

Designing and executing a cosmic ray experiment

Phys150 Special topics

David Stuart, UC Santa Barbara



Overview of the class

Why?

Lab courses are missing many aspects needed to prepare for real research:
Exploration & originality missing. Instruments rarely understood deeply.
Enrollment growth has left many students without research opportunities.
I'm testing a potential way to address that. This course is an experiment.

What?

Design and build an experiment, with some originality and details.
Develop the measurement and data analysis plan.
Build apparatus, collect data, write analysis software. Iterate.
Extract conclusions from the experiment and write a paper about it.
I've chosen a measurement of cosmic ray properties, because it loosely relates to my own research and is feasible given recent technologies.

How?

I'll give you enough info in lectures to understand the techniques,
then you work "in lab" to use the techniques to do your experiment.

Course administration

Read the syllabus

Sign up for 4 units — will count for elective lab credit.

Phys150 defaults to variable units. If you can't fit 4 units, contact me.

Grades:

Lab work and logbooks 40%

Homework 20% — some practical examples of tools & techniques.

Final paper 20% — details on expectations for this will come later.

Final exam 20% — Will test whether you understood vs tagged along.

Team work:

You can work alone or collaborate on ideas and data collection.

Keep your own log, collect “some of” your own data, & write your own paper.

Give credit for who did what, e.g., “used analysis program written by Alex”.

Labs: Time(s) to be determined.

First hour will introduce idea, then you work whenever you see fit.

We will schedule blocks of time when help is available.

Please fill new doodle poll today; select all options that are possibilities.

Wednesday 2-3 PM? Thursday 2-3 PM? Friday 2-3 PM?

Course administration

Logbook:

Record what you do *as you do it*.

Don't make it a literary project. Just "think out loud".

Be complete but concise.

Make it quick to find information; you're the audience for a real logbook.

Include photos, plots, raw data, source code, links to useful resources.

It is a resource for later when you are preparing an article.

Homework #1 due by Thursday's class.

- Create your ELog account.
- Make an ELog entry by Thursday with a brief description of your background.

Programming, eg Phys129L?

Electronics, eg Phys127AL?

Research work?

Hobby work?

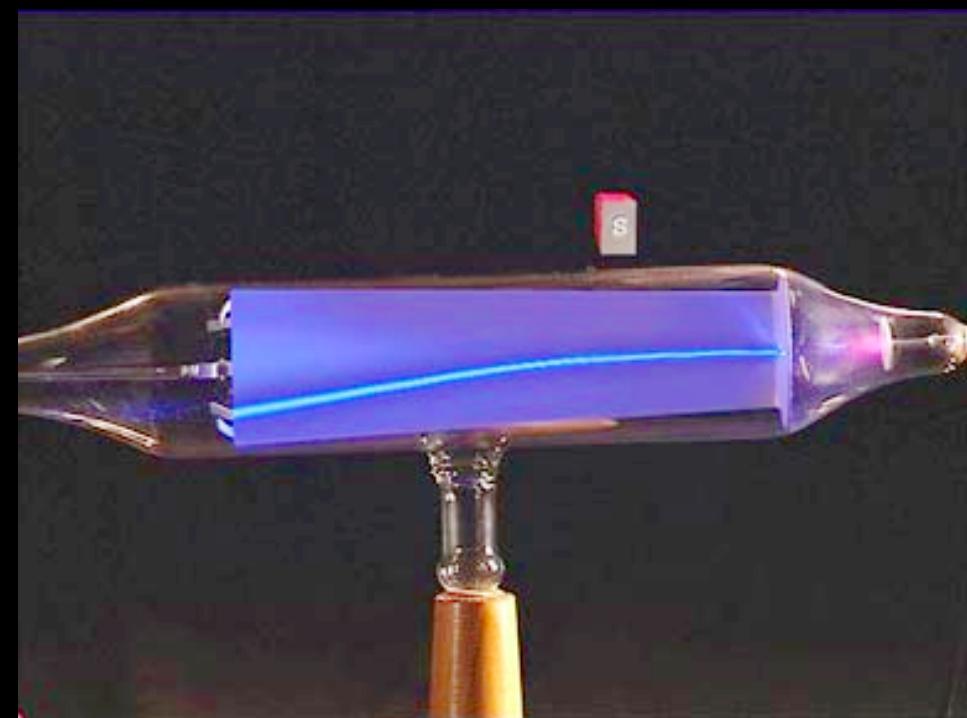
Treat this as a 3 minute answer to an interview question for a summer research position: "Tell me about yourself and why you would be a good choice for the position?"

- Post a photo or plot of some sort into your ELog to learn how to do it.

Review of radioactivity

You will measure properties of cosmic radiation, so let's start by reviewing radiation, radioactivity, and how to detect it. Radiation = “rays” is a historical misnomer.

First detected as Cathode Rays, which are electrons ejected from the cathode and attracted to the anode in a low pressure tube. They caused the gas to glow, and also any phosphorescent coatings.



Detection and measurement based on interaction of electrons with matter. Your experiment will similarly detect and measure cosmic rays by designing an apparatus where you observe them interacting with it.

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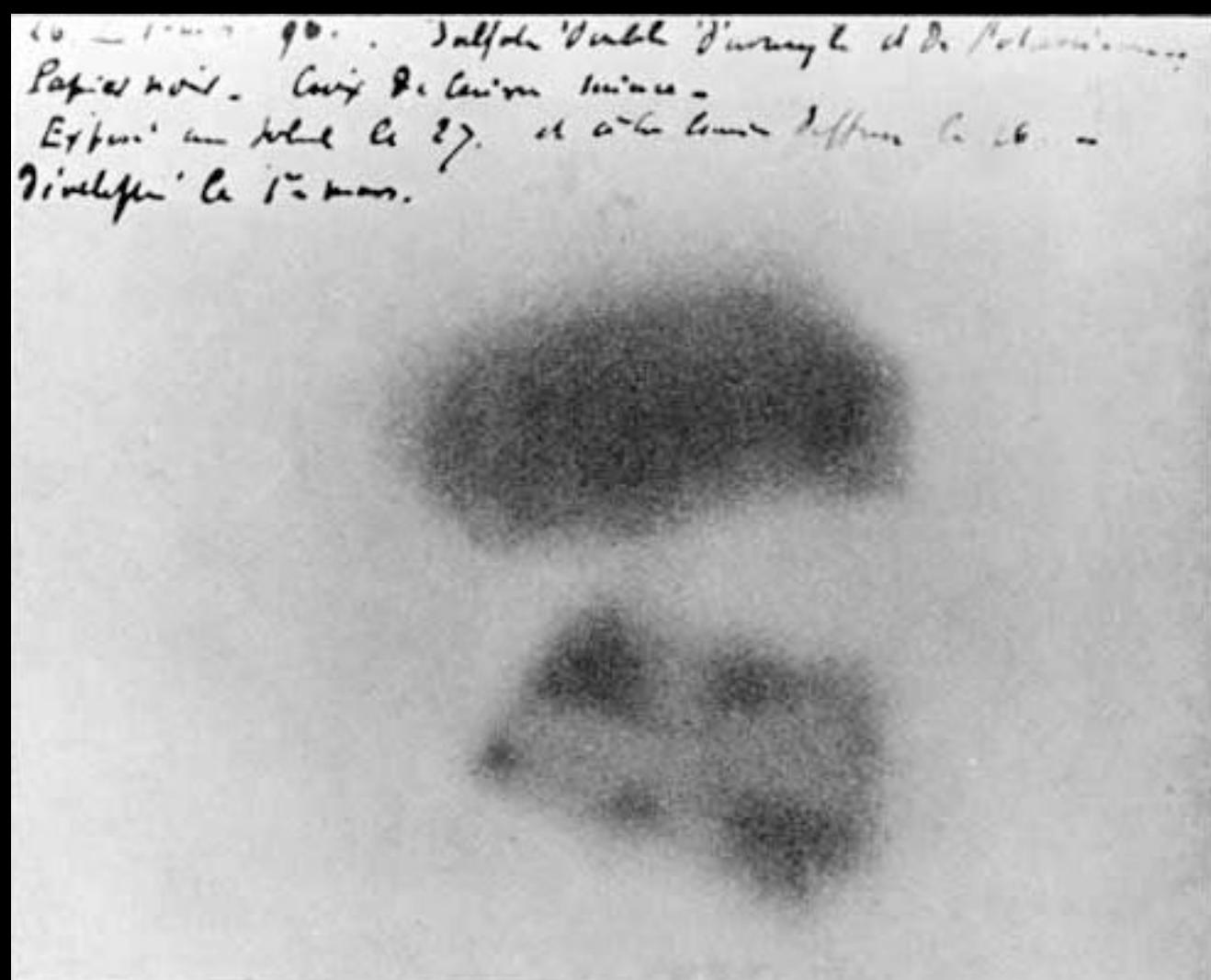
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Then x-rays detected because other phosphorescent coatings glowed even if the path of the electrons was blocked by a thick material. Found that photographic film was sensitive to it.



Review of radioactivity

Becquerel observed a similar effect from naturally occurring rocks containing Uranium. So there is also *spontaneous* radiation, i.e., radioactivity.



Review of radioactivity

Marie Curie studied these “Uranium rays” as her thesis.
Used a new device, called an electroscope.

Charge pushes a thin gold “leaf”
away from another metal piece;
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Uranium rays caused nearby air
to conduct electricity so the
charge bled off the electroscope.

→ **Ionizing** radiation.



Review of radioactivity

Marie Curie studied these “Uranium rays” as her thesis.
Used a new device, called an electroscope.

Methodically studying this led to realization that the Uranium salts contain some other element much more active than Uranium.

Discovered:
Polonium
Radium

Coined the term radioactivity.

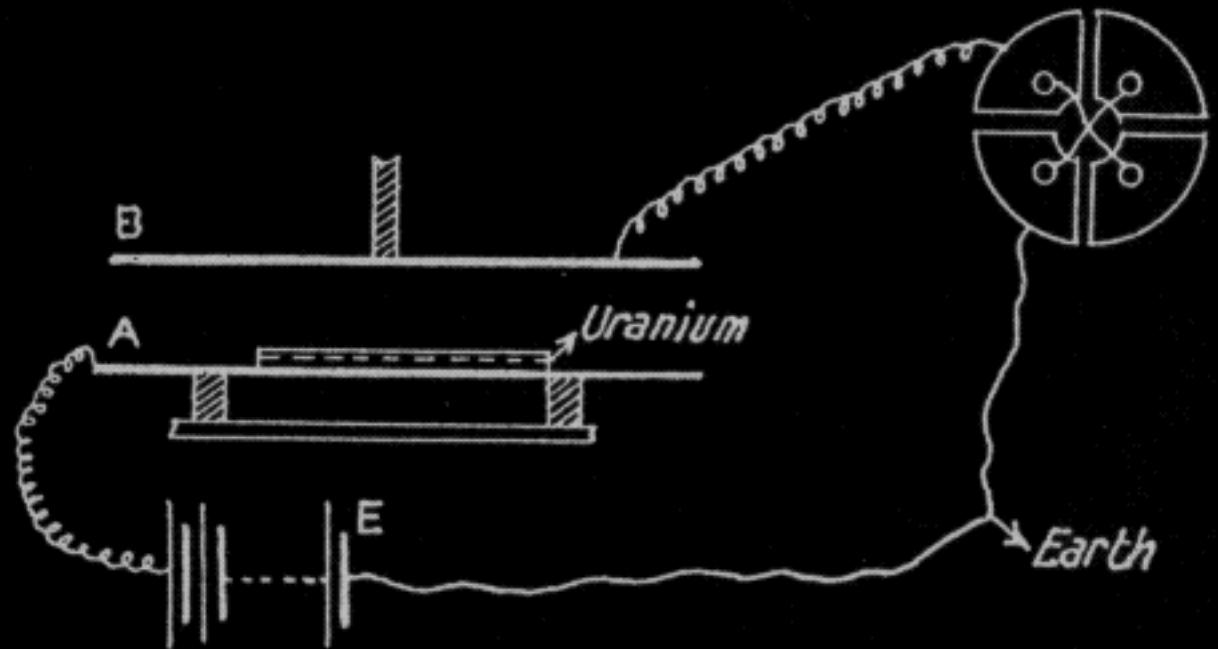


Review of radioactivity

Rutherford studied the penetration properties of U rays

Covered Uranium layer
with varying thickness
of aluminum and found
multiple components:

- A). barely penetrating
- B). moderately penetrating
- C). very penetrating rays

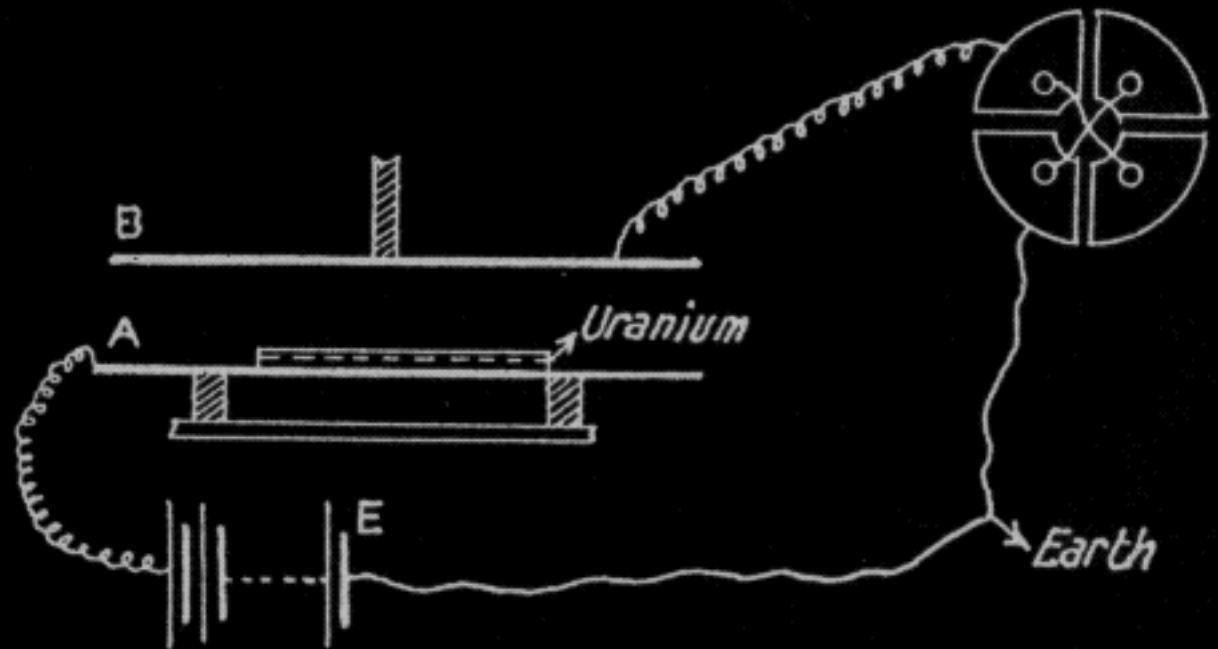


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That “review” just told you the names of the people and that there are three types, labeled with letters.

That is a history and vocabulary lesson, not science.

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That is a history and vocabulary lesson, not science.

It is nice to know the history.

It is good to learn how progress was made.

It is better to learn how to make new progress.

The key to this progress was the technology:

Developing it,
understanding it, and
using it to see something new.

Getting preachy

There is a difference between facts and knowledge.

In this case:

Facts = α , β , γ

Knowledge = what the three types correspond to, and why

Science = figuring it out in the first place, and figuring out what they reveal about the atom and nature.

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Goal of this class is for you to do some science.

The lectures will give you some related facts and knowledge.

But you can look up facts on your own too. Indeed, you should!

So, how do you figure out that there are “three types”.

Demo with geiger counter.

<https://www.youtube.com/watch?v=wsspFQn0mWM>



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Being roughly quantitative can be sufficient to learn a lot quickly.

A rough estimate is a quick way to develop an idea that leads to a hypothesis. You can then plan a careful measurement to test it.

For example, we could invent a method to precisely count the beeps as we precisely vary the thickness and then analyze that data to identify three categories.

That same idea applies everywhere.

See the big picture first, roughly; then develop a detailed plan.

We won't do the exercise of discovering the three types.

Instead, we'll study something else you may have noticed about the geiger counter in the video.

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It clicks even when the sources are not near it. Why?



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So we better understand how the detector functions.

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Detector malfunction?

So we better understand how the detector functions.

Open it and look, or better yet design and build it yourself.

How a geiger counter works

Geiger and Muller, Rutherford's students; did Rutherford scattering measurement by looking for tiny phosphorescence flashes. Arduousness drove Geiger to invent a better way.

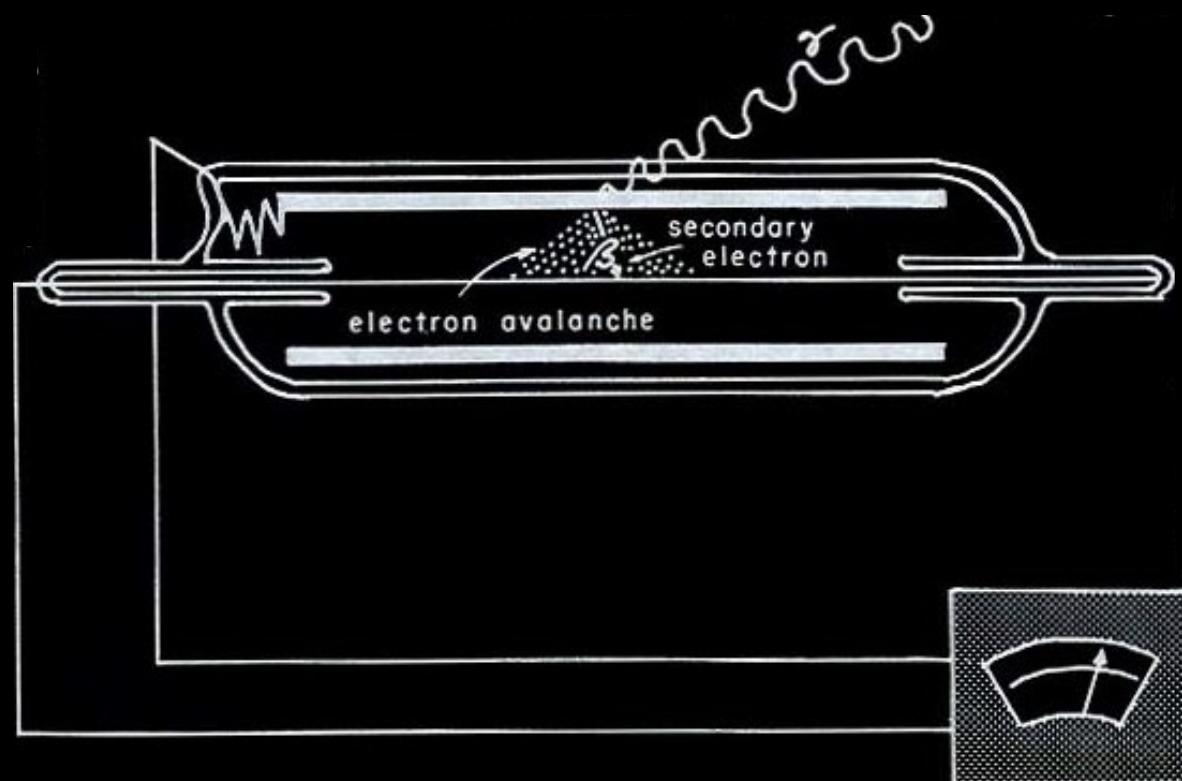
How a geiger counter works:

Radiation ionizes gas.

Electron accelerates in HV.

It causes more ionization.

Avalanche leads to a large current pulse, even from a single electron-ion pair.

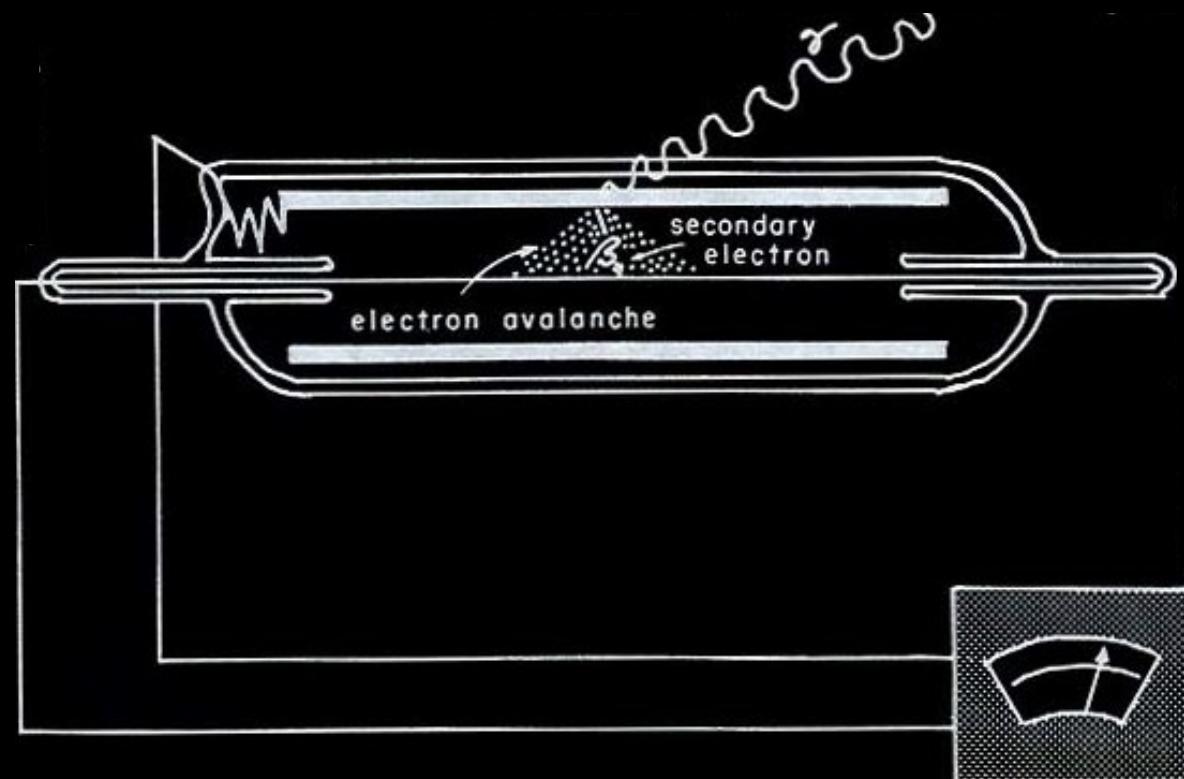


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Note that understanding the details of the detector helps avoid biases.

E.g., for detecting the three types of radiation, there is a bias from alphas not being able to penetrate the glass, and it only detects *ionizing* radiation.



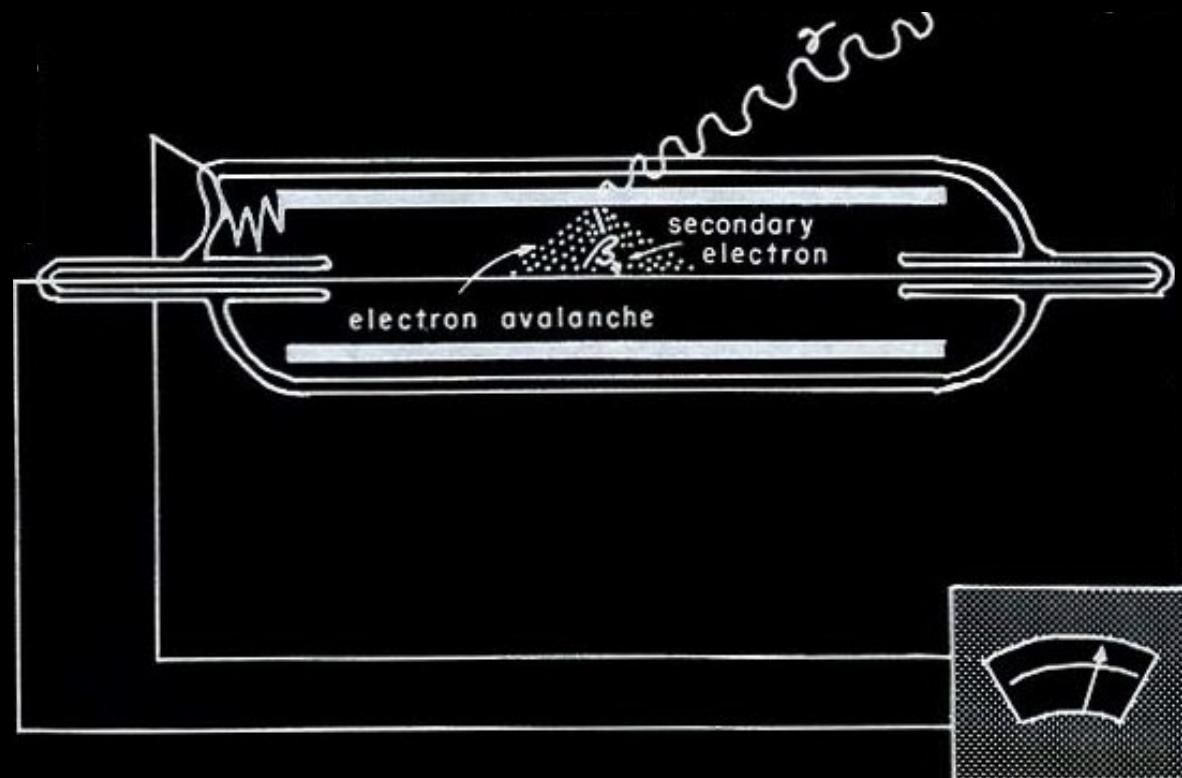
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E.g., could put a series of these together. Could then watch the absorption develop, see that gammas only interact in one place, and then see that some gammas interact more than once.

⇒ Discover Compton scattering.

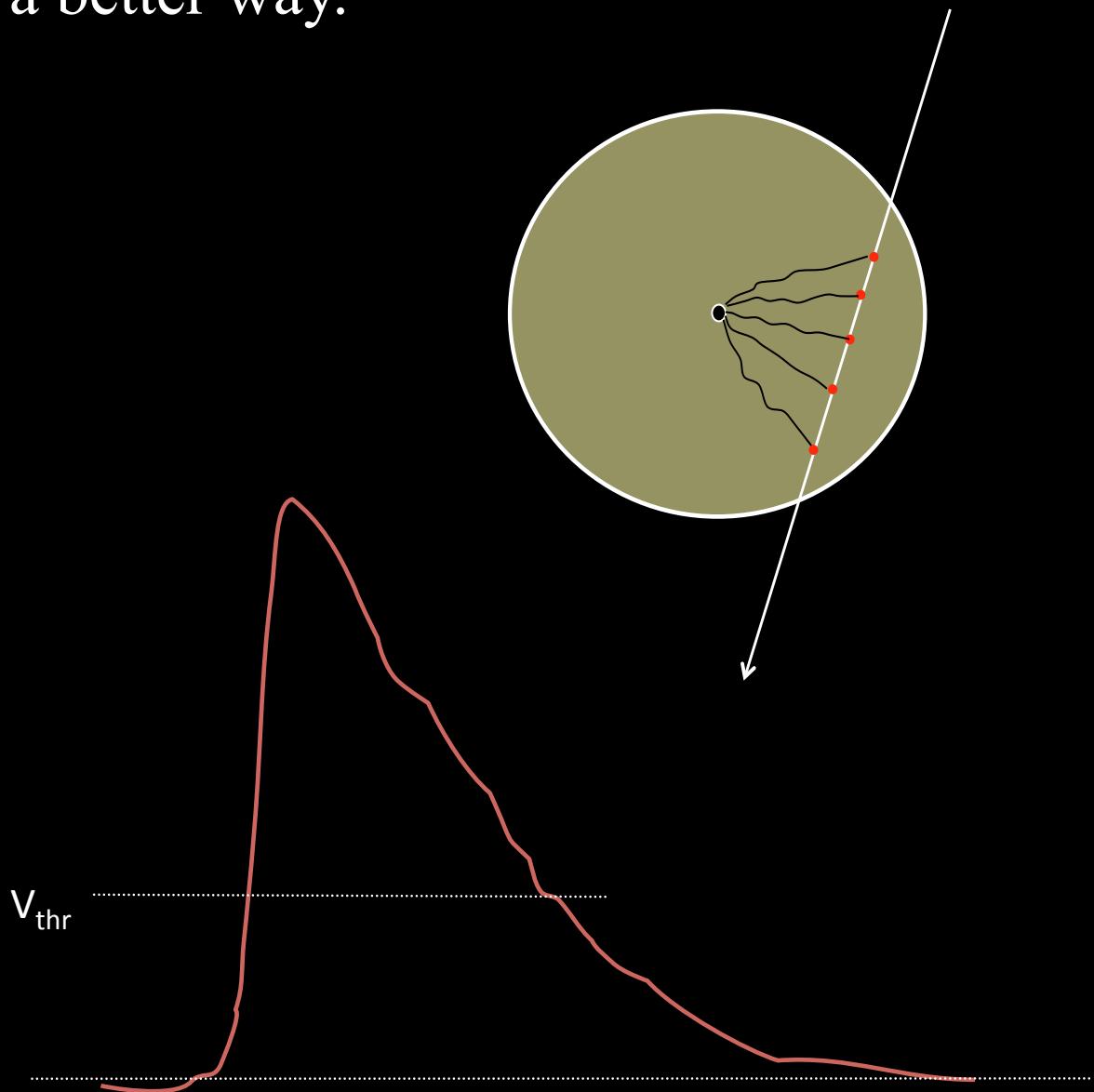


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E.g., could lower the HV so current pulse is proportional to number of primary ions and hence either gamma energy or beta path length.



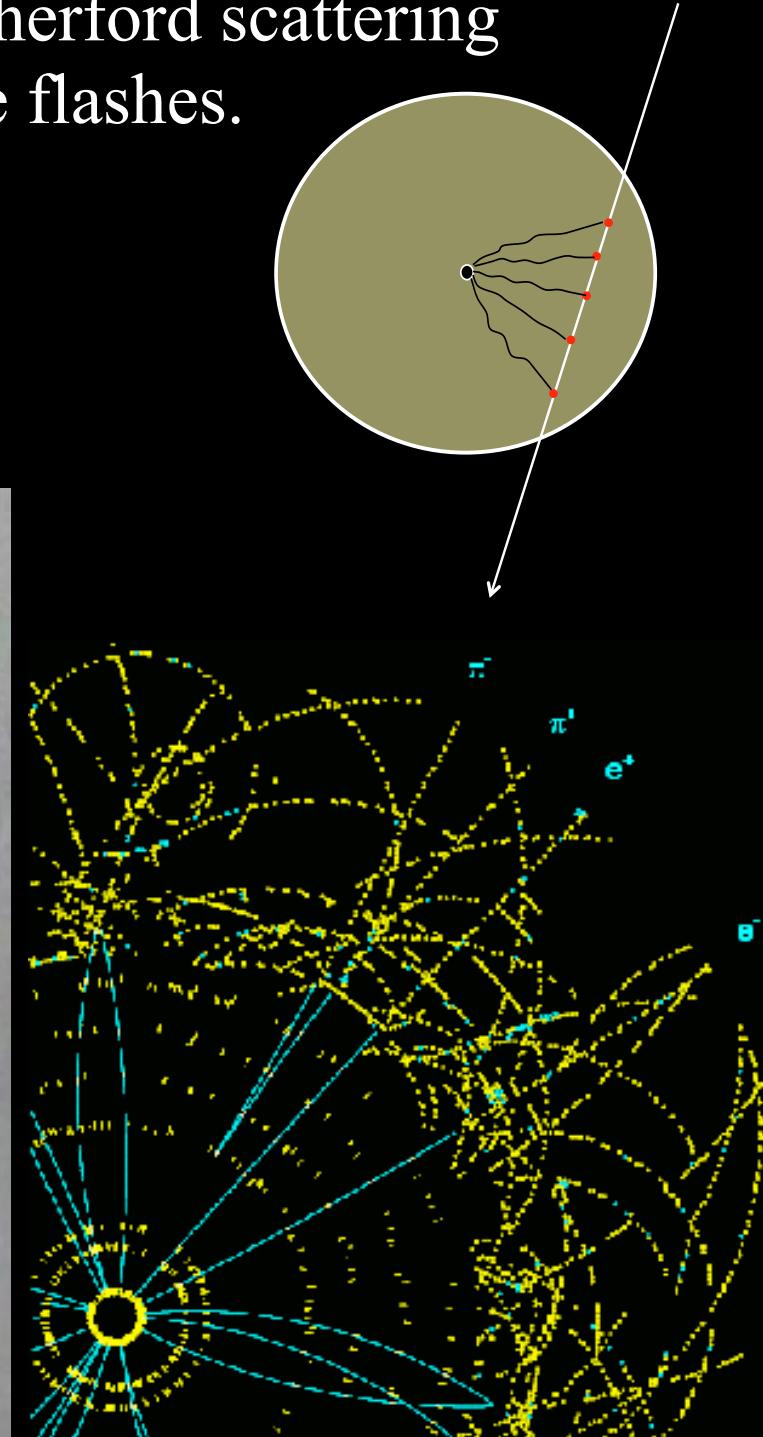
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Drift of electrons means that relative time of arrival measures position of closest approach. Stacking a bunch of these gives a view of the path.



Key idea in these detectors is amplification

The avalanche of ionization turns a small number of electrons into a detectable signal.

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Even earlier on, cloud chambers amplified a trail of individual ions into a visible trail by condensing a droplet on each ion that seeds the condensation.



The disadvantage of a cloud chamber is that it is non-electronic, so slow. The wire amplification has the disadvantage that it requires high voltage and flammable gas.

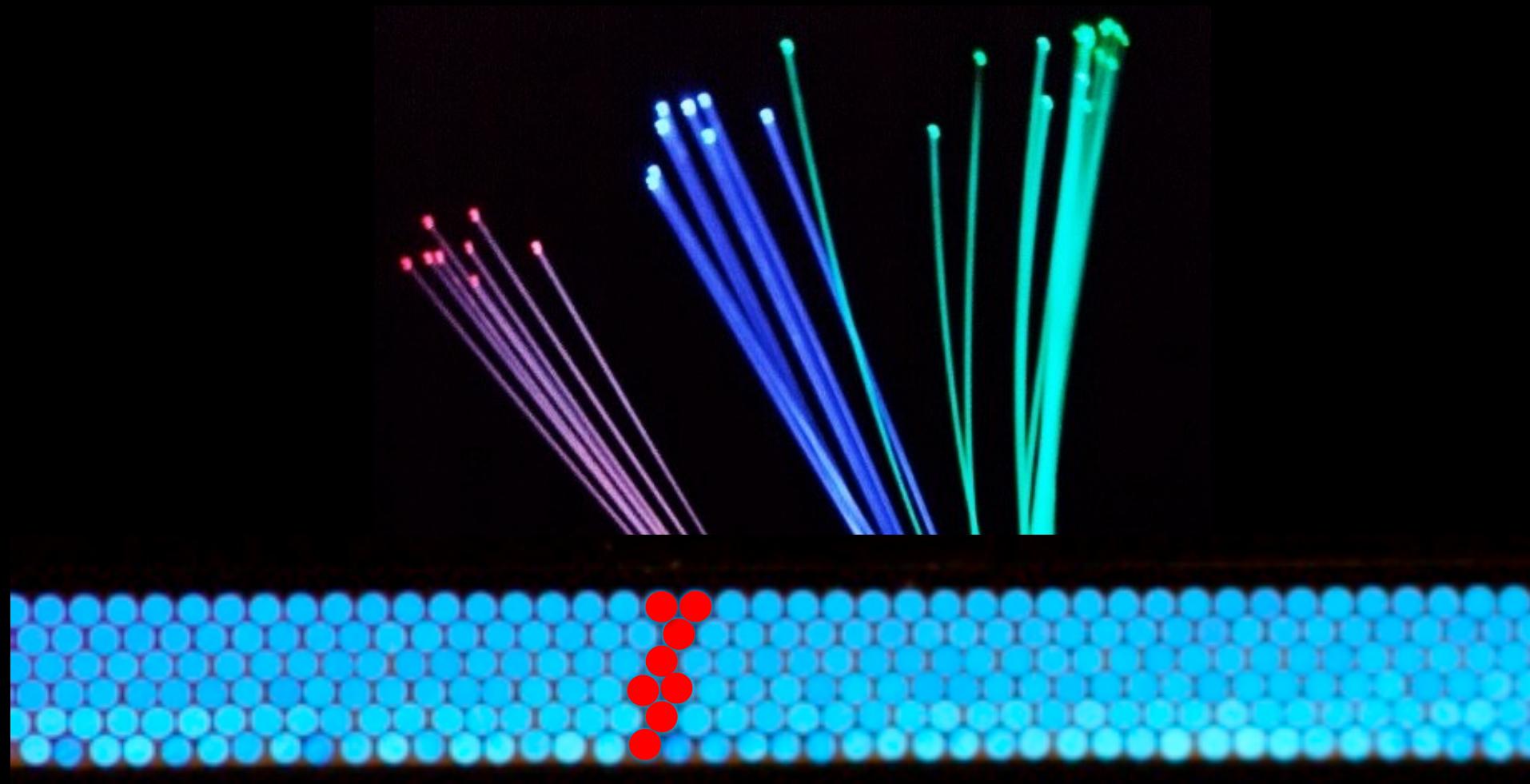
There is a simpler way, which is what we will use for detectors in this class.

Scintillation

Some energy deposit is atomic excitation as well as ionization.

Atoms de-excite by giving off a photon or two. Get $O(10)$ photons/mm.

If we could detect weak light signals, just a few photons, then we can detect the path with simple materials, e.g., plastic scintillator based fibers.



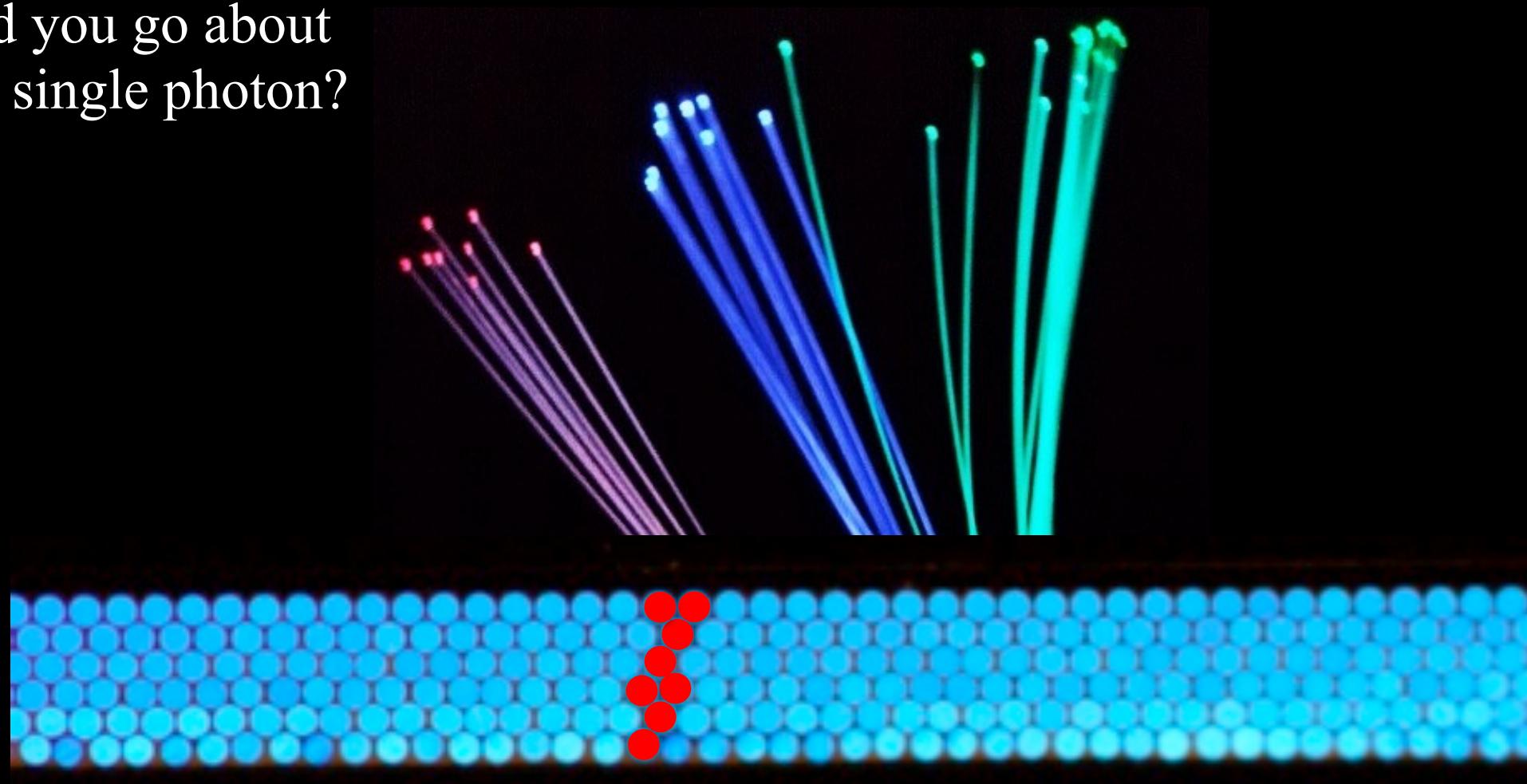
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How would you go about detecting a single photon?



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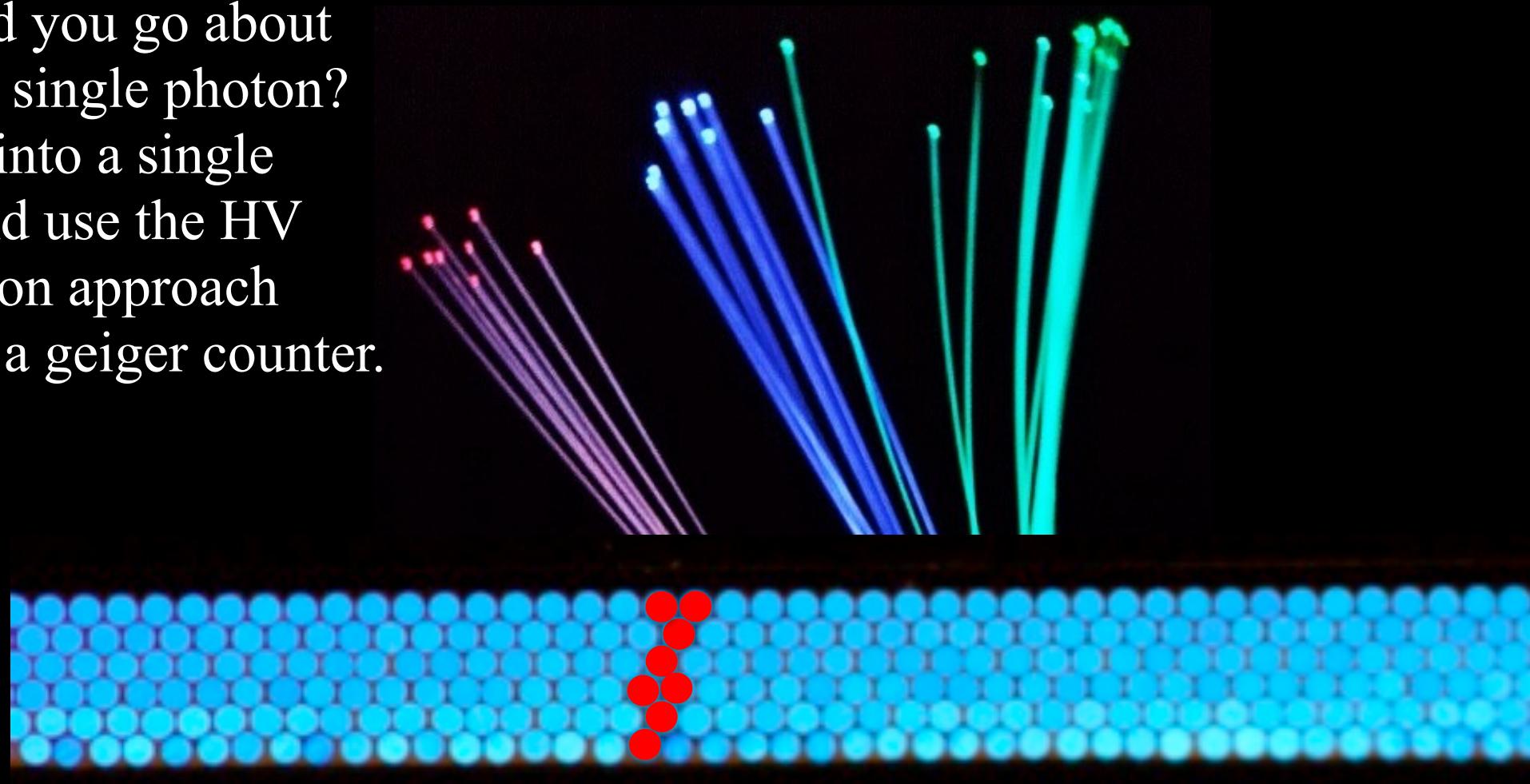
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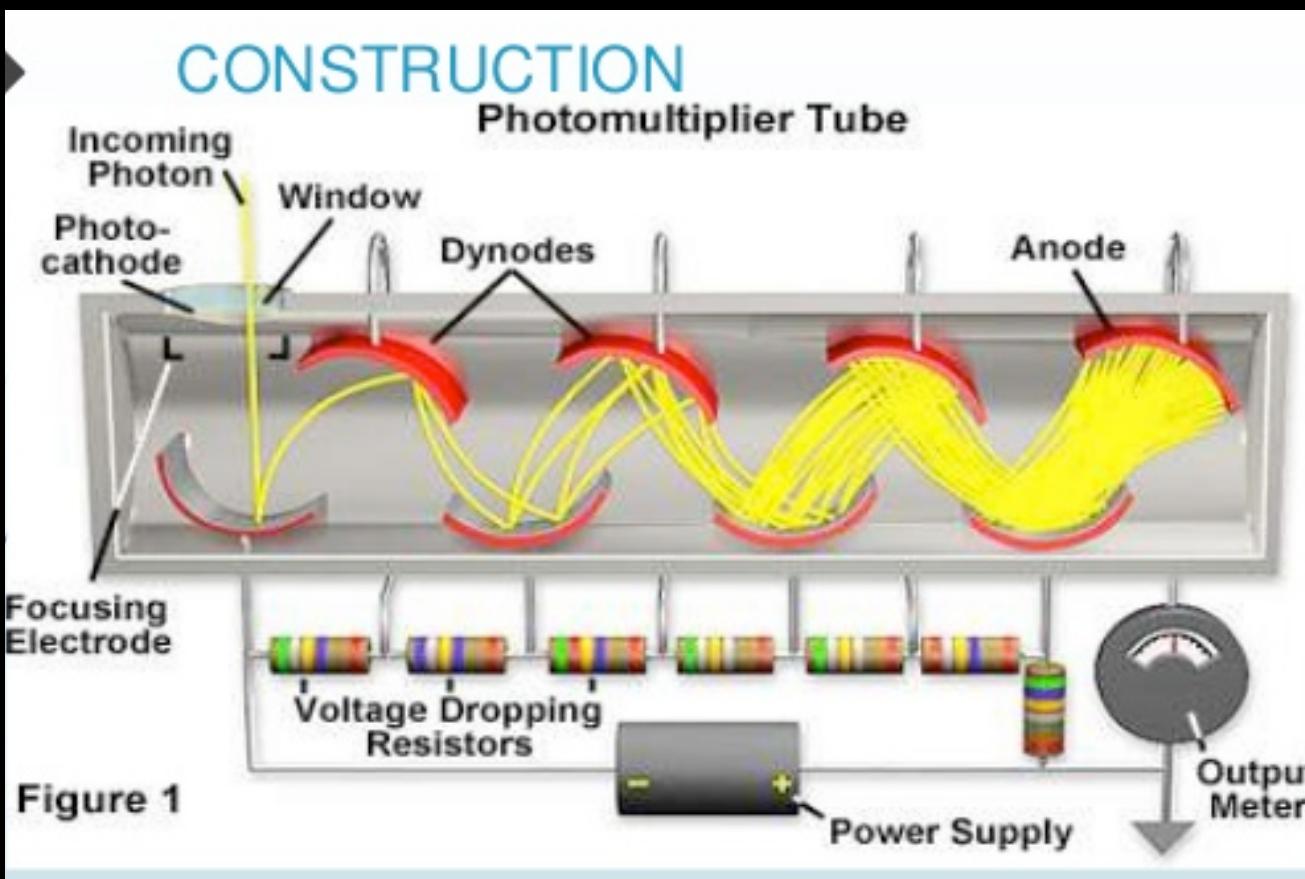
How would you go about detecting a single photon?

Convert it into a single electron and use the HV amplification approach just like in a geiger counter.



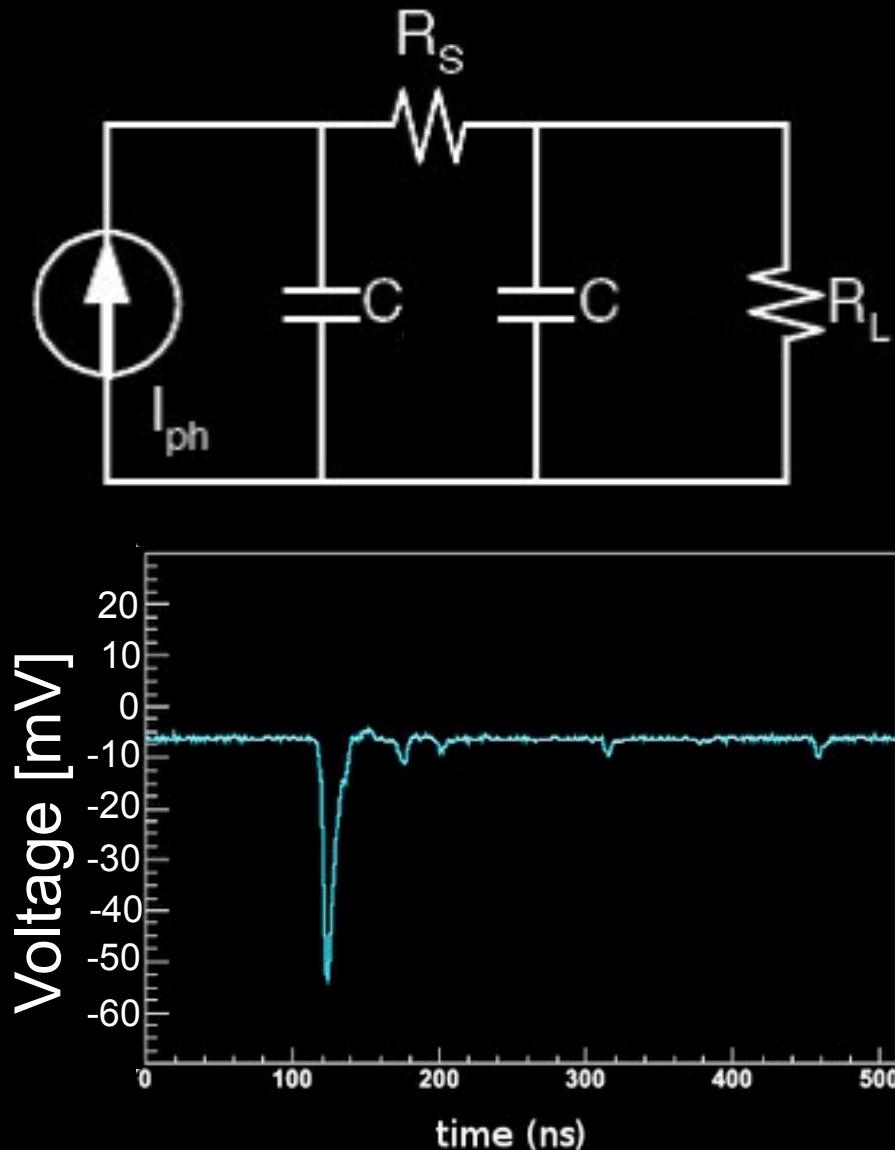
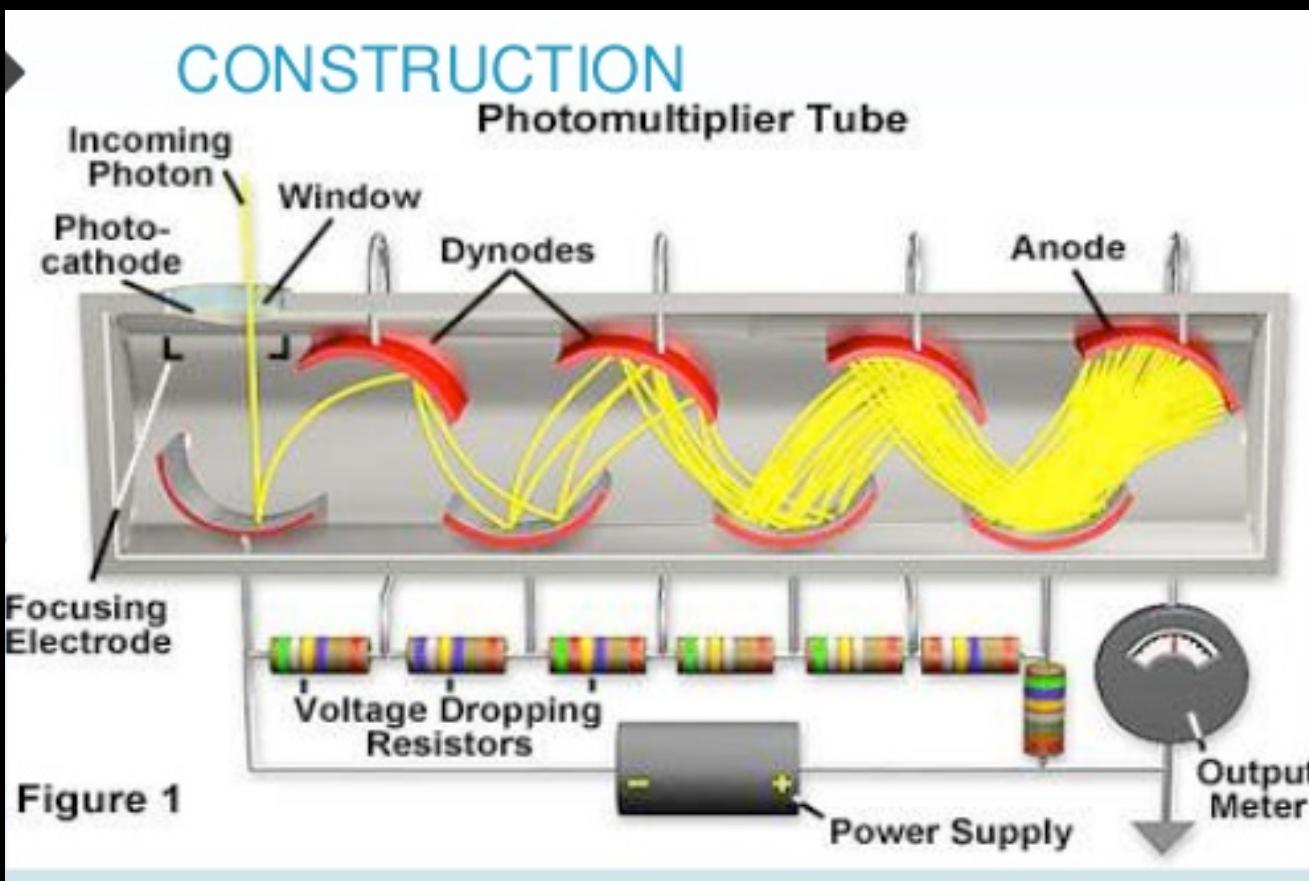
Photomultiplier tube = PMT

A photomultiplier converts photons to electrons through the photo-electric effect and then amplifies them with a large electric field.



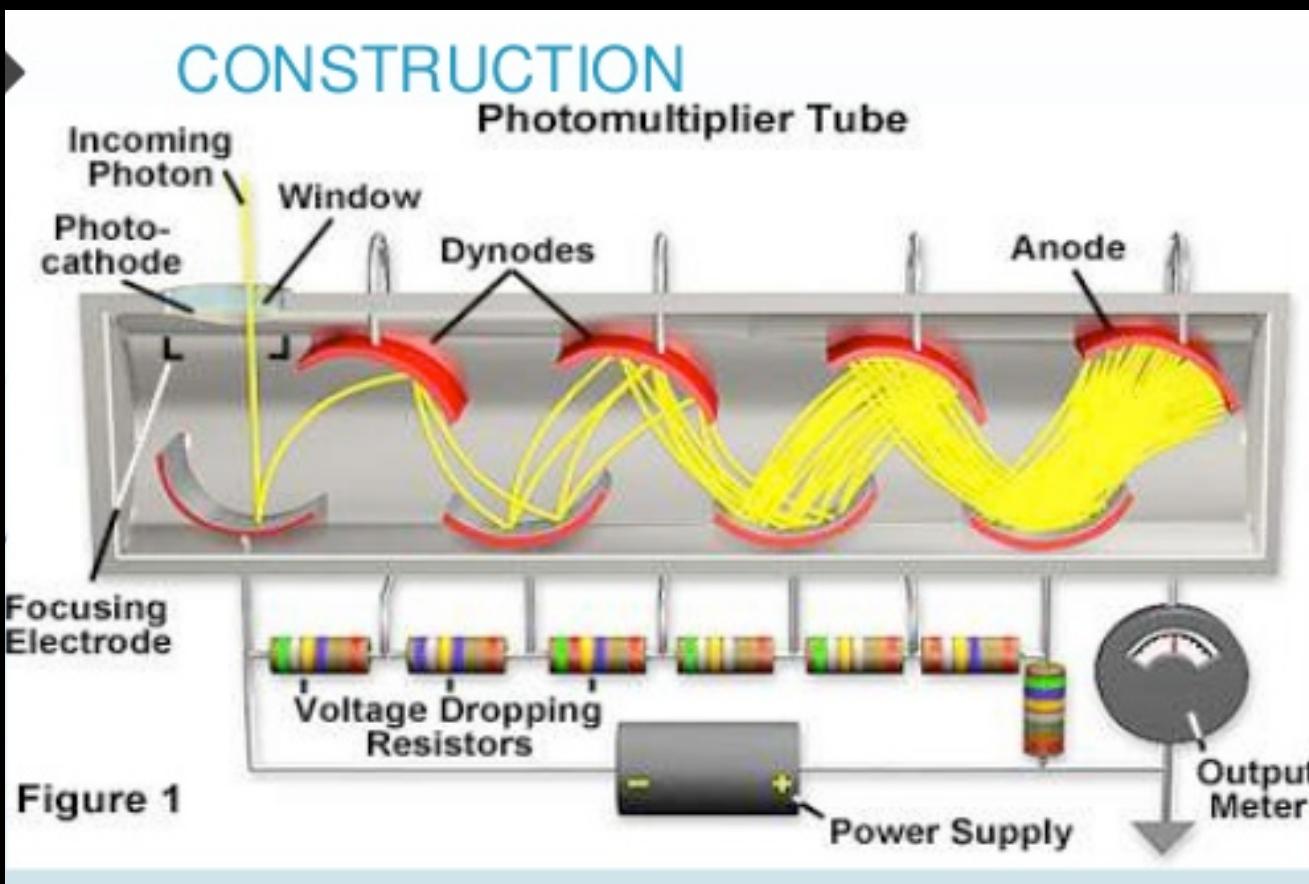
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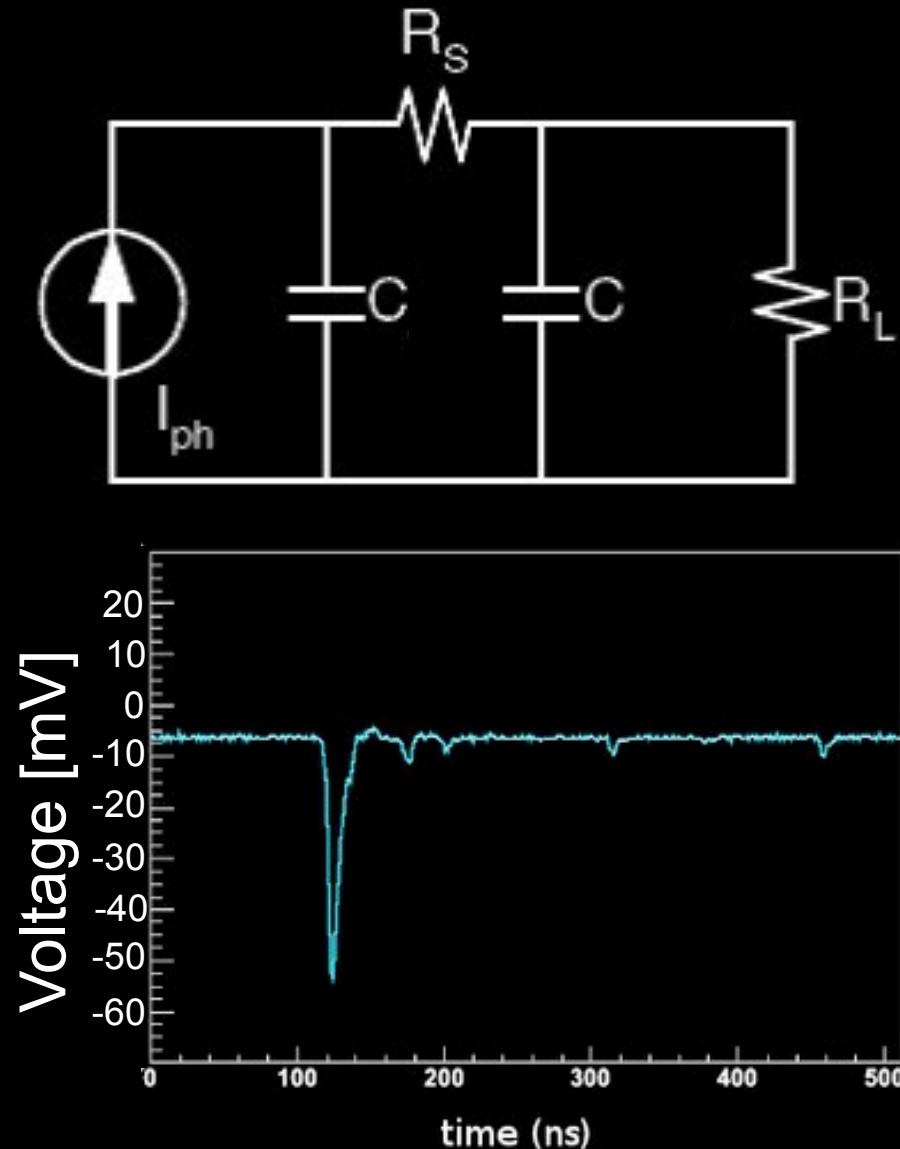


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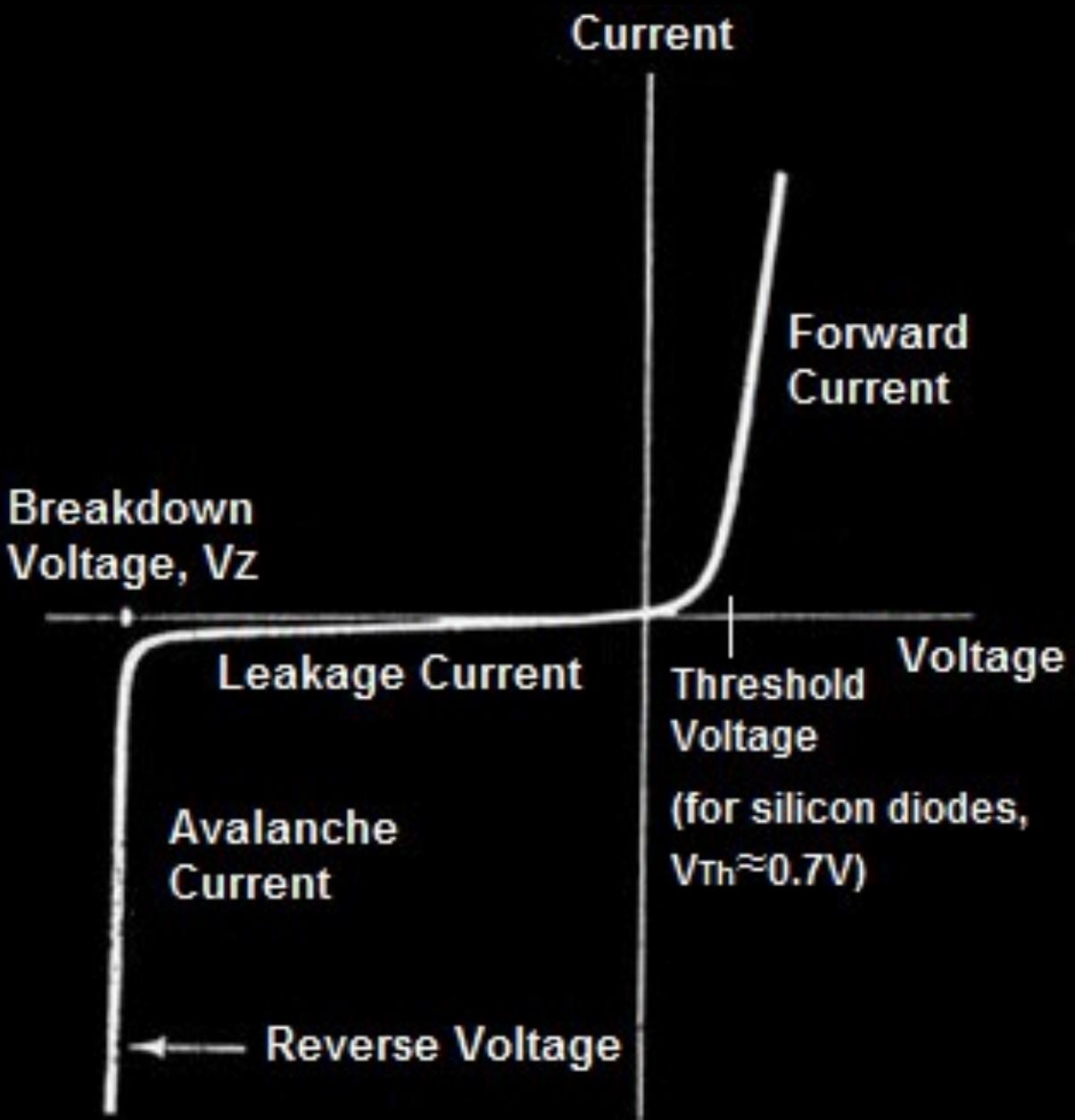
Go learn a bit about PMTs.



A new, simpler, lower voltage, silicon photomultiplier = SiPM

A newer technology uses silicon diodes and an avalanche process to more easily detect single photons.

If we apply a reverse bias voltage of $V_b \approx -V_Z$ then a single photon produces an electron-hole pair that accelerates in the high field to produce more. That avalanche causes the diode to become a short giving a large current pulse.



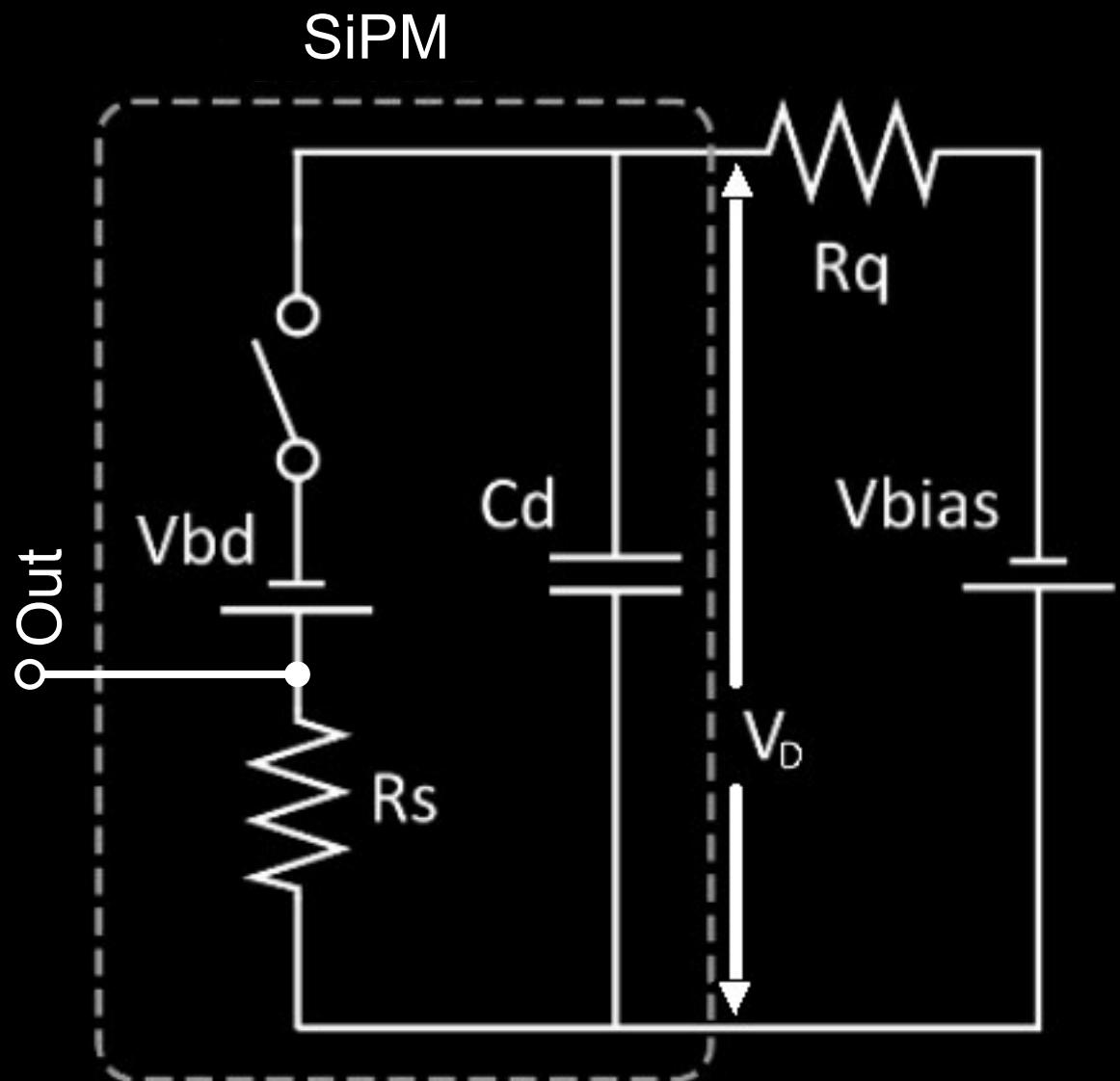
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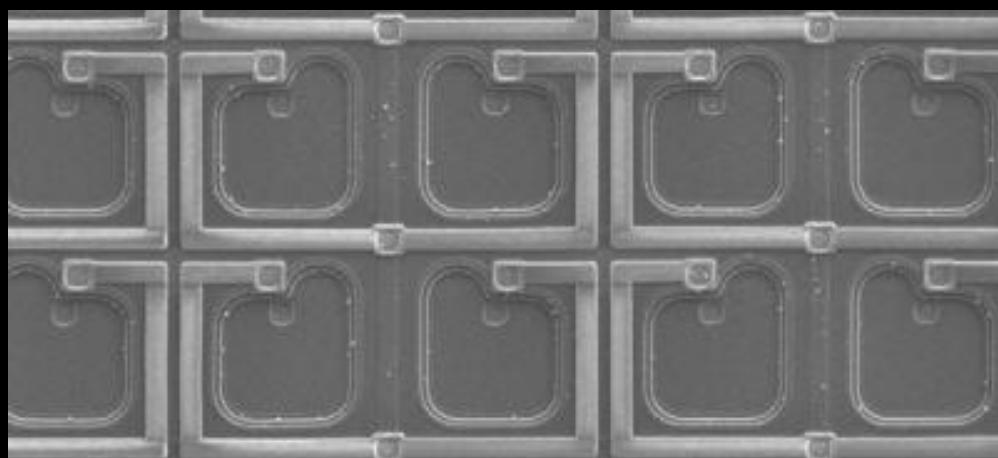
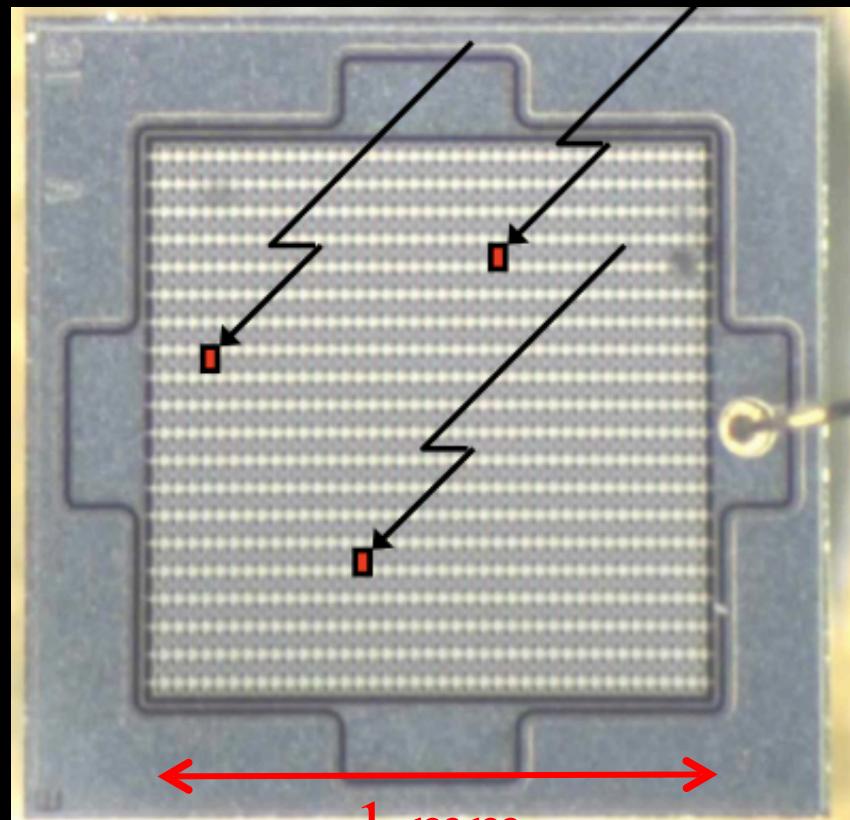
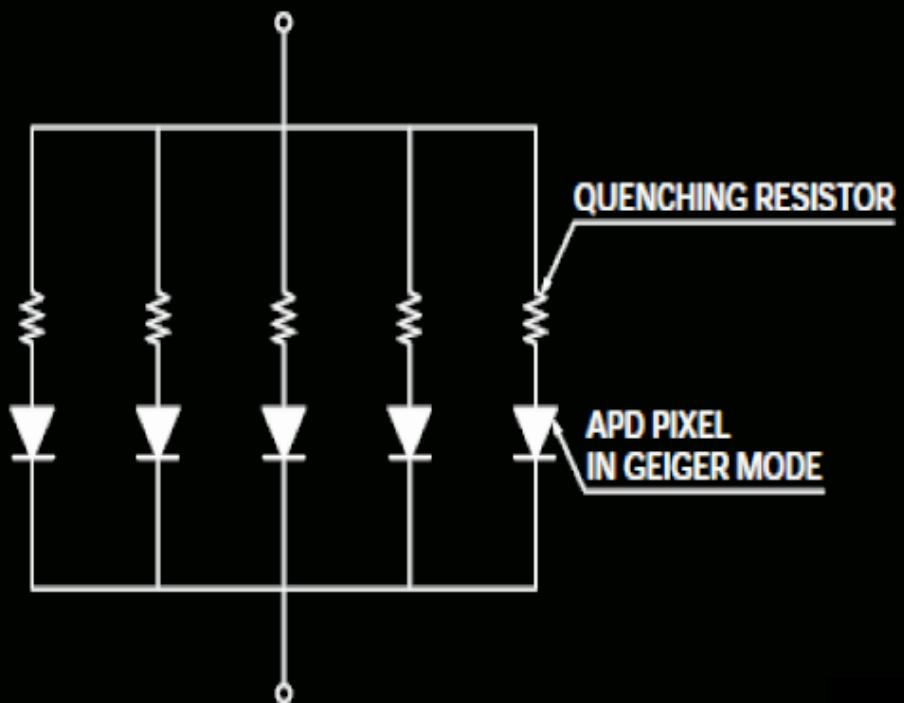
This gives the same size voltage pulse across R_S for ≥ 1 photon as it does for =1 photon.



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A newer technology uses silicon diodes and an avalanche process to more easily detect single photons.

Photons can be *counted* by arranging an array of these “Avalanche photodiodes” (APDs) together.



A new, simpler, lower voltage, silicon photomultiplier = SiPM

Go learn about SiPMs.

Start with a coarse overview, then find a paper that you scan through and maybe read enough of to get a general idea.

Put a link to useful resources in your ELog so you can go back to get more depth later if/when needed.

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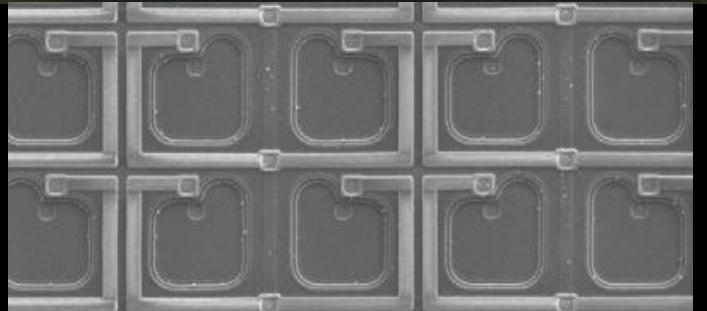
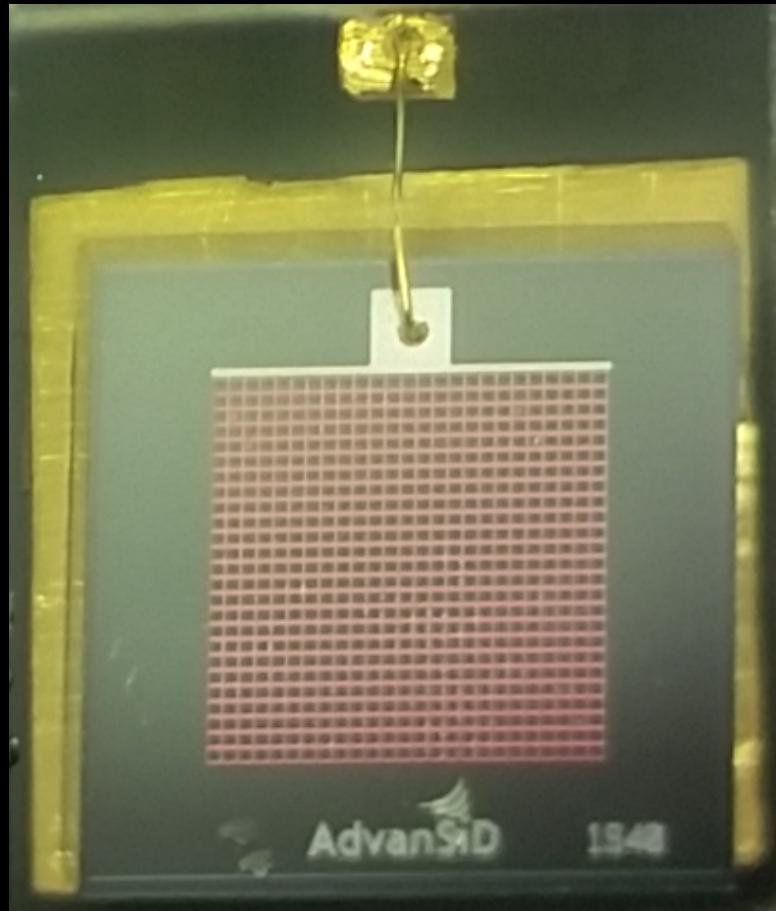
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So, let's look carefully enough to see light come in one photon at a time.

Observing light one photon at a time

For this we will use a pre-built SiPM circuit.
You will “build your own” later in the class.

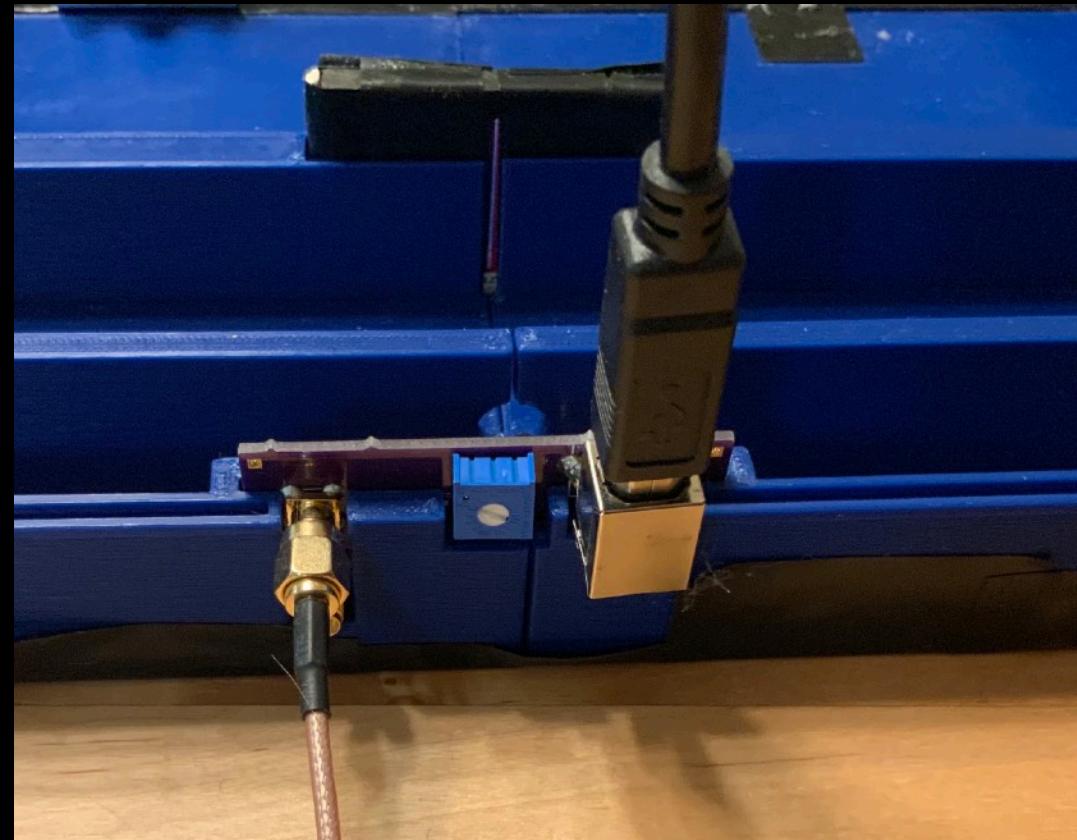


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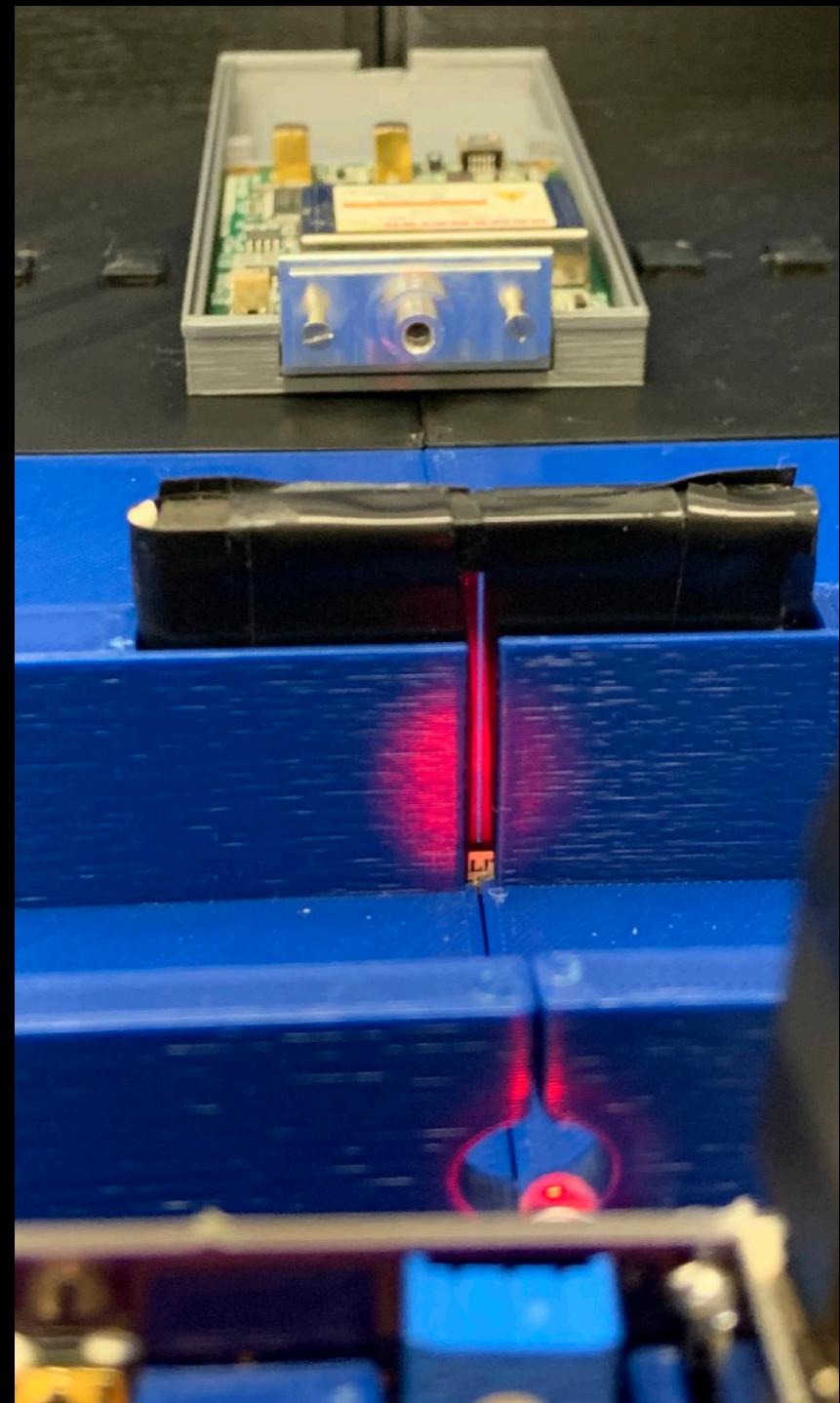


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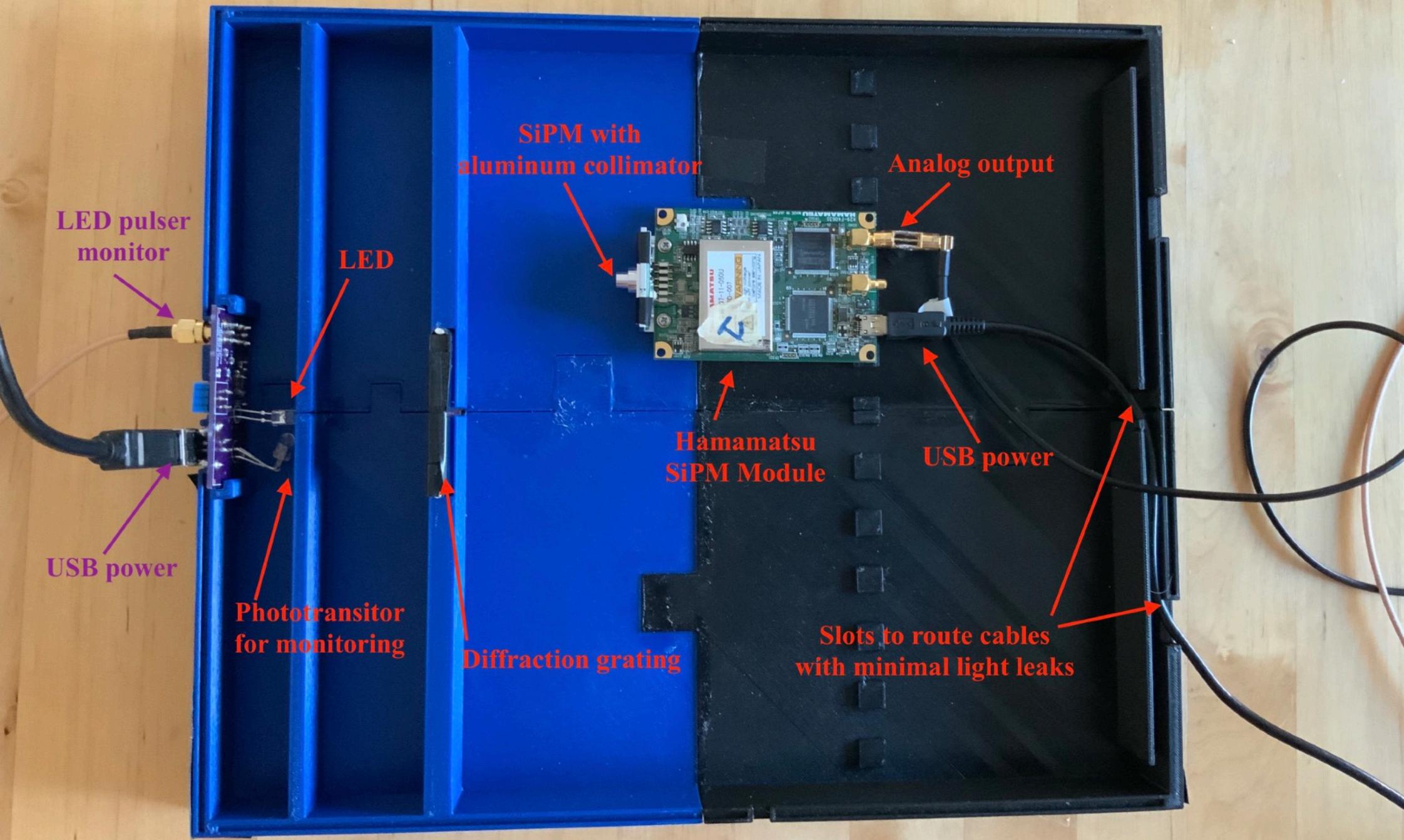
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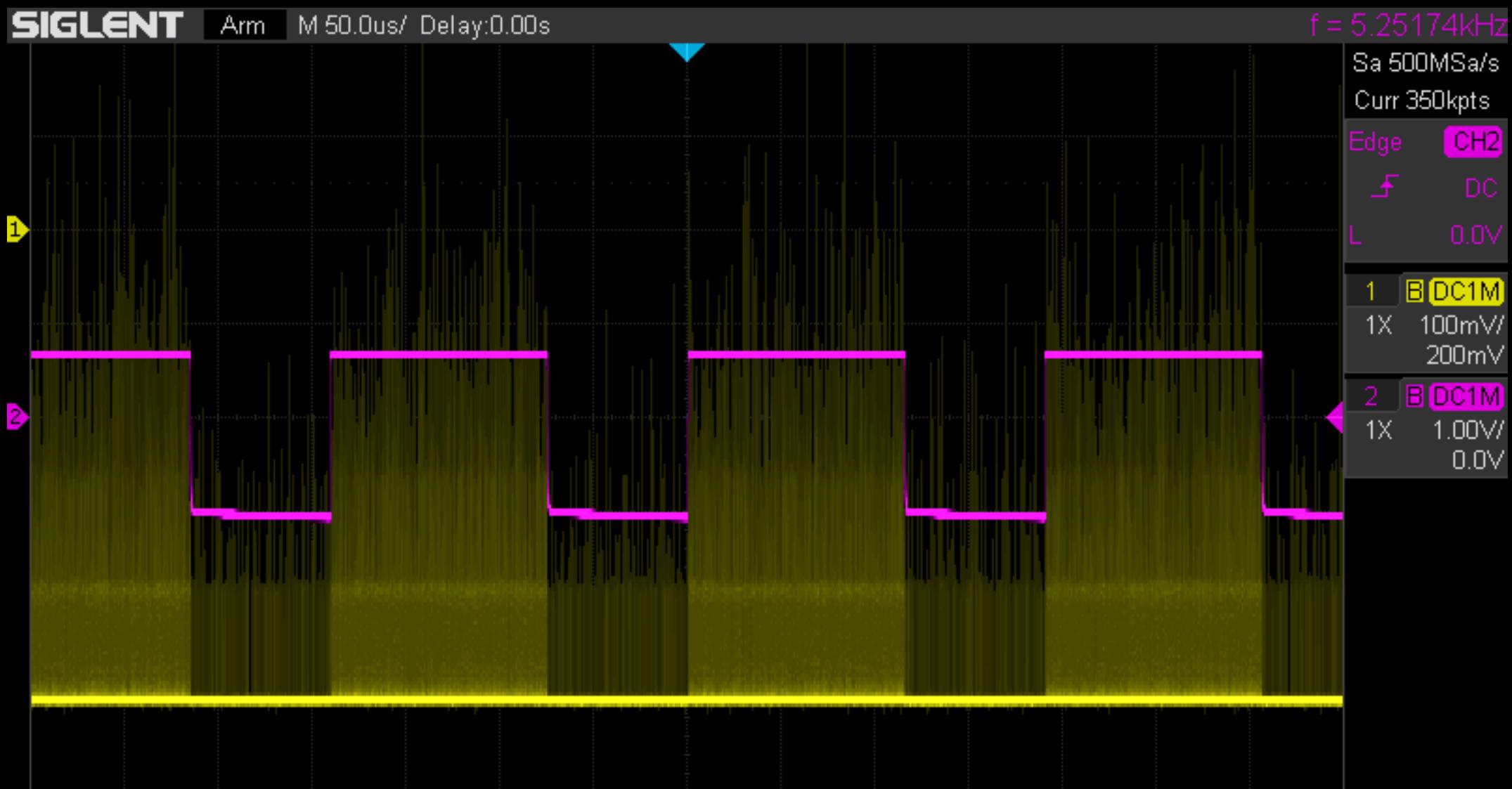
Better make it “light tight” to reduce
background light.



Observing light one photon at a time

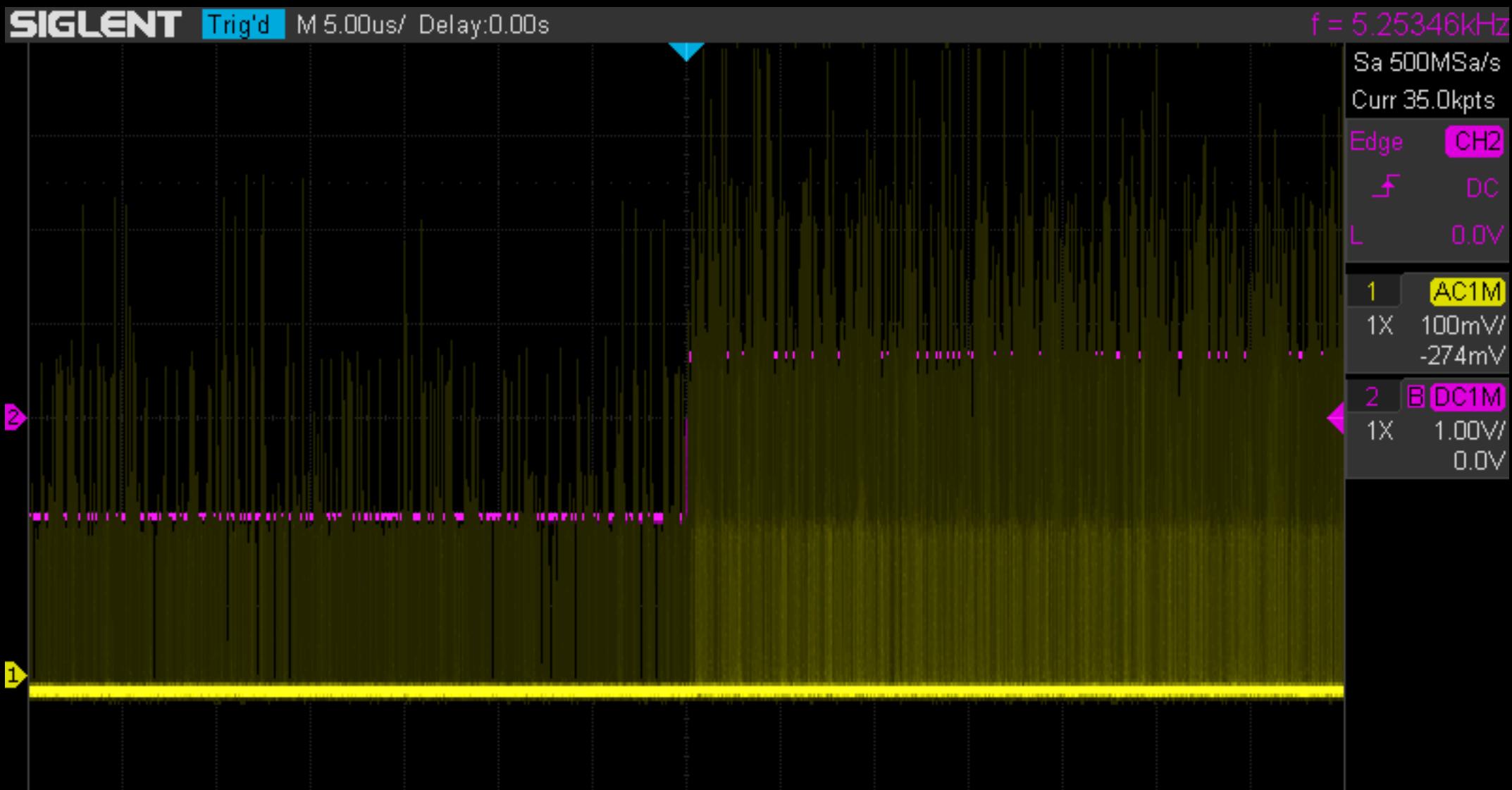


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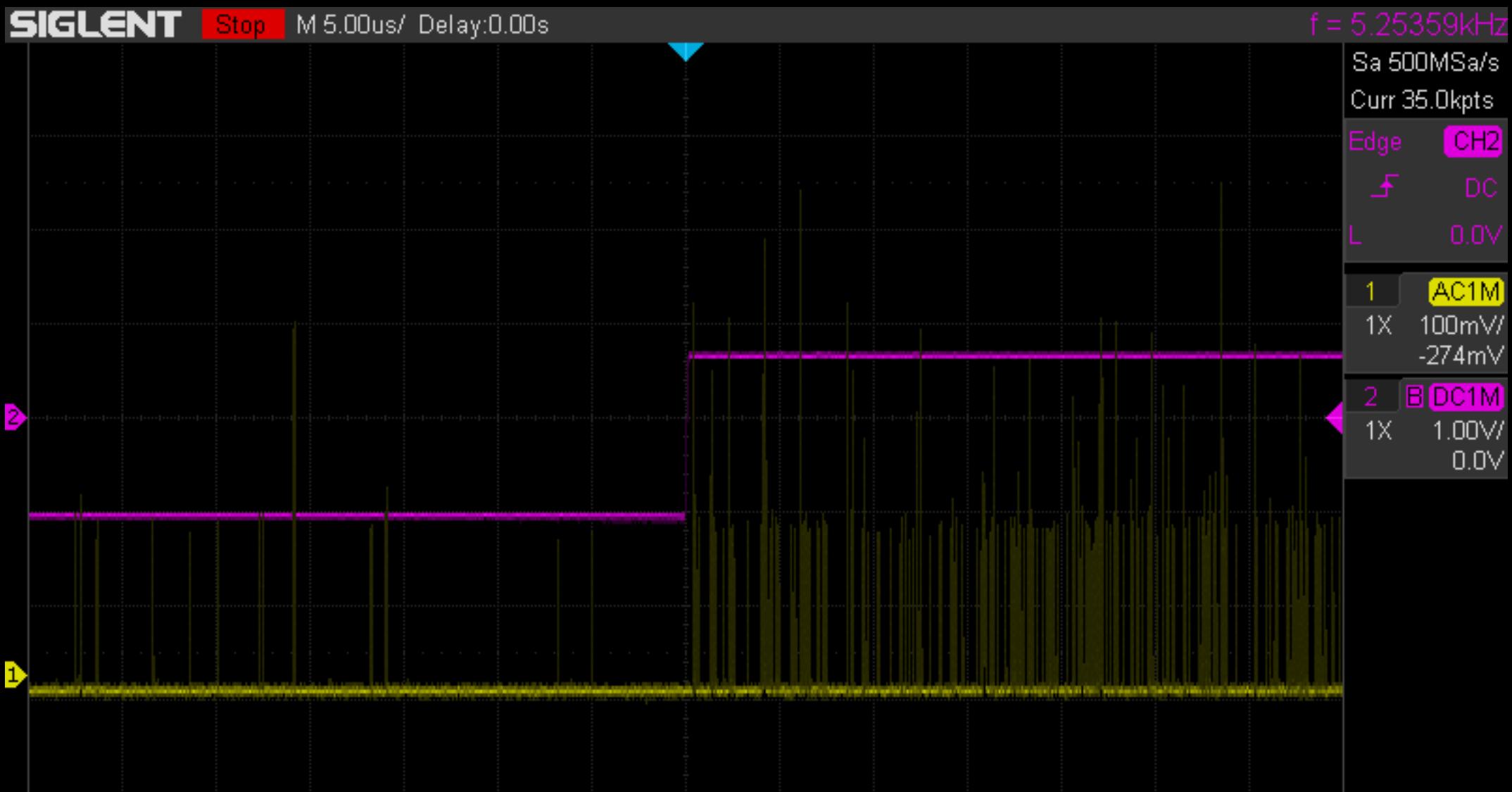
This is a view of the scope looking at the SiPM output on CH1 and the LED pulse on CH2. It is actually an integrated image of many triggers.

Observing light one photon at a time



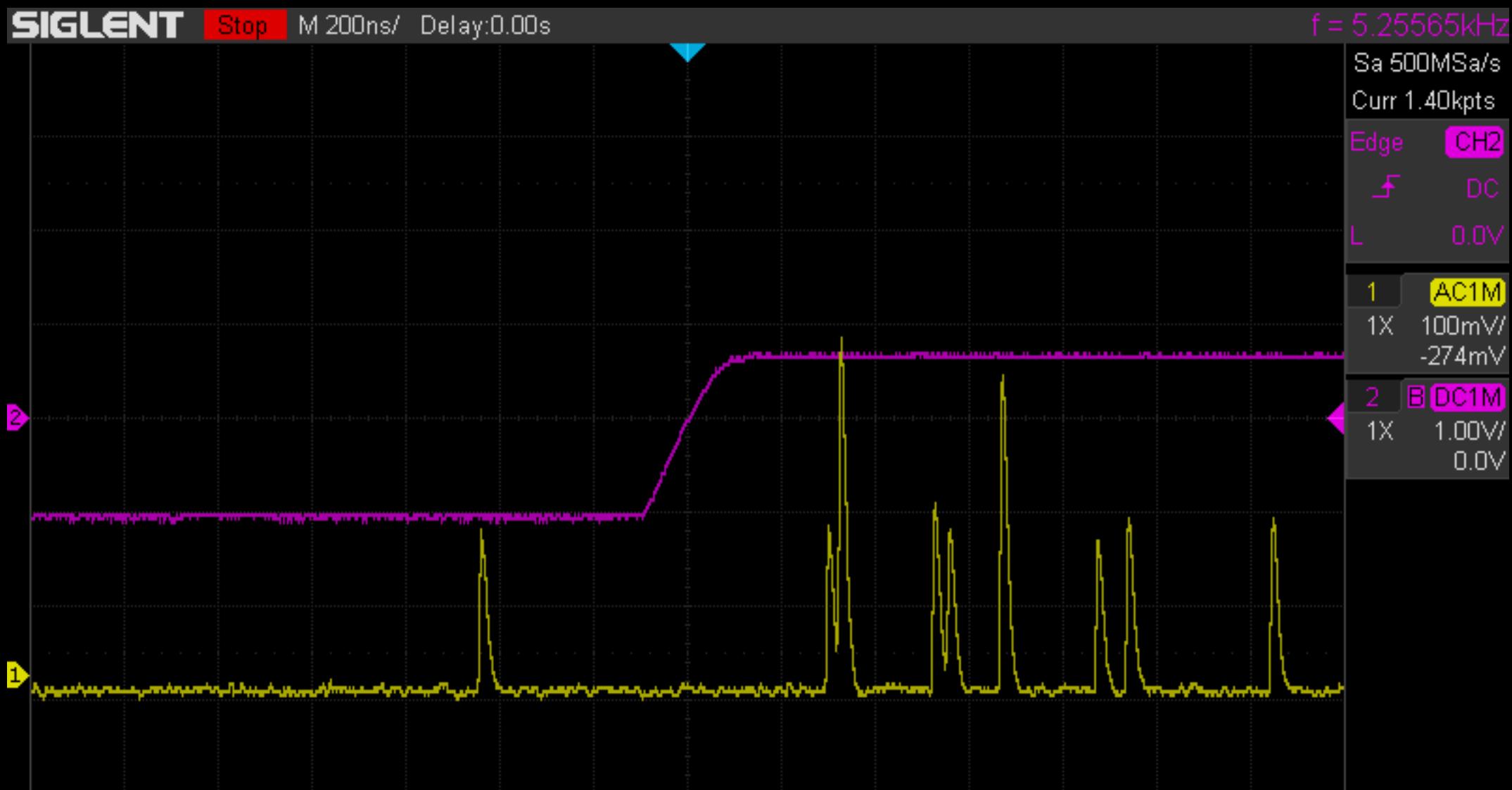
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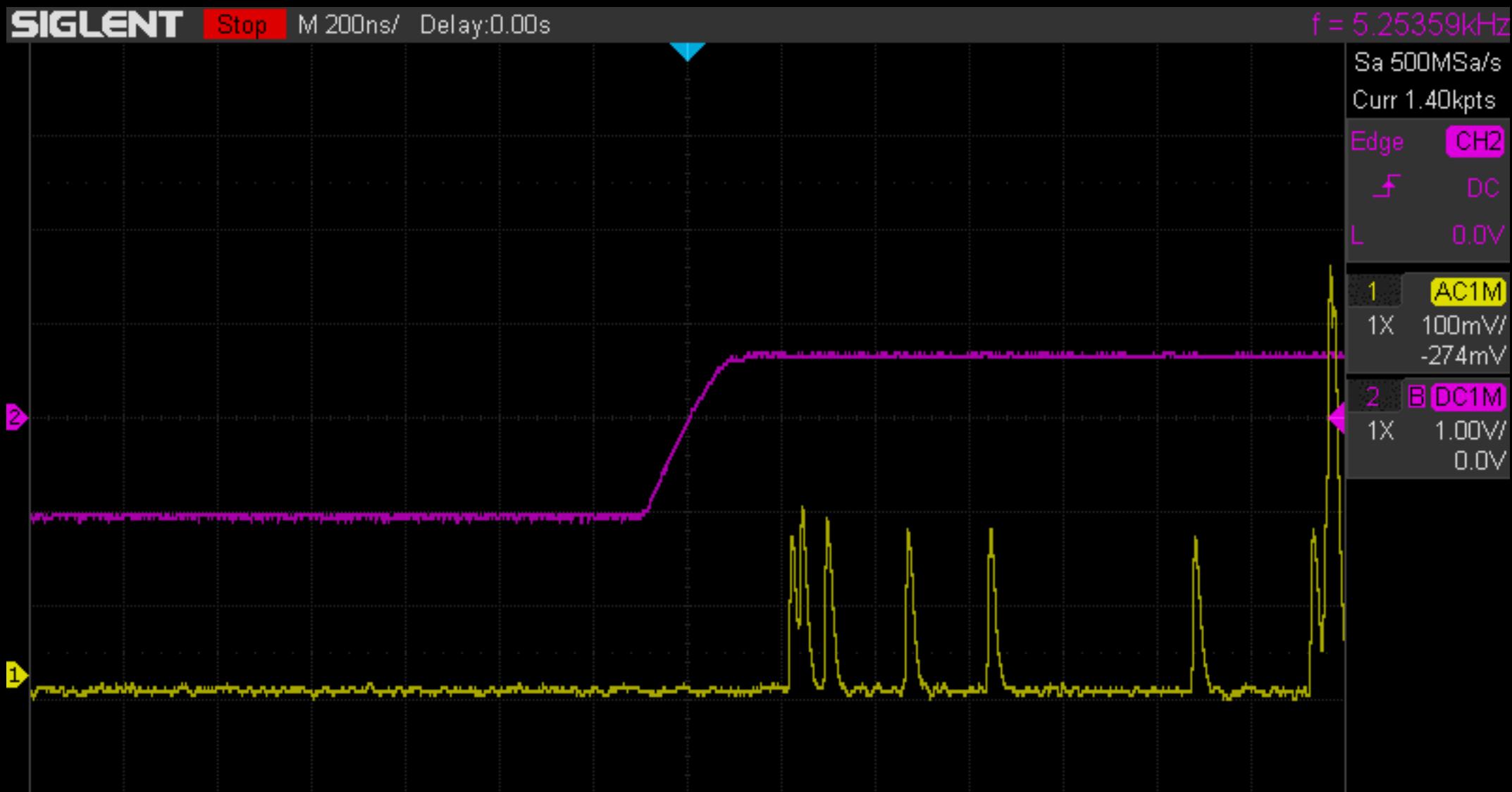
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Observing light one photon at a time



This is a view of the scope looking at the SiPM output on CH1 and the LED pulse on CH2. It is a single capture from one LED flash. Zoomed in time wise by a factor of 25.

Observing light one photon at a time



This is a view of the scope looking at the SiPM output on CH1 and the LED pulse on CH2. It is an animation of several sequential LED flashes. Zoomed in time wise by a factor of 25.

Observing light one photon at a time

This shows that the light is detected as “forest of discrete pulses”, ie photons.

Observing light one photon at a time

This shows that the light is detected as “forest of discrete pulses”, ie photons. It is worth noting a few observations that generate questions:

- 1). Some photons come before the LED turns on.
- 2). There is a delay of ≈ 100 ns between the LED pulse and the first photons.
- 3). Most pulses are about 200 mV high, but some are 400 mV or even 600 mV.
- 4). The 200 mV pulses are mostly the same height but there is a small variation.

Why?

How could you test the hypotheses you develop for explaining these observations?

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- You may not have time to test the hypotheses, due to other priorities, but thinking about them helps you recognize related observations later.

To study the details, we move from a 1st coarse view to a more quantitative approach. Process a lot of events and look at the *distribution* of arrival time, pulse height, etc.

Analyzing photons in LED pulser

Process a lot of events and look at the *distribution* of arrival time, pulse height, etc.
Most oscilloscopes allow you to save the waveforms as $V(t)$ in a data file (eg CSV).
It is usually slow and arduous.

I will use a [DRS](#) waveform digitizer to save data.

It saves the data in various formats, including an XML format that is easily parsed.

```
<?xml version="1.0" encoding="ISO-8859-1"?>
<!-- created by MXML on Sun Dec 27 20:19:26 2020 -->
<DRS0SC>
  <Event>
    <Serial>1</Serial>
    <Time>2020/12/27 20:19:26.555</Time>
    <HUnit>ns</HUnit>
    <VUnit>mV</VUnit>
    <Board_2988>
      <Trigger_Cell>188</Trigger_Cell>
      <Scaler0>30</Scaler0>
      <CHN1>
        <Data>-135.584,3.0</Data>
        <Data>-134.529,1.9</Data>
        <Data>-133.578,0.8</Data>
        <Data>-132.474,-0.3</Data>
        <Data>-131.555,-2.2</Data>
        <Data>-130.500,-1.0</Data>
        <Data>-129.445,0.3</Data>
```

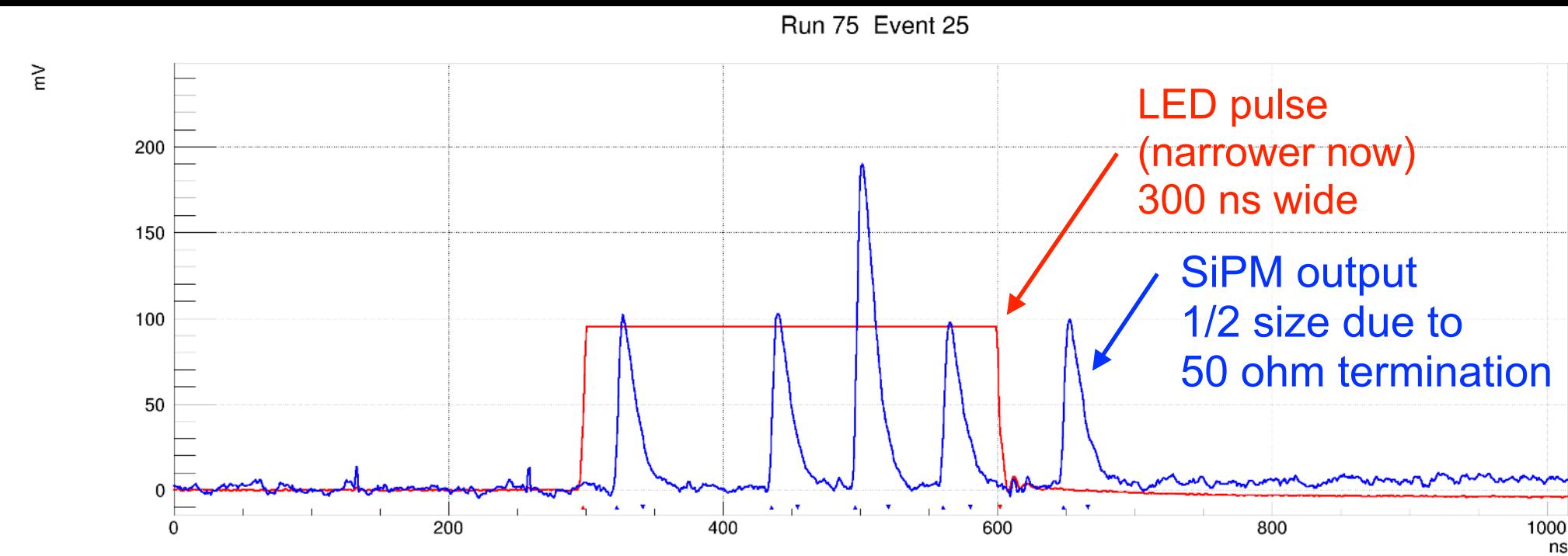
Analyzing photons in LED pulser

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Note two differences from previous oscilloscope views.



Analyzing photons in LED pulser

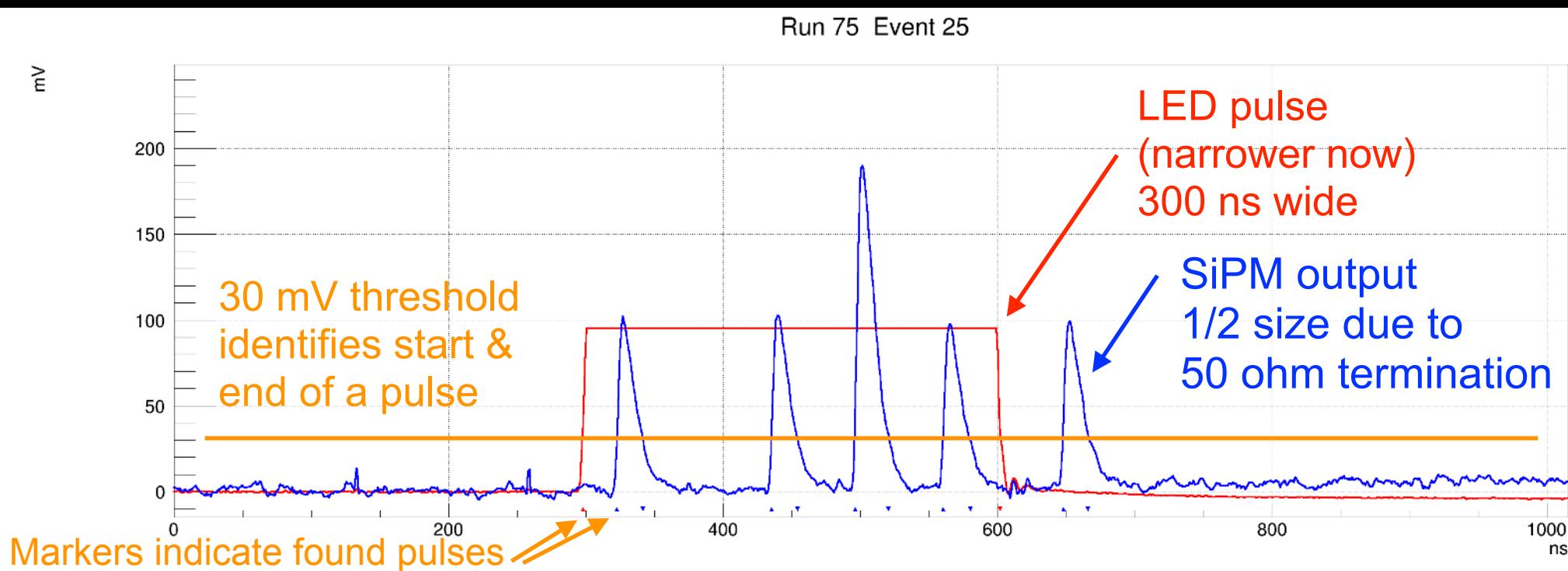
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Can algorithmically identify each pulse and save & analyze info about all pulses.



Analyzing photons in LED pulser

Process a lot of events and look at the *distribution* of arrival time, pulse height, etc.

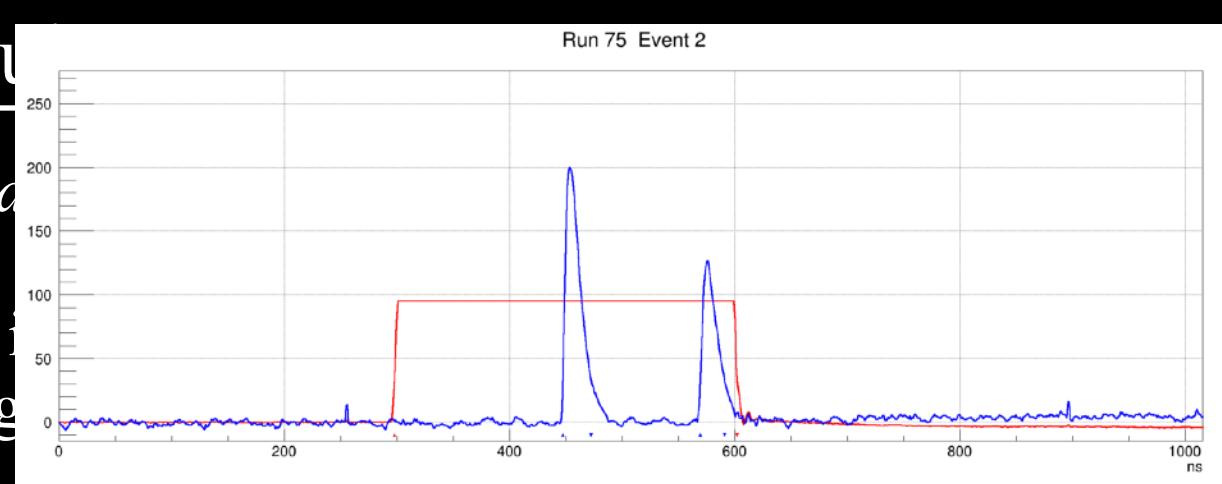
Save the information about each pulse into a new “distilled” data format. Such data is called an `ntuple`, following the mathematical concept.

Each line is one pulse, each column is a different observable for that pulse.

Analyzing photons in LED pu

Process a lot of events and look at the q

Save the information about each pulse
Such data is called an ntuple, following



Each line is one pulse, each column is a different observable for that pulse.

| Event # | t_in_run | t_between_events | # of pulses in event | # of pulses in CH1 | # of pulses in CH2 | # of pulses in CH3 | # of pulses in CH4 | RMS of channel | Channel # for pulse | Pulse # within channel | Time (ns) of pulse | Area of pulse (nVs) | Height of pulse (mV) | Width of pulse (ns) |
|---------|-----------|------------------|----------------------|--------------------|--------------------|--------------------|--------------------|----------------|---------------------|------------------------|--------------------|---------------------|----------------------|---------------------|
| 1 | 0.0000000 | 0.0000000 | 2 | 1 | 1 | 0 | 0 | 0.12421 | 1 | 0 | 297.335 | 26.509 | 95.011 | 304.52 |
| 1 | 0.0000000 | 0.0000000 | 2 | 1 | 1 | 0 | 0 | 0.97036 | 2 | 0 | 524.729 | 2.4030 | 116.08 | 27.597 |
| 2 | 0.0289993 | 0.0289993 | 3 | 1 | 2 | 0 | 0 | 0.16039 | 1 | 0 | 297.772 | 29.116 | 94.997 | 304.46 |
| 2 | 0.0289993 | 0.0289993 | 3 | 1 | 2 | 0 | 0 | 1.96286 | 2 | 0 | 447.577 | 3.1643 | 199.94 | 24.706 |
| 2 | 0.0289993 | 0.0289993 | 3 | 1 | 2 | 0 | 0 | 1.96286 | 2 | 1 | 569.603 | 1.9781 | 126.74 | 21.563 |
| 3 | 0.0359993 | 0.0069999 | 3 | 1 | 2 | 0 | 0 | 0.30539 | 1 | 0 | 296.961 | 25.254 | 95.076 | 304.11 |
| 3 | 0.0359993 | 0.0069999 | 3 | 1 | 2 | 0 | 0 | 1.56348 | 2 | 0 | 553.774 | 1.1561 | 90.305 | 19.174 |
| 3 | 0.0359993 | 0.0069999 | 3 | 1 | 2 | 0 | 0 | 1.56348 | 2 | 1 | 588.842 | 1.3664 | 105.31 | 18.257 |

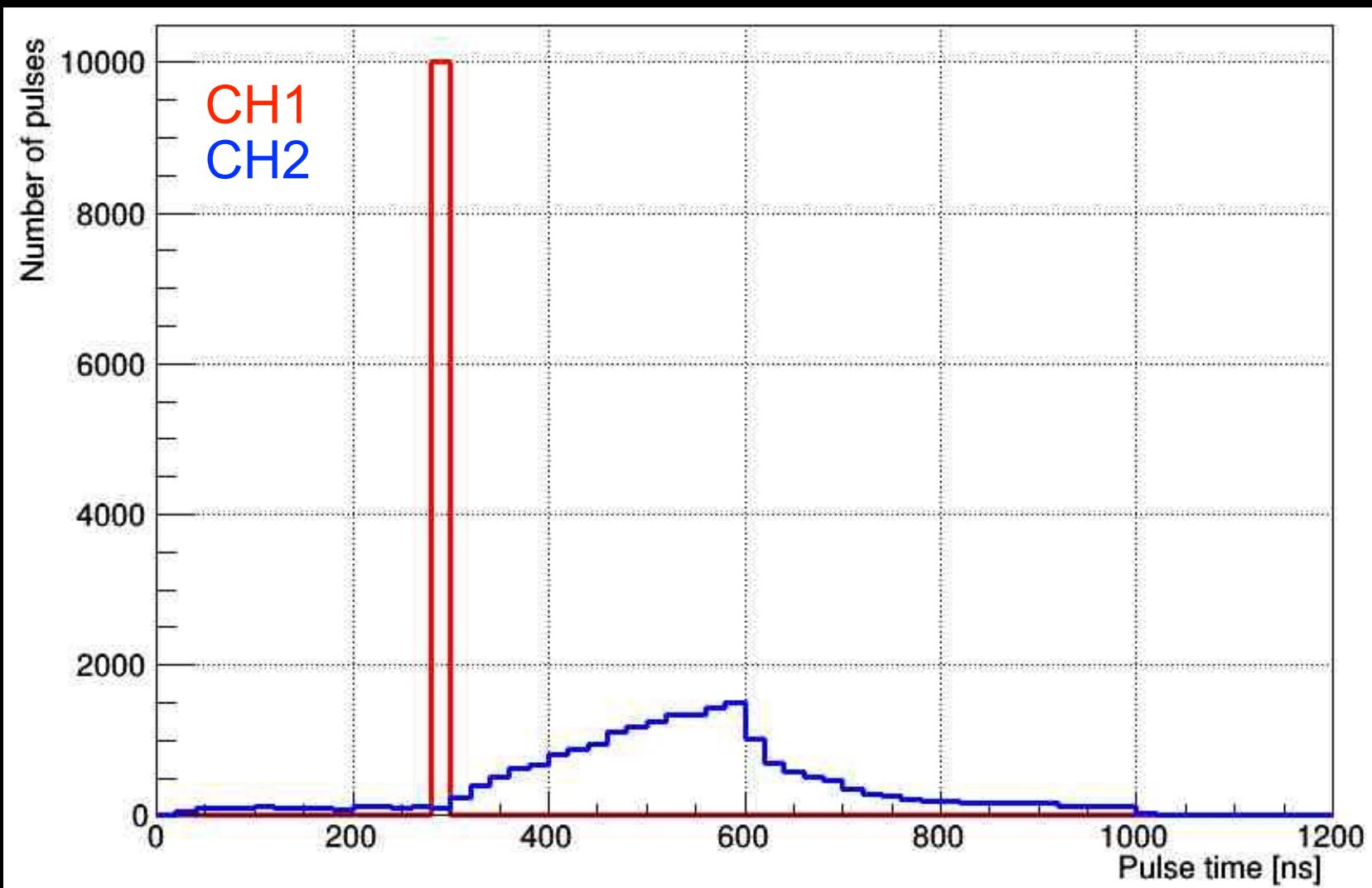
Analyzing photons in LED pulser

We can then develop fairly simple tools to analyze this distilled data.

E.g., make a histogram of the time of pulses.

A histogram is a common way to analyze data.

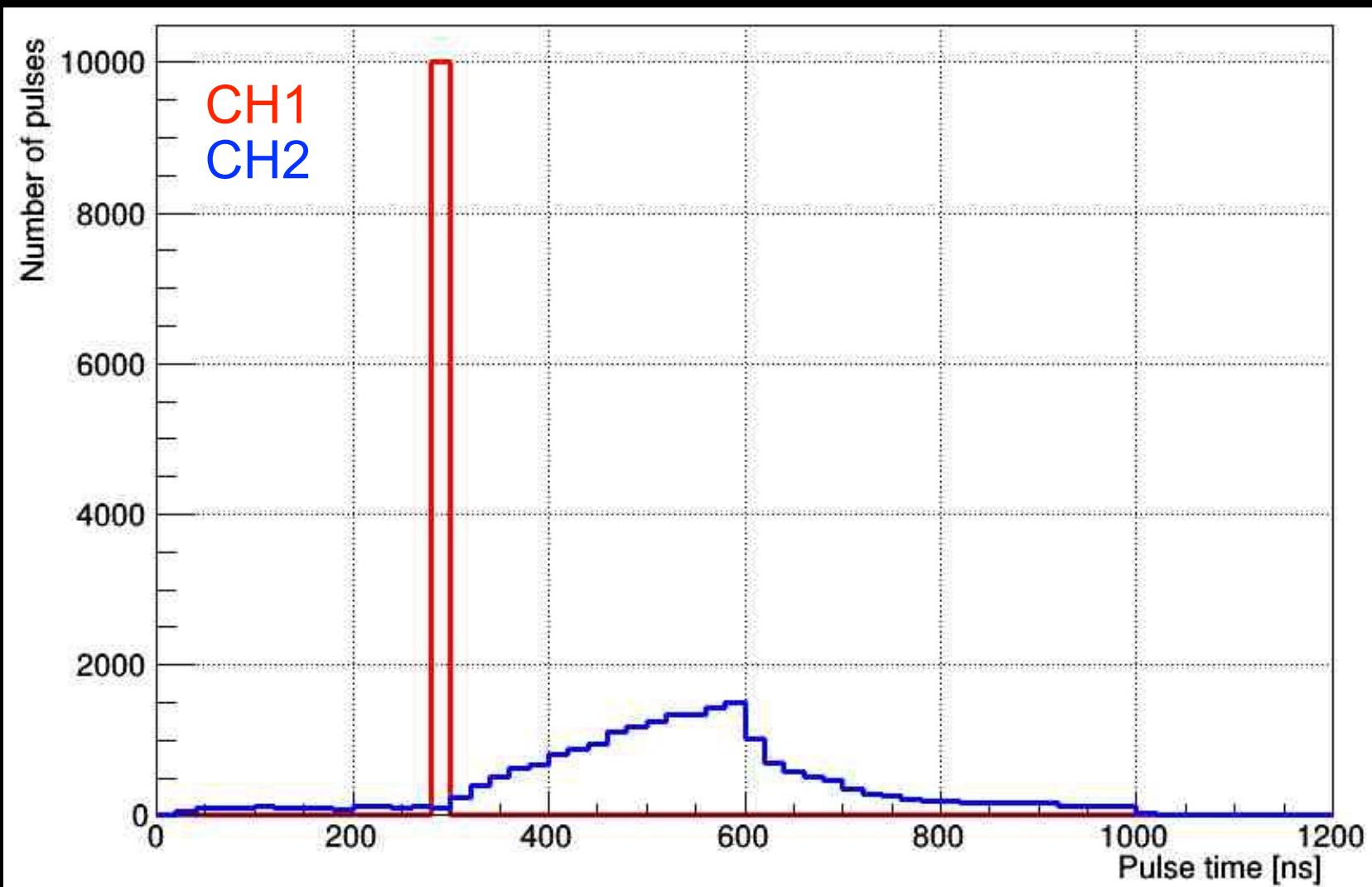
You will do this as an exercise in lab. Phys129L or plenty of online tutorials.



Analyzing photons in LED pulser

Histogram of the time of pulses.

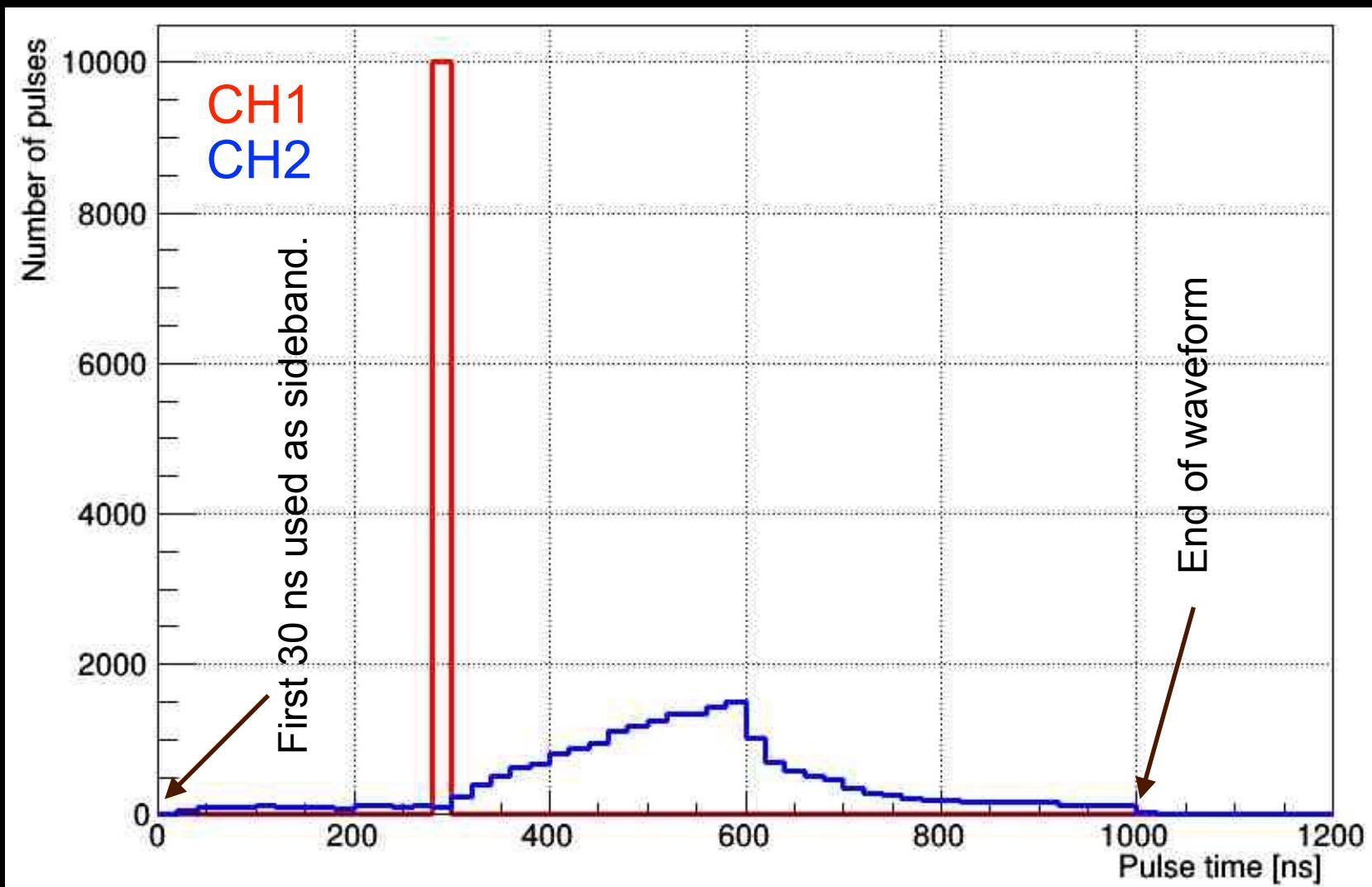
What observations can you make, or what conclusions can you draw?



Analyzing photons in LED pulser

Histogram of the time of pulses.

What observations can you make, or what conclusions can you draw?

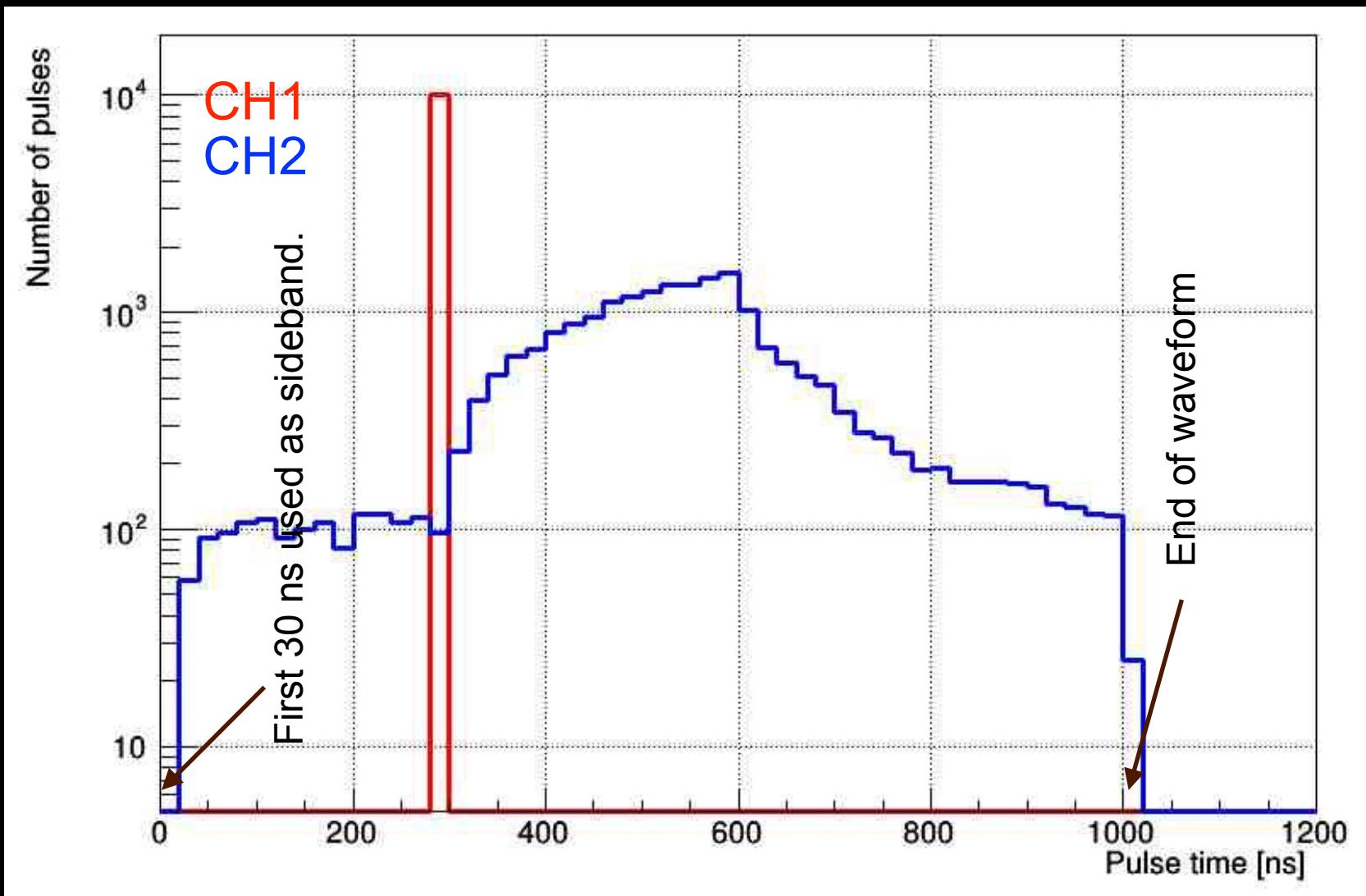


Analyzing photons in LED pulser

Histogram of the time of pulses.

What observations can you make, or what conclusions can you draw?

Using a logarithmic scale for the y-axis better shows the rarer entries.

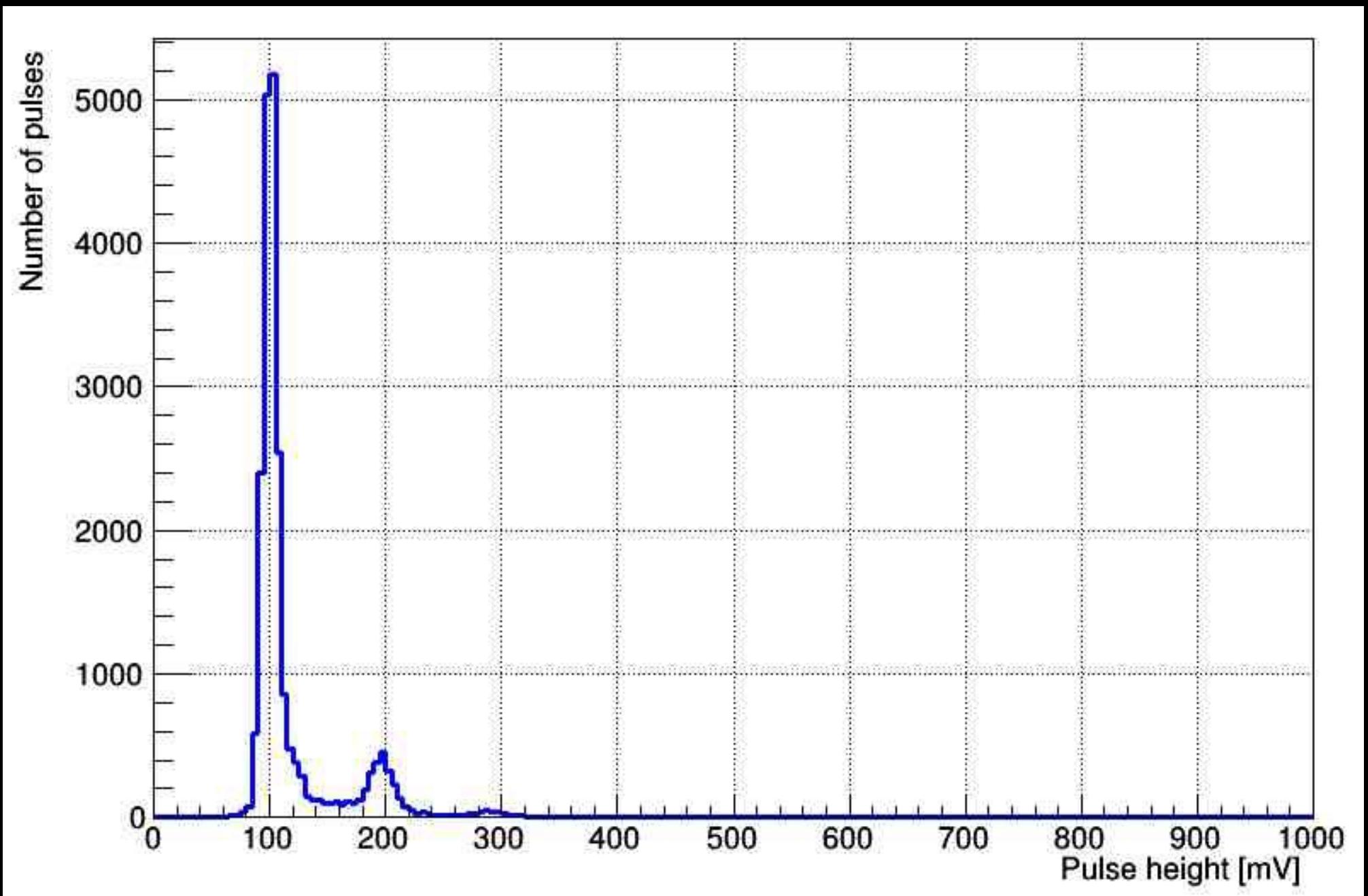


Analyzing photons in LED pulser

What else should we plot? What do we expect it to show? What can it teach us?

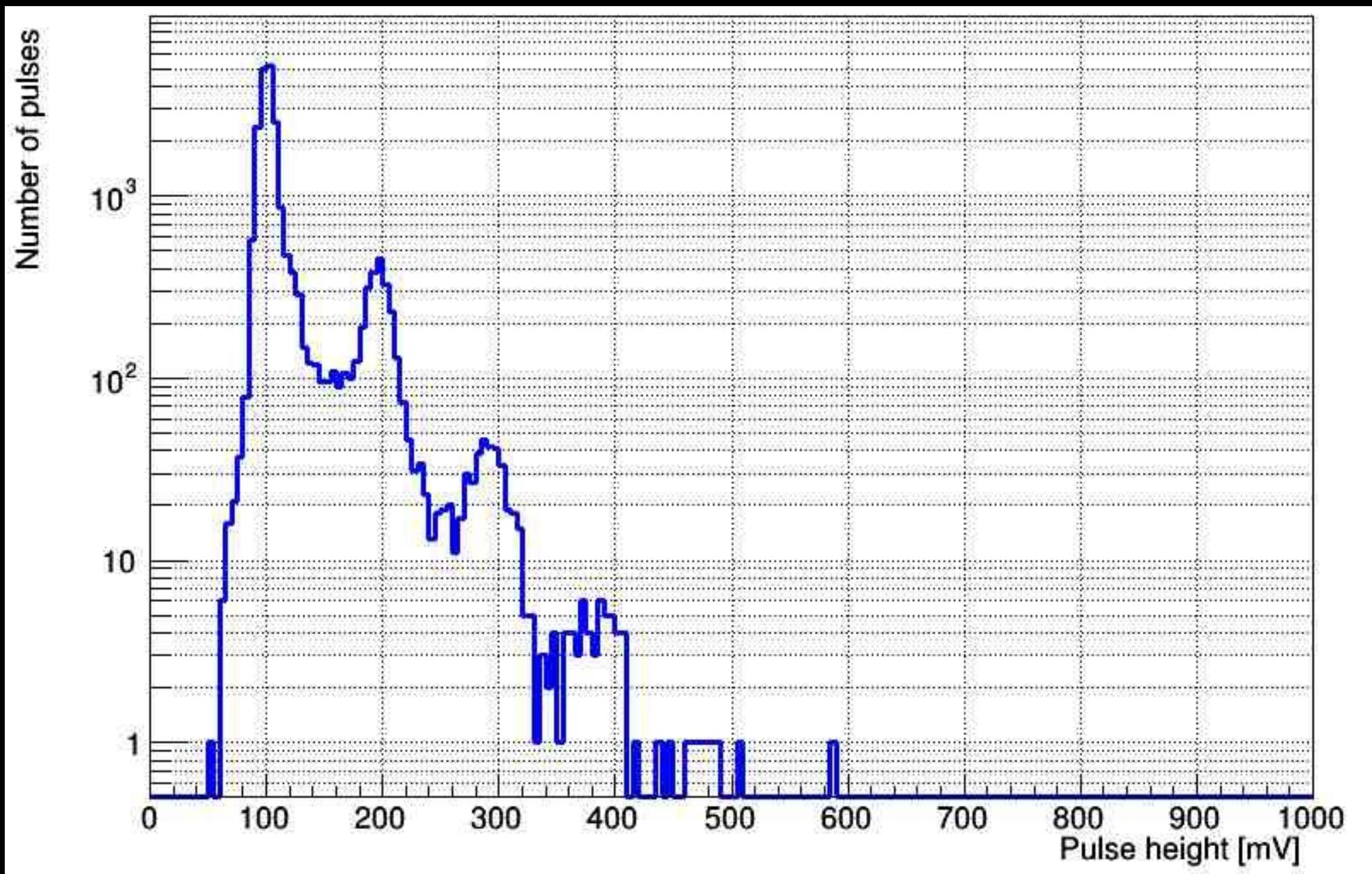
Analyzing photons in LED pulser

Distribution of pulse height.



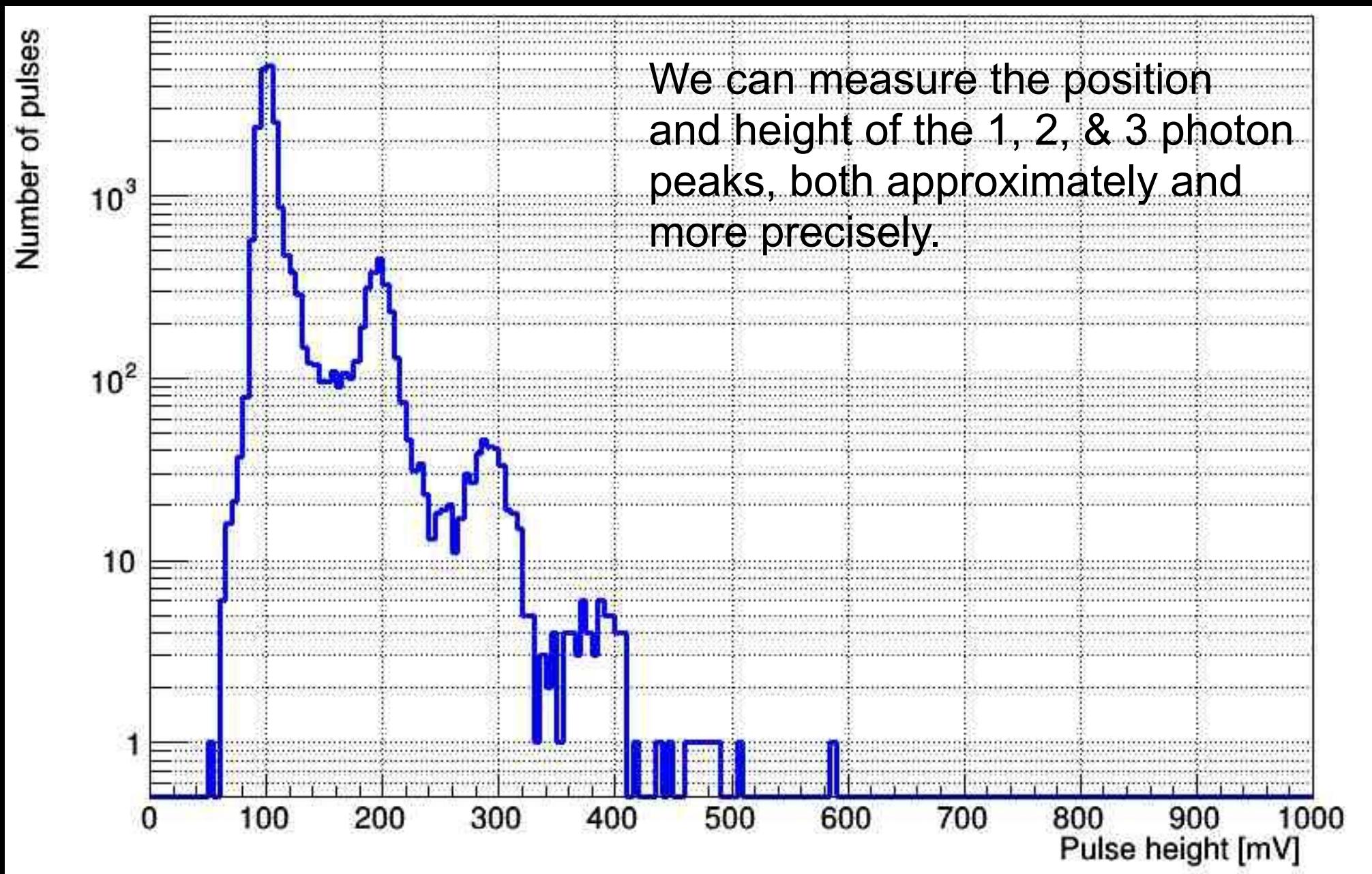
Analyzing photons in LED pulser

Distribution of pulse height, with a logarithmic y-axis scale to show rarer cases.



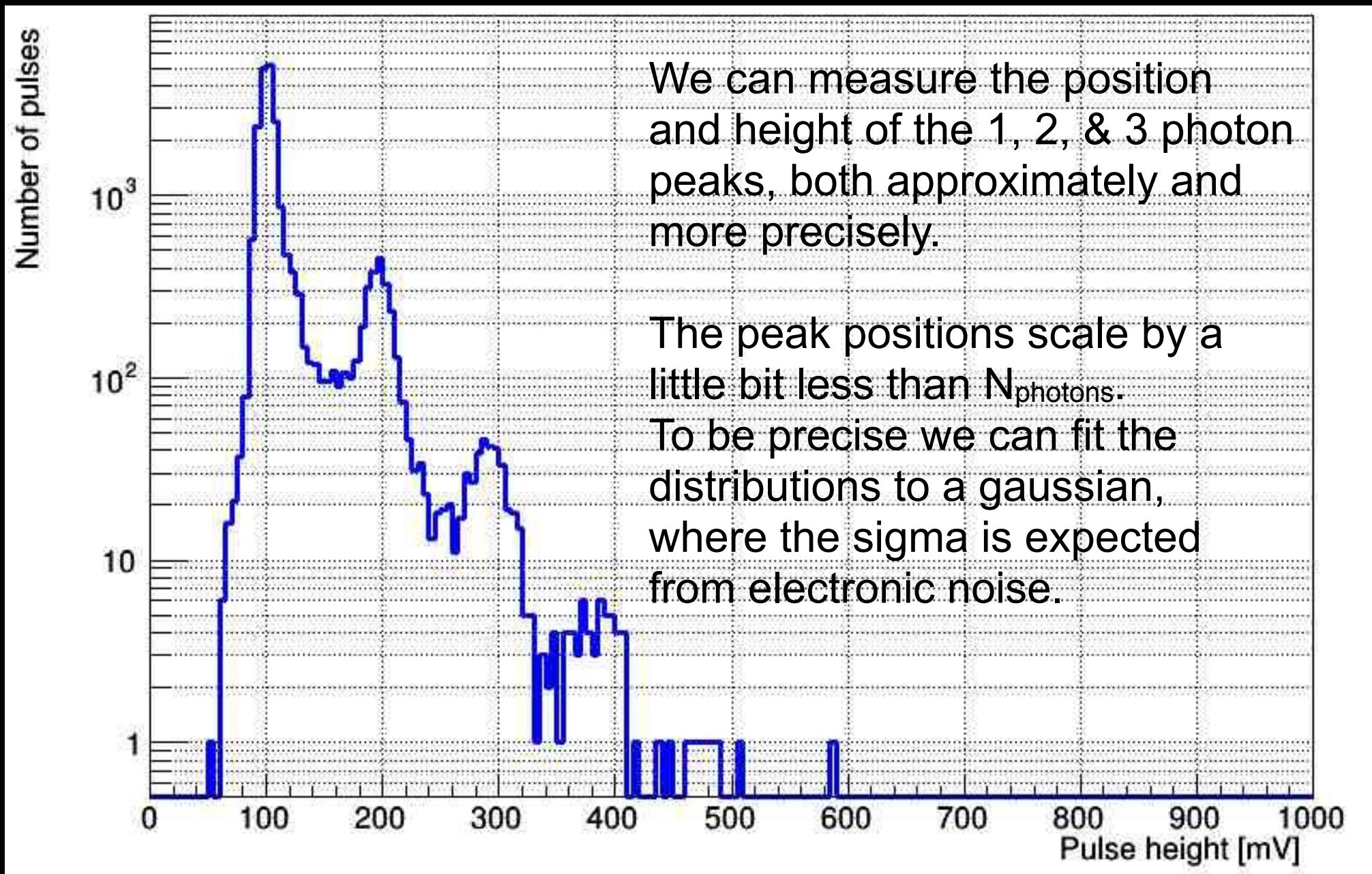
Analyzing photons in LED pulser

Distribution of pulse height, with a logarithmic y-axis scale to show rarer cases.



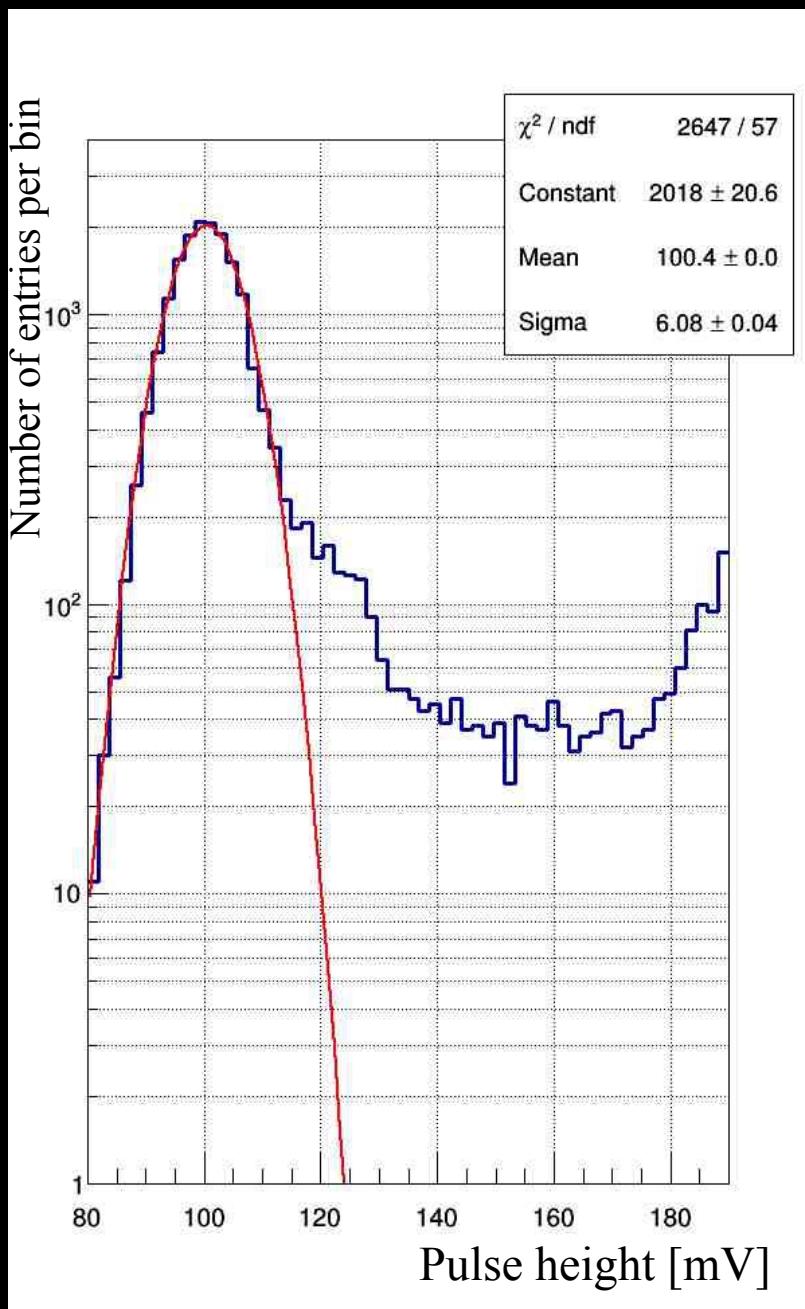
Analyzing photons in LED pulser

Distribution of pulse height, with a logarithmic y-axis scale to show rarer cases.



Analyzing photons in LED pulser

Fit a gaussian to the region near 1-photon.

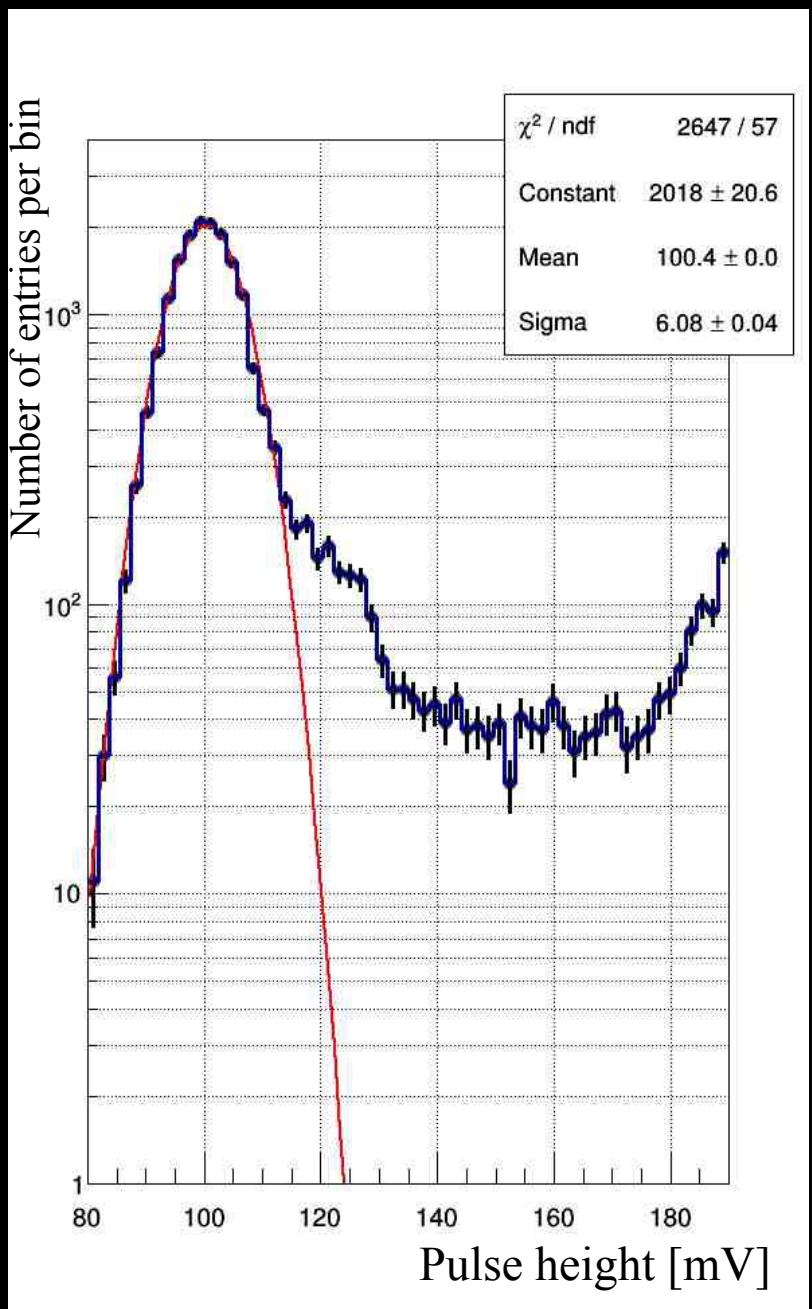


Things to note:

- Gaussian looks like parabola on log scale.
- Sigma is half-width at half maximum.
- Chi-squared is improbably large → bad fit.
- “Shoulder” at about 120-130 mV.
- “Filler” between 100 and 200 mV.

Analyzing photons in LED pulser

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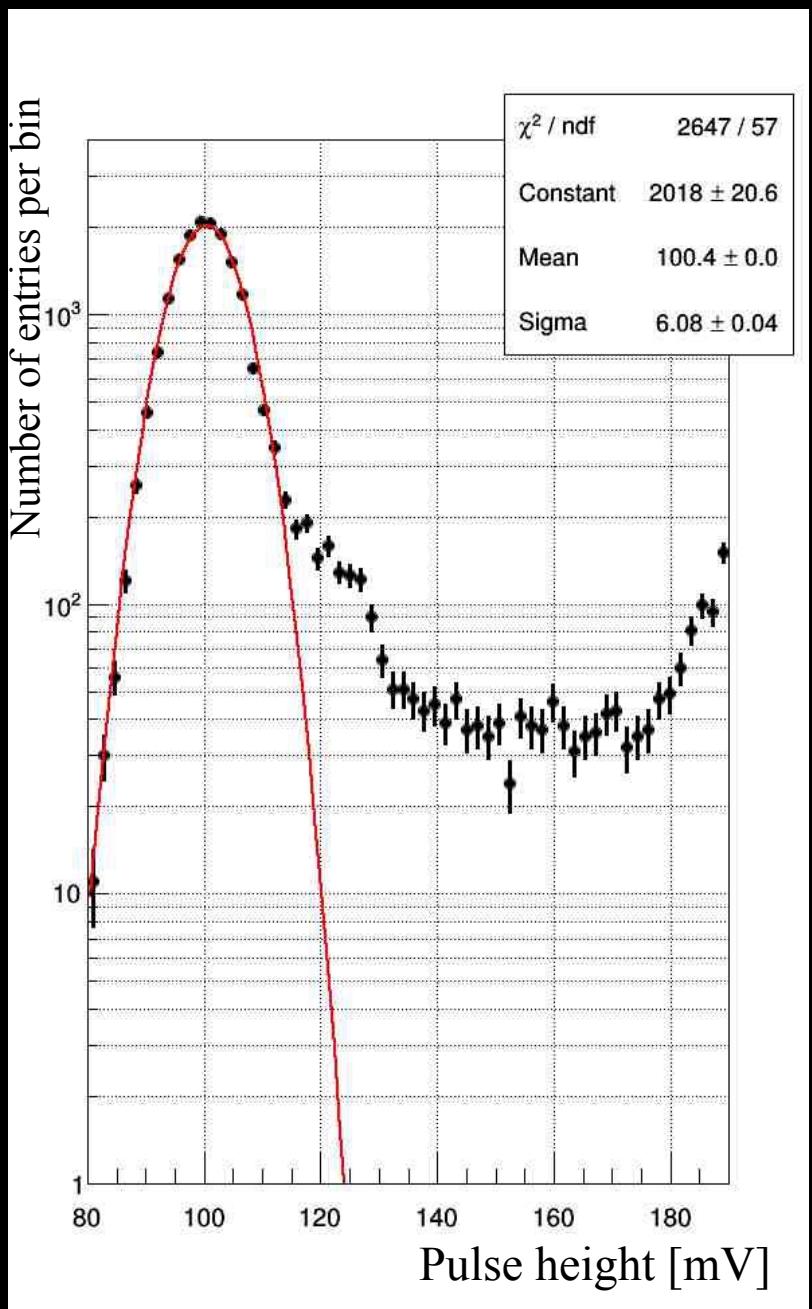
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Least-squares fit uses the error bars for each bin. The y-axis values are “counts” of how many pulses were seen with a height in the bin’s range. The uncertainty on an observed number, N , of counts is given by $\text{sqrt}(N)$.

Analyzing photons in LED pulser

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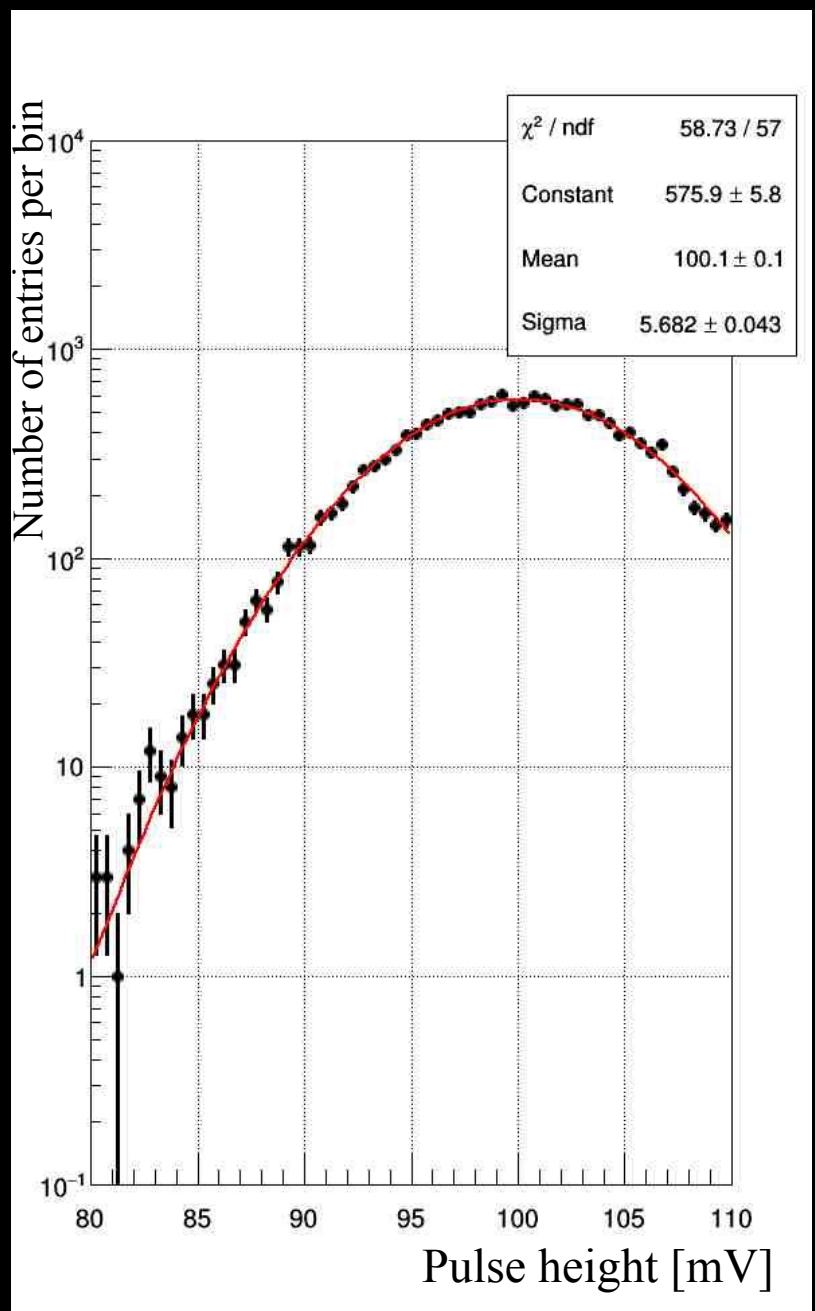
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Cleanest to show a histogram with lines when the errors are not shown and without the lines if the errors are shown.

Analyzing photons in LED pulser

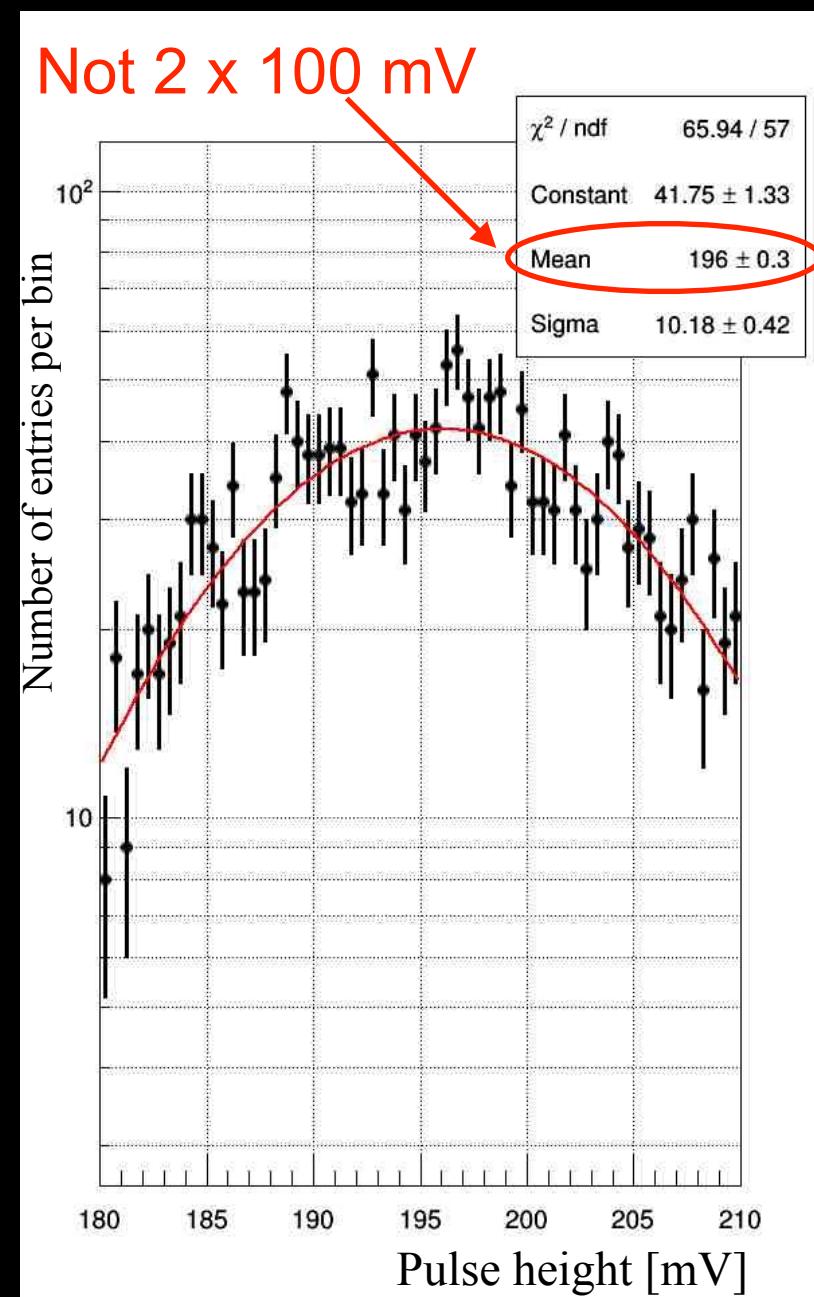
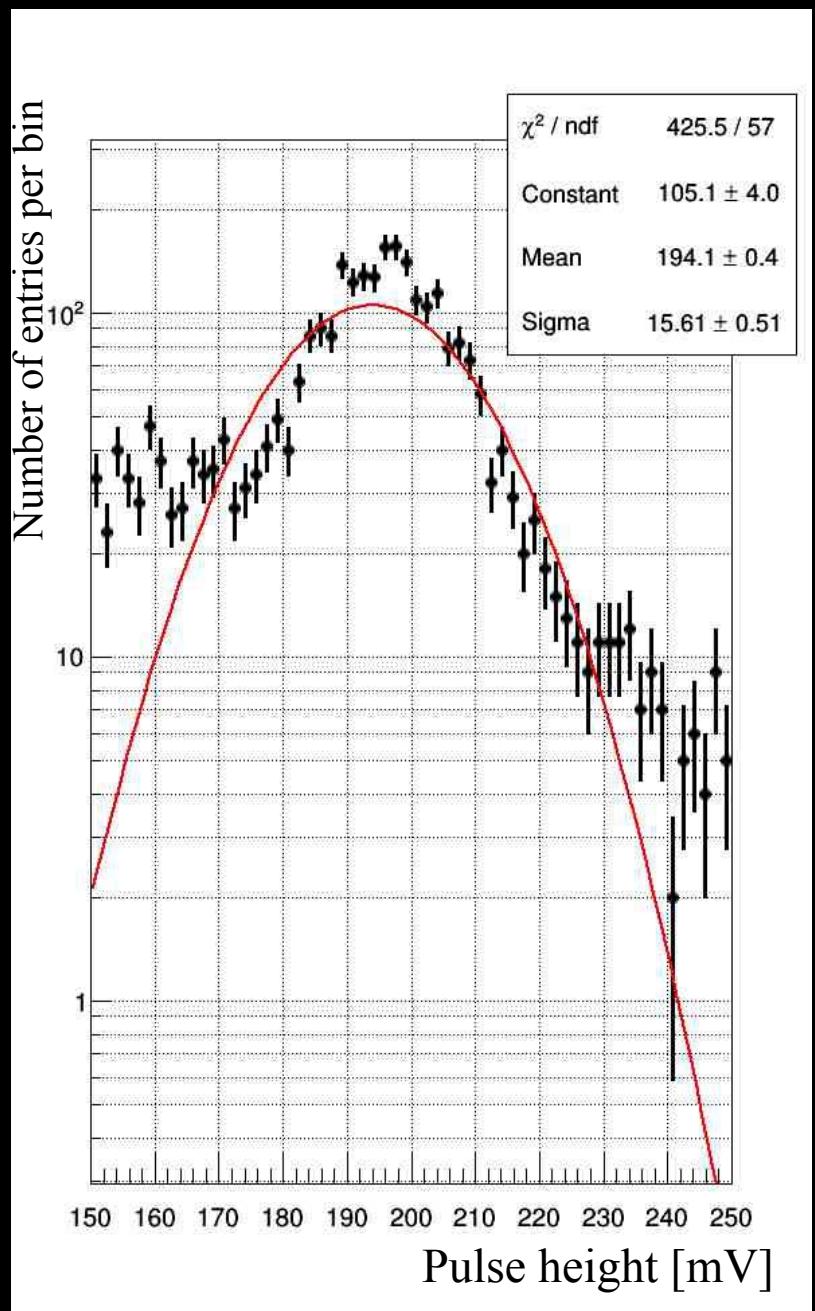
Distribution of pulse height, with a logarithmic y-axis scale to show rarer cases.



Zoom in and only fit the region without a bias from the "shoulder" or "filler".
Chi-squared now indicates a good fit.
Mean is consistent with 100 mV.

Analyzing photons in LED pulser

Do the same thing around the 2-photon peak region.



Analyzing photons in LED pulser

This illustrates how you can learn a lot by looking coarsely for effects, and then extract details about phenomena by making a few plots from a big dataset.

Ability to do such data analysis is a useful skill for research opportunities. E.g.,
“There is a hint that the N -photon peak size does not scale exactly as N .
Here is a file with a pile of data, go see if you can understand that effect in detail.”

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In a real research project you would need to figure out how to do that yourself. Start with a mix of existing skills and google & collaborate for the rest.

Then you should document what you did and what you found, including all the “blind alleys”, so you have ready answers for questions that arise when you present your work.

Analyzing photons in LED pulser

In lab you will analyze this dataset to learn whatever you can from it.

As preparation, your second homework assignment is:

- 1). Read about “least squares fit” and “chi-squared”.
- 2). Calculate the probability for the chi-squared values for the four fits shown.
- 3). Think of at least one possible reason why there may be a high shoulder at about 120 mV. What plot could you make from the data to test that hypothesis.
- 4). Think of at least one possible reason why the 2-photon peak is not at twice the 1-photon peak, i.e., 196 mV instead of 200 mV.

Write your homework as an entry in your ELog.

Due by Saturday at 6PM.

This is not “busy-work”, just what you’d normally do as follow up to that analysis.

You are free to brainstorm with classmates; that is important in research. However, your ELog post should acknowledge anyone who contributed key ideas, e.g., “Discussion with W. Blitzer provided insights for this idea.”

Many papers include acknowledgements like:

“We thank P. Dirac and G. Rivera for useful discussions.”

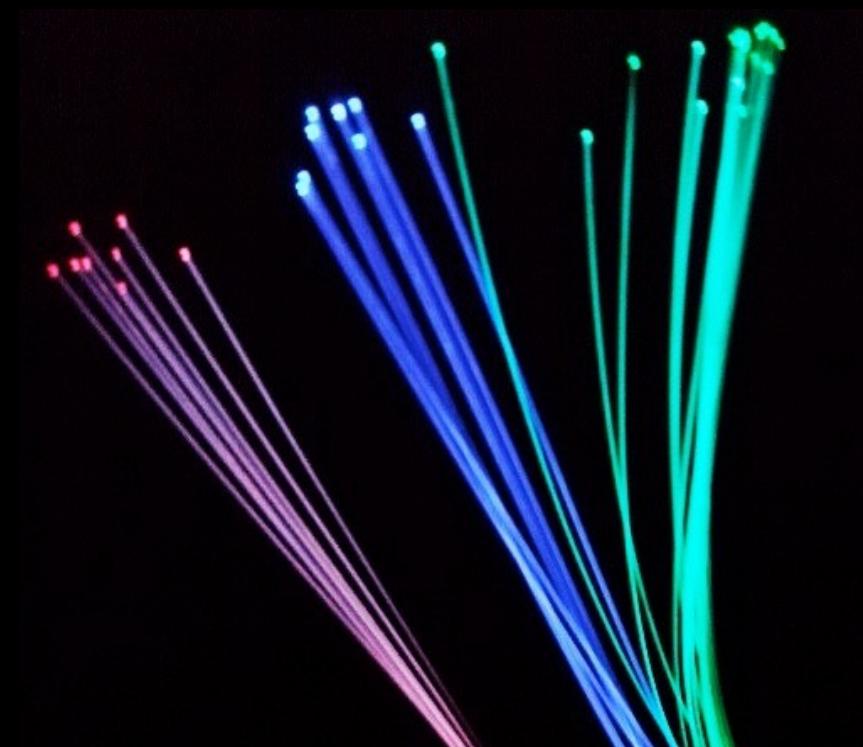
Detecting radiation with light

With the ability to detect single photons, we should be able to detect radiation based on photons emitted during de-excitation after ionization.

This is called “scintillation light”.

It can be optimized by choosing a detector material with complex organic molecules that have many energy states to produce near-UV photons as they de-excite.

Several companies make these,
mostly for medical imaging and
for the oil exploration market.



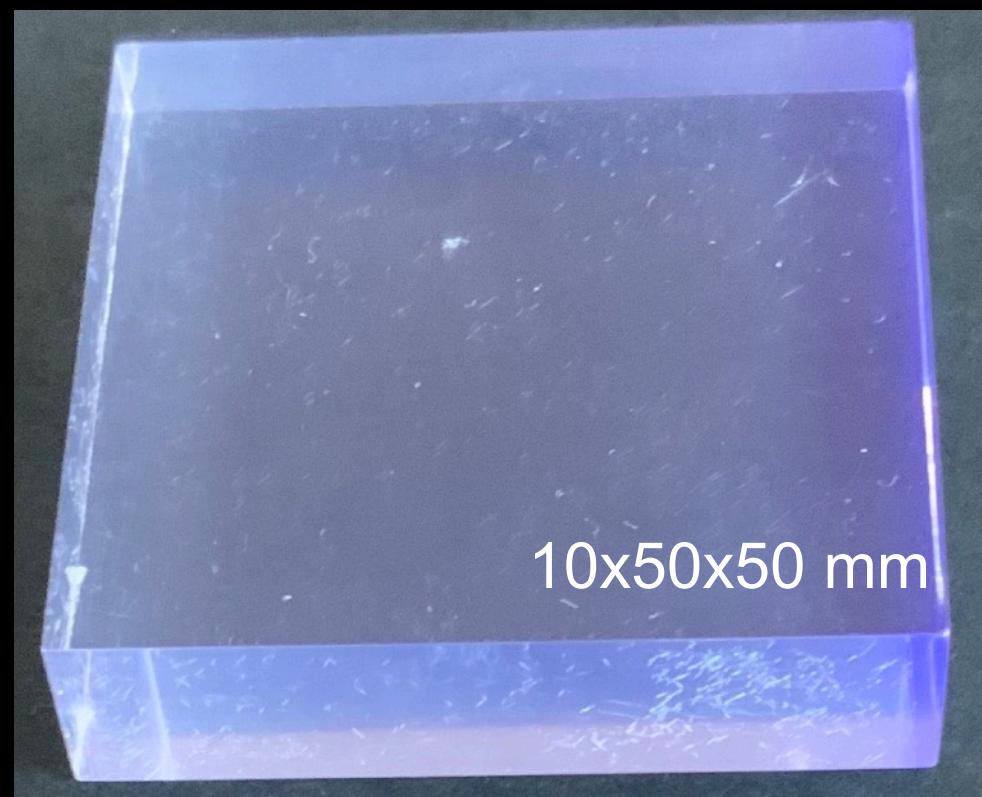
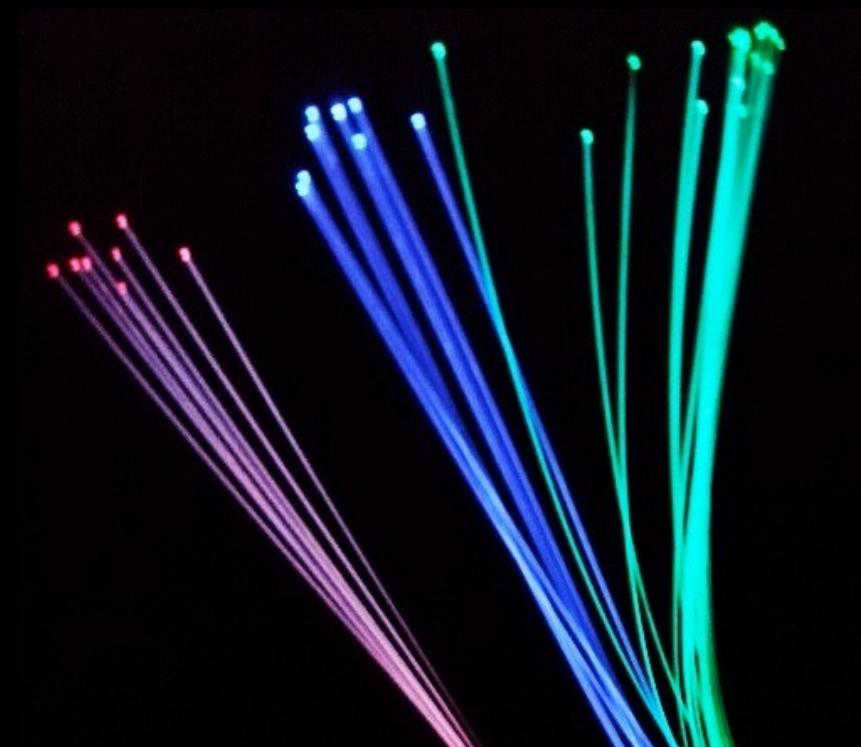
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Detecting radiation with light

With the ability to detect single photons, we should be able to detect radiation based on photons emitted during de-excitation after ionization.

Let's try to measure scintillation photons from a beta source on this little bar, placed in the "dark box". We'll look at this data next time.

