

NCTS-TCA Summer Student Program 2026
Mini-Workshop

Radiative Processes and Transport



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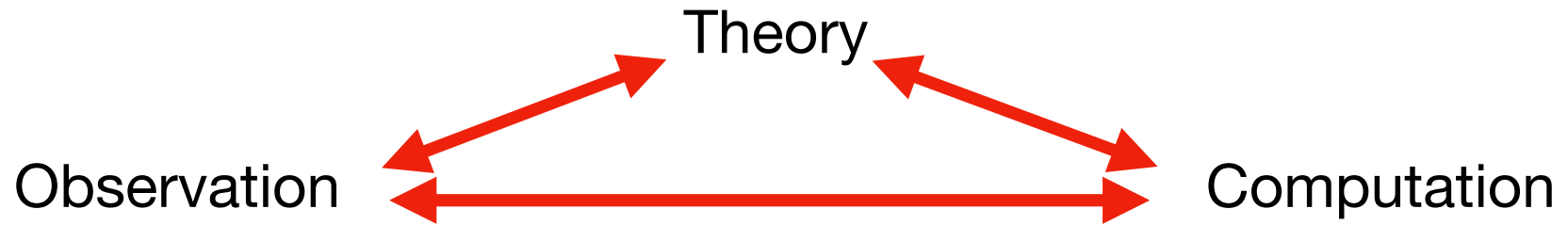


Astronomy and Astrophysics an Observational Science

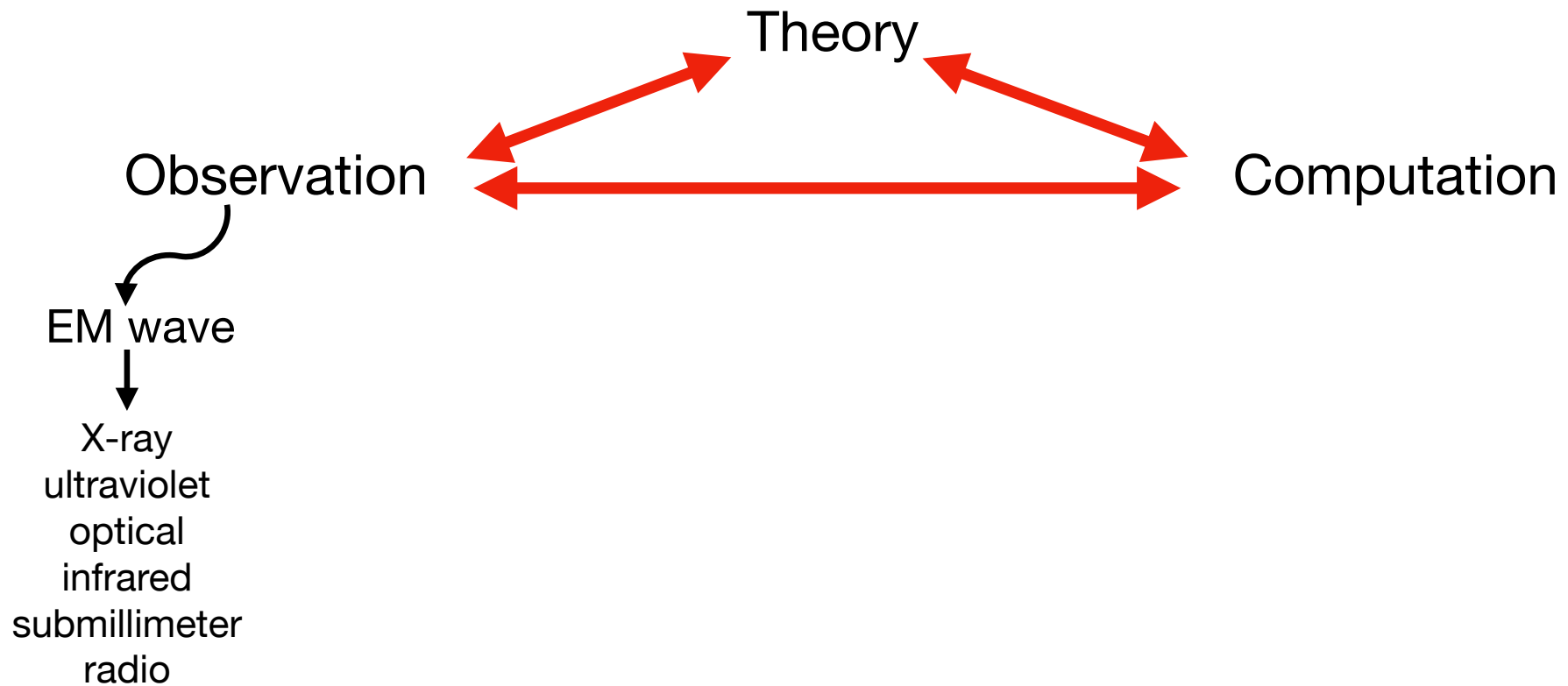


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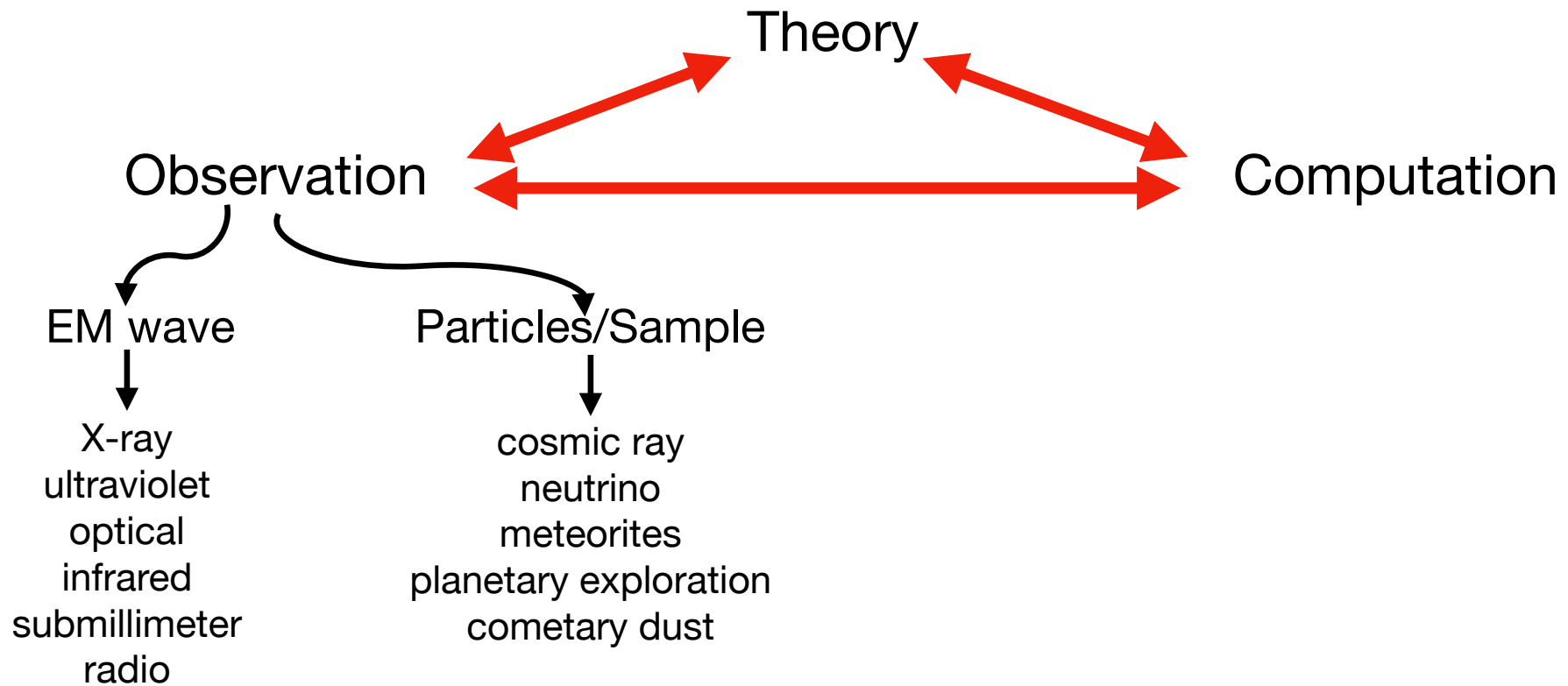
Astronomy and Astrophysics an Observational Science



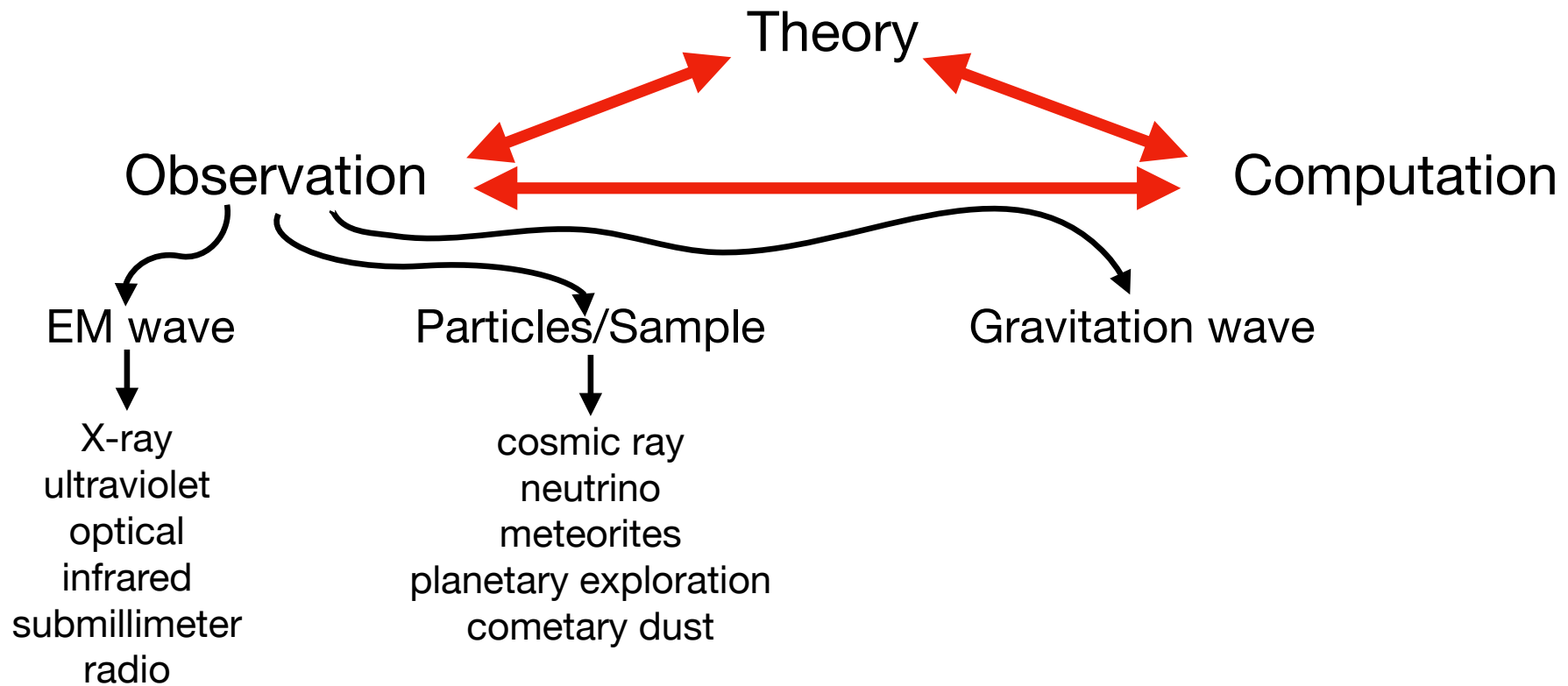
Astronomy and Astrophysics an Observational Science



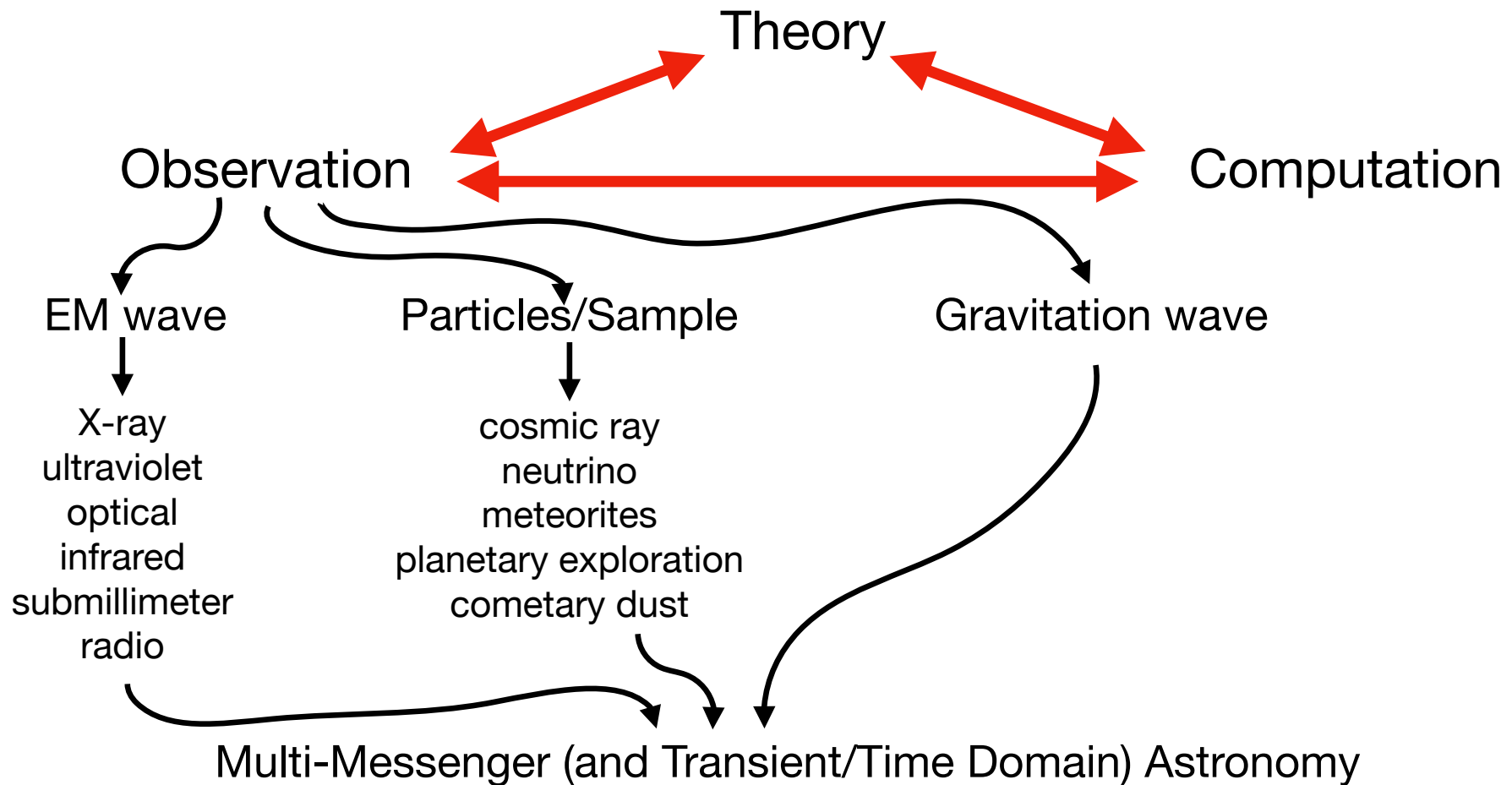
Astronomy and Astrophysics an Observational Science



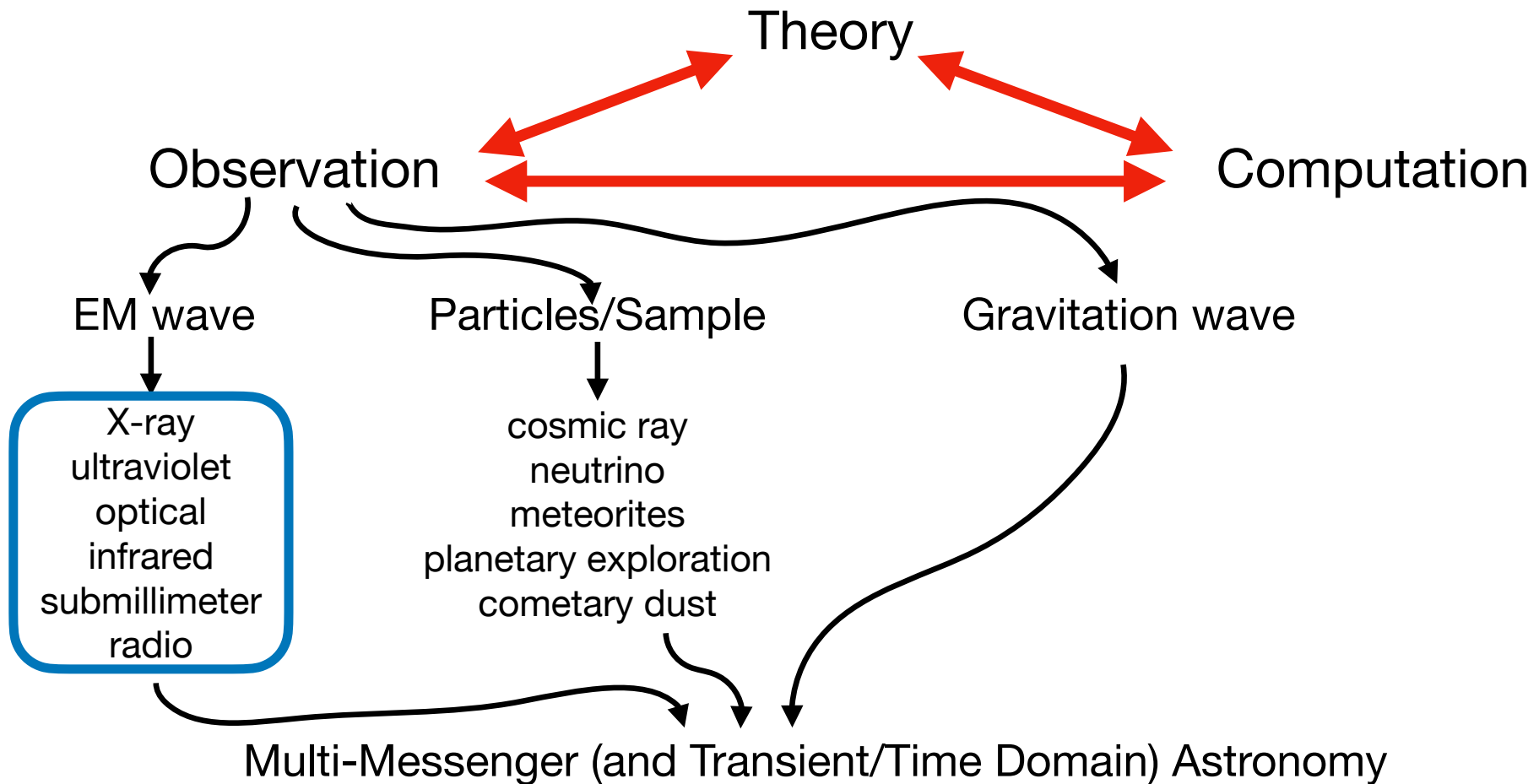
Astronomy and Astrophysics an Observational Science



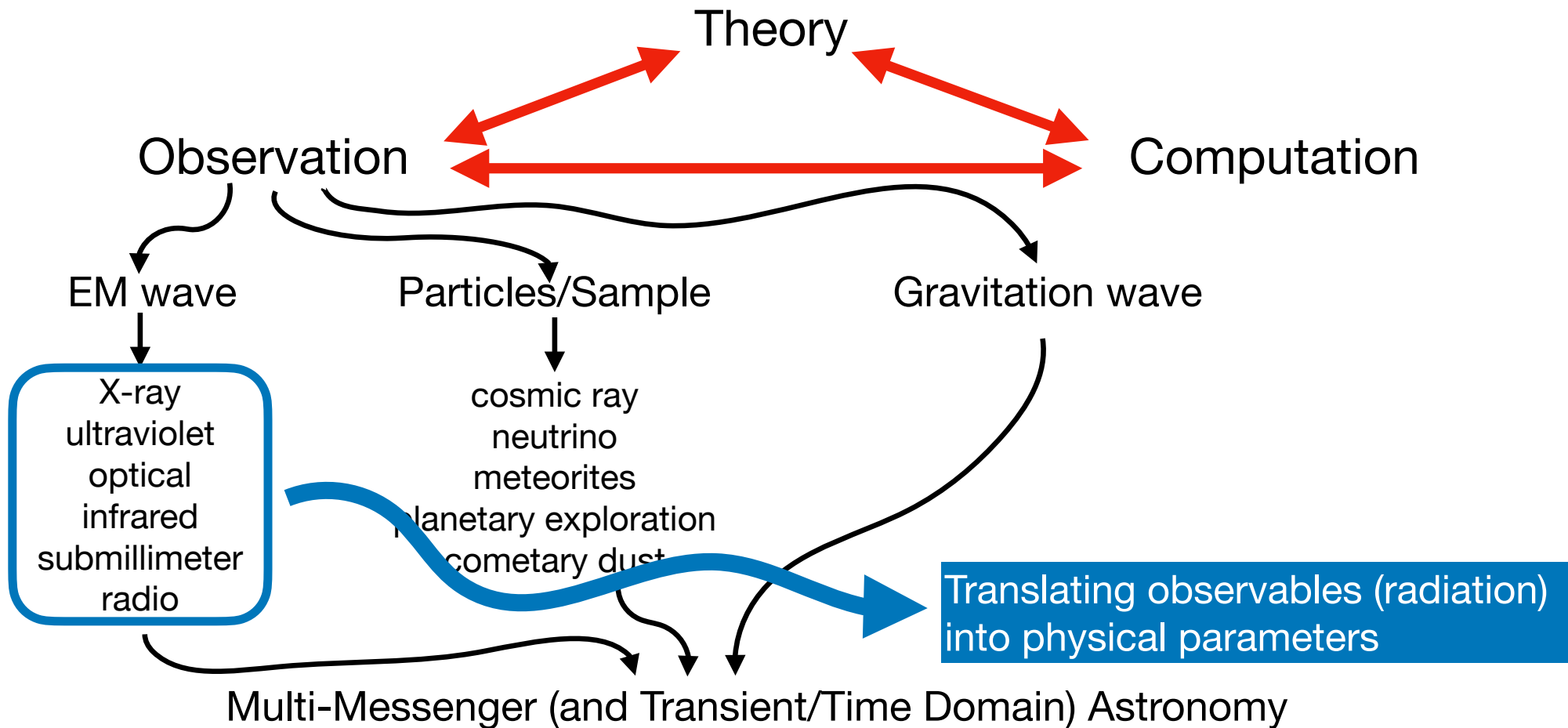
Astronomy and Astrophysics an Observational Science



Astronomy and Astrophysics an Observational Science

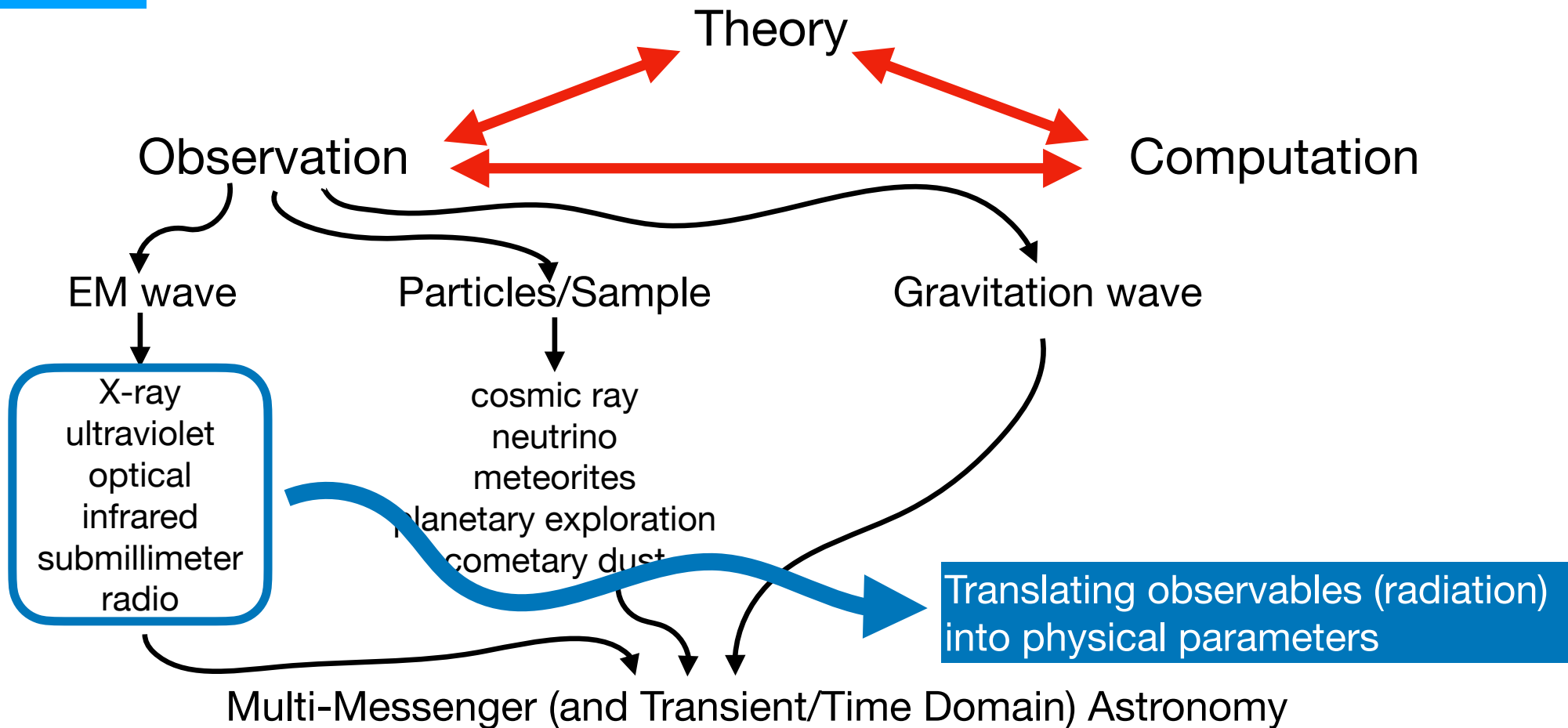


Astronomy and Astrophysics an Observational Science

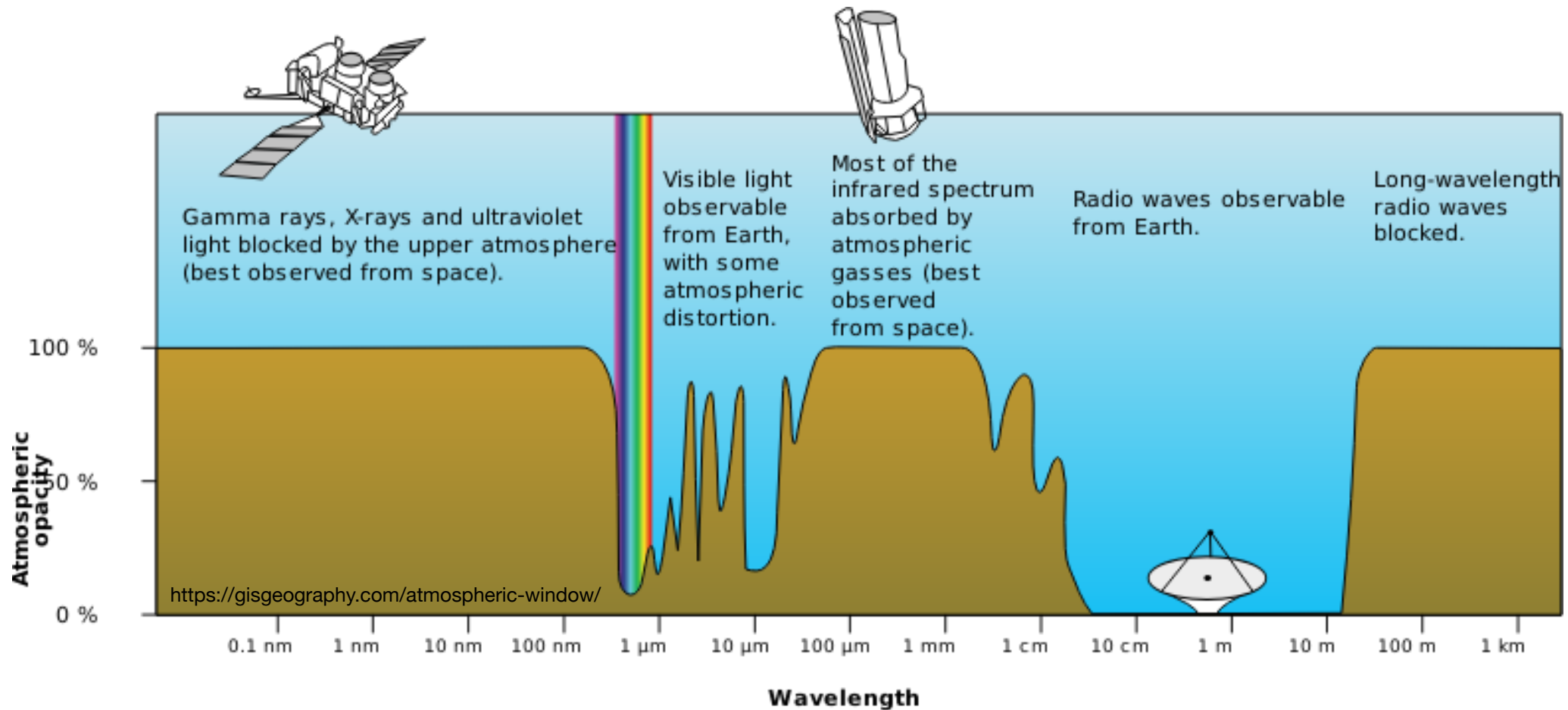


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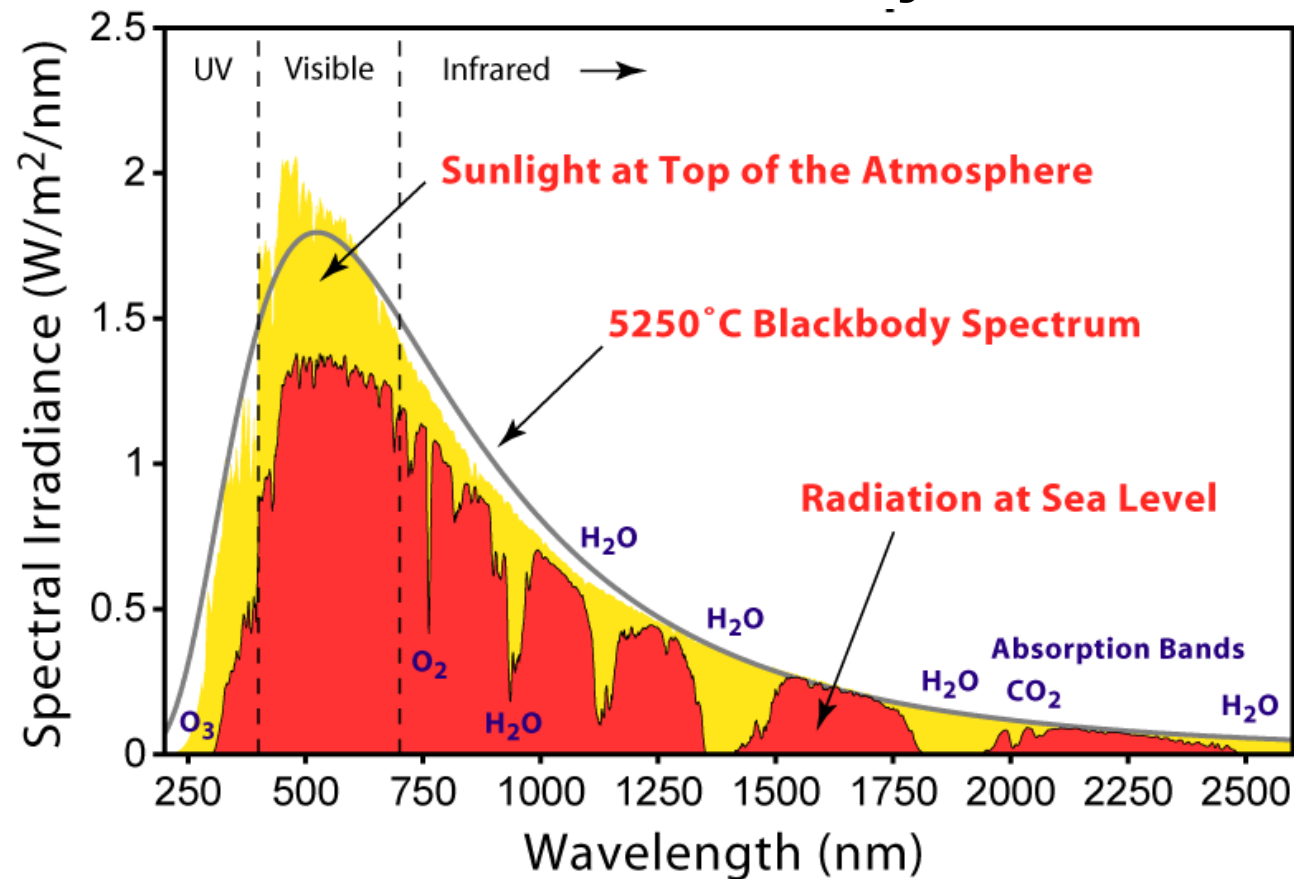
Astronomy and Astrophysics an Observational Science



Electromagnetic Wave and Atmospheric Window



Solar Radiation Spectrum as a Blackbody



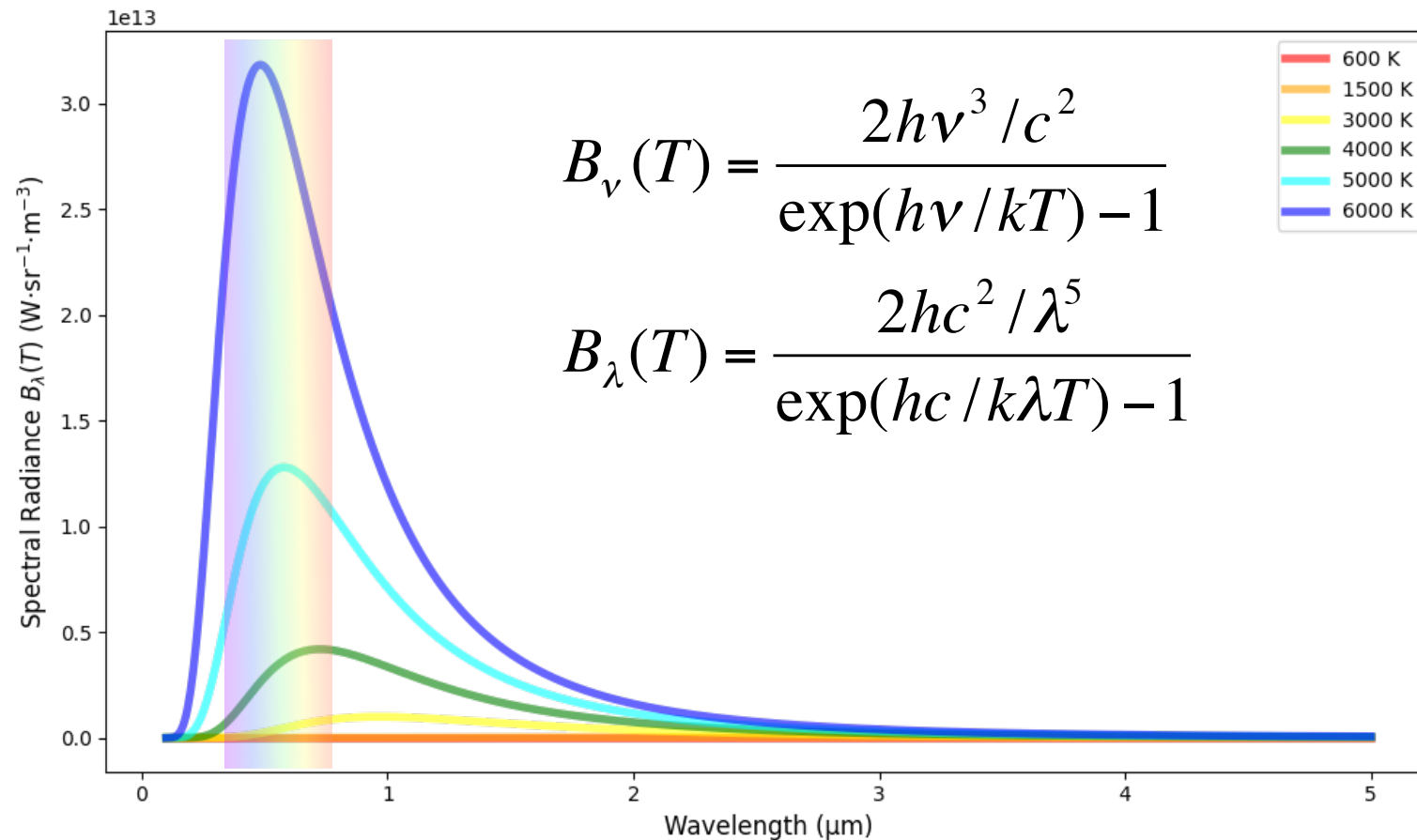
<https://physics.stackexchange.com/questions/130209/how-can-it-be-that-the-sun-emits-more-than-a-black-body>

Radiation at Multiple Wavelengths - Blackbody Radiation and Planck's Law

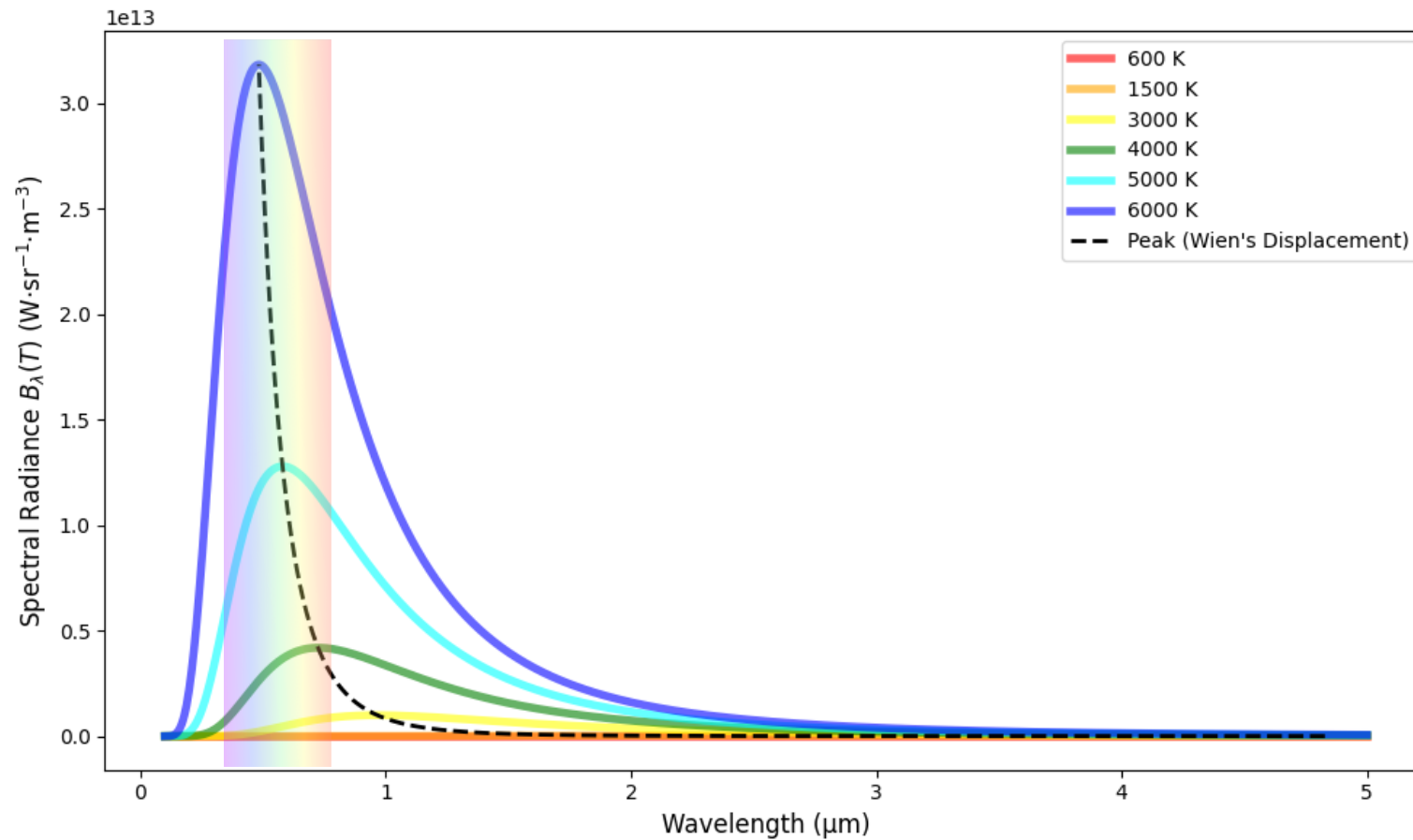
$$B_{\nu}(T) = \frac{2h\nu^3 / c^2}{\exp(h\nu / kT) - 1}$$

$$B_{\lambda}(T) = \frac{2hc^2 / \lambda^5}{\exp(hc / k\lambda T) - 1}$$

Radiation at Multiple Wavelengths - Blackbody Radiation and Planck's Law

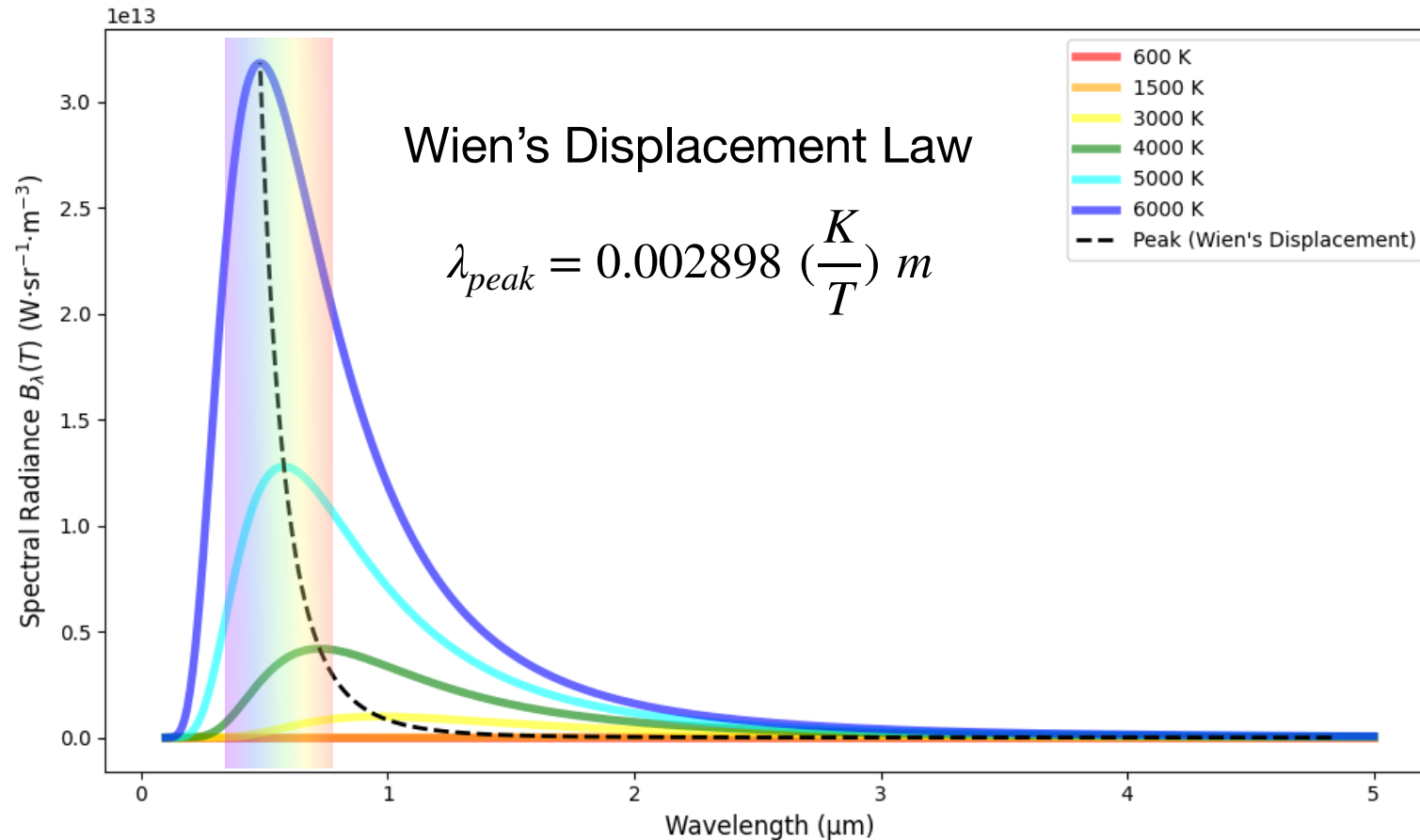


Radiation at Multiple Wavelengths - Blackbody Radiation and Planck's Law

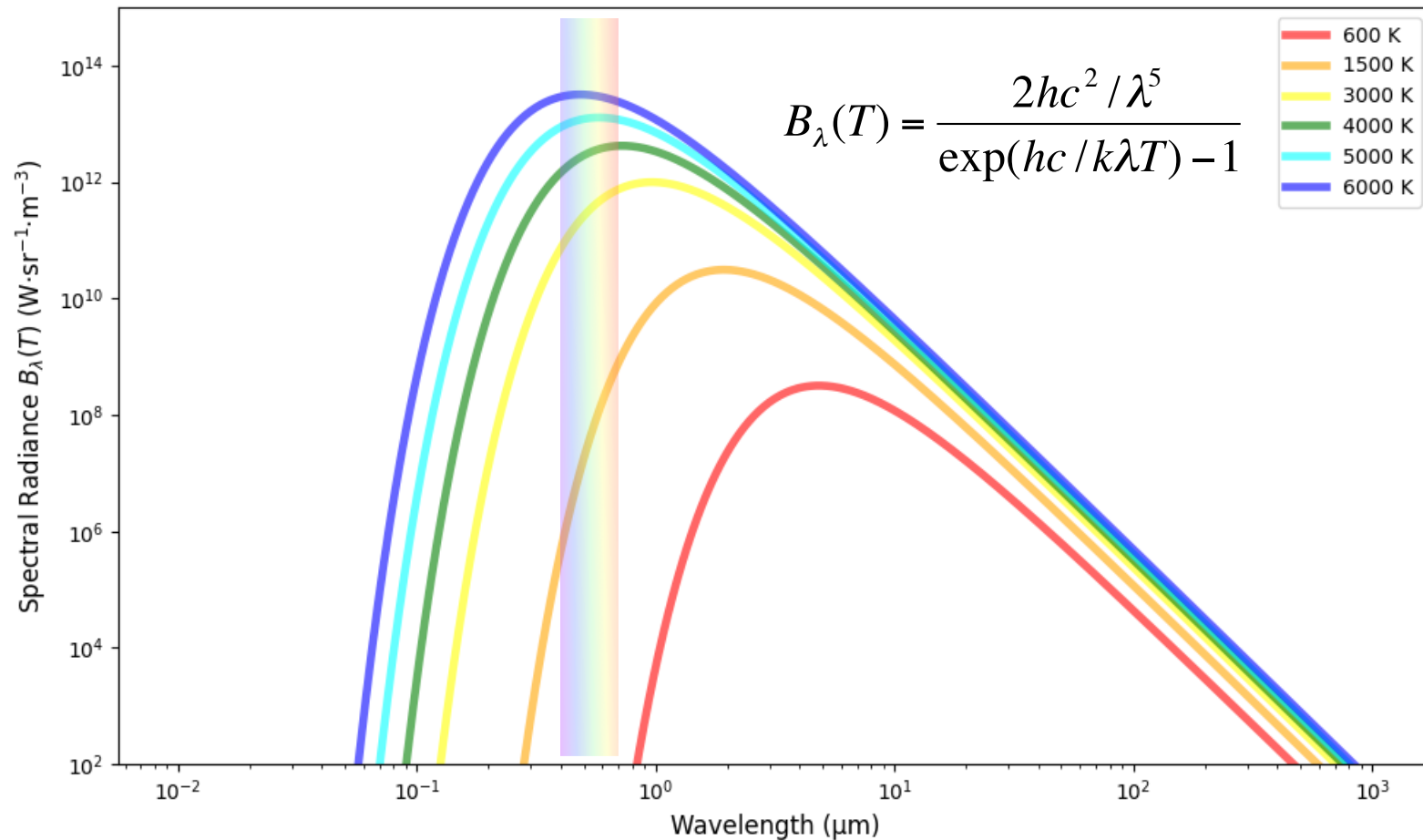


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Radiation at Multiple Wavelengths - Blackbody Radiation and Planck's Law

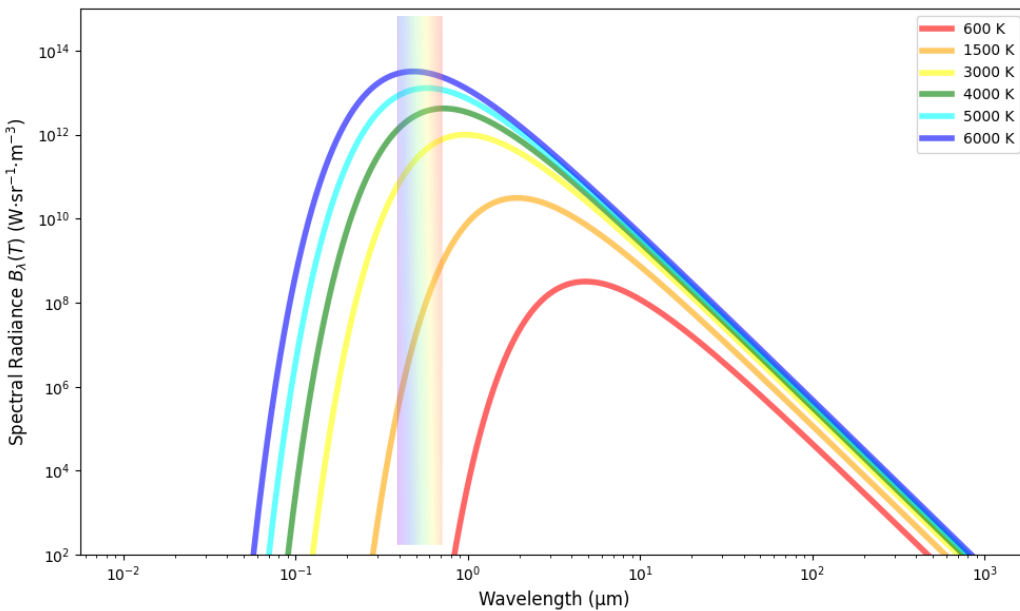


Radiation at Multiple Wavelengths - Blackbody Radiation and Planck's Law

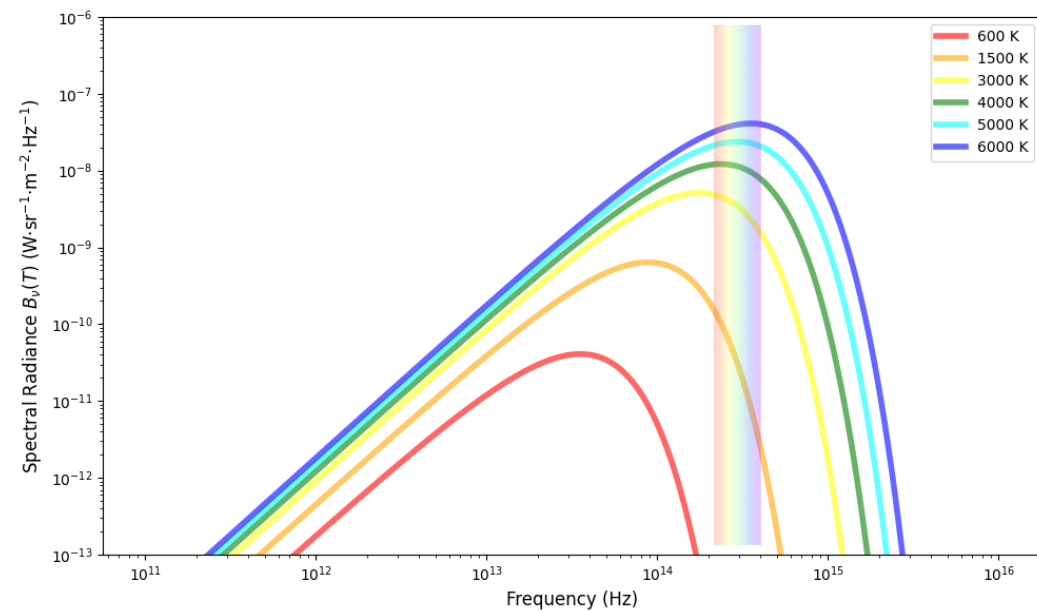


Radiation at Multiple Wavelengths - Blackbody Radiation and Planck's Law

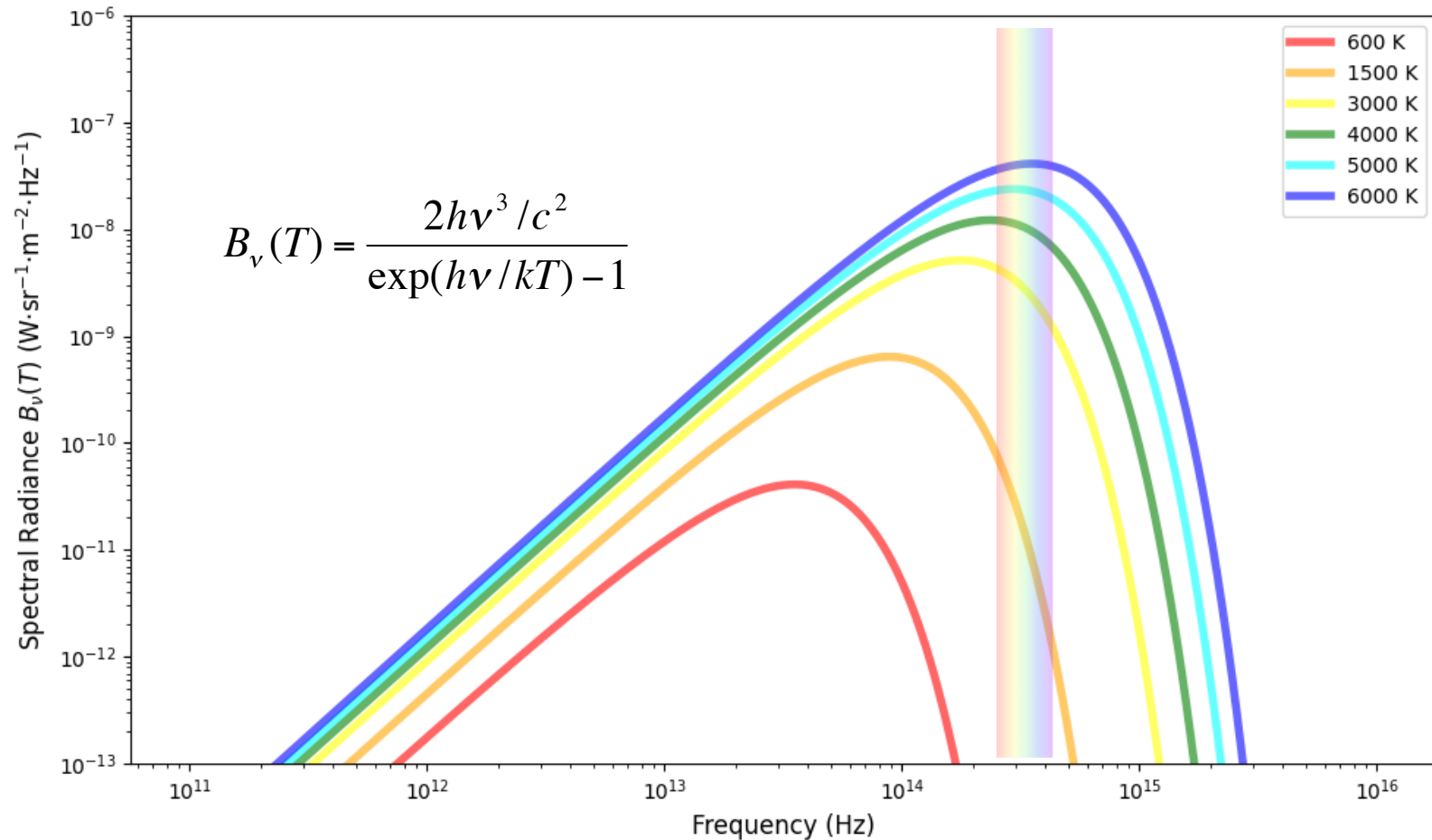
$$B_{\lambda}(T) = \frac{2hc^2 / \lambda^5}{\exp(hc / k\lambda T) - 1}$$



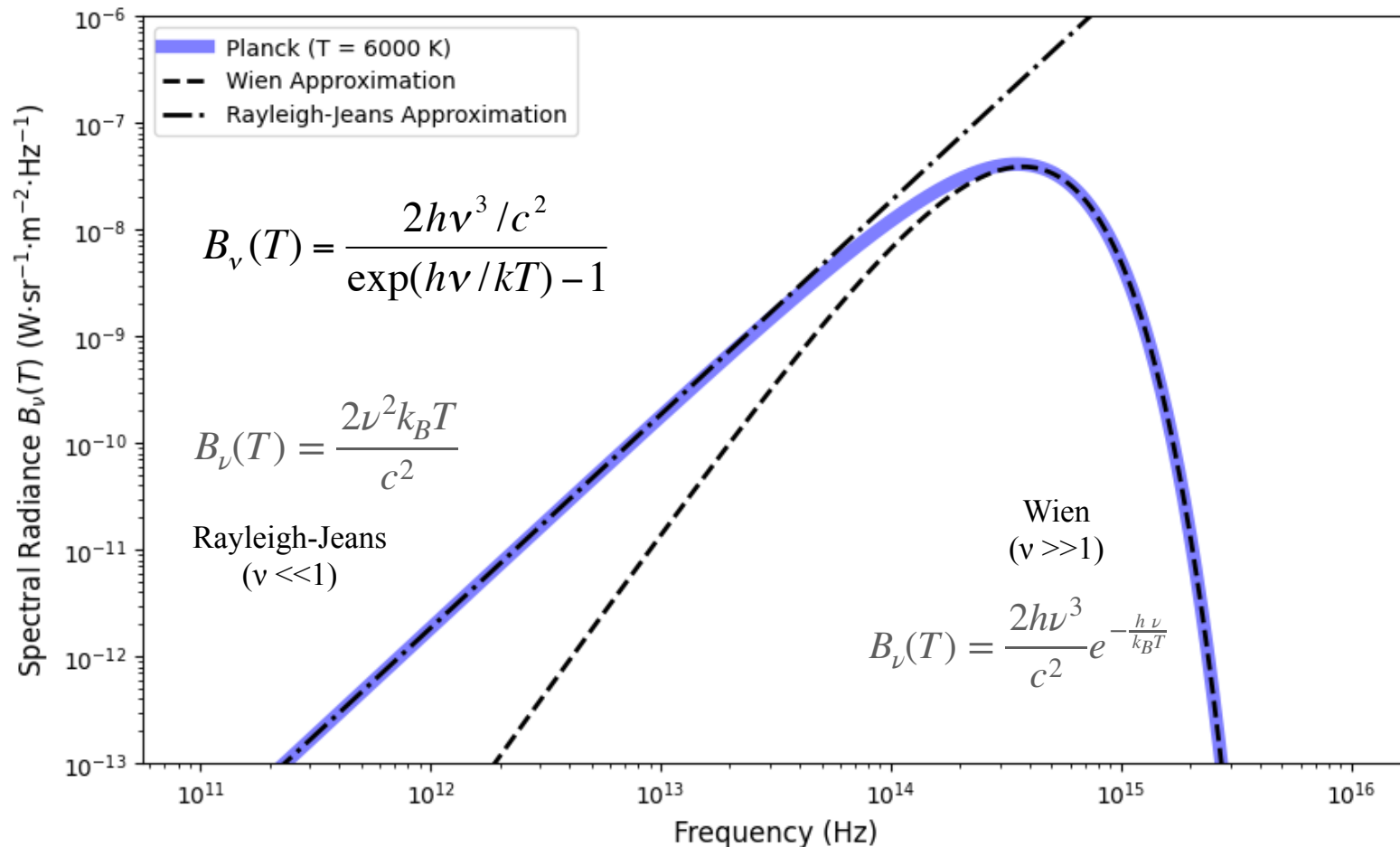
$$B_{\nu}(T) = \frac{2h\nu^3 / c^2}{\exp(h\nu / kT) - 1}$$



Radiation at multiple wavelengths - Blackbody Radiation

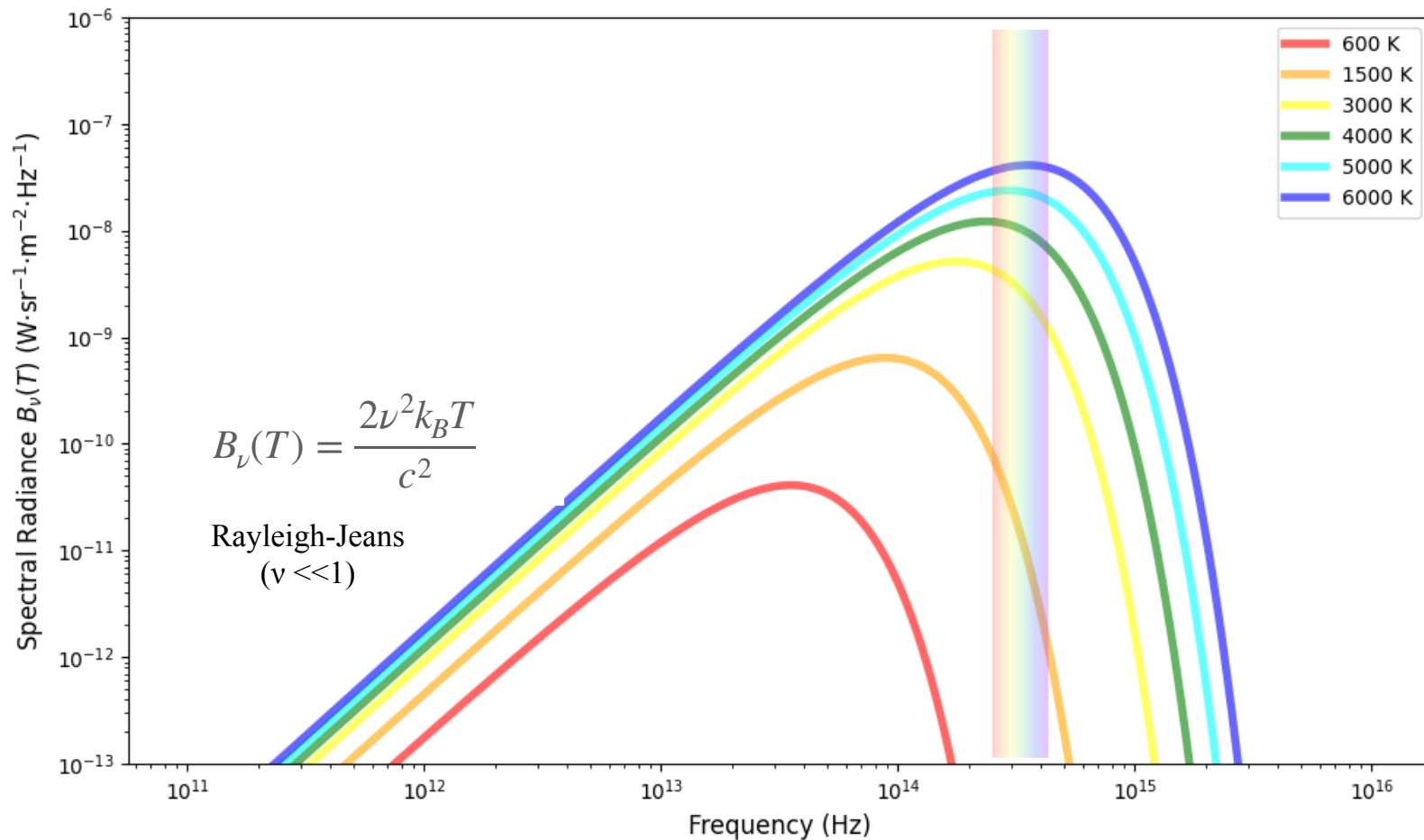


Radiation at multiple wavelengths - Blackbody Radiation

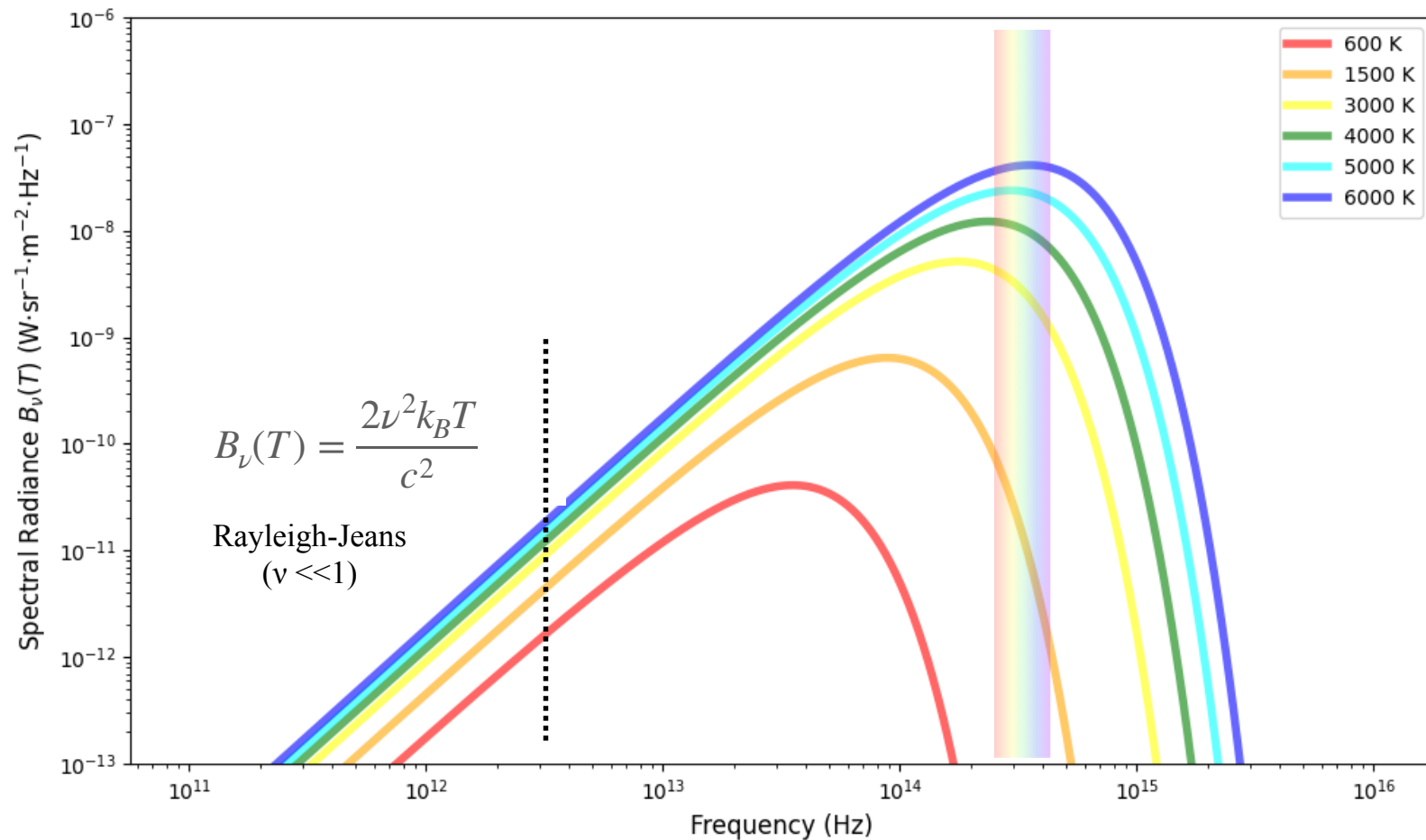


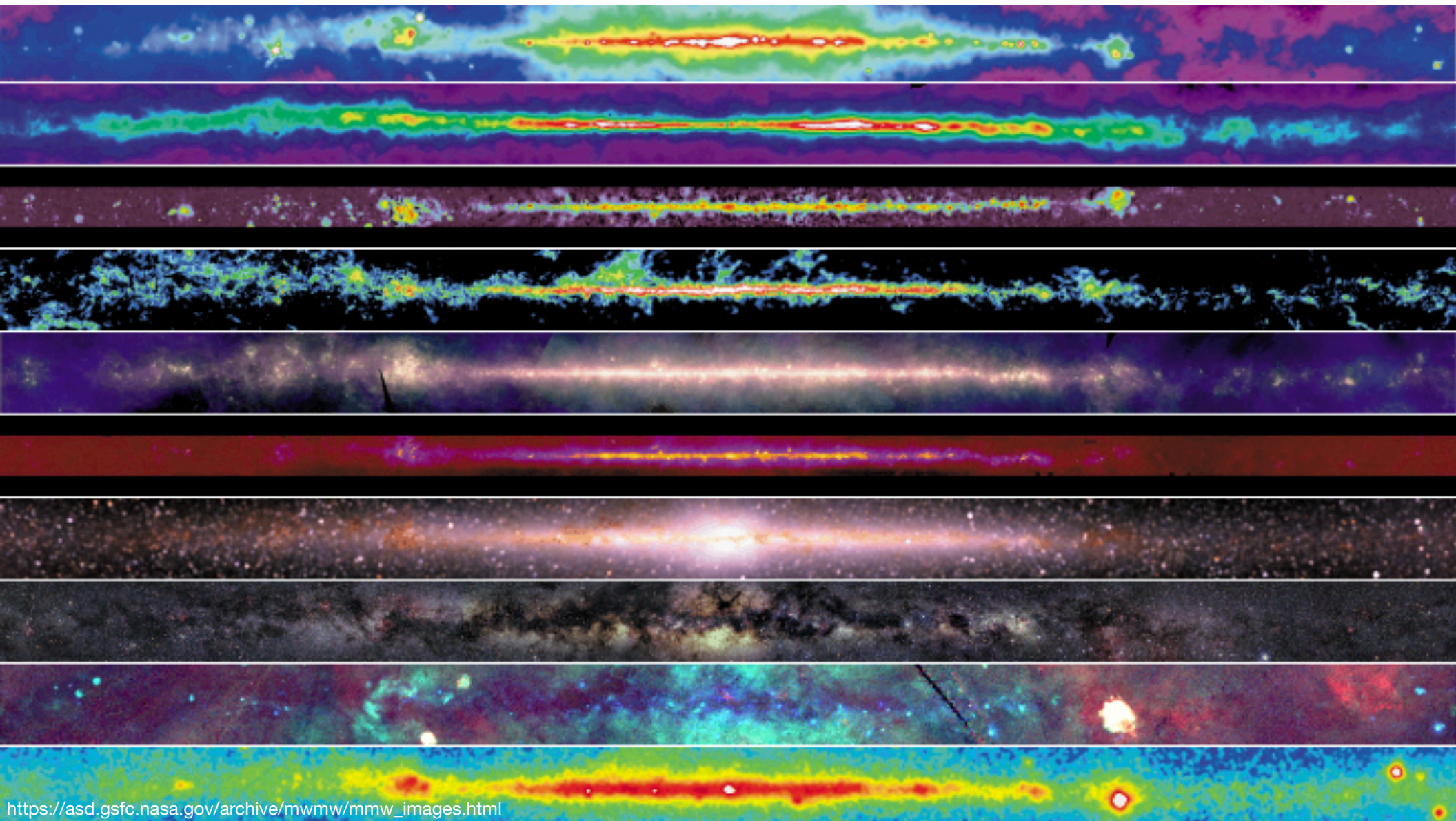
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Radiation at multiple wavelengths - Blackbody Radiation

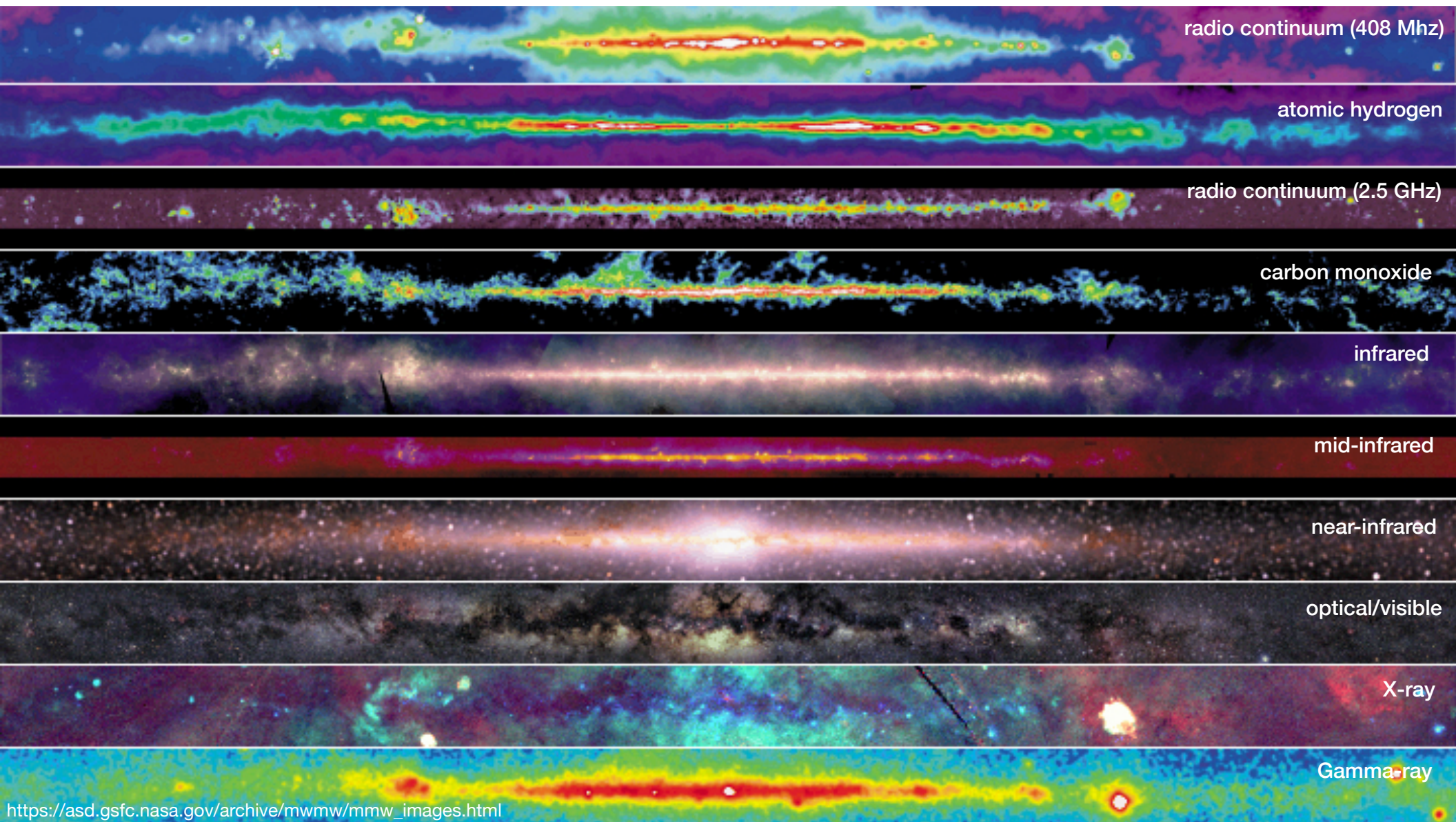


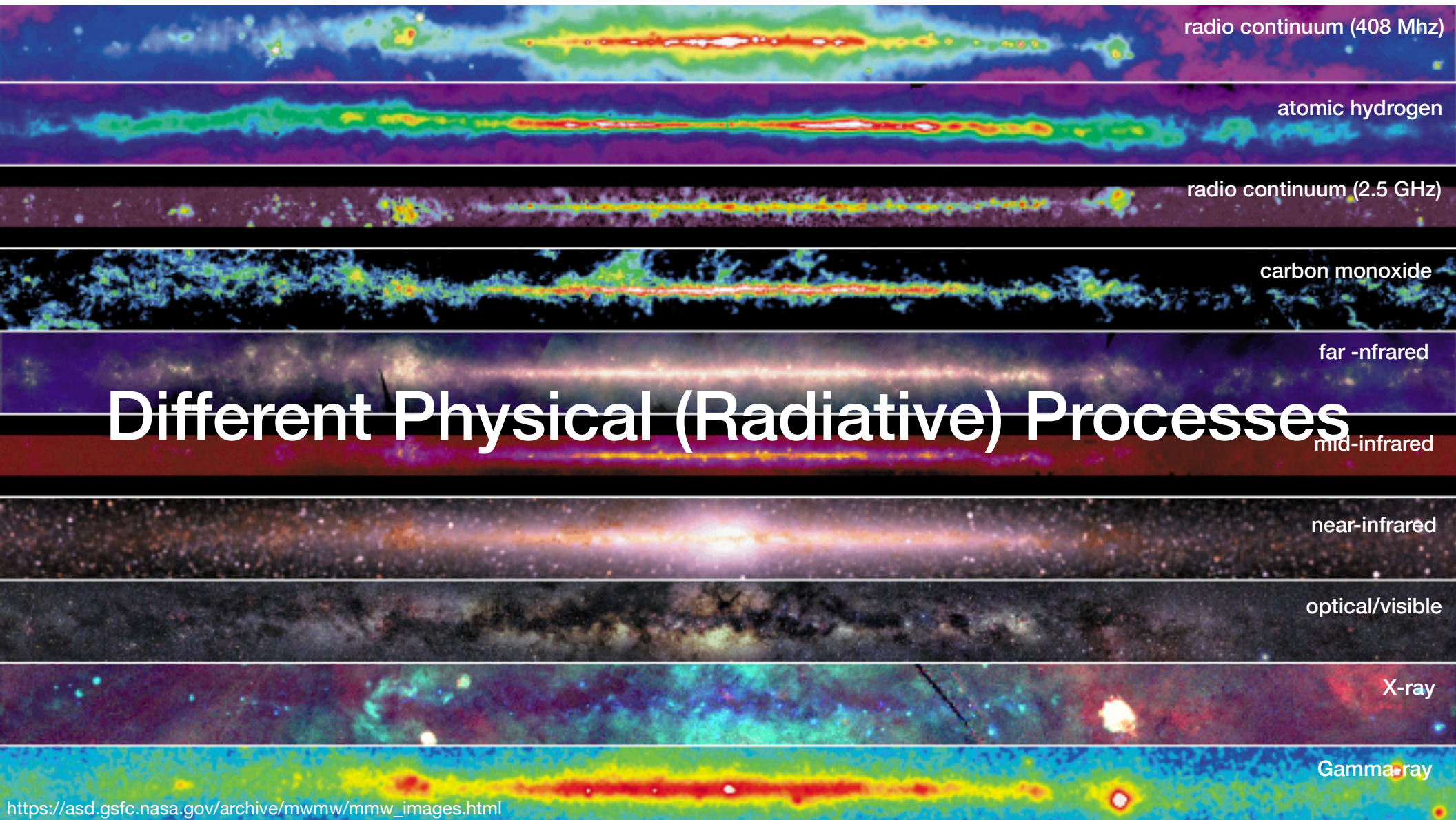
Radiation at multiple wavelengths - Blackbody Radiation





https://asd.gsfc.nasa.gov/archive/mmw/mmw_images.html





**Transport (of EM Waves) =
Radiative Transfer**

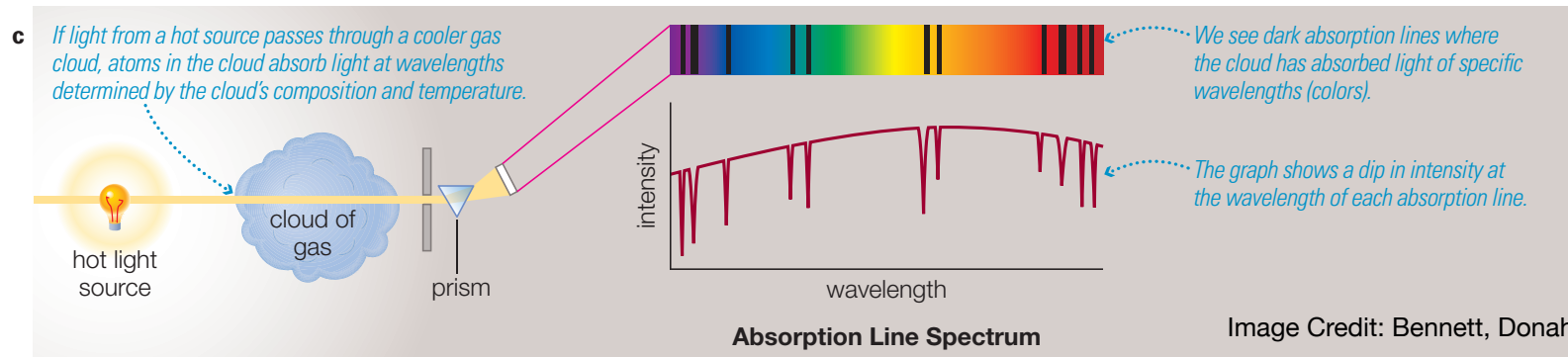
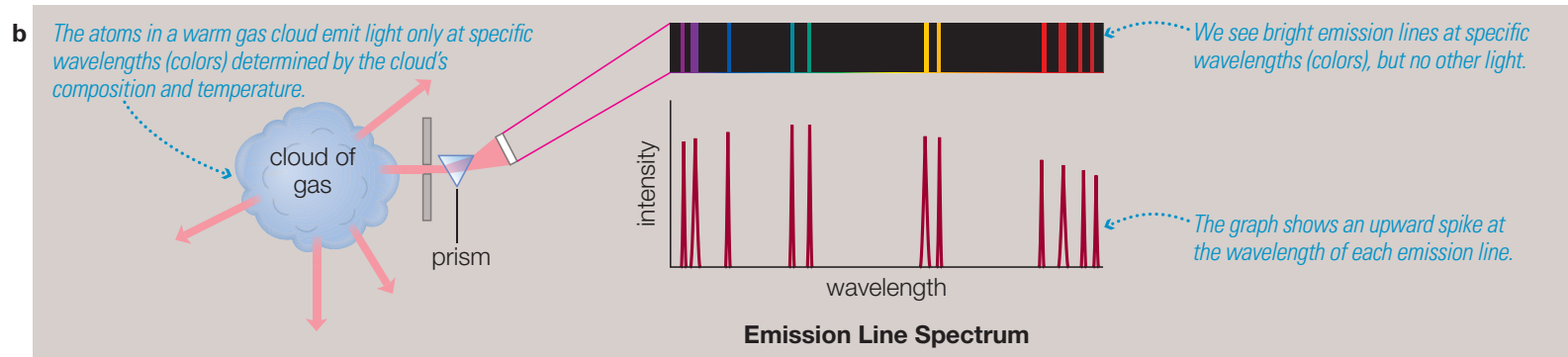
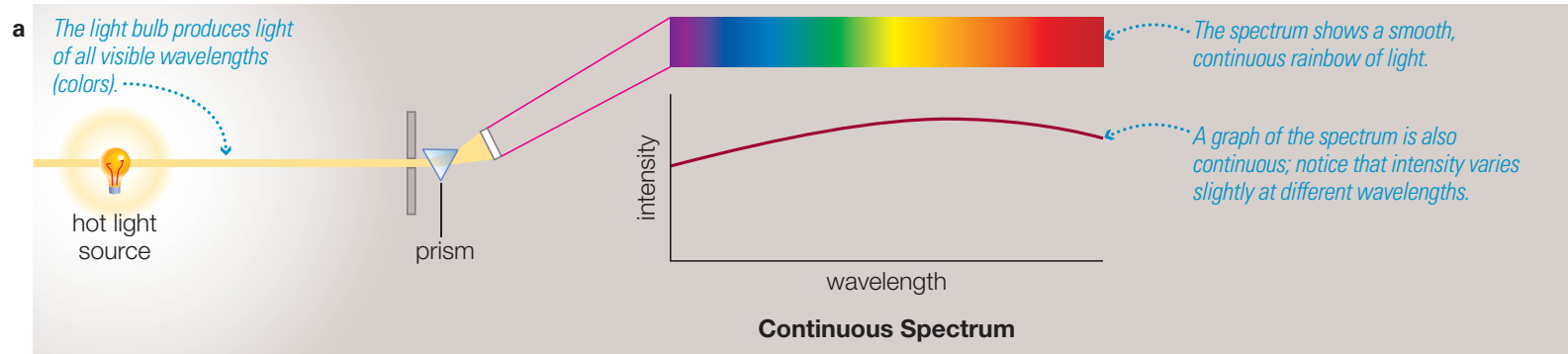


Image Credit: Bennett, Donahue, Schneider, Voit

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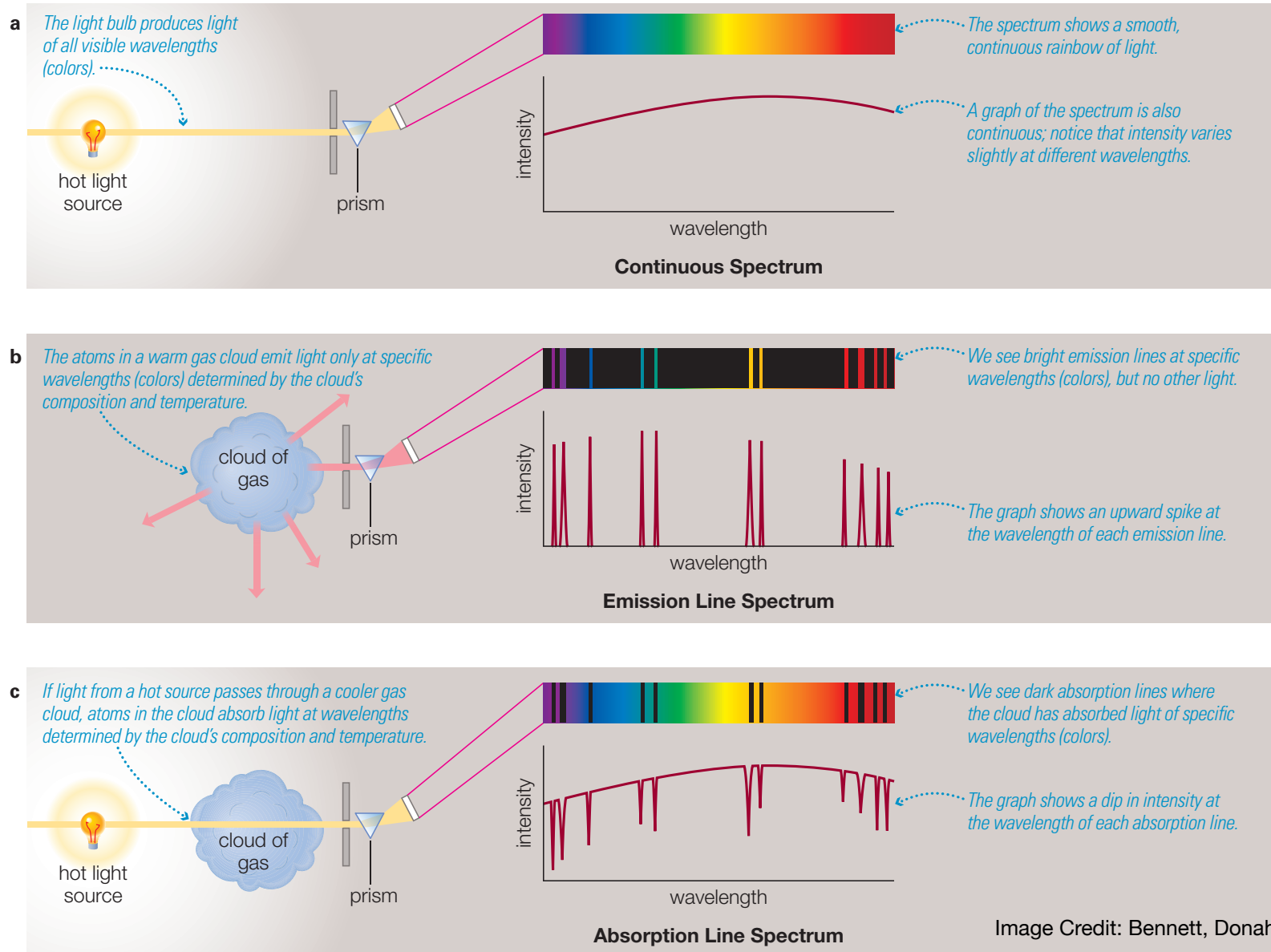
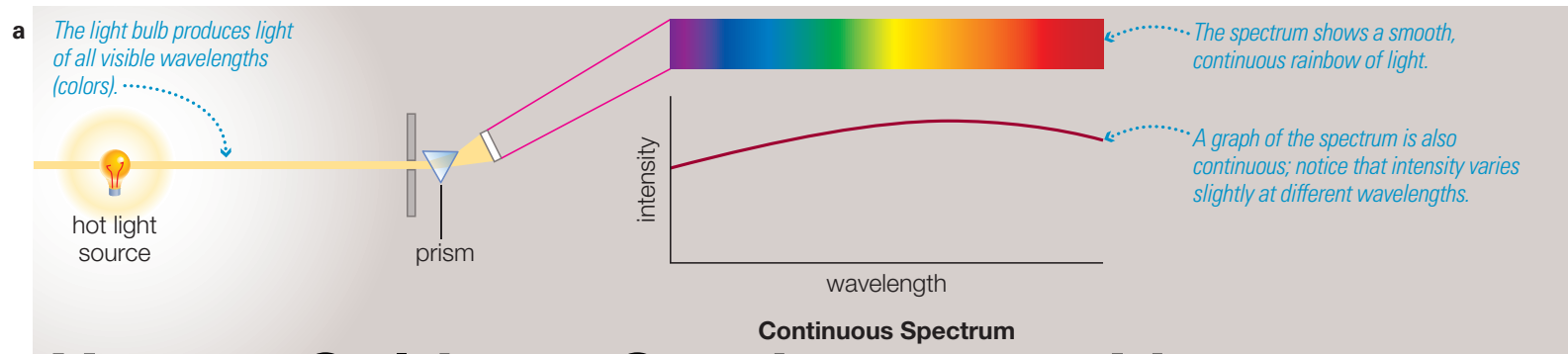
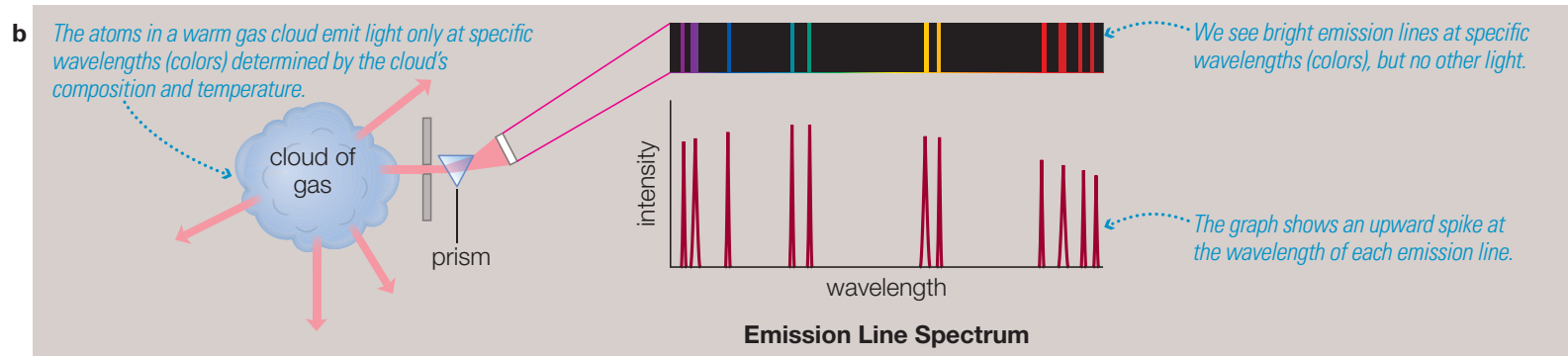


Image Credit: Bennett, Donahue, Schneider, Voit



Hot vs. Cold Continuum vs. Line



Foreground vs. Background

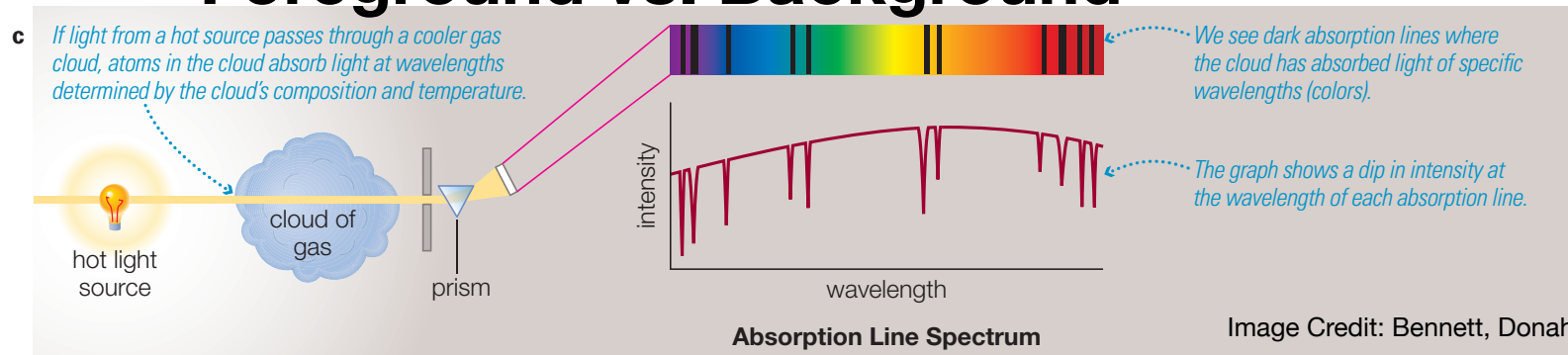
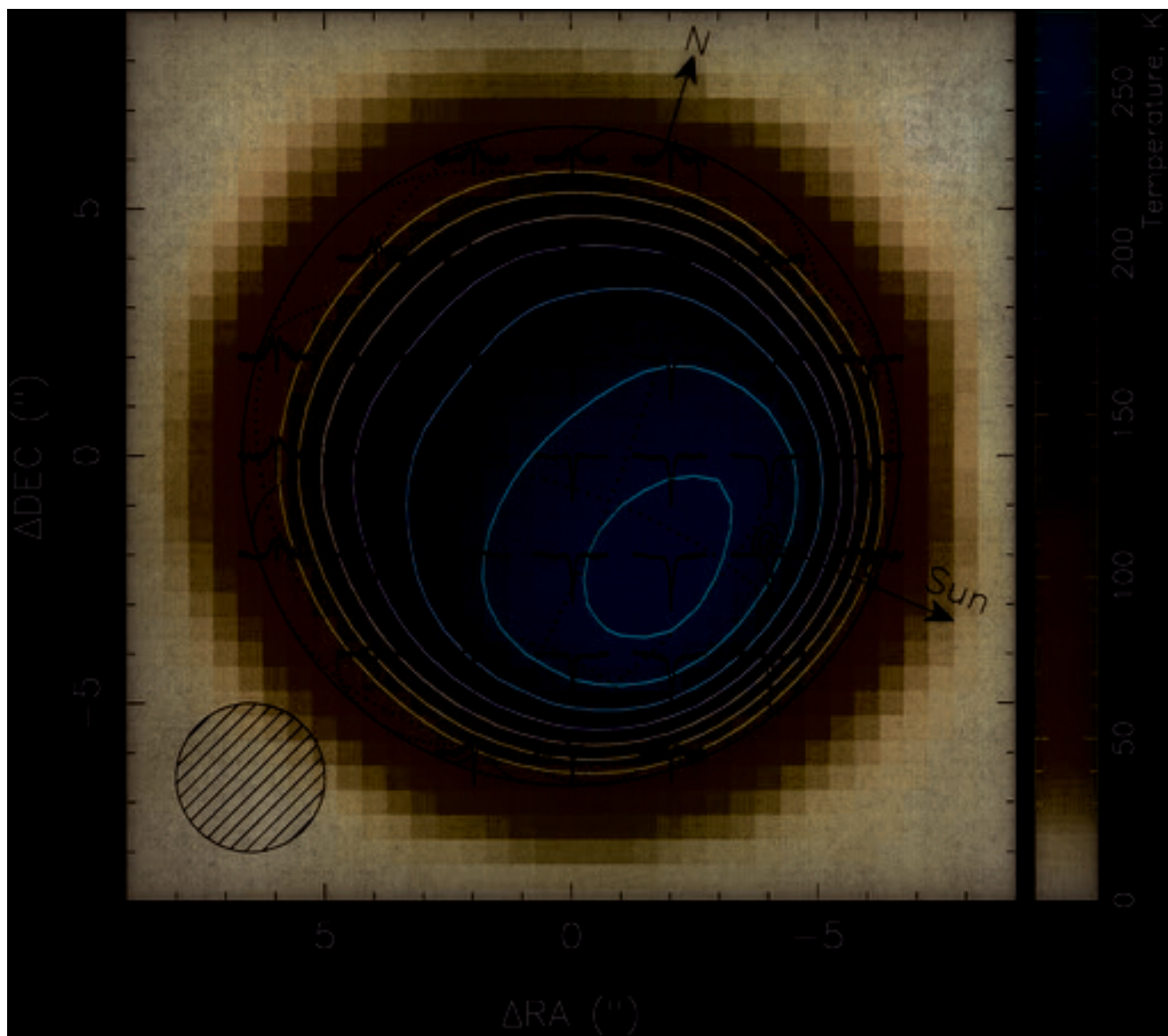
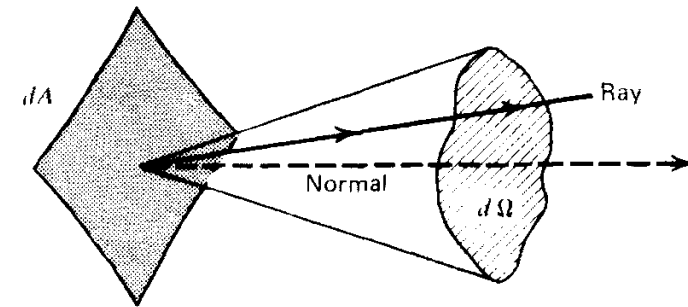


Image Credit: Bennett, Donahue, Schneider, Voit



Radiation Fundamentals: How bright is it?

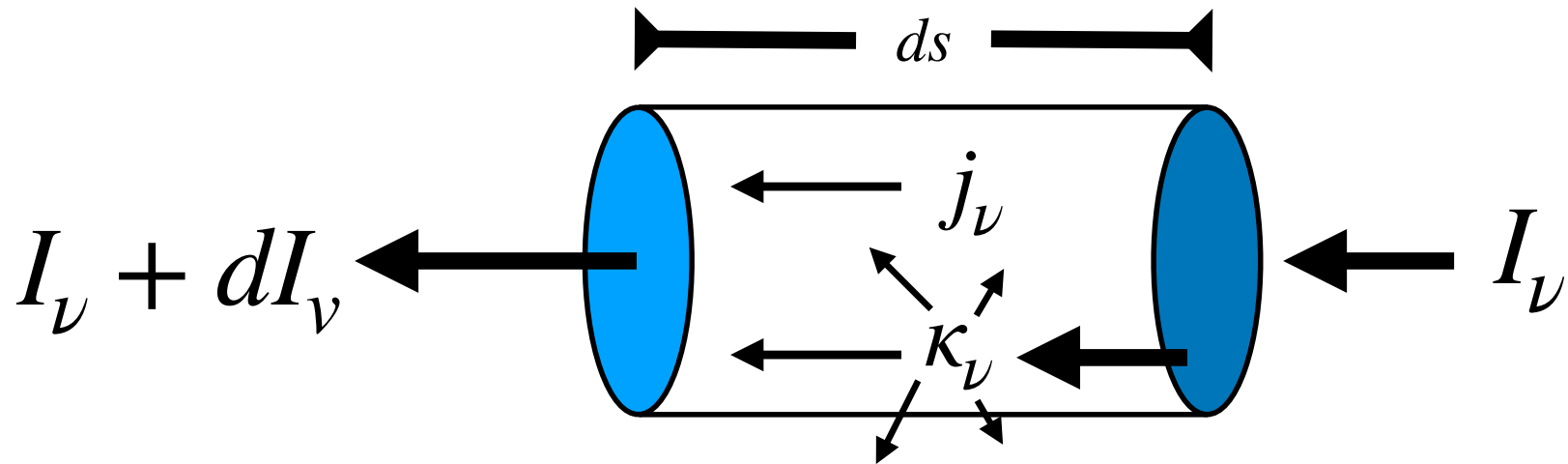
- Specific Intensity I_ν : $dE = I_\nu d\sigma \cos\theta d\omega d\nu dt$
 - or Intensity, or Brightness, or Brightness Temperature
 - rate of energy transport, along a particular direction, per unit area, per unit solid angle, and per unit frequency
 - conserved along a ray through free space
 - unit: e.g. $\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \text{Sr}^{-1}$ or $\text{W m}^{-2} \text{Hz}^{-1} \text{Sr}^{-1}$
- Flux Density S_ν (or F_ν) : $\int I_\nu(\omega \cos(\theta)) d\omega$
- Flux F : $\int S_\nu d\nu$
 - energy per time per area, depends on the relative position of source and the observer
- Power P : $\int F d\sigma$
 - or Luminosity
 - energy per time given off by a source



Geometry for normally incident rays.

Image Credit: Rybicki and Lightman

Radiative Transfer (of EM wave)



Radiative Transfer (of EM wave)

- Basic equation of (radiative) transfer

- $dI_\nu = j_\nu ds - \alpha_\nu I_\nu ds$

- j_ν : emission coefficient

- α_ν : absorption or extinction coefficient (cm^{-1}) = $\kappa_\nu \rho$ where κ_ν is the mass absorption coefficient

- Both j_ν and α_ν are functions of intrinsic properties and physical conditions of the medium

- $\frac{dI_\nu}{\alpha_\nu ds} = -I_\nu + \frac{j_\nu}{\alpha_\nu}$

- $S_\nu \equiv \frac{j_\nu}{\alpha_\nu}$; $d\tau_\nu \equiv \alpha_\nu ds$, where τ_ν is the optical depth

$$\frac{dI_\nu}{d\tau} = -I_\nu + S_\nu$$

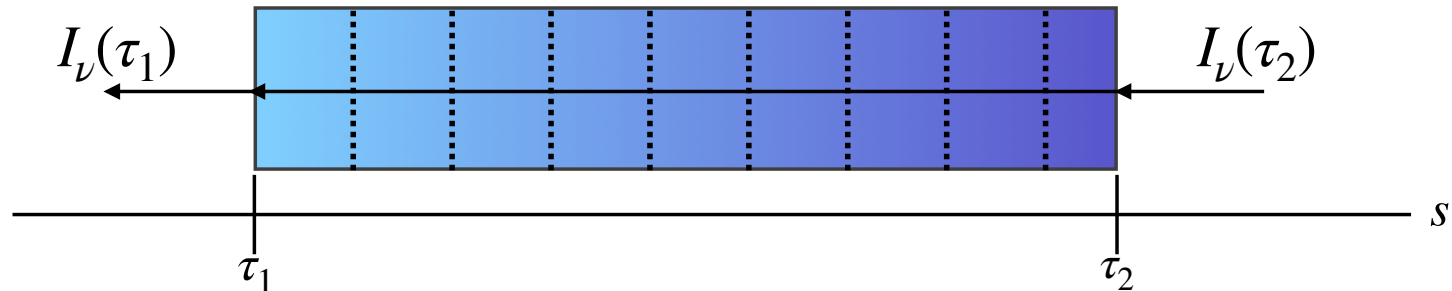
Radiative Transfer (of EM wave)

- Differential form

- $\frac{dI_\nu}{d\tau} = -I_\nu + S_\nu$

- A general solution in integral form (considering a one dimension plane parallel slab geometry)

- $I_\nu(\tau_1) = I_\nu(\tau_2) e^{-(\tau_2-\tau_1)} + \int_{\tau_1}^{\tau_2} S_\nu(t) e^{-(t-\tau_1)} dt$



Radiative Transfer (of EM wave)

- Differential form

- $\frac{dI_\nu}{d\tau} = -I_\nu + S_\nu$

- A general solution in integral form (considering a one dimension plane parallel slab geometry)

- $I_\nu(\tau_1) = I_\nu(\tau_2) e^{-(\tau_2-\tau_1)} + \int_{\tau_1}^{\tau_2} S_\nu(t) e^{-(t-\tau_1)} dt$

- The above equation can be fully solved if S_ν is known. However, $S_\nu (\equiv j_\nu/\alpha_\nu)$ generally depends on the (local) radiation field. Namely, the emission and absorption properties of the medium depend on I_ν . Hence, given the physical condition, one needs to solve I_ν and S_ν numerically and iteratively.

Radiative Transfer (of EM wave)

- Differential form

- $\frac{dI_\nu}{d\tau} = -I_\nu + S_\nu$

- A general solution in integral form (considering a one dimension plane parallel slab geometry)

- $I_\nu(\tau_1) = I_\nu(\tau_2) e^{-(\tau_2-\tau_1)} + \int_{\tau_1}^{\tau_2} S_\nu(t) e^{-(t-\tau_1)} dt$

- Think about special cases

- No foreground emission term, namely, first term only
- No background emission term, namely, second term only
- constant source function in optically thick case vs. optically thin case



**Mechanisms (of EM Waves) =
Radiative Processes**

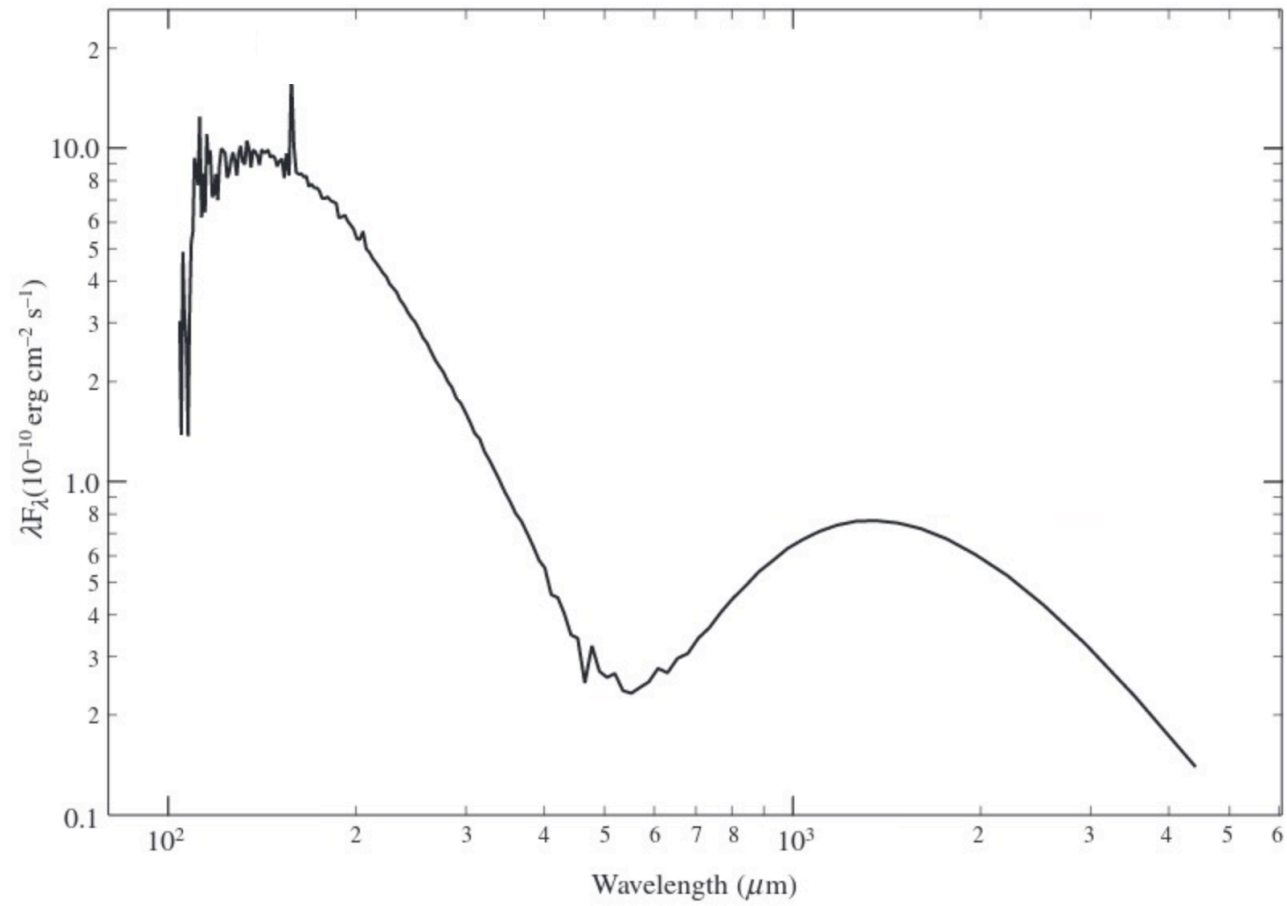


Figure 1.3

The integrated spectrum of the galactic plane as observed by the *Cosmic Background Explorer* (COBE) satellite.

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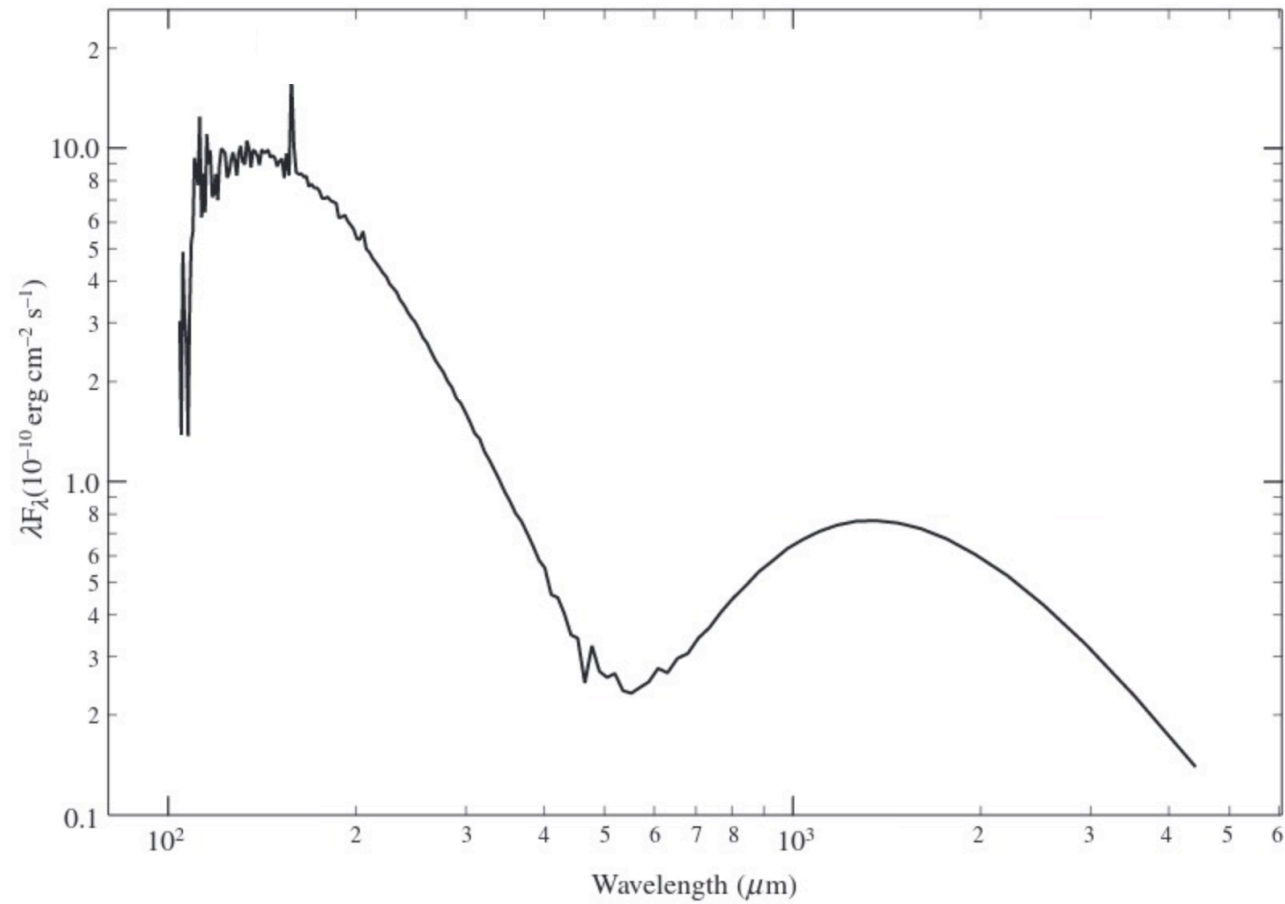


Figure 1.3

The integrated spectrum of the galactic plane as observed by the *Cosmic Background Explorer* (COBE) satellite.

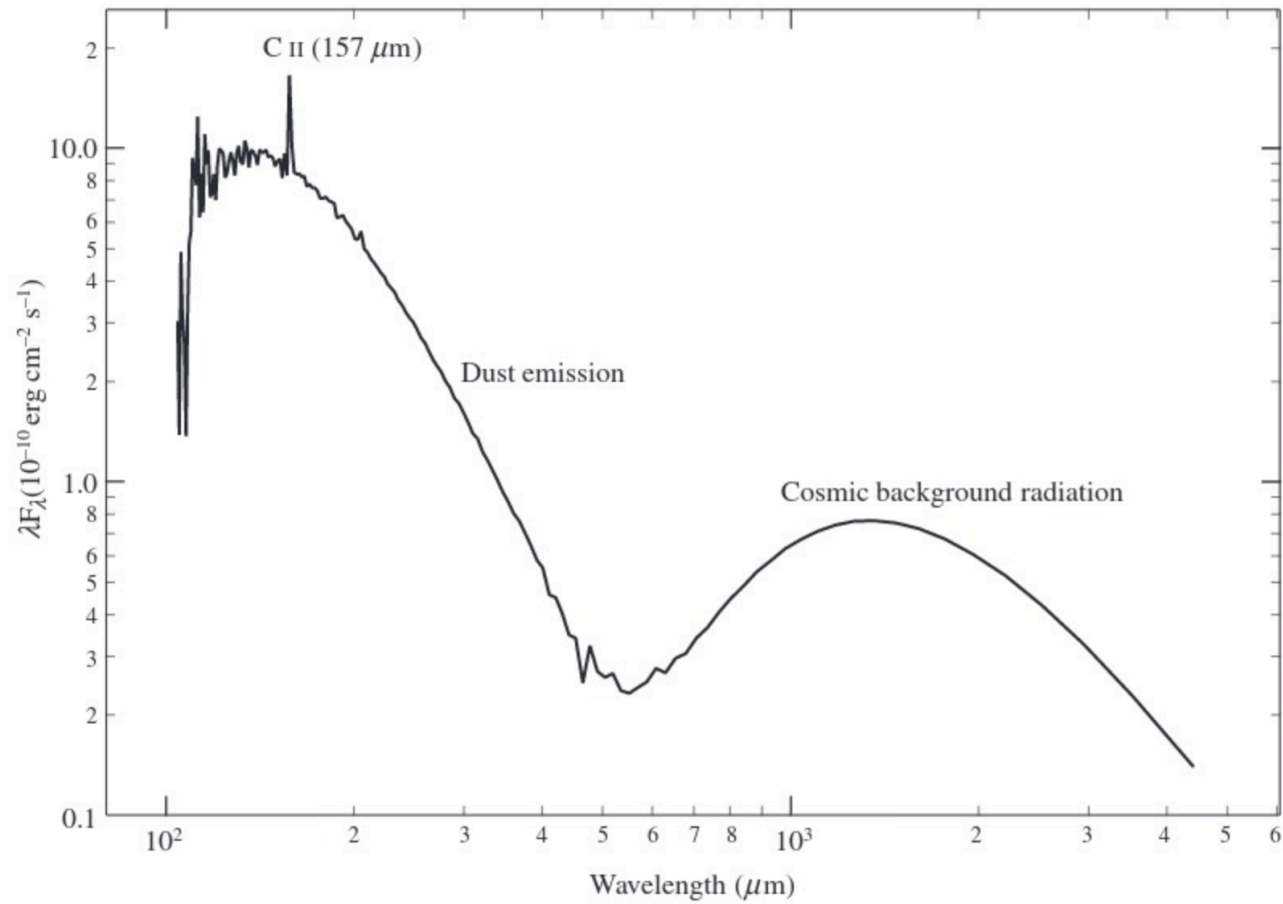
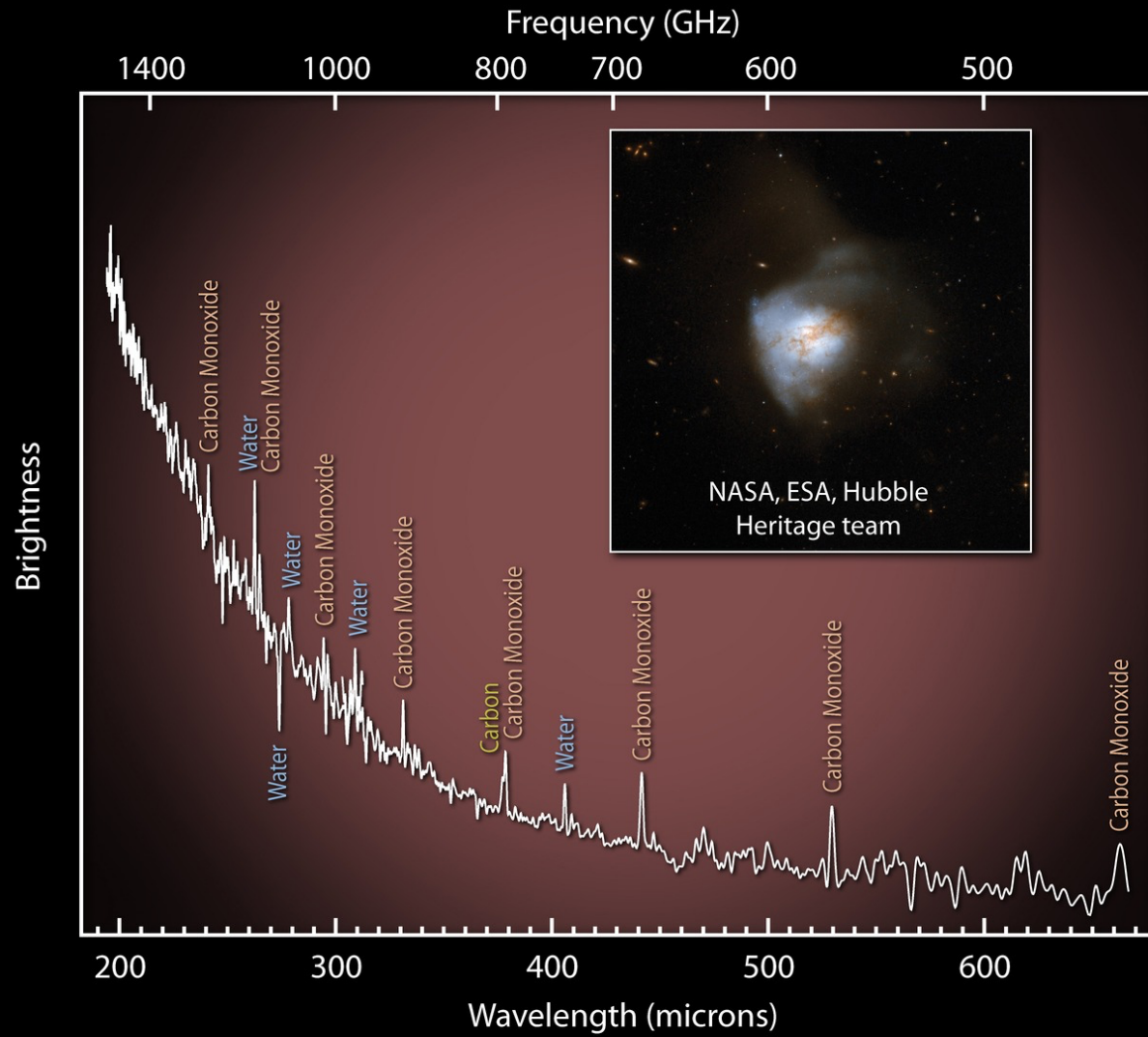


Figure 1.3

The integrated spectrum of the galactic plane as observed by the *Cosmic Background Explorer* (COBE) satellite. Other than the cosmic background radiation, which is seen over the whole sky, the ISM shows strong continuum emission from cool dust of a temperature of ~ 20 K. A line due to ionized carbon is also prevalent on the galactic plane.



Arp 220

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Radiative Processes (of EM wave)

Continuum
(SED: spectral Energy Distribution)

Line
(Intensity, Frequency Center and Width, or Profile)

Thermal
(characterized by a single
(kinetic) temperature)

Free-Free
Dust
Inverse Compton Scattering

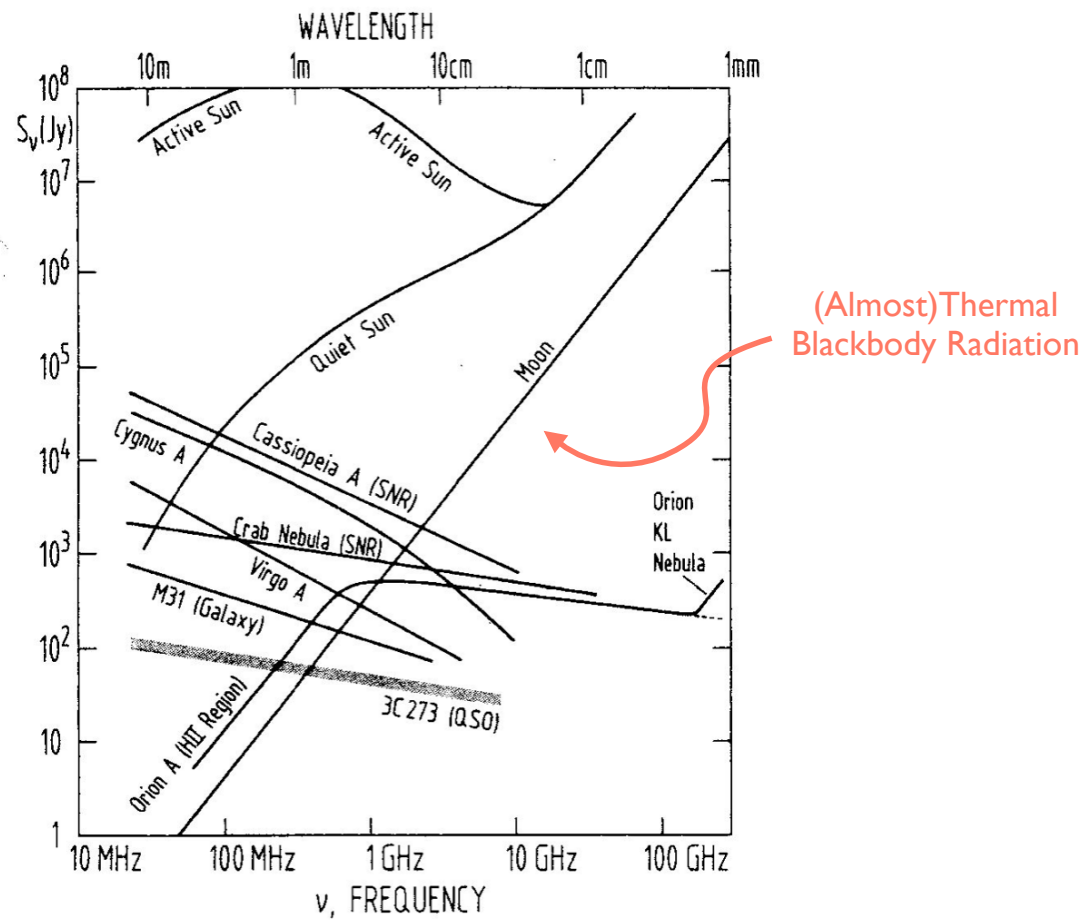
Atomic (Recombination)
Molecular/Ionic Line

Non-Thermal
(characterized NOT by a single
(kinetic) temperature) but
energy distribution, e.g.)

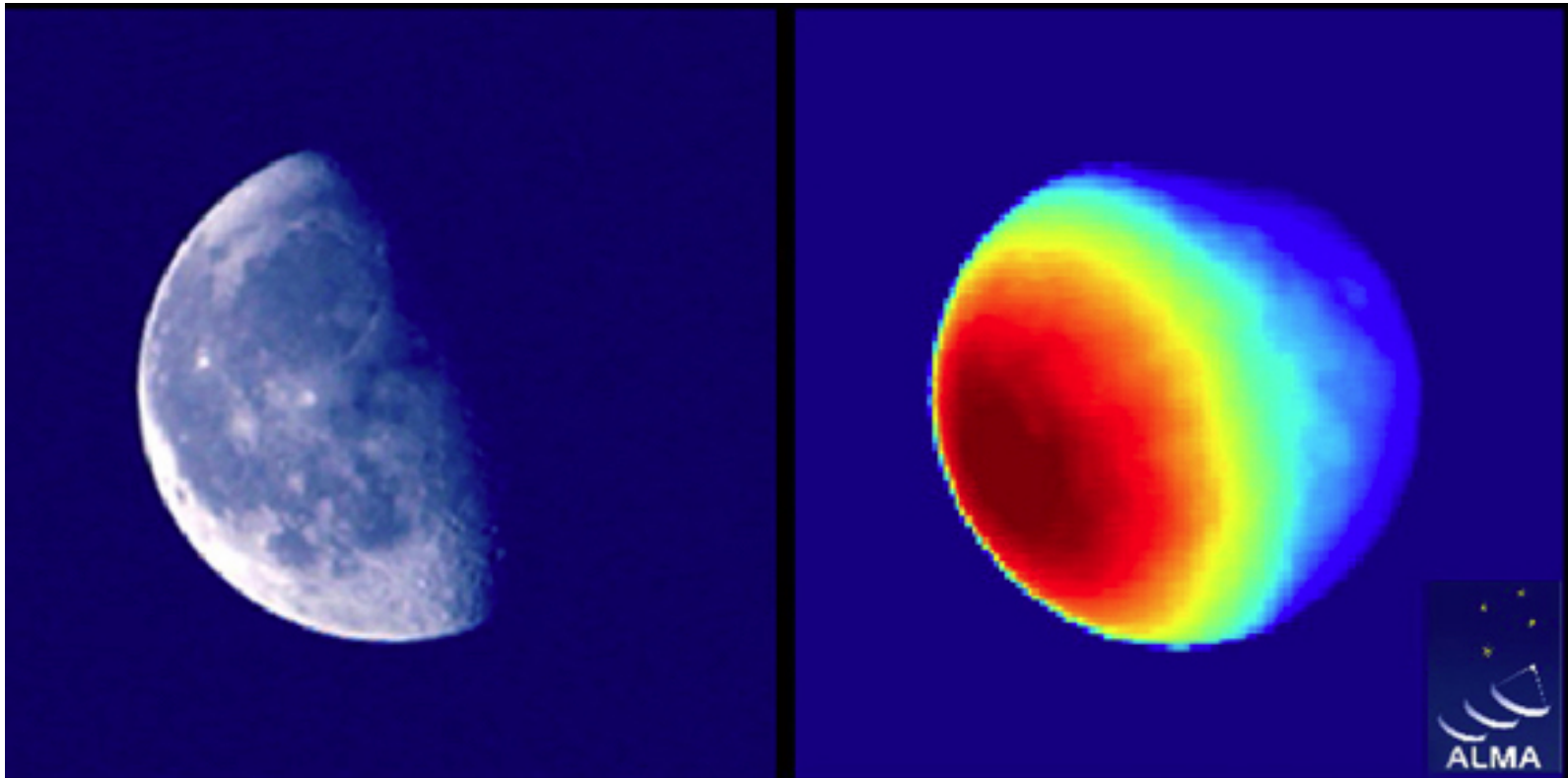
Synchrotron

Maser

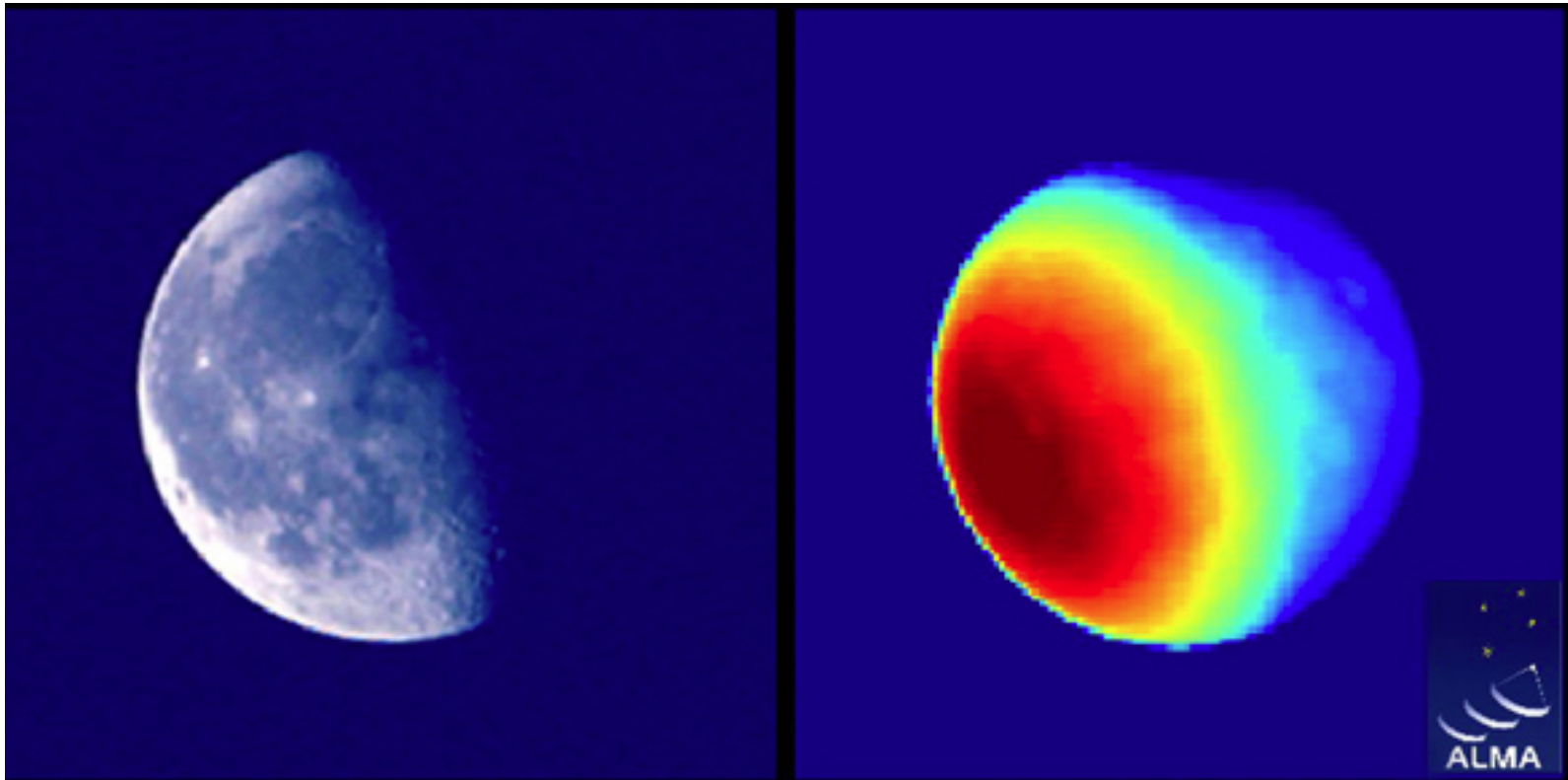
Spectral Energy Distribution (in radio regime)



The Power Spectrum (in radio regime)



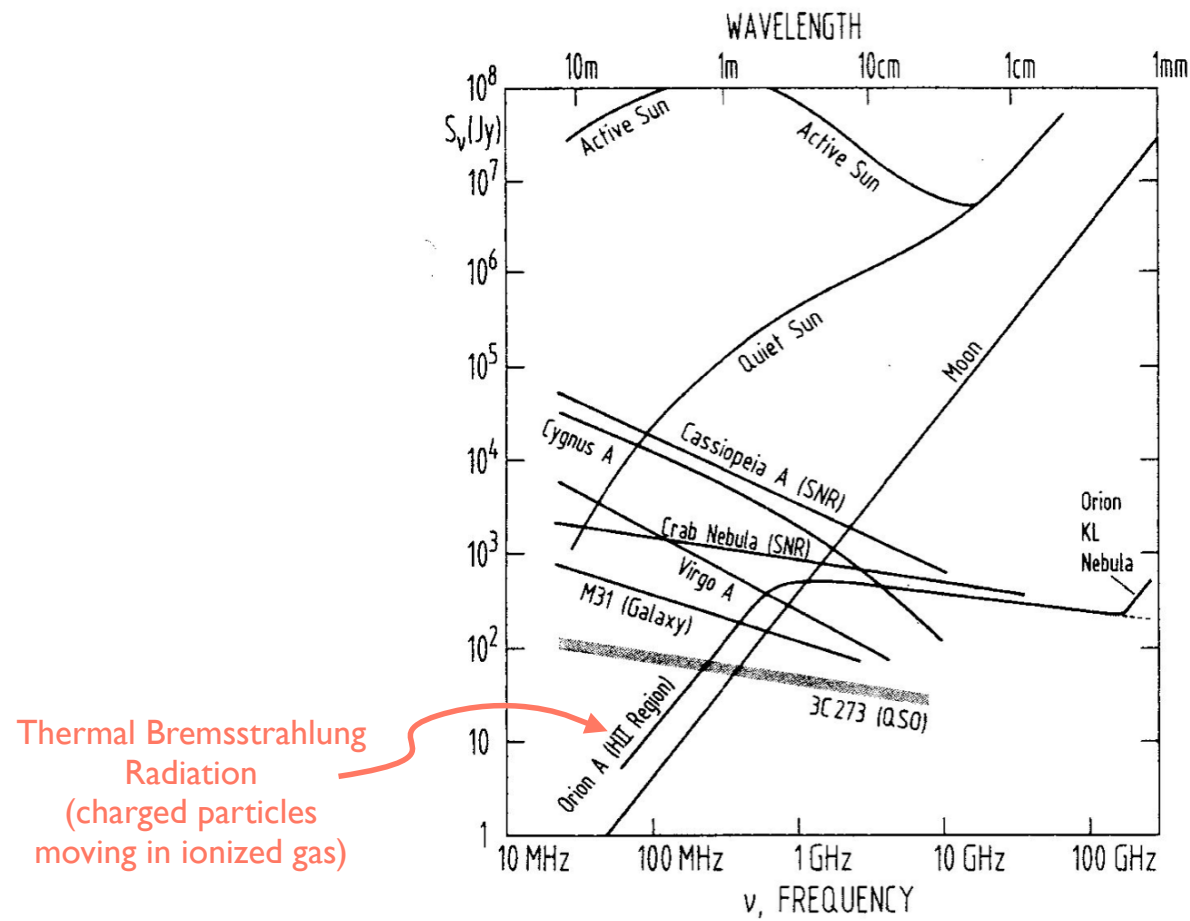
The Power Spectrum (in radio regime)



First radio image of the Moon taken with a 12-meter ALMA antenna. The optical image at left shows the sunlight reflected by the Moon's surface, whereas the radio image shows the physical temperature distribution of the Moon. The ALMA image clearly shows the temperature distribution of the Moon, including weak radio emission from the dark side of the Moon.

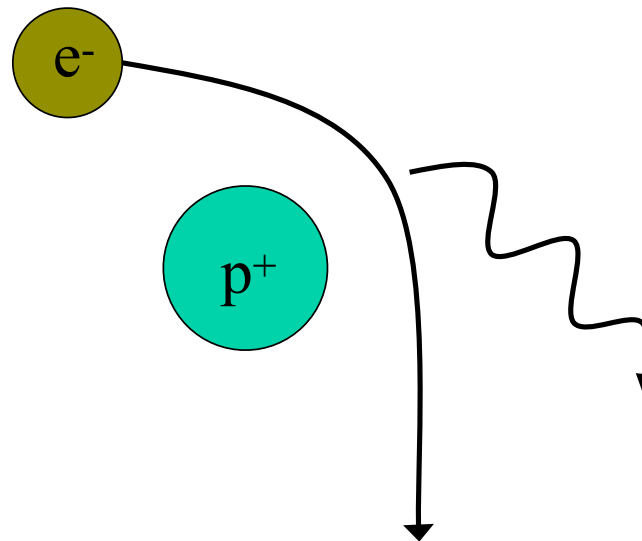
(Source: <https://public.nrao.edu/gallery/moon-as-seen-by-alma/>)

Spectral Energy Distribution (in radio regime)



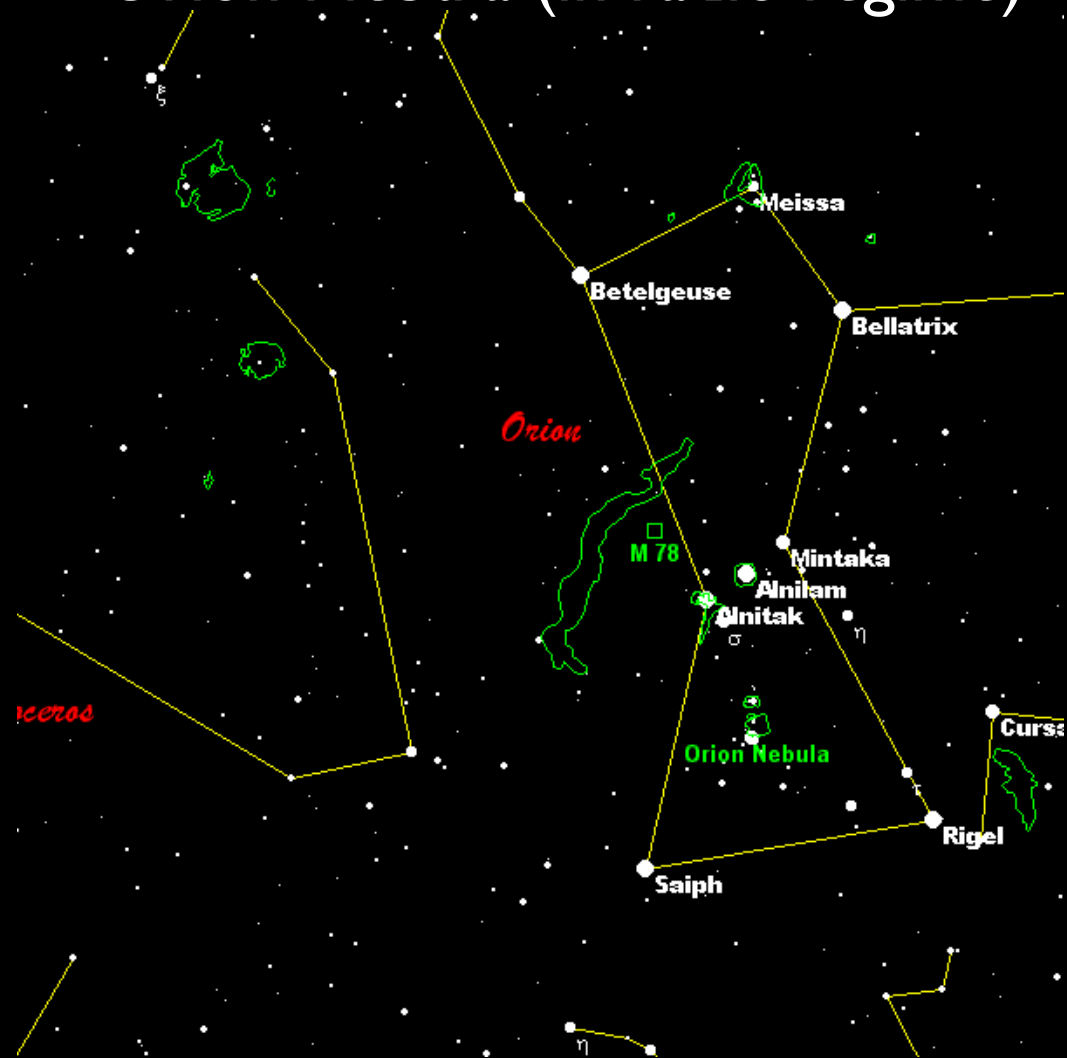
Radiative Process (Free-Free)

Bremsstrahlung (free-free)

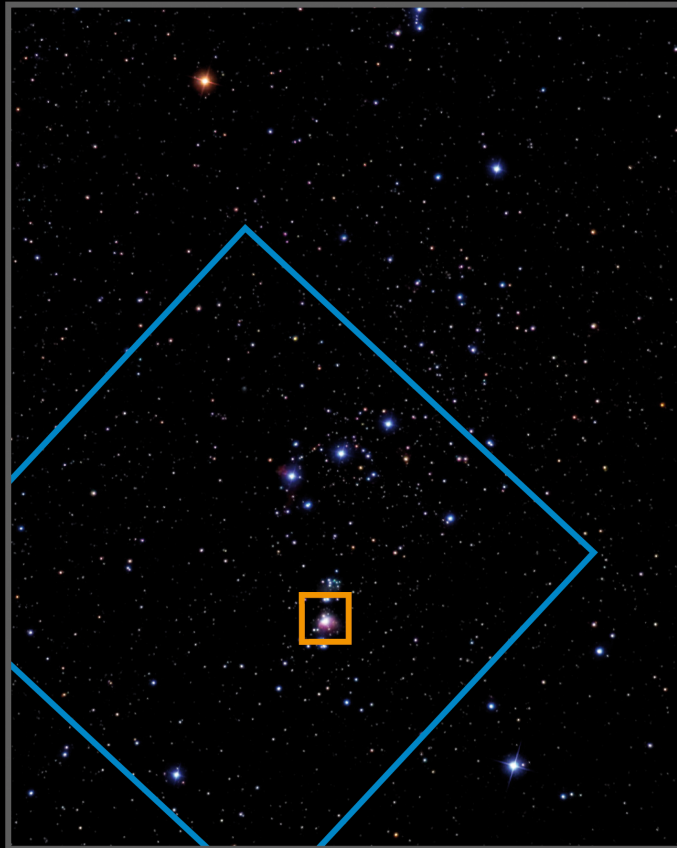


Ionized gas:
e.g., H II region
Intracluster medium

Orion Nebula (in radio regime)

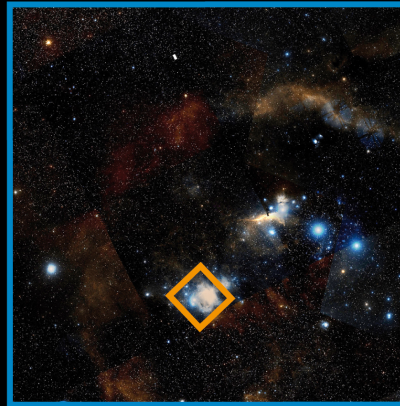


The Orion Nebula

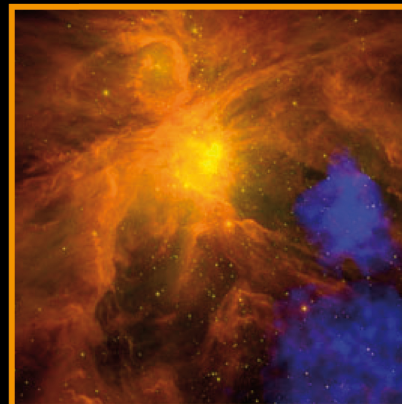
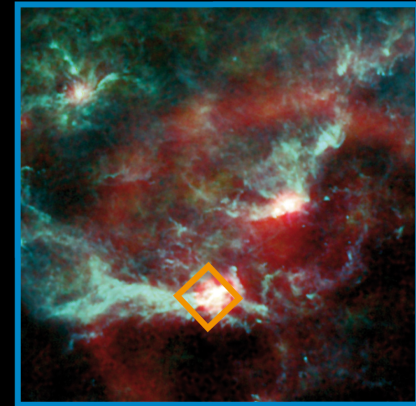


VISIBLE
ground-based observatory (Kosmos Gazeas)

VISIBLE
ground-based observatory
Digitized Sky Survey



MICROWAVE & SUB-MM
Planck satellite



MID-INFRARED (orange/yellow)
Spitzer Space Telescope
X-RAY (blue)
XMM-Newton space observatory



VISIBLE & NEAR-INFRARED
Hubble Space Telescope

Orion Nebula (in radio regime)

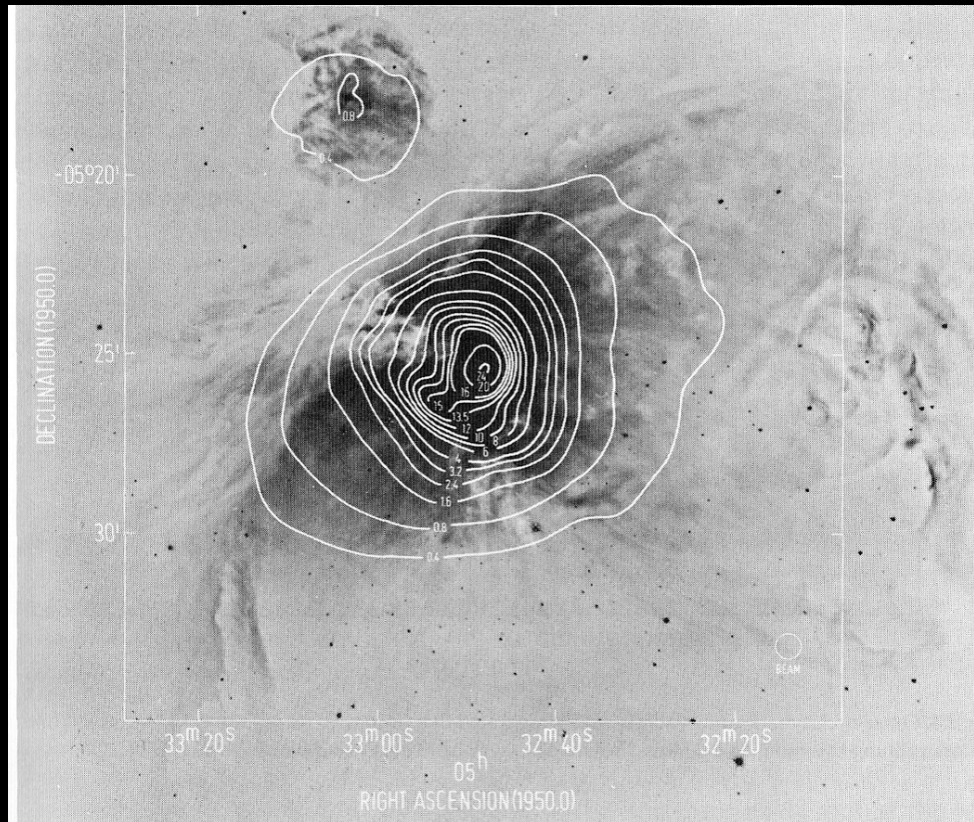


Fig. 2.3. The 23-GHz radio continuum contours, in units of main-beam brightness temperature, on an optical photo in H α and [NII] of NGC 1976 (Orion A, M42), below, and NGC 1982 (M43), above. The angular resolution is 42", which at the distance of Orion A, corresponds to a linear resolution of 0.10 pc (Wiley and Doyle, 1984).

Spectral Energy Distribution (in radio regime)

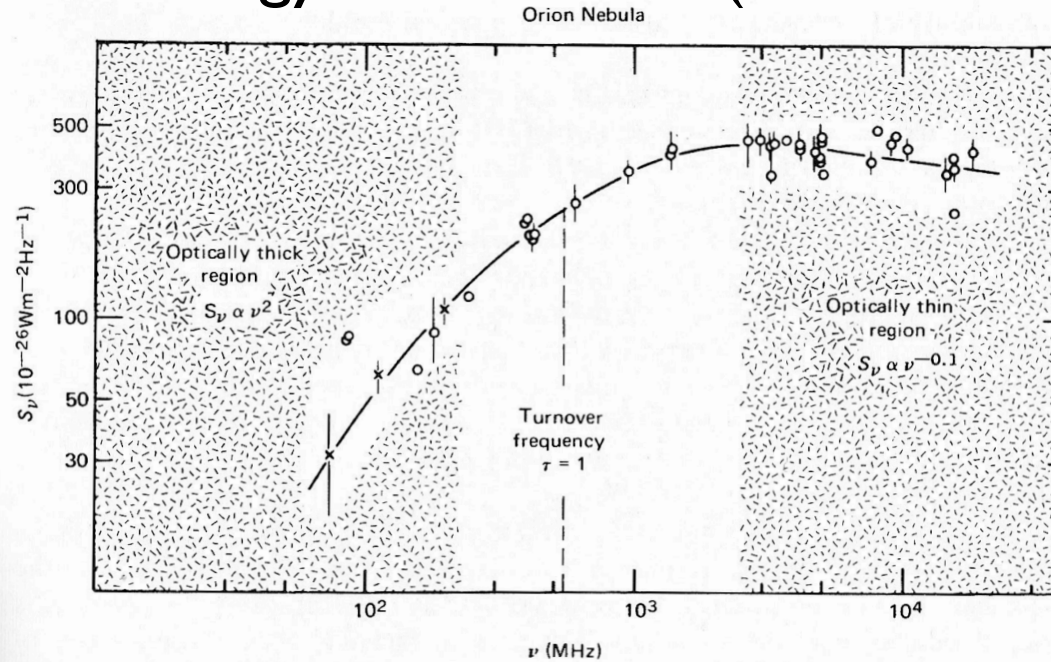


Fig. 2.2. Spectral flux density of the Orion Nebula plotted against frequency. The shaded regions mark the optically thick and thin regions of the spectrum. (Reprinted with permission by Gordon and Breach Science Publishers from: Terzian, Y. and Parrish A., *Astrophysical Letters*. Vol. 5(1970), pp. 261.

$$\tau_\nu \approx 8.235 \times 10^{-2} \left(\frac{T_e}{K}\right)^{-1.35} \left(\frac{\nu}{\text{GHz}}\right)^{-2.1} \left(\frac{EM}{\text{pc cm}^{-6}}\right) \alpha(\nu, T)$$

$$\frac{EM}{\text{pc cm}^{-6}} = \int \left(\frac{n_e}{\text{cm}^{-3}}\right)^2 d\left(\frac{s}{\text{pc}}\right)$$

$$\alpha(\nu, T) \sim 1$$

Spectral Energy Distribution (in radio regime)

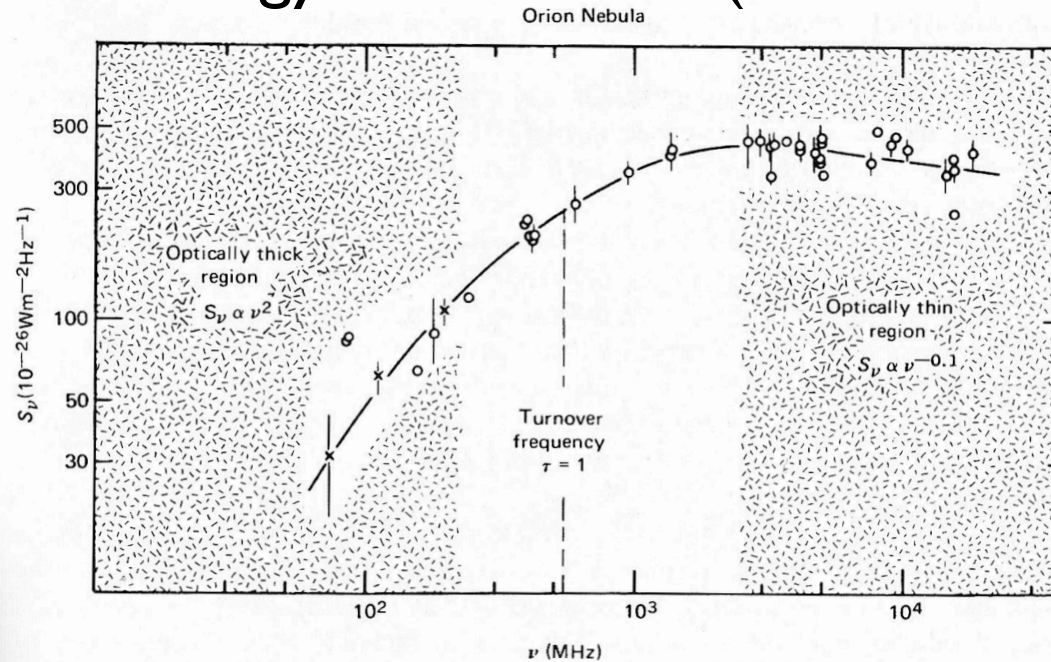


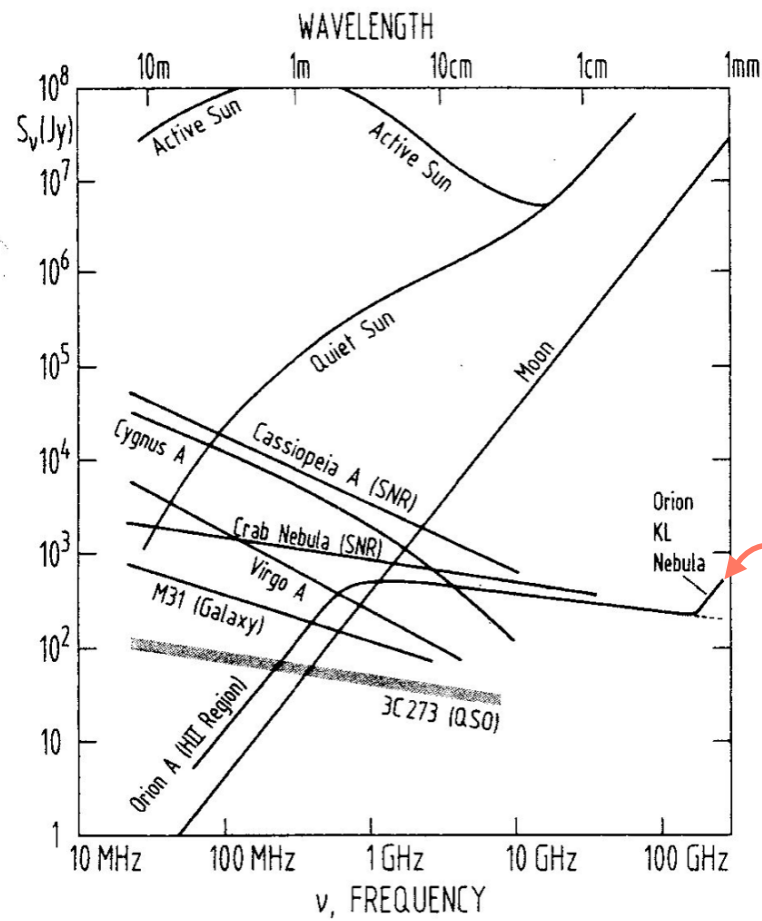
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Emission Measure

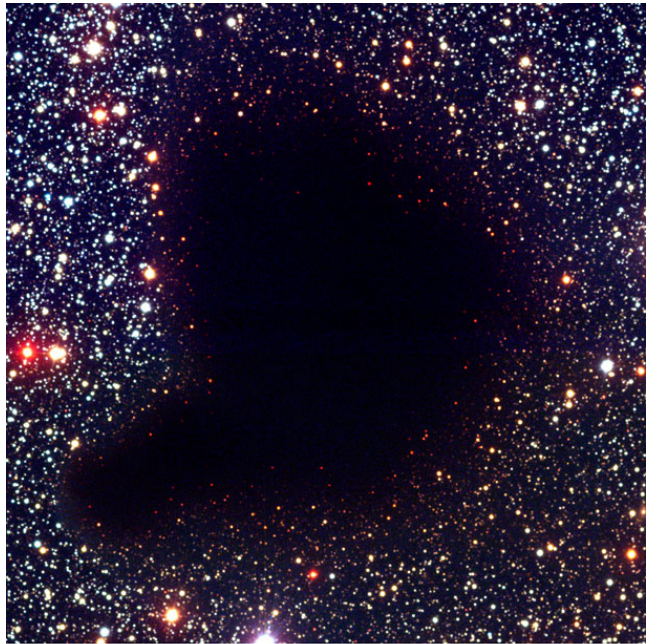
$$\frac{EM}{\text{pc cm}^{-6}} = \int \left(\frac{n_e}{\text{cm}^{-3}} \right)^2 d\left(\frac{s}{\text{pc}} \right)$$

Spectral Energy Distribution (in radio regime)

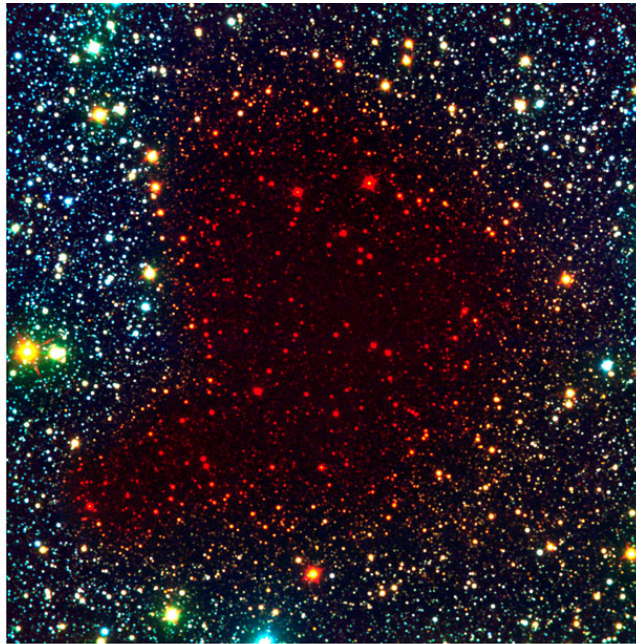


Thermal
(Almost Blackbody)
Greybody Radiation
(by dust particles)

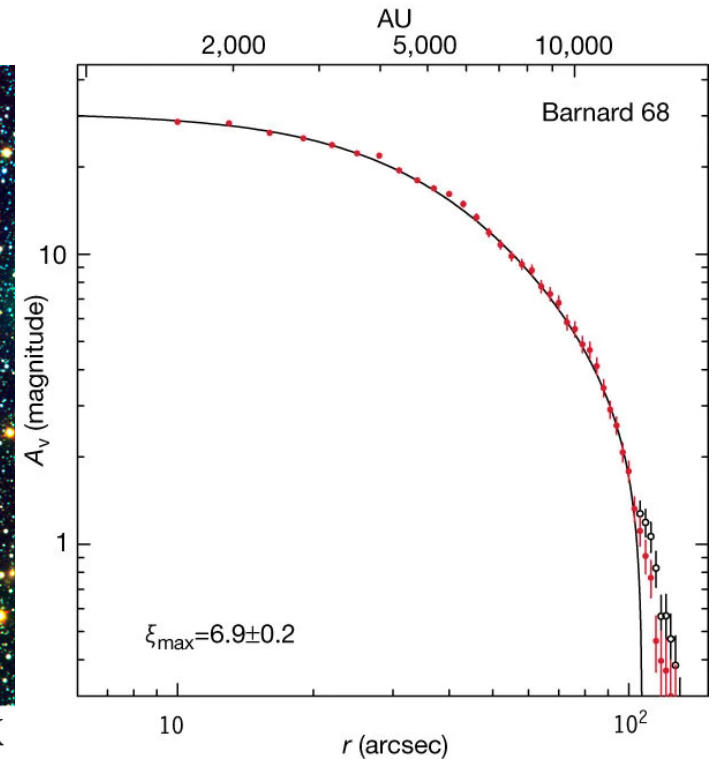
Bok Globule B68



B, V, I

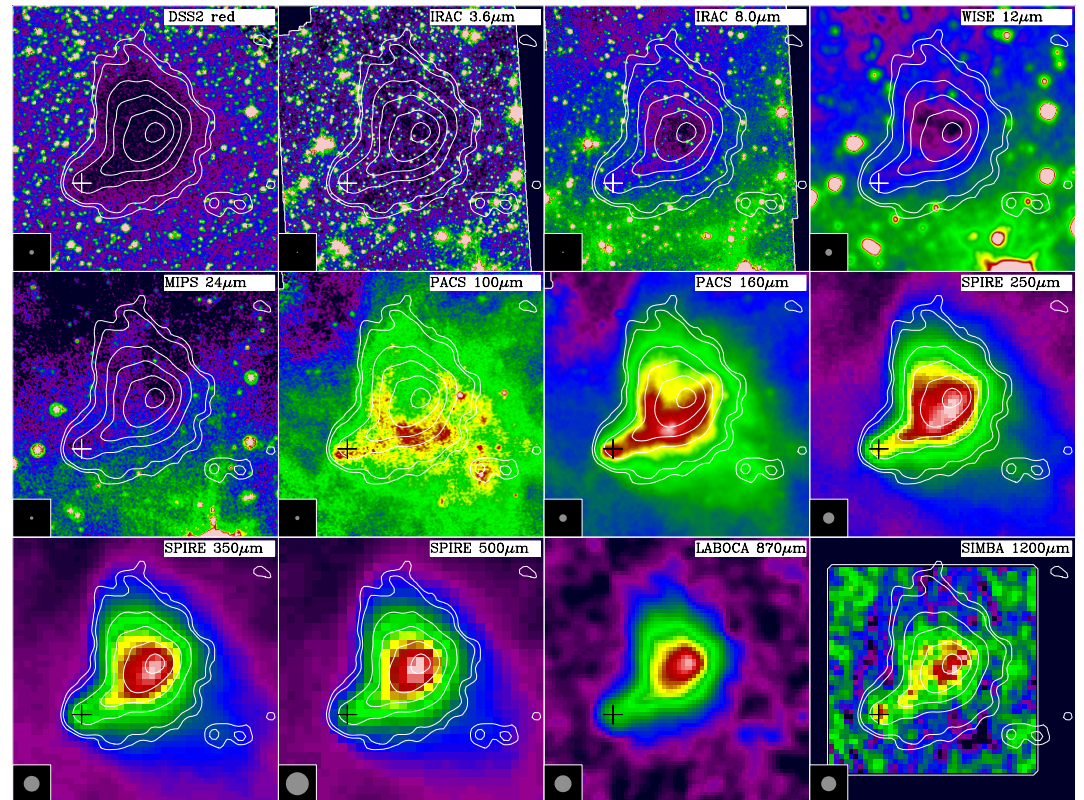
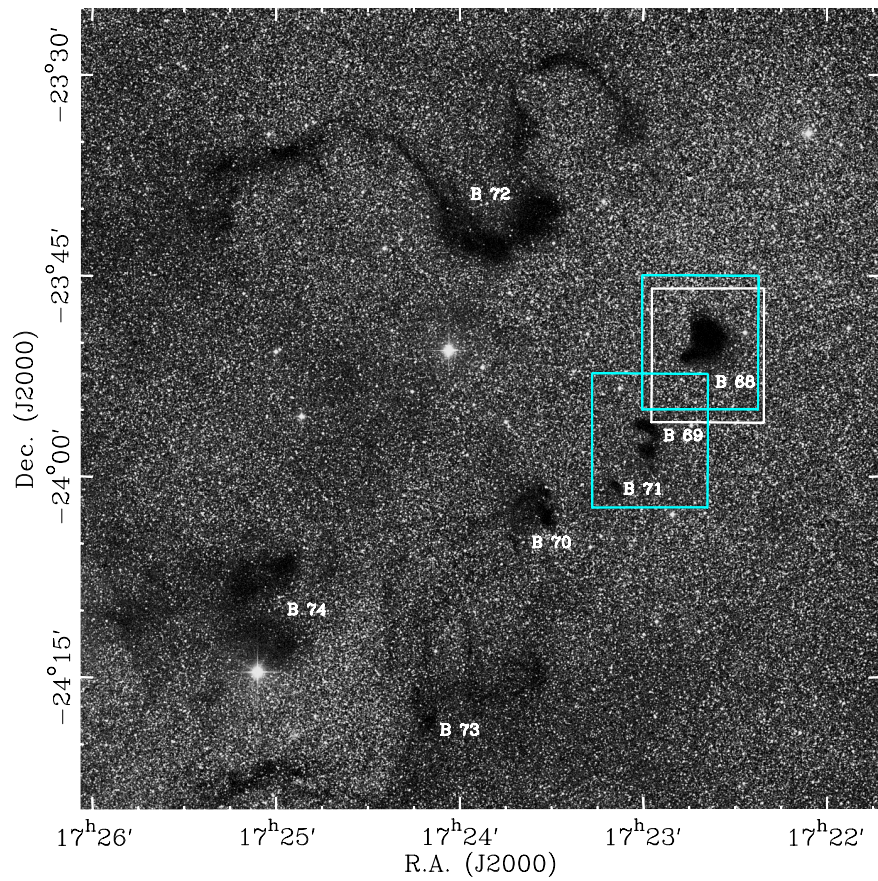


B, I, K



Alves et al. (2001)

Bok Globule B68

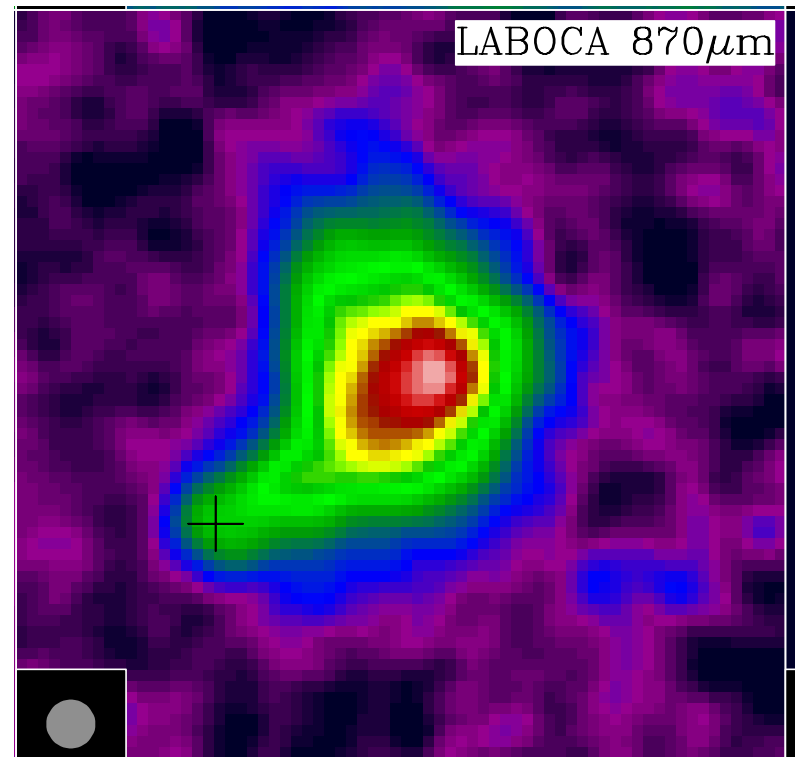
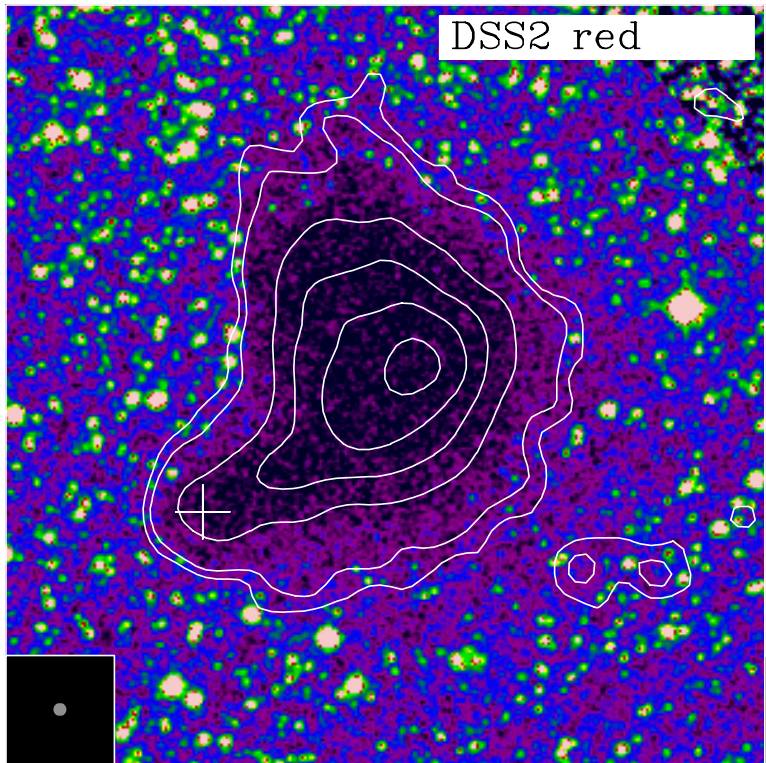


Nielbock et al. (2012) A&A

Bok Globule B68

Recall radiative transfer:

(1) hot background vs. cold foreground + (2) optical depth+ (3) filling factor

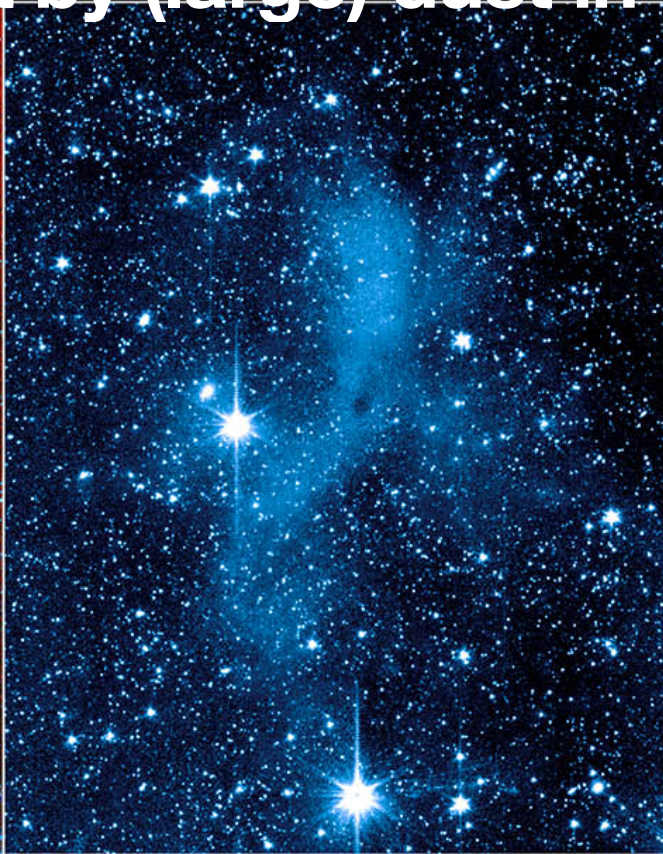


Nielbock et al. (2012)

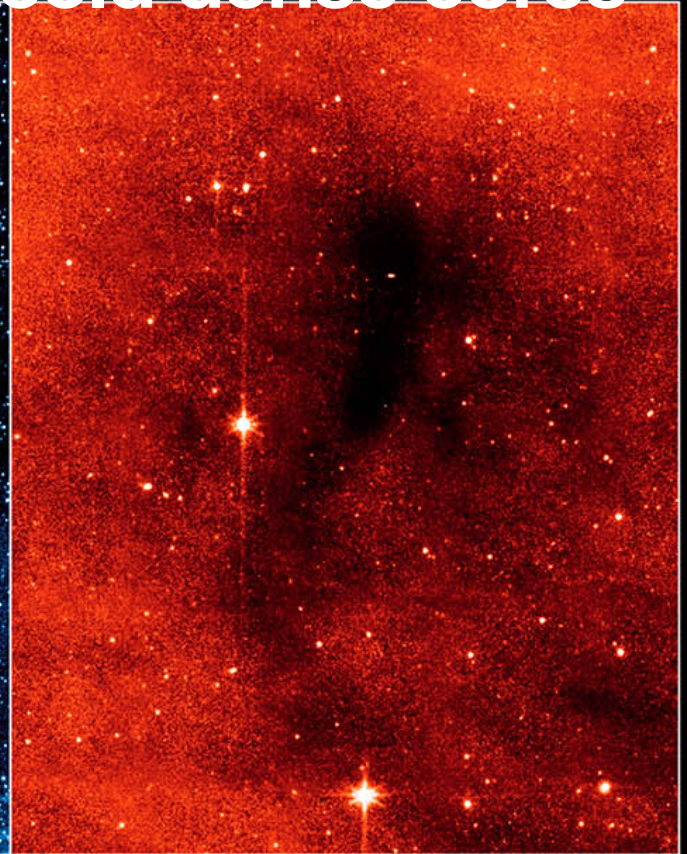
scattered IR light by (large) dust in cold dense cores



Composite Image (3.6–8.0 microns)



"Coreshine" (3.6 microns)



Dark Cloud Core (8.0 microns)

"Coreshine" in the L183 Dark Cloud

NASA / JPL-Caltech / L. Pagani (Observatoire de Paris/CNRS)

Spitzer Space Telescope • IRAC

sig10-020

Radiative Process (Thermal Dust)

- dust extinction (absorption + scattering) and (nearly BB) emission

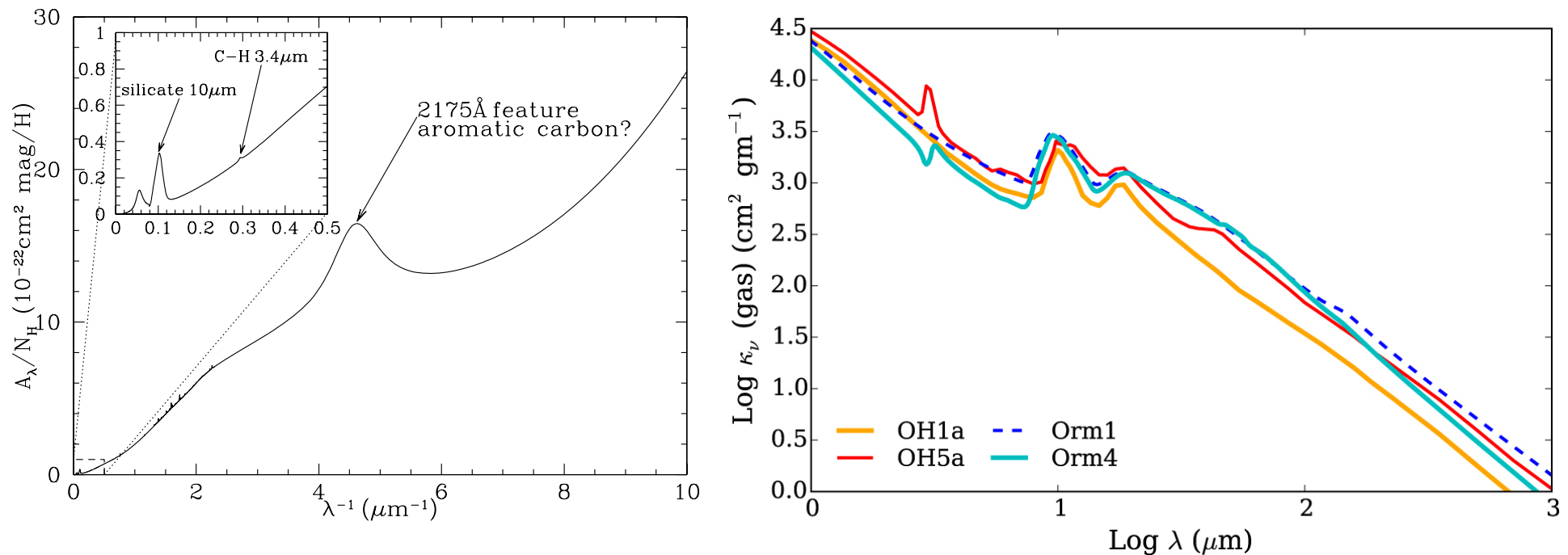


Figure 21.1 Extinction versus inverse wavelength λ^{-1} on a typical sightline in the local diffuse ISM. The inset shows the extinction at $\lambda > 2 \mu\text{m}$.

Webb et al. (2017)

Draine (Physics of Interstellar and Intergalactic Medium)

Radiative Process (Thermal Dust)

$$S_\nu(\nu) = \Omega \left(1 - e^{-\tau(\nu)}\right) \left(B_\nu(\nu, T_d) - I_{bg}(\nu)\right) \quad (5)$$

with

$$\tau(\nu) = N_H m_H \frac{M_d}{M_H} \kappa_d(\nu)$$

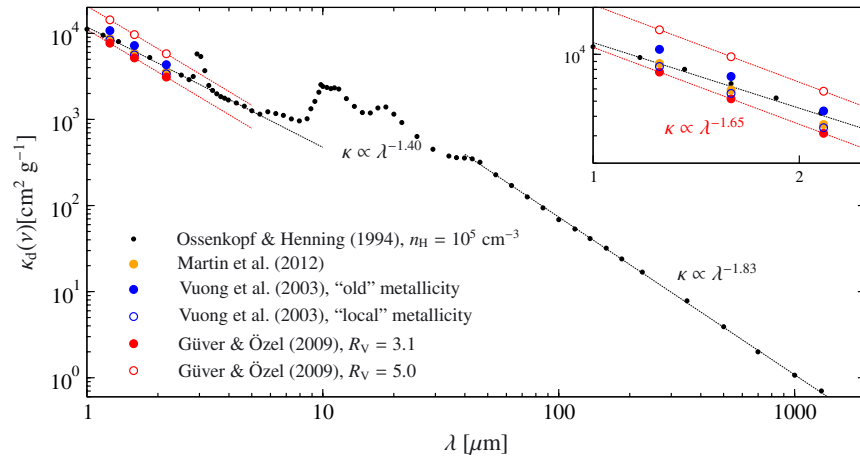


Fig. 4. Dust opacities taken from [Ossenkopf & Henning \(1994\)](#) (coagulated, with thin ice mantles, $n_H = 10^5 \text{ cm}^{-3}$) and from [Cardelli et al. \(1989\)](#), derived by using a gas-to-dust ratio of 150 ([Sodroski et al. 1997](#)). Different ratios of N_H/A_λ have been used ([Vuong et al. 2003](#); [Güver & Özel 2009](#); [Martin et al. 2012](#)) when applying Eqs. (3) and (4). The insert shows an enlargement of the range covered by the *JHK* bands.

(6)

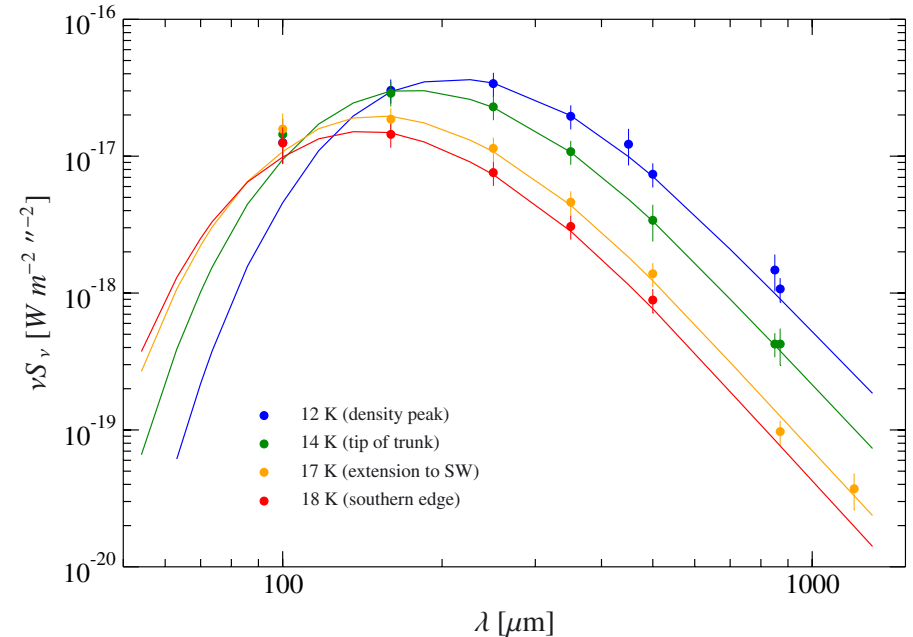


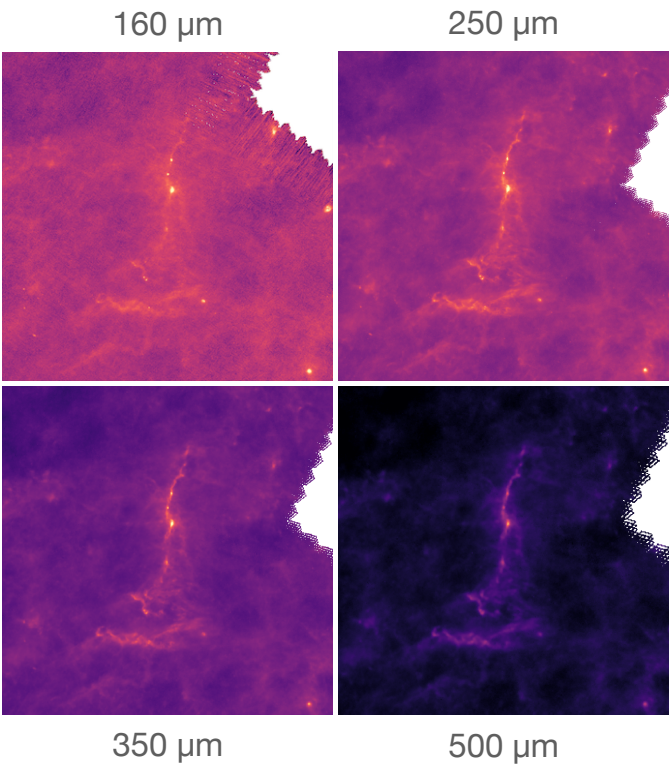
Fig. 5. Spectral energy distributions at four selected positions across B68. The dots represent $10'' \times 10''$ pixel values extracted from the maps that are used for the modified black body fitting. The solid curves are the SEDs fitted for a given dust temperature and column density.

Nielbock et al. (2012)

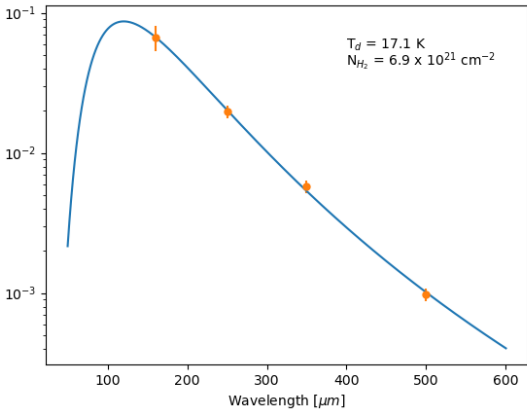
Slide Credit: Seamus Clarke

Column density estimation

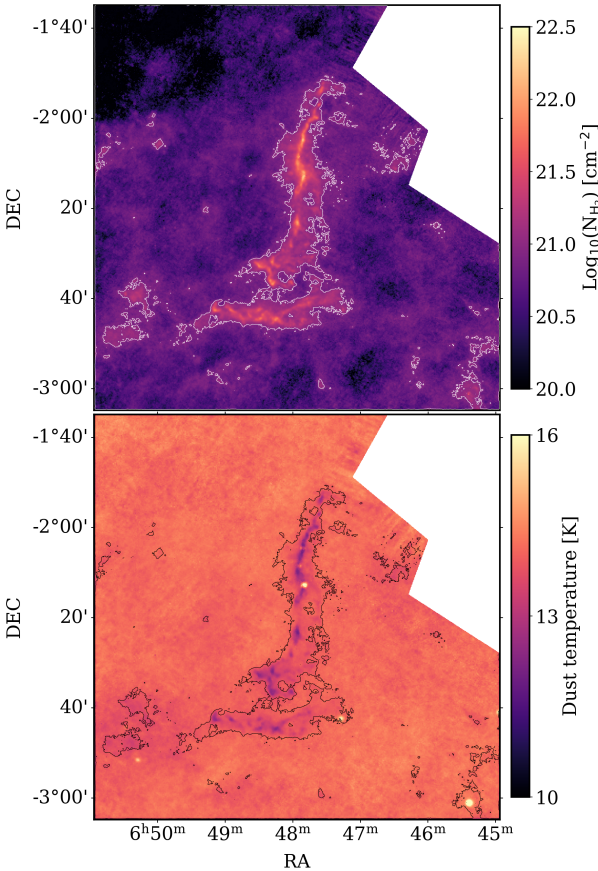
Fitting spectral energy distributions



$$I_{\nu,\text{obs}} = \tau_{\nu} B_{\nu}(T_d) = \kappa_{\nu} N_d B_{\nu}(T_d)$$



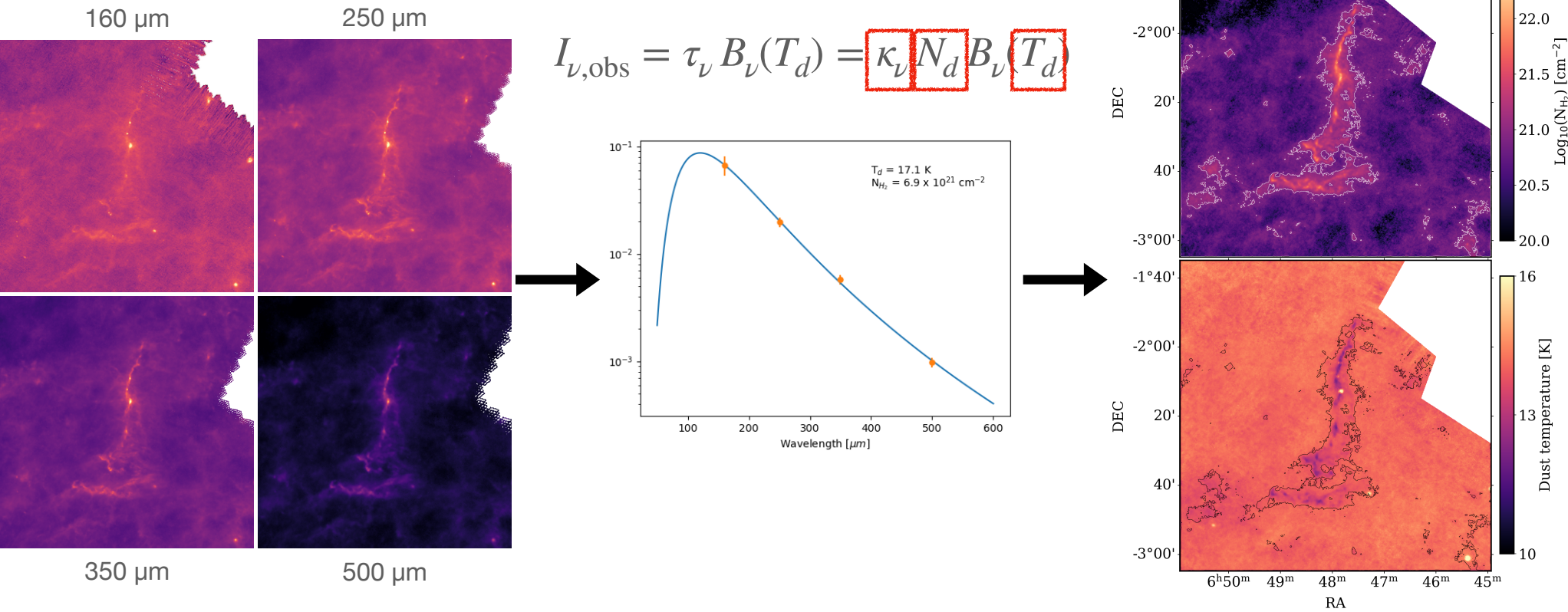
Recall : Background Radiation



Slide Credit: Seamus Clarke

Column density estimation

Fitting spectral energy distributions



Radiative Process (Thermal Dust)

A.2. Radiative transfer

A.2.1. Equation of radiative transfer

The intensity emitted by a medium of temperature T and of optical depth τ_ν at the frequency ν is given by the equation of radiative transfer, which reads

$$I_\nu = B_\nu(T) (1 - e^{-\tau_\nu}) \quad (\text{A.6})$$

in the case of local thermal equilibrium. Here B_ν is the Planck function. For the optical depth,

$$\tau_\nu = \int \kappa_\nu \varrho \, ds, \quad (\text{A.7})$$

where κ_ν is the (specific) absorption coefficient (i.e., per mass) or dust opacity. If most hydrogen is in molecules, the optical depth can be related to the column density of molecular hydrogen,

$$N_{\text{H}_2} = \int n_{\text{H}_2} \, ds = \int \frac{\varrho}{\mu_{\text{H}_2} m_{\text{H}}} \, ds = \frac{1}{\mu_{\text{H}_2} m_{\text{H}} \kappa_\nu} \int \kappa_\nu \varrho \, ds, \quad (\text{A.8})$$

and thus

$$N_{\text{H}_2} = \frac{\tau_\nu}{\mu_{\text{H}_2} m_{\text{H}} \kappa_\nu}, \quad (\text{A.9})$$

where n_{H_2} is the particle density of hydrogen molecules. This reads in a usable form

$$N_{\text{H}_2} = 2.14 \times 10^{25} \, \text{cm}^{-2} \tau_\nu \left(\frac{\kappa_\nu}{0.01 \, \text{cm}^2 \, \text{g}^{-1}} \right)^{-1}, \quad (\text{A.10})$$

$$I_\nu \approx B_\nu(T) \tau_\nu. \quad (\text{A.11})$$

A.4.1. Flux per beam and column density

Equations (A.9, A.11, A.18) relate optical depth, column density, intensity, and the observed flux per beam with each other. Rearrangement yields

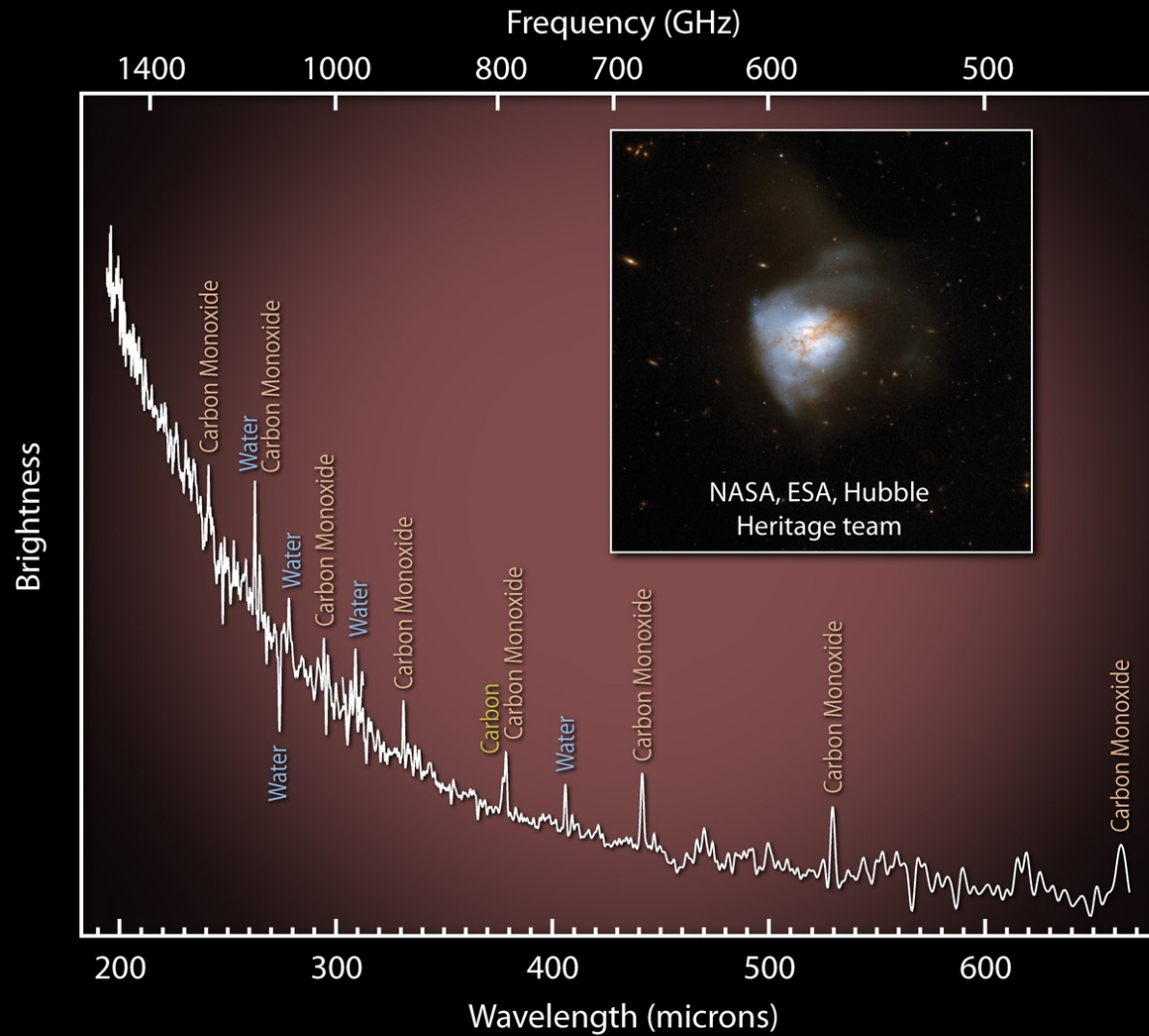
$$N_{\text{H}_2} = \frac{F_\nu^{\text{beam}}}{\Omega_{\text{A}} \mu_{\text{H}_2} m_{\text{H}} \kappa_\nu B_\nu(T)}, \quad (\text{A.26})$$

which reads

$$N_{\text{H}_2} = 2.02 \times 10^{20} \, \text{cm}^{-2} \left(e^{1.439(\lambda/\text{mm})^{-1}(T/10 \, \text{K})^{-1}} - 1 \right) \left(\frac{\lambda}{\text{mm}} \right)^3 \cdot \left(\frac{\kappa_\nu}{0.01 \, \text{cm}^2 \, \text{g}^{-1}} \right)^{-1} \left(\frac{F_\nu^{\text{beam}}}{\text{mJy beam}^{-1}} \right) \left(\frac{\theta_{\text{HPBW}}}{10 \, \text{arcsec}} \right)^{-2} \quad (\text{A.27})$$

in useful units.

Kauffmann et al. (2008)



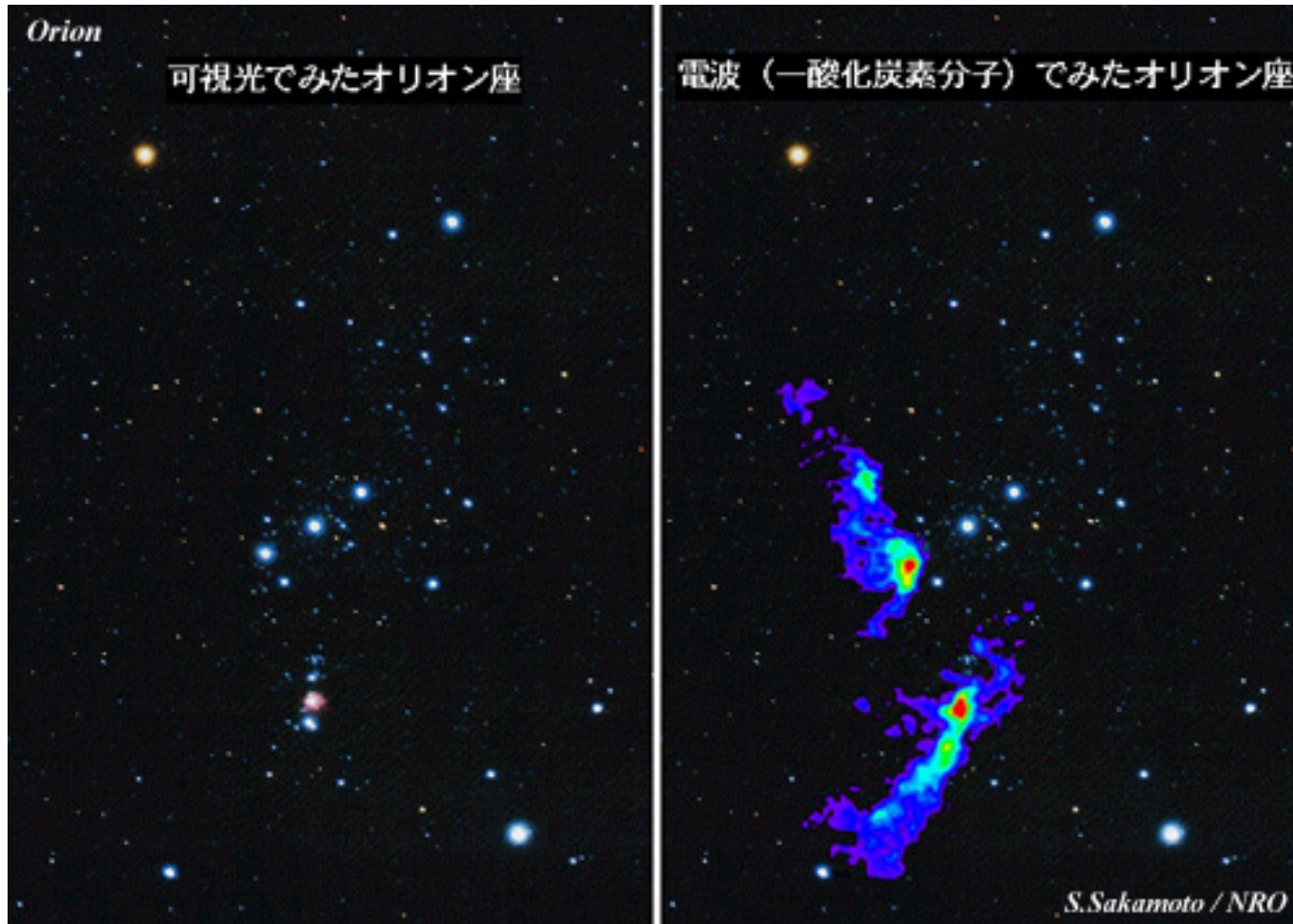
Arp 220

© ESA and the SPIRE consortium

Radiative Process (Spectral Line)

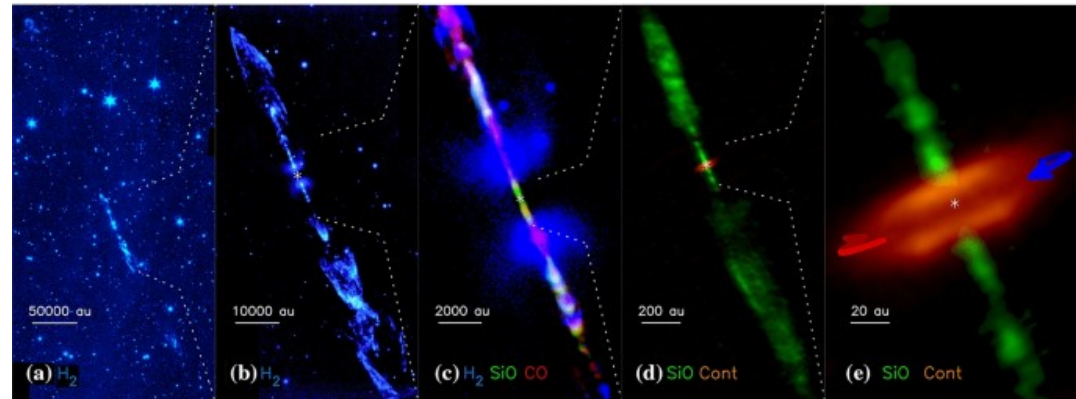
Radiation at specific wavelengths between discrete energy levels

Radiative Process (Spectral Line)



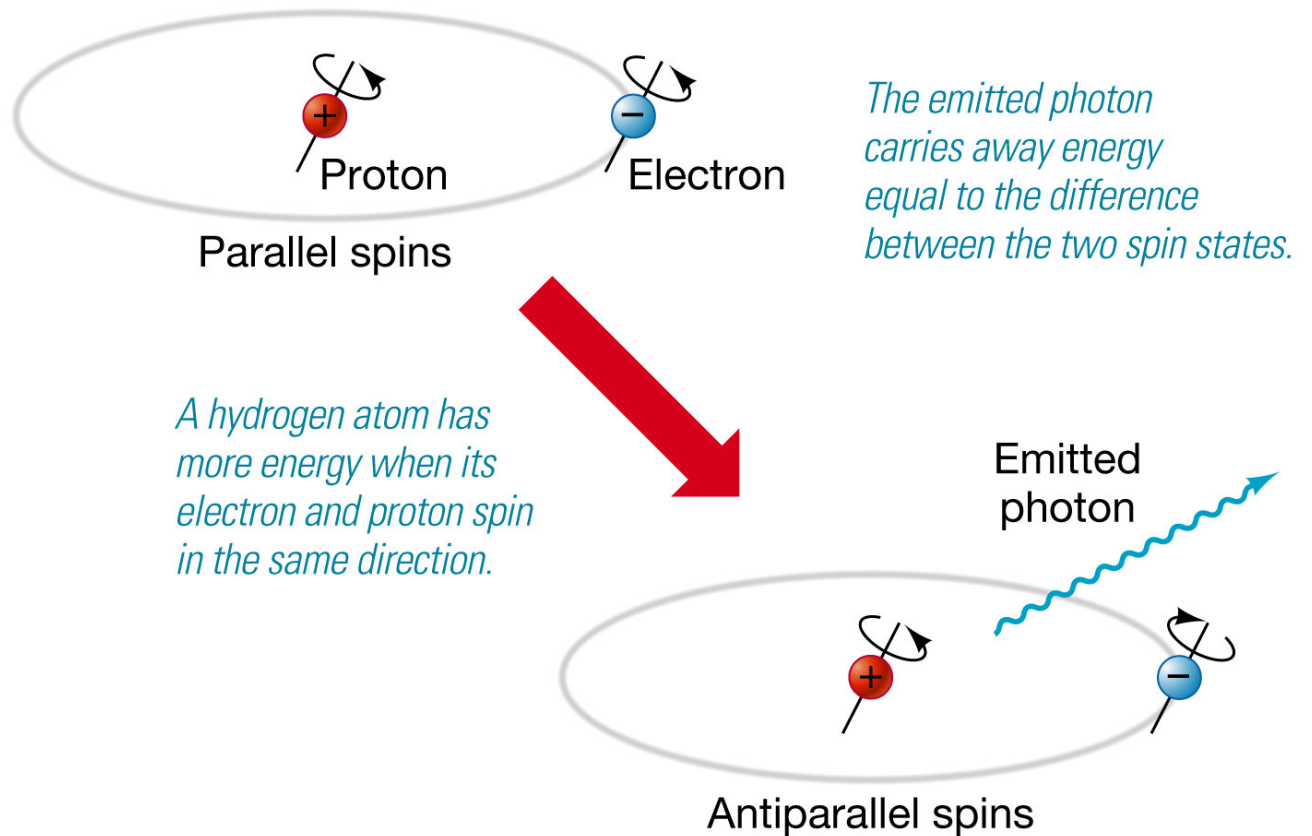
Radiative Process (Spectral Line)

- (Atomic/Ionic) Electronic
 - $\sim 1\text{-}10\text{ eV}$
 - optical - UV wavelengths
 - H α , [OIII], [SII]
- (Molecular) Vibrational
 - $\sim 0.01\text{-}1\text{ eV}$
 - (near to mid) infrared wavelengths
 - e.g. H₂ @ 2.12 μm
- (Molecular) Rotational
 - $\sim 0.01 - 0.0001\text{ eV}$
 - microwave, (sub)millimeter wavelengths
 - e.g. CO, NH₃, SiO, CH₃OH



18.4 21-Centimeter Radiation

Interstellar gas emits low-energy radiation, due to a transition in the hydrogen atom

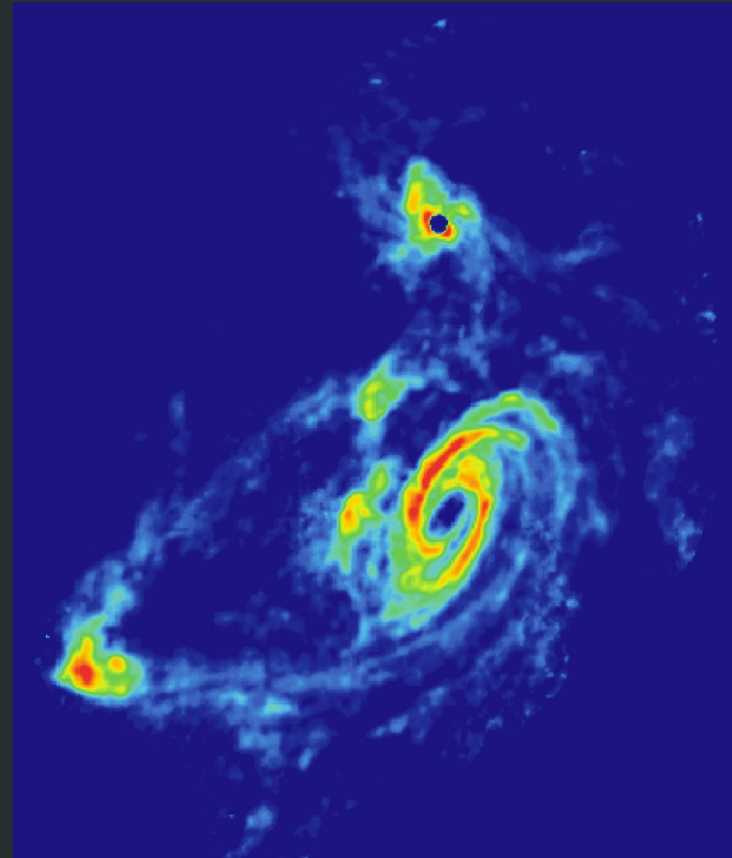


TIDAL INTERACTIONS IN M81 GROUP

Stellar Light Distribution

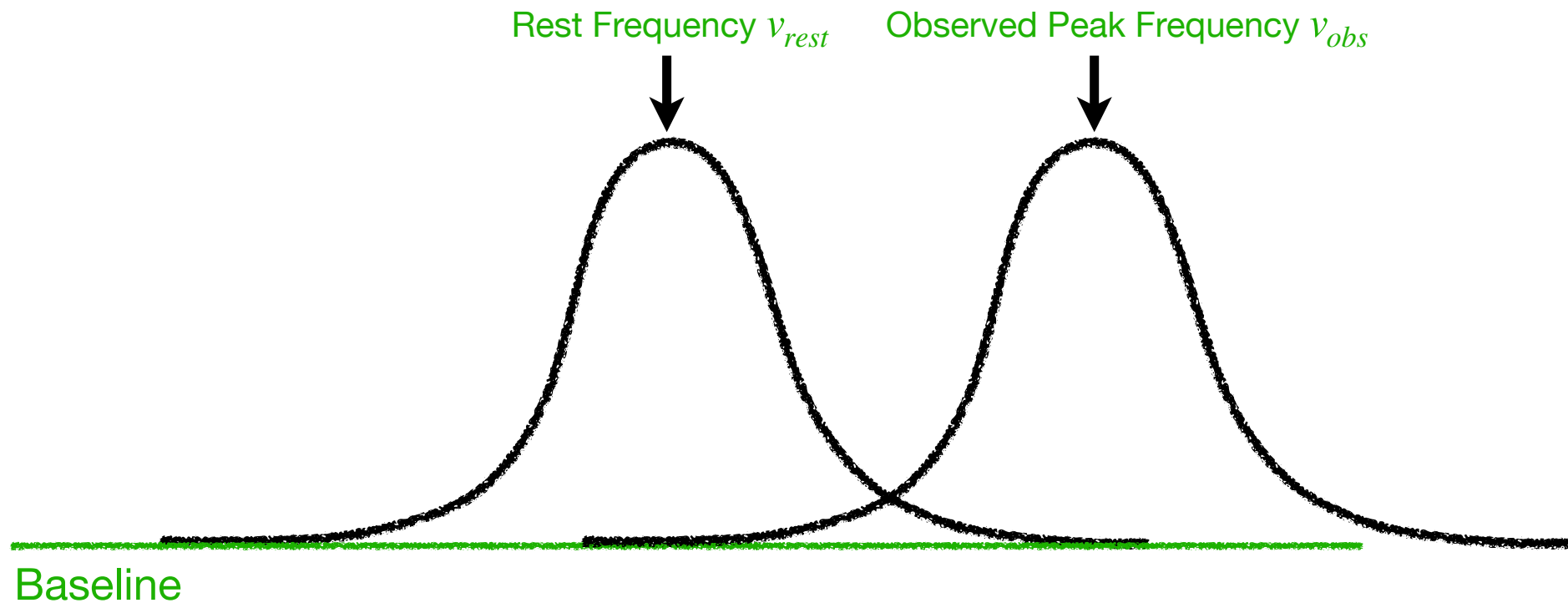


21 cm HI Distribution



(NRAO Archive)

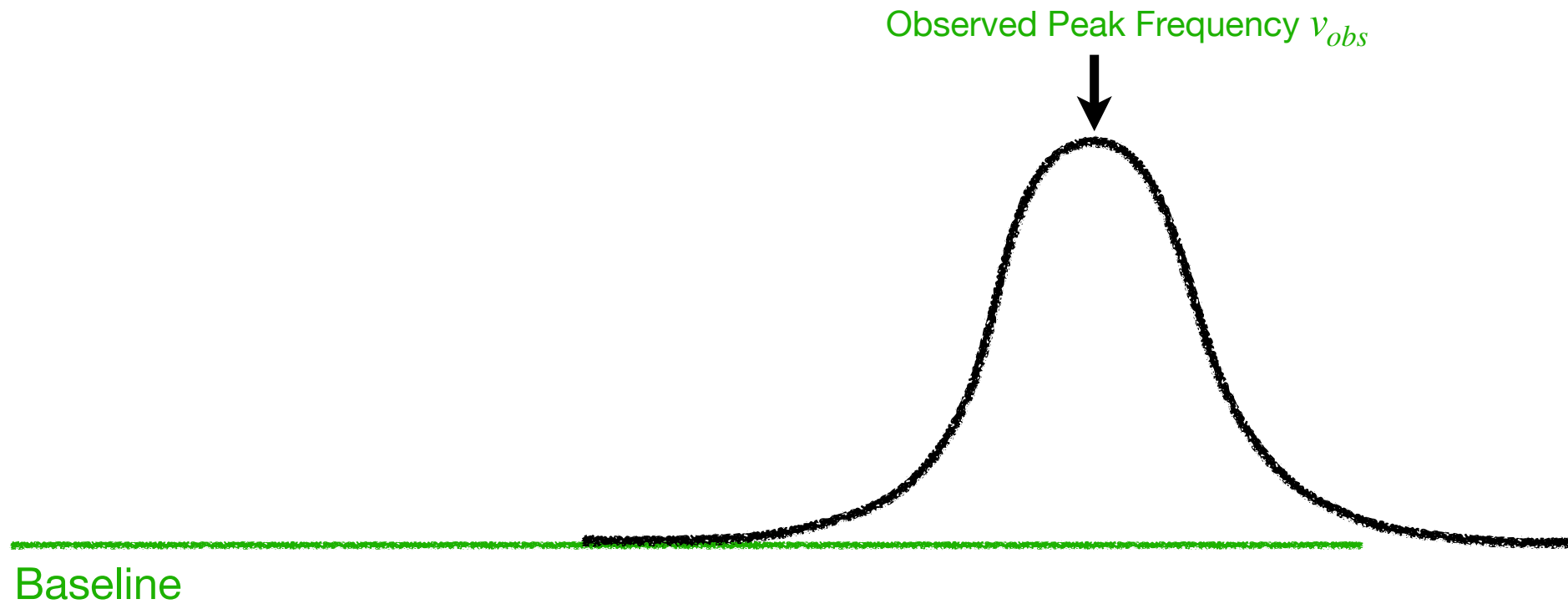
Radiative Process (Spectral Line)



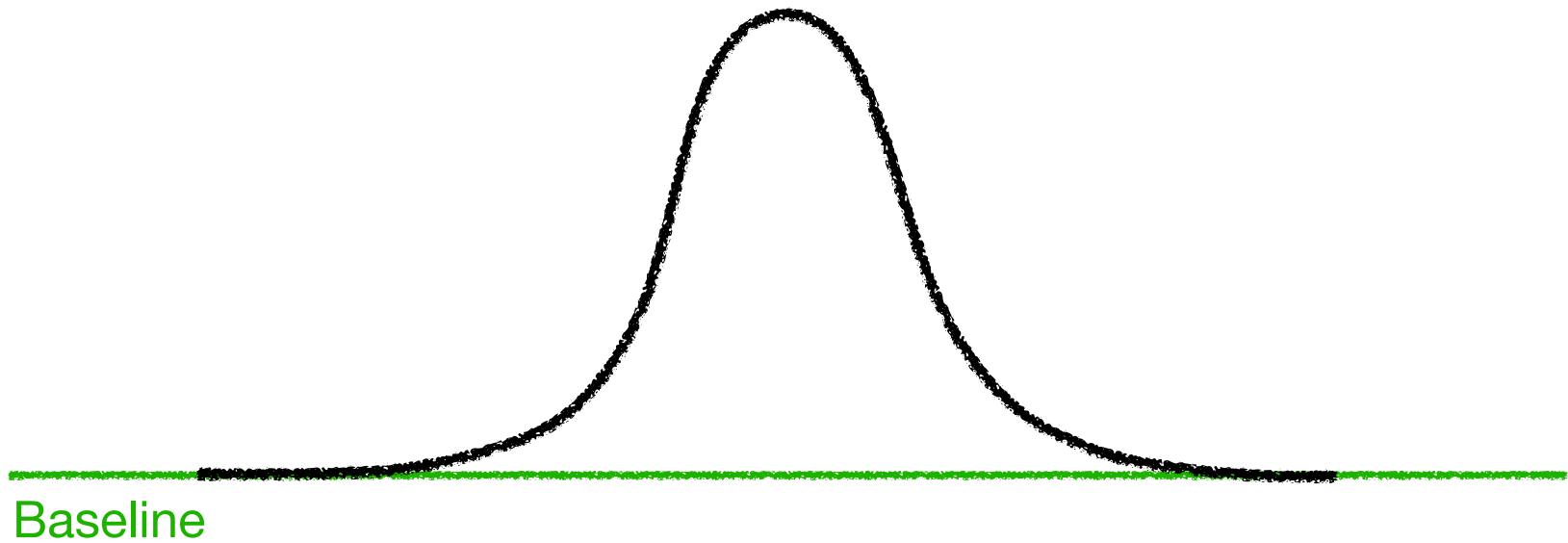
Doppler Shift /Bulk velocity

$$\frac{\Delta \nu}{\nu_{rest}} = \frac{\nu_{obs} - \nu_{rest}}{\nu_{rest}} = \frac{\Delta V}{c} = \frac{V}{c}$$

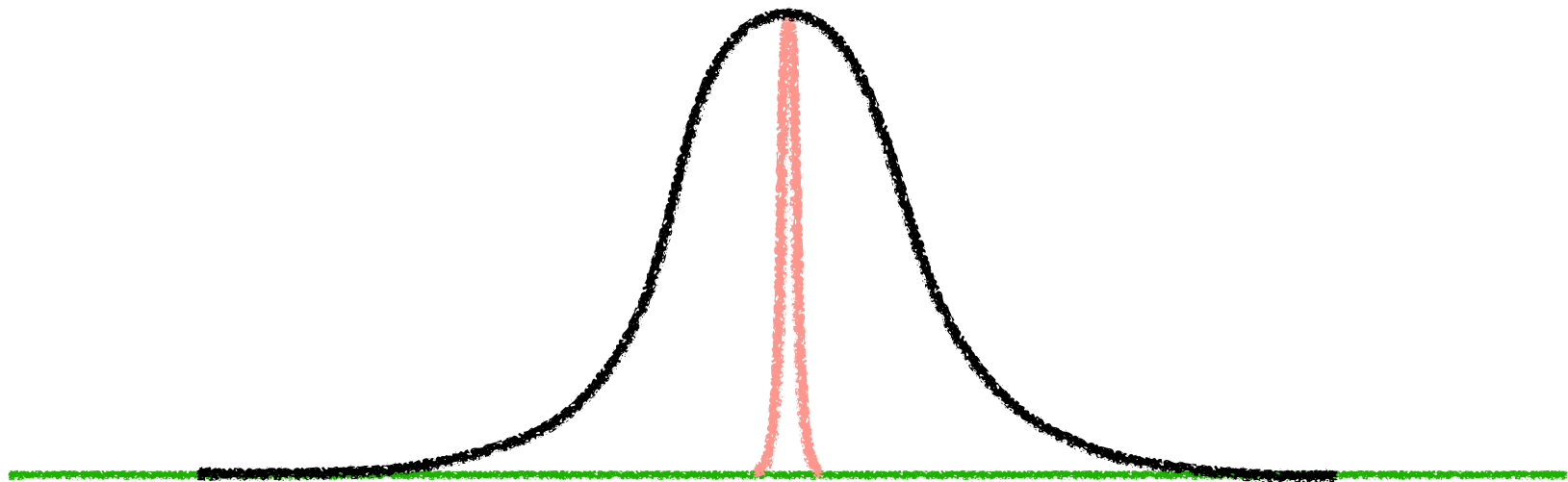
Radiative Process (Spectral Line)



Radiative Process (Spectral Line)



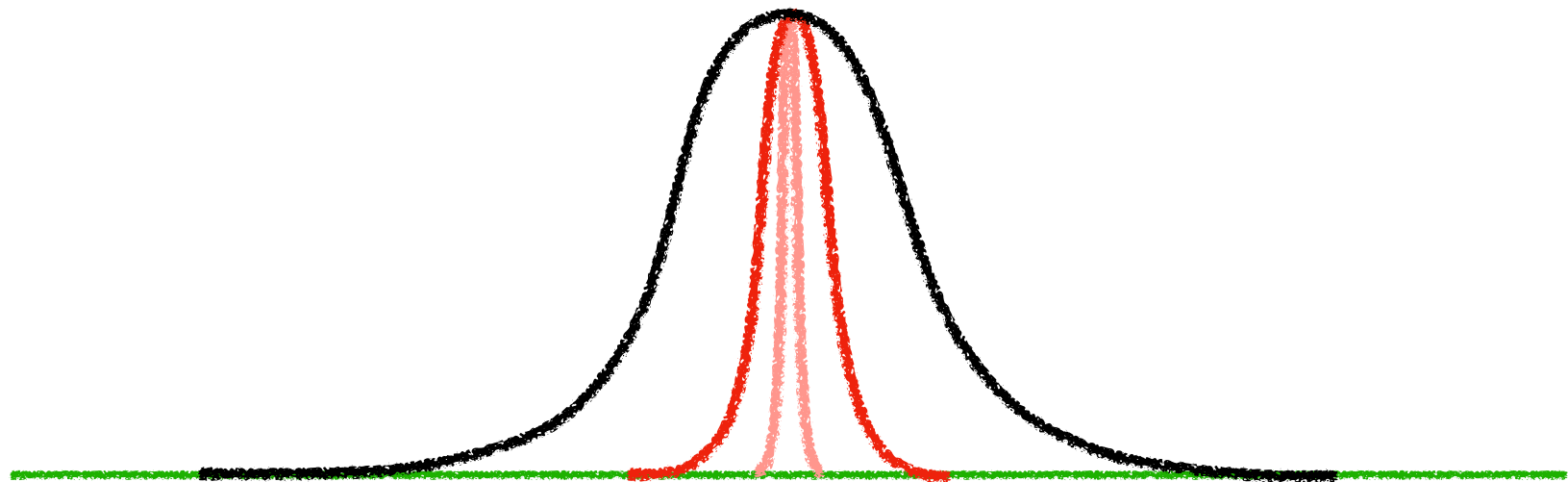
Radiative Process (Spectral Line)



Baseline

Natural Broadening (Lorentzian): $\sim 10^{-5}$ nm

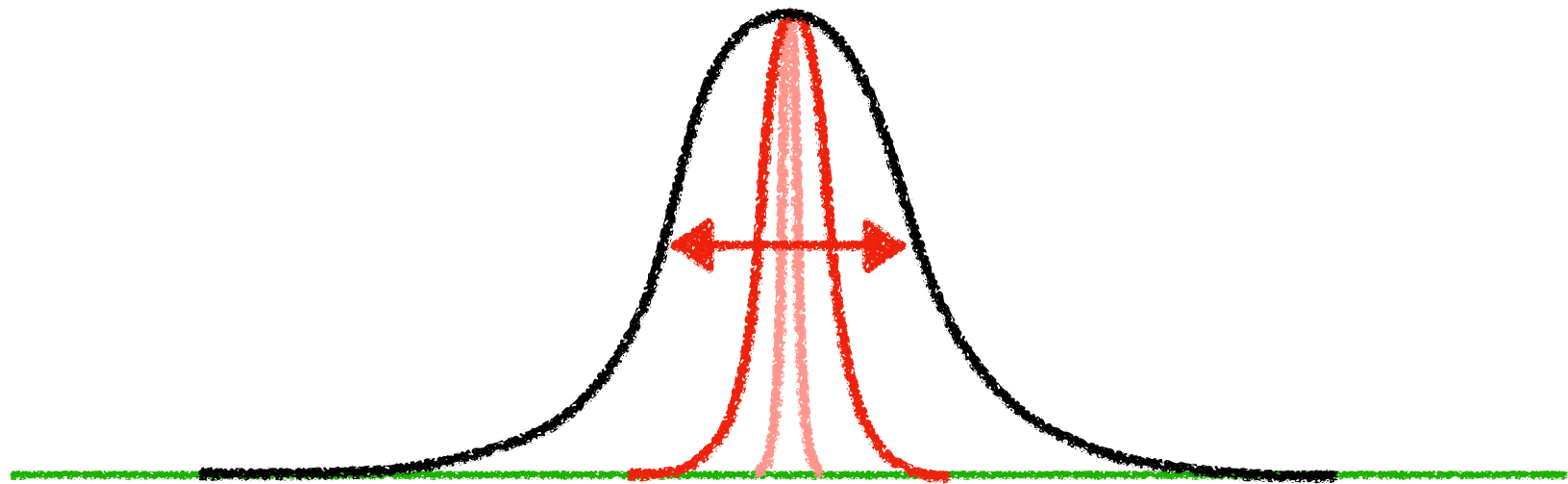
Radiative Process (Spectral Line)



Baseline

Thermal (Doppler) Broadening: $\frac{\Delta\nu}{\nu} \propto \sqrt{\frac{kT_k}{m}}$

Radiative Process (Spectral Line)

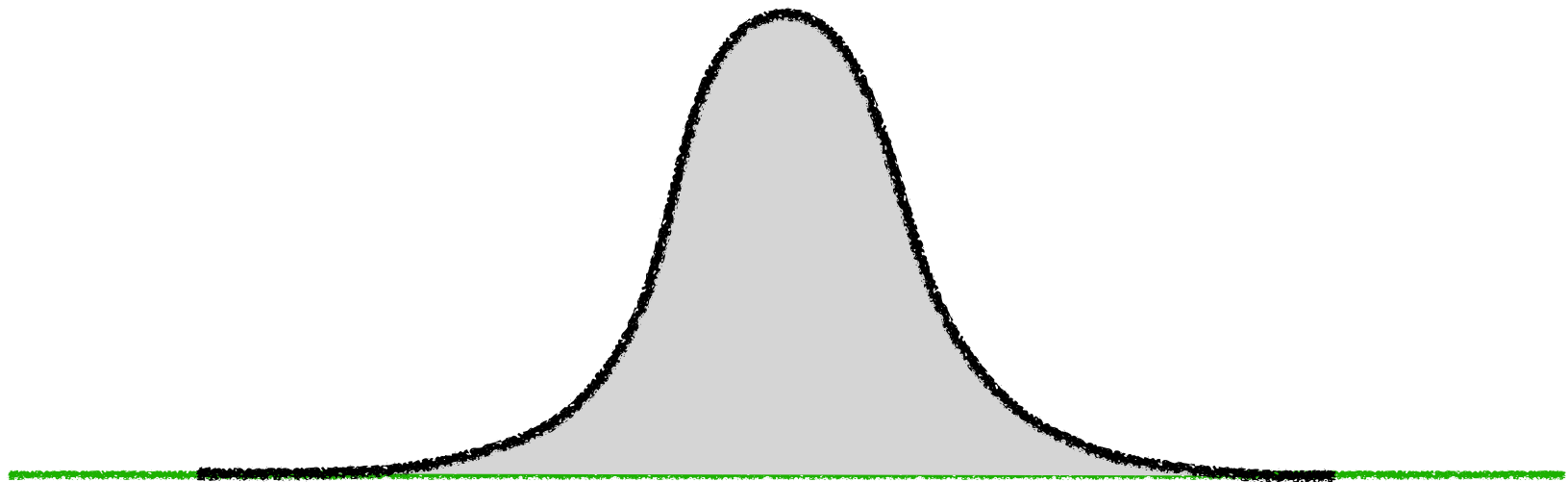


Baseline

Unresolved Motion

Additional (non-thermal) Broadening: Turbulent (Doppler) Broadening (Gaussian)
Pressure Broadening (Lorentzian)

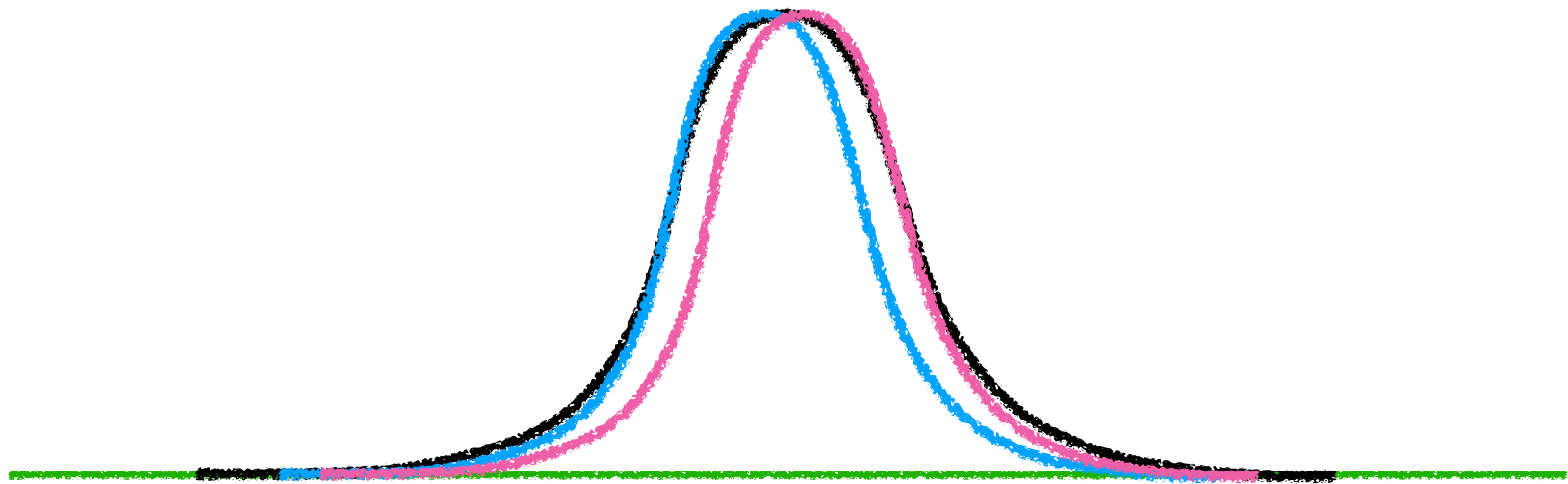
Radiative Process (Spectral Line)



Baseline

Peak $I_{\nu, peak}$ and Integrated Intensity $\equiv \int I_{\nu} d\nu$: opacity (= # of particles)

Radiative Process (Spectral Line)



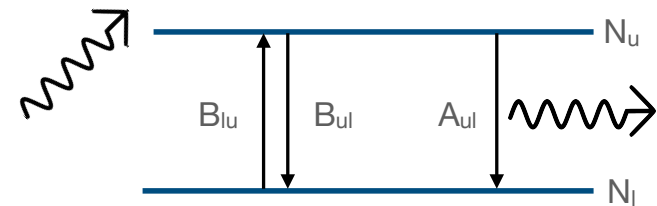
Baseline

Polarization : Magnetic Field (through Zeeman splitting)

Slide Credit: Seamus Clarke

Population levels and excitation

Emissivity and absorption



$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu$$

So how do we go about determining these two quantities?

Energy per photon

Rate of photon release per unit volume

Per steradian

Line profile

$$j_\nu = \frac{h\nu_{ul}}{4\pi} A_{ul} N_u \phi(\nu)$$

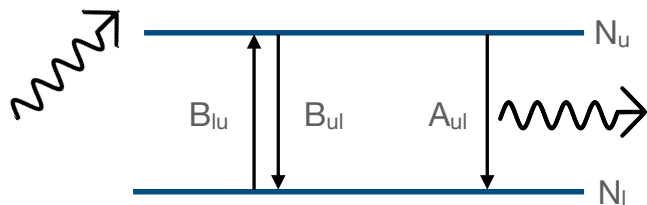
Rate of photon absorption per unit volume per unit intensity

$$\alpha_\nu = \frac{h\nu_{ul}}{4\pi} (N_l B_{lu} - N_u B_{ul}) \phi(\nu)$$

$N_l B_{lu} I$ = Rate of stimulated absorption

Population levels and excitation

Einstein's relations



Einstein's relations

$$A_{ul} = \frac{2h\nu_{ul}^3}{c^2} B_{ul}$$
$$g_u B_{ul} = g_l B_{lu}$$

Assume that LTE is valid

$$\frac{N_u}{N_l} = \frac{g_u}{g_l} e^{-(E_u - E_l)/k_B T} = \frac{g_u}{g_l} e^{-h\nu_{ul}/k_B T_{ex}}$$

$$j_\nu = \frac{h\nu_{ul}}{4\pi} A_{ul} N_u \phi(\nu)$$

$$\alpha_\nu = \frac{h\nu_{ul}}{4\pi} (N_l B_{lu} - N_u B_{ul}) \phi(\nu)$$

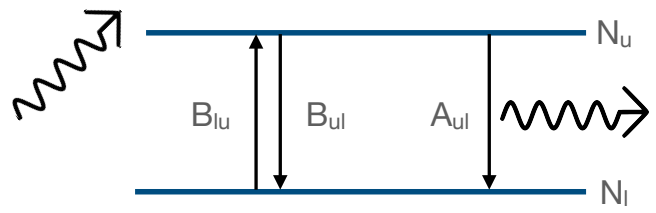


$$\alpha_\nu = \frac{c^2}{8\pi\nu_{ul}^2} (e^{h\nu_{ul}/k_B T_{ex}} - 1) A_{ul} N_u \phi(\nu)$$

$$S_\nu = \frac{2h\nu_{ul}^3}{c^2} \frac{1}{(e^{h\nu_{ul}/k_B T_{ex}} - 1)} = B_\nu(T_{ex})$$

Population levels and excitation

Einstein's relations



Einstein's relations

$$A_{ul} = \frac{2h\nu_{ul}^3}{c^2} B_{ul}$$
$$g_u B_{ul} = g_l B_{lu}$$

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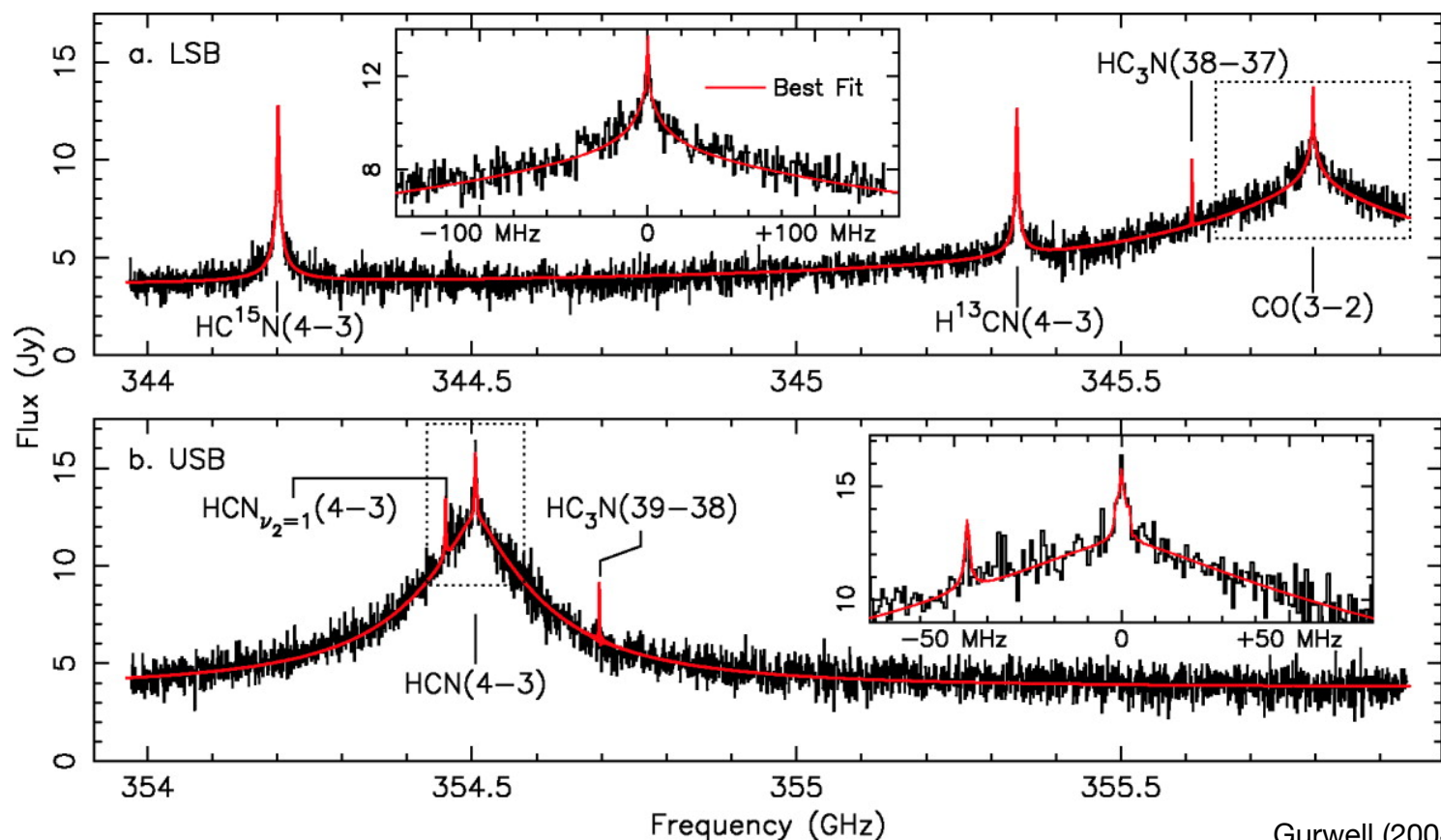


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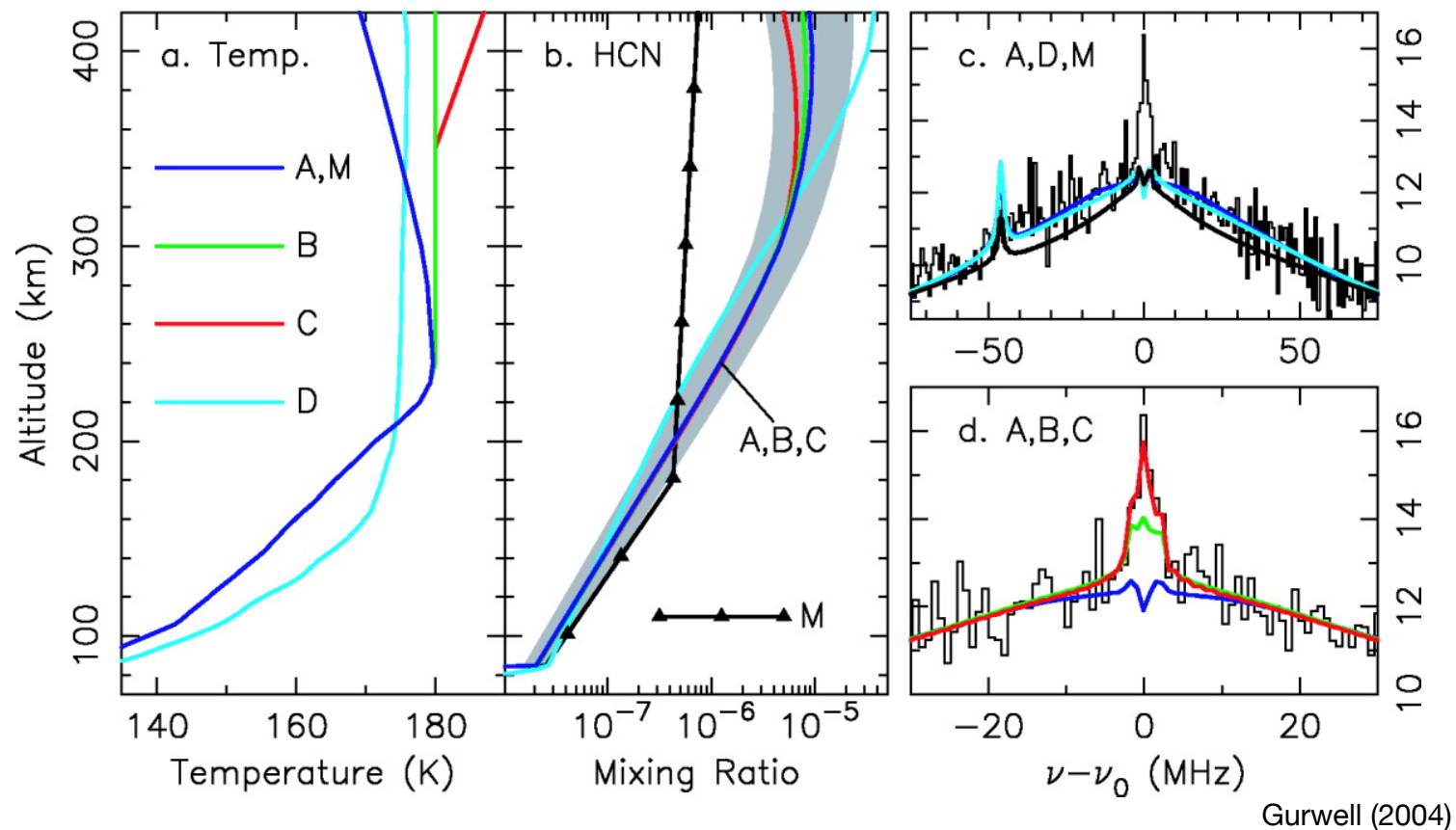
Radiative Process (Line Broadening)

Submillimeter Observations of Titan: Global Measures of Stratospheric Temperature, CO, HCN, HC₃N, and the Isotopic Ratios ¹²C/¹³C and ¹⁴N/¹⁵N



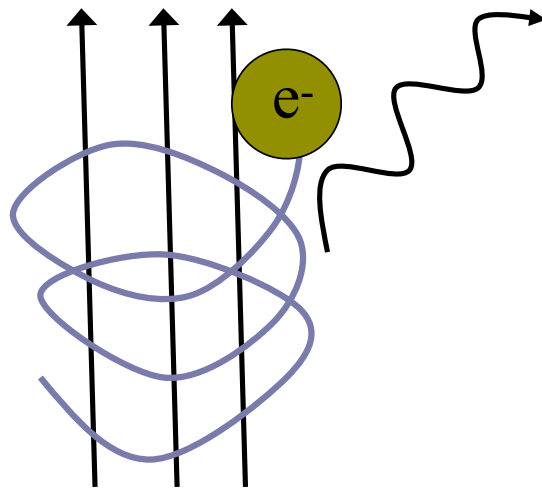
Radiative Process (Line Broadening)

Submillimeter Observations of Titan: Global Measures of Stratospheric Temperature, CO, HCN, HC₃N, and the Isotopic Ratios ¹²C/¹³C and ¹⁴N/¹⁵N



Radiative Process (Synchrotron)

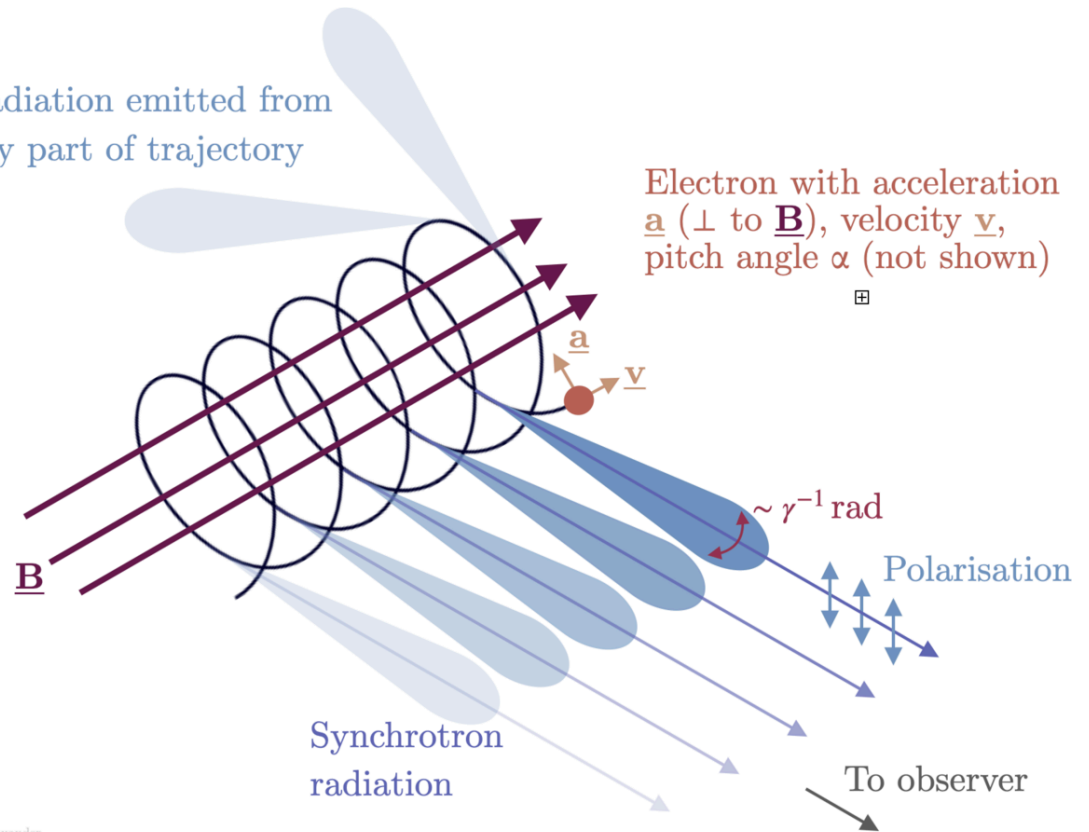
Synchrotron (magnetic bremsstrahlung)



B Supernovae
AGN jet

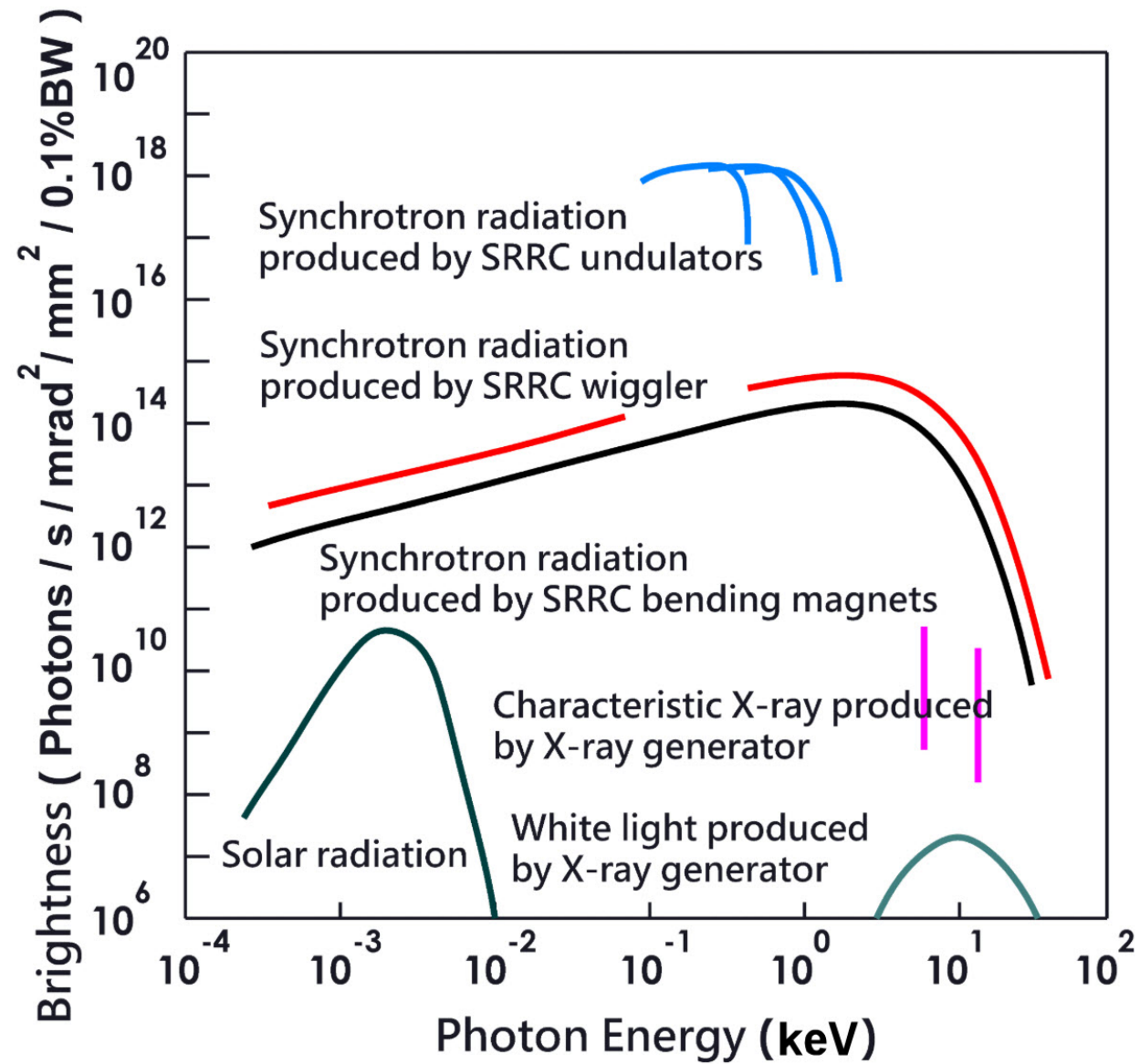
Image Credit: Hiro Hirashita

Radiation emitted from
any part of trajectory

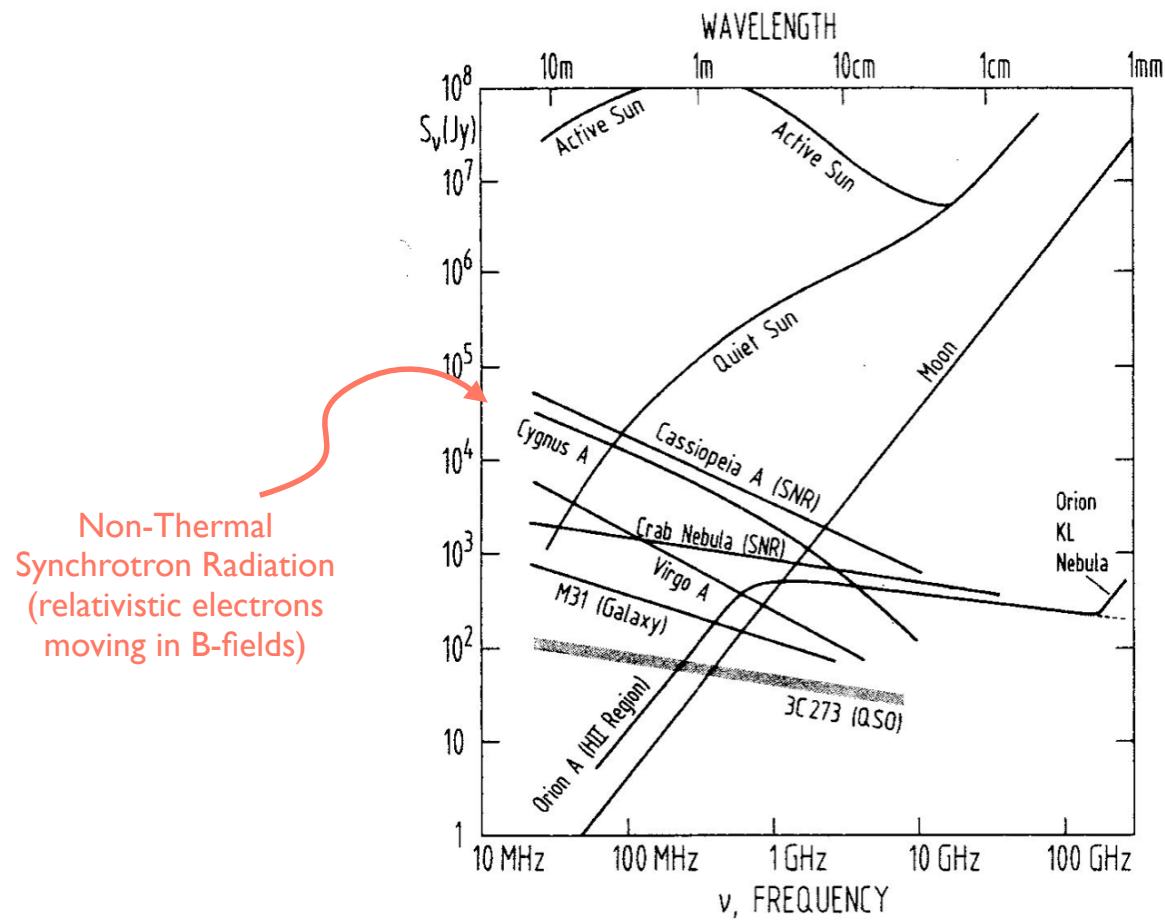


Emma Alexander

https://en.wikipedia.org/wiki/Synchrotron_radiation



Spectral Energy Distribution (in radio regime)



Spectral Energy Distribution (in radio regime)

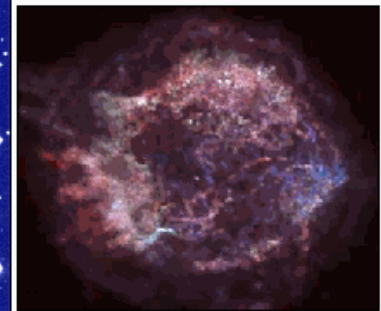
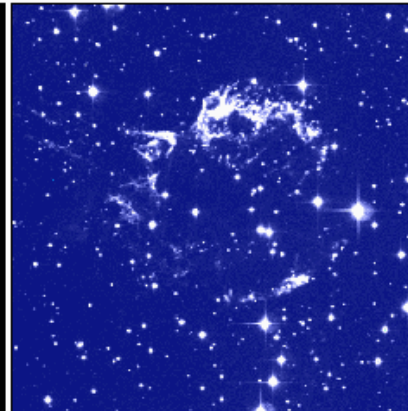
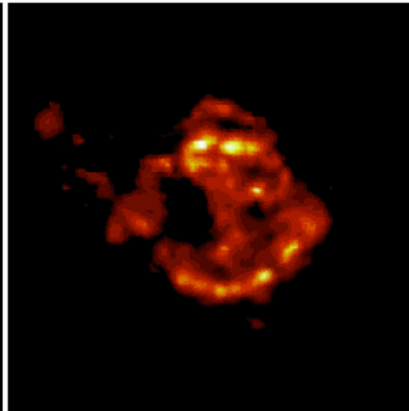
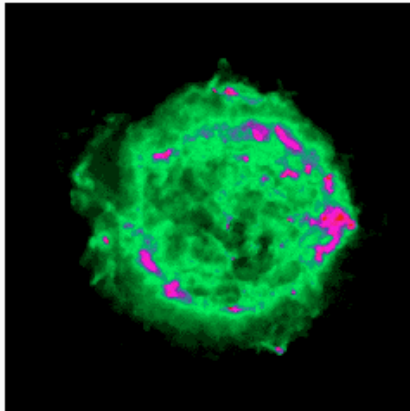
Cassiopeia A: a star that died in ~ 1700

RADIO

INFRARED

OPTICAL

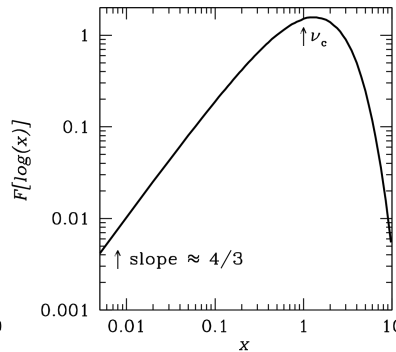
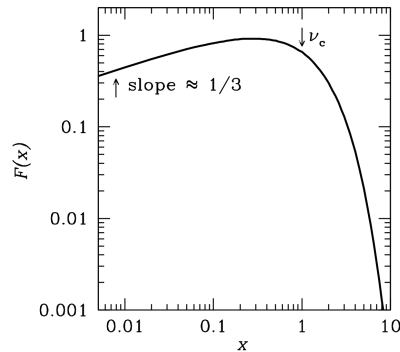
XRAY



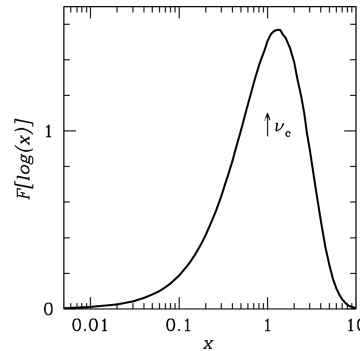
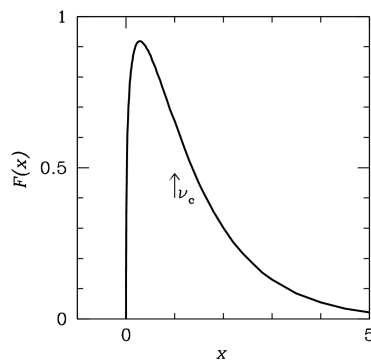
Synchrotron Radiation (single particle)

- synchrotron radiation

- spectrum
$$P(\nu) = \frac{\sqrt{3}e^3 B \sin\alpha}{m_e c^2} \left(\frac{\nu}{\nu_c}\right) \int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta) d(\eta) \quad \text{with} \quad \nu_c = \frac{3}{2} \gamma^2 \nu_G \sin\alpha$$



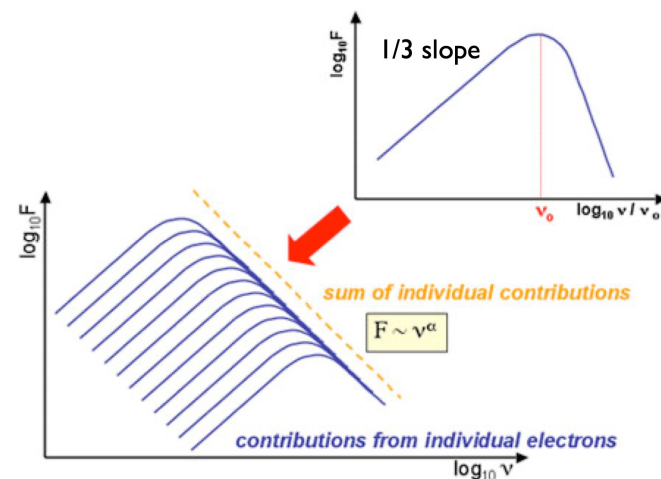
relatively flat spectrum at frequencies lower than the critical frequency and tailing off roughly at the maximum frequency



$$\nu_c = \left(\frac{3}{2} \sin\alpha\right) \left(\frac{E}{mc^2}\right)^2 \frac{eB}{2\pi m_e c} \propto E^2 B_{\perp}$$

$$\nu_{max} \approx \pi \gamma^2 \nu_G \sin\alpha \propto \gamma^2 B_{\perp}$$

Synchrotron Spectrum



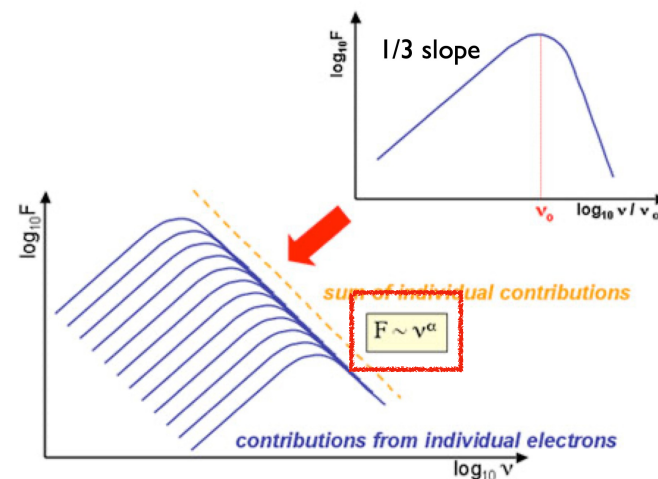
- Powerlaw.
- Observed spectrum is a superposition of the individual electron spectra.

Strong dependence on the Lorentz factor

$$\nu_{max} = \nu_e \gamma^2 \quad P_e \sim 2 \gamma^2 U_{mag}$$

- Since ($\gamma \gg 1$) this boosts the emission frequency of synchrotron emission into the radio domain.

Synchrotron Spectrum



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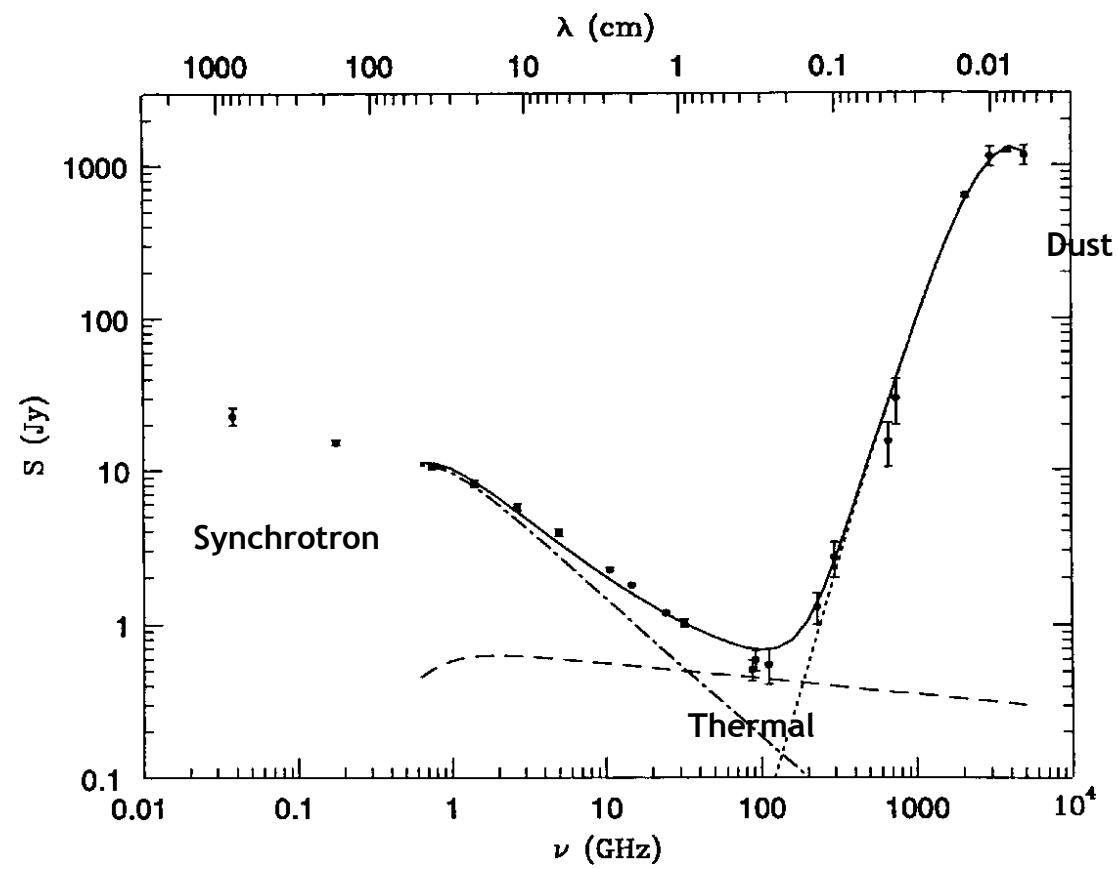
Galactic Radio Astronomy - SNR

- SNR in extragalactic sources : e.g. M82



Credit: Josh Marvil (NM Tech/NRAO), Bill Saxton (NRAO/AUI/NSF), NASA

“Nonthermal emission” Synchrotron emission: electrons spiraling around a magnetic field at relativistic velocities.



Radiative Process (Inverse Compton)

(Inverse) Compton Radiation

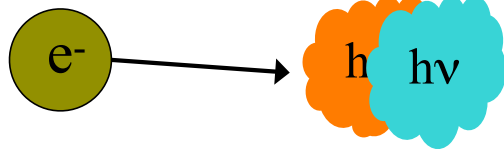
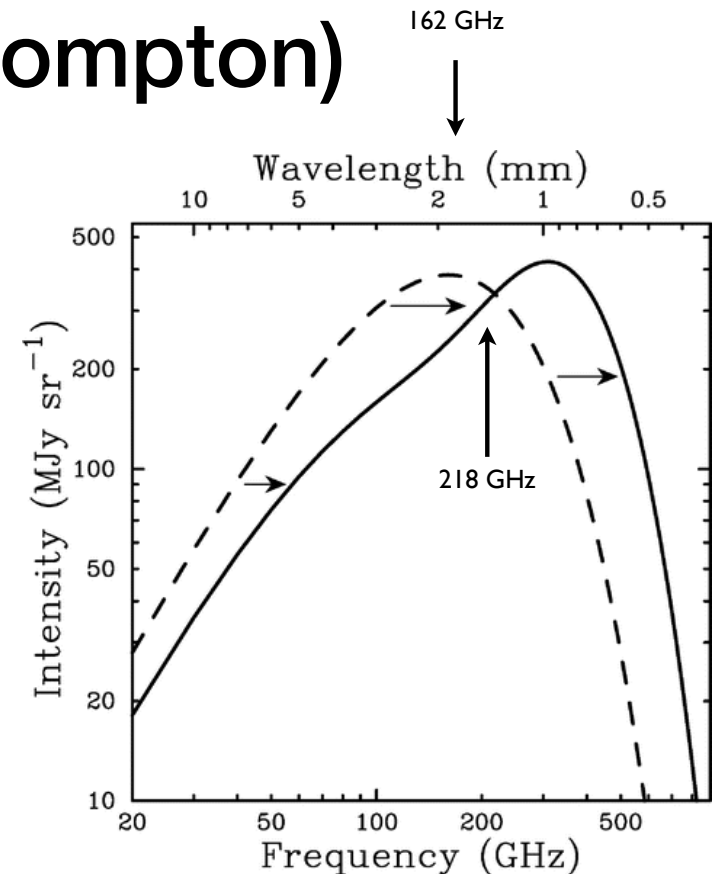


Image Credit: Hiro Hirashita

Intracluster medium
(Sunyaev-Zeldovich effect)
AGN jet, accretion disk

- Sunyaev-Zel'dovich effect
 - Sunyaev & Zel'dovich (1970)
 - CMB photons interact with 10^8 K plasma in clusters, typically extend on the Mpc scale (angular size of several arcmins)
 - no confirmed results until late 1990's



$$\frac{\Delta T}{T} = \frac{2kT_e}{m_e c^2} \sigma_T N_e L$$

$$\sigma_T = \frac{8\pi}{3} \left(\frac{e^2}{m_e c^2} \right)^2 = 6.65 \cdot 10^{-25} \text{ cm}^2$$

$$= 2.24 \cdot 10^{-34} T_e N_e L$$

Radiative Process (Inverse Compton)

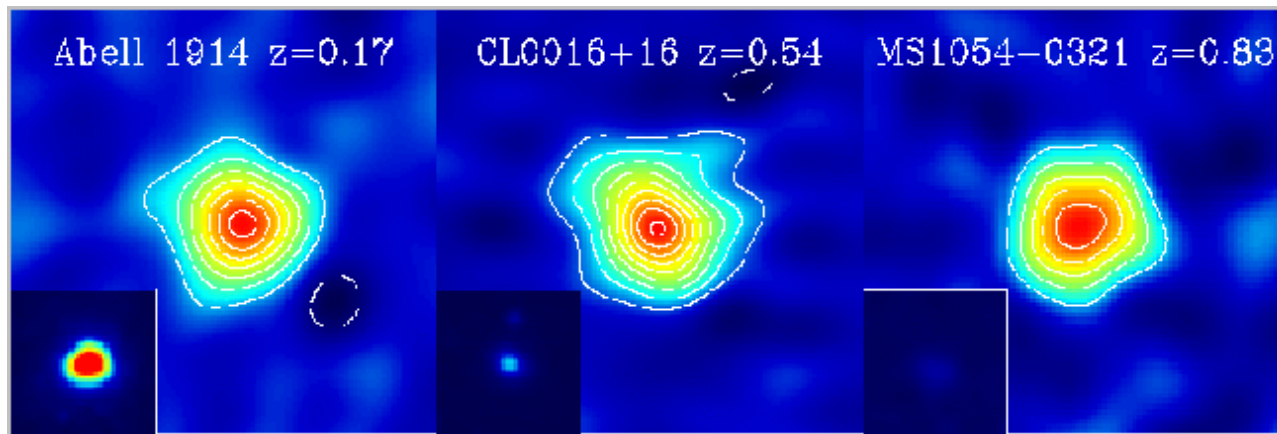
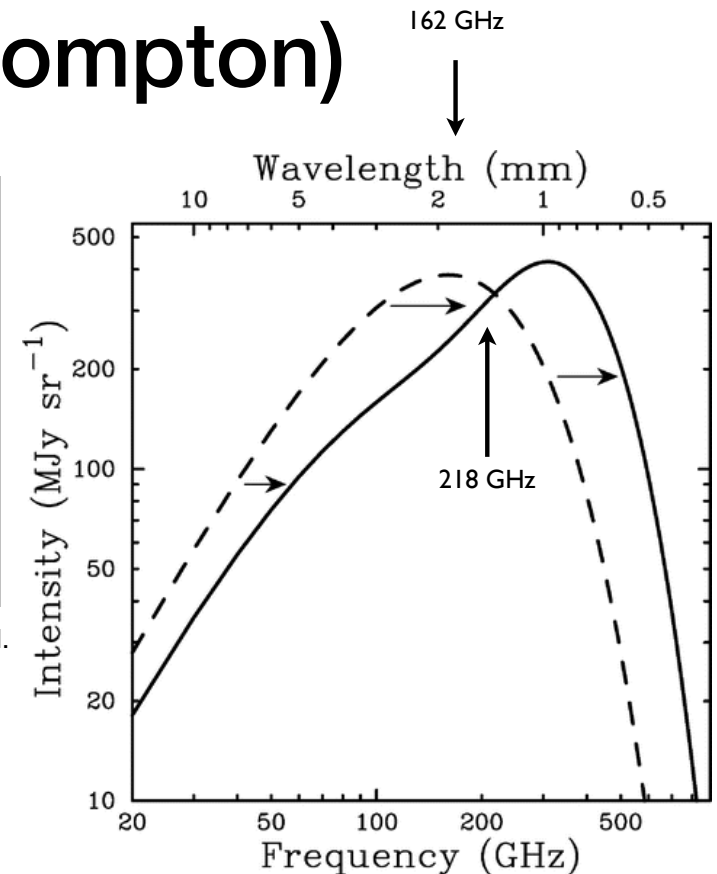


Image Credit: Carlstrom et al.

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Radiative Process (Inverse Compton)

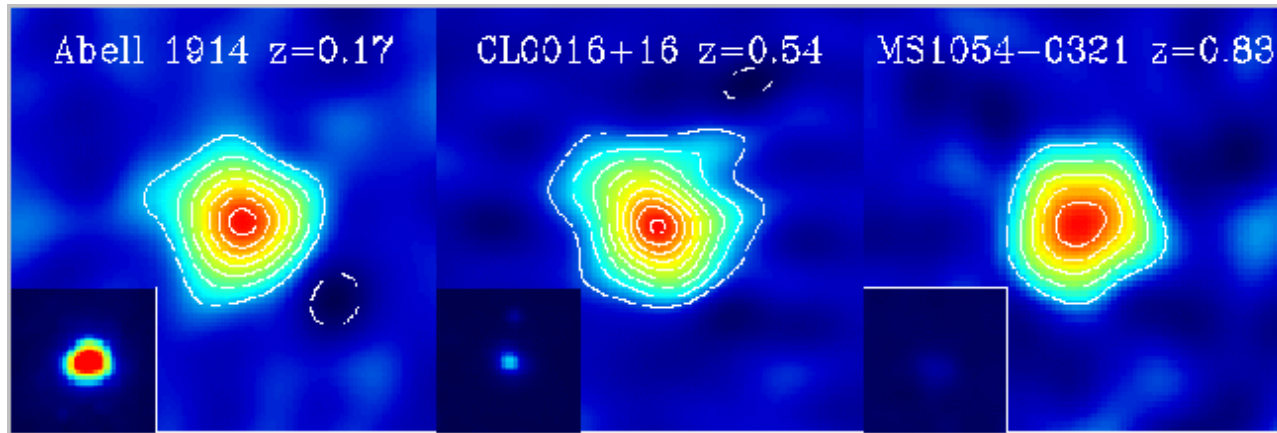
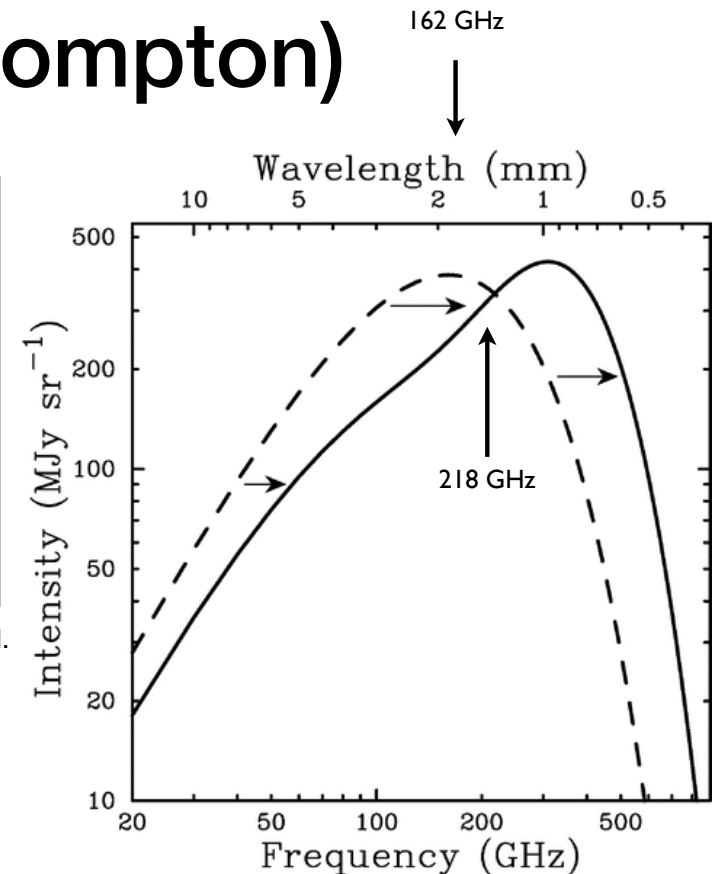


Image Credit: Carlstrom et al.

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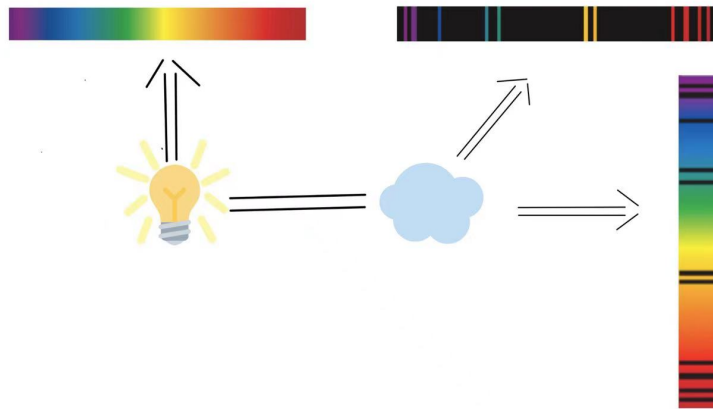
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$$= 2.24 \cdot 10^{-34} \boxed{T_e N_e L}$$

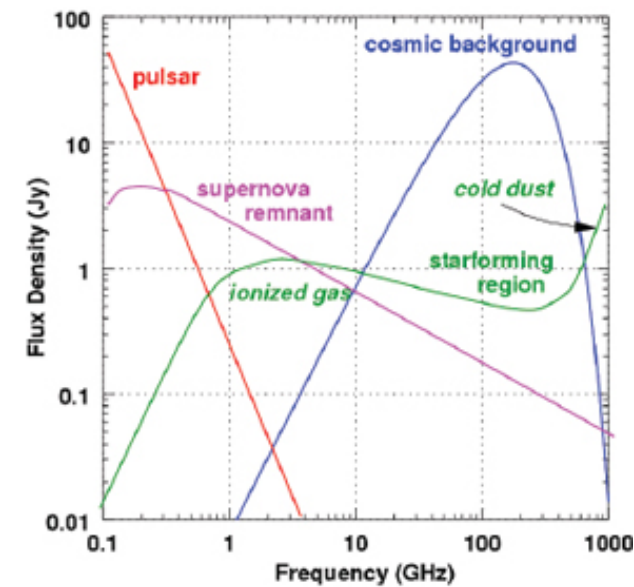
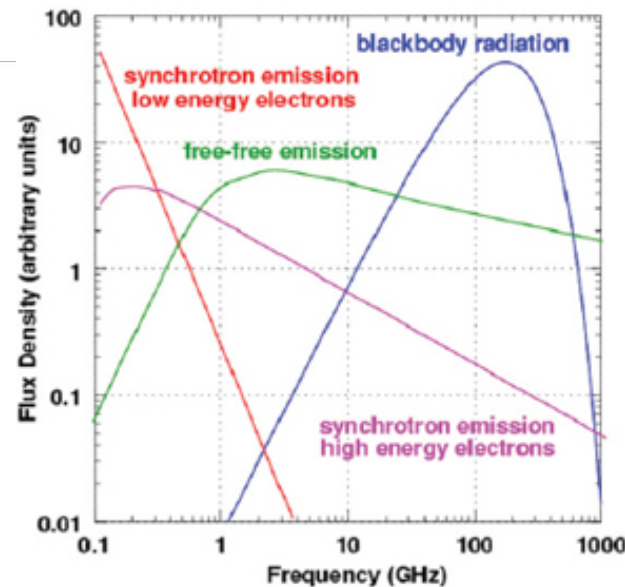
Take Home Message -

Think about what physical parameters can we extract?

Radiative Transfer



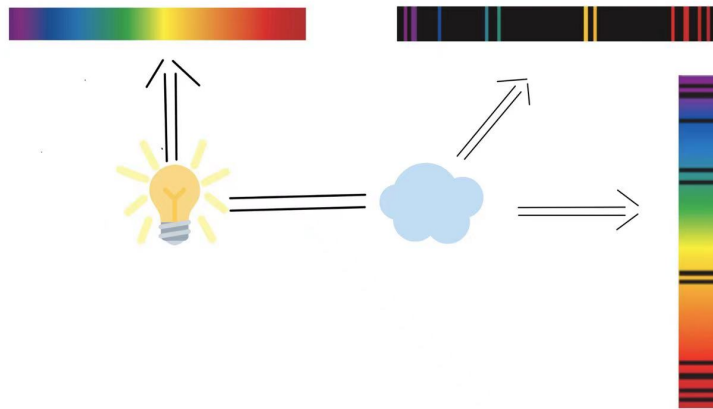
Radiative Processes



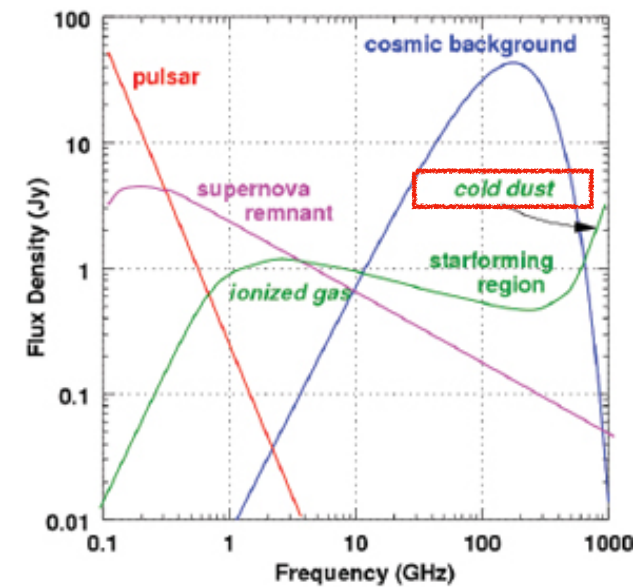
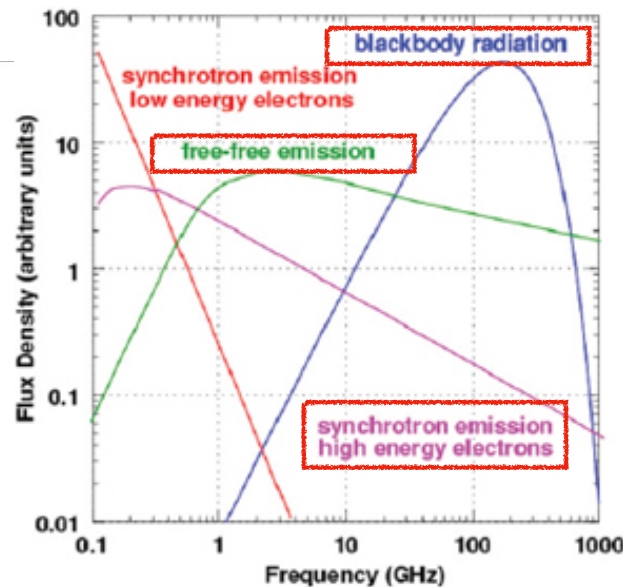
Take Home Message -

Think about what physical parameters can we extract?

Radiative Transfer



Radiative Processes





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