


Radio Astronomy

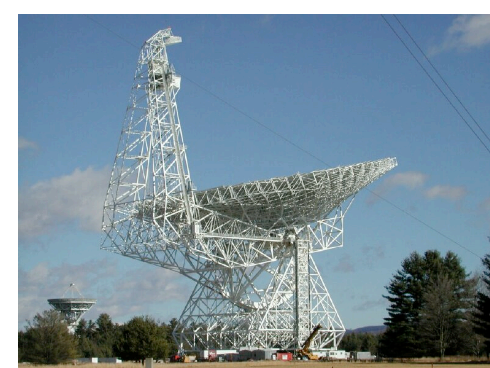
Lecture 4

Emission Mechanisms in Radio Astronomy

Lecturer: Jason Hessels (hessels@astron.nl)

B0.209 - April 11th, 2013



Emission Mechanisms in Radio Astronomy

Lecture outline

- Thermal emission processes

  Blackbody radiation, free-free emission

- Spectral line emission

  Radio-recombination lines, 21-cm line, molecular lines, MASERs

- Non-thermal emission processes

  Cyclotron emission, synchrotron emission, inverse Compton, synchrotron self-Compton, pulsar emission

- Propagation effects
- Bringing it all together

"Boson Astronomy"

Understanding the emission/absorption of electromagnetic radiation is key to astronomy... but it's not our only window on the Universe.

Boson Astronomy: Photon astronomy (Radio-Gamma), Graviton astronomy (GWs)

Pneumatic Astronomy: Acoustic waves, magnetohydrodynamic waves

Particle Astronomy: Cosmic-rays, neutrinos, meteorites

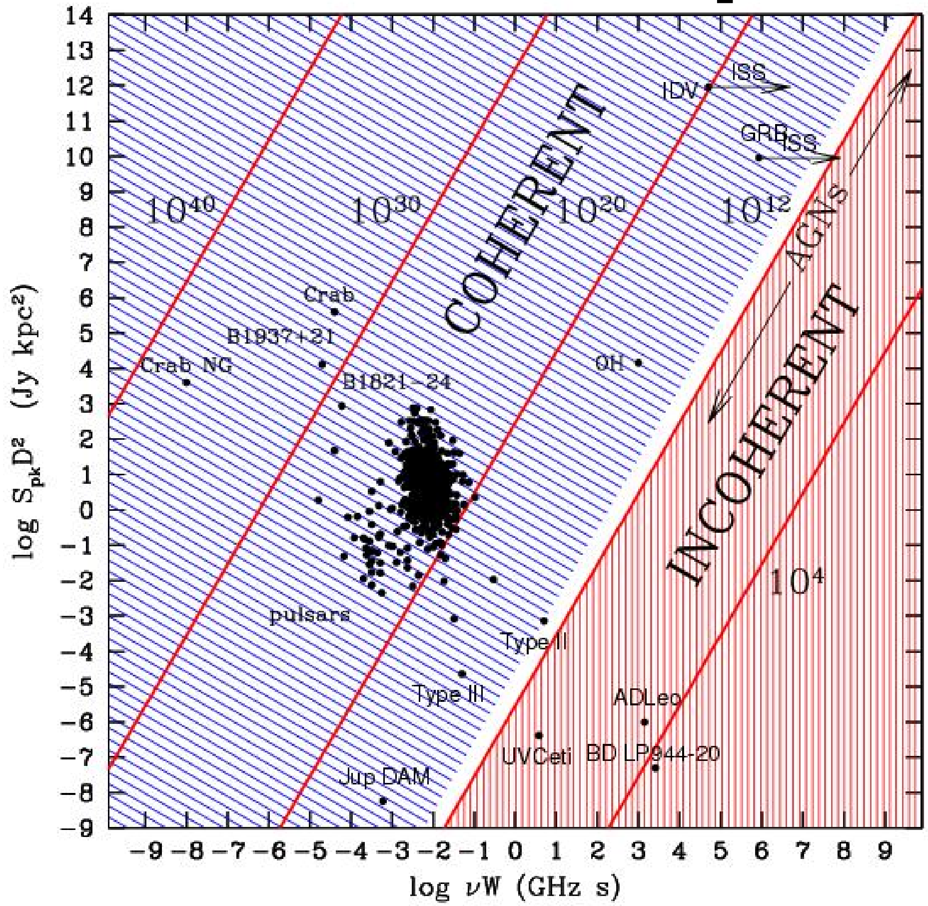
Direct Techniques: Space probes, manned exploration

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.

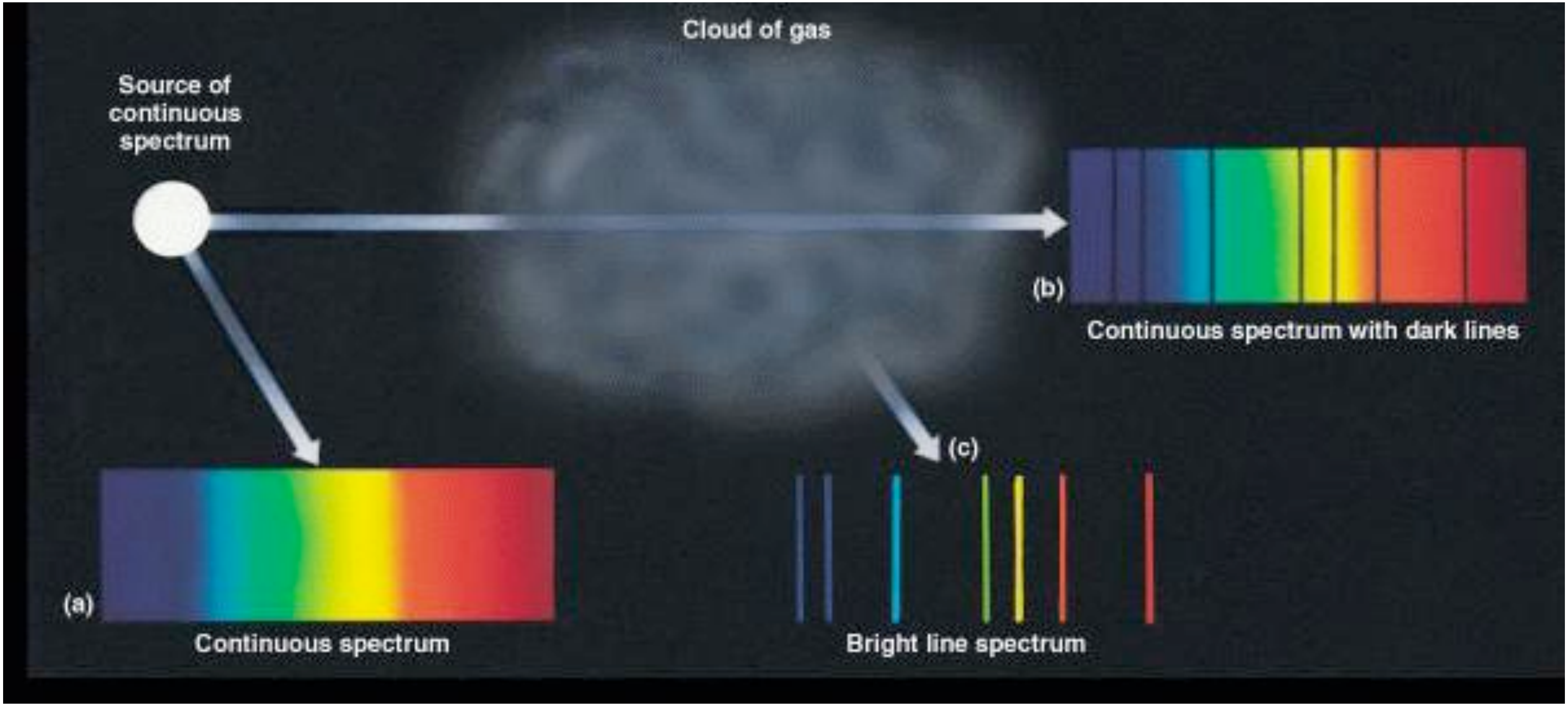
$$\lambda = \frac{c}{\nu} = \frac{hc}{E}$$

Brightness Temperature



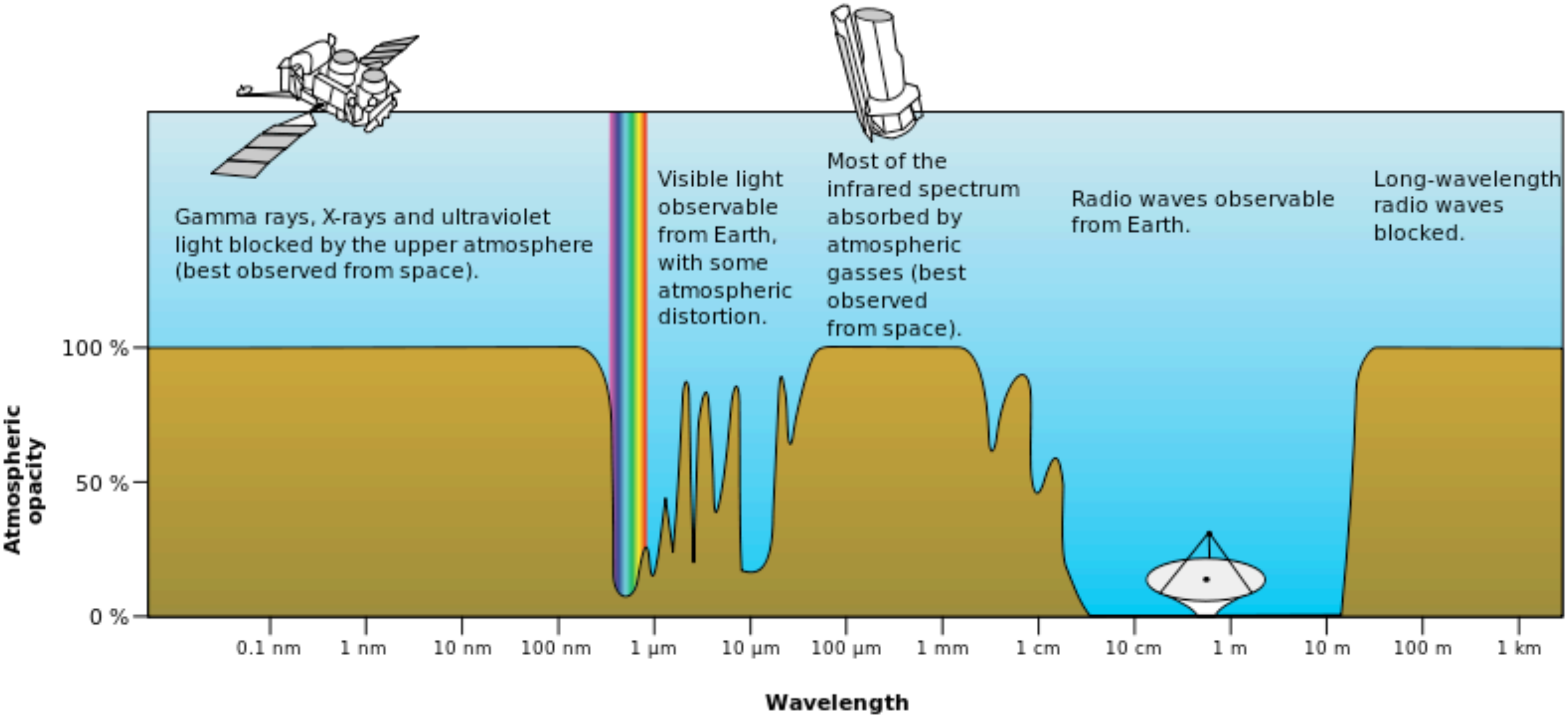
• Brightness temperature: the equivalent temperature of a blackbody emitting the same intensity.

Continuum vs. Line Emission



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

EM Spectrum

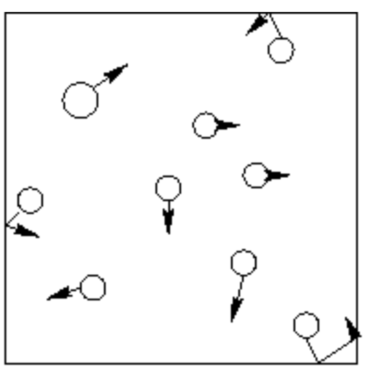


- Only optical/IR and radio pass through the atmosphere.
- Radio window: 1cm - 30m / 10MHz - 30 GHz (or more)

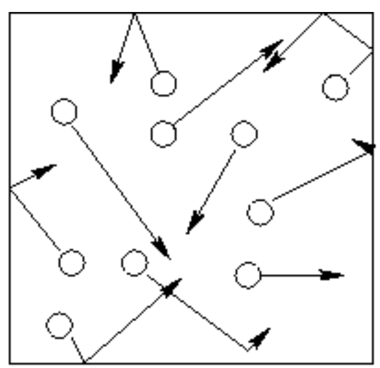
Thermal Emission Processes

Thermal Emission

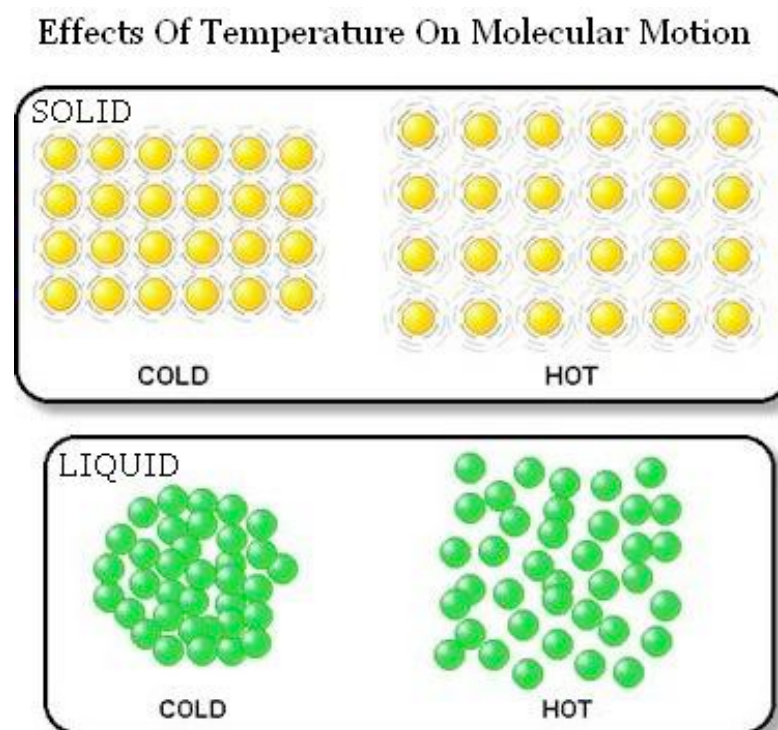
- Any object with a temperature above 0K emits thermal radiation.
- Temperature is related to particle motion.



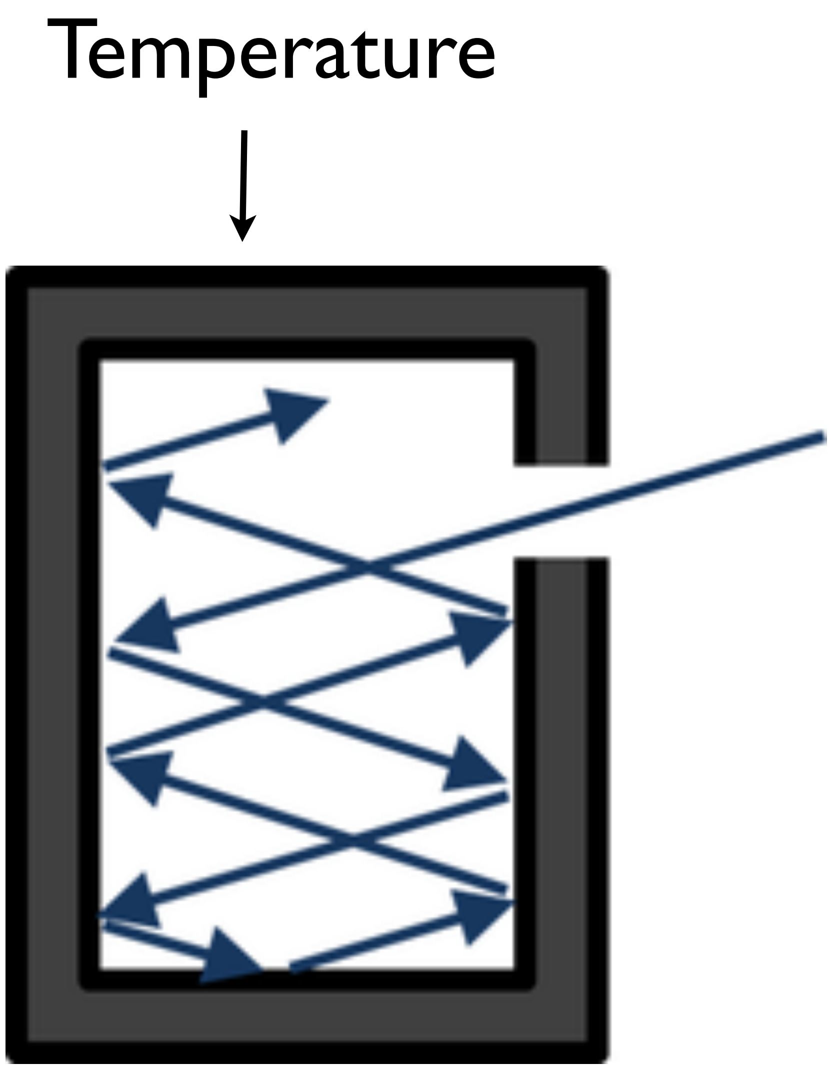
Cool gas, fewer and less energetic collisions



Hot gas, more and more energetic collision

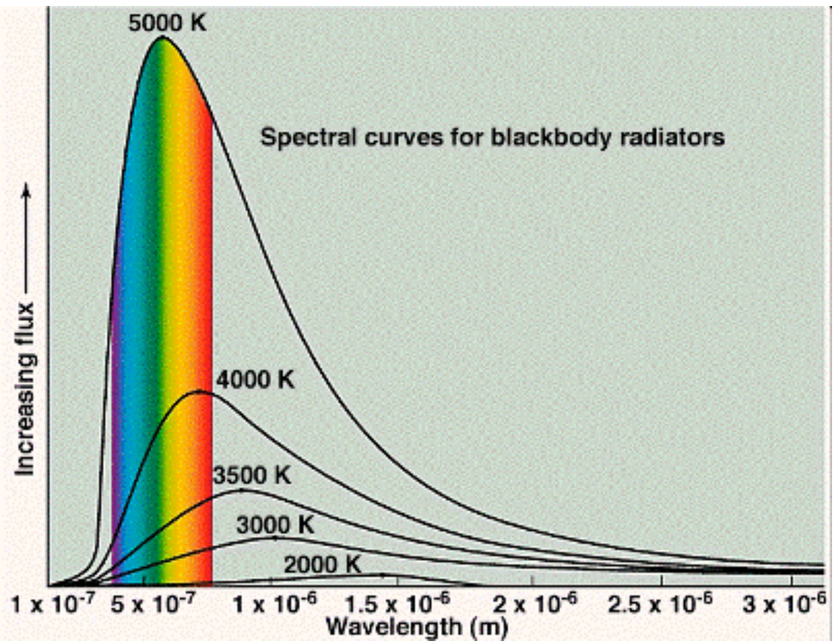


Blackbody



- A true blackbody *only absorbs* radiation and reflects none.
- Blackbody reaches a thermal equilibrium and re-radiates in the characteristic "blackbody spectrum".

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

Steffan - Boltzmann Law: $E = \sigma T^4$

$\sigma = 5.6705 \times 10^{-5}$ erg - cm^{-2} - K^{-4}- sec^{-1}

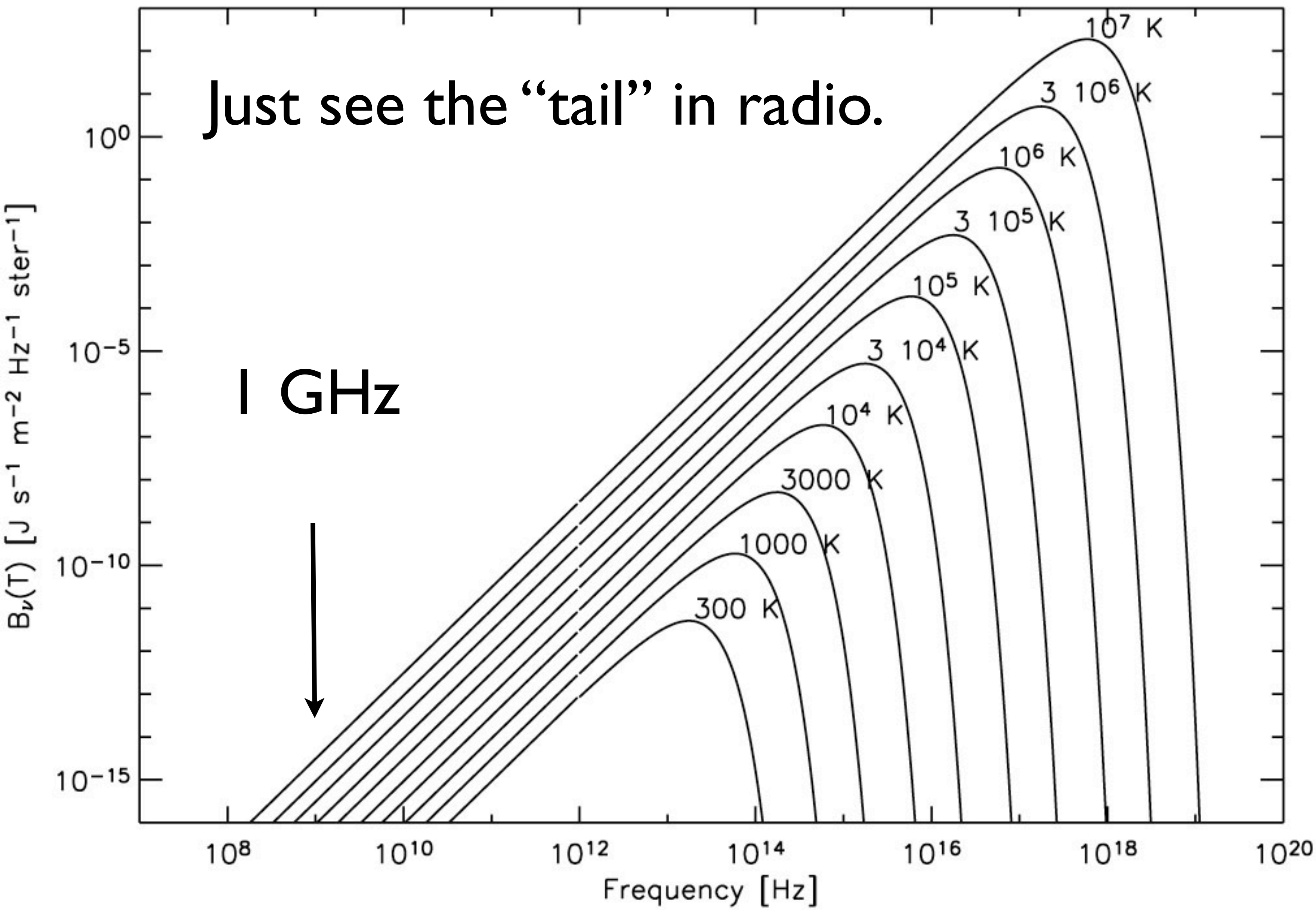
(Steffan - Boltzmann Constant)

Wien Displacement Law: $\lambda_{Max} = \dfrac{3 \times 10^{7}}{T}$

(λ in Angstroms T in Kelvin)

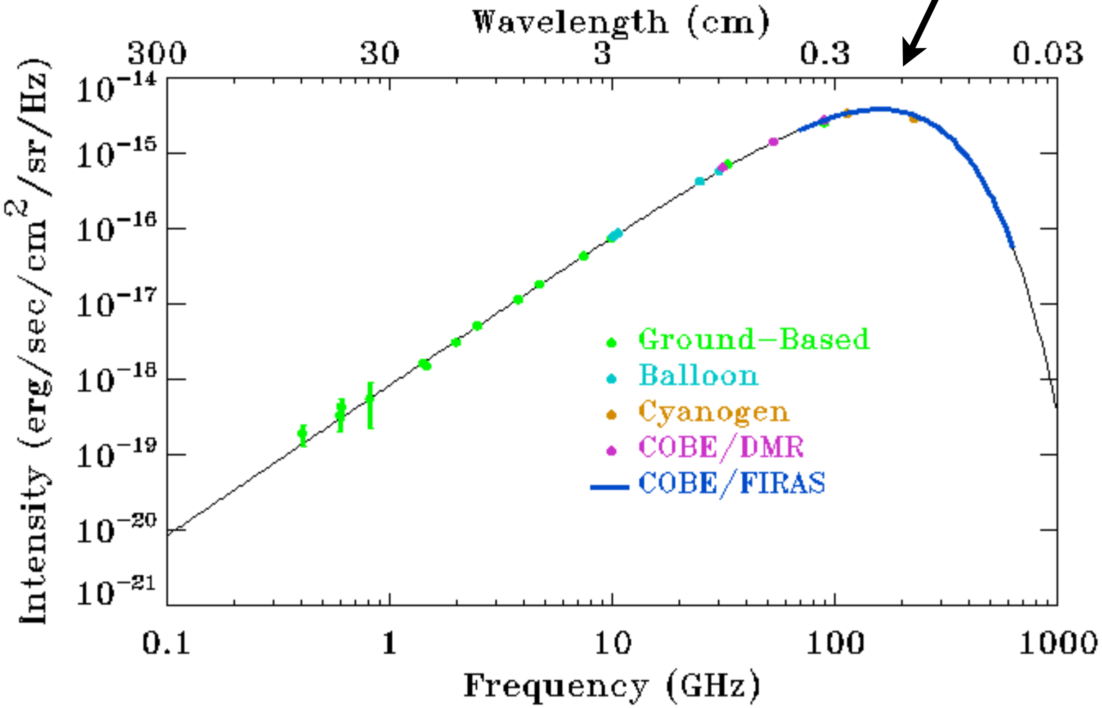
- Stefan-Boltzman Law: total emitted energy increases rapidly with temperature.
- Wien's Law: peak frequency depends on temperature.

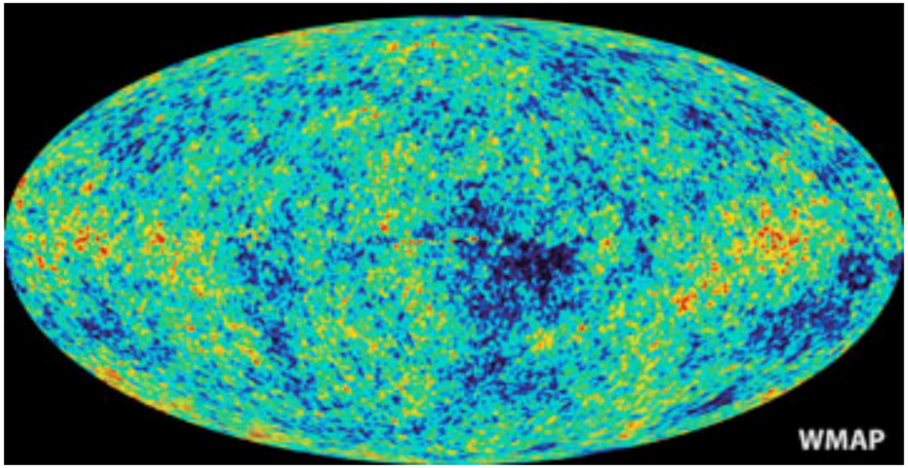
Blackbody Radiation



CMB: The Perfect Blackbody

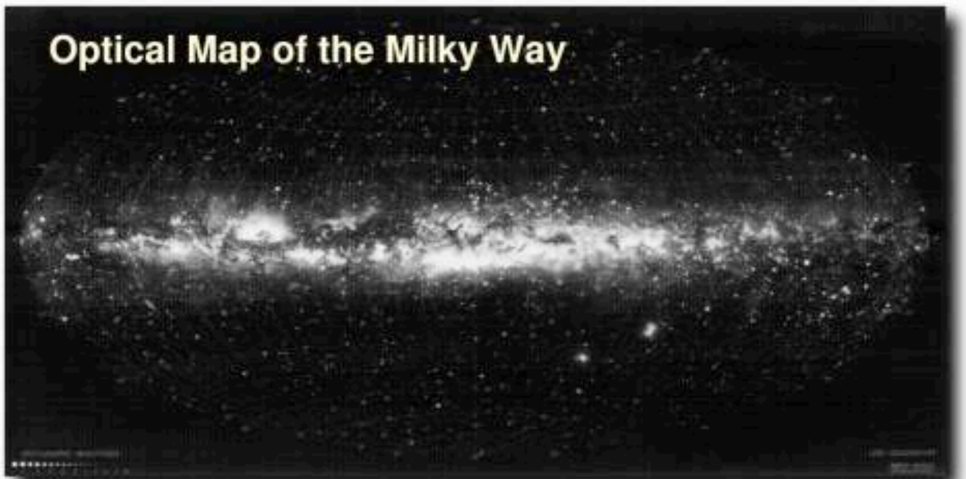
Spectrum peaks around 200GHz

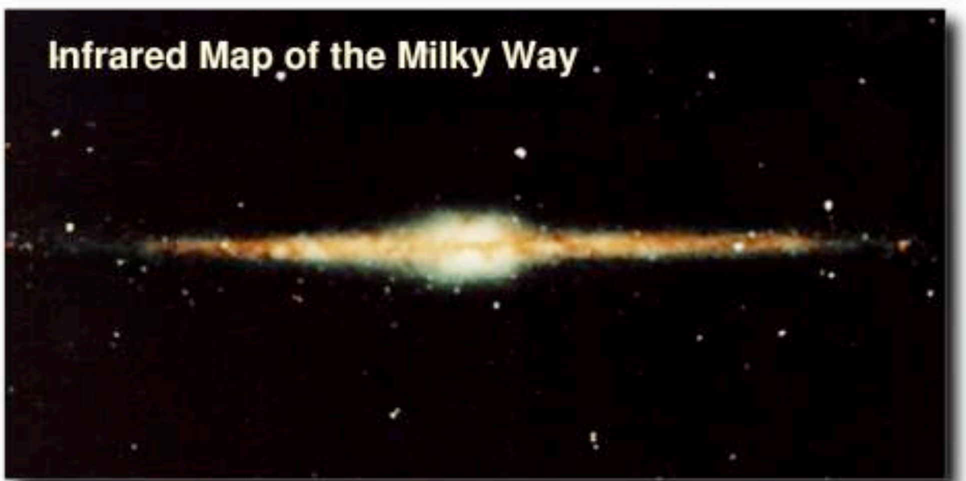




The CMBR has a thermal blackbody spectrum at a temperature of 2.72548±0.00057 K

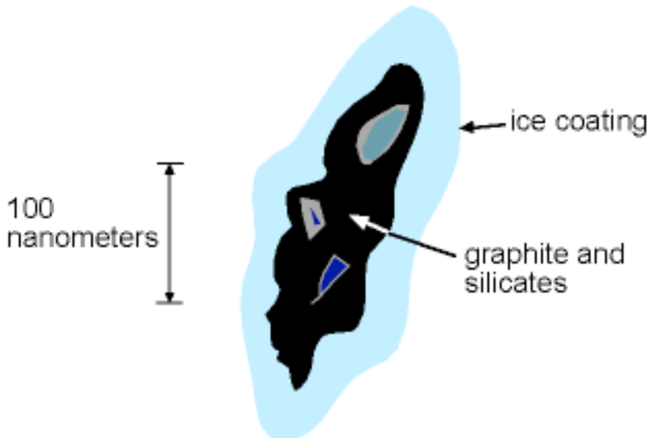
Thermal Emission from Dust



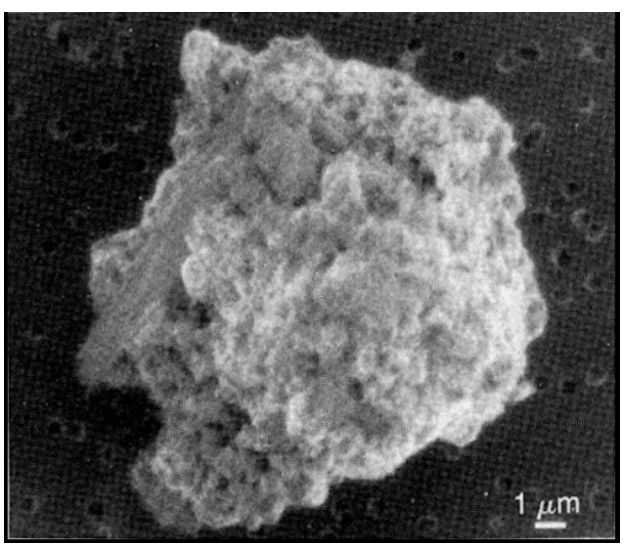


- Blackbody radio emitters are extremely cool, < 10K.
- For example, dark dust clouds in the Milky Way.
- Also dust with T ~ 50K, which is redshifted.

Thermal Emission from Dust

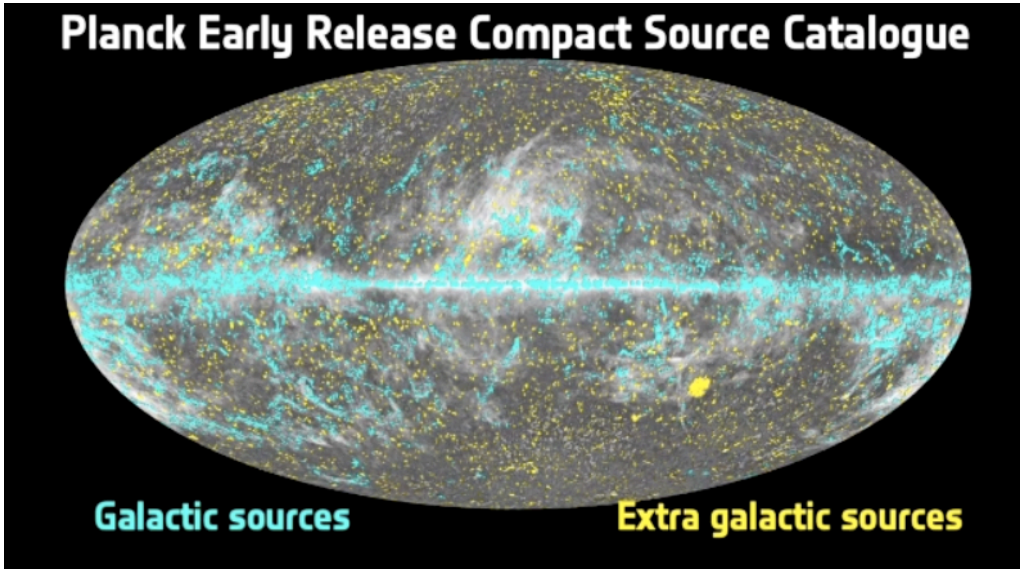


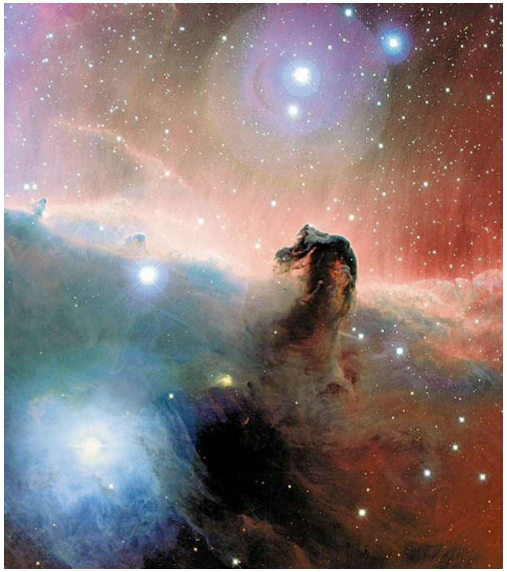
A typical dust grain (note the tiny scale!).



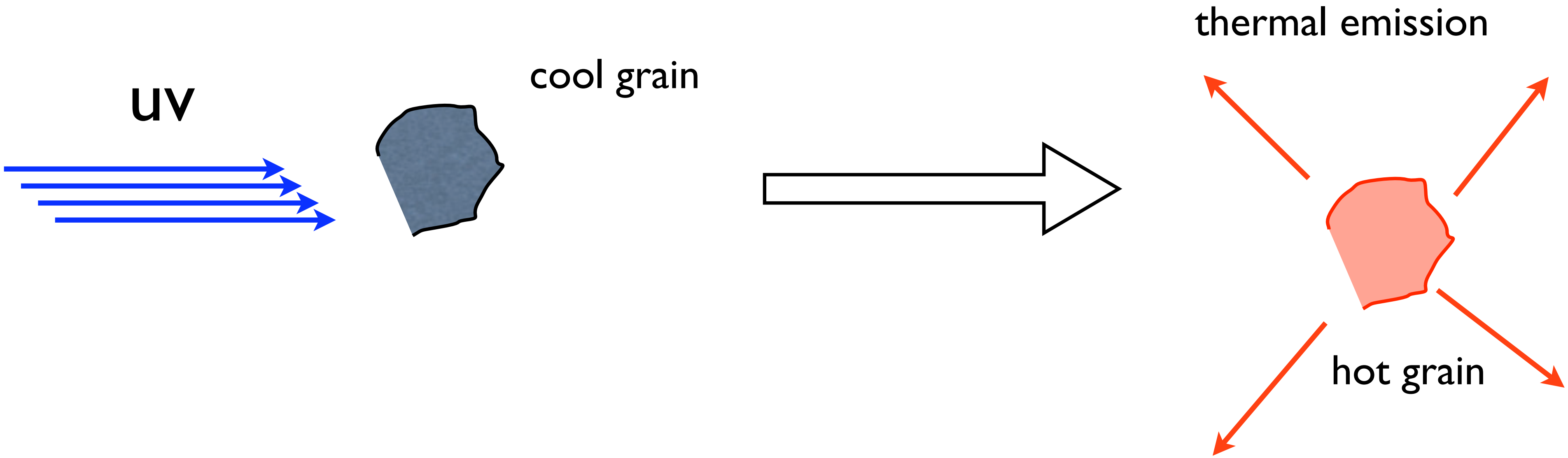
- Silicate or graphite dust grains, sometimes coated with ice.
- Average size ~0.1mm, more smaller grains, less bigger grains.
- In star-forming regions, the nebular dust can be re-heated.
- Dust radiates as a "grey body" (extra emissivity factor).

Thermal Emission from Dust

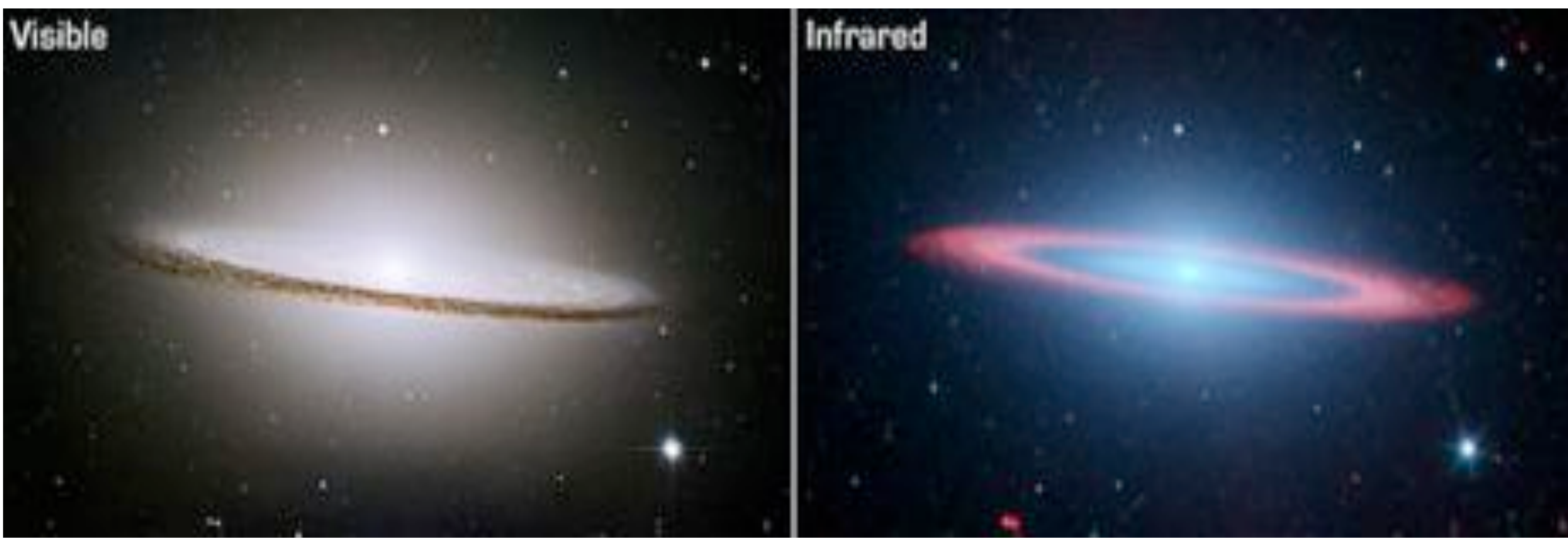




- Can find dust in H_2 (molecular) clouds, where M(dust)/M(H_2) ~ 0.01.
- Dust emission from star-forming regions in which the dust can be heated (emit above radio band).

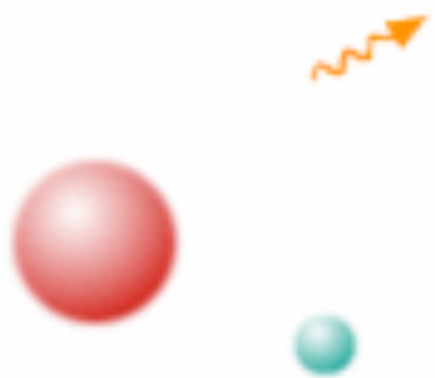


Slide from M. Garrett



Dust absorption (optical) *Dust emission (FIR)*

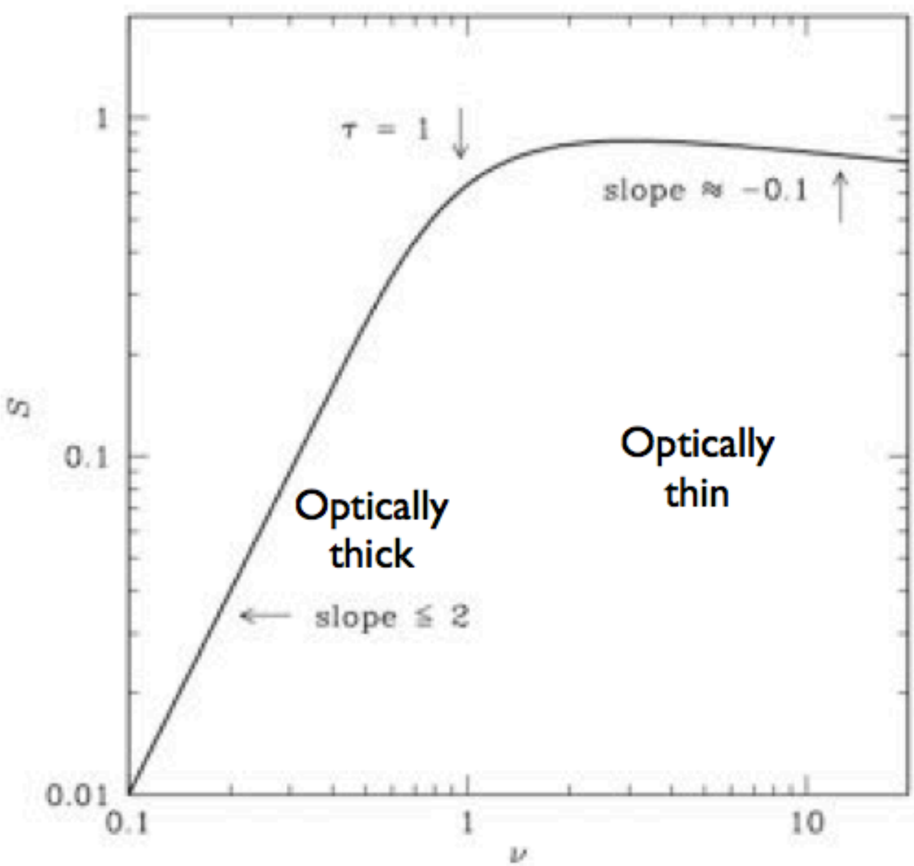
Free-Free Emission
a.k.a. thermal bremsstrahlung



Electron passing by an ion

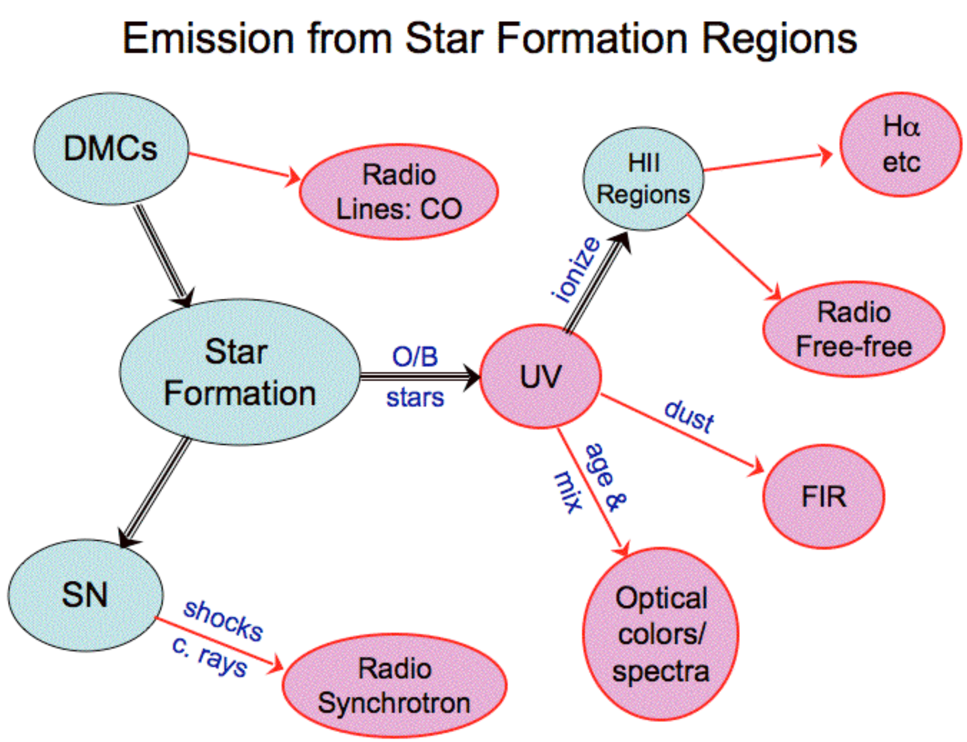
- Consider an ionized gas (plasma).
- Such a plasma emits radiation continuously.
- Much of visible Universe is a diffuse, hot (10^4K) plasma.
- Not in thermal equilibrium. Too diffuse to absorb/emit photons regularly.

Free-Free Spectrum



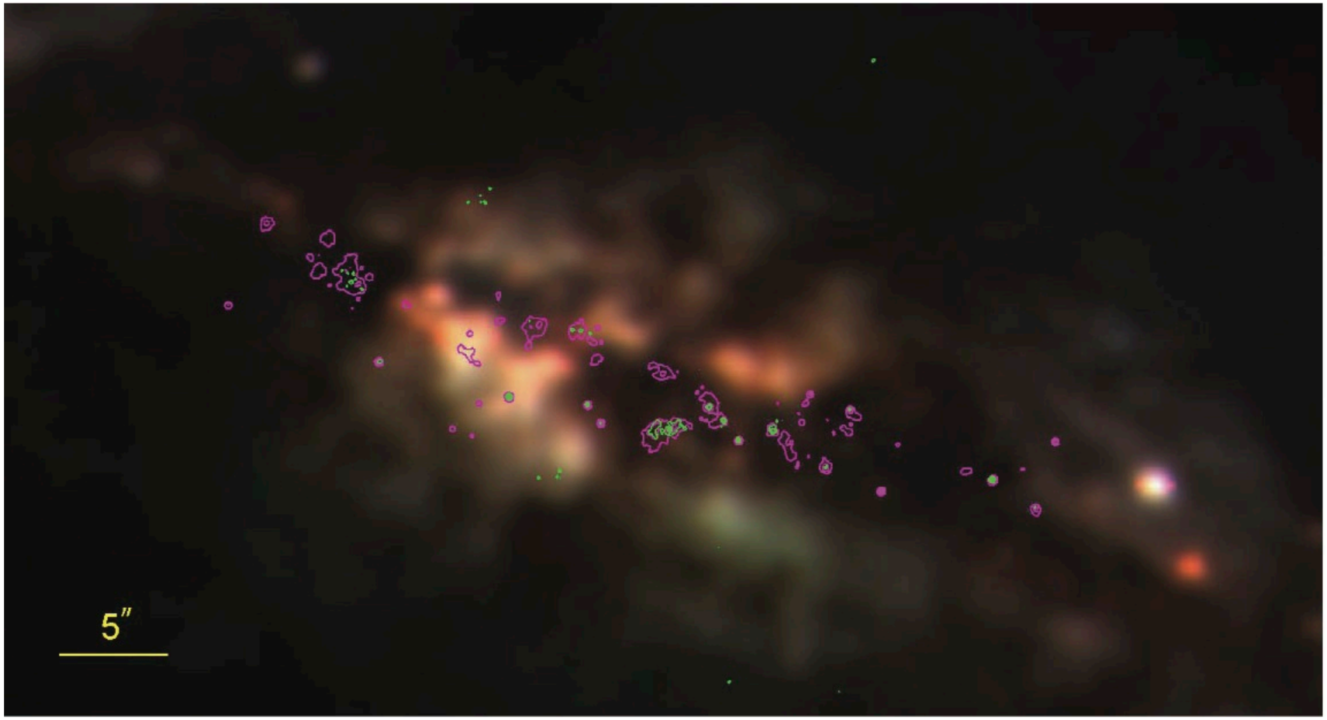
- Spectrum almost "flat" (frequency independent) in the optically thin regime.
- Spectrum approaches that of a blackbody as the optical depth increases. At low-frequencies photons cannot escape easily and undergo many absorptions and emissions.

Free-Free Emission
a.k.a. thermal bremsstrahlung



- Ionized gas around star forming region.
- Ionized gas around active galactic nuclei (AGN).

Free-Free Emission from Star-Formation Regions



M82 in radio continuum at high (~0.2") resolution. Magenta contours are 2cm emission, green contours are 7mm. Nearly all of the radio emission comes from the obscured region, shown by comparing to the false color VRI image from Spitzer SINGS, Tsai et al. 2009.

Spectral Line Emission

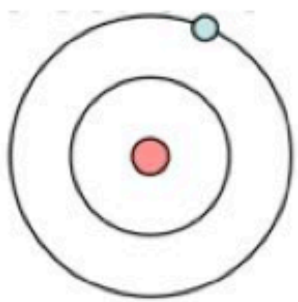
Radio Spectral Lines

Remember why emission/absorption lines are important

- Atoms and molecules have different, *quantized*, energy states.
- Measure frequency, strength, width and profile of line.
- Probe kinematic state of the emitting material.
- Probe density, temperature, and relative abundance.
- 21-cm line the most famous and most important, but there are many others.

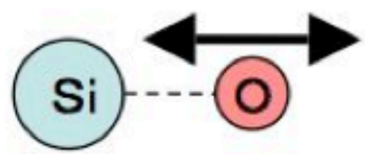
Radio Spectral Lines

Optical/UV



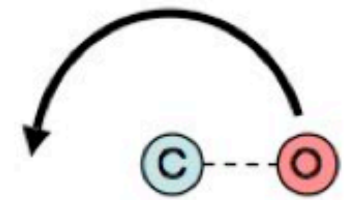
atomic
electronic transitions
(~eV)

IR



molecular
vibrational transitions
(~0.1-0.01eV)

Radio



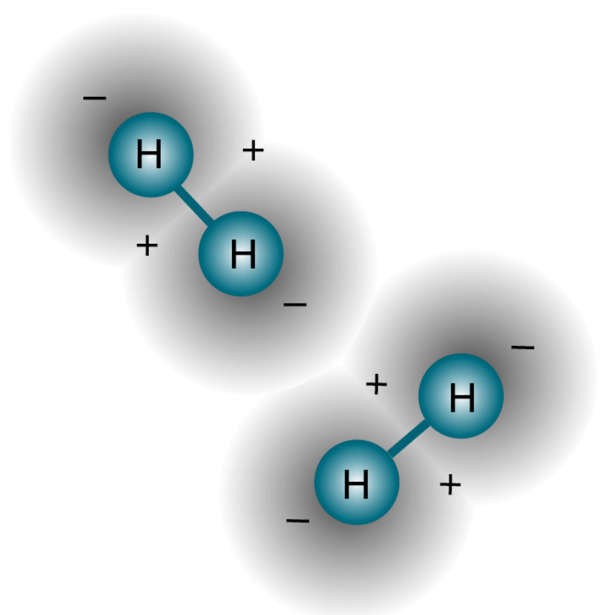
molecular
rotational transitions
~0.001eV

- Unlike optical, often dealing with molecular rotation transitions.

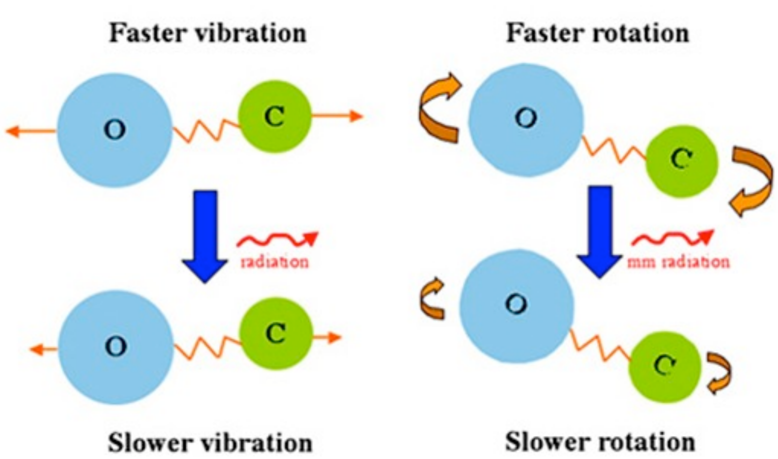
Molecular Lines

- More "complicated" than for atomic lines.
- Radio line emission results from vibrational and rotational transitions.
- About half the mass of the ISM in molecular hydrogen (H_2).
- About 1% of the cloud mass is dust, which causes extinction.
- Cloud temperatures typically 10-20K, with densities $n(H_2) \sim 10^4 cm^{-3}$.

Tracing Molecular Hydrogen



- Molecular hydrogen (H_2) is hard to detect because it has no dipole moment.
- CO (carbon monoxide) is the second most abundant molecule and can be used as a tracer for H_2.
- The ratio between CO luminosity and H_2 mass is $\sim 10^5$.



The frequency of the emitted photon is:

$$\nu = \Delta E_{rot}/h = (h/4\pi)\, J/I$$

For any reasonable numbers ν lies in the mm and sub-mm domain e.g. J=1 to 0 => ν=115.2712 GHz.

Other CO tranasitions: 115, 230, 346, 461, 576, 691, …GHz

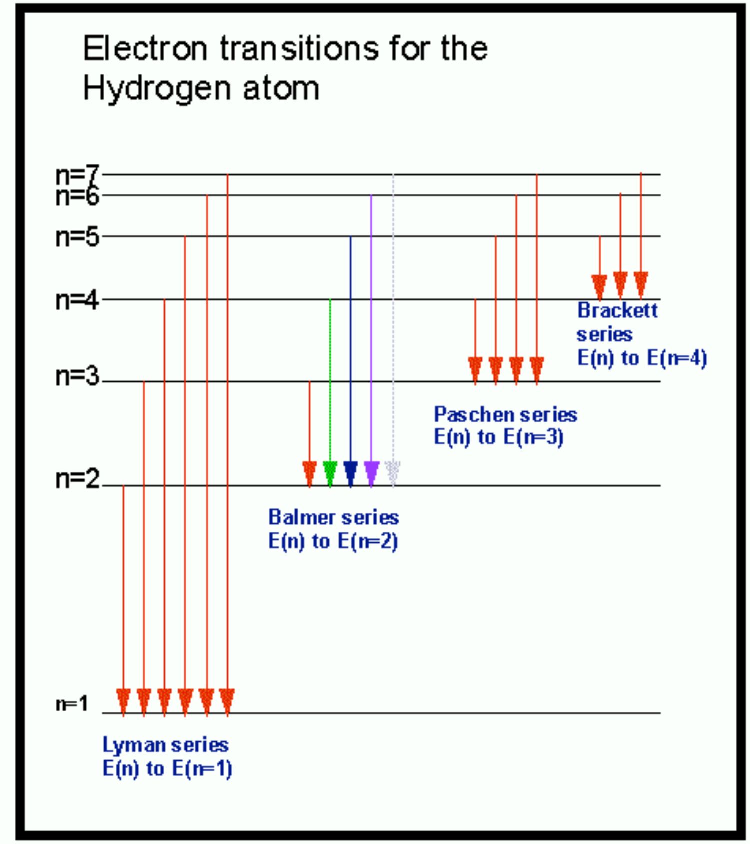
Radio Recombination Lines

$\nu = 3.3E15\,(1/m^2 - 1/n^2)$ (in Hz)

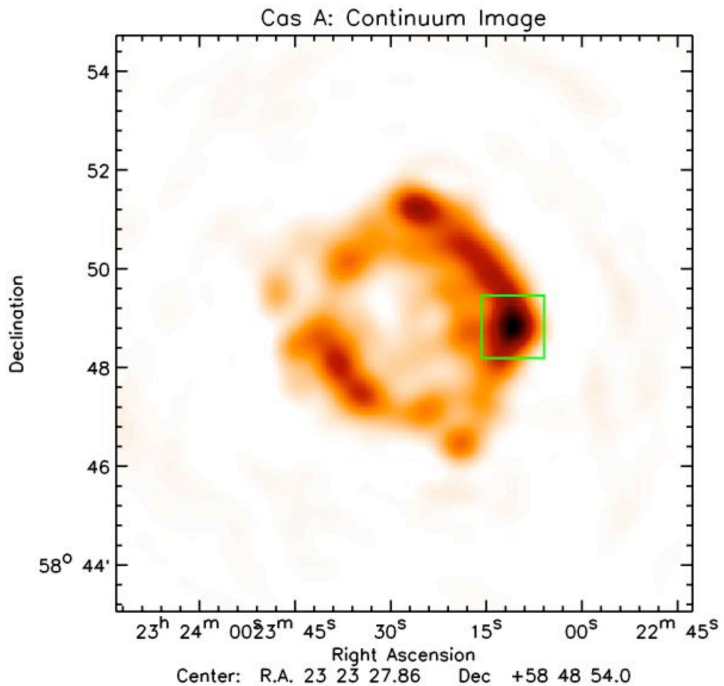
Hydrogen atom

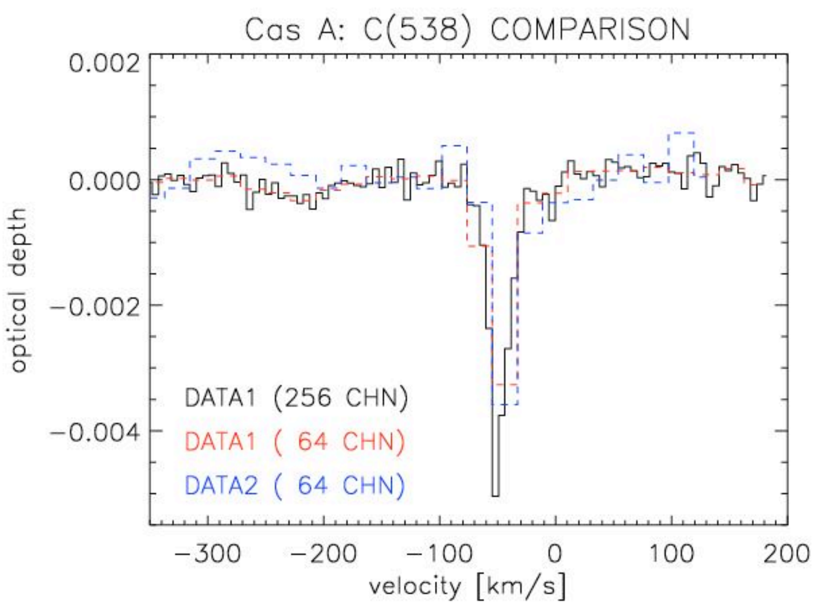
H600alpha: 30MHz
H109alpha: 5GHz
H40alpha: 100GHz

Recall alpha is delta(n) = 1
beta is delta(n) = 2



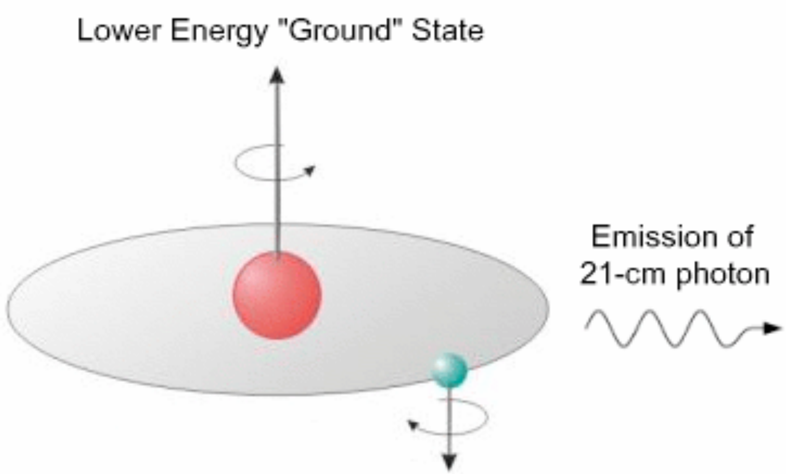
Radio Recombination Lines





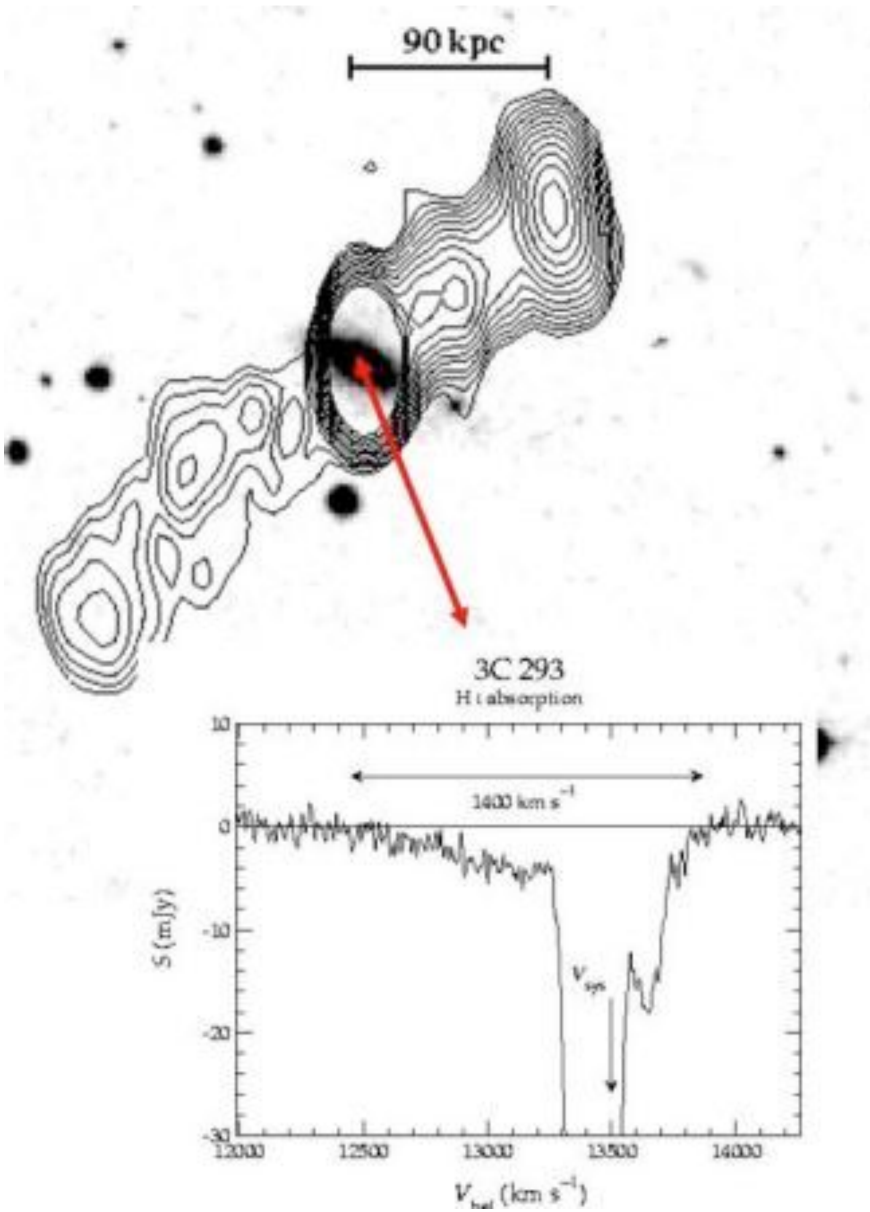
- Only radio lines that *are* due to electronic transitions.
- Quantum numbers need to be very high (> 100).
- HII can show RRLs from electrons cascading down into the ground state.
- *Weak and hard to detect:* only 0.1-1% of the continuum.
- Emerging area for LOFAR.

21-cm Line of Hydrogen



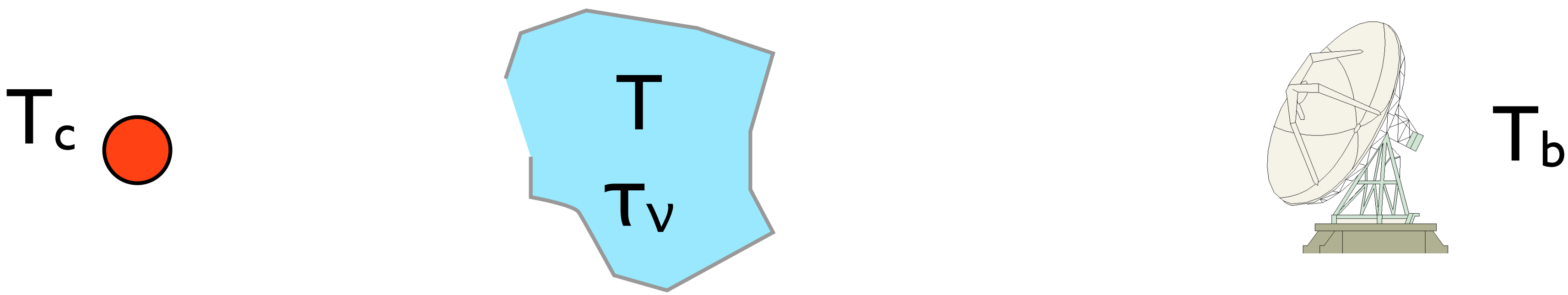
- Recall: hyperfine structure in hydrogen.
- Undoubtedly the most important line for radio astronomy.
- Think of protons and electrons as spinning distributions of charge each creating a magnetic field (i.e. "spin").
- Chance of Hydrogen randomly flipping its spin configuration is very low (spontaneous flipping once in ~11 million years).
- HI emission is collisionally induced (in ISM, typical timescale of ~200 years).

21-cm Line Absorption



- Depends on temperature of background continuum source and the intervening H1 cloud.

21-cm Line Absorption



$$T_b(\nu) = T_c\, e^{-\tau_\nu} + T(1-e^{-\tau_\nu})$$

The excess brightness temperature from the cloud is:

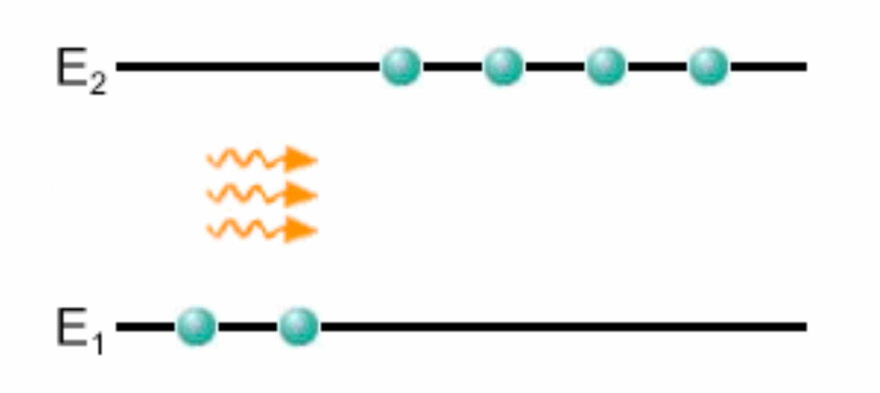
$$\Delta T_b(\nu) = T_b(\nu) - T_c = e^{-\tau_\nu} + T(1-e^{-\tau_\nu}) = (T-T_c)(1-e^{-\tau_\nu})$$

or $\Delta T_b(\nu) = T - T_c \quad (\tau_\nu >> 1)$ and $\Delta T_b(\nu) = (T-T_c)\,\tau_\nu \quad (\tau_\nu << 1)$

If $T > T_c$ ==> emission line; if $T < T_c$ ==> absorption line

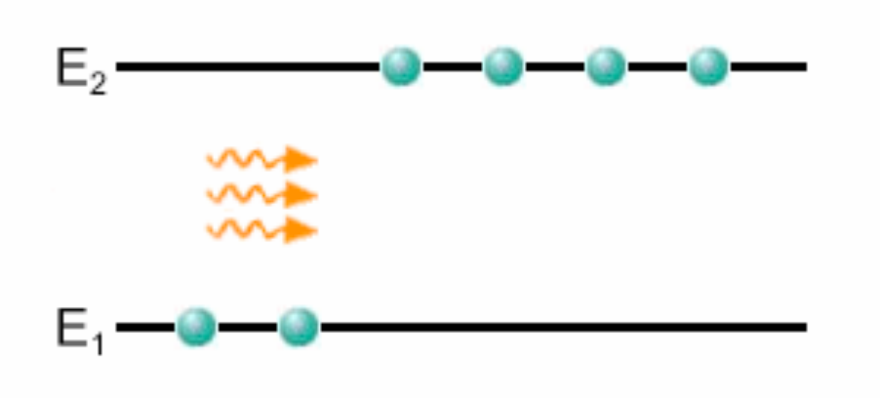
MASER Emission

MASER: "Microwave Amplification by Stimulated Emission of Radiation"



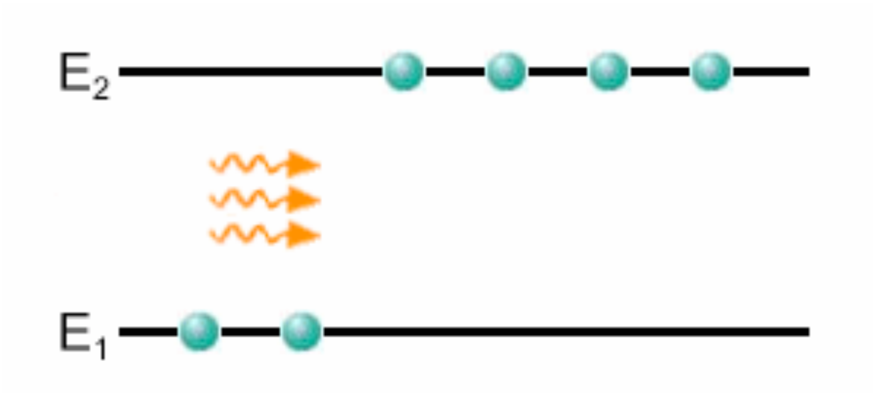
- A "radio LASER".
- Associated with molecules.
- Ensemble of molecules pumped to a higher-energy state (population inversion, E_2 not too different than E_1).
- Requires an energy source to pump the molecules.

MASER Emission



- Naturally occur in molecular clouds and the envelopes of old stars.
- Often associated with star-forming regions.
- Common lines from Hydroxyl (OH), silicon oxide (SiO), water (H_20), methanol (CH_3OH), ammonia (NH_3), and formaldehyde (H_2CO).

MASER Emission



- MASERs show:
- Month-year variability.
- Narrow line widths (< 1km/s).
- High brightness temperatures (10^{10}K).
- Are compact.
- Polarization.

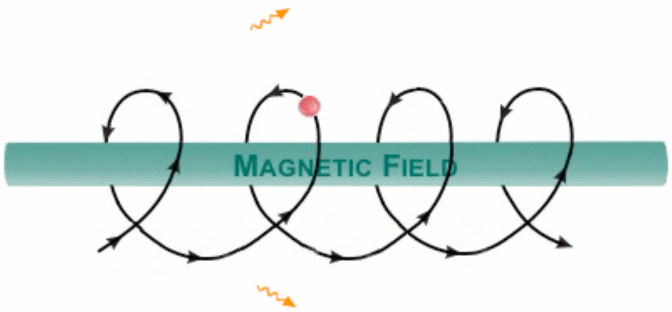
List of important radio spectral lines (< 1 THz)

1. Deuterium (DI) 327.384 MHz
2. Hydrogen (HI) 1420.406 MHz
3. Hydroxyl radical (OH) 1612.231 MHz
4. Hydroxyl radical (OH) 1665.402 MHz
5. Hydroxyl radical (OH) 1667.359 MHz
6. Hydroxyl radical (OH) 1720.530 MHz
7. Methyladyne (CH) 3263.794 MHz
8. Methyladyne (CH) 3335.481 MHz
9. Methyladyne (CH) 3349.193 MH
10. Formaldehyde (H2CO) 4829.660 MHz
11. Methanol (CH2OH) 6668.518 MHz
12. Ionized Helium Isotope (3HeII) 8665.650 MHz
13. Methanol (CH3OH) 12.178 GHz
14. Formaldehyde (H2CO) 14.488 GHz
15. Cyclopropenylidene (C3H2) 18.343 GHz
16. Water Vapour (H2O) 22.235 GHz
17. Ammonia (NH3) 23.694 GHz
18. Ammonia (NH3) 23.723 GHz
19. Ammonia (NH3) 23.870 GHz
20. Silicon monoxide (SiO) 42.519 GHz
21. Silicon monoxide (SiO) 42.821 GHz
22. Silicon monoxide (SiO) 42.880 GHz
23. Silicon monoxide (SiO) 43.122 GHz
24. Silicon monoxide (SiO) 43.424 GHz
25. Carbon monosulphide (CS) 48.991 GHz
26. Deuterated formylium (DCO+) 72.039 GHz
27. Silicon monoxide (SiO) 86.243 GHz
28. Formylium (H13CO+) 86.754 GHz
29. Silicon monoxide (SiO) 86.847 GHz
30. Ethynyl radical (C2H) 87.300 GHz
31. Hydrogen cyanide (HCN) 88.632 GHz
32. Formylium (HCO+) 89.189 GHz
33. Hydrogen isocyanide (HNC) 90.664 GHz
34. Diazenylium (N2H) 93.174 GHz
35. Carbon monosulphide (CS) 97.981 GHz
36. Carbon monoxide (C18O) 109.782 GHz
37. Carbon monoxide (13CO) 110.201 GHz

41. Carbon monoxide (C17O) 112.359 GHz
42. Carbon monoxide (CO) 115.271 GHz
43. Formaldehyde (H213CO) 137.450 GHz
44. Formaldehyde (H2CO) 140.840 GHz
45. Carbon monosulphide (CS) 146.969 GHz
46. Water vapour (H2O) 183.310 GHz
47. Carbon monoxide (C18O) 219.560 GHz
48. Carbon monoxide (13CO) 220.399 GHz
49. Carbon monoxide (CO) 230.538 GHz
50. Carbon monosulphide (CS) 244.953 GHz
51. Hydrogen cyanide (HCN) 265.886 GHz
52. Formylium (HCO+) 267.557 GHz
53. Hydrogen isocyanide (HNC) 271.981 GHz
54. Dyazenulium (N2H+) 279.511 GHz
55. Carbon monoxide (C18O) 312.330 GHz
56. Carbon monoxide (13CO) 330.587 GHz
57. Carbon monosulphide (CS) 342.883 GHz
58. Carbon monoxide (CO) 345.796 GHz
59. Hydrogen cyanide (HCN) 354.484 GHz
60. Formylium (HCO+) 356.734 GHz
61. Dyazenulium (N2H+) 372.672 GHz
62. Water vapour (H2O) 380.197 GHz
63. Carbon monoxide (C18O) 439.088 GHz
64. Carbon monoxide (13CO) 440.765 GHz
65. Carbon monoxide (CO) 461.041 GHz
66. Heavy water (HDO) 464.925 GHz
67. Carbon (CI) 492.162 GHz
68. Water vapour (H218O) 547.676 GHz
69. Water vapour (H2O) 556.936 GHz
70. Ammonia (15NH3) 572.113 GHz
71. Ammonia (NH3) 572.498 GHz
72. Carbon monoxide (CO) 691.473 GHz
73. Hydrogen cyanide (HCN) 797.433 GHz
74. Formylium (HCO+) 802.653 GHz
75. Carbon monoxide (CO) 806.652 GHz
76. Carbon (CI) 809.350 GHz

Non-thermal Emission Processes

Non-thermal Emission



- Emission increases towards longer wavelengths.
- Synchrotron is the most common mechanism.
- Electrons (typically) accelerated by magnetic field.
- First identified in the 1940s as an interfering signal in particle accelerators.

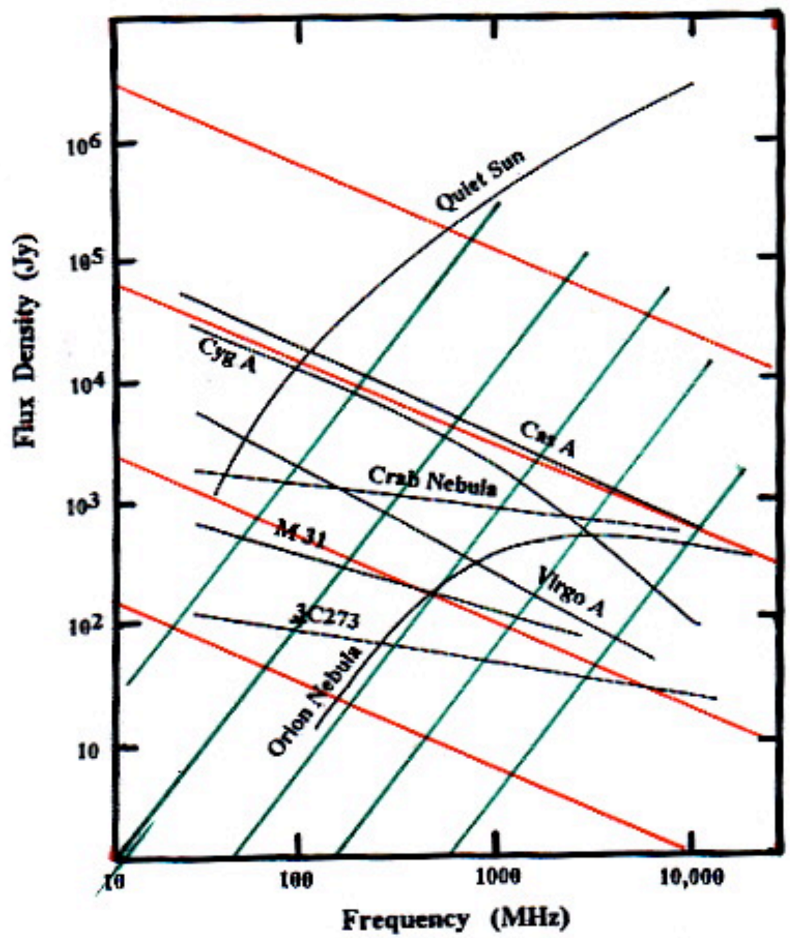
Grote Reber

(1911-2002)

- Mystery of low-energy (non-thermal, synchrotron) emission.
- Also the beginning of high-energy astrophysics.

Thermal / non-thermal

$S \propto \nu^{-0.8}$ (synchrotron with $N(E) \propto E^{-2.6}$)



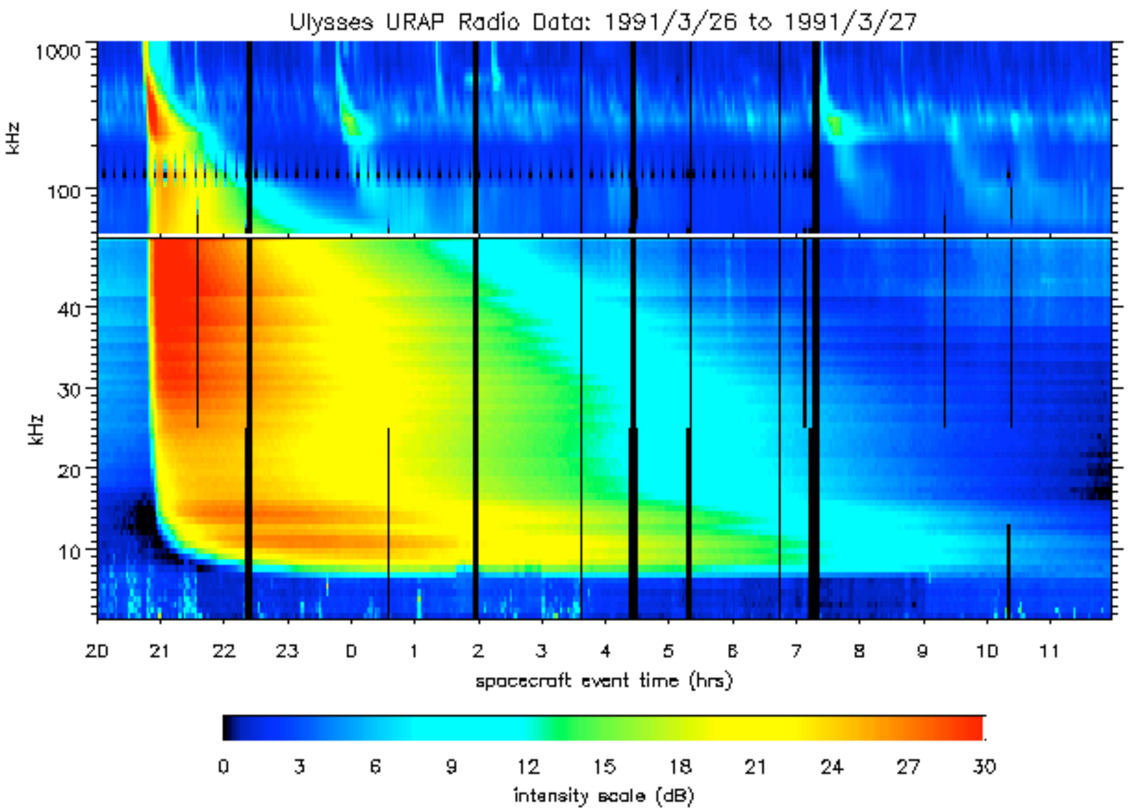
$S \propto \nu^2$ (blackbody)

Cyclotron Emission

Derive
Cyclotron frequency

- Non-relativistic case of an electron spiraling along magnetic field lines.
- ISM typically has B = microGauss fields.
- Cyclotron (gyro) frequency of ~3Hz in ISM (not observable radio emission).

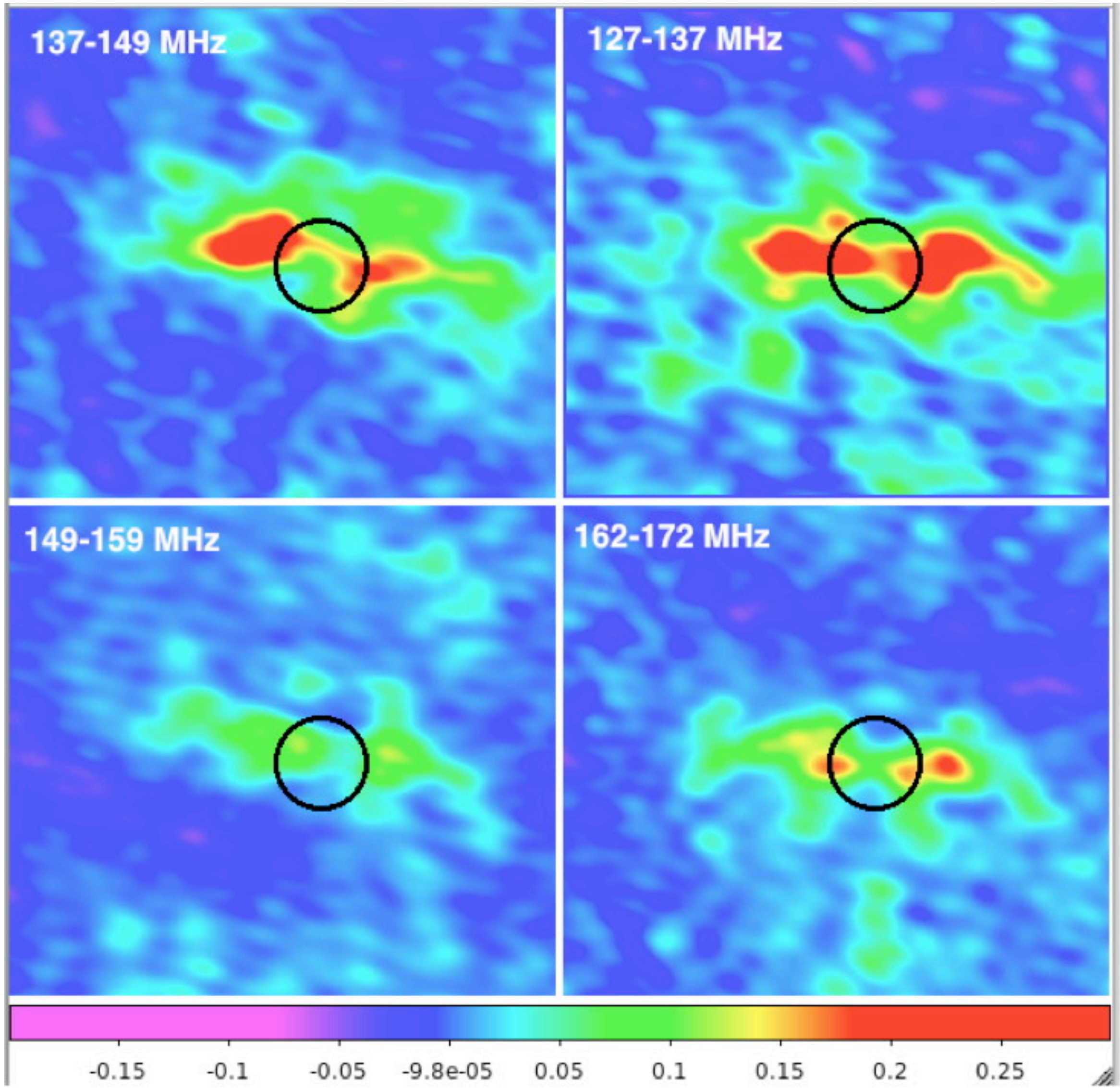
Cyclotron Emission



Sun (below 1MHz)

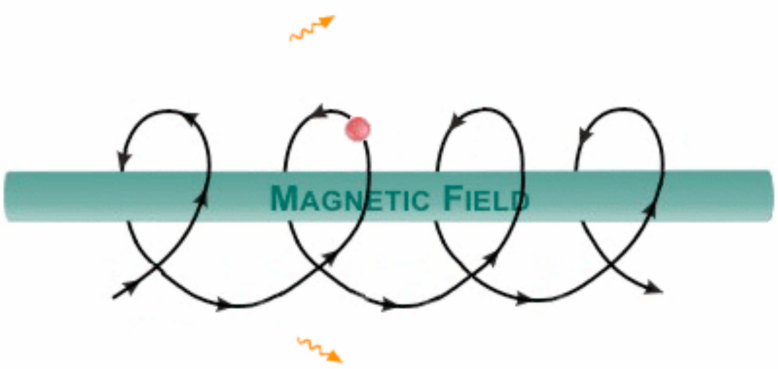
- Higher B-field in Earth (~1G), Sun (~300G), Jupiter and Saturn.
- Magnetic stars.
- *Much* higher B-fields in white dwarfs (10^6G) and neutron stars (10^{8-15}G).

Cyclotron Emission



- Jupiter radiation belt with LOFAR.

Synchrotron Emission



$$m = \gamma m_e$$

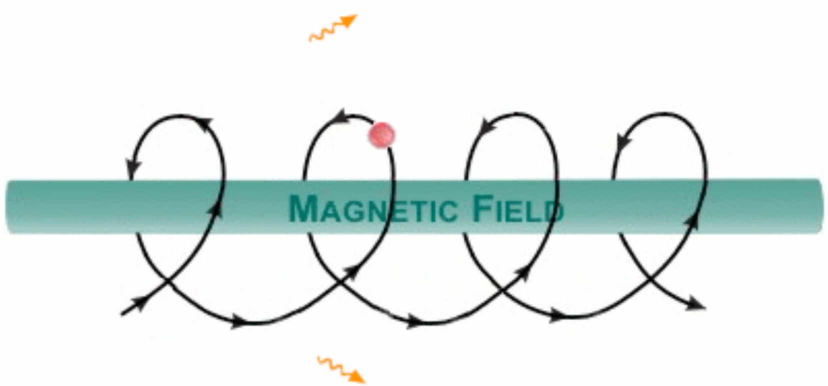
where $\gamma = (1-(v/c)^2)^{-1/2}$

- 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 (cyclotron radiation typically not detectable).

Synchrotron Emission

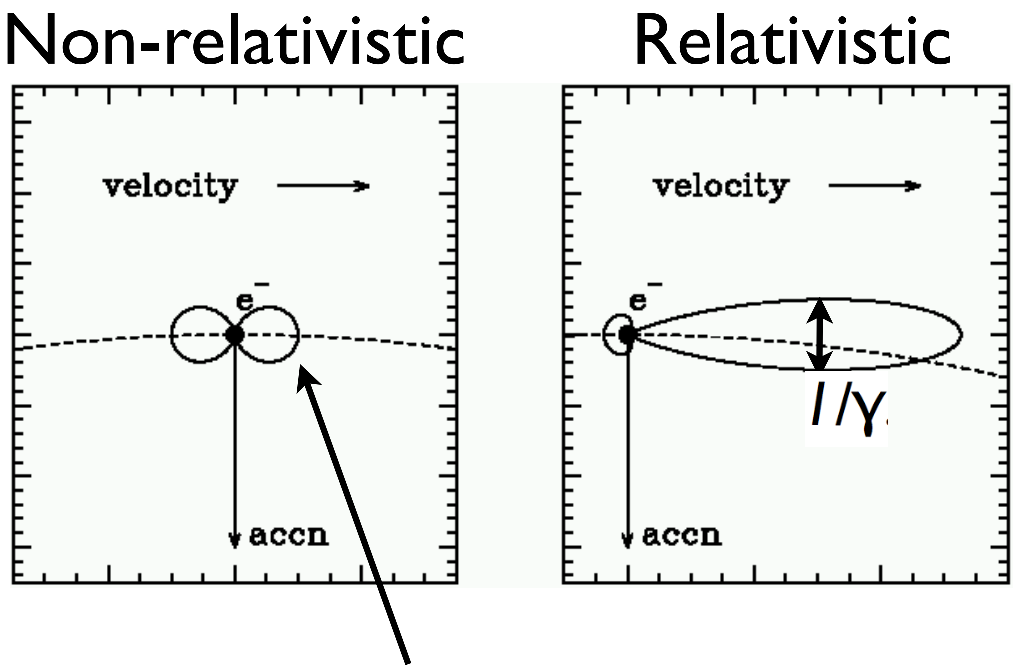
- Relativistic particles mean that the emitted energy does not depend purely on the B-field (see Cyclotron emission) but also on the energy of the particles (electrons) themselves, b.c. relativistic mass.
- Power-law spectrum.
- Spectrum describes the energy distribution of the seed electrons.

Synchrotron Emission



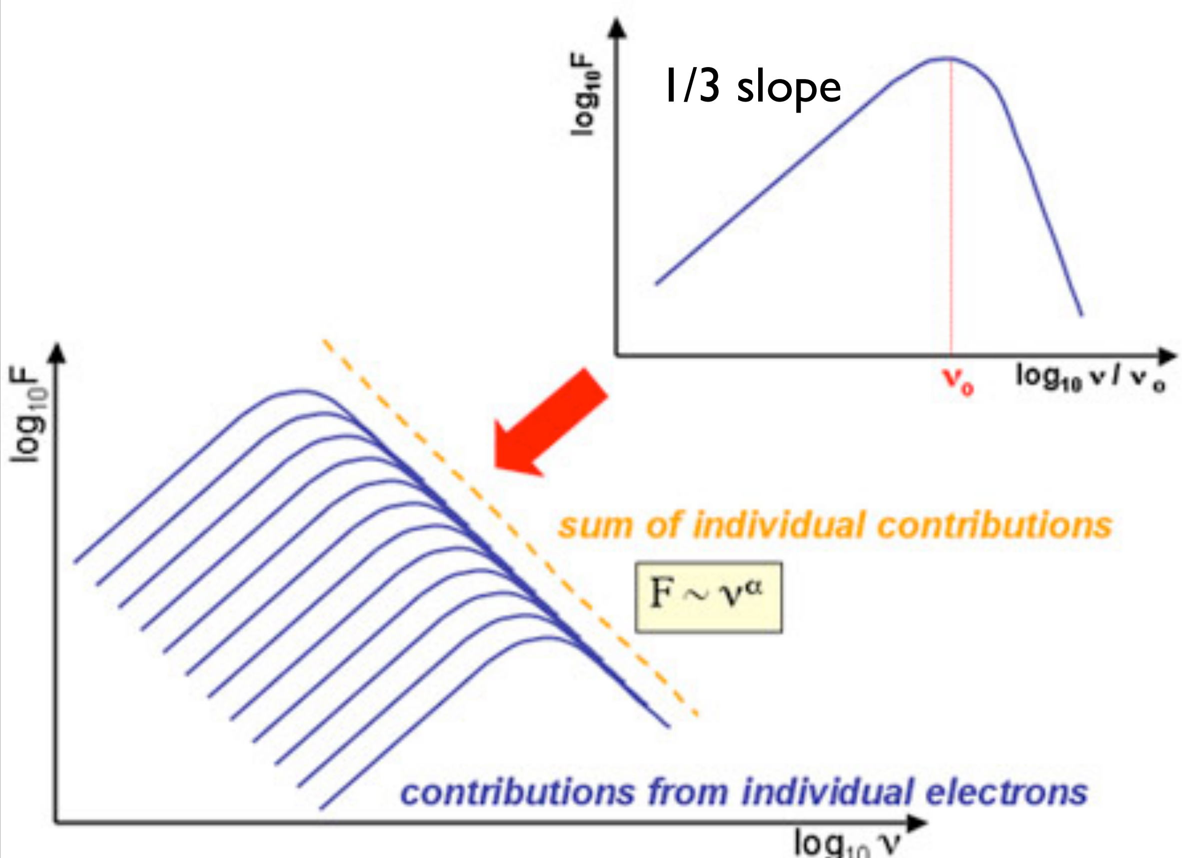
- To maintain synchrotron emission, a continuous supply of relativistic electrons is necessary.
- Typical energy sources include supernova remnants, quasars, or other types of active galactic nuclei.
- Signal is polarized because of magnetic directionality.

Synchrotron Emission



- 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 Spectrum



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

Synchrotron Spectrum

Strong dependence on the Lorentz factor

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

Larger B-field increases the emission frequency and energy loss rate

$$\nu_{max}\ \alpha^{al}\ E^2 B \qquad dE/dt\ \alpha^{al}\ E^2 B^2$$

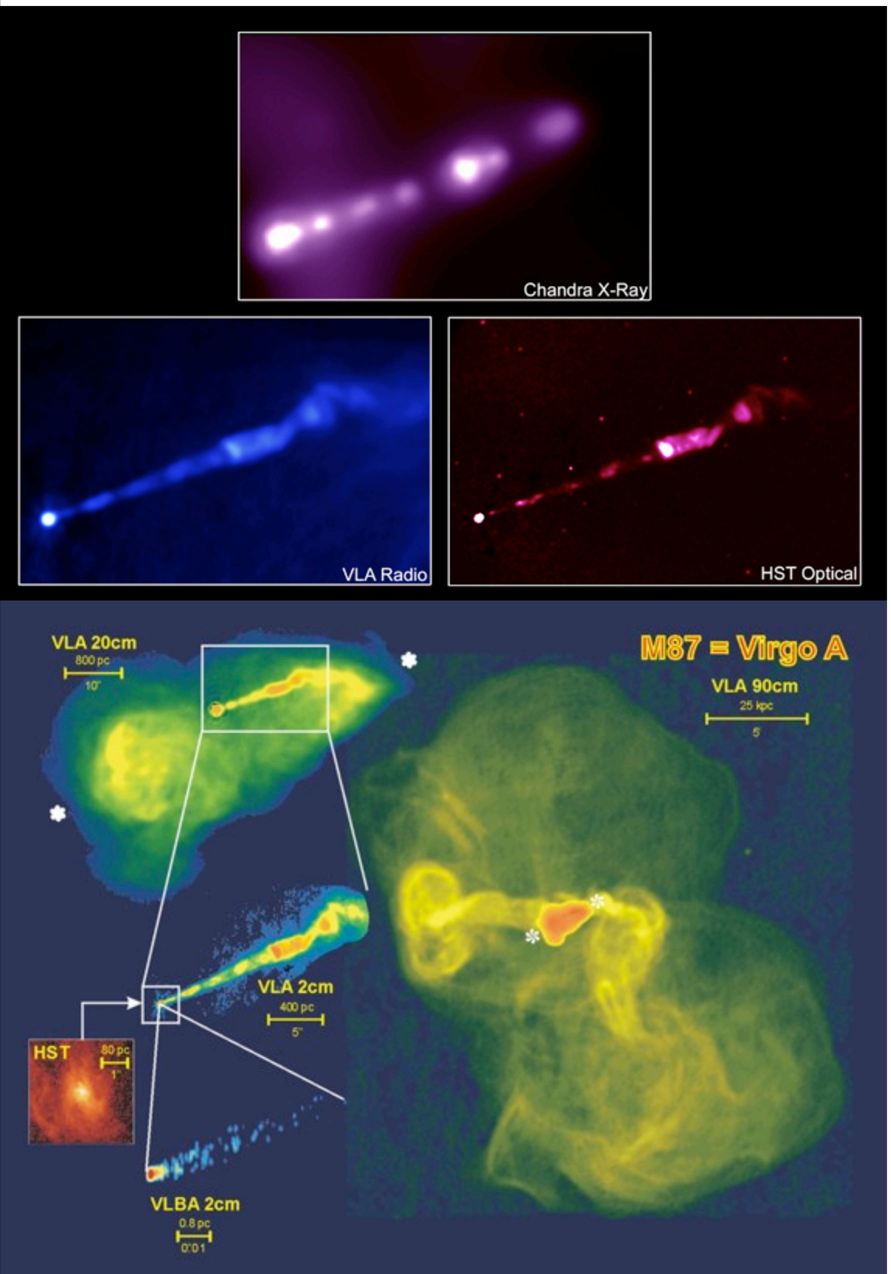
Power-law distribution of electron energies

$$N(E)\ \ \alpha^{al}\ E^{-\beta} \quad \text{where } \beta \text{ is} \sim 5/2$$

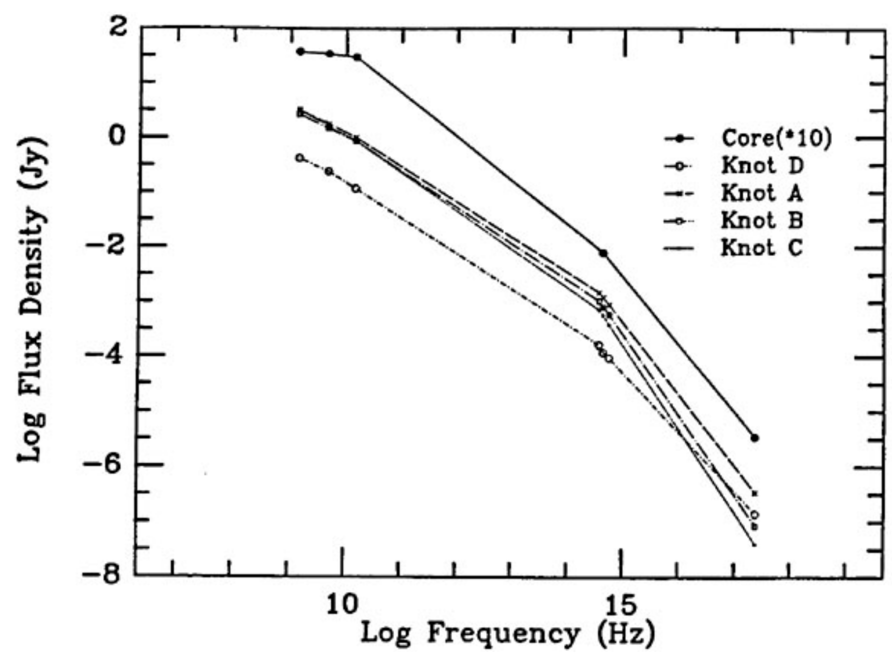
Power-law (photon) spectrum

$$S(\nu)\ = \alpha^{al}\ \nu^{(1-\beta)/2} \qquad S(\nu)\ \ \alpha^{al}\ \nu^{-0.75} \ \text{For } \beta = 5/2.$$

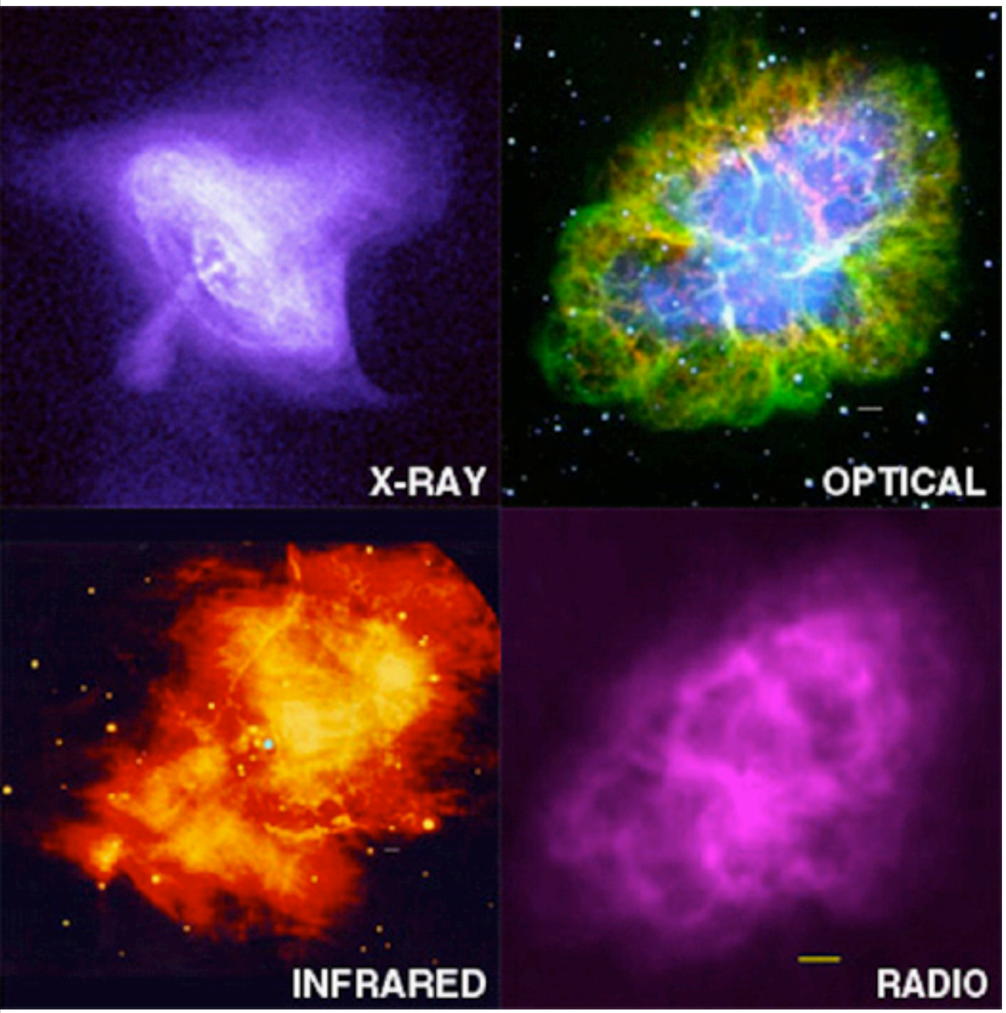
Synchrotron Emission



- Multi-wavelength synchrotron emission from an AGN jet.
- Reflects the power-law electron energy distribution.

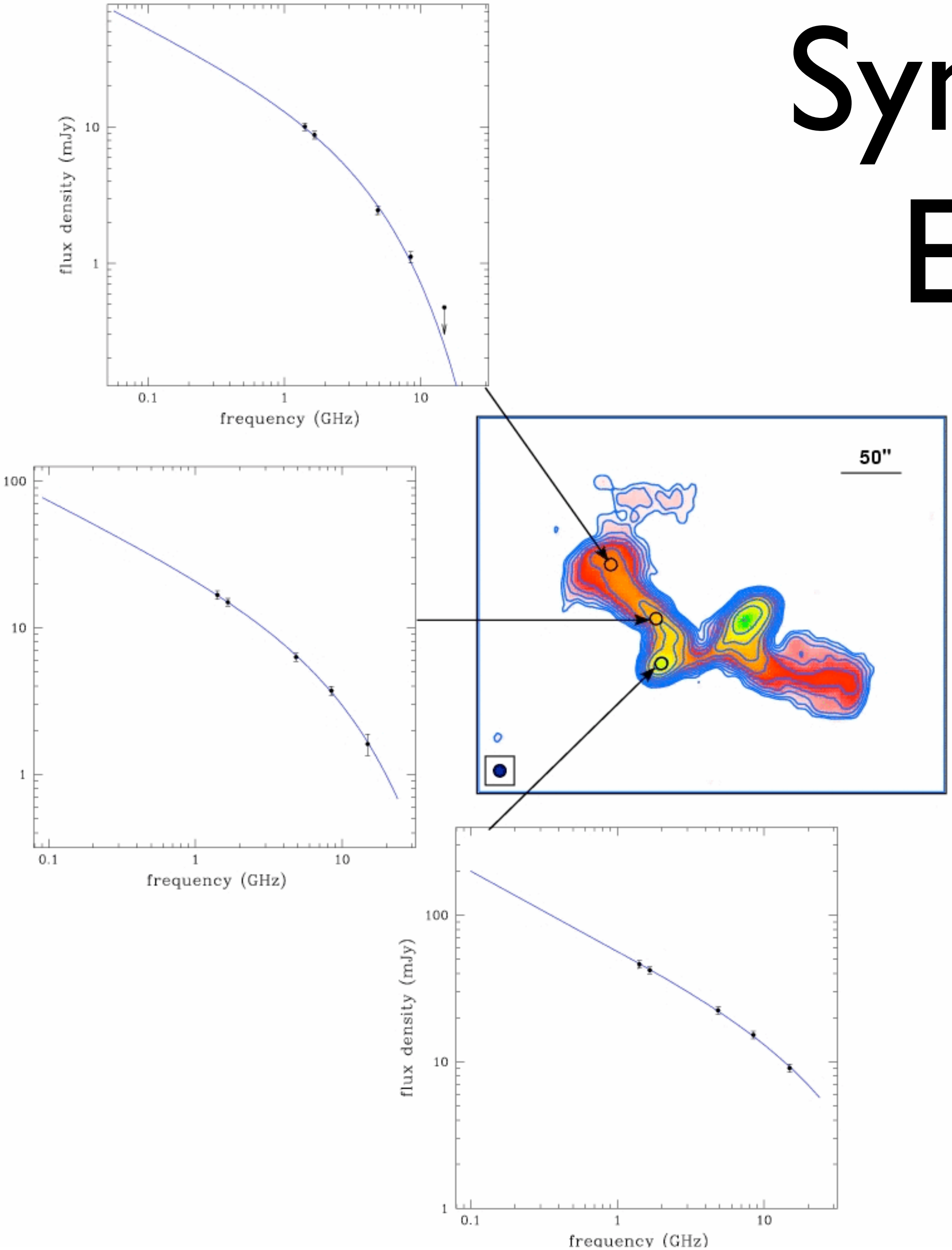


Synchrotron Emission



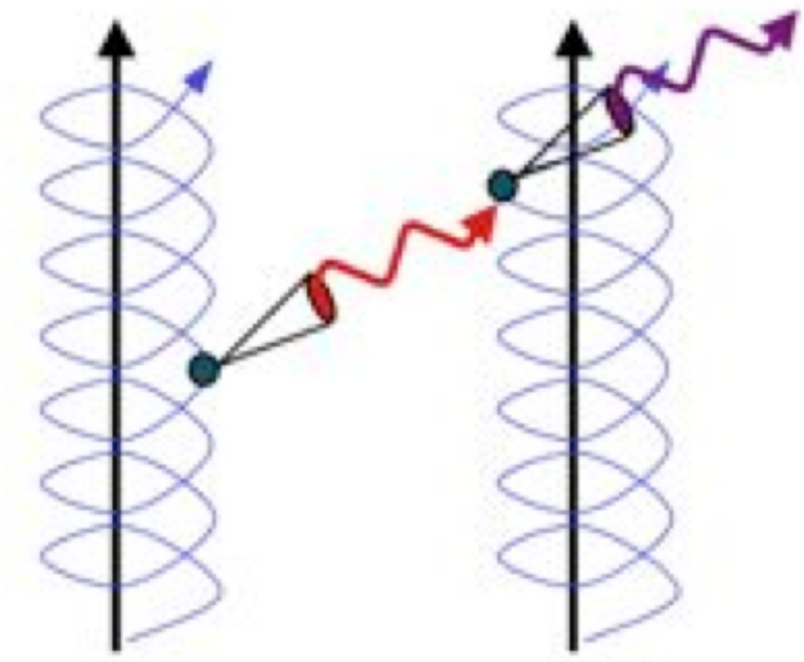
- Another example of multi-frequency synchrotron.
- Spectral aging: high-energy electrons, emitting at the highest frequencies, lose energy more quickly (E vs. E^2).
- Causes an extra steepening at the highest frequencies.

Synchrotron Emission



- Spectral aging in the radio galaxy NGC326.

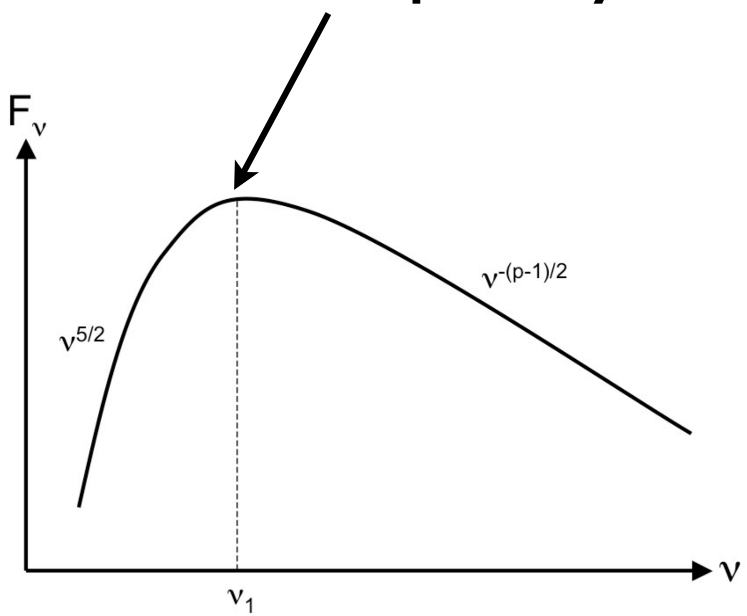
Synchrotron Self-Absorption



- Principle of "detailed balance": any mechanism that can emit radiation can also absorb it.
- What happens to the steep powerlaw 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

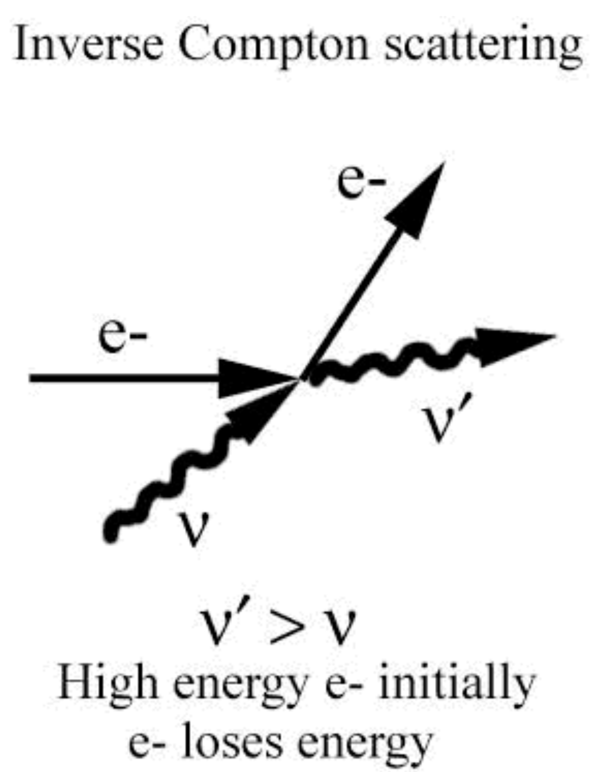


Optically thick

Optically thin

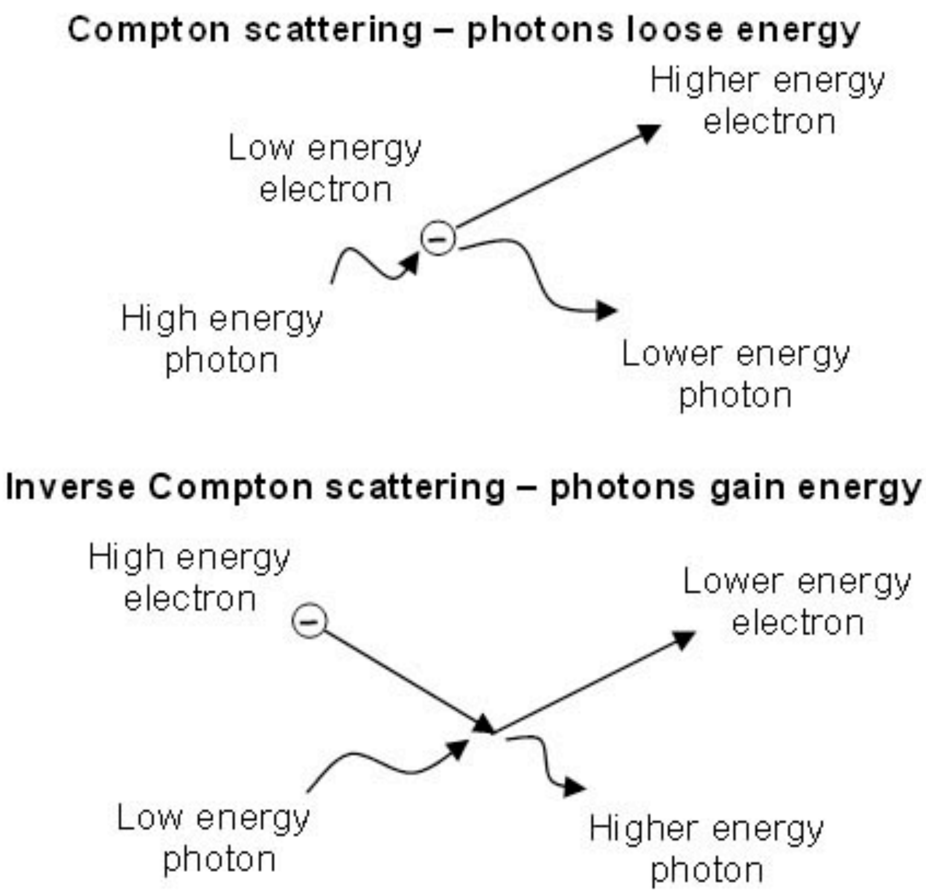
- When the brightness temperature becomes equal to the electron temperature, the source becomes opaque.
- A self-absorbed source has a 5/2 powerlaw spectrum.
- Turnover frequency related to electron density.

Inverse Compton Scattering



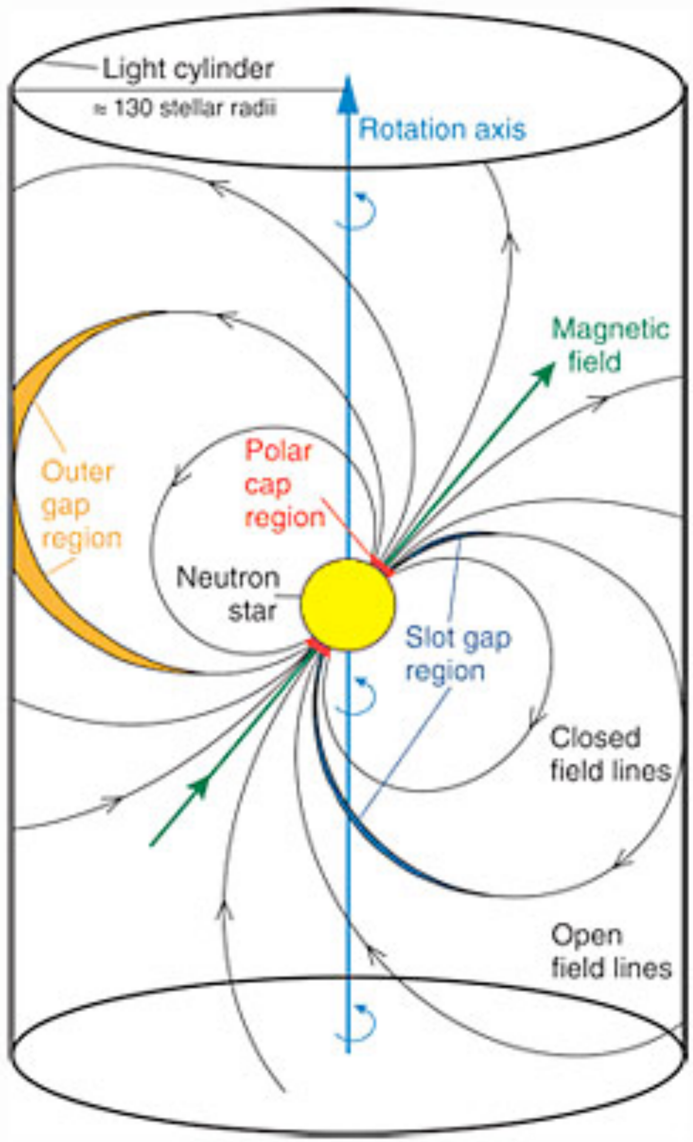
- Low-energy photons scattered to higher energies by relativistic electrons.
- Seed photons from, e.g., the CMB.
- Observed near synchrotron sources (sources of relativistic electrons).

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.

Pulsar Emission



- Enormous brightness temperatures.
- Exact emission mechanism still eludes us.
- Must be a coherent process.
- Emits pulsations from low-frequency radio up to GeV gamma-rays.
- See lecture 9 for more details.

Propagation Effects

Propagation Effects

Observed signal

Emitted signal

Dispersion

Faraday rotation

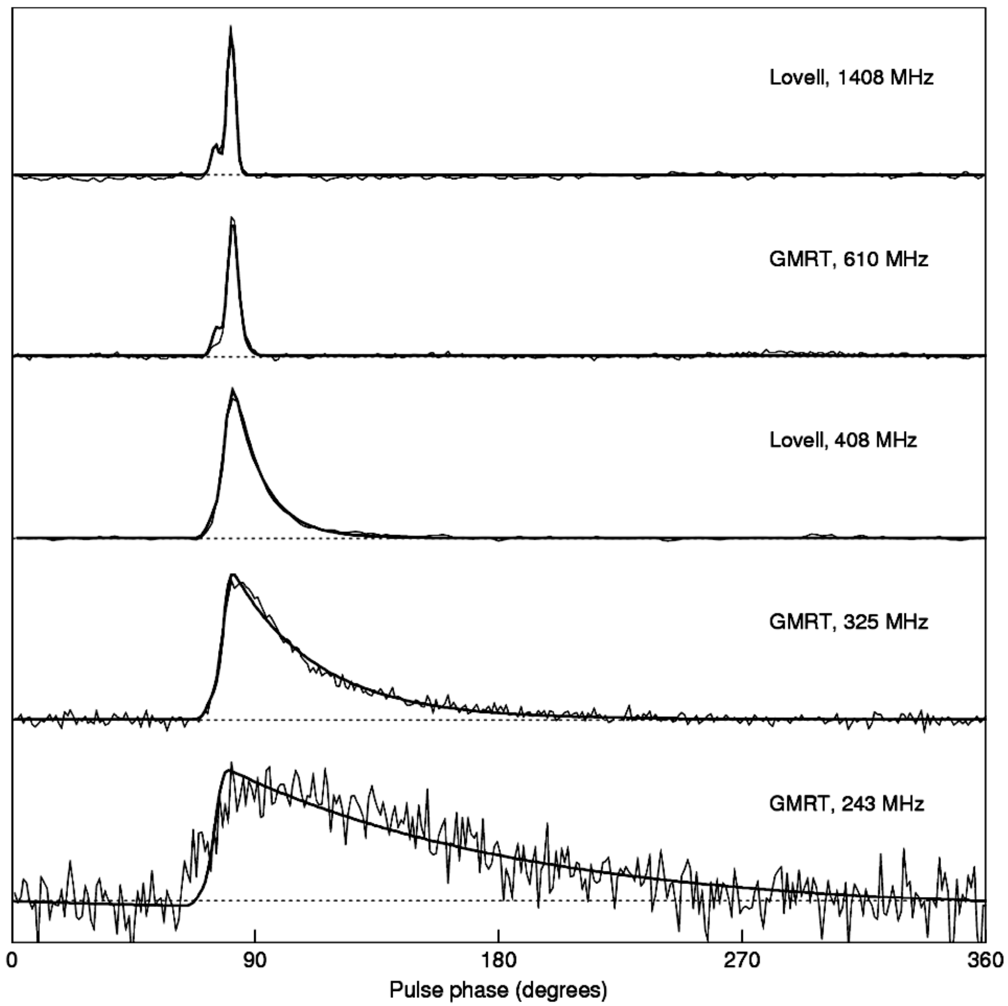
$$I(t) = g_r g_d S(t) * h_{\mathrm{DM}}(t) * h_d(t) * h_{\mathrm{Rx}}(t) + N(t)$$

Refractive and diffractive scintillation

Scattering

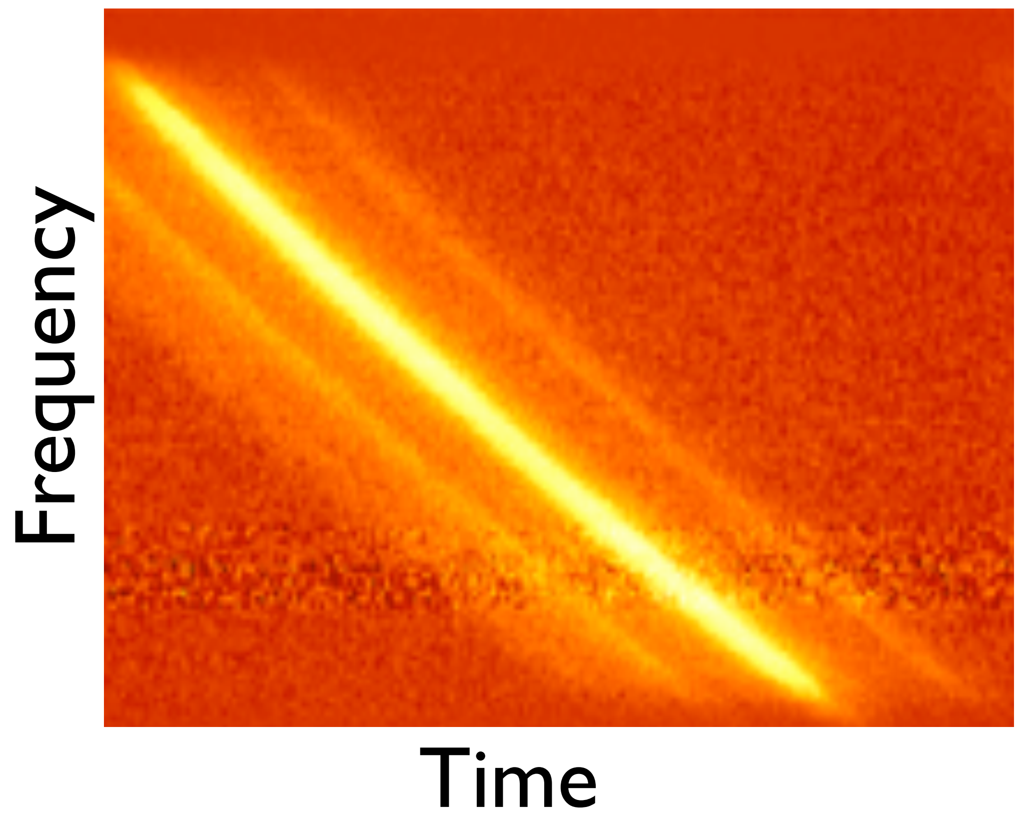
Instrumental noise

Scattering



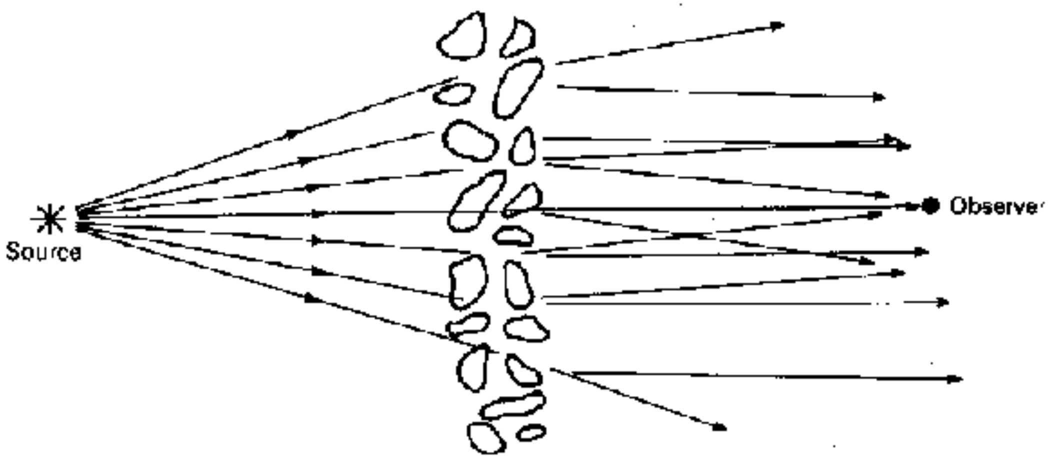
- Multi-path propagation.
- Asymmetric scattering tail, roughly follows an exponential decay.

Dispersion



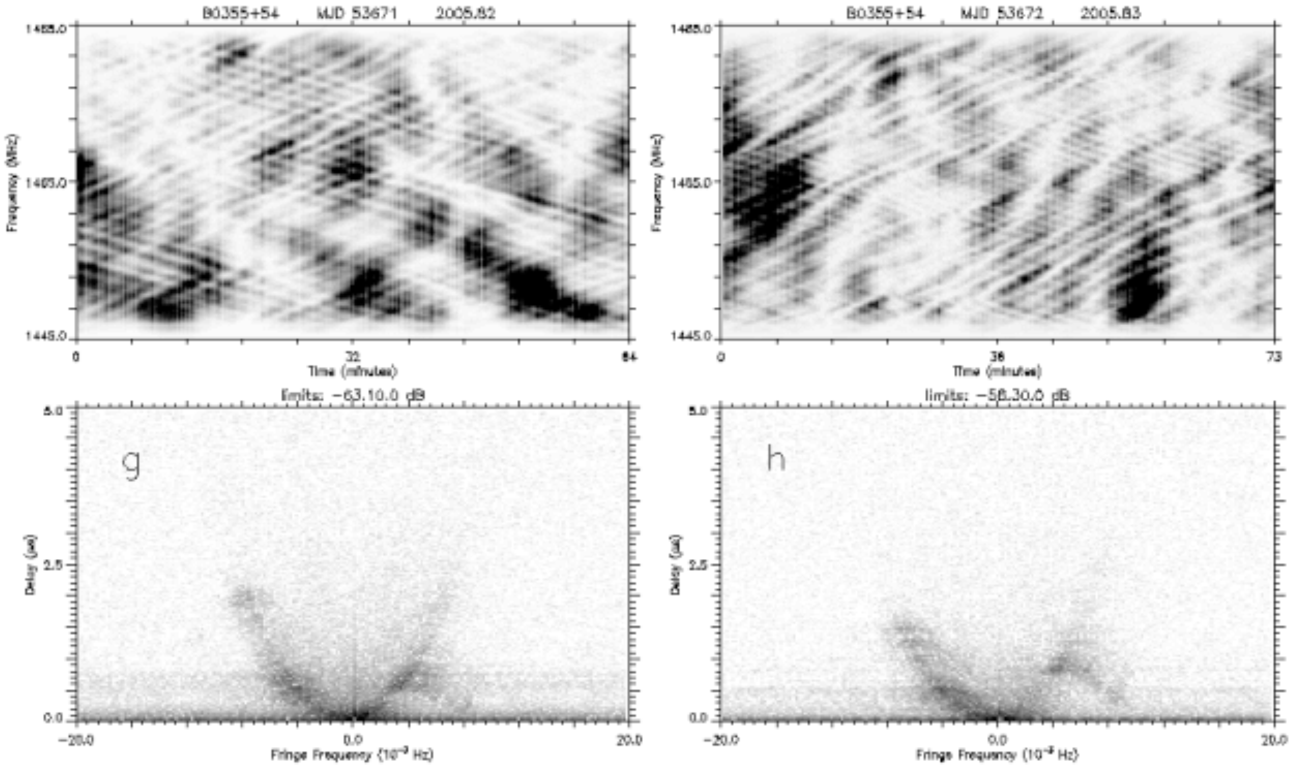
- Frequency dependent travel time.
- Signal arrives quadratically later at low frequencies.
- Delay also linearly proportional to the "dispersion measure" - i.e. the total electron content along the line-of-sight.

Scintillation



- Constructive/ destructive interference.
- Each line-of-sight gives typical time and frequency scintillation scales.

Secondary Spectra



- Measure distance to intervening screens.

Bringing it all together

Overview of common radiation processes in the radio spectrum and their environment

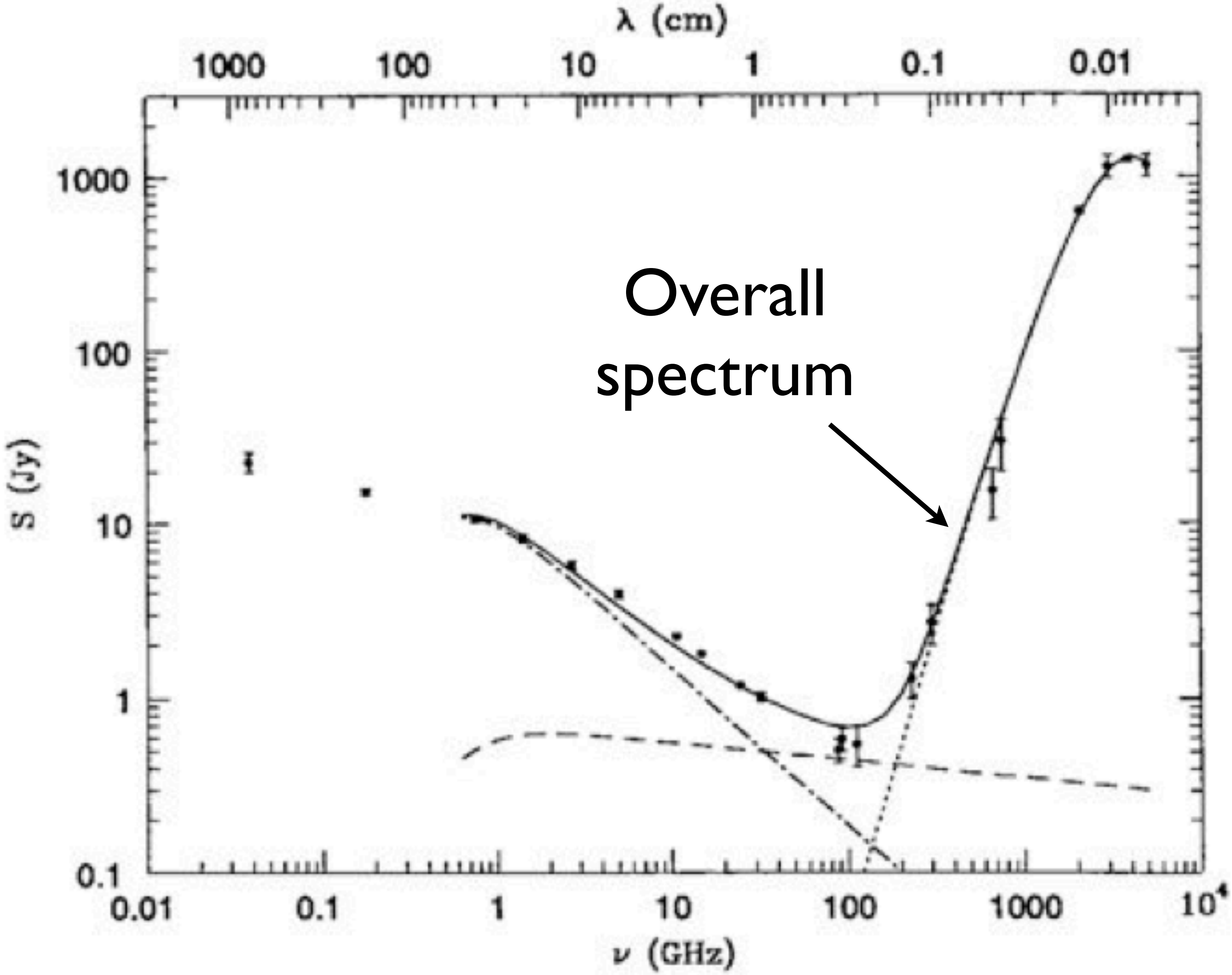
λ	Spectral line	Continuum
metre, cm and mm	Neutral Hydrogen (HI) 21cm fine structure line - neutral gas Hydrogen recombination lines -ionised gas; OH, H20, SiO Masers - dense, warm molecular gas; Molecular rotation lines - cold molecular gas	Thermal Bremsstrahlung (free-free emission) – HII regions Synchrotron Radiation – Jets in radio Galaxies, pulsars, shocks in supernovae, cosmic ray electrons in the magnetic fields of normal galaxies etc., acceleration of electrons in stellar and planetraty systems Thermal emission from dust – cold, dense gas.
sub-mm (and FIR)	Molecular Rotation Lines – warm, dense gas. Solid State features (silicates) –dust Hydrogen recombination lines – ionised HII regions.	Thermal emission - warm dust

Courtesy M. Garrett

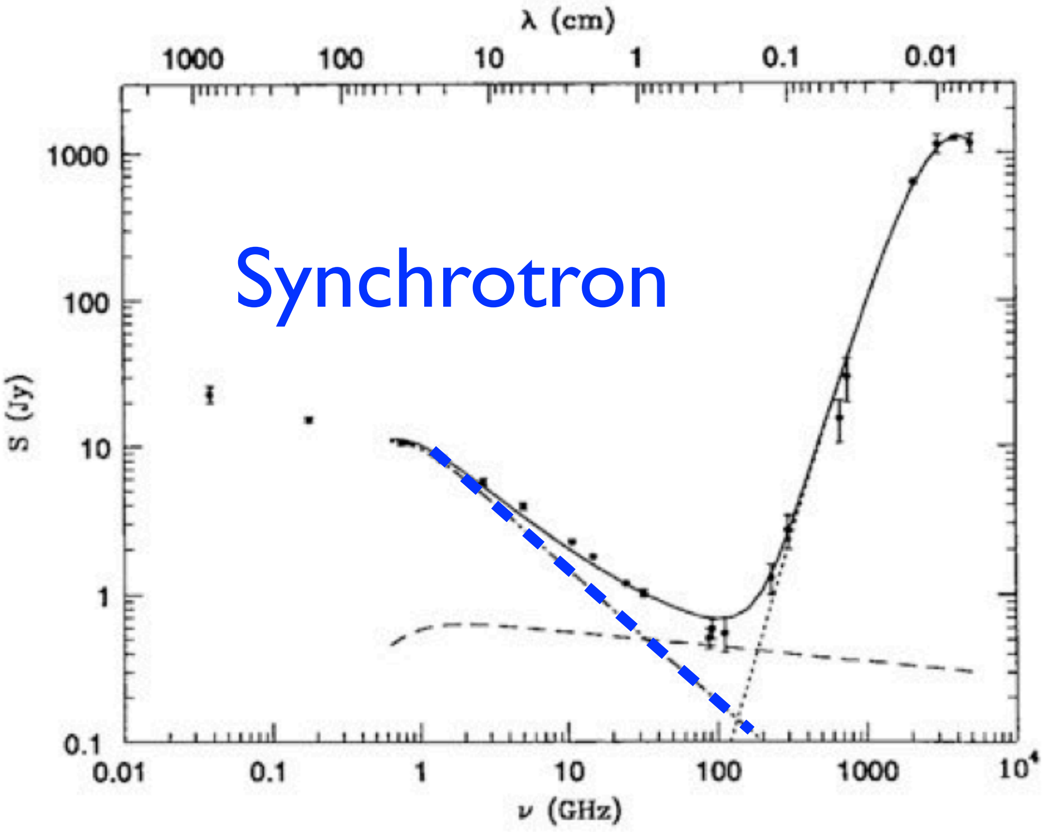
Bringing it all together

- Thermal (blackbody), free-free, and synchrotron emission/absorption can describe the continuum spectrum of many (extra-)galactic sources.

Star-forming galaxy M82

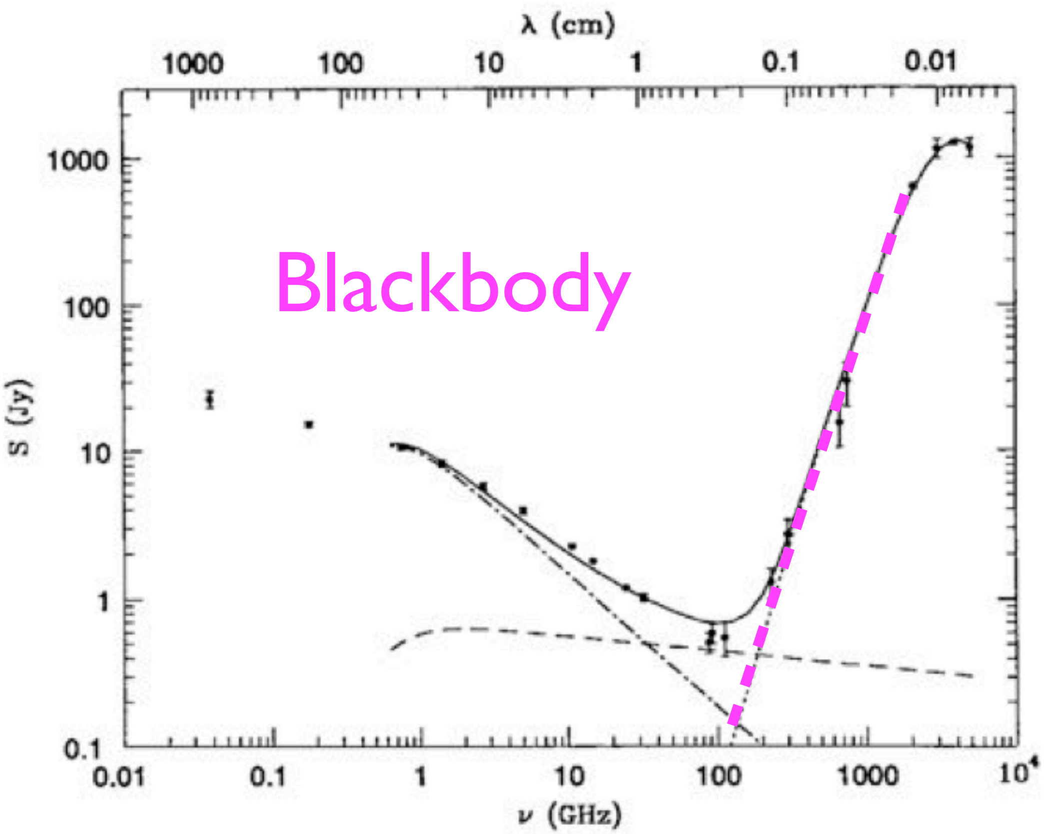


Star-forming galaxy M82



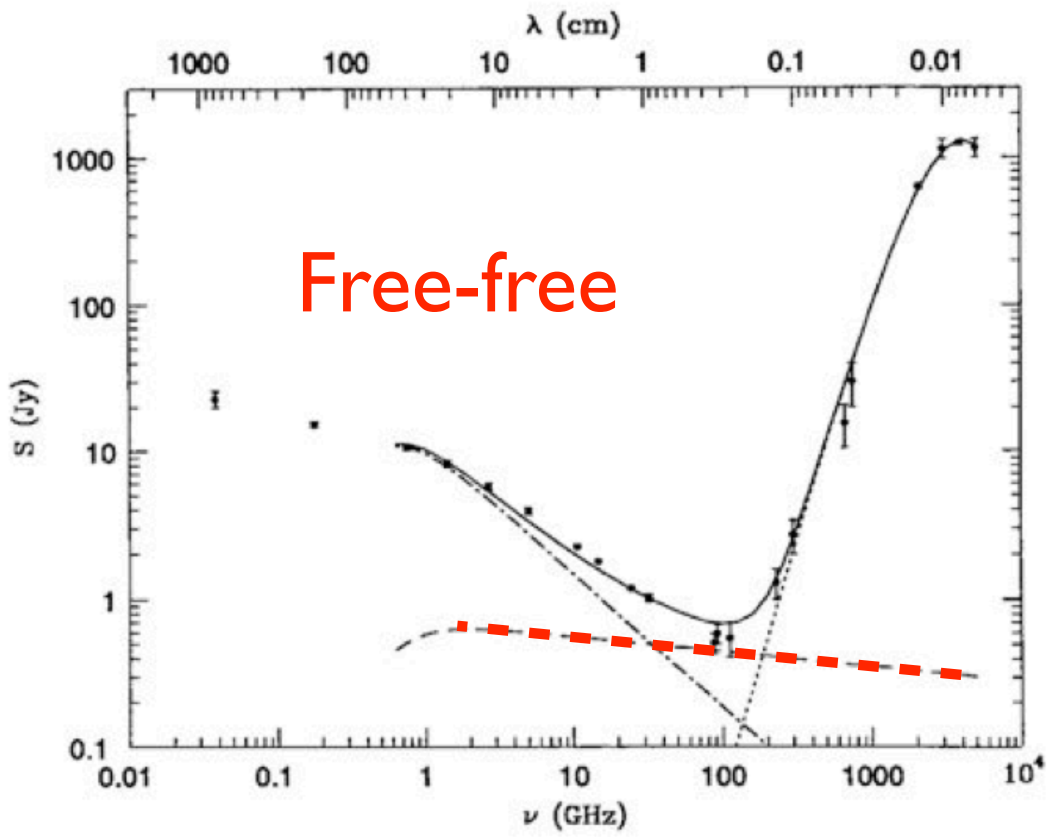
- Cosmic-ray electrons in the galaxy's magnetic field.
- SNe create the seed electrons.

Star-forming galaxy M82



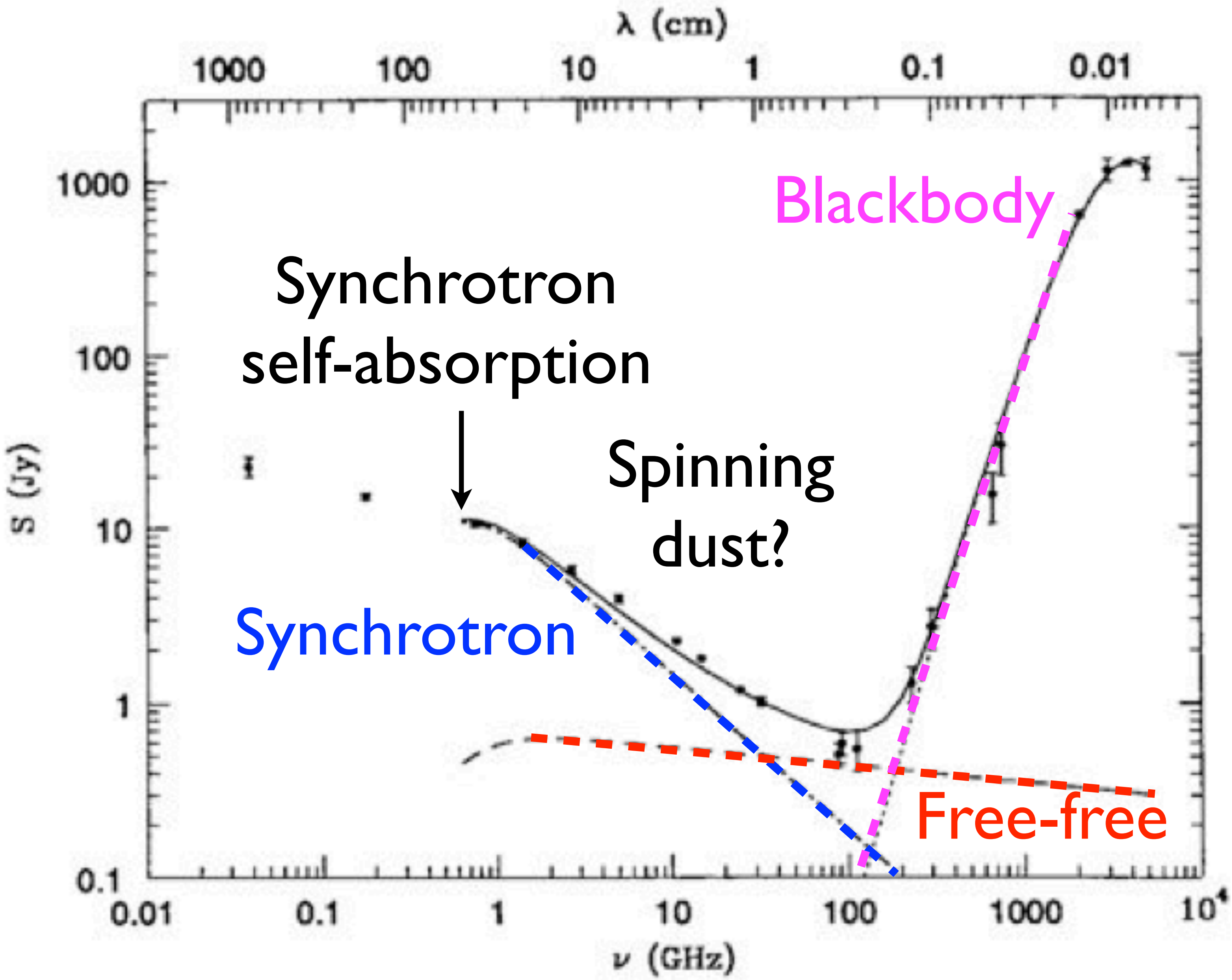
- Dust heated by uv-photons.
- Tail in IR, but can be redshifted into the radio band.

Star-forming galaxy M82

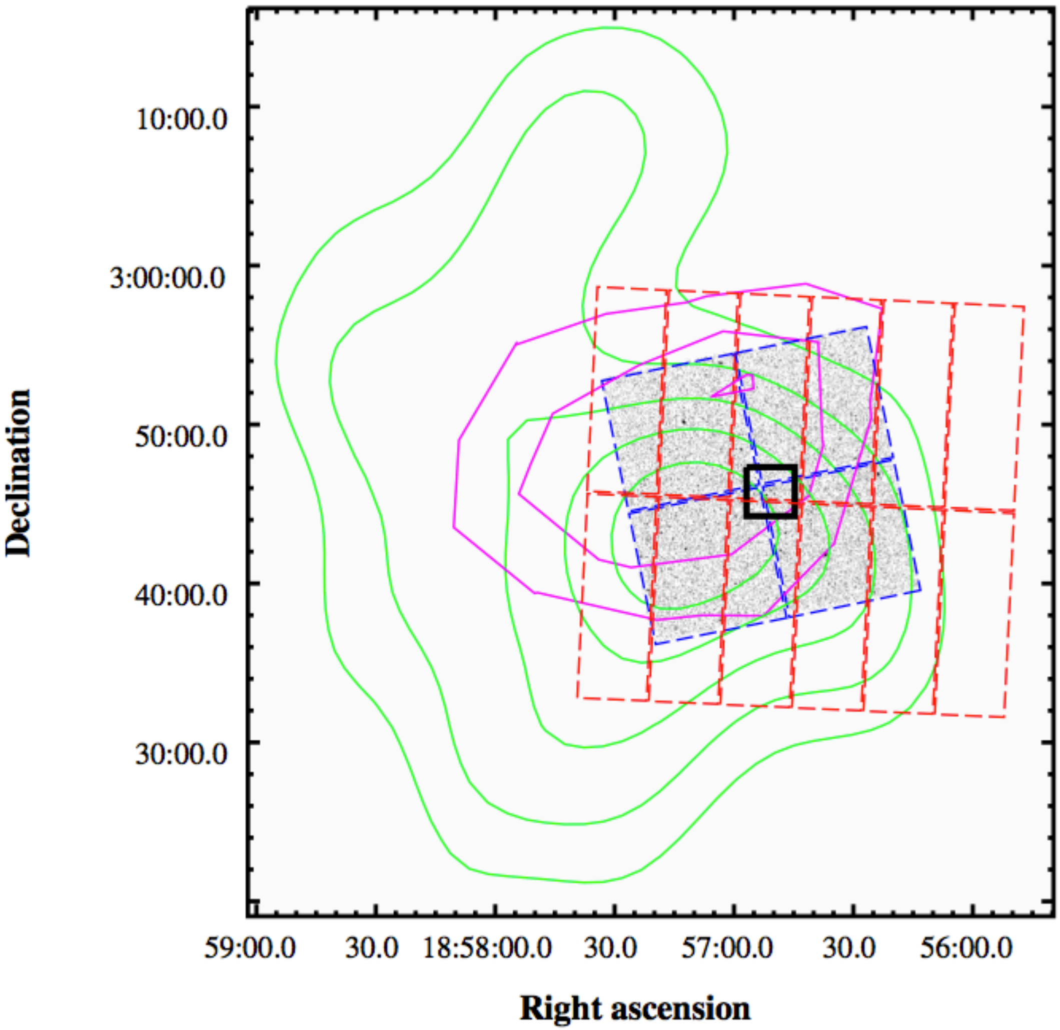


- Tenuous, ionized gas.
- HII regions.

Star-forming galaxy M82



TeV Pulsar Wind Nebulae



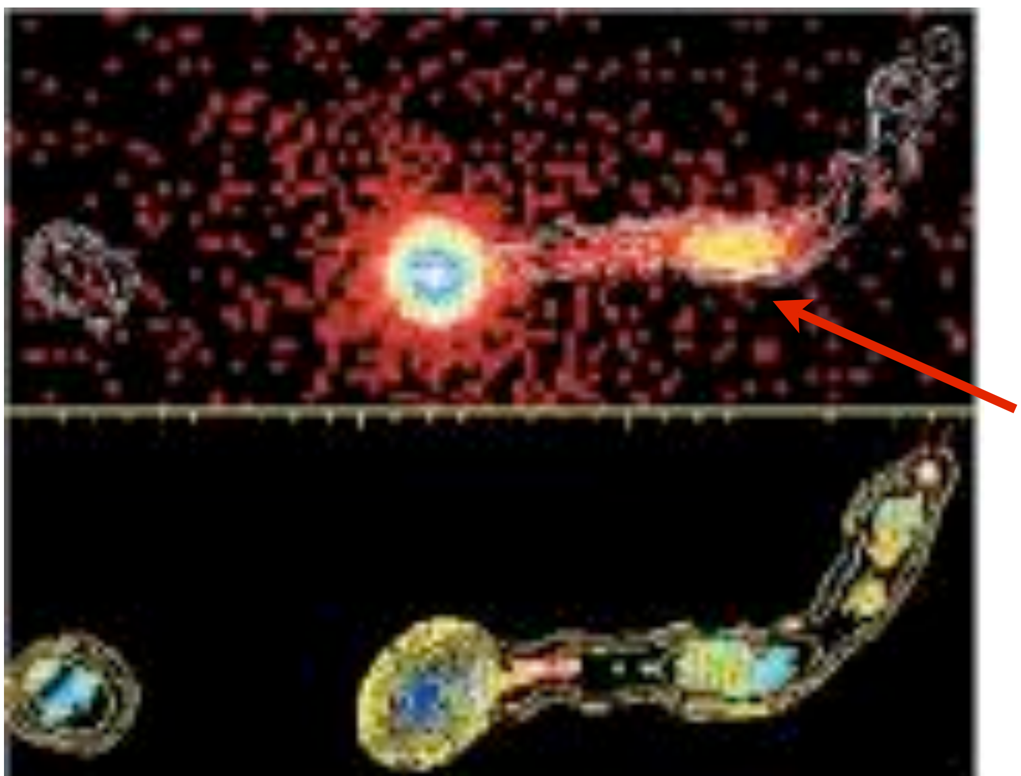
- Inverse Compton?
- Seed photons from the CMB.

Synchrotron Self-Compton

N.B. A photon scattered by an electron with Lorentz factor γ, increases its energy by γ^2.

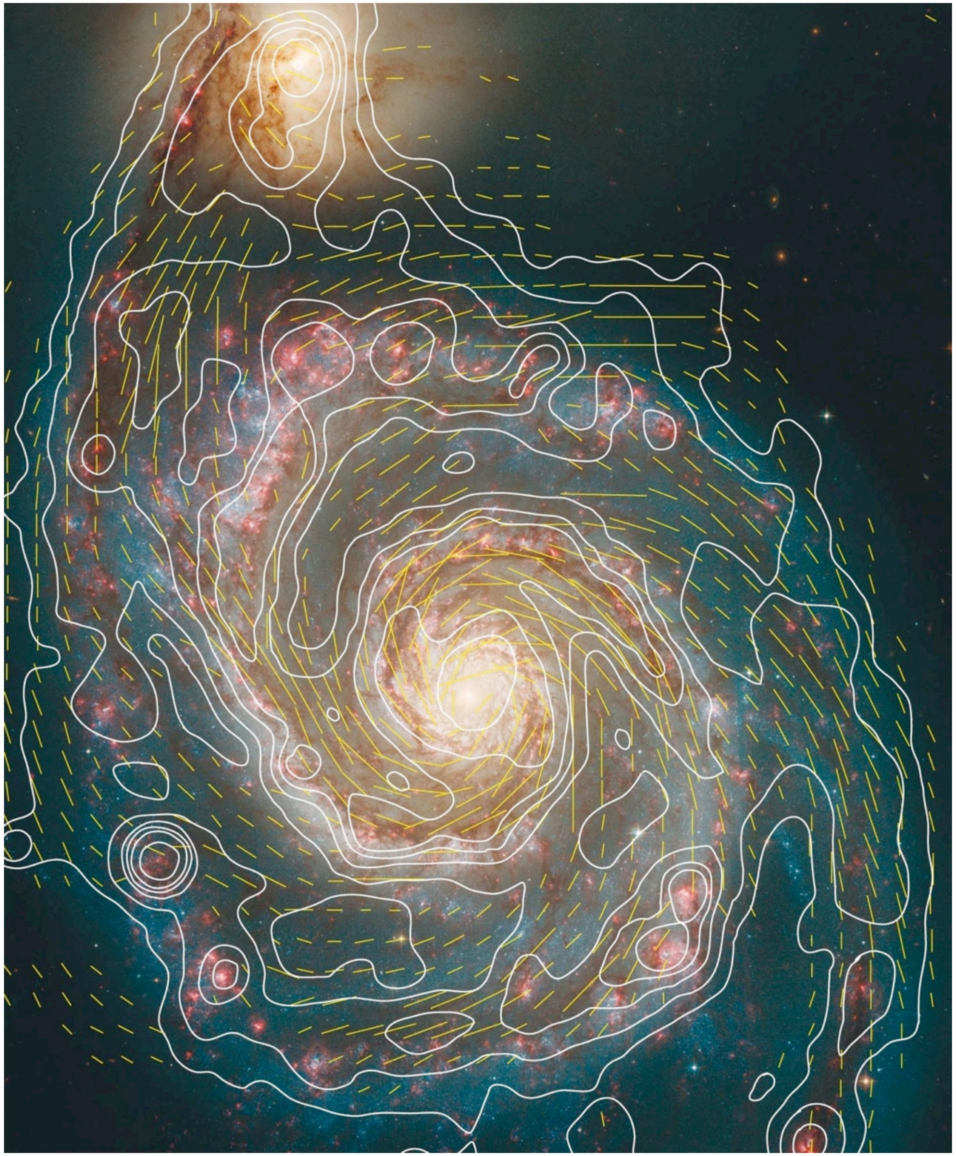
This means that a radio photon in synchrotron source can find itself upscattered by a factor of ~ 10^8 i.e. into the x-ray region of the e-m spectrum!

In the case of compact AGN, the self-Compton mechanism is believed to be more important than synchrotron radiation losses as responsible for cooling the relativistic electron population.
The mechanism limits the brightness temperature of radio sources to $T_b \sim 10^{12}$ K.



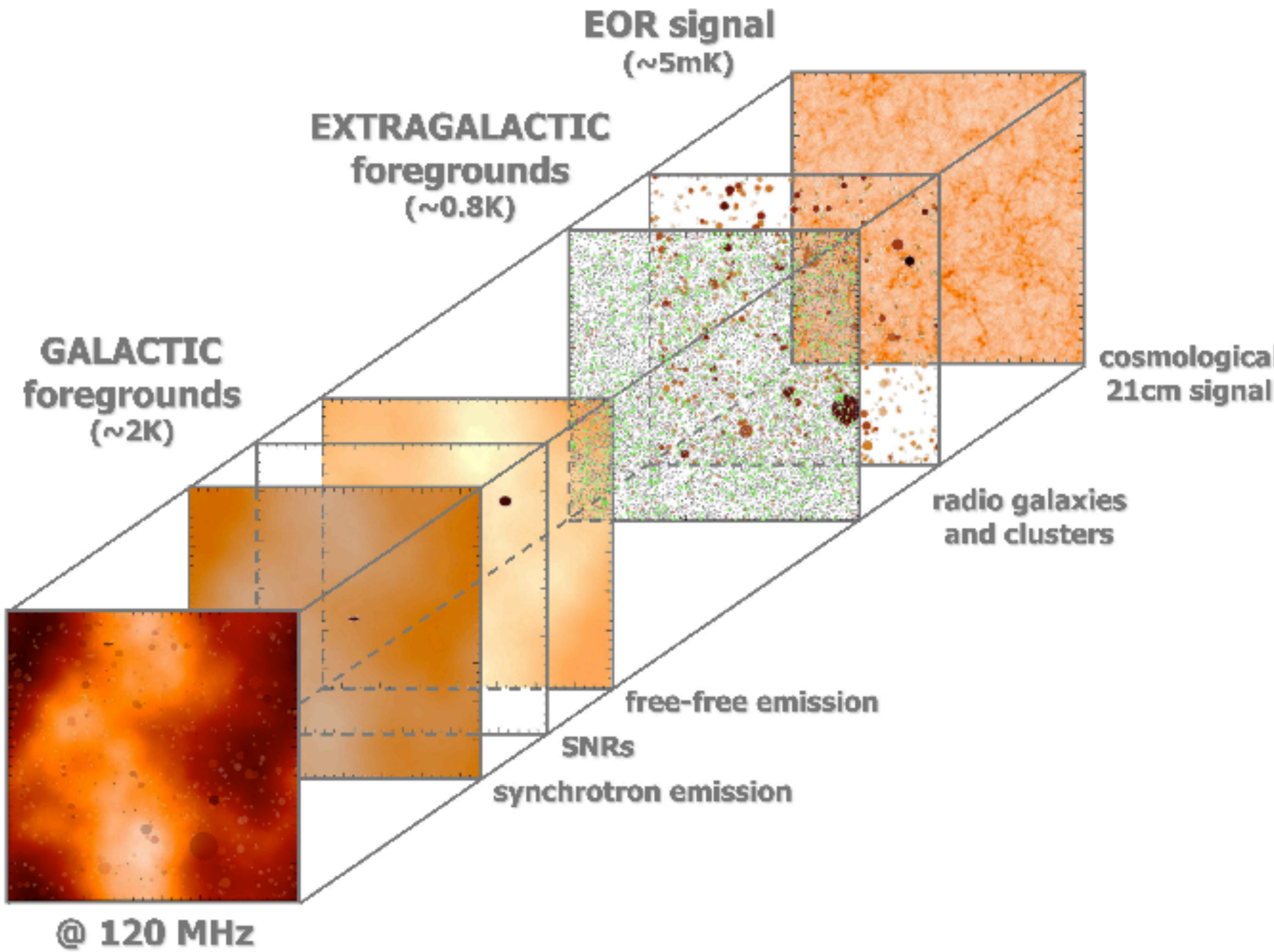
Left: X-ray emission (false colours) with radio contours superimposed. The xray hotspot is believed to be due to SSC.

Map Magnetic Fields



- Contours: VLA and Effelsberg radio data at 5GHz.
- Optical image from Hubble.
- Direction of lines indicated magnetic field vector.
- Length of lines indicate B-field strength.
- Derived based on polarization of synchrotron emission.

EOR Foregrounds



Sources

Radiative Processes in Astrophysics (Rybicki & Lightman)

NRAO: http://www.nrao.edu/index.php/learn/radioastronomy/radiowaves

Wikipedia: http://en.wikipedia.org/wiki/Radio_astronomy

Other course slides (see links on course wiki page):

http://www.astron.nl/astrowiki/doku.php?id=uva_msc_radioastronomy_2013

Many figures taken from Garrett.

Questions?