Physics 307L

Spring 2021

Prof. Darcy Barron

Reminders

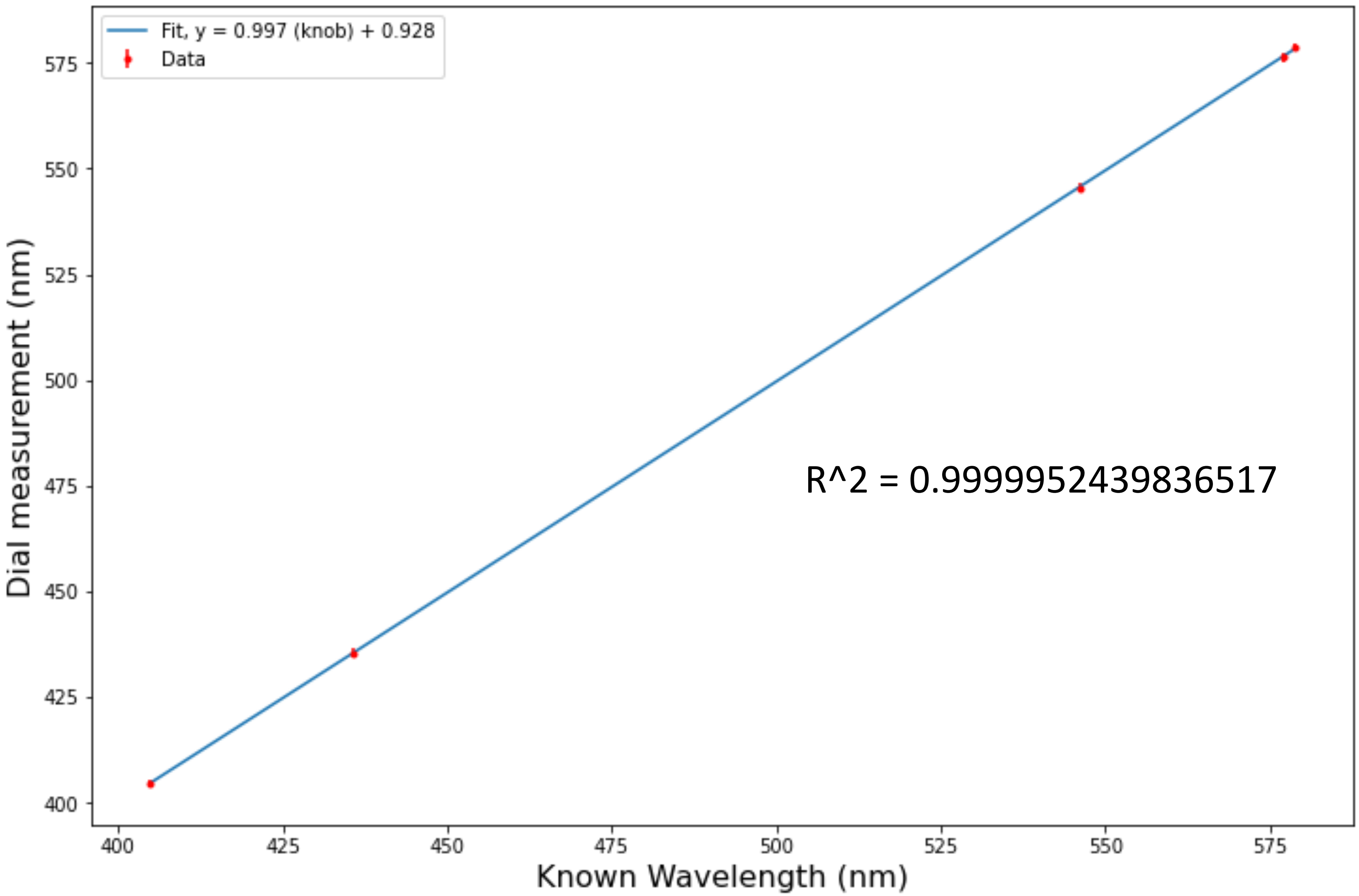
- Schedule of assignment due dates through the end of the semester is now posted on wiki, and in Teams
  - https://ghz.unm.edu/juniorlab/index.php?title=Schedule_Spring_2021#Course_Schedule
- **Schedule for Talk 2 is posted, first talks April 19, 26**
  - To get full credit, you need to submit your slides at least 1 hour ahead of time (submit through assignment in Teams)
- Try to wear lab-safety-appropriate long pants and closed-toed shoes, especially if you are working on an experiment with clear hazards (high voltage, lead bricks)
- Send an email and stay home if you aren't feeling well

Error Analysis

- Some steps in error analysis so far
  - Estimating uncertainties from equipment
  - Repeating measurements to estimate uncertainty
  - Propagating uncertainties
  - Plotting and correlating data
  - Choosing how to combine separate measurements, and possibly rejecting/cleaning data
  - Least-squares fitting with errors in both dimensions
- There are many techniques for fitting and analyzing your experimental data to understand its statistics and sources of **random/statistical error**

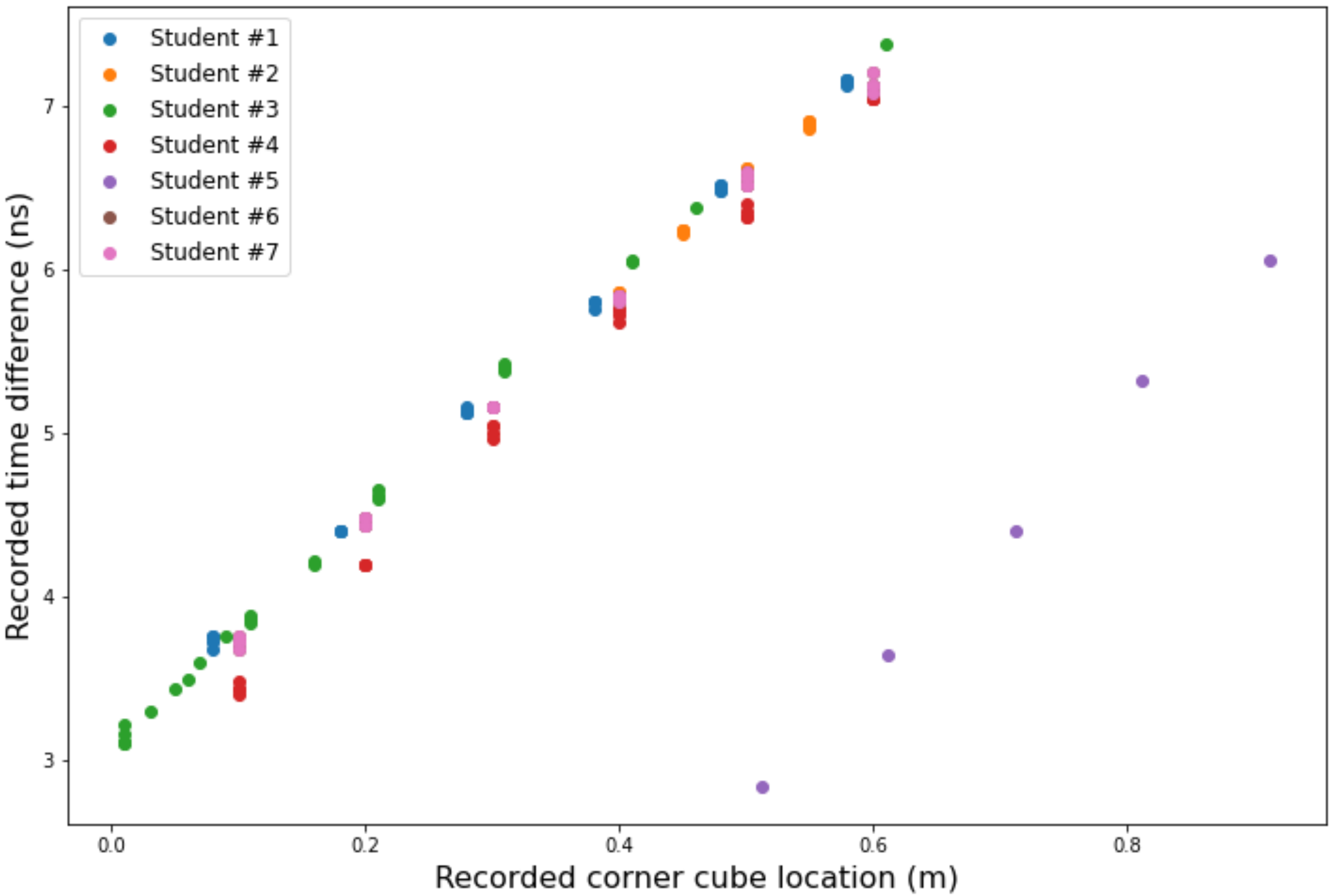
Chauvenet's Criterion

- If you make N measurements of a single quantity x, Chauvenet's criterion gives a simple test for deciding whether to reject a 'suspect value'
- $t_{sus} = \frac{|x_{sus} - \bar{x}|}{\sigma_x}$
- $n = N \times Prob(outside\ t_{sus}\sigma)$
  - Use Appendix A to look up values
- If n < 0.5, then it is reasonable to reject x_{sus}

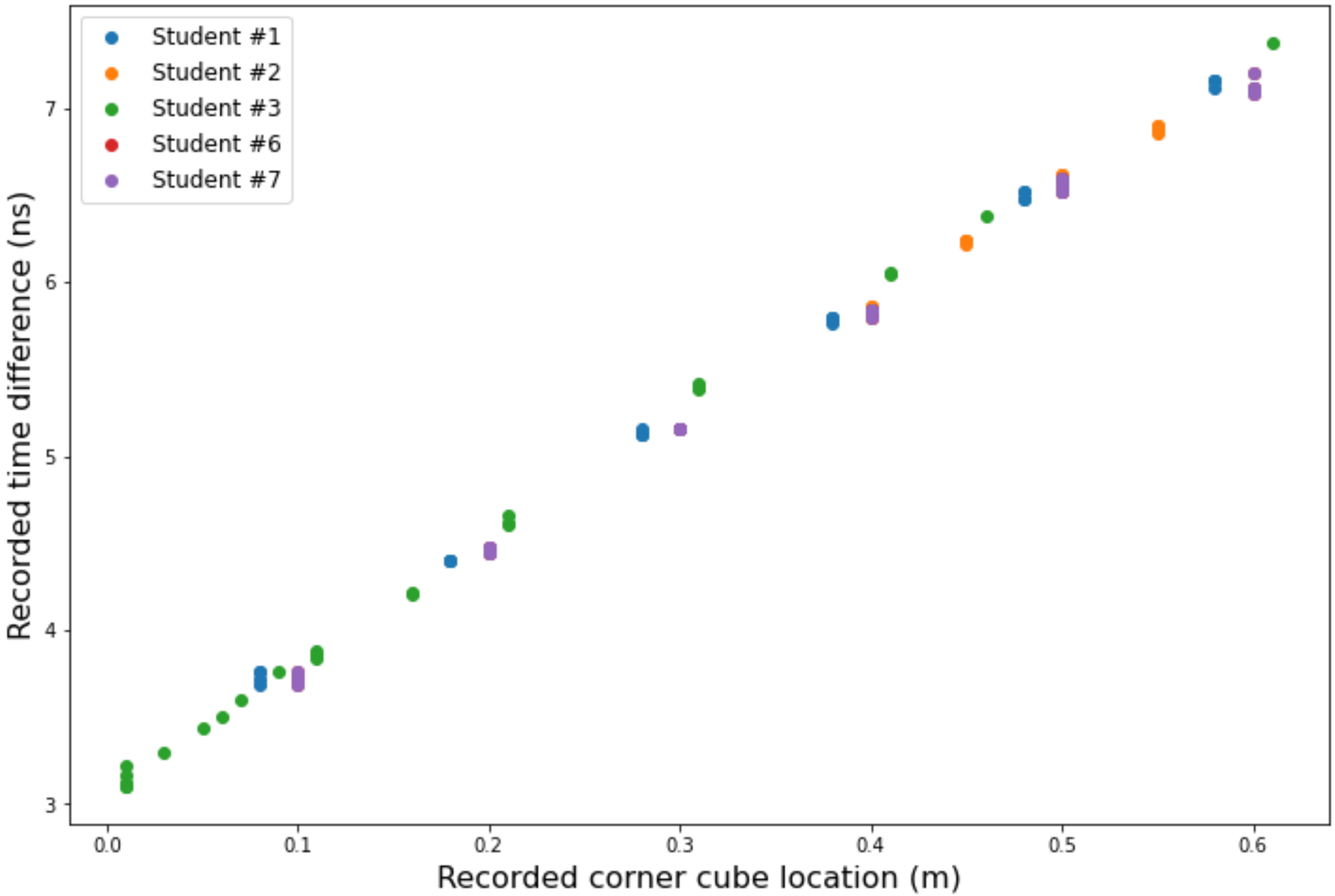


The slope = 0.9974273274123038, with uncertainty 0.0012558490265354887 The intercept = 0.9282554690792497, with uncertainty 0.6452914621011211

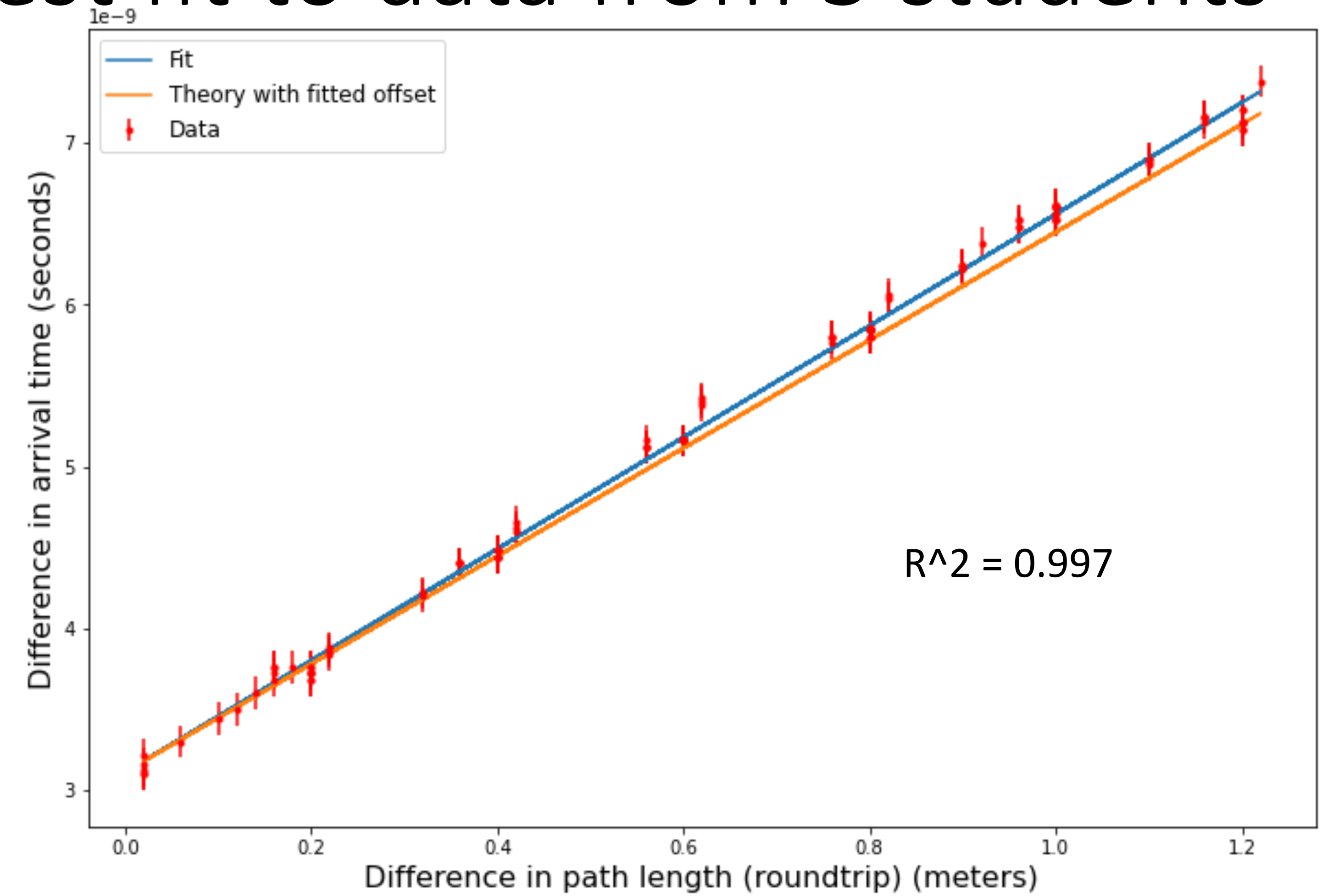
Speed of Light Data – Our Class



Speed of Light Data – Our Class Scrubbed of Inconsistent Data



Speed of Light Data – Our Class
Best fit to data from 5 students




```
The slope = 3.447069224225864 8e-09, with uncertainty 1.741025266191759e-11
The intercept = 3.111703798698238e-09, with uncertainty 1.298000077865901e-11
The speed of light = 290101513.76480633
```

Can we reject the hypothesis that the speed of light is 299,700,000 m/s in our lab?

How do we estimate systematic errors?

- We have identified some straightforward examples, which are closely related to how we estimate uncertainty from equipment
  - Systematic error in approach to measure distance
    - Front vs back vs middle of a line or edge
    - Especially relevant for us when combining measurements from different students
  - Systematic error from backlash in a knob
  - Systematic error from calibration of oscilloscope
  - Other examples?

How do we estimate systematic errors, in experiments with unknown results?

- Experimental design can sometimes lend itself to measuring a ‘null’ result (or at least a consistent result) which helps quantify systematic errors
- **Example (Balmer Series):** We could carefully compare line position with knob going one direction, to line position going the other direction. Since we expect it to be the same, we can compare to understand the magnitude of the systematic error coming from backlash.
- You could either take data in a consistent direction to avoid backlash, or quantify its effect on your data (for example, if it is negligible compared to another unavoidable error)

How do we estimate systematic errors, in experiments with unknown results?

- Experimental design can sometimes lend itself to measuring a ‘null’ result (or at least a consistent result) which helps quantify systematic errors
- **Example (Speed of Light)**: We cannot claim that we are measuring the speed of light with our setup, since there are systematic errors beyond our capability of measuring.
  - Need an absolute reference for time to calibrate
- We could still use the setup to accurately measure the index of refraction of a material. **Why?**

How do we estimate systematic errors, in experiments with unknown results?

- Experimental design can sometimes lend itself to measuring a ‘null’ result (or at least a consistent result) which helps quantify systematic errors
- **Example (Poisson Statistics):** We measured the background rate **without a radioactive source** to quantify the expected level of signal from other sources (cosmic rays, other radioactive elements in surroundings, background noise in detector)
    - This background follows nice Poisson statistics, but can be considered a systematic effect
    - Can’t tell exactly where each ‘hit’ came from, can only quantify expected level of background hits

How do we estimate systematic errors, in experiments with unknown results?

- What if we can't do direct measurements?

Simulating experiments

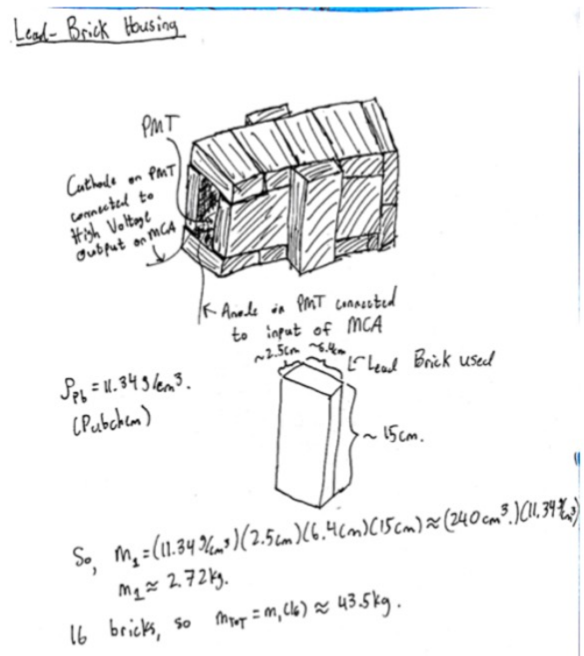
- Often in real experiments, analytical calculations, estimates, and experimental data are not sufficient to fully understand the magnitude of sources of error, and how they can interact
- Systematic errors also typically have random fluctuations, and can fluctuate up and add together all at once making a big outlier in your data
- Very important to understand sources of uncertainty for reporting new results

Simulating experiments

- Many decisions to be made and justified on how to set up a full simulation
  - What ‘shortcuts’ are ok and why?
  - What effects are important to model accurately?
  - What framework to use to allow for future capacity?
  - What resources are available?
  - What are the limitations of the simulation?
- How does simulation compare to actual data?

Poisson Statistics Modeling

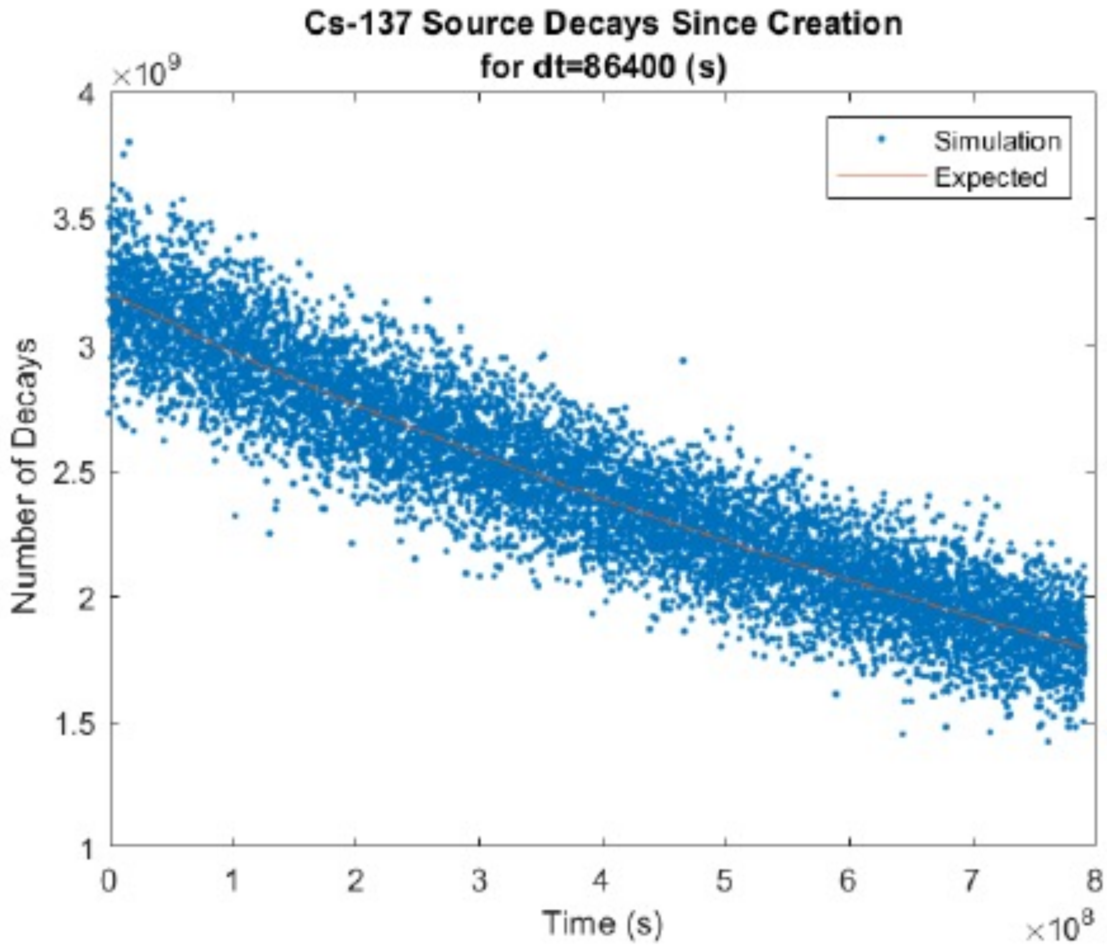
- We set up a ‘toy model’ for understanding the experiment and what would be needed to simulate it accurately.
- This can be useful for designing an experiment and understanding its limitations



Poisson Statistics Modeling

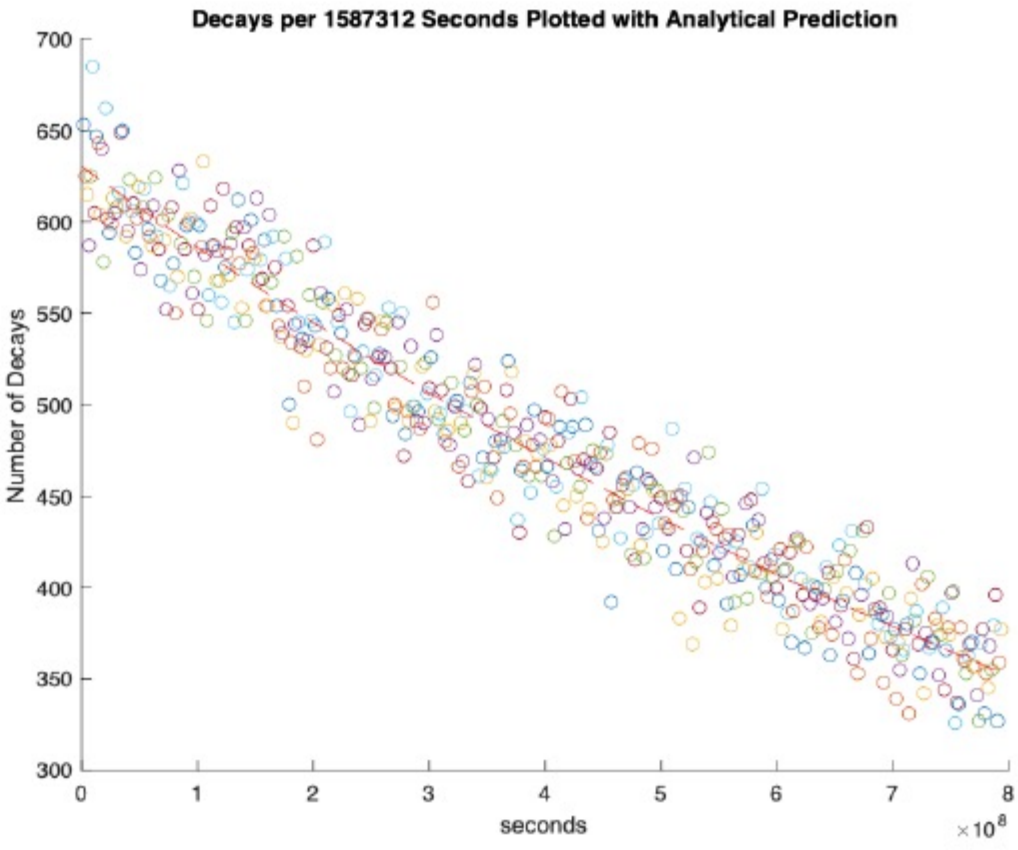
- https://trinket.io/glowscript/8060842cfb

Poisson Statistics Modeling

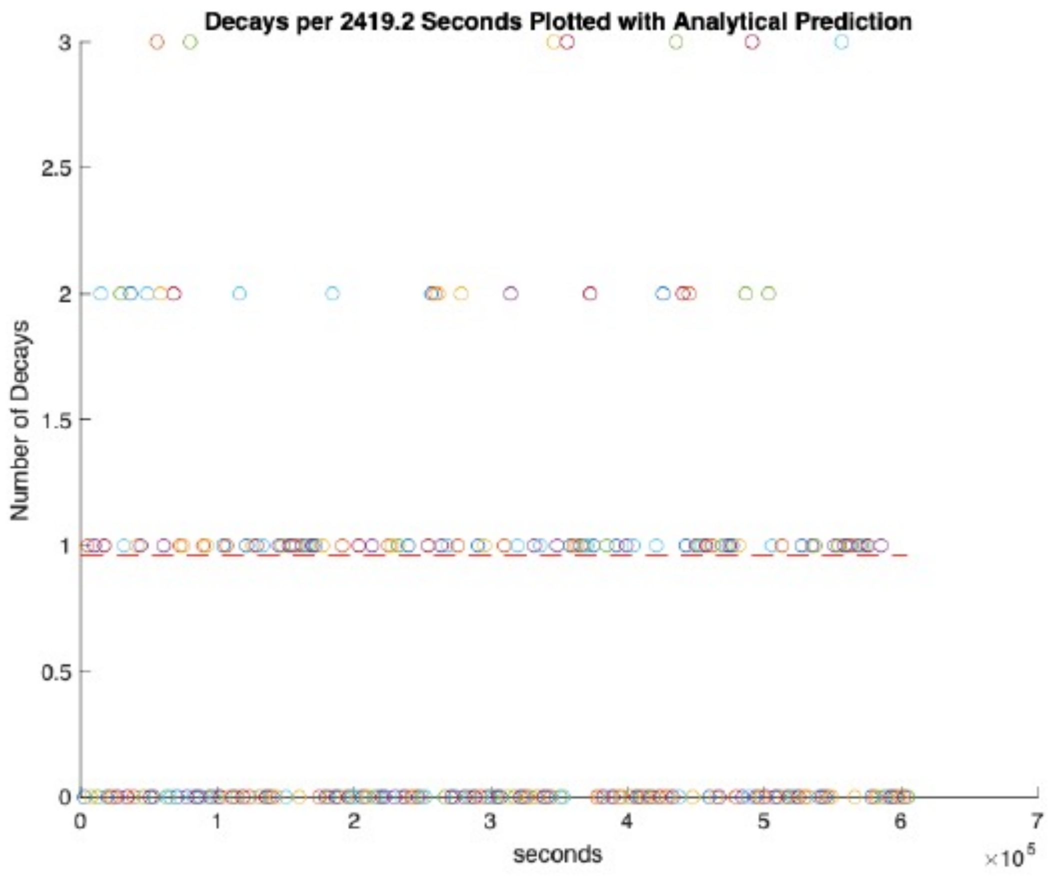


$$\Delta N(t) = N_0 \frac{dt}{\tau} e^{-t/\tau}$$

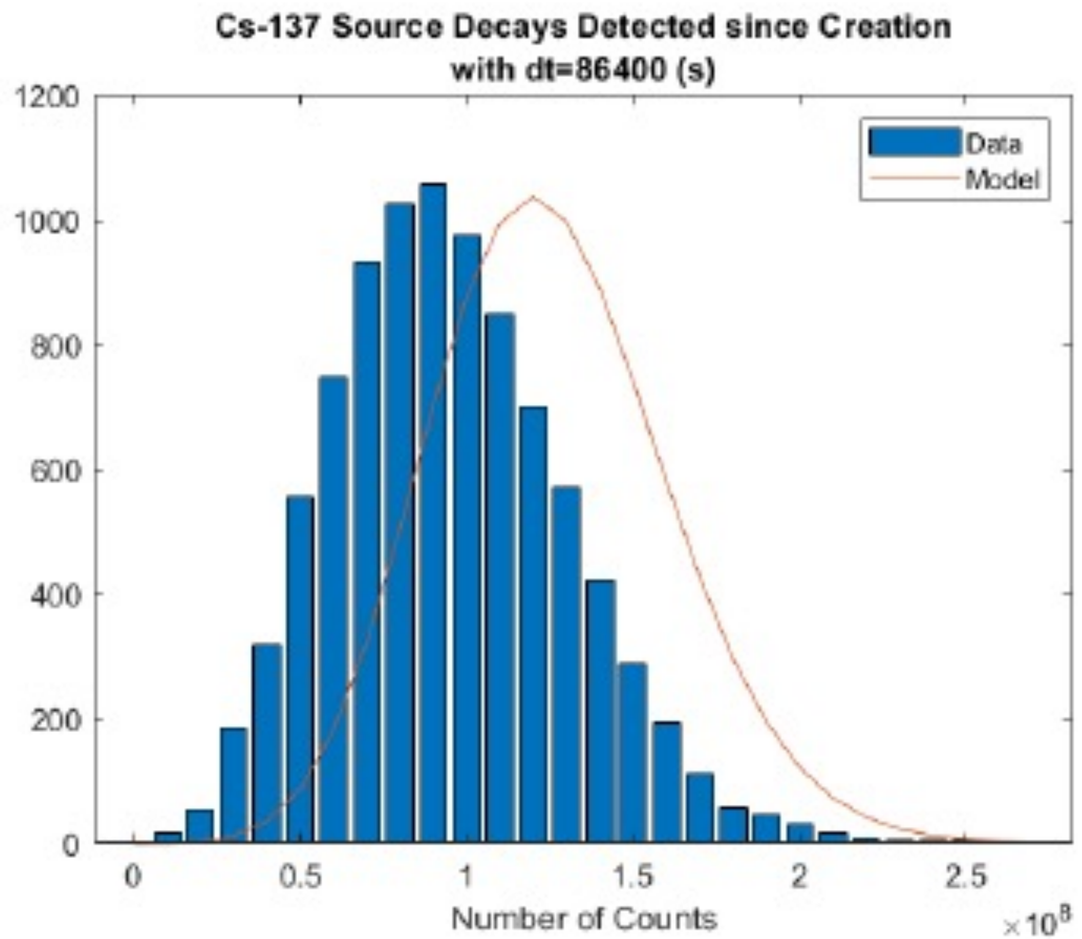
Poisson Statistics Modeling



Poisson Statistics Modeling



Poisson Statistics Modeling



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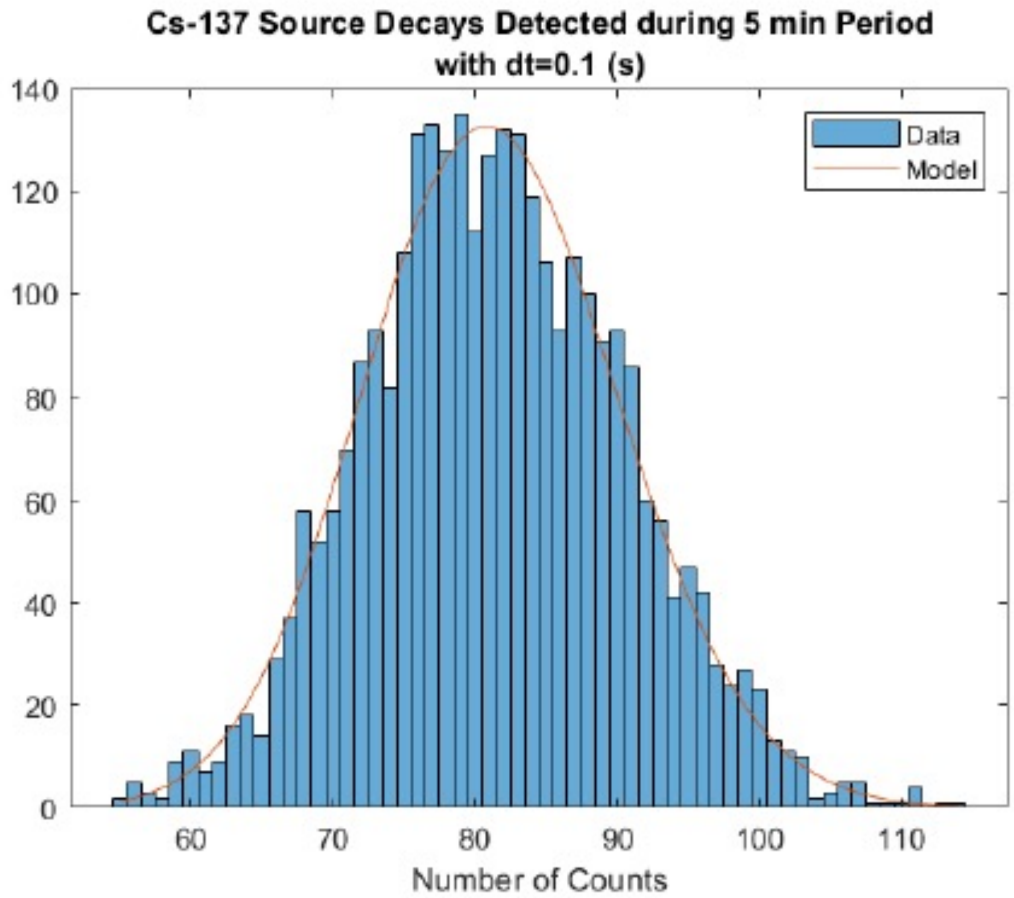
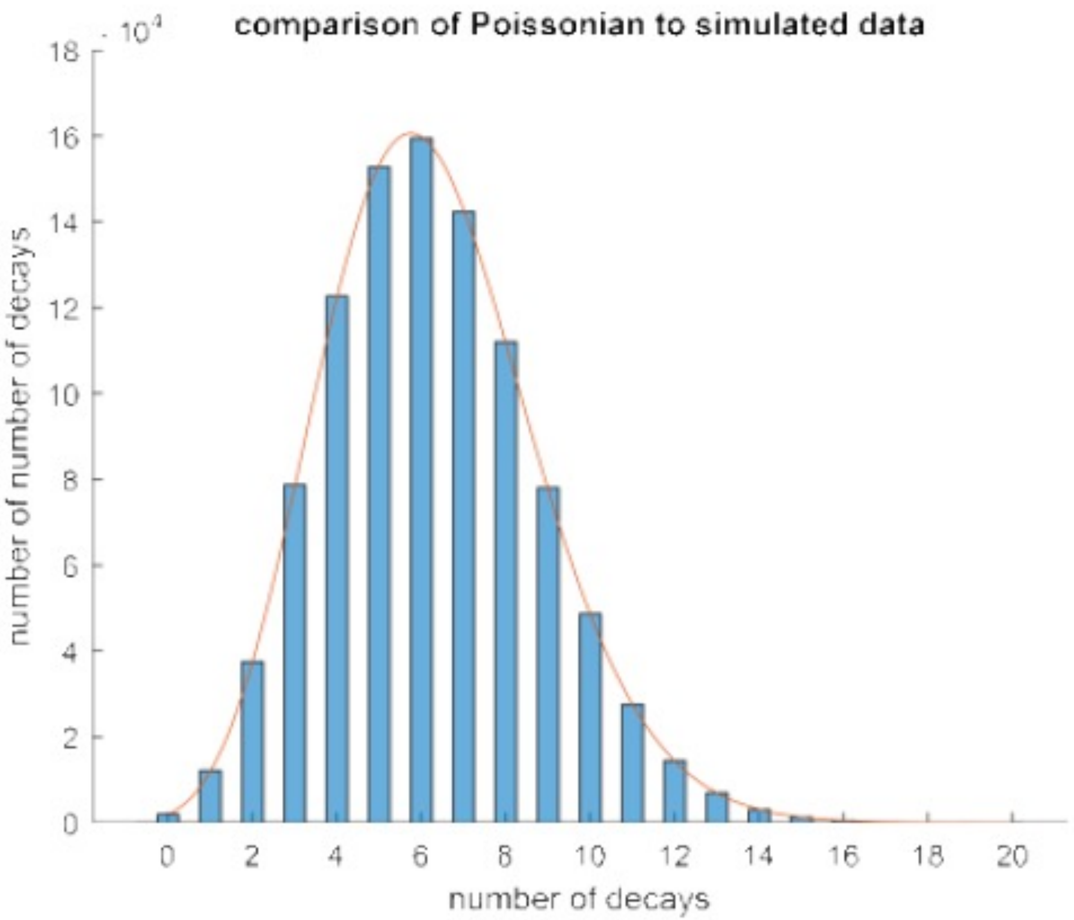


Poisson Statistics Modeling



Accounting for Experimental Uncertainties (from Friday's colloquium by Holger Mueller)

0.16 ppb systematic errors

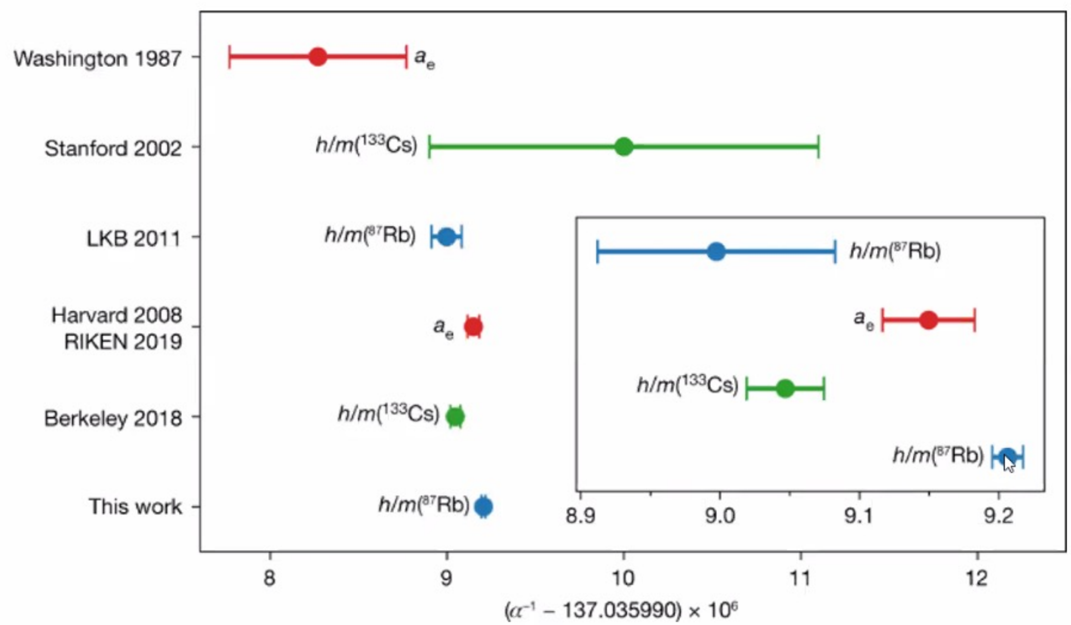
Effect	Sect.	Value	$\delta\alpha/\alpha$ (ppb)
Laser Frequency	1	N/A	-0.24 ± 0.03
Acceleration Gradient	4A	[illegible]$=(2.13 \pm 0.01)\times10^{-6}/s^2$	-1.69 ± 0.02
Gouy phase	3	w_0=3.21±0.008 mm, z_0=0.5±1.0 m	-3.60± 0.03
Wavefront Curvature	12	$\langle r^2\rangle^{1/2}$=0.58 mm	0.15 ± 0.03
Beam Alignment	5	N/A	0.05 ± 0.03
BO Light Shift	6	N/A	0 ± 0.004
Density Shift	7	$\rho=10^6$ atoms/cm^3	0 ± 0.003
Index of Refraction	8	$n_{cloud}-1=30\times10^{-12}$	0 ± 0.03
Speckle Phase Shift	4B	N/A	0 ± 0.04
Sagnac Effect	9	N/A	0 ± 0.001
Mod. Frequency Wavenumber	10	N/A	0 ± 0.001
Thermal Motion of Atoms	11	N/A	0 ± 0.08
Non-Gaussian Waveform	13	N/A	0 ± 0.03
Parasitic Interferometers	14	N/A	0 ± 0.03
Total Systematic Error			-5.33 ± 0.12
Total Statistical Error			± 0.16
Electron Mass (18)		$5.48579909067\times10^{-4}$ u	± 0.02
Cesium Mass (4,17)		132.9054519615 u	± 0.03

Big

'New'

Accounting for Experimental Uncertainties (from Friday's colloquium by Holger Mueller)

The future of α



Morel, Yao, Cladé, and Guellati-Khélifa 2020, Nature **588,** 61–65