Today’s lecture plan

- Light quanta:
  - yet another invention of Einstein’s in 1905
  - discovery of the light quanta: Compton scattering
- Worldline and energy-momentum of the photon
- System of photons
- Photons create mass
- Hawking radiation

1905: Einstein’s miraculous year

- Another fundamental Einstein’s paper from 1905:

  Einstein, A. “Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt.” *Ann. Phys.* **17**, 132−148 (1905).

  ("On a ***heuristic*** point of view concerning the production and transformation of light")

- Note that this is being widely called “the photoeffect paper”. Yet, the photoeffect was just one of the three *examples* where the notion of light quanta was good at explaining the results (the other two are ionization of gases by UV light and the Stokes rule (photoluminescence)).

- Another curious note: the Royal Swedish Academy of Sciences awarded Einstein’s Nobel Prize for “photoeffect” because they *would not recognize the quantizaton of light or the relativity*.

1922: Compton's x-ray scattering experiment

- Arthur Compton studied scattering of x-rays by different materials and found one peculiarity: the spectrum of back-scattered x-rays looked the same for all materials!
- He correctly concluded that this scattering was caused by objects which are the same in all material: the electrons. The way to quantitatively explain the spectra was to use the quantum theory of light.

PHYSICAL REVIEW

A QUANTUM THEORY OF THE SCATTERING OF X-RAY
BY LIGHT ELEMENTS

BY ARTHUR H. COMPTON

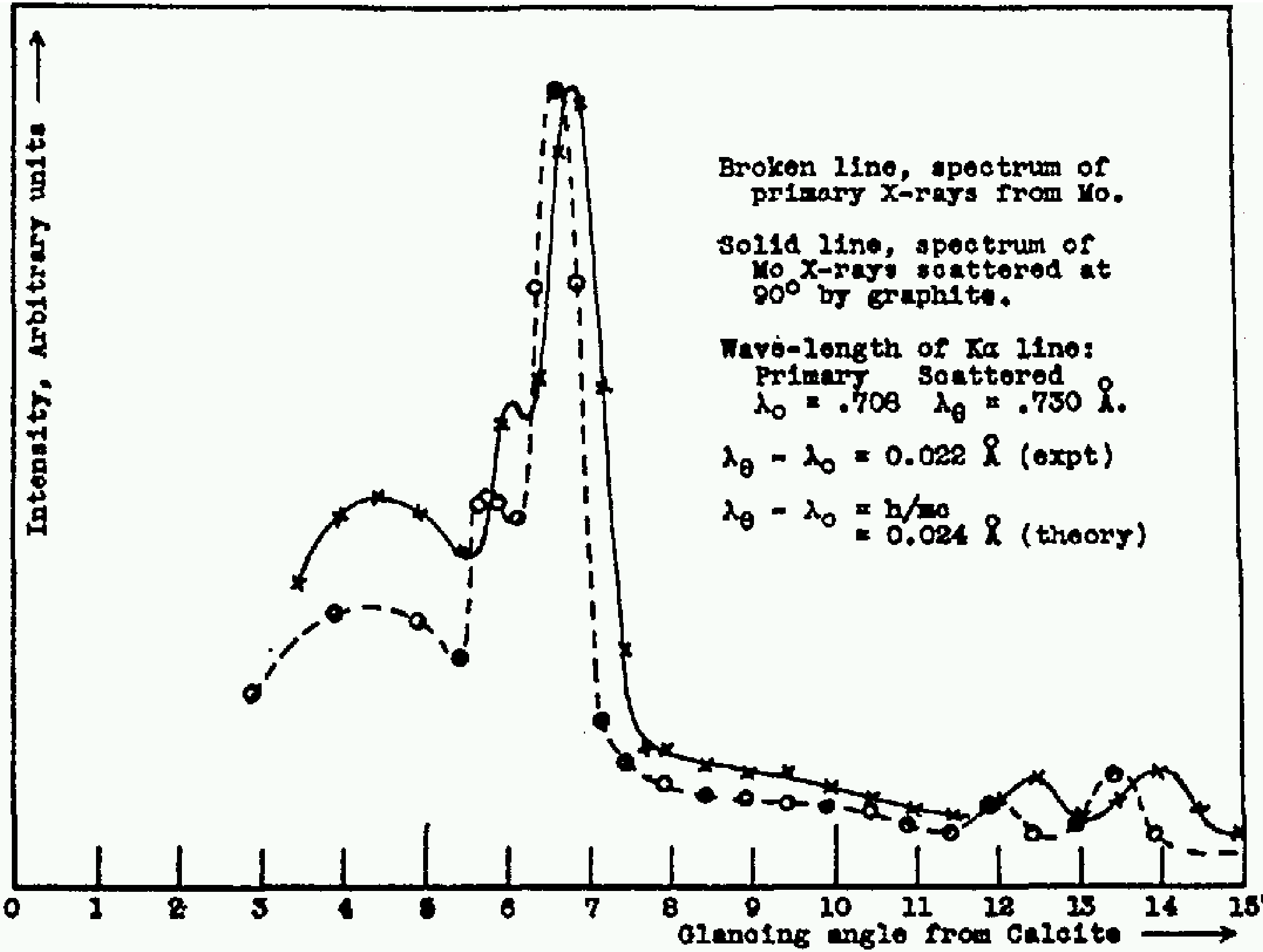

Fig. 4. Spectrum of molybdenum X-rays scattered by graphite, compared with the spectrum of the primary X-rays, showing an increase in wave-length on scattering.

Photon mass???

- Photon mass is *postulated* to be zero. It has not been measured to be zero – yet! Measuring zero *precisely* is not an easy task, but the precision is improving all the time.

(A side note: neutrinos were thought to be massless as well; latest evidence is: they **do** have mass, small but non-zero.)

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New Experimental Limit on the Photon Rest Mass with a Rotating Torsion Balance

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(Received 24 August 2002; published 26 February 2003)

A rotating torsion balance method is used to detect the product of the photon mass squared and the ambient cosmic vector potential A_e. The signal is modulated by rotating the torsion balance to ensure the effectiveness of detection for all possible orientations of the vector potential. The influences of sidereal disturbances of environment are also removed by virtue of this modulation method. The experimental result shows $\mu_\gamma^2 A_e < 1.1 \times 10^{-11}$ T m/m^2, with μ_γ^{-1} as the characteristic length associated with photon mass. If the ambient cosmic vector potential A_e is 10^{12} T m due to cluster level fields, we obtain a new upper limit on photon mass of 1.2×10^{-51} g.

DOI: 10.1103/PhysRevLett.90.081801 PACS numbers: 12.20.Fv, 14.70.Bh, 98.80.Cq

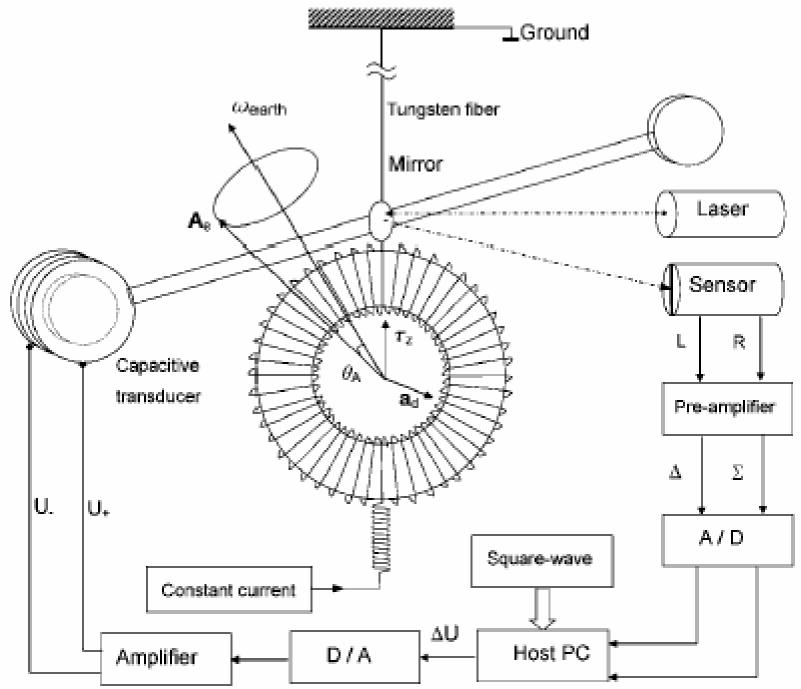
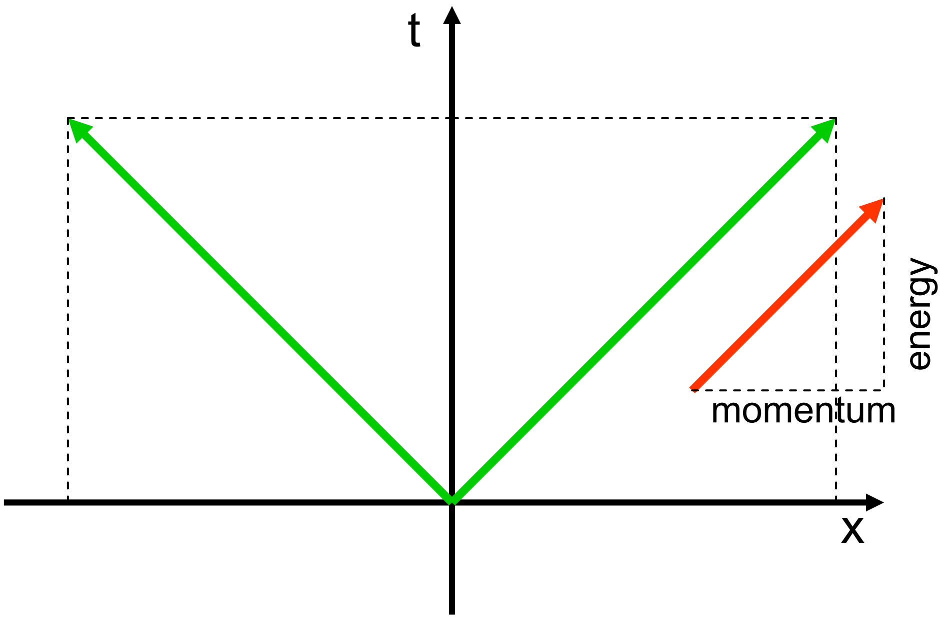


FIG. 1. The experimental setup of the rotating torsion balance. The magnetic dipole vector potential moment $\boldsymbol{a}_d$ arising from the toroidal coil interacts with the cosmic vector potential $\boldsymbol{A}_e$ to produce a torque on the torsion balance. This torque associated with the effect of photon mass varies with time according to the rotation of the torsion balance.

Photon as a particle: spacetime map

• Go back to the spacetime map for a moment. Photons travel at speed of light, and intervals between events connected by photons are light-like, i.e. they are equal to zero. They are always connected by 45° lines.

• The energy-momentum of the photon points in the same direction as the worldline of a photon, i.e. also at 45° to the axes.



Energy = momentum

- The two main consequences of the light-like character of the photon energy-momentum 4-vector are:
  - photon mass is equal to zero
  - photon energy is equal to (magnitude of) its momentum: E = |***p***|
- What are some typical photon energies? (In some *real* units, please)

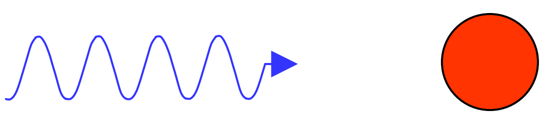
Photon source	**Energy**	**Wavelength**
Radio waves:	~ 10^{-8} eV	~ 100 m
Radar	~ 10^{-6} eV	~ 1 cm
Visible light	~ 2 eV	~ 500 nm
UV light	~ 10 eV	~ 100 nm
x-rays	~ 20 keV	~ 0.5 Å
γ-rays	~ 1 GeV	~ 1 fm

Energy-momentum diagram of Compton experiment

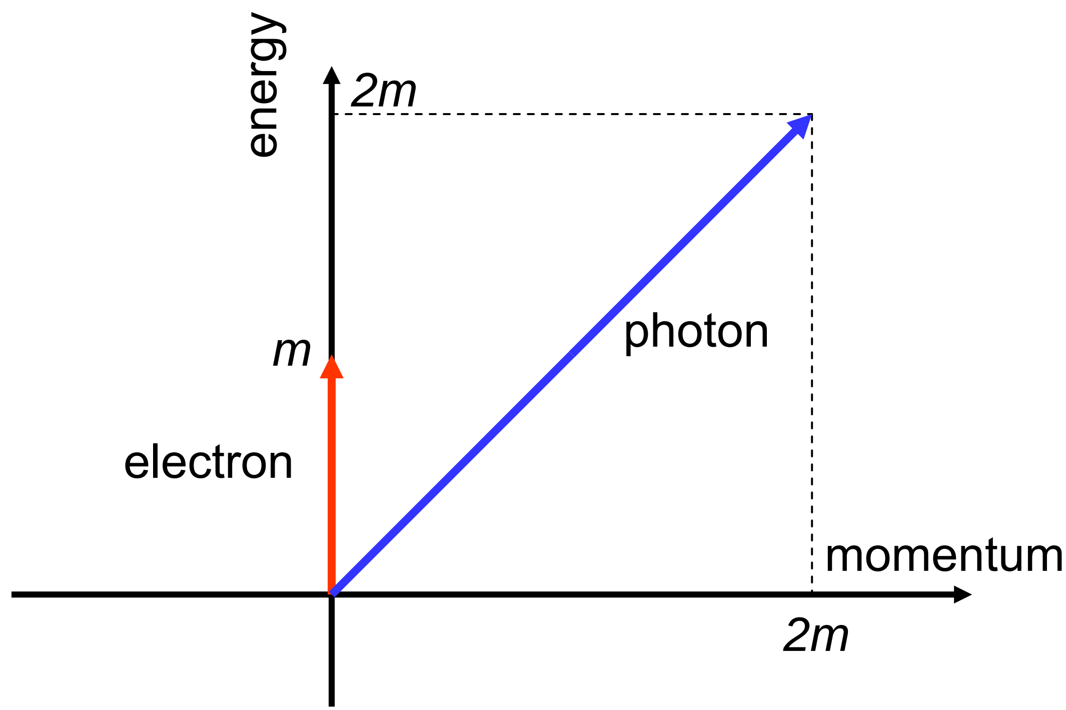
• Before the scattering, we have an electron of mass *m* at rest, and a photon moving at v = 1; we assign it a momentum 2*m* and energy 2*m*.

• Note: photons are tricky: whatever momentum they have, they *always* move at the same speed (in vacuum)! Lousy 60 Hz photons from the AC outlet and ultra-extra-hard γ-rays travel together!

photon | electron

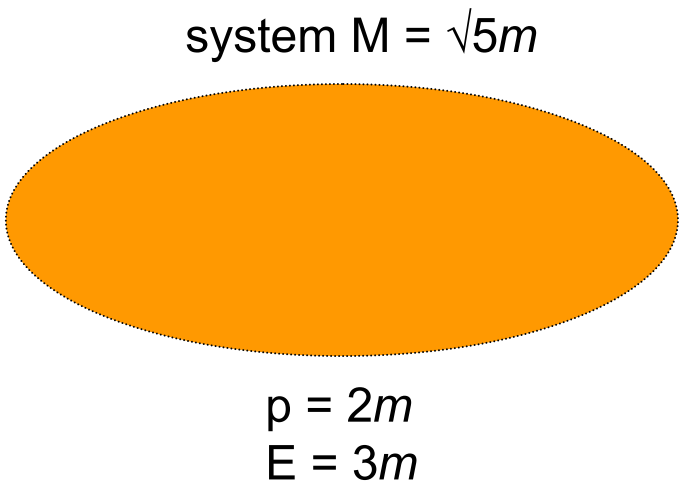


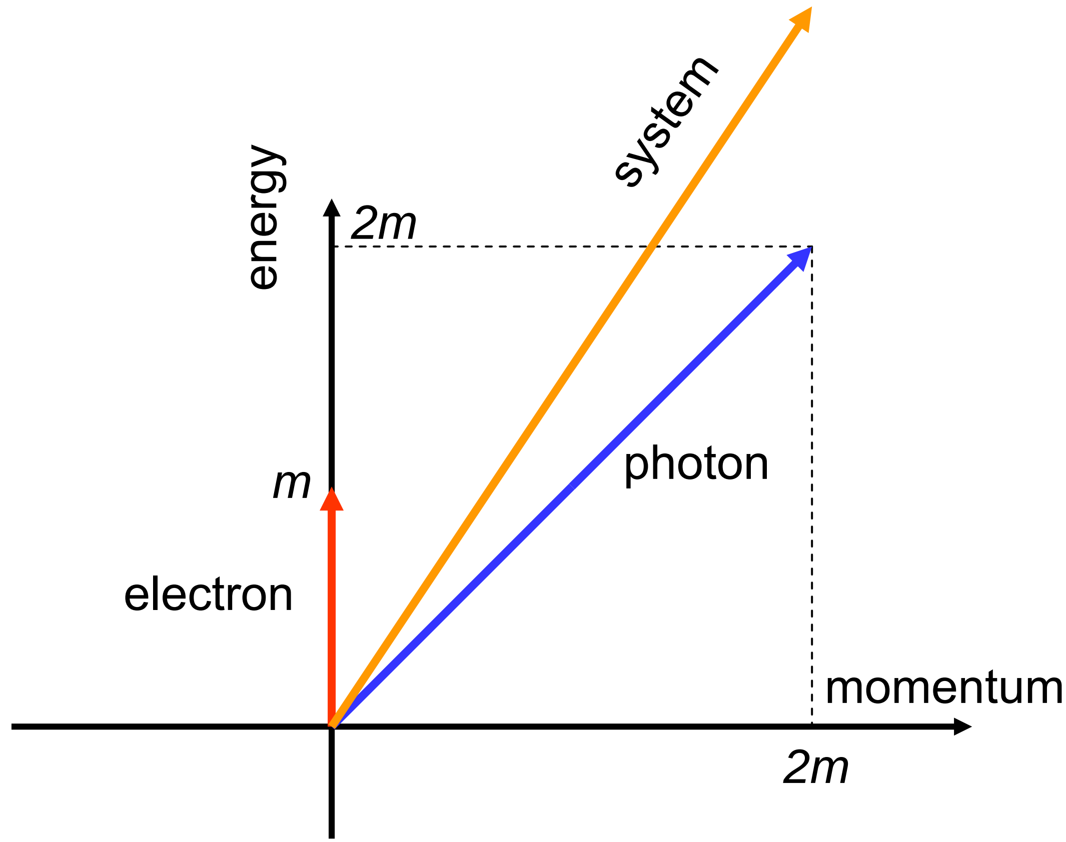
photon	electron
v = 1	v = 0
p = 2*m*	p = 0
E = 2*m*	E = *m*



The system as a whole

- The photon-electron system has total momentum of 2*m* and total energy of *m* + 2*m* = 3*m*, so its mass (the magnitude of the energy-momentum 4-vector) is $M = (E^2 - p^2)^{1/2} = (9m^2 - 4m^2)^{1/2} = \sqrt{5}m$. The system as a whole is a lot heavier than the electron by itself, even though all we've added is a *massless* particle!





After the collision: the components

- The photon is flying back (backwards scattering), but with lower momentum and energy, the electron is kicked forward.
- To conserve energy and momentum, we must have:

$$p_e + p_p = 2m$$

$$E_e + E_p = 3m.$$

- Using $p_p = E_p$ and $E_e^2 - p_e^2 = m^2$ we find that:

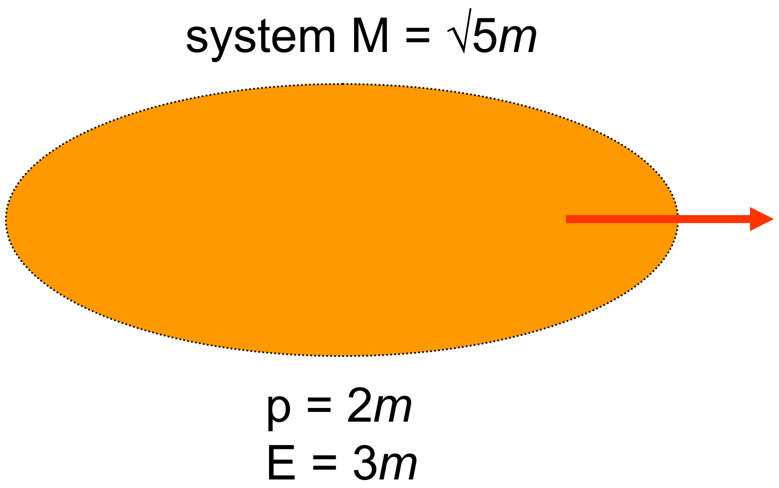
$$p_e = 12/5m \text{ and } E_e = 13/5m$$

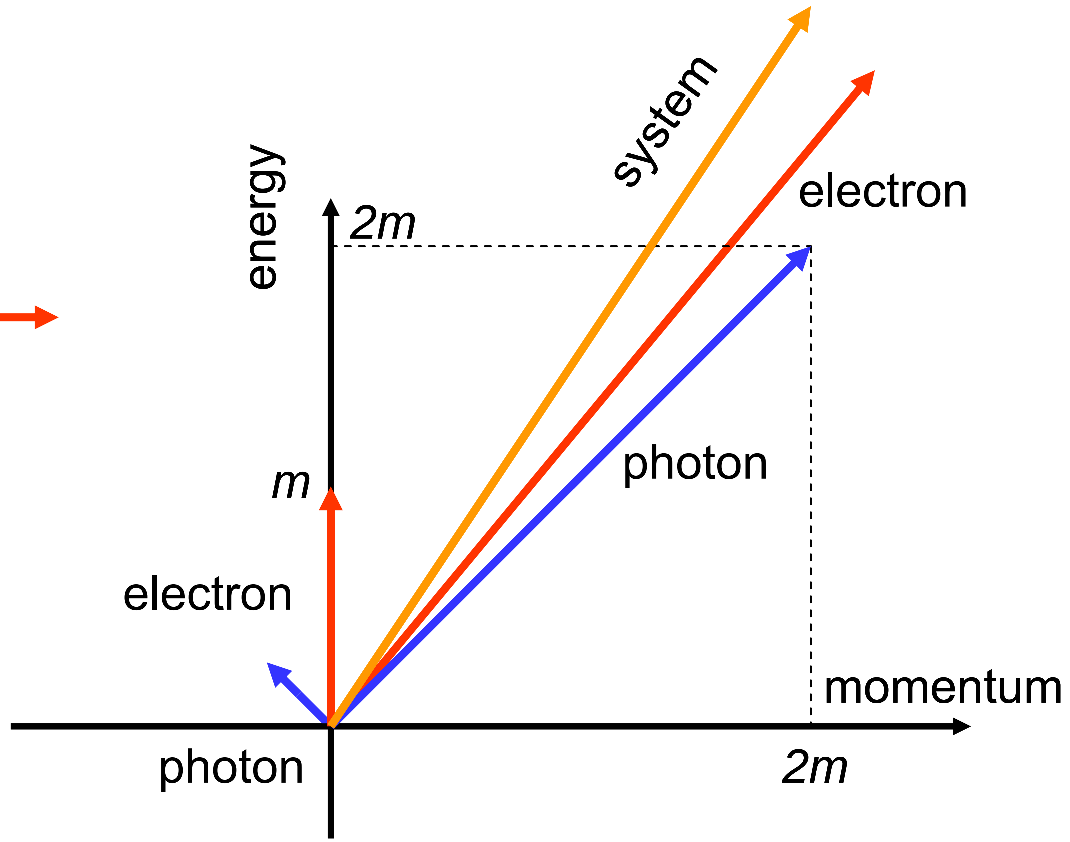
$$p_p = - 2/5m \text{ and } E_p = 2/5m.$$

- Knowing electron's total energy we can calculate its $\gamma = E_e/m = 13/5$. This corresponds to the speed of $v = (1 - \gamma^{-2})^{1/2} = (1 - 25/169)^{1/2} = 12/13$. Very fast!
- The recoiled photon has lost $(2 - 2/5)m = 8/5m$, or 80% of its energy.

After the collision: the system

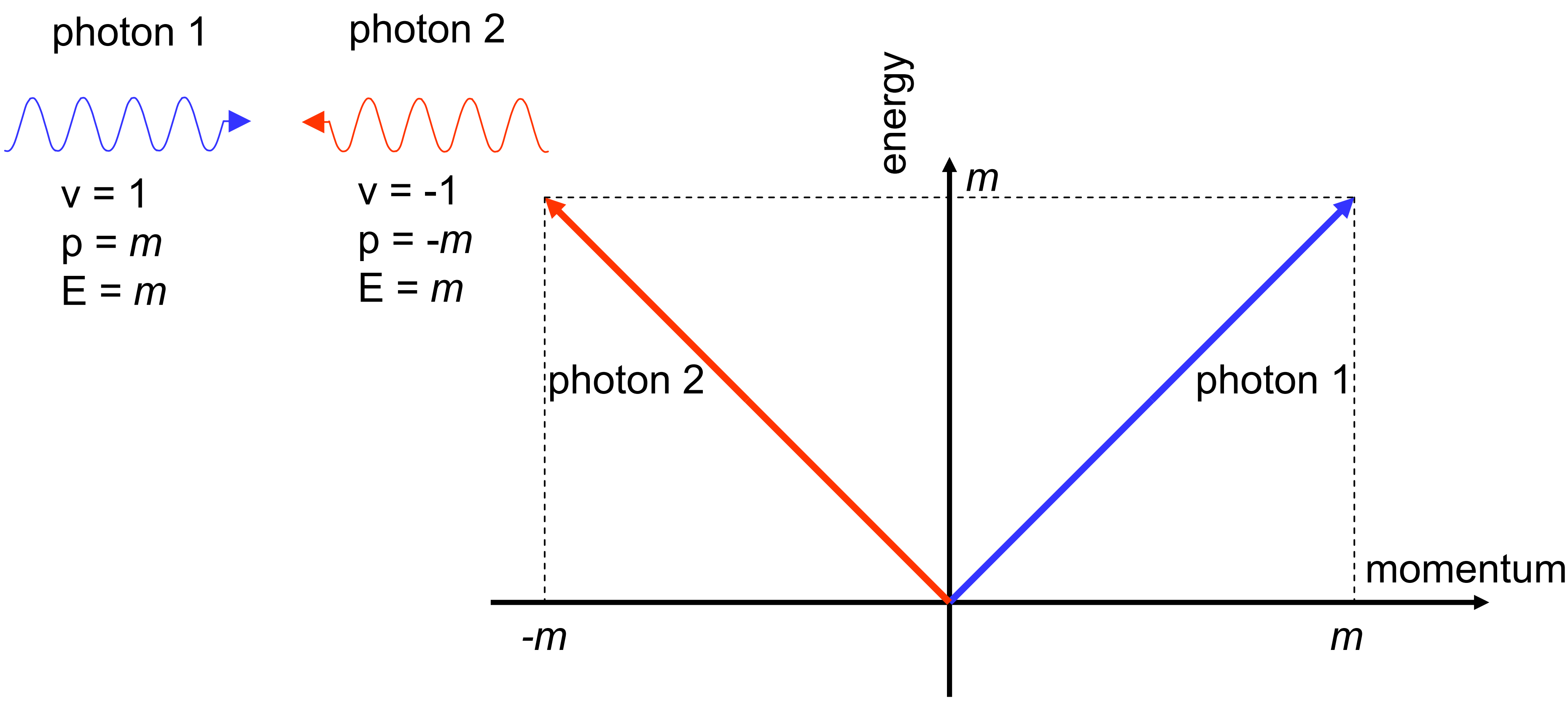
- The system energy-momentum vector will remain the same – it must conserve!





A simpler system: two photons

• Consider two photons flying head-on, each with energy *m*. Their momenta are then *m* and –*m* (equal and opposite).

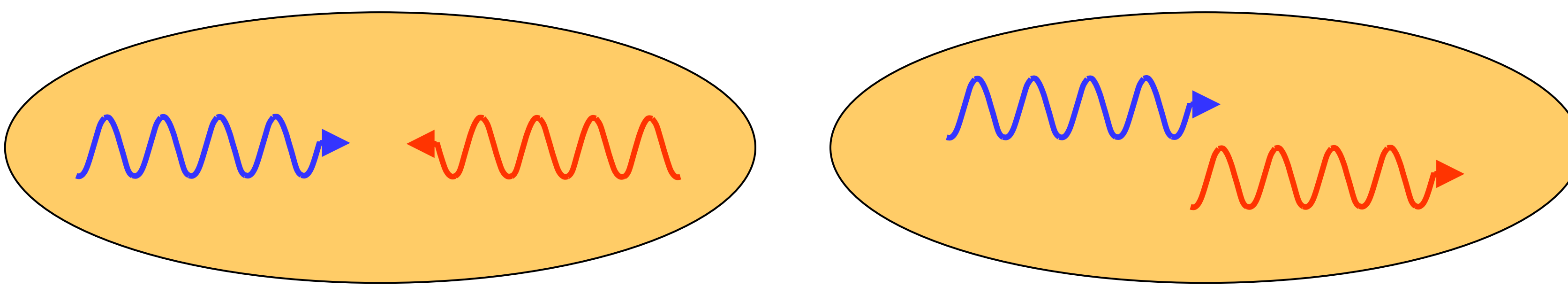


The system has mass!

- Total energy of the system: $E = E_{red} + E_{blue} = m + m = 2m$.
- Total momentum of the system: $p = p_{red} + p_{blue} = -m + m = 0$.
- Magnitude of the energy-momentum 4-vector (= system mass):

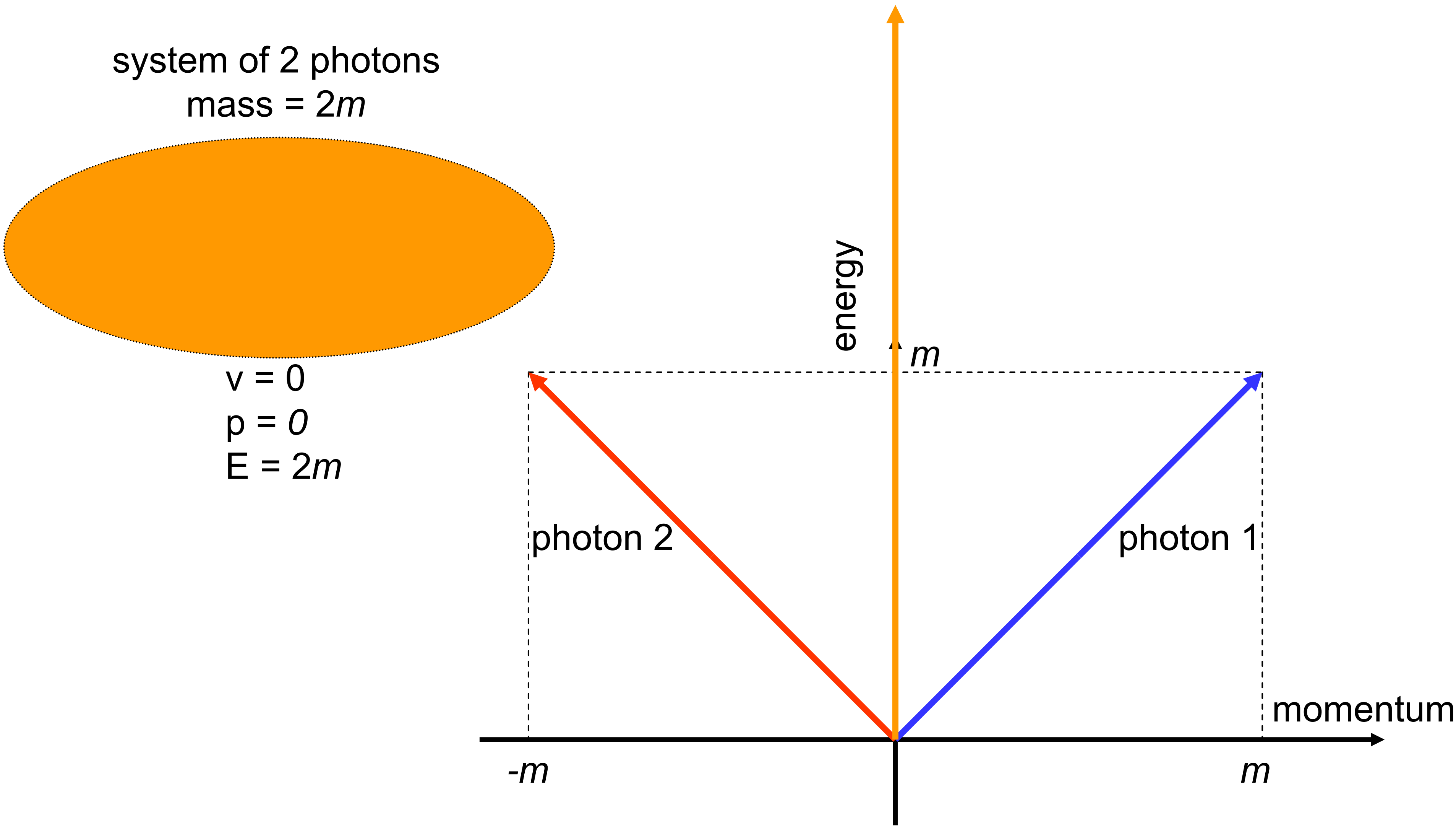
$$M = (E^2 - p^2)^{1/2} = [(2m)^2 - 0^2]^{1/2} = 2m$$

- Two massless particles, when put together, have a mass! Apparently, in physics $0 + 0 \neq 0$, at least sometimes.
- A special case of two (or more) photon system that is massless is when all photons are going in the same direction. Then, $E = |\mathbf{p}|$, and the mass is zero.



$m \neq 0$ $m = 0$

Two-photon system on energy-momentum diagram



Photons create mass

• If a system of photons has mass, or mass is added to massive particles when photons are included in the system, can photons be converted into massive particles? Yes!

• We'll consider two examples:

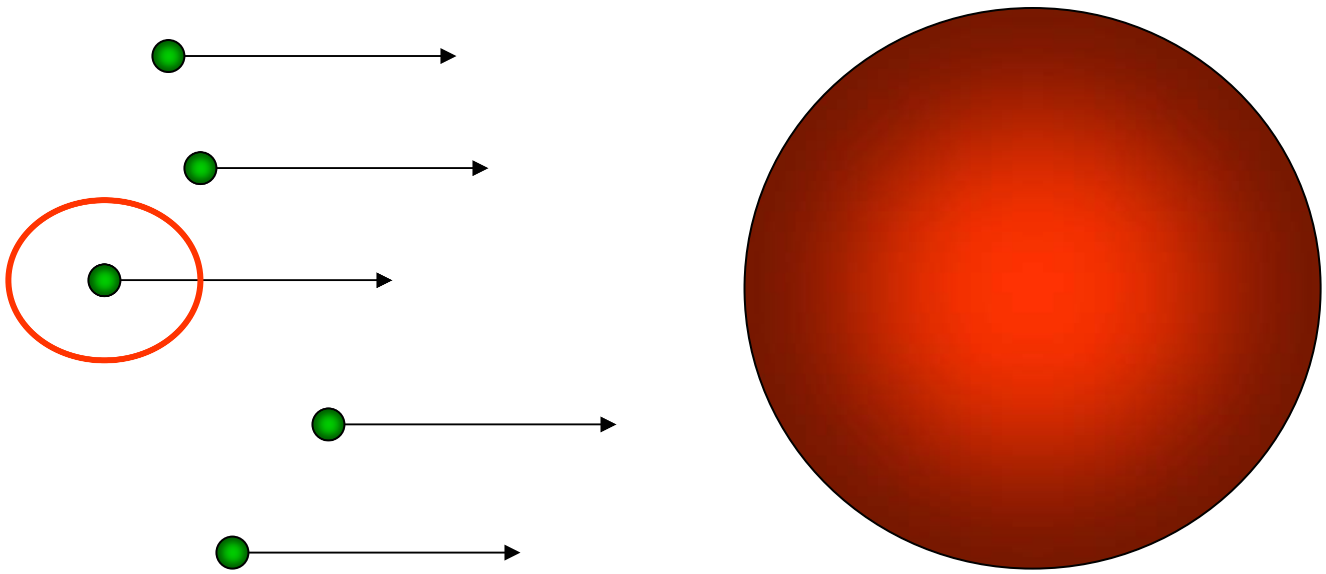
- a single photon strikes an electron and creates an electron-positron pair
- two photons collide and create an electron-positron pair

• Example #1 is very common and happens when high-energy γ-rays interact with matter. This is one of the effects of the "ionizing radiation".

• Example #2 is far less common. Why?

Cross sections

- The answer is in the "cross section" of the interaction – the effective transverse size of colliding particles. We can sort of have a feel for transverse size of massive particles (although in theory electron is a point-particle). But what is the "size" of the photon??? The bottom line is: photon cross section is tiny.

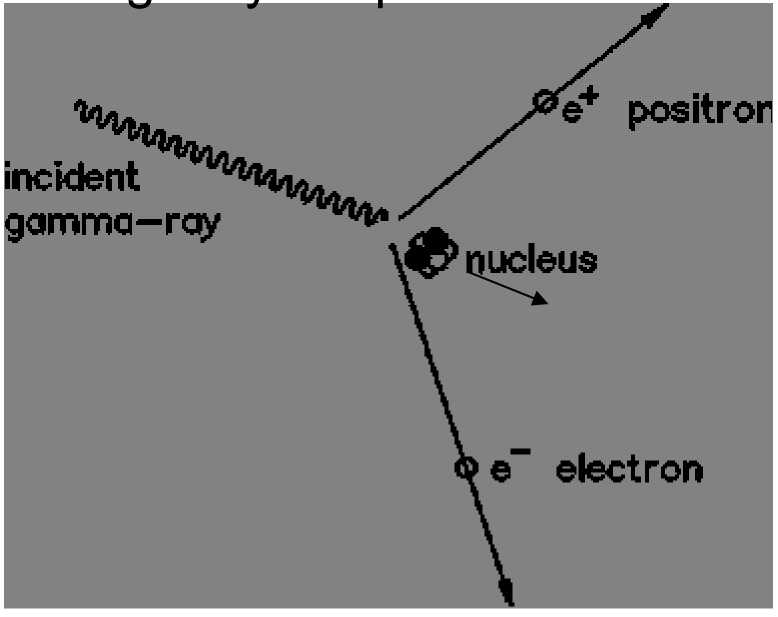


Pair production

• What energy should the γ-ray photon have to produce a pair?

• Well, an electron-positron pair has a mass of $2m \approx 1.022\ MeV/c^2$ or about 1.822×10^{-30} kg – twice the mass of a single electron, so that would be bare minimum for the photon energy.

• Actually, more energy is needed. Why? To conserve momentum! Remember: if a photon brings in an amount *x* of energy, it brings the same amount *x* of momentum to the system. The electron (or nucleus in the below figure) will *recoil* in the direction of photon's motion. The recoil energy has to be brought by the photon in *addition* to the two electron masses.

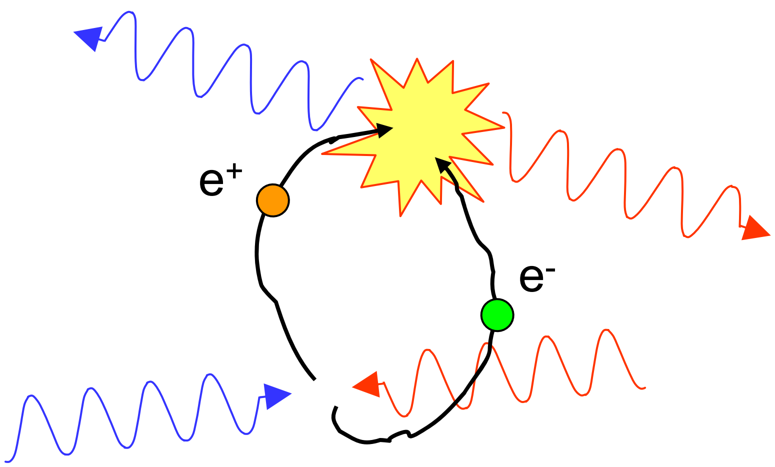


Pair production by two photons

• As pointed out, a very rare process, at least nowadays. It requires very high “concentration” of high-energy photons. And I mean, high. Ridiculously high.

• So high that if such density is reached, photons will collide to create pairs of particle-antiparticle (not necessarily electron-positron), which will immediately annihilate to make new photons.

• And this is exactly what was happening in the early Universe. The early Universe was *opaque* – photons did not travel far in it.



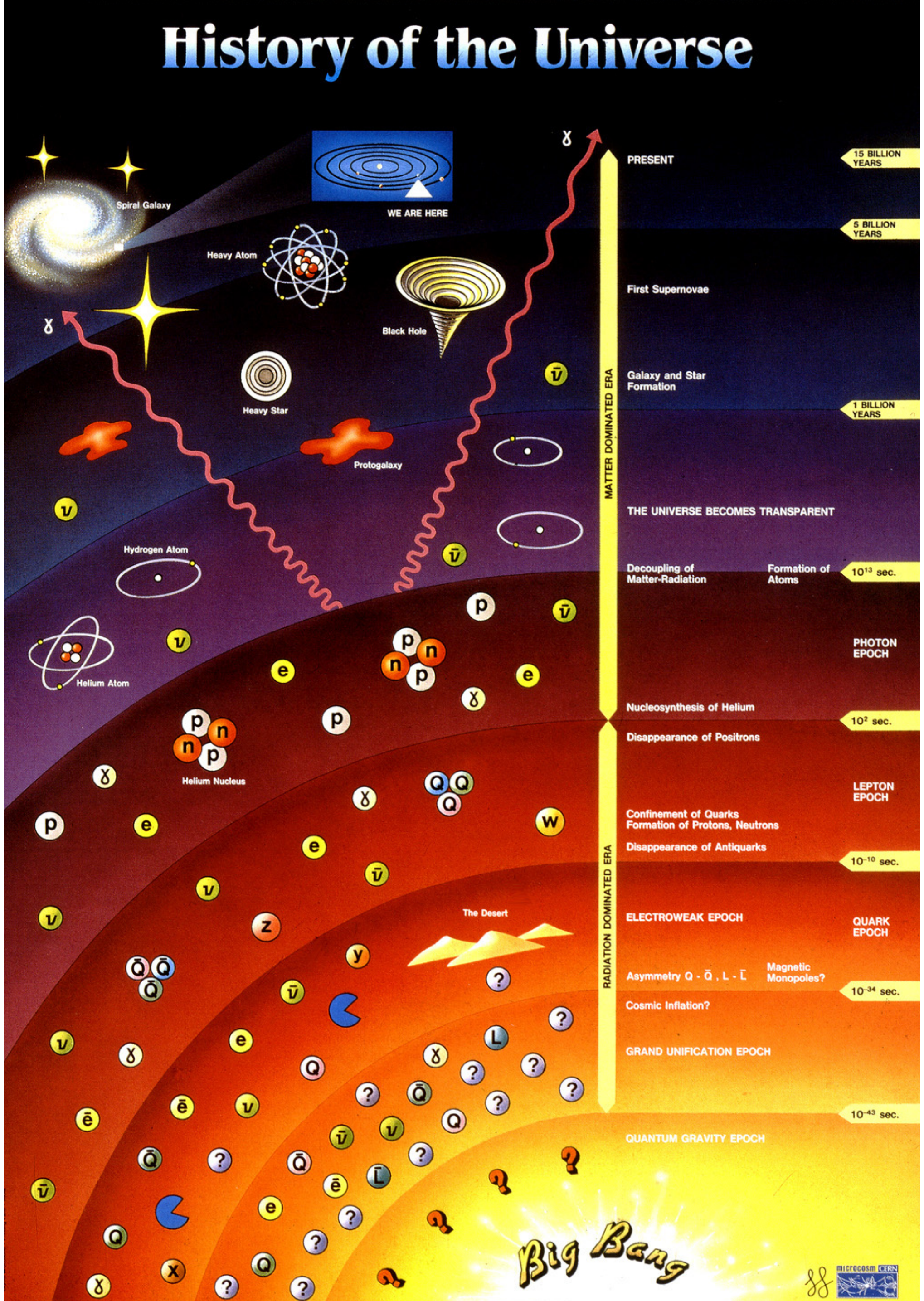


image courtesy of CERN

Black Holes and Hawking radiation

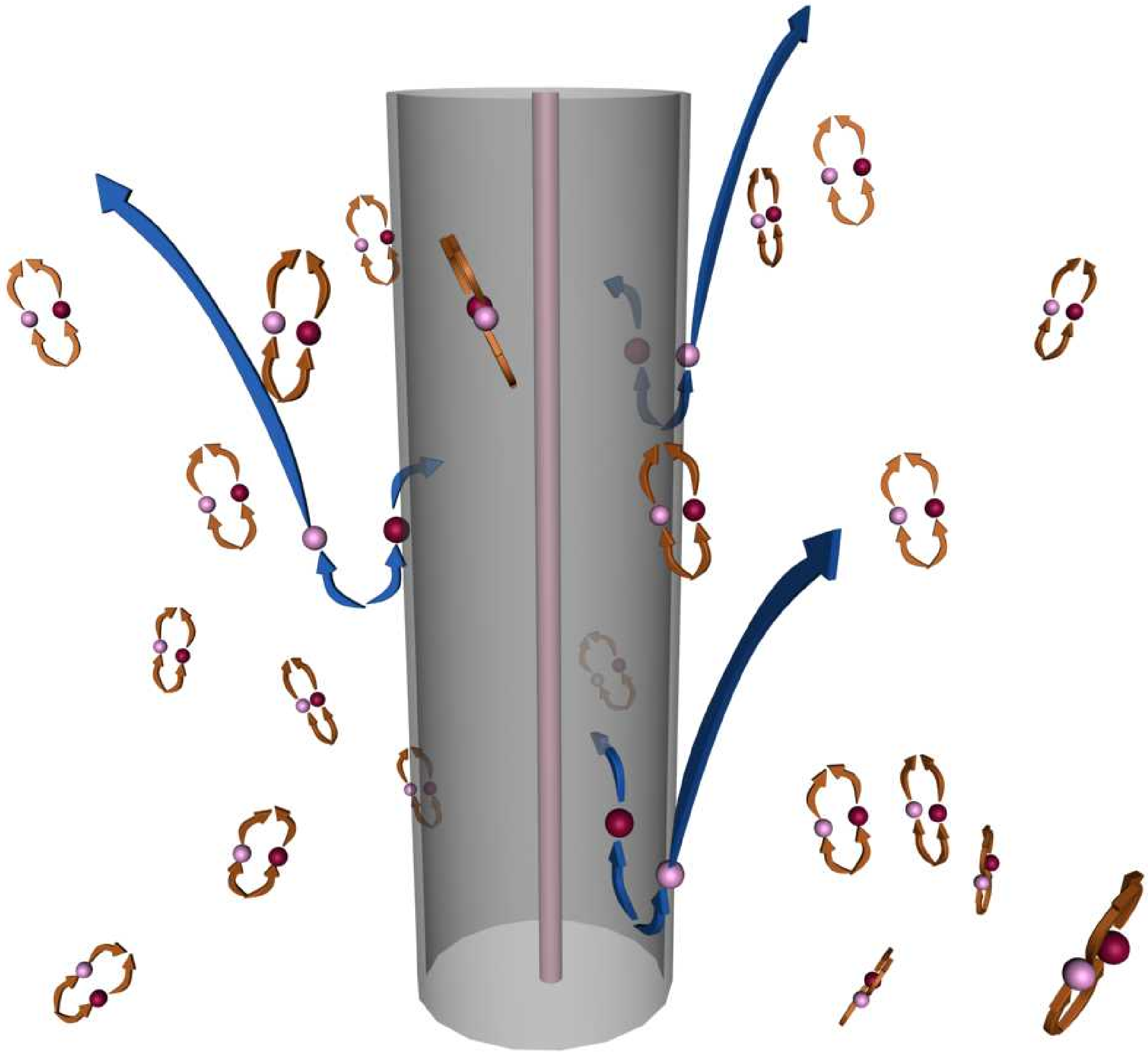
• Quantum mechanics predicts another mechanism for pair production: the vacuum.

• Quantum-mechanical vacuum is not an empty space. The Heisenberg uncertainty principle dictates that if vacuum is a *particular* quantum state, then it must have very large *fluctuations*.

• These fluctuations manifest themselves as *spontaneous pair production* from the *virtual photons* in vacuum. The produced *virtual* pairs almost immediately annihilate back into virtual photons.

• However, presence of very large *tidal forces* (remember?), as in the vicinity of a large mass, can rip the pairs apart before they annihilate. The virtual particles are brought into the real world by gravity.

• Hawking radiation: thermal radiation emitted by Black holes through virtual pair production near the event horizon.



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