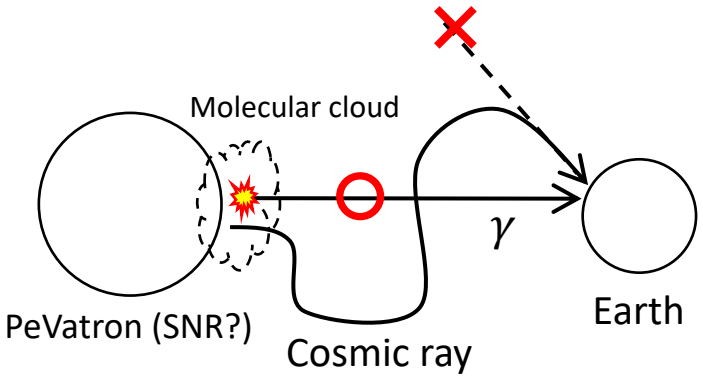
# Backup slides

# Origin of High-energy cosmic rays

Energy spectrum of all particles




M. Amenomori et al. *ApJ*, 678, 1165 (2008)



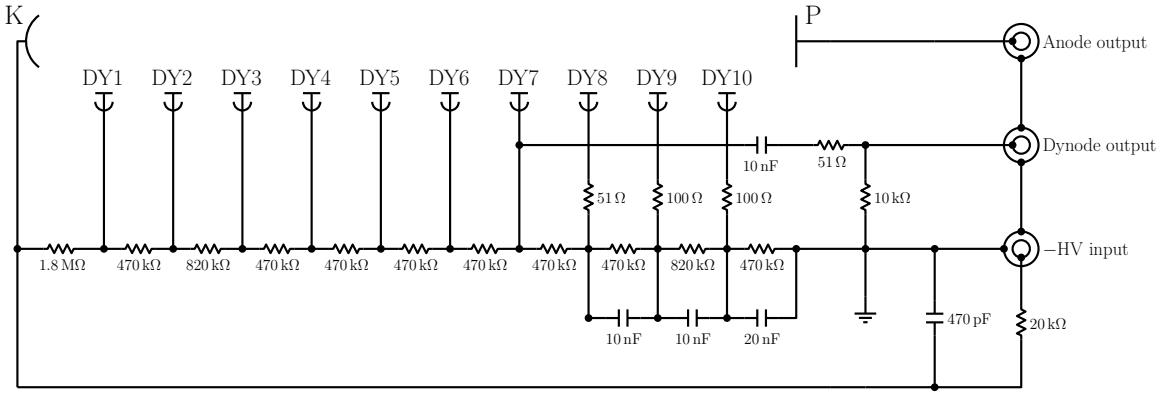

Indirect observation of cosmic rays:

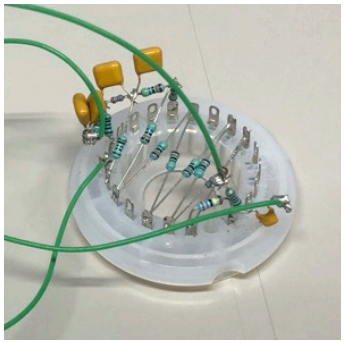
$$p(\mathrm{PeV}) + p \rightarrow p + p + \pi^0 + \pi^{\pm}$$

$\pi^0 \rightarrow 2\gamma$ (sub-PeV)

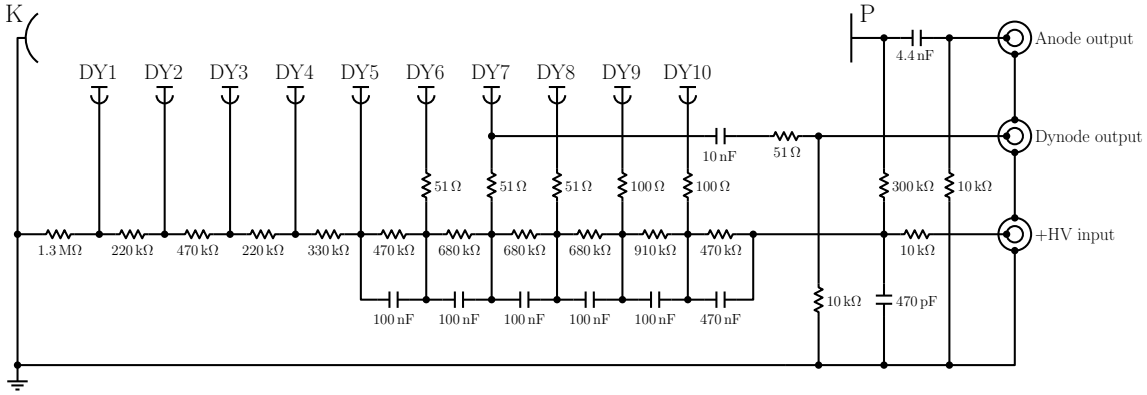
# Voltage divider (1): Circuits

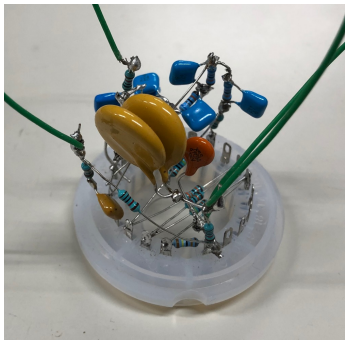
## Normal divider (This time)



## Tapered divider (Next step)



Already created and ready to be tested!

# Voltage divider(2): Voltage distribution ratio

## Sum of ratios normalized by 100

Dynode readout | Anode readout

| K | DY1 | DY2 | DY3 | DY4 | DY5 | DY6 | DY7 | DY8 | DY9 | DY10 | P |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Nomal** | 25 | 6.25 | 12.5 | 6.25 | 6.25 | 6.25 | 6.25 | 6.25 | 6.25 | 12.5 | 6.25 |
| **Tapered** | 21.1 | 3.51 | 7.02 | 3.51 | 5.26 | 7.02 | 10.5 | 10.5 | 10.5 | 14.0 | 7.02 |

## Accumulation of ratios

| K | DY1 | DY2 | DY3 | DY4 | DY5 | DY6 | DY7 | DY8 | DY9 | DY10 | P |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Nomal** | 25 | 31.3 | 43.8 | 50.0 | 56.3 | 62.5 | 68.8 | 75.0 | 81.3 | 93.8 | 100 |
| **Tapered** | 21.1 | 24.6 | 31.6 | 35.1 | 40.4 | 47.4 | 57.9 | 68.4 | 78.9 | 93.0 | 100 |

# Measurement Procedure

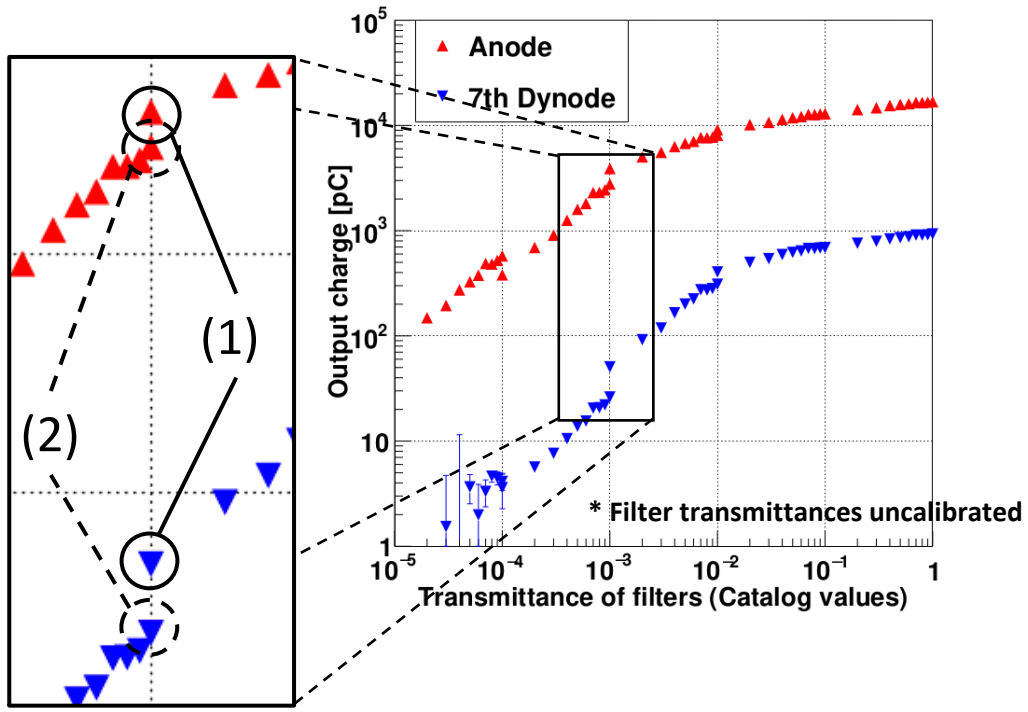
✓ Increased transmittance gradually and measured ADC value for 1,000 events.

| Transmittance (Catalog value) | |
|---|---|
| First filters | Second filters |
| 1 | 1 |
| $10^{-1}$ | 0.9 |
| $10^{-2}$ | 0.8 |
| $10^{-3}$ | 0.7 |
| $10^{-4}$ | 0.6 |
| $10^{-5}$ | 0.5 |
| $10^{-6}$ | 0.4 |
| $10^{-7}$ | 0.3 |
| | 0.2 |
| | 0.1 |

| Measurement number (1,000 events each) | Filter transmittance | | |
|---|---|---|---|
| | Fisrt | Second | **Total** |
| 1 | $10^{-7}$ | 0.1 | **$1 \times 10^{-8}$** |
| 2 | | 0.2 | **$2 \times 10^{-8}$** |
| ⋮ | | ⋮ | ⋮ |
| 10 | | 1 | **$1 \times 10^{-7}$** |
| 11 | $10^{-6}$ | 0.1 | **$1 \times 10^{-7}$** |
| 12 | | 0.2 | **$2 \times 10^{-7}$** |
| ⋮ | ⋮ | ⋮ | ⋮ |
| 79 | 1 | 0.9 | **0.9** |
| 80 | | 1 | **1** |

# Systematic errors of ND filters (1)

| Transmittance (Catalog value) | |
|---|---|
| First filters | Second filters |
| 1 | 1 |
| $10^{-1}$ | 0.9 |
| $10^{-2}$ | 0.8 |
| $10^{-3}$ | 0.7 |
| $10^{-4}$ | 0.6 |
| $10^{-5}$ | 0.5 |
| $10^{-6}$ | 0.4 |
| $10^{-7}$ | 0.3 |
| | 0.2 |
| | 0.1 |




| | Transemittance | | |
|---|---|---|---|
| | First | Second | **Total** |
| (1) | $10^{-3}$ | 1 | $10^{-3}$ |
| (2) | $10^{-2}$ | 0.9 | $10^{-3}$ |

If filter transmittances is correct, the charges should be equal in cases (1) and (2).

✓ Filter transmittances are <u>not equal to the catalog values.</u>

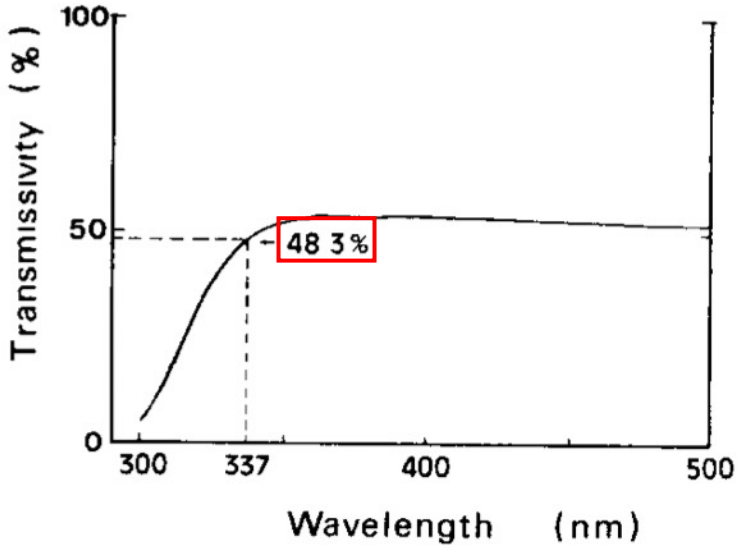
# Systematic errors of ND filters (2)

| First filters | | Second filters | |
|---|---|---|---|
| Catalog value | Measured value | Catalog value | Measured value |
| 1 | 1 | 1 | 1 |
| $10^{-1}$ | | 0.9 | 0.906 |
| $10^{-2}$ | | 0.8 | 0.836 |
| $10^{-3}$ | | 0.7 | 0.846 |
| $10^{-4}$ | | 0.6 | 0.658 |
| $10^{-5}$ | | 0.5 | 0.569 |
| $10^{-6}$ | | 0.4 | 0.475 |
| $10^{-7}$ | | 0.3 | 0.337 |
| | | 0.2 | 0.258 |
| | | 0.1 | 0.139 |

← Measured value: For UV laser **(405 nm )**

| First attenuator | | Second attenuator | |
|---|---|---|---|
| Catalog value | Measured value | Catalog value | Measured value |
| $10^{-1}$ | 0.112 | 0.9 | 0.813 |
| $10^{-2}$ | $8.1\times10^{-3}$ | 0.8 | 0.683 |
| $10^{-3}$ | $5.3\times10^{-4}$ | 0.7 | 0.653 |
| $10^{-4}$ | $9.4\times10^{-5}$ | 0.6 | 0.553 |
| $10^{-5}$ | $3.6\times10^{-6}$ | 0.5 | 0.483 |
| $10^{-6}$ | $1.1\times10^{-7}$ | 0.4 | 0.408 |
| | | 0.3 | 0.290 |
| | | 0.2 | 0.220 |
| | | 0.1 | 0.129 |

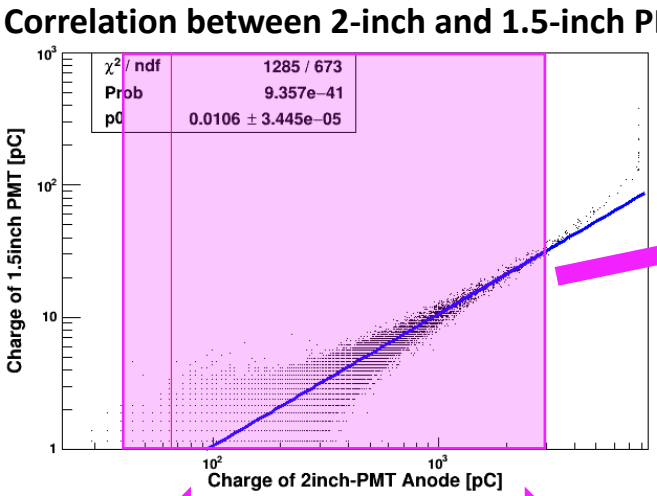
↑ Measured value: For nitrogen gas laser **(337 nm )**



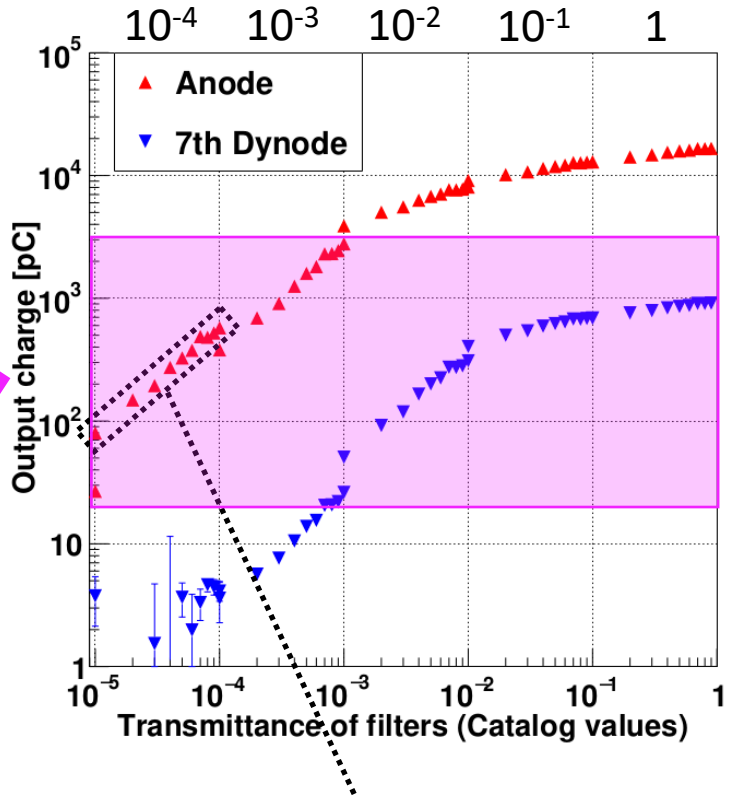

M. NISHIZAWA et al., NIM, A285, p532-539, 1989.

# Measurement of filter transmittance (1): Second filters

✓ Measured Using 2-inch PMT




Linearity range of 2-inch PMT




(1st = $10^{-4}$, 2nd = 0.1, 0.2, …, 1)

| Transmittance (Catalog value) | |
|---|---|
| First filters | Second filters |
| 1 | 1 |
| $10^{-1}$ | 0.9 |
| $10^{-2}$ | 0.8 |
| $10^{-3}$ | 0.7 |
| $10^{-4}$ | 0.6 |
| $10^{-5}$ | 0.5 |
| $10^{-6}$ | 0.4 |
| $10^{-7}$ | 0.3 |
| | 0.2 |
| | 0.1 |

Digit adjustment

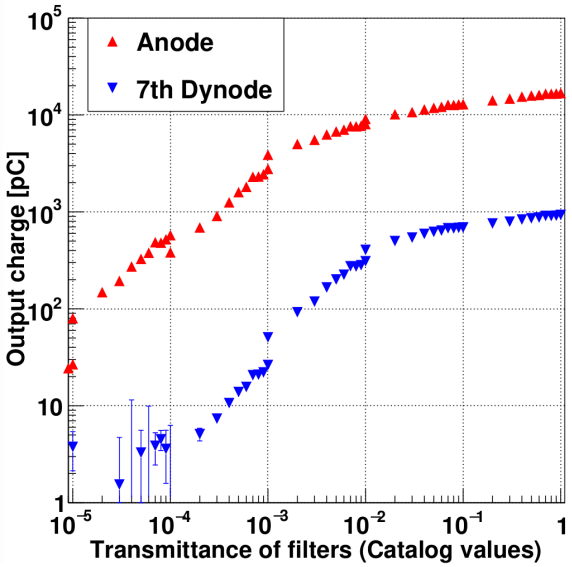
Adjustment by 10% each

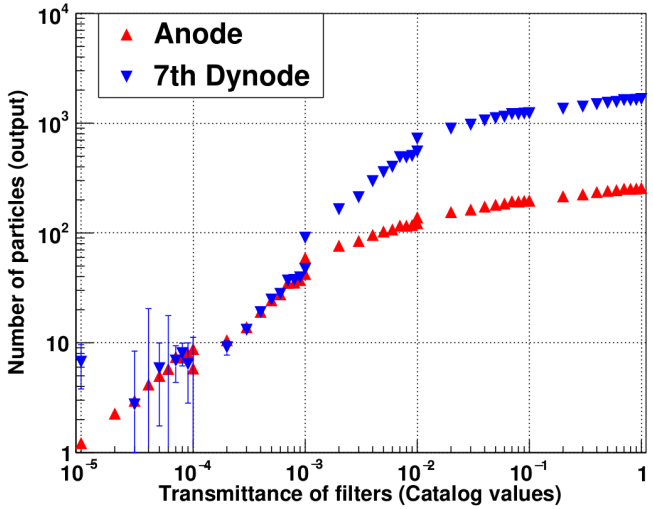
**Transmittances of second filters:**

$$T_{2nd} \equiv \frac{\mathrm{Charge}(1_{st}=10^{-4},\ 2_{nd}=0.1,0.2,\cdots,0.9)}{\mathrm{Charge}(1_{st}=10^{-4},\ 2_{nd}=1)}$$

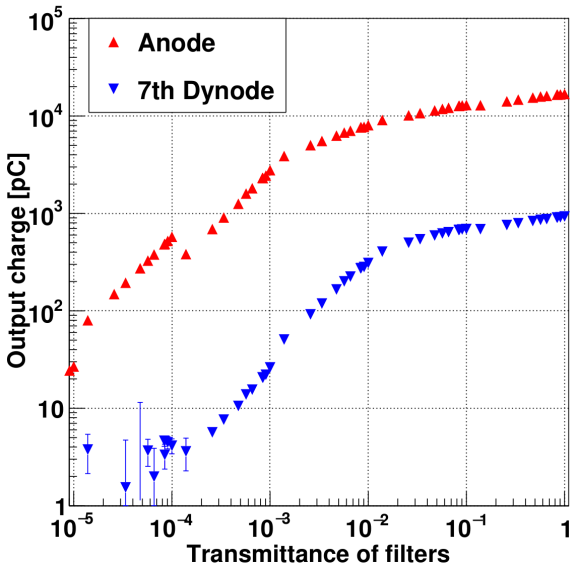
# Measurement of filter transmittance (1): Second filters

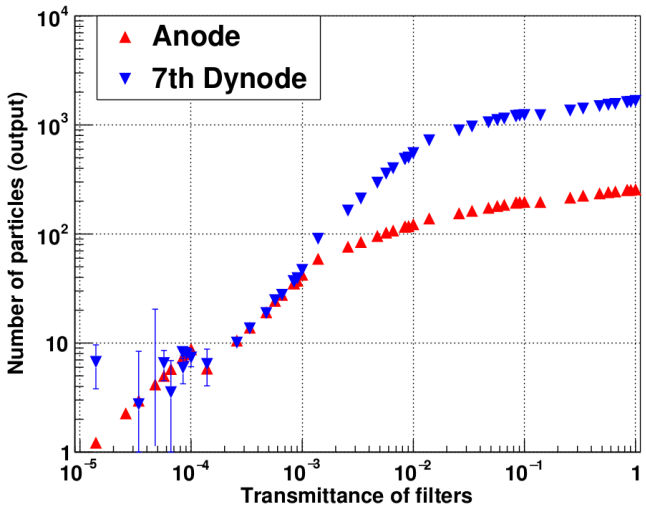
## Before calibration




## After calibration

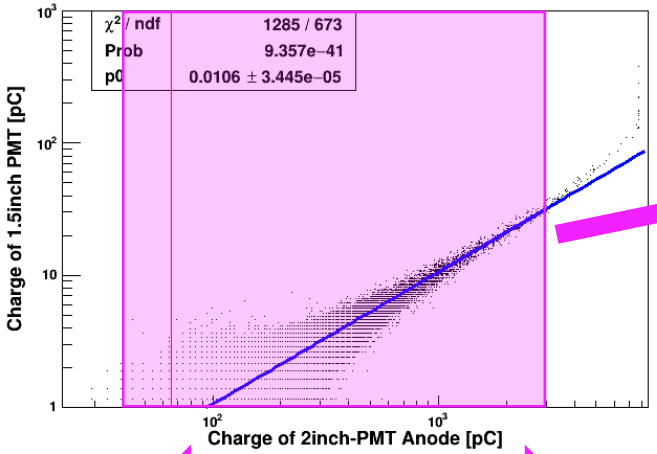


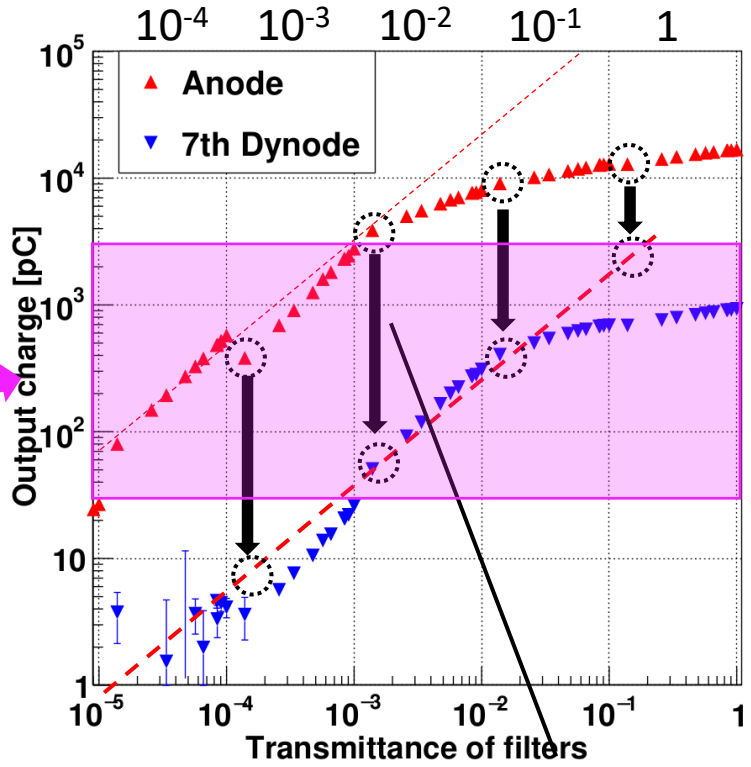
# Measurement of filter transmittance (2): First filters

✓ Plan to measure with 2-inch PMT

**Correlation between 2-inch and 1.5-inch PMT**



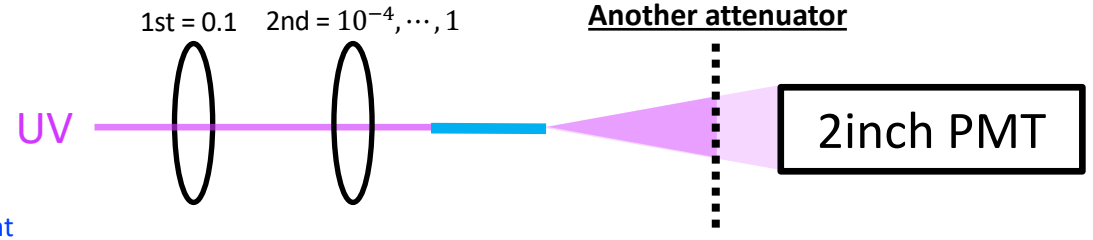

Linearity range of 2-inch PMT




| Transmittance (Catalog value) | |
|---|---|
| First filters | Second filters |
| 1 | 1 |
| $10^{-1}$ | 0.9 |
| $10^{-2}$ | 0.8 |
| $10^{-3}$ | 0.7 |
| $10^{-4}$ | 0.6 |
| $10^{-5}$ | 0.5 |
| $10^{-6}$ | 0.4 |
| $10^{-7}$ | 0.3 |
| | 0.2 |
| | 0.1 |

Digit adjustment

Adjustment by 10% each




**Transmittances of second filters:**

$$T_{1st} \equiv \frac{\mathrm{Charge}(1_{st}=10^{-4,-3,-2,-1}, 2_{nd}=0.1)}{\mathrm{Charge}(1_{st}=1, 2_{nd}=0.1)}$$