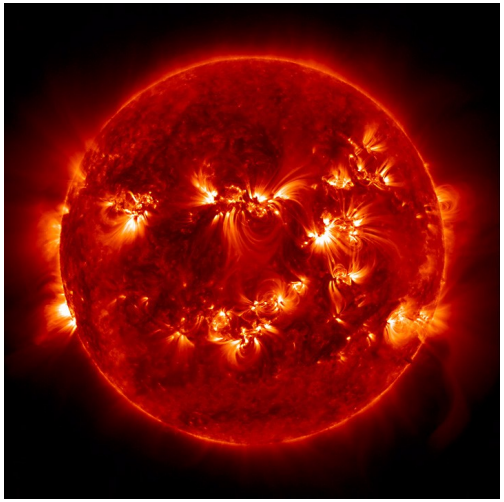
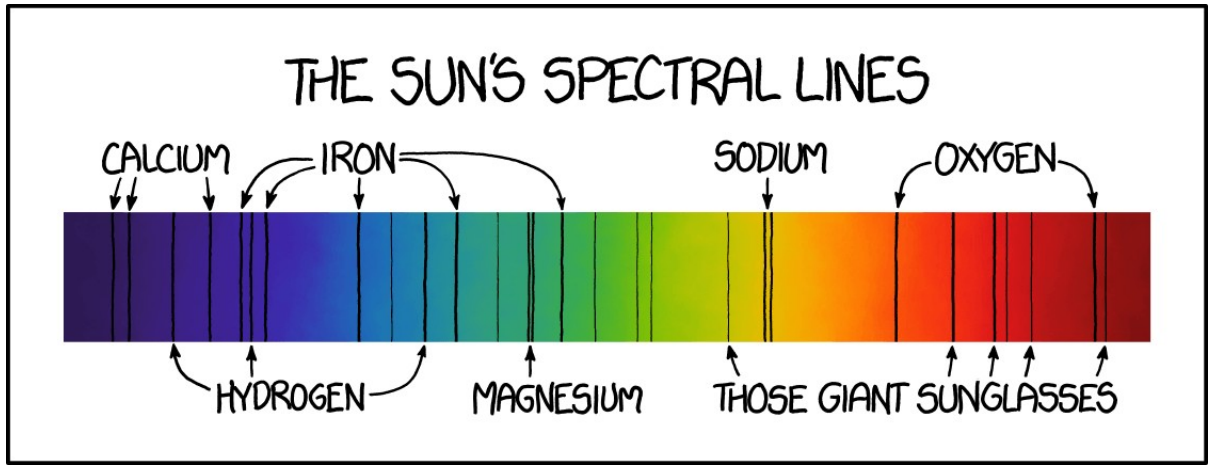
PHYS 7810 / COLLAGE2021:
Solar Spectral Line Diagnostics





Lecture 01: Intro to Solar Spectroscopy

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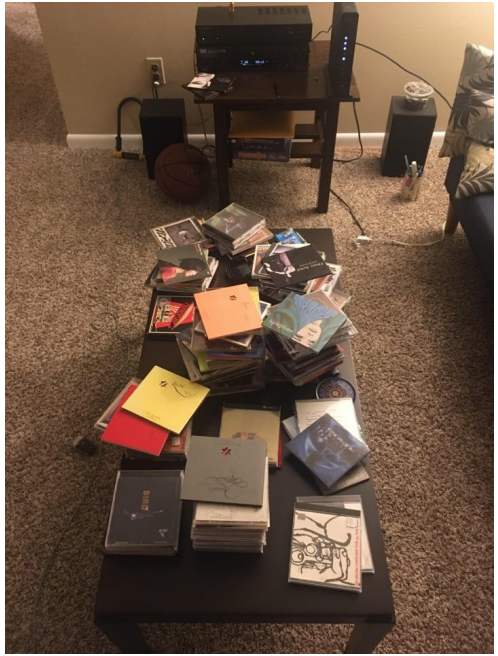
About the course

- **Solar:** the physical situation we are considering is the atmosphere of the Sun. This brings some assumptions about temperatures, densities, magnetic fields, etc
- **Spectral Line:** a feature in the **spectrum** that is a signature of (mostly atomic) **bound-bound** transition
- **Diagnostics:** we will see how to use spectral lines to understand what happens in the **atmosphere of the Sun**

About me

- I am a visiting faculty at CU Boulder, working at LASP and NSO
- My main interest are actually spectral lines : modeling, interpretation and “inference” – figuring out model parameters from the data
- I also like a lot:
  Bayesian inference
  Exoplanets
  Pizza
  Basketball
  Video, board and card games
  Collecting and listening to CDs



And I like teaching

- Last two falls: Phys 4510 : Optics at CU Boulder – great fun for me!
- Last three springs: COLLAGE / HALE / Phys7810 course.
- It's a **collaborative** (meaning there is usually more than one lecturer), **graduate course** that was started here in Boulder and deals with various aspects of Heliophysics.
- The goal is to get students interested in Solar Physics, prepared for independent research and familiar with modern methods.
- https://nso.edu/students/collage/

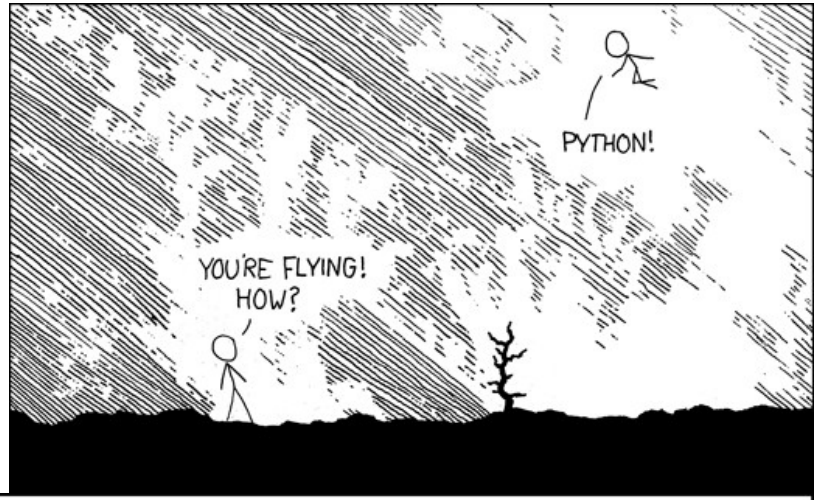
Which brings us to this year's topic!

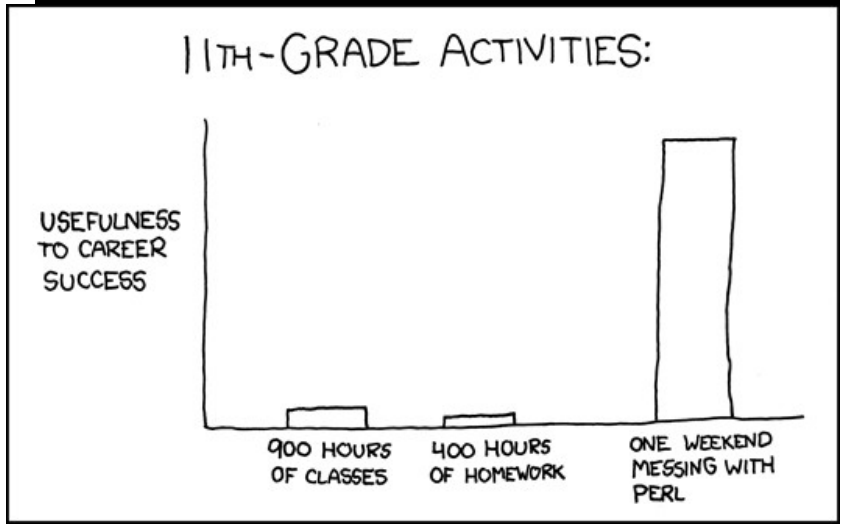
Aim: Get you equipped with theoretical and practical (numerical, coding) skills and knowledge to:

- Understand why there are spectral lines in the solar spectra and how they can be used.
- Understand (and model) how the atmospheric model influences the line shape.
- If needed, plan appropriate observations to solve your scientific problems.
- If interested, delve deeper into atomic physics and radiative transfer intricacies

How do we achieve it?

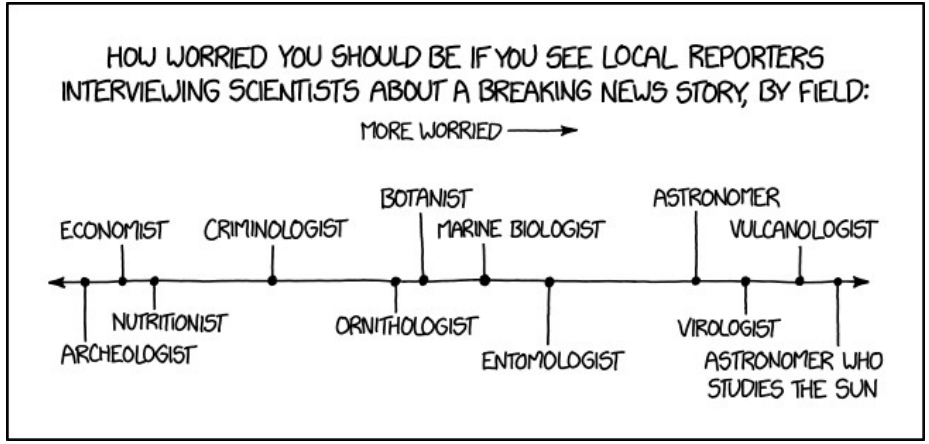
- **Lectures!** First on general theory and then applications to various solar phenomena/region
- **Hands-on Exercises!** Using data from instruments, simulations and state-of-the-art radiative transfer codes. Most likely in *python*
- **Discussions!** Either during the class, individually via e-mail, or publicly via discord (see the webpage)
- **Homework!** One per block, combining theoretical problems, project-oriented problems, as well as handling the data





Technical stuff

- Zoom lectures Tuesday / Thursday **3:55 – 5:10 pm**
- Everything recorded, and together with slides and brief description, uploaded to: https://nso.edu/students/collage/collage-2021/
- Discord at: https://discord.gg/8JWC6SRvbY
- We split hands-on exercises over the spring break, so you can participate seamlessly and not miss anything
- That's about it,
  let's go to beautiful equations!



I like repeating things, so you will hear this a lot

- To understand spectral line formation process, we need to understand both

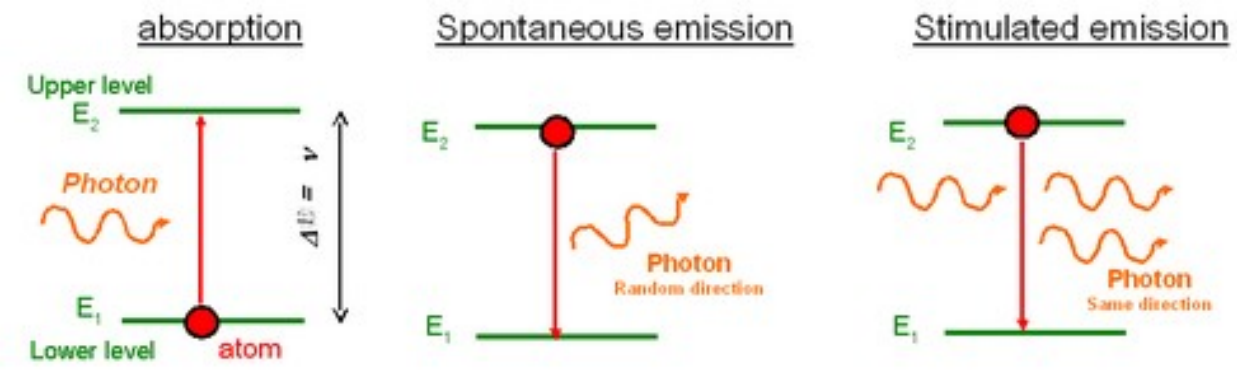
  Macroscopic phenomena
  (propagation of the light throughout the atmosphere of the Sun)

  with

  Microscopic phenomena
  (absorption / emission processes in bound bound transitions)

Or to put it in pictures:

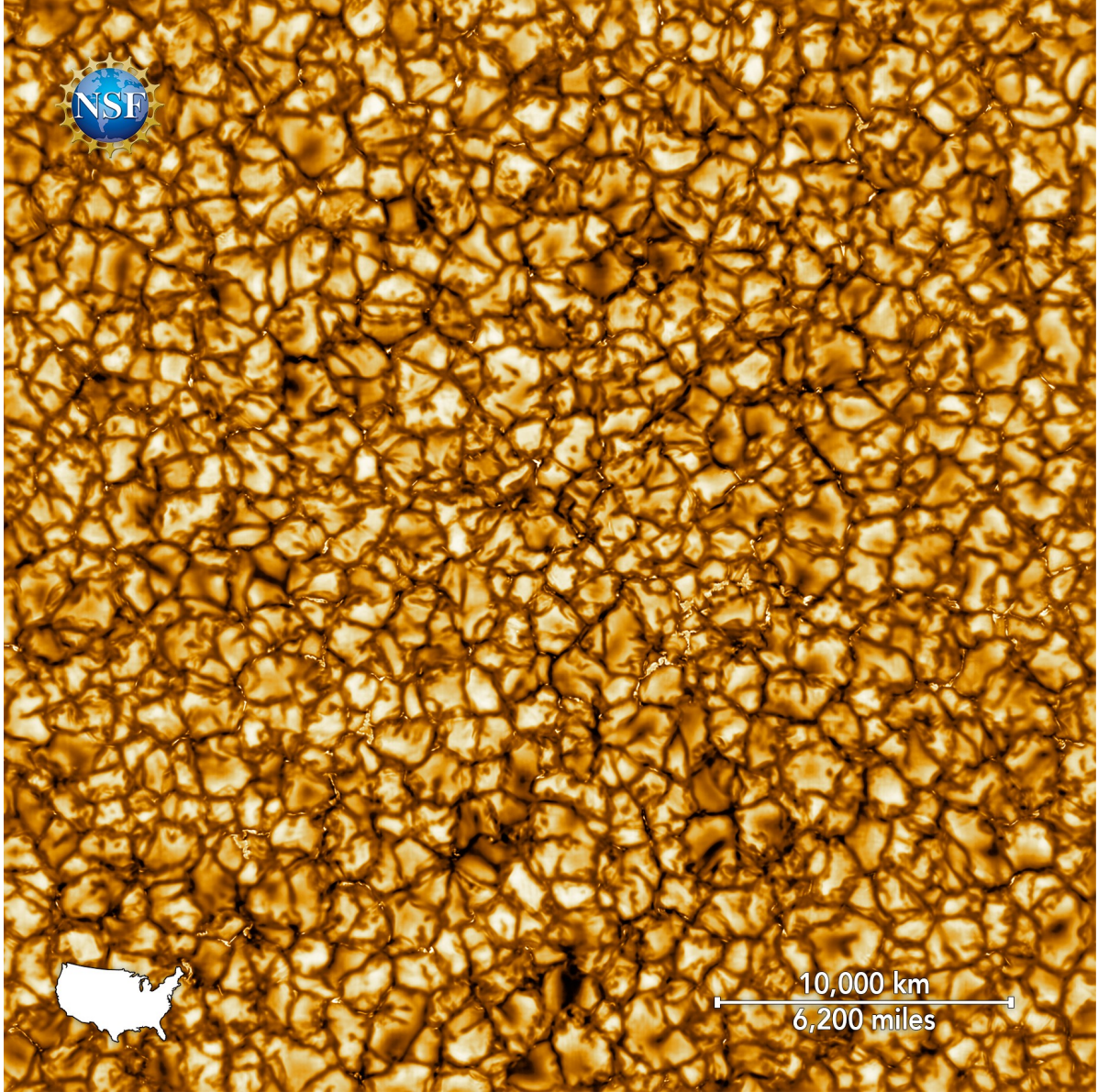
- Absorption and emission of photons happen on the atomic level:



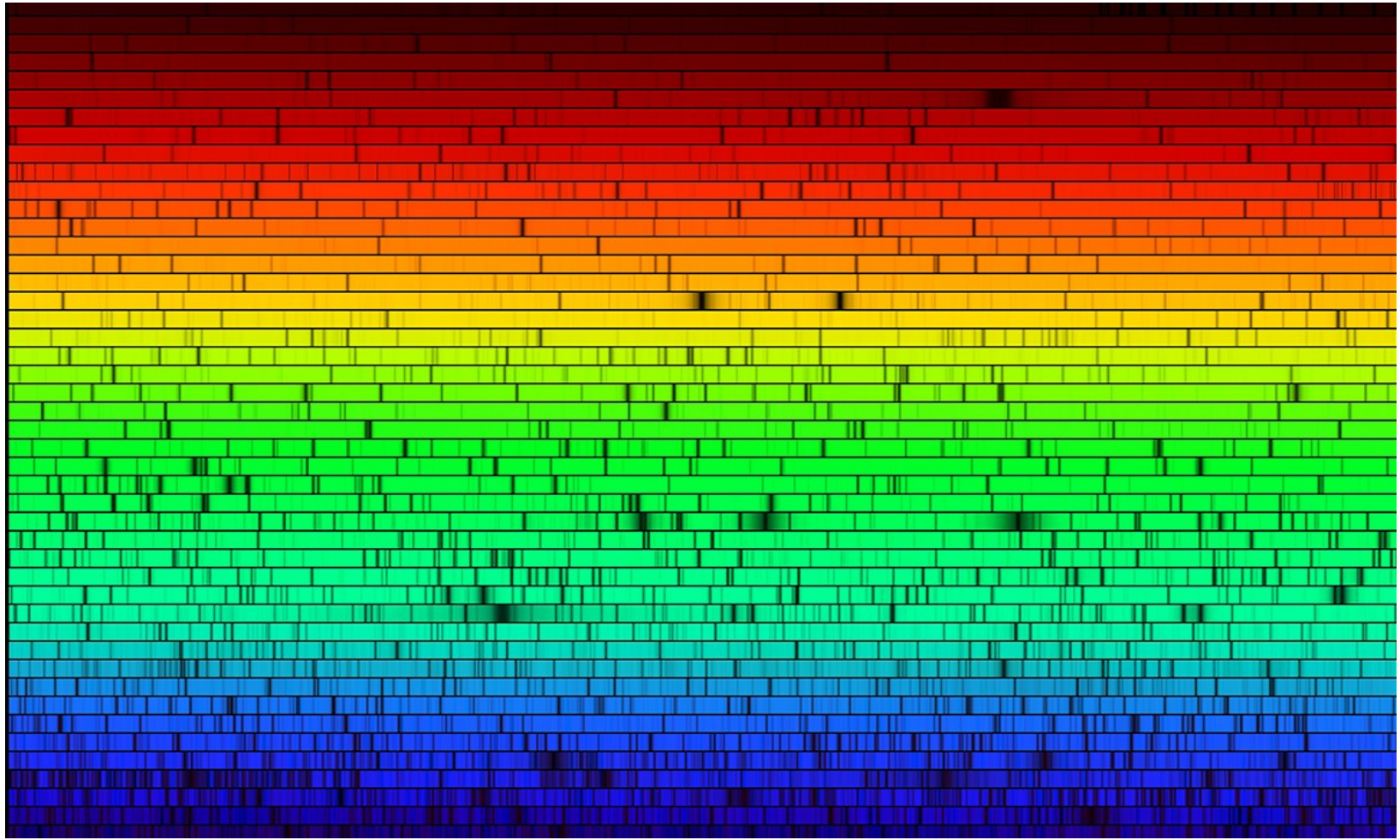
- We are actually, today, going to go through a very brief history of spectral lines and the birth of modern physics

Solar atmosphere consists of, well, atoms and ions

- This is an image made by DKIST solar telescope, built and operated by National Solar Observatory
- This is a so called “broadband” image
- What we see is the light coming from the “surface” of the Sun



Separate the light by wavelengths, and obtain a spectrum



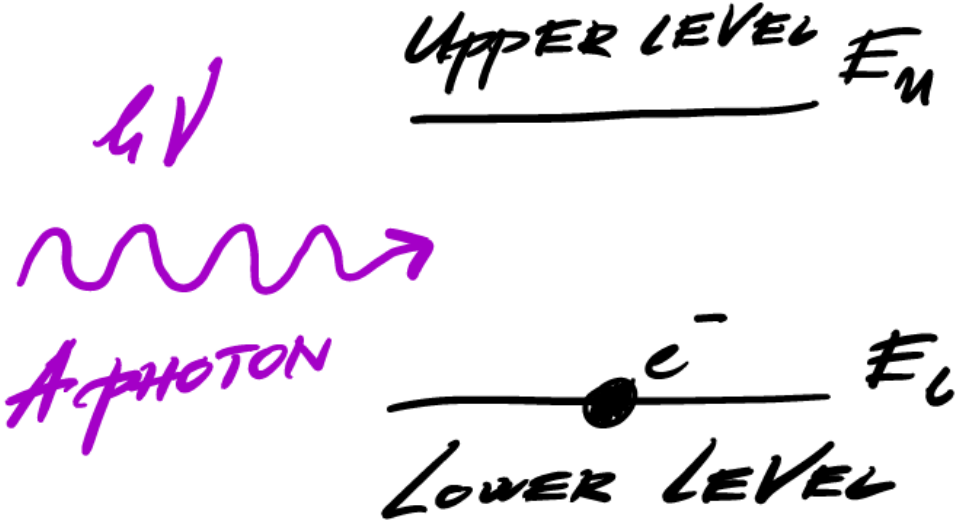
Source: N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

Actually…

- We can, to some extent, combine these two
- Yes, we can obtain very detailed spectra from each of the pixels
- In addition to that, can we get **polarization** information about each spectrum
- We can refer to this discipline (field?) as *High Resolution Spectropolarimetry*

But let's take it easy! I want us to kick of with some questions (some of them are actually taken from reddit)

- How does any photon reach exactly the energy needed to excite a particular atom?



$$h\nu = \frac{hc}{\lambda} = E_2 - E_1$$

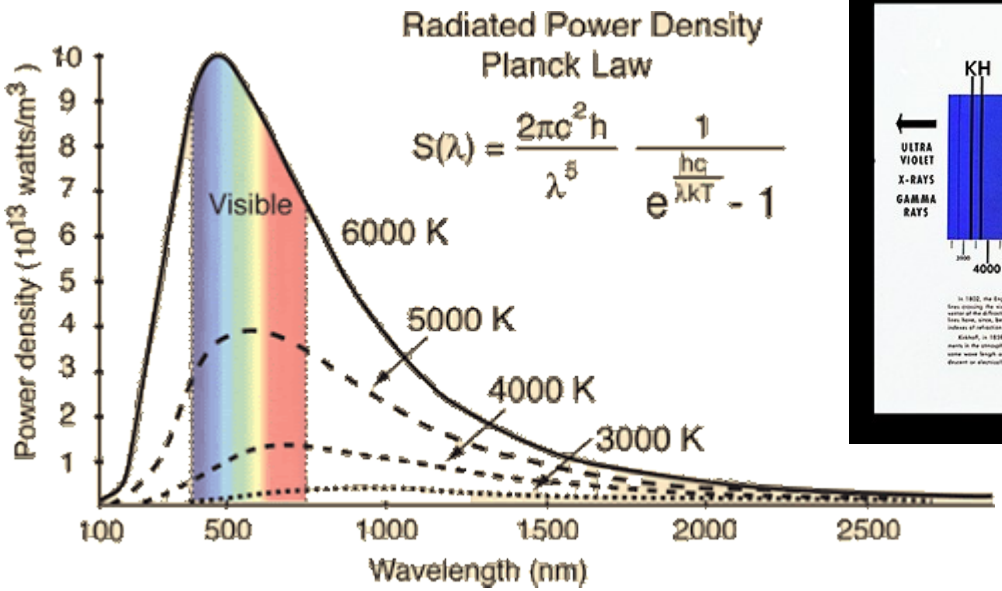
- Well, what are the odds that a photon with that very very VERY exact energy level would come passing by in any reasonable amount of time?

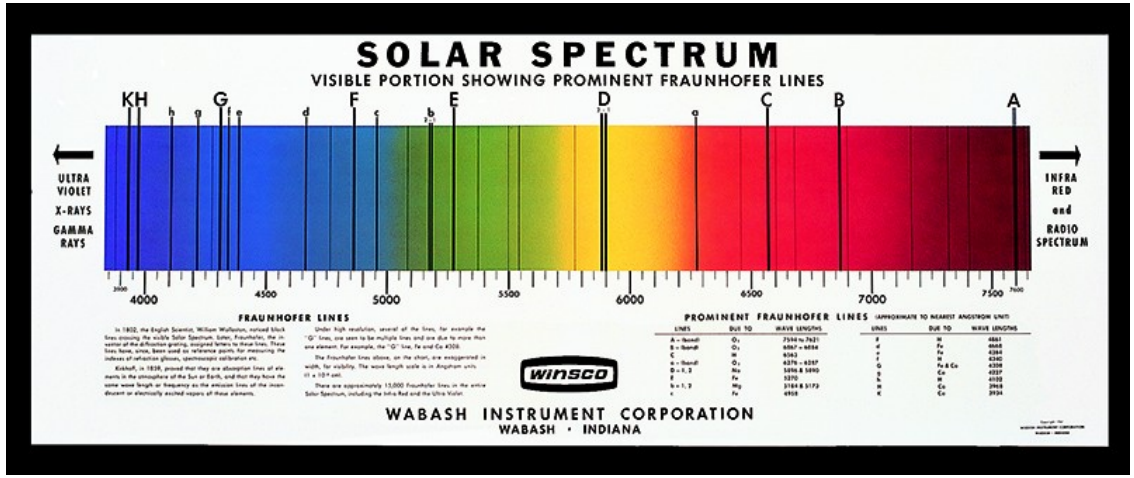
Answer 1

- There is no such thing as “exact” energy, both the energies of the photon and the levels are uncertain (or smeared if you prefer)
- Even more so because of of the so called “damping”
- And then there is Doppler effect
- We will learn about all these things when we talk about spectral line absorption / emission

Question 2

- Can something that radiates like a blackbody have spectral lines?





Credits: Wabash Instrument Corporation

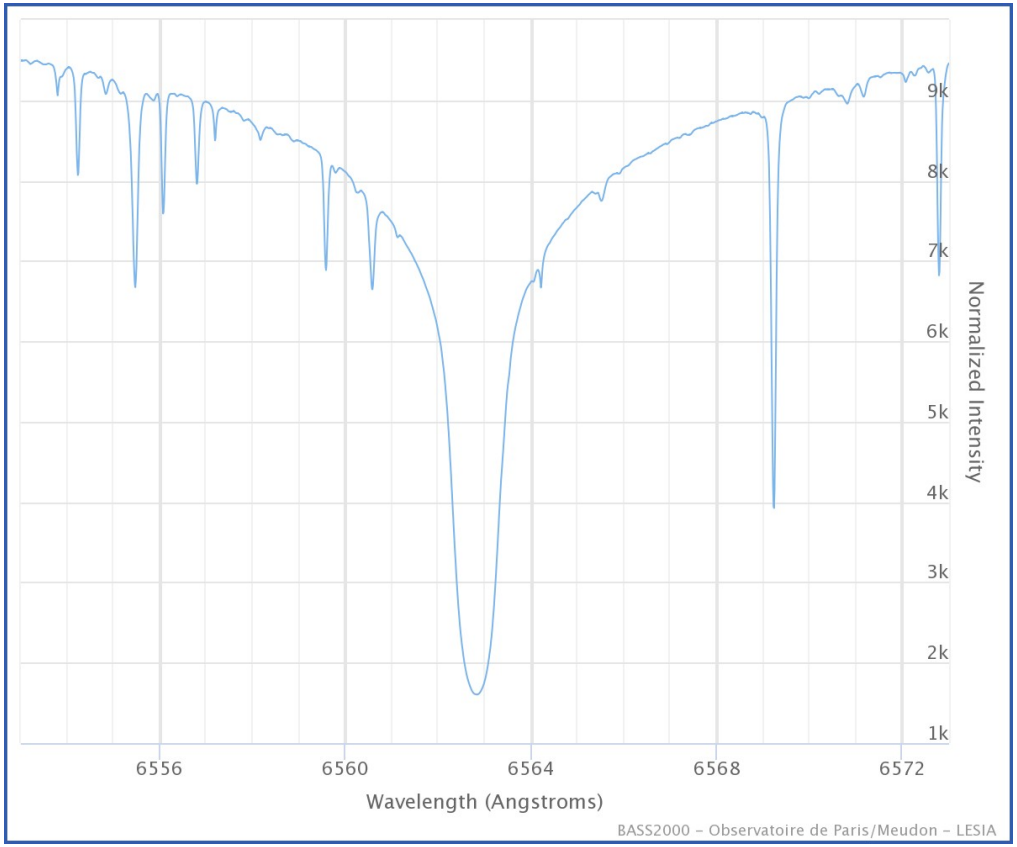
Answer 2

- Technically – no!
- Blackbody is a specific idealization, a body in a complete thermal equilibrium.
- Such an object emits completely continuous spectrum, according to Planck's Law
- Sun, for example, deviates from blackbody spectrum and also exhibits spectral lines, so it's not a blackbody.
- Anyone has a handy argument why it can't be a blackbody?

Question 3

- Why do the spectral lines, even very strong ones, (almost) never reach zero intensity? (This one is hard)

- Famous H-alpha line of Hydrogen ($2^{nd} \rightarrow 3^{rd}$ level)
- Note that this is usually the way we want to look at the spectral lines, not really as dark smudges

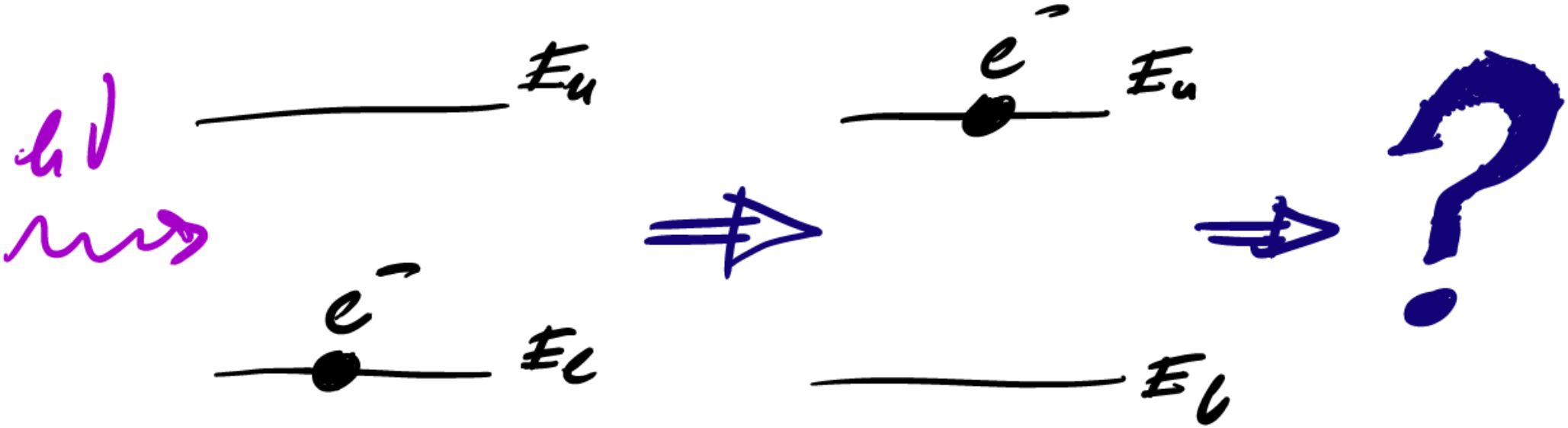


Answer 3

- Contrary to what we are mostly taught, there are no “absorption” or “emission” spectra.
- Both the emission and absorption processes happen in line transitions. It depends on their balance and the object in question whether the spectral line will be “absorption line” or “emission line”
- It is a bit extreme viewpoint, but I might convince you of this over the semester ;)
- Specifically, in a blackbody, absorption and emission are “balanced” in such way, so that even line processes exist, spectral line is not visible as a feature in the spectrum (think a bit about this one in your spare time)

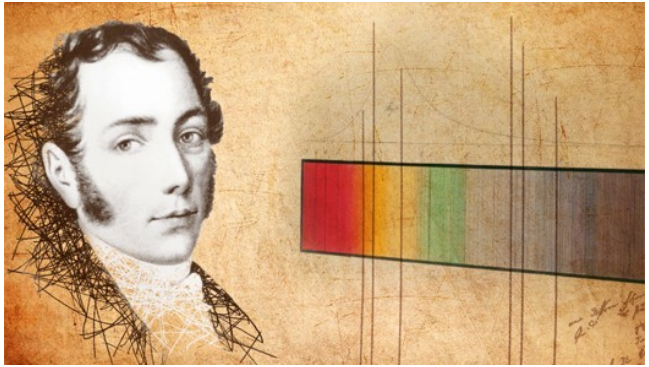
Question 4

- What happens with an atom that was excited due to a photon absorption?

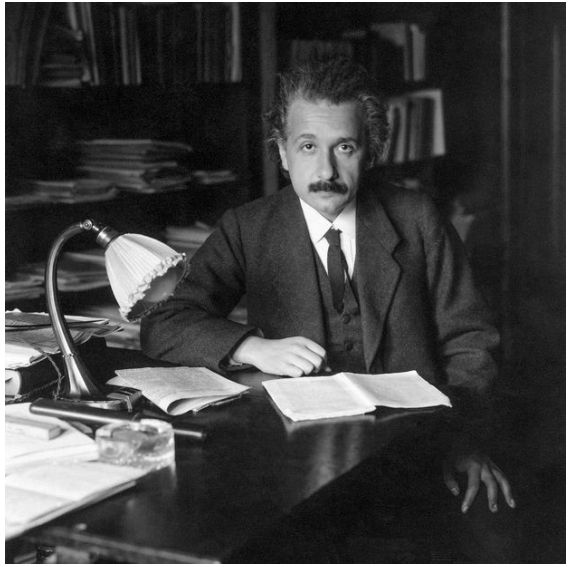


Answer 4

- Contrary to a popular belief, the electron does not necessary de-excite by emitting another photon
- Even if there were no other levels to consider transitions to, this atom could de-excite **through a collision,** which means it would transfer its energy to another particles around and turn it into kinetic energy of the gas
- Note that, in this case, photon truly disappeared
- We will use this to understand the assumption of so called **Local Thermodynamic Equilibrium (LTE)** that is valid for the cases when our plasma is dense enough (e.g. photosphere of the Sun)

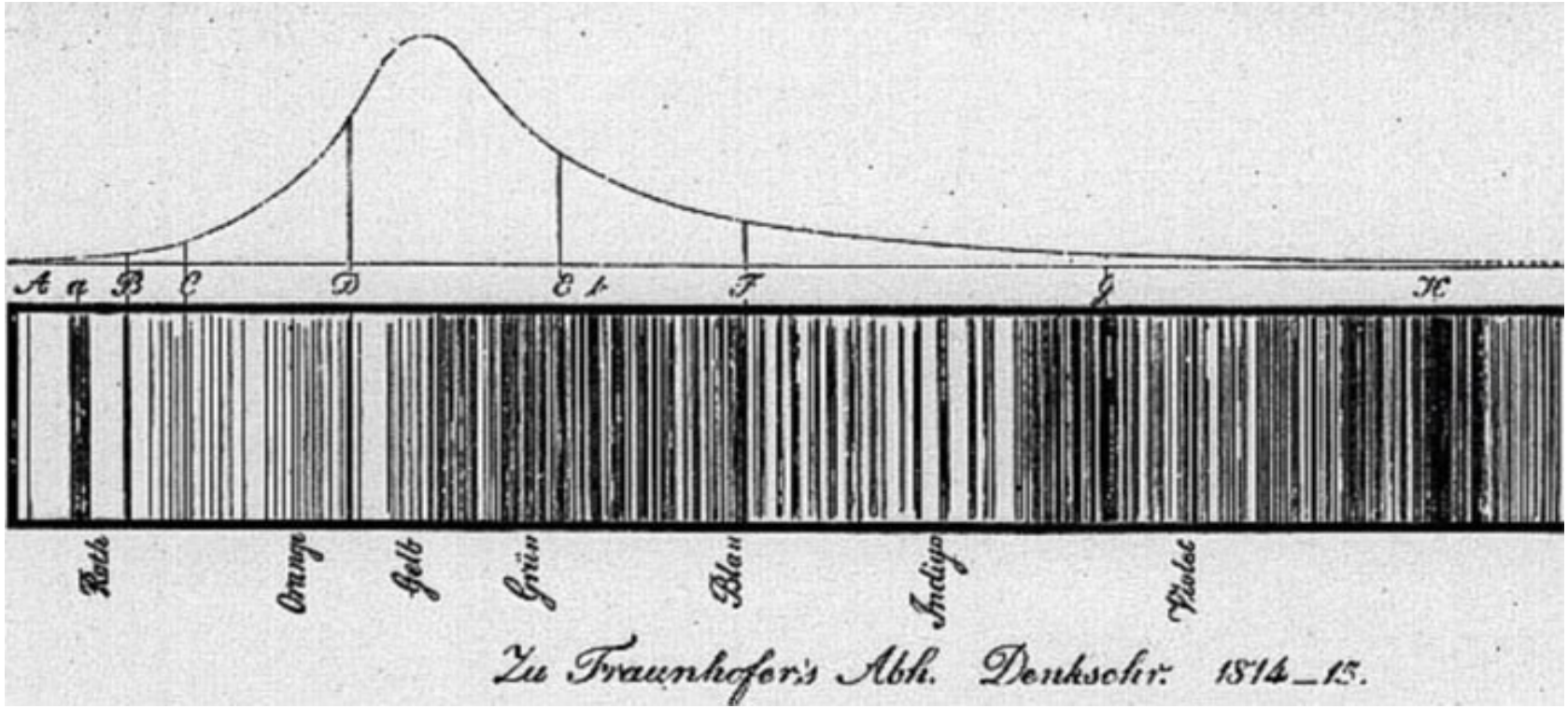


A brief history of spectra, photons, spectral lines and all that!



We start with a fantastic work of Fraunhofer

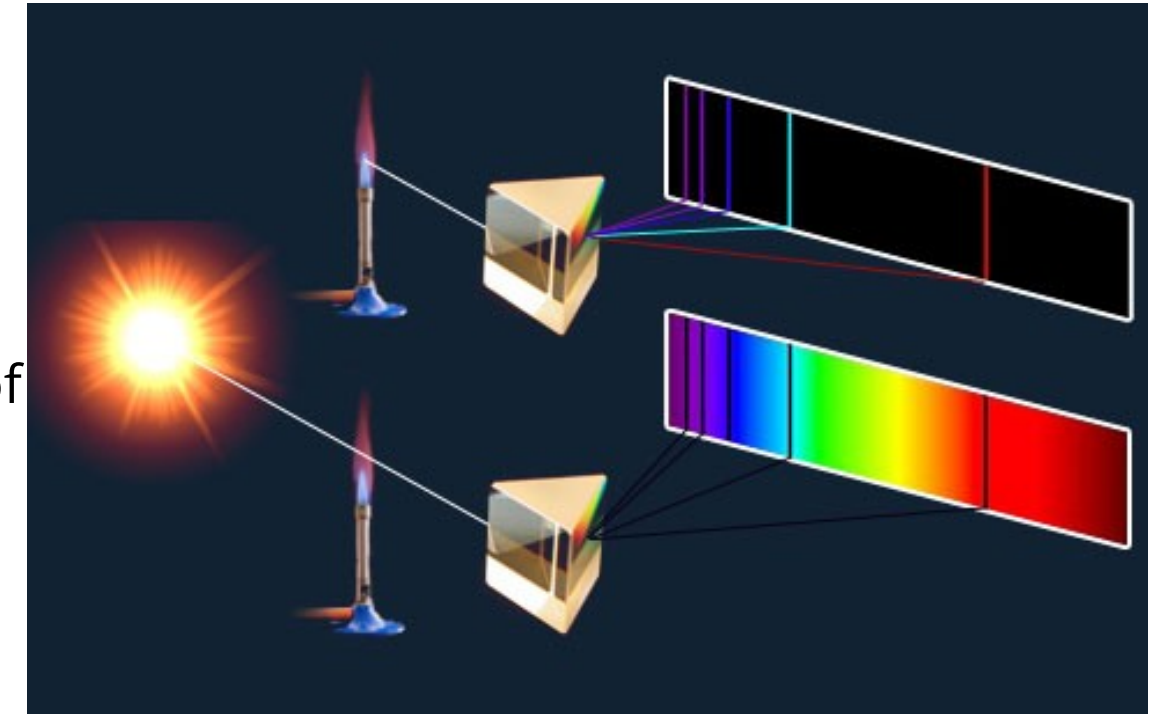
- The distribution below looks like a blackbody. Yet there are spectral lines. We still refer them as Fraunhofer lines.



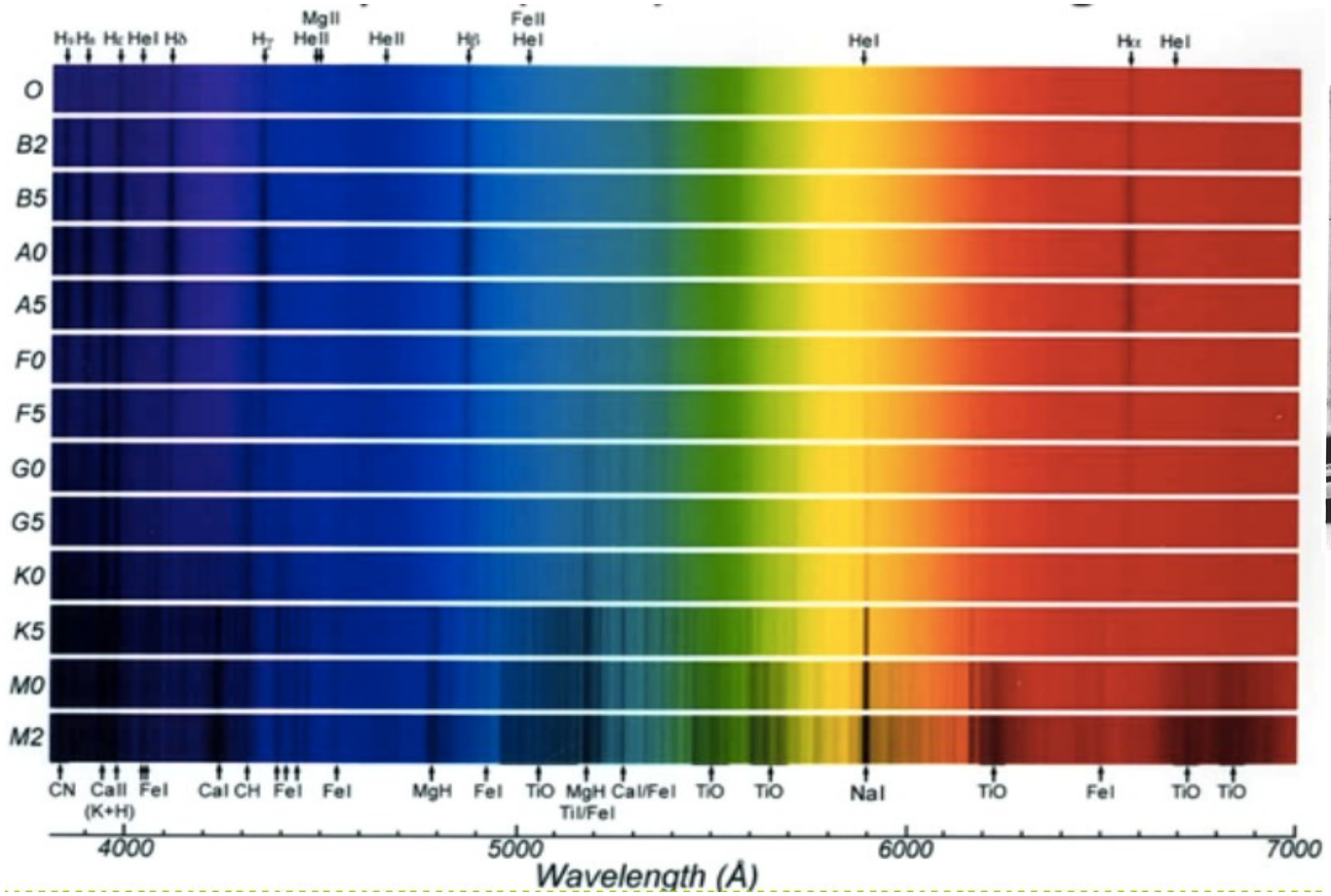
Credits: Wikipedia

Some time after that – Kirchhoff and Bunsen experiments

- In different physical regimes, same gases exhibit absorption or emission spectra
- This eventually led them to relate laboratory lines to solar lines
- And confirm that the Sun is built of various gases!
- Of course, not all the lines were identified (cough Helium cough)



We studied these spectral lines ever since



Annie Jump Cannon, Harvard classification.

Credits: NOAO/AURA/NSF

But let’s take it easy

- It’s obvious that some elements like to absorb at some wavelengths, and other elements at the other ones
- Does it tell us anything about the structure of atoms, and the nature of EM radiation?
- Spectroscopy certainly played a role and was interwoven with fundamental discoveries in physics in the first part of XX century

List, preferably in order of appearance, atomic models emerging at the end of XIX and the start of XX century?

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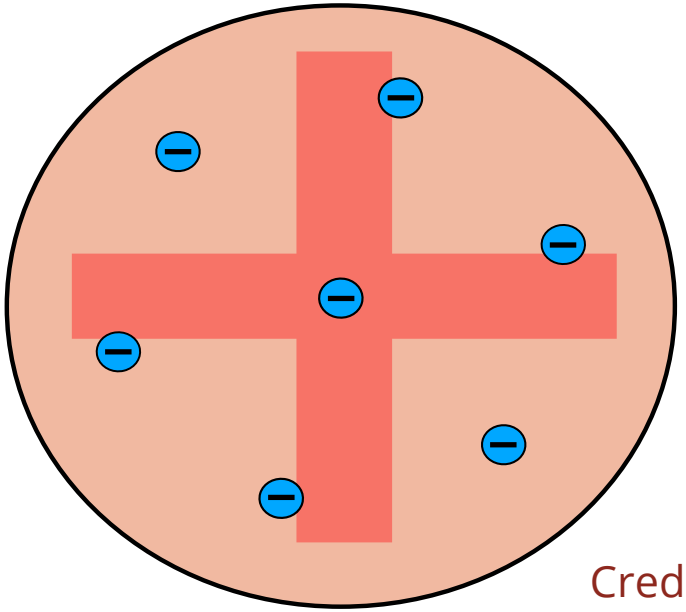
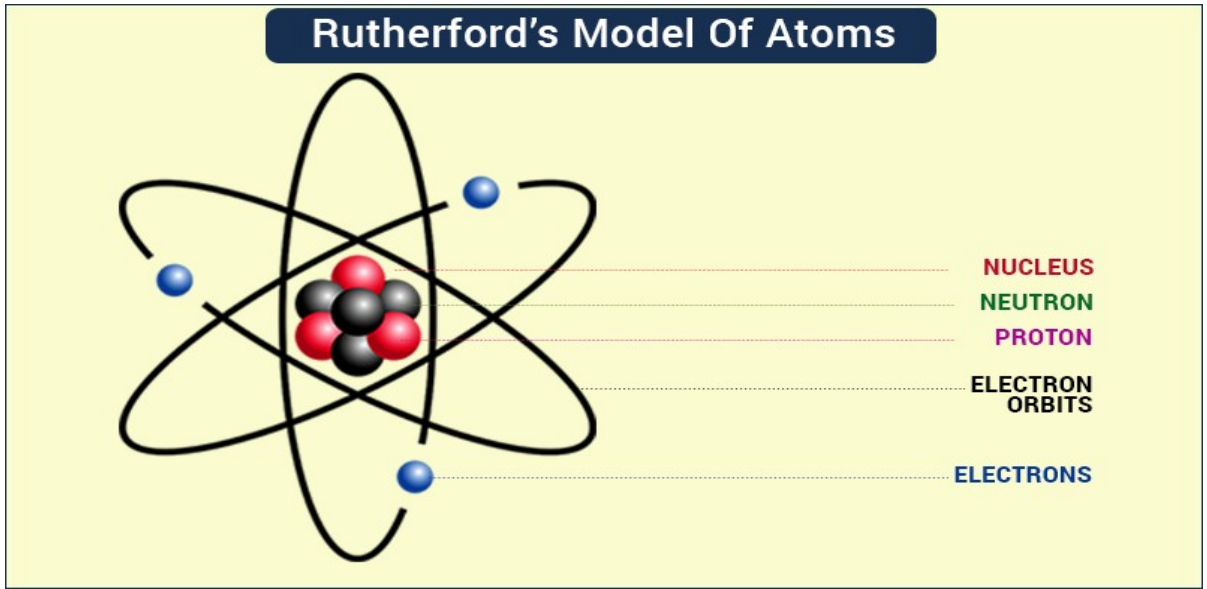
- Thomson's (plum pudding model)
- Electrons immersed in a positive "blob" of an atom
- Disproved by Rutherford's experiments who showed the core is really small



Credits: Wikipedia

List, preferably in order of appearance, atomic models emerging at the end of XIX and the start of XX century?

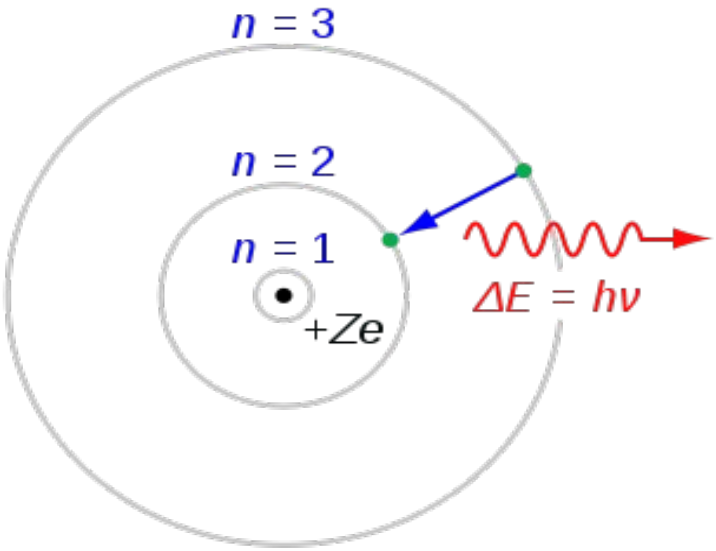
- Rutherford's (orbital or planetary) model
- Core is small and positive electrons rotate around in some sort of orbits
- Disproven by classical electrodynamics – electrons would radiate and fall onto the core



Credits: BYJU's

Bohr's atomic model

- Similar to Rutherford's but it solved the instability problem by postulates
- Only the orbits with specific radii are allowed and these are stable. Electrons transit between these by receiving and letting go quanta of energy
- Replaced by Quantum theory but that is a story for another time



$$h\nu = E_u - E_l = R(\frac{1}{n_l^2} - \frac{1}{n_u^2})$$

This fit extremely well with Einstein’s paper about light quanta

- 1905, four papers, and what a paper. Annis Mirabilis (Wunderjahr) for Albert Einstein.
- As Sean Carroll would put it: “Einstein is underrated”
- "On a Heuristic Viewpoint Concerning the Production and Transformation of Light":

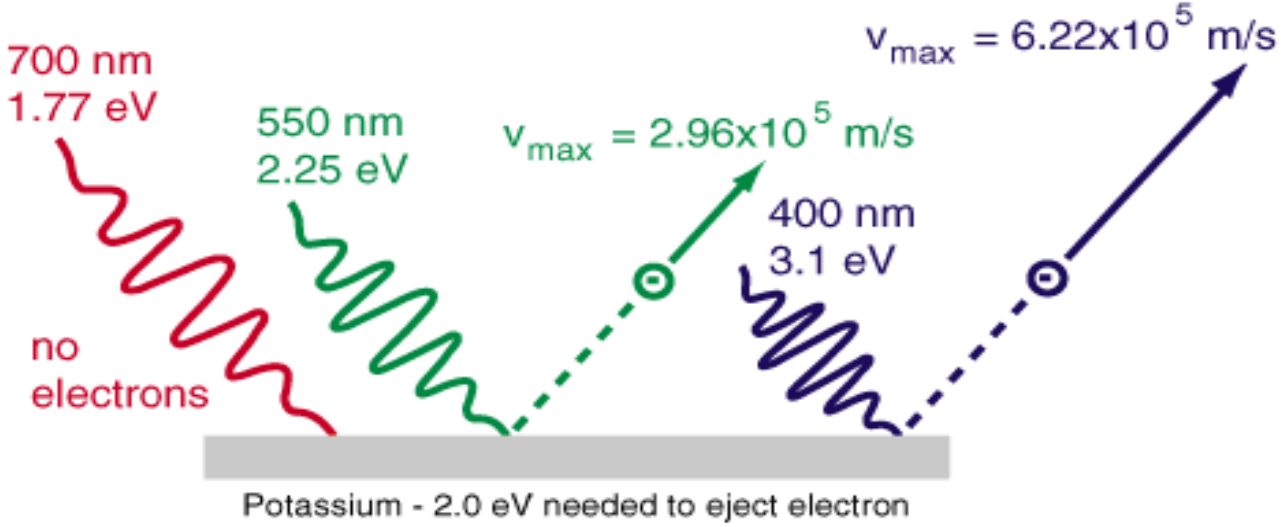
  A profound formal difference exists between the theoretical concepts that physicists have formed about gases and other ponderable bodies, and Maxwell's theory of electromagnetic processes in so-called empty space. While we consider the state of a body to be completely determined by the positions and velocities of an indeed very large yet finite number of atoms and electrons, we make use of continuous spatial functions to determine the electromagnetic state of a volume of space, so that a finite number of quantities cannot be considered as sufficient for the complete determination of the electromagnetic state of space.

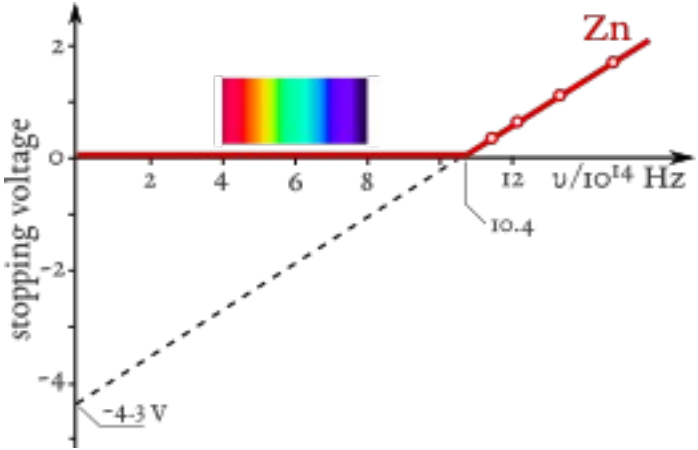
  [... this] leads to contradictions when applied to the phenomena of emission and transformation of light.

Photoelectric effect

- Photons indeed behave as particles, and we actually could prove the equation below. Fantastic! Can you really think Einstein was against QM?

$$E_{photon} = h\nu$$

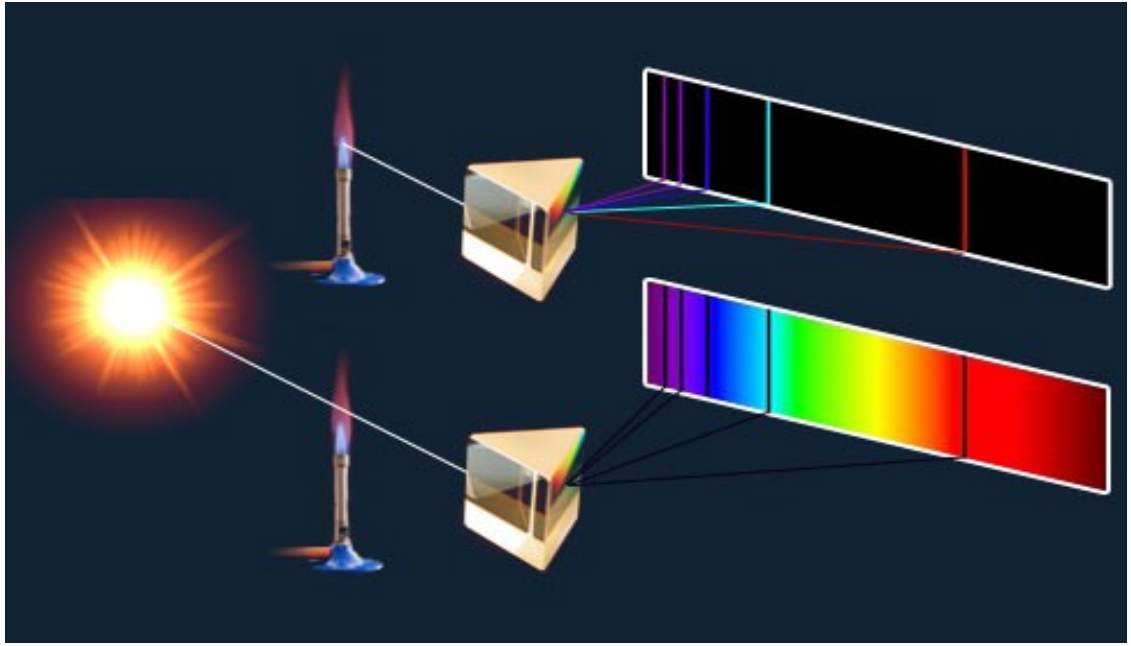


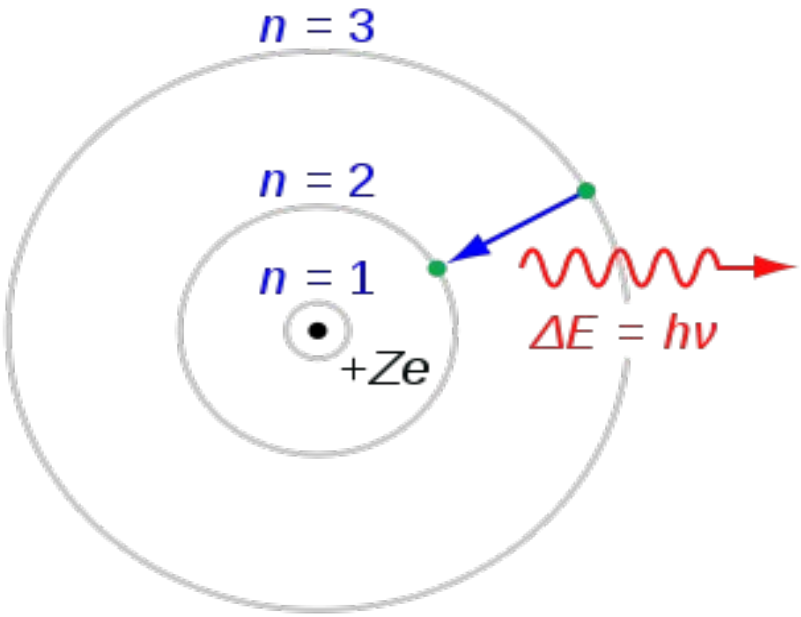


Photoelectric effect

We care about the spectral lines

- We can now completely understand Kirchhoff and Bunsen's experiment by invoking Bohr's atomic model (or something similar)



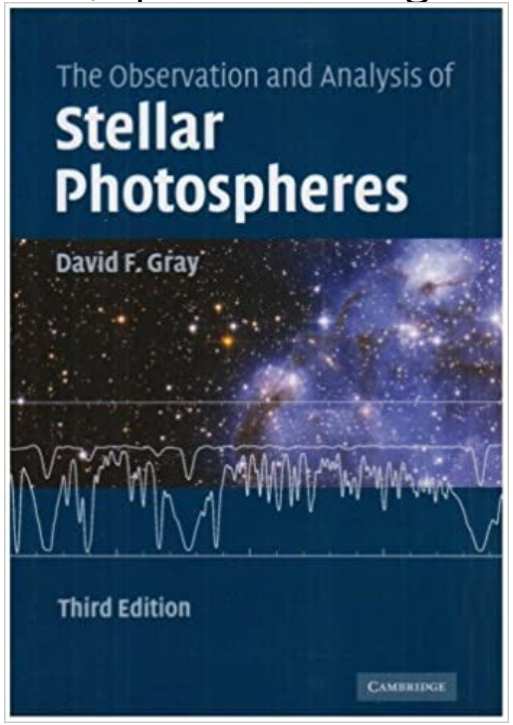


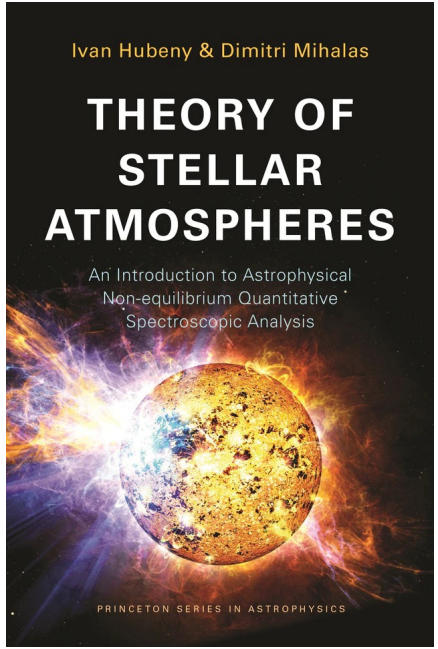
So to understand the spectral lines we have to:

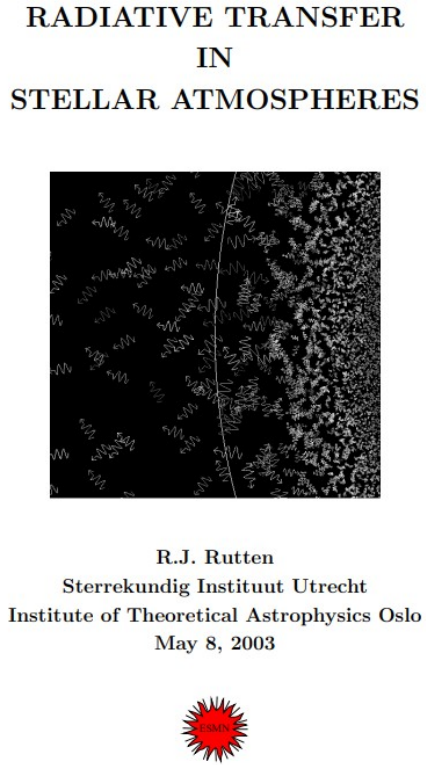
- Understand how atoms absorb and emit light, that is, interact with photons
- How this processes respond to physical conditions (temperature, pressure, velocity, magnetic field)
- Try to figure out or model how the physical conditions vary in the atmosphere of the Sun (next class we will talk more about the atmosphere itself)
- Use all this to calculate how much of the radiation leaves the solar atmosphere and reaches our instruments.
- For this we use **radiative transfer**

Radiative Transfer

- A formalism that puts together micro-physics of absorption/emission processes with analytical and numerical methods of solving particular differential equations that allow us to describe transport of the light through given medium, with the final goal of calculating (modeling) spectral, spatial and angular distribution of the intensity of the light.







All pain, fear, tears and frustration are contained in this one equation:

Coefficient of the emission of the medium

$$\frac{dI(\vec{r}, \mathbf{n}, \lambda)}{ds} = j(\vec{r}, \mathbf{n}, \lambda) - \chi(\vec{r}, \mathbf{n}, \lambda) I(\vec{r}, \mathbf{n}, \lambda)$$

Change of our quantity of interest (intensity), over the elementary geometrical path.

Coefficient of the absorption of the medium

But, more about this in the next class!

- We will define the (specific, monochromatic) intensity
- As well as emission and absorption coefficients
- We will transform RTE in a more commonly used form and define two new quantities (Source function and optical depth/path)
- And look for some simple solutions
- We will finish by trying to figure out where and how we actually have to solve the RTE and what is the intensity we are seeing.
- Have a good weekend and see you on Tuesday!