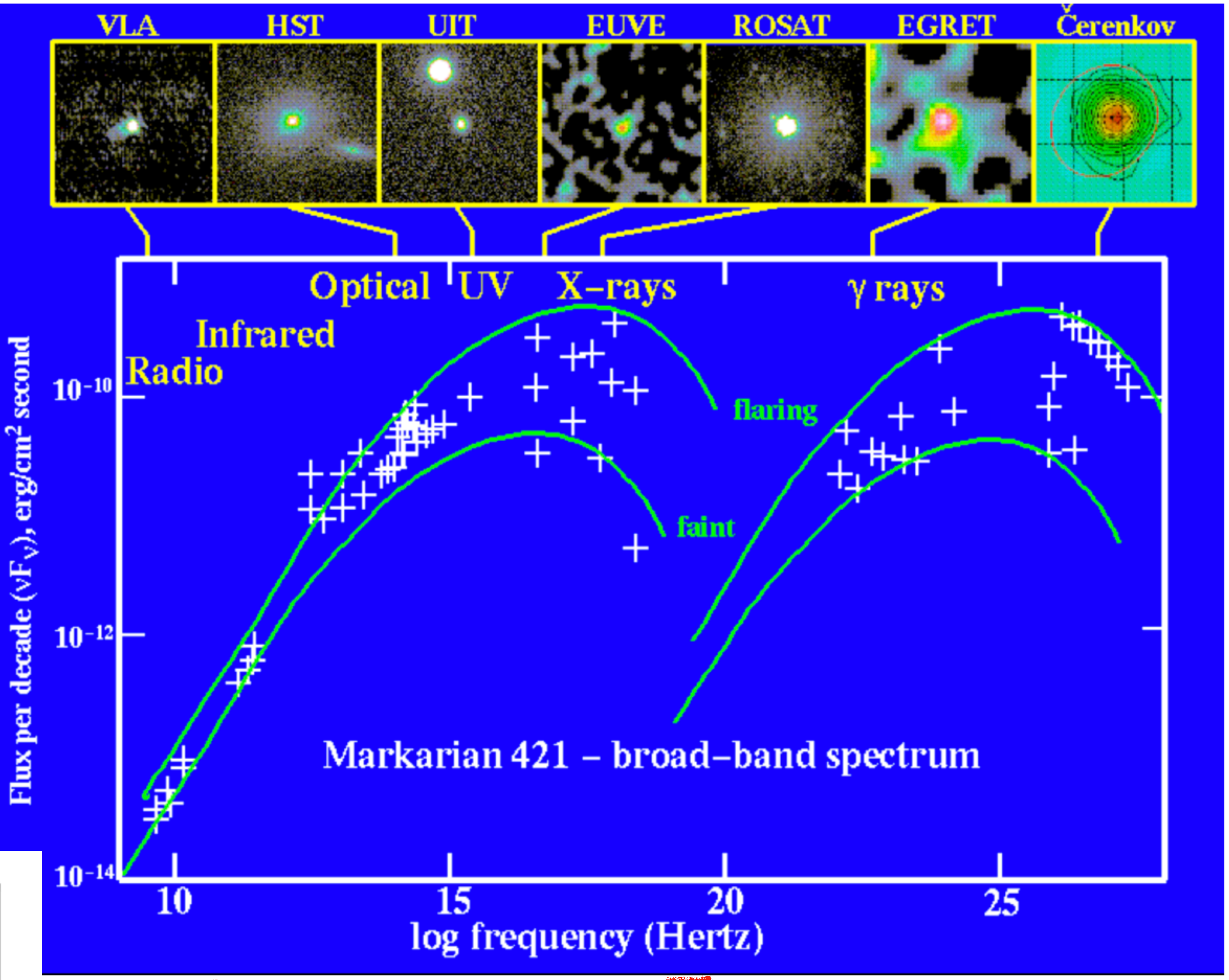
Inverse Compton scattering

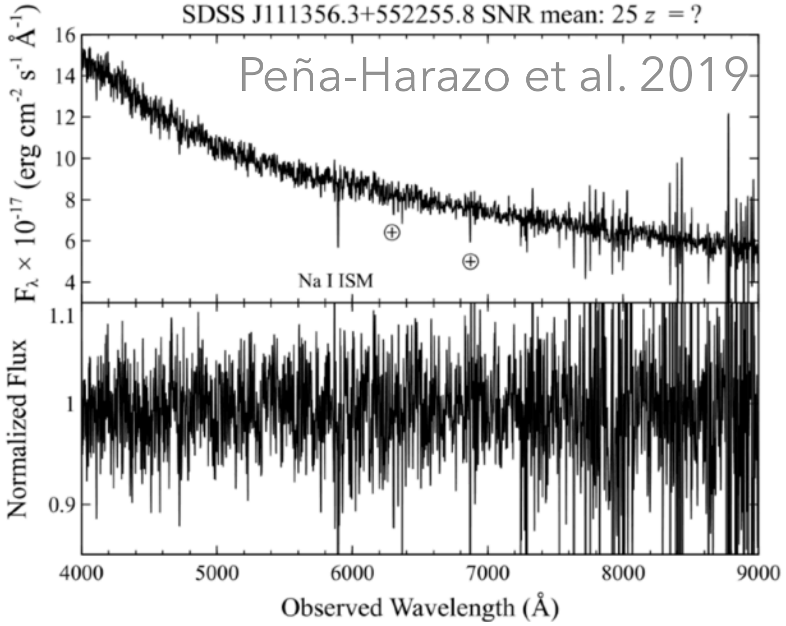
Blazar: active galaxy whose relativistic jet is oriented close to the line of sight



Ghisellini&Celotti 2002

$$\boxed{\frac{<\nu'>}{\nu} \sim \frac{4}{3}\gamma^2}$$

$\gamma \sim 10^4$



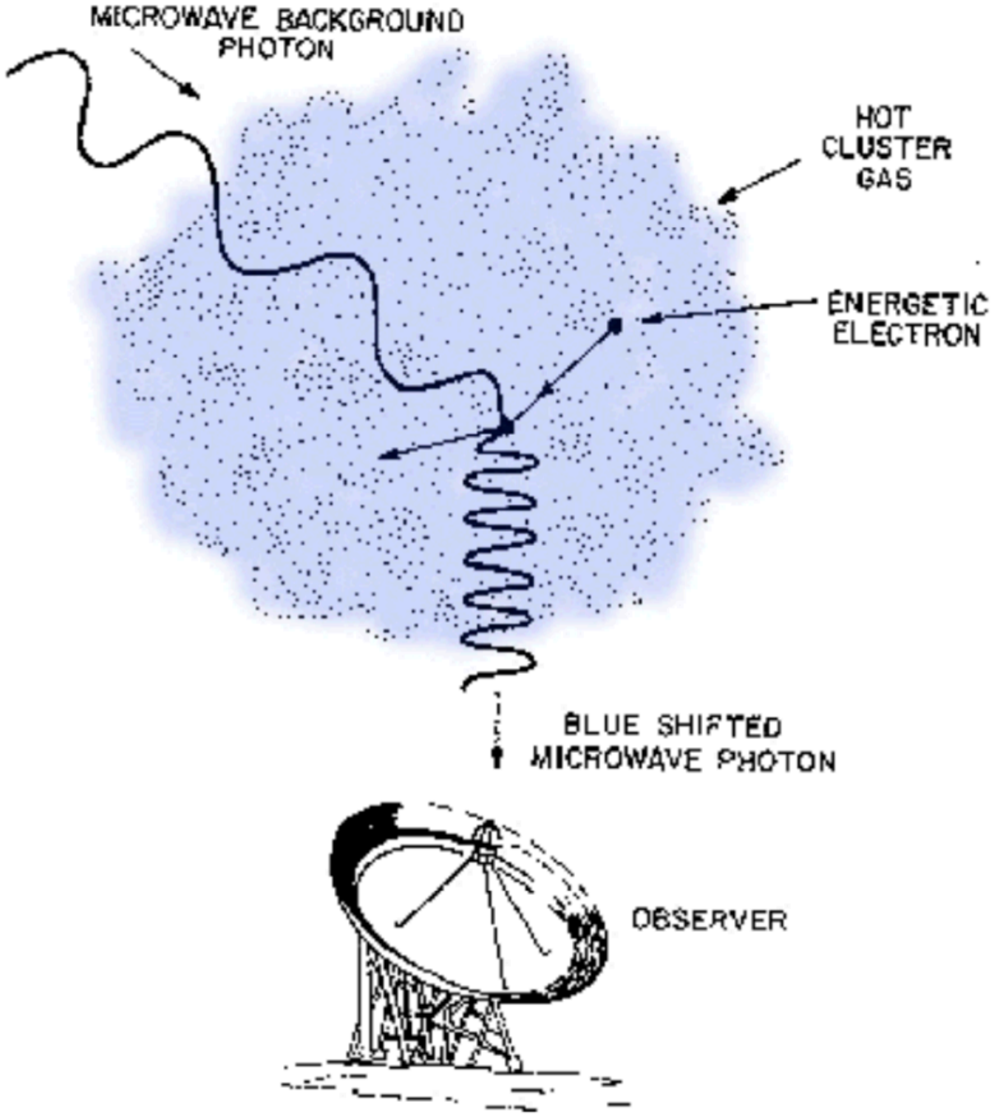
Peña-Harazo et al. 2019

Sunyaev-Zeldovich effect

Spectral distortion of the cosmic microwave background due to IC scattering of CMB photons with electrons from hot foreground sources, such as galaxy clusters. The net effect is a shift toward higher frequencies of CMB photons.

Thermal SZ: due to thermal motion of hot electrons. It has a characteristic spectral shape, that is a flux decrease in the Rayleigh-Jeans part of the spectrum and a flux increase in the Wien region

Kinematic SZ: due to the peculiar motion of the foreground source with respect to the rest-frame of the CMB. The net motion of the scattering electrons imparts a Doppler shift to the scatter photons



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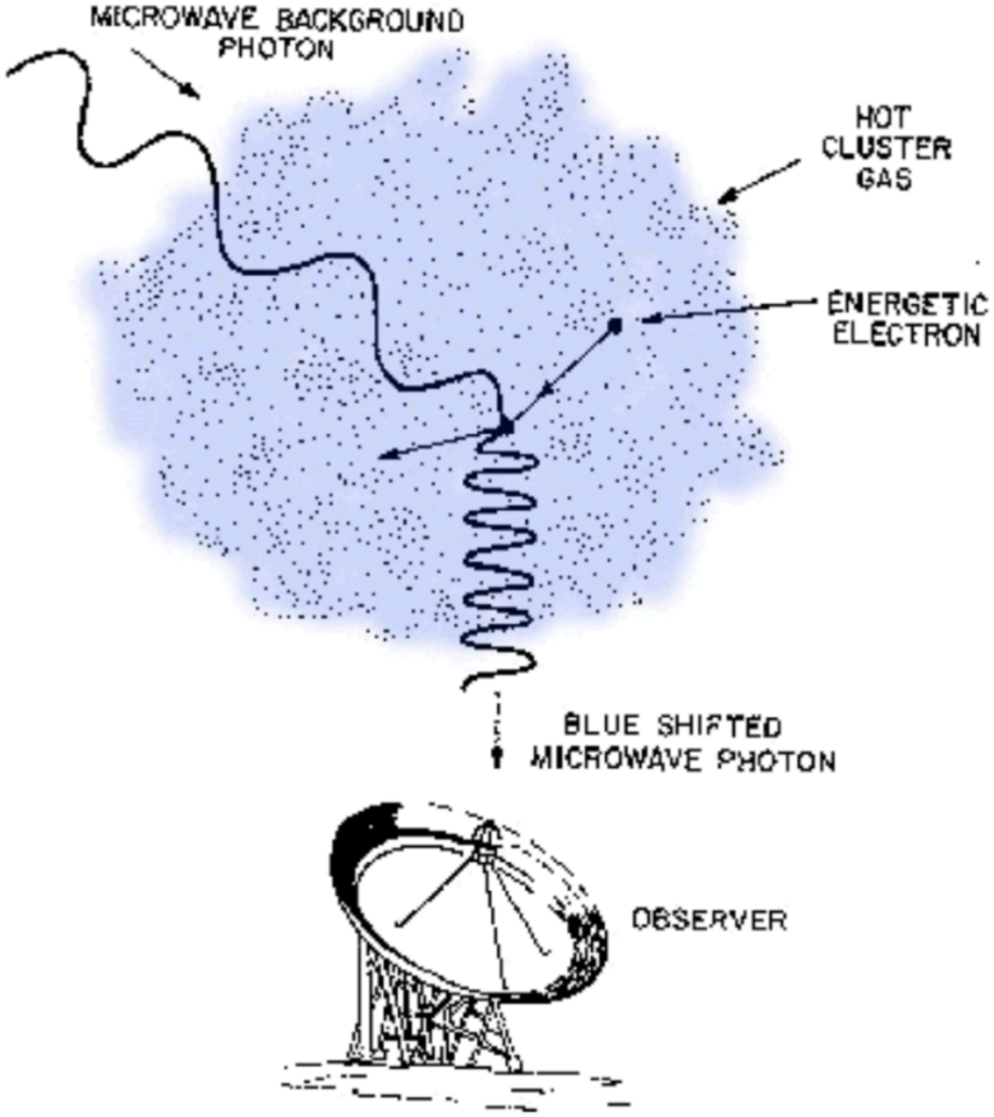
$$\frac{E'-E}{E} \propto \gamma^2 - 1 \sim \frac{v^2}{c^2} \sim \frac{3kT_e}{m_e c^2}$$

energy
exchanged via
scattering



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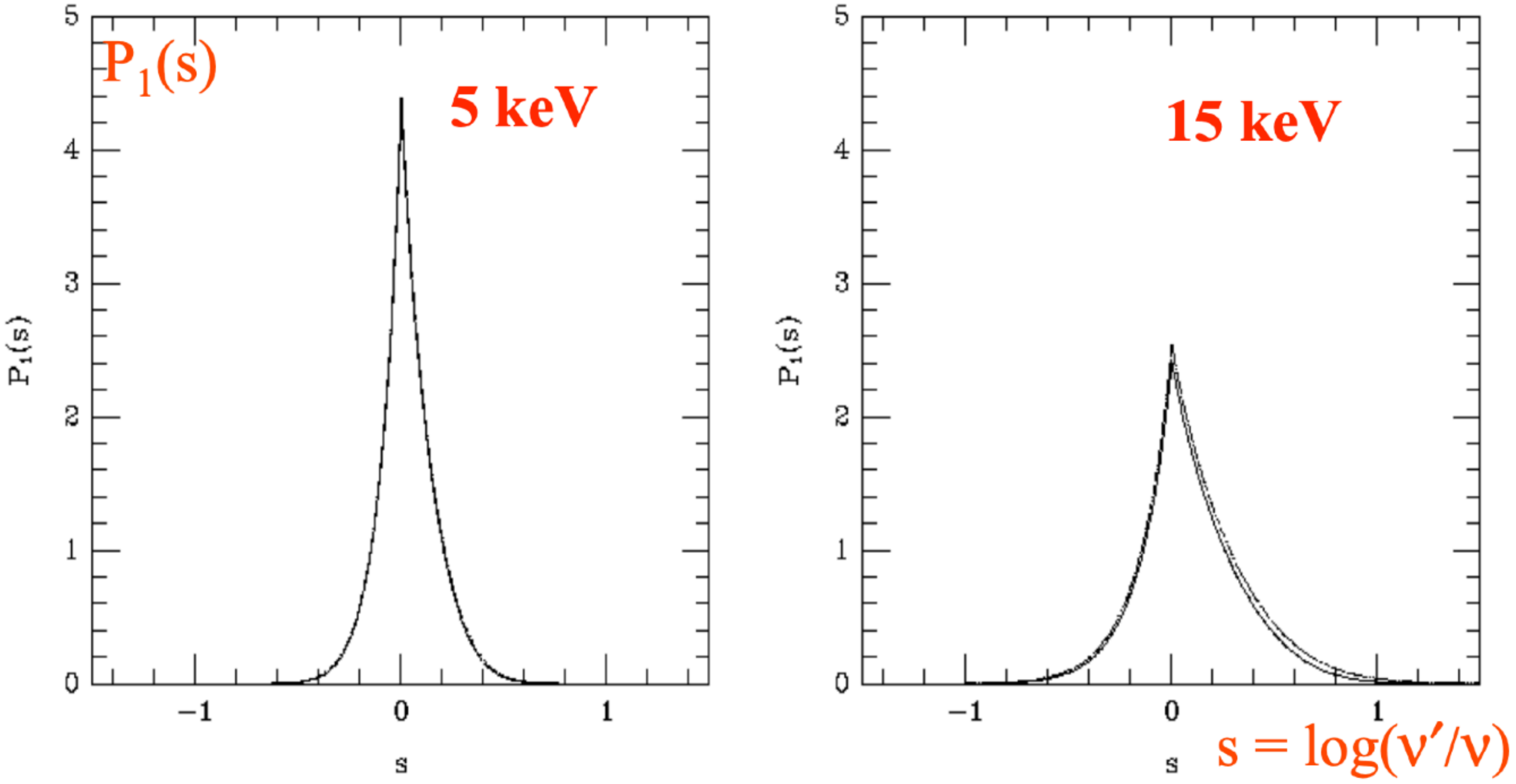

The distribution of scattered photon frequencies is significantly asymmetric: on average there is a frequency increase

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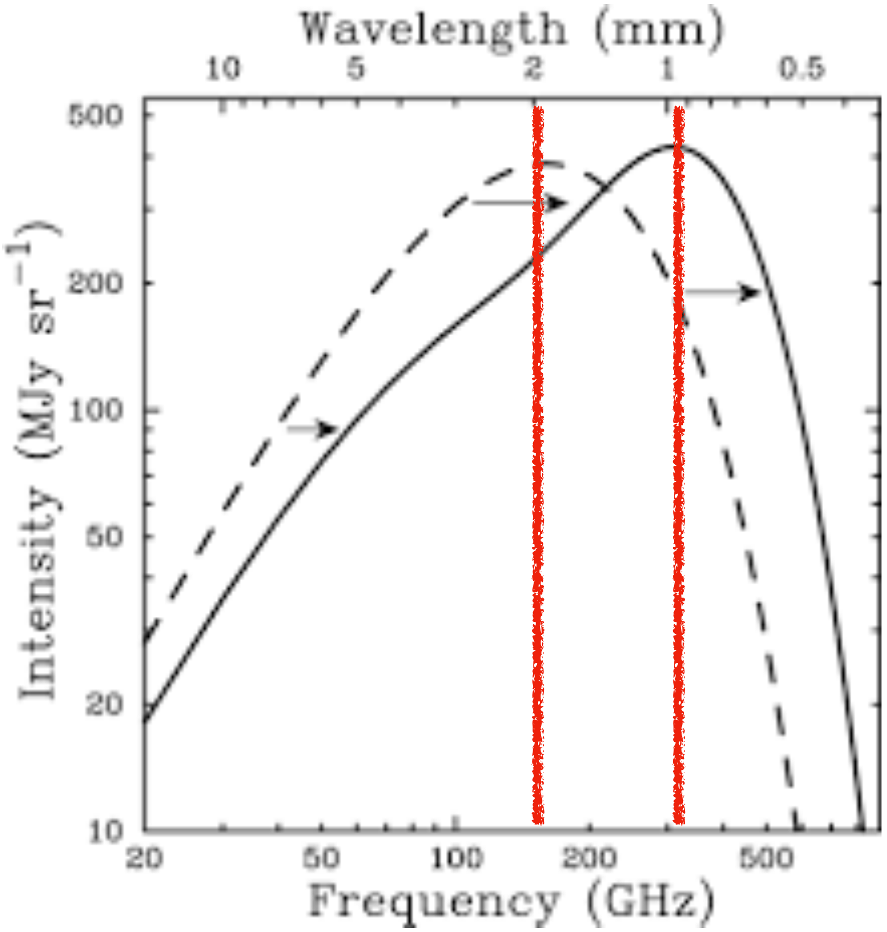
Thermal SZ

$$\frac{dI\nu}{I_\nu} = -y\frac{xe^x}{e^x-1}[4 - xcoth(x/2)]$$

$$x = \frac{2\pi\hbar\nu}{k_bT}$$ normalized frequency

$$y = \int \sigma_T n_e \frac{k_bT_e}{m_ec^2} dl$$ Compton-y parameter

number of interactions



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Thermal SZ

At low frequencies

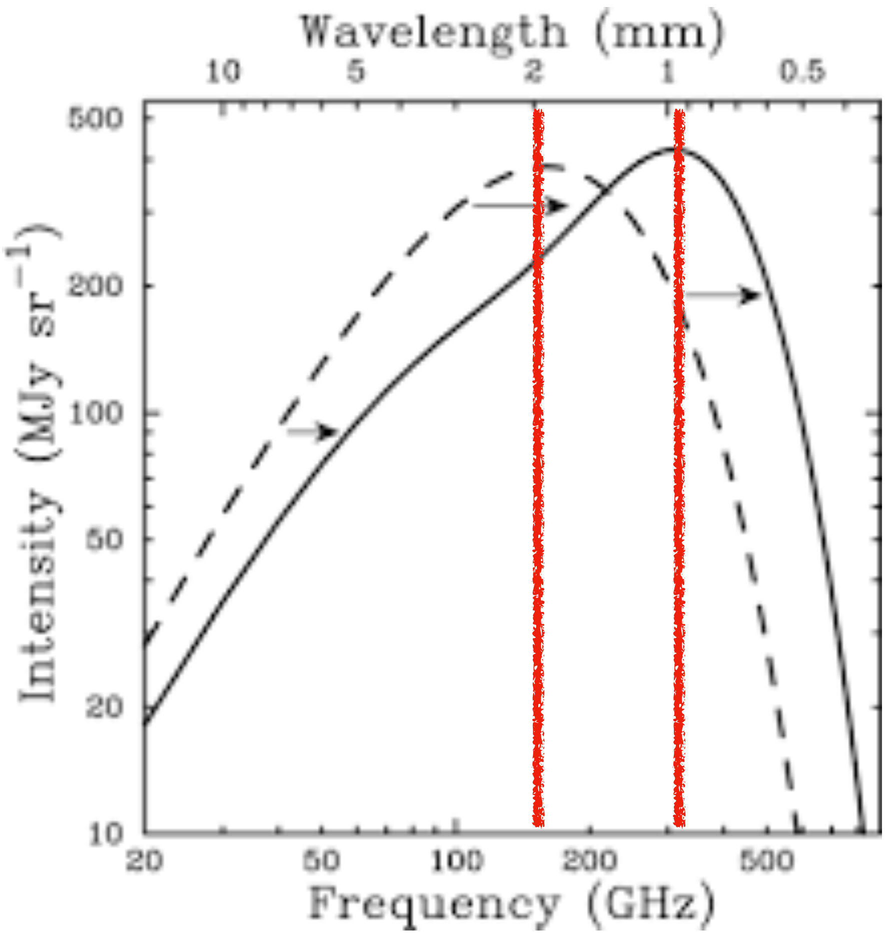
$$\frac{dI\nu}{I_\nu} = \frac{dT_{\rm SZ}}{T} = -2y$$

$$y = \int \sigma_T n_e \frac{k_b T_e}{m_e c^2} dl$$

Compton-y parameter

number of interactions

Independent of redshift



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Kinetic SZ

$$\frac{dT_{SZ}}{T} = -\frac{V_p}{c}\tau$$

Net doppler effect due to V_p , the peculiar velocity of the cluster with respect to the Hubble flow. $V_p>0$($V_p<0$) corresponds to lower(higher) temperature

$V_p>0$ away from the the observer

$$\tau = \int \sigma_T n_e dl$$

optical depth

Sunyaev-Zeldovich effect

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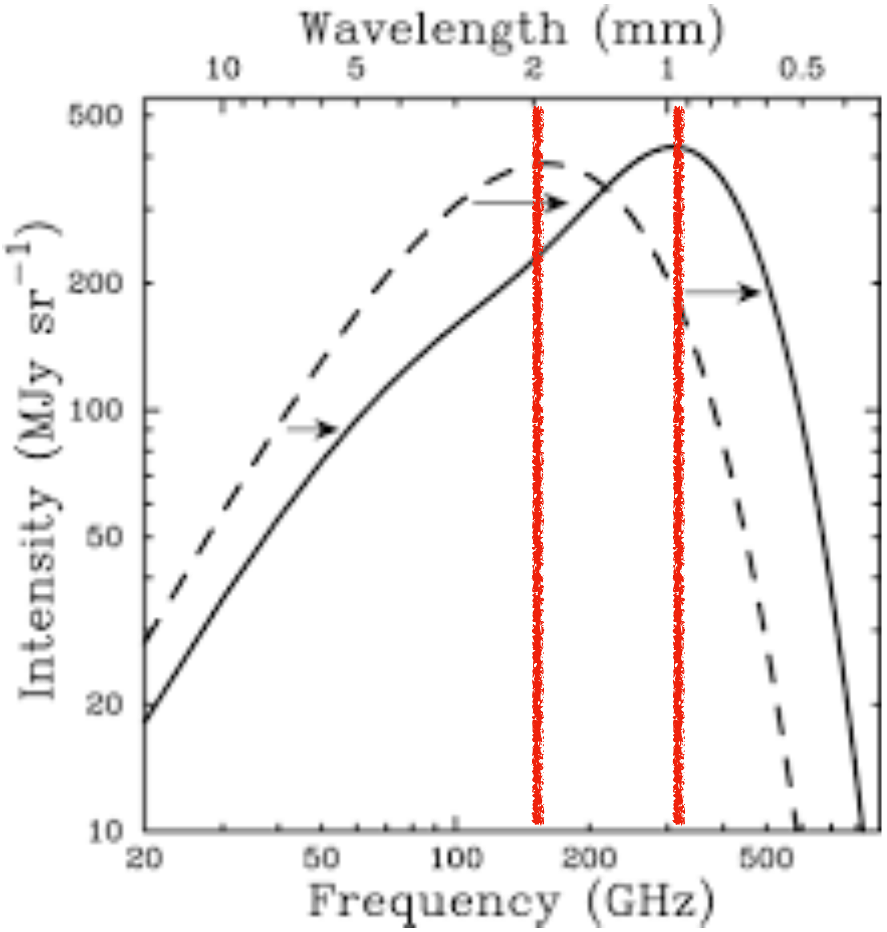

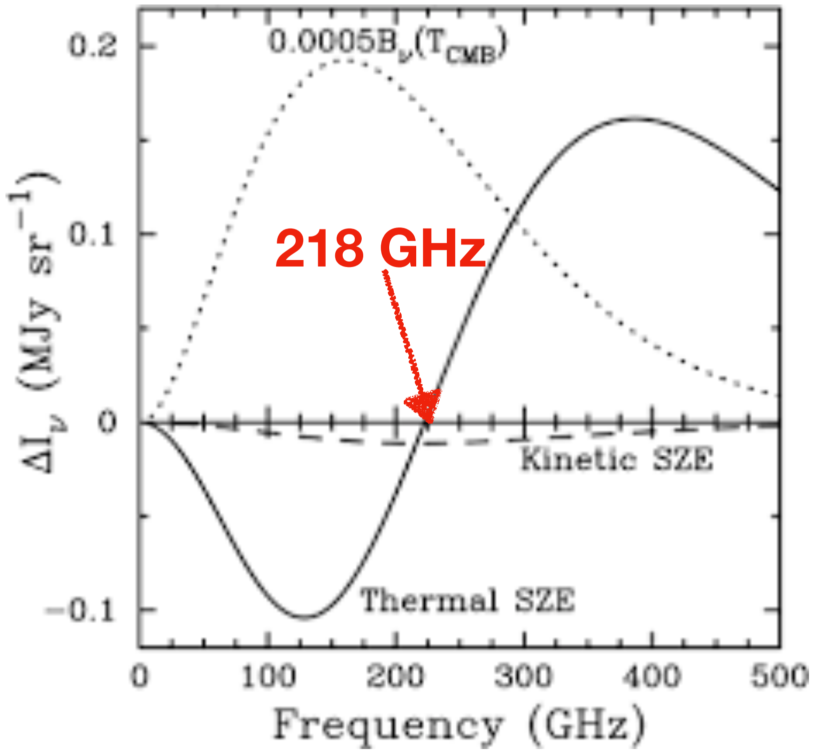

Sunyaev & Zeldovich 1980

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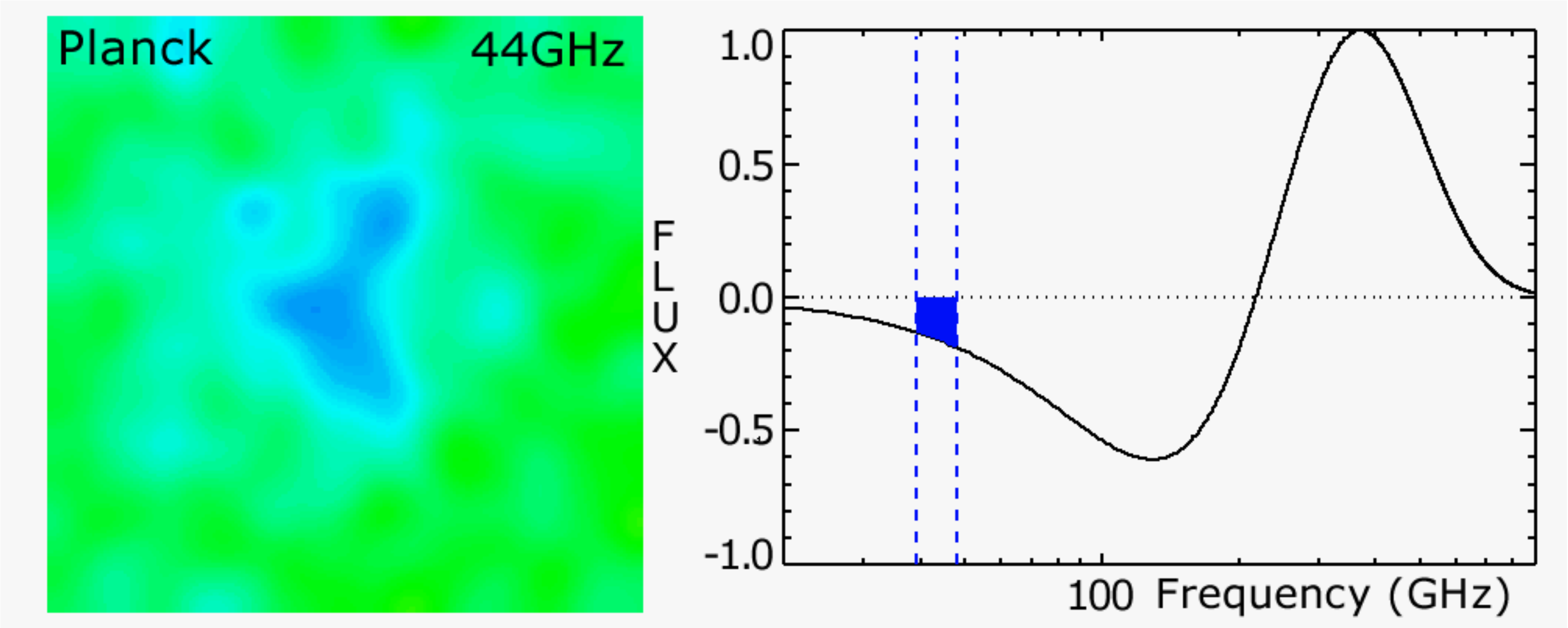
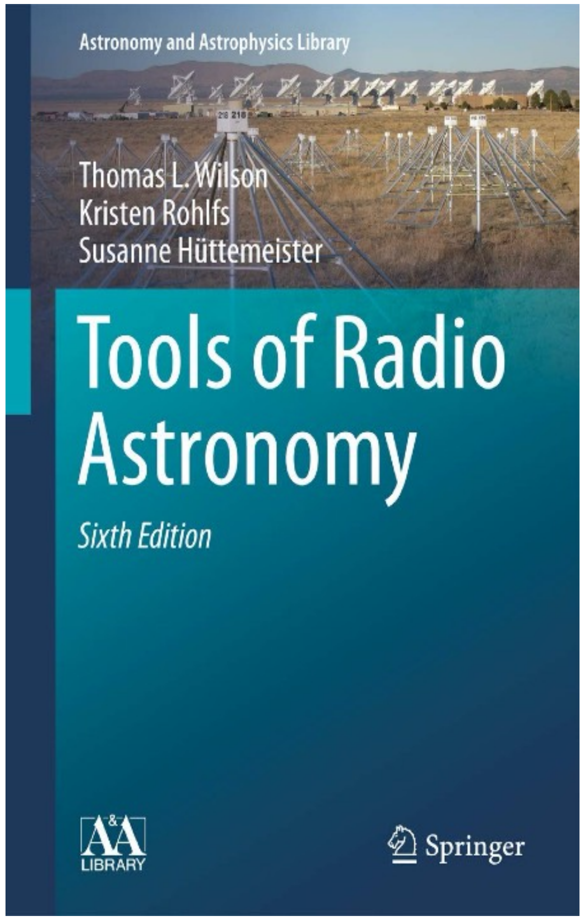


Summary of

Radiative processes relevant to radioastronomy

A solid knowledge of the astrophysics behind radio observables is necessary to achieve a complete understanding of the various phenomena/astrophysical sources that will be investigated in this course.

Line emission/absorption processes



Astronomy and Astrophysics Library

Thomas L. Wilson
Kristen Rohlfs
Susanne Hüttemeister

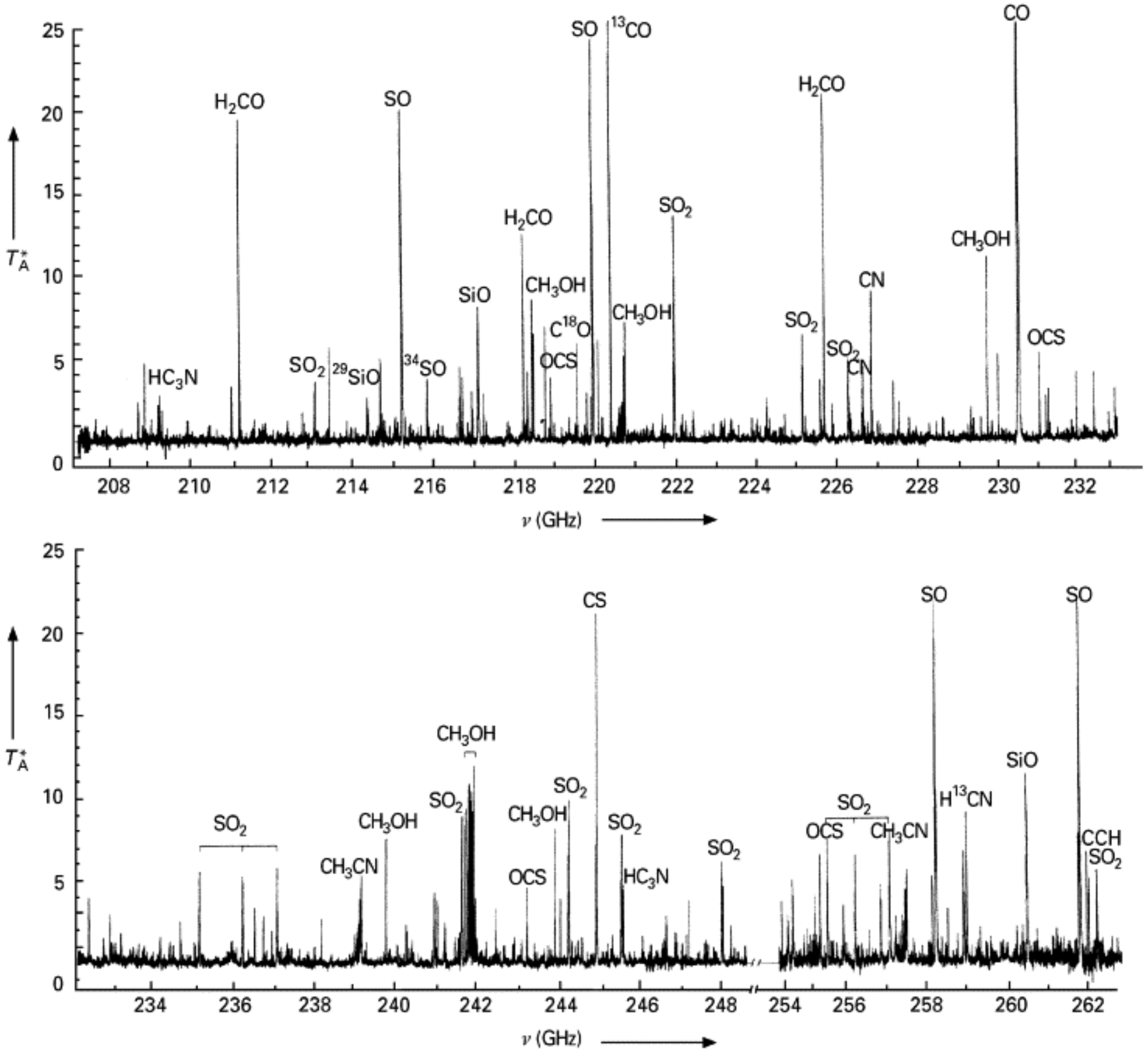
Tools of Radio Astronomy

Sixth Edition

A&A LIBRARY

Springer

Chapters 12, 13, 14, 15, 16

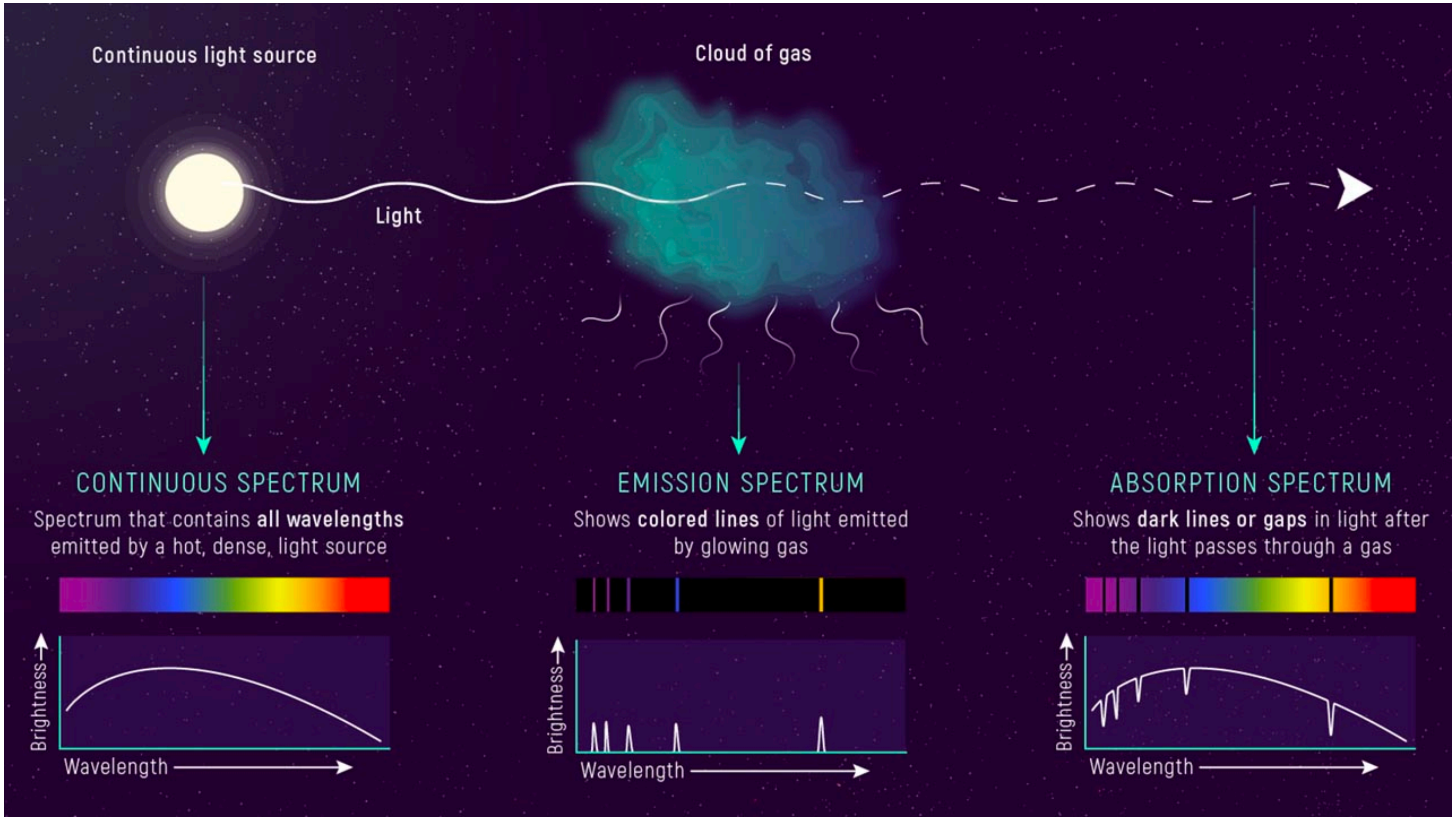


Orion nebula, radio spectrum

Basic definitions

$$\frac{dI_\nu}{ds} = -k_\nu I_\nu + \epsilon_\nu$$

ϵ_ν emission coefficient
k_ν absorption coefficient



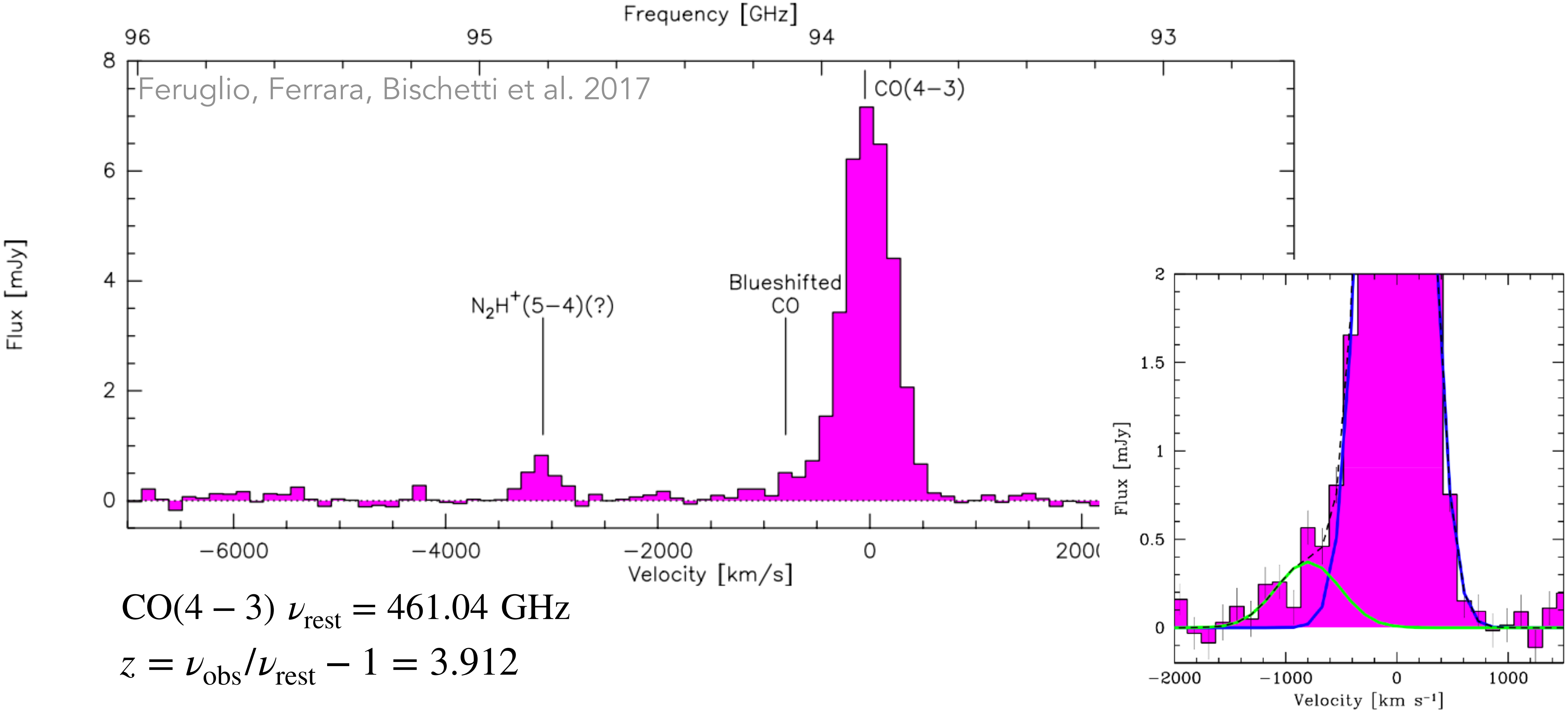
Thermal black body
Thermal free-free
Synchrotron
Inverse Compton

Rotational transitions (molecules)
Fine structure transitions (e.g. [CII])
Hyperfine structure transitions (H 21cm)
Amplified stimulated emission (masers)

Basic definitions

Emission/absorption lines are powerful diagnostics of physical and chemical conditions in astronomical objects. The rest-frequency of each line is unique and identifies the emitting atom or molecule.

- ✳ Line intensity is related to the number of emitting atoms/molecules: physical conditions of the source medium
- ✳ Frequency shift with respect to the laboratory frequency: distances can be measured. Frequency shift with respect to the source rest-frame: (gas) dynamics
- ✳ Line width is related to the physical conditions of the absorbing and emitting atoms/molecules (mass, turbulence)


Feruglio, Ferrara, Bischetti et al. 2017

$$\mathrm{CO}(4-3)\ \nu_{\mathrm{rest}} = 461.04\ \mathrm{GHz}$$

$$z = \nu_{\mathrm{obs}}/\nu_{\mathrm{rest}} - 1 = 3.912$$

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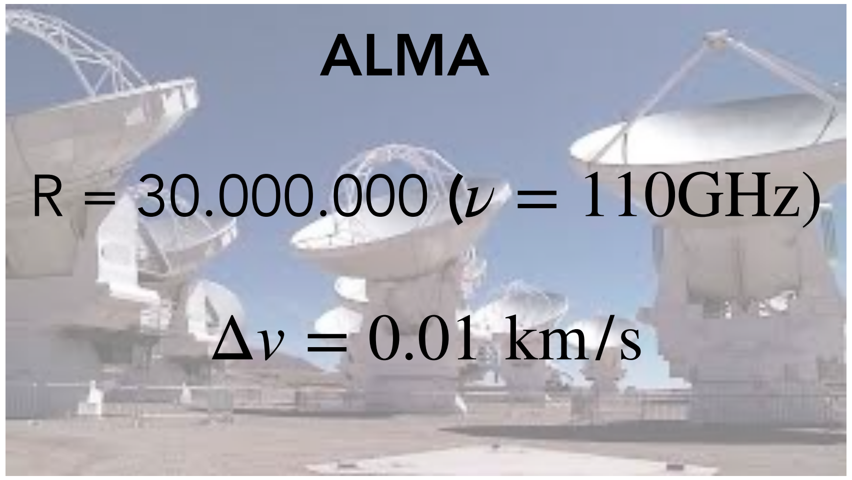
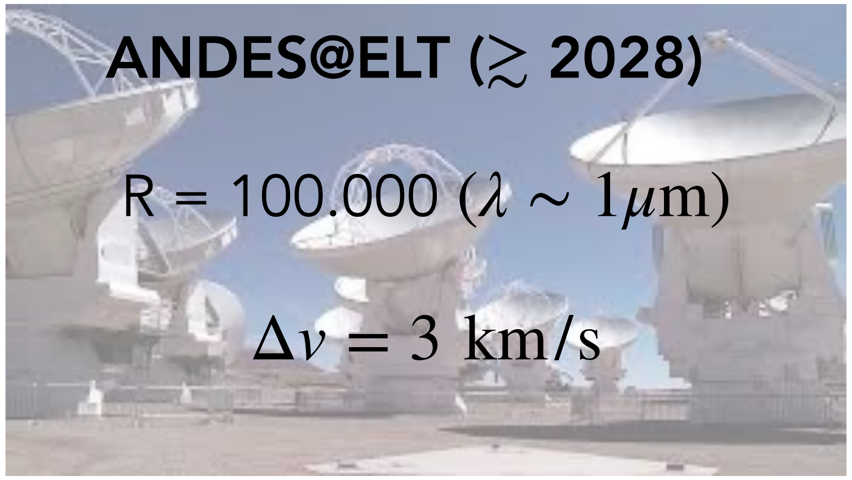
The importance os spectral lines in astronomy broadened considerably with the extension of observations into the radio regime. Observing at low frequencies allows to easily achieve high-spectral resolution

$$R = \frac{\Delta \nu}{\nu}$$


ALMA

R = 30.000.000 ($\nu = 110\mathrm{GHz}$)

$\Delta v = 0.01\ \mathrm{km/s}$

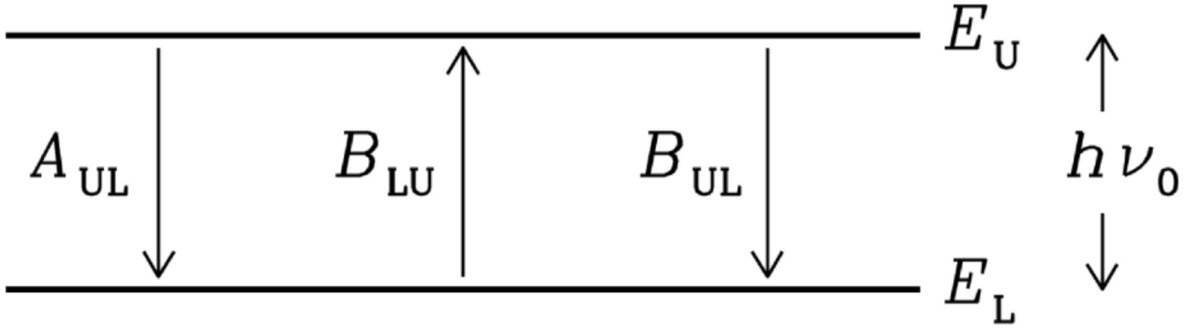

ANDES@ELT ($\gtrsim$ 2028)

R = 100.000 ($\lambda \sim 1\mu\mathrm{m}$)

$\Delta v = 3\ \mathrm{km/s}$

Line radiative transfer

The interaction of radiation with an atom/molecule by the emission and absorption of photons can be described by the Einstein coefficients:



A_{UL} spontaneous emission (s^{-1})

B_{UL} stimulated emission ($m^3\ J^{-1}\ s^{-2}$)

B_{LU} absorption

Considering **a single atom/molecule** with two energy levels E_U and E_L, the photon emitted or absorbed during a transition has an energy $E_\gamma = h\nu_0 = E_U - E_L$. If the system in a <u>stationary state</u>, the numbers of emitted and absorbed photons are equal, and the Einstein coefficients are linked by the relation

$$\boxed{N_U A_{UL} + N_U B_{UL}\bar{U} = N_L B_{LU}\bar{U}}$$

where $\bar{U} = \frac{4\pi}{c}\int_0^\infty I_\nu \phi(\nu) d\nu$ is the profile-weighted average radiation field density (J m^{-3} Hz^{-1})

$\int_0^\infty \phi(\nu) d\nu = 1$ where $\phi(\nu)$ is the normalized profile function of the emission/absorption line

N_U, N_L are the number of atoms/molecules per unit volume in state U,L

Einstein coefficients

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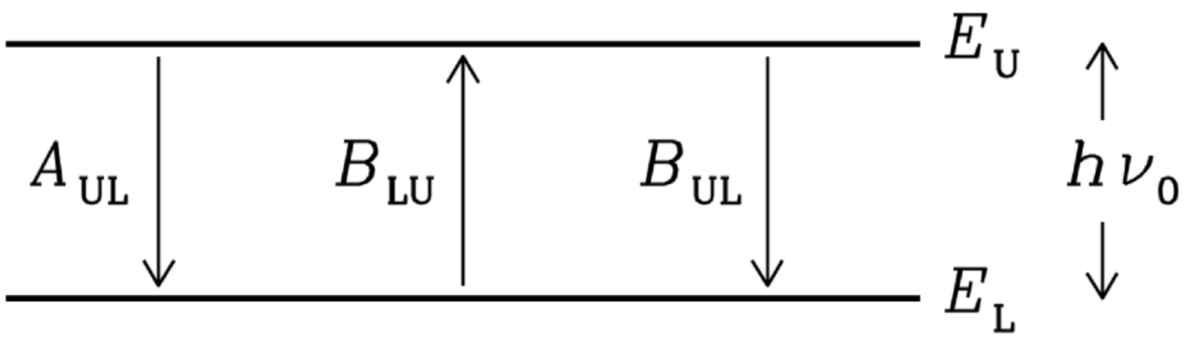

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$$\boxed{N_U A_{UL} + N_U B_{UL}\bar{U} = N_L B_{LU}\bar{U}}$$

If the system is in TE, the different levels are populated according to the Boltzmann distribution:

$$\frac{N_U}{N_L} = \frac{g_U}{g_L} exp\left(-\frac{h\nu_o}{kT}\right)$$

g_U, g_L statistical weights, i.e. the numbers of distinct physical states having energies E_U, E_L

H atom	$g_n=2n^2$
molecule	$g_J = 2J+1$
H 21 cm	$g_U=3$, $g_L=1$

(If the system is not in TE: T—>T_b)

Einstein coefficients

Solving for $\bar{U}$ we have:

$$\bar{U} = \frac{A_{UL}}{\frac{N_L}{N_U}B_{LU} - B_{UL}} \sim \frac{4\pi}{c} I_{\nu_0} = \frac{4\pi}{c}\frac{2h\nu_0^3}{c^2}\frac{1}{exp(-h\nu_0/kT) - 1}$$

for all T

Planck radiation law

Boltzmann

From which we find that Einstein coefficients are not independent:

$$\boxed{g_L B_{LU} = g_U B_{UL}}$$

$$\boxed{A_{UL} = \frac{8\pi h\nu_0^3}{c^3} B_{UL}}$$

Equations of detailed balance

All three coefficients can be computed if one (e.g. A_{UL}) is known

Although we assumed TE for simplicity of the derivation, the equations of balance relate the coefficients of individual atoms or molecules, for which the macroscopic statistical concept of TE is meaningless. They are valid for all macroscopic systems, whether or not they are in TE or in LTE.

Line radiative transfer

$$\frac{dI_\nu}{ds} = -k_\nu I_\nu + \epsilon_\nu$$

ϵ_ν emission coefficient

k_ν absorption coefficient

In the case of line radiation, the emission and absorption coefficients can be related to Einstein coefficients, that is to the atomic properties of the matter.

Three processes contribute to I_ν:

$$dP_e(\nu) = h\nu_0 \underbrace{N_U A_{UL}}_{\text{\# of spont em per unit V and time}} \phi(\nu) dV \frac{d\Omega}{4\pi} d\nu$$

Total power emitted spontaneously (for each system transitioning from E$_U$ to E$_L$)

$$dP_a(\nu) = h\nu_0 \underbrace{N_L B_{LU} \frac{4\pi}{c}}_{\text{\# of abs per unit V and time}} I_\nu \phi(\nu) dV \frac{d\Omega}{4\pi} d\nu$$

Total power absorbed

where $dV = d\sigma ds$

$$dP_s(\nu) = h\nu_0 N_U B_{UL} \frac{4\pi}{c} I_\nu \phi(\nu) dV \frac{d\Omega}{4\pi} d\nu$$

Total power for the stimulated emission

$$\boxed{dP_e(\nu) - dP_a(\nu) + dP_s(\nu) = dI_\nu d\Omega d\sigma d\nu}$$

definition of brightness
(specific intensity)

Line radiative transfer

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k_ν absorption coefficient

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“net” absorption coefficient

$$\boxed{\frac{dI_\nu}{ds} = -\overbrace{\frac{h\nu_0}{c}(N_L B_{LU} - N_U B_{UL})\phi(\nu)}^{k_\nu} I_\nu + \overbrace{\left(\frac{h\nu_0}{4\pi}\right) N_U A_{UL}\phi(\nu)}^{\epsilon_\nu}}$$

stimulated emission is typically considered as a “negative” absorption

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stimulated emission is typically considered as a “negative” absorption

In LTE the Kirchoff’s law implies that $\frac{\epsilon_\nu}{k_\nu} = B_\nu(T) = \frac{2h\nu^3}{c}\frac{1}{exp(-h\nu/kT) - 1}$ (using also Boltzmann)

Expliciting k_ν we obtain: $\boxed{k_\nu = \frac{c^2}{8\pi\nu_0^2}\frac{g_U}{g_L} N_L A_{UL}[\underbrace{1}_{\substack{\text{ordinary}\\ \text{absorption}}} - \underbrace{exp(-h\nu_0/kT)}_{\substack{\text{stimulated}\\ \text{emission}}}]\phi(\nu)}$

Line radiative transfer

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In the Rayleigh-Jeans regime we have $h\nu_0 << kT$

$$[1 - exp(-h\nu_0/kT)] \sim h\nu_0/kT << 1$$

Stimulated emission nearly cancels ordinary absorption and significantly reduces the net line opacity at radio frequencies.

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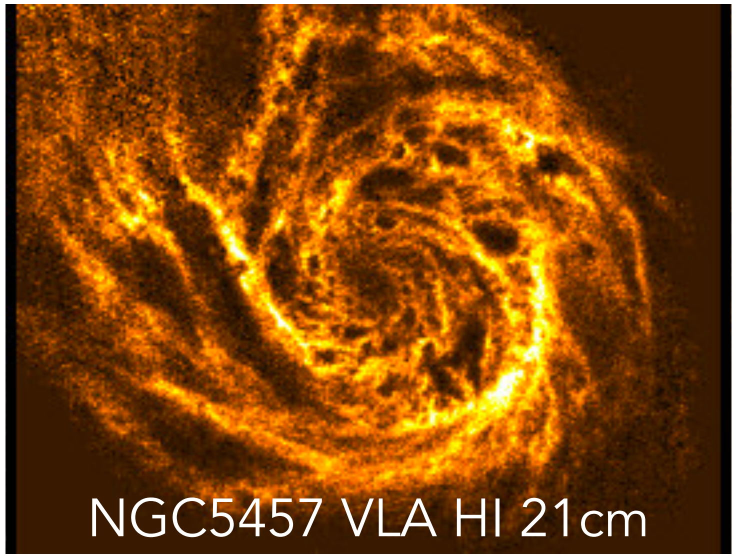
In this regime $k_\nu \propto T^{-1}$ and $B_\nu \propto T$, their product does not depend on T. This implies that the brightness of an optically thin ($\tau << 1$) emission line

$$I_\nu \sim B_\nu(T)\tau \qquad\qquad (d\tau_\nu = -k_\nu ds)$$

can be ~independent of the gas temperature (while it is proportional on the column density of the emitting gas via N_L).


NGC5457 VLA HI 21cm

Thus e.g. the HI line flux of an optically thin galaxy is proportional to the total mass of neutral hydrogen in the galaxy but says nothing about its temperature.