modern physics

the quantum revolution

➜ all the physics I've shown you so far is "deterministic"

➜ if you precisely measure the condition of a system at some point in time

➜ and you know the "equations of motion"

➜ you can predict what will happen for evermore

➜ the "clockwork" universe

for example

- projectile motion
- planets orbiting the sun
- electric and magnetic fields from charges and currents

➜ physics was viewed this way until the turn of the 20^{th} century

➜ when some simple experiments forced us to rethink our views

the quantum revolution

➜ we now think of fundamental physics as “probabilistic”

➜ we can only calculate the relative odds of any particular event occurring

(*at least at microscopic scales*)

the quantum revolution

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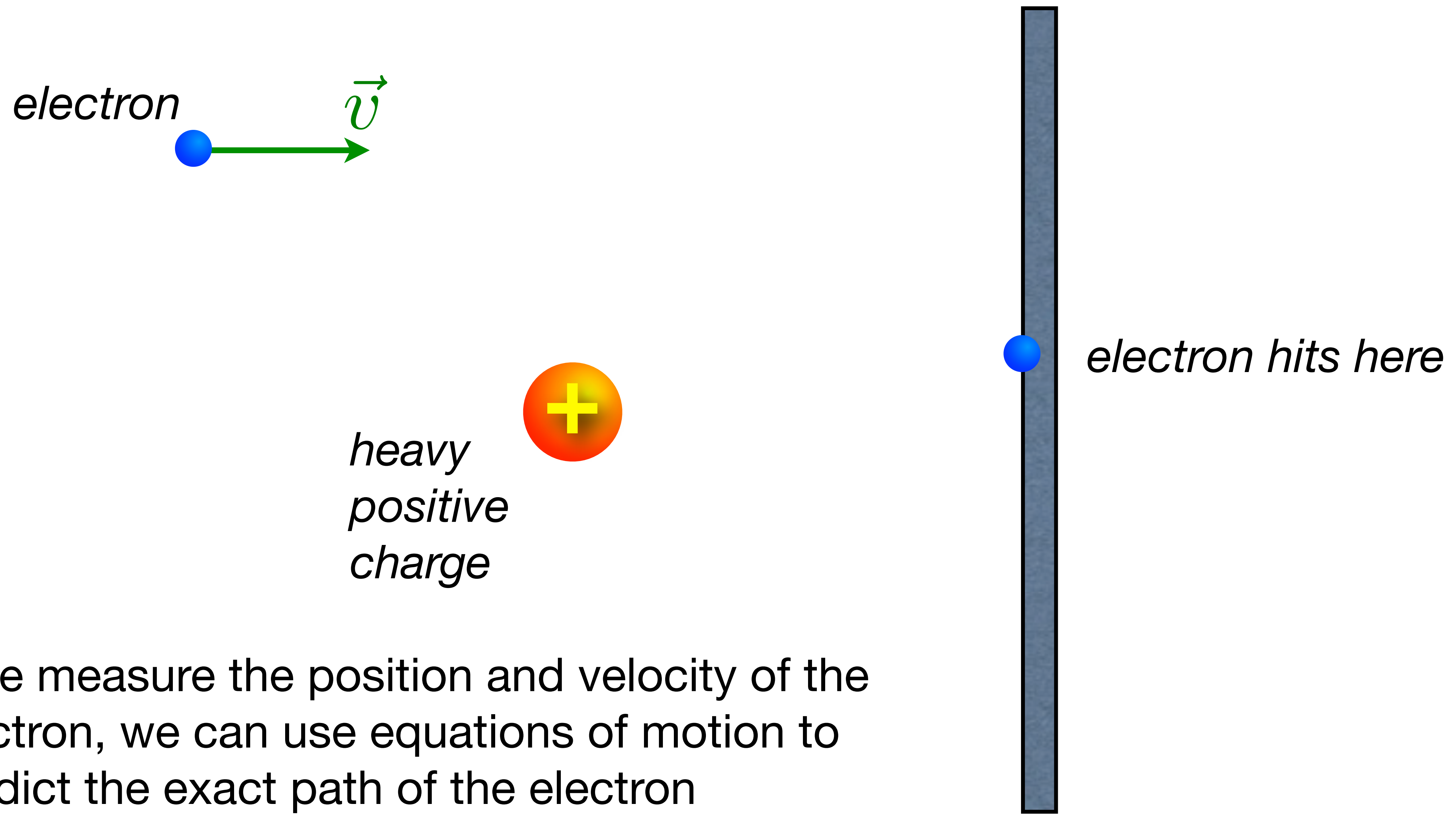
➜ e.g. in classical electromagnetism :



if we measure the position and velocity of the electron, we can use equations of motion to predict the exact path of the electron

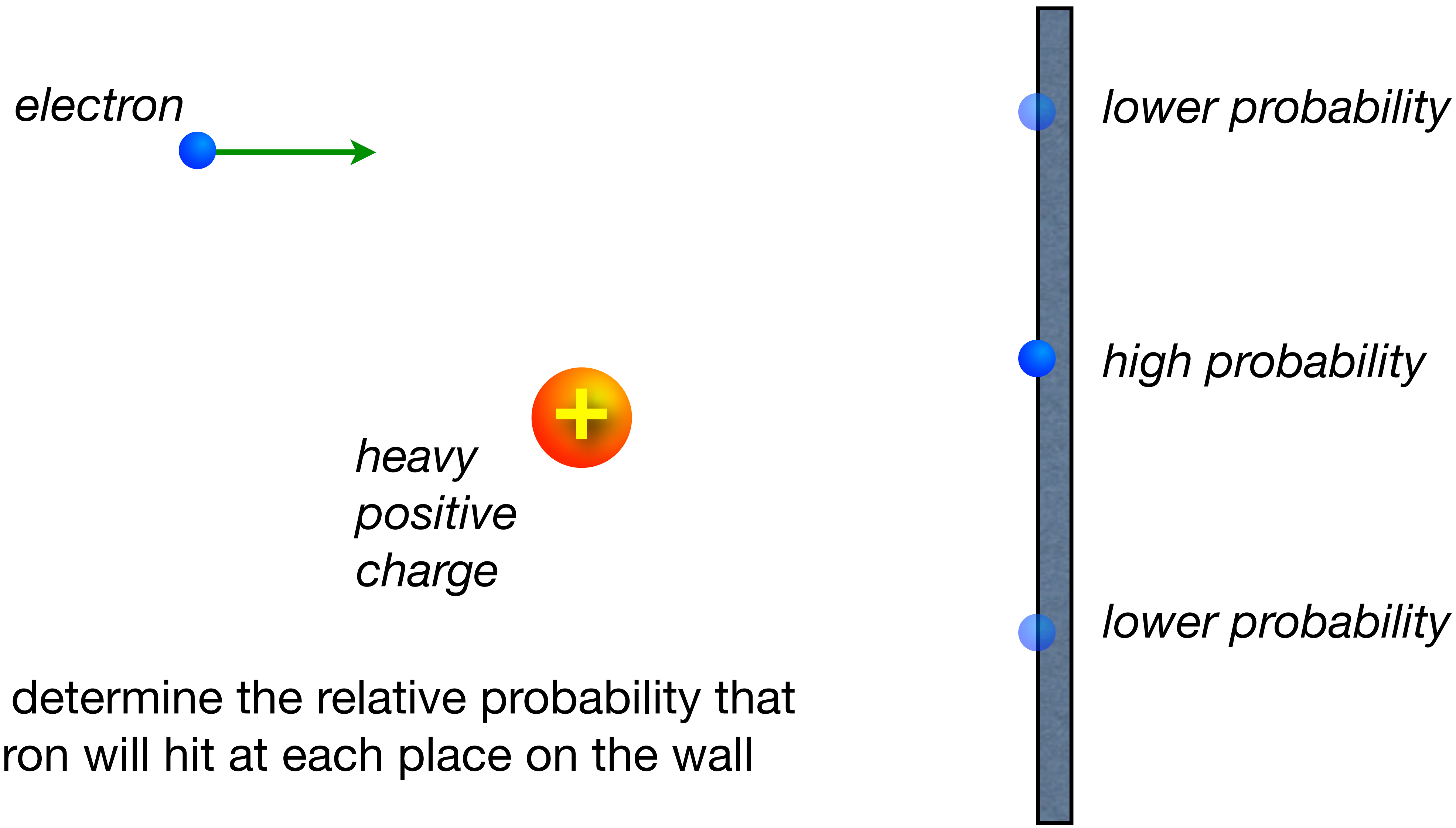
the quantum revolution

➜ we now think of fundamental physics as “probabilistic”

➜ we can only calculate the relative odds of any particular event occurring

(*at least at microscopic scales*)

➜ e.g. in the quantum theory :



can only determine the relative probability that
the electron will hit at each place on the wall

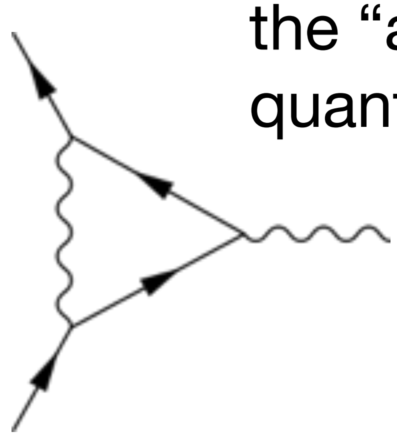
the quantum revolution

➜ we now think of fundamental physics as "probabilistic"

➜ we can only calculate the relative odds of any particular event occurring

(*at least at microscopic scales*)

➜ and yet our probabilistic theories are still incredibly precise



the "anomalous magnetic moment" of the electron can be predicted by quantum theory and measured in experiment

these two numbers agree to **ten significant figures**

the quantum revolution

➜ how did we come to this ?

➜ **TRYING TO EXPLAIN EXPERIMENTAL RESULTS !**

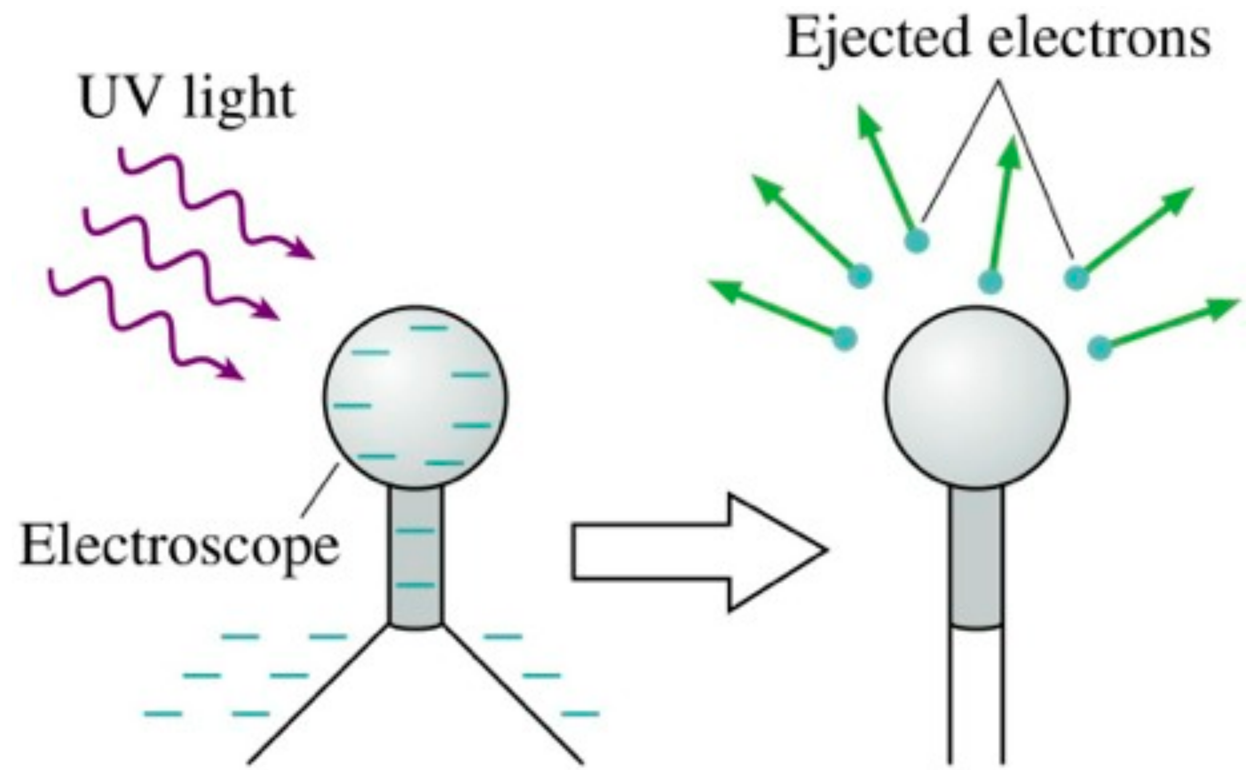
the scientific method

➜ one of the first ‘troubling’ results was the ‘photoelectric effect’

the photoelectric effect

➜ a simple experimental observation

➜ shine UV light onto a charged electroscope and it discharges



Ultraviolet light discharges a negatively charged electroscope by causing it to emit electrons.

➜ OK, interesting, let’s do a controlled experiment, varying properties of the light and the metal and see what happens

the photoelectric effect

➜ experimental observations:

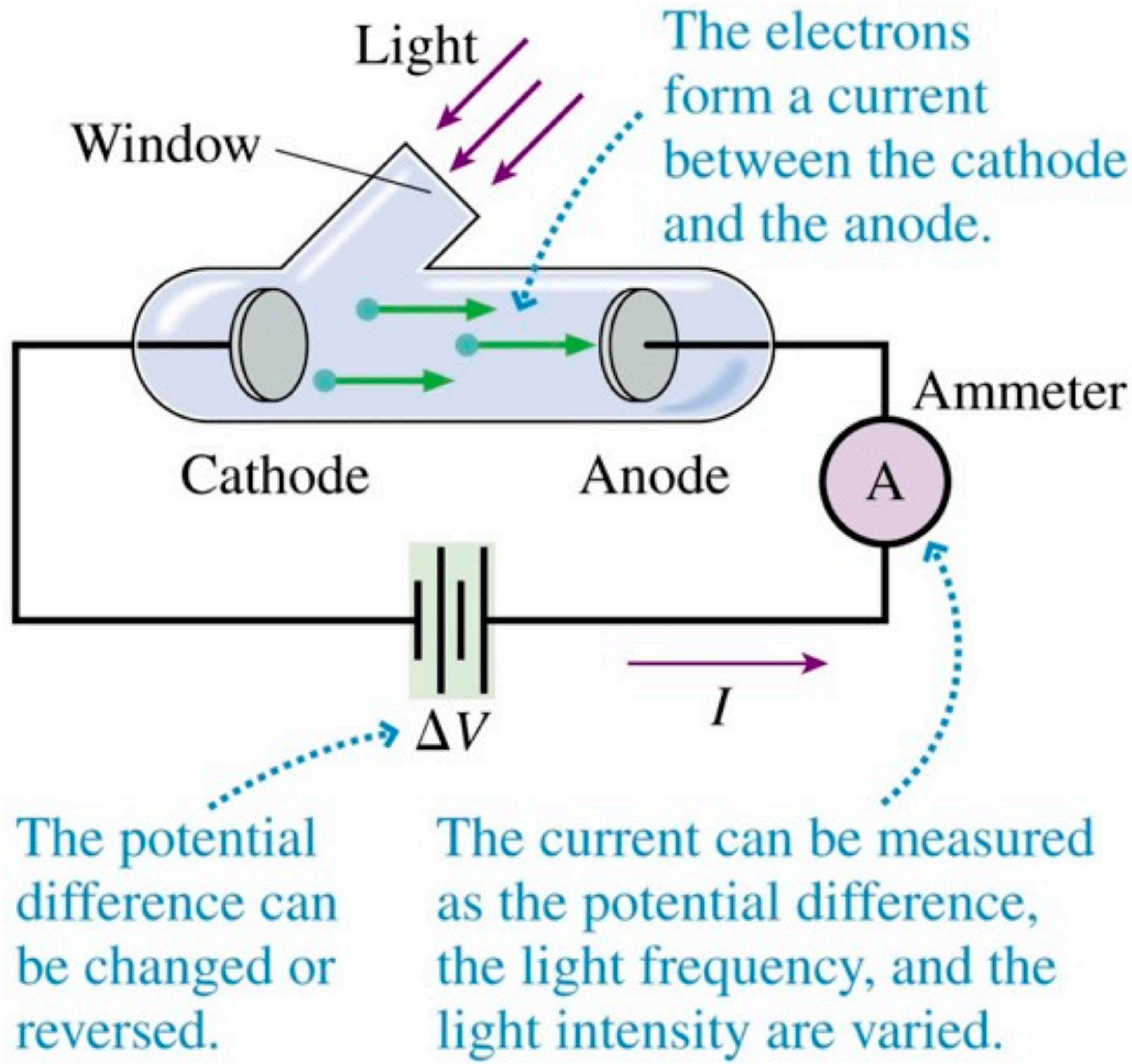
1. the current flowing increases in proportion to the intensity of the light

2. the current appears without time delay when the light is switched on

3. current only flows for light with frequency above some threshold, $f > f_0$

4. the value of the threshold frequency f_0 depends on the metal the cathode is made from

5. reversing and increasing the potential, the current flow can be stopped, and the potential required, $-V_{stop}$, is independent of the light intensity



the photoelectric effect

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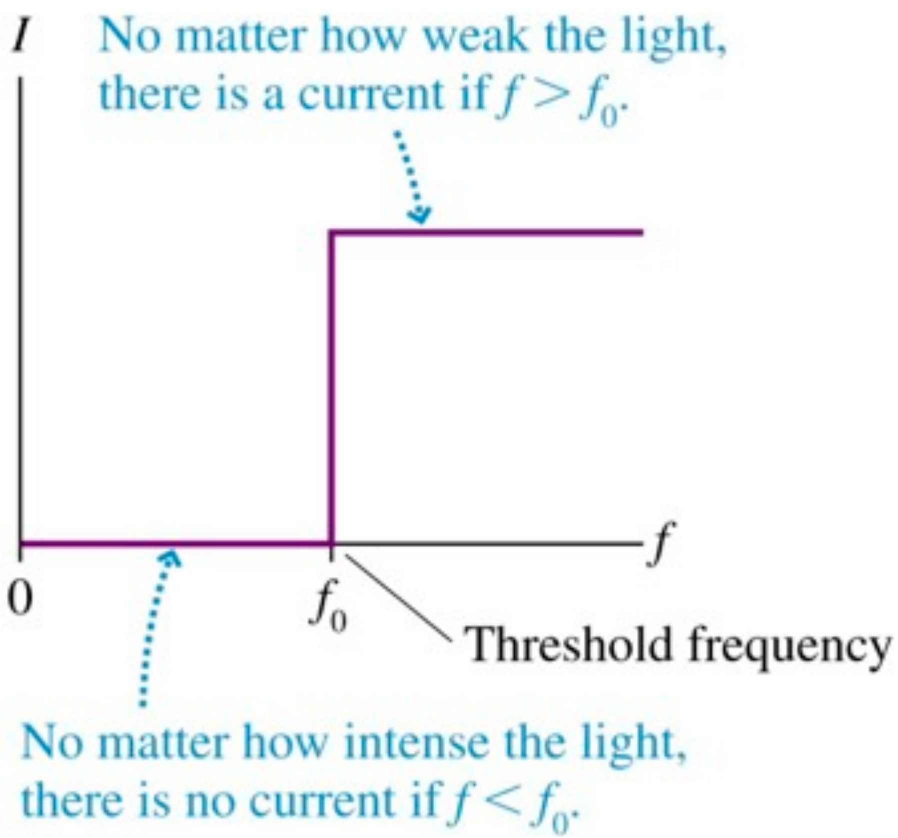

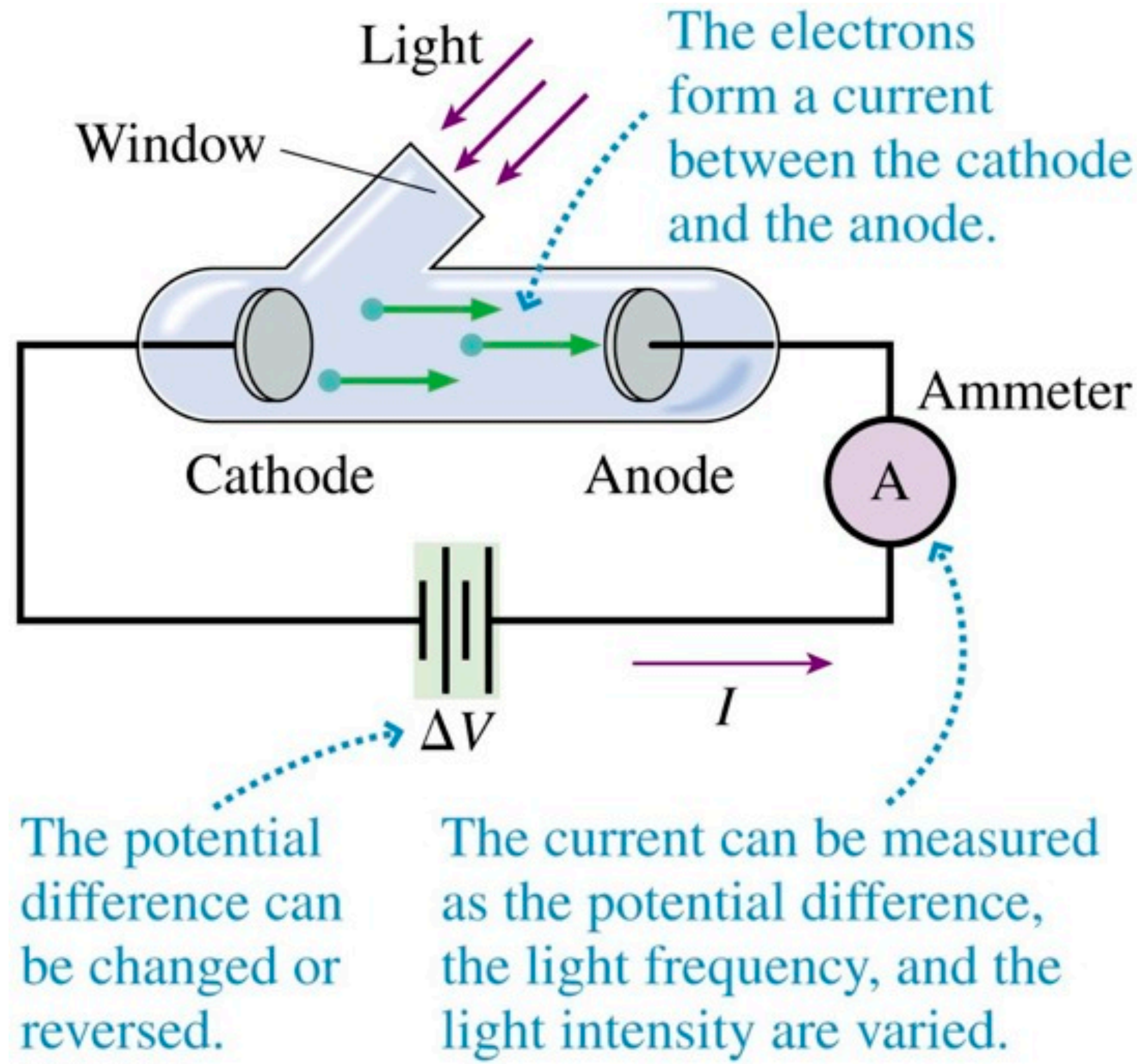

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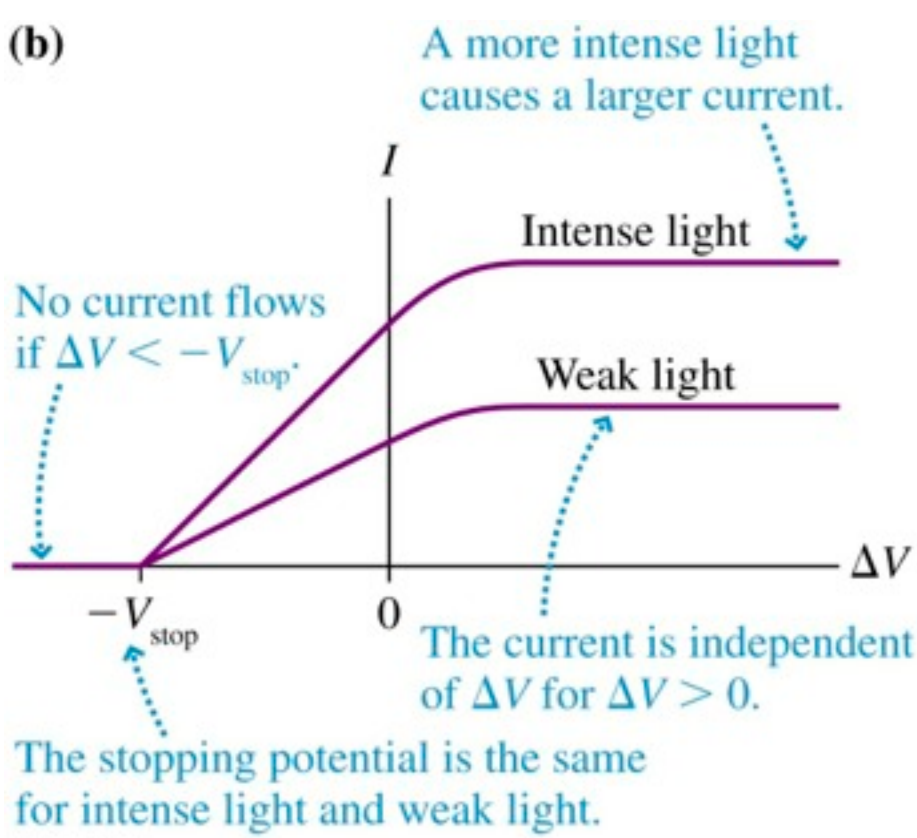
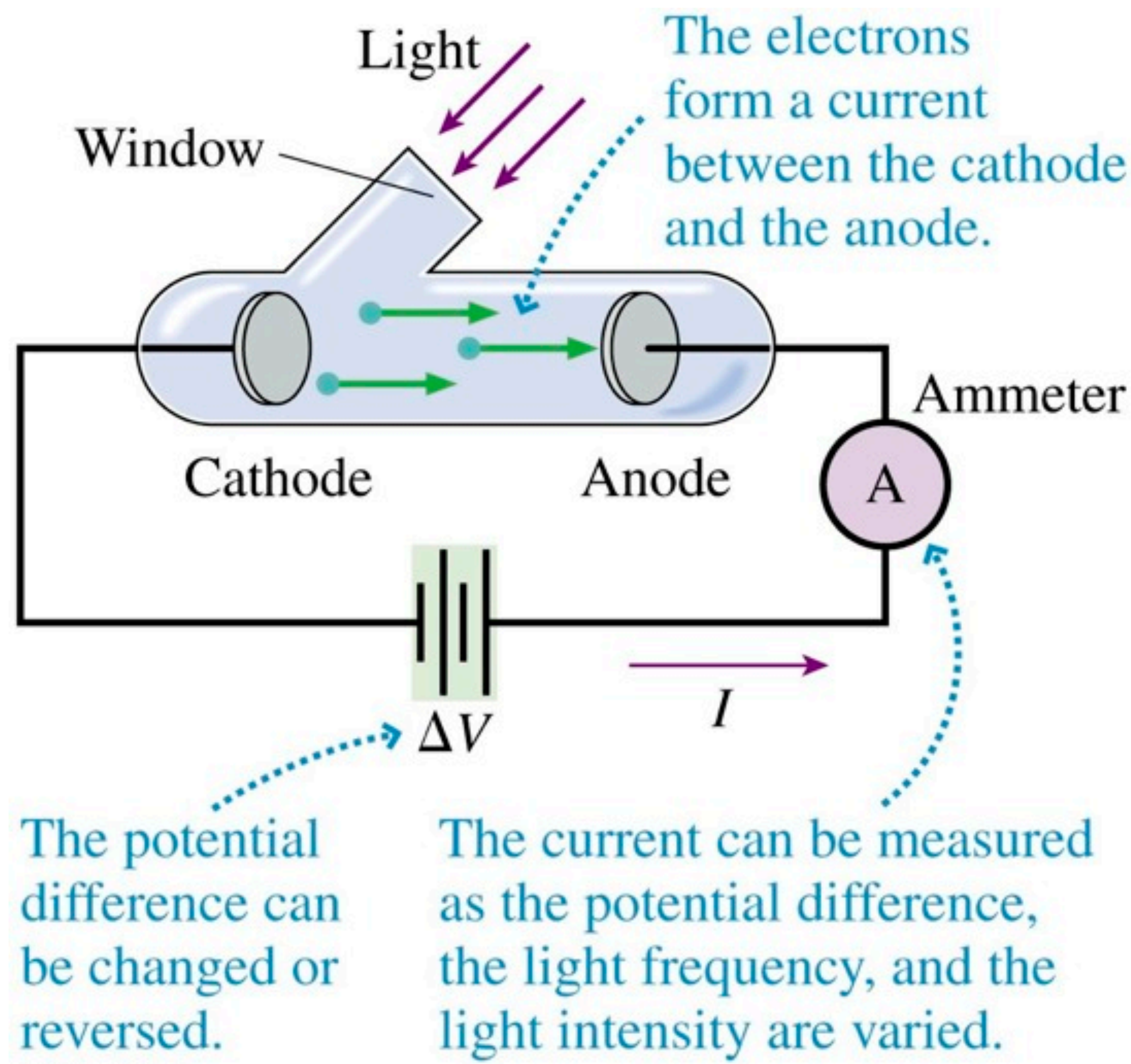
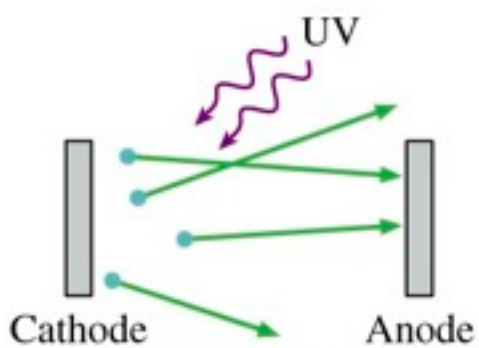


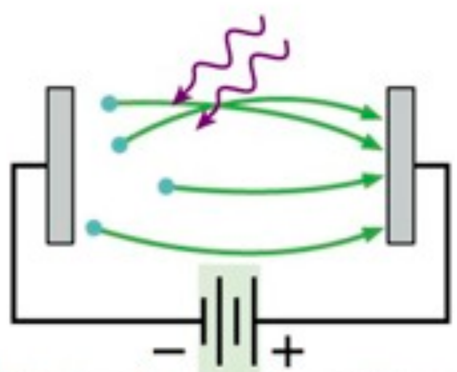


the photoelectric effect

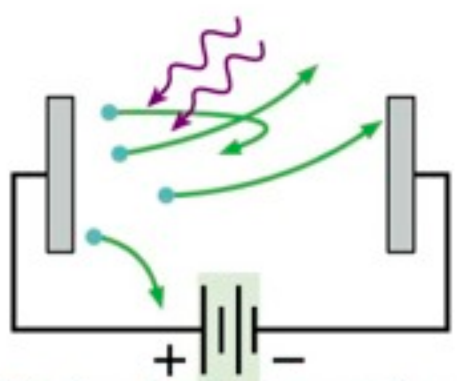
applied voltage dependence



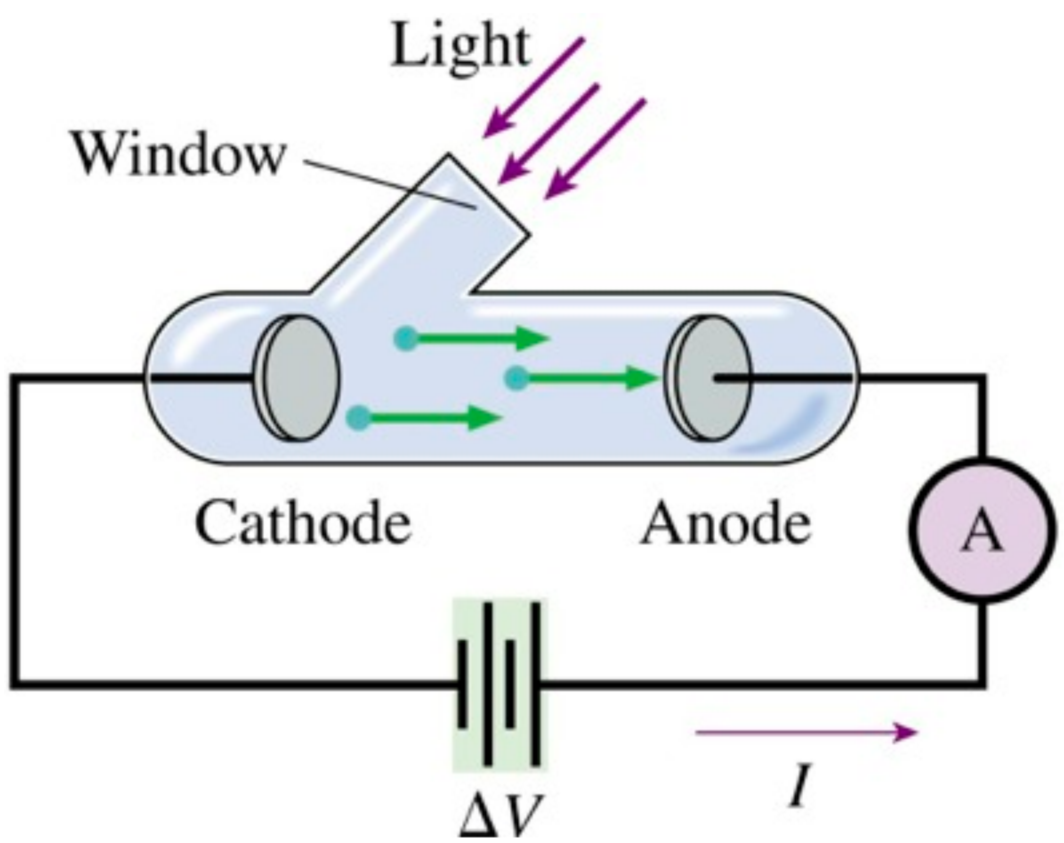
$\Delta V = 0$: The electrons leave the cathode in all directions. Only some reach the anode.



$\Delta V > 0$: Biasing the anode positive creates an electric field that pushes all the electrons to the anode.



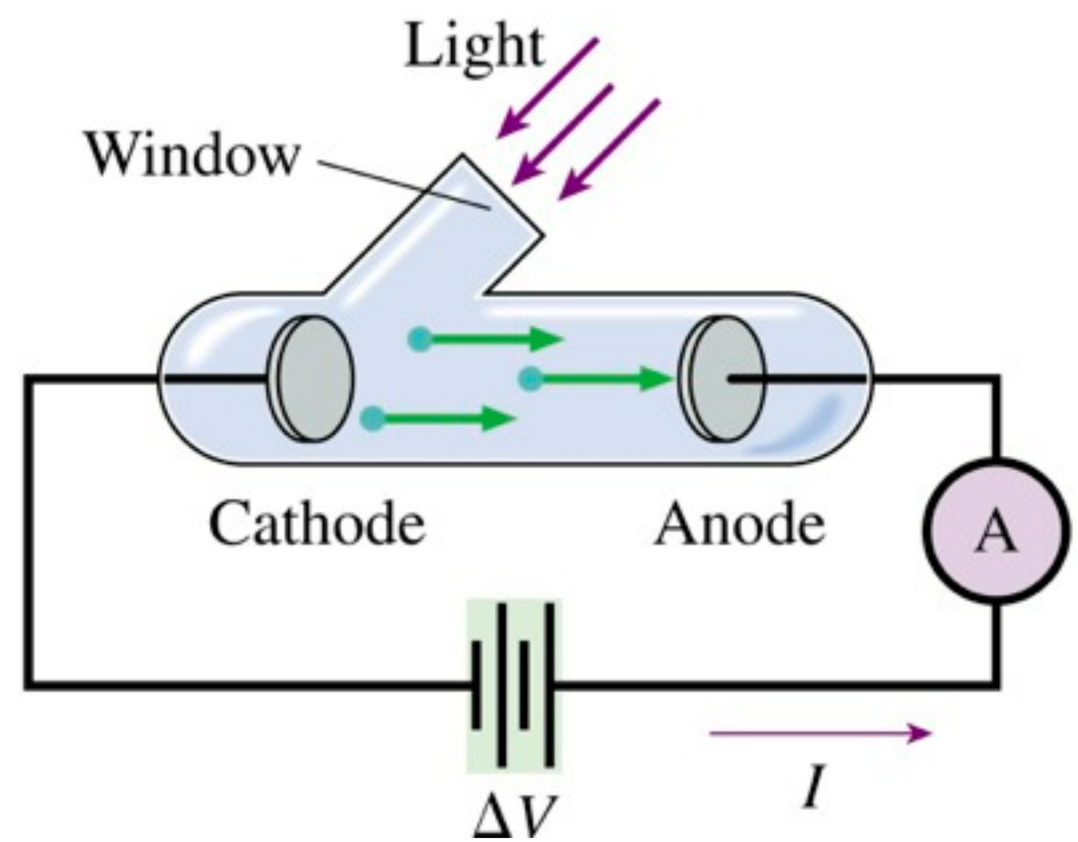
$\Delta V < 0$: Biasing the anode negative repels the electrons. Only the very fastest make it to the anode.



when $\boldsymbol{\Delta V = -V_{stop}}$ even the fastest electrons don't make it ⇒ no current

the photoelectric effect

explain by conservation of energy



the light provides energy to the electrons

it 'costs' a certain amount of energy to pull the electron out of the metal

whatever is left over goes into kinetic energy of the freed electron

$$K = E_{\rm light} - E_{\rm metal}$$

maybe the 'cost' can vary depending how 'deep' the electron is in the metal

but there is a minimum cost and hence a maximum K.E.

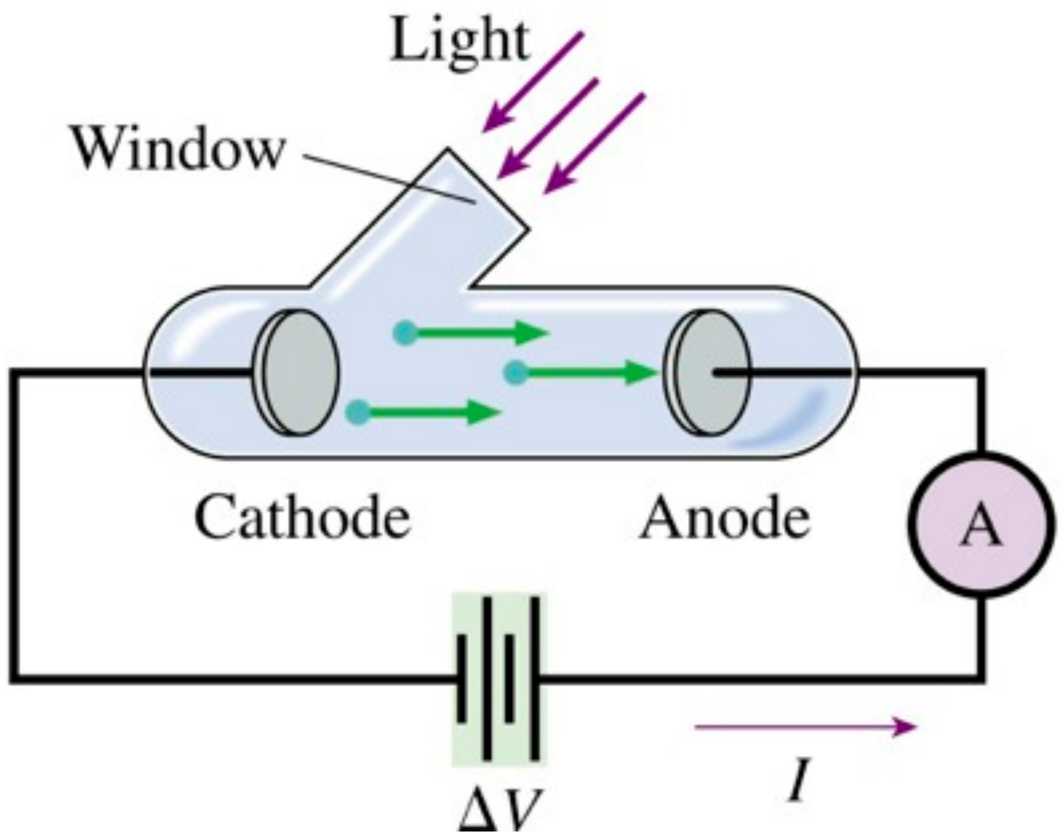
$$K_{\rm max} = E_{\rm light} - \phi$$

then $\boldsymbol{\Delta V = -V_{\rm stop}}$ corresponds to the energy needed to stop $K_{\rm max}$

$$K_{\rm max} = eV_{\rm stop}$$

the photoelectric effect

so what's the problem ?



2. the current appears without time delay when the light is switched on

3. current only flows for light with frequency above some threshold, $f > f_0$

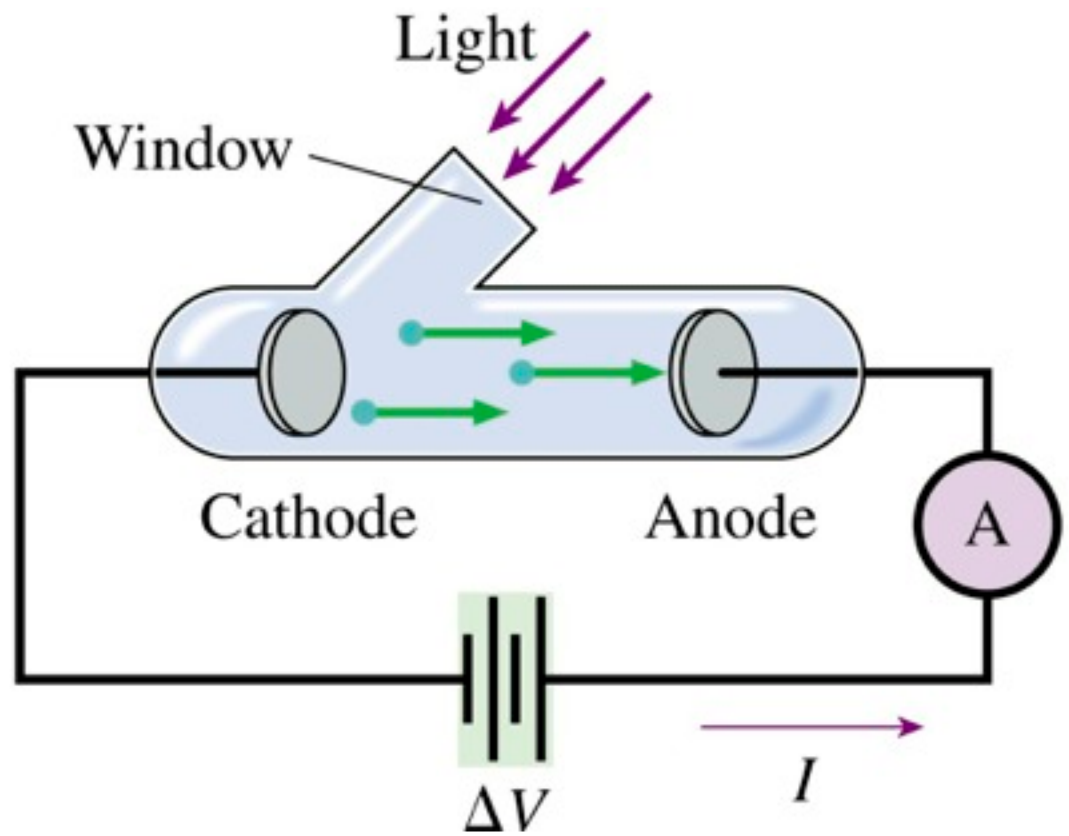
our wave theory of electromagnetism says that energy arrives continuously, with more energy arriving for more intense light

the frequency should be irrelevant !

the photoelectric effect

the solution :

light arrives not as a continuous wave, but in packets of energy, or *quanta*, now called *photons*



the energy of each photon is given by

$$E = hf$$

where ***f*** is the frequency of the light

and ***h*** is a universal constant

Planck's constant

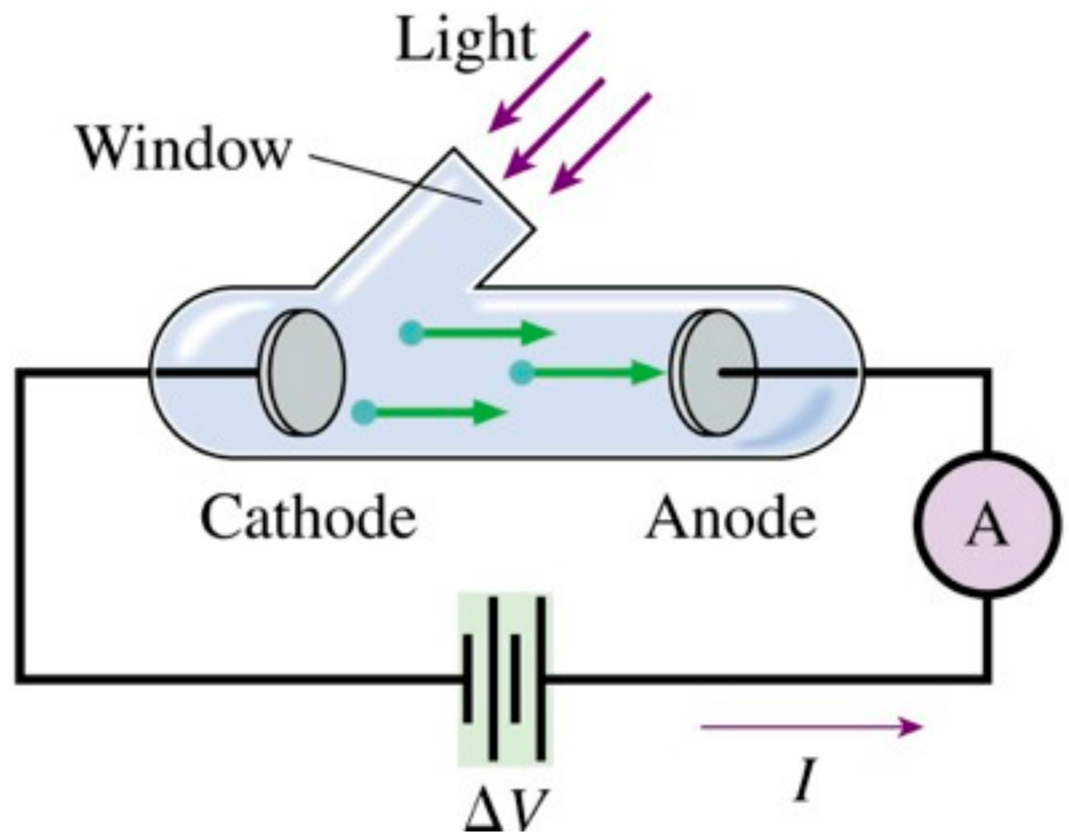
$$h = 6.6261 \times 10^{-34}\,\mathrm{Js}$$

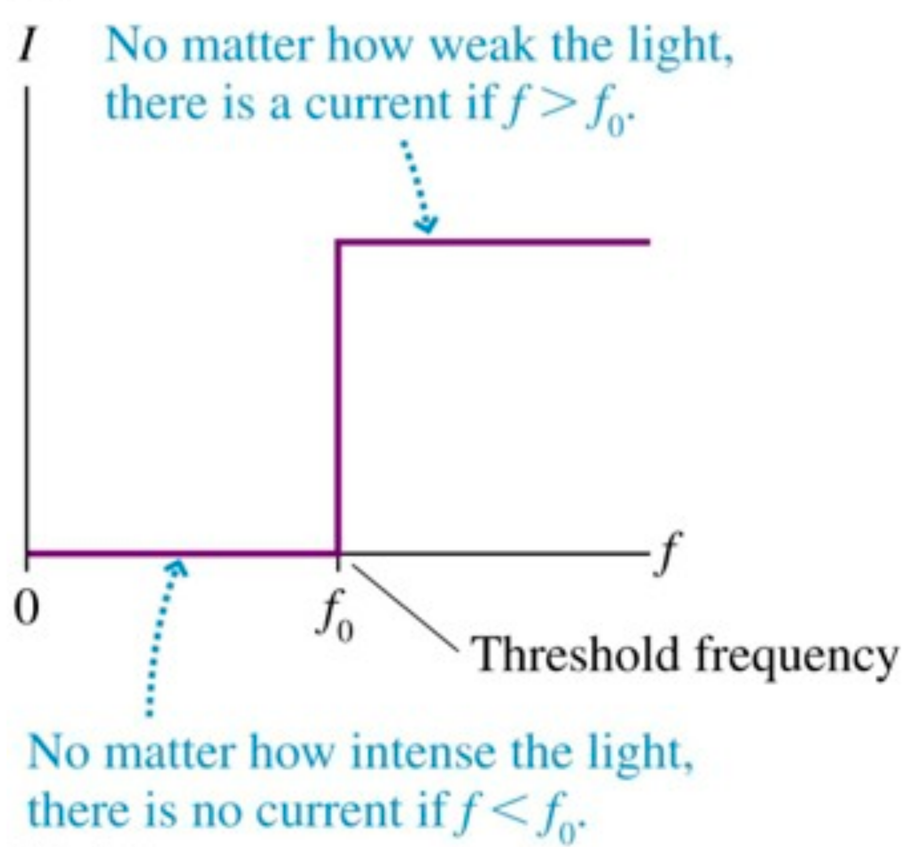
higher frequency light is made of particles which each have higher energy

the solution :

if the frequency of the light is too low, a single photon doesn't have enough energy to overcome the work function

$$hf_0 = \phi$$

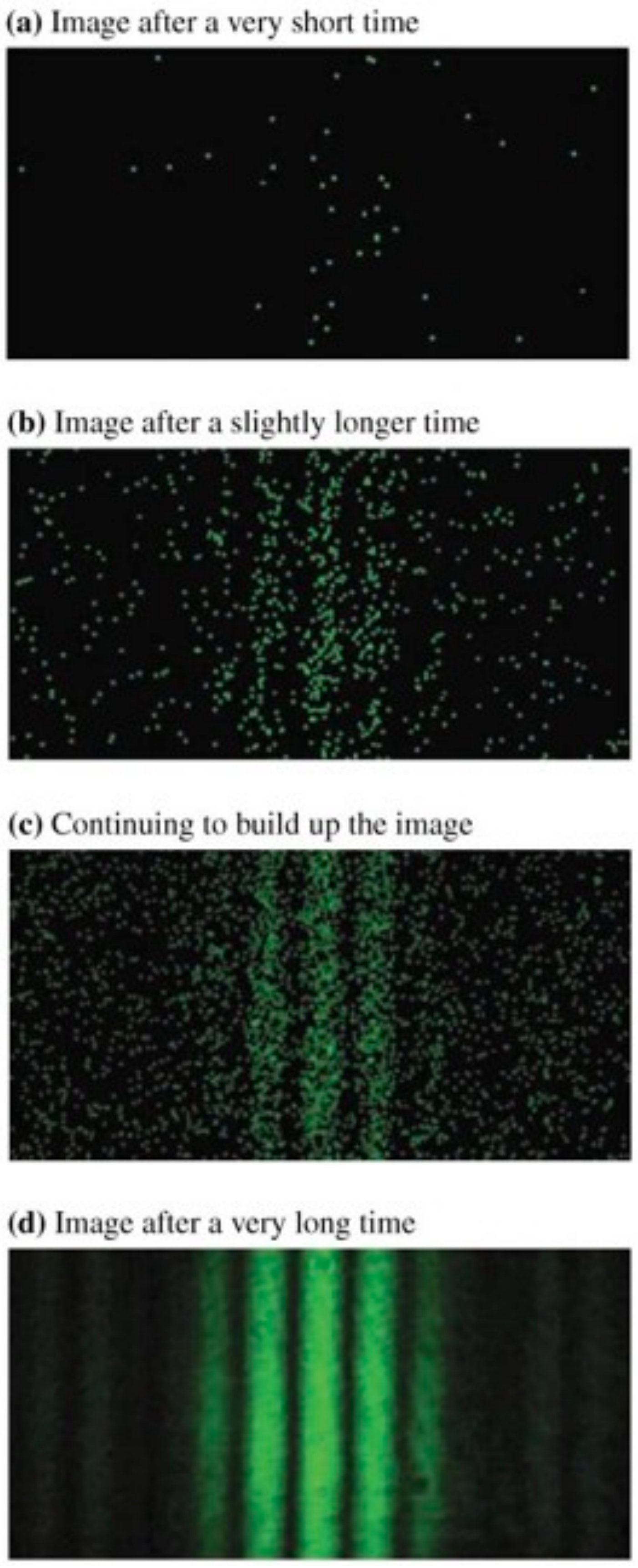




light is particles now ? really ?

sorry, but yes ...

consider a double slit experiment
performed with light of very low intensity



some aspects of light are
wave-like *e.g. interference pattern*
and some are
particle-like *e.g. the individual arrival*

don't like this ? it's going to get worse !

light is particles now ? really ?

but we don't "see" individual light particles !

let's crudely estimate the photon rate from a lightbulb:

say the bulb emits 50 W of light energy
50 W = 50 J/s

typical optical light wavelength = 500 nm

$$f = \frac{c}{\lambda} = \frac{3 \times 10^8\,\mathrm{m/s}}{5 \times 10^{-7}\,\mathrm{m}} = 6 \times 10^{14}\,\mathrm{s}^{-1}$$

energy of one photon

$$E_\gamma = hf \approx 6.6 \times 10^{-34}\,\mathrm{Js} \times 6 \times 10^{14}\,\mathrm{s}^{-1}$$
$$= 4 \times 10^{-19}\,\mathrm{J}$$

number of photons emitted in one second

$$N_\gamma = \frac{50\,\mathrm{J}}{4 \times 10^{-19}\,\mathrm{J}} \approx 10^{20}$$

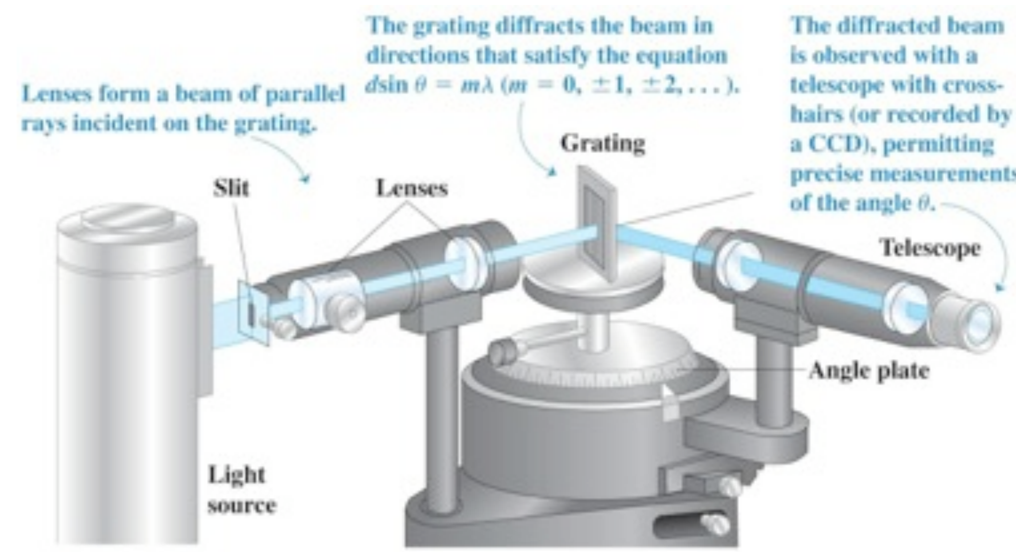
a huge number, no wonder we don't notice the individual particles

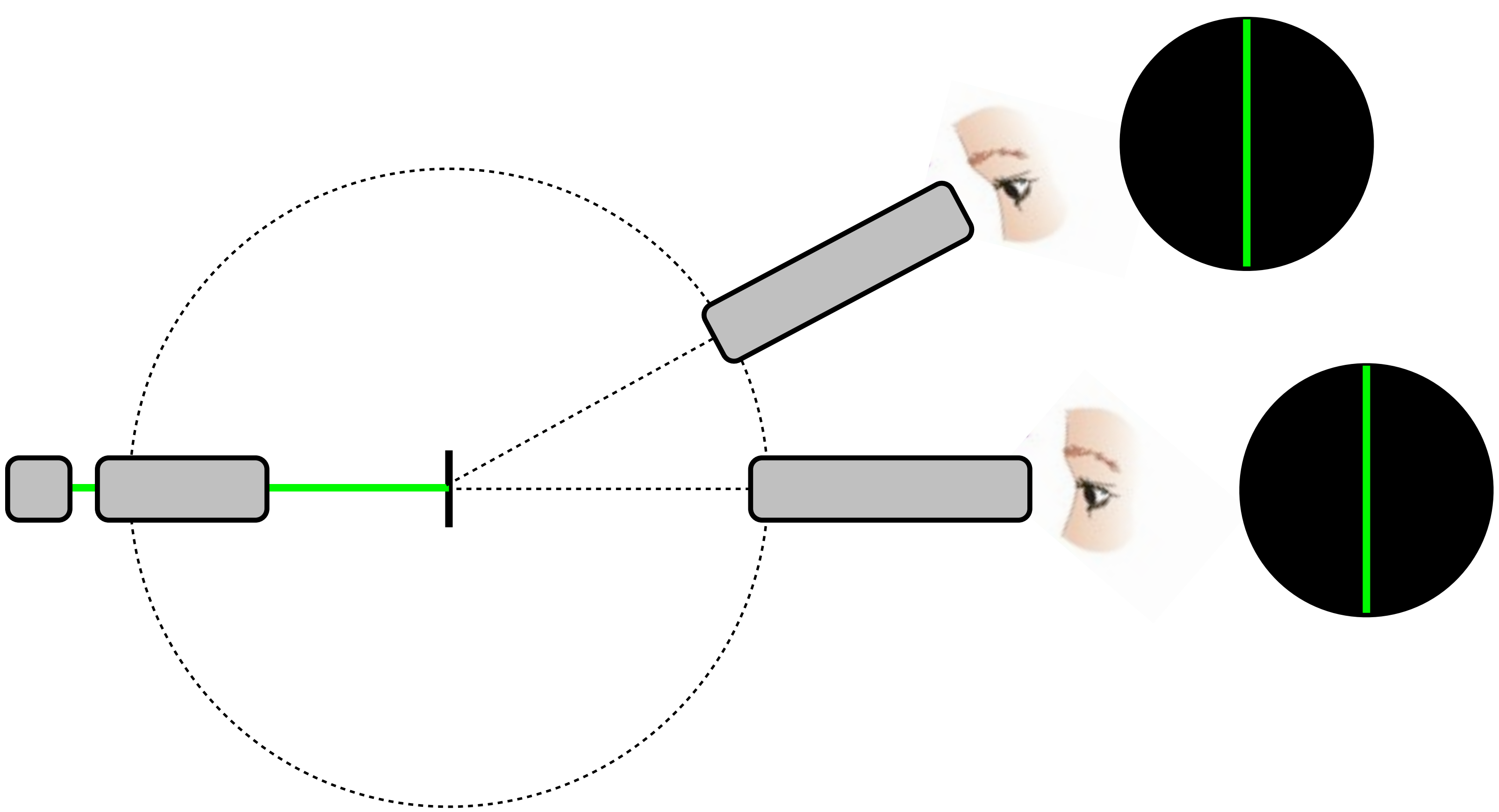
‘lumpy’ energy

➜ there are other experiments that suggest energy can come in discrete amounts

➜ atomic spectroscopy

➜ diffraction grating spectrometer

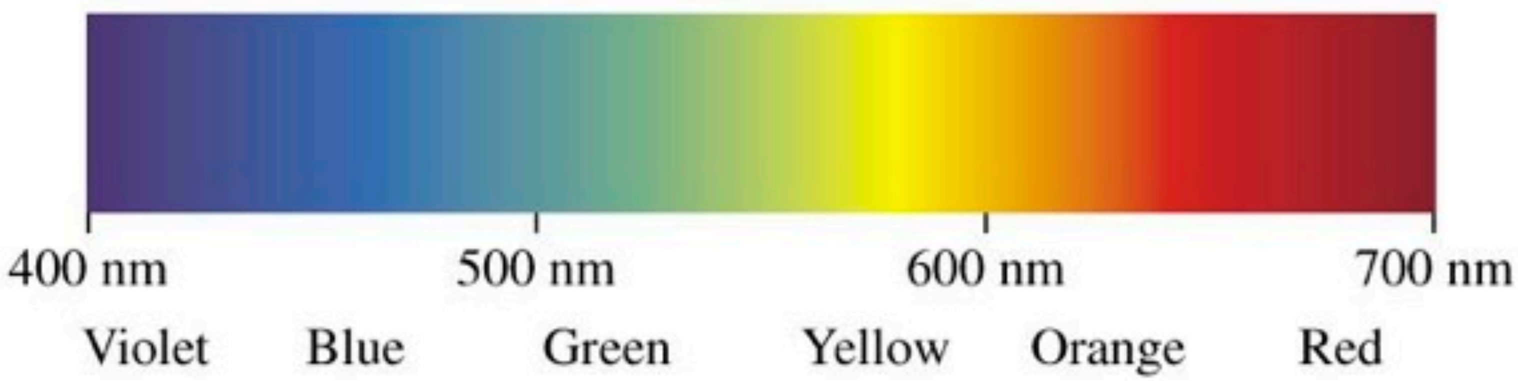




atomic spectroscopy

➜ diffraction grating spectrometer results

(a) Incandescent lightbulb

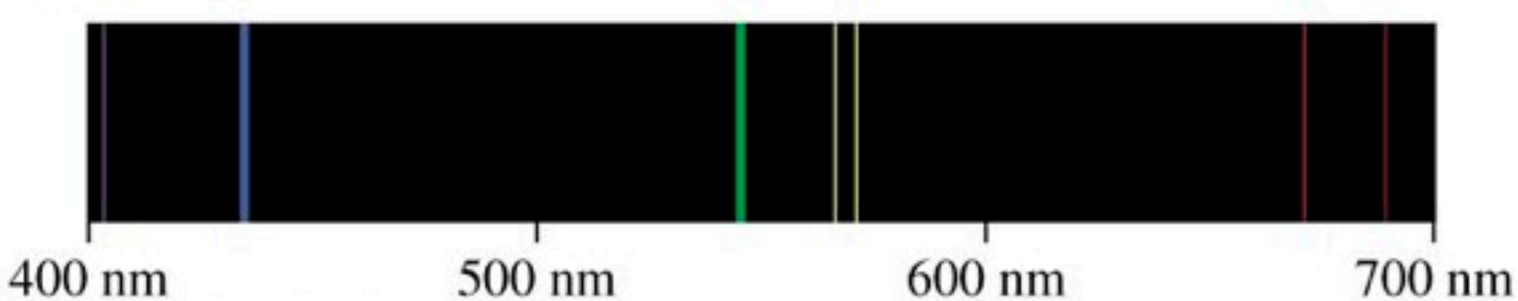


continuous spectrum - all colors

(b) Hydrogen

discrete spectra
- only certain special wavelengths

(c) Mercury



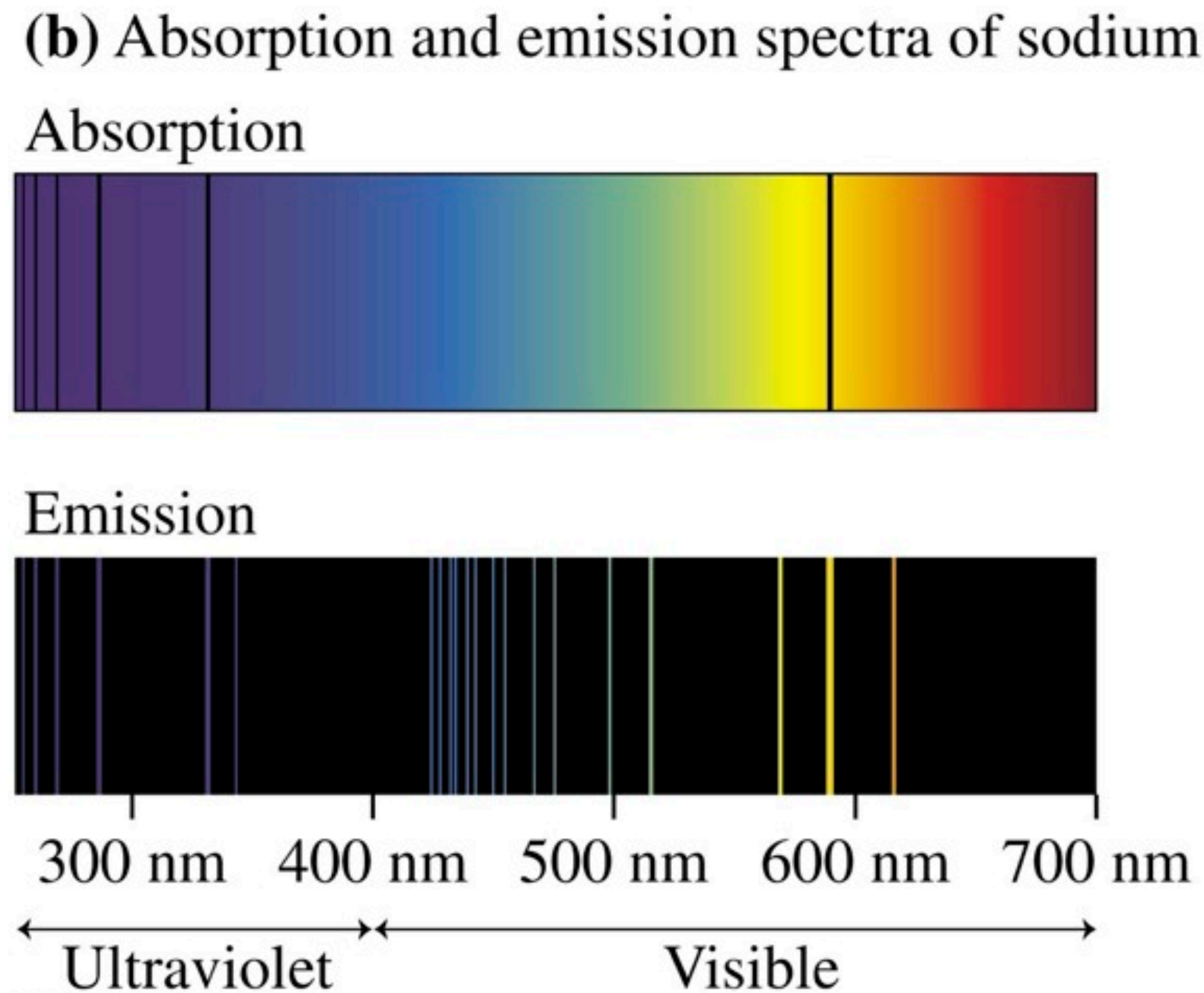
only certain photon energies are emitted by ‘excited’ atoms

energy of an atom

➜ can also do ‘absorption’ experiments - shine **white light** through a gas and put the resulting light through a diffraction grating

a few discrete lines

many more discrete lines



energy conservation

➜ propose an atom can emit or absorb a photon

emission

'excited' atom $E_{\rm i}$

less 'excited' atom $E_{\rm f}$

photon hf

energy conservation $E_{\rm i} = E_{\rm f} + hf$

absorption

less 'excited' atom $E_{\rm i}$

photon hf

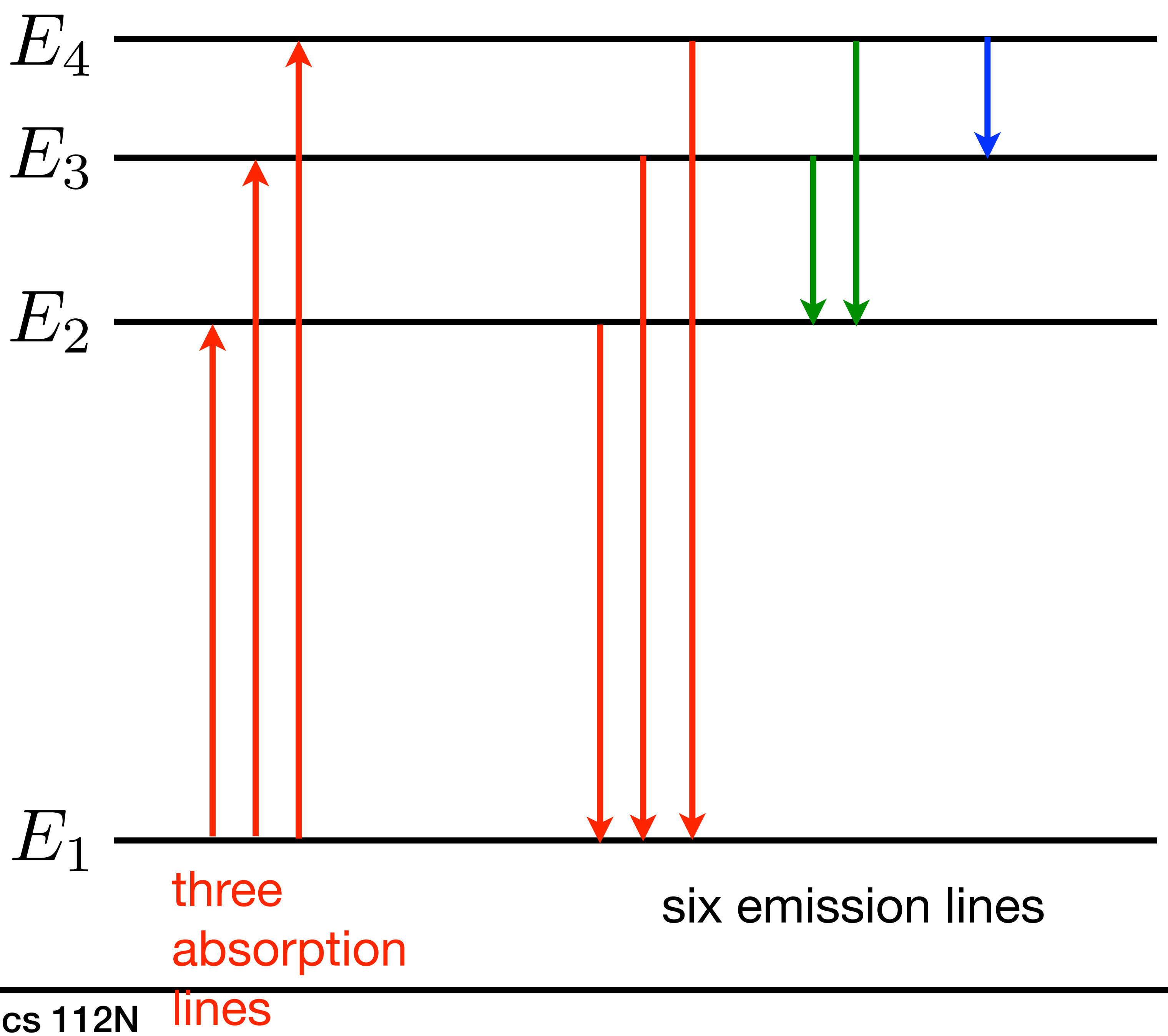
'excited' atom $E_{\rm f}$

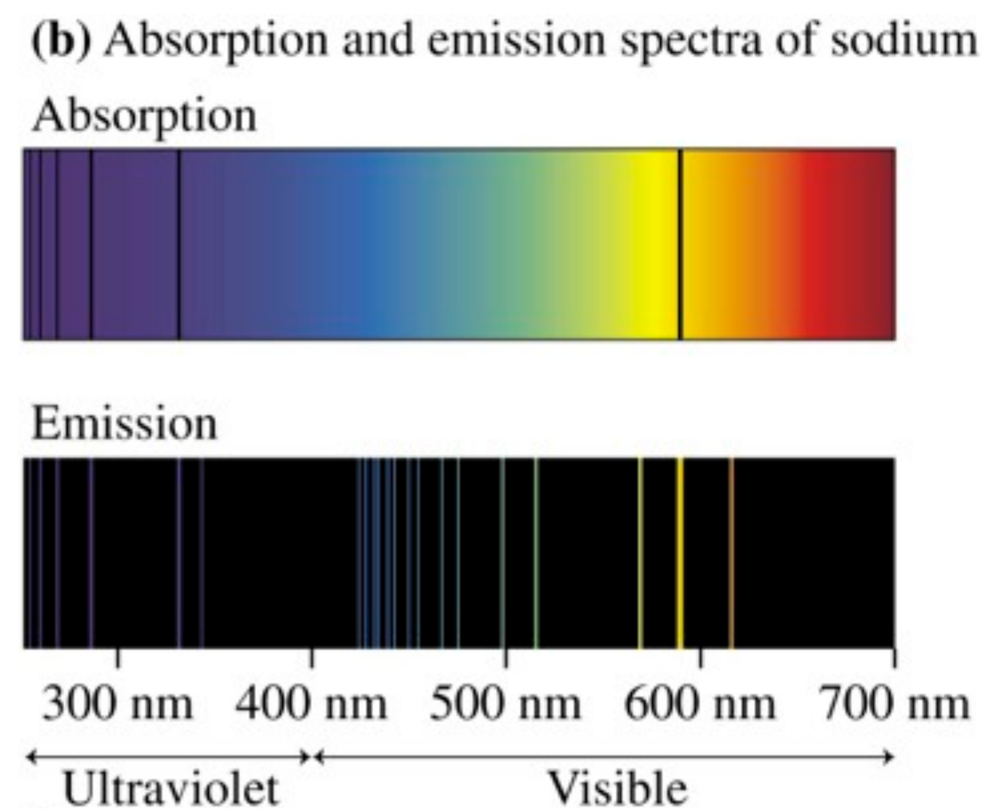
energy conservation $E_{\rm f} = E_{\rm i} + hf$

discrete atomic energies

➜ the emission and absorption spectra can be described assuming only certain discrete energies are allowed

e.g. a hypothetical atom





lowest allowed energy
"ground state"

discrete atomic energies

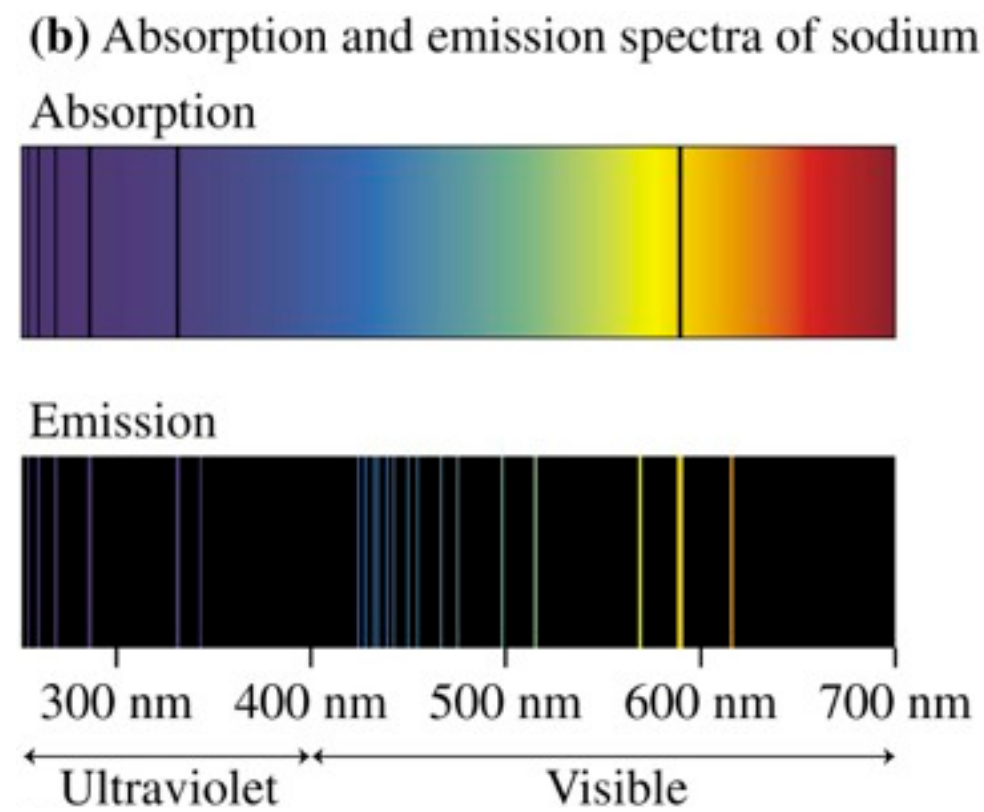
➜ it is useful to know that the typical energy scale for atomic levels is electron-Volts

e.g. ΔE ~ 2 eV

photon $E_\gamma = hf = \dfrac{hc}{\lambda}$

$$\lambda = \frac{hc}{E_\gamma}$$

$$\lambda \approx \frac{1.3 \times 10^{-6}\,\text{eV m}}{E_\gamma}$$



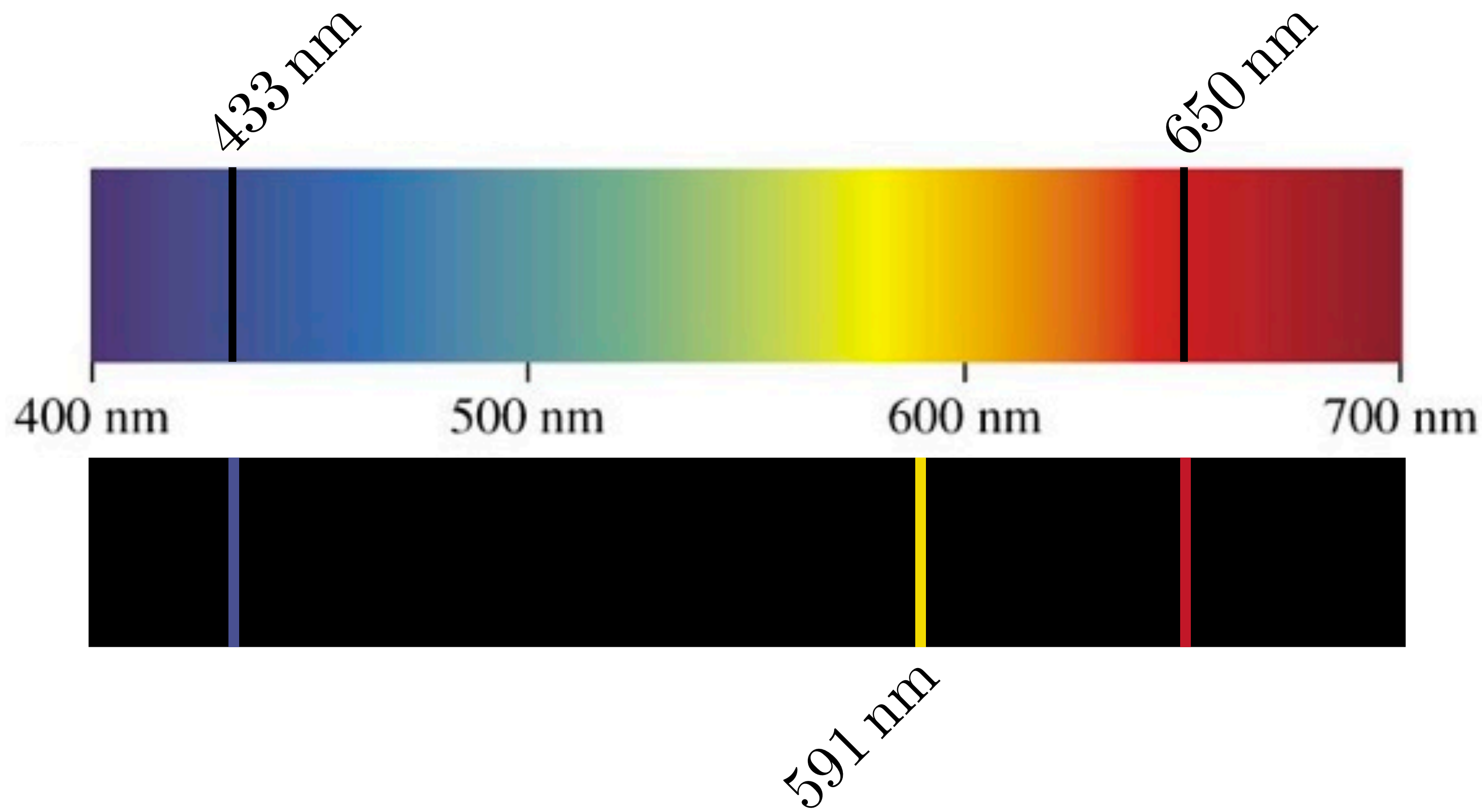
$$\lambda \approx 0.65 \times 10^{-6}\,\text{m} \approx 650\,\text{nm}$$

➜ visible light from atomic transitions !

chemistry is physics at scales measured in eV

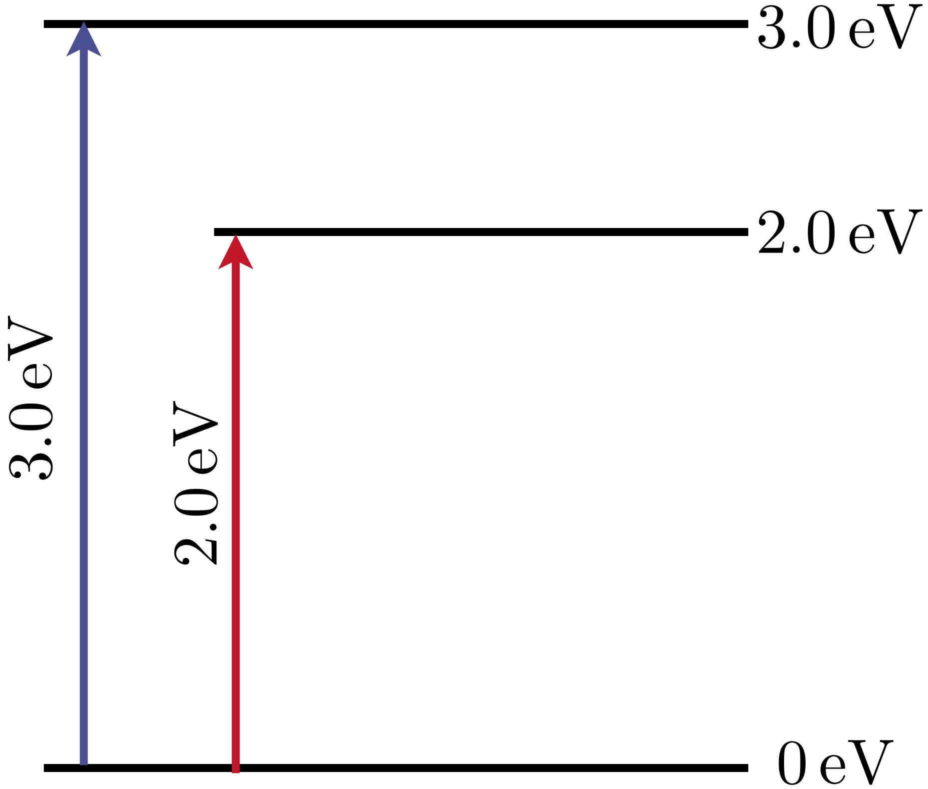
atomic energy levels from spectra

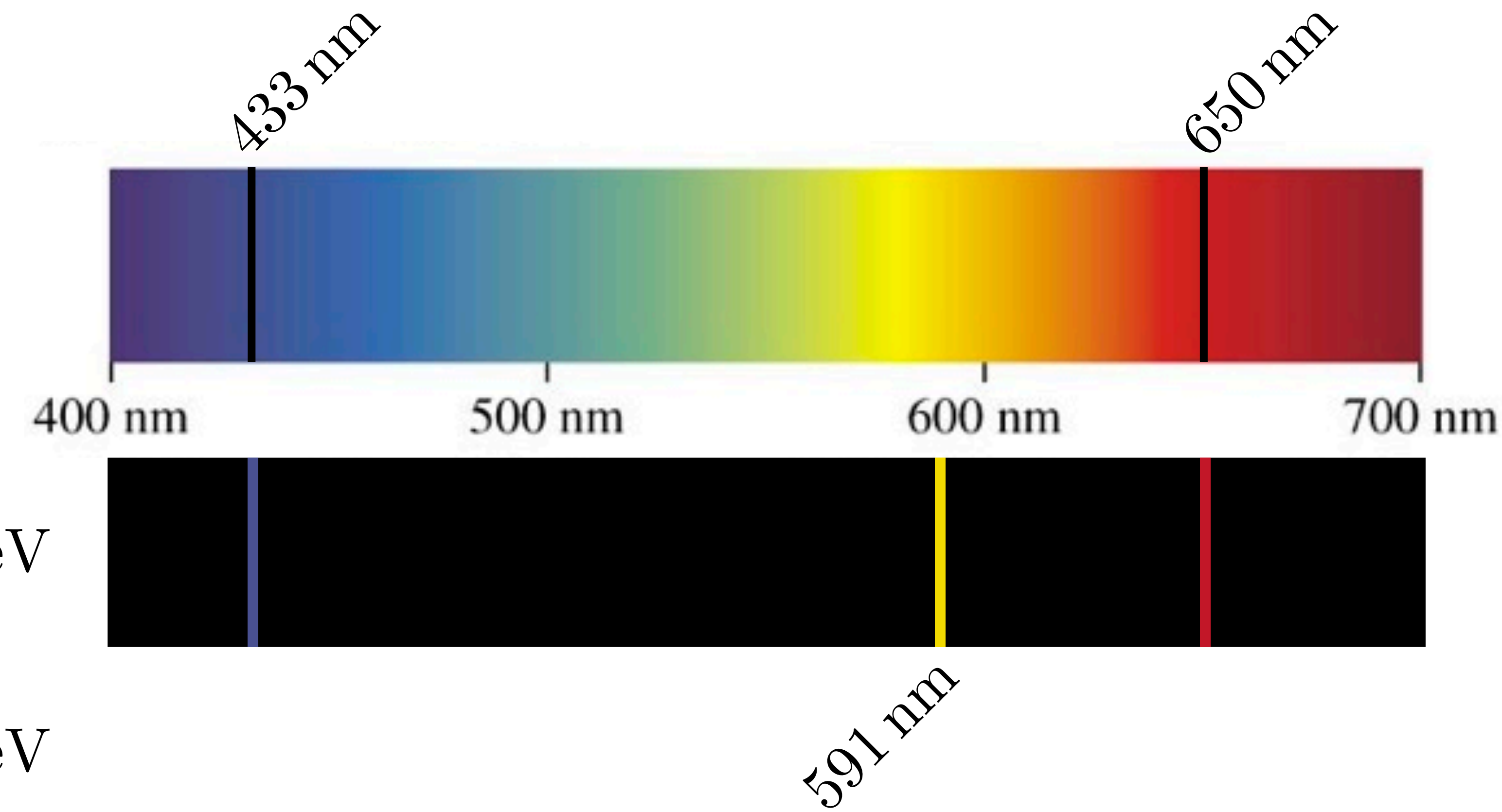
➜ suppose we measured the following visible absorption and emission spectra from a particular atom



➜ if the atom has only four energy levels, can we determine their energies ?

atomic energy levels from spectra





$$\Delta E = E_\gamma = \frac{hc}{\lambda}$$

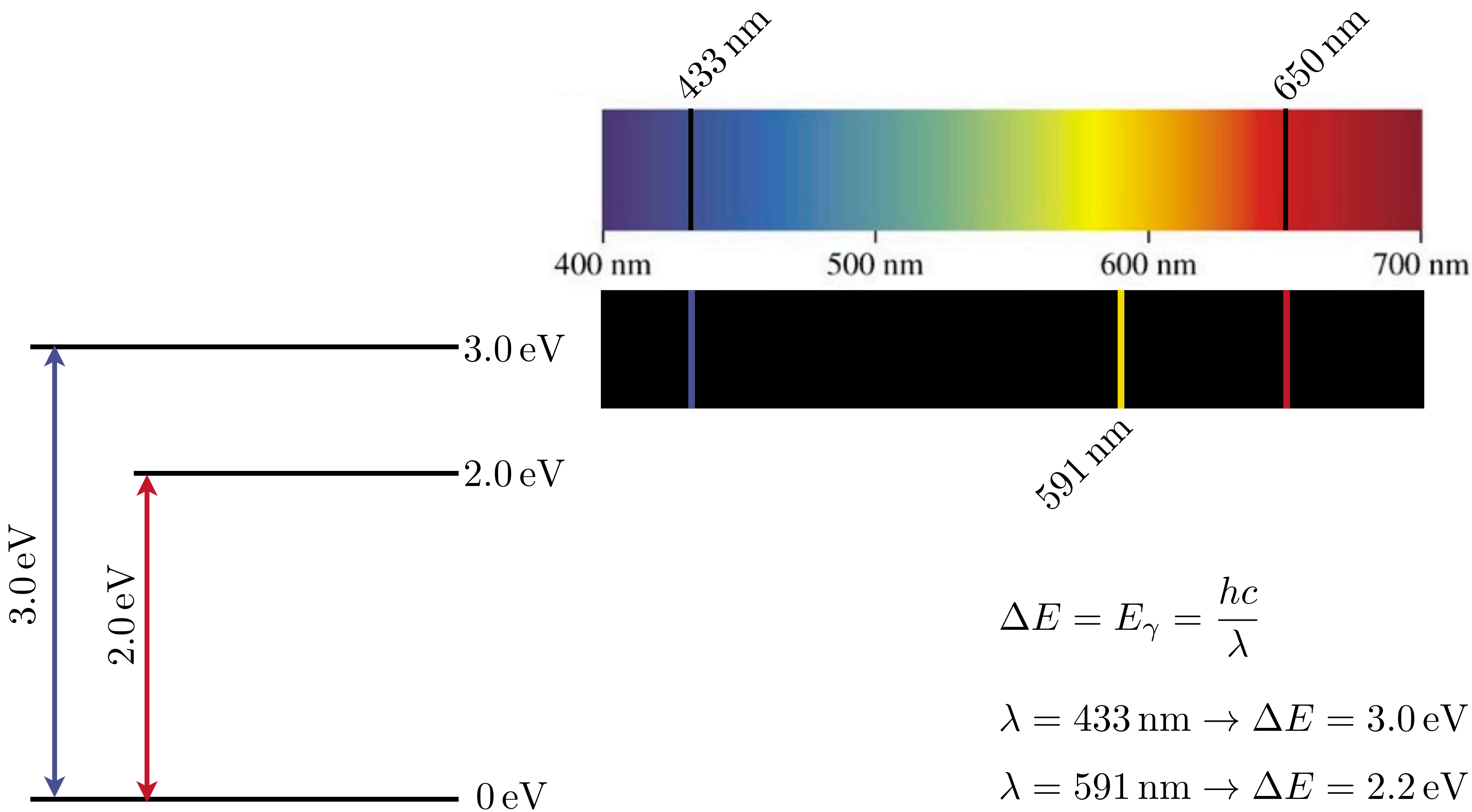
$$\lambda = 433\,\text{nm} \to \Delta E = 3.0\,\text{eV}$$

$$\lambda = 591\,\text{nm} \to \Delta E = 2.2\,\text{eV}$$

$$\lambda = 650\,\text{nm} \to \Delta E = 2.0\,\text{eV}$$

absorption ⇒ starting from ground state

atomic energy levels from spectra



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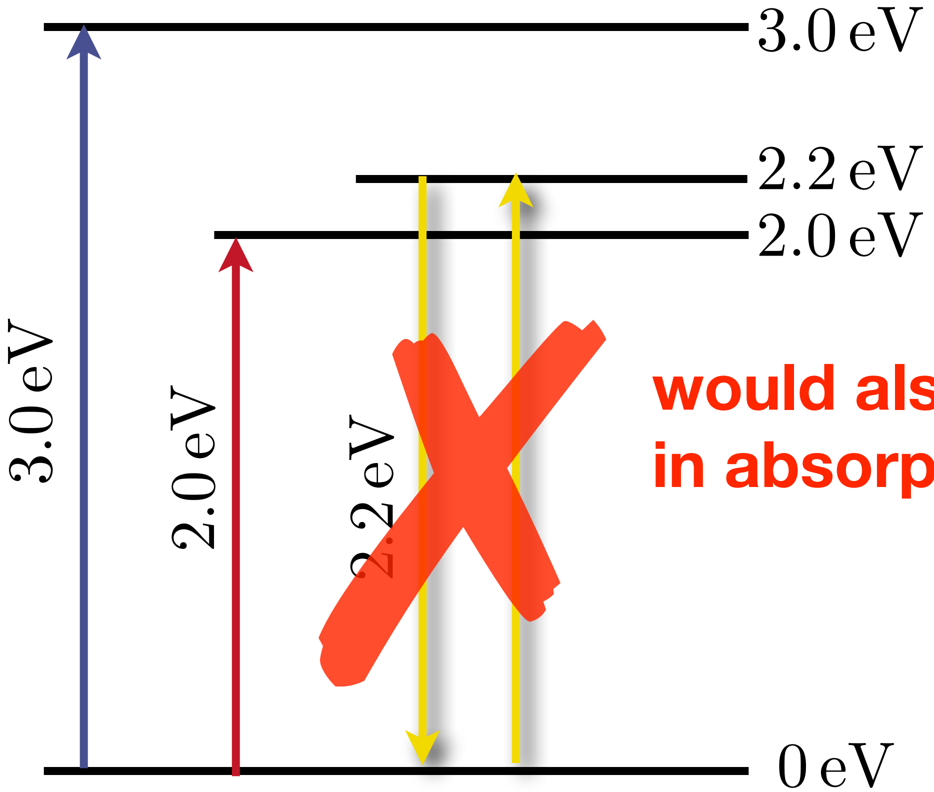
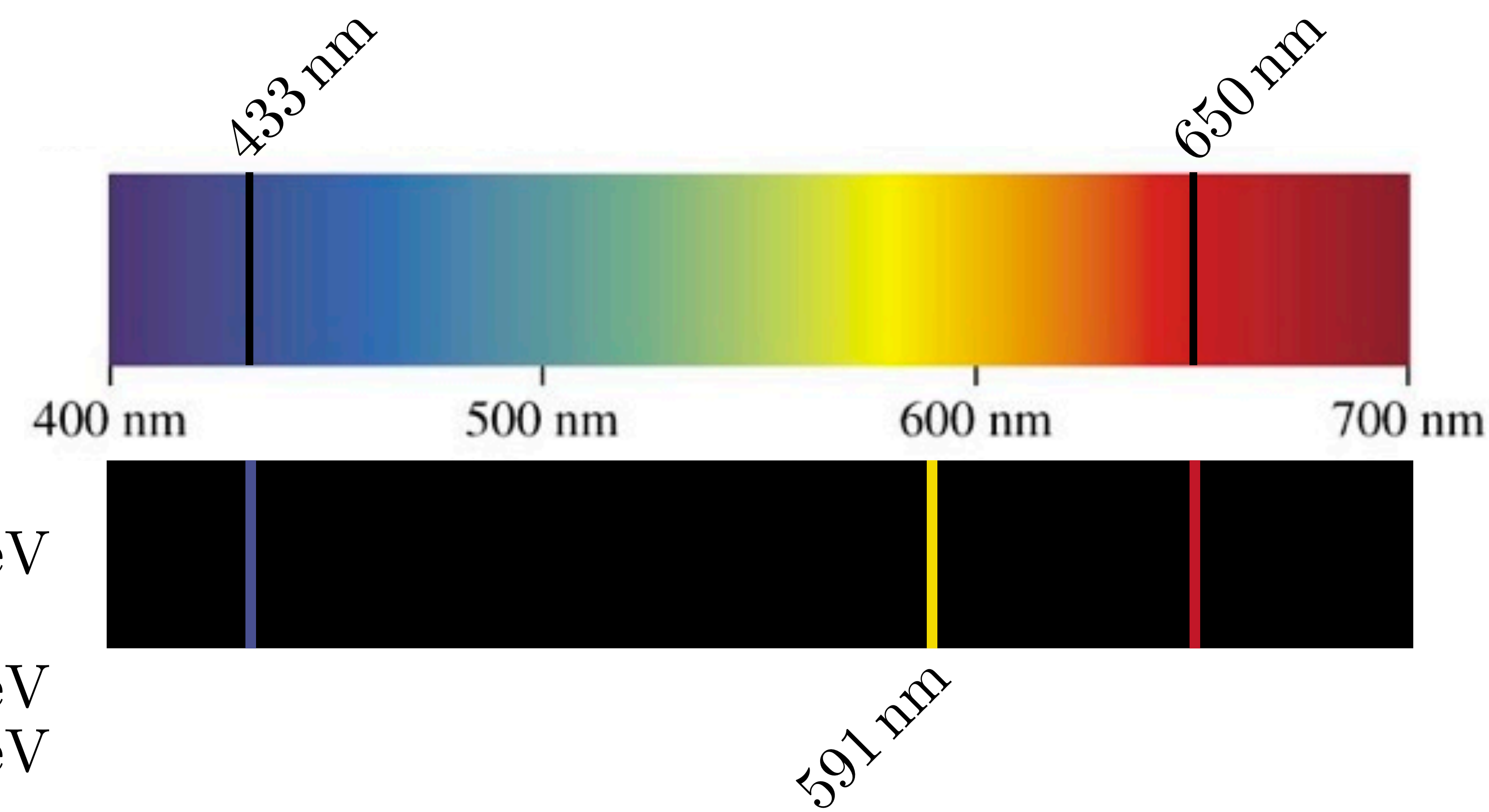
emission ⇒ between any two levels

atomic energy levels from spectra





would also appear in absorption

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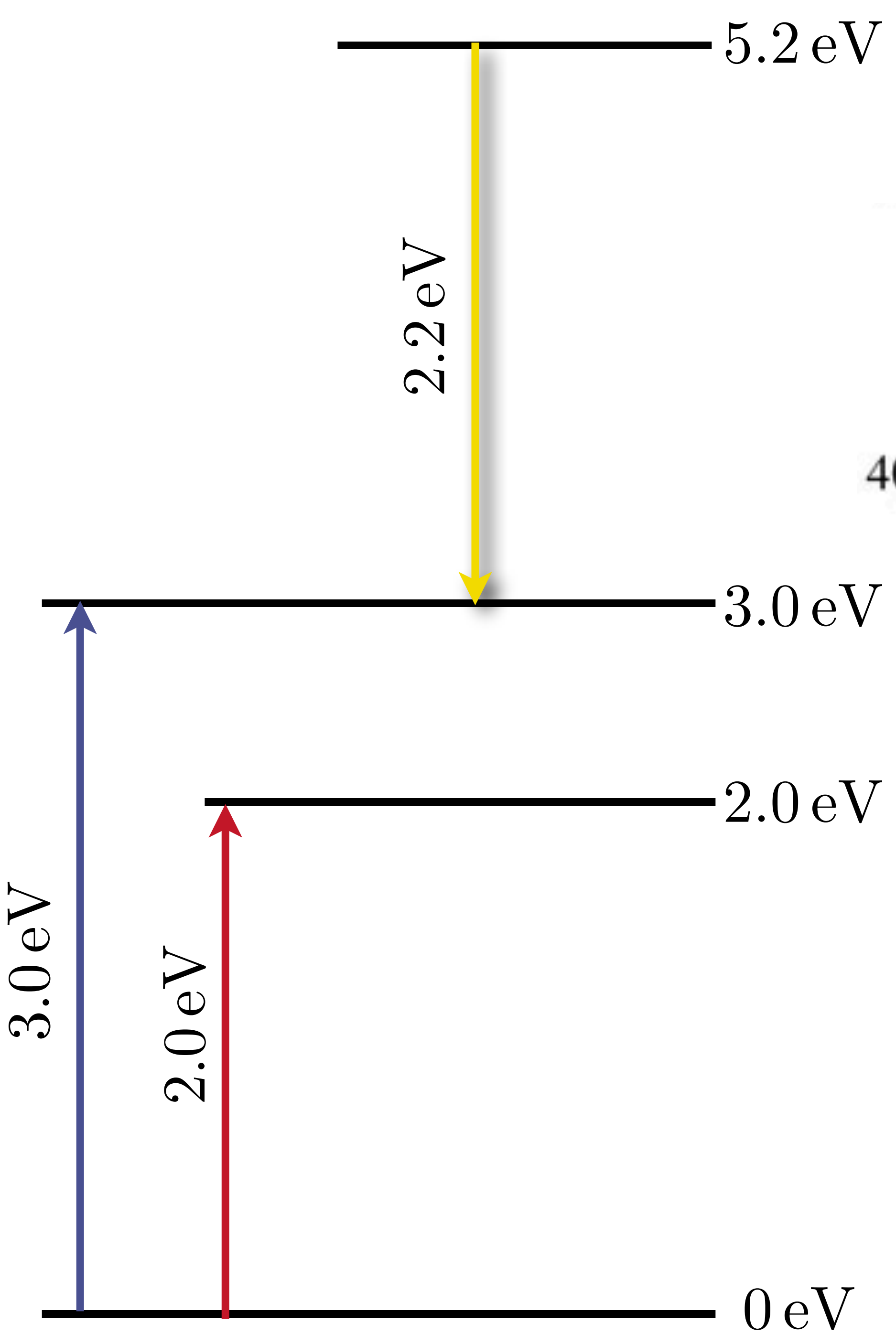
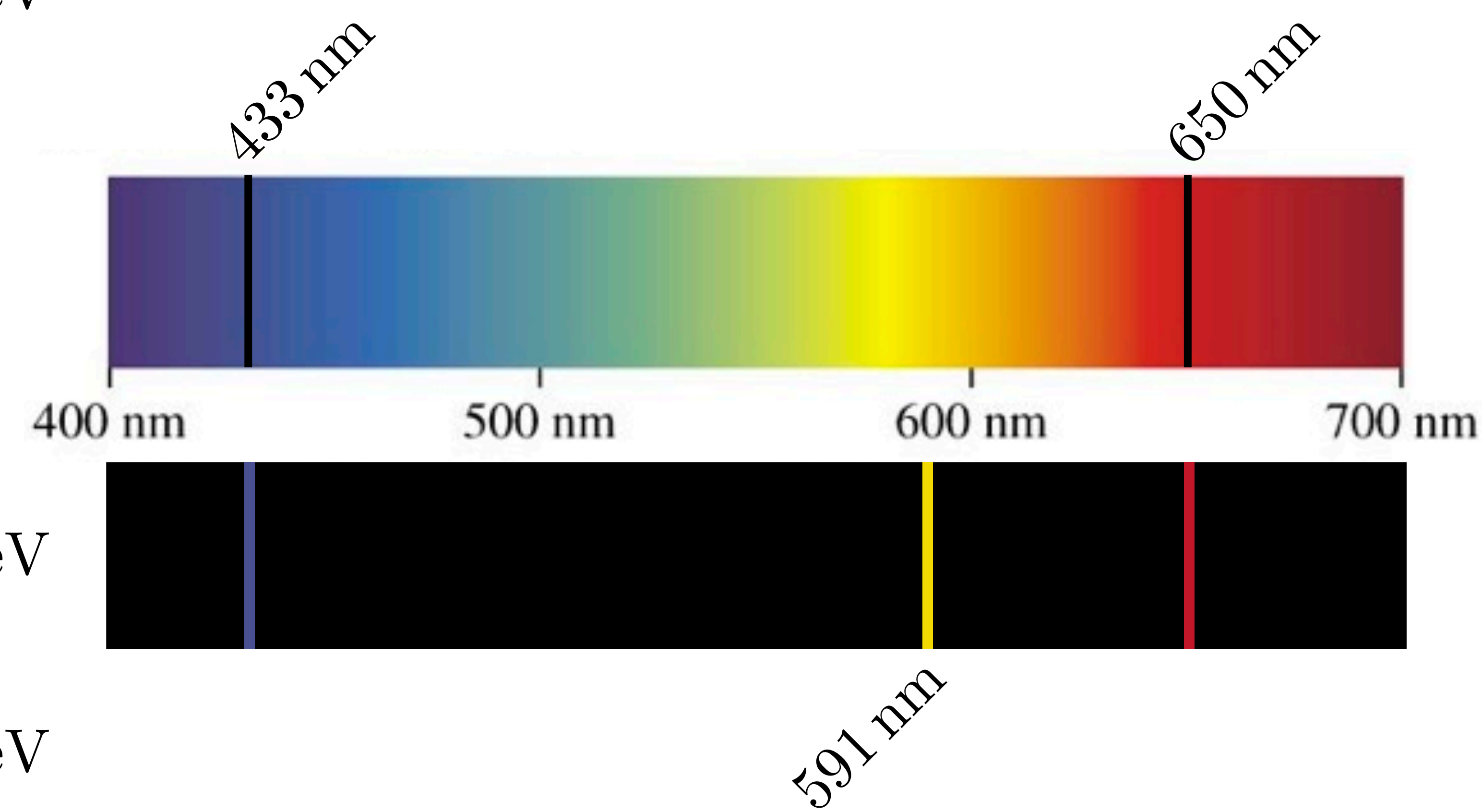
emission ⇒ between any two levels

atomic energy levels from spectra





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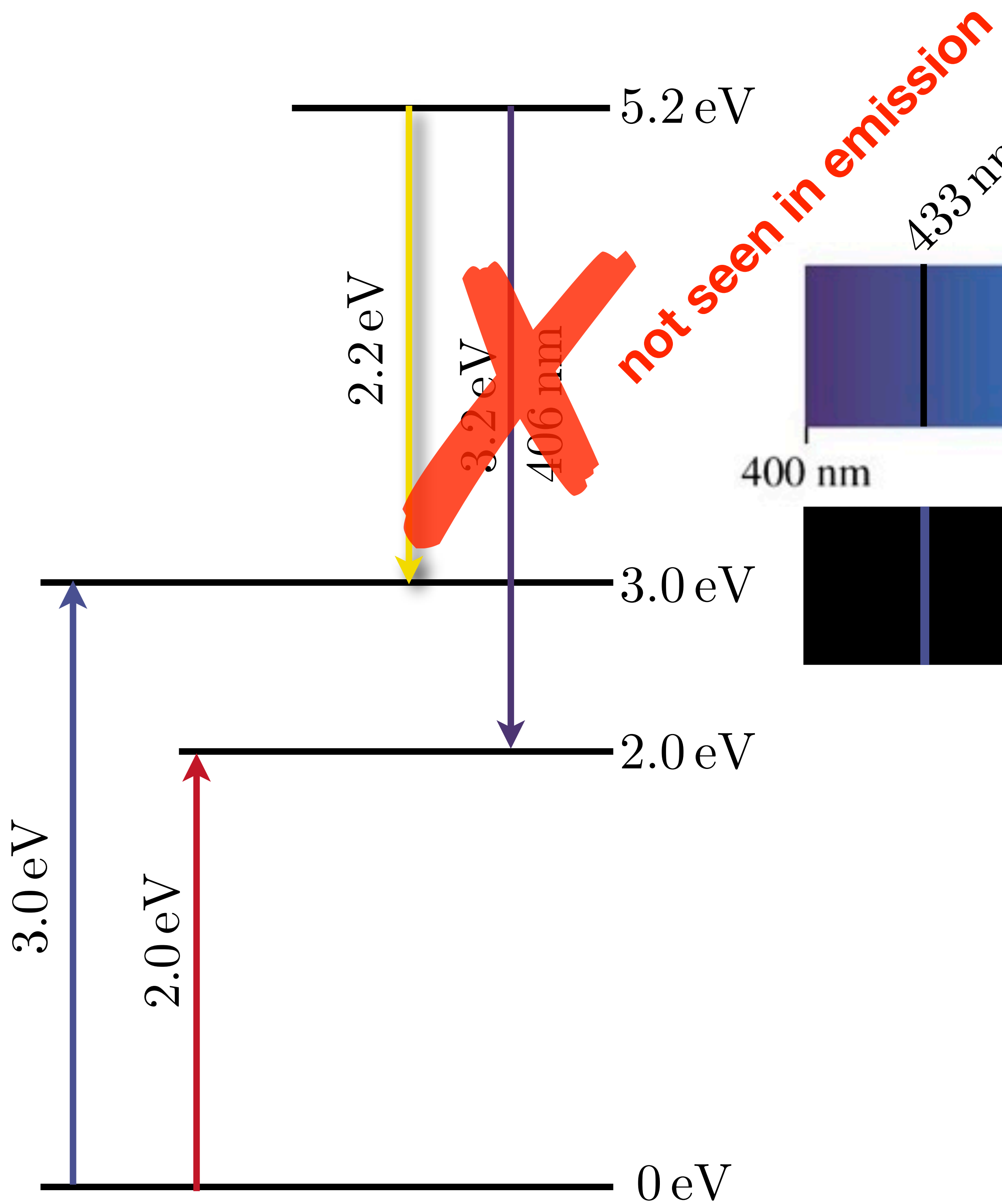
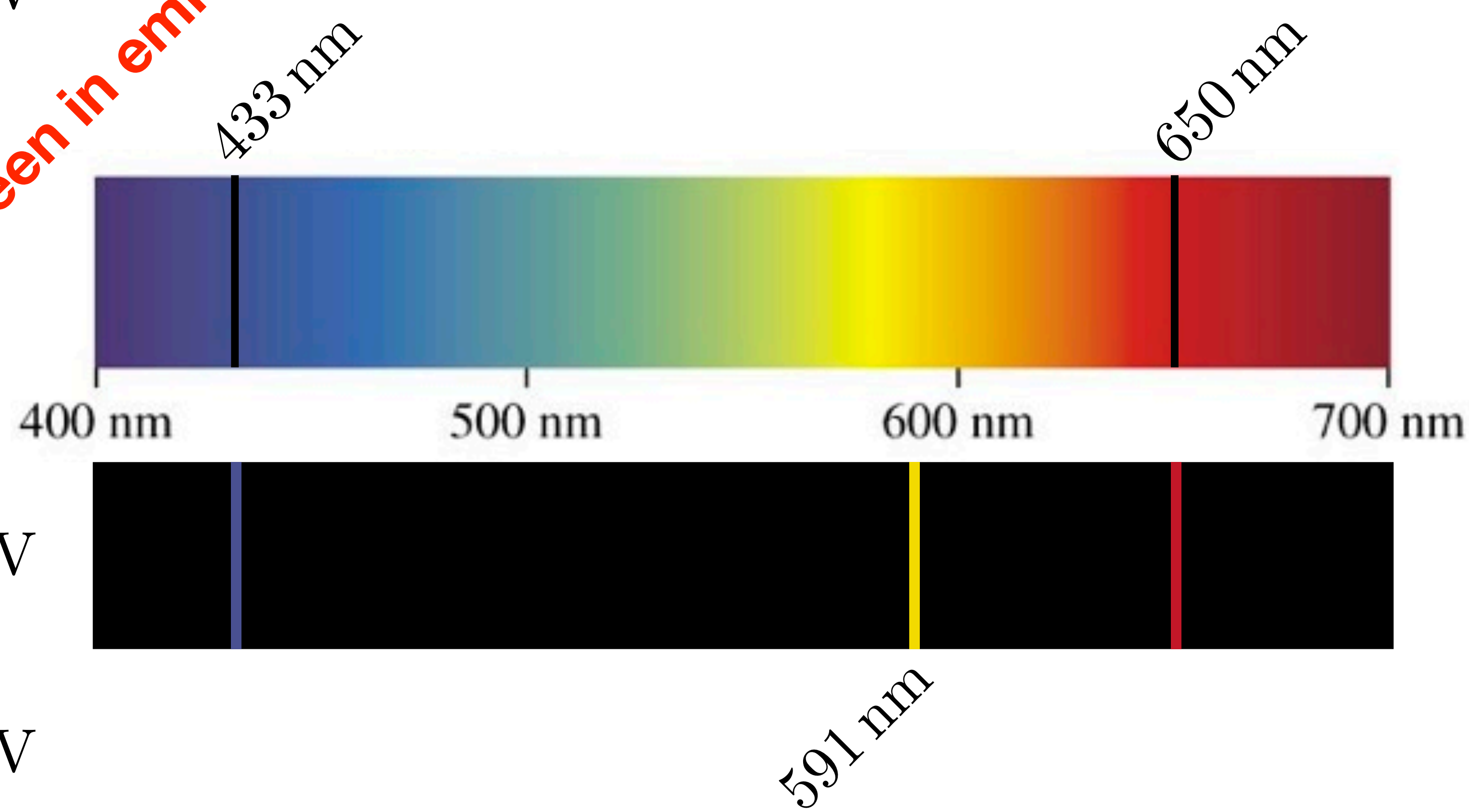
atomic energy levels from spectra





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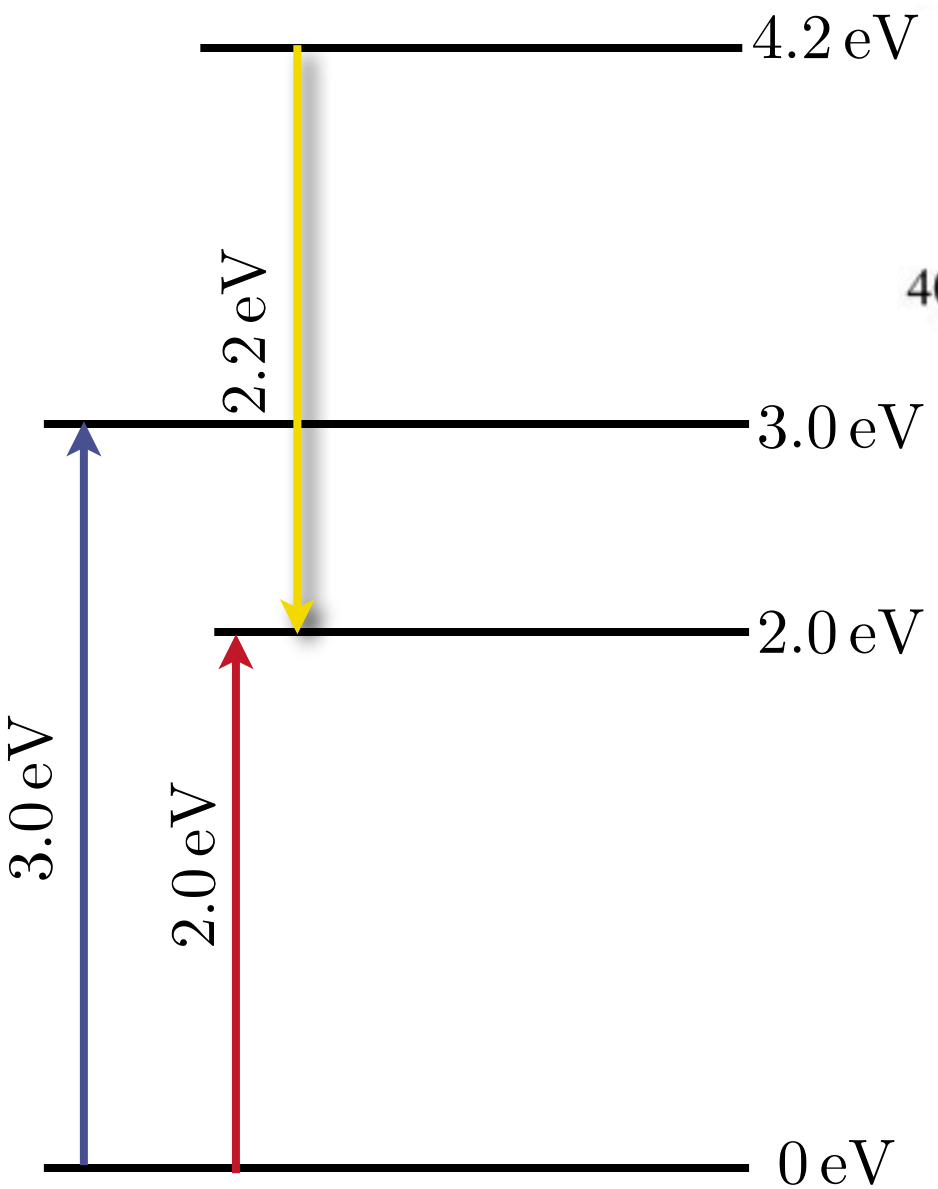
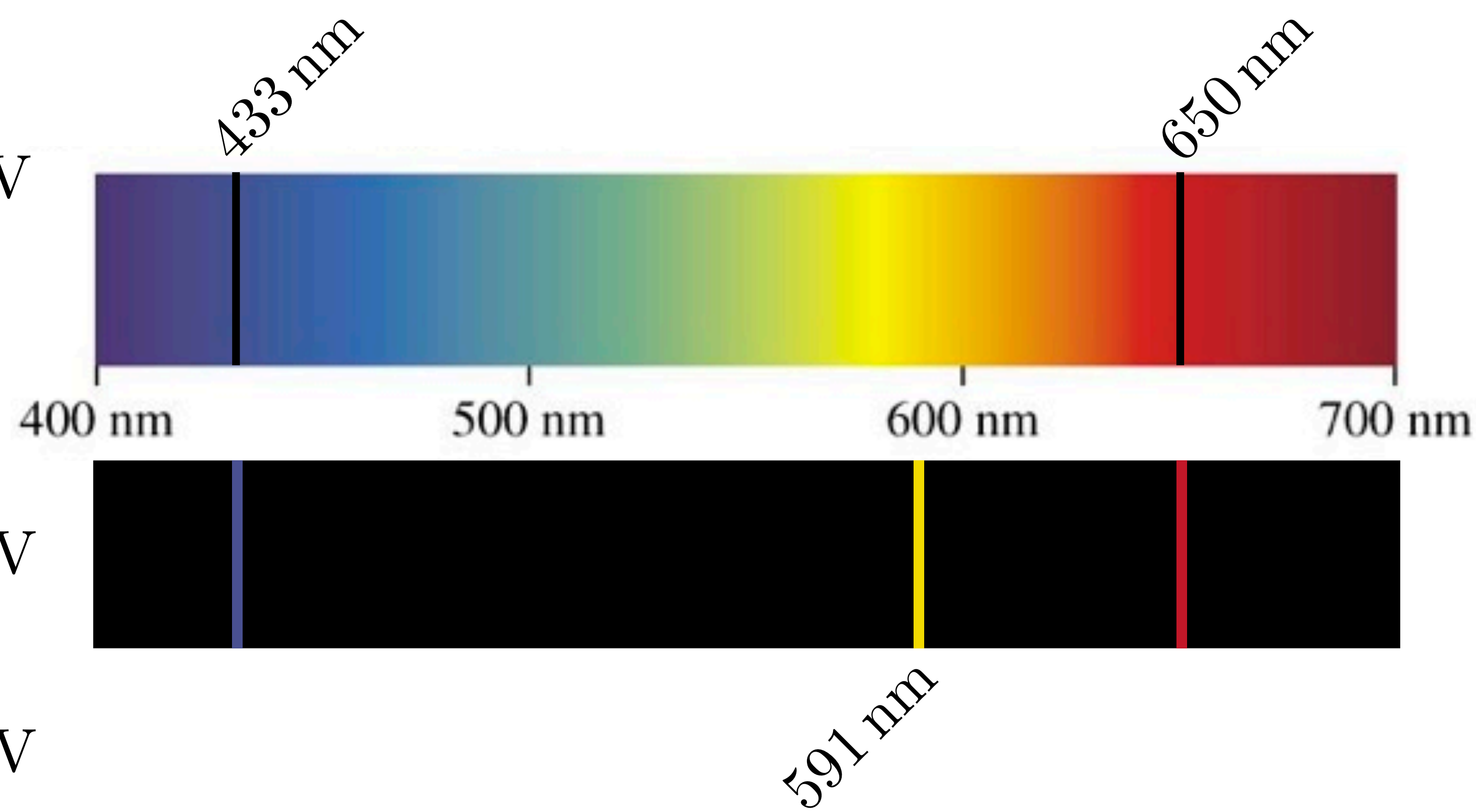
atomic energy levels from spectra





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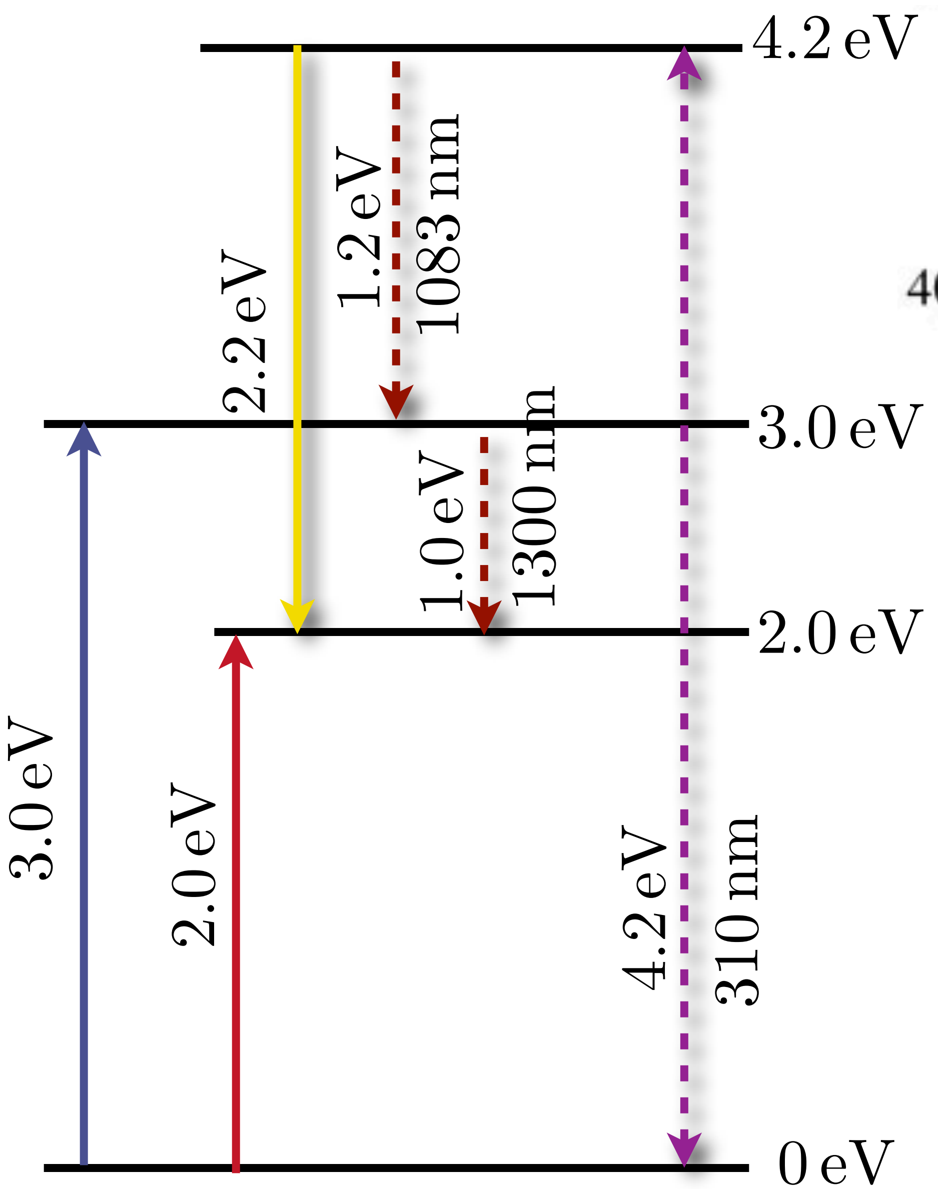
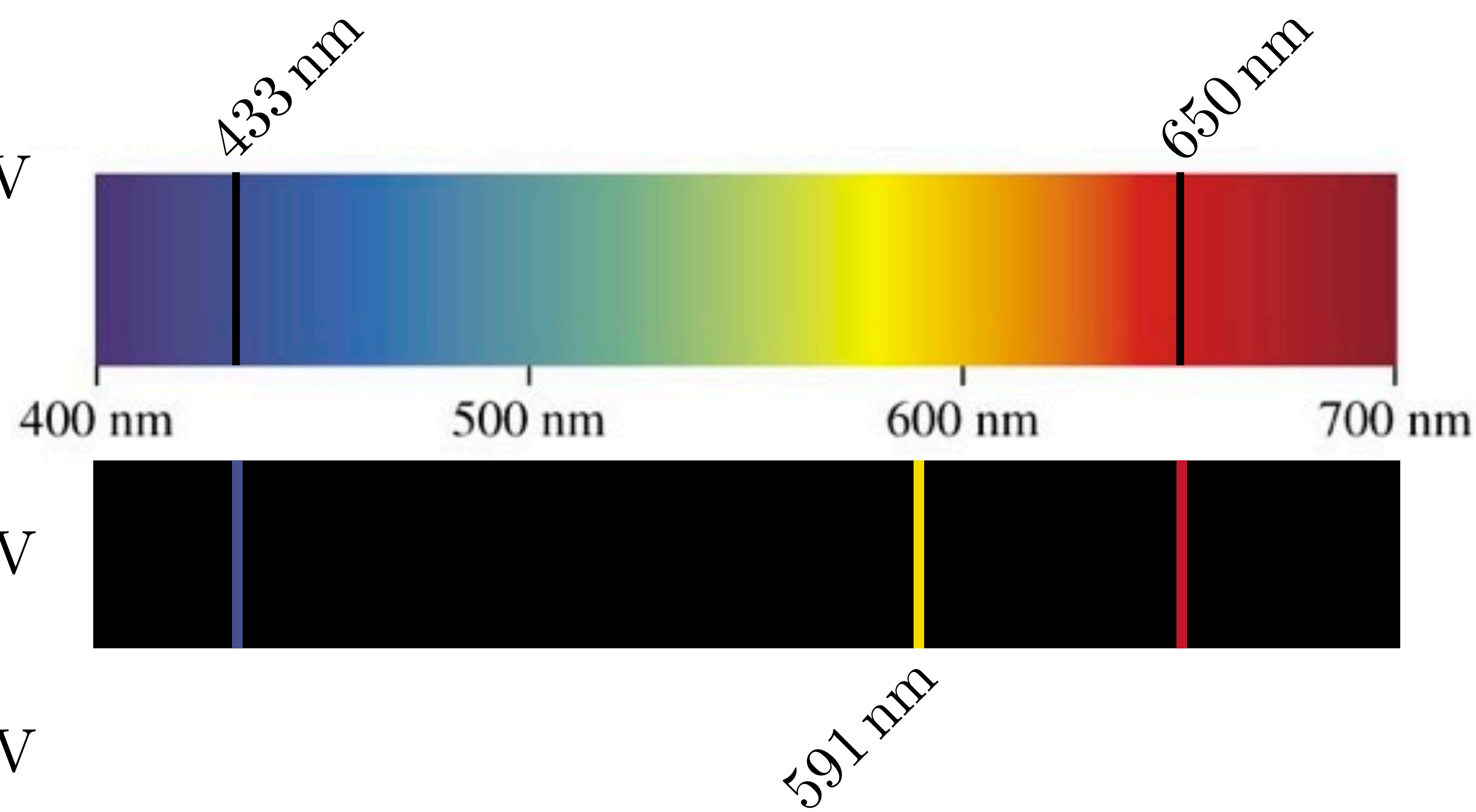
atomic energy levels from spectra





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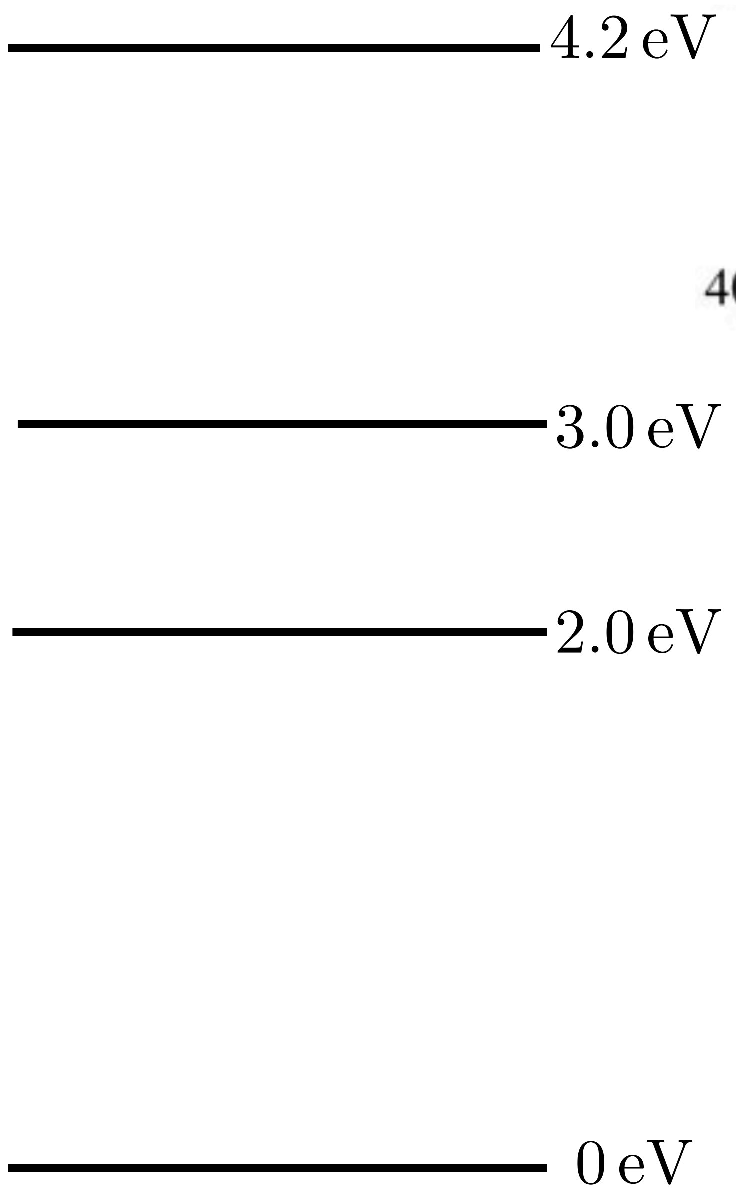
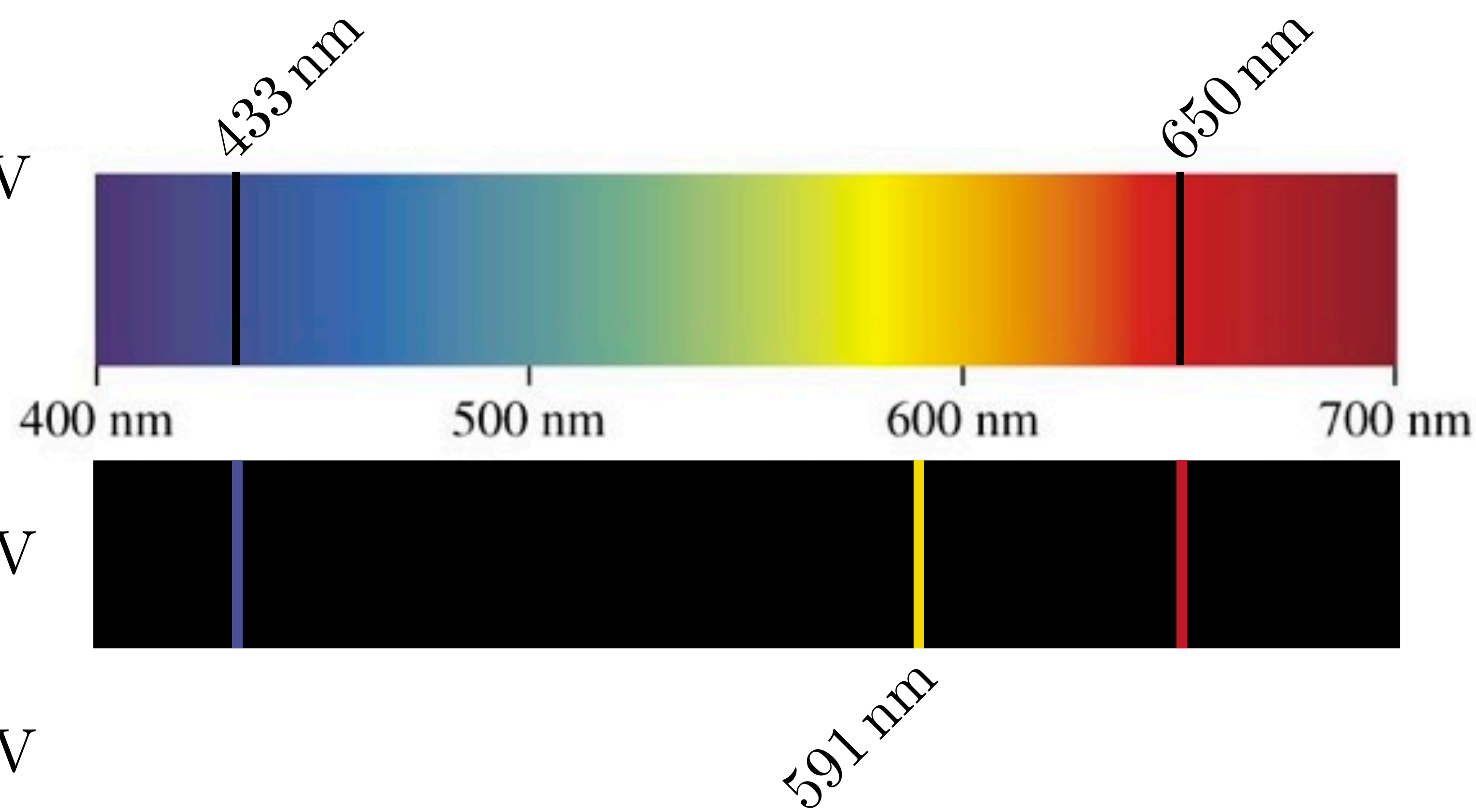
atomic energy levels from spectra





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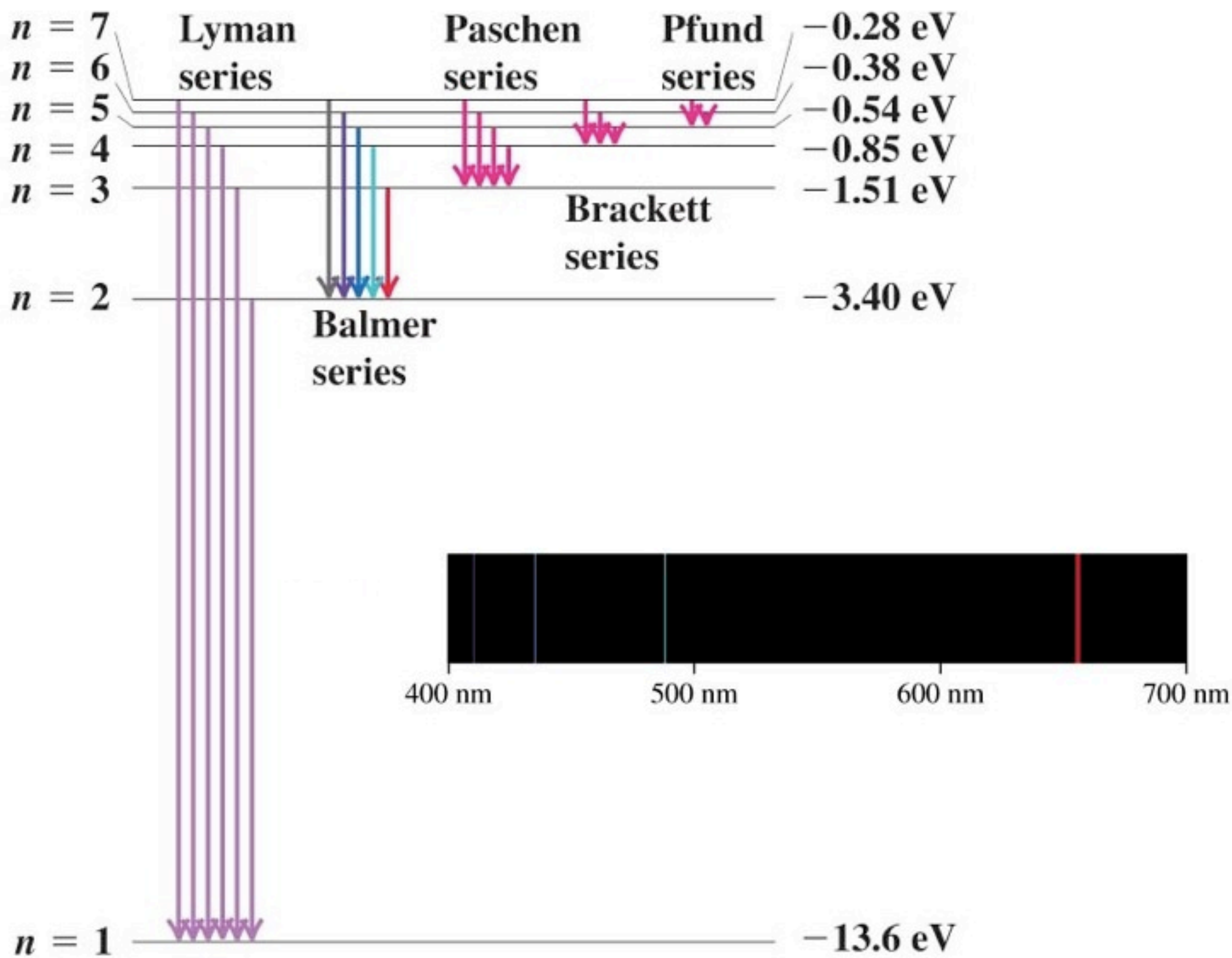
hydrogen energy level spectrum



what's going on inside the atom ?

➜ we think that atoms contain

➜ negatively charged light electrons

➜ positively charged heavy protons

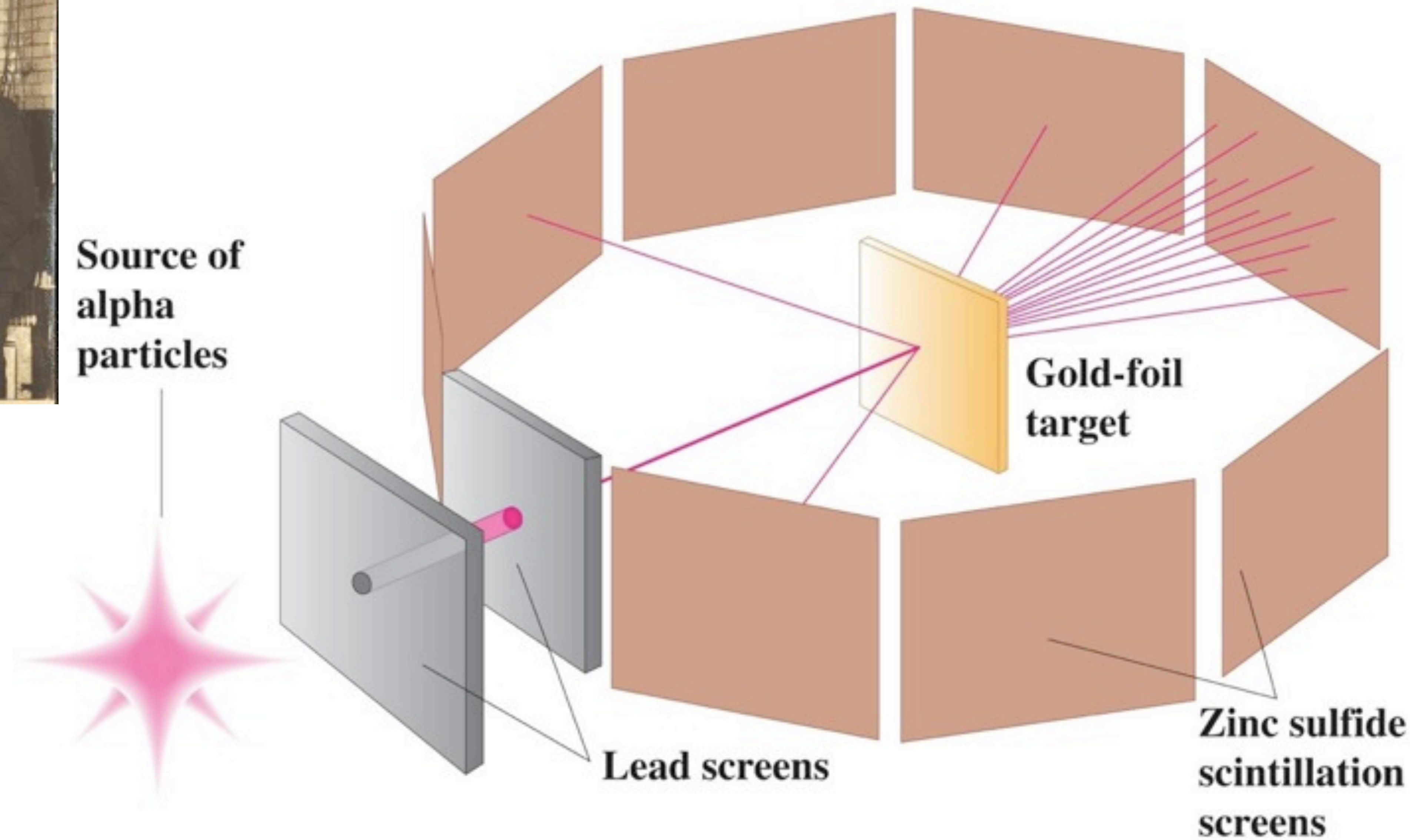
in equal numbers to ensure atoms are overall uncharged

➜ but how are they distributed ?

➜ J.J. Thomson who discovered the electron thought the charges were evenly distributed throughout the atom

what's going on inside the atom ?

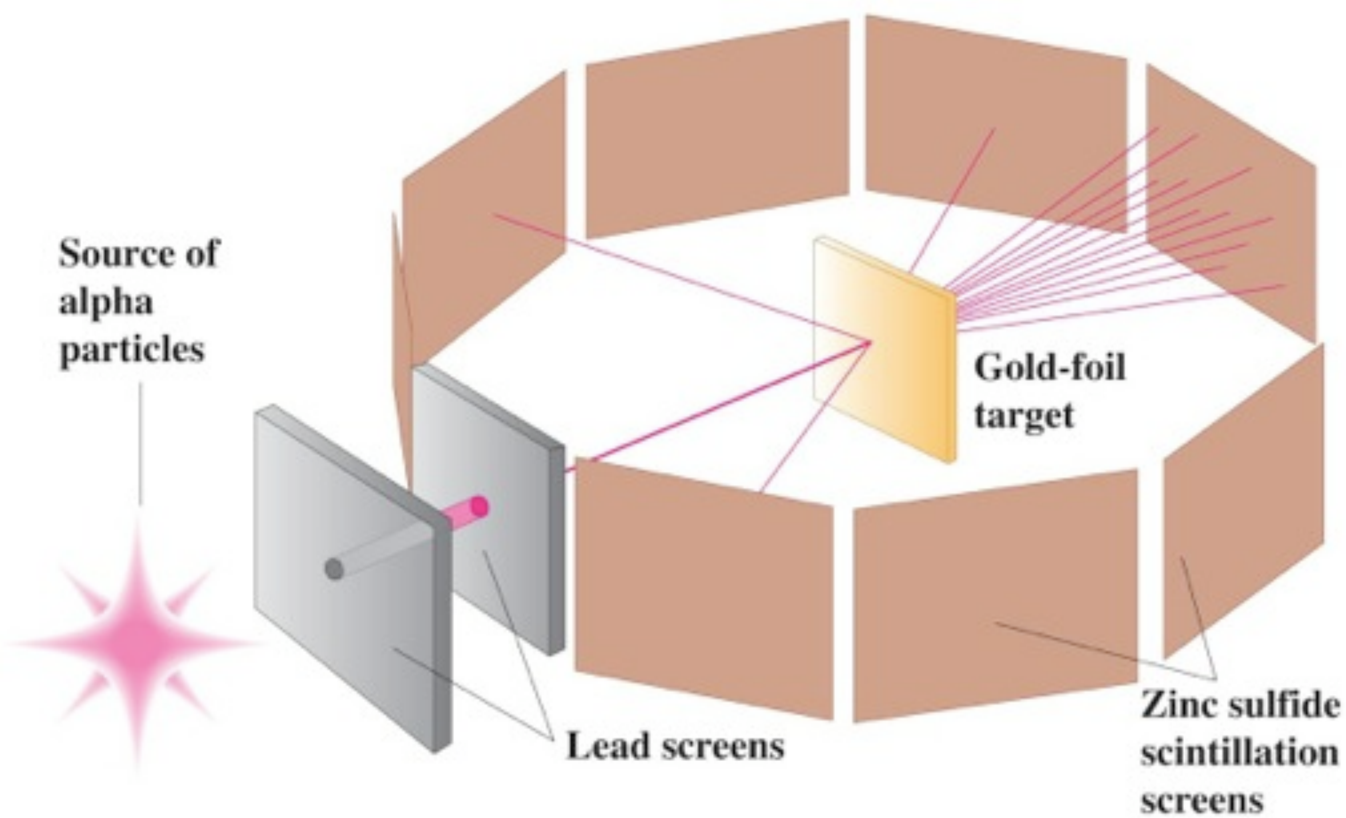
➜ need more experimental results ... Rutherford, Geiger and Marsden

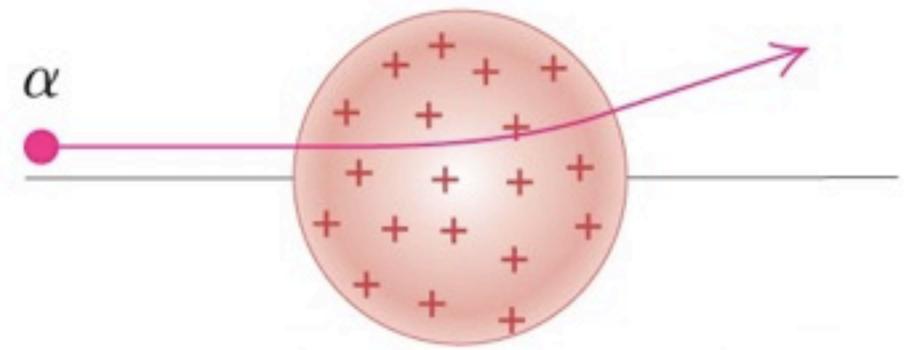


➜ bounce ('scatter') alpha particles off atoms - watch where they go

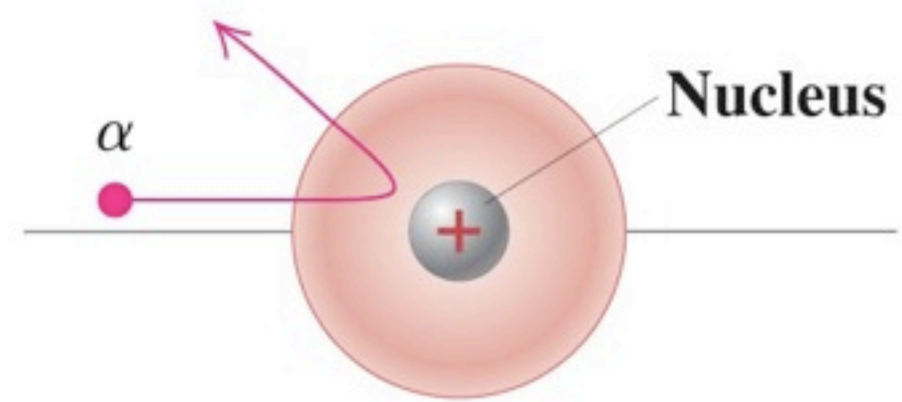
Rutherford scattering & the atomic nucleus

➜ some of the alpha particles get scattered back toward the source





Thomson's model of the atom: An alpha particle is scattered through only a small angle.



Rutherford's model of the atom: An alpha particle can be scattered through a large angle by the compact, positively charged nucleus.

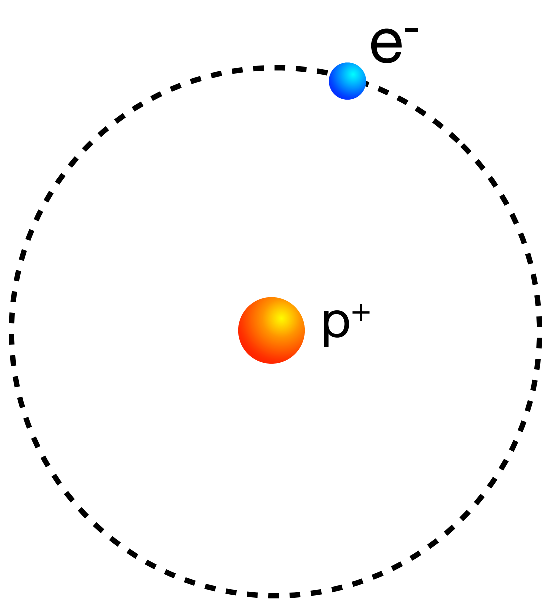
➜ protons tightly bound in a tiny atomic nucleus
➜ electrons much further out

the planetary model of the atom

➜ consider the simplest atom : hydrogen - one electron and one proton

➜ classical electromagnetism - Coulomb’s law

➜ circular motion of the electron around the nucleus ?

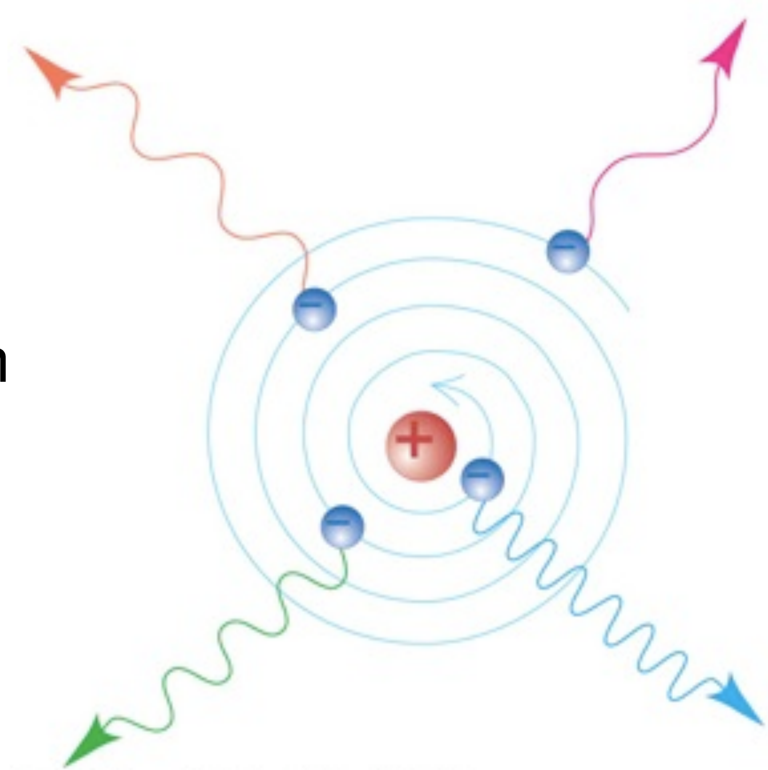


➜ but any energy is possible in this model

➜ disagrees with the spectroscopy experiments

➜ accelerating charges radiate e/m waves in classical electromagnetism

➜ continuous loss of energy



➜ atoms aren’t stable in this model

investigating electrons

➜ maybe we need a better theory of electrons and other ‘matter’ particles before trying to understand atoms

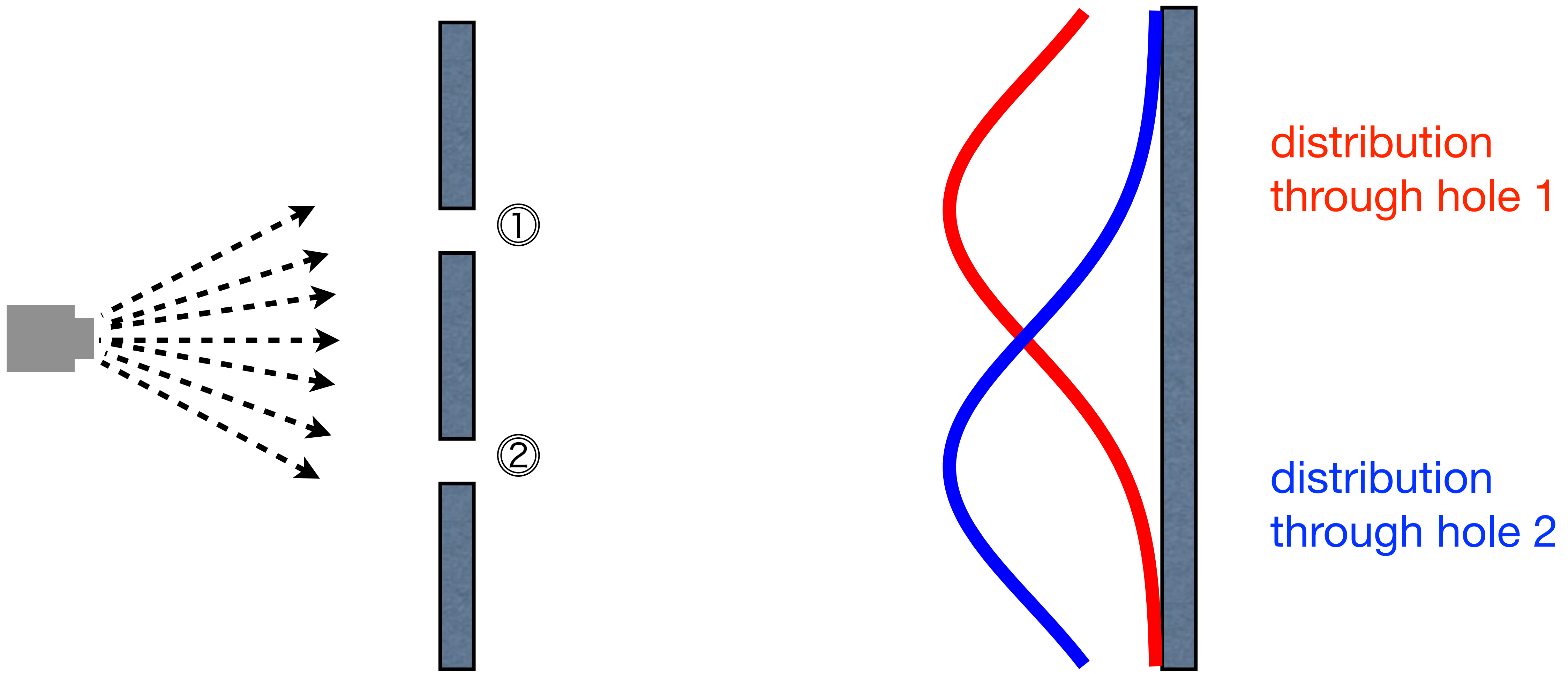
➜ back to the two-slit experiment

two slits with particles - bullets

➜ machine gun spraying bullets at two slits

two slits with particles - bullets

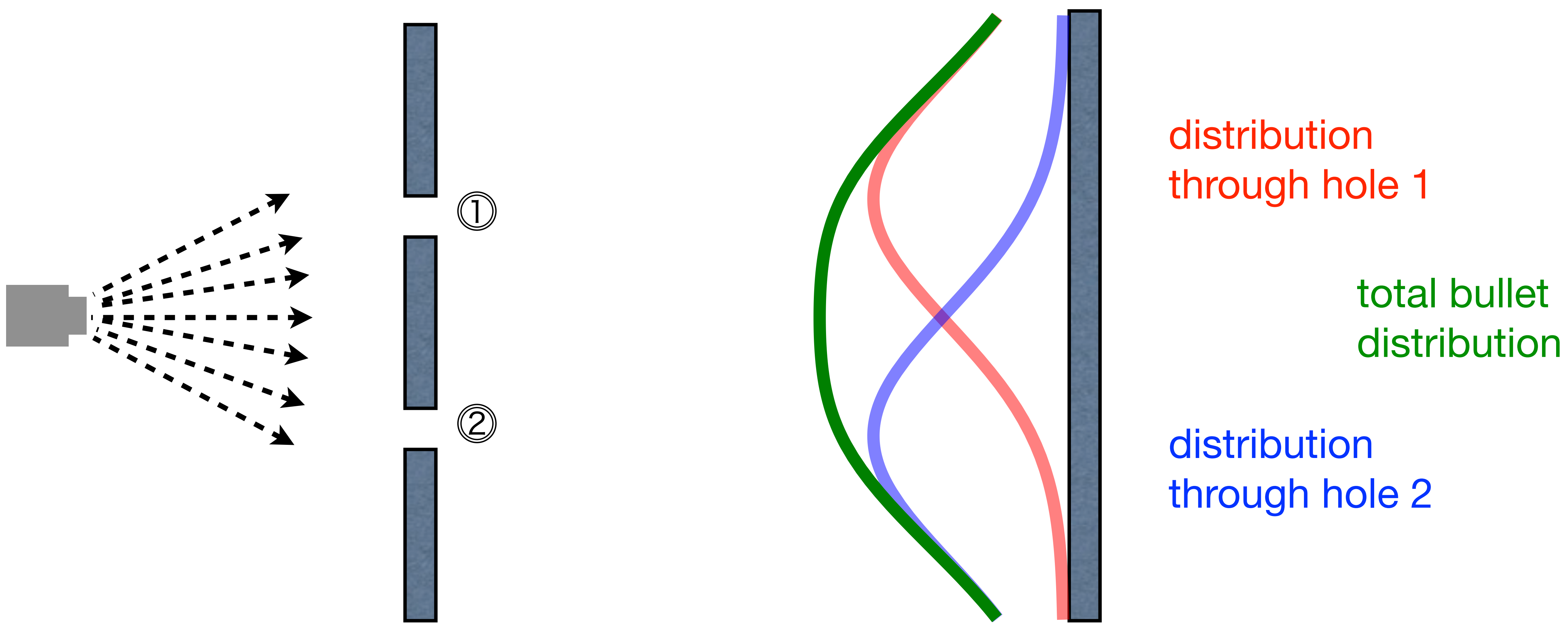
➜ machine gun spraying bullets at two slits



➜ bullets arrive one at a time - particles !

two slits with particles - bullets

➜ machine gun spraying bullets at two slits

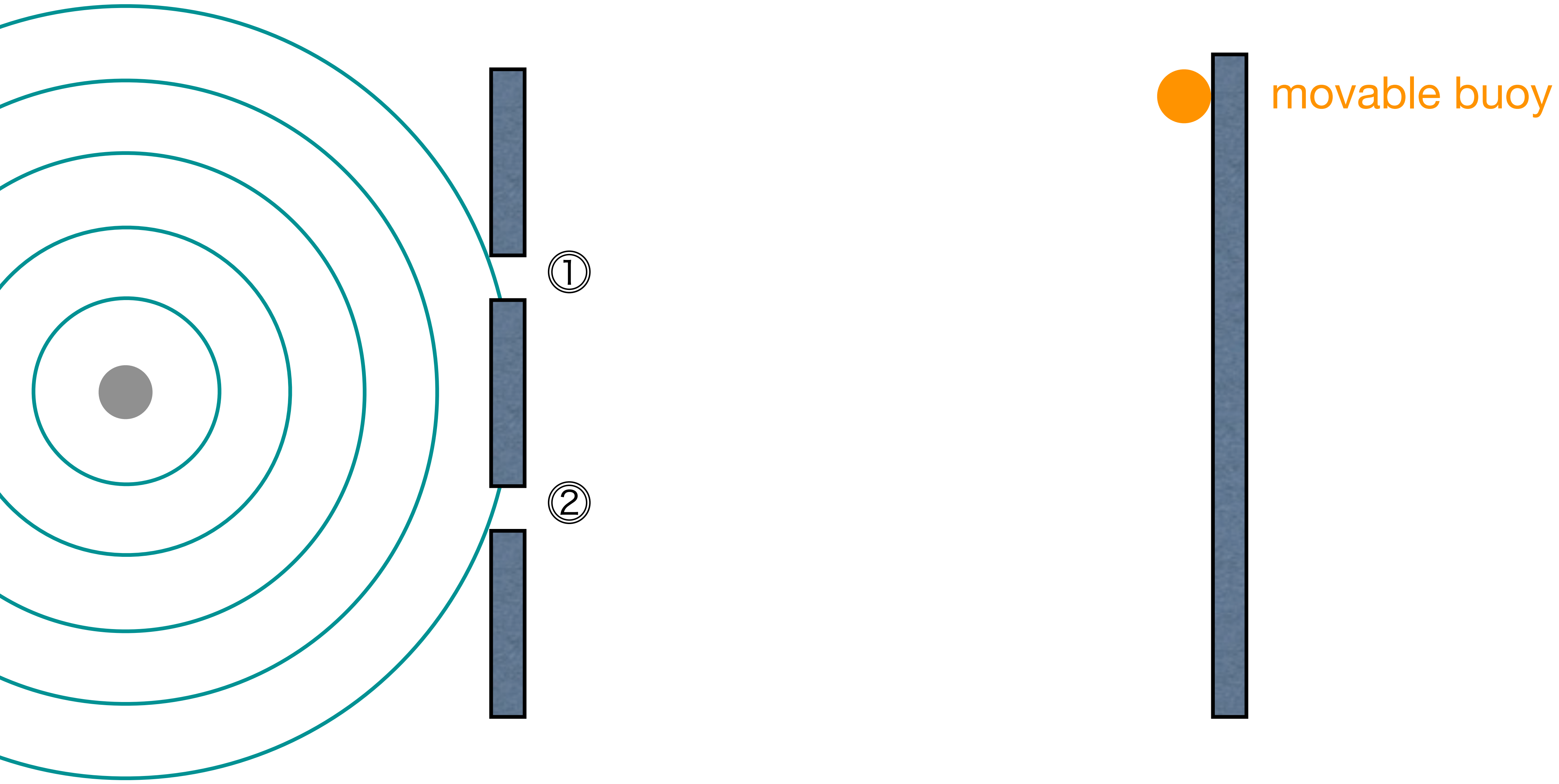


JUST A STRAIGHT SUM

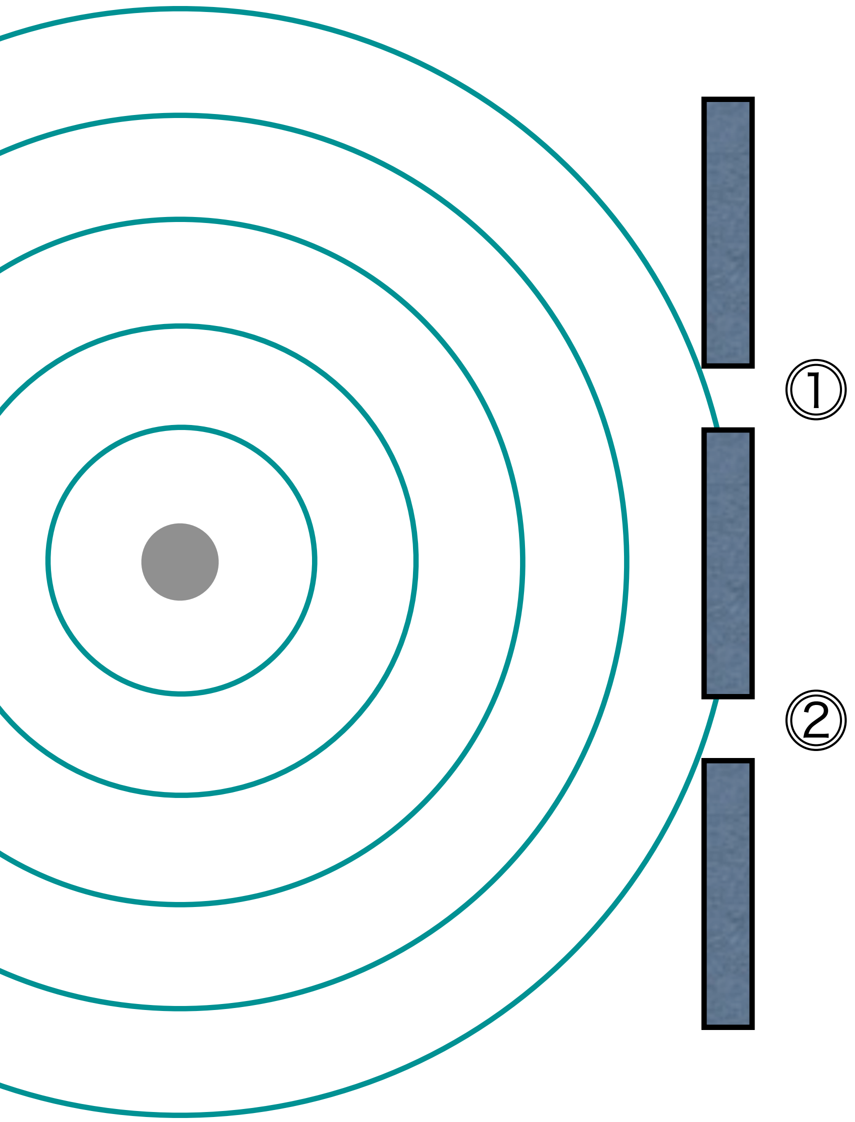
any given bullet either went through hole 1 or hole 2

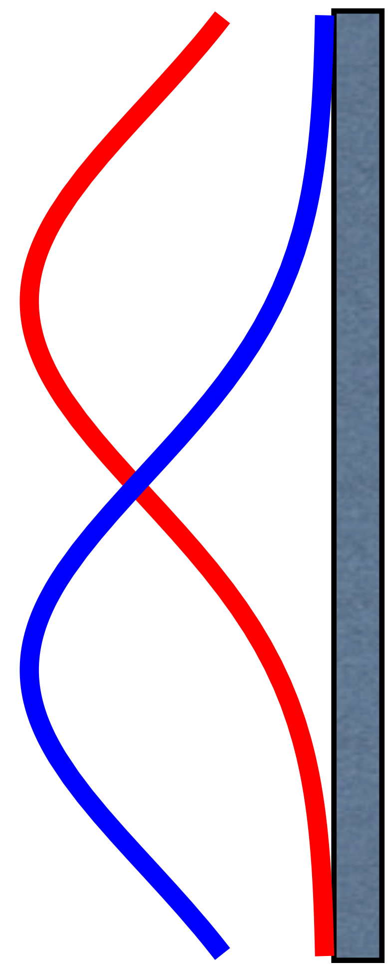
two slits with waves - water

➜ set up two slits in a water bath, generate waves with a forced bob



two slits with waves - water



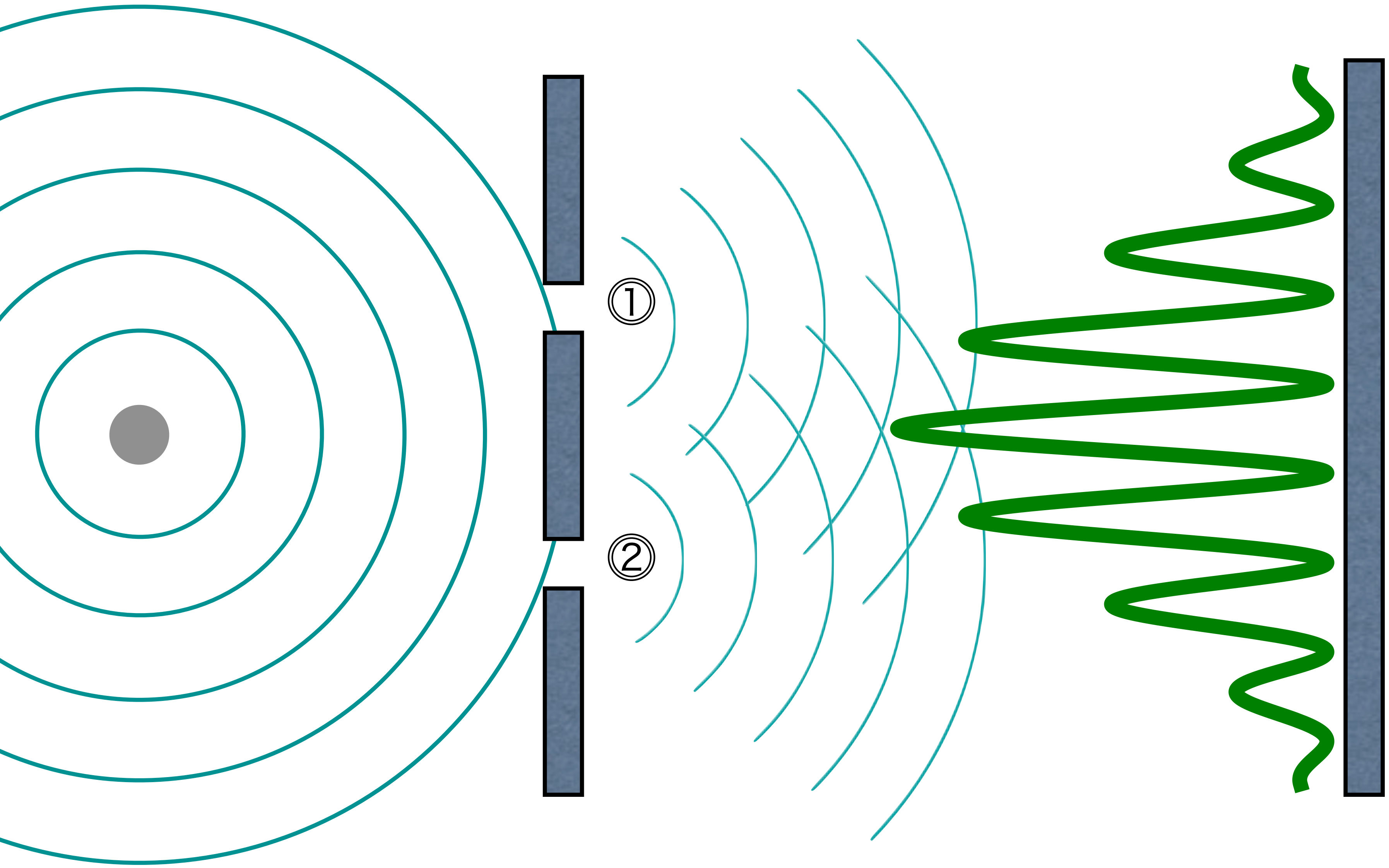


buoy oscillation with
just hole 1 open

buoy oscillation with
just hole 2 open

➜ waves arrive continuously - waves !

two slits with waves - water



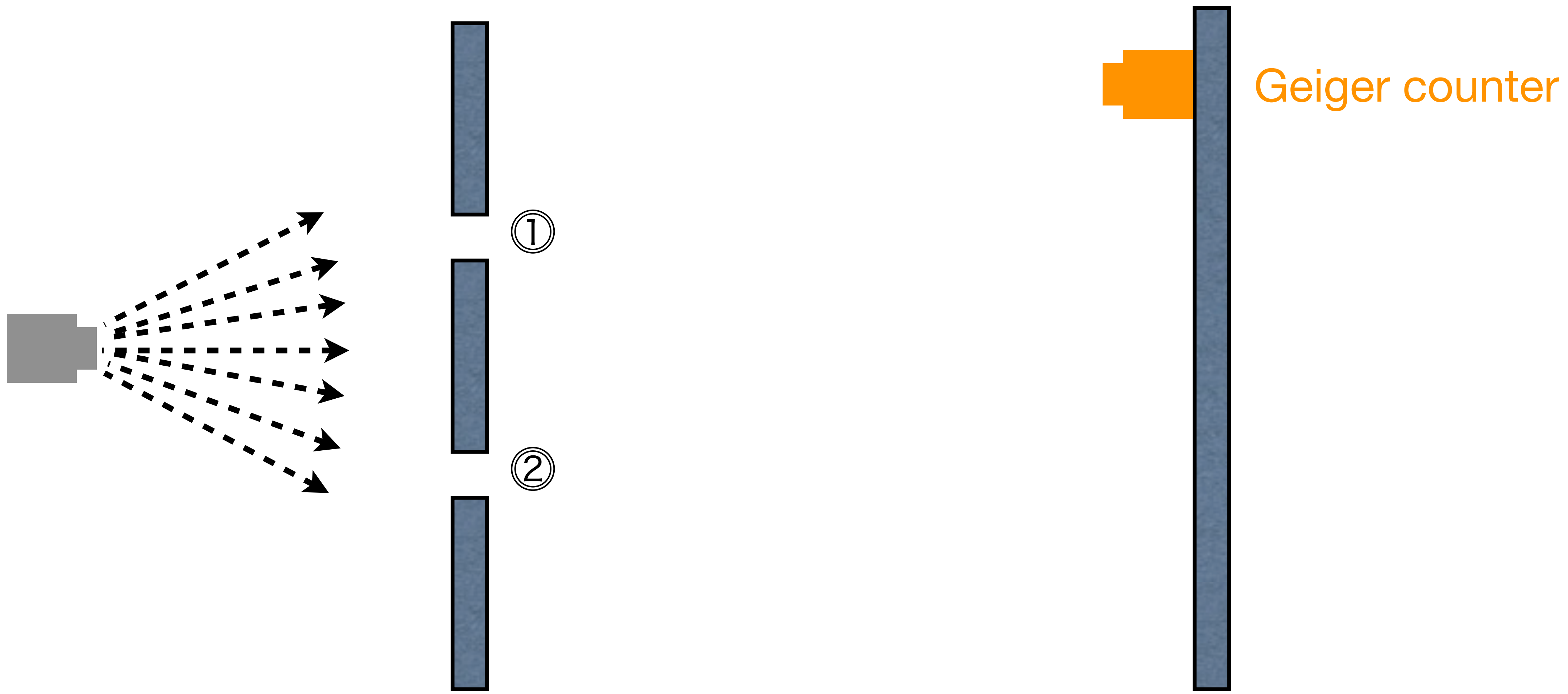
both holes open
wave intensity

INTERFERENCE

both holes are required !

two slits with subatomic particles - electrons

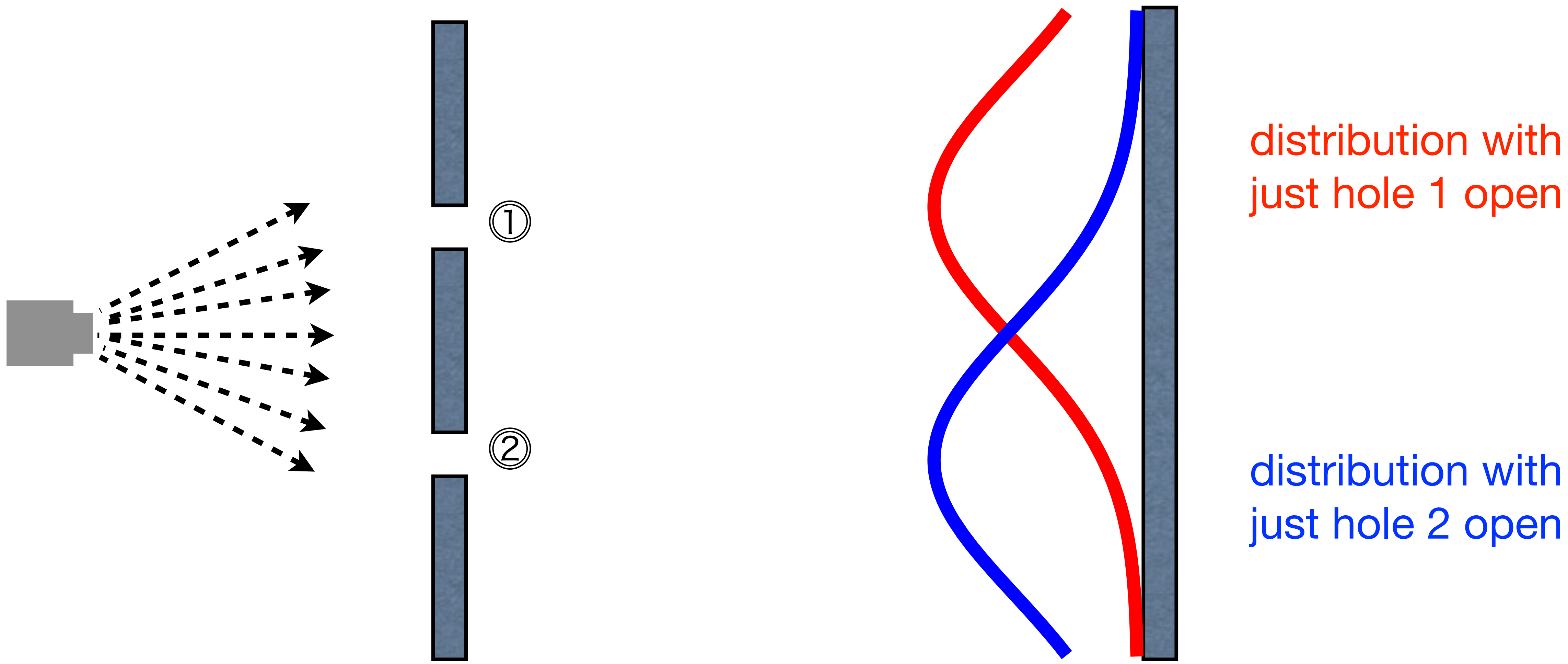
➜ use an ‘electron gun’ - source of electrons



➜ electrons arrive one at a time - particles !

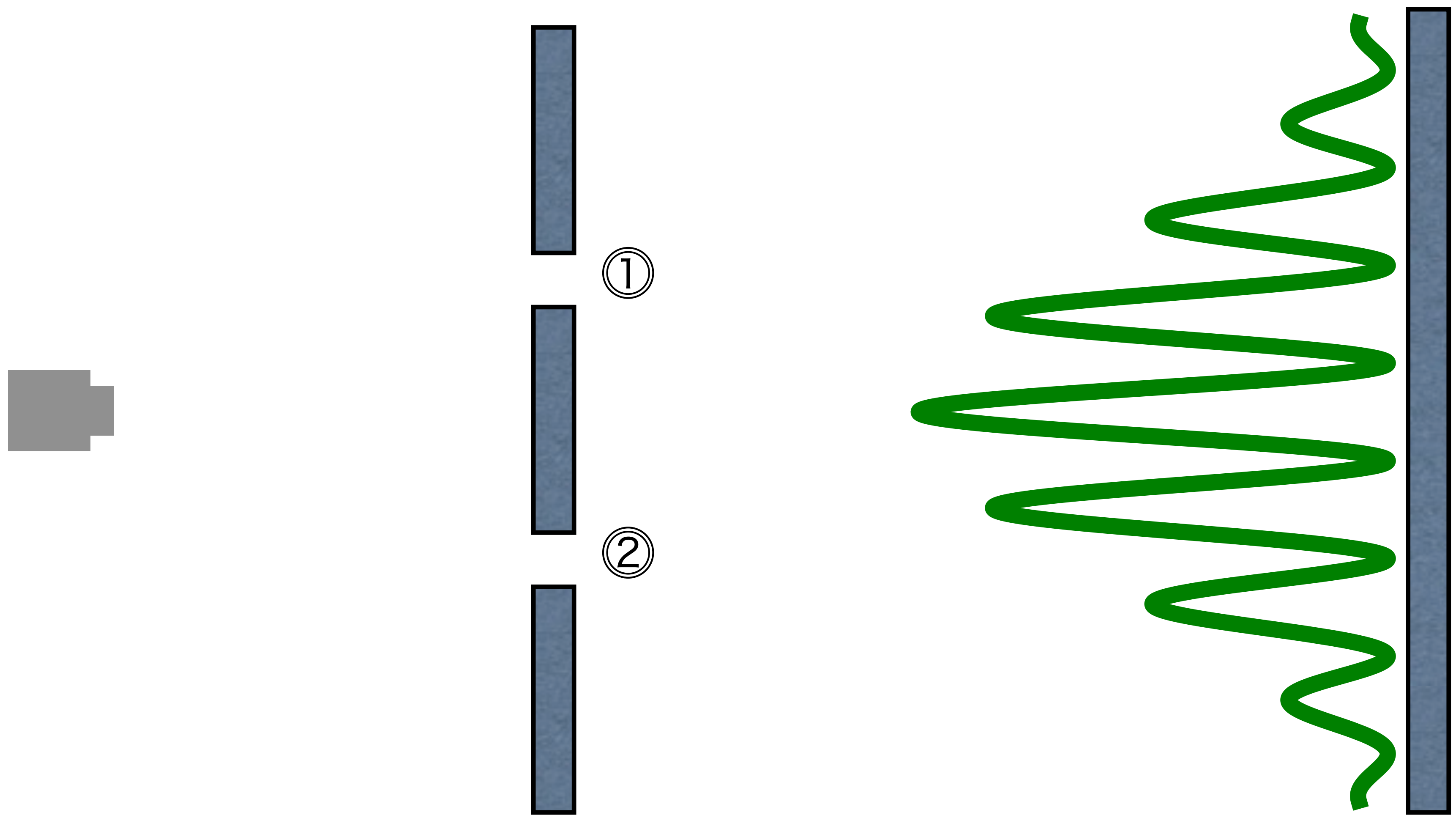
two slits with subatomic particles - electrons

➜ use an ‘electron gun’ - source of electrons



two slits with subatomic particles - electrons

➜ use an ‘electron gun’ - source of electrons



both holes open
count the electrons

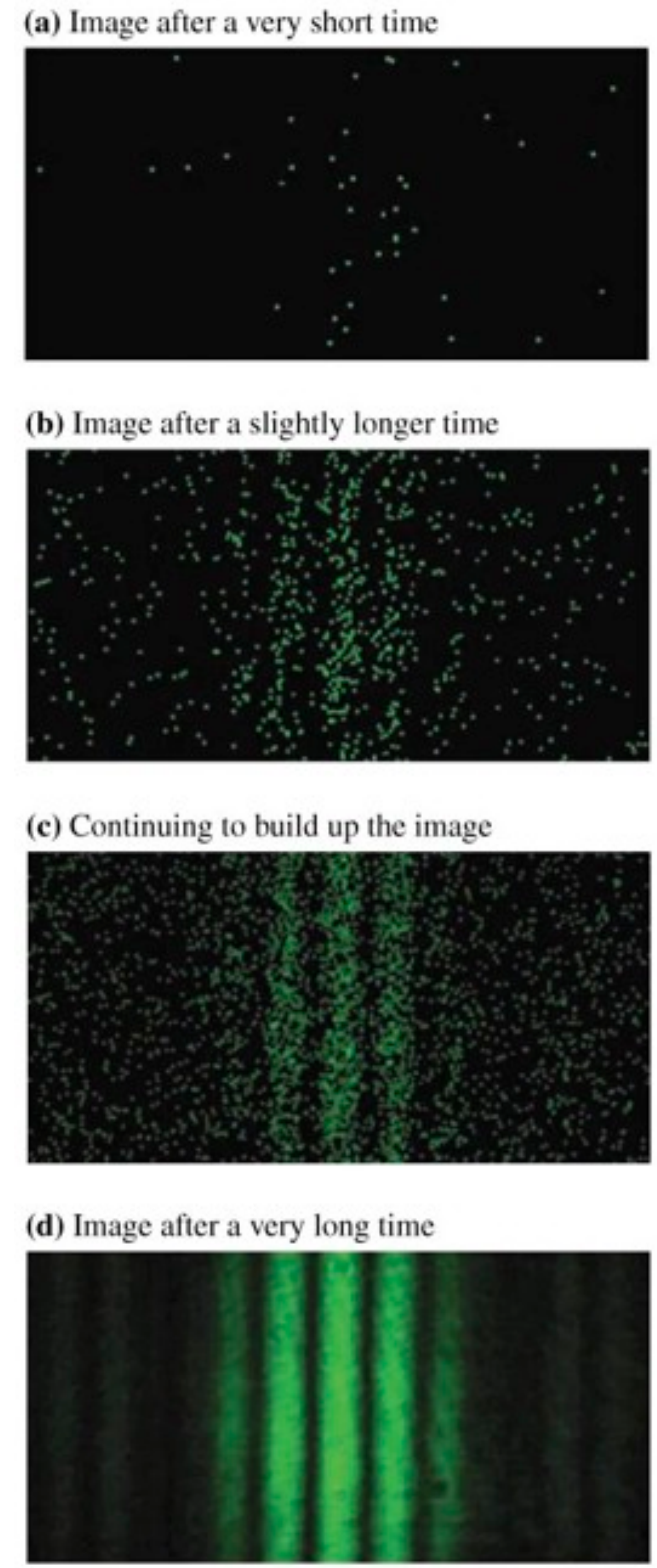
INTERFERENCE !?

electrons behaving as waves ?

waves when traveling, particles on arrival ?

➜ ok, so we have a picture where light and matter have a wave-particle duality

➜ consider the two-slit experiment with a low-intensity source



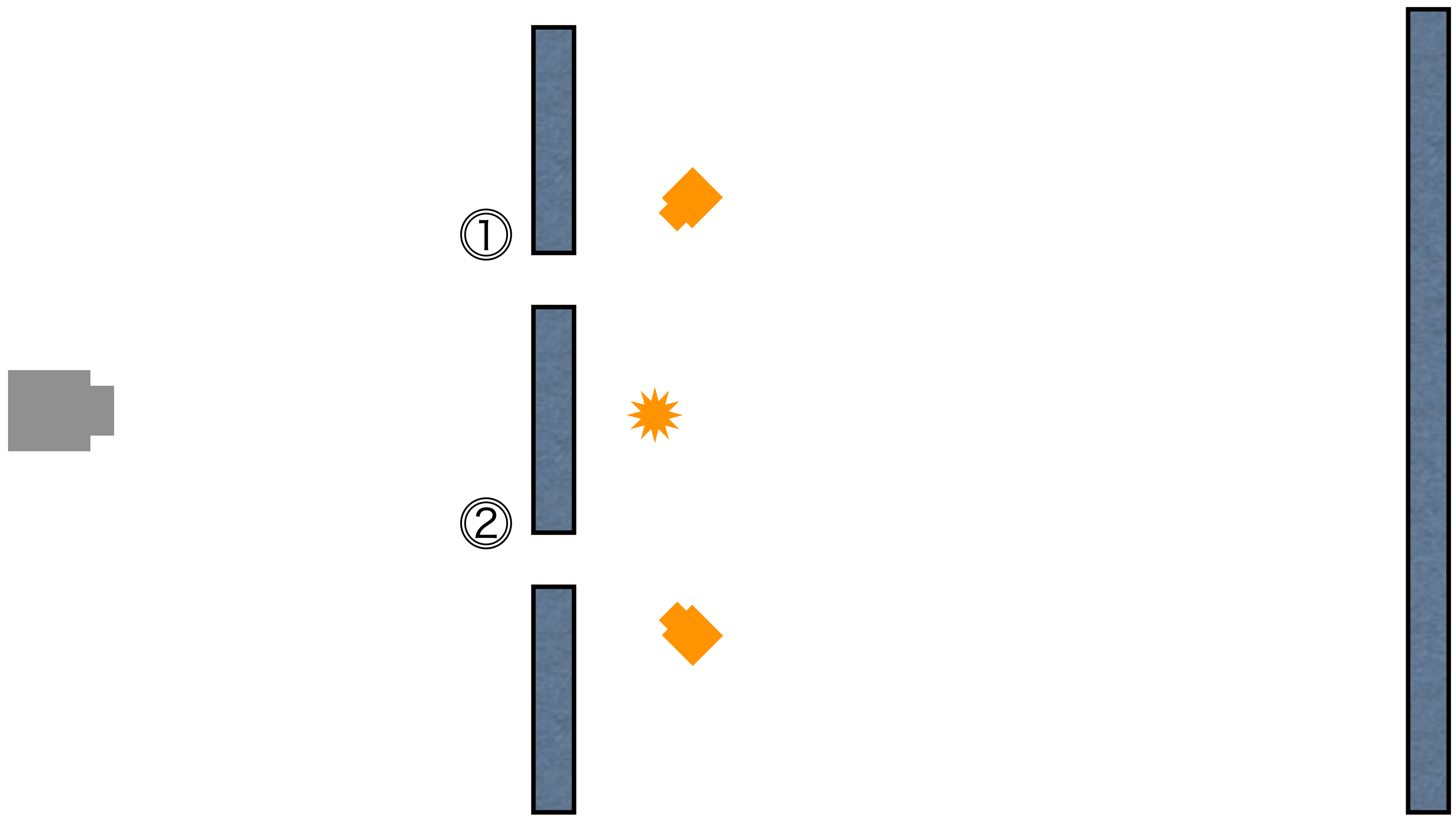
➜ OK, this is really weird, how does a single electron 'interfere' with itself ?

watching the electrons

➜ i'm going to say something obviously crazy :

➜ an electron goes through BOTH slits !

➜ that's easy to disprove, just watch the slits



watching the electrons

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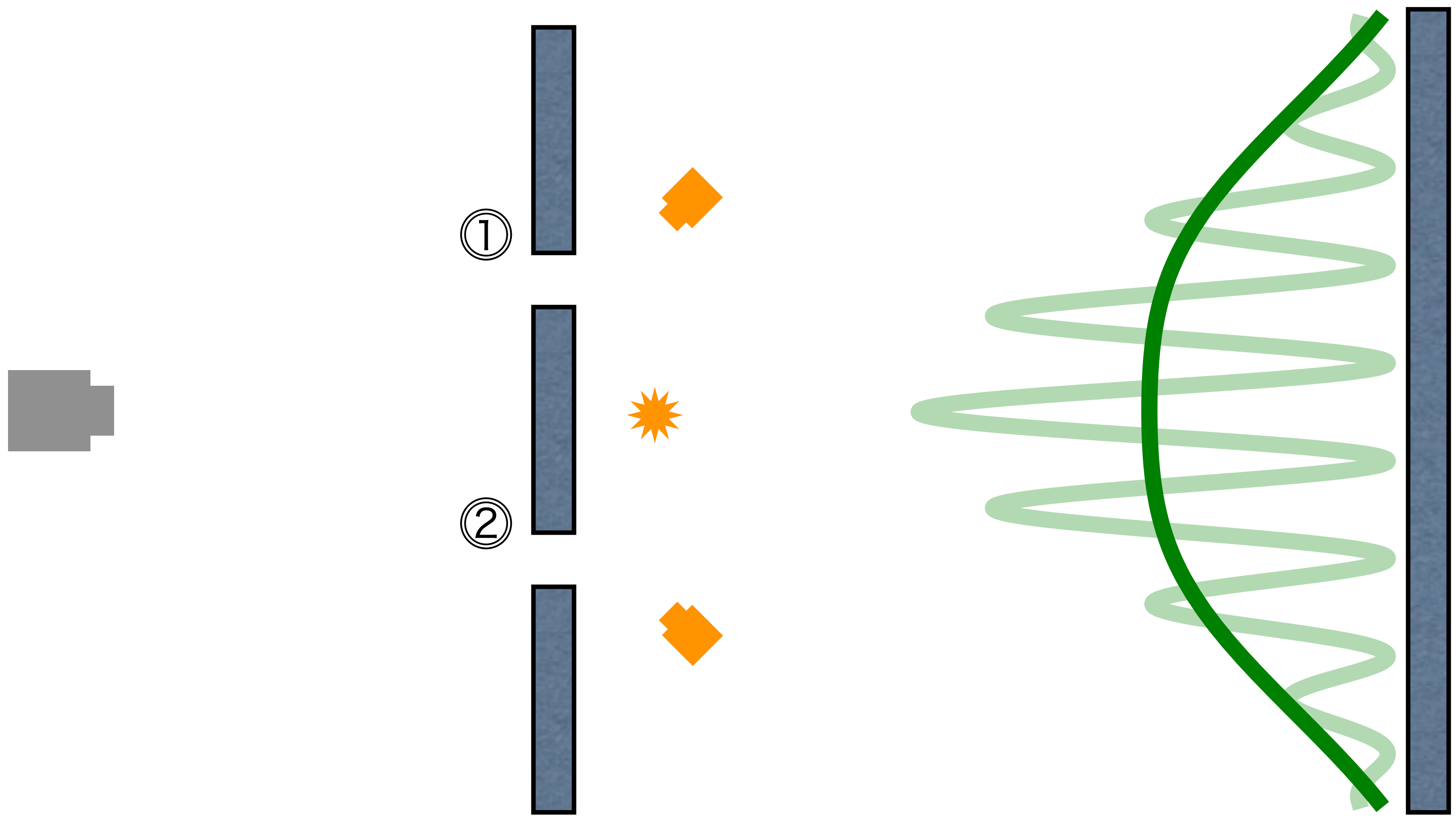


when we detect which hole the electron went through, the interference pattern disappears !

the only explanation is that if you don’t detect which hole the electron went through, **it went through both**

what the .... !?

welcome to quantum physics !

probabilistic though ?

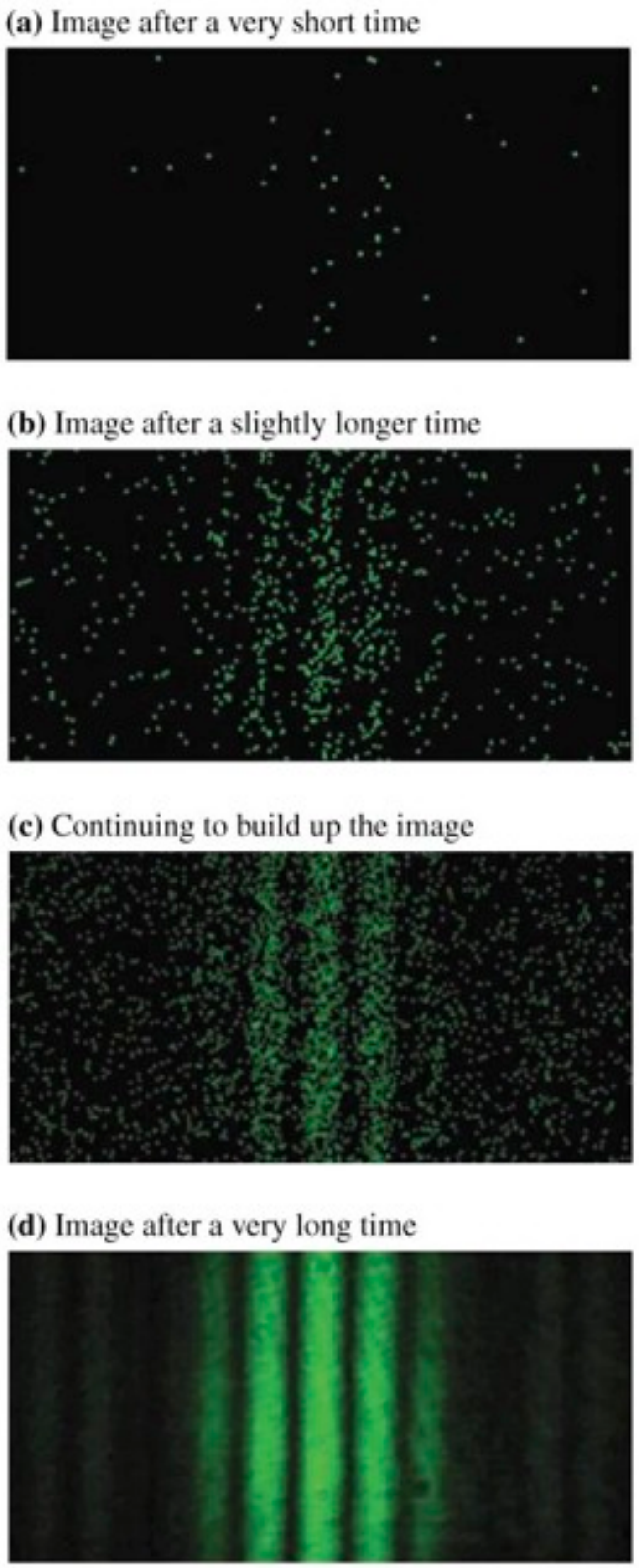
➜ ok, so we have a picture where light and matter have a wave-particle duality

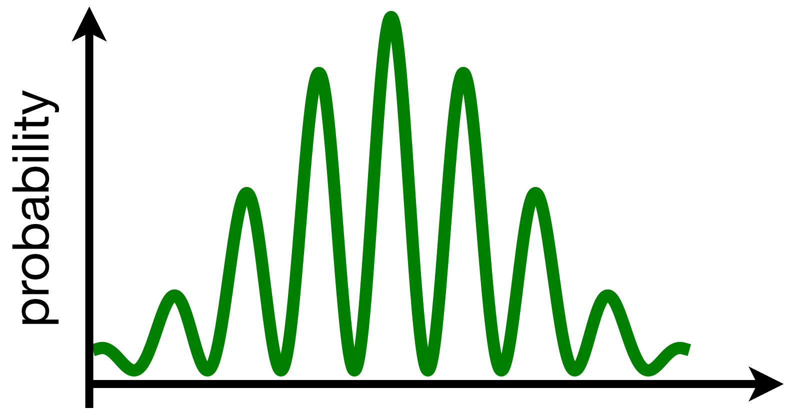
➜ but what does this have to do with physics no longer being “deterministic” ?

➜ consider the two-slit experiment with a low-intensity source

➜ repeating the experiment many times, the first electrons/photons hit at different locations each time

➜ we can only say that there’s a **probability distribution** for the electrons/photons, we can’t predict where any particular electron/photon will end up



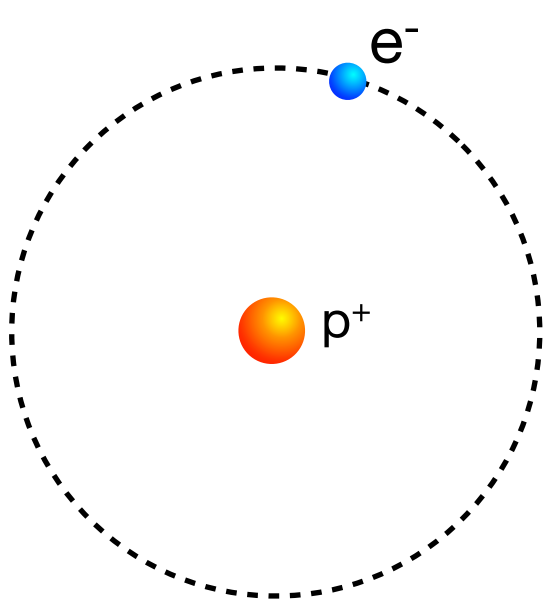


the planetary model of the atom

➜ consider the simplest atom : hydrogen - one electron and one proton

➜ classical electromagnetism - Coulomb's law

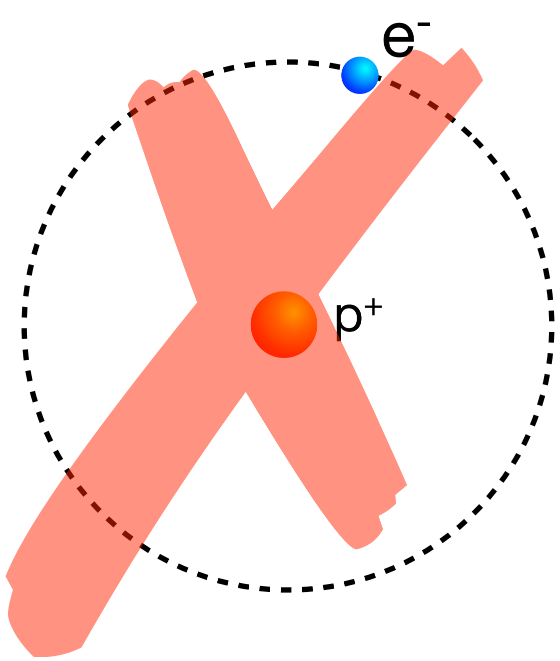
➜ circular motion of the electron around the nucleus ?



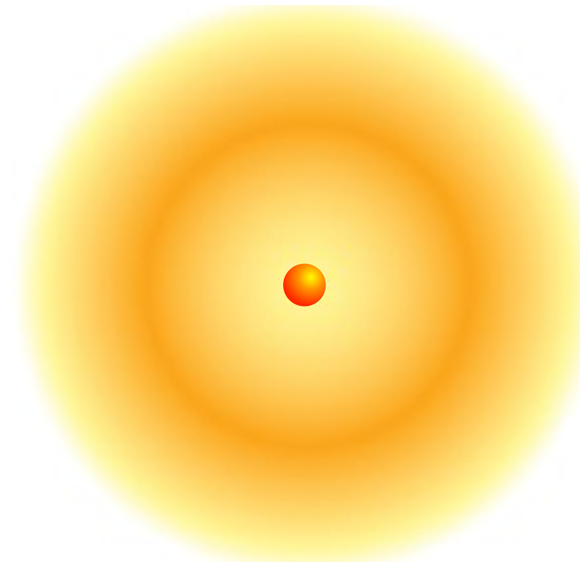
➜ this is a deterministic picture

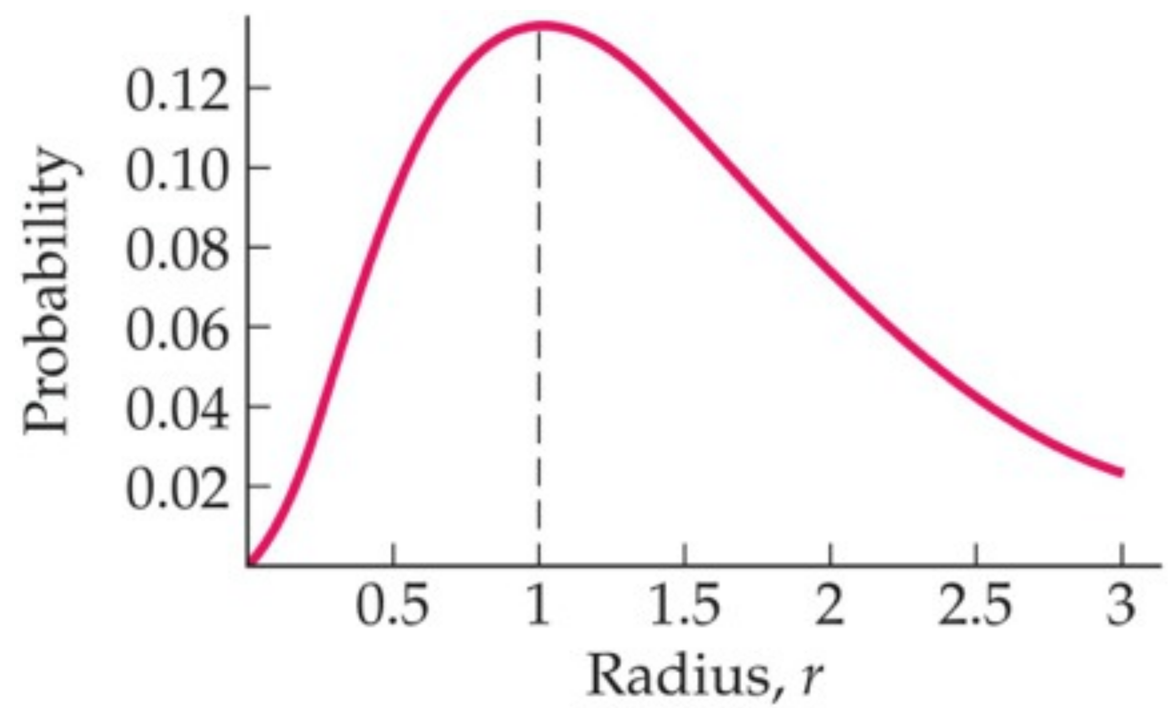
the quantum picture of the atom

➜ consider the simplest atom : hydrogen - one electron and one proton



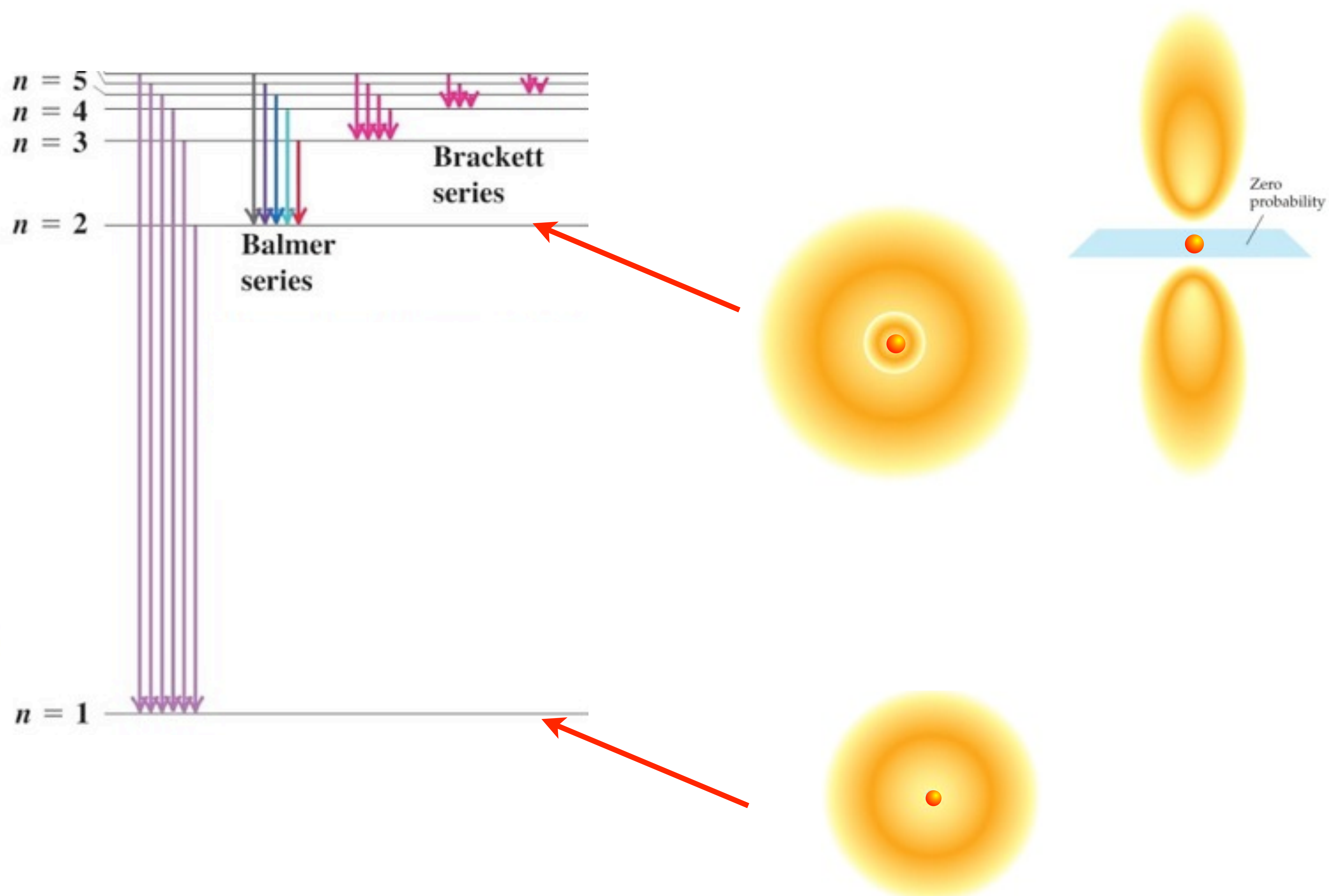
➜ electron **probability distributions**





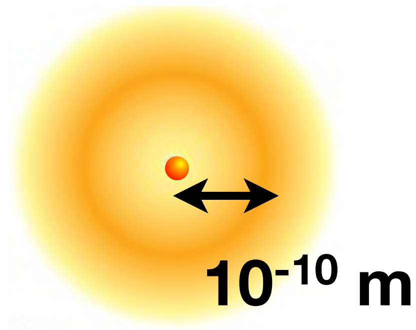
the quantum picture of hydrogen

➜ electron **probability distributions**



the quantum picture of the atom

➜ electron **probability distributions**



typical 'size' of an atom

matter waves

Rev. Mod. Phys., Vol. 60, No. 4, October 1988

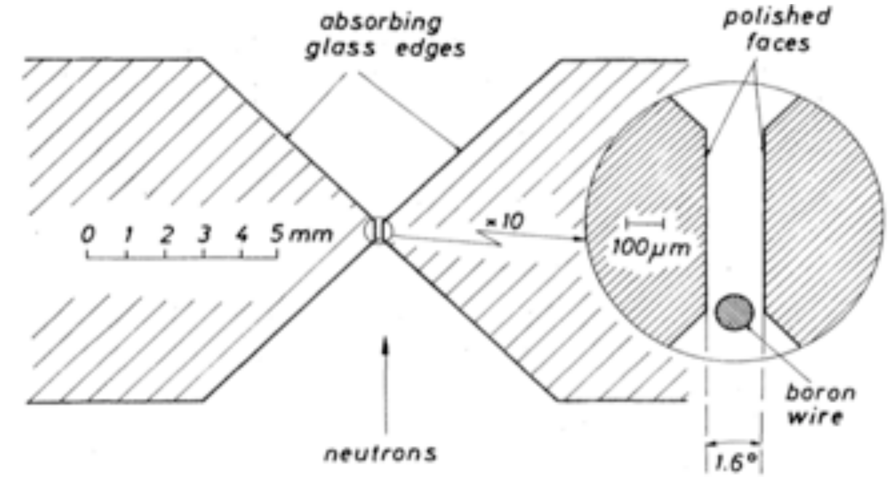
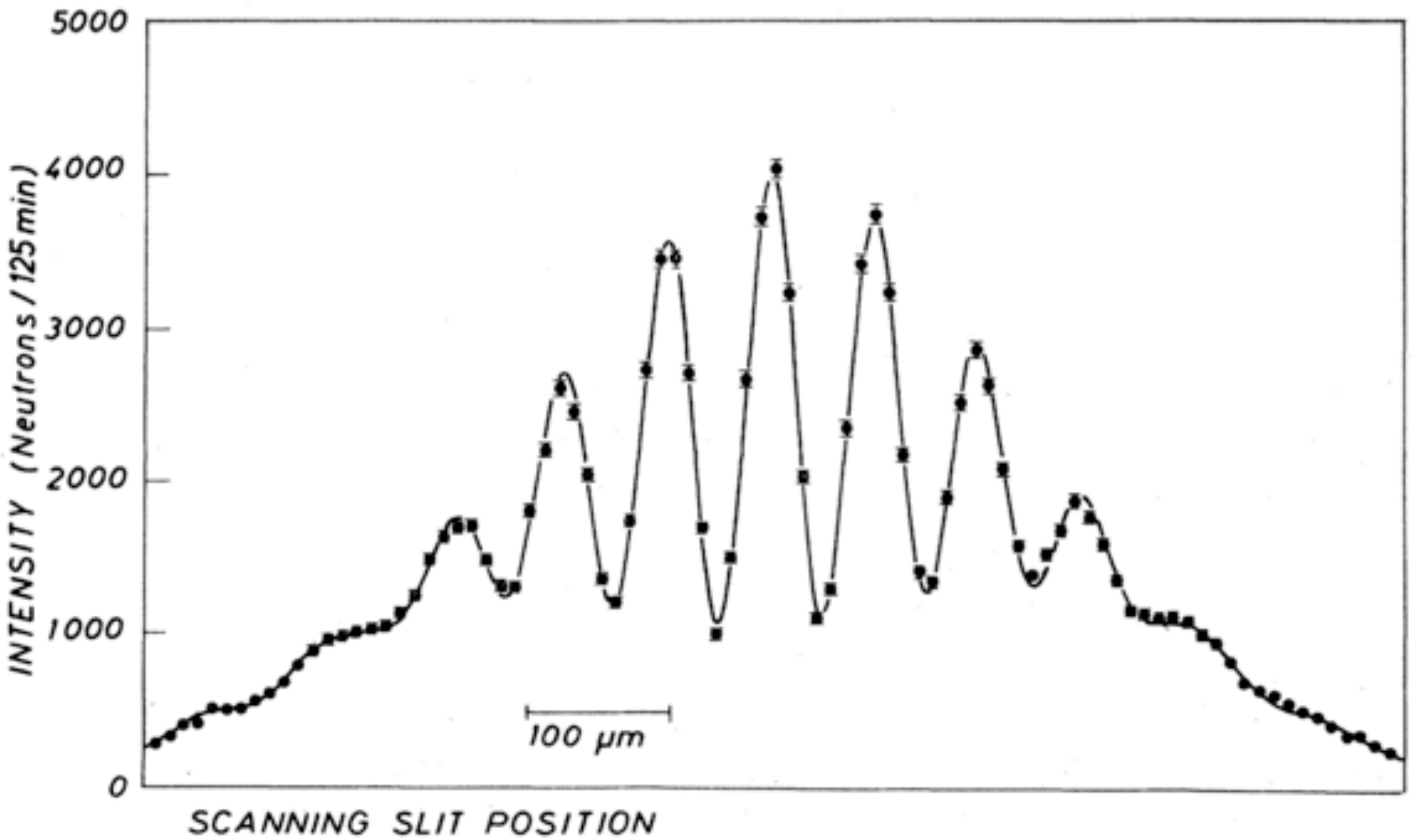


FIG. 6. Horizontal section through the double slit.

➜ beam of cold neutrons on a double slit



$$R = 5.0\,\mathrm{m}$$

$$d = 104\,\mu\mathrm{m}$$

$$\Delta y = R\frac{\lambda}{d}$$

$$\Delta y \sim 90\,\mu\mathrm{m}$$

$$\lambda \sim 1.9 \times 10^{-9}\,\mathrm{m}$$

➜ de Broglie wavelength

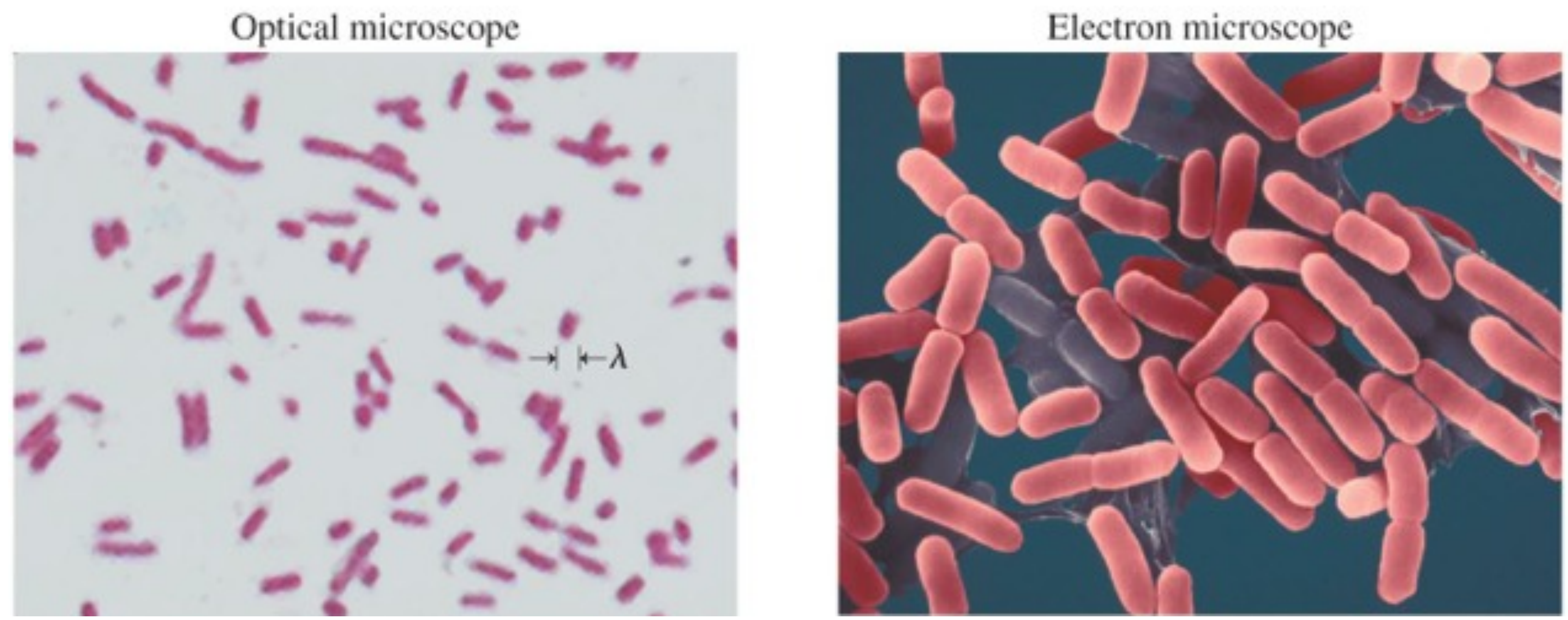
$$p = \frac{h}{\lambda}$$

Planck's constant

$$h = 6.6261 \times 10^{-34}\,\mathrm{Js}$$

matter waves

➜ the electron microscope



nuclear physics

➜ in order to understand the physics of the atomic nucleus, we need a result from special relativity, probably the most famous equation ever

$$E = mc^2$$

➜ this equation states that a particle of mass *m*, even when at rest, should be considered to have an energy of *E*

➜ energy and mass are somewhat interchangeable concepts

➜ we believe that the atomic nucleus is an aggregation of protons and neutrons

proton : positive electrical charge, mass = 1.672621777(74)×10^{-27} kg

neutron : no electrical charge, mass = 1.674927351(74)×10^{-27} kg

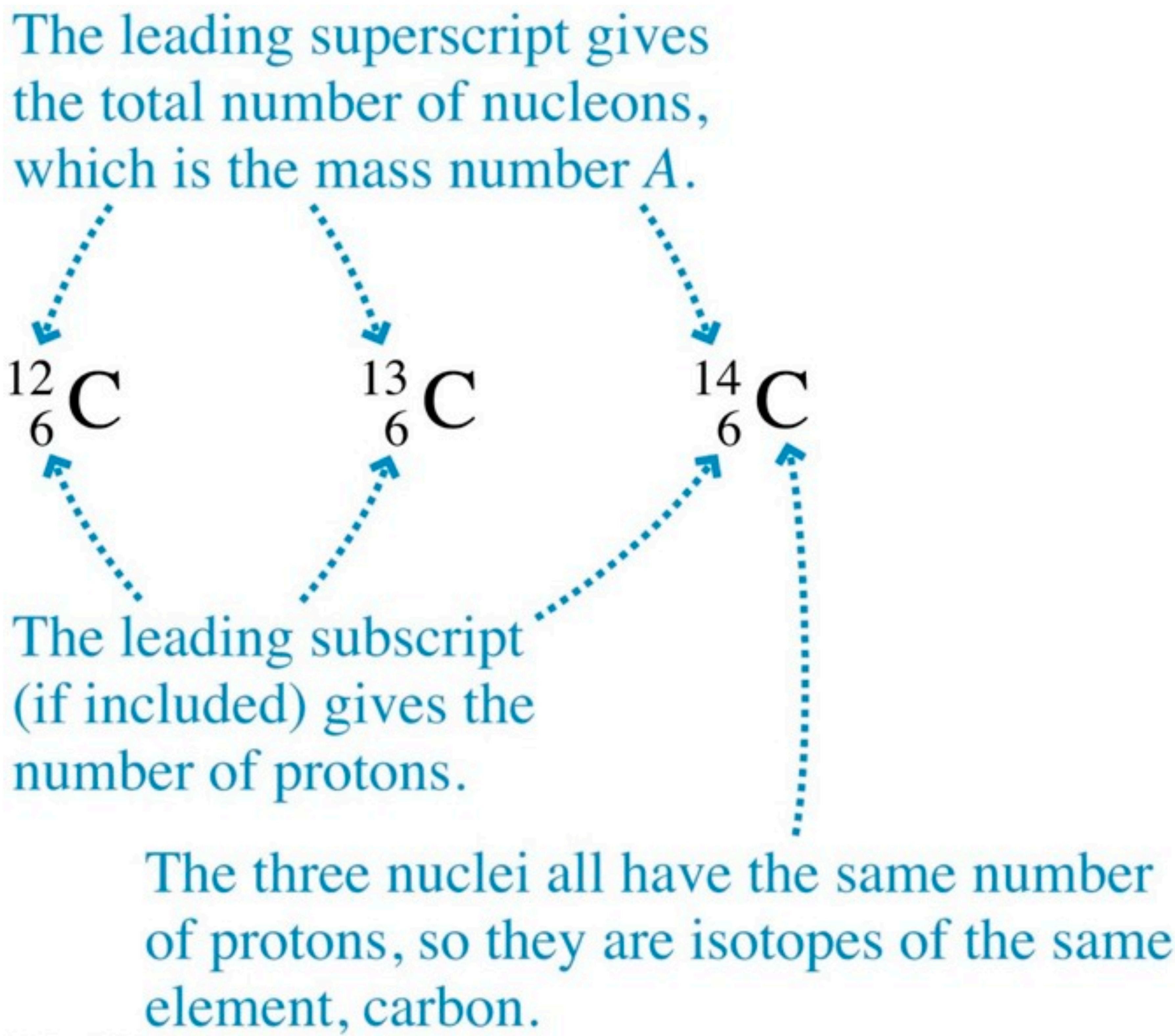
in 'atomic mass units', u

m_p = 1.0072764668 u
m_n = 1.0086649160 u

nuclear physics

➜ notation for nuclei

$${}^{A}_{Z}\mathrm{X}$$



Z = number of protons, "atomic number"

N = number of neutrons, "neutron number"

A* = *N*+*Z = "mass number"

nuclear physics

➜ for all stable nuclei we find that the mass of the nucleus is **LESS** than the summed mass of the protons & neutrons that make it up

➜ e.g. Carbon-12 $^{12}\mathrm{C}$ has 6 protons and 6 neutrons

$$6m_p + 6m_n = 12.0956\,\mathrm{u}$$

$$m(^{12}\mathrm{C}) = 11.9967\,\mathrm{u}$$

$$m(^{12}\mathrm{C}) = 6m_p + 6m_n - E_\mathrm{B}/c^2$$

"binding energy" $E_\mathrm{B}/c^2 = 0.0989389\,\mathrm{u}$

$$E_\mathrm{B} = 92.161\,\mathrm{MeV}$$

nuclear physics features scales from keV to MeV

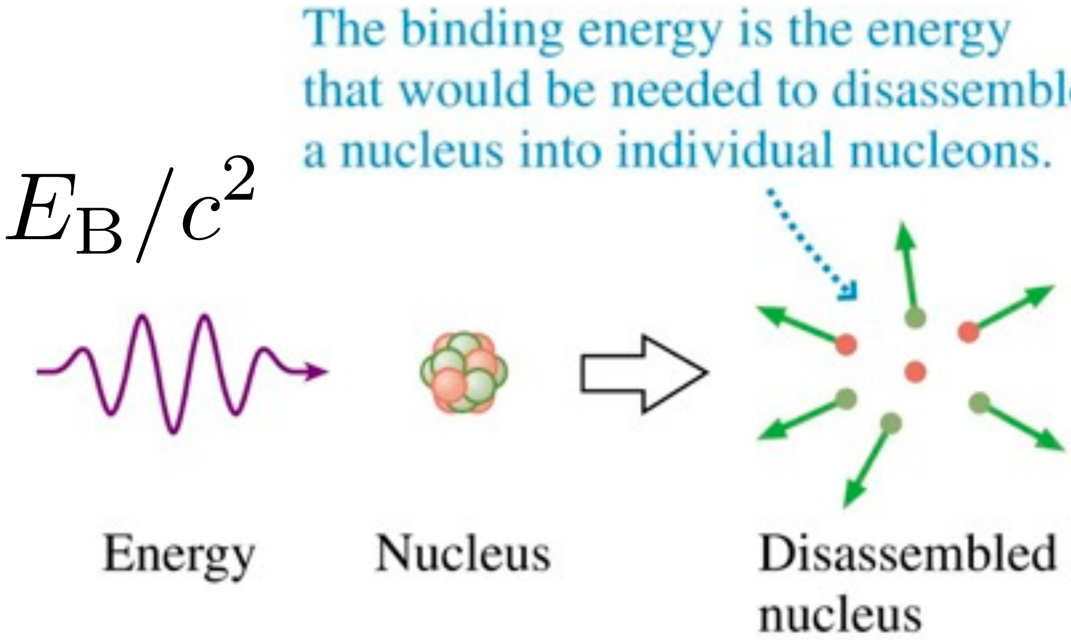
nuclear physics

➜ for all stable nuclei we find that the mass of the nucleus is **LESS** than the summed mass of the protons & neutrons that make it up

➜ why doesn't the nucleus fall apart into protons and neutrons ?

➜ it can't - wouldn't conserve energy

$$m({}^{A}_{Z}\mathrm{X}) = Zm_p + (A-Z)m_n - E_{\mathrm{B}}/c^2$$



➜ but the protons are all positively charged - repelling each other !

➜ must be some other force at work, holding everything together, than is stronger than Coulomb's law

➜ **the 'strong' nuclear force**

the strong nuclear force

➜ experimentally determined properties of nuclei suggest that the strong nuclear force

➜ is equally strong and attractive for protons and neutrons

➜ has a short range, it is much stronger than Coulomb's law only for distances ~ 10^{-15} m

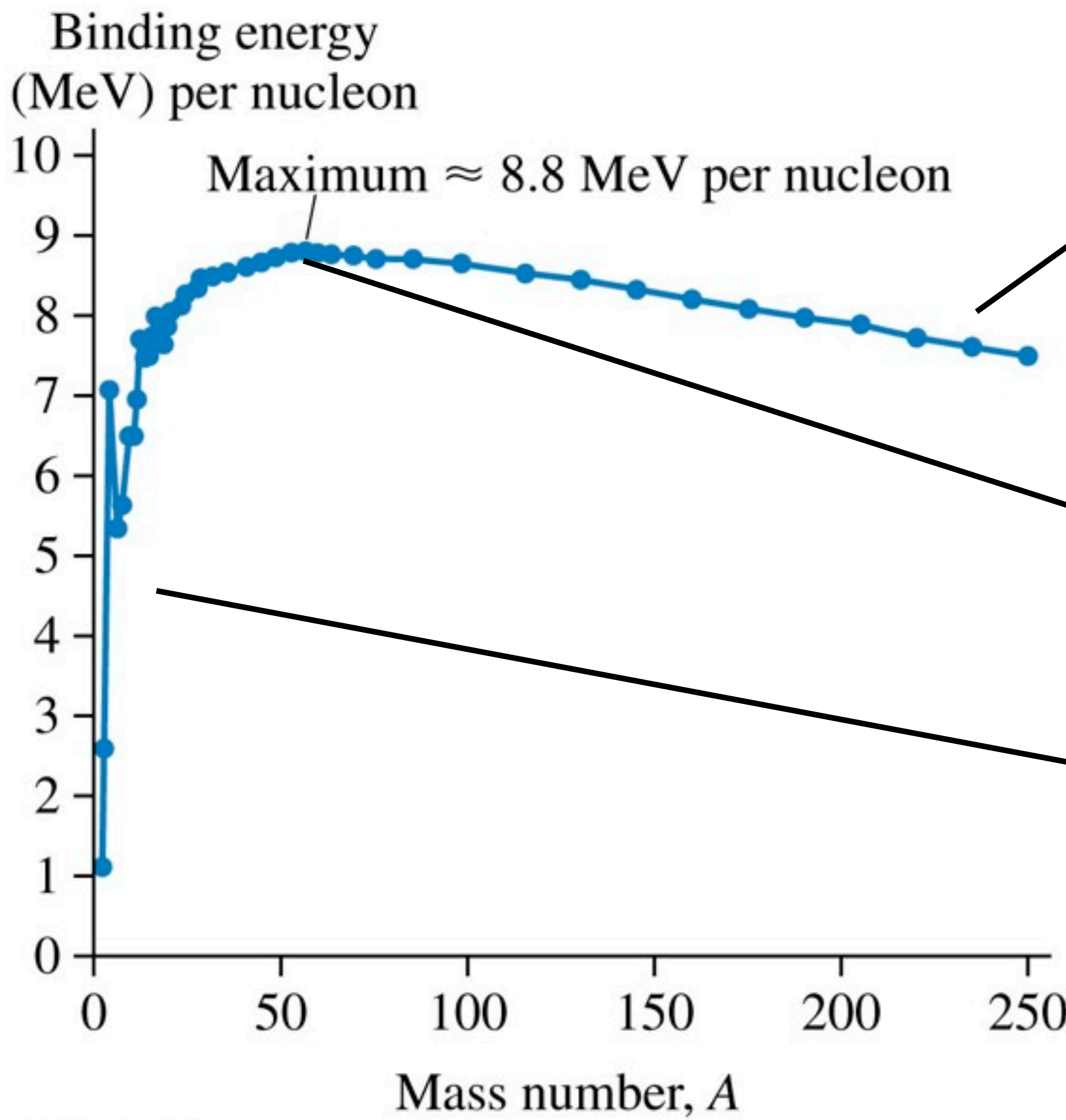
➜ the short range of the strong nuclear force causes the nucleus to be much smaller than the atom

$$R_{\mathrm{atom}} \sim 10^{-10}\,\mathrm{m}$$

$$R_{\mathrm{nucl.}} \sim 10^{-15}\,\mathrm{m}$$

nuclear binding energies

➜ a graph of binding energy per nucleon



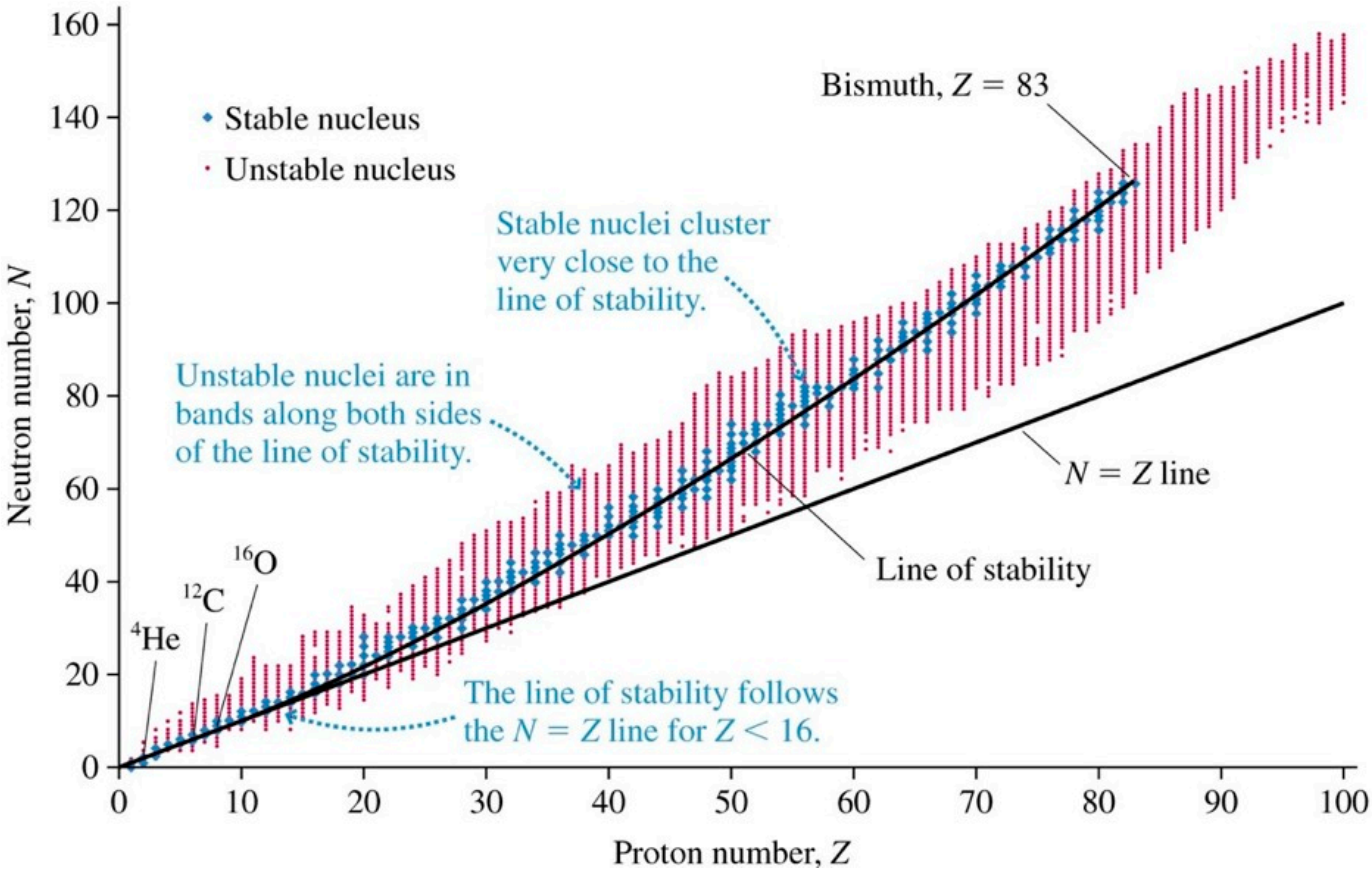
larger nuclei are less tightly bound

somewhere around Iron we have the tightest binding

smaller nuclei are less tightly bound

any nucleus ?

➜ not all possible combinations of neutrons and protons are stable nuclei



nuclear decay

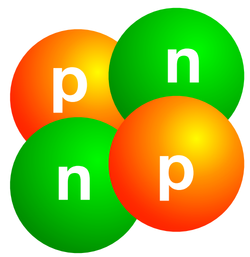
➜ what happens to the unstable nuclei ?

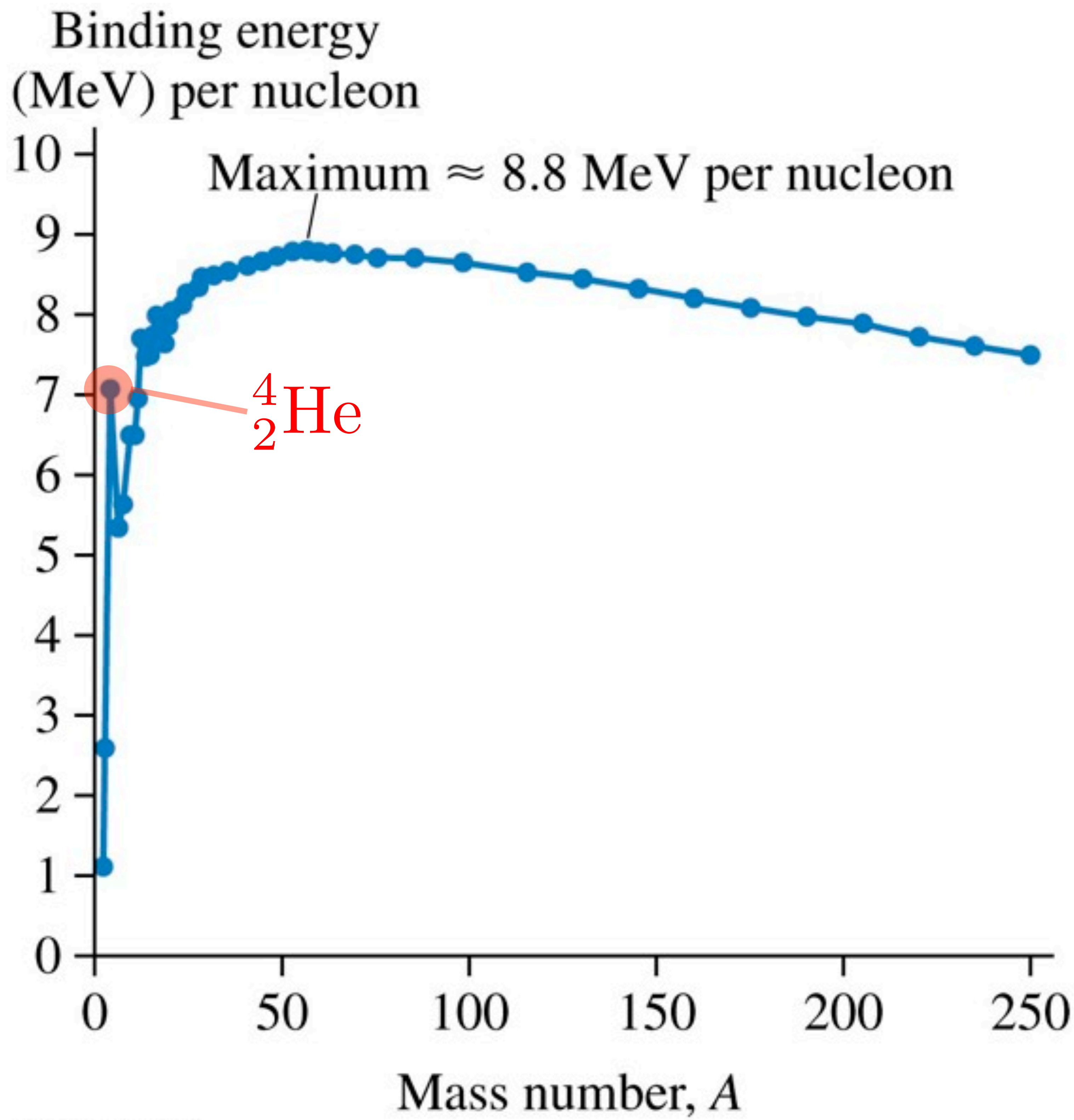
➜ they undergo 'decay' by emitting particles and transforming into other nuclei

➜ lots of ways in which this can happen, focus on three important ways

alpha decay

➜ the nucleus $^4_2\mathrm{He}$ is very tightly bound and stable - sometimes called an α-particle





alpha decay

➜ the nucleus $^{4}_{2}\mathrm{He}$ is very tightly bound and stable - sometimes called an α-particle

➜ many unstable nuclei decay by emitting an alpha particle

$$^{A}_{Z}\mathrm{X} \rightarrow \, ^{A-4}_{Z-2}\mathrm{Y} + \alpha$$

➜ alpha particles typically do not penetrate far into matter

beta decay

➜ the neutron is actually an unstable particle - a lone neutron will decay within 15 minutes

$$n \rightarrow p^+ + e^- + \bar{\nu}_e$$

➜ this conserves energy :

```
mn = 1.0086649160 u
-------------------
mp = 1.0072764668 u
me = 0.0005485799 u
mν = 0 ?
```

+ kinetic energy

➜ placed in a nucleus, a neutron can become stable, or nearly stable

➜ but occasionally some nuclei do decay by beta emission

$${}^{A}_{Z}\mathrm{X} \rightarrow {}^{\;\;A}_{Z+1}\mathrm{Y} + e^- + \bar{\nu}_e$$

➜ beta particles typically penetrate further into matter than alpha particles

gamma decay

➜ in the same way that an atom can have excited energy states, so can a nucleus

➜ without changing the number of protons and neutrons, a nucleus can ‘de-excite’ by emitting a gamma particle

$$ {}^{A}_{Z}\mathrm{X}^{\star} \to {}^{A}_{Z}\mathrm{X} + \gamma $$

➜ a gamma particle is just a photon with very short wavelength (high energy)

➜ gamma particles typically penetrate matter easily, usually need large blocks of lead or concrete to stop them

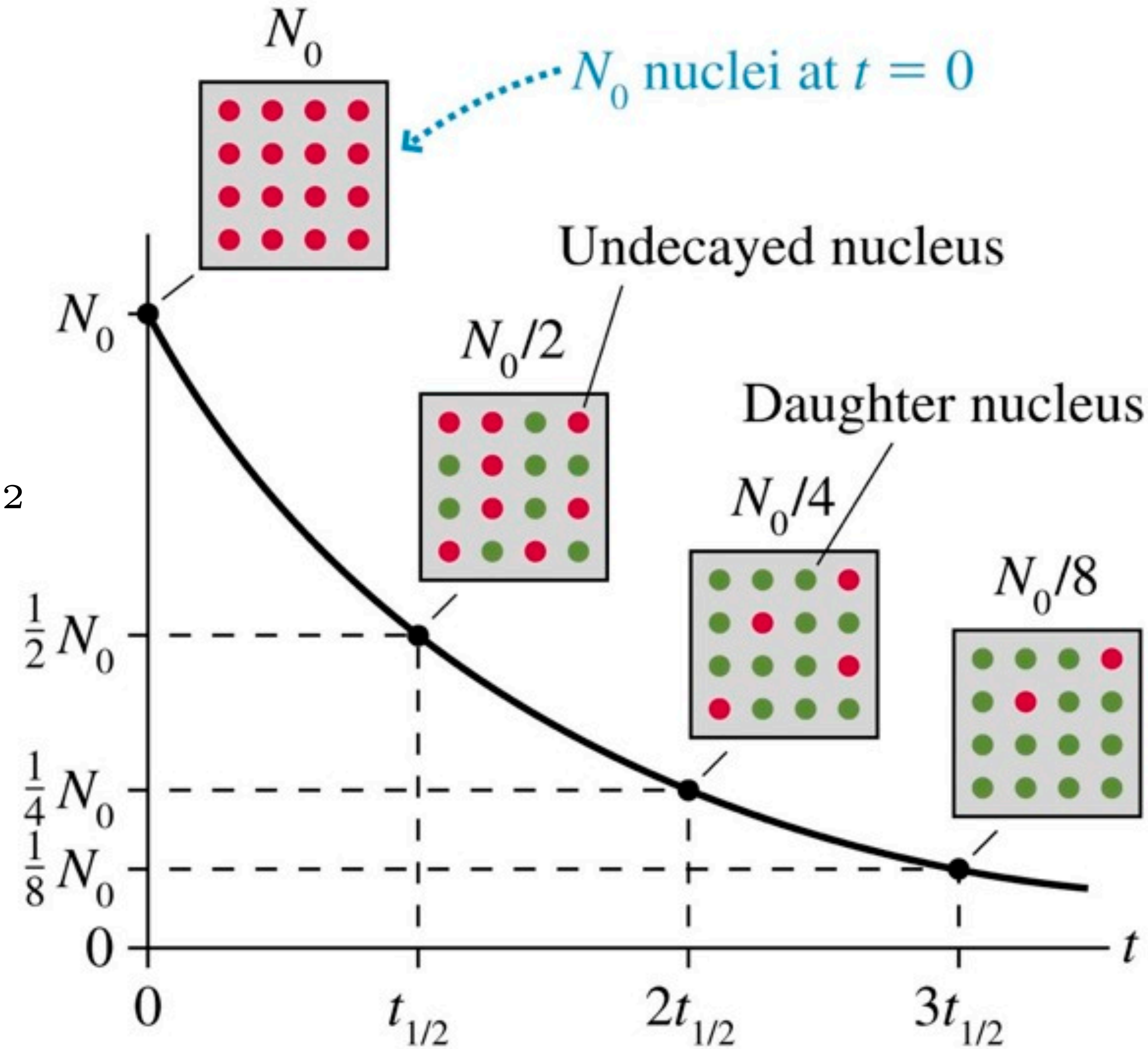
rates of decay

➜ nuclei are found to decay exponentially (on the average)

$$N = N_0 \, e^{-\lambda t}$$

➜ can be expressed in terms of a 'half-life', $t_{1/2}$

$$N = N_0 \left(\tfrac{1}{2}\right)^{t/t_{1/2}}$$



➜ but we can't predict when any particular nucleus will decay, only the probability

rates of decay

rates of decay

rates of decay

$$t = t_{1/2}$$

N_0=36, should be 18 remaining on average

1. 17

1. 14

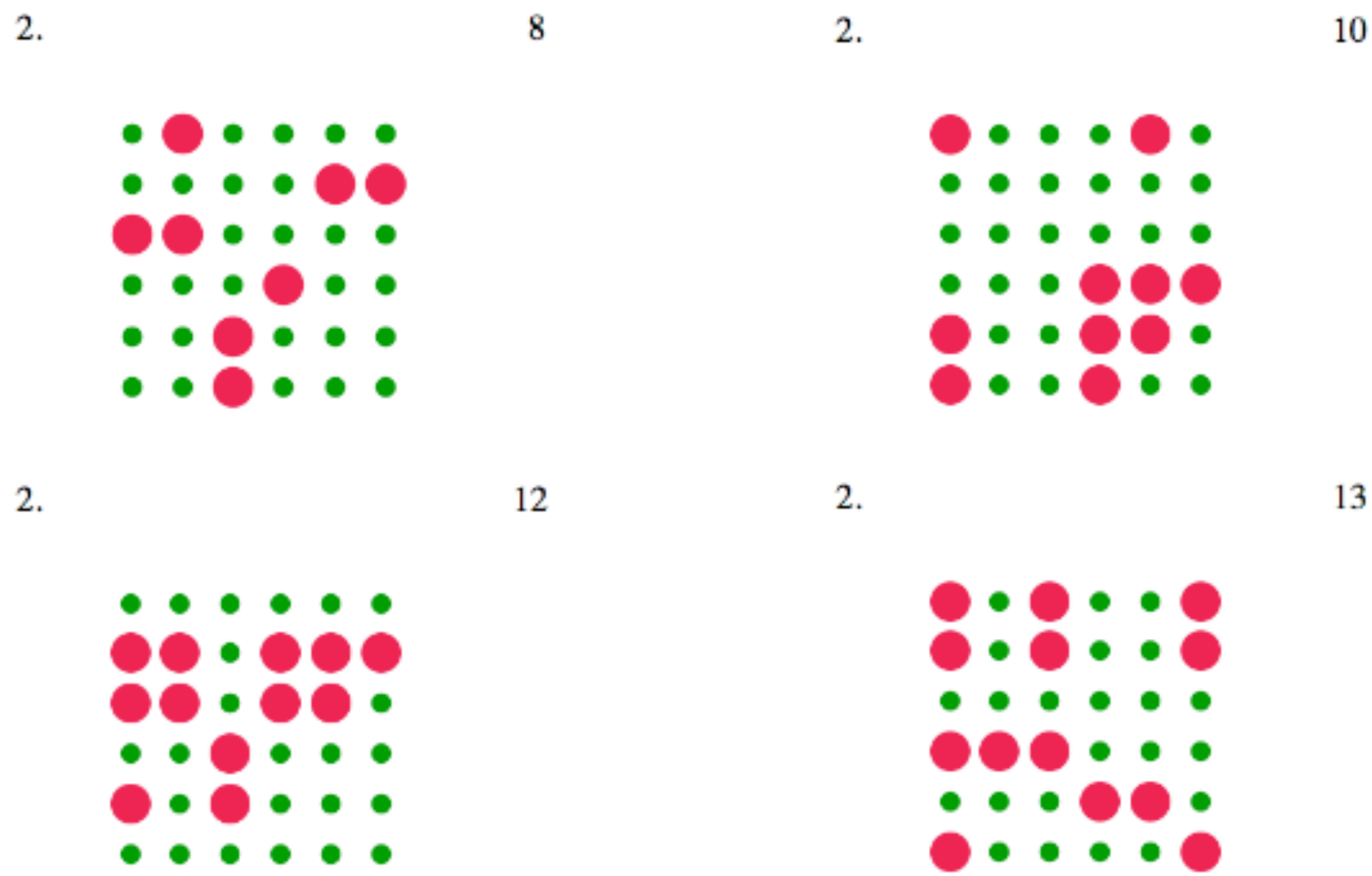
1. 20

1. 22

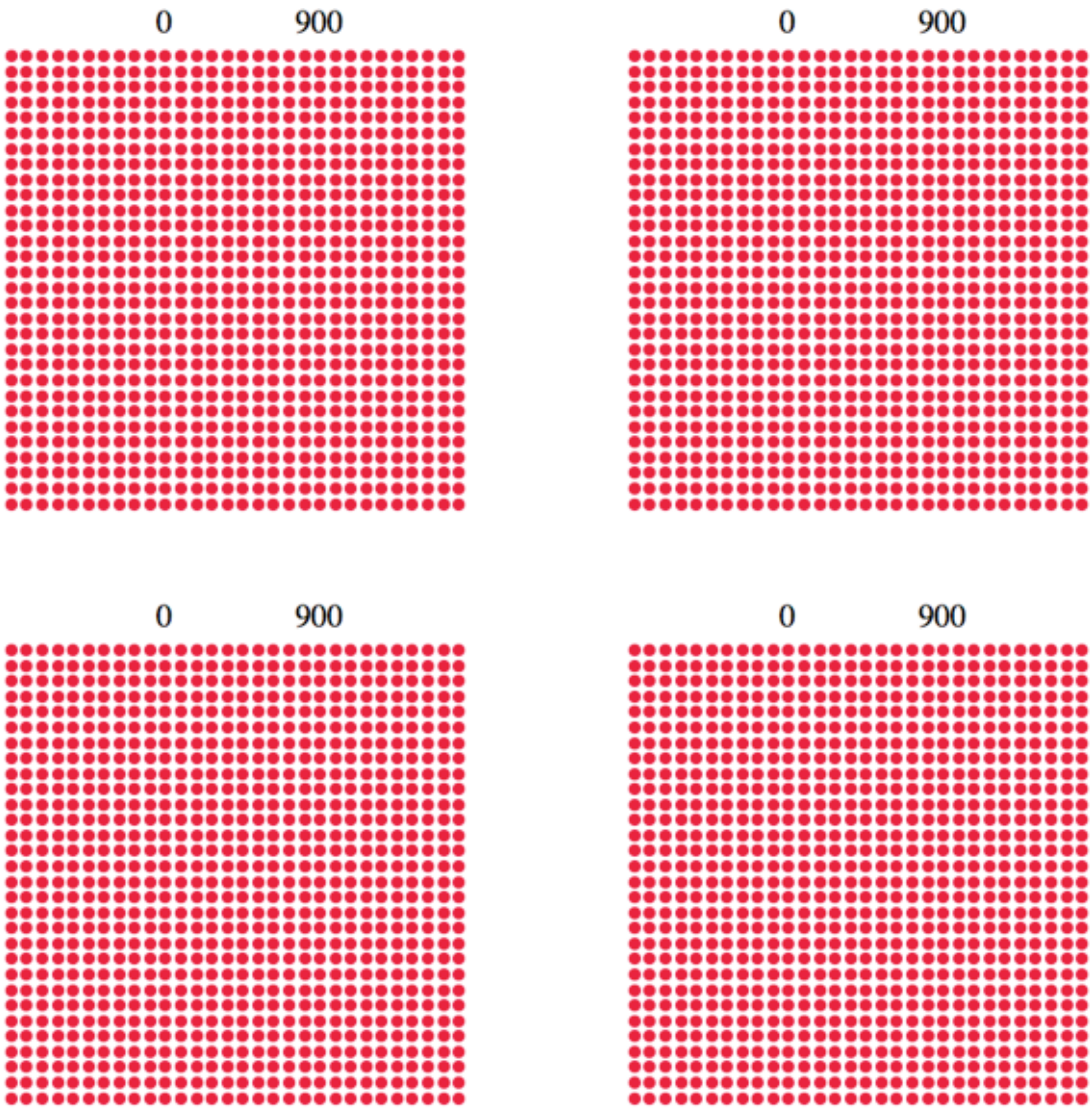
rates of decay

$t = 2t_{1/2}$

N_0=36, should be 9 remaining on average

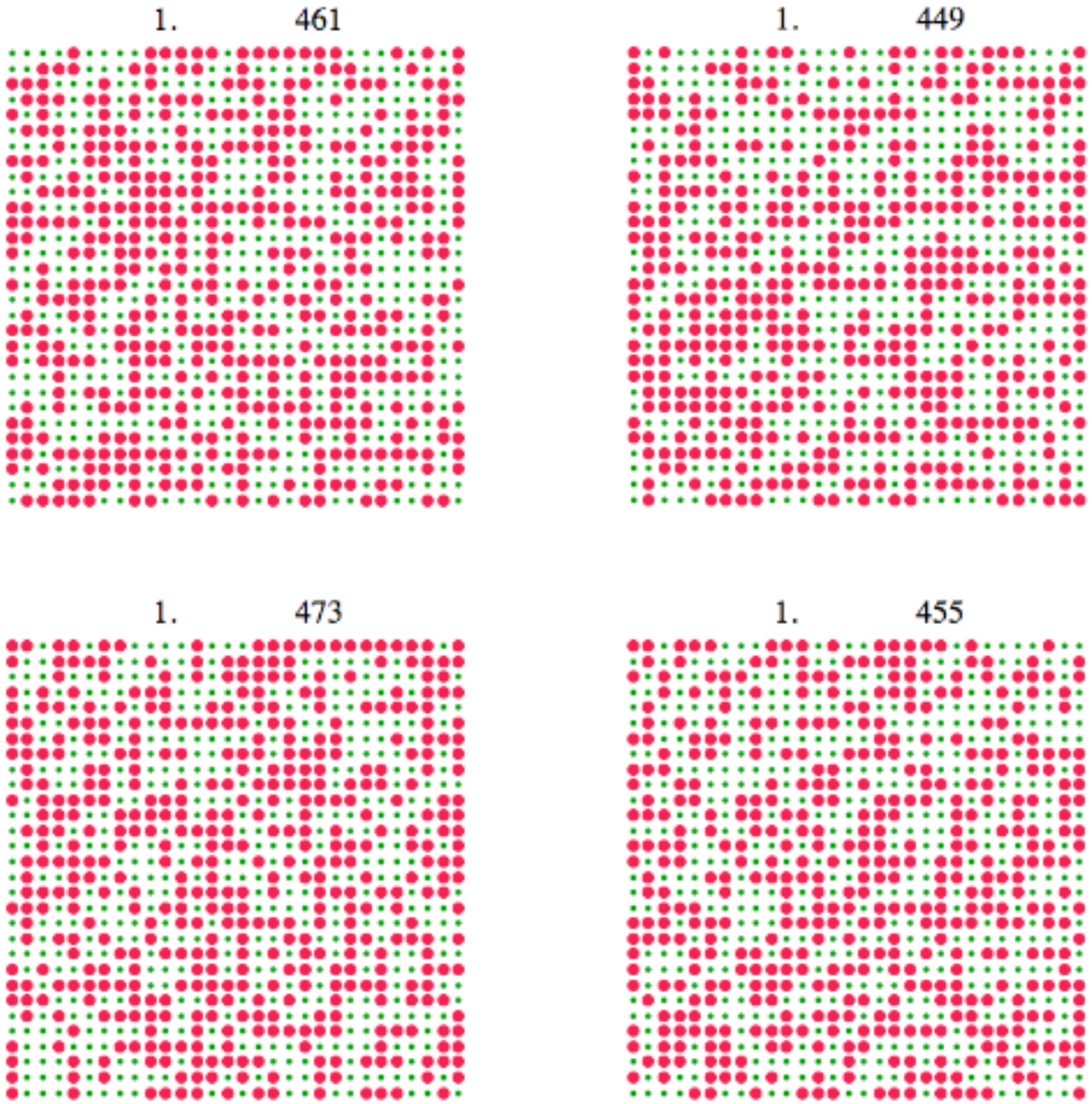


rates of decay



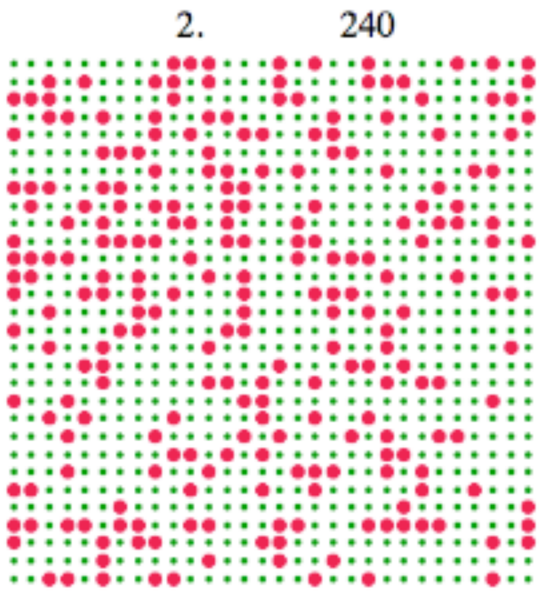
rates of decay

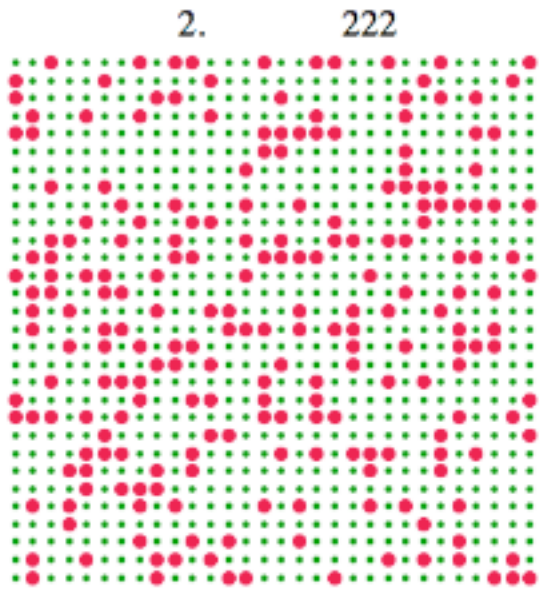
$t = t_{1/2}$ N_0=900, should be 450 remaining on average

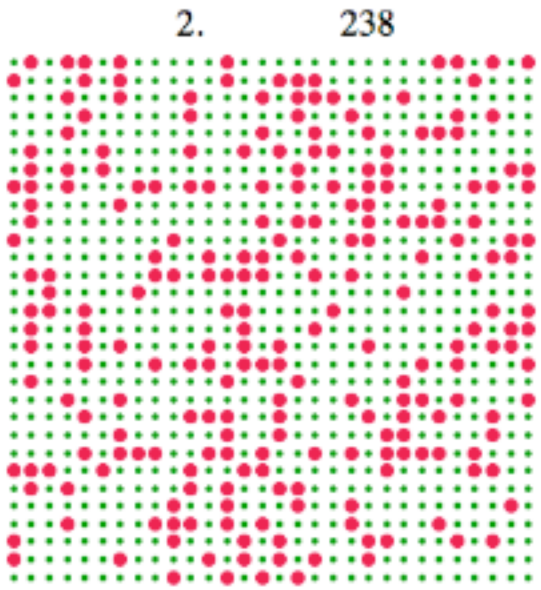


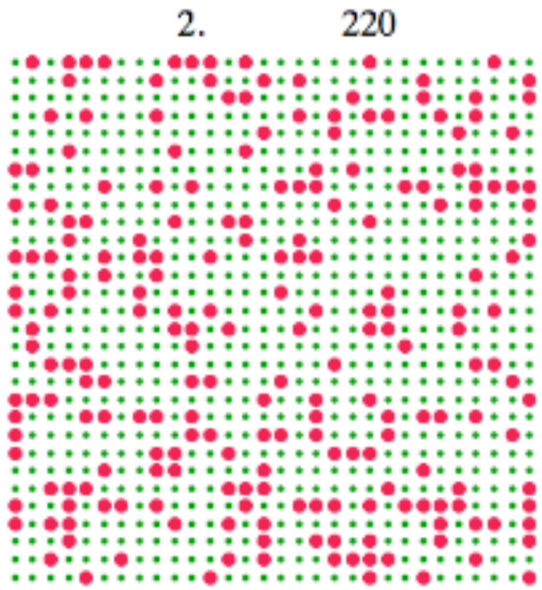
rates of decay

$t = 2t_{1/2}$ N_0=900, should be 225 remaining on average









nuclear fission

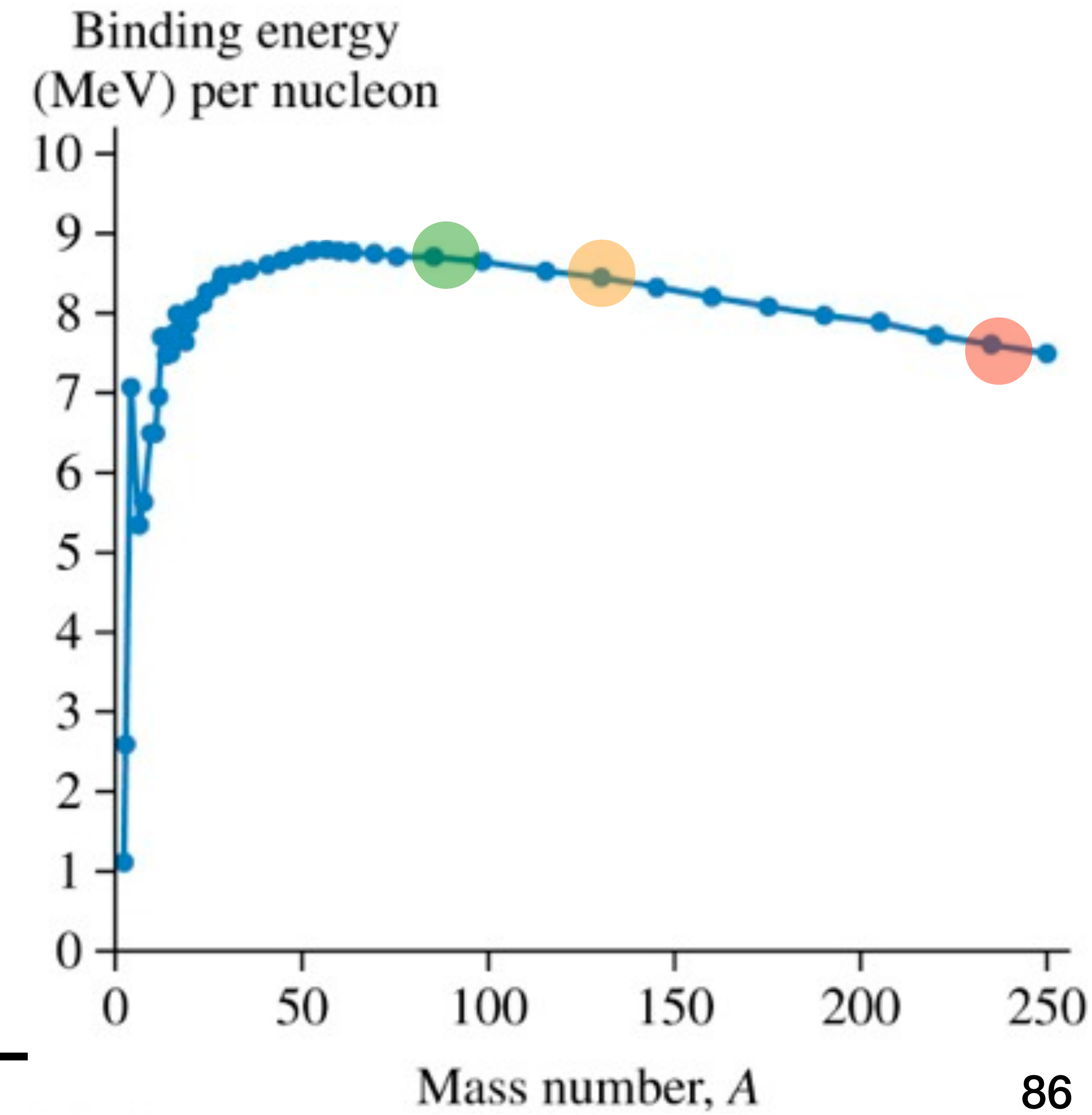
➜ when nuclei split into two or more smaller nuclei

➜ **spontaneous fission** - an unstable nucleus splits without external stimulus

➜ **induced fission** - an nucleus splits after absorbing a neutron

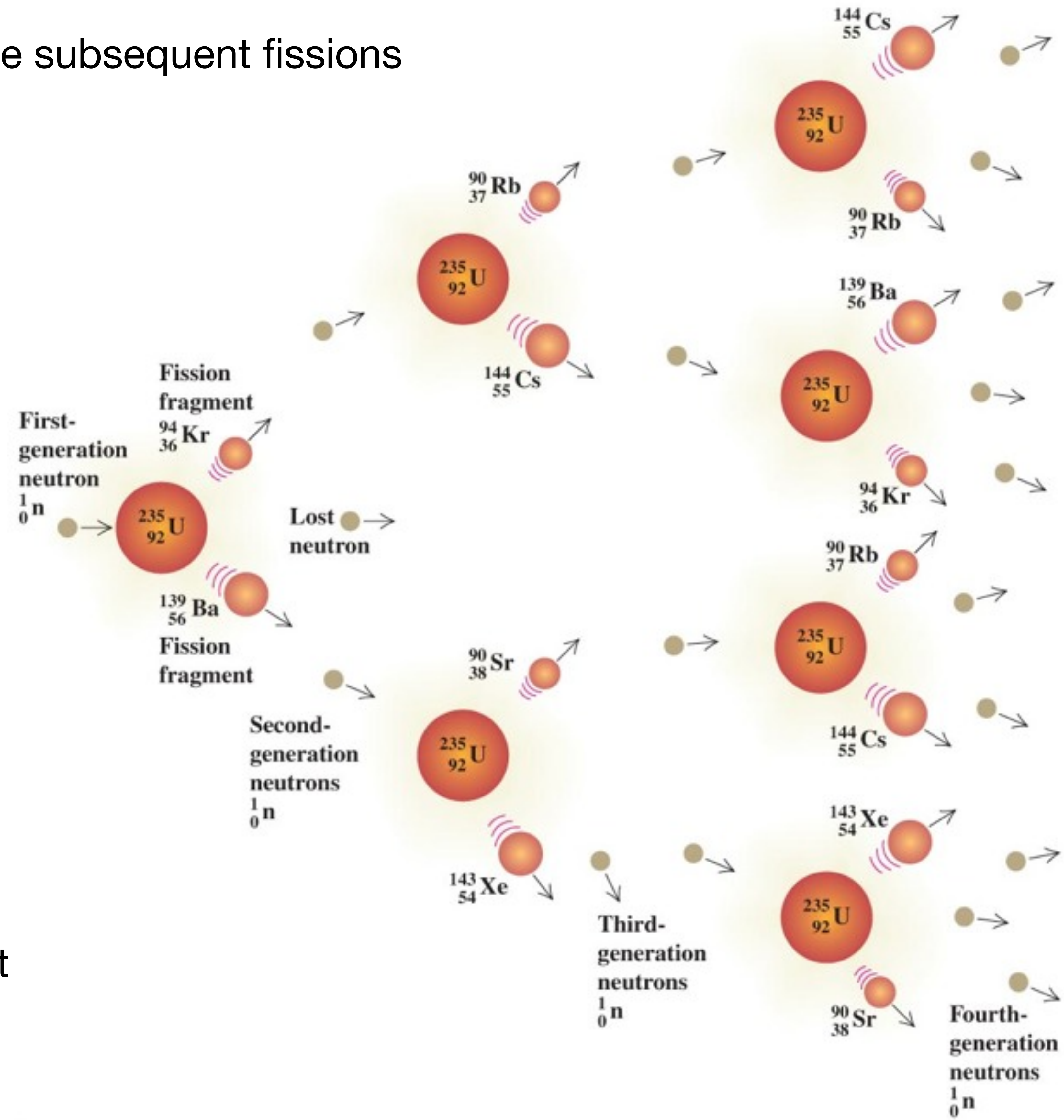
e.g. $^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{94}_{36}\mathrm{Kr} + {}^{139}_{56}\mathrm{Ba} + 3\,^{1}_{0}\mathrm{n}$

energy released as kinetic energy



nuclear fission - a chain reaction

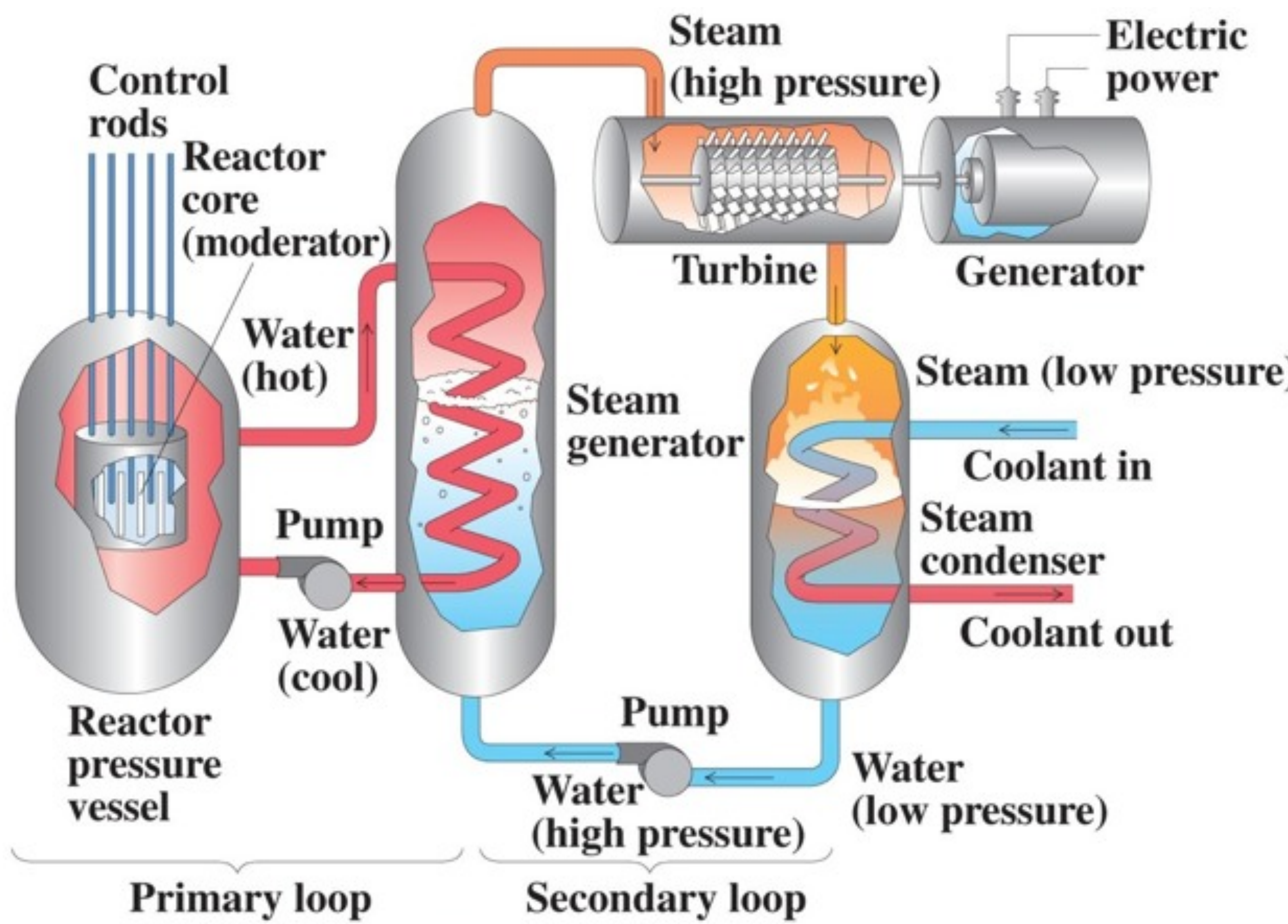
➜ released neutrons can induce subsequent fissions



turn uranium into heat
- power generation
- or a bomb

nuclear fission - a chain reaction

➜ released neutrons can induce subsequent fissions



turn uranium into heat
- power generation

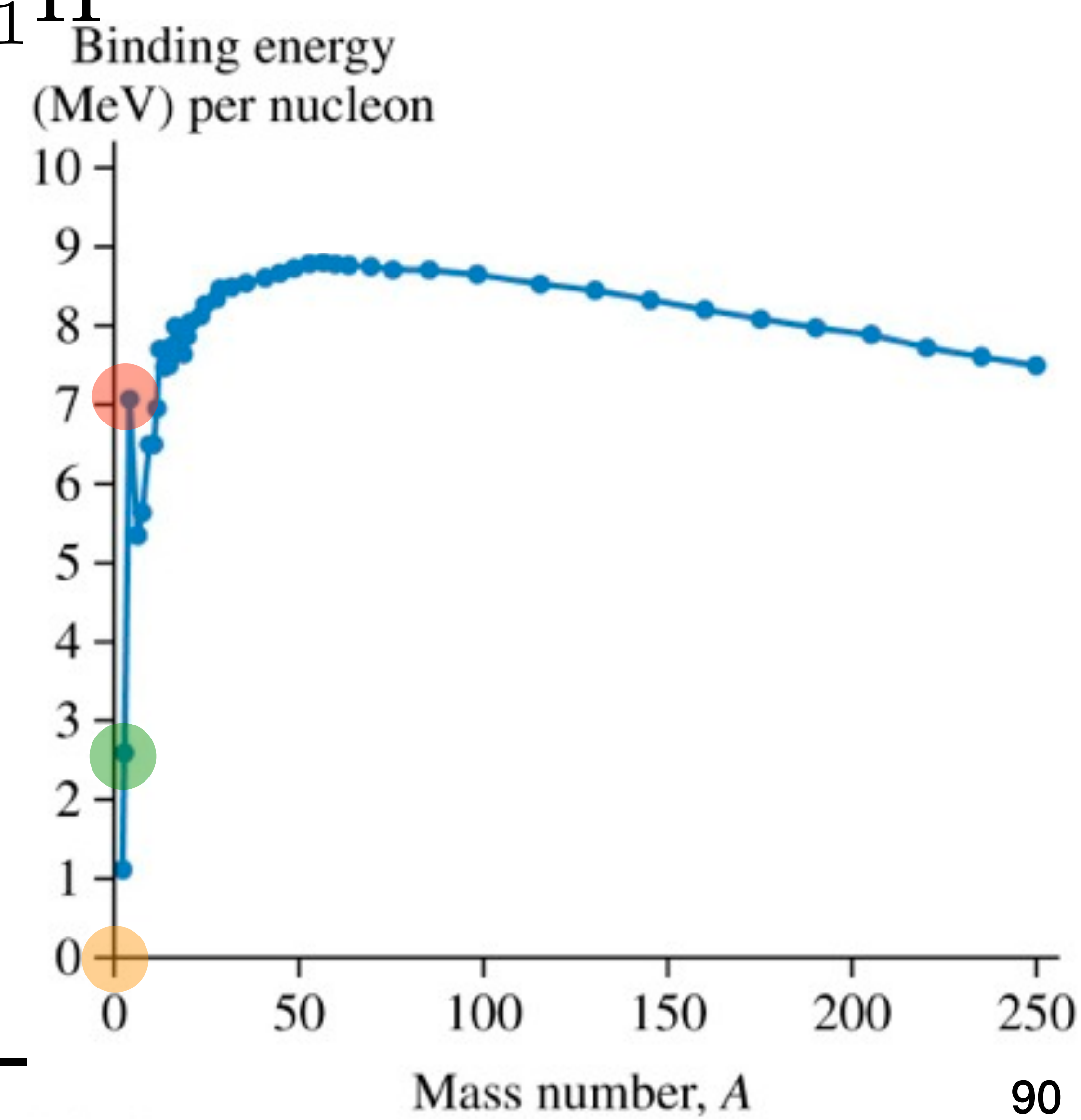
nuclear fusion

➜ when light nuclei are forced together, they can sometimes **fuse** into a heavier nucleus

e.g. $${}^1_1\mathrm{H} + {}^1_1\mathrm{H} \to {}^2_1\mathrm{H} + e^+ + \nu_e$$

$${}^1_1\mathrm{H} + {}^2_1\mathrm{H} \to {}^3_2\mathrm{He} + \gamma$$

$${}^3_2\mathrm{He} + {}^3_2\mathrm{He} \to {}^4_2\mathrm{He} + {}^1_1\mathrm{H} + {}^1_1\mathrm{H}$$



energy released as kinetic energy

nuclear fusion

➜ when light nuclei are forced together, they can sometimes **fuse** into a heavier nucleus

e.g. $${}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \to {}^{2}_{1}\mathrm{H} + e^{+} + \nu_e$$

$${}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \to {}^{3}_{2}\mathrm{He} + \gamma$$

$${}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \to {}^{4}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H}$$

➜ the positively charged nuclei have to be **forced** together, overcoming the electrostatic repulsion

➜ can occur if the nuclei are moving fast

➜ a superheated plasma ?

➜ inside a star ?

➜ this is how our sun generates energy

power generation from 1 kg of fuel

➜ suppose we have :

  ➜ 1 kg of carbon to burn (and all the oxygen we need)

  ➜ 1 kg of uranium to fission

  ➜ 1 kg of hydrogen to fuse (and the means to get them to fuse)

    ➜ how much energy can we get out in principle from each process ?

power generation from 1 kg of fuel

➜ suppose we have :

➜ 1 kg of carbon to burn (and all the oxygen we need)

• about 5×10^{25} atoms

• about 2 eV per atom (typical chemical scale)

$$(2\,\mathrm{eV}) \times (1.6 \times 10^{-19}\,\mathrm{C}) \times (5 \times 10^{25}) \sim 2 \times 10^{7}\,\mathrm{J} \sim 4\,\mathrm{kW\,hr}$$

• waste product is CO_2

~ 1 TV for a day

➜ 1 kg of uranium to fission

• about 3×10^{24} atoms

• about 200 MeV per atom (typical nuclear scale)

$$(200 \times 10^{6}\,\mathrm{eV}) \times (1.6 \times 10^{-19}\,\mathrm{C}) \times (3 \times 10^{24}) \sim 1 \times 10^{14}\,\mathrm{J} \sim 3 \times 10^{7}\,\mathrm{kW\,hr}$$

• waste products are radioactive

~ all the TVs in Virginia for a day

➜ 1 kg of hydrogen to fuse

• about 6×10^{26} atoms

• about 30 MeV per atom (typical nuclear scale)

$$(30 \times 10^{6}\,\mathrm{eV}) \times (1.6 \times 10^{-19}\,\mathrm{C}) \times (6 \times 10^{26}) \sim 3 \times 10^{15}\,\mathrm{J} \sim 8 \times 10^{8}\,\mathrm{kW\,hr}$$

• waste is Helium

~ all the TVs in the USA for a day

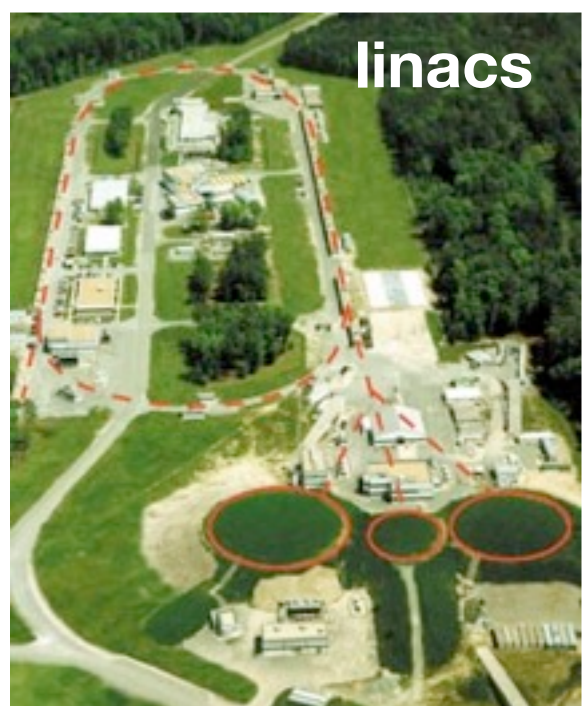
particle physics

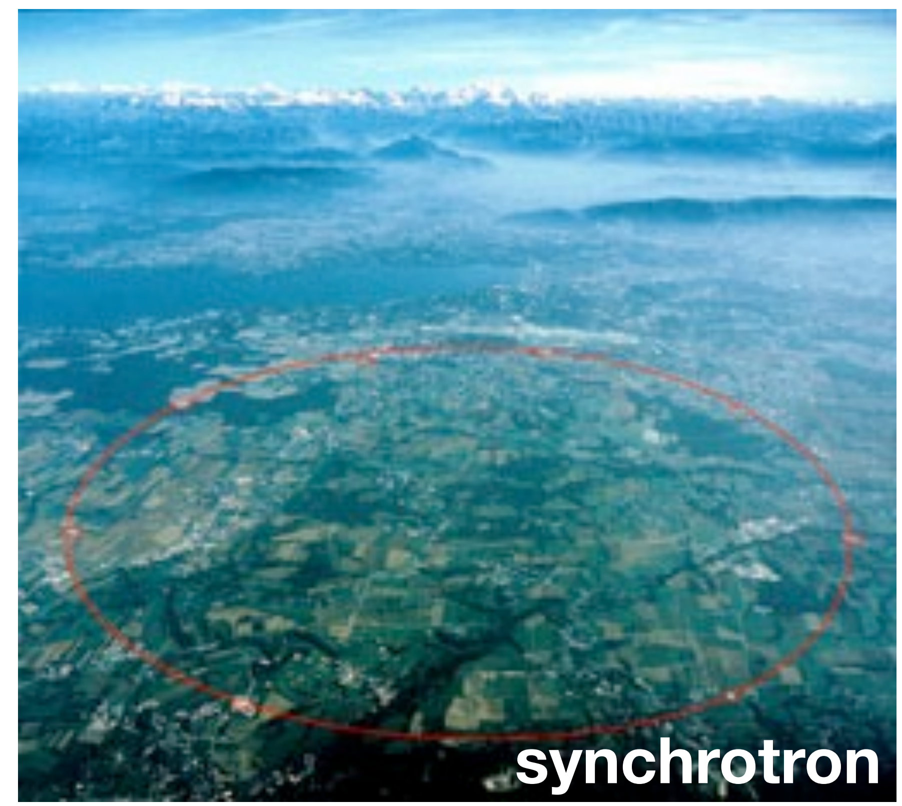
➜ electrically charged particles can be accelerated using electric fields

➜ their directions can be changed using magnetic fields

➜ physical basis of **particle accelerators**

accelerator





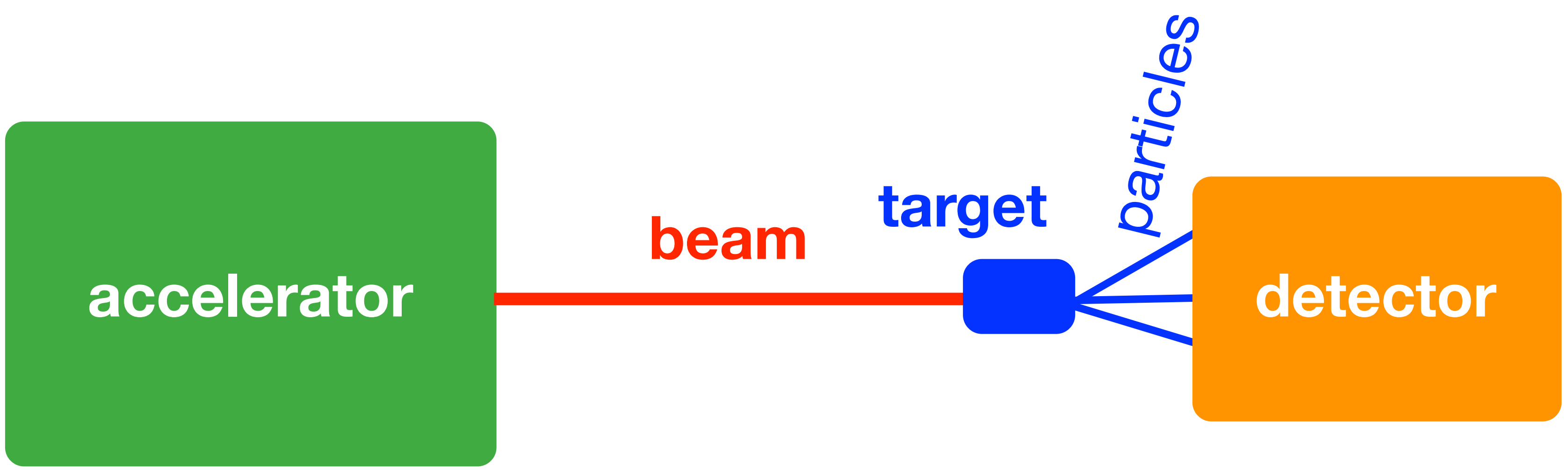
particle physics

➜ electrically charged particles can be accelerated using electric fields

➜ their directions can be changed using magnetic fields

➜ physical basis of **particle accelerators**

➜ particles can be detected by the effect they have on matter



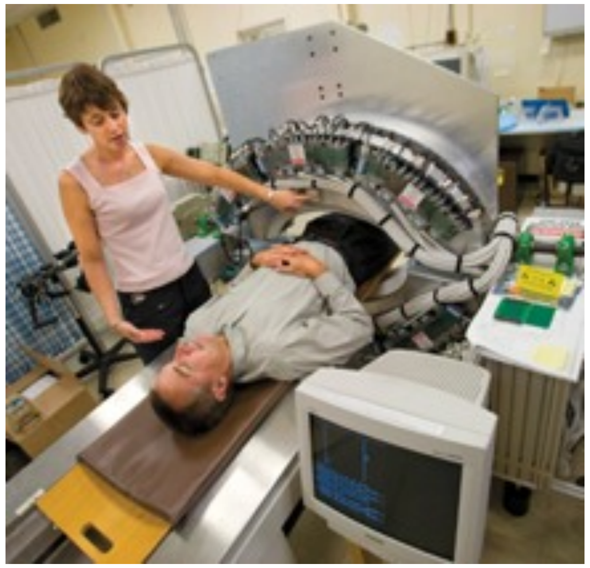
(or beam-beam in a 'collider')

particle physics

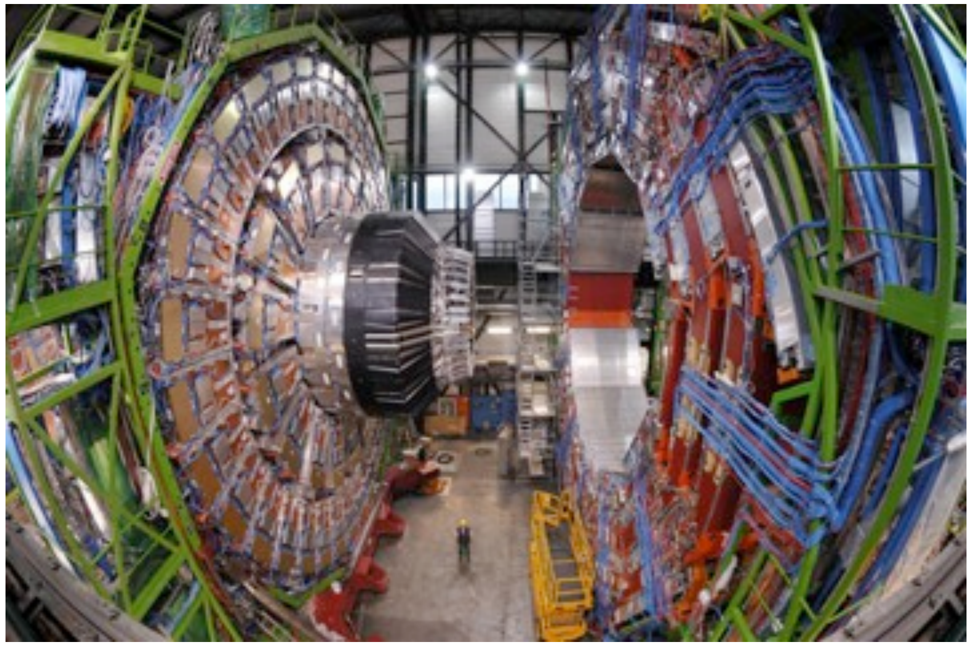
➜ electrically charged particles can be accelerated using electric fields

➜ their directions can be changed using magnetic fields

➜ physical basis of **particle accelerators**



detector



particle physics

➜ particle number is not conserved

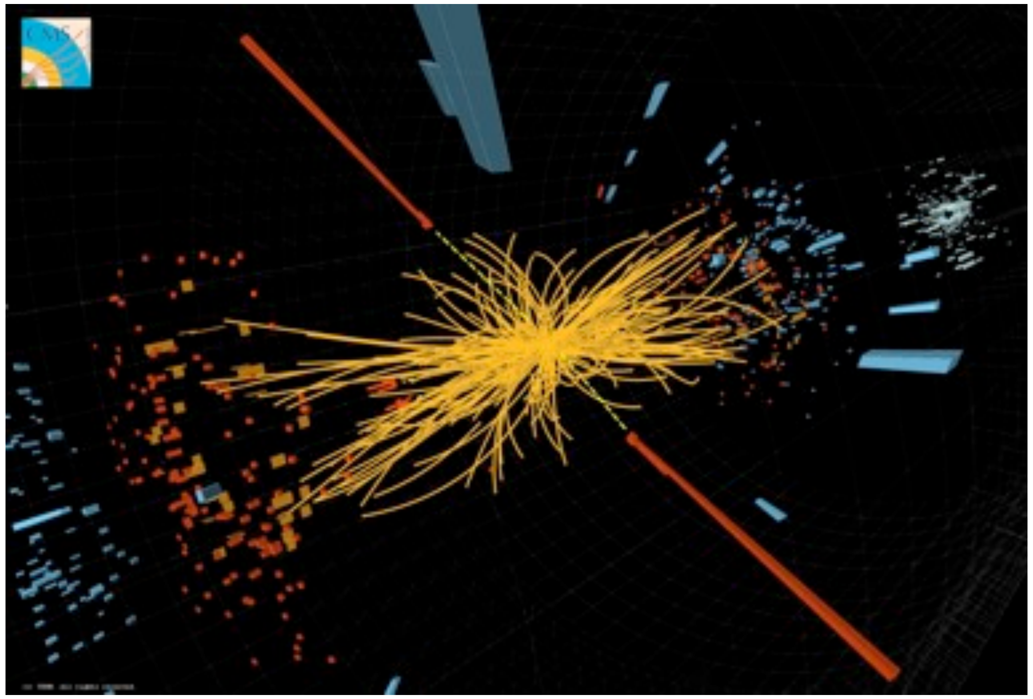
➜ new particles produced ‘out of beam energy’ $E = mc^2$

e.g. proton beam on a proton target, sometimes produce a ‘pion’

$$p + p \rightarrow p + p + \pi^0$$

➜ the more energy in the beams, the heavier the particles you can produce

➜ and the greater the number of lighter particles !



particle physics

➜ particle number is not conserved

➜ new particles produced ‘out of beam energy’ $E = mc^2$

e.g. proton beam on a proton target, sometimes produce a ‘pion’

$$p + p \to p + p + \pi^0$$

➜ the more energy in the beams, the heavier the particles you can produce

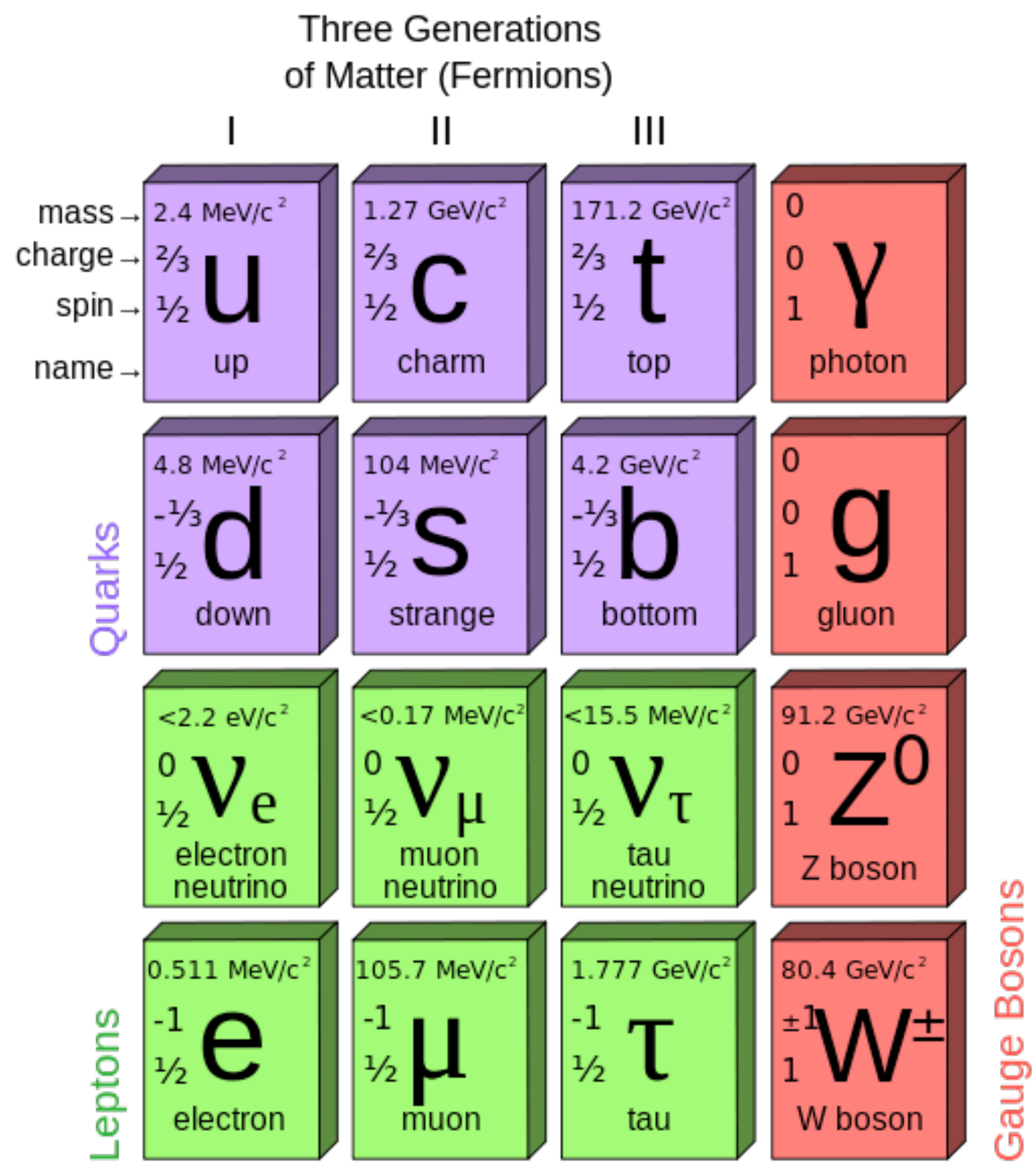
➜ produce everything you can and try to understand the results

➜ lead us to the ‘Standard Model’ of particle physics

the standard model

- ➜ **QUARKS**
  - ➜ building blocks of proton, neutron ...
- ➜ **LEPTONS**
  - ➜ electrons, neutrinos & ‘copies’
- ➜ **GAUGE BOSONS**
  - ➜ photons (electromagnetism)
  - ➜ gluons (strong nuclear force)
  - ➜ W/Z (‘weak’ nuclear decays)

... & the **Higgs Boson** ?

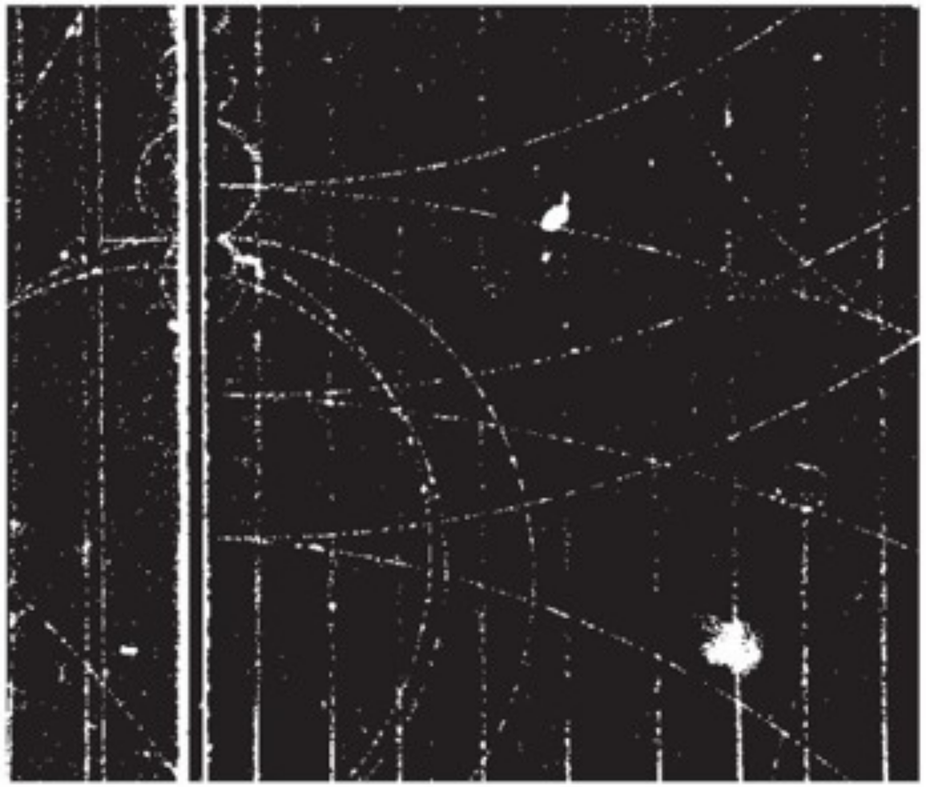


antiparticles

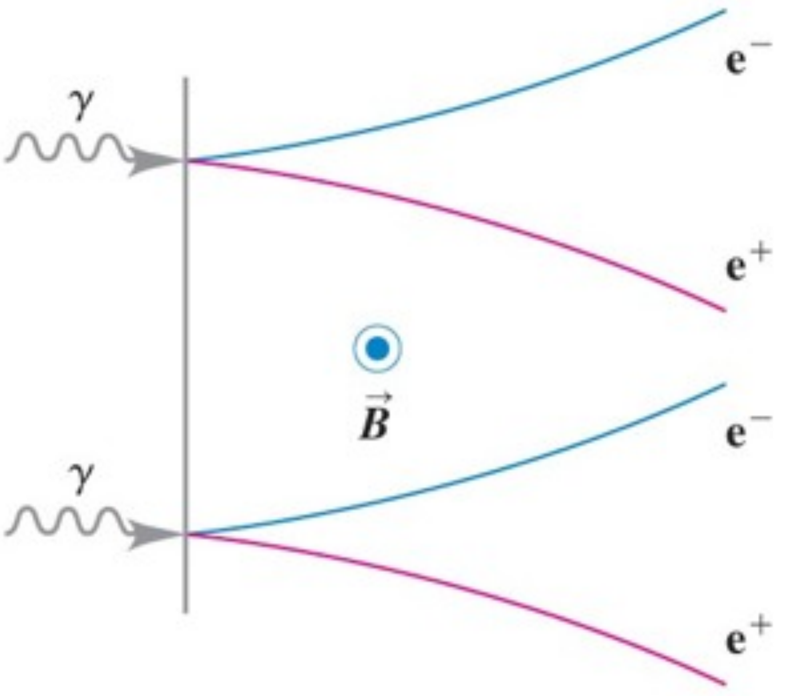
➜ our modern theories of particles are only consistent if there also exist 'anti-particles'

➜ e.g. as well as the common electron there must be an 'anti'-electron (positron)

➜ eventually these anti-particles, which are not common in nature, were artificially produced and detected



(a)



(b)

➜ why are antiparticles so rare in nature - nobody really knows !

particle-antiparticle annihilation

➜ when an electron and a positron meet at the same place there is a probability that they will 'annihilate' into two photons

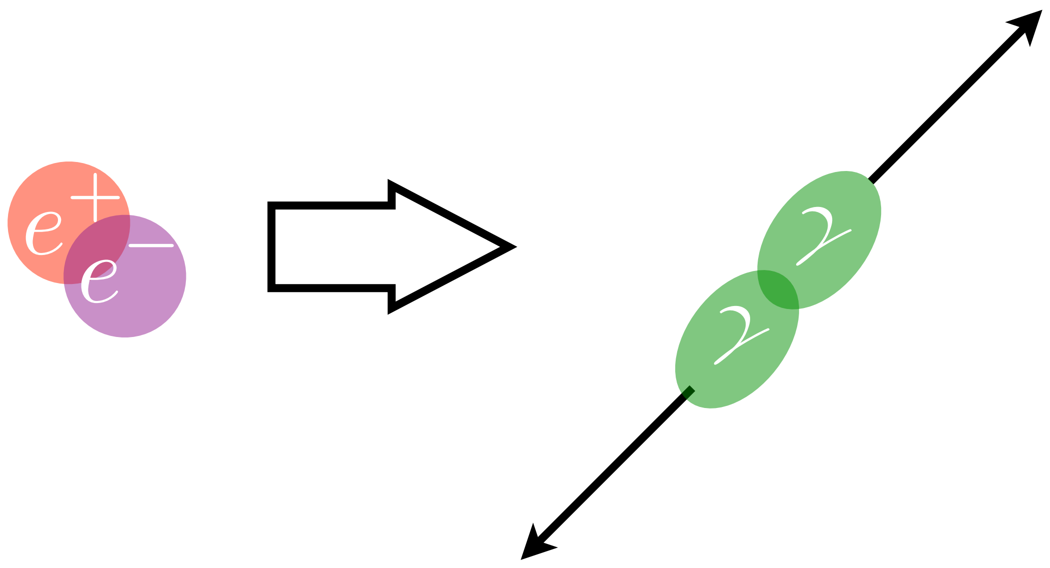
$$e^+ + e^- \rightarrow \gamma + \gamma$$

$$E_{\mathrm{tot.}} = 2 \cdot m_e c^2 = 2 \cdot E_\gamma$$

$$E_\gamma = m_e c^2 = 511\,\mathrm{keV}$$

$$E_\gamma = \frac{hc}{\lambda} \qquad \lambda \sim 10^{-12}\,\mathrm{m}$$

a gamma ray



useful ?

➜ but this stuff is all completely impractical, right ?

NO !

➜ even if you think that exploring the universe's fundamental rules isn't important,

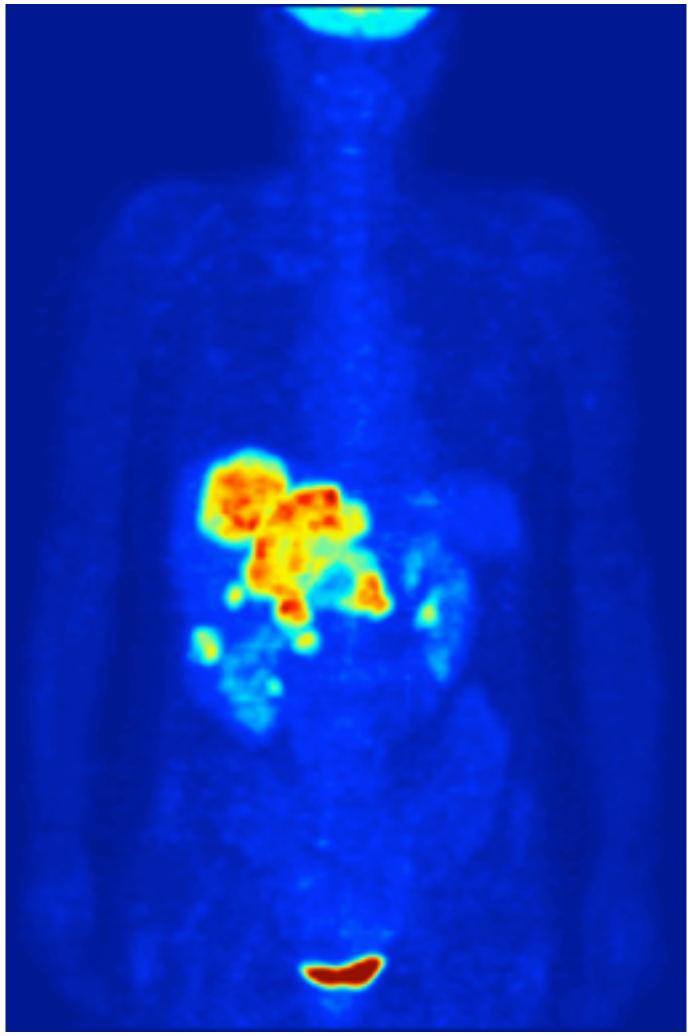
➜ spinoffs of this research are saving lives ...

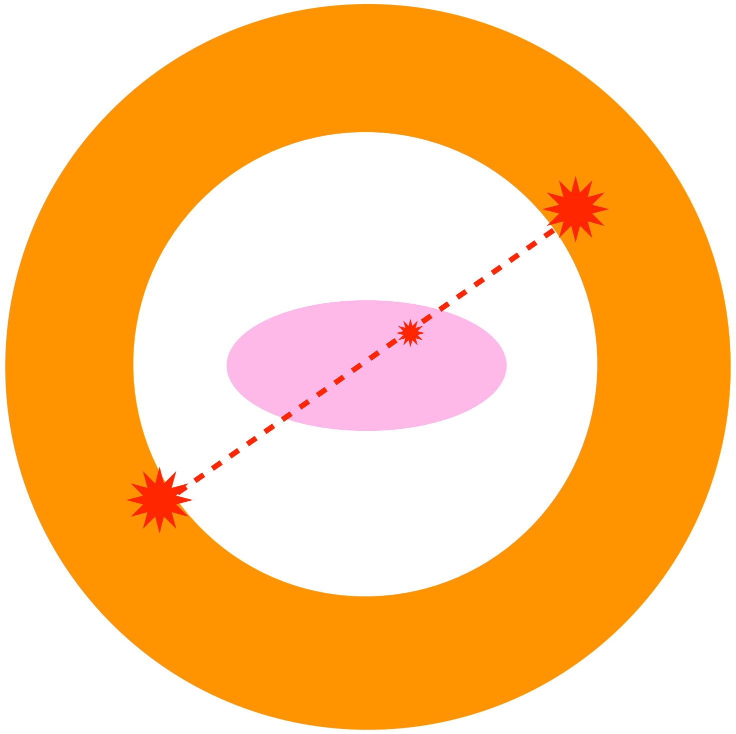
➜ just one example ....

a PET scanner

➜ important medical use of particle-antiparticle annihilation

➜ the **positron emission tomography** scanner





a PET scanner

➜ glucose doped with a radioactive isotope that decays by positron emission, e.g. $^{18}\mathrm{F}$

$$^{18}\mathrm{F} \to \, ^{18}\mathrm{O} + e^{+} + \nu_e$$

with a 110 minute half-life

underlying particle decay is

$$p^{+} \to n + e^{+} + \nu_e$$

and really it is

$$u \to d + e^{+} + \nu_e$$

➜ role of theoretical particle physics : understanding annihilation & gamma rays

➜ role of particle physics detectors : detecting gamma rays

➜ role of particle accelerators : making unstable ^{18}F from stable ^{18}O

$$p + \, ^{18}\mathrm{O} \to \, ^{18}\mathrm{F} + n$$

10 MeV protons from a cyclotron onto ^{18}O enriched water