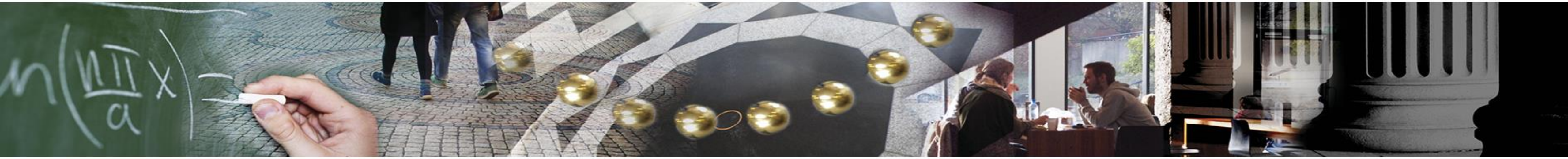
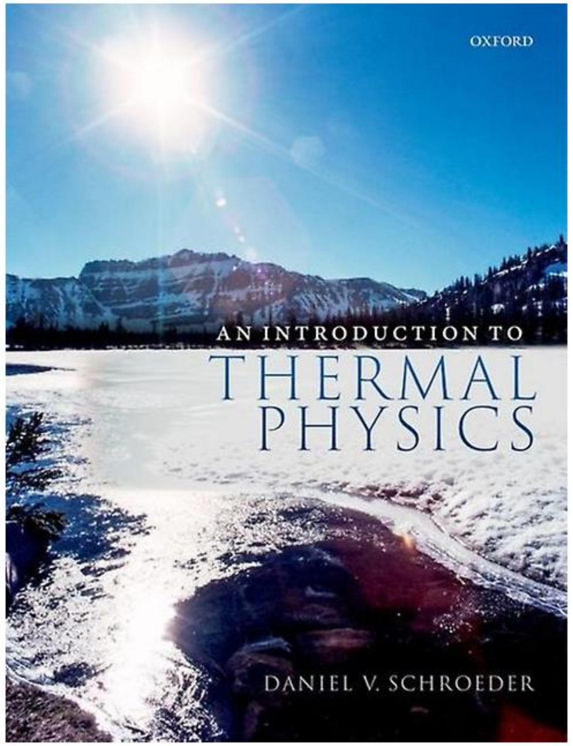


UiO : University of Oslo

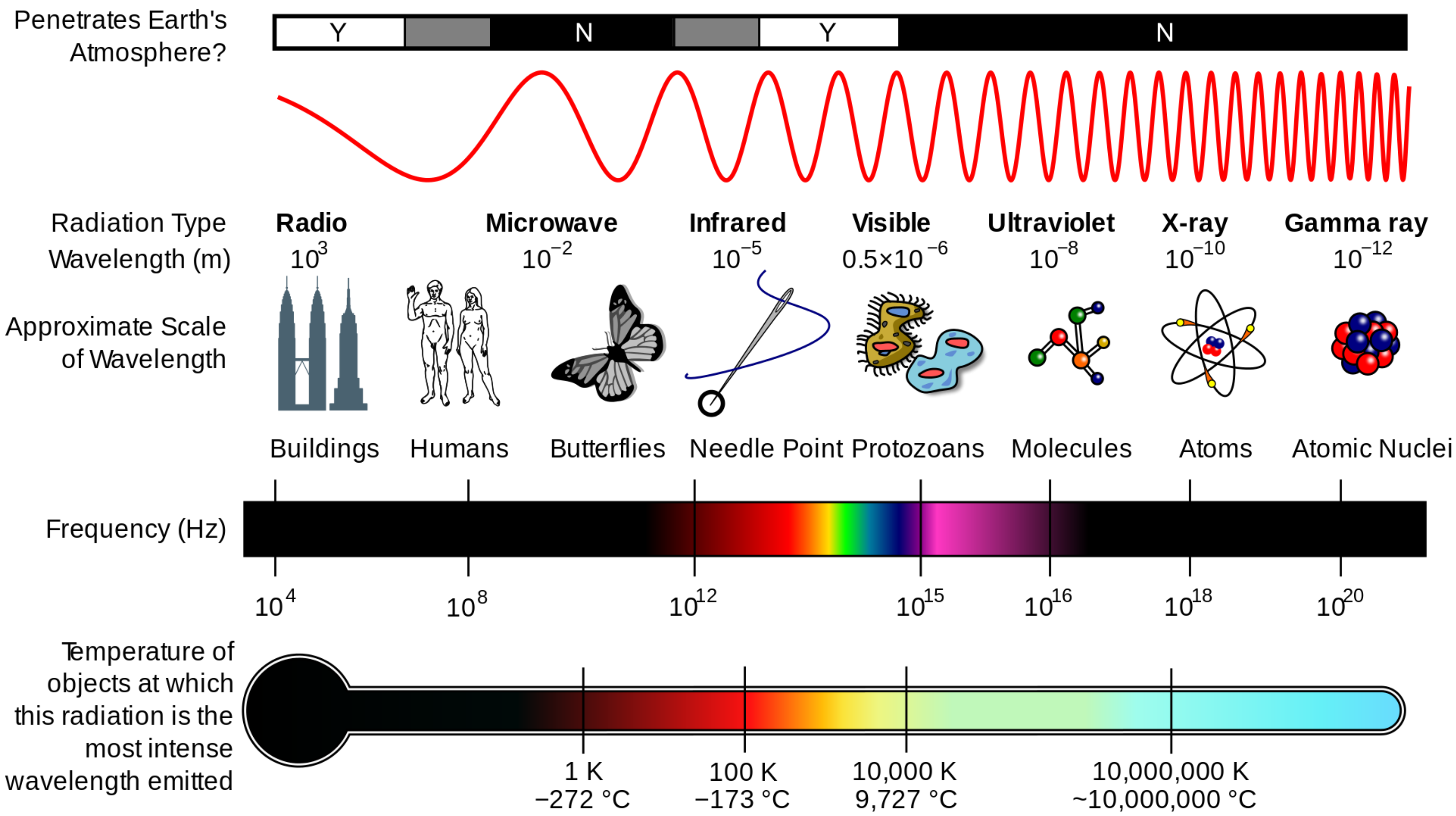
Blackbody radiation

7.4 Blackbody Radiation



Electromagnetic spectrum

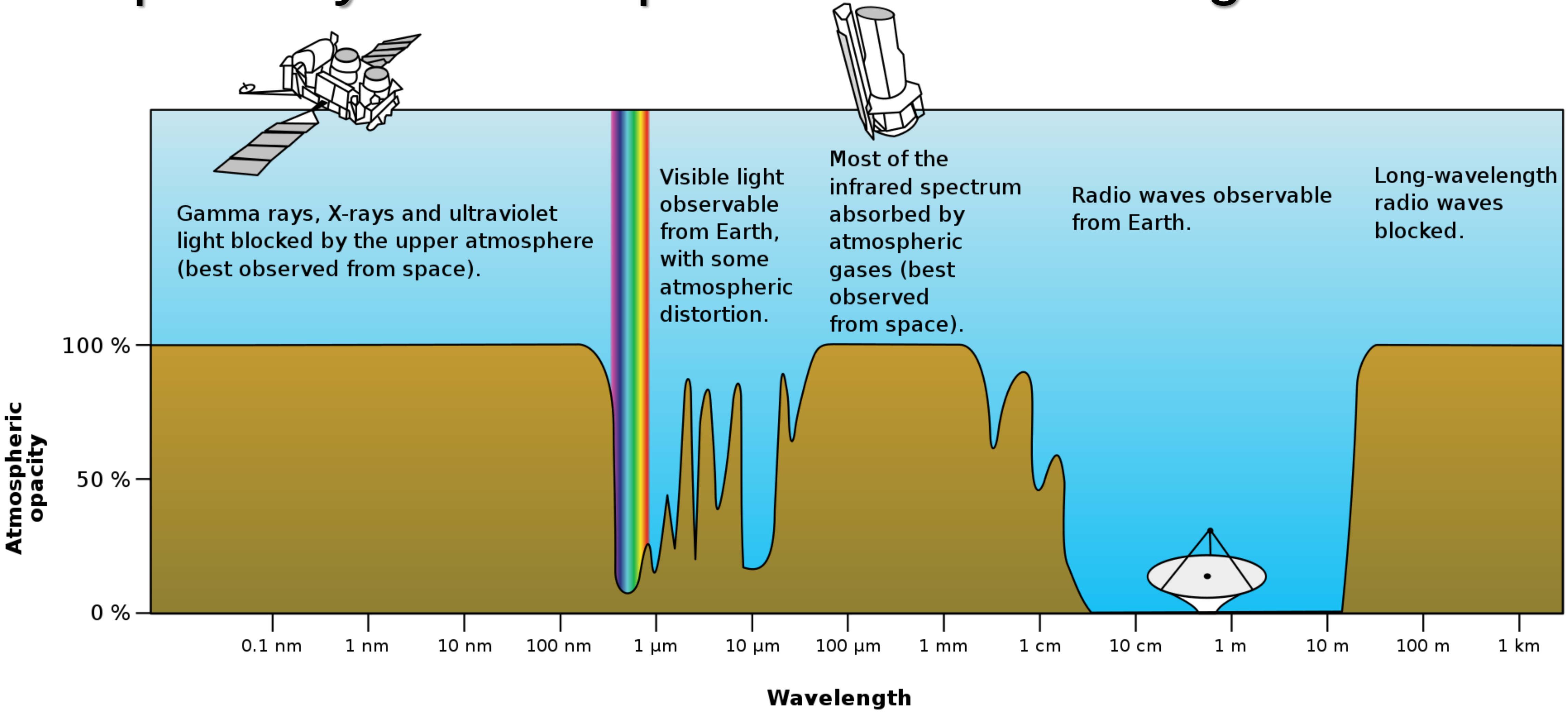
Blackbody radiation is the thermal electromagnetic radiation within or surrounding a body in thermodynamic equilibrium with its environment.



https://en.wikipedia.org/wiki/Electromagnetic_spectrum#/media/File:EM_Spectrum_Properties_edit.svg

Inductiveload, NASA

Transparency of atmosphere for electromagnetic radiation

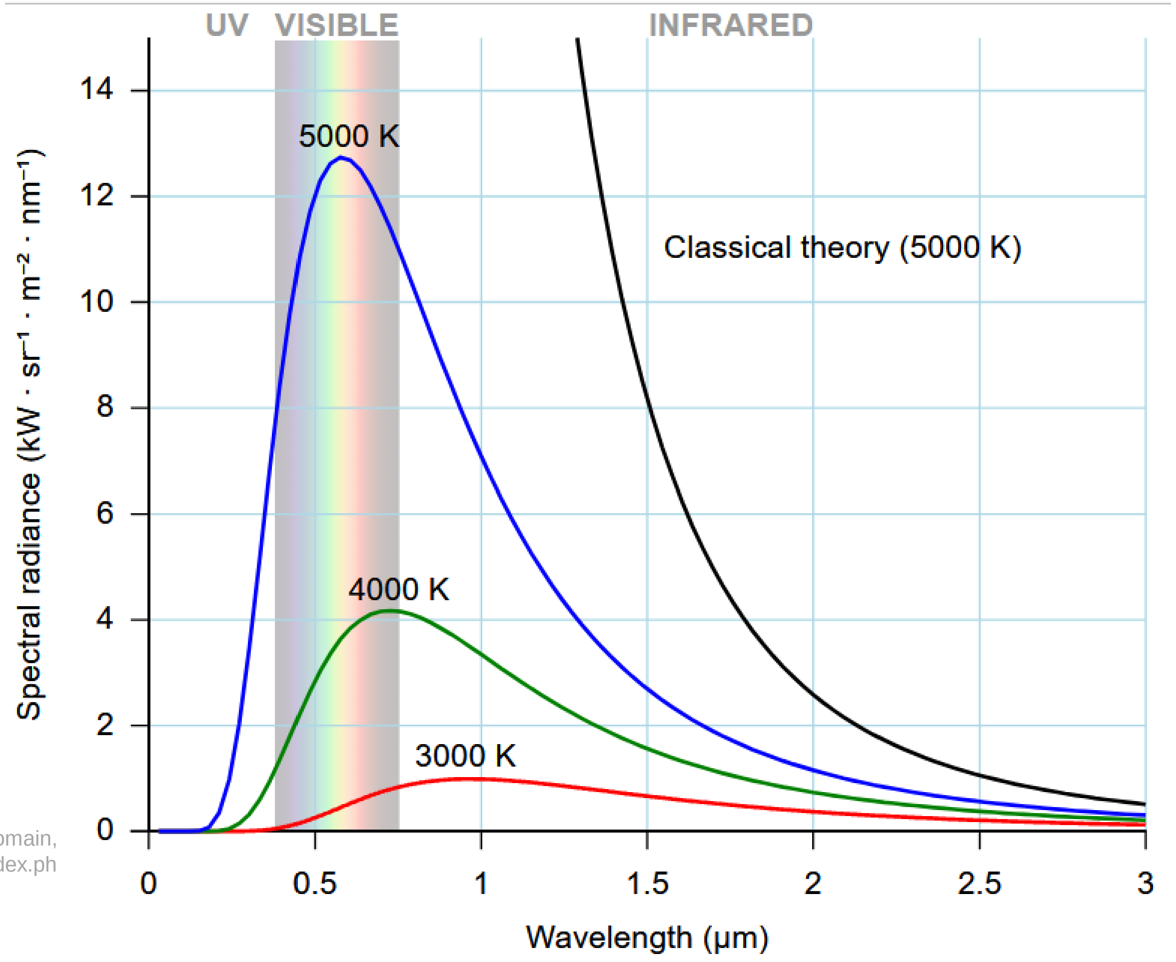


https://upload.wikimedia.org/wikipedia/commons/3/34/Atmospheric_electromagnetic_opacity.svg

Transparency of atmosphere is different for different wavelengths.

Blackbody radiation

- A blackbody is an idealized non-reflective body, which has specific spectrum of wavelengths λ inversely related to their intensity (at high λ).
- The spectrum of wavelengths depend only on the body's temperature.



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$$\epsilon = \hbar\omega = \frac{hc}{\lambda}$$

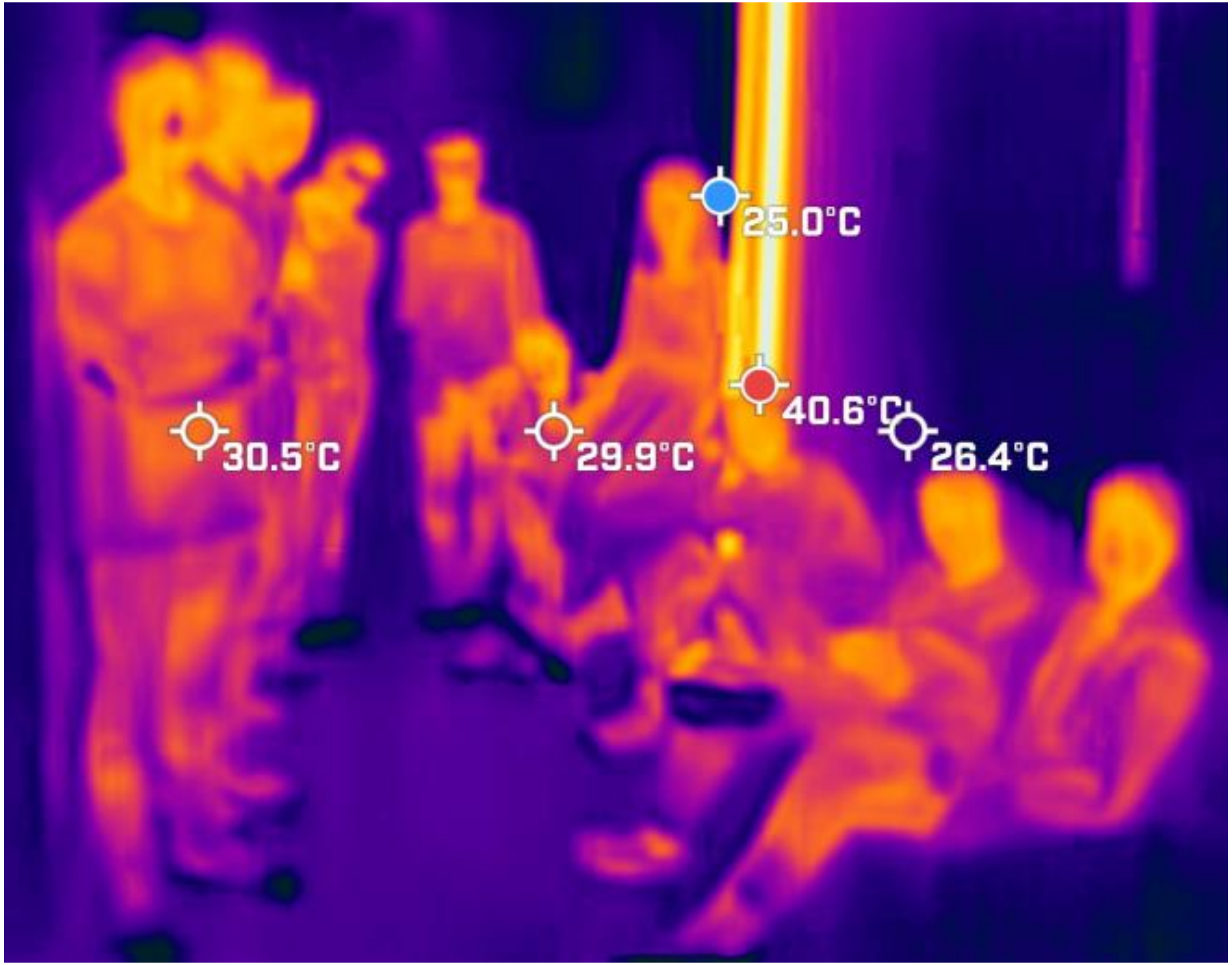
$$\hbar = \frac{h}{2\pi}$$

h is Planck constant
$h = 6.626\ 10^{-34}\ J/Hz$

Are we emitting visible light?

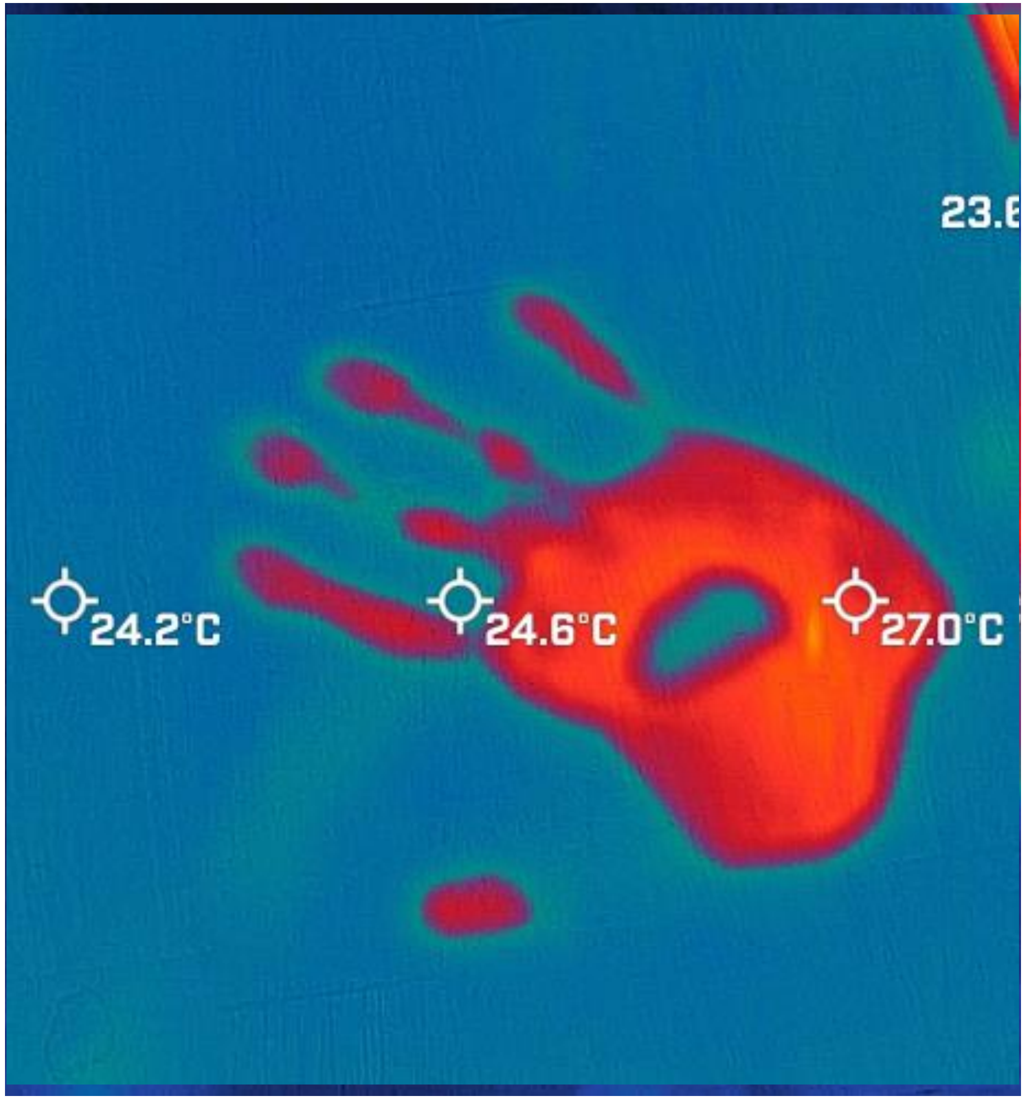
FYS2160students radiation

FYS2160students radiation

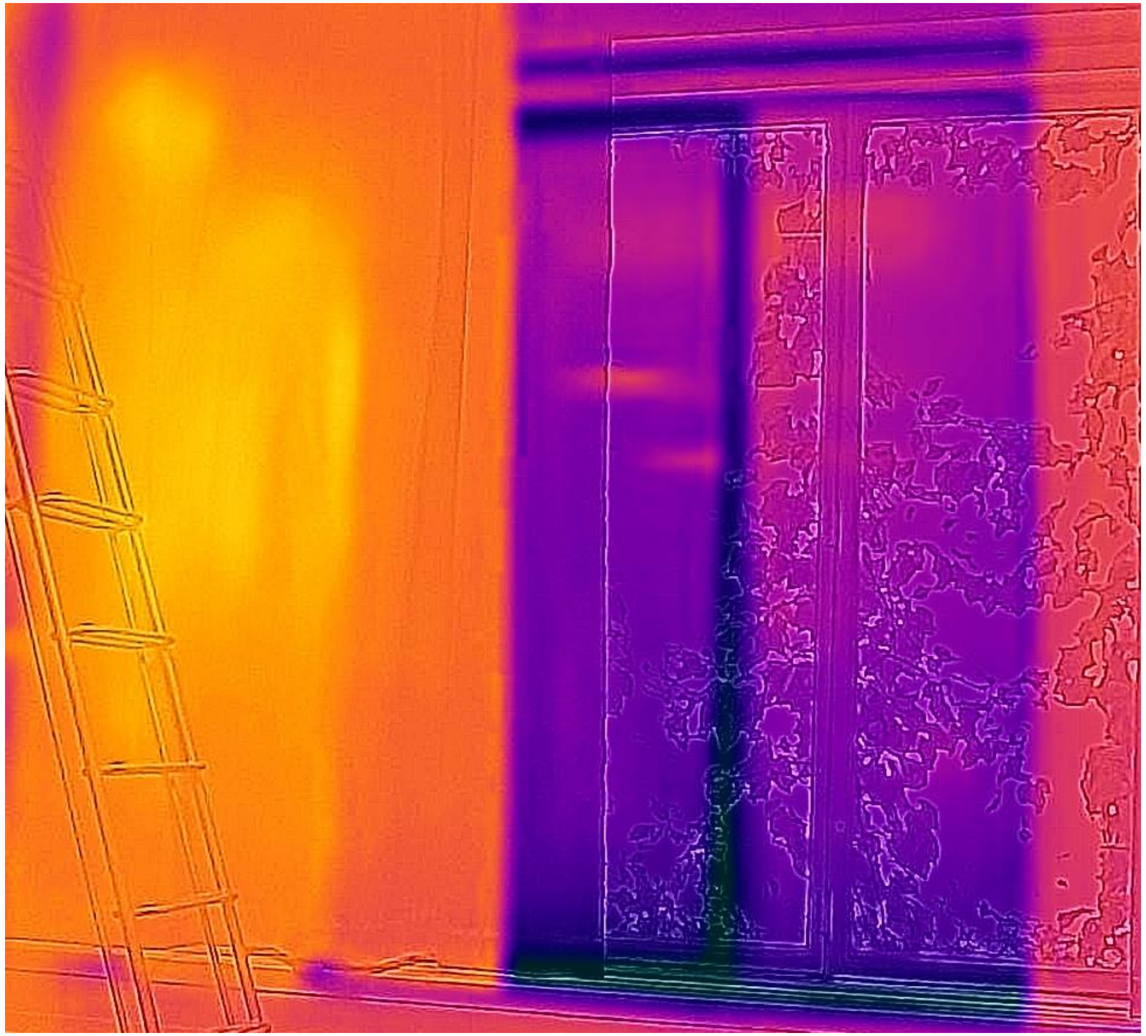


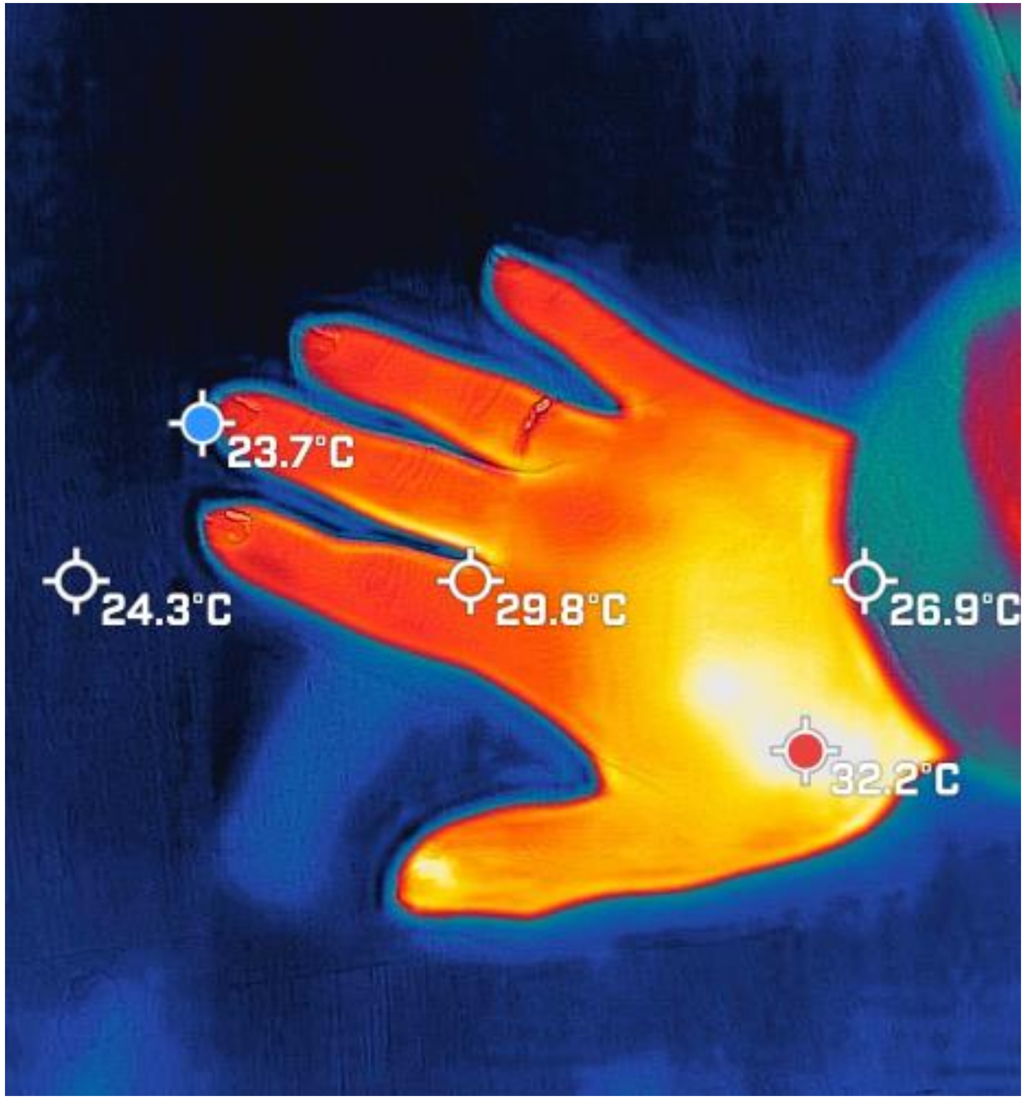
Dark matter

Detection of “crime”

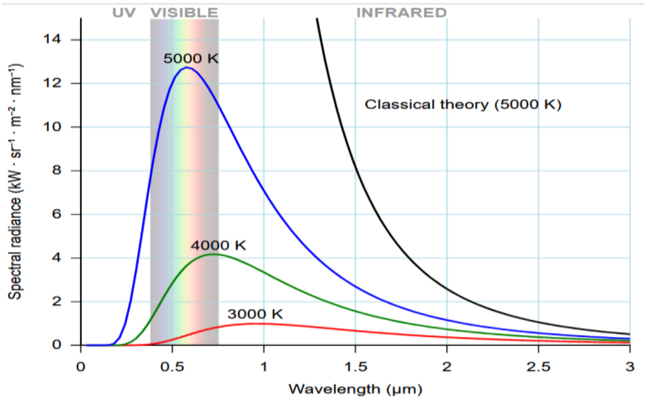


Detection of "crime"





Ultraviolet Catastrophe



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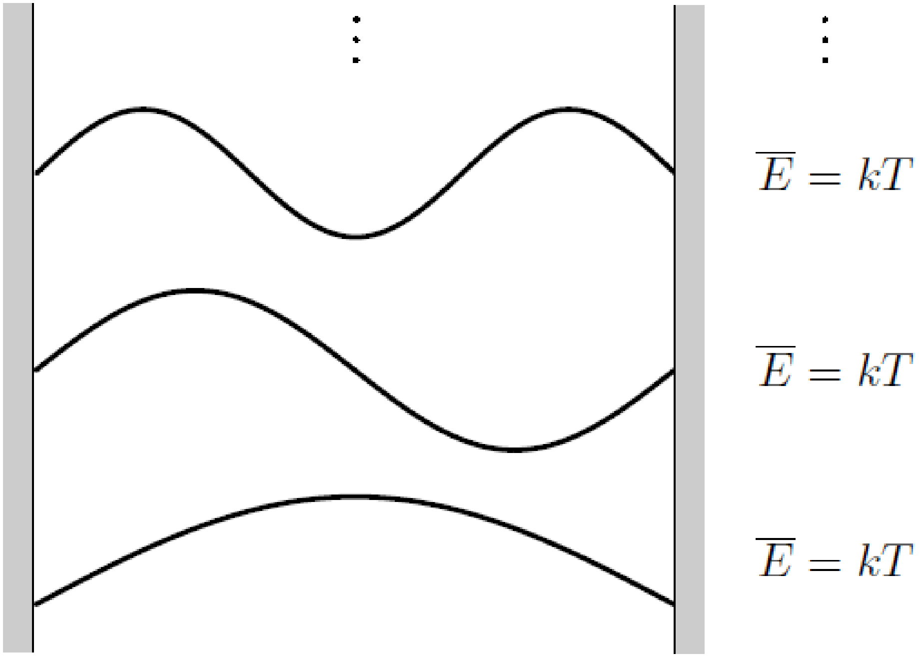
- In classical physics, electromagnetic radiation inside a box is treated as a combination of various standing-wave patterns.
- Each standing-wave pattern behaves as a harmonic oscillator with frequency f = c/ λ, two degrees of freedom and with an average thermal energy of 2·1/2·kT.
- Since the total number of oscillators in the electromagnetic field is infinite, the total thermal energy should also be infinite.
- This paradox is named ultraviolet catastrophe because the infinite energy would come mostly from very short wavelengths.

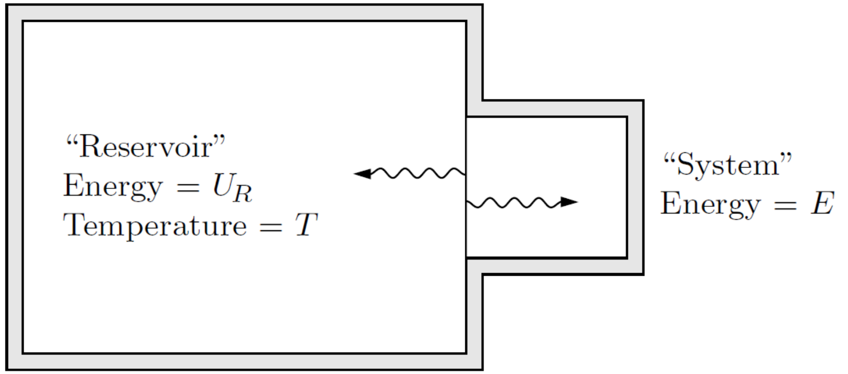


DVS

- Attempts to solve this paradox led to the birth of quantum mechanics.

Boltzmann statistics

Boltzmann statistics calculates probability of the system in the contact with reservoir having energy E. This probability is proportional to multiplicity of reservoir: $P(E) = C\Omega_R(E)$



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$$\Omega_R(E) = A\Omega_R(0) \quad S_R(E) = k\ln\Omega_R(0) + k\ln A$$

$$\Delta S_R = k\ln A \qquad \Delta U = T\Delta S - P\Delta V + \mu\Delta N$$

$$E = -\Delta U_R = -T\Delta S_R \qquad \Delta S_R = -\frac{E}{T}$$

$$A = e^{-E/kT} \qquad P(E) = AC\Omega_R(0)$$

$$P(s) = \frac{1}{Z}e^{-\frac{E(s)}{kT}}$$

$$Z = \sum_s e^{-\frac{E(s)}{kT}}$$

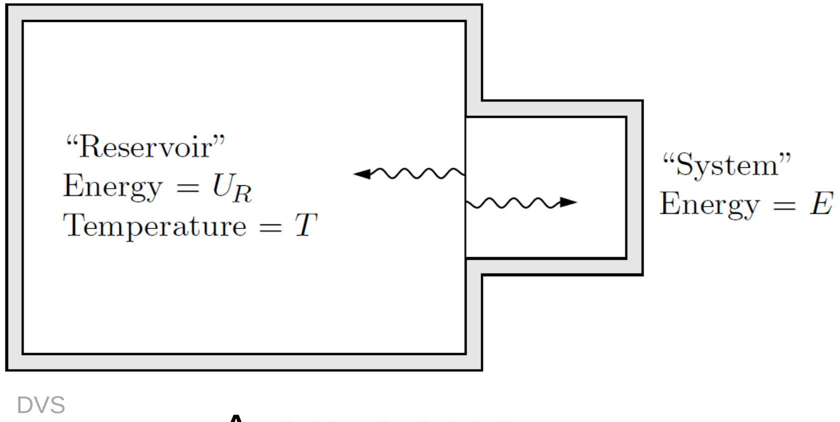
Boltzmann distribution

A is Boltzmann factor $e^{-\frac{E}{kT}}$

$$P(E) = e^{-E/kT}C\Omega_R(0) = \frac{1}{Z}e^{-E/kT}.$$

Planck Distribution

Canonical ensemble



The immediate solution of the paradox comes from Boltzmann distribution for quantized electromagnetic waves named Planck distribution, in which energy comes in units hf.

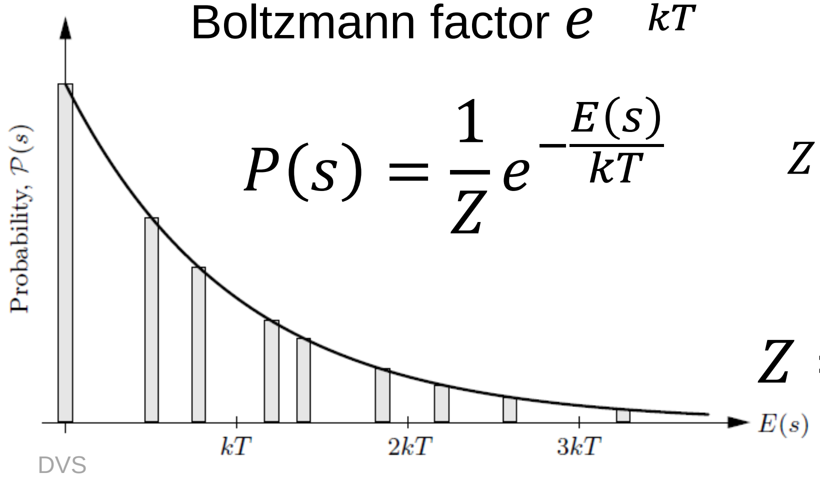
Boltzmann factor $e^{-\frac{E(s)}{kT}}$

$$E(s) = 0, hf, 2hf, \ldots.$$

$$P(s) = \frac{1}{Z} e^{-\frac{E(s)}{kT}}$$

Z is the partition function, $\beta = \frac{1}{kT}$

$$Z = \sum_s e^{-\frac{E(s)}{kT}} = \frac{1}{1 - e^{-\beta hf}}$$



Average energy

$$\bar{E} = \frac{1}{Z} \sum_s E(s) e^{-\frac{E(s)}{kT}}$$

$$\bar{E} = -\frac{1}{Z}\frac{\partial Z}{\partial \beta} = \frac{hf}{e^{\frac{hf}{kT}} - 1}$$

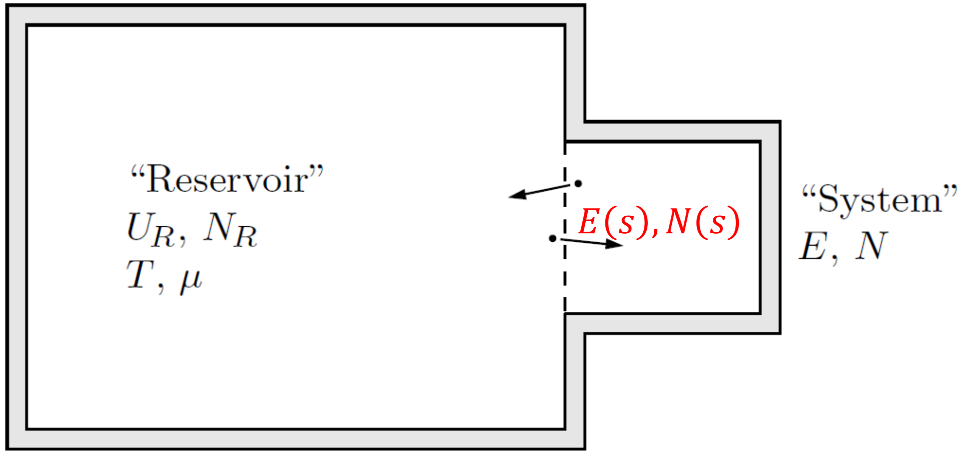
- According to the Planck distribution, short-wavelength modes with $hf \gg kT$ are exponentially suppressed.
- The total number of electromagnetic oscillators that strongly contribute to the energy inside the box is finite.
- The ultraviolet catastrophe does not occur.
- Energy quantization is the necessary condition and it is the size of the energy units, compared to kT, that provides the exponential suppression factor. Elementary particles in this distribution are named photons.

Grand canonical distribution for photons?

Gibbs factor $e^{-\frac{E(s)-\mu N(s)}{kT}}$

Probability distribution $\mathcal{P}(s) = \frac{1}{\mathcal{Z}} e^{-\frac{E(s)-\mu N(s)}{kT}}$

Grand partition function $\mathcal{Z} = \sum_s e^{-\frac{E(s)-\mu N(s)}{kT}}$



DVS

Planck distribution

$$\bar{E} = \frac{hf}{e^{\frac{hf}{kT}} - 1}$$

$$\bar{n} = \frac{1}{e^{\frac{hf}{kT}} - 1}$$

Number of photons

Bose - Einstein distribution

$$\bar{n} = \frac{1}{e^{\frac{hf-\mu}{kT}} - 1} \qquad (\epsilon = hf)$$

Planck distribution is Bose - Einstein distribution with chemical potential equal to zero. This comes from the fact that photons can be created or destroyed in any quantity. Their total number is not conserved.

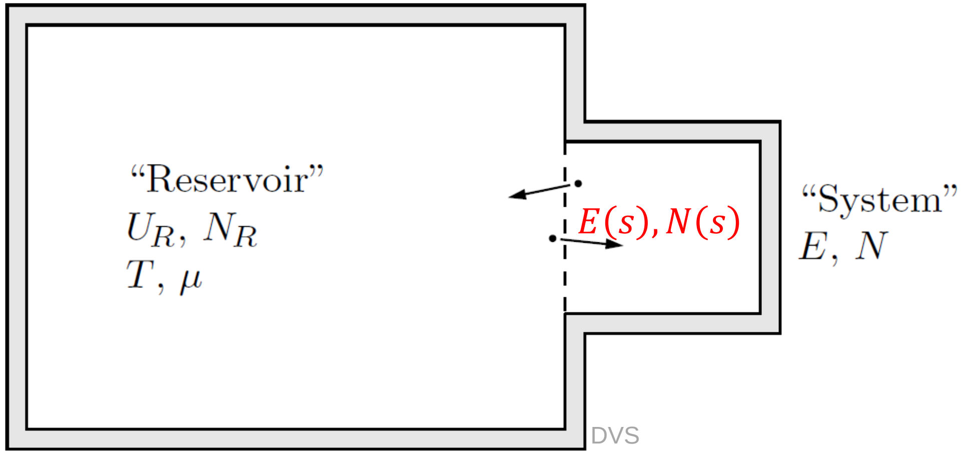
The chemical potential for a gas of photons in a box is zero.

Grand canonical distribution for quantum particles

Gibbs factor $e^{-\frac{E(s)-\mu N(s)}{kT}}$

Probability distribution $\mathcal{P}(s) = \frac{1}{\mathcal{Z}} e^{-\frac{E(s)-\mu N(s)}{kT}}$

Grand partition function $\mathcal{Z} = \sum_s e^{-\frac{E(s)-\mu N(s)}{kT}}$



Bose - Einstein distribution

$$\bar{n}_{BE} = \frac{1}{e^{\frac{\epsilon-\mu}{kT}} - 1} \quad (\epsilon = hf)$$

Fermi-Dirac distribution

$$\bar{n}_{FD} = \frac{1}{e^{\frac{\epsilon-\mu}{kT}} + 1}$$

Planck distribution

$$\bar{n} = \frac{1}{e^{\frac{hf}{kT}} - 1}$$

Number of photons

Planck distribution is Bose - Einstein distribution with chemical potential equal to zero. This comes from the fact that photons can be created or destroyed in any quantity. Their total number is not conserved. If one imposes μ by grand canonical distribution, this can only be done with $\mu = 0$.

The chemical potential for a gas of photons in a box is zero.

Comparison of distributions

$$F = -kTln(Z)$$
$$\mu = +\left(\frac{\partial F}{\partial N}\right)_{T,V}$$
$$Z = \frac{Z_1{}^N}{N!} = \frac{Z_1{}^N}{N!}$$
$$lnN! \approx N(lnN - 1)$$

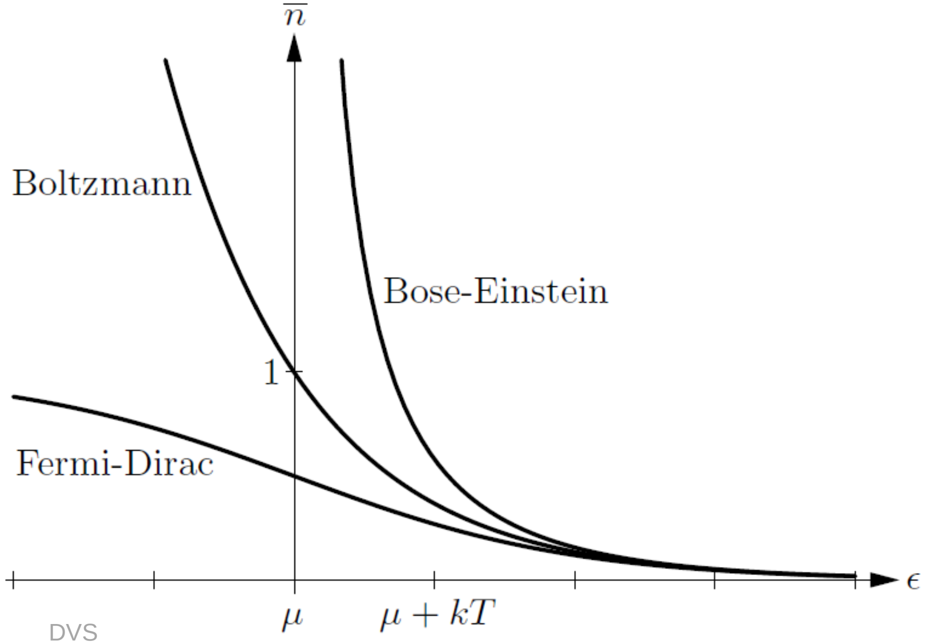
For the Boltzmann distribution: $P(s) = \frac{1}{Z_1} e^{-\frac{\epsilon}{kT}}$ $\quad \mu = -kTln\left(\frac{Z_1}{N}\right)$

$$\bar{n}_{Boltzmann} = \frac{1}{Z_1} N e^{-\frac{\epsilon}{kT}} = e^{-\frac{\epsilon}{kT}} e^{\frac{\mu}{kT}} = e^{-\frac{(\epsilon-\mu)}{kT}}$$

$$\bar{n}_{Boltzmann} = e^{-\frac{(\epsilon-\mu)}{kT}} \qquad \bar{n}_{FD} = \frac{1}{e^{\frac{\epsilon-\mu}{kT}} + 1} \qquad \bar{n}_{BE} = \frac{1}{e^{\frac{\epsilon-\mu}{kT}} - 1}$$

When $\varepsilon \gg \mu$, the exponent is very large, one can neglect the 1 in the denominator of Fermi-Dirac and Bose-Einstein distributions, and both are reduced to the Boltzmann distribution. The precise condition for the three distributions to agree is: $\epsilon - \mu \gg kT$.

To apply the distributions to any particular system, one needs to know what the energies of all the states are.



Planck Spectrum

Integrating energy over all states and taking into account momentum quantization and specific dispersion law for photons : $\epsilon = pc$, where p is momentum and c is speed of light, it is possible to find total energy per unit of volume U/V as function of ϵ or phonon frequency $f = \epsilon / h$:

$$\frac{U}{V} = \int_0^{\infty} \frac{8\pi\epsilon^3/(hc)^3}{e^{\epsilon/kT} - 1} d\epsilon \,.$$

The integrand is the energy density per unit of photon energy, or the spectrum of the photons:

$$u(\epsilon) = \frac{8\pi\epsilon^3}{(hc)^3(e^{\epsilon/kT} - 1)} \,. \qquad \frac{x^3}{e^x - 1}$$

Introducing $x = \epsilon / kT$,

$$\frac{U}{V} = \frac{8\pi(kT)^4}{(hc)^3} \int_0^{\infty} \frac{x^3}{e^x - 1} dx \,.$$

$\epsilon = 2.82kT$

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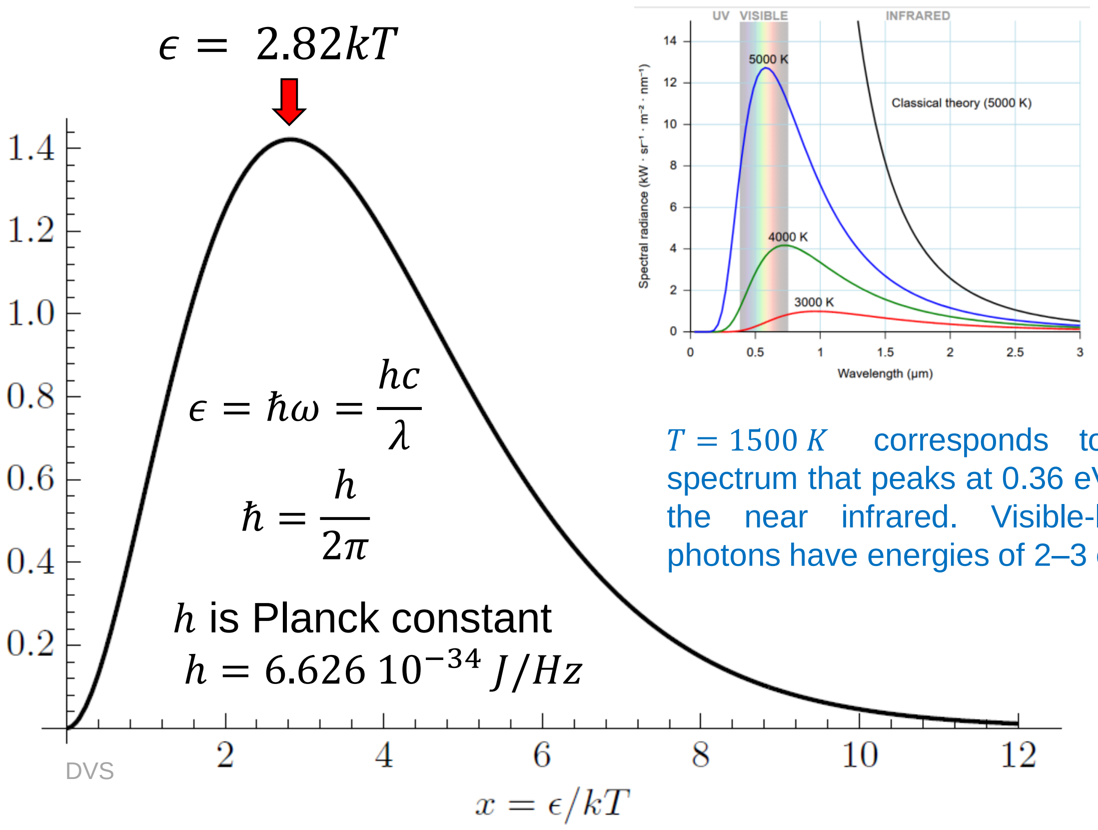


$$\epsilon = \hbar\omega = \frac{hc}{\lambda}$$

$$\hbar = \frac{h}{2\pi}$$

h is Planck constant
$h = 6.626\ 10^{-34}\ J/Hz$

$T = 1500\ K$ corresponds to a spectrum that peaks at 0.36 eV, in the near infrared. Visible-light photons have energies of 2–3 eV.

The spectrum peaks at $x = 2.82$, or $\epsilon = 2.82kT$. Higher temperatures give higher photon energies: **Wien's law.**

Total energy of phonon gas

$$\frac{U}{V} = \frac{8\pi^5 (kT)^4}{15(hc)^3}$$

- The energy density is proportional to fourth power of the temperature. If the temperature is doubled, the amount of electromagnetic energy inside increases by a factor of $2^4 = 16$.
- Total electromagnetic energy inside a typical oven is quite small. At cookie-baking temperature of about 460 K, the energy per unit volume is 3.5 10^{-5} J/m^3. This is tiny compared to the thermal energy density of the air inside the oven of about 10^3 J/m^3.
- The formula for energy density can be obtained as:

$$U = (constant)\frac{VkT}{(\lambda)^3},$$

where λ is temperature-dependent de Broglie wavelength for the photons, $\lambda = h/p = hc/E = hc/kT$.

Ice melting enthalpy 3.3355 10^5 J/kg

The heat of vaporization of water is about 2.260 10^6 J/kg

Air has a density of approximately 1.225 kg/m^3

Heat capacity and entropy of phonon gas

Total energy density: $\frac{U}{V} = \frac{8\pi^5 (kT)^4}{15(hc)^3}$

$$C_V = \left(\frac{\partial U}{\partial T}\right)_V = 4aT^3, \qquad a = \frac{8\pi^5 k^4 V}{15(hc)^3}.$$

- Heat capacity of phonon gas is proportional to T^3:
- Entropy of phonon gas is: $S = \frac{4}{3}aT^3$.

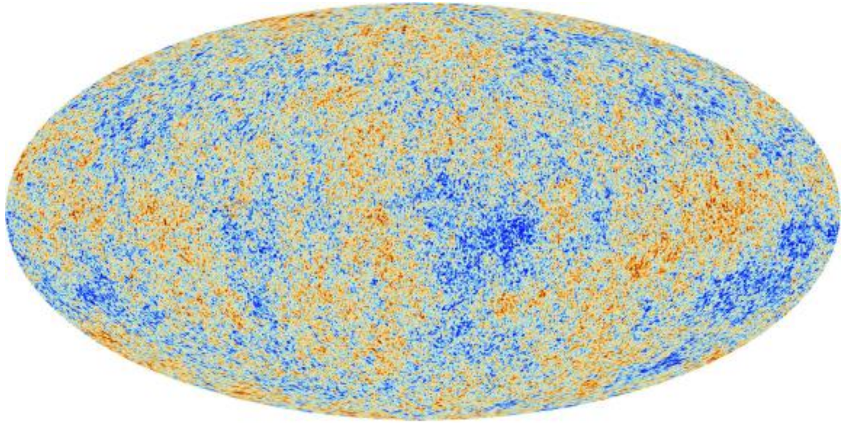
$$dU = TdS - PdV + \mu dN \qquad \frac{dU}{dT} = C_V = T\frac{dS}{dT}$$

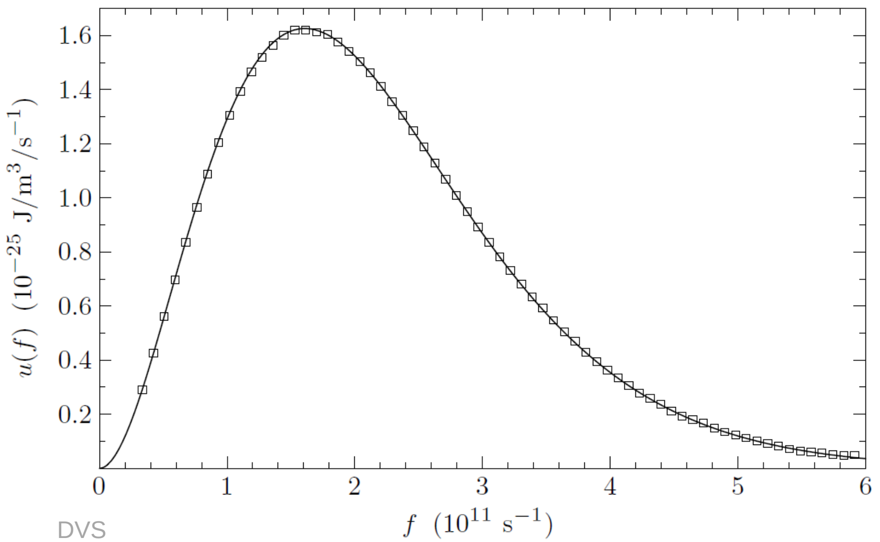
$$S(T) = \int_0^T \frac{C_V(T')}{T'}\,dT' = 4a\int_0^T (T')^2\,dT' = \frac{4}{3}aT^3$$

$$S = \frac{32\pi^5 V}{45}\left(\frac{kT}{hc}\right)^3.$$

The Cosmic Background Radiation

- The radiation that fills the entire observable universe has an almost perfect thermal spectrum at a temperature of 2.73 K.
- The radiation is thought to be left from a time when the universe was filled with ionized gas that interacted strongly with electromagnetic radiation. At that time, the temperature was more like 3000 K.
- Since universe has expanded a thousand-fold in all directions, the photon wavelengths have been stretched according to Doppler effect preserving the shape of the spectrum, but shifting the effective temperature down to 2.73 K.
- The peak of the spectrum corresponds to wavelengths of about a millimeter, in the far infrared. These wavelengths don't penetrate Earth atmosphere. The spectrum is best measured from the satellites above atmosphere.



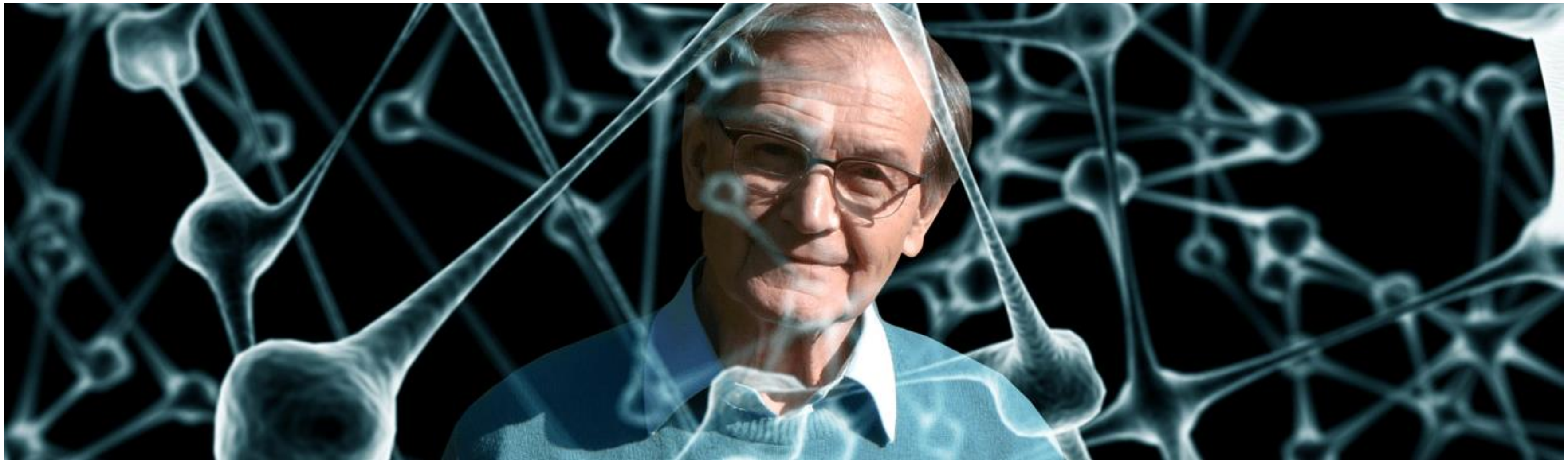


DVS

Spectrum of the cosmic background radiation, as measured by the Cosmic Background Explorer satellite.

UiO : University of Oslo

Quantum brain and coherent radiation



https://i2.wp.com/static.nautil.us/12256_7880d7226e872b776d8b9f23975e2a3d.png

Hameroff, S.: Quantum computation in brain microtubules? The Penrose–Hameroff 'Orch OR' model of consciousness. Philos. Trans. R. Soc. Lond., Ser A, Math. Phys. Sci. 356, 1869 (1998).

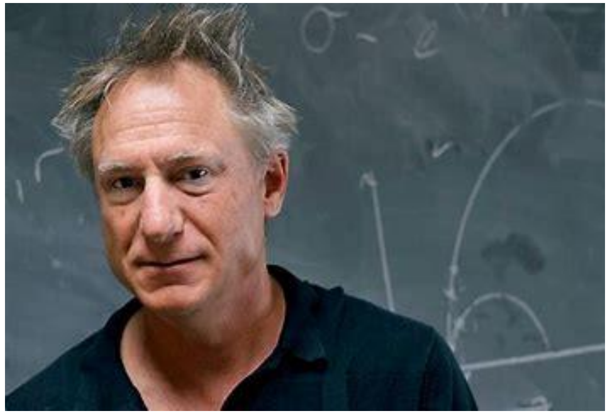
http://www.starpod.us/wp-content/uploads/2012/08/hameroff-2.jpg

Quantum brain: a spin approach

A New Spin on the Quantum Brain

https://www.quantamagazine.org/a-new-spin-on-the-quantum-brain-20161102/

Weingarten, C.P., Doraiswamy, P.M., Fisher, M.P.A.: A new spin on neural processing: quantum cognition. Front. Hum. Neurosci. 10, 541 (2016).



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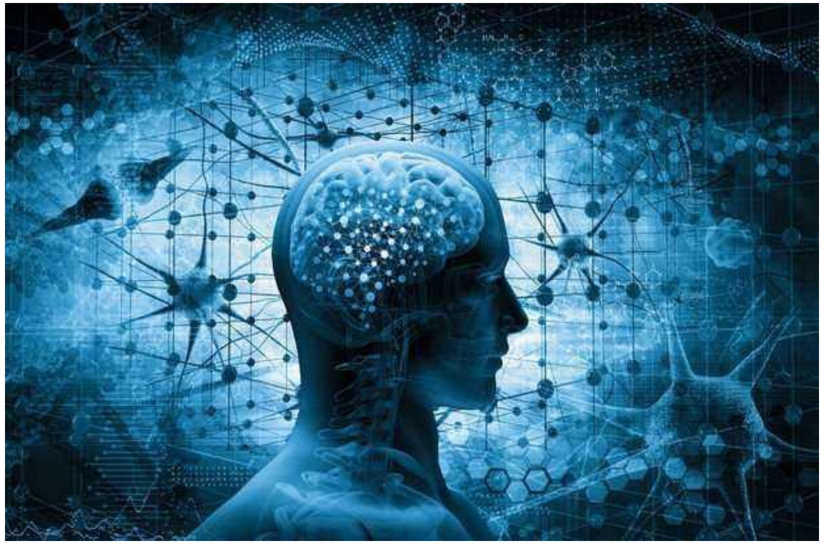
https://mattbelair.com/wp-content/uploads/2018/02/Galactic-Alchemist-for-web.jpg



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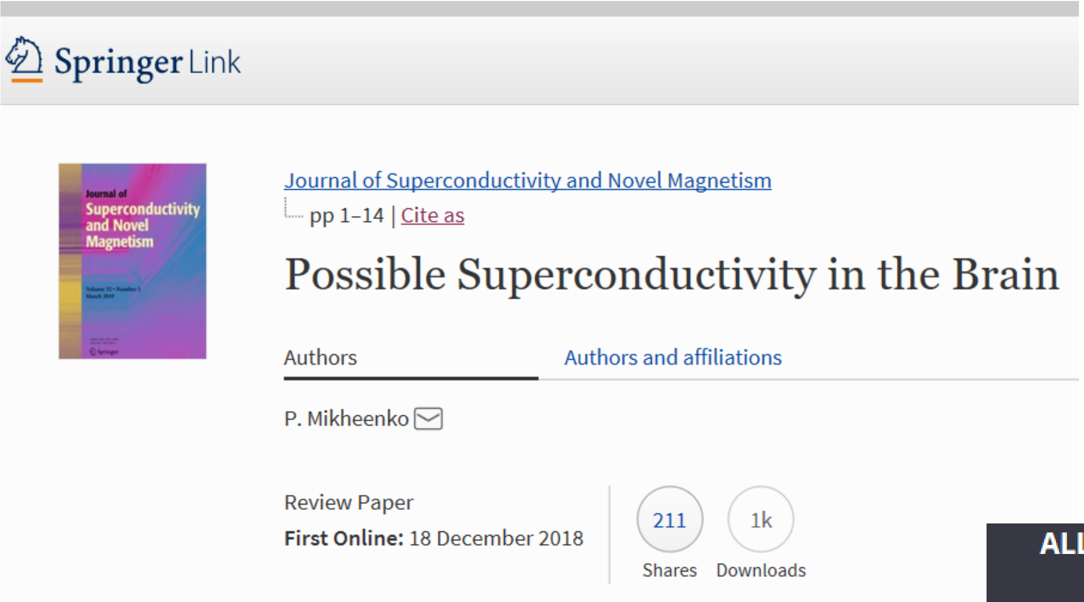
Quantum superconducting brain?

https://www.epfl.ch/campus/spiritual-care/wp-content/uploads/2018/10/quantum-mind.jpg

Possible superconductivity in the brain

https://link.springer.com/article/10.1007/s10948-018-4965-4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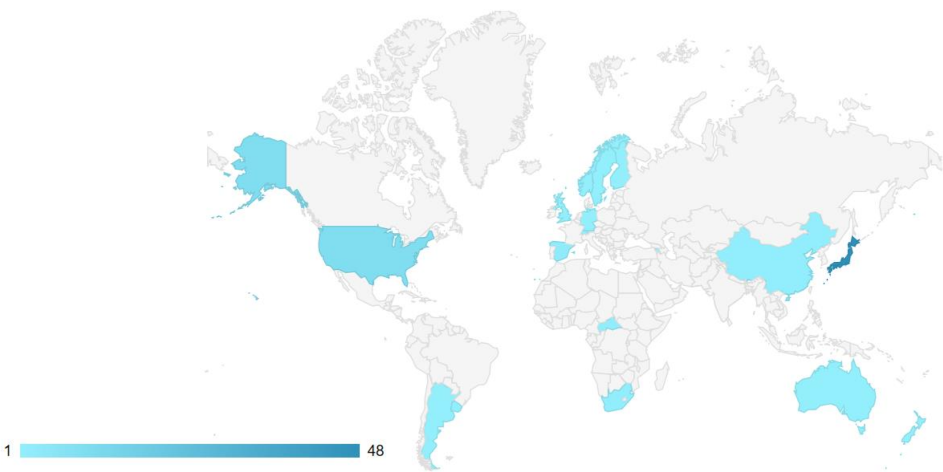

ALL RESEARCH OUTPUTS	OUTPUTS FROM JOURNAL OF SUPERCONDUCTIVITY & NOVEL MAGNETISM
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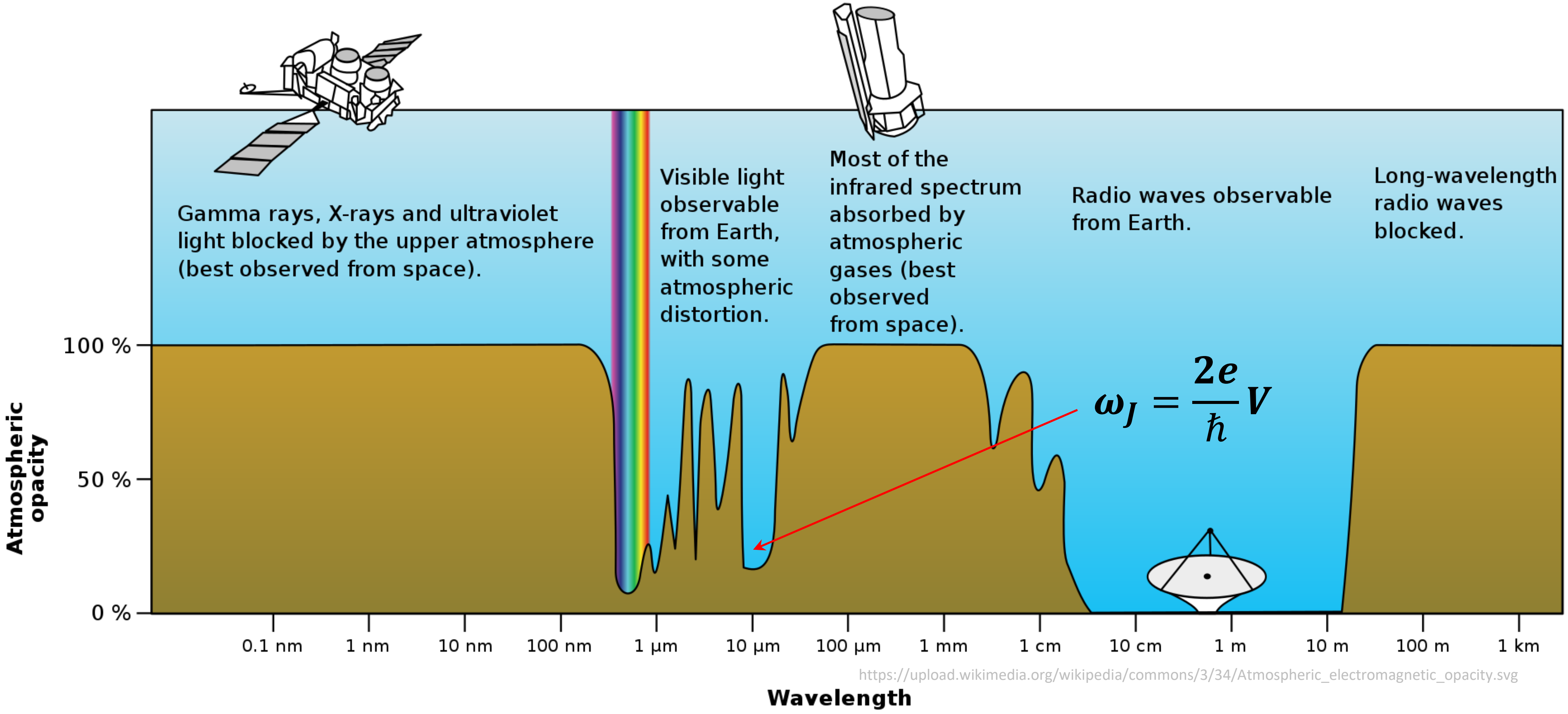
Josephson generation in living organisms



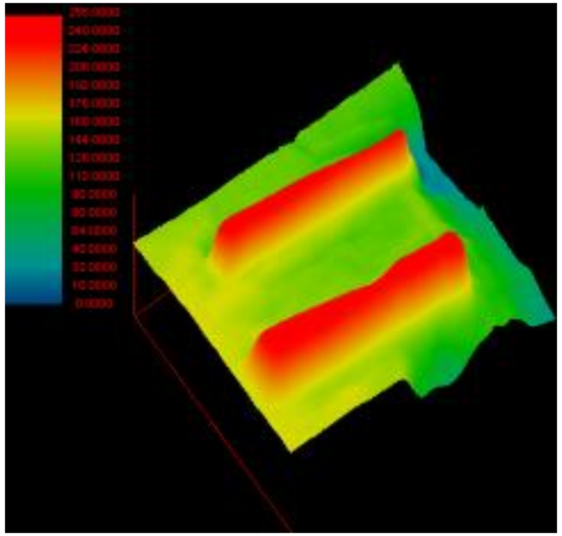
Typical voltages in a human body vary between 20 and 200 mV with the average membrane potential of about 70 mV. These voltages correspond to 4.8, 48.4 and 16.9 THz if generated by normal conductor and to 9.6, 96.8 and 33.8 THz if generated by Josephson junctions. The corresponding wavelengths are in the range from 3.1 to 31 µm in superconducting and 6.2 to 62 µm in normal case. The Josephson membrane-potential voltage could produce radiation with wavelength **8.8 µm**, which is in the transparency window for surrounding atmosphere.

Flir One Pro

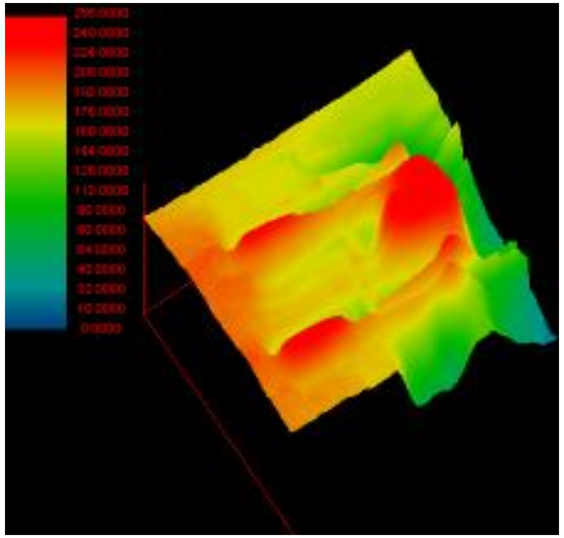
8000 to 15000 nm

Most night vision devices operate in the near-IR wavelengths, of 750 to 1400 nm, but the FLIR One™, as with most thermography cameras, captures long-IR radiation of 8000 to 15000 nm (8-15 µm).

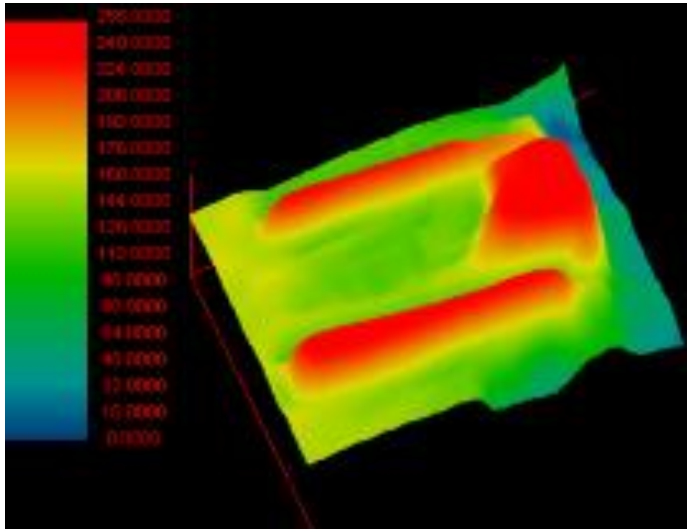
Emission from brain slice with graphene (repeat)



0 V



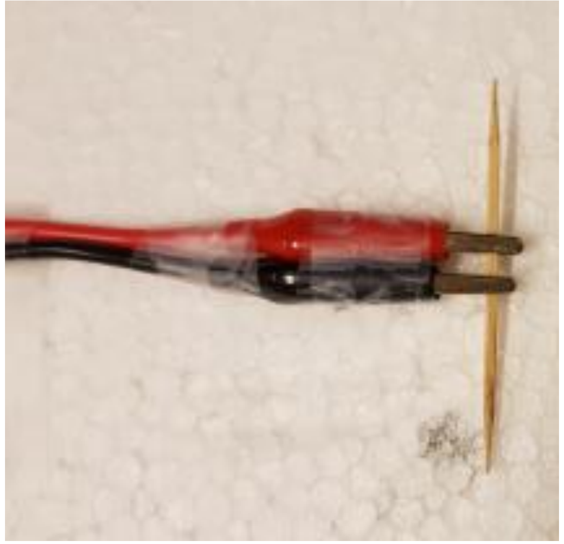
40 V



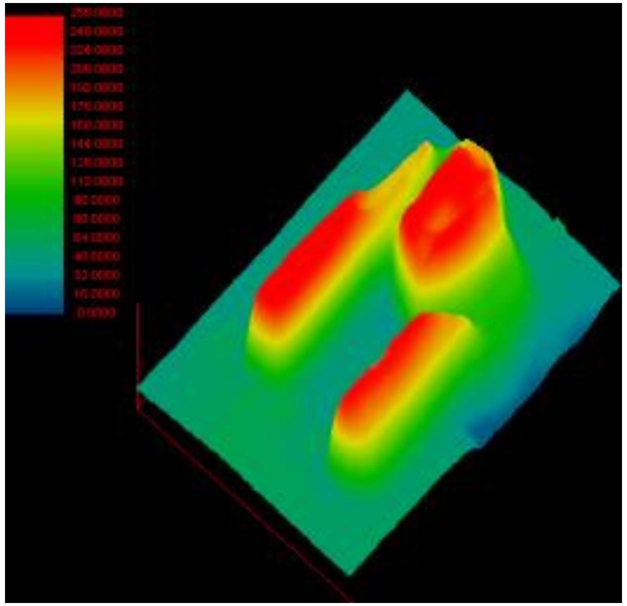
50 V

Emission in the sample with graphene starts later than in initial experiment

Brain slice experiment



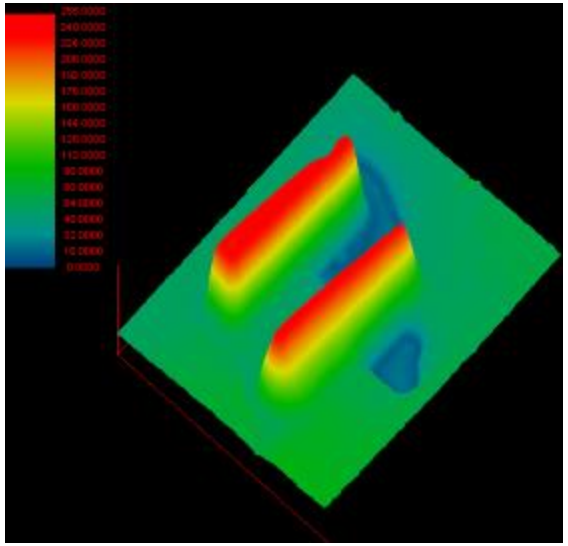
Control experiment



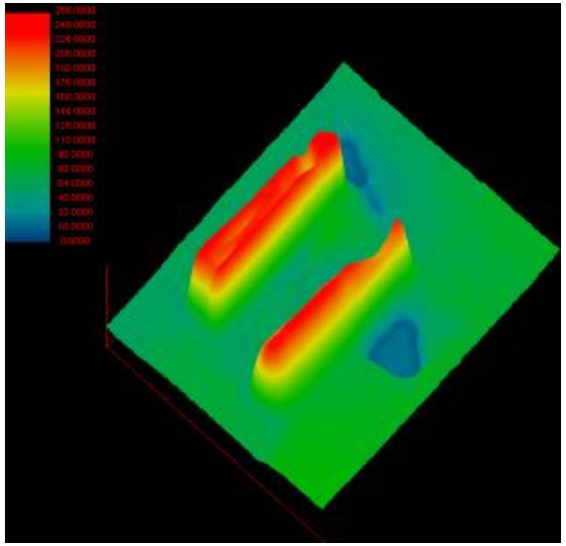
50 V, first experiment with graphene

Emission from chemically fixed brain slice

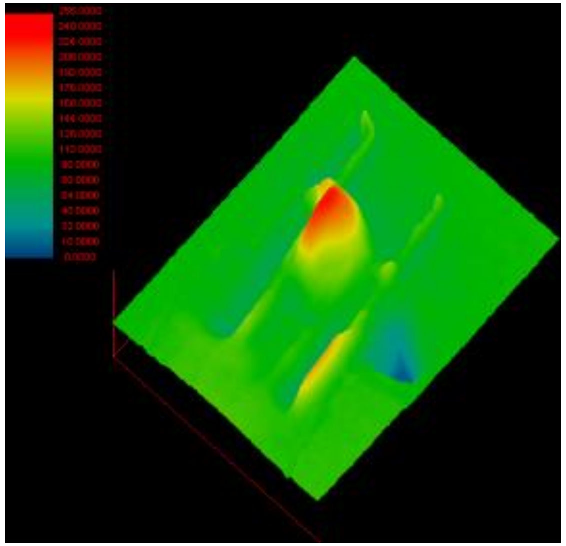
Strong emission from the brain slice starts at about 20 V



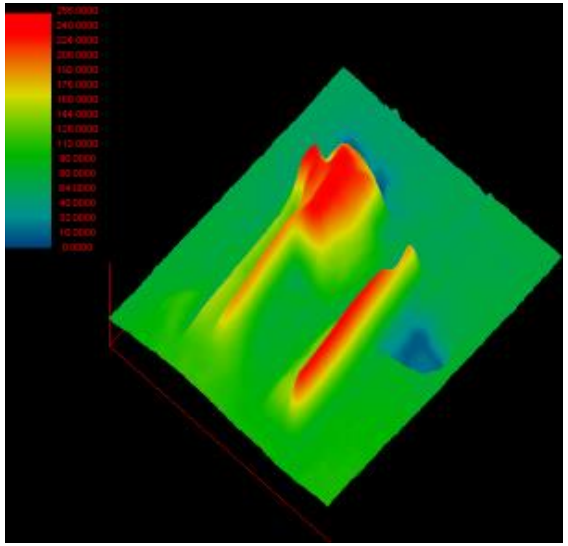
0 V



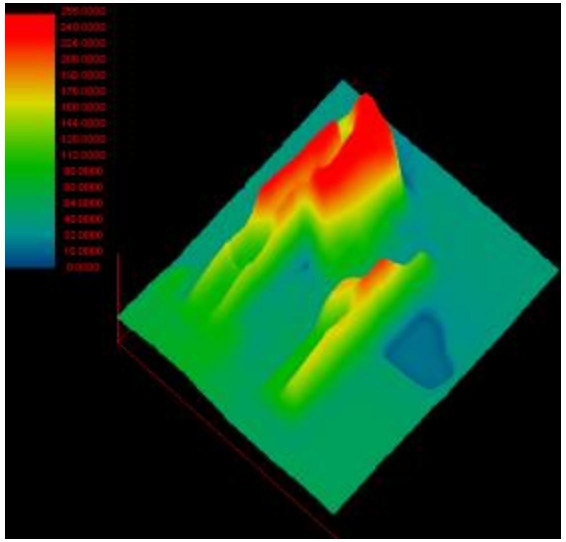
13.8 V



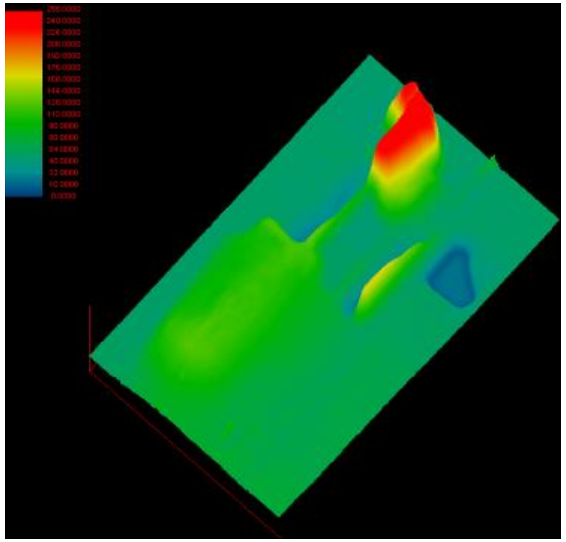
18.9 V



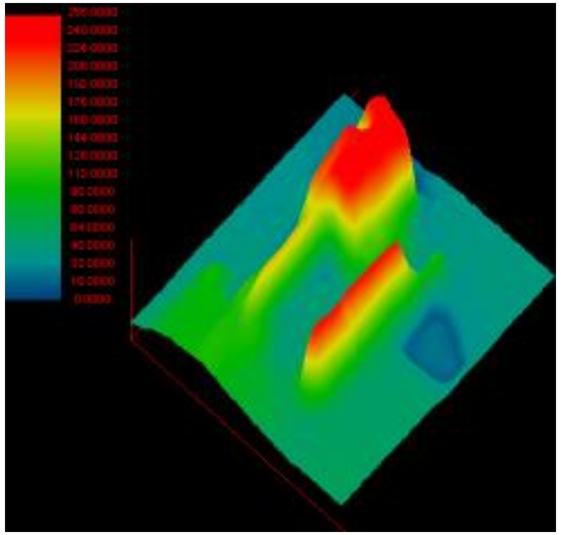
22.8 V



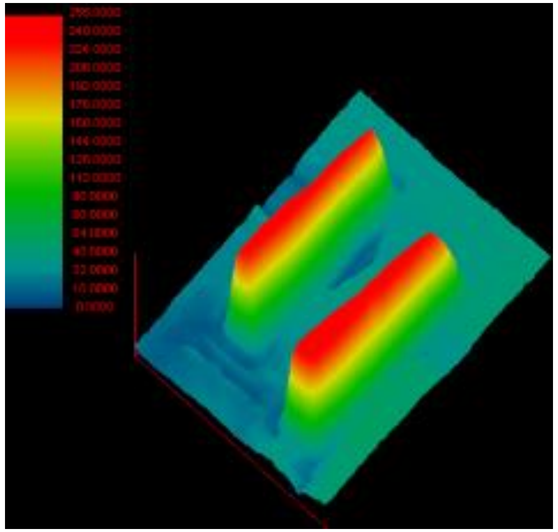
32.3 V



37.6 V

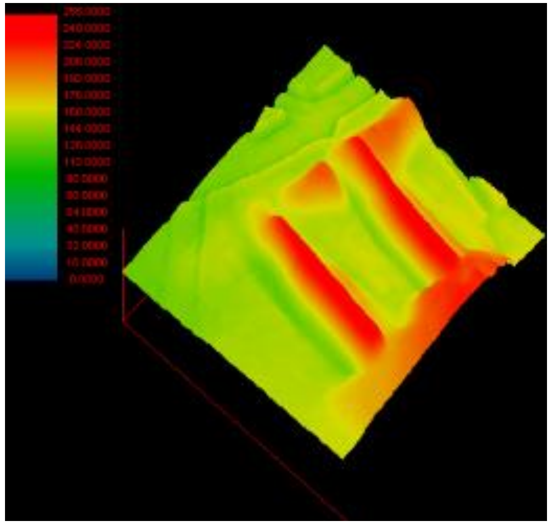


50.1 V

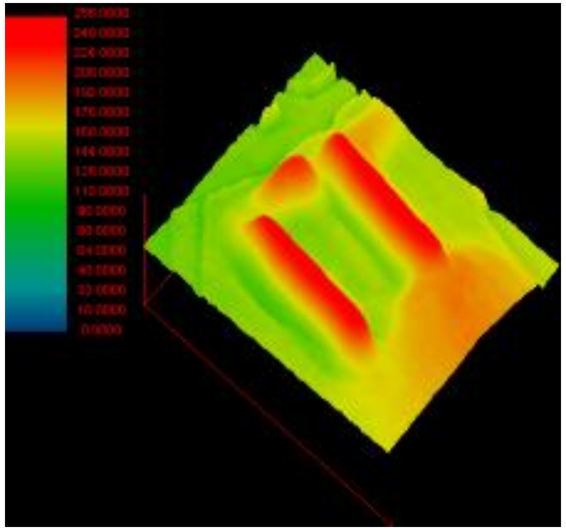


Control, wood, 50 V

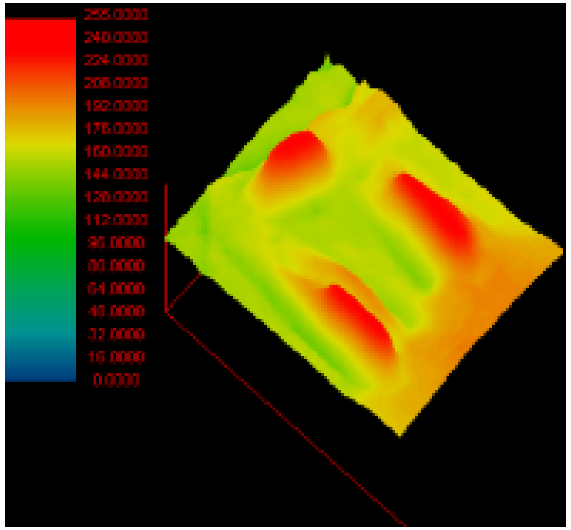
Emission from kalanchoe, after first experiment



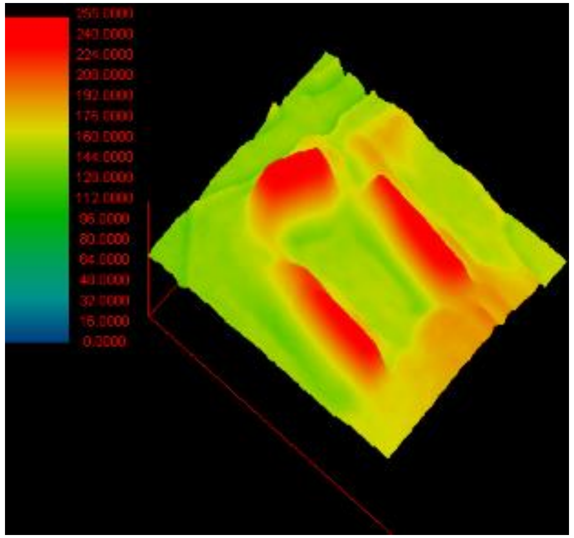
0 V



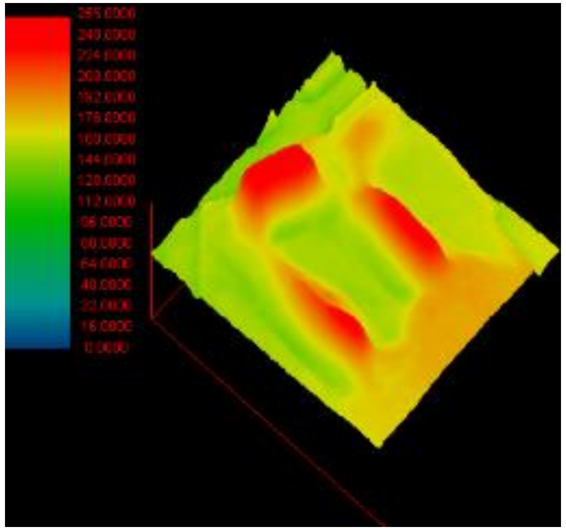
10 V



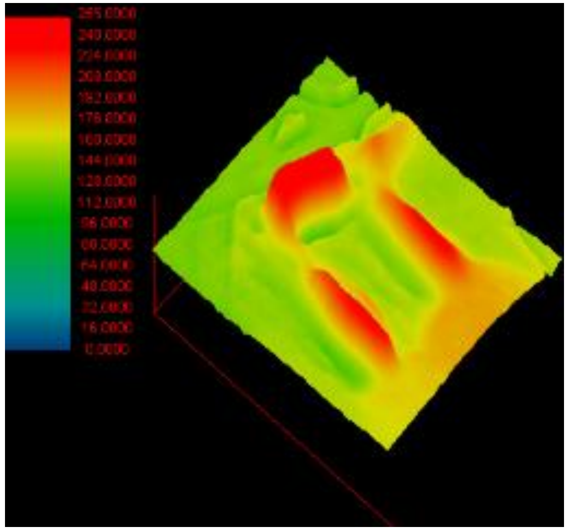
20 V



30 V



40 V



50 V

Effect is strong with admixture of heating.

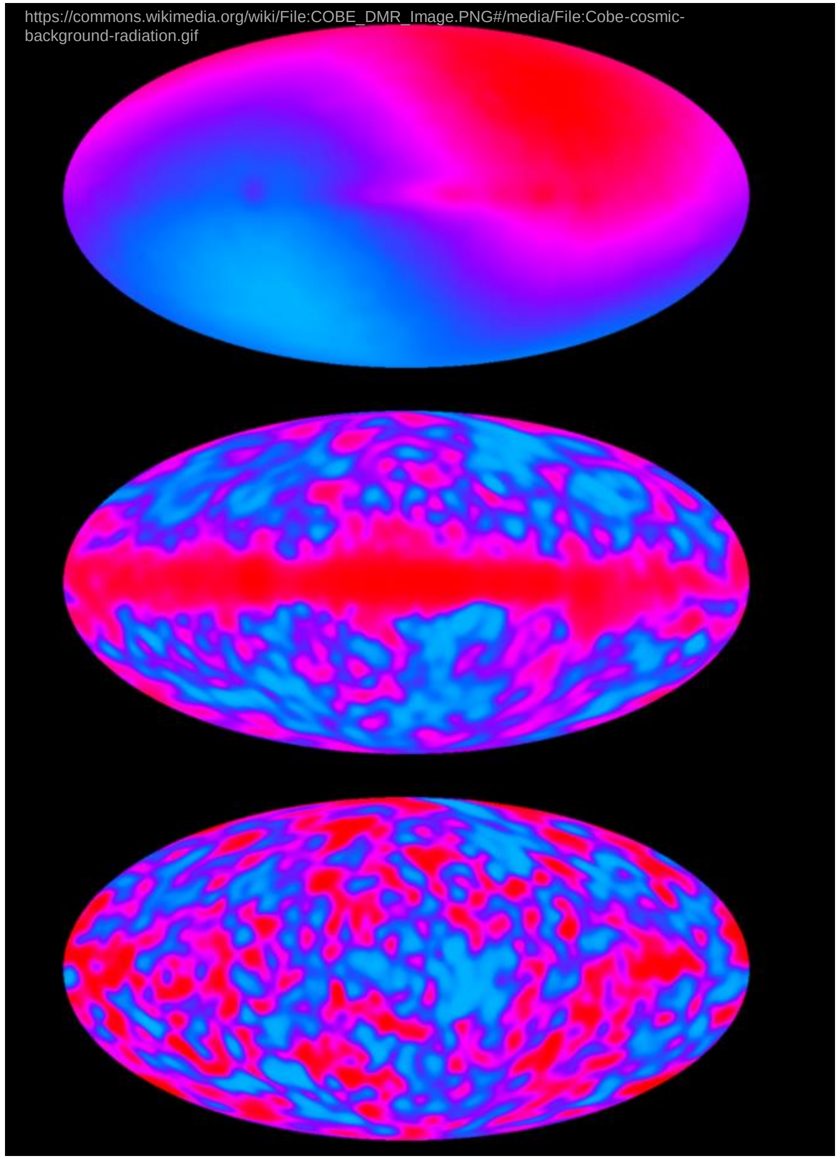
Other properties of Cosmic Background Radiation

$$\frac{U}{V} = \frac{8\pi^5 (kT)^4}{15(hc)^3} \qquad S = \frac{32\pi^5 V}{45}\left(\frac{kT}{hc}\right)^3$$

- The total energy in the cosmic background radiation is only 0.26 MeV/m^3. It is much smaller than average energy density of ordinary matter (a proton per cubic meter on cosmic scale) of 1000 MeV/m^3.
- In contrast to energy, the entropy of the background radiation (1.5 10^9)k is much bigger than that of ordinary matter, which is a few k per cubic meter.

1 eV =1.6 10^{-19} J

First 2-years Cosmic Background Explorer satellite data: In the pictures, the plane of the Milky Way Galaxy is horizontal across the middle of them. Top: uncorrected temperature map; middle: corrected for the dipole term due to velocity of observer; bottom: further corrected image removing the contribution of our galaxy.



Photons escaping through a hole

- All photons travel at the same speed regardless of their wavelengths. Therefore, low-energy photons will escape through the hole with the same probability as high-energy photons, and the spectrum of the photons coming out of hole must be the same as the spectrum of the photons inside box.
- Detailed geometrical calculations show that the power emitted per unit area $\frac{\mathbb{W}}{A}$ is $\frac{cU}{4V}$. With accuracy of ¼ it could be derived just taking into account dimensionality of available parameters.

$$\frac{\mathbb{W}}{A} = \frac{cU}{4V} \qquad \frac{U}{V} = \frac{8\pi^5 (kT)^4}{15(hc)^3} \qquad \frac{\mathbb{W}}{A} = \sigma T^4 \qquad \sigma = \frac{2\pi^5 k^4}{15h^3c^2} = 5.67\ 10^{-8}\,\frac{W}{m^2K^4}$$

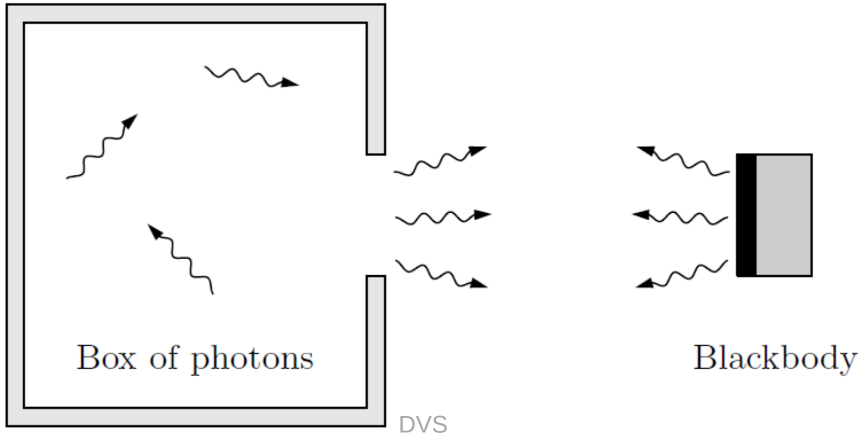
Stefan's law
discovered empirically in 1879

Stefan-Boltzmann constant

- **Stefan's law** for photons emitted from a hole in a box also applies to photons emitted by any nonreflecting ("**black**") surface at temperature T. Such radiation is therefore called **blackbody radiation**.

Blackbody Radiation

Stefan's law in application to photons emitted by nonreflecting ("black") surface.



$$\mathbb{W} = Ae\sigma T^4$$

A is the object's surface area.
e is emissivity.

- If the objects are of the same size, each will absorb the same fraction of the other's radiation.
- Suppose that the blackbody does not emit the same amount of power as the hole. Perhaps it emits somewhat less. Then more energy will flow from the hole to the blackbody than from the blackbody to the hole, and the blackbody will gradually get hotter. This violates the second law of thermodynamics.
- If the blackbody emits more radiation than the hole, then the blackbody gradually cools off while the box with the hole gets hotter. Again, this violates the second law of thermodynamics.
- **The entire spectrum of radiation emitted by the blackbody must be the same as for the hole.**
- If object is not black, emissivity e is introduced. It equals 1 for a perfect blackbody, and 0 for a perfectly reflective surface. Thus, **good reflector is poor emitter**, and **poor reflector is good emitter**.

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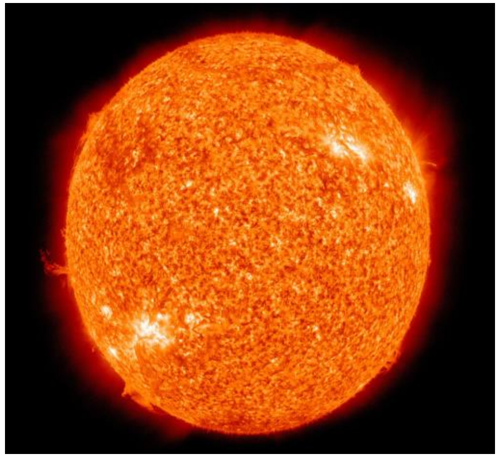
The Sun and the Earth

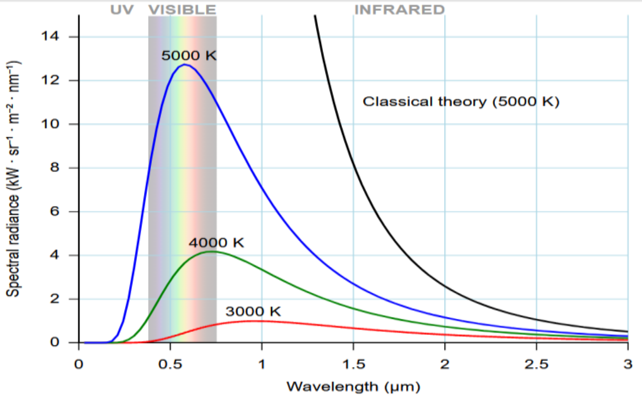


NASA/SDO (AIA) - http://sdo.gsfc.nasa.gov/assets/img/browse/2010/08/19/20100819_003221_4096_0304.jpg

Stefan's law $\frac{\mathbb{W}}{A} = e\sigma T^4$ $\sigma = 5.67\ 10^{-8} \frac{W}{m^2 K^4}$

The Sun's Magnetic Field is about to Flip | NASA

- The Stefan's law can be applied to sun as radiating object.
- Earth receives from the sun radiation of 1370 W/m^2 known as the **solar constant** S_k. From earth's radius (6370 km) and the distance from the sun of 150 million kilometers, sun's total energy output or luminosity $\mathbb{W}$ is 3.9 10^{26} watts.
- The sun's radius (≈700 000 km) is a little over 100 times the earth's. Its surface area is then 6.1 10^{18} m^2.
- Assuming an emissivity e equal to one, the temperature of the sun ($T = \left(\frac{\mathbb{W}}{Ae\sigma}\right)^{1/4}$) is 5800 K.
- This gives maximum of spectrum at a photon energy of $\epsilon = 2.82\,kT = 1.41\,eV$, which corresponds to a wavelength of 880 nm, in the near infrared. This agrees well with experiment. Therefore, **much of the sun's energy is emitted as visible light.**
- The sun's spectrum is approximately given by the Planck formula.
- A tiny fraction of the sun's radiation is absorbed by the earth, warming the surface to a temperature suitable for life.



By Darth Kule - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=10555337

Equilibrium surface temperature of Earth

- On average, the earth is in thermal equilibrium. It also emits radiation into space, approximately at the same rate as it is receiving it from sun. The balance between absorption and emission gives a way to estimate the earth's equilibrium surface temperature.
- First approximation is to consider earth as a perfect blackbody at all wavelengths. The power absorbed by earth is the **solar constant** S_k times the earth's cross-sectional area as viewed from the sun, πR^2, where R is earth's radius. The emission is from all surface: $4\pi R^2$. The equilibrium condition is:

$$S_k \pi R^2 = 4\pi R^2 \sigma T^4. \qquad T = \left(\frac{S_k}{4\sigma}\right)^{1/4} = \left(\frac{1370\ \frac{W}{m^2}}{4 \cdot 5.67\ 10^{-8}\ \frac{W}{m^2 K^4}}\right)^{1/4} = 279\ K.$$

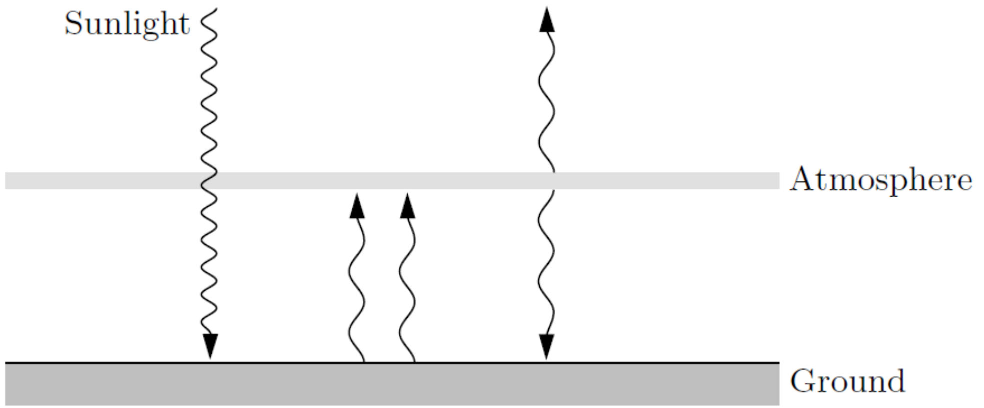
The estimated value is very close to the measured average temperature of $288\ K$ ($15\ ℃$).

- However, the earth is not a perfect blackbody, and about 30% of the sunlight is reflected directly back into the space. This would decrease average temperature down to $255\ K$.
- The counterbalancing (although not perfect) effect is the reflection of radiation from opaque atmosphere.

Greenhouse effect

$$T = \left(\frac{S_k}{4\sigma}\right)^{1/4}$$

The atmosphere can be modelled in single-layer approximation:



DVS

- In the single-layer approximation, surface of the planet receives twice the energy that is provided by the sun.
- According to this equation for T, the surface temperature would increase by a factor of $2^{1/4}$, i.e. to $303\ K$.
- Since atmosphere is not a single layer, its complex effect leads to measured $288\ K$.
- Evidently **due to human activity, earth is out of equilibrium and slowly warming**. This could have strong consequences for the climate and influence human population as a whole.
- The advanced modelling of the climate clarifying greenhouse effect is awarded Nobel Prize in Physics 2021.

UiO University of Oslo

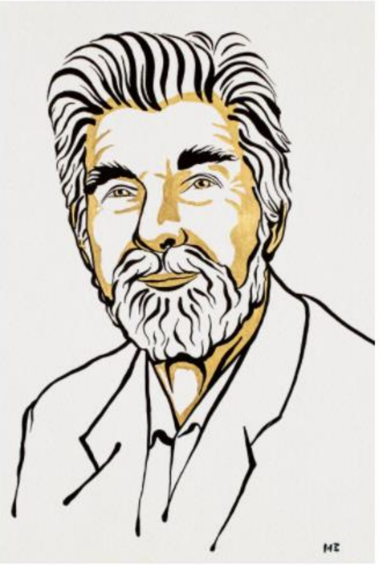
Nobel Prize in Physics 2021

https://www.nobelprize.org/prizes/physics/2021/summary/

Ill. Niklas Elmehed © Nobel Prize Outreach

Syukuro Manabe

Prize share: 1/4



Ill. Niklas Elmehed © Nobel Prize Outreach

Klaus Hasselmann

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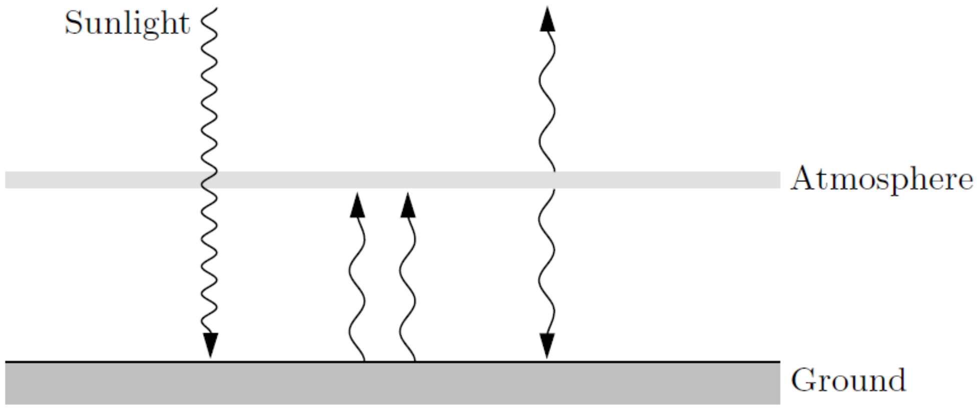
Giorgio Parisi

Prize share: 1/2

The Prize is awarded "for groundbreaking contributions to our understanding of complex systems" with one half jointly to Syukuro Manabe and Klaus Hasselmann "for the **physical modelling of Earth's climate, quantifying variability and reliably predicting global warming**" and the other half to Giorgio Parisi "for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales."



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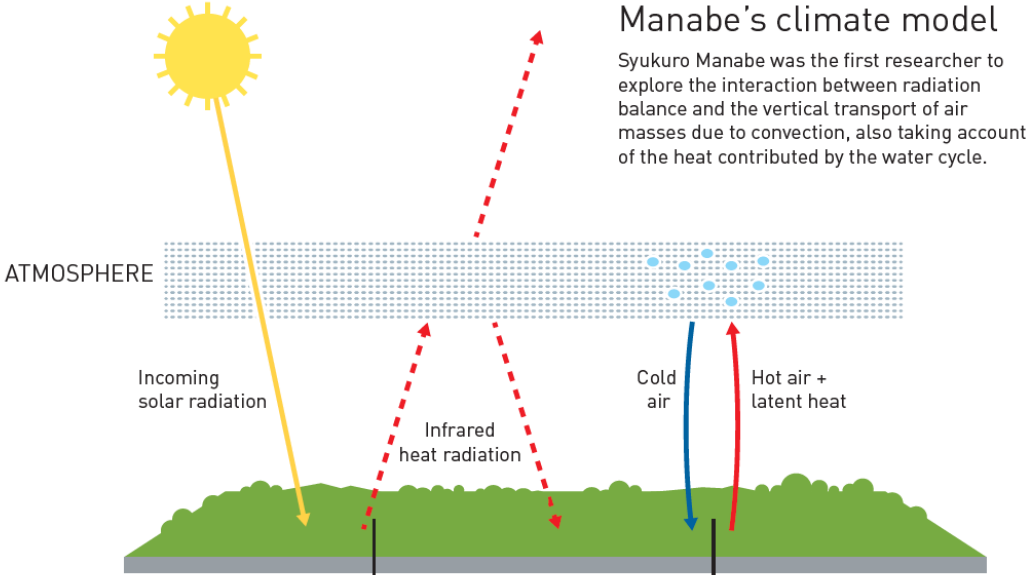

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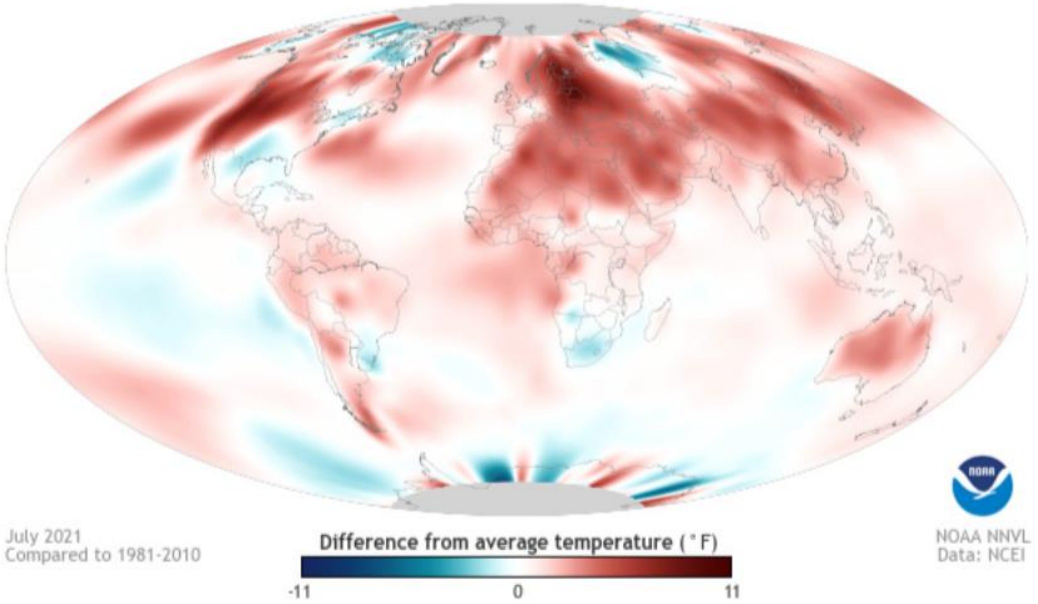
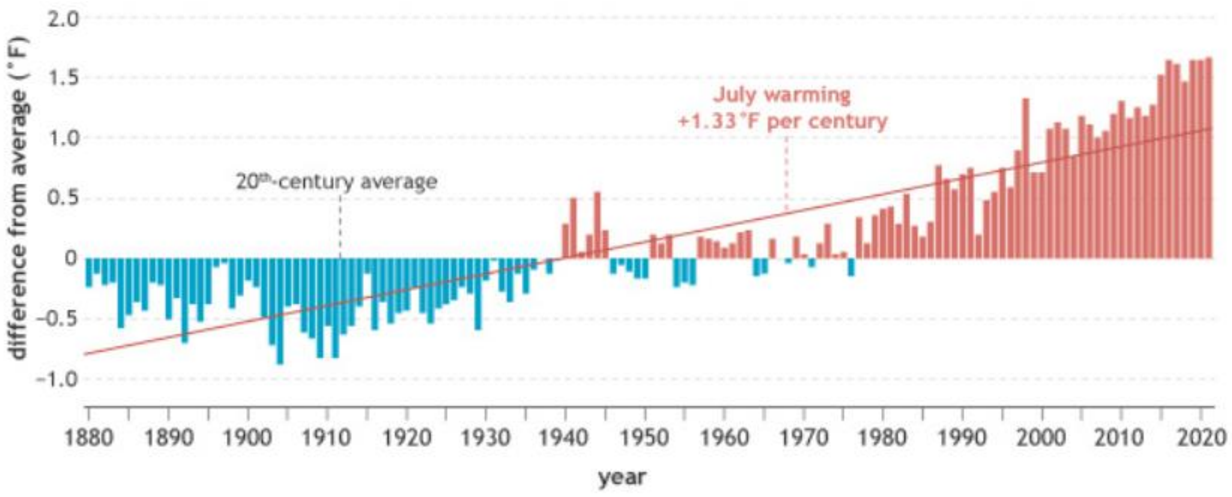
Greenhouse effect 2021

The July 2021 global surface temperature was 0.93 °C above the 20th-century average of 15.8 °C . It was the highest for July in the 142-year record. This value was 0.01 °C higher than the previous record set in 2016, and repeated in 2019 and 2020.



Global July temperatures compared to average (1880-2021)



https://www.climate.gov/news-features/understanding-climate/earths-hottest-month-was-record-hot-2021

There are several consequences and scenarios (mostly negative) for global warming.

Summary

- Blackbody radiation is electromagnetic radiation from non-reflective body with specific spectrum of wavelengths defined by its temperature.
- Boltzmann distribution for quantized electromagnetic waves (Planck distribution) is a solution for paradox of ultraviolet catastrophe.
- Planck distribution is Bose - Einstein distribution with chemical potential equal to zero. Chemical potential of photons is zero.
- The energy density of photon gas is proportional to fourth power of the temperature.
- The radiation that fills the entire observable universe has an almost perfect thermal spectrum at a temperature of 2.73 K.
- Greenhouse effect accelerating warming of the planet, is consequence of the human activity.