Introduction to Radio Astronomy

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Metropolitan State University of Denver

Undergraduate Alfalfa Workshop 2018

ALFALFA

Undergraduate Alfalfa Workshop 2018

Hey Tweeters: the proper hashtags for this meeting are:

#UAT18

#GBO

#GBT

#TULLYSPOCKETFISHERMAN

This talk sponsored by:

Tully's Pocket Fisherman

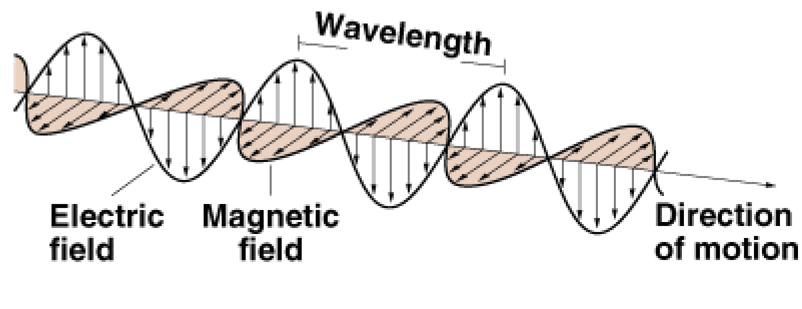
NOW WITH 3.5 TO 4 TIMES EXTRA SPIN

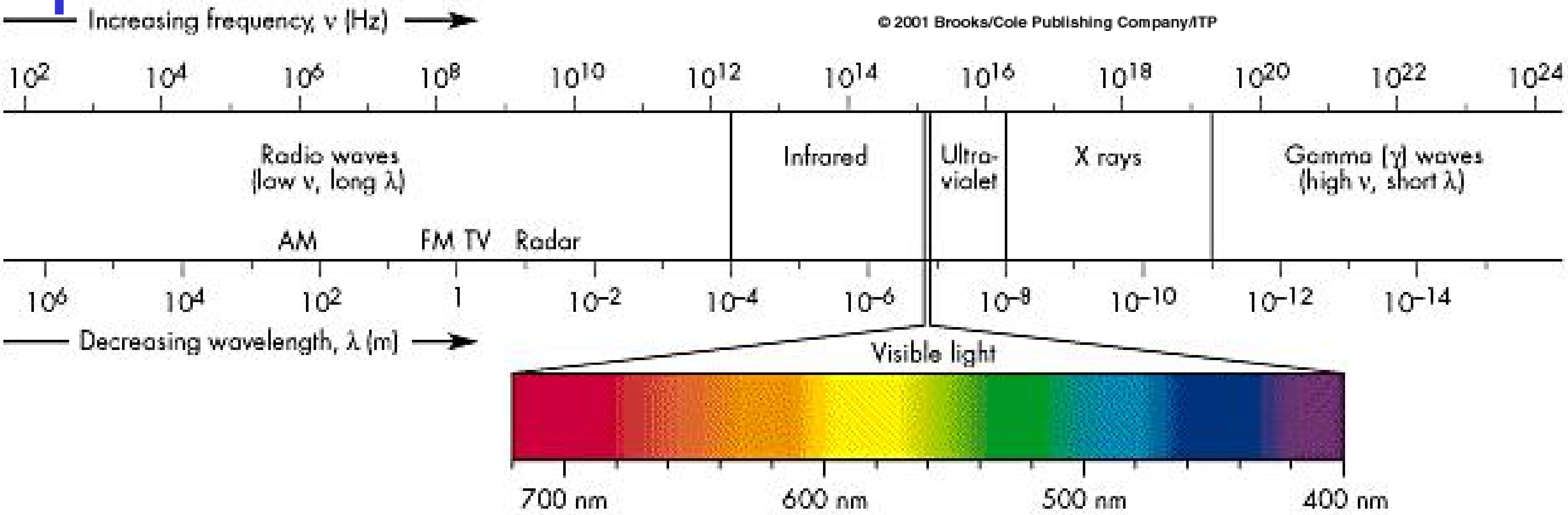
Introduction to Radio Astronomy

1) Stuff in space
2) Telescopes
3) Neutral Hydrogen (HI)

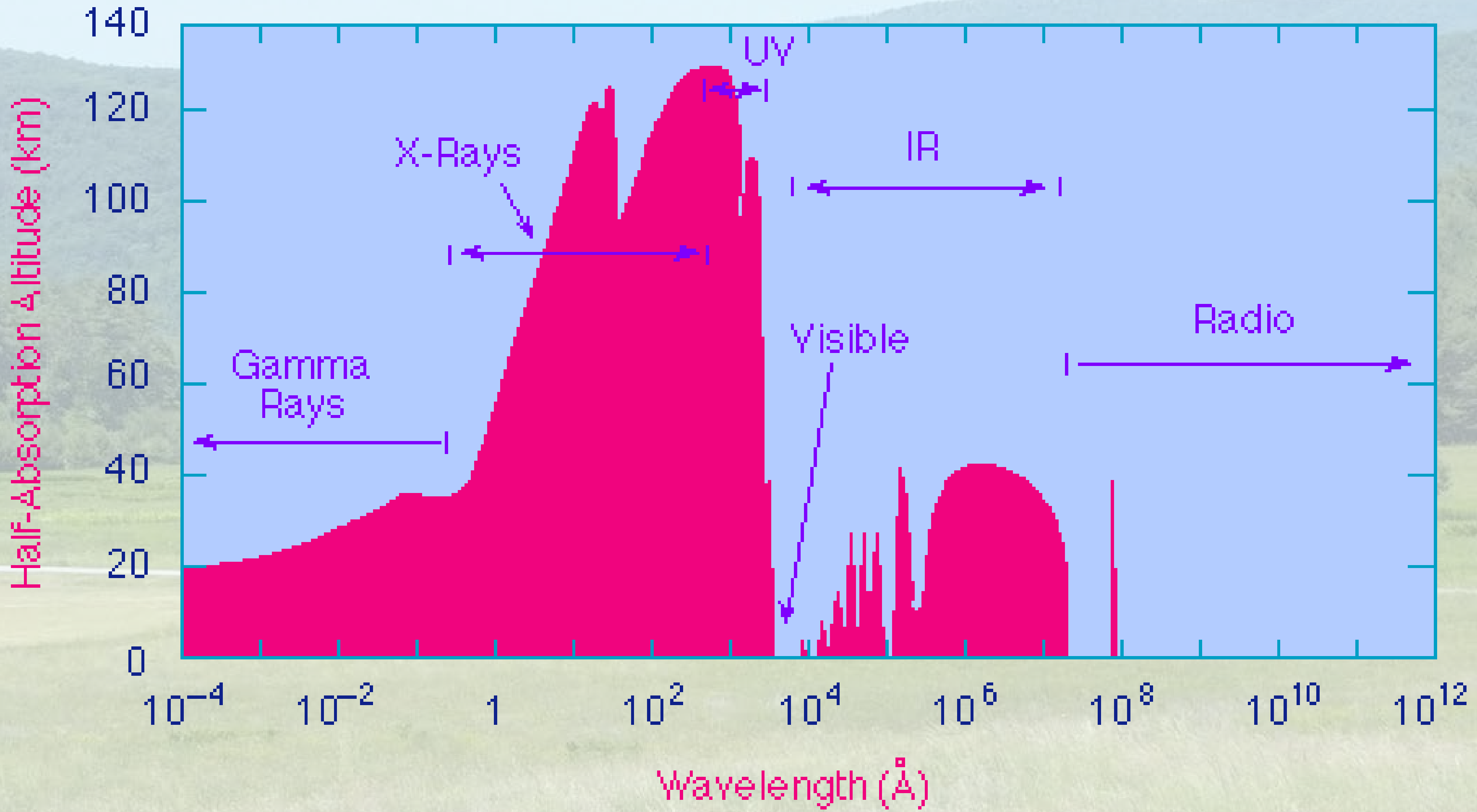
For an excellent rigorous introduction to radio astronomy:
https://science.nrao.edu/opportunities/courses/era

The Electromagnetic Spectrum

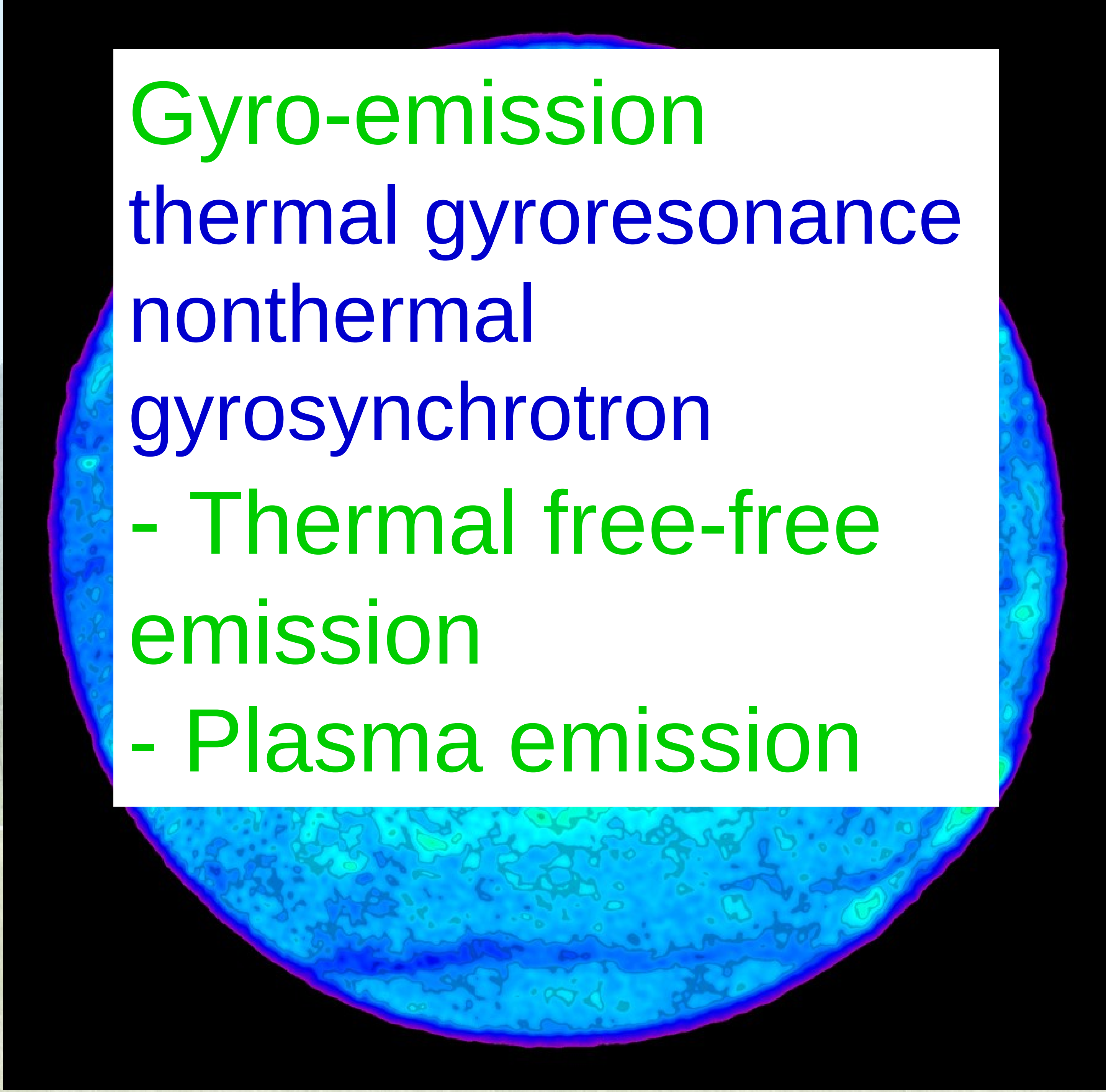




Atmospheric windows



The Sun at 5 GHz



Gyro-emission

thermal gyroresonance

nonthermal gyrosynchrotron

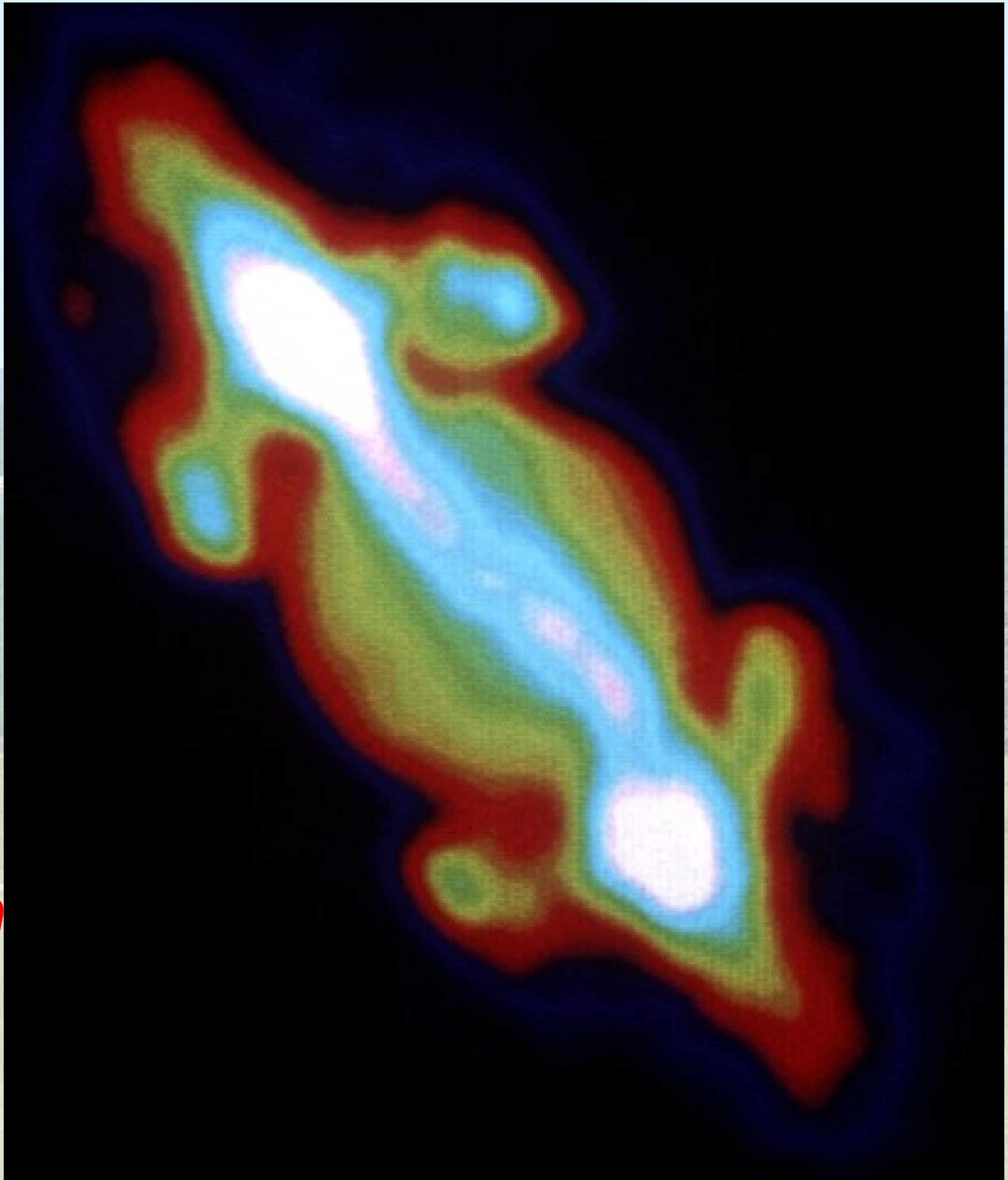
- Thermal free-free emission

- Plasma emission

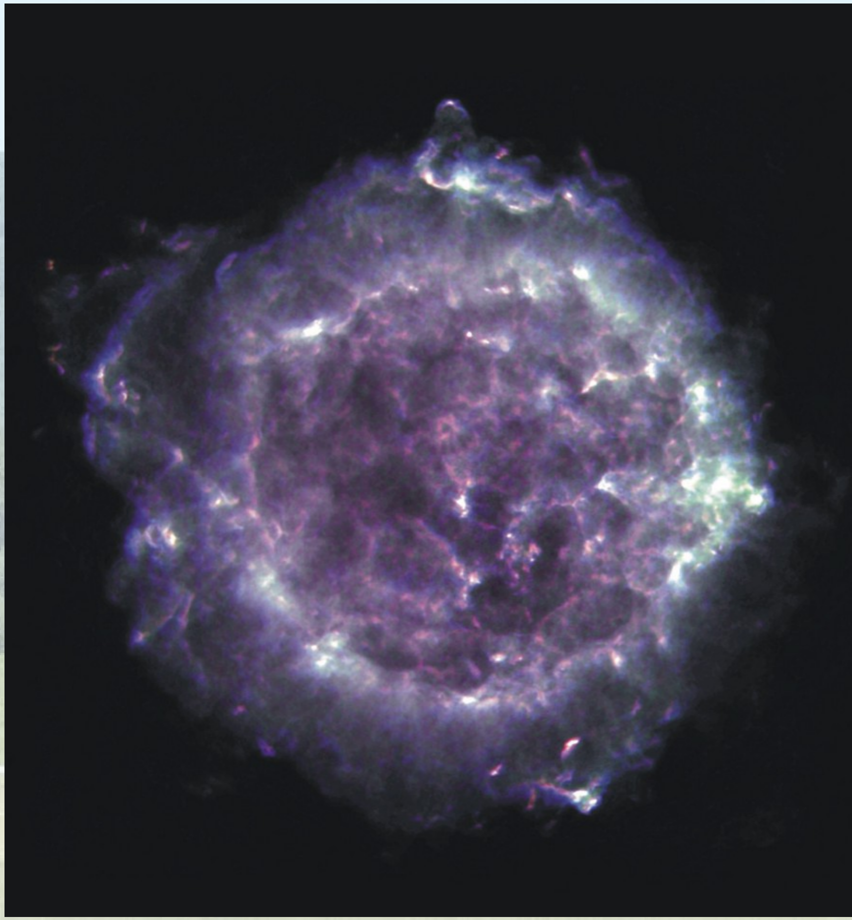
Jupiter

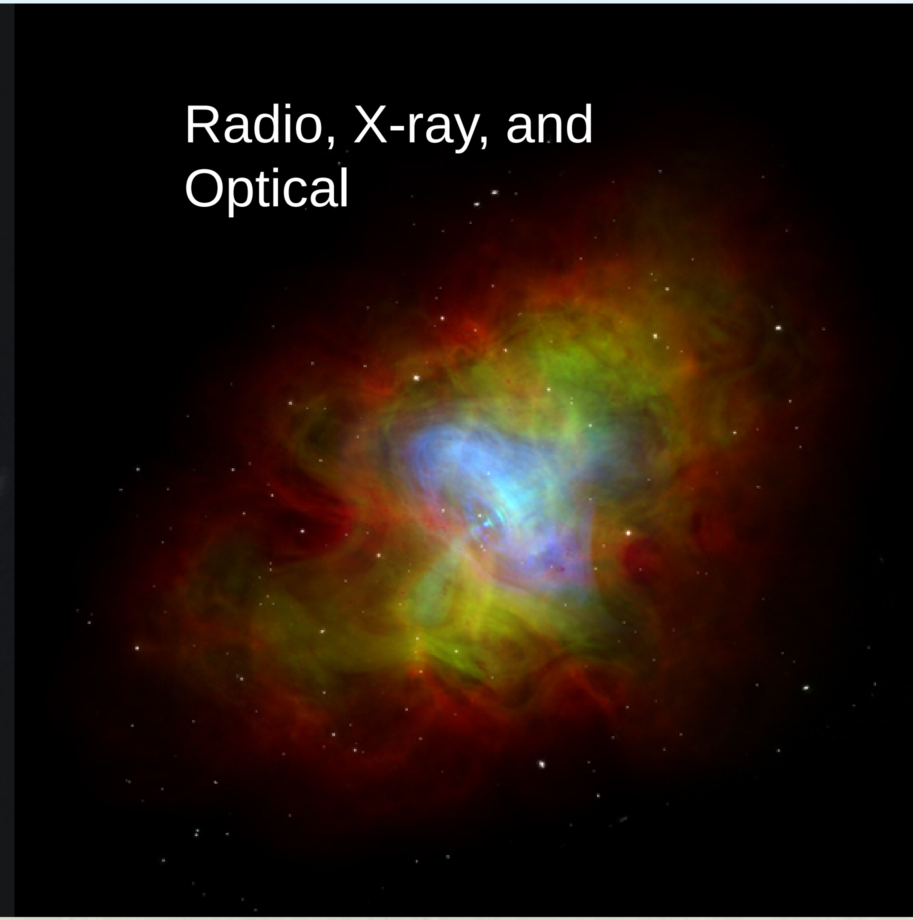
Students: What do you think is causing the radio emission of Jupiter?

Synchrotron Radiation



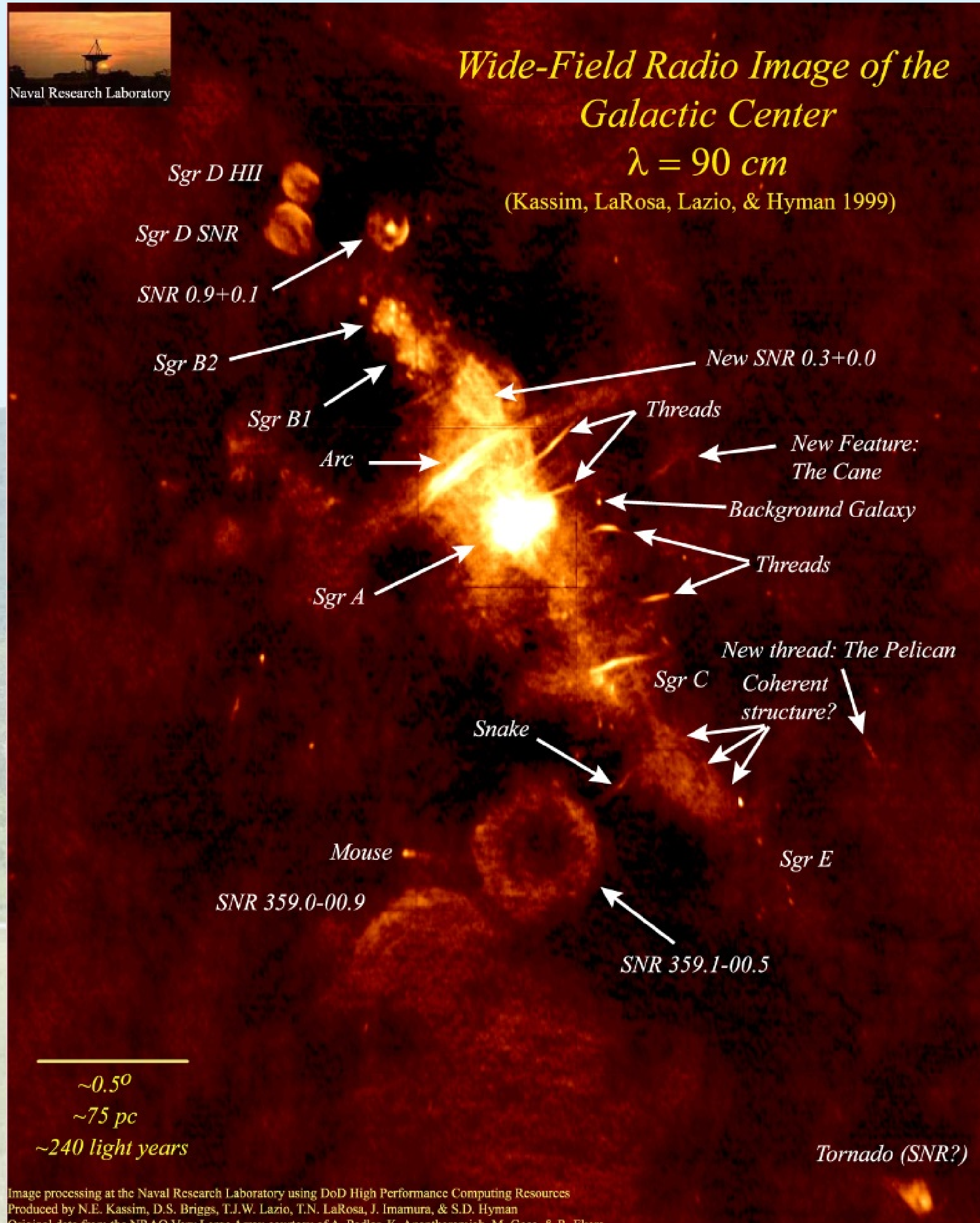
Supernova Remnants



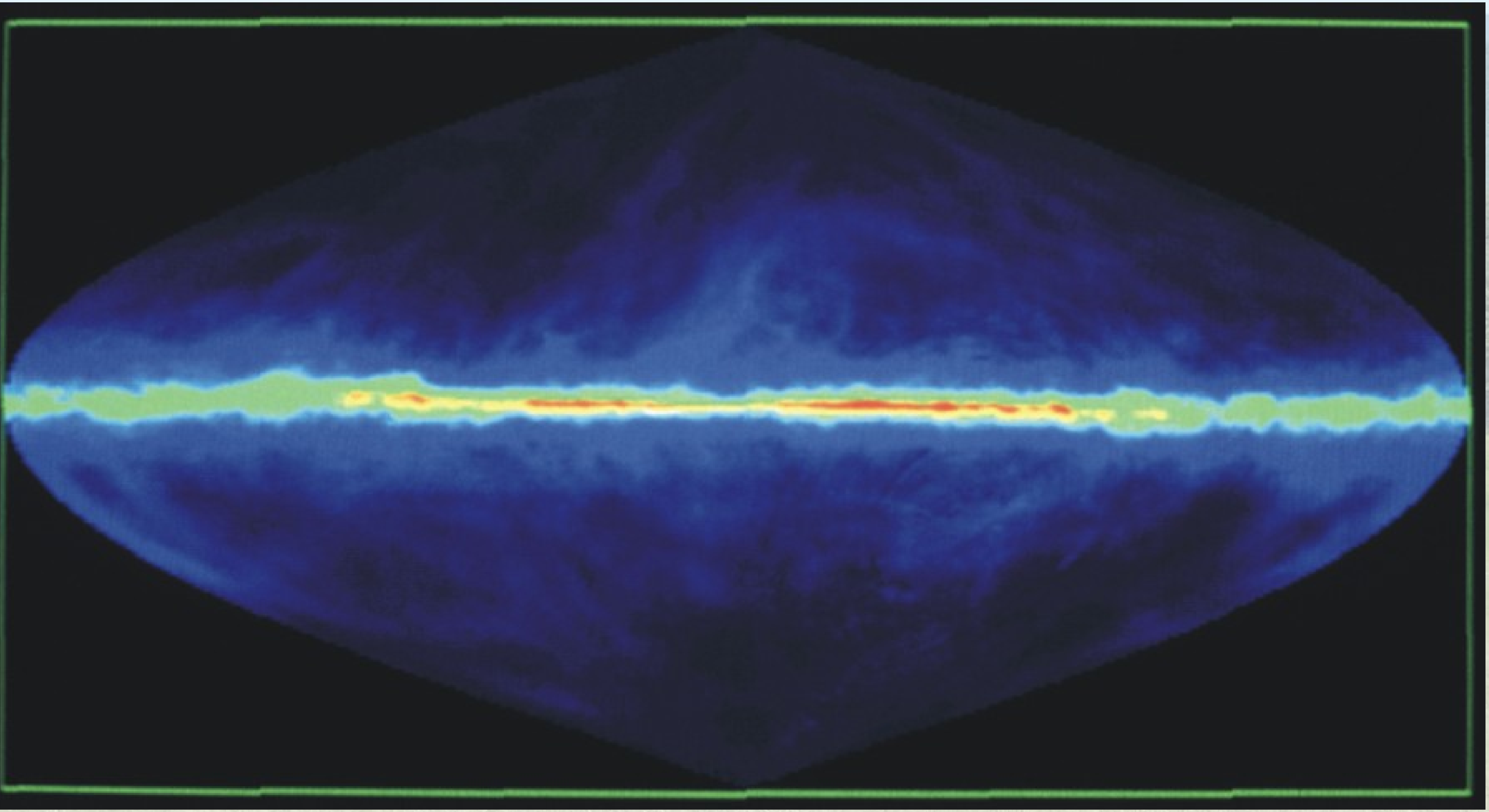


Cassiopeia A

Crab Nebula


Naval Research Laboratory
Wide-Field Radio Image of the Galactic Center
λ = 90 cm
(Kassim, LaRosa, Lazio, & Hyman 1999)
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Sgr B1
New SNR 0.3+0.0
Threads
New Feature: The Cane
Arc
Background Galaxy
Threads
Sgr A
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5
~0.5°
~75 pc
~240 light years
Tornado (SNR?)
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources
Produced by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura, & S.D. Hyman
Original data from the NRAO Very Large Array courtesy of A. Pedlar, K. Anantharamiah, M. Goss, & R. Ekers

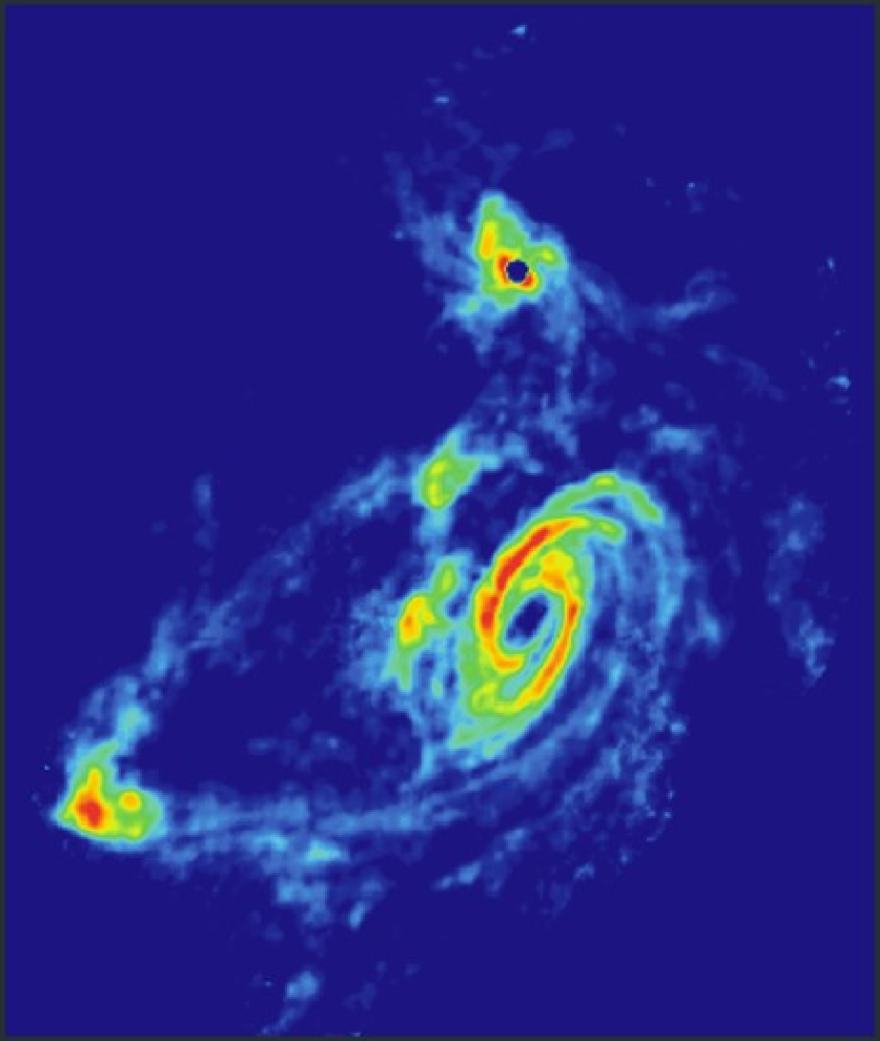
Neutral Hydrogen (HI) in galactic coordinates



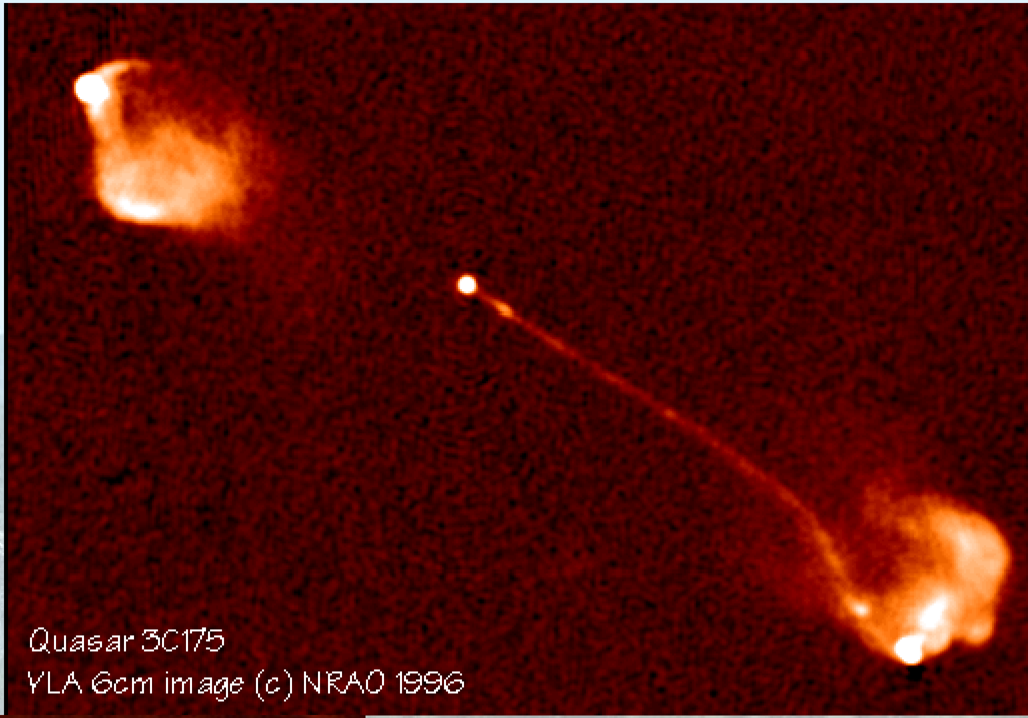
TIDAL INTERACTIONS IN M81 GROUP

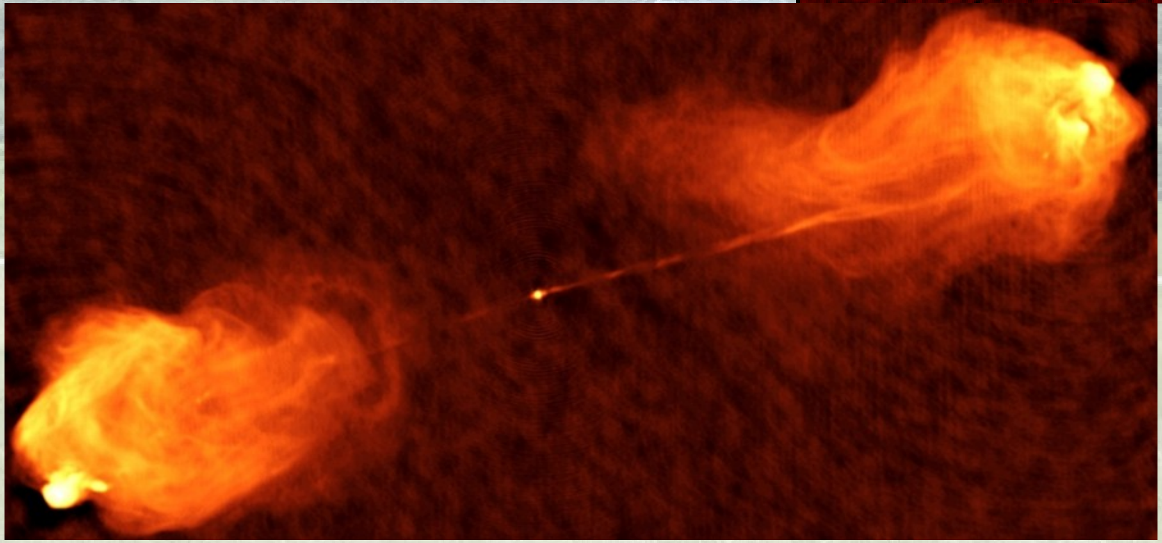
Stellar Light Distribution

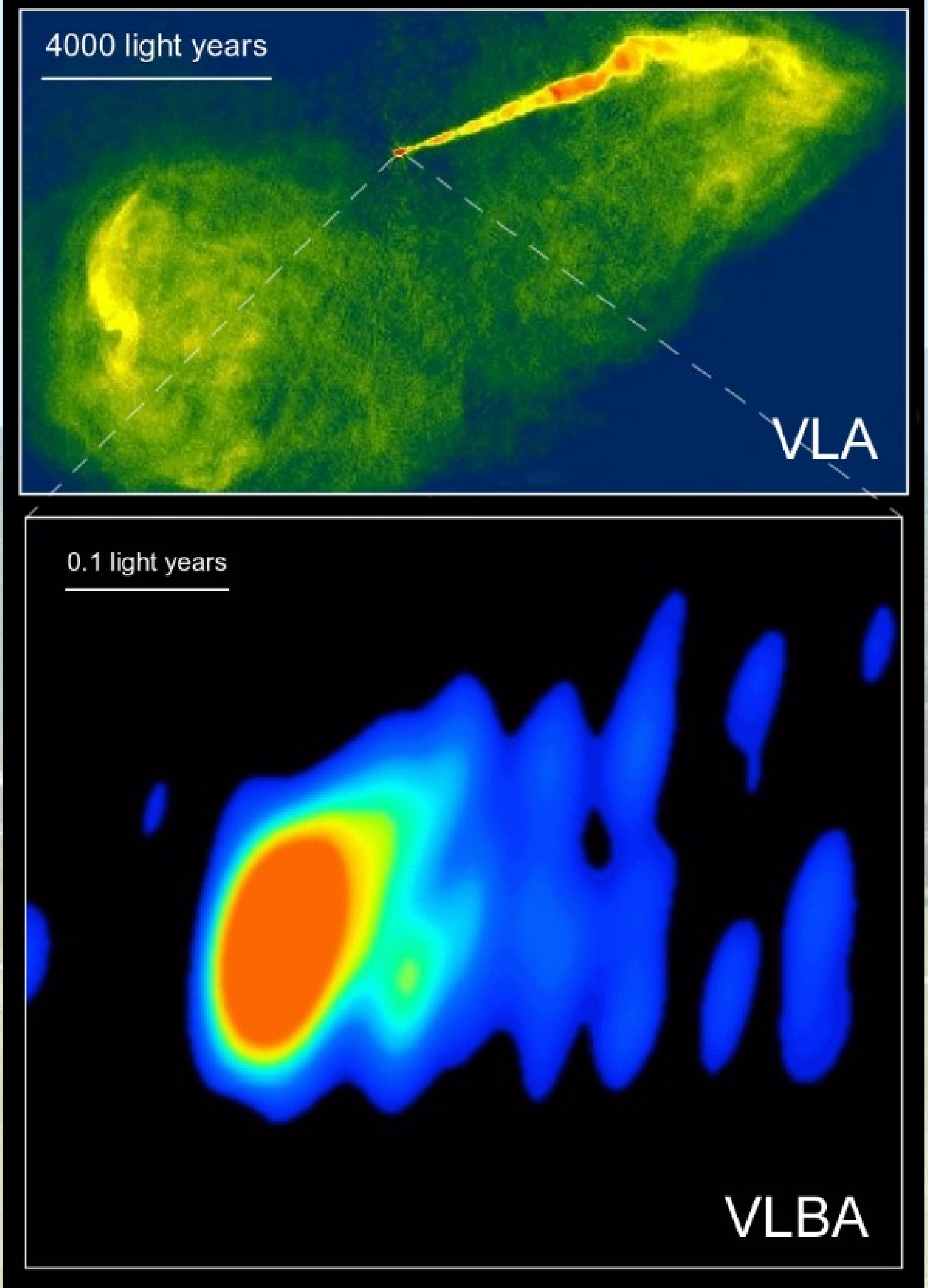
21 cm HI Distribution



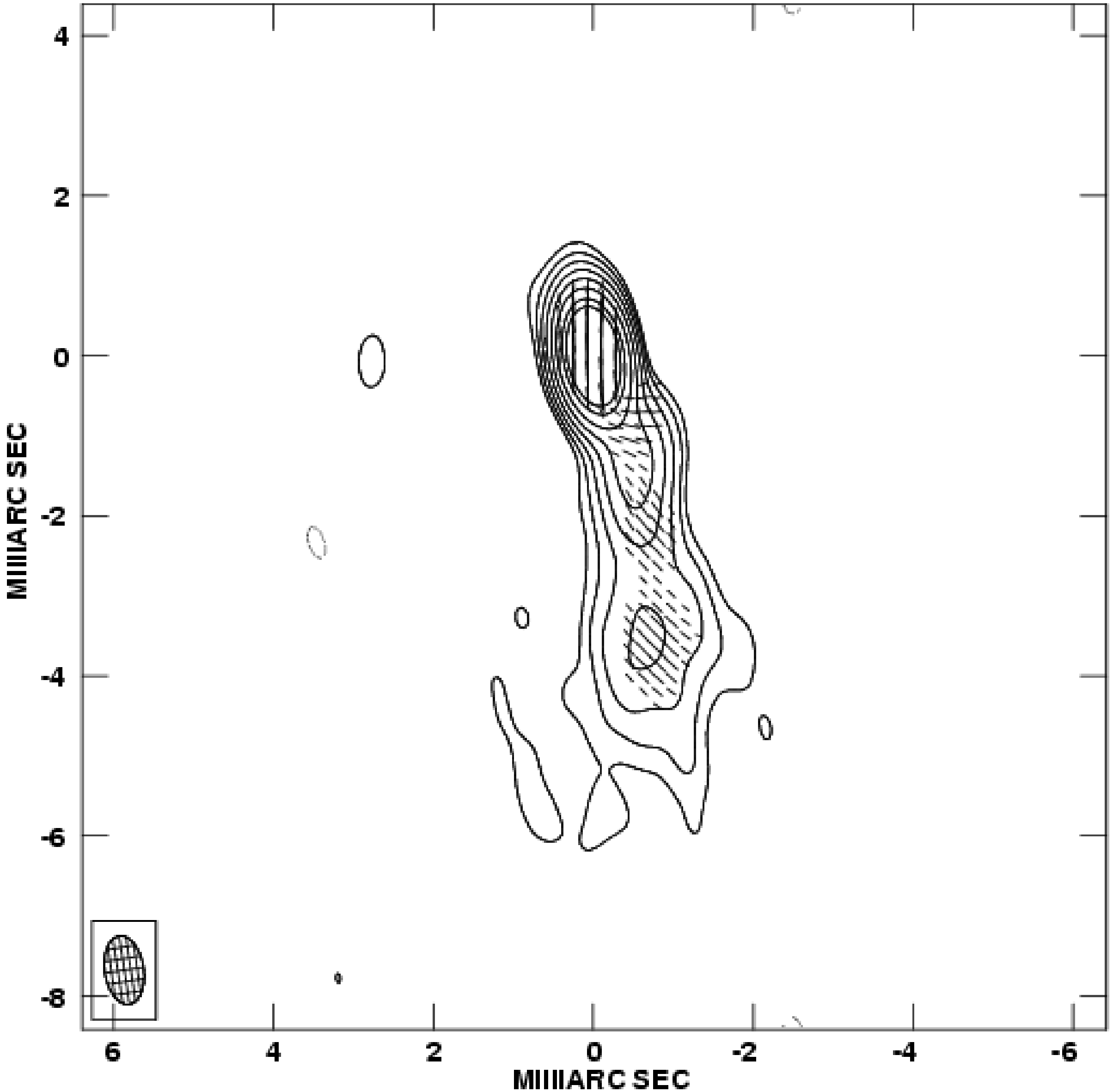
“Radio Galaxies” Lobes are 100000 l-yr across






4000 light years
VLA
0.1 light years
VLBA

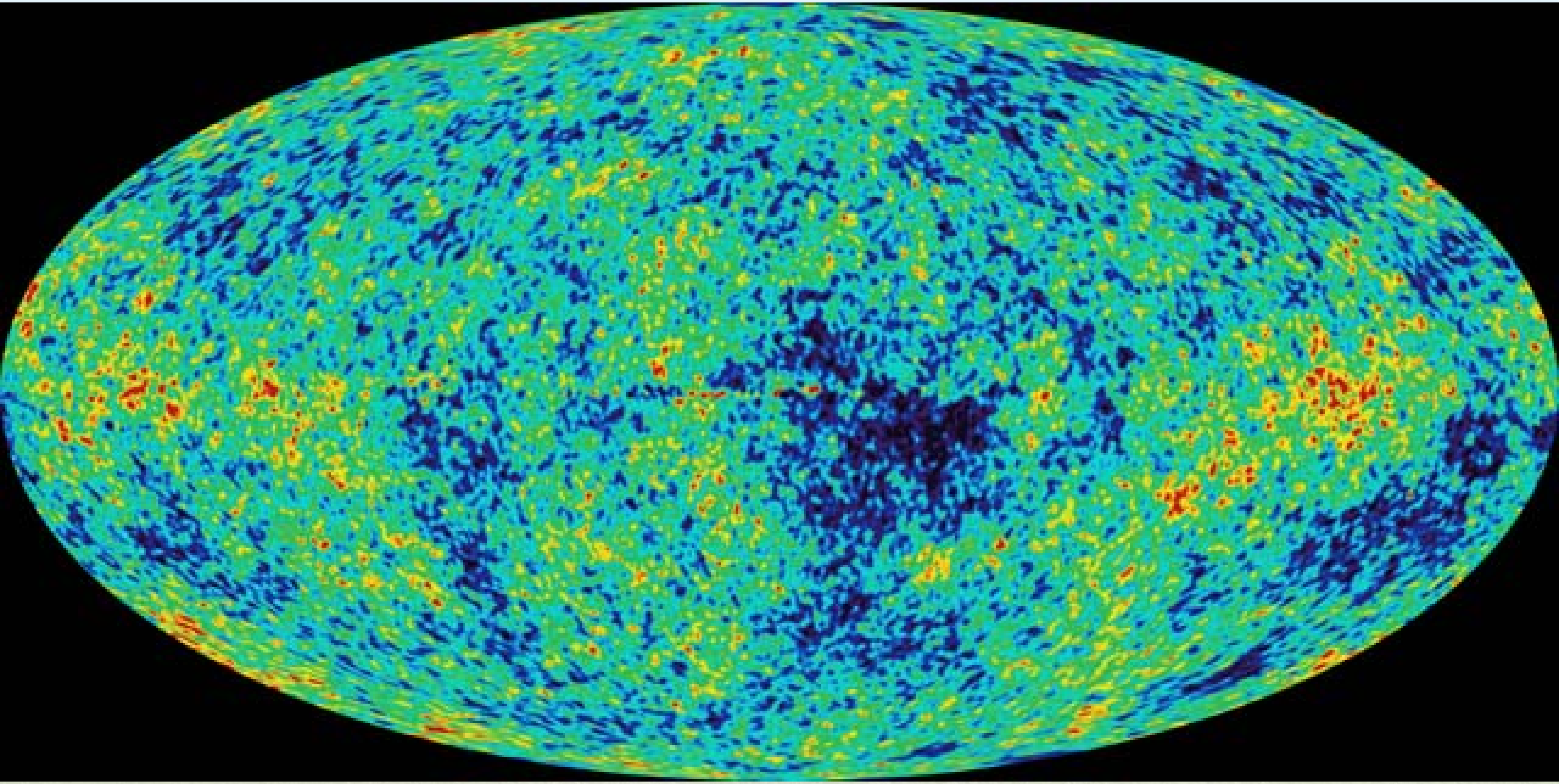
Plot file version 1 created 04-AUG-2003 20:28:00
BLLAC IPOL 15353.459 MHZ BLLAC-U-DIF.ICL001.1



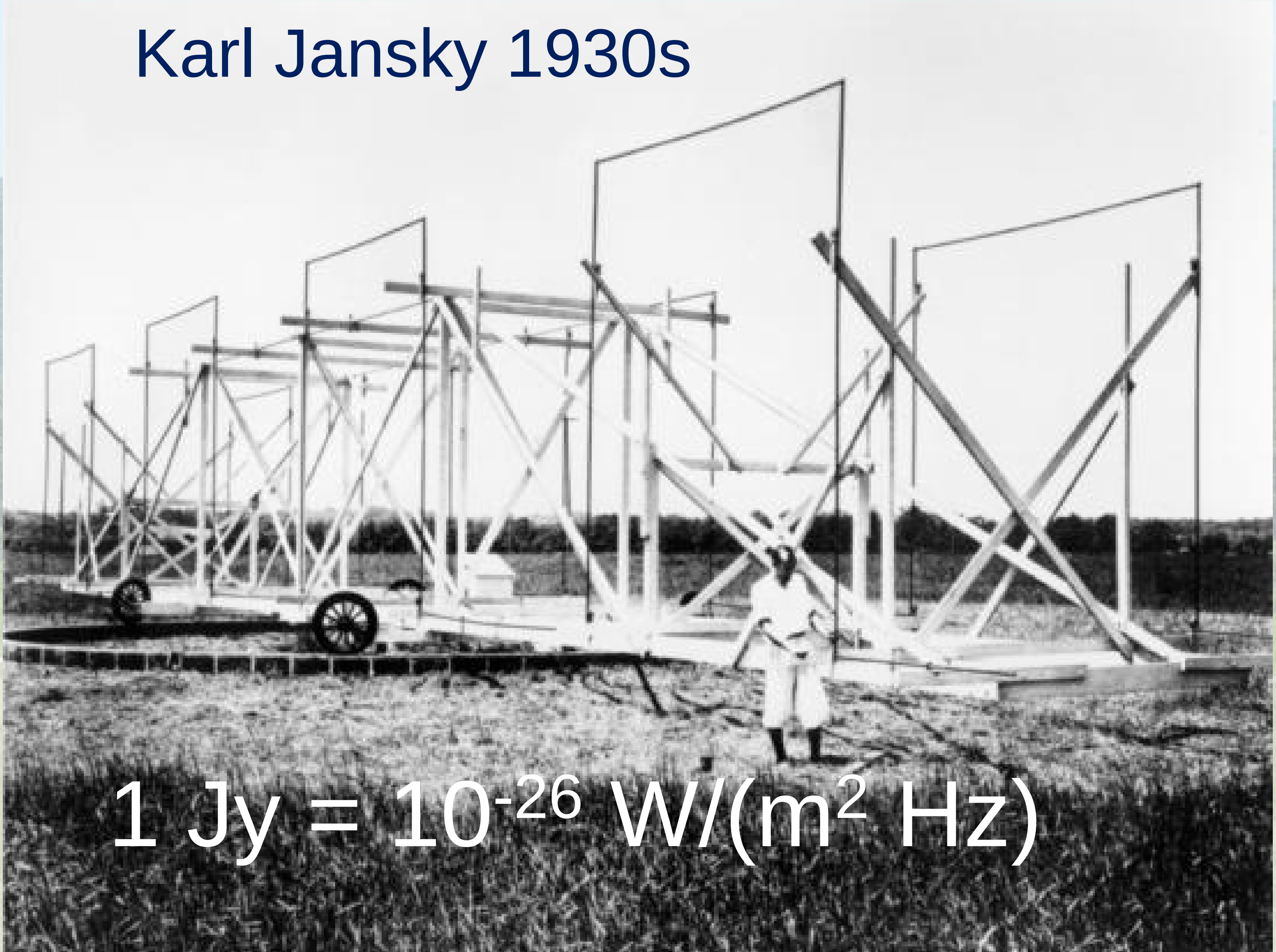
Center at RA 22 02 43.29139 DEC 42 16 39.9798
Peak contour flux = 3.5094E+00 JY/BEAM
Levs = 1.000E-02 * (-1, 1, 2, 4, 8, 16, 32, 64,
98)
Pol line 1 milli arcsec = 1.0000E-01 JY/BEAM

3C75 in radio and X-ray

Cosmic Microwave Radio Background



Telescopes

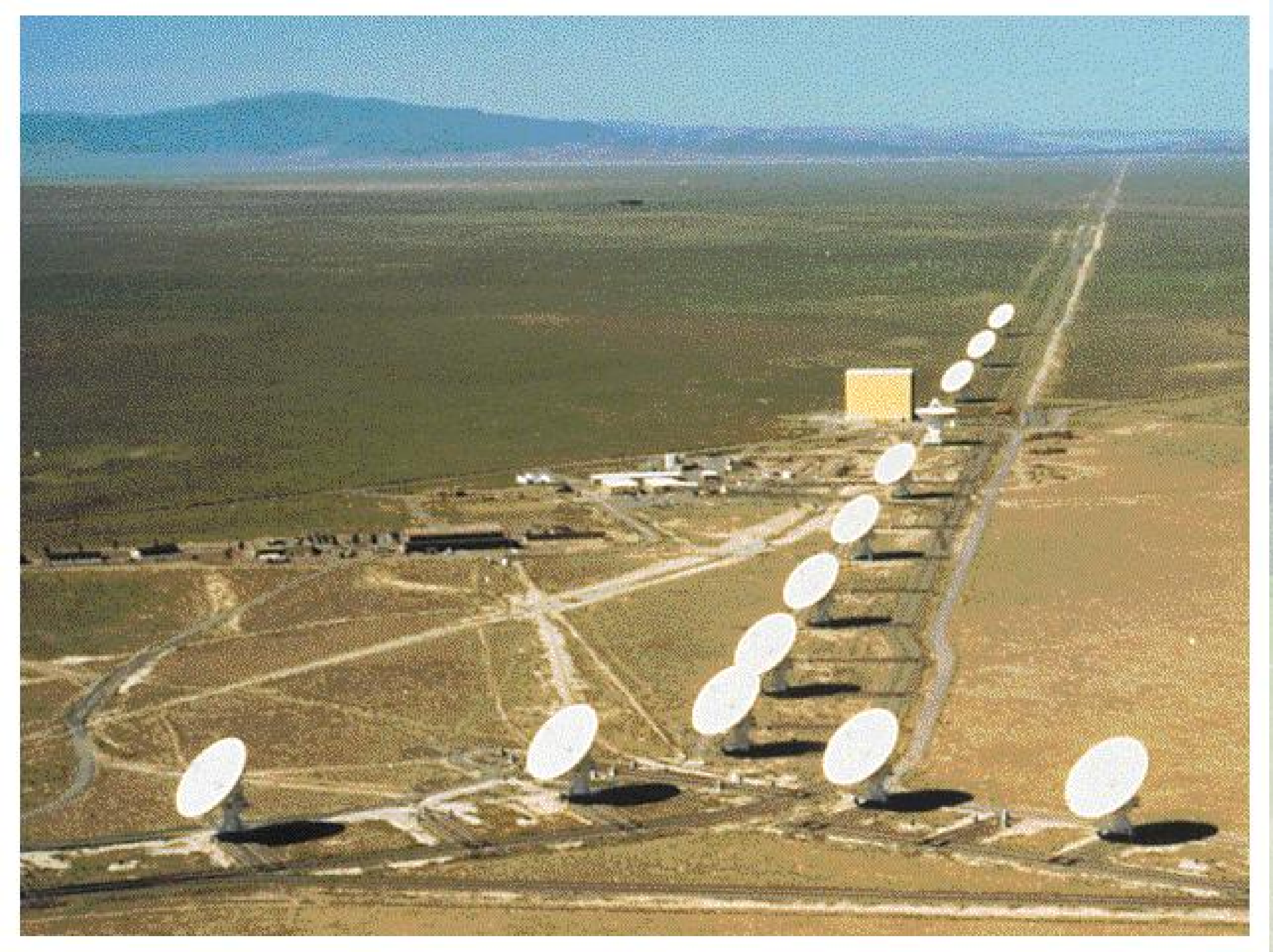


Karl Jansky 1930s

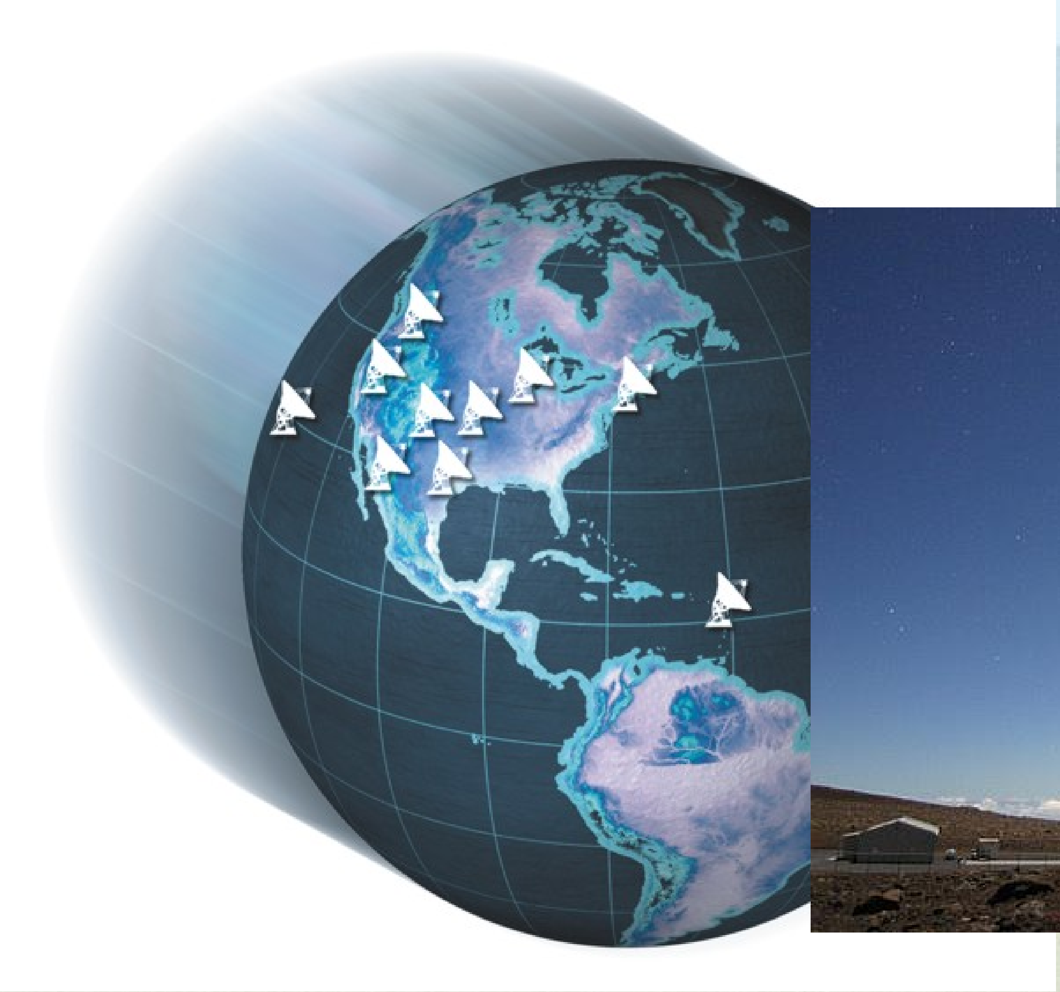
$1\ \text{Jy} = 10^{-26}\ \text{W}/(\text{m}^2\ \text{Hz})$

Arecibo (Puerto Rico) 300m (1963)

The VLA in Socorro, NM
(1975, upgraded 2010)



Very Long Baseline Array - VLBA (1994)



Robert C. Byrd Green Bank Telescope (2000) (110 m)

ALMA (Atacama Large Millimeter/Submillimeter Array) 2013

FAST: Five-hundred-meter Aperture Spherical Telescope (2016)

Radio Emission from Celestial Objects

Thermal Emission

- H II Objects: Free-Free emission

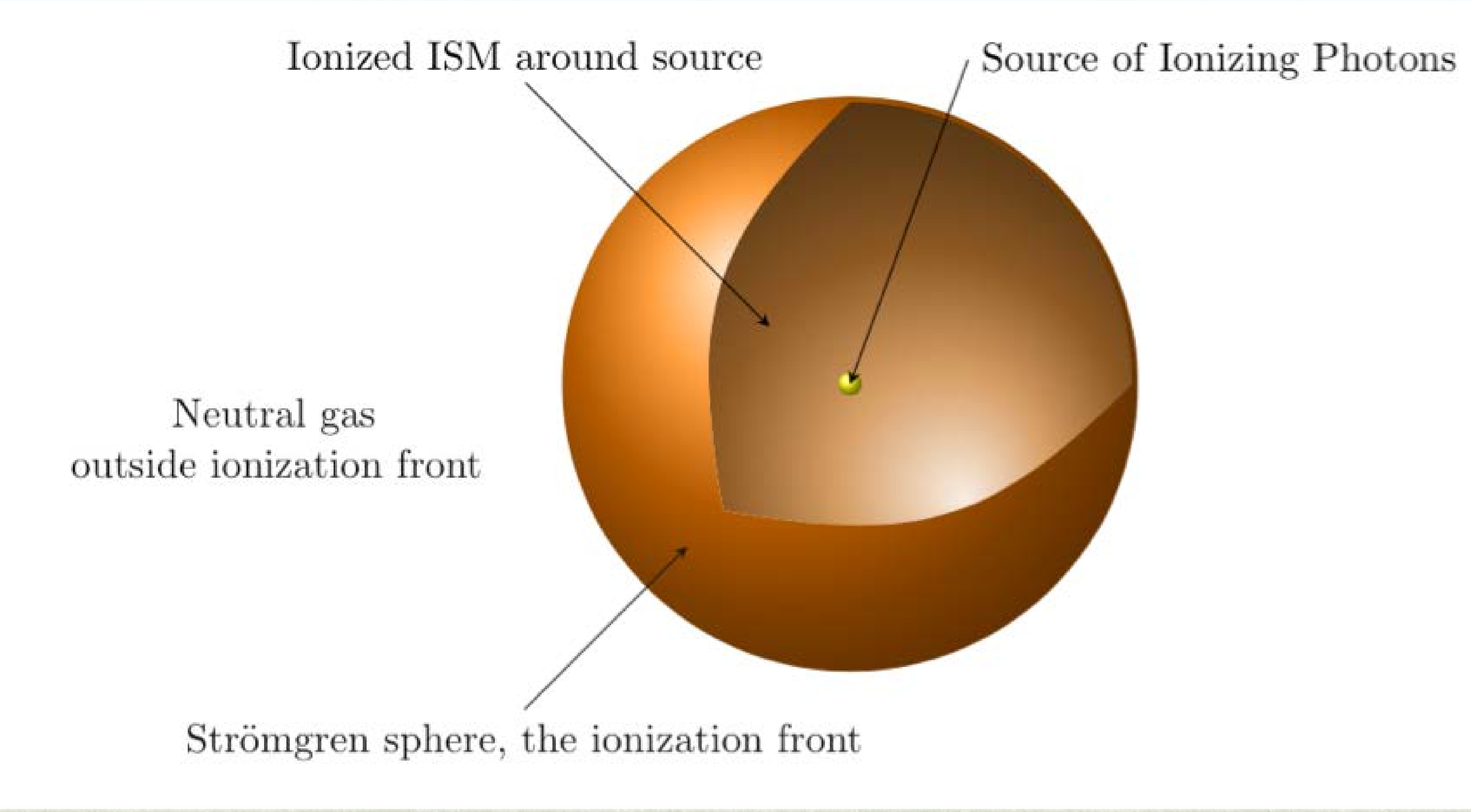
Non-Thermal Emission

- Synchrotron

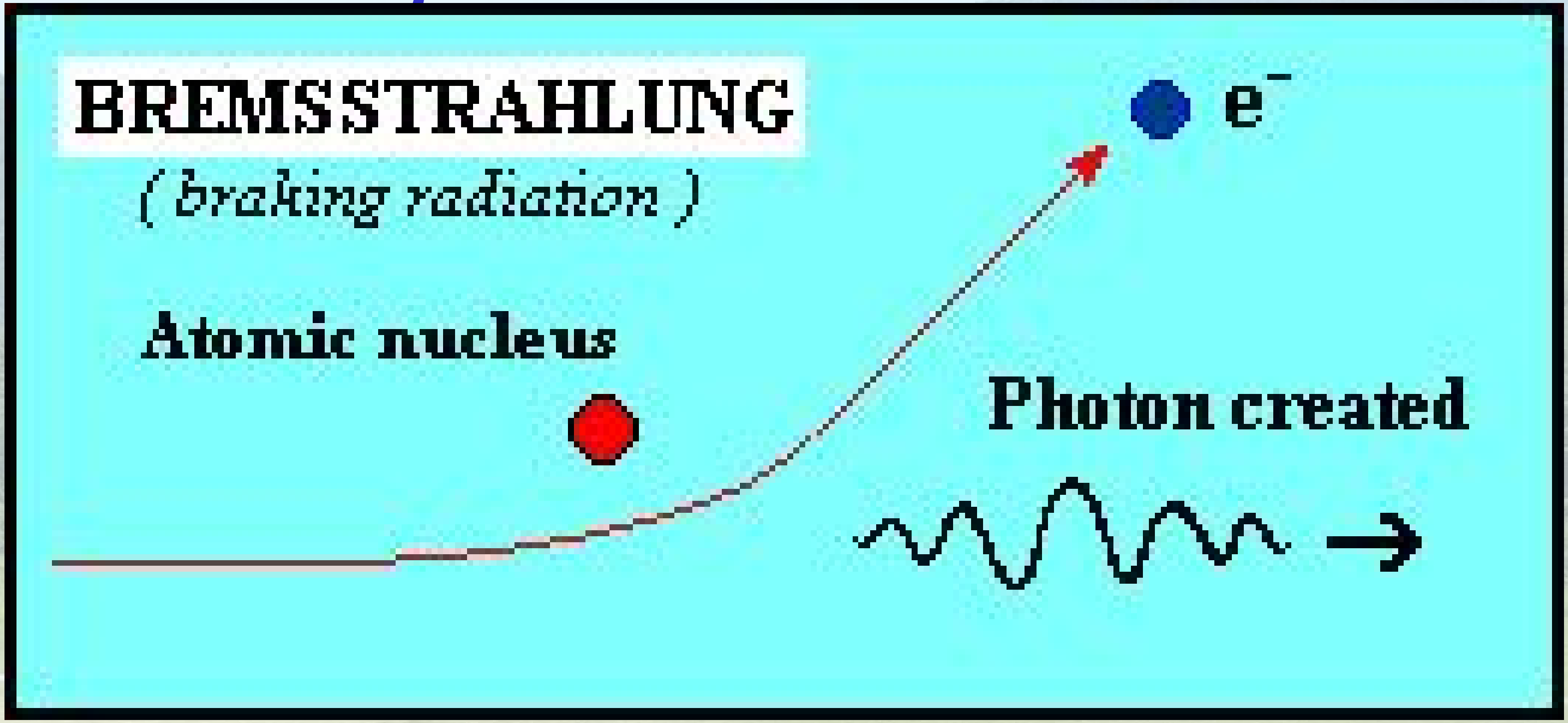
Spectral Lines

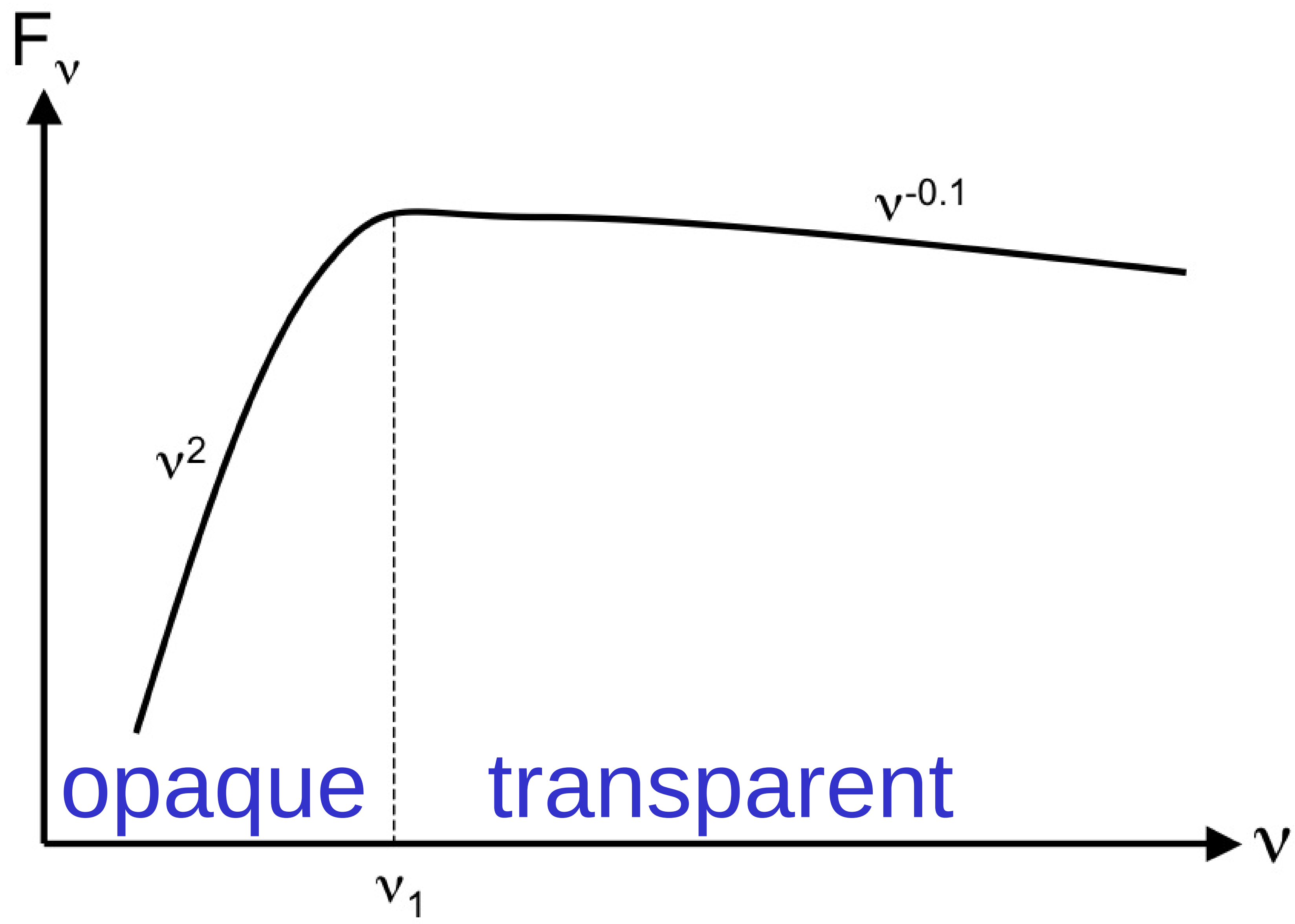
- HI, Molecules (CO)

H II regions

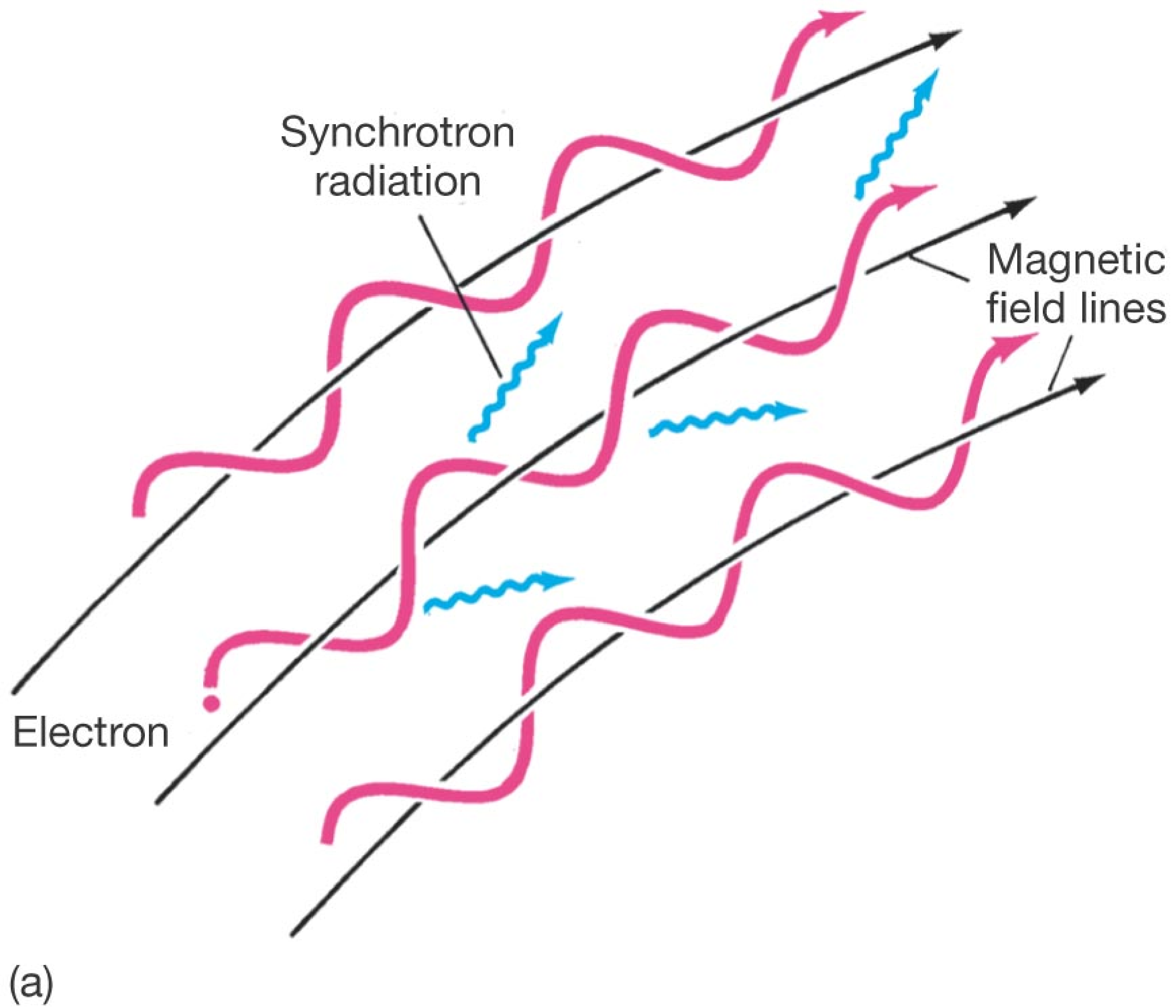

Ionized ISM around source
Source of Ionizing Photons
Neutral gas
outside ionization front
Strömgren sphere, the ionization front

Bremsstrahlung a.k.a Braking Radiation

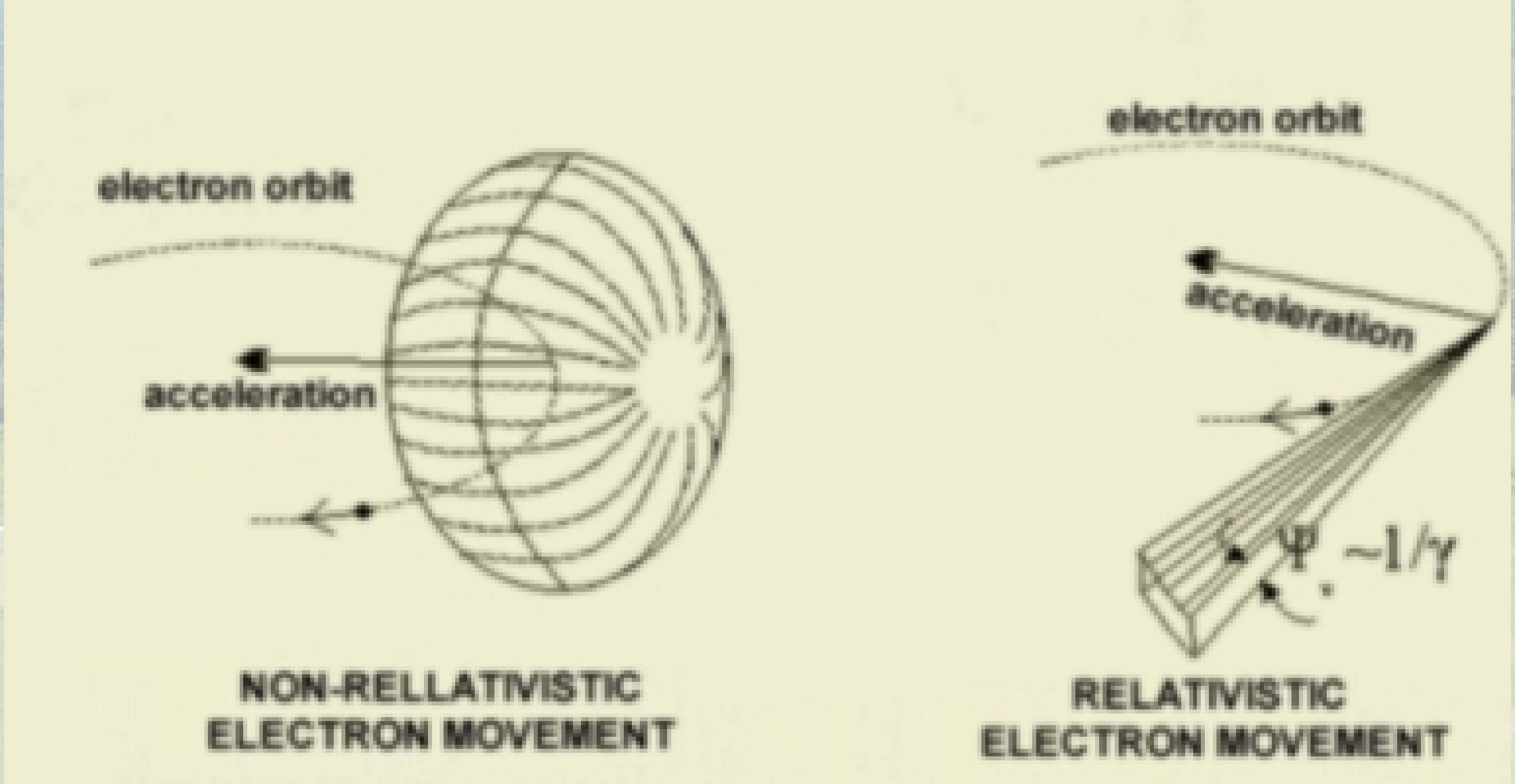


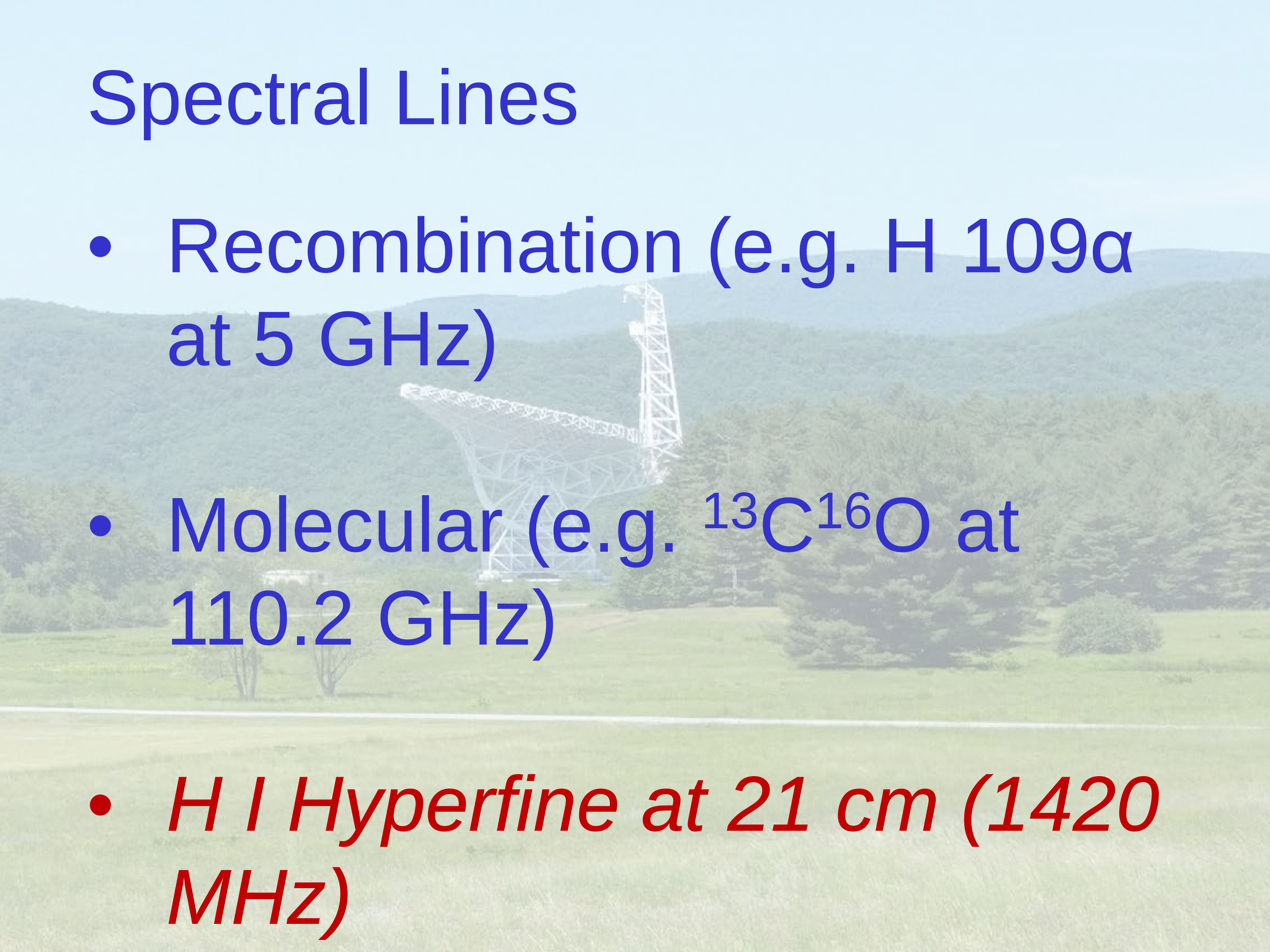

F_ν
$\nu^{-0.1}$
ν^2
opaque
transparent
ν
ν_1

Synchrotron Emission



Relativistic electrons in magnetic fields

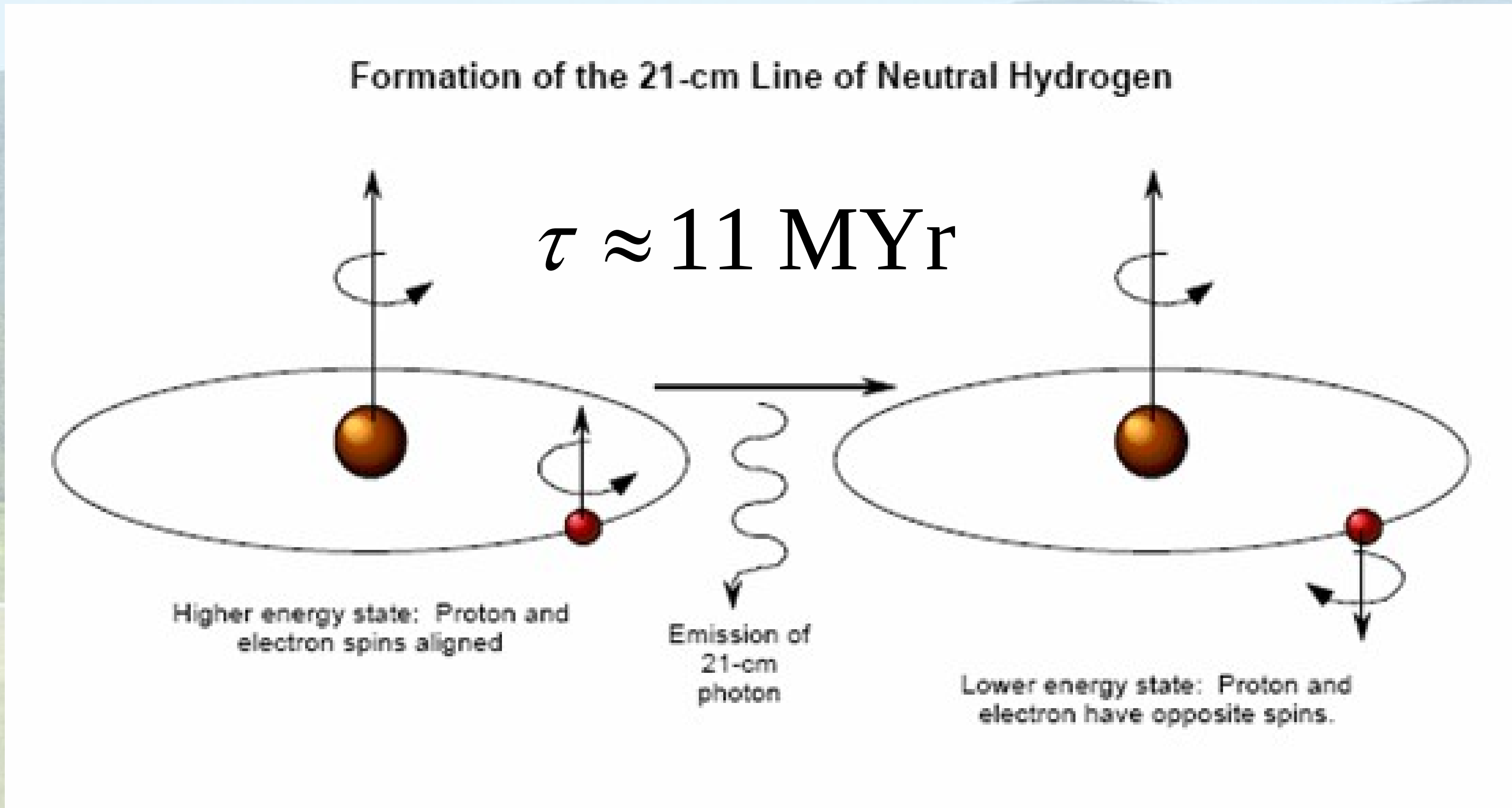




Spectral Lines

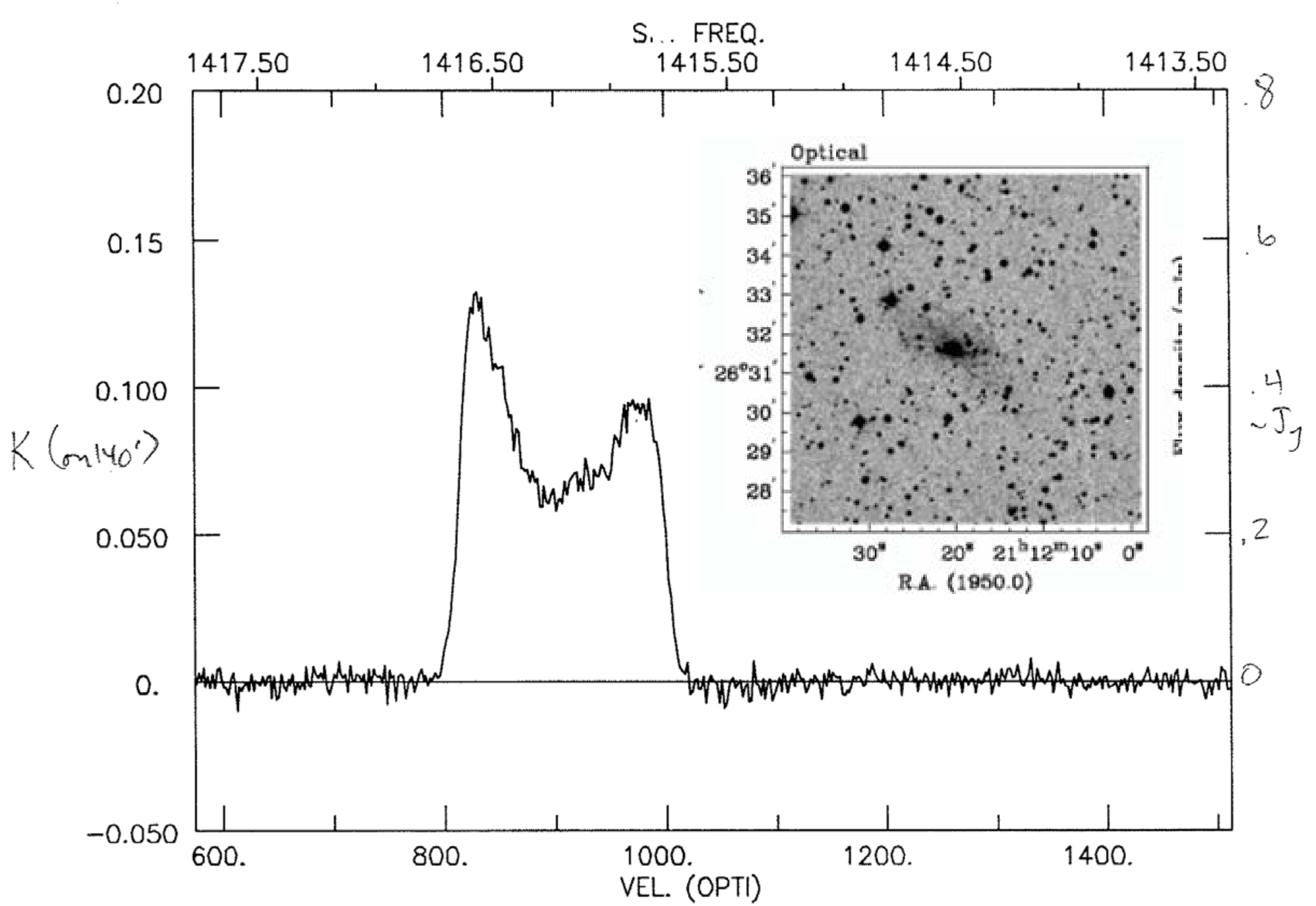
- Recombination (e.g. H 109α at 5 GHz)
- Molecular (e.g. $^{13}C^{16}O$ at 110.2 GHz)
- *H I Hyperfine at 21 cm (1420 MHz)*

21 cm <=> 1420 MHz



$$\tau \approx 11 \text{ MYr}$$

UGC 11707- spiral galaxy



Stolen from Scott Ransom (NRAO/ UV)

What do radio telescopes do?

Radio telescopes convert EM waves into output power as a function of radio freq v and time t

The astrophysical signals are *incredibly* weak and are measured in Janskys: $1\ \mathrm{Jy} = 10^{-26}\,\mathrm{W\ m^{2}\ Hz^{-1}}$

Almost all of the power we measure is ***noise***

We usually talk about power in terms of temperature as the units are better, as converted using Boltzmann's constant:

$$k_B = 1.38 \times 10^{-23}\,\mathrm{J\ K^{-1}}$$

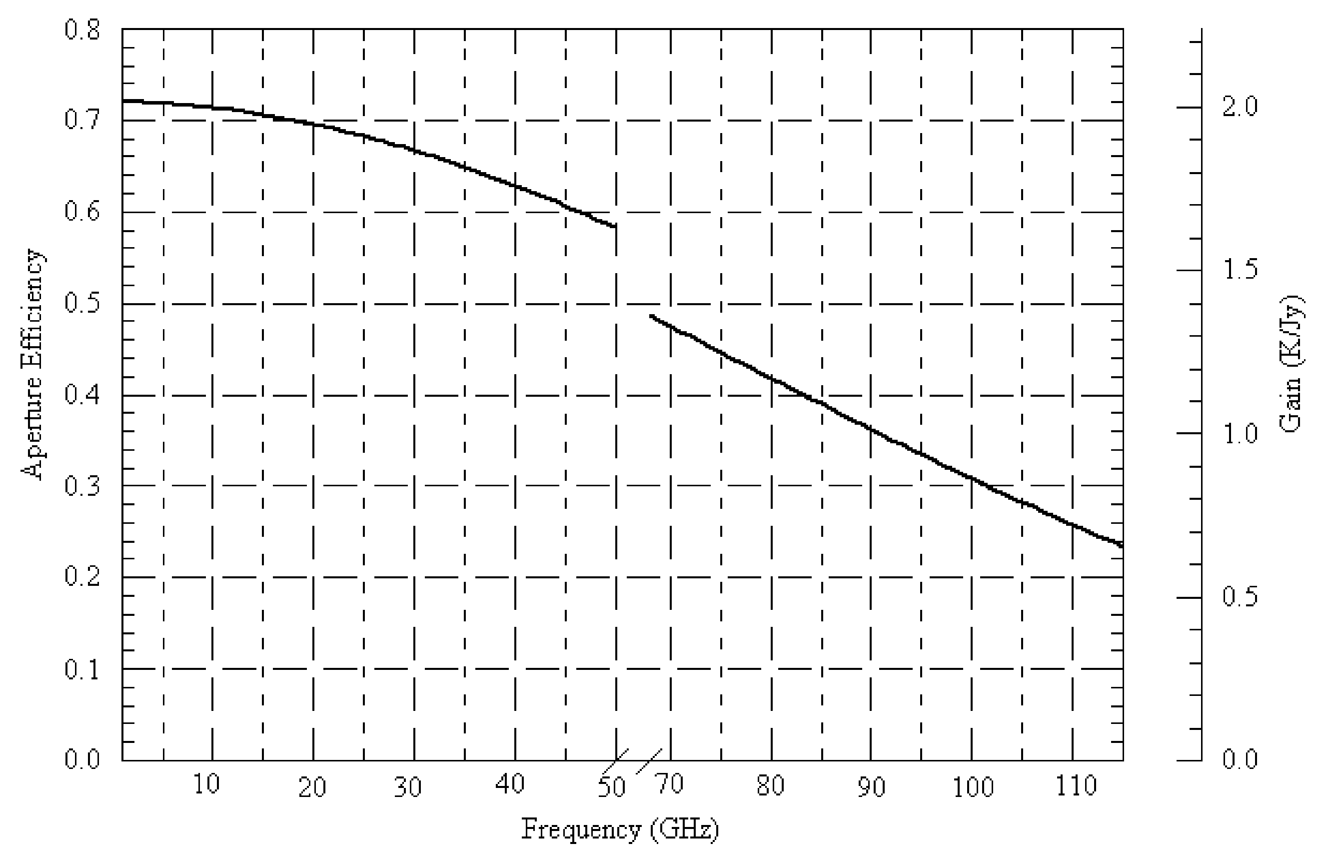
Radio Telescope Characteristics (stolen from Jessica Rosenberg)

- The *power* collected by an antenna is approximately:!

$$P = S * A * \Delta\nu$$

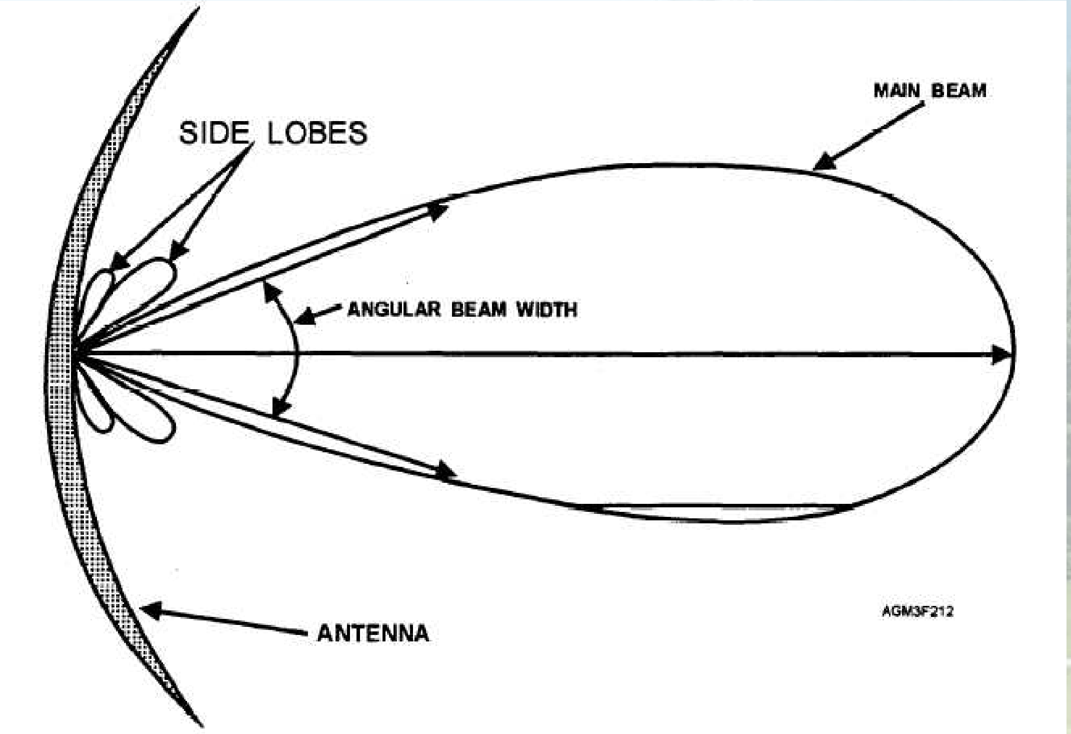
- S = flux at Earth, A = antenna area, $\Delta\nu =$ frequency
- interval or bandwidth of measured radiation!
- The *gain* of an antenna is given by: $G = 4\pi A / \lambda^2$
- *Aperture efficiency* is the ratio of the effective collecting area to the actual collecting area!

Aperture Efficiency v. Freq (GBT, theoretical)

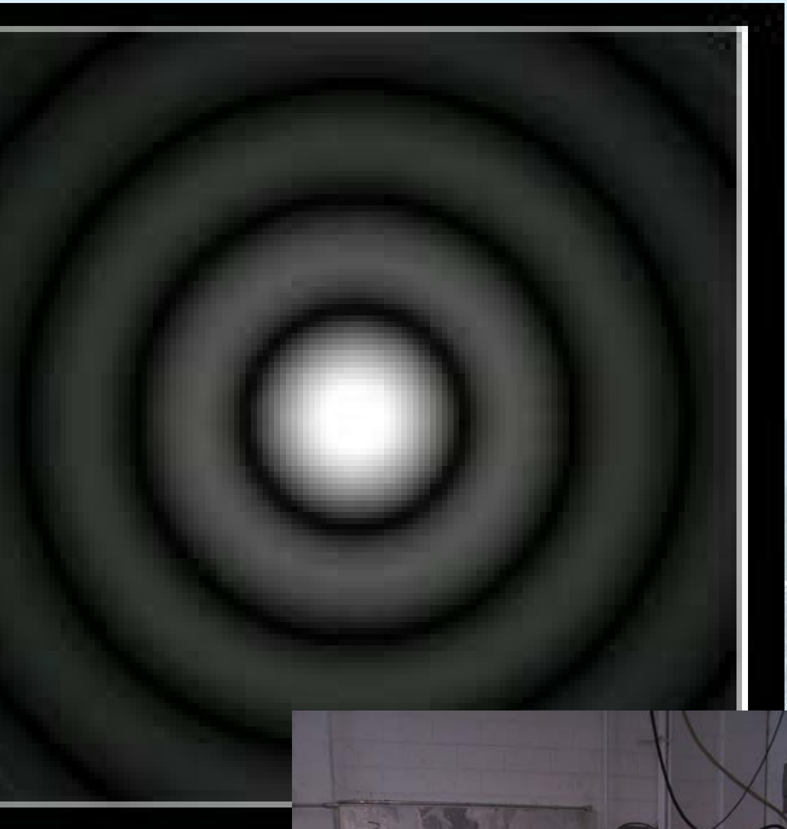


Beam width and sidelobes

Imagine sending power OUT of an antenna- how would that power distribute itself on the sky?

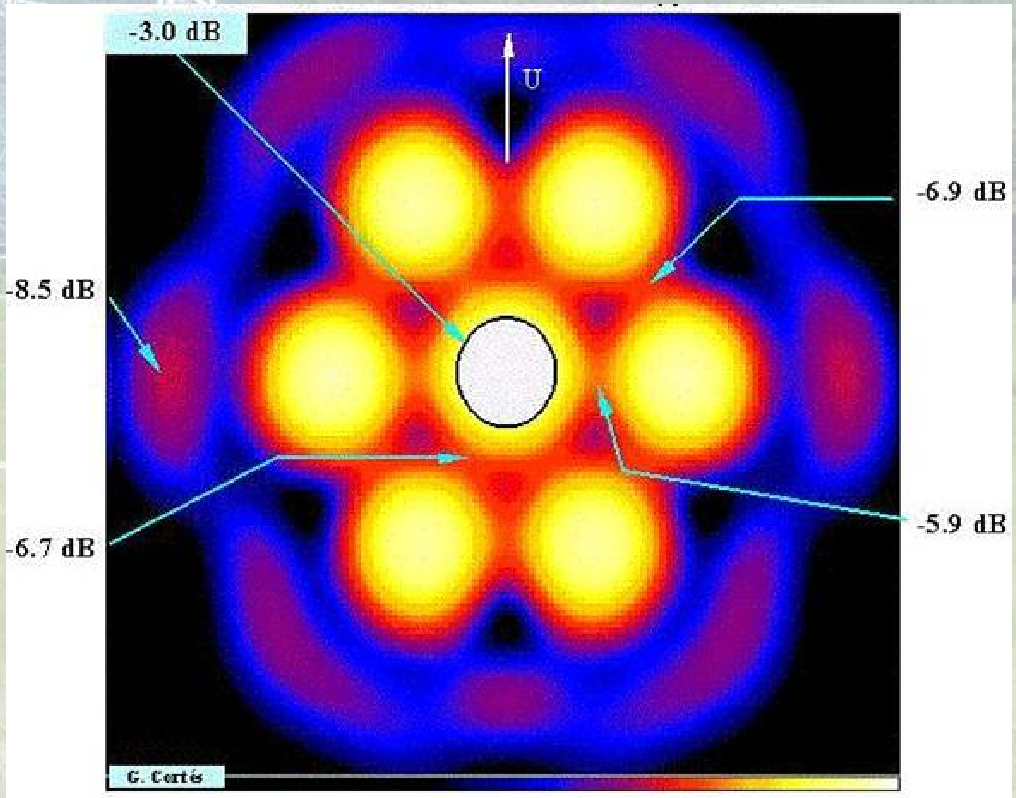


Big apertures = smaller beams=better resolution



Circular aperture

ALFA beam



Radio Telescope Characteristics

Temperatures

- In radio astronomy power is often measured in “temperature” - the equivalent temperature of a blackbody producing the same power!
- **System temperature T_{sys}**: temperature of blackbody producing same power as telescope and instrumentation without a source (T_r is kept low ~20K)

$$T_{\mathrm{s}} = T_{\mathrm{cmb}} + T_{\mathrm{rsb}} + \Delta T_{\mathrm{source}} + [1 - \exp(-\tau_{\mathrm{A}})]T_{\mathrm{atm}} + T_{\mathrm{spill}} + T_{\mathrm{r}} + \cdots$$

Radio Telescope Characteristics

Temperatures

- **Brightness temperature:** Flux density per unit solid angle of a *source* measured in units of equivalent blackbody temperature- non thermal sources often have extremely high **T_B**

$$T_\mathrm{b}(\nu) \equiv \frac{I_\nu c^2}{2k\nu^2}.$$

I is the spectral brightness or intensity

Radio Telescope Characteristics

Temperatures

- **Antenna temperature:** The flux density transferred to the receiver by the antenna. Some of the incoming power is lost, represented by the aperture efficiency!

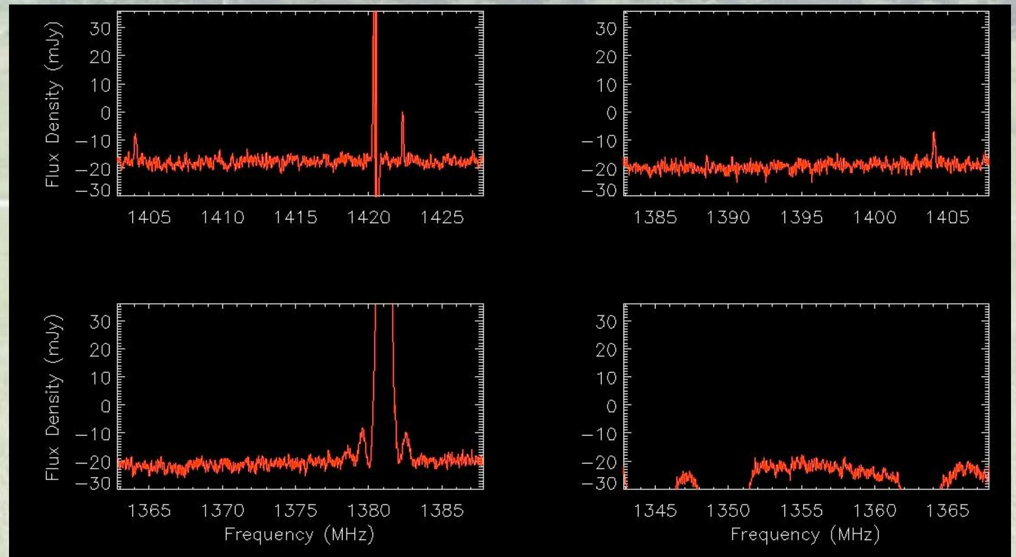
$$P_\nu = kT$$

Nyquist approximation

$$\boxed{T_{\mathrm{A}} \equiv \frac{P_\nu}{k}.}$$

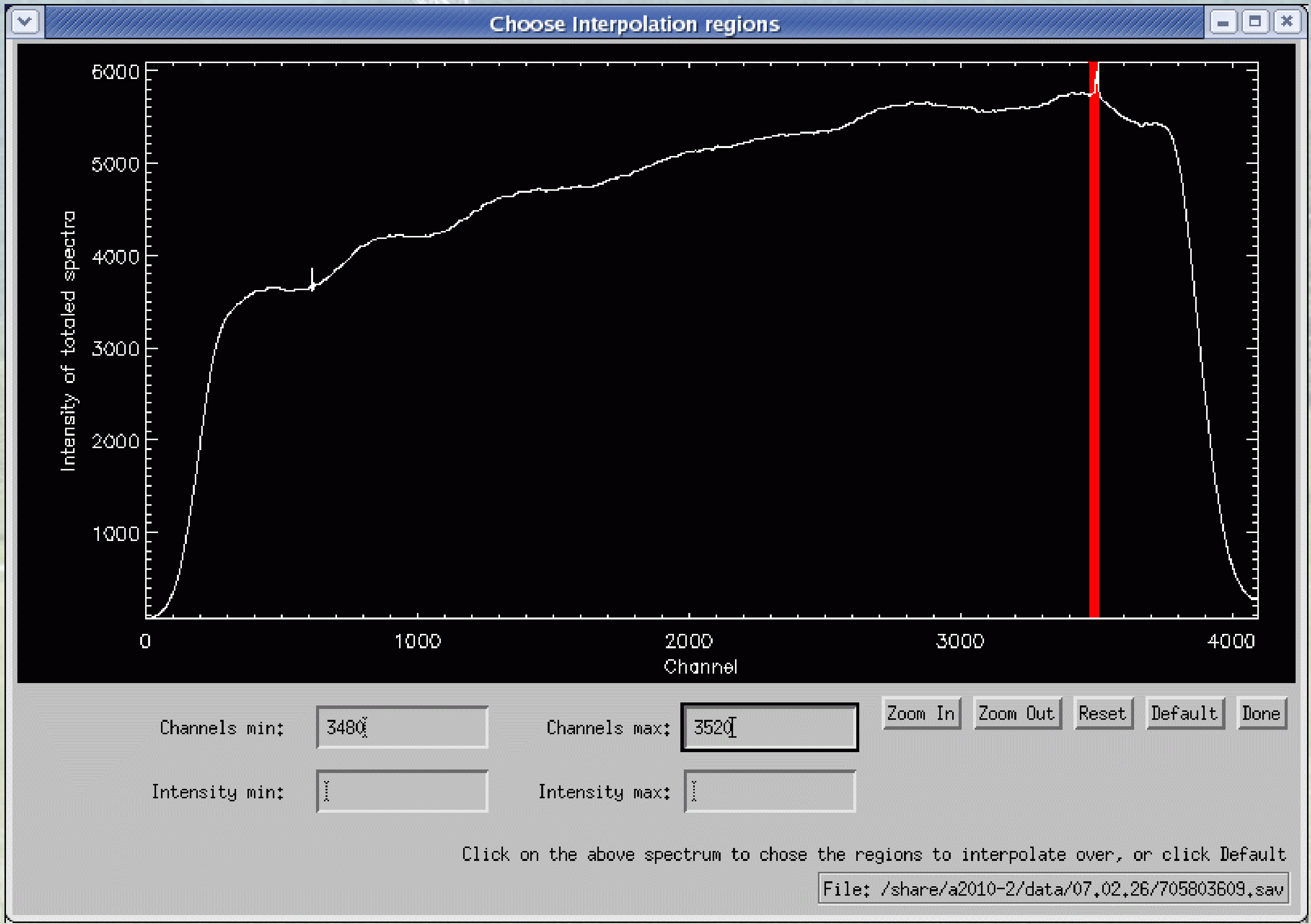
Bandpass

- The frequency response: sensitivity per *channel*
- Separated into N channels that have individual $\Delta\nu$



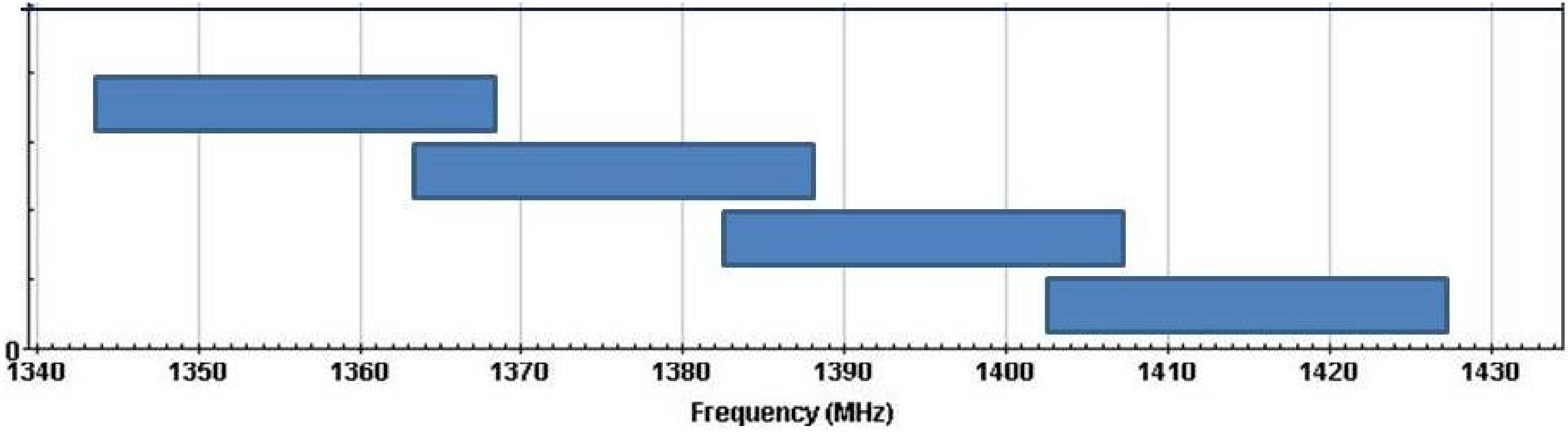
Bandpass

- Sensitivity loss at either end is typical: usually discarded



WAPP search mode

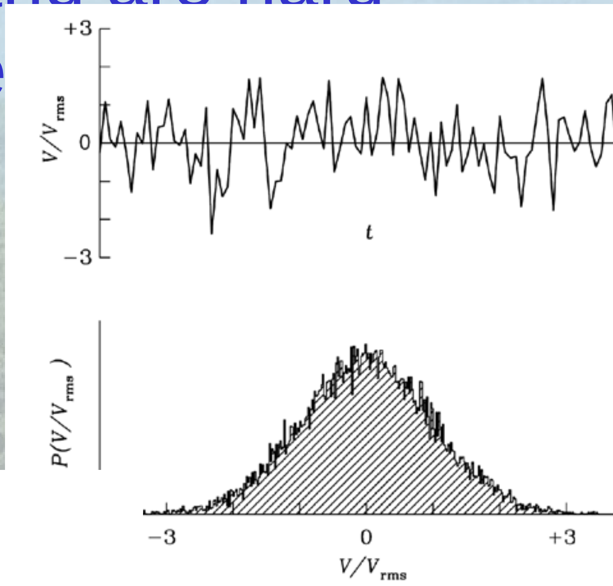
Since we do not know the redshift of our targets, we configure the WAPP spectrometer so that each quadrant (or "board" in WAPP-speak) covers a 25 MHz bandpass. We then set the center frequency of the boards so that they are offset by 20 MHz, yielding a total coverage of about 85 MHz, from ~1343 MHz to ~1428 MHz.



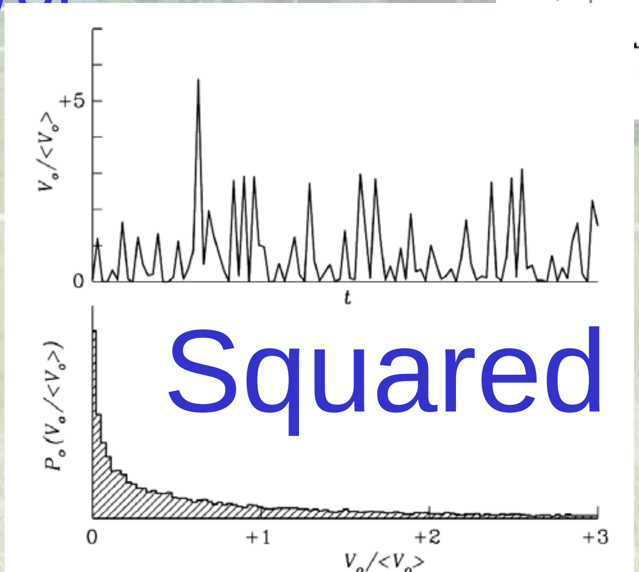
This shows the WAPP bandpass setup for a single polarization; the WAPPS record both polarizations separately, and normally we average them right away.

• Radiometers

- Antennas produce voltages
- Those voltages have mean of 0 and are hard to average to a measurable value



- Radiometers “detect” a signal, typically by squaring it so that it can be measured and/or integrated



Squared voltages

Radiometers

- Band-limited signal voltages enter
- Nyquist-sampled, it has N = 2Δv samples per sec. (i.e. sample rate is twice the bandwidth)
- Square-law detector squares voltages
- Integrator averages them. Becomes more gaussian with time via central limit theorem.
- Standard deviation goes down as $N^{1/2}$

Integrate for time τ

The RMS error on the measured noise temperature of a signal (i.e. Tsys) is:

$$\sigma_T \approx \frac{T_{\rm s}}{\sqrt{\Delta\nu\,\tau}}$$

Observing Schemes! (via j.r.)

- Position switching helps remove systematics in data!
- Reduced spectrum = (ON-OFF)/OFF!
- – ON: Target source observation!
- – OFF: blank sky observed over the same altitude and azimuth path traveled by target (on source). !
- – corrections for local environmental noise as well as background sky noise !
- Two polarizations can be compared to identify RFI or
- averaged to improve signal for an unpolarized source!

ALFALFA Observing Technique: HI 21 cm Observing in Action

- **Drift scan:** telescope is fixed, the position change is driven by the rotation of the Earth!
- Baseline shape is removed using spectra that are adjacent in time and space!
- Because the telescope does not move, the systematic noise does not change making the data easier to correct!

This slide is the final slide

Happy Fishin’ y’all