Precision Atomic Spectroscopy of Lithium

Mike Rowan

1. Why do we study atoms?
2. What is atomic spectroscopy?
3. What is a frequency comb?
4. Why Lithium?
5. What have I worked on this year?

We study atoms because…

- Atoms are relatively simple

  Good theoretical understanding of atoms

  We can make models and calculations

- We can control them well by use of lasers

  Extreme accuracy of measurements serve as tests of our understanding

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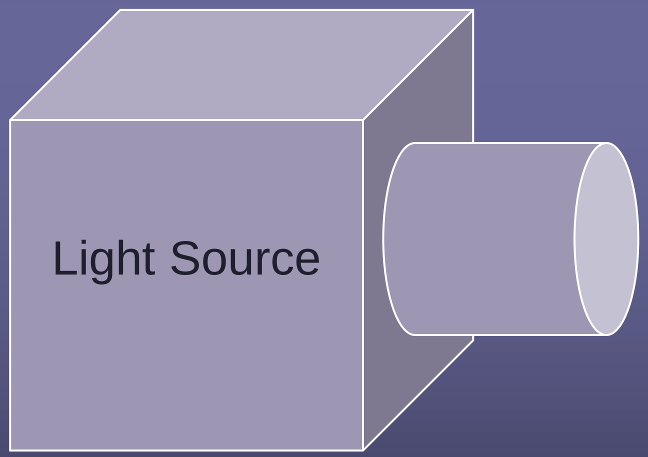
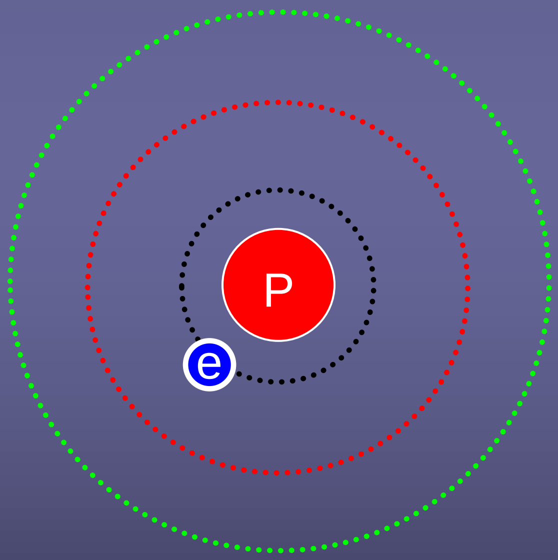
High-precision experiments provide tests of fundamental physics

- Fundamental constants – are they changing?
- General relativity
- Weak interaction q
- Quantum electrodynamics

How do we study atoms?

- Spectroscopy – the use of light emission and absorption to study matter
- First, we excite an atom using light
- Energy of a photon proportional to frequency (color); *$E=hv$*





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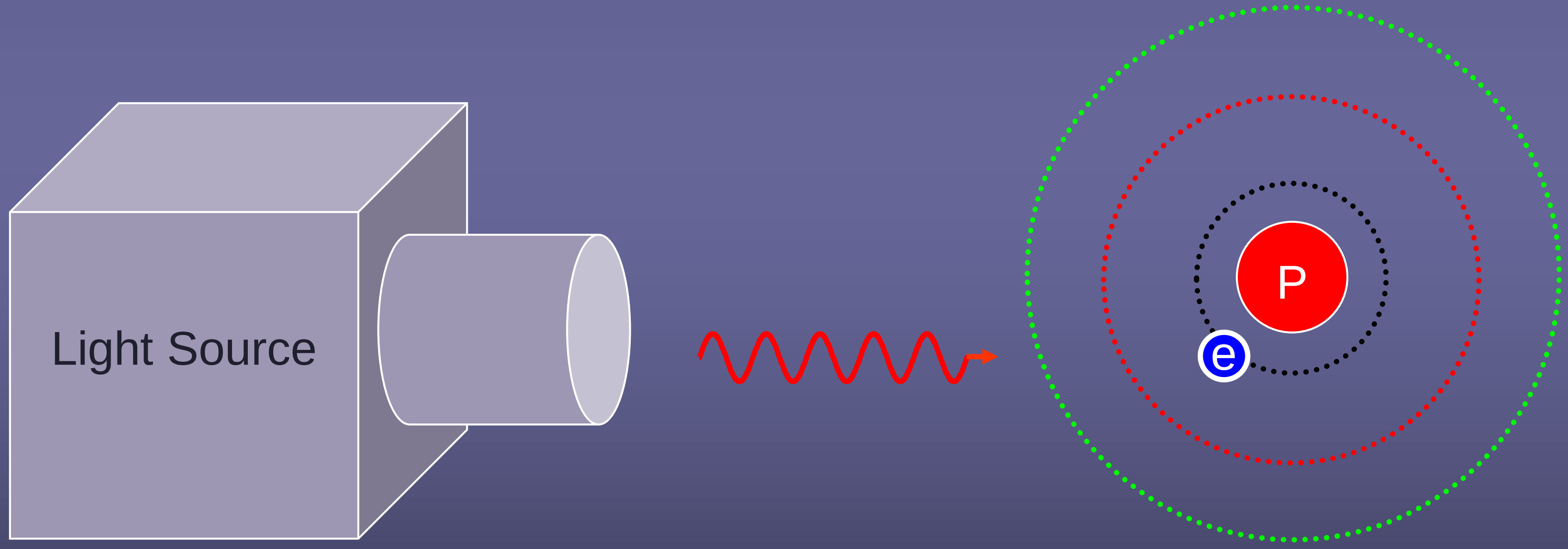

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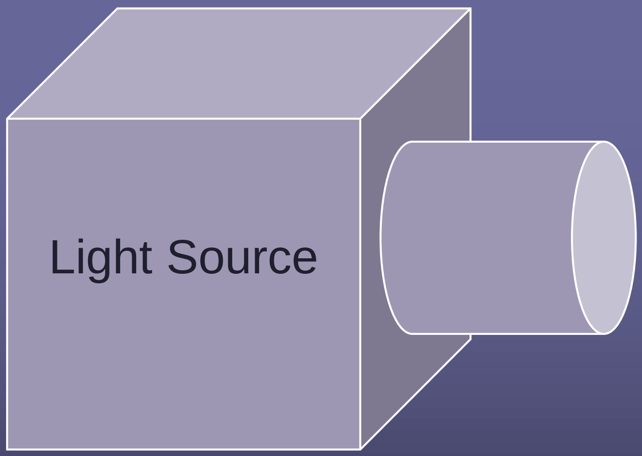

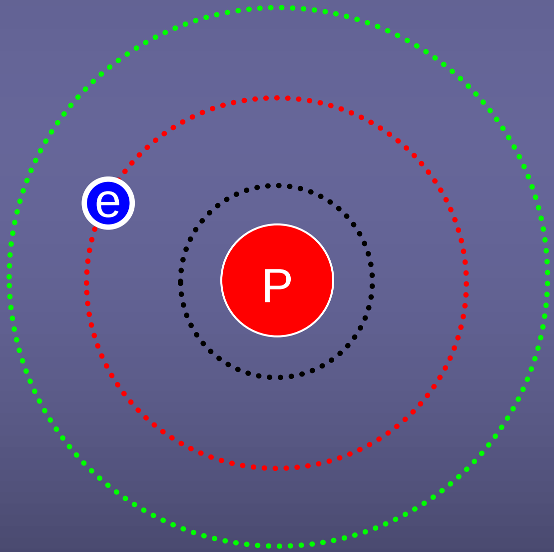

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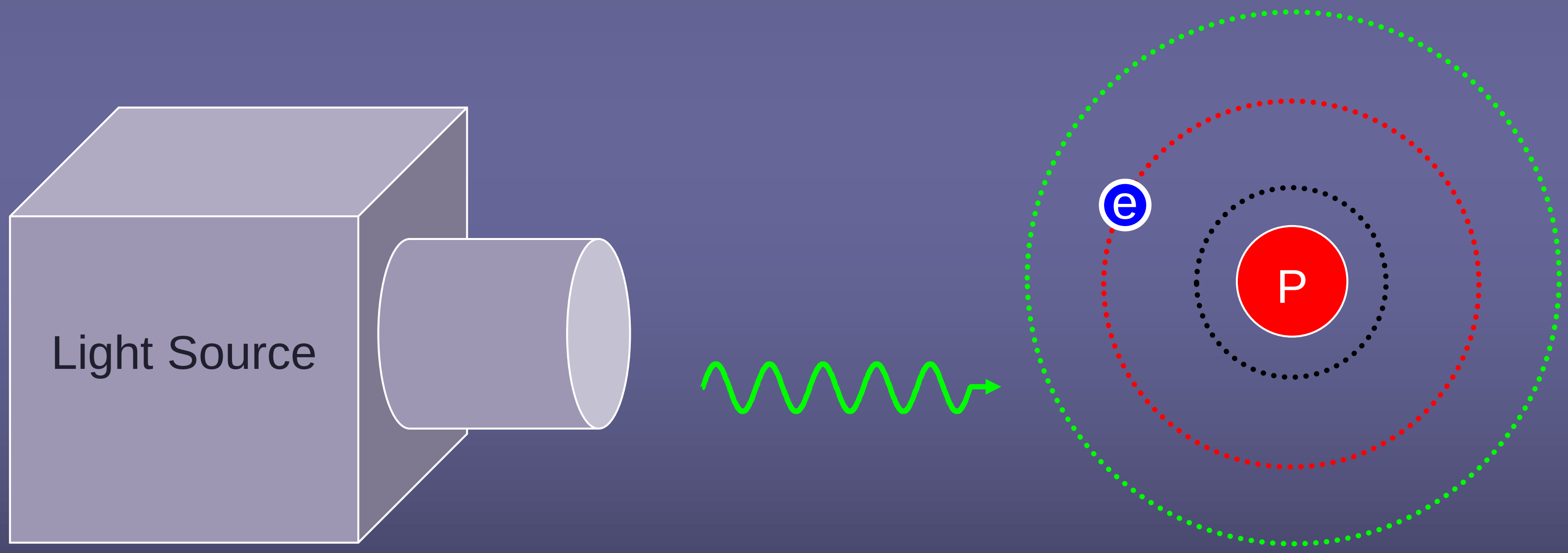

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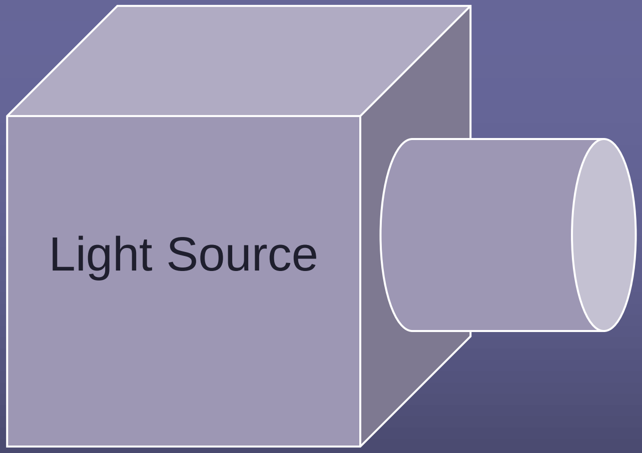

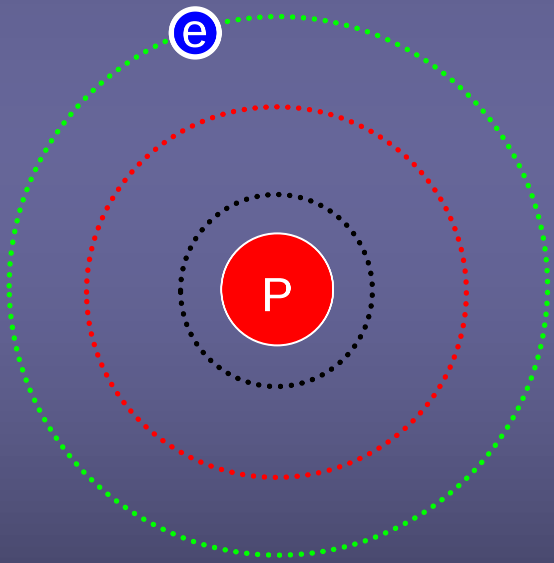

Transition!

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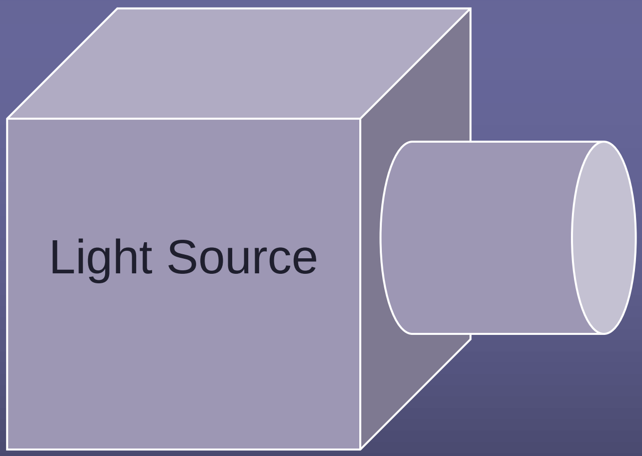

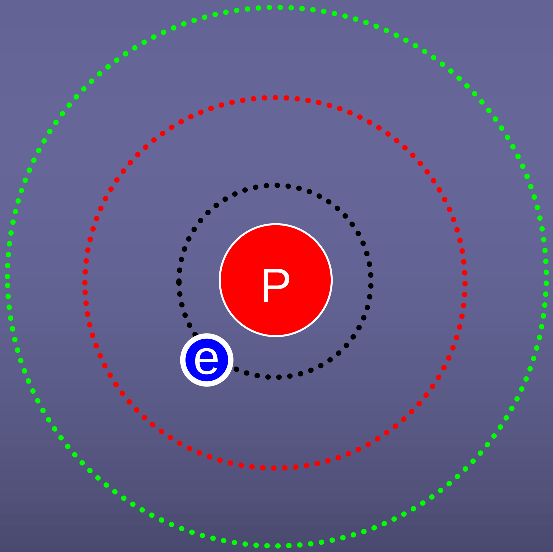

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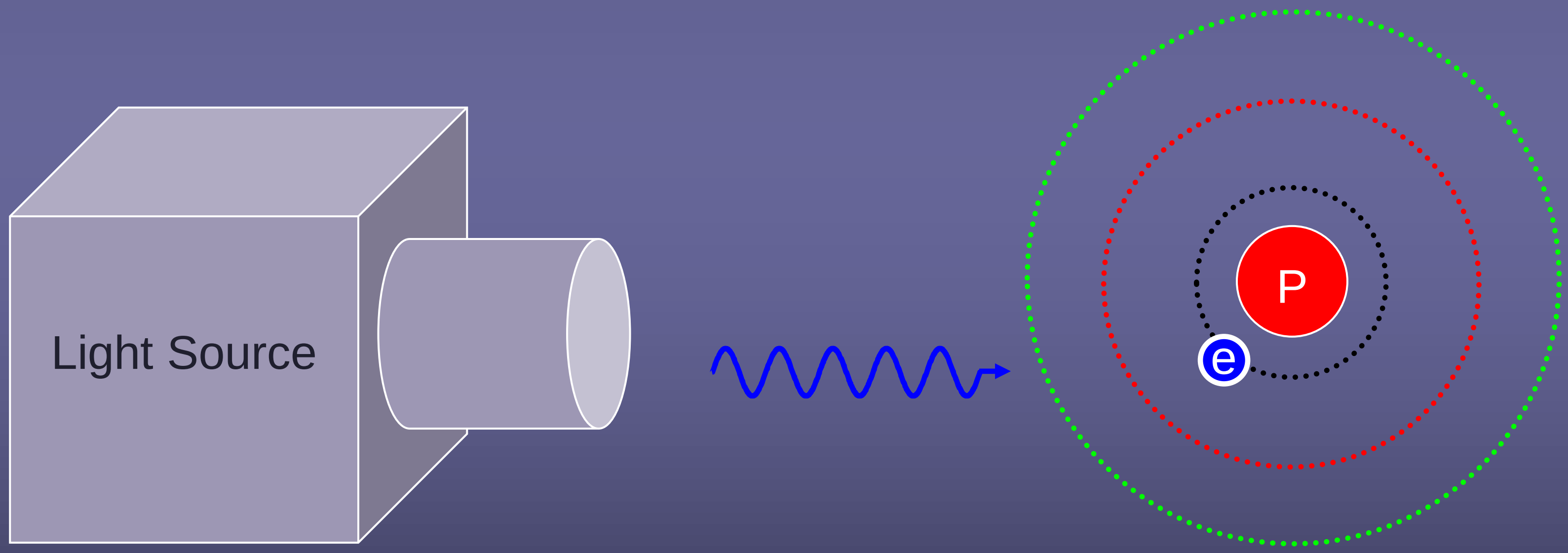

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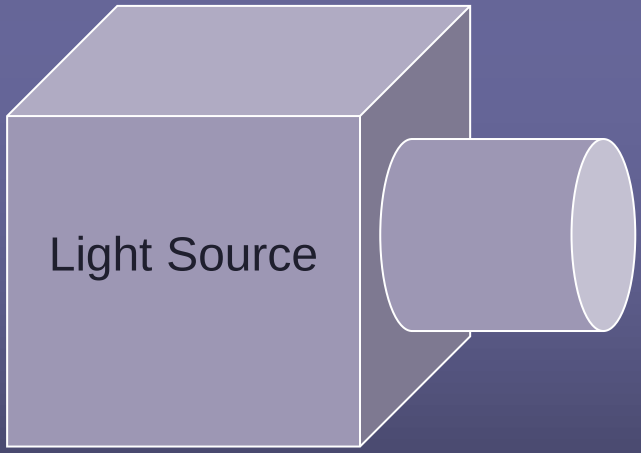

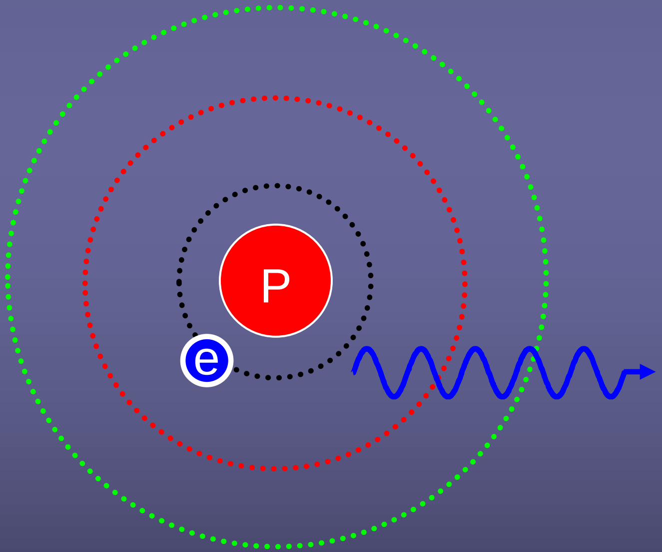

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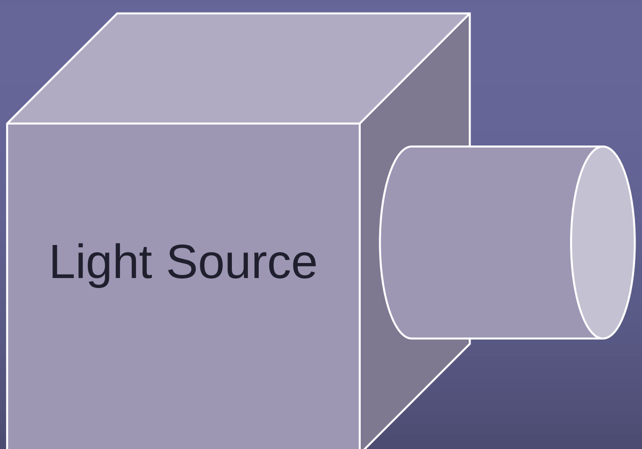

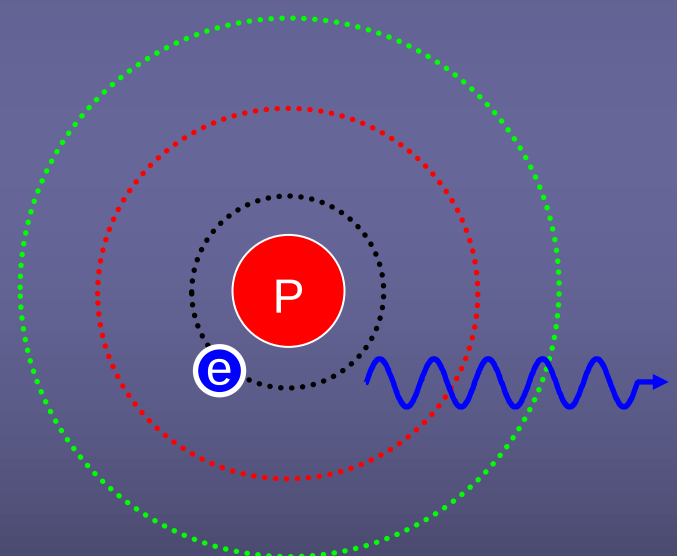

No Transition

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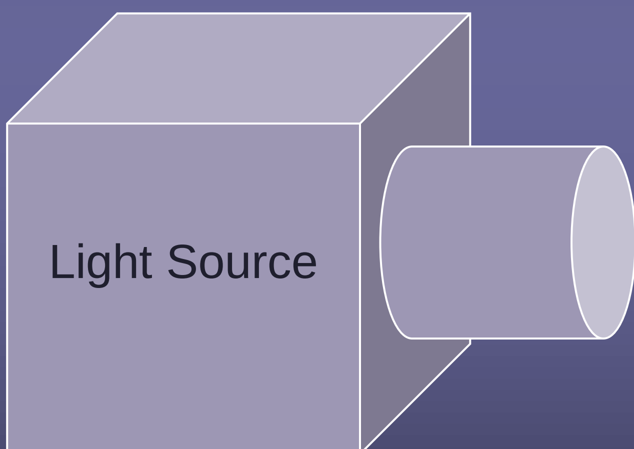
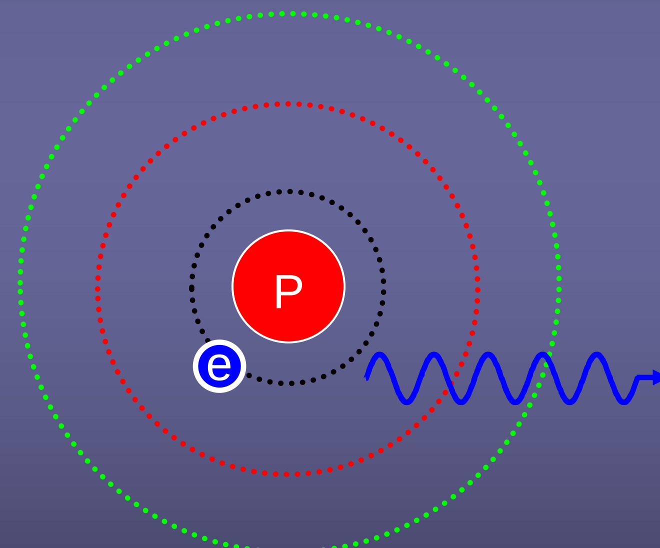
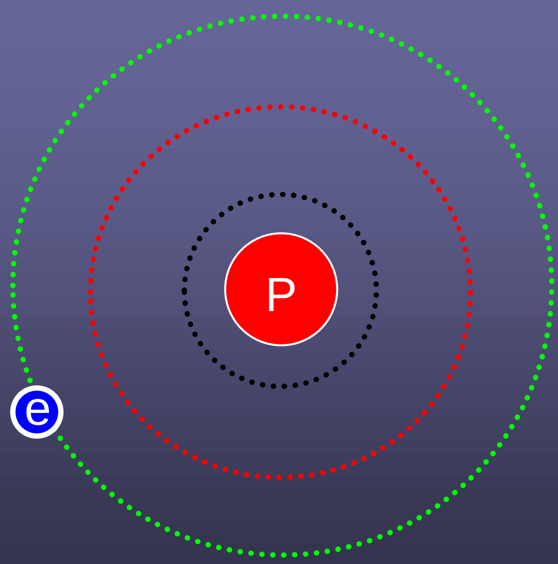




Light must have the right frequency to result in a transition

How do we study atoms?

- An atom in the excited state then decays, producing fluorescence
- We detect the light using a photomultiplier tube (PMT)
- Intensity of the light indicates the population of atoms in the excited state



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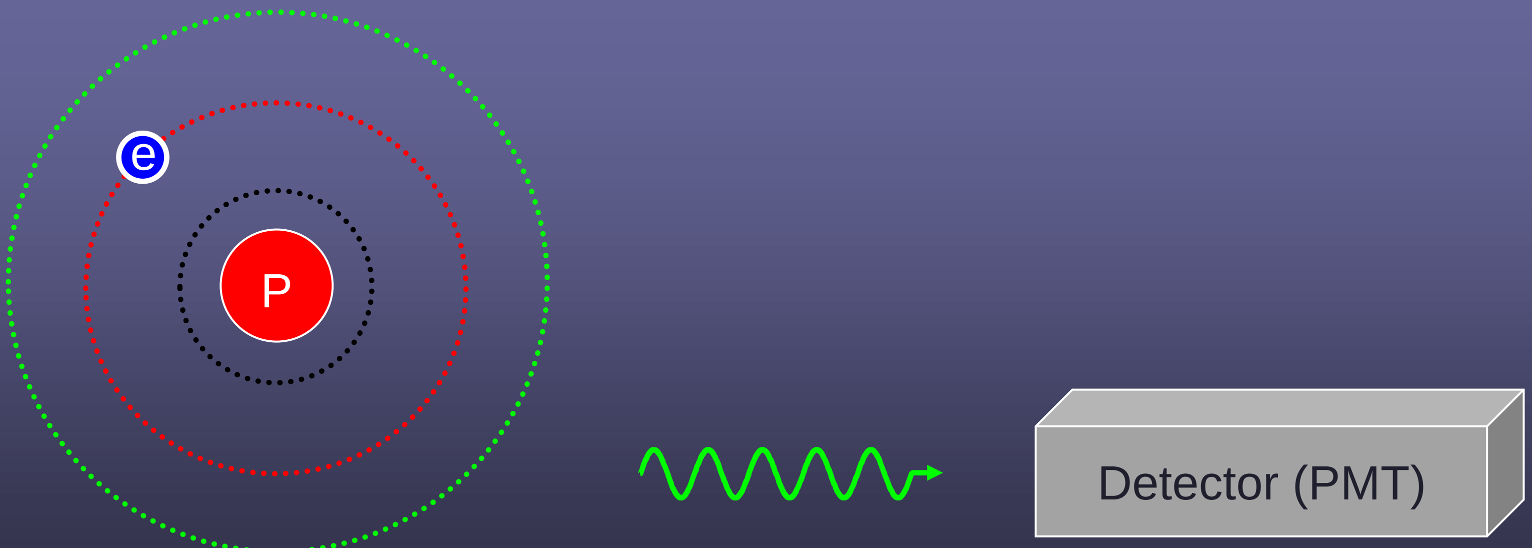
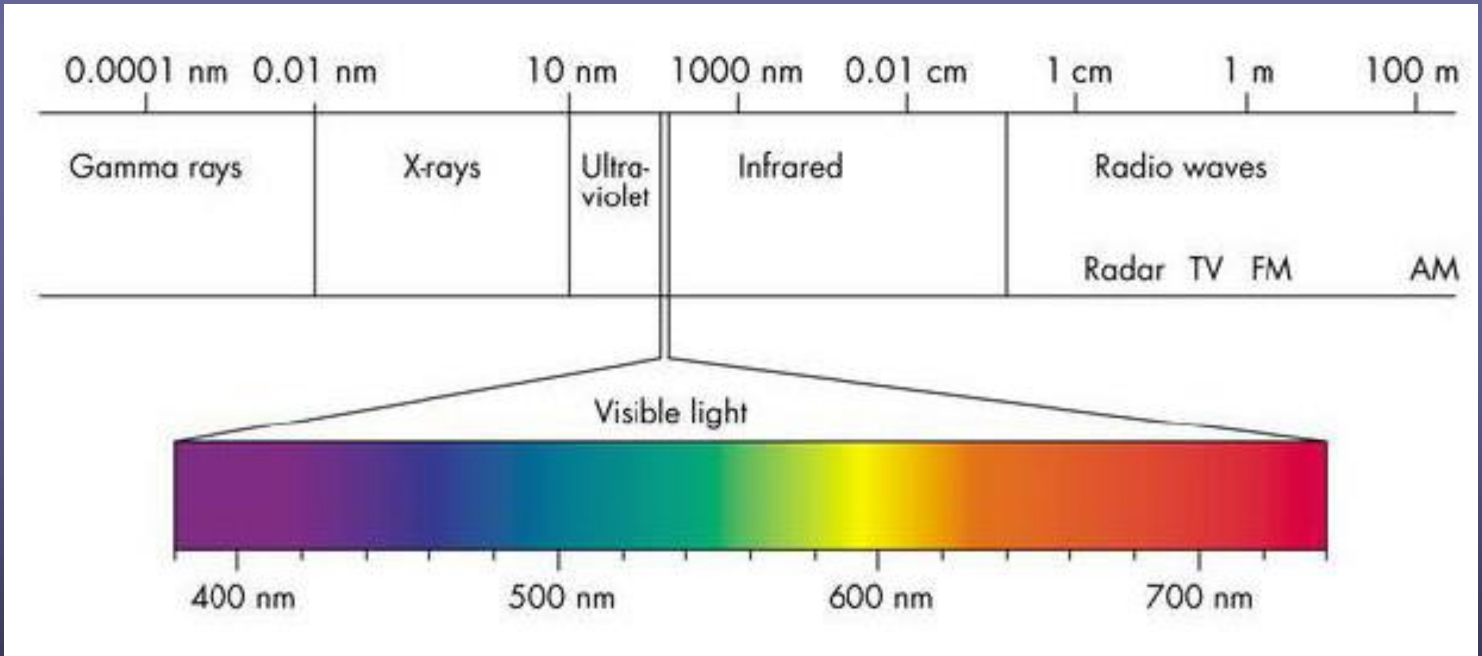


How do we study atoms?

- We measure the frequency (color) of the light that causes transitions
- Strongest transitions are in visible region



How do we study atoms?

- However, frequencies of light are very high – on the order of

400,000,000,000,000 Hz

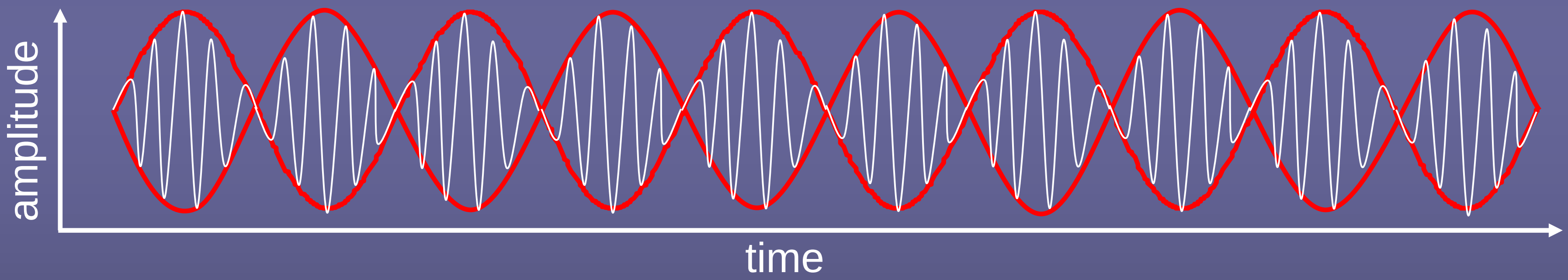
- Modern electronics can only respond at about

10,000,000,000 Hz

- To get around this, we use "interference" to produce a measurable frequency

Interference

- The rate of a beat is the difference of two frequencies – it results from the interference of two slightly different frequencies
- We hear this as a periodic variation in volume

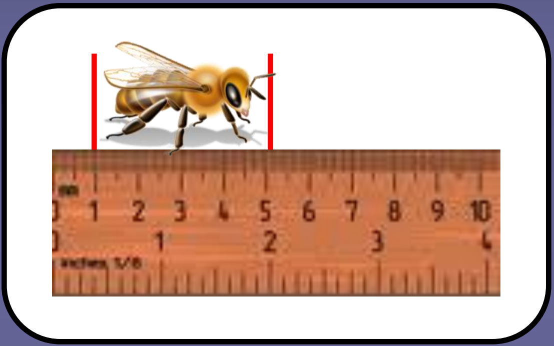


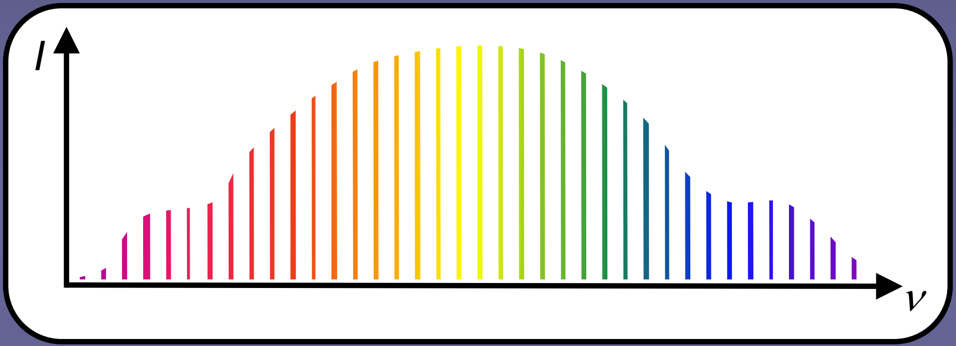
- If you know one frequency and you know the beat frequency, then you can determine the second frequency
- By interfering frequencies of visible light, we get a beat frequency that is in the radio range – this is measurable

How do we measure frequencies of light?

- We make a “light ruler”

Comb Equation: $\nu_n = n\, f_{rep} + f_0$





Ruler: Number of ticks
Offset
Spacing between ticks

Optical Frequency Comb: Mode number
Offset frequency
Frequency spacing

- This structure is called an optical frequency comb – a set of equidistantly spaced spectral lines
- By interfering different colors in the comb, we can produce radio frequencies that we can control

Why lithium?

- It is simple (like a noble gas and an electron)
- Since it is simple, theory is good
- Two stable isotopes
- Disagreement among previous measurements

The Periodic Table of the Elements

1 **H** Hydrogen 1.00794																	2 **He** Helium 4.003
3 **Li** Lithium 6.941	4 **Be** Beryllium 9.012182											5 **B** Boron 10.811	6 **C** Carbon 12.0107	7 **N** Nitrogen 14.00674	8 **O** Oxygen 15.9994	9 **F** Fluorine 18.9984032	10 **Ne** Neon 20.1797
11 **Na** Sodium 22.989770	12 **Mg** Magnesium 24.3050											13 **Al** Aluminum 26.981538	14 **Si** Silicon 28.0855	15 **P** Phosphorus 30.973761	16 **S** Sulfur 32.066	17 **Cl** Chlorine 35.4527	18 **Ar** Argon 39.948
19 **K** Potassium 39.0983	20 **Ca** Calcium 40.078	21 **Sc** Scandium 44.955910	22 **Ti** Titanium 47.867	23 **V** Vanadium 50.9415	24 **Cr** Chromium 51.9961	25 **Mn** Manganese 54.938049	26 **Fe** Iron 55.845	27 **Co** Cobalt 58.933200	28 **Ni** Nickel 58.6934	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.723	32 **Ge** Germanium 72.61	33 **As** Arsenic 74.92160	34 **Se** Selenium 78.96	35 **Br** Bromine 79.904	36 **Kr** Krypton 83.80
37 **Rb** Rubidium 85.4678	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.90585	40 **Zr** Zirconium 91.224	41 **Nb** Niobium 92.90638	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium (98)	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.90550	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.8682	48 **Cd** Cadmium 112.411	49 **In** Indium 114.818	50 **Sn** Tin 118.710	51 **Sb** Antimony 121.760	52 **Te** Tellurium 127.60	53 **I** Iodine 126.90447	54 **Xe** Xenon 131.29
55 **Cs** Cesium 132.90545	56 **Ba** Barium 137.327	57 **La** Lanthanum 138.9055	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.9479	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.207	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.217	78 **Pt** Platinum 195.078	79 **Au** Gold 196.96655	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.3833	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98038	84 **Po** Polonium (209)	85 **At** Astatine (210)	86 **Rn** Radon (222)
87 **Fr** Francium (223)	88 **Ra** Radium (226)	89 **Ac** Actinium (227)	104 **Rf** Rutherfordium (261)	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (263)	107 **Bh** Bohrium (262)	108 **Hs** Hassium (265)	109 **Mt** Meitnerium (266)	110 (269)	111 (272)	112 (277)	113	114				
				58 **Ce** Cerium 140.116	59 **Pr** Praseodymium 140.90765	60 **Nd** Neodymium 144.24	61 **Pm** Promethium (145)	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.964	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.92534	66 **Dy** Dysprosium 162.50	67 **Ho** Holmium 164.93032	68 **Er** Erbium 167.26	69 **Tm** Thulium 168.93421	70 **Yb** Ytterbium 173.04	71 **Lu** Lutetium 174.967
				90 **Th** Thorium 232.0381	91 **Pa** Protactinium 231.03588	92 **U** Uranium 238.0289	93 **Np** Neptunium (237)	94 **Pu** Plutonium (244)	95 **Am** Americium (243)	96 **Cm** Curium (247)	97 **Bk** Berkelium (247)	98 **Cf** Californium (251)	99 **Es** Einsteinium (252)	100 **Fm** Fermium (257)	101 **Md** Mendelevium (258)	102 **No** Nobelium (259)	103 **Lr** Lawrencium (262)

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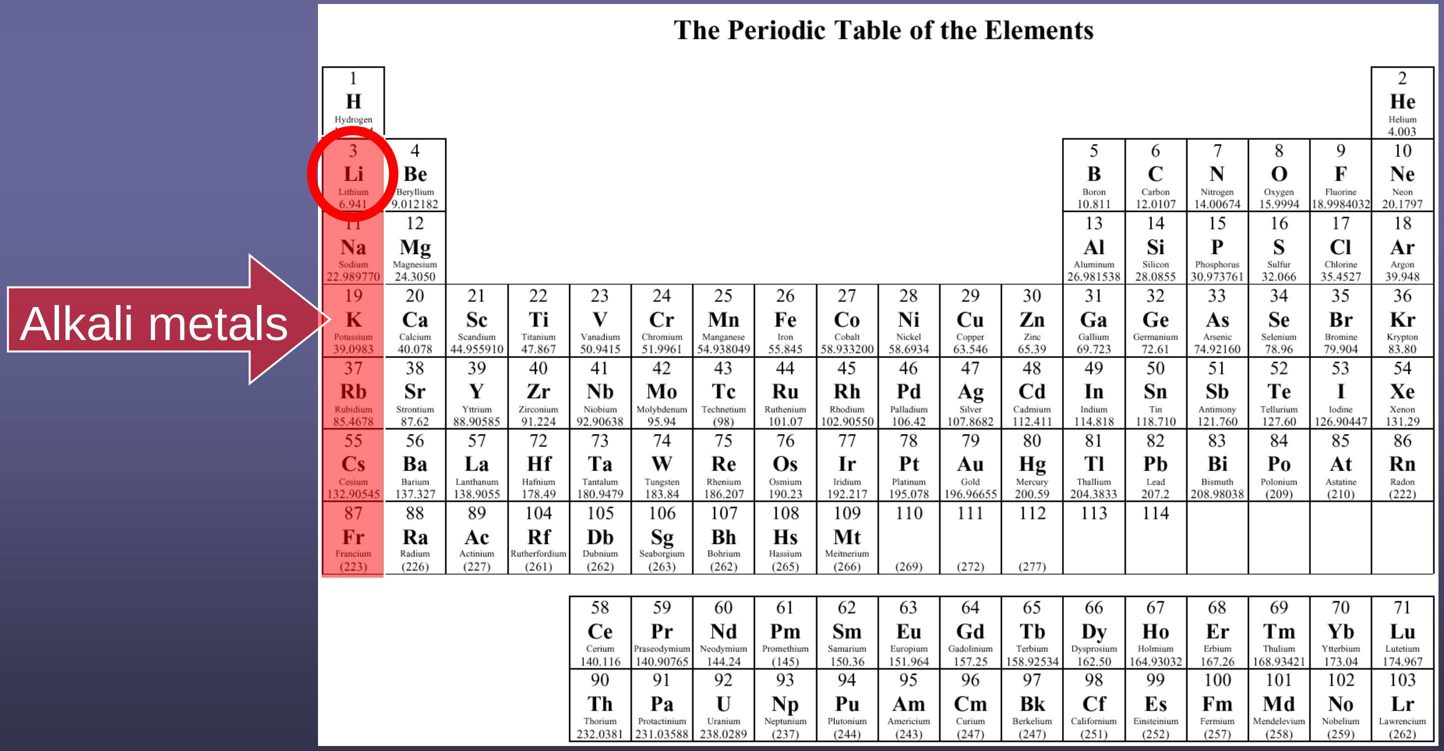

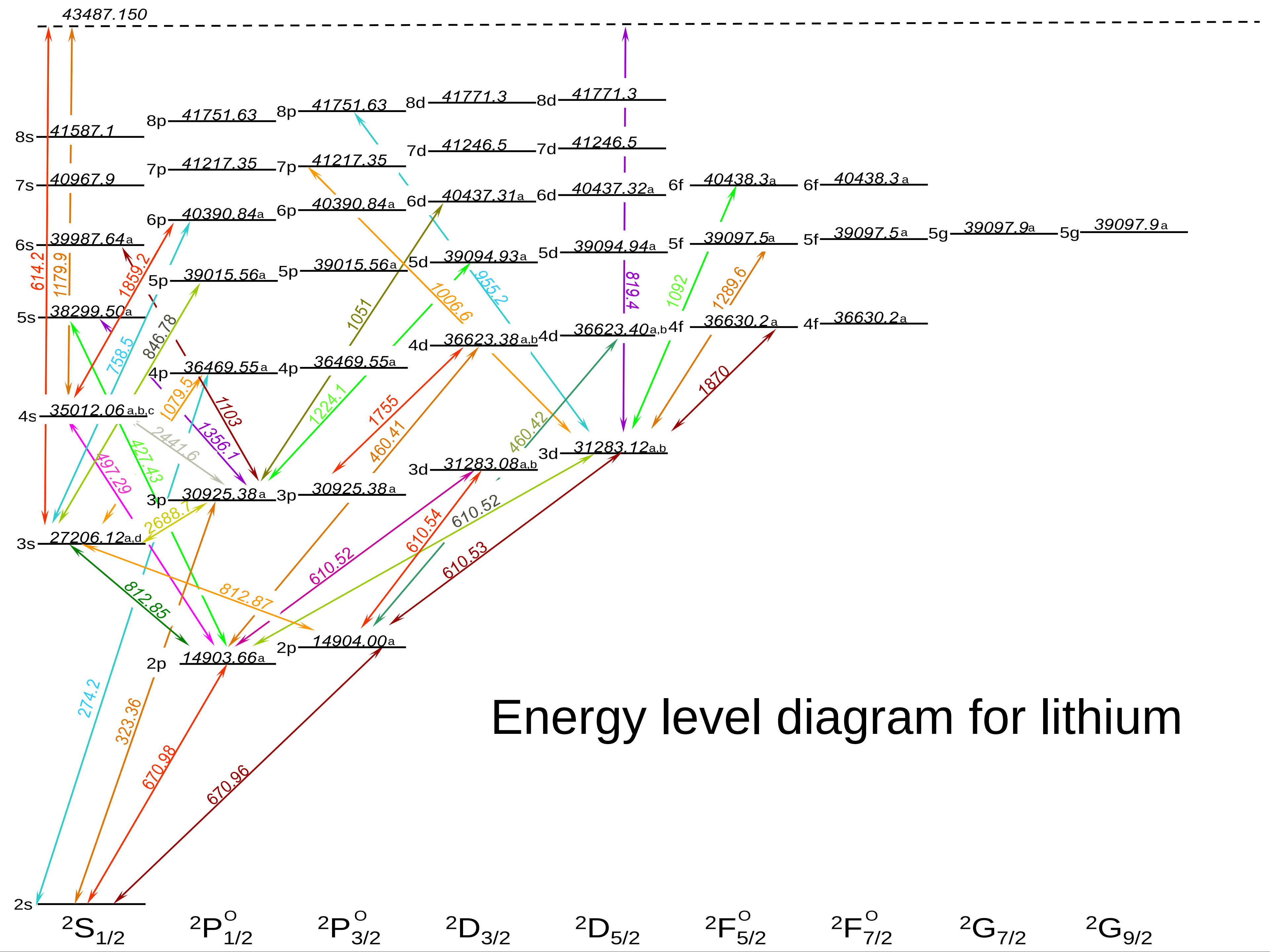

43487.150
8s 41587.1
7s 40967.9
6s 39987.64a
5s 38299.50a
4s 35012.06a,b,c
3s 27206.12a,d
2s
8p 41751.63
7p 41217.35
6p 40390.84a
5p 39015.56a
4p 36469.55a
3p 30925.38a
2p 14903.66a
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3p 30925.38a
2p 14904.00a
8d 41771.3
7d 41246.5
6d 40437.31a
5d 39094.93a
4d 36623.38a,b
3d 31283.08a,b
8d 41771.3
7d 41246.5
6d 40437.32a
5d 39094.94a
4d 36623.40a,b
3d 31283.12a,b
6f 40438.3a
5f 39097.5a
4f 36630.2a
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1356.1
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610.52
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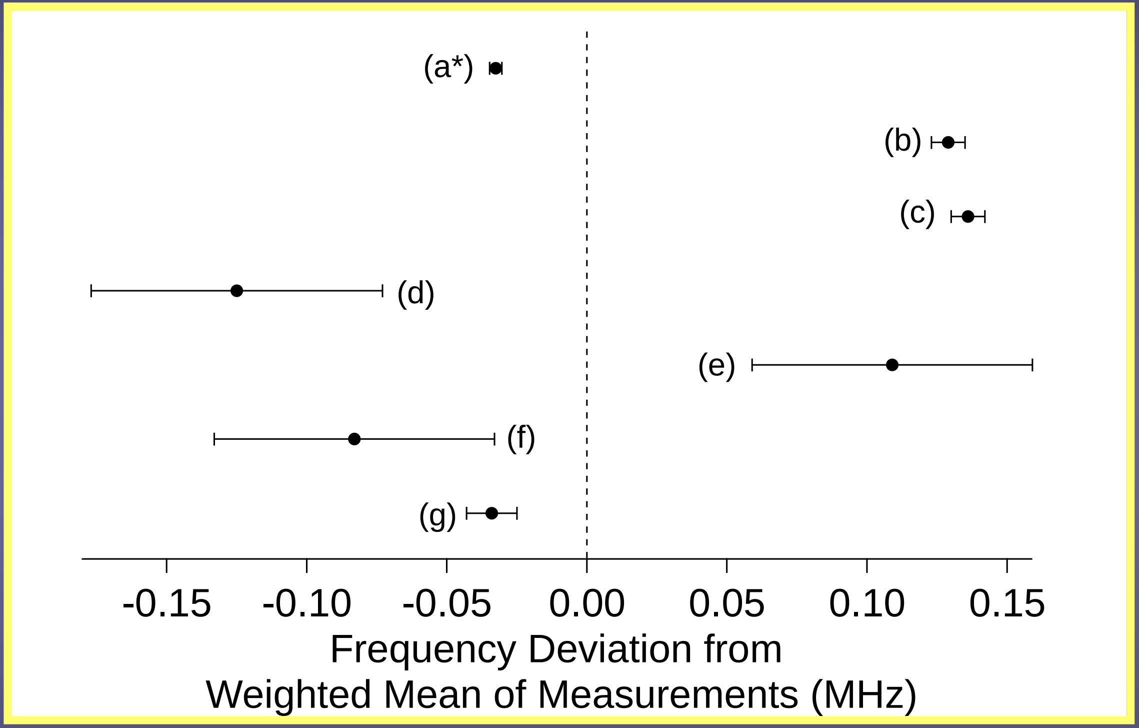
610.52
610.53
819.4
1092
1289.6
1870
$^2S_{1/2}$
$^2P^O_{1/2}$
$^2P^O_{3/2}$
$^2D_{3/2}$
$^2D_{5/2}$
$^2F^O_{5/2}$
$^2F^O_{7/2}$
$^2G_{7/2}$
$^2G_{9/2}$
Energy level diagram for lithium

Theory has small error bars

^{7}Li D1 Hyperfine Structure Splitting



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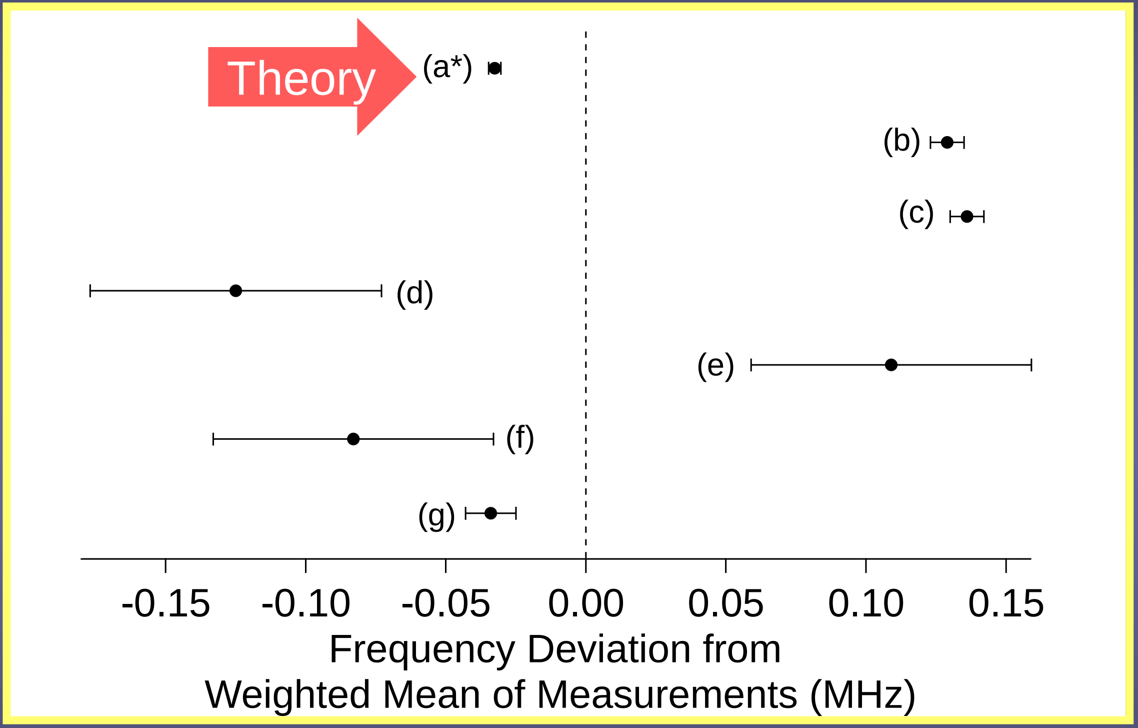
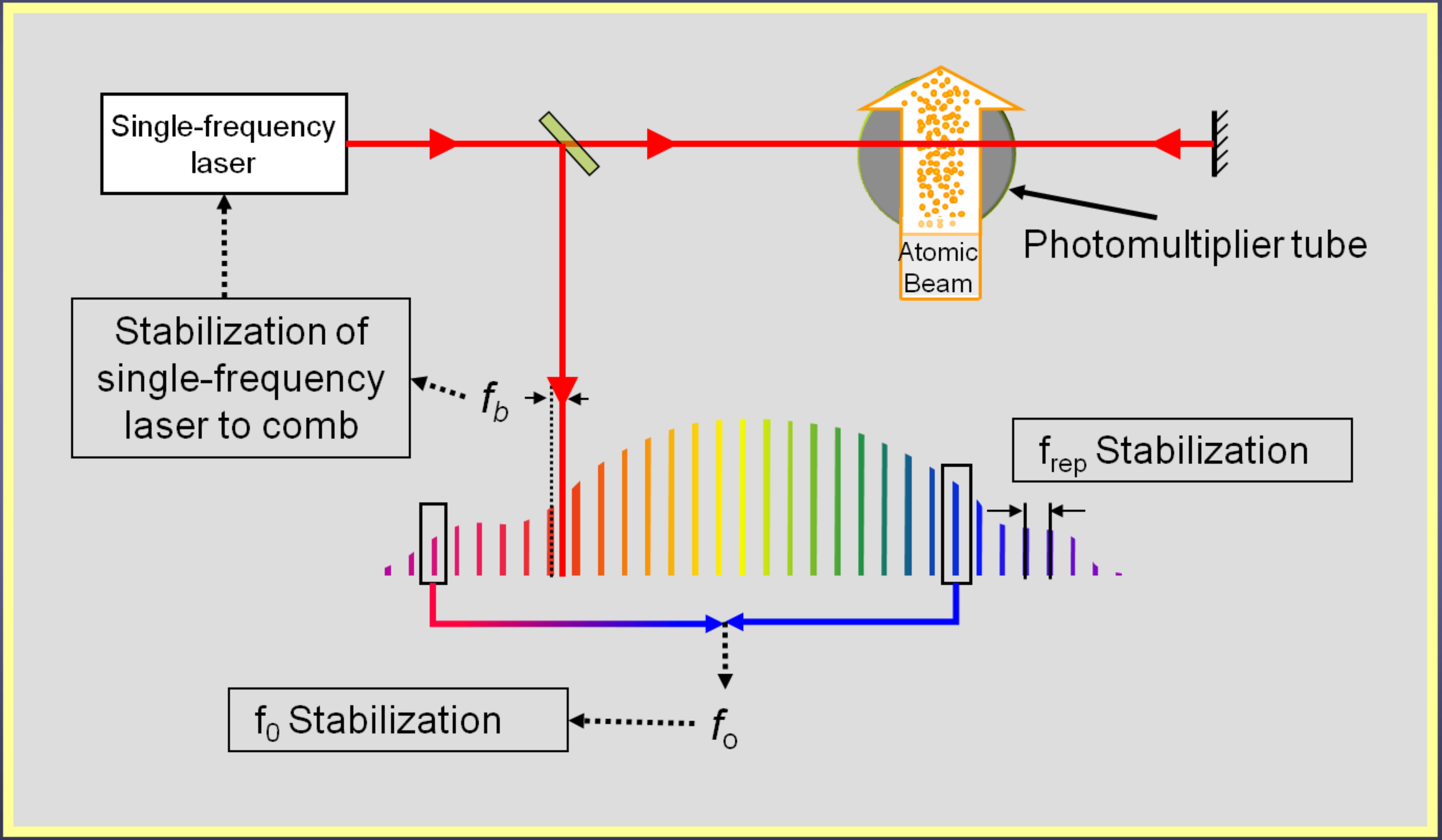


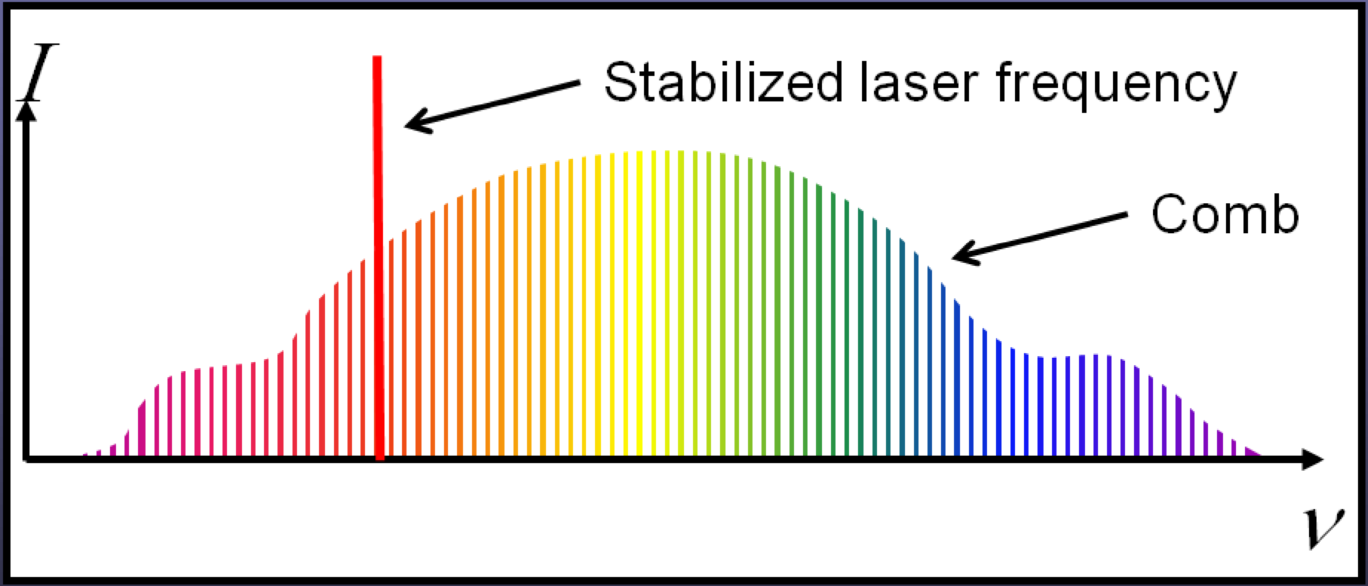
- Error bars for theory are very small – experiment should be able to do better than current measurements
- Possibly incorrect data analysis or systematic effects

Experimental Setup

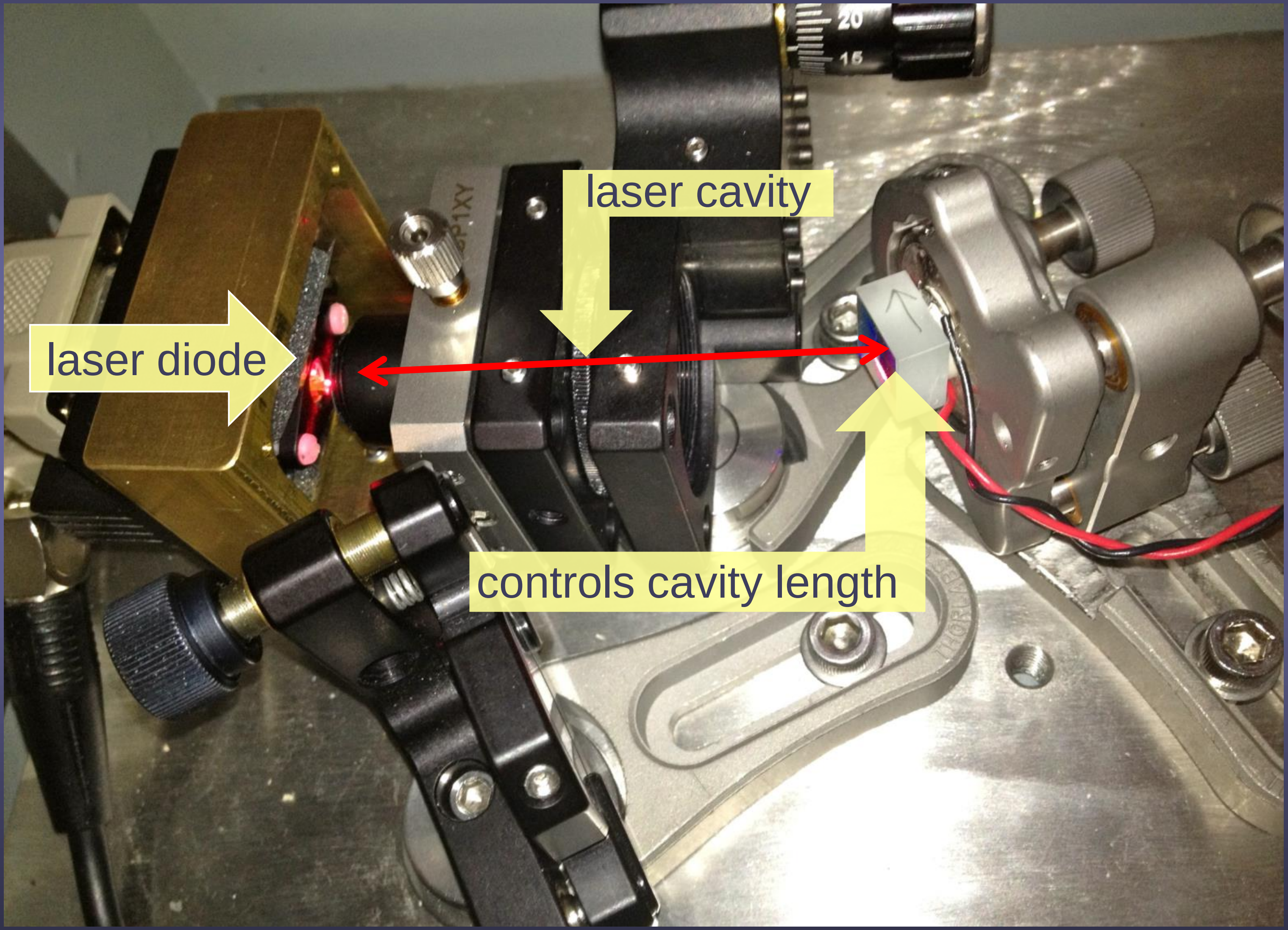


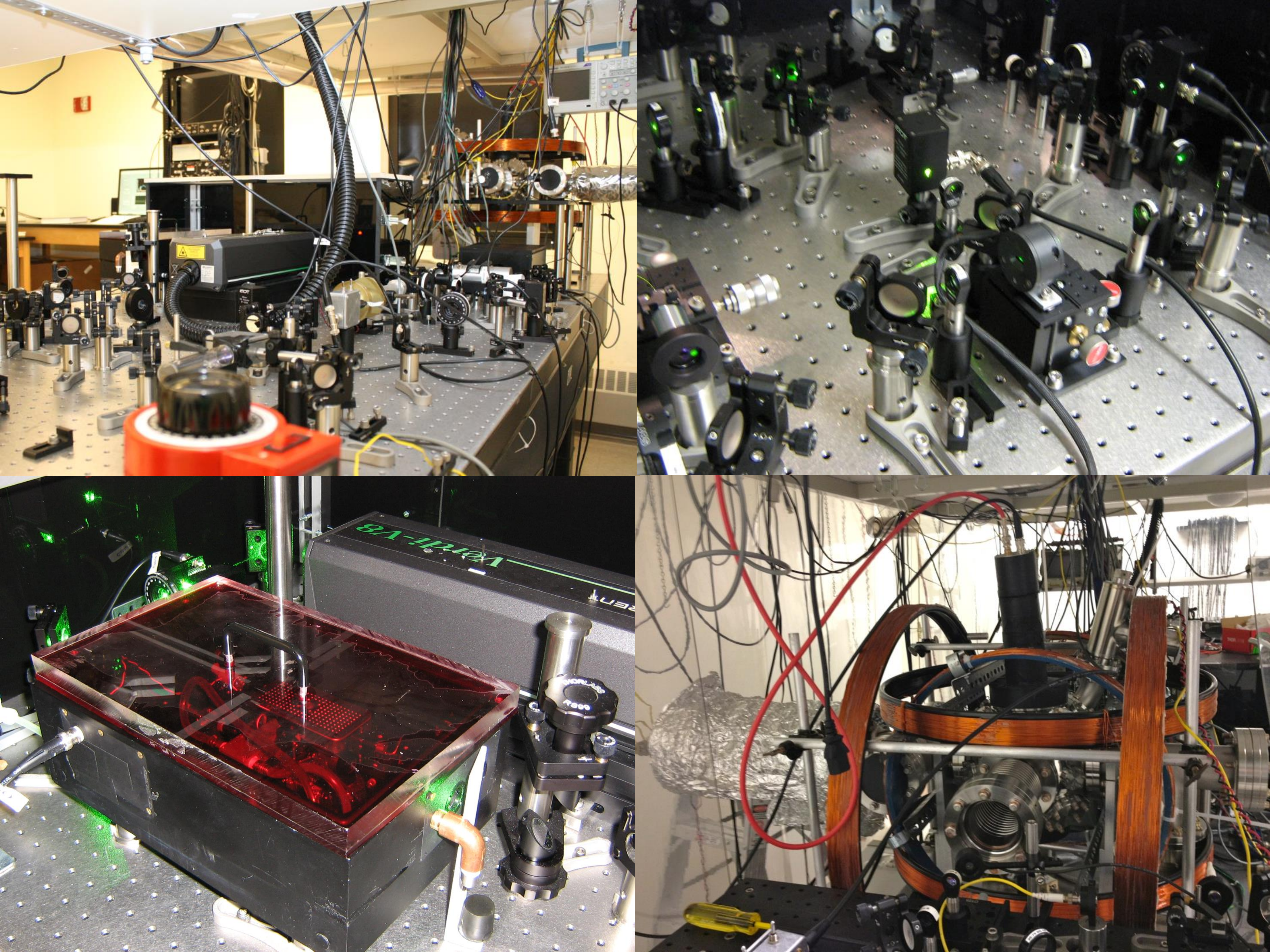
Experimental Setup

- A diode laser is *stabilized* to the frequency comb
- Frequency of diode laser is known and controlled



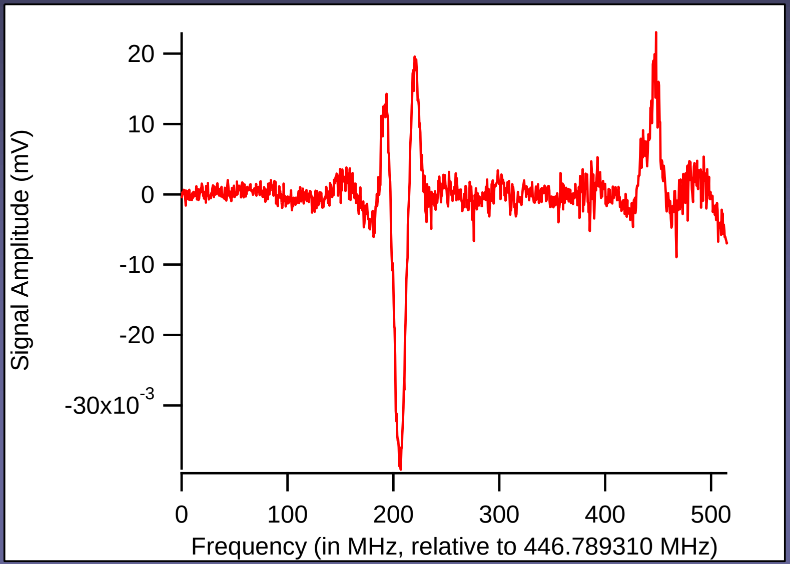
Single-frequency laser

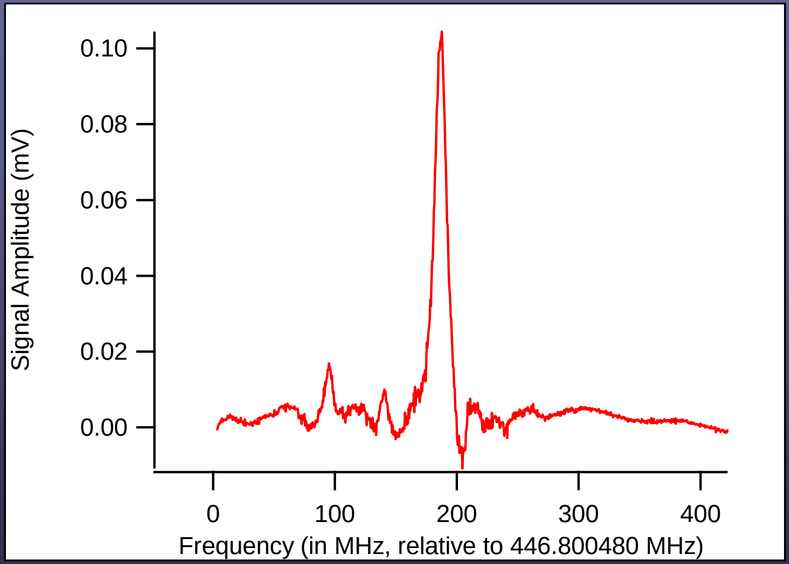


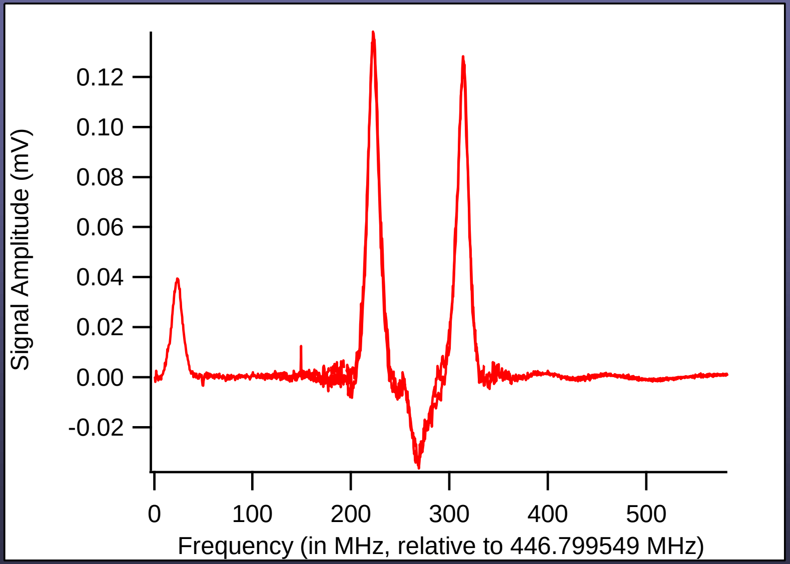

Verdi-V8

Recent Data

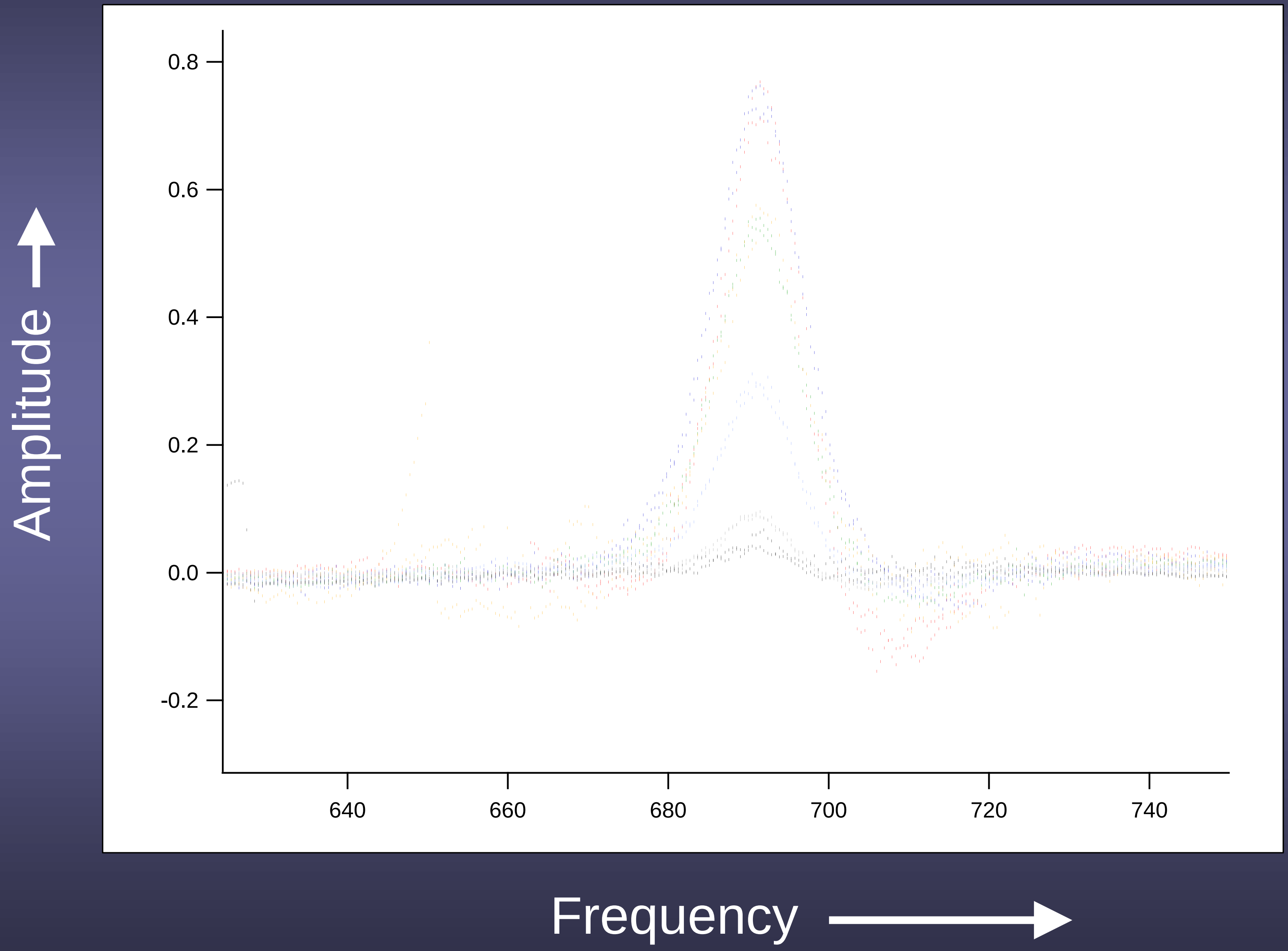
- These graphs show where resonances occur
- Different functions are used to fit the raw data
- Still have unexplained bumps in the fits







Peak Amplitude vs. Power



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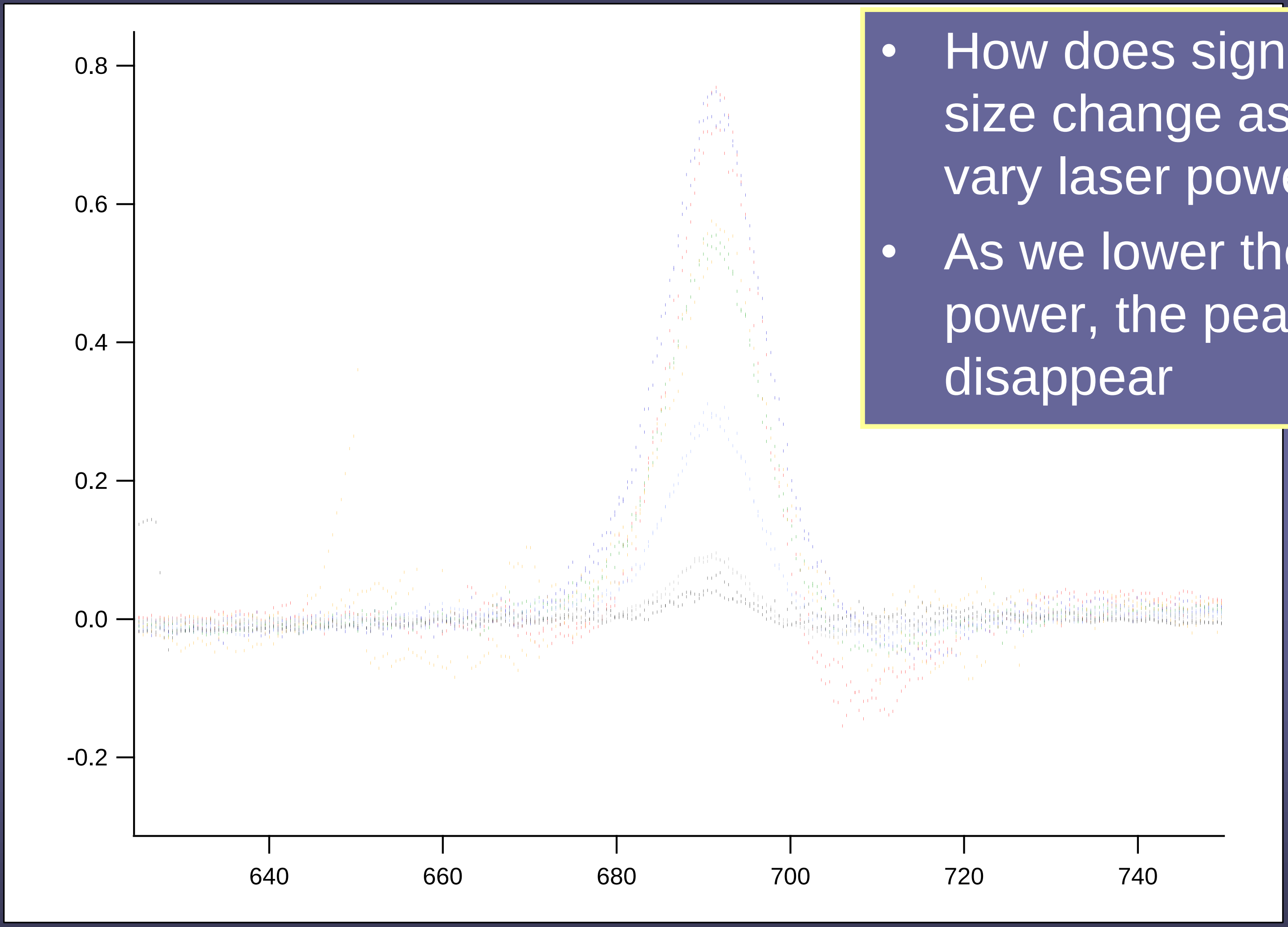


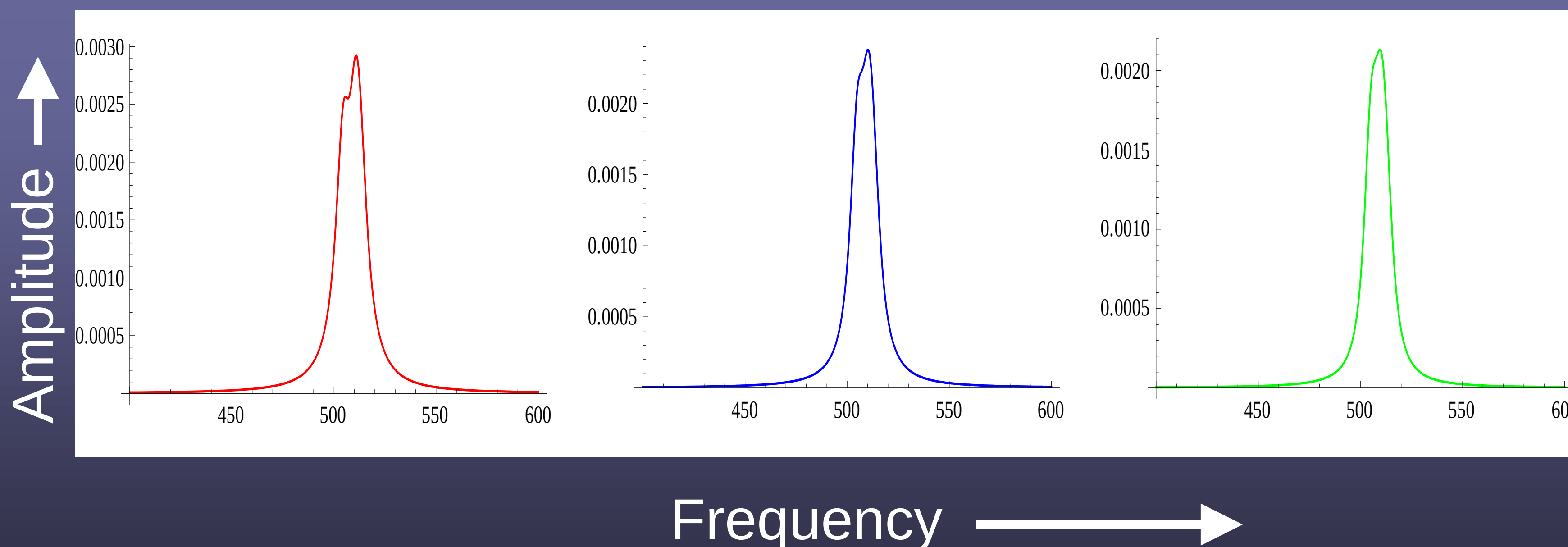
Amplitude

Frequency

- How does signal size change as we vary laser power?
- As we lower the power, the peaks disappear

Future Work

- Model Spectra
- Analyze Data
- Investigate polarization angle



Acknowledgements

- Prof. Jason Stalnaker
- Jacob Baron (honors student last year)
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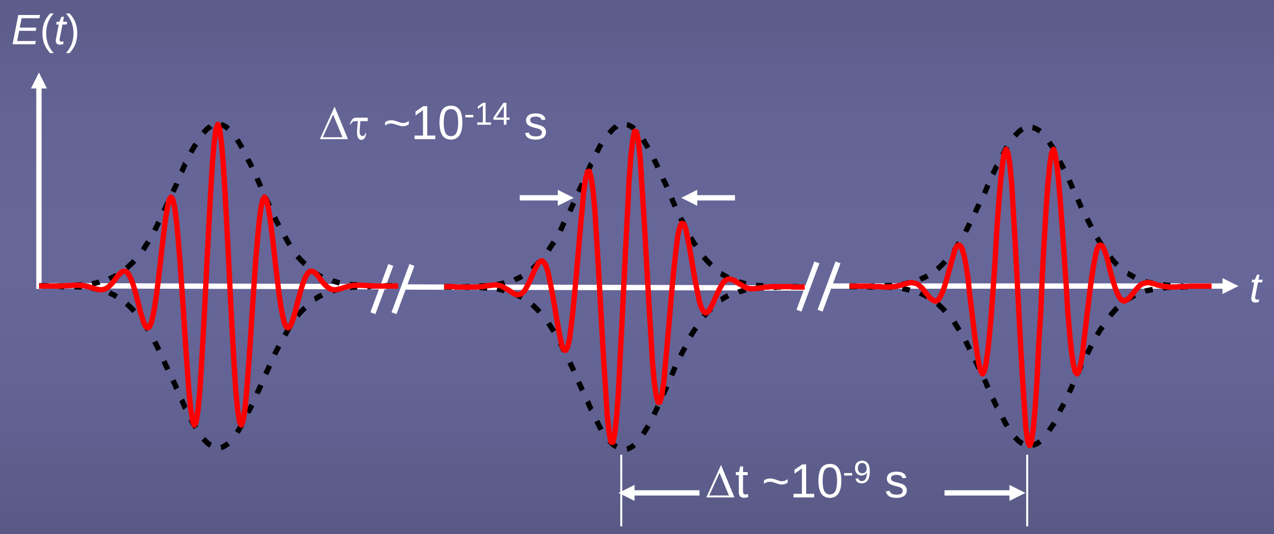
- Bill Marton for machining the nozzle
- Scott Diddams for assistance with the Ti:Sapphire oscillator
- Office of Undergraduate Research
- NIST Precision Measurements Grant
- OCRFs and MMUFs

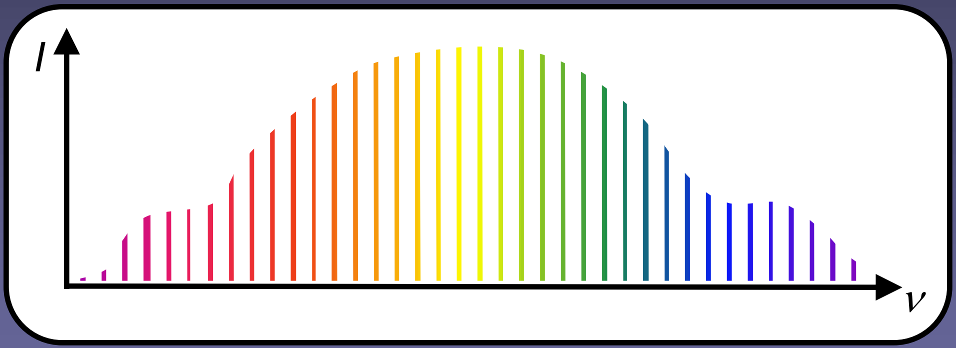
How do we make a frequency comb?

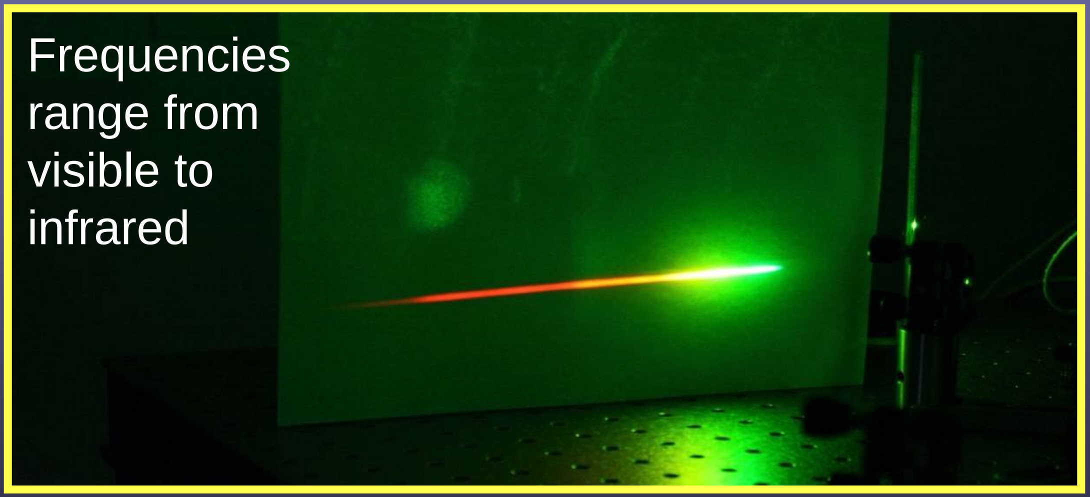
- The comb is produced by a series of ultrashort pulses



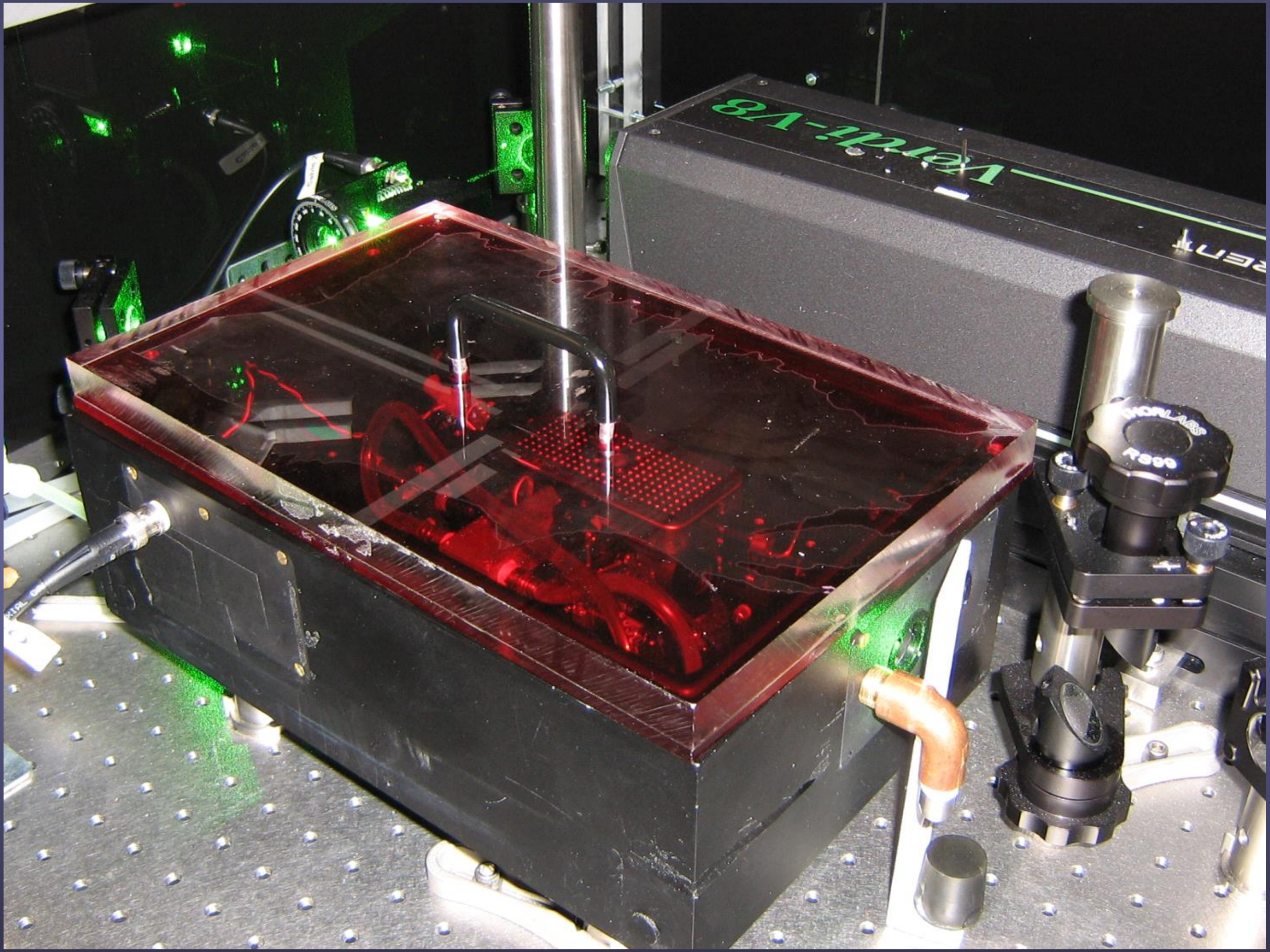
- Phase coherence of the pulses leads to interference and the generation of an optical frequency comb.
- Pulses are produced by a modelocked laser

Frequency Comb





Frequency Comb



Interference

- What's the frequency?

  Frequency # 1:

  Frequency # 2:

Interference

- What's the frequency?

    Frequency # 1:

    Frequency # 2:

- If one frequency is known
  → Interference can give you the second

Interference

- What's the frequency?

  Frequency # 1: 440 Hz

  Frequency # 2:

- If one frequency is known
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Interference

- What's the frequency?

  Frequency # 1: 440 Hz

  Frequency # 2:

- If one frequency is known
  → Interference can give you the second

  Frequency # 1 + Frequency # 2:

Interference

- What's the frequency?

  Frequency # 1: 440 Hz

  Frequency # 2:

- If one frequency is known
  → Interference can give you the second

  Frequency # 1 + Frequency # 2:

- Frequency of beat note is difference of two frequencies

Interference

- What's the frequency?

Frequency # 1: 440 Hz

Frequency # 2:

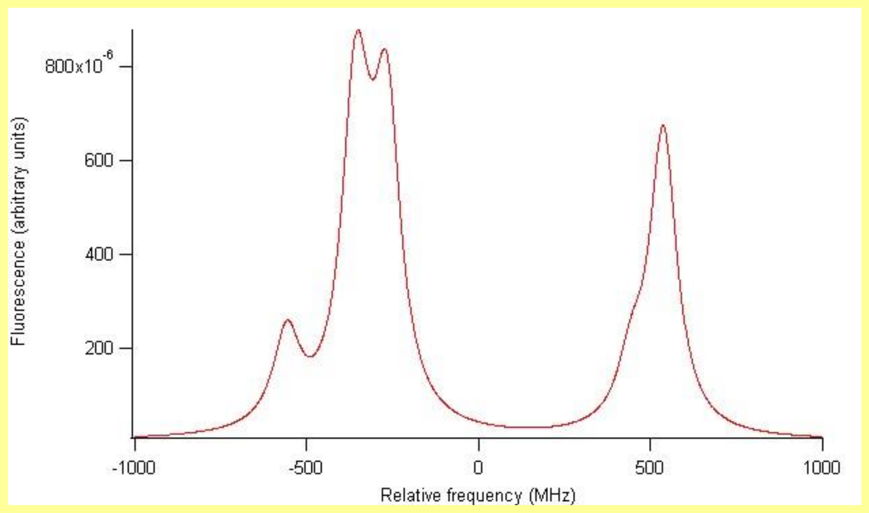
- If one frequency is known
→ Interference can give you the second

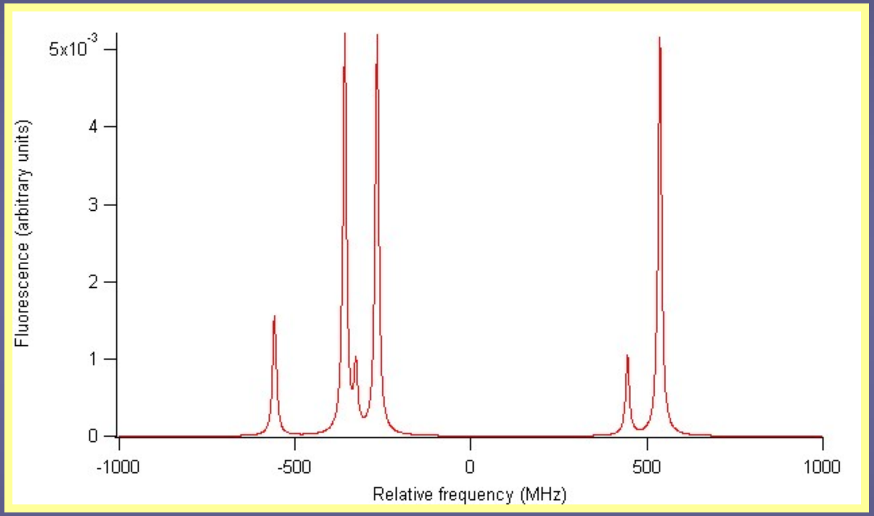
Frequency # 1 + Frequency # 2:

- Frequency of beat note is difference of two frequencies

- Do the same thing with optical frequencies
Optical Frequencies Interfere → Radio Frequency Beat Note

How will the new nozzle improve the data?

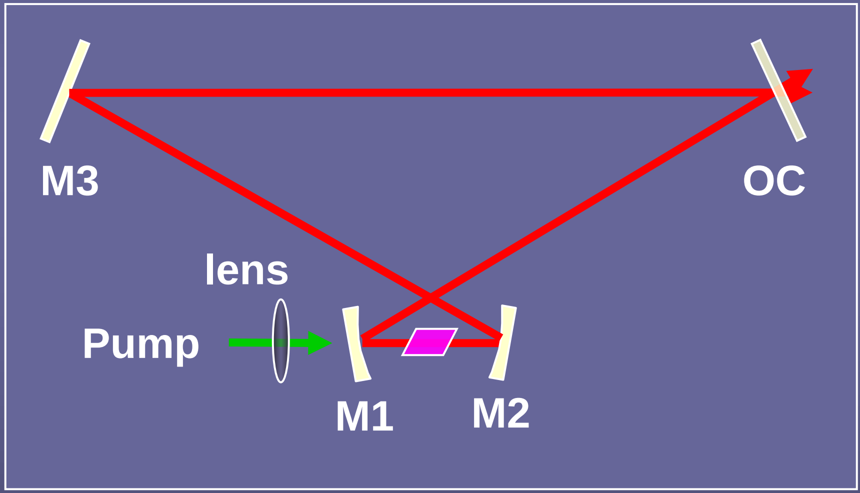


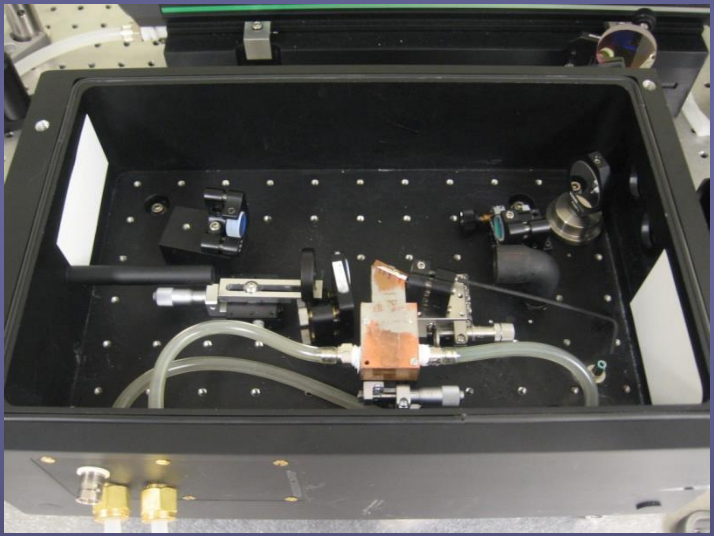


Old nozzle: peaks are less resolved

New nozzle: more structure observed

How do we make a frequency comb?



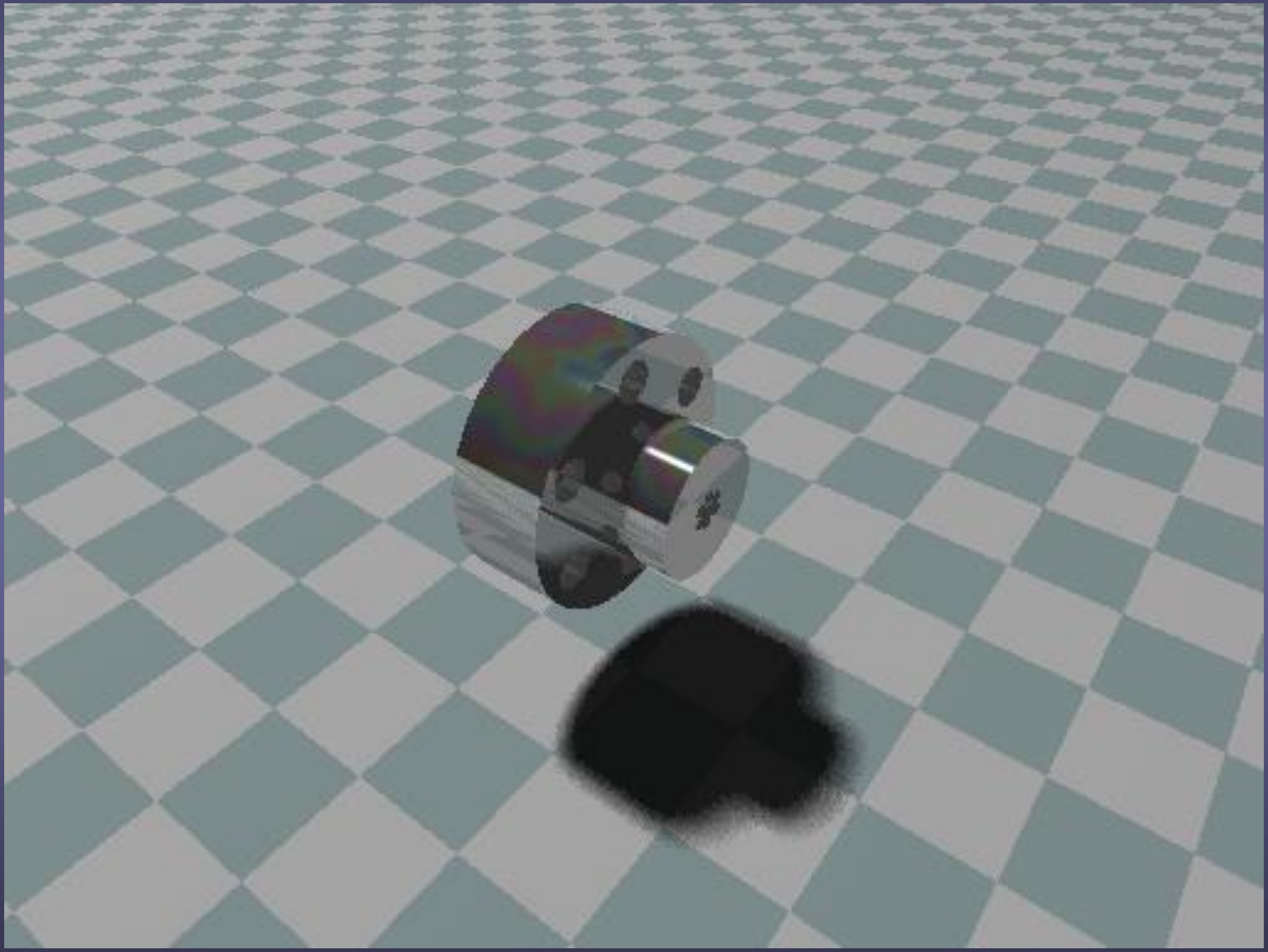


Other changes since old data

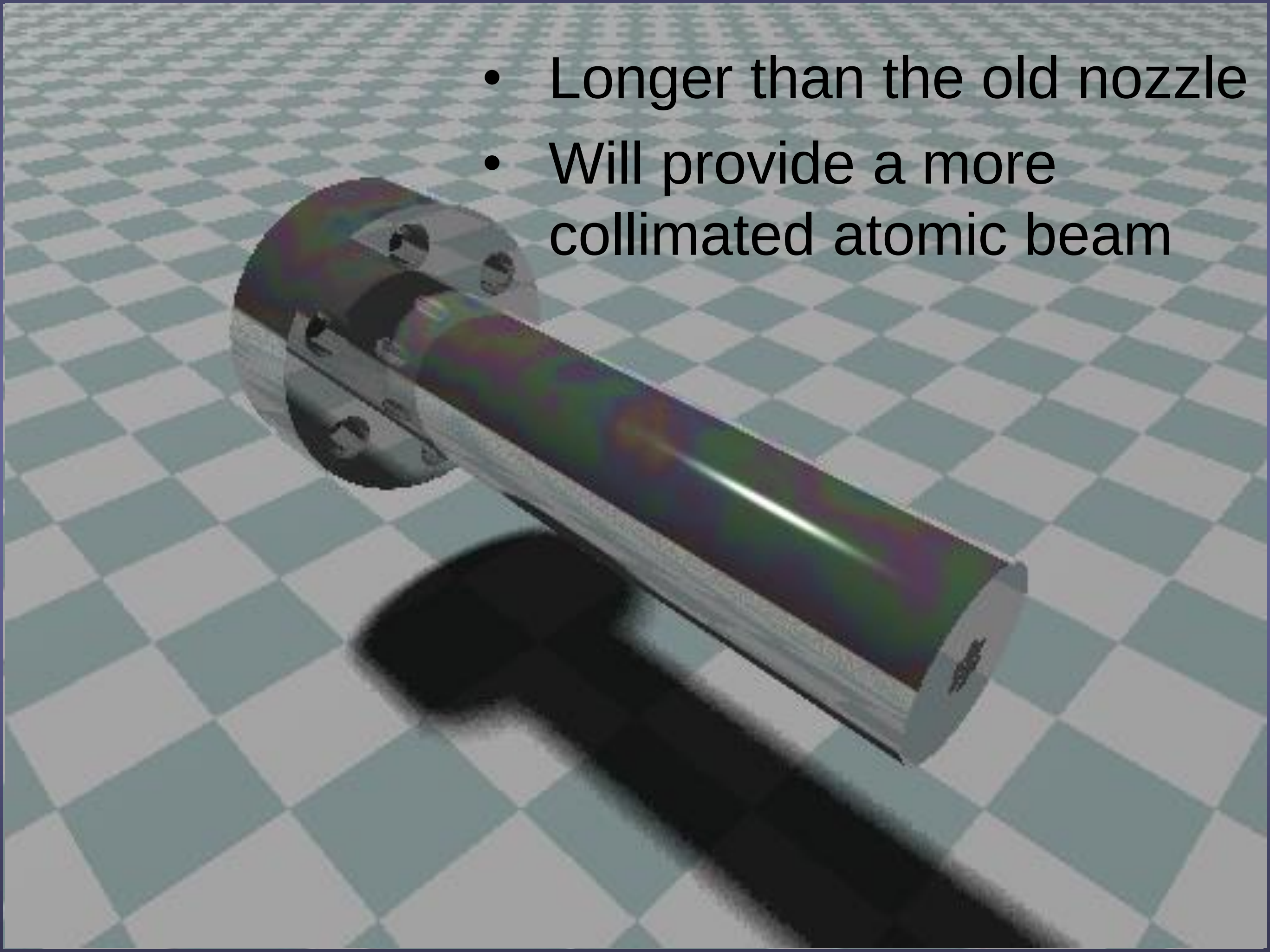
- Lithium supply in oven has been replenished

- Earth's magnetic field at center of oven has been compensated with coils
- Improved laser stability

Old Nozzle …



…New Nozzle!



- Longer than the old nozzle
- Will provide a more collimated atomic beam