Photomultiplier Tube Physics and Operation

Carlos Hernandez Faham
Brown University
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Afterpulsing!

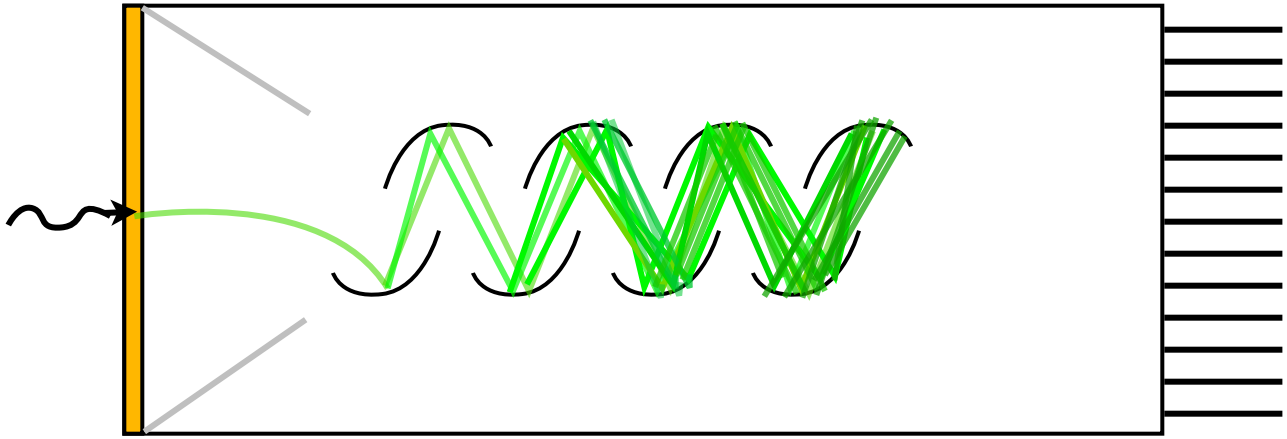
"Photomultiplier tube?

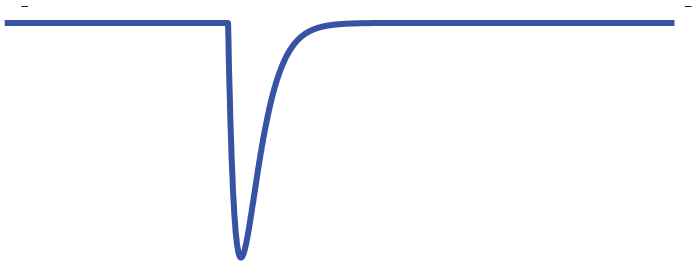
What is that?"

- Well-known dark matter theorist touring our lab

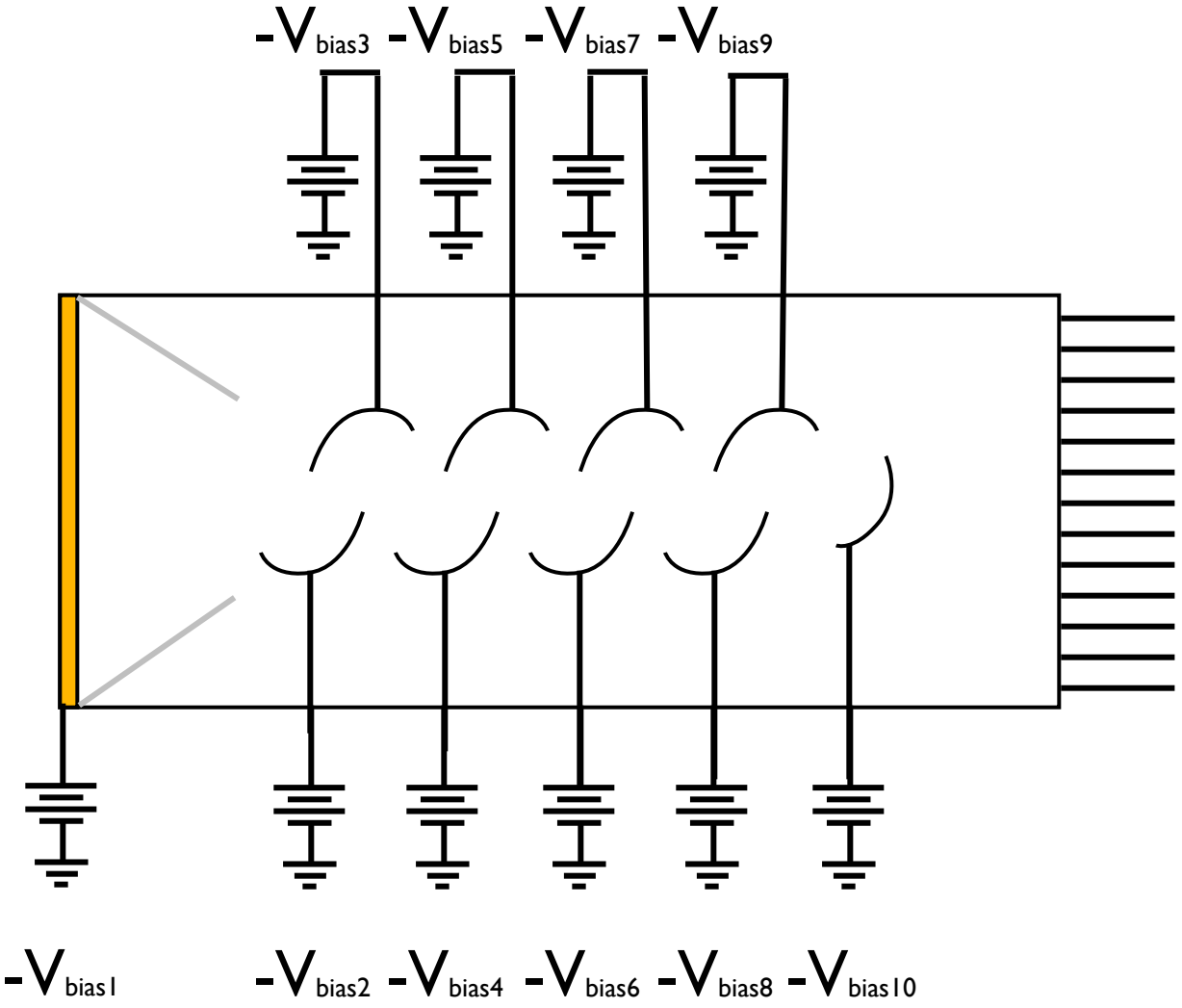
Photoelectric, Electron Multiplier

~~Photomultiplier~~ Tube

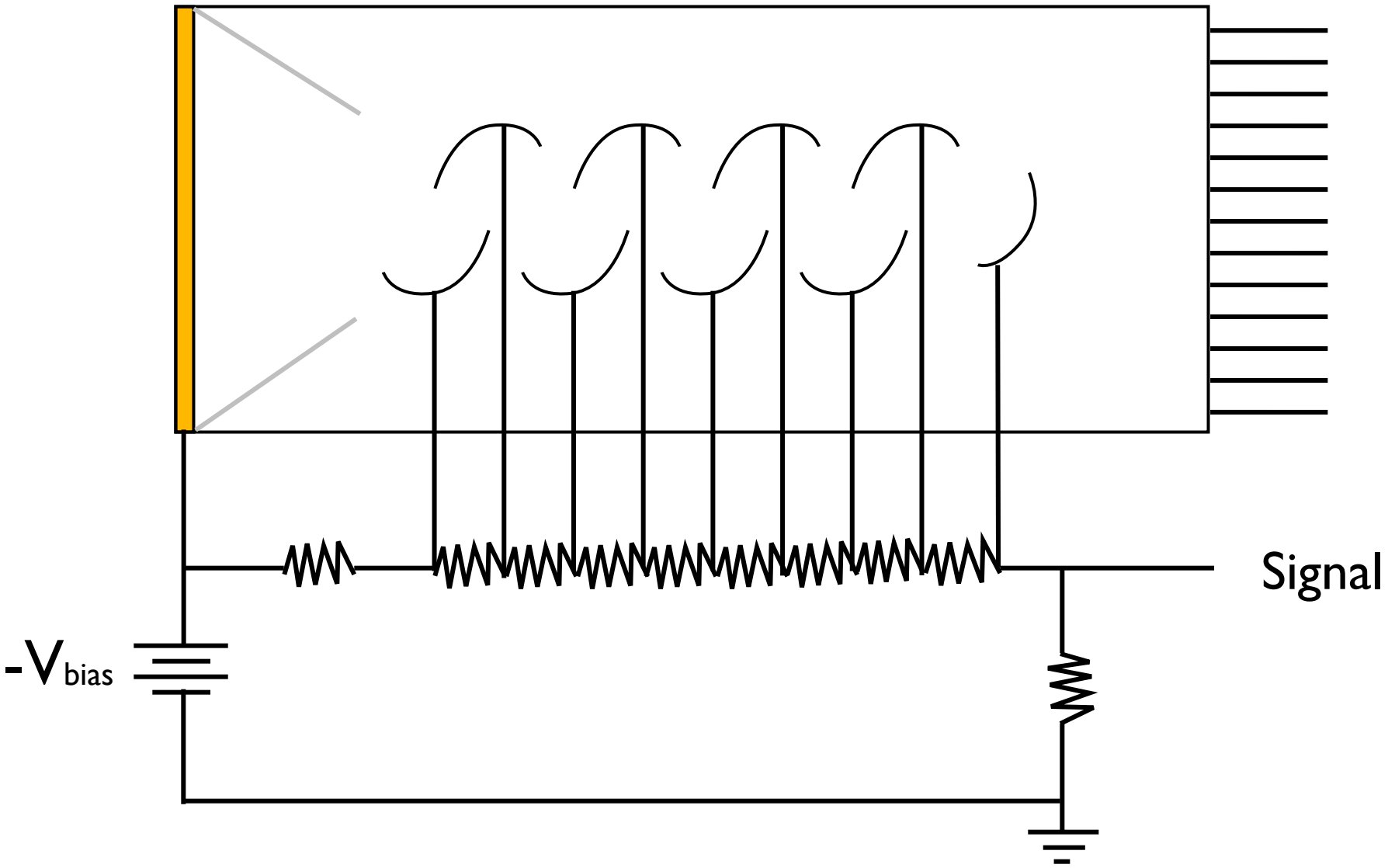




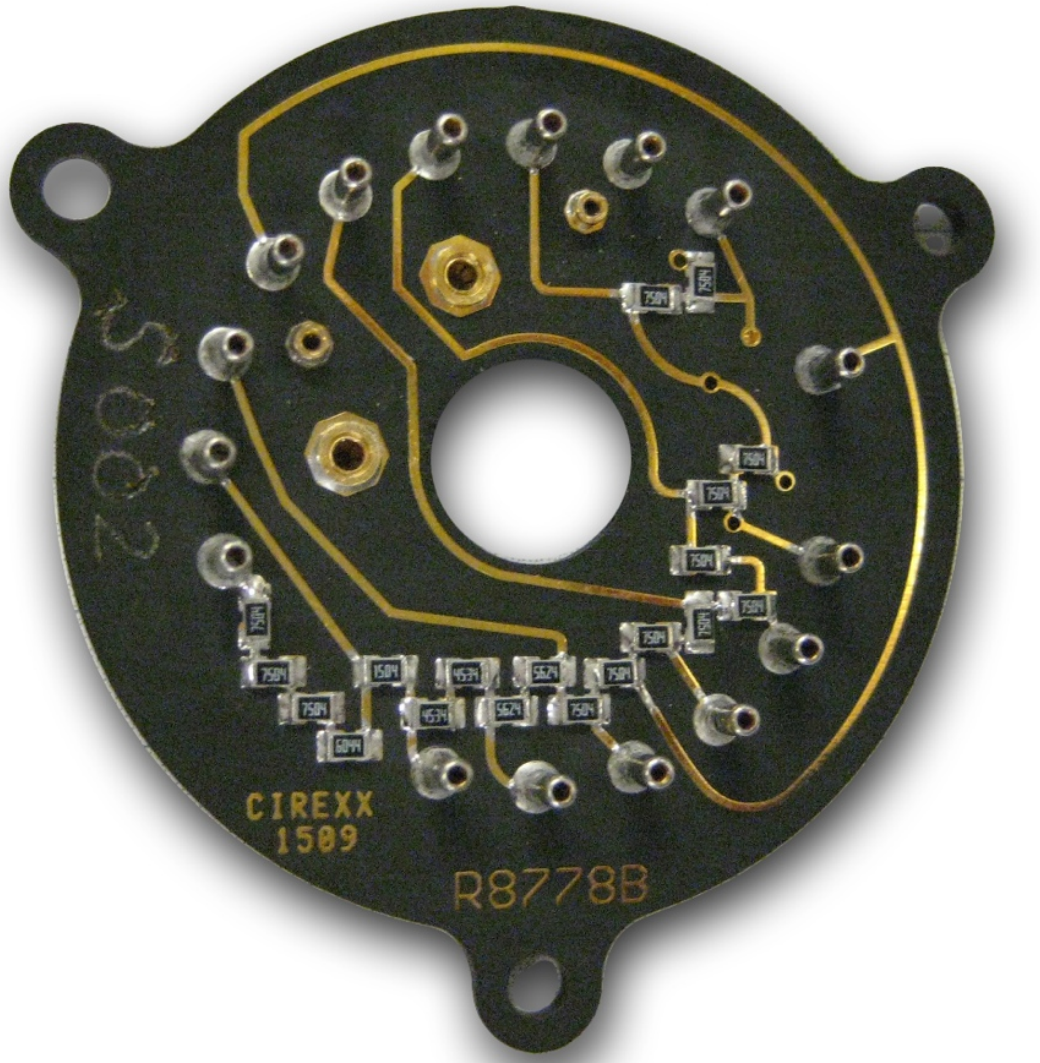
Biasing

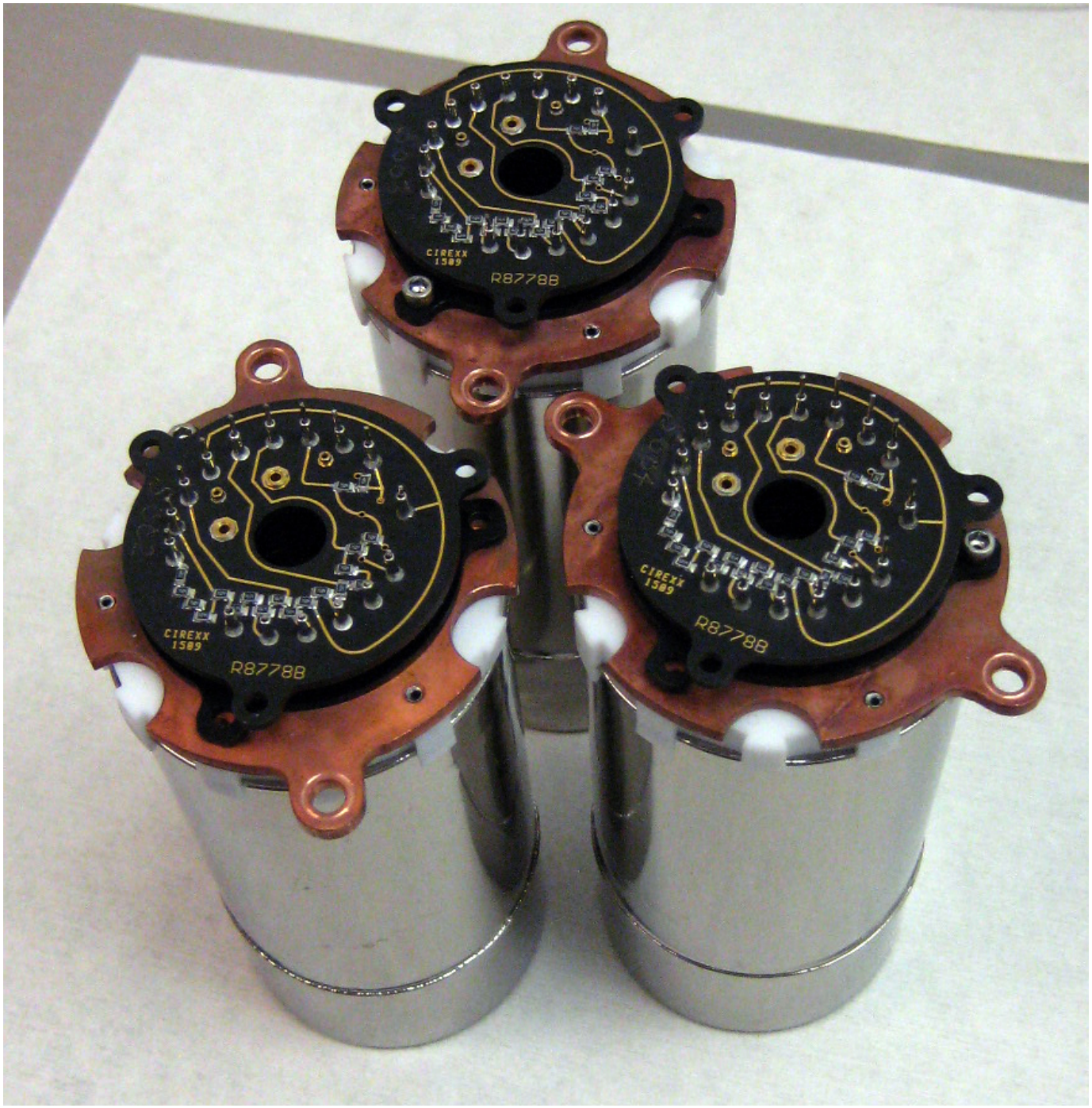

-V bias3
-V bias5
-V bias7
-V bias9
-V bias1
-V bias2
-V bias4
-V bias6
-V bias8
-V bias10

Biasing



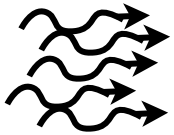
Biasing - Using a resistor chain base

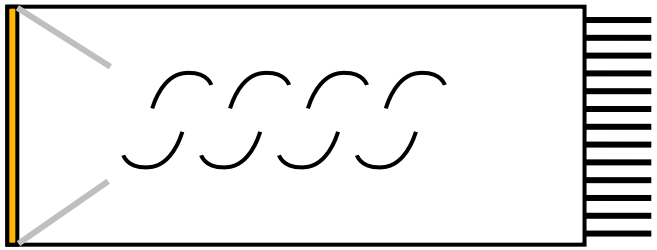


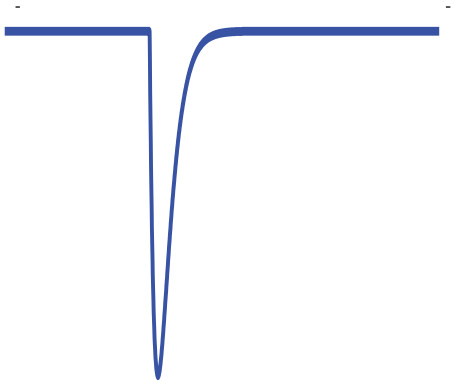

CIREXX
1589
R8778B
CIREXX
1589
R8778B
CIREXX
1589
R8778B

How do you use a PMT

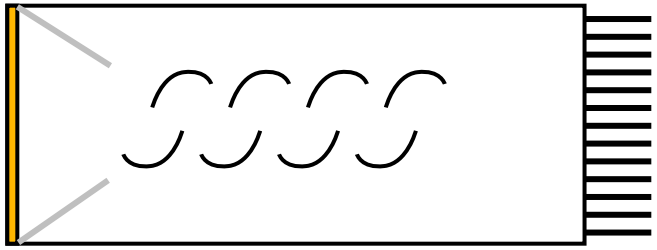
A

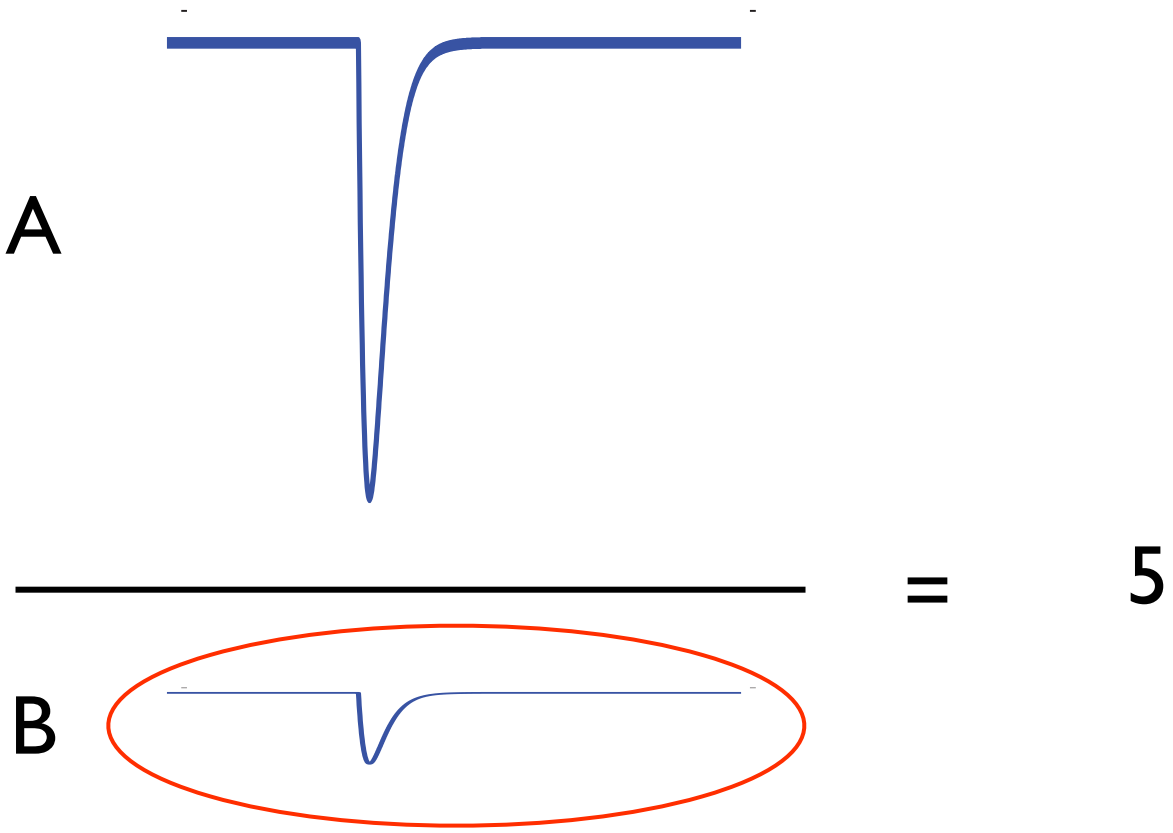




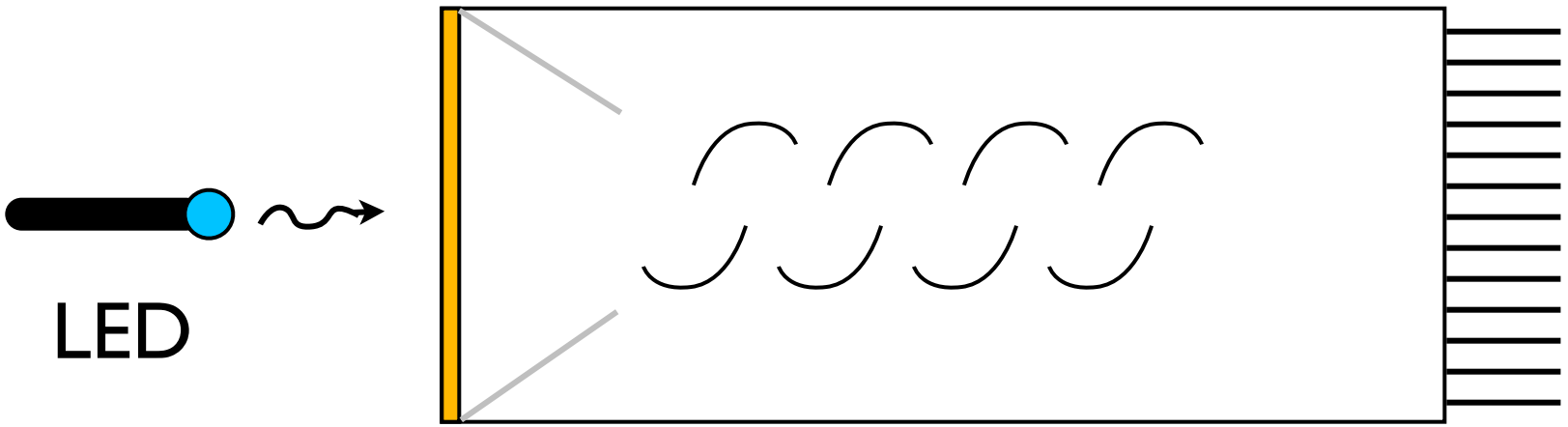


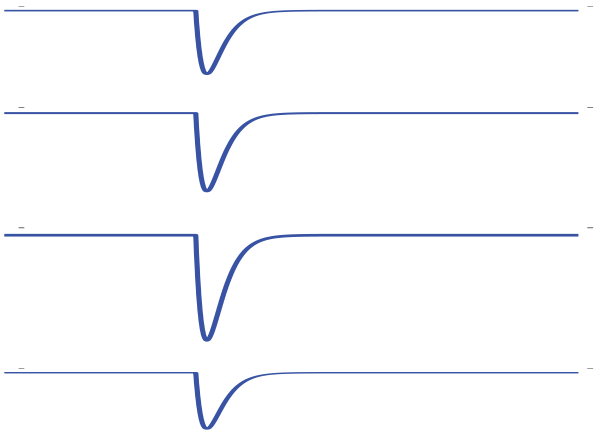
B




A
B
=
5
Single Photoelectron

Gain Calibration





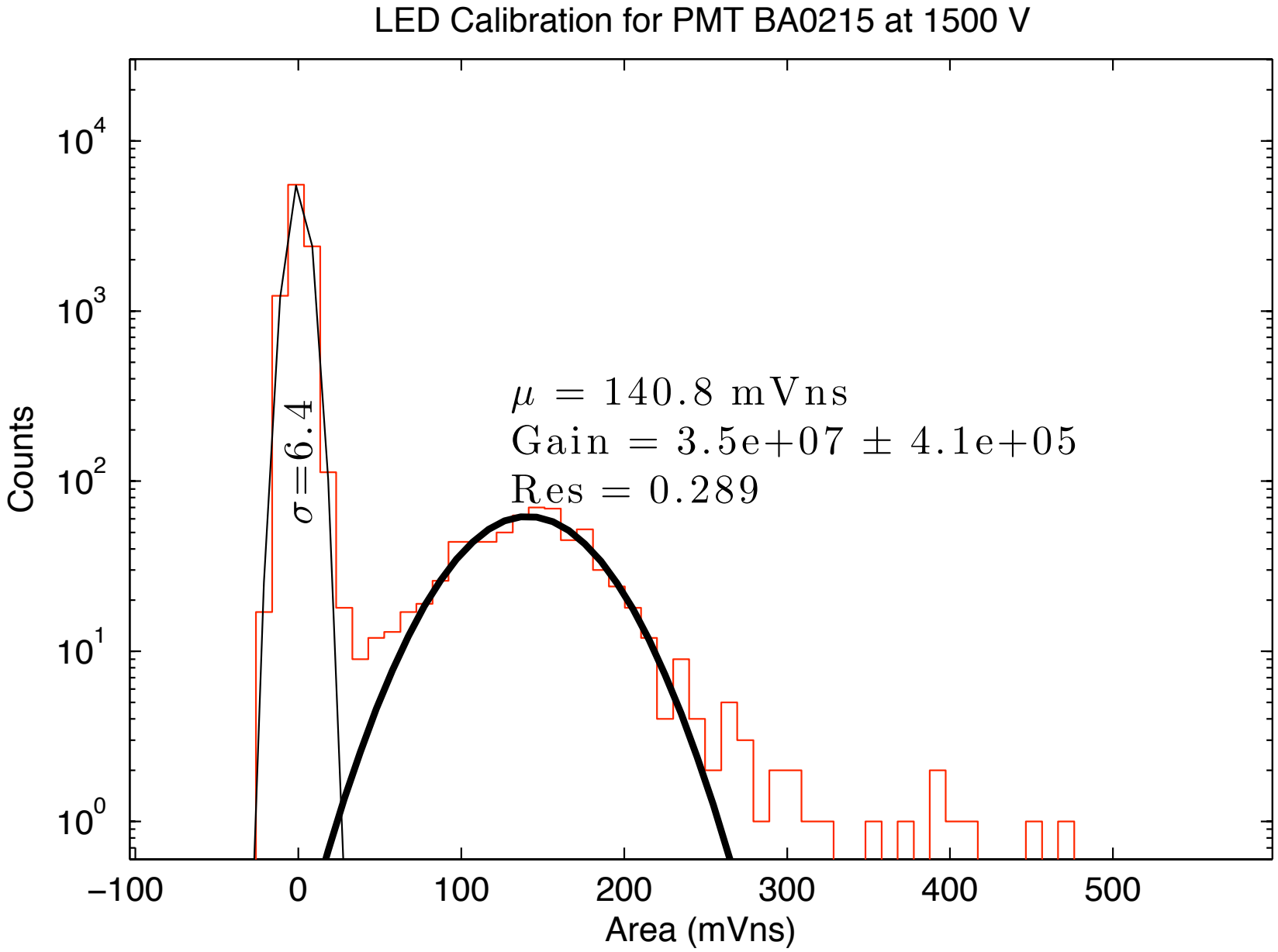
Gain Calibration

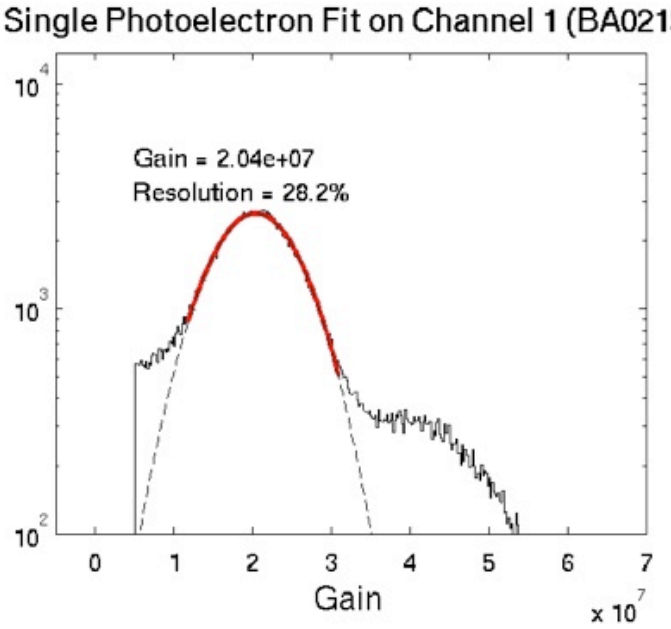
$$P(n;\mu) = \frac{\mu^n e^{-\mu}}{n!}$$

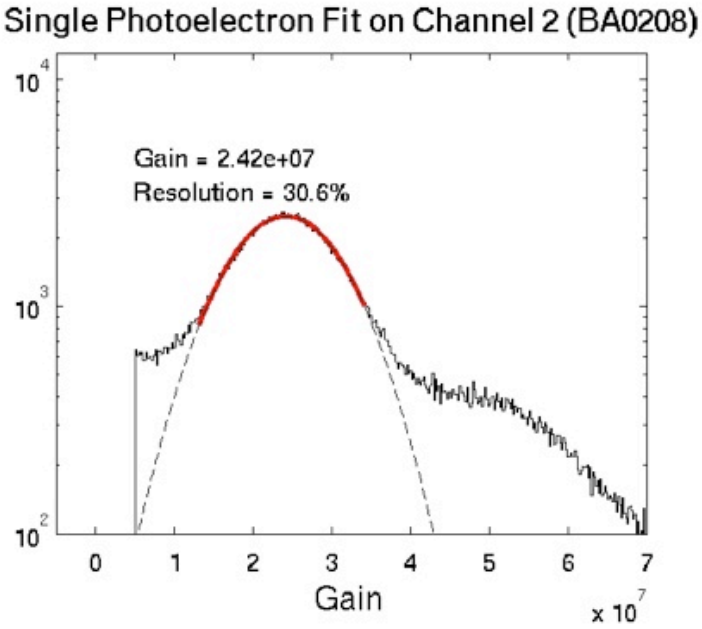
$$P(2) = 0.1 \cdot P(1)$$

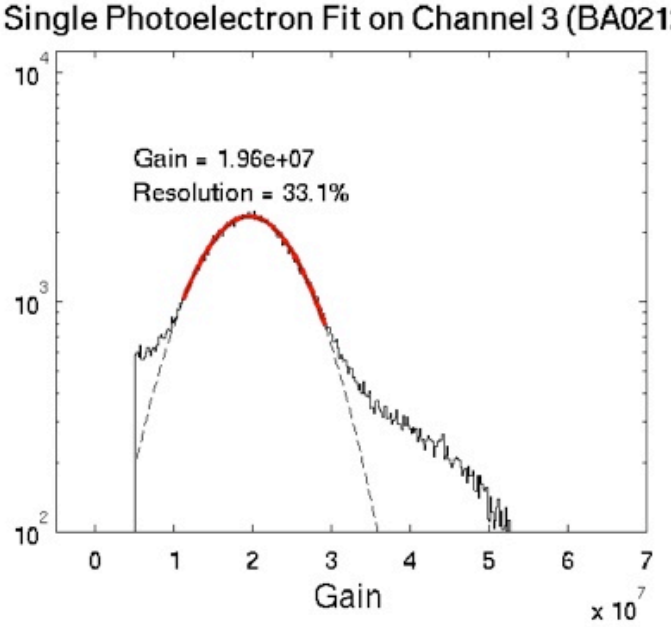
$$\frac{\mu^2 e^{-\mu}}{2} = \mu e^{-\mu} \Rightarrow \mu = 0.2$$

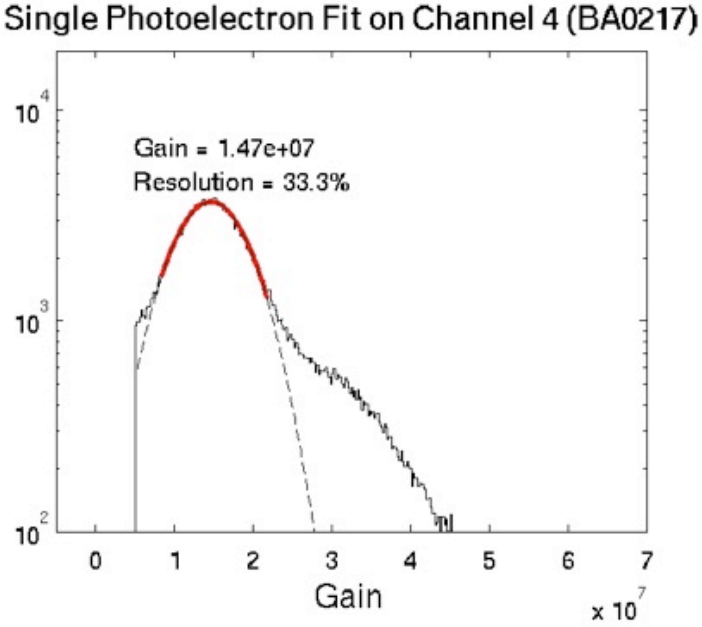
$$P(0) = e^{-0.2} = 0.82$$

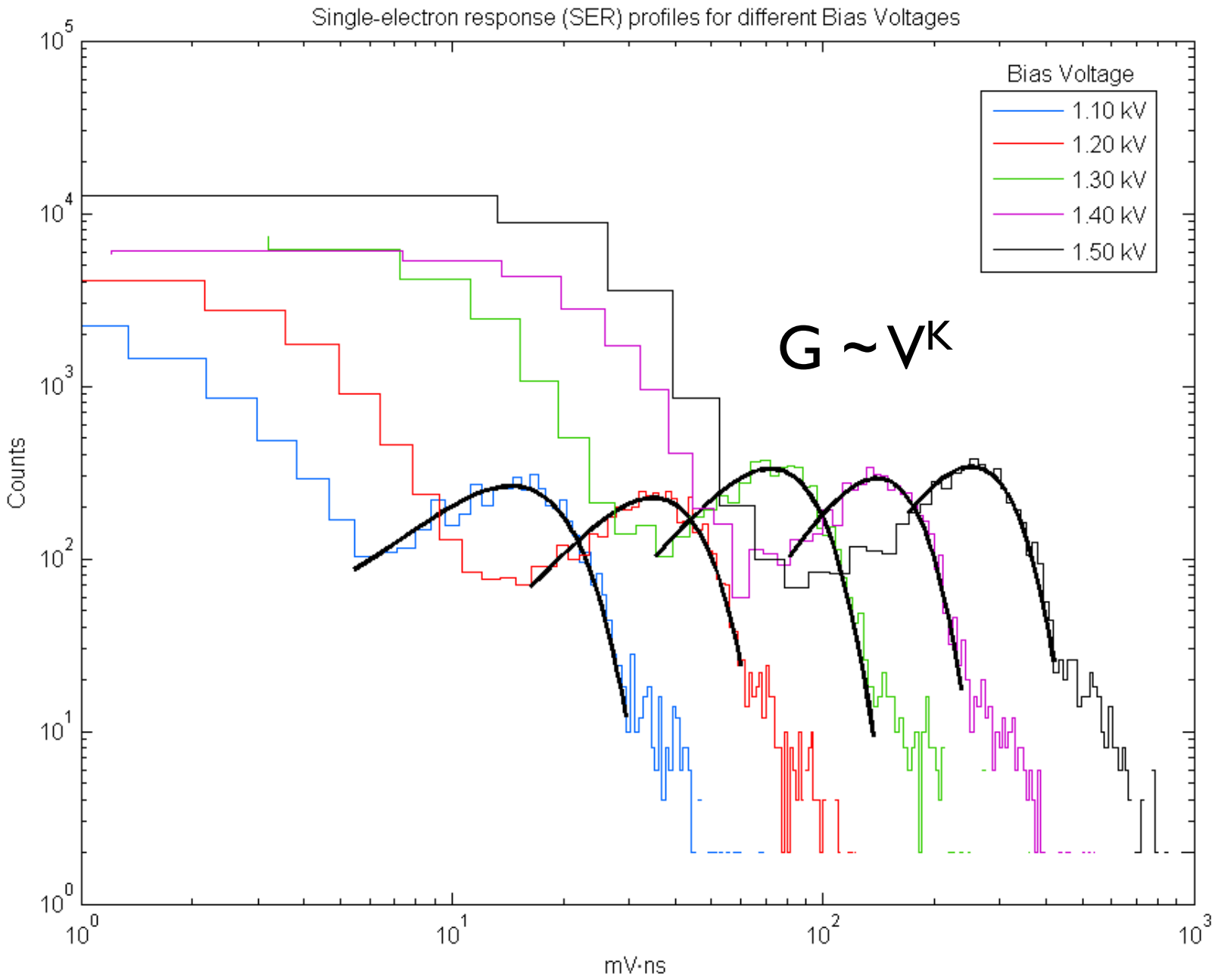

LED Calibration for PMT BA0215 at 1500 V
Counts
Area (mVns)
σ=6.4
μ = 140.8 mVns
Gain = 3.5e+07 ± 4.1e+05
Res = 0.289

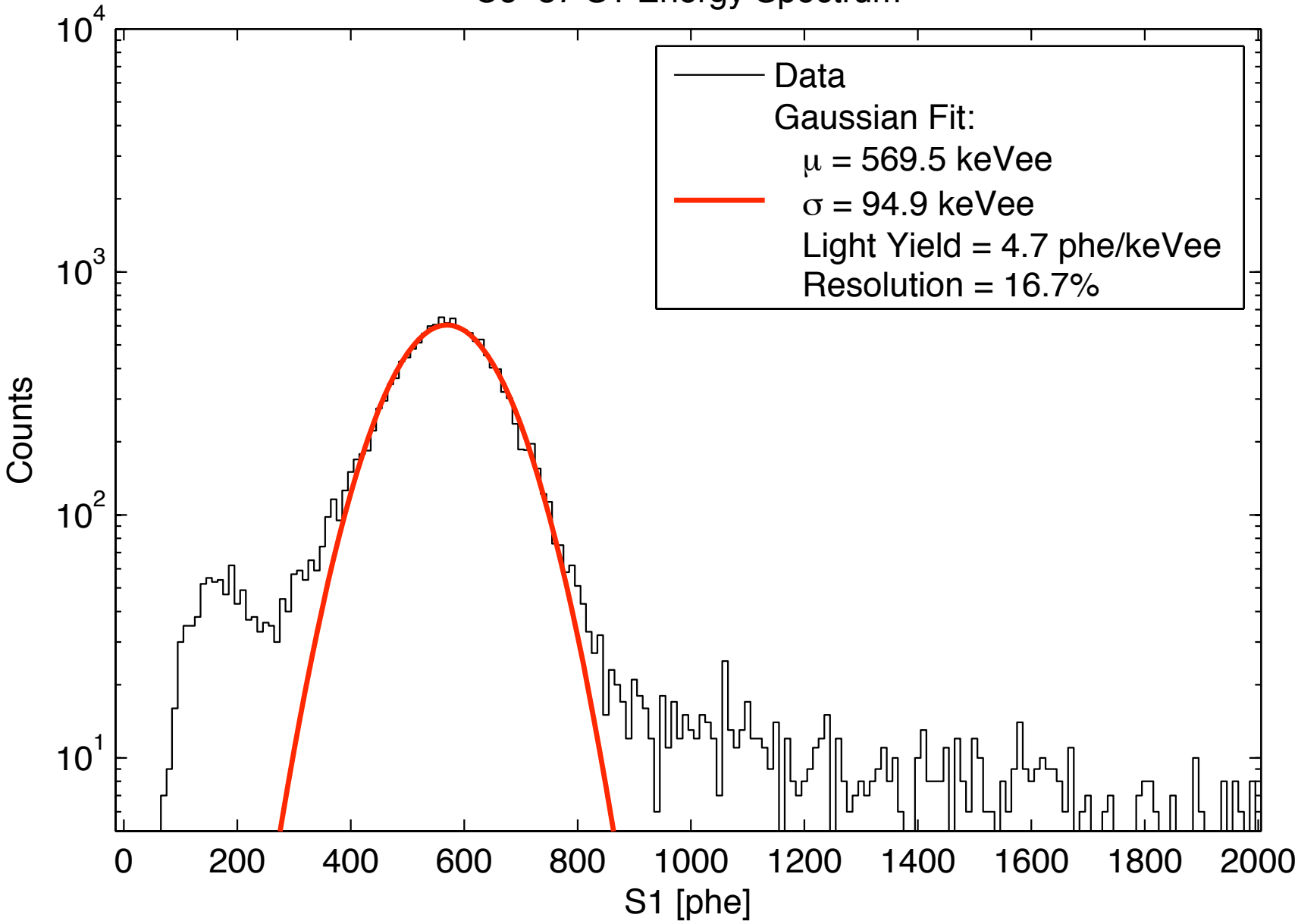

Single Photoelectron Fit on Channel 1 (BA0215)
Gain = 2.04e+07
Resolution = 28.2%
Gain
x 10^7


Single Photoelectron Fit on Channel 2 (BA0208)
Gain = 2.42e+07
Resolution = 30.6%
Gain
x 10^7


Single Photoelectron Fit on Channel 3 (BA0212)
Gain = 1.96e+07
Resolution = 33.1%
Gain
x 10^7


Single Photoelectron Fit on Channel 4 (BA0217)
Gain = 1.47e+07
Resolution = 33.3%
Gain
x 10^7

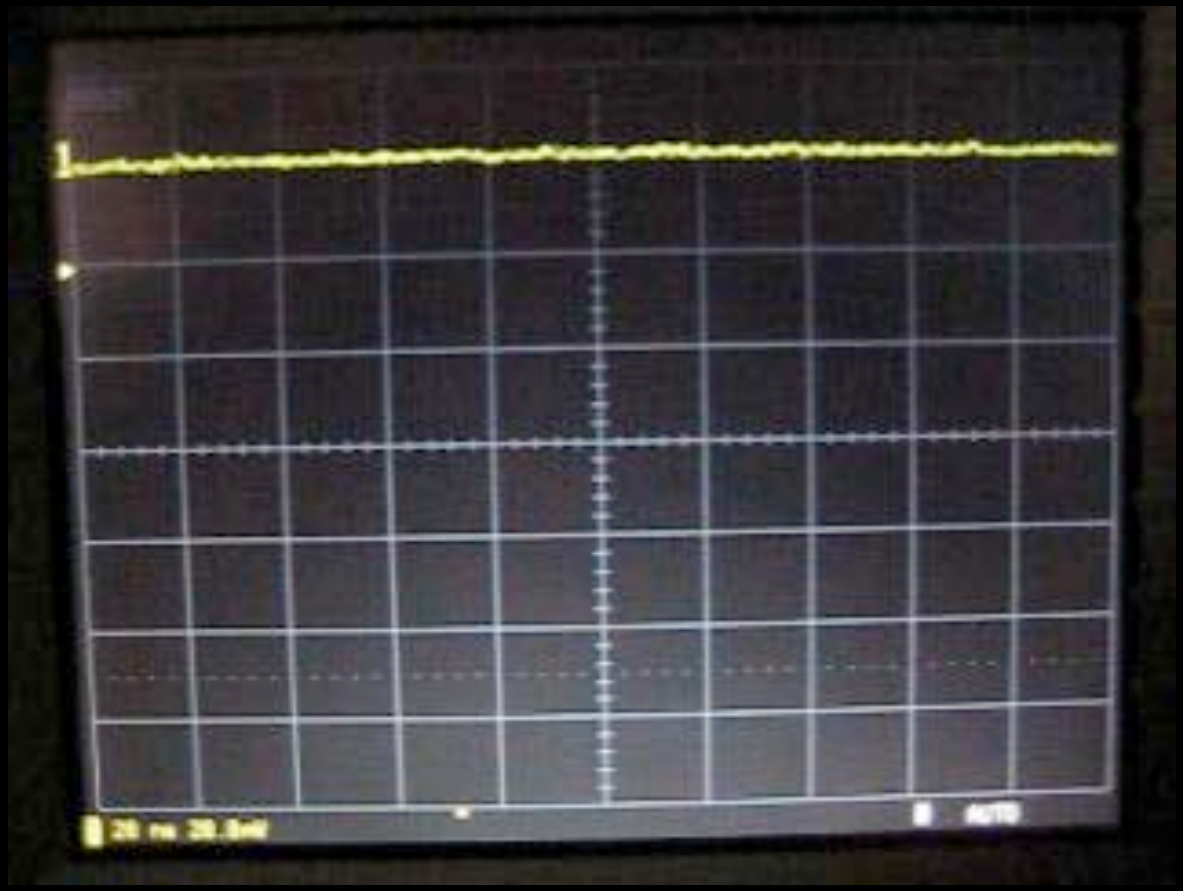

Single-electron response (SER) profiles for different Bias Voltages
Bias Voltage
1.10 kV
1.20 kV
1.30 kV
1.40 kV
1.50 kV
G ~ V^K
Counts
mV·ns
10^0
10^1
10^2
10^3
10^4
10^5


Co–57 S1 Energy Spectrum
Data
Gaussian Fit:
μ = 569.5 keVee
σ = 94.9 keVee
Light Yield = 4.7 phe/keVee
Resolution = 16.7%
Counts
S1 [phe]
10^4
10^3
10^2
10^1
0
200
400
600
800
1000
1200
1400
1600
1800
2000

Advantages:

High gain (single-photoelectron signals)
Low-noise
Large detection area
Fast response
Low radioactivity has been achieved

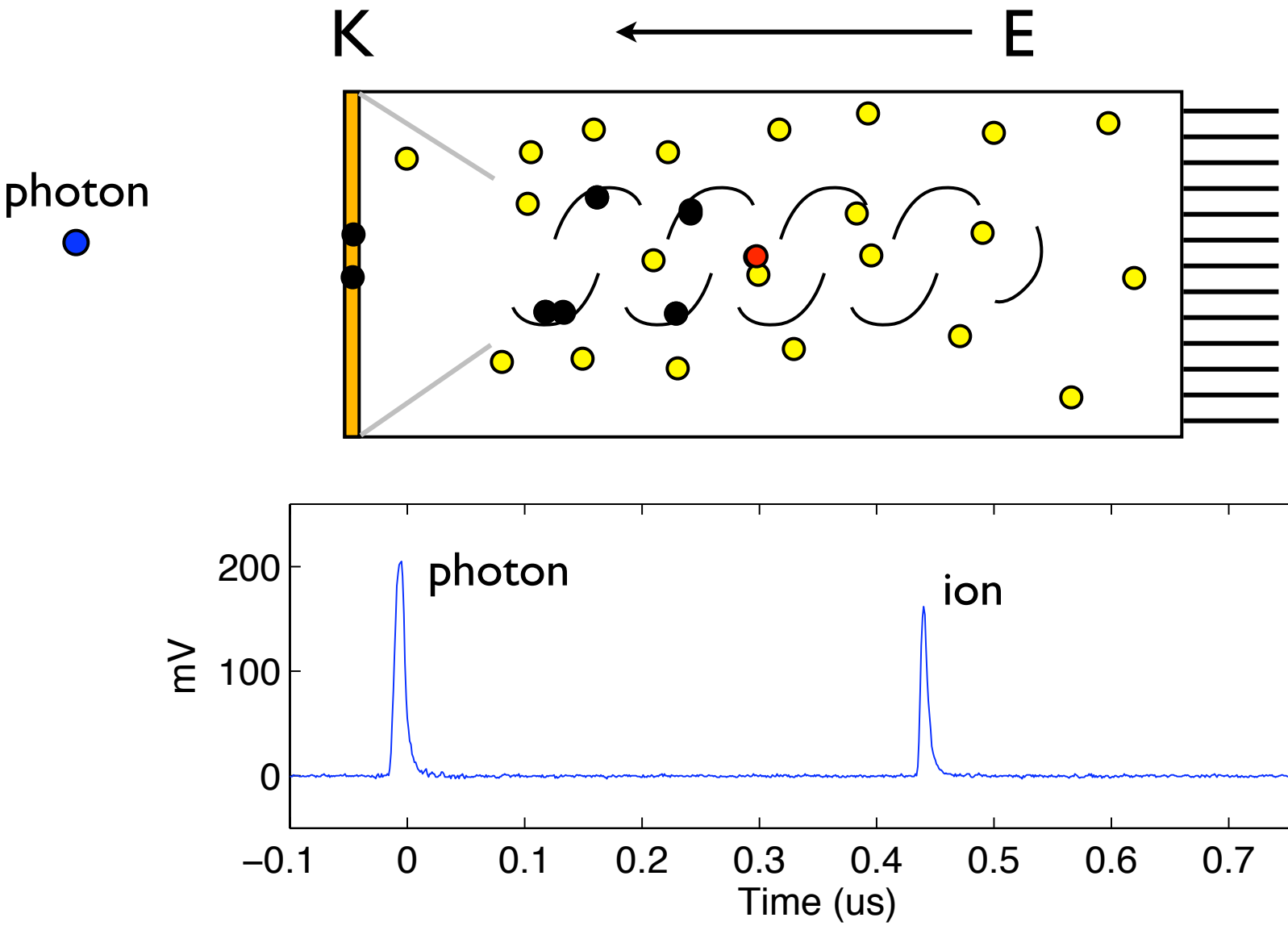
Video

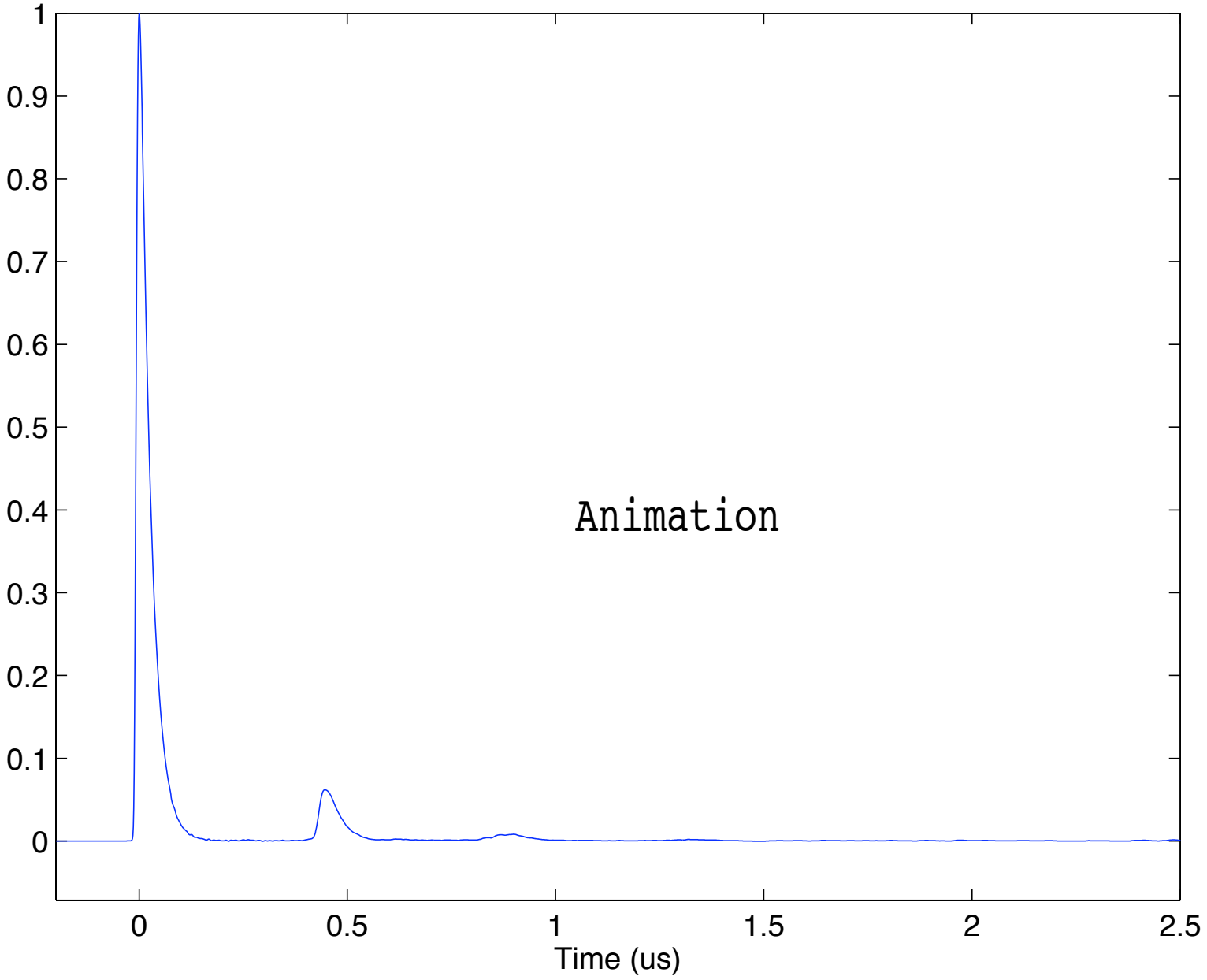


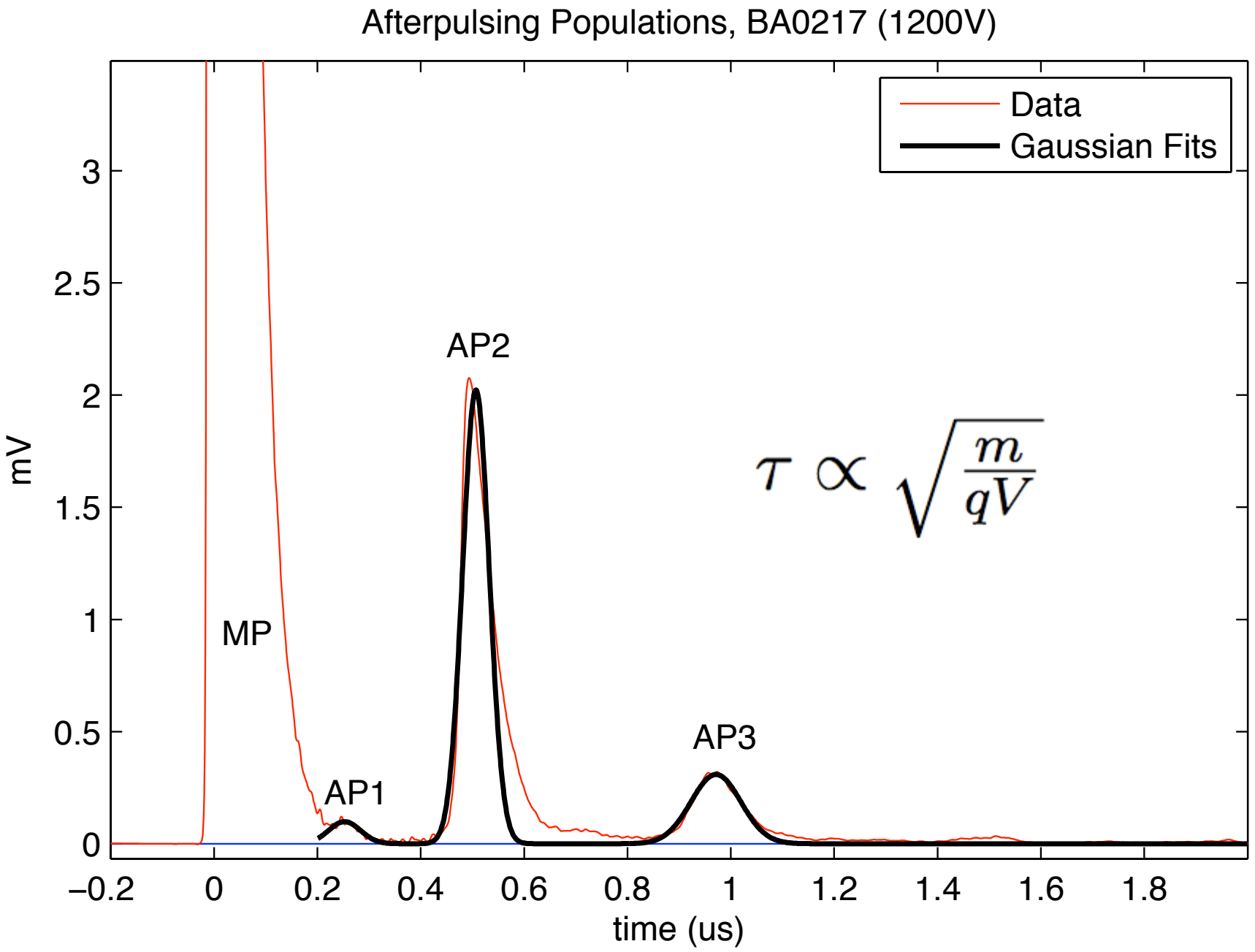
Dark Current

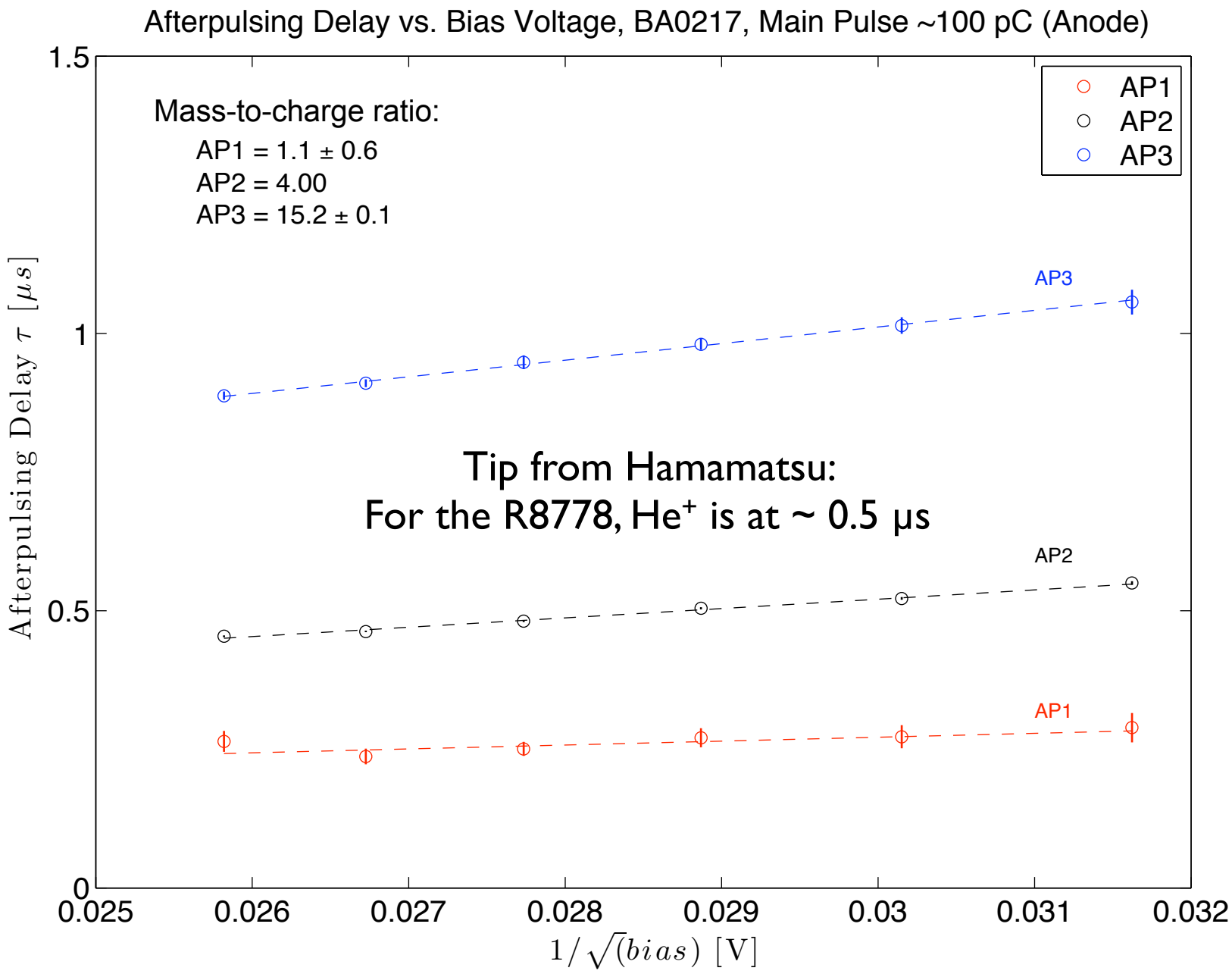
Thermionic emission
Field emission
Afterpulsing (ion feedback)
Radioactivity
Cosmic rays

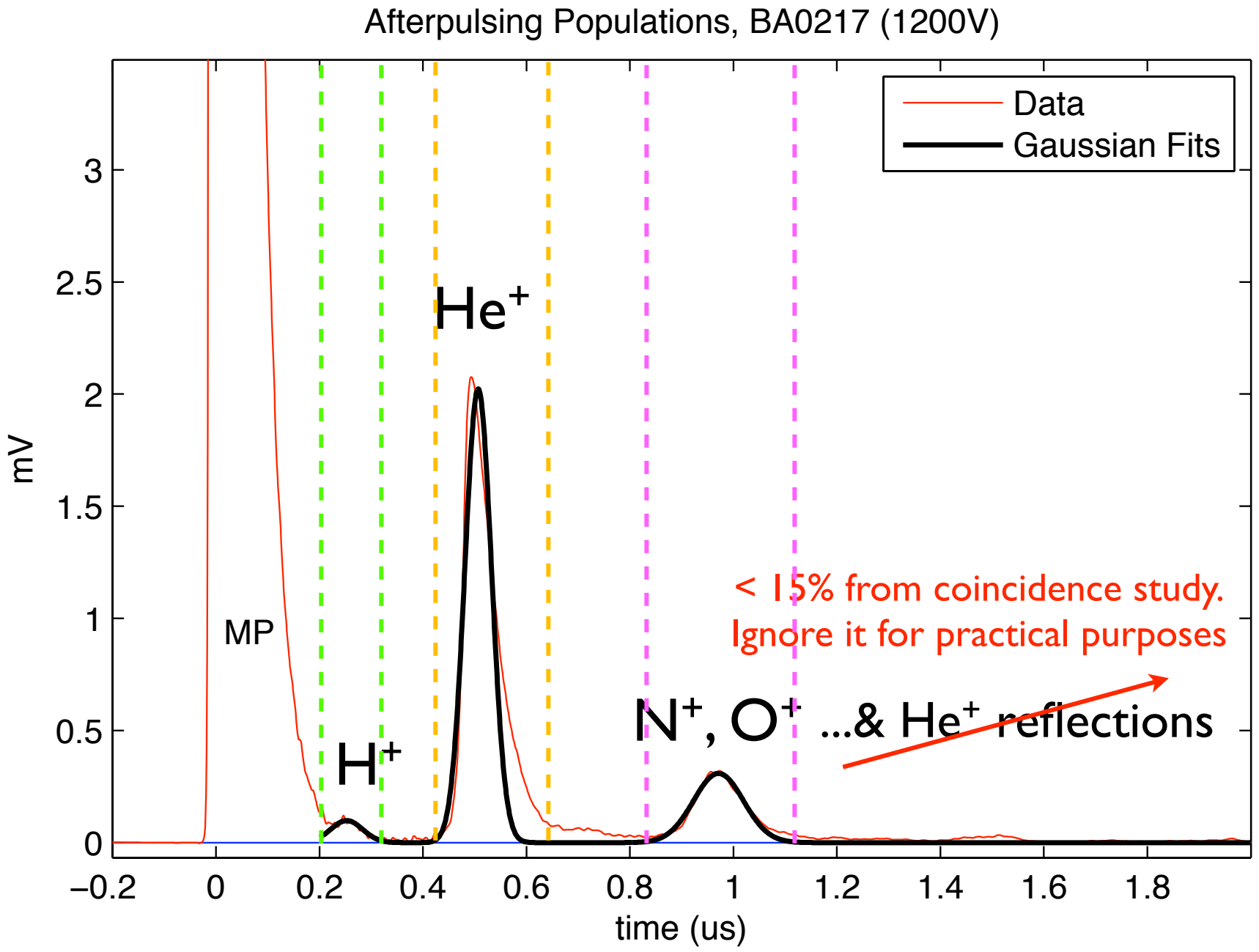
Ion feedback ("afterpulsing")



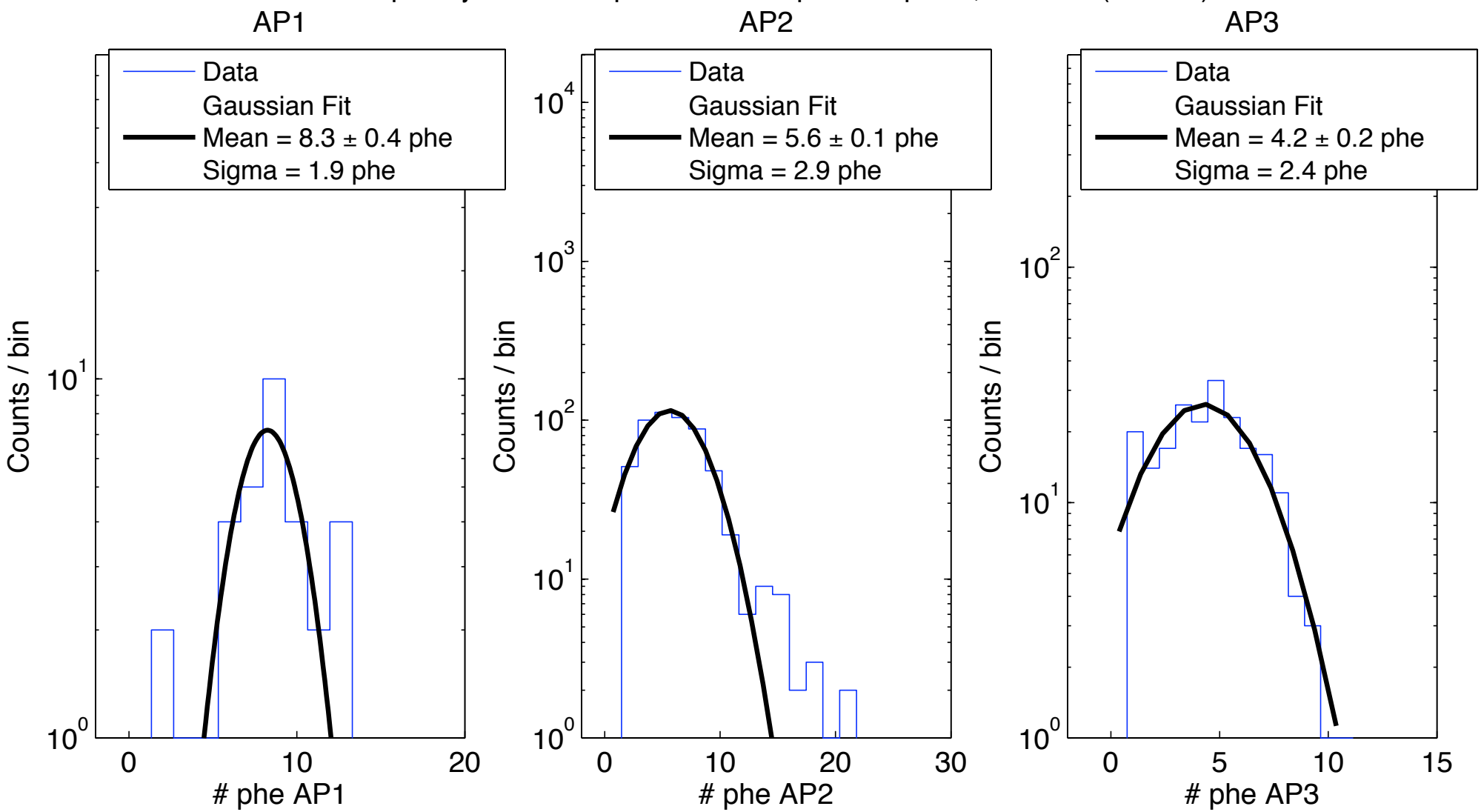

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
Time (us)
Animation

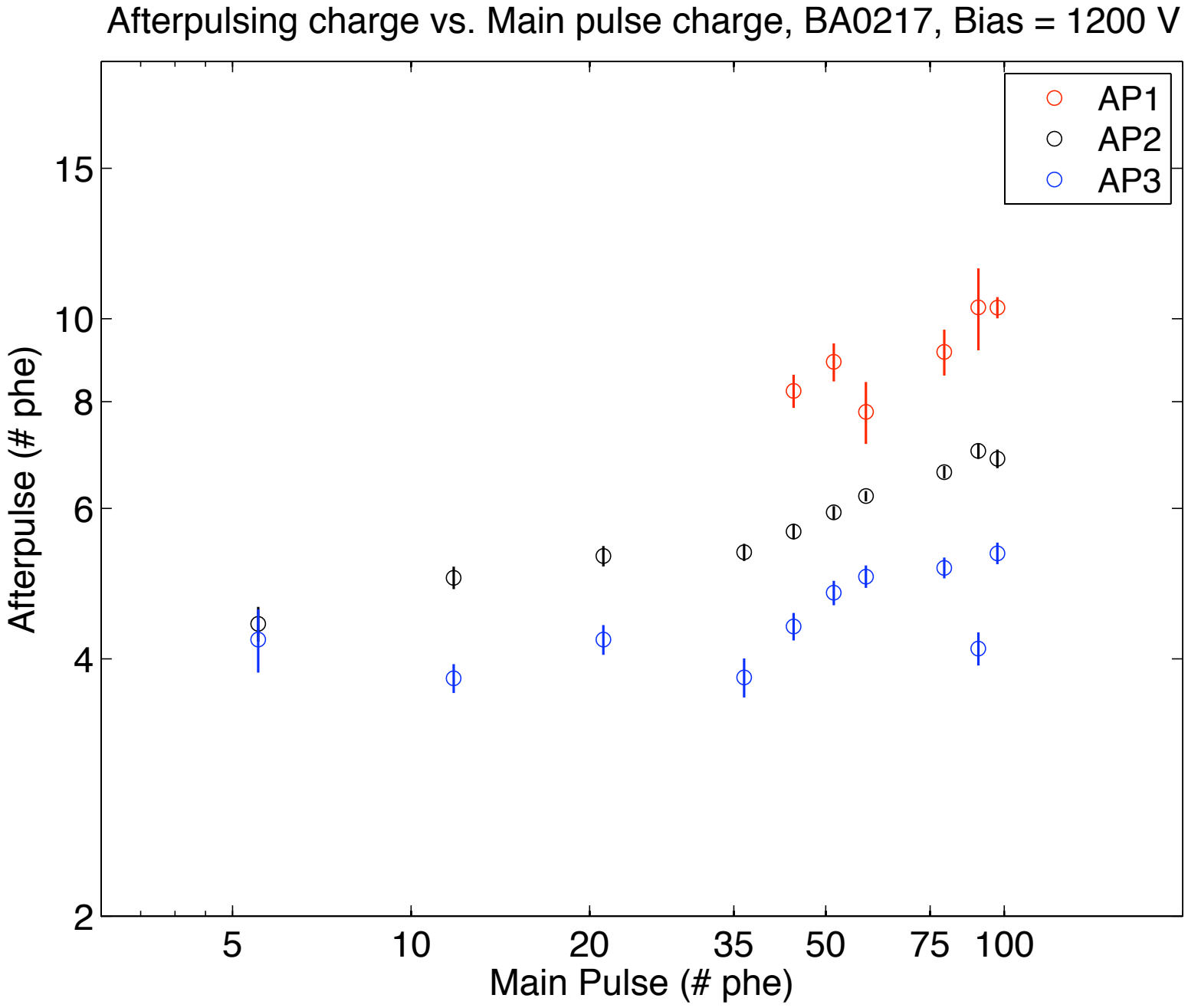

Afterpulsing Populations, BA0217 (1200V)
Data
Gaussian Fits
mV
time (us)
MP
AP1
AP2
AP3
$\tau \propto \sqrt{\frac{m}{qV}}$

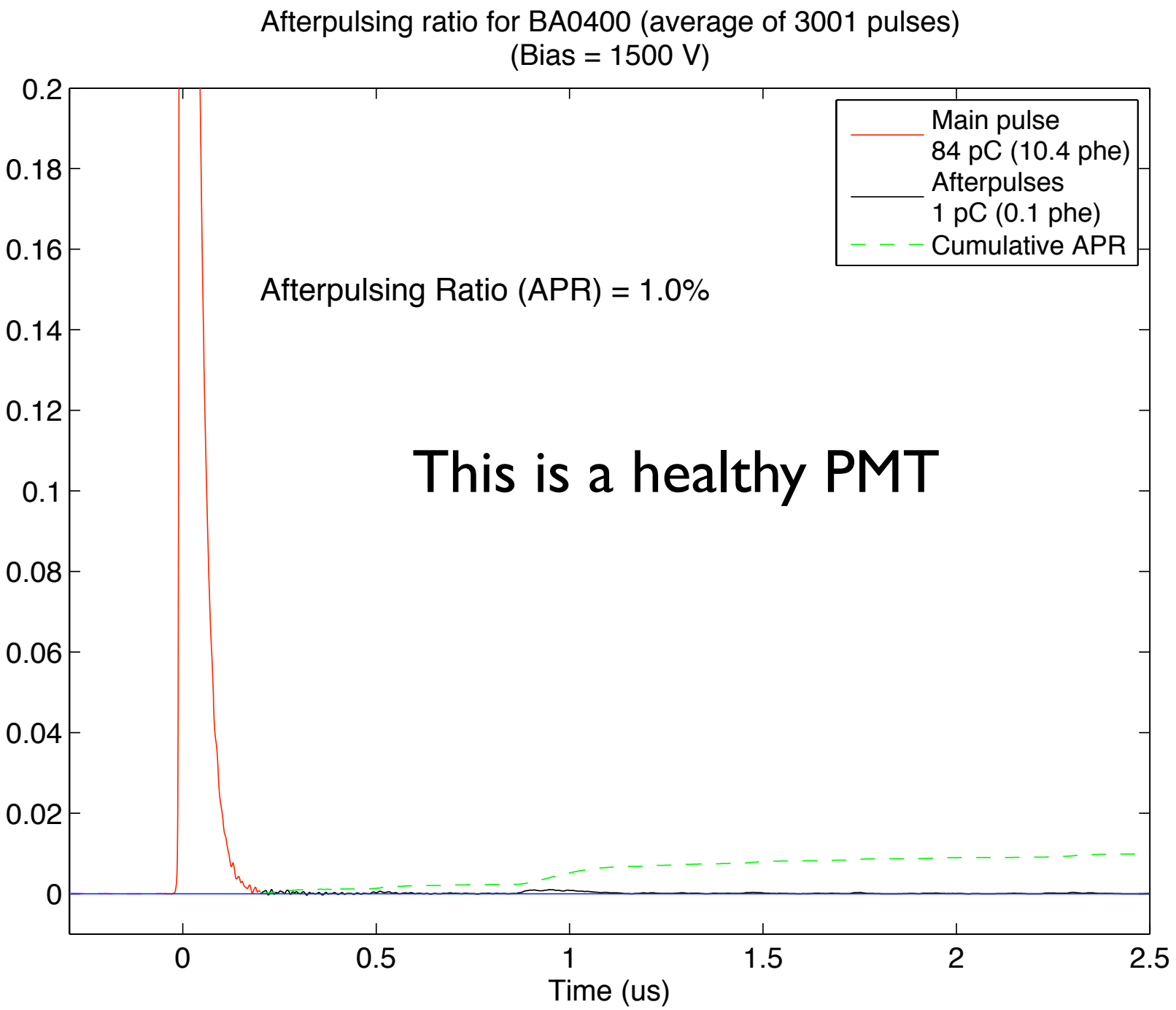

Afterpulsing Delay vs. Bias Voltage, BA0217, Main Pulse ~100 pC (Anode)
Mass-to-charge ratio:
AP1 = 1.1 ± 0.6
AP2 = 4.00
AP3 = 15.2 ± 0.1
AP1
AP2
AP3
Tip from Hamamatsu:
For the R8778, He+ is at ~ 0.5 μs
Afterpulsing Delay τ $[\mu s]$
$1/\sqrt{(bias)}$ [V]
1.5
1
0.5
0
0.025
0.026
0.027
0.028
0.029
0.03
0.031
0.032

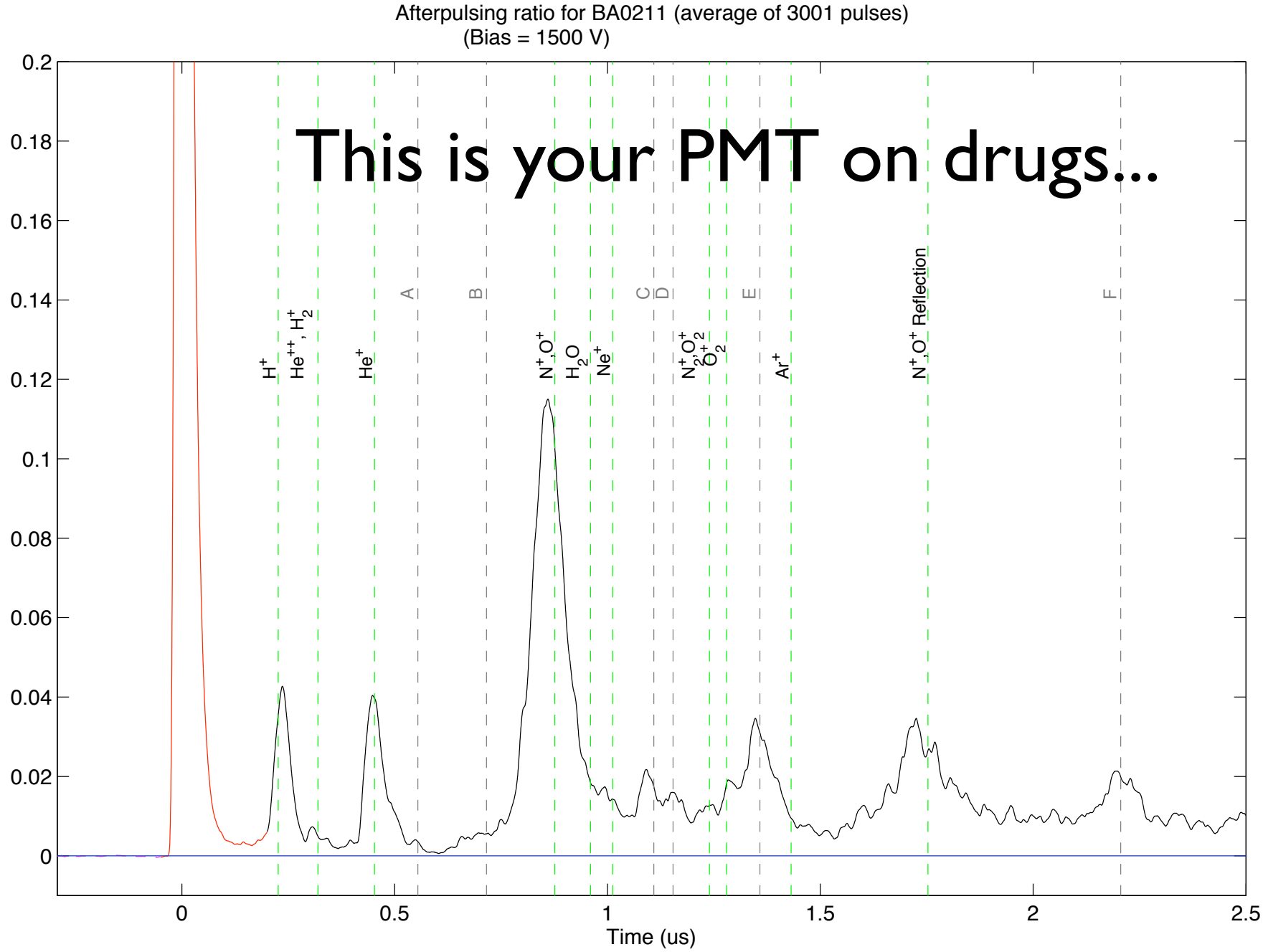

Afterpulsing Populations, BA0217 (1200V)
Data
Gaussian Fits
mV
time (us)
MP
H+
He+
N+, O+ ...& He+ reflections
< 15% from coincidence study.
Ignore it for practical purposes

Mean # phe ejected from photocathode per afterpulse, BA0217 (1200 V)




Afterpulsing charge vs. Main pulse charge, BA0217, Bias = 1200 V
AP1
AP2
AP3
Afterpulse (# phe)
15
10
8
6
4
2
5
10
20
35
50
75
100
Main Pulse (# phe)


Afterpulsing ratio for BA0400 (average of 3001 pulses)
(Bias = 1500 V)
Main pulse
84 pC (10.4 phe)
Afterpulses
1 pC (0.1 phe)
Cumulative APR
Afterpulsing Ratio (APR) = 1.0%
This is a healthy PMT
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
2.5
Time (us)


Afterpulsing ratio for BA0211 (average of 3001 pulses)
(Bias = 1500 V)
This is your PMT on drugs...
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
2.5
Time (us)
H+
He++, H2+
He+
A
B
N+,O+
H2O
Ne+
C
D
N2+,O2+
O2+
E
Ar+
N+,O+ Reflection
F

Other PMT Imperfections

Linearity
QE
CE
Resolution
Angular response
Magnetic Field Effects

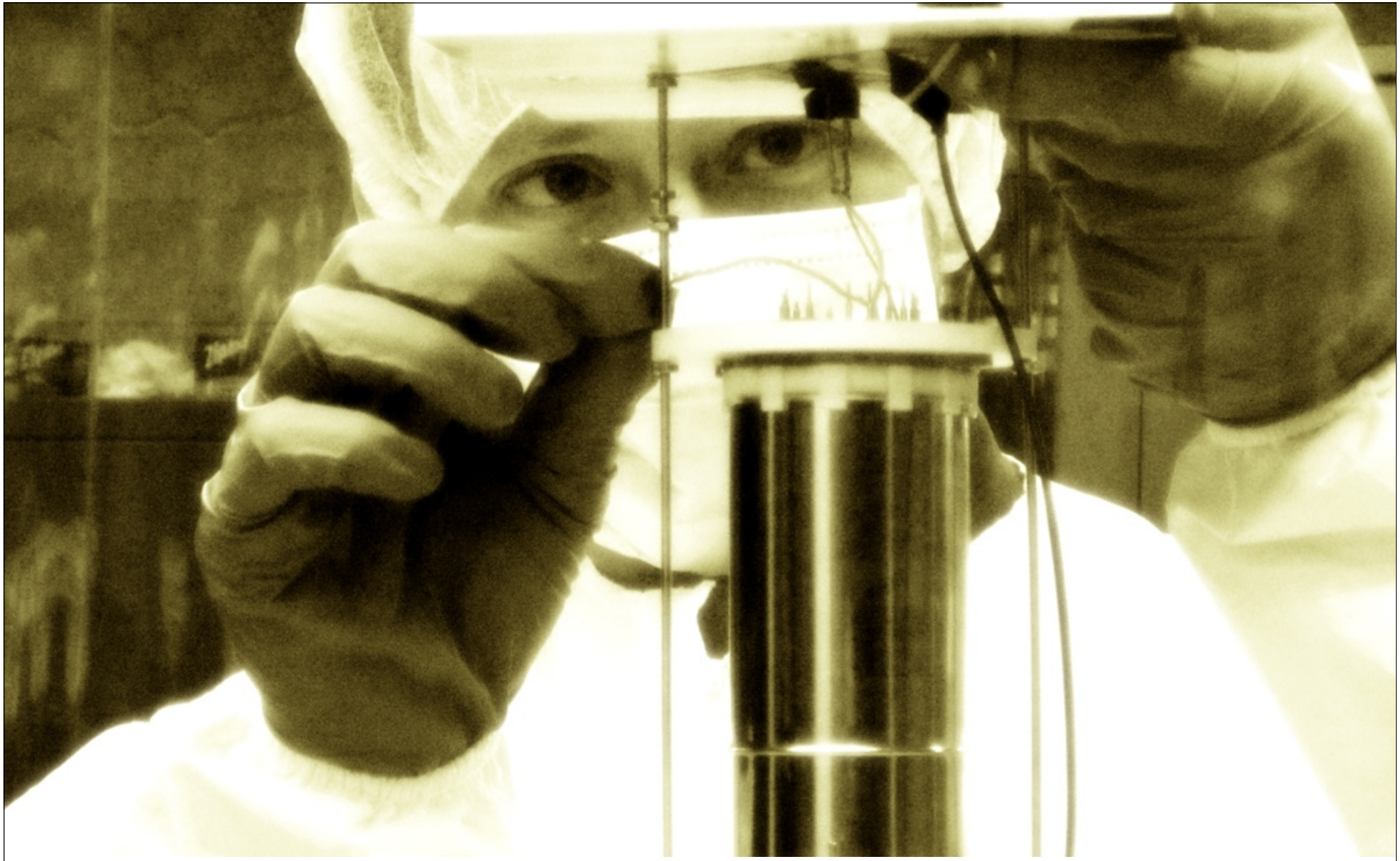
Concluding Remarks

Effective photo-detection devices

Widely used

Many advantages: high gain, low noise, fast response, etc.

Some disadvantages that we have to be aware of
(dark current, AP, non-linearity, low QE, etc.)



Treat them well