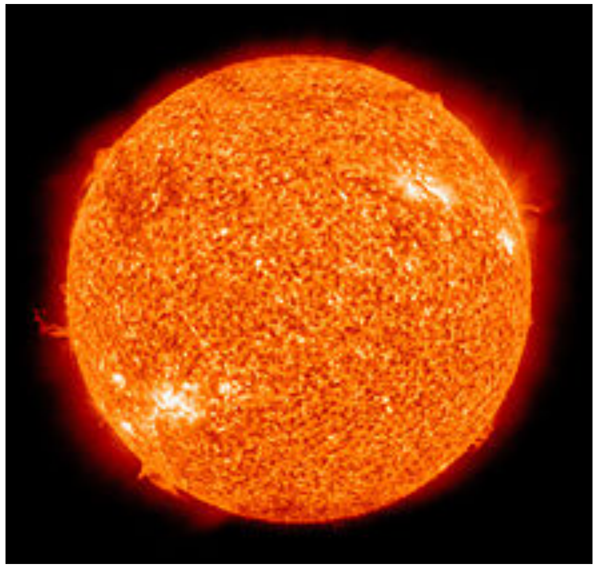
Cosmology
Lecture 9

The Cosmic Microwave Background Part 1: The radiation content of the Universe

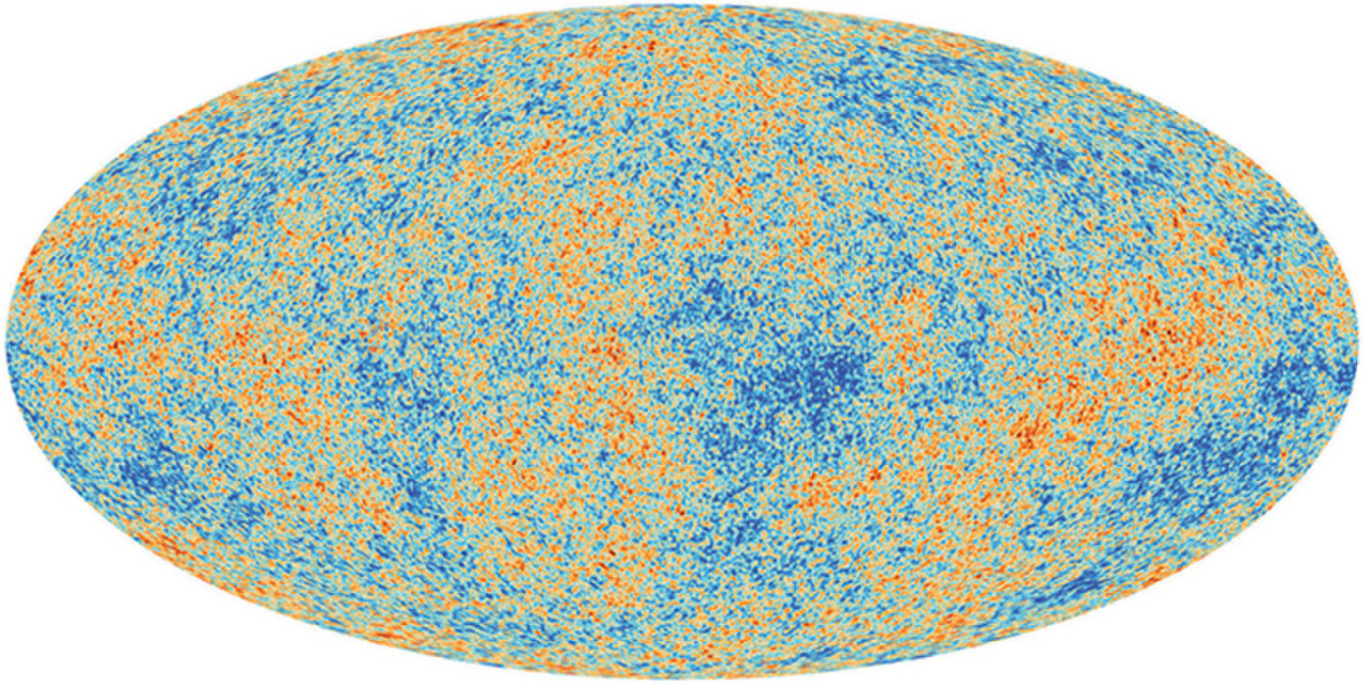
Lectures

Sources of photons in the Universe



Stars:
From galaxy surveys, the density of stars in the Universe corresponds to:
$1.7 \times 10^{8}\ L_{Sun}\ \mathrm{Mpc}^{-3}$

If, for a very rough upper limit, we assume that all these stars have been shining for the entire history of the Universe (4.5×10^{17} s), they have emitted:
$E_{stars} = 10^{-15}\ \mathrm{J\ m^{-3}}$



Cosmic Microwave Background:
The CMB is a black body with T=2.7 K. We can calculate its energy density using:

$$E = \alpha T^4$$

where:

$$\alpha = \frac{\pi^2}{15} \frac{k^4}{\hbar^3 c^3}$$

giving:
$E_{CMB} = 4 \times 10^{-14}\ \mathrm{J\ m^{-3}} = 0.2606\ \mathrm{MeV\ m^{-3}}$

The number density of CMB photons

While the energy density of CMB photons is small: 4 x 10^{-14} J m-3

Because each CMB photon has a very low energy:

$$hf_{\rm mean} = 6.34 \times 10^{-4}\ {\rm eV}$$

The number density of CMB photons is very high:

$$n_\gamma = \frac{0.2606 \times 10^6}{6.34 \times 10^{-4}} = 4.107 \times 10^8\ {\rm m}^{-3}$$

compared to the number density of Baryons:

$$n_{\rm b} = \frac{\Omega_{\rm b,0}\varepsilon_{c,0}}{E_{\rm b}} = \frac{0.048 \times 4890\ {\rm MeV\ m}^{-3}}{939\ {\rm MeV}} = 0.25\ {\rm m}^{-3}$$

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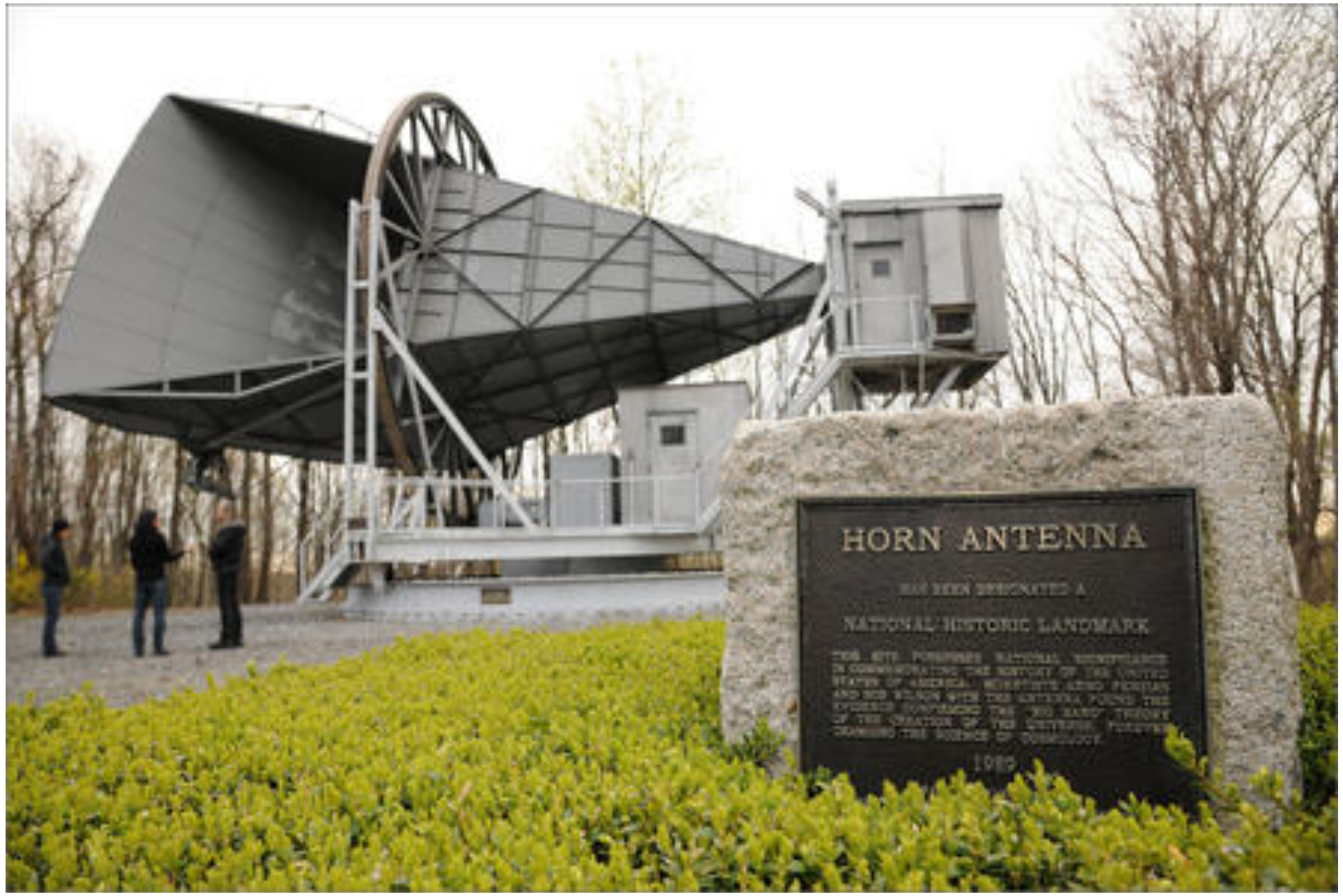
Meaning that there is (,was, and will be) about 1.6 billion CMB photons for every Baryon in the Universe.

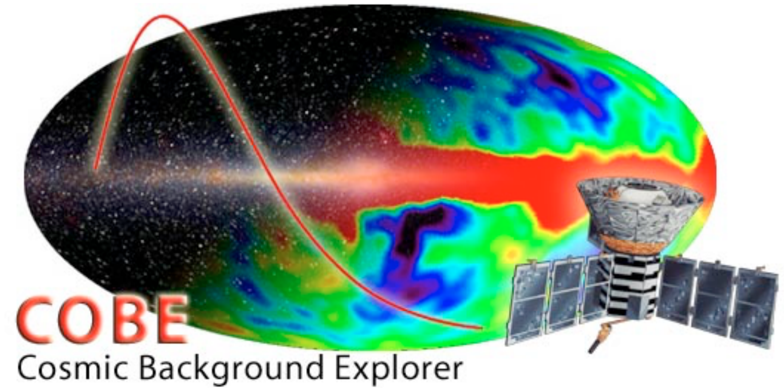
Observing the CMB



The CMB was first detected by Penzias and Wilson in the mid-1960s as excess emission that did not vary with hour or season.

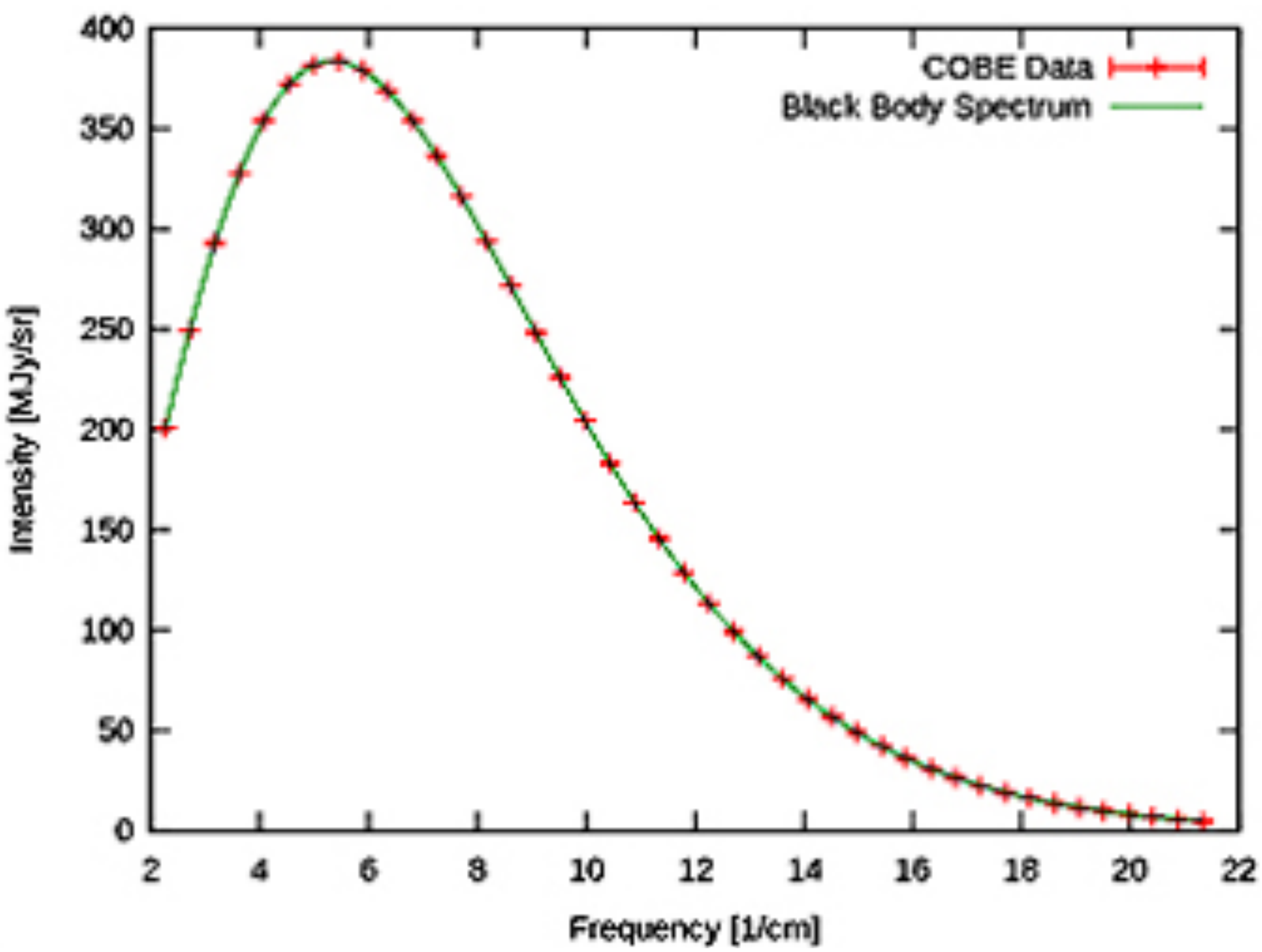
However, characterising the spectrum of the CMB took much longer, as most CMB photons are absorbed by water in the Earth's atmosphere.

Space-based observations of the CMB

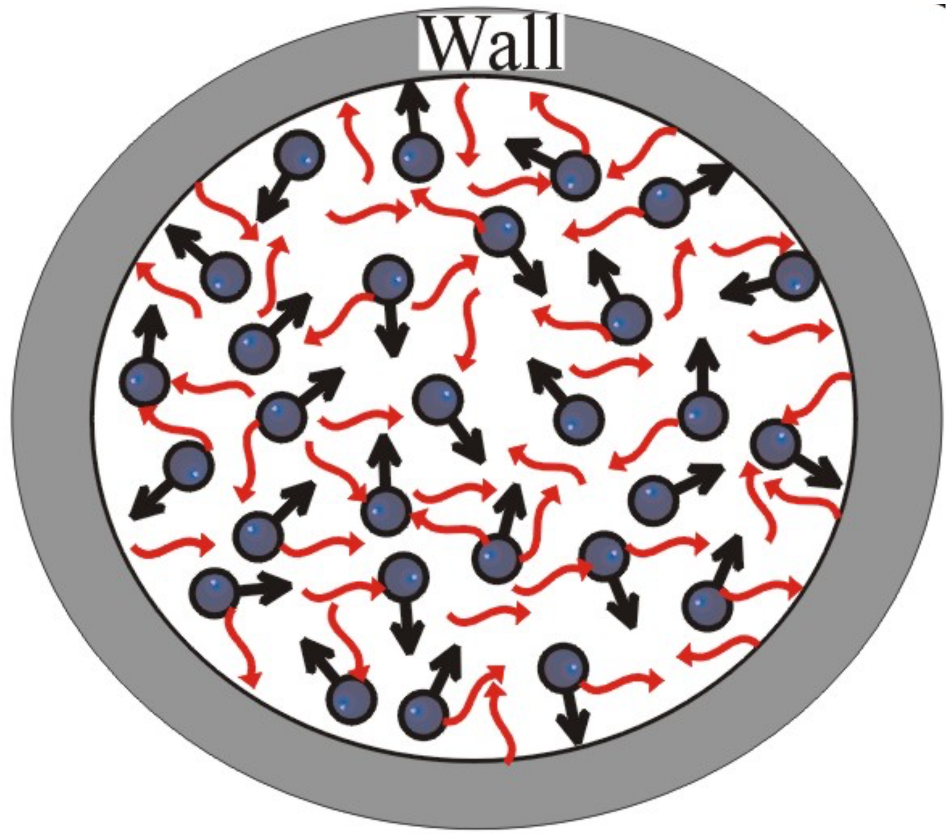


In 1992, the COBE satellite was launched to measure the spectrum of the CMB across a wide range of frequencies.

From it, astronomers discovered that at all positions, the spectrum of the CMB is a perfect blackbody (to within measurable tolerances):



CMB as a blackbody



The fact that the CMB has a (near) perfect blackbody spectrum tells us something very important:

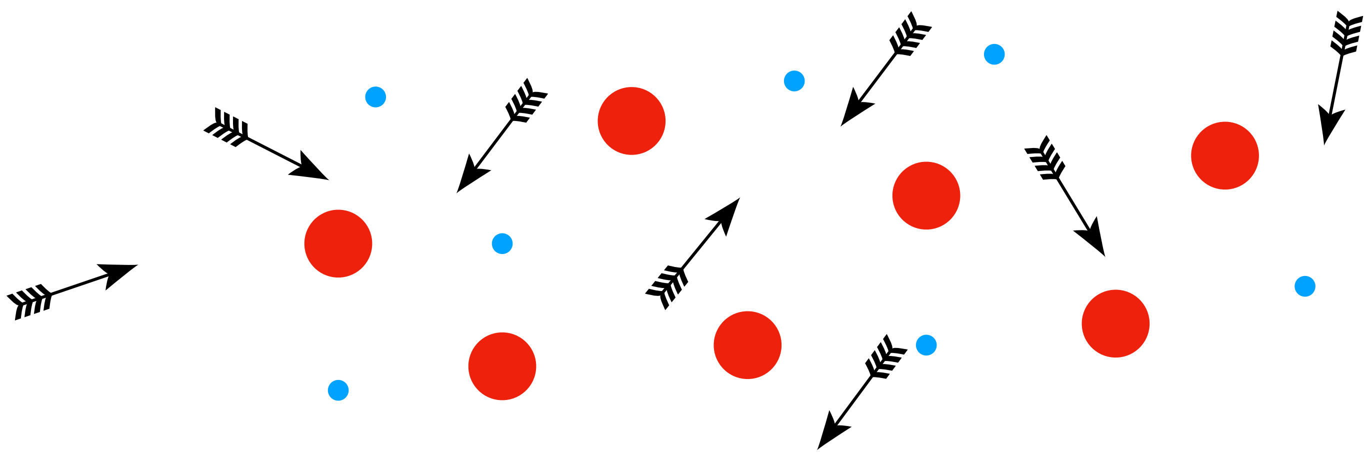
- when the CMB was produced, the Universe was opaque, dense and hot. In other words, it was a blackbody.

This is exactly what we'd expect if the Universe was once much smaller and much hotter than it is today, which is, in turn, what we'd expect in the Big Bang model.

But why isn't the Universe still a blackbody?

The early ionised Universe:

In the early Universe (z>1380):



In the early Universe, the typical CMB photon had an energy higher than the ionisation energy of H.

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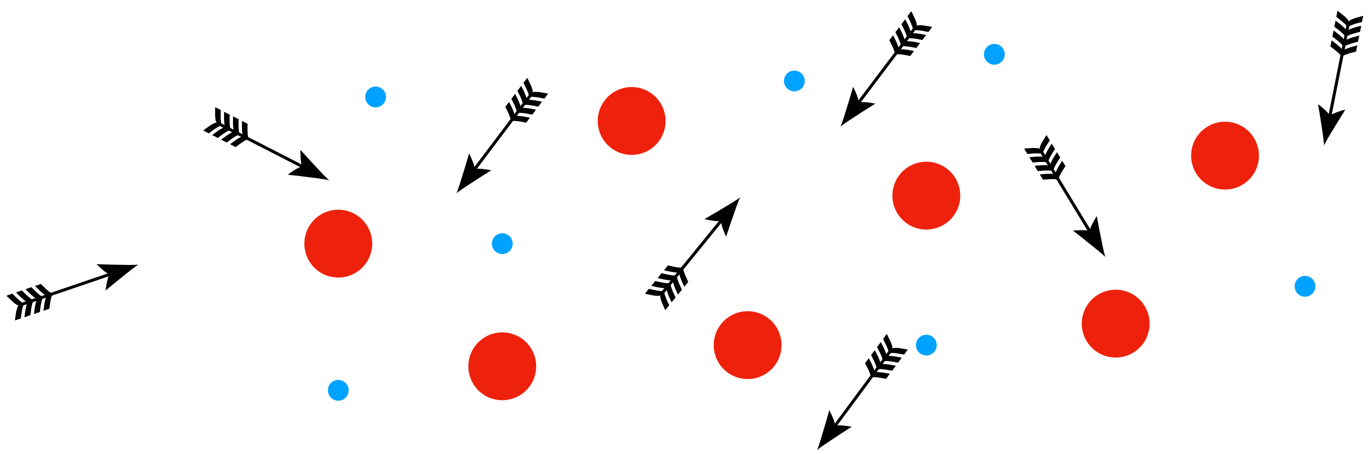

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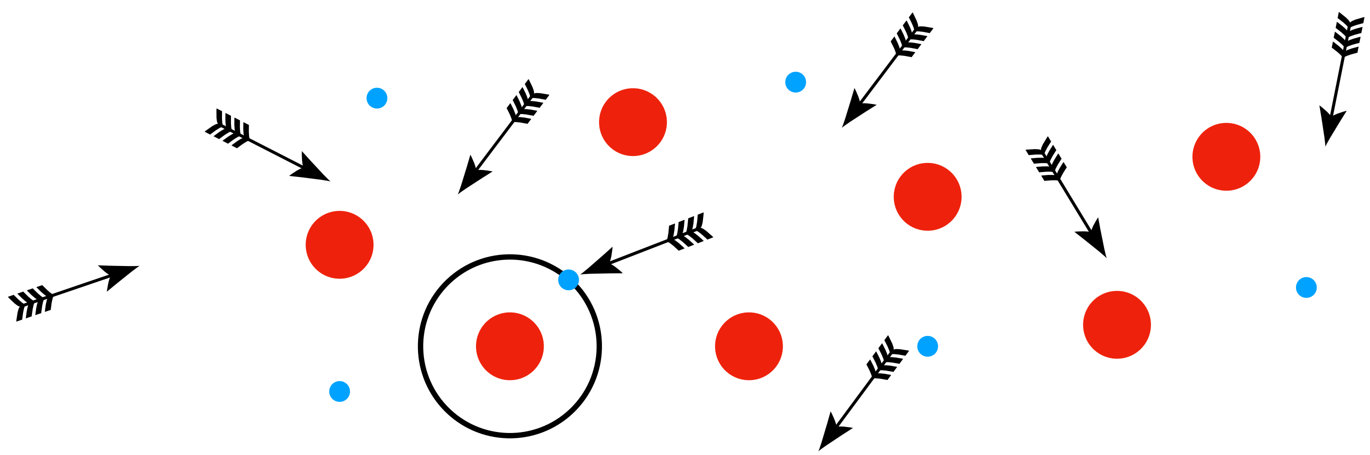

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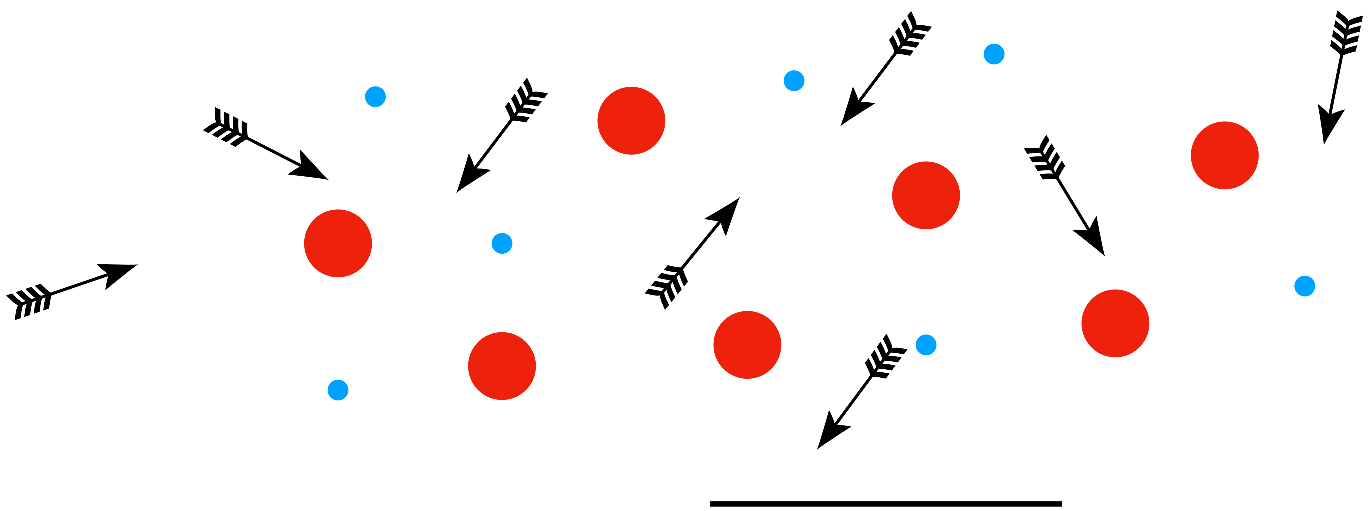

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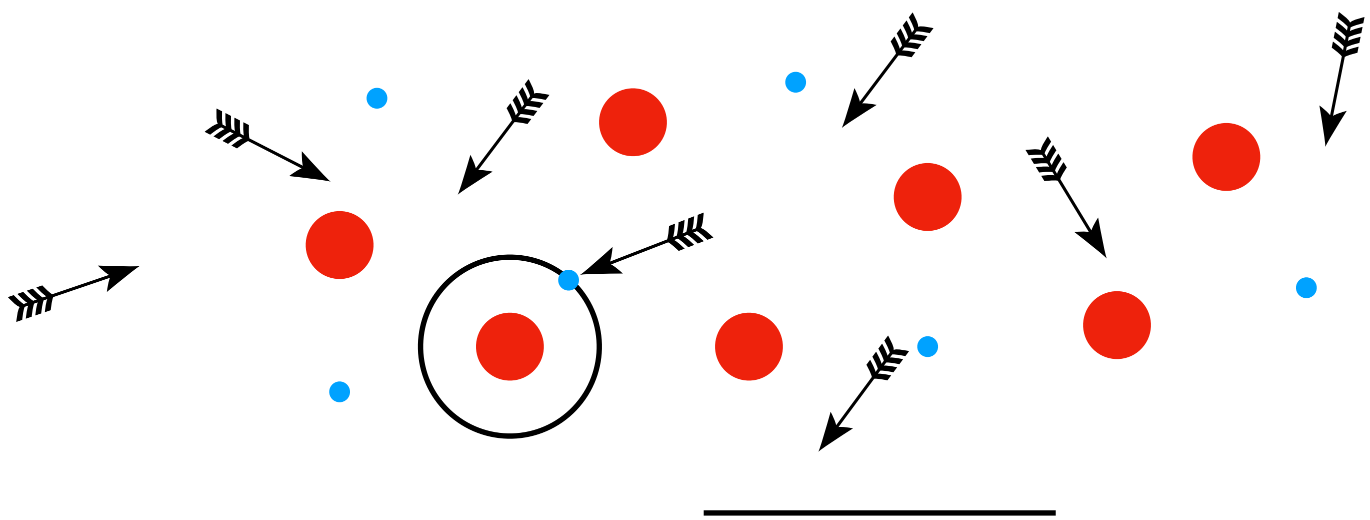

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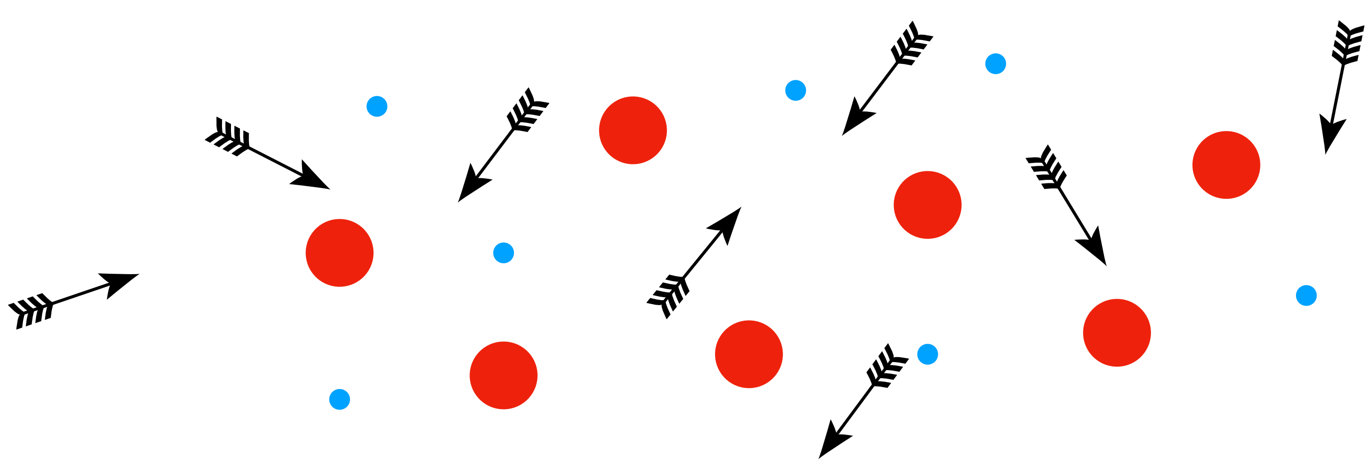


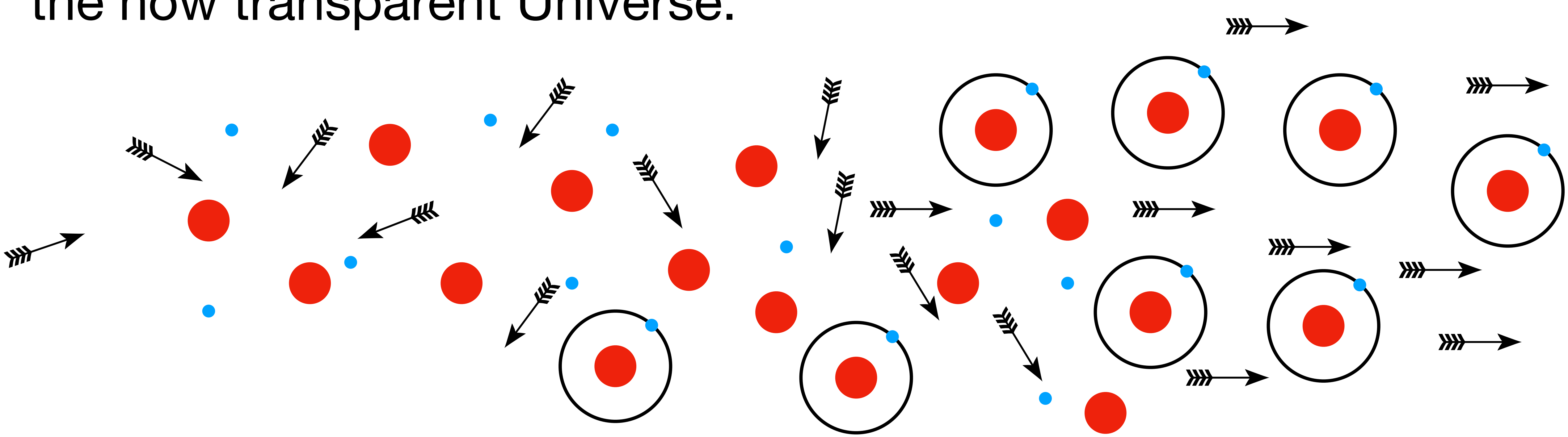
The free electrons have a high scattering cross section to photons, so the photons, electrons and protons remain in equilibrium.

Recombination

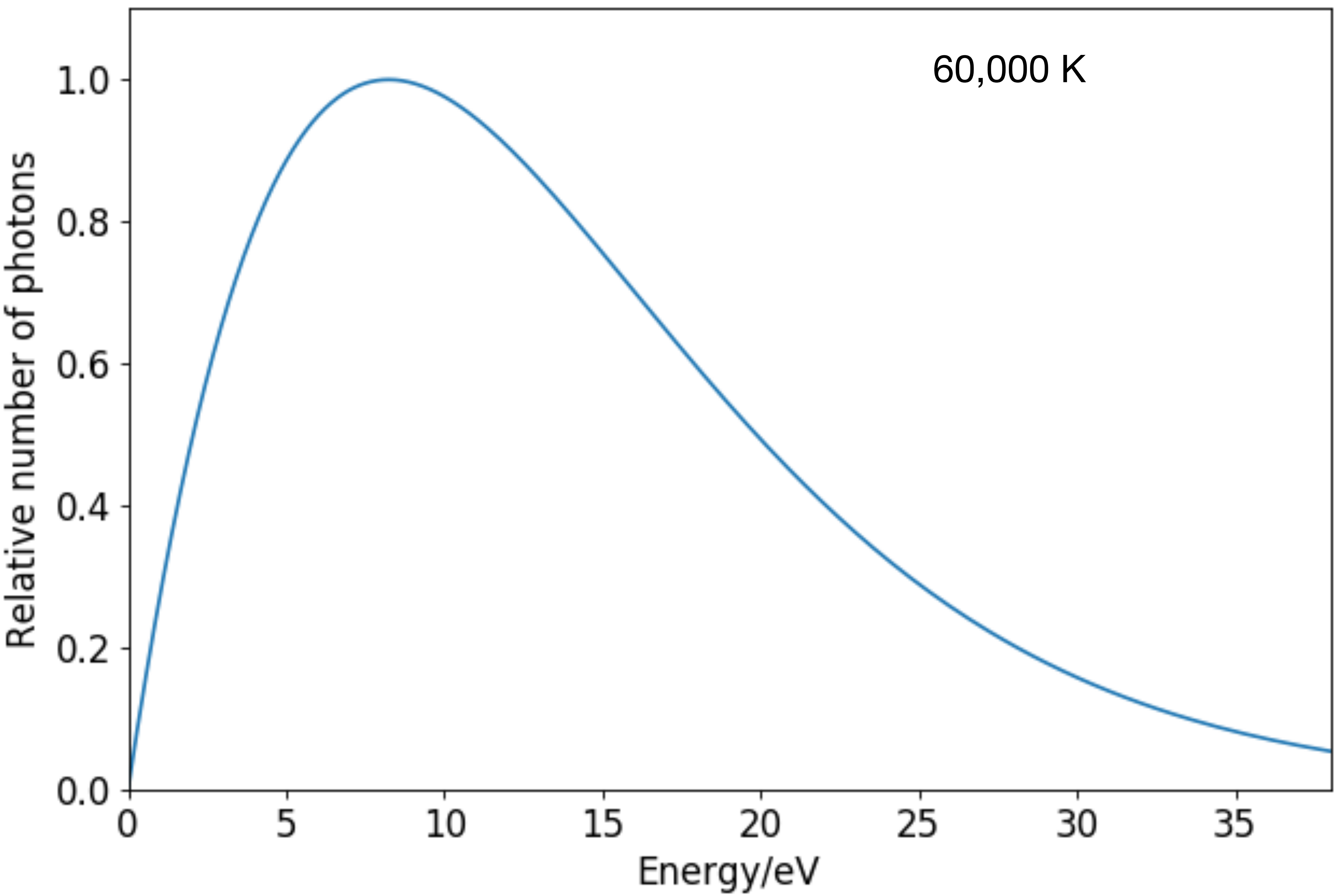
Eventually, the Universe cools enough for there to be insufficient numbers of high-energy photons to keep Hydrogen ionised.

After this point:

- Hydrogen atoms are not typically destroyed;
- Electrons are bound to protons;
- So photons become decoupled from the electrons and protons;
- The Baryonic matter in the Universe ceases to be a blackbody;
- The low-energy CMB photons stream unencumbered throughout the now transparent Universe.



When does recombination occur?



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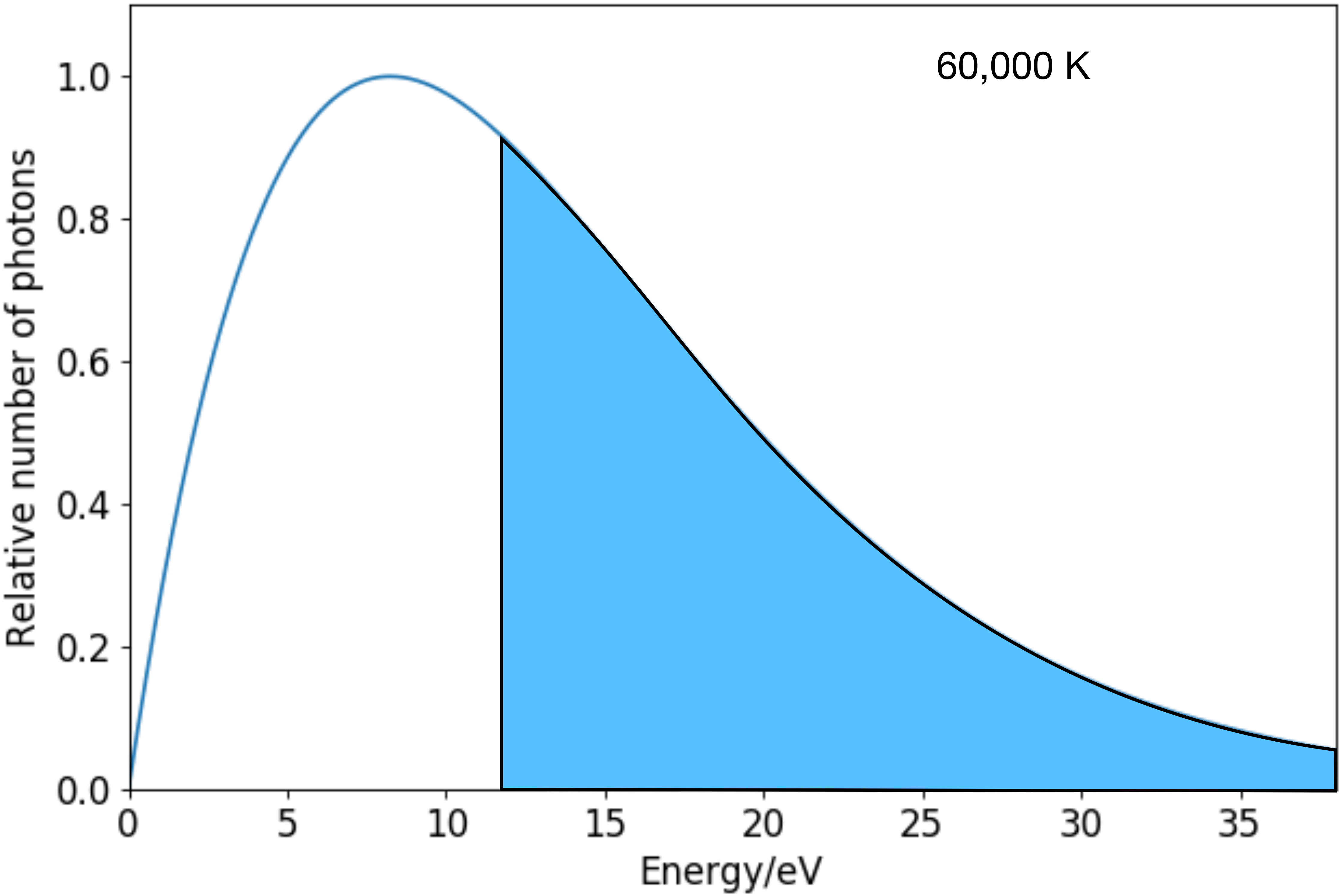

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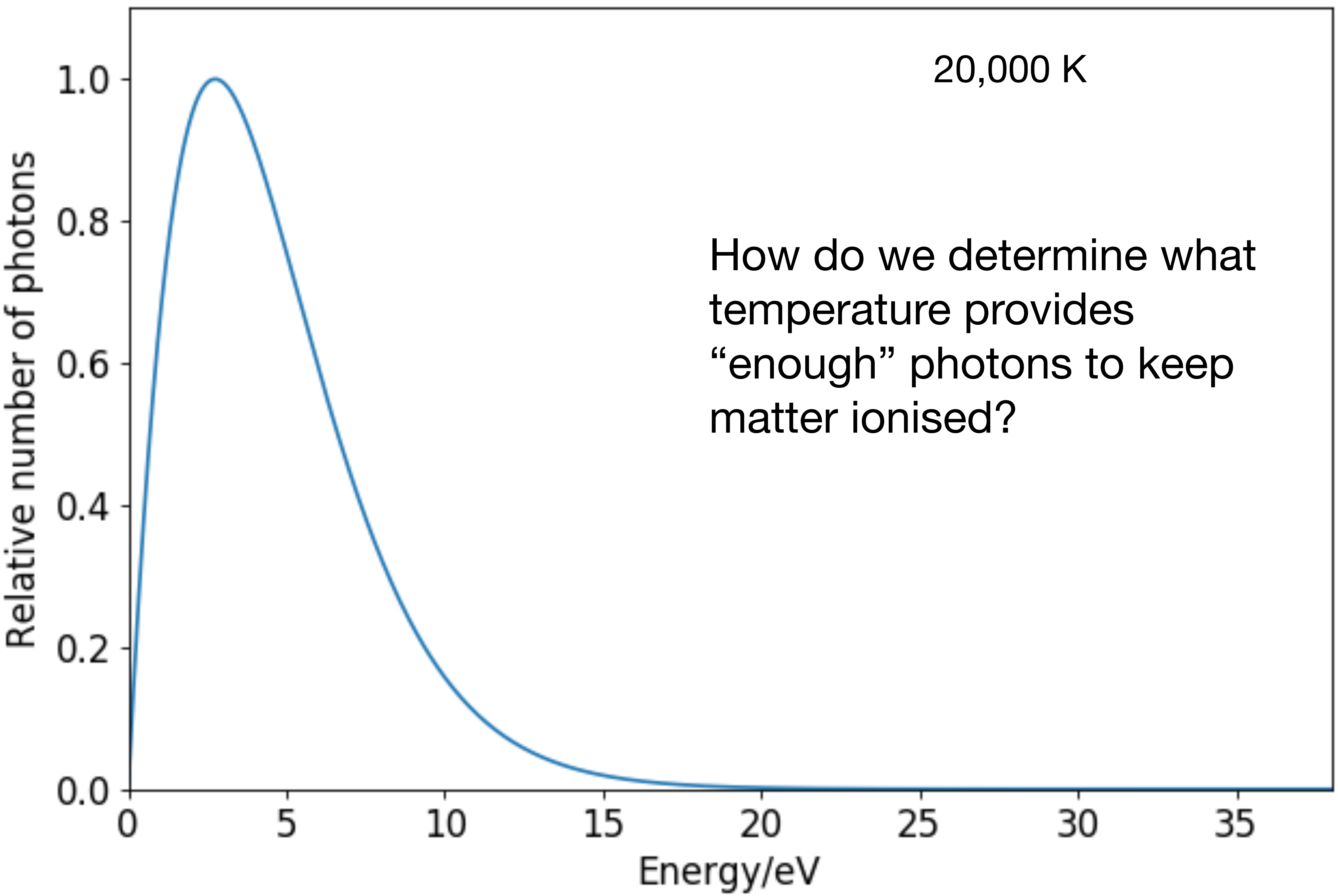

How do we determine what temperature provides “enough” photons to keep matter ionised?

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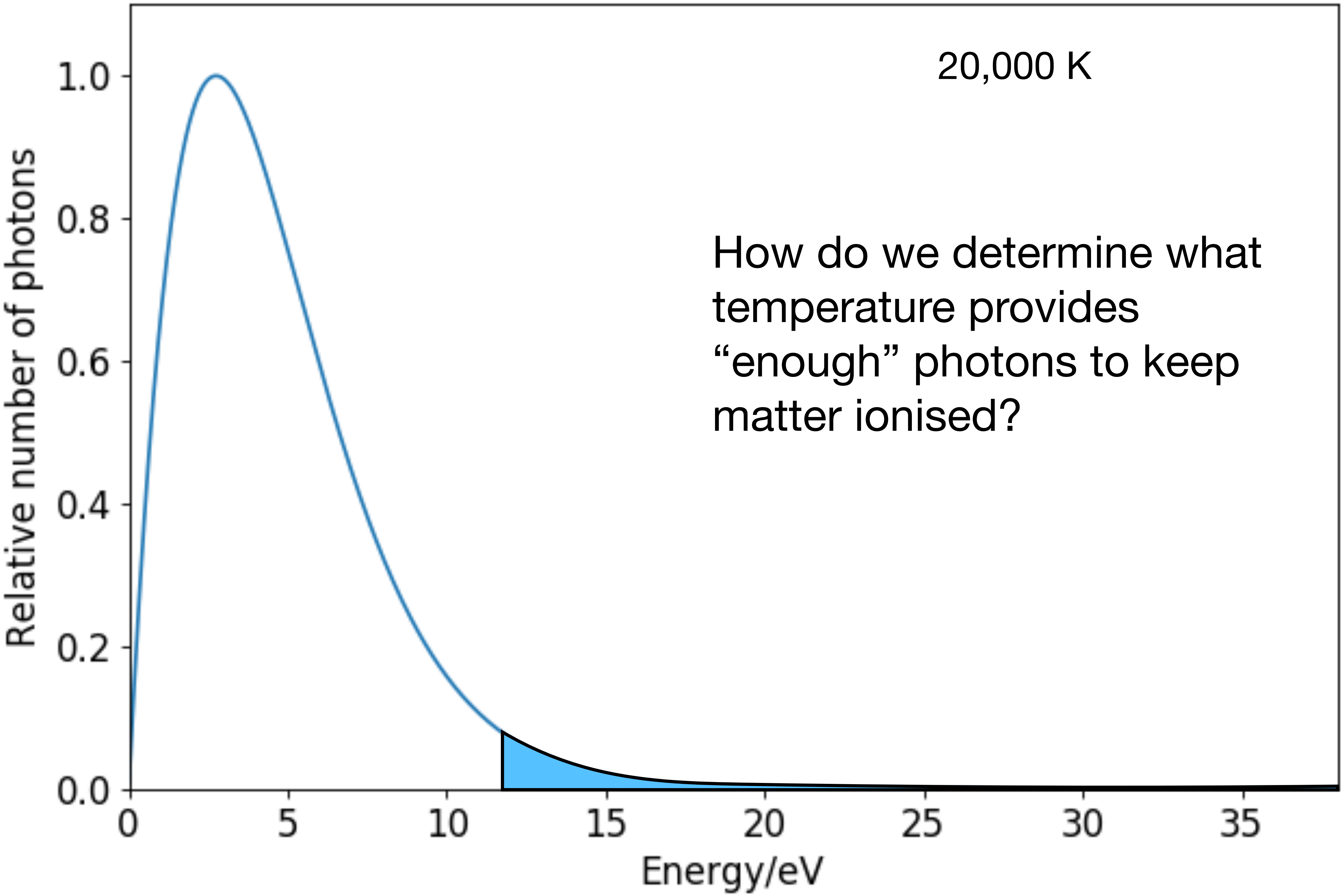


How do we determine what temperature provides "enough" photons to keep matter ionised?

The ionisation state of a gas

To determine the ionisation state of a gas, we use the **Saha equation**.

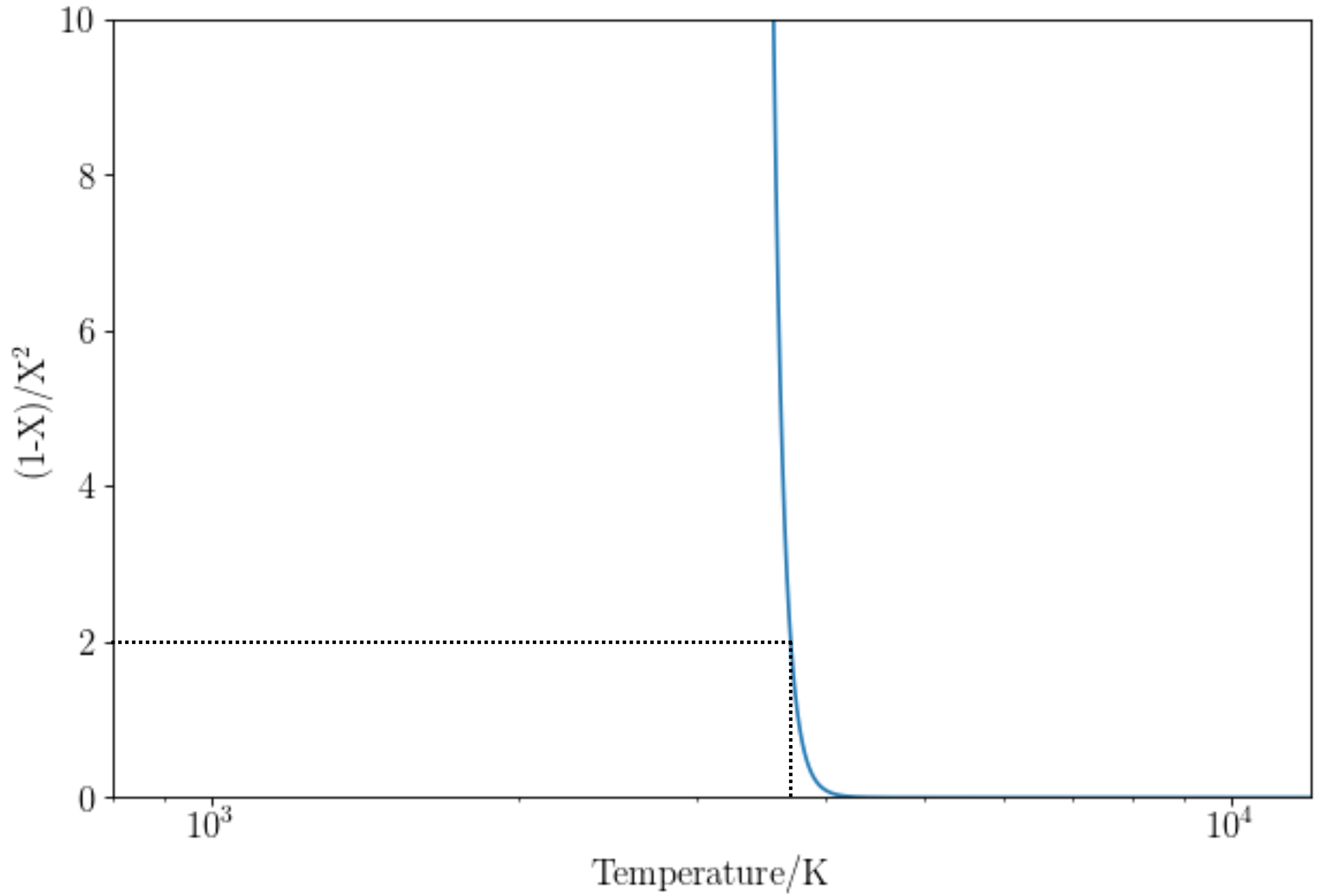
You encountered the Saha equation in the PHY305: Stellar Atmospheres course.

The Saha equation tells us the ratio of ionised to neutral atoms in a gas of a given temperature, *T*:

$$\frac{n_H}{n_p n_e} = \left(\frac{m_e k T}{2\pi\hbar^2}\right)^{-3/2} \exp\left(\frac{Q}{kT}\right)$$

where *Q* is the ionisation energy of the atom.

The temperature of recombination



X = 1/2 corresponds to $(1\text{-}X)/X^2 = 2$ which, reading from plot, corresponds to T=3760 K

When did recombination happen?

When the temperature of the Universe was 3760 K.

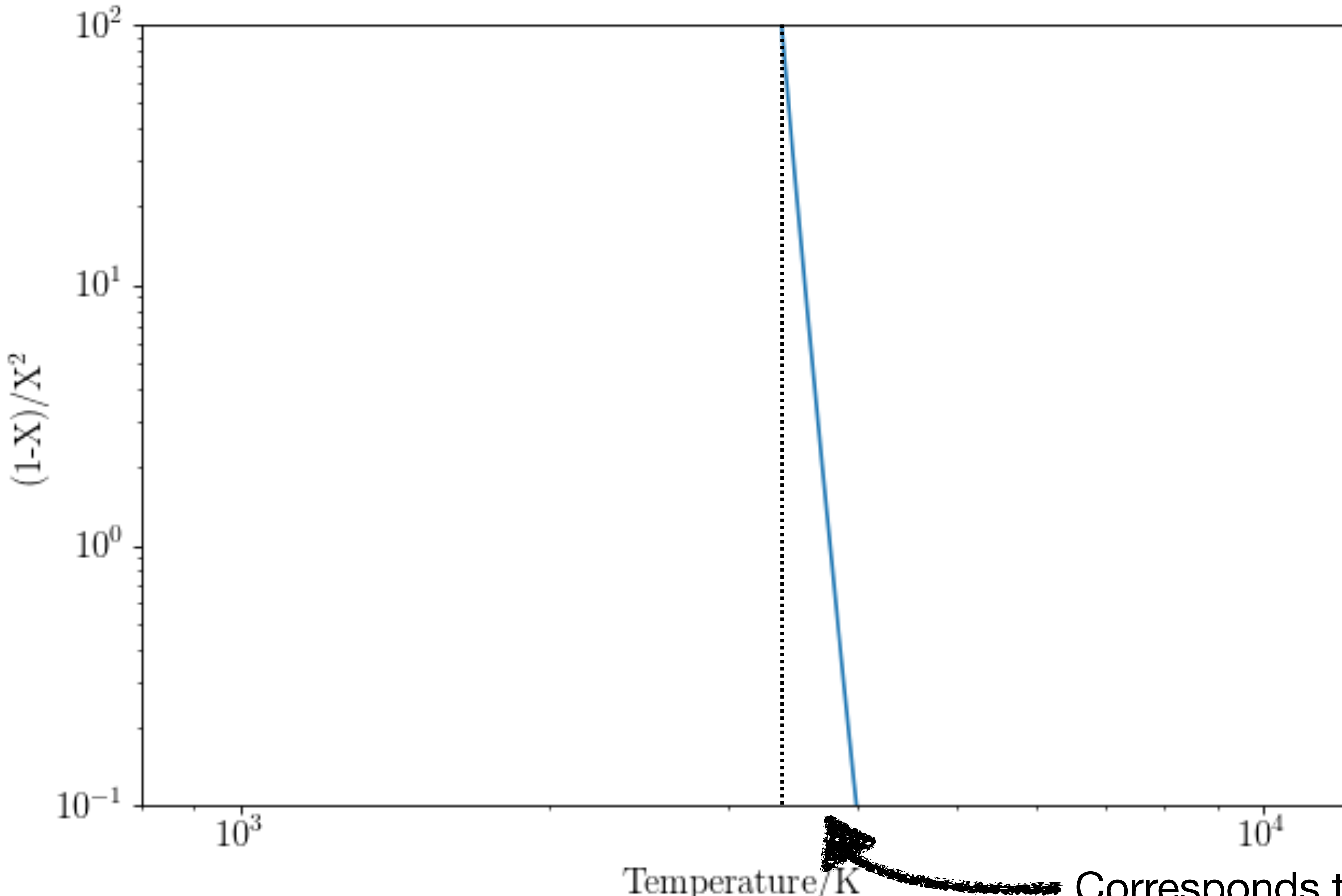
Using $T(a) = T_0/a$ (where T_0=2.755 K) this corresponds to:
$a(t) = 2.755/3760 = 7.3\text{x}10\text{-}4$
(i.e., when the Universe was about 1000 times smaller than today)

Which corresponds to a redshift of:
$z = 1/a(t) = 1376$

Which, in the Benchmark Model, corresponds to:
250,000 years after the Big Bang

The process of recombination

Although we have assumed X=1/2 to define the point of recombination, the actual process was not instantaneous:



X=0.9

X=0.5

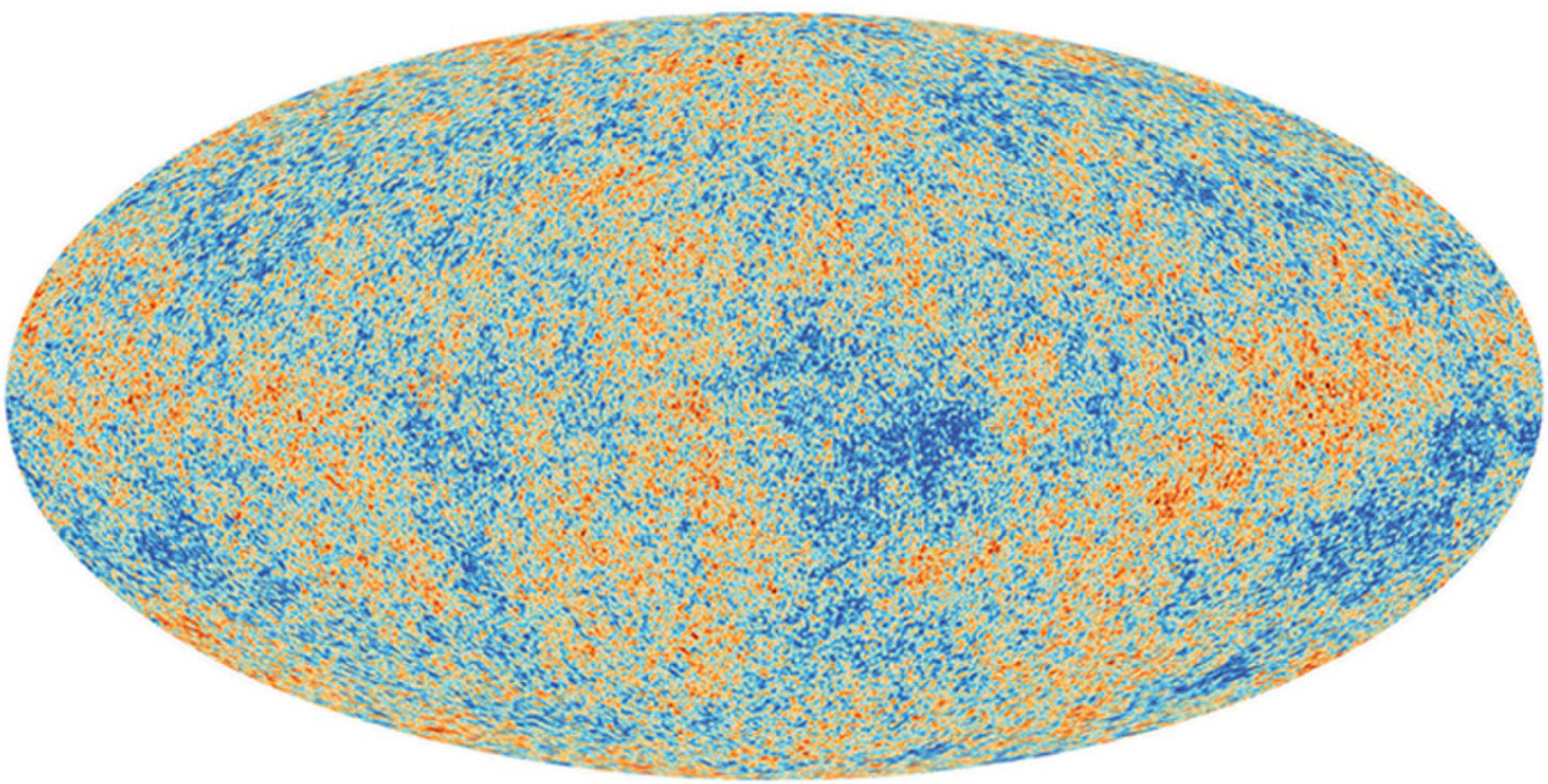
X=0.1

Corresponds to 70000 years

Photon decoupling

As we saw, once the protons and electrons have combined, photons are (largely) free to stream through the Universe without interacting with matter.

They are gradually redshifted as the Universe expands to produce the cosmic microwave background we see today:



Getting the feel for it:

CMB photons *massively* outnumber the number of other photons in the Universe.

There are roughly 1.6 billion CMB photons for every Baryon in the Universe.

The blackbody form of the CMB tells us that, at some earlier time, radiation and matter were in close thermal equilibrium.

This equilibrium broke when the number density of ionising photons dropped to a small number allowing protons and electrons to recombine.

The left-over photons have been streaming through the Universe ever since.