15th September. 2016

new

Applying a SiPM response function to 7608 SiPMs of AHCAL physics prototype

CALICE meeting at Arlington Texas
K. Kotera, DESY/Shinshu University

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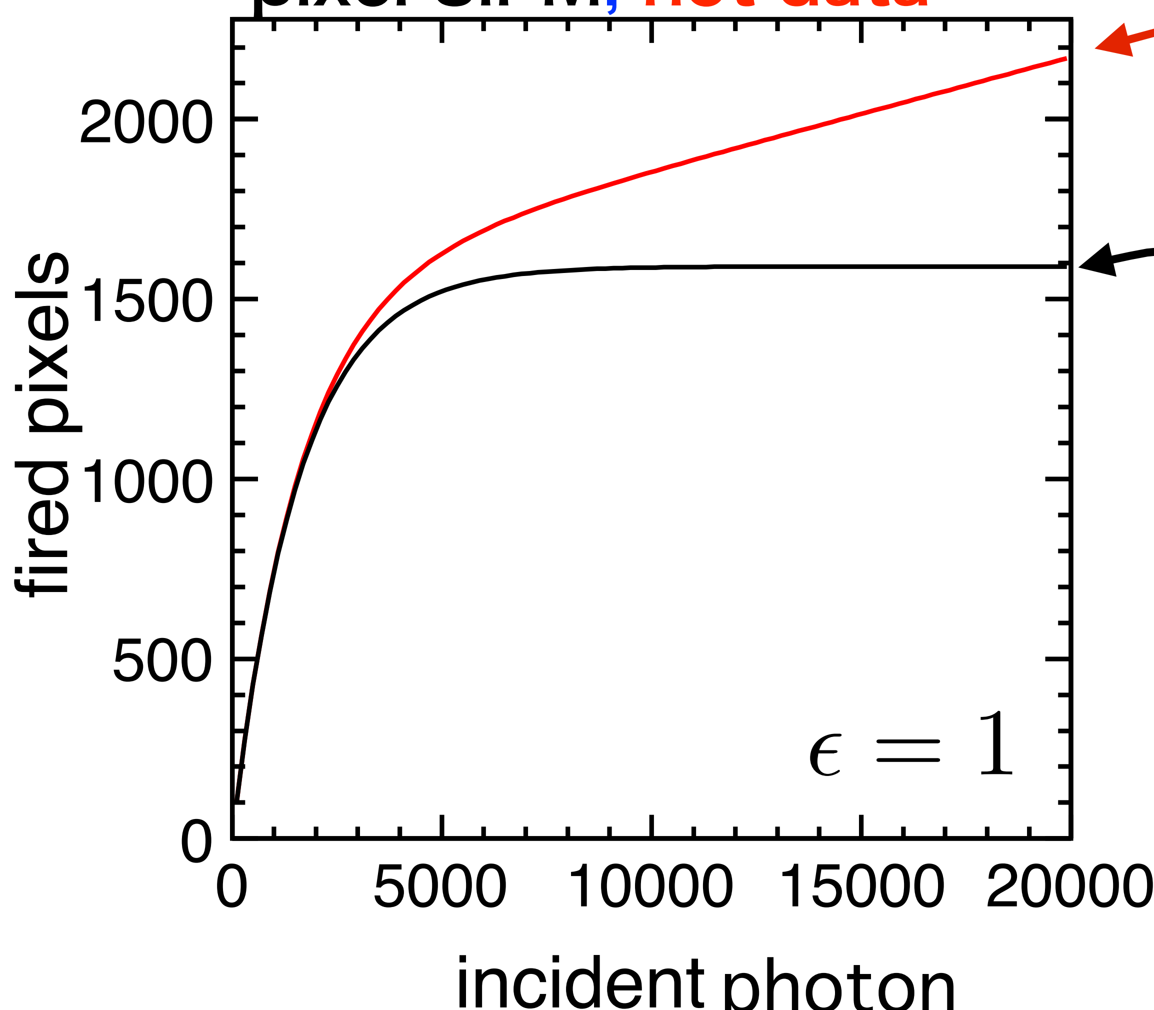
Motivation: Linear response after saturation

Often we see like red curve w/ fast recovery SiPMs

Equation plot of 1600 pixel SiPM, not data



? not completely saturating

conventional function =LO

$$N_{\rm fire} = N_{\rm pix}\left(1 - e^{-\epsilon N_{\rm in}/N_{\rm pix}}\right)$$

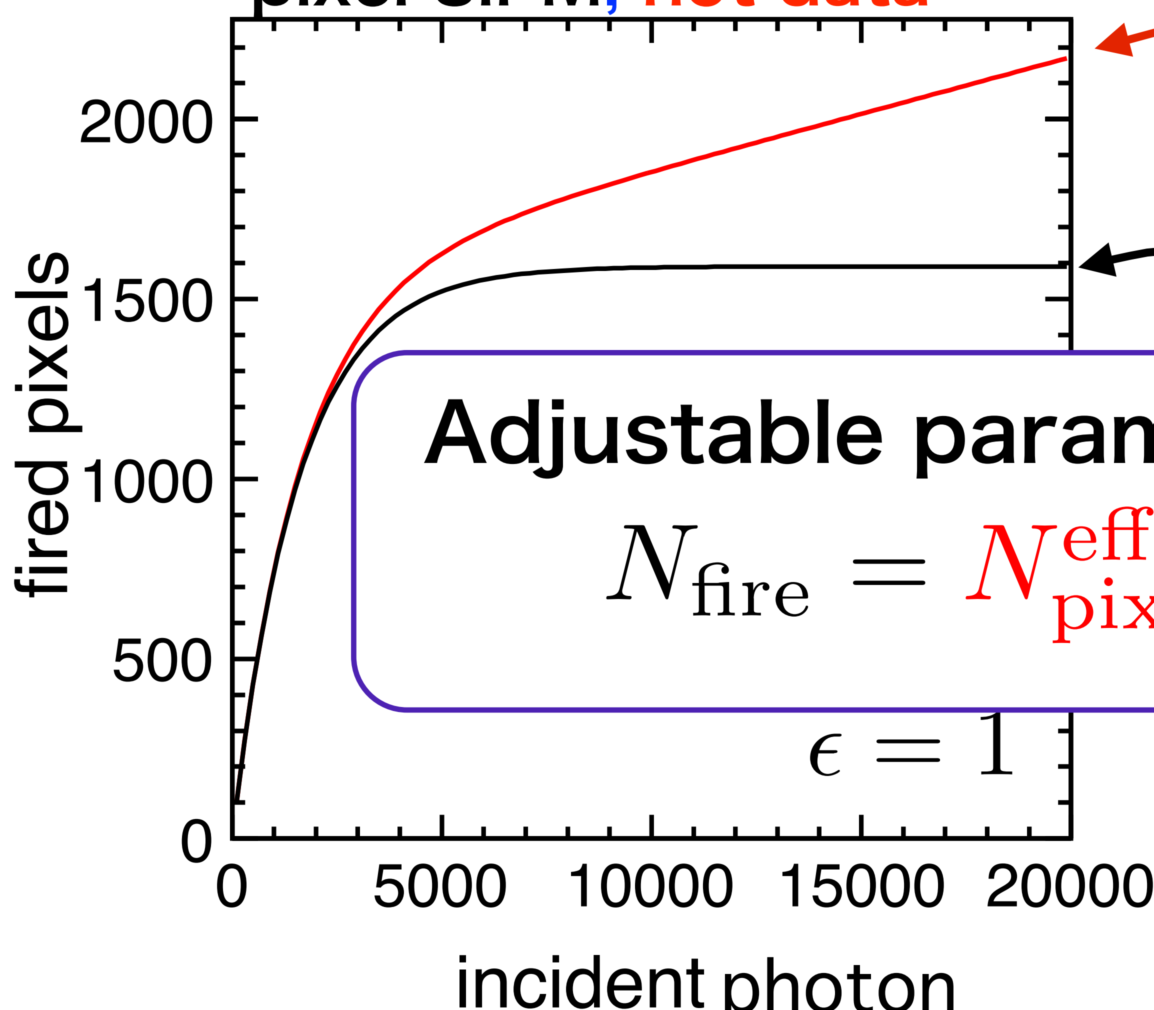
$N_{\rm fire}$:the number of fired pixels,
ϵ :photon detection efficiency (PDE),
$N_{\rm in}$:the number of incident photons,
$N_{\rm pix}$:the number of pixels.

We think this comes from reactivation of pixels in a few nano seconds after fired.

Motivation: Linear response after saturation

Often we see like red curve w/ fast recovery SiPMs

Equation plot of 1600 pixel SiPM, not data



? not completely saturating

conventional function =LO

$$N_{\rm fire} = N_{\rm pix}\left(1 - e^{-\epsilon N_{\rm in}/N_{\rm pix}}\right)$$

Adjustable parameter

$$N_{\rm fire} = N_{\rm pix}^{\rm eff}\left(1 - e^{\epsilon N_{\rm in}/N_{\rm pix}^{\rm eff}}\right)$$

...fired pixels,

...on efficiency (PDE),

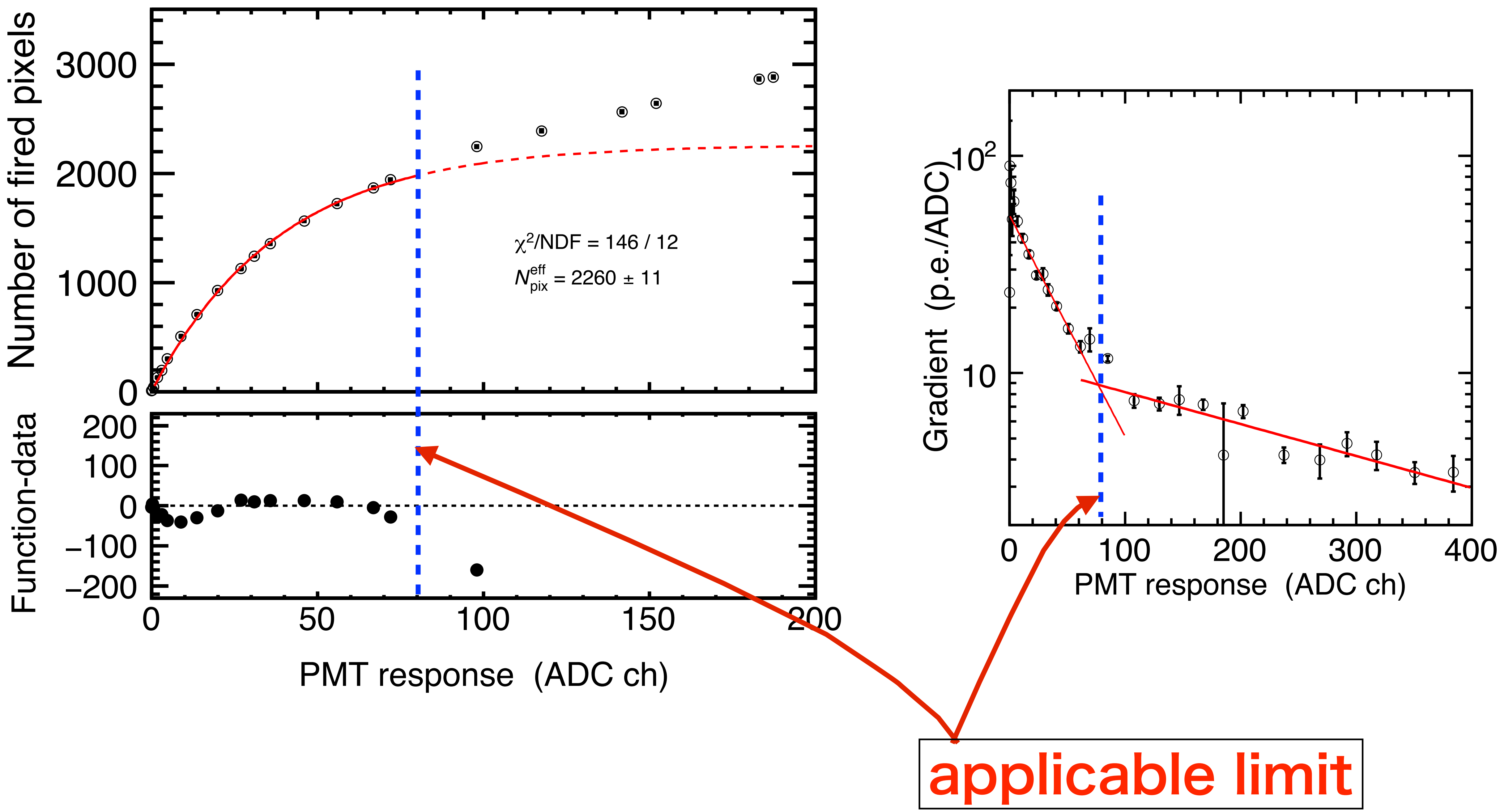
...ncident photons,

$N_{\rm pix}$:the number of pixels.

We think this comes from reactivation of pixels in a few nano seconds after fired.

Example of N_{pix}^{eff} (LO')

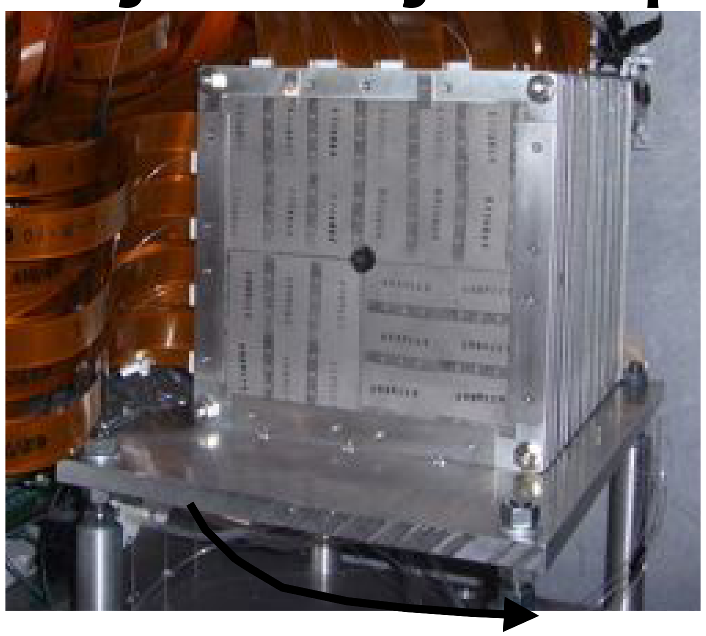
- Calibration for ScECAL physics prototype.
- 1600 pix was measured as 2260 pix (N_{pix}^{eff}).



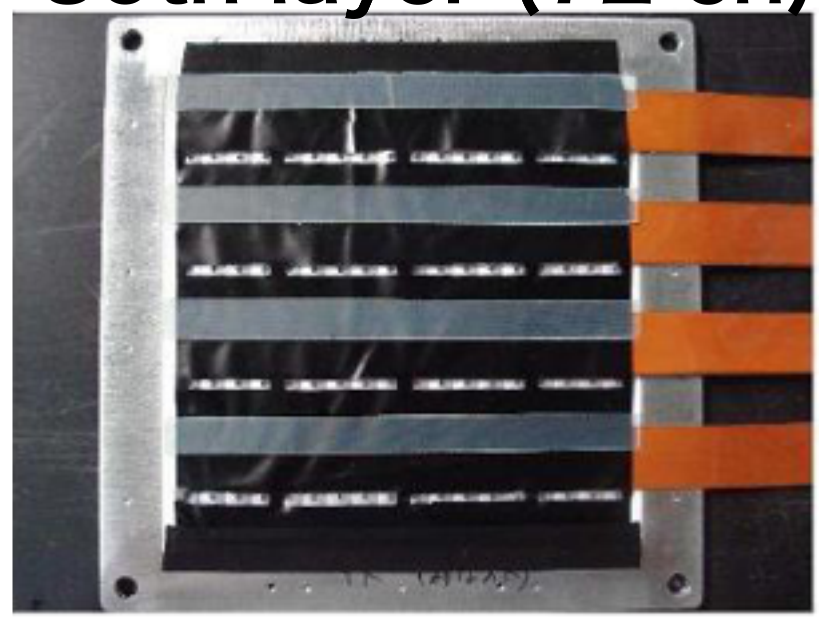
Sample DATA (taken by W. Choi in Shinshu 2010)

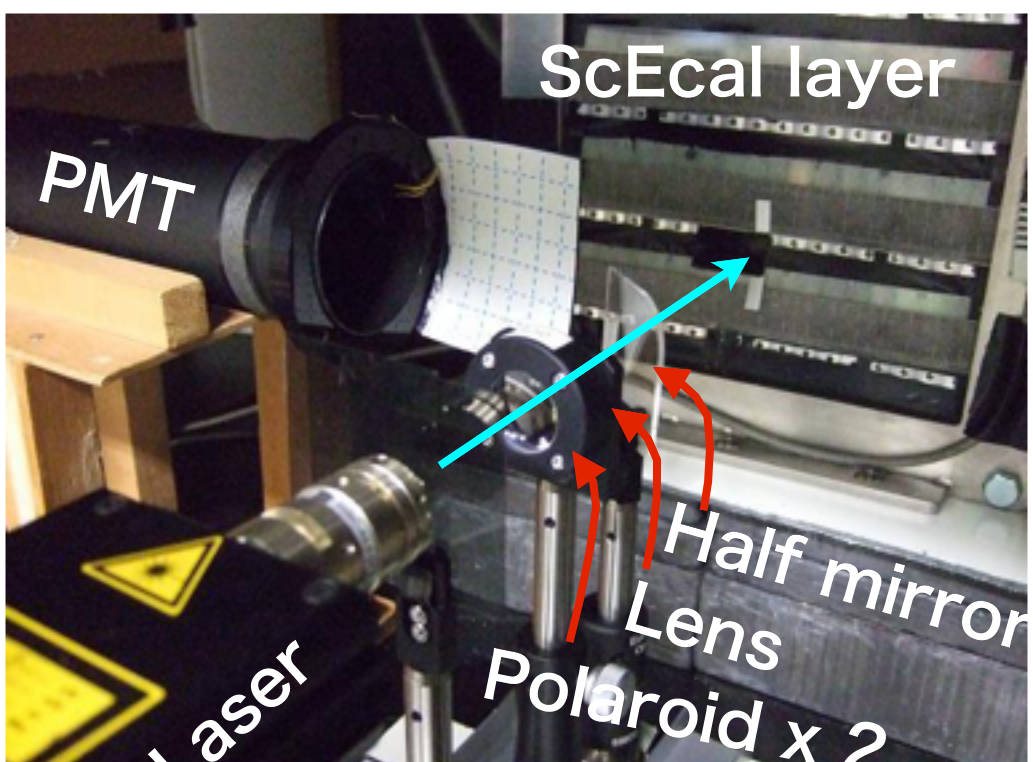
72 channels of 30th layer of ScECAL prototype with 1600 pix MPPC

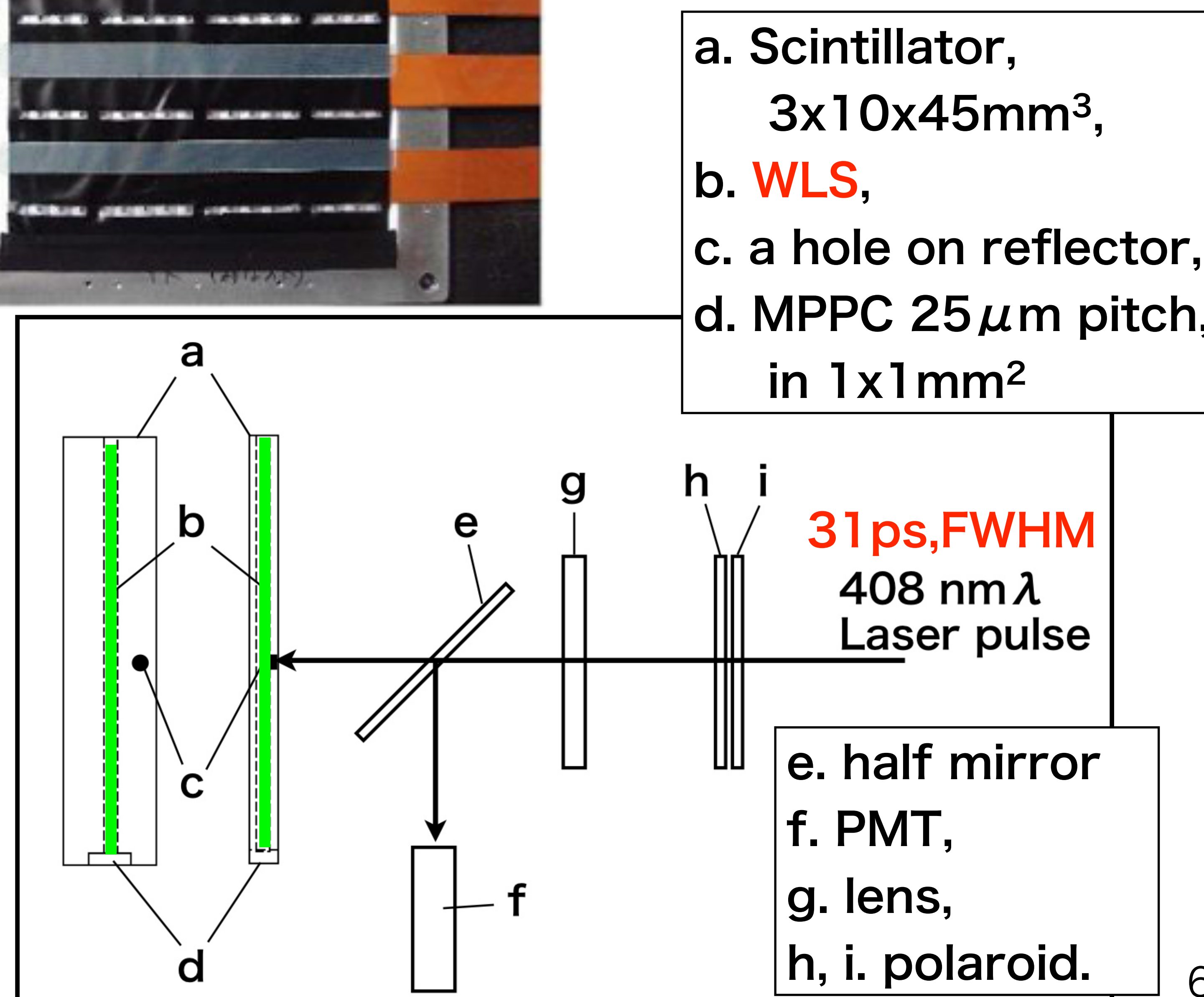
30 layer-Physics proto.



30th layer (72 ch)







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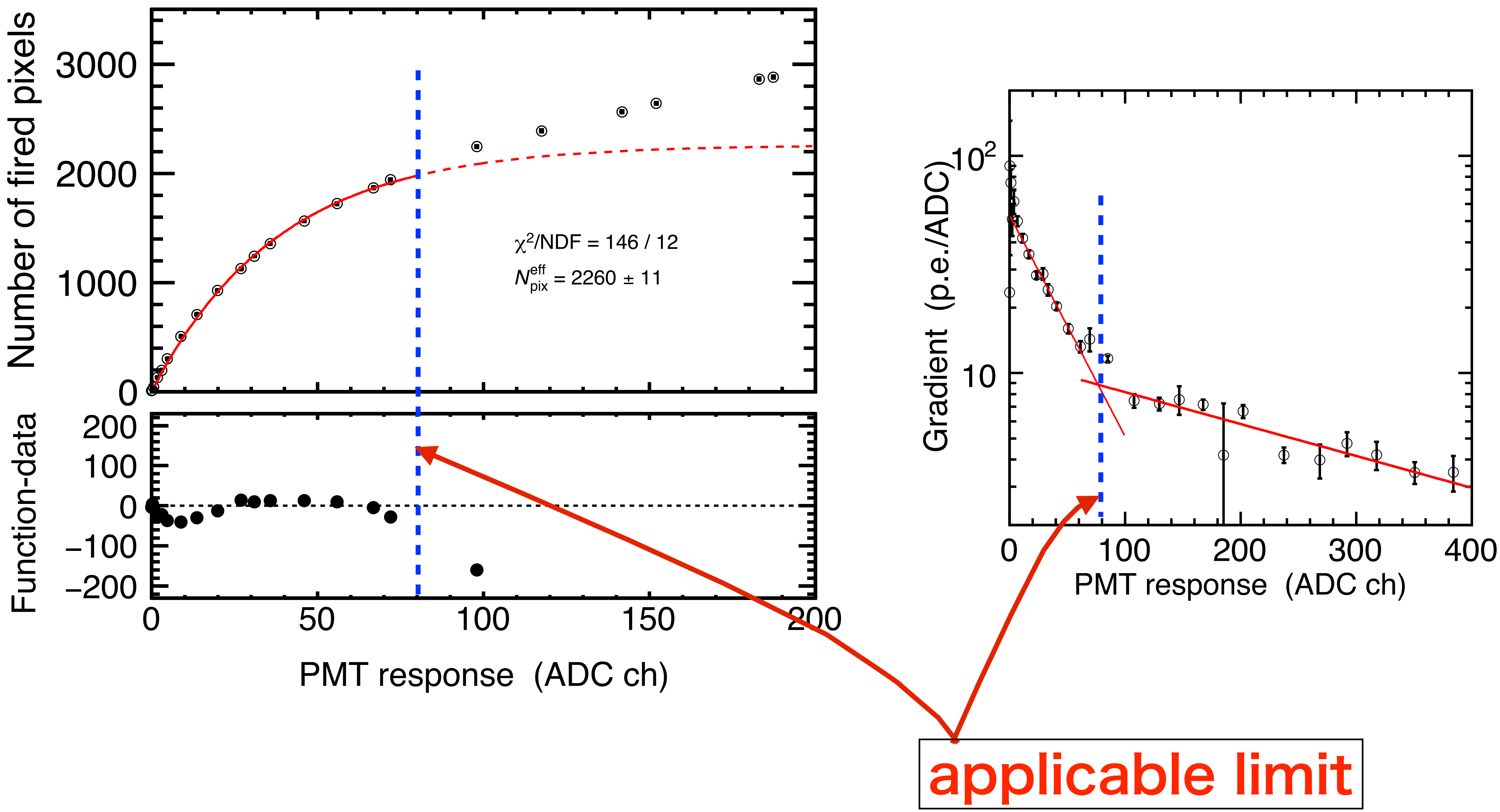

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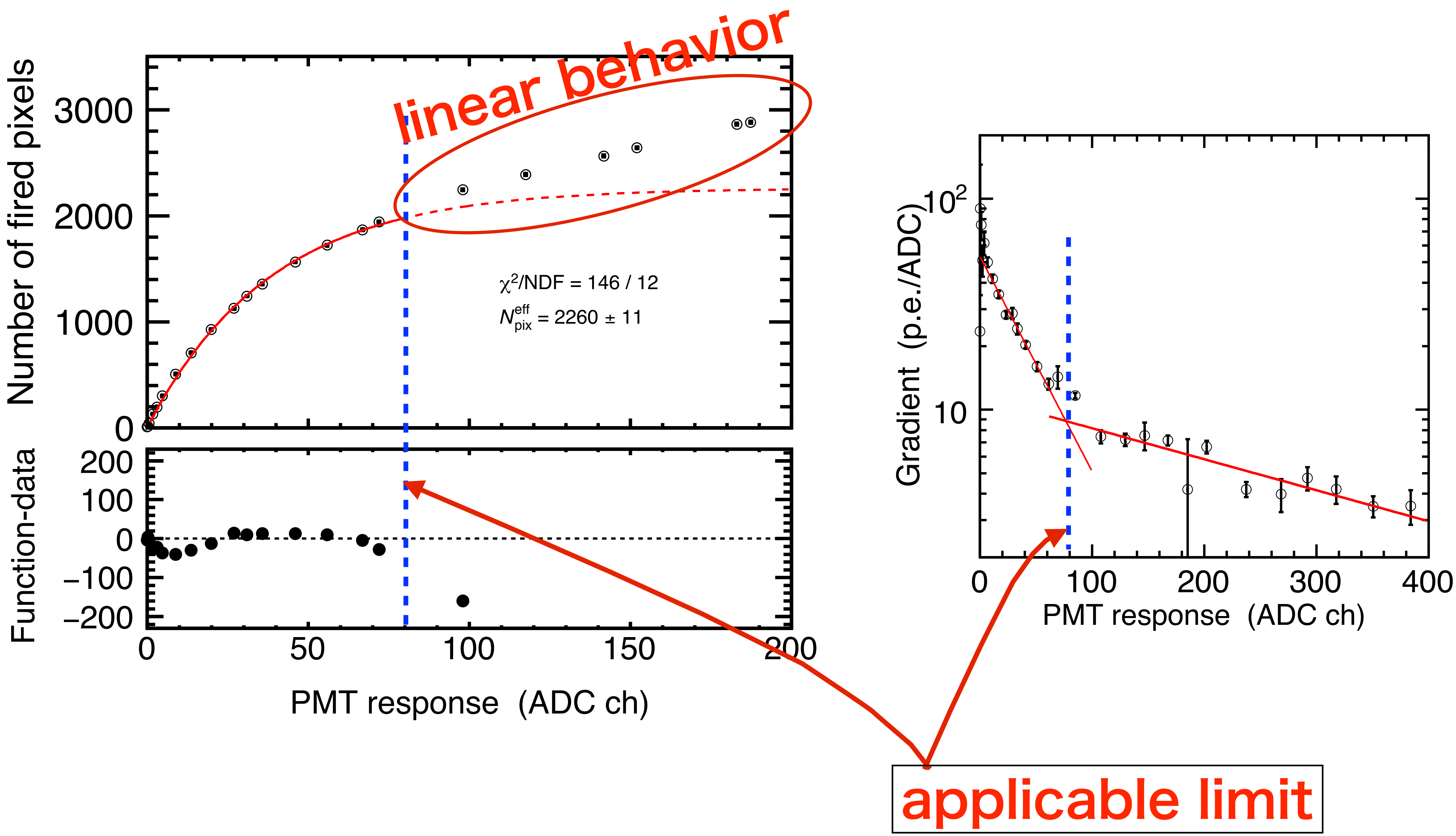
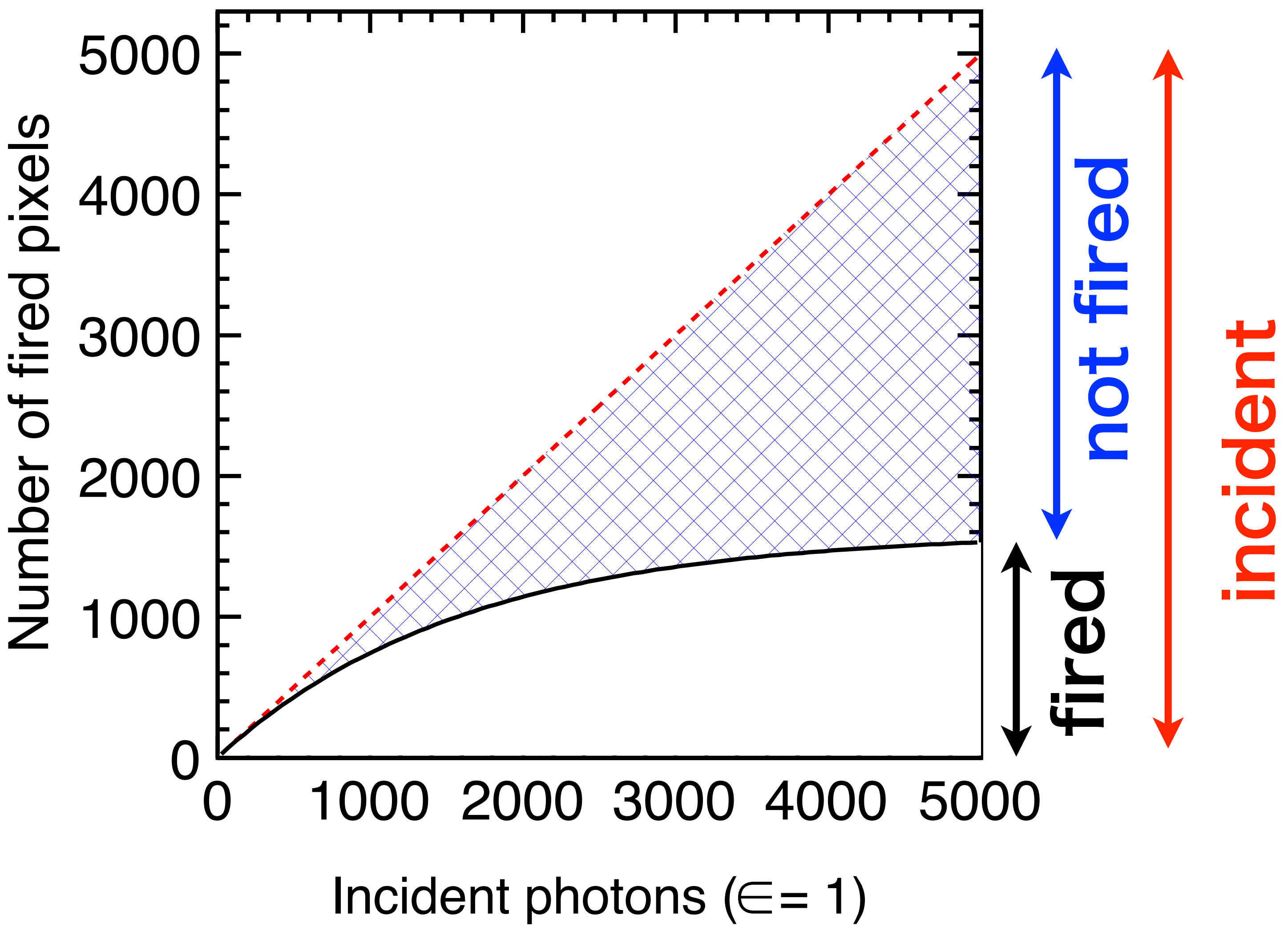


Idea: think which photons can hit a reactivated pixels

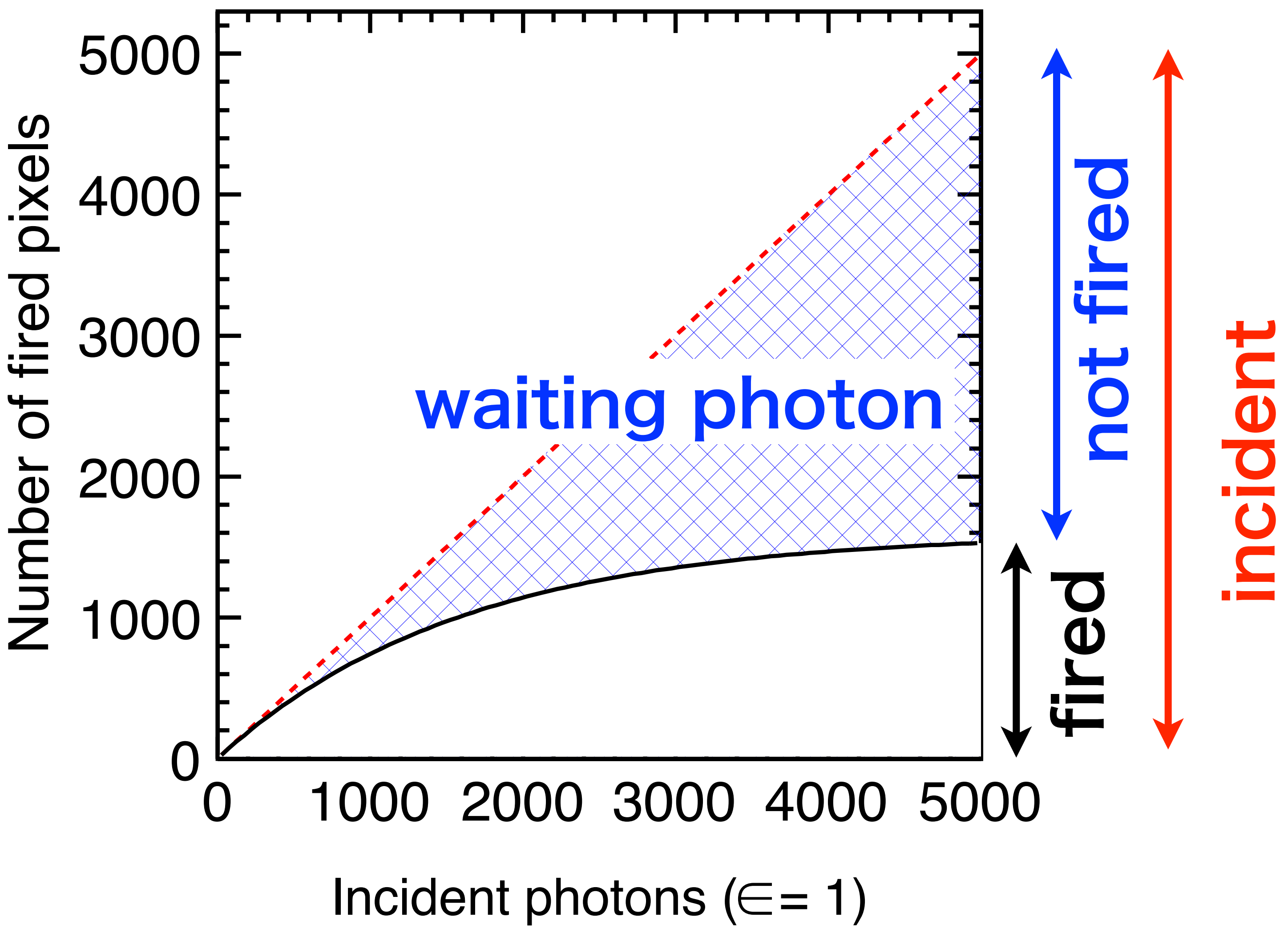


Not fire photons can make the next contributions

$$N_R = \epsilon N_{\rm in} - LO$$

$$N_{\rm fire}^{\rm NLO} = LO + \alpha N_R$$

Idea: think which photons can hit a reactivated pixels



Not fire photons can make the next contributions

waiting photons

$$N_R = \epsilon N_{\rm in} - LO$$

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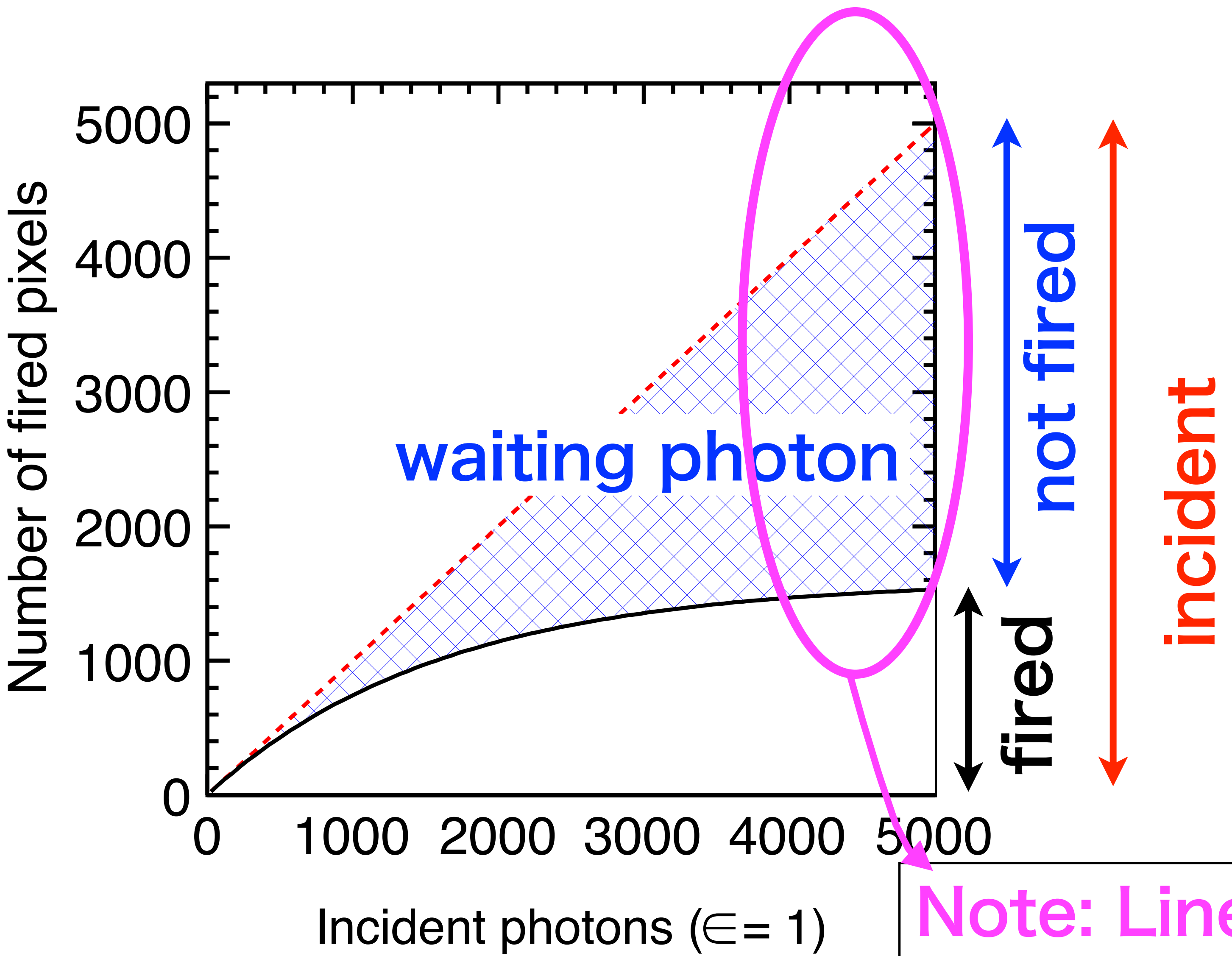
Idea: think which photons can hit a reactivated pixels

Not fire photons can make the next contributions



waiting photons

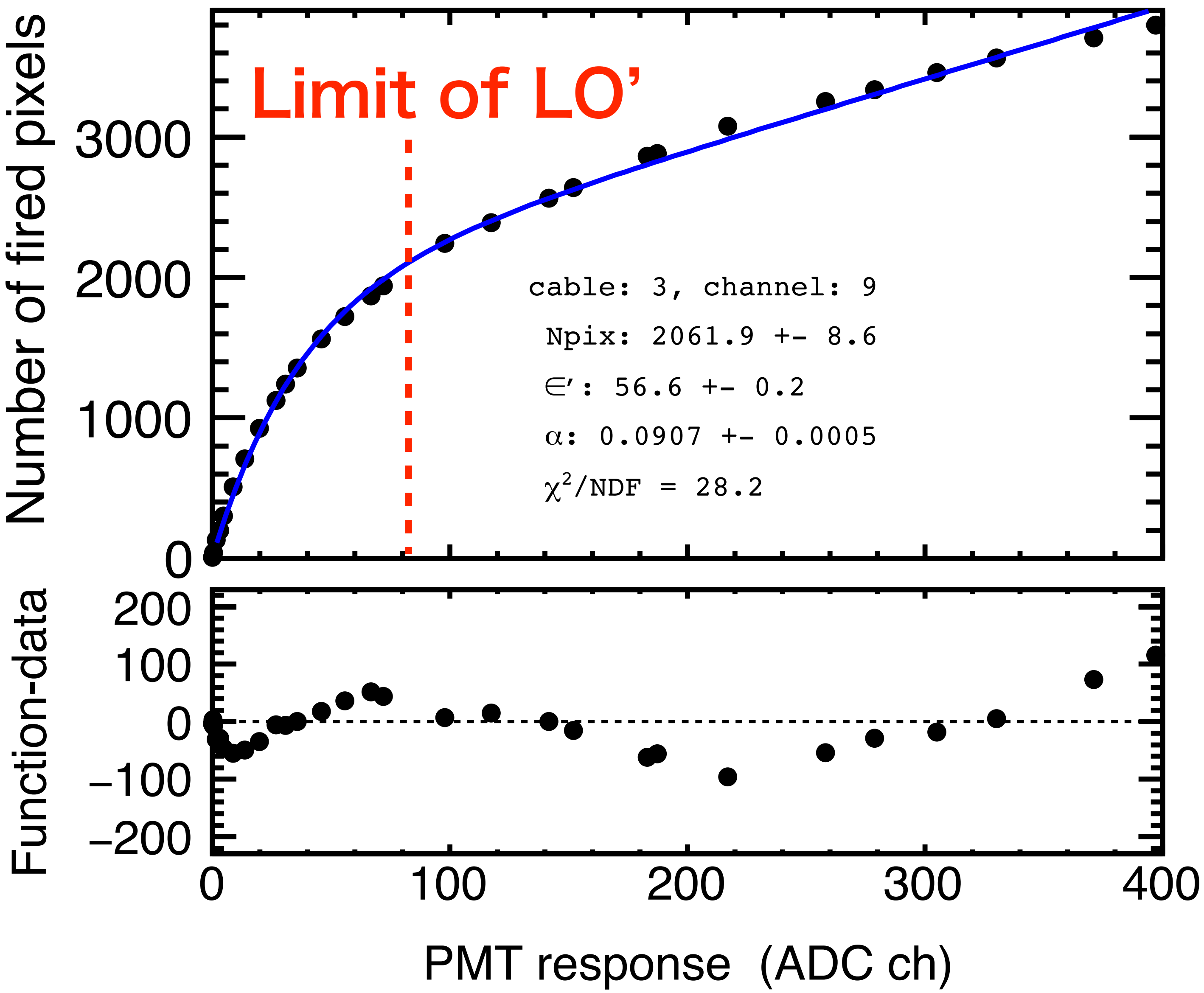
$$N_R = \epsilon N_{\mathrm{in}} - LO$$

$$N_{\mathrm{fire}}^{\mathrm{NLO}} = LO + \alpha N_R$$

Note: Linear of N_R @ high light region—after enough saturation

Reason, why we see linear like behavior

Fitting with NLO



Fit region increased

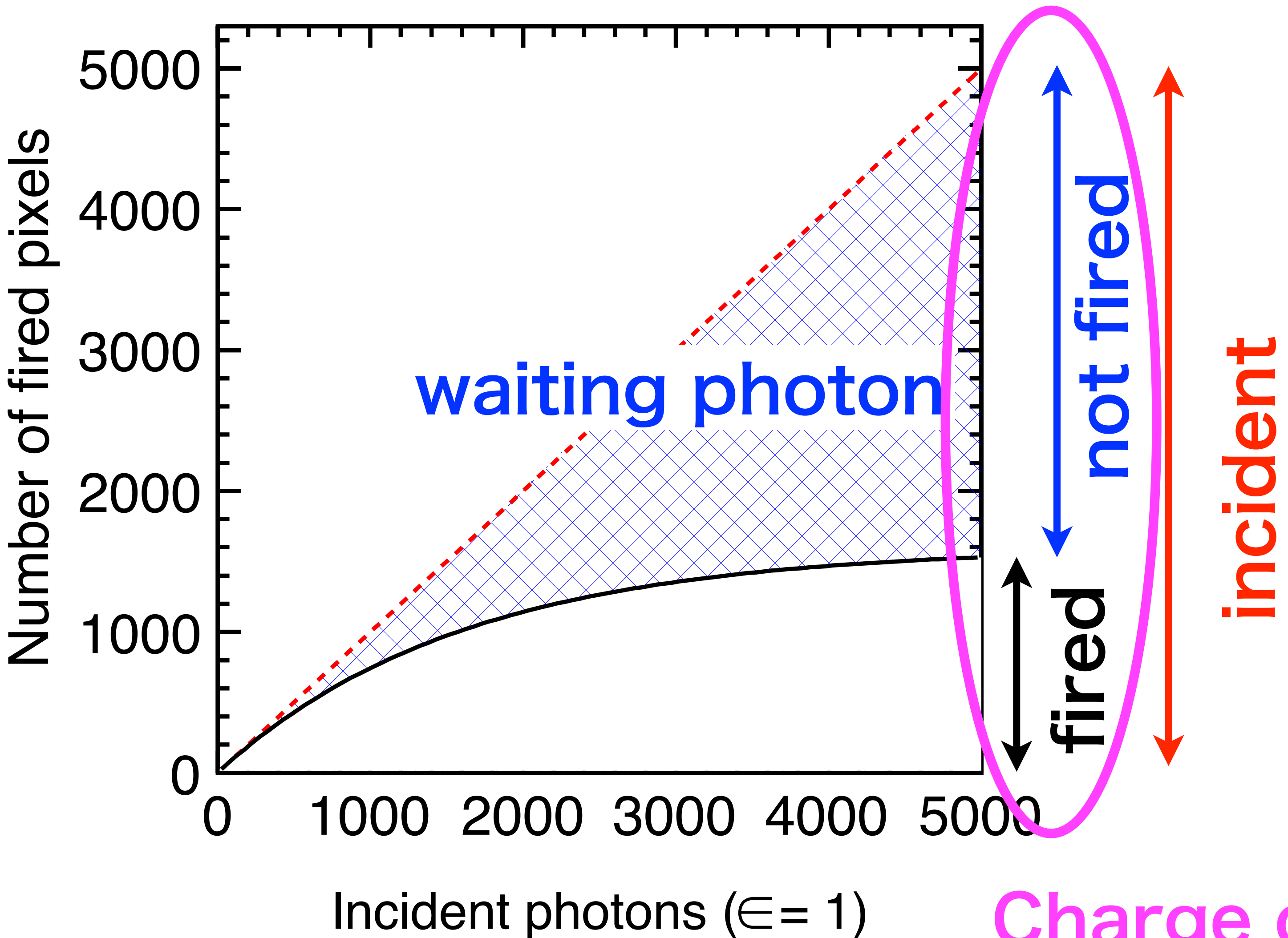
However,

Fitting is not enough well both

- highly saturated region
- small fired pixel region

Too simple

Consider Charge contribution by a photon



Not fire photons can make the next contributions

waiting photons

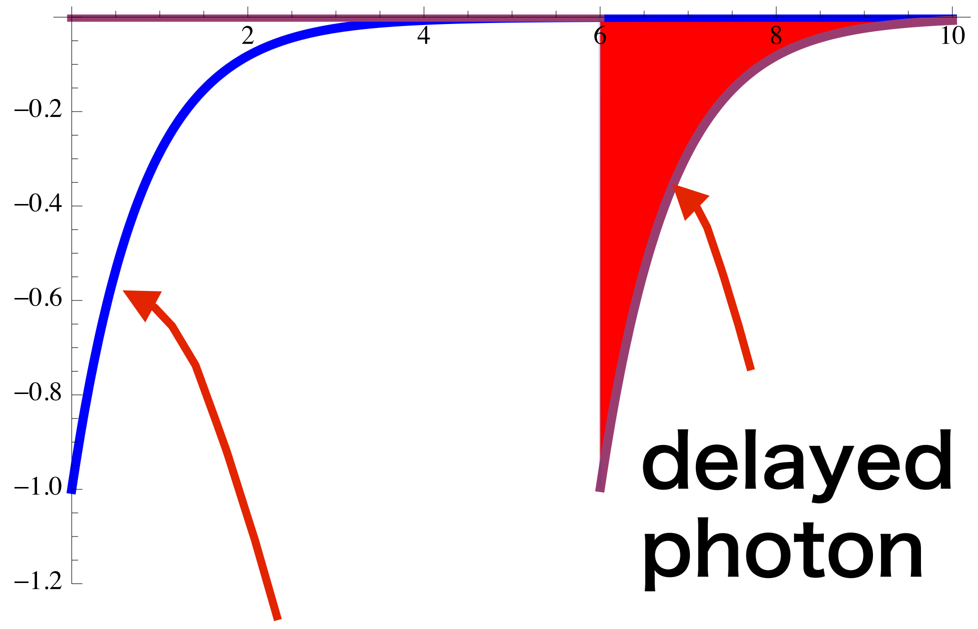
$$N_R = \epsilon N_{\rm in} - LO$$

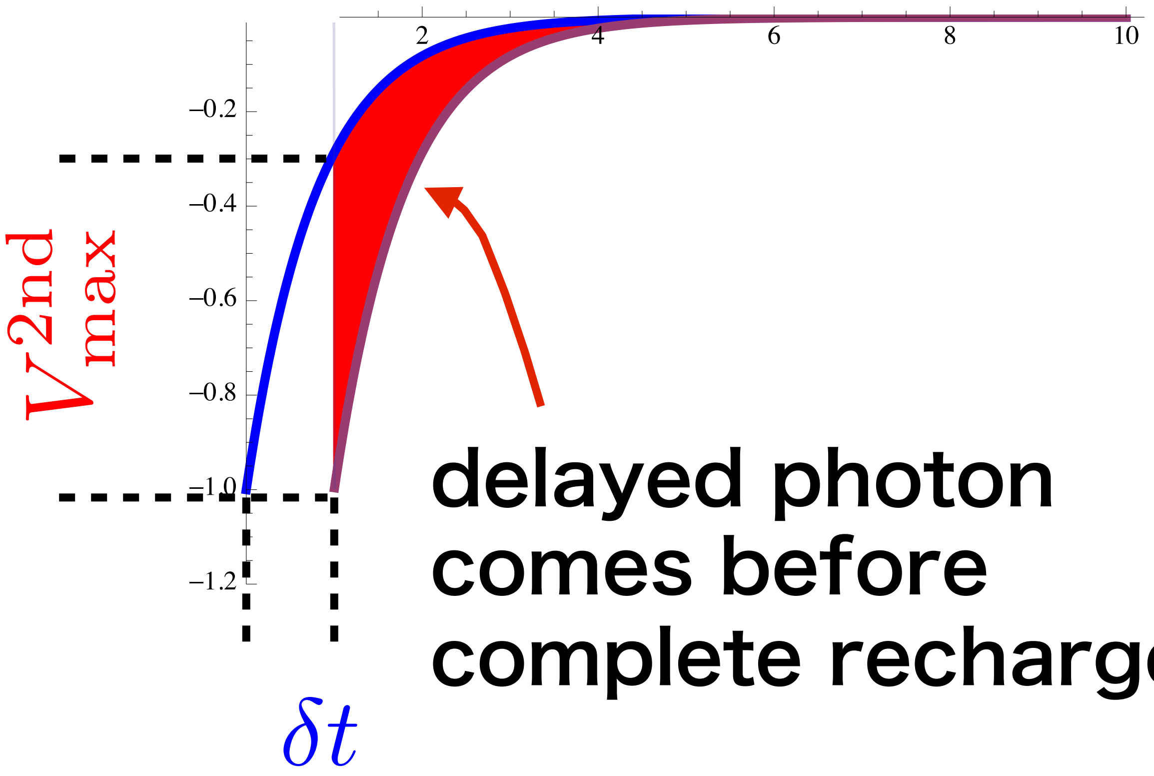
$$N_{\rm fire}^{\rm NLO} = LO + \alpha N_R$$

Charge contribution by a photon should be a function of #photon/pix.

not fired / fired

Consider Charge contribution by a photon (case multi-photons come)





pulse shape ~ recovery of a pixel.

$$V_{\max} \mathrm{e}^{-t/\tau_R}$$

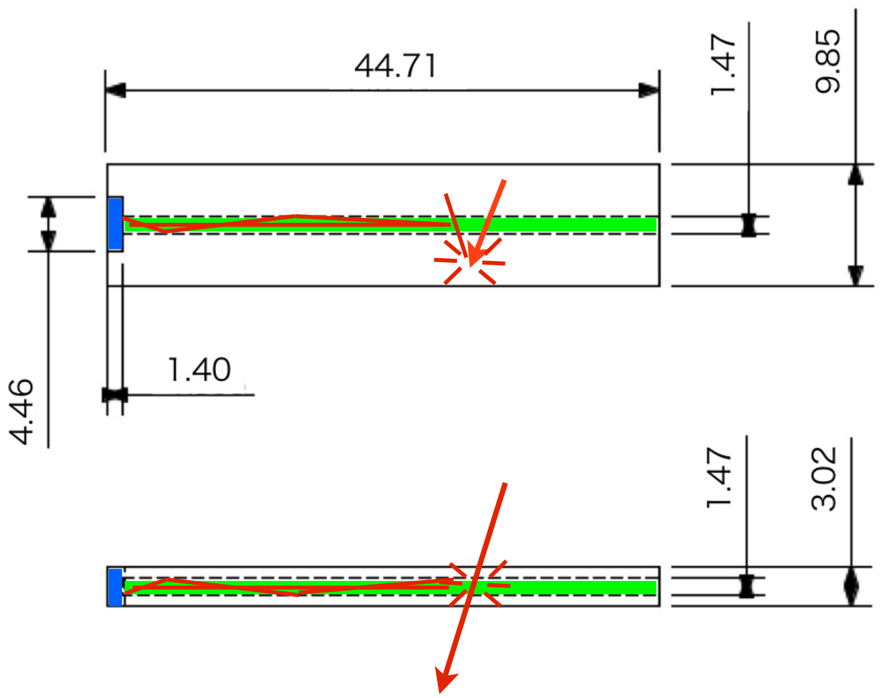
$$\tau_R = R_{\mathrm{quench}} C_{\mathrm{pixel}}$$

$$V_{\max}^{2\mathrm{nd}} = 1 - \mathrm{e}^{-\delta t/\tau_R}$$

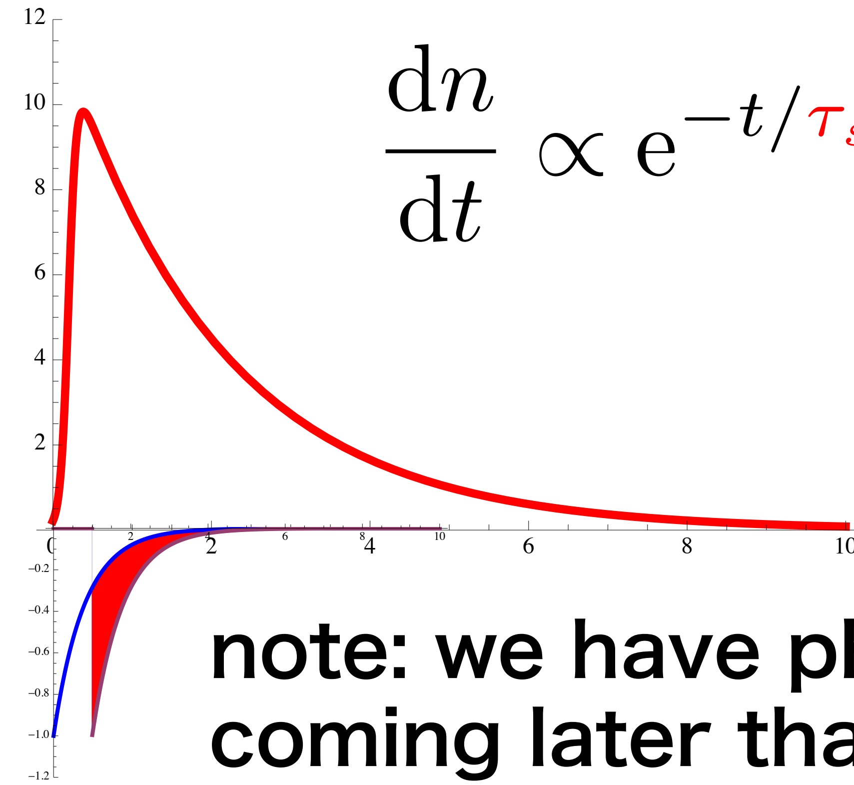
charge by the second photon Q_1 is :as Q_0 is full charge case,

$$Q_1 = Q_0(1 - \mathrm{e}^{-\delta t/\tau_R})$$

Time distribution of photons
—Charge by jth photon



photons come from WLS fiber



note: we have photons coming later than τ_s.

Suppose: we have k photons waiting for…

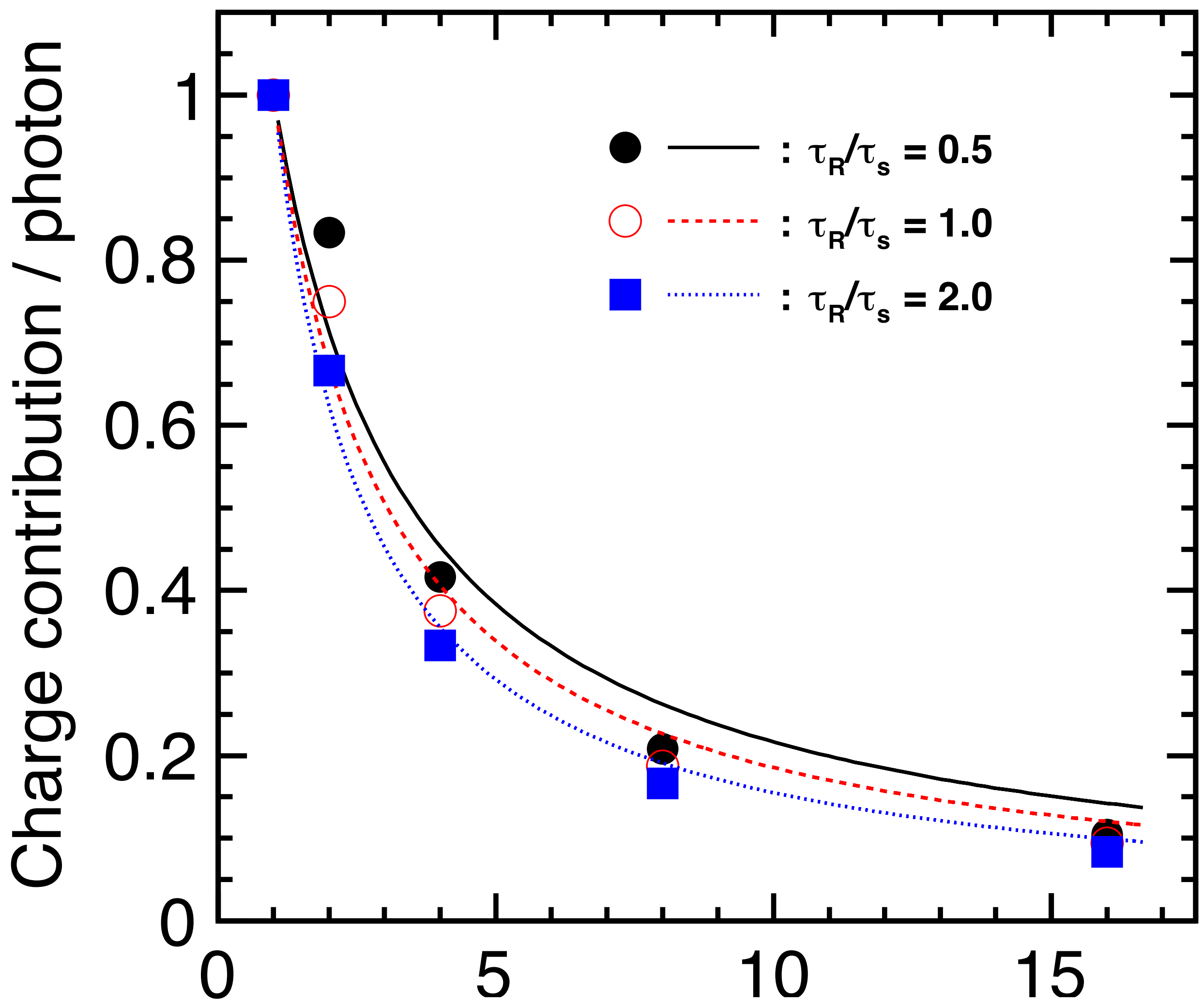
First: we have k candidate ➡ τ_s/k

second we have k-1; $\tau_s/(k-1)$, then $\tau_s/(k-2)\cdots\tau_s$

j th rate ; $\tau_j = \tau_s/(k-j+1)$

D. Jeans arXiv:1511.06528

Plot of $Q^{(k)}/k$



$$\langle \#\mathrm{photon}/\mathrm{pixel}_{\mathrm{fired}} \rangle = \langle k \rangle$$

$$Q^{(k)}/k =$$

$$Q_0 \left[1 + \sum_{j=2}^{k} \left\{ 1 - \frac{\zeta}{\zeta + (k+1-j)^{-1}} \right\} \right] / k$$

curve $= \dfrac{\beta + 1}{\beta + k}$

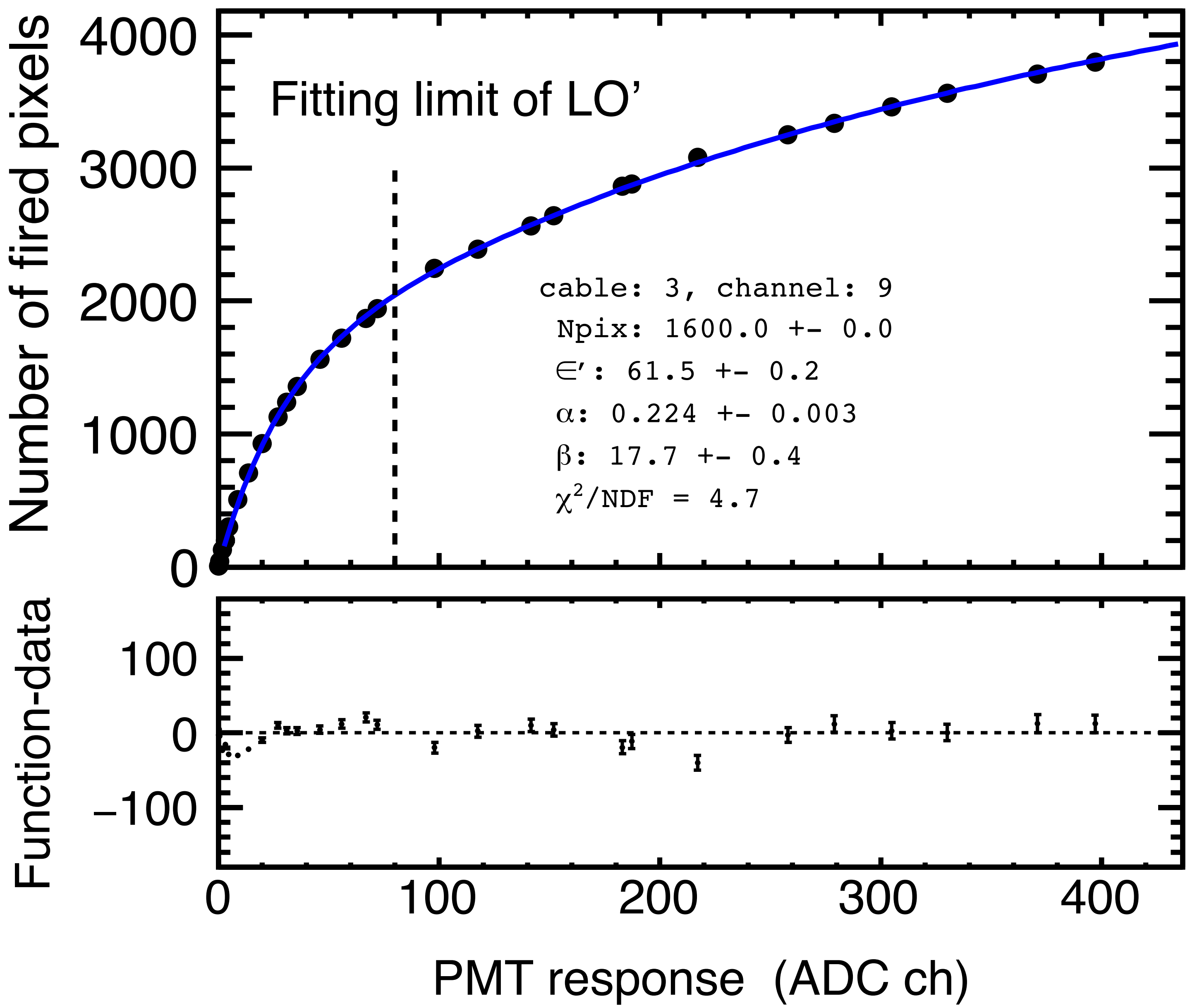
inverse proportion

$$\langle \#\mathrm{photon}/\mathrm{pixel}_{\mathrm{fired}} \rangle = \langle k \rangle = \frac{\epsilon N_{\mathrm{in}}}{LO}$$

$$N_{\mathrm{fire}}^{\mathrm{NLO}'} = N_{\mathrm{fire}}^{\mathrm{NLO}} \frac{\beta + 1}{\beta + \epsilon N_{\mathrm{in}}/LO}$$

Fitting with NLO’

$$N_{\text{fire}}^{\text{NLO}'} = N_{\text{fire}}^{\text{NLO}} \frac{\beta + 1}{\beta + \epsilon N_{\text{in}} / LO}$$



high saturated region

- good agreement

small light region

- modified

Npix was fixed @ 1600
only one additional
free parameters to LO’

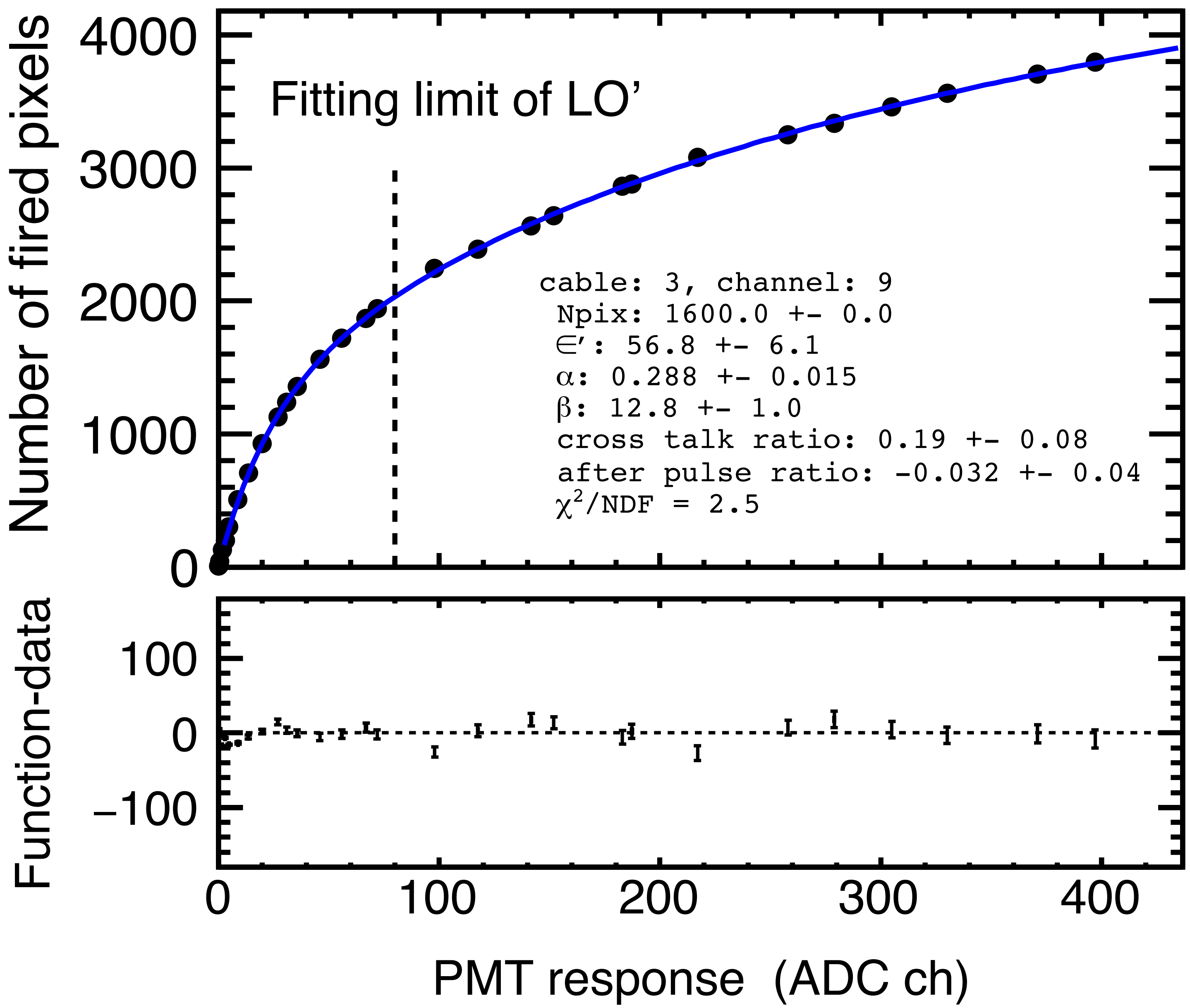
If Npix was free:

$\langle N_{\text{pix}} \rangle$ **= 1583±29**

(72 sample)

Considering Xtalk and After pulse

$$NLO'_{\mathrm{C.A}} = NLO' \times (1 + P_C \mathrm{e}^{-\epsilon N_{\mathrm{in}}/N_{\mathrm{pix}}})(1 + P_A)$$



Npix was fixed @ 1600

$\langle P_C \rangle$ = 0.22±0.02

$\langle P_C \rangle_{direct}$ = 0.11±0.02

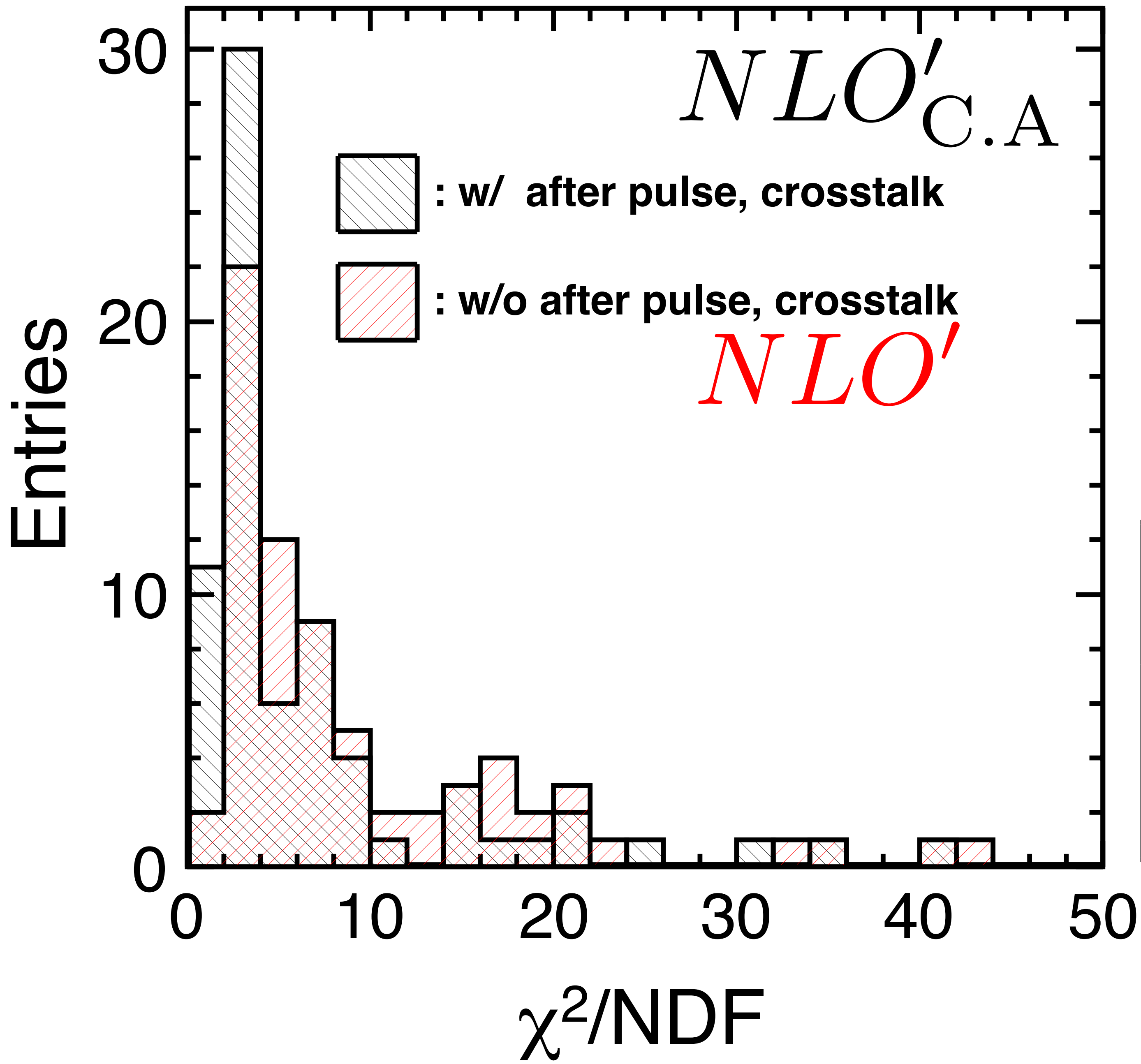
$\langle P_A \rangle$ = 0.08±0.02

$\langle P_A \rangle_{direct}$ = 0.1

High crosstalk ratio requires additional knowledge.

χ^2/NDF

$$NLO'_{\mathrm{C.A}} = NLO' \times (1 + P_C \mathrm{e}^{-\epsilon N_{\mathrm{in}}/N_{\mathrm{pix}}})(1 + P_A)$$



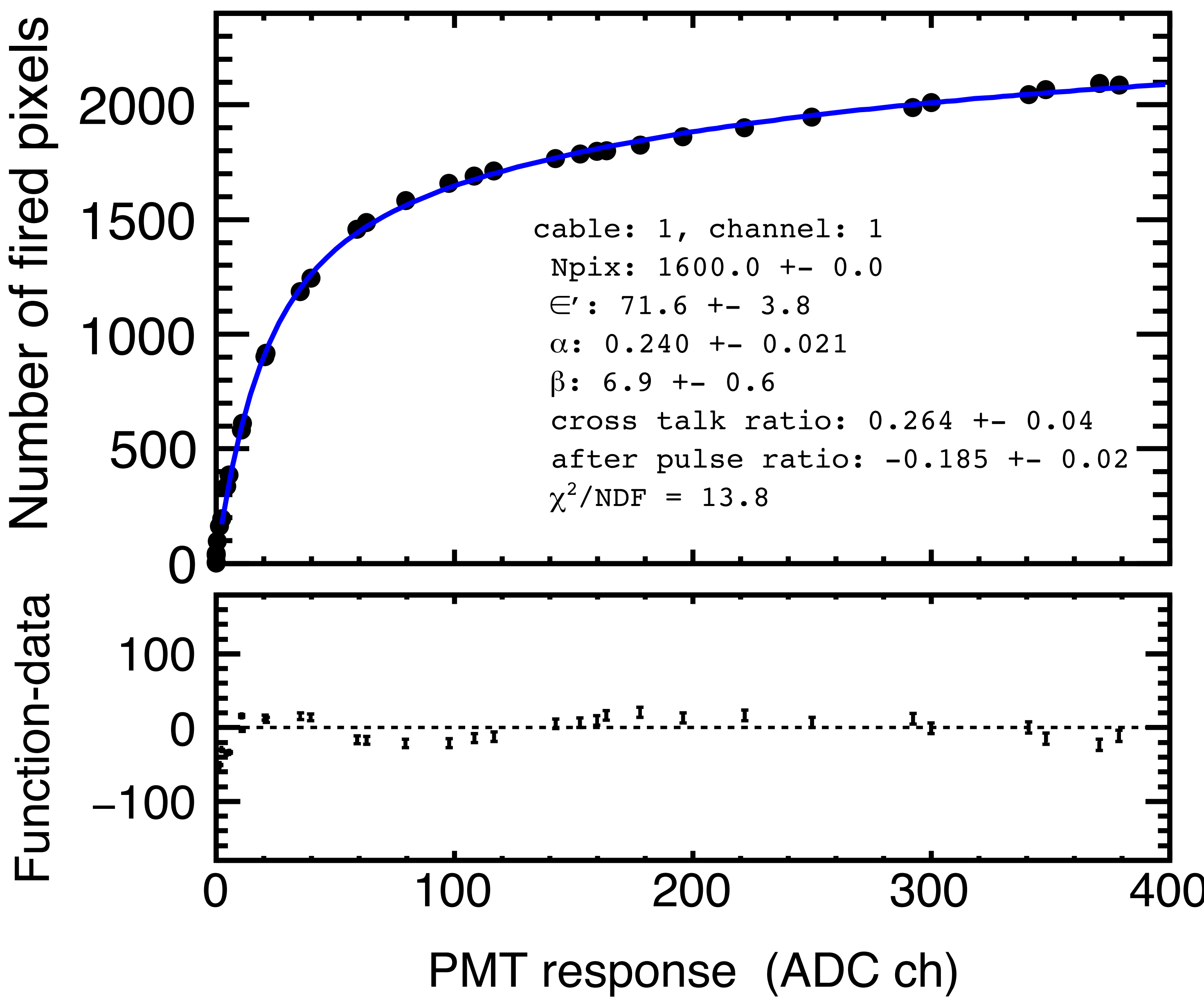
Uncertainty of each data point is statistical one.

most channel < 10 for both NLO' NLO'C.A

	NLO'	$NLO'_{C.A}$
$<\chi^2/q>$	9.4±9.0(RMS)	6.9±7.9(RMS)

Fast pulse input

$NLO'_{\mathrm{C.A}}$: applied to scinti-MPPC w/o WLS fiber



	WLS fiber	
	w/	w/o
α	0.30	0.24
β	12	6.9

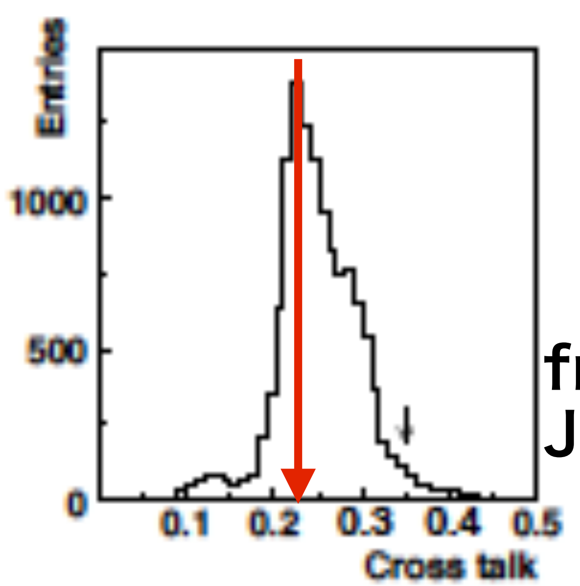
recovery
α: large ⟷ small

pulse width/recov.time
β: large ⟷ small

Applying to 7608 SiPM data of AHCAL physics prototype

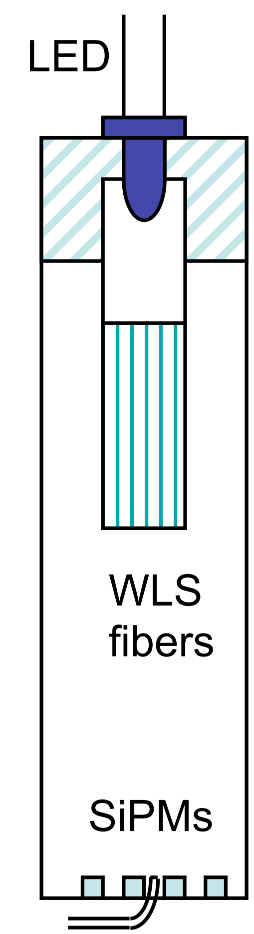
ITEP SiPM

- 1156 pixels/(1.1×1.1mm²)
- Recovery time: 20ns (from CALICE JINST 5 P05004),
- LED UV light via Y11 WLS, at dV = 2V,
- Xtalk : < 35%, MPV~22%,



from CALICE JINST 5 P05004

naked SiPM w/o scintillator

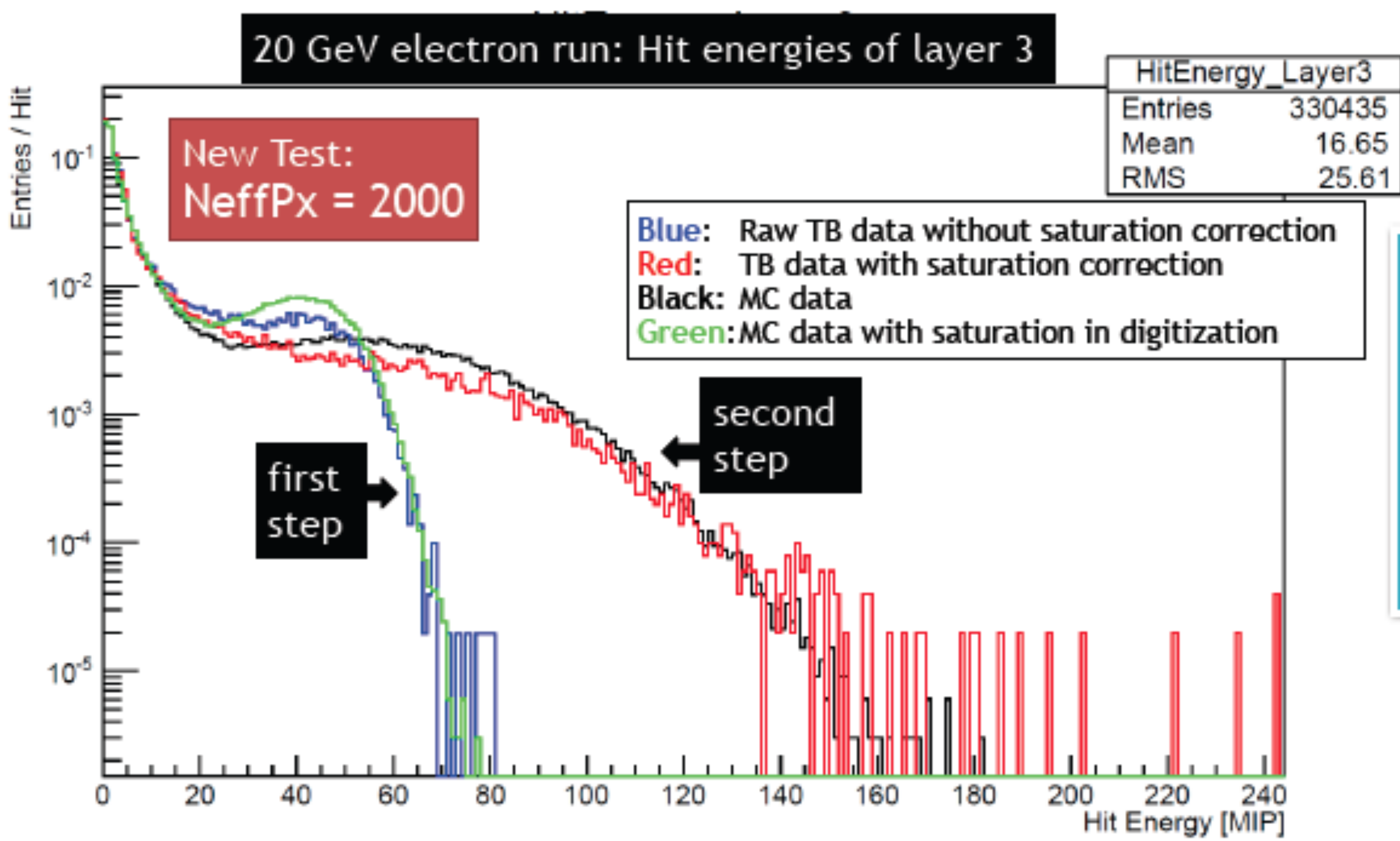


Motivation

CERN TB 2015: Ongoing analysis at Mainz

3. Missing calibration of SiPM saturation effects:

Number of effective pixels (*NeffPx*) has a large impact on saturation correction in high energy region.

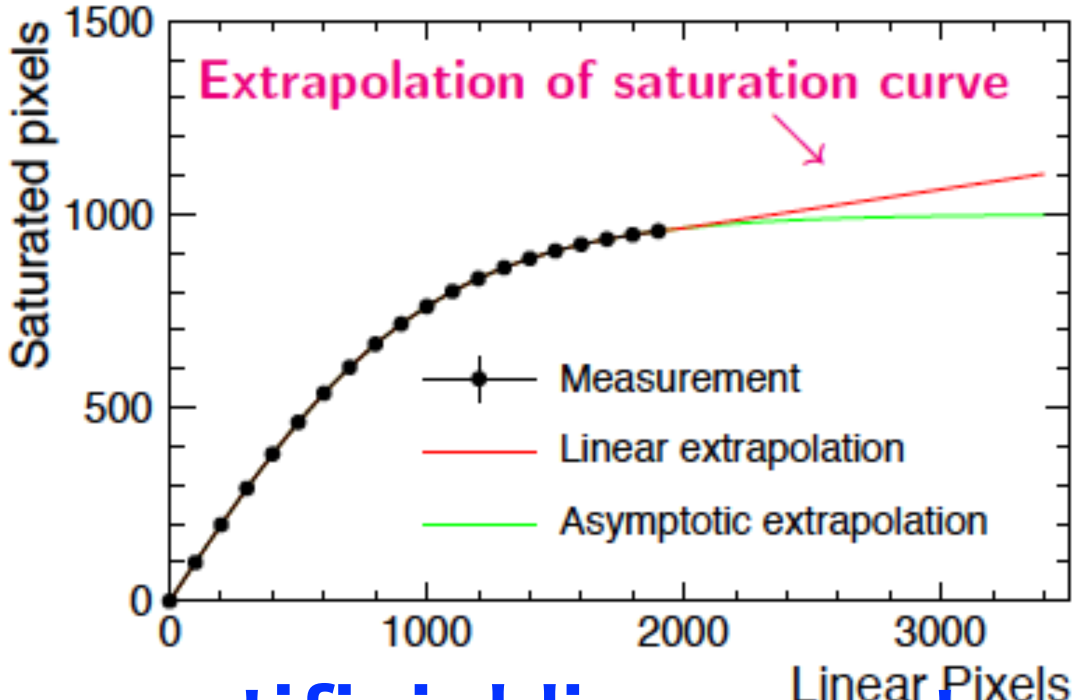


- First result looks promising and is in reasonable region.
- Has to be confirmed.

Motivation

Felix's (Eva Sicking's) talked at LCWS Whistler: W-AHCAL

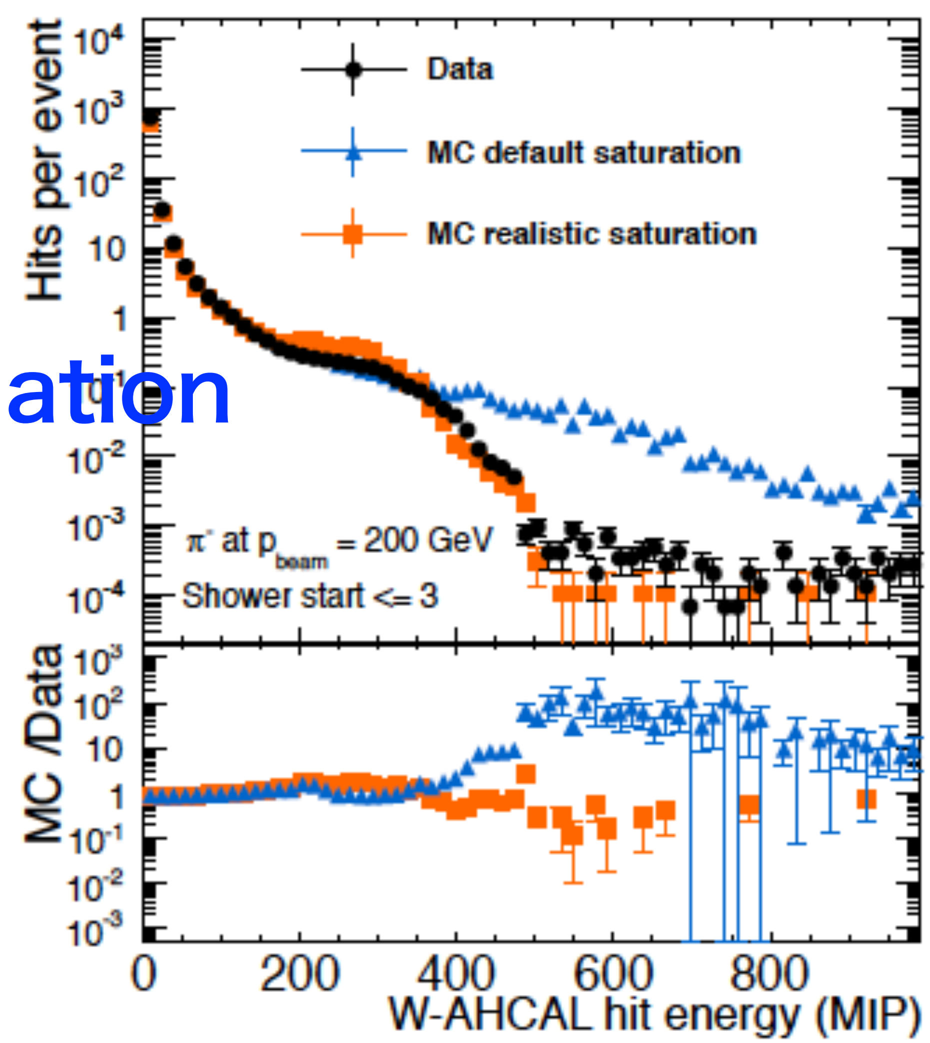
More realistic saturation simulation



Rather artificial linear extrapolation

- **Data**
  - Linear extrapolation in reconstruction
- **MC with default saturation**
  - Linear extrapolation in digitization and reconstruction
- **MC with more realistic saturation**
  - Asymptotic extrapolation in digitization, linear extrapolation in reconstruction

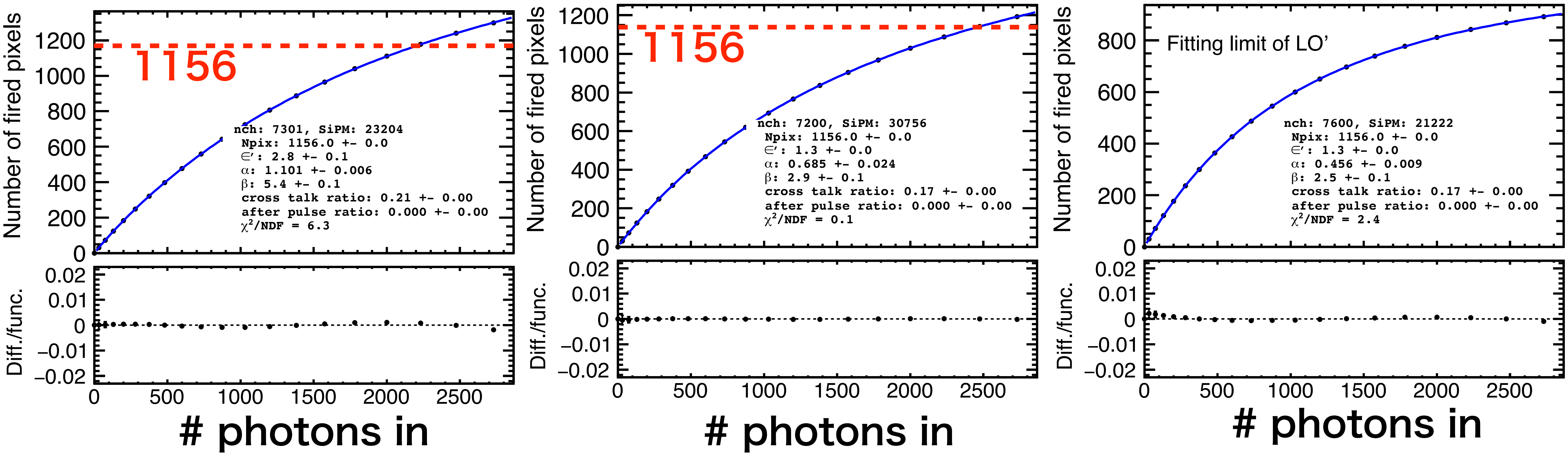
- Hit energy distribution in data can be described well by more realistic MC
- Energy resolution values increase, especially at high beam momenta



ITEP SiPM in AHCAL physics prototype

fitting example/7608, various fired/in

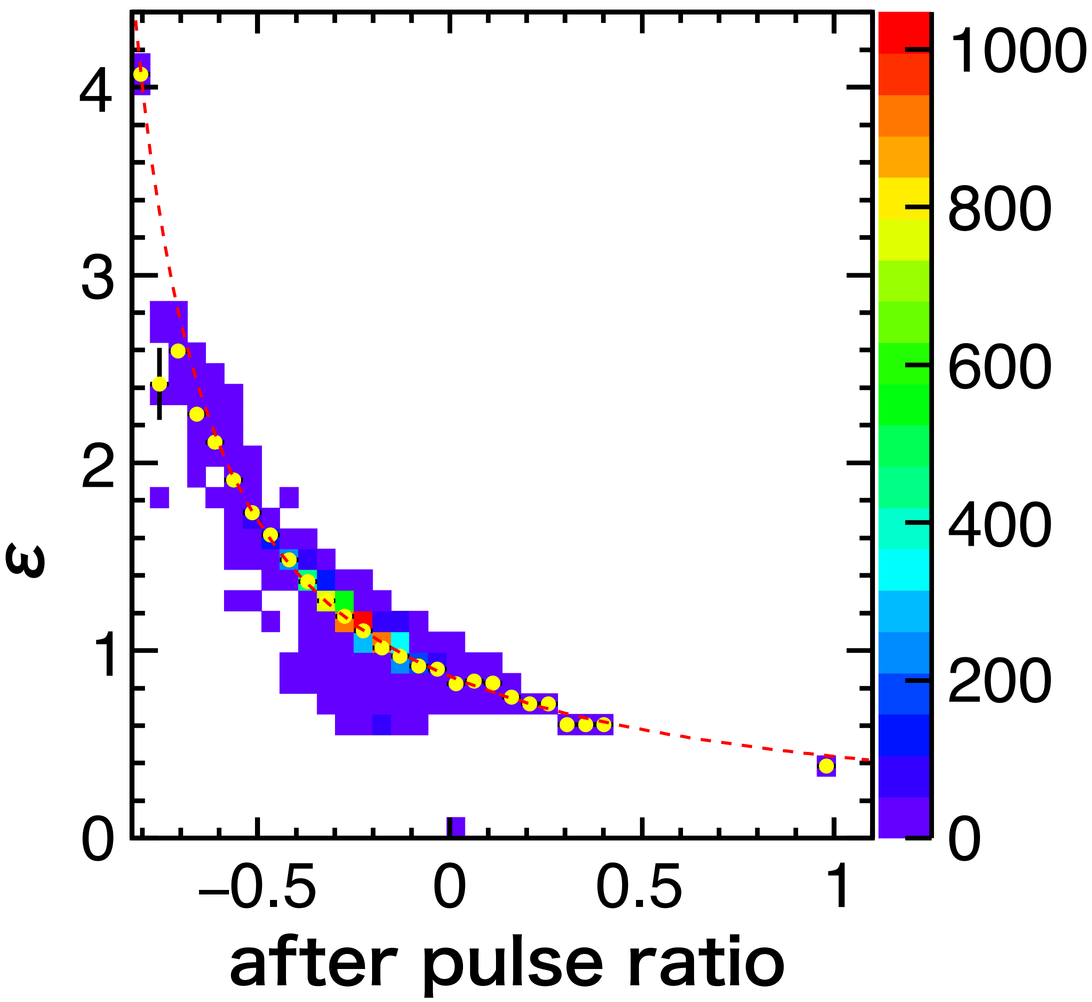
Npix: fixed at 1156



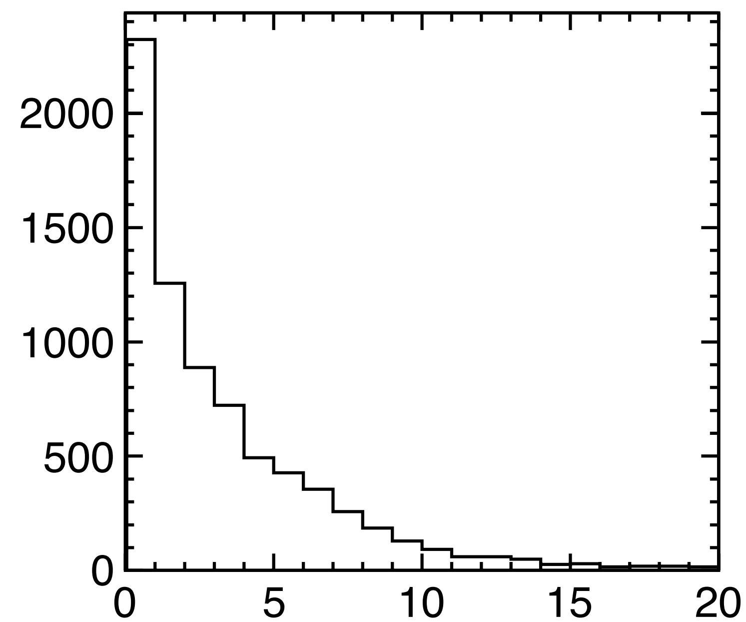
(# photons in: normalized at small number of fired pixels)

Fitting: 7608 samples takes ~22min(0.17sec/ch)➡ light function

ITEP SiPM in AHCAL physics prototype
some parameters

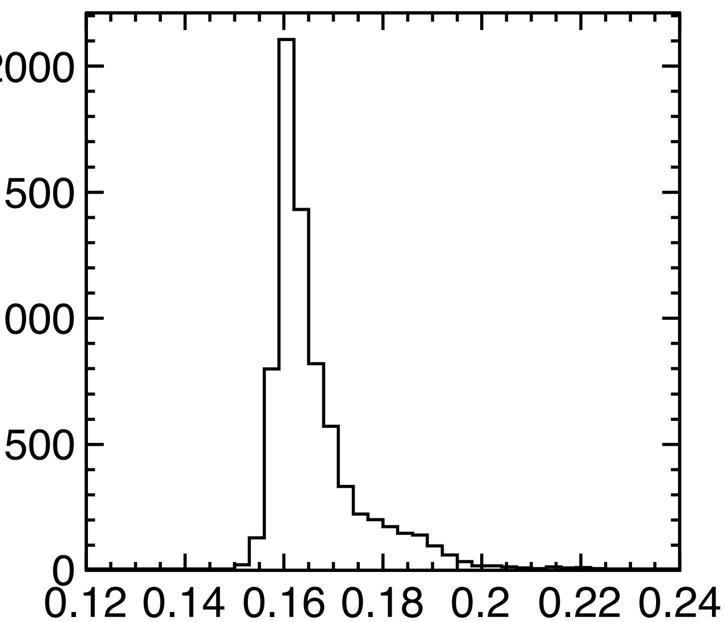


χ^2/NDF

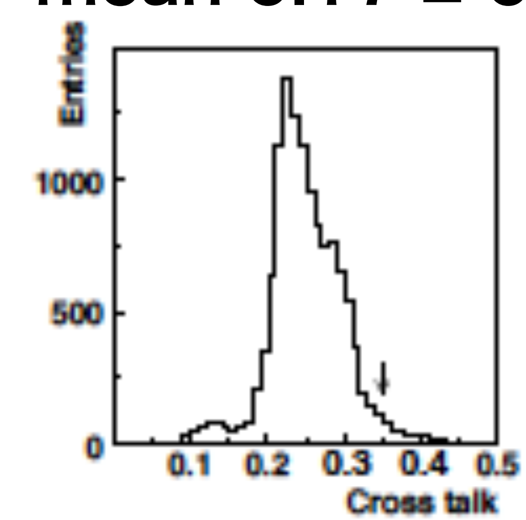


χ^2/NDF < 20
7425ch/7608ch

crosstalk ratio



mean 0.17 ± 0.01



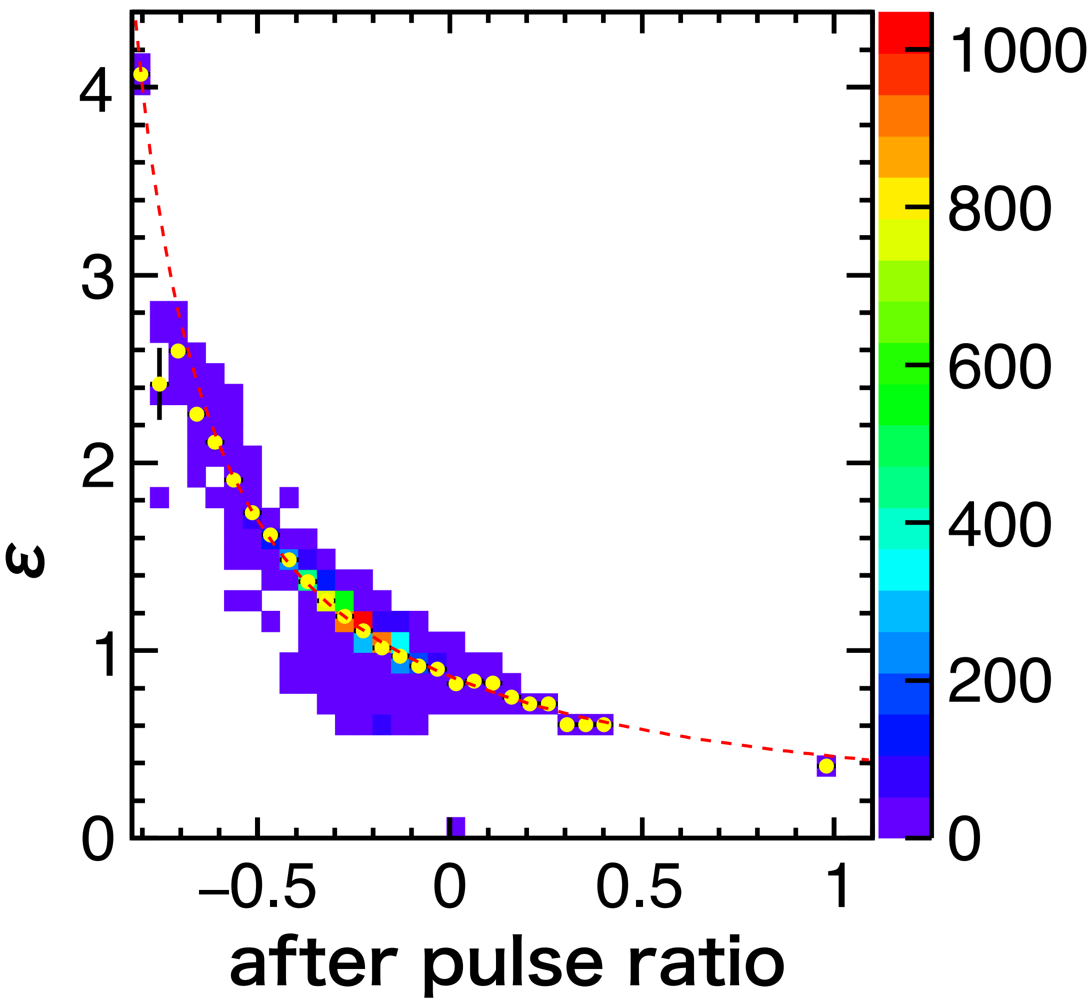
$$NLO'_{\mathrm{C.A}} = NLO' \times (1 + P_C \mathrm{e}^{-\epsilon N_{\mathrm{in}}/N_{\mathrm{pix}}})(1 + P_A)$$

$$\epsilon = \frac{0.88}{1.02 + \mathrm{afterPulse}}$$

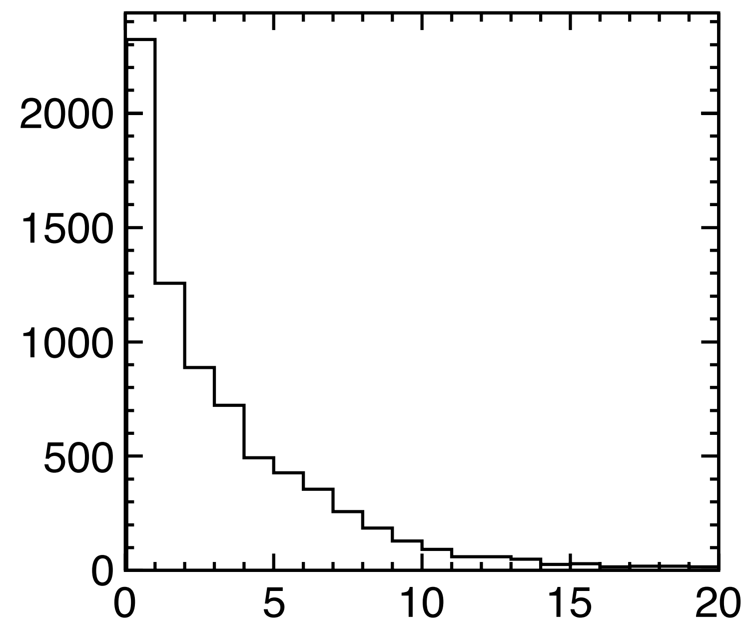
: in our simple model, P_afterpulse is a scale factor in N_fired (no effect on shape).

negative peak (-0.28) indicates some systematics.

ITEP SiPM in AHCAL physics prototype
some parameters

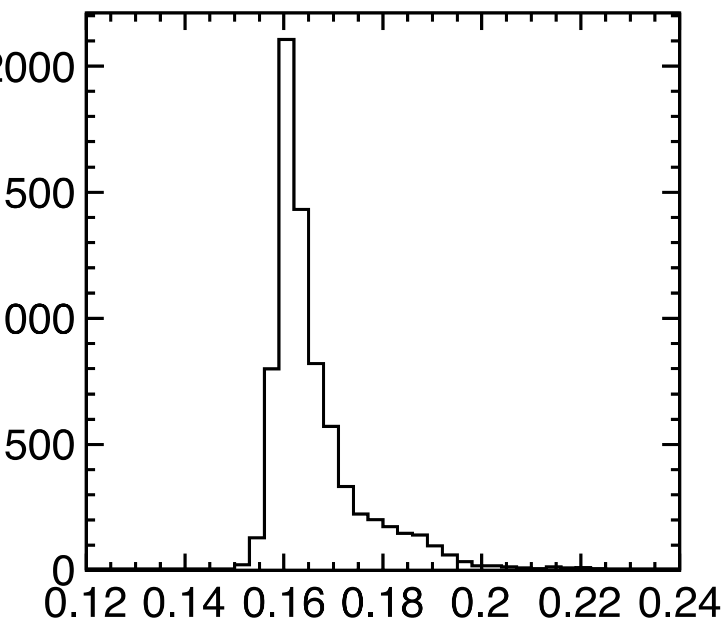


χ^2/NDF



χ^2/NDF < 20
7425ch/7608ch

crosstalk ratio



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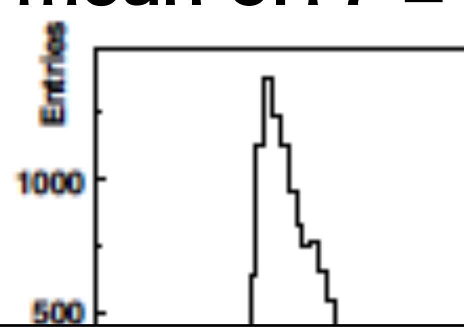


Our function works well for also ITEP SiPMs in AHCAL

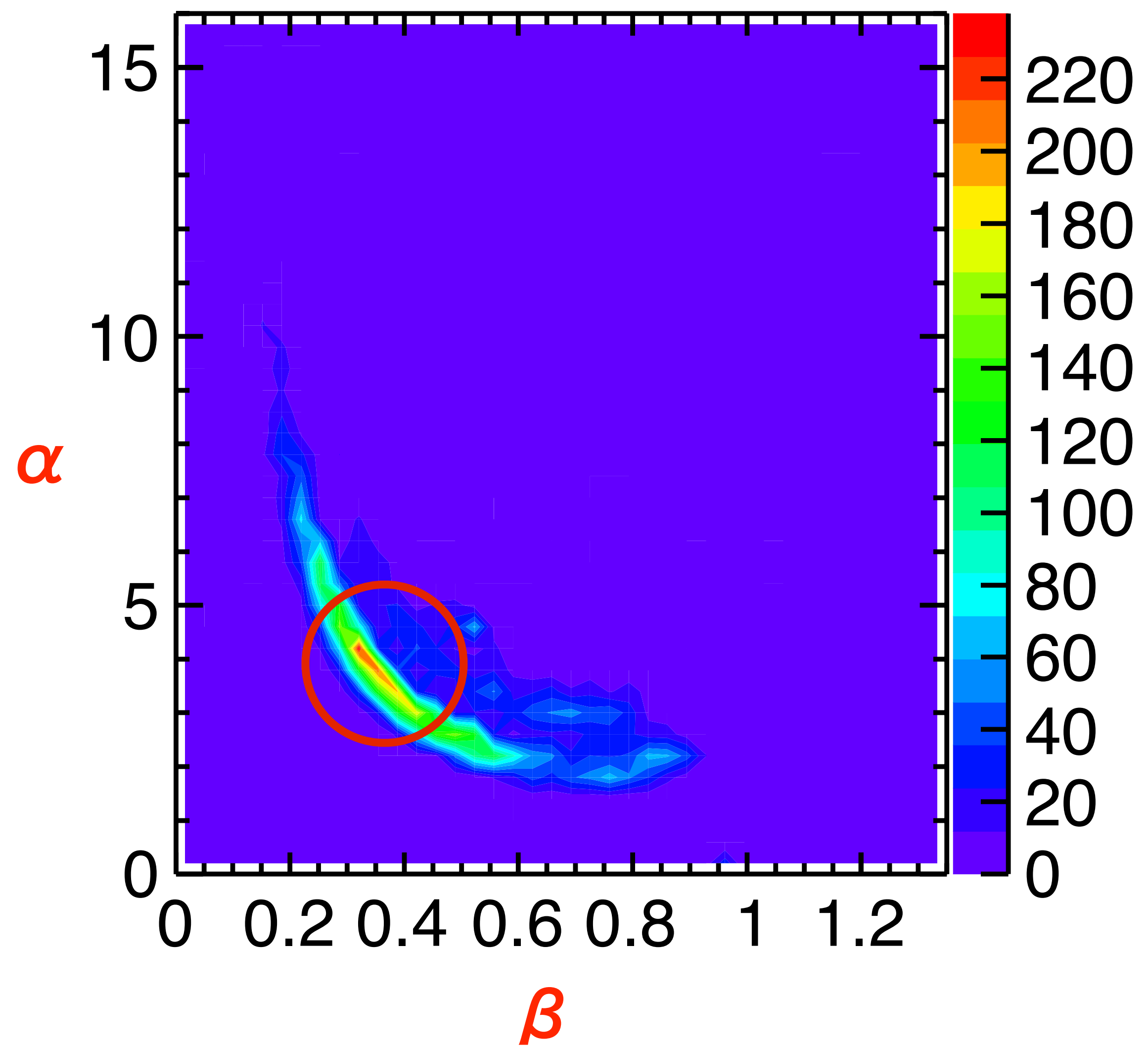
α vs. β

$$LO = N_{\rm pix}\left(1 - e^{-\epsilon N_{\rm in}/N_{\rm pix}}\right)$$

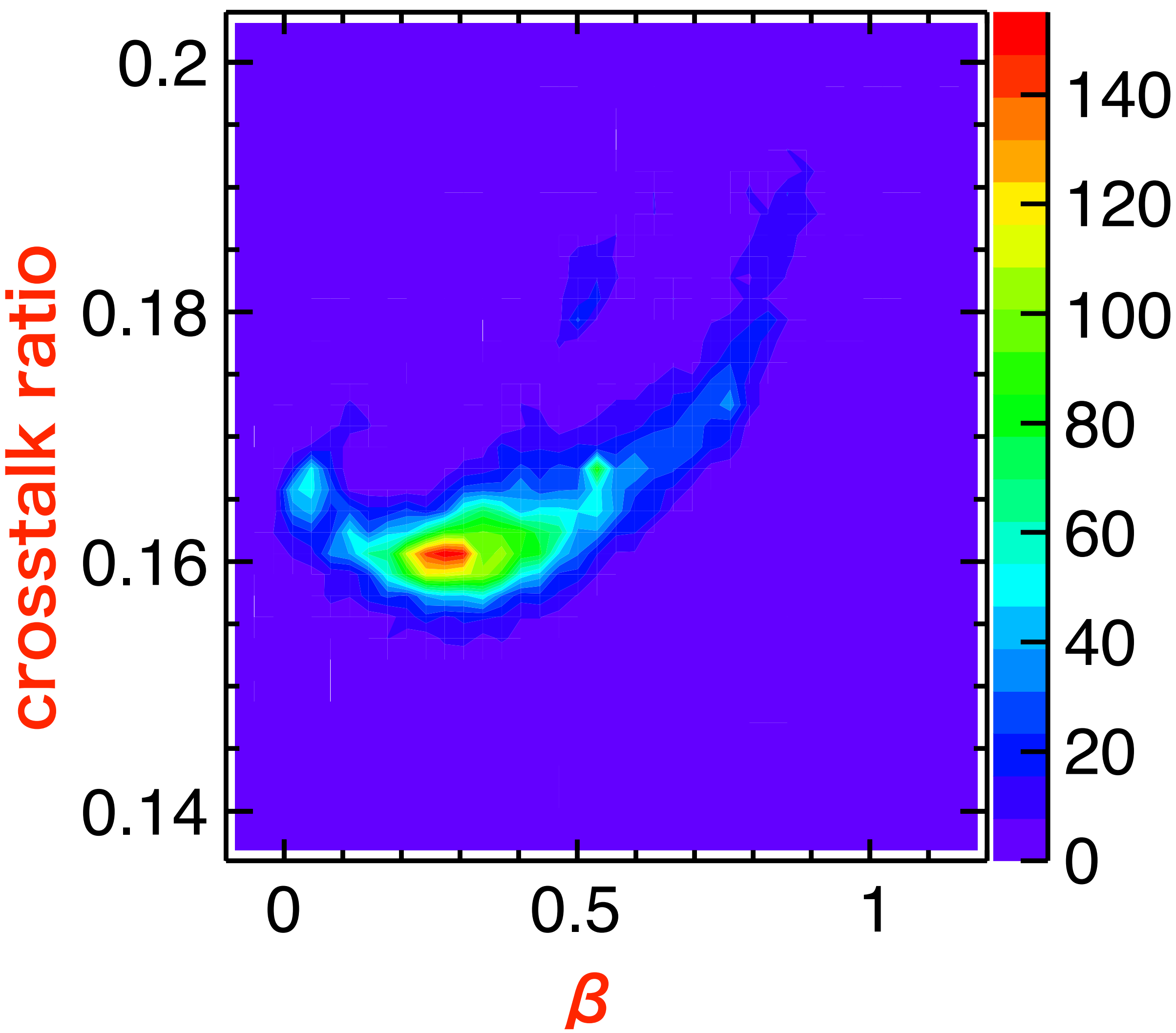
$$N_{\rm fire}^{\rm NLO} = LO + \alpha N_R$$

$$N_{\rm fire}^{\rm NLO'} = N_{\rm fire}^{\rm NLO}\frac{\beta + 1}{\beta + \epsilon N_{\rm in}/LO}$$

α and β have a relation with each other.
However, a clear peak indicates that those both have meanings of existences respectively.



crosstalk ratio vs. β



- Correlation between cross-talk ratio and β has a clear peak and no clear correlation (only small amount of large β has correlation.
- without crosstalk correction, fitting results are very much degrading

β and crosstalk individually affect on the shape of function

Three parameters α, β, and crasstalk ratio are individually required.

Summary

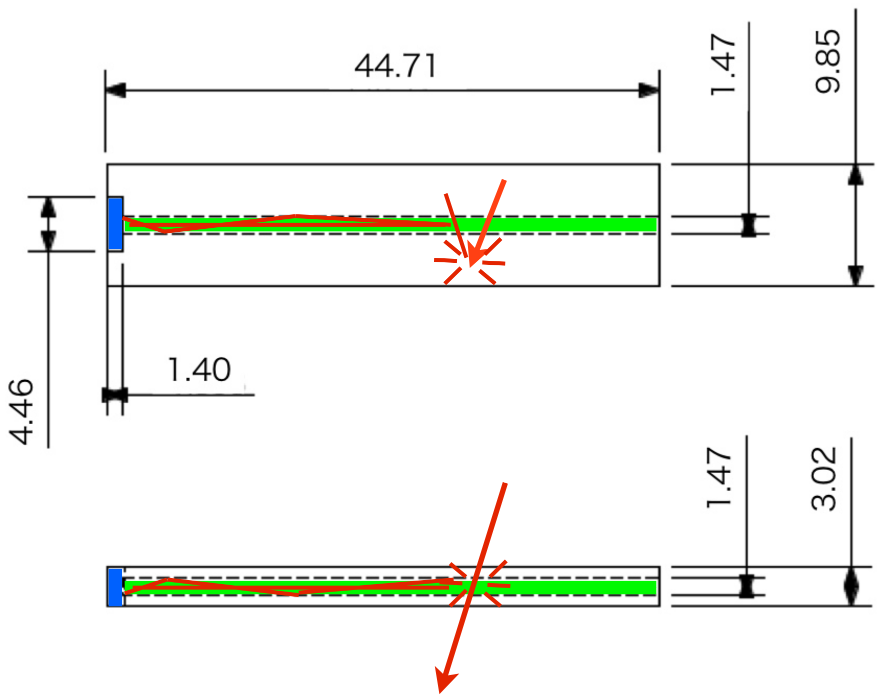
- We developed functions having high performance to represent SiPM behavior in wide ranges.
- Light function (0.17sec/fit).
- The function models reactivating pixels in a event more carefully than taking the number of effective pixels;
  - the number of photons fire reactivated pixels,
  - charge contribution par one photon is implemented by an approximation of the first principle method.
- Crosstalk and after pulse models improves fitting performance, whereas it did not work with LO'(N_{pix}^{eff}).
- The function successfully worked on 7608 SiPM for AHCAL physics prototype.

Next

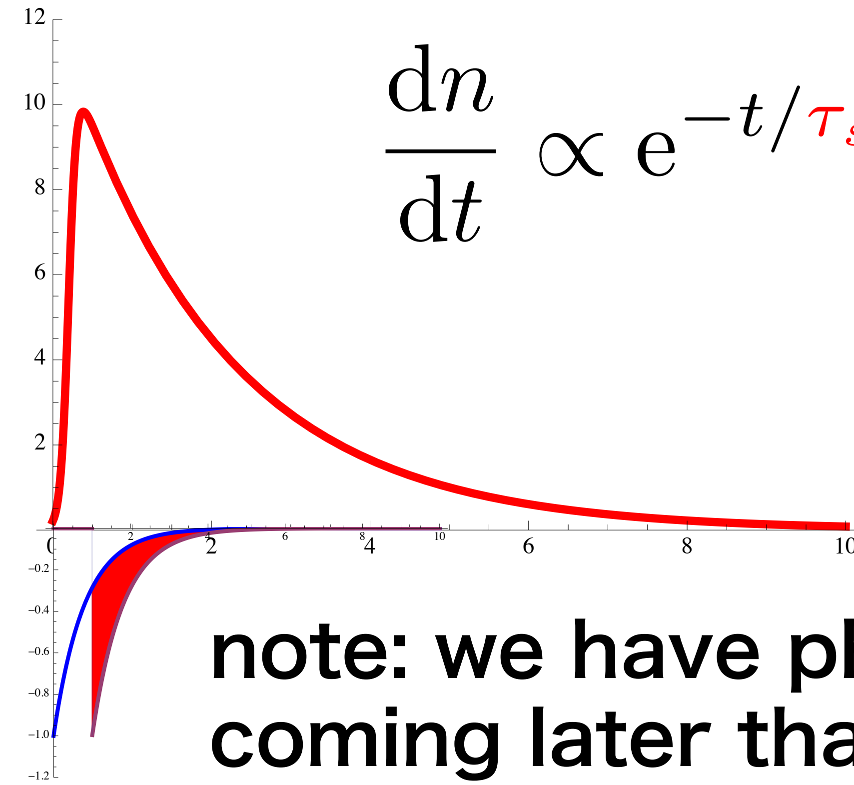
- Understand detail effects of individual parameters.
- Usage in calibration procedure.

Backup

Time distribution of photons
—Charge by jth photon



photons come from WLS fiber



note: we have photons coming later than τ_s.

Incorrect: no effect in $\tau_s < \tau_R$.

Suppose: we have k photons waiting for...

First: we have k candidate ➡ τ_s/k

second we have k-1; $\tau_s/(k-1)$, then $\tau_s/(k-2)\cdots\tau_s$

j th rate ; $\tau_j = \tau_s/(k-j+1)$

by D. Jeans

Charge by ks photons on a cell

charge by the jth photon

$$Q_j = Q_0 \int_0^\infty dt \frac{1}{\tau_j} \mathrm{e}^{-t/\tau_j} (1 - \mathrm{e}^{-t/\tau_R})$$

$$\tau_j = \tau_s/(k - j + 1)$$

$$= Q_0 \Big(1 - \frac{\tau_R}{\tau_R + \tau_j}\Big)$$

$$= Q_0 \Big(1 - \frac{\zeta}{\zeta + (k - j + 1)^{-1}}\Big)$$

$$\zeta = \tau_R/\tau_s$$

charge by ks photons

$$Q^{(k)} = Q_0 \Big\{ 1 + \sum_{j=2}^{k} \Big(1 - \frac{\zeta}{\zeta + (k - j - 1)^{-1}}\Big)\Big\}$$

D. Jeans arXiv:1511.06528

Hamamatsu MPPC (2008)

Hamamatsu MPPC: corresponding to S10362-11-25P

1600pixels/(1×1mm^2)

Recovery time: 4ns,

at dV = 3V,

crosstalk : 11% measured in lab,

after pulse : 10% from some references.

408nm 31ps (FWHM) Laser via Scintillator + Y11 WLS,

Y11 decay time: 11ns

Purpose of developing functions

Practical usage in experiments using SiPMs
in wide range of number of photons,

- detector calibration,
- simulation of detector responses

based on much reasonable—detail—model of SiPM phenomena than current others.

Data

CALICE DATA base we can access it using CaliceSoft.

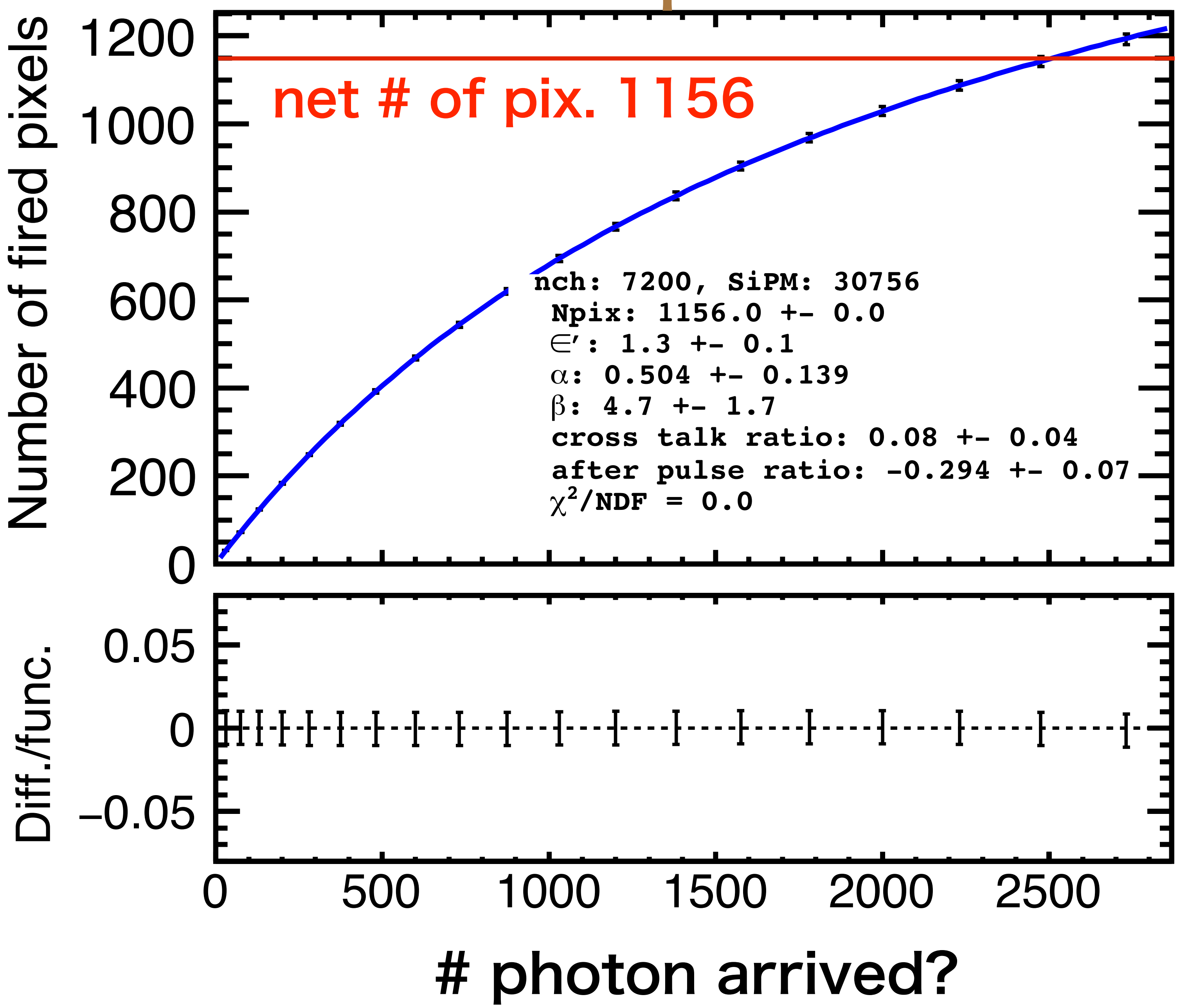
each data (7608) has:
- one SiPM ID
- 20 data of # photons injected,
- 20 data of fired pixels corresponding,
- no uncertainty information.

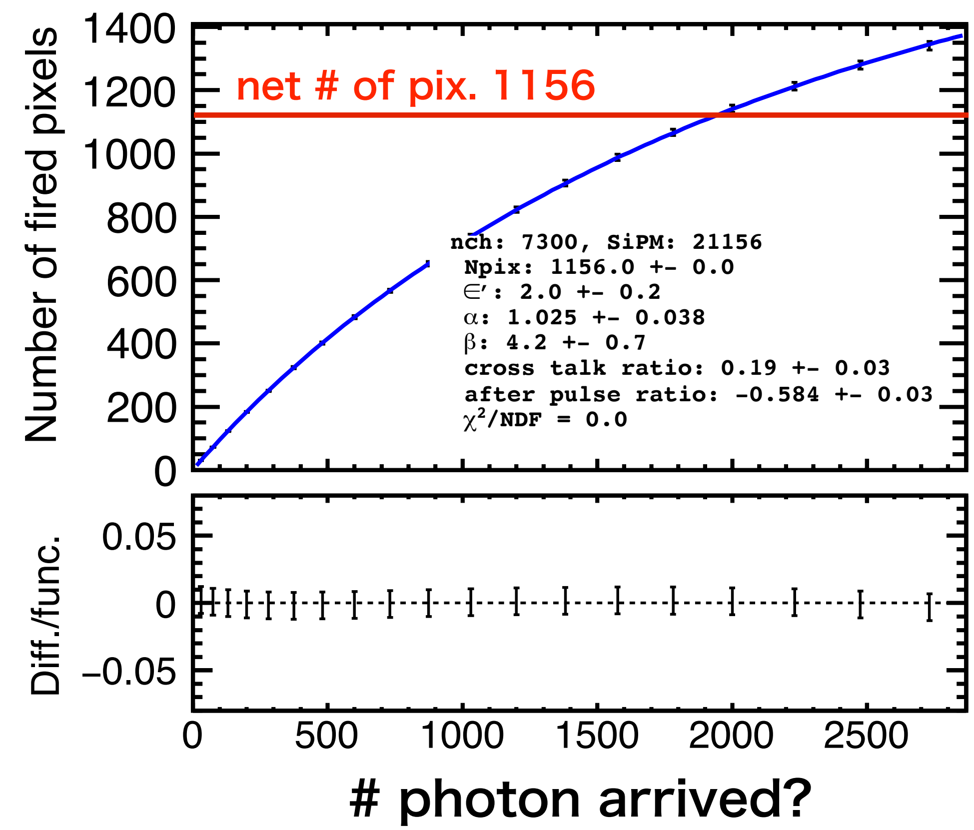
- Wrote a processor to read and create a TTree.

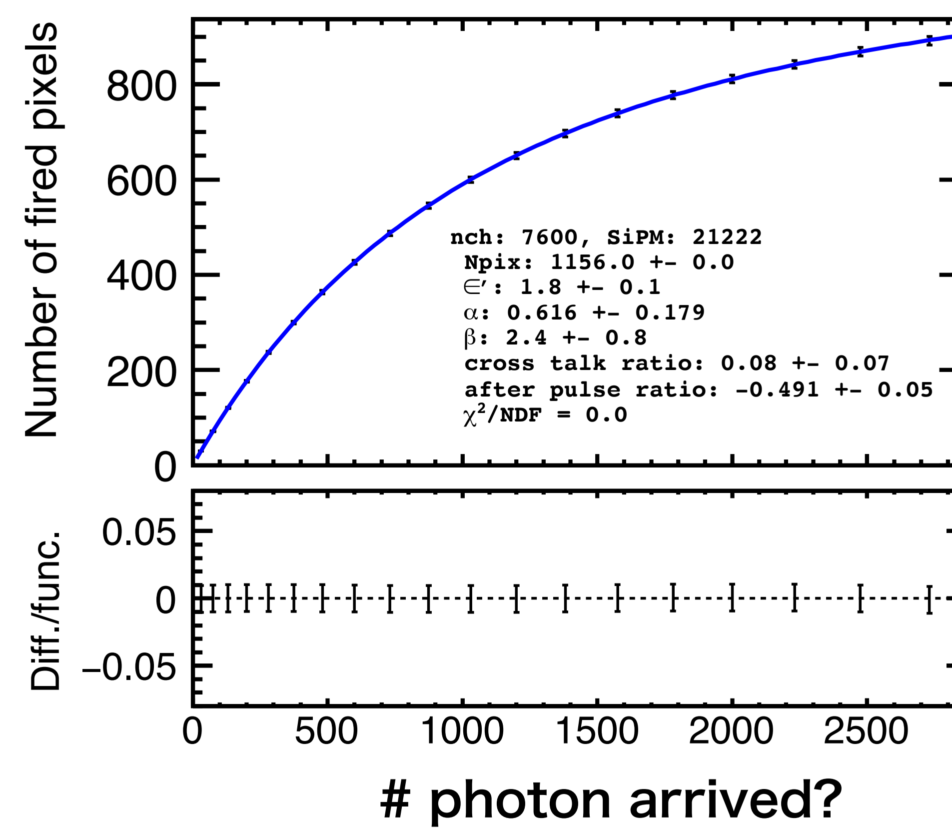
Applying our function to # of fired pix. as a function of # of photons injected.

Some example of fitting

Each error #photons × 0.01





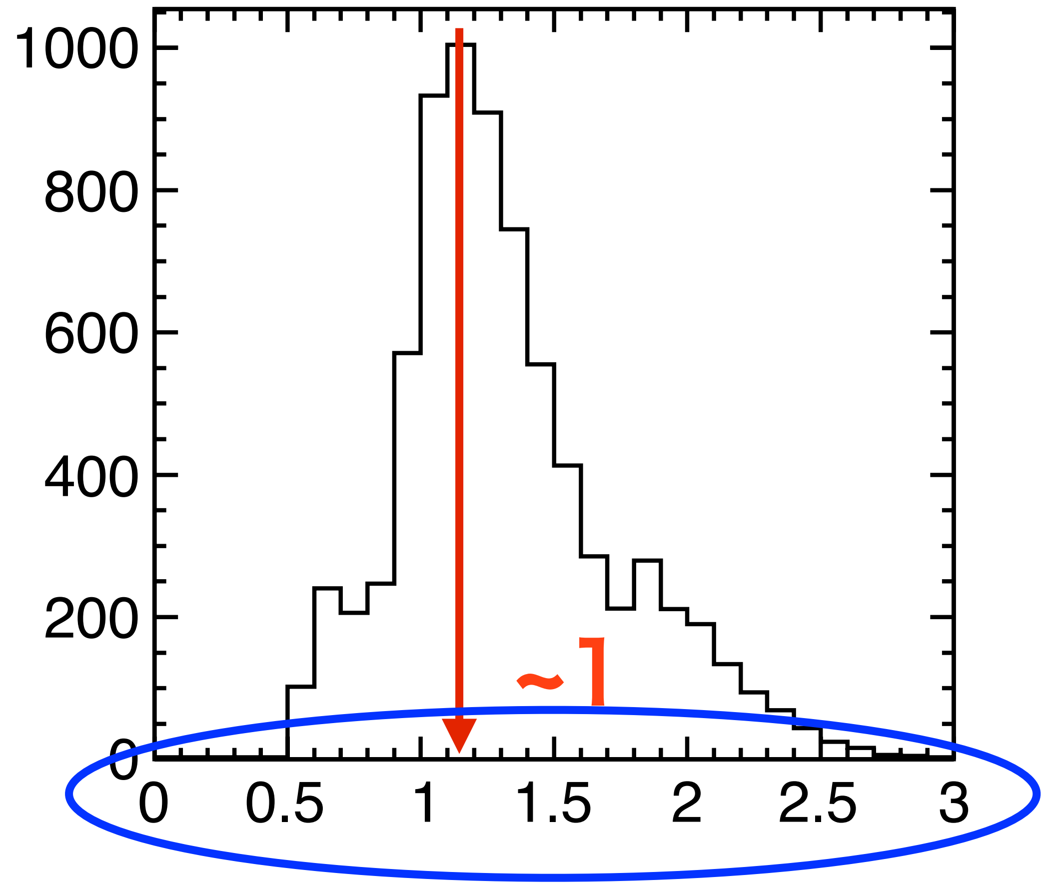


Fine fitting result.

Too large error estimation :(

Evaluation of fitting (good)
example

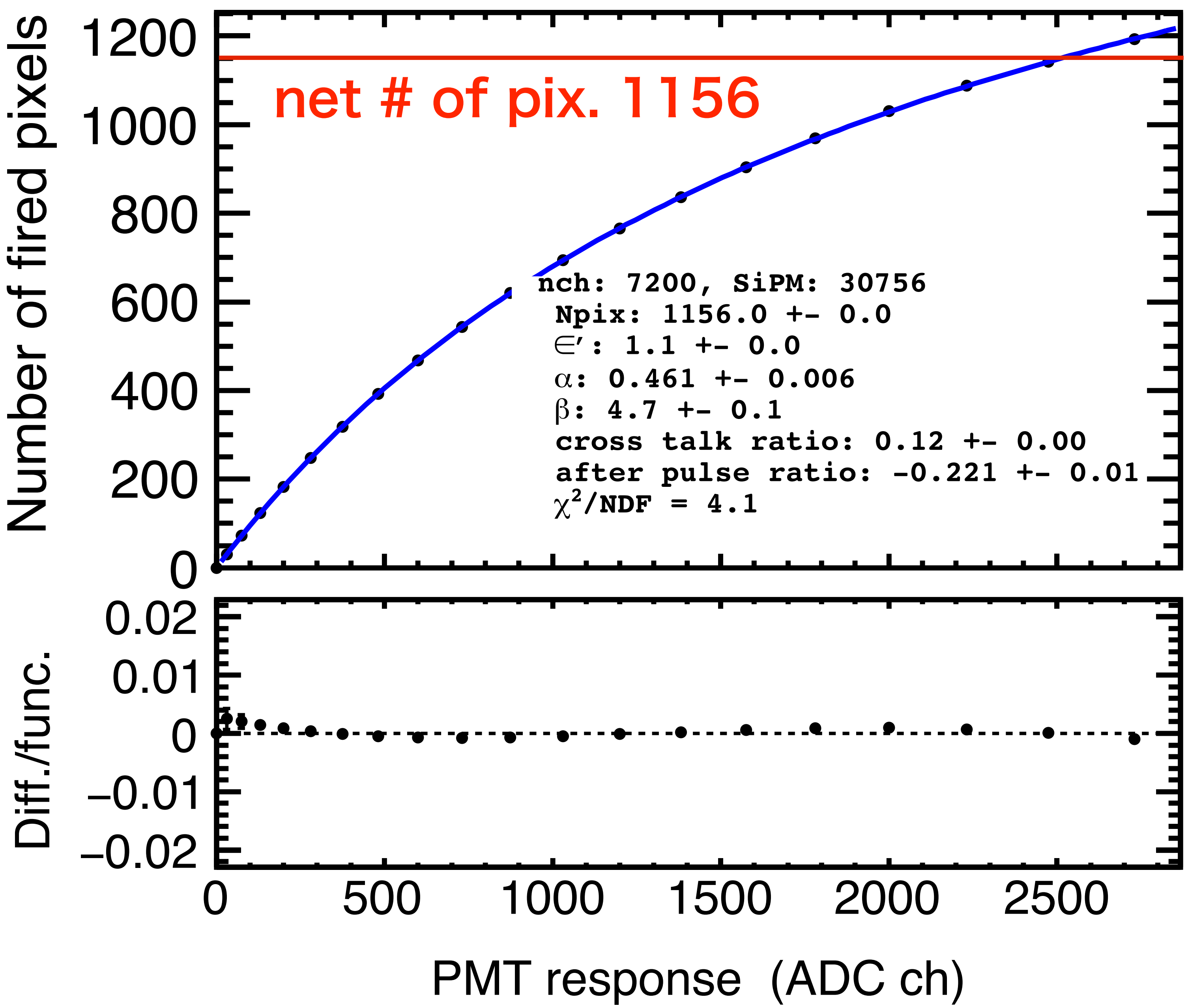
PMT, PDE scale factor: ϵ

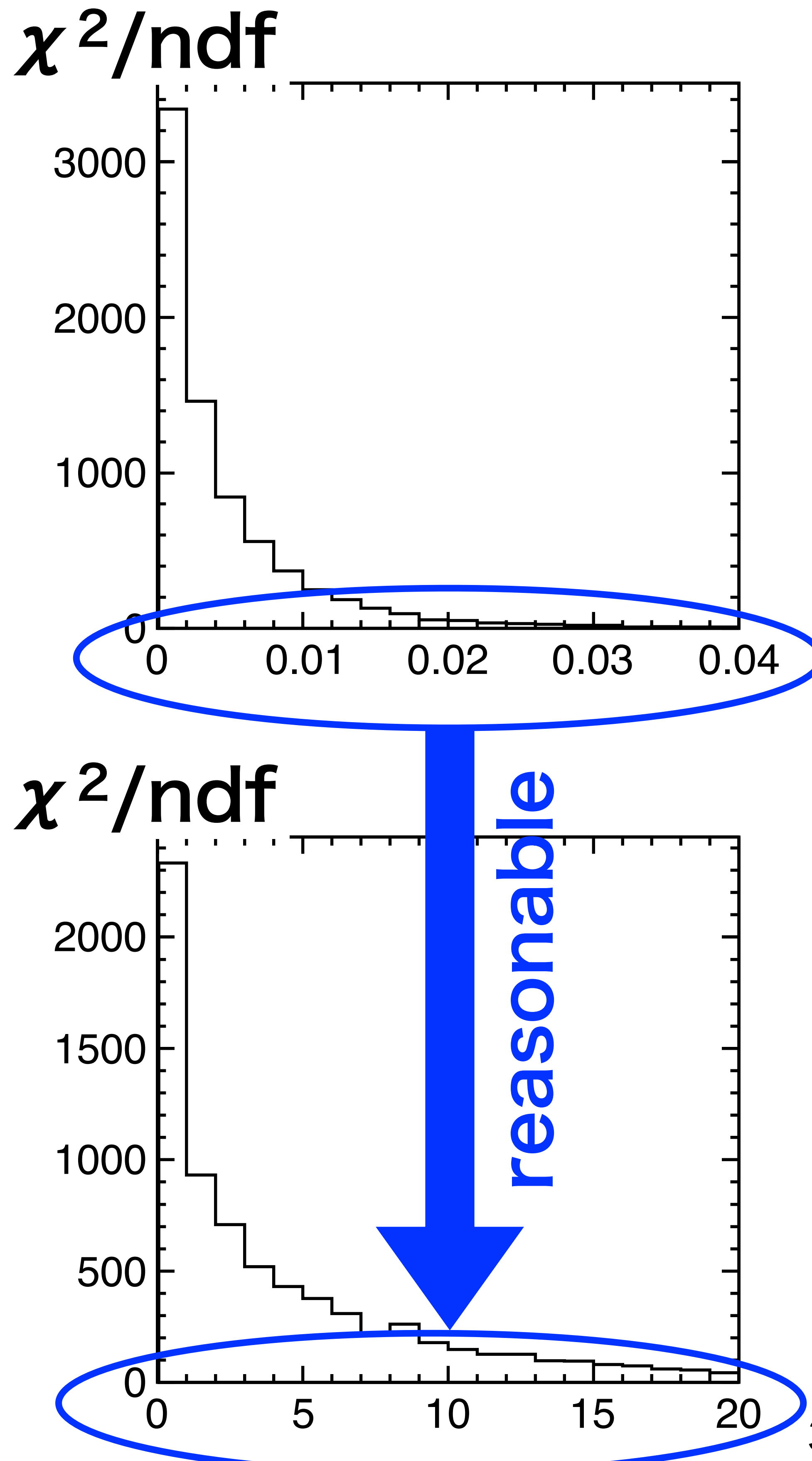


#photon arrived was already normalized at small p.e. response. (linear pixels?)

Error estimation trial (sqrt)

Error = √(N_fired) × 0.01 適当

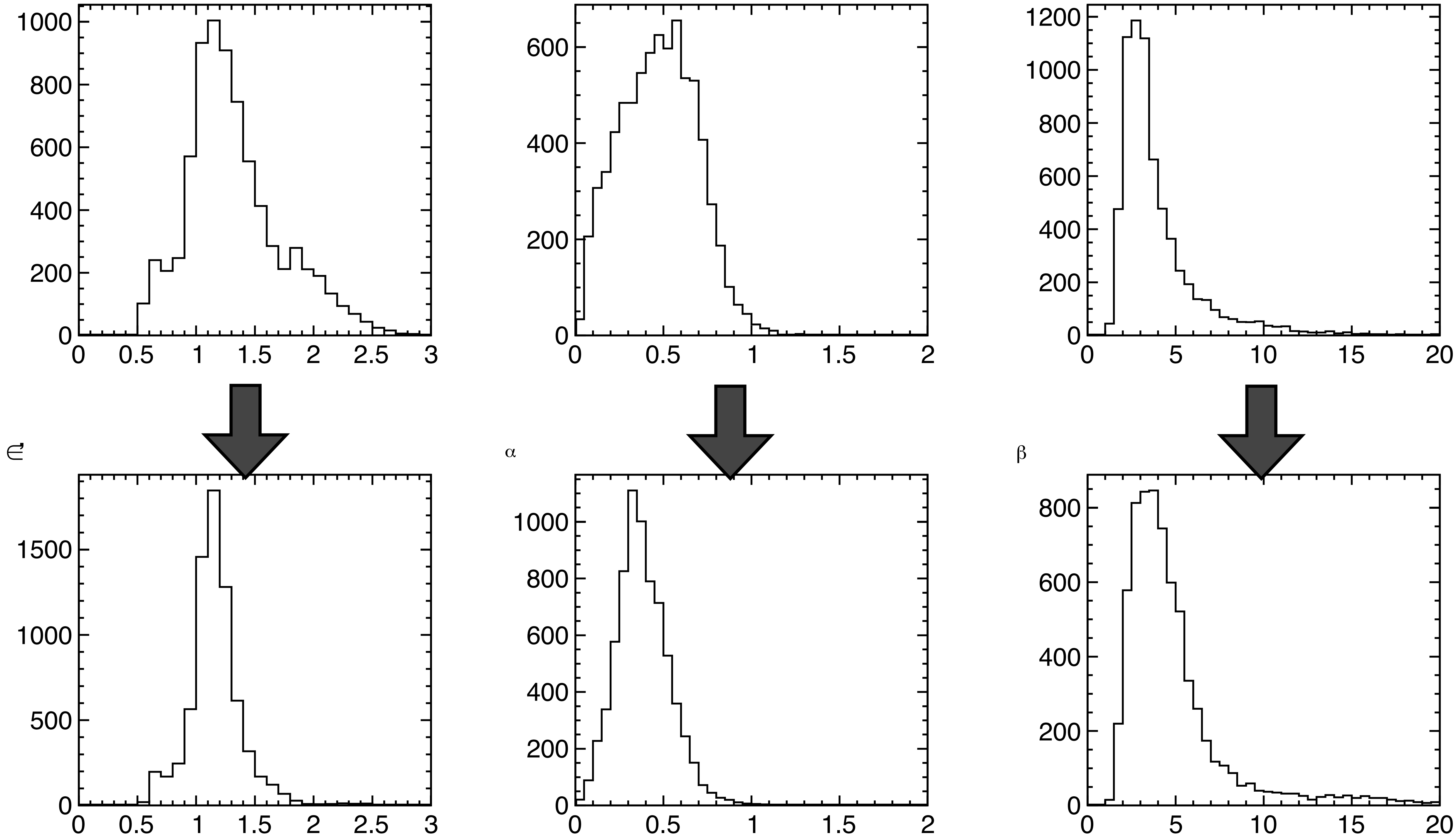




- a bit reasonable error
- S structure ....

Parameters with error∝√(#photon)

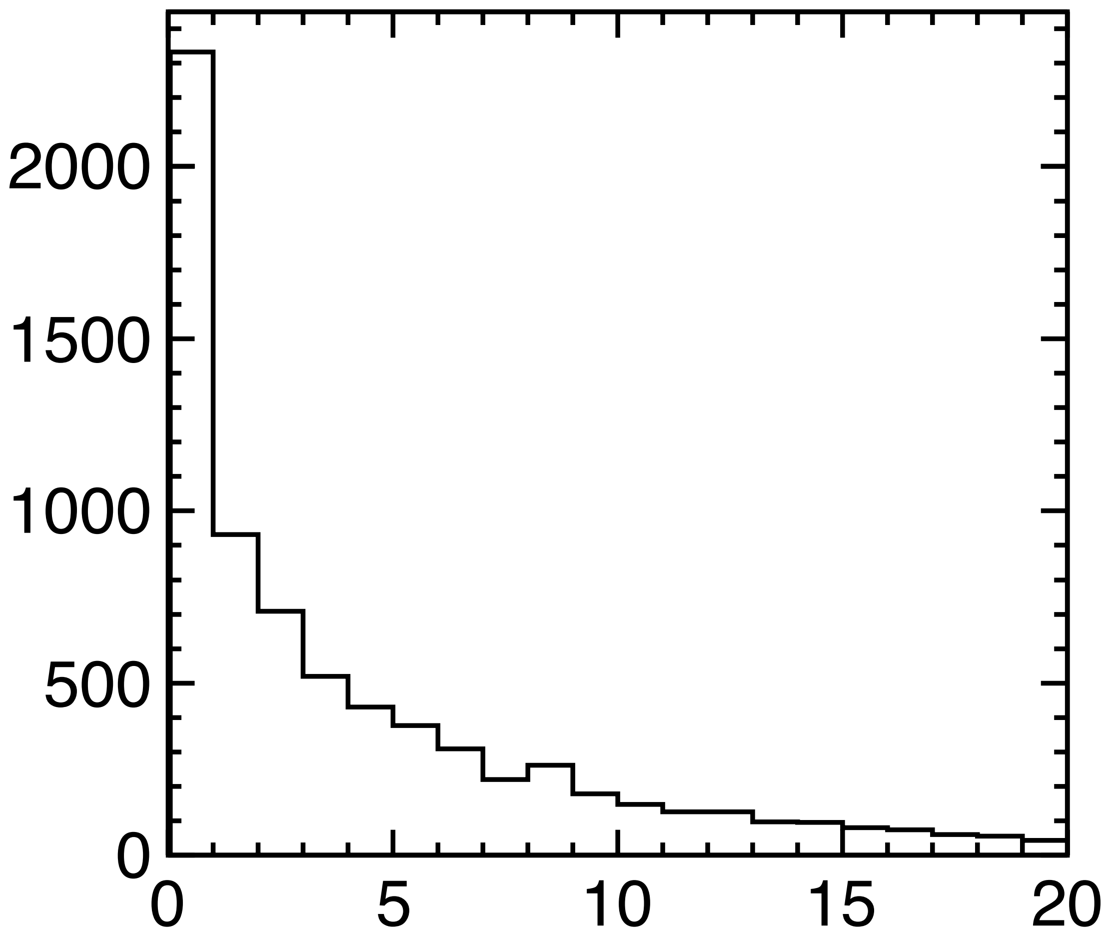
ε PMT, PDE scale factor | α Recovery parameter | β # photons/cell effect



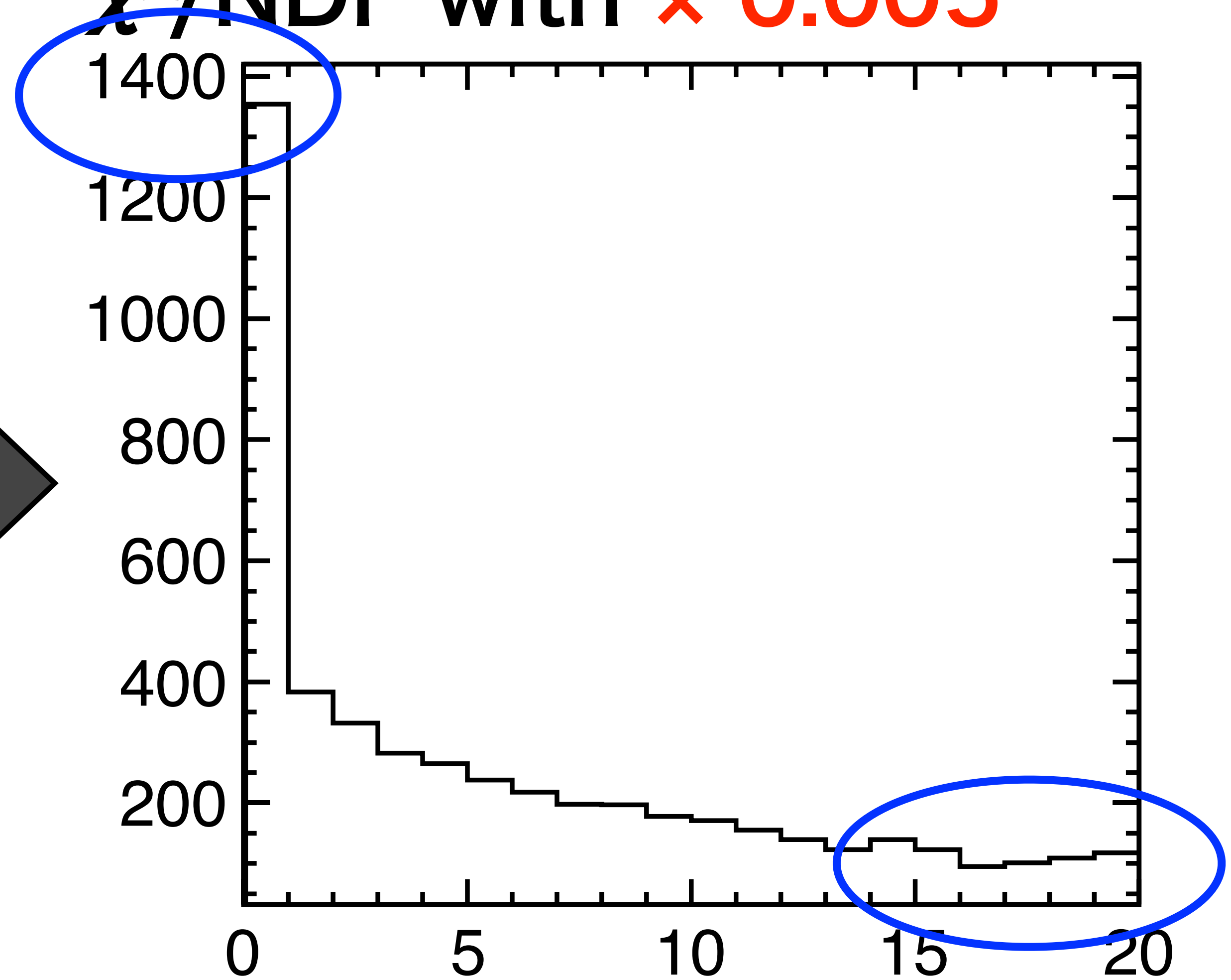
Error = sqrt(N_fired) × 0.01 makes parameter distributions to be narrower ➡ better estimation

√(#photon)× 0.01 or 0.005?

χ^2/NDF with × 0.01



χ^2/NDF with × 0.005



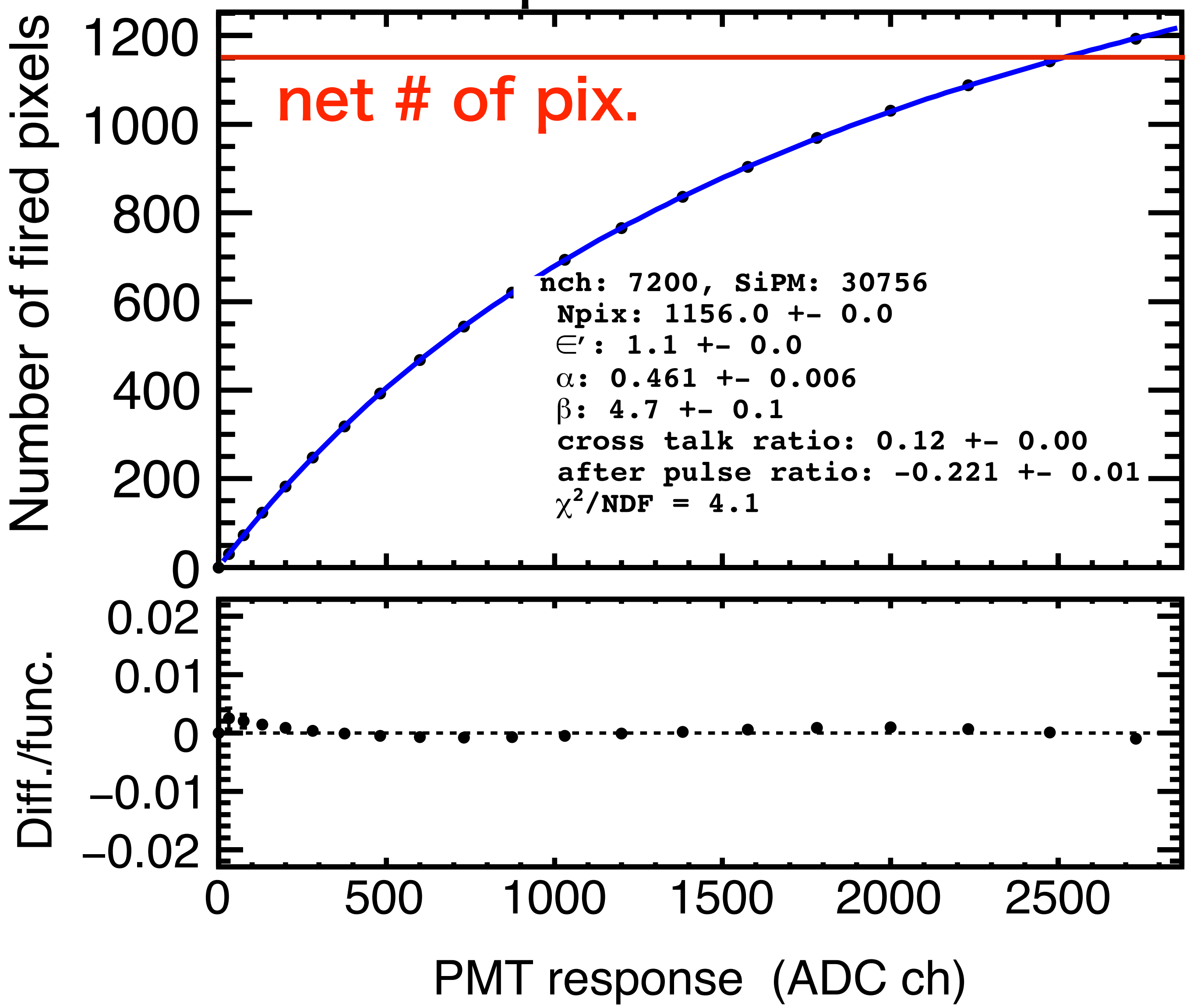
χ^2/NDF < 20: 7178channels

χ^2/NDF < 20: 4918ch

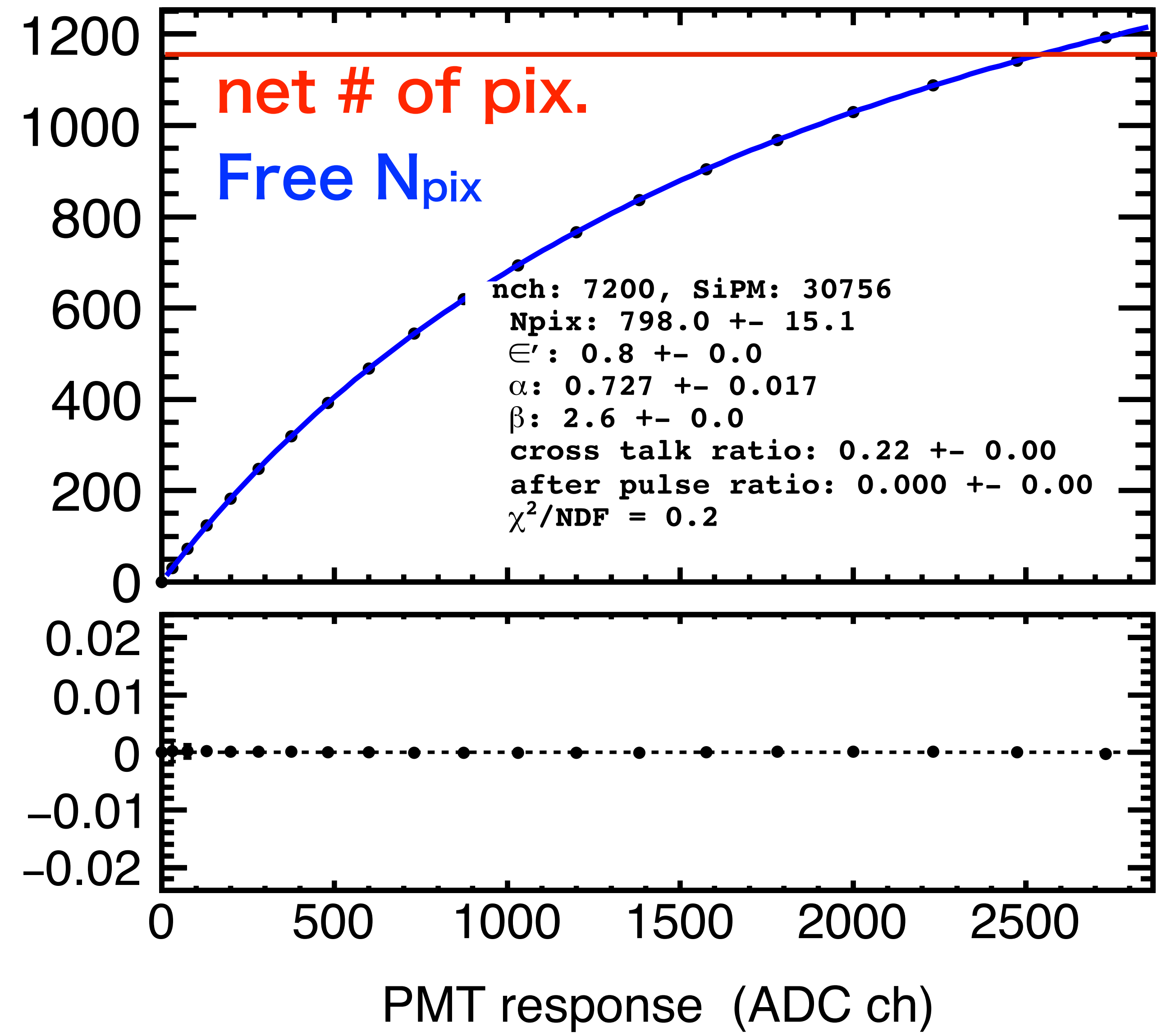
Too small error estimation makes fits.

Example of fitting results

Fixed N_{pix} at 1156



Current best fitting



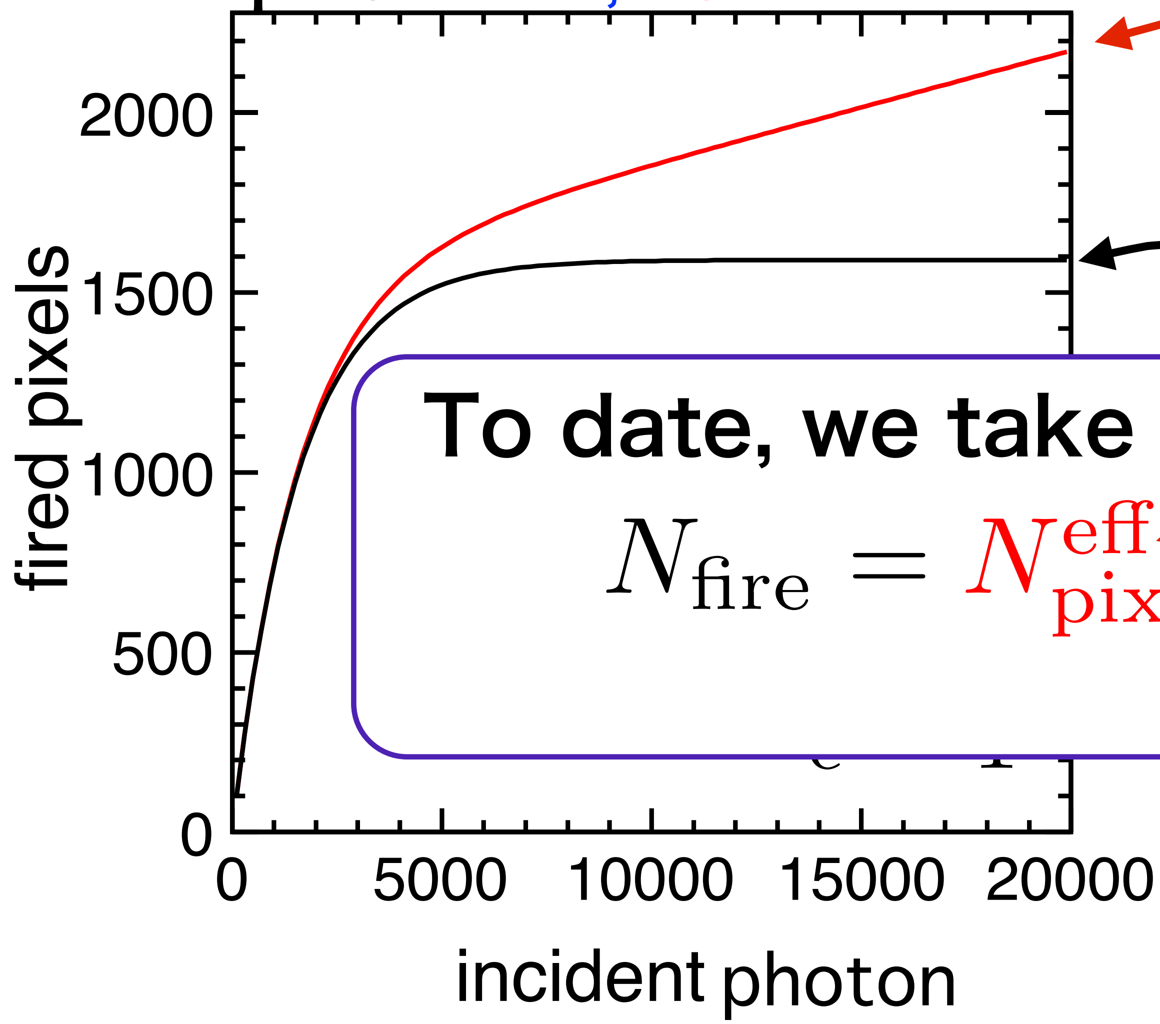
Next step

apply to calibration?

Motivation: Linear response after saturation

Often we see like red courve especially w/ MPPC

Equation plot of 1600 pixel SiPM, not data



? not completely saturating

conventional function

$$N_{\rm fire} = N_{\rm pix}\left(1 - e^{\epsilon N_{\rm in}/N_{\rm pix}}\right)$$

…ired pixels,

…orizontal direction,

…ncident photons,

…pixels.

To date, we take

$$N_{\rm fire} = N_{\rm pix}^{\rm eff}\left(1 - e^{\epsilon N_{\rm in}/N_{\rm pix}^{\rm eff}}\right)$$

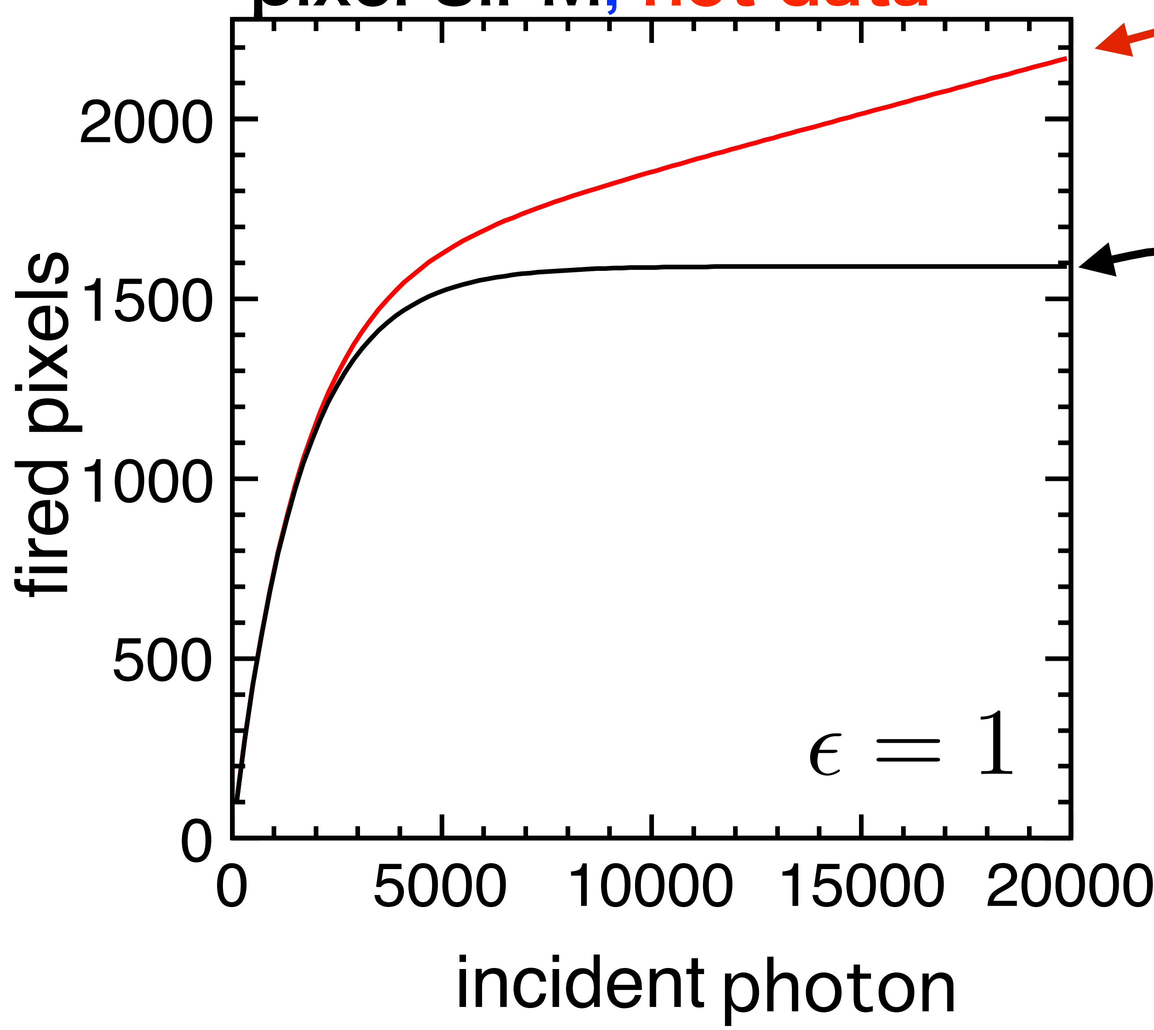
for such a case.

We think this comes from reactivation of pixels in a few nano seconds after fired.

Motivation: Linear response after saturation

Often we see like red courve especially w/ MPPC

Equation plot of 1600 pixel SiPM, not data



? not completely saturating

conventional function =LO

$$N_{\rm fire} = N_{\rm pix}\left(1 - {\rm e}^{\epsilon N_{\rm in}/N_{\rm pix}}\right)$$

$N_{\rm fire}$:the number of fired pixels,

ϵ :photon detection efficiency (PDE),

$N_{\rm in}$:the number of incident photons,

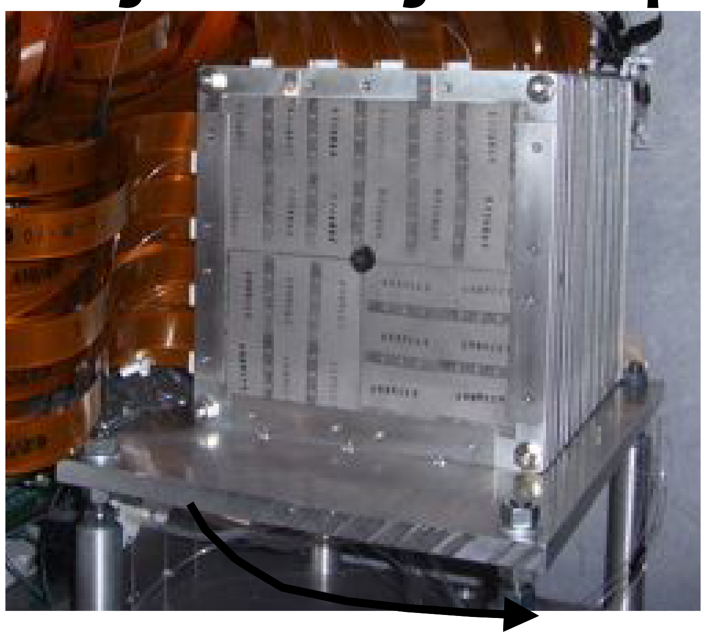
$N_{\rm pix}$:the number of pixels.

We think this comes from reactivation of pixels in a few nano seconds after fired.

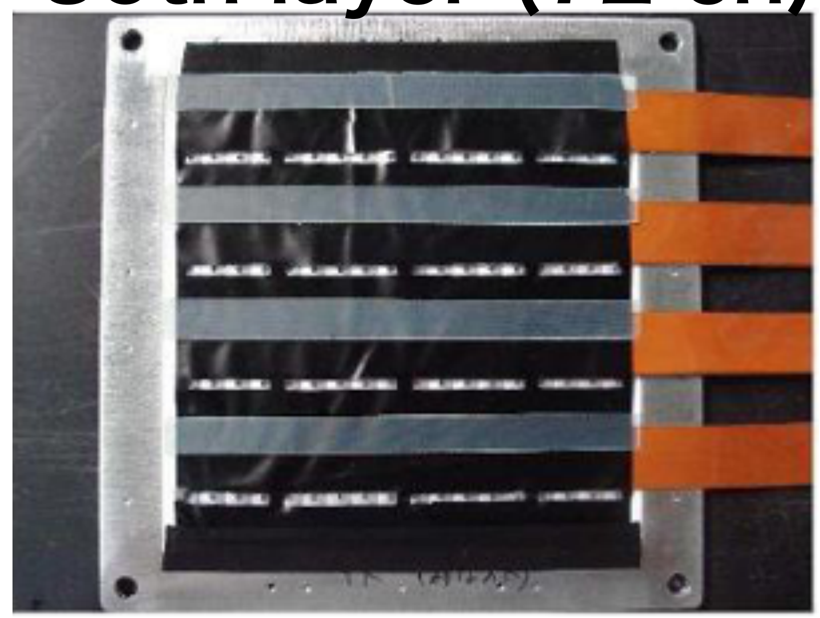
Sample DATA (taken by W. Choi in Shinshu 2010)

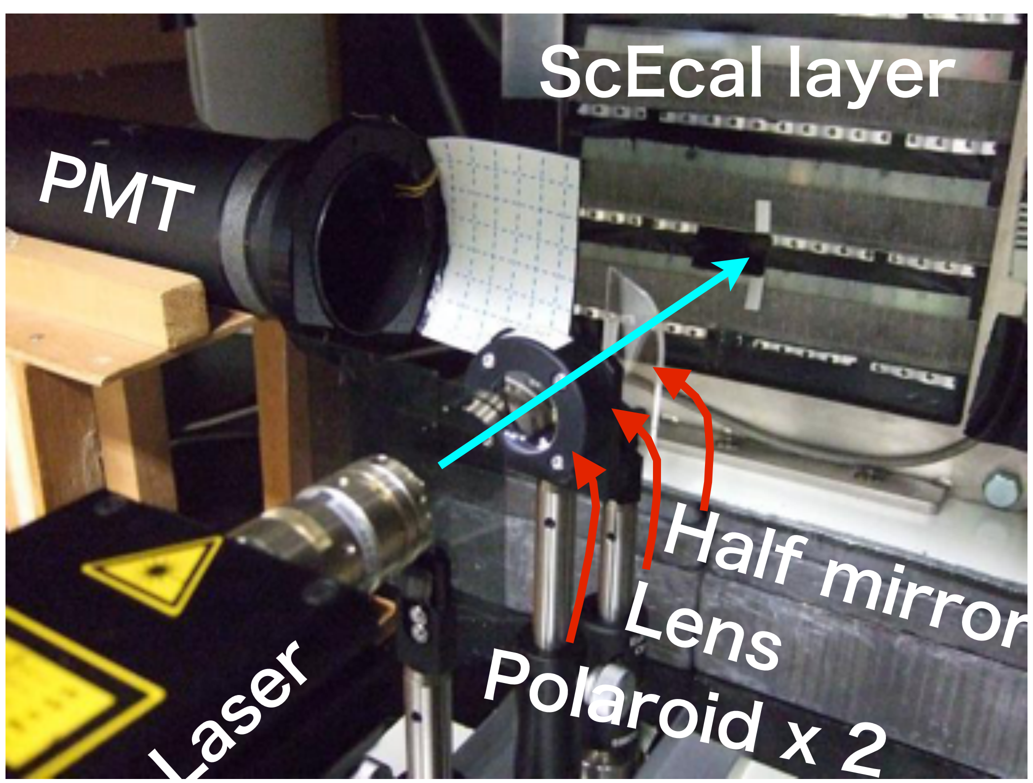
72 channels of 30th layer of ScECAL prototype with 1600 pix MPPC

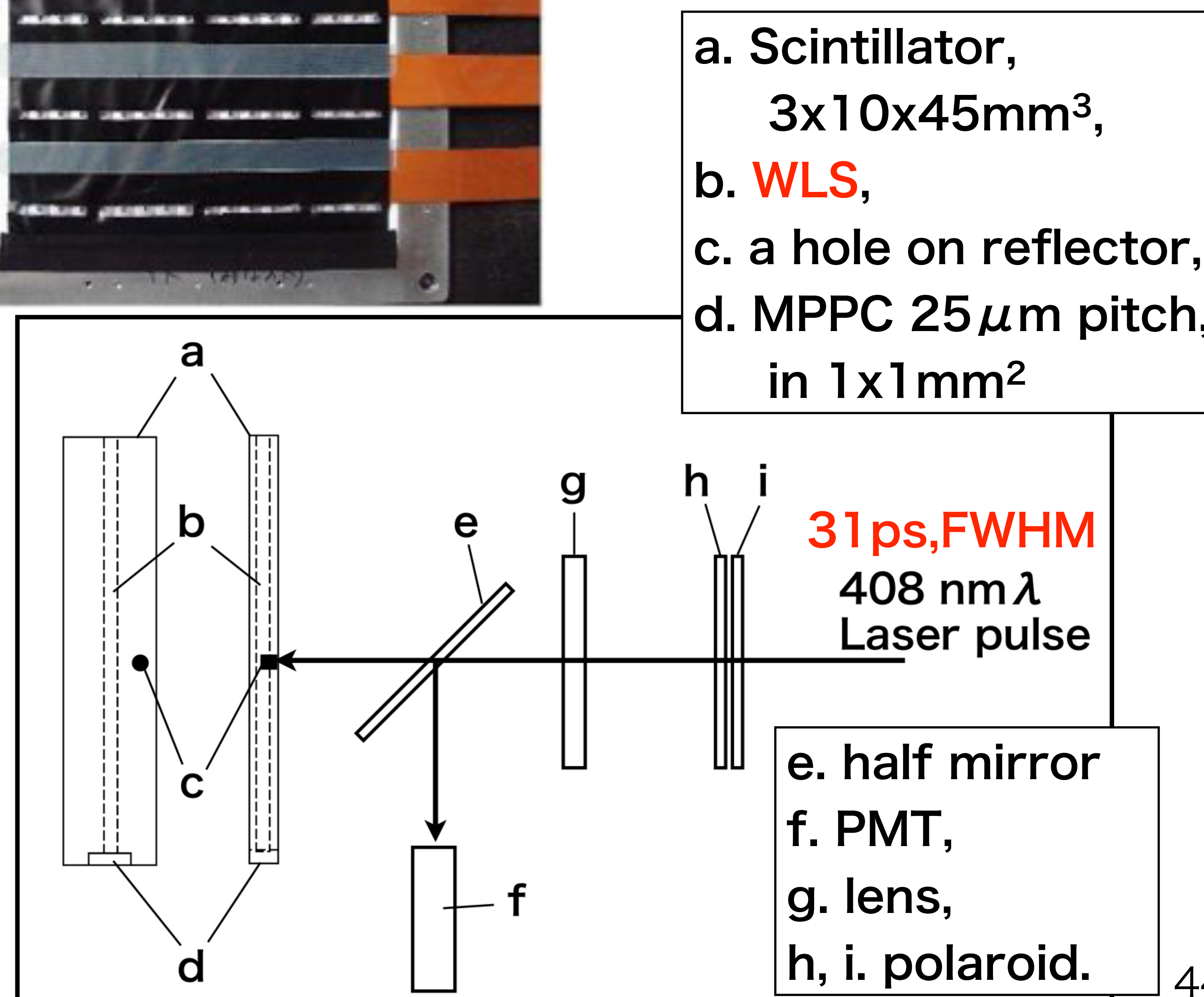
30 layer-Physics proto.



30th layer (72 ch)







Some remind of ScECAL response curve

Hamamatsu MPPC

1600pixels/(1×1mm^2)

Recovery time: 4ns,

408nm 31ps Laser via Scintillator + Y11 WLS,

at dV = 3V,

crosstalk : 11% measured in lab,

after pulse : 10% from some references.

Contents

1. Brief introduction to the response function using ScECAL case,
2. Applying to AHCAL data,
3. Discussion on parameters and fitting conditions.