Essentials of Radio and (Sub-)Millimeter Astronomy

Fabian Walter (MPIA)

Lecture 2

Radiation Fundamentals, Emission mechanisms

slides: Essential Radio Astronomy by NRAO (Condon & Ransom)
+ lectures by Ohio State University Professor Adam Leroy
+ ASTRON's Dr. Jason Hesse

https://www.astron.nl/astrowiki/lib/exe/fetch.php?media=ra_uva:2017:ra_uva_lecture4_2017.pdf

Like most other fields of astronomy, radio astronomy deals largely with measuring light from astronomical sources and using that light to understand the physics of the universe.

Carefully book-keeping this light is essential.

- **Intensity** is the energy from a source per time, per area, per angle on the sky.
  Intensity is conserved along a ray through space.

- **Flux** is the energy from a source per time, per area.
  Flux depends on the relative positions of source and observer.

- **Luminosity** is the energy per time given off by a source.
  Luminosity is an intrinsic property of a source.

- **Specific** versions of these quantities measure energy per unit bandwidth (or wavelength) and are the most common formulation of these quantities.
  Flux density and specific intensity are the most common measures of light.

Like most other fields of astronomy, radio astronomy deals largely with measuring light from astronomical sources and using that light to understand the physics of the universe.

Carefully book-keeping this light is essential.

- **Intensity** is the energy from a source per time, per area, per angle on the sky.
  Intensity is conserved along a ray through space.

- **Flux** is the energy from a source per time, per area.
  Flux depends on the relative positions of source and observer.

- **Luminosity** is the energy per time given off by a source.
  Luminosity is an intrinsic property of a source.

- **Specific** versions of these quantities measure energy per unit bandwidth (or wavelength) and are the most common formulation of these quantities.
  Flux density and specific intensity are the most common measures of light.

Like most other fields of astronomy, radio astronomy deals largely with measuring light from astronomical sources and using that light to understand the physics of the universe.

Carefully book-keeping this light is essential.

- **Intensity** is the energy from a source per time, per area, per angle on the sky. ***Intensity is conserved along a ray through space***.

- **Flux** is the energy from a source per time, per area. ***Flux depends on the relative positions of source and observer***.

- **Luminosity** is the energy per time given off by a source. ***Luminosity is an intrinsic property of a source***.

- **Specific** versions of these quantities measure energy per unit bandwidth (or wavelength) and are the most common formulation of these quantities. ***Flux density and specific intensity are the most common measures of light***.

Like most other fields of astronomy, radio astronomy deals largely with measuring light from astronomical sources and using that light to understand the physics of the universe.

Carefully book-keeping this light is essential.

- **Intensity** is the energy from a source per time, per area, per angle on the sky. ***Intensity is conserved along a ray through space***.

- **Flux** is the energy from a source per time, per area. ***Flux depends on the relative positions of source and observer***.

- **Luminosity** is the energy per time given off by a source. ***Luminosity is an intrinsic property of a source***.

- **Specific** versions of these quantities measure energy per unit bandwidth (or wavelength) and are the most common formulation of these quantities. ***Flux density and specific intensity are the most common measures of light***.

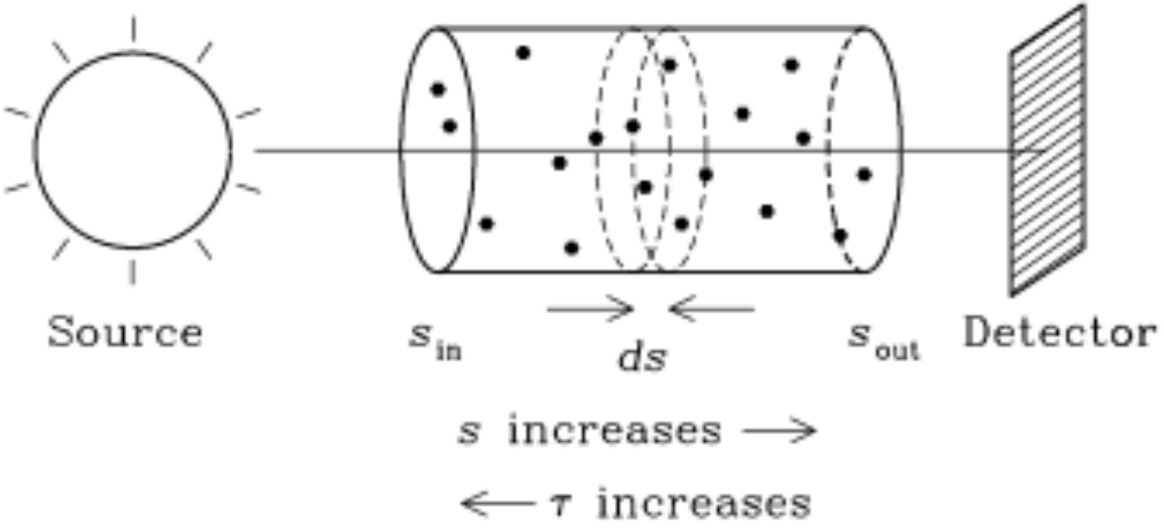
The Ray Optics Approximation

treat light as a beam of energy that flows in a straight line.

- this is okay as long as the system being considered is big compared to of the light.
- i.e., don’t worry about wave effects at this scale
- this is the framework for the Equation of Radiative Transfer, flux, intensity, etc.

A ray of light traveling in a straight line…

ERA illustration of radiative transfer



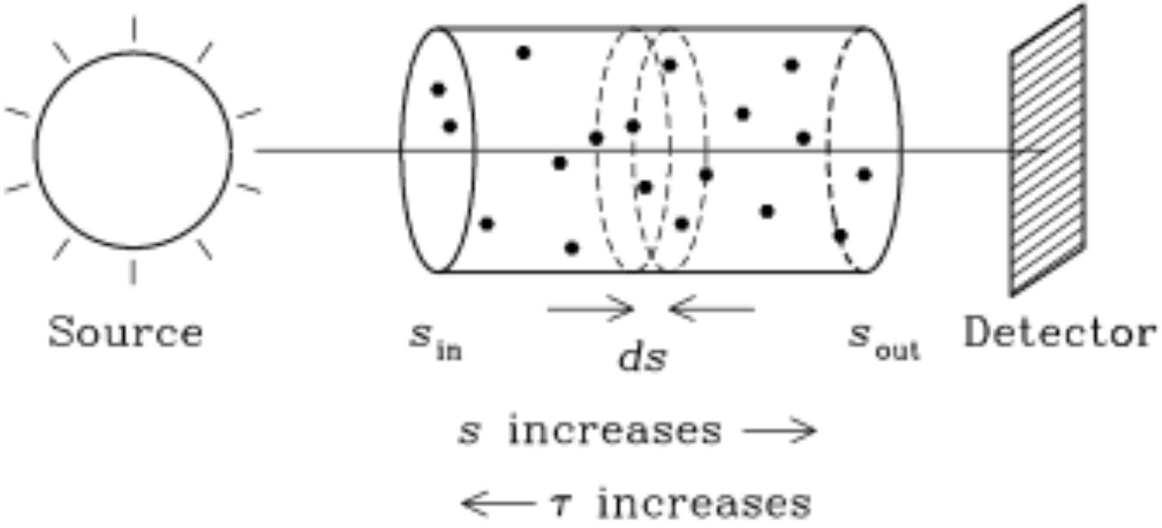
The Ray Optics Approximation

treat light as a beam of energy that flows in a straight line.

- this is okay as long as the system being considered is big compared to of the light.
- i.e., don’t worry about wave effects at this scale
- this is the framework for the Equation of Radiative Transfer, flux, intensity, etc.

A ray of light traveling in a straight line…

ERA illustration of radiative transfer



Brightness and Intensity

Brightness or **Intensity** is the energy through a fiducial area per time per solid angle of sky.

- “**specific**” intensity is the intensity per unit frequency (or per unit wavelength)
- Specific intensity: how much energy does a detector pick up from a patch of sky every second over a given small bit of bandwidth (frequency range)?
- The area is projected area normal to a line to the source, so there’s a cos θ term.

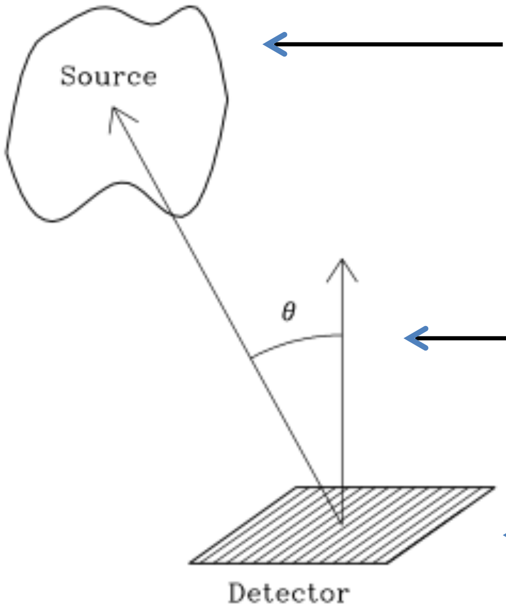
Power (energy per time)

$$\boxed{I_\nu \equiv \frac{dP}{\cos\theta d\sigma\, d\nu\, d\Omega}}$$

Area

Bandwidth

Solid Angle



The source covers a certain solid angle on the sky for the detector…

The projection of the detector towards the source is diminished by cos θ

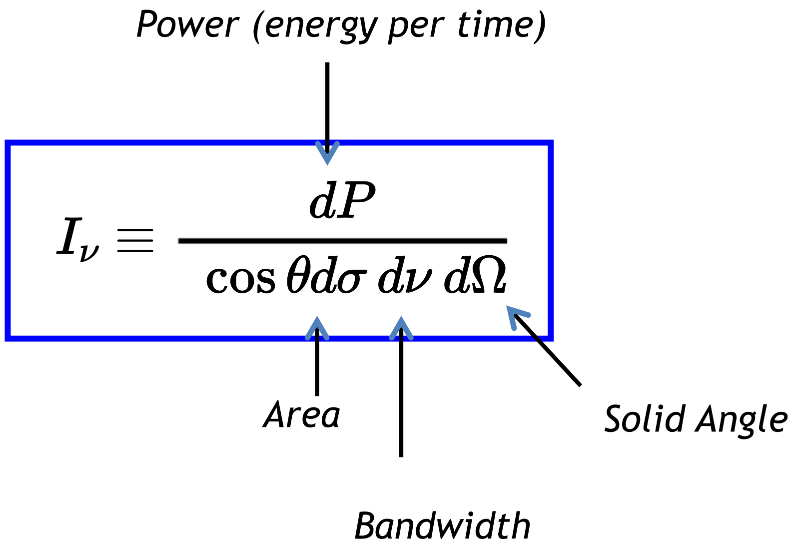
The detector has a certain area…

ERA illustration of brightness.

Brightness and Intensity

Brightness or **Intensity** is the energy through a fiducial area per time per solid angle of sky.

- **“specific”** intensity is the intensity per unit frequency (or per unit wavelength)
- Specific intensity: how much energy does a detector pick up from a patch of sky every second over a given small bit of bandwidth (frequency range)?
- The area is projected area normal to a line to the source, so there’s a cos θ term.



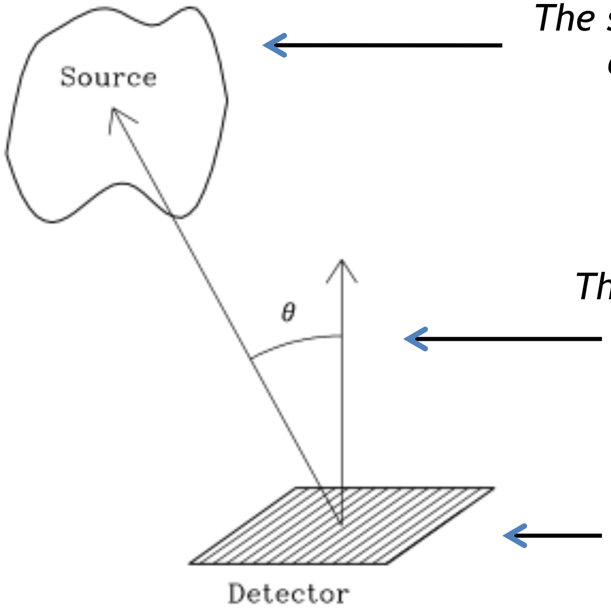
Power (energy per time)

$$\boxed{I_\nu \equiv \frac{dP}{\cos\theta d\sigma\, d\nu\, d\Omega}}$$

Area

Bandwidth

Solid Angle



The source covers a certain solid angle on the sky for the detector…

The projection of the detector towards the source is diminished by cos θ

The detector has a certain area…

ERA illustration of brightness.

Flux (Density)

Flux is the energy through a fiducial area per time.

- **"specific"** flux or **flux density** is the flux per unit bandwidth or wavelength.
- Flux is related to intensity by an integral over solid angle (plus projection).
- Unlike intensity, flux is not conserved. It depends on the source-observer distance.

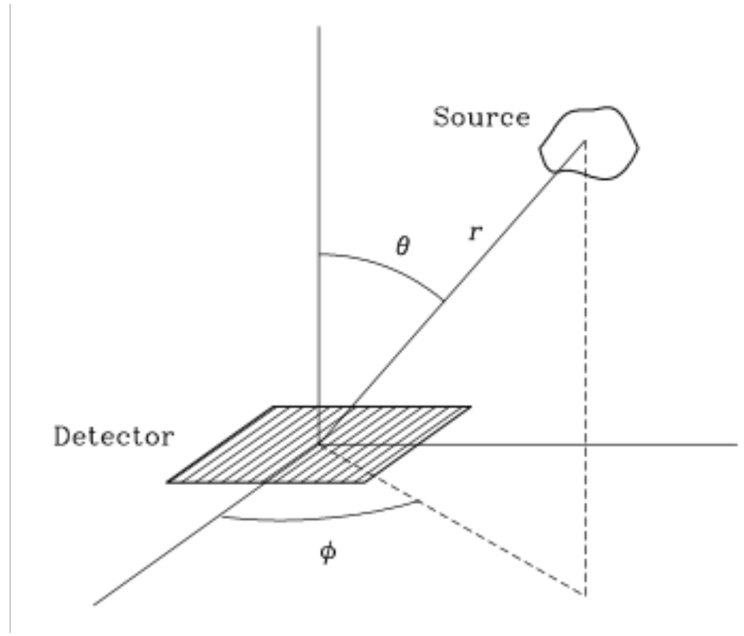
Intensity of the source

projection term (often vanishes)*

$$\boxed{S_\nu \equiv \int_{\mathrm{source}} I_\nu(\theta,\phi)\cos\theta d\Omega}$$

Solid angle of the whole source – this depends on distance (more distant things subtend smaller angles)

** For a small source with a detector pointed at it.*



ERA illustration of flux.

(Specific) Luminosity

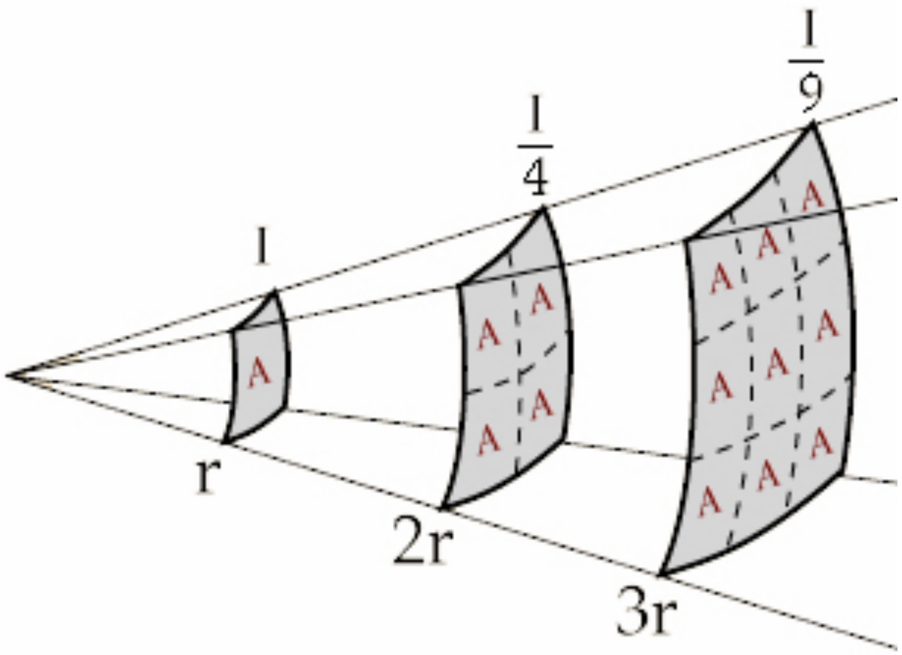
Luminosity is the energy per time emitted by a source.

- **“specific”** luminosity or **luminosity density** is the luminosity per unit bandwidth.
- Luminosity is an intrinsic property of a source with no dependence on any observer.
- For an isotropic emitter, luminosity relates to observed flux via the inverse square.

Flux (energy per time per area) of the source at an observer

$$\boxed{L_\nu = 4\pi d^2 S_\nu}$$

Area of a sphere over which all light has been spread from an isotropic source.

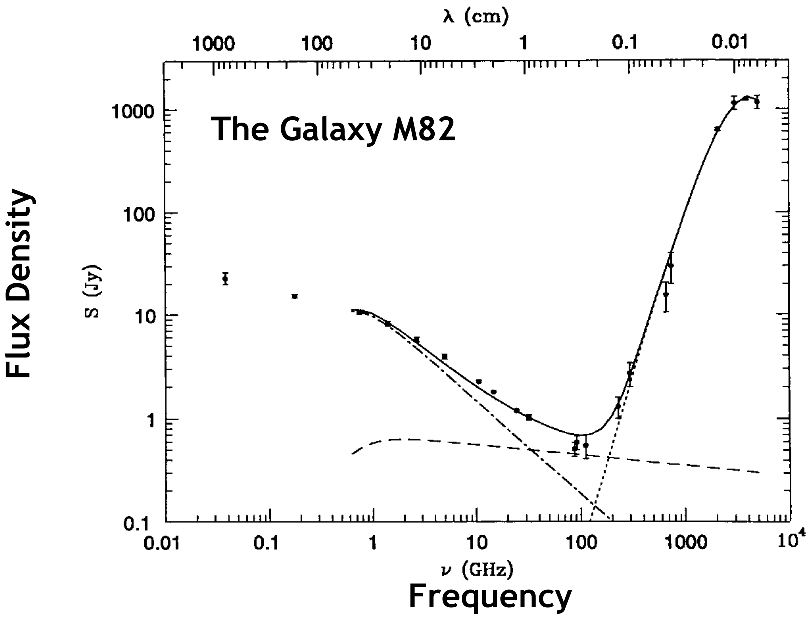


Swiped from internet (leydenscience.org).

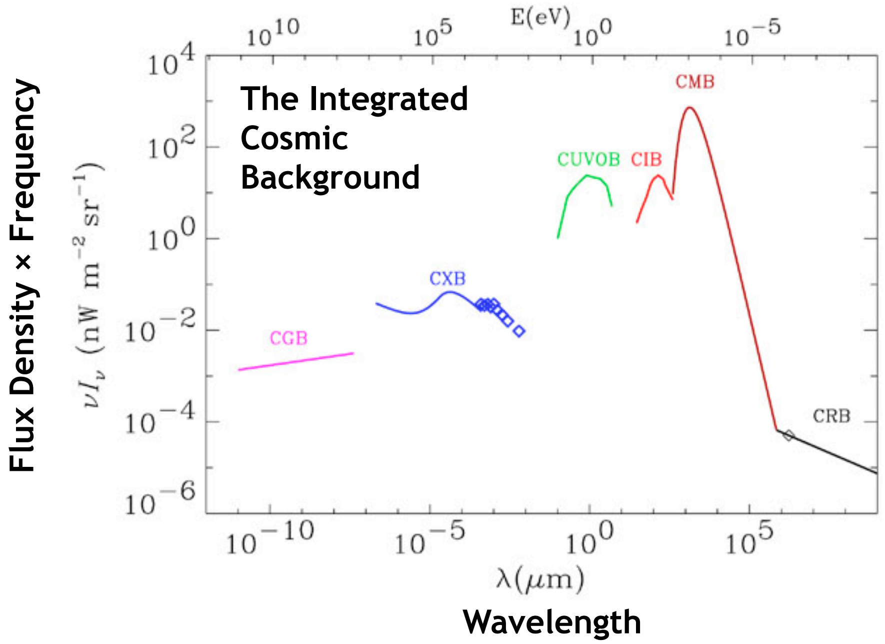
“Specific” vs. Integrated Quantities

We work largely with **specific** quantities (i.e., energy/flux/intensity per bandwidth).

- Real sources have spectral shapes and so vary in power per bandwidth.
- The basic relations for specific intensity, etc., hold for integrated versions.
- Be careful! For energetics plot or compare νI_ν when comparing across ν.



(ERA) Spectrum of M82 – flux density varies dramatically (this is why we use it)

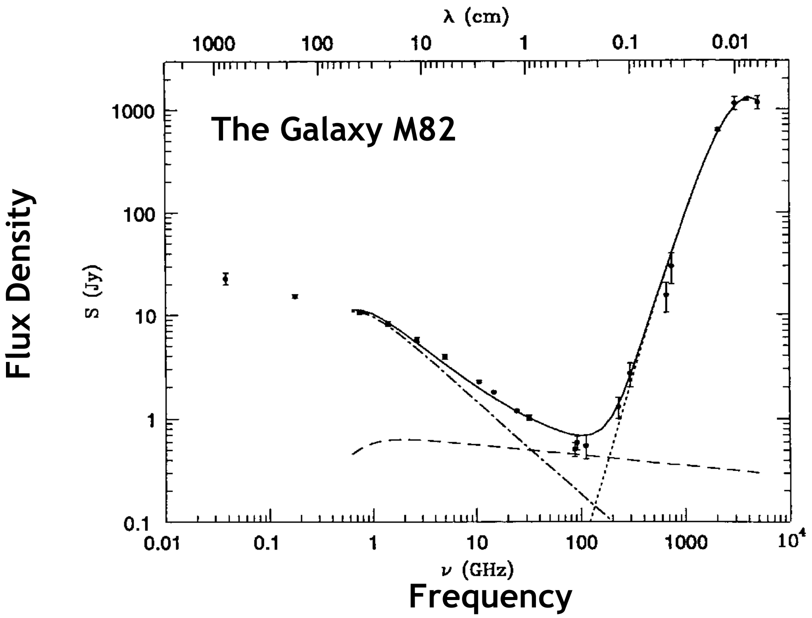


(ERA) see first lecture - total Universe SED

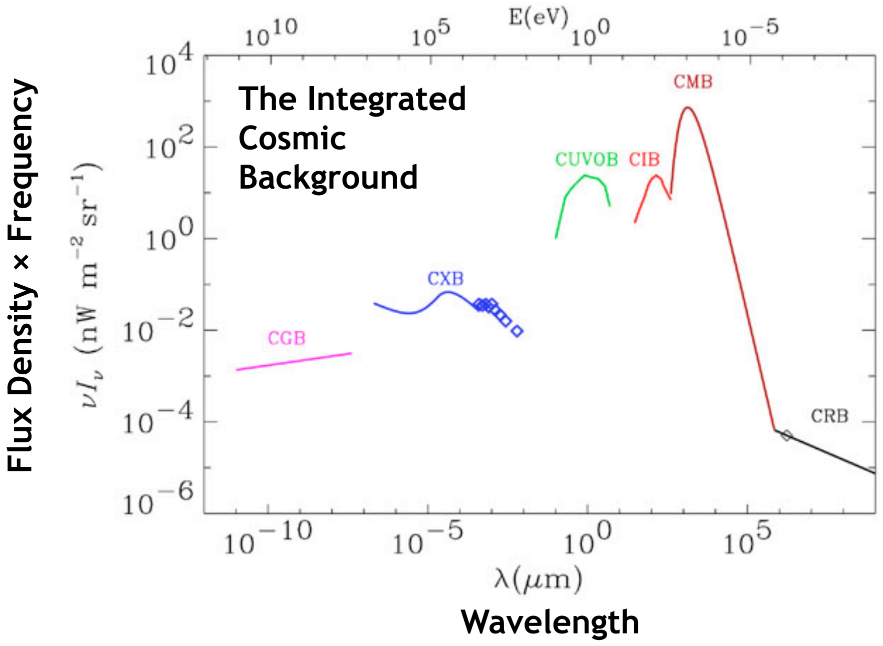
“Specific” vs. Integrated Quantities

We work largely with **specific** quantities (i.e., energy/flux/intensity per bandwidth).

- Real sources have spectral shapes and so vary in power per bandwidth.
- The basic relations for specific intensity, etc., hold for integrated versions.
- Be careful! For energetics plot or compare νI_ν when comparing across ν.



(ERA) Spectrum of M82 – flux density varies dramatically (this is why we use it)



(ERA) total Universe SED

Units of Flux, Intensity, and Luminosity

Unit conventions for these quantities vary by field.

Flux density in CGS is erg/s/cm^2/Hz and in radio astronomy is most often bookkept in Janskies, where 1 Jy = 10^{-23} erg/s/cm^2/Hz = 10^{-26} J/s/m^2/Hz.

Occasionally single dish radio telescopes use other units for extended sources.

Specific Intensity in CGS is erg/s/cm^2/Hz/sr is the energy from a source per time, per area, per angle on the sky.

Megajanskies per steradian (in the IR)

Janskies per beam (telescopes focused on point sources, often interferometers, see Problem Set 1 for the ugly details; we will talk more about this later)

Kelvin (in "brightness temperature", defined shortly, often single dish radio telescopes, we will also talk more about this later)

Specific Luminosity in CGS is erg/s/Hz. In practice it varies a lot with the science. Normalization to a specific luminosity of a known source (like the Sun) is common.

Units of Flux, Intensity, and Luminosity

Unit conventions for these quantities vary by field.

Flux density in CGS is erg/s/cm^2/Hz and in radio astronomy is most often bookkept in Janskies, where 1 Jy = 10^{-23} erg/s/cm^2/Hz = 10^{-26} J/s/m^2/Hz.

Occasionally single dish radio telescopes use other units for extended sources.

Specific Intensity in CGS is erg/s/cm^2/Hz/sr is the energy from a source per time, per area, per angle on the sky.

Megajanskies per steradian (in the IR)

Janskies per beam (telescopes focused on point sources, often interferometers, see Problem Set 1 for the ugly details; we will talk more about this later)

Kelvin (in "brightness temperature", defined shortly, often single dish radio telescopes, we will also talk more about this later)

Specific Luminosity in CGS is erg/s/Hz. In practice it varies a lot with the science. Normalization to a specific luminosity of a known source (like the Sun) is common.

Units of Flux, Intensity, and Luminosity

Unit conventions for these quantities vary by field.

Flux density in CGS is erg/s/cm^2/Hz and in radio astronomy is most often bookkept in Janskies, where 1 Jy = 10^{-23} erg/s/cm^2/Hz = 10^{-26} J/s/m^2/Hz.

Occasionally single dish radio telescopes use other units for extended sources.

Specific Intensity in CGS is erg/s/cm^2/Hz/sr is the energy from a source per time, per area, per angle on the sky.

Megajanskies per steradian (in the IR)

Janskies per beam (telescopes focused on point sources, often interferometers)

Kelvin (in "brightness temperature", defined later, often single dish radio telescopes)

Radiative Transfer

To use light, we need to understand how the intensity a ray of light changes as it travels through space or through an astrophysical source. This is **radiative transfer**.

In free space the Equation of Radiative Transfer is incredibly simple. In words:

Specific intensity is conserved along a ray.

So:

The change in intensity

*Along an infinitesimal path of length **s***

$$\frac{dI_\nu}{ds} = 0$$

is zero.

Radiative transfer is boring in free space …

Radiative Transfer - Absorption

Things get more interesting when light moves through a medium.

That medium may **absorb** a fraction of light from the ray …
… or it may **emit** new light that joins the ray.

We bookkeep fractional absorption per unit length along a path:

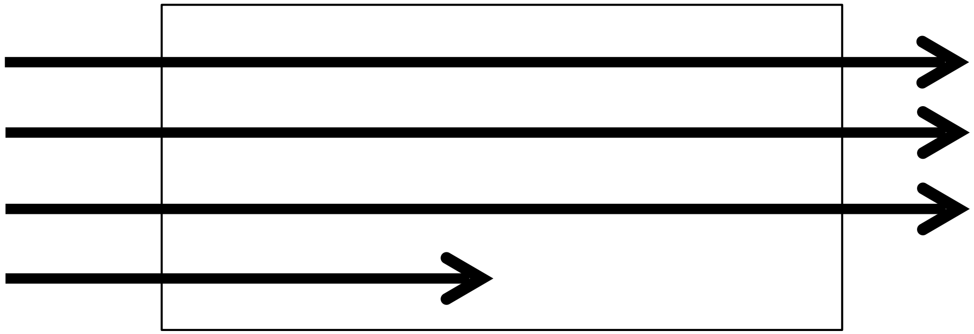
*The **absorption coefficient** (a property of the material)*

The fractional change In intensity

$$\frac{dI_\nu}{I_\nu} = -dp_\nu = -\kappa_\nu ds$$

The path length

The chance of a photon (given parcel of light) being absorbed.



κ_ν The linear absorption coefficient (probability per length).

(also will see, e.g., per mass)

Radiative Transfer - Emission

We bookkeep intensity gained per unit length along a path:

The coefficient of emissivity (intensity gained per path length). →

$$\boxed{\epsilon_\nu \equiv \frac{dI_\nu}{ds}}$$

← *The absolute change In intensity*

← *The path length*

So then the change in a rays intensity as it moves through material is:

absorption *emission*

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

This is the basic Equation of Radiative Transfer.

Radiative Transfer - Optical Depth

Rather than some unknown length **s** along the line of sight, we often bookkeep radiative transfer in an optical system in terms of **optical depth**.

This is labeled **τ** measured from the observed towards the source.

$$\int_{s_{\text{in}}}^{s_{\text{out}}} \frac{dI_\nu}{I_\nu} = -\int_{s_{\text{in}}}^{s_{\text{out}}} \kappa_\nu(s')ds' = \ln I_\nu \Big|_{s_{\text{in}}}^{s_{\text{out}}}$$

$$\boxed{\tau_\nu \equiv \int_{s_{\text{out}}}^{s_{\text{in}}} -\kappa_\nu(s')ds'}$$

$$I_\nu(s_{\text{out}}) = I_\nu(s_{\text{in}}) \times \exp\left[-\int_{s_{\text{in}}}^{s_{\text{out}}} \kappa_\nu(s')ds'\right]$$

That is: optical depth is the dimensionless factor giving **the number of *e*-foldings by which a rays intensity is diminished traveling through a medium** (i.e., how opaque it is).

Recap - Light and Radiative Transfer

In the limit appropriate for most astronomical systems, we bookkeep light as specific intensity, flux density, and specific luminosity. **Units can vary a lot by subfield.**

Intensity is conserved for a ray traveling in free space. But for a ray traveling in a real medium, absorption and emission contribute to the Equation of Radiative Transfer.

Integrated absorption through a source is bookkept as dimensionless optical depth, measured from the observed into the source. Sources with $\tau < 1$ are “optically thin”, those with $\tau > 1$ are “optically thick.”

Absorption and emission coefficients for a source in local thermodynamic equilibrium are related by the blackbody (thermal) spectrum according to Kirchoff’s laws.

Recap - Light and Radiative Transfer

In the limit appropriate for most astronomical systems, we bookkeep light as specific intensity, flux density, and specific luminosity. **Units can vary a lot by subfield.**

Intensity is conserved for a ray traveling in free space. But for a ray traveling in a real medium, absorption and emission contribute to the Equation of Radiative Transfer.

Integrated absorption through a source is bookkept as dimensionless optical depth, measured from the observed into the source. Sources with $\tau < 1$ are “optically thin”, those with $\tau > 1$ are “optically thick.”

Absorption and emission coefficients for a source in local thermodynamic equilibrium are related by the blackbody (thermal) spectrum according to Kirchoff’s laws.

Recap - Light and Radiative Transfer

In the limit appropriate for most astronomical systems, we bookkeep light as specific intensity, flux density, and specific luminosity. **Units can vary a lot by subfield.**

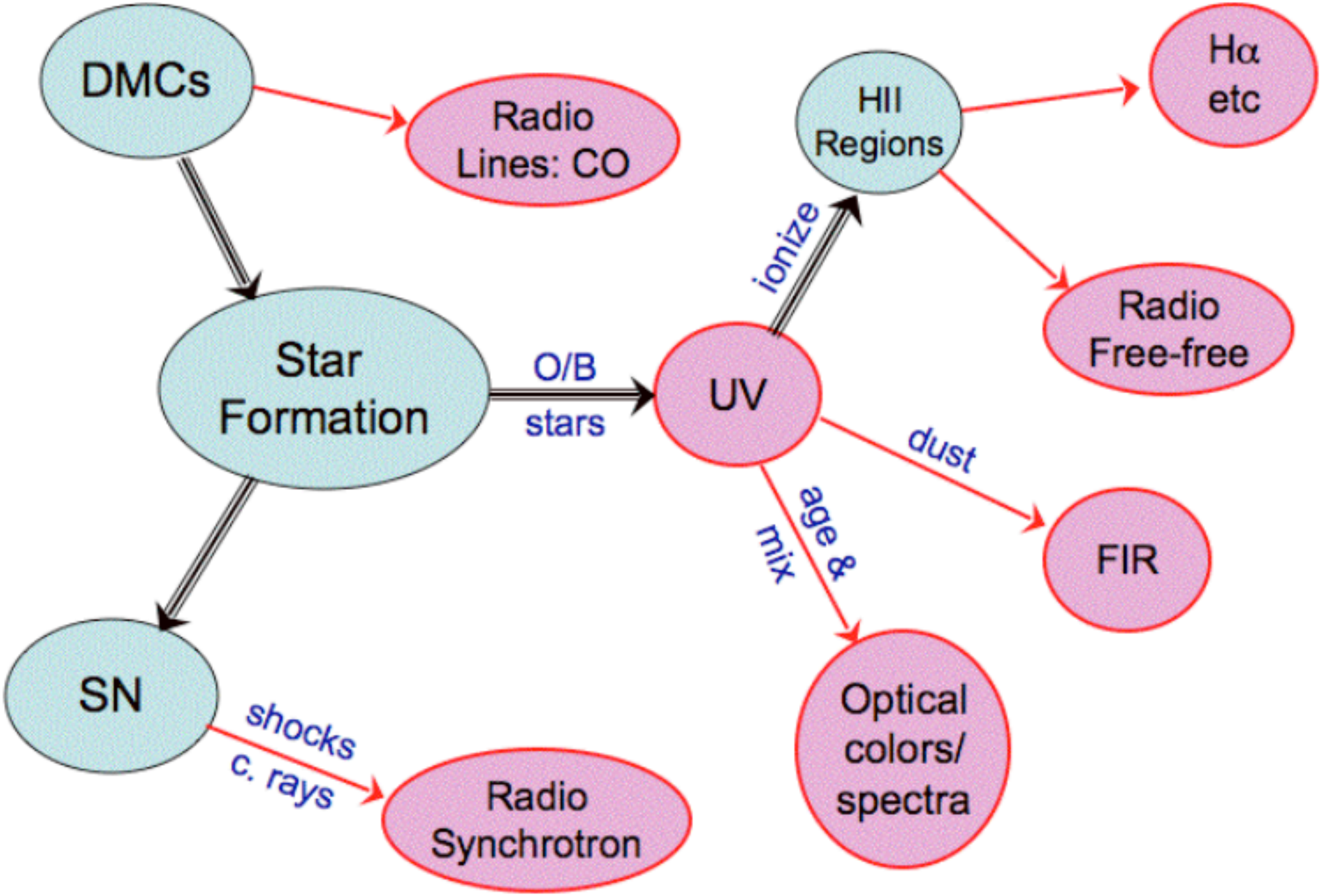
Intensity is conserved for a ray traveling in free space. But for a ray traveling in a real medium, absorption and emission contribute to the Equation of Radiative Transfer.

Integrated absorption through a source is bookkept as dimensionless optical depth, measured from the observed into the source. Sources with $\tau < 1$ are “optically thin”, those with $\tau > 1$ are “optically thick.”

Absorption and emission coefficients for a source in local thermodynamic equilibrium are related by the blackbody (thermal) spectrum according to Kirchoff’s laws.

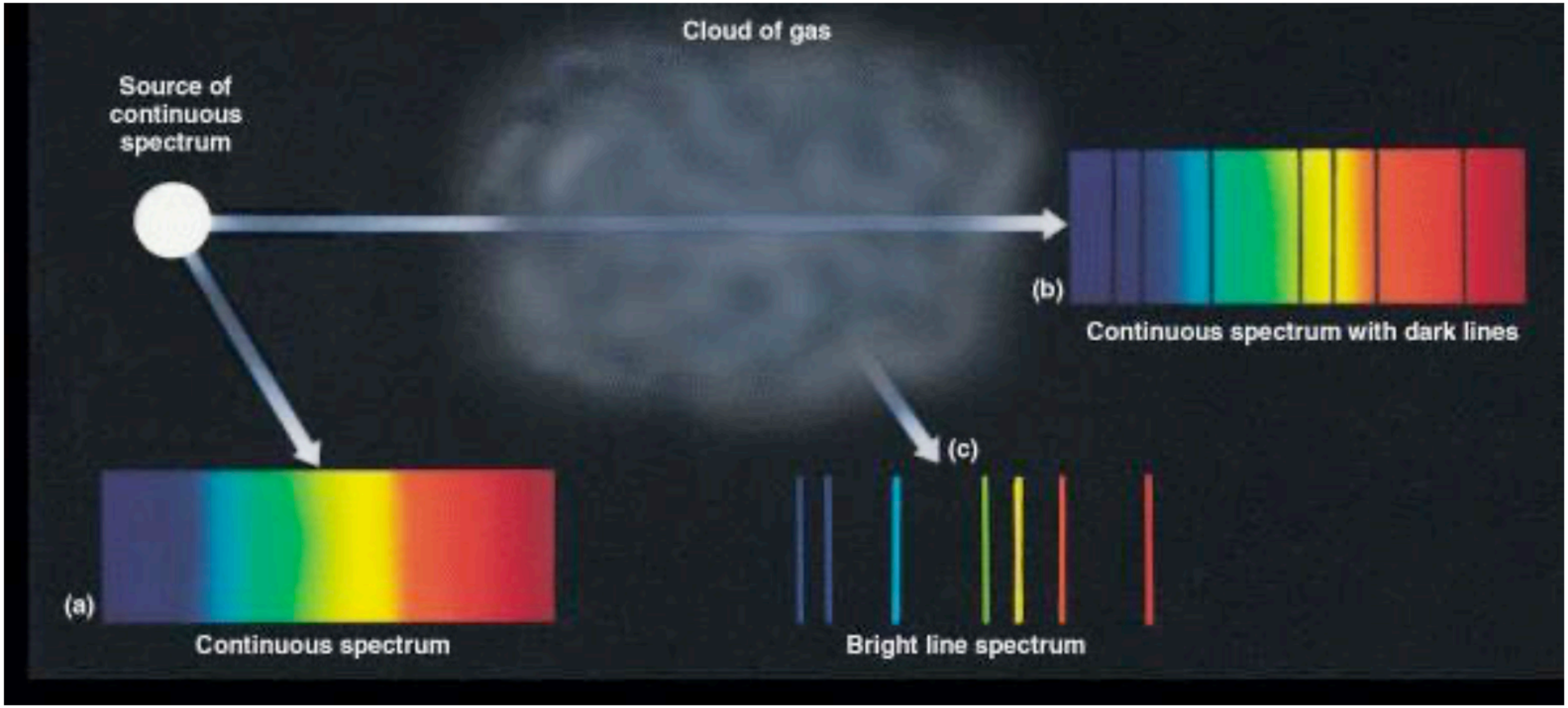
Emission Mechanisms

Emission from Star Formation Regions



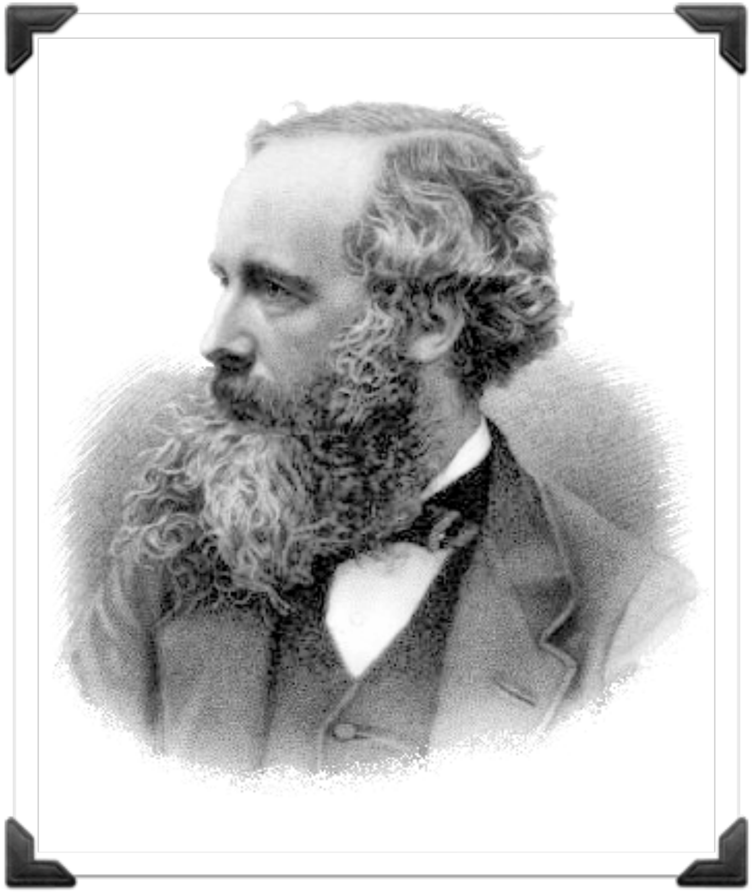
today: continuum emission

Continuum vs. Line Emission



- Continuum: wide-range of particle energies.
- Line: discrete energies due to transitions in atoms or molecules.

Maxwell 1862: physical description of light through electromagnetic waves

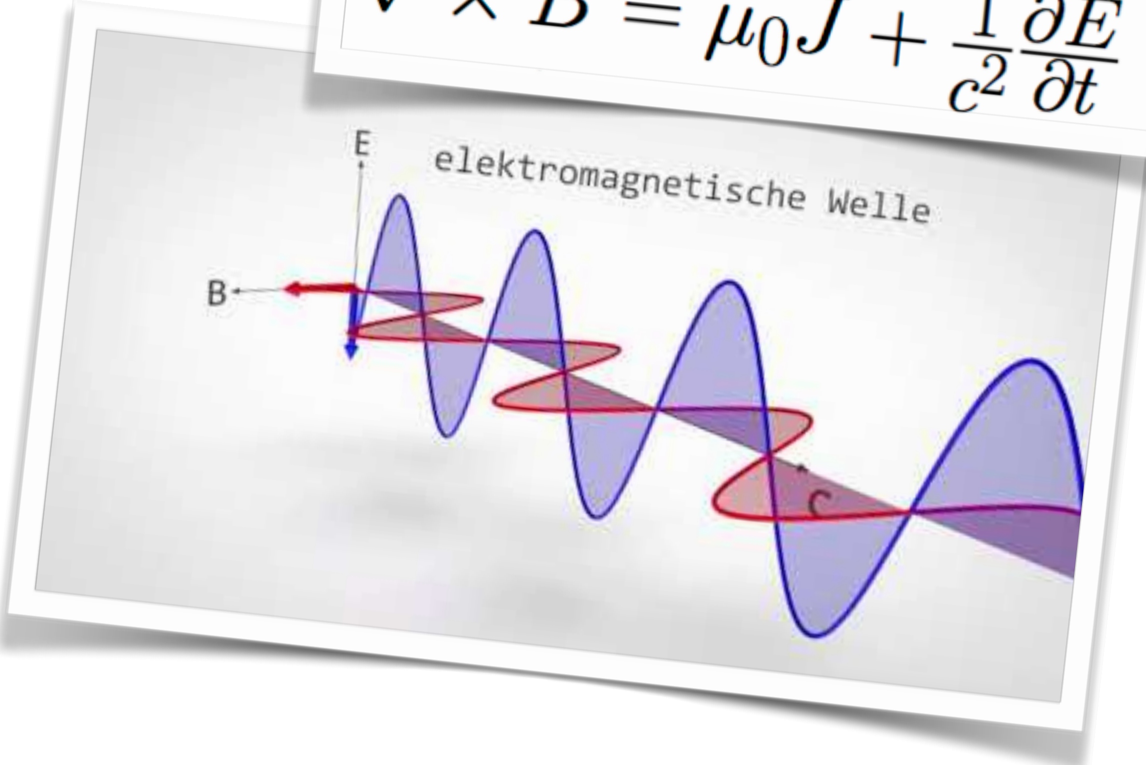


$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$



Emission Mechanisms

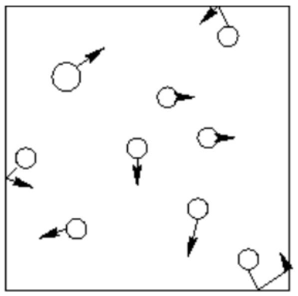
- EM radiation is emitted by accelerated charged particles.
- Thermal emission depends only on the temperature of the emitting object.
- Non-thermal emission does not depend on temperature.
- Photon frequency proportional to energy.

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

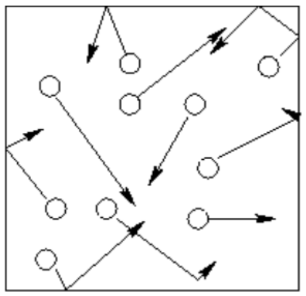
Blackbody Radiation

Thermal Emission

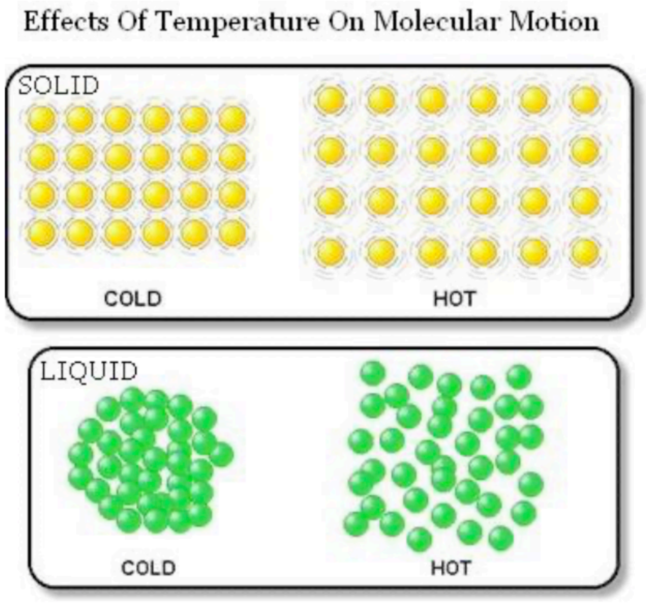
- Any object with a temperature above 0K emits thermal radiation.
- Temperature is related to particle motion.



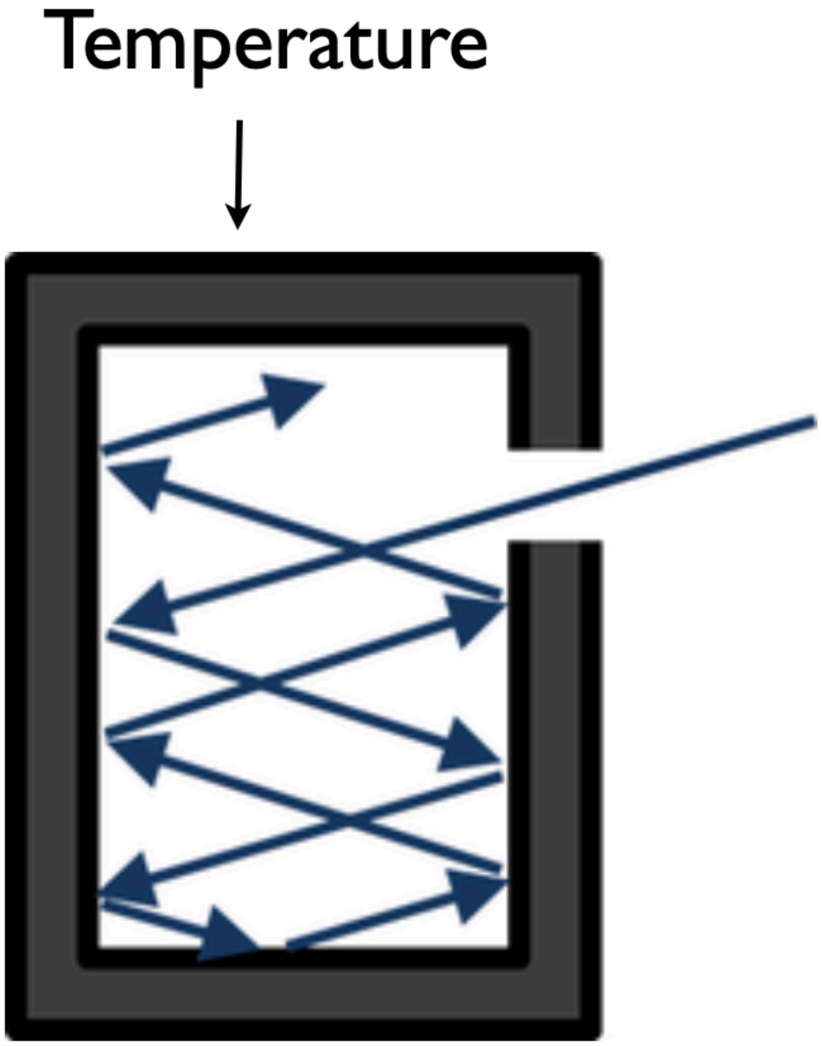
Cool gas, fewer and less energetic collisions



Hot gas, more and more energetic collision



Blackbody Radiation



A true blackbody *only absorbs* radiation and reflects none.

- Blackbody reaches a thermal equilibrium and re-radiates in the characteristic “blackbody spectrum”.

Blackbody Radiation

The spectrum of thermal radiation or the **blackbody (or Planck) spectrum** is one of the most commonly used expressions in astronomy.

It is the function for any source in local thermodynamic equilibrium (‘black body’)

It is used to define intensity units for many radio applications (“brightness temperature”).

$$\boxed{B_\nu = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}}$$

$B_\nu(T)$ is the spectral radiance (the power per unit solid angle and per unit of area normal to the propagation) density of frequency v radiation per unit frequency at thermal equilibrium at temperature T.
h is the Planck constant;
c is the speed of light in a vacuum;
k is the Boltzmann constant;
v is the frequency of the electromagnetic radiation;
T is the absolute temperature of the body.

Blackbody Radiation

The spectrum of thermal radiation or the **blackbody (or Planck) spectrum** is one of the most commonly used expressions in astronomy.

It is the function for any source in local thermodynamic equilibrium (‘black body’)

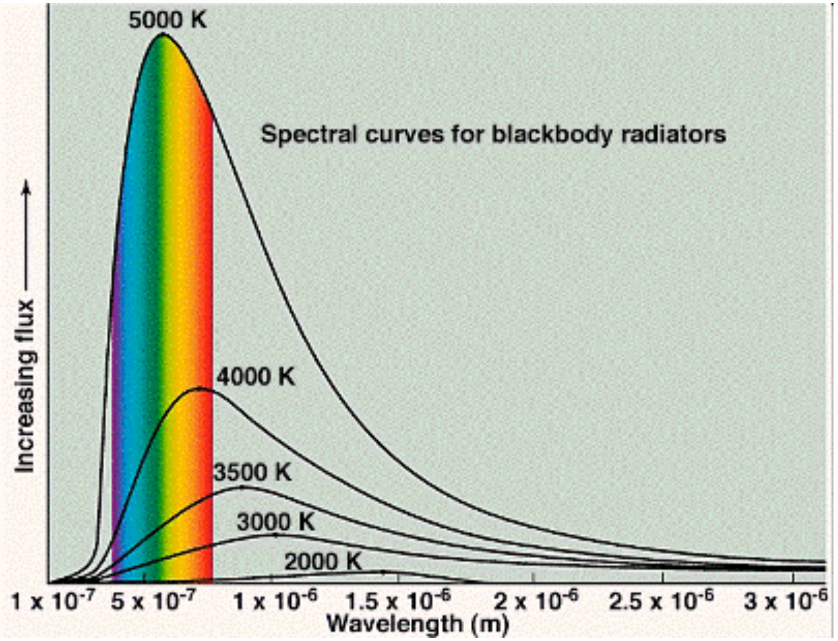
It is used to define intensity units for many radio applications (“brightness temperature”).

$$\boxed{B_\nu = \frac{2h\nu^3}{c^2}\frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}}$$

derivation: quantum mechanics
or ERA webpage

$B_\nu(T)$ is the spectral radiance (the power per unit solid angle and per unit of area normal to the propagation) density of frequency v radiation per unit frequency at thermal equilibrium at temperature T.
h is the Planck constant;
c is the speed of light in a vacuum;
k is the Boltzmann constant;
v is the frequency of the electromagnetic radiation;
T is the absolute temperature of the body.

Blackbody Radiation



- Intensity and spectrum *depends only on temperature*.
- Blackbody spectrum described by Planck's law.
- Even relatively cool objects (e.g. the Earth) peak well above the radio band (in infrared).

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

Blackbody Radiation

Stefan-Boltzman Law

$$j^{\star} = \sigma T^4$$

$$\sigma = \frac{2\pi^5 k_B^4}{15h^3 c^2} = 5.670374419x10^{-8}\frac{W}{m^2 K^4}$$

Stefan-Boltzman constant

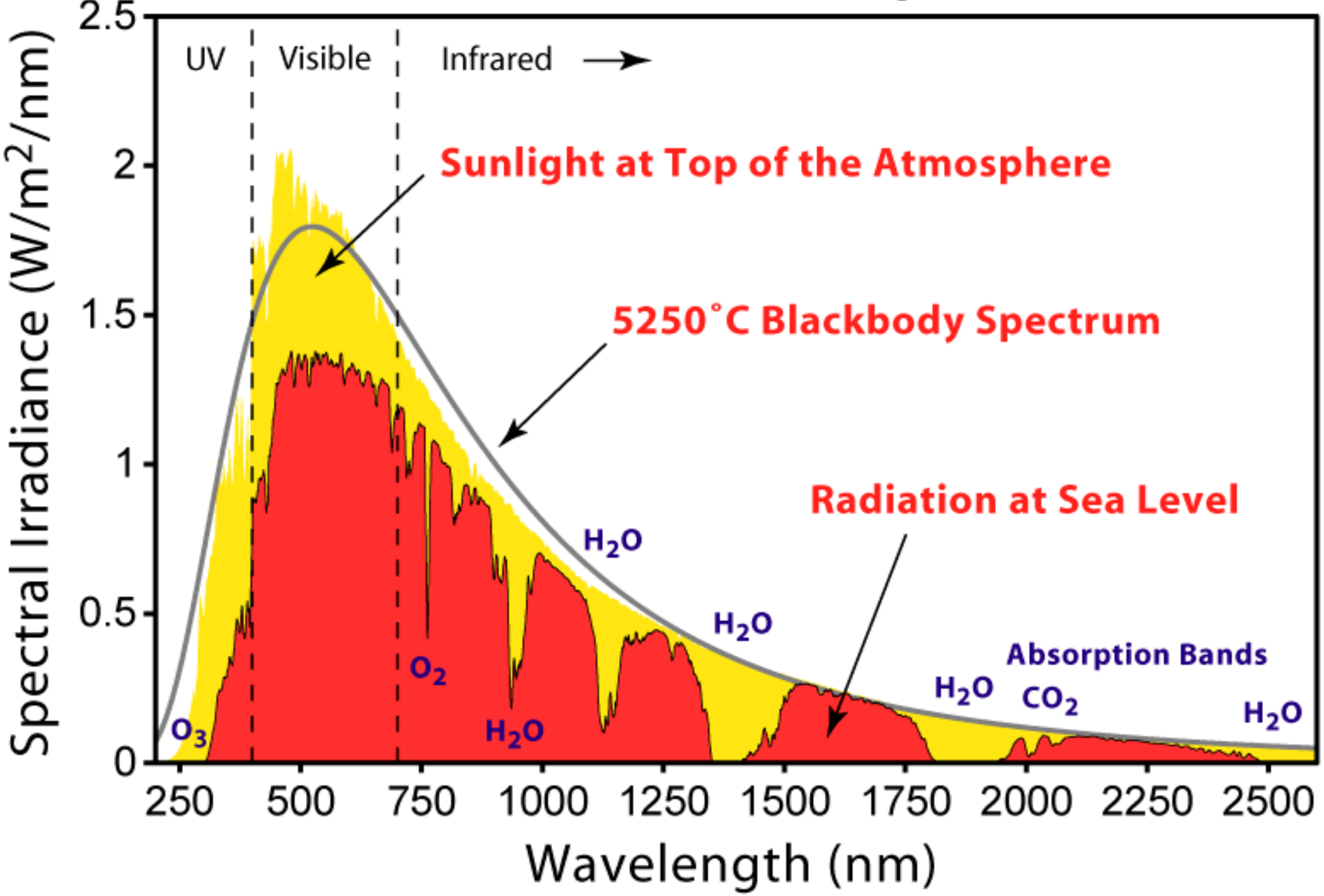
Wien's Law

$$\lambda_{\max} = \frac{2897{,}8\,\mu\mathrm{m\,K}}{T}$$

(i.e. frequency ~ Temperature)

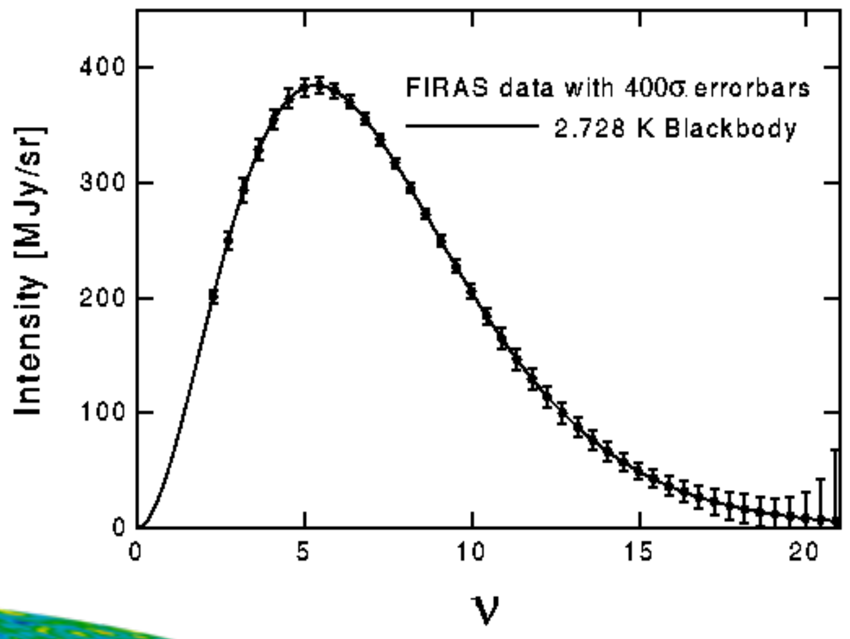
- Stefan-Boltzman Law: total emitted energy increases rapidly with temperature.
- Wien's Law: peak frequency depends on temperature.

Solar Radiation Spectrum

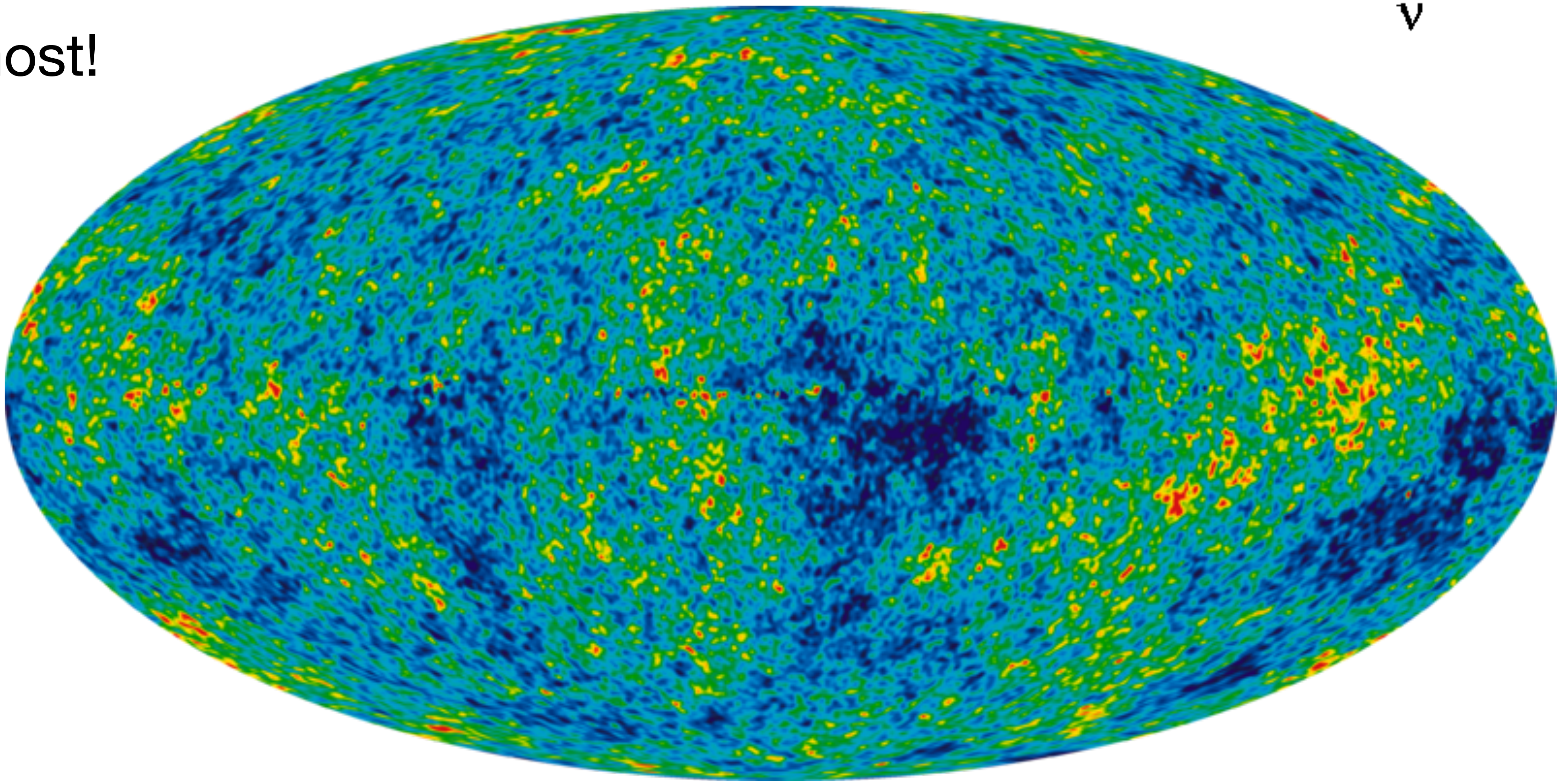


physics.stackexchange.com

CMB: almost perfect black body!

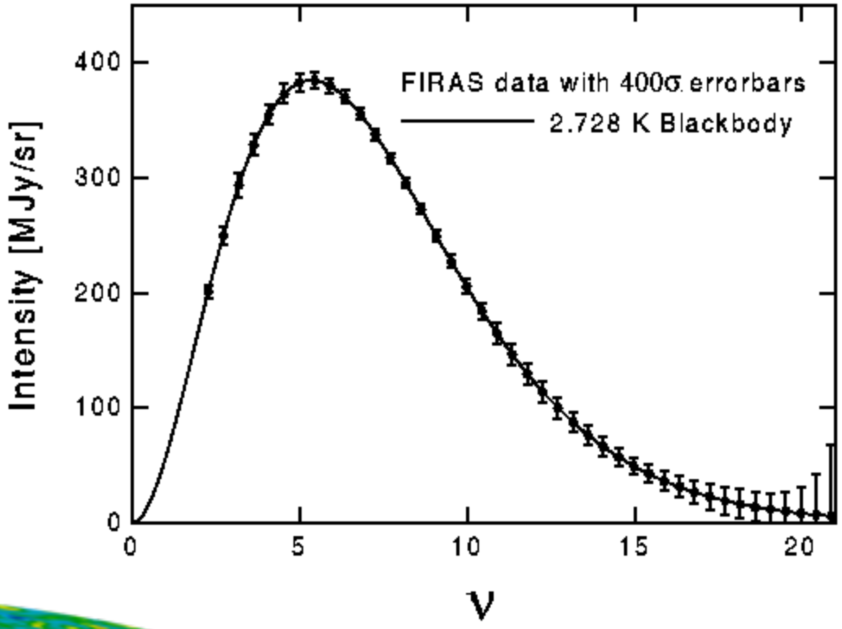


almost!

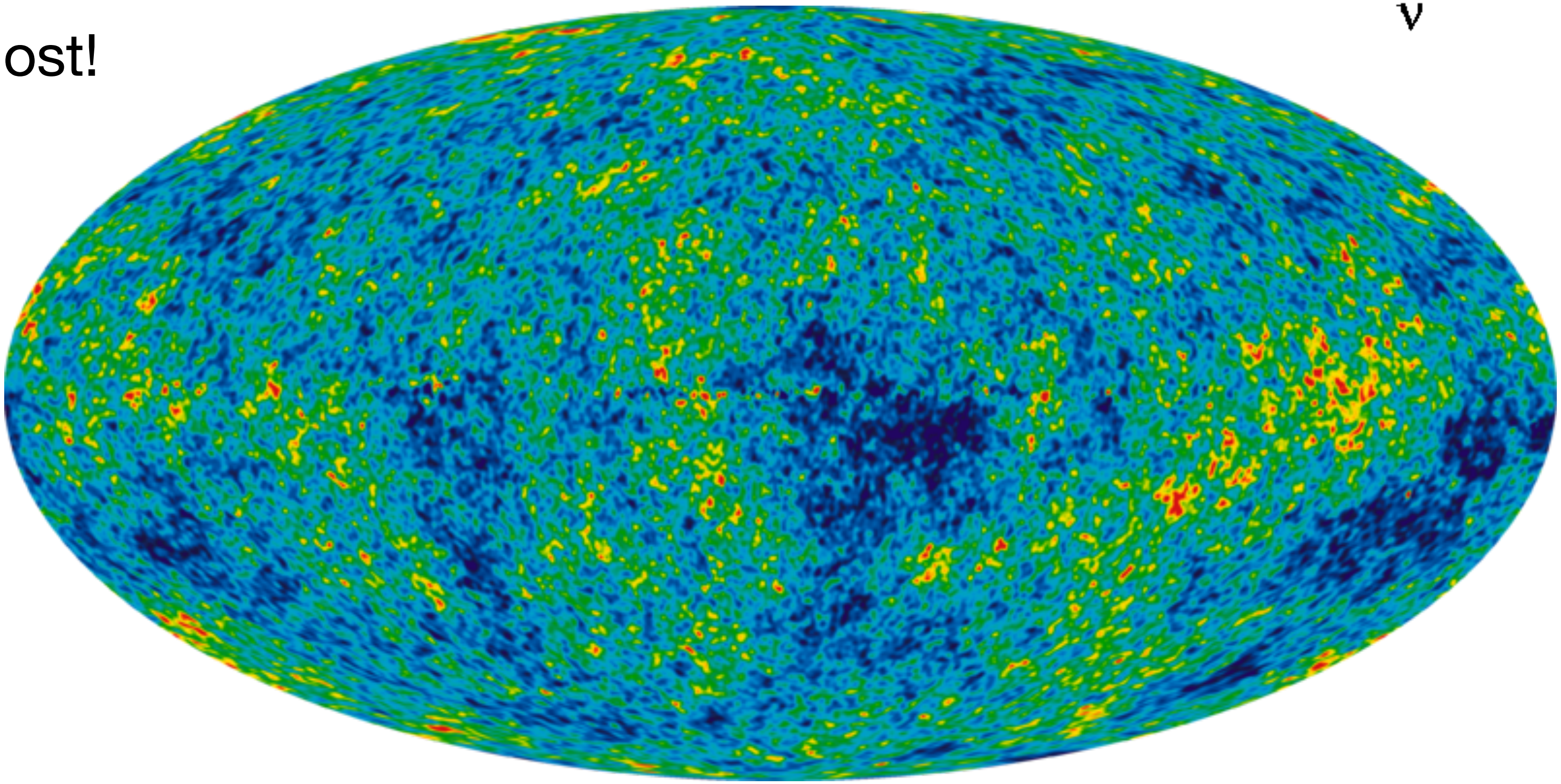


WMAP + https://ned.ipac.caltech.edu/level5/Bothun2/Bothun1_1_10.html

CMB: almost perfect black body!

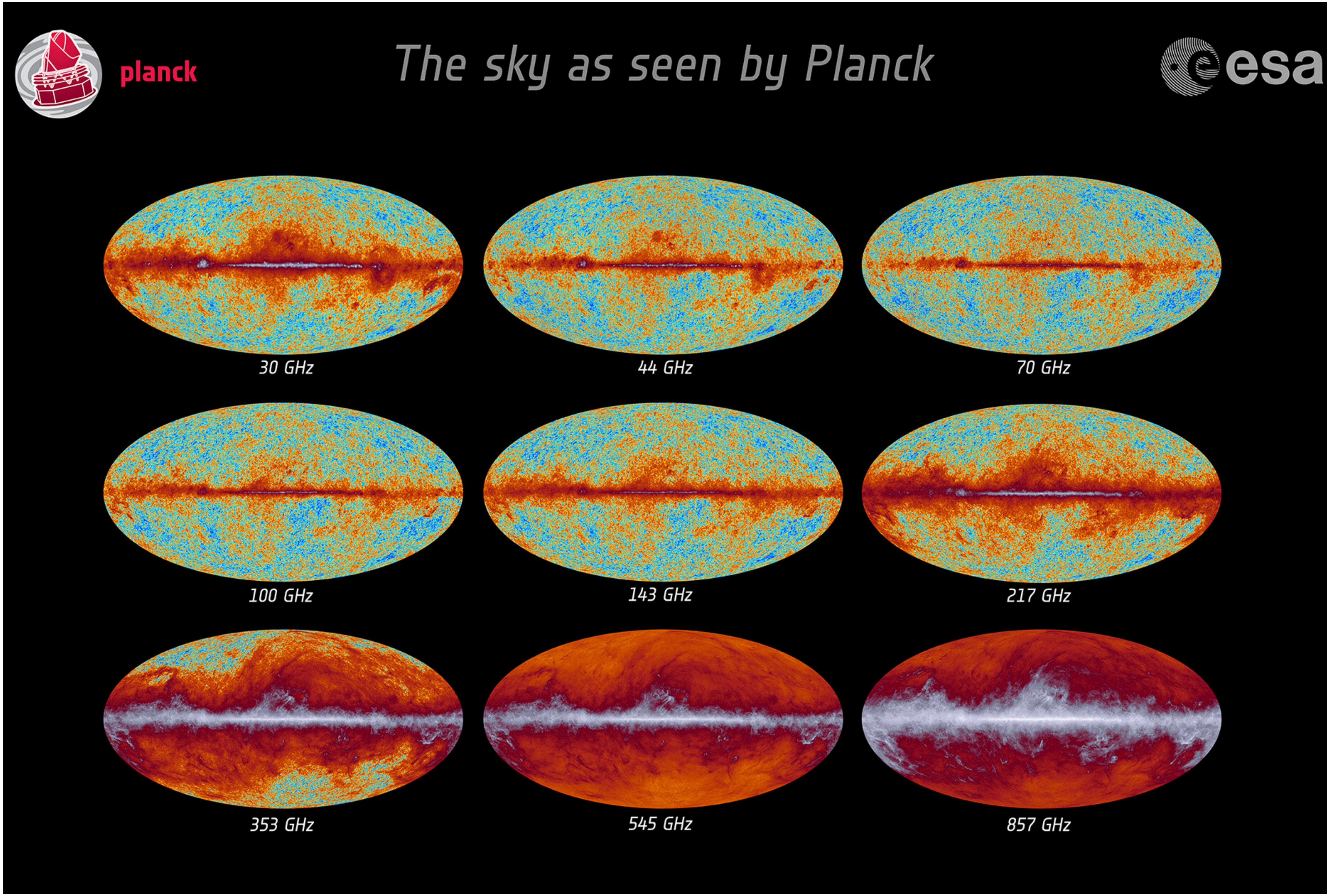


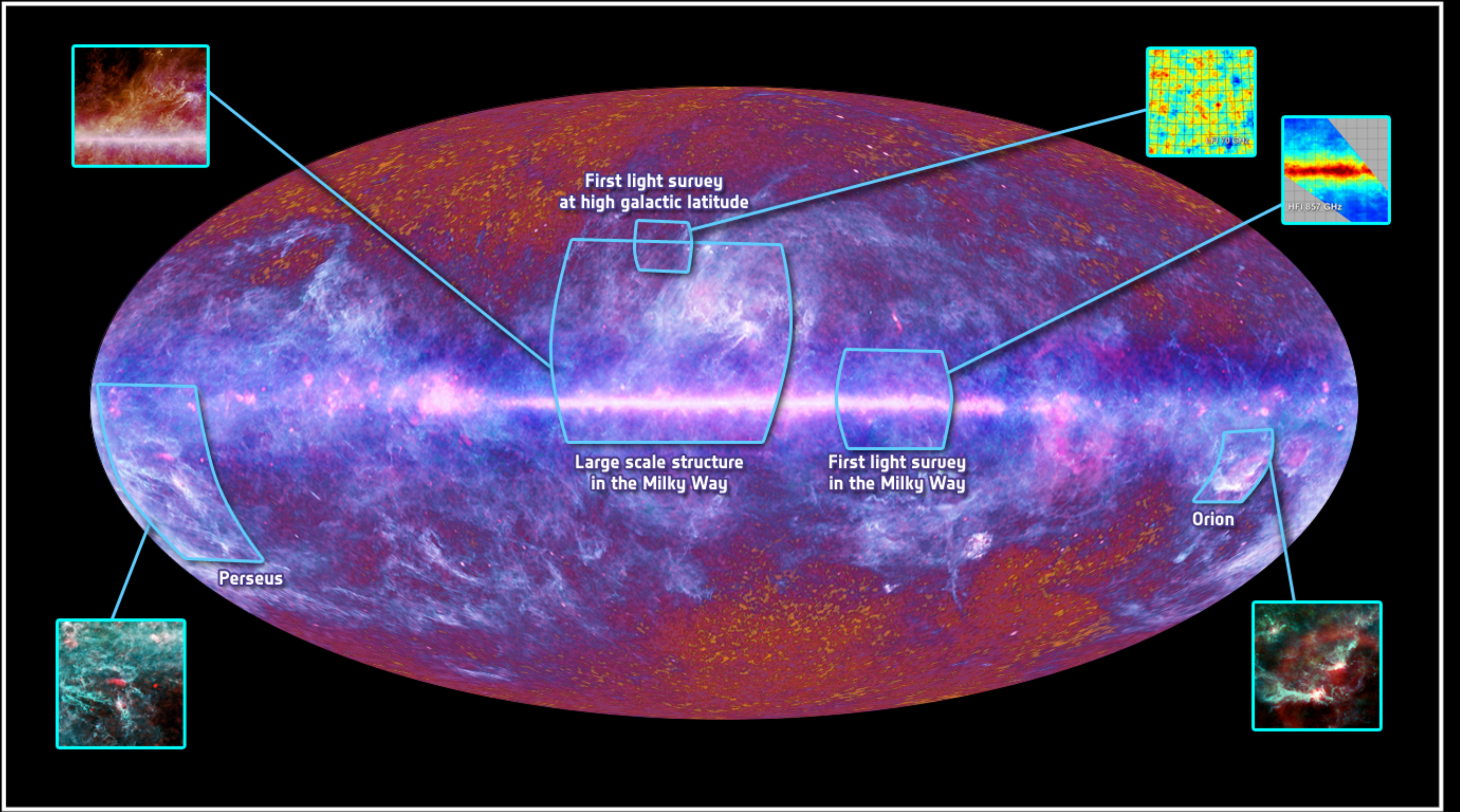
almost!



WMAP + https://ned.ipac.caltech.edu/level5/Bothun2/Bothun1_1_10.html

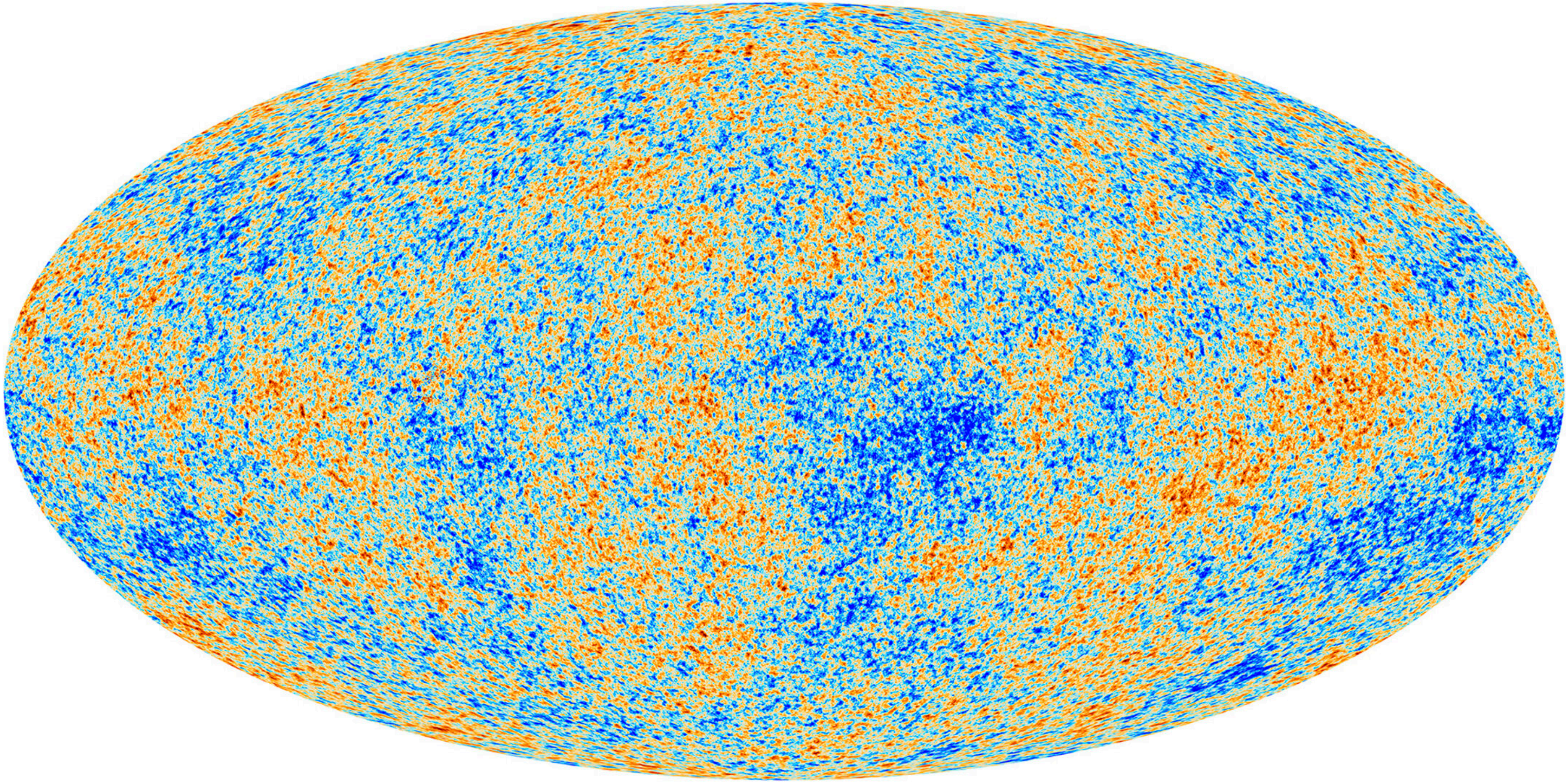
actual Planck observations — there is a lot of foreground dust!





The Planck one-year all-sky survey

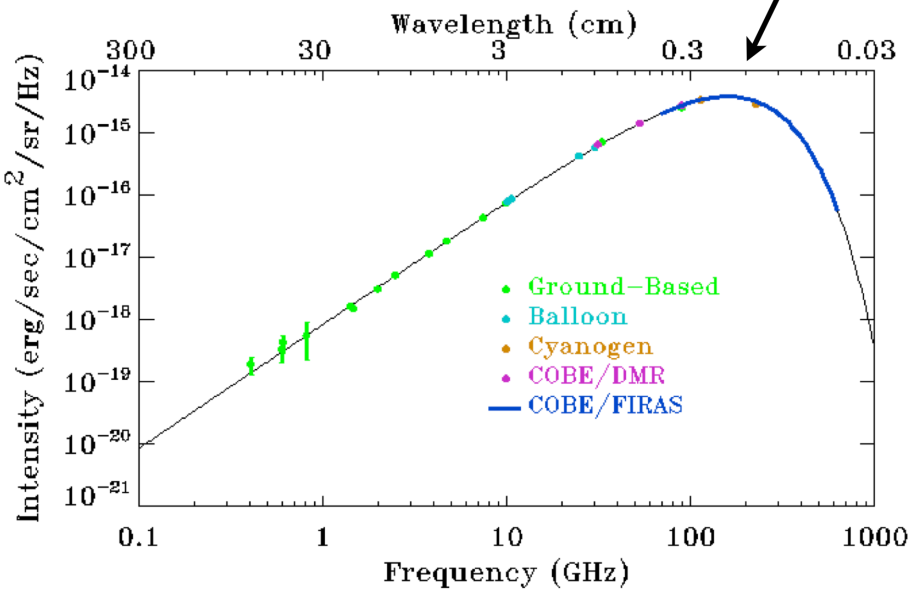
After removal of Milky Way and extragalactic sources
(note: not trivial at all!)

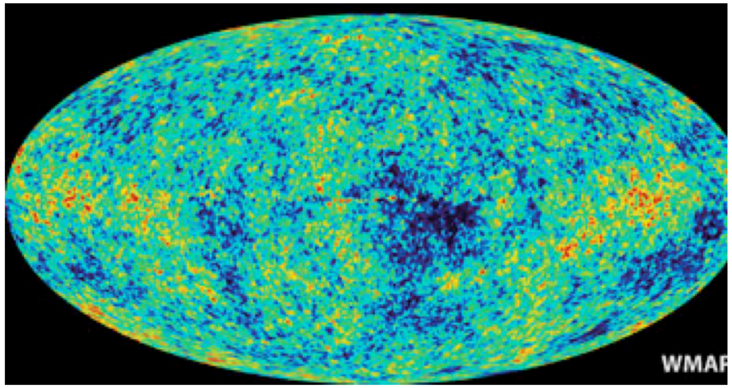


Blackbody Radiation

CMB: The Perfect Blackbody

Spectrum peaks around 200GHz

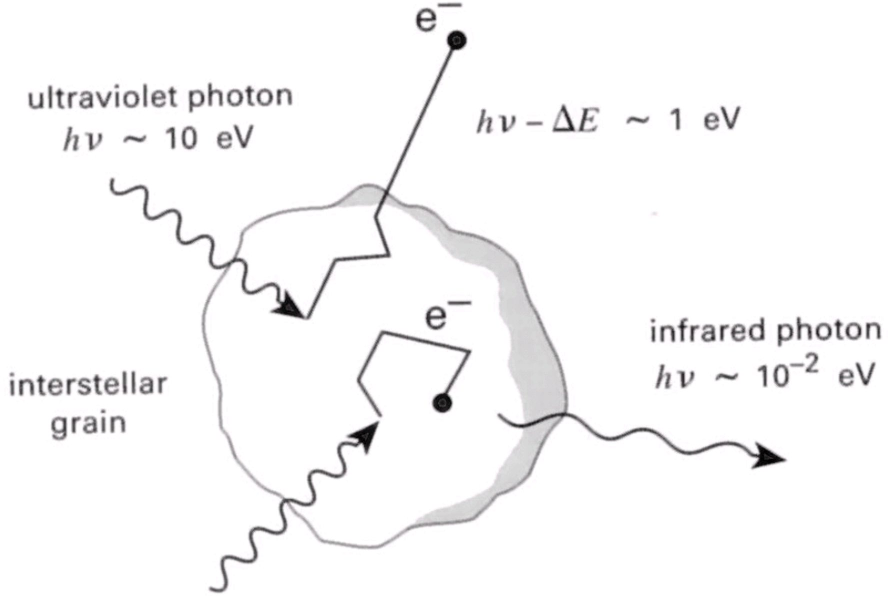




The CMBR has a thermal blackbody spectrum at a temperature of 2.72548±0.00057 K

Blackbody Radiation

even dust (to first order) can be approximated by a black body (‘modified black body’) — more on this later



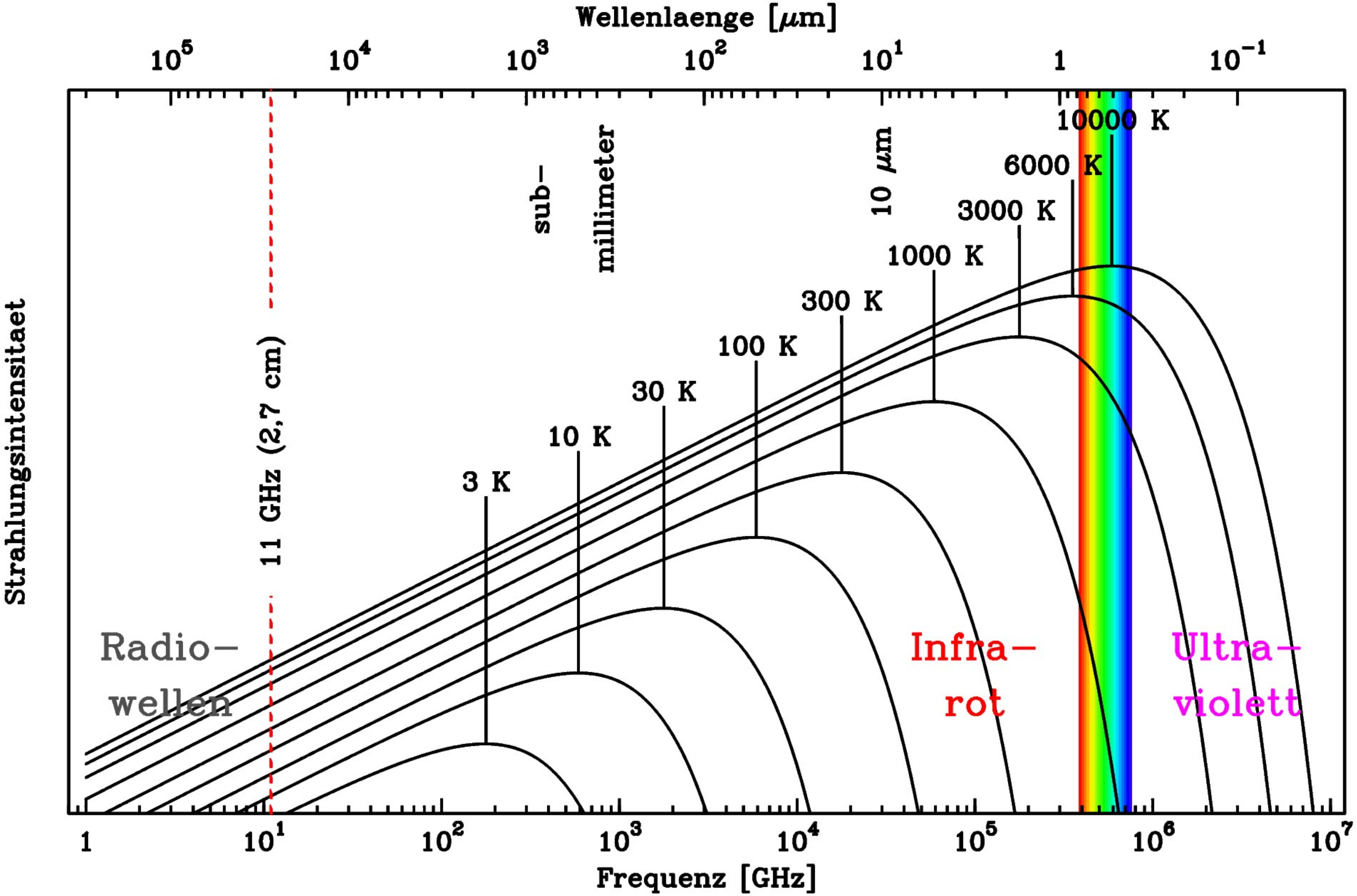
A dust grain is hit by a UV photon. Sometimes, the energy is transformed within a photoelectrical event into kinetic energy of an electron that can leave the grain and eventually hits and heats a gas molecule.

In most cases, the electron remains inside the dust grain and excites lattice vibrations that are eventually transformed into IR photons that are being emitted.

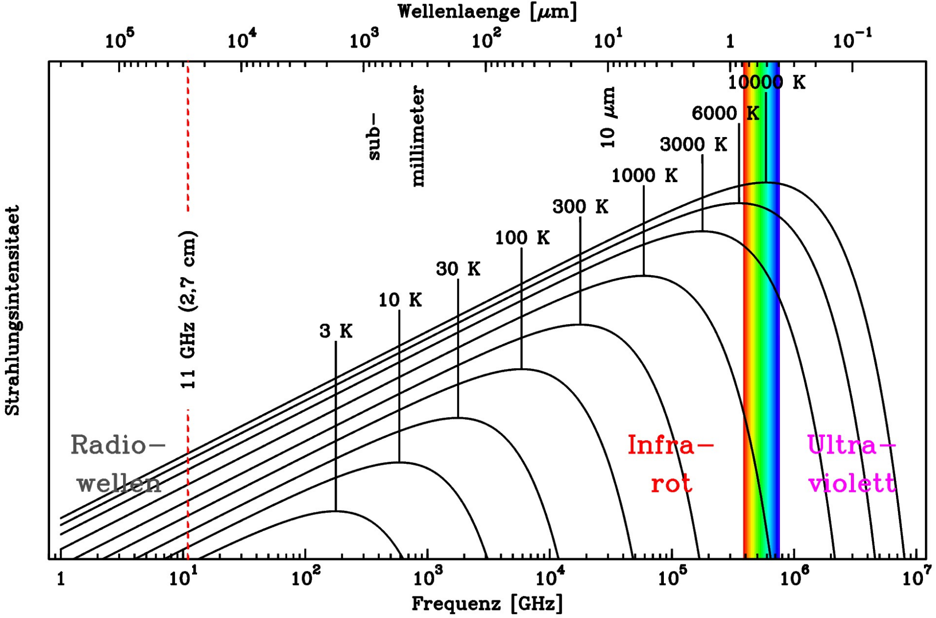
more on dust: next lecture!

Blackbody Radiation

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



Blackbody Radiation



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

- Often in radio we can only see the tail (“Rayleigh-Jeans tail”) of the blackbody radiation (and this is often well below the sensitivity of our radio telescopes anyway).

- Even objects at room temperature peak well above the radio window (even well above the 1000GHz upper frequency of ALMA).
- Thermal emitters that produce radio waves are therefore very cool, i.e. < 100 Kelvin

Blackbody Radiation

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

Taylor expansion for small $\frac{h\nu}{kT}$:

$$\exp\left(\frac{h\nu}{kT}\right) - 1 \approx 1 + \frac{h\nu}{kT} + \cdots - 1 \approx \frac{h\nu}{kT}$$

yields: $$B_\nu\left(\nu, T\right) \approx \frac{2h\nu^3}{c^2}\frac{kT}{h\nu} = \frac{2kT\nu^2}{c^2}$$

Rayleigh Jeans approximation holds when hν << kT

Blackbody Radiation – Brightness Temperature

The commonly used (in radio) **Rayleigh Jeans approximation** holds when hν << kT.

$$B_\nu = \frac{2\nu^2}{c^2} kT$$

Beyond just convenience, this is used as a unit of intensity throughout radio astronomy.

… especially for single dish telescopes where calibration occurs with reference to a source of known temperature.

The “brightness temperature” is:

$$T_B = \frac{c^2}{2k\nu^2} I_\nu$$

When you hear intensity expressed in units of “Kelvin” this is what people mean.

Note that this is defined rigorously for any intensity, not dependent on being a blackbody (but it becomes an increasingly weird unit).

Blackbody Radiation – Brightness Temperature

The commonly used (in radio) **Rayleigh Jeans approximation** holds when hν << kT.

$$B_\nu = \frac{2\nu^2}{c^2} kT$$

Beyond just convenience, this is used as a unit of intensity throughout radio astronomy.

… especially for single dish telescopes where calibration occurs with reference to a source of known temperature.

The “brightness temperature” is:

$$T_B = \frac{c^2}{2k\nu^2} I_\nu$$

When you hear intensity expressed in units of “Kelvin” this is what people mean.

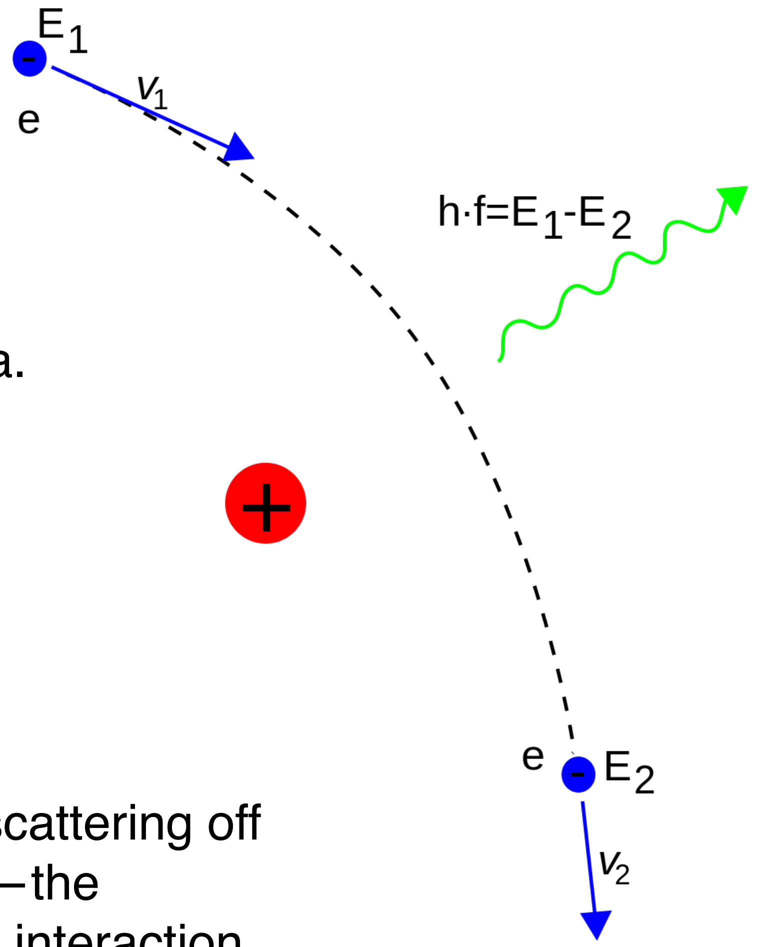
Note that this is defined **for any intensity**, not dependent on being a blackbody (but it becomes an increasingly weird unit).

- E.g., the highest observed brightness temperatures in the Universe approach ~10^38 K and can be found in the nanosecond-long giant pulses generated by the Crab Pulsar.

Free Free Radiation

“bremsstrahlung”, “free free”, “thermal radio” all mean the same thing.

Free-Free Radiation



- Consider an ionized gas (plasma).
- Such a plasma emits radiation continuously.
- Much of visible Universe is a diffuse, hot (1E4 K) plasma.
- Not in thermal equilibrium. Too diffuse to absorb/emit photons regularly.

produced by free electrons scattering off ions without being captured—the electrons are free before the interaction and remain free afterward

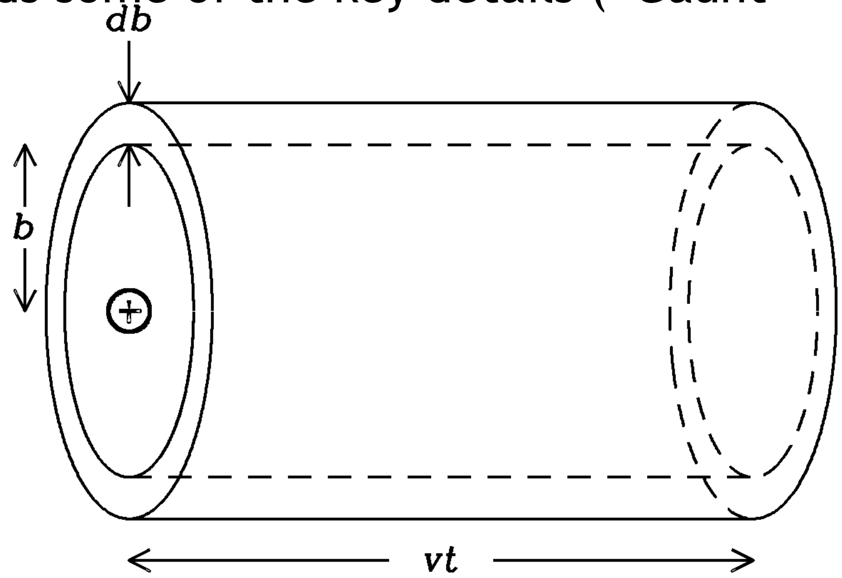
Free Free Radiation

Free-Free Radiation

Free-Free Emission

Derivation —> NRAO ERA webpages. Idea:

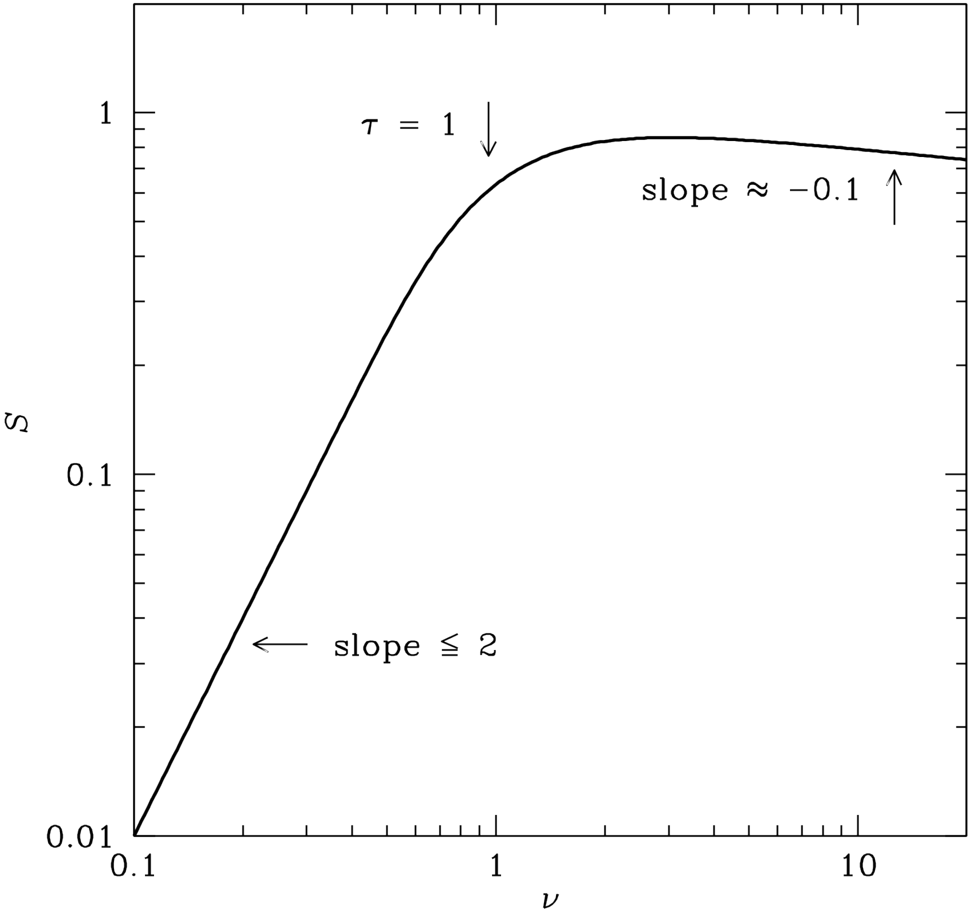
- Electrons bent only weakly during passage by a proton.
- Only the acceleration towards the proton (the "bending") matters in this case.
- The spectrum of a single passage depends on the properties of one particle swinging by.
- The spectrum of a population of particles convolves this with a Maxwellian distribution convolved with a range of "impact parameters."
- The range of viable impact parameters holds some of the key details ("Gaunt factor").



Free Free Radiation

Free-Free Radiation

Radio spectrum of an HII region (derivation see ERA)

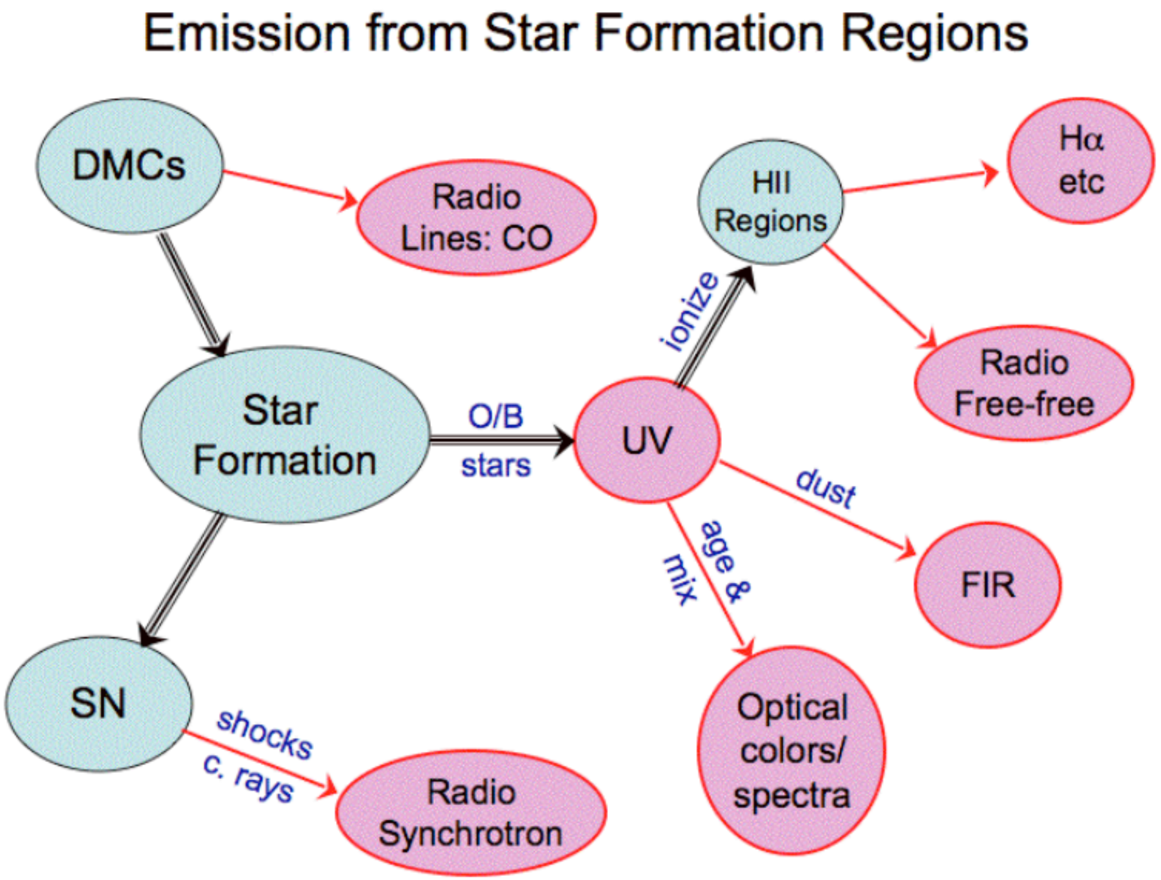


- Spectrum almost "flat" (frequency independent) in the optically thin regime.
- Spectrum approaches that of a blackbody as the optical depth increases. At low- frequencies photons cannot escape easily and undergo many absorptions and emissions.

we typically observe the 'flat' part

observations measure free electrons —> measure for ionisation and thus star formation rate

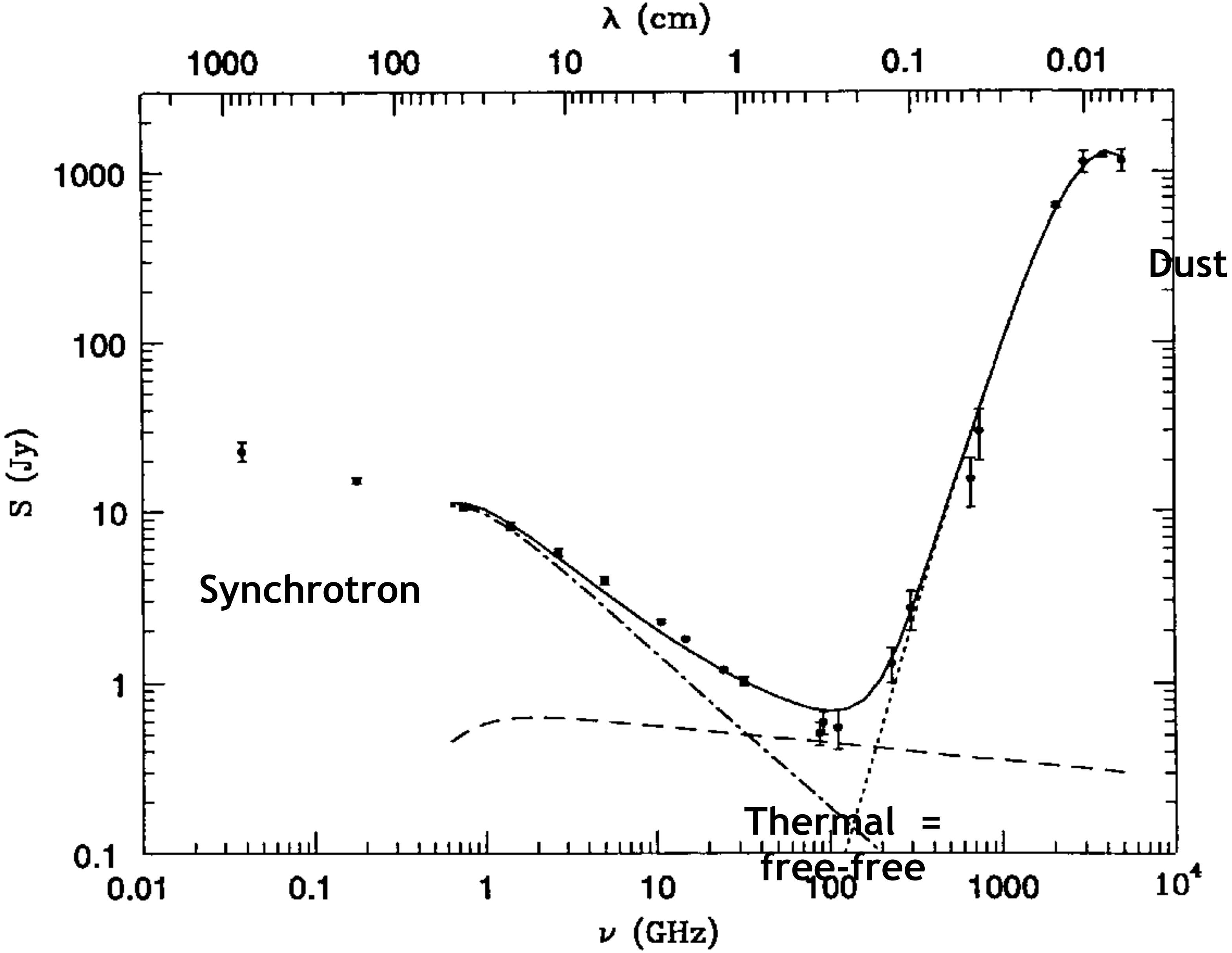
Free-Free Radiation



- Ionized gas around star forming region.

Free-Free Radiation

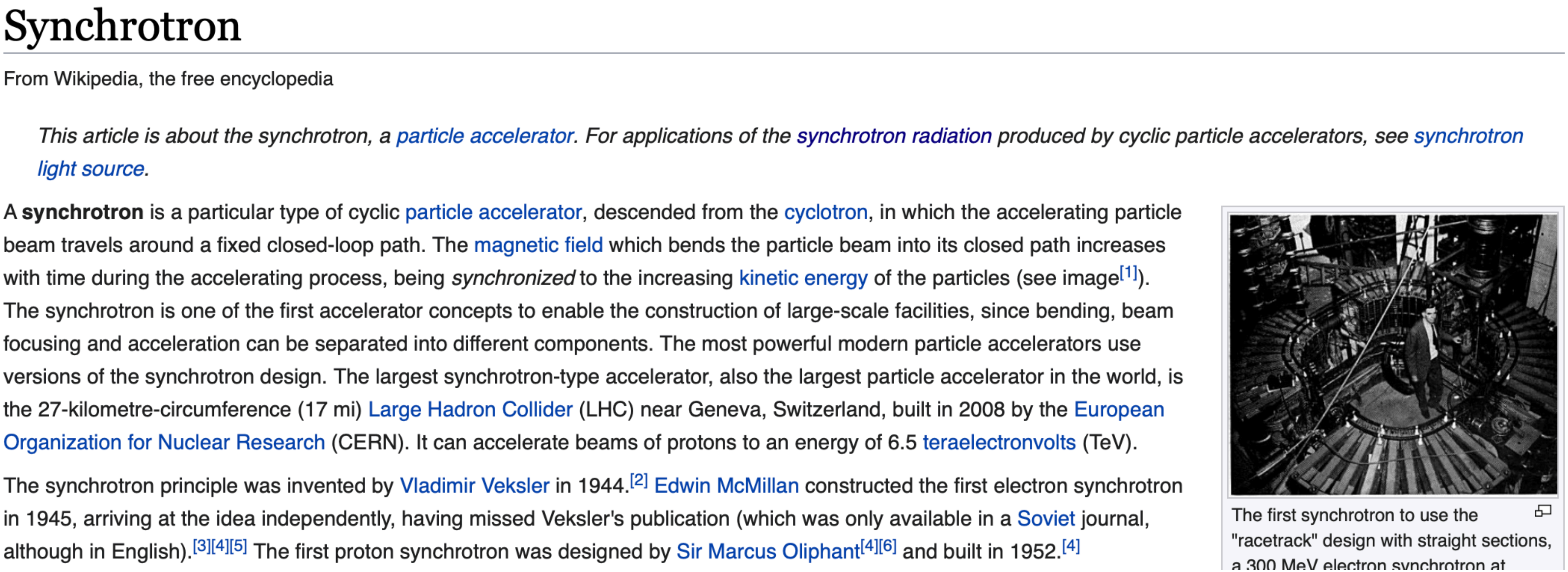
- This is the "weakest" of the three mechanisms (sort of) so that it is typically dominant only over the 30-100 GHz range (higher, dust dominates; lower, synchrotron).



Synchrotron Radiation

also called: magnetobremsstrahlung

Synchrotron Radiation



Synchrotron

From Wikipedia, the free encyclopedia

This article is about the synchrotron, a particle accelerator. For applications of the synchrotron radiation produced by cyclic particle accelerators, see synchrotron light source.

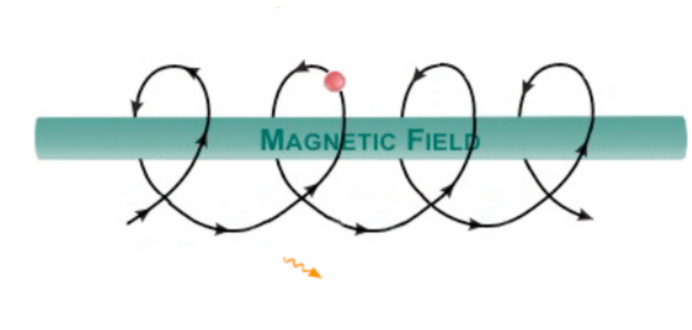
A **synchrotron** is a particular type of cyclic particle accelerator, descended from the cyclotron, in which the accelerating particle beam travels around a fixed closed-loop path. The magnetic field which bends the particle beam into its closed path increases with time during the accelerating process, being *synchronized* to the increasing kinetic energy of the particles (see image[1]). The synchrotron is one of the first accelerator concepts to enable the construction of large-scale facilities, since bending, beam focusing and acceleration can be separated into different components. The most powerful modern particle accelerators use versions of the synchrotron design. The largest synchrotron-type accelerator, also the largest particle accelerator in the world, is the 27-kilometre-circumference (17 mi) Large Hadron Collider (LHC) near Geneva, Switzerland, built in 2008 by the European Organization for Nuclear Research (CERN). It can accelerate beams of protons to an energy of 6.5 teraelectronvolts (TeV).

The synchrotron principle was invented by Vladimir Veksler in 1944.[2] Edwin McMillan constructed the first electron synchrotron in 1945, arriving at the idea independently, having missed Veksler's publication (which was only available in a Soviet journal, although in English).[3][4][5] The first proton synchrotron was designed by Sir Marcus Oliphant[4][6] and built in 1952.[4]

The first synchrotron to use the "racetrack" design with straight sections, a 300 MeV electron synchrotron at

- First identified in the 1940s as an interfering signal in particle accelerators.

Synchrotron Radiation



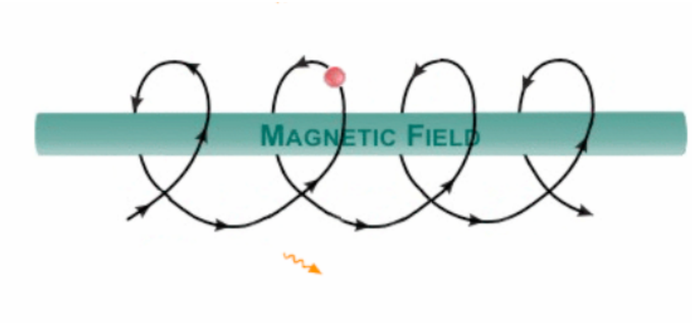
Acceleration of (ultra-) relativistic charged particles (typically electrons) in a magnetic field.

- Particles spiral along magnetic field lines.
- Emission frequency related to velocity of the particle.
- Electrons need to be traveling relativistically to be detectable astronomically
- Spectrum describes the energy distribution of the seed electrons.

To maintain synchrotron emission, a continuous supply of relativistic electrons is necessary.

- Typical energy sources include supernova remnants, quasars, or other types of active galactic nuclei.

Synchrotron Radiation



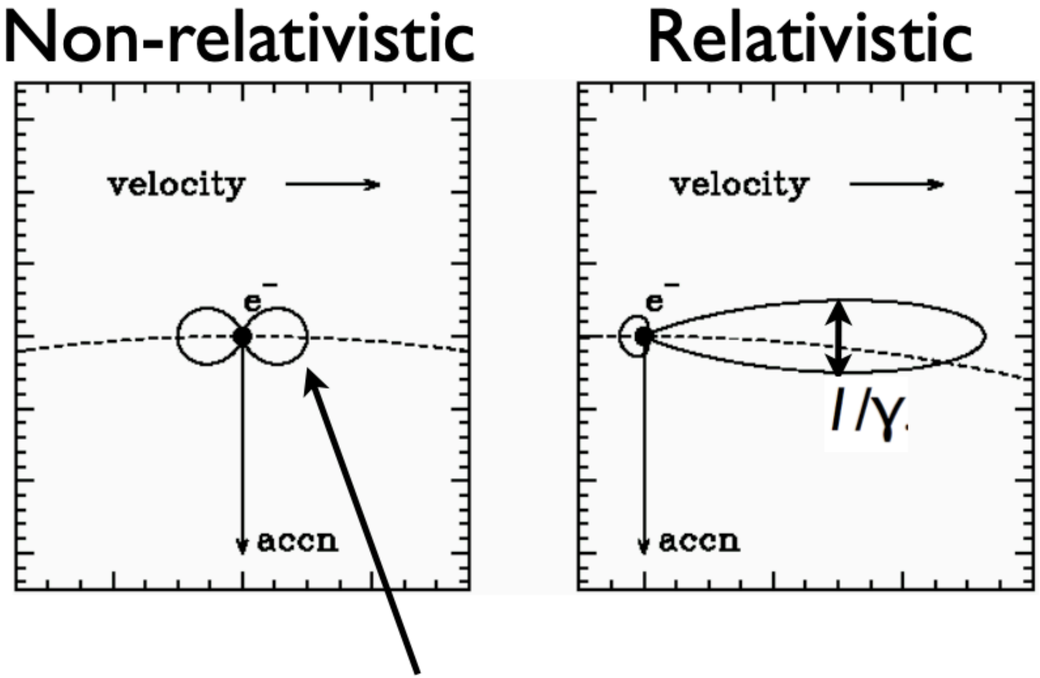
Acceleration of (ultra-) relativistic charged particles (typically electrons) in a magnetic field.

- Particles spiral along magnetic field lines.
- Emission frequency related to velocity of the particle.
- Electrons need to be traveling relativistically to be detectable astronomically
- Spectrum describes the energy distribution of the seed electrons.

To maintain synchrotron emission, a continuous supply of relativistic electrons is necessary.

- Typical energy sources include supernova remnants, quasars, or other types of active galactic nuclei.

Synchrotron Radiation



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

- Relativistic motion causes beaming (opening angle related to the Lorentz factor).
- Lorentz factor boosts the emission frequency into the observable radio range (even for a weak B- field).

Synchrotron Radiation

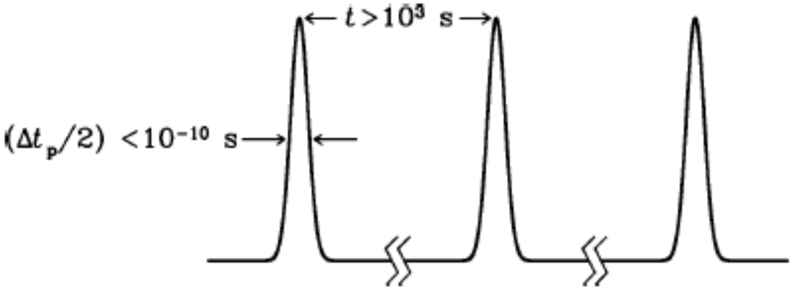
Synchrotron radiation comes from highly relativistic cosmic ray electrons spiraling around a magnetic field.

Relativity gives you a power that depends on the Lorentz factor

$$\boxed{\langle P \rangle = \frac{4}{3}\sigma_{\mathrm{T}}\beta^2\gamma^2 c U_{\mathrm{B}}}$$

The radiation pattern is a series of very rapid spikes of emission with long lulls as the electron spirals by and hits you with its heavily beamed signal:

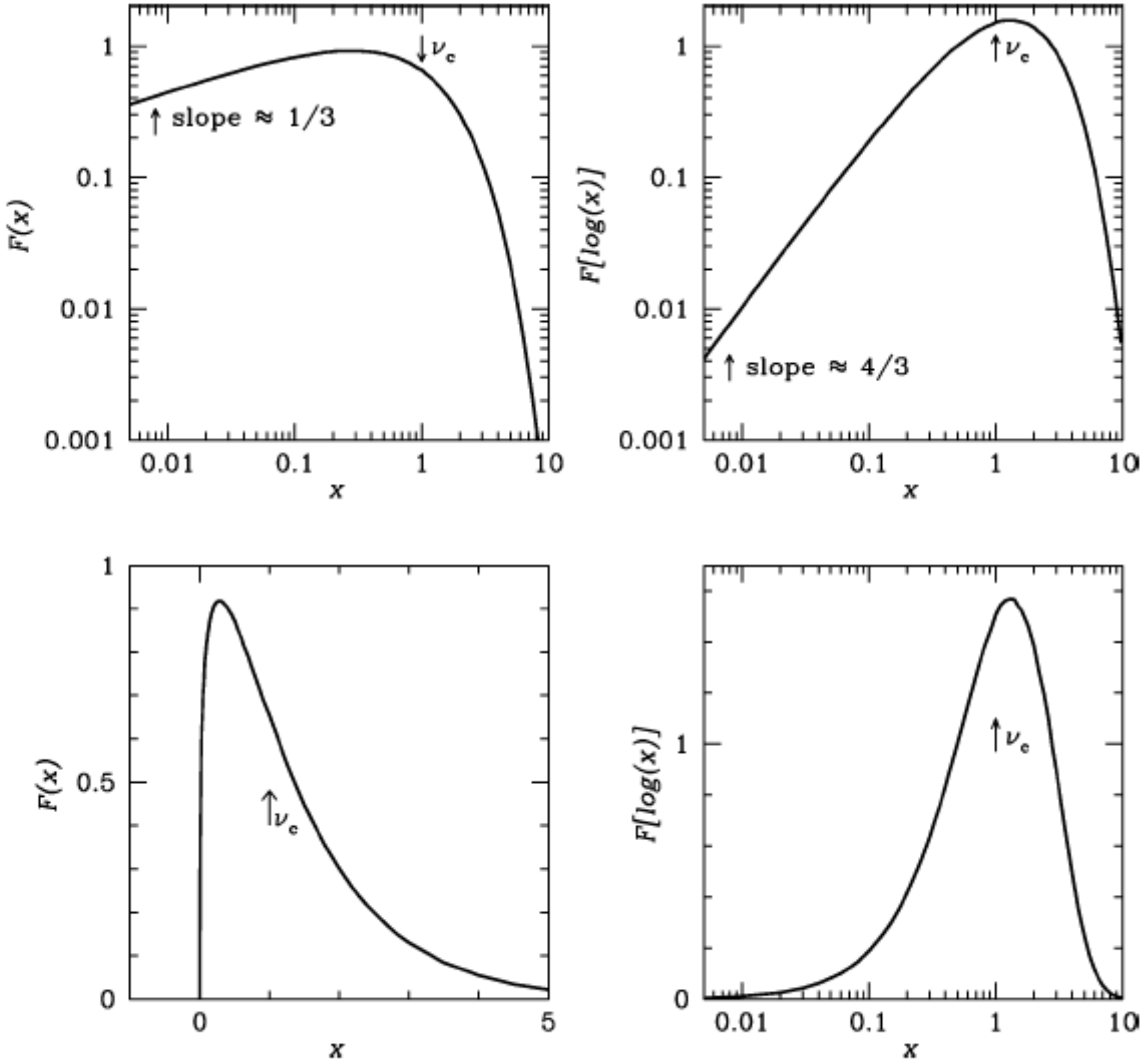
Producing a time series of power like this:



Relativistic aberration transforms the dipole power pattern of Larmor radiation in the electron rest frame (dotted curve) into a narrow searchlight beam in the observer's frame.

Synchrotron Radiation

That gives you a spectrum like this **for each individual electron**:



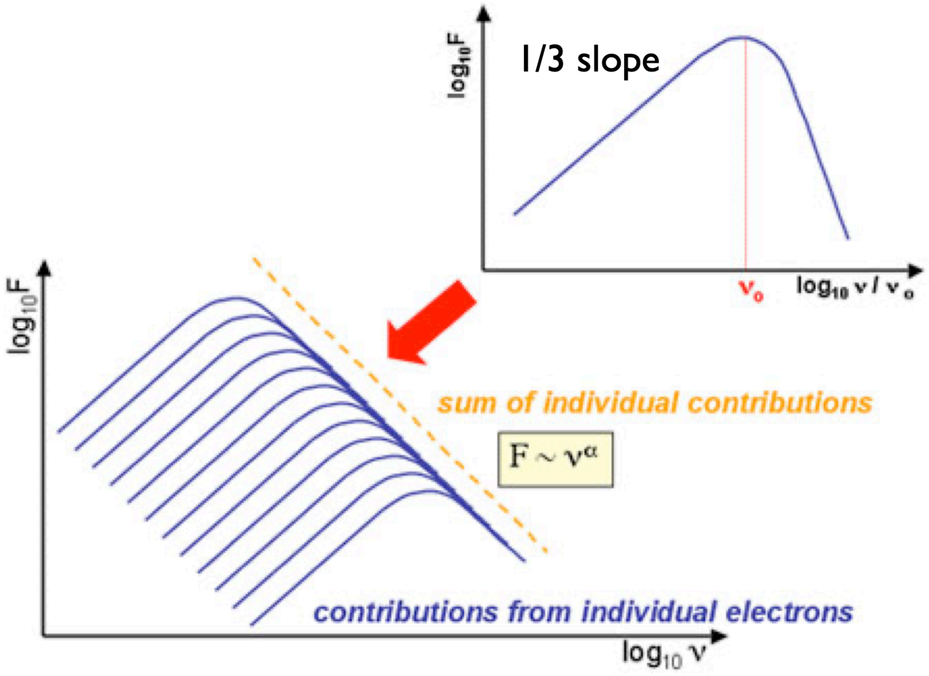
x = nu/nu_c

nu_c: critical frequency (energy where electron emits most strongly)

Note: all panels plot the same spectrum (log vs. linear…)

Synchrotron Spectrum

Synchrotron Radiation



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

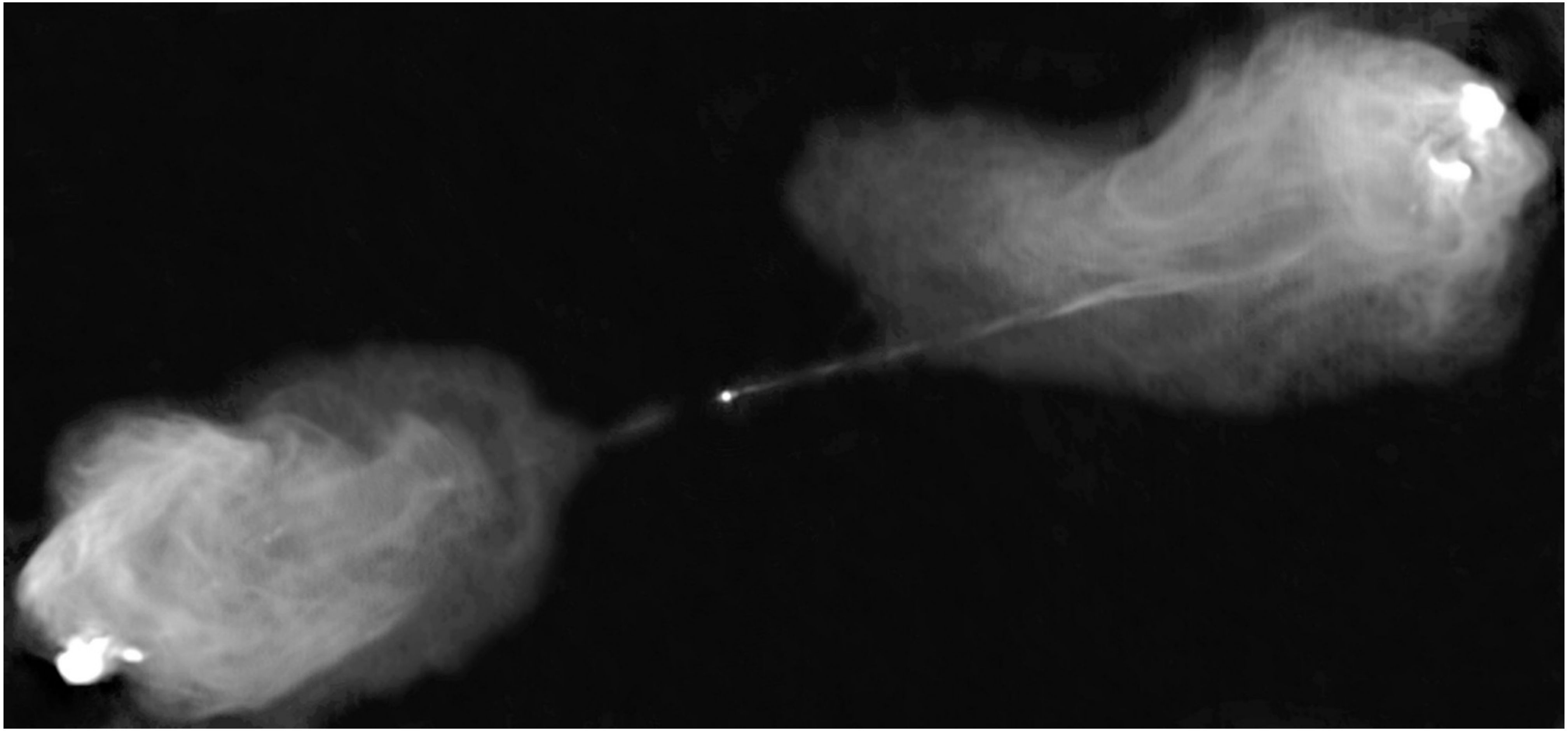
Strong dependence on the Lorentz factor

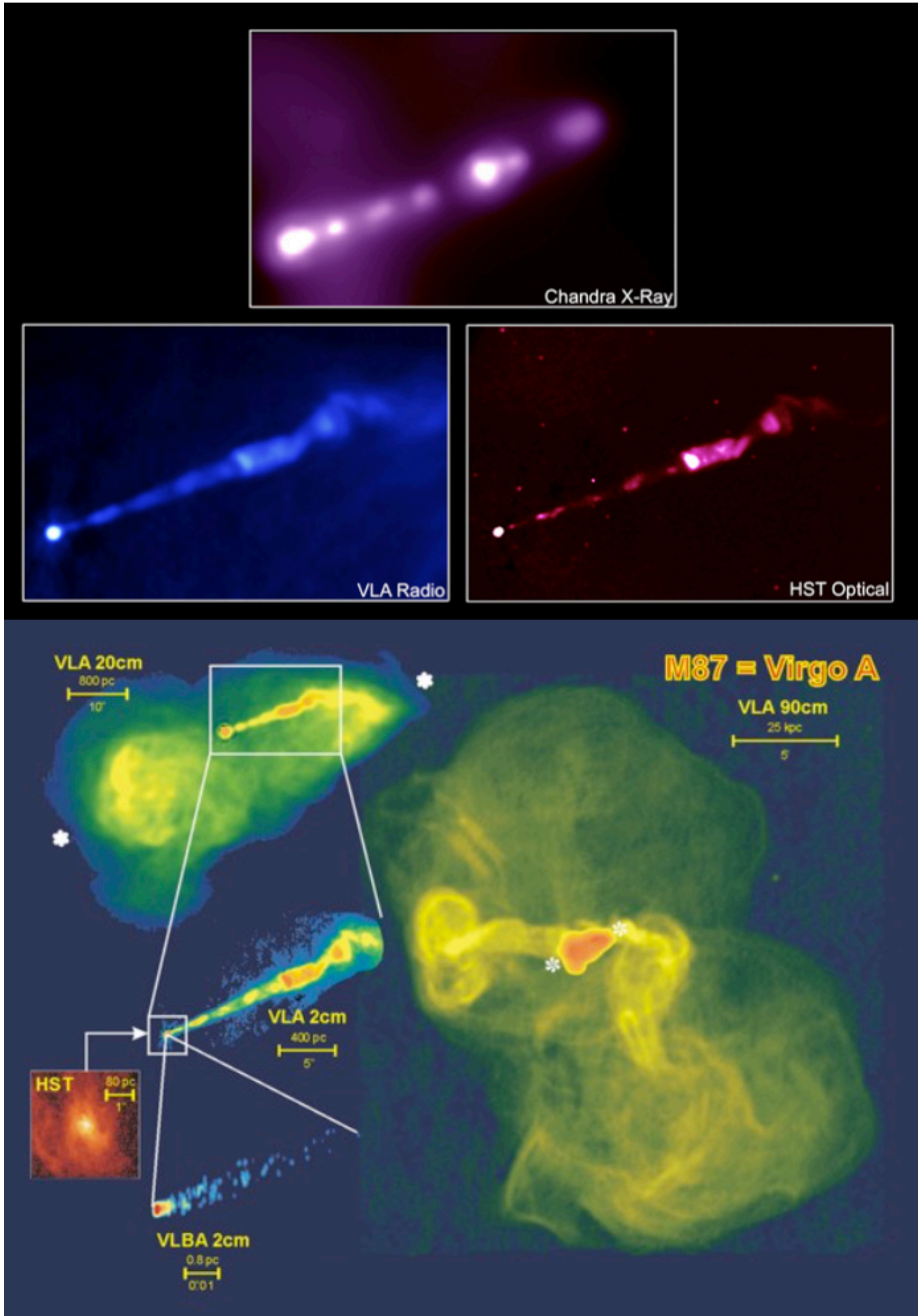
$$\nu_{max} = \nu_e \gamma^2 \qquad P_e \sim 2\, \gamma^2\, U_{mag}$$

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

Synchrotron Radiation

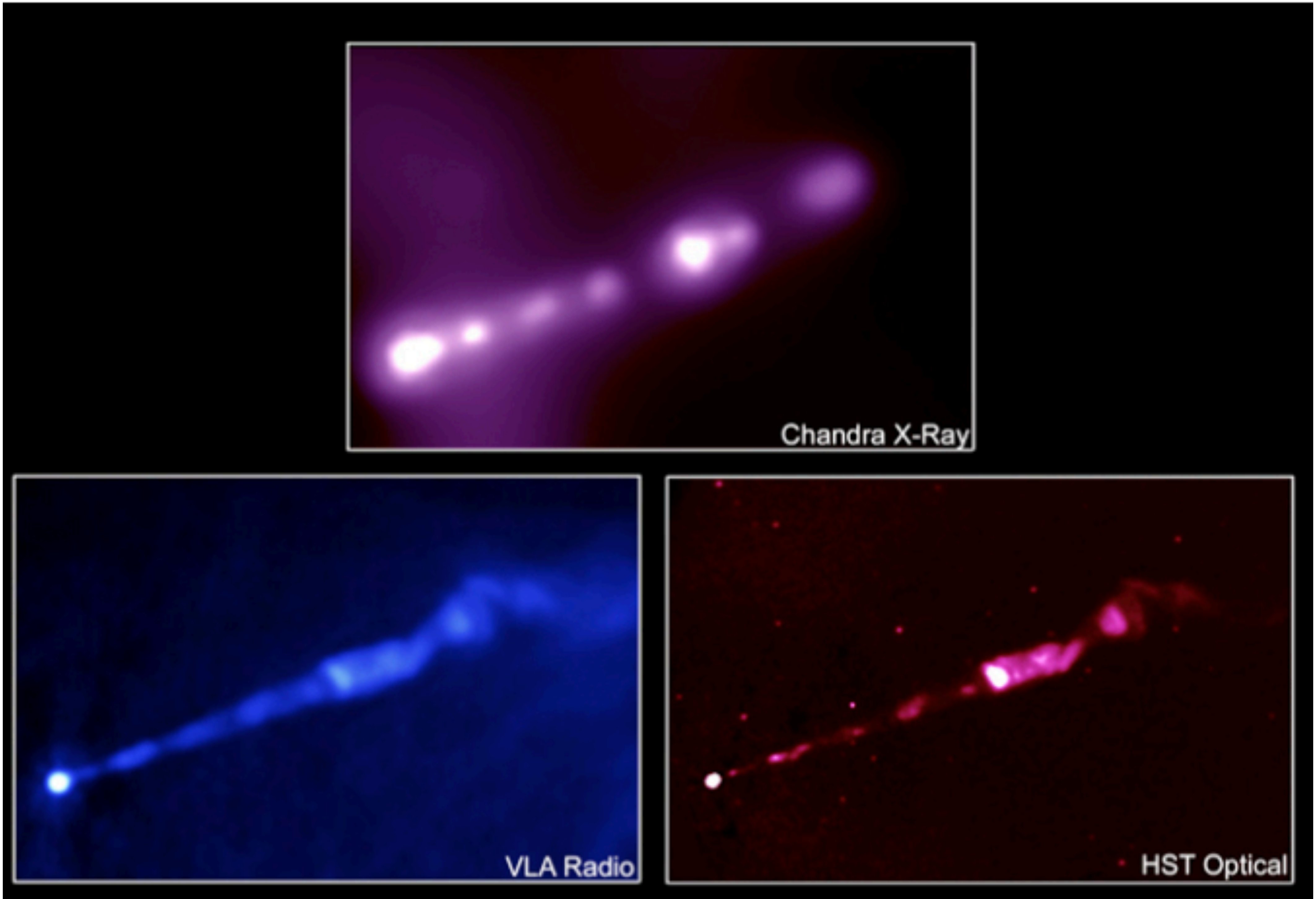
The radio galaxy Cygnus A as an example

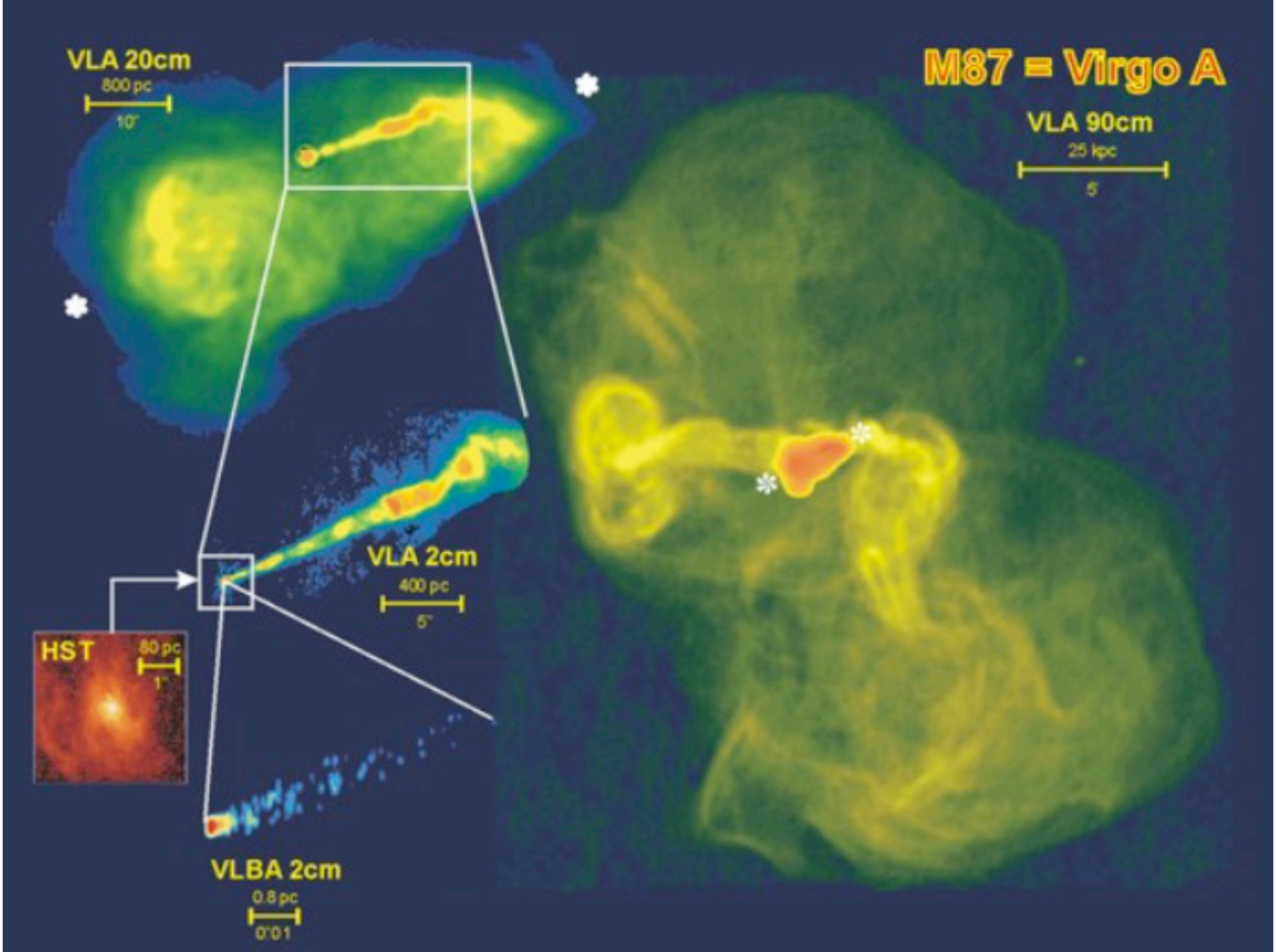


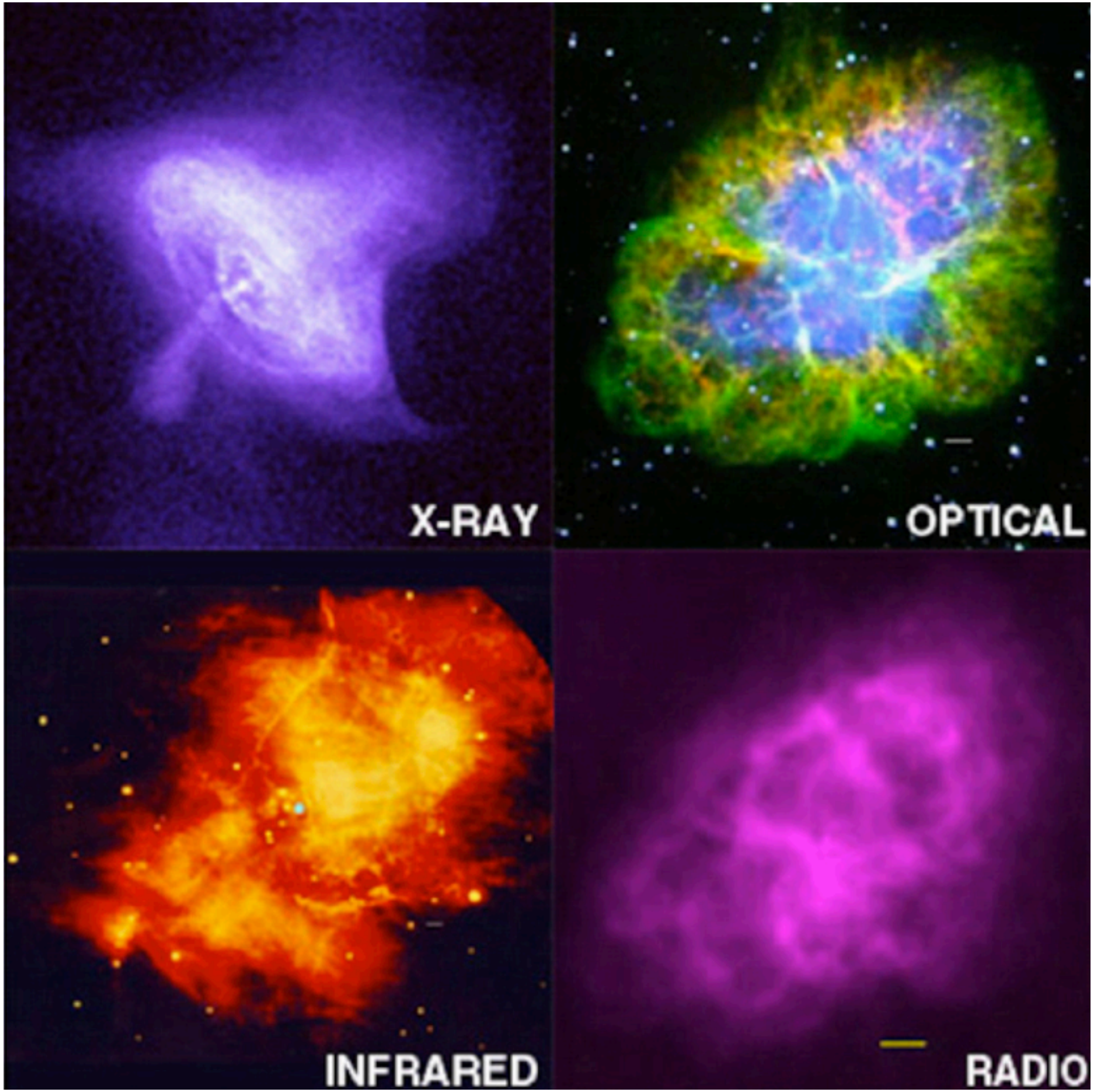


- Multi-wavelength synchrotron emission from an AGN jet.
- note: morphology almost the same!

all synchrotron!!



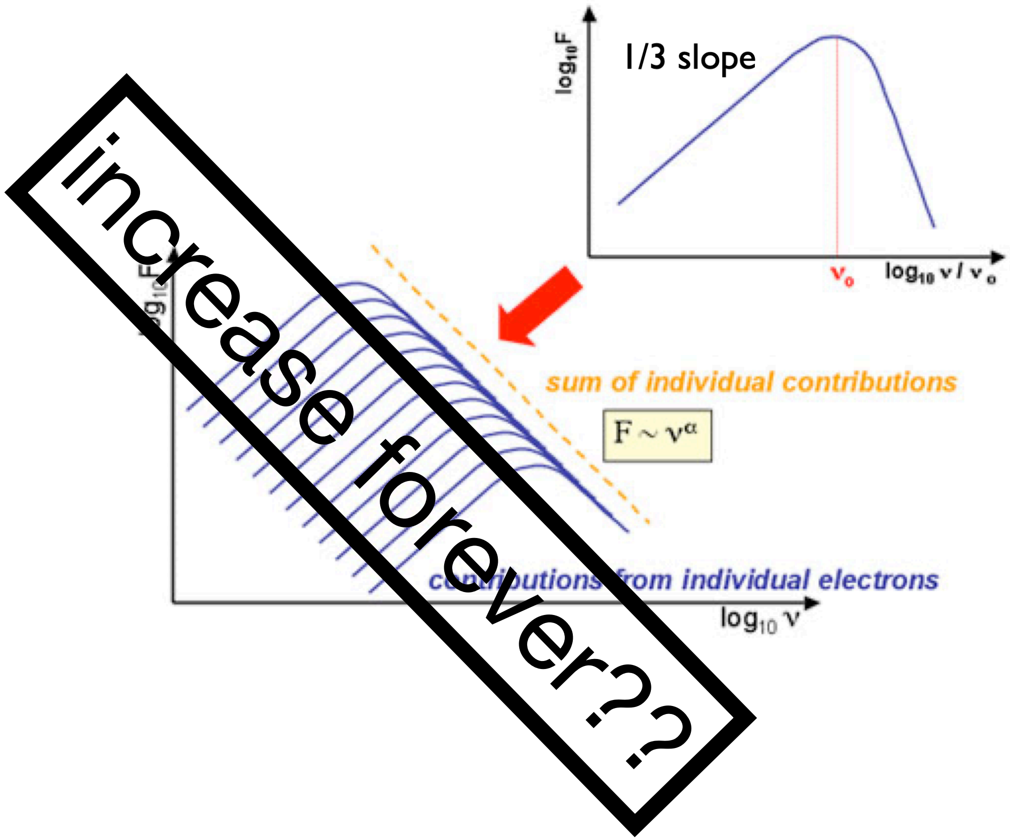

M87 = Virgo A
VLA 20cm
800 pc
10"
VLA 90cm
25 kpc
5'
VLA 2cm
400 pc
5"
HST
80 pc
1"
VLBA 2cm
0.8 pc
0"01



Crab Nebula:

- Another example of multi-frequency synchrotron emission

Synchrotron Radiation



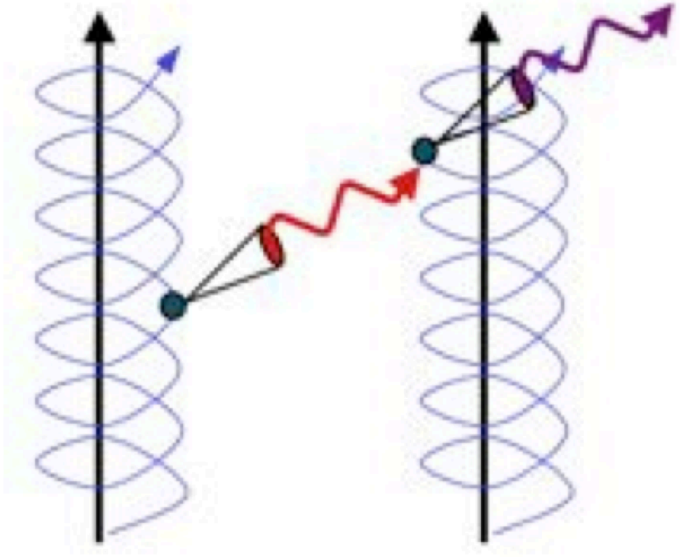
- Powerlaw.
- Observed spectrum is a superposition of the individual electron spectra.

Strong dependence on the Lorentz factor

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

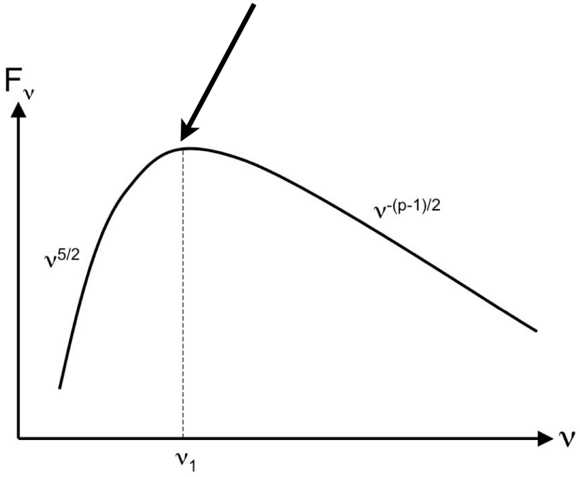
- Since ($\gamma >> 1$) this boosts the emission frequency of synchrotron emission into the radio domain.

Synchrotron Self-Absorption



- Principle of "detailed balance": any mechanism that can emit radiation can also absorb it.
- What happens to the steep power-law spectrum of synchrotron radiation at lower and lower frequencies (can't increase forever)?
- Happens in compact sources at low frequencies (i.e. when they become optically thick).

Synchrotron Self-Absorption



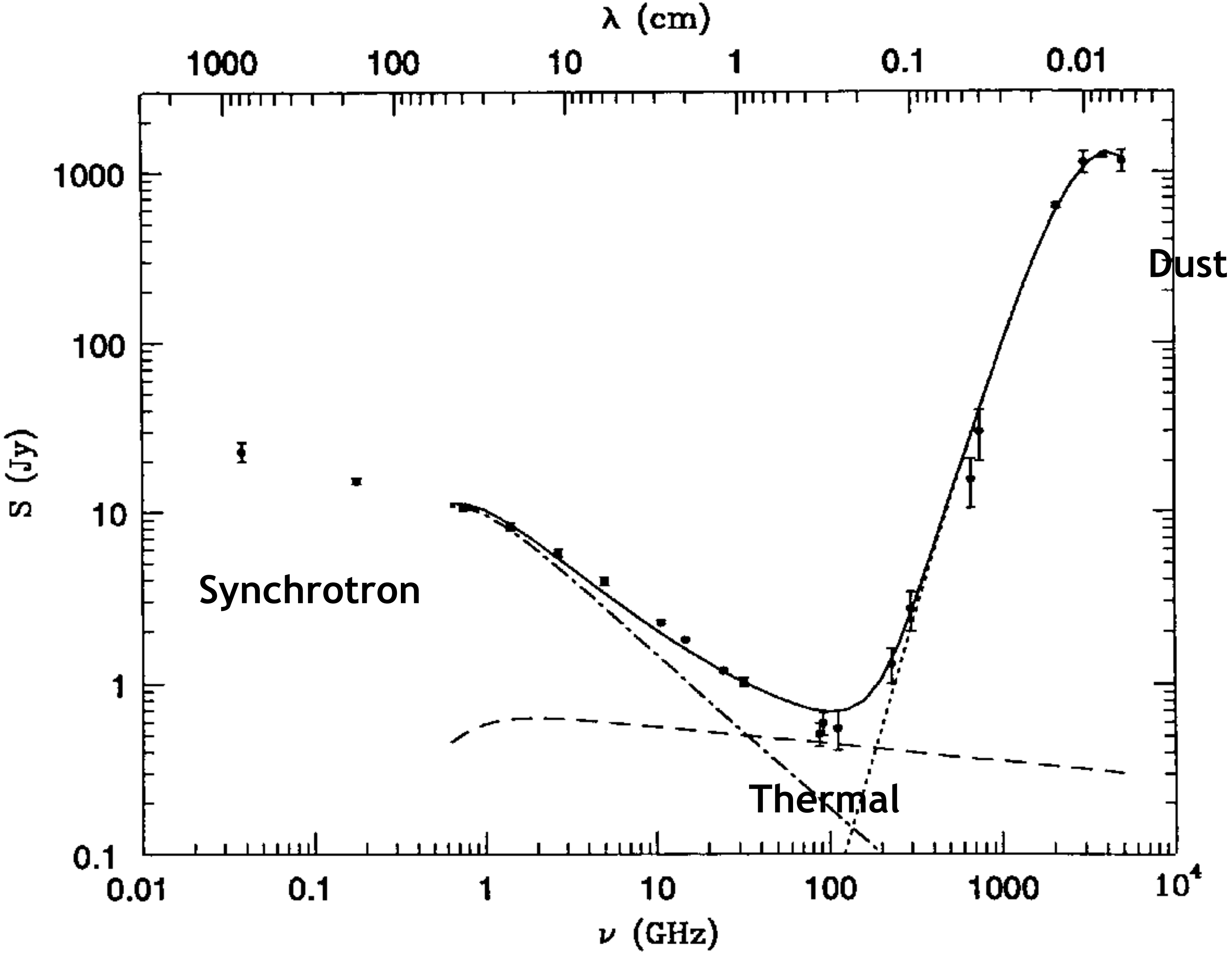
Turnover frequency

Optically thick

Optically thin

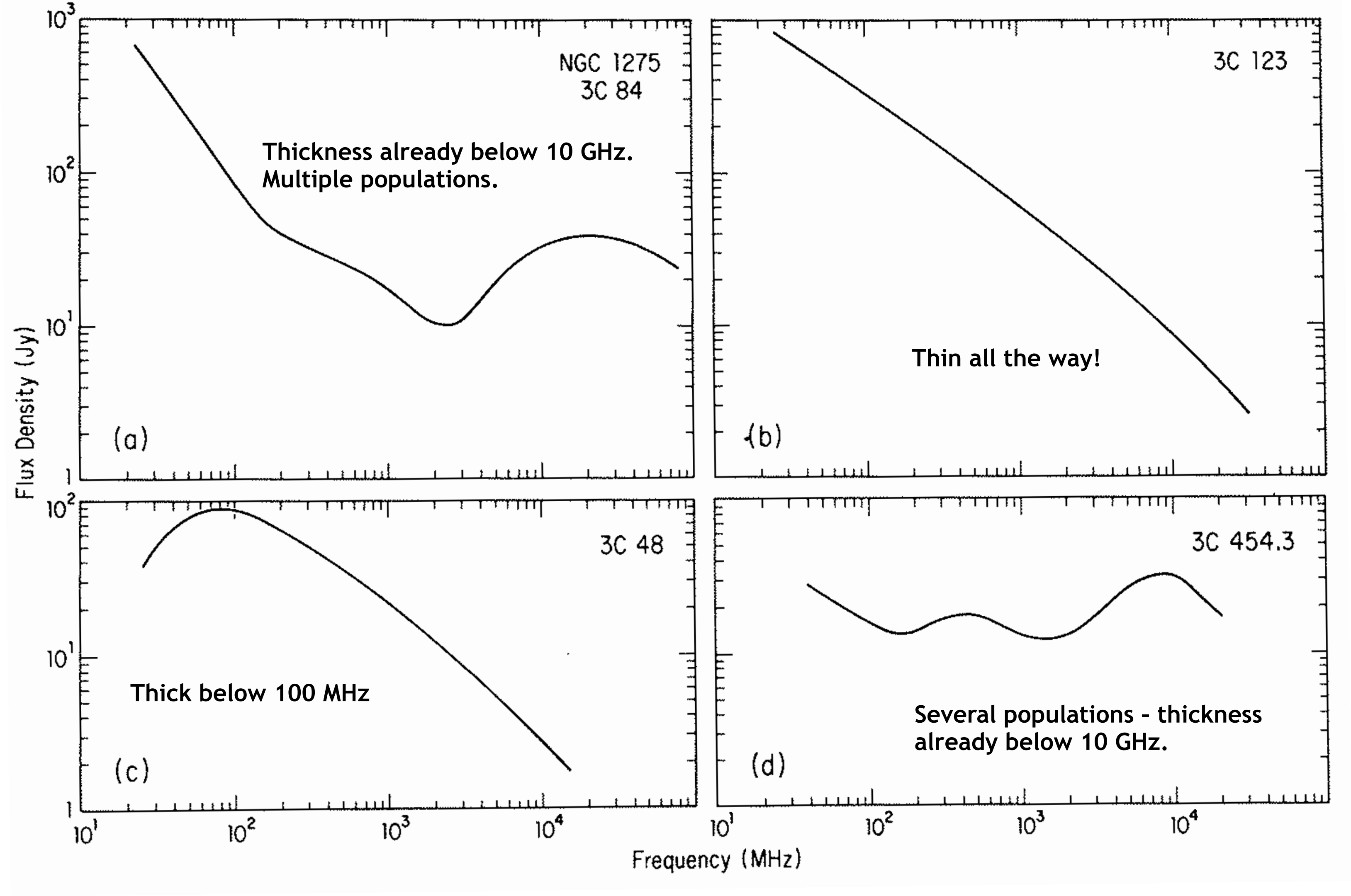
- When the brightness temperature becomes equal to the electron temperature, the source becomes opaque.
- A self-absorbed source has a 5/2 powerlaw spectrum.
- Turnover frequency related to electron density.

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



Synchrotron Spectra

example spectra: self-absorption, geometrically complex structures (B-fields etc).



Thickness already below 10 GHz. Multiple populations.

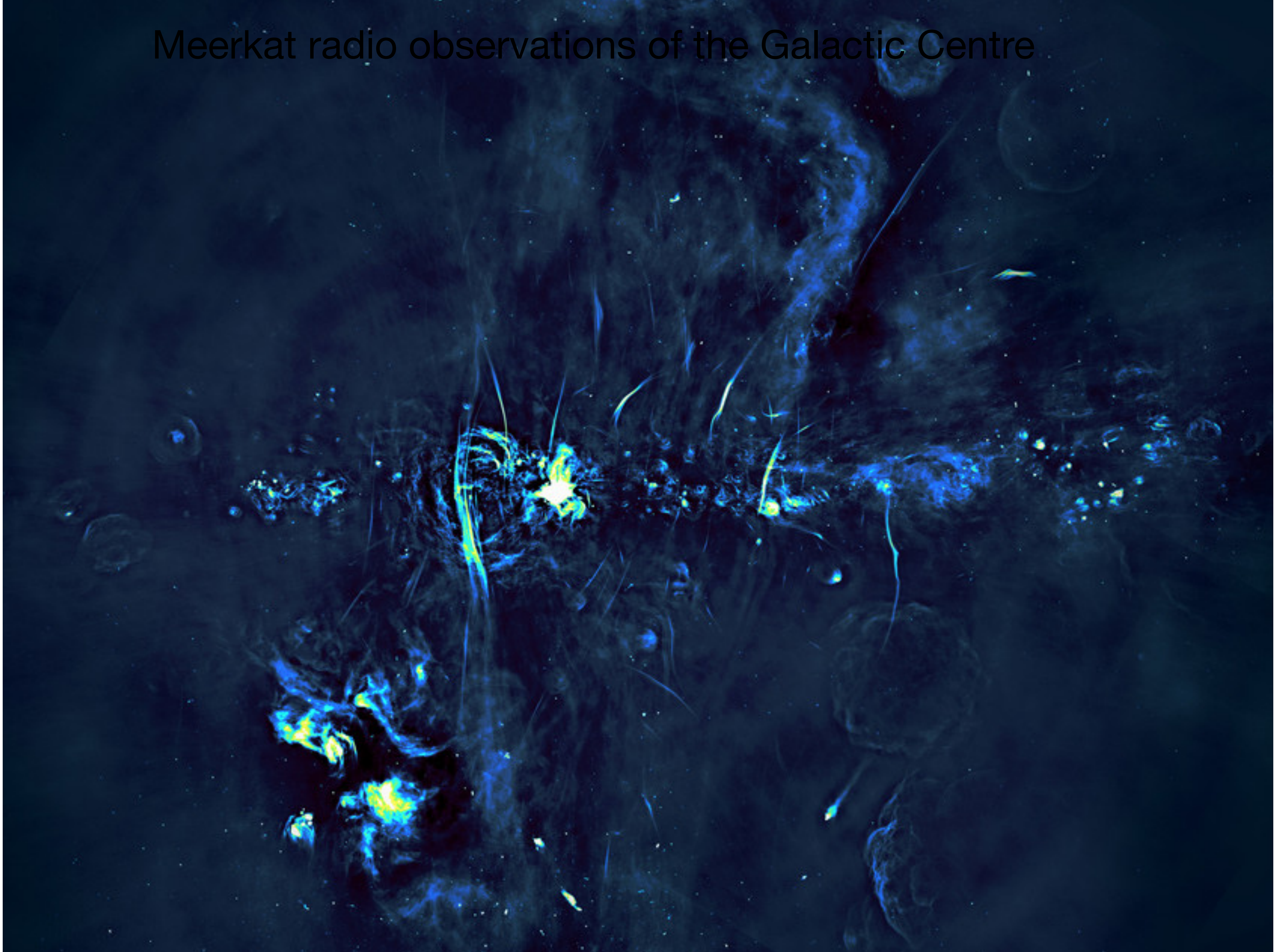
Thin all the way!

Thick below 100 MHz

Several populations – thickness already below 10 GHz.

From ERA: Figure 5.8: Representative spectra of radio galaxies and quasars. The radio source 3C 84 in the nearby galaxy NGC 1275 contains a very compact nuclear component that is opaque below about 20 GHz. The radio galaxy 3C 123 is transparent at all plotted frequencies, and energy losses steepen its spectrum above a few GHz. The quasar 3C 48 is synchrotron self-absorbed only below 100 MHz, while the quasar 3C 454.3 contains structures of different sizes that become opaque at different frequencies.

Meerkat radio observations of the Galactic Centre



Summary: Synchrotron Radiation

Acceleration by a magnetic field produces Synchrotron Radiation

The lightest charged particles (i.e. electrons) are accelerated more than relatively massive protons and heavier ions, so electrons account for virtually all of the radiation observed.

The character of Synchrotron depends on the speeds of the electrons and the strength of the magnetic fields

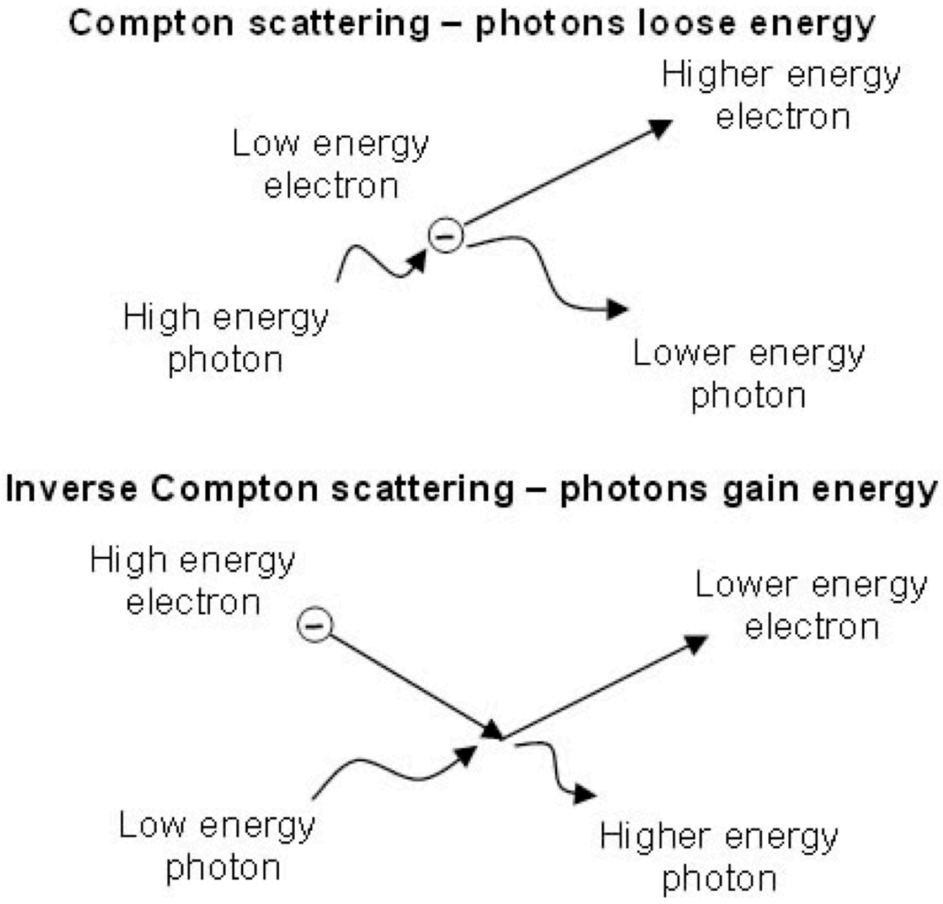
Synchrotron radiation accounts for most of the radio emission from active galactic nuclei (AGNs) thought to be powered by supermassive black holes in galaxies and quasars, and it dominates the radio continuum emission from star-forming galaxies below ~30 GHz.

Sent moving through a magnetic field, charged particles sweep out a helical path.

…**relativistic** particles (derivation see ERA)

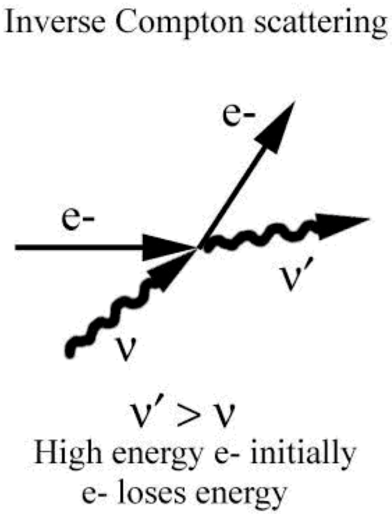
Compton Scattering

Synchrotron Self-Compton



- Synchrotron emission provides the low-energy photons that can be up-scattered by other relativistic electrons.
- Photon scattered by a relativistic electron increases its energy by the Lorentz factor squared.

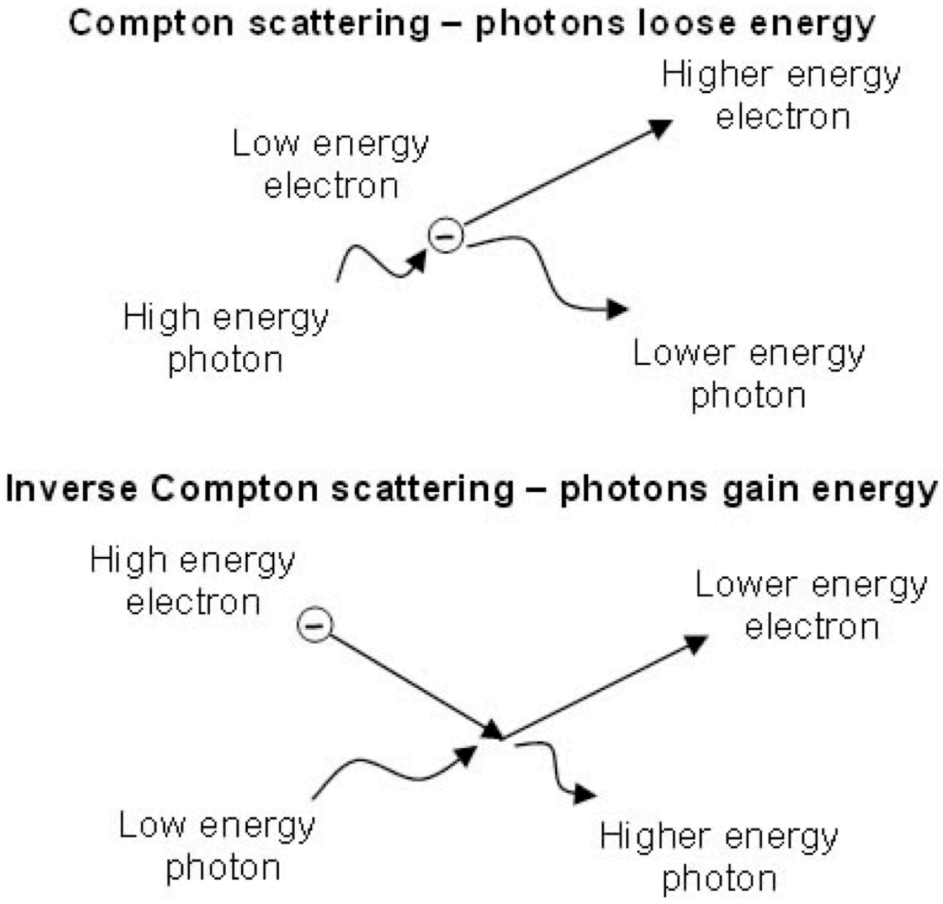
Inverse Compton Scattering



- Low-energy photons scattered to higher energies by relativistic electrons.
- Seed photons from, e.g., the CMB.
- Observed near synchrotron sources (sources of relativistic electrons).

Compton Scattering

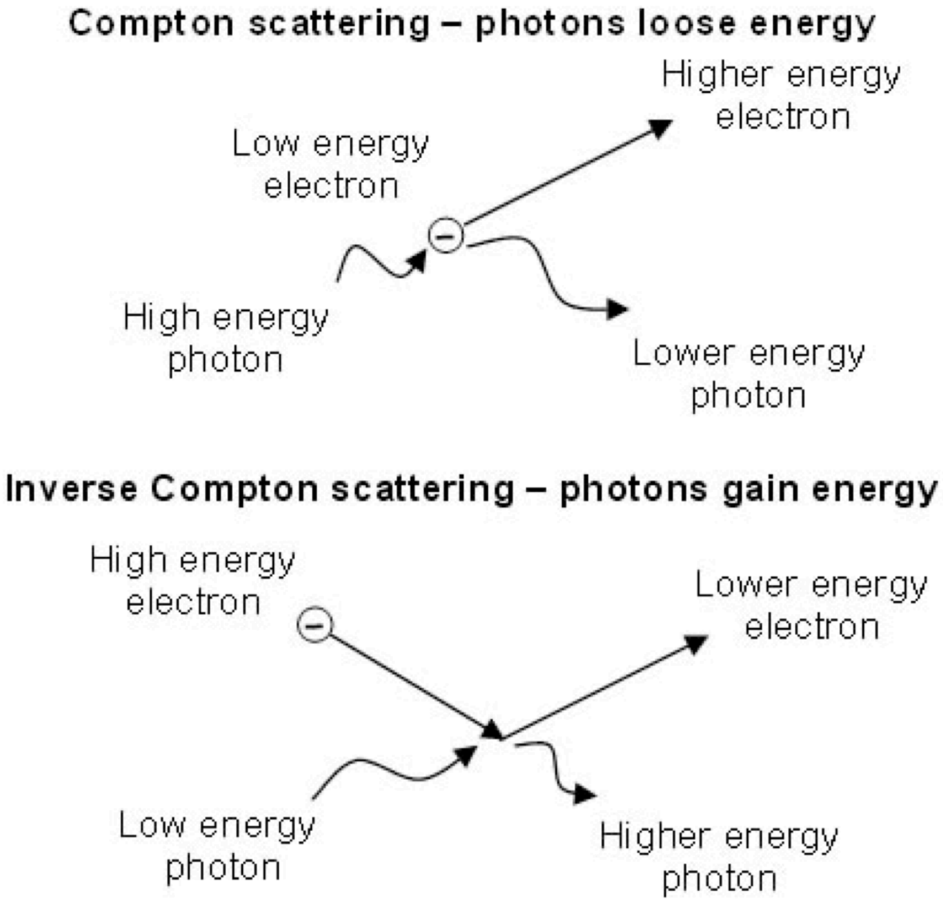
Synchrotron Self-Compton


Compton scattering – photons loose energy

Inverse Compton scattering – photons gain energy

- Synchrotron emission provides the low-energy photons that can be up-scattered by other relativistic electrons.
- Photon scattered by a relativistic electron increases its energy by the Lorentz factor squared.

Synchrotron Self-Compton

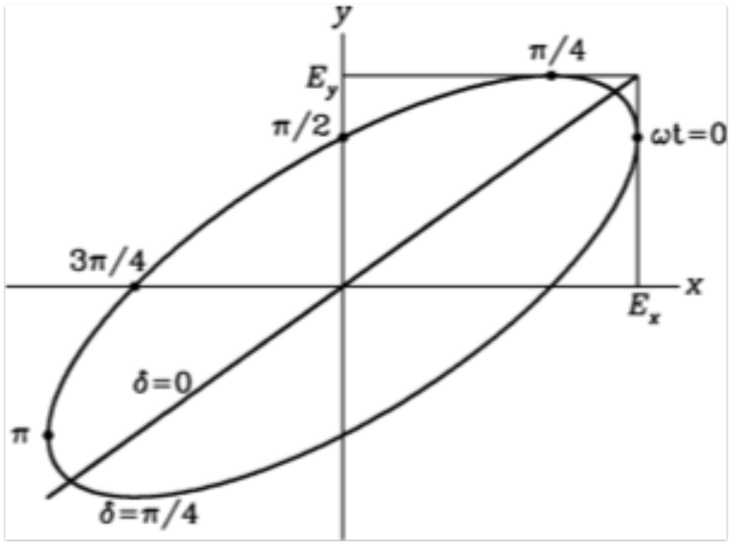


- Synchrotron emission provides the low-energy photons that can be up-scattered by other relativistic electrons.
- Photon scattered by a relativistic electron increases its energy by the Lorentz factor squared.

Polarization

Polarization

Having ignored the wavi-ness of light for a while, let's return to two wave aspects: **polarization** and the emission from an individual accelerated charge.



From ERA – a plane wave traveling towards us

Treat light as a wave traveling towards us (in the z direction). Then in general:

The field along the X axis *The field along the Y axis*

$$\vec{E} = [\hat{x}E_\mathrm{x}\exp(i\phi_\mathrm{x}) + \hat{y}E_\mathrm{y}\exp(i\phi_\mathrm{y}]\exp[i(k\hat{z} - \omega t)]$$

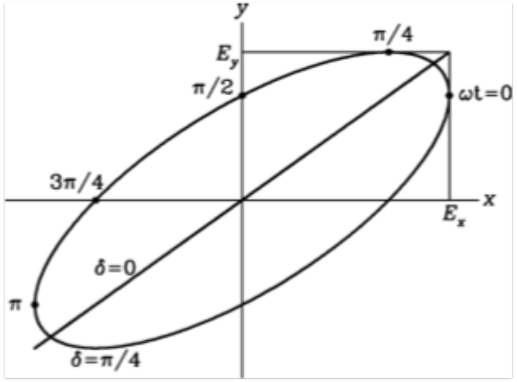
The total transverse electric field ($E^2 = E_x^2 + E_y^2$)

Phases for the x and y fields, the difference is a phase offset between X and Y

The phase + wavelength term along z (travel)

Polarization

So very generally, as the wave travels, the X and Y components of the field can have the same or different magnitudes, go up and down together (in phase), out of phase, or in some combination. Define the phase difference $\delta = \Phi_x - \Phi_y$ for convenience.



$$\vec{E} = [\hat{x}E_{\mathrm{x}}\exp(i\phi_{\mathrm{x}}) + \hat{y}E_{\mathrm{y}}\exp(i\phi_{\mathrm{y}}]\exp[i(k\hat{z} - \omega t)]$$

Consider two special cases:

(1) $\Phi_x = \Phi_y$ so that the x and y fields go up and down in synch. In this case the light is said to be **linearly** polarized.

(2) $E_x = E_y$, but with a phase difference of π/2 then the net field will rotate as it moves, with x peaking totally out of phase with y. In this case the wave is said to be **circularly** polarized. Convention of rotation is the x clockwise through y is “right handed.”

Stokes Parameters

Generally, the polarization of light can be bookkept using the **Stokes Parameters**, which combine E_x, E_y, and δ.

$$\begin{aligned} I &= \langle E_{\mathrm{x}}^2 + E_{\mathrm{y}}^2 \rangle \\ Q &= \langle E_{\mathrm{x}}^2 - E_{\mathrm{y}}^2 \rangle \\ U &= \langle 2E_{\mathrm{x}}E_{\mathrm{y}} \cos\delta \rangle \\ V &= \langle 2E_{\mathrm{x}}E_{\mathrm{y}} \sin\delta \rangle \end{aligned}$$

Stokes I gives the total amplitude of the radiation, polarized or not.

Amount of **linear polarization** comes from combining **Stokes Q** and **Stokes U:**

$$\sqrt{Q^2 + U^2} = \sqrt{E_x^4 + E_y^4 + 4E_x^2E_y^2\cos^2\delta - 2E_x^2E_y^2}$$

$$\frac{Q}{U} = \frac{E_x^2 - E_y^2}{2E_xE_x\cos\delta} \longleftarrow$$

Depends on the angle of linear polarization.

Stokes Parameters

Generally, the polarization of light can be bookkept using the **Stokes Parameters**, which combine E_x, E_y, and δ.

$$
\begin{aligned}
I &= \langle E_{\mathrm{x}}^2 + E_{\mathrm{y}}^2 \rangle \\
Q &= \langle E_{\mathrm{x}}^2 - E_{\mathrm{y}}^2 \rangle \\
U &= \langle 2E_{\mathrm{x}}E_{\mathrm{y}} \cos\delta \rangle \\
V &= \langle 2E_{\mathrm{x}}E_{\mathrm{y}} \sin\delta \rangle
\end{aligned}
$$

Amount of **circular polarization** comes from the magnitude of **Stokes V** (sin δ term).

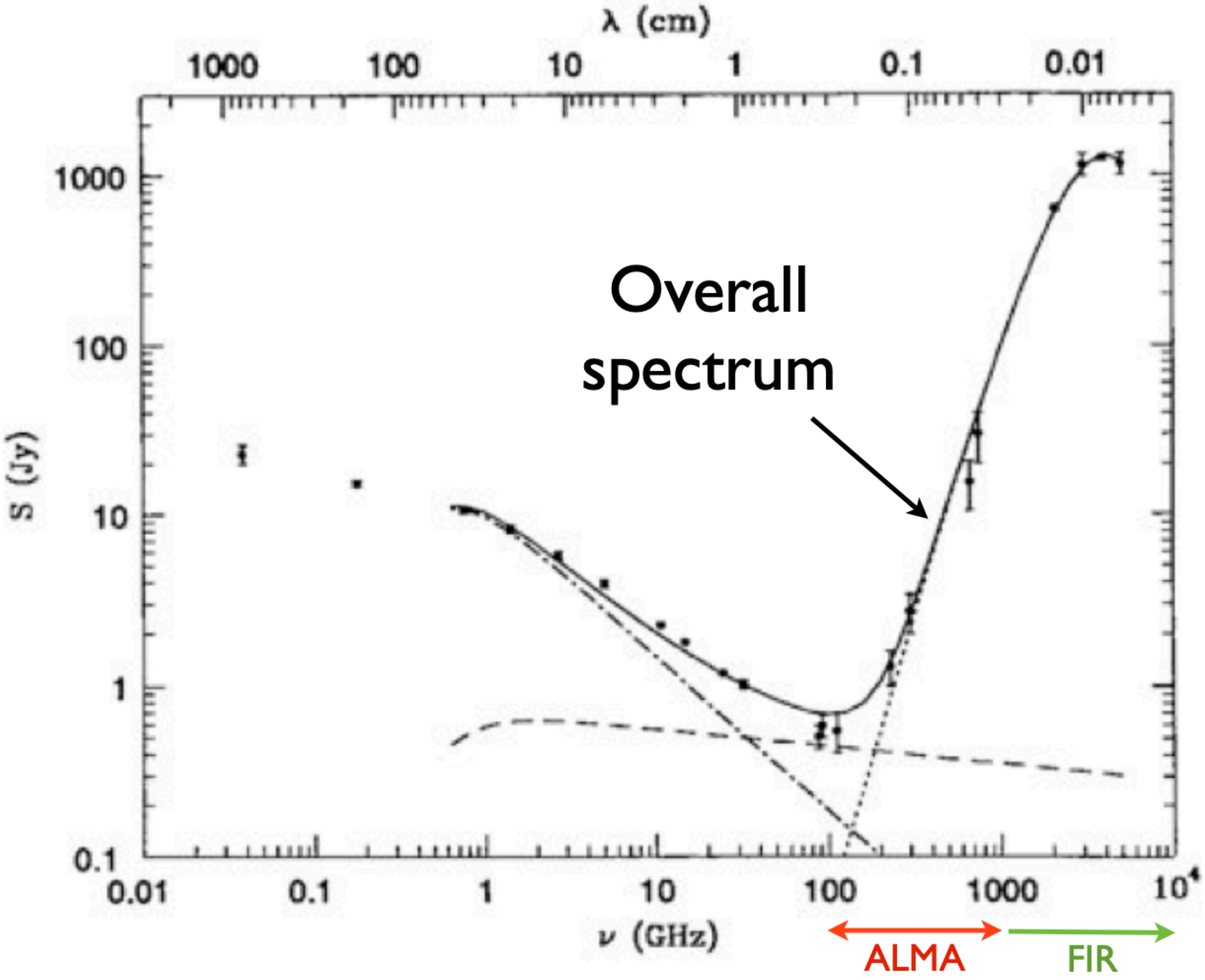
Adding up Q, U, and V quadratically get the total amplitude of linear and circular polarization combined:

$$I_{\mathrm{p}} = (Q^2 + U^2 + V^2)^{1/2}$$

Then $\mathbf{I_p / I}$ gives the total degree of polarization for an object. This is always < 1 and often << 1 (10% is pretty strongly polarized in astronomy terms).

Example: M82

Example: star-forming galaxy M82

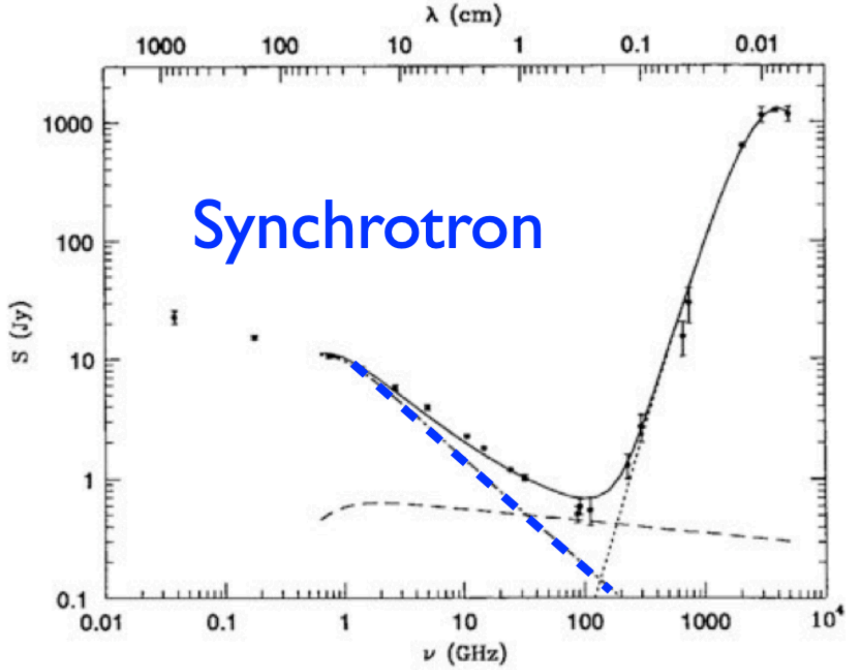


Overall spectrum

ALMA

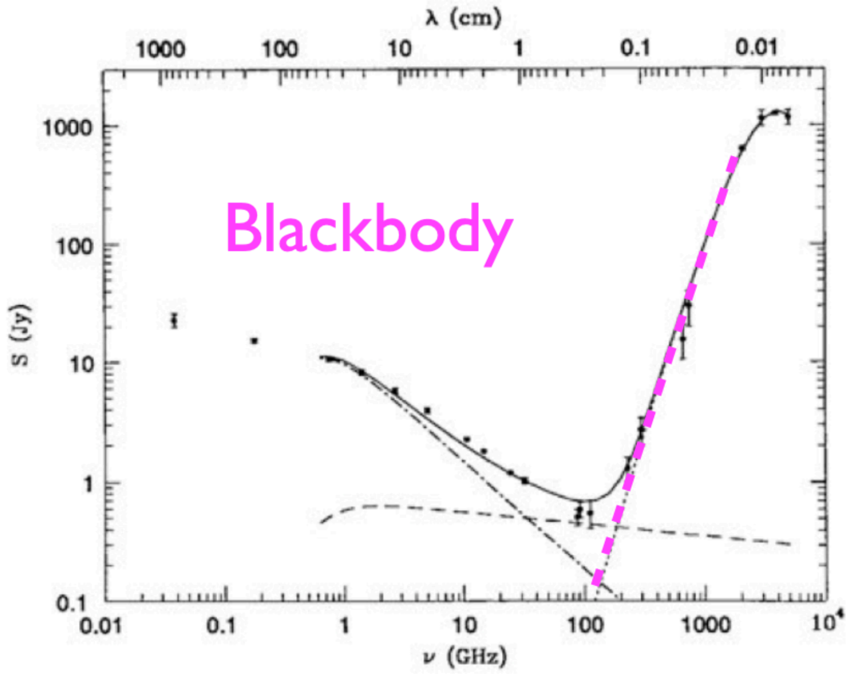
FIR

Example: star-forming galaxy M82



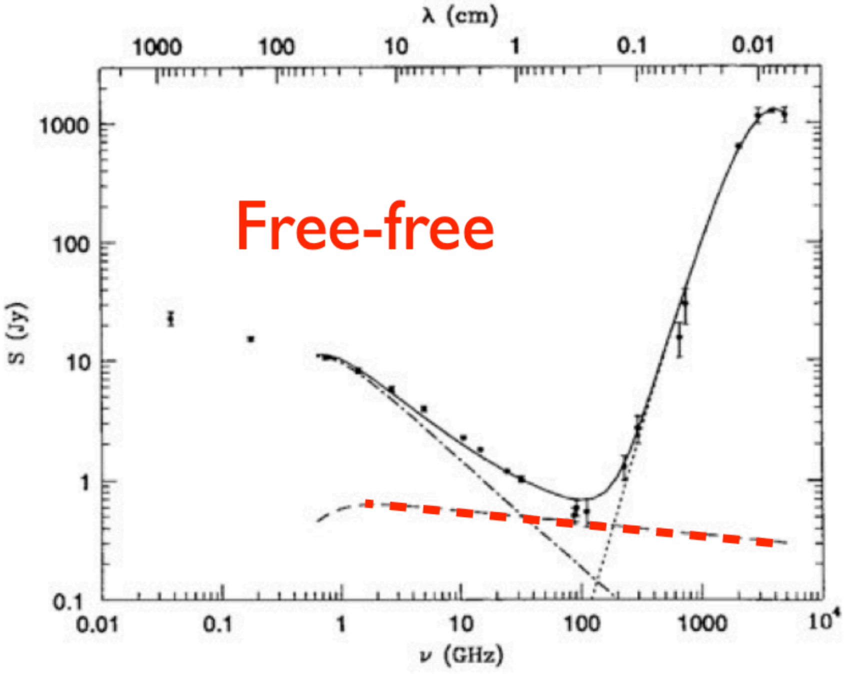
- Cosmic-ray electrons in the galaxy's magnetic field.
- SNe create the seed electrons.
- Note turnover.

Example: star-forming galaxy M82



- Dust heated by uv-photons.
- Tail in IR, but can be redshifted into the radio band.

Example: star-forming galaxy M82



- Tenuous, ionized gas.
- HII regions.