

Infrared and Multispectral Imaging

TSBB09 Image Sensors

Jörgen Ahlberg

Contents of today's lecture

- Light, radiation, matter
- Thermal imaging
 - Cameras
 - Applications
- Multi/hyperspectral
 - What?
 - Why?
 - How?
- Demo

Light & Radiation





From where comes the radiation that I see?

Emitted

Transmitted

Reflected

Absorbed



F. W. Herschel



Symphony No. 15 (1762)

<https://open.spotify.com/track/okQcVlkww2LJQ49KXnklVe>

Caroline & William Herschel

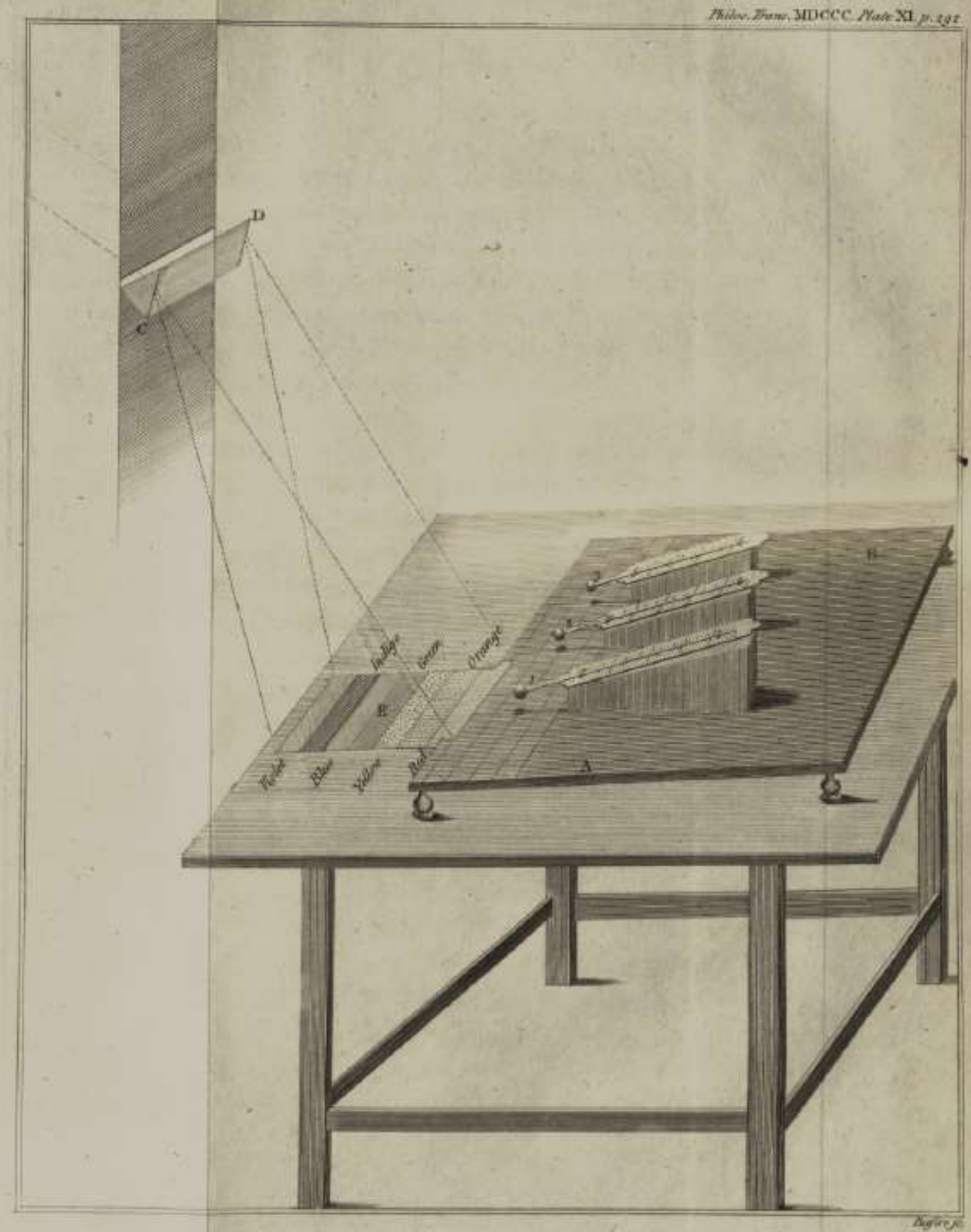
- 1 planet
- 4 moons
- 8 comets
- 5000 other objects

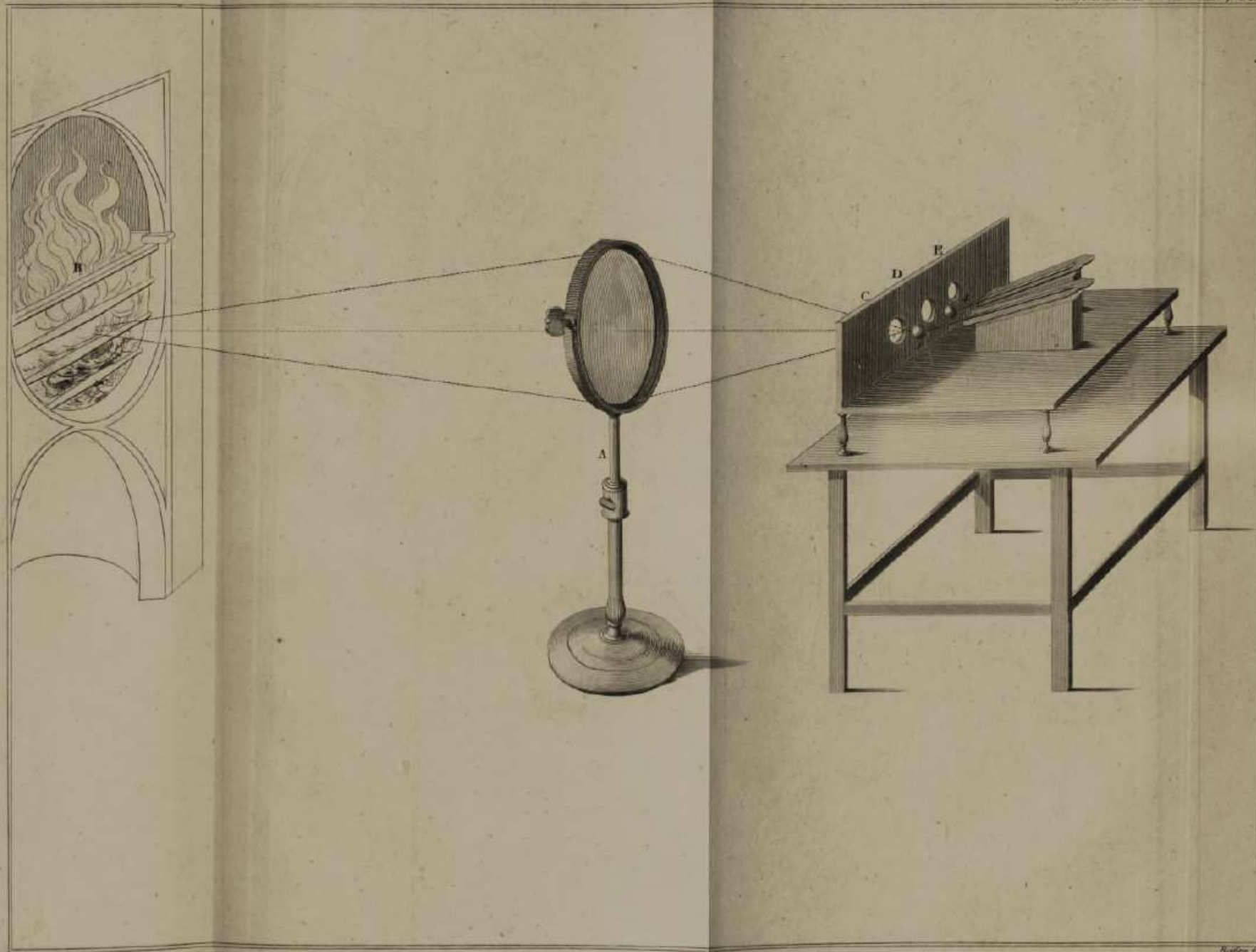


Herschel 1800a

“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

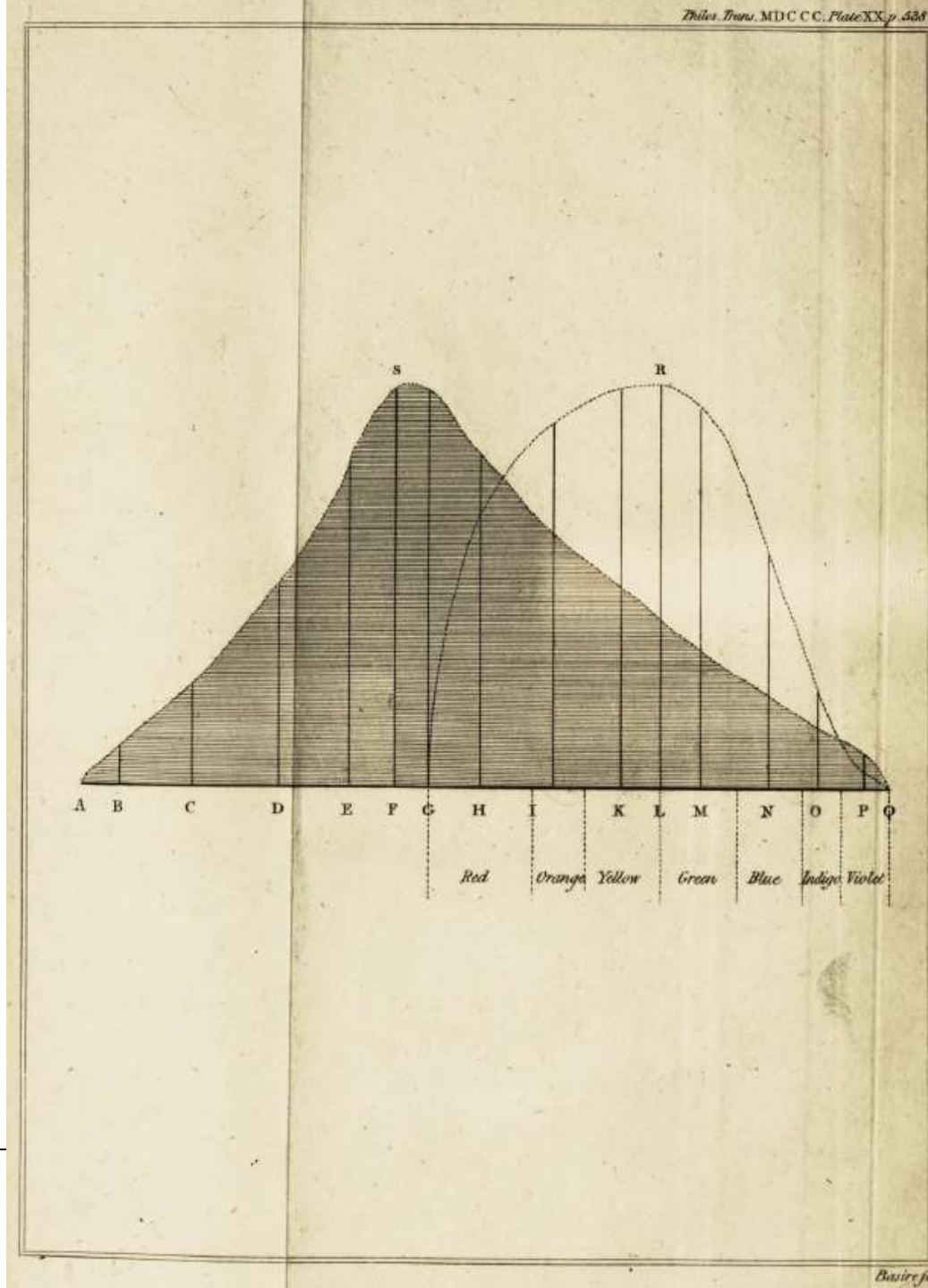


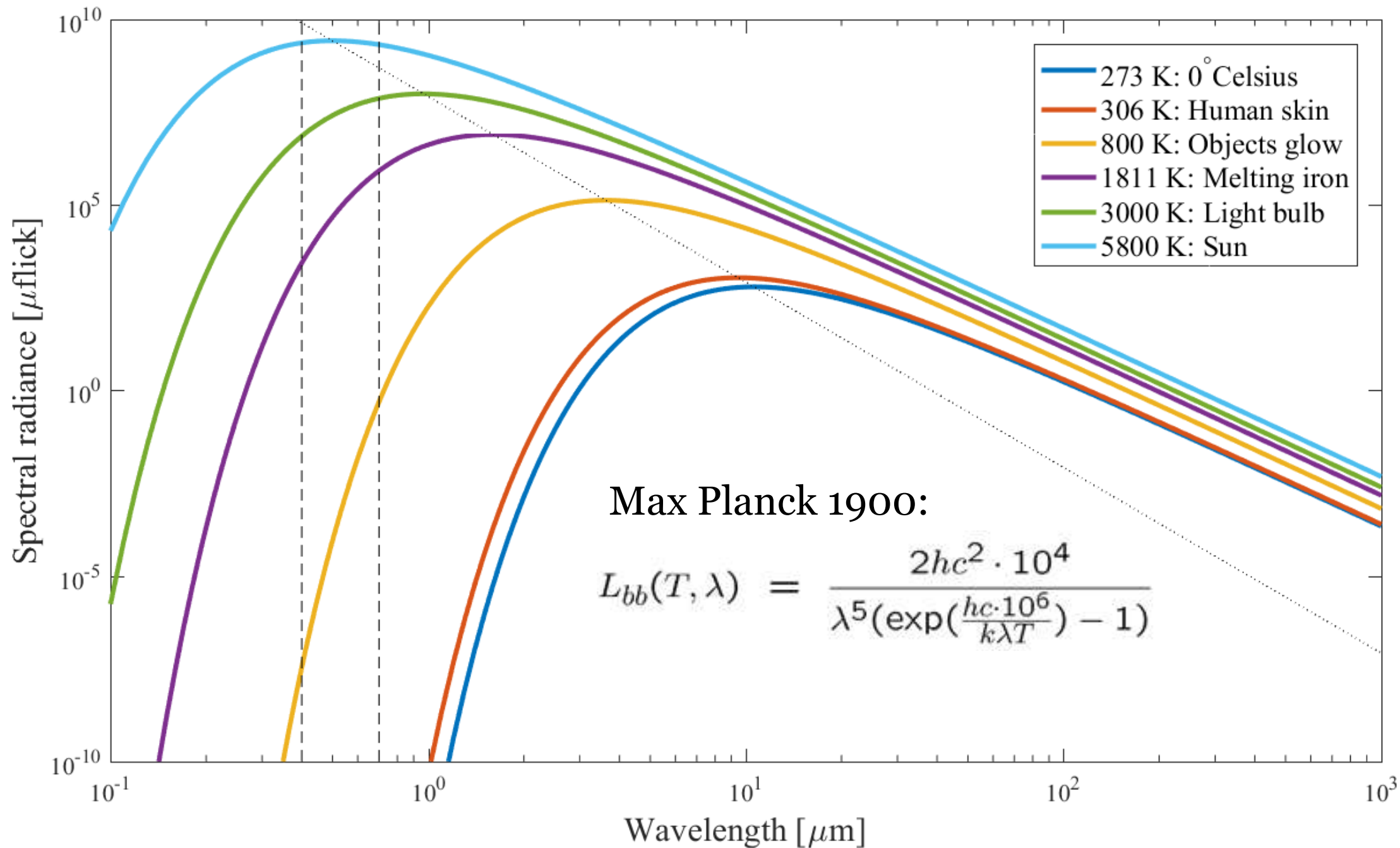


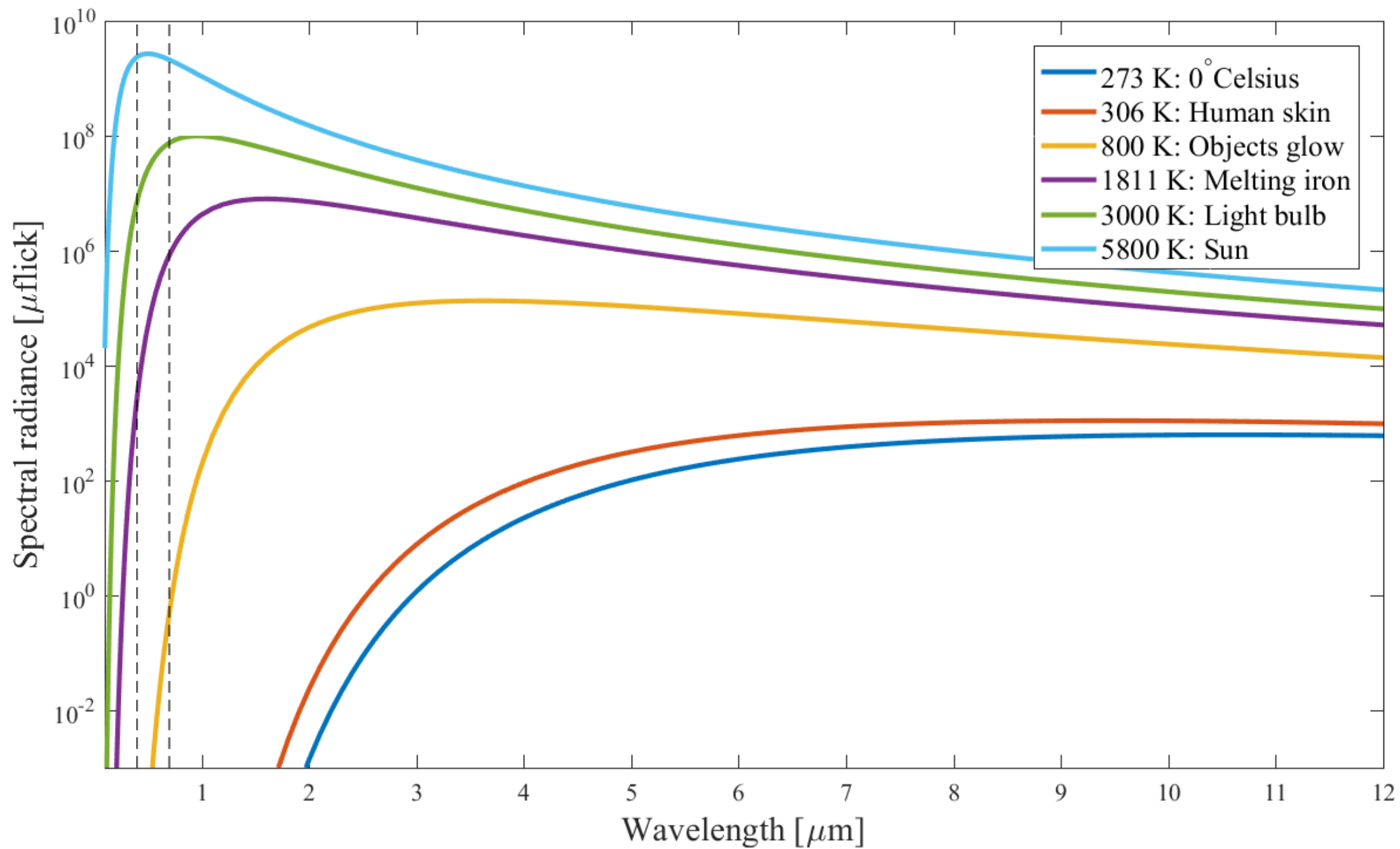
Herschel 1800b, c

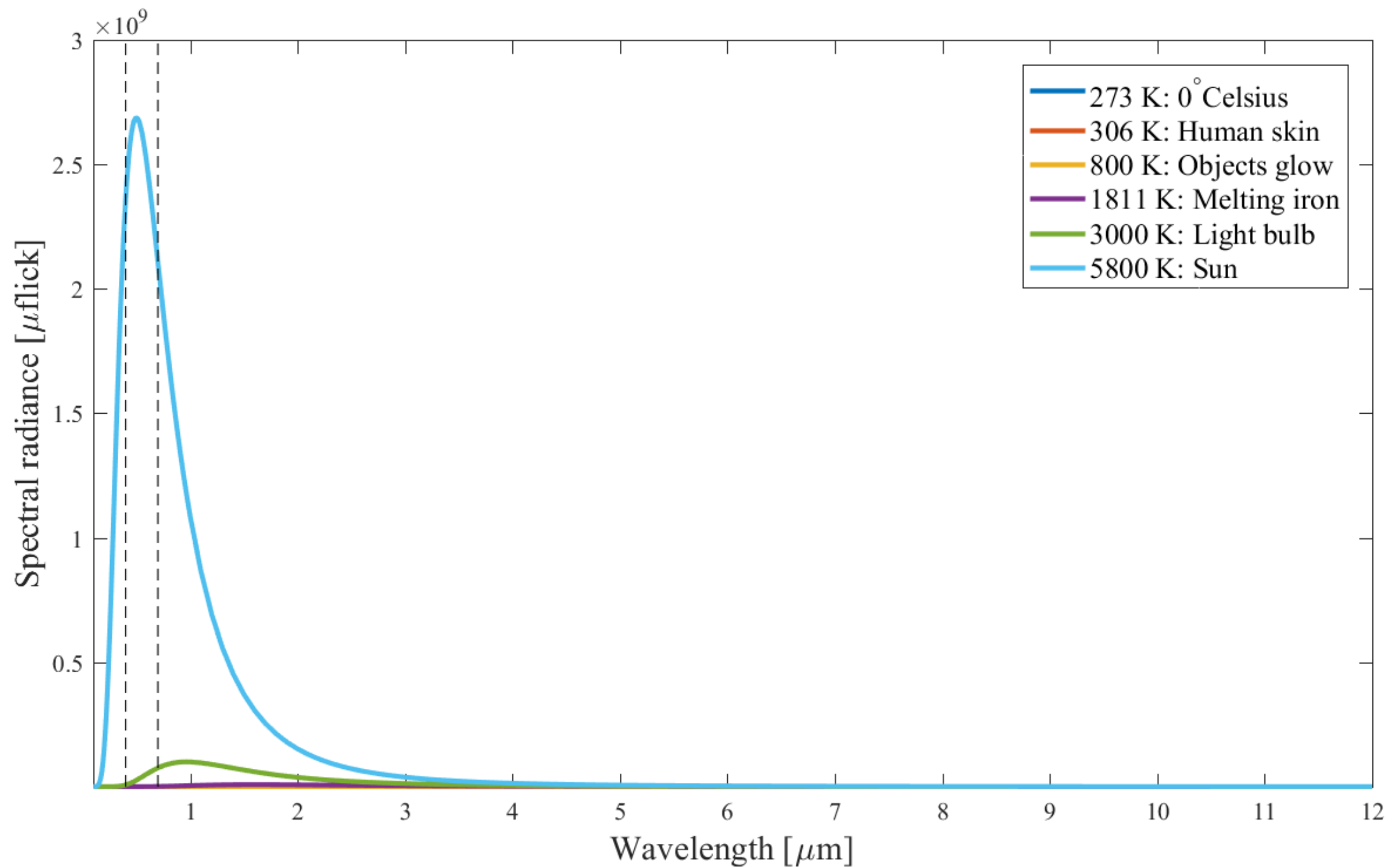
F. W. Herschel, "Experiments on the Solar, and on the Terrestrial Rays that Occasion Heat; With a Comparative View of the Laws to Which Light and Heat, or Rather the Rays Which Occasion Them, are Subject, in Order to Determine Whether They are the Same, or Different. Part I," *Philos. Trans. R. Soc.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

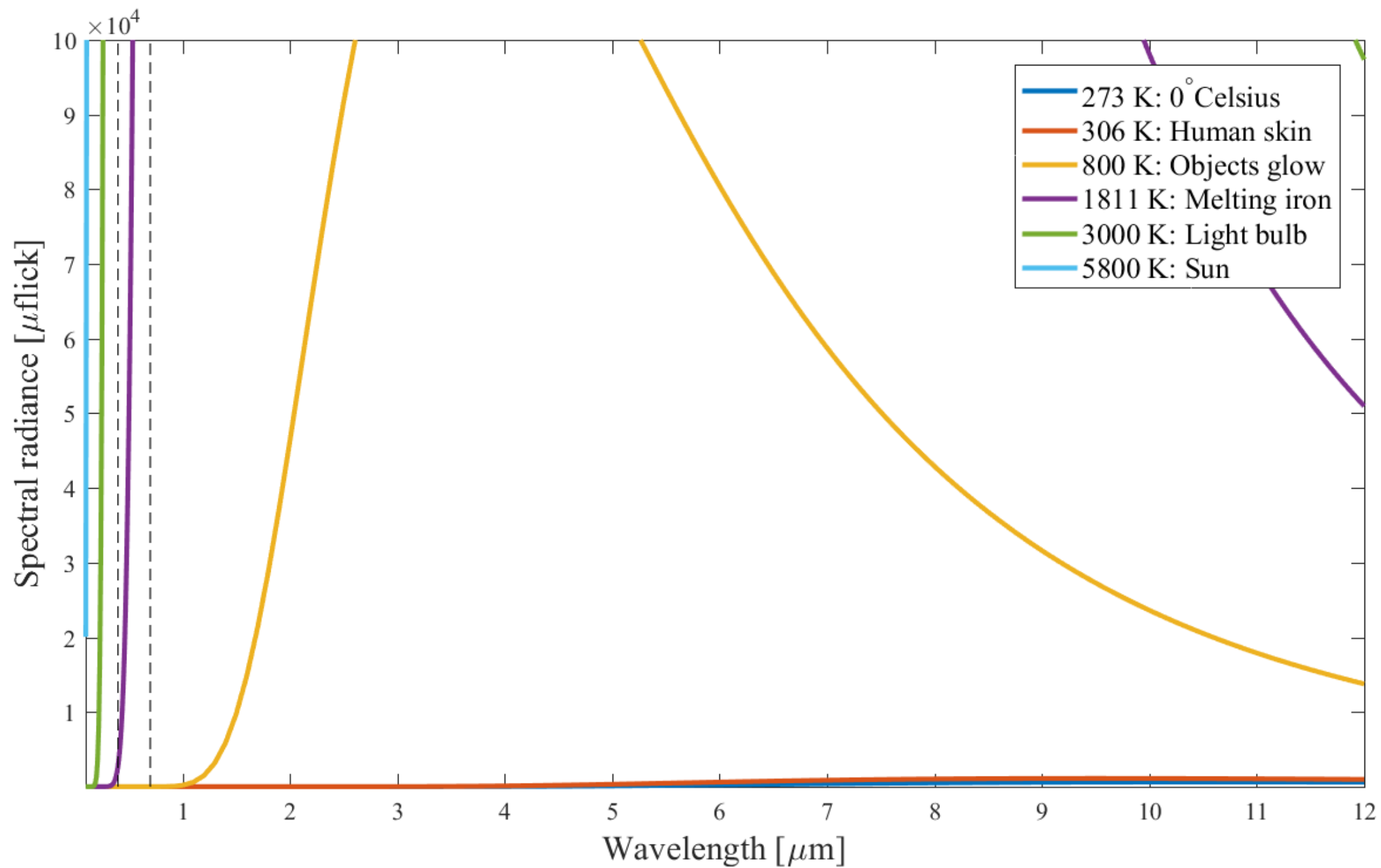
F. W. Herschel, "Experiments on the Solar, and on the Terrestrial Rays that Occasion Heat; With a Comparative View of the Laws to Which Light and Heat, or Rather the Rays Which Occasion Them, are Subject, in Order to Determine Whether They are the Same, or Different. Part II," *Philos. Trans. R. Soc.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



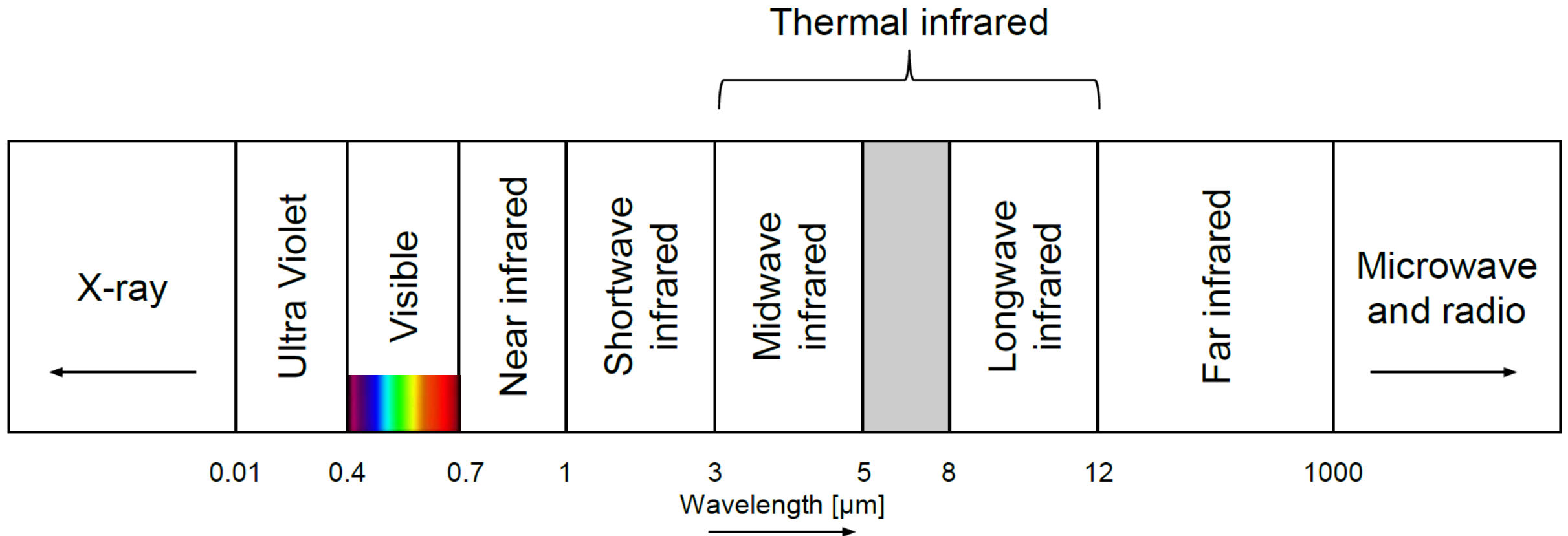




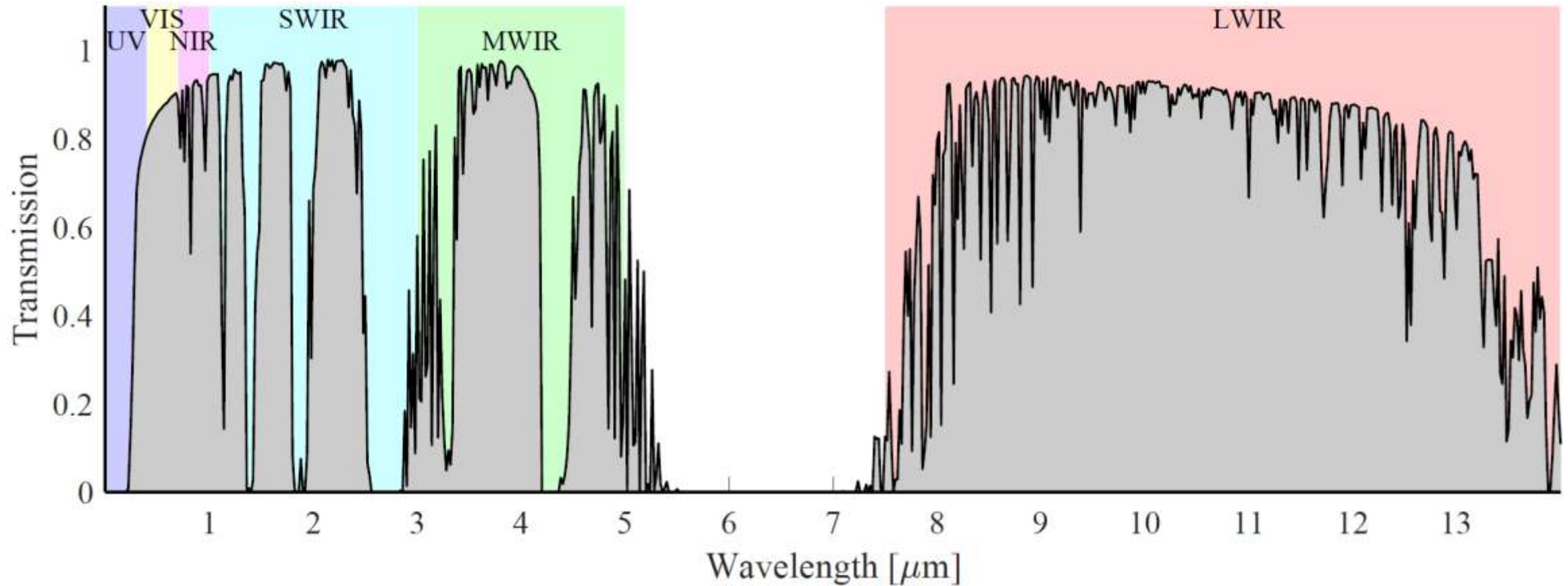




Why this particular division?



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:

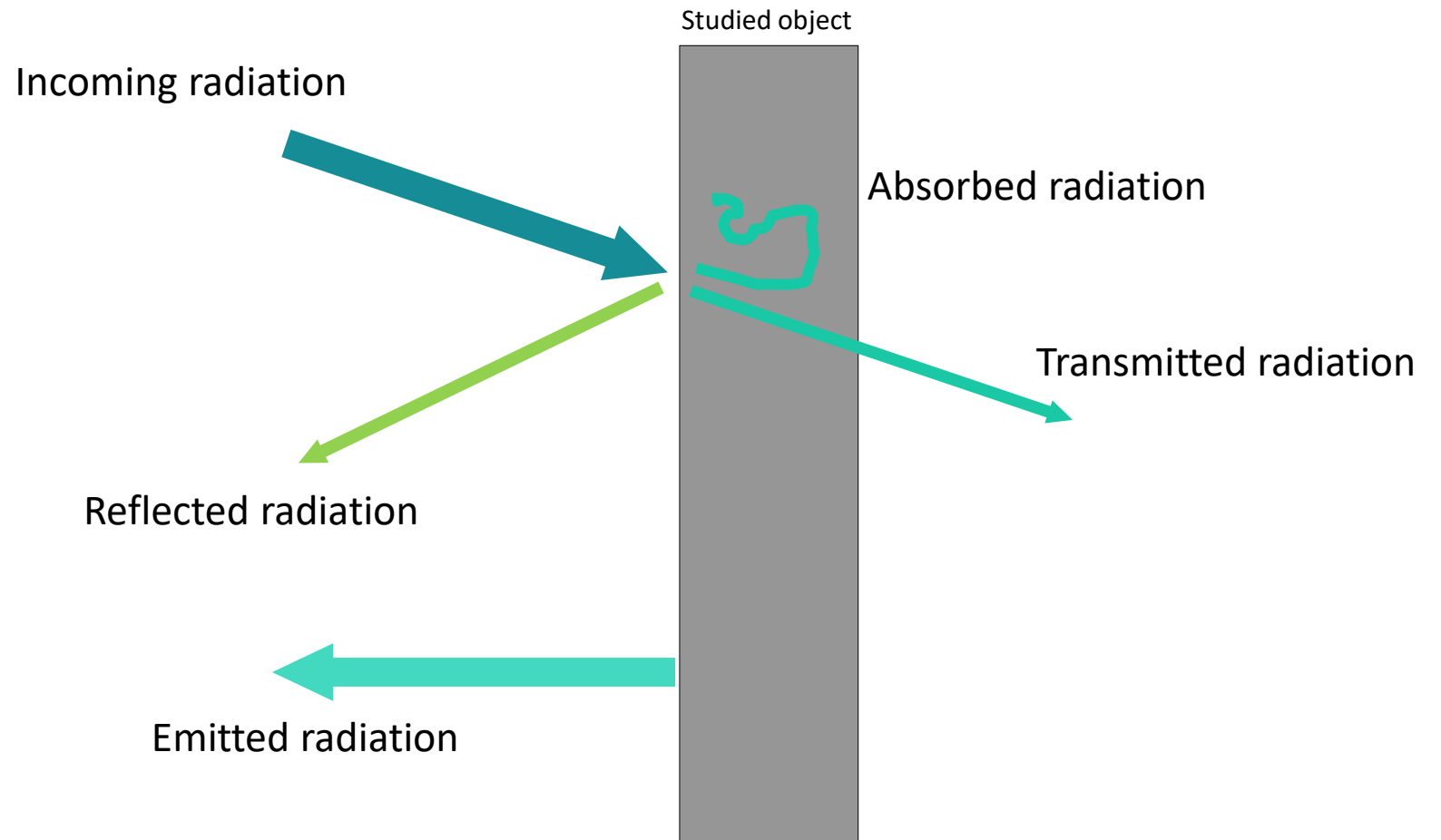
There are other subdivisions!
For example, astronomers use:

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

Radiation & Matter

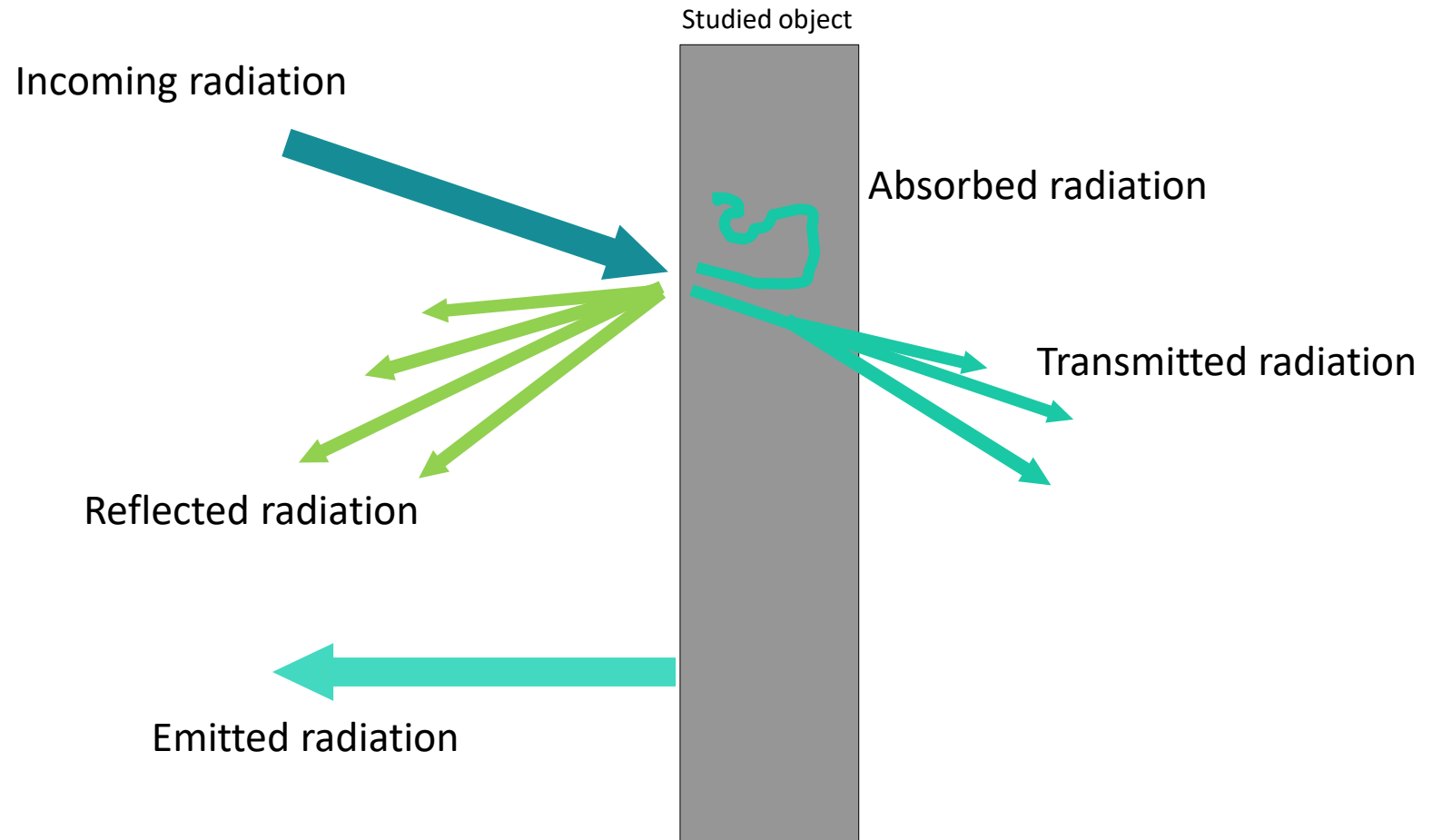
Radiation and matter

- Absorbed
- Reflected
- Transmitted
- Emitted



Radiation and matter

- Absorbed
- Reflected
- Transmitted
- Emitted
- Scattered
- Diffracted



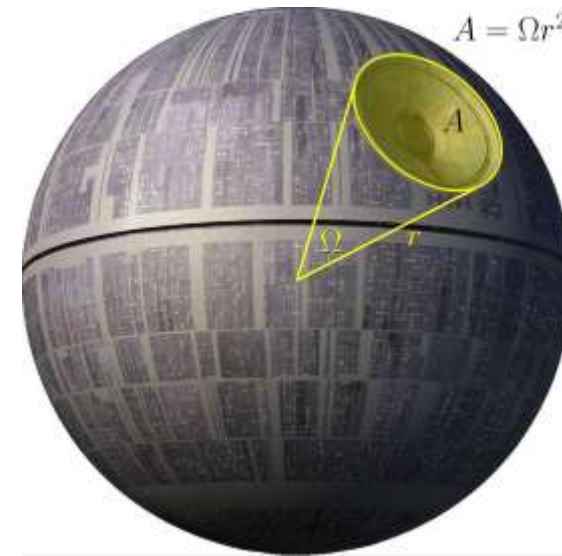
$$\alpha = \varepsilon$$

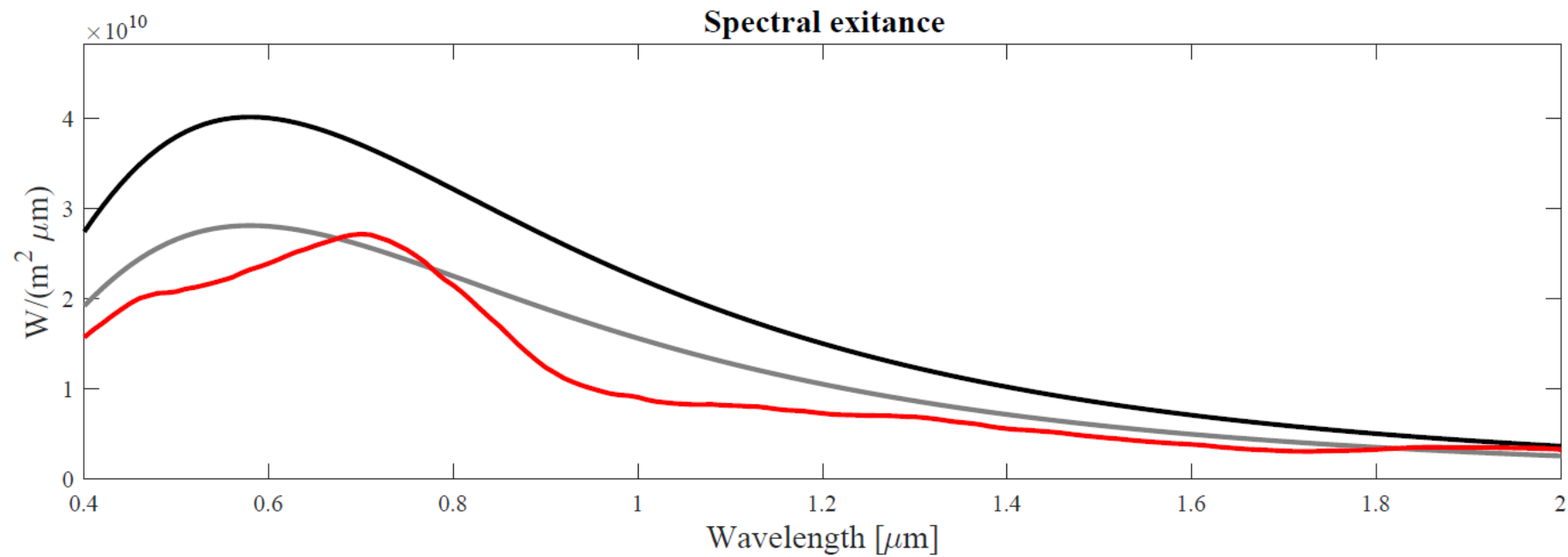
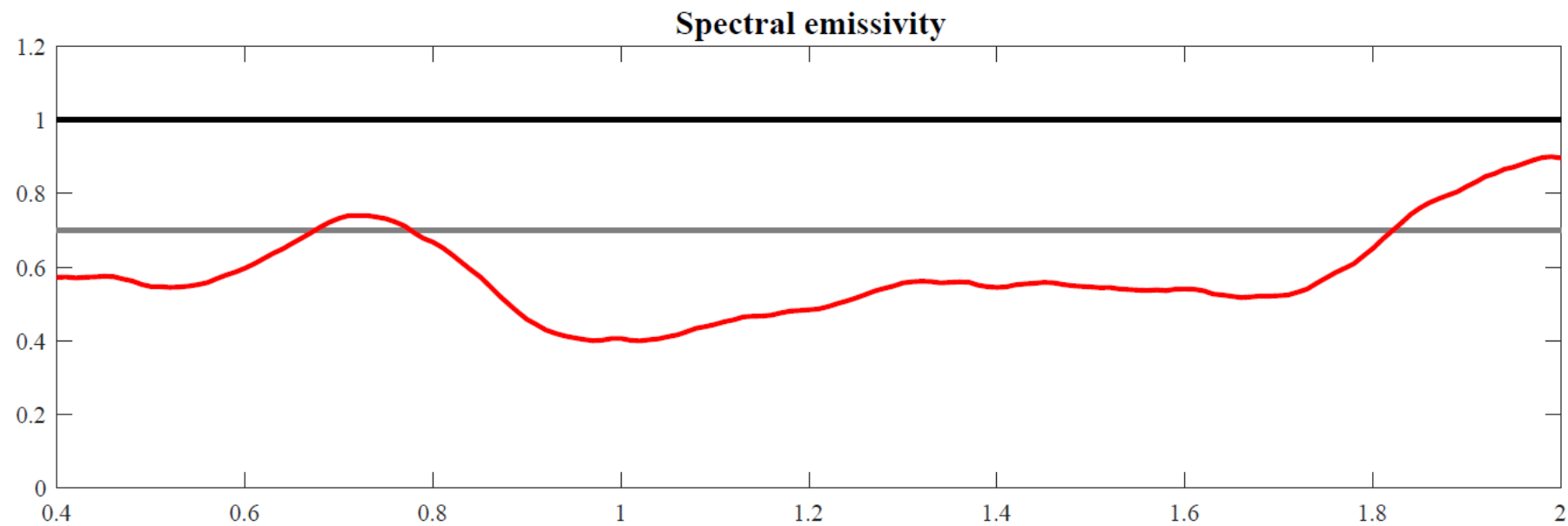
$$\alpha + \tau + \mathbf{r} = 1$$

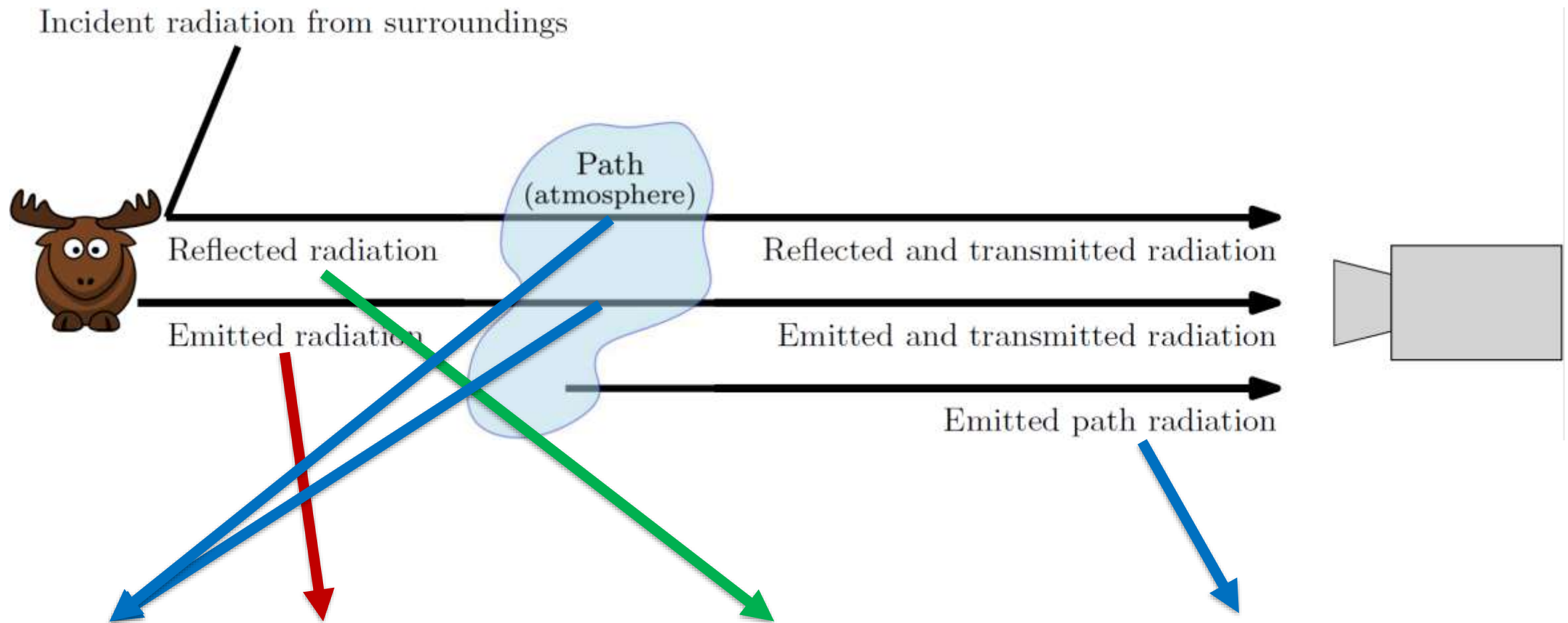
$$\alpha(\lambda) + \tau(\lambda) + \mathbf{r}(\lambda) = 1$$

- Absorptivity α
 - Emissivity ε
 - Transmittance τ
 - Reflectance r
-
- $\alpha + \tau + r = 1$
 - Dependent on wavelength and angle!
 - Commonly: τ or r close to zero.

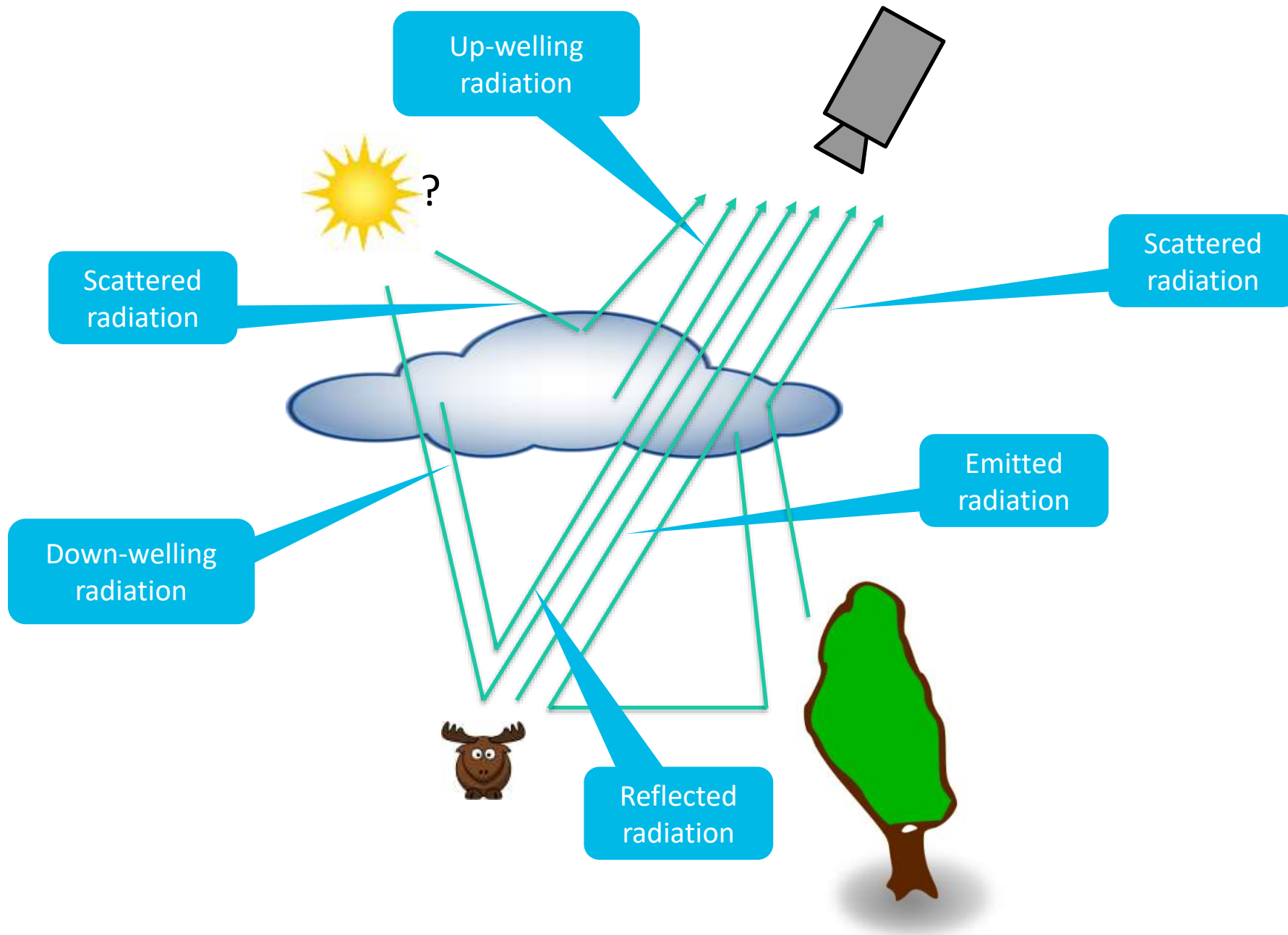
- (Radiant) Flux Φ [W]
- Radiance L [W / m² sr]
- Irradiance E [W / m²]







$$\tau(\lambda) \cdot (\epsilon_{\text{obj}}(\lambda) \cdot B(T_{\text{obj}}, \lambda) + (1 - \epsilon_{\text{obj}}(\lambda)) \cdot E(\lambda)) + (1 - \tau(\lambda)) \cdot B(T_{\text{atm}}, \lambda)$$



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 and radiation

- 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.

Thermal cameras

Thermal cameras

			
Defence		Thermography	
Imaging (non radiometric)		Temperature measuring (radiometric)	

<p>Low-end</p> 	<p>Medium</p> 	<p>Advanced</p> 	<p>Automation, monitoring, R&D</p> 
<p>SWIR</p> 	<p>High performance for R&D</p> 	<p>High resolution for R&D</p> 	<p>Gas finder cameras</p> 

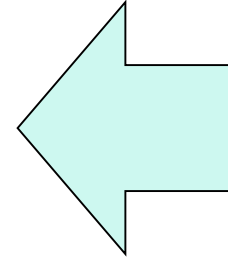
Cooled and uncooled cameras

Sensor type / material		Used for
Cooled		
Mercury cadmium telluride	MCT	SWIR – LWIR
Indium antimonide	InSb	NIR – LWIR
Strained Layer Superlattice	SLS	MWIR, LWIR
Un-cooled		
Charged-coupled device	CCD	VNIR
Active-pixel sensor	APS / CMOS	VNIR
Indium gallium arsenide	InGaAs	NIR, SWIR
Microbolometer		LWIR

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

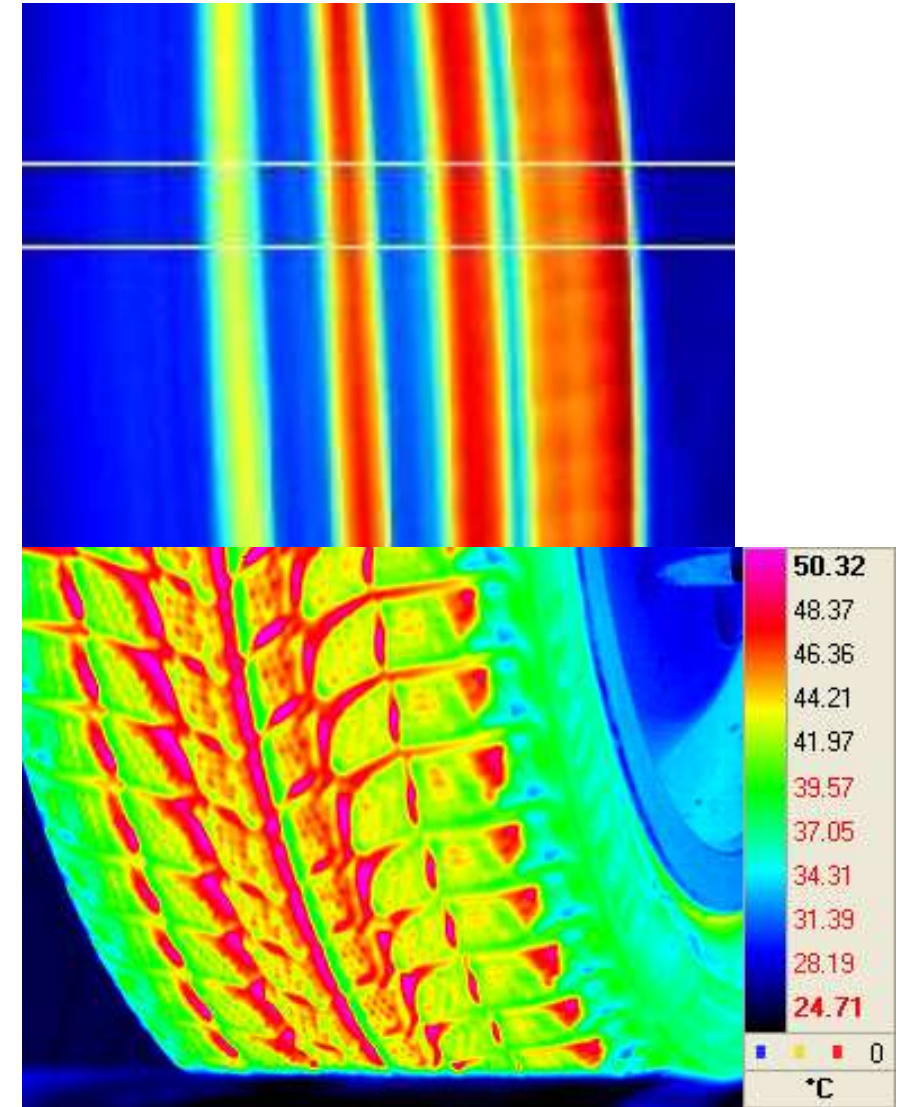
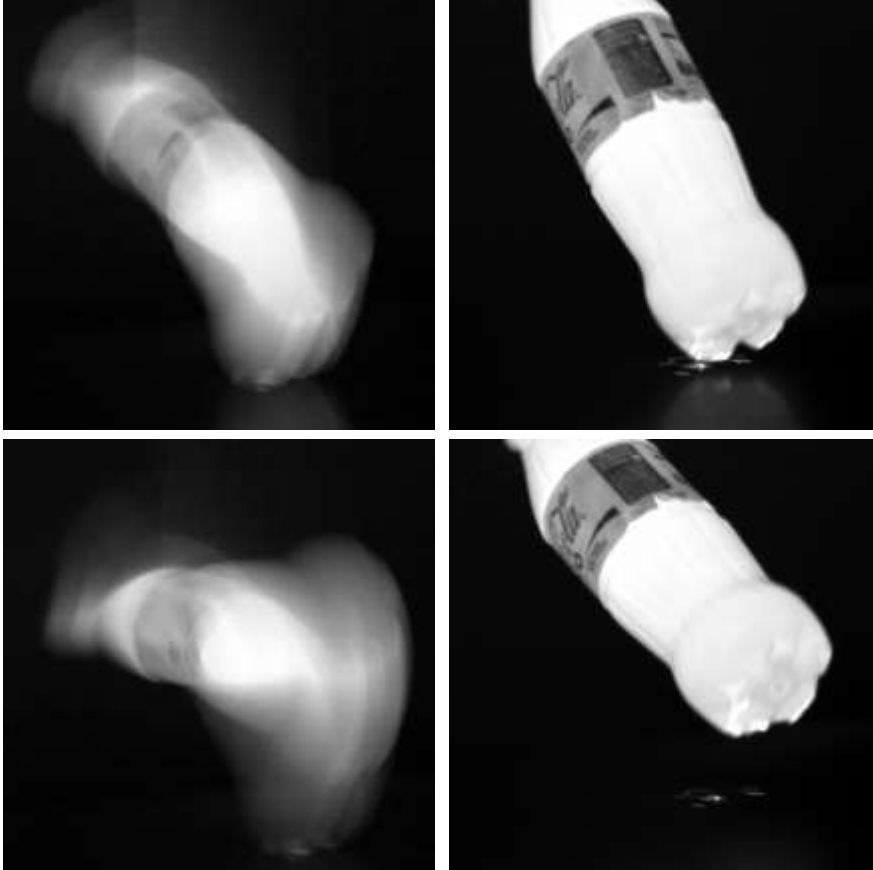


Cooled cameras

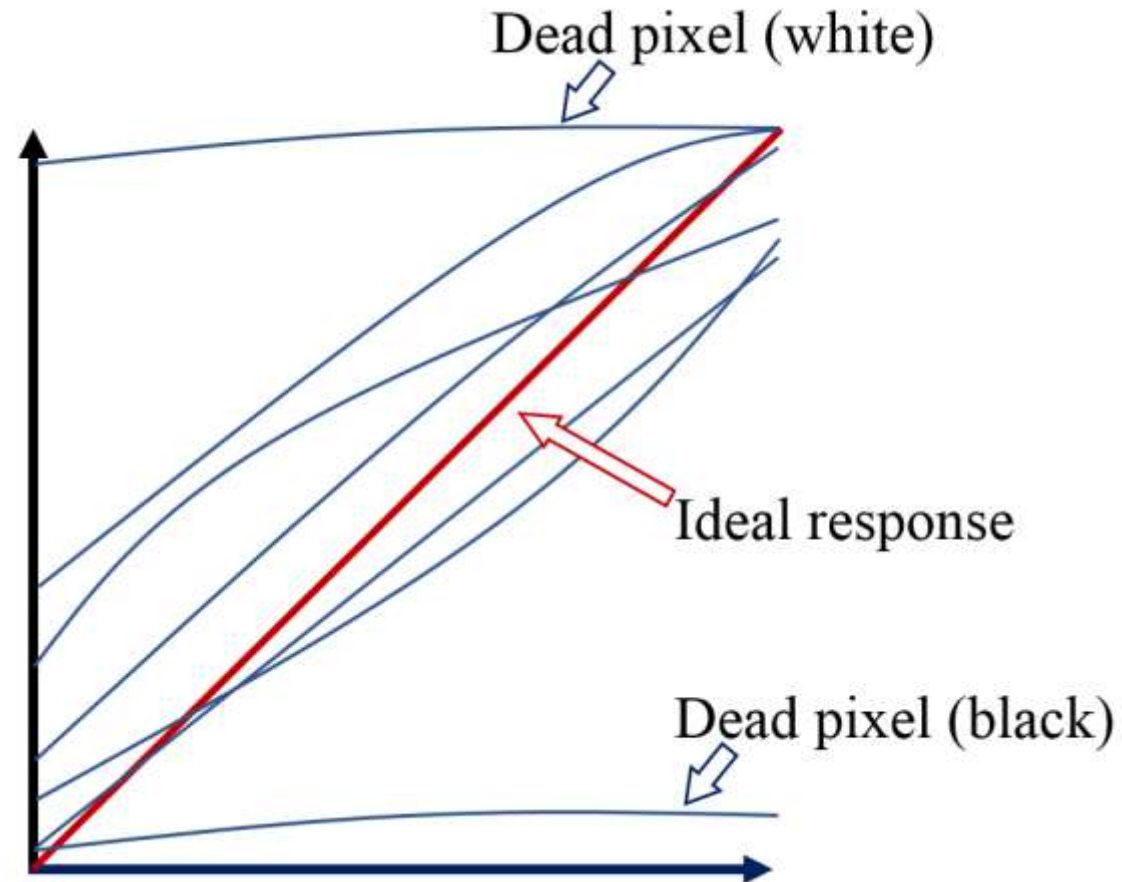
- High spatial resolution
- High temperature resolution
- Fast
- Loud
- Heavy
- Large
- Expensive



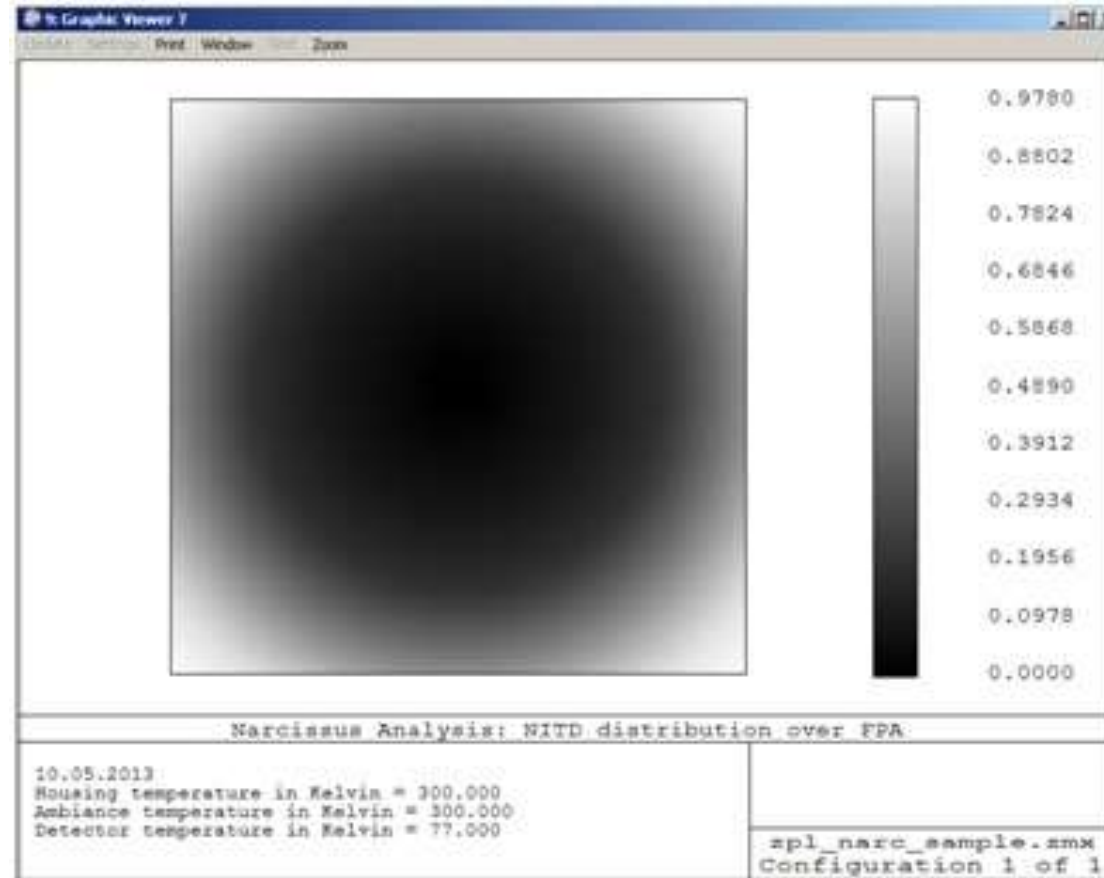
Cooled vs uncooled



Calibration and NUC

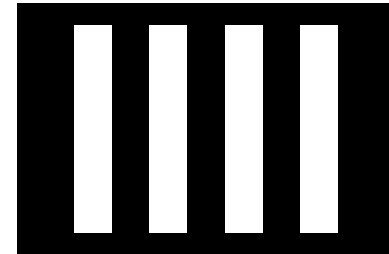


Narcissus



Performance measures

- NETD: Noise Equivalent Temperature Difference
- MRTD: Minimum Resolveable Temperature Difference
- NEP: Noise Equivalent Power
- Normalized Detectivity D^*
 - Independent of detector size and speed



$$NEP = \frac{\sigma^2}{R} \left[\frac{W}{\sqrt{Hz}} \right]$$

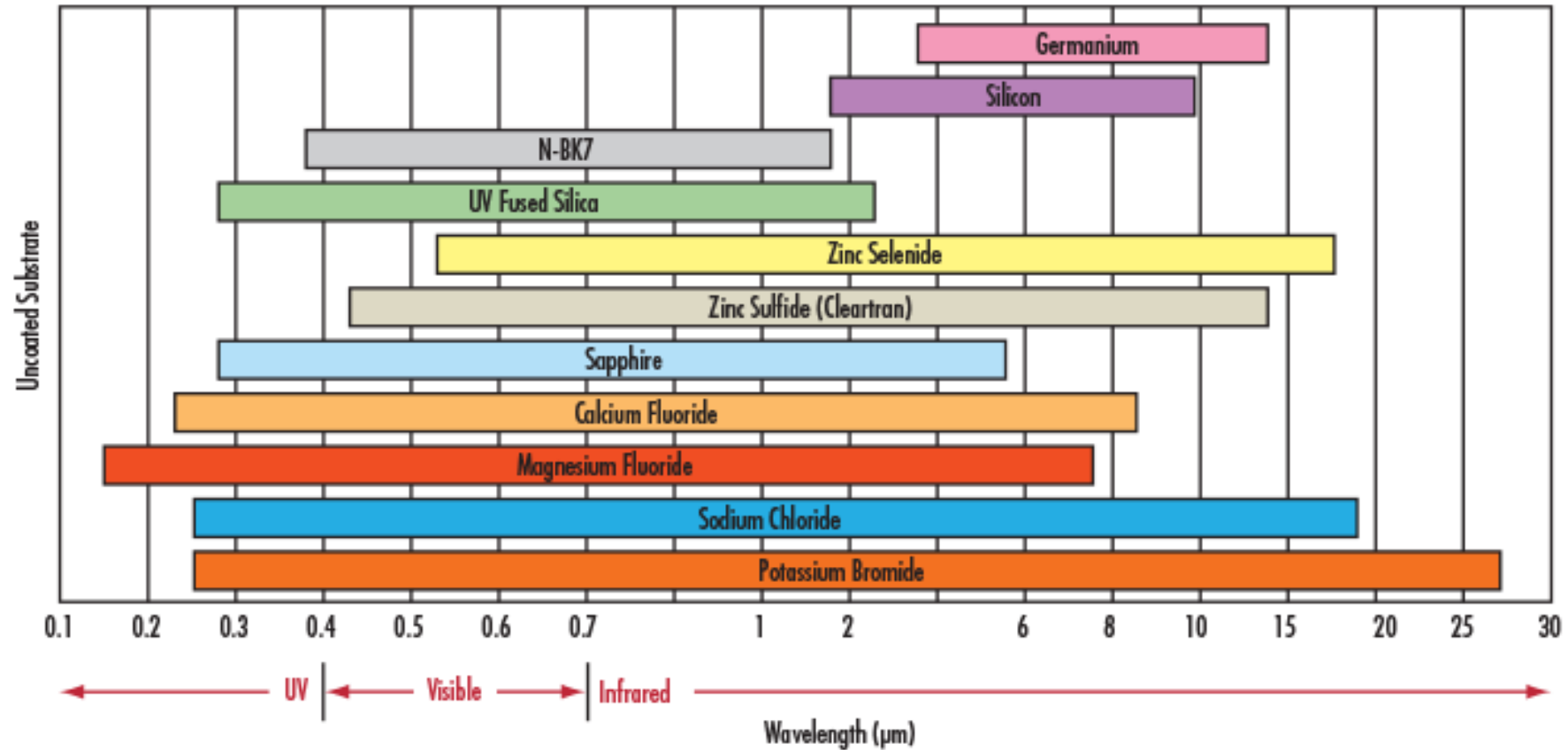
$$D^* = \frac{\sqrt{A} \Delta f}{NEP} = \frac{R \sqrt{A}}{\sigma^2} \left[\frac{cm \sqrt{Hz}}{W} \text{ or Jones} \right]$$

Optics for thermal cameras

Parameters

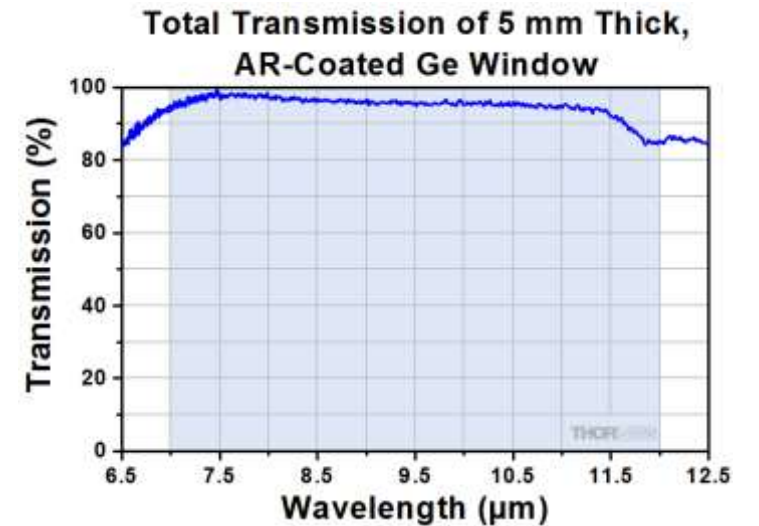
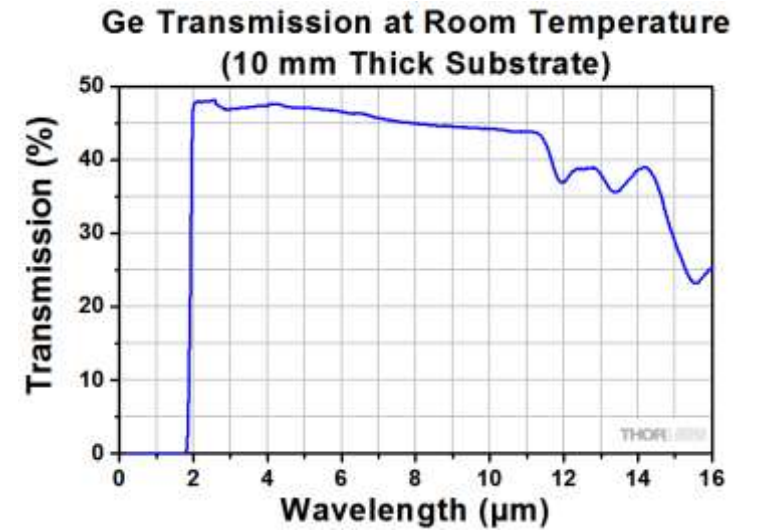
- Durability
- Refractive index
- Variability due to heat
- Cost
- Transmittance

Materials



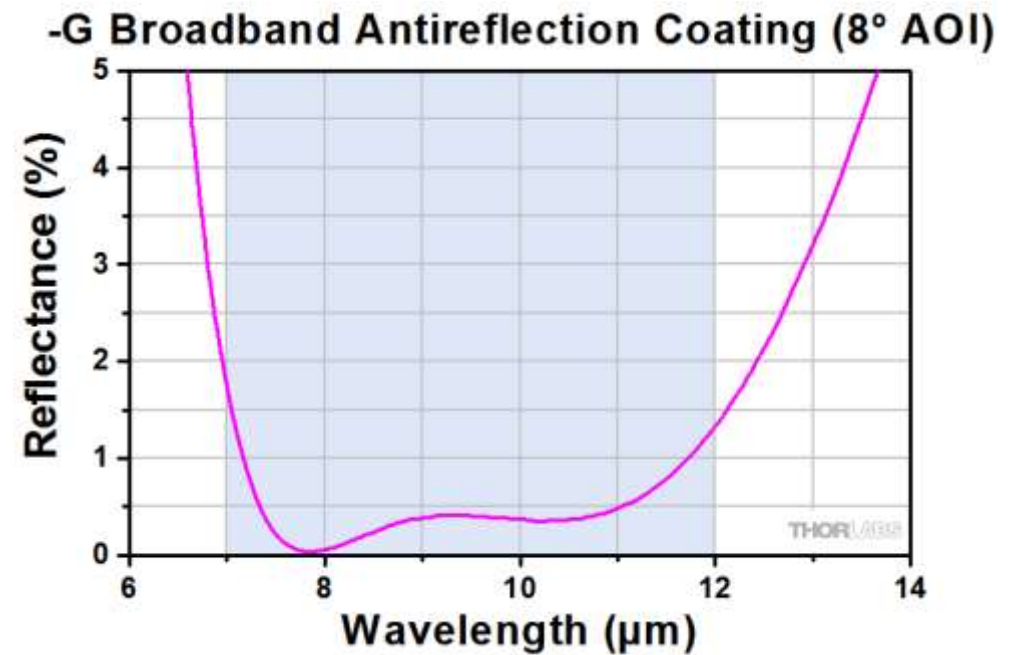
Lens materials: Germanium

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



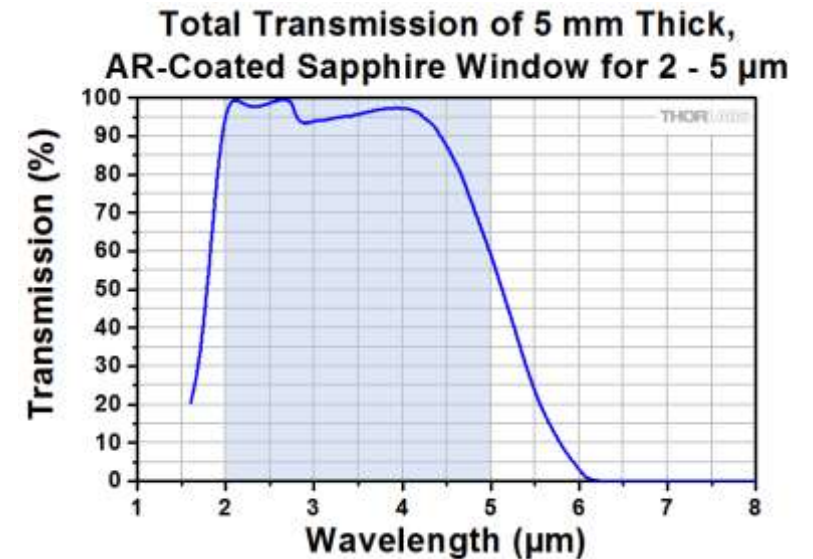
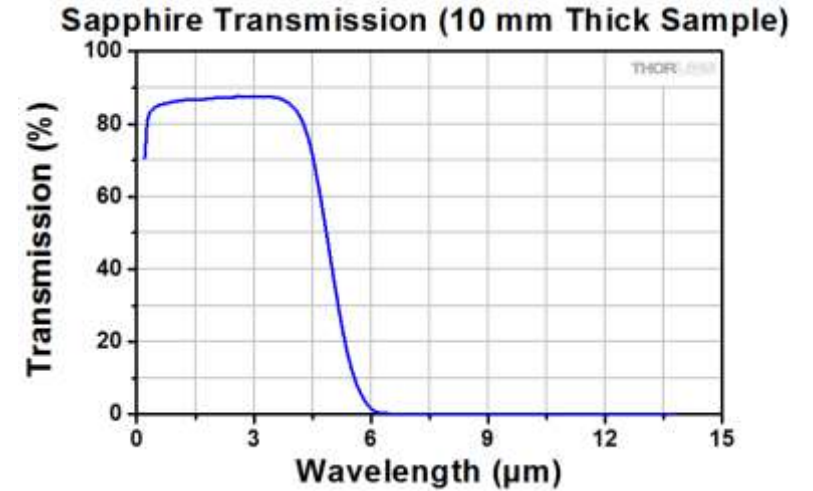
Lens materials: Zinc Selenide

- Transmits even better than Germanium!
- KH 120 ☹️
- Toxic



Lens materials: Sapphire

- Durable (KH 2200).
- Good transmittance in VIS-MWIR.



A note on color



Visual



White hot

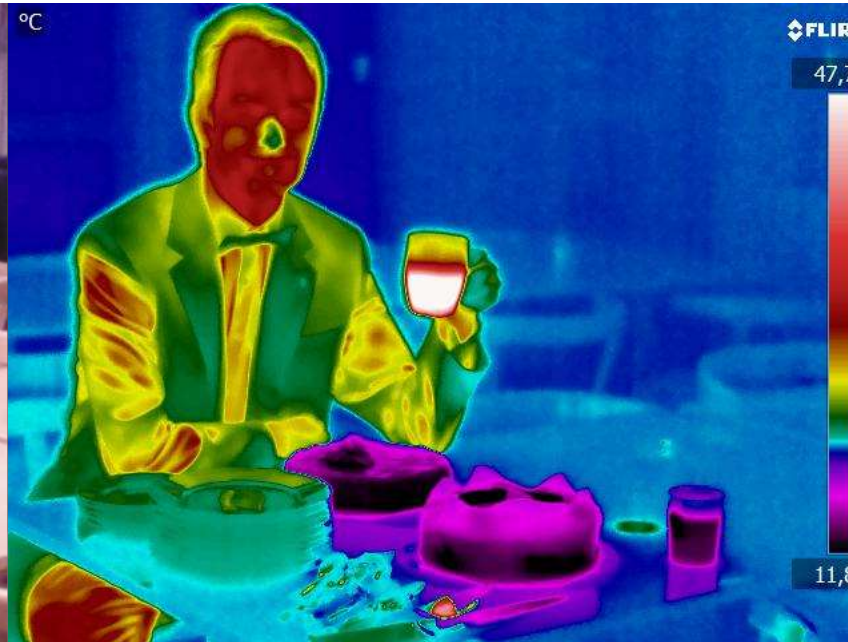


Black hot

A note on color



Visual



Rainbow



Iron

Summary: Thermal cameras

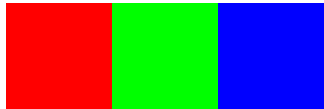
- Cooled vs uncooled
 - Cooled: Loud, cumbersome, expensive, fast, sensitive.
- Sensors: Thermal detectors vs photon detectors
- Optics: Transmitting in different bands
- The most common thermal camera: Uncooled bolometer camera for LWIR with Germanium lens.
- Calibrations: Narcissus, NUC, Drift

Multi- and hyperspectral imaging

What is multi/hyperspectral imaging?



Greyscale image – one band



Color image – three bands



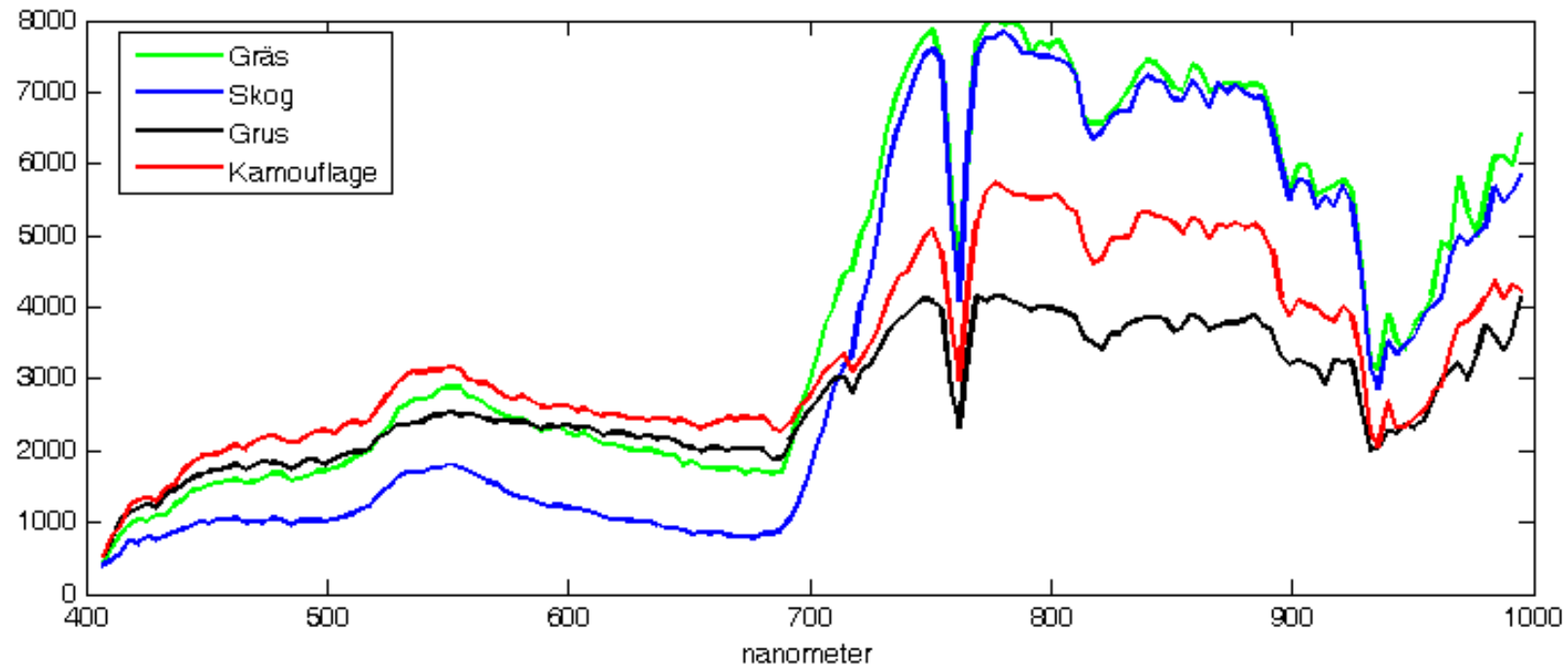
Multispectral image – several bands



...

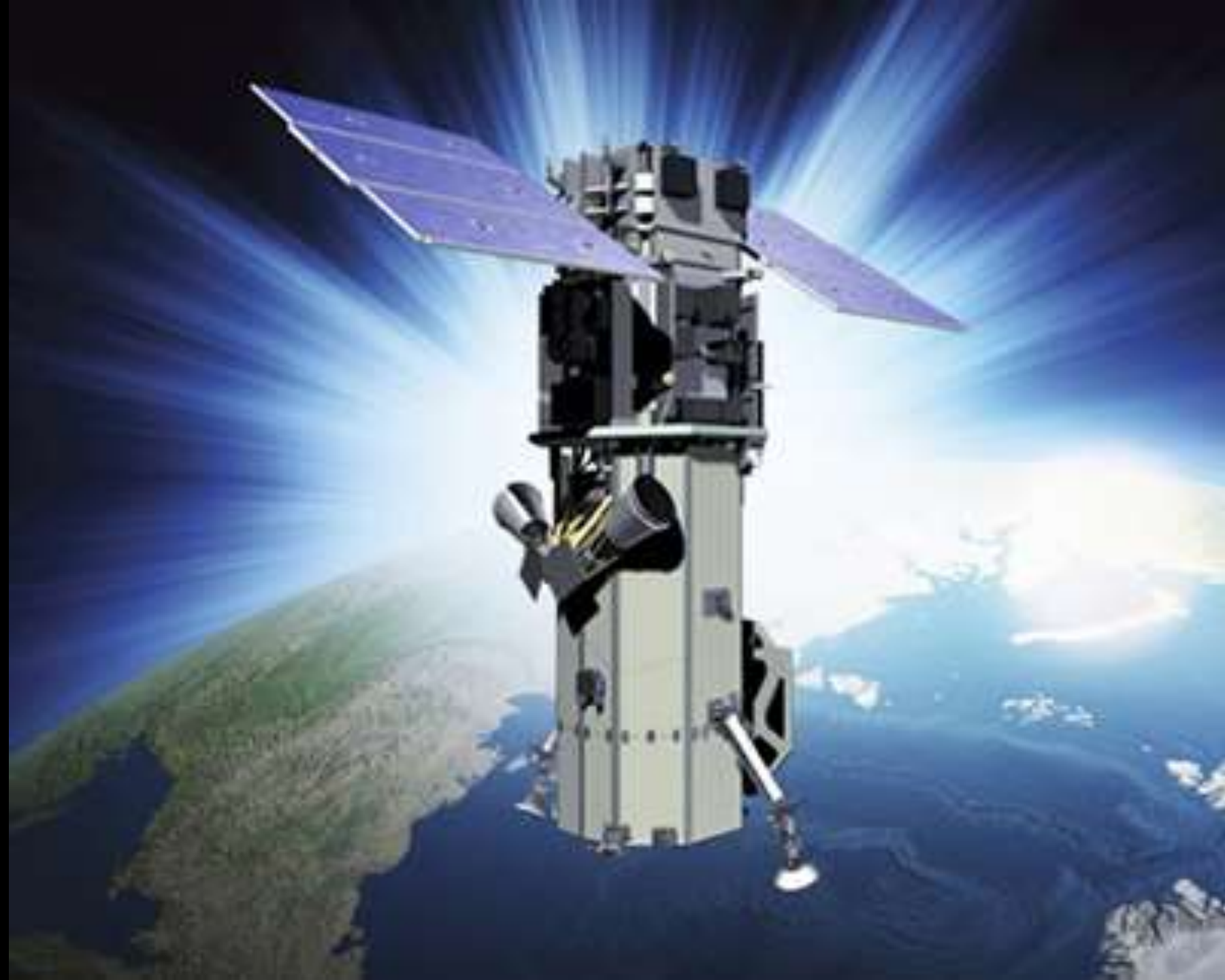
Hyperspectral image –
many contiguous bands

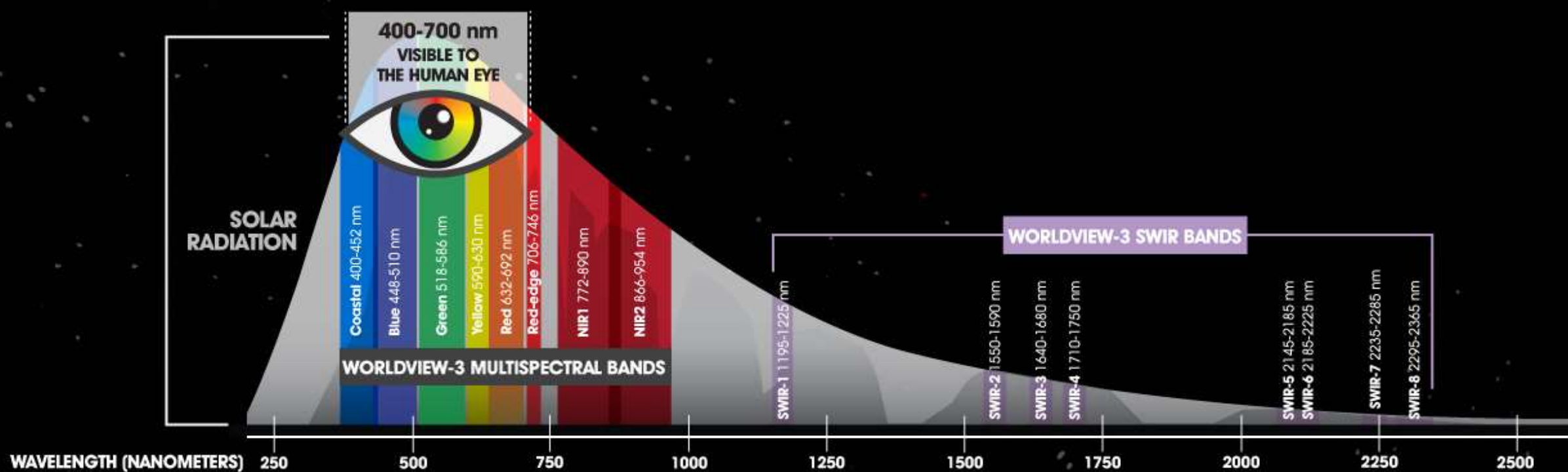
Why multi/hyperspectral images?



Applications

- Defence
- Mineralogy
- Land-use classification
- Precision farming
- Food inspection
- Environmental monitoring
- ...





CUSTOMER APPLICATIONS

Numerous Commercial / Defense / Military Applications

Feature Extraction / Change Detection

Natural Disasters / Flooding / Man-made Materials and Structures

Pan / Pan Sharpened /
Multispectral Imagery

Soil / Vegetation

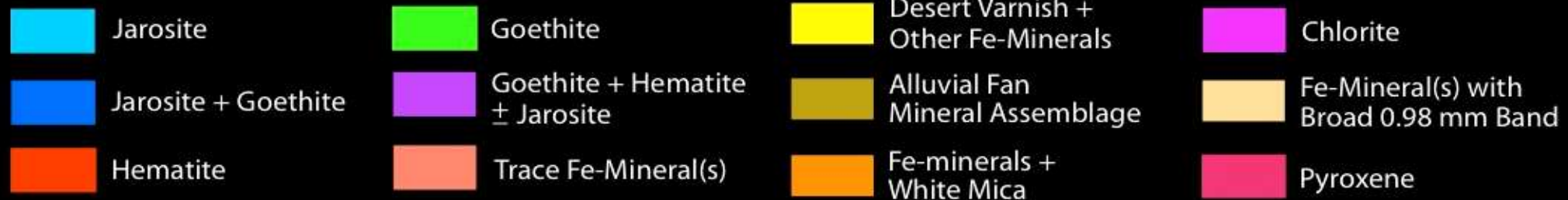
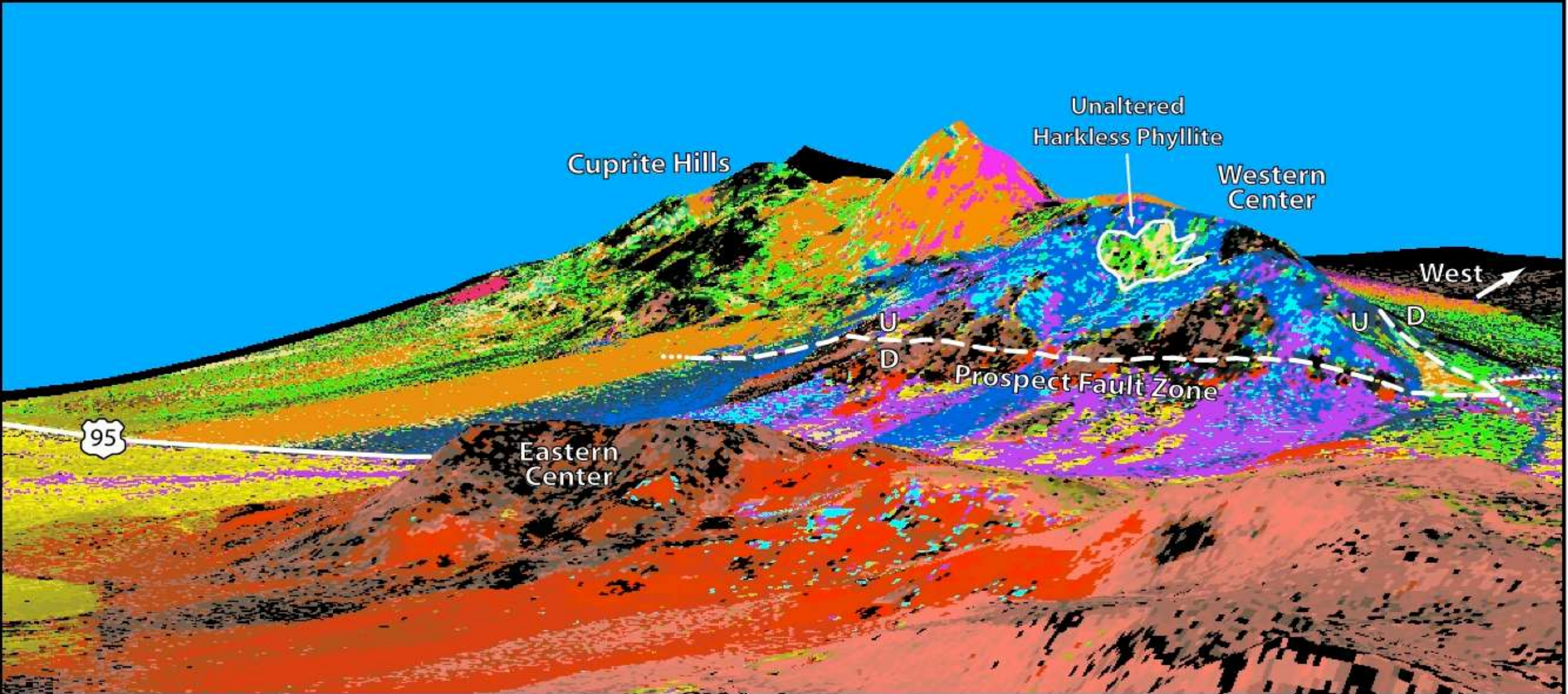
Mining

Land Classification

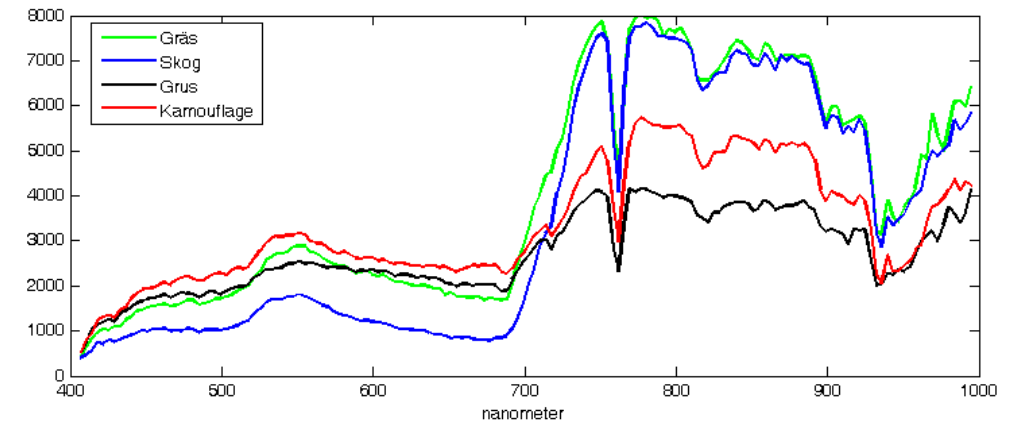
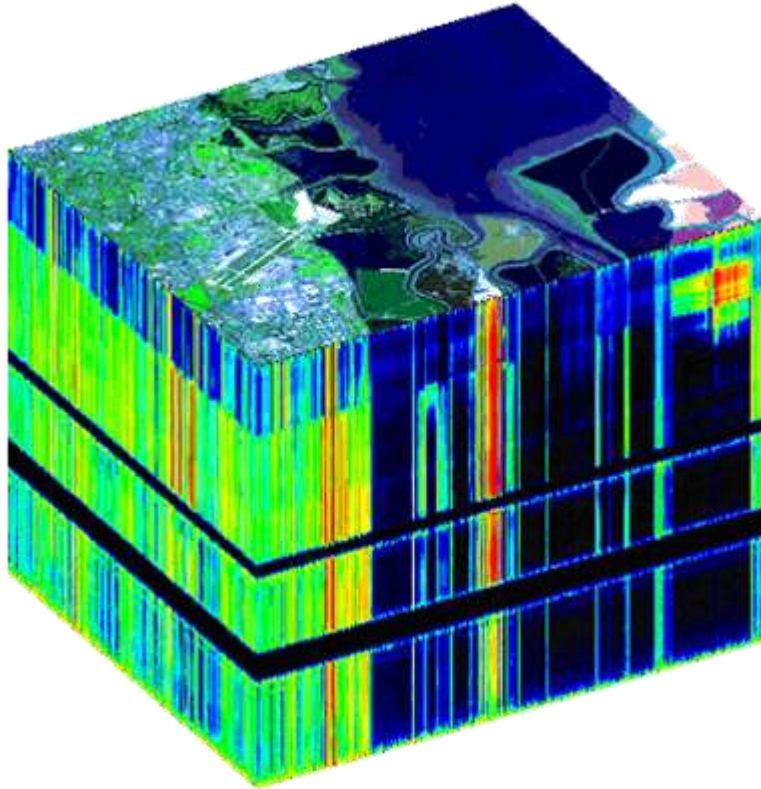
Bathymetry /
Coastal
Applications

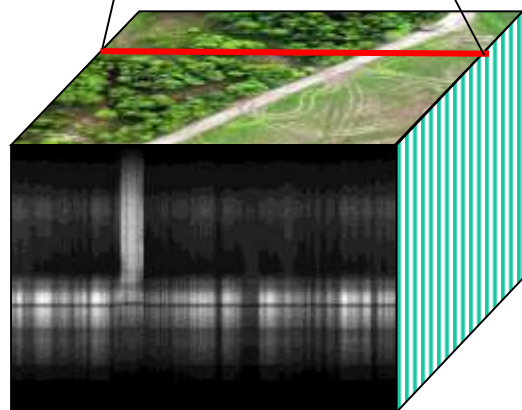
Oil and Gas

Geology

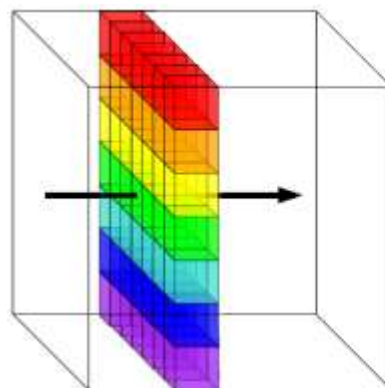


The data cube

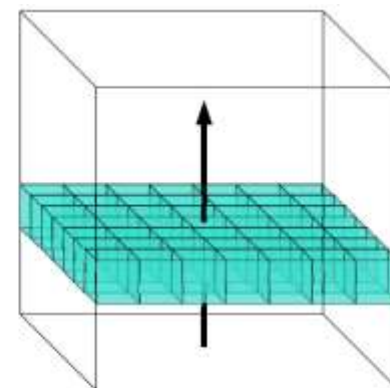




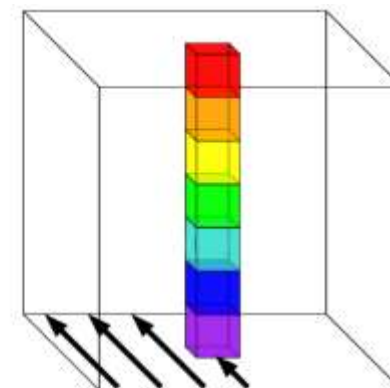
de



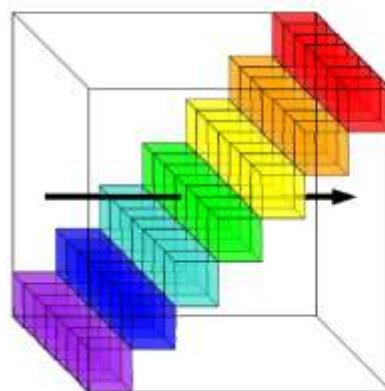
a



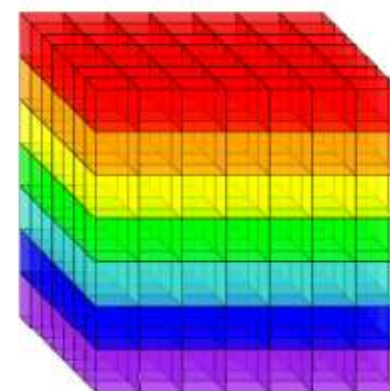
b



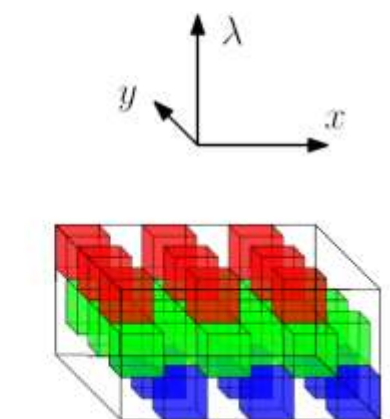
c



d



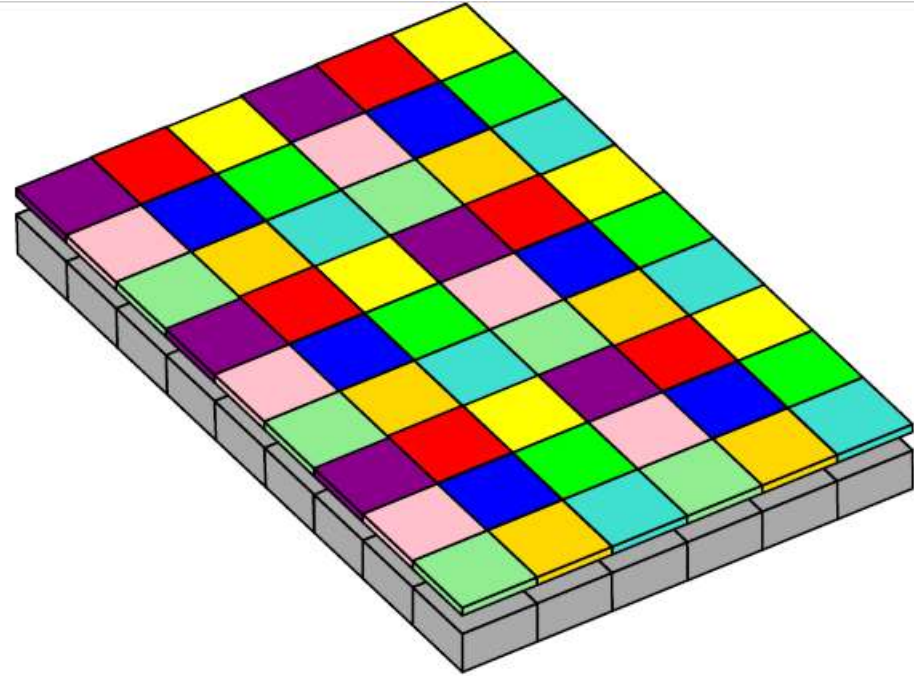
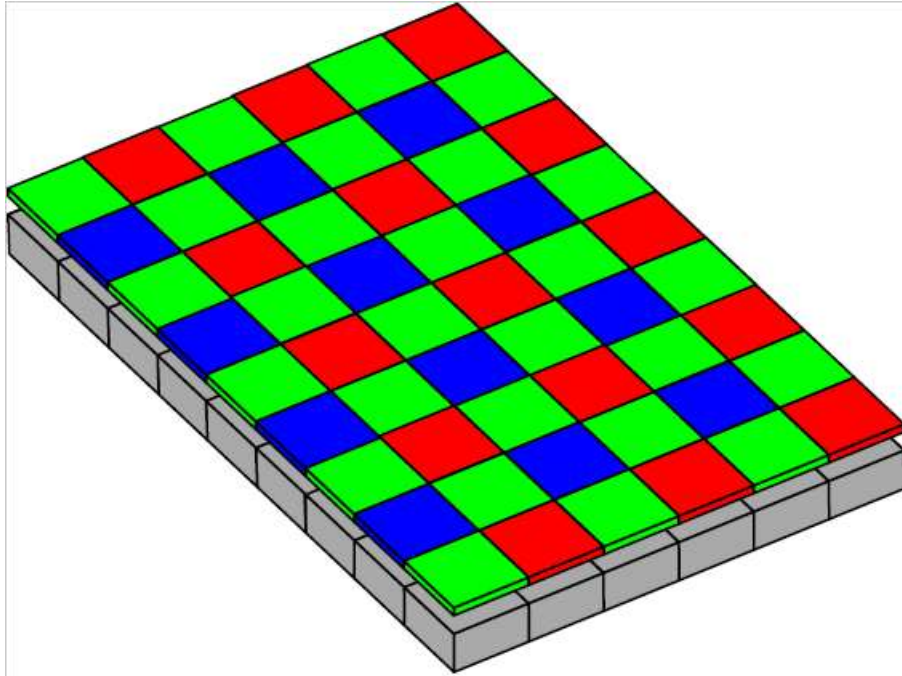
e



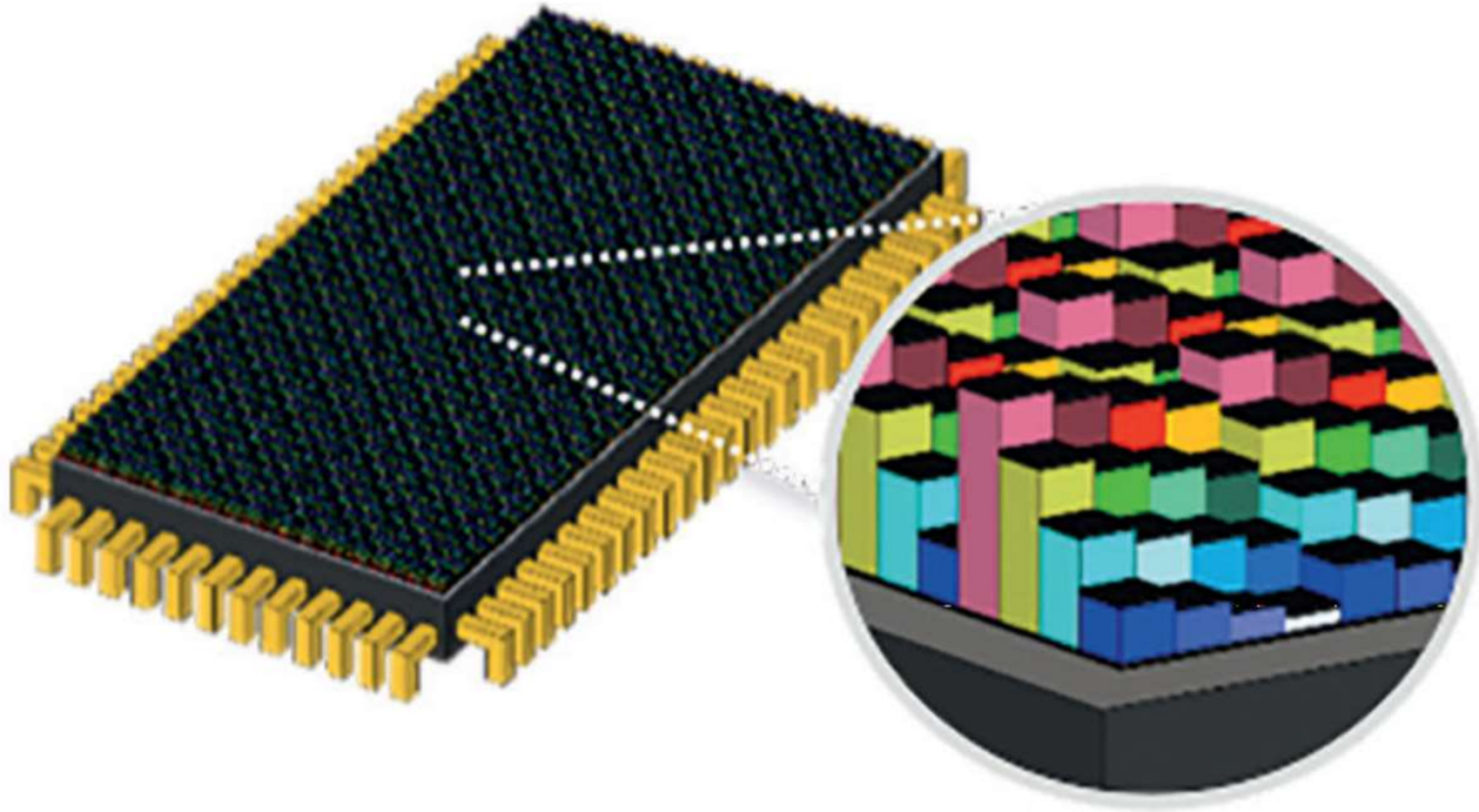
f

Multispectral cameras

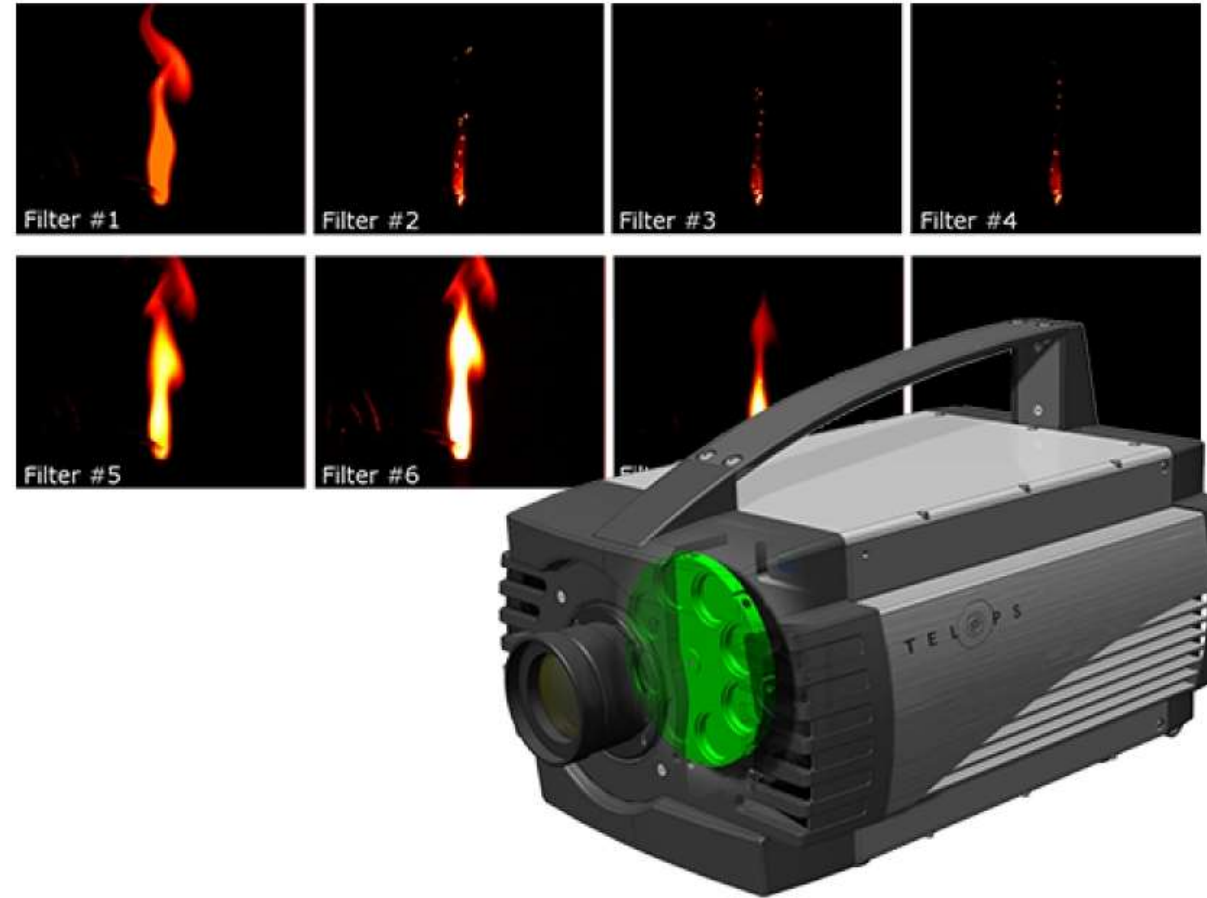
Filter mosaics



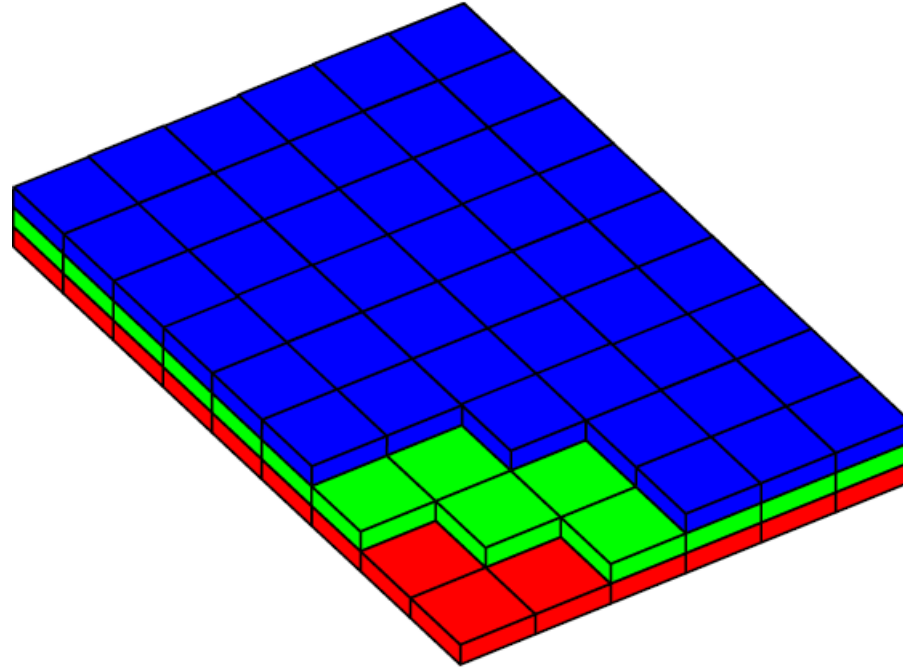
16-band sensor from IMEC



Filter wheels

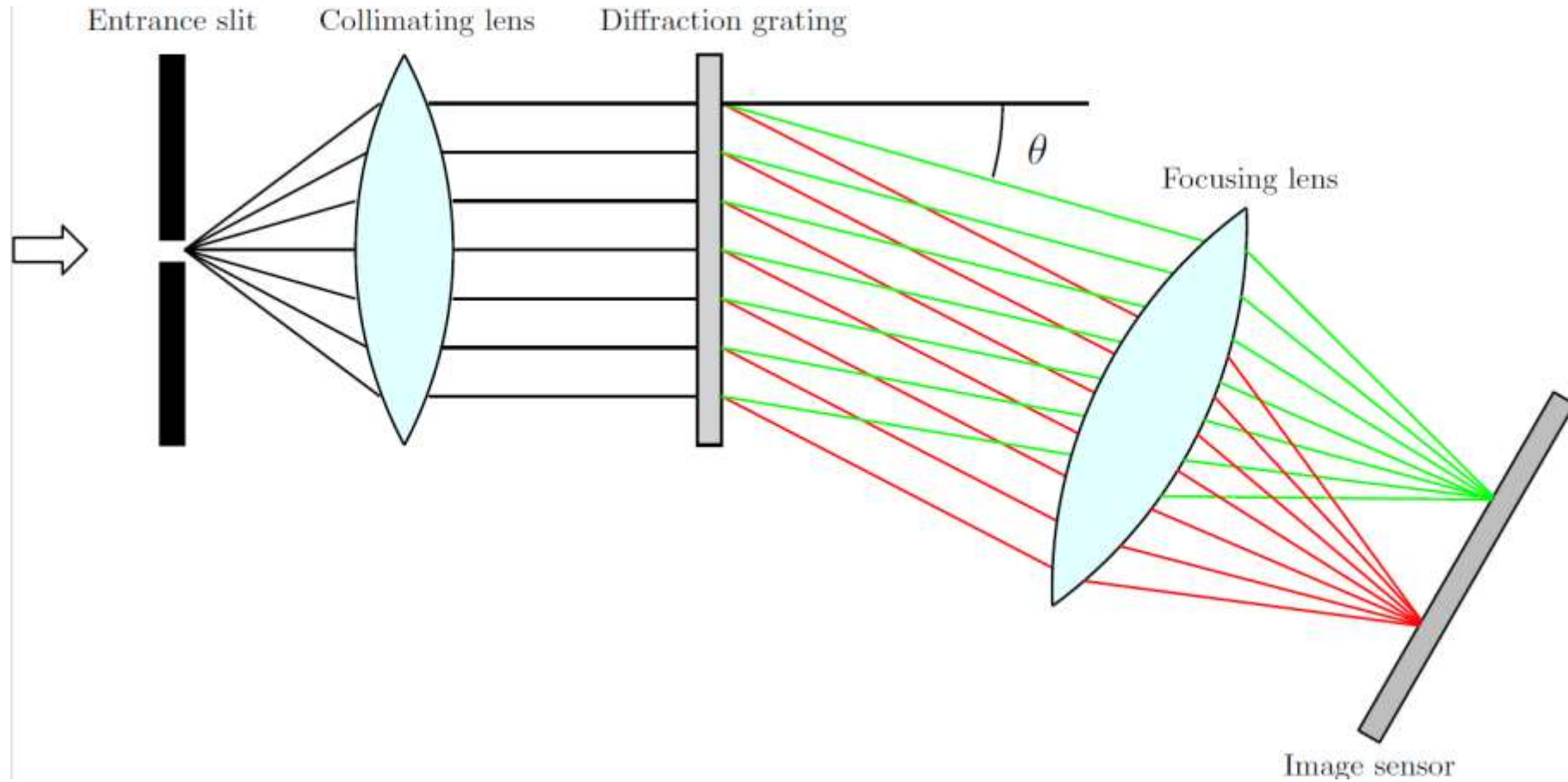


Multi-layer sensors

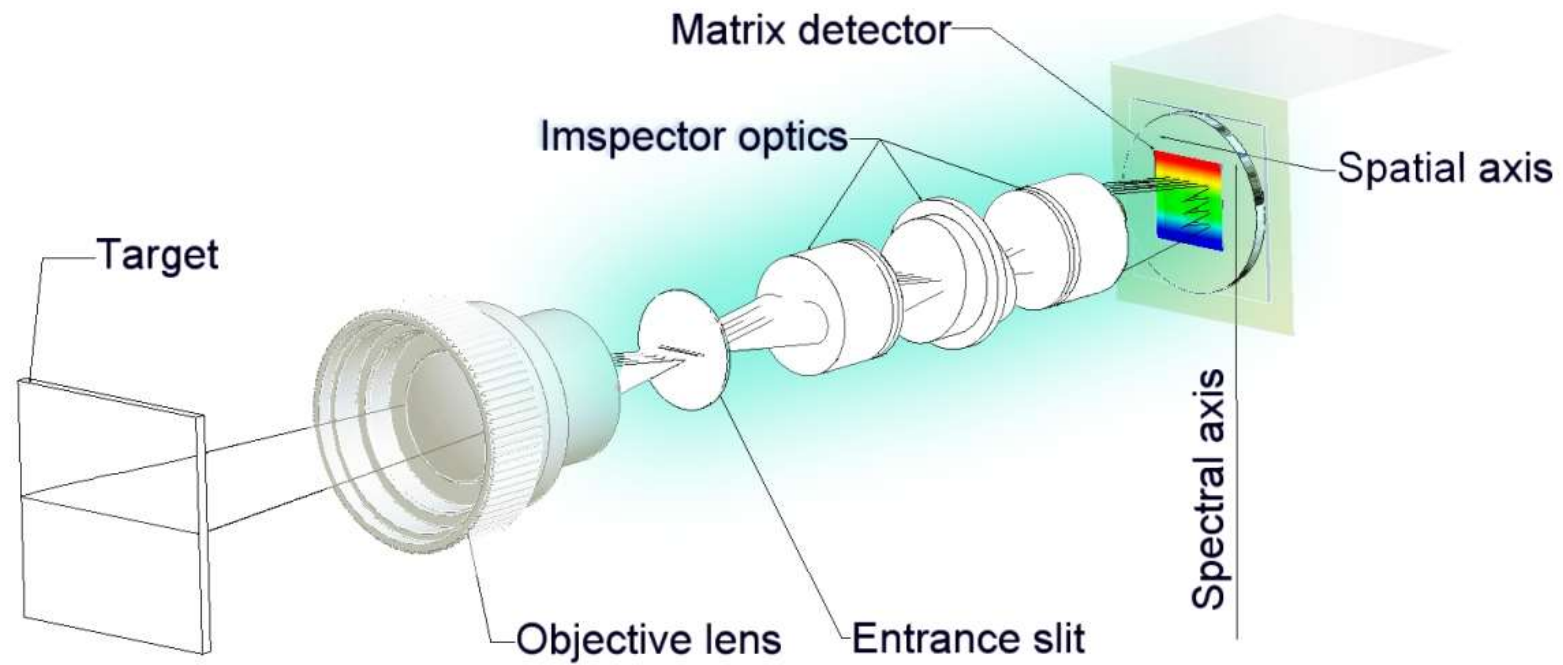


Hyperspectral cameras

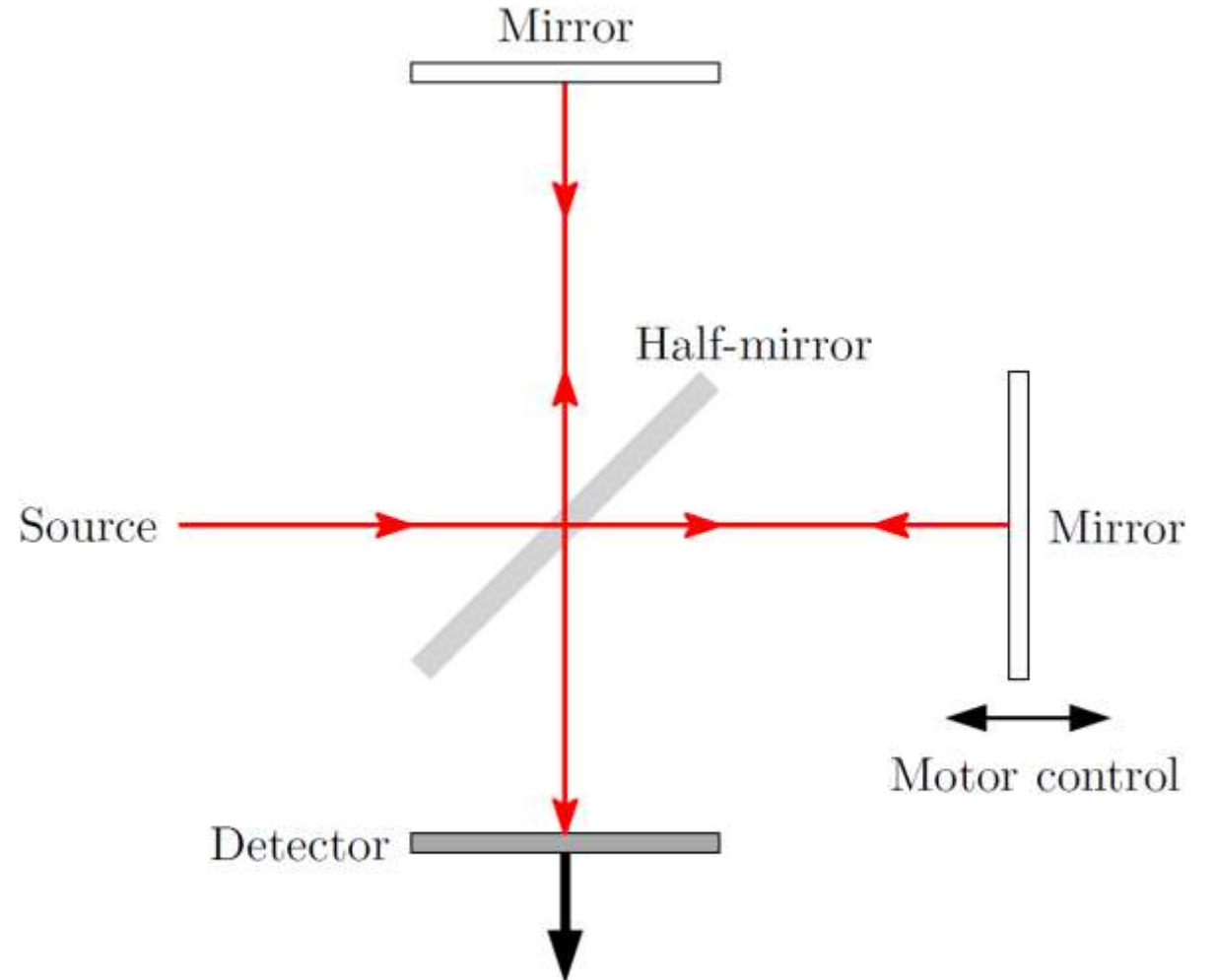
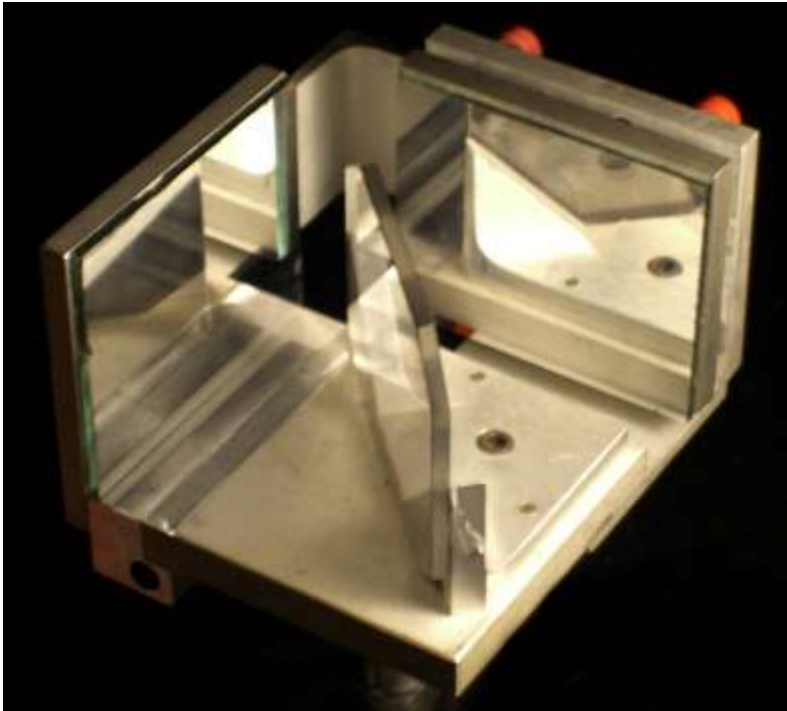
Diffraction grating



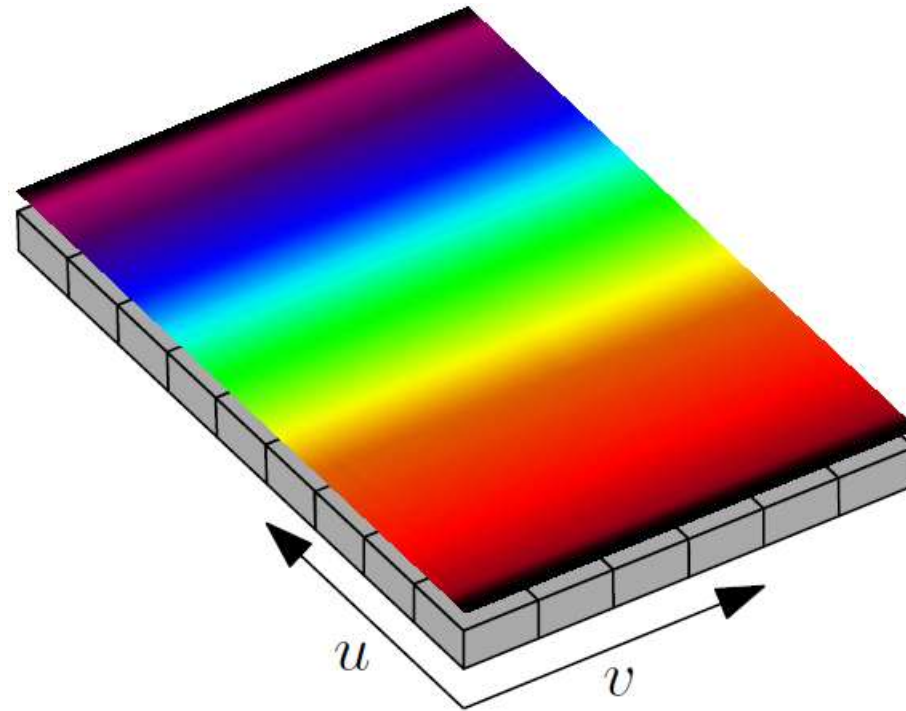
Specim



Interferometer



Continuously variable optical band-pass filter



Summary: Multi/hyperspectral

- Use multiple wavebands to see better!
- Recognize materials in one pixel!
- Many ways of making M/HS cameras.
- Applications: Mostly remote sensing and military, others upcoming, especially life sciences and agriculture.