A radio astronomy primer

Maurilio Pannella – mpannella@units.it - May 2021

Agenda and Outline of this primer

6 May
- What is radio astronomy
- Historical background
- Physical processes

25 May
- Collecting radio signals
- A brief introduction to interferometry

27 May
- Radio astronomy and galaxy evolution
- The present and future of radio astronomy

Online resources

- Essential Radio Astronomy (James J. Condon and Scott M. Ransom)
  https://www.cv.nrao.edu/~sransom/web/xxx.html

- Principles of Interferometry, IMPRS School 2014 (Hans-Rainer Klöckner)
  http://www3.mpifr-bonn.mpg.de/staff/hrk/HRK_LECTURE.html

- 16th NRAO Synthesis Imaging Workshop 2018
  https://science.nrao.edu/science/meetings/2018/16th-synthesis-imaging-workshop

- Radio Astronomy Course (Prof. Dale E. Gary)
  https://web.njit.edu/~gary/728/

- 10th IRAM Millimeter Interferometry School
  https://www.iram-institute.org/EN/content-page-367-7-67-367-0-0.html

- Sixth European Radio Interferometry School (ERIS2015)
  https://www.eso.org/sci/meetings/2015/eris2015.html

Why we should know more about radio astronomy…

- Precision cosmology
- The dark side of galaxy evolution
- Black hole activity
- Atomic hydrogen and molecular gas
- General relativity
- Dark matter

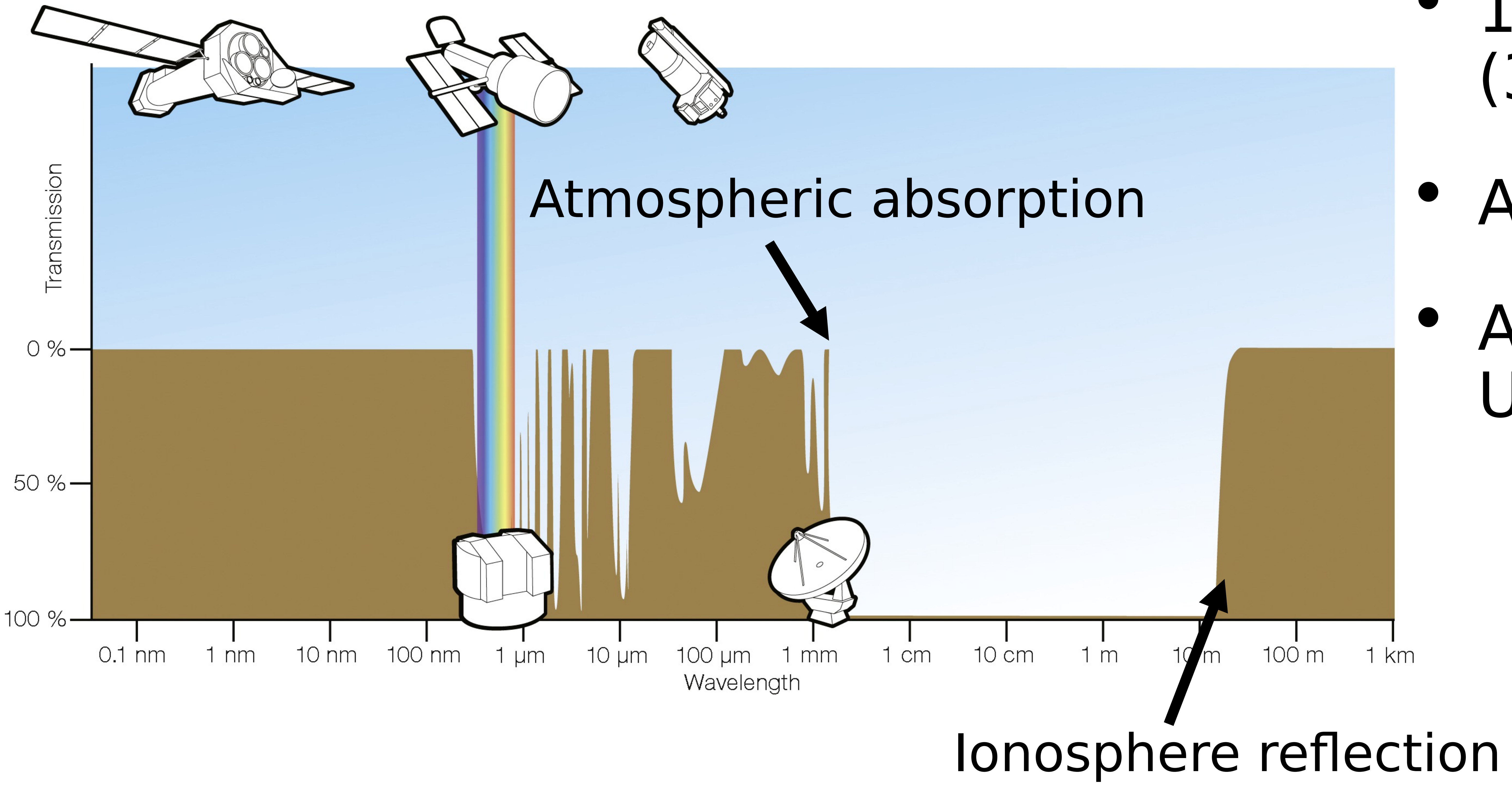
and many other good reasons….

Why we should know more about radio astronomy…

- Ground based observatories
- Steel (antennae) and electronics (fibers and correlators)
- Major facilities being built/planned all over the world
- Radio astronomy has become more user friendly
- Italian Astronomy community is involved in a number of major projects (LOFAR, MeerKAT+ and SKA)

What is radio astronomy

Radio astronomy is the study of natural radio emission from celestial sources.



- 1 THz(0.3mm) — 10 MHz (30m)
- A sky always “dark”
- A “parallel” and unexpected Universe

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Green Bank Telescope (100mdish)

The 5 GHz sky

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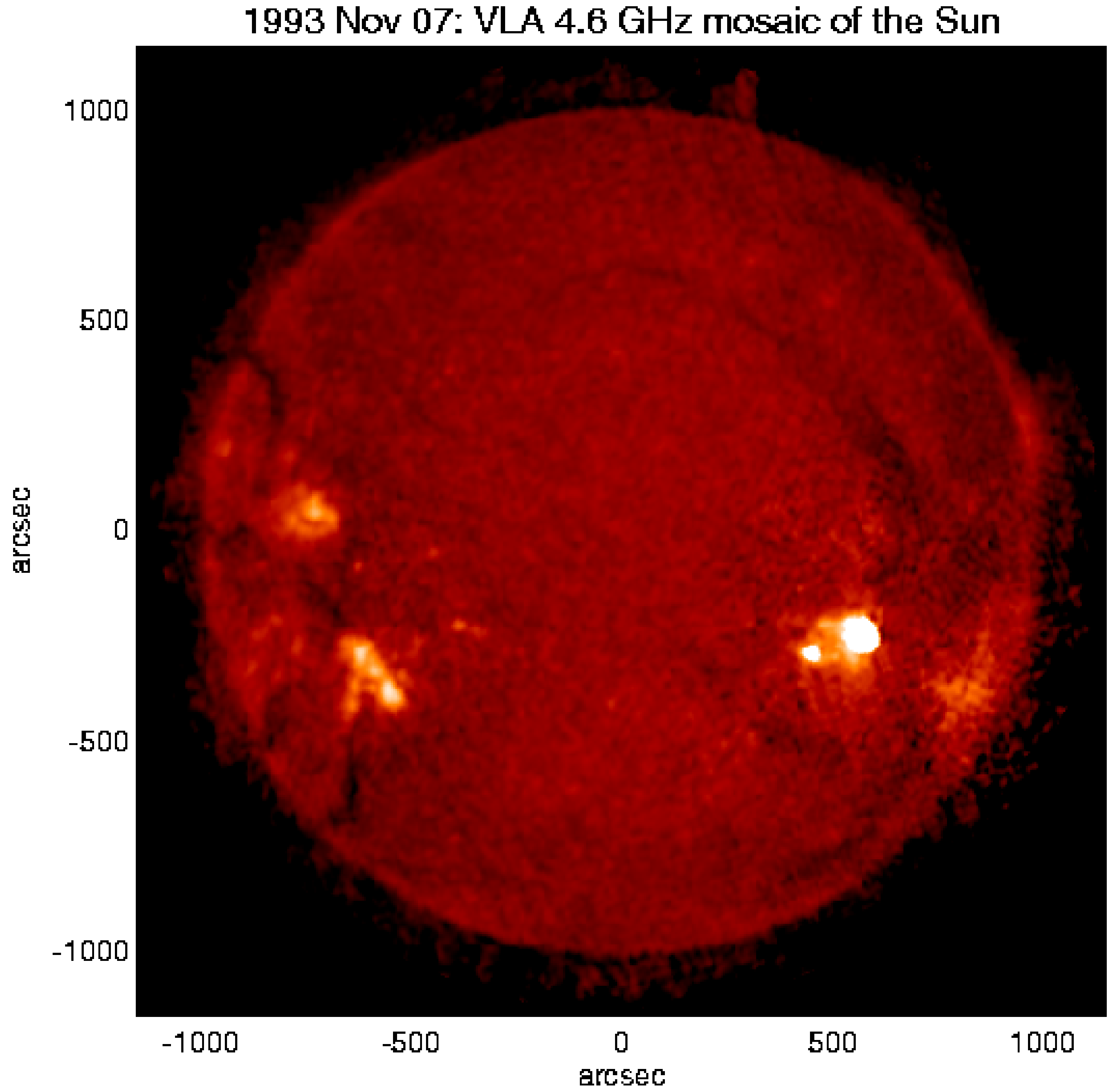

The Sun at 4.6 GHz

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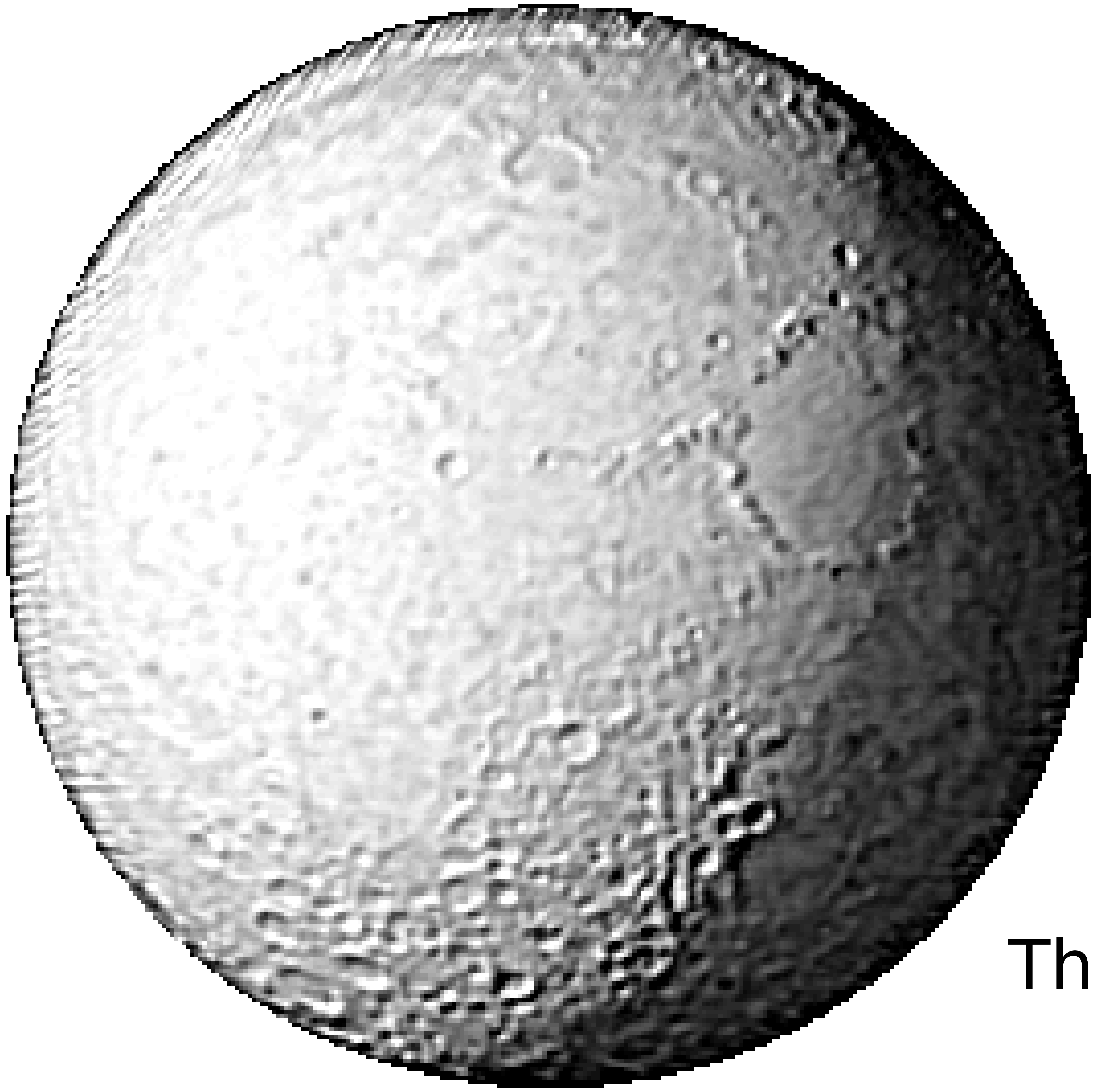

The Moon at 850 micron

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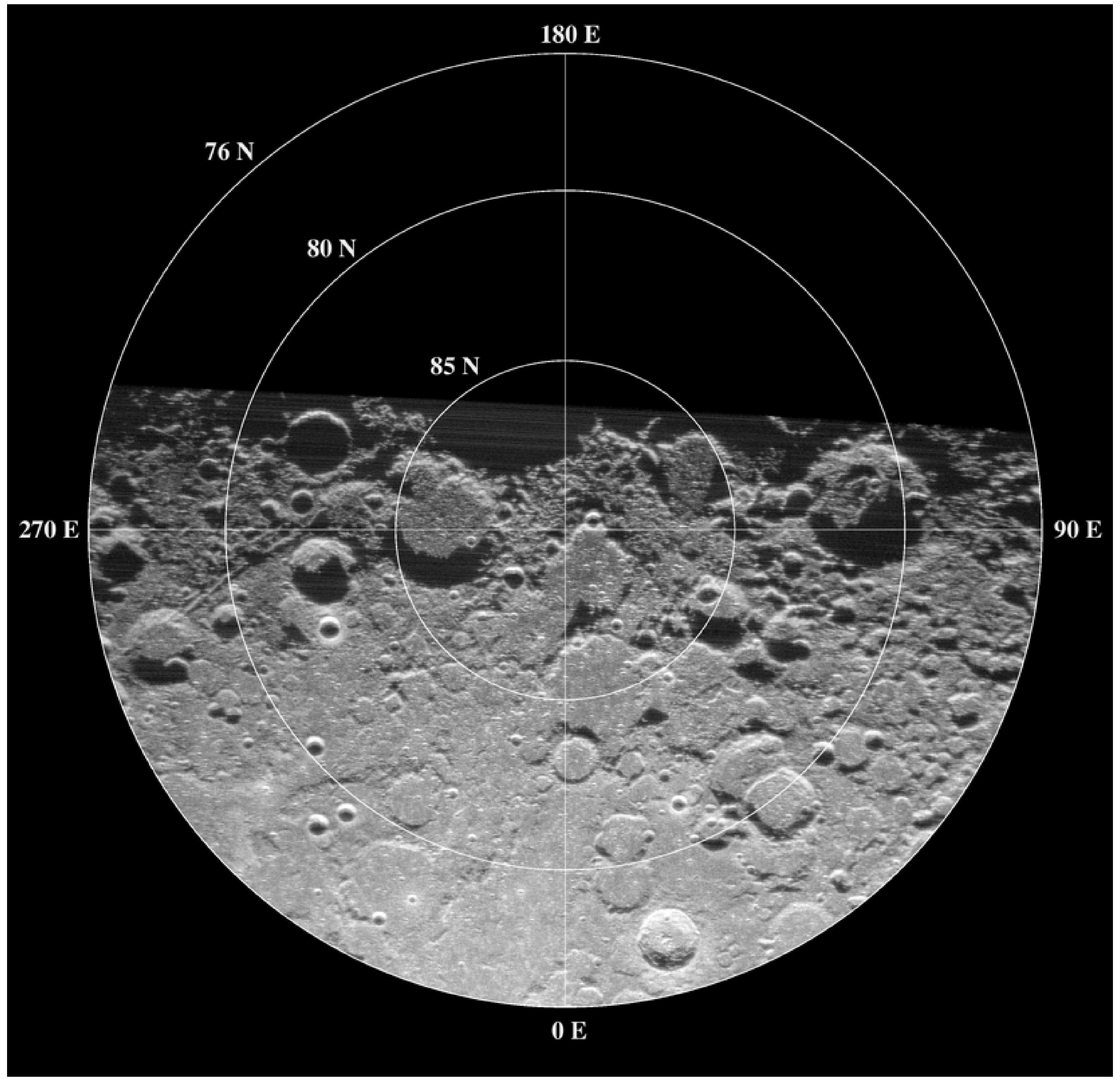

Arecibo+GBT radar image at 70 cm

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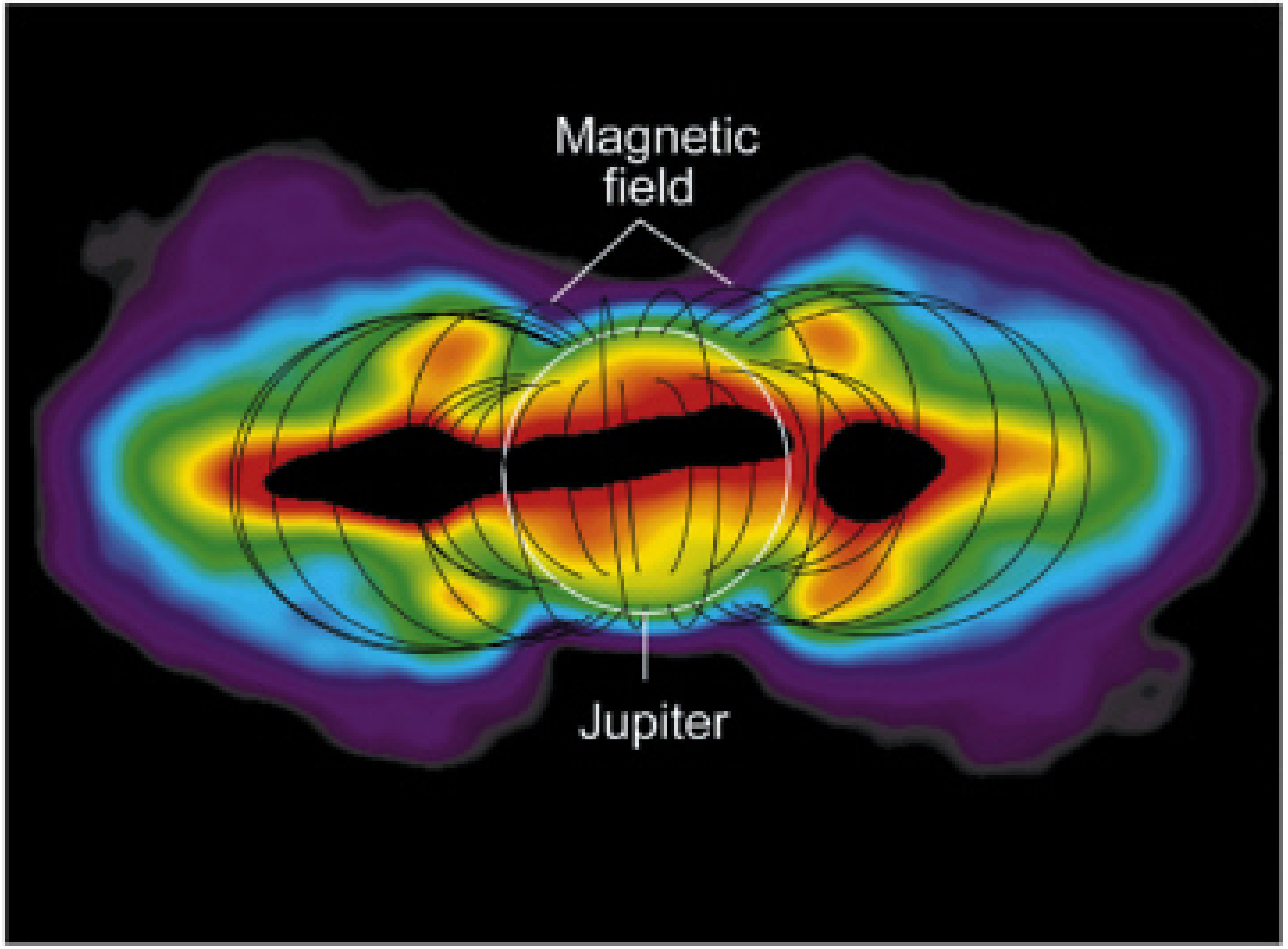

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Jupiter – NRAO Very Large Array

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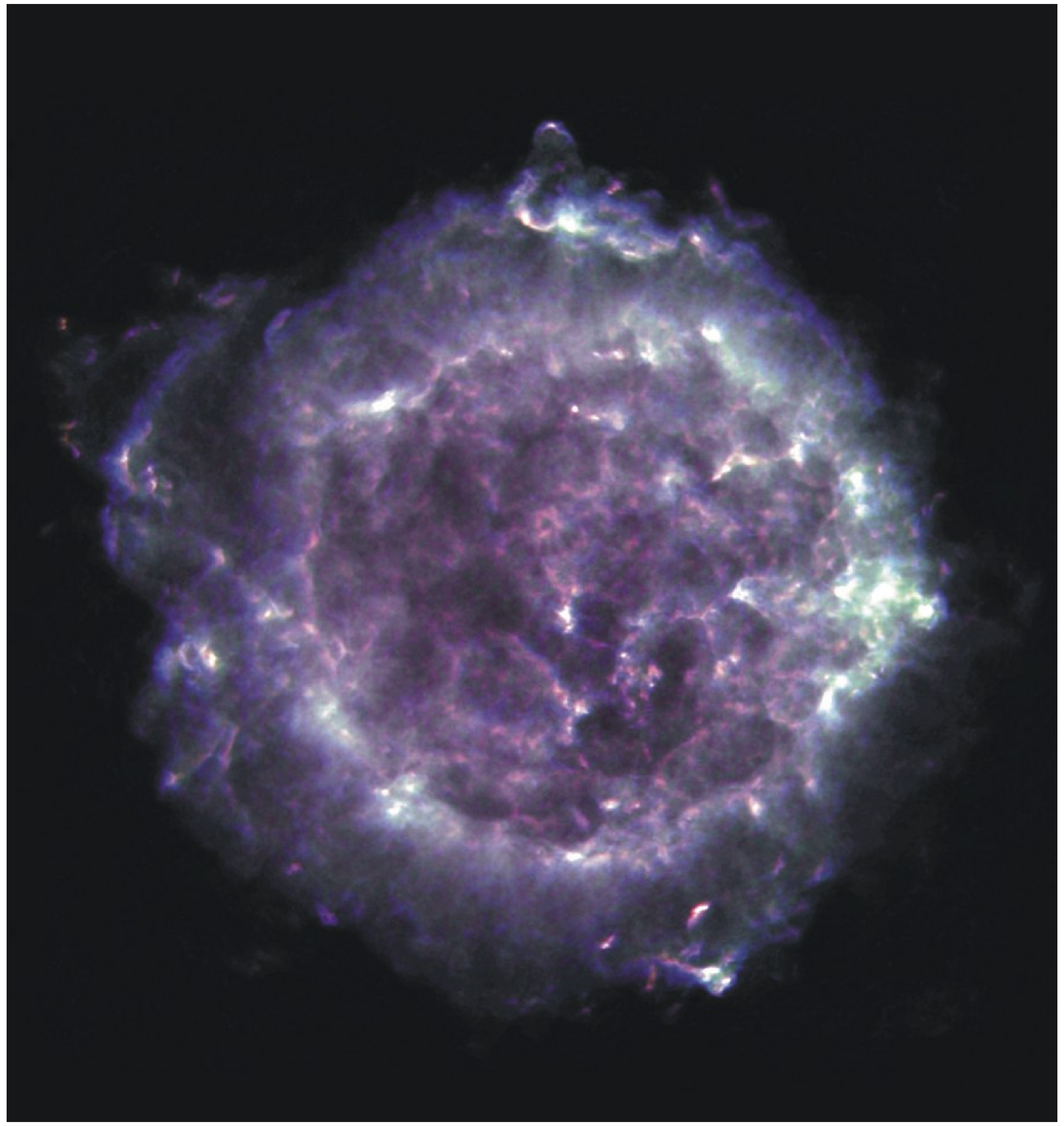

Cas A supernova remnant

VLA 1.4/5/8.4 GHz

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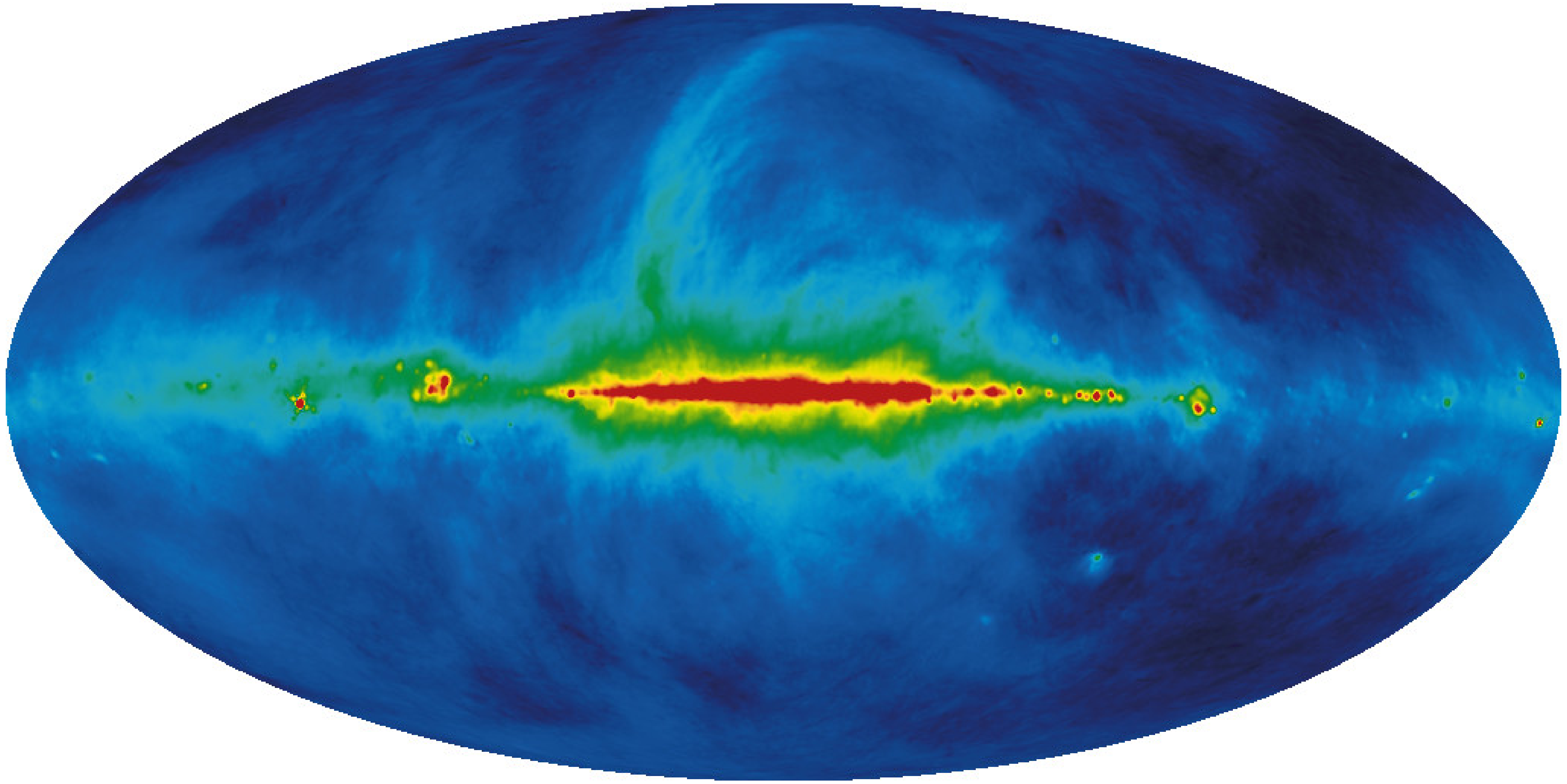

All-sky 408 MHz continuum

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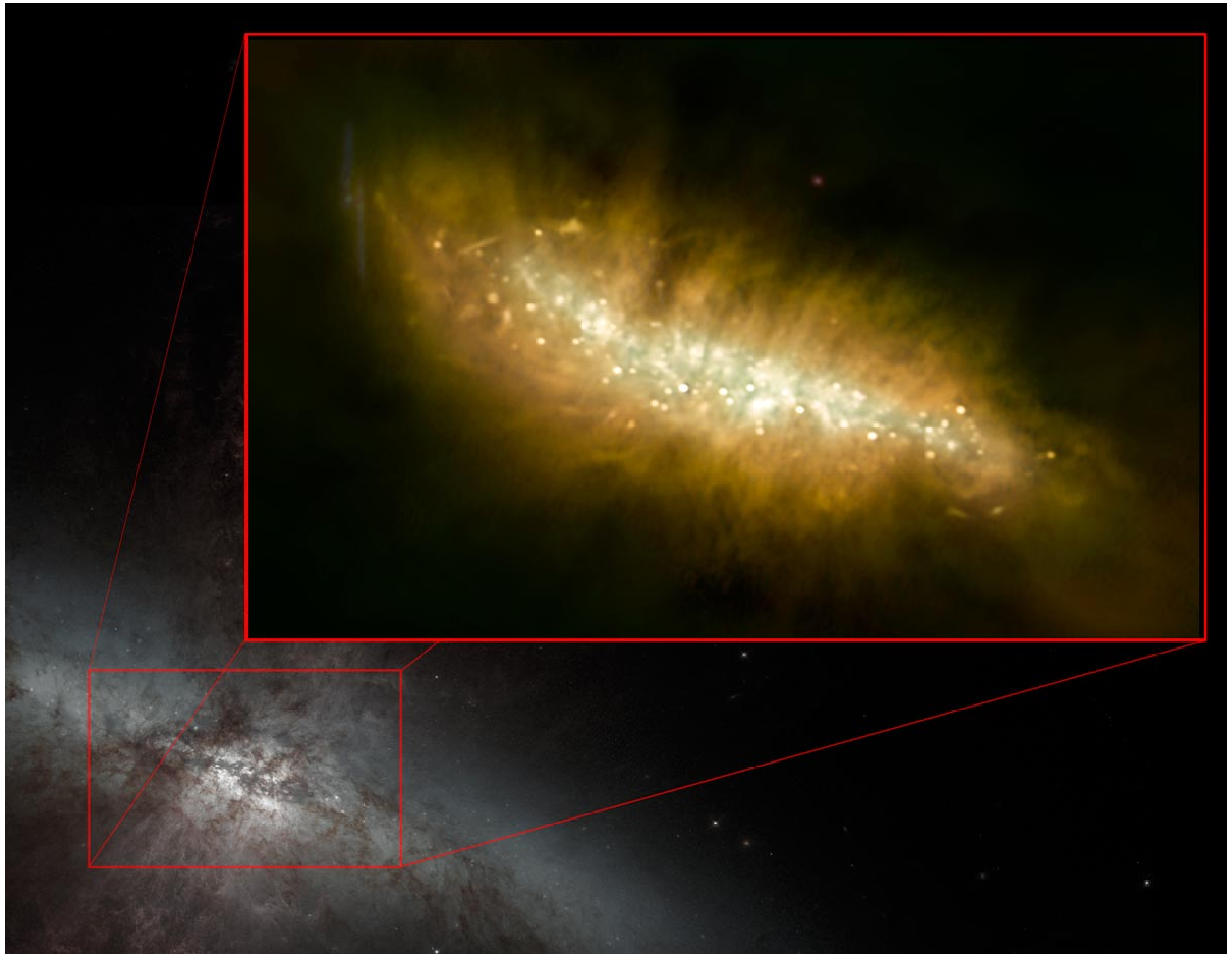

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M82 - a nearby typical star-forming galaxy

radio continuum

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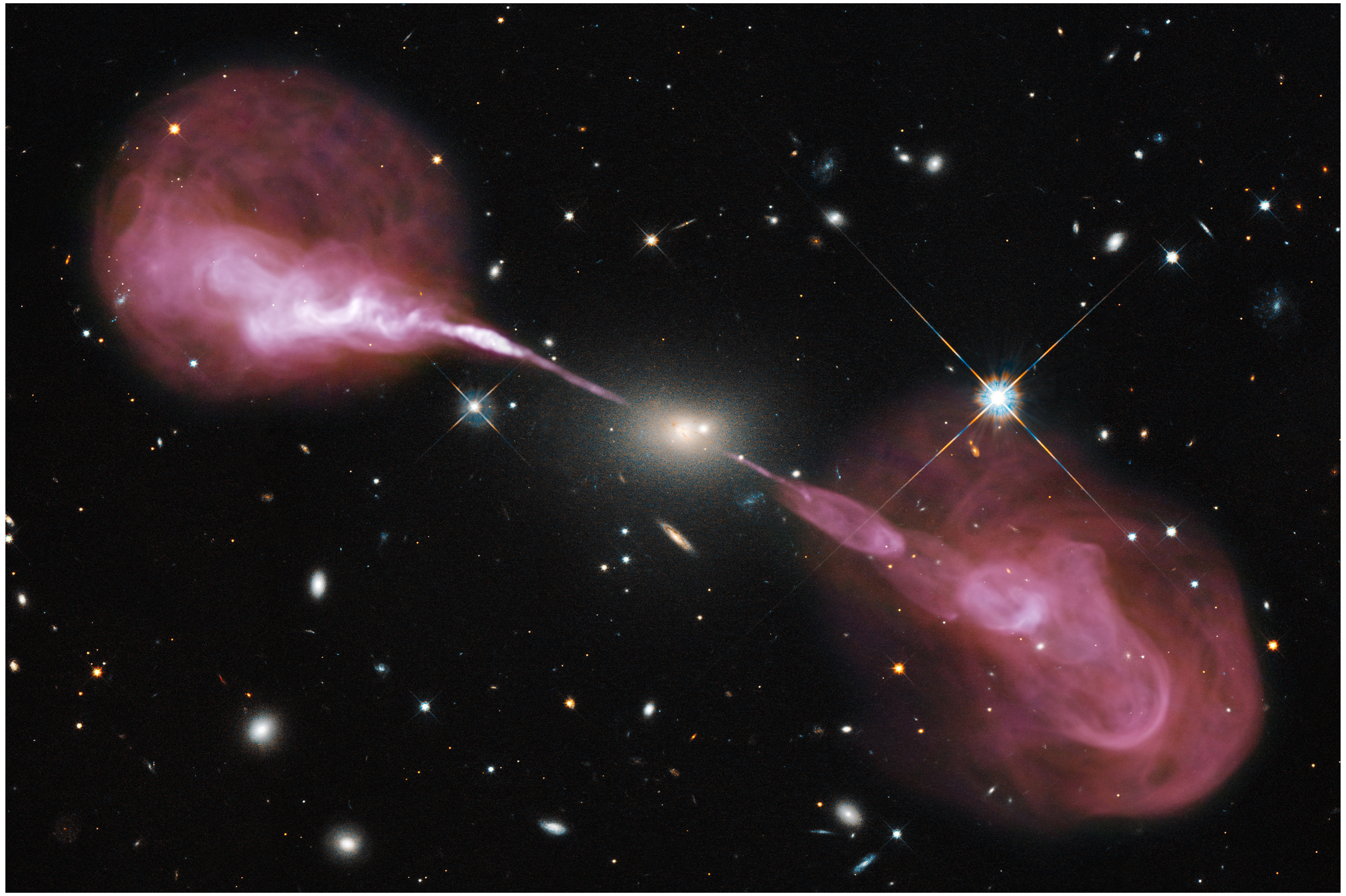

Hercules A (3C 348) VLA+HST imaging

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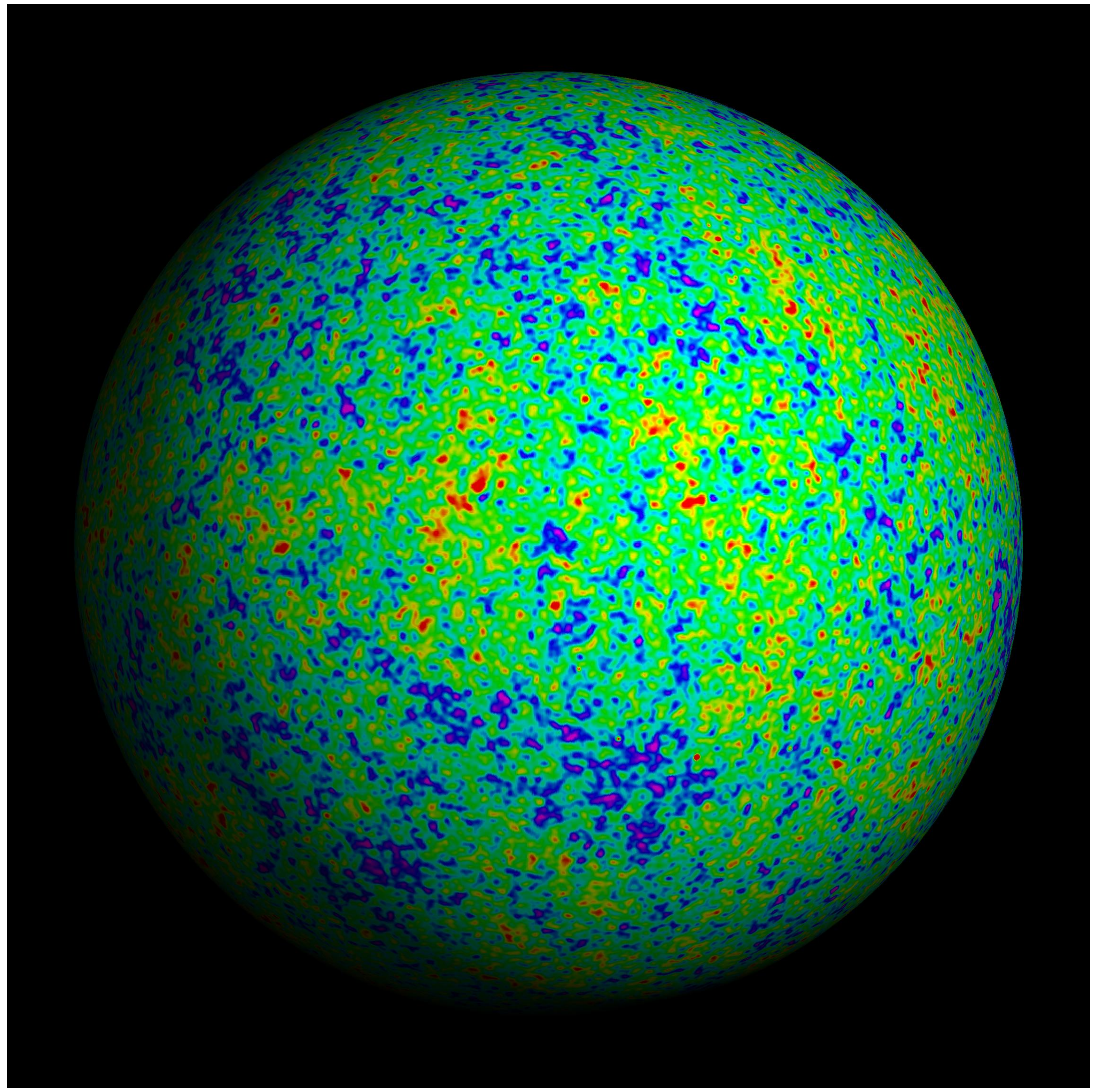

CMB fluctuations — WMAP 23-94 GHz mapping

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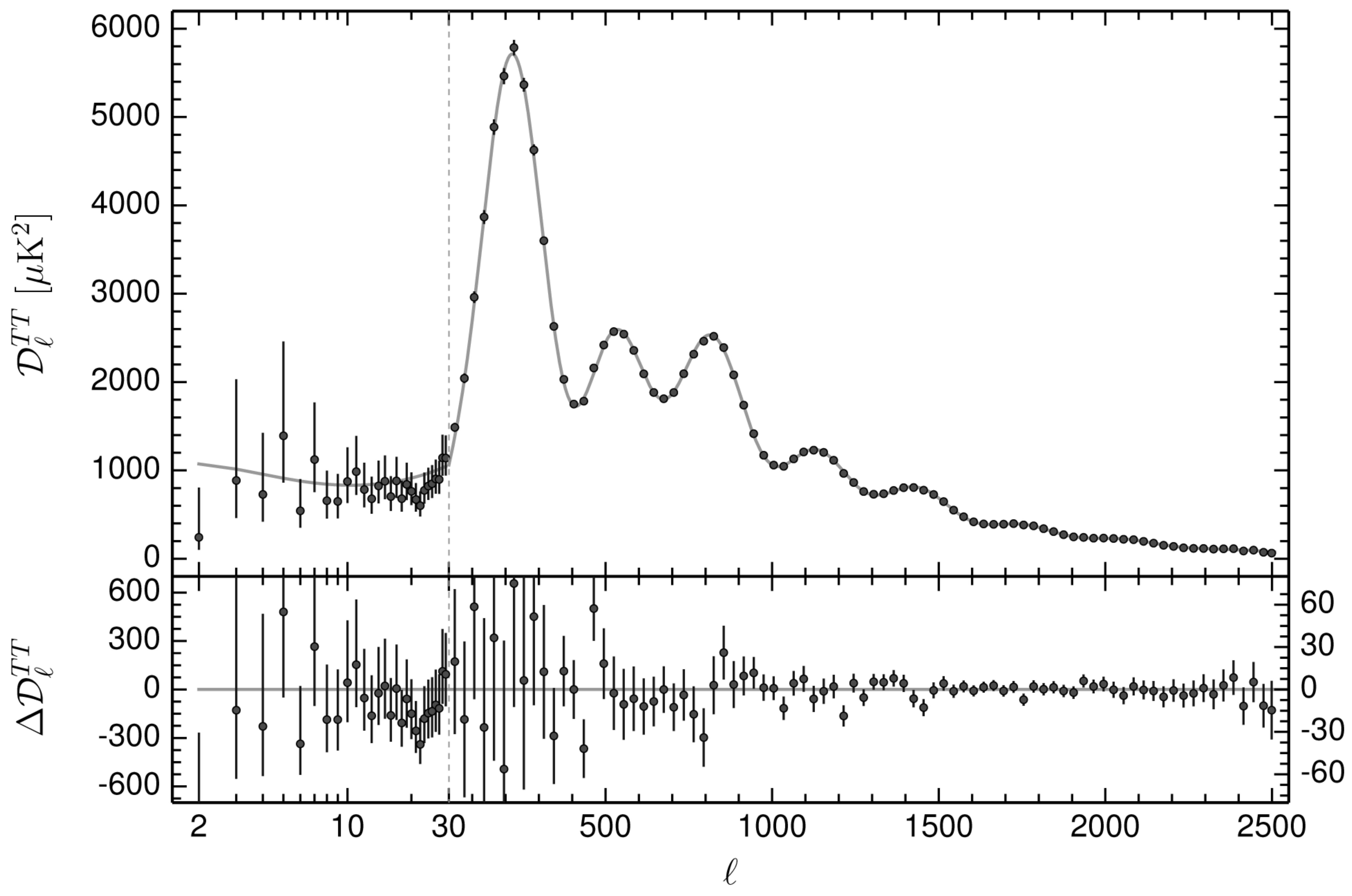

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Power spectrum of CMB fluctuations — Plank satellite

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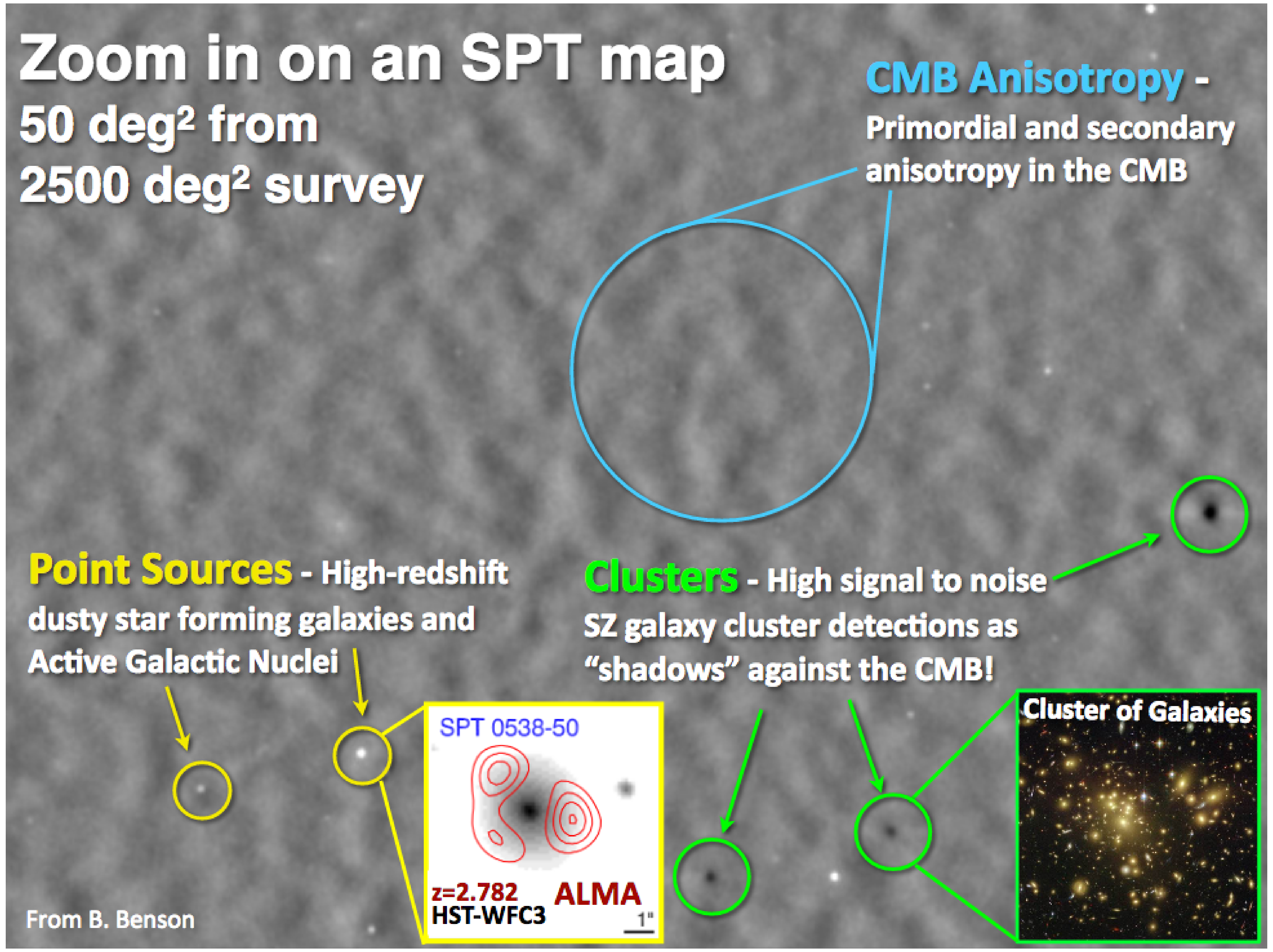

South Pole Telescope (90/150/220 GHz)

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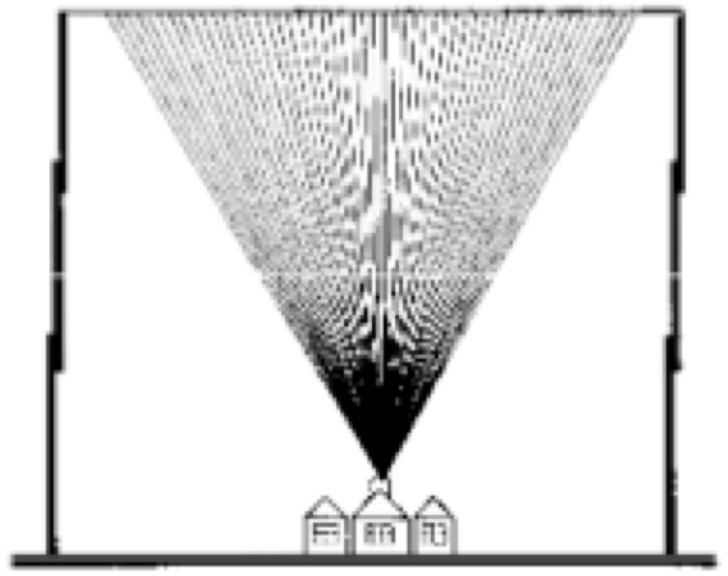
Historical background

Marconi invented the ground antenna and experimented with antenna arrays. He realised that the directivity (gain) of his array was as important as the total power radiated. Images: Marconi's array at Poldhu Corwall where the first transatlantic signals were transmitted and received (Newfoundland).



Below: Receiving antenna borne by a kite in St. Johns, Newfoundland, Canada

Guglielmo Marconi

— 1909 Nobel Prize in Physics —

“wireless telegraphy”

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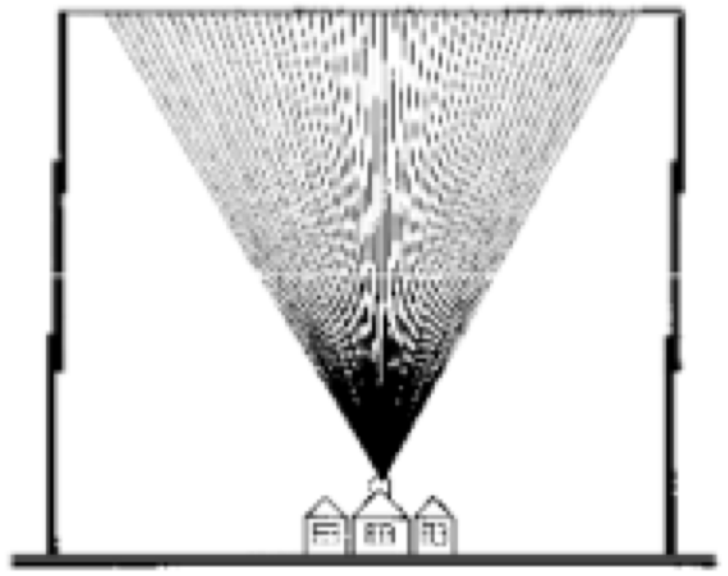

Guglielmo Marconi

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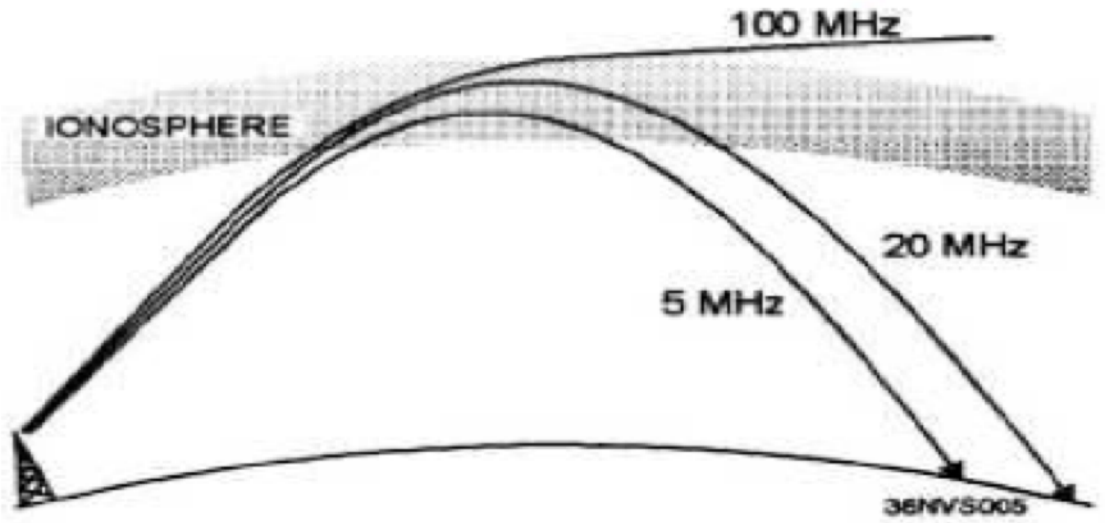
Below: Receiving antenna borne by a kite in St. Johns, Newfoundland, Canada

Marconi's success led to the discovery of the ionosphere (right) & its reflective and refractive properties w.r.t. (low-frequency) radio wave propogation:



Historical background

Alexander Graham Bell invents the telephone - Bell telephone Company created in 1877 - it will play a significant role in radio astronomy over the next 100 years:

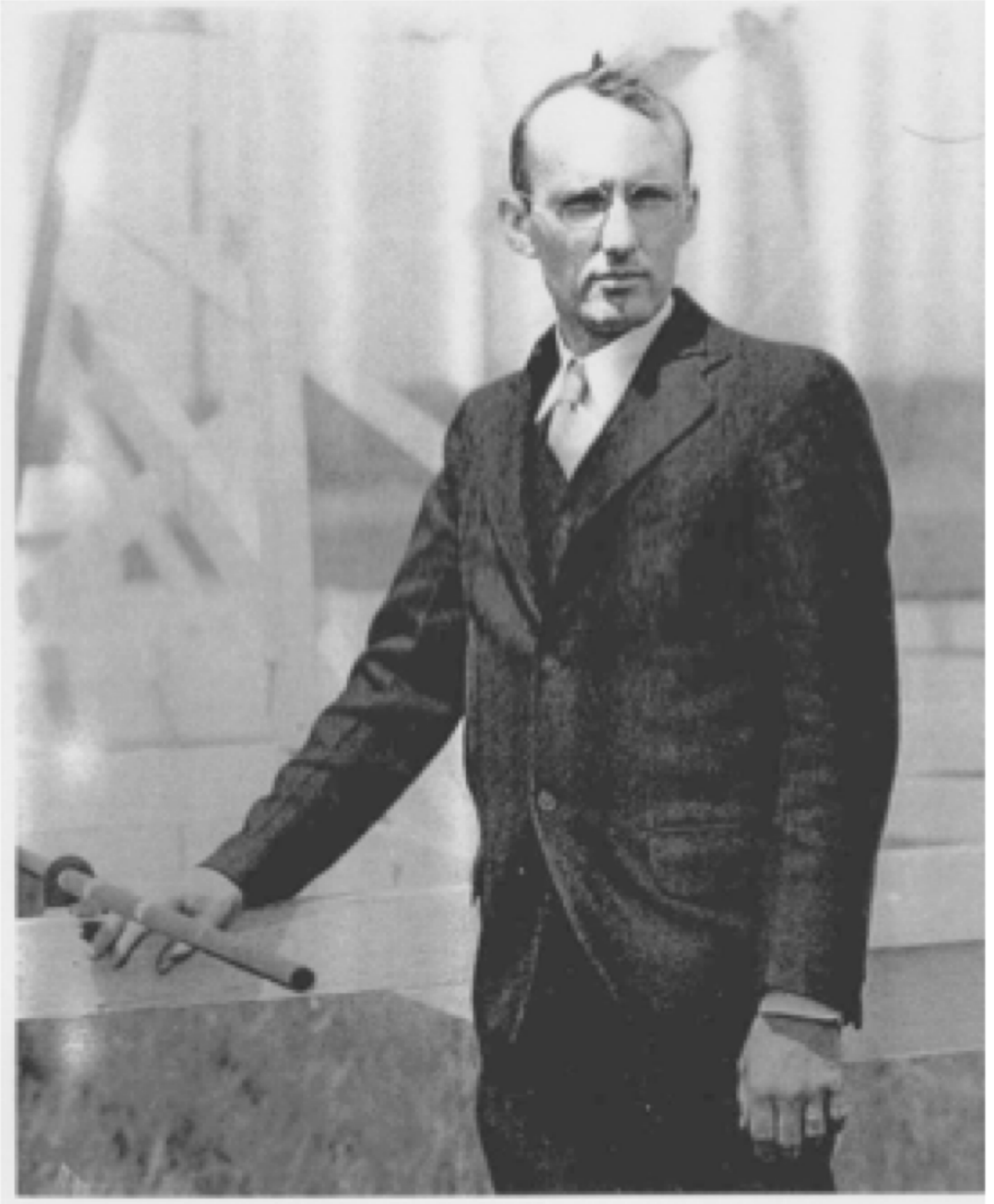


FIG. 1—Karl Guthe Jansky, about 1933.

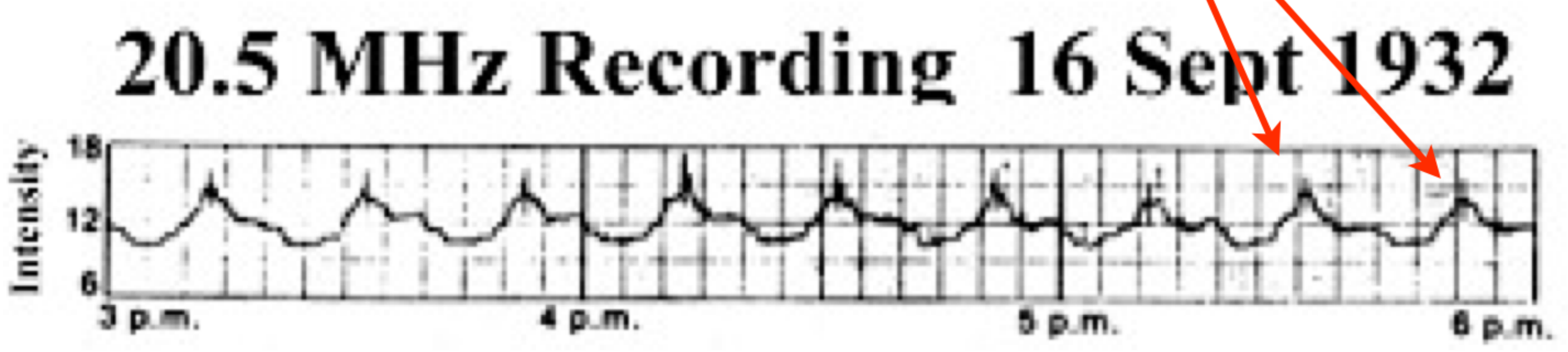
1930's Karl Jansky - communication engineer at Bell Laboratory begins to investigate sources of radio noise that adversely affected communications - cross-country, transatlantic etc.

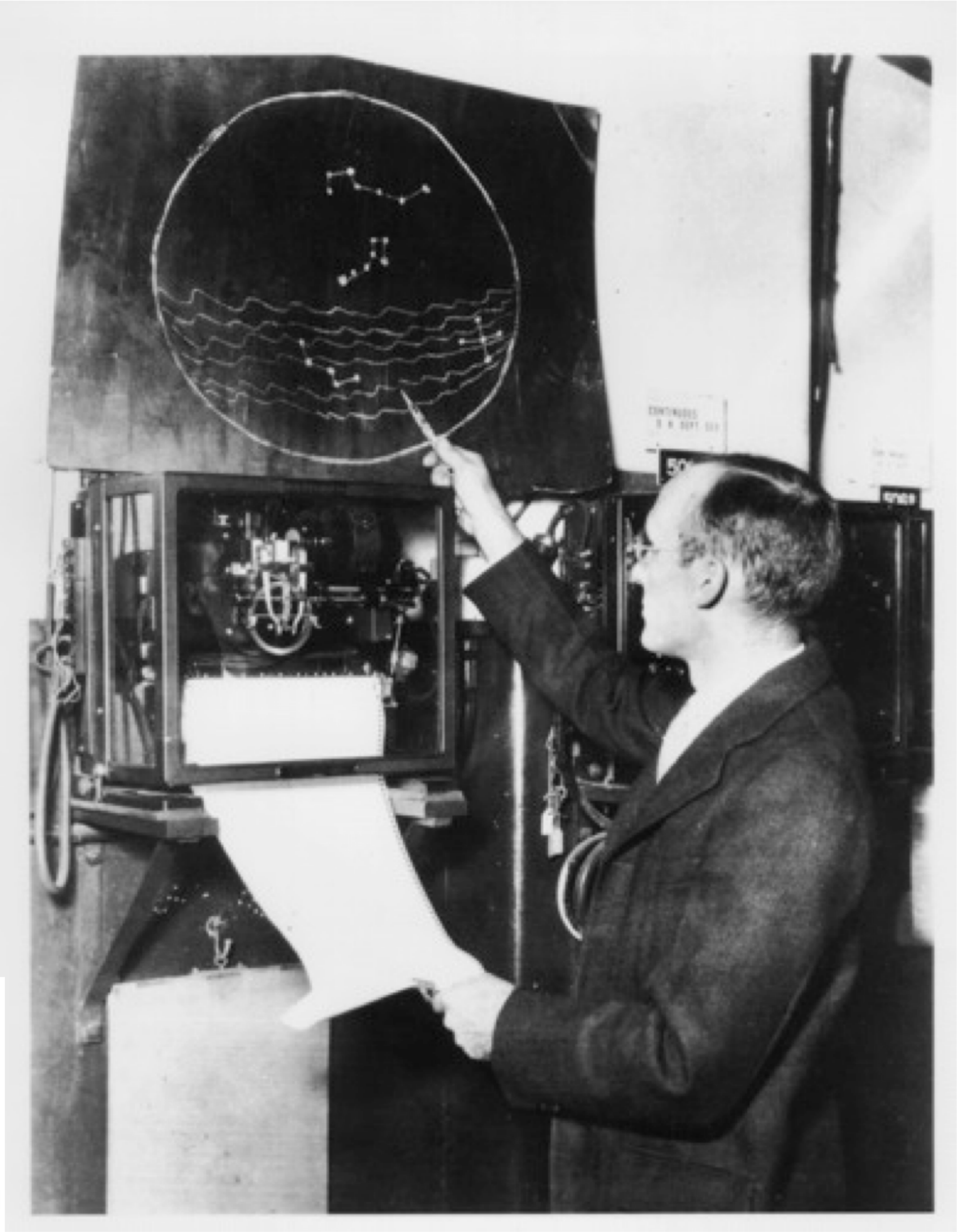
Identified thunderstorms (near and far) and something else....

Historical background

1932 Discovery of cosmic radio waves (Karl Jansky):

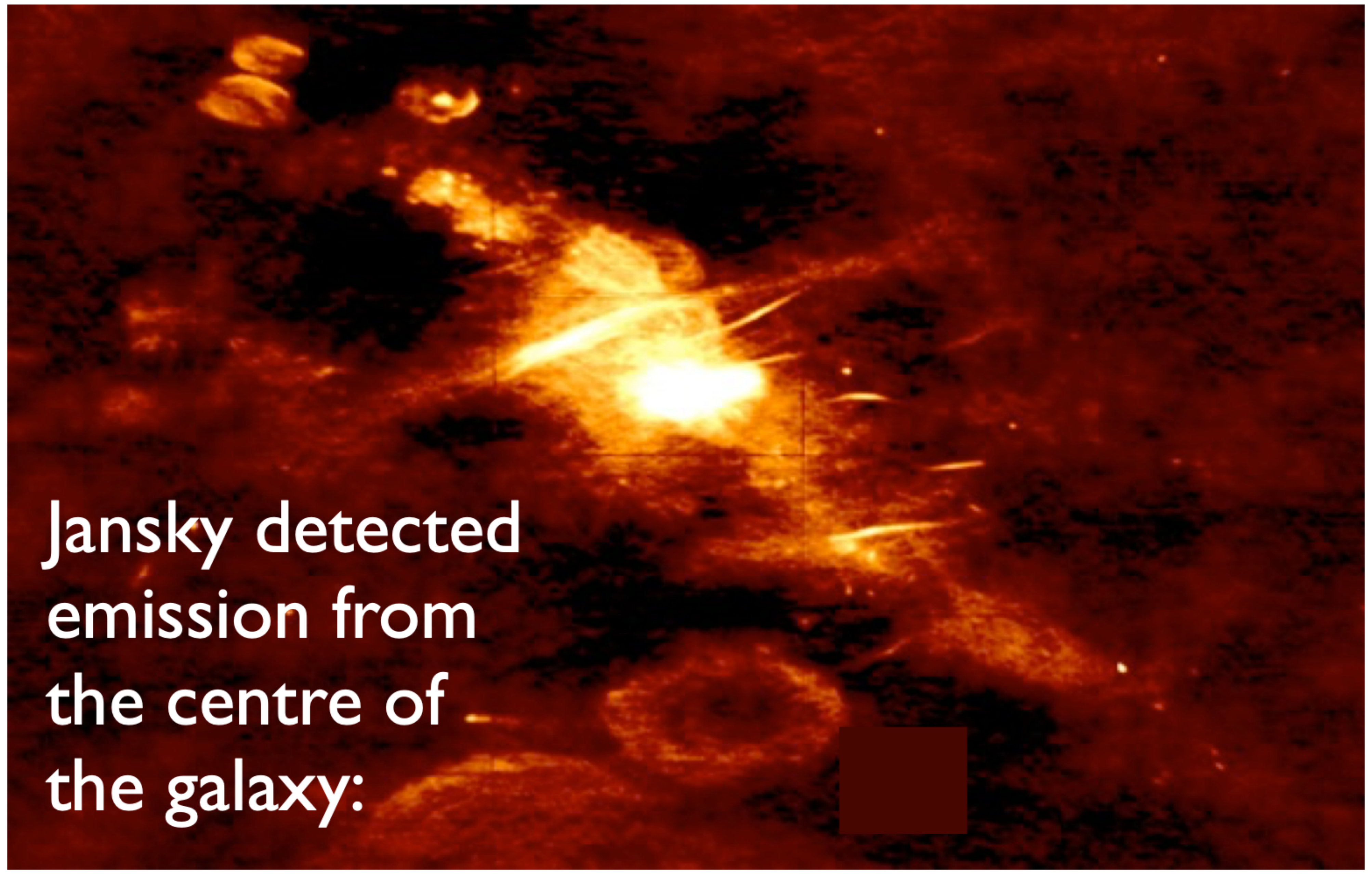
Galactic centre





Historical background

New York Times:



"There is no indication of any kind, that these results are the form of some intelligence striving for intra-galactic communication."

NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

DIRECTION IS UNCHANGING

Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

ITS INTENSITY IS LOW

Only Delicate Receiver Is Able to Register—No Evidence of Interstellar Signaling.

Discovery of mysterious radio waves which appear to come from the centre of the Milky Way galaxy was announced yesterday by the Bell Telephone Laboratories. The discovery was made during research studies on static by Karl G. Jansky of the radio research department at Holmdel, N. J., and was described by him in a paper delivered before the International Scientific Radio Union in Washington.

The galactic radio waves, Mr. Jansky said, differ from the cosmic rays and also from the phenomenon of cosmic radiation, described last week before the American Philosophical Society at Philadelphia by Dr. Vesto M. Slipher, director of the Lowell Observatory at Flagstaff, Ariz.

Unlike the cosmic ray, which comes from all directions in space, does not vary with either the time of day or the time of the year, and may be either a photon or an electron, the galactic waves, Mr. Jansky pointed out, seem to come from a definite source in space, vary in intensity with the time of day and time of the year, and are distinctly electro-magnetic waves that can be picked up by a radio set.

New Waves Have High Frequency.

The cosmic radiation discovered by Dr. Slipher is a mysterious form of light apparently radiated independently of starlight, originating, Dr. Slipher concluded, at some distance above the earth's surface, and possibly produced by the earth's atmosphere.

The galactic radio waves, the announcement says, are short waves, 14.6 meters, at a frequency of about 20,000,000 cycles a second. The intensity of these waves is very low, so that a delicate apparatus is required for their detection.

Unlike most forms of radio disturbances, the report says, these newly found waves do not appear to be due to any terrestrial phenomena, but rather to come from some point far off in space—probably far beyond our solar system.

If these waves came from a terrestrial origin, it was reasoned, then they should have the same intensity all the year around. But their intensity varies regularly with the time of day and with the seasons, and they get much weaker when the earth, moving in its orbit, interposes itself between the radio receiver and the source.

A preliminary report, published in the Proceedings of the Institute of Radio Engineers last December, described studies which showed the presence of three separate groups of static: Static from local thunderstorms, static from distant thunderstorms, and a "steady hiss type static of unknown origin." Further studies this year determine the unknown origin of this third type to be from the direction of the centre of the Milky Way, the earth's own home galaxy.

Direction of Arrival Fixed.

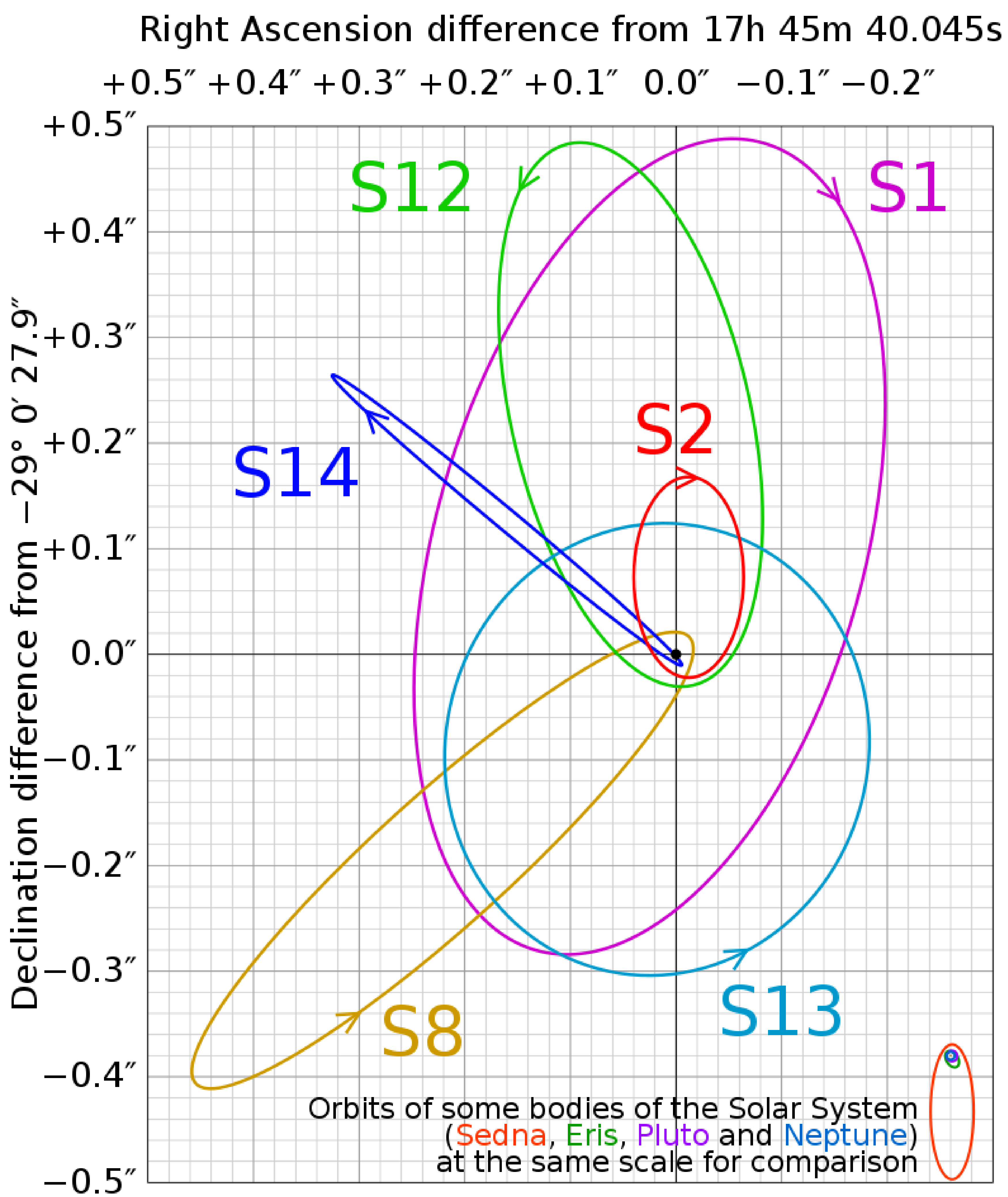
The direction from which these waves arrive, the announcement asserts, has been determined by investigations carried on over a considerable period. Measurements of the horizontal component of the waves were taken on several days of each month for an entire year, and by an analysis of these readings at the end of the year their direction of arrival was disclosed.

"The position indicated," it was explained, "is very near to the point where the plane in which the earth revolves around the sun crosses the centre of the Milky Way, and also to that point toward which the solar system is moving with respect to the other stars.

"Further verification of this direction is required, but the discovery, like that of the cosmic rays and of cosmic radiation, raises many cosmological questions of extreme interest."

There is no indication of any kind, Mr. Jansky replied to a question, that these galactic radio waves constitute some kind of interstellar signalling, or that they are the result of some form of intelligence striving for intra-galactic communication.

Historical background (and back to the future)



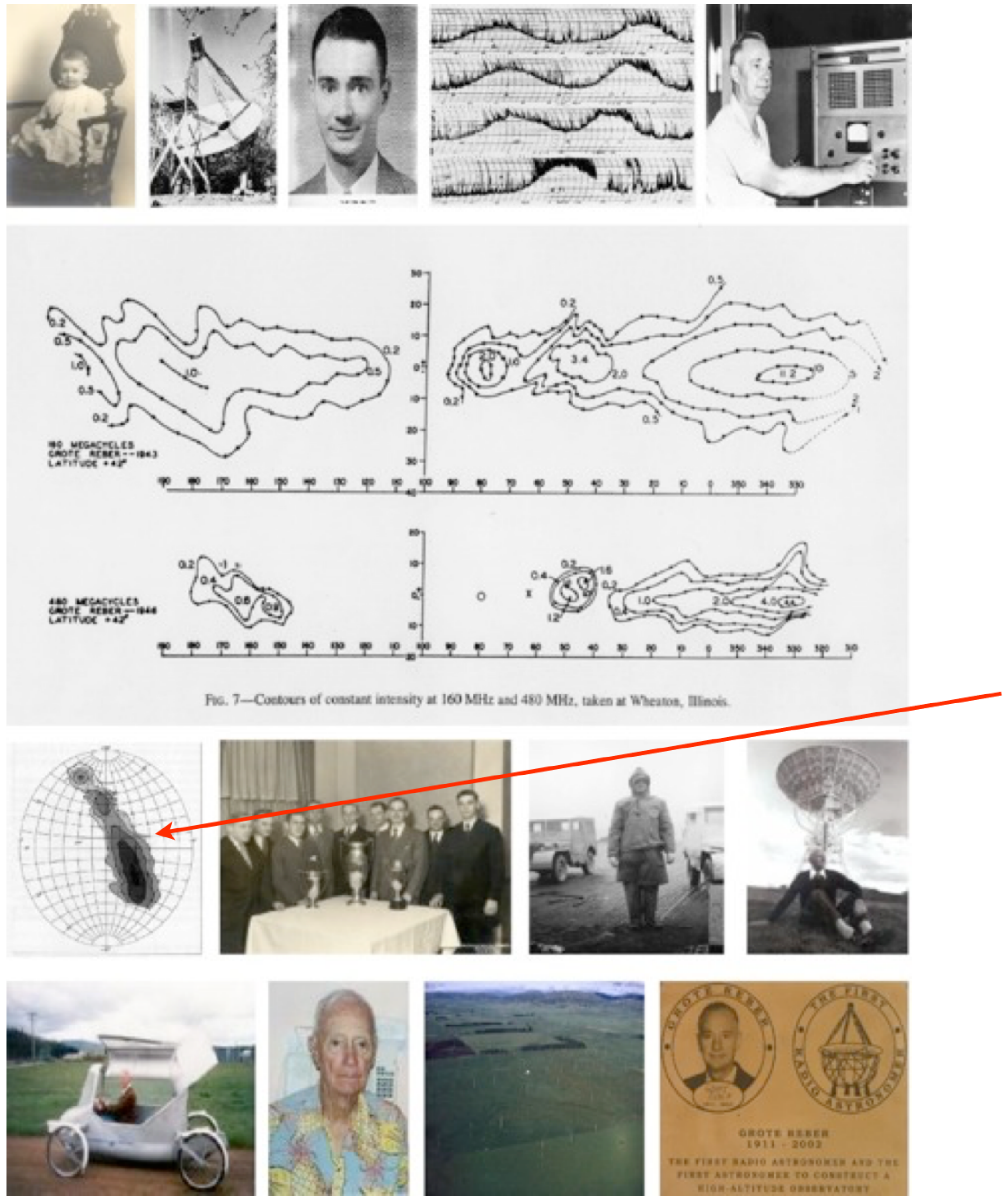
The Nobel Prize in Physics 2020 was divided, one half awarded to **Roger Penrose "for the discovery that black hole formation is a robust prediction of the general theory of relativity"**,

the other half jointly to **Reinhard Genzel and Andrea Ghez "for the discovery of a supermassive compact object at the centre of our galaxy."**

The stars' orbits are the most convincing evidence yet that a supermassive black hole is hiding in Sagittarius A*. This black hole is estimated to weigh about **4 million solar masses, squeezed into a region no bigger than our solar system**

Historical background

The first radio astronomer (Grote Reber)



Built the first parabolic radio telescope:

- "Good" angular resolution

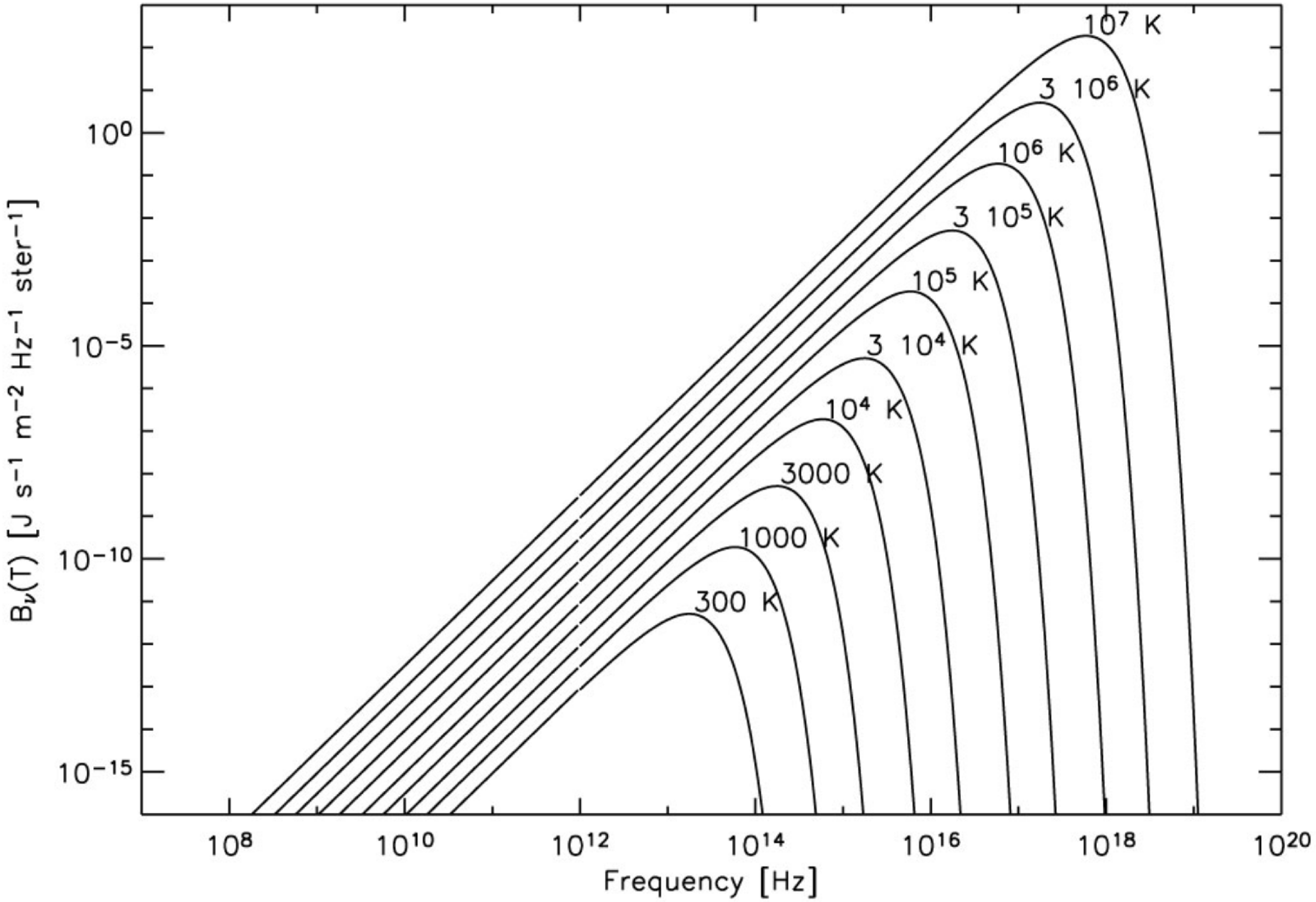
- Good visibility of the sky

- Detected Milky Way, Sun, Cas-A, Cyg-A, Cyg-X @ 160 & 480 MHz (ca. 1939-1947).

- Published his results in ApJ

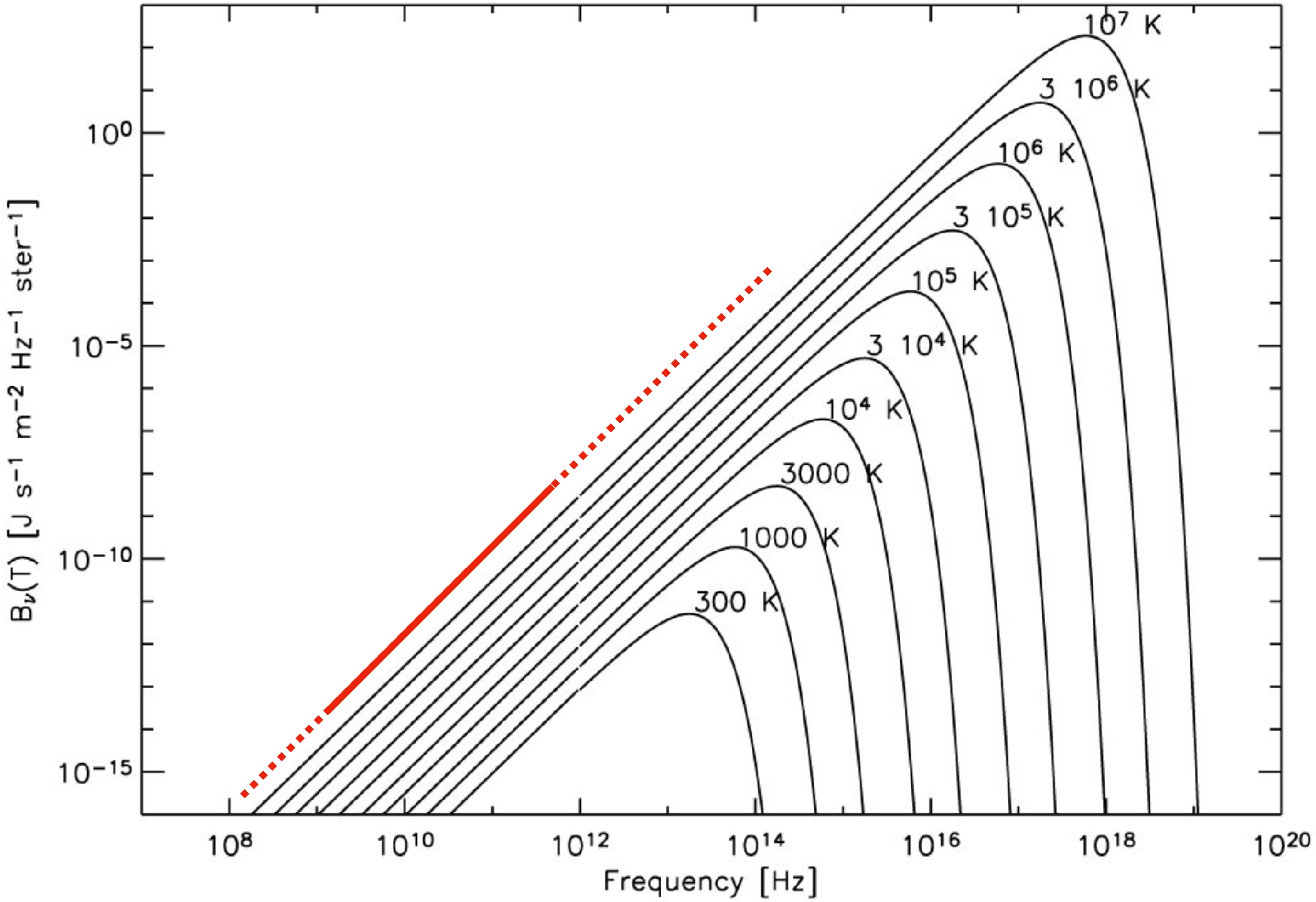
- Multi-frequency observations

Historical background



- Planckian “thermal” emission
- Wien displacement law

Historical background



- Planckian "thermal" emission
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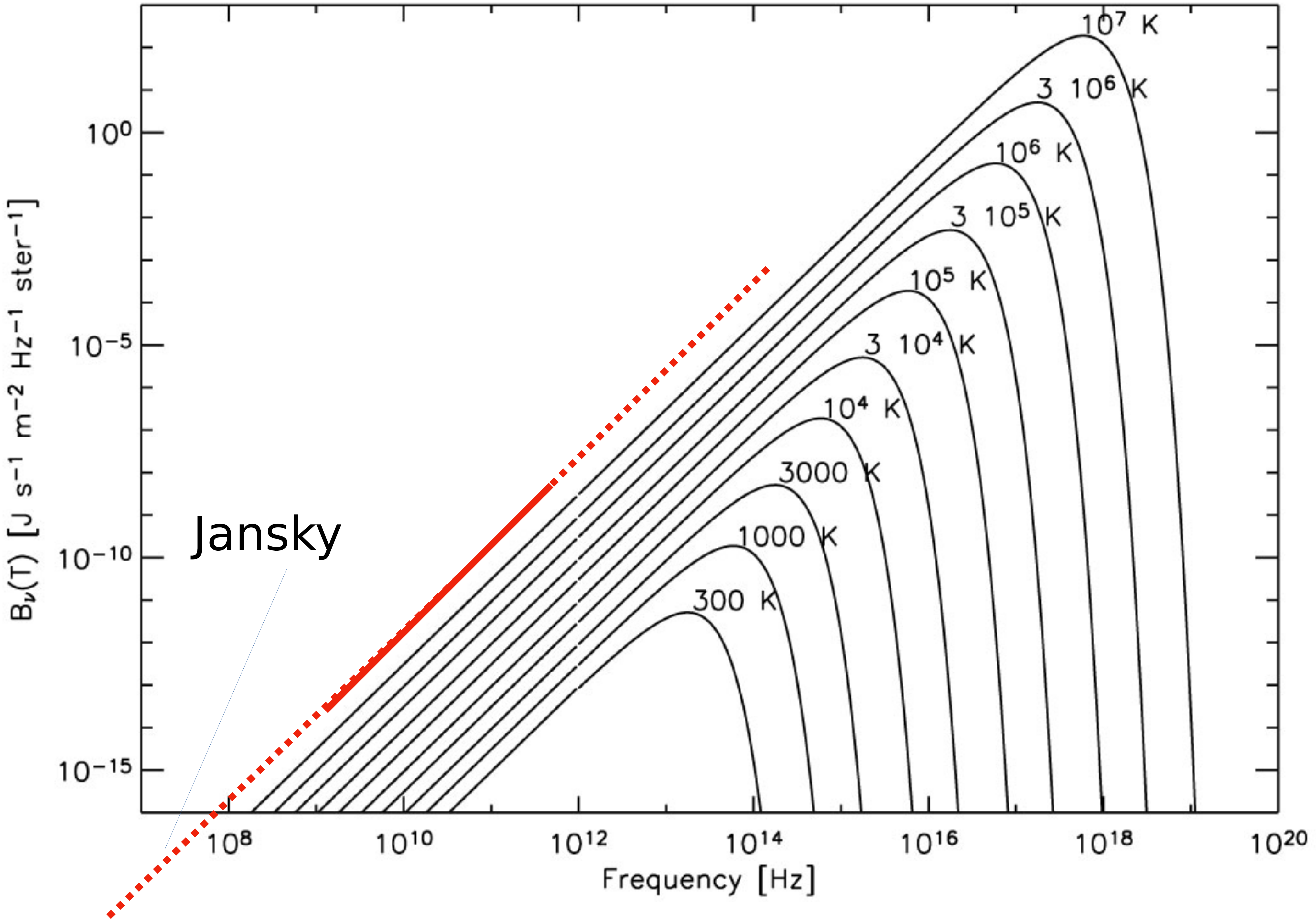
- RJ approximation at low freq

Historical background



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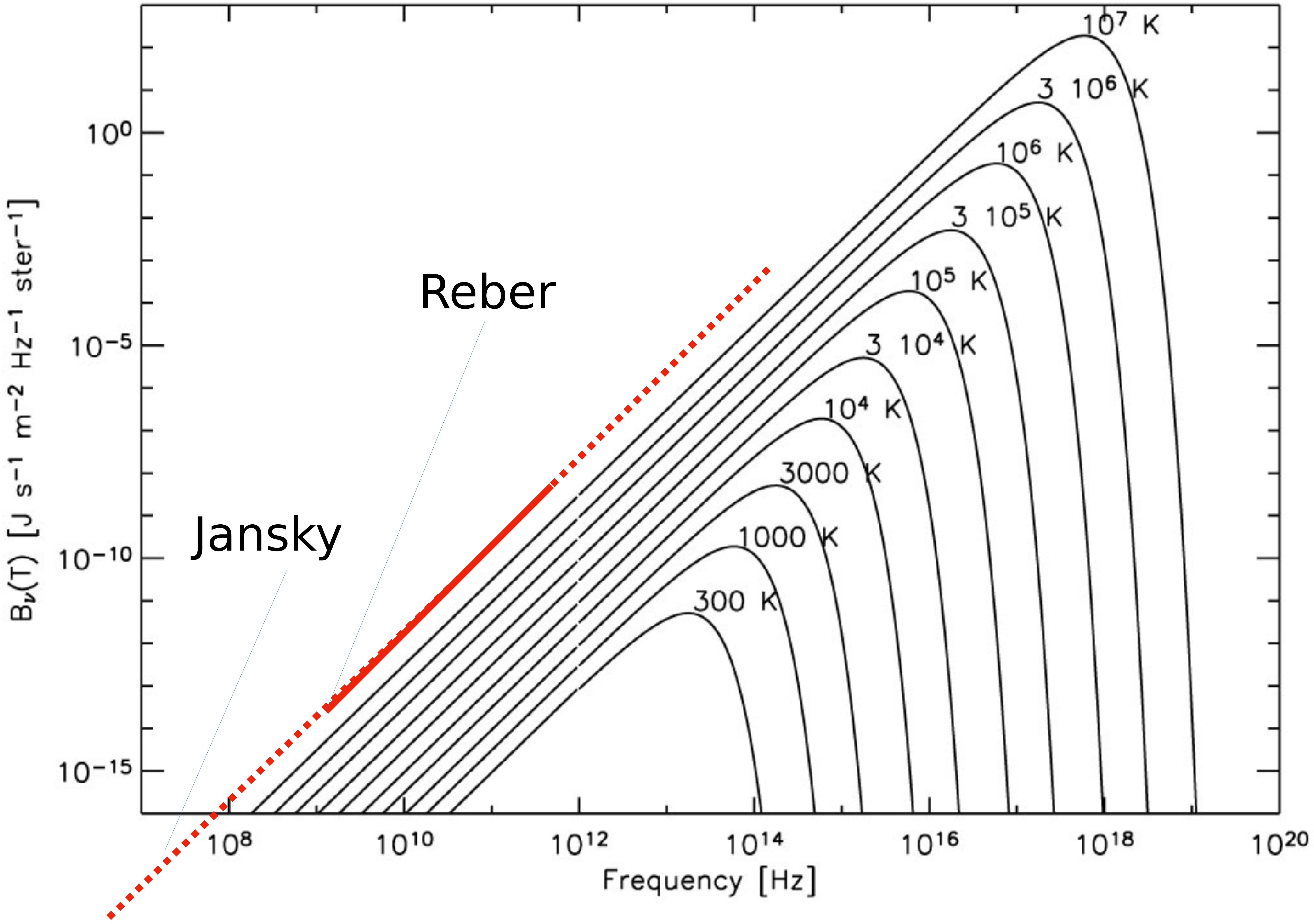

- Planckian "thermal" emission
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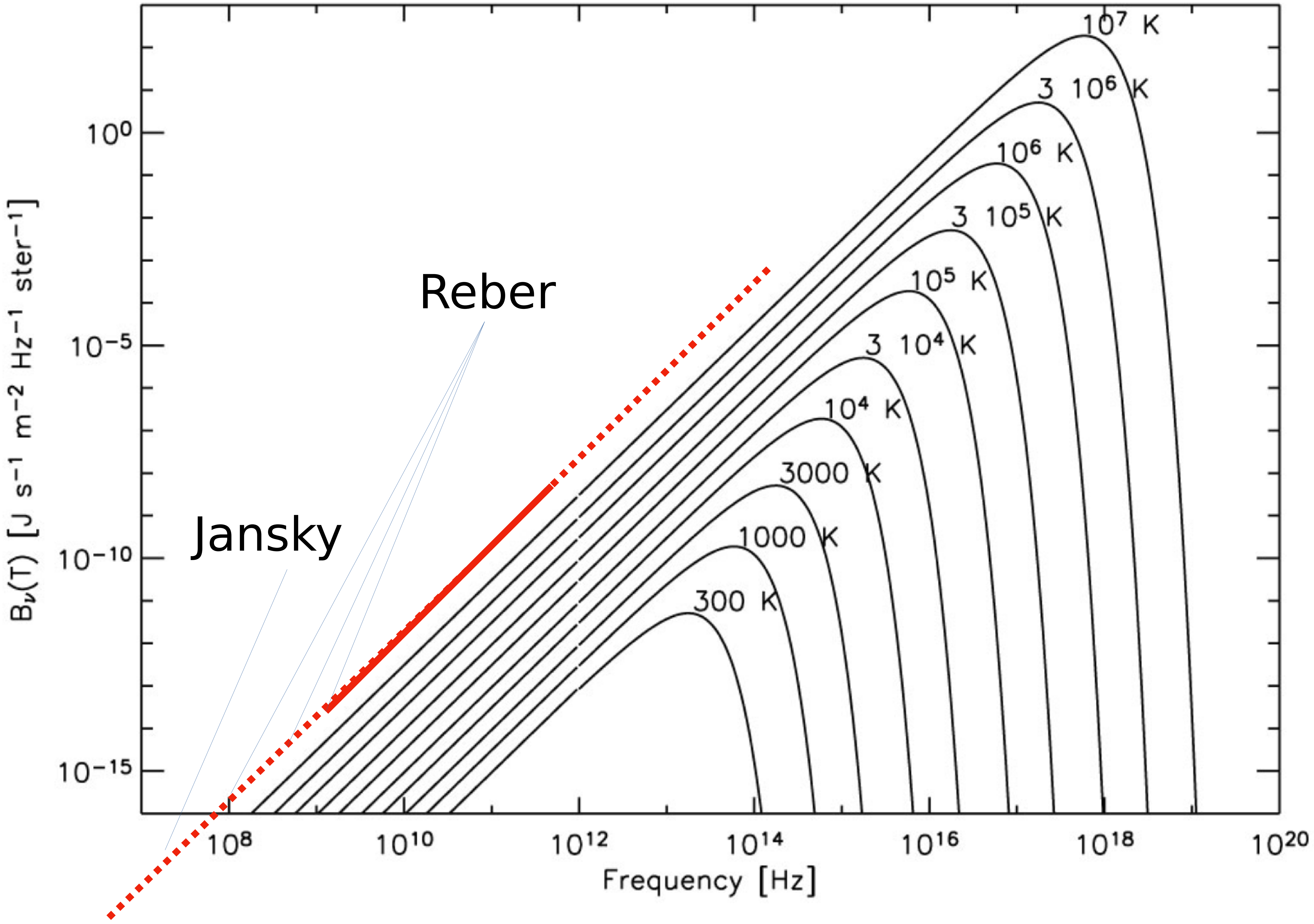
- No detection at 3 GHz

Historical background



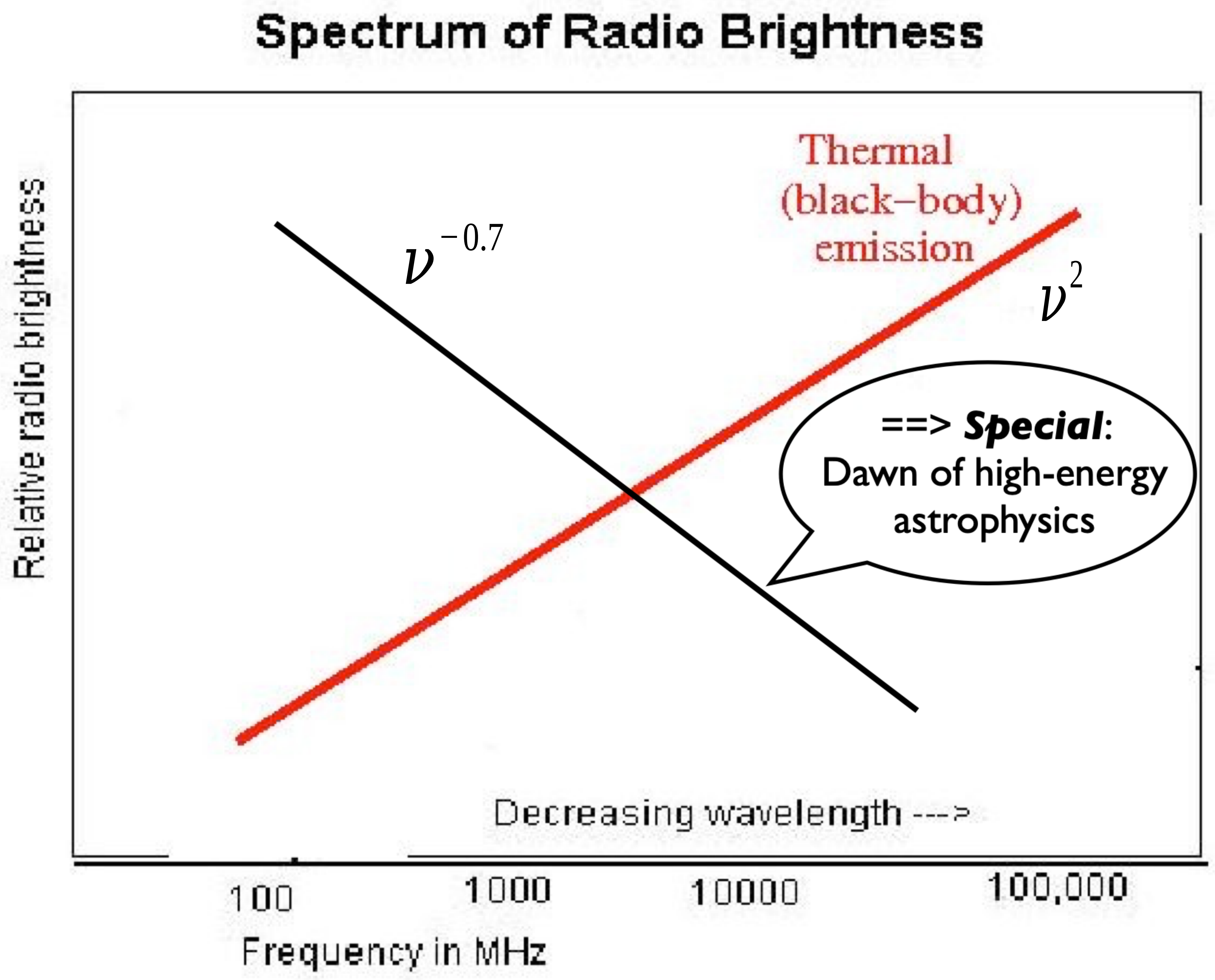
- Planckian “thermal” emission
- Wien displacement law
- RJ approximation at low freq

- No detection at 3 GHz
- 160/480 MHz detections but…

Historical background

The things that make radio astronomy "special":

Reber's multi-frequency observations revealed the non-thermal nature of radio emission (UNEXPECTED!)



Historical background

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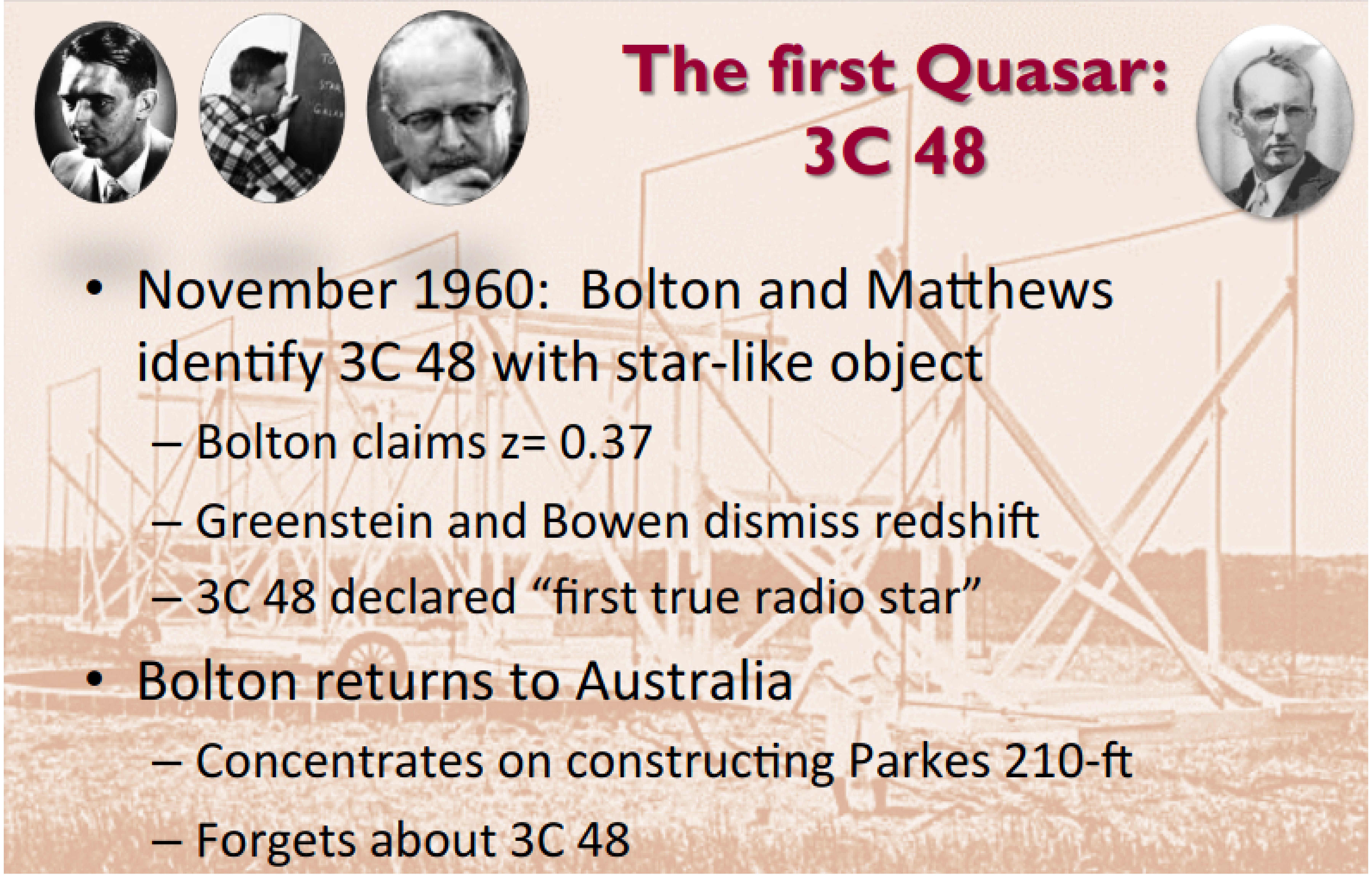
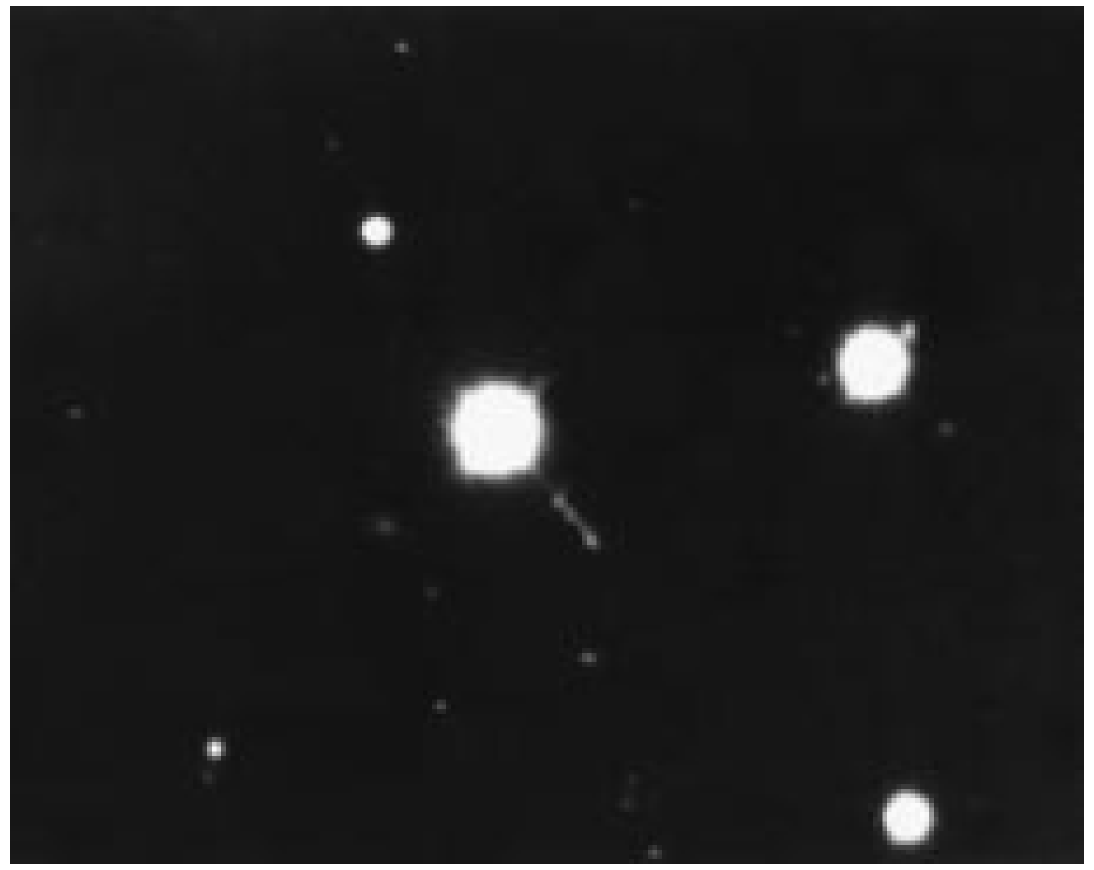


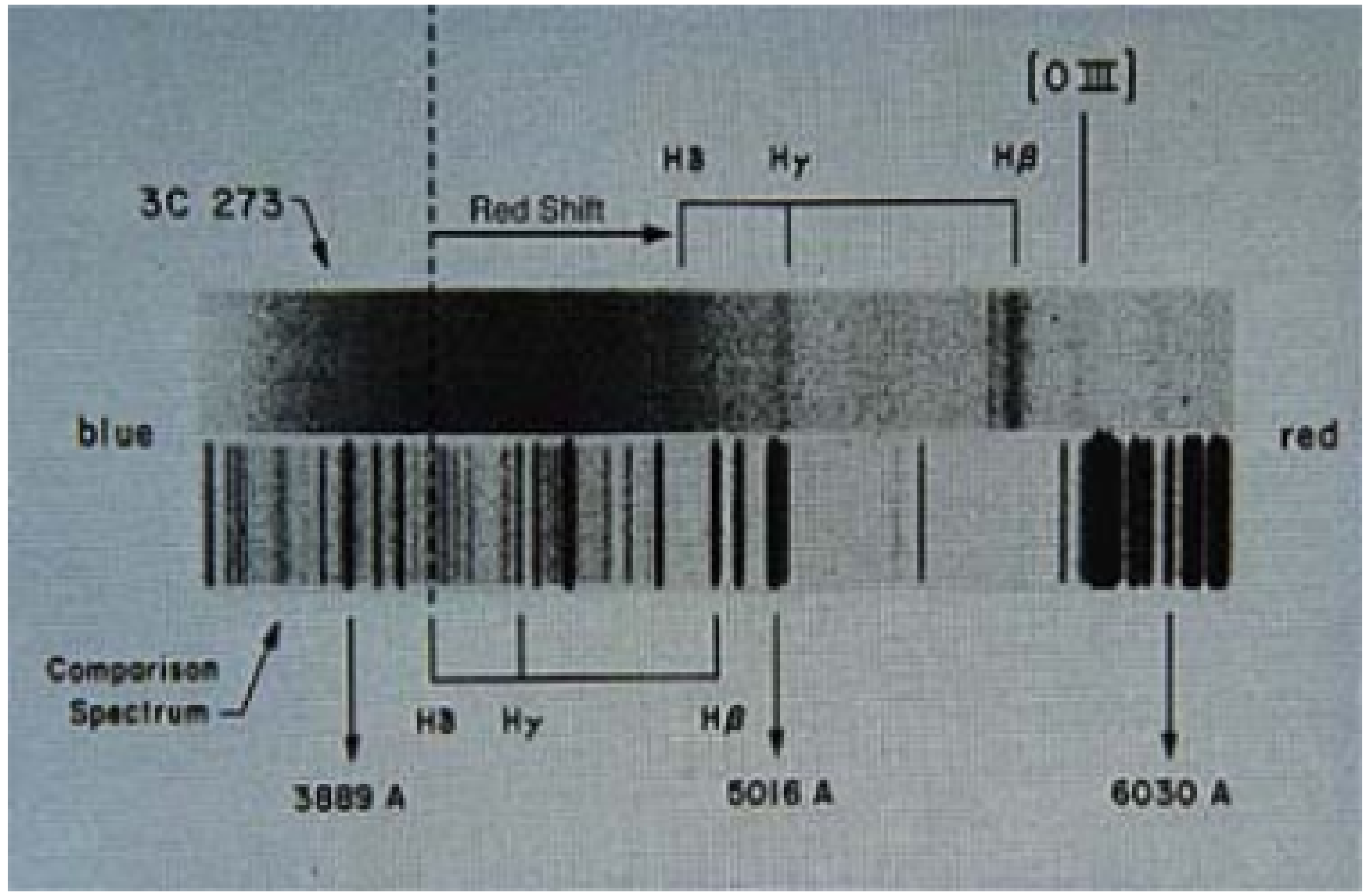
Historical background

Discovery of Quasars -1963

In the 1950s/60s the great challenge was to identify radio sources with optical counterparts.

In 1963 one of the brightest radio sources then known, 3C273, was identified with a faint blue 13th mag star-like source (Hazard et al. Nature)...

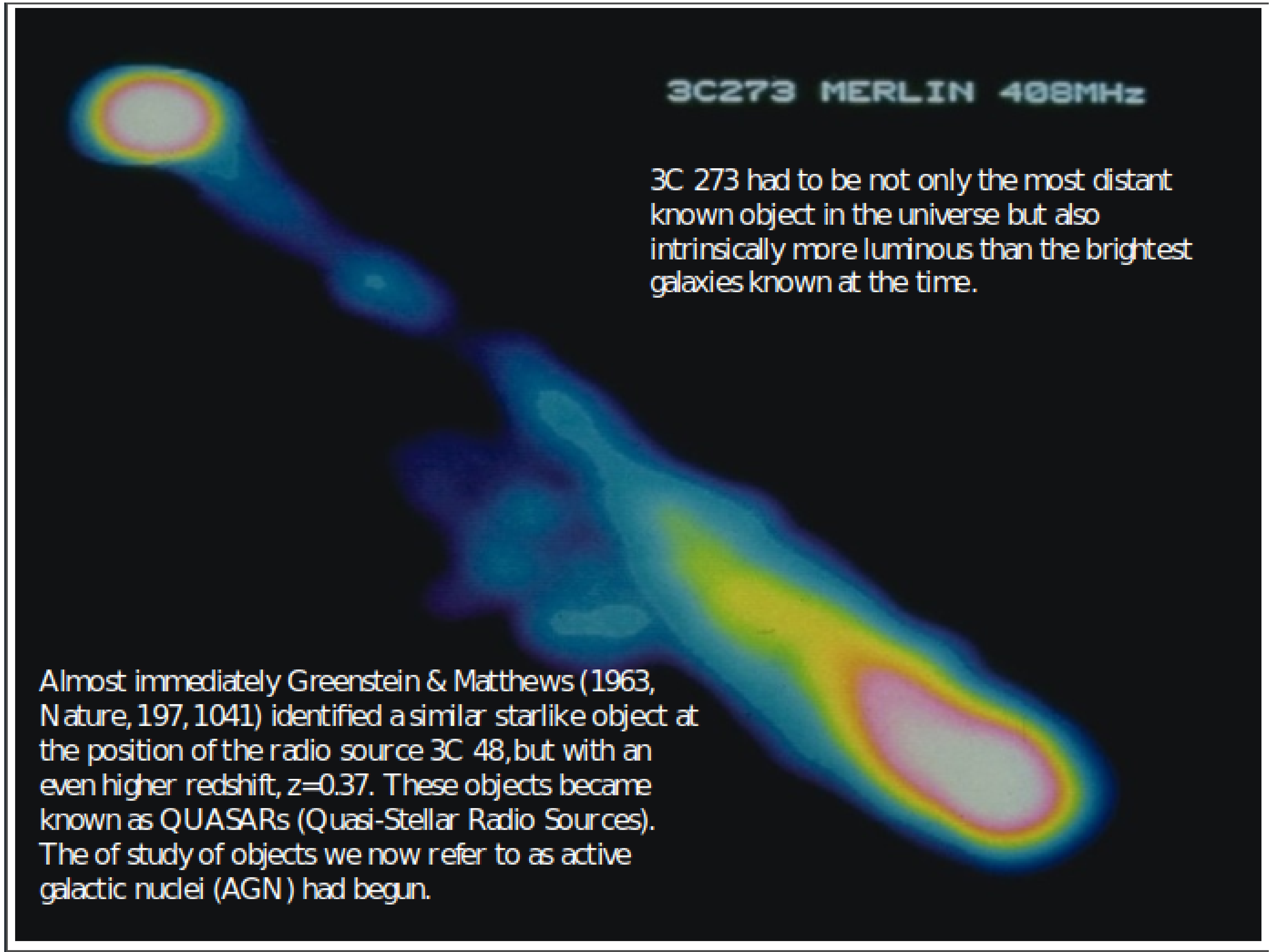




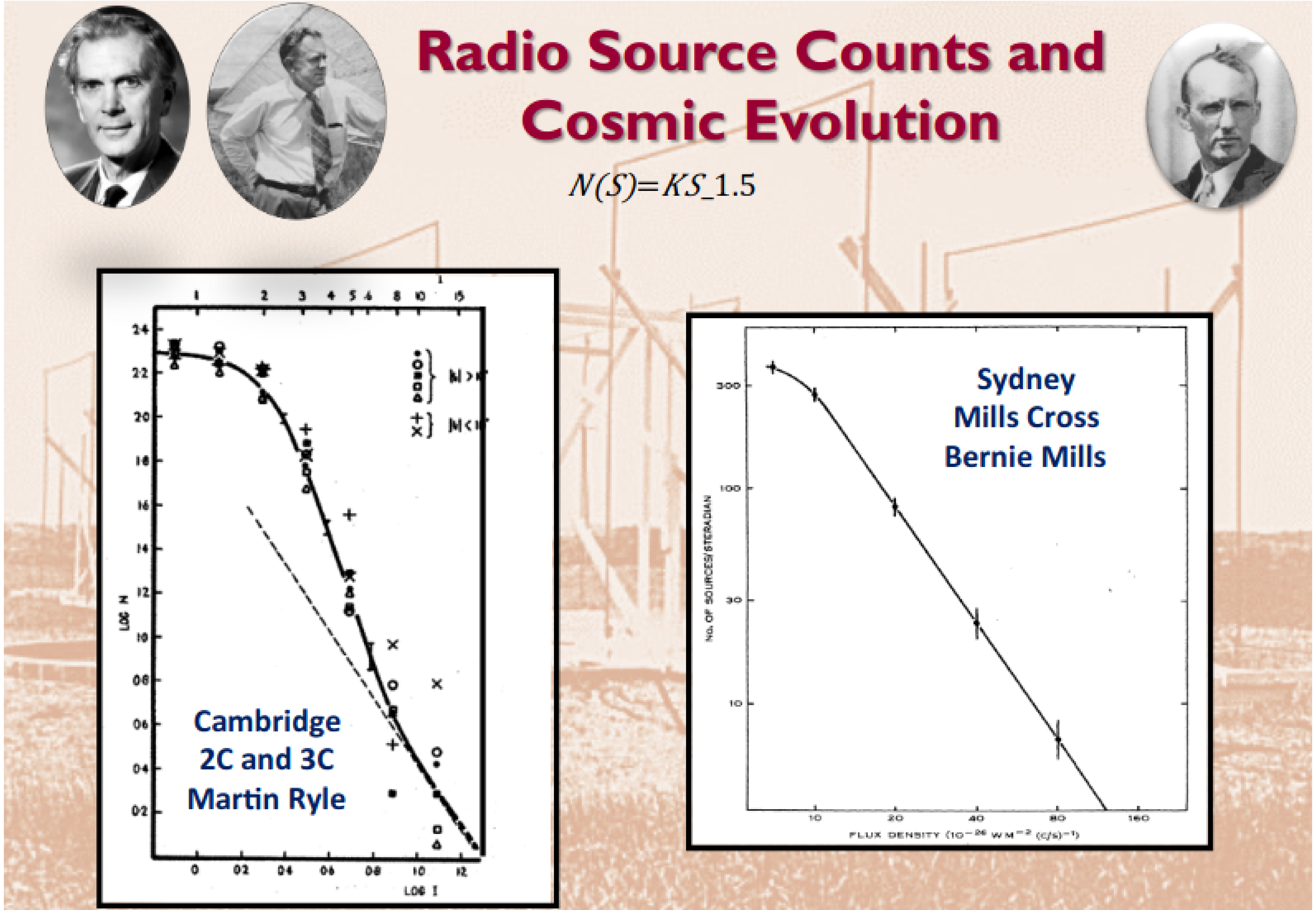
Maarten Schmidt (1963, Nature, 197, 1040) examined a visible spectrum of this "star" and identified the characteristic spectrum of emission lines in the Balmer series of hydrogen Doppler-shifted to longer wavelengths by 16 percent!

$z = 0.16$

Historical background



Historical background

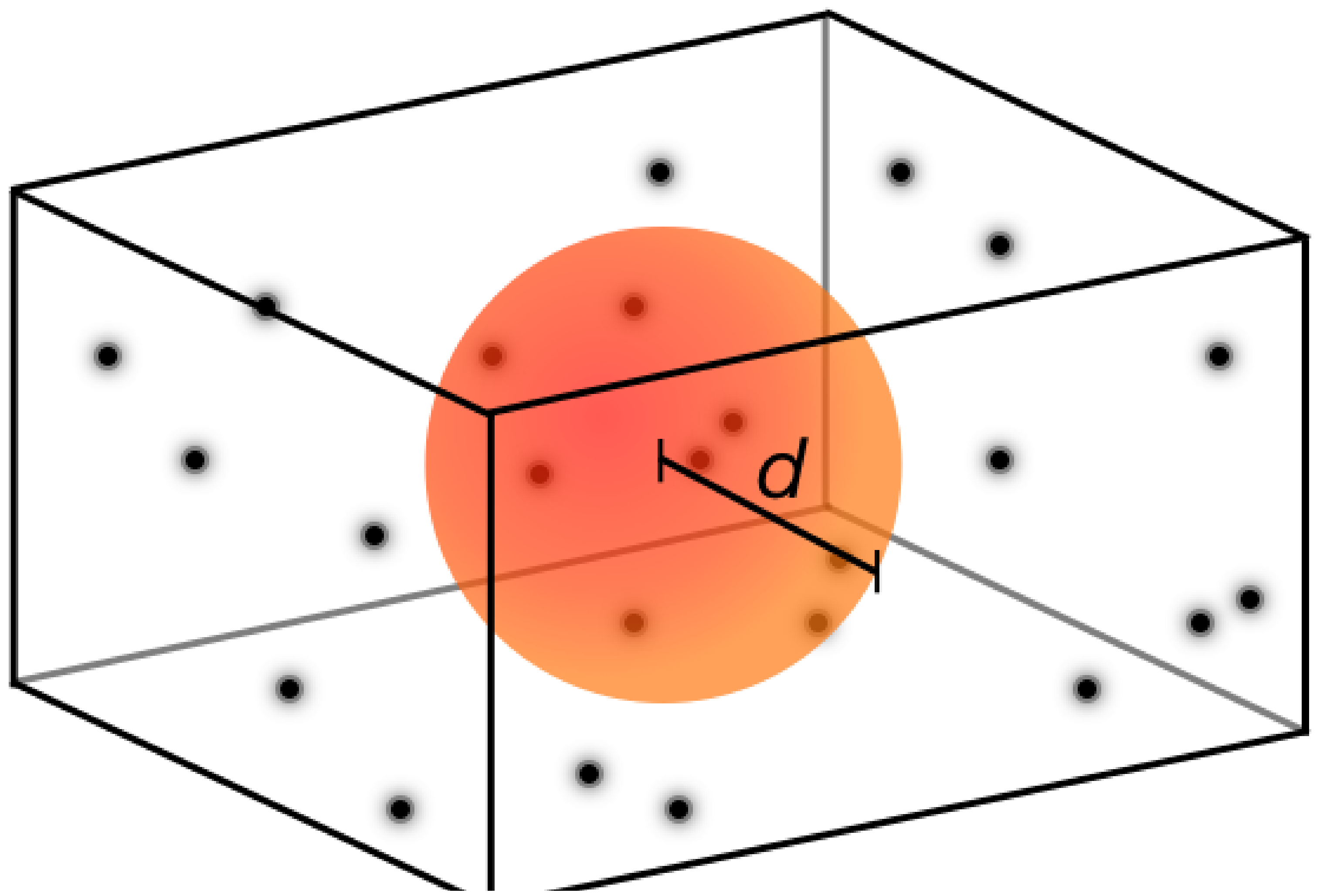


Historical background

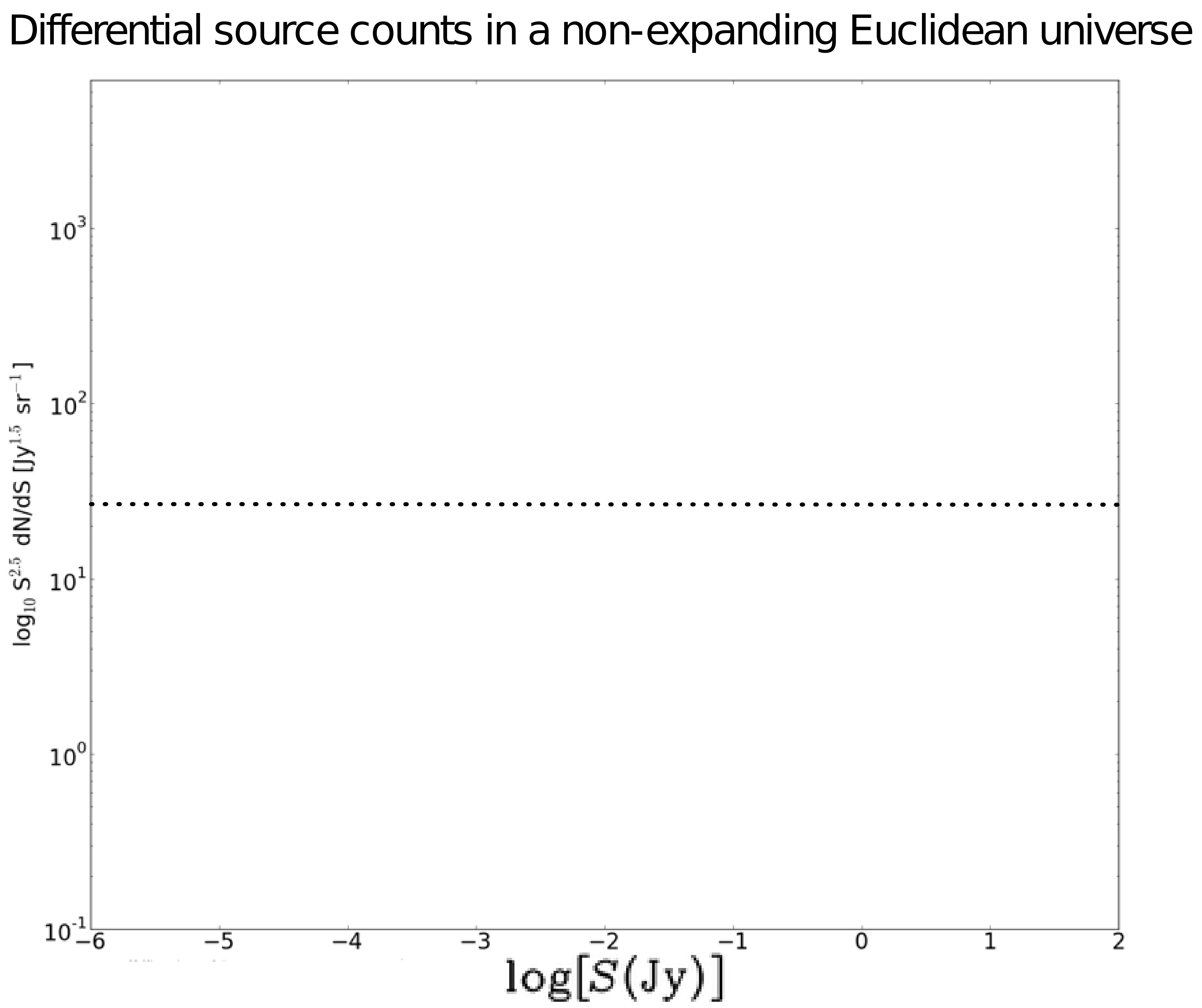
A non-expanding Euclidean (i.e. zero curvature) universe filled with luminosity L sources with number density n contains $N = 4\pi n d^3/3$ sources out to distance d.

Since the flux density $S = L \,/\, 4\pi d^2$

the source counts $N(S) \propto S^{-3/2}$ and $dN/dS \propto S^{-5/2}$.

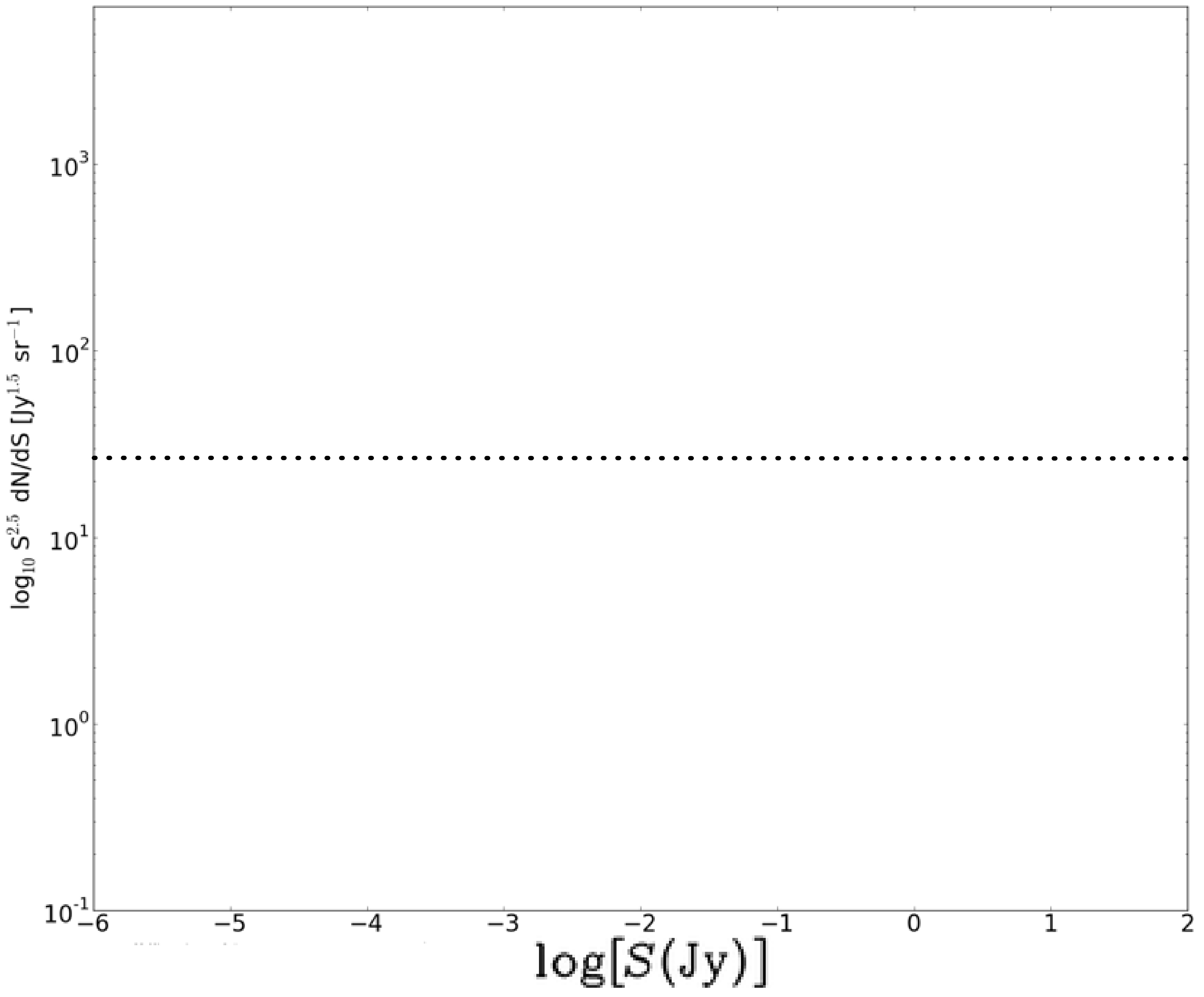


Historical background

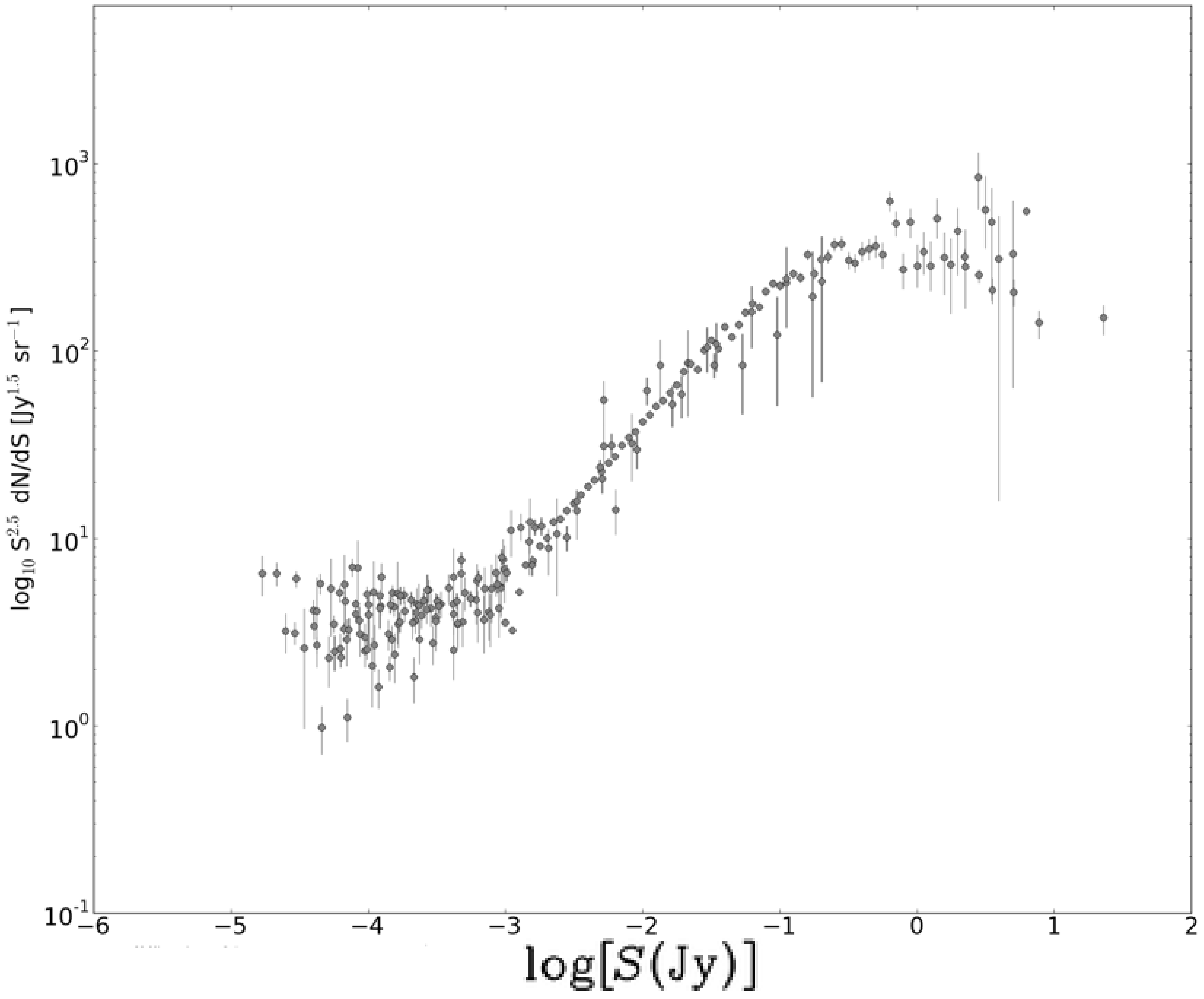


Historical background

Differential source counts in a non-expanding Euclidean universe



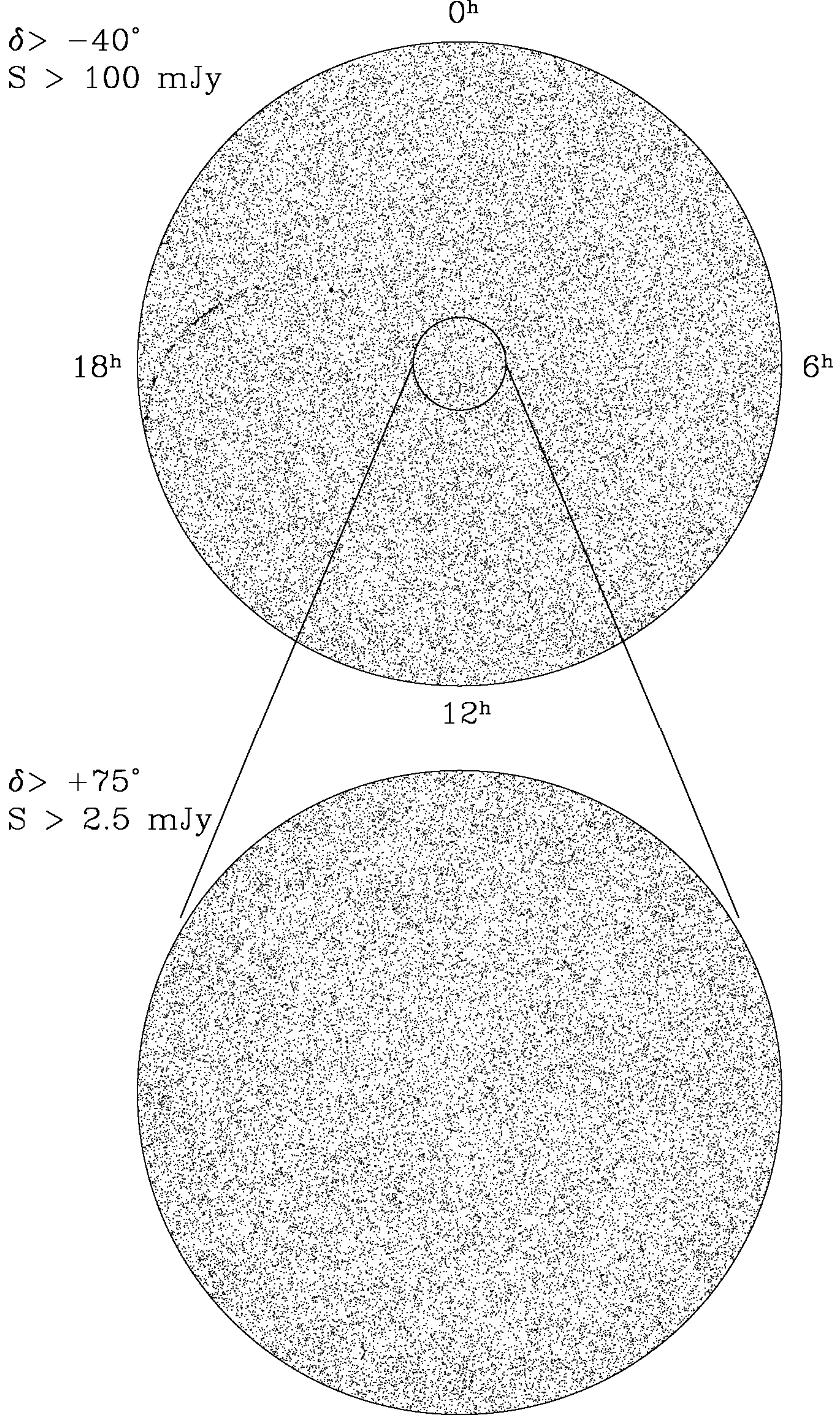
Observed Euclidean-normalised differential source counts



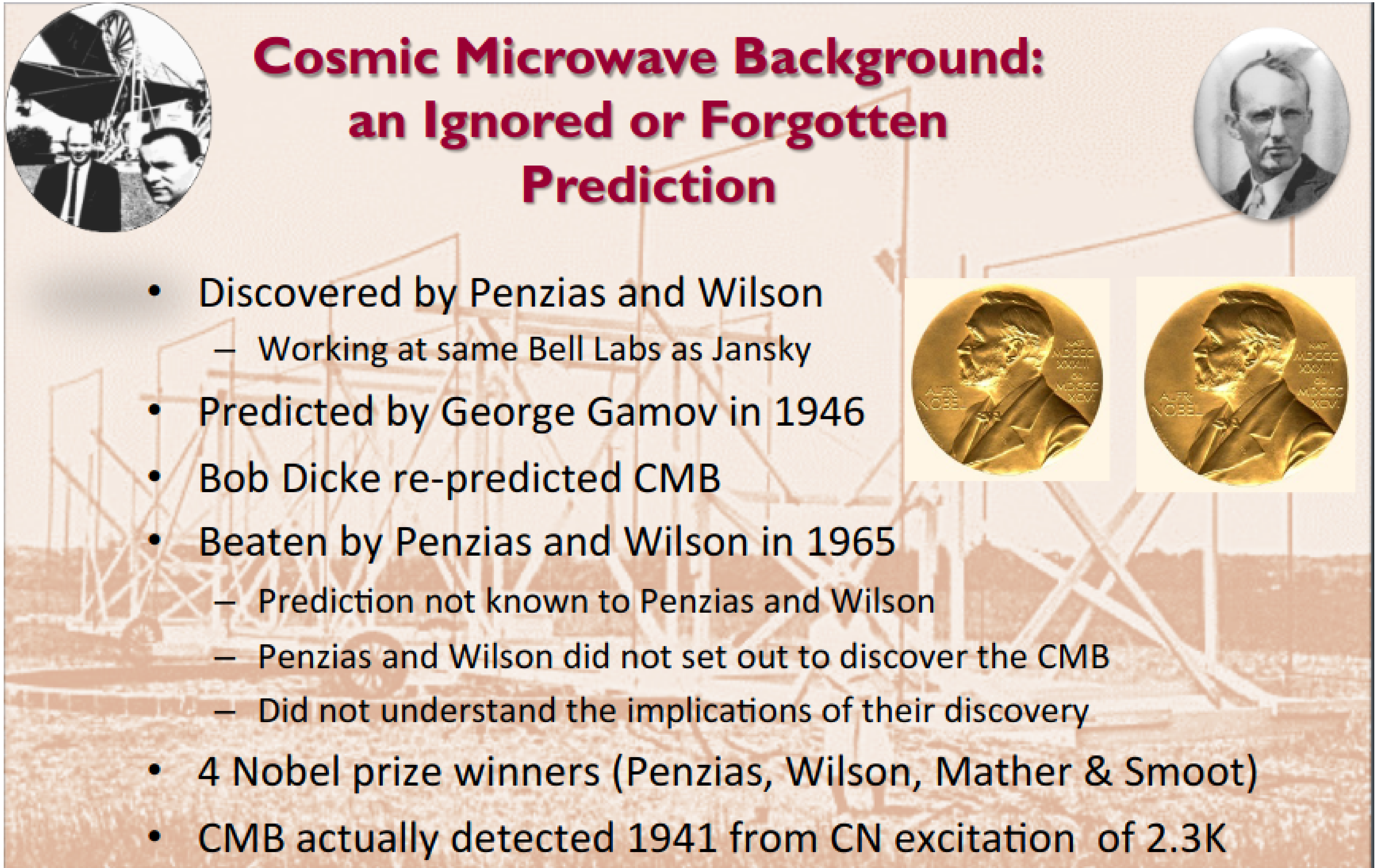
Historical background

Years before the discovery of the CMB, radio “stars’’ provided evidences that the Universe was:

- Highly isotropic
- Homogeneous
- Expanding
- (<1% anisotropy due to Earth motion)



Historical background



Historical background

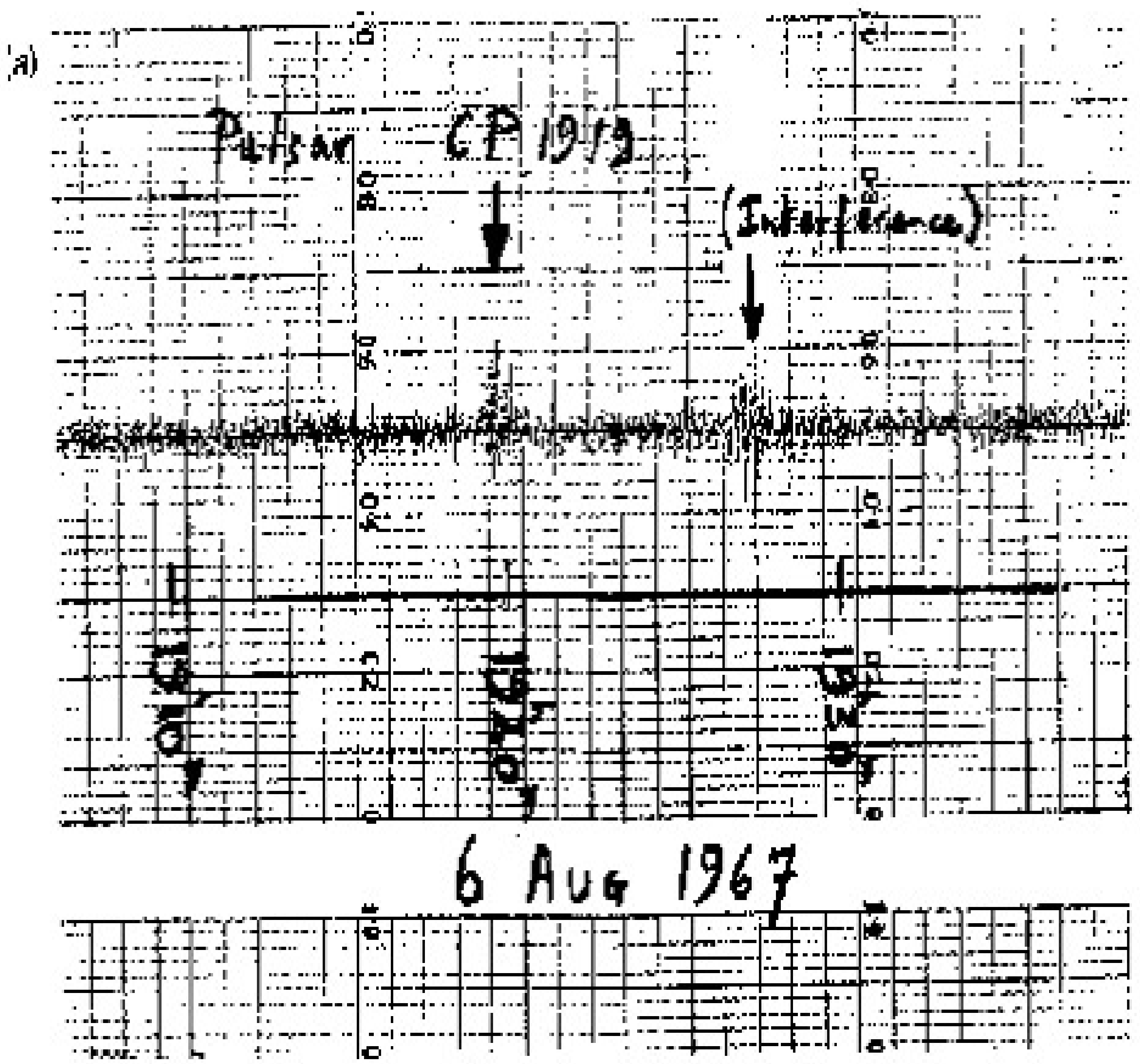
Discovery of Pulsars -1967

Pulsars discovered by Jocelyn Belll-Burnell (PhD student) and Anthony Hewish, as a by-product of Interplanetary Scintilation Studies (ISS) in Cambridge.

The signal was recorded on chart paper - telescope produced about 30 metres per day!

Jocelyn carefully waded through the paper (and interference), and started to notice an unusual source that appear to be periodic (T ~ 2 secs) she called this "scruff".

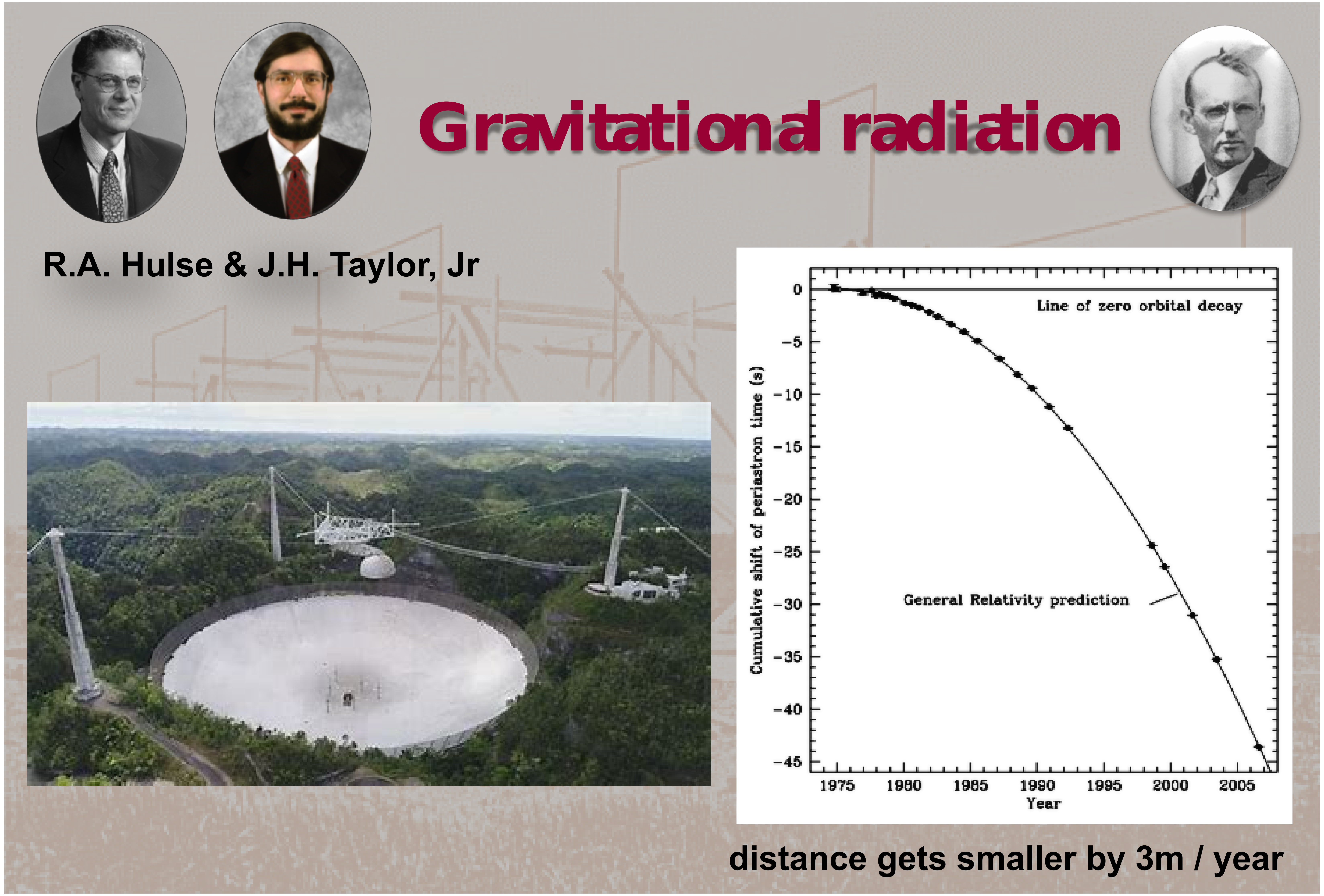
By 1968, four periodic sources had been discovered.

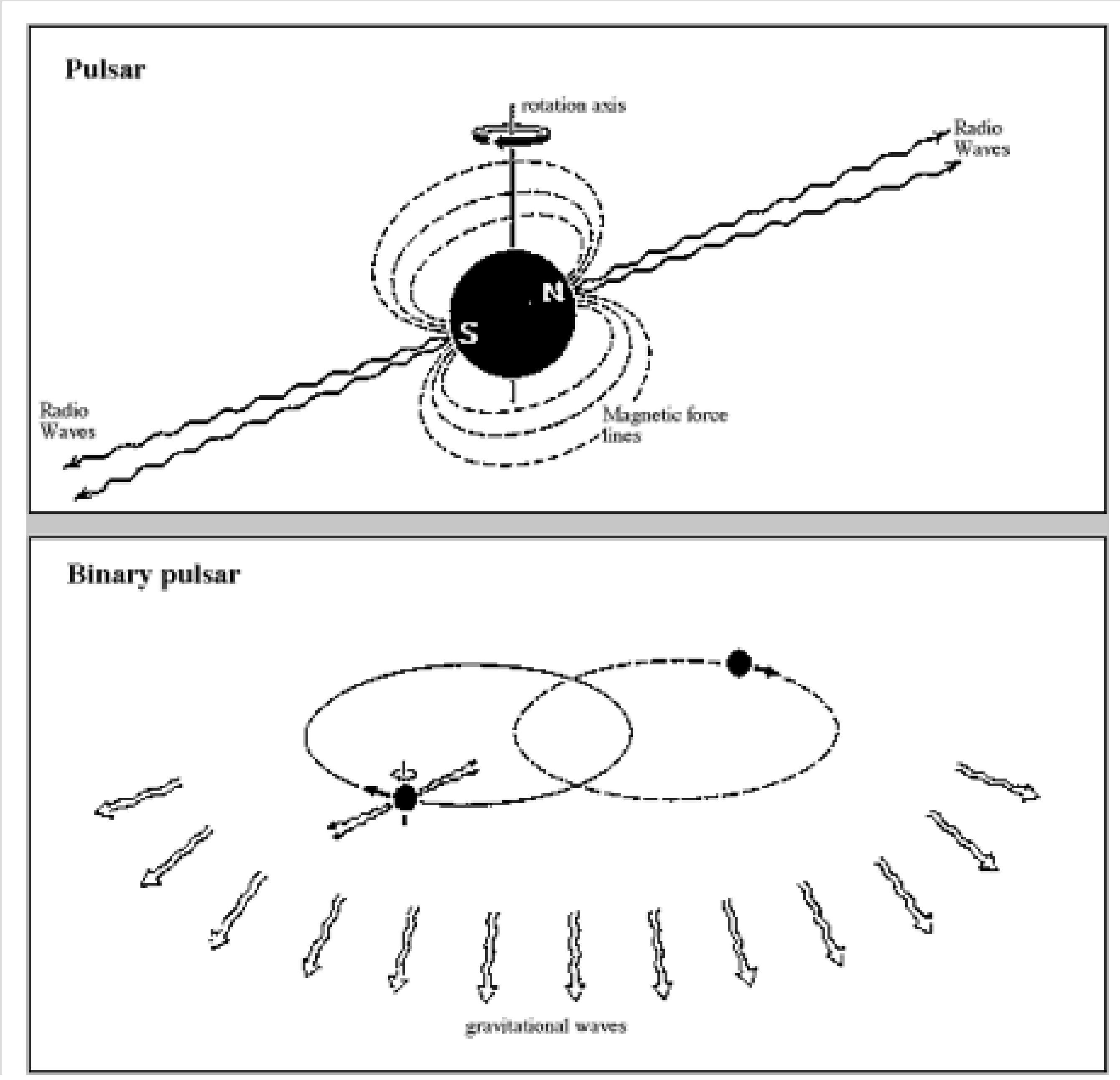


After instrumental causes were ruled out, other physical explanations were considered - including that the signal were being beamed to us by other intelligent life-forms in the galaxy.

See youtube "**2009: Pulsars (Bell Burnell)**"

Historical background

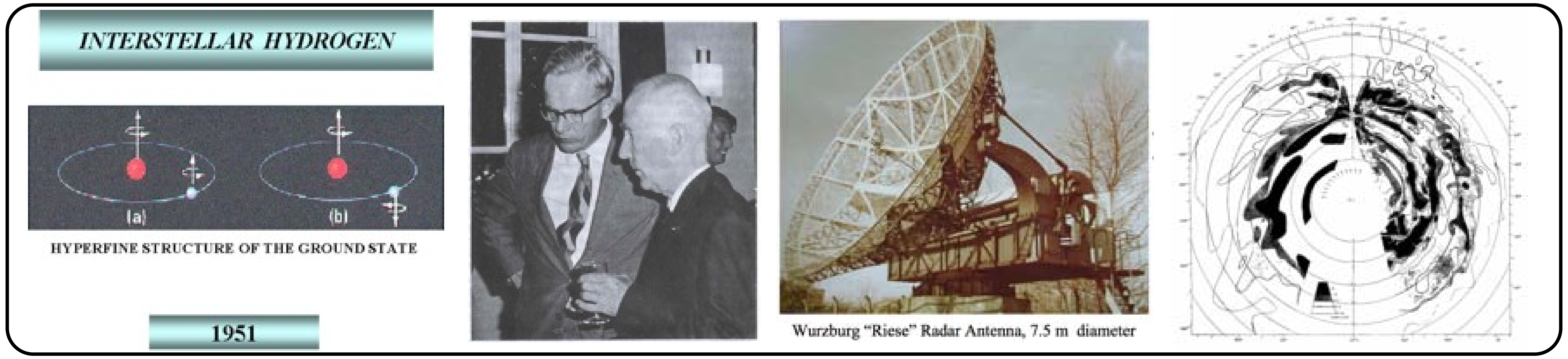




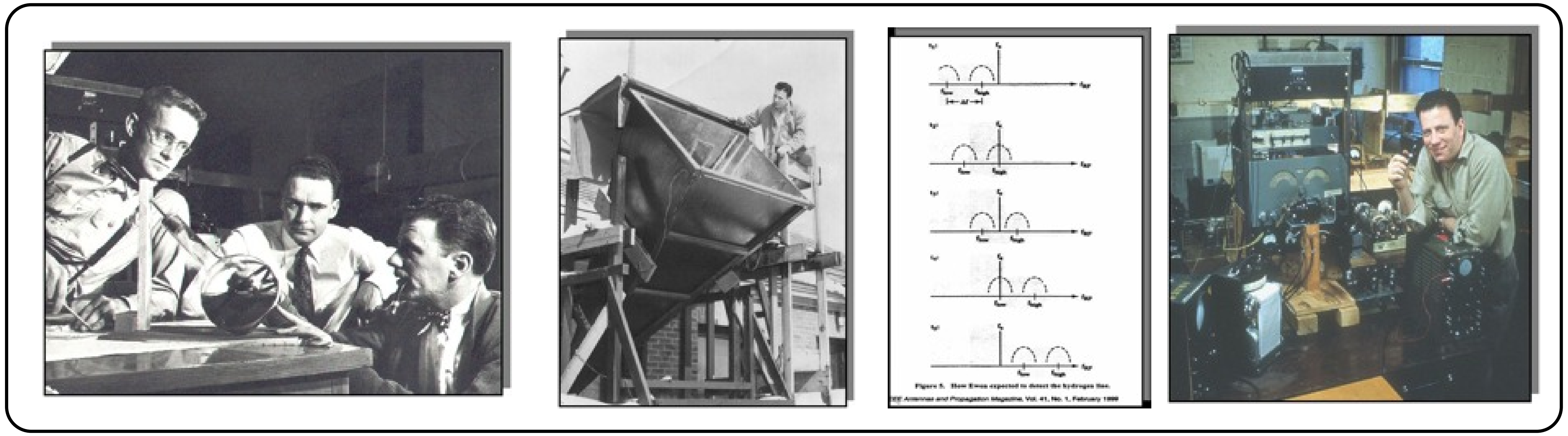
Historical background

Radio Spectral Lines - neutral hydrogen

1944: van der Hulst predicts discrete 1420 MHz (21 cm) emission from neutral Hydrogen (HI).

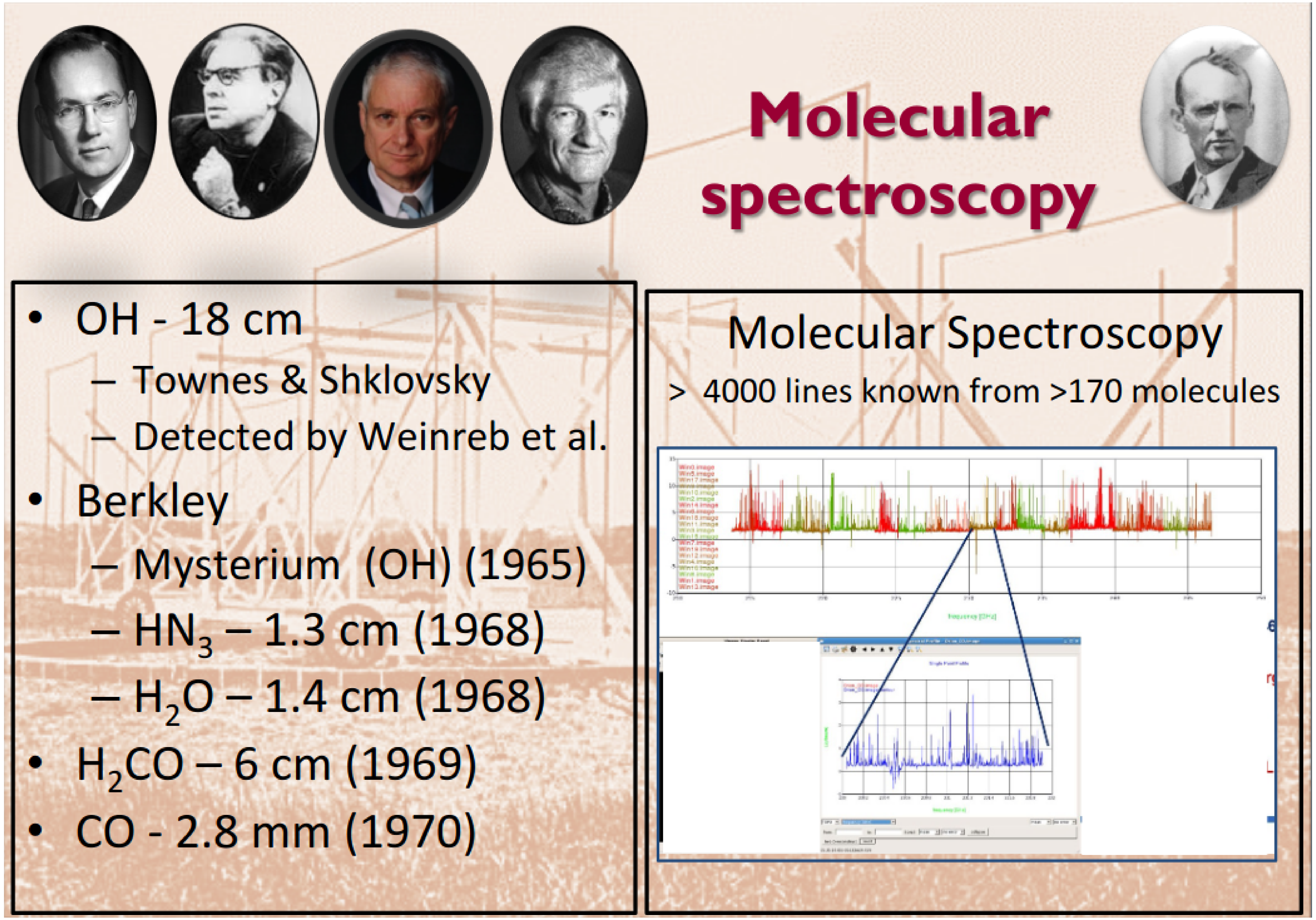


1951: HI detected by Ewen & Purcell and Oort & Muller.



Special: Radio astronomy traces the FIRST and most ABUNDANT element in the Universe.

Historical background



Historical background

Years	Invention
1930s	Horn fed parabolic reflector
1940s	**Cliff Interferometer**
1940s	Dicke Receiver
1950s	**Two element interferometer**
1960s	**Aperture Synthesis**
1960s	Autocorrelation spectrometer
1960s	**Computer assisted data analysis**
1960s	**Independent-oscillator-tape-recording-interferometry**
1960s	Cryogenically cooled radiometers
1970's	**CLEAN and Self Calibration**
1980s	**Space VLBI**

Radio emission and its physical processes

Continuum emission

- Thermal
  — Bremsstrahlung radiation
- Nonthermal
  — Synchrotron

Line emission

— HI 21cm

— Molecular lines

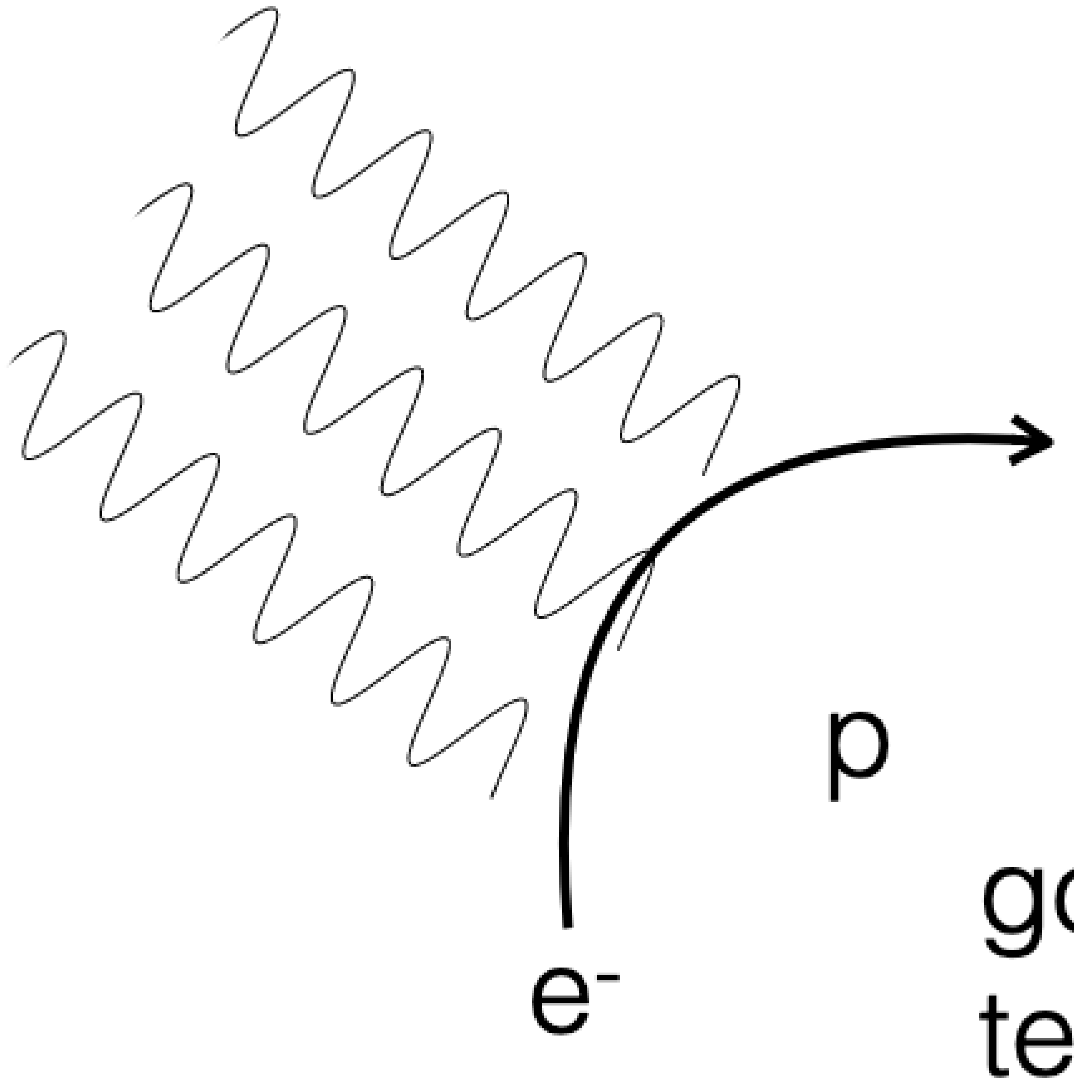
— Recombination lines

— Masers

Pulsars

Radio emission and its physical processes

Bremsstrahlung (a.k.a. free-free) emission



optically thin, thermal emission from ionized gas : HII regions etc.

good for estimating density & temperature of ionized gas

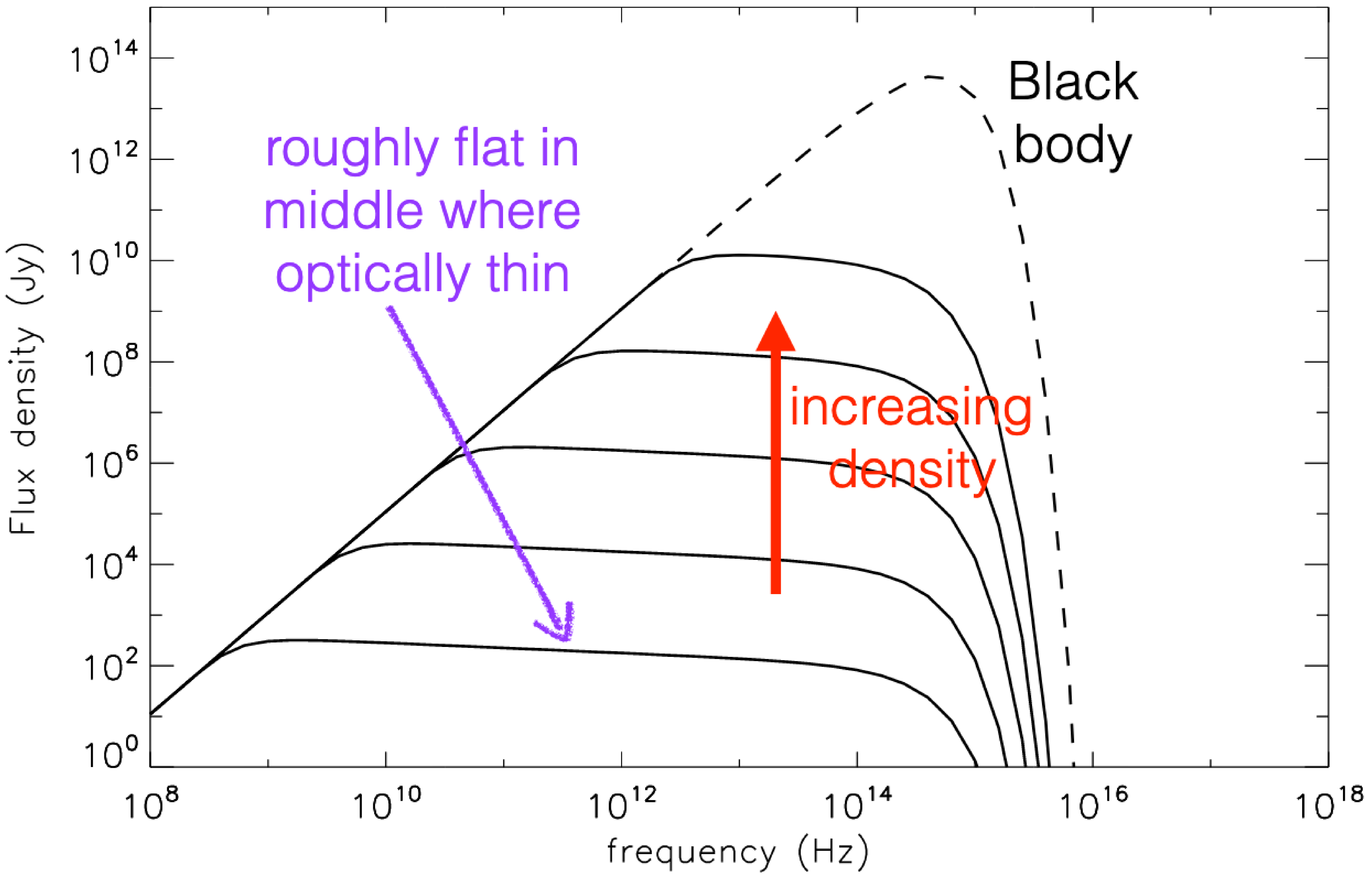
- counting ionizing photons
- inferring star formation rate

$$j_{ff}(\nu) = \frac{8}{3}\left(\frac{2\pi}{3}\right)^{1/2} \frac{e^6}{m_e^{3/2} c^3} \frac{n_e n_i}{(k_B T)^{1/2}} g_{ff}(\nu, T) e^{-h\nu/k_B T}$$

emission coefficient (e.g. erg s^{-1} cm^{-3} Hz^{-1} $ster^{-1}$)

Radio emission and its physical processes

$$j_{ff}(\nu) = \frac{8}{3}\left(\frac{2\pi}{3}\right)^{1/2} \frac{e^6}{m_e^{3/2} c^3} \frac{n_e n_i}{(k_B T)^{1/2}} g_{ff}(\nu, T) e^{-h\nu/k_B T}$$ + radiative transfer



Radio emission and its physical processes

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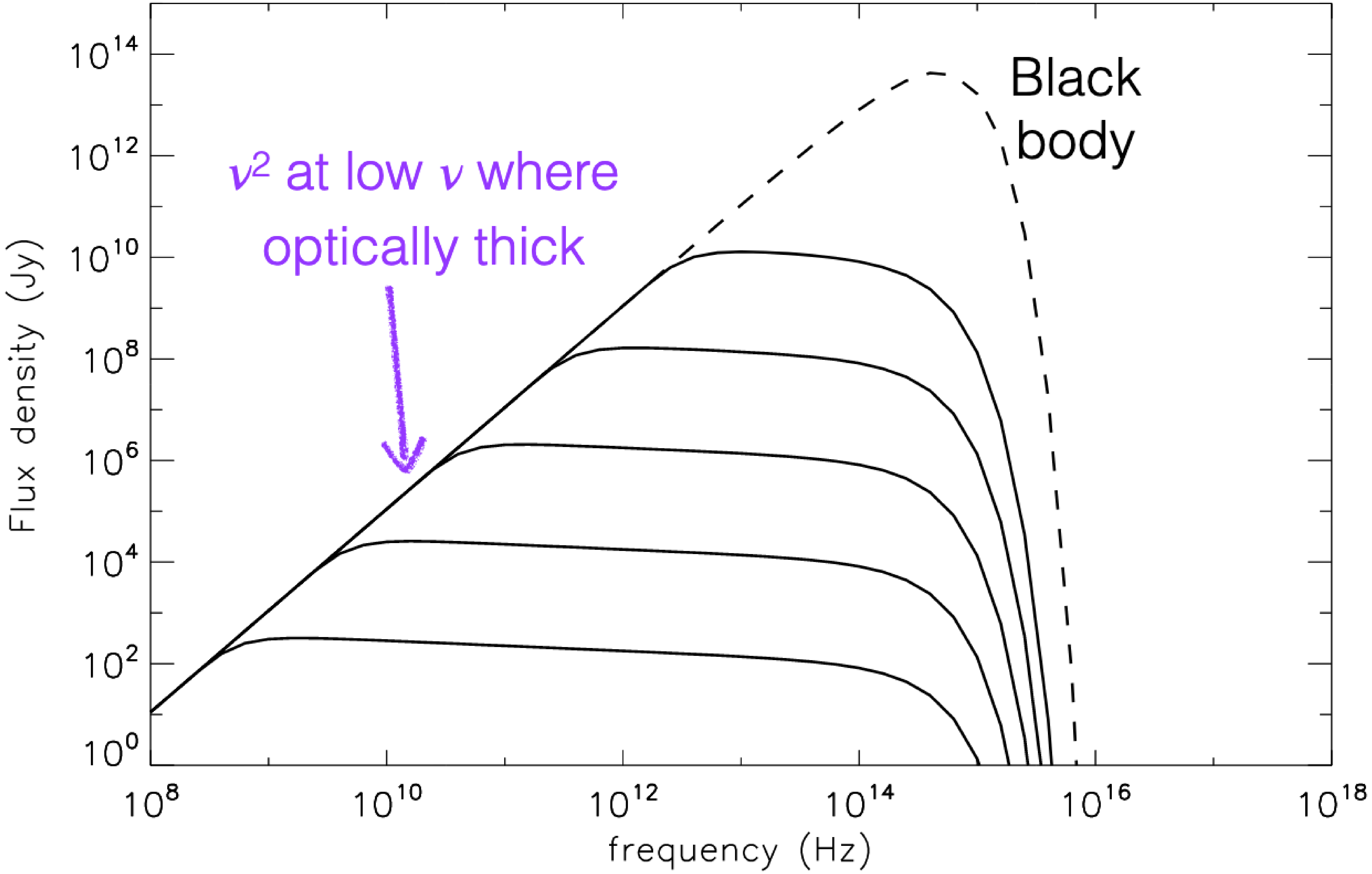

Radio emission and its physical processes

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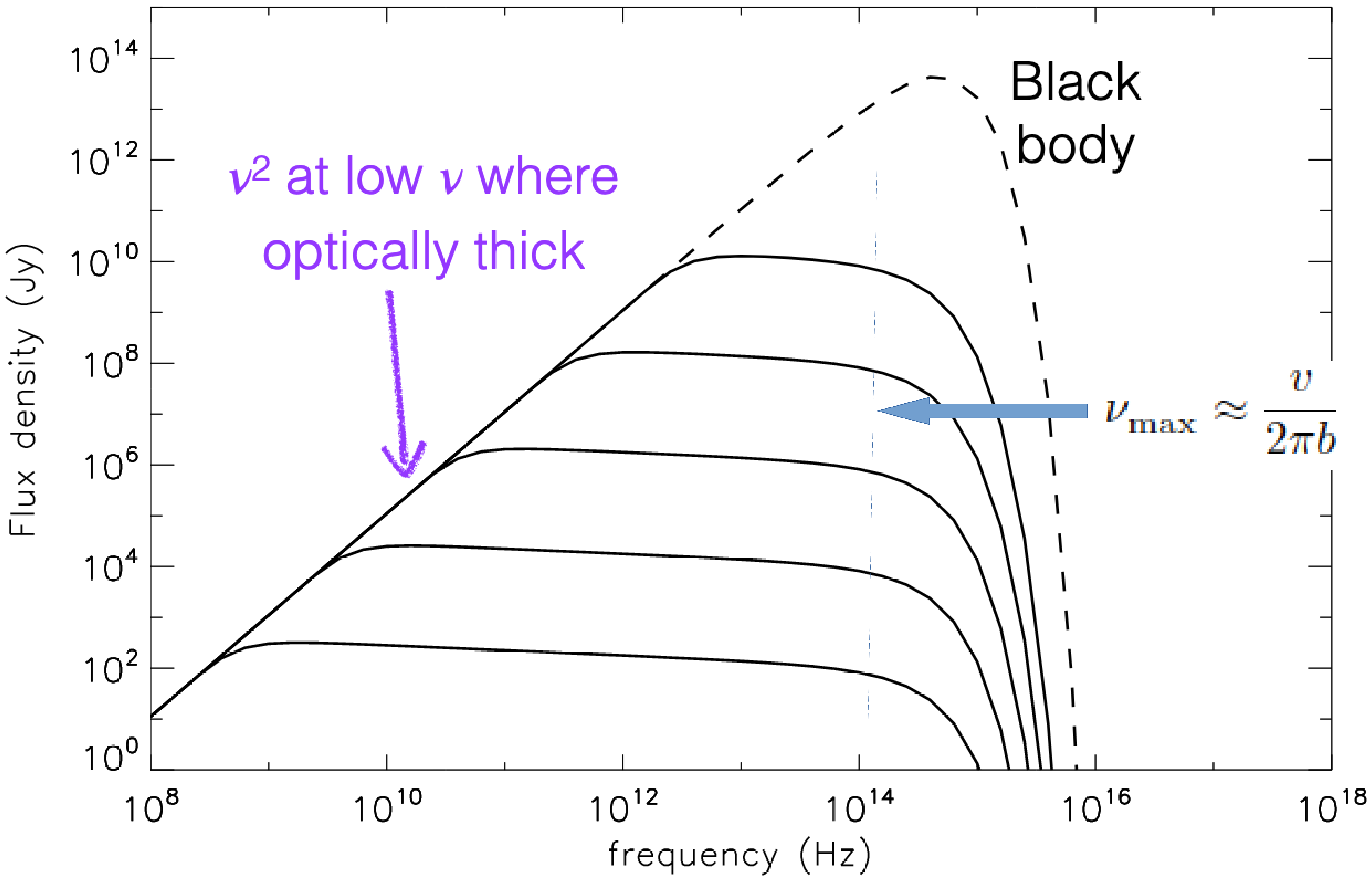
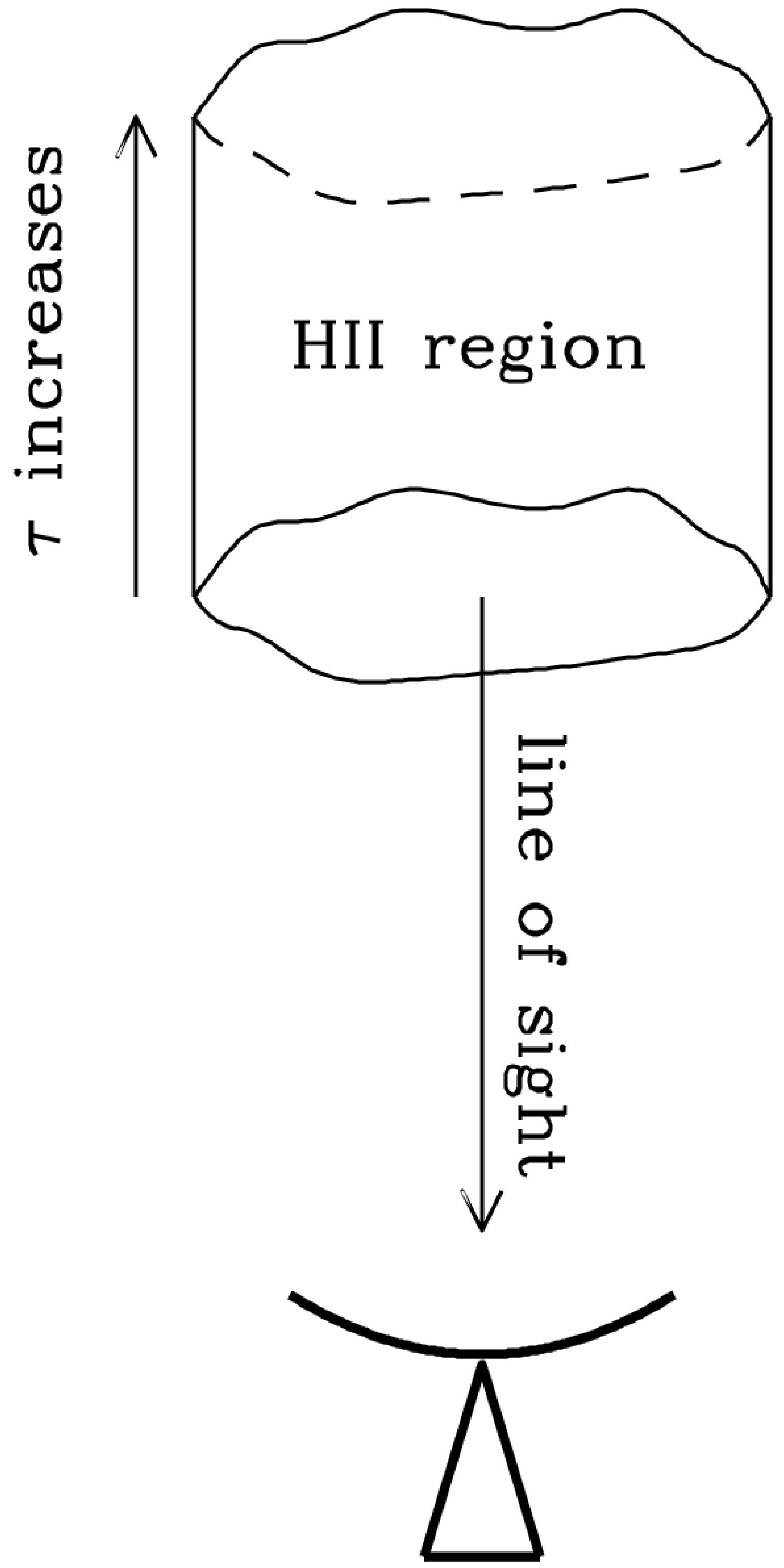


Radio emission and its physical processes



In the region/frequency range where τ << 1:

$$\left(\frac{Q_{\rm H}}{\rm s^{-1}}\right) \approx 6.3 \times 10^{52}\left(\frac{T}{10^4\ \rm K}\right)^{-0.45}\left(\frac{\nu}{\rm GHz}\right)^{0.1}\left(\frac{L_\nu}{10^{20}\ \rm W\ Hz^{-1}}\right)$$

Production rate of ionizing photons ⟷ **Free-free spectral luminosity**

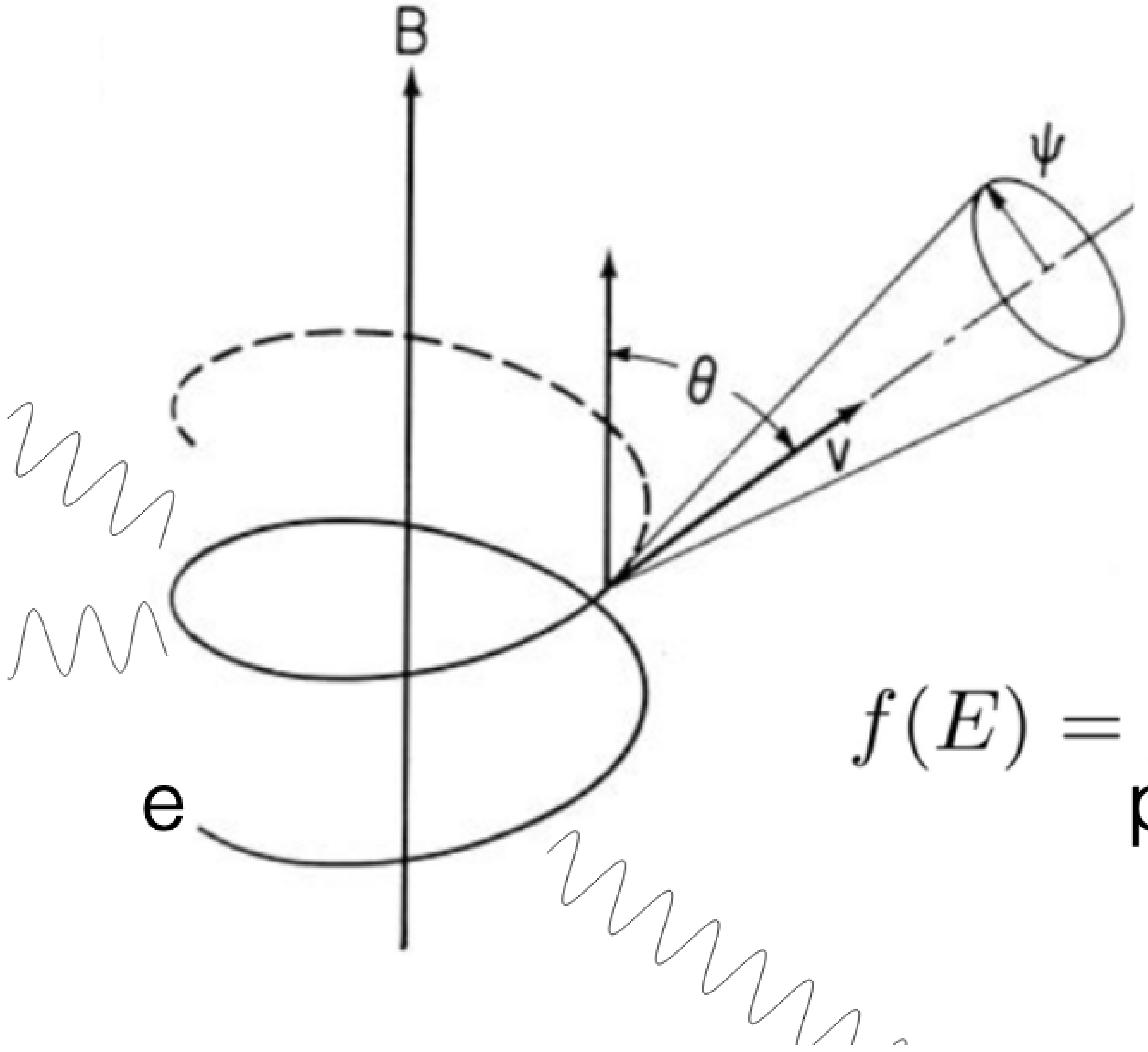
↕

Number of massive short lived stars ⟷ **Galaxy star formation rate**

Radio emission and its physical processes

Synchrotron emission

nonthermal (usu: relativistic) electrons in a B field
polarized emission!
can get particle energies, n and B



$$\nu_c = \frac{3}{4\pi}\gamma^2\frac{eB}{mc}\sin\theta$$

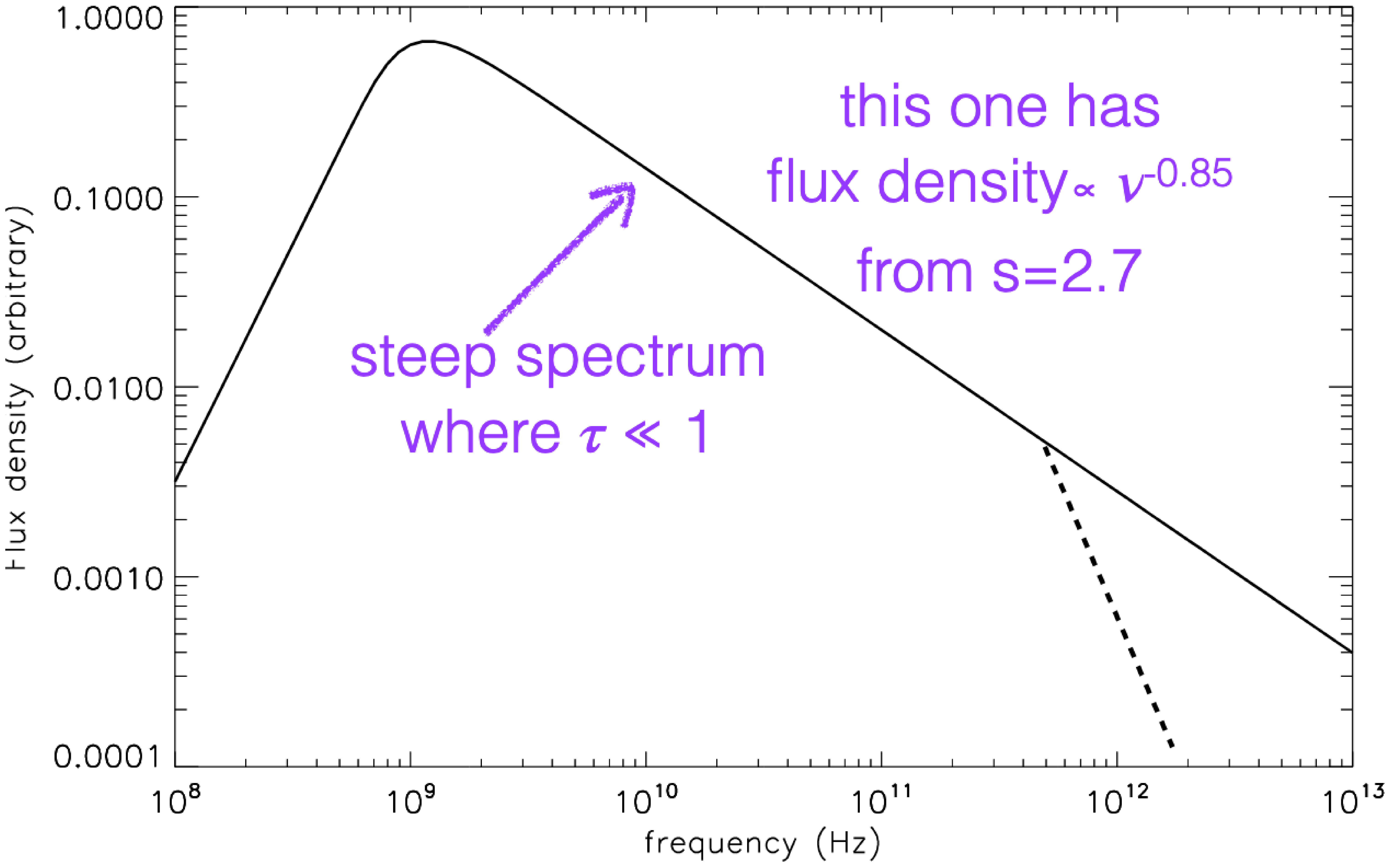
An electron of energy γ ($E = \gamma mc^2$) radiates at this frequency.

$$f(E) = f_o E^{-s}$$

power law distribution of electron energies

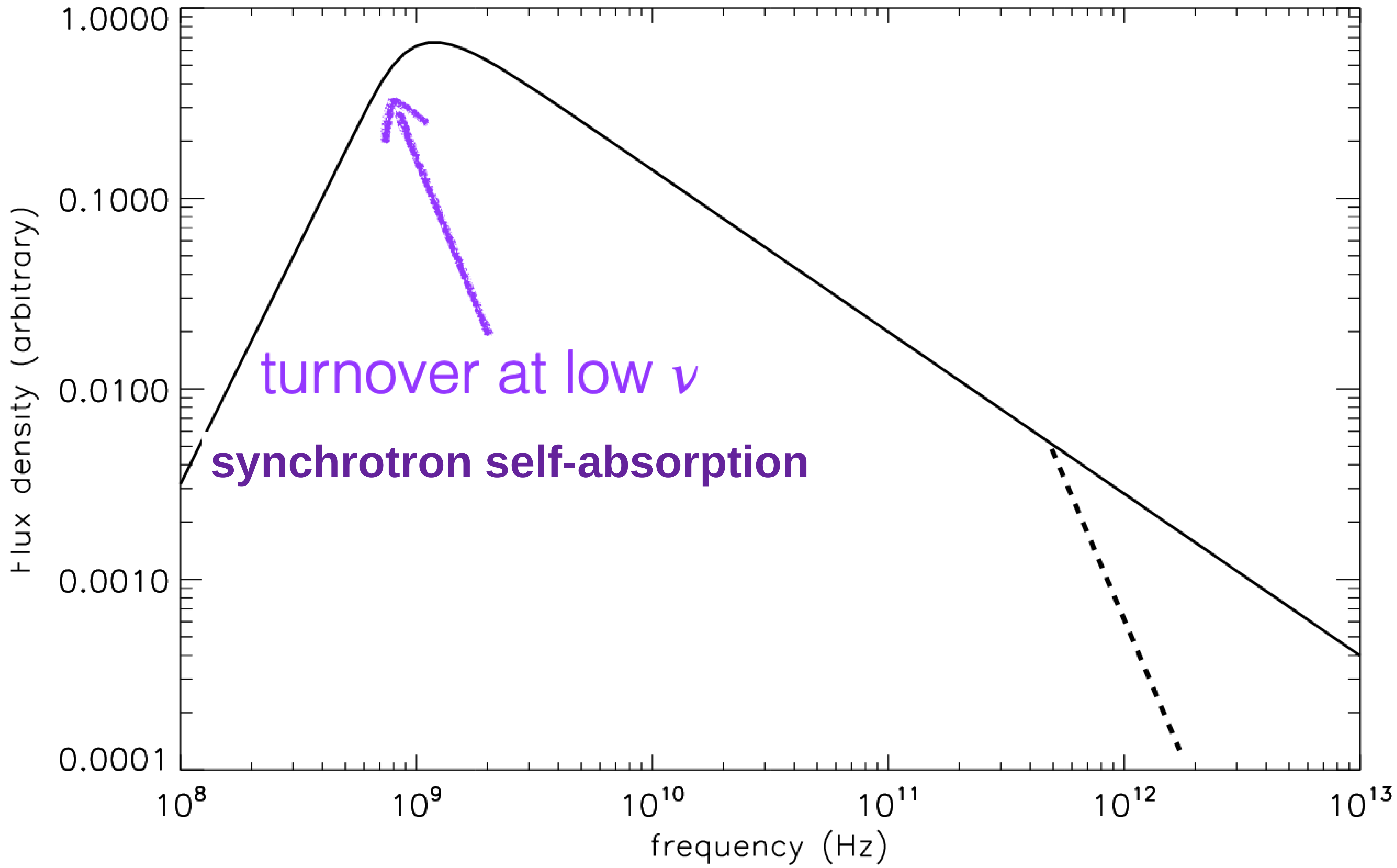
Radio emission and its physical processes

$j_{sy}(\nu) \propto P_o\, B^{(s+1)/2}\, f_o\, \nu^{-(s-1)/2}$ + radiative transfer



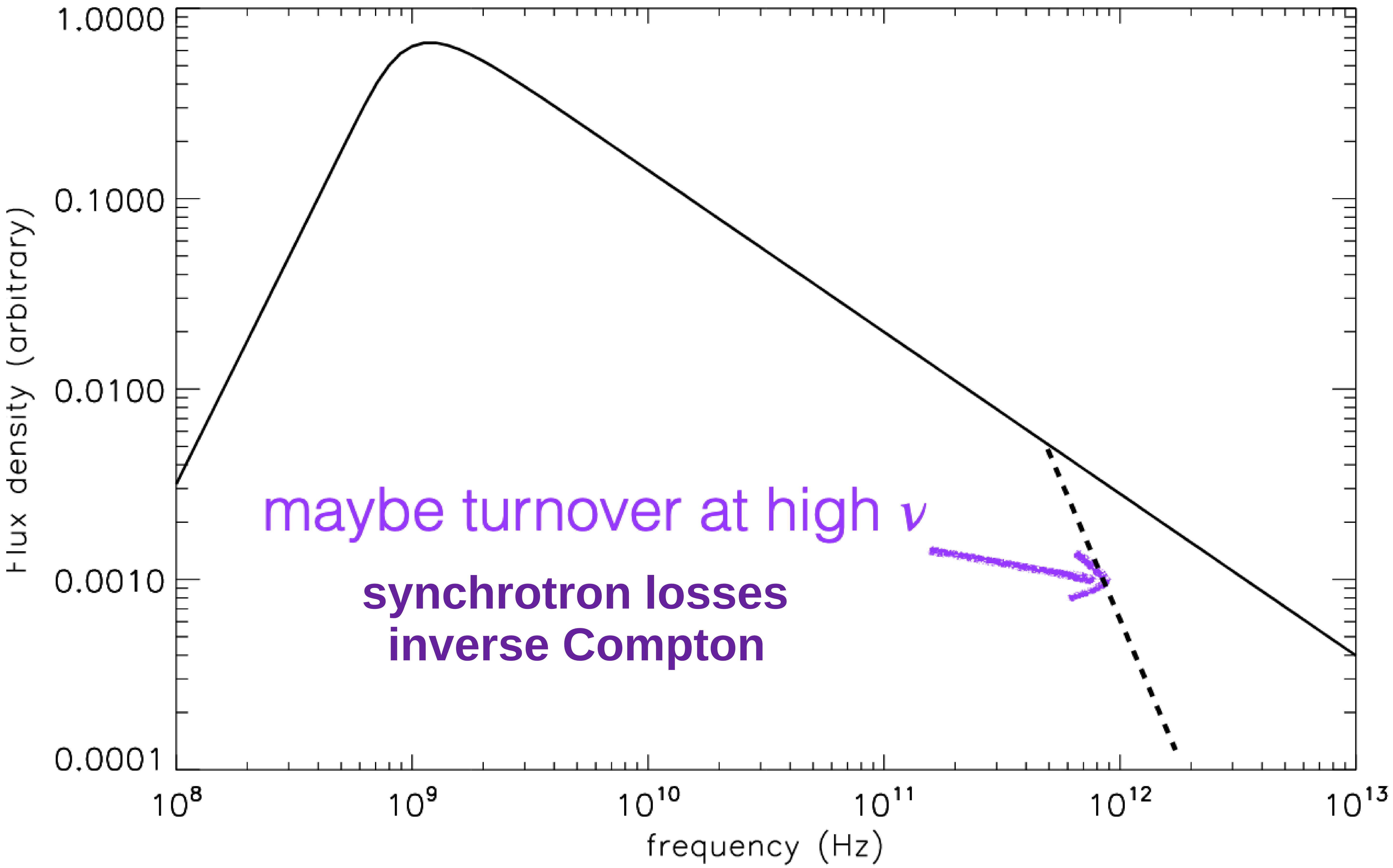
Radio emission and its physical processes

$$j_{sy}(\nu) \propto P_o\, B^{(s+1)/2}\, f_o\, \nu^{-(s-1)/2}$$ + radiative transfer

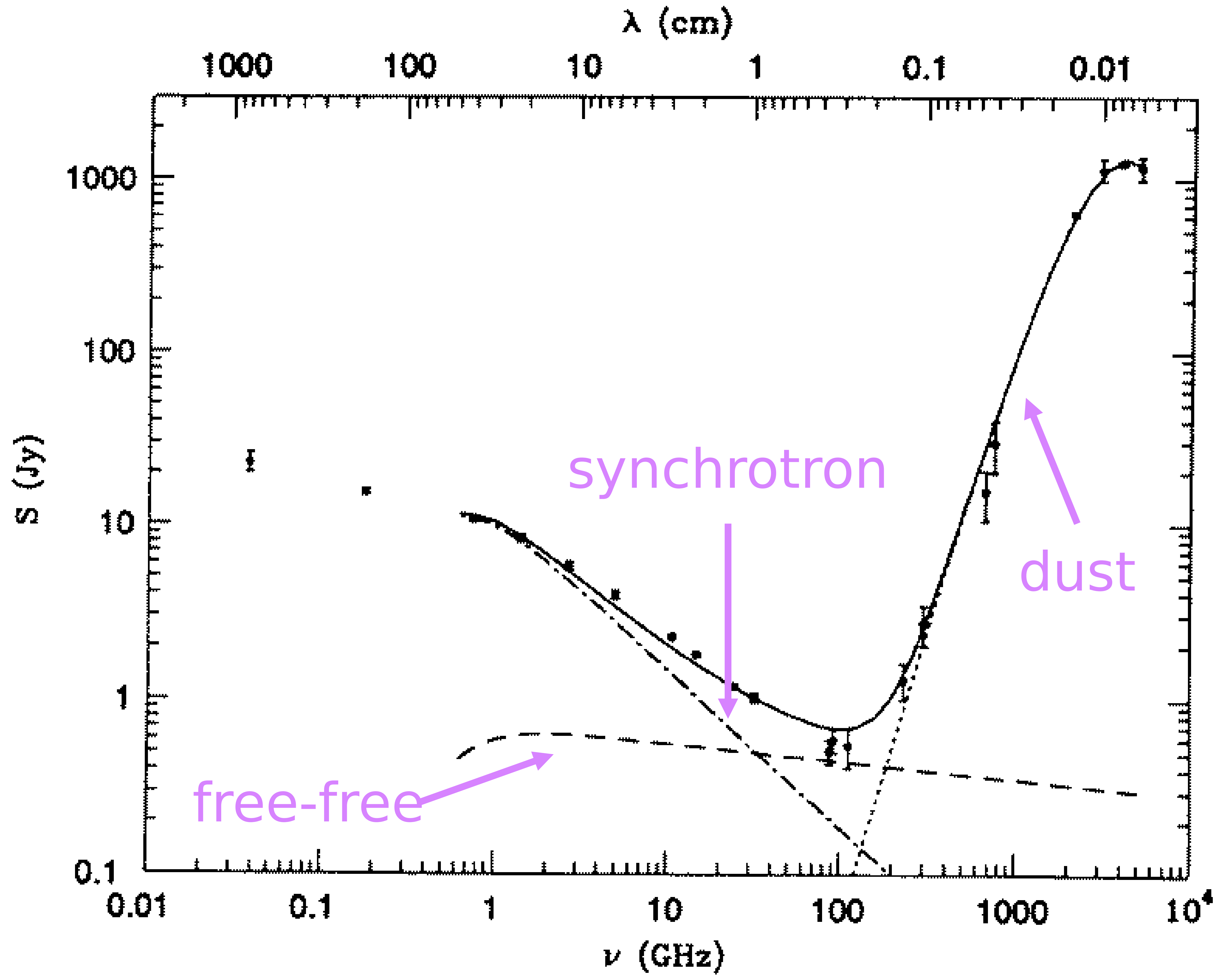


Radio emission and its physical processes

$$j_{sy}(\nu) \propto P_o\, B^{(s+1)/2}\, f_o\, \nu^{-(s-1)/2} + \text{radiative transfer}$$



Radio emission and its physical processes



Multi-frequency observations of M82
a prototypical star-forming galaxy
in the local Universe

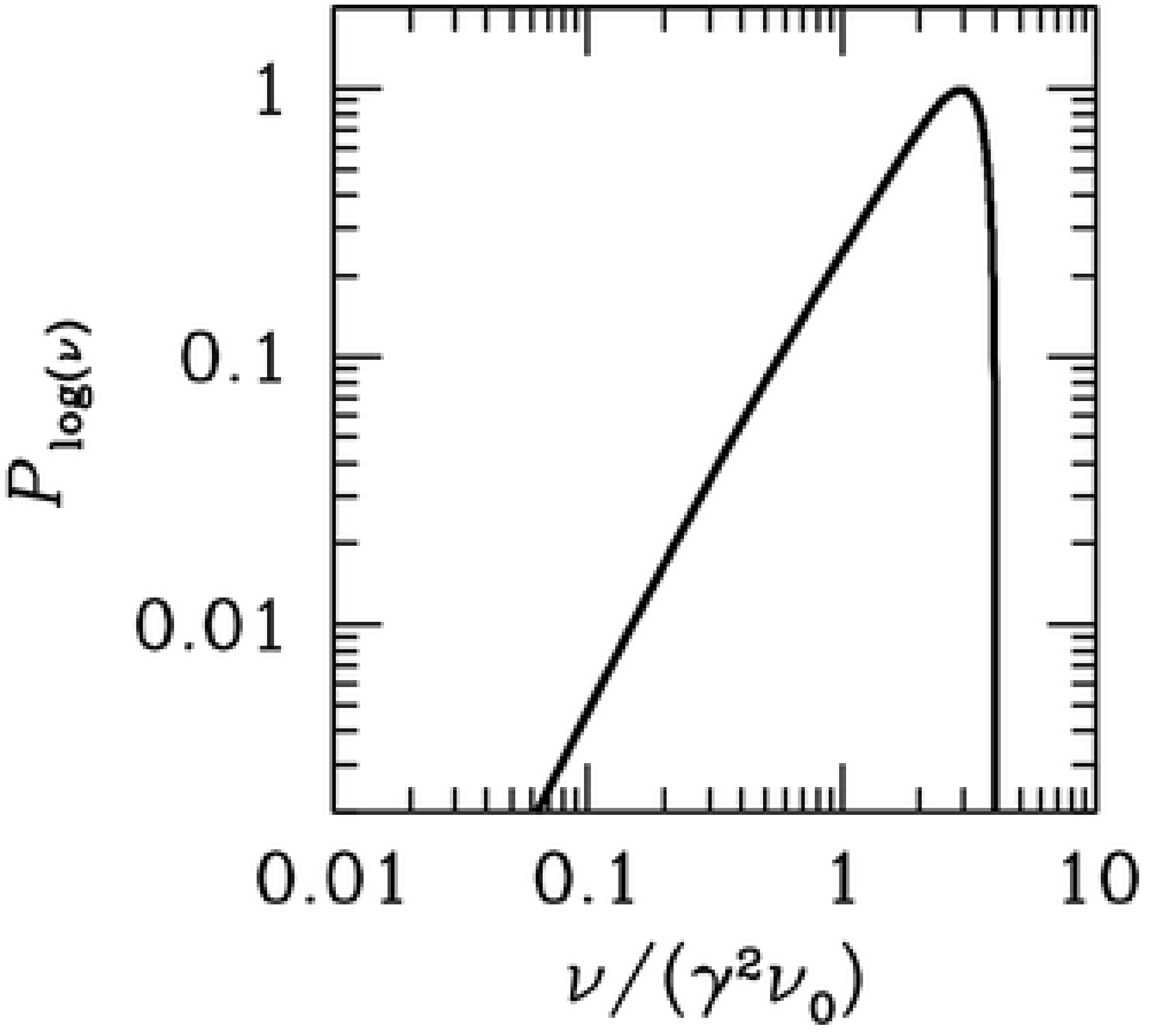
Radio emission and its physical processes

Inverse Compton emission

upscattering of radiation photons by relativistic electrons

$$\frac{P_{\rm IC}}{P_{\rm syn}} = \frac{U_{\rm rad}}{U_B}\,.$$

The percentage of power loss is directly proportional to energy density of the radiation field



$$\frac{\langle\nu\rangle}{\nu_0} = \frac{4}{3}\gamma^2\,.$$

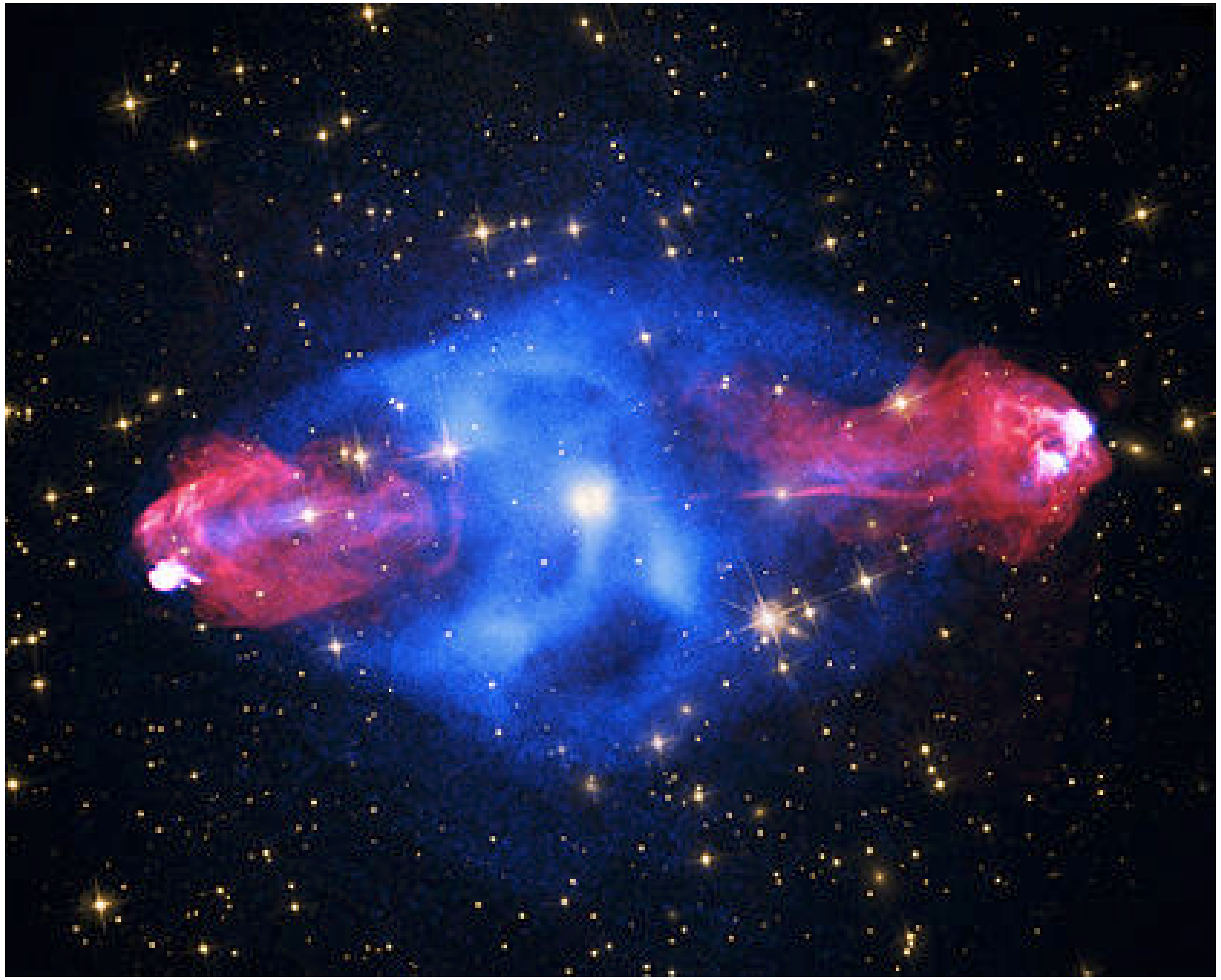
$$\langle\nu\rangle = 10^9\ {\rm Hz}\ \frac{4}{3}\left(10^4\right)^2 \approx 1.3\times10^{17}\ {\rm Hz}$$

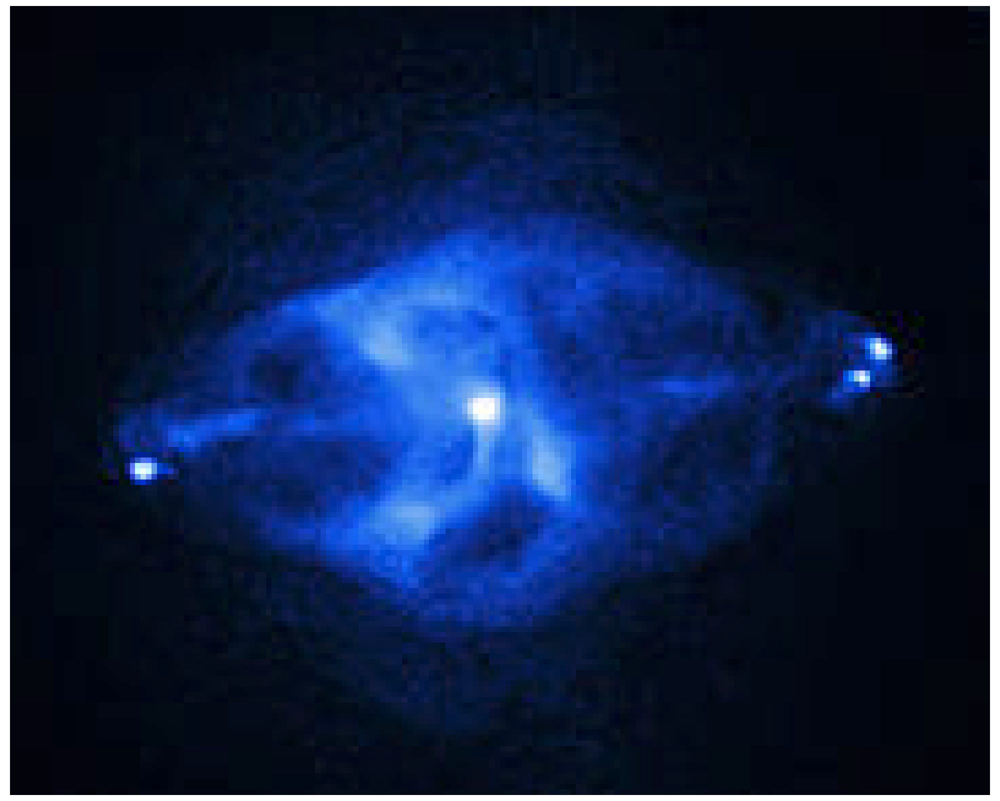
Drain energy from cosmic-ray electrons that produce radio radiation and use it to produce X-ray radiation!

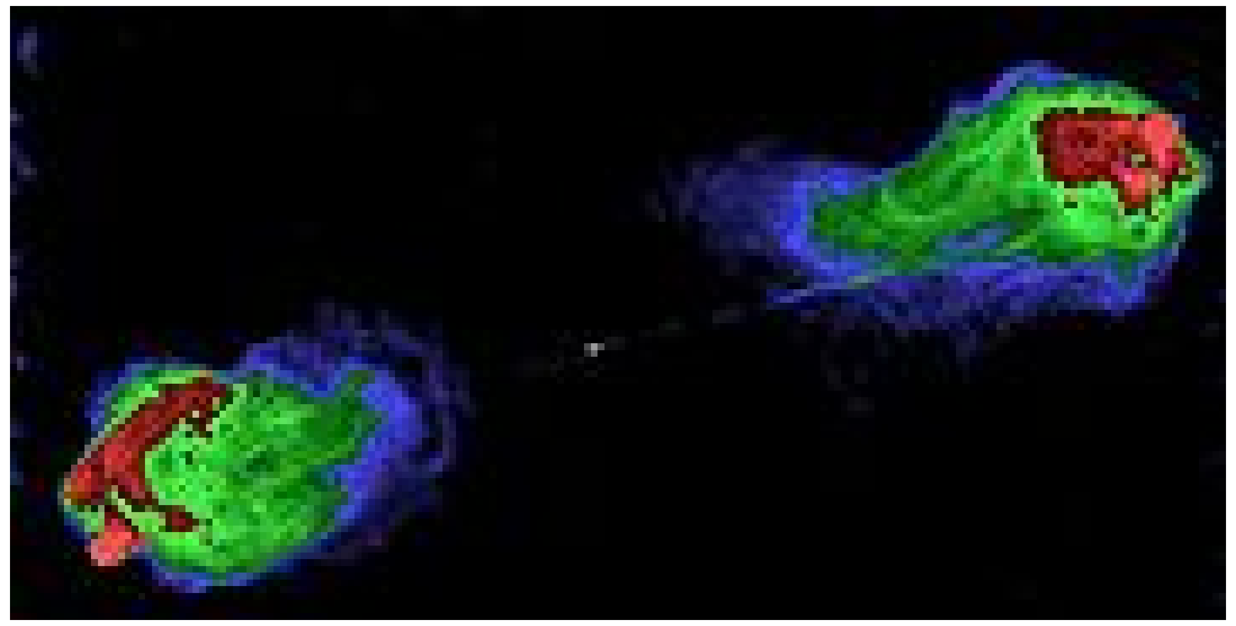
Radio emission and its physical processes

Inverse Compton emission

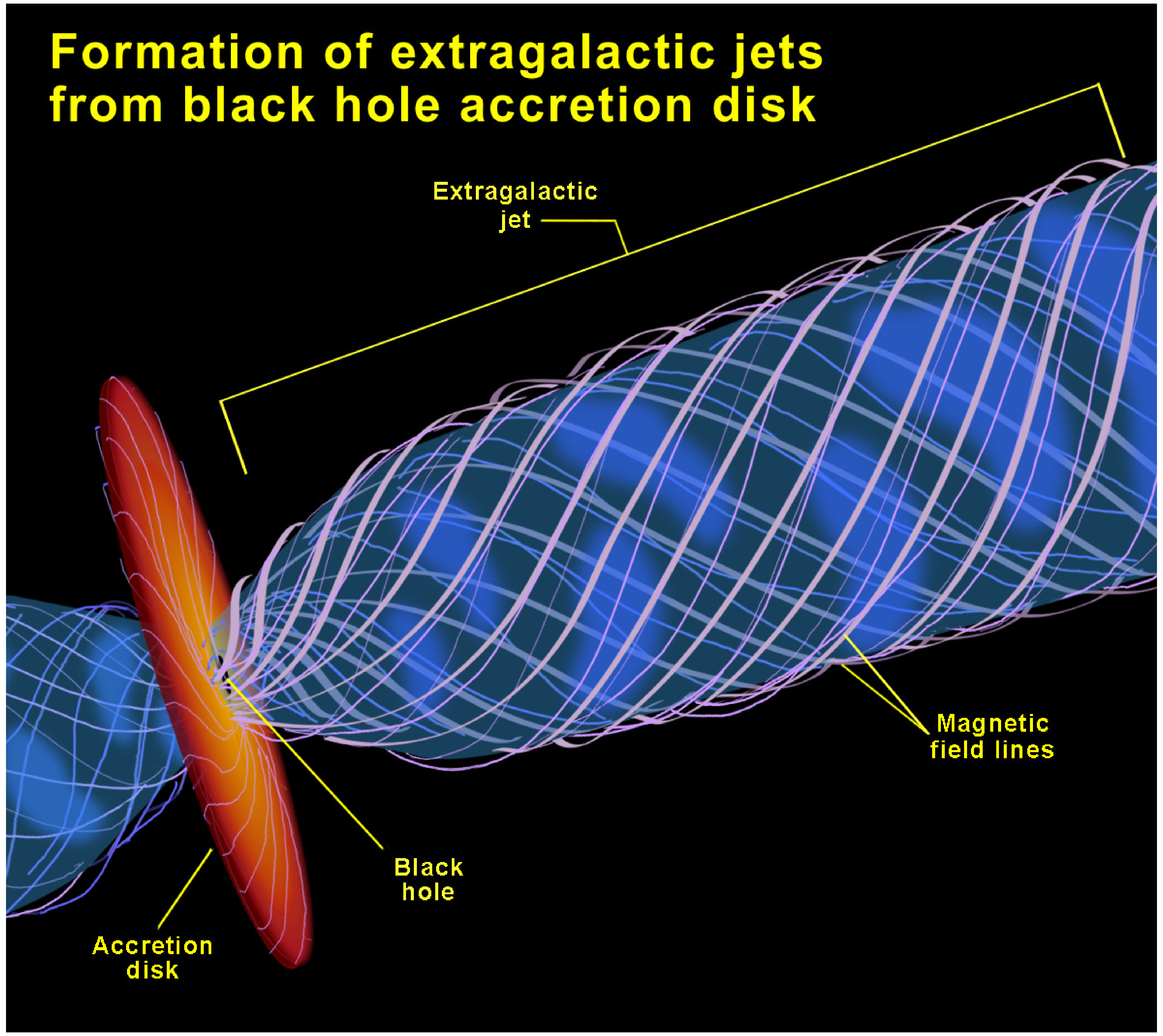
Cygnus A (one of the brightest radio sources in the sky...)







Radio emission and its physical processes

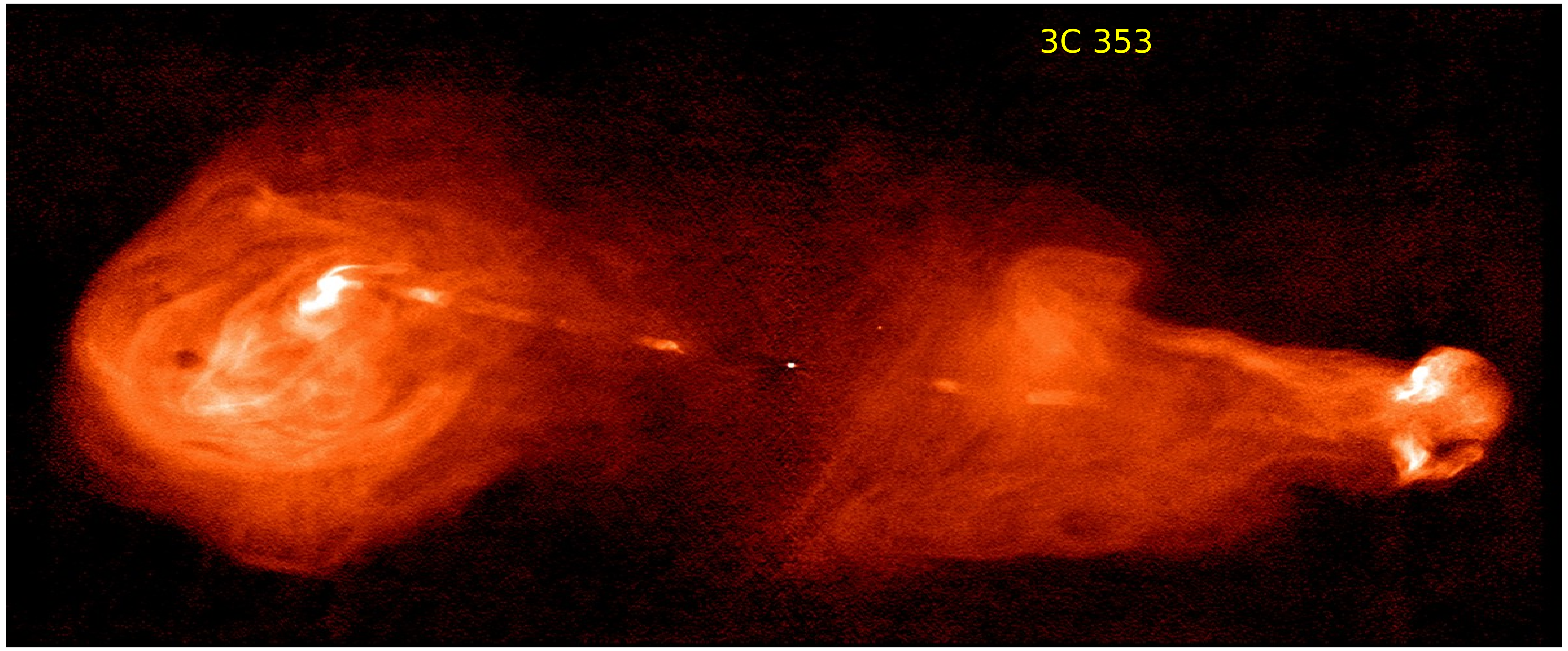


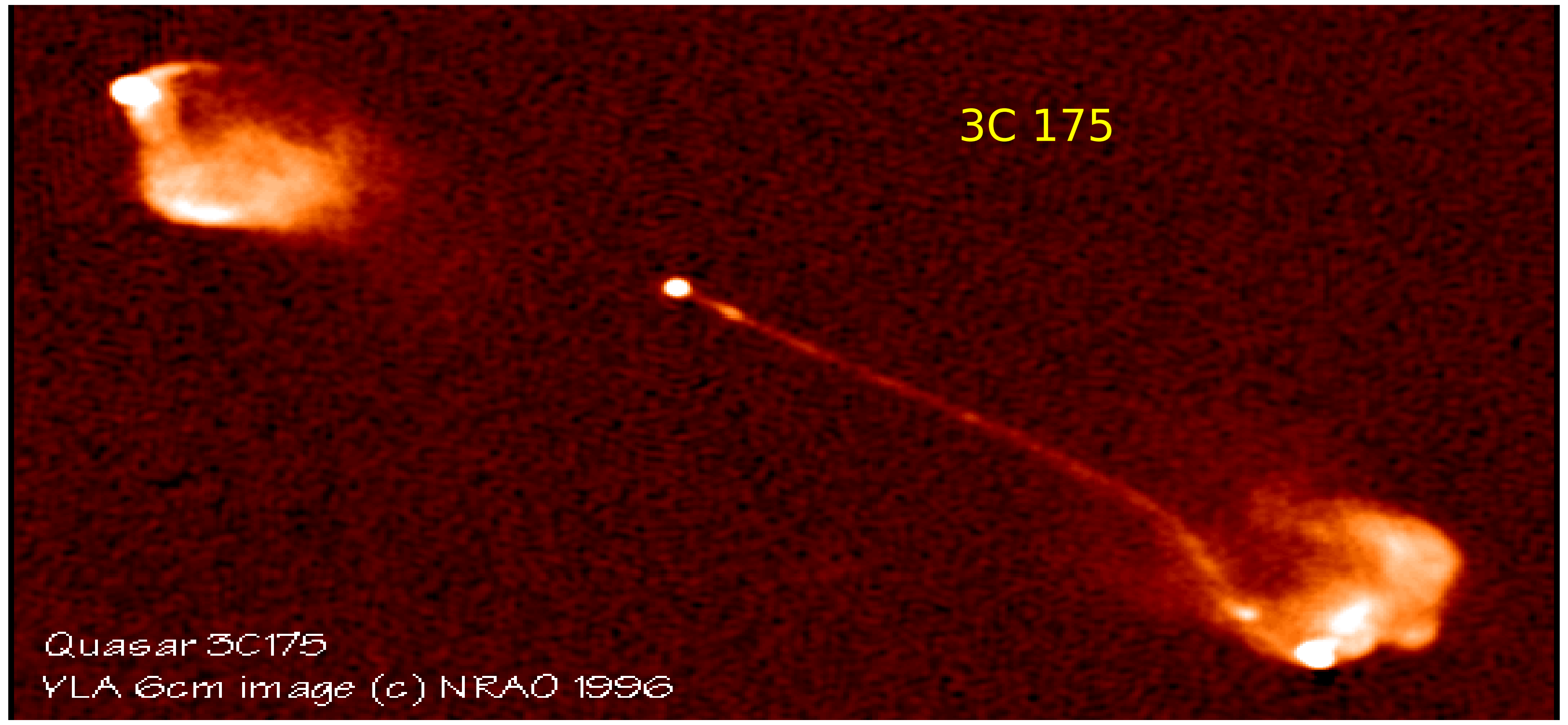
Radio Jets

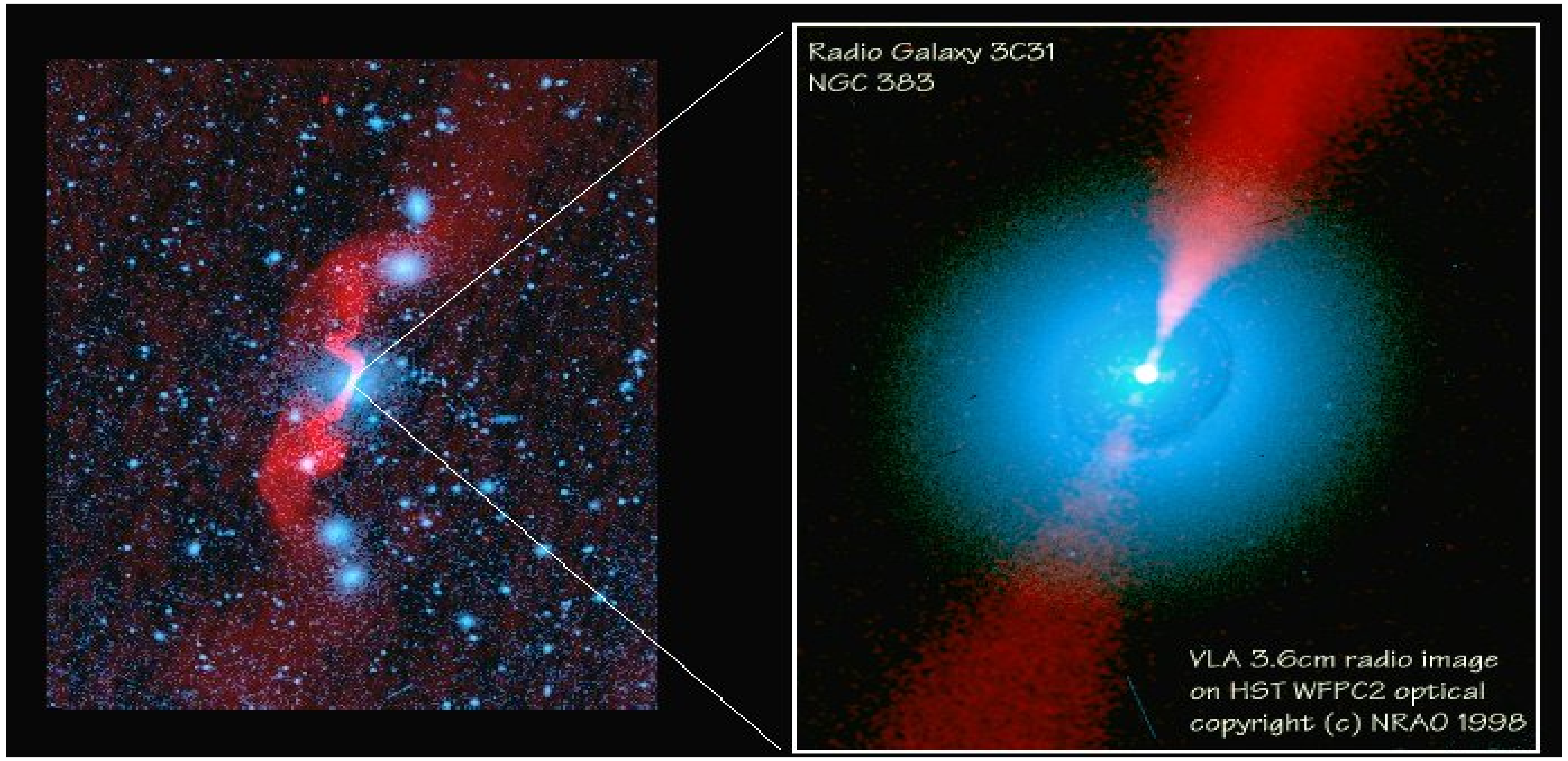
- Accretion of gas onto a massive central black hole releases tremendous amounts of energy

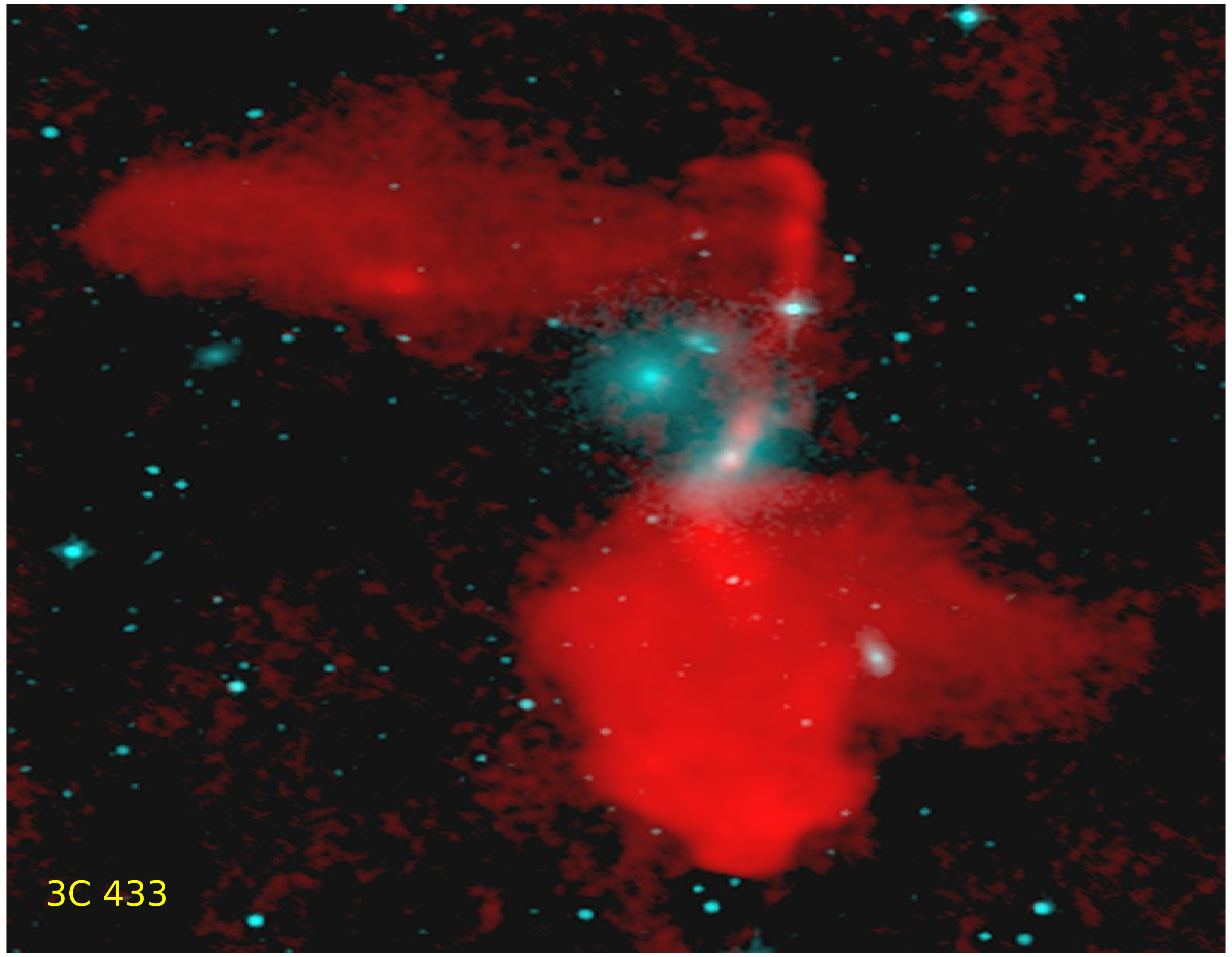
- Magnetic field collimates outflow and accelerates particles to close to the speed of light

Radio emission and its physical processes









Radio emission and its physical processes

Although the interstellar medium (ISM) of our Galaxy is dynamic, it tends toward a rough pressure equilibrium because mass motions with speeds up to the speed of sound try to reduce pressure gradients. Temperatures equilibrate more slowly, so there are wide ranges of temperature T and particle number density n consistent with a given pressure p and the **ideal gas law**

$$\boxed{p = nkT\,.} \qquad (7.1)$$

Typical ISM pressures lie in the range $p/k = nT \sim 10^3$–10^4 cm^{-3} K [58]. Radiative cooling by spectral-line emission depends strongly on temperature, so most of the ISM exists in several distinct *phases* having comparable pressures but quite different temperatures:

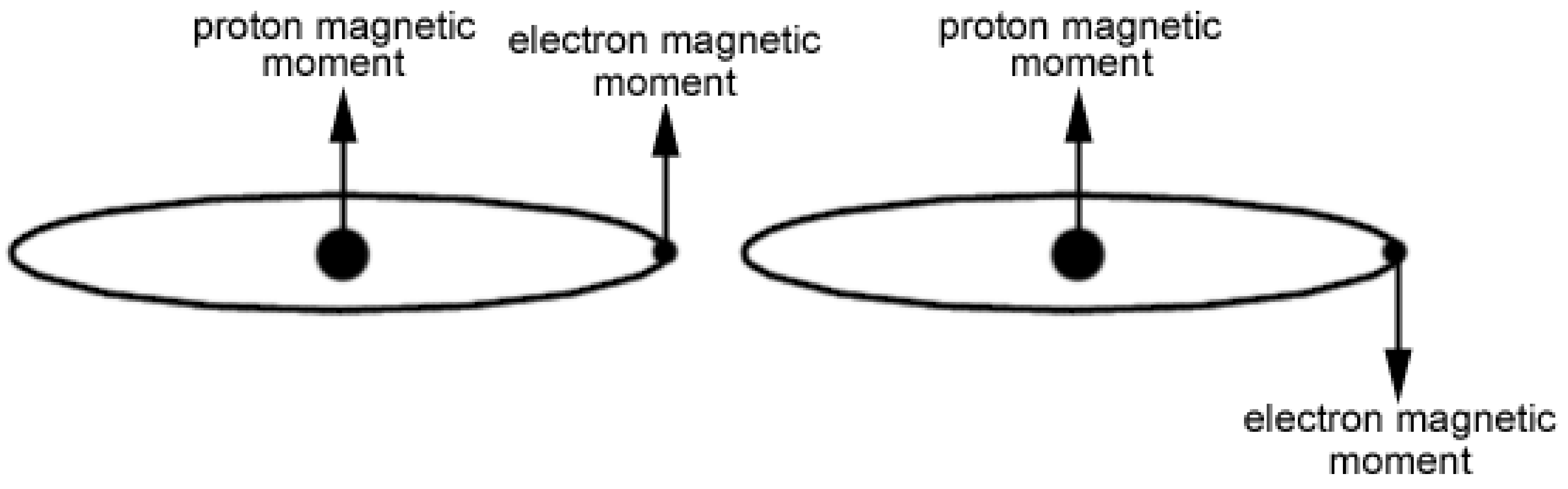
1. cold (10s of K) dense molecular clouds
2. cool ($\sim 10^2$ K) neutral HI gas
3. warm ($\sim 5 \times 10^3$ K) neutral HI gas
4. warm ($\sim 10^4$ K) ionized HII gas
5. hot ($\sim 10^6$ K) low-density ionized gas (in *bubbles* formed by expanding supernova remnants, for example)

All but the hottest phase are sources of radio spectral lines.

"Essential Radio Astronomy"

Radio emission and its physical processes

Neutral hydrogen (HI) atoms are abundant and ubiquitous in low-density regions of the ISM



They are detectable in the ≈21 cm (1420.40575 MHz) hyperfine line

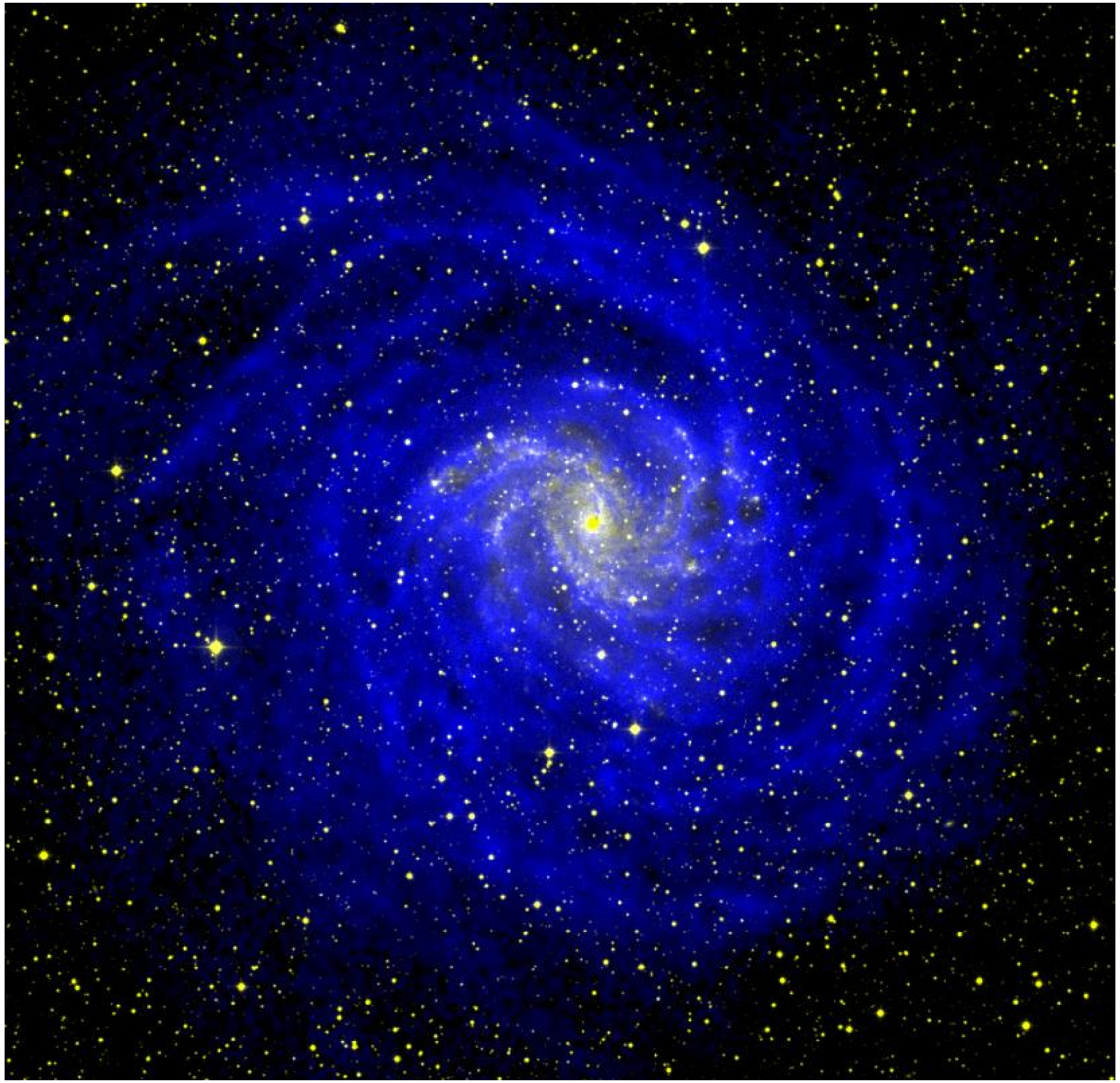
An extremely useful tool for studying gas in the ISM of external galaxies and tracing the large-scale distribution of galaxies in the Universe.

Radio emission and its physical processes

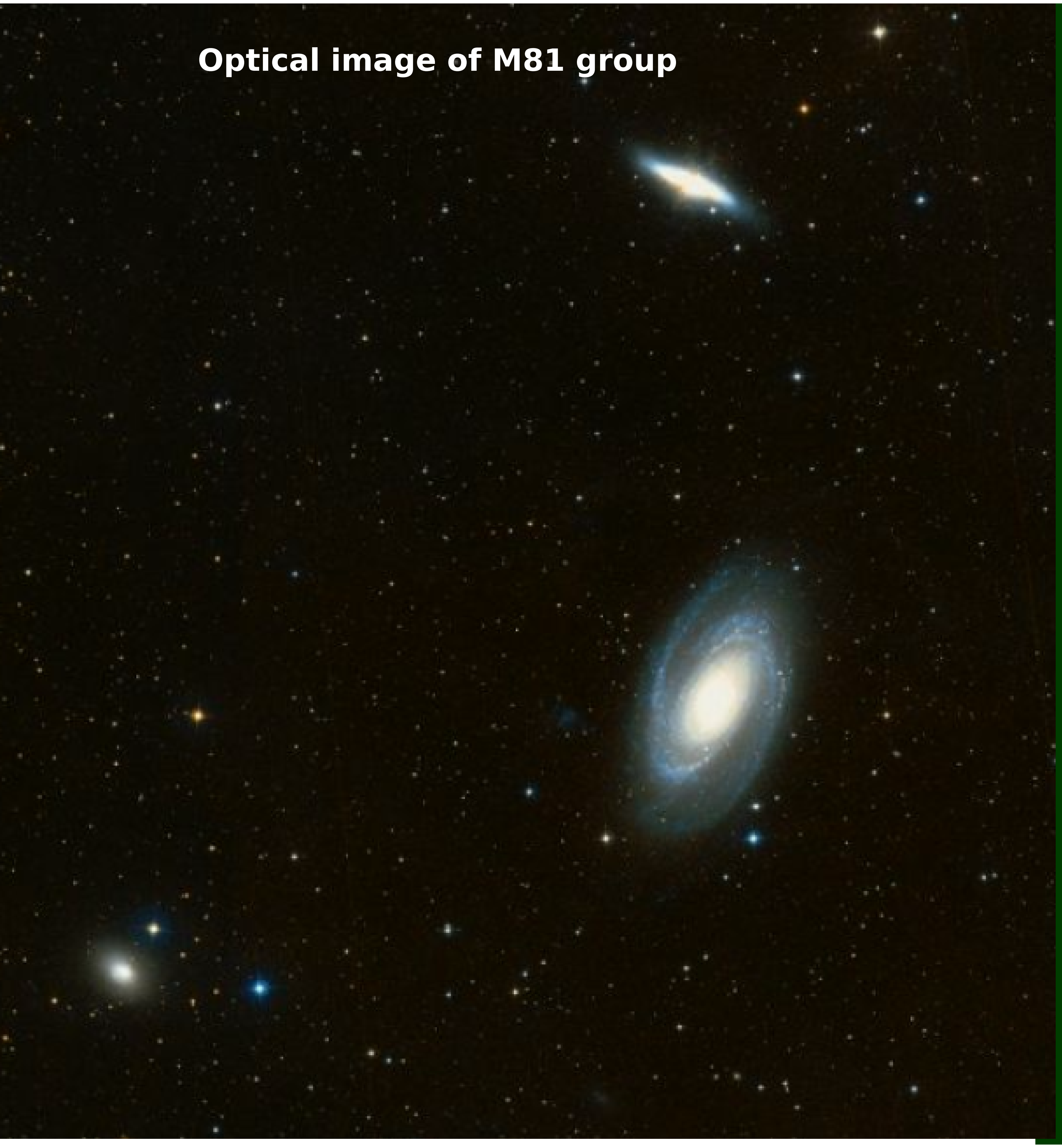
B/W=optical image of NGC 6946 from Digital Sky Survey

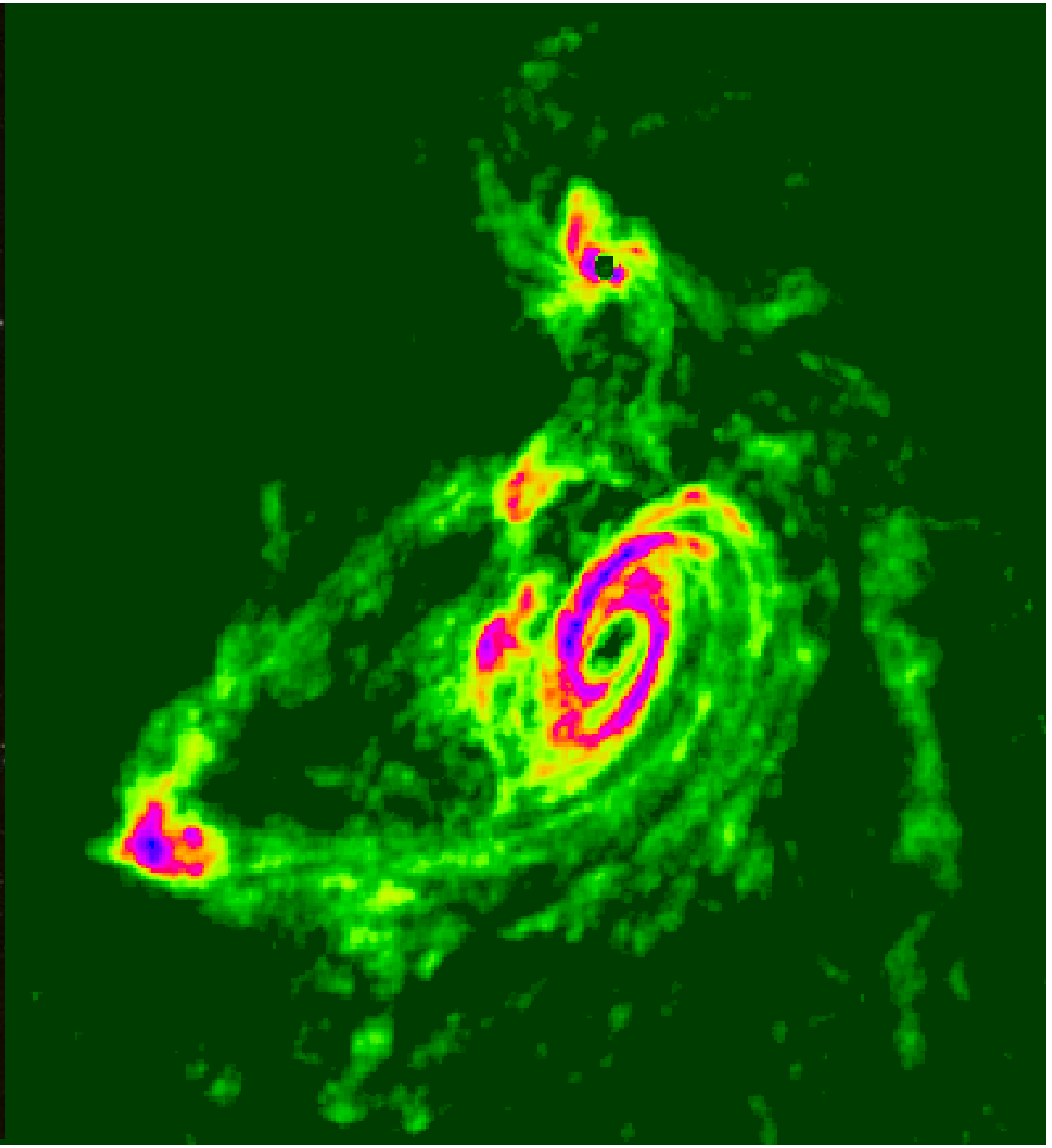
Blue=Westerbork Synthesis Radio Telescope 21 cm image of Neutral Hydrogen

Hydrogen usually much more extended than stars



Radio emission and its physical processes





VLA 12-pointing mosaic Yun et al. 1994

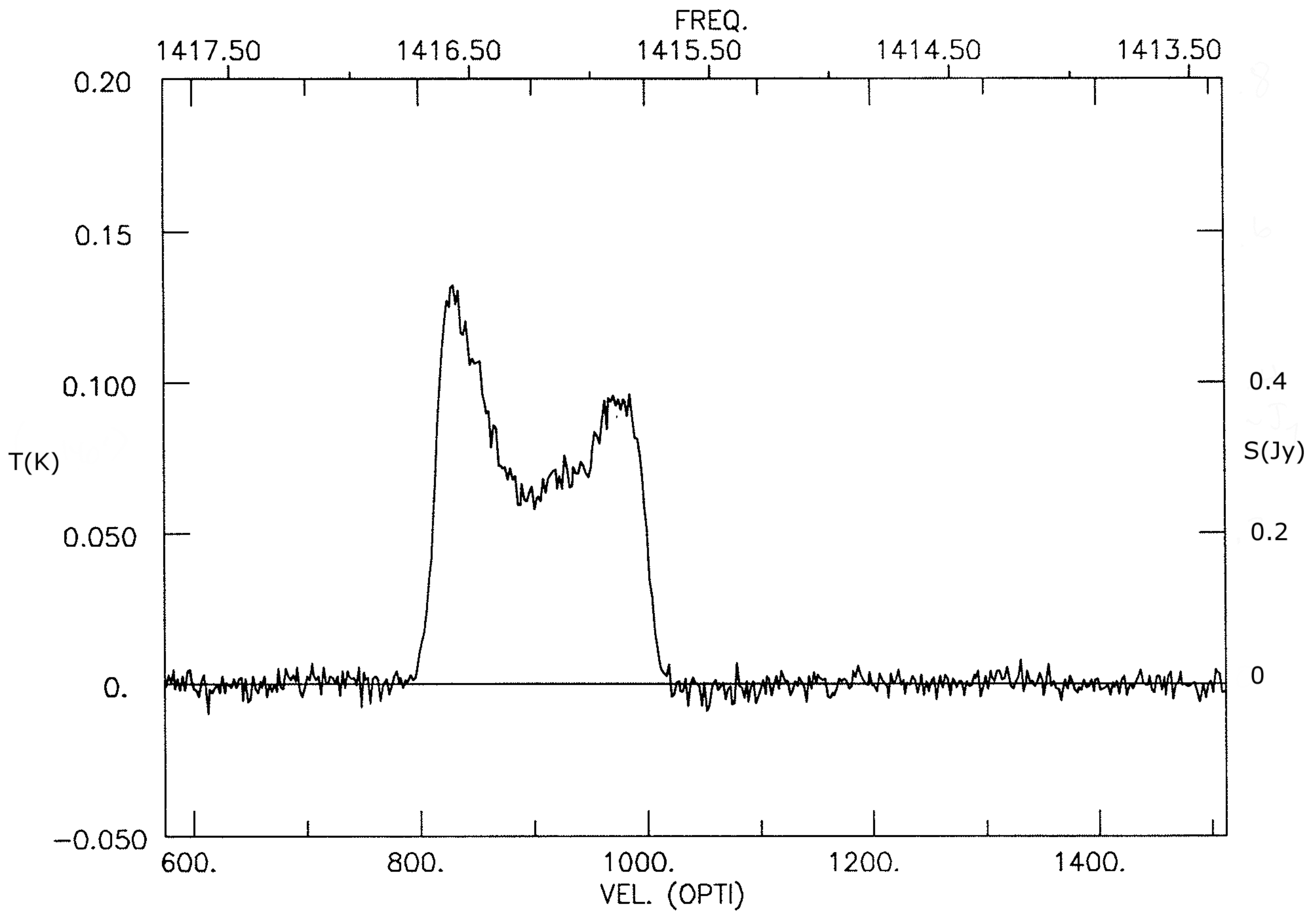
Neutral Hydrogen is the raw fuel for all star formation

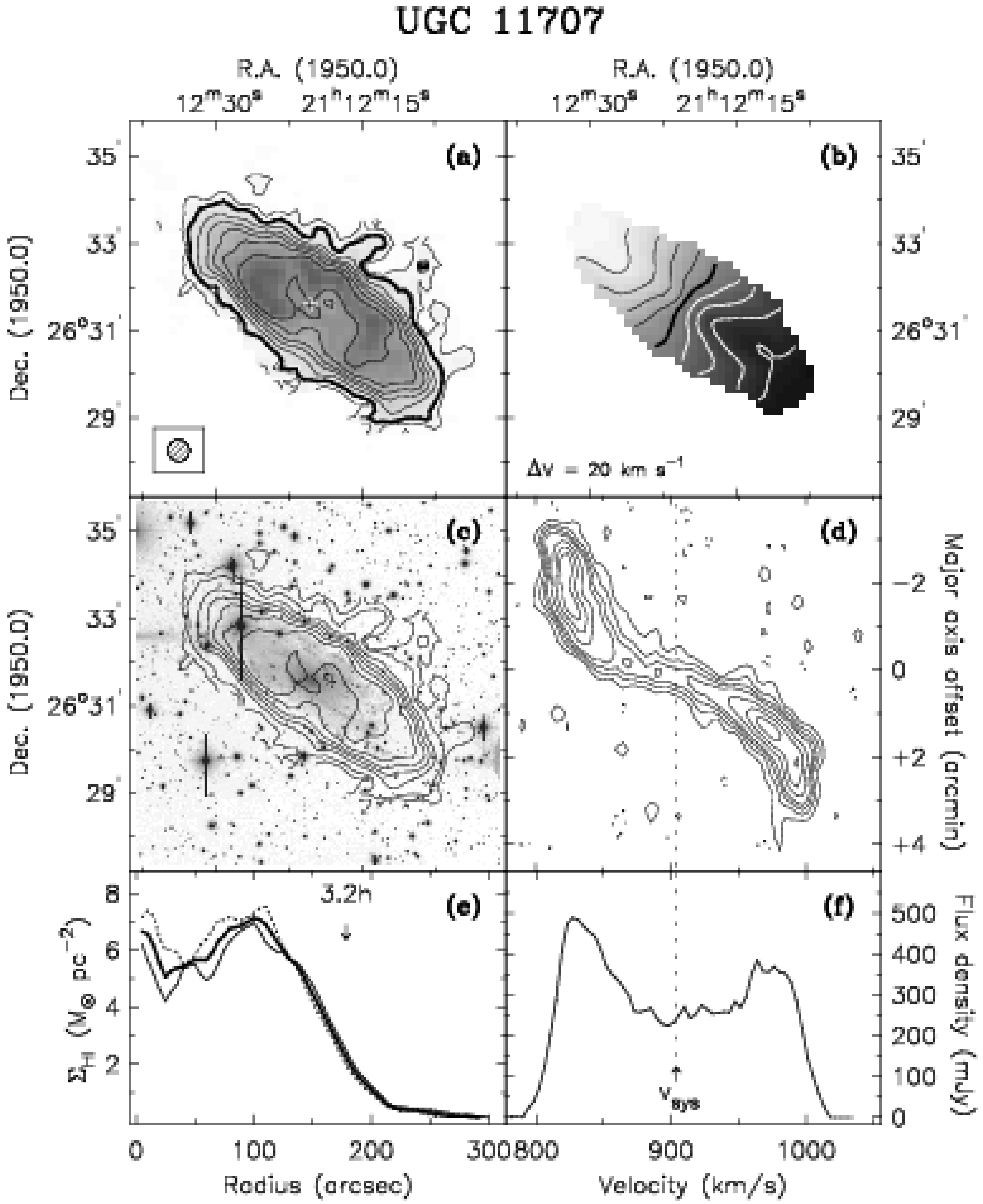
Hydrogen usually much more extended than stars

Hydrogen usually much more extended than galaxies…

…and can be used to trace past galaxy interactions

Radio emission and its physical processes





Radio emission and its physical processes

Molecular rotational and vibrational modes

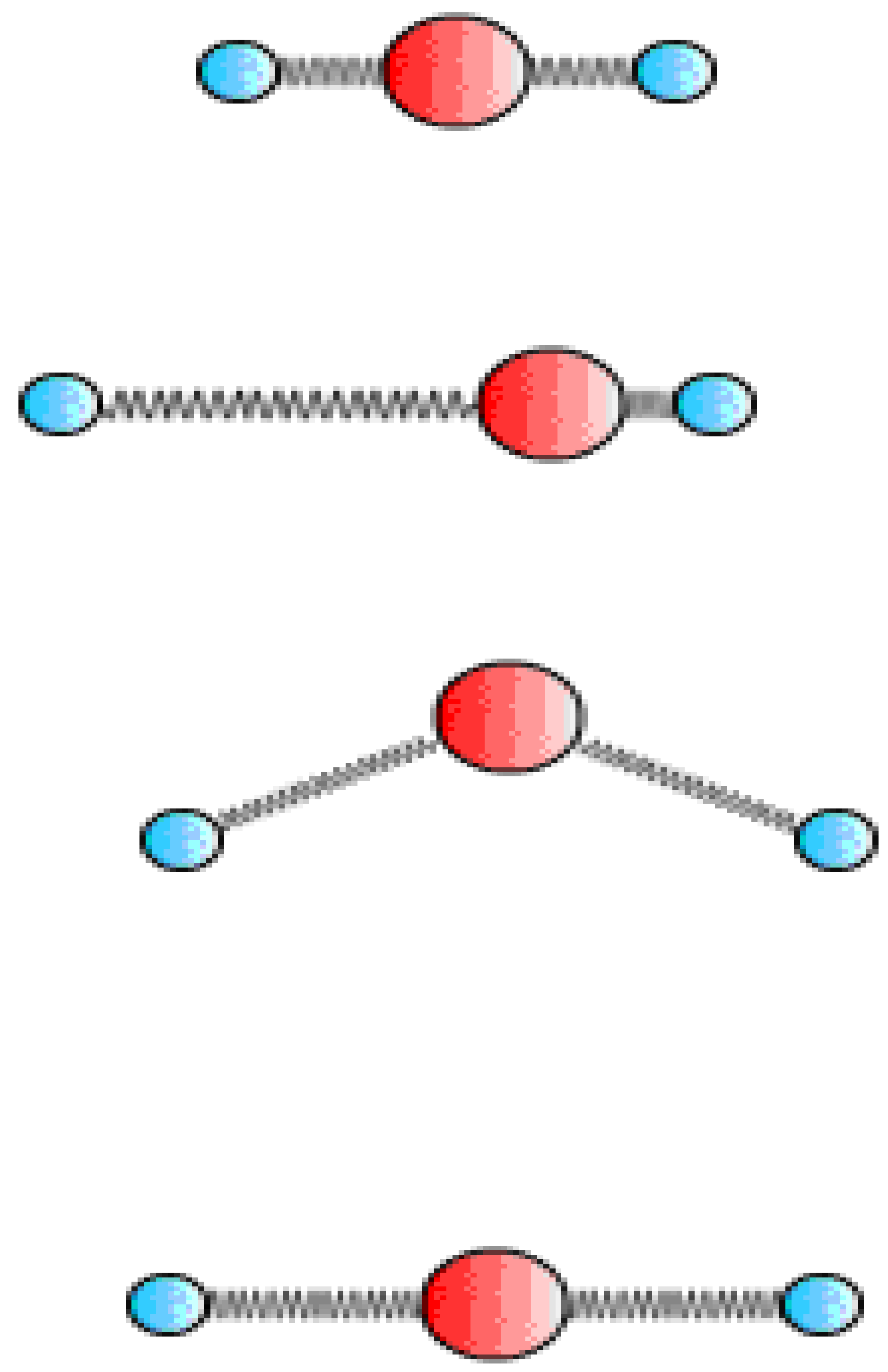
Commonly observed molecules in space:

- **Carbon Monoxide (CO)**
- **Water (H_2O), OH, HCN, HCO^+, CS**
- **Ammonia (NH_3), Formaldehyde (H_2CO)**

Less common molecules:

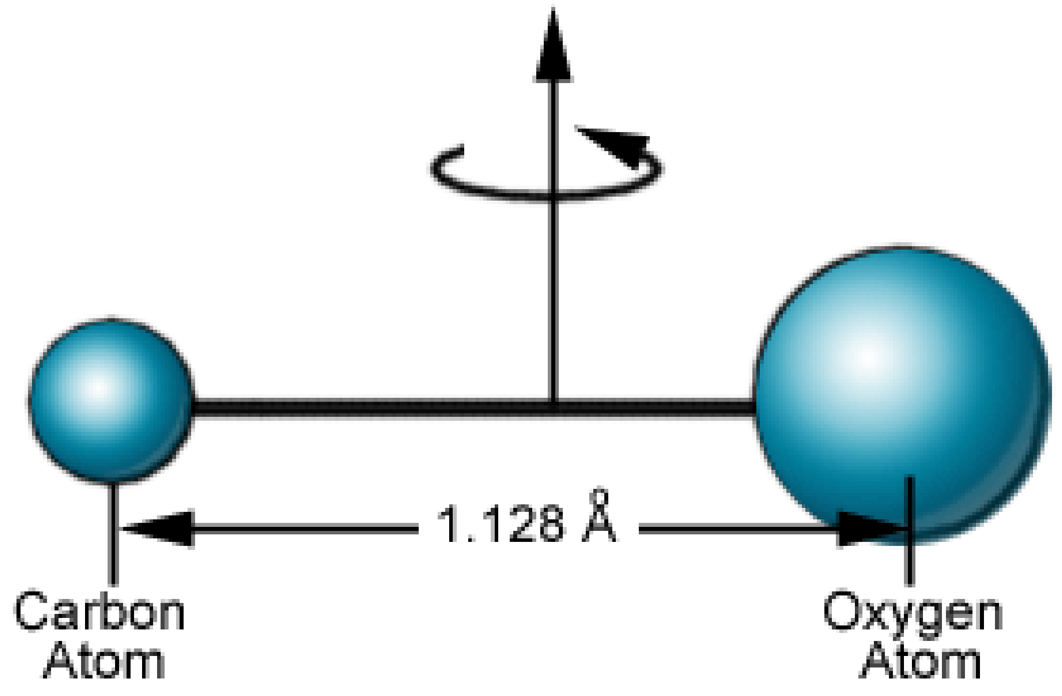
- **Sugar, Alcohol, Antifreeze (Ethylene Glycol)**

Large, heavy molecules in cold clouds may be seen at centimeter wavelengths, but smaller and lighter molecules emit only at millimeter and sub-mm wavelengths.



Radio emission and its physical processes

H_2 is the most abundant molecule in the Universe …makes up most of the molecular ISM in galaxies but is basically invisible in emission!



Polar molecules, i.e. molecules with a permanent dipole moment, like the carbon monoxide molecule radiate at their rotation frequencies:

$$\nu = \frac{hJ}{4\pi^2 m r_e^2}$$

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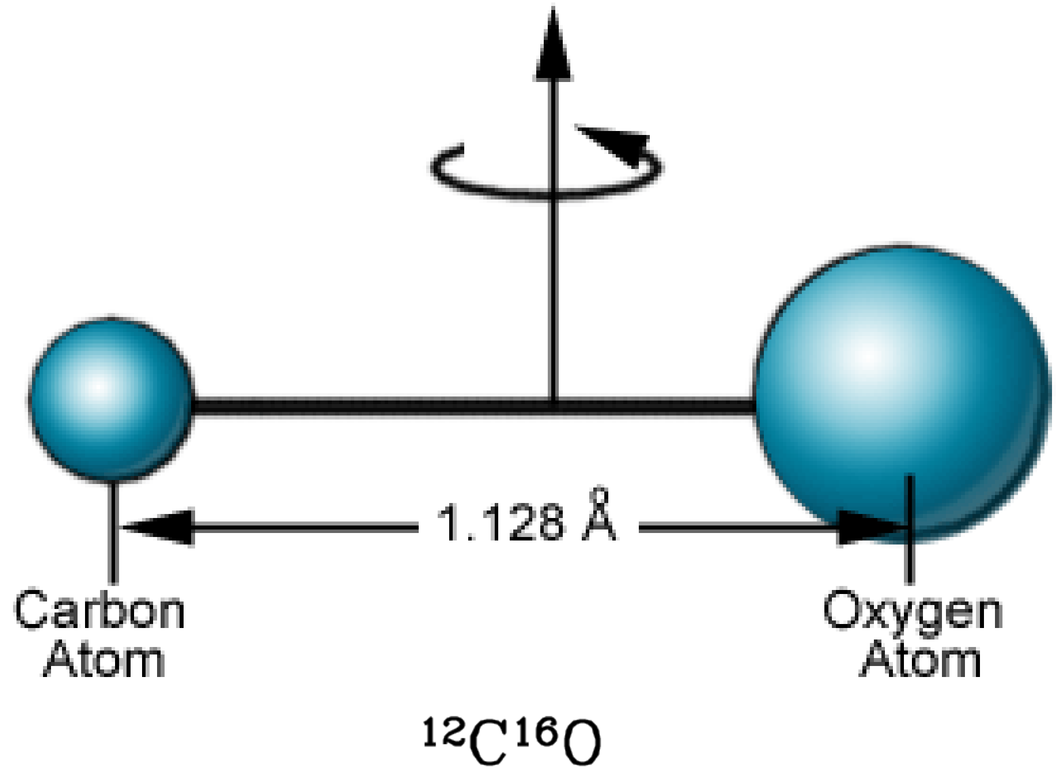

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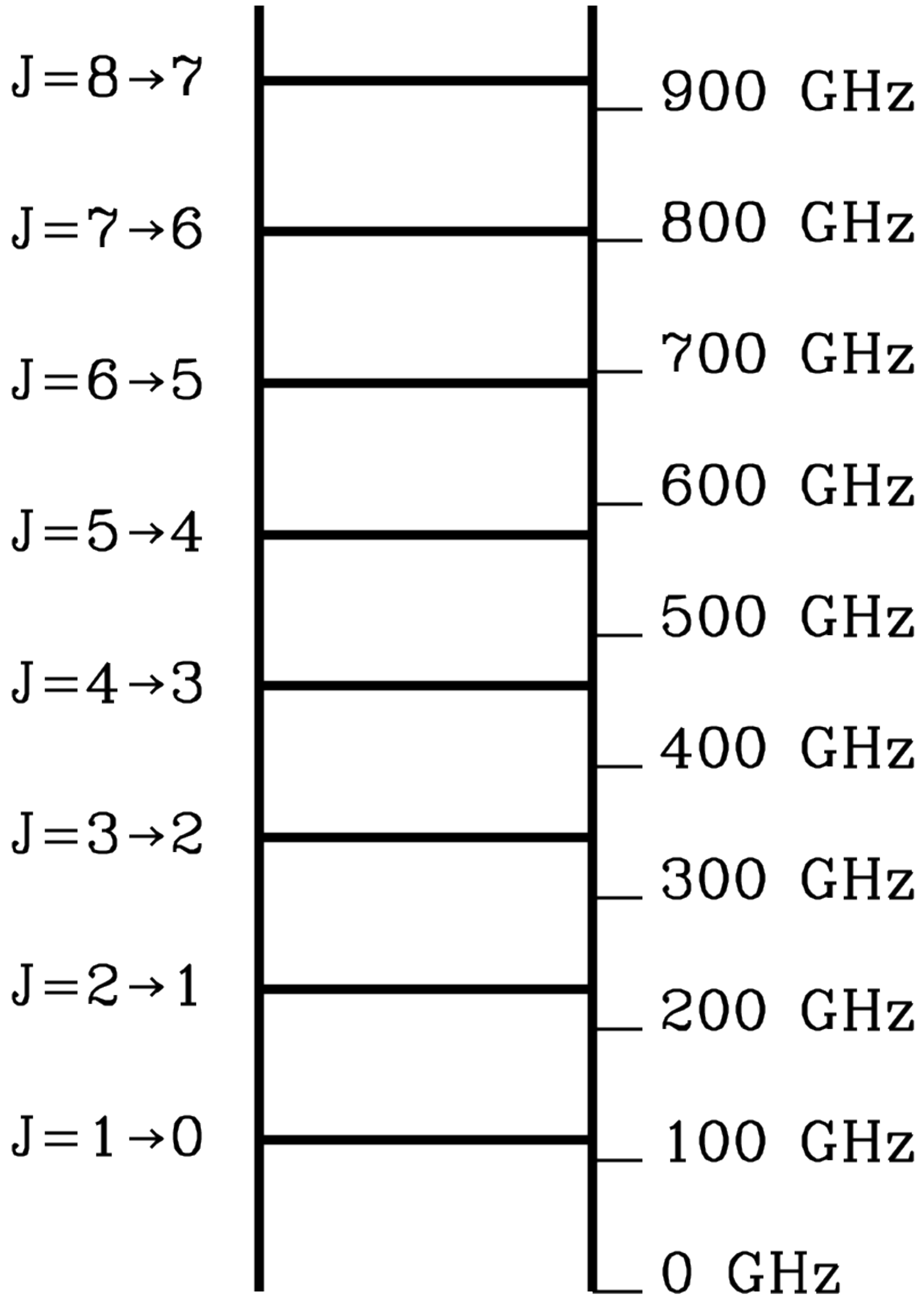

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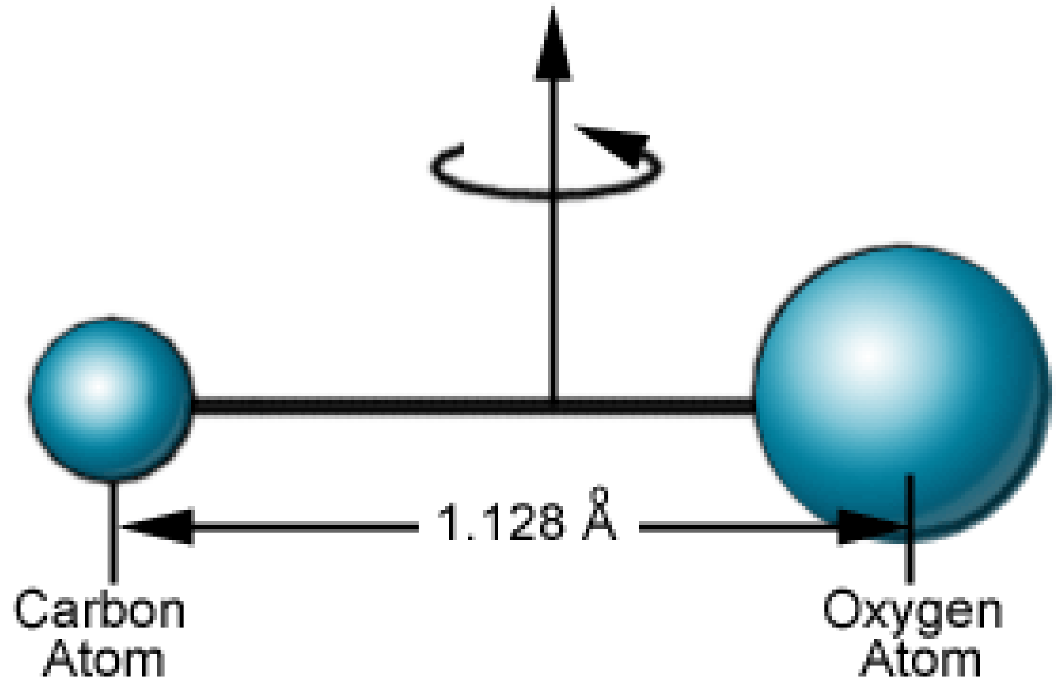
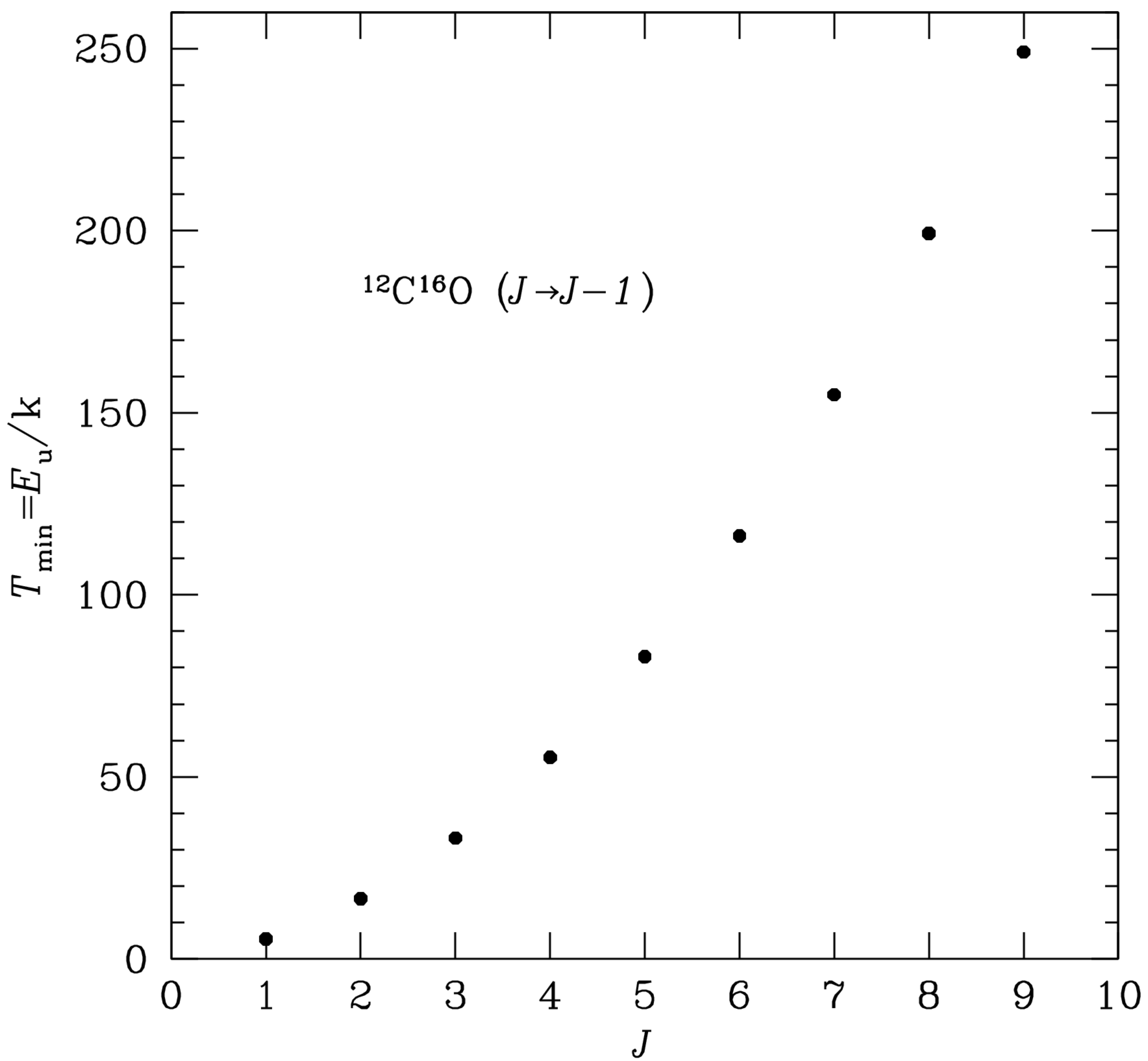
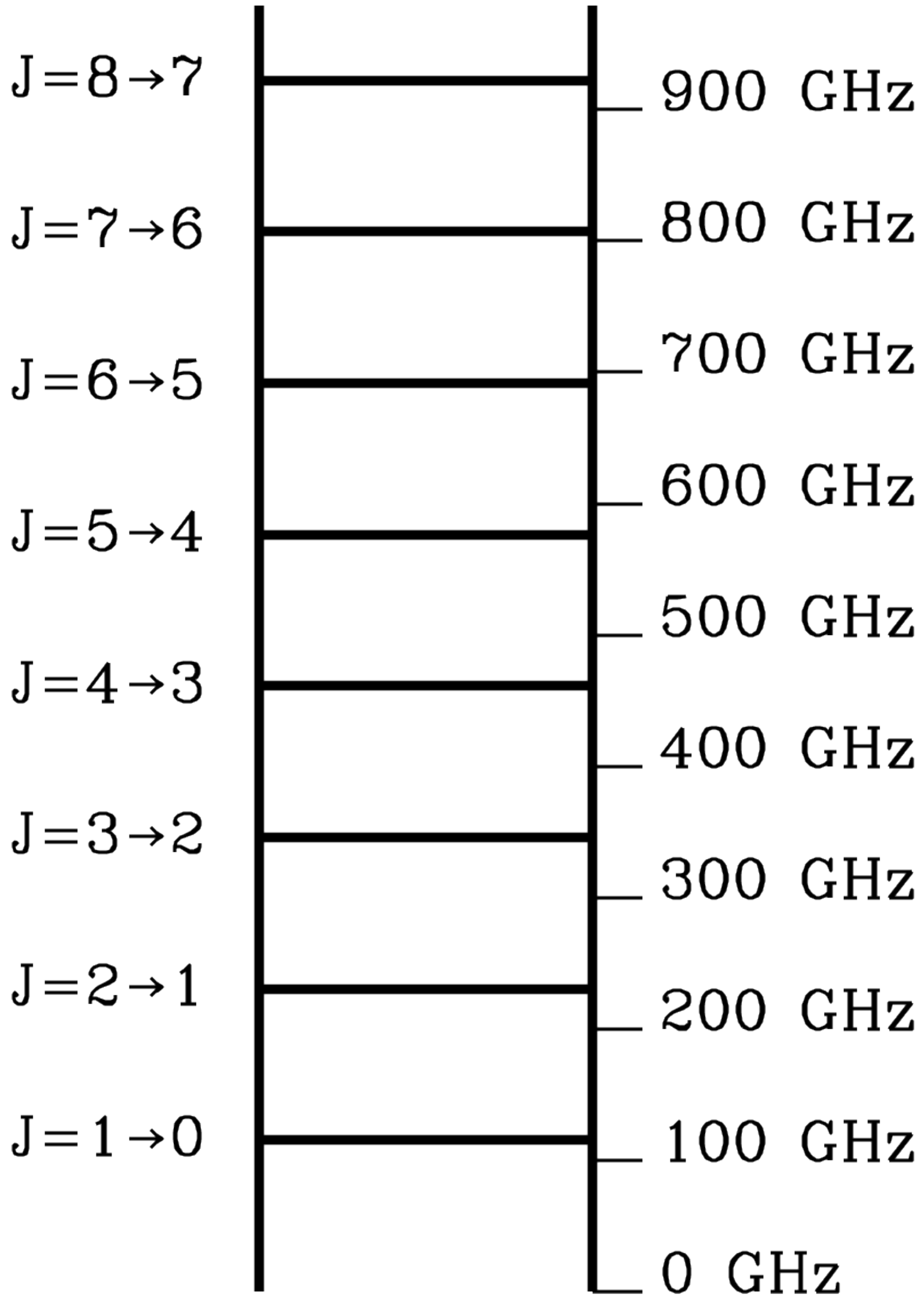


$^{12}C^{16}O$

$$\nu = \frac{hJ}{4\pi^2 m r_e^2}, \qquad J = 1, 2, \ldots .$$

$$T_{\rm min} \approx \frac{\nu h (J+1)}{2k}$$



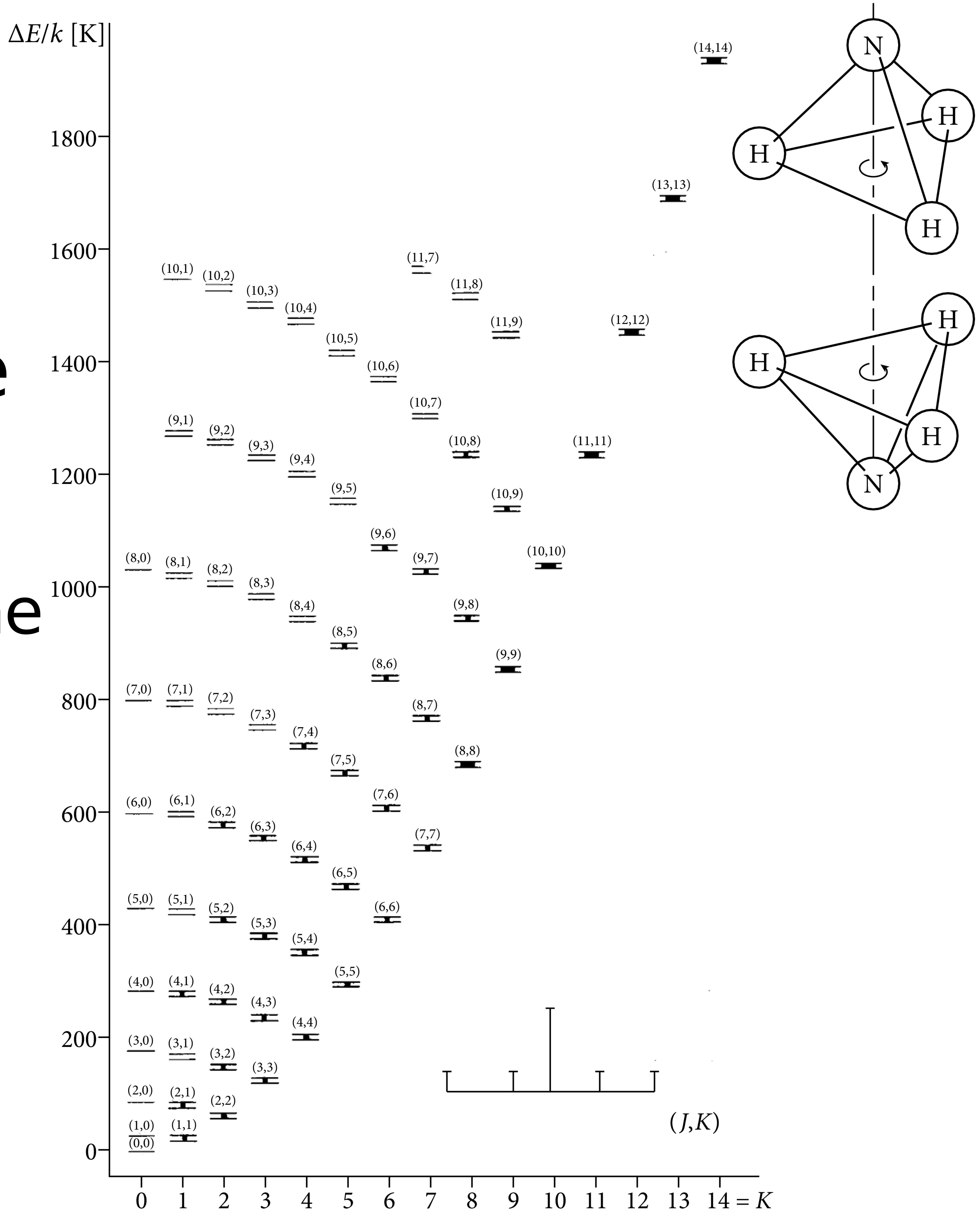


Radio emission and its physical processes

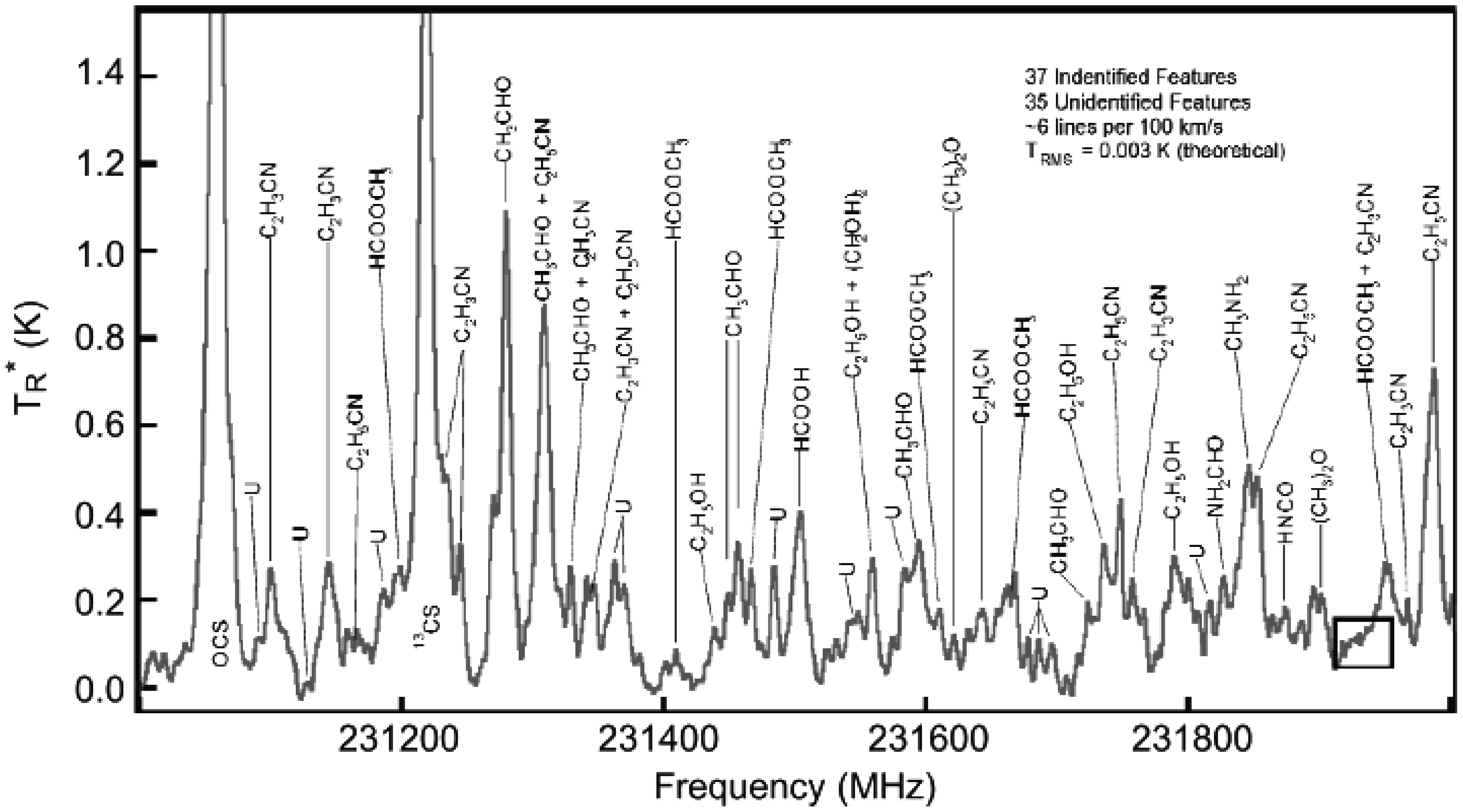
Nonlinear molecules such as the symmetric-top ammonia (NH_3) with two distinct rotational axes have more complex spectra consisting of many parallel ladders.

Transitions between the two spin states of the nitrogen atom cause the line splitting shown and yield emission at frequencies near 24 GHz.

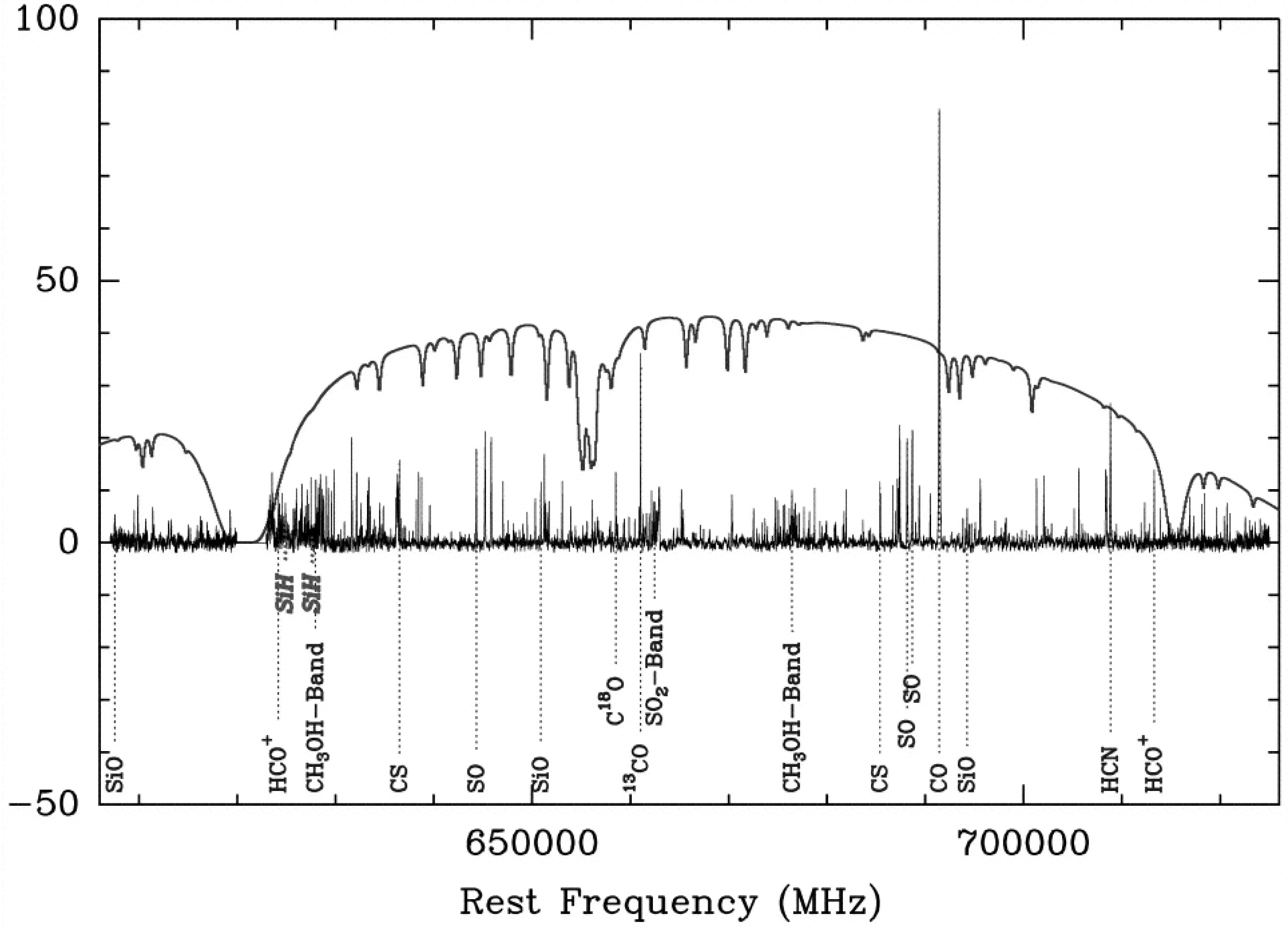
NH_3 is a very useful thermometer for molecular clouds



Radio emission and its physical processes



molecular cloud SgrB2(N) near the Galactic center



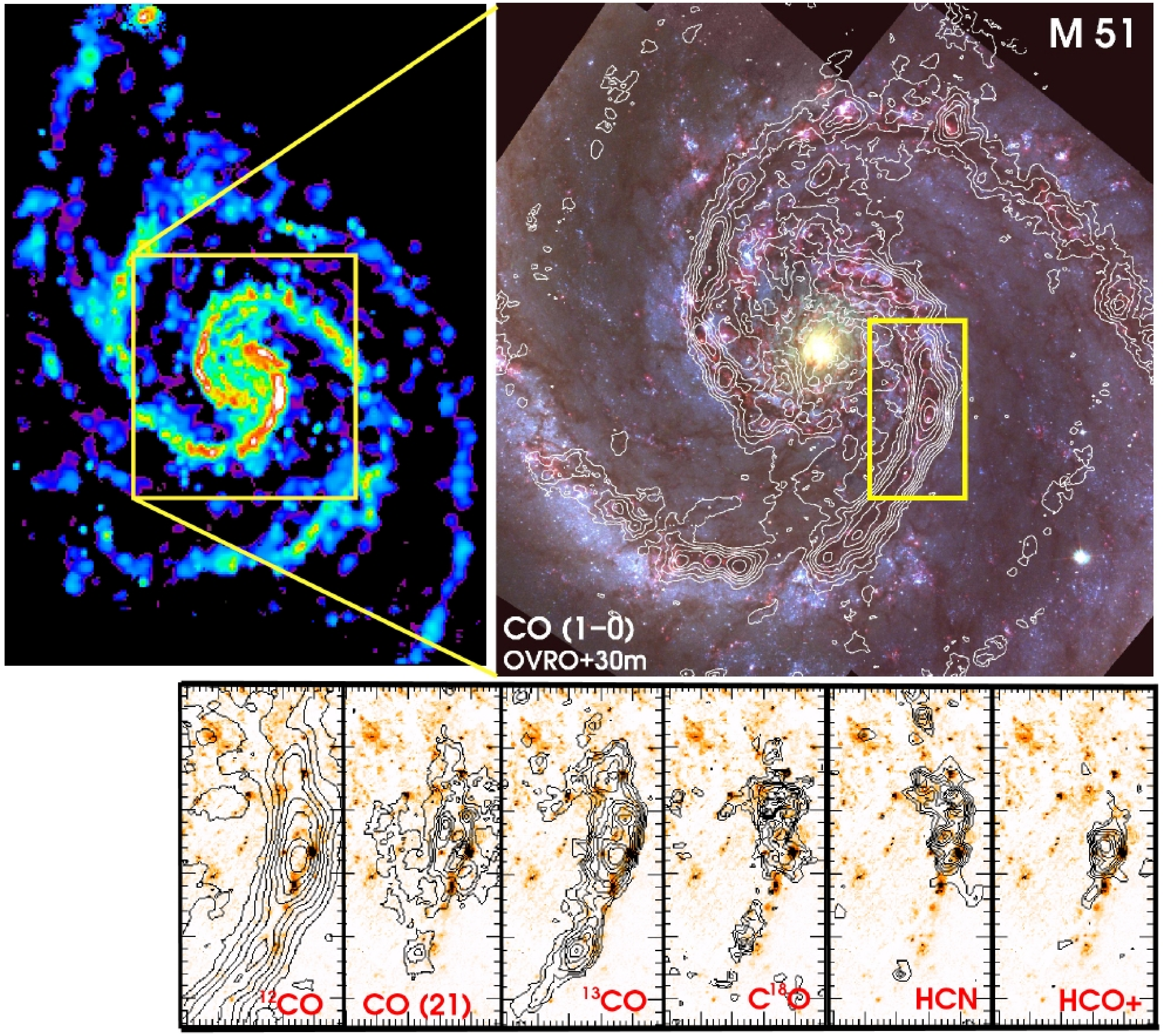
Orion KL region

Radio emission and its physical processes

M51 – The Whirlpool galaxy

First multi-transitions studies

- **GMCs**
- **arms physical conditions**
- **dust properties**
- **star formation**

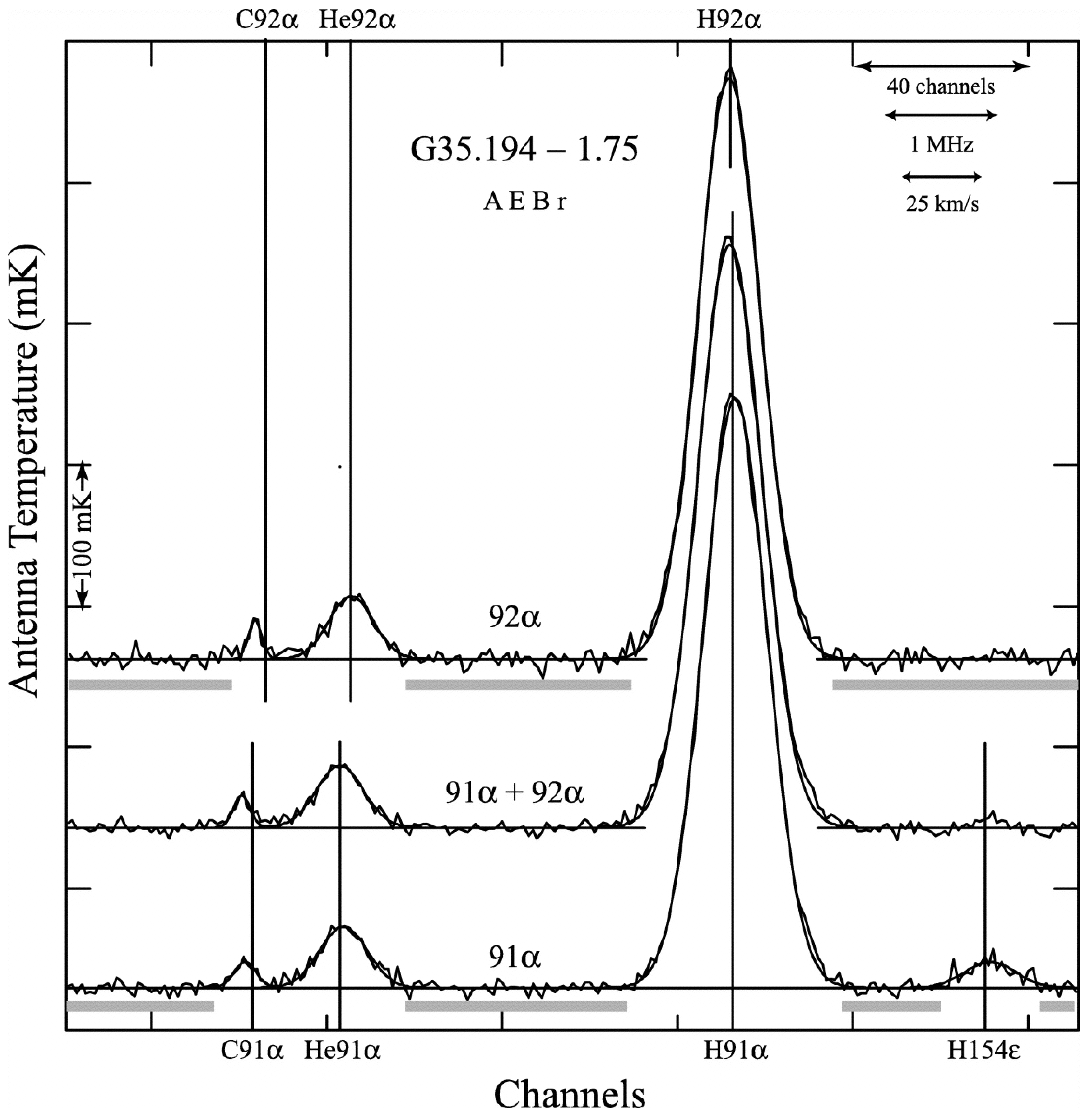


Radio emission and its physical processes

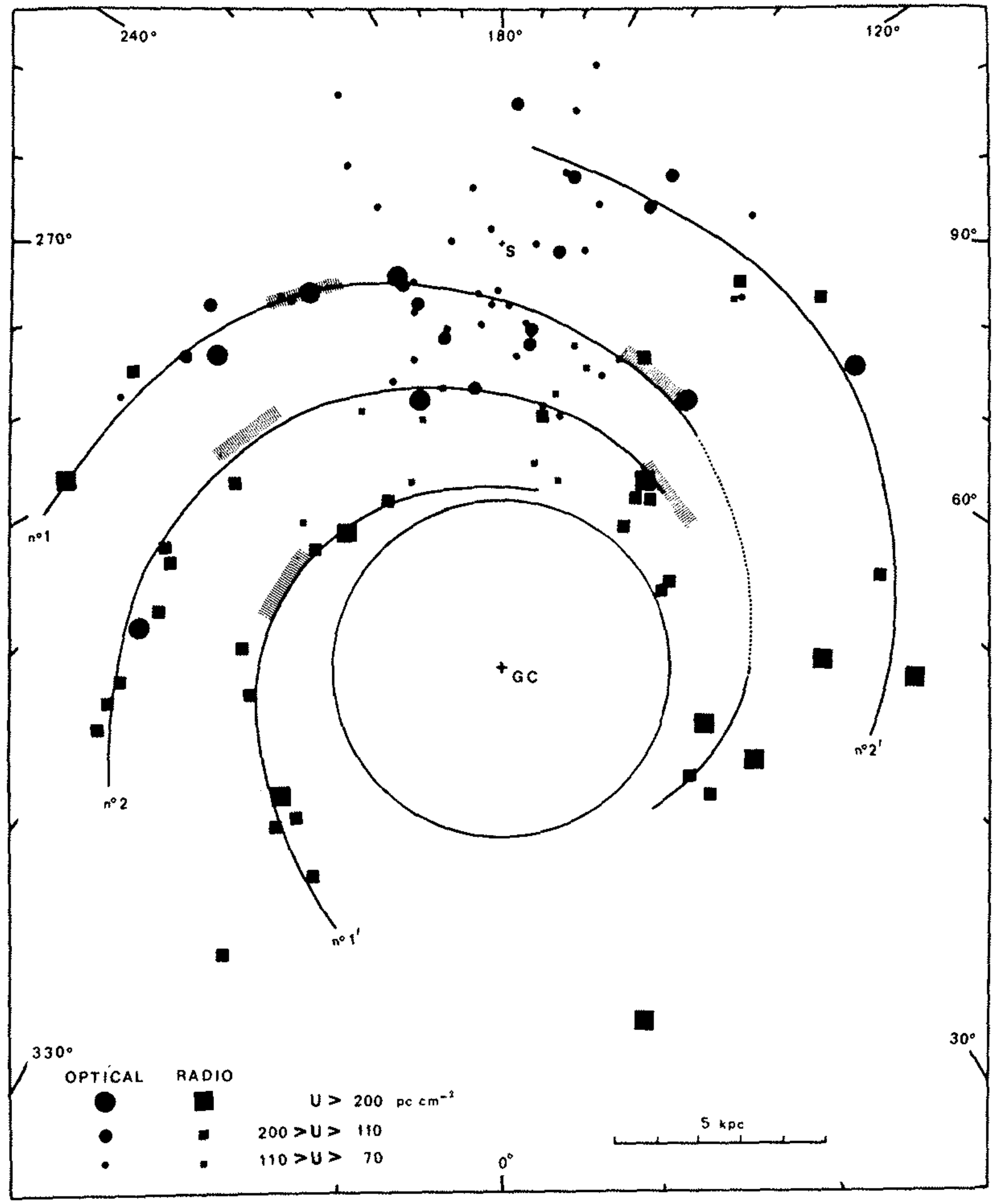
Recombination lines produced by high-n transitions are observed in the radio window.

These lines can be used to effectively study the physical properties of HII regions:

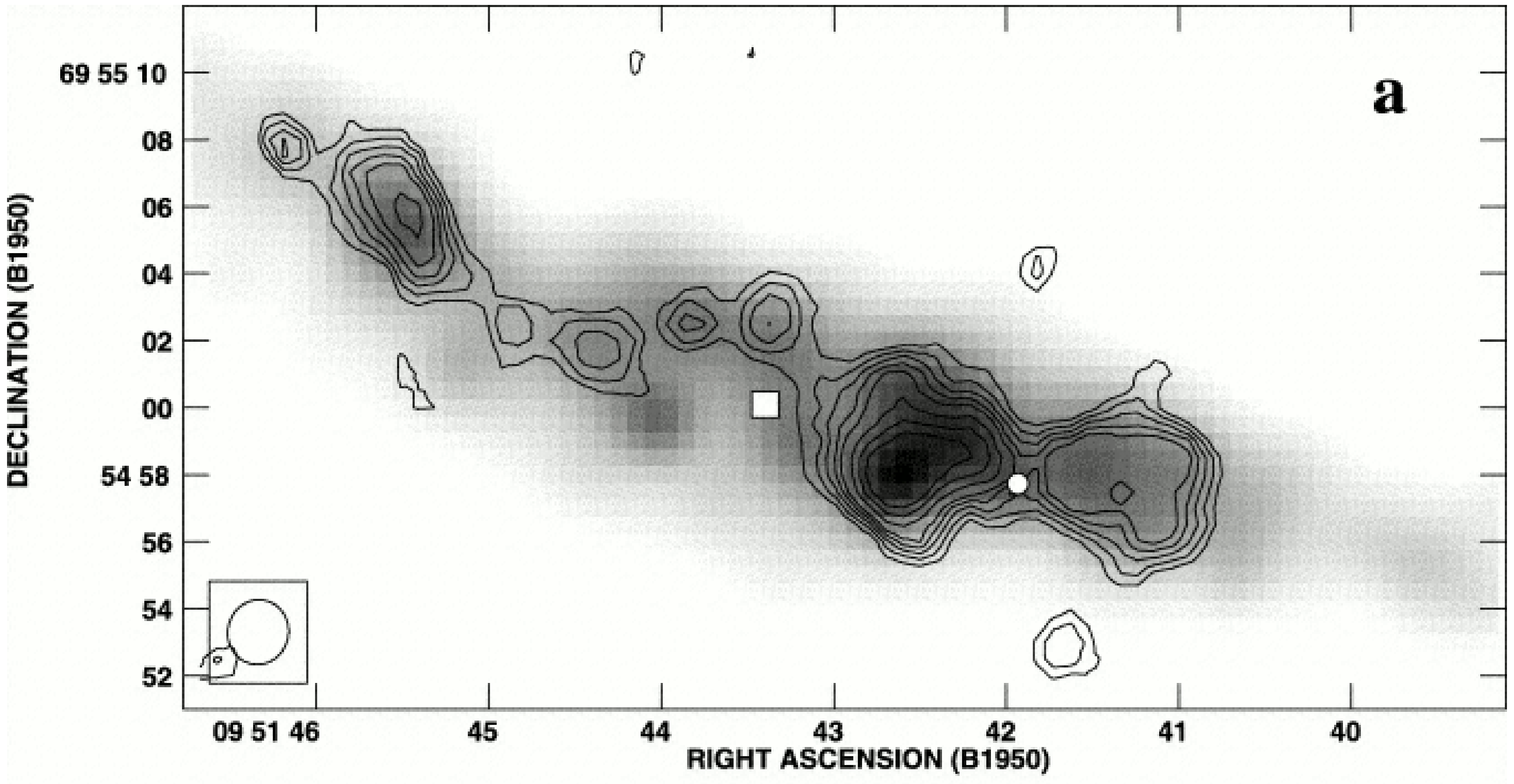
- the electron temperatures of HII regions
- the metal content of the galaxy
- the spatial distribution and kinematics of HII regions



Radio emission and its physical processes



The spiral pattern of our Galaxy in plan view, as traced by Hα (circles) and radio recombination lines (squares)



M82 imaged in H92α (contours) and 8.3 GHz continuum (gray scale).

Radio recombination line strengths are much less affected by dust extinction than optical lines (e.g., the Hα and Hβ lines)

Radio recombination lines are useful indicators of the ionization rates and hence star-formation rates in dusty galaxies.

Radio emission and its physical processes

Maser (microwave amplification by stimulated emission of radiation