Aalto University
School of Electrical Engineering

Radiation and Emission mechanisms

Introduction to Space, 25.2. & 4.3.2019

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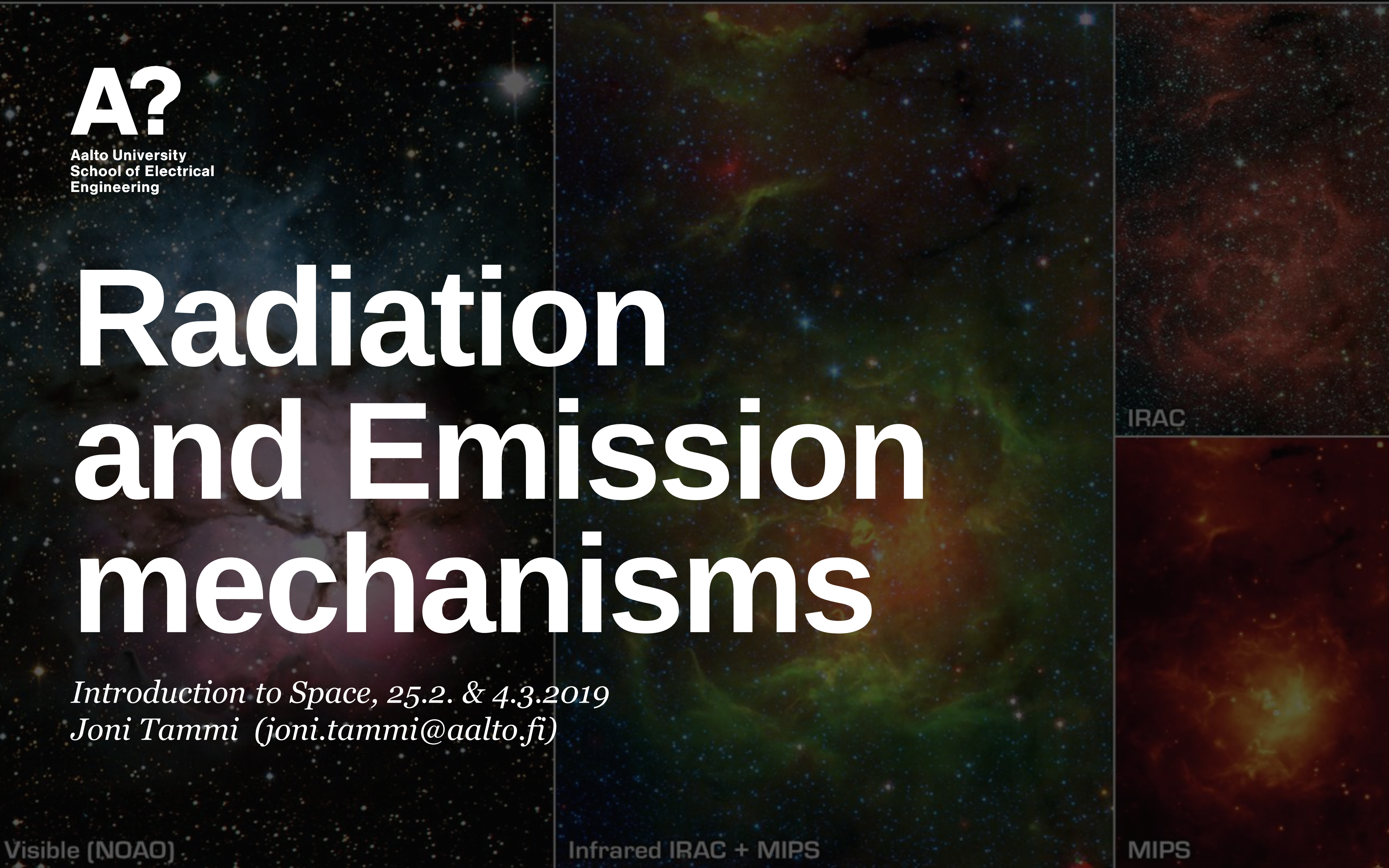


Next two weeks' topics: EM radiation

Radiation concepts

- Luminosity, flux density, brightness
- Spectrum, spectral index
- Emission and absorption

- Very basic radiative transfer
- Opaqueness / transmission
- Optical depth

Emission mechanisms

- Thermal vs nonthermal
- Mechanisms
  - *Blackbody*
  - *Lines (emission and absorption)*
  - *Bremsstrahlung*
  - *Synchrotron*
  - *Inverse Compton*

& in the exam

After these weeks, you should be able to …

Explain and apply basic concepts:

- Solid angle, inverse square law, …
- Flux, flux density, luminosity, brightness, …
- Frequency vs. wavelength vs. energy
- Emission and absorption
- Spectrum, Spectral energy distribution

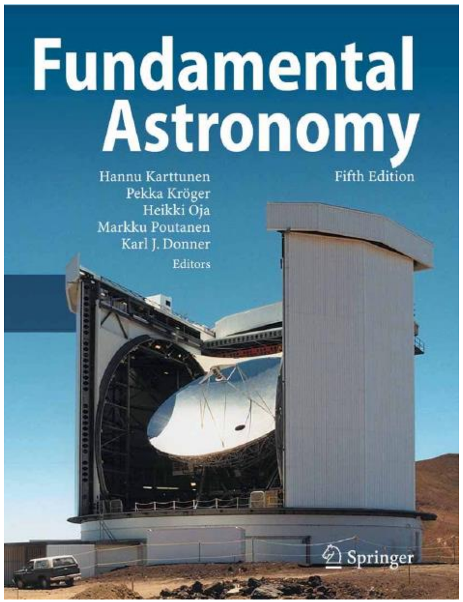
Describe basic mechanisms, and solve simple problems:

- How EM radiation is produced?
- What different production mechanisms are relevant in different objects in space?
- Basic problems:
  - *If we know the **properties** of a source, what kind of EM emission can we expect to **observe** from it?*
  - *If we **observe** EM emission from a source, what kind of **properties** can we expect the source to have?*

Reading material

Fundamental Astronomy

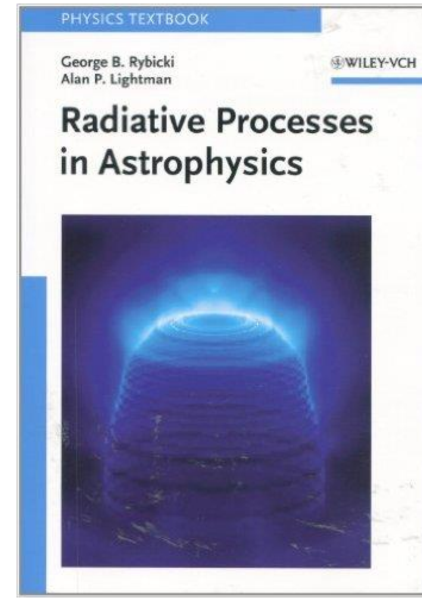
Publisher's link *Google books*



Basics: Fundamental Astronomy Ch 4 & 5
Details: Radiative Processess in Astrophysics, Ch 1

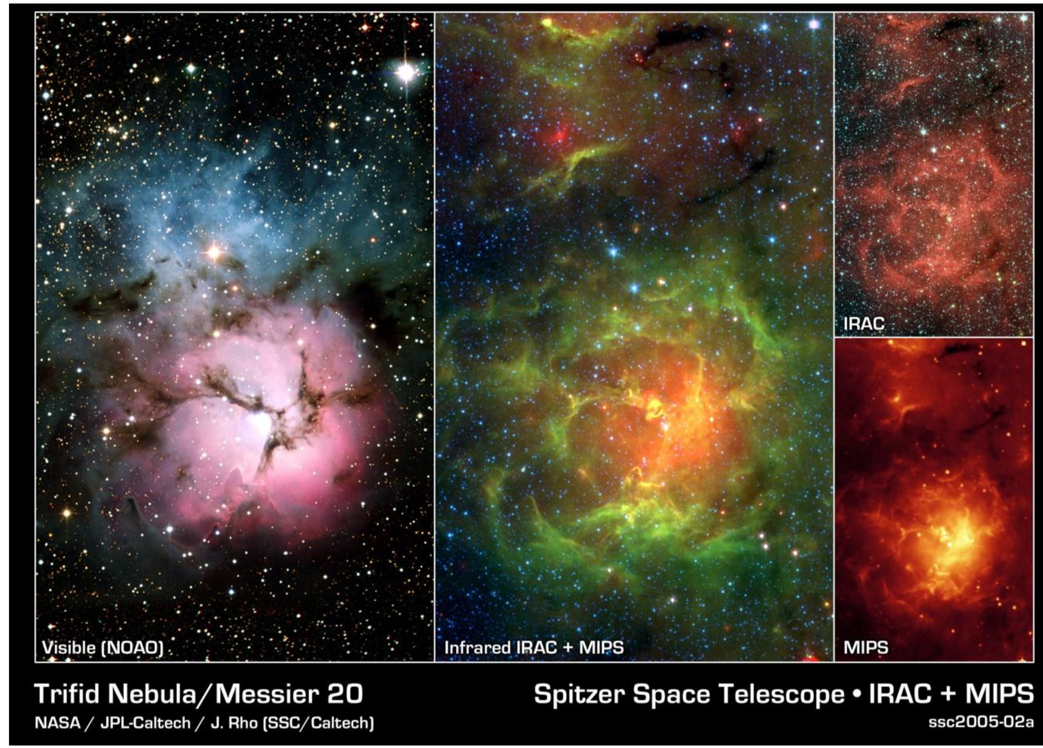
Radiative Processes in Astrophysics

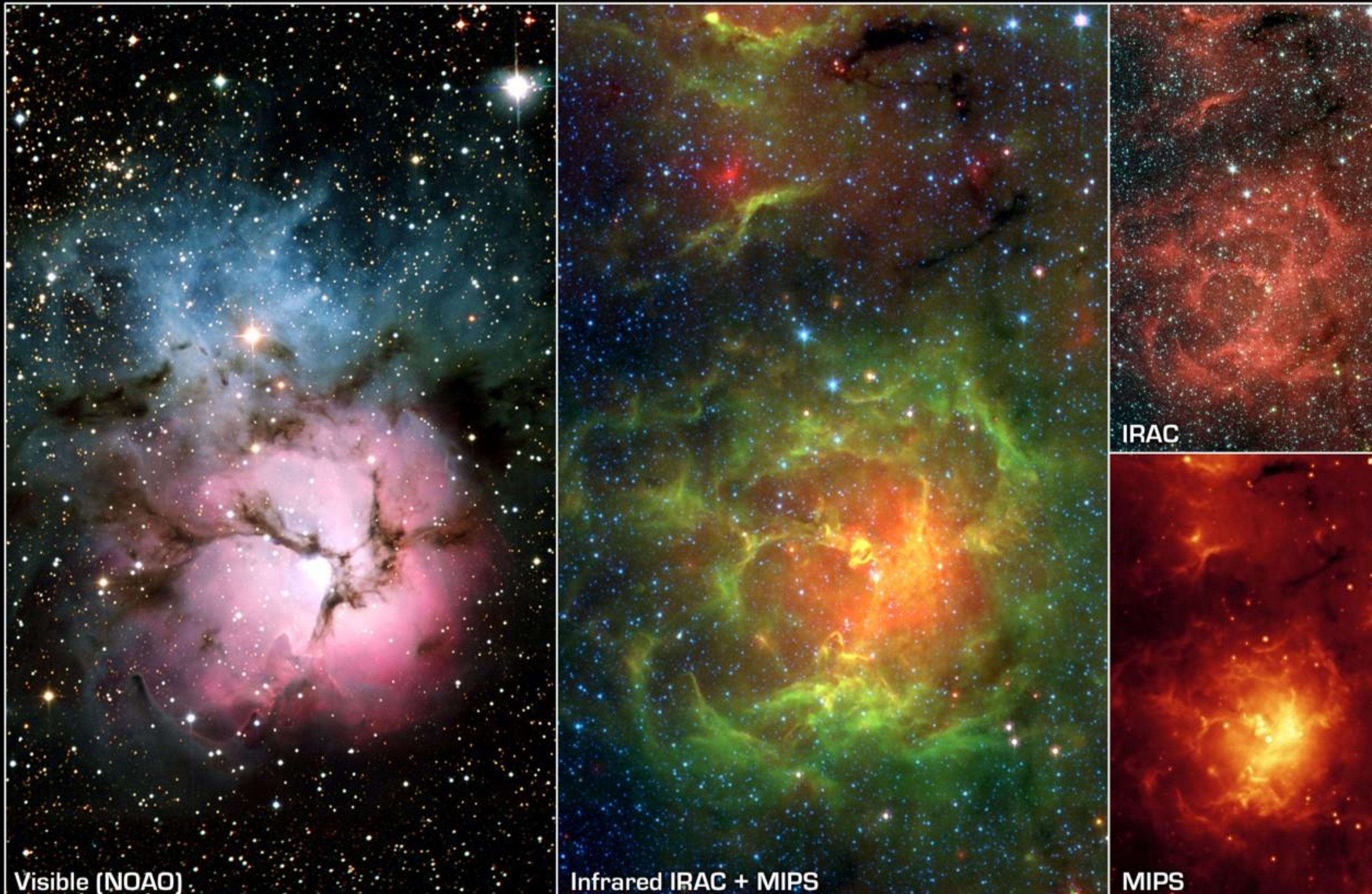
Publisher's link *Google books*



Why emission mechanism?

- Different wavelengths / frequencies tell different things.
- Different emission mechanisms measure different things.



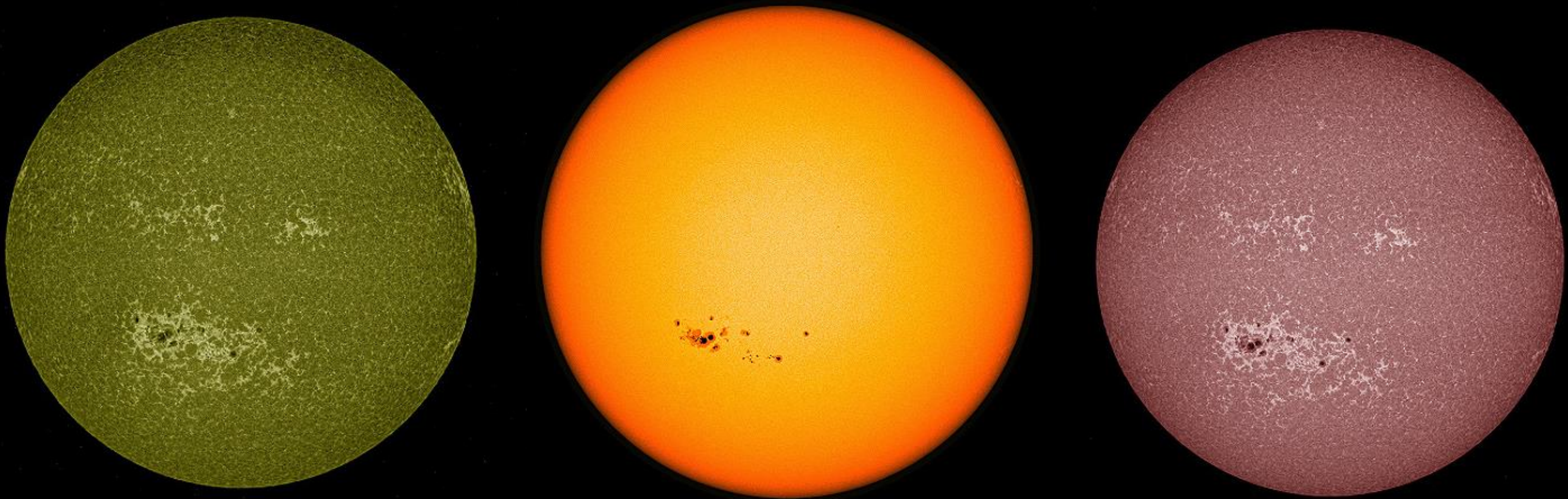


Trifid Nebula/Messier 20

NASA / JPL-Caltech / J. Rho (SSC/Caltech)

Spitzer Space Telescope • IRAC + MIPS

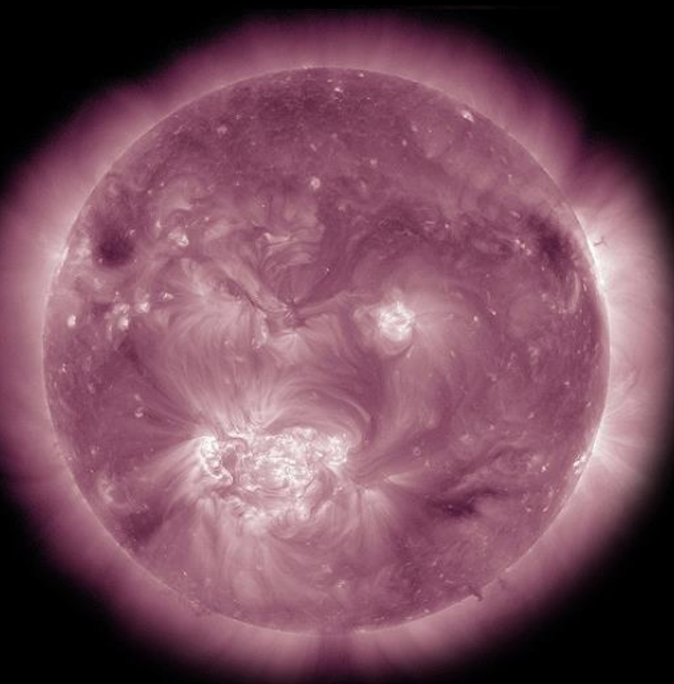
ssc2005-02a



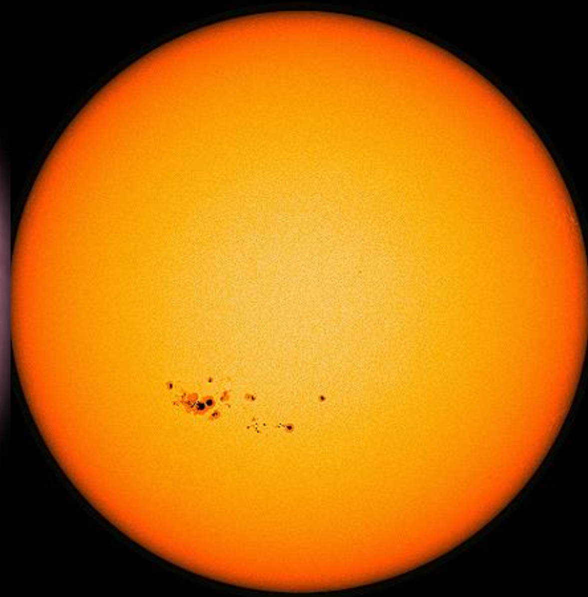
AIA 1600 Å
10,000 Kelvin
Upper photosphere
Transition region

HMI Continuum
Matches visible light
Photosphere

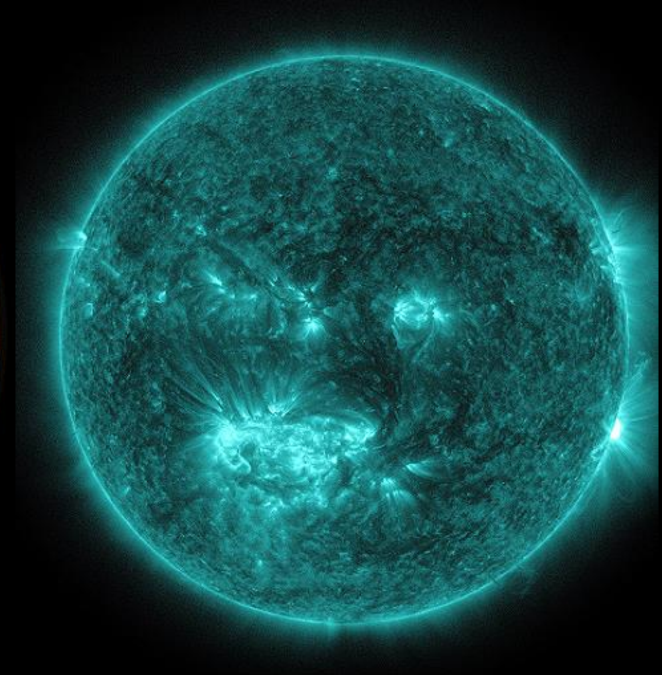
AIA 1700 Å
4500 Kelvin
Photosphere



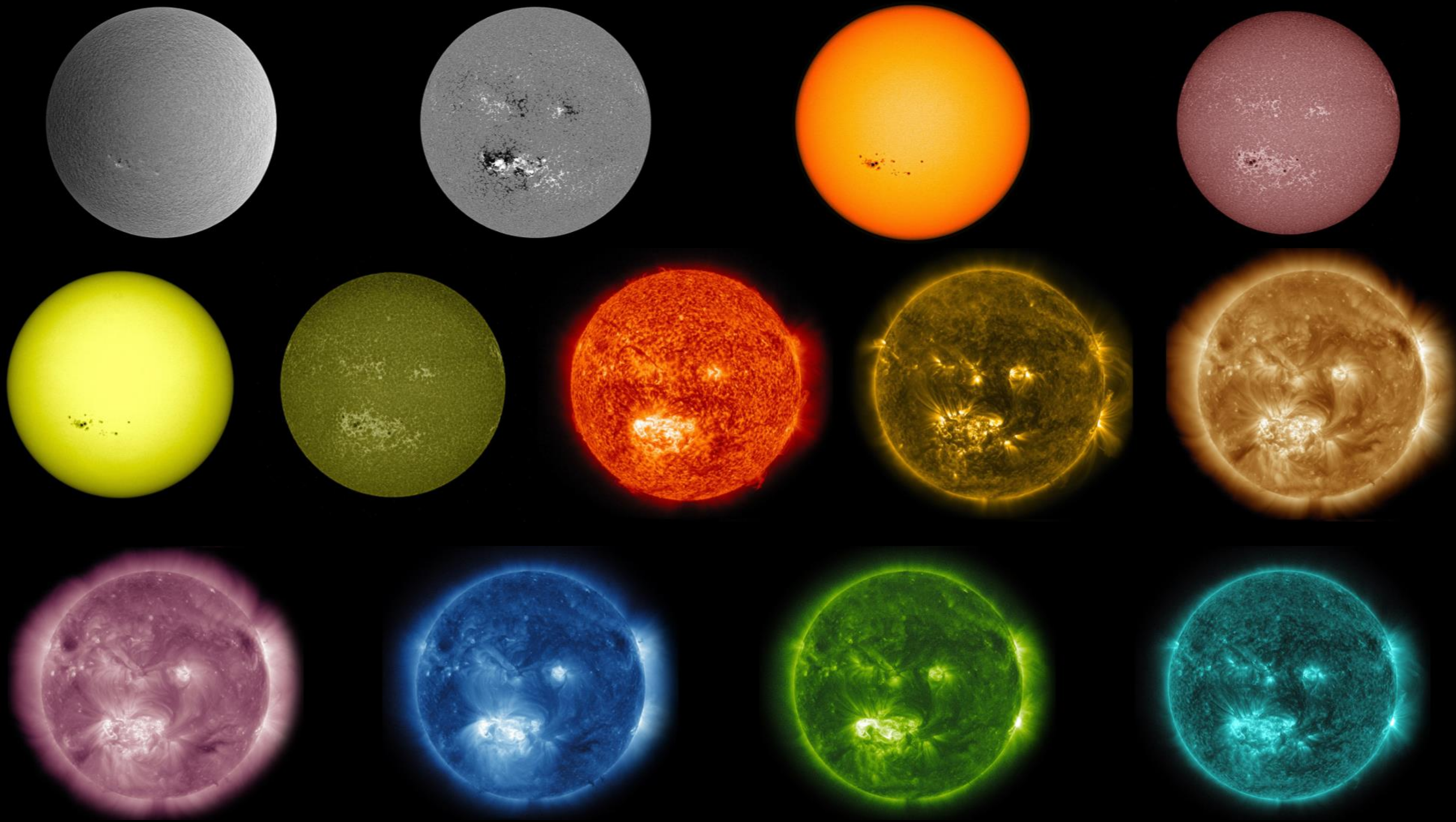
AIA 211 Å
2 million Kelvin
Active regions



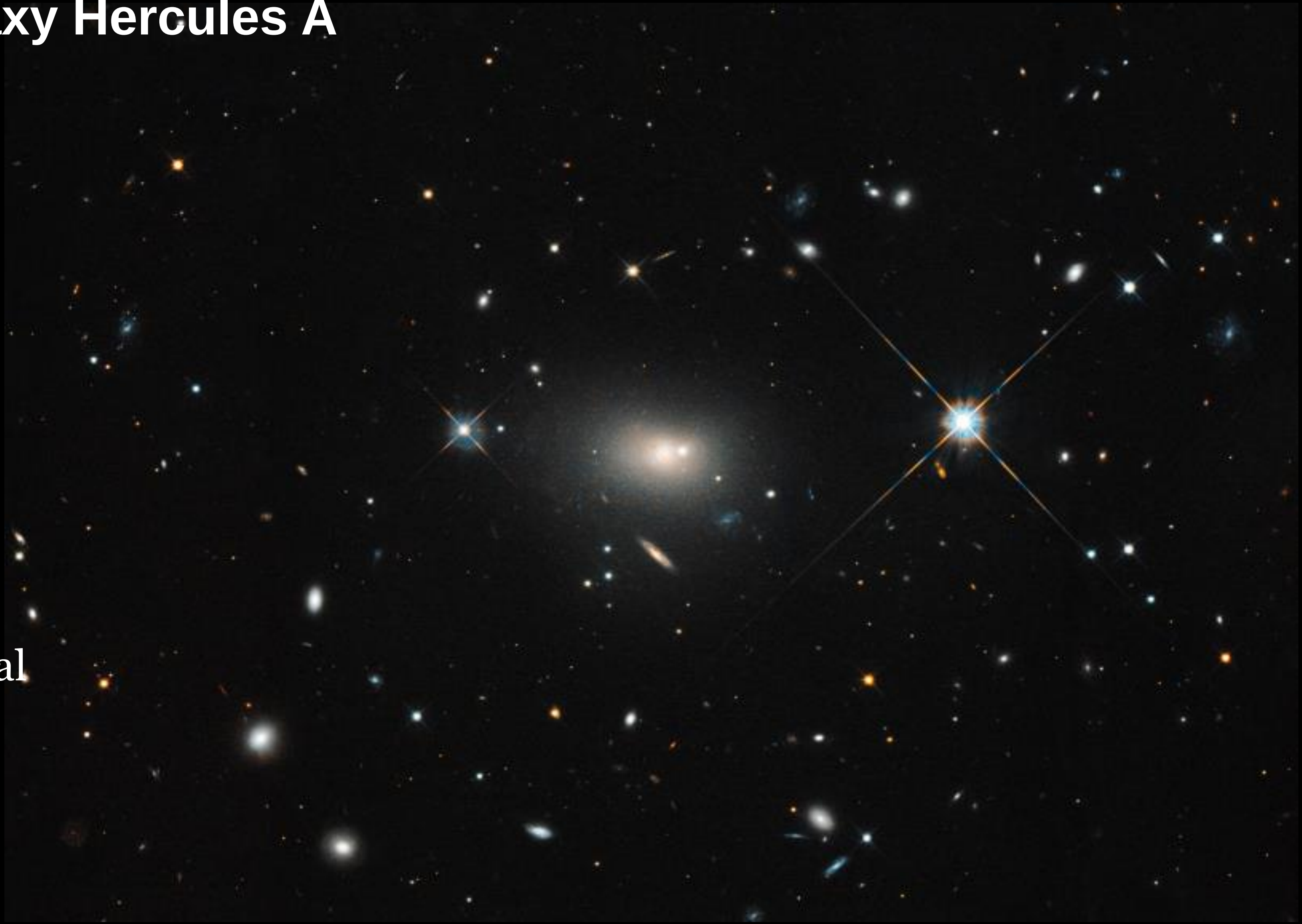
HMI Continuum
Matches visible light
Photosphere



AIA 131 Å
10 million Kelvin
Flaring regions



Galaxy Hercules A

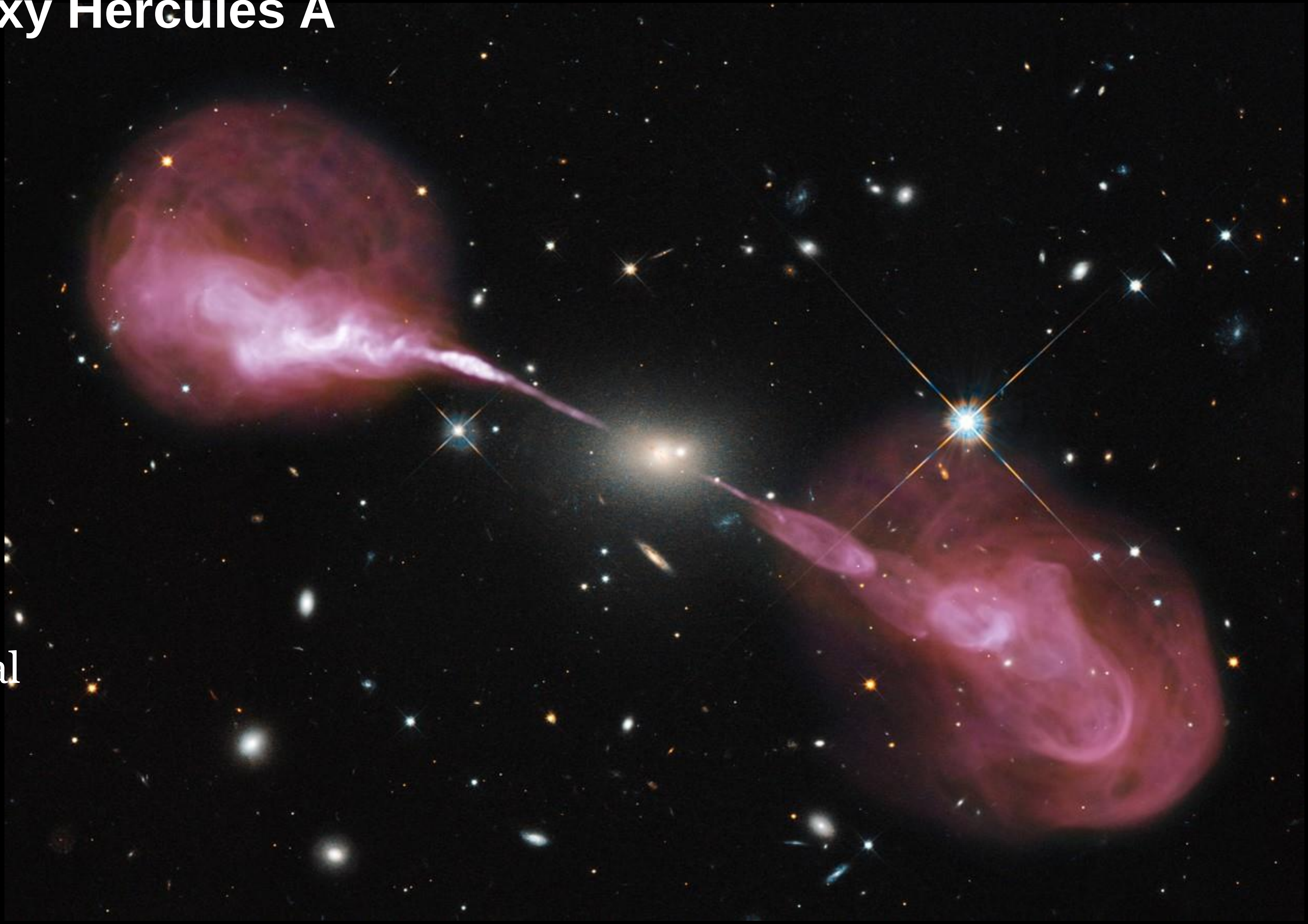


Optical

Galaxy Hercules A

Radio

Galaxy Hercules A

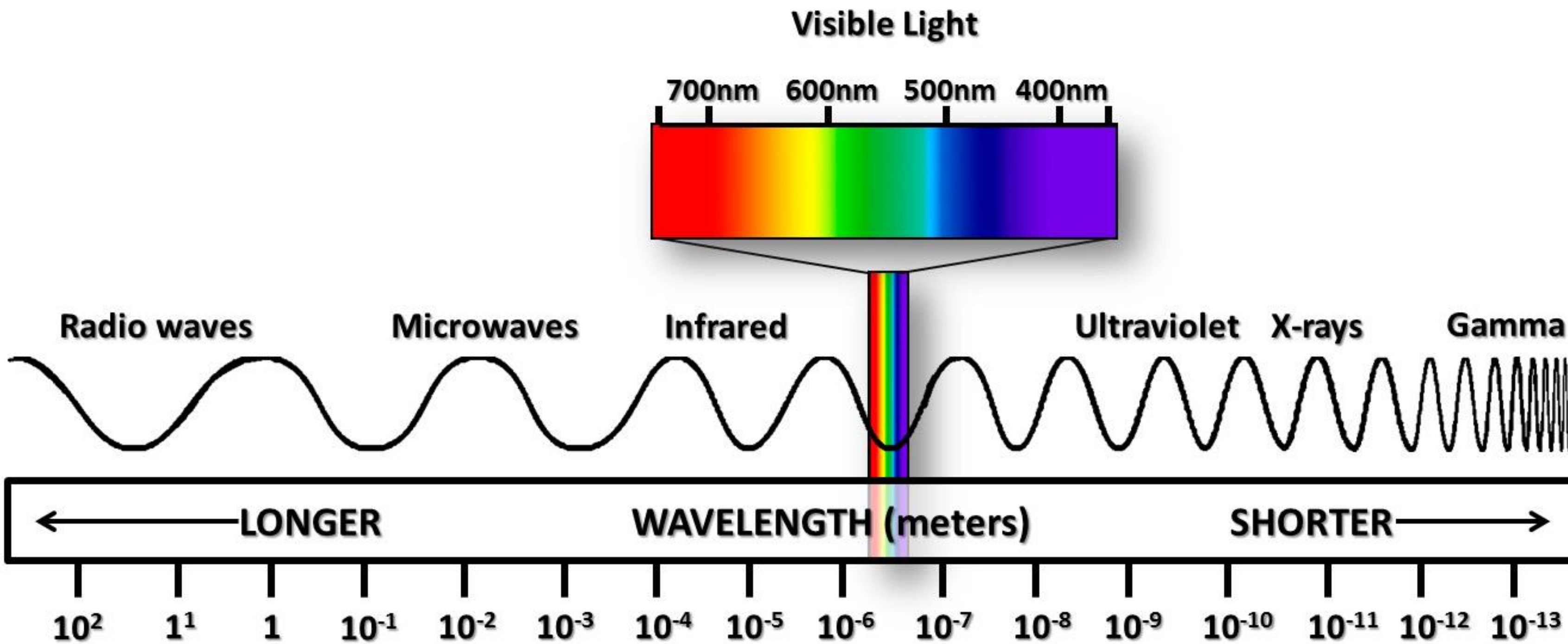


Optical

Radio

Basic concepts and quantities

Electromagnetic radiation



Wavelength vs. Frequency vs. Energy

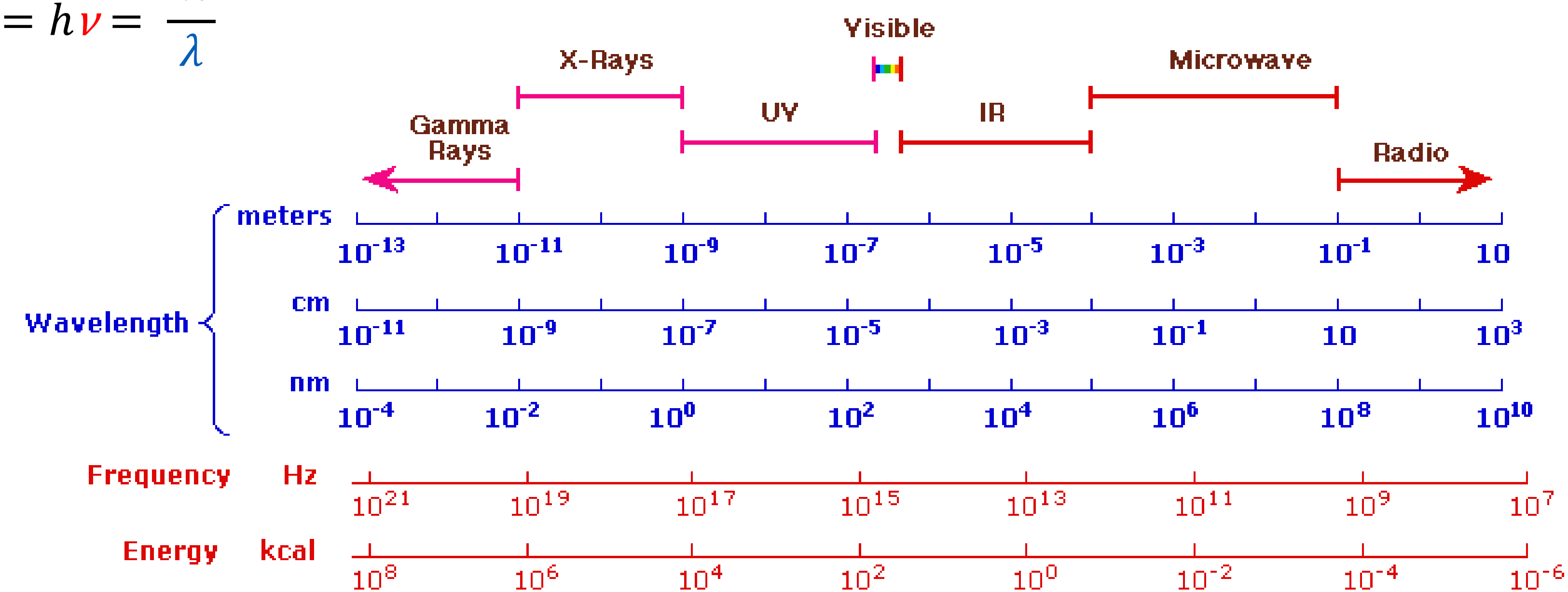
Frequency: ν or f (Hz, GHz, ...)
Wavelength: λ (m, nm, Å, ...)
Energy: E (J, eV, erg, ...)

Speed of light:
$c \approx 3 \times 10^8$ m/s

Planck's constant:
$h \approx 6.626 \times 10^{-34}$ J·s
$\approx 4.136 \times 10^{-15}$ eV·s

$$\nu = \frac{c}{\lambda} \Leftrightarrow \lambda = \frac{c}{\nu}$$

$$E = h\nu = \frac{hc}{\lambda}$$



Characteristic features in spectra

Spectrum

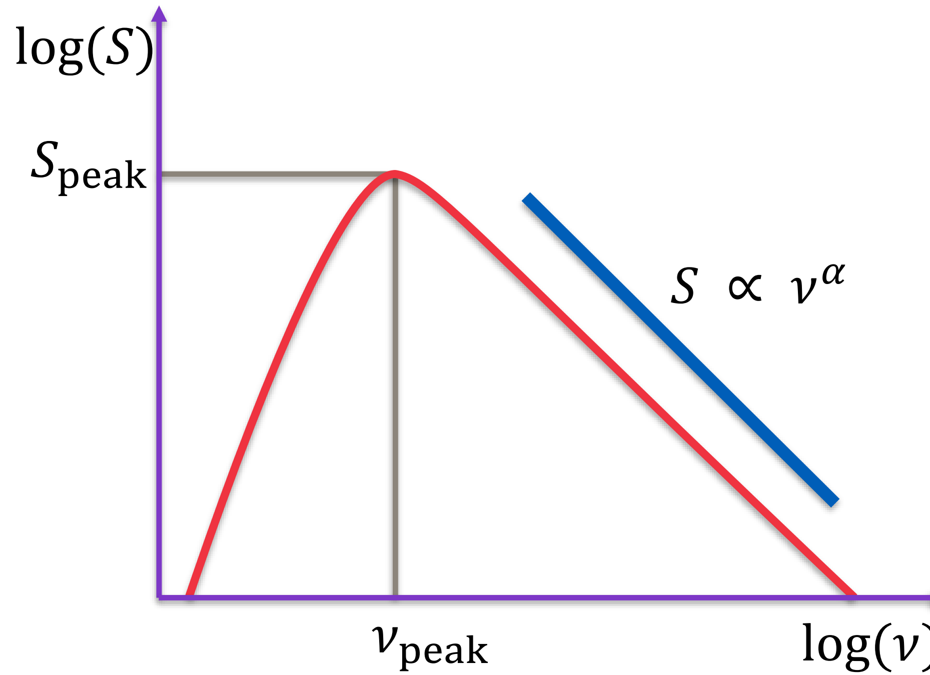
- How much radiation per frequency or wavelength.

Spectral index *α*

- "Slope" of spectrum at some point.

Break

- Turnovers or steepenings in the spectrum



Caution: terminology and symbols

Terms used differently

- Same names used for different quantities.
- Different names used for same quantities.
- Names don't matter, physical quantities do.
- Dimensional analysis is your friend!

What's dimensional analysis?
→ http://bfy.tw/4K78

Units

- Some use **SI**, some use **cgs**, some use other, most use both.

In particular:

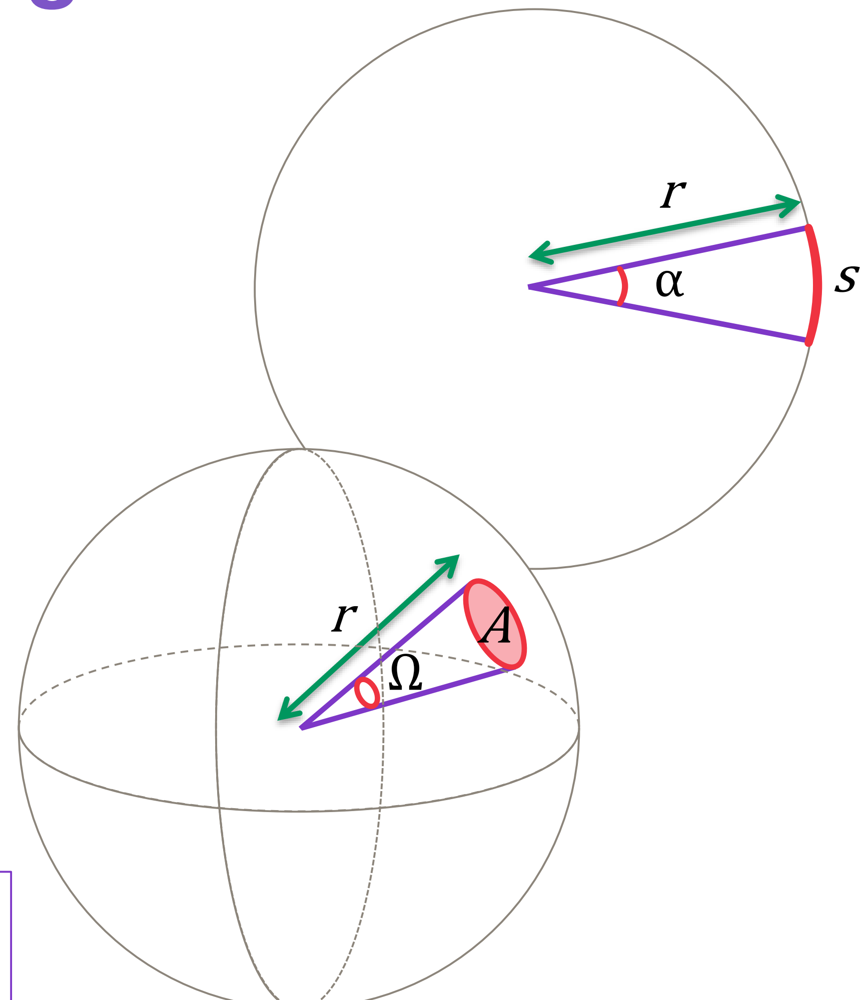
- *F*, *f*, *I*, *S*, *R*, … – all are used to denote *flux*, and …
- *Flux* is used to mean flux, flux density, spectral irradiance, brightness, spectral flux density, monochromatic flux, brightness, …
- Intensity, specific intensity, irradiance, radiant intensity, surface brightness, …

Various quantities with SI units and dimensions:
https://en.wikipedia.org/wiki/Template:SI_radiometry_units

Background: solid angle

Angles in three dimensions

- (Plane) angle α:
  "1D angle in 2D space"
  - $\alpha = s/r$ (radians)
  - Circumference $= 2\pi r$
    → Full circle $= 2\pi$ rad $= 360°$
    or 1 rad $= 180°/\pi$
- **Solid angle Ω**:
  "2D angle in 3D space"
  - $\Omega = A/r^2$ (steradians)
  - Area: $A = 4\pi r^2$
    → full sphere $= 4\pi$ sterad

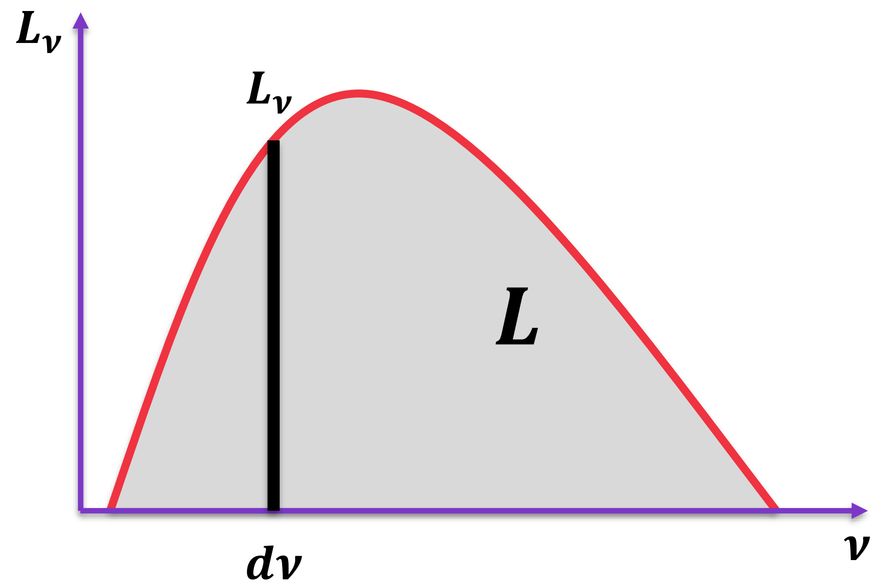


You can also use *square degrees* instead of *steradians* in the same way you can use *degrees* instead of *radians*. Just remember to convert all units accordingly.

Main quantities used this week

A distant object emits photons

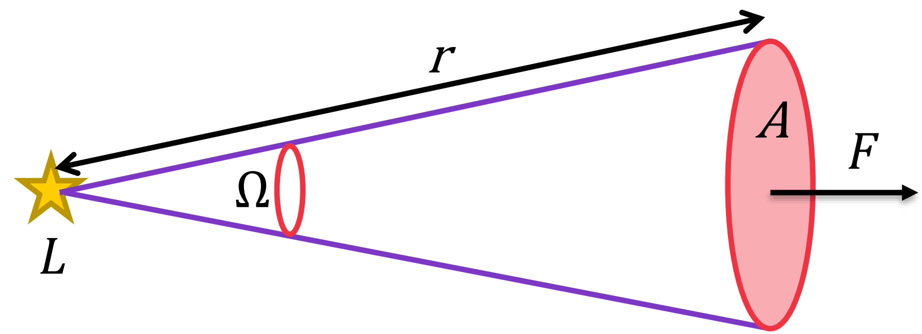
- **Energy flux** L_ν [W / Hz] is the flow of energy (or luminosity) at a certain frequency ν.
- **Luminosity** $L = \int_0^\infty L_\nu \, d\nu$ [W] is the total flow of energy per unit time, over all frequencies.
  - *Determines the radiative **power** (i.e. energy per time).*
    *→ unit **W** (or J/s, or erg/s, …)*



Main quantities used this week

Flux F

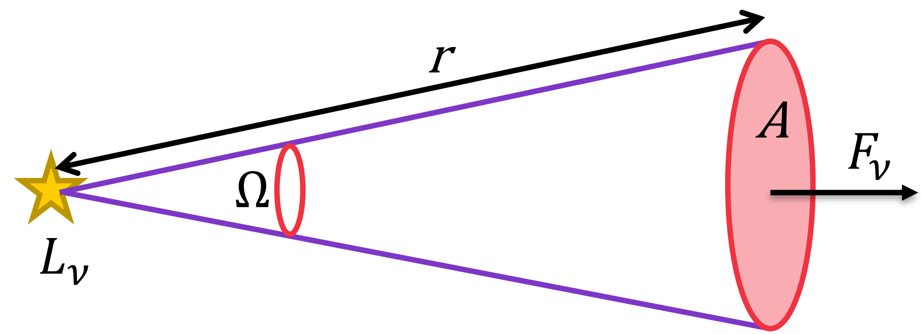
- *"Brightness of an object."*
- The amount of energy crossing a unit area (normal to the source direction) in unit time, over all frequencies. [W / m²]
- [energy] · [time]$^{-1}$ · [area]$^{-1}$
  → [power] · [area]$^{-1}$
  → W m^{-2}



Main quantities used this week

Flux density F_ν (or F_λ)

- *"Brightness of an object at certain frequency band."*
- Flux F per unit bandwidth.
- Can be flux per ν or λ:
  - F_ν, *units* $\mathrm{W\,m^{-2}Hz^{-1}}$
  - F_λ, *units* $\mathrm{W\,m^{-2}nm^{-1}}$ *(or* $\mu\mathrm{m}$, Å , …*)*
  - $F = \nu\, F_\nu$ *and* $F = \lambda\, F_\lambda$
- E.g. $F_\nu = \frac{L_\nu}{4\,\pi\, r^2}$ for isotropic point source



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  - $F = \nu\, F_\nu$ *and* $F = \lambda\, F_\lambda$
- E.g. $F_\nu = \dfrac{L_\nu}{4\,\pi\, r^2}$ for isotropic point source

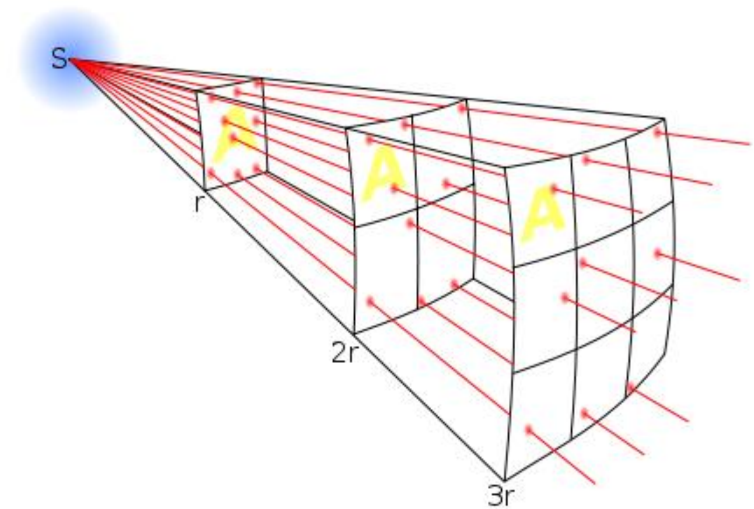
- Dimensions and units:
  - With frequency:
    [flux] · [frequency]$^{-1}$
    → [power] · [area]$^{-1}$ · [frequency]$^{-1}$
    → $\mathrm{W\,m^{-2}\,Hz^{-1}}$
  - With wavelength:
    [flux] · [wavelength]$^{-1}$
    → [power] · [area]$^{-1}$ · [wavelength]$^{-1}$
    → [power] · [[length]^2]$^{-1}$ · [length]$^{-1}$
    → $\mathrm{W\,m^{-3}}$ *or* $\mathrm{W\,m^{-2}\,nm^{-1}}$ *or* $\mathrm{W\,m^{-2}\,\mu m^{-1}}$
- Common non-SI units:
  - *Jansky*, $1\ \mathrm{Jy} = 10^{-26}\ \dfrac{\mathrm{W}}{\mathrm{m^2\ Hz}} = 10^{-23}\ \dfrac{\mathrm{erg}}{\mathrm{s\ cm^2\ Hz}}$
  - *Solar Flux Units*, $1\ \mathrm{SFU} = 10^4\ \mathrm{Jy}$

Main quantities used this week

Inverse square law:

- Same amount of ”rays”, but the surface increases as $A \propto r^2$.

→ Density decreases as $F \propto \frac{1}{r^2}$.

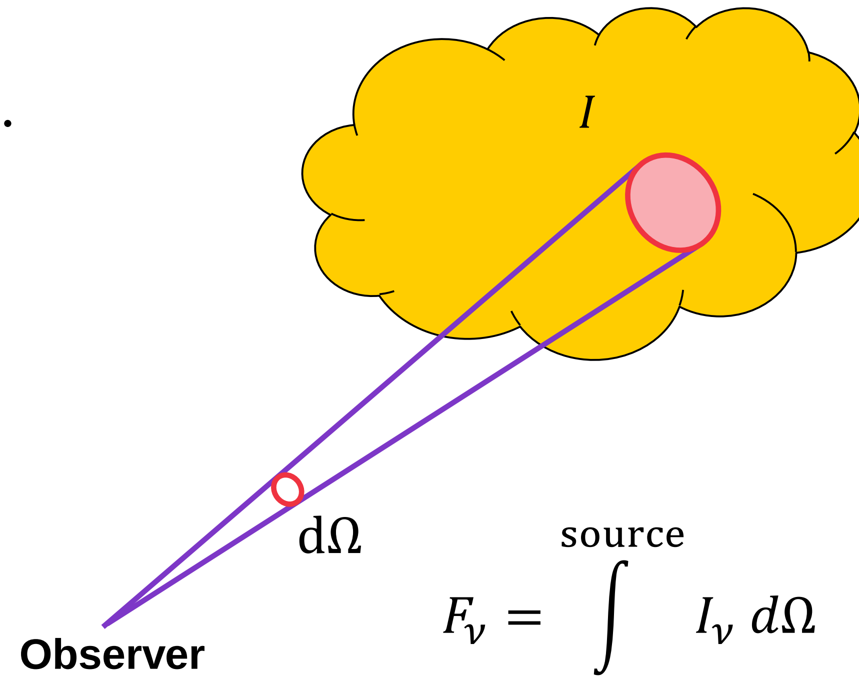


Main quantities used this week

Intensity I, **Specific intensity** I_ν

- "*Surface brightness.*"
- Flux (density) per unit solid angle.
- Does *not* depend on the distance. (Even though F_ν does.)

Does not conflict with the inverse square law.



$$F_\nu = \int_{\Omega}^{\text{source}} I_\nu \, d\Omega$$

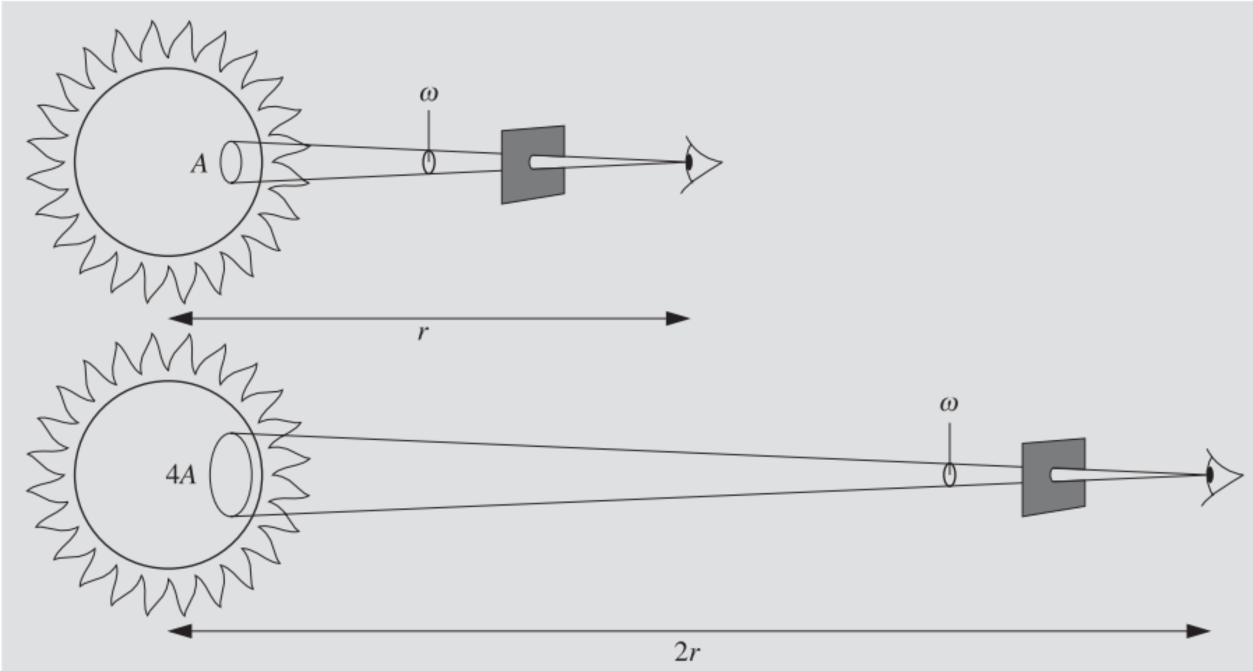


Fig. 4.4. An observer sees radiation coming from a constant solid angle ω. The area giving off radiation into this solid angle increases when the source moves further away ($A \propto r^2$). Therefore the surface brightness or the observed flux density per unit solid angle remains constant

”Fundamental astronomy”
Karttunen et al. (5th ed.)
Chapter 4

Main quantities used this week

Intensity I, **Specific intensity** I_ν

- *"Surface brightness."*
- Flux (density) per unit solid angle.
- Does *not* depend on the distance. (Even though F_ν does.)

- *"How much energy flows through a detector in some time, at some across some frequency range, from some direction."*
- $I_\nu \equiv \frac{dE}{dA\, dt\, d\nu\, d\Omega} = \frac{dP}{dA\, d\nu\, d\Omega}$
- $[I_\nu] = \frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{Hz}\ \mathrm{sr}}$

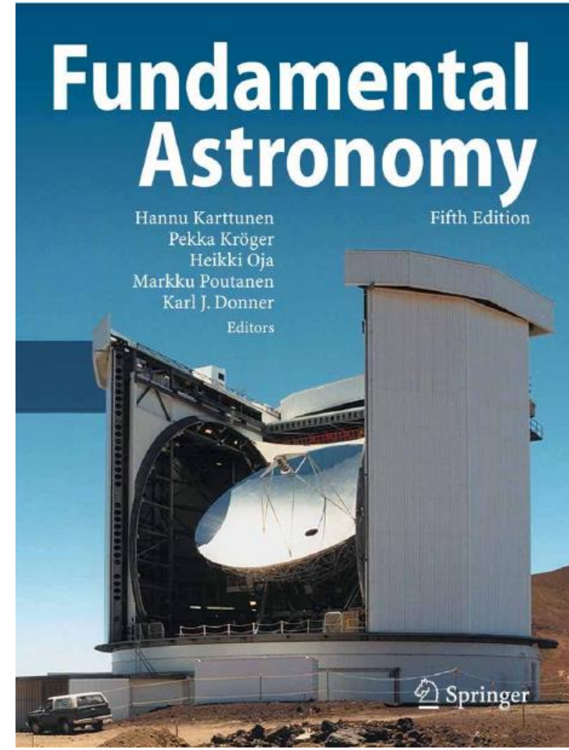
dP *Power*
dA *Surface area (detector)*
$d\nu$ *Frequency range*
$d\Omega$ *Solid angle*

- $I_{\text{total}} = \int_0^\infty I_\nu\ d\nu$

You'll get use to it (if you choose to)

1. **It's not that difficult/confusing when you get to use them.**
2. **Different names and symbols don't matter that much.**
3. **(Almost) Everything can be deduced from the units used.**

Fundamental Astronomy book
Chapter 4
- "Photometric Concepts and Magnitudes"



Optical depth & optical thickness

Summary sufficient for today:

- How much light/radiation comes through something *at some frequency* → optical thickness (at that frequency).
- Optically thin ⇔ 100 % through the source/object *transparent*
- Optically thick ⇔ 0 % through the source/object is *opaque*

A big effect on what we see
- **Optically thin** source: we see radiation from the whole volume.
- **Optically thick** source: we see only the surface.

(Many objects in between: we see part of the volume, but not all the way through.)

http://coolcosmos.ipac.caltech.edu/cosmic_kids/learn_sirtf/infrared.html

So far you should be able to answer:

How to calculate solid angle of an object?

What is the difference between luminosity and energy flux?

From the inverse square law it follows that ____________________ falls $\propto 1/r^2$.

A receiver (camera, telescope, antenna, …) only detects certain wavelenghts. Therefore the quantity it measures is ______________.

Sun's total radiative output is x watts. What is maximum power you can get from a 100%-effective 1 m^2 solar panel on Mars?

Star Y is n times brighter (total luminosity) and m times larger (diameter) than the Sun.

- How far away it needs to be in order to appear as bright as the Sun?
- How far away do we need to take a 100-watt lightbulb before it looks as bright as the star ?

Electromagnetic emission mechanisms

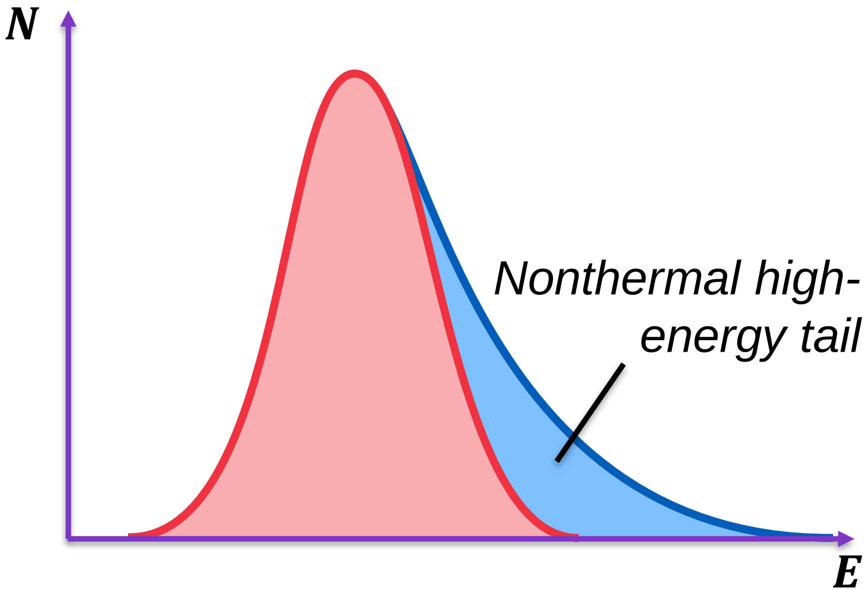
Emission mechanisms

Underlying things to remember

- Accelerating charge → photons.
- Photon energy ($E = h\nu$) comes from somewhere.
- Emission and absorption
  - *Photon produced vs. photon lost.*

- Particles create photons → particle properties and environment determine what processes are present.
- Thermal vs. nonthermal plasma
  - *Energy distribution of particles*
  - *Maxwell-Boltzmann or "something else"*

Emission mechanisms



- Particles create photons → particle properties and environment determine what processes are present.
- Thermal vs. nonthermal plasma
  - *Energy distribution of particles*
  - *Maxwell-Boltzmann or "something else"*

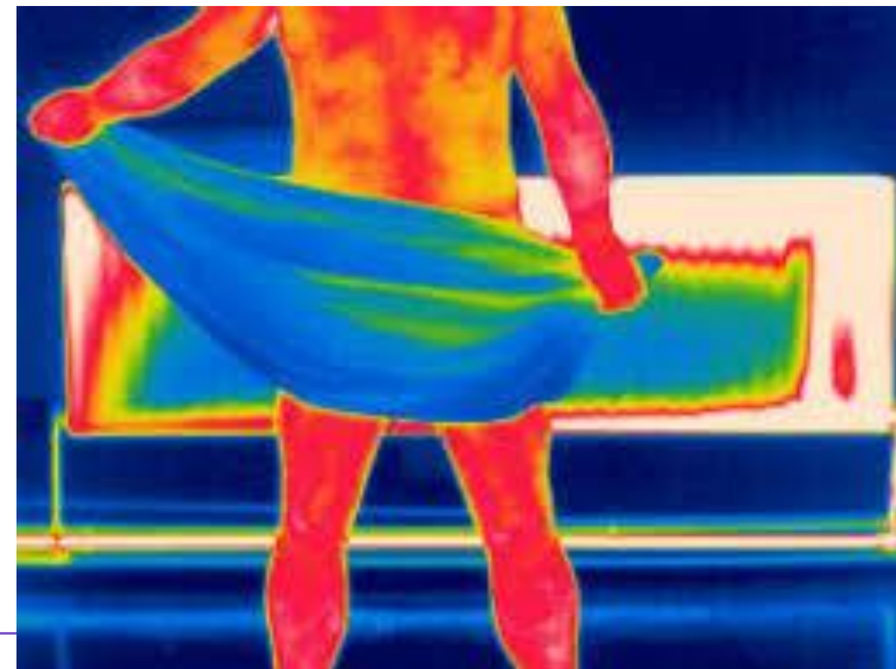
Blackbody radiation

***Blackbody*:**

An ideal object that absorbs all radiation and re-emits 100% of the energy. Does not reflect or scatter any radiation.

Examples: stars are very good blackbodies.

In practice often blackbody = thermal emission



Blackbody radiation

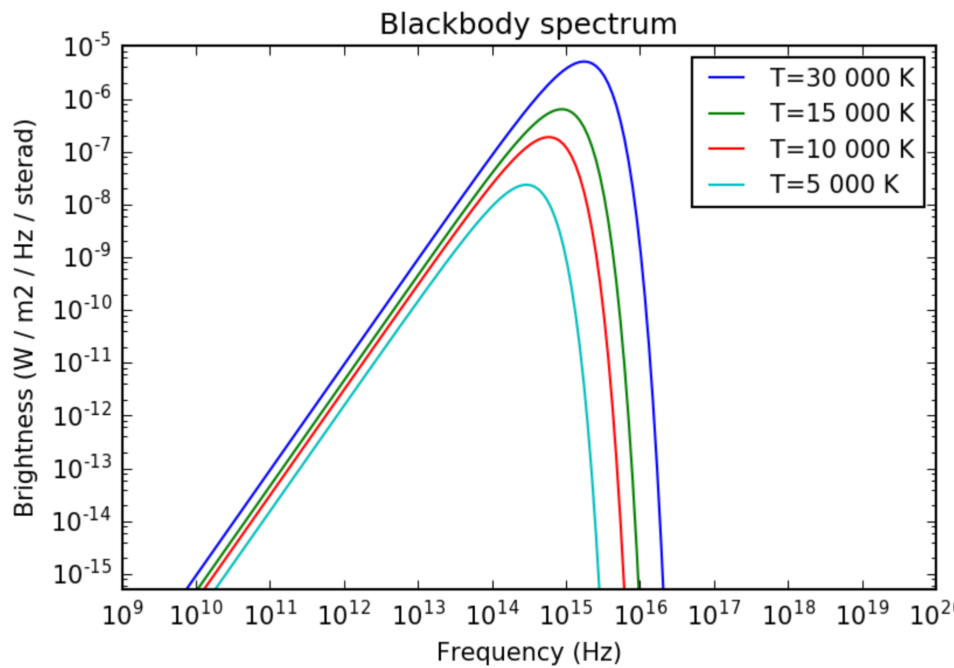
- Object at temperature T(K) emits a blackbody spectrum.
- ”Ideal absorber and emitter in thermal equilibrium with it’s environment.”

- Spectrum from **Planck’s law**:

$$I_\nu(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{k_\mathrm{B}T}}-1}$$

$$I_\lambda(\lambda,T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda k_\mathrm{B}T}}-1}$$

Boltzmann constant: $k_\mathrm{B} \cong 1.381 \times 10^{-23}\ \mathrm{J\,K^{-1}}$
Planck constant: $h \cong 6.626 \times 10^{-34}\ \mathrm{J\,s}$



Blackbody radiation

Peak frequency
→ temperature

- Peak from **Wien's displacement law**:

$$\lambda_{\max} = \frac{b}{T} \approx \frac{0.00290 \text{ m K}}{T}$$

$$\nu_{\max} \approx 5.879 \times 10^{10} \frac{\text{Hz}}{\text{K}} T$$

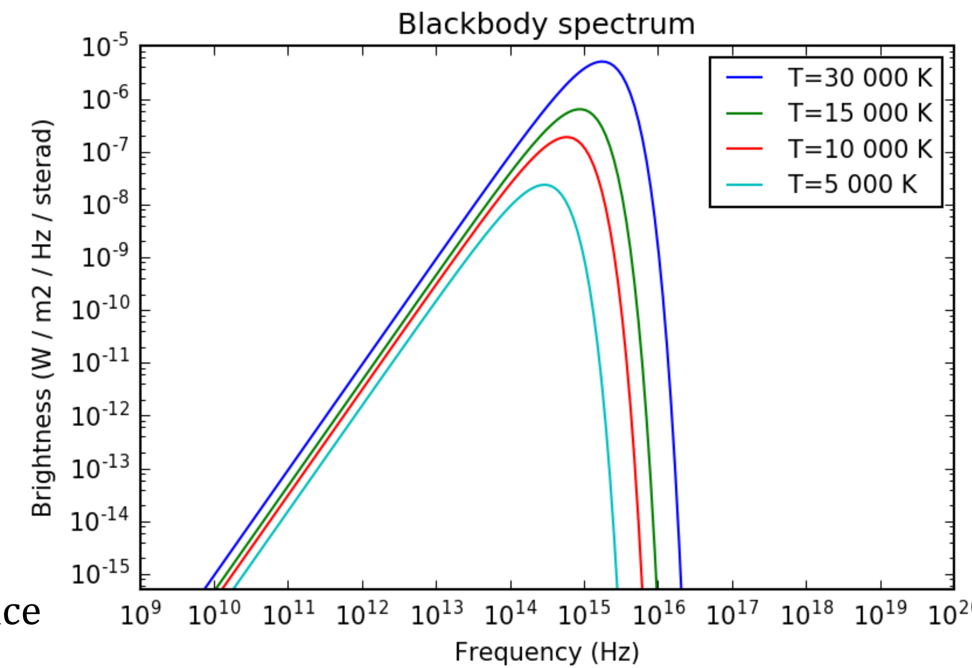
- For simple estimates: $T\,\lambda_{\max} \approx 3 \text{ mm K}$

- Total radiated energy (per unit area, across all wavelengths) from **Stefan-Boltzmann law**:

$$j = \sigma T^4$$

- Total radiated energy over a closed surface surrounding the emitter:

$$L = 4\pi r^2\, \sigma T^4$$

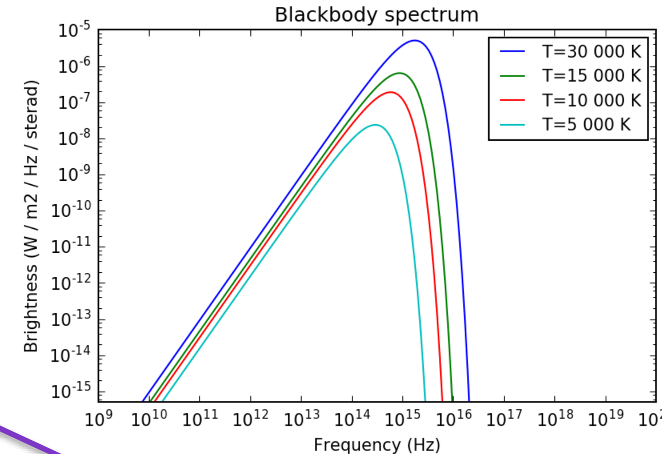


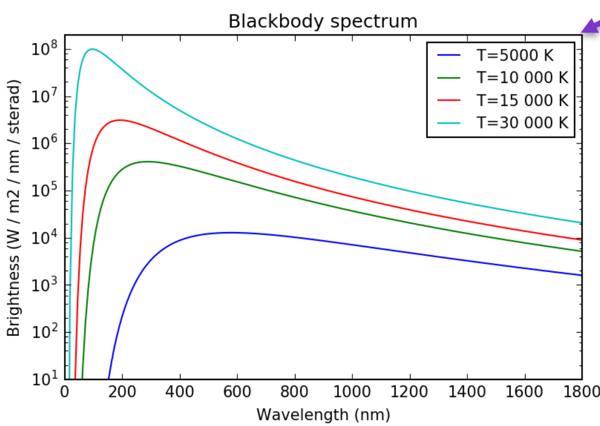
Wien's displacement constant: $b \cong 2.898 \times 10^{-3}$ m K
Stefan-Boltzmann constant: $\sigma \cong 5.671 \times 10^{-8}$ W m^{-2}K^{-4}

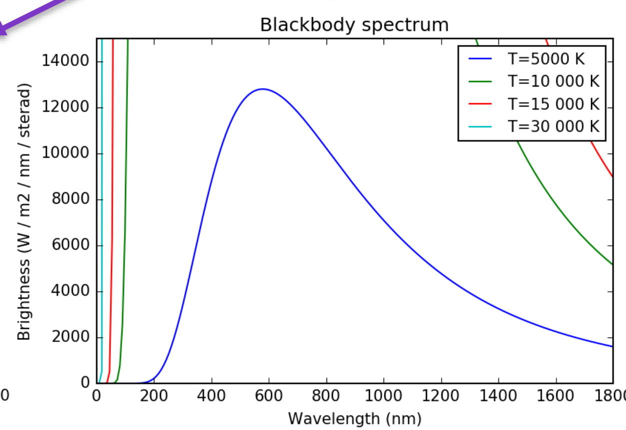
Blackbody radiation

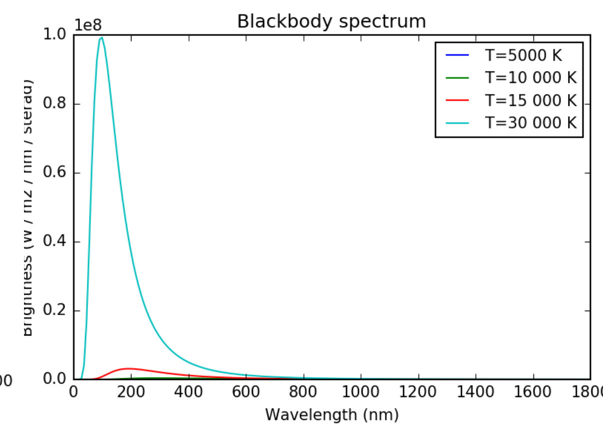
- **Caution:** Equations using frequency and wavelength are not simply inverese of each others even though $\nu = \frac{c}{\lambda}$ & $\lambda = \frac{c}{\nu}$.
- Same spectrum looks completely different when plotted differently. Some use I_ν, some I_λ, learn to use and like both.
- Also:
  - Linear vs. logarithmic
  - *lin-lin, lin-log, log-lin, log-log*

Same source









Blackbody radiation

- Planck's law: $I_\nu(\nu,T) = \frac{2h\nu^3}{c^2} \boxed{\frac{1}{e^{\frac{h\nu}{k_B T}}-1}}$
- In many case we are well above/below the peak frequency, and can use simpler approximations:
  - **If $h\nu \gg kT$**, then $\frac{1}{e^{\frac{h\nu}{k_B T}}-1} \approx e^{\frac{h\nu}{k_B T}}$

    and $I_\nu(\nu,T) \xrightarrow{h\nu \gg kT} \frac{2h\nu^3}{c^2} e^{\frac{-h\nu}{k_B T}}$
  - **If $h\nu \ll kT$**, then $e^{\frac{h\nu}{k_B T}} \approx 1 + \frac{h\nu}{k_B T}$

    and $I_\nu(\nu,T) \xrightarrow{h\nu \ll kT} \frac{2\nu^2 k_B T}{c^2}$

- High frequencies (or low temperatures): **Wien law / formula**, for $h\nu \gg kT$

$$I_\nu(\nu,T) = \frac{2h\nu^3}{c^2} e^{\frac{-h\nu}{k_B T}}$$

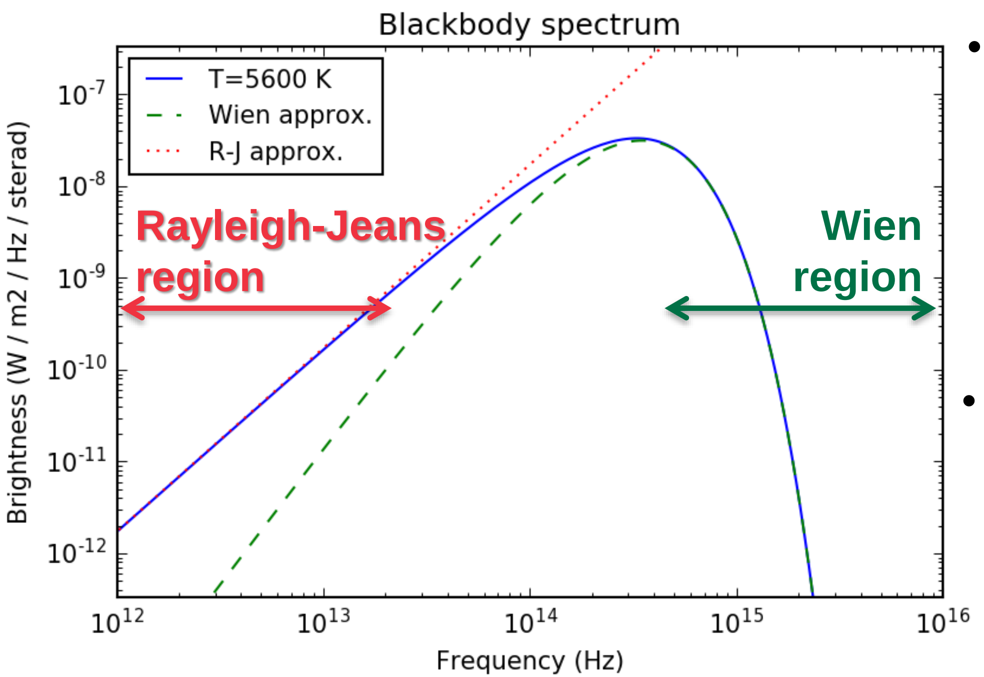
$$I_\lambda(\lambda,T) = \frac{2hc^2}{\lambda^5} e^{\frac{-hc}{\lambda k_B T}}$$

- Low frequencies (or high temperatures): **Rayleigh-Jeans law / formula**, for $h\nu \ll kT$

$$I_\nu(\nu,T) = \frac{2\nu^2 k_B T}{c^2}$$

$$I_\lambda(\lambda,T) = \frac{2ck_B T}{\lambda^4}$$

Blackbody radiation



- High frequencies (or low temperatures): **Wien approximation**, for $h\nu \gg kT$

$$I_\nu(\nu,T) = \frac{2h\nu^3}{c^2} e^{\frac{-h\nu}{k_B T}}$$

$$I_\lambda(\lambda,T) = \frac{2hc^2}{\lambda^5} e^{\frac{-hc}{\lambda k_B T}}$$

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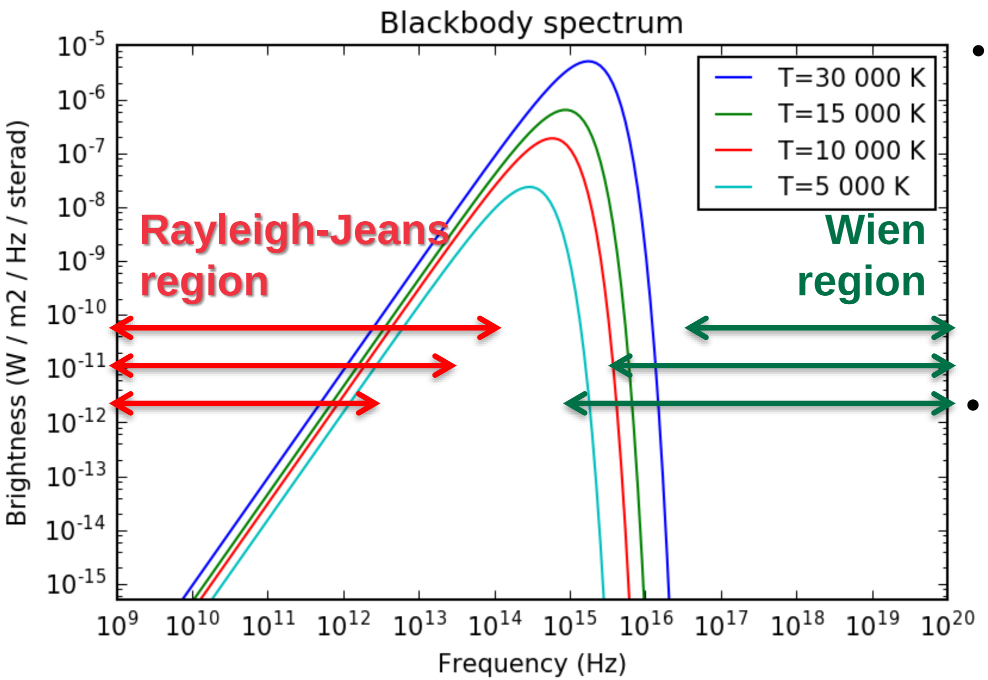
Blackbody radiation



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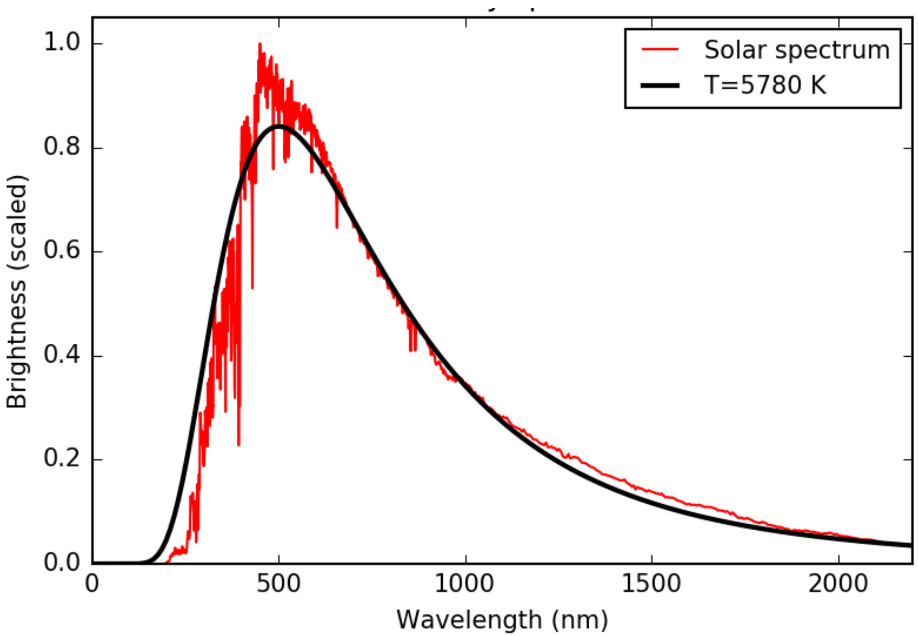
Blackbody radiation

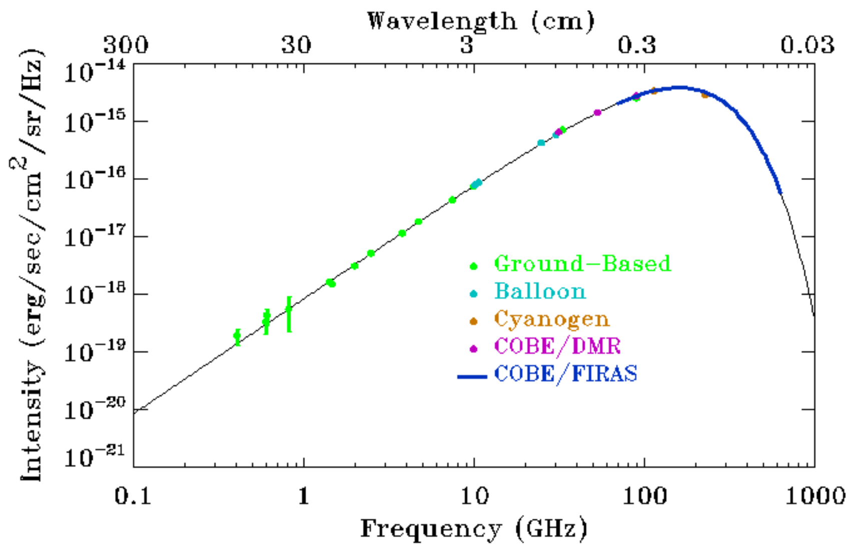
Sun and stars

- $T \approx 5780\ K$



Cosmic Microwave Background

- $T \approx 2.725\ K$



Details: practice session

So far you should be able to answer:

- The Wien displacement law tells us that ______________________________ .
- Rayleigh-Jeans law tells us that the intensity increases as ______________ of the frequency at low frequencies.
- According to Wien law, the intensity _______________ at high frequencies.
- Stefan-Boltzmann law states that the blackbody flux increases as _________.

- Given a BB spectrum, **calculate the temperature** of the source.
- Given the templerature of an object, **calculate/draw the BB spectrum**.

An object radiates blackbody; calculate:

- Peak ν or λ of the spectrum
- Brightness at $\nu \ll \nu_{\mathrm{peak}}$ & $\nu \gg \nu_{\mathrm{peak}}$
- Total energy radiated
- Total flux density
- Total luminosity

A small radio telescope can detect sources that are brighter than 1 Jy at 15 GHz. Can it detect Mars?
(Needed/given information: Mars' apparent size on the sky and distance from the Sun, Sun's temparature.)

Aalto University
School of Electrical
Engineering

End of lecture 1:
Radiation and thermal emission

Next week lecture 2:
Blackbody recap, Non-thermal emission mechanisms