ALPACA Experiment

Andes Large area PArticle detector for Cosmic ray physics and Astronomy

ALPACA実験用2インチ径PMTのダイナミックレンジの拡張

Dynamic-range extension of 2-inch-diameter PMT for ALPACA experiment

東大宇宙線研 D1 川島 輝能

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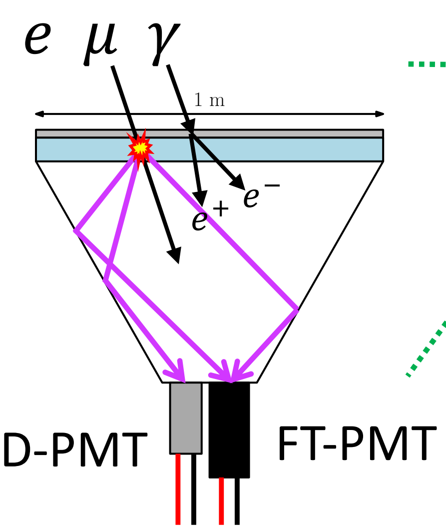
The ALPACA experiment (2025-)

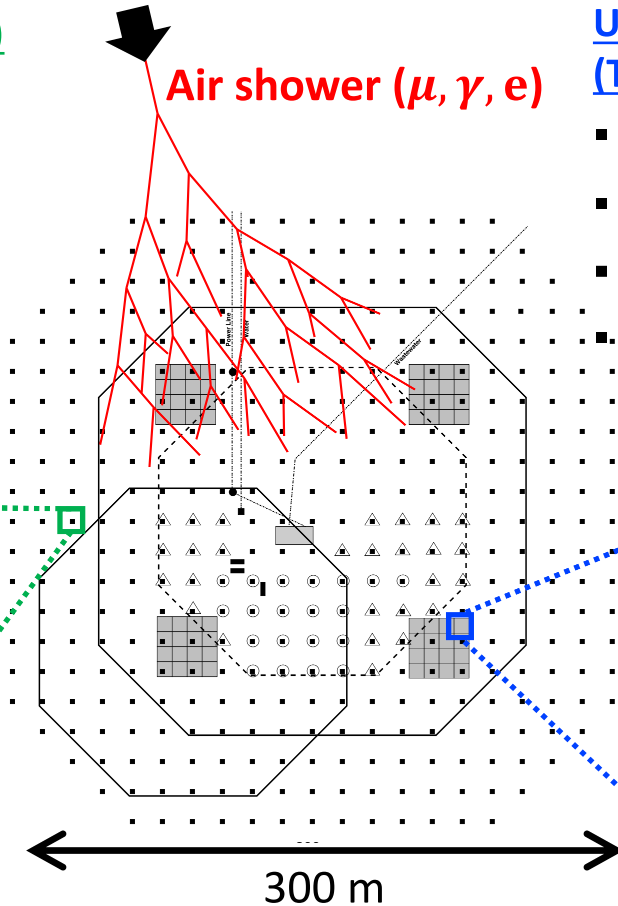
✓ **Goal: Gamma-ray observation from <u>sub-PeV energies</u> in the southern sky**

Gamma ray or BG cosmic ray

<u>Surface air shower Detectors (SDs)</u>
<u>(Coverage: 83,000 m^2)</u>

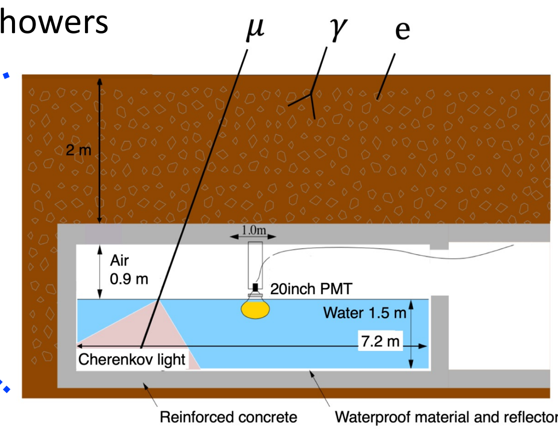
- 1 m^2 Scintillation detector (× 401)
- Wide dynamic range is achieved by using <u>two PMTs with different gains</u>
- Determine the primary energy and its arrival direction



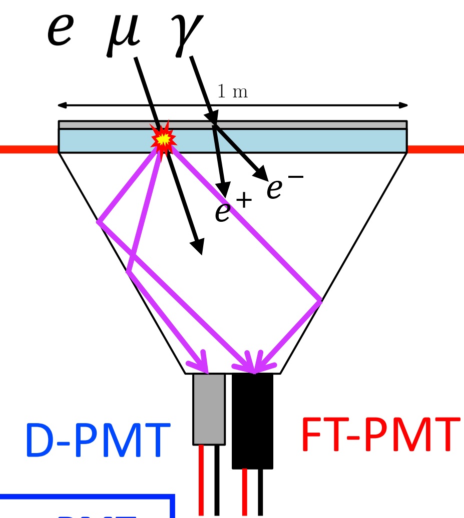


<u>Underground Muon Detectors (MDs)</u>
<u>(Total area: 3,600 m^2)</u>

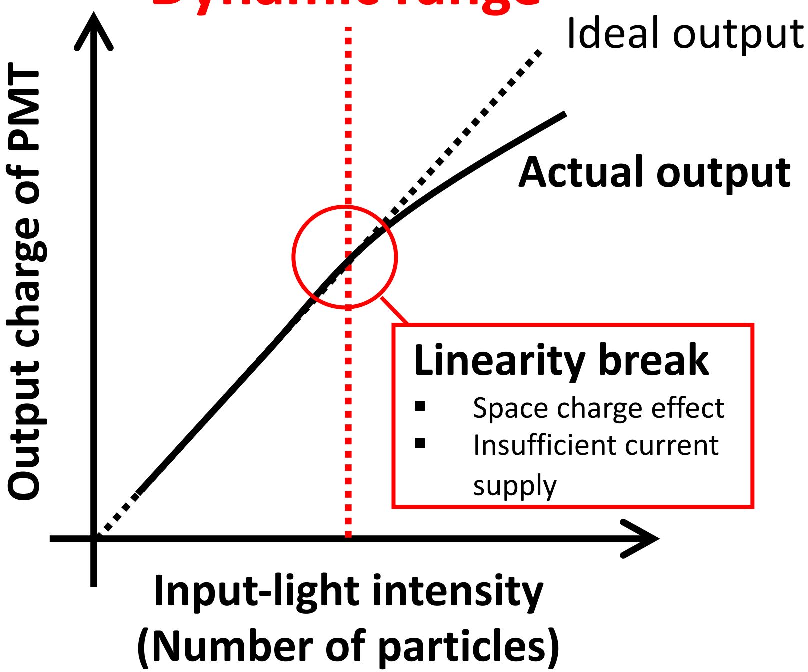
- Under 2 m soil
- 56 m^2 / cells × 64 cells
- A 20-inch PMT is installed each cell
- Discriminate between gamma rays and cosmic rays by the number of muons in showers



Motivation of this research



- Why need to extend the dynamic range of 2-inch-diameter PMT?



Wide Dynamic range PMT
(up to several thousands of particles)

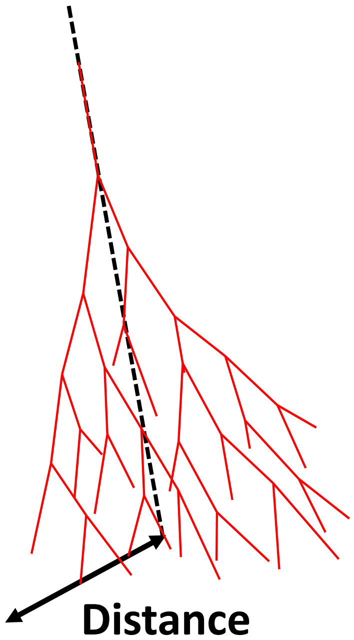
1.5-inch ϕ

Fast Timing PMT
Mainly used to determine direction
(up to several tens of particles)

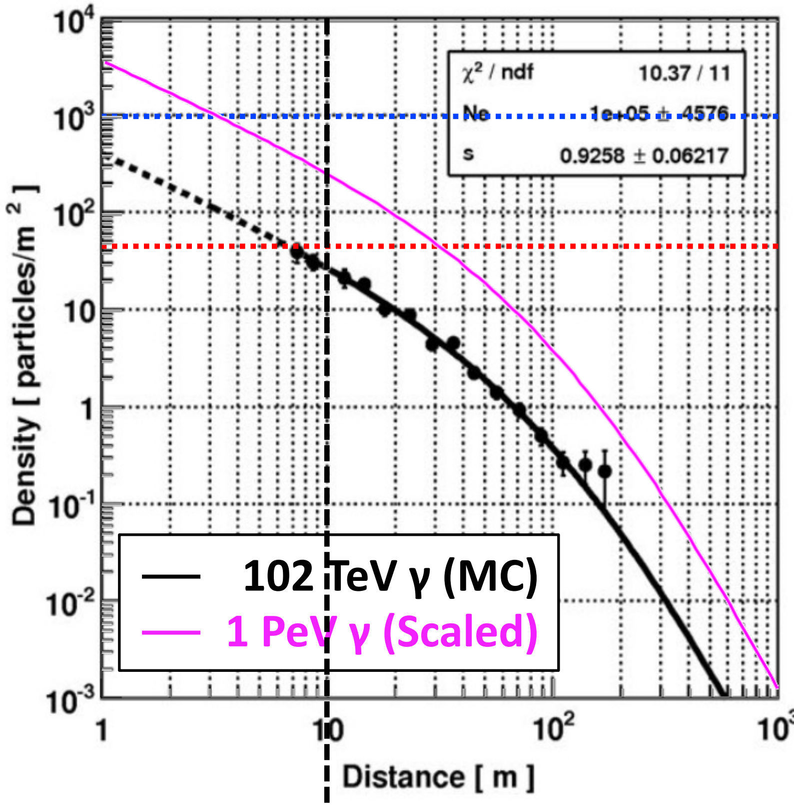
2-inch ϕ

✓ Extending the dynamic range of FT-PMT enables the experiment **w/ only FT-PMTs**

Required dynamic range for ALPACA



Lateral distribution



Target: 1,000 particles

The number of particles detectable by FT-PMT:
≲ several tens of particles

K. Kawata, et al., Experimental Astronomy, 44:1-9 (2017).

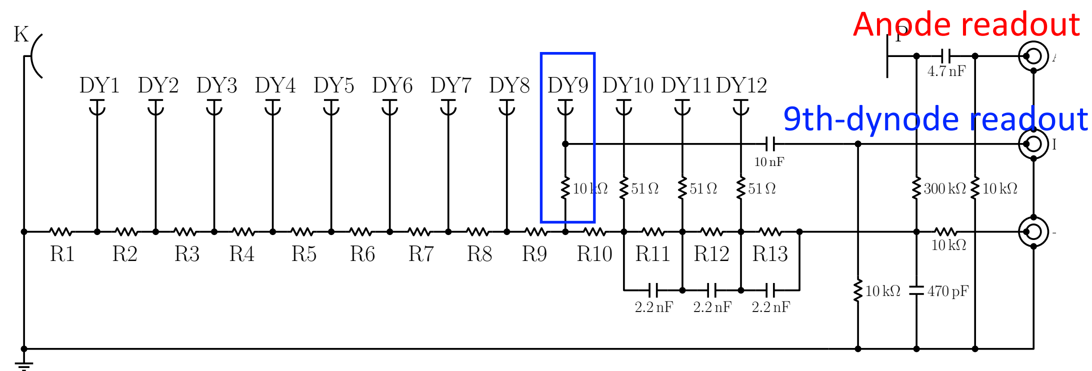
Use data for energy reconstruction

✓ Need to extend the dynamic range of FT-PMT up to **~1,000 particles** equivalent to a few PeV gamma-ray shower

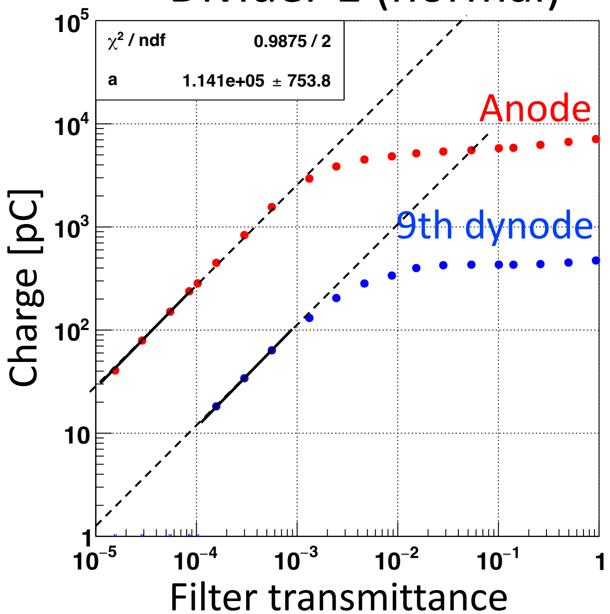
Results reported at 2023 Autumn Meeting

<u>R7725 (2-inch-diameter PMT)</u>

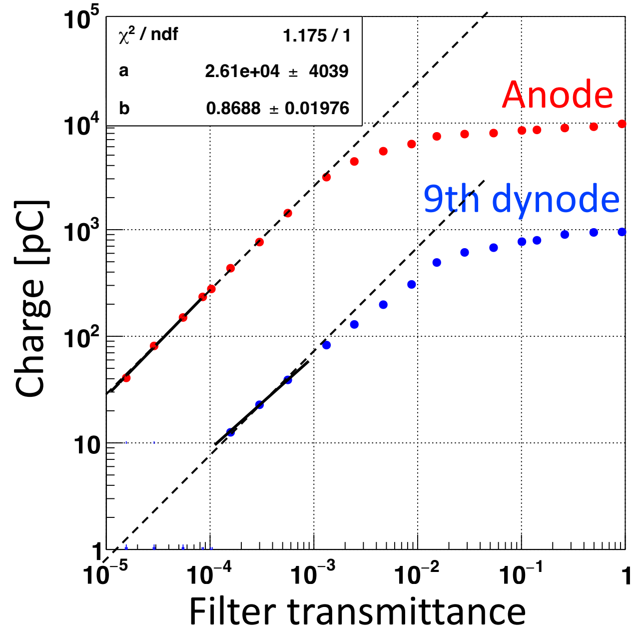
- Made by Hamamatsu Photonics K.K.
- High voltage: 1750 V (Max.: 2000 V)
- Number of dynodes: **12**
- Made **three dividers** with different ratios of voltage distributions



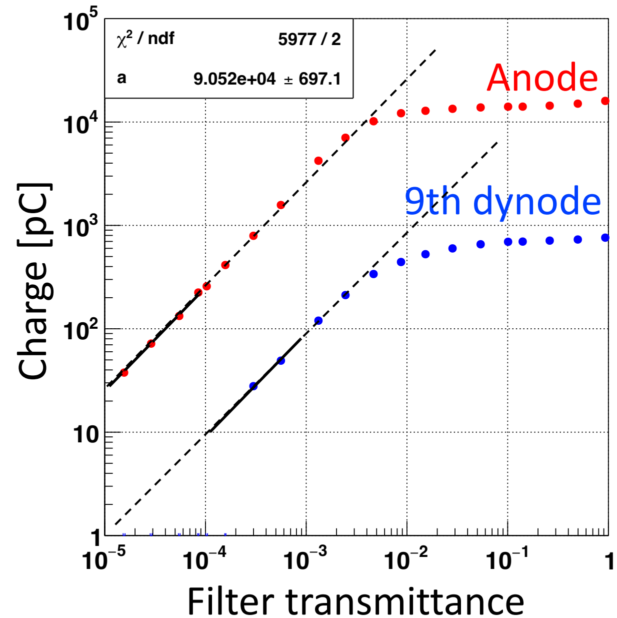
Divider 1 (normal)



Divider 2



Divider 3



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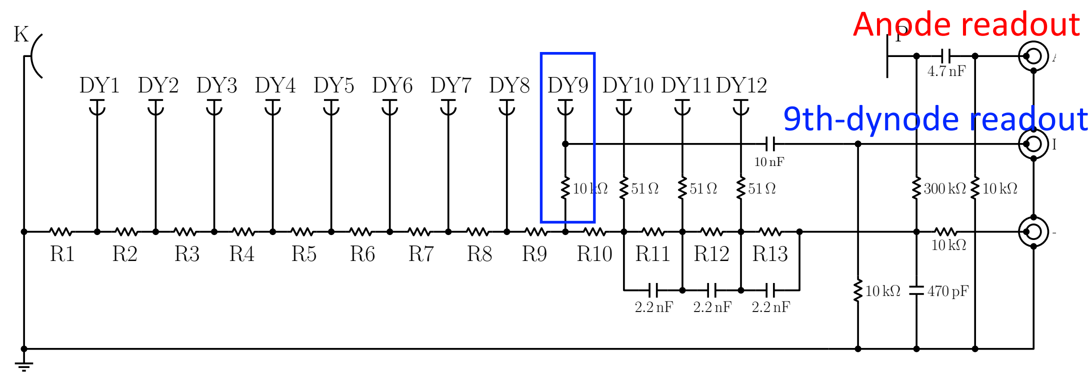
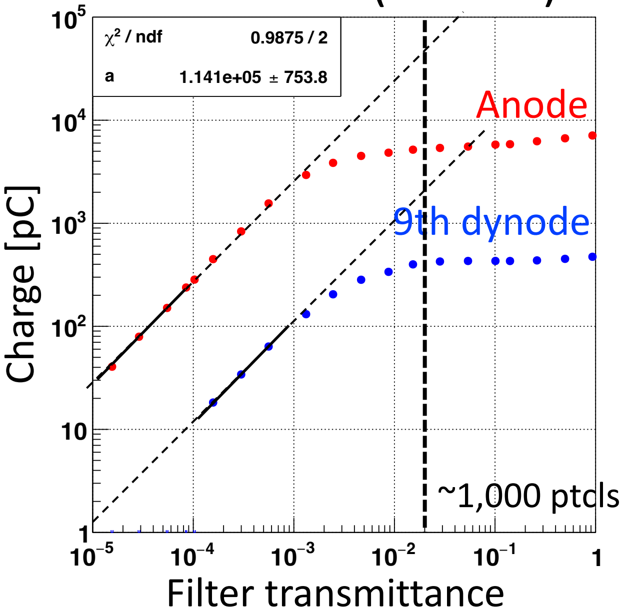
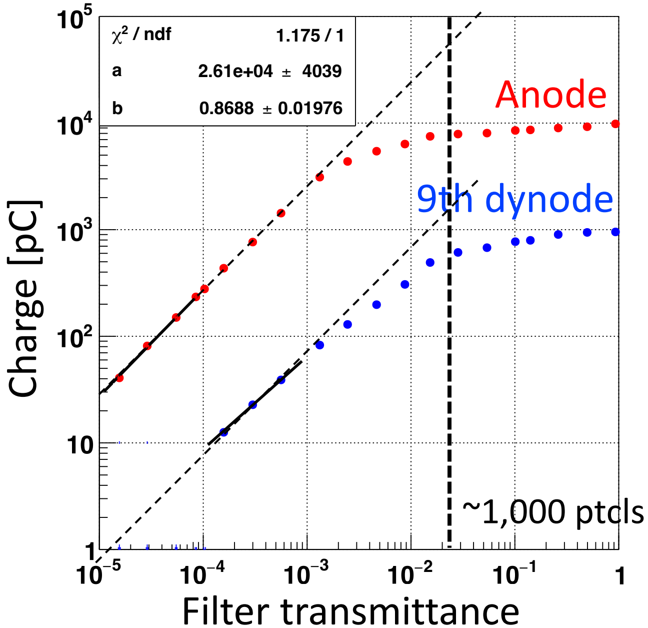


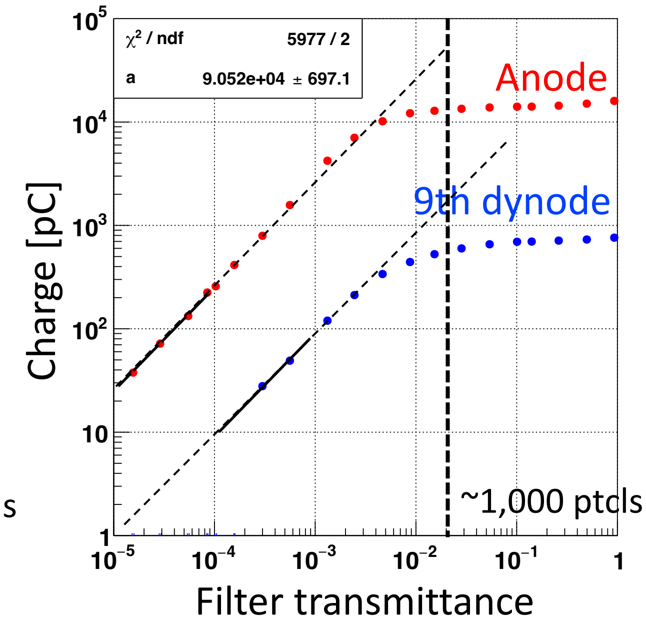
Divider 1 (normal)



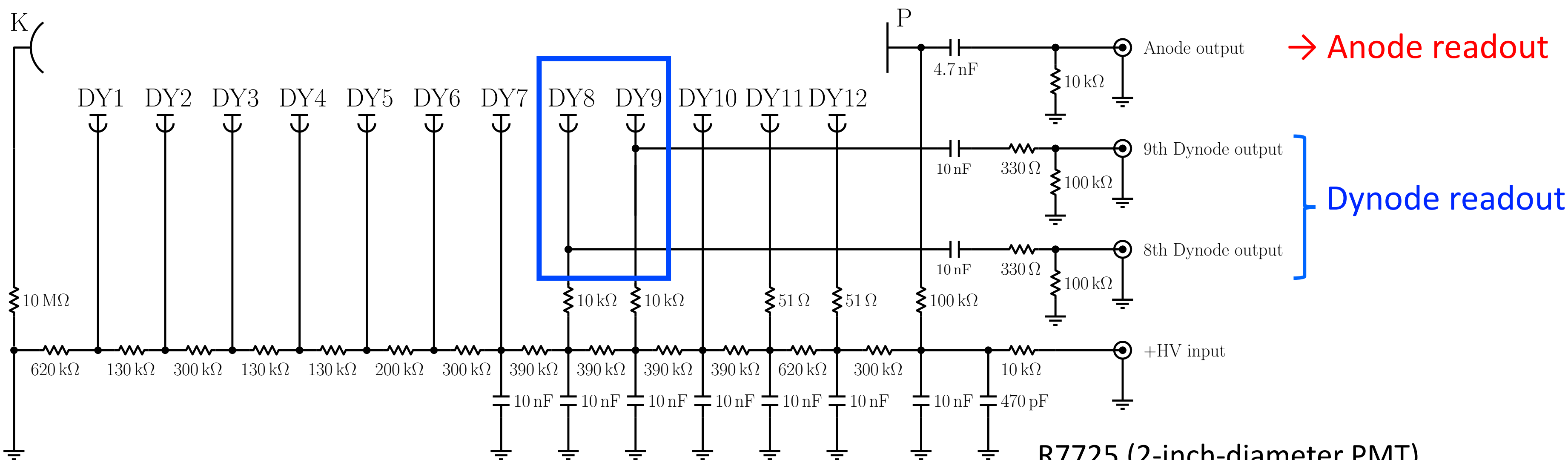
Divider 2



Divider 3



Divider design for ALPACA 2024



R7725 (2-inch-diameter PMT)

- Made by Hamamatsu Photonics K.K.
- High voltage: 1750 V (Max.: 2000 V)
- Number of dynodes: **12**

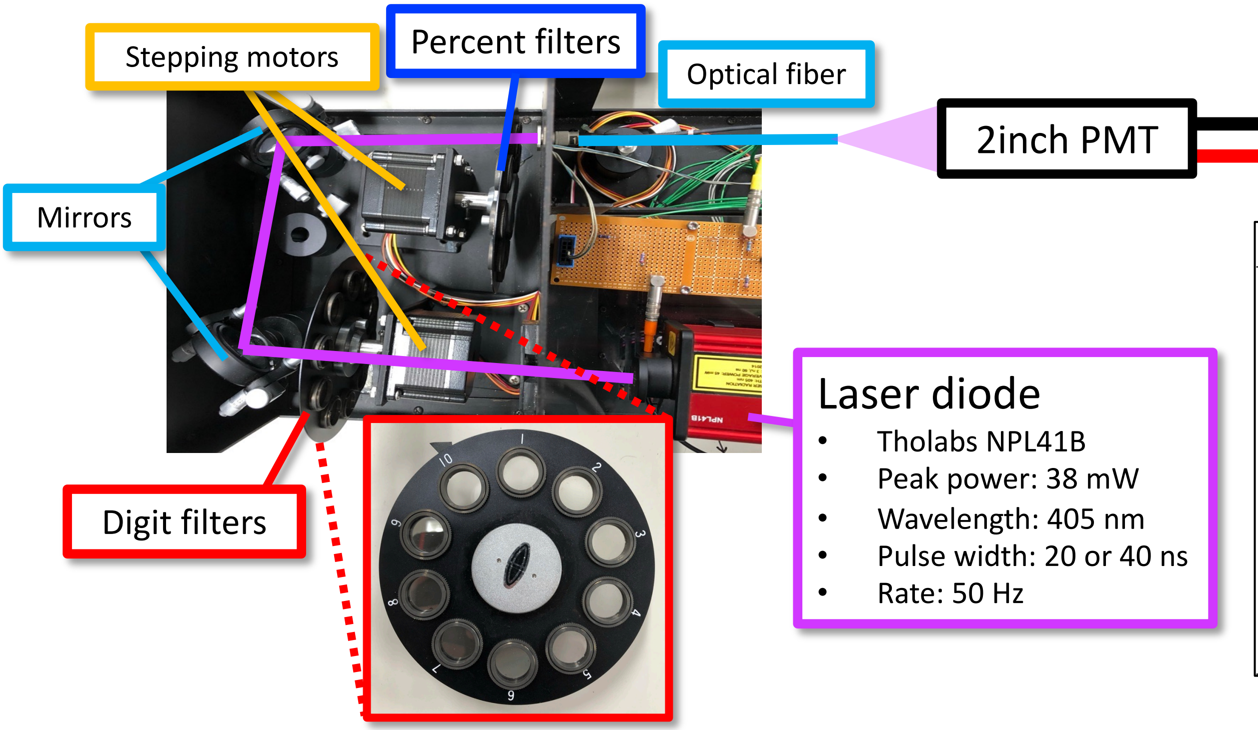
Voltage distribution ratios

Electrode	**K**	**DY1**	**DY2**	**DY3**	**DY4**	**DY5**	**DY6**	**DY7**	**DY8**	**DY9**	**DY10**	**DY11**	**DY12**	**P**
Normal	21.4	5.65	11.1	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	11.1	5.65	
This time	14.5	3.03	6.99	3.03	3.03	4.66	6.99	9.09	9.09	9.09	9.09	14.5	6.99	

- The total resistance is ~4.3 MΩ.
- The sum of the ratios from the cathode (K) to the anode (P) is normalized to 100.
- The tapered ratio referred to the previous study* using the same PMT.

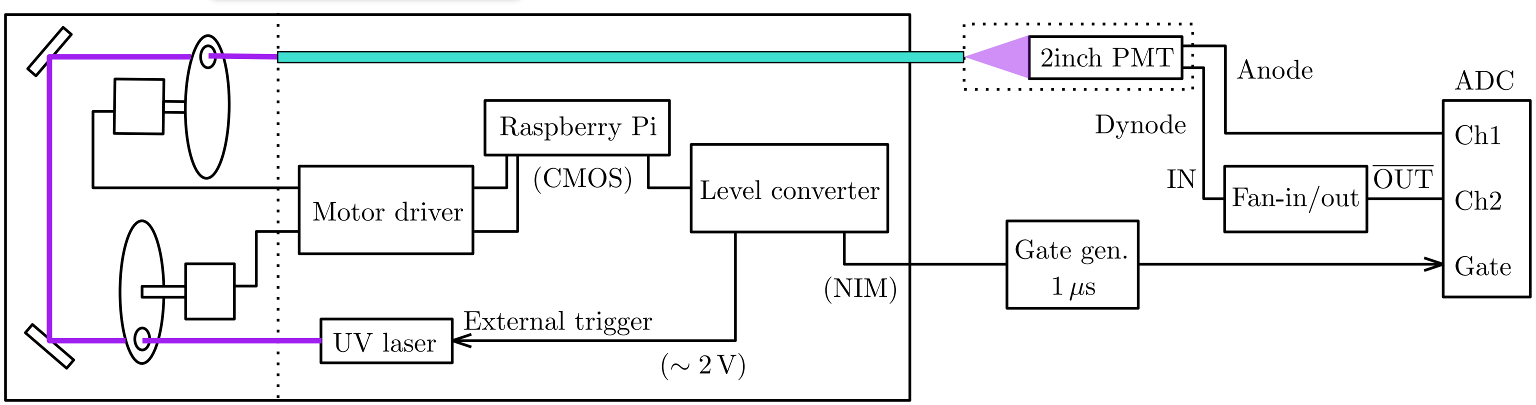
* Y. Zhang et al., JINST, 12, P11011 (2017).

Irradiation system of pulse laser to test PMT linearity



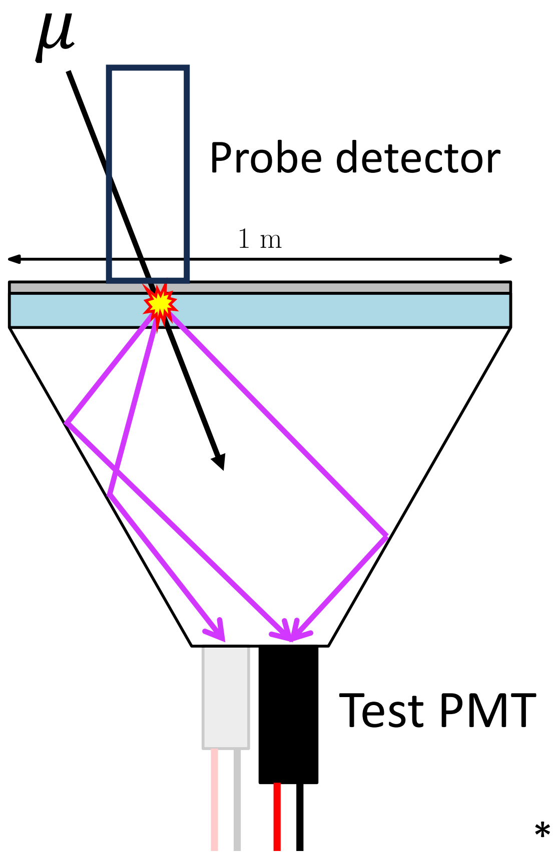
Filter transmittance

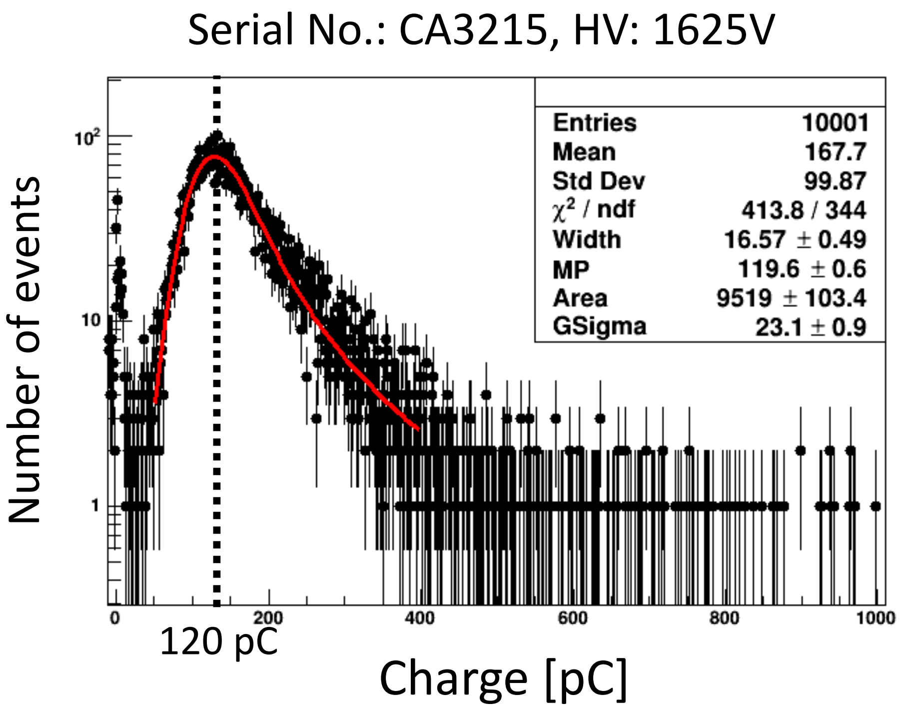
m, n	Digit filter	% filter
1	$(1.08 \pm 0.01) \times 10^{-1}$	0.828 ± 0.004
2	$(0.939 \pm 0.021) \times 10^{-2}$	0.767 ± 0.006
3	$(0.587 \pm 0.004) \times 10^{-3}$	0.801 ± 0.003
4	$(1.11 \pm 0.02) \times 10^{-4}$	0.594 ± 0.004
5	$(0.475 \pm 0.021) \times 10^{-5}$	0.518 ± 0.003
6		0.410 ± 0.002
7		0.282 ± 0.002
8		0.210 ± 0.002
9		0.123 ± 0.001



MIP measurement

✓ Gain is set at high voltages so that the signal amount of one particle corresponds to 120 pC/ptcl.

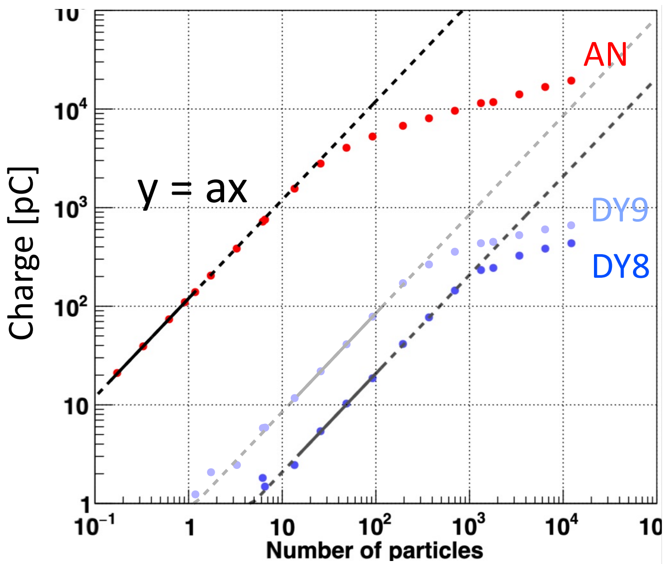


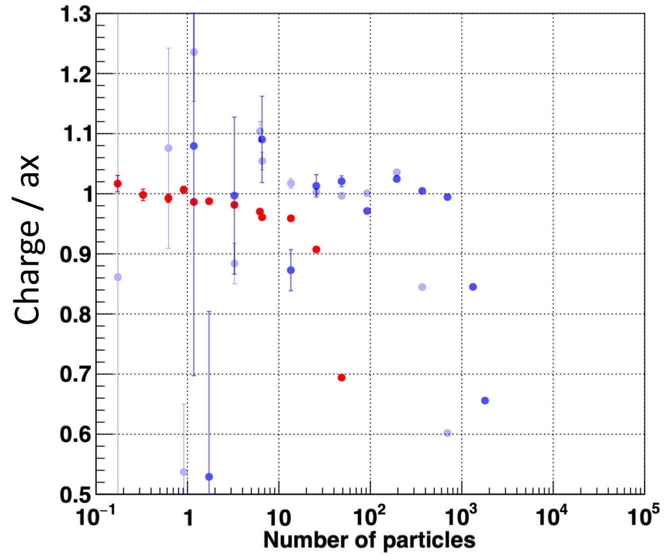


*Convoluted Landau and Gaussian Fitting Function.
(See langau.C: https://root.cern/doc/master/langaus_8C.html)

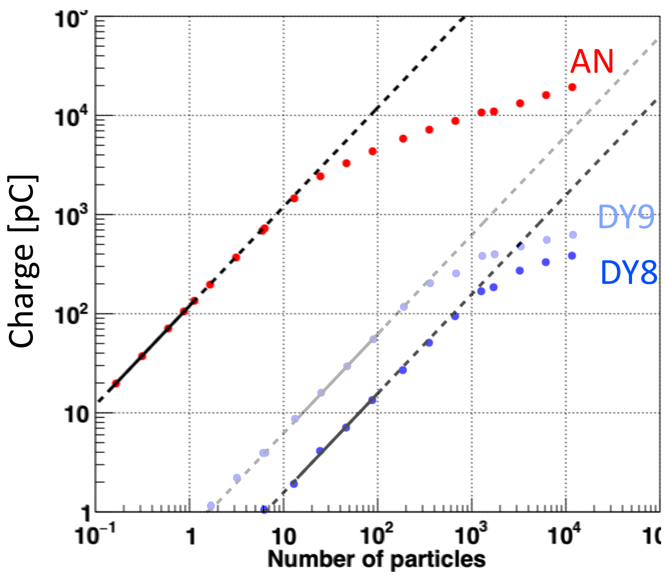
Measurement results of PMT linearity

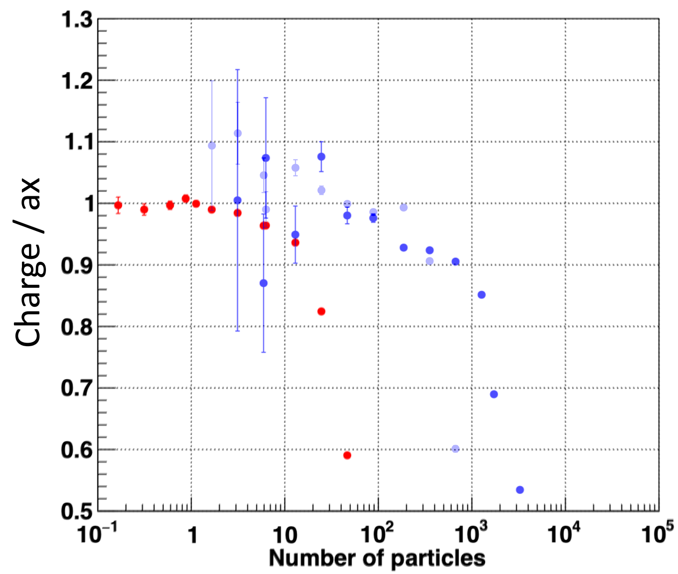
Serial No.: CA3215, HV: 1625V





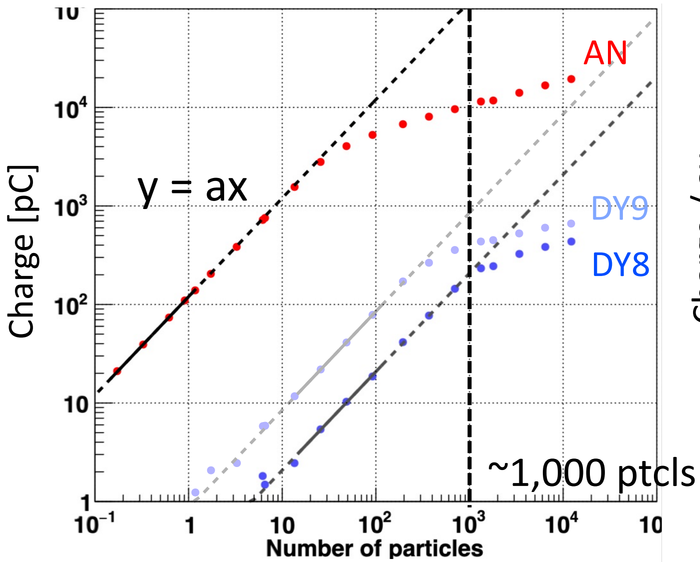
Serial No.: CA3511, HV: 1565V

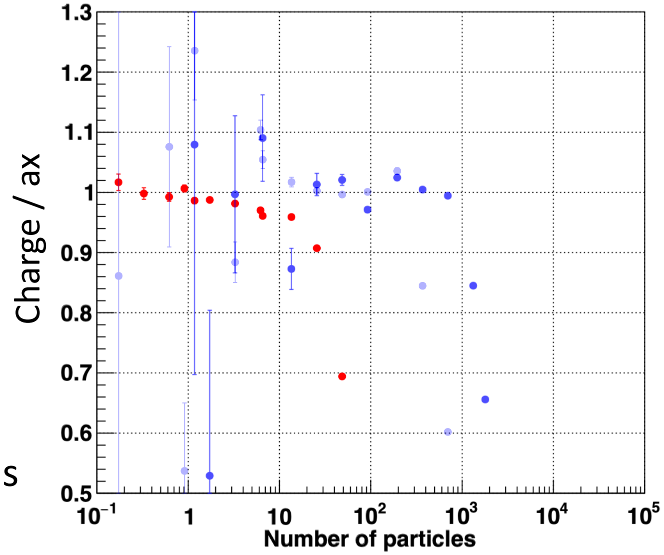




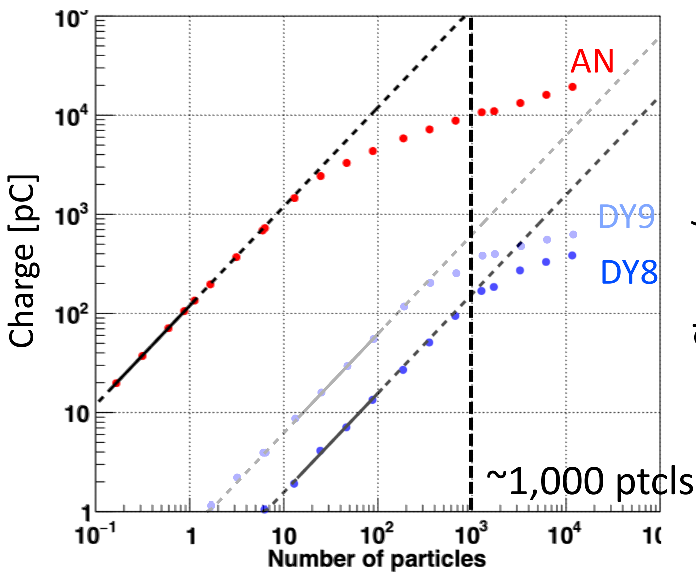
Measurement results of PMT linearity

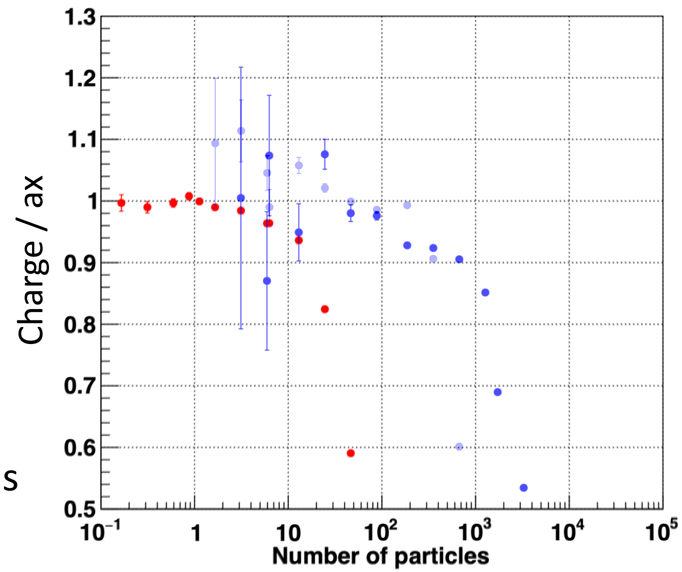
Serial No.: CA3215, HV: 1625V





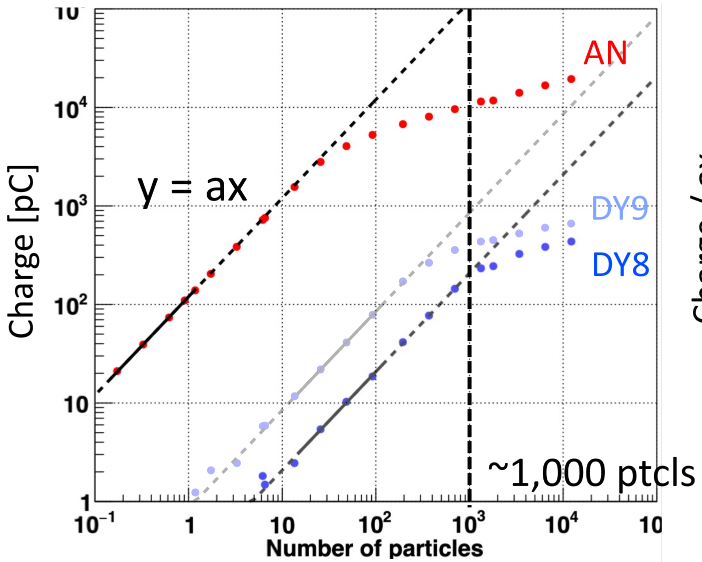
Serial No.: CA3511, HV: 1565V

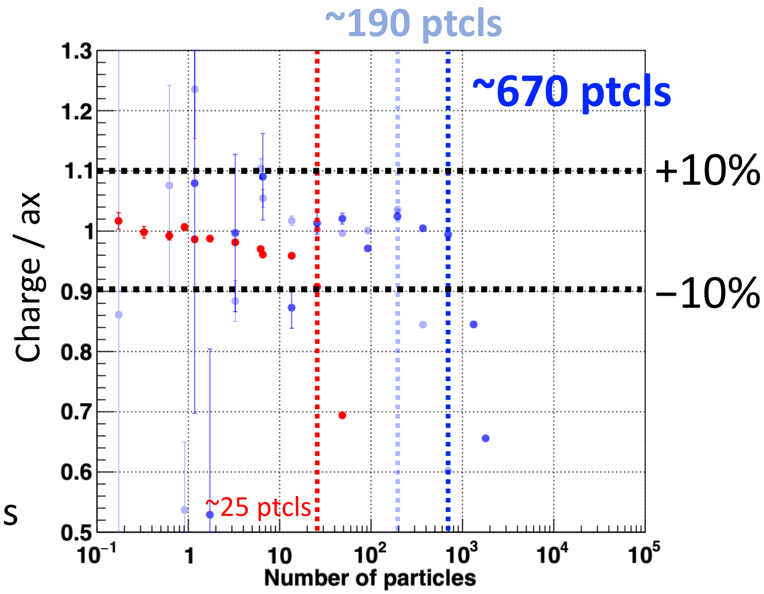




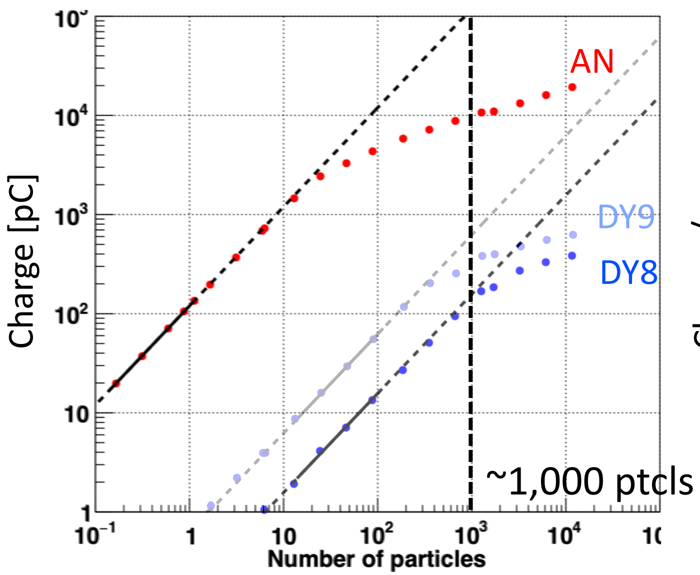
Measurement results of PMT linearity

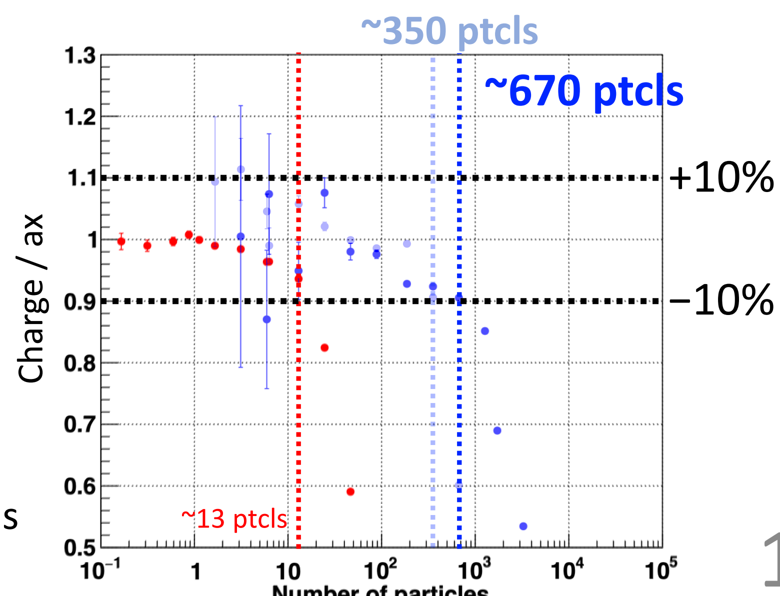
Serial No.: CA3215, HV: 1625V



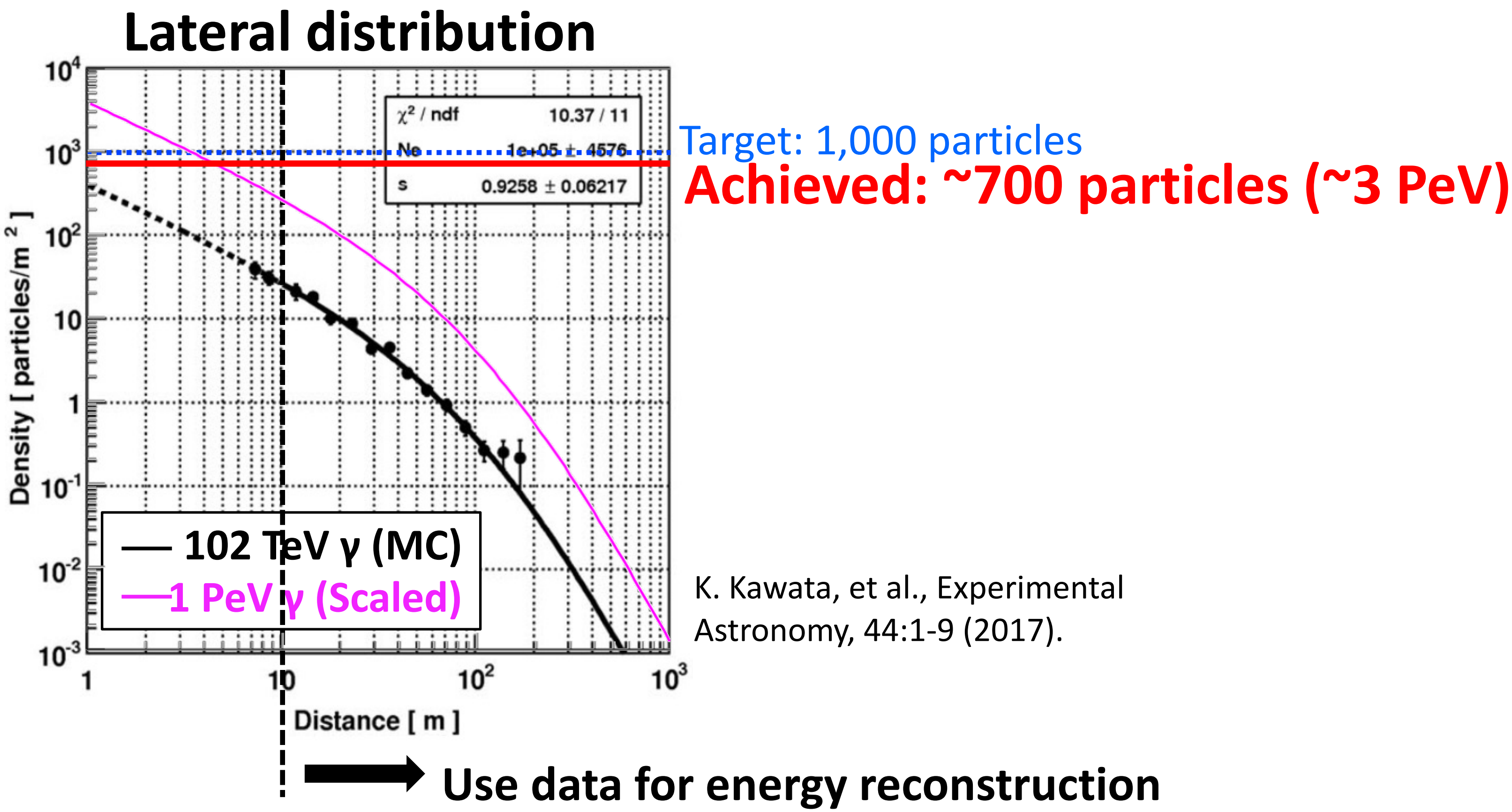


Serial No.: CA3511, HV: 1565V





What has been accomplished in this study



K. Kawata, et al., Experimental Astronomy, 44:1-9 (2017).

✓ The 8th-dynode readout enables us to measure up to ~3PeV.
→ **almost achieved target**

✓ Even the 9th dynode allows us to measure up to at least 1PeV.

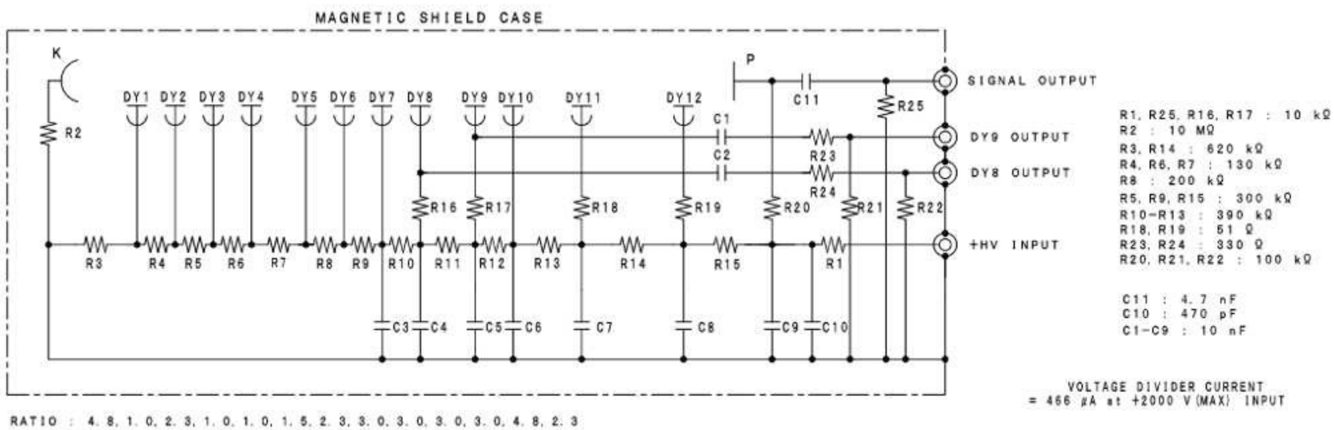
Divider design fixed for ALPACA 2024

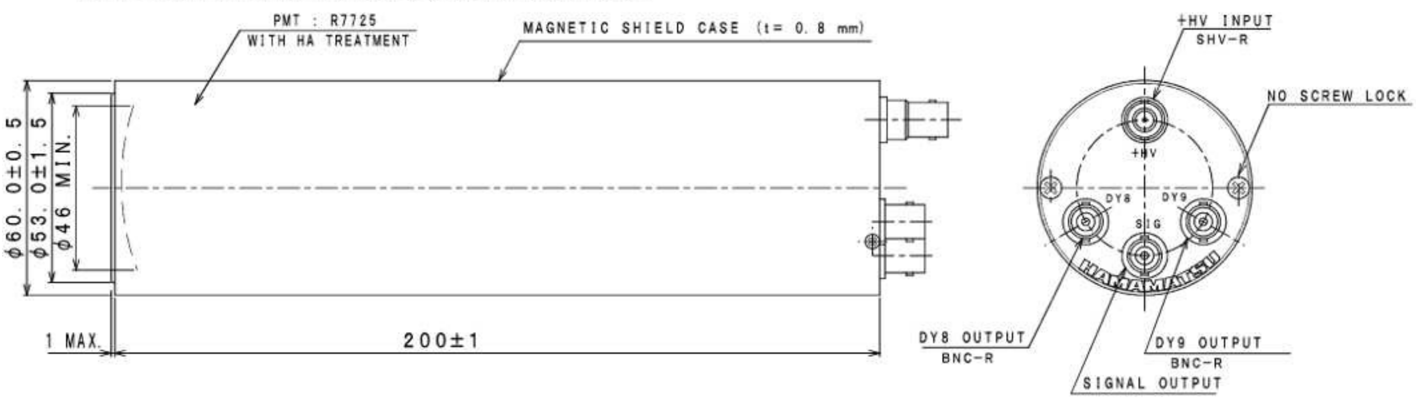
H11284-50-02

For ALPACA experiments, Fast Time Response,

52 mm (2 inch) Diameter, Bialkali Photocathode, 12-stage, Head-on Type

HAMAMATSU
PHOTON IS OUR BUSINESS





VOLTAGE DISTRIBUTION RATIO AND SUPPLY VOLTAGE

Electrodes	K	Dy1	Dy2	Dy3	Dy4	Dy5	Dy6	Dy7	Dy8	Dy9	Dy10	Dy11	Dy12	P
Ratio	4.8	1	2.3	1	1	1.5	2.3	3	3	3	3	4.8	2.3	

Supply Voltage: +1750 V, K: Cathode, Dy: Dynode, P: Anode

Summary

- The ALPACA experiment will start the observation of sub-PeV gamma rays in the southern hemisphere in 2025.
- Each 1m^2 scintillation detector needs a dynamic range of up to 1,000 particles (a few PeV).
- Attempted to extend the dynamic range of 2-inch PMT, R7725 by two methods, anode/dynode readouts and tapered divider.

☆Dynamic range extended up to 700 particles (~3 PeV) with 8th-dynode signal.
→ **almost achieved target**

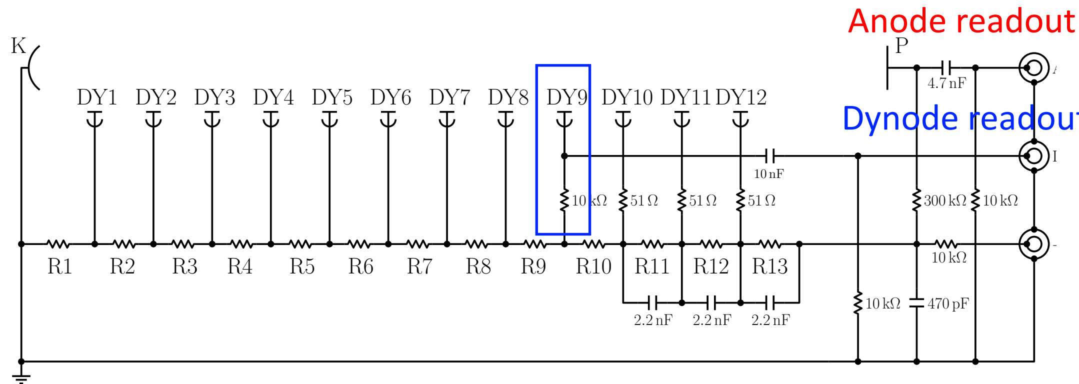
☆Hamamatsu Photonics K.K. checked the divider circuit, including withstand voltage, and found no problems
→ The design was fixed for ALPACA 2024 (model number: **H11284-50-02**)

☆We already placed a large order with Hamamatsu Photonics K.K.

Backup slide

Designs of the voltage dividers made in this research

R7725 (2-inch-diameter PMT)
- Made by Hamamatsu Photonics K.K.
- High voltage: 1750 V (Max.: 2000 V)
- Number of dynodes: **12**
  → Higher gain than R7724
- Made **three dividers with different ratios** (Normal, Tapered 1 & Tapered2)



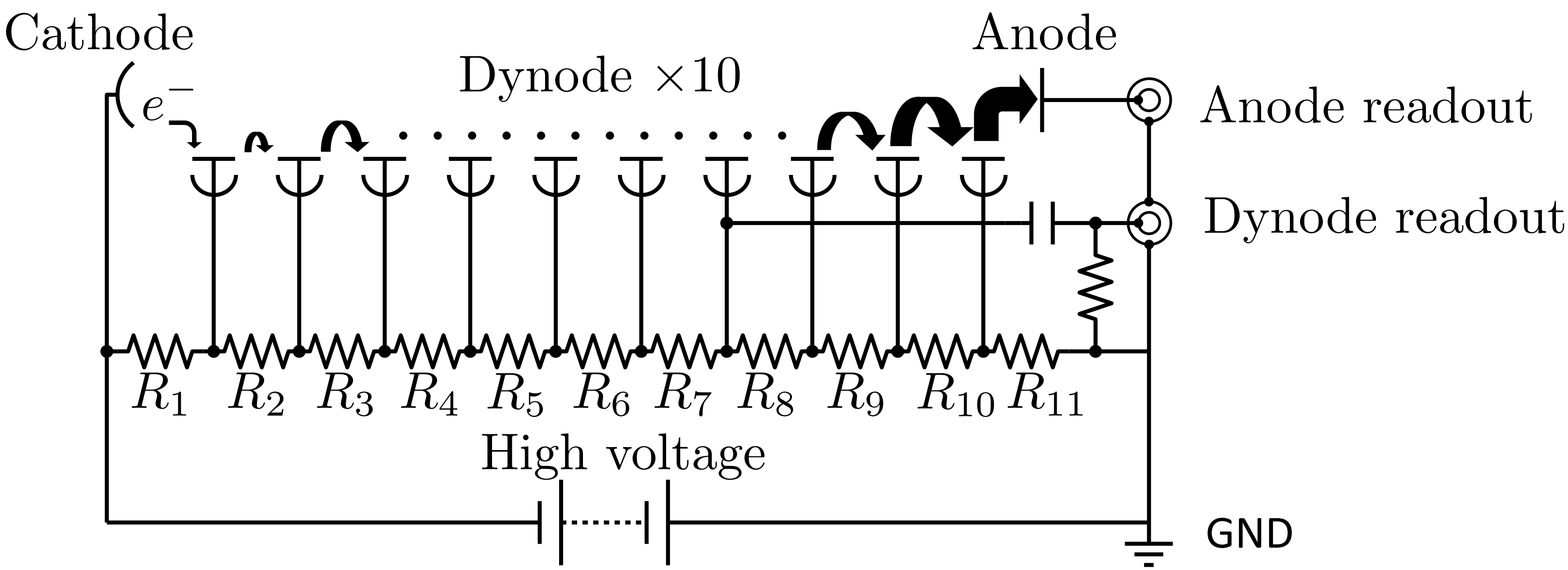
Voltage distribution ratios

Electrode	K	DY1	DY2	DY3	DY4	DY5	DY6	DY7	DY8	DY9	DY10	DY11	DY12	P
Normal	21.4	5.65	11.1	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	11.1	5.65	
Tapered 1	14.5	3.03	6.99	3.03	3.03	4.66	6.99	9.09	9.09	9.09	9.09	14.5	6.99	
Tapered 2	8.39	4.20	8.39	4.20	4.20	4.20	4.20	4.20	5.13	6.29	8.39	19.1	19.1	

- Each ratio is calculated from the catalog values of the resistances used.
- The total resistance of each divider is ~4.3 MΩ.
- The sum of the ratios from the cathode (K) to the anode (P) is normalized to 100.
- The "Tapered 1" ratio referred to the previous study* using the same PMT.

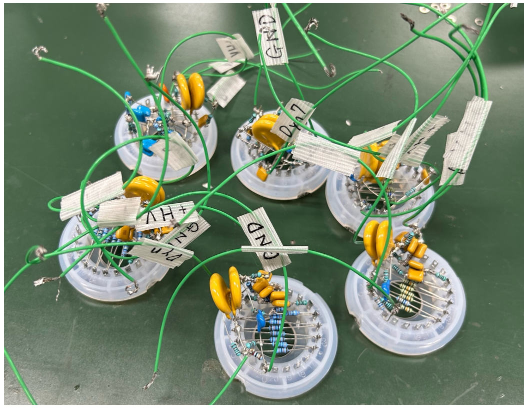
* Y. Zhang et al., JINST, 12, P11011 (2017).

How to extend the dynamic range of PMT??



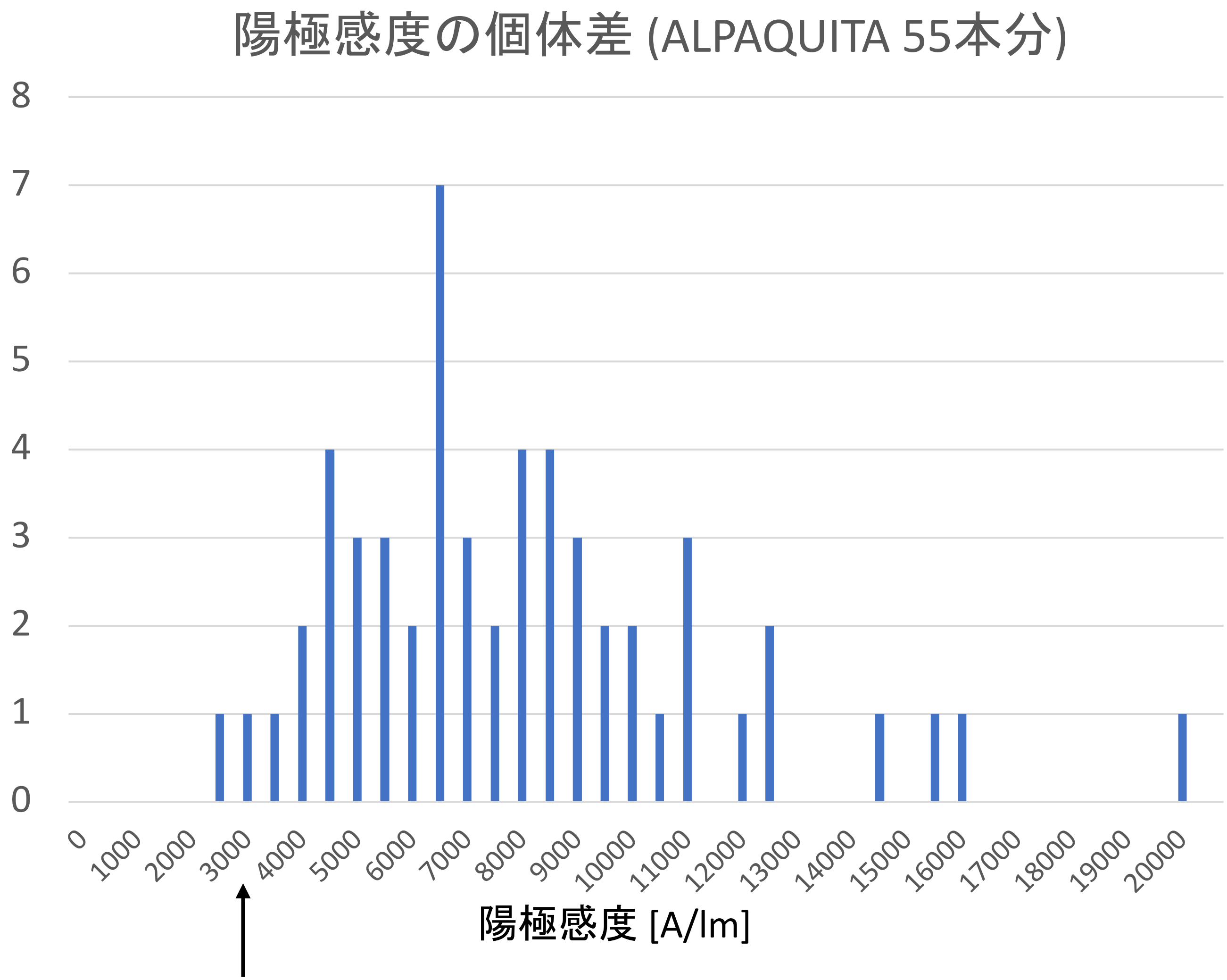
Dynamic-range-extension method

1. <u>Dynode readout</u>
   ○ Less expensive than using two PMT
   × One more channel needed than the tapered PMT
2. <u>Divider of tapered-voltage ratio</u>
   ○ Even less expensive than dynode readout
   × Decreased gain



	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}
Normal	1	1	1	1	1	1	1	1	1	1	1
Tapered	1	1	1	1	1	1	2	2	3	4	4

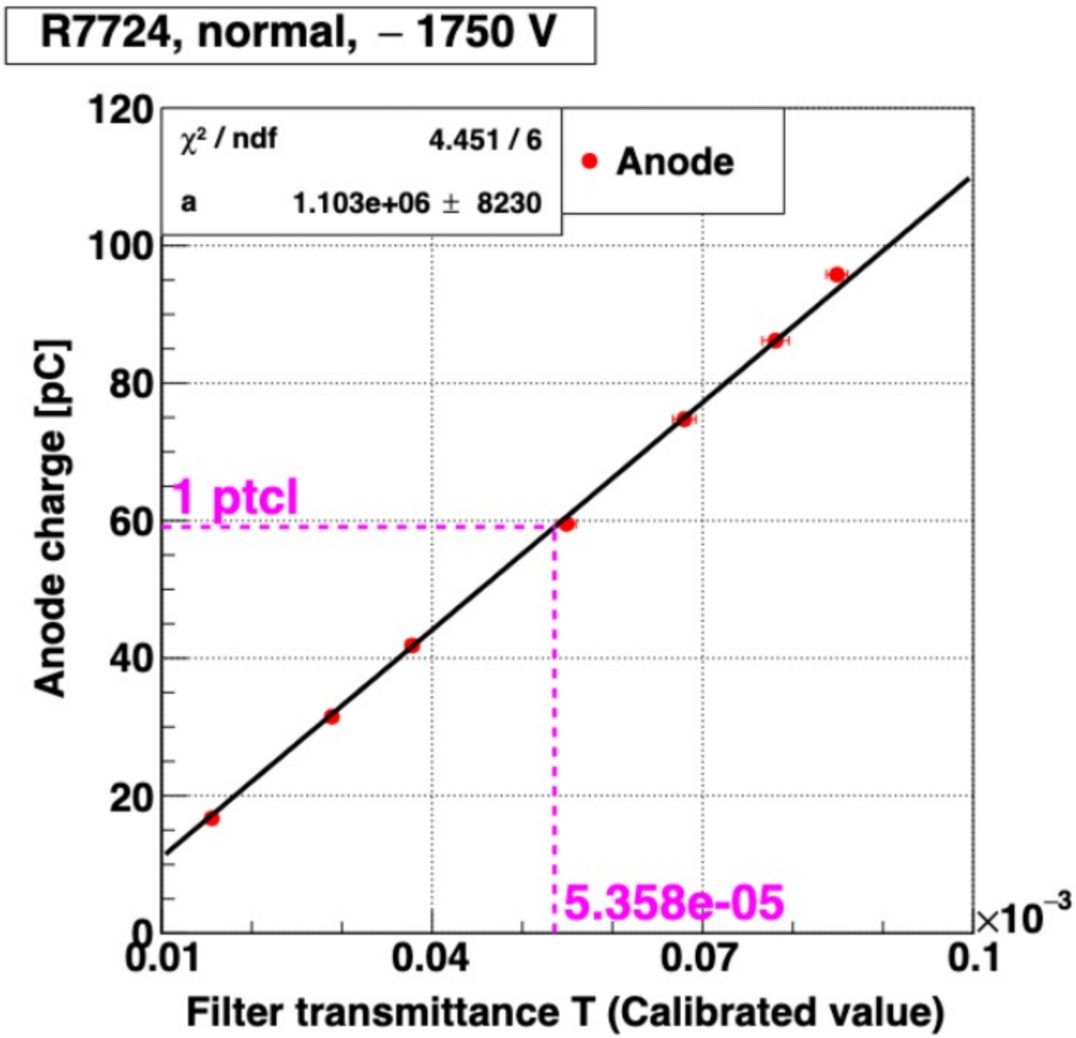
H11284 (球R7725) ゲイン個体差



本研究で使用している個体は 3,230 A/lm

Conversion of UV-light intensity to the number of particles

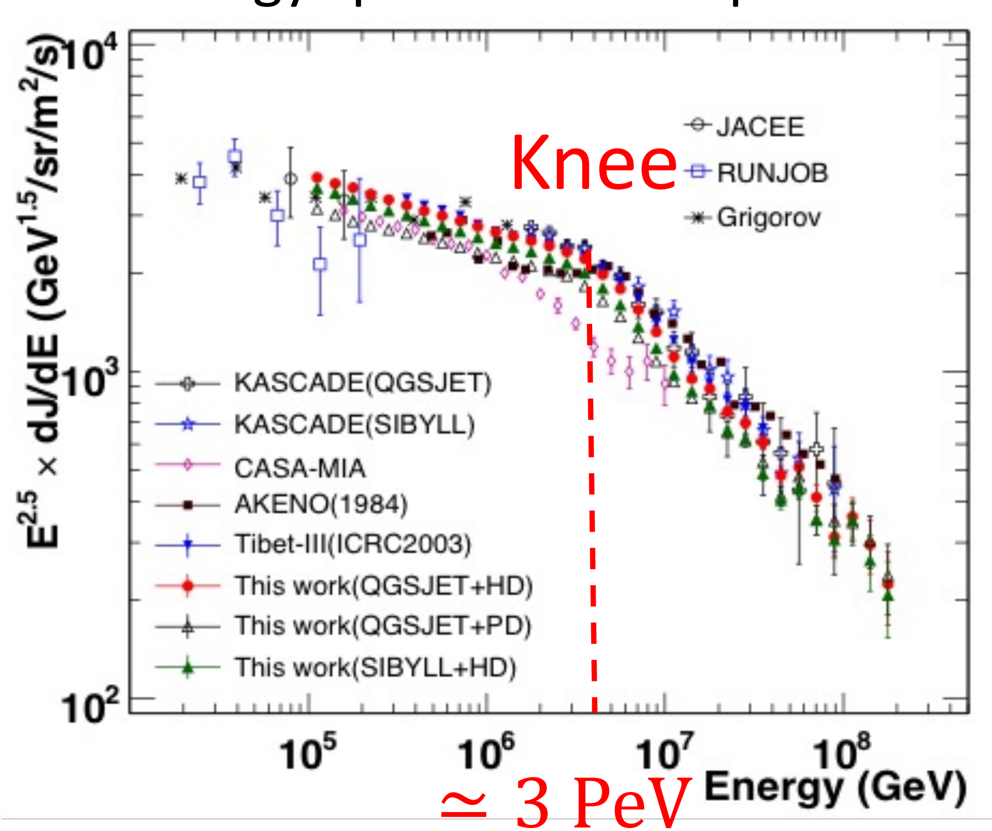
✓ Estimate the conversion factor from filter transmittance to the number of ptcls.



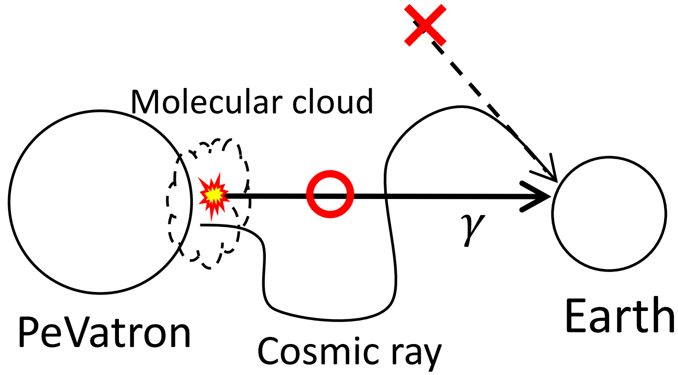
Origin of PeV cosmic rays

PeVatron: PeV-cosmic-ray accelerators in our galaxy

Energy spectrum of all particles



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



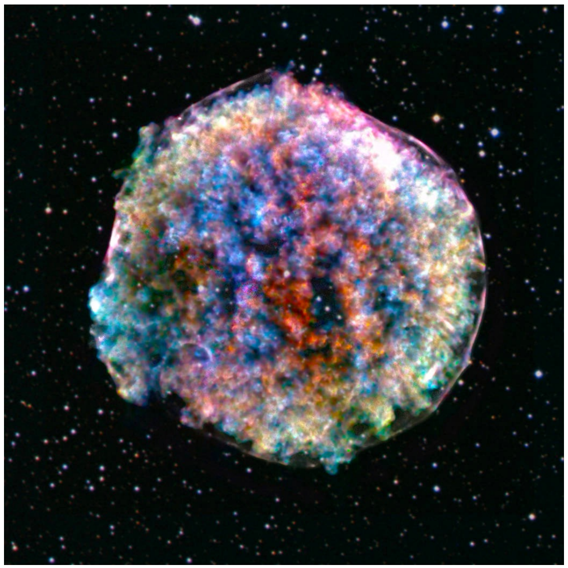
Indirect observation of cosmic rays:

$$p(\mathrm{PeV}) + p \to \pi^0 + X$$

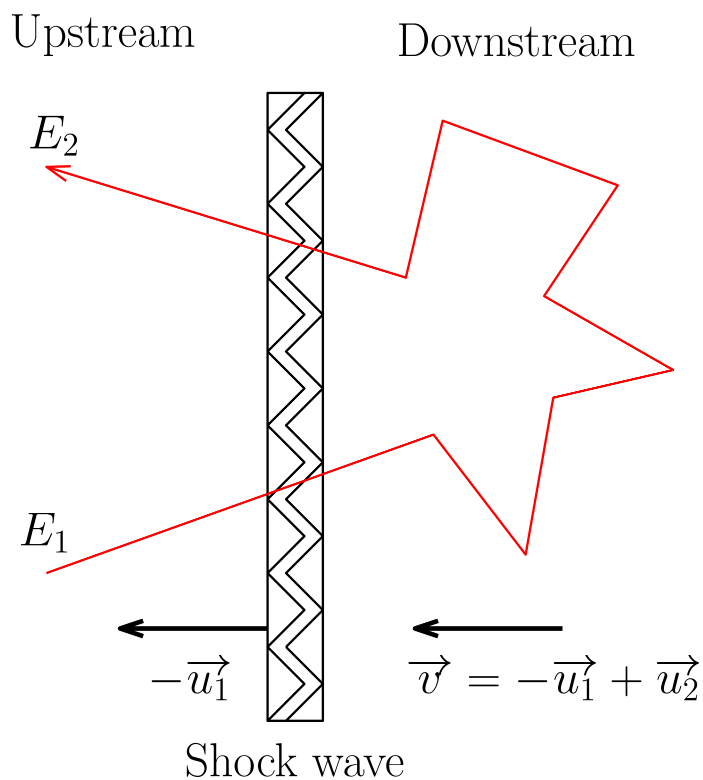
$$\pi^0 \to \gamma + \gamma \text{ (sub-PeV)}$$

PeVatron candidate: Supernova remnant (SNR)

Diffusive shock acceleration



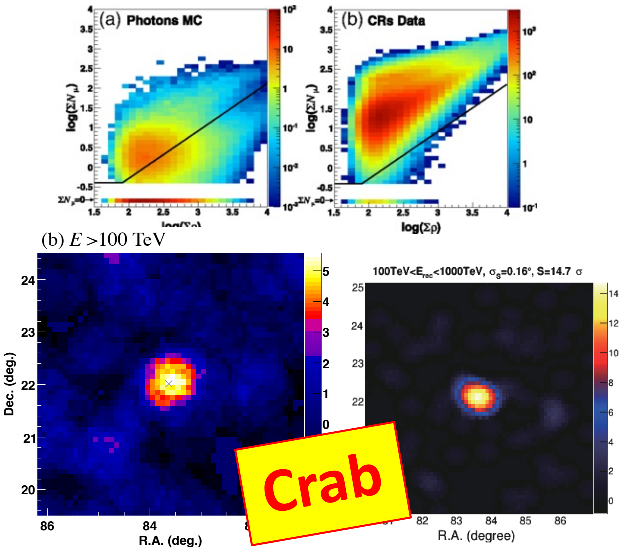
https://www.nasa.gov/image-feature/the-tycho-supernova-death-of-a-star



+ Cosmic-ray propagation

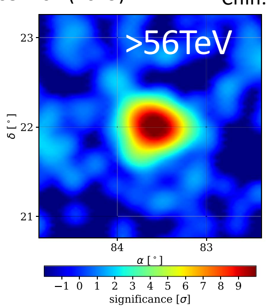
Spectral index of cosmic rays ($\Gamma \sim -2.7$) can be explained.

Sub-PeV gamma-ray observation

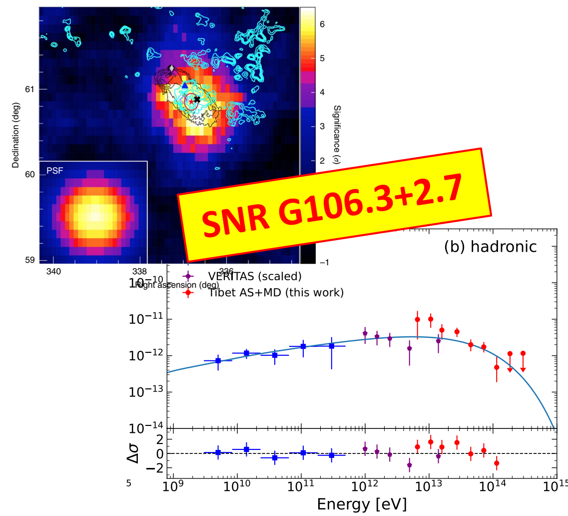


Tibet AS γ Collaboration, PRL 123, 051101 (2019)

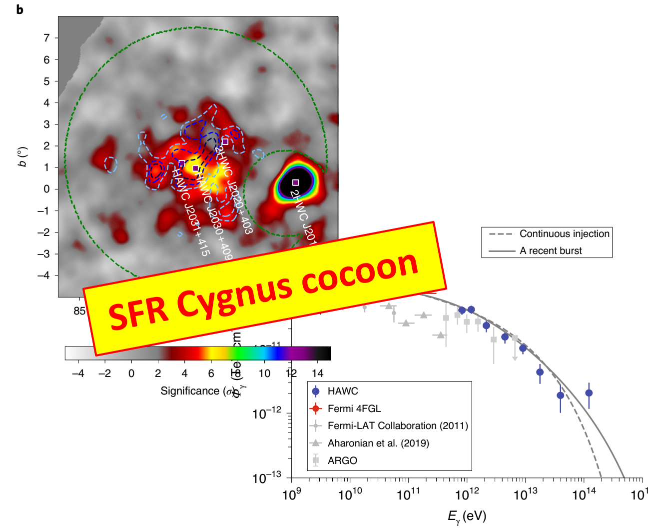
LHAASO Collaboration, Chin. Phys. C45, 023002 (2021)



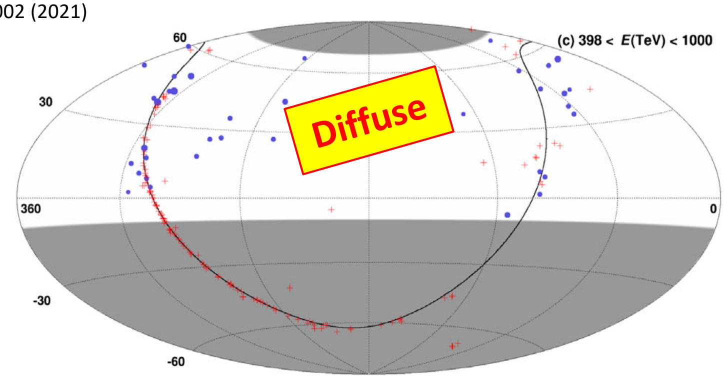
HAWC Collaboration, ApJ 881:134 (2019)



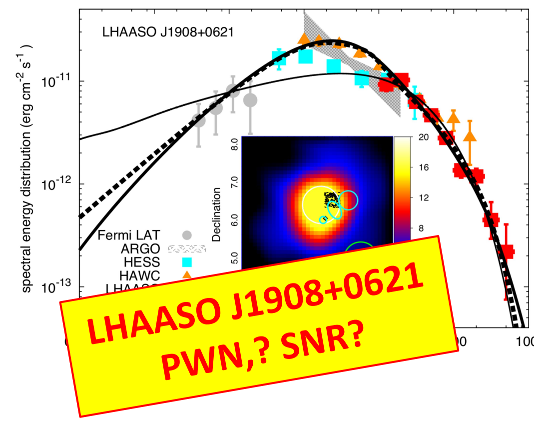
Tibet AS γ Collaboration, Nature Astron., 5, 460-464 (2021)



HAWC Collaboration, Nature Astron., 5, 465-471 (2021)



Tibet AS γ Collaboration, PRL 126, 141101 (2021)

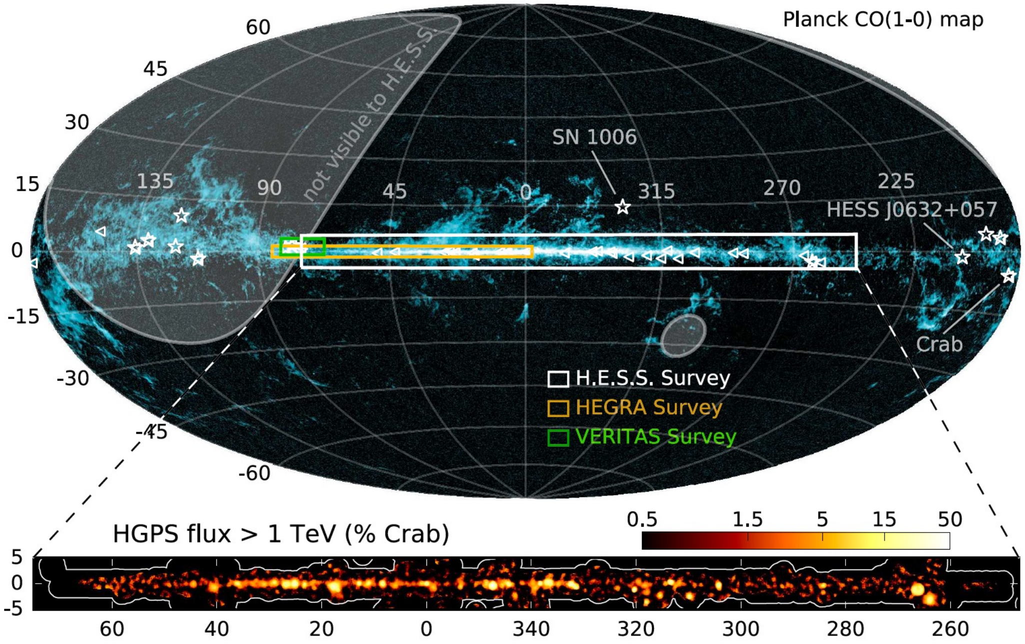


LHAASO Collaboration, Nature, 594, 33-36 (2021)

PeVatron searches have been mainly performed in the northern sky

Let’s start southern sky survey!!

TeV gamma-ray map by H.E.S.S. Galactic Plane Survey



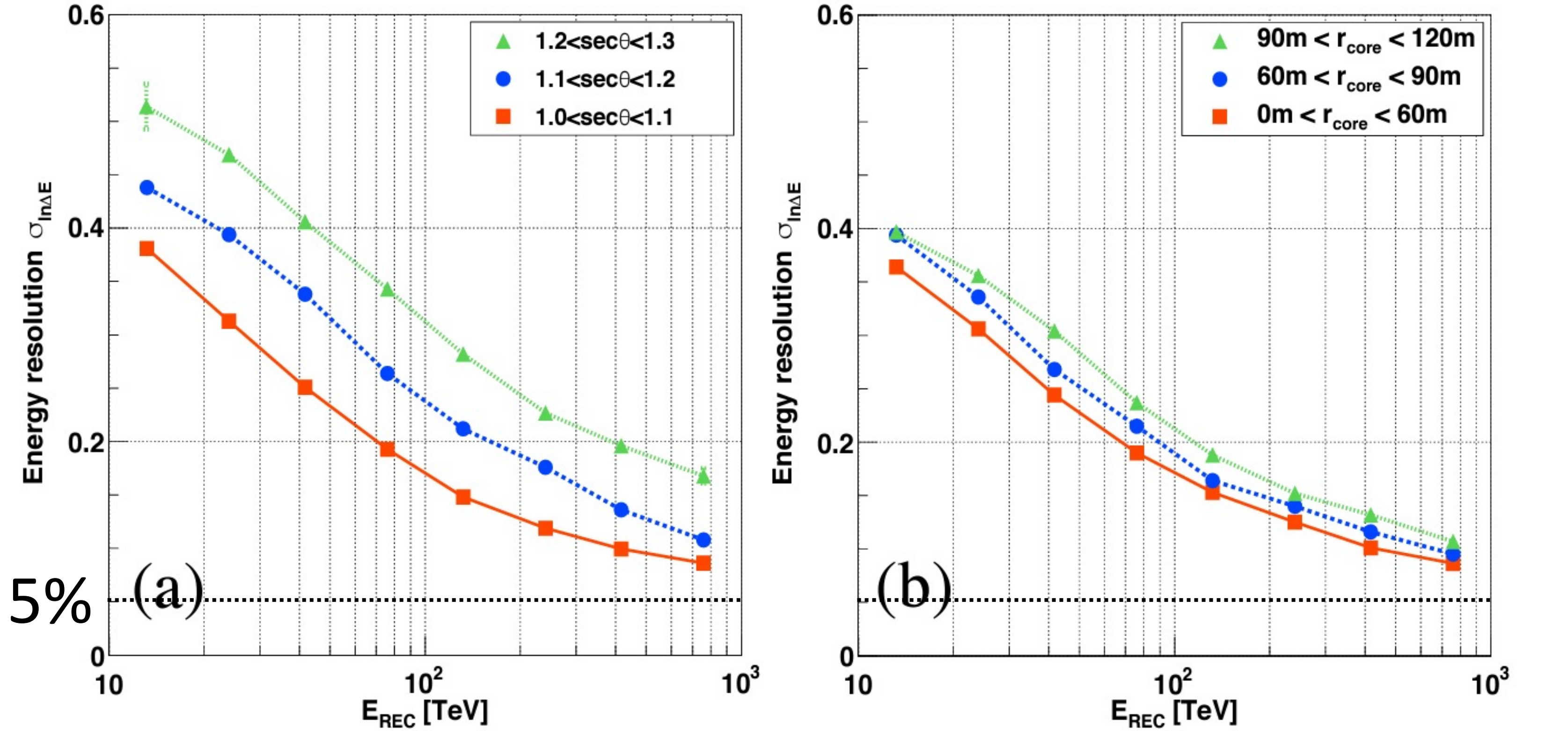
H.E.S.S. Collaboration, A&A 612, A1 (2018).

- ✓ So many high-energy gamma-ray sources found in the southern sky (~100 sources in HGPS)
- ✓ Some sources, including GC, are prominent PeVatron candidates

Performance of ALPACA

Location	4,740 m above sea level (16°23′S, 68°08′W)
Effective area	$\sim 83,000\,\mathrm{m}^2$
Mordal energy	~ 5 TeV
Angular resolution	$\sim 0.2°$ @100 TeV
Energy resolution	$\sim 20\,\%$ @100 TeV
Field of view	~ 2 sr
Duty cycle	$\sim 100\,\%$
CR rejection power	$> 99.9\,\%$ @100 TeV (γ-rays efficiency $\sim 90\,\%$)

Energy resolution of ALPACA



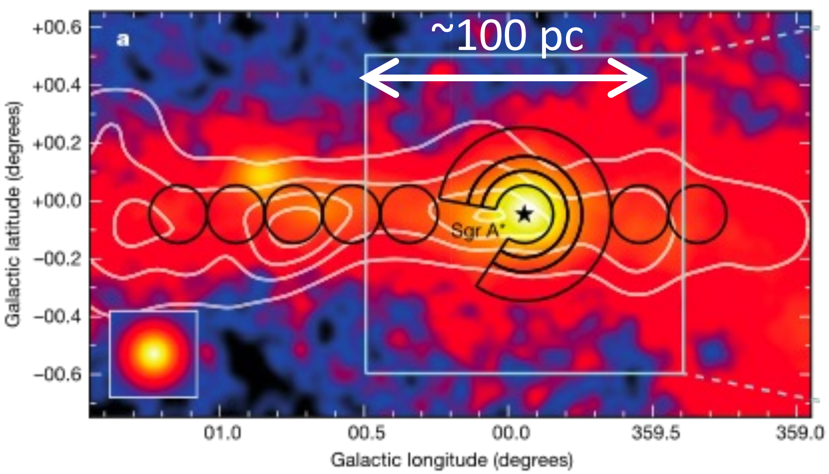
M. Amenomori *et al.*, Phys. Rev. Lett. **123**, 051101 (2019).

ダイナミックレンジの線形性のずれが5%以内
であることが必要

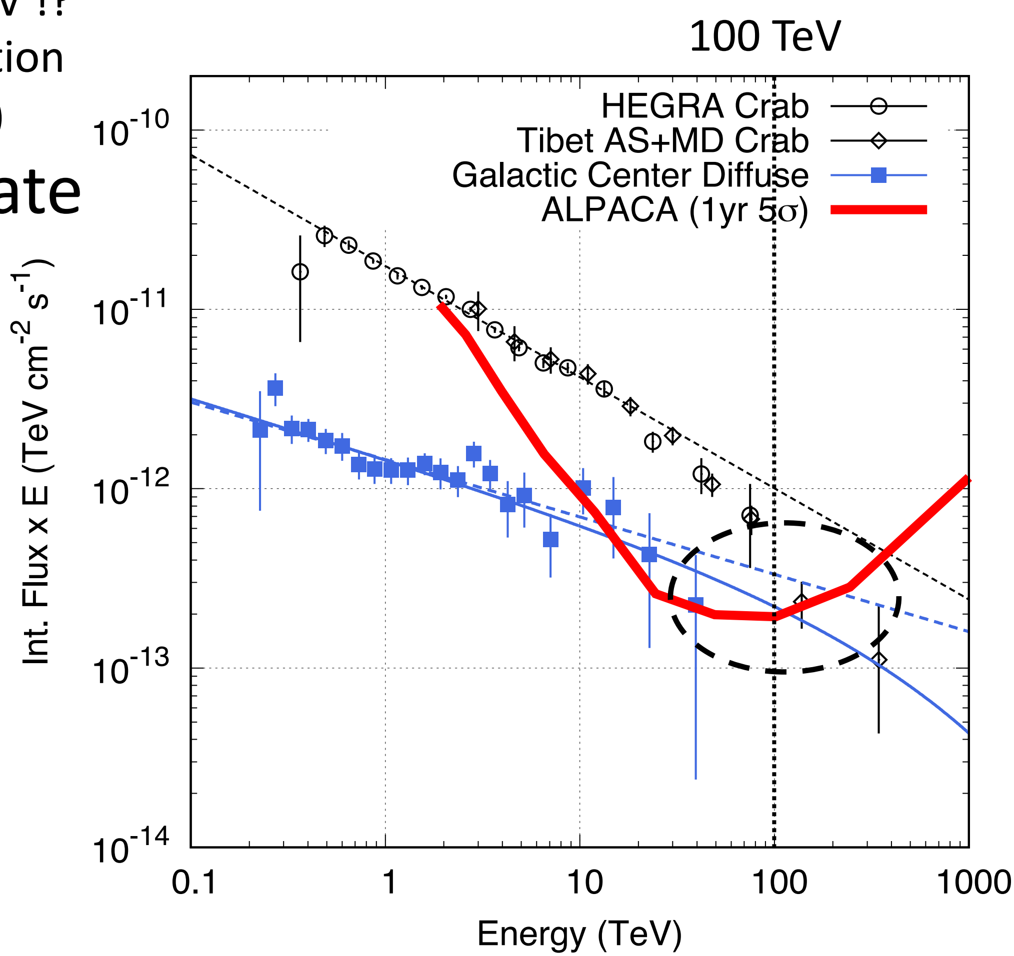
ALPACA sensitivity to the Galactic Center

- Hard spectral index (~-2.3) toward sub-PeV !?
- Correlation with molecular cloud distribution
- Diffuse gamma-ray component (CR origin)

→ Promising PeVatron candidate

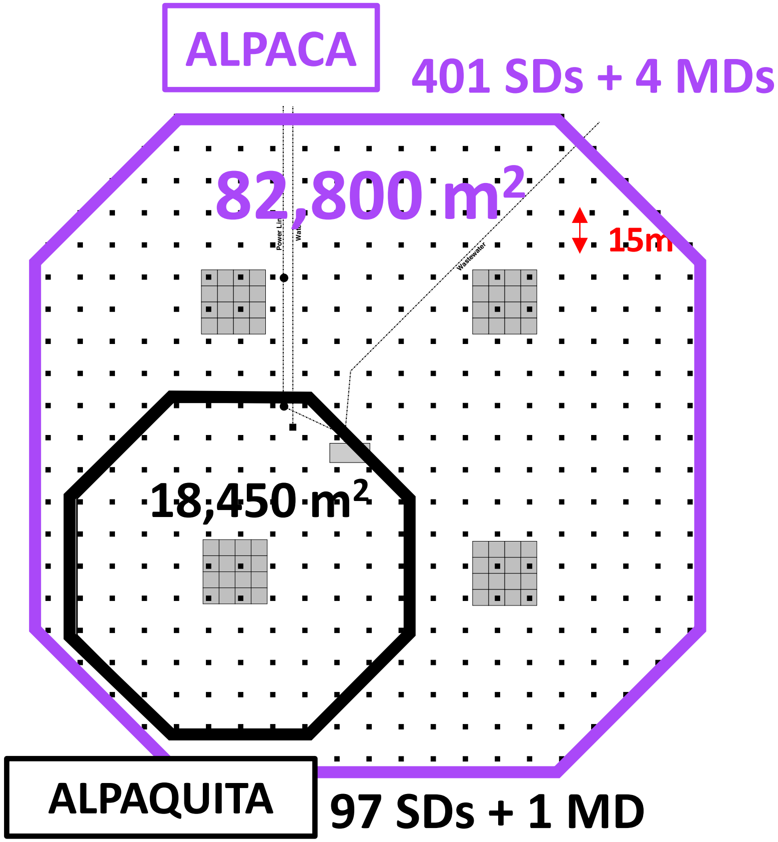


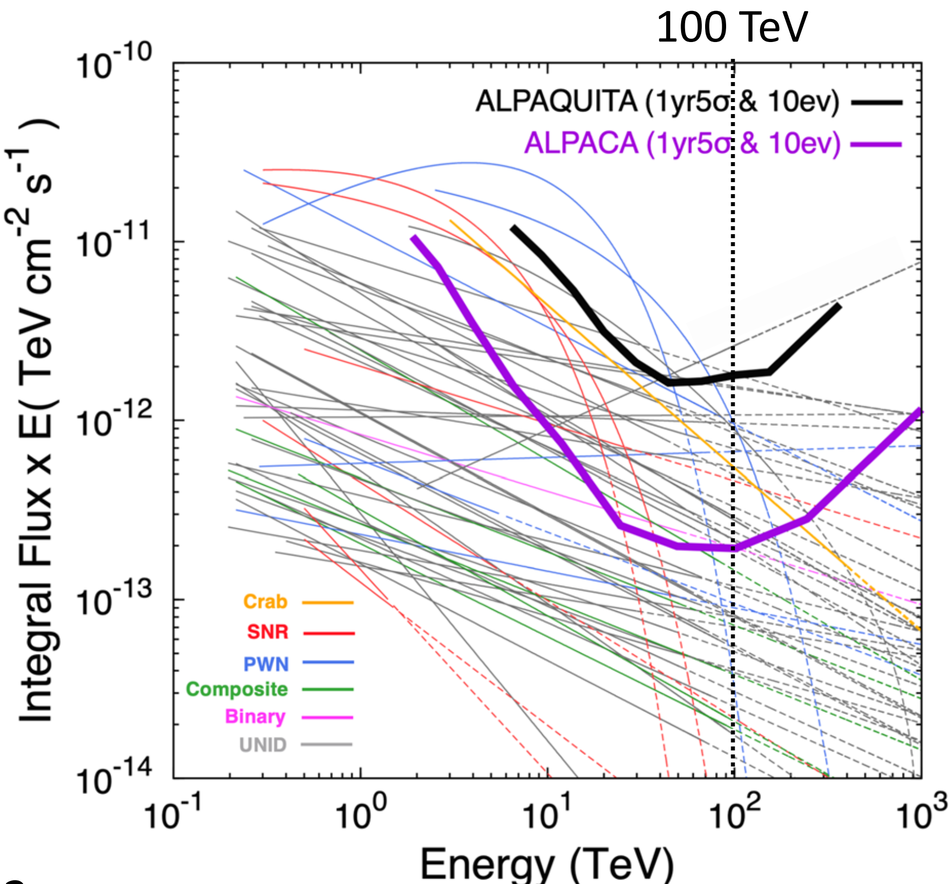
H.E.S.S. Collaboration, Nature 531, 476–479 (2016).



✓ ALPACA can detect GC abv. 100 TeV in one year

Prototype array: ALPAQUITA (2022-)



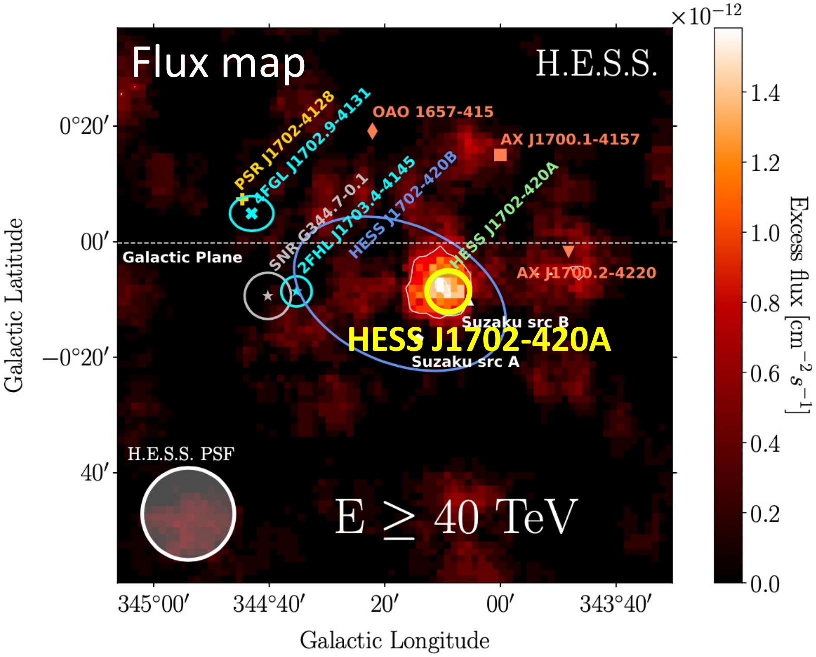


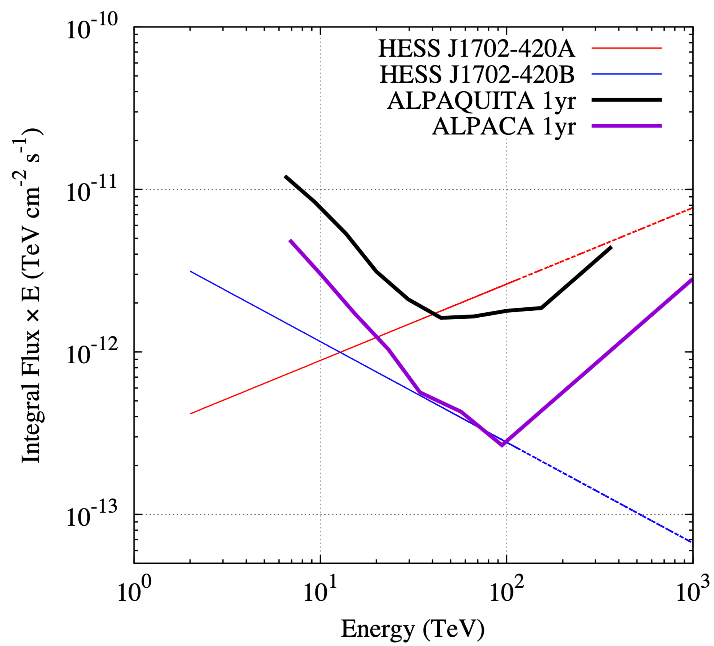
S.Kato et al., Experimental Astronomy (2021) 52:85-107

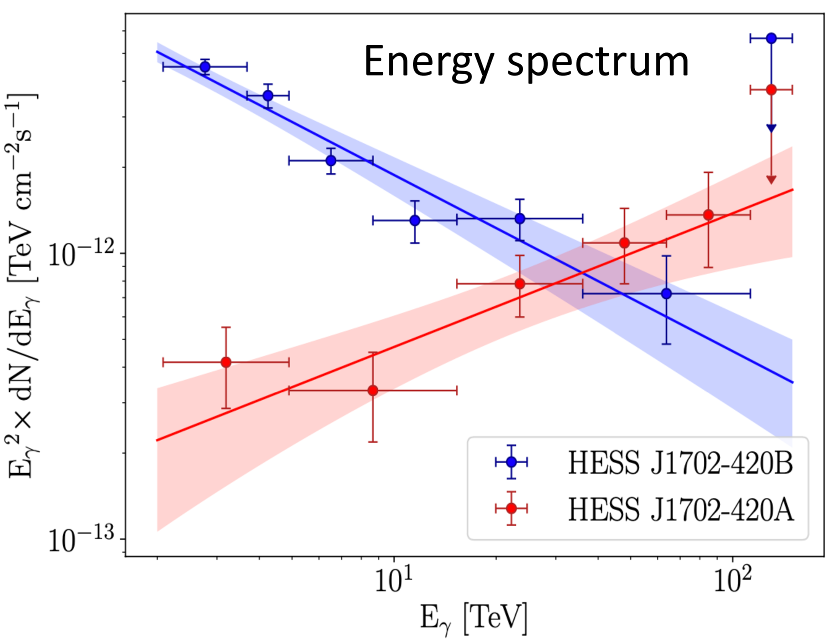
- Start data taking on september 2022
- 1 MD construction to be completed in 2023

✓ ALPAQUITA can detect some gamma-ray sources abv. 10 TeV in one year

HESS J1702-420A: Unidentified Gamma-Ray Source



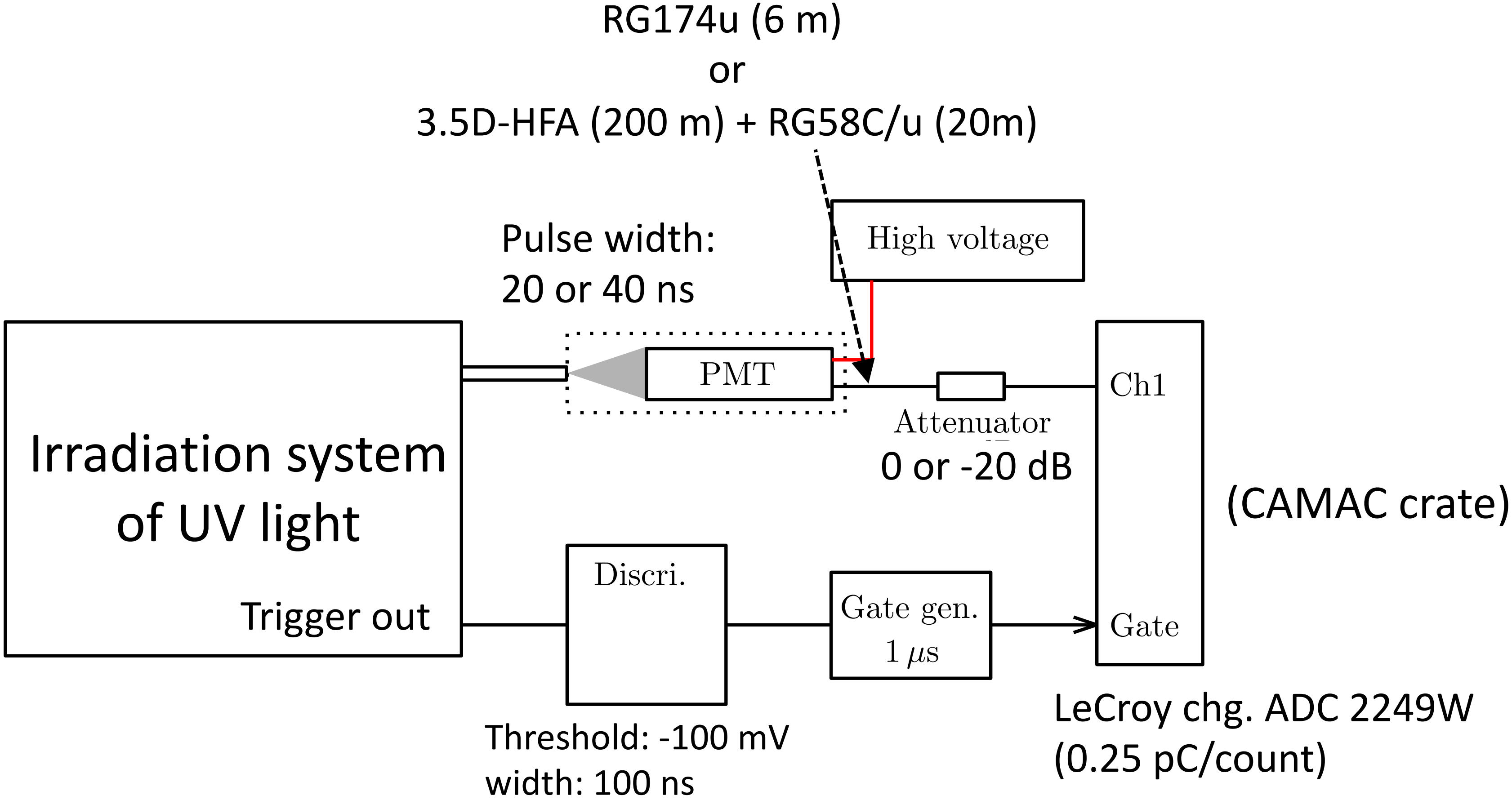




- Point source (ArXiv:2106.06405v2)
- Hard spectral index (Γ〜1.5)
- No clear correlation with the ISM (from radio, IR, mm,…)

- Hot science topic for ALPAQUITA such as
  - Detection byd. 300 TeV?
  - Cutoff exists?
  - Maximal CR energy (PeVatron?)

Data acquisition system



- ✓ Intensity of the UV laser light is constant
  → <u>Need to adjust the intensity with filters</u>

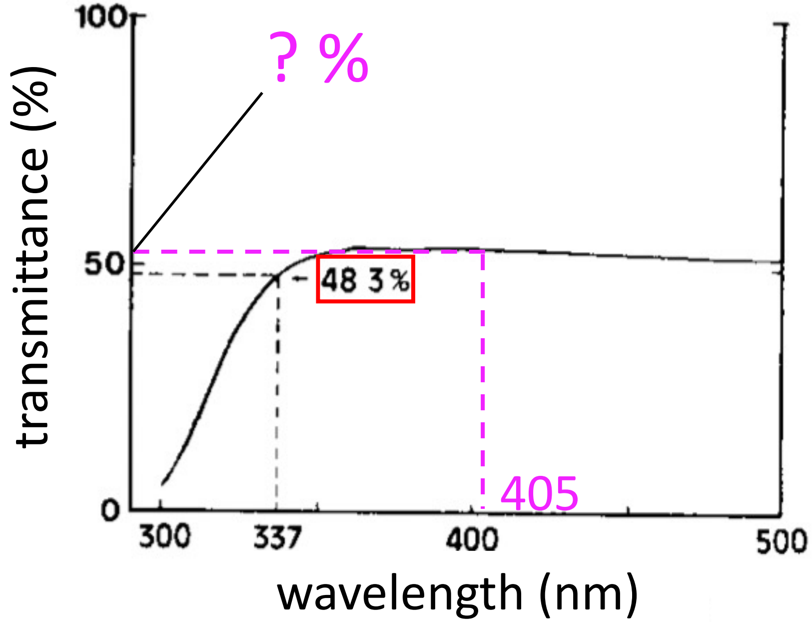
Filter transmittance

↓ **Catalog values and measured value using nitrogen gas laser (337 nm)**

Digit filters | % filters

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

*Measured by spectrometer (Hitachi 228A)



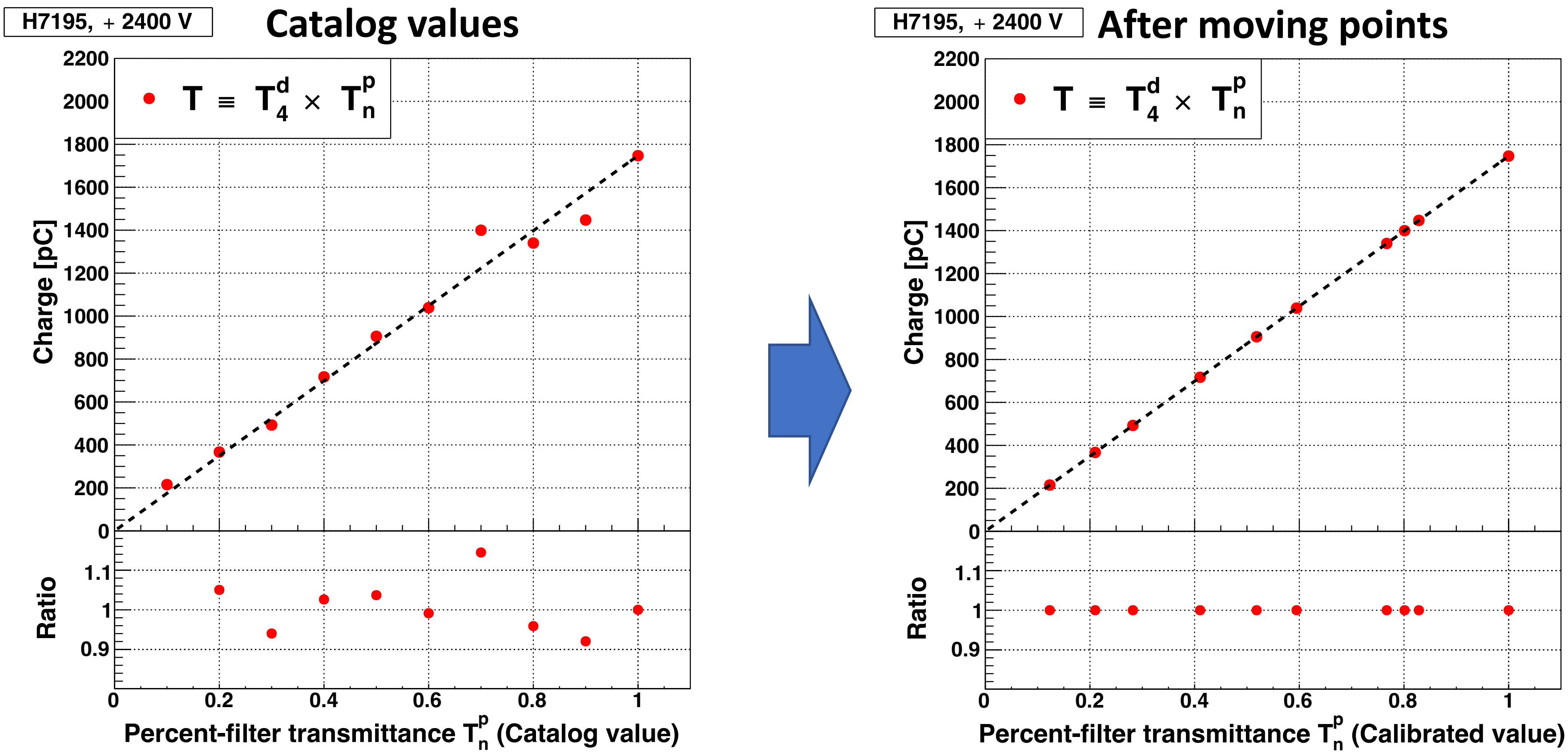
M. Nishizawa et al., Nuclear Inst. and Methods in Physics, A285, p532-539 (1989).

✓ Each transmittance needs re-measurement using the UV laser (405 nm).

Measurement transmittances of the % filters

- ✓ To determine the transmittance of each filter, data points are moved along the horizontal direction so that they are put on the dashed line

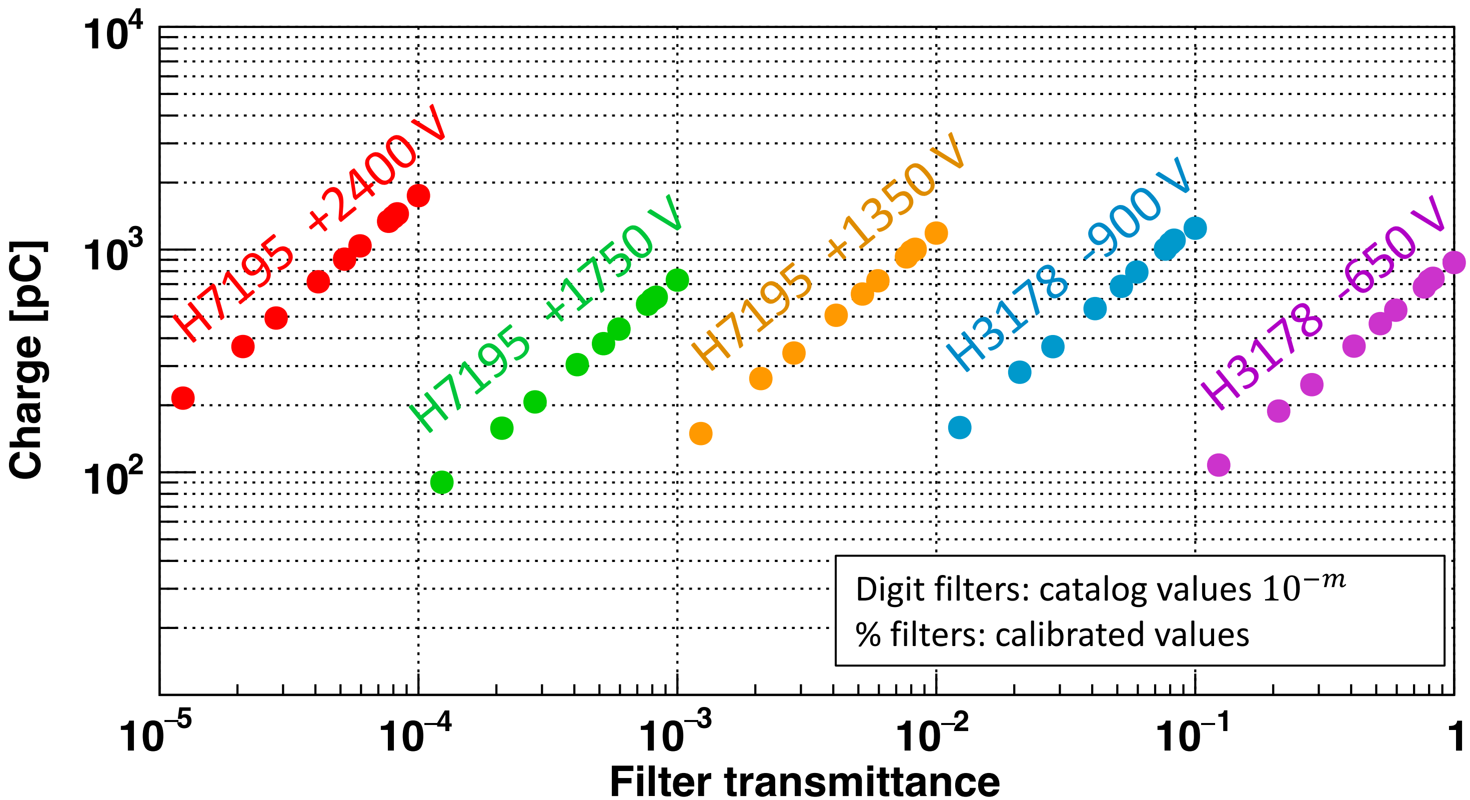
T^{d}_{m}: digit filter w/ the catalog value of transmittance 10^{-m}
T^{p}_{n}: % filter w/ the catalog value of transmittance $1-0.1\times n$



Transmittances of % filters have been determined!

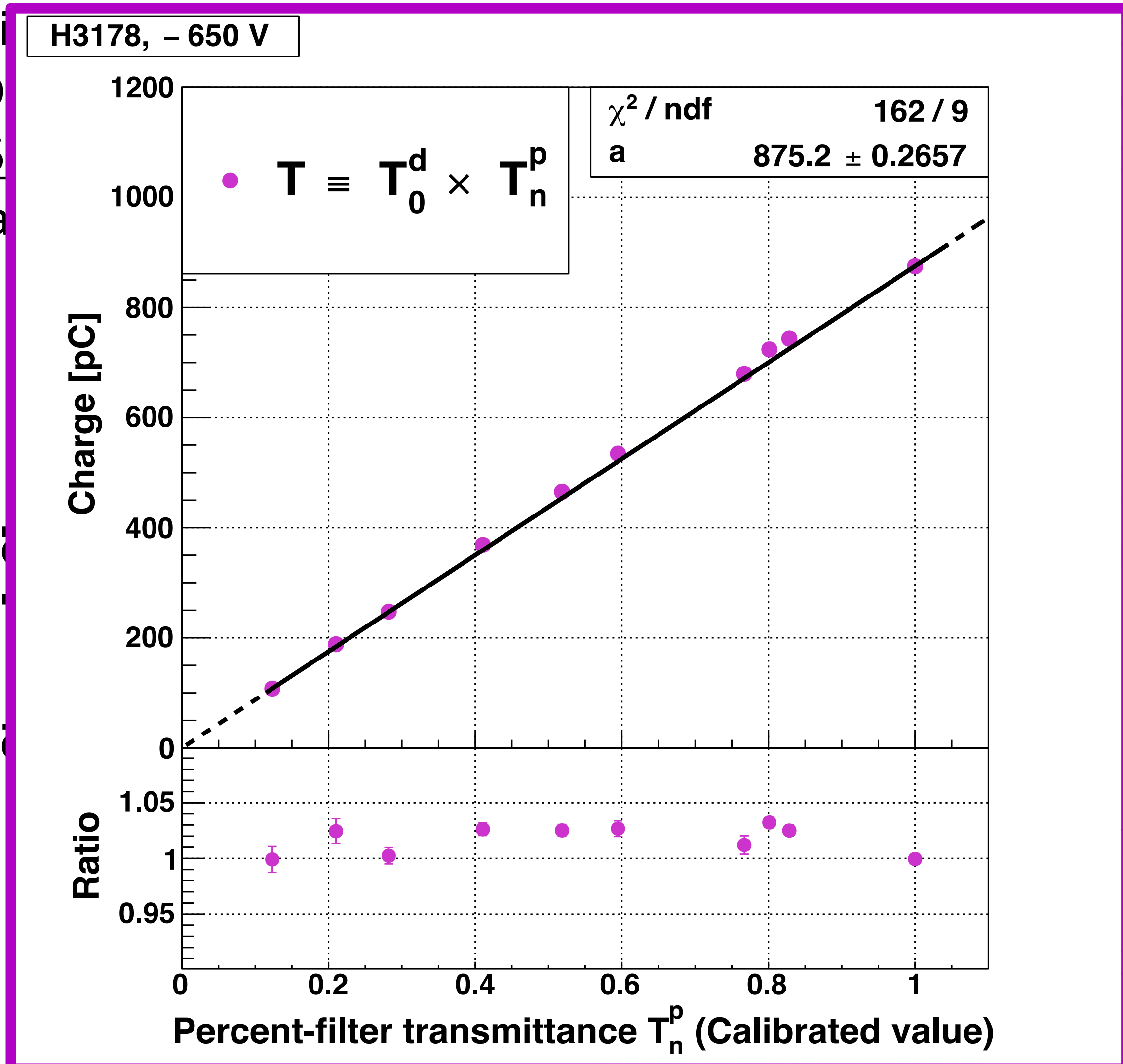
Measurement of transmittances of the digit filters

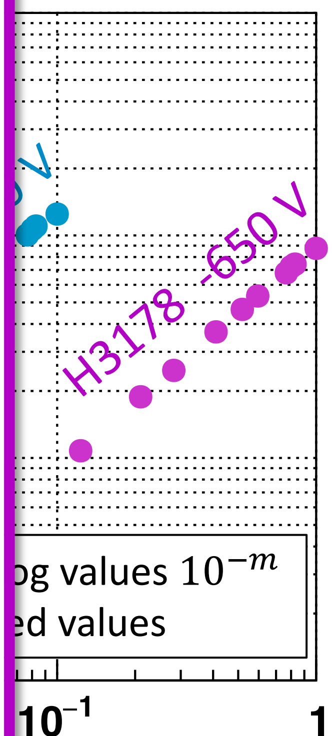
- ✓ Linearity range of PMT is typically about two orders of digits
  - ➢ Difficult to measure transmittances of all digit filters with a single PMT and HV
- ✓ <u>H7195 (2-inch ϕ) and H3178 (1.5-inch ϕ)</u> were used for each digit, and each HV was adjusted to measure in the linear region.



Measurement of transmittances of the digit filters

- ✓ Lineari … s
  - ➢ D … ith a single PMT and HV
- ✓ H7195 … h digit,
  and ea …





Measurement of transmittances of the digit filters

- ✓ Lineari … s
  - ➢ D … ith a single PMT and HV
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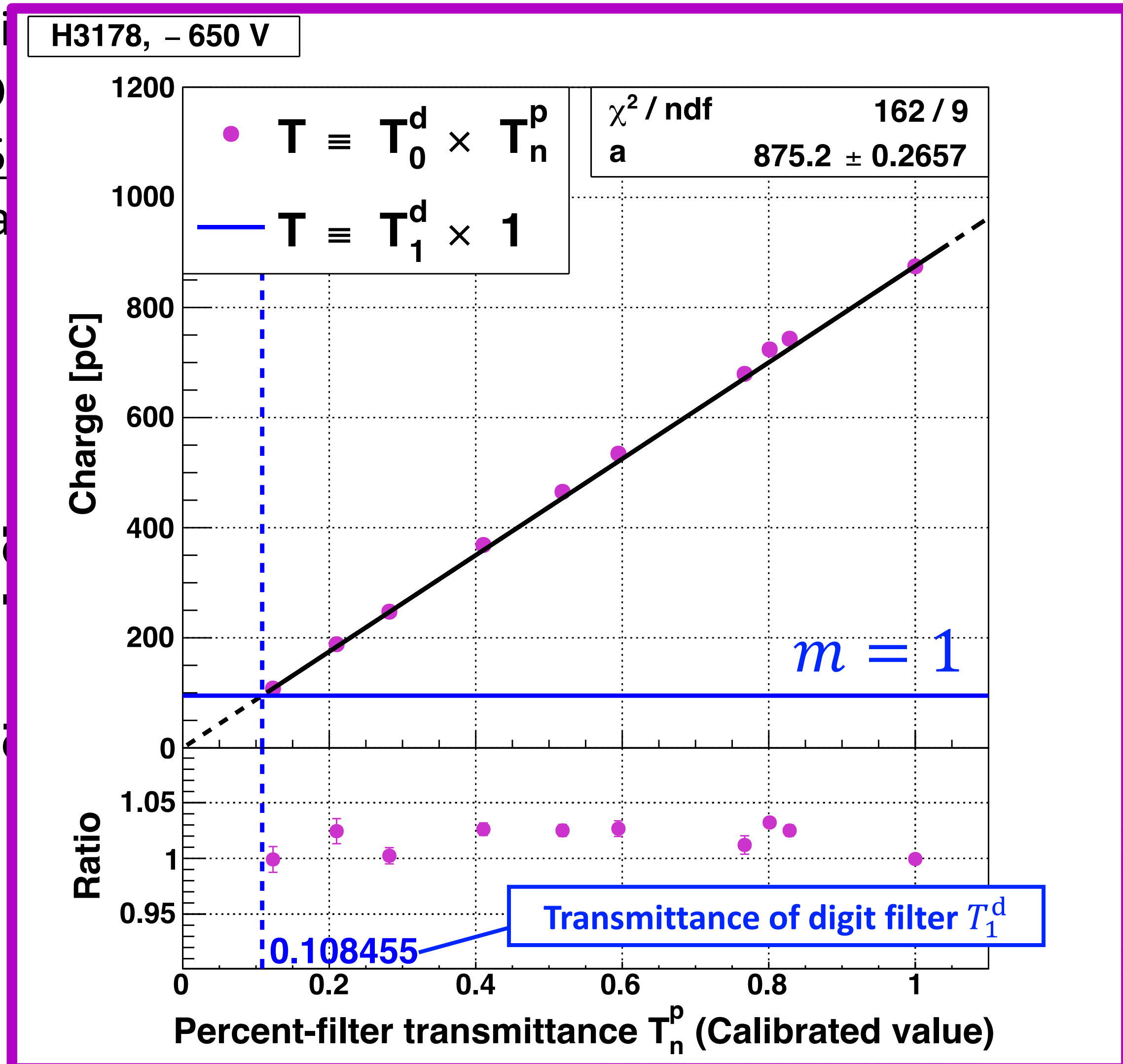
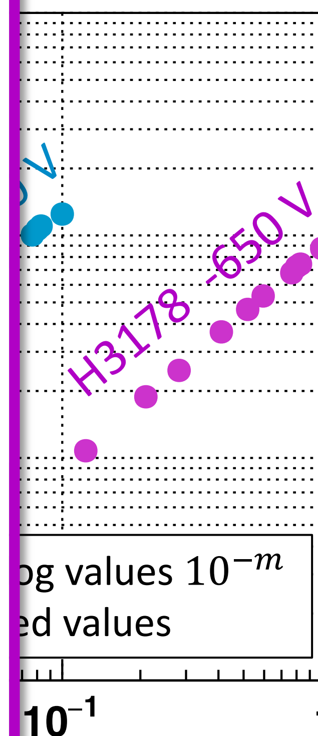
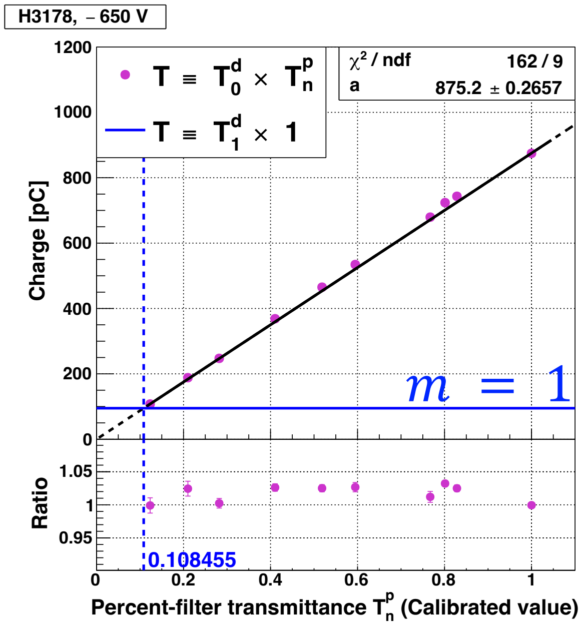
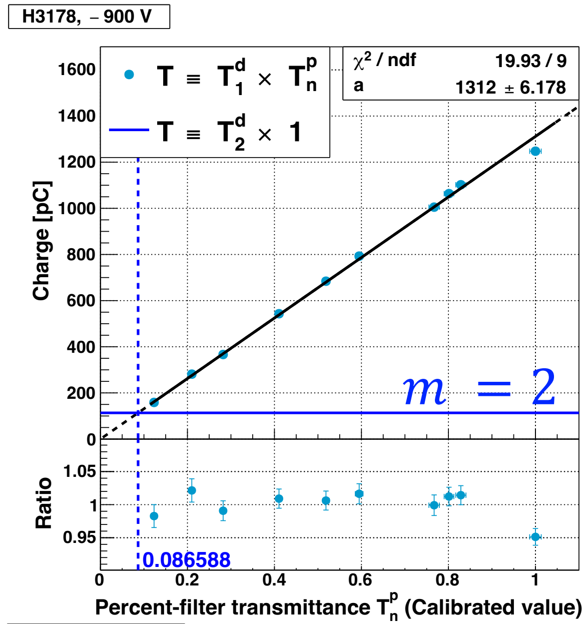
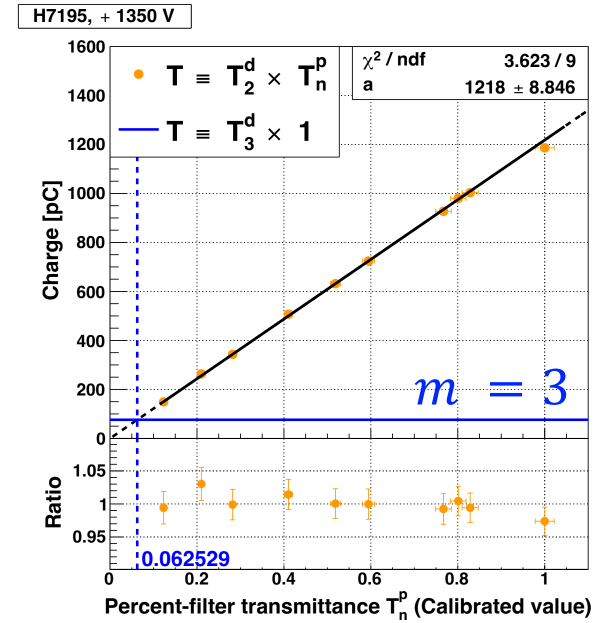


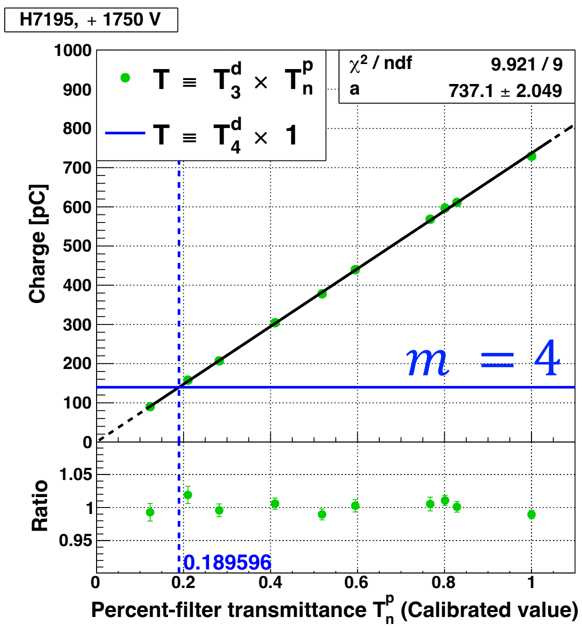


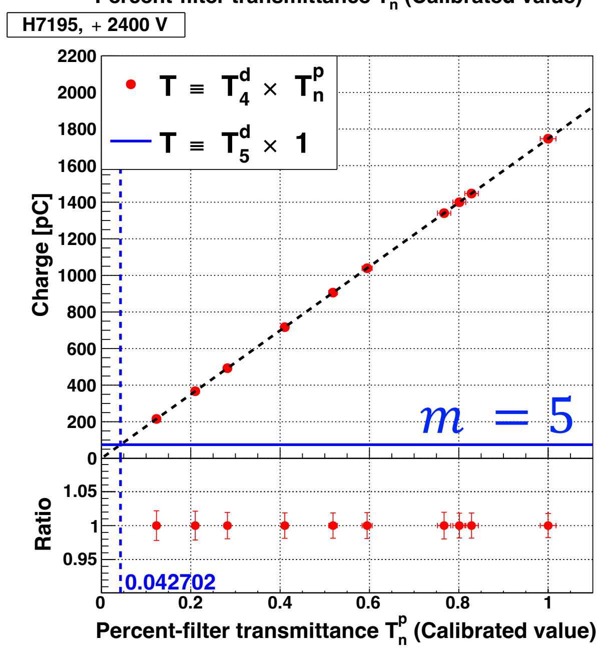
Measurement of transmittances of the digit filters







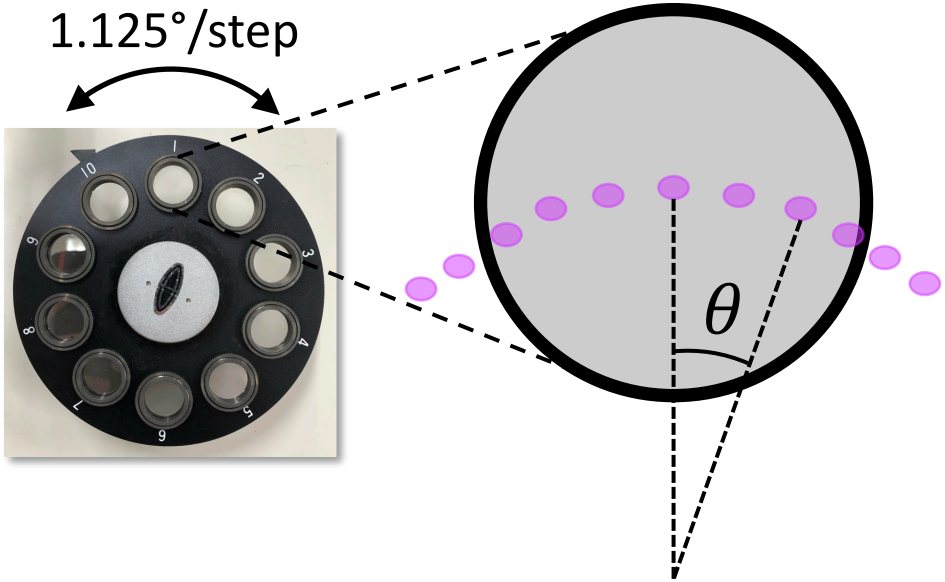




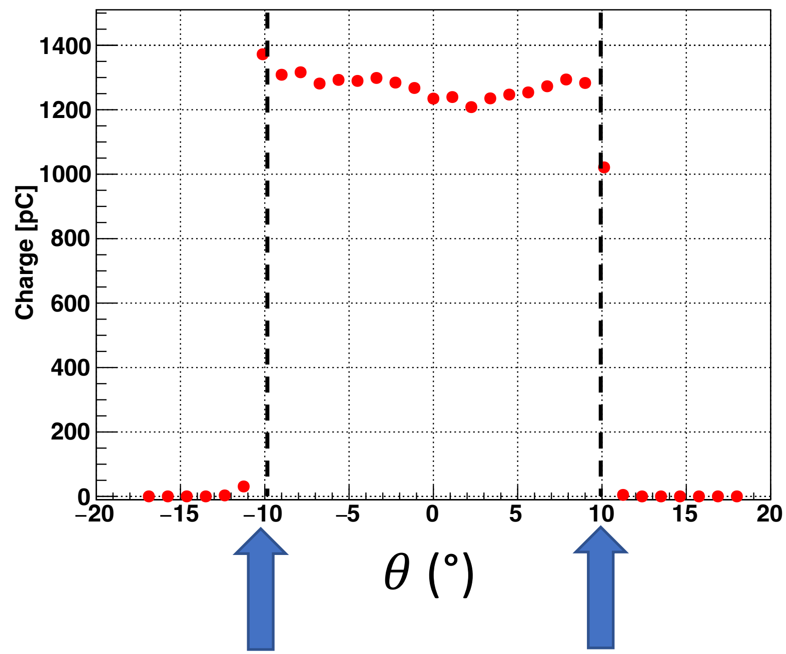
T_m^{d}: Digit filter w/ the catalog value of transmittance 10^{-m}

T_n^{p}: % filter w/ the catalog value of transmittance $1 - 0.1 \times n$

Uniformity of the filter transmittance



An example of
the measured uniformity (T_1^{d})

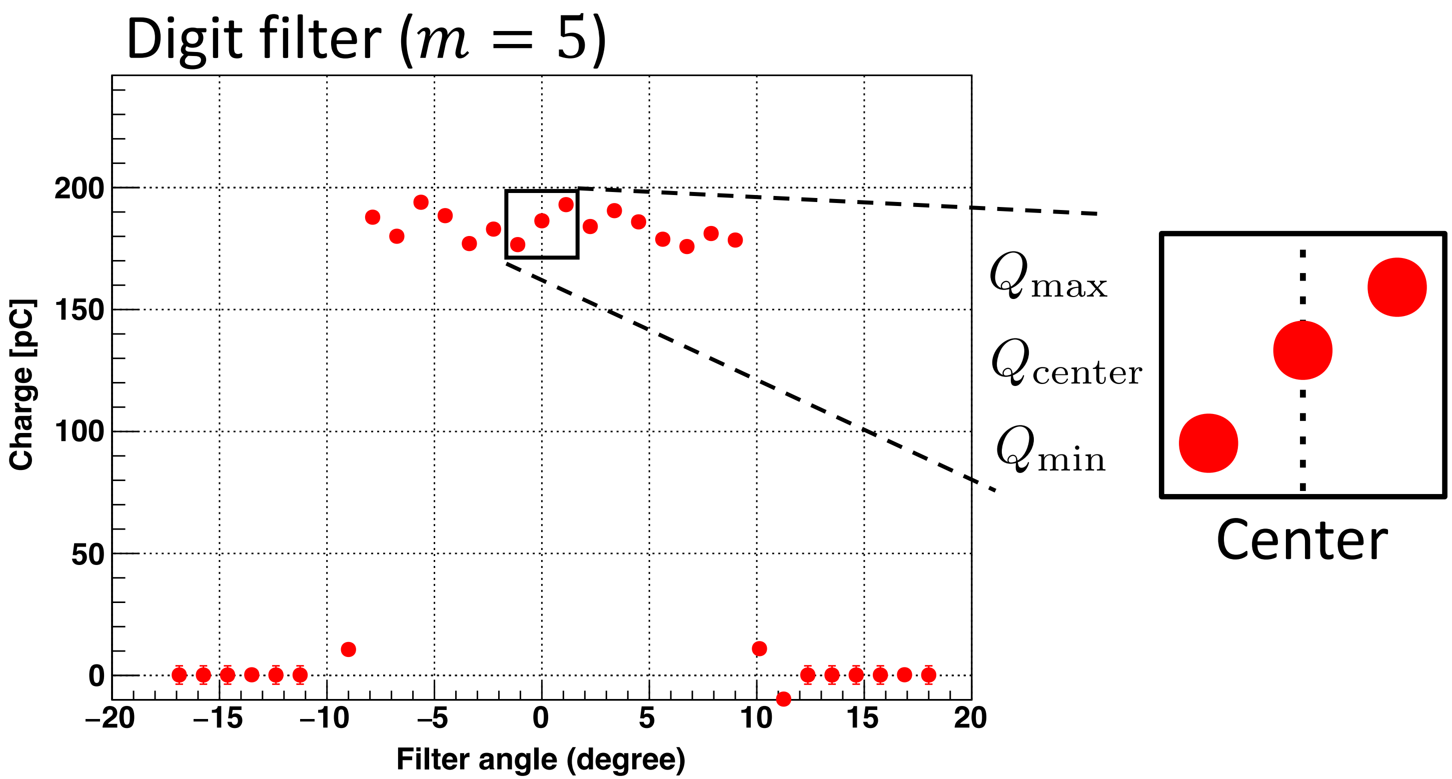


Edges of the filter

- ✓ The middle of the two edges is regarded as <u>the center of the filter ($\theta = 0°$)</u>
- ✓ Non-uniformity of
  - % filters: ~5%
  - digit filters: ~10%
- ✓ The filter's center is put on the path of the laser in all measurements

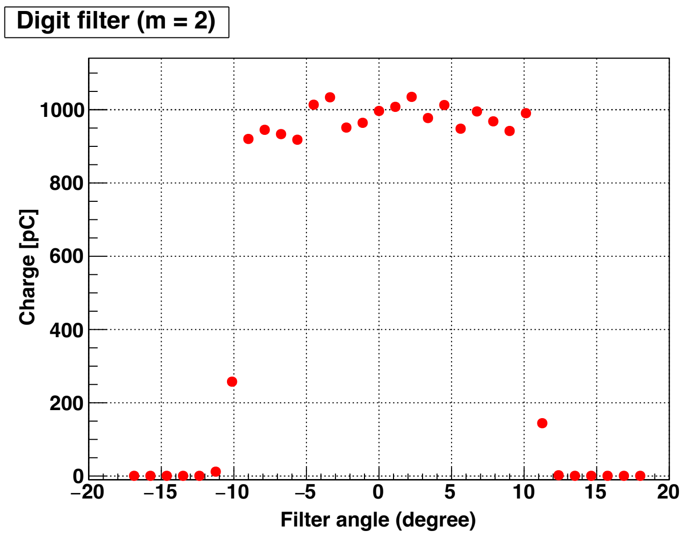
Systematic uncertainty in transmittance

- ✓ Accuracy of the control of the motor is $\simeq 1°$ (1 step)
- ✓ Systematic uncertainty is evaluated using the data points at $\theta = 0°, \pm 1.125°$

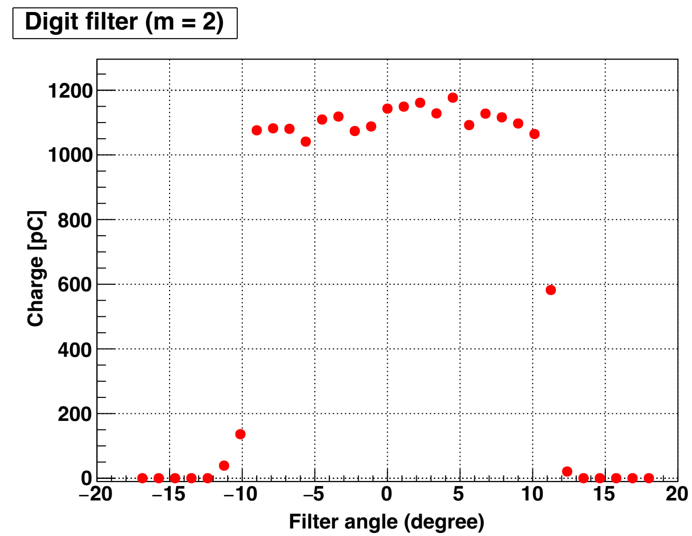


$$\text{Systematic error of filter transmittance } [\%] \equiv \frac{\left(Q_{\mathrm{max}} - Q_{\mathrm{min}}\right)/2}{Q_{\mathrm{center}}} \times 100$$

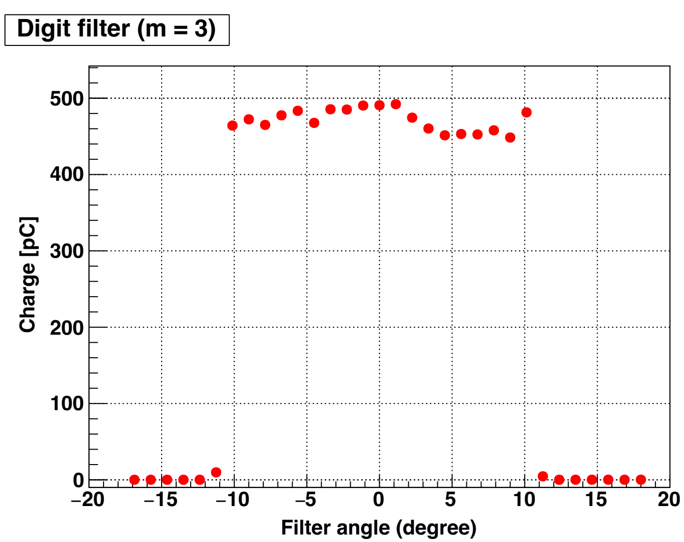
透過率一様性の再現性



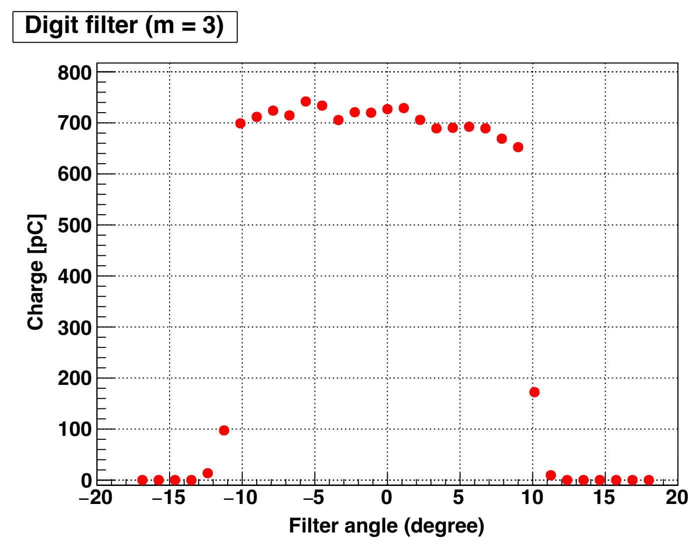
Digit filter (m = 2)
Charge [pC]
Filter angle (degree)



Digit filter (m = 2)
Charge [pC]
Filter angle (degree)

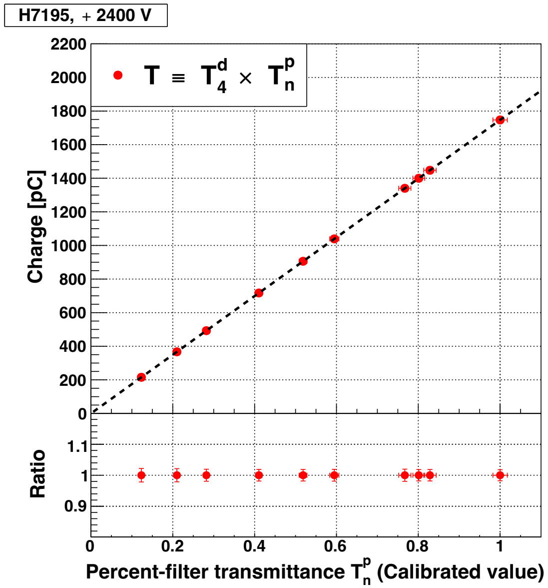


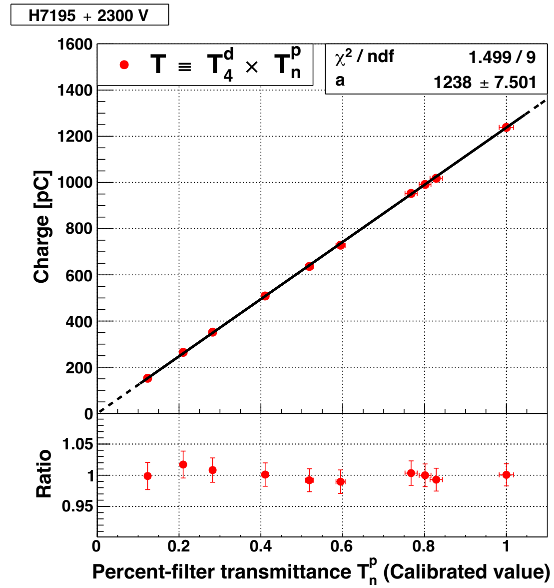
Digit filter (m = 3)
Charge [pC]
Filter angle (degree)

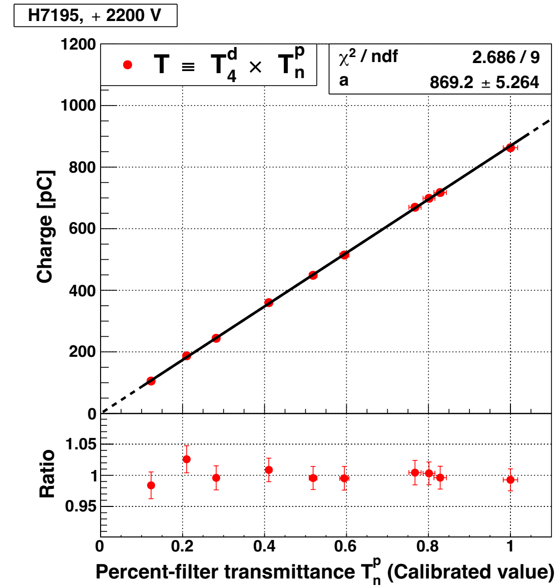


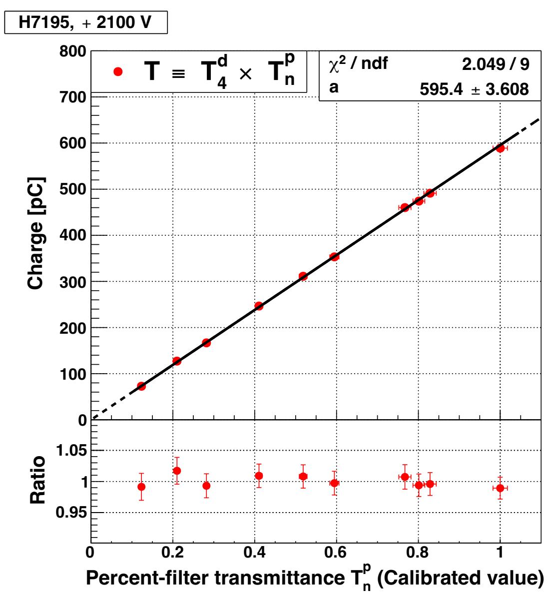
Digit filter (m = 3)
Charge [pC]
Filter angle (degree)

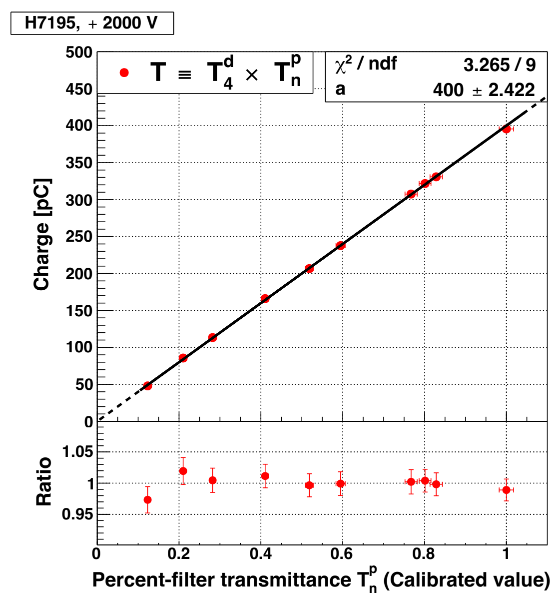
%フィルター透過率の確認







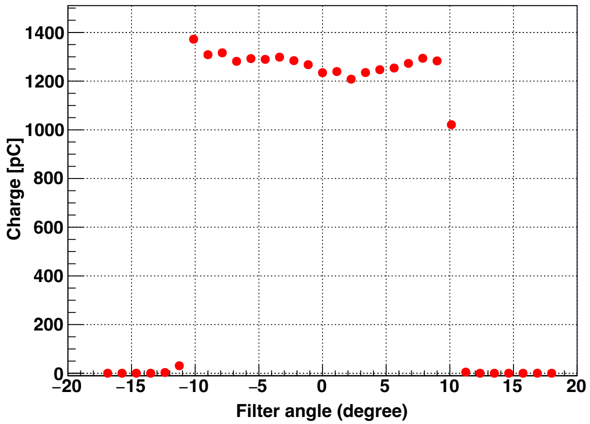




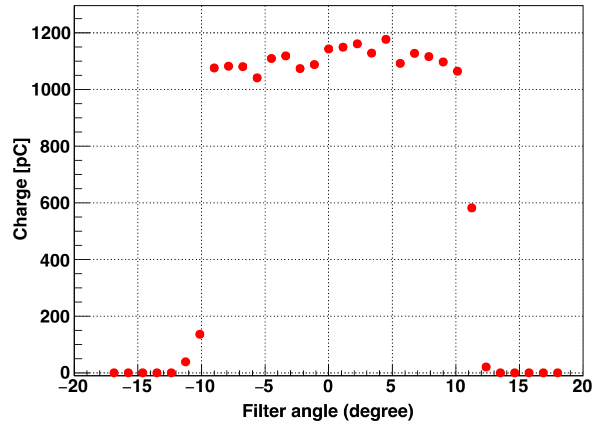
桁フィルターの一様性

$$(\text{Catalog value of } T^{\mathrm{d}}_{m}) = 10^{-m} \quad (m = 0,\ 1,\ 2, \cdots,\ 5)$$

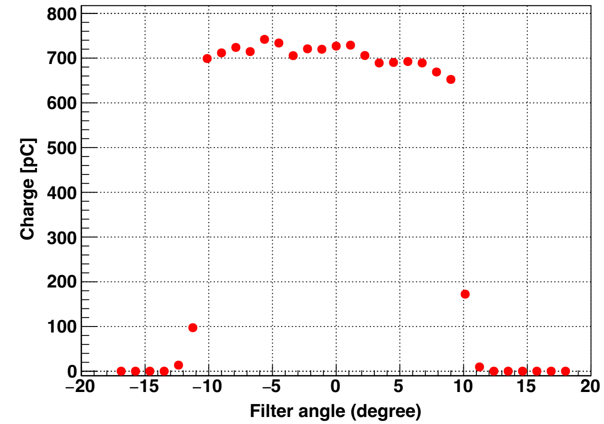
$m = 1$



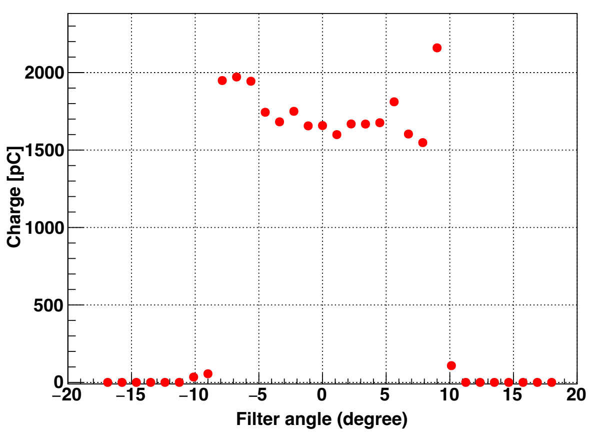
$m = 2$



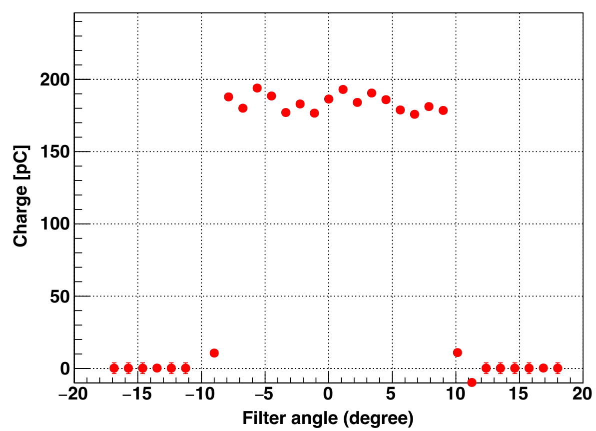
$m = 3$



$m = 4$



$m = 5$



パーセントフィルターの一様性

$$(\text{Catalog value of } T_n^{\mathrm{p}}) = 1 - 0.1 \times n \quad (n = 0,\ 1,\ 2, \cdots,\ 9)$$