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für Radioastronomie

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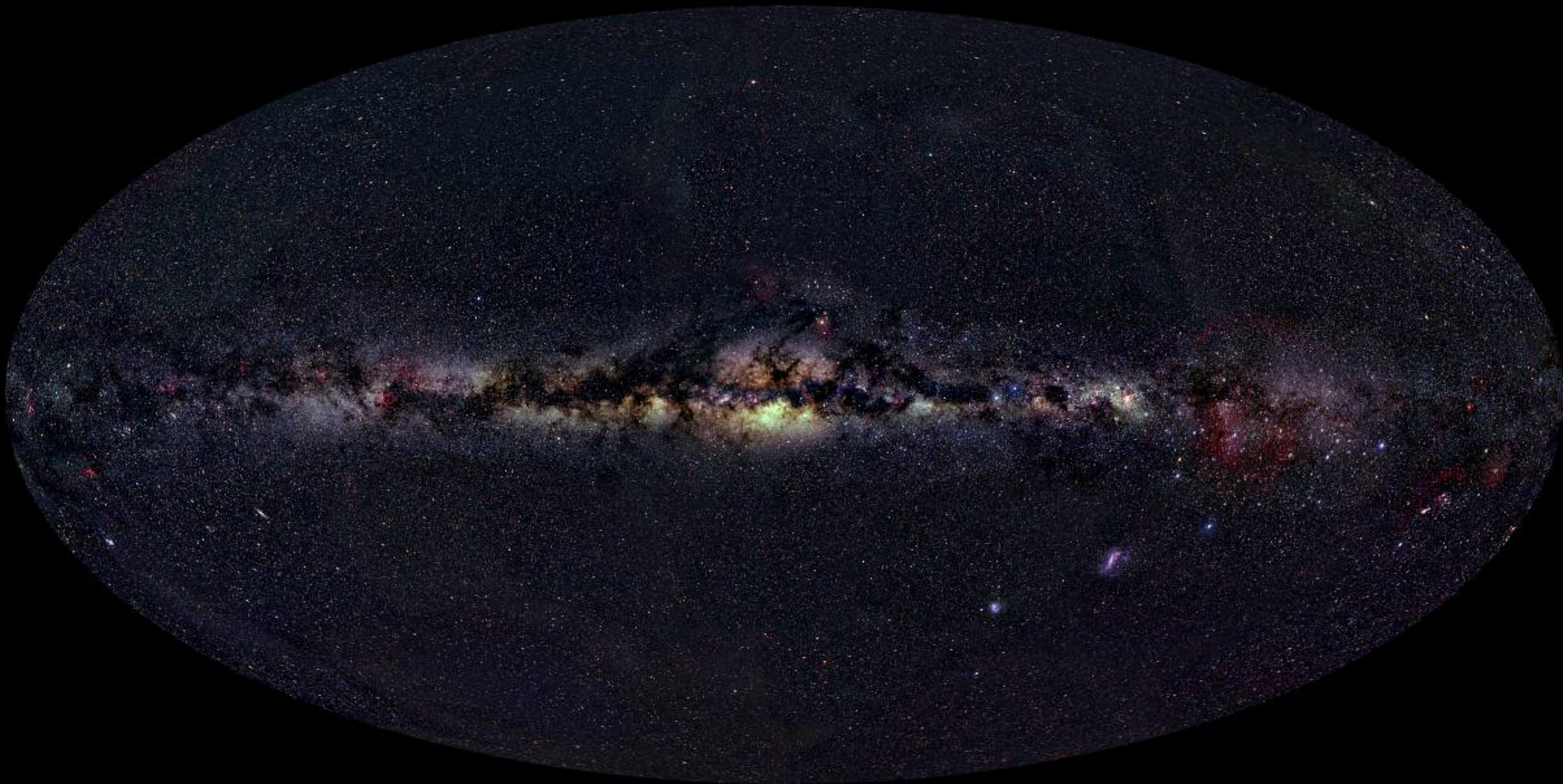
Bonn/Effelsberg - Sep 27 to Oct 1, 2010

Welcome!

The visible sky



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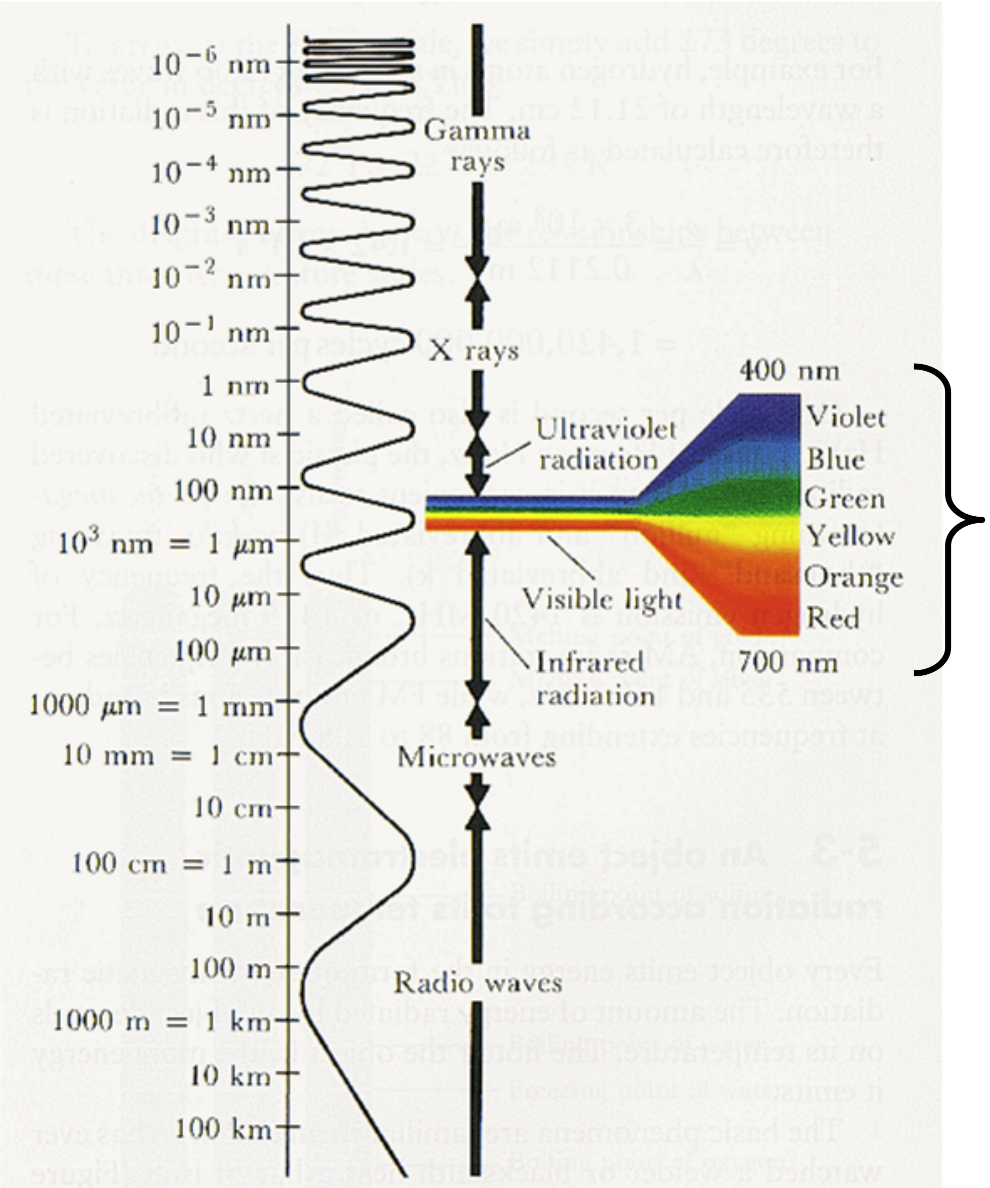
There is more than visible light:
The Electromagnetic Spectrum



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There is more than visible light:
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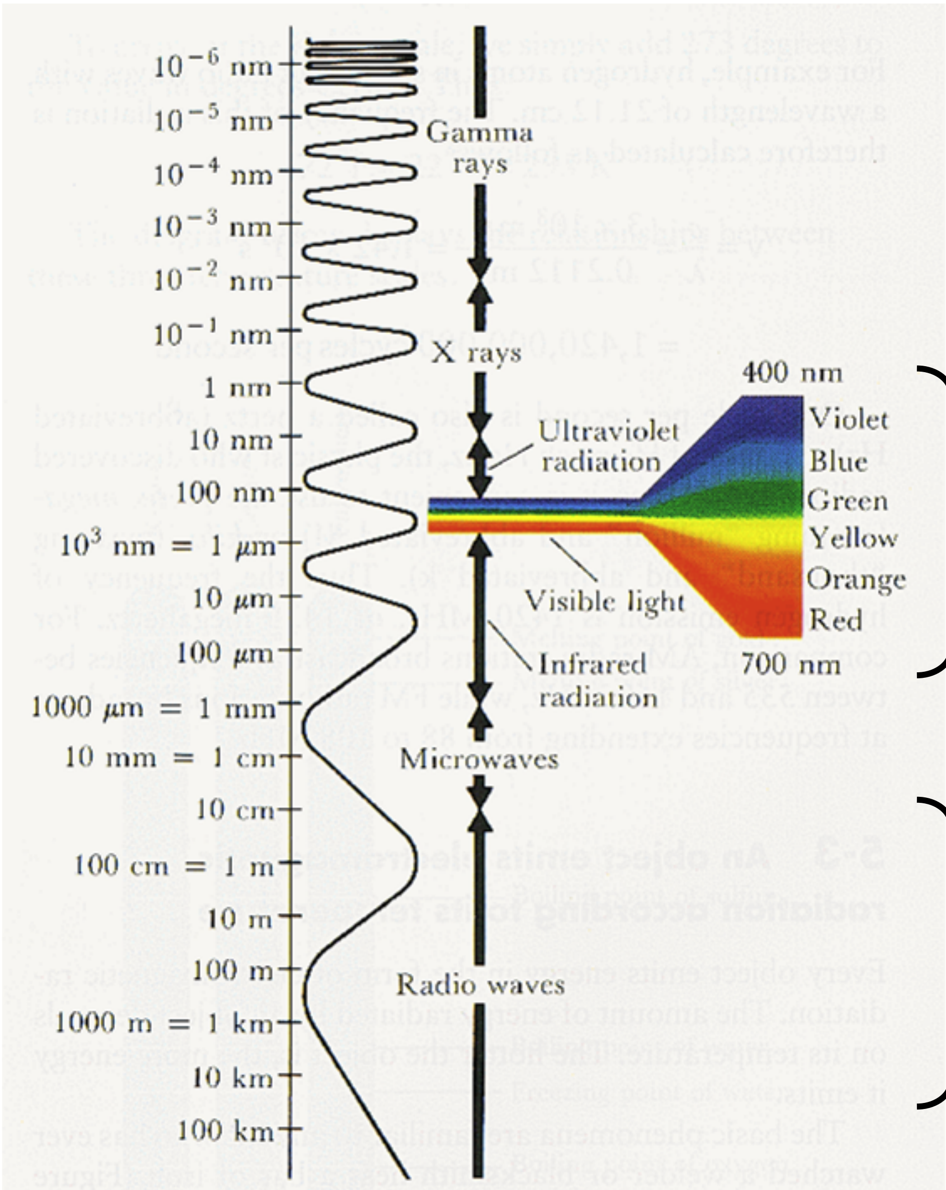
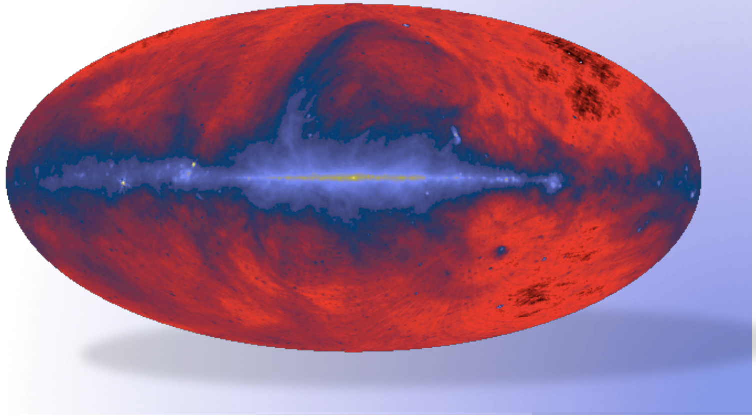
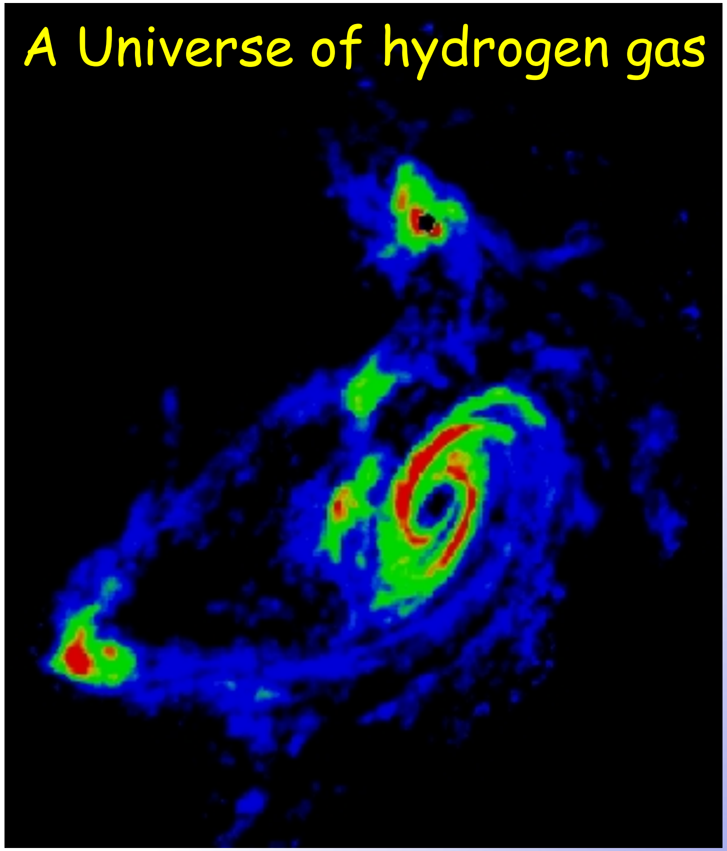




Why do we do radio astronomy?

- Radio waves penetrate dust: e.g. view into inner Galaxy
- Sharpest images in all astronomy
- Gives vastly different view of universe, e.g.



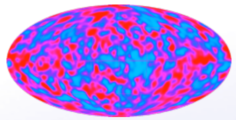
- Discovery of new objects!

Radio Astronomy

Most of the fundamental astrophysical discoveries
of the last century were made by radio astronomers, e.g.

- Pulsars
- Gravitational waves
- Extra-solar planets

- Cosmic Microwave Background
- Quasars and radio galaxies



- Gravitational lenses
- Jets and super-luminal motions
- Dark matter
- Interstellar molecules
- Masers and megamasers

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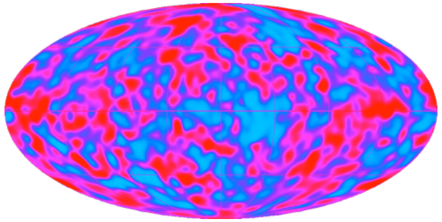
High precision fundamental physics

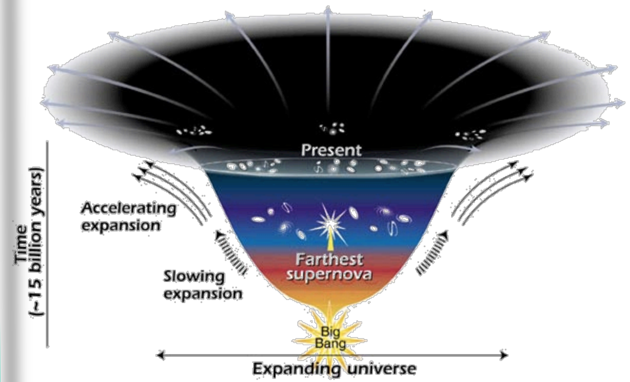
- More than"astronomy" – astrophysics & fundamental physics
- Example:

Measuring the cosmos



The Universe...

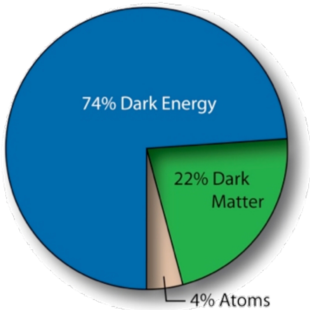
... is 13.75 ± 0.13 Billion years old



... flat to a measuring accuracy of better than 1%

... only 4.49±0.28% consists of baryons

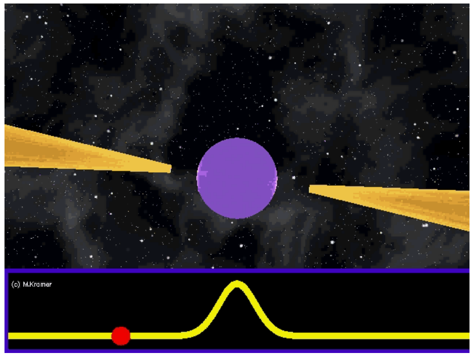
... but 73.31±0.38% is due to "Dark Energy"

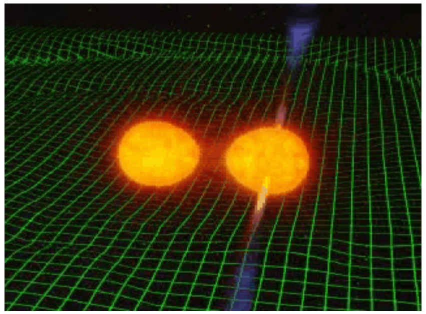


Is general relativity correct?

High precision fundamental physics

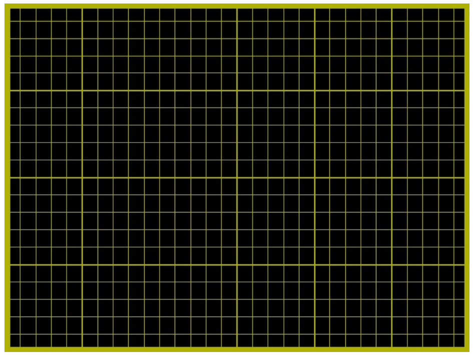
- More than“astronomy“ – astrophysics & fundamental physics
- Example: Using natural cosmic clocks

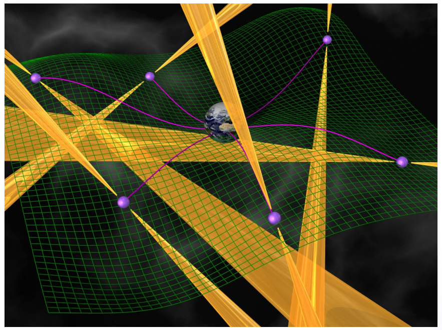




Orbit shrinks every day

by 7.42±0.09 mm



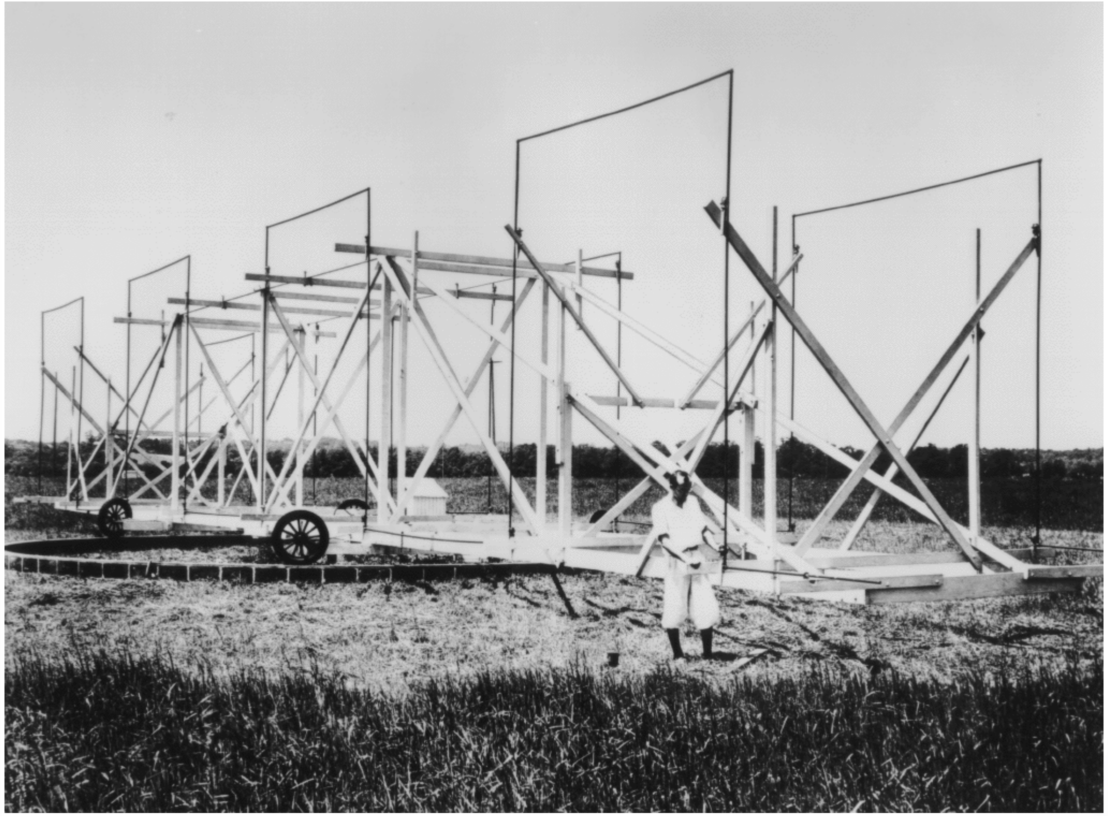


„Movement of Earth

at $<10^{-14}$ m level!

Karl Jansky (1905-1950)

Discovered cosmic radio waves in 1933, while hunting interfering "static", for Bell Telephone Labs.

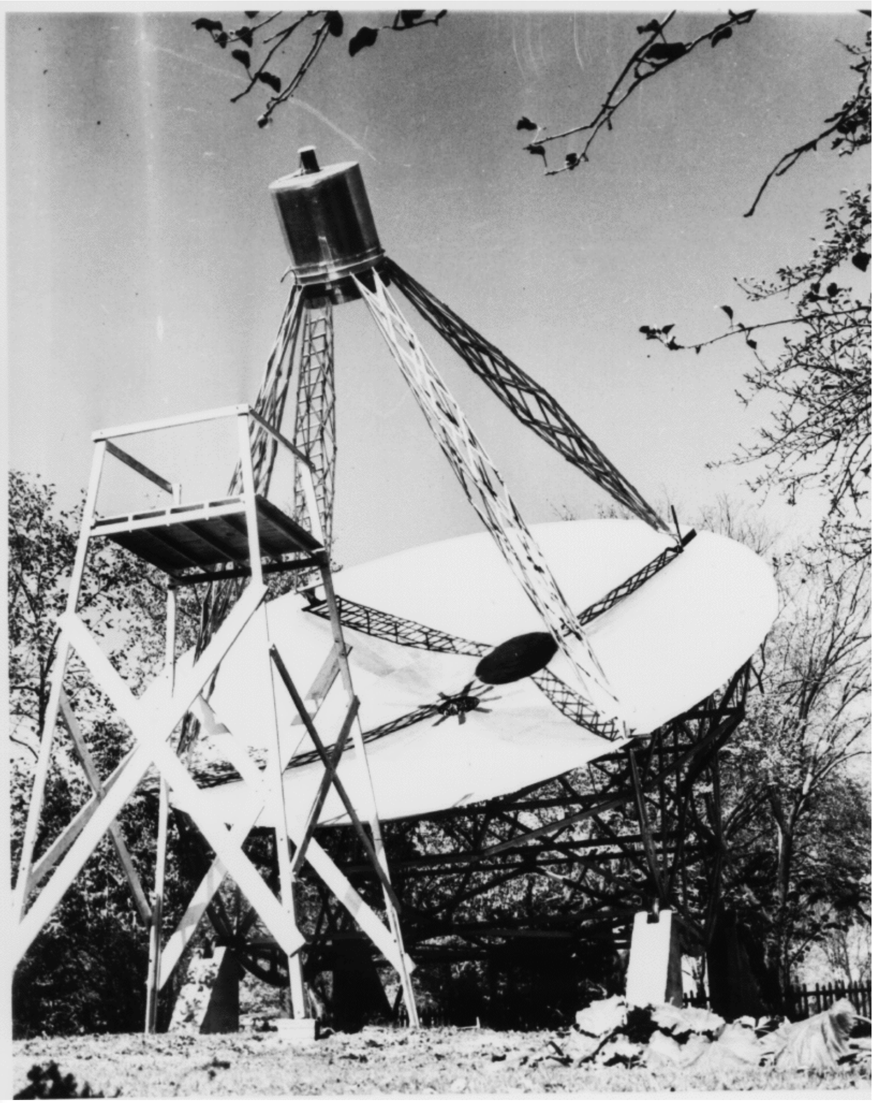


"Merry-go-round" antenna in New Jersey, running on wheels from model-T Ford.

14.5-m wavelength

Most static comes from the centre of the Milky Way.

Grote Reber (1911-2002)



Home-made dish to follow-up Jansky's discovery.

1938 Confirmation at 1.9-m wavelength.

Published first radio maps of the Milky Way.

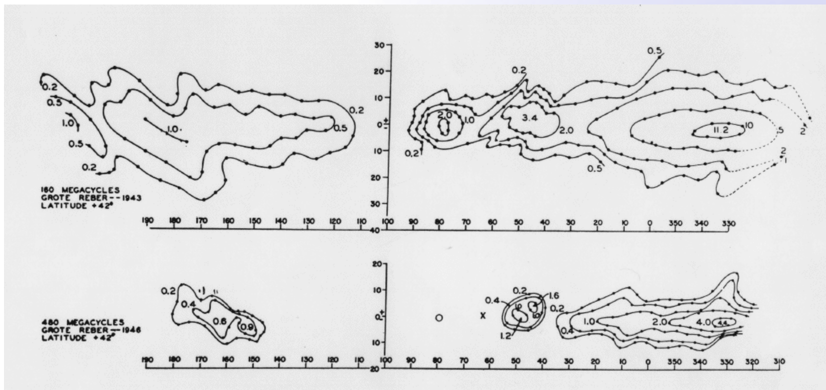
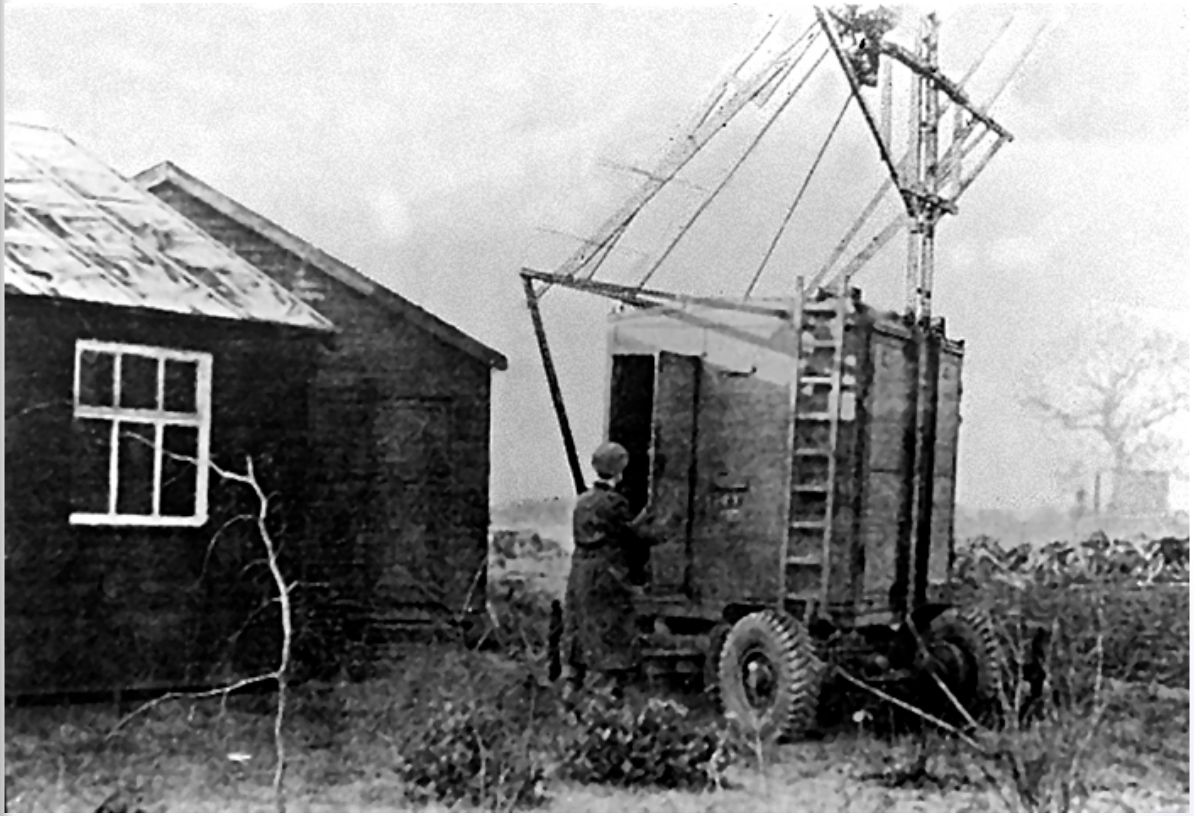


Fig. 7—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.

First Day at Jodrell Bank

Bernard Lovell established his experimental station south of Manchester, in December 1945.



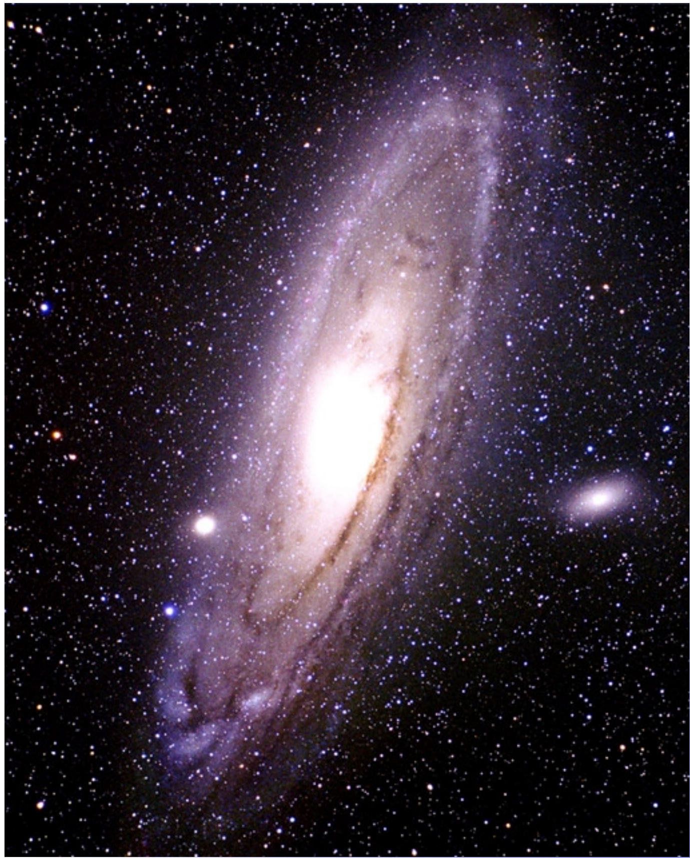
Radio/radar equipment from WW2 used to search for the origin of false radar echoes: cosmic rays?

1946: echoes due to meteors.

Transit Telescope

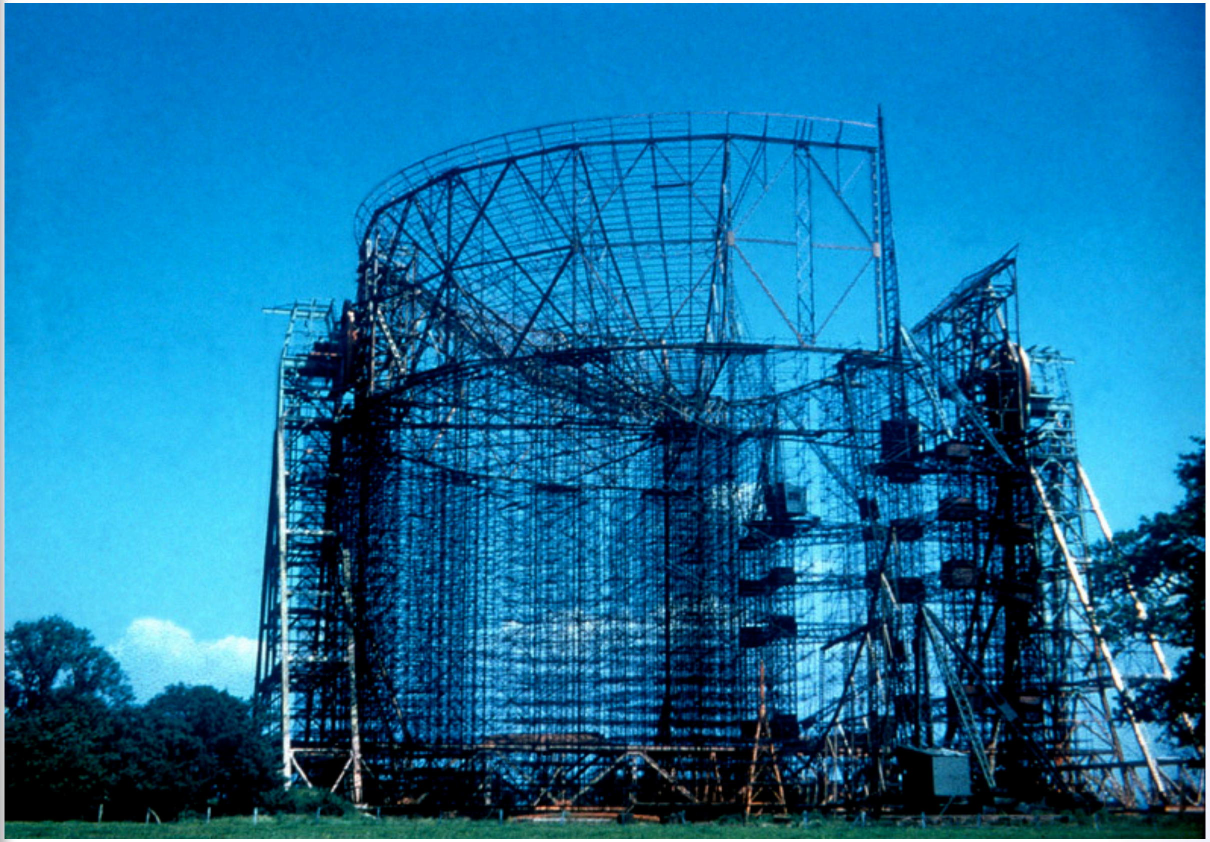
Jodrell Bank 218-foot (66m) transit telescope, built to look for weak radio emission from cosmic rays, discovered M31 in 1950.

The first extragalactic radio source: a large galaxy like our own, at a distance of 2 million light years.



The Lovell Telescope (MkI)

The first big dish: a 250-ft (76m) fully steerable radio telescope built 1952-1957.



The dish was redesigned during construction, so that it could observe the 21-cm hydrogen line.

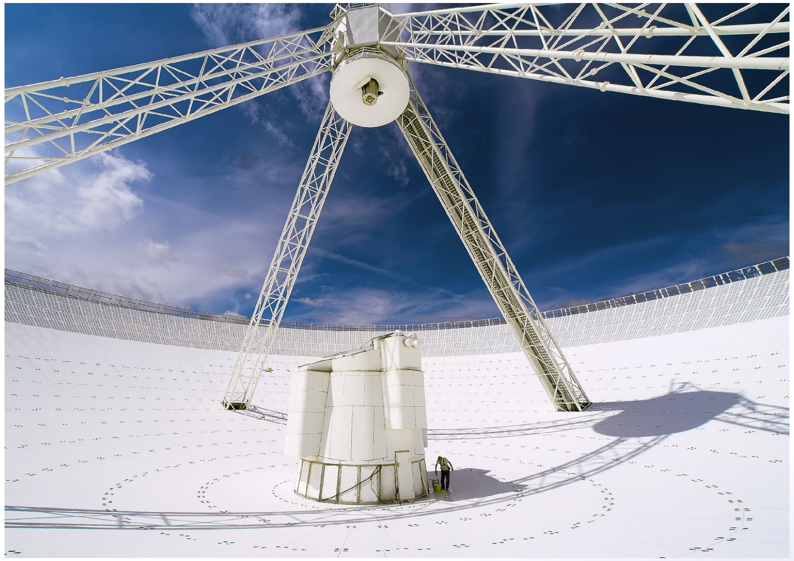
90 miles of scaffolding were used.

The Big Dishes

Lovell 76-m

The Big Dishes

Effelsberg 100-m



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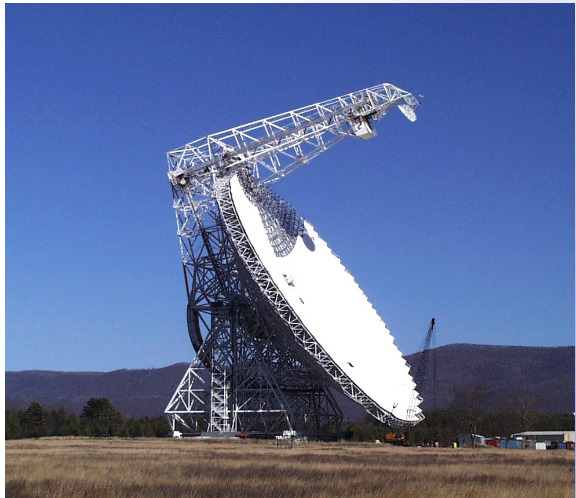
The Big Dishes

Greenbank 100m x 110m



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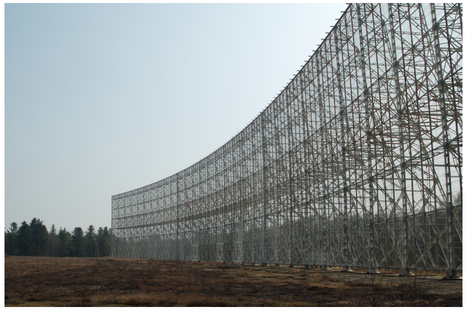
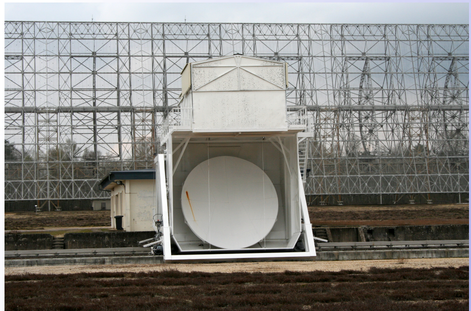
The Big Dishes

Nancay: 100-m equivalent





The Big Dishes

Arecibo: 300-m

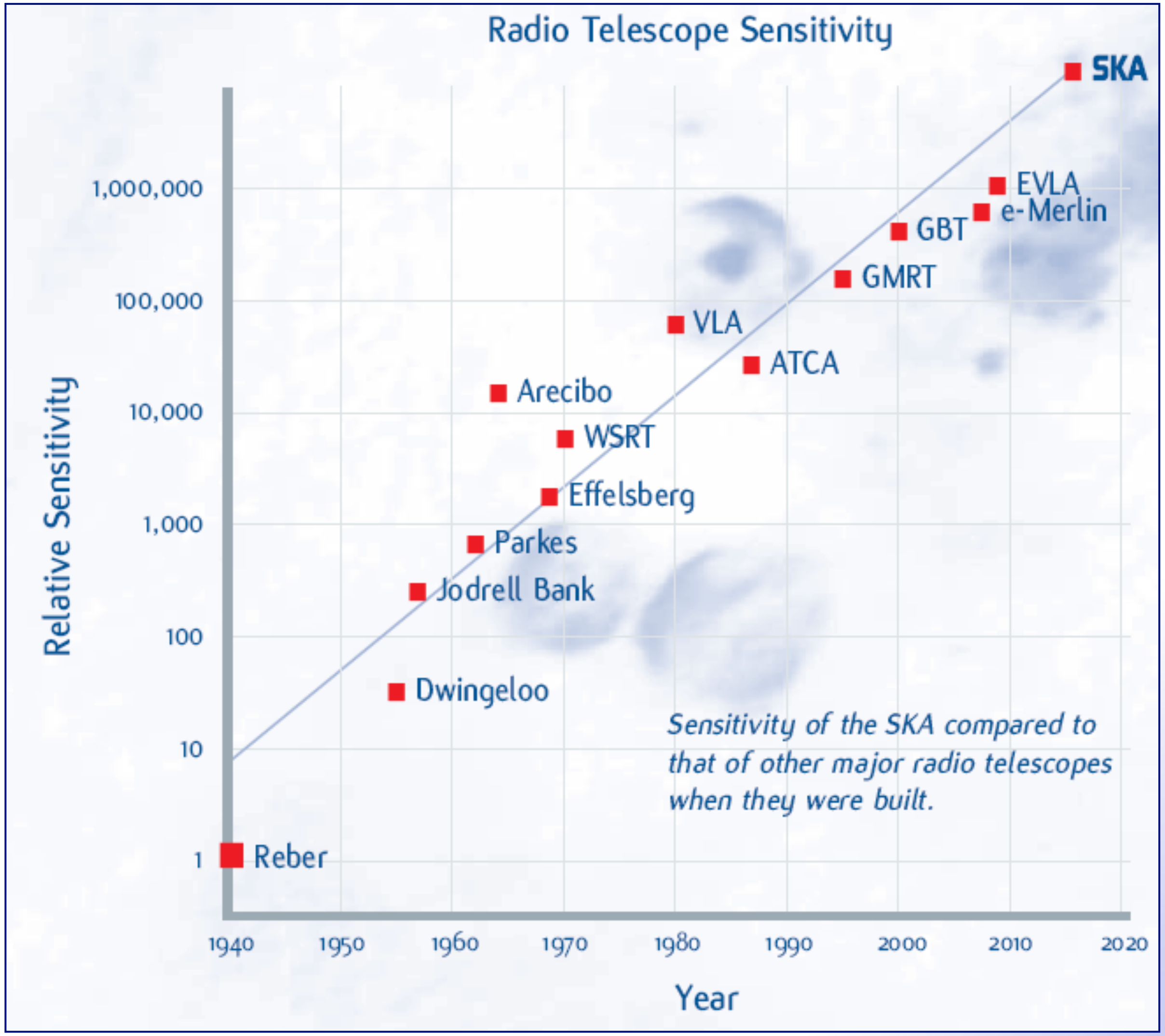
The Big Dishes

Sardina: 64-m - yesterday!

The Big Dishes

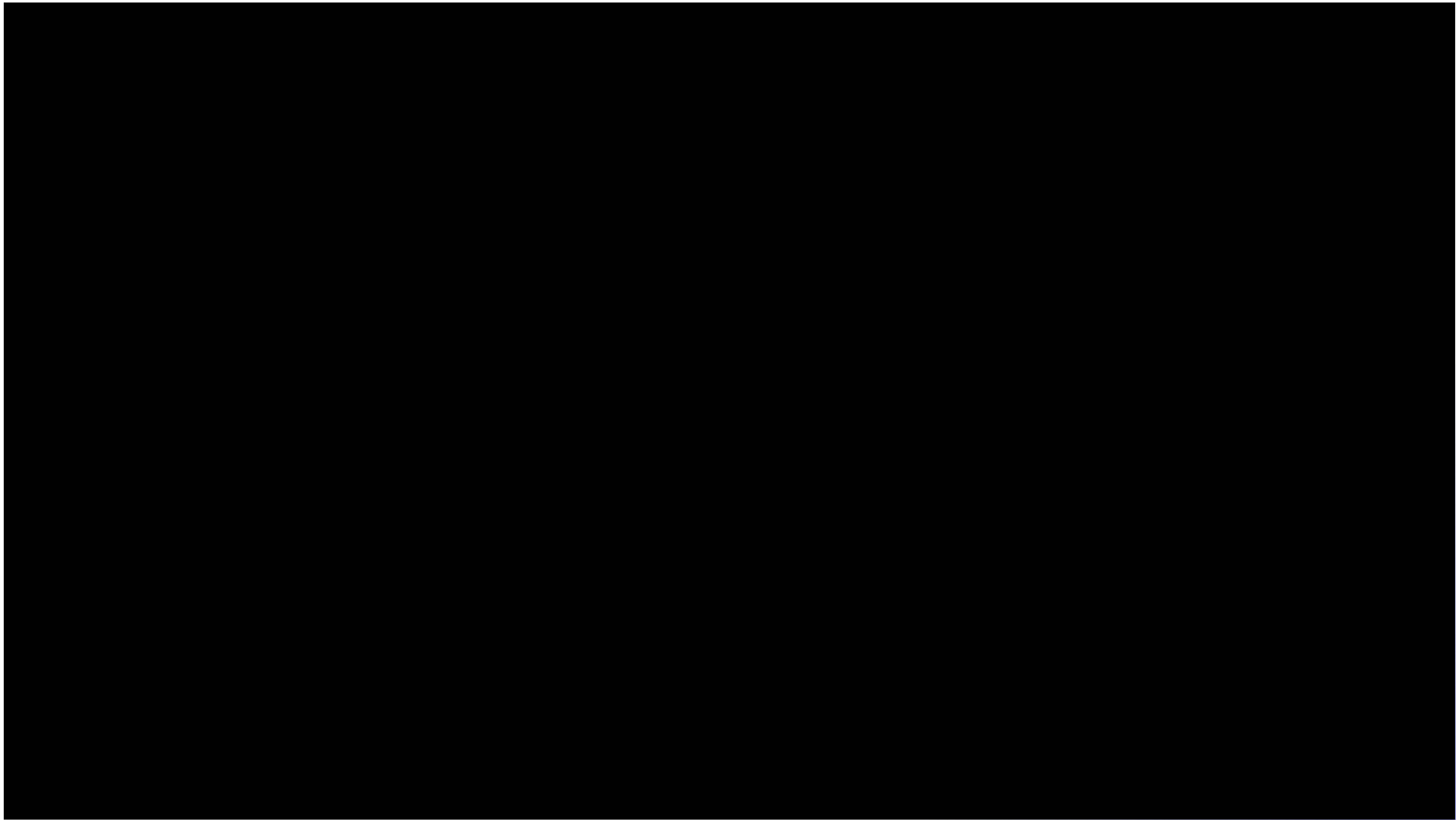
Parkes: 64-m

Radio Astronomy Sensitivity



60 dB improvement in 40 years: 1 μJy = 10^{-32} W m^{-2} Hz^{-1}

New telescopes mostly Arrays and interferometers



If your science requires the large scale structure, there's probably

NO ALTERNATIVE

to including Single Dish data

For both resolution and large-scale structure you need to combine single dish and interferometer data.

Single Dish Observing

- **Good response to small spatial frequencies**
- **Sensitivity:**
  - Sensitivity in **Jy** (point source) depends just on **collecting area**, SD or Interferometer.
  - Sensitivity in brightness temperature **K** (extended emission) gets WORSE as (Max.Baseline) squared, for the same collecting area – i.e. roughly as $\mathbf{(d/D)^2}$
    - 100-meter single dish: ~2 K/Jy
    - 1-mile max baseline aperture synthesis telescope: ~1600 K/Jy
- Ability to map very extended areas quickly (see survey speed)
- May provide large collecting area with manageable electronic complexity

- **Simplicity**: One receiver, not N receivers, nor N.(N-1)/2 correlations
- BUT *relatively* easy to implement large imaging arrays, including bolometers, which can increase mapping speed by orders of magnitude.
- Multi-frequency receivers relatively easy investment

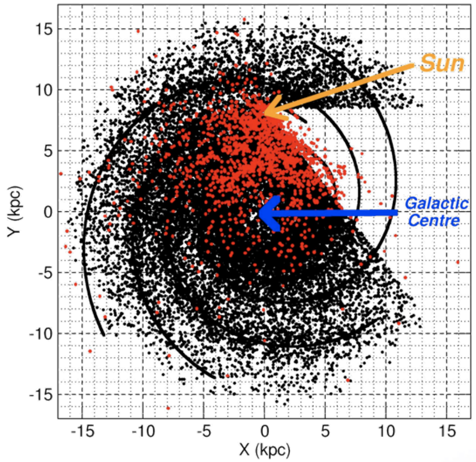
- **Flexibility**:
- Relative ease of upgrading, customizing hardware to an experiment
- Relative ease of implementing radar tx systems
- A single large dish can add significant sensitivity to (e.g.) VLBI arrays
- Software possibly simpler: "Conceptually" easier to understand for novice astronomers. (But this is inexcusable!)

Practical Single Dish vs. Interferometer issues

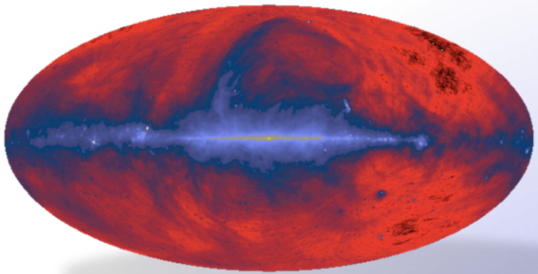
- Single dishes have limited response to high spatial frequencies
- Mechanical complexity replaces electronic complexity
- Susceptibility to instrumental drifts in gain and noise –
  no correlation advantage of interferometers
- Interferometers can *in principle* give high sensitivity and high total collecting area.
- Aperture synthesis imaging is a form of multi-beaming - arguably obtaining more information from the radiation falling on a telescope than is possible with a single dish.

Single Dishes are good for...

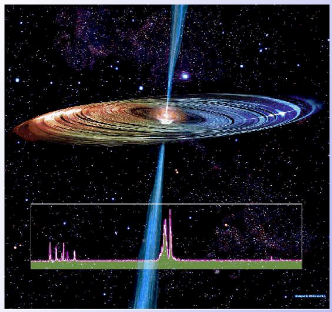
- Pulsar observations, e.g. >99% of known pulsars have been found with single dishes



- Large-area/large structure surveys:



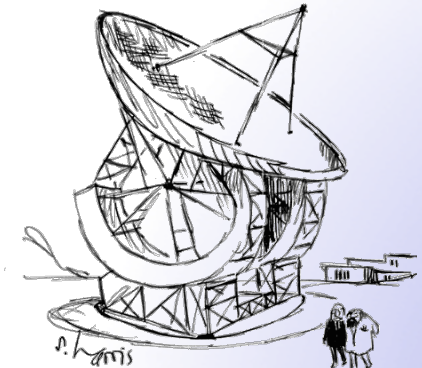
- Point sources:



And much more...!

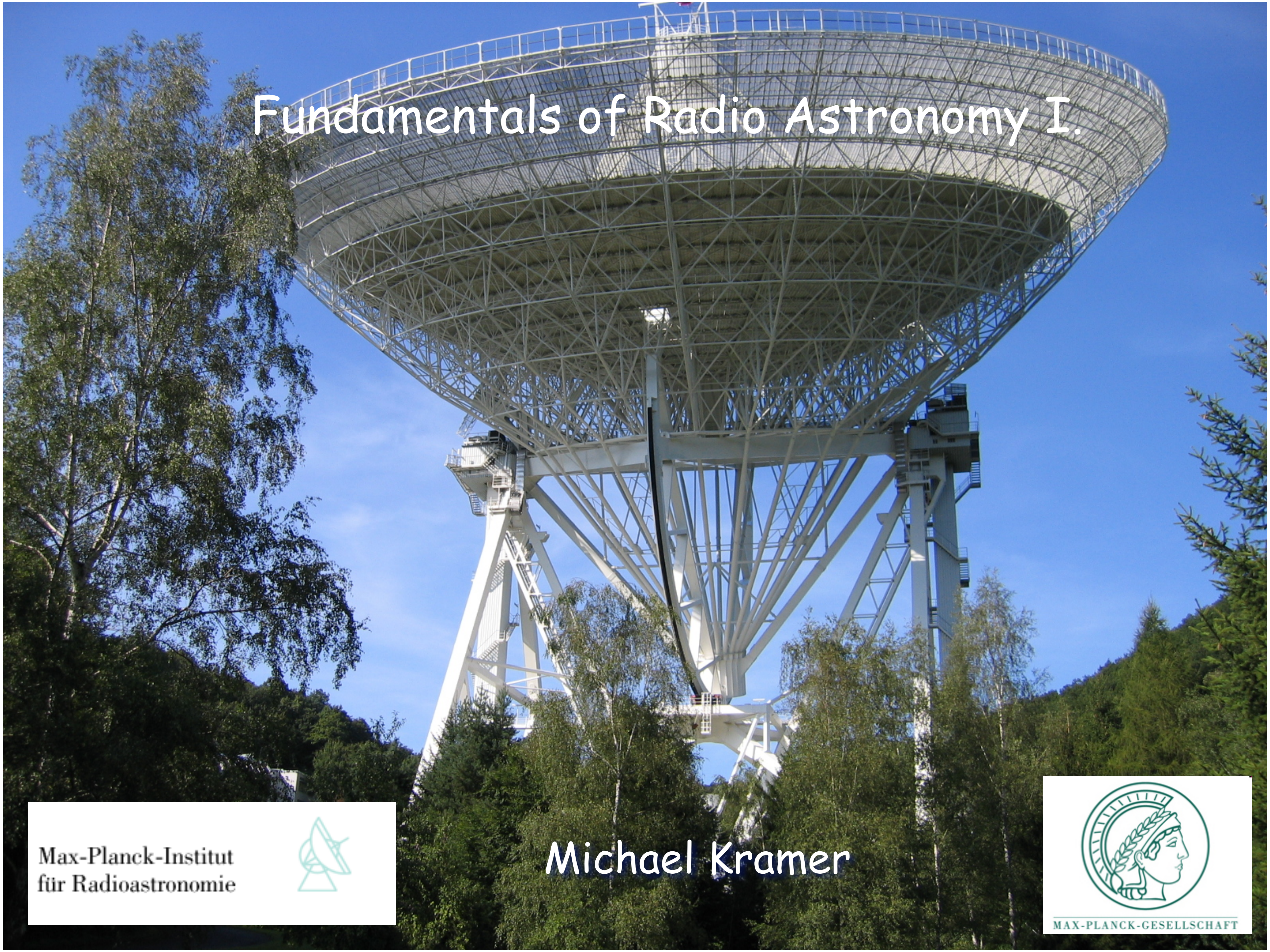
This week…

- A series of lectures, real observing, hands-on and tutorials
- Coverage of (nearly) all topics related to single-dish
- Insight into current research
- Lecturer & tutors by experts from
  - Argelander Institut der Universität Bonn
  - Jodrell Bank Centre for Astrophysics, University of Manchester
  - INAF/Osservatorio Astronomico di Cagliari, Sardinia
  - MPI für Radioastronomie
- Hopefully, a lot of fun also…!



"We sent a message to any extraterrestrial beings in deep space. It was picked up by an observatory in Great Britain. They didn't understand it."

Fundamentals of Radio Astronomy I.



Michael Kramer

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Outline

- The radio sky
- Thermal vs. non-thermal emission
- Free-free emission (thermal bremsstrahlung)
- Synchrotron emission
- Radiation transfer (self-absorption)
- Pulsars and their radiation
- Spectral lines
- HI emission

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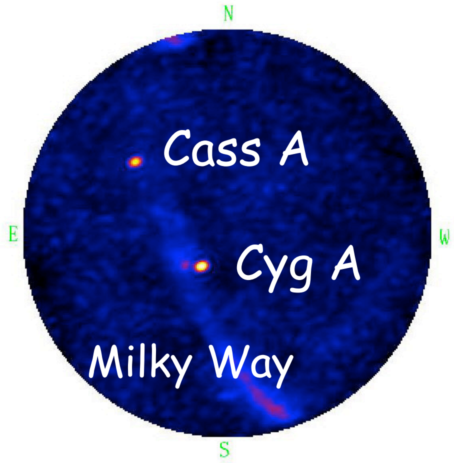
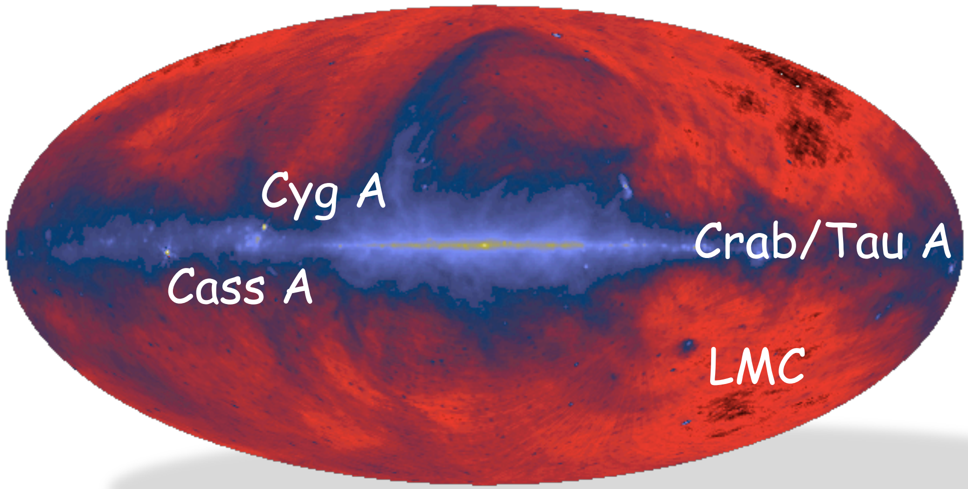
The Radio Sky



HBA – 60s@120MHz



Effelsberg/Jodrell/Parkes – 480MHz

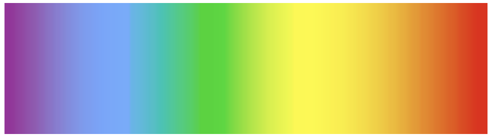
- Most dominant source in the radio sky is the Sun (10^5 Jy)
- Next strongest: radio galaxy Cygnus-A (Cyg A, 10^4 Jy)

  supernova remnant Cassiopeia-A (Cas A, 10^4 Jy)
- Others: supernova remnants, radio galaxies, pulsars etc.

Sources of Radio Emission

- Electromagnetic emission (and hence radio!) is produced by the acceleration of charged particles or atomic transitions:

Continuum emission:



Line emission:

- We distinguish between thermal and non-thermal emission.

Thermal vs. Non-thermal Emission

Thermal processes:

Energy distribution of particles is thermal,

i.e. it can be described simply by temperature

Usually: blackbody

thermal bremsstrahlung

Non-thermal processes:

Energy distribution of particles is not thermal, e.g. relativistic particles

Usually: non-thermal bremsstrahlung

inverse Compton scattering

synchrotron radiation

Thermal Emission

- Blackbody radiation: see JK's lecture, e.g. thermal emission from dust

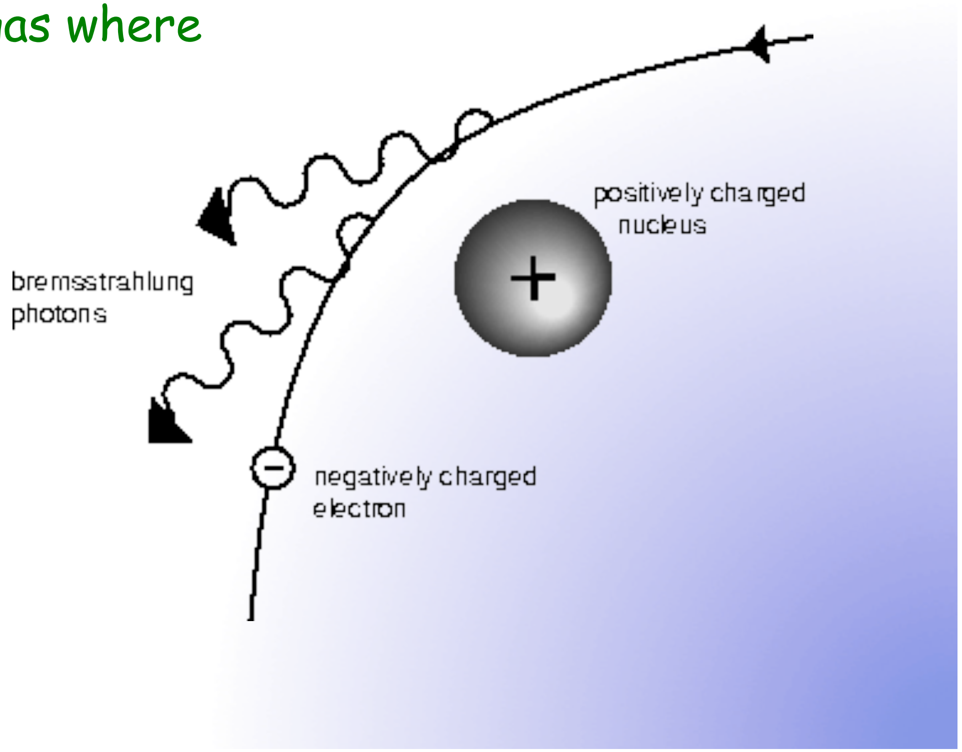
Thermal Emission

- Blackbody radiation: see JK's lecture, e.g. thermal emission from dust
- Free-free emission = "Thermal Bremsstrahlung"

Charged particle slows down by emitting photon

Particle is unbound (free) before and after

Important for hot ionized gas where
electrons move in field
of ionized atoms



Thermal Emission

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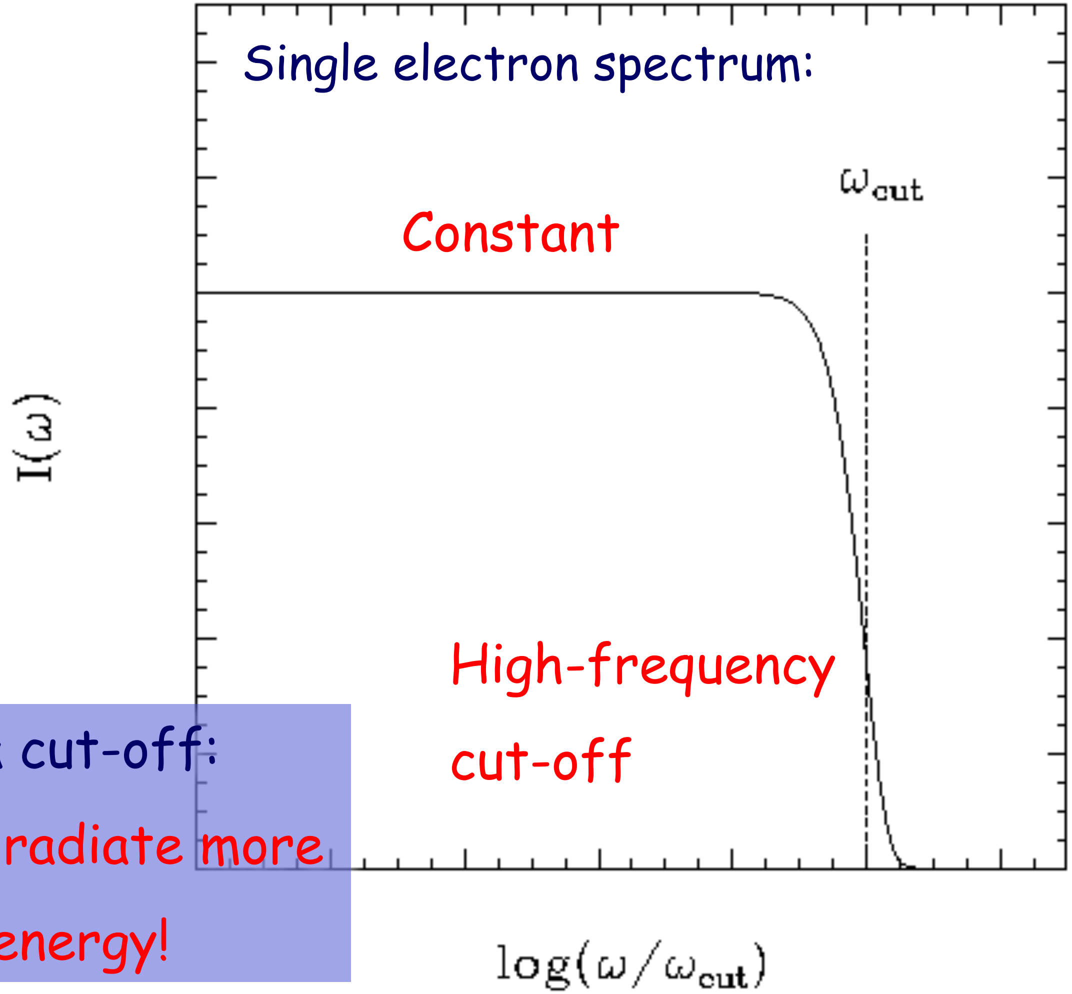


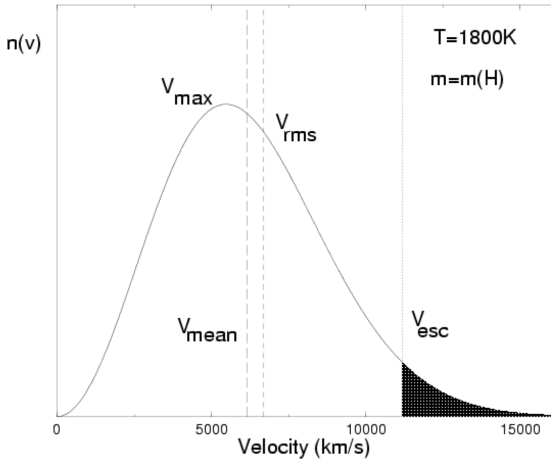
There must be a cut-off:

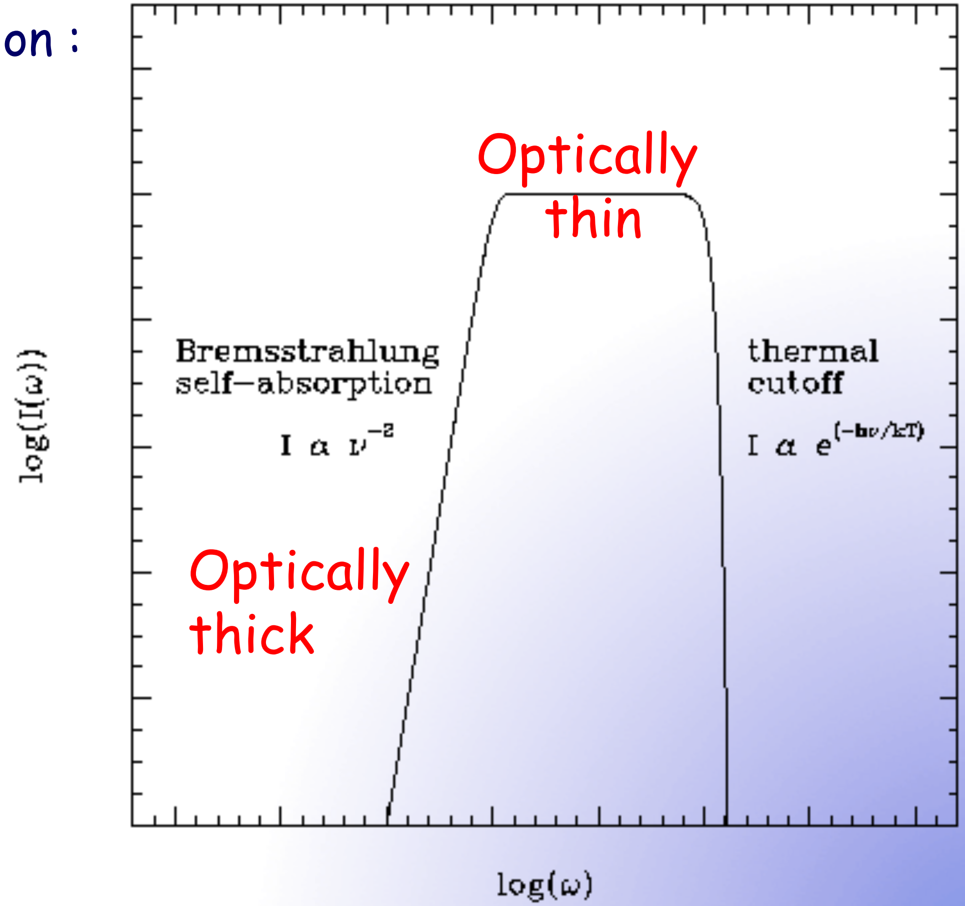
Electron cannot radiate more than its kinetic energy!

Thermal Emission

- Blackbody radiation: see JK's lecture, e.g. thermal emission from dust
- Free-free emission = "Thermal Bremsstrahlung"

Spectrum from thermal distribution :



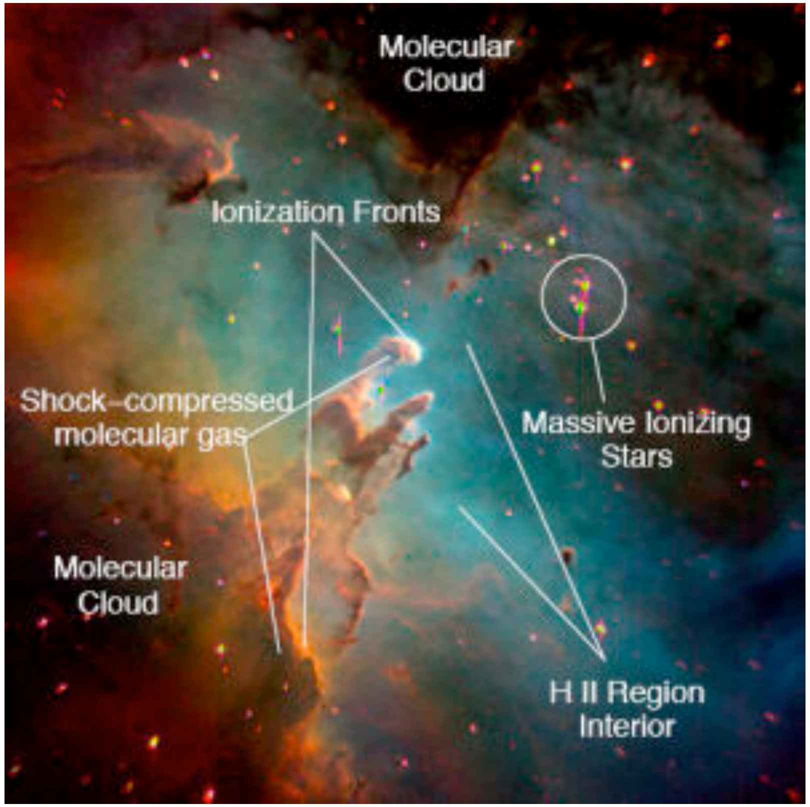


Need to consider raditation transfer!!

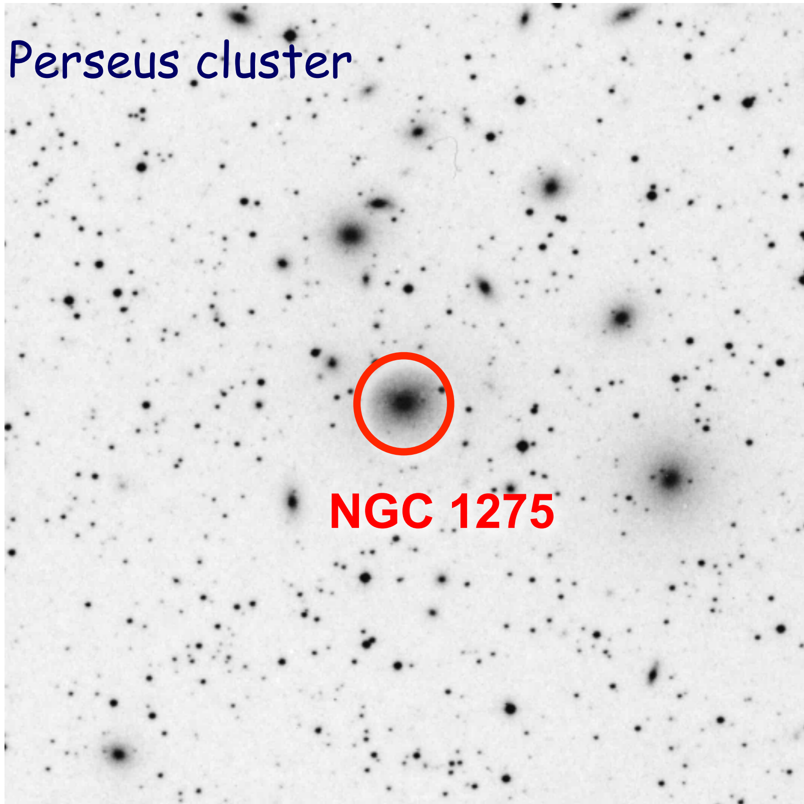
Thermal Emission

- Blackbody radiation: see JK's lecture, e.g. thermal emission from dust
- Free-free emission = "Thermal Bremsstrahlung"

  Examples:



HII regions

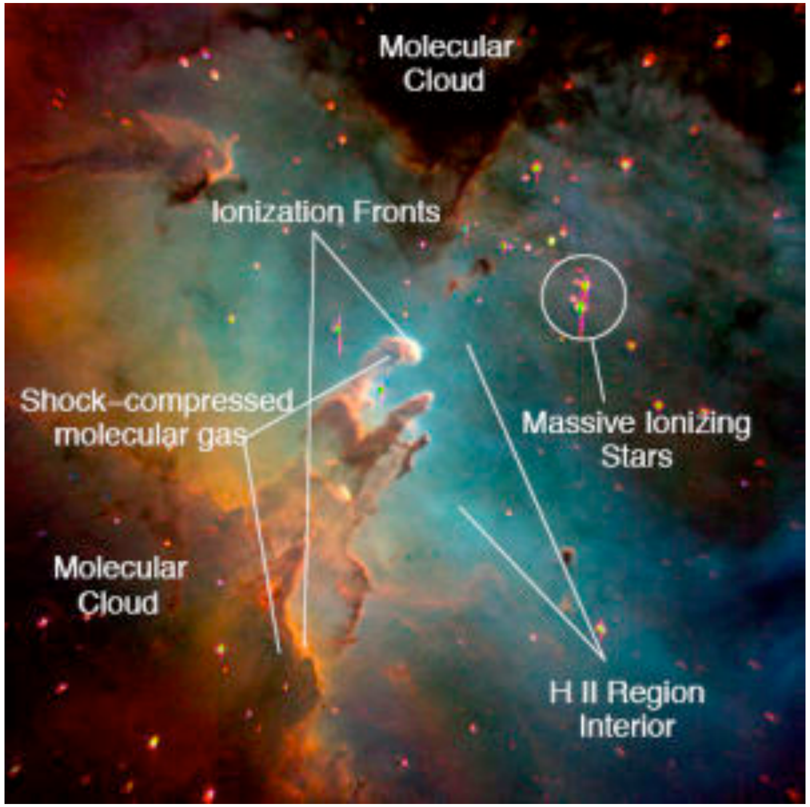


Hot gas in cluster of galaxies

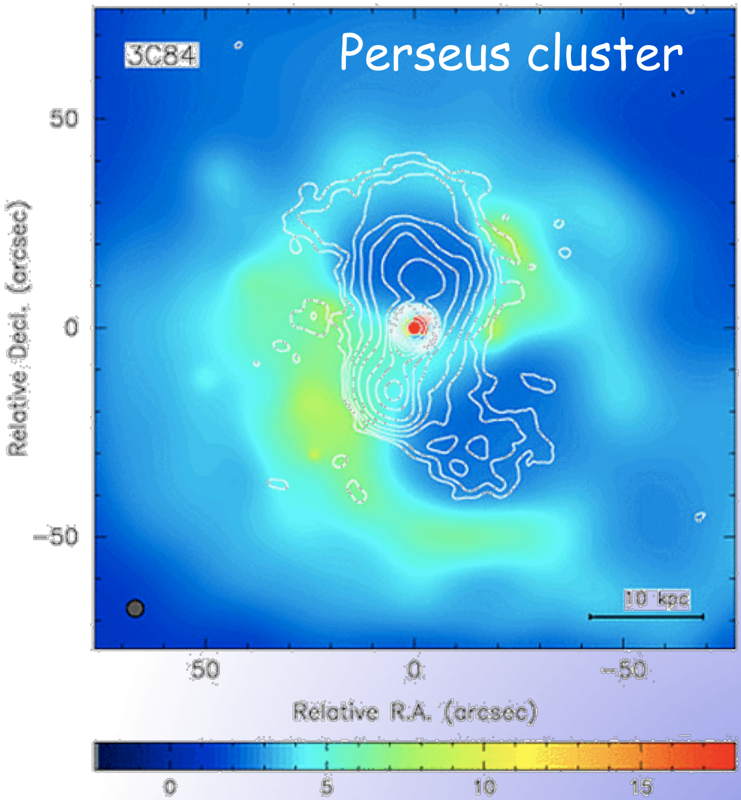
Thermal Emission

- Blackbody radiation: see JK's lecture, e.g. thermal emission from dust
- Free-free emission = "Thermal Bremsstrahlung"

  Examples:



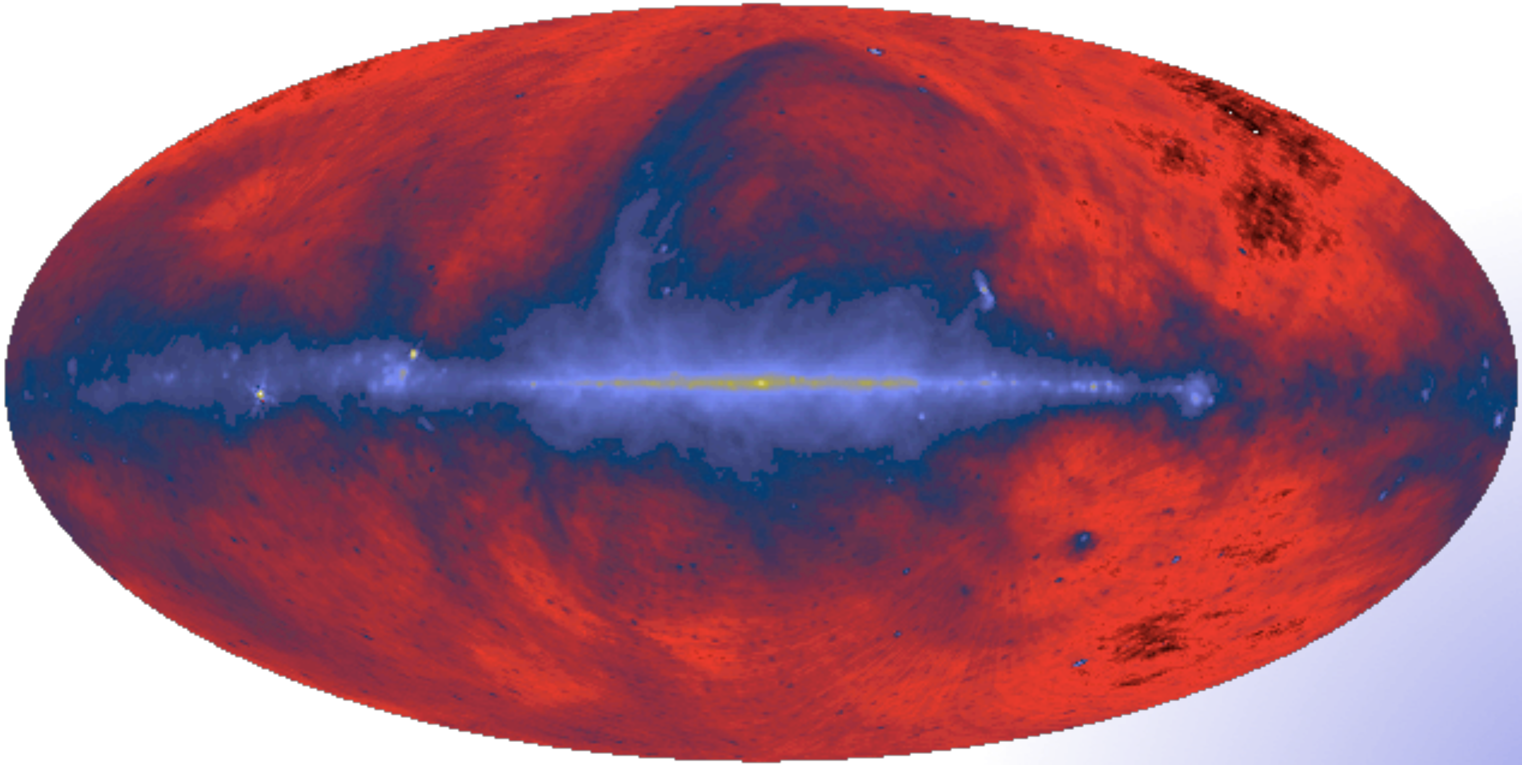
HII regions



Hot gas in cluster of galaxies

Non-thermal Emission

- Thomson (CMB!) and Compton scattering: mostly high energy
- Synchrotron emission:



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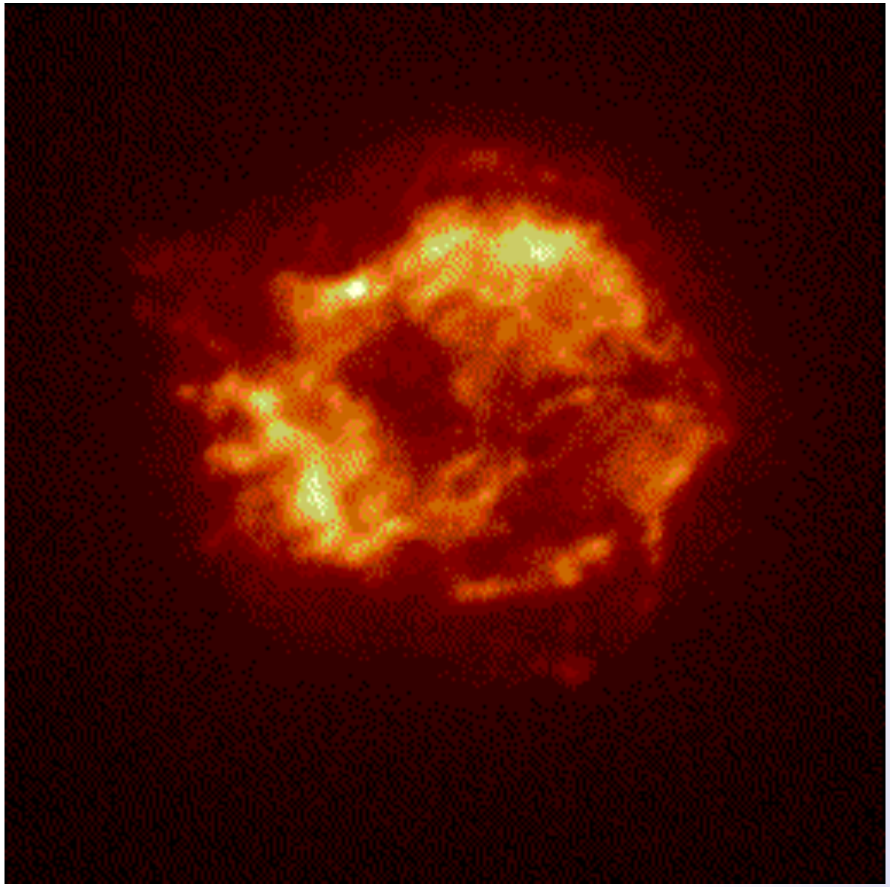

Cassiopeia A (Cas A)

Non-thermal Emission

- Thomson (CMB!) and Compton scattering: mostly high energy
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Non-thermal Emission

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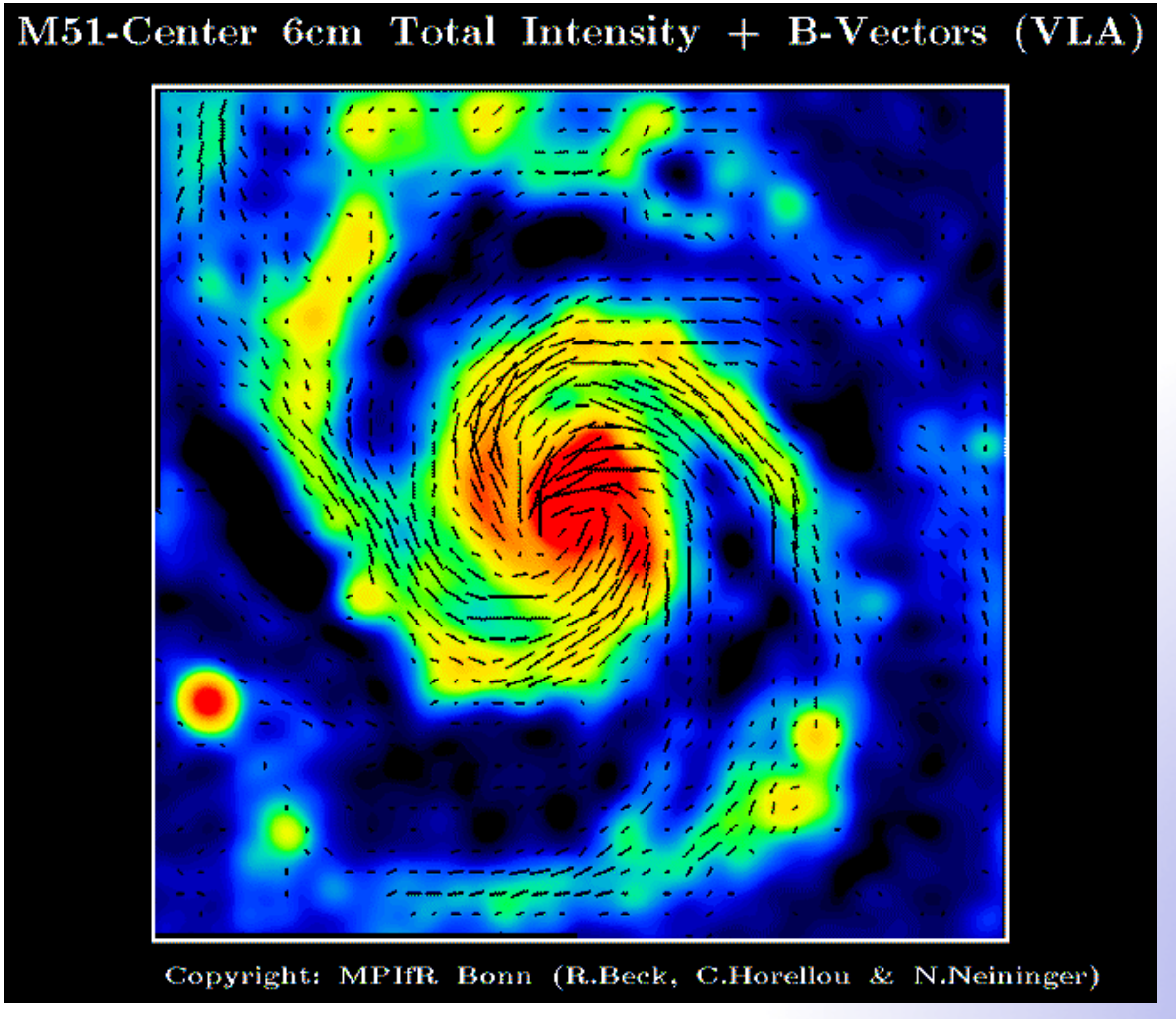

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Synchrotron Emission

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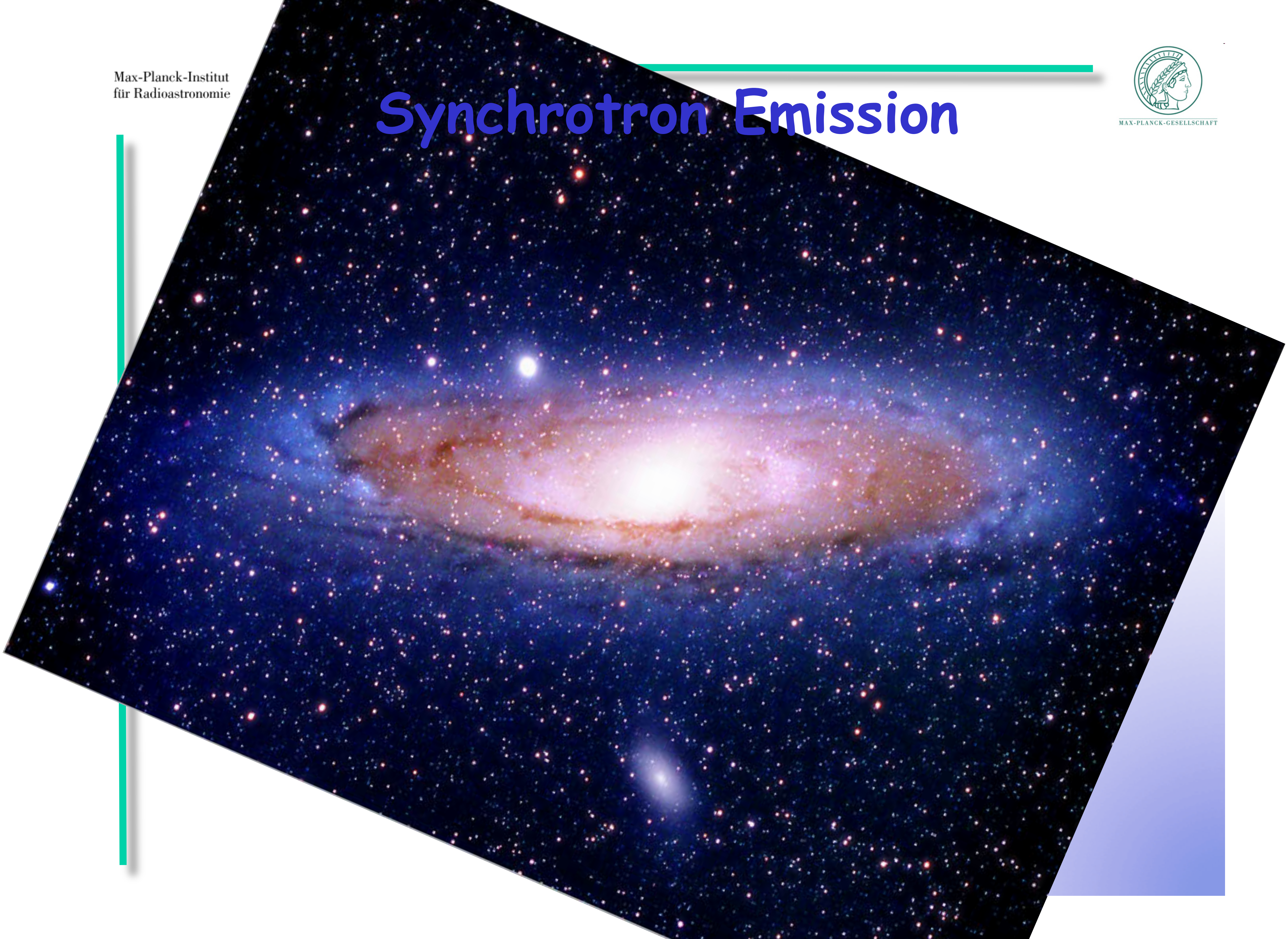

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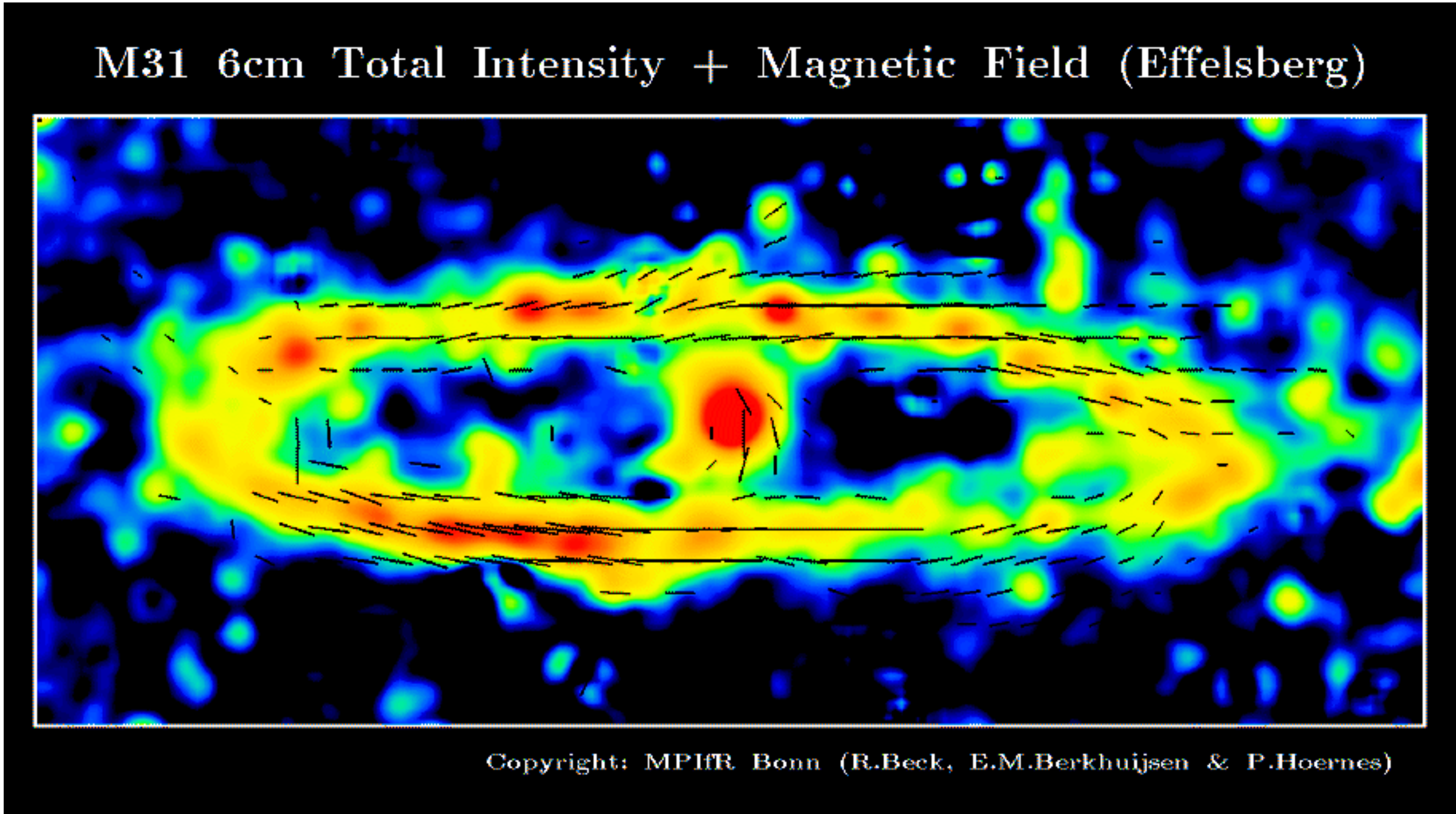
Synchrotron Emission



Non-thermal Emission

- Thomson (CMB!) and Compton scattering: mostly high energy
- Synchrotron emission:

Charged particle moving in magnetic field

Particle is accelerated and

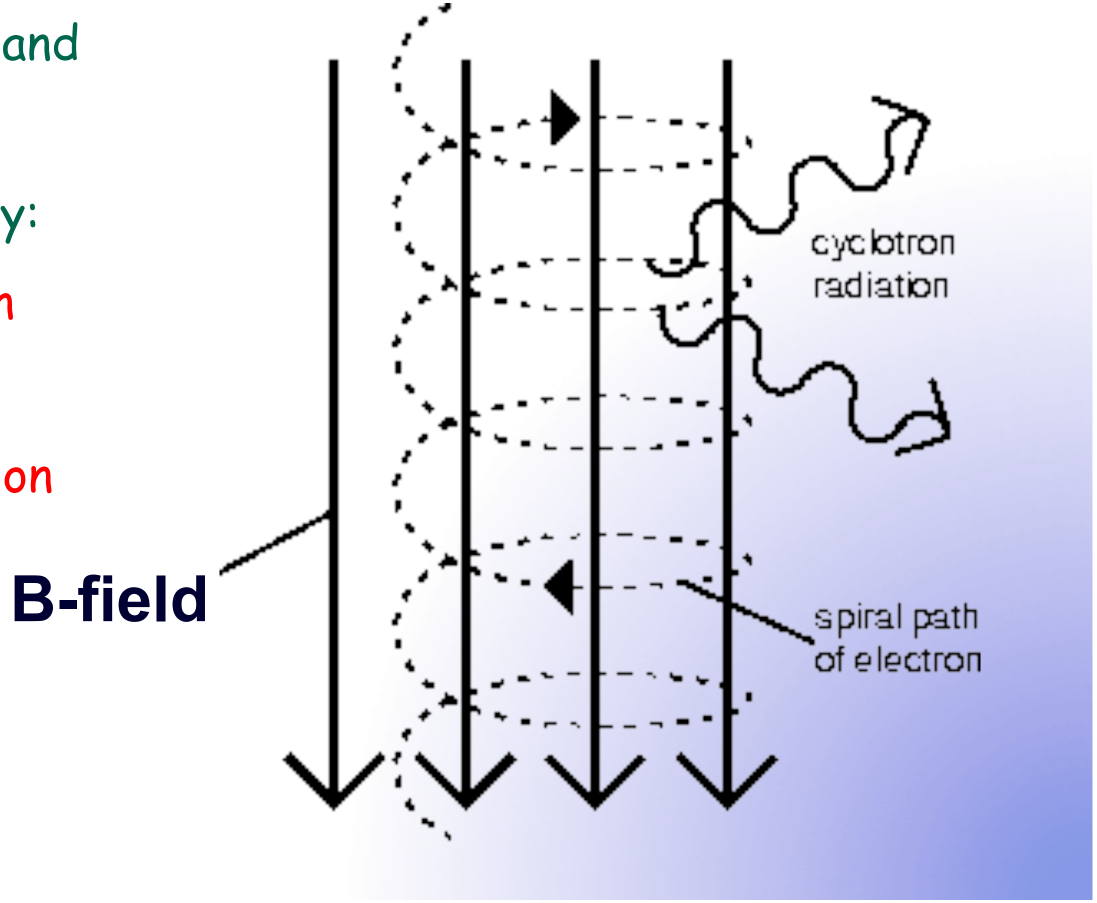
hence radiates

Non-relativistic velocity:

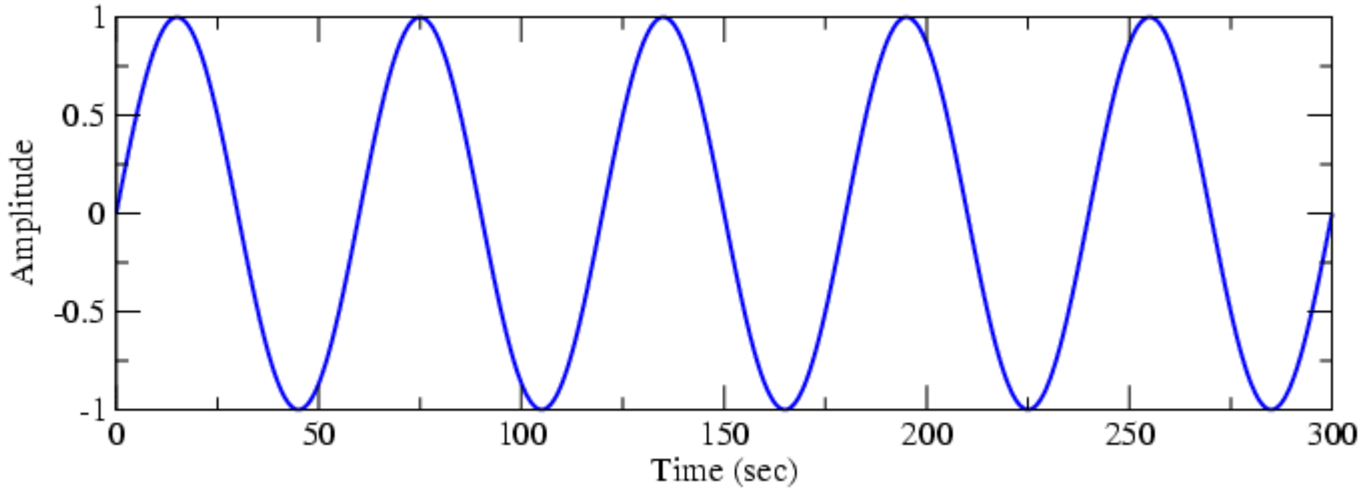
Cyclotron emission

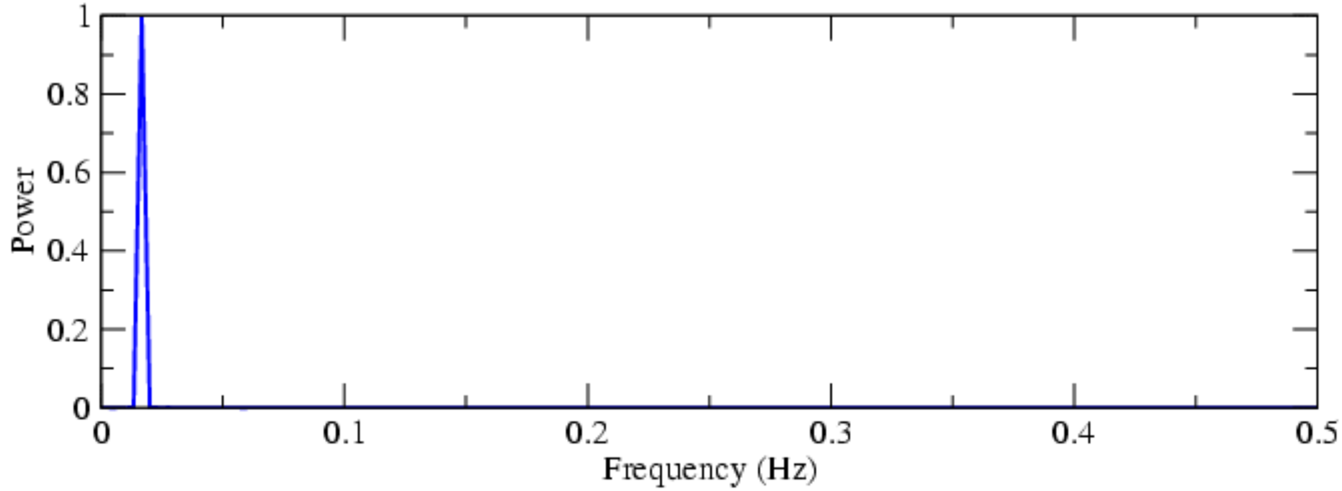
Relativistic velocity:

Synchrotron emission



Cyclotron emission





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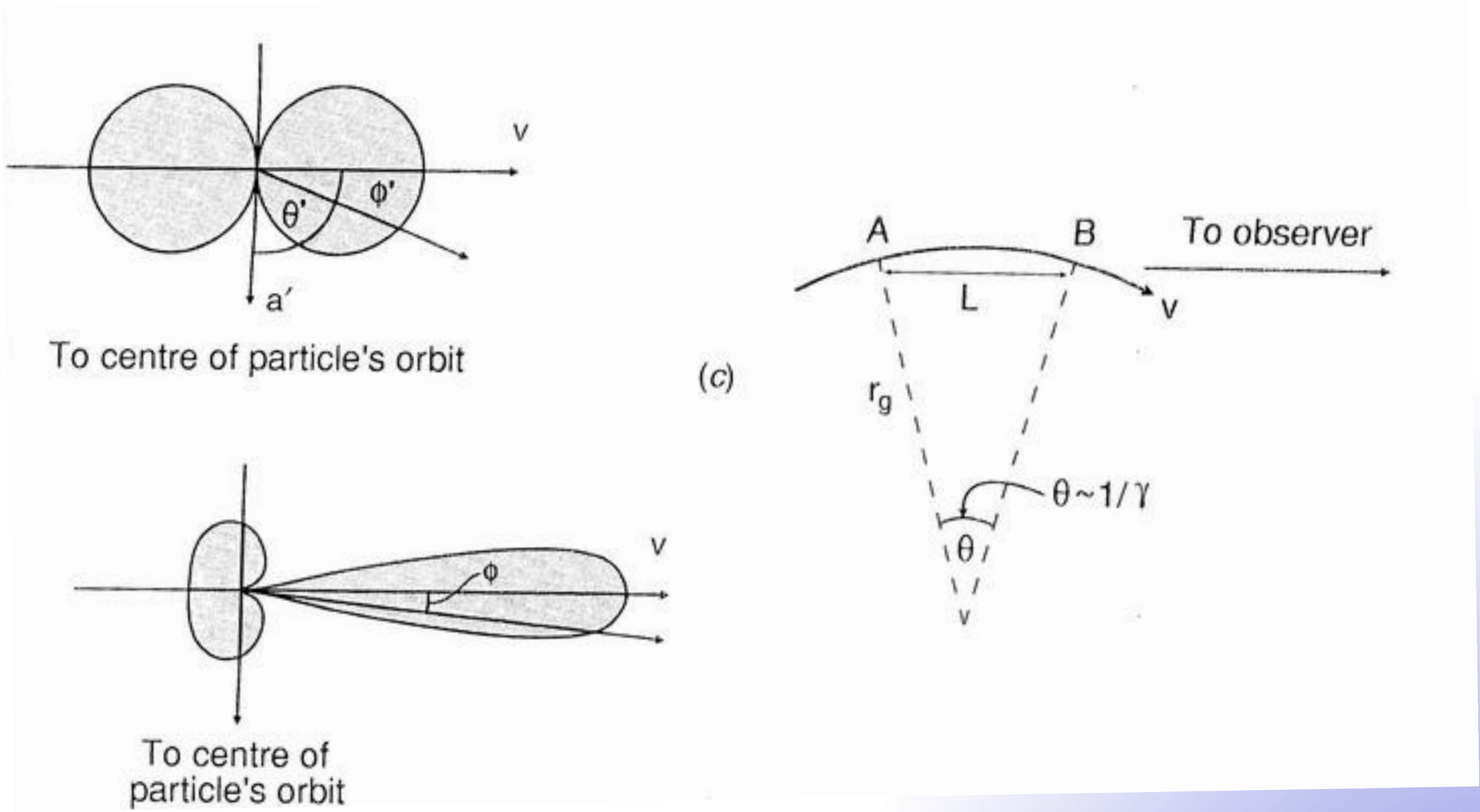
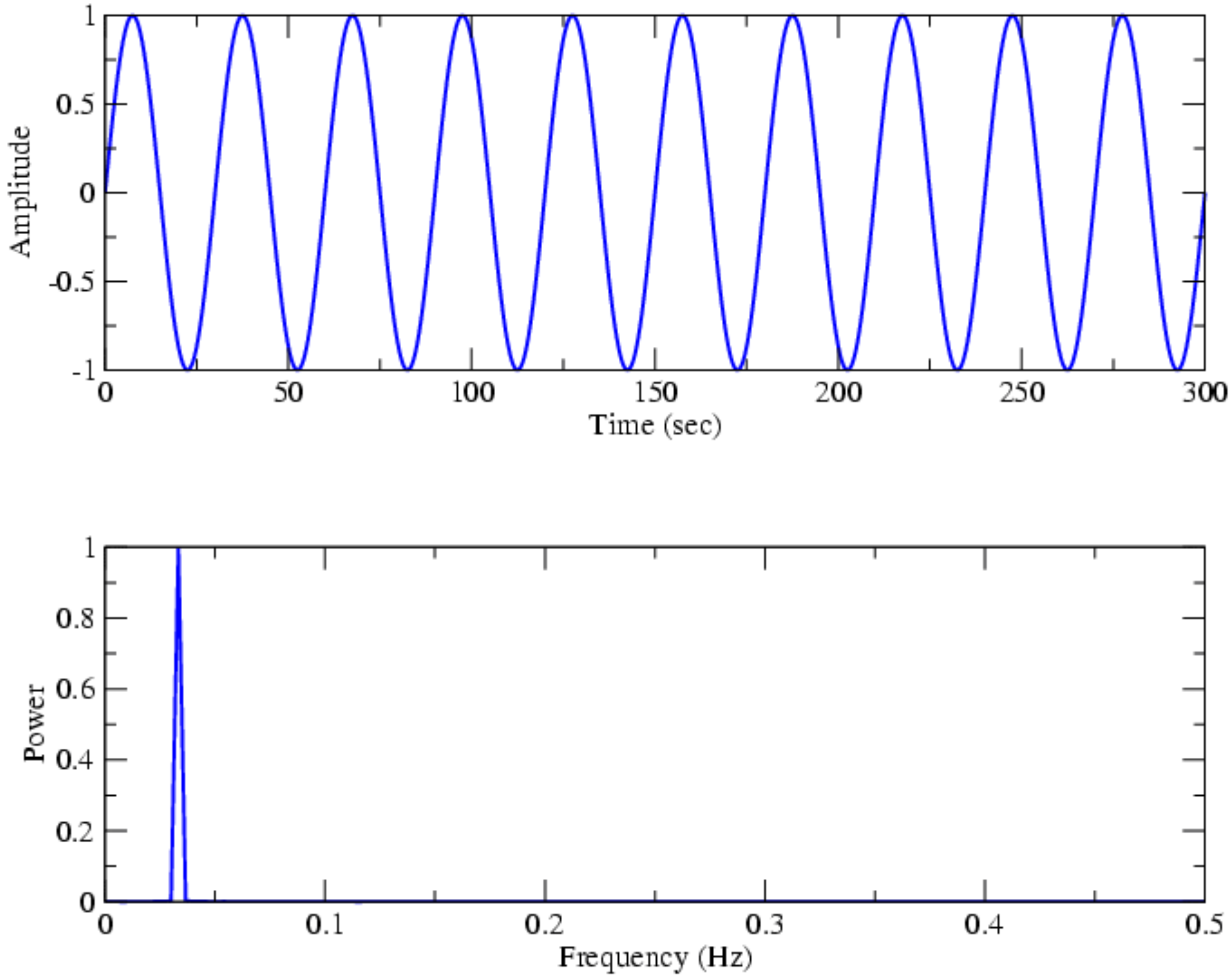
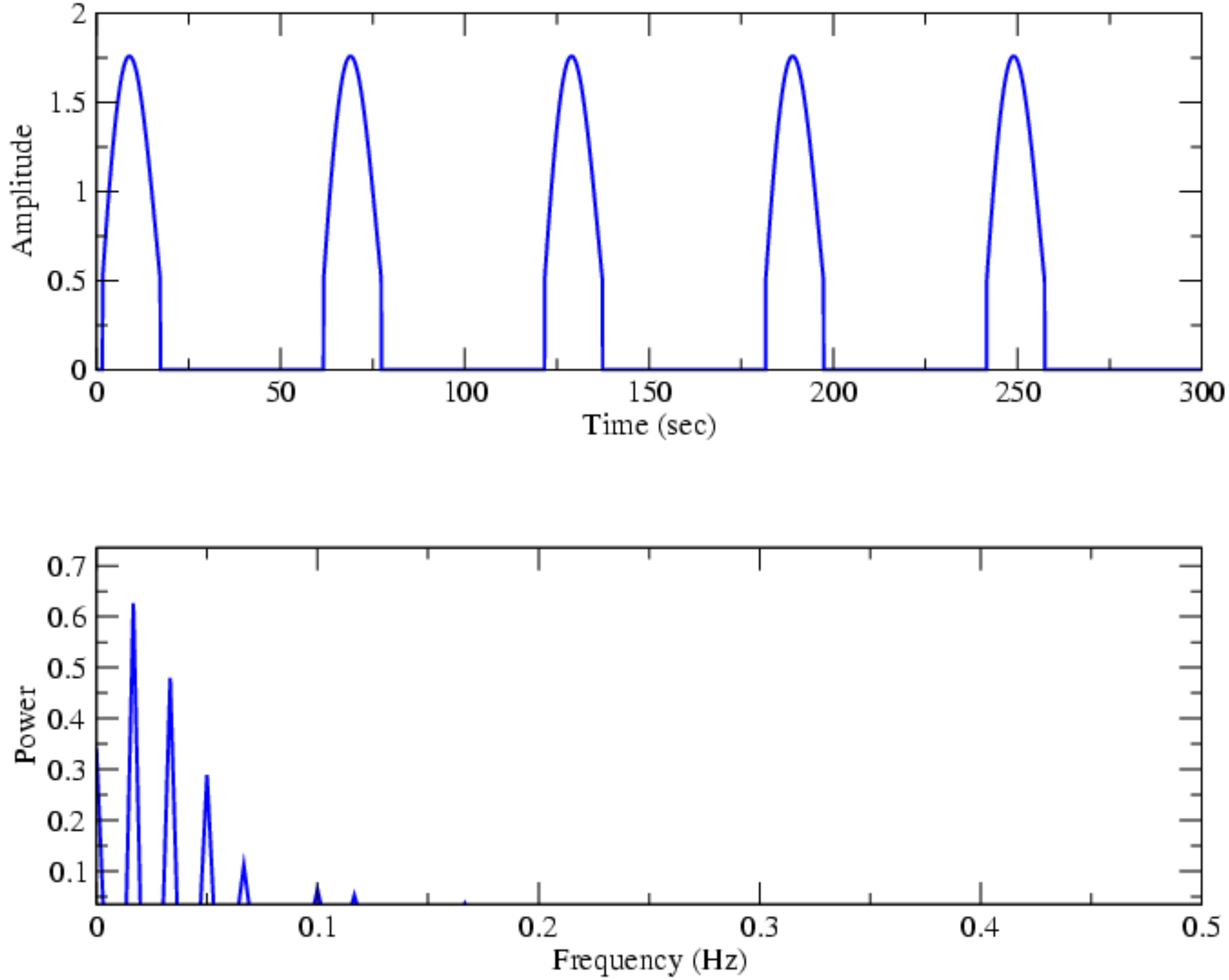
Mildly relativistic motion



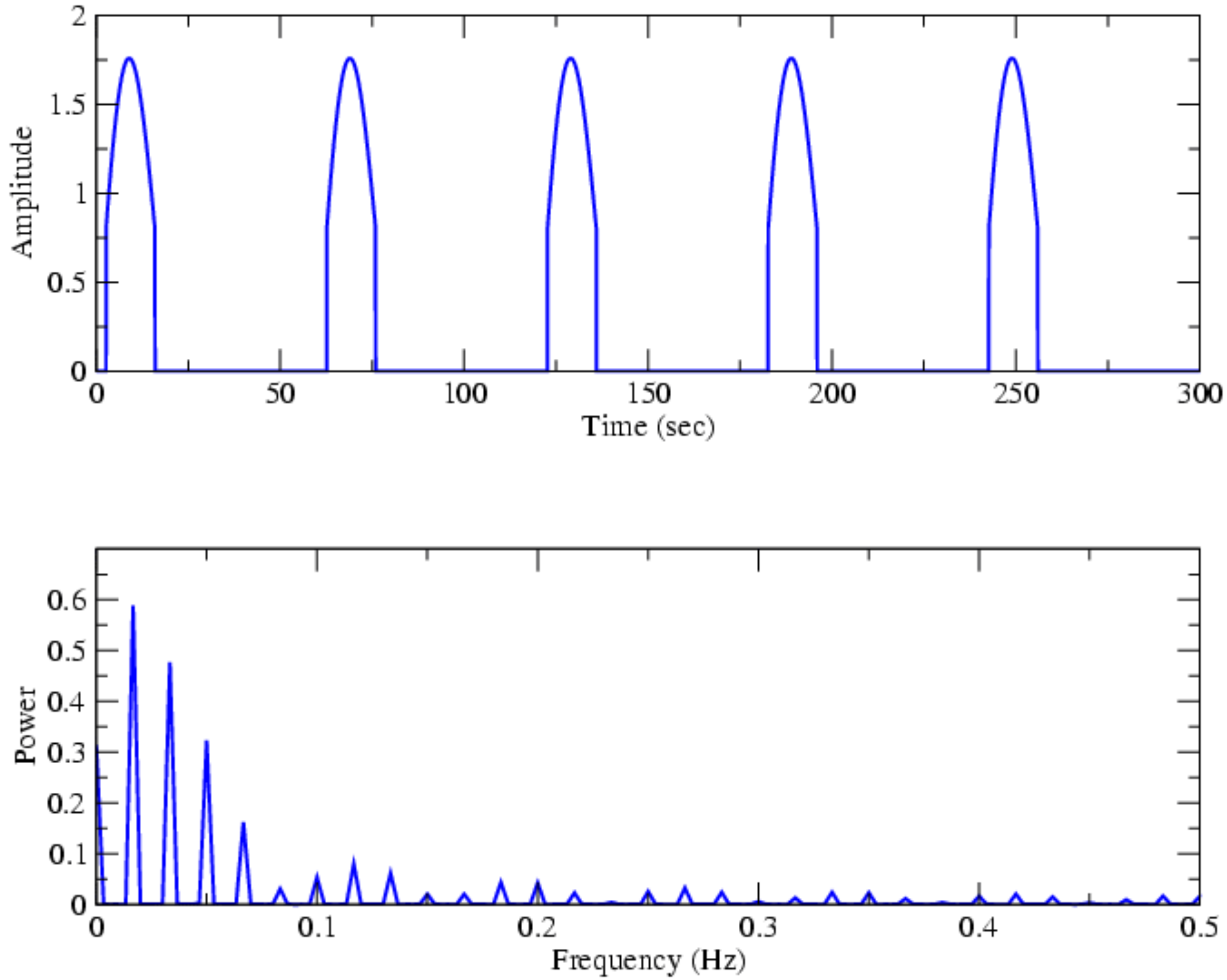
Digression: Fourier Transforms



Digression: Fourier Transforms

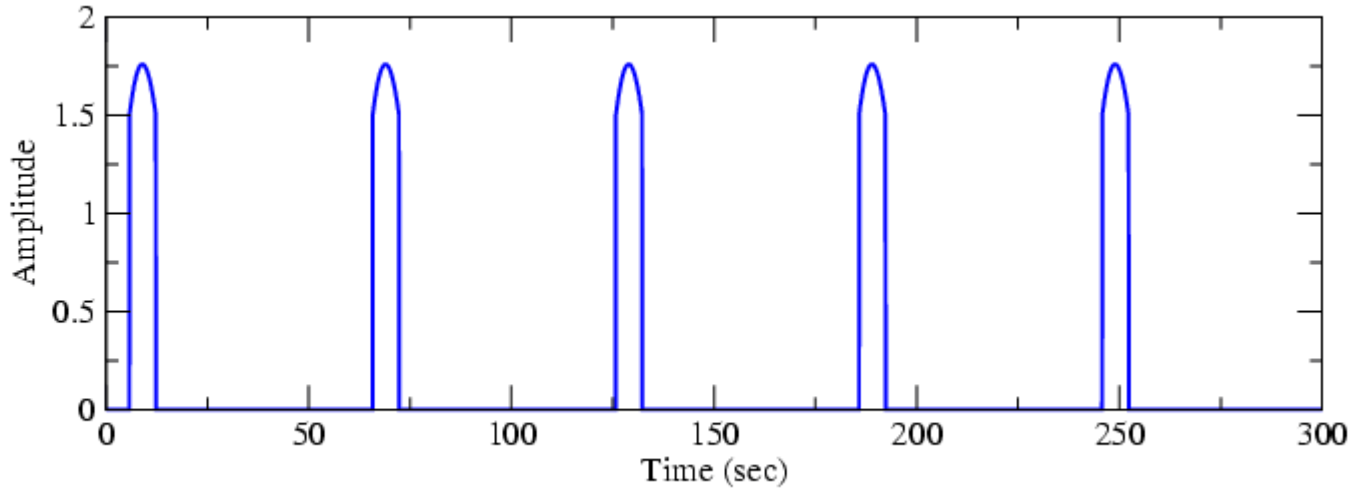


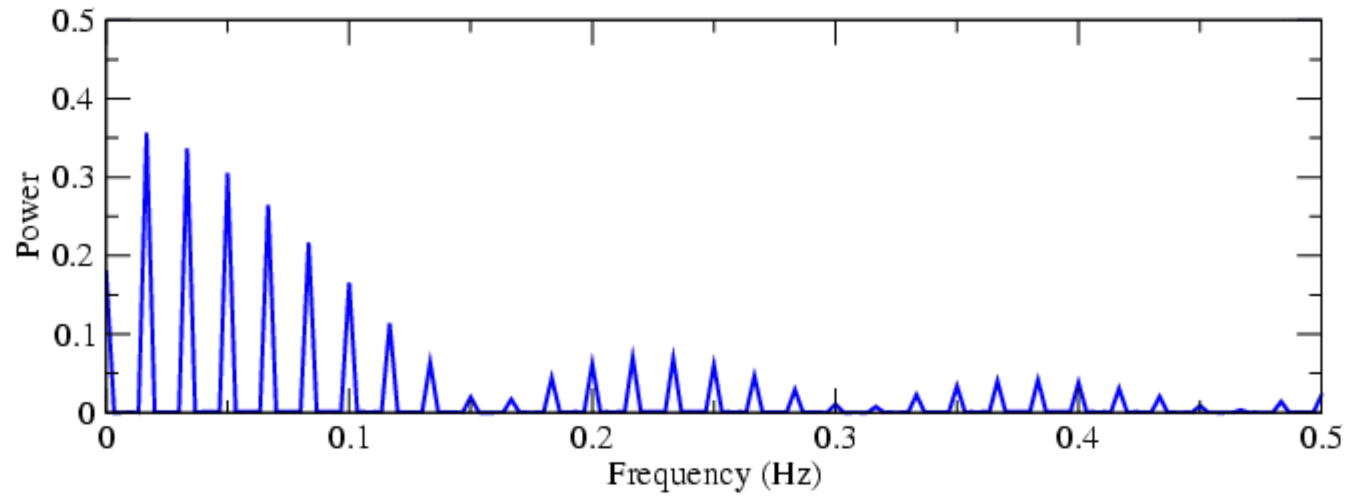
Digression: Fourier Transforms



Max-Planck-Institut
für Radioastronomie

Mildly relativistic motion





For faster e⁻, even sharper pulses:

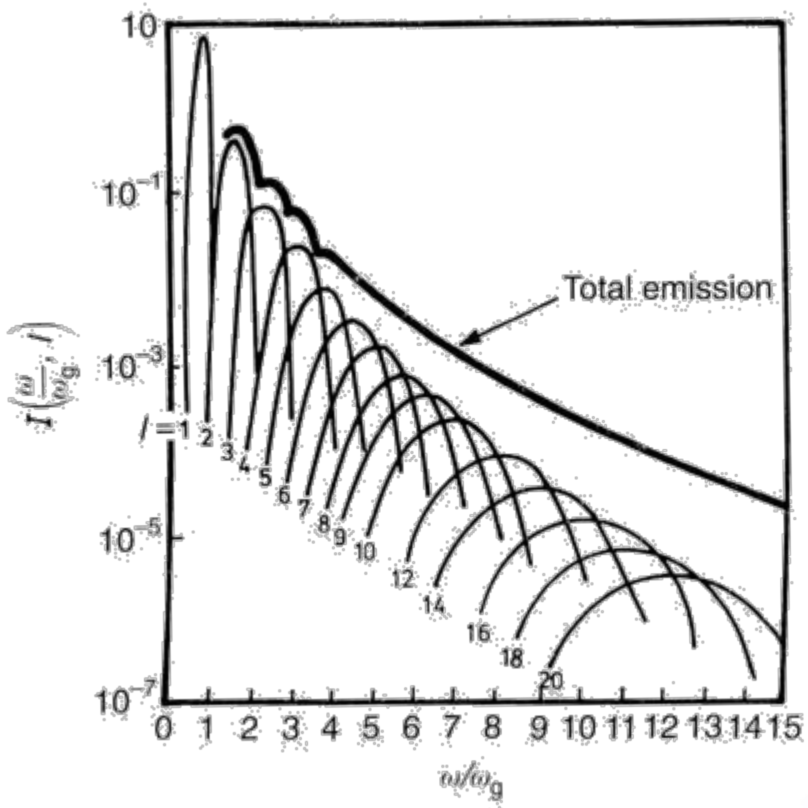
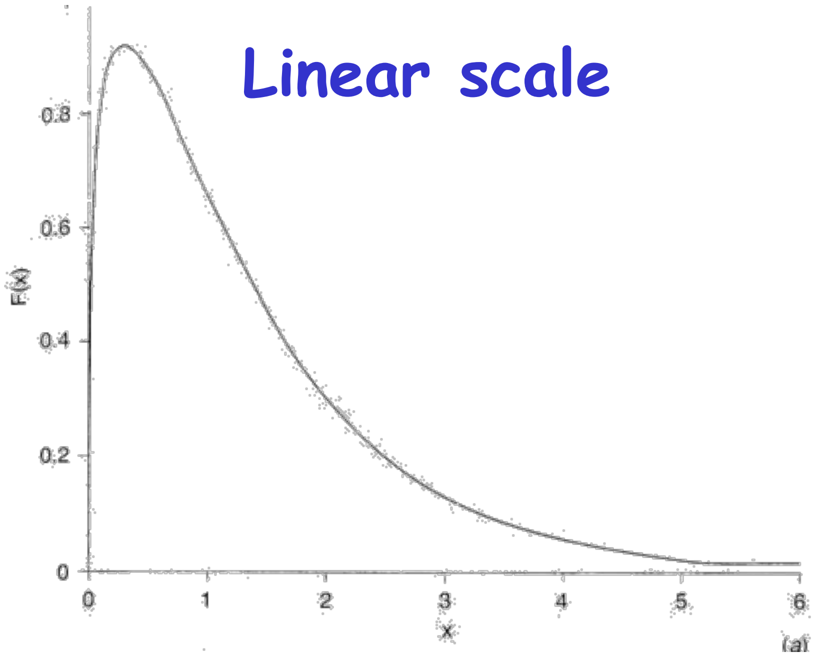


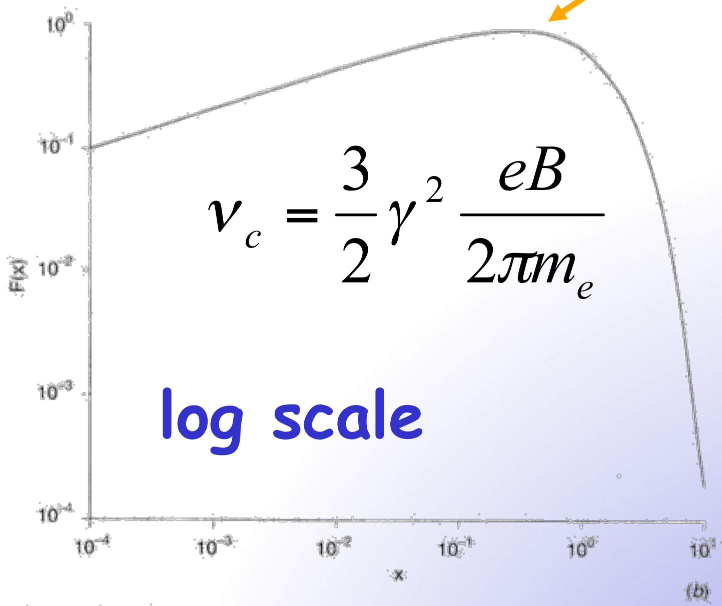
Figure 18.3. The spectrum of emission of the first 20 harmonics of mildly relativistic cyclotron radiation. The electron has $v = 0.4c$. (After G. Bekafi (1966). *Radiation processes in plasmas*, p. 203. New York: John Wiley and Sons, Inc.)

Single relativistic electron: synchrotron emission

Linear scale



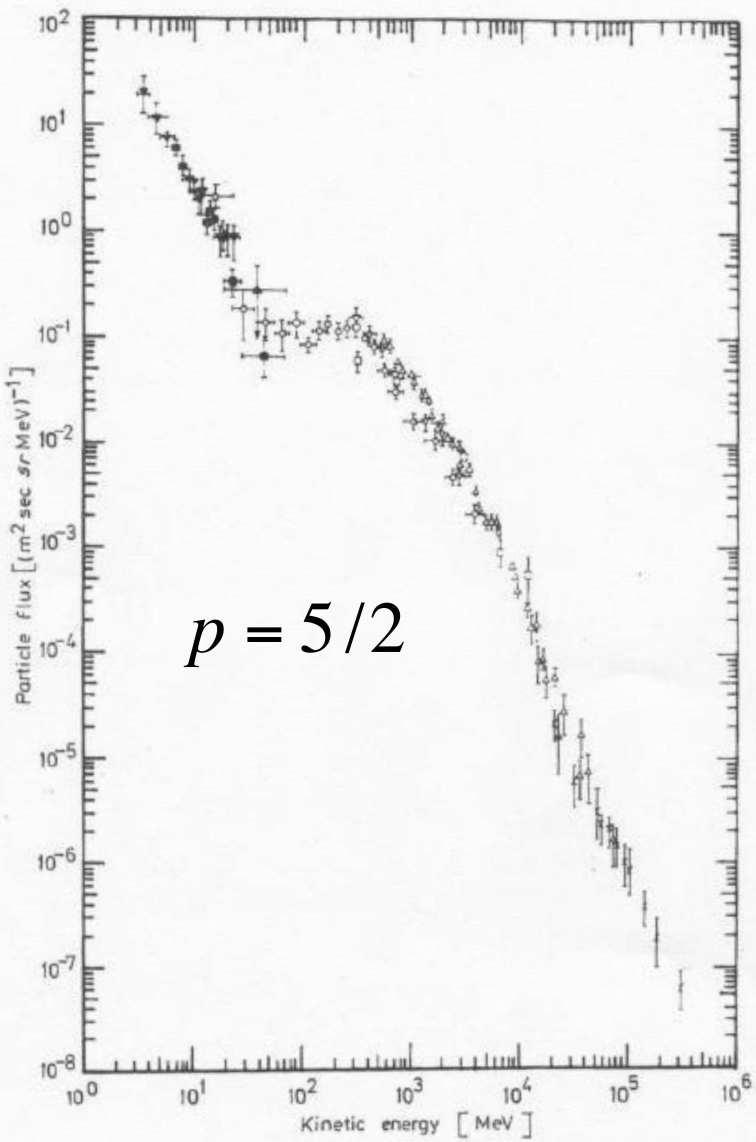
Peak frequency (in log space)



$$\nu_c = \frac{3}{2}\gamma^2 \frac{eB}{2\pi m_e}$$

log scale

Spectrum of primary Cosmic Ray



- Observed Galactic synchrotron emission produced by cosmic ray electrons with a relativistic energy distribution

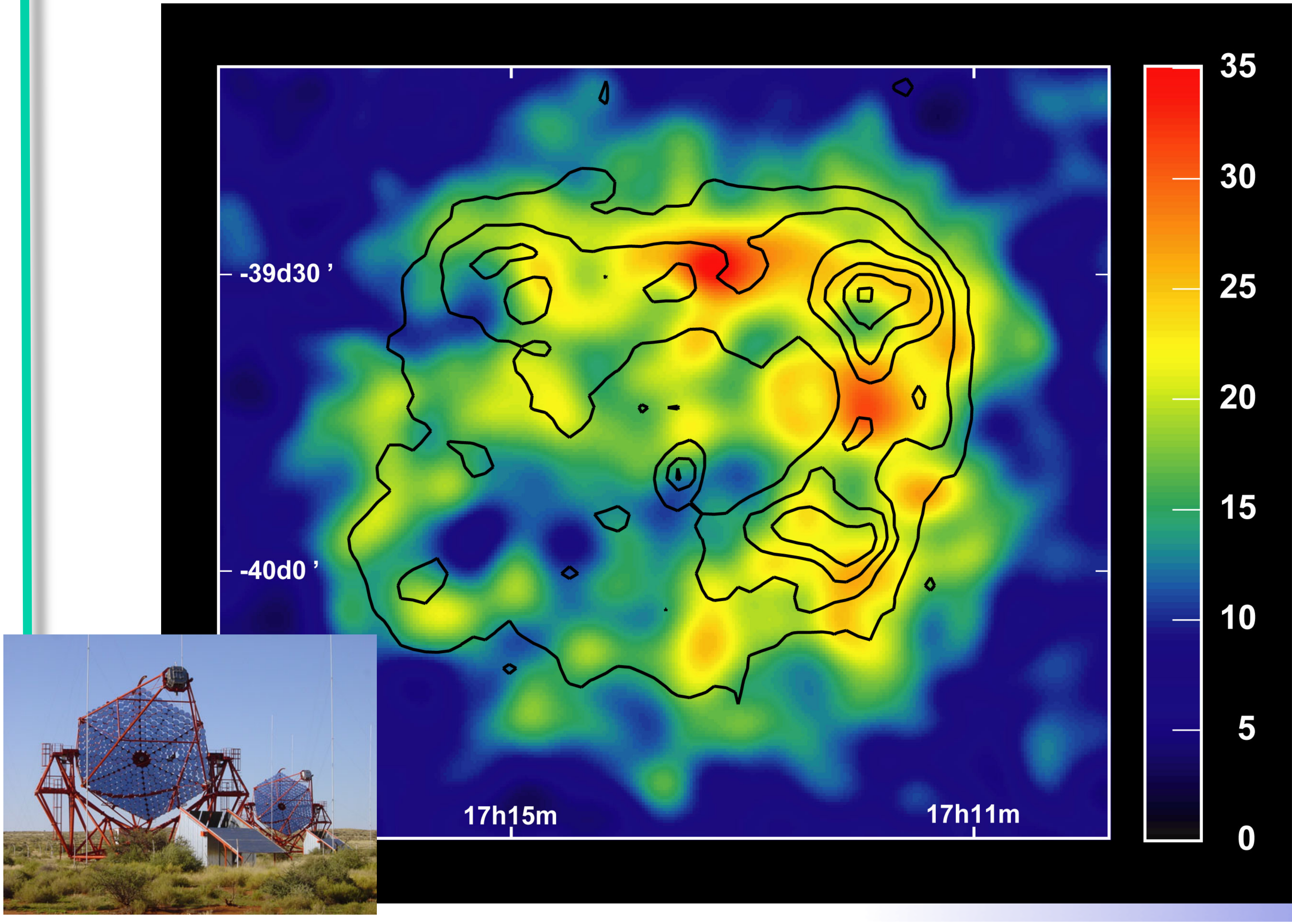
$$N(E)dE = \kappa E^{-p} dE$$

In general:

Particles (2% electrons, 98% protons and atomic nuclei)

Gamma-ray photons produced in collisions of high energy particles

Origin: accelerators, e.g. SNRs

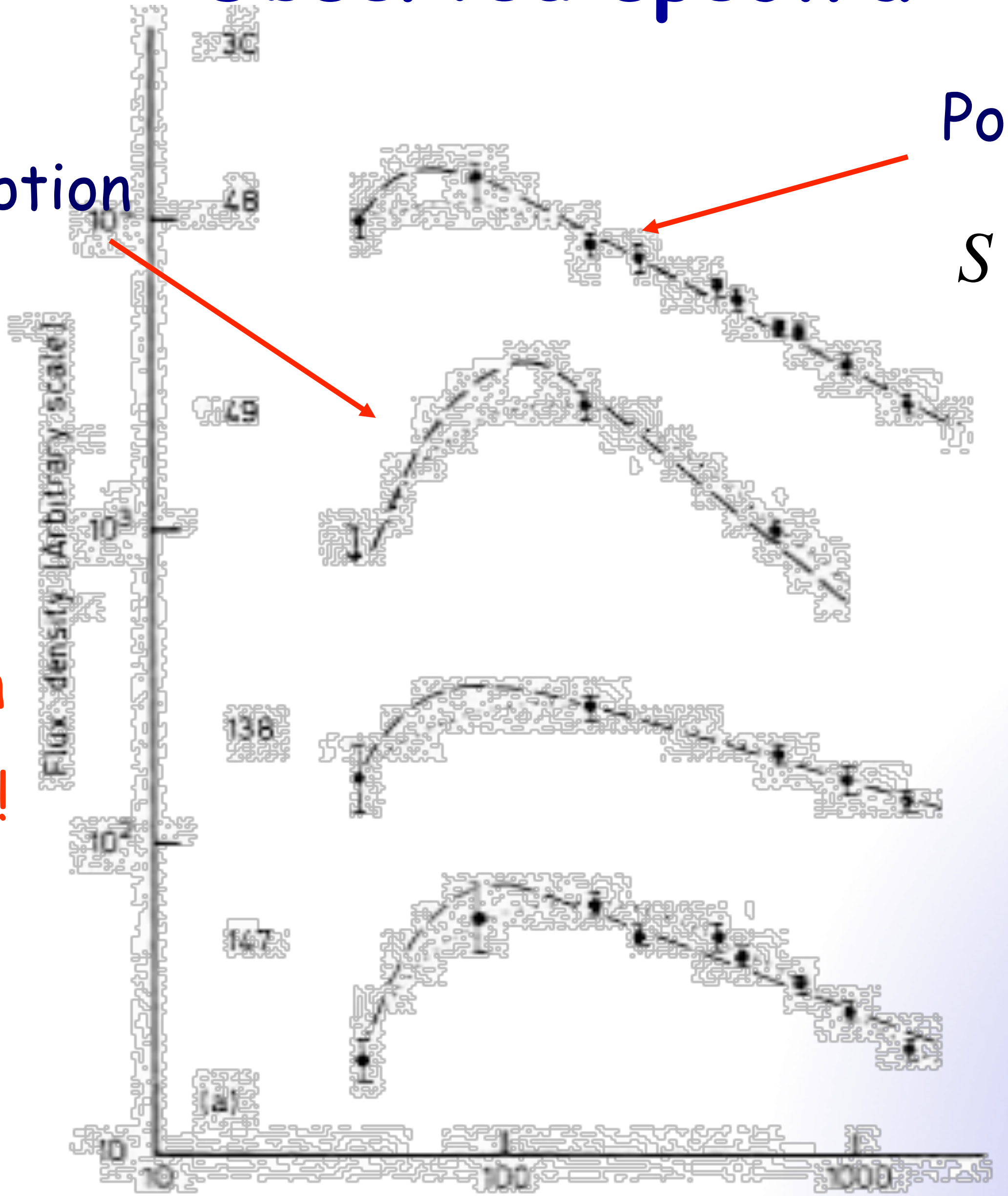


Observed spectra

Self-absorption

Power-law

$$S \propto \nu^{-\alpha} \propto \nu^{-\frac{p-1}{2}}$$

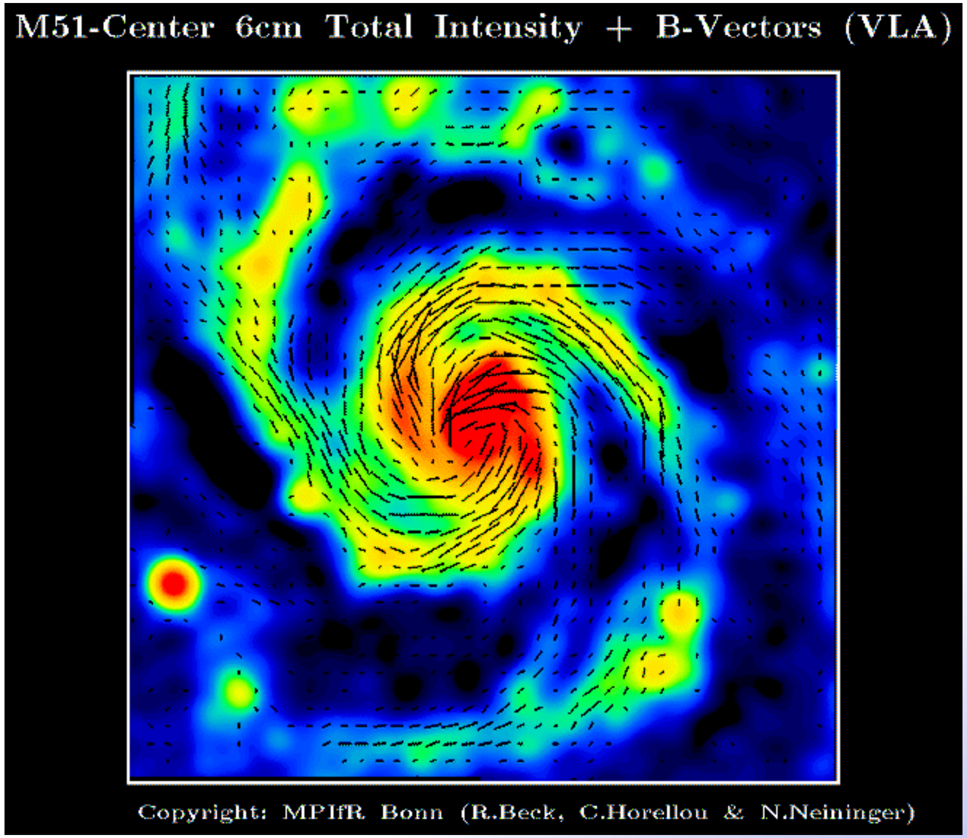


Look at radiation transfer!

For p=5/2,

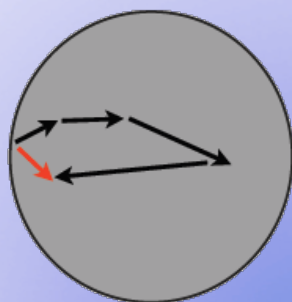
α=0.75

Synchrotron Emission: Polarization

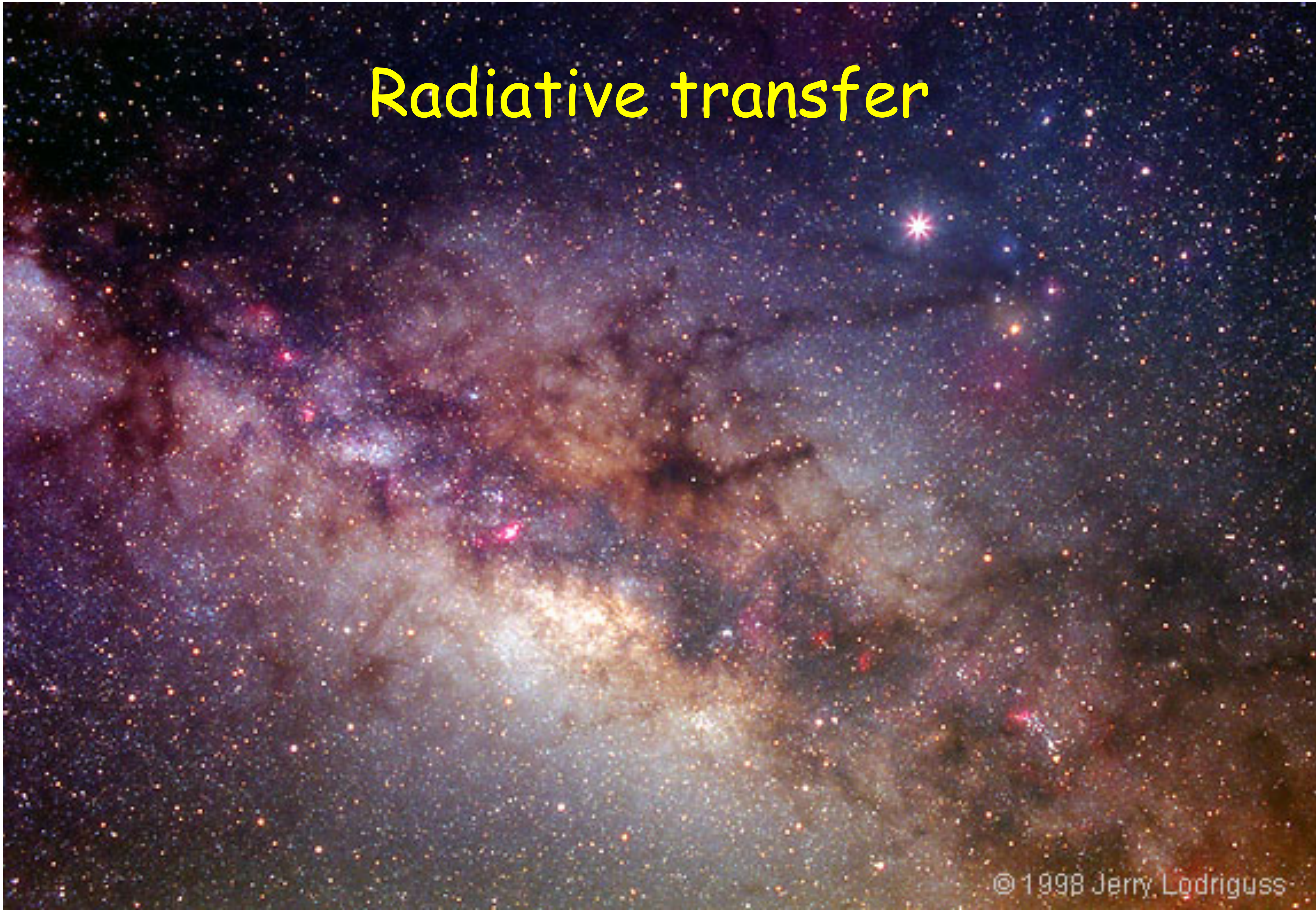


- Emission is linearly polarized perpendicular to B-field
- maximum degree of polarisation: $\Pi = \frac{p+1}{p+7/3} \approx 72\%$
- Observed degree usually lower:

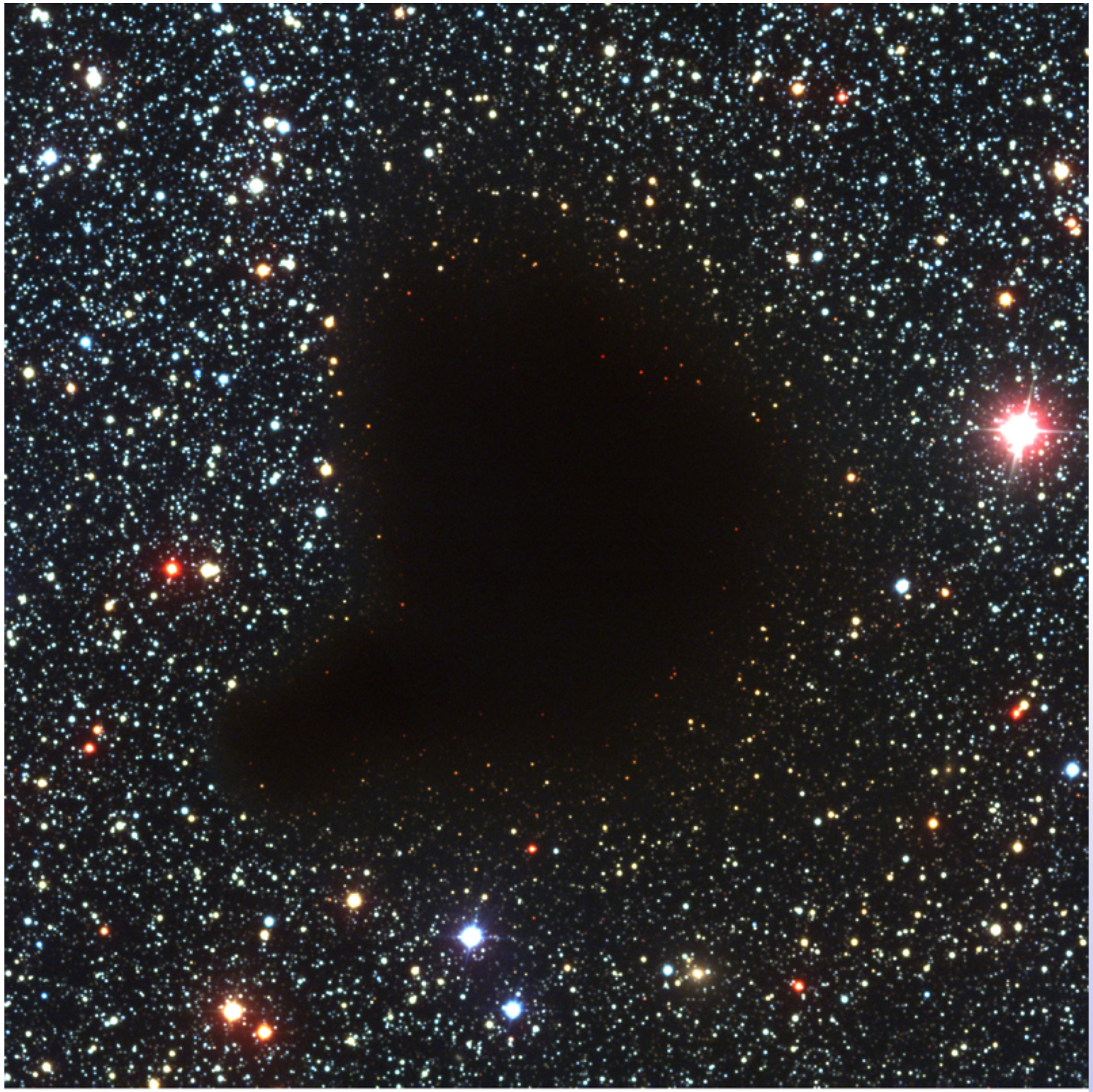
  in-beam depolarisation



Radiative transfer



Dust in the ISM

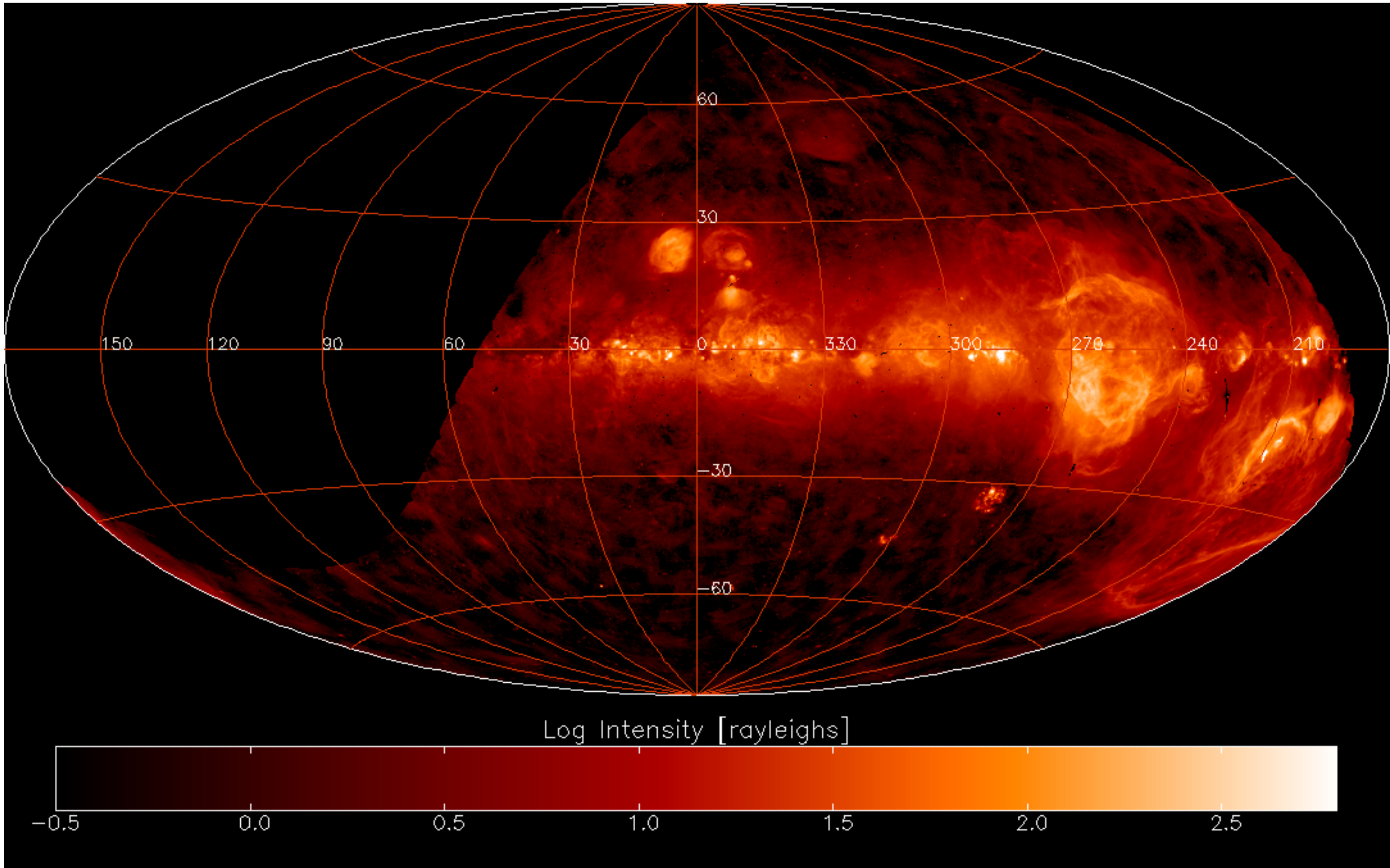


The "Black Cloud" B68
(VLT ANTU + FORS1)

ESO PR Photo 20a/99 (30 April 1999)

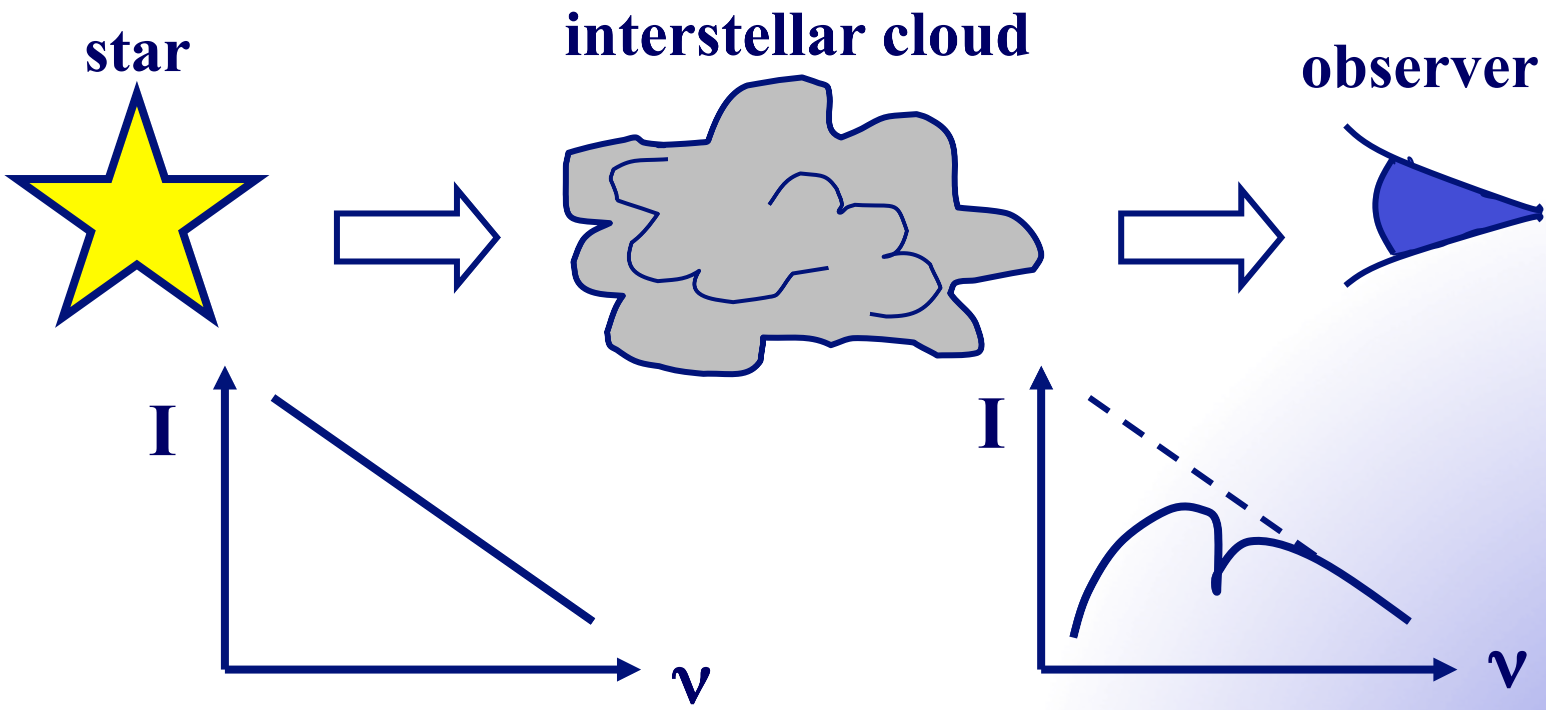
But ISM not only absorbs but also emits...

Emitting warm interstellar medium:

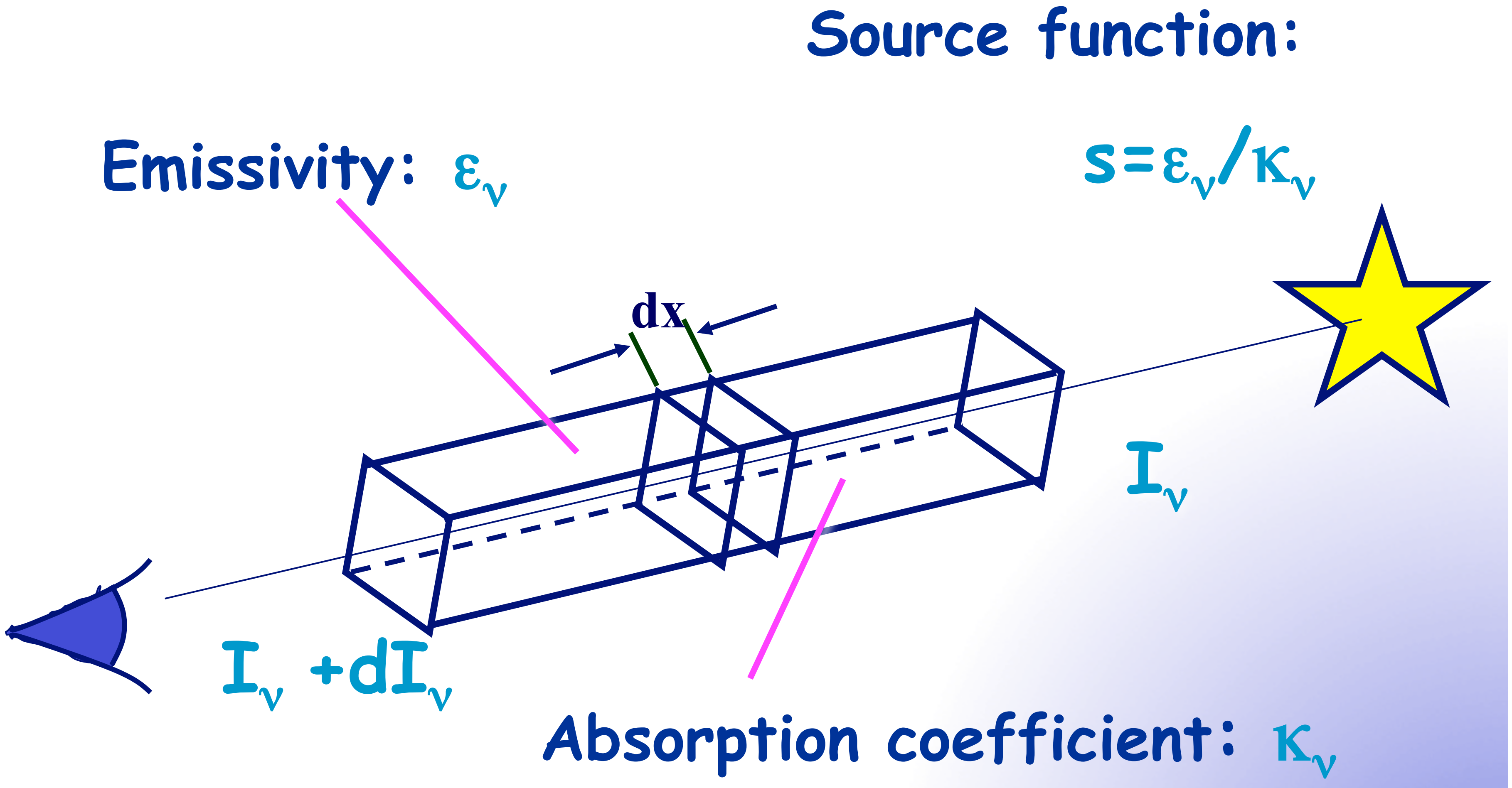


Emitting plasma in Orion Nebula

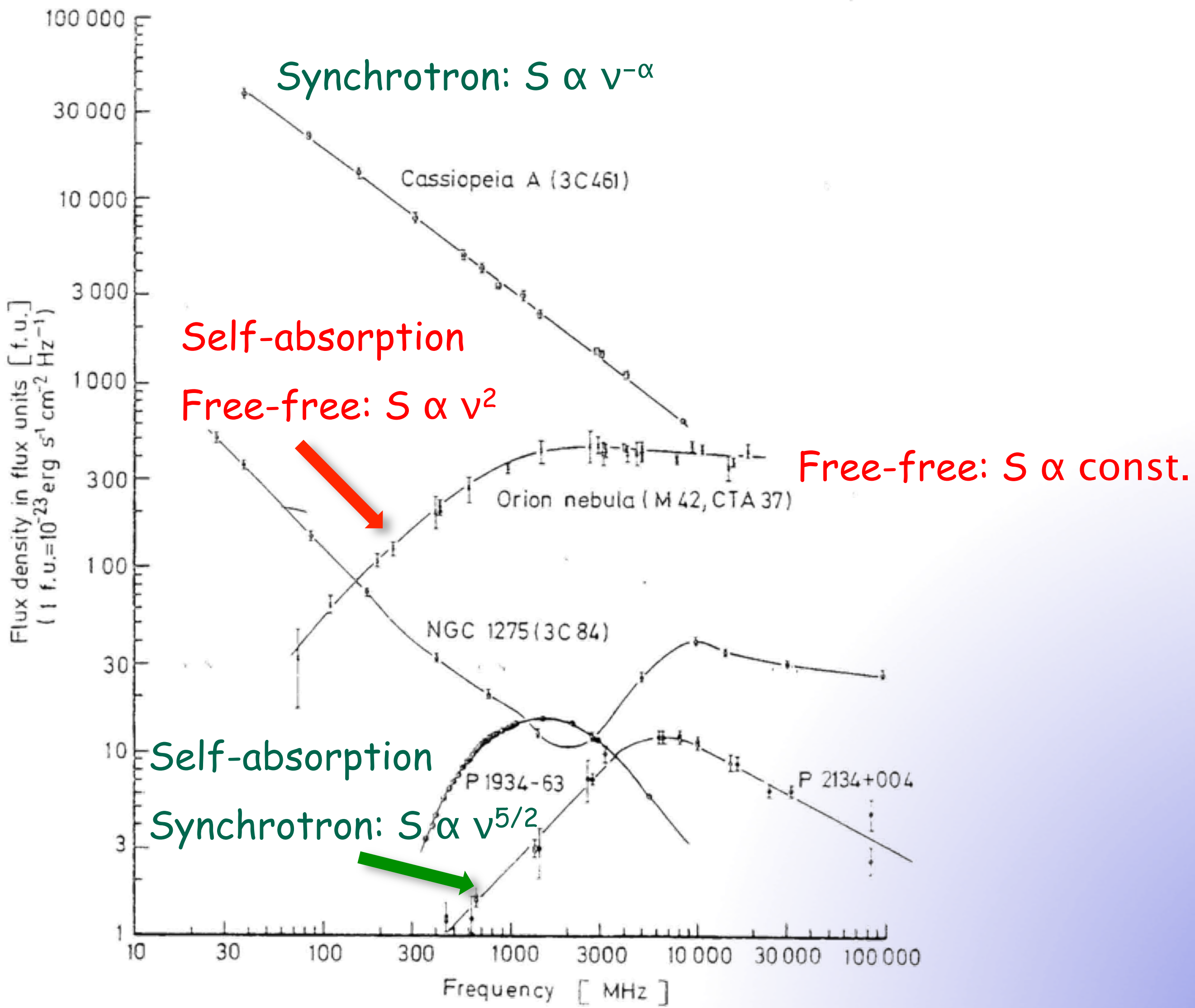
Radiative transfer



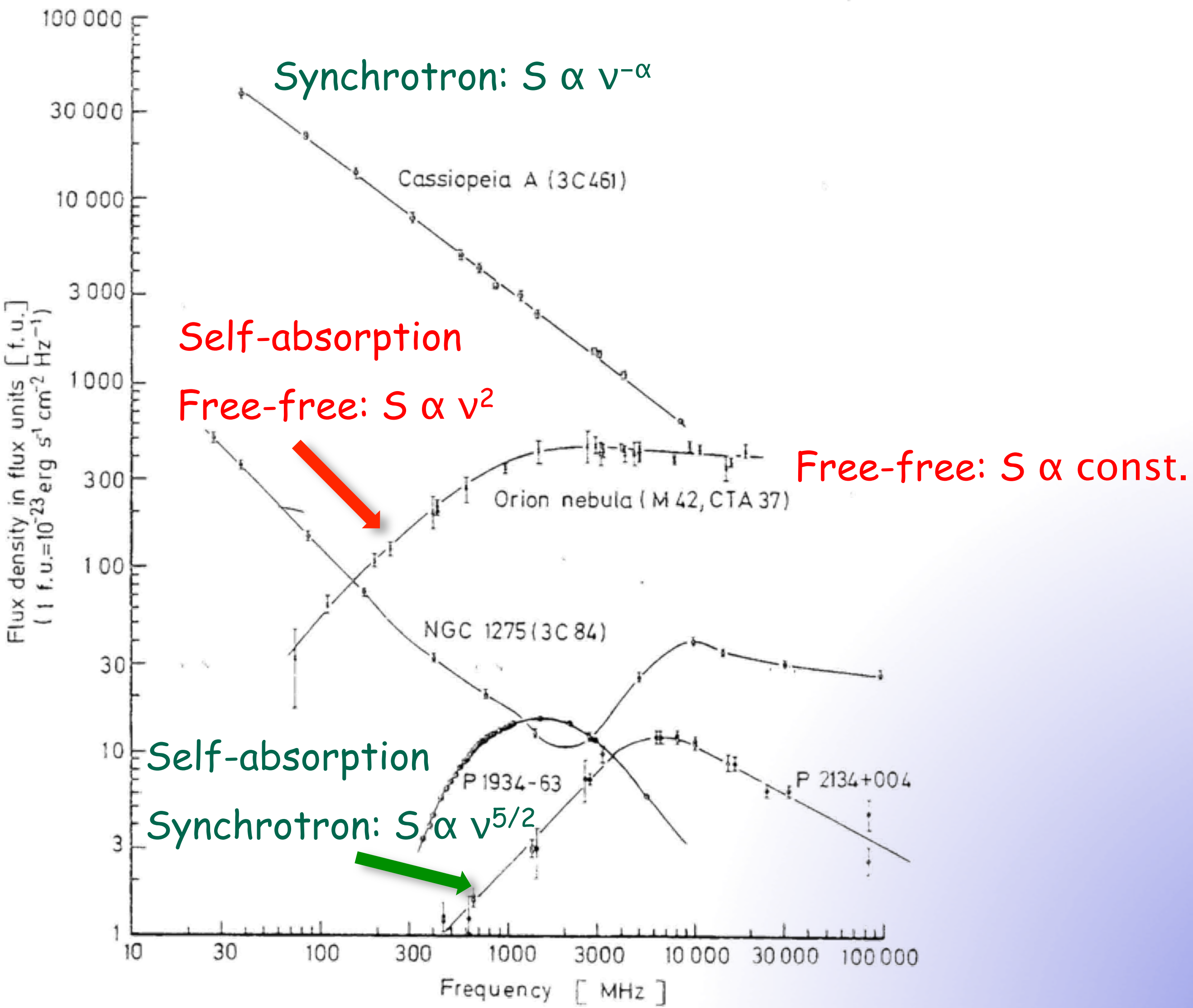
Radiative transfer



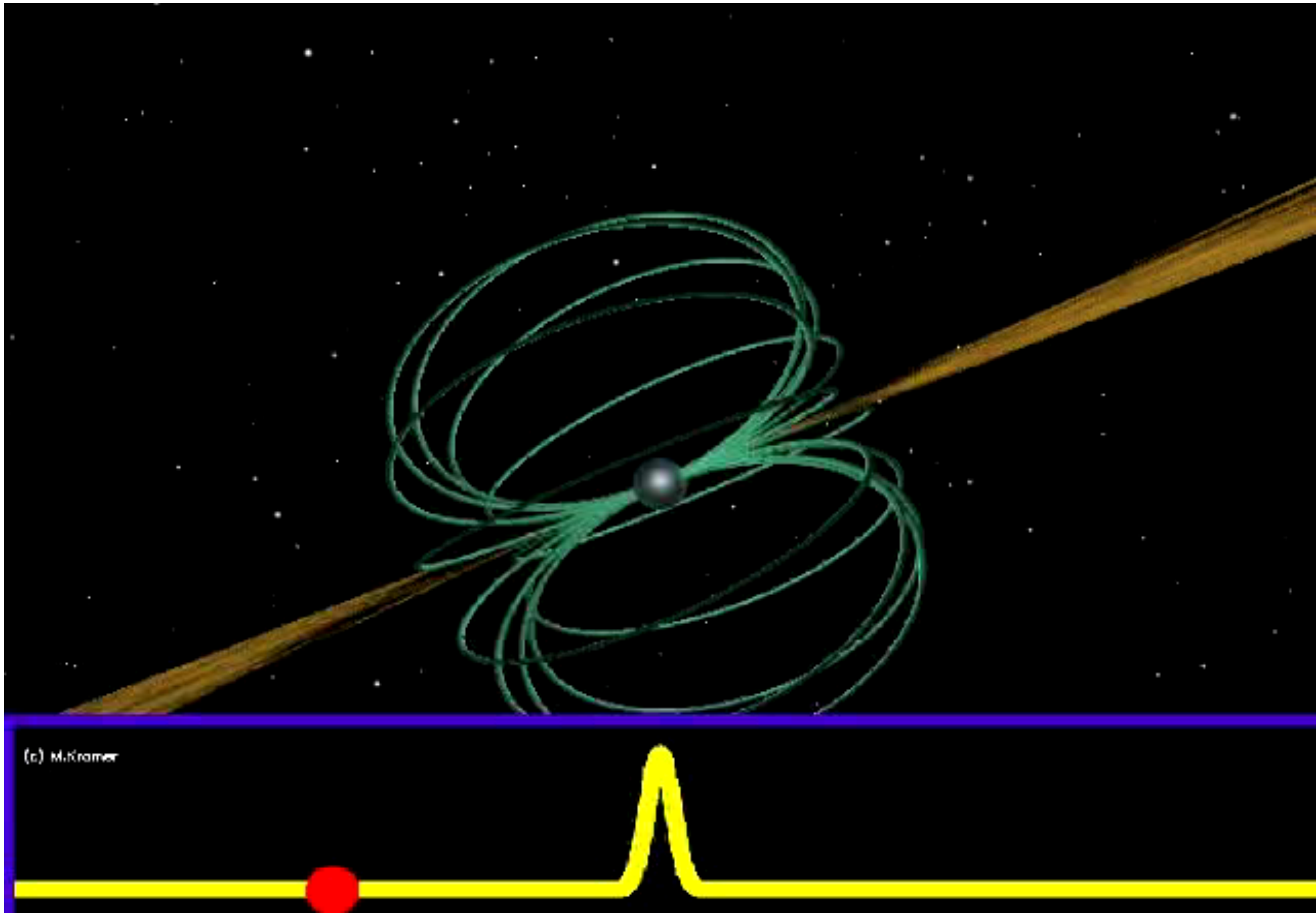
Radiative transfer



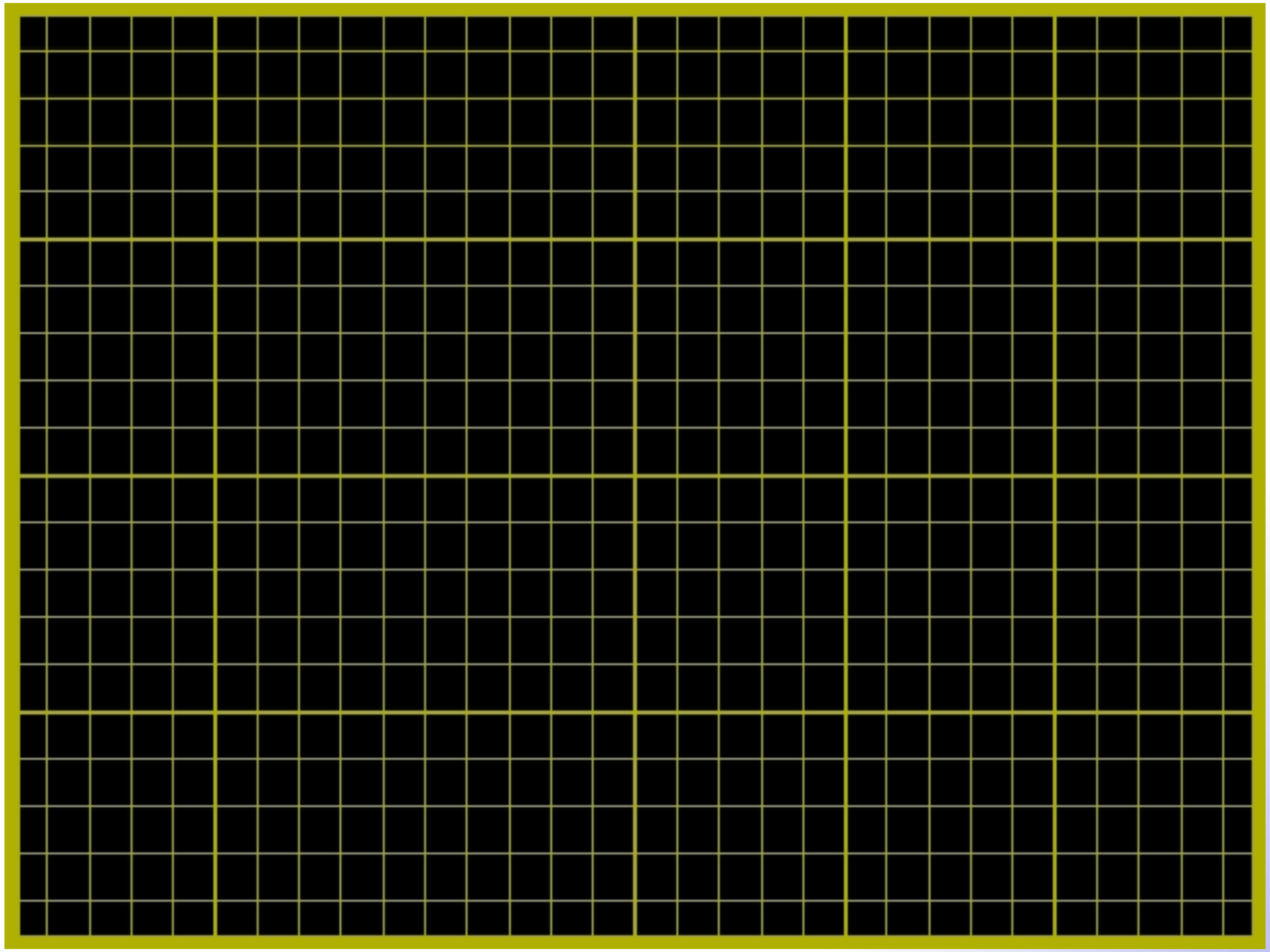
Radiative transfer



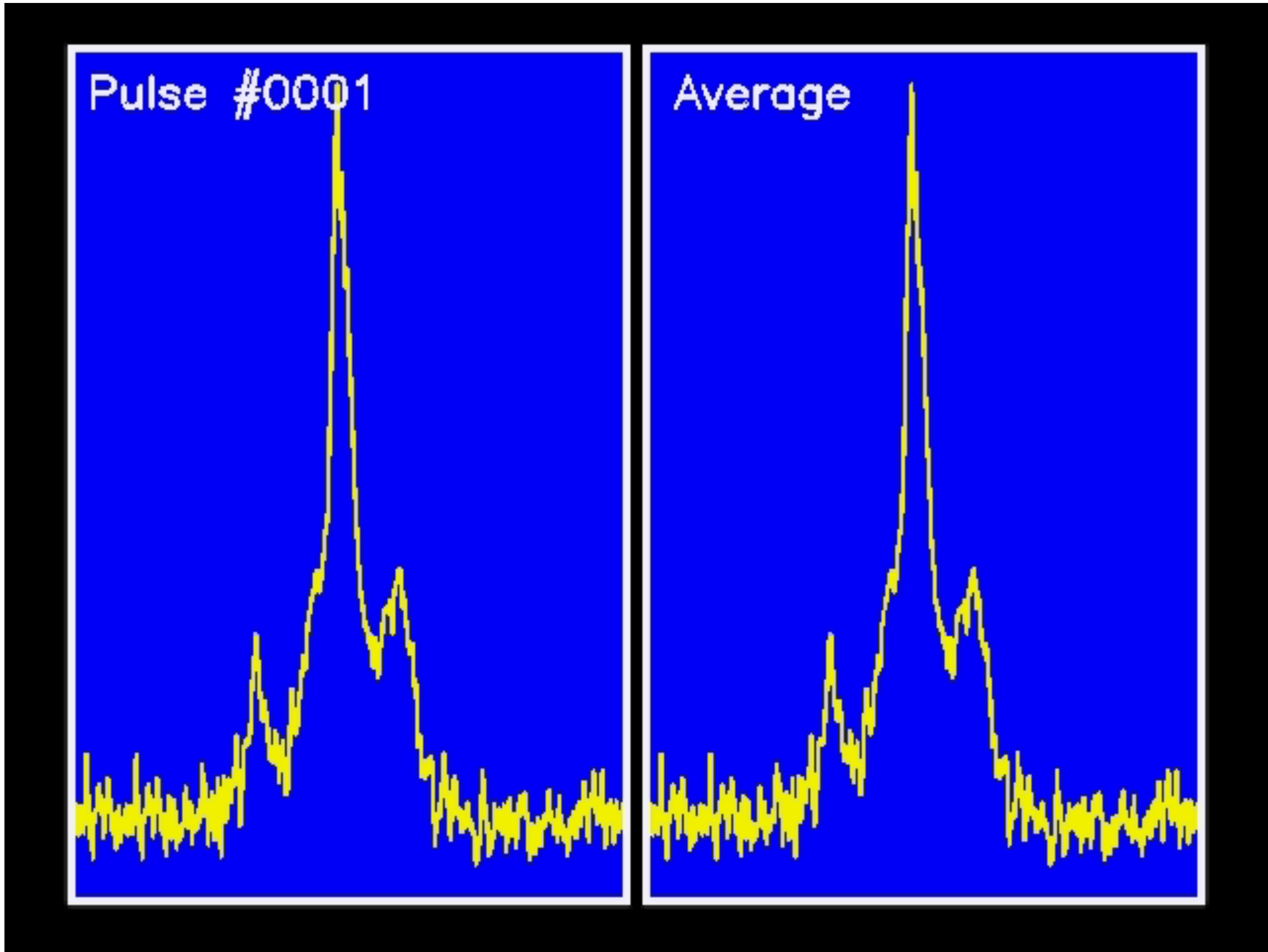
Pulsars



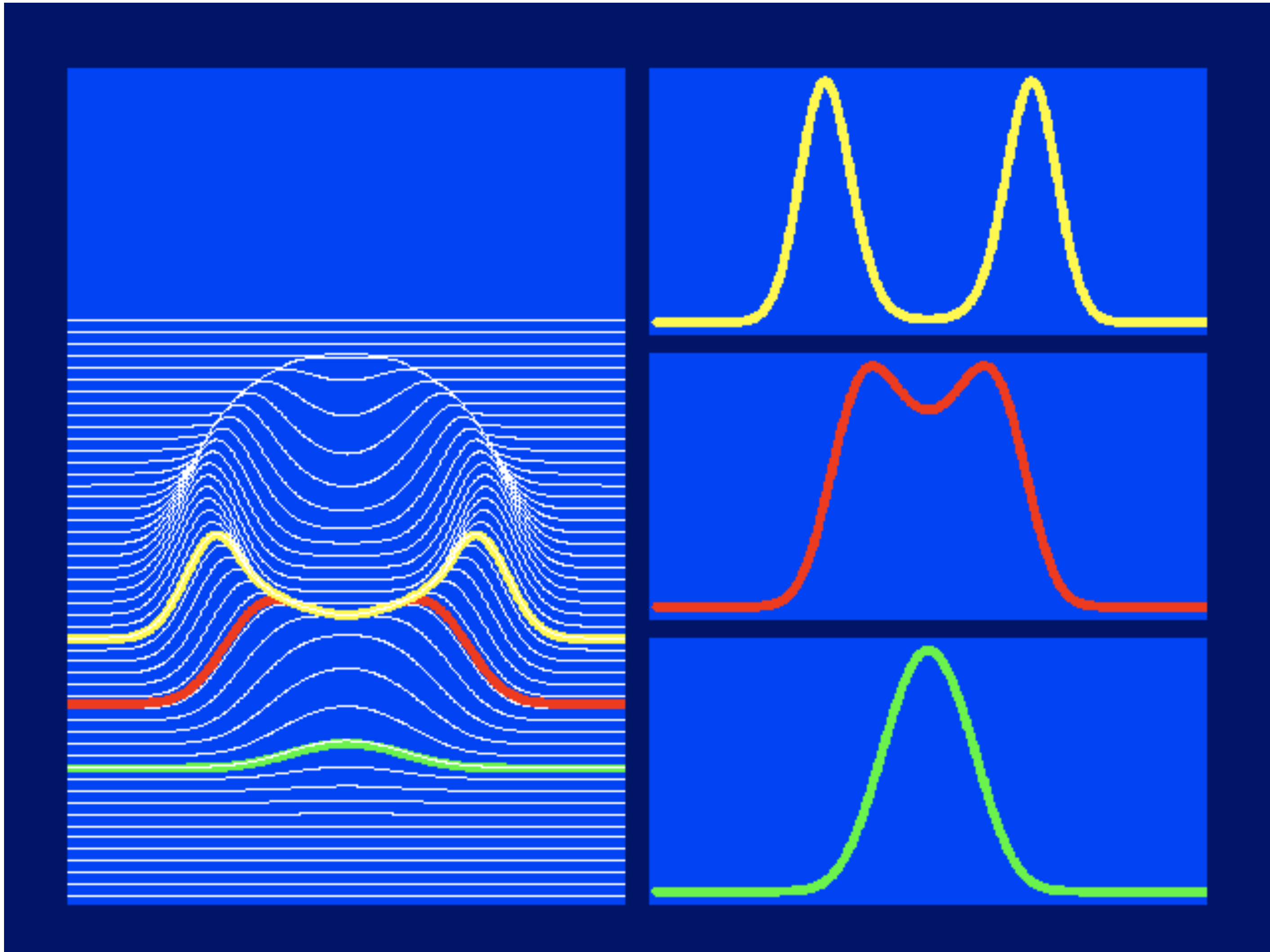
Single pulses are different



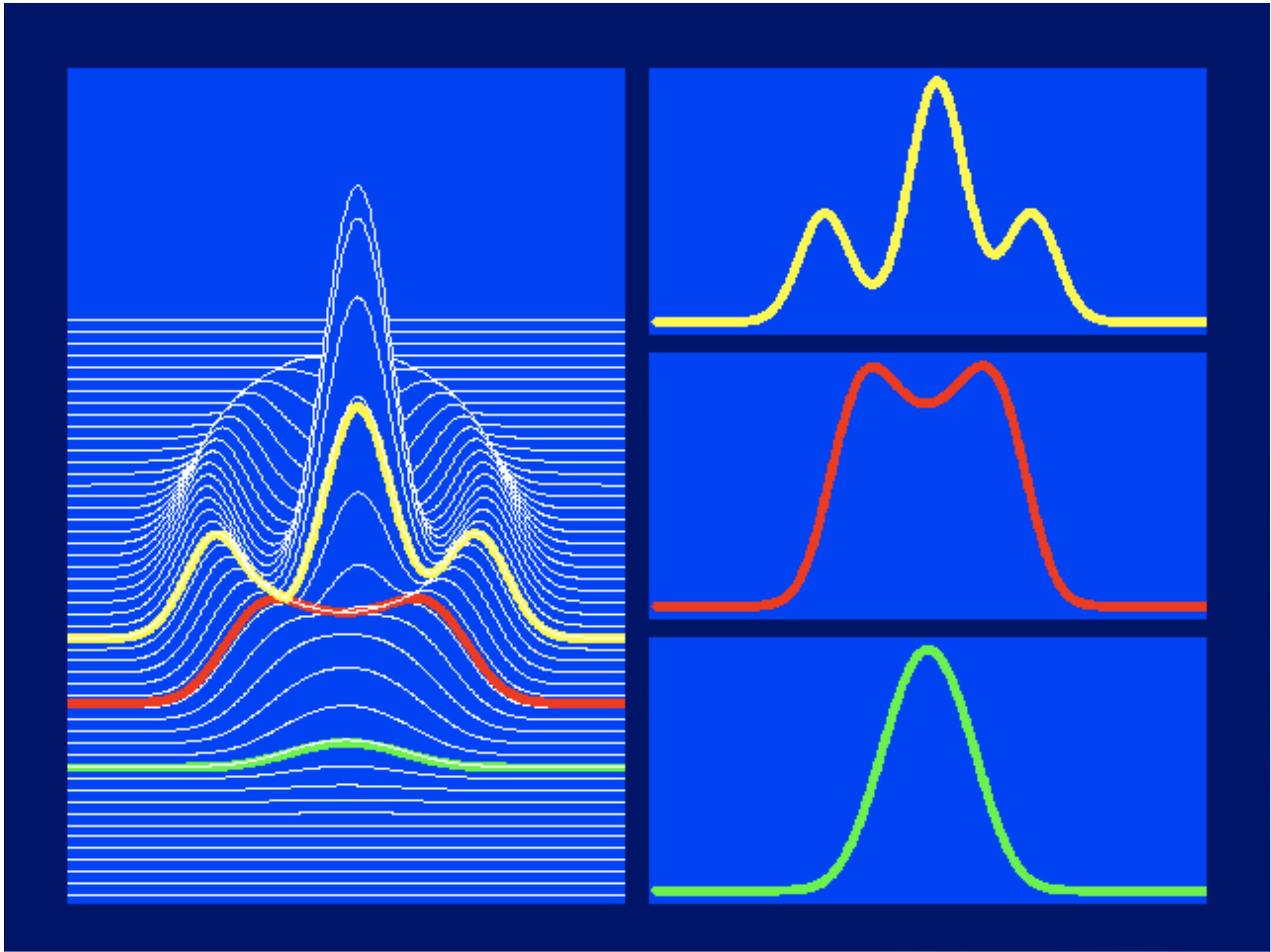
...but average pulse shape is stable



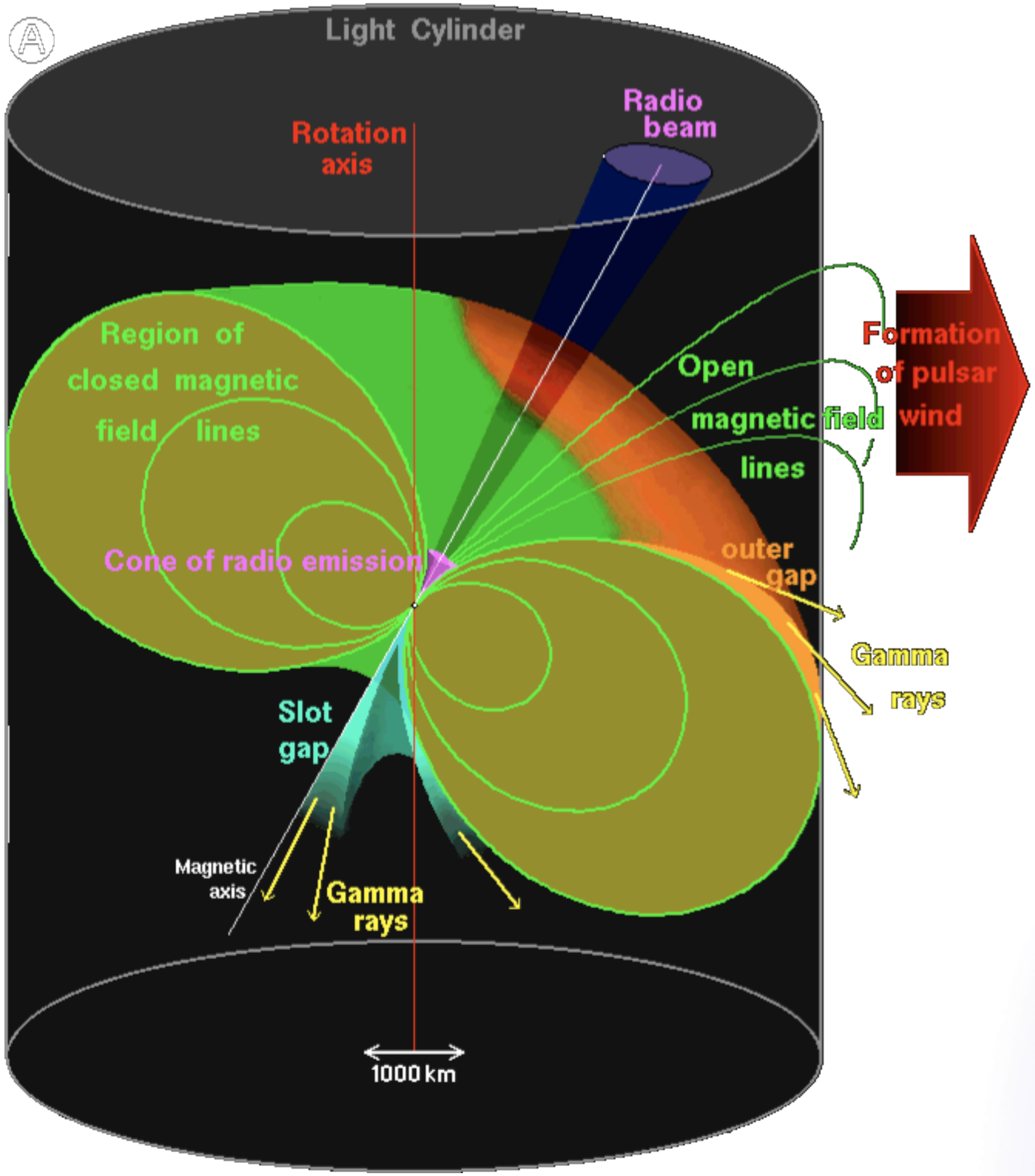
Profile determined by line-of-sight



Profile determined by line-of-sight



Straw-man design of a pulsar model



rotation induces electric quadrupole field

$$F_{el} / F_{grav} = 10^{12}$$

charges pulled out of surface, shielding force

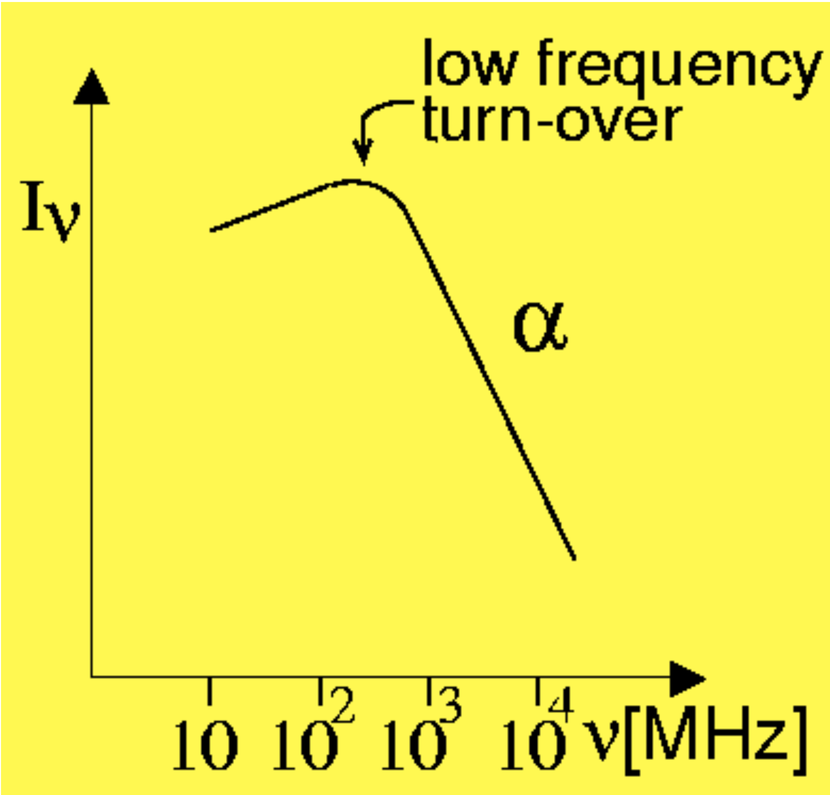
plasma fills surrounding co-rotation with pulsar light cylinder: $v = R_L \Omega = c$

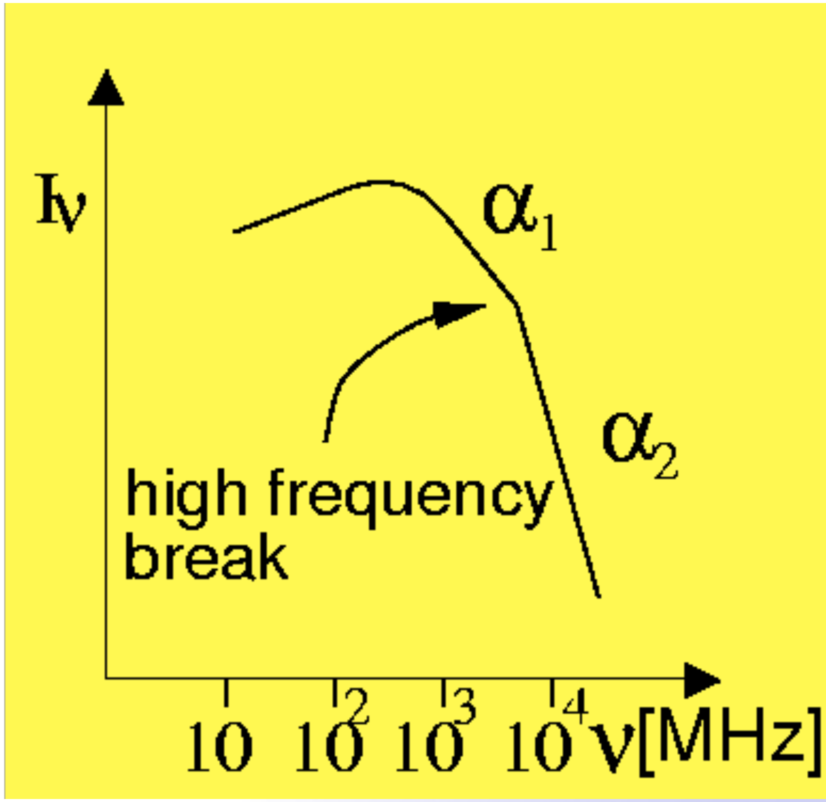
open and closed fieldlines

coherent emission, $T_b > 10^{31}$K

MASER emission?

Radio spectrum of pulsars

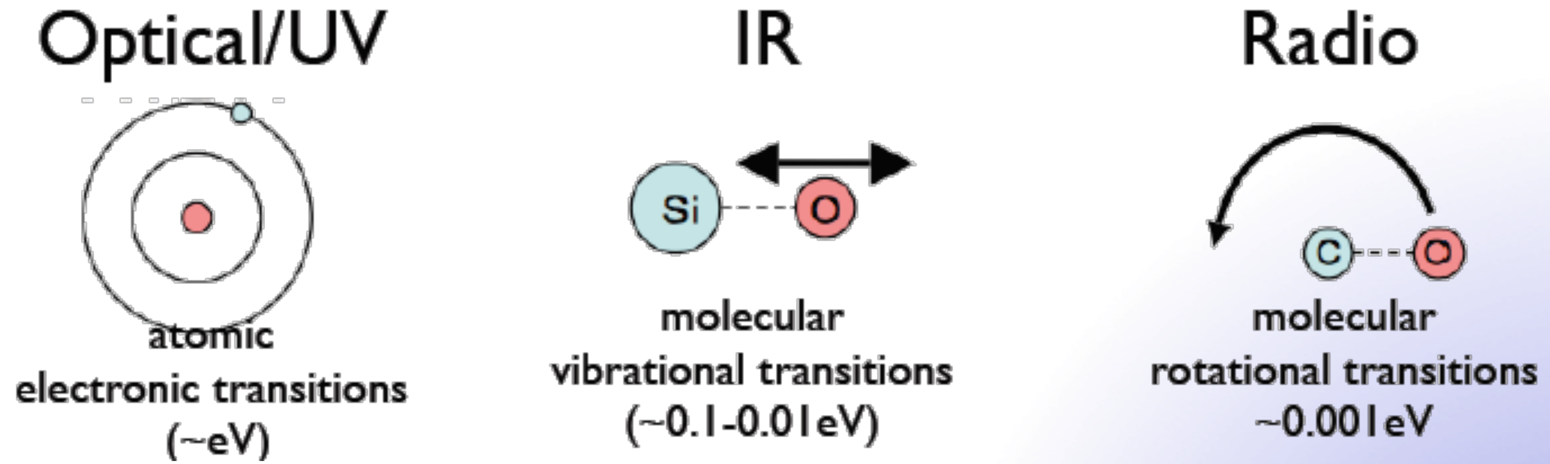




- Pulsars have a steep spectrum (mean: $\nu^{-1.7}$)
- Maximum intensity around 400 MHz
- Emission is up to 100% polarised

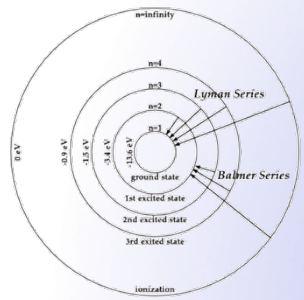
Spectral line emission

- Unlike the continuum processes spectral line emission occurs only at specific discrete frequencies.
- Line emission involves changes in the internal energy of atoms and molecules that have very specific allowed (quantised) values.



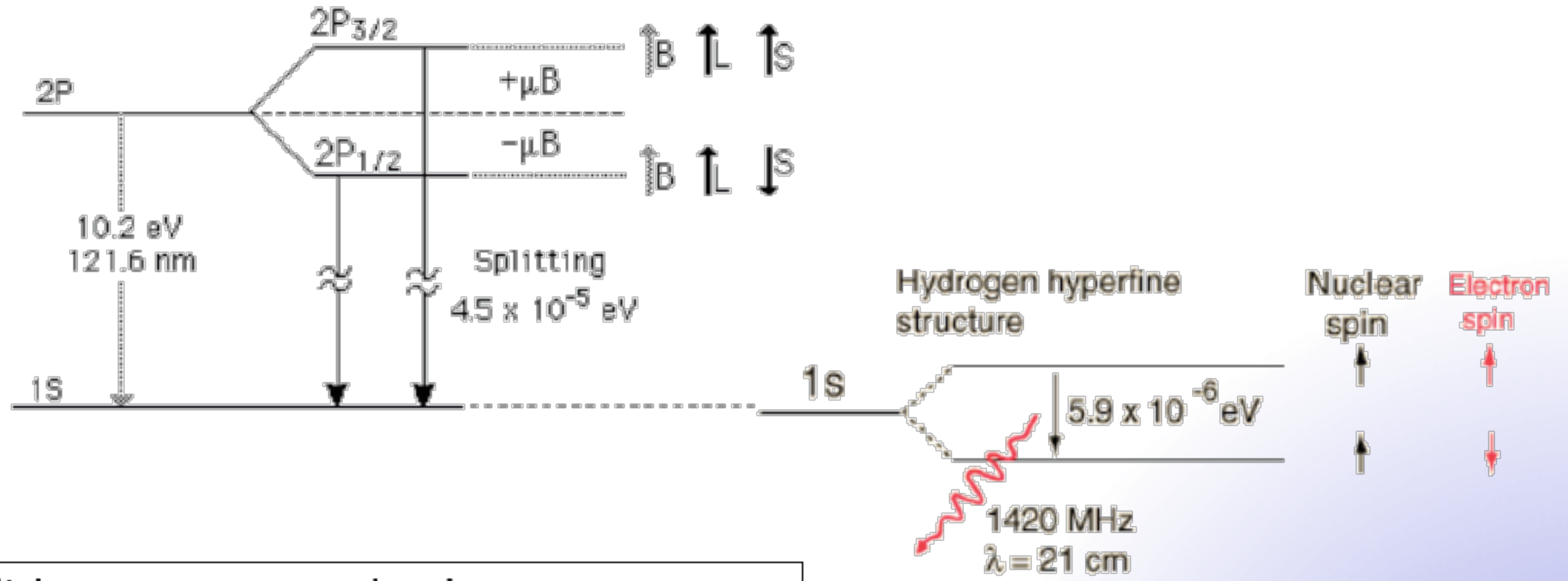
Also, recombination lines in radio

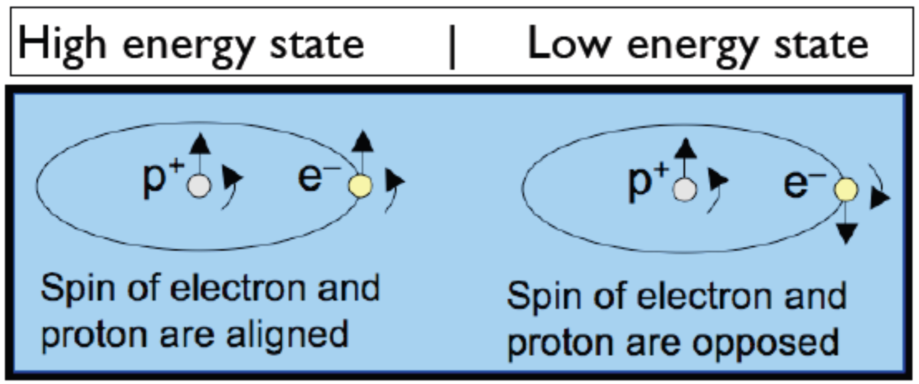
for large n:



Neutral Hydrogen Line

- The 21 cm HI line is produced by magnetic hyperfine splitting in the electronic ground state of the H-atom

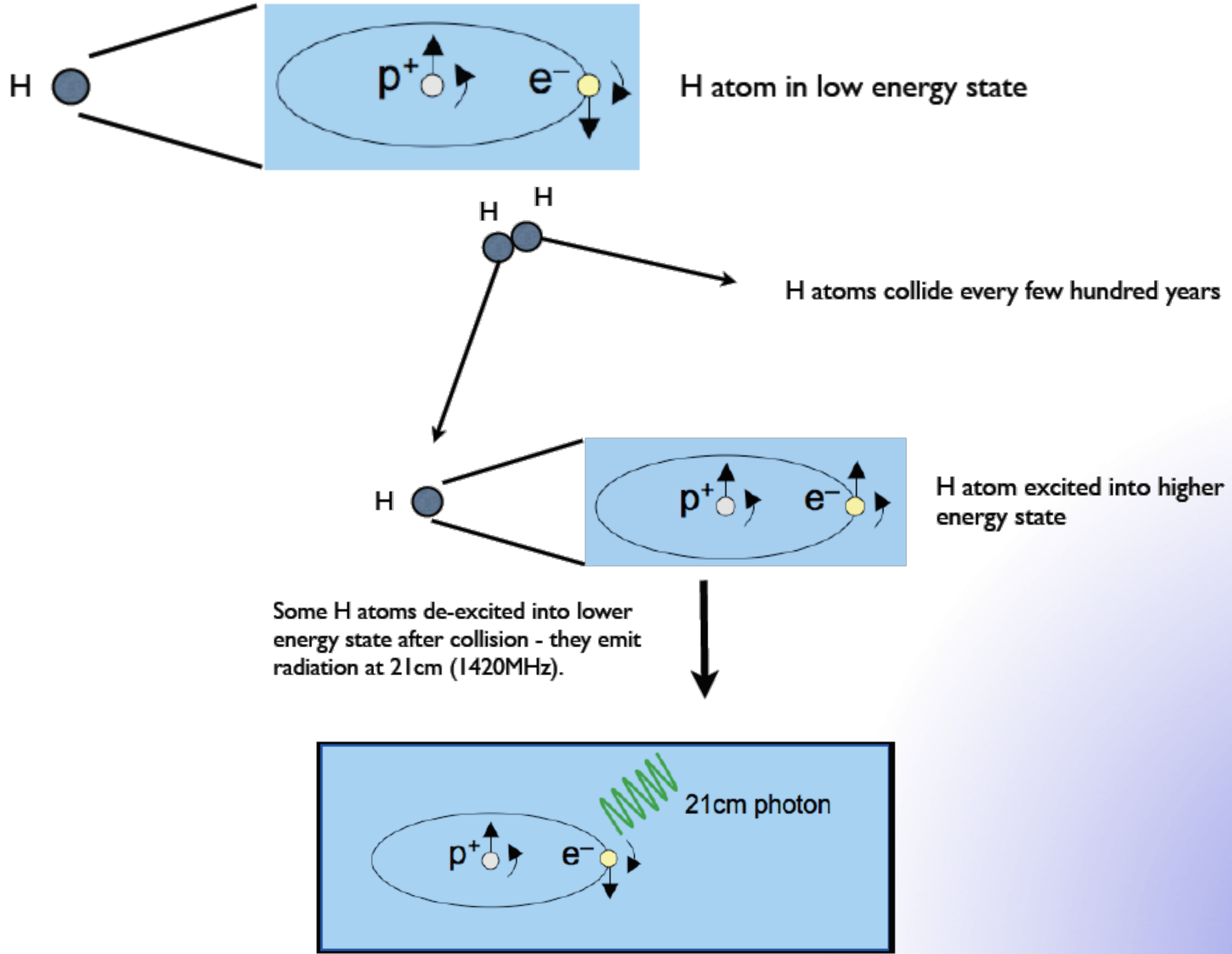




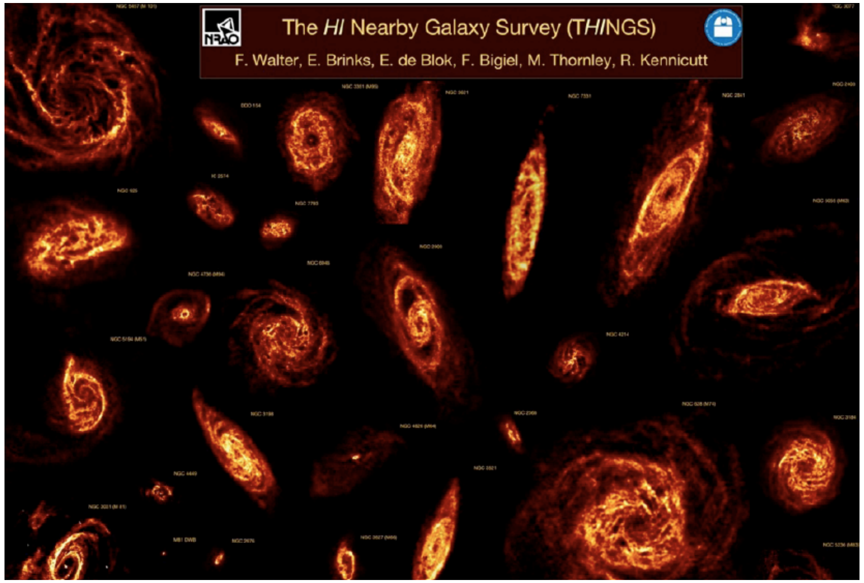
The very small energy difference between the 2 states (dE ~ 6 μeV) corresponds to 21cm line:

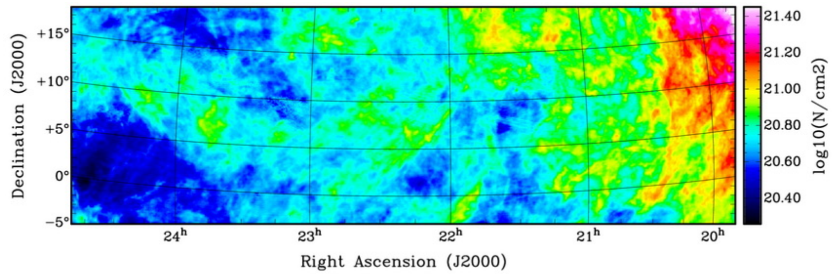
v=1420..40575 MHz

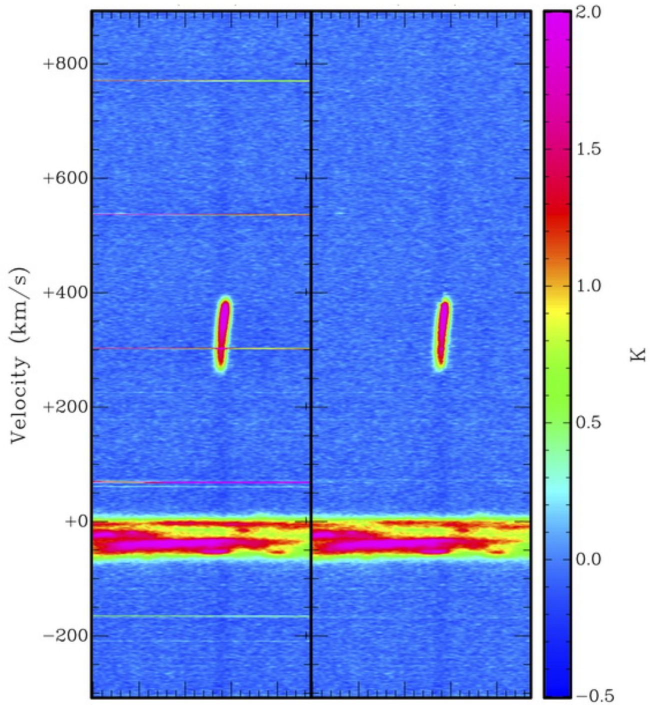
Neutral Hydrogen Line



Neutral Hydrogen Line







- More about spectral lines later…
- Now, we know how the sources look like, let's see how you measure them