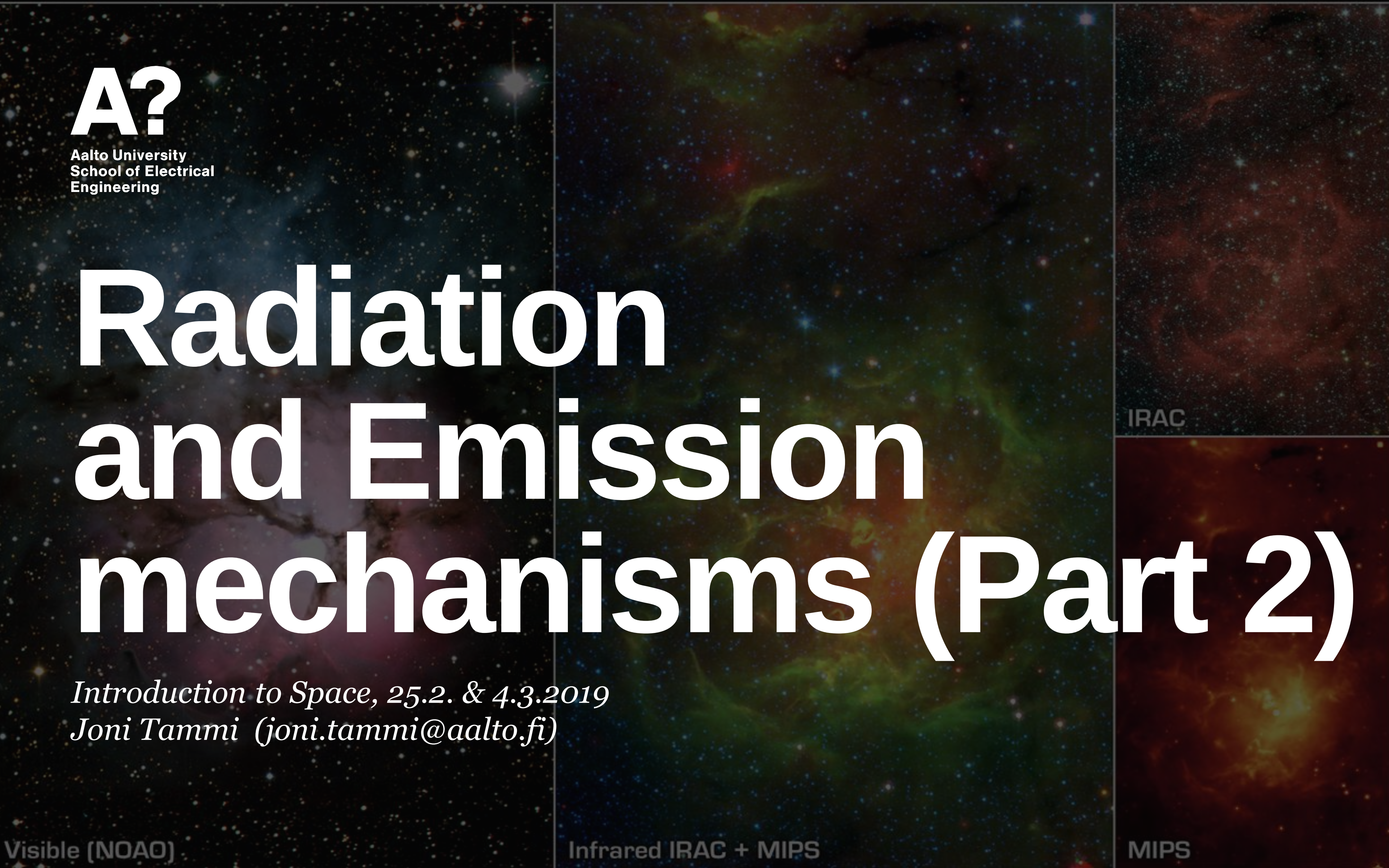
Aalto University
School of Electrical
Engineering

Radiation and Emission mechanisms (Part 2)

Introduction to Space, 25.2. & 4.3.2019
Joni Tammi (joni.tammi@aalto.fi)



Electromagnetic emission mechanisms

Emission mechanisms

Underlying things to remember

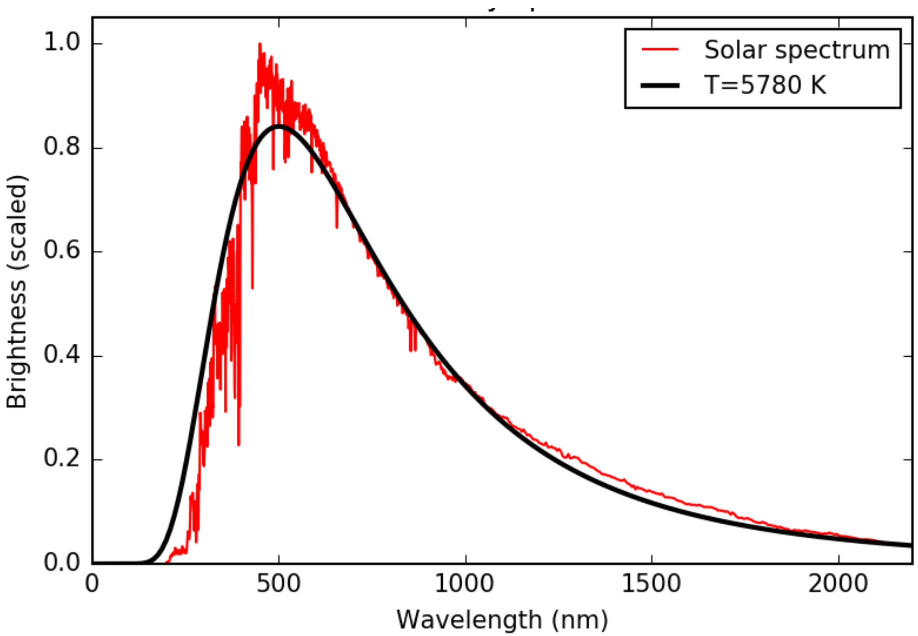
- Accelerating charge → photons.
- Photon energy ($E = h\nu$) comes from somewhere.
- Emission and absorption
  - *Photon produced vs. photon lost.*

- 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”*

Blackbody radiation

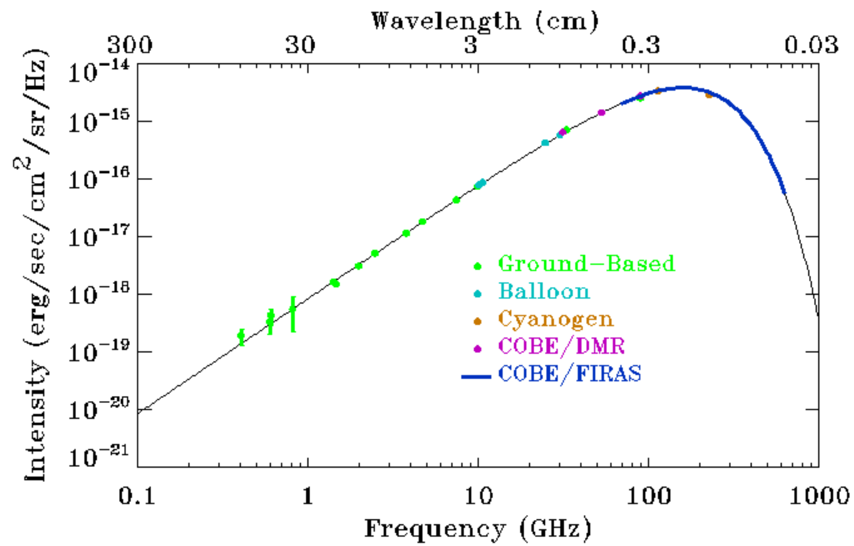
Sun and stars

- $T \approx 5780\ K$



Cosmic Microwave Background

- $T \approx 2.725\ K$



Details: practice session

Aalto University
School of Electrical
Engineering

End of lecture 1:
Radiation and thermal emission

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

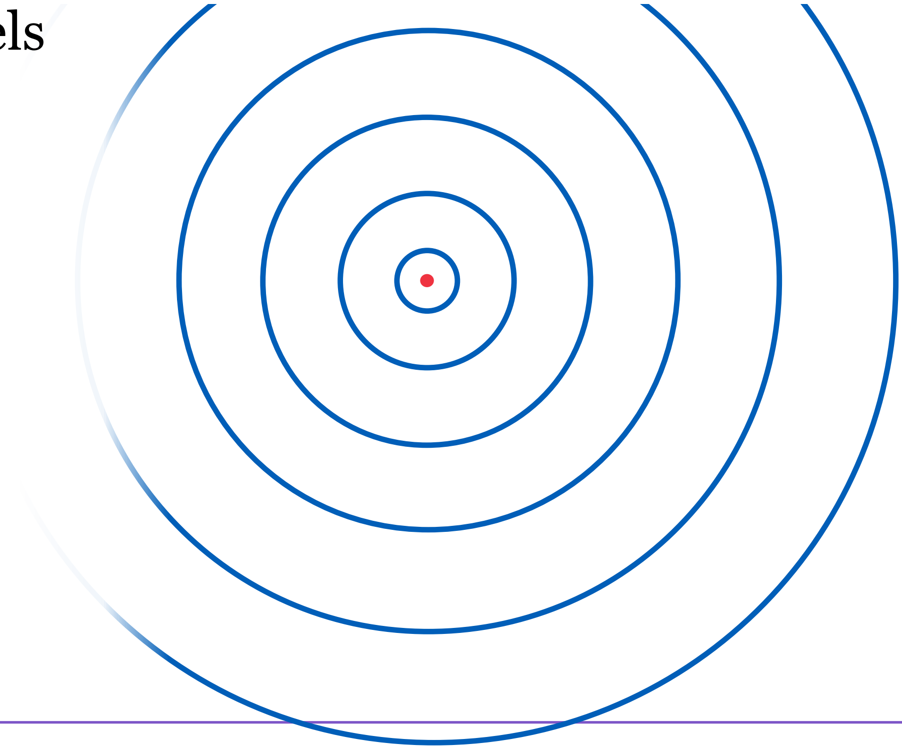
Line emission (and absorption)

Lines: Emission & Absorption

Electron energy states

- Quantised energy levels

Bohr model for hydrogen atom:

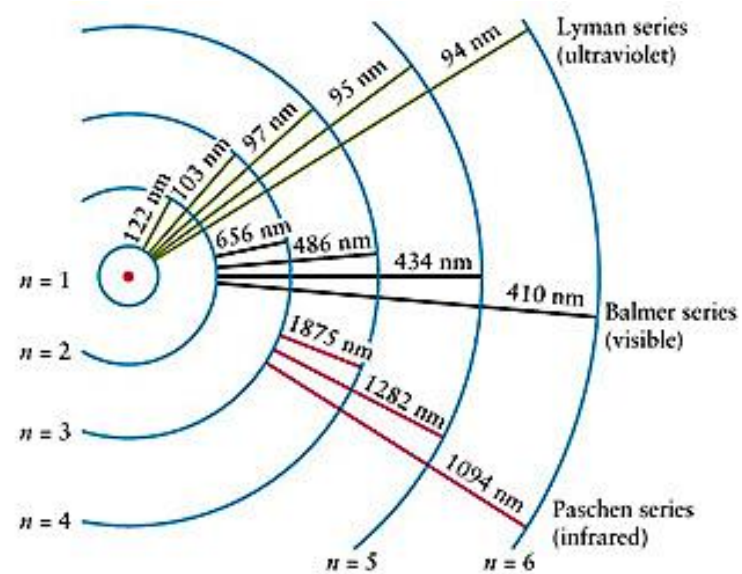


Lines: Emission & Absorption

Electron energy states

- Quantised energy levels
- Exact energy difference between states ("orbits")
- Change between states – takes or gives exactly the right amount of energy $E = h\nu = \frac{hc}{\lambda}$

Bohr model for hydrogen atom:

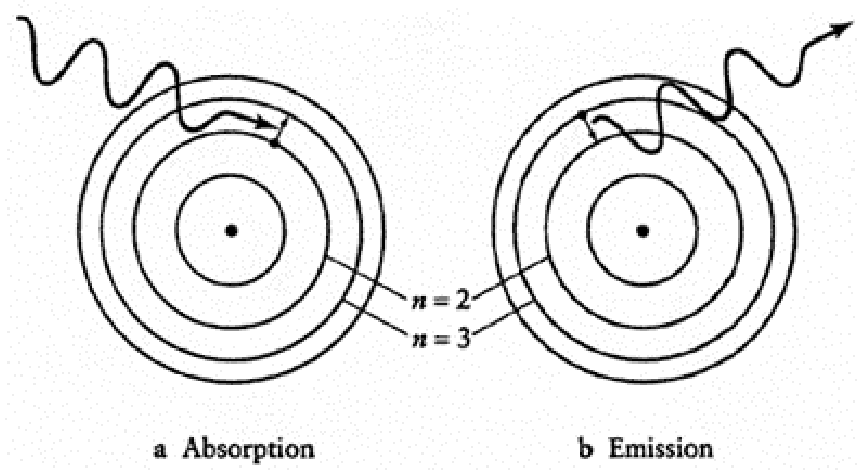


Balmer series spectrum:

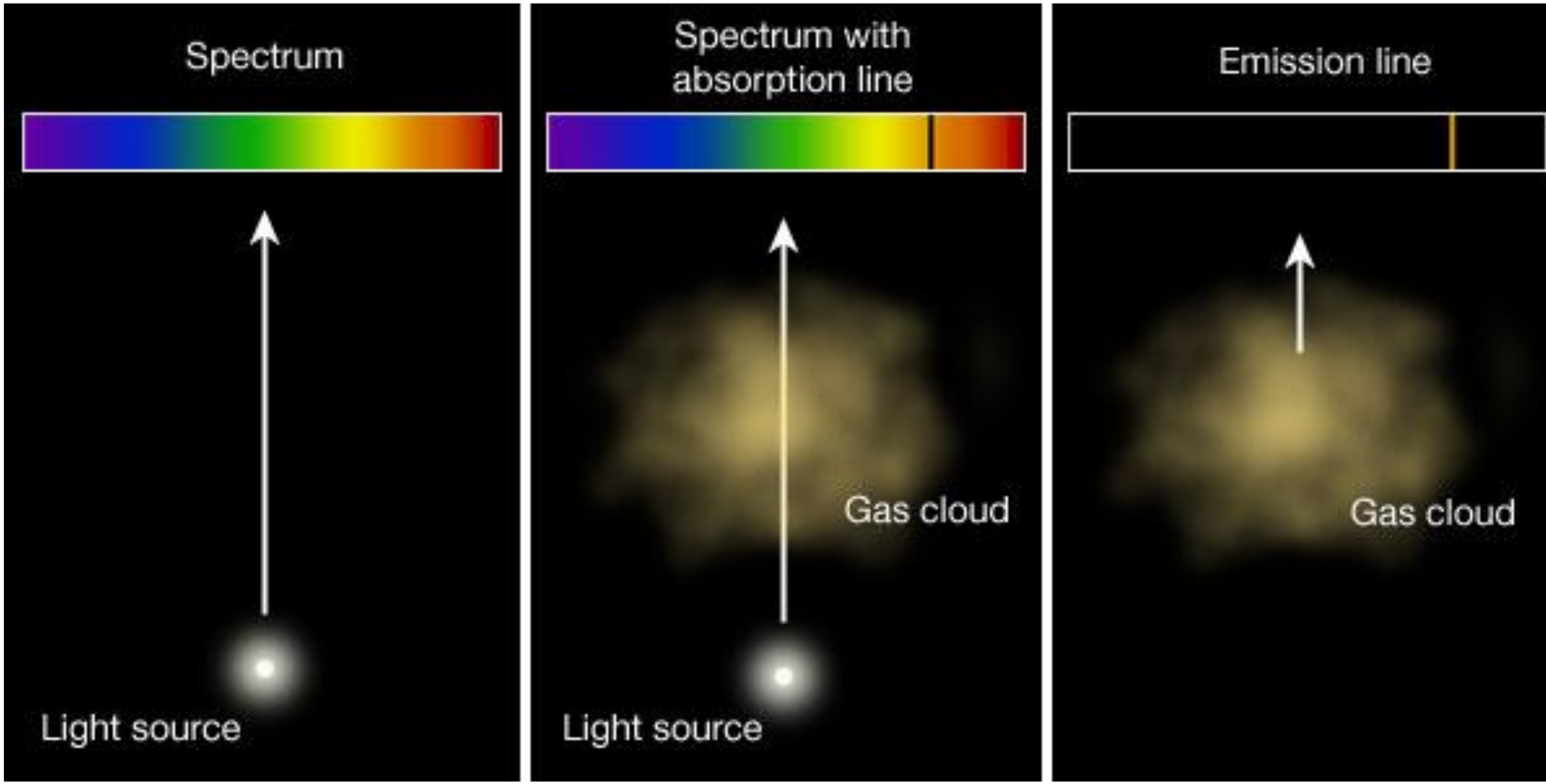
Lines: Emission & Absorption

Electron energy states

- Quantised energy levels
- Exact energy difference between states (”orbits”)
- Change between states – takes or gives exactly the right amount of energy $E = h\nu = \frac{hc}{\lambda}$
- Emit/absorb photons with corresponding ν (or λ)



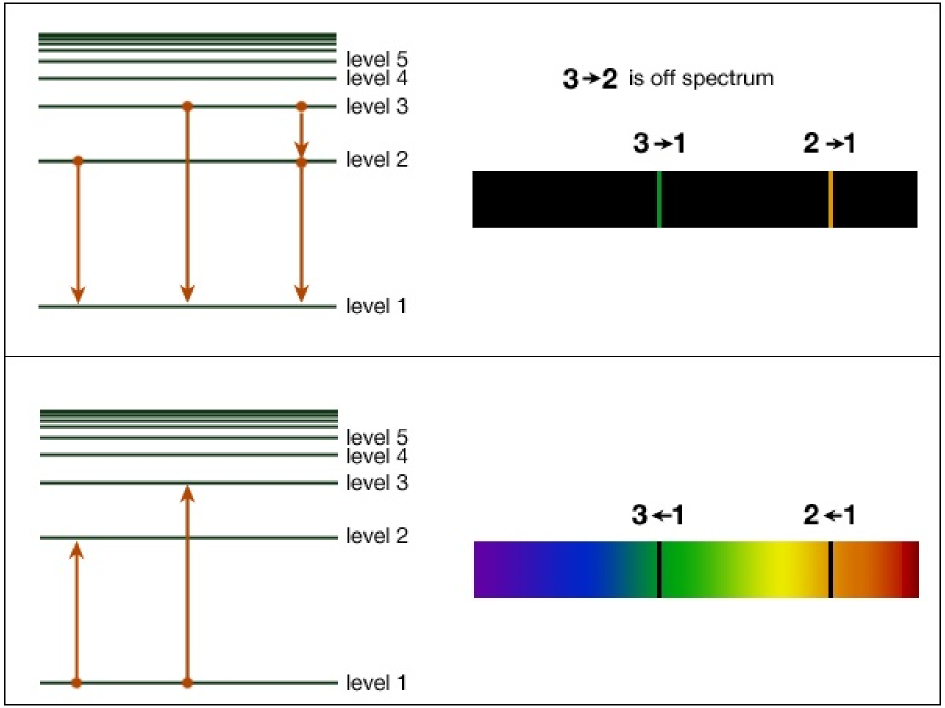
Lines: Emission & Absorption



Lines: Emission & Absorption

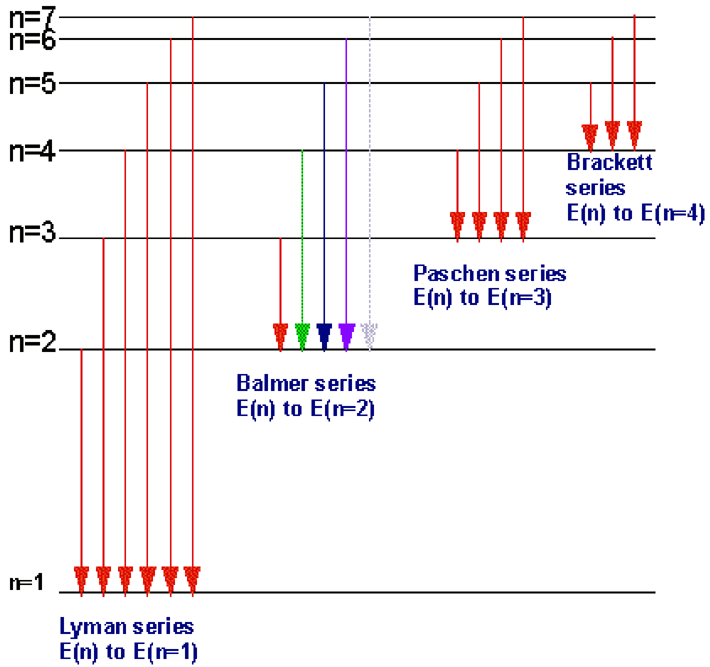
Gas made of atoms/molecules

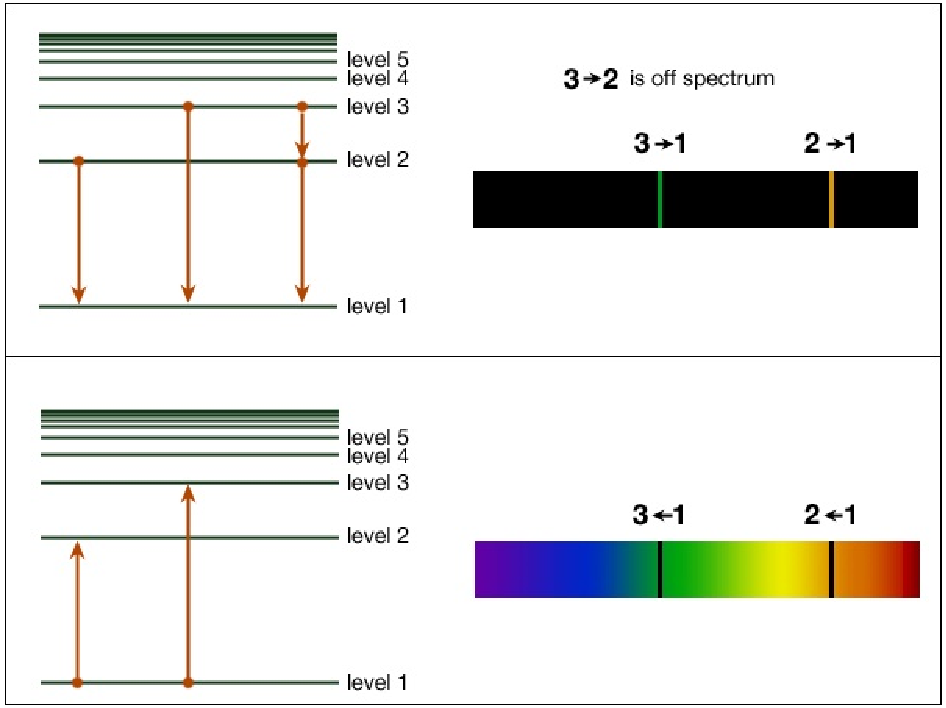
- Gas emits/absorps photons with specific wavelegths.
- A line in spectrum
  - *"One atom, one photon"*
    → the more atoms, the stronger the line.
  - *Same wavelength regardless of process (emission/absorption).*
- Frequency depends on the atom/molecule, not e.g. on temperature.



Lines: Emission & Absorption

Electron transitions for the Hydrogen atom

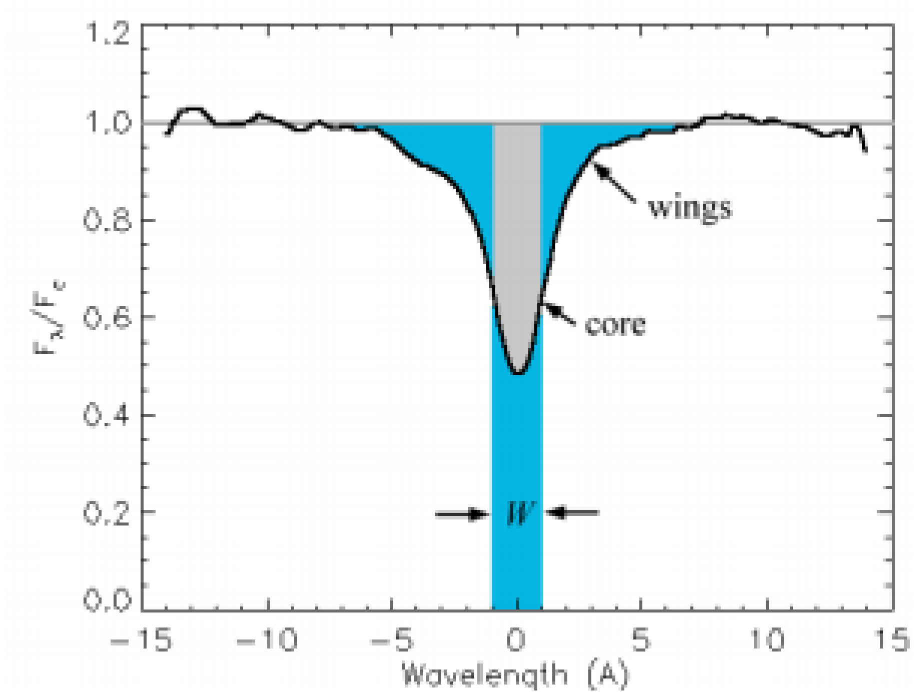




Lines: Emission & Absorption

(Observed) Line profile

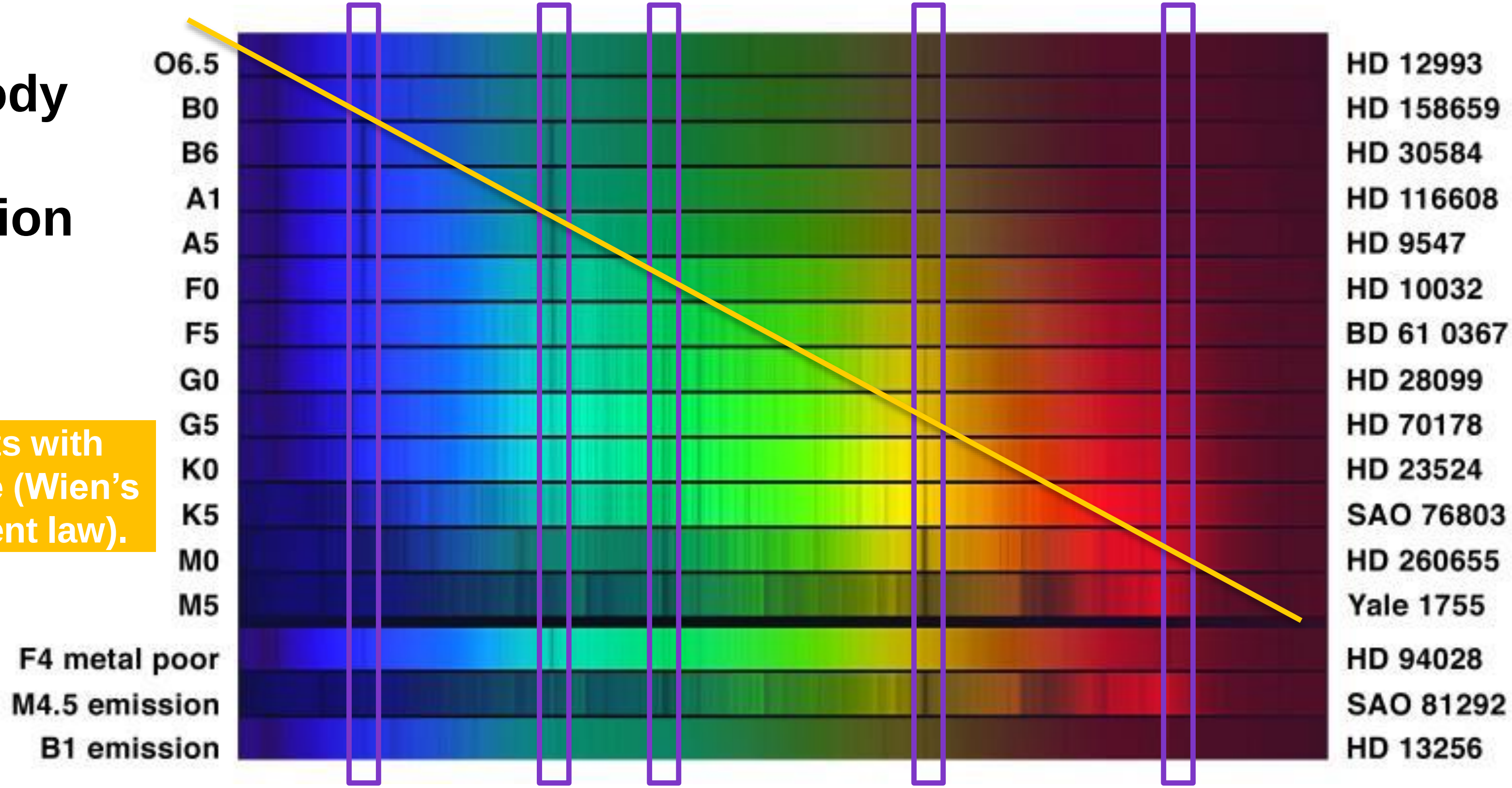
- Not infinitely sharp.
- Broader profile due to
  - *Natural width (uncertainty principle)*
  - *Thermal Doppler broadening*
  - *Pressure effects*
- Shape: Voigt profile



Example: Star spectra

Blackbody
+
absorption lines

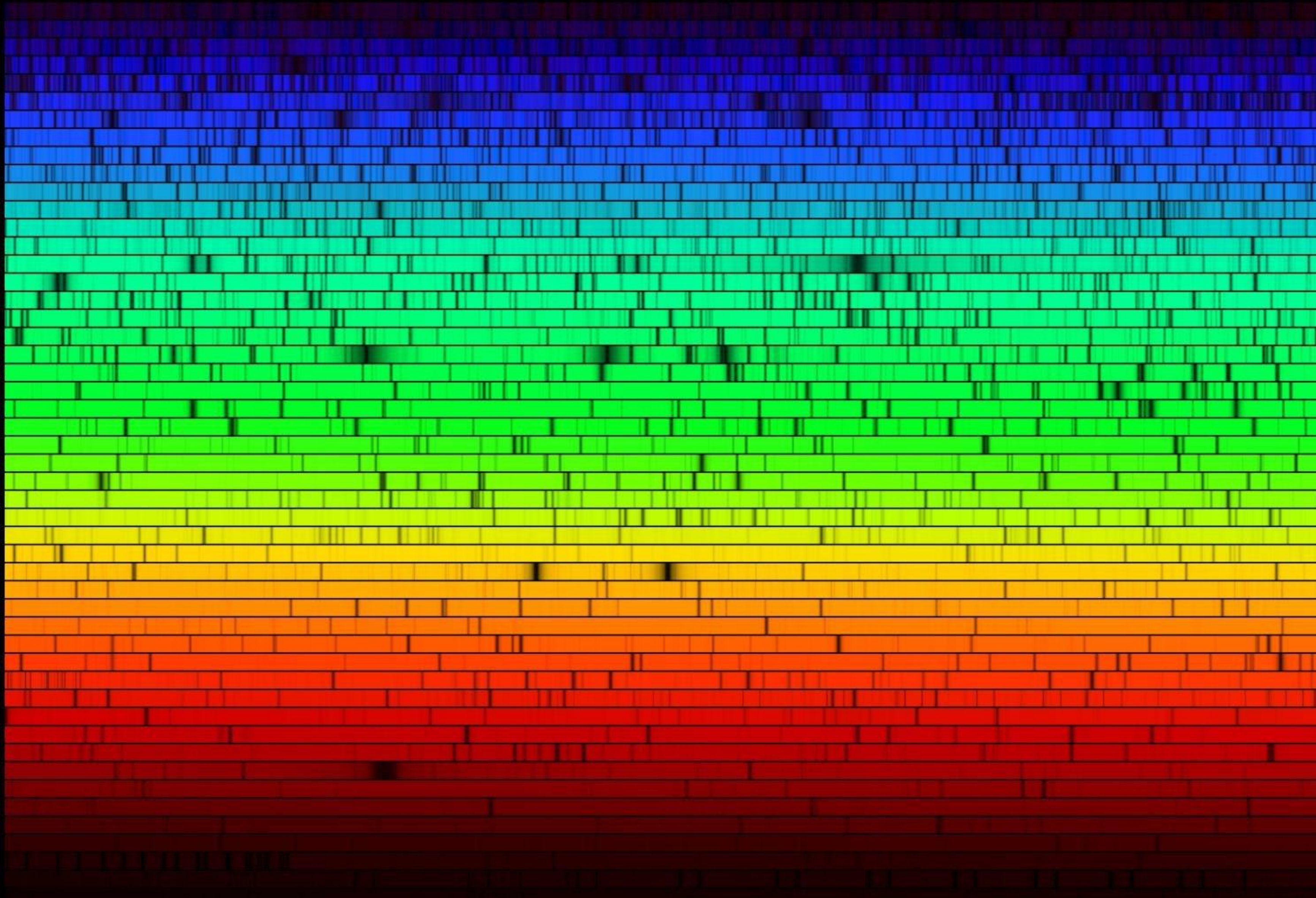
Peak shifts with temperature (Wien's displacement law).



http://apod.nasa.gov/apod/ap040418.html

Lines at the same frequency because it only depends on atomic properties, not temperature of the object.

Sun

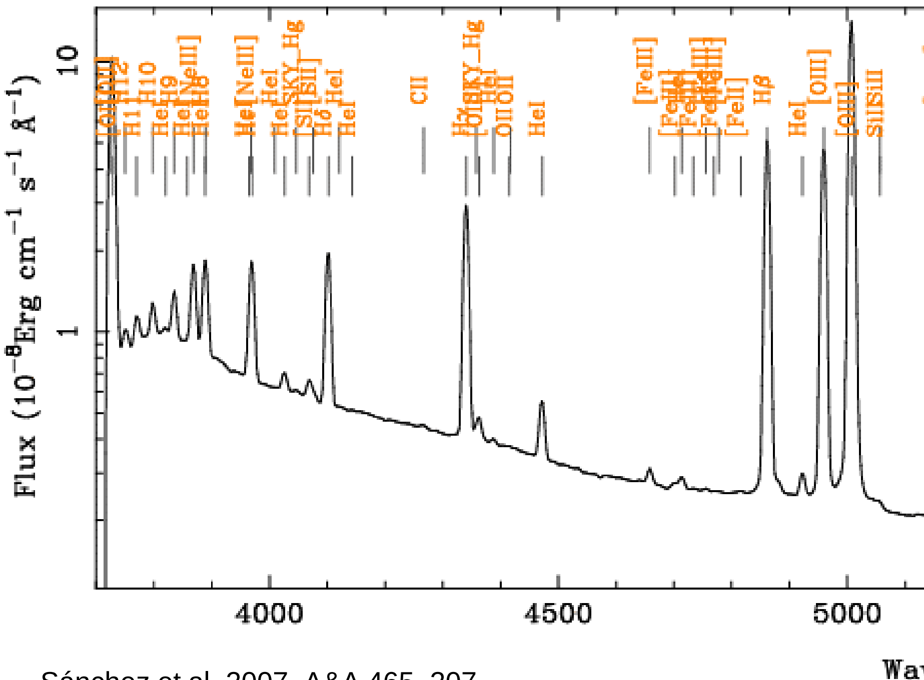


Example: The Orion nebula

Example: The Orion nebula

- **Emission nebula**
  - In constellation Orion
  - ~1350 ly away
  - ~20 ly in size
  - ~2000 M_{Sun}
- **H II region**
  - Ionised atomic hydrogen
  - T up to 10 000 K

Example: The Orion nebula



Wavelength Lab. (Å)	Wavelength Obs. (Å)	Flux[1]	Line Id.	Wavelength Lab. (Å)	Wavelength Obs. (Å)	Flux	Line Id.
3726.03	3724.94	35 219.70	[OII]	5006.84	5006.99	143 002.31	[OIII]
3728.82	3730.08	40 670.09	[OII]	5056.02	5055.80	35.09	SiII
3750.15	3751.09	676.63	H12	5056.35	5056.35	39.79	SiII
3770.63	3771.25	1574.32	H11	5158.81	5157.92	52.29	[FeII]
3797.90	3798.18	2550.31	H10	5197.90	5195.79	25.86	[NI]
3819.64	3819.54	876.94	HeI3819	5199.00	5199.49	76.77	SKY_NI
3835.39	3835.15	3391.71	H9	5200.26	5201.02	142.51	[NI]
3857.53	3853.55	561.27	HeI	5270.40	5270.64	171.06	[FeIII]
3868.75	3868.59	8266.59	[NeIII]	5360.00	5359.94	6.06	SKY?
3888.65	3887.97	4416.27	HeI	5461.00	5461.07	215.29	SKY_HgI
3889.05	3890.22	3957.53	H8	5517.71	5517.71	284.96	[ClIII]
3964.73	3967.69	3634.16	HeI	5537.88	5537.89	281.24	[ClIII]
3967.46	3968.09	642.14	[NeIII]	5577.00	5576.40	789.97	SKY_OI
3970.07	3969.20	5478.41	H	5577.31	5578.10	791.73	[OI]
4009.27	4007.41	318.24	HeI	5685.00	5684.97	118.17	SKY_NaI
4026.21	4026.00	722.02	HeI	5754.64	5754.66	400.01	[NII]
4046.00	4046.02	32.09	SKY_HgI	5770.00	5769.91	15.66	SKY?
4068.60	4068.39	458.02	[SII]	5790.00	5790.04	1.16	SKY?
4076.35	4074.88	159.72	[SII]	5875.62	5875.56	7538.90	HeI
4101.74	4101.56	12 021.26	H	5893.00	5892.61	348.91	SKY_NaI D
4120.86	4121.23	53.23	HeI	5930.00	5927.95	123.02	SKY?
4143.76	4148.23	23.02	HeI	5957.61	5957.11	41.97	SiII
4267.15	4265.12	85.48	CII	5958.58	5957.49	12.78	OI
4340.47	4340.32	23 860.65	H	5978.97	5978.80	81.35	SiII
4358.00	4364.15	113.00	SKY_HgI	6000.00	6000.26	12.91	SKY?
4363.21	4366.76	831.27	[OIII]	6046.40	6046.57	41.92	OI
4387.93	4379.43	125.13	HeI	6240.00	6239.95	60.97	SKY?
4414.91	4471.37	1937.47	OII	6265.00	6264.91	30.67	SKY?
4416.98	4418.47	62.93	OII	6300.00	6299.33	297.01	SKY_OI
4471.50	4412.41	97.99	HeI	6300.30	6301.39	362.98	[OI]
4658.10	4658.22	379.59	[FeIII]	6312.10	6312.27	950.13	[SIII]
4701.62	4701.26	123.43	[FeIII]	6330.00	6329.99	46.28	SKY?
4713.20	4713.36	279.38	HeI	6347.09	6347.30	141.11	SiII
4733.93	4735.80	40.15	[FeIII]	6363.78	6363.72	208.24	[OI]
4754.83	4755.52	62.28	[FeIII]	6370.36	6370.53	107.90	SiII
4769.60	4775.10	62.48	[FeIII]	6548.03	6547.63	10 743.11	[NII]
4777.88	4783.04	29.99	[FeIII]	6562.82	6562.87	171 573.70	H
4815.55	4815.82	82.38	[FeII]	6583.41	6583.52	32 494.66	[NII]
4861.33	4861.41	50 768.69	H	6678.15	6678.37	1907.79	HeI6678
4921.93	4922.20	201.94	HeI	6716.39	6716.47	2354.08	[SII]
4958.91	4959.02	47 337.07	[OIII]	6730.85	6731.27	3447.13	[SII]

Sánchez et al. 2007, A&A 465, 207

http://www.aanda.org/articles/aa/full/2007/13/aa6620-06/aa6620-06.right.html

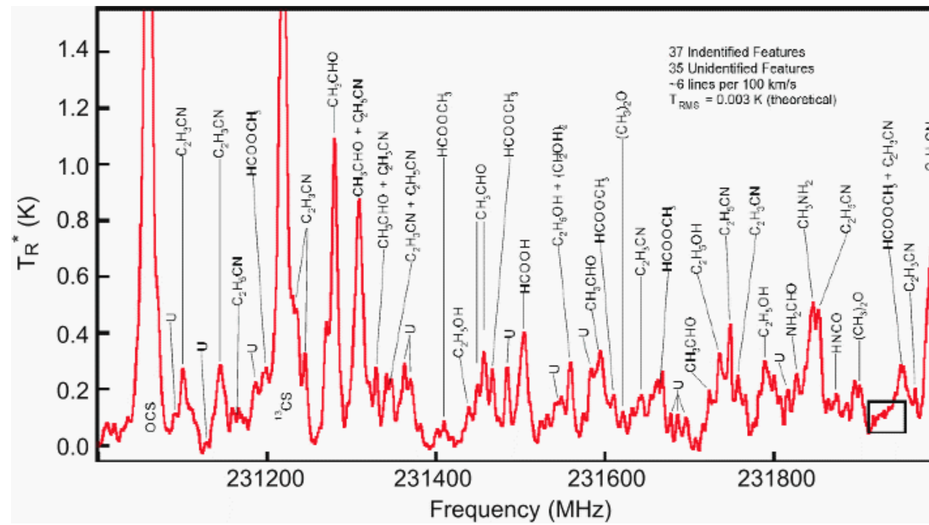
Molecular lines

Atoms

- Energy states from electron

Molecules

- More dimension → more ways to change energy state.
  - *Vibration: transition between consecutive vibrational states.*
  - *Rotation: transition between rotational states.*
- More details: https://en.wikipedia.org/wiki/List_of_interstellar_and_circumstellar_molecules

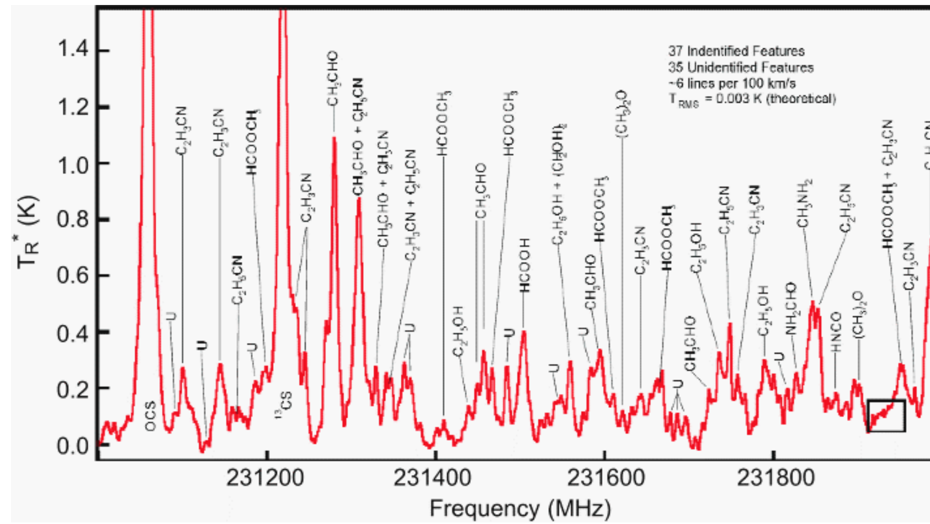


Molecular cloud near the Galactic centre

Example: Molecular clouds in space

- **Sgr B2**: Molecular cloud near the Galactic centre.
- 150 ly in size
- *T* varies between 40—300 K

- Dozens of known molecules (including alcohol).
- Dozens of *unknown* molecule lines.



Molecular cloud near the Galactic centre

Example: Aurora Borealis

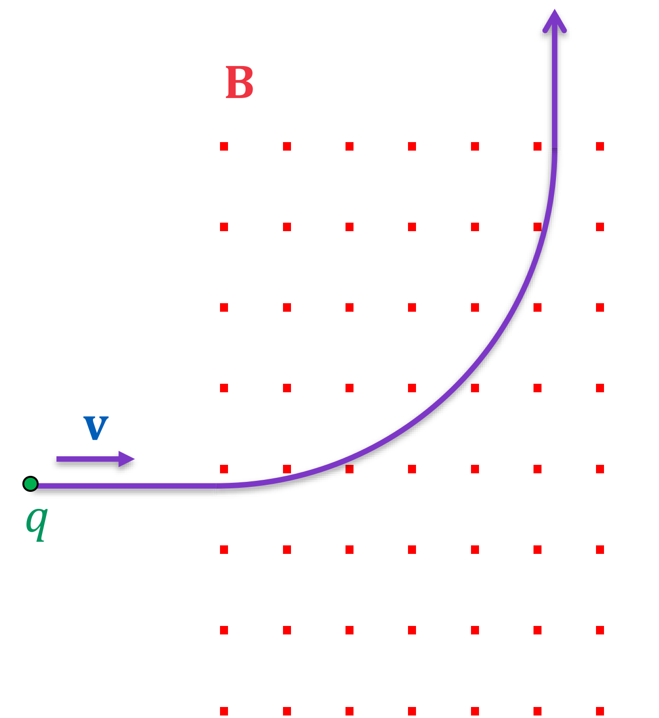
- High-energy particles excite atmospheric atoms/molecules.
- Oxygen: green, orange-red
- Nitrogen: blue, red

Synchrotron emission

Synchrotron emission

Charged particle moving in magnetic field

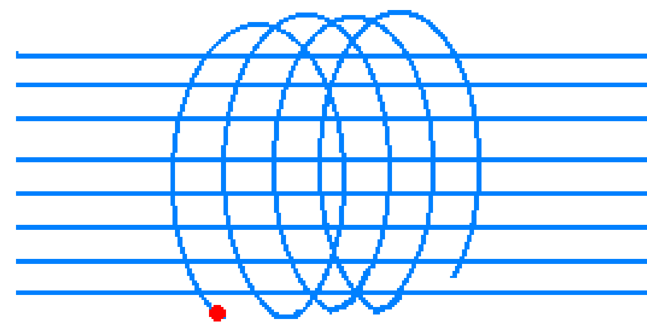
- Lorentz force $\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$
- Where $\mathbf{v}$ & $\mathbf{B}$ are vectors for the particle velocity and magnetic field. q is the charge of the particle.
- $\mathbf{F} = m\,\mathbf{a}$
  → acceleration → EM emission
- Cyclotron emission
- Synchrotron emission when $v \rightarrow c$, i.e. from relativistic particles



Synchrotron emission

Astrophysical sources

- Large-scale magnetic fields
→ continuous acceleration
→ continuous emission
- $\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) = m\,\mathbf{a}$, so synchrotron emission tells us something about
  - *Particle energies (not speeds, because all relativistic particles have almost the same speed, $v \approx 1\ c$).*
  - *Particle charge and mass.*
  - *Magnetic field strength.*

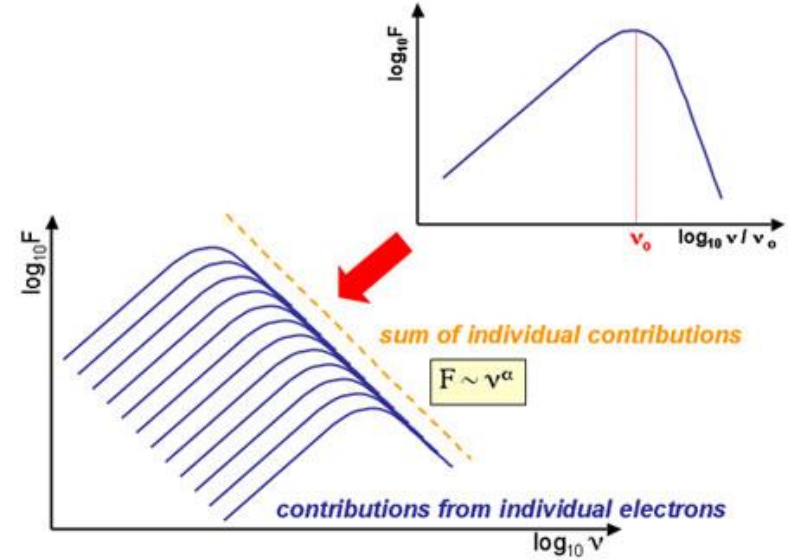


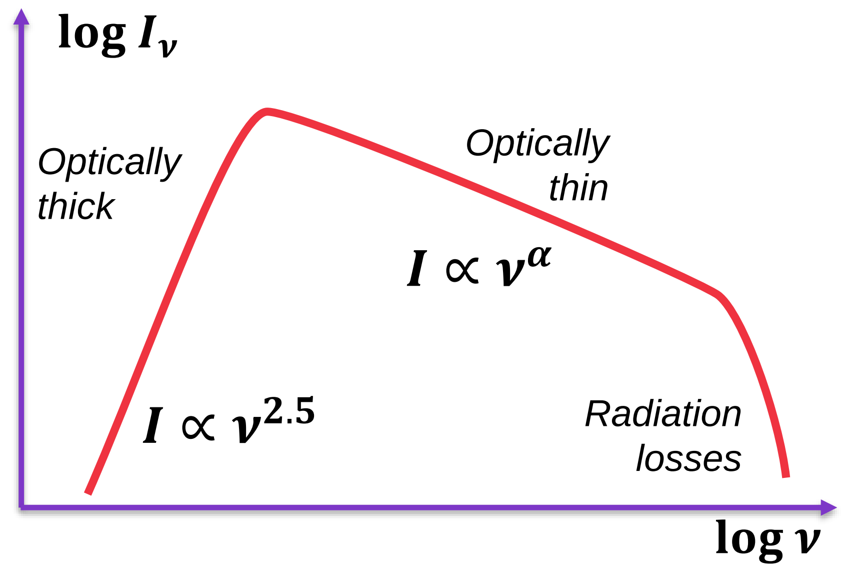
Gyroradius $r_g = \frac{\gamma\, m\, v_\perp}{|q|B}$
where $\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$.

Synchrotron emission

Synchrotron spectrum

- A single electron emits a specific spectrum → an electron population emits a specific spectrum
- Power law spectral index
- Different ”breaks” in synchrotron spectrum tell different things
    - *Lowest and highest particle energies*
    - *Magnetic field strength*
    - *Particle density*
    - *Particle energy distribution*

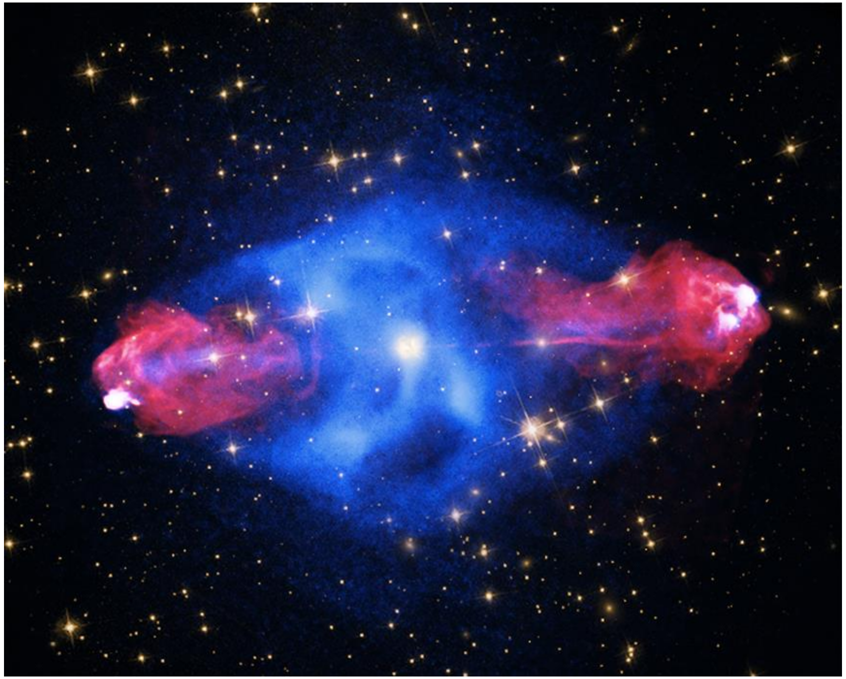




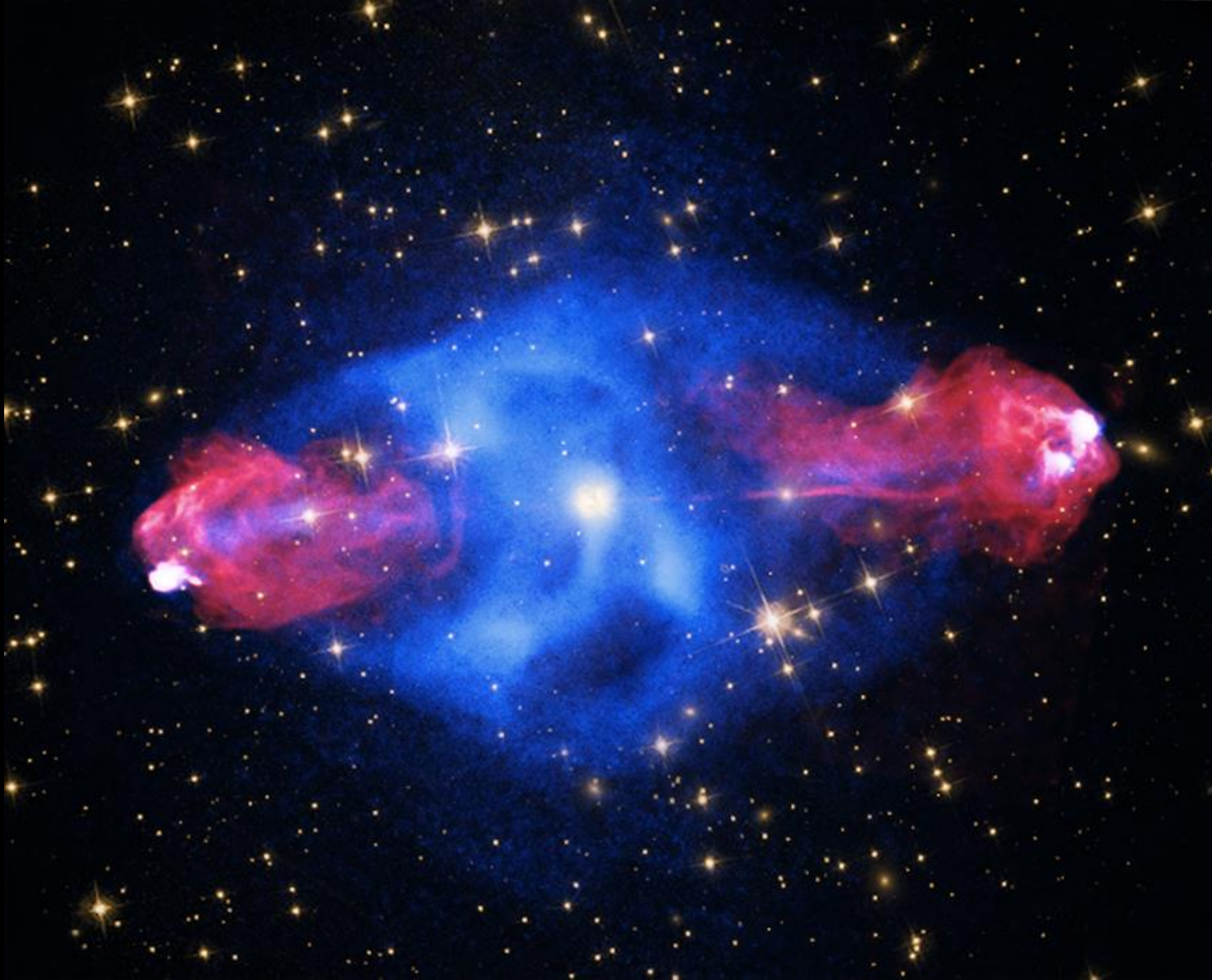
Synchrotron

Quasars (active galaxies)

- Jets of relativistic plasma inside magnetic "pipelines"
- Charged particles
  + relativistic speeds
  + strong magnetic fields
  = synchrotron emission
- E.g. ~all radio emission from quasars is synchrotron



http://apod.nasa.gov/apod/ap150124.html

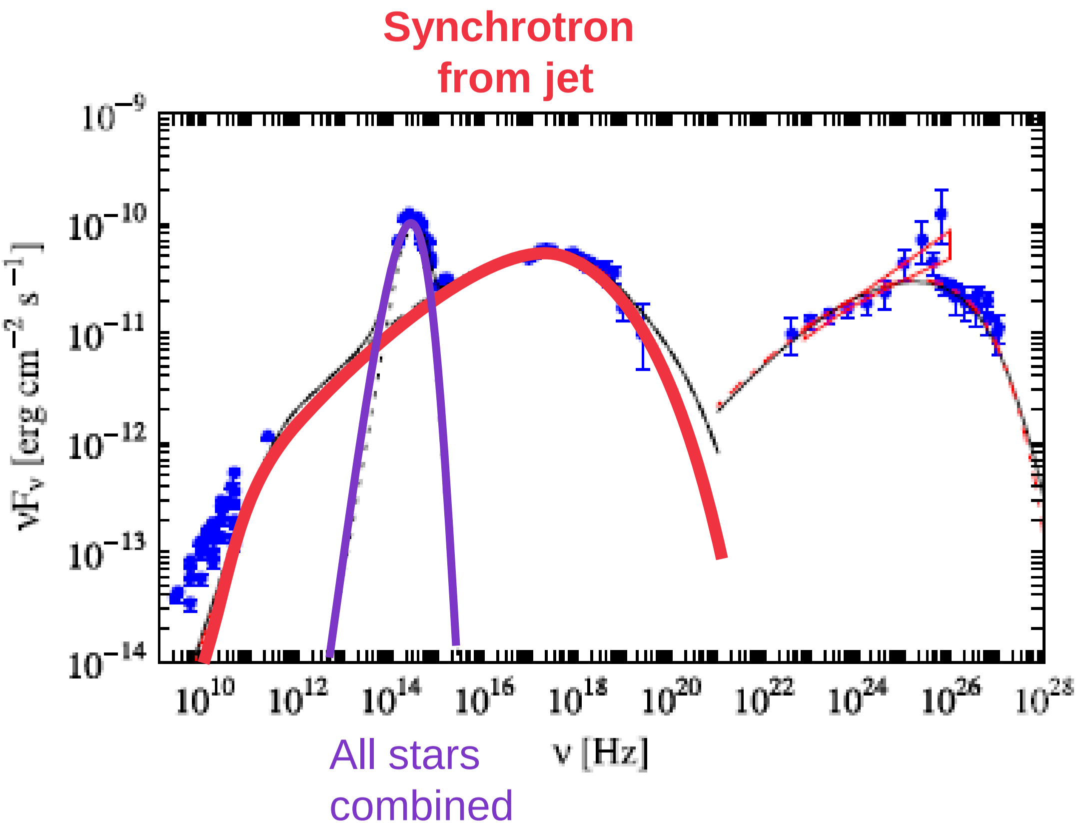


X-rays

Optical

Radio

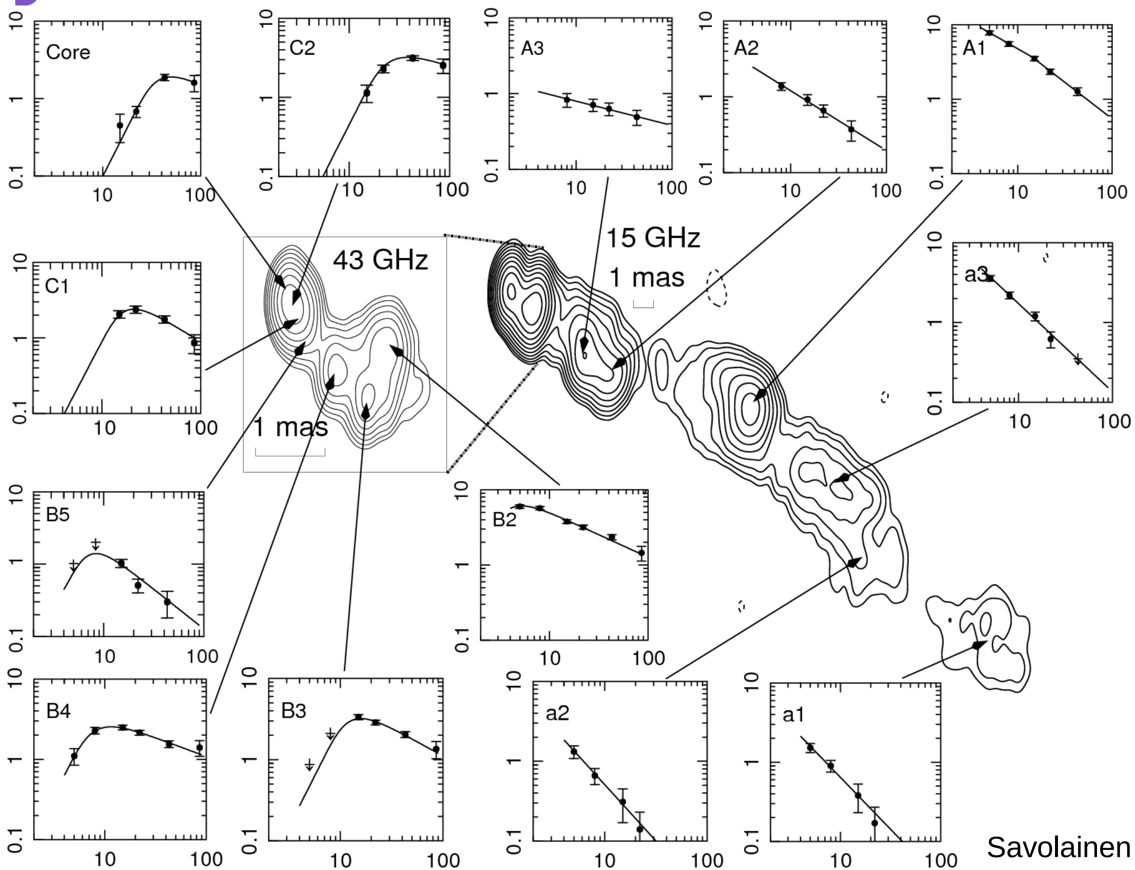
Synchrotron



N.B. This is not the spectrum $F_\nu(\nu)$, but Spectral Energy Distribution $\nu \cdot F_\nu(\nu)$.
Benefit of using SED instead of spectrum:

1. *Clearer picture*
2. *Area under the curve = how much energy is emitted.*

Synchrotron



Savolainen et al. 2008

Example:
Active Galactic Nuclei, jet from the central black hole.

Different parts are modelled with synchrotron spectra to get information about the jet and its environment.

Inverse Compton scattering

Inverse Compton scattering

Compton scattering

- High-energy **photon** ”hits” a low-energy **particle**, and is scattered.
- Photon loses energy to the particle.

Results:

- Low energy particle
  → high-energy particle.
- High-energy photon
  → low-energy photon.

Inverse Compton scattering

- High-energy **particle** ”hits” a low-energy **photon.**
- Particle loses energy to the photon.

Results:

- High energy particle
  → lower-energy particle.
- Low-energy photon
  → high-energy photon.

Inverse Compton scattering

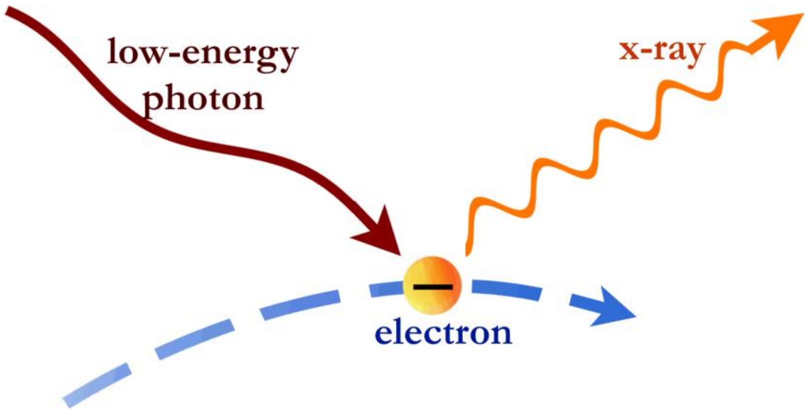
In case of relativistic particles

- $\nu_{\text{after}} \sim \nu_{\text{before}}\,\gamma^2$
- Particle's "Lorentz factor"

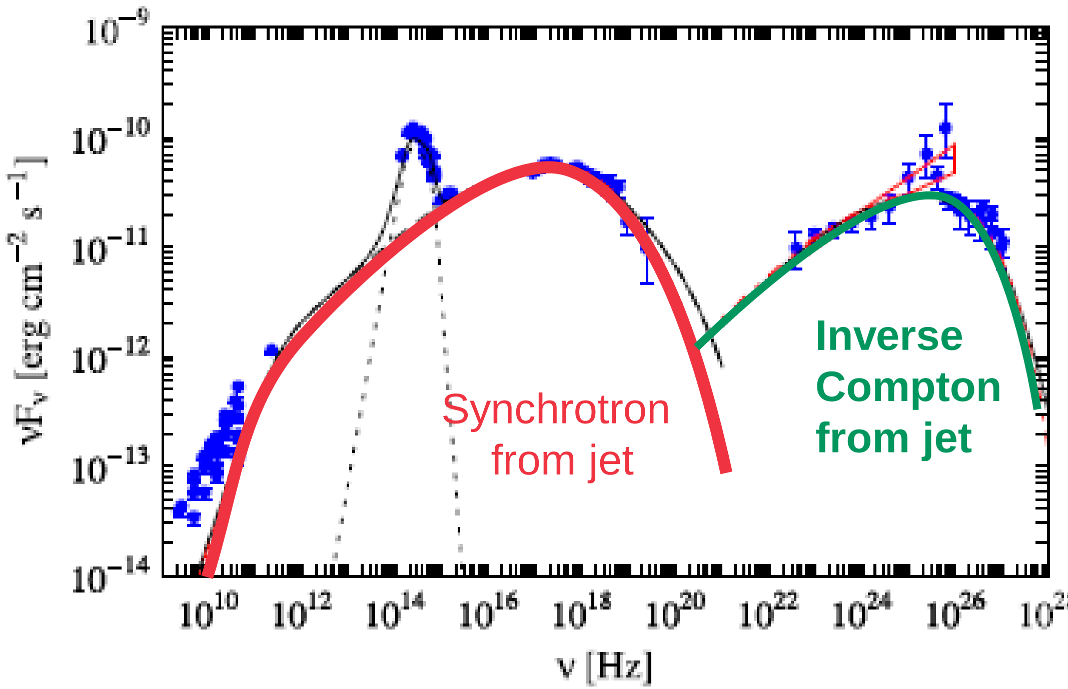
$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

$v = 0.99\,c \rightarrow \gamma \approx 7$
$v = 0.999\,c \rightarrow \gamma \approx 22$
$v = 0.9999\,c \rightarrow \gamma \approx 71$

- In a typical case, for example
  $\gamma = 10^4$ and
  $\nu_{\text{after}} \sim 10^8\,\nu_{\text{before}}$



Inverse Compton scattering

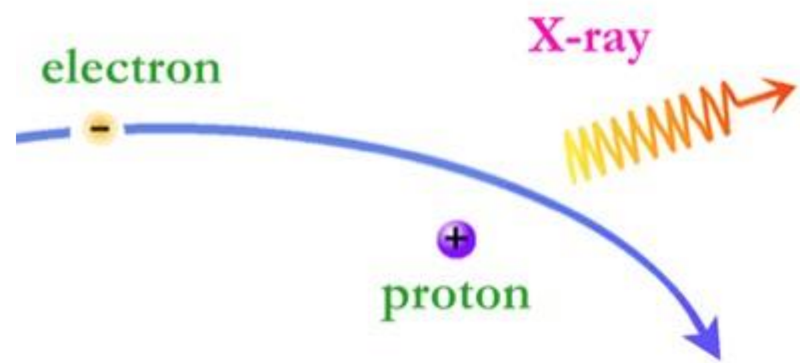


Example:
Synchrotron spectrum is ”copied” and moved to higher frequencies by 8 orders of magnitude

Bremsstrahlung (free-free emission)

Bremsstrahlung (free-free emission)

- Electron is scattered by a massive ion
  → velocity vector changes
  → acceleration
  → EM emission (photon)
- Bremsstrahlung [de]
  = braking radiation [en]
  = jarruuntumissäteily [fi]
- AKA free-free emission; particles are free in the beginning, and free in the end



Bremsstrahlung (free-free emission)

Depends on

- Density of (radiating) electrons
- Density of (scattering) ions
- Temperature (speed of electrons)
- Charge of ions

Example (to study the units):

- $\epsilon \approx 1.6 \times 10^{-28}\, T^{-1/2}\, n_e^2$
- $[\epsilon] = \mathrm{W\,m^{-3}}$

Hot ionised gas or plasma, e.g.

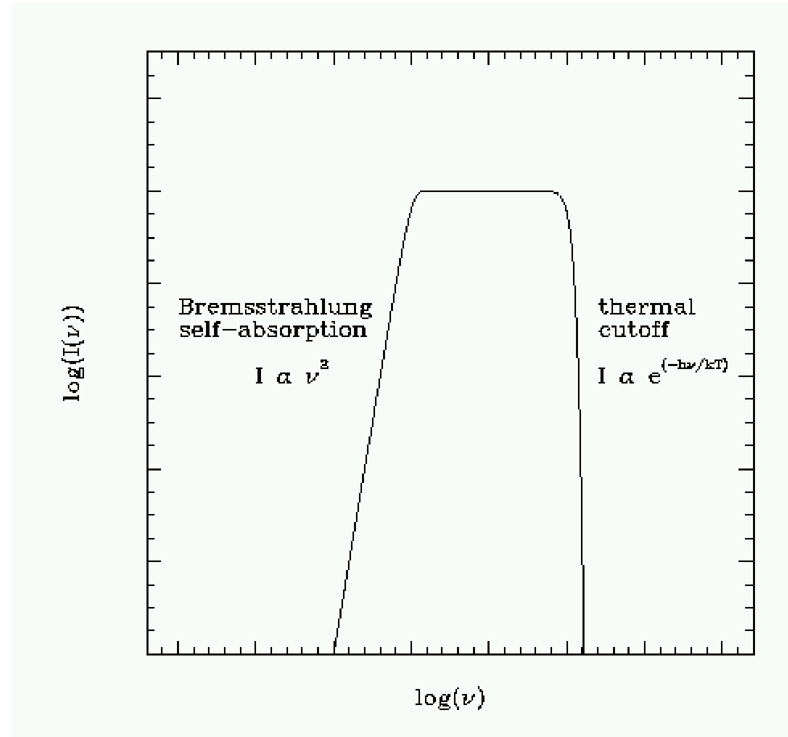
- *Temperatures ~ 10^4–10^6 K*
- *H II regions (ionised interstellar hydrogen)*
- *Around hot stars*
- *Hot and dense plasma near accreting black holes*
- *Galaxy cluster*

Bremsstrahlung (free-free emission)

Bremsstrahlung spectrum

- Continuous
- Flat between cutoffs
- High-energy thermal cutoff
  - *Depends only on temperature*
  - $\frac{h\nu}{kT} = 1 \quad or \quad \nu \approx 2.1 \times 10^{10}\, T$
  - *Can be used to determine plasma temperature*
- Low-energy cutoff (self-absorption)

- **Special case:**
  - Relativistic bremsstrahlung (T not applicable anymore)



http://www.astro.utu.fi/~cflynn/astroII/l3.html

Examples of radiation application

Real-life examples

Estimating size

- Synchrotron-emitting electrons move in circular/spiral trajectories, with radius determined by energy and magnetic field.

Real-life application:
We measure the size of object, and calculate the particle energy.
→ *What can we learn about he magnetic field strength?*

Estimating age

- Electrons with energy E radiate at power P
→ electrons lose their energy in timescale $t = \frac{E}{P}$.

Real-life application:
We know that the source is centuries old, but we calculate the energy loss timescale to be just days.
→ *What can we infer about the source?*

Summary

& 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?*