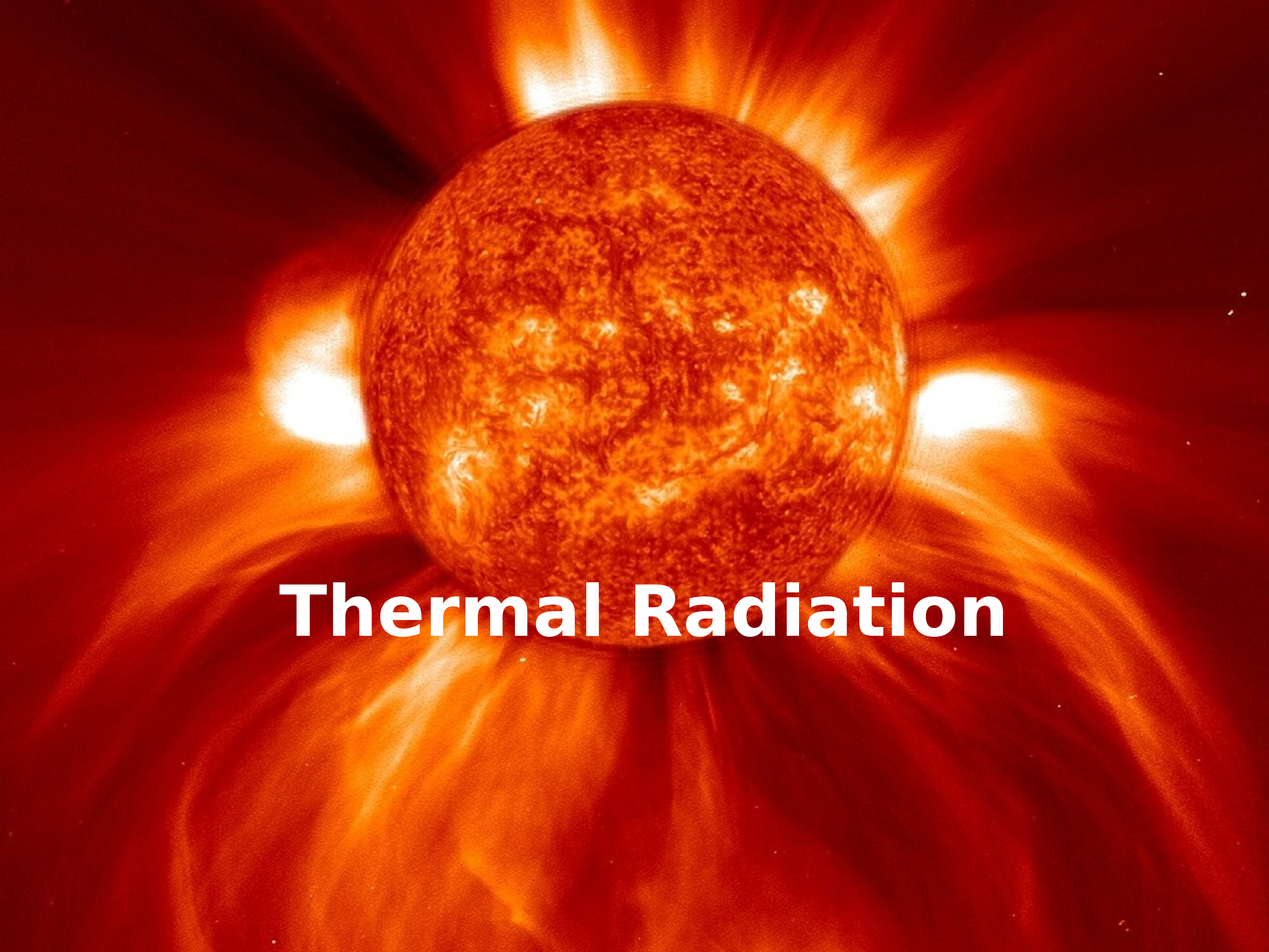


Thermal Radiation

Thermal Equilibrium

Thermal Radiation is radiation emitted by **matter** in thermal equilibrium

Thermal Equilibrium: Two physical systems are in thermal equilibrium if no heat flows between them when they are connected by a path permeable to heat.

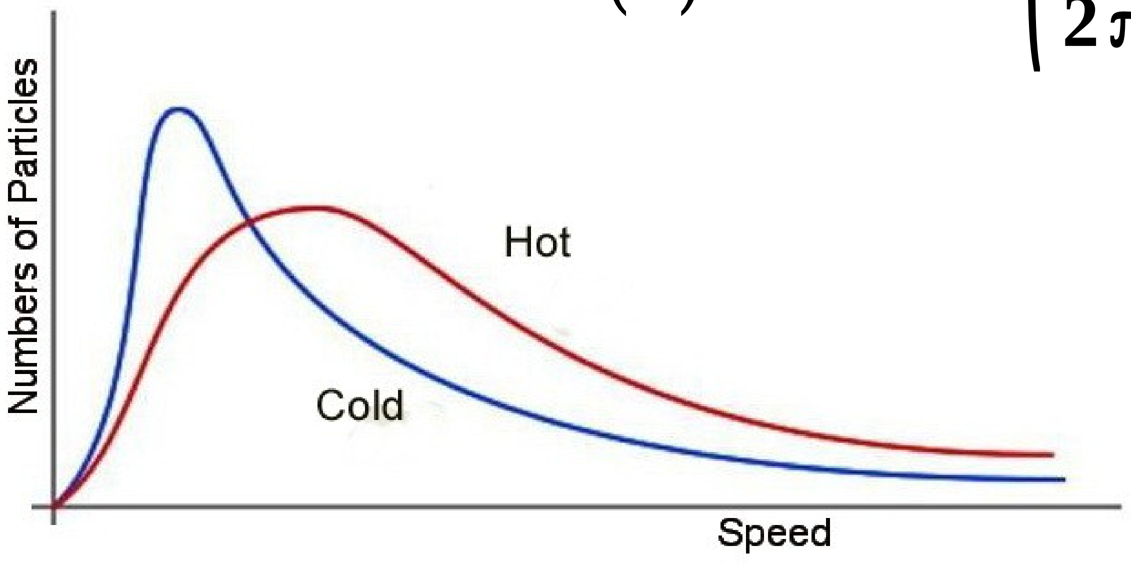
Important: there is a reason why I highlighted the word **matter**. Indeed radiation does not necessarily need to be in thermal equilibrium to have thermal radiation.

Matter in Thermal Equilibrium

Suppose to have a plasma in thermal equilibrium (*thermal plasma*). What does this mean in terms of micro-physical properties of the matter?

Probability distribution function of (non-relativistic) velocities is the Maxwell-Boltzmann distribution:

$$F(v)\,dv = 4\pi v^2 \left(\frac{m}{2\pi k T}\right)^{3/2} e^{-mv^2/2kT}\,dv$$



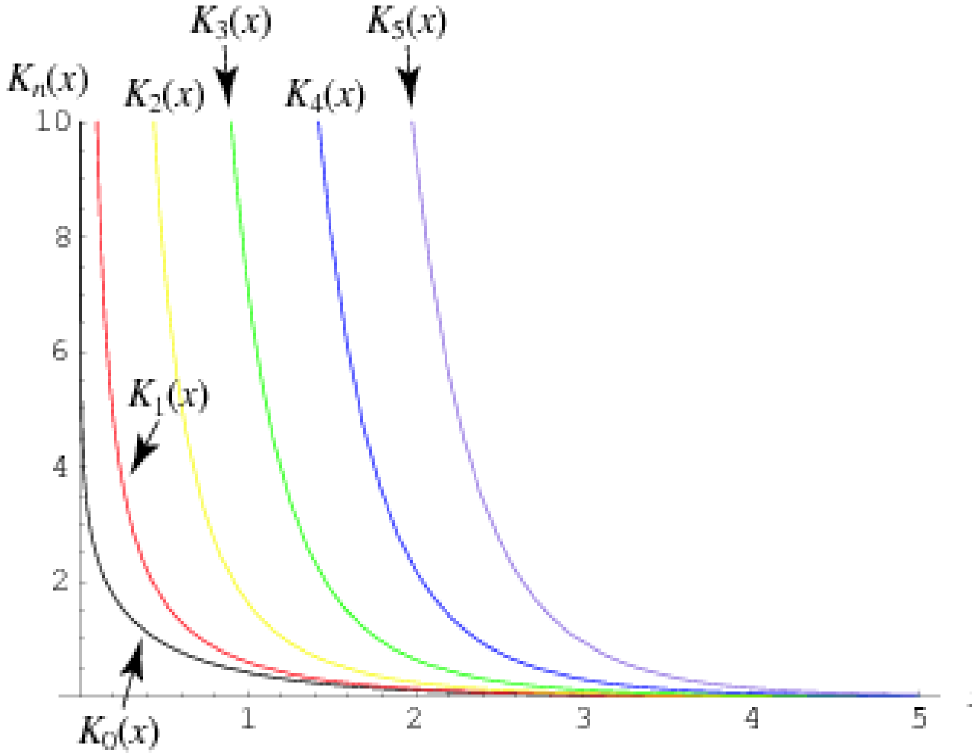
Matter in Thermal Equilibrium

The Maxwell-Boltzmann distribution written in this way is valid only for non-relativistic particles. We will find many astrophysical systems where particles have relativistic speeds and they emit thermal radiation.

$$p = \gamma \beta m c$$

$$F(p)\,dp = \frac{p^2 e^{-\gamma\Theta}}{\Theta m^3 c^3 K_2(1/\Theta)}\,dp$$

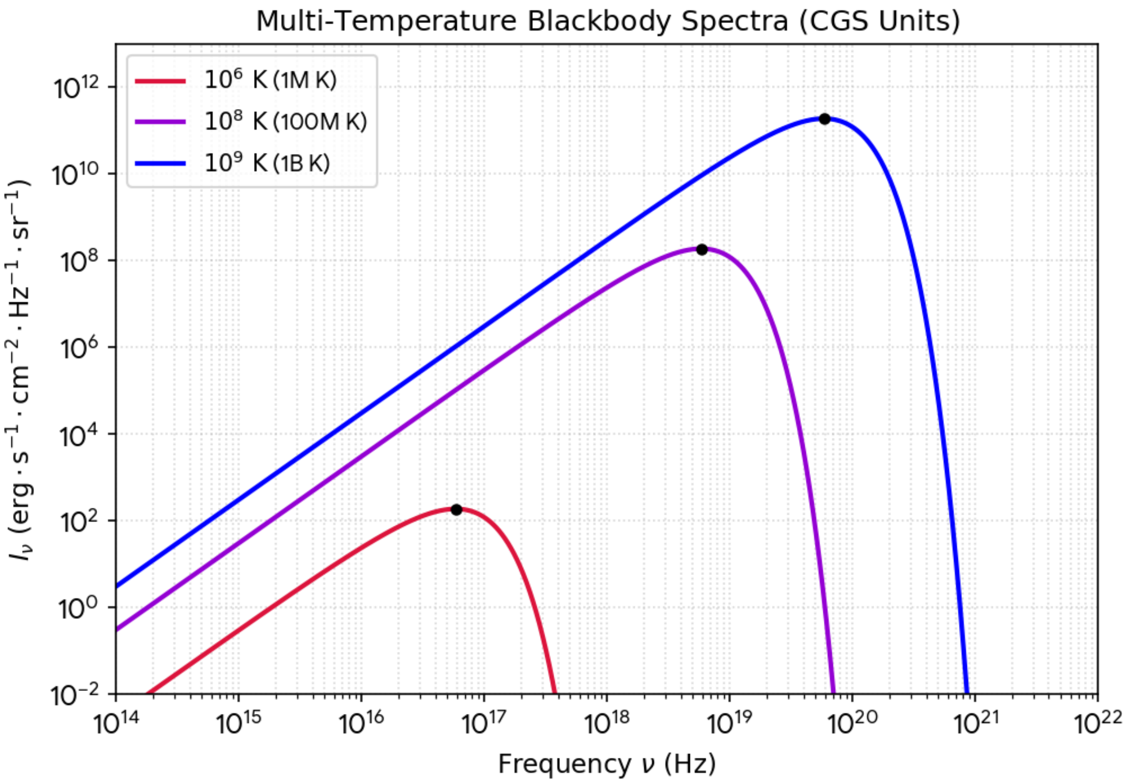
Modified Bessell Function of the 2nd kind



This form is valid in BOTH the relativistic and non-rel. limit

Properties of the Planck Spectrum

$$I_\nu = B_\nu(T) = \frac{2h\nu^3/c^2}{\exp(h\nu/kT) - 1}$$



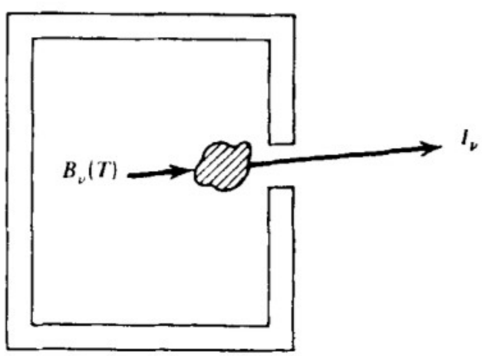
Thermal emission produces photons that can hardly reach gamma-ray energies.

This is because even a T=10^9 K blackbody produces at most photons with energy ~ 1MeV.

Kirchoff's Law

If you place a body with temperature T inside a cavity in thermal equilibrium, what will happen?

The cavity + body is *still a blackbody enclosure* at temperature T (remember we just said that it does not matter how the enclosure is made)



Therefore the source function of the body is:

$$S_\nu = B_\nu(T) \rightarrow j_\nu = \alpha_\nu B_\nu(T)$$

Remember: the source function is the ratio of local emission to absorption; it describes the balance point that the local matter imposes on the radiation field, inside the material or at the surface.

Thermal Radiation	$S_\nu = B_\nu(T)$
Blackbody Radiation	$I_\nu = B_\nu(T)$

Planck Spectrum

As we have stated before an example of thermal radiation is blackbody radiation.
But the opposite is not generally true: thermal radiation is not necessarily blackbody radiation

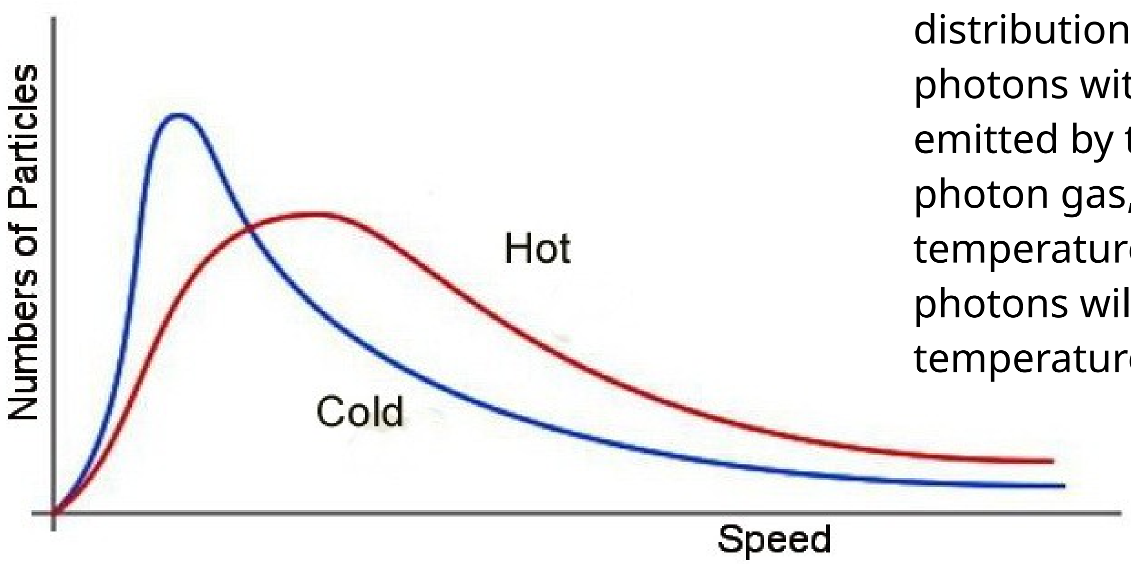
Blackbody → Thermal

Thermal $\nrightarrow$ Blackbody

Blackbody radiation is generated by an optically thick medium emitting thermal radiation

Blackbody Radiation as a Photon Gas

In a classical ideal gas with massive particles, the energy of the particles is distributed according to a Maxwell–Boltzmann distribution. This distribution is established as the particles collide with each other, exchanging energy (and momentum) in the process. In a photon gas, there will also be an equilibrium distribution, but photons do not collide with each other (except under very extreme conditions, see two-photon physics), so the equilibrium distribution must be established **by other means**.

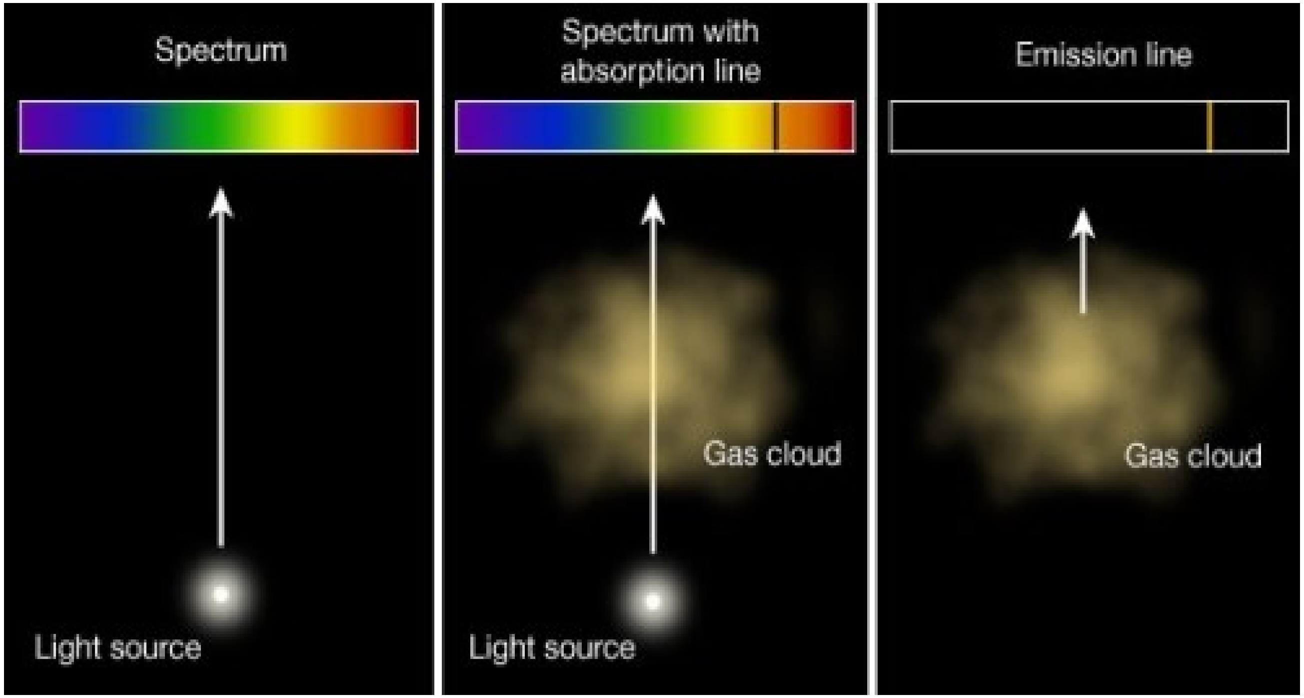


The most common way that an equilibrium distribution is established is by the interaction of the photons with matter. If the photons are absorbed and emitted by the walls of the system containing the photon gas, and the walls are at a particular temperature, then the equilibrium distribution for the photons will be a black-body distribution at that temperature.

Understanding Kirchhoff's Law

Now we are in position to understand Kirchhoff's laws in the light of the equation of radiative transfer.

1. A hot dense gas produces light with a continuous spectrum.
2. A hot dense gas surrounded by a cool tenuous gas produces light with a continuous spectrum which has gaps at discrete wavelengths.
3. A hot tenuous gas produces light with emission lines at discrete wavelengths



Understanding Kirchhoff's Law

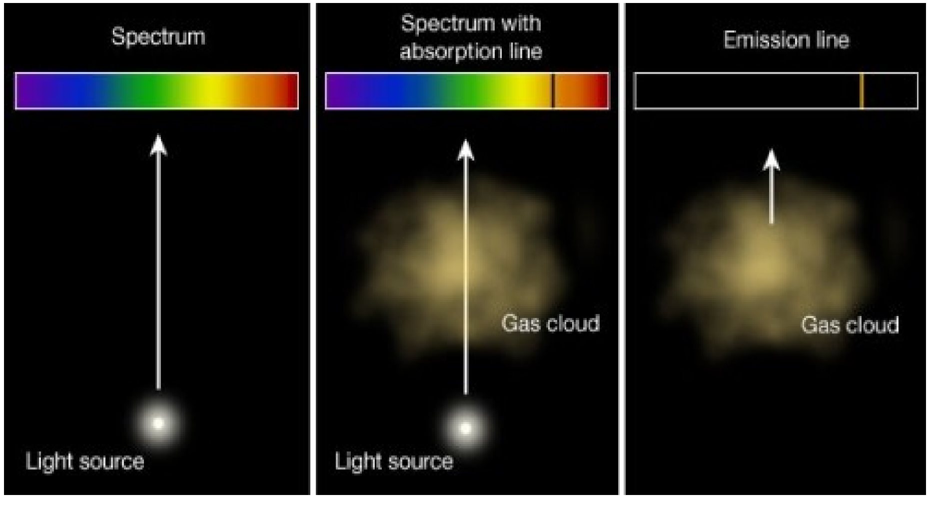
1. A hot dense gas produces light with a continuous spectrum.

Consider (for simplicity) that the initial surface brightness is zero $I_\nu(0)=0$

Then: $I_\nu = S_\nu(1-e^{-\tau_\nu})$

Since the gas is dense, the optical depth is >>1. Therefore: $I_\nu = S_\nu = B_\nu$

And this implies that what you will see is a blackbody spectrum (Planck spectrum)



Understanding Kirchhoff’s Law

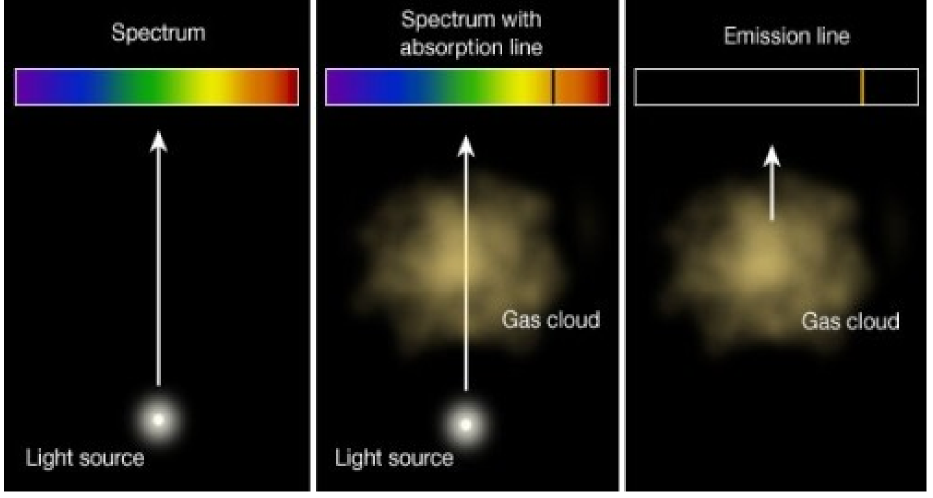
2. A hot dense gas surrounded by a cool tenuous gas produces light with a continuous spectrum which has gaps at discrete wavelengths.

In this case there is a background (initial) specific emissivity, i.e., the one of the hot gas which we know is a blackbody. Therefore: $I_\nu(0) = B_\nu$

The cold gas instead is not emitting (or, more correctly, has negligible emission when compared to the hot gas and thus: $S_\nu \approx 0$

Therefore: $I_\nu = B_\nu e^{-\tau_\nu}$

The intensity is a Planck continuum, lowered where the optical depth is high. And where does the optical depth become high? Only at those frequencies that correspond to the absorption energies of the cold atoms. Thus, we see absorption lines.

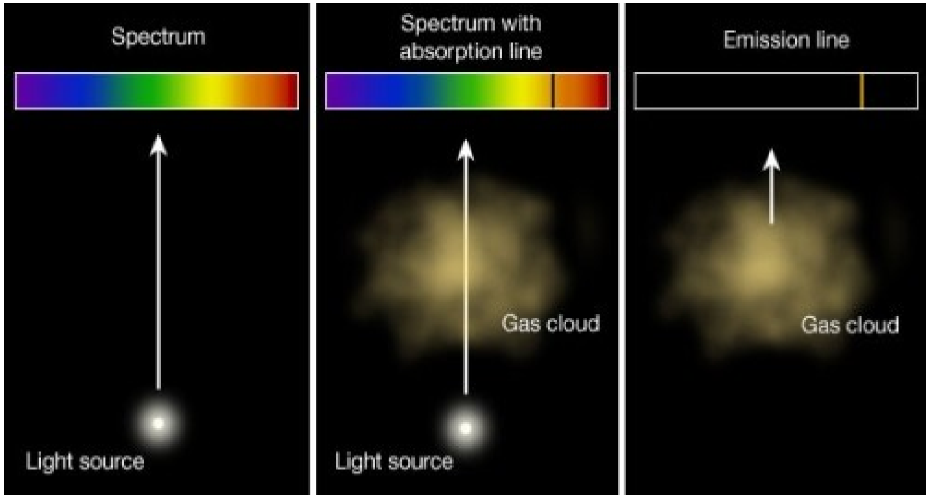


Understanding Kirchhoff's Law

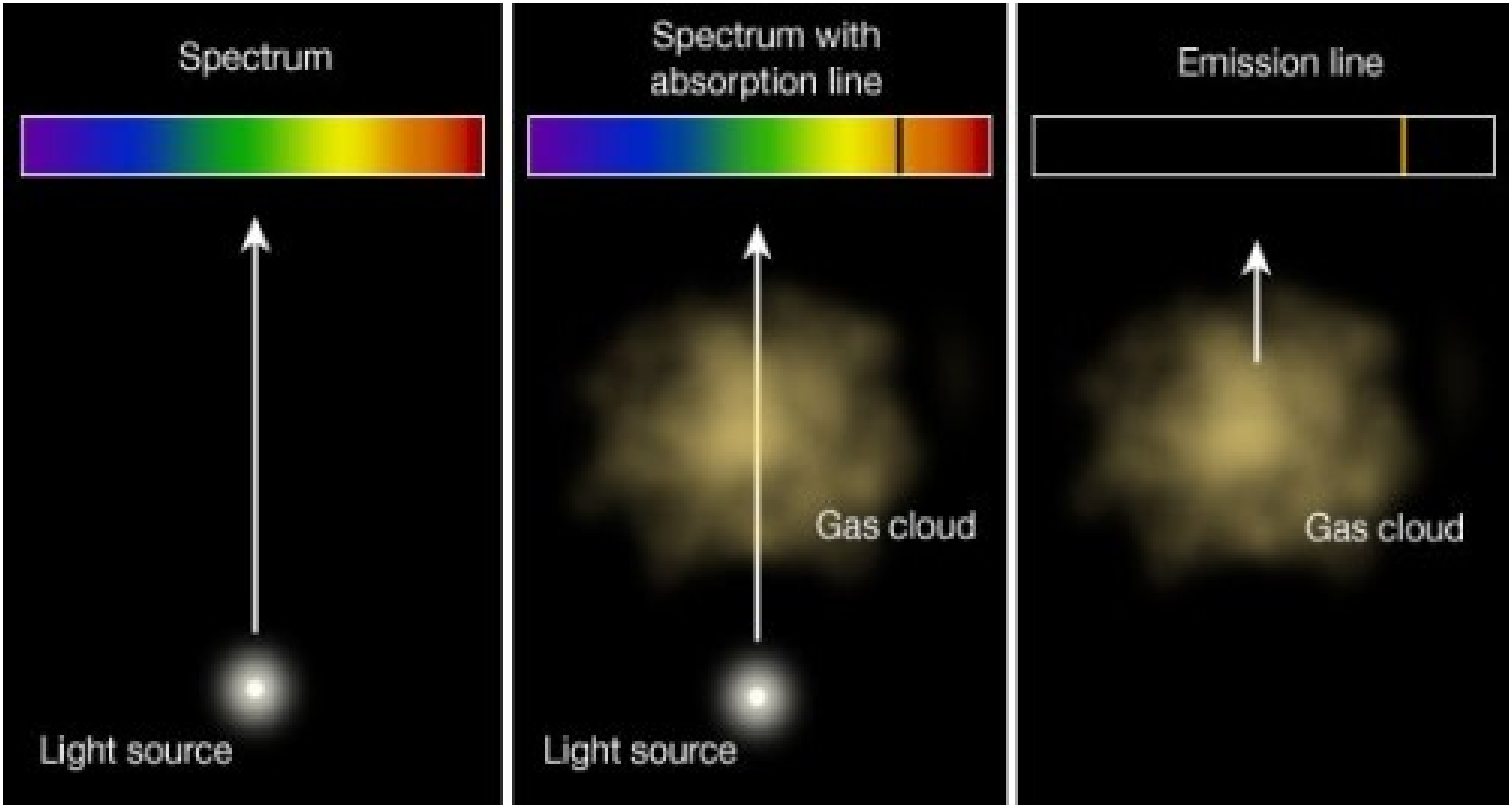
3. A hot tenuous gas produces light with emission lines at discrete wavelengths

In the optically thin case $I_\nu = S_\nu (1 - e^{-\tau_\nu}) \approx S_\nu (1 - 1 + \tau_\nu) = S_\nu \tau_\nu$

The intensity will be high where the optical depth is high. Since there is no background intensity, these are seen as emission lines.



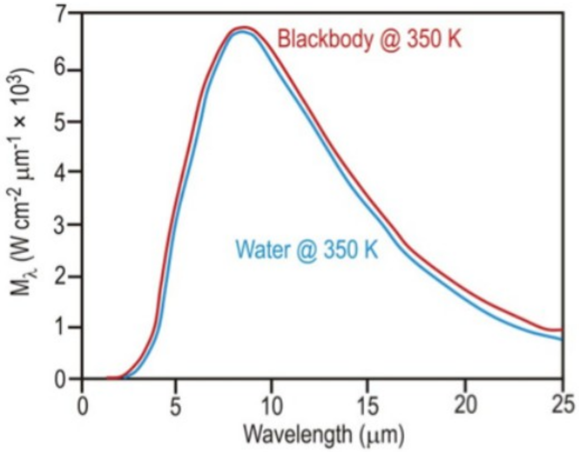
Principle of Detailed Balance



At equilibrium, each elementary process should be equilibrated by its reverse process.

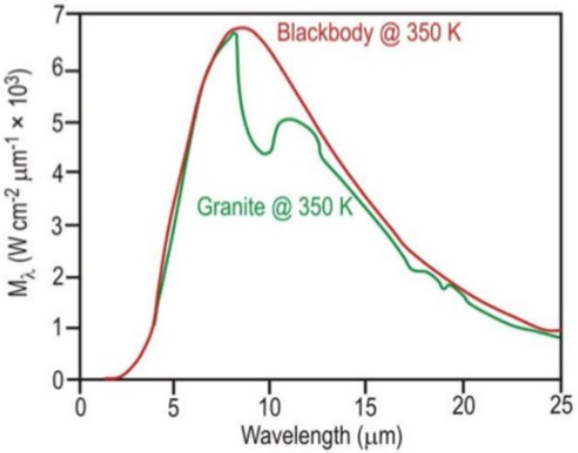
This principle has been derived here by using Kirchhoff's law, which requires that matter is in thermal equilibrium. However, as we will see it is valid also for non-thermal emission

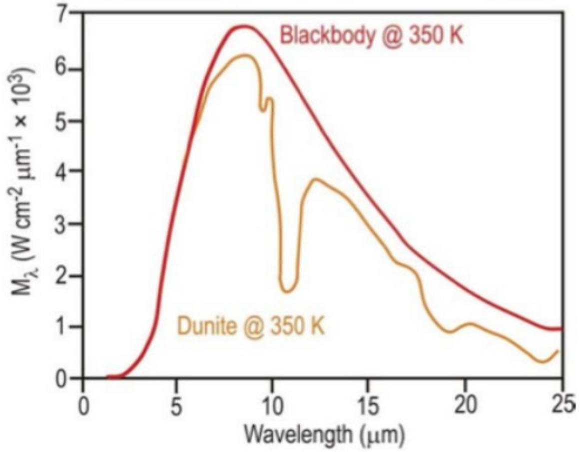
Clarification on Kirchhoff's Law



$$S_\nu = \frac{j_\nu}{\alpha_\nu} = B_\nu(T)$$

A good absorber is a good emitter
A good emitter is a good absorber



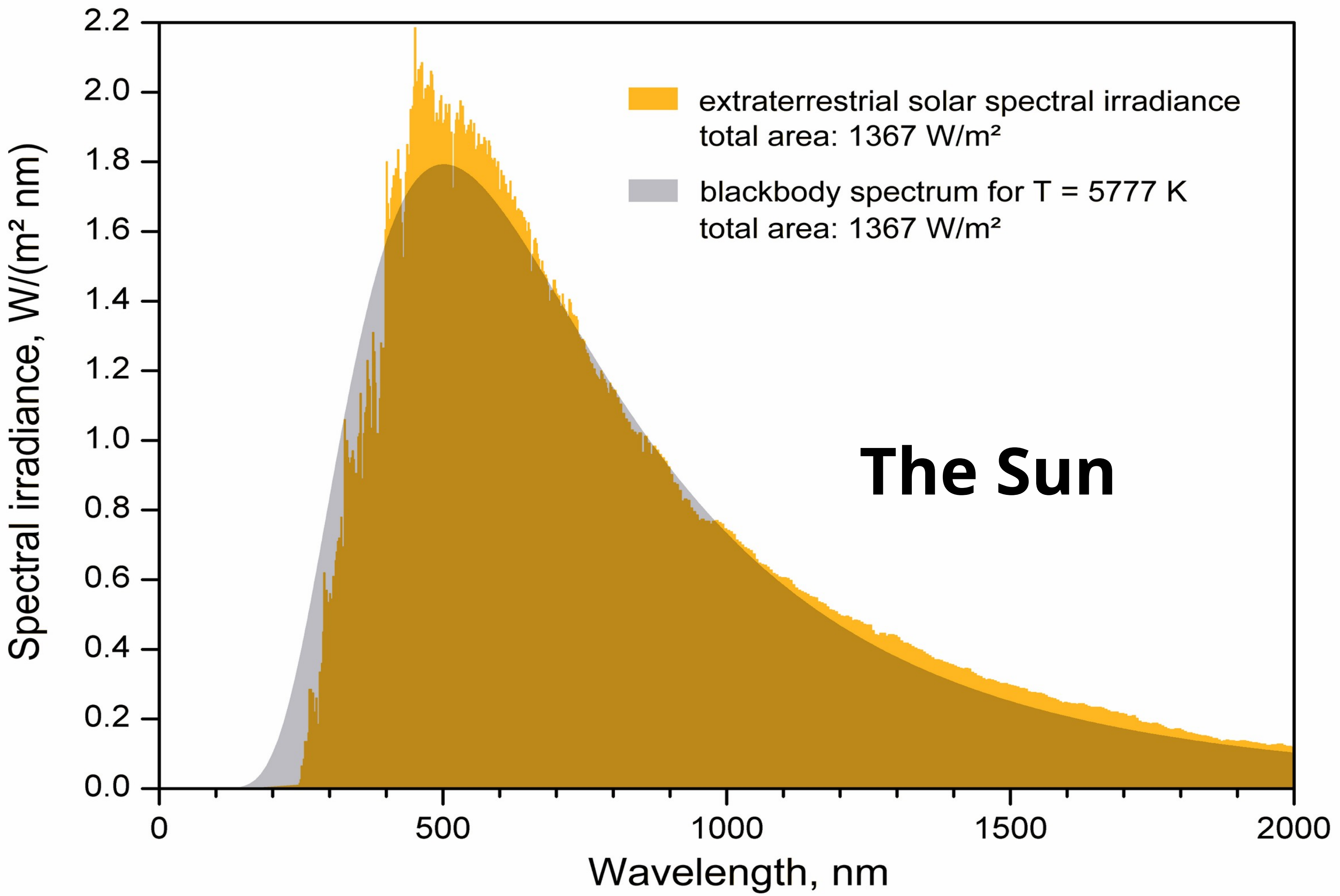


Another intuitive rule:
-The source function is a property of the **emitting material**
-The specific intensity if a property of the **radiation field**

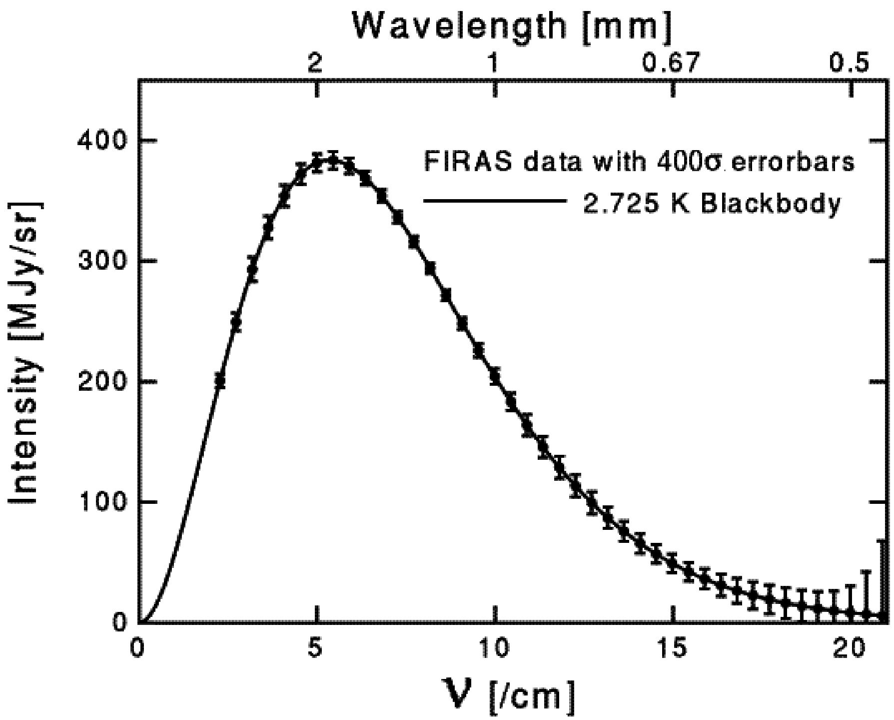
It was proved for objects in fully thermodynamic equilibrium but it is applicable to any object in thermal equilibrium.

It is NOT applicable for non-thermal emitters (e.g., synchrotron, shocks, etc.)

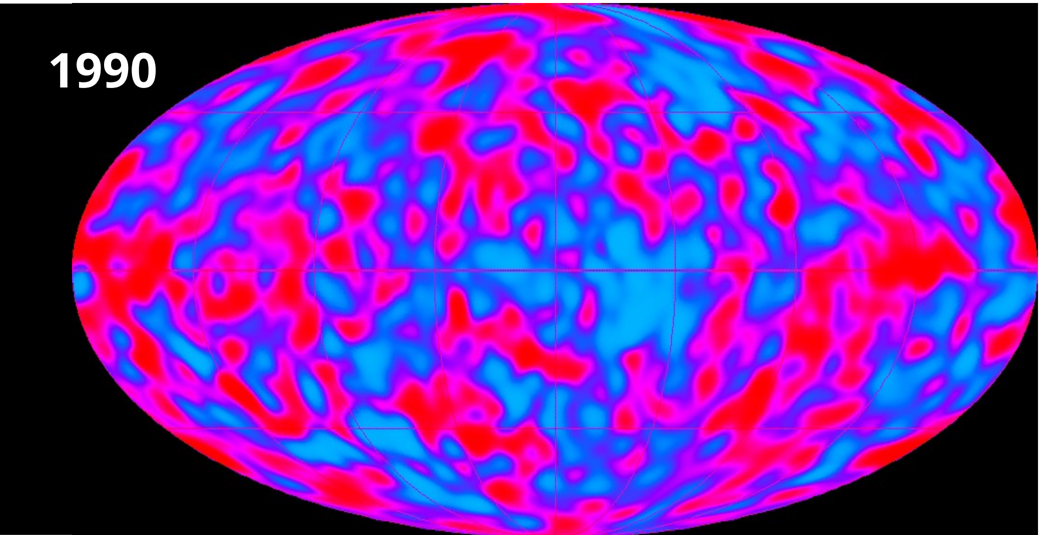
Stellar Spectra: blackbody emitters

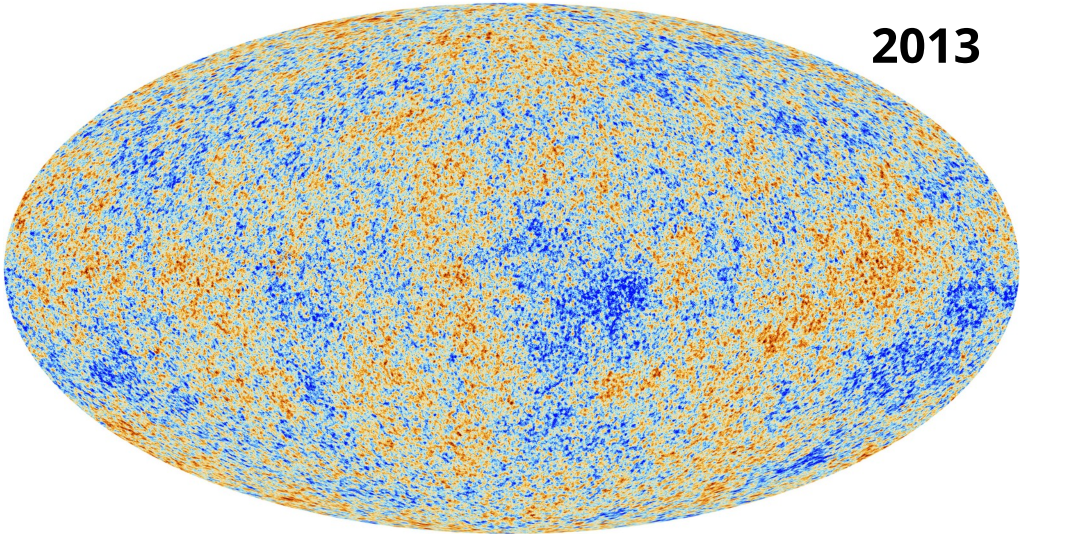


Cosmic Microwave Background

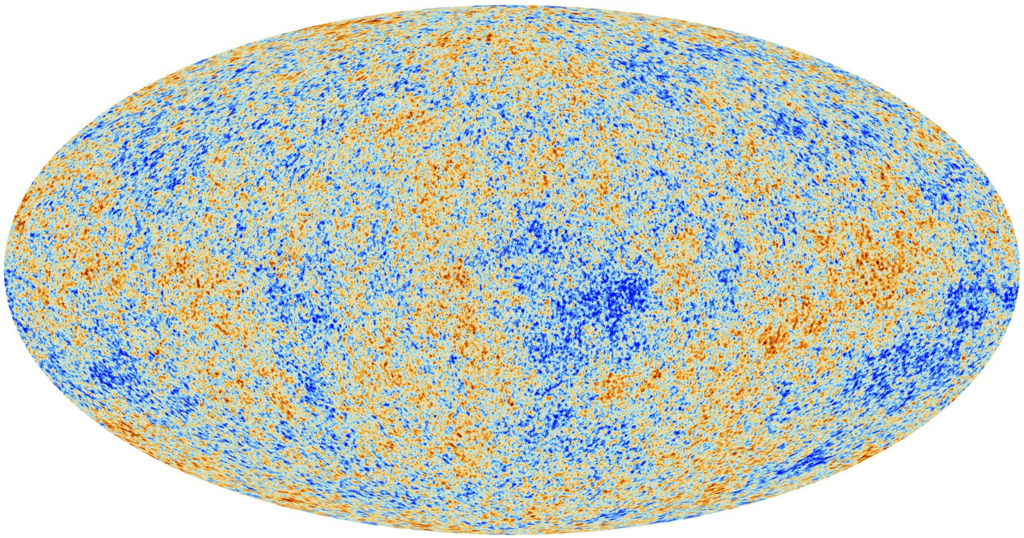


Deviation from a 2.725 K Blackbody: 1/100.000





Cosmic Microwave Background



CMB shows that radiation in the early universe was close to a perfect BB.

Therefore, since a BB has maximum entropy, radiation was in thermal equilibrium.

Matter was also in thermal equilibrium since it has thermalized radiation in such a perfect way.

Question: why do we say then that the Universe was born with a very **low** entropy? CMB seems to suggest the exact opposite. How is this possible?