AGA5802
Astrofísica Observacional

- **Astrophysical information:** photons and other messengers. Aspects of the measurements: position, flux/intensity, variability, spatial resolution, spectral resolution, spectral coverage, polarization, S/N.

Bibliography: Astronomy Methods, To Measure the Sky, Lena, ...

Prof. Jorge Meléndez

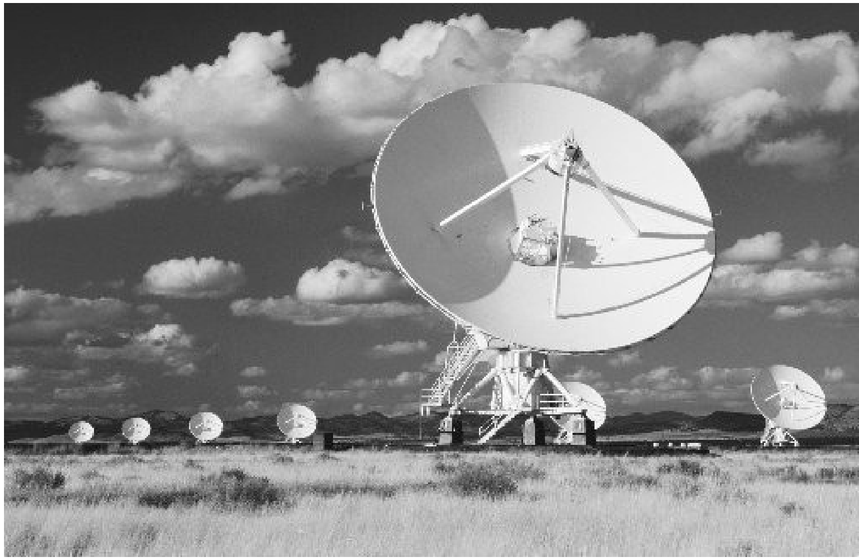
Observational Astrophysics: points to discuss in class today

- Different regions of the spectrum
- What is the continuum/line of the spectrum?
- Define solid angle
- Do we observe specific intensity or flux?
- Parameter space of observations: λ, spatial & time resolution, intensity/flux, polarization

Photon astronomy

- **Most astrophysics is based on fotons (electromagnetic waves)**

VLA

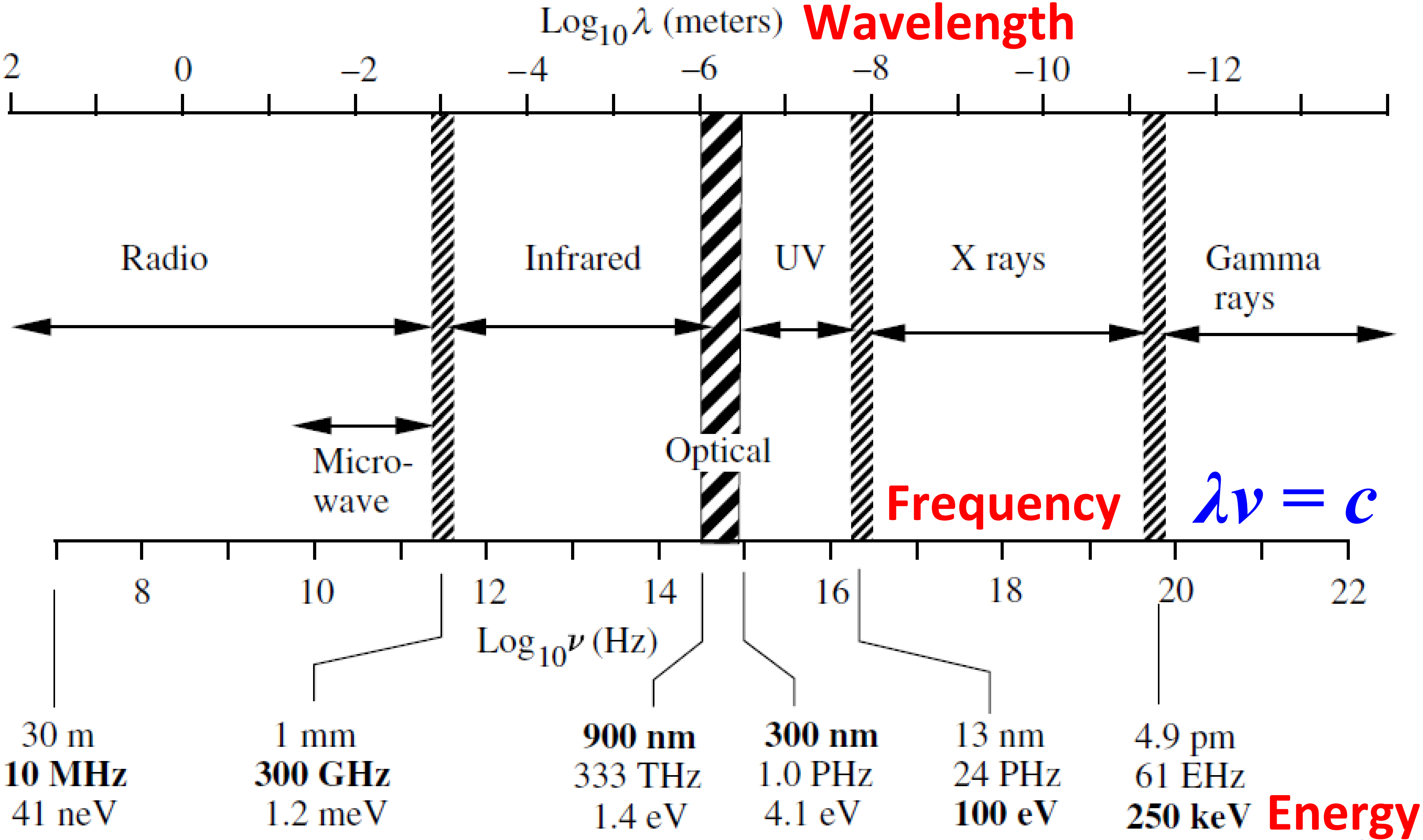


Gemini North

Gregor 1.5m
solar telescope
Tenerife

Compton gamma-ray observatory

Electromagnetic spectrum



Wavelength

Frequency $\lambda\nu = c$

Energy $E = h\nu$

Figure 2.1. The approximate "bands" of the electromagnetic spectrum. The boundaries are not well defined. Radio waves extend further to the left, but the earth's ionosphere is opaque for the most part below about $\nu = 30$ MHz. Gamma rays extend to the right by many more factors of 10. Values of the boundaries are given in several units below the figure. Among these, commonly used values are shown in boldface. Note that 1 nm = 10 angstroms.

From Astronomy Methods, H. Bradt

Wavelength (λ), Frequency (ν), Energy (E)

- $\lambda\nu = c$

c : speed of light in a vacuum,

$c = 2.9979 \times 10^{8}$ m/s ≈ 3.0×10^{8} m/s

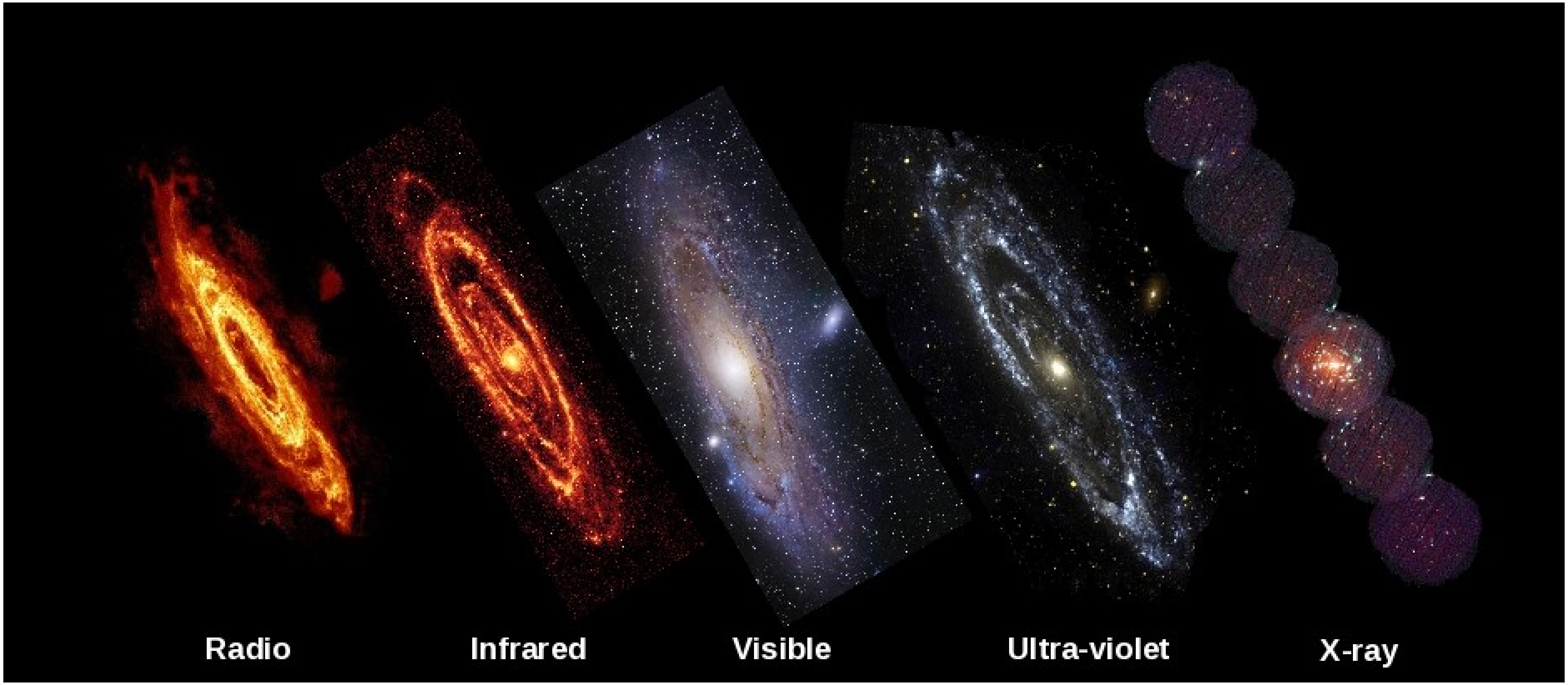
- 1 μm = 10 000 Å (infrared/optical)
- 1 nm = 10 Å (x ray)
- Wavenumber $\sigma = 1/\lambda$ (usually in cm^{-1})
- Angular wavenumber $k = 2\pi/\lambda$

- $E = h\nu$ (J), $h = 6.626\,069 \times 10^{-34}$ J s (Planck constant)

- 1 eV = $1.602\,176 \times 10^{-19}$ J

From Astronomy Methods, H. Bradt

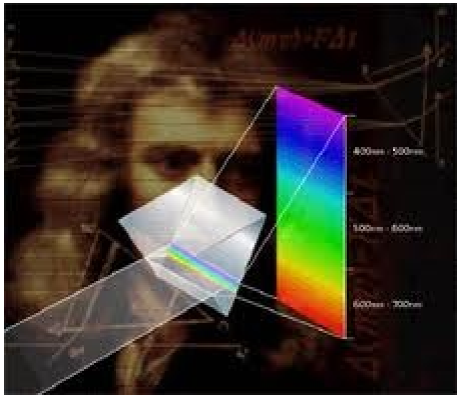
Multi-wavelength Astronomy



HOT → short wavelength
COLD → long wavelength

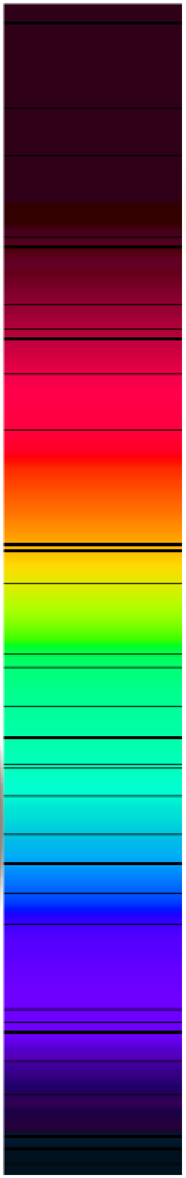
http://planck.cf.ac.uk/science/mm-wave-astronomy

Continuous (optical) spectrum



Newton (1666)

Line spectrum



Joseph von Fraunhofer
(1787-1826)

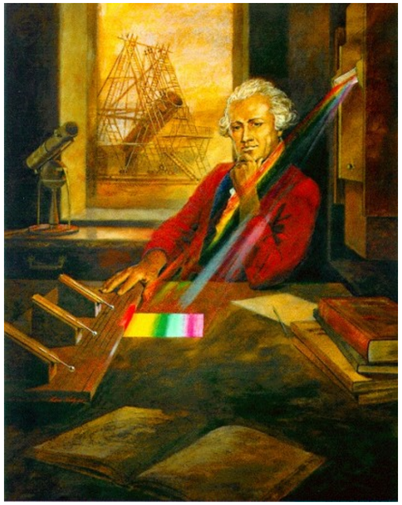
Fraunhofer
(1817)
574 lines

William Hyde Wollaston
(1766-1828)

Wollaston
(1802)
7 lines

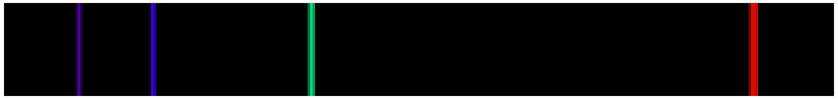
Infrared spectrum

William Herschel (1800)

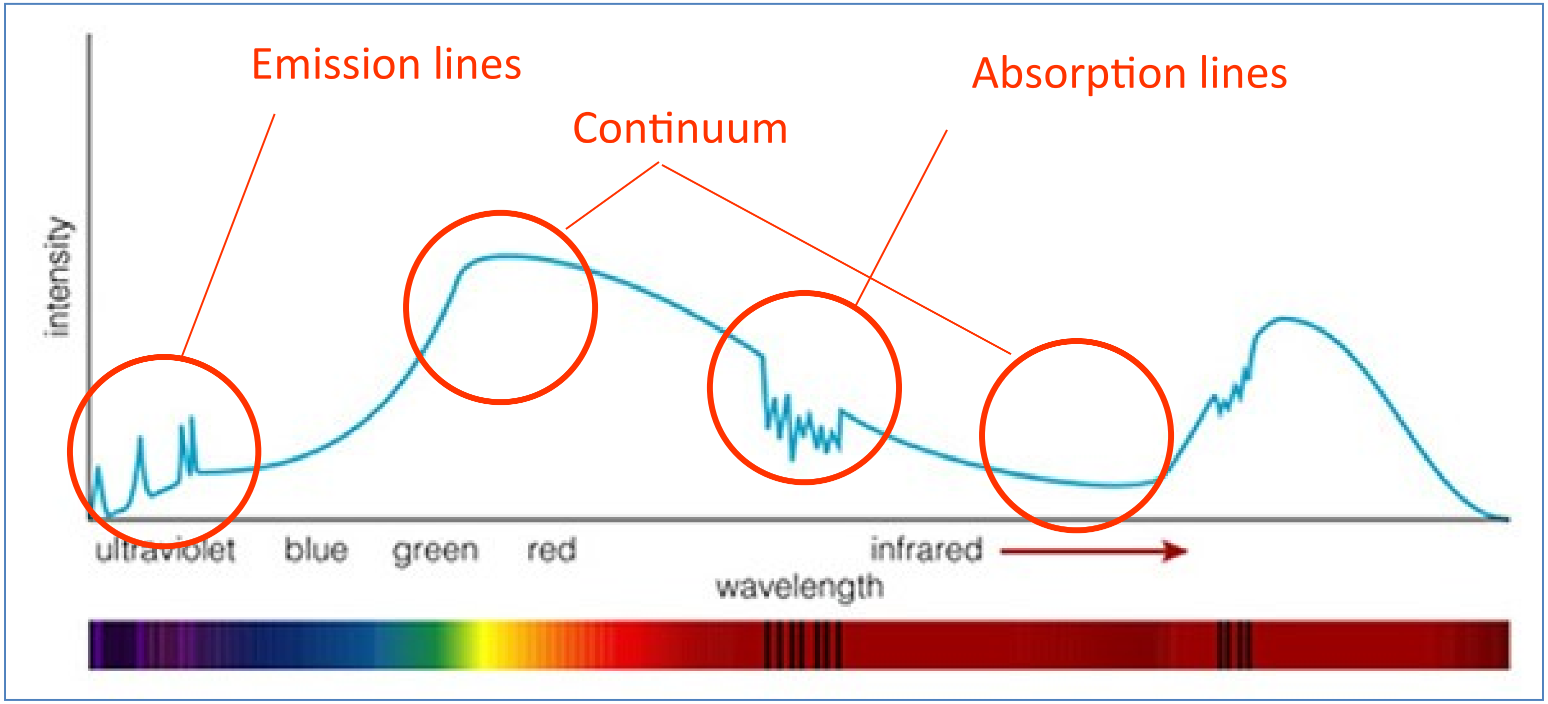


Emission spectrum

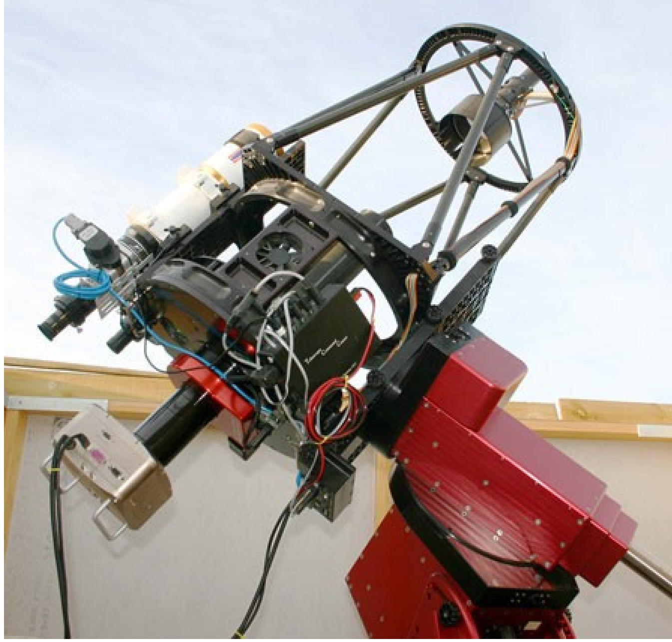
John Herschel (son of William) and
William Henry Fox Talbot, 1820s



A Spectrum:
Flux (or **Intensity**) vs. Wavelength



Monocromatic flux F_λ or F_ν



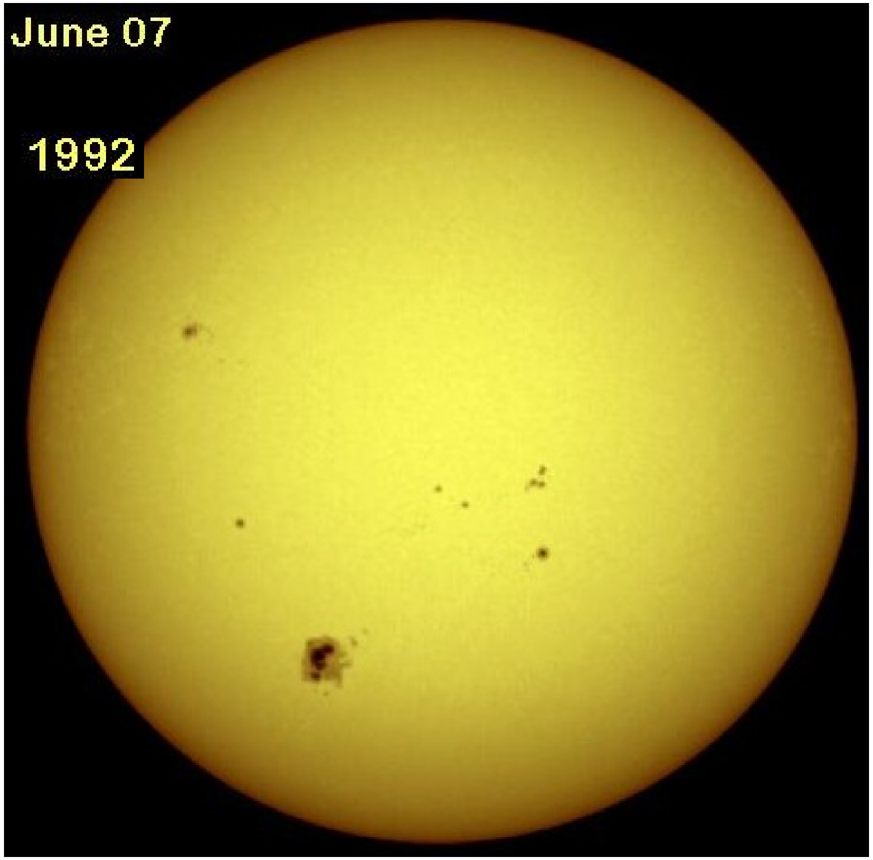
Usually we measure flux (through counts in the detector), the amount of energy collected from a source

$$F_\lambda = \frac{energia}{\Delta A\, \Delta t\, \Delta\lambda}$$

The flux F_λ (or F_ν) is the *amount of energy per unit of time passing through a unit area per unit interval of wavelength (or frequency)*

Units: erg m^{-2} s^{-1} nm^{-1} Or: erg m^{-2} s^{-1} Hz^{-1}

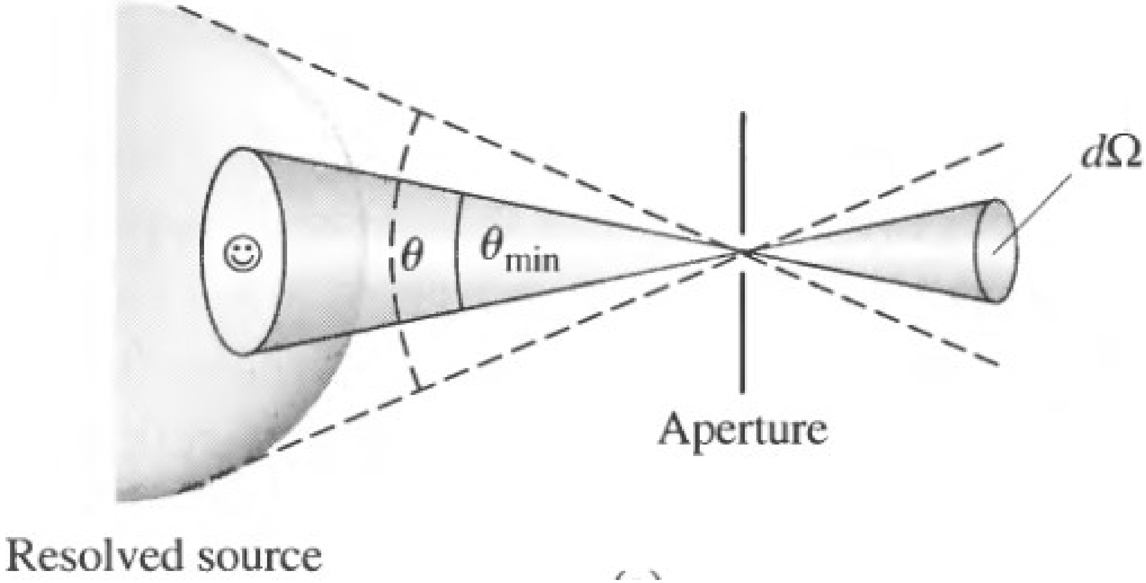
Measurement of energy: Intensity vs. Flux



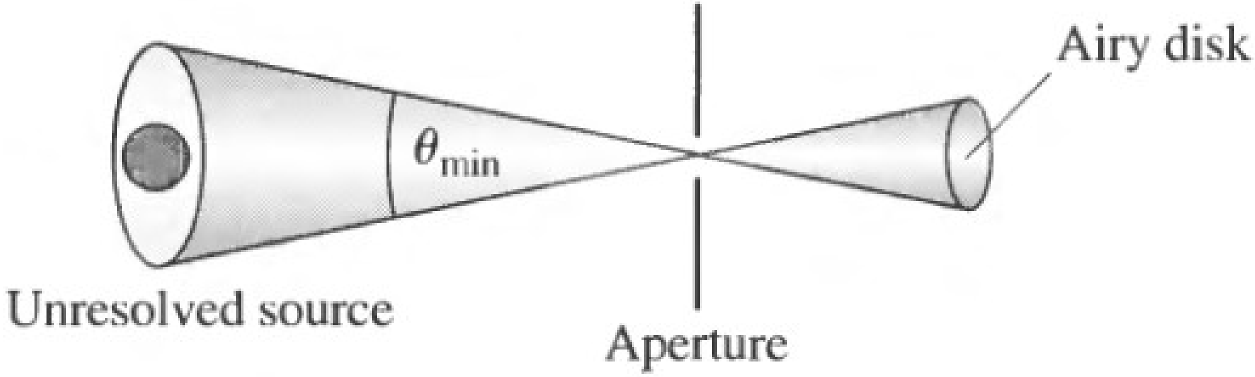
http://solarscience.msfc.nasa.gov/surface.shtml

http://www.twanight.org/newtwan/photos.asp?ID=3001503

Resolved source: measurement of **specific intensity**



Unresolved source: measurement of **flux**



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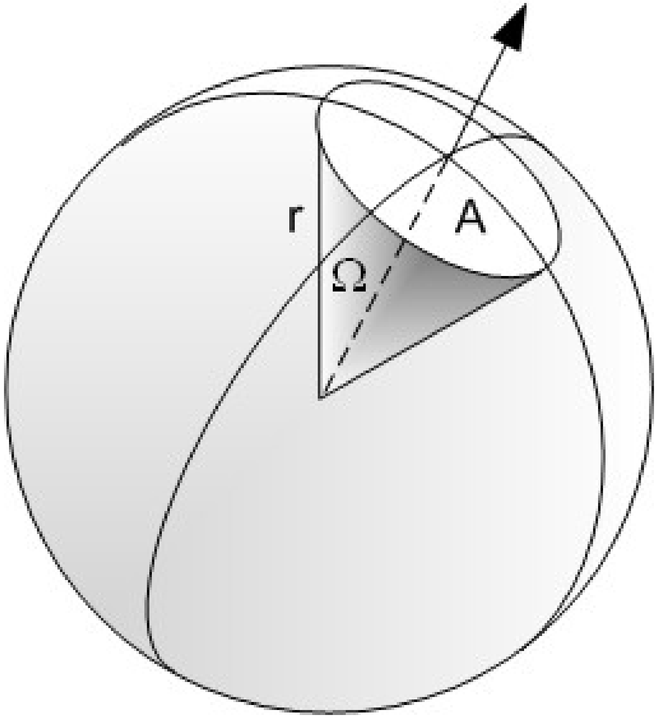
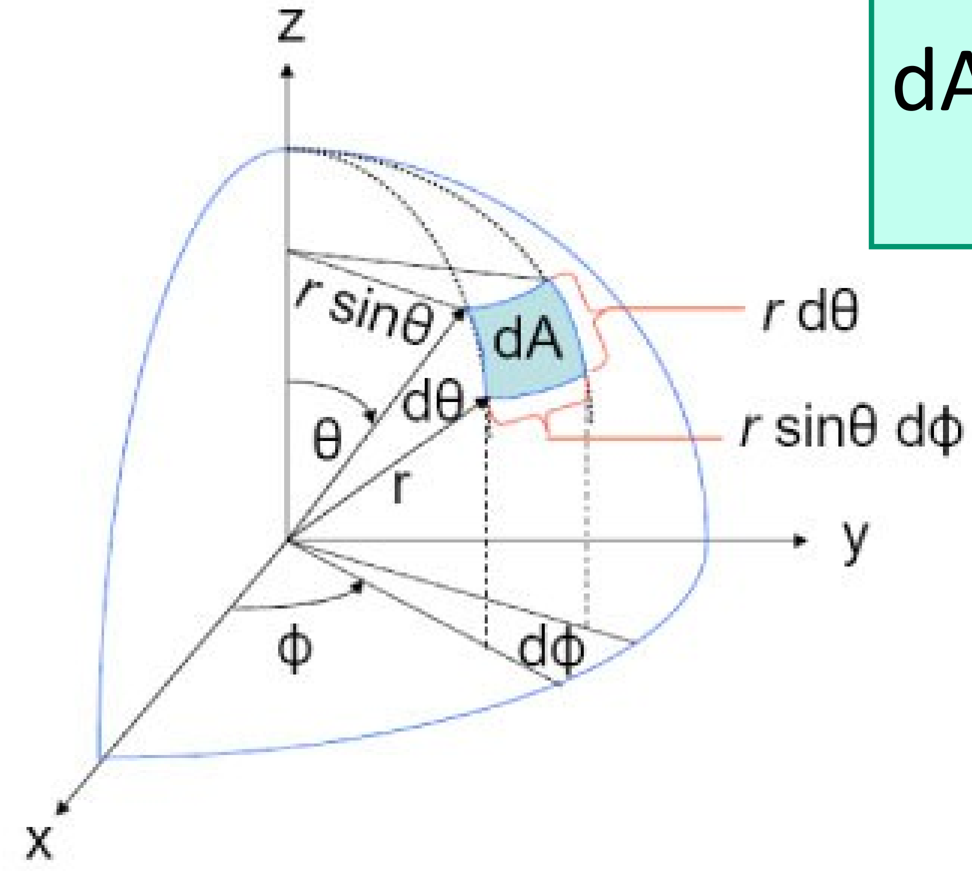
Solid angle

angle subtended by an object of area *A* at a distance *r*



$$\Omega = A/r^2$$

Solid angle in spherical coordinates

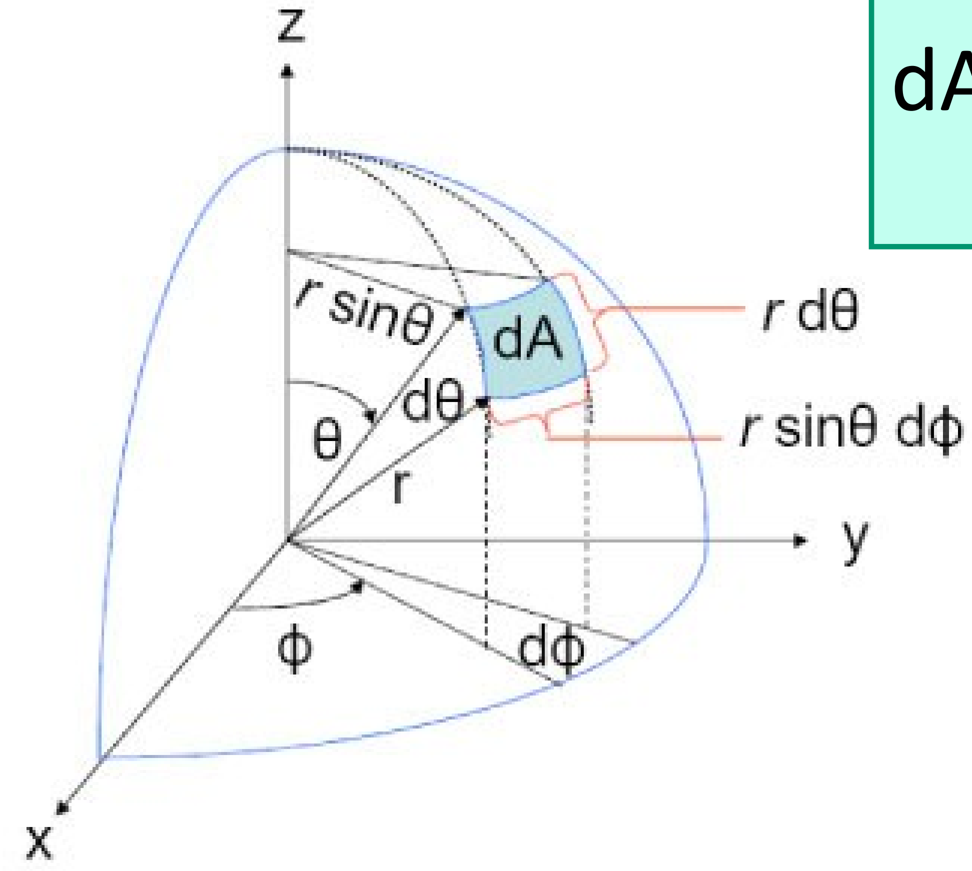


differential area

$$dA = (r\, d\theta)\,(r\, \mathrm{sen}\theta\, d\phi) = r^2\, \mathrm{sen}\theta\, d\theta\, d\phi$$

$$\Omega = A/r^2$$

Solid angle in spherical coordinates



differential area

$$dA = (r\, d\theta\ )\ (r\ \mathrm{sen}\theta\ d\phi\ )$$
$$= r^2\ \mathrm{sen}\theta\ d\theta\ d\phi$$

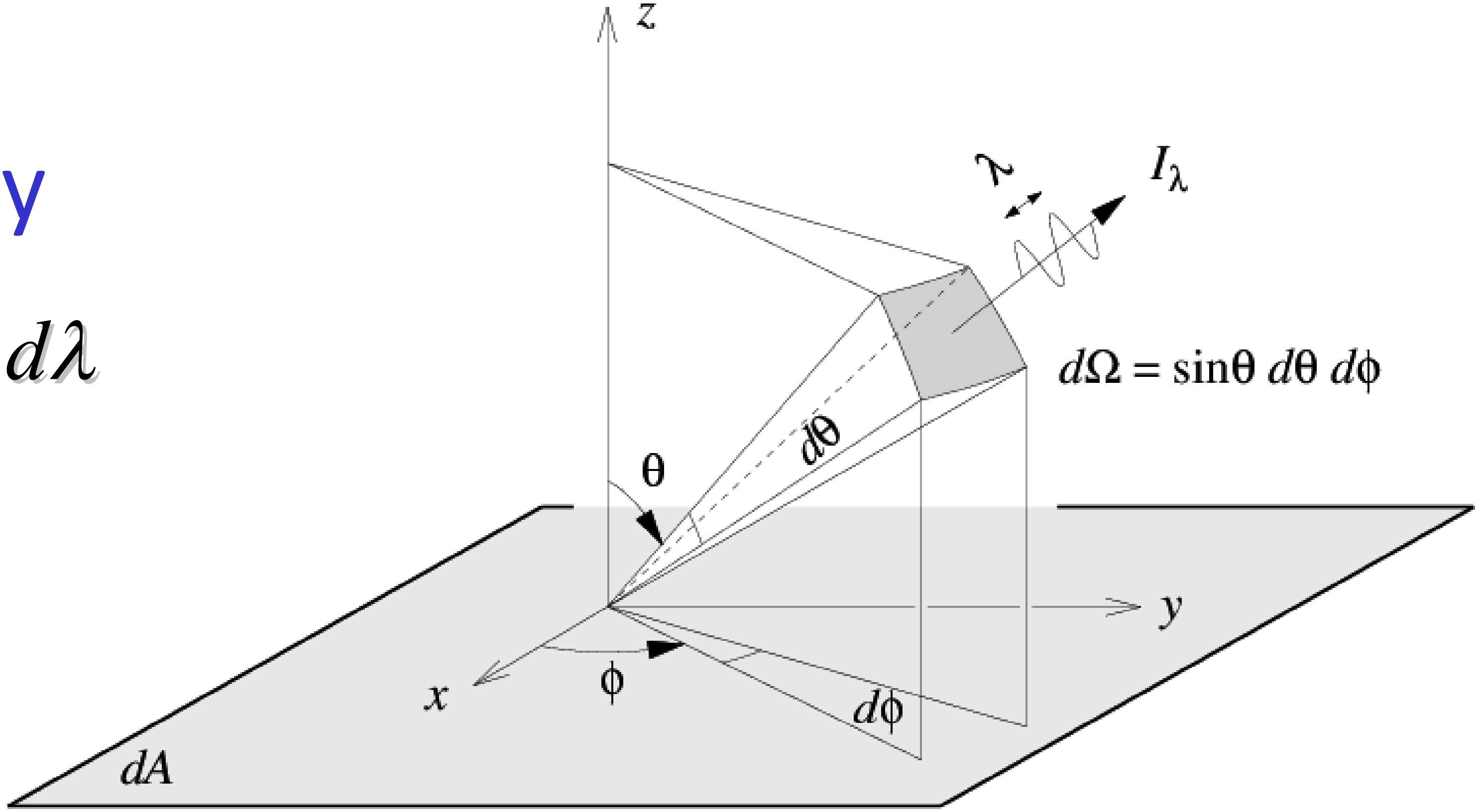
$$\Omega = A/r^2$$

Differential solid angle subtended by area dA:

$$d\Omega = \mathrm{sen}\theta\ d\theta\ d\phi$$

Specific intensity

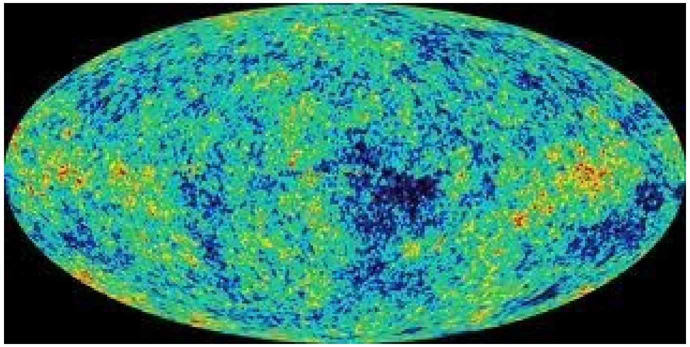
$$I_\nu \, d\nu = I_\lambda \, d\lambda$$



$$I_\nu = \lim_{dA\,d\Omega\,d\nu\,dt \to 0} \left(\frac{\Delta E_\nu}{\cos\theta \, dA \, d\Omega \, d\nu \, dt} \right)$$

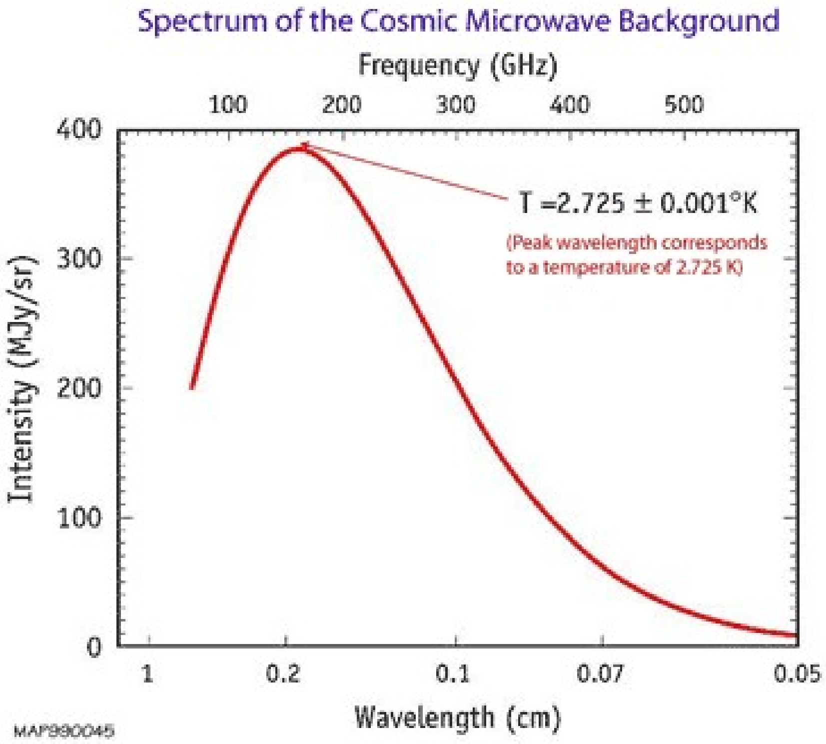
I_ν : energy passing through area $A_\perp$ perpendicular to radiation ($dA\cos\theta$), per unit $d\Omega$, per unit in frequency interval ($d\nu$), per time unit (dt).

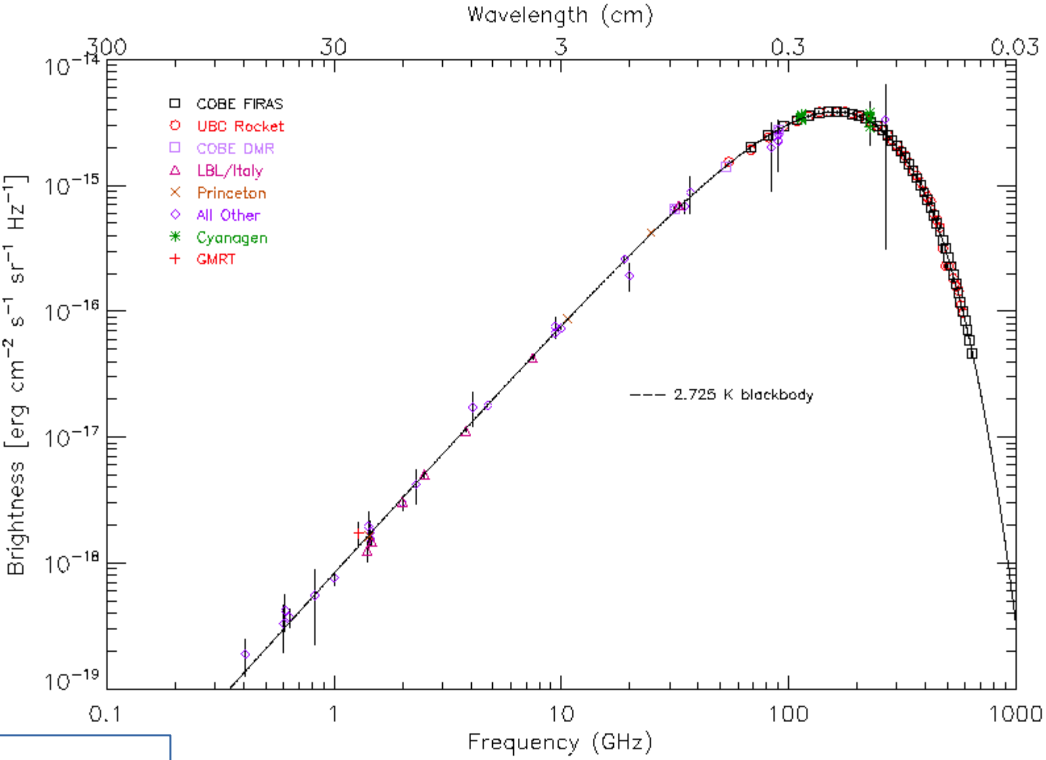
I_ν (erg cm^{-2} sr^{-1} Hz^{-1} s^{-1}) , I_λ (erg cm^{-2} sr^{-1} Å^{-1} s^{-1})



Example: CMB is almost a perfect black body

Blackbody: Ideal absorber (absorbs all incident light)





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

Ex. specific intensity: center of the Sun’s disk

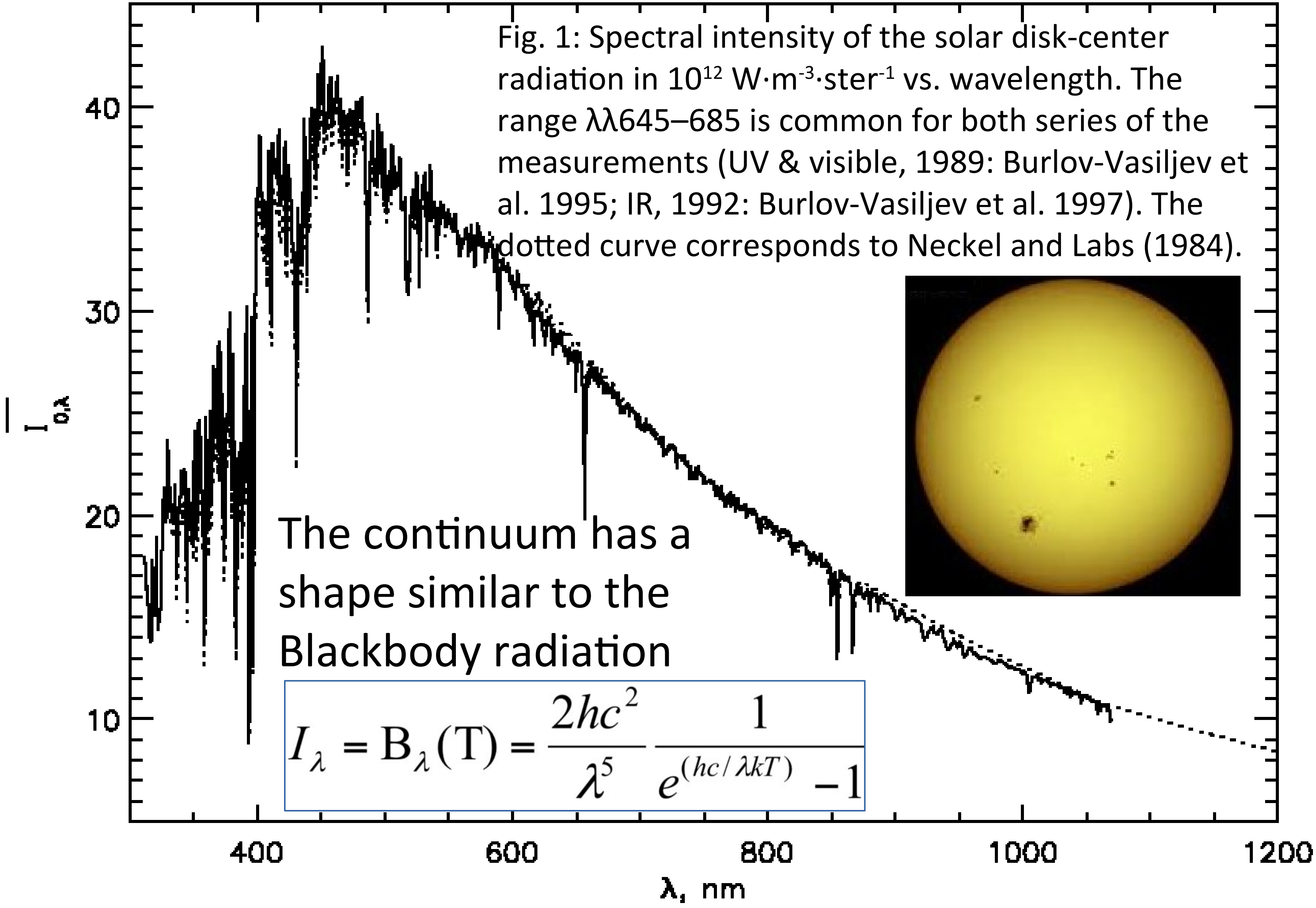


Fig. 1: Spectral intensity of the solar disk-center radiation in 10^{12} W·m^{-3}·ster^{-1} vs. wavelength. The range λλ645–685 is common for both series of the measurements (UV & visible, 1989: Burlov-Vasiljev et al. 1995; IR, 1992: Burlov-Vasiljev et al. 1997). The dotted curve corresponds to Neckel and Labs (1984).

The continuum has a shape similar to the Blackbody radiation

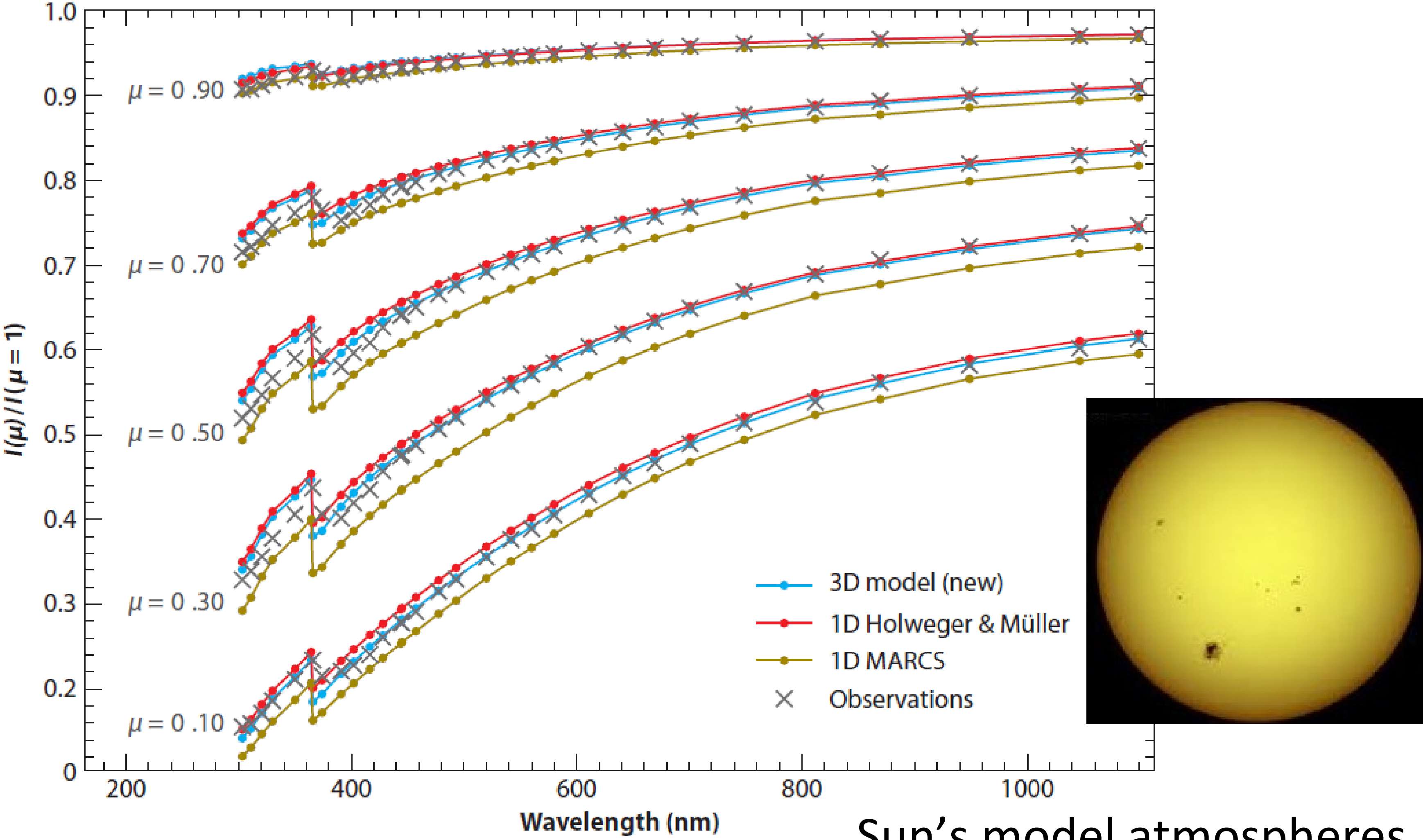
$$I_\lambda = \mathrm{B}_\lambda(\mathrm{T}) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{(hc/\lambda kT)}-1}$$

http://www.mao.kiev.ua/sol_ukr/bmv/bmv_2.html

Sun’s center-limb intensity variation

Martin Asplund,[1] Nicolas Grevesse,[2] A. Jacques Sauval,[3] and Pat Scott[4]

Annu. Rev. Astron. Astrophys. 2009. 47:481–522



Comparison of the predicted continuum center-to-limb variation as a function of wavelength for different solar model atmospheres against observations (Neckel & Labs 1994). The results for five different viewing angles μ are shown from near disk center ($\mu = 0.9$) to close to the limb ($\mu = 0.1$). All intensities are normalized to the corresponding disk-center intensities. The 3D hydrodynamical model (Trampedach et al., in preparation) used in this review outperforms even the Holweger & Müller (1974) semiempirical model, which was designed to satisfy this diagnostic (Pereira et al., in preparation). As for all 1D theoretical model atmospheres, the MARCS (Gustafsson et al. 2008) model has a too steep temperature gradient, which manifests itself in a poor agreement with the center-to-limb variation.

Sun’s model atmospheres can be constrained using C-L intensity observations

Flux F_λ

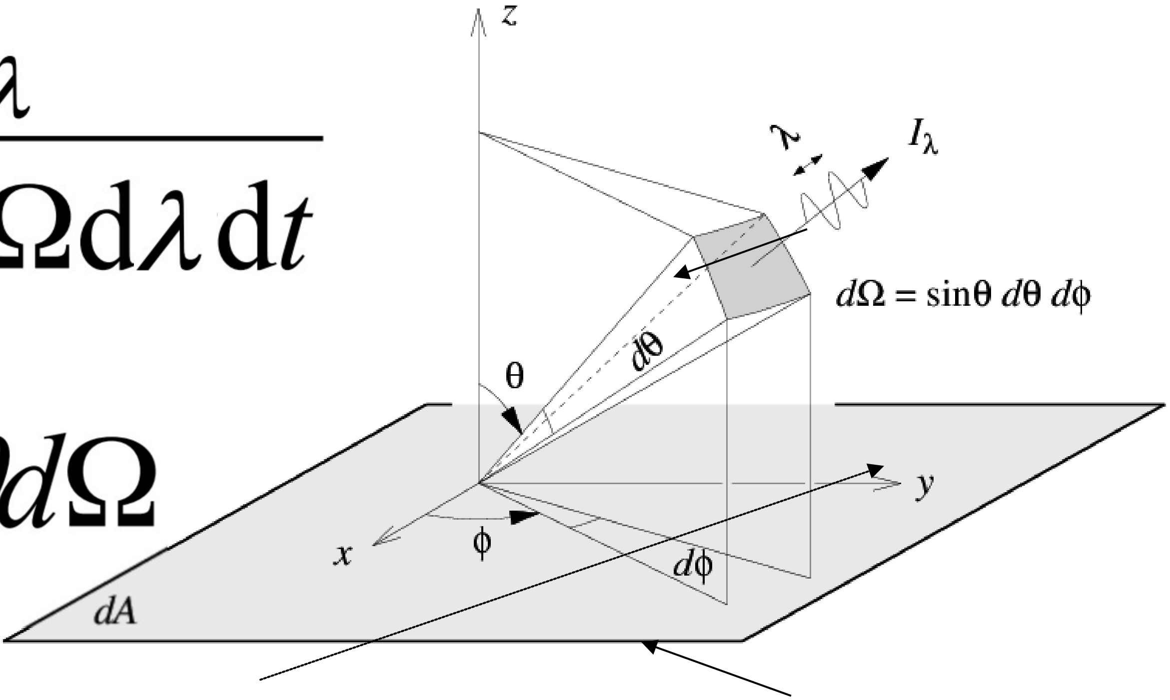
$$F_\lambda = \frac{\sum_{\Omega} \Delta E_\lambda}{\mathrm{d}A\,\mathrm{d}\lambda\,\mathrm{d}t}$$

F_λ : energy passing through an area ($\mathrm{d}A$), per unit of wavelength ($\mathrm{d}\lambda$), per unit of time ($\mathrm{d}t$).

F_ν (erg cm^{-2} Hz^{-1} s^{-1}), F_λ (erg cm^{-2} Å^{-1} s^{-1})

$$I_\lambda = \frac{\Delta E_\lambda}{\cos\theta\,\mathrm{d}A\,\mathrm{d}\Omega\,\mathrm{d}\lambda\,\mathrm{d}t}$$

$$F_\lambda = \int I_\lambda \cos\theta\, d\Omega$$



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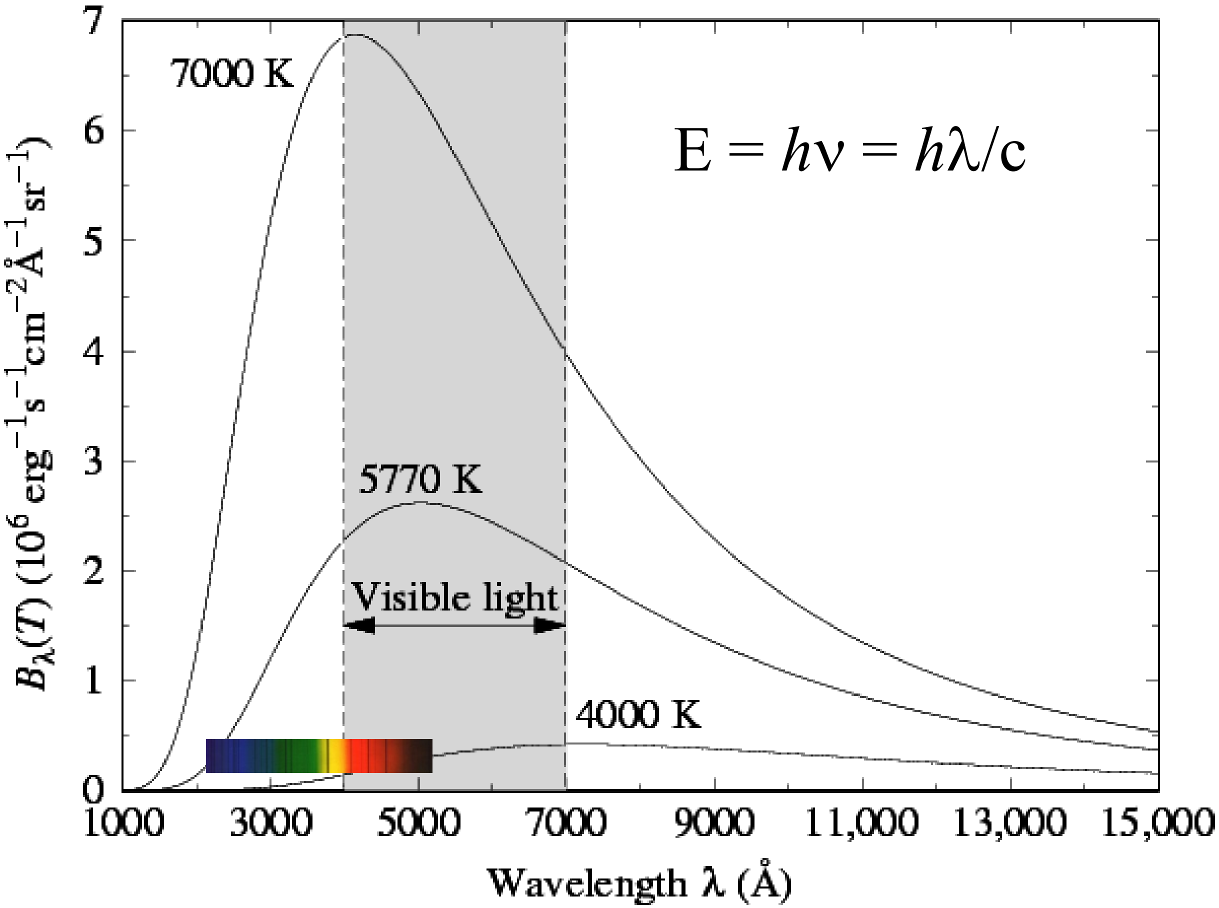
We usually say that stars radiate as a black body (B_λ), but in stars we mostly measure fluxes and not specific intensity ($F_\lambda \neq B_\lambda$).



At the surface of stars: $F_\lambda \sim \pi B_\lambda$

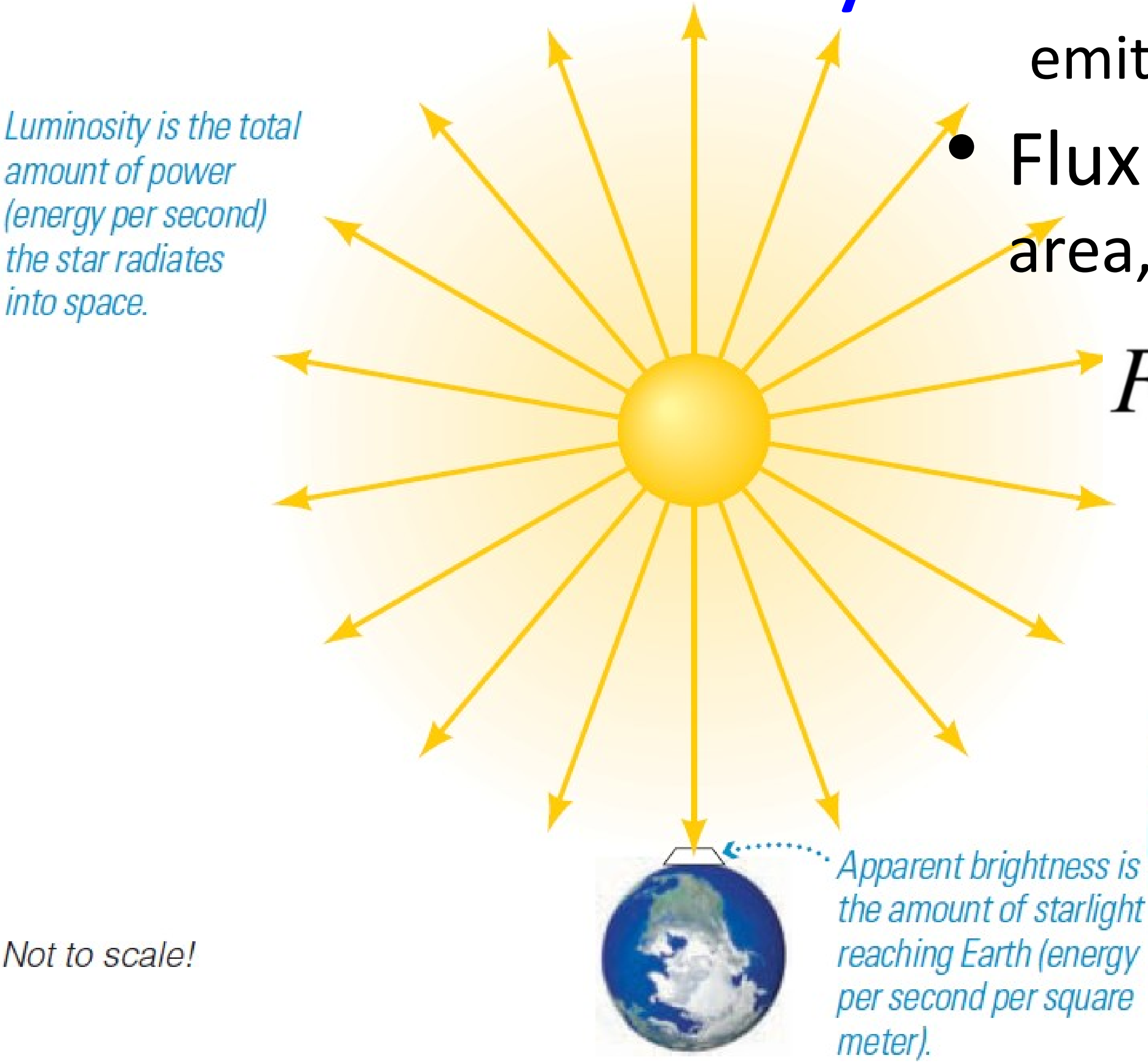
$$I_\lambda = B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{(hc/\lambda kT)} - 1}$$

The Astrophysical Flux F_λ is defined as $F_\lambda = F_\lambda/\pi \rightarrow F_\lambda \sim B_\lambda$

Flux & Luminosity

- Luminosity : energy emitted by time unit
- Flux : Luminosity by unit area, depends on distance

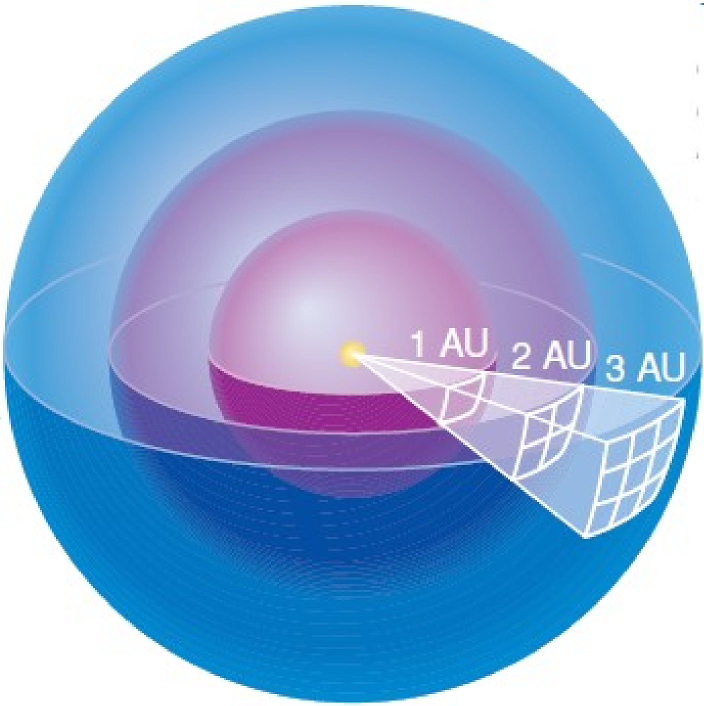
$$F(r) = \frac{L}{4\pi r^2}$$



Luminosity is the total amount of power (energy per second) the star radiates into space.

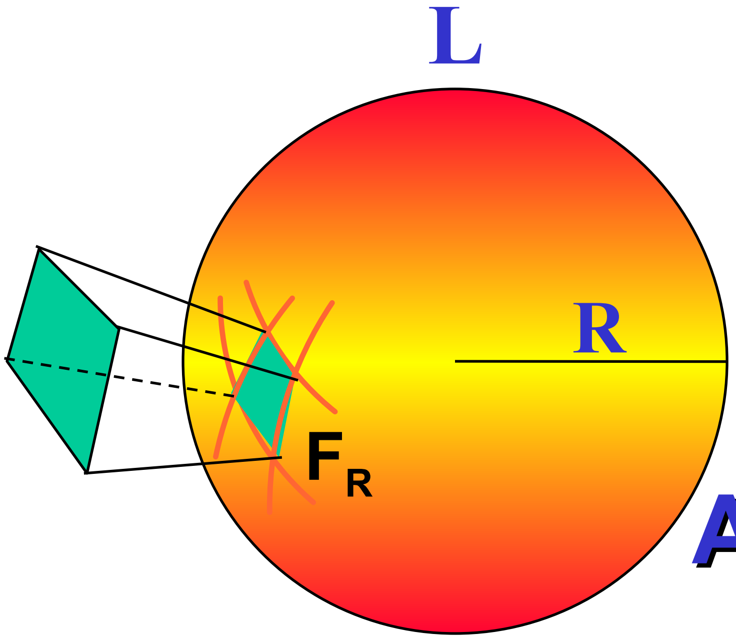
Apparent brightness is the amount of starlight reaching Earth (energy per second per square meter).

Not to scale!



Surface solar flux

Power emitted by the Sun per unit area

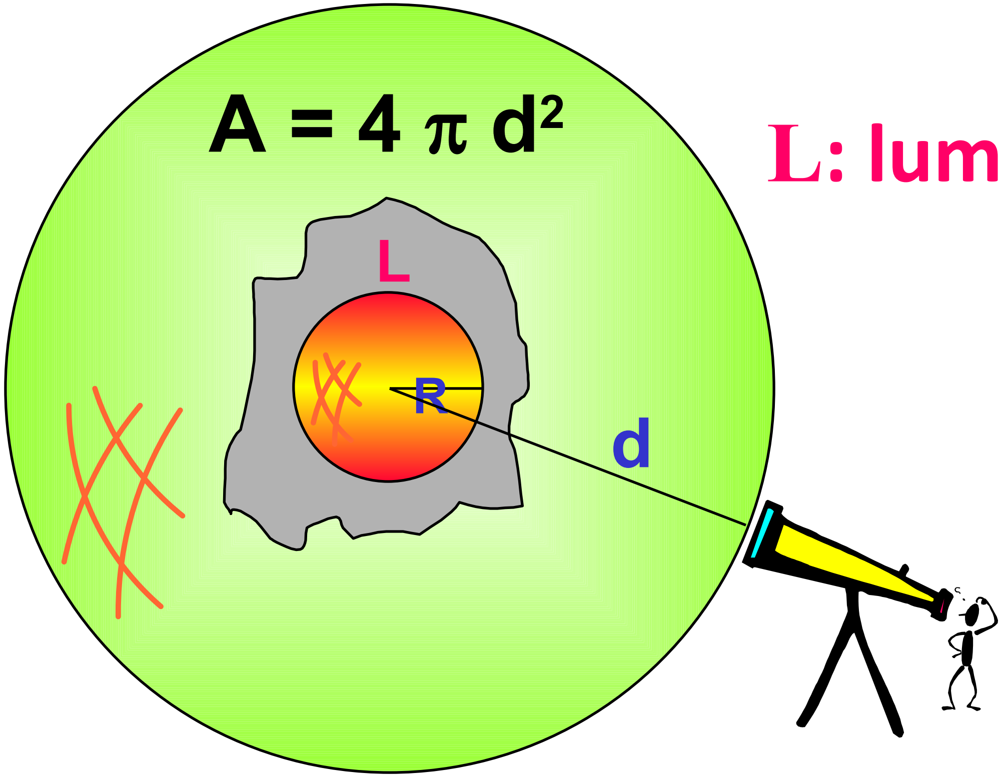


$A_{Surface} = 4\pi R^2$

$$F_R = L / (4\pi R^2)$$

Solar Flux at distance d

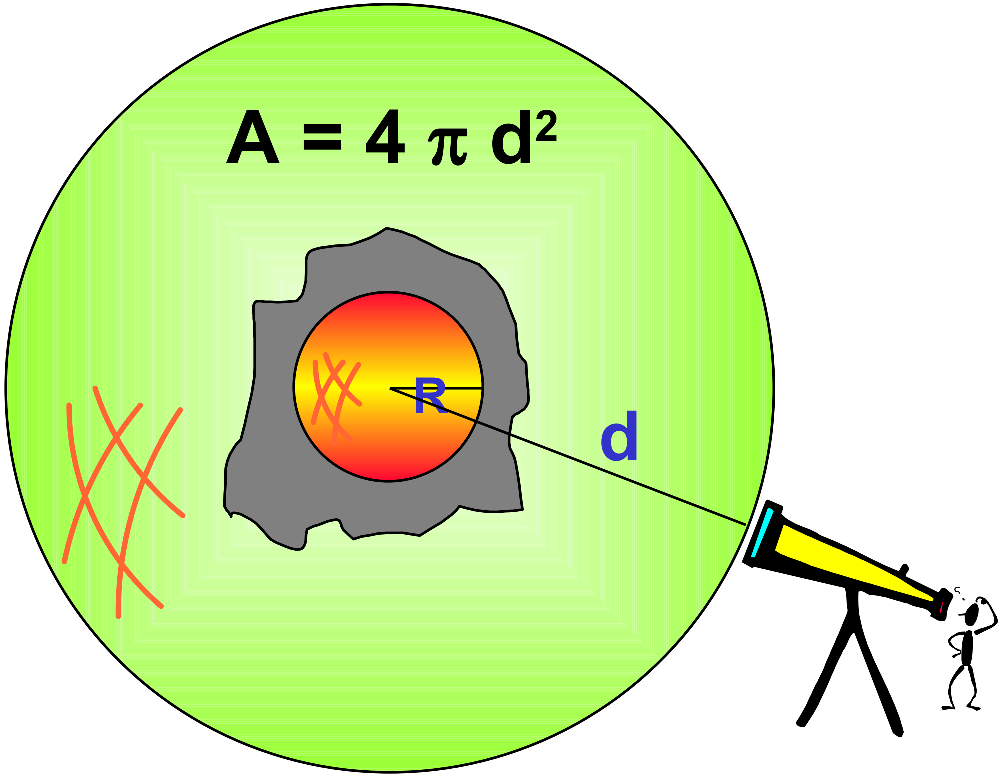
Power per unit area at a distance d from the Sun



L: luminosity

$$f = f_d = L / (4\pi d^2)$$

Variation of Flux as a function of distance d



$$f_d = L / (4\pi d^2)$$

$$F_R = L / (4\pi R^2)$$

$$\boxed{f_d = F_R (R/d)^2}$$

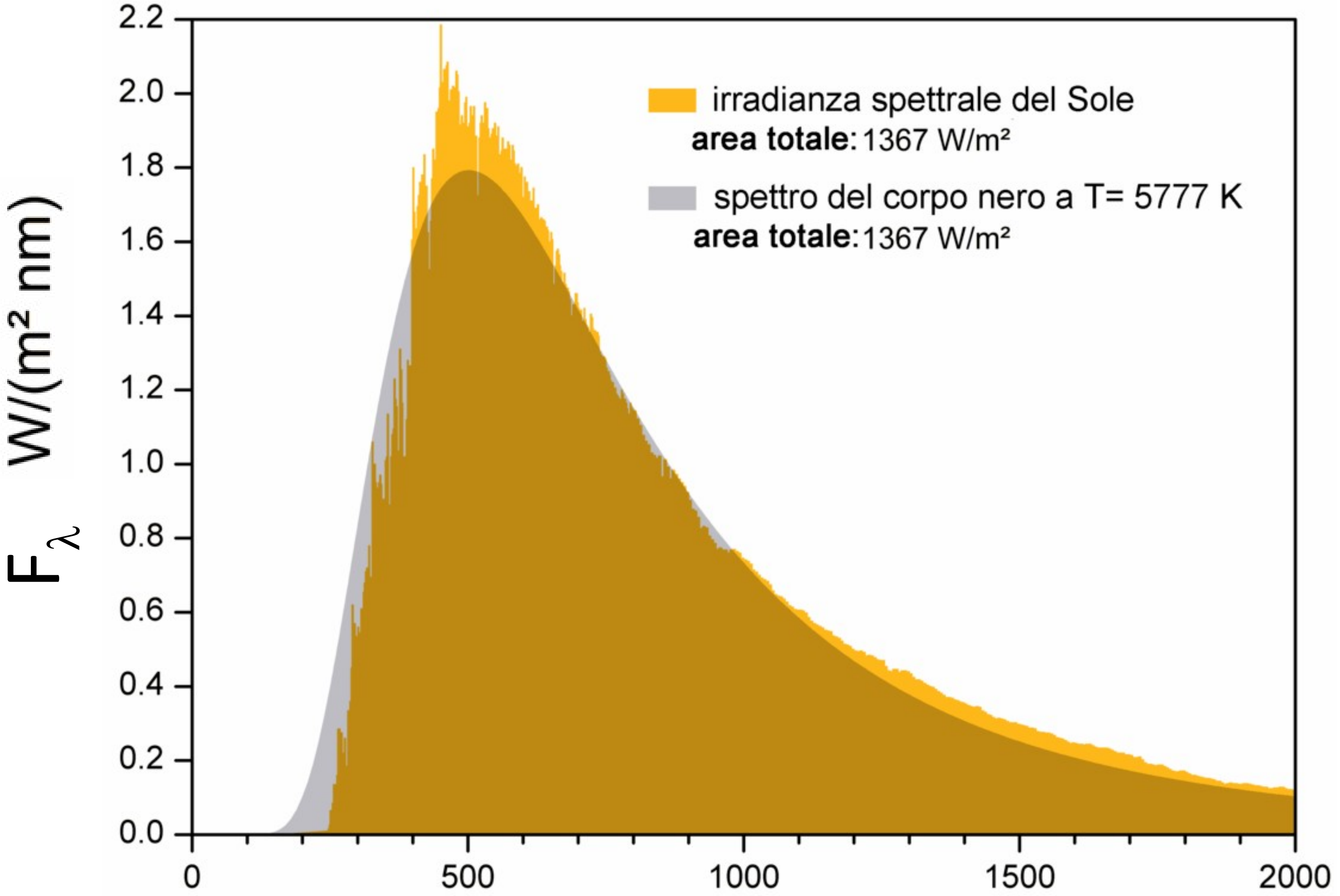
Assuming a star emits roughly as a blackbody:

Flux at surface (radius R): $F_\lambda = \pi B_\lambda$

Flux f_λ at distance d:

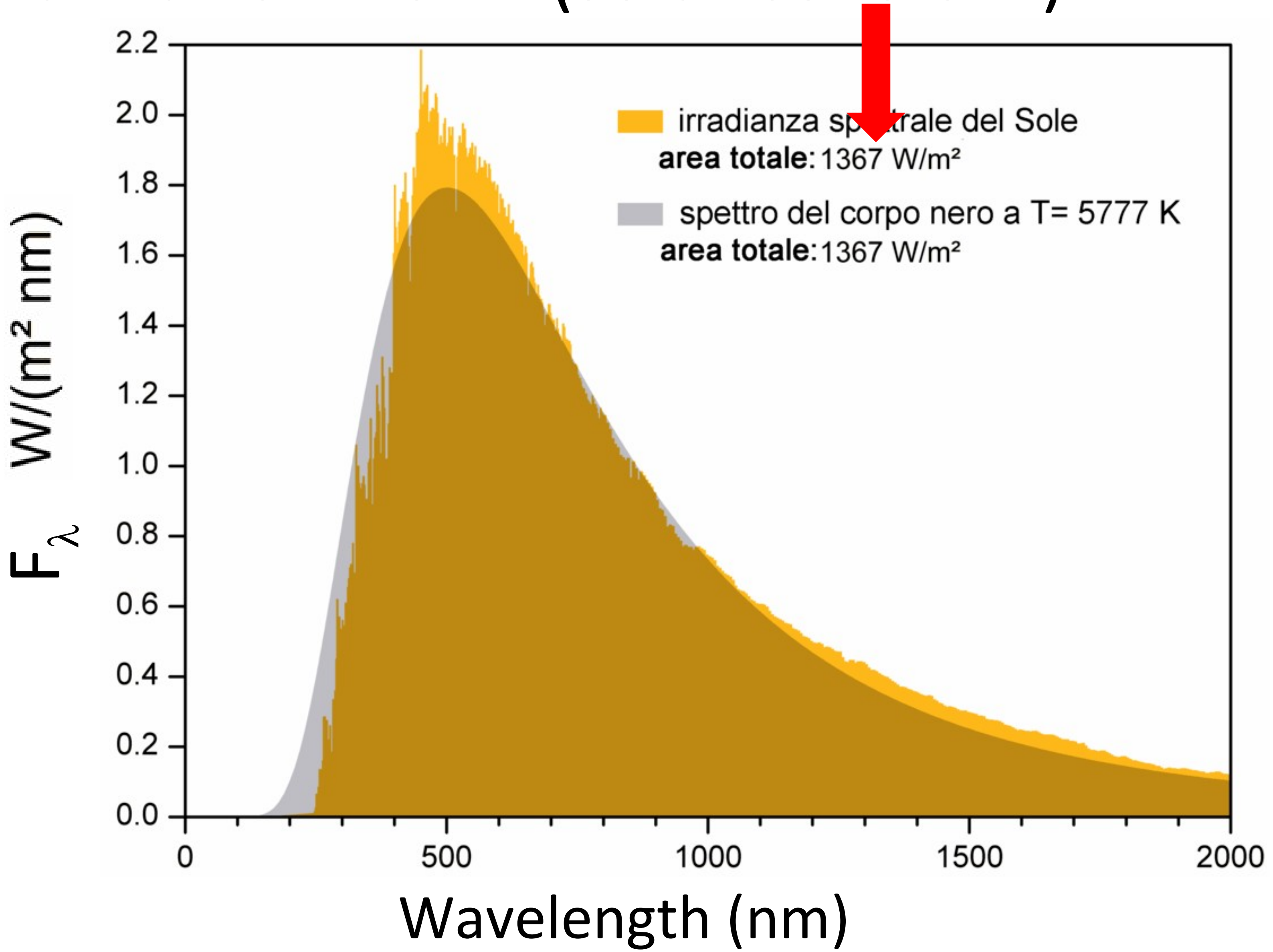
$$f_\lambda = (R/d)^2 F_\lambda = (R/d)^2 \pi B_\lambda$$

Solar Flux at 1 U.A. (spectral irradiance)

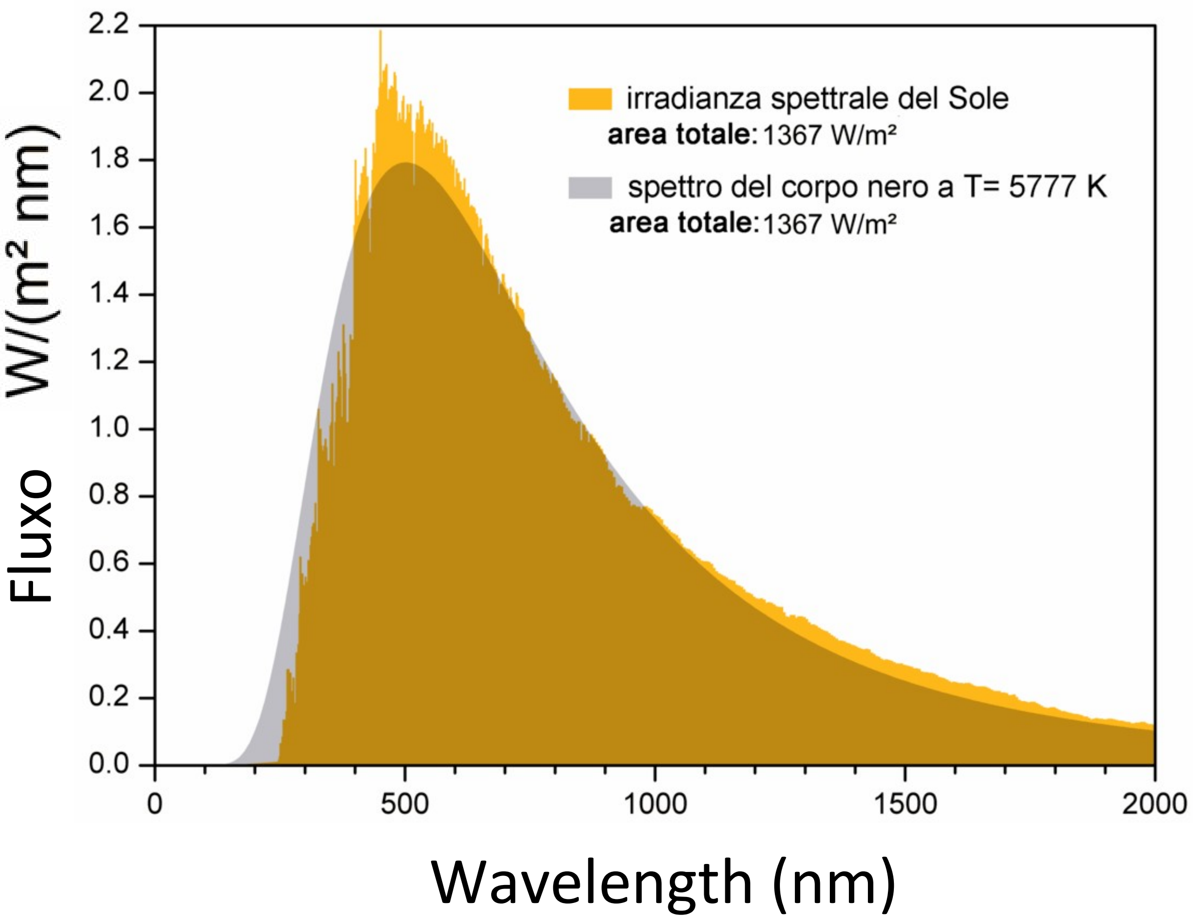


Wavelength (nm)

Total flux at 1 U.A. (solar constant)



Effective temperature (T_{eff}): temperature that a blackbody of the same total flux *F* (at the star surface)



$$F = \sigma T_{eff}^{\ 4}$$

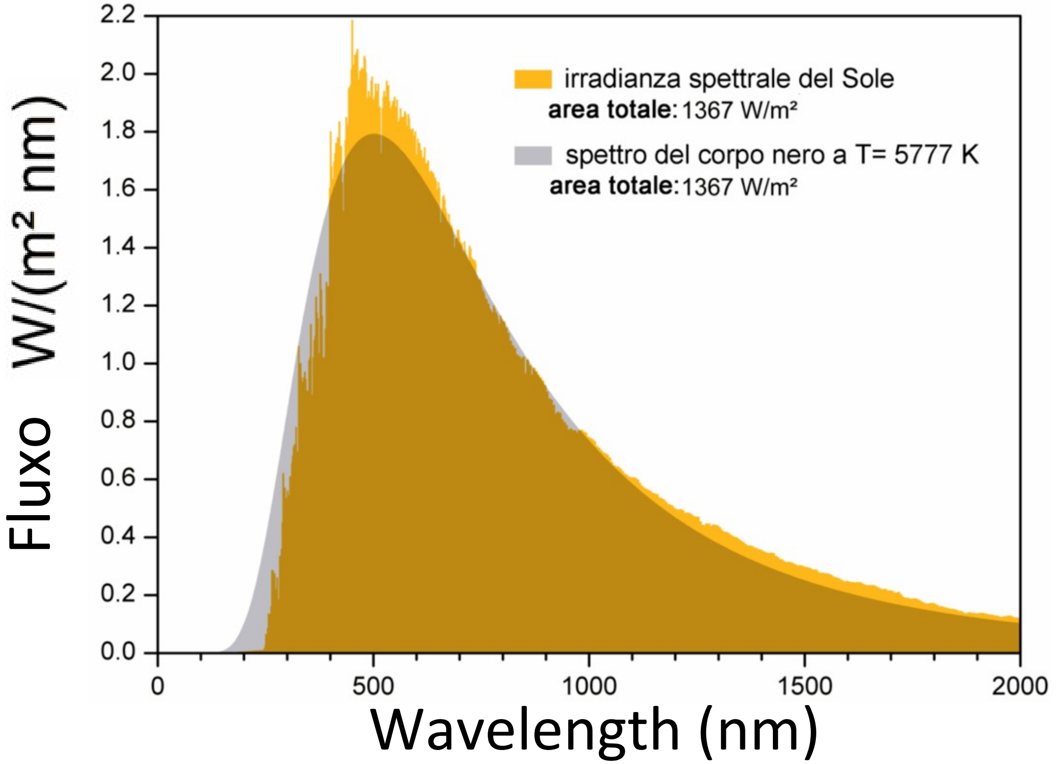
Stefan–Boltzmann law for a blackbody

Wavelength (nm)	Solar Flux above Earth's atmosphere (Wm^{-2} nm^{-1})
300	0.5359
310	0.6220
320	0.7151
330	0.9619
360	0.9759
390	1.0338
420	1.7404
450	2.0050
480	2.0270
510	1.9270
540	1.8980
570	1.8400
610	1.7280
656	1.5240
690	1.4200
740	1.2980
800	1.1480
905	0.8932
948	0.7869
1040	0.6881
1100	0.6062
1200	0.5016
1320	0.4168
1395	0.3589
1520	0.2928
1630	0.2435
1740	0.1908
1860	0.1445
2005	0.1130

Neckel & Labs (1981)

Improved Data of Solar Spectral Irradiance

These are solar fluxes measured at 1 A.U. and corrected for the absorption of the Earth's Atmosphere (fluxes above Earth's atmosphere)



Flux of star 56 Ari

A&A 509, A28 (2010)

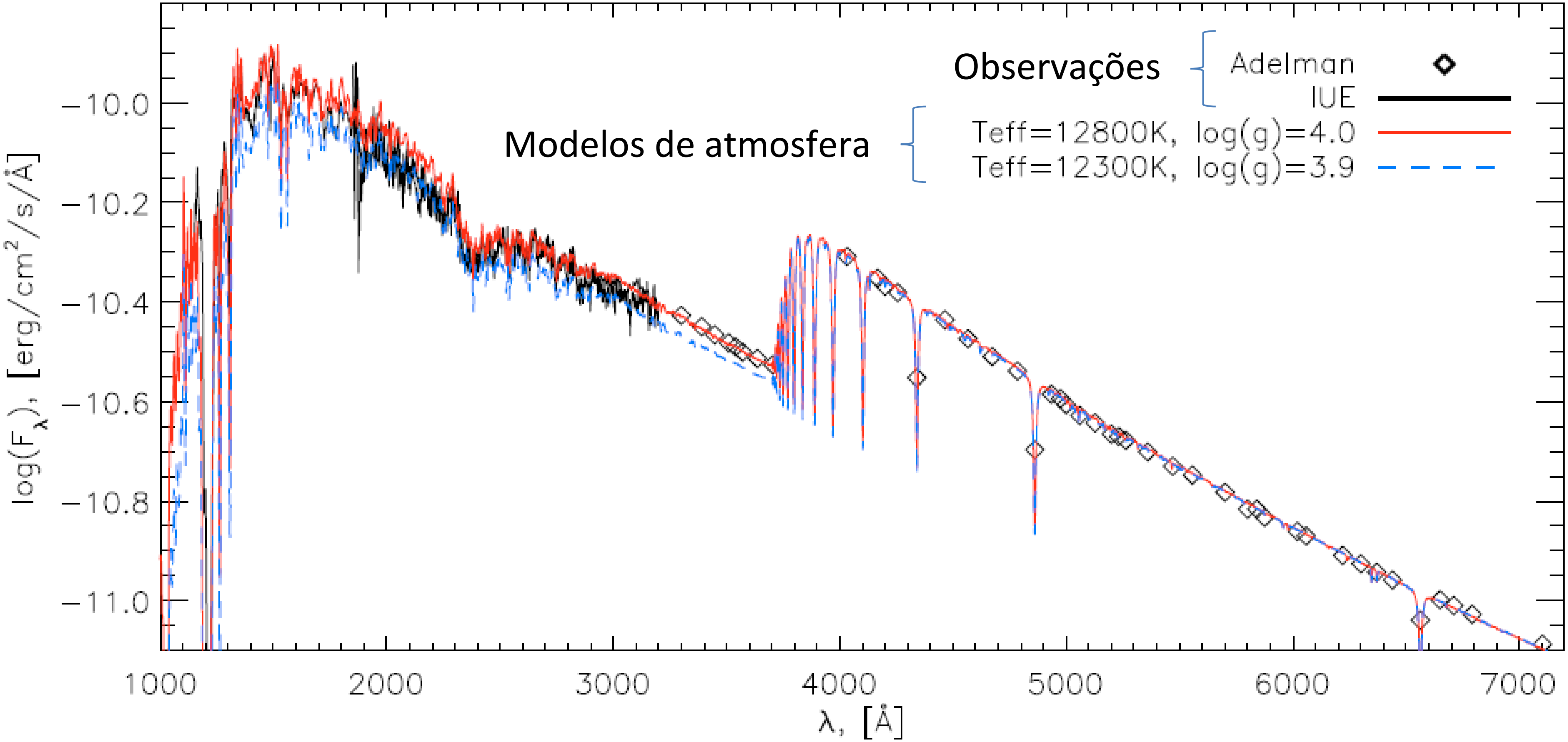
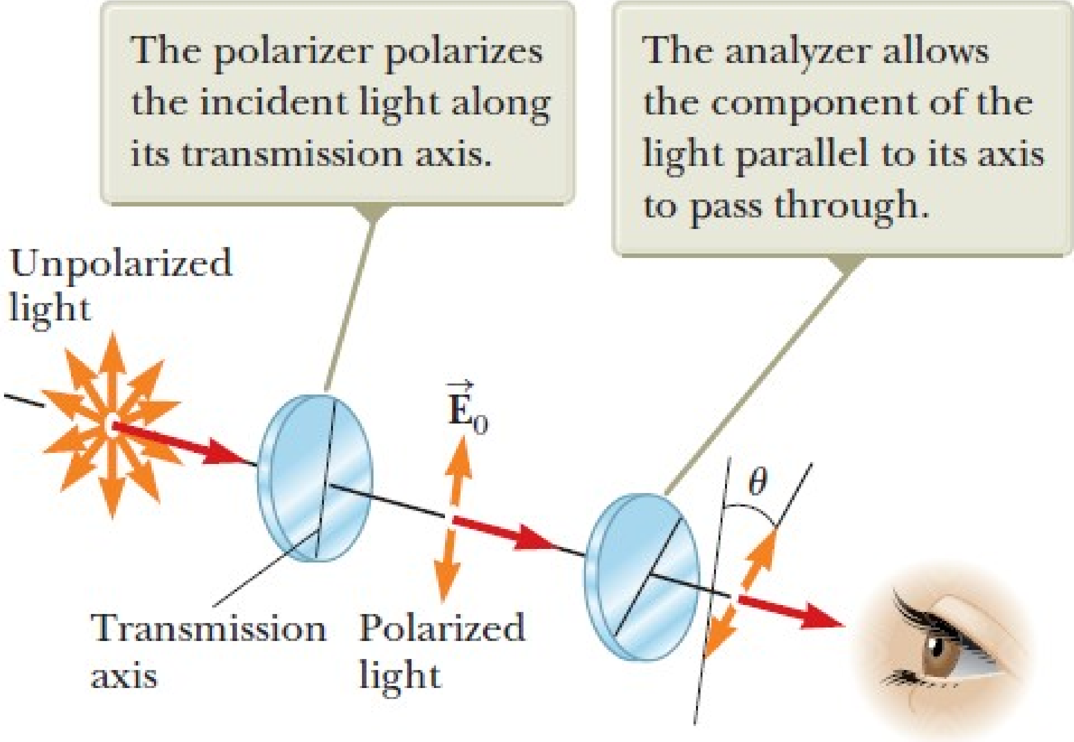


Fig. 1. Comparison of the observed and computed spectral energy distributions of 56 Ari. Theoretical models correspond to $T_{\rm eff}$ = 12 300 K, log(g) = 3.9 and $T_{\rm eff}$ = 12 800 K, log(g) = 4.0. The model fluxes have been convolved with an *FWHM* = 10 Å Gaussian kernel for a better view.

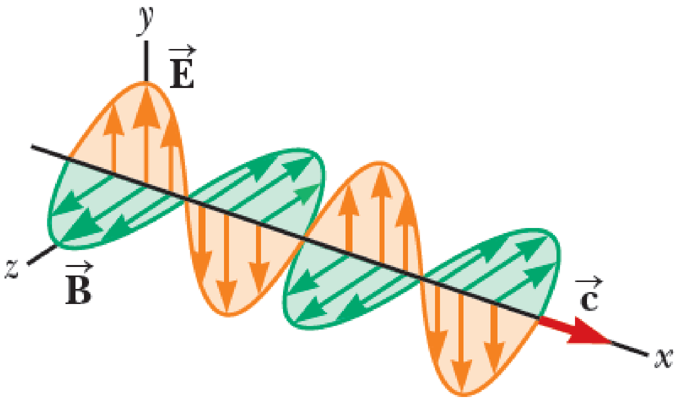
D. Shulyak[1], O. Kochukhov[2], G. Valyavin[3], B.-C. Lee[4], G. Galazutdinov[5], K.-M. Kim[4], I. Han[4], and T. Burlakova[6]

Polarization

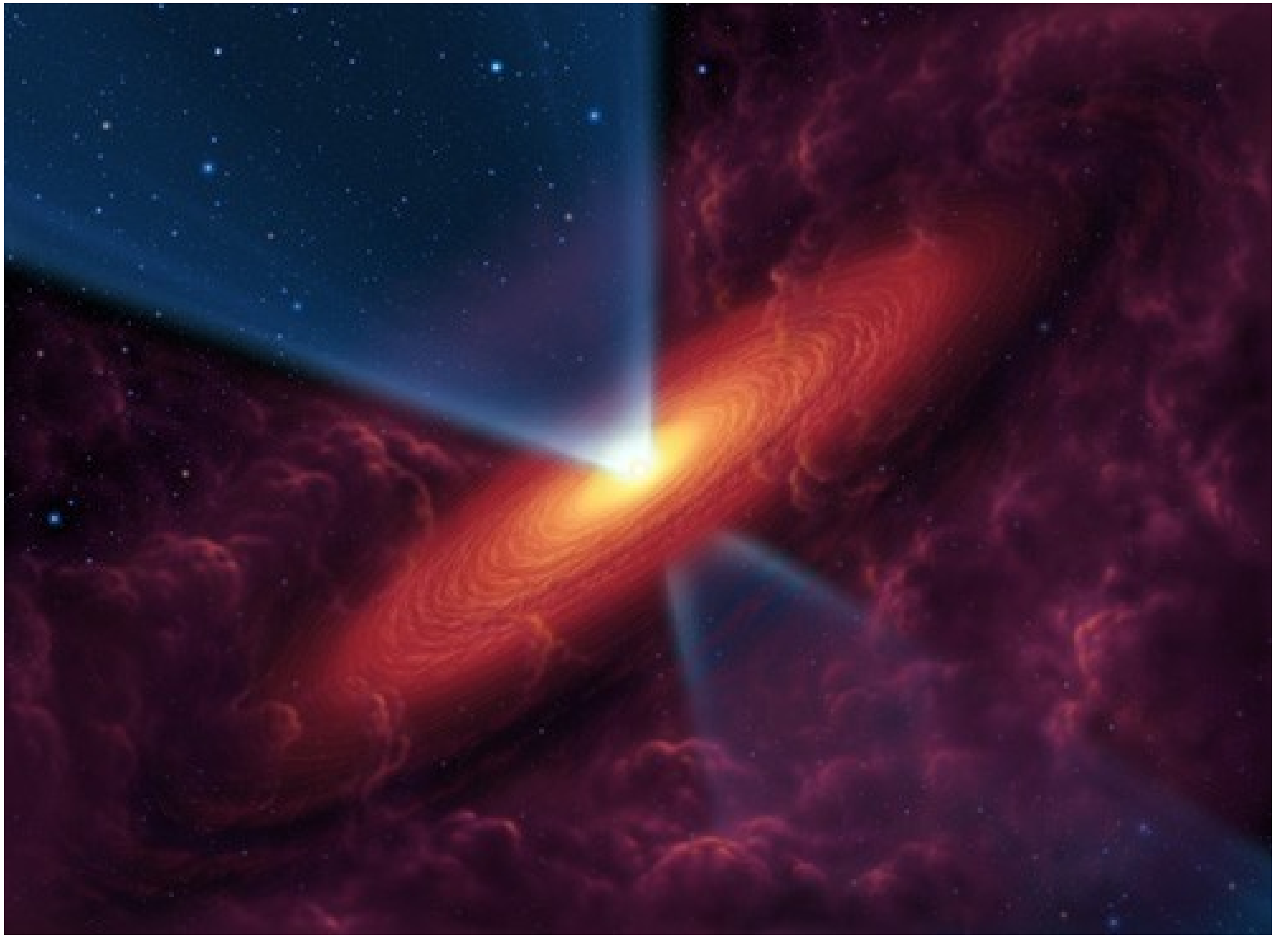
1669: Bartholinus discovers double refraction in calcite


The polarizer polarizes the incident light along its transmission axis.

The analyzer allows the component of the light parallel to its axis to pass through.

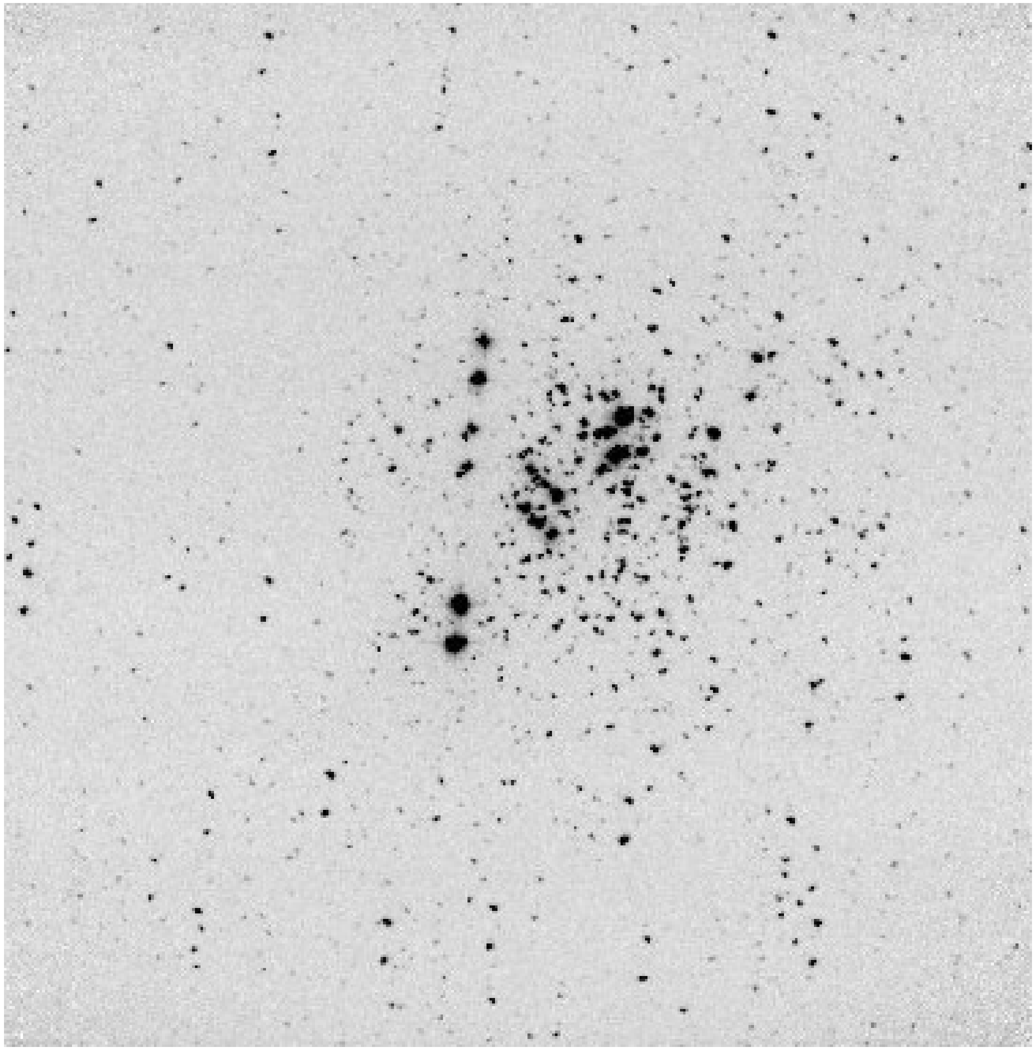


Polarization due to envelopes or disks



http://subarutelescope.org/Pressrelease/2005/08/31/index.html

Cluster NGC 4755 observed with IAG polarimeter



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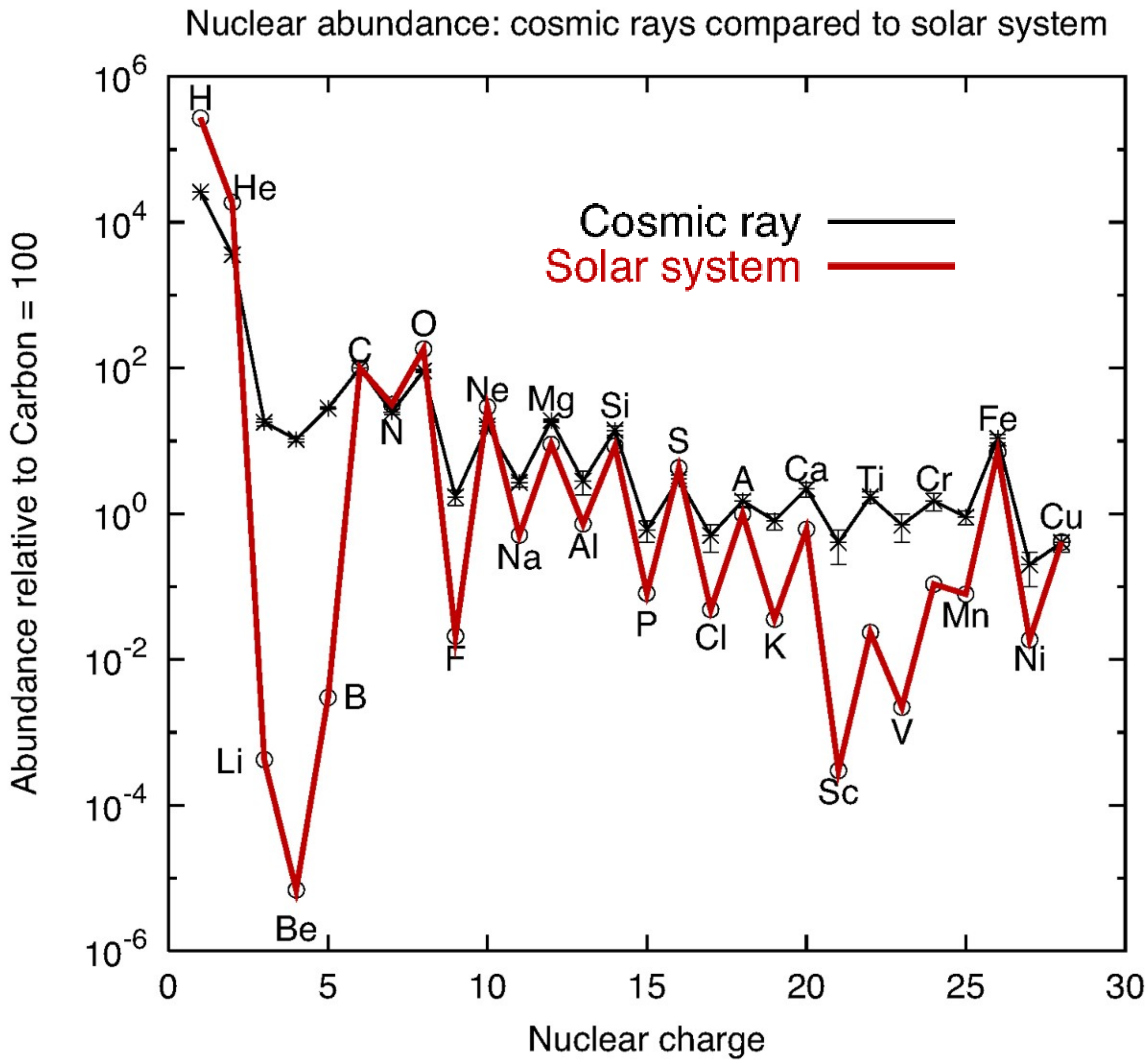
Non-photon astronomy

- **Cosmic rays**
- **Solar system bodies + pre-solar dust grains**
- **Neutrinos**
- **Gravitational waves**

Cosmic rays

- Matter (mostly p+ and heavier atomic nuclei) at high energies $E = \frac{mc^2}{\sqrt{1 - v^2/c^2}}$
- Galactic CR change direction due to $F = q(\mathbf{v} \times \mathbf{B})$
- Some CR are very energetic (SN, AGN?)

Cosmic rays composition



- Li-6, Be and B are originated in cosmic rays !

http://imagine.gsfc.nasa.gov/docs/science/know_l2/cosmic_rays.html

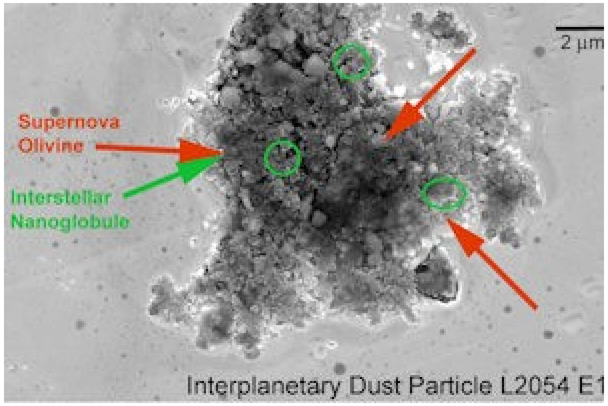
Exemplo: *spallation* (espalação; quebra/fissão) do carbono, por por bombardeio de raio cósmico de próton

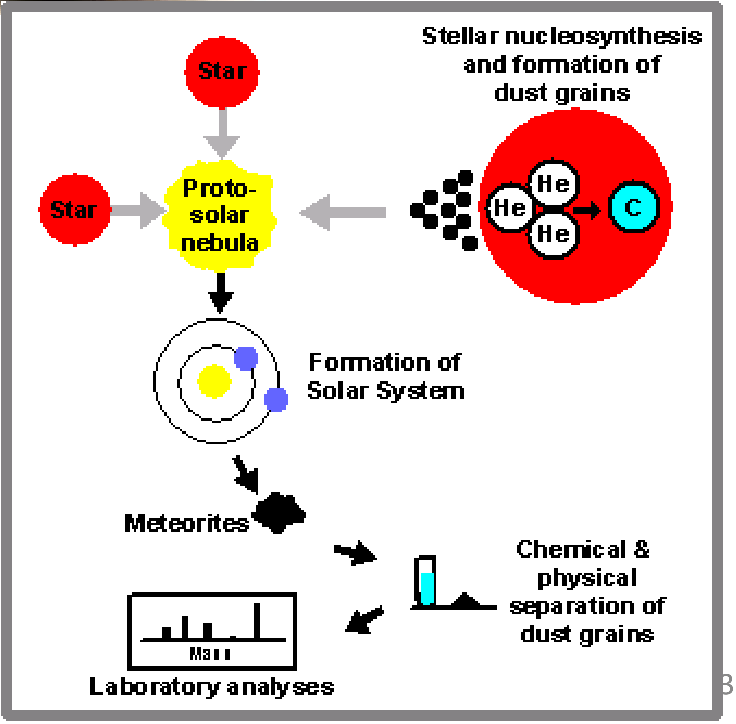
$${}^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{11}_{5}B + 2\,{}^{1}_{1}H$$

$$\rightarrow {}^{10}_{5}B + {}^{3}_{2}He$$

$$\rightarrow {}^{9}_{4}Be + {}^{3}_{2}He + {}^{1}_{1}H$$

Solar system bodies (e.g. Meteorites) and pre-solar dust grains





Aspects of the measurements

Position	Movements *(e.g. proper motions, planets, parallax)*
Flux, intensity Photometry	Absolute & differential photometry *(e.g. temperatures, stellar Populations, photometric redshift)*
Temporal variability	Explosions, light curves *(e.g., variable stars, microlensing, SN)*
Spatial resolution	Limited by atmosphere or diameter of the telescope *(black hole @ Galactic center)*
Spectral coverage & resolution	Spectrographs *(aim is to achieve maximum coverage and in some cases max spectral resolut.)*
Polarization	Stokes parameters *(important to study different physical processes and geometry)*

Inspired by slide of Prof. Claudia Villegas (INPE)

Parameter space of observations

- Wavelength coverage

(+ spectral resolution)

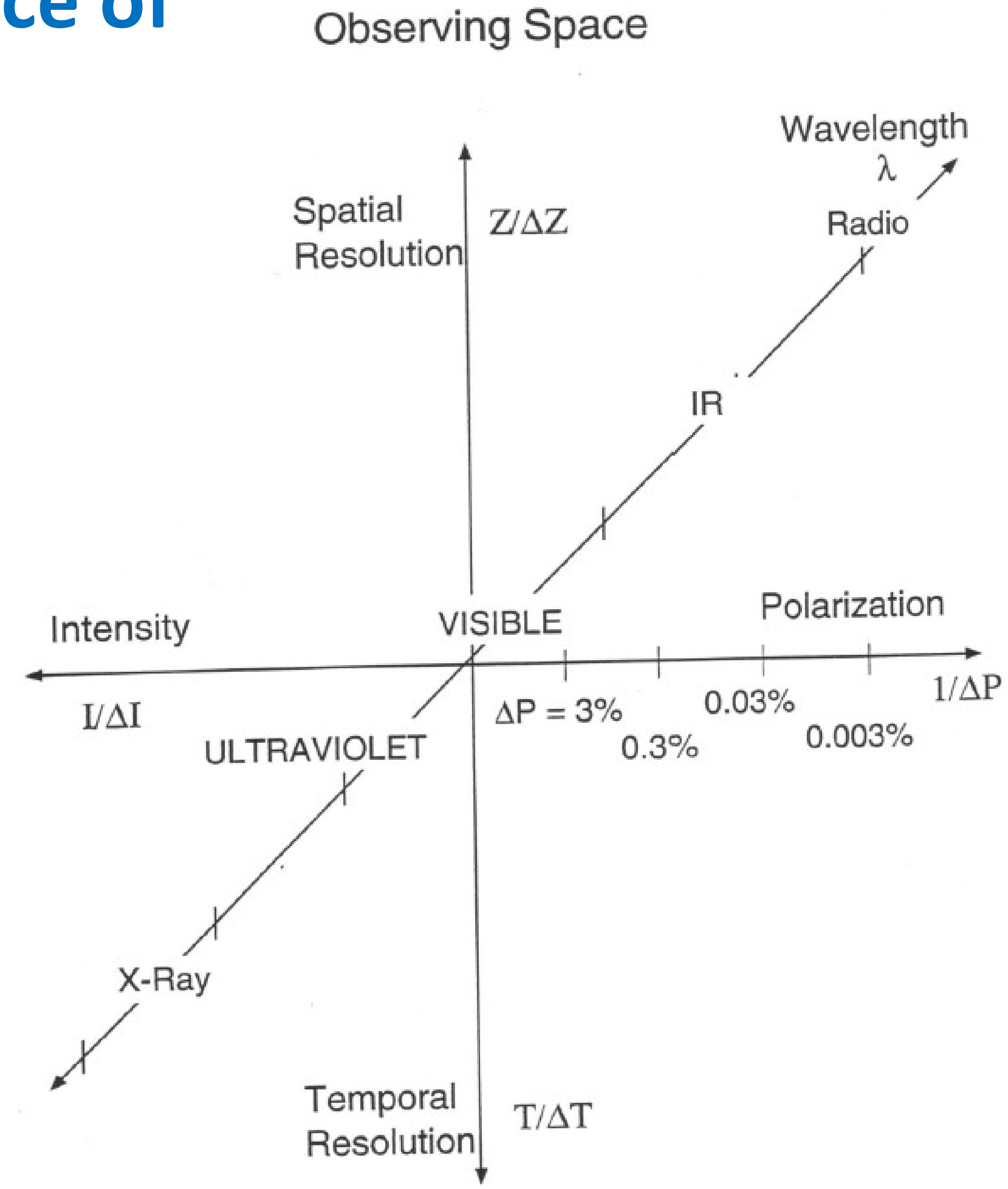
- Flux or Intensity
  (absolute + relative)
- Spatial Resolution

(+ absolute positions)

- Temporal Resolution

(+ time series)

- Polarization



From Nordsieck (1996)