The Ultraviolet catastrophe
Cavity: a metal box:
The electric field component of the electromagnetic radiation is analogous to the string, & forms standing waves in the box:

Classical physics (i.e. equipartition theorem, without the restriction $k_B T \gg$ level spacing) predicts that each of these modes gets $k_B T$ ~ an oo amount of energy in the box!

In 1D: $W_n = nW_1 \Rightarrow$ modes are evenly spaced in frequency.
However, in 3D, there are a number of similar ways to fit half-wavelengths into the cavity, and one can show that the frequency spacing between modes is $\propto \frac{1}{n^2} \Rightarrow$ as you go to higher frequencies (the ultraviolet end of the spectrum), the infinitude of energy density gets even more extreme!

$p_T = \frac{\text{energy}}{\text{vol}}$ for a 1 Hz band of frequencies

$T = 1500^\circ K$

1900: Max Planck cures the catastrophe by assuming that each electromagnetic standing wave mode can only take on quantized values of energy: $0, h\nu, 2h\nu, ... n\hbar\nu$

By requiring agreement with the classical result for the limit $k_B T \gg h\nu$, he showed that the probability of a normal mode having a "quanta" of energy is $\propto e^{- n\hbar\nu / k_B T}$. Qualitatively, this means that the high $\nu$ modes, which are the most problematic for the ultraviolet catastrophe, are unlikely to be excited at all. He was also able to find the value of $\hbar$, now known as "Planck's constant": $\hbar = 6.626_{-34}^{+43} \text{ Js}$
The agreement between Planck's theory and experiment was remarkable:

![Graph](image)

\( T = 1595^\circ K \)

However, most scientists of the time considered this to be a "math trick", and didn't believe that the energy of electromagnetic radiation was really quantized.

---

The **Photoelectric effect** (another argument for photons)

- For \( V = 0 \), one finds that electrons are ejected from the cathode only by light with \( \lambda > \lambda_0 \); even very intense light of lower frequencies yields no electrons.

- For light \( \lambda > \lambda_0 \), one can measure the maximum KE of the ejected electrons by finding the "stopping potential", i.e. the negative voltage \( V_0 \) applied to the anode that reduces the current of electrons to zero.

---

Einstein (1905): It takes an energy \( W \) (the "work function") to eject an electron from the cathode. The energy of light is quantized into units \( * E = h\gamma * \)

Thus, the KE of the electron is \( KE = eV_0 = h\gamma - W \).

The measured value of \( h \) matched Planck's value!
1923: Compton Scattering (yet another argument for photons)

\[
\text{light} \xrightarrow{h\nu, \lambda} e^- \quad \rightarrow \quad e^+ \xrightarrow{h\nu', \lambda'}
\]

Before \quad \rightarrow \quad \text{after}

To analyze, we apply cons. of energy (using \( E=h\nu \)) & cons. of momentum:

\[ E^2 = p^2c^2 + h^2c^4 \quad \Rightarrow \quad E_{ph} = p_{ph}c \]

(comparing this with \( E=h\nu \) gives)

\[ p = \frac{h \lambda}{c} \]

The analysis shows exactly the experimentally-observed dependence of frequency shift on scattering angle.

Single Photon detection: Photomultiplier tubes

![Diagram of photomultiplier tube]

- 0V
- 200V
- 6000V
- Glass
- Low W metal
- Single photoelectron
- 4000V
- Vacuum
- Anode (metal)
- 8000V
- Impact of photoelectron accelerated to 2000 eV produces many electrons
- Detectable electron pulse