Thermal Imaging for Energy Applications

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Agenda

1.	Light & radiation
2.	Radiation & matter
3.	Thermal cameras
4.	Applications
5.	Thermal monitoring of district heating
6.	Camera demo

Break!

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Part 1

Light & Radiation

From where comes the radiation that I see?

Emitted

Transmitted

Reflected

Absorbed

Friedrich Wilhelm (Frederick William) Herschel

Symphony No. 15 (1762)

https://open.spotify.com/track/0kQcVlkwv2LJQ49KXnklVe

Caroline & William Herschel

- 1 planet
- 4 moons
- 8 comets
- 5000 other objects

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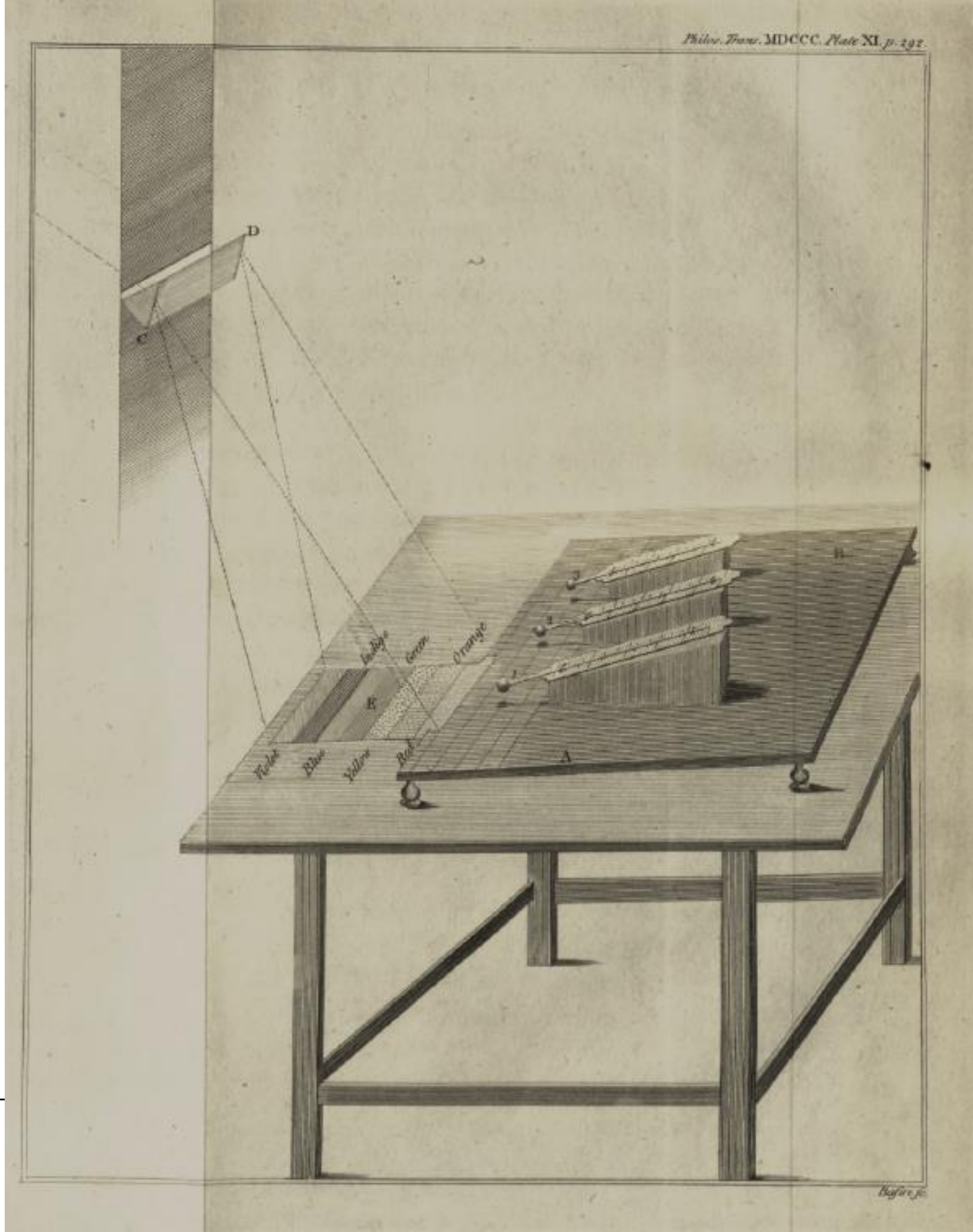
Herschel 1800a

"In this case, radiant heat will at least partly, if not chiefly, consist, if I may be permitted the expression, of invisible light; that is to say, of rays coming from the sun, that have such a momentum as to be unfit for vision."

F. W. Herschel, "Experiments on the refrangibility of the invisible rays of the Sun," *Philos. Trans. R. Soc.*, vol. 90, pp. 284–292, 1800.
doi: 10.1098/rstl.1800.0015



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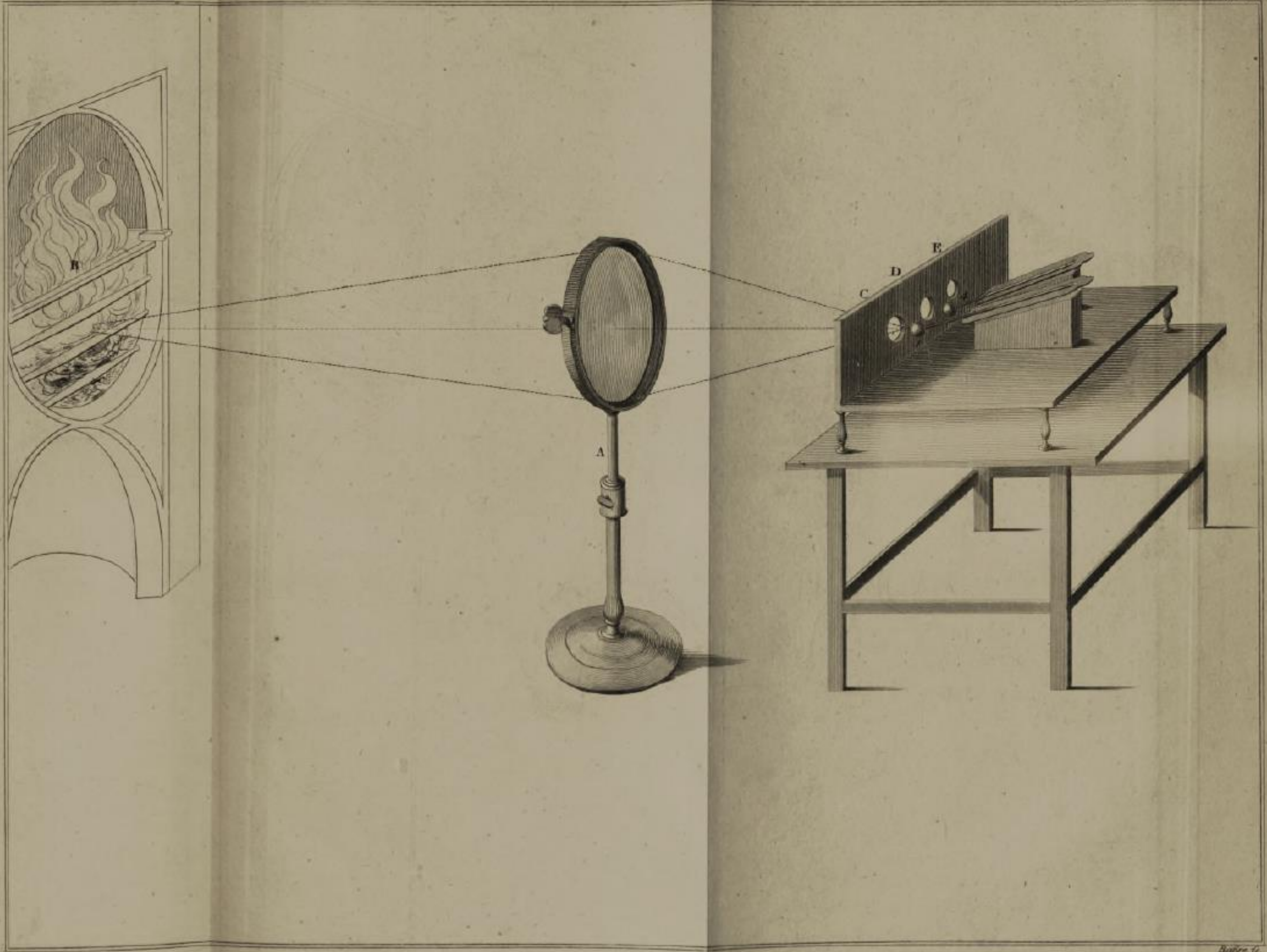
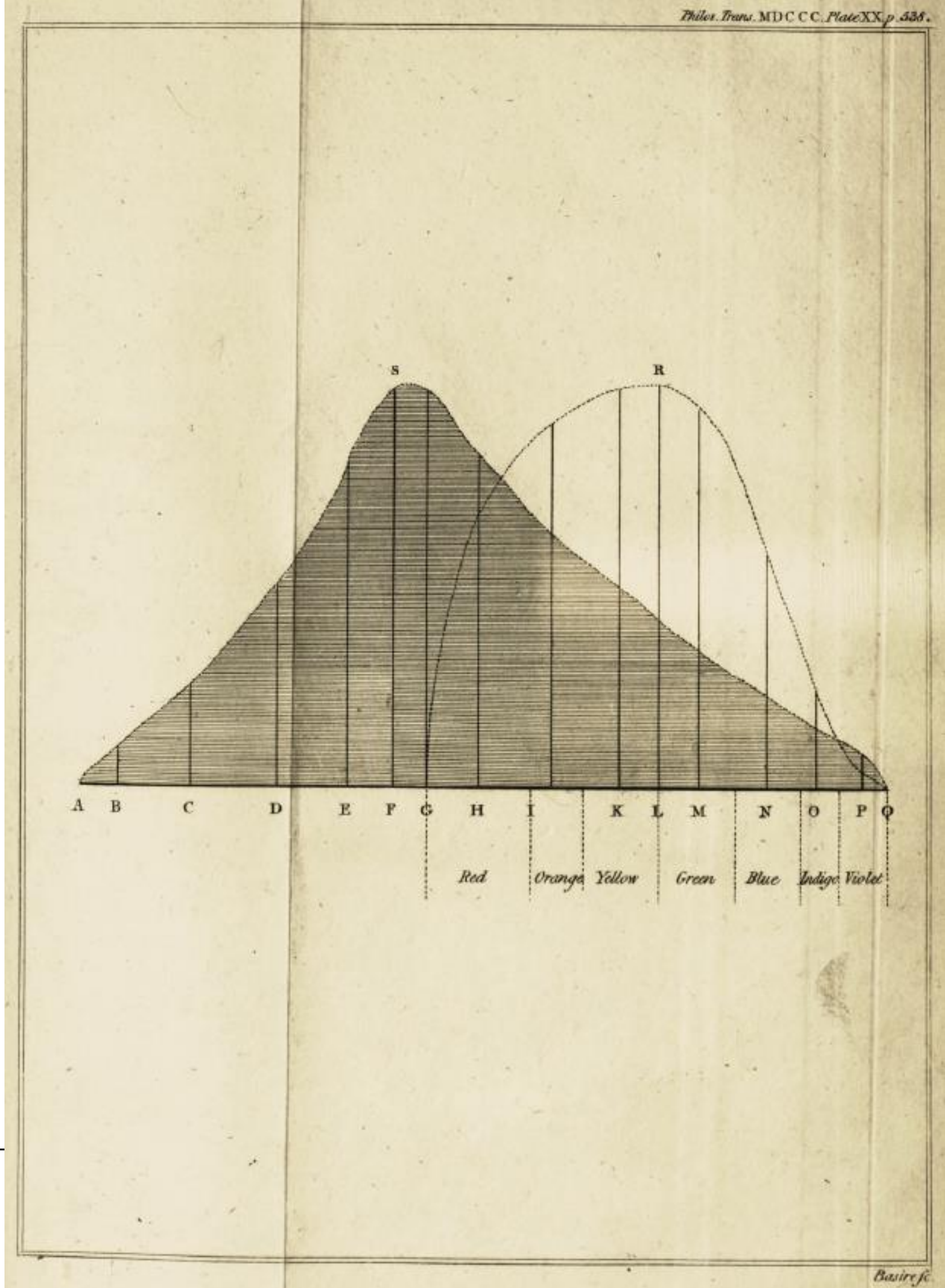


Basire sc.

Herschel 1800b, c

F. W. Herschel, “Experiments on the Solar, and on the Terrestrial Rays that Occasion Heat; With a Comparative View of the Laws to Which Light and Heat, or Rather the Rays Which Occasion Them, are Subject, in Order to Determine Whether They are the Same, or Different. Part I,” *Philos. Trans. R. Soc. London*, vol. 90, pp. 293–326, Jan. 1800.
doi: 10.1098/rstl.1800.0016

F. W. Herschel, “Experiments on the Solar, and on the Terrestrial Rays that Occasion Heat; With a Comparative View of the Laws to Which Light and Heat, or Rather the Rays Which Occasion Them, are Subject, in Order to Determine Whether They are the Same, or Different. Part II,” *Philos. Trans. R. Soc. London*, vol. 90, pp. 437–538, Jan. 1800.
doi: 10.1098/rstl.1800.0020



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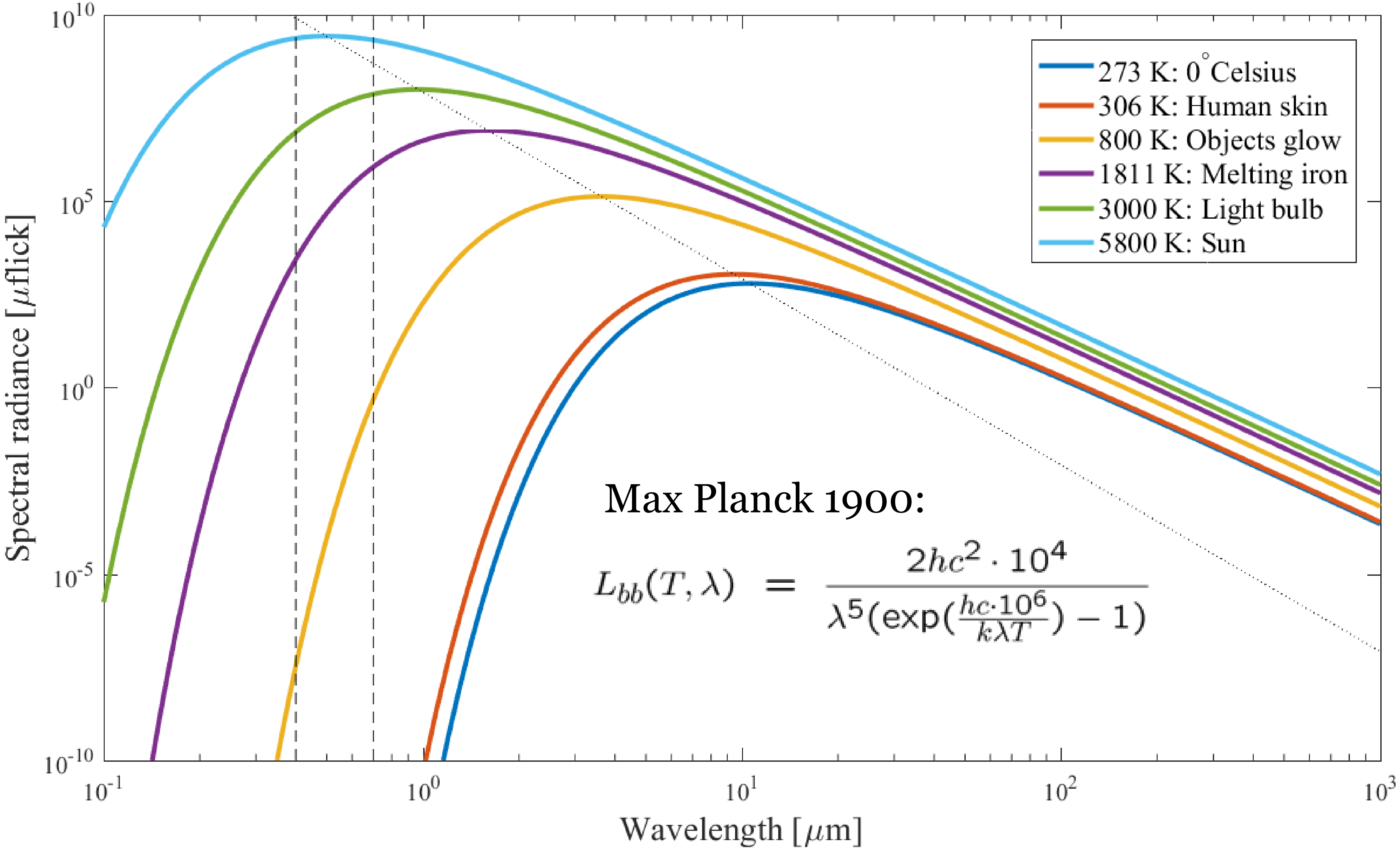
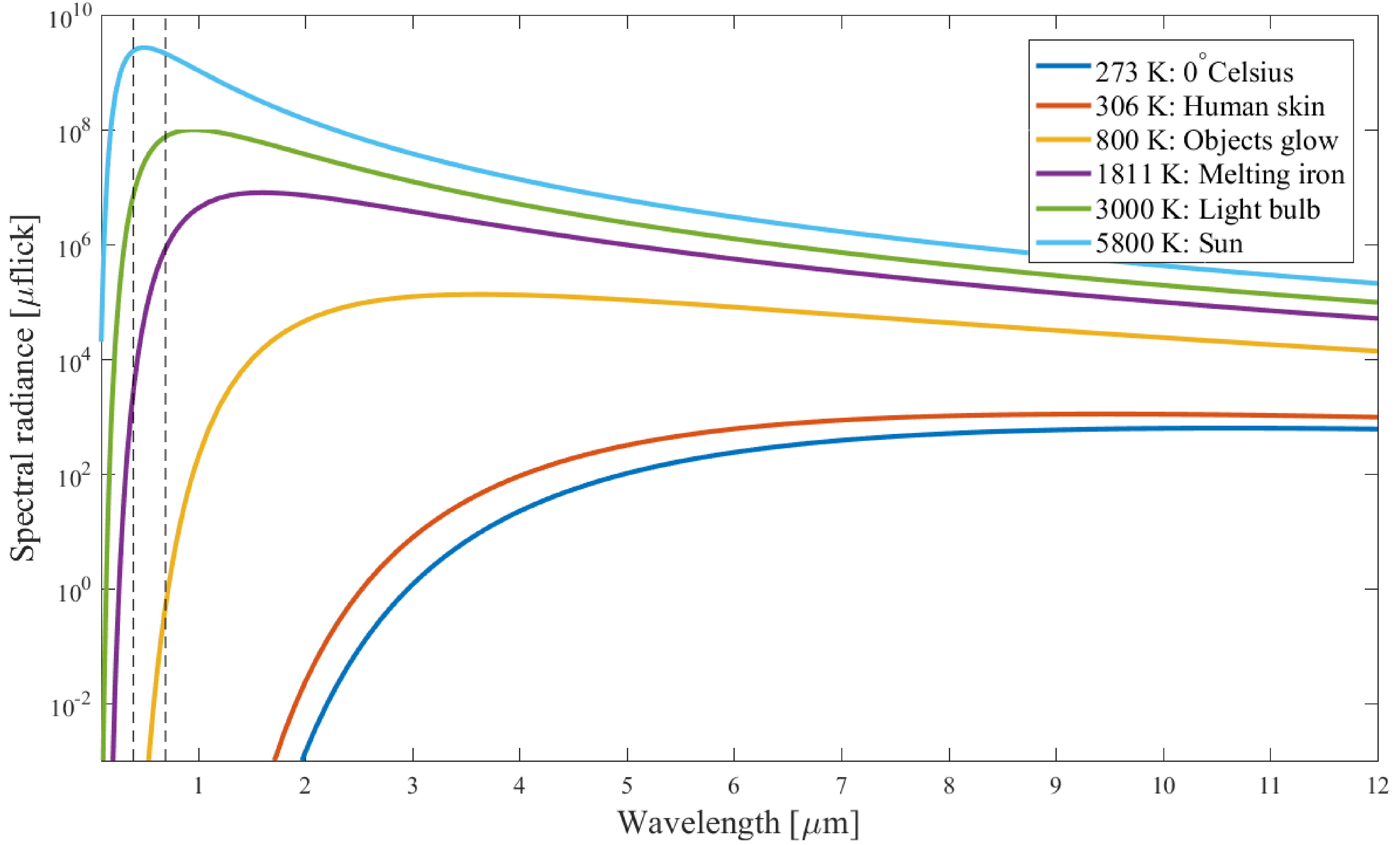
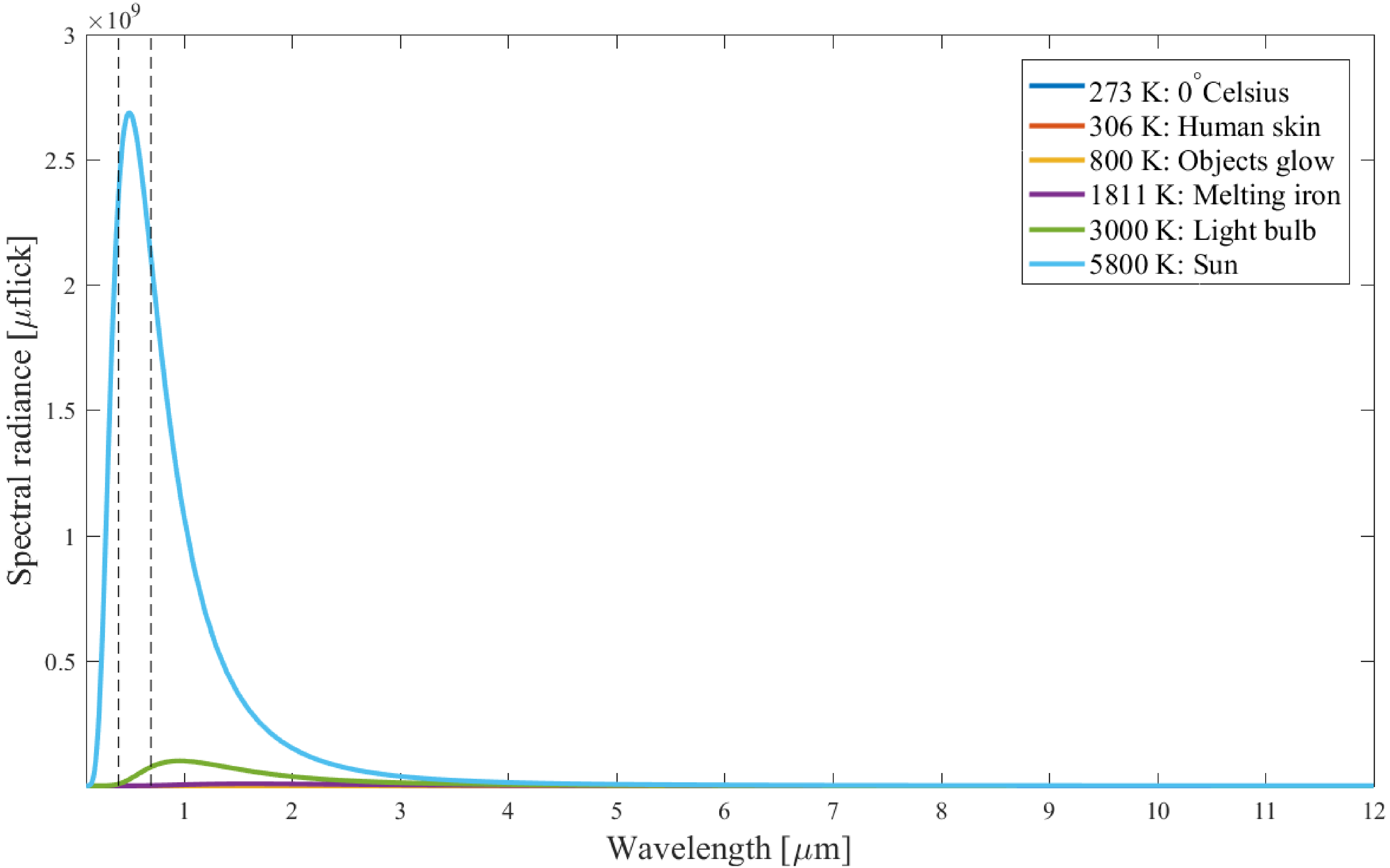


Max Planck 1900:

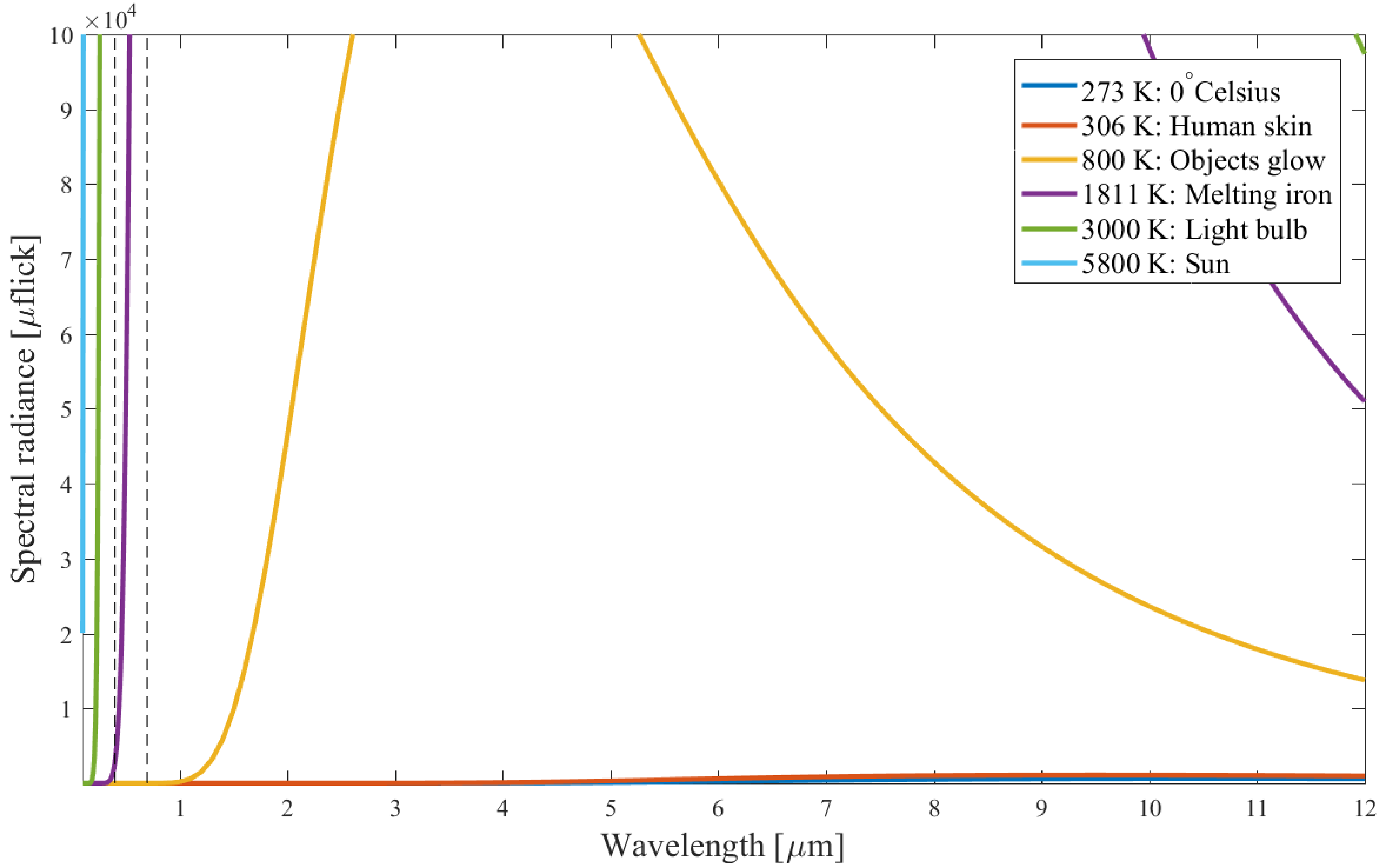
$$L_{bb}(T,\lambda) = \frac{2hc^2 \cdot 10^4}{\lambda^5(\exp(\frac{hc \cdot 10^6}{k\lambda T}) - 1)}$$



10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
Spectral radiance [μflick]
1 2 3 4 5 6 7 8 9 10 11 12
Wavelength [μm]
273 K: 0°Celsius
306 K: Human skin
800 K: Objects glow
1811 K: Melting iron
3000 K: Light bulb
5800 K: Sun

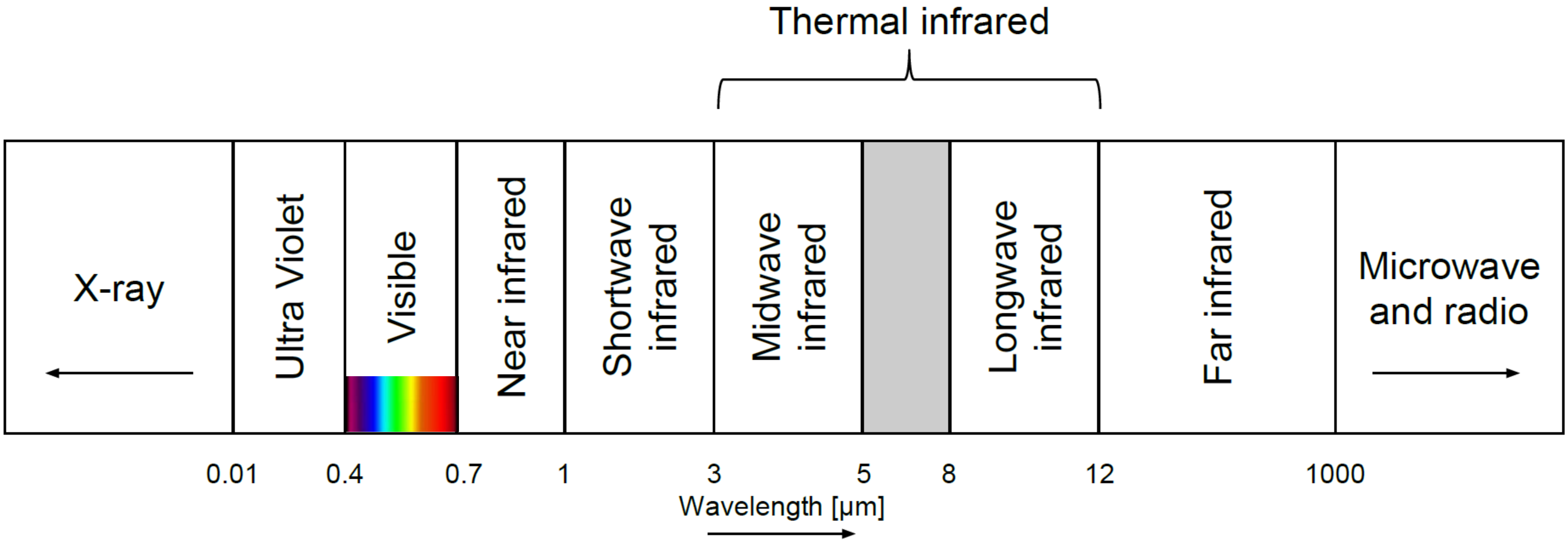


$\times 10^9$
3
2.5
2
1.5
1
0.5
Spectral radiance [μflick]
1
2
3
4
5
6
7
8
9
10
11
12
Wavelength [μm]
273 K: 0° Celsius
306 K: Human skin
800 K: Objects glow
1811 K: Melting iron
3000 K: Light bulb
5800 K: Sun



×10^4
10
9
8
7
6
5
4
3
2
1
Spectral radiance [μflick]
1
2
3
4
5
6
7
8
9
10
11
12
Wavelength [μm]
273 K: 0° Celsius
306 K: Human skin
800 K: Objects glow
1811 K: Melting iron
3000 K: Light bulb
5800 K: Sun

Domains and wavelengths and bands



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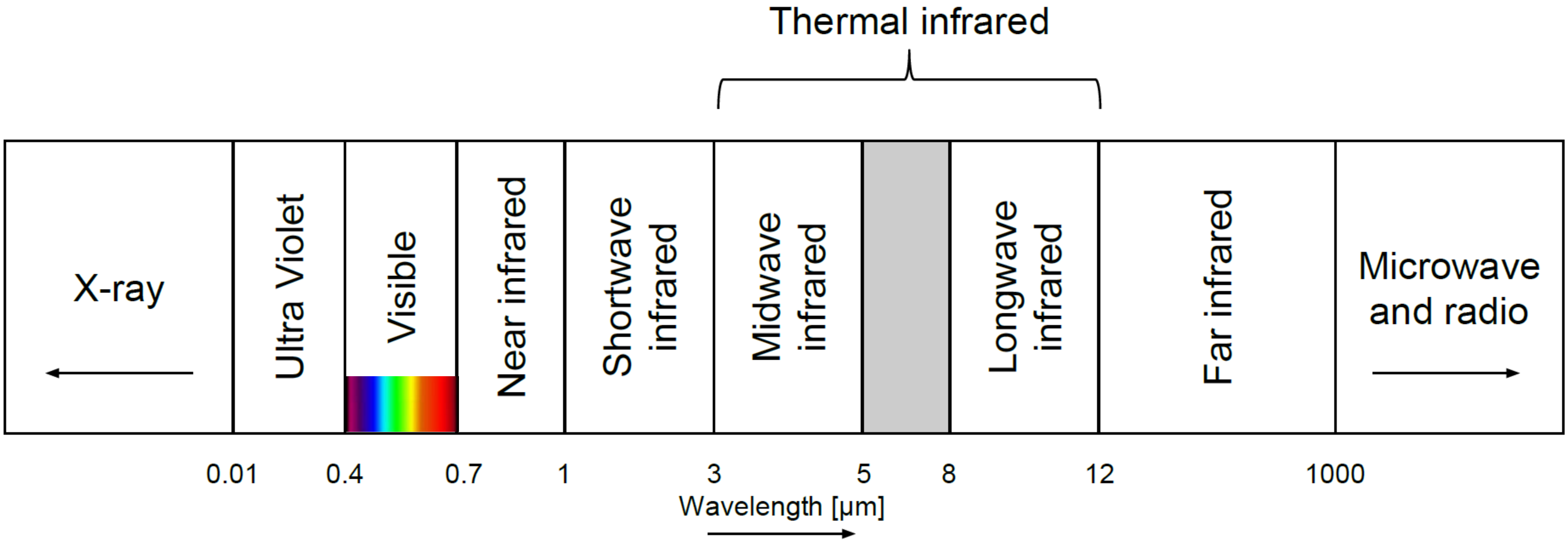
Why this particular division?



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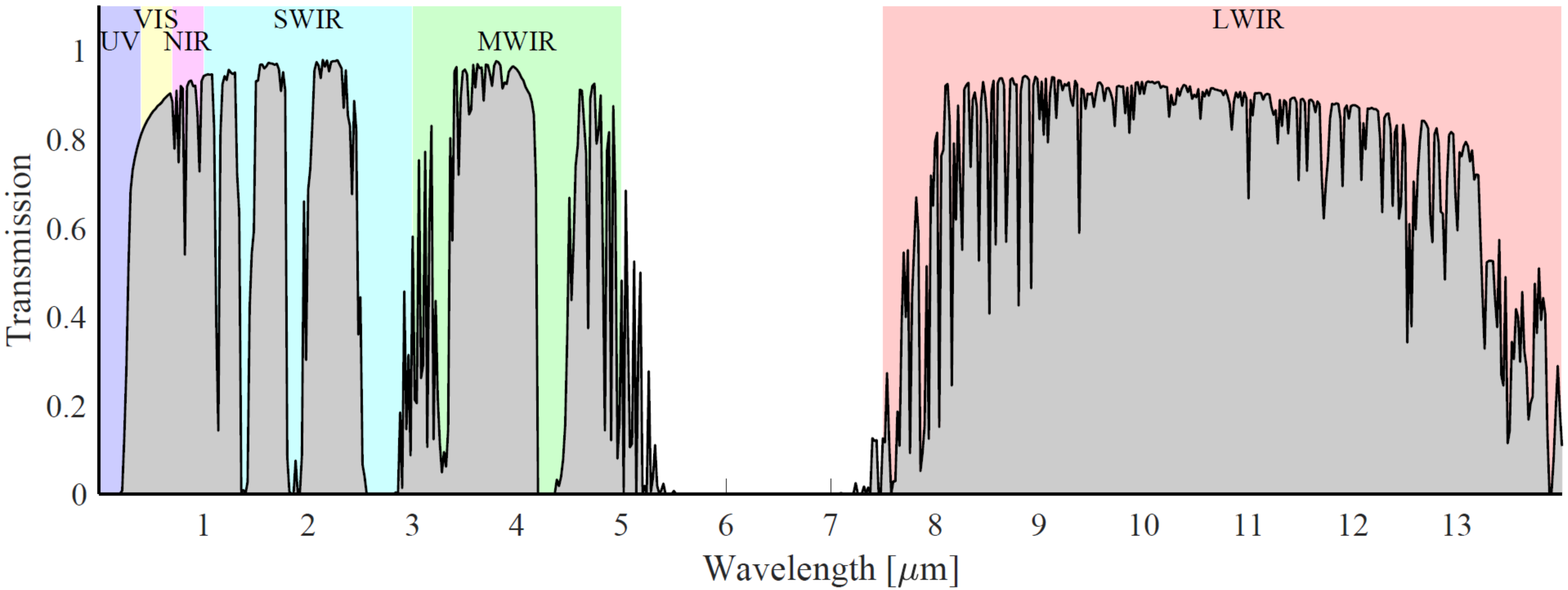
Reason 1: Atmospheric transmission



Reason 2: Behaviour

- Reflective domain
- Emissive domain

Reason 3: Sensors

- VNIR: Silicon (CCD, CMOS)
- SWIR: InGaAs sensors
- MWIR: InSb and MCT sensors
- LWIR: MCT and bolometer sensors

Note:
There are other subdivisions!
For example, astronomers use:

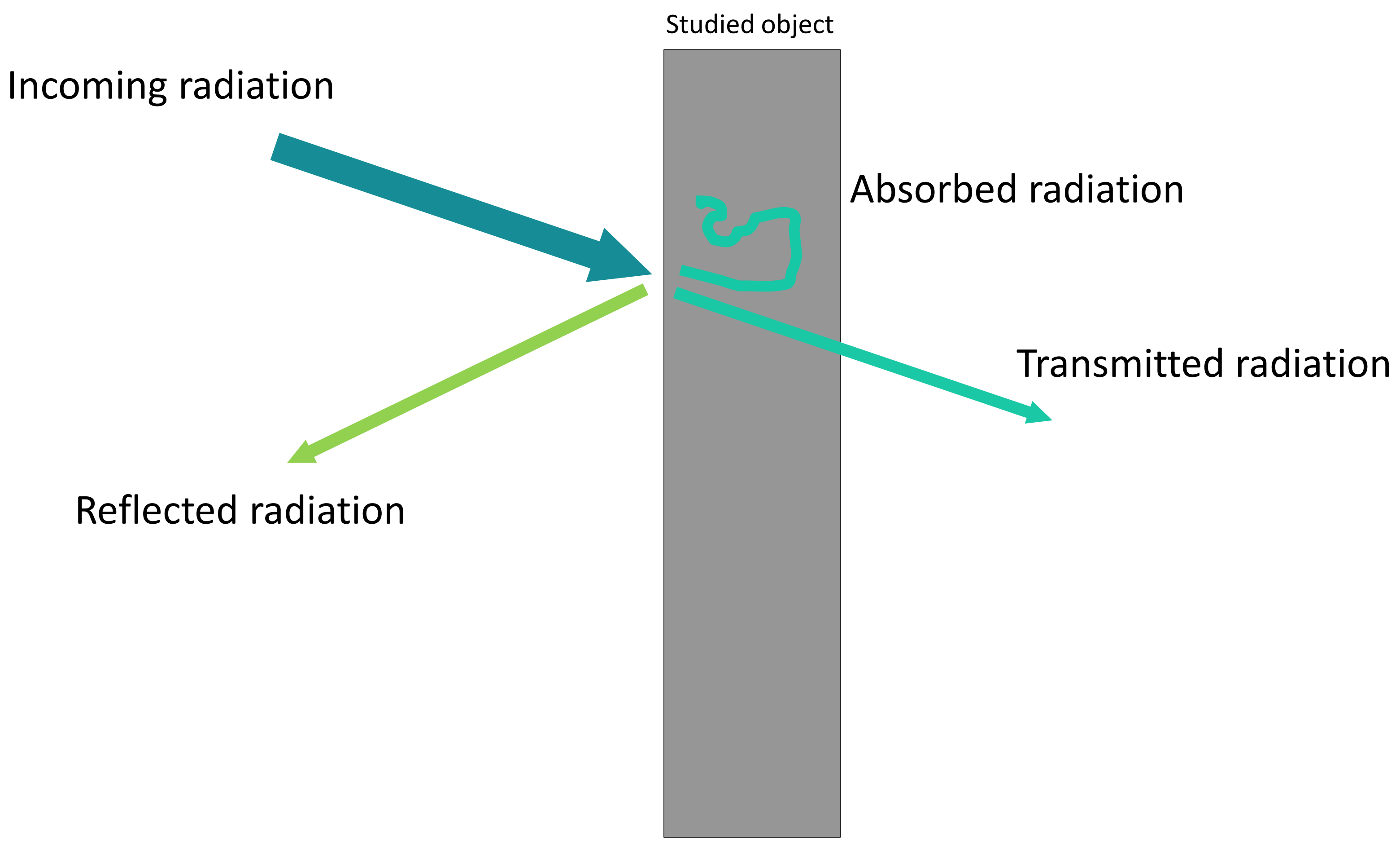
- NIR 0.7-5
- MIR: 5-(25...40)
- FIR: (25-40)-

Part 2

Radiation & Matter

Radiation and matter

- Absorbed
- Reflected
- Transmitted

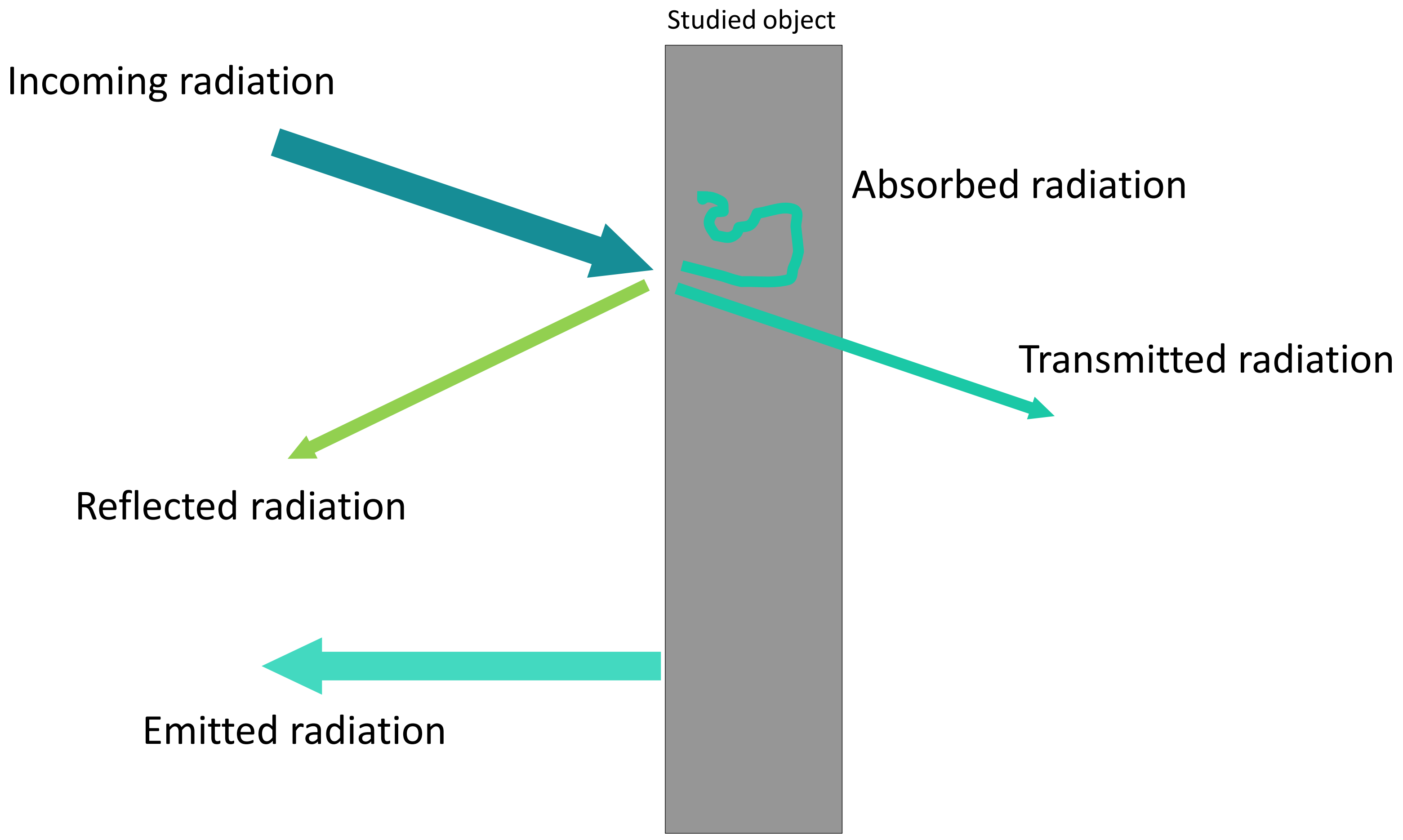


$$\alpha + \tau + r = 1$$

$$\alpha(\lambda) + \tau(\lambda) + r(\lambda) = 1$$

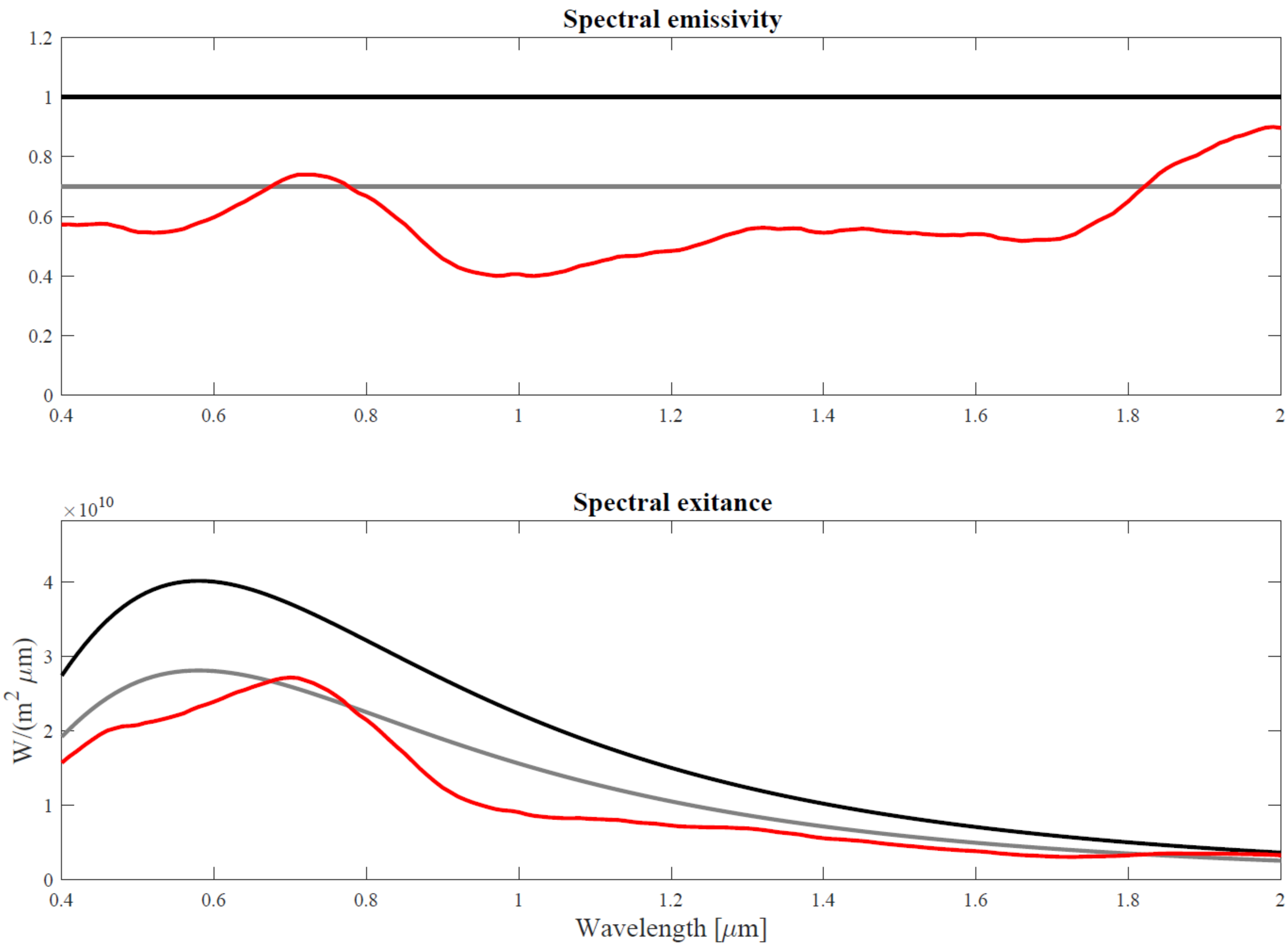
Radiation and matter

- Absorbed
- Reflected
- Transmitted
- Emitted



Emissivity (ε)

$$\alpha = \varepsilon$$



Spectral emissivity
1.2
1
0.8
0.6
0.4
0.2
0
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Spectral exitance
×10^10
W/(m^2 μm)
4
3
2
1
0
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Wavelength [μm]

Outgoing radiation

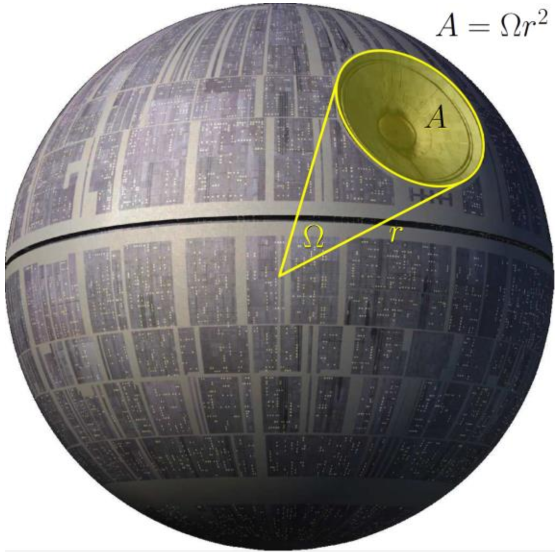
Incoming radiation

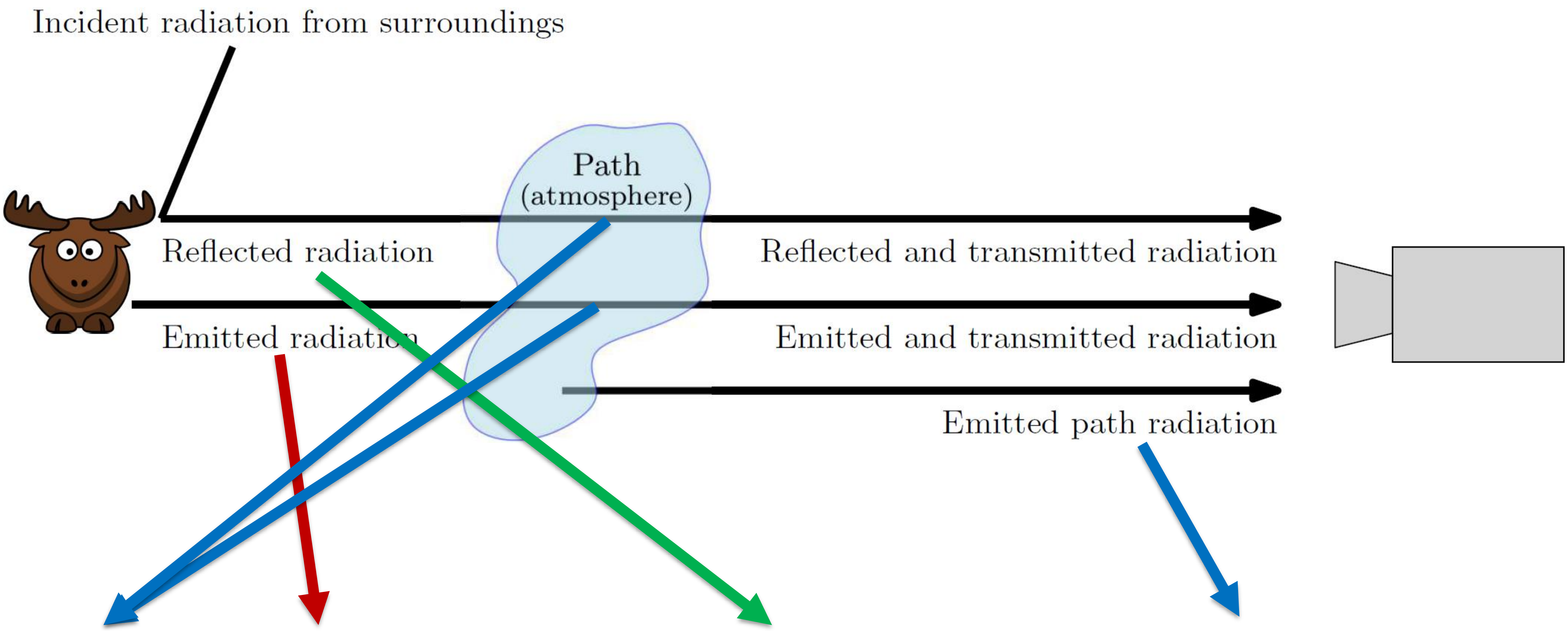
- Absorptivity α
- Emissivity ε
- Transmittance τ
- Reflectance r

- (Radiant) Flux Φ [W]
- Irradiance E [W / m²]
- Exitance M [W / m²]
- Radiance L [W / m² sr]

steradian

- α + τ + r = 1
- Dependent on wavelength and angle!
- Commonly: τ or r close to zero.




Incident radiation from surroundings
Path
(atmosphere)
Reflected radiation
Reflected and transmitted radiation
Emitted radiation
Emitted and transmitted radiation
Emitted path radiation

From object to sensor

- A sensor integrates the incoming energy over a certain bandwidth.
- The at-sensor radiance is (mainly and typically) the sum of
  1. Radiation emitted by the object and transmitted through the path;
  2. Radiation reflected by the object transmitted through the path;
  3. Radiation emitted by the path;
  4. Radiation scattered by the path.
- This does not equal the temperature of the object!

Summary: Light, radiation and matter

- Radiators: Blackbodies, greybodies, general objects.
- Properties: Emissivity, absorptivity, reflectance, transmittance.
- Radiation often measured as flux, radiance, and irradiance.
- Domains: Reflective vs emissive.
- Bands: UV, VIS, NIR, VNIR, SWIR, MWIR, LWIR, TIR, FIR.

Part 3

Thermal cameras

Thermal cameras

Defence

Civilian

Thermography

Imaging
(non radiometric)

Temperature measuring
(radiometric)

Handheld

Industrial

High-end (defence)

High-end (science)

Uncooled cameras

- Pyro-electric detectors
- Microbolometers

The common detector in handheld and industrial IR cameras.

Internal radiation

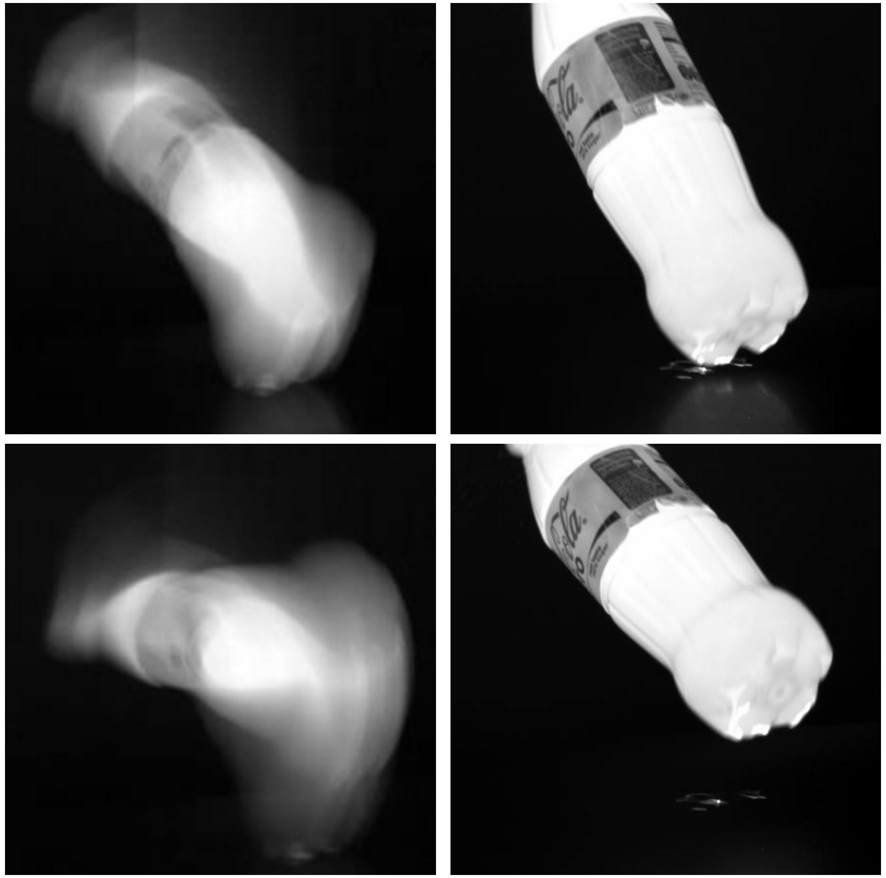
- Much of the radiation hitting the sensor is emitted by the camera
  - 90% is a realistic value
- Thus:
  - One or more internal thermometers
  - On-board processing

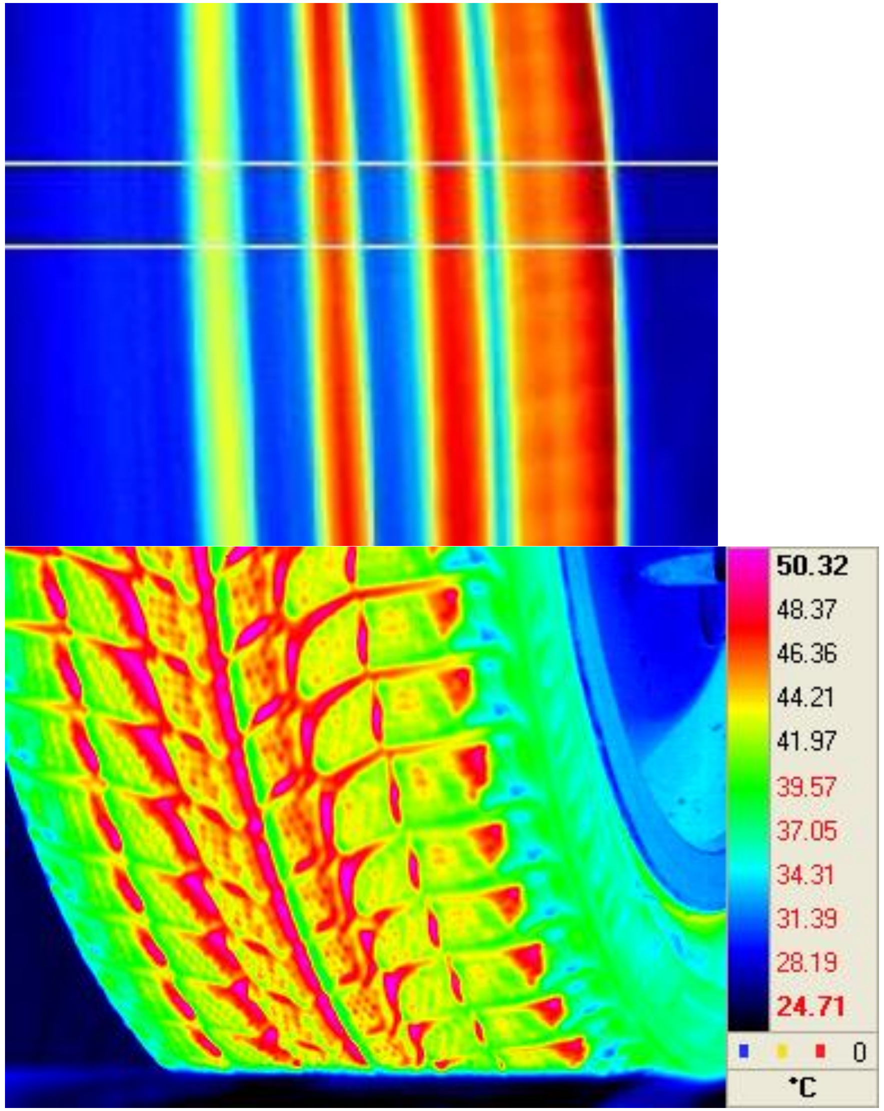
3 thermometers in this one!

Cooled cameras

- High spatial resolution
- High temperature resolution
- Fast
- Loud
- Heavy
- Large
- Expensive

Cooled vs uncooled



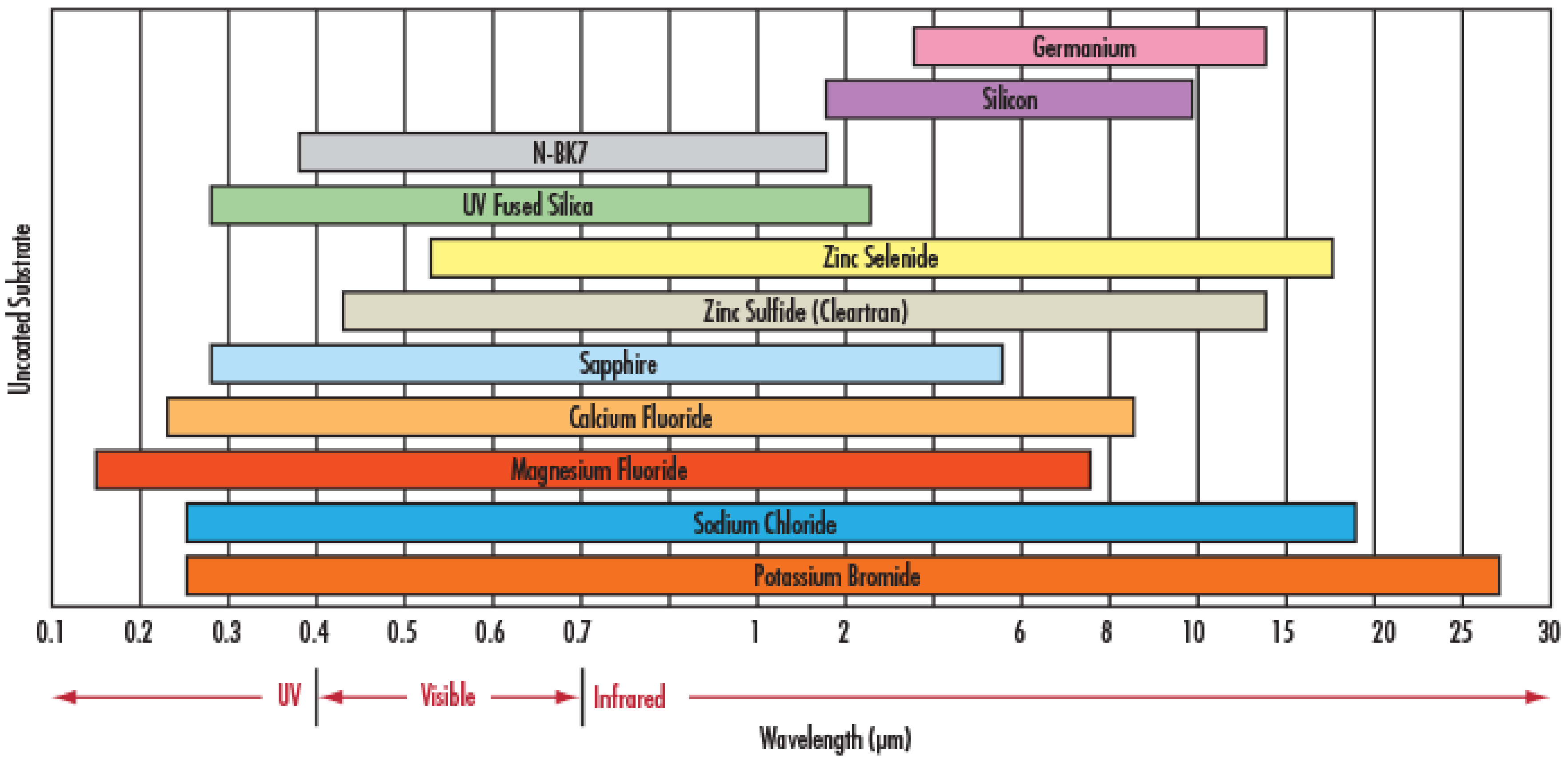


Optics for thermal cameras

Parameters

- Durability
- Refractive index
- Variability due to heat
- Cost
- Transmittance

Materials



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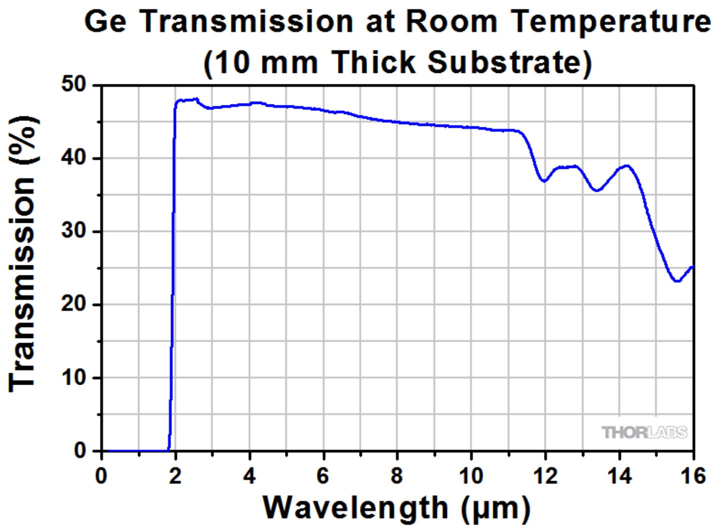
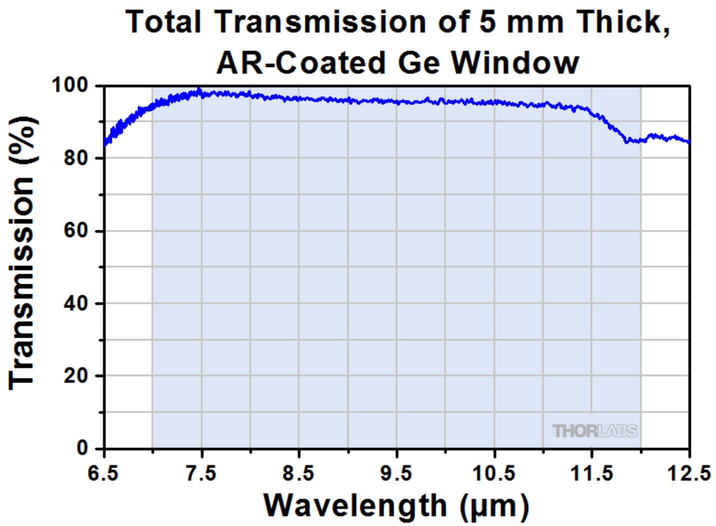
Lens materials: Germanium

- Good for MWIR and LWIR (with AR coating)
- Durable (KH 780)
- High refractive index (4.0)
- Transmittance drops with temperature!





A note on color

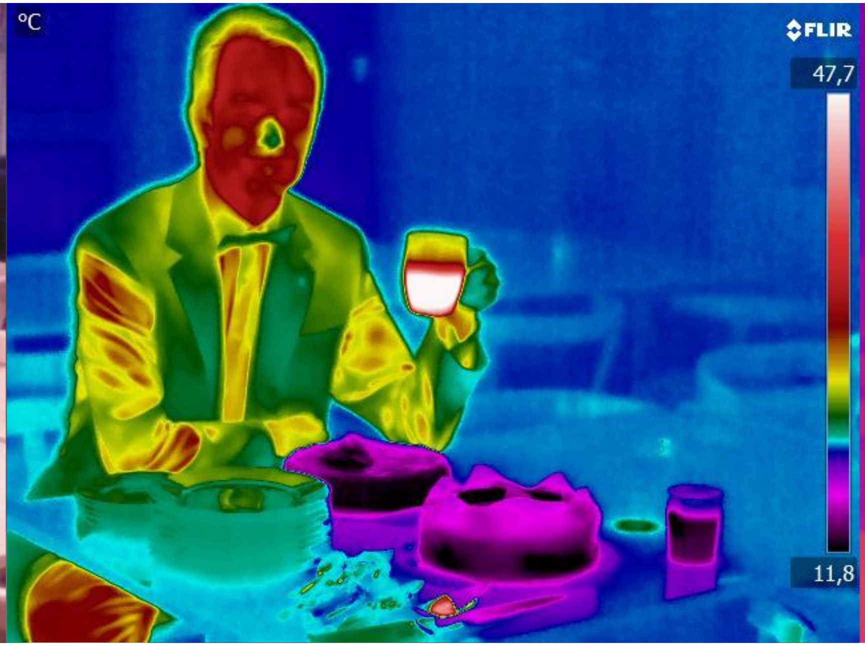
Visual

White hot

Black hot

A note on color

Visual



Rainbow

Iron

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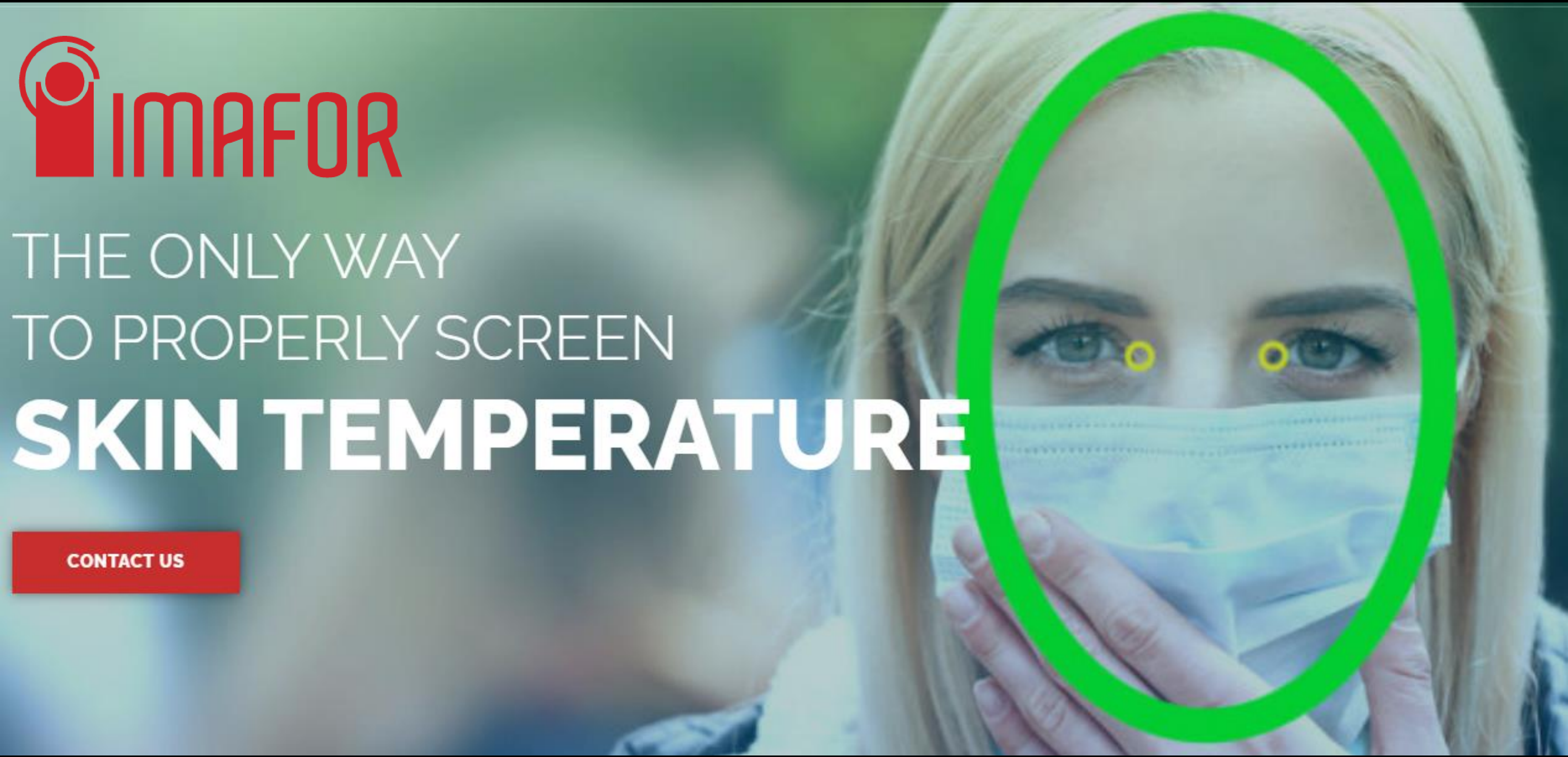
Summary: Thermal cameras

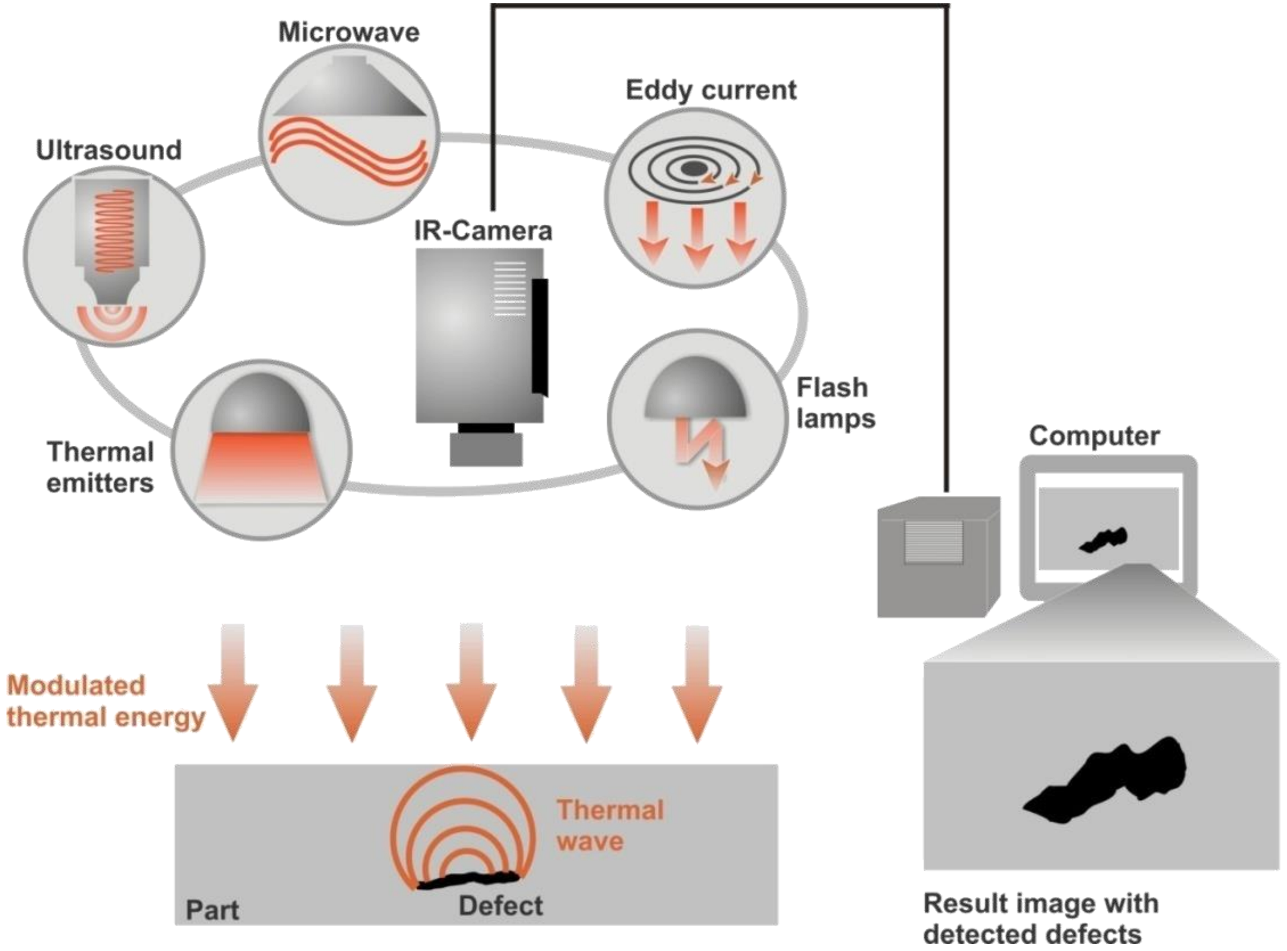
- Cooled vs uncooled
  - Cooled: Loud, cumbersome, expensive, fast, sensitive.
- Sensors: Thermal detectors vs photon detectors
- Optics: Transmitting in different bands
- The most common thermal camera: Uncooled bolometer camera for LWIR with Germanium lens.

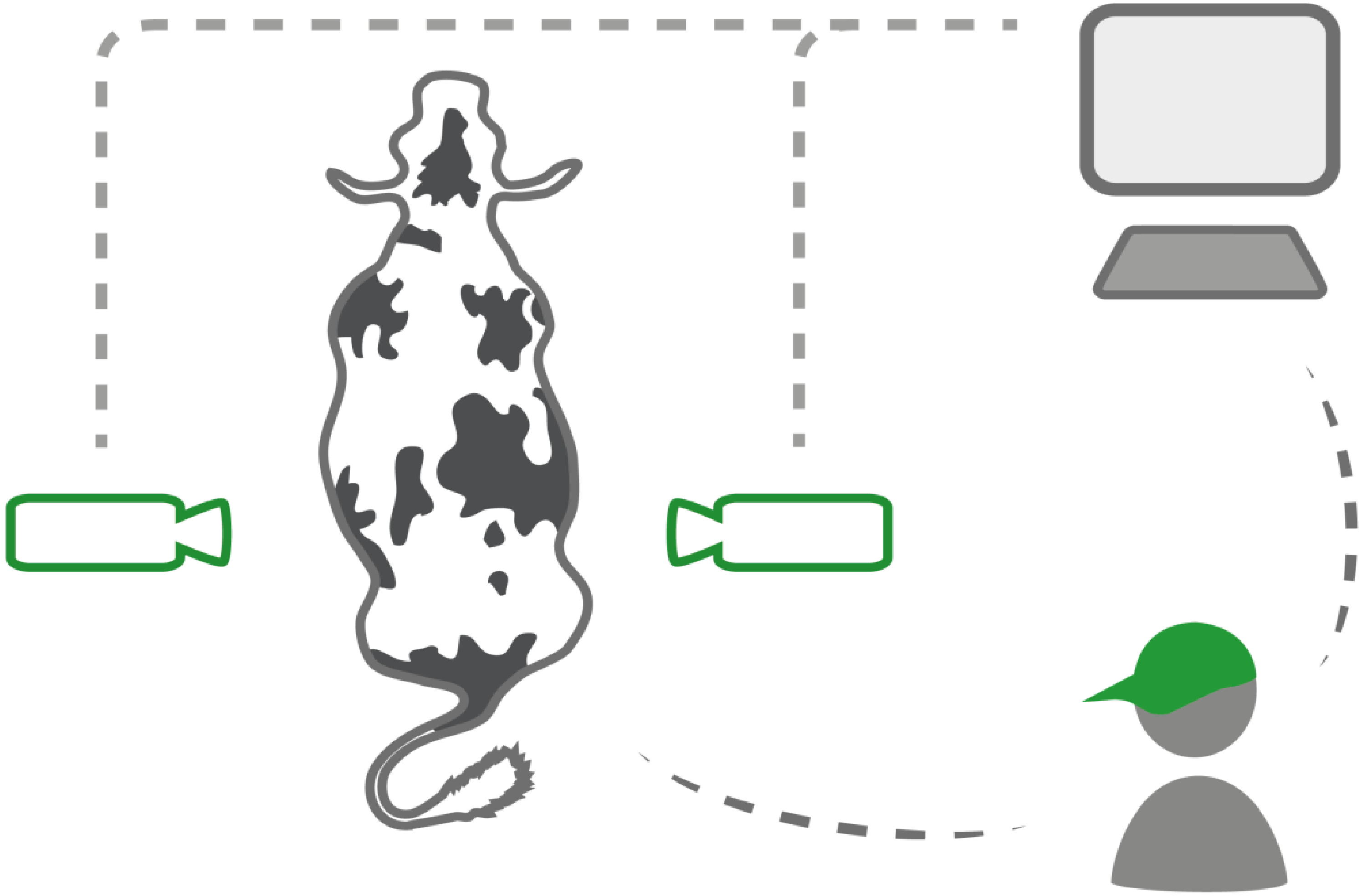
Part 4

Applications


IMAFOR
THE ONLY WAY
TO PROPERLY SCREEN
SKIN TEMPERATURE
CONTACT US

Non-destructive testing



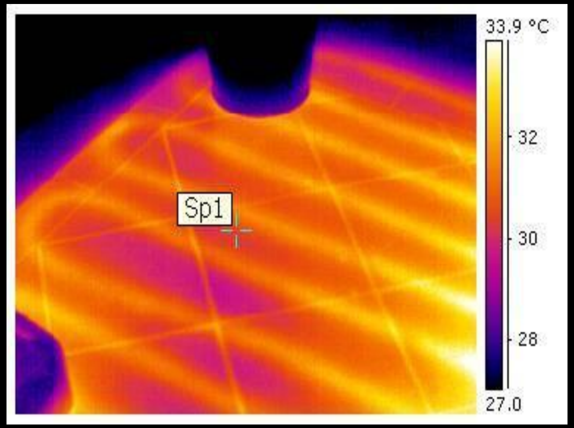


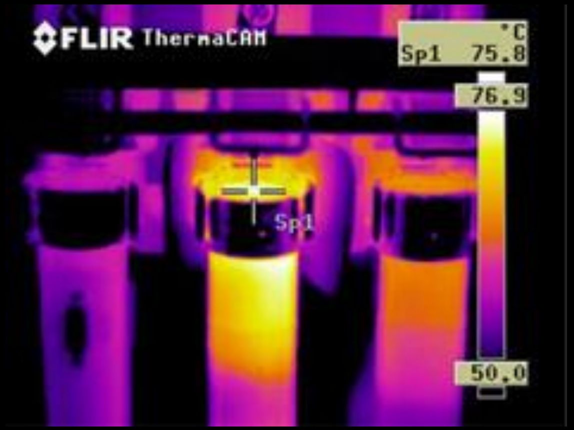
agricam

Energy applications?

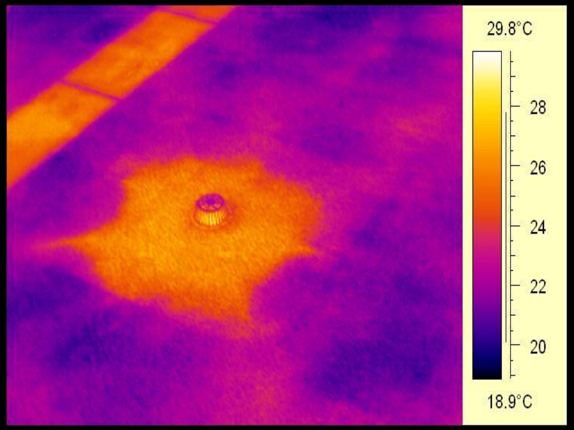
- Piles of garbage or biofuel can catch fire
  - Use thermal cameras to detect fires.
- It is critical in turbines and rotors that they are free from defects.
  - Use thermal cameras to detect defects.
- Energy losses typically leads to unwanted heat
  - Use a thermal cameras to detect and measure energy losses.

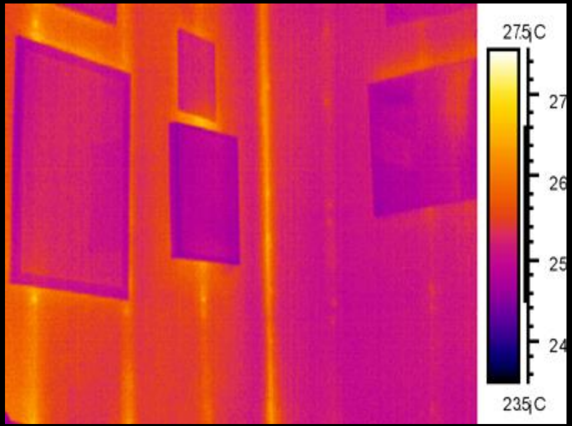

FLIR
°C
19
6
2/27/05 9:32:07 p e=0.95

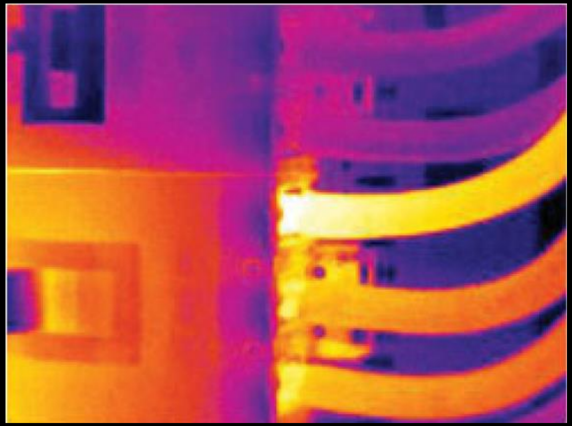

33.9 °C
32
30
28
27.0
Sp1

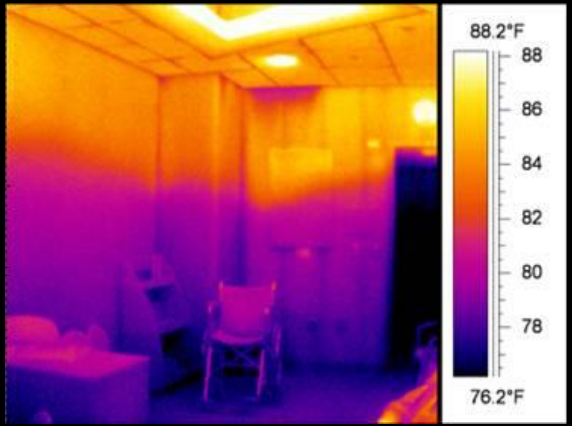

FLIR ThermaCAM
°C
Sp1 75.8
76.9
50.0
Sp1

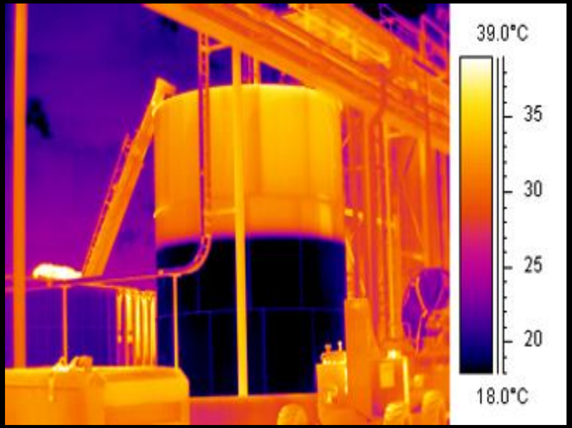

INDICATOR
Littelfuse
POWR-PRO
BRUSH
ECSR 60

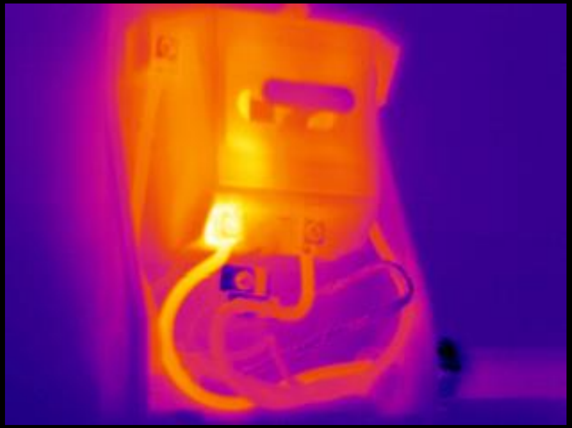

29.8°C
28
26
24
22
20
18.9°C

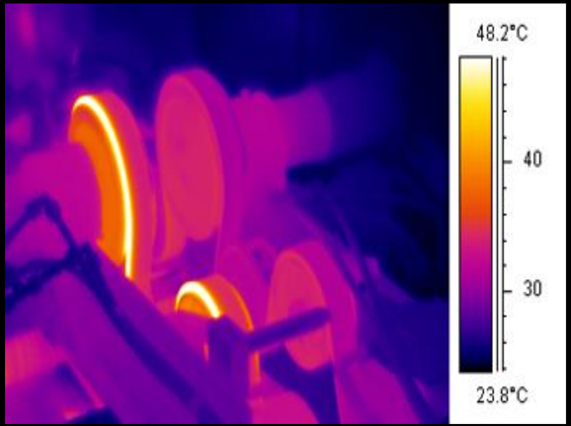
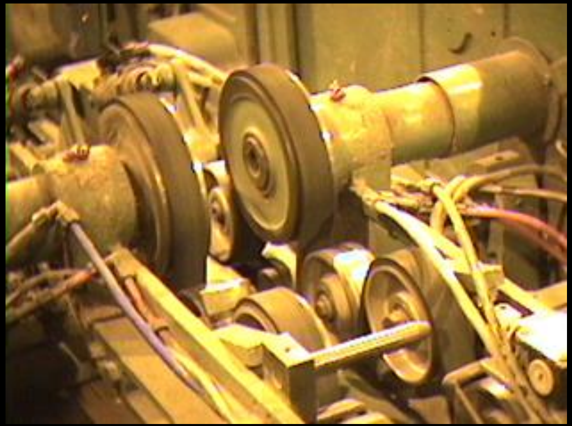
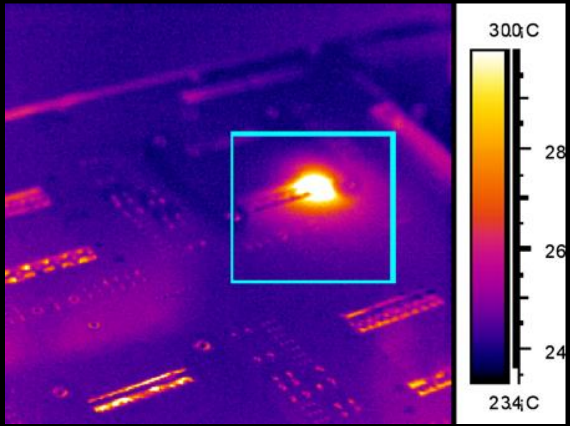
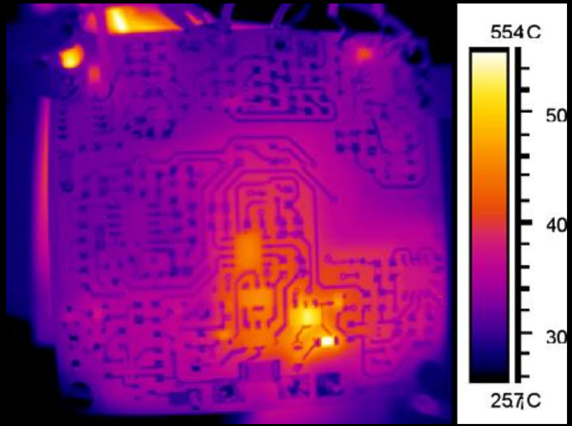
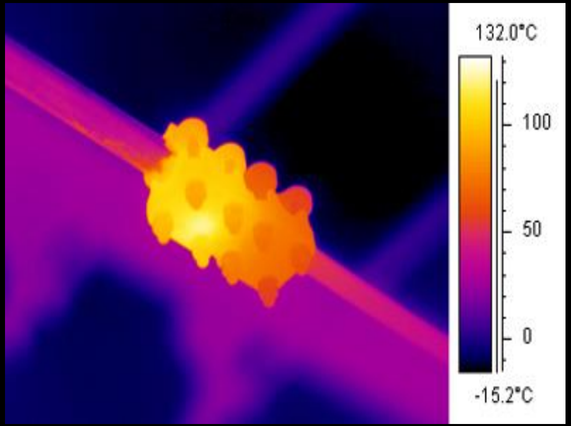
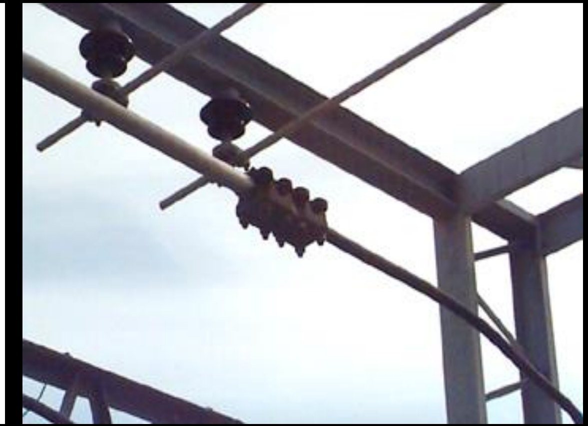
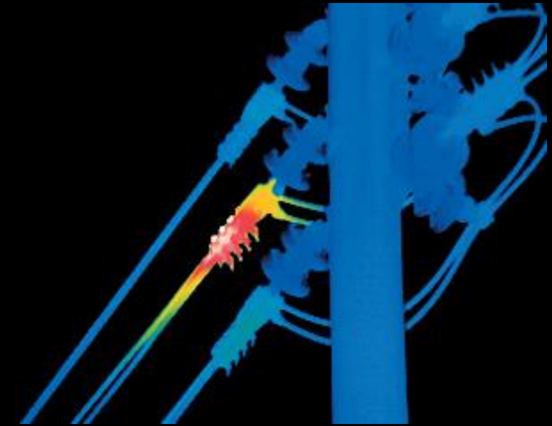

27.5C
27
26
25
24
23.5C



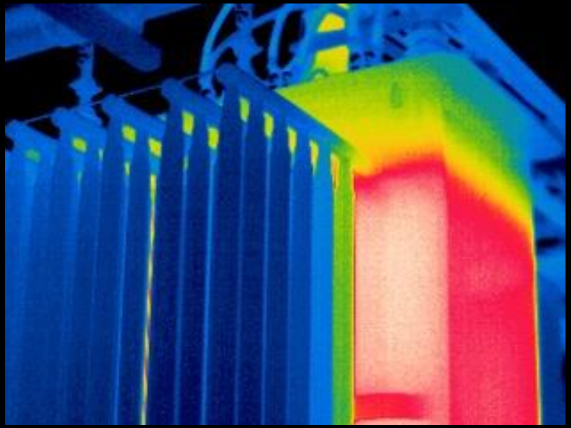

88.2°F
88
86
84
82
80
78
76.2°F

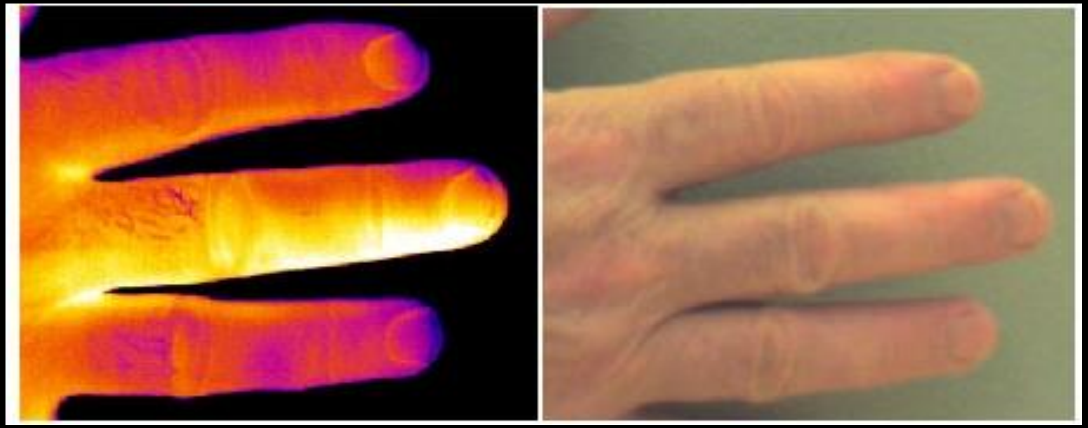

39.0°C
35
30
25
20
18.0°C




48.2°C
40
30
23.8°C


30.0°C
28
26
24
23.4°C

55.4°C
50
40
30
25.7°C

132.0°C
100
50
0
-15.2°C



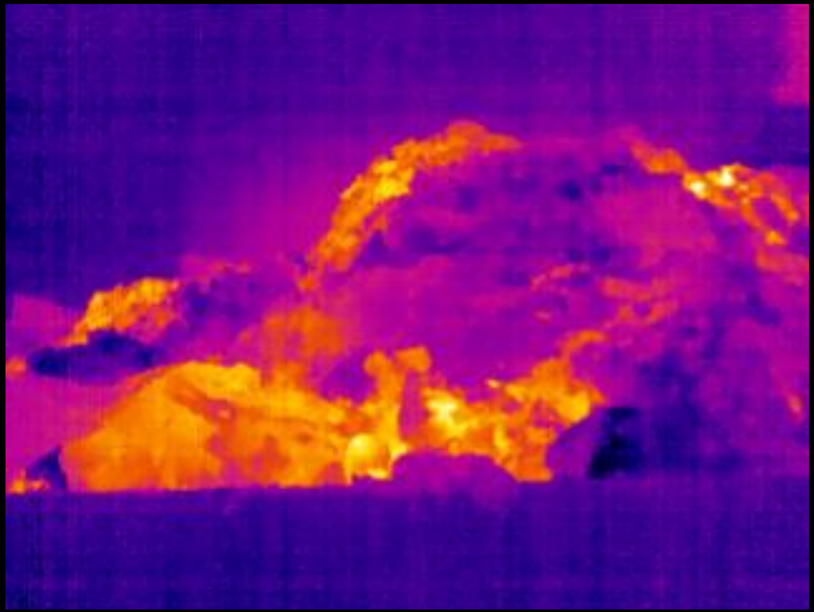
6/28/2000



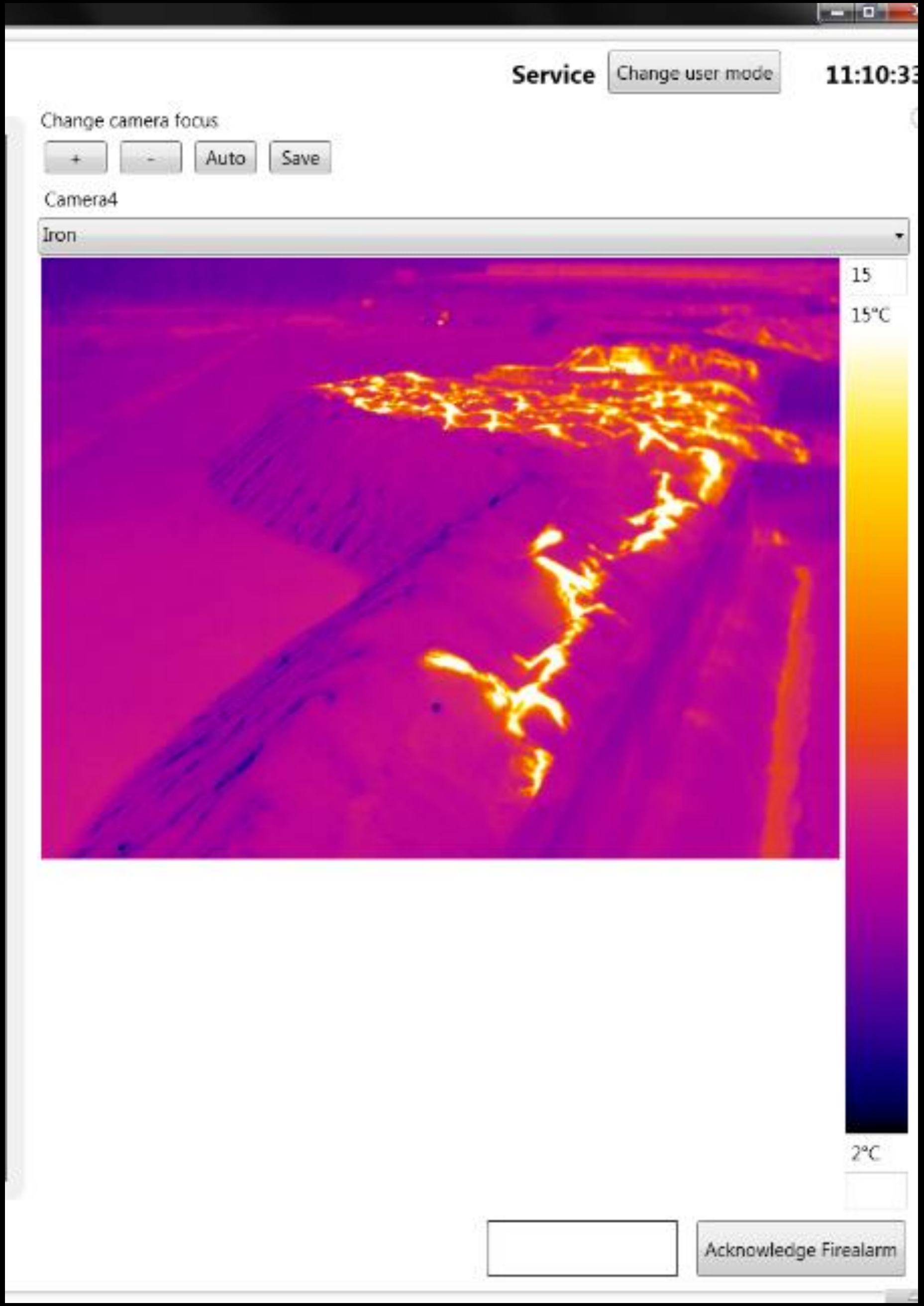
6/27/2000


°C
7.3
3.2
FLIR
FOV 24 Dist = 2.0 Trefl = 20.0 ε = 0.96


°C


Spot 9.7 °C
Box
Max. 58.6
Min. -3.9
34.5
-4.9


Service
Change user mode
11:10:33
Change camera focus
+
-
Auto
Save
Camera4
Iron
15
15°C
2°C
Acknowledge Firealarm

Number

- Fires per year in Sweden: 200-300

Costs

- Yearly total cost: 150-350 MSEK
- Average cost per fire: 500 000 SEK
- Yearly amount of destroyed or damaged stuff: 6500-7500 ton

Environment

- The emissions av dioxines from fires in waste depositis can exceed the total emissions from all waste incineration plants in the country with a factor 10.