“Absolute” Calibration of PMT

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Talk Outline

1. **Introduction: Principle of PMT**
2. **NIST Standard Silicon Photodiode**
3. **Uncertainties, Concerns Specific to PMTs**
4. **Suggestions and Proposal to our Community**

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1. Introduction: Principle of PMT
2. NIST Standard Silicon Photodiode
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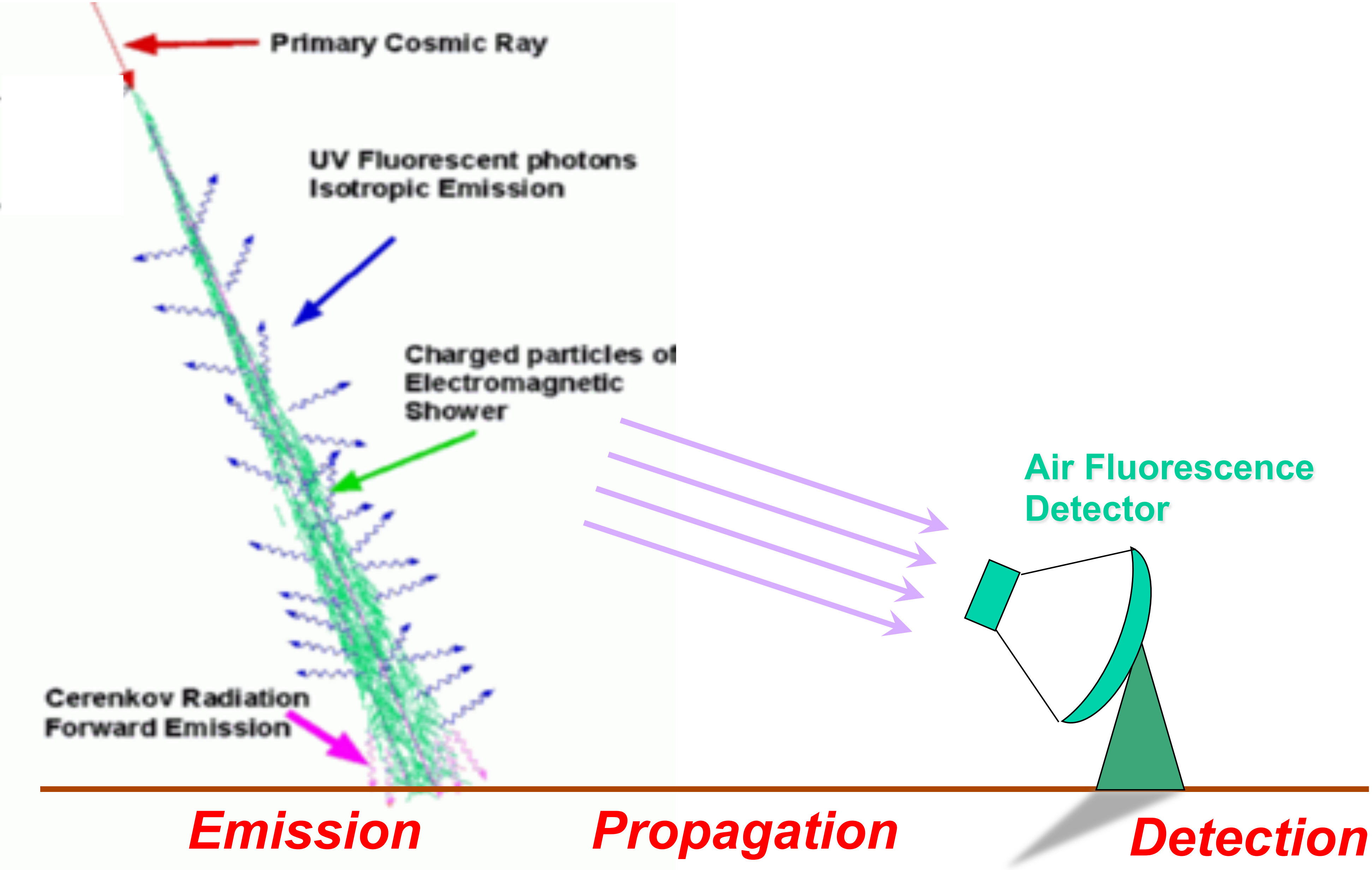
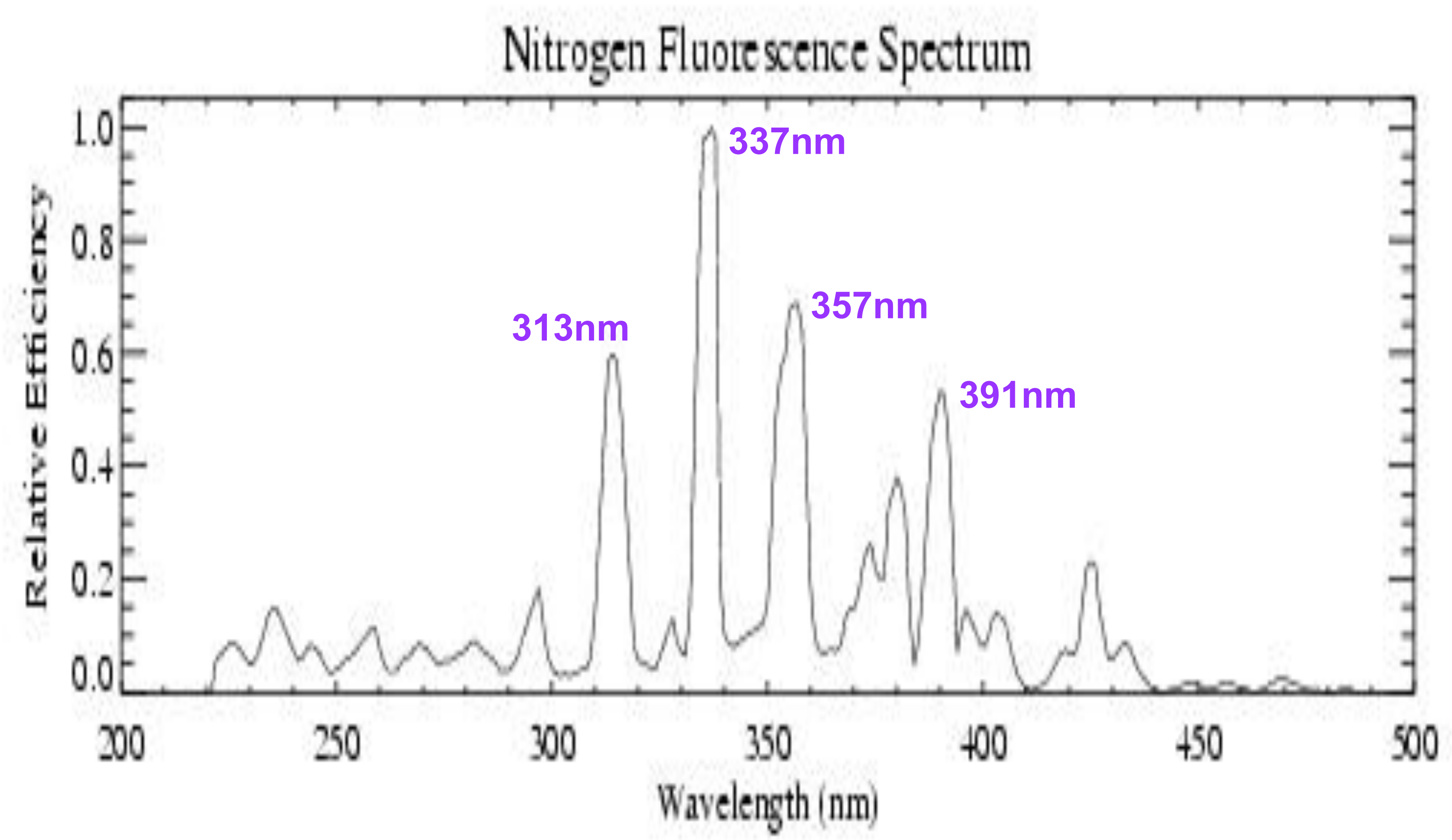
Emission, Propagation and Detection of Fluorescent Photons

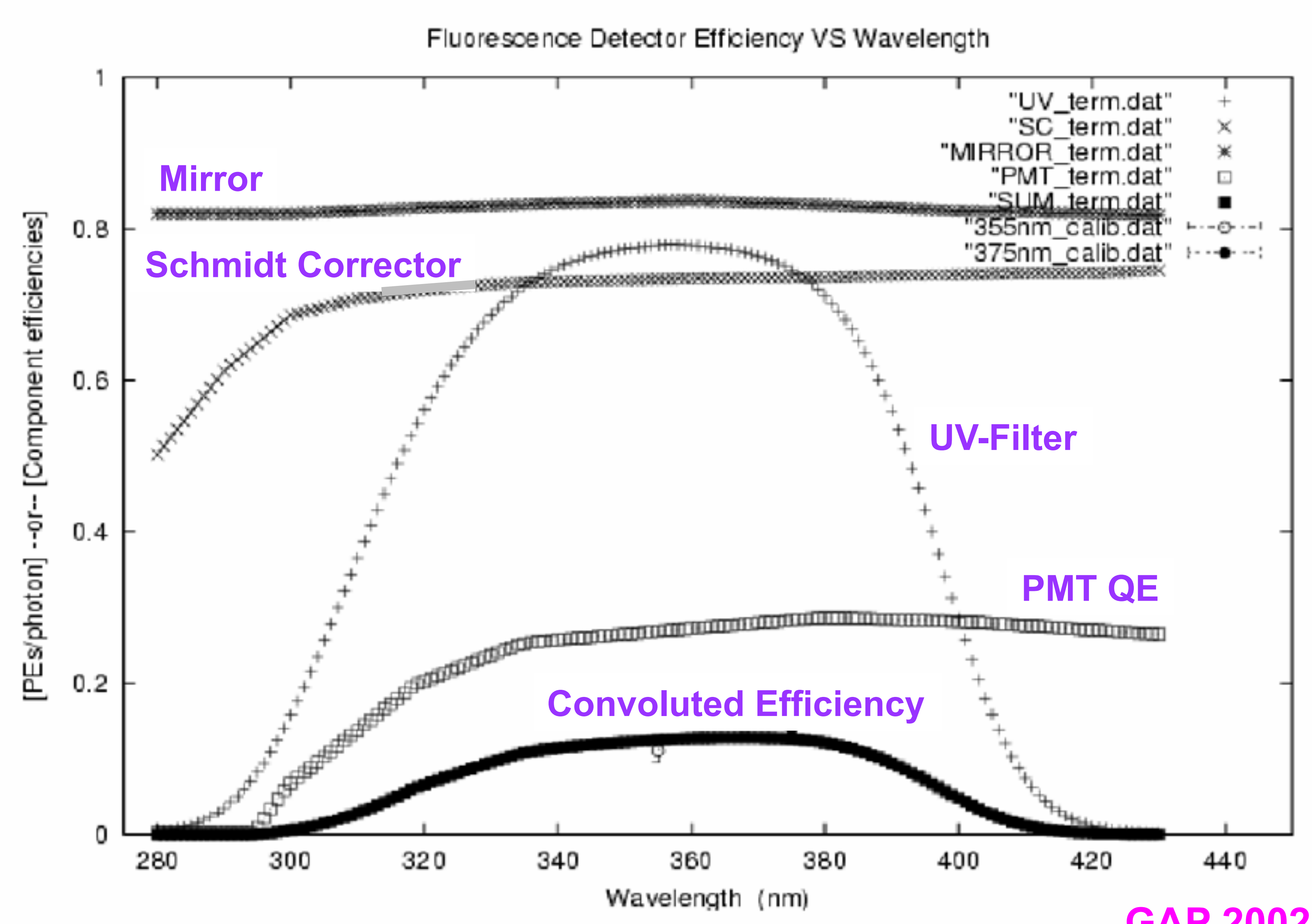


Emission Spectrum of Nitrogen Fluorescence



From HiRes

Photon Detection Efficiency of Auger FD

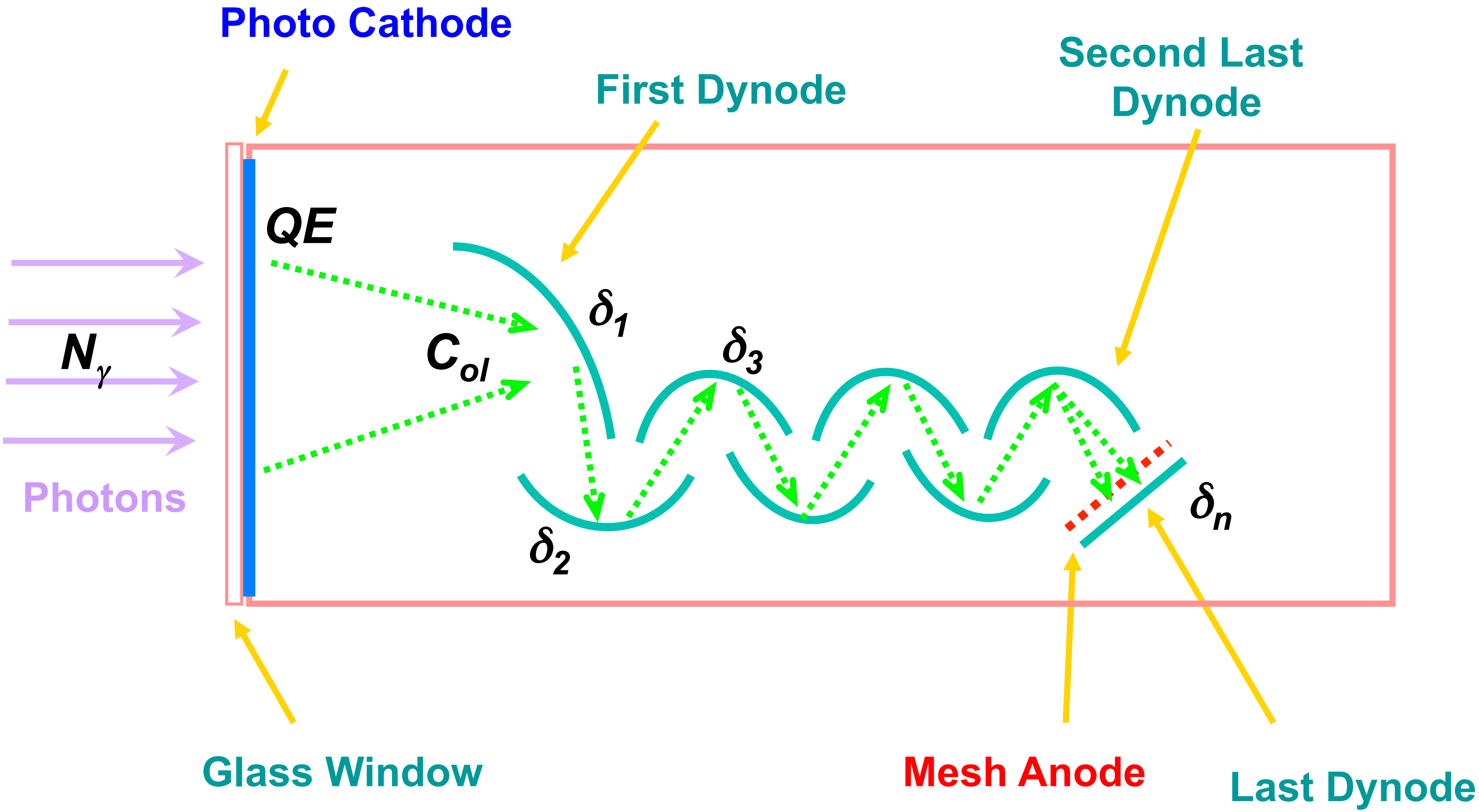


GAP 2002-029

Principle of PMT

- How PMT Works
- Fundamental Parameters of PMT
  - Quantum Efficiency (QE)
  - Photoelectron Collection Efficiency (C_{ol})
  - Gain (G)
  - Excess Noise Factor (ENF)
  - Energy Resolution (σ/E)
- How to Measure These Parameters
- Some Remarks

Structure of Linear-focus PMT



Quantum Efficiency (QE)

- **Definition:**

$$QE \equiv \frac{(\#Emitted\_Photoelectrons)}{(\#Insident\_Photons)}$$

$$= \frac{N_{pe}}{N_{\gamma}}$$

- **How to measure:**
  - **Connect all the dynodes and the anode.**
  - **Supply more than +100V for 100% collection efficiency.**
  - **Measure the cathode current (I_C).**
  - **Compare I_C with that of PMT with known QE.**

Collection Efficiency (C_{ol})

Definition

$$C_{ol} \equiv \frac{(\#PE\_captured\_by\_1st\_Dynode)}{(\#Emitted\_Photoelectrons)}$$

How to measure

- Measure the Cathode current (I_C).
- Add 10^{-5} ND filter in front of PMT.
- Measure the counting rate of the single PE (S).
- Take the ratio of $S \times 1.6 \times 10^{-19} \times 10^5 / I_C$.

Detective Quantum Efficiency (DQE)

➢ Definition:

$$DQE \equiv \frac{(\#PE\_captured\_by\_1st\_Dynode)}{(\#Insident\_Photons)}$$

$$= QE \cdot C_{ol}$$

- *Often confused as QE by "Physicists"*

➢ How to measure:

- Use a weak pulsed light source (so that >90% pulse gives the pedestal.)
- Measure the counting rate of the single PE (S).
- Compare S with that of PMT with known DQE.

Gain (G_P)

- **Definition by Physicists:**

$$\boxed{G_P \equiv \delta_1 \cdot \delta_2 \cdot \delta_3 \cdots \delta_n}$$

(δ_i = Gain of the i-th dynode)

- **How to measure:**
  - Use a weak pulsed light source (so that >90% pulse gives the pedestal.)
  - Measure the center of the mass of Single PE charge distribution of the Anode signal (Q_A).
  - Take the ratio of $Q_A/1.6\times10^{-19}$.

Gain (G_I)

- **Definition by Industries:**

$$\boxed{G_I \equiv C_{ol} \cdot \delta_1 \cdot \delta_2 \cdot \delta_3 \cdots \delta_n}$$

(**δ_i = Gain of the i-th dynode)**

- **How to measure:**
  - **Measure the Cathode current (I_C).**
  - **Add 10^{-5} ND filter in front of PMT.**
  - **Measure the Anode current (I_A).**
  - **Take the ratio of $I_A \times 10^5 / I_C$.**

$$\boxed{G_I = C_{ol} \cdot G_P}$$

Anode Signal (E)

- **Definition:**

$$
\begin{aligned}
E &= N_\gamma \cdot QE \cdot C_{ol} \cdot \delta_1 \cdot \delta_2 \cdot \delta_3 \cdots \delta_n \\
&= N_\gamma \cdot QE \cdot G_I = N_{pe} \cdot G_I \\
&= N_\gamma \cdot QE \cdot C_{ol} \cdot G_p \\
&= N_\gamma \cdot DQE \cdot G_p
\end{aligned}
$$

(by Industries)

(by Physicists)

(N_γ = No. of Incident Photons)

(N_{pe} = No. of Photo-electrons)

Energy Resolution (σ/E)

- **In ideal case:**

$$\frac{\sigma}{E} = \frac{\sqrt{N_\gamma}}{N_\gamma} = \sqrt{\frac{1}{N_\gamma}}$$

- **In reality:**

$$\frac{\sigma}{E} = \sqrt{\frac{ENF}{N_\gamma \cdot QE \cdot C_{ol}} + \left(\frac{ENC}{N_\gamma \cdot QE \cdot C_{ol} \cdot G_P}\right)^2}$$

– **QE**	**Quantum Efficiency**
– **C_{ol}**	**Collection Efficiency:**
– **ENF**	**Excess Noise Factor (from Dynodes)**
– **ENC**	**Equivalent Noise Charge (Readout Noise)**

Excess Noise Factor (ENF)

- **Definition:**

$$\boxed{ENF \equiv \frac{\sigma^2_{Output}}{\sigma^2_{Input}}}$$

- **In case of PMT:**

$$\boxed{ENF = 1 + \frac{1}{\delta_1} + \frac{1}{\delta_1 \cdot \delta_2} + \cdots + \frac{1}{\delta_1 \cdot \delta_2 \cdots \delta_n}}$$

- **How to measure:**
  - **Set N_{pe} = 10-20 (for nice Gaussian).**
  - **Measure σ/E of the Gaussian distribution.**
  - **ENF is given by**

$$\boxed{ENF = (\sigma/E)^2 (N_{pe} \cdot C_{ol})}$$

Remarks

- **Don't try to estimate *N_{pe}* or *N_γ* from σ/E !**

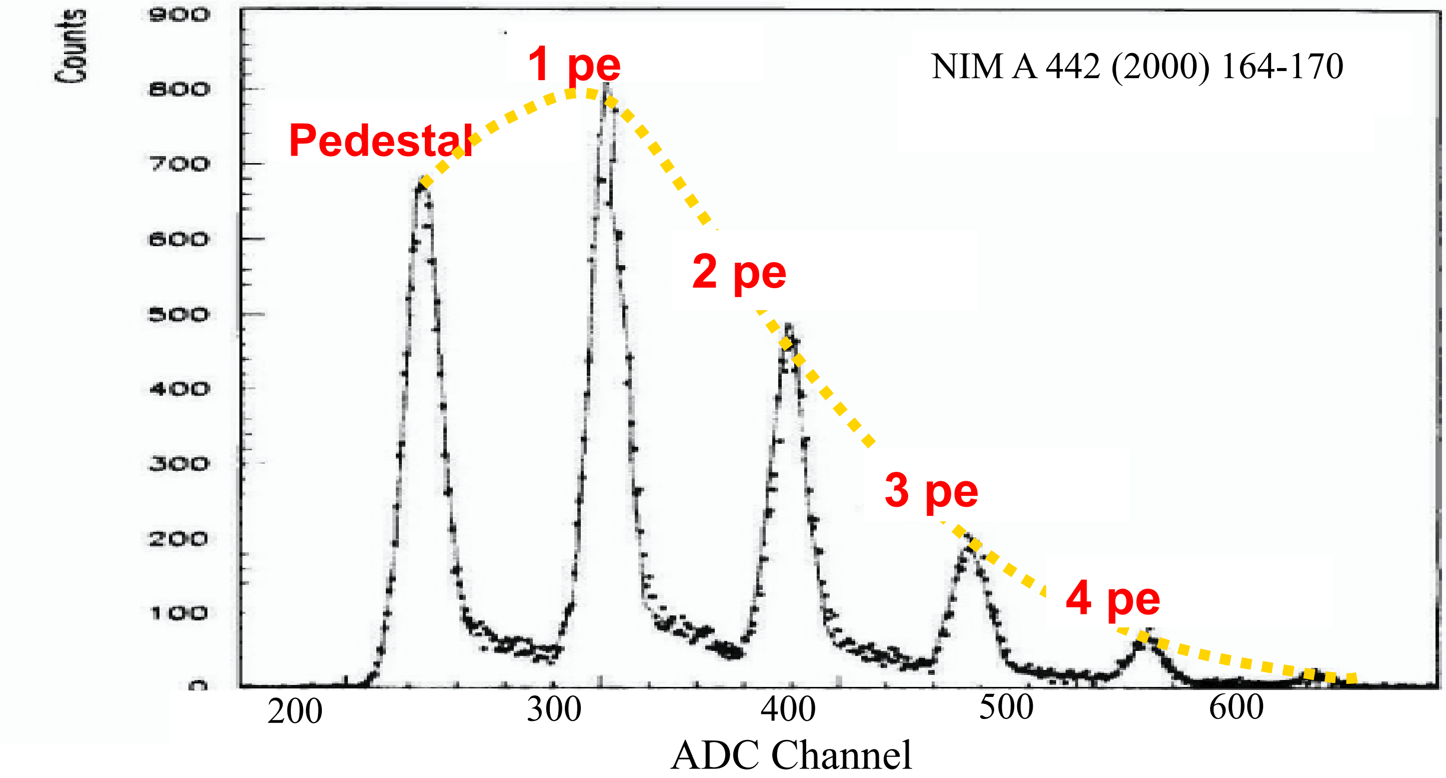
$$\frac{\sigma}{E} \xcancel{\neq} \sqrt{\frac{1}{N_{pe}}} = \sqrt{\frac{1}{N_\gamma \cdot QE}}$$

$$\frac{\sigma}{E} = \sqrt{\frac{ENF}{N_\gamma \cdot QE \cdot C_{ol}}}$$

(Assuming ENC is negligible.)

Resolution of Hybrid Photodiode (HPD)

- HPD can count 1, 2, 3… PE separately.
  - ENF=1.0

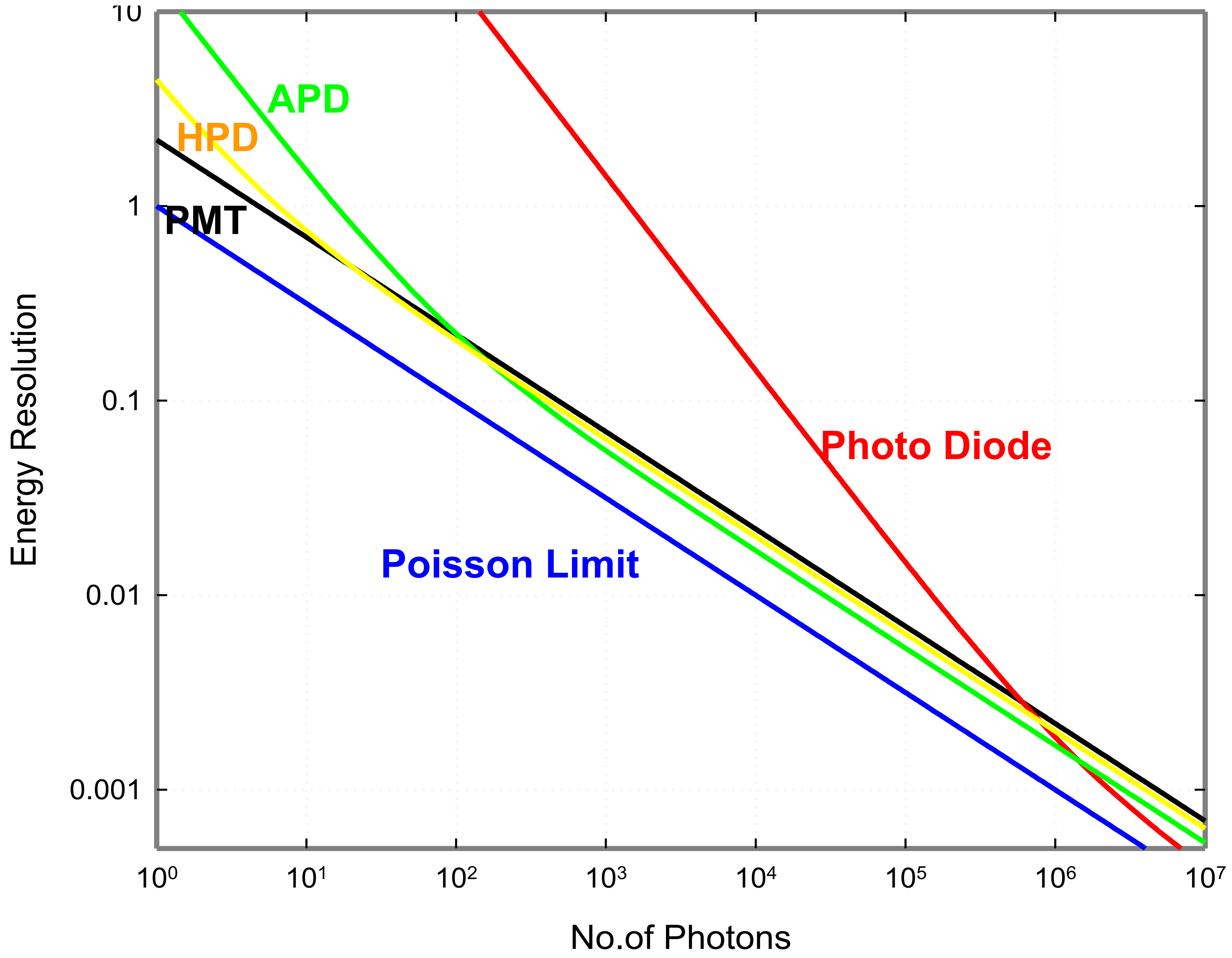


- But it is still suffering from poor QE.
  - We can never beat the Poisson statistics !

Typical Values and Resolution of Various Photon Detectors

	QE	C_{ol}	δ_i	ENF	G	ENC	σ/E
Ideal	1.0	1.0	1000	1.0	10^6	0	$\sqrt{1/N}$
PMT	0.3	0.9	10	1.3	10^6	10^3	$\sqrt{4/N}$
PD	0.8	1.0	-	1.0	1	10^3	$\sqrt{1.4/N+(1000/N)^2}$
APD	0.8	1.0	2	2.0	100	10^3	$\sqrt{3/N+(14/N)^2}$
HPD	0.3	0.95	1000	1.0	10^3	10^3	$\sqrt{3/N+(3/N)^2}$
HAPD	0.3	0.95	1000	1.0	10^5	10^3	$\sqrt{3/N}$

Energy Resolution vs. N_γ



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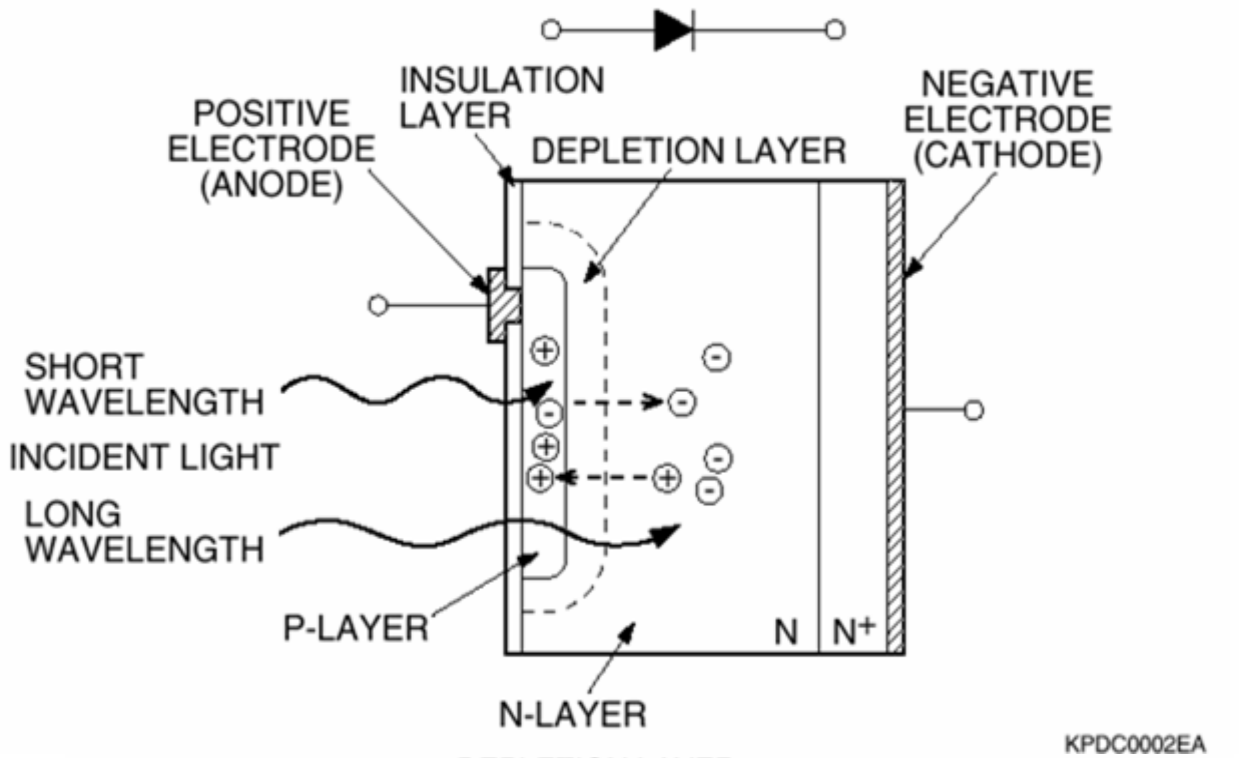
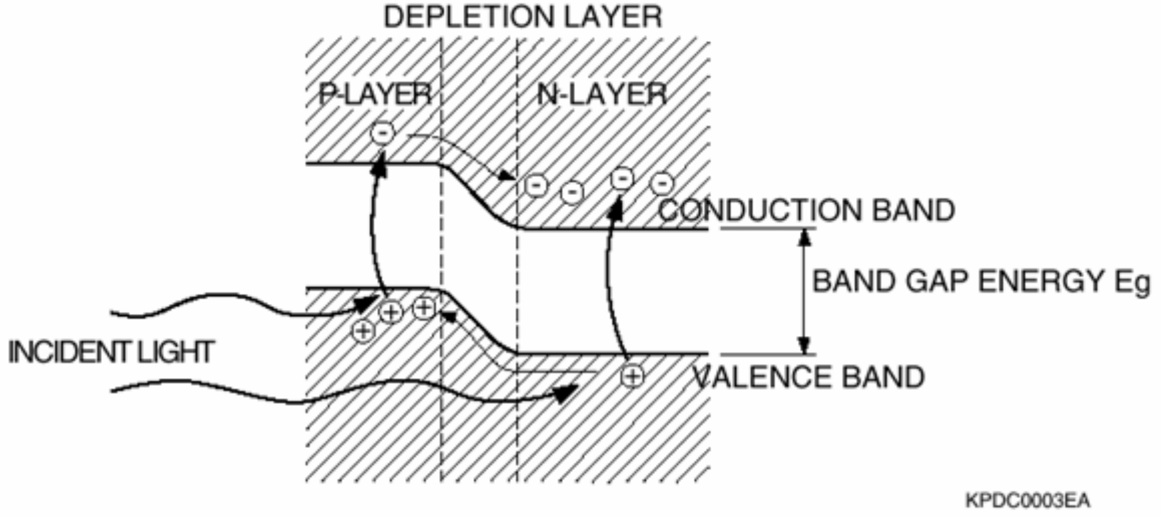
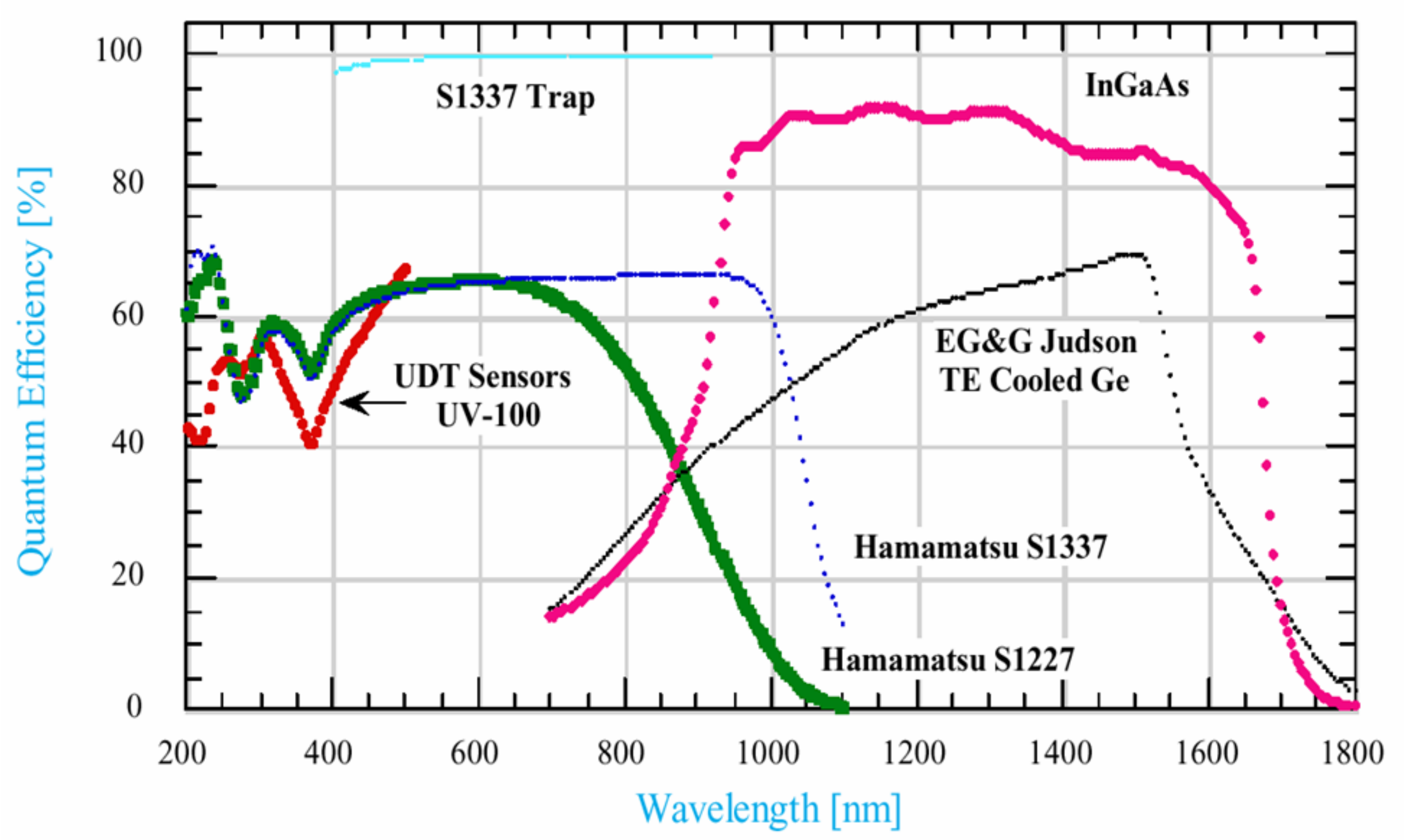
Principle of Silicon Photodiode

- **Gain = 1.0**
- **QE ~ 100%**
- **Extremely Stable**
- **Large Dynamic Range**

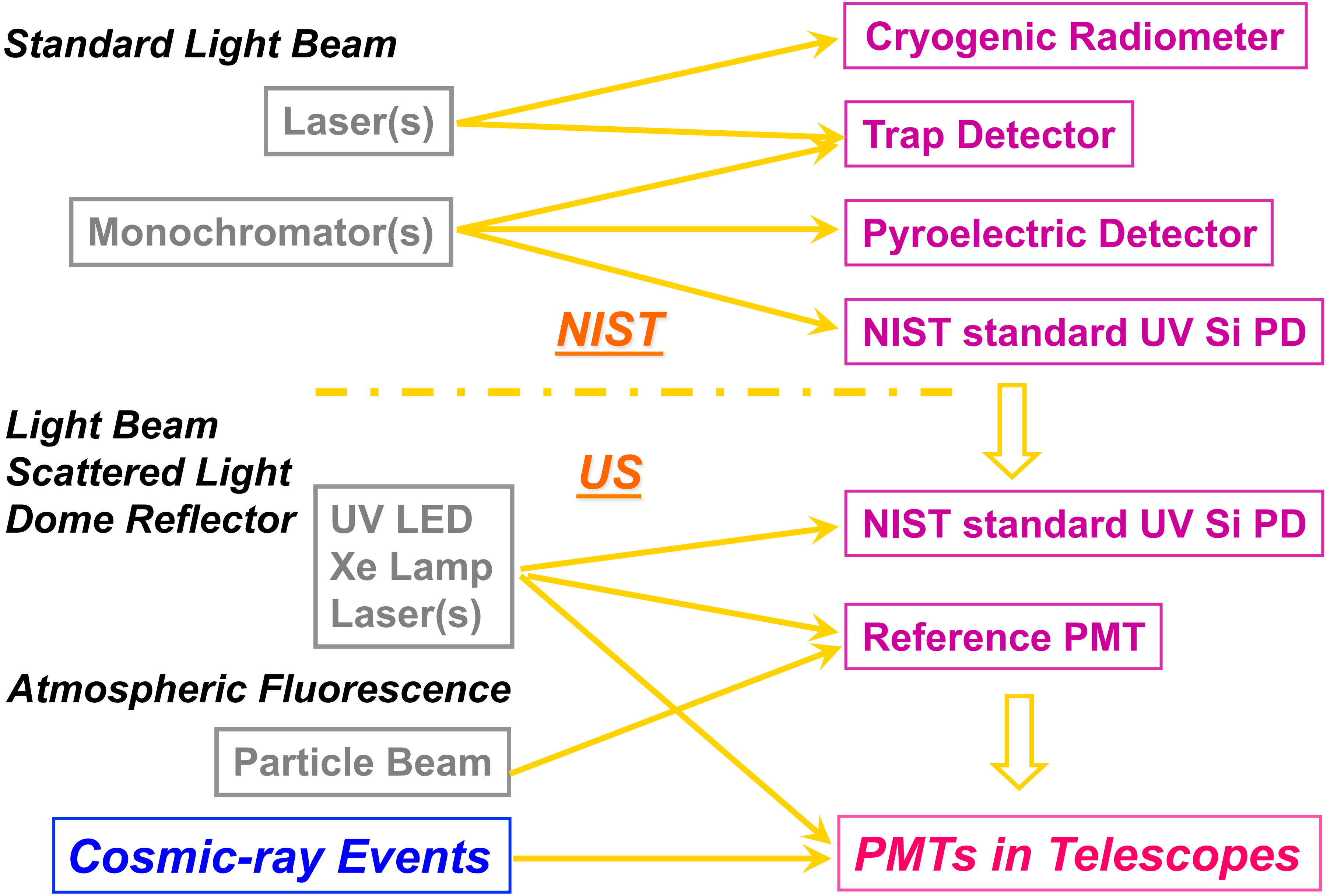




Quantum Efficiencies of NIST Standards (Si, InGaAs and Ge photodiodes)



Propagation Chain of Absolute Calibration of Photon Detectors



Standard Light Beam

Laser(s)

Monochromator(s)

Cryogenic Radiometer

Trap Detector

Pyroelectric Detector

NIST standard UV Si PD

NIST

US

Light Beam
Scattered Light
Dome Reflector

UV LED
Xe Lamp
Laser(s)

NIST standard UV Si PD

Reference PMT

Atmospheric Fluorescence

Particle Beam

Cosmic-ray Events

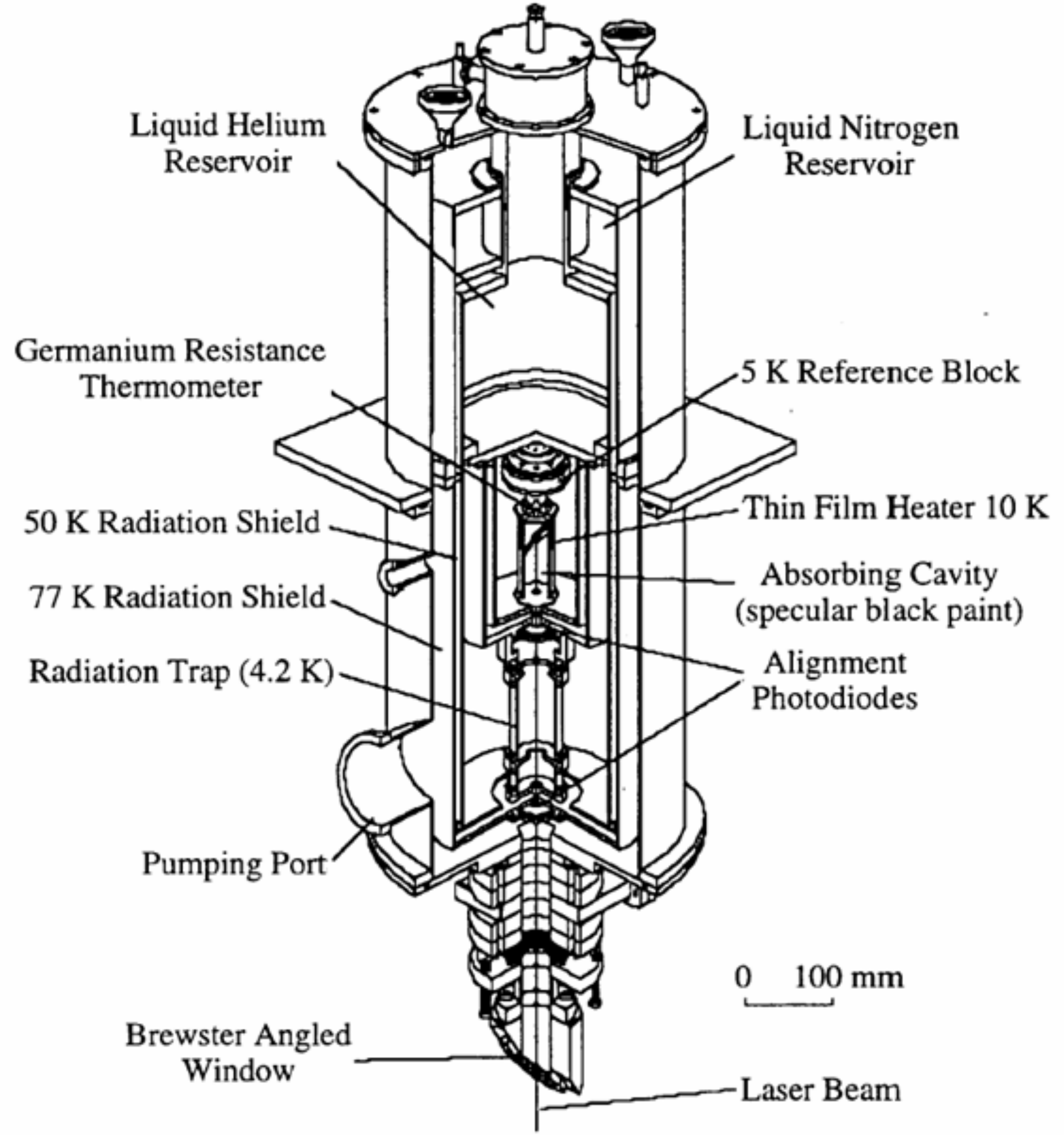
PMTs in Telescopes

NIST High Accuracy Cryogenic Radiometer (HACR)

- **Shoot a laser to a black body of 4.2°K.**
- **Balance heat by electrical power which produces resistive heating.**

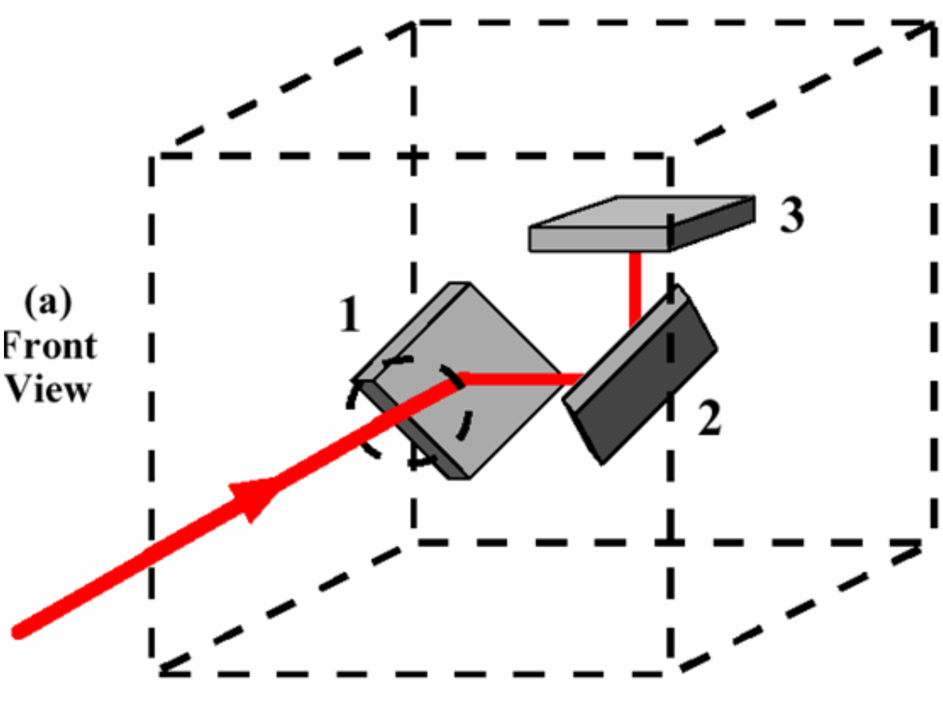
⇩

- **Uncertainty is 0.021% (at 1mW).**

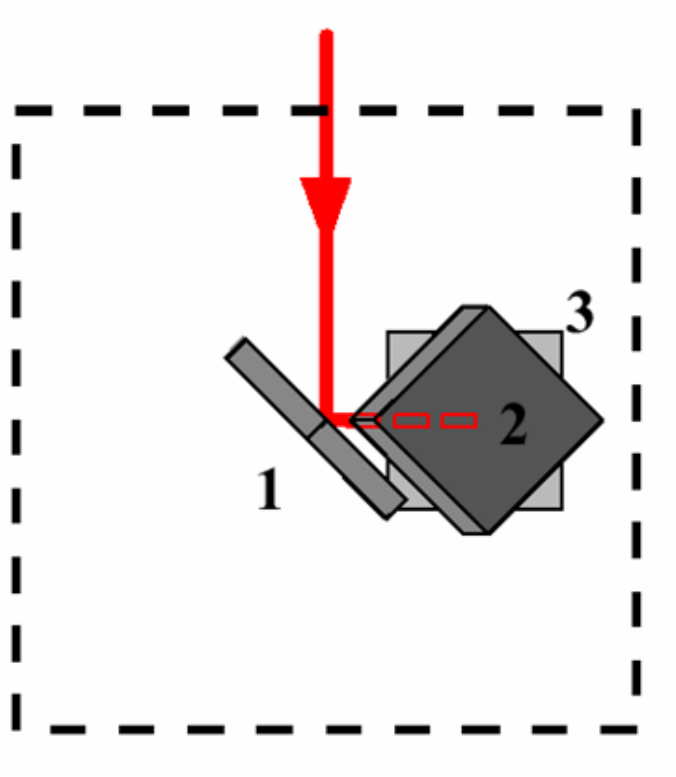


Trap Detector

- ~99.5% efficiency of trapping.
- Uncertainty is 0.05%.

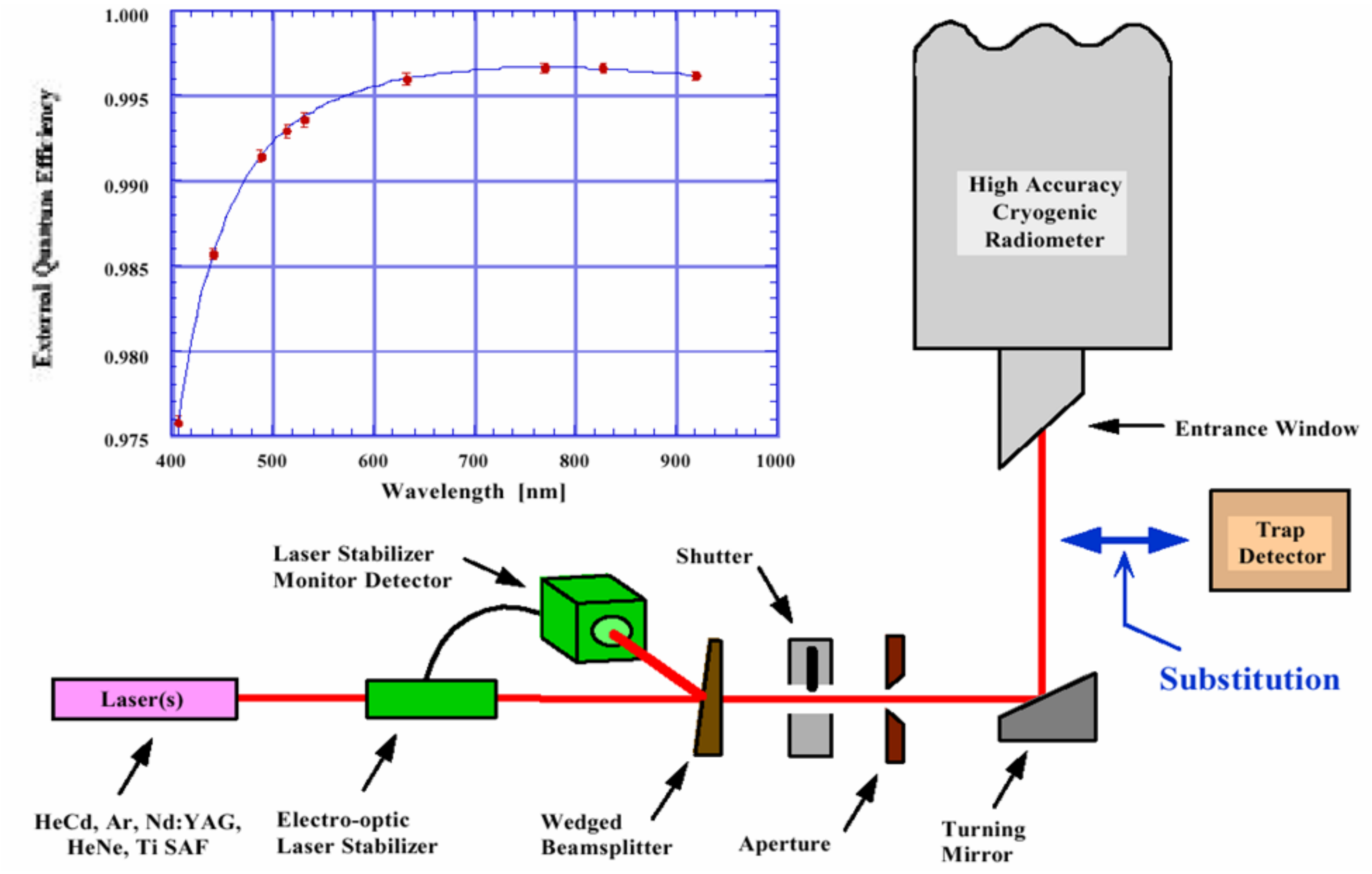


Front View

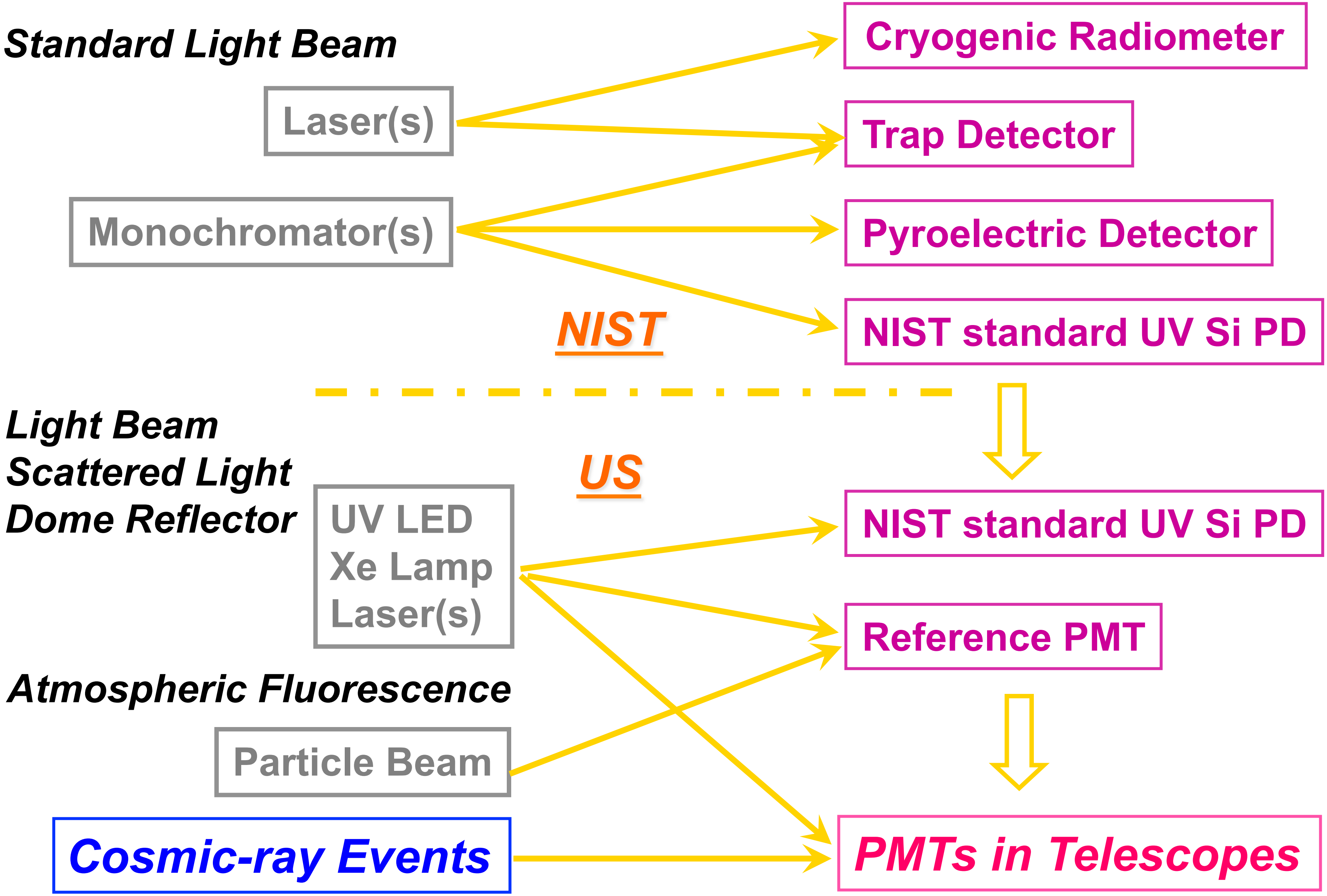


Bottom View

Scale transfer by substitution method with the HACR



Propagation Chain of Absolute Calibration of Photon Detectors



Standard Light Beam

Laser(s)

Monochromator(s)

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NIST standard UV Si PD

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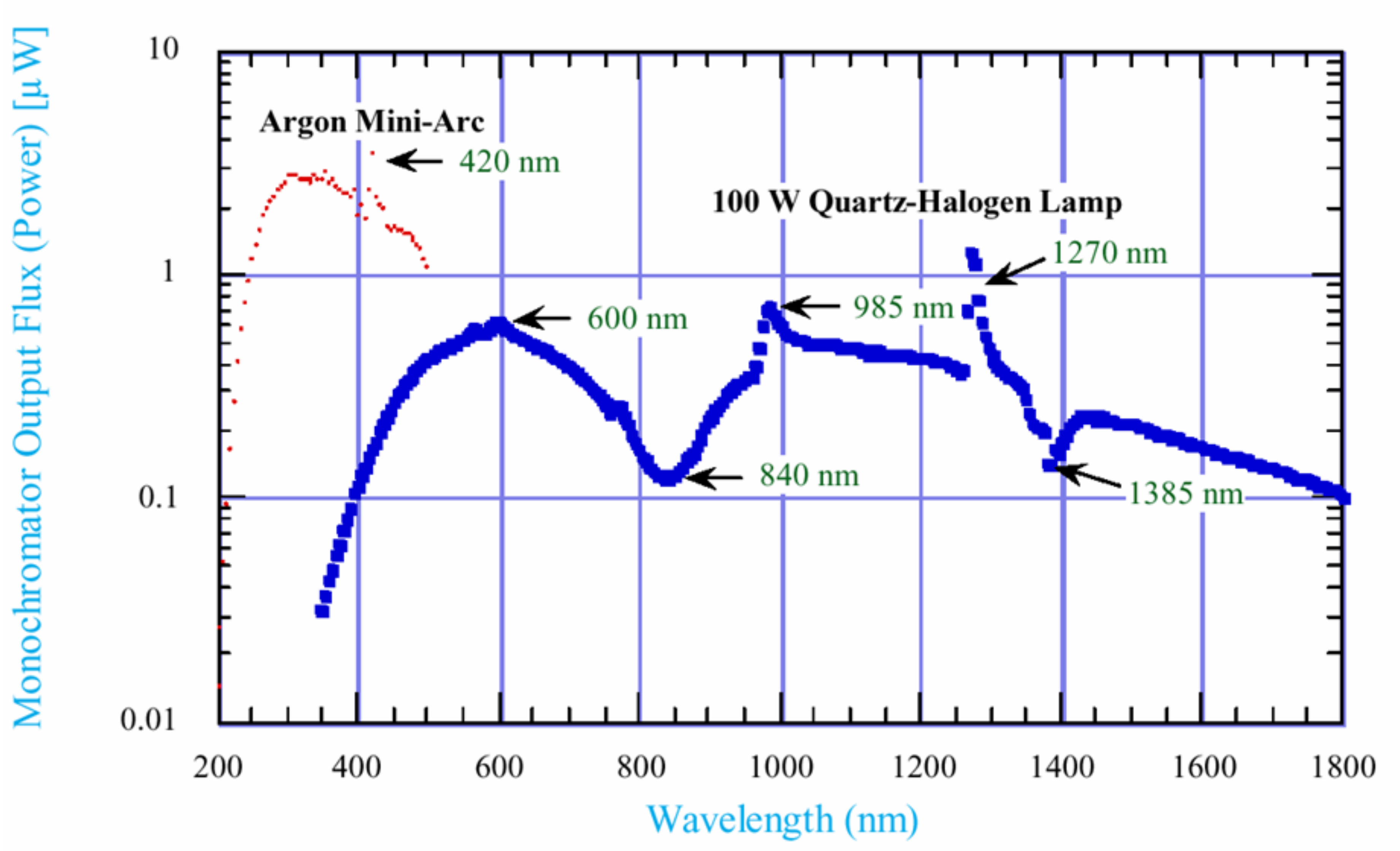
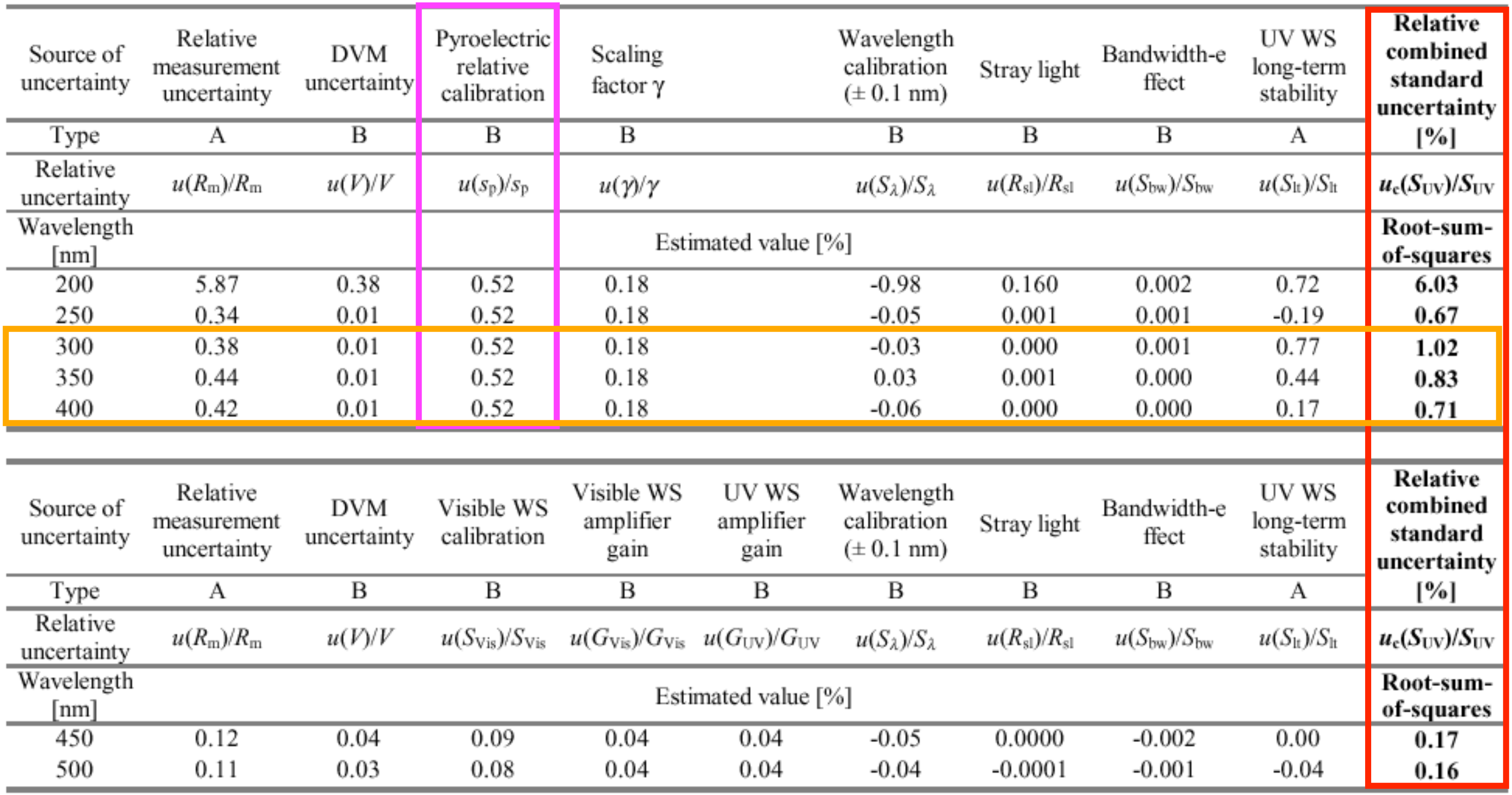
PMTs in Telescopes

Spectral output flux of the UV and visible to near-IR monochromators



UV Working Standard Uncertainty

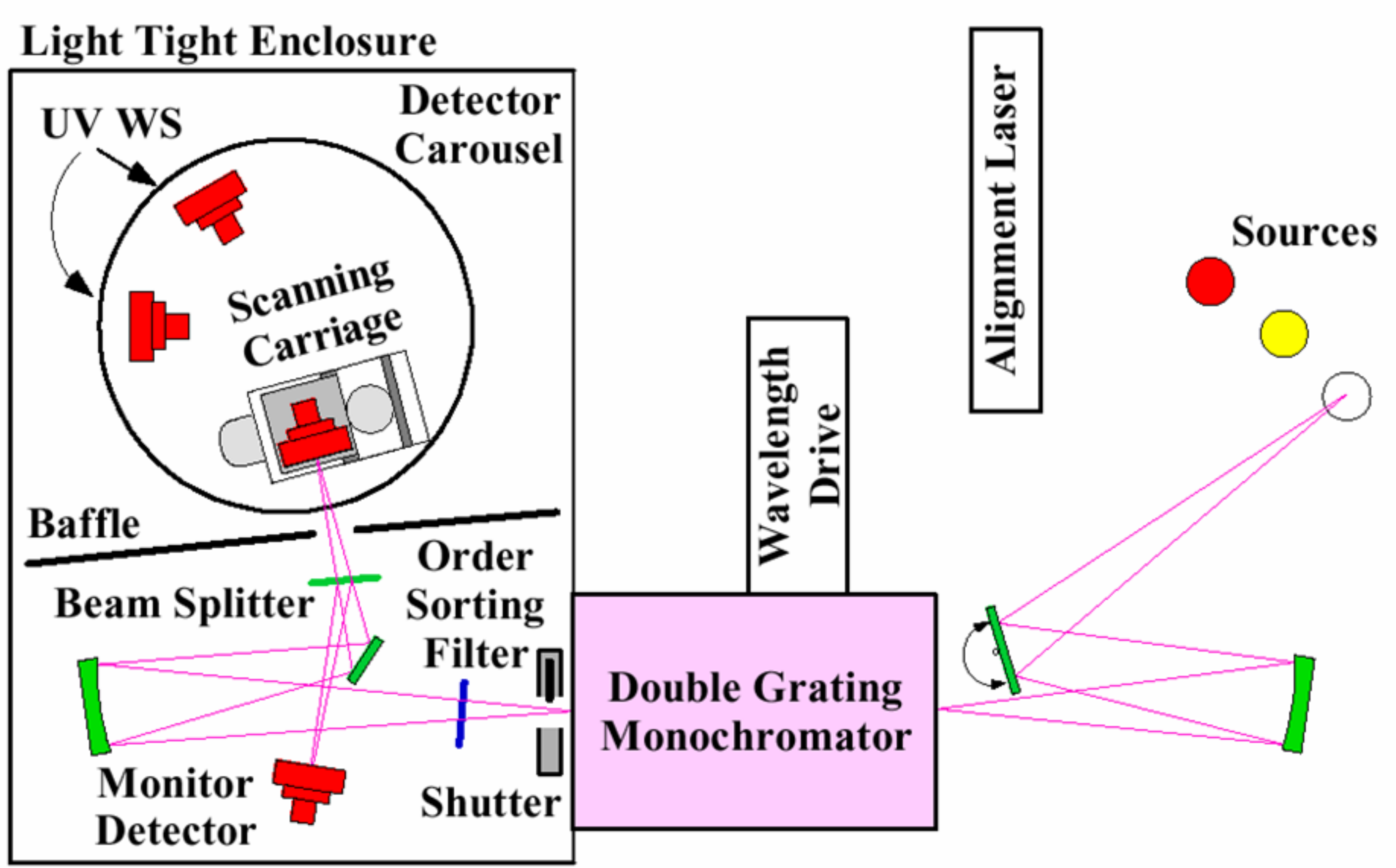
Transfer from Pyroelectric (relative) and Scaling with Visible WS (absolute).



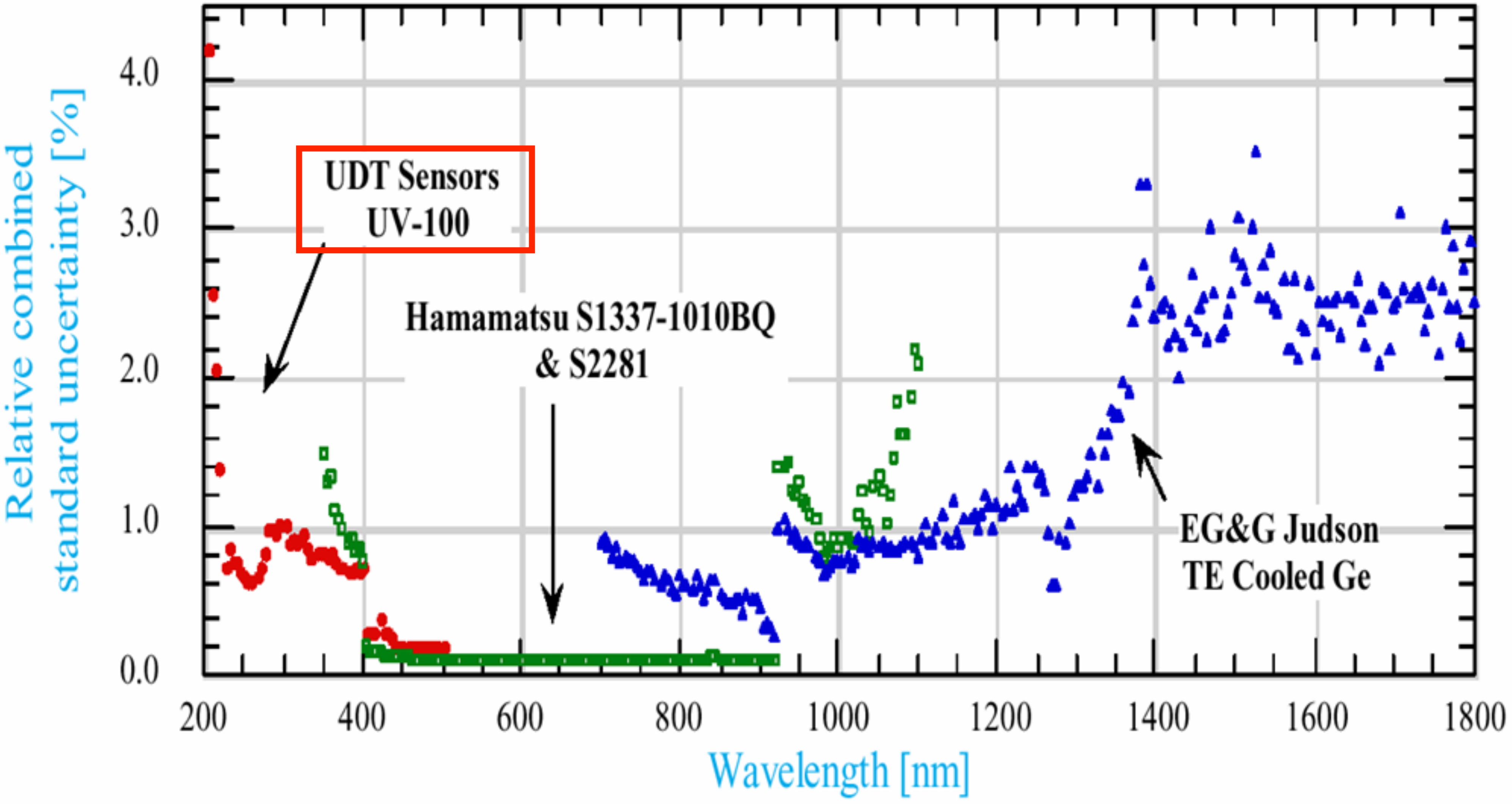
Source of uncertainty	Relative measurement uncertainty	DVM uncertainty	Pyroelectric relative calibration	Scaling factor γ	Wavelength calibration (± 0.1 nm)	Stray light	Bandwidth-effect	UV WS long-term stability	**Relative combined standard uncertainty [%]**
Type	A	B	B	B	B	B	B	A	
Relative uncertainty	$u(R_m)/R_m$	$u(V)/V$	$u(s_p)/s_p$	$u(\gamma)/\gamma$	$u(S_\lambda)/S_\lambda$	$u(R_{sl})/R_{sl}$	$u(S_{bw})/S_{bw}$	$u(S_{lt})/S_{lt}$	$\boldsymbol{u_c(S_{UV})/S_{UV}}$
Wavelength [nm]	Estimated value [%]								**Root-sum-of-squares**
200	5.87	0.38	0.52	0.18	-0.98	0.160	0.002	0.72	**6.03**
250	0.34	0.01	0.52	0.18	-0.05	0.001	0.001	-0.19	**0.67**
300	0.38	0.01	0.52	0.18	-0.03	0.000	0.001	0.77	**1.02**
350	0.44	0.01	0.52	0.18	0.03	0.001	0.000	0.44	**0.83**
400	0.42	0.01	0.52	0.18	-0.06	0.000	0.000	0.17	**0.71**

Source of uncertainty	Relative measurement uncertainty	DVM uncertainty	Visible WS calibration	Visible WS amplifier gain	UV WS amplifier gain	Wavelength calibration (± 0.1 nm)	Stray light	Bandwidth-effect	UV WS long-term stability	**Relative combined standard uncertainty [%]**
Type	A	B	B	B	B	B	B	B	A	
Relative uncertainty	$u(R_m)/R_m$	$u(V)/V$	$u(S_{Vis})/S_{Vis}$	$u(G_{Vis})/G_{Vis}$	$u(G_{UV})/G_{UV}$	$u(S_\lambda)/S_\lambda$	$u(R_{sl})/R_{sl}$	$u(S_{bw})/S_{bw}$	$u(S_{lt})/S_{lt}$	$\boldsymbol{u_c(S_{UV})/S_{UV}}$
Wavelength [nm]	Estimated value [%]									**Root-sum-of-squares**
450	0.12	0.04	0.09	0.04	0.04	-0.05	0.0000	-0.002	0.00	**0.17**
500	0.11	0.03	0.08	0.04	0.04	-0.04	-0.0001	-0.001	-0.04	**0.16**

Ultraviolet Spectral Comparator Facility (UV SCF)

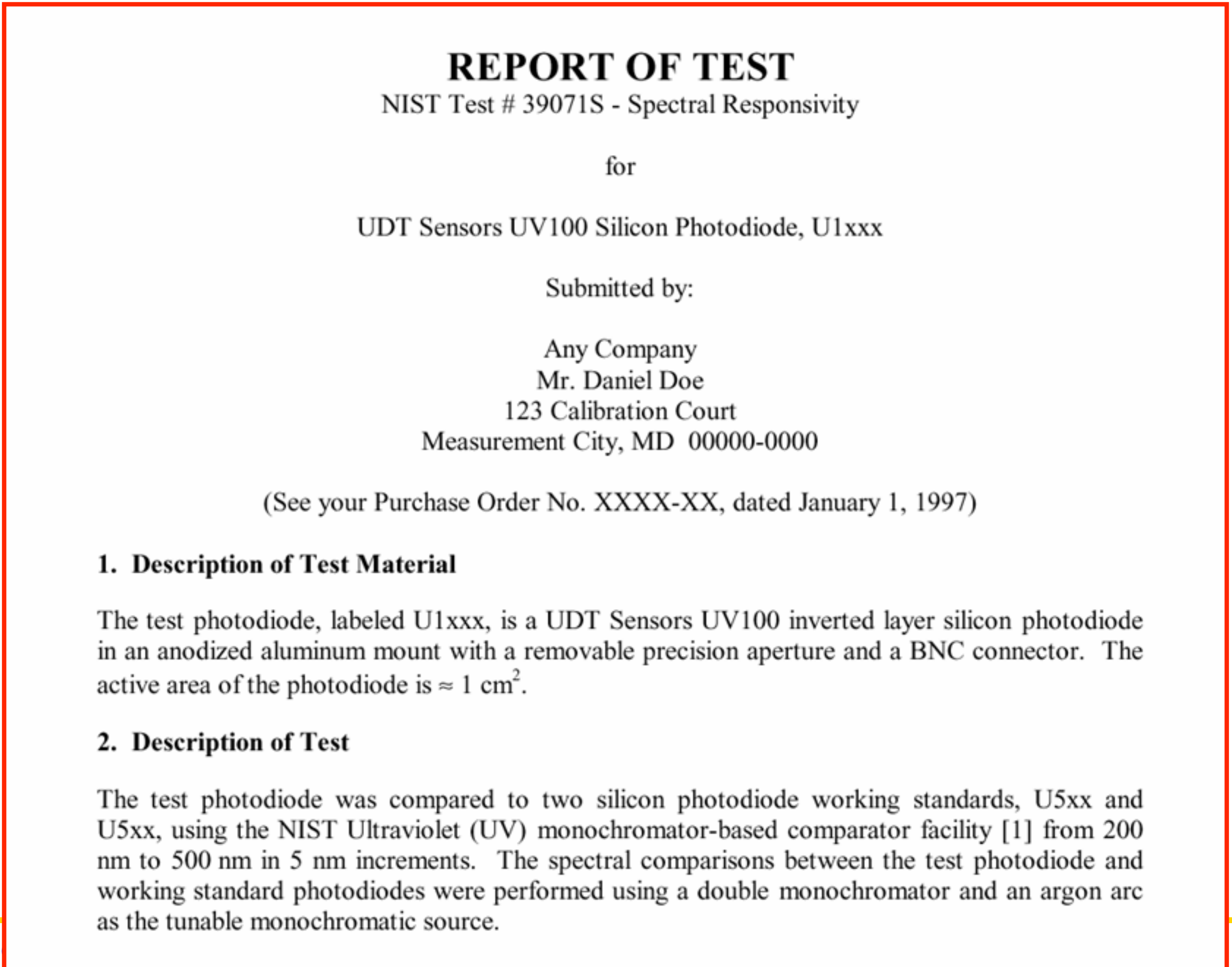


Transfer to test (customer) detectors relative combined standard uncertainty



(Note: Relative standard uncertainty at 200 nm is 6.5 %.)

Example of “Report of Test”



REPORT OF TEST

NIST Test # 39071S - Spectral Responsivity

for

UDT Sensors UV100 Silicon Photodiode, U1xxx

Submitted by:

Any Company
Mr. Daniel Doe
123 Calibration Court
Measurement City, MD 00000-0000

(See your Purchase Order No. XXXX-XX, dated January 1, 1997)

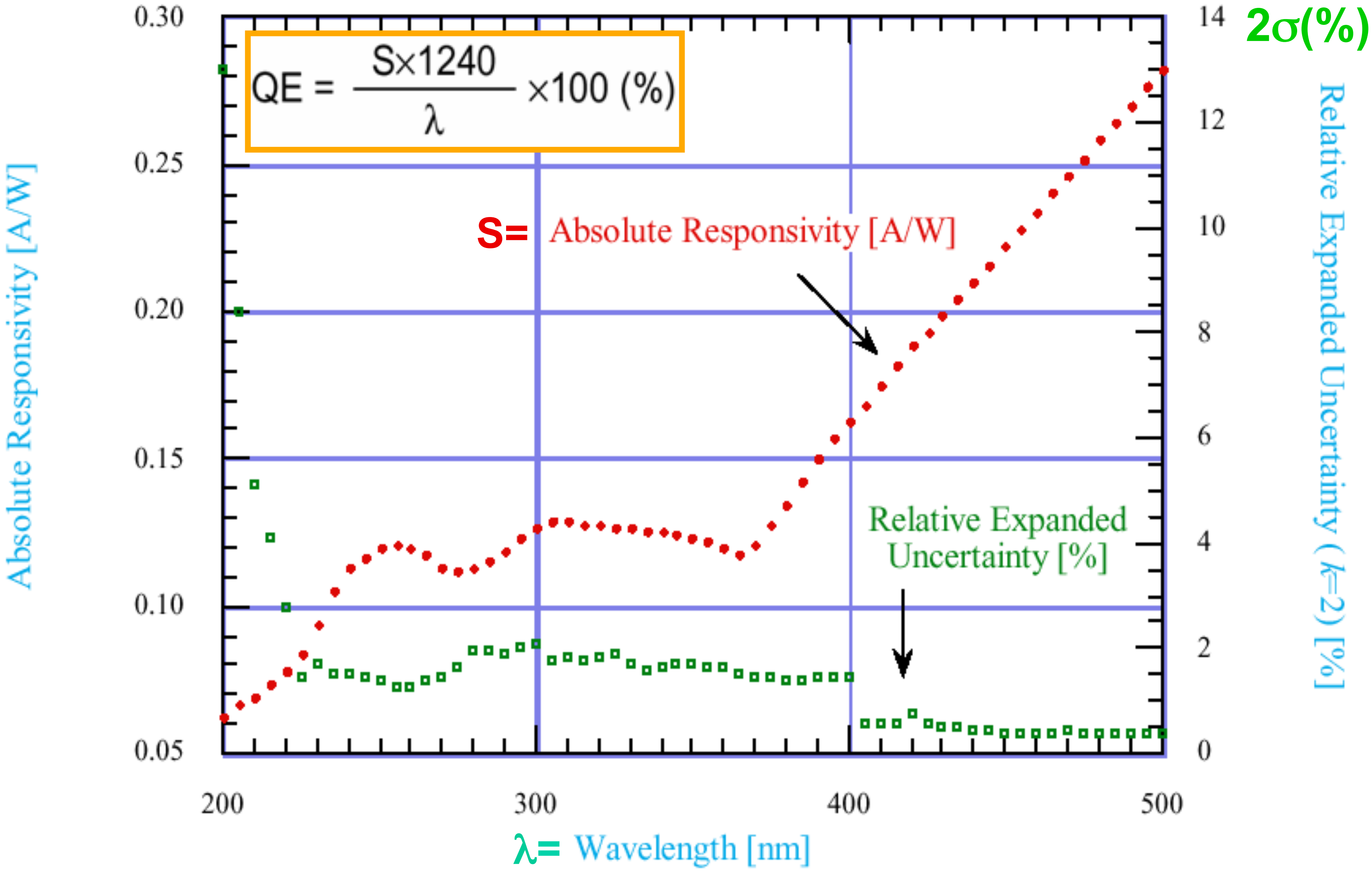
1. Description of Test Material

The test photodiode, labeled U1xxx, is a UDT Sensors UV100 inverted layer silicon photodiode in an anodized aluminum mount with a removable precision aperture and a BNC connector. The active area of the photodiode is ≈ 1 cm^2.

2. Description of Test

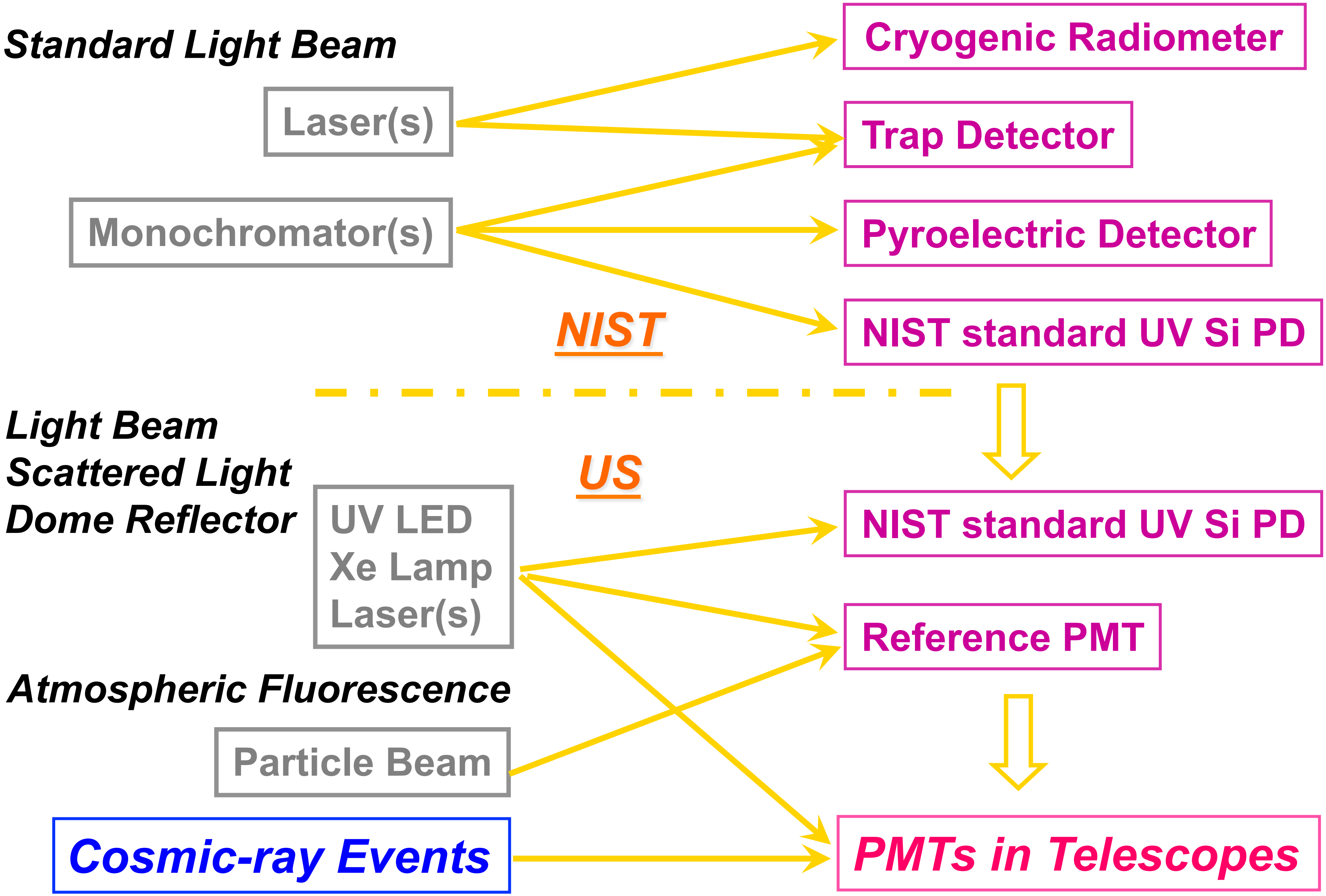
The test photodiode was compared to two silicon photodiode working standards, U5xx and U5xx, using the NIST Ultraviolet (UV) monochromator-based comparator facility [1] from 200 nm to 500 nm in 5 nm increments. The spectral comparisons between the test photodiode and working standard photodiodes were performed using a double monochromator and an argon arc as the tunable monochromatic source.

Absolute Spectral Responsivity of Silicon Photodiode U1xxx



$$QE = \frac{S \times 1240}{\lambda} \times 100\ (\%)$$

Propagation Chain of Absolute Calibration of Photon Detectors



Standard Light Beam

Laser(s)

Monochromator(s)

Cryogenic Radiometer

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Pyroelectric Detector

NIST standard UV Si PD

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Light Beam
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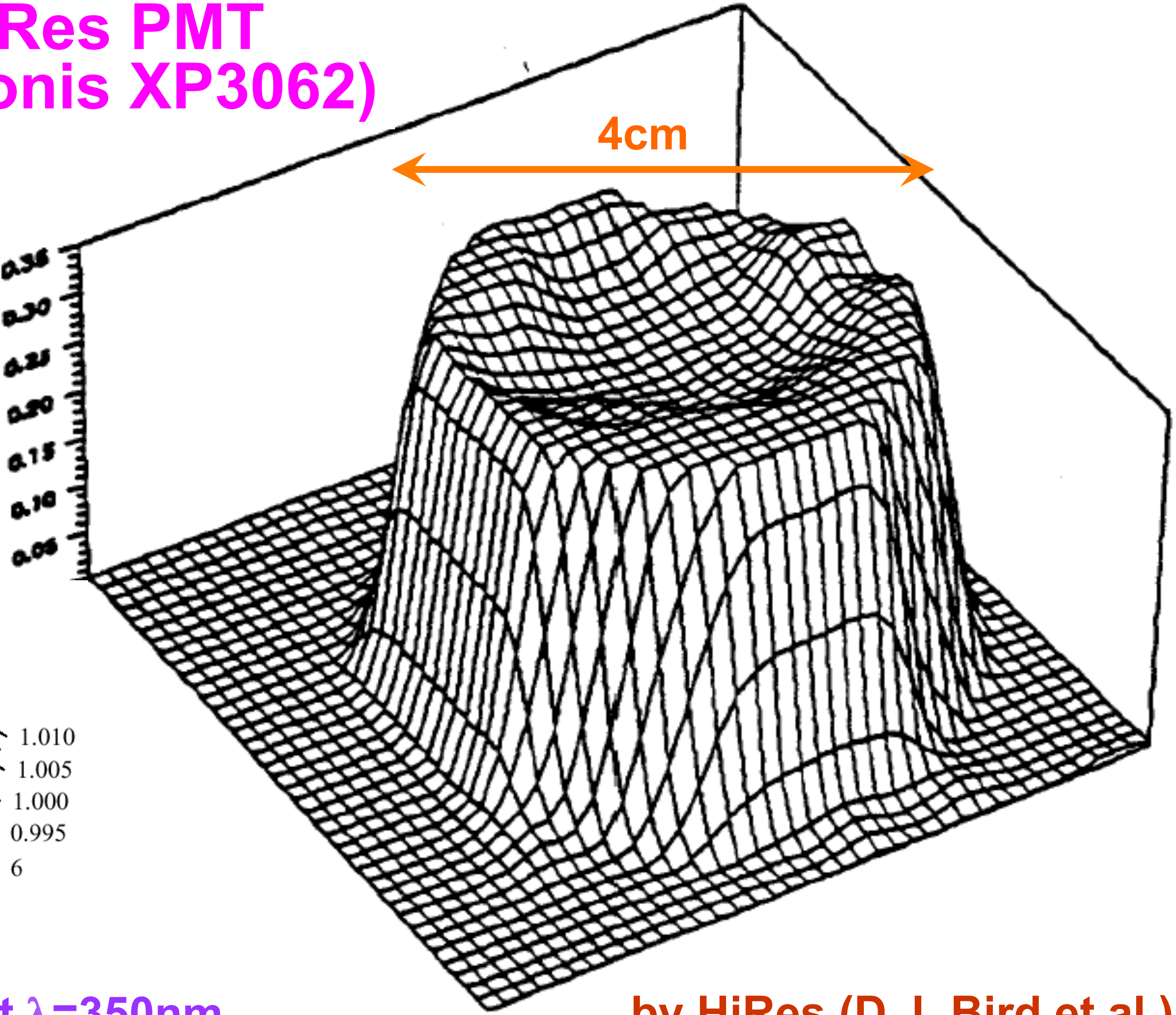
Uncertainties Specific to PMTs

- PMTs are not perfect. There are many issues to be concerned:
  - Cathode and Anode Uniformity
  - Wave Length Dependence of QE
  - Photon Incident Angles
  - Effect of Magnetic Field
  - Non Linearity
  - Temperature Dependence
  - Long-term Stability

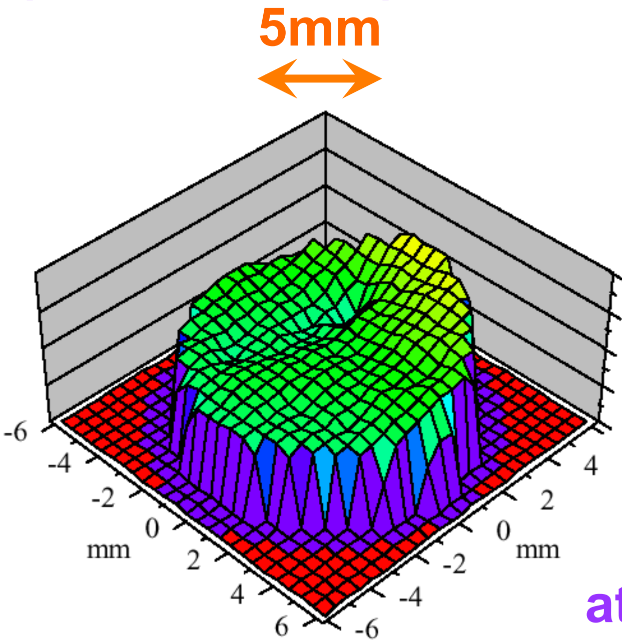
Cathode Uniformity and Area Correction

HiRes PMT
(Photonis XP3062)



by HiRes (D.J. Bird et al.)

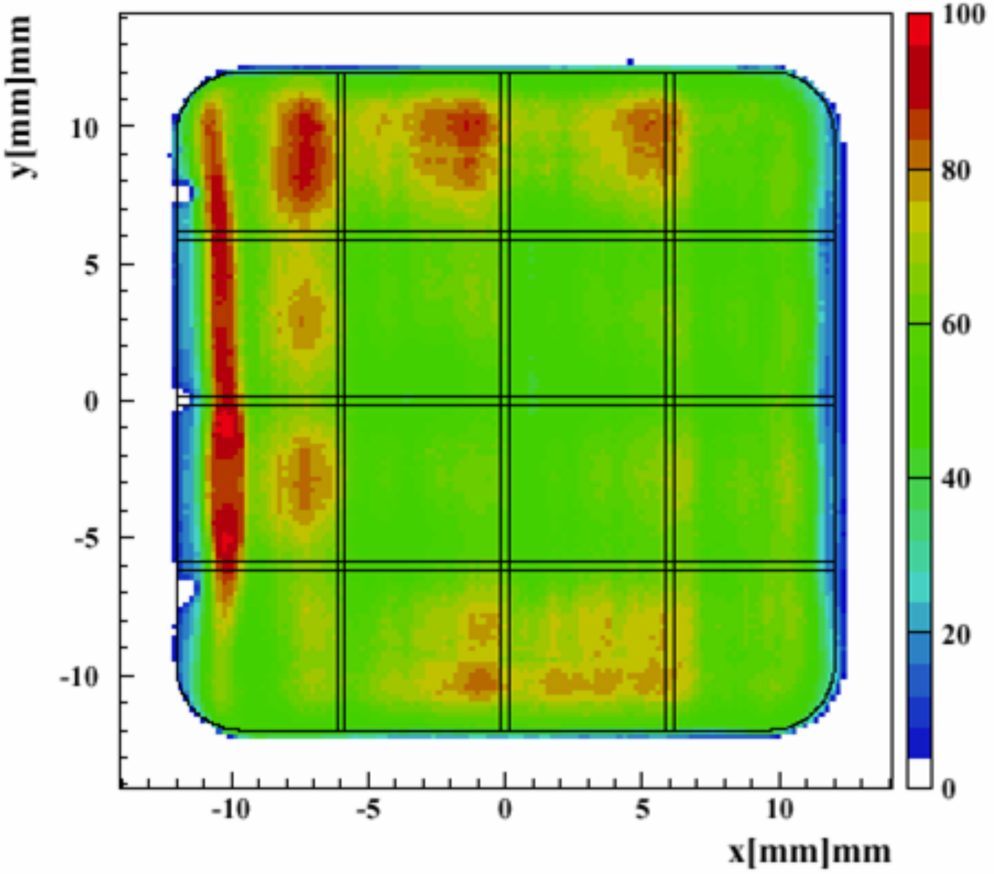
NIST SiPD
(UDT UV100)



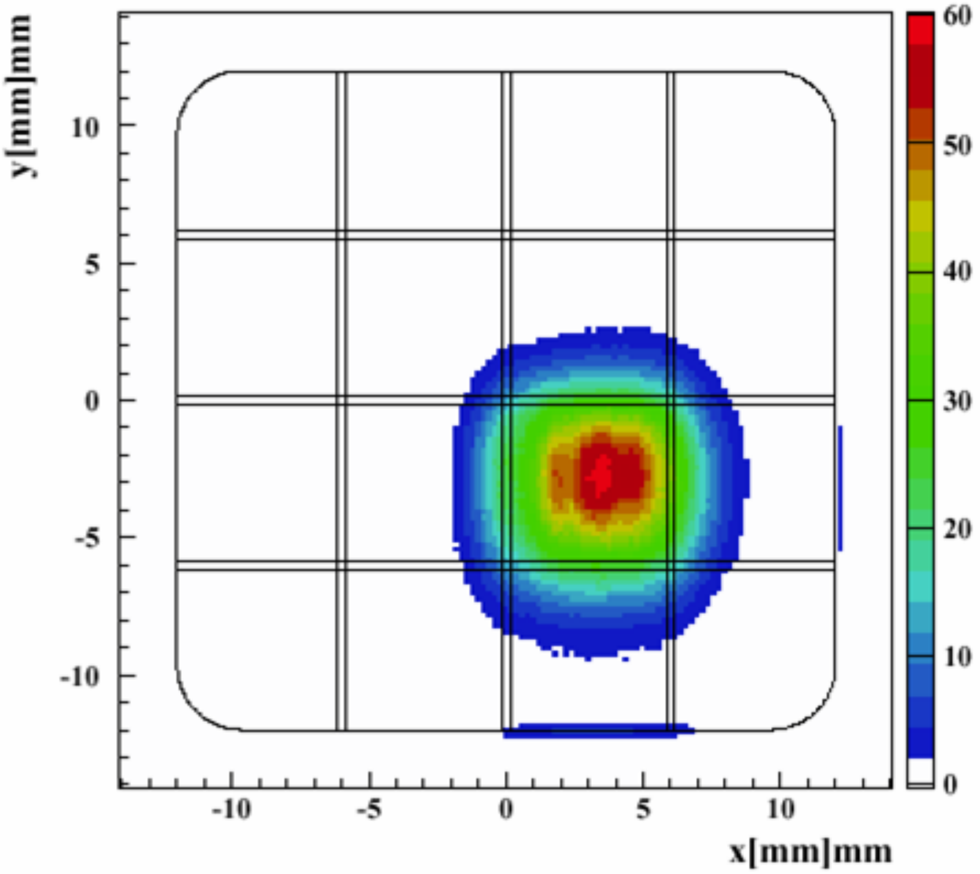
at λ=350nm

Sensitivity Map of 16-Pixel PMT for EUSO (R8900-M16F-S12)

Total Sum of 16 Pixels

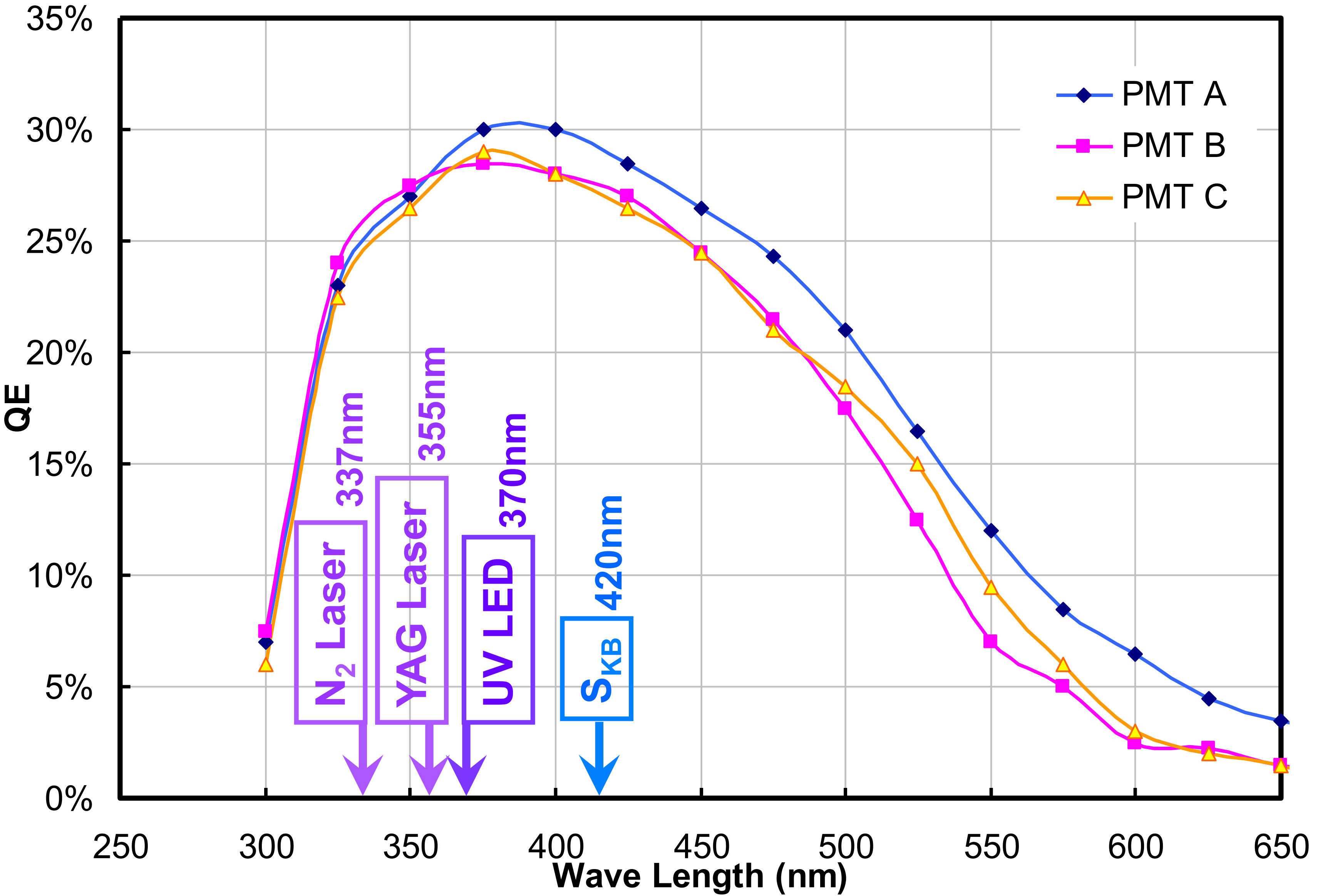


Signal on One Pixel



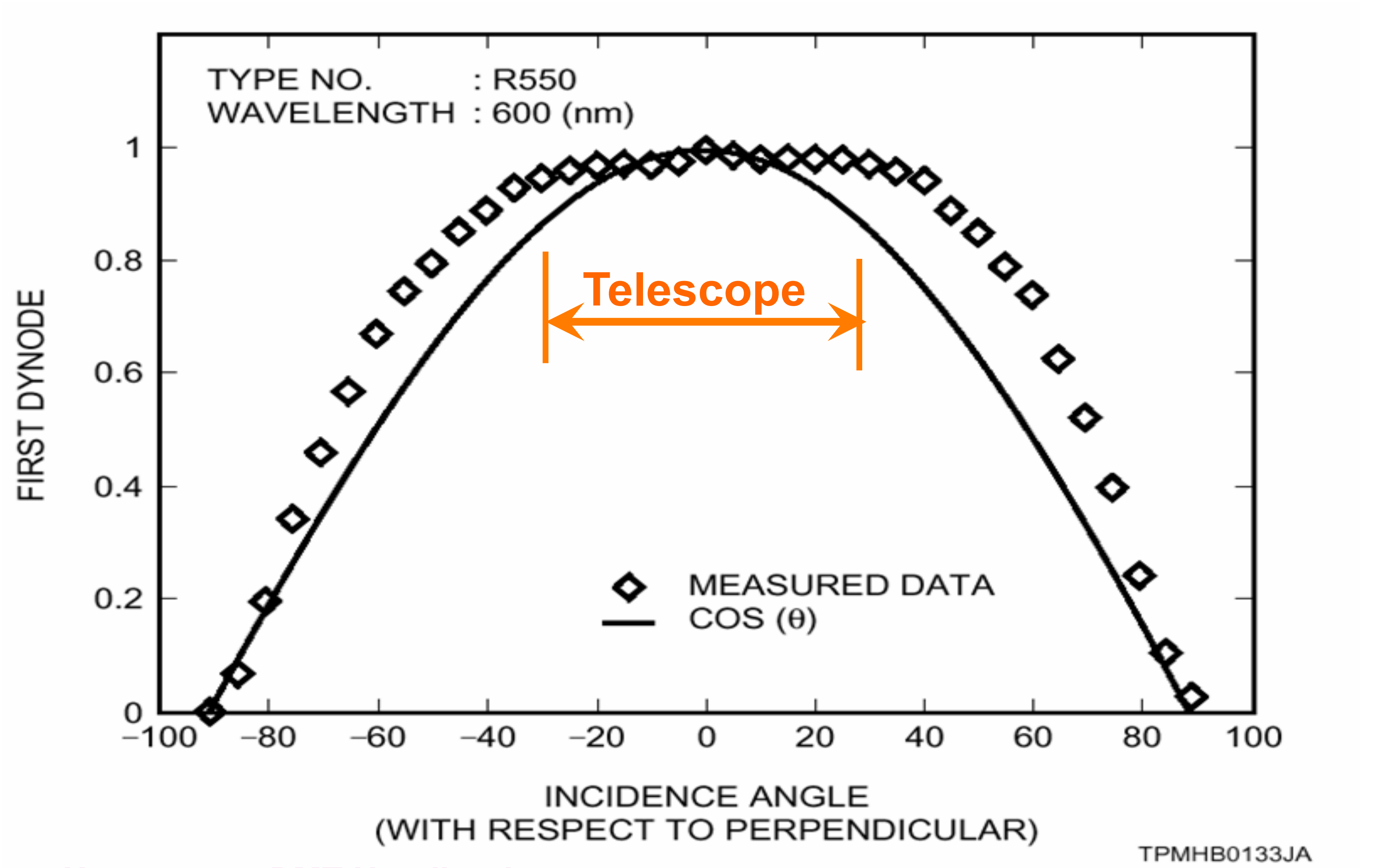
by RIKEN/EUSO Focal Surface Subgroup

Typical QE of HiRes PMTs (Photonis XP3062)



Measured by Photonis

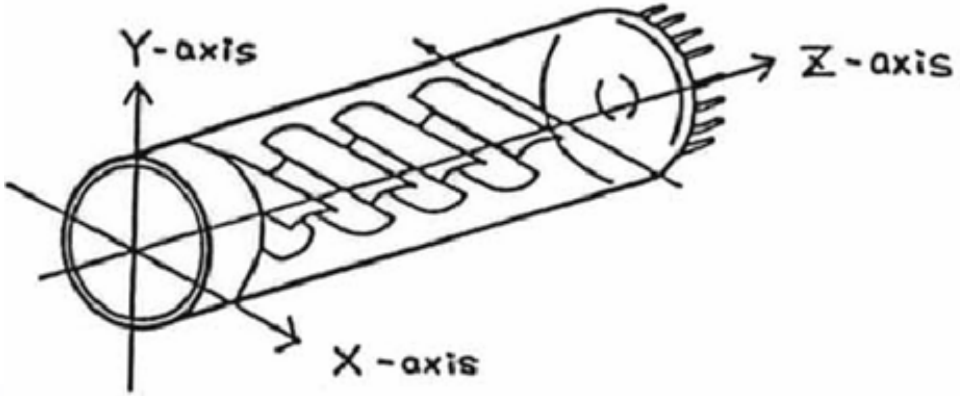
Typical Angle Dependence of QE

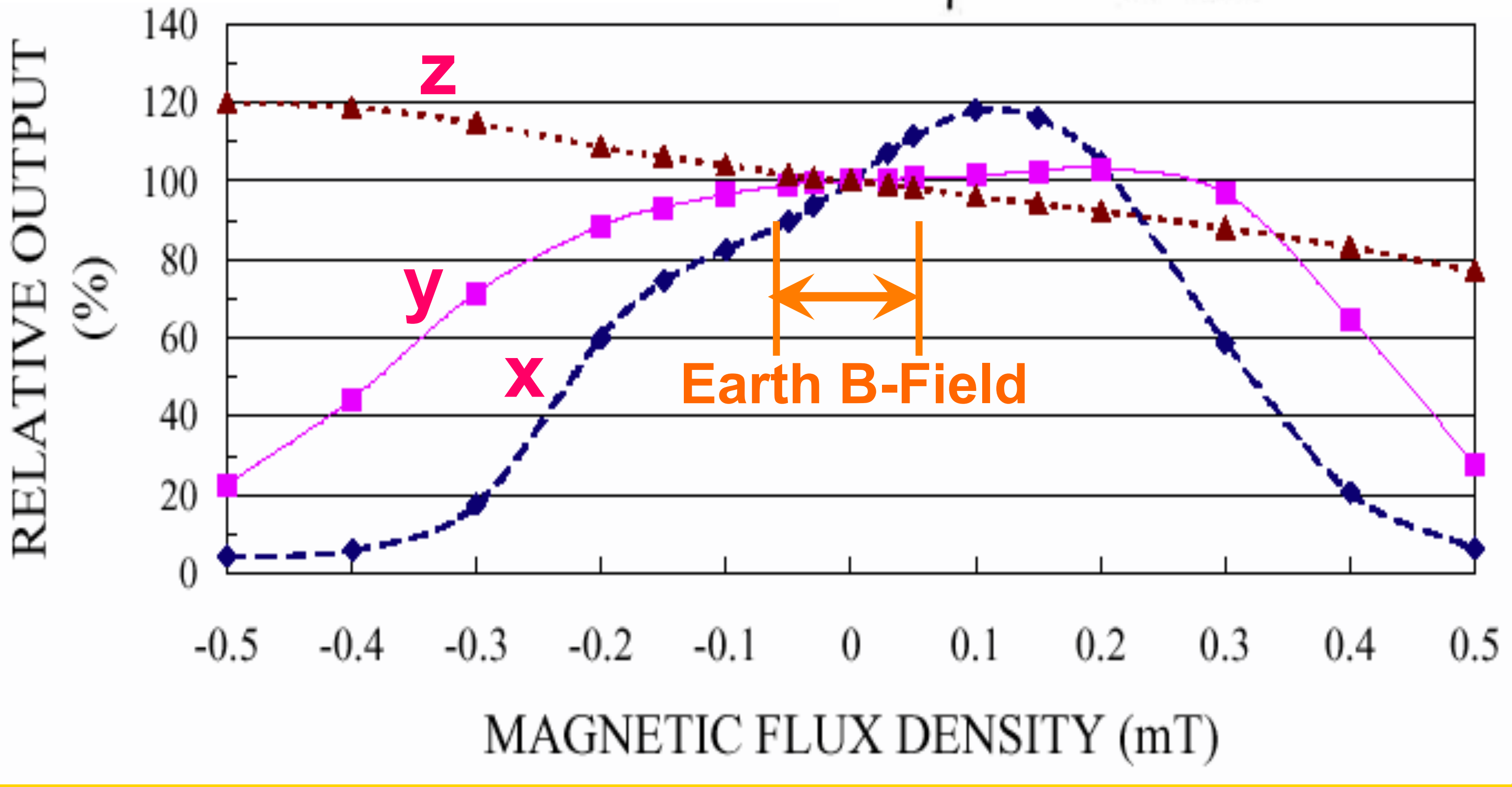


From Hamamatsu PMT Handbook

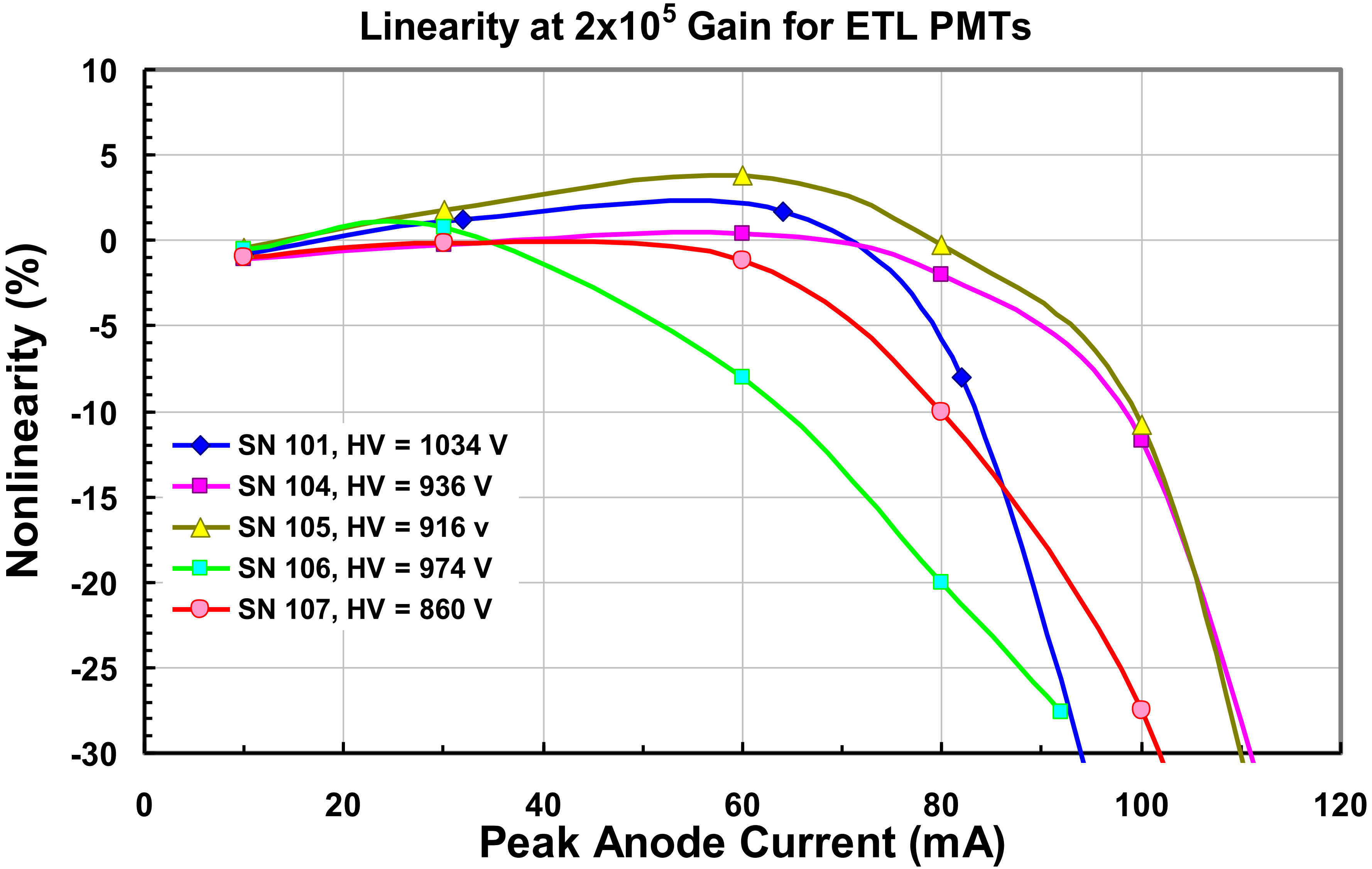
Effect of Magnetic Field on Liner-focus 2” PMT

Hamamatsu 2” PMT (R7281-01)



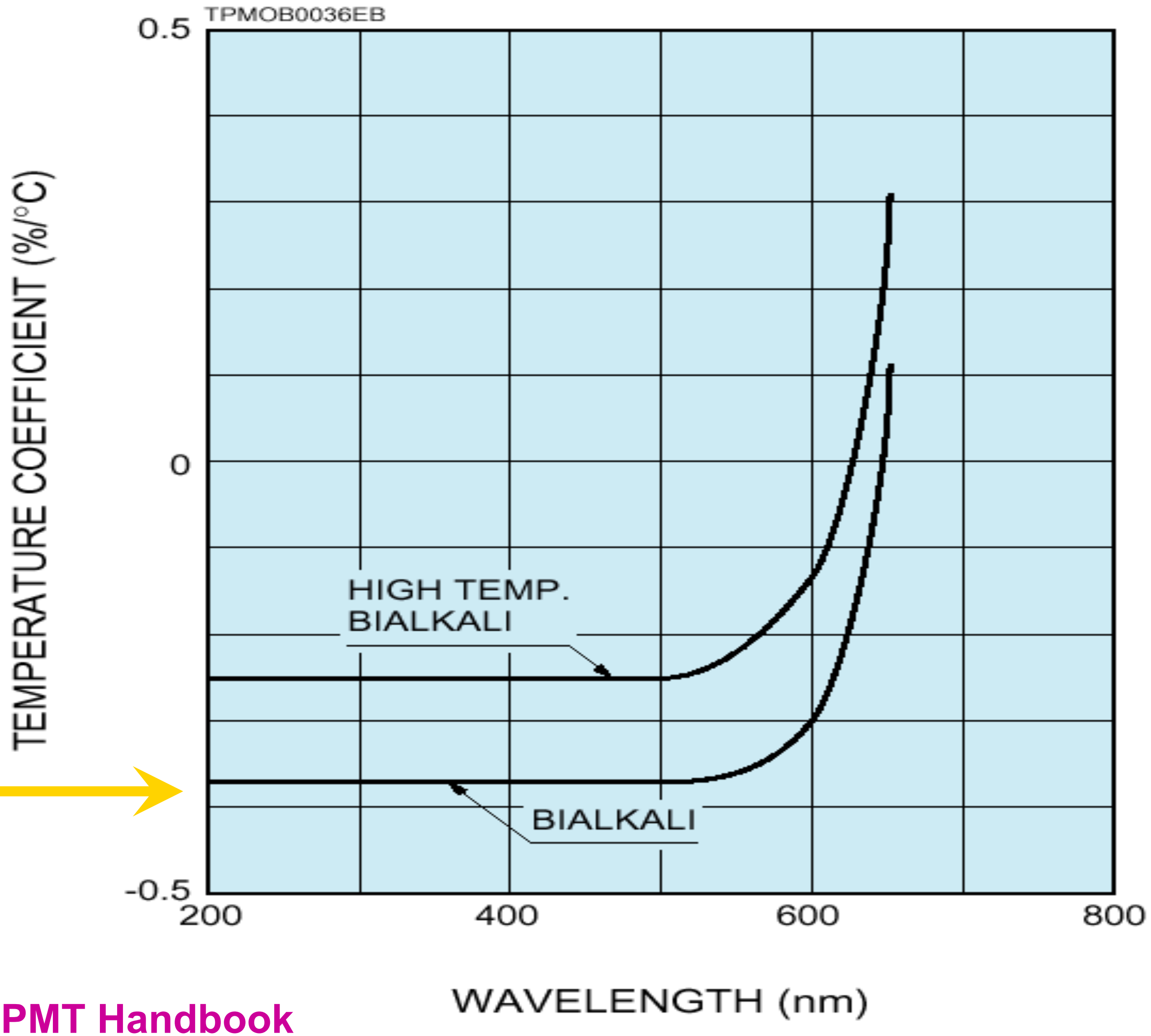


Linearity of ETL 8” PMT



at UCLA PMT Test Facility

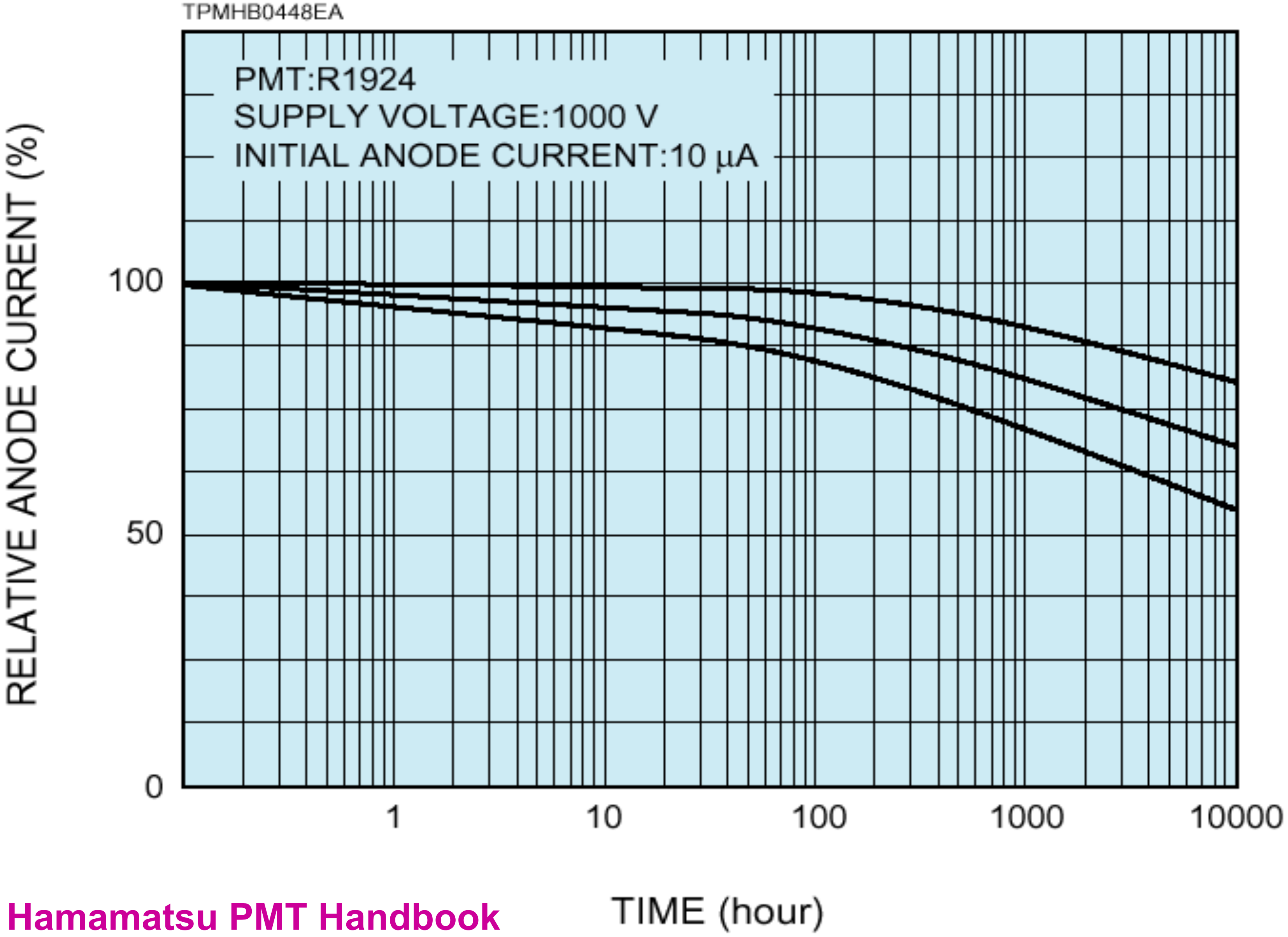
Typical Temperature Coefficients of Anode Sensitivity



-0.4%/°C

From Hamamatsu PMT Handbook

Typical Long-term Stability



From Hamamatsu PMT Handbook

PMT vs. Silicon Photo Diode

Source of Systematic Error	Si PD	PMT	Systematic Uncertainty
(Absolute) Quantum Efficiency	~0.7	0.2-0.3	3%
Wave-length Dependence of QE	±1%	± 10%	5%
Cathode Uniformity	±1%	±10%	5%
Photo-Electron Collection Efficiency	0.99	0.8-0.95	10%
Gain	1.0	10^{5-7}	5%
Voltage Dependence of Gain	None	$\propto HV^6$	3%
Anode (Gain) Uniformity	±1%	±30%	10%
Effect of Earth Magnetic Field	None	±10%	10%
Temperature Dependence	None	-0.4%/°C	3%
Incident Angle Dependence	±1°	±30°	10%
Intensity Correction (ND filter)	1	10^{-5}	5%
Area Correction	5mm ϕ	5cm ϕ	5%
Non Linearity	None	±5%	3%
Rate Dependence	None	±5%	3%
Long Term Stability	Stable	±5%/year	5%
Total Systematic Uncertainty	1%		25%

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4. **Suggestions and Proposal to our Community**

UCLA PMT Test Facility

- **15 years of experience to develop and evaluate new PMTs.**

KTeV CsI Calorimeter	¾” & 1½” Linear-focus
CDF Shower Max	Multi-pixel (R5900-M16)
Auger SD	8-9” Hemispherical

- **We can measure:**
  - (Absolute) Quantum Efficiency
  - Collection Efficiency
  - Gain and Dark Current vs. HV
  - Single PE Distribution
  - Excess Noise Factor
  - Cathode and Anode Uniformity
  - Dark Pulse Rate and After Pulse Rate
  - Temperature Dependence
  - Non Linearity

Proposal to Evaluate PMTs from HiRes, Auger-FD and EUSO at UCLA

- We propose to evaluate the sample PMTs from:
  - Auger-FD
  - HiRes
  - EUSO
  - Beam Tests
  - Reference PMTs

Mutual Comparison

- We plan to add more equipments to measure:
  - Effect of Magnetic Field
  - Photon Incident-angle Dependence
  - Long-term Stability
  - …

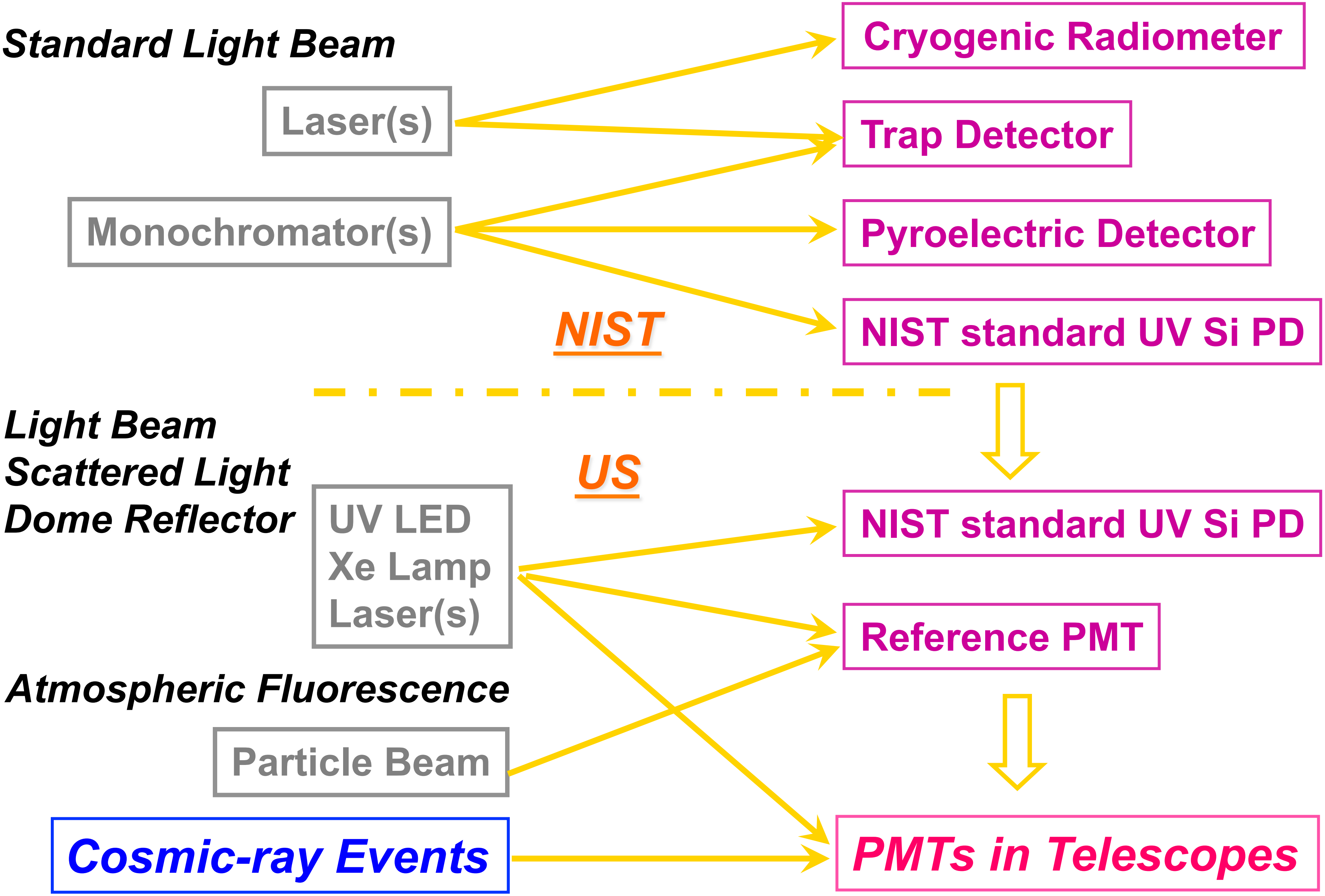
How to Minimize Systematic Uncertainties

- **Don't try to measure QE, Collection Efficiency and Gain separately.**
  - **Just measure all three together (with a mirror, UV filter etc. as well). ⇒ "End-to-end Calibration"**
  - **Prepare the "absolutely-calibrated" light source.**
- **Make sure that the "absolutely-calibrated" light source has the same characteristics as cosmic-ray fluorescence signals.**
  - **Same wave length**
  - **Same angular distribution on the PMT surface**
  - **Uniform over the PMT surface**
  - **Same pulse width and intensity**
- **Calibrate in situ, monitor external environment.**
  - **Same (Earth) magnetic field**
  - **Same temperature**
  - **Same supplied HV**

How to Minimize Systematic Uncertainties at Beam Tests

- Don't try to measure QE, Collection Efficiency and Gain separately.
  - Just measure all three together (with a mirror, UV filter etc. as well). ⇒ "End-to-end Calibration"
  - Prepare the "absolutely-calibrated" light source.
- Make sure that the "absolutely-calibrated" light source has the same characteristics as beam test fluorescence signals.
  - Same wave length
  - Same angular distribution on the PMT surface
  - Uniform over the PMT surface
  - Same pulse width and intensity
- Calibrate in situ, monitor external environment.
  - Same (Earth) magnetic field
  - Same temperature
  - Same supplied HV

Propagation Chain of Absolute Calibration of Photon Detectors



Standard Light Beam

Laser(s)

Monochromator(s)

Cryogenic Radiometer

Trap Detector

Pyroelectric Detector

NIST standard UV Si PD

NIST

US

Light Beam
Scattered Light
Dome Reflector

UV LED
Xe Lamp
Laser(s)

NIST standard UV Si PD

Reference PMT

Atmospheric Fluorescence

Particle Beam

Cosmic-ray Events

PMTs in Telescopes

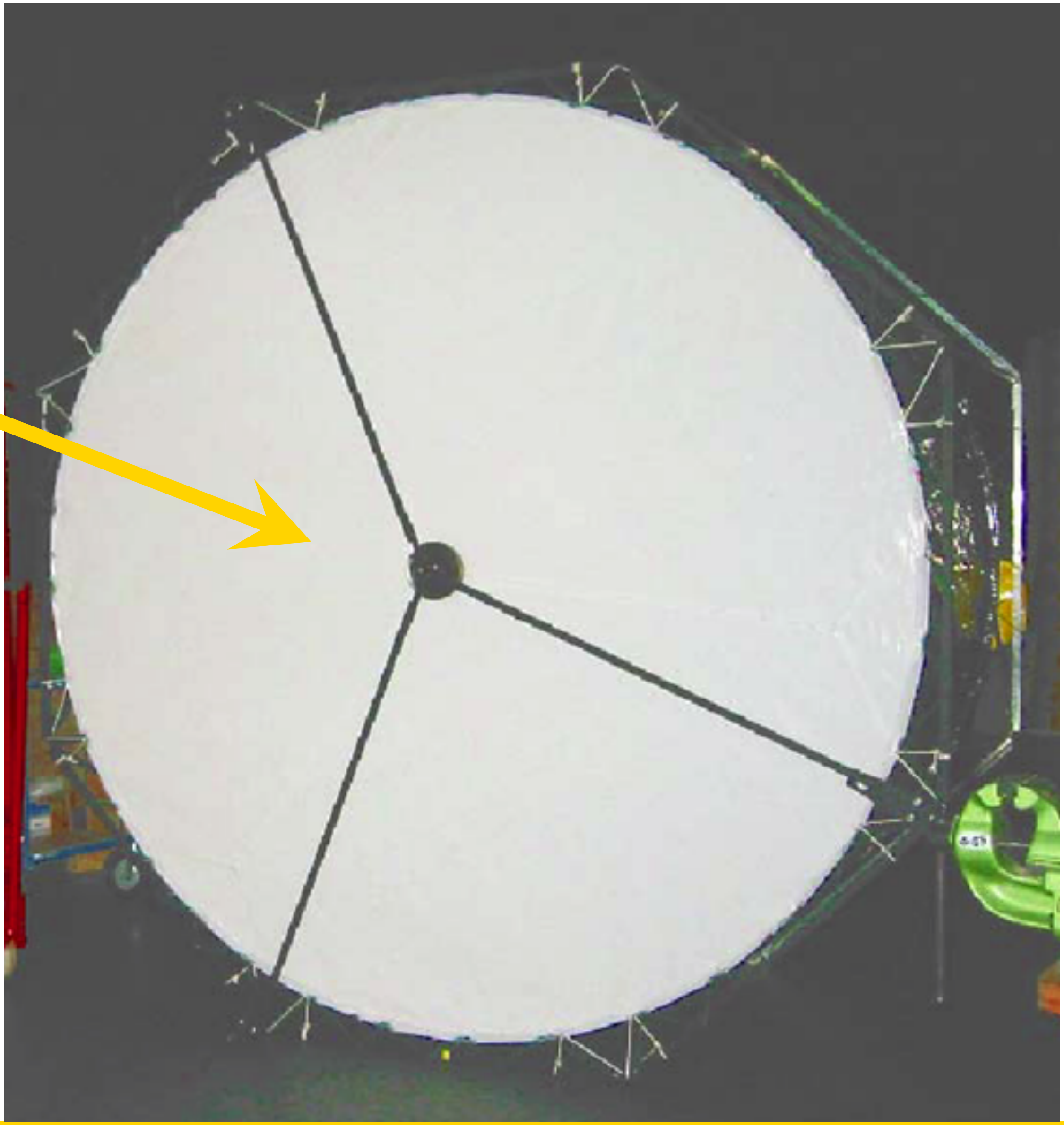
How to absolutely calibrate the PMTs in Telescope

- Prepare a stable light source and an "absolutely calibrated photon detector".
- Measure the "absolute photon flux" from the light source, going into the real telescope by the calibrated photon detector above.
- Measure the PMT output signal (ADC counts) in the telescope.
- Constantly monitor the relative change of the photon intensity from the calibration light source.

Light Source for Auger-FD

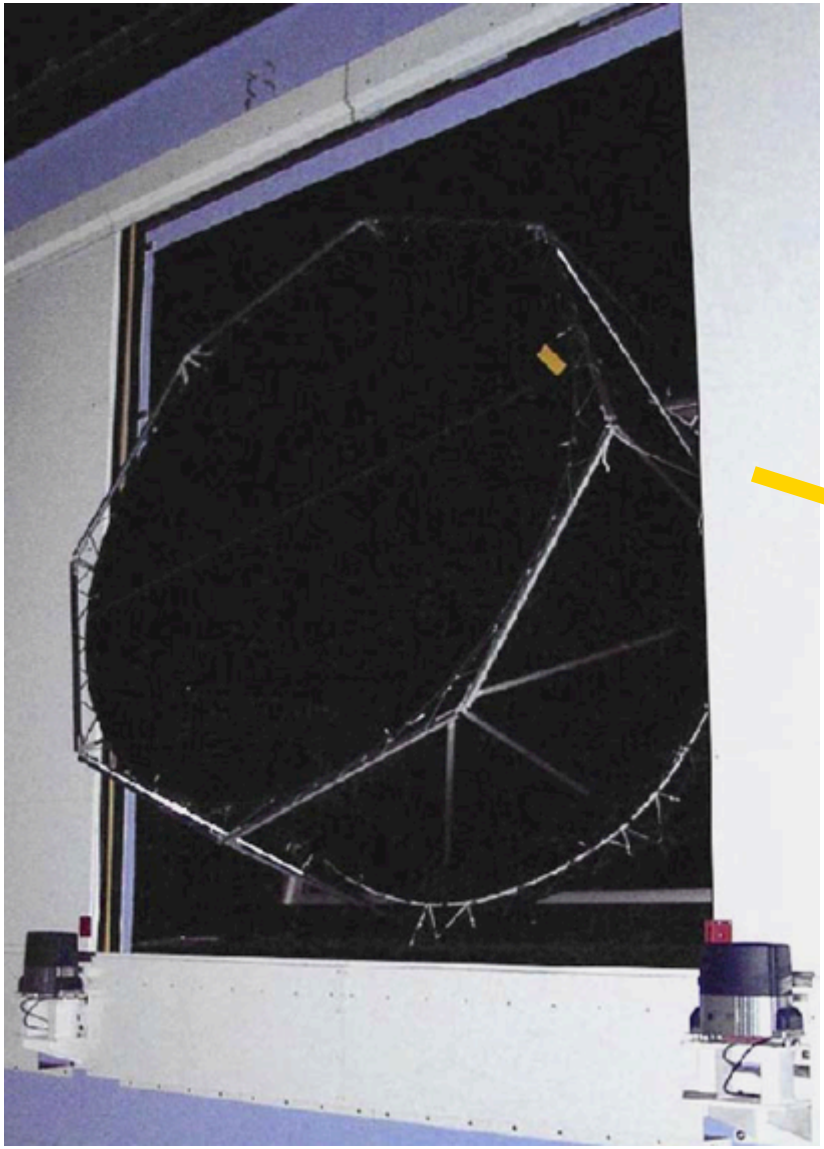
UV LED
Light Source (15cm ϕ)

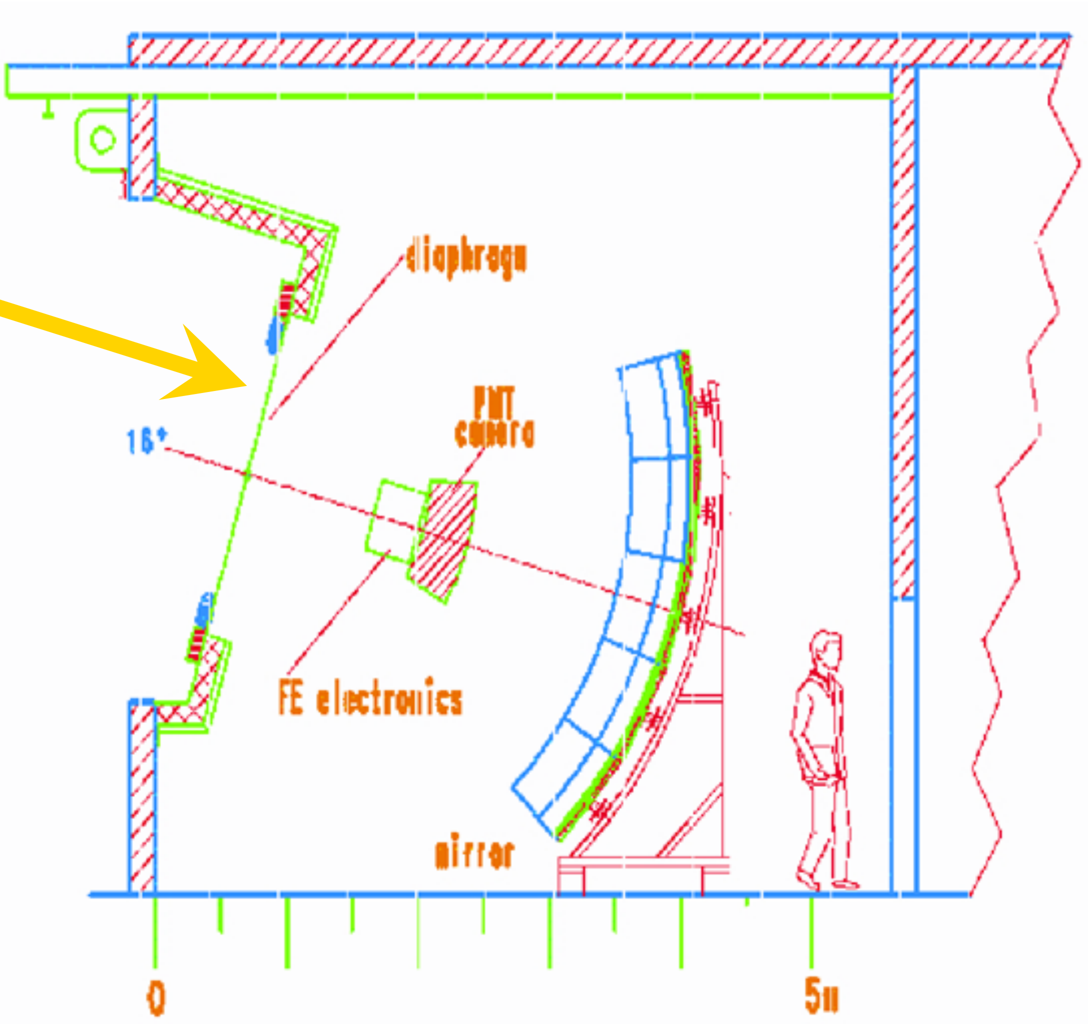
Drum (2.5m ϕ, 1,4m deep)



By Jeff Brack

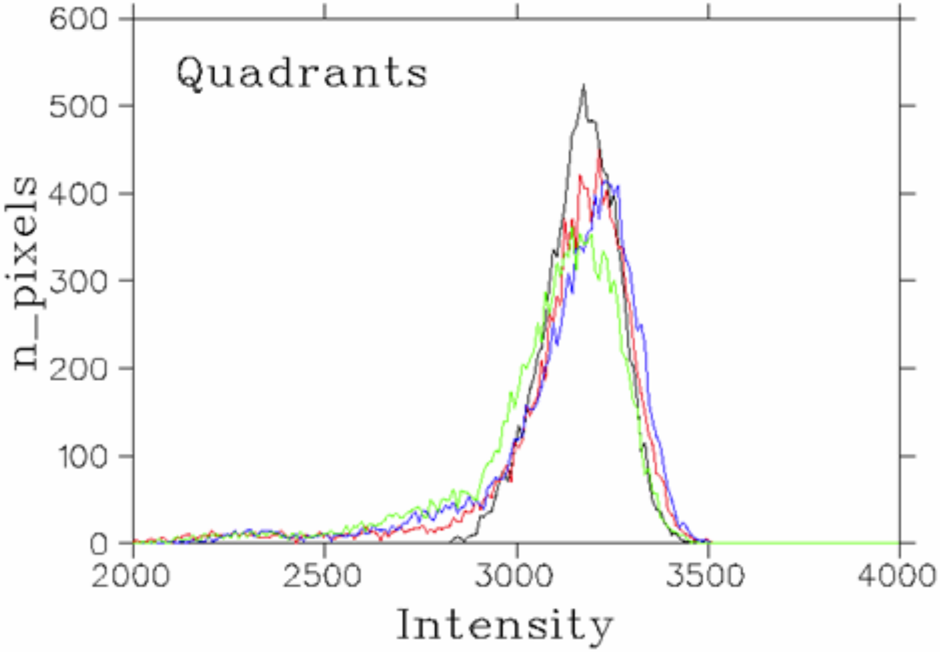
Drum mounted at the aperture of Bay 4 at Los Leones

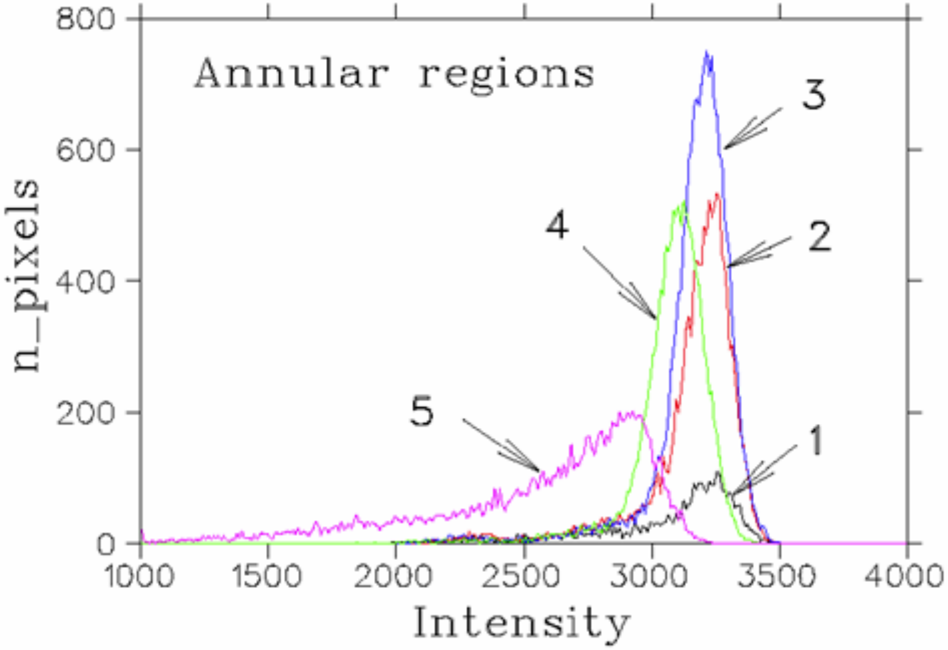


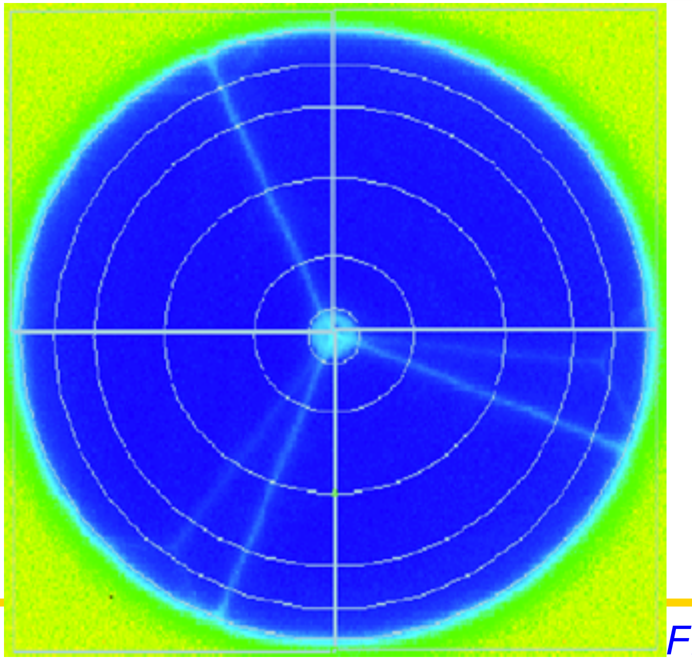


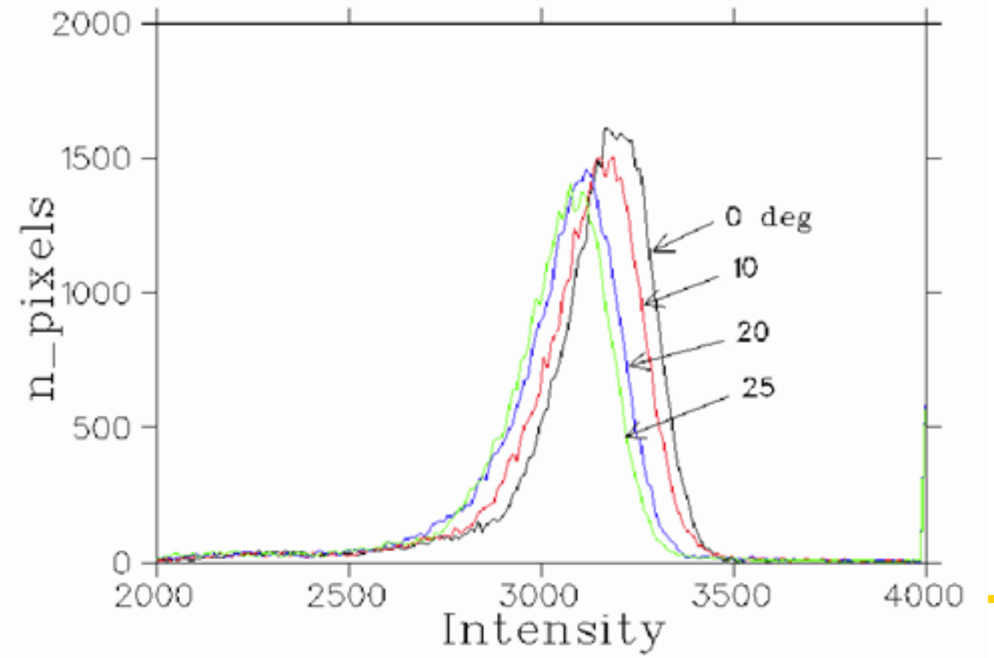
Uniformity of lights emitted from the Drum

By Jeff Brack









Systematic Uncertainty after End-to-end Calibration

Source of Systematic Error	Si PD	PMT	Sys. Uncertainty	
			Before	After
(Absolute) Quantum Efficiency	~0.7	0.2-0.3	3%	3%
Wave-length Dependence of QE	±1%	± 10%	5%	5%
Cathode Uniformity	±1%	±10%	5%	-
Photo-Electron Collection Efficiency	0.99	0.8-0.95	10%	-
Gain	1.0	10^{5-7}	5%	-
Voltage Dependence of Gain	None	$\propto HV^6$	3%	3%
Anode (Gain) Uniformity	±1%	±30%	10%	3%
Effect of Earth Magnetic Field	None	±10%	10%	-
Temperature Dependence	None	-0.4%/°C	3%	-
Incident Angle Dependence	±1°	±30°	10%	3%
Intensity Correction (ND filter)	1	10^{-5}	5%	5%
Area Correction	5mm ϕ	5cm ϕ	5%	5%
Non Linearity	None	±5%	3%	3%
Rate Dependence	None	±5%	3%	3%
Long Term Stability	Stable	±5%/year	5%	5%
Total Systematic Uncertainty	1%		25%	12%

Conclusion

- Absolute calibration of PMT (in Lab) is absolutely nontrivial. *Don't try it*.
- The most important is to develop the absolutely calibrated "standard candle" which exactly mimics the physics signal.
- Then calibrate your telescope in situ.

Acknowledgements

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Yuji Yoshizawa	(Hamamatsu)

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- This talk is available at

http://www.physics.ucla.edu/~arisaka/hires/

  - pmt_calibration.pdf (2.6M)
  - pmt_calibration.ppt (3.3M)