Introduction to Radio Astronomy

Laura Spitler
Lise Meitner Research Group Leader
Max-Planck-Institut für Radioastronomie

Unifying view on cosmic interacting matter
Bad Honnef
21 January 2026

MAX-PLANCK-GESELLSCHAFT

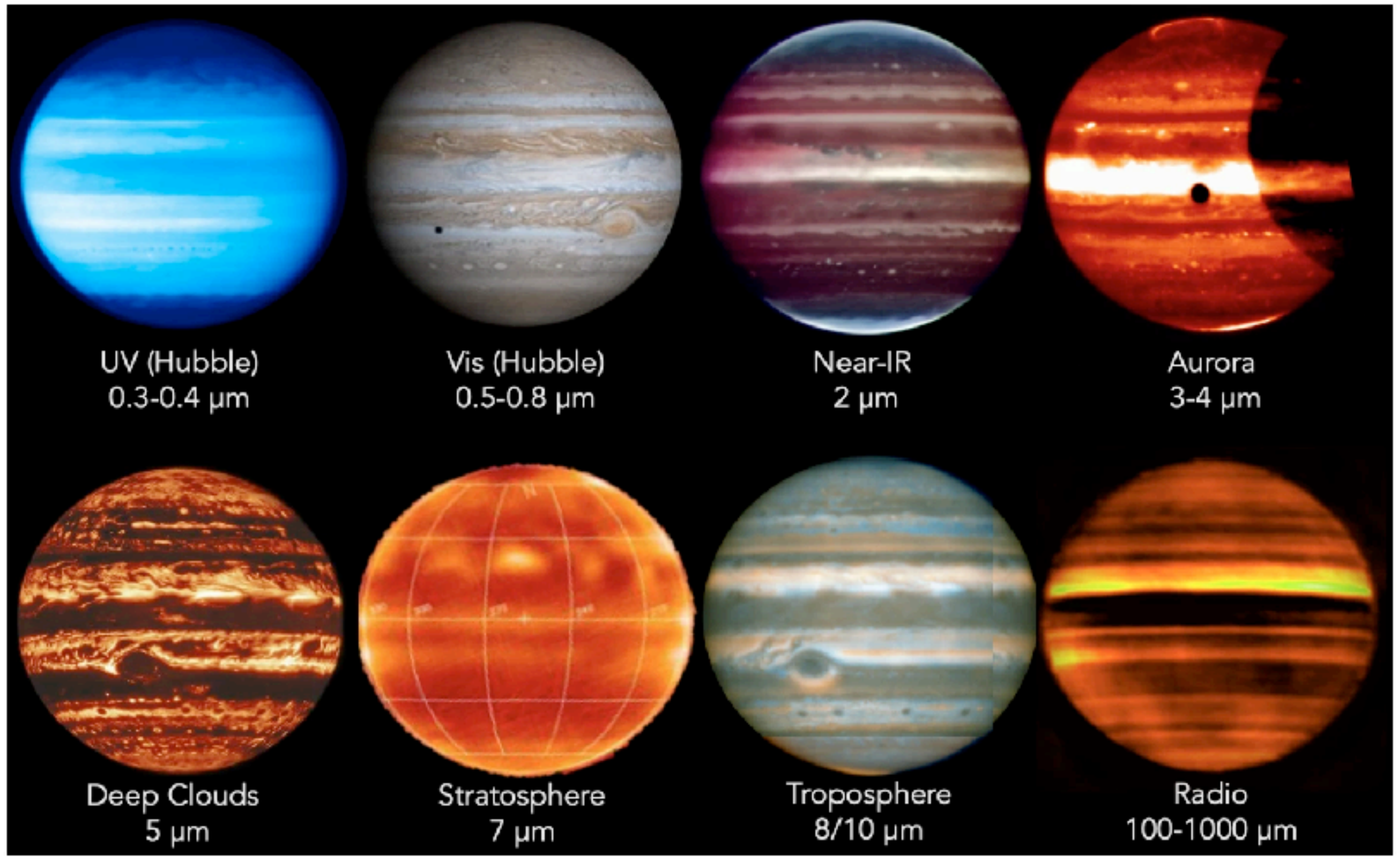
Max-Planck-Institut
für Radioastronomie

Talk agenda

- Radio astronomy basics
- Emission mechanisms
- Pause for discussion / questions
- Radio telescopes
- Radio frequency interference
- Science example: Kolmogorov turbulence in the ISM
- Discussion / questions

Multi-wavelength astronomy

Jupiter



Milky Way galaxy

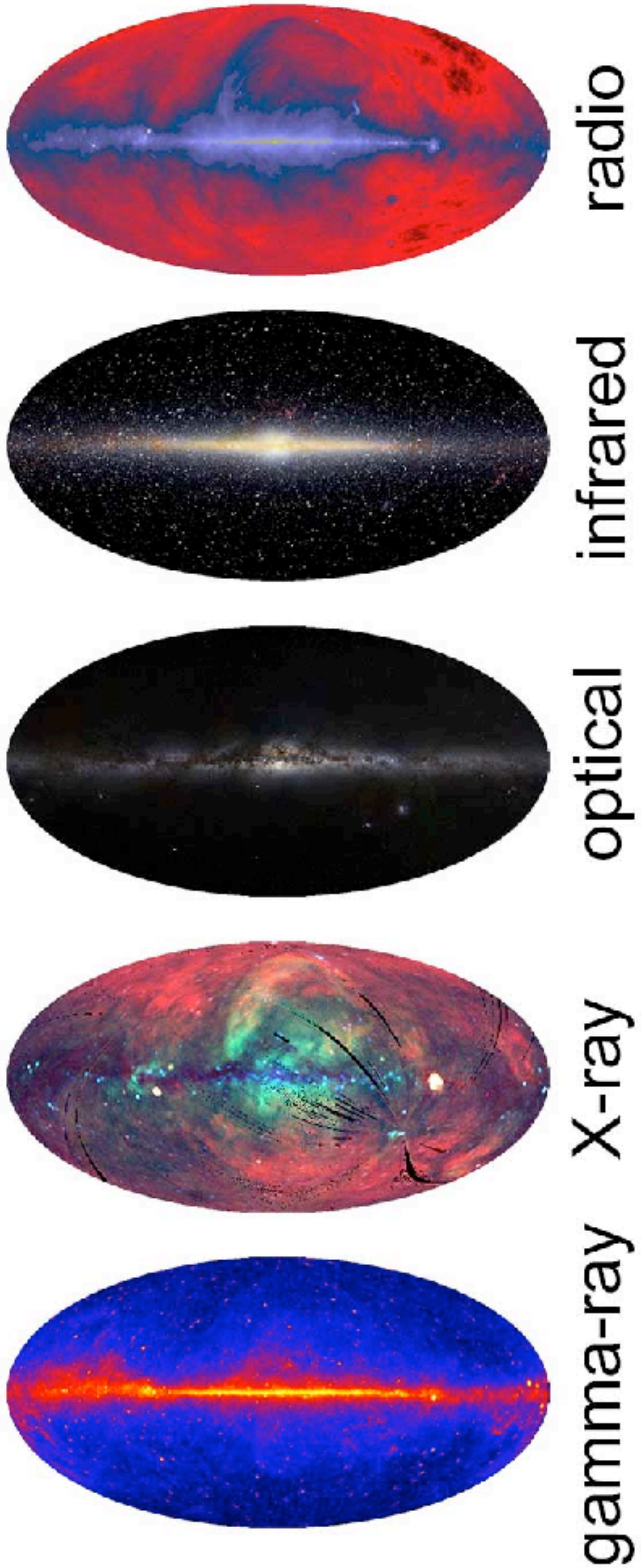


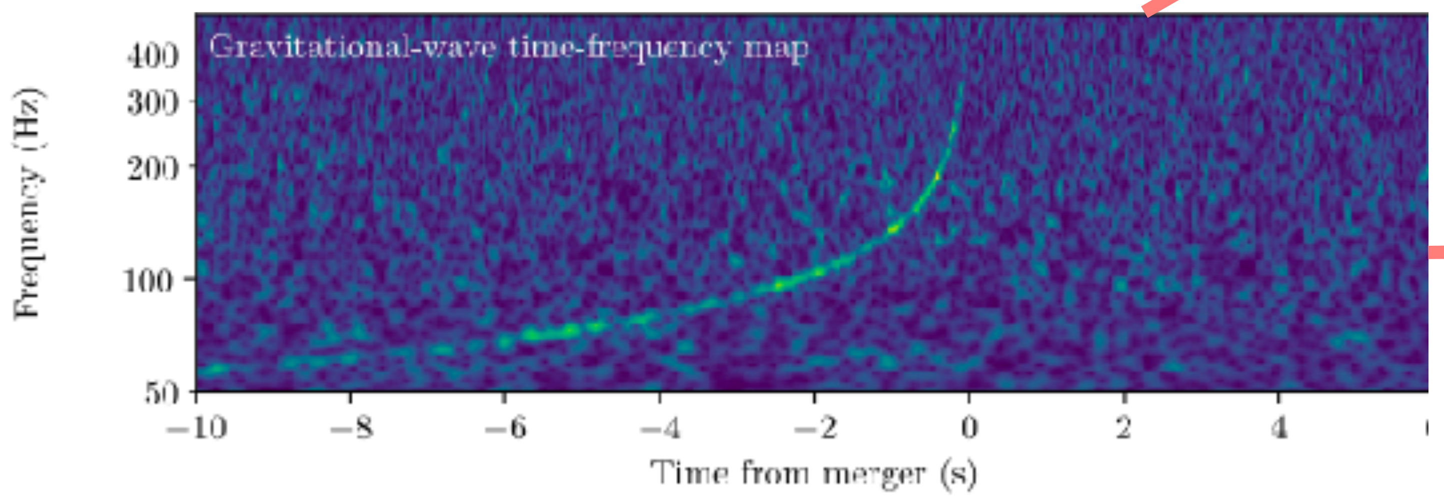
Image credits:
(left) Fletcher et al, 2023
(right) Credits: radio: Haslam et al. 1982; infrared: NASA; optical: ESO/S. Brunier;
X-ray: Max Planck Institute for Extraterrestrial Physics and S. L. Snowden;
gamma-ray: NASA/DOE/Fermi LAT Collaboration

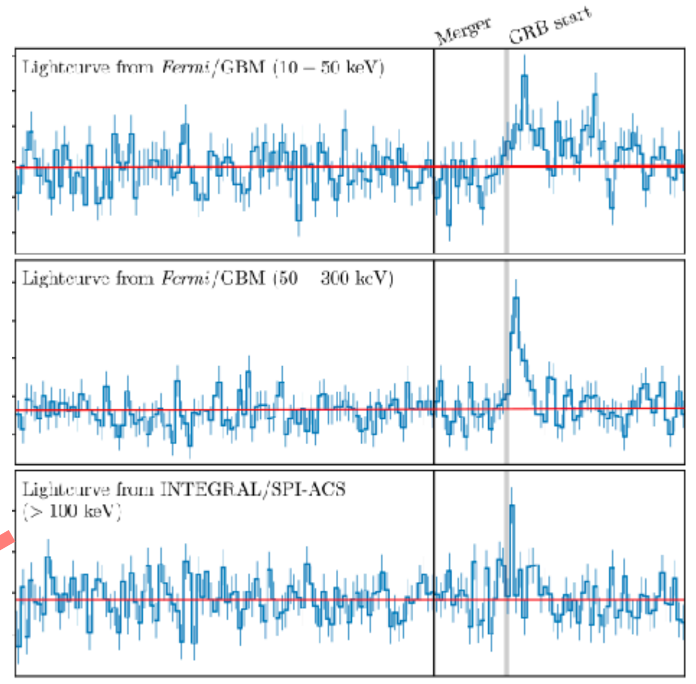
Multi-messenger

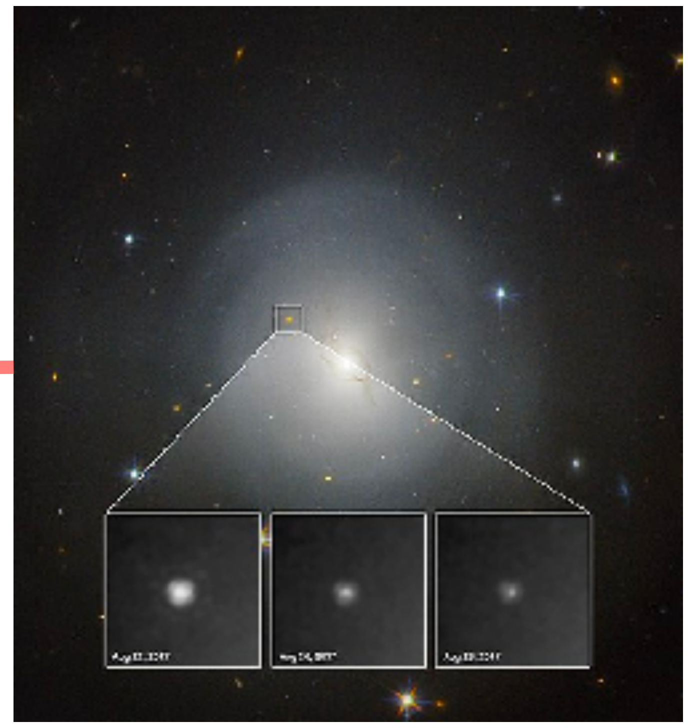
Multi-wavelength

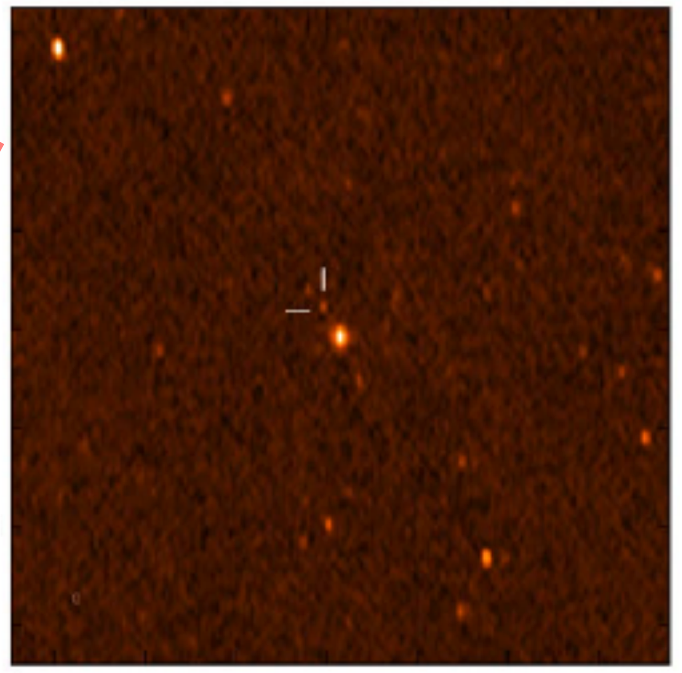
Time variability

GW 170817









GRB 170817A

kilonova

radio afterglow

Image credits:

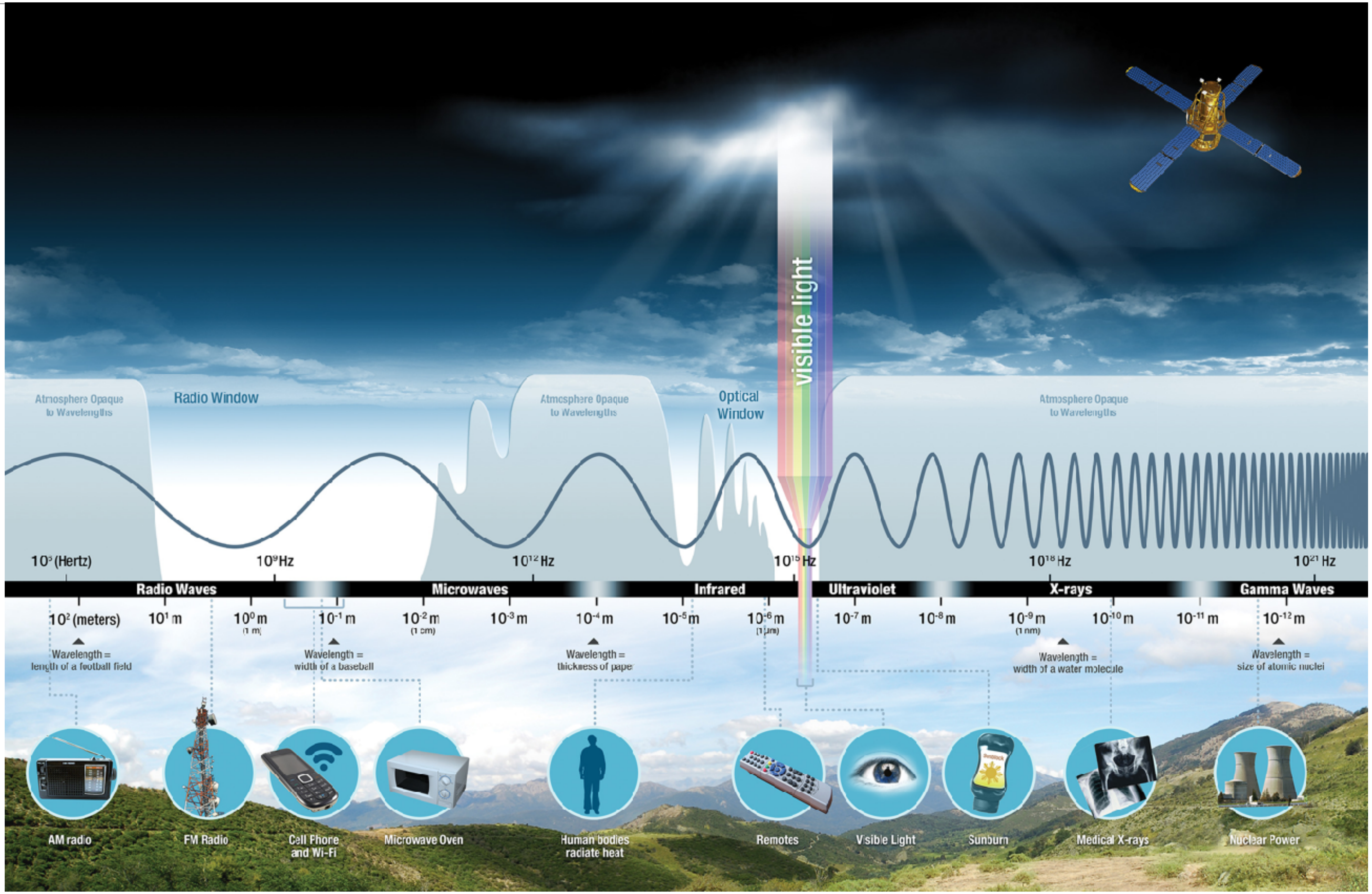
B. P. Abbott *et al* 2017 *ApJL* **848** L13

NASA and ESA. Acknowledgment: A.J. Levan (U. Warwick), N.R. Tanvir (U. Leicester), and A. Fruchter and O. Fox (STScI)

Hallinan *et al* 2017, Science, 358, 6370

Electromagnetic spectrum

- Frequency range =
  - 30 MHz to 300 GHz
- Wavelength range =
  - 10 m to 1 mm
- Lower limit:
  - Absorption in Earth's ionosphere
- Upper limit:
  - Absorption in Earth's atmosphere



Radio astronomy bands

- Common to refer to radio astronomy observing frequencies or receivers according to the IEEE standards for radar bands
- “L-band receiver”
- “observations at S-band”

Radar-frequency bands according to IEEE standard[17]

Band designation	Frequency range	Explanation of meaning of letters
HF	0.003 to 0.03 GHz	High frequency[18]
VHF	0.03 to 0.3 GHz	Very high frequency[18]
UHF	0.3 to 1 GHz	Ultra-high frequency[18]
L	1 to 2 GHz	Long wave
S	2 to 4 GHz	Short wave
C	4 to 8 GHz	Compromise between S and X
X	8 to 12 GHz	Used in World War II for fire control, X for cross (as in crosshair). Exotic.[19]
K_u	12 to 18 GHz	*Kurz*-under
K	18 to 27 GHz	German: *Kurz* (short)
K_a	27 to 40 GHz	*Kurz*-above
V	40 to 75 GHz	
W	75 to 110 GHz	W follows V in the alphabet[20]
mm or G	110 to 300 GHz[note 1]	Millimeter[17]

Credit: Wikipedia

Rayleigh Jeans Law & Brightness Temperature

- Planck law for black body radiation:

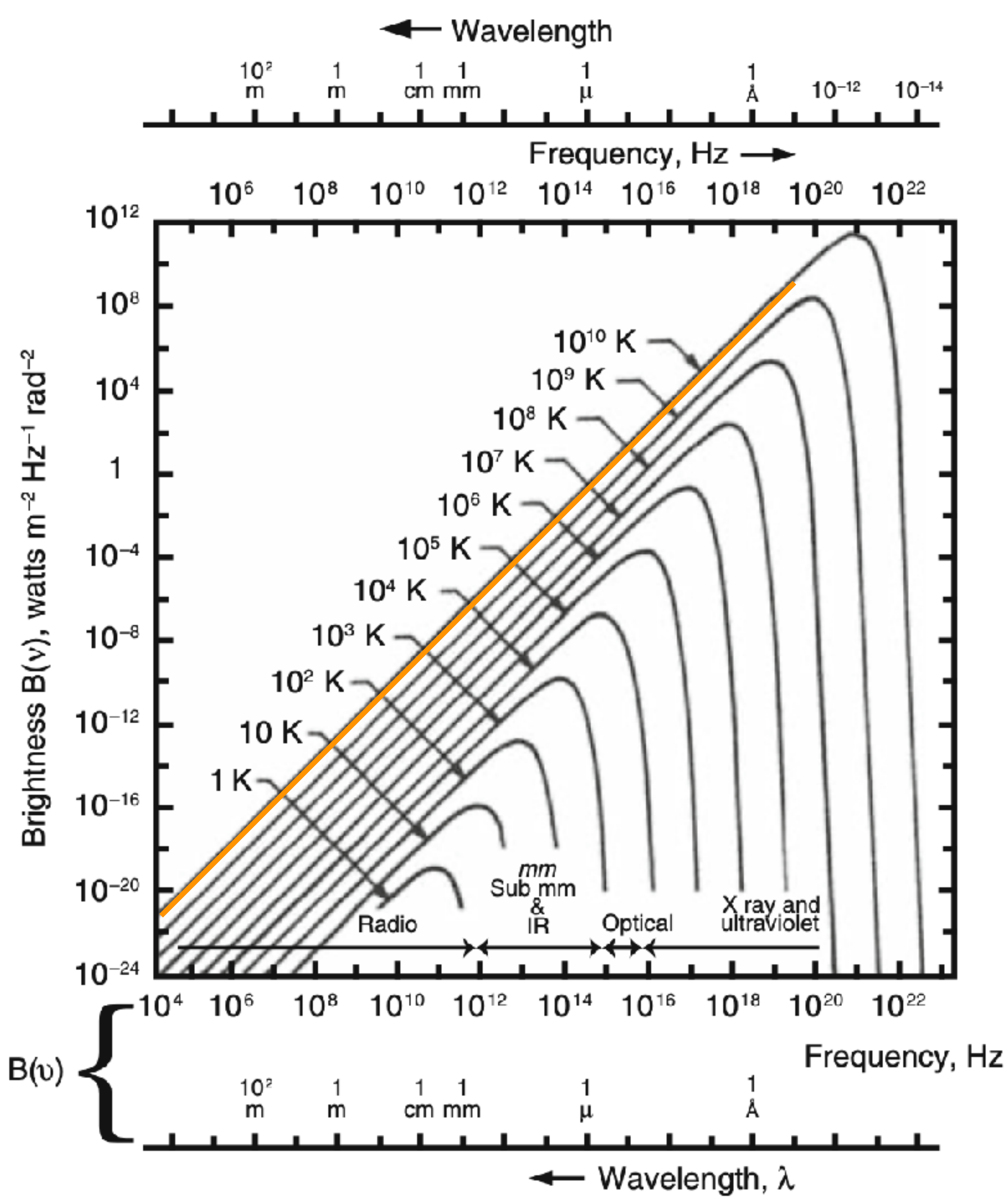
$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

- When $h\nu << kT \rightarrow$ Rayleigh-Jeans Law

$$B(\nu, T) = \frac{2\nu^2}{c^2}kT$$

- Brightness Temperature:

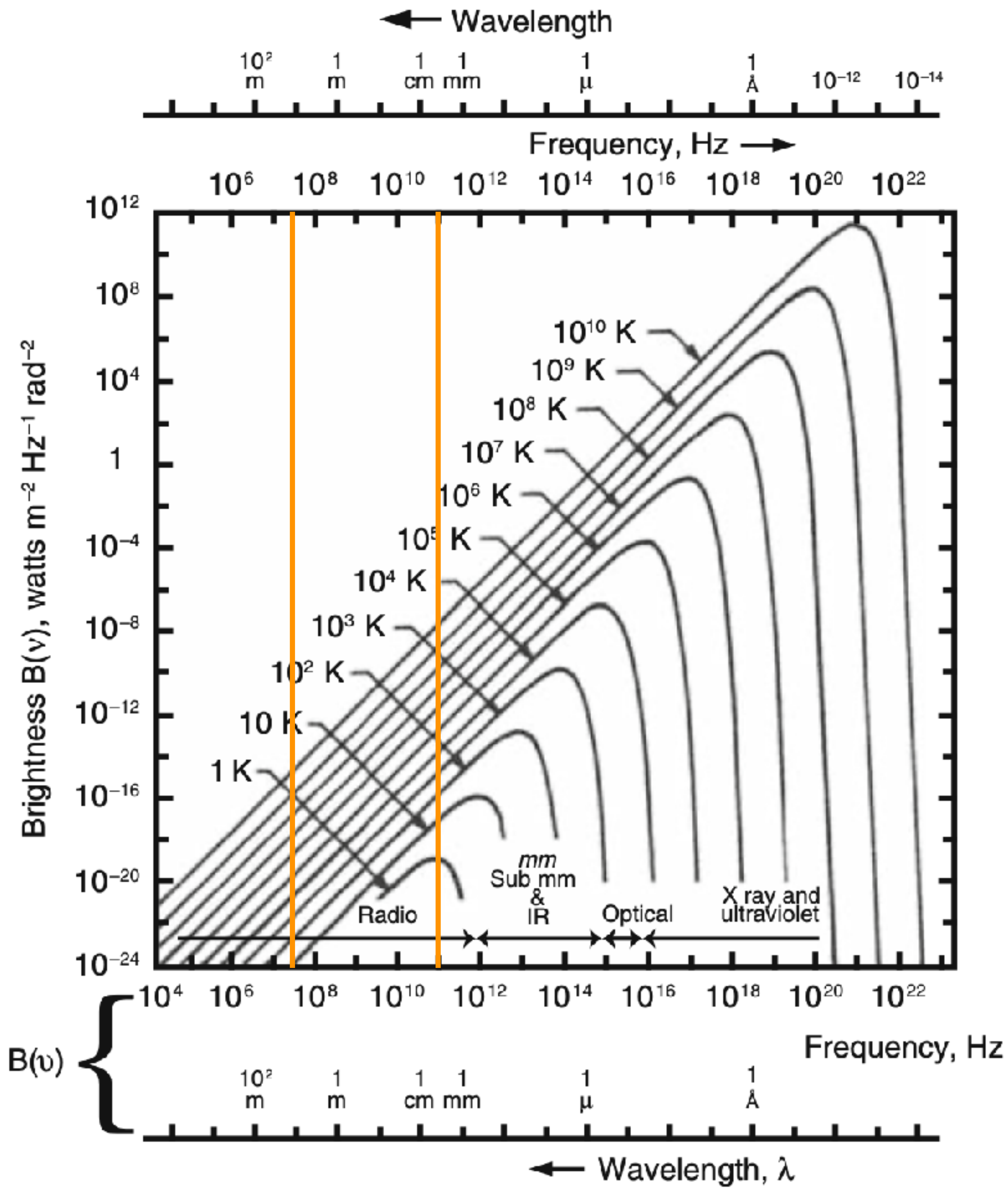
$$T_b = \frac{c^2}{2k\nu^2}B_\nu$$



Credit: Wilson, Rohlfs, Hüttenmeister

Rayleigh Jeans Law & Brightness Temperature

- Brightness Temperature:
  - $T_b = \frac{c^2}{2k\nu^2} B_\nu$
  - Intrinsic brightness related directly to a temperature
- Blackbody radiation does not play a major role in radio astronomical emissions
- Brightness temperature generally does not correspond to a thermal temperature
  - $T_b >> T_{\text{thermal}} \rightarrow$ non-thermal emission processes



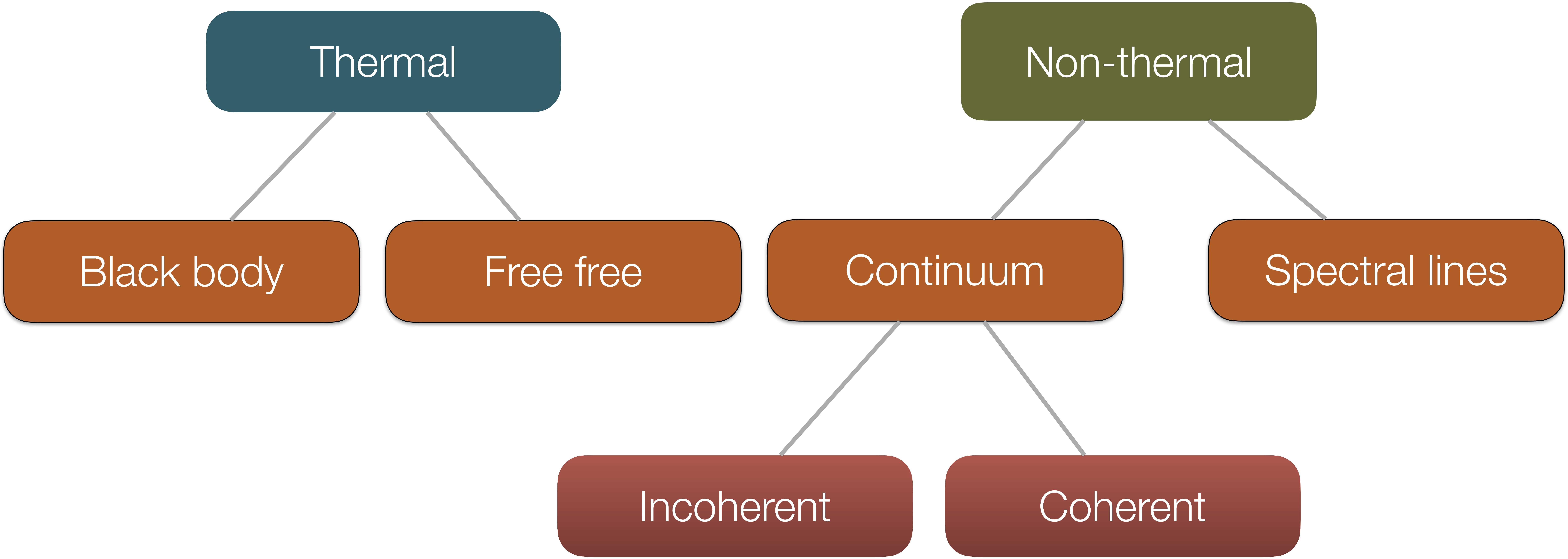
Credit: Wilson, Rohlfs, Hüttenmeister

Standard unit: Jansky

- Flux density (observed quantity):
- $$\mathrm{Jy} = 10^{-23} \frac{\mathrm{erg}}{\mathrm{s\ cm^2\ Hz}}$$
- $$\mathrm{Jy} = 10^{-26} \frac{\mathrm{W}}{\mathrm{m^2\ Hz}}$$

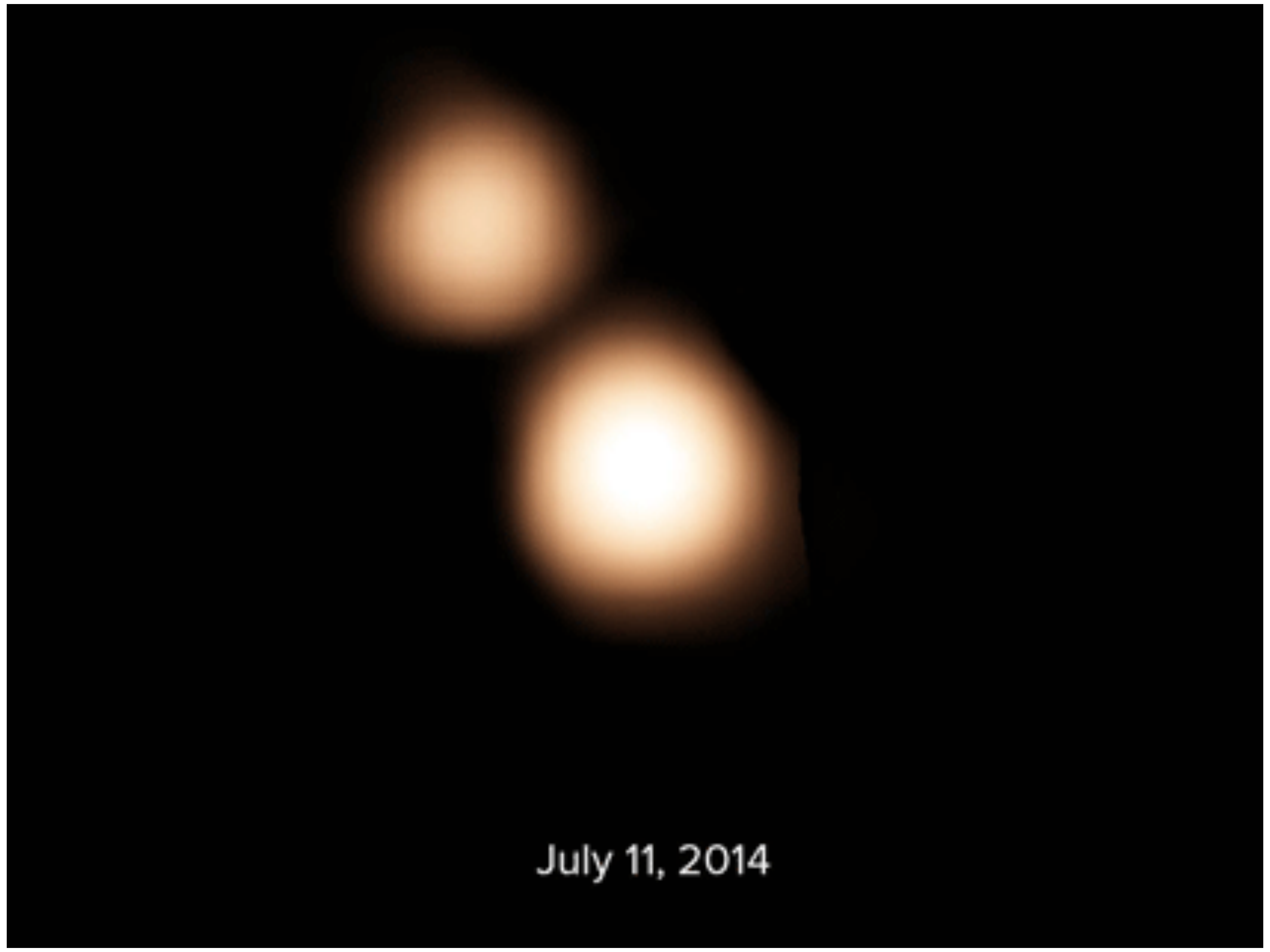
- A few thousand sources > 10 Jy at 1.4 GHz
- 1 Jy source actually quite bright
- LTE signal transmitted from the Moon is about 10 Jy

Emission mechanisms



Black body emission

- Thermal emission from cold solar system objects such as dwarf planets can be observed is millimeter and sub-millimeter regime (>100 GHz)
- Right: Atacama Large Millimeter Array (ALMA) observation Is Pluto and Charon
- ALMA imaging observation used to measure a more precise position of the dwarf planet prior to the fly by of the New Horizons satellite

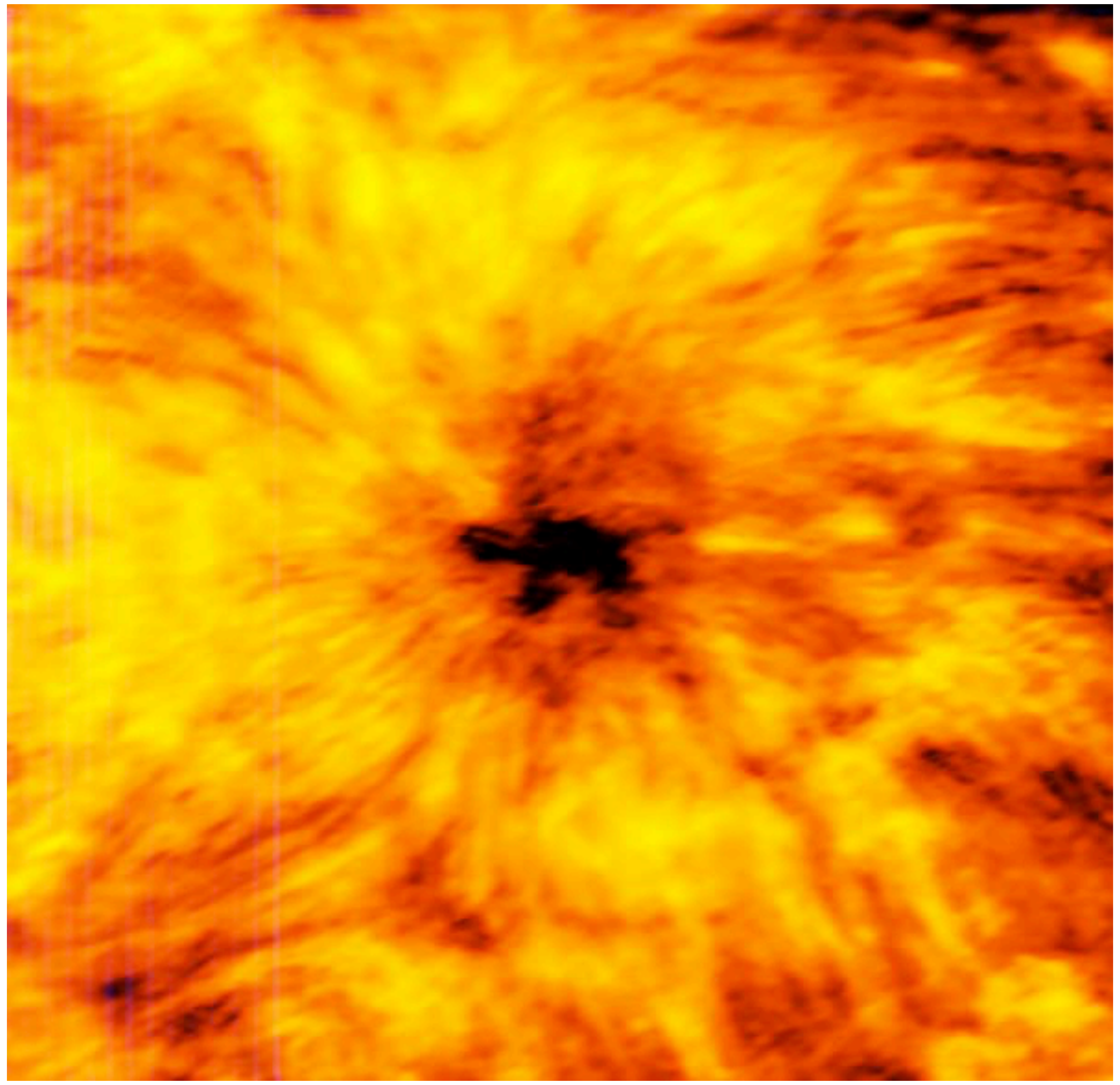


Credit: B. Saxton (NRAO/AUI/NSF)

Thermal emission of Sun

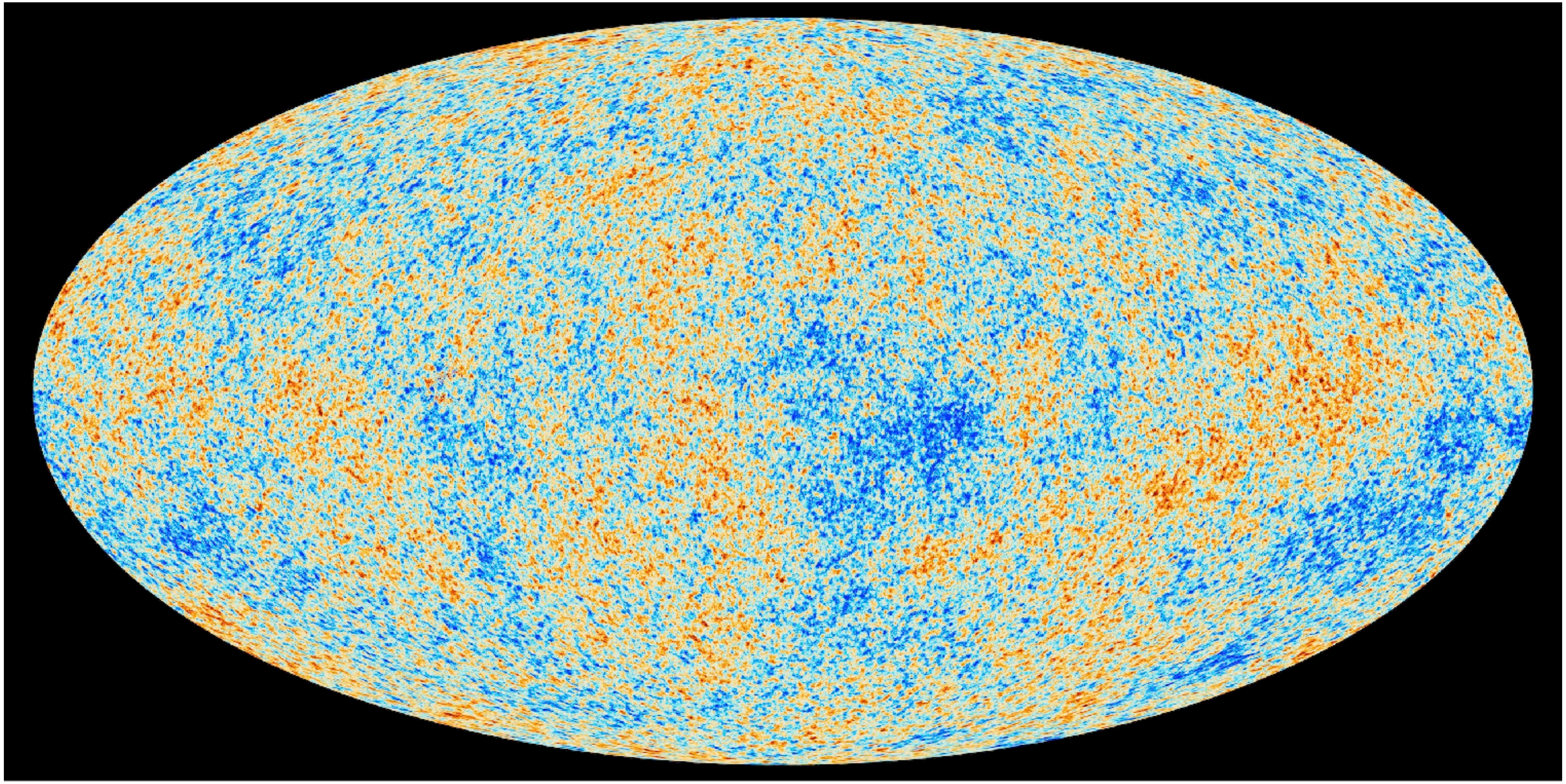
- 3 mm (100 GHz) observation with the Atacama Large Millimeter Array (ALMA)
- Intensity measures thermal temperature of electrons in the chromosphere
- Complement observations at ~1 GHz frequencies, which probe coronal structures

Image of a sunspot



Credit: NRAO/AUI/NSF

Cosmic microwave background



Credit: ESA and the Planck Collaboration

Free free emission

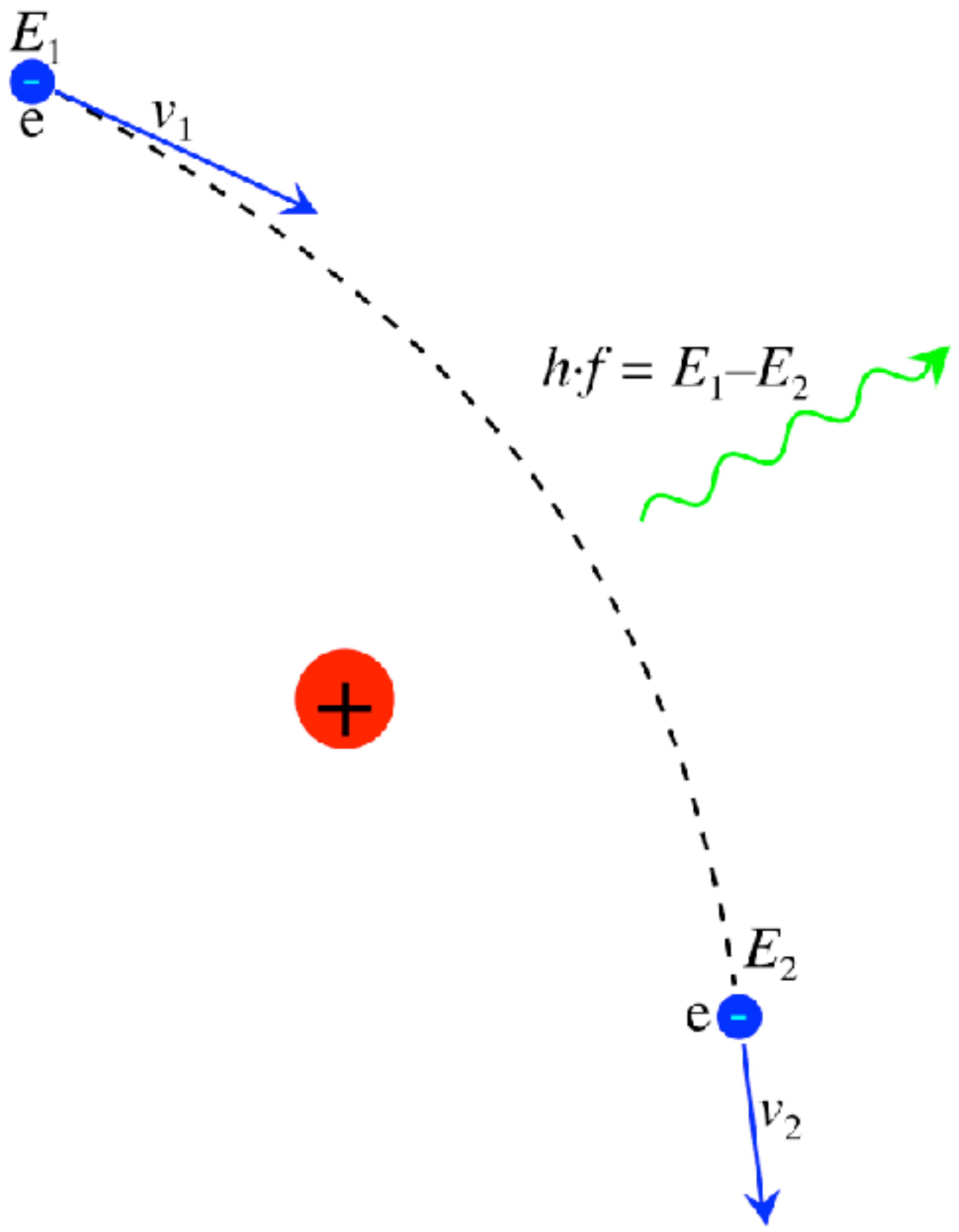
- Bremsstrahlung (“braking radiation”) from hot, astrophysical plasmas
- “HII regions” (HII = ionized hydrogen)
    - Region where young stars are ionizing the surrounding gas and heating it up
    - $T = 10^4$ K
- Galaxies: generally sub-dominate to synchrotron except at high frequencies or in HII regions

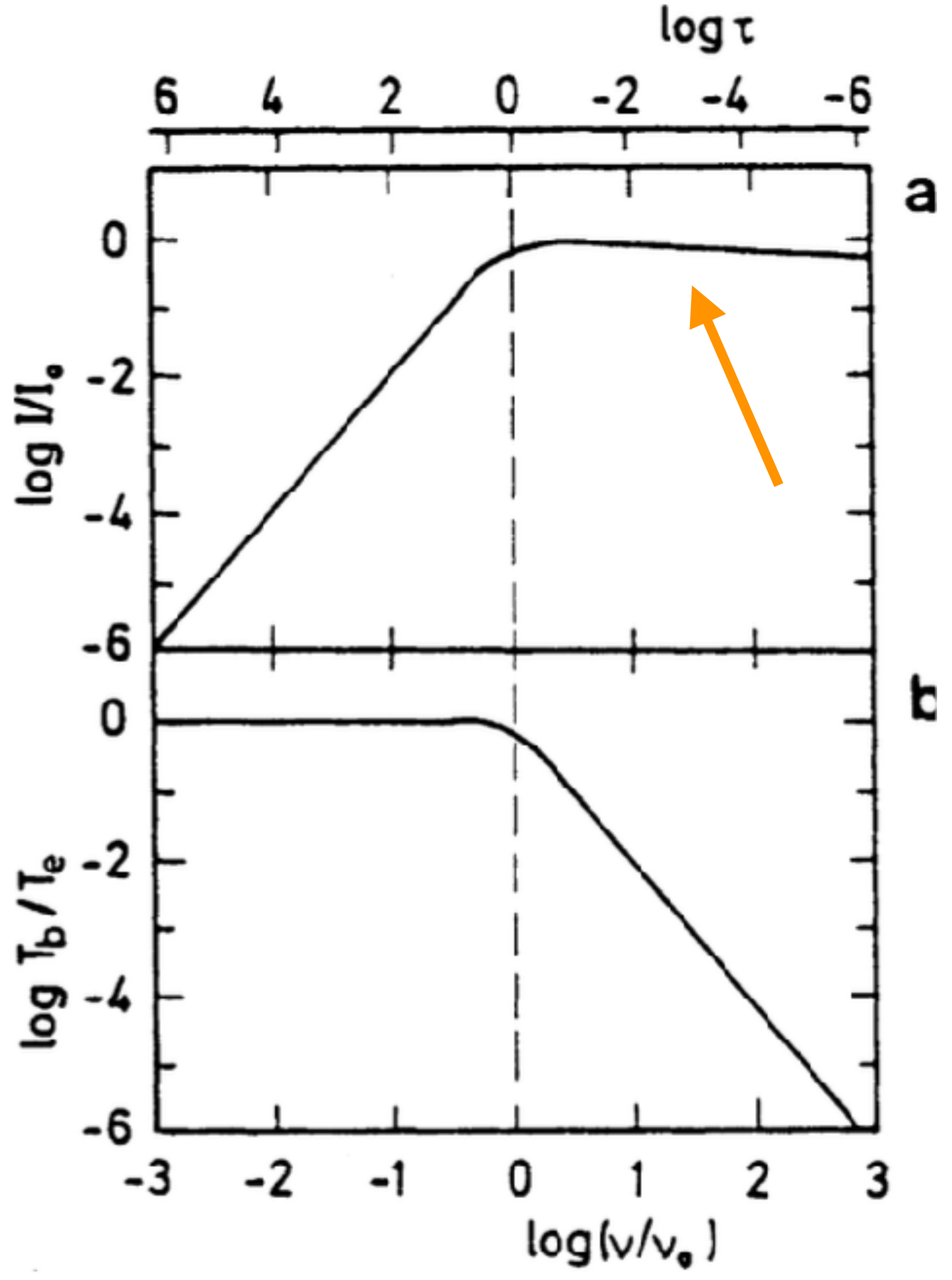
JWST image at the near IR of Tarantula Nebula

Credit: Wikipedia

Free free emission

- Bremsstrahlung ("braking radiation")
  - Charged particle is accelerated by another changed particle.
  - Loss in kinetic energy is transferred into a photon
- Integrate over a distribution of electrons with temperature T_e
- Observationally:
  - Hotter plasma is brighter
  - Spectrum is flat if the plasma is in the optically thin regime ($\tau << 1$)

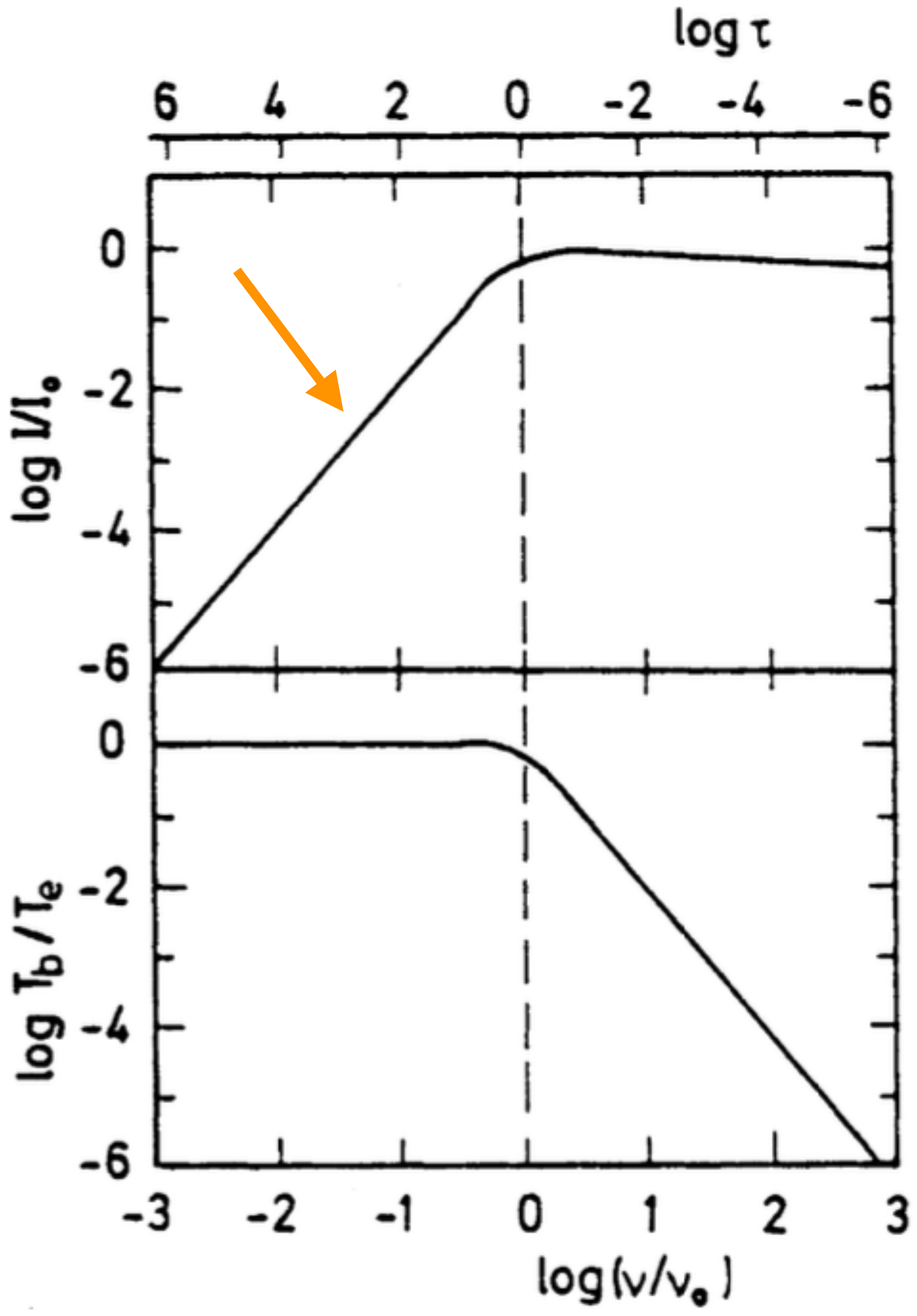




Credit:
(left) Wikipedia
(right) *Tools of Radio Astronomy*

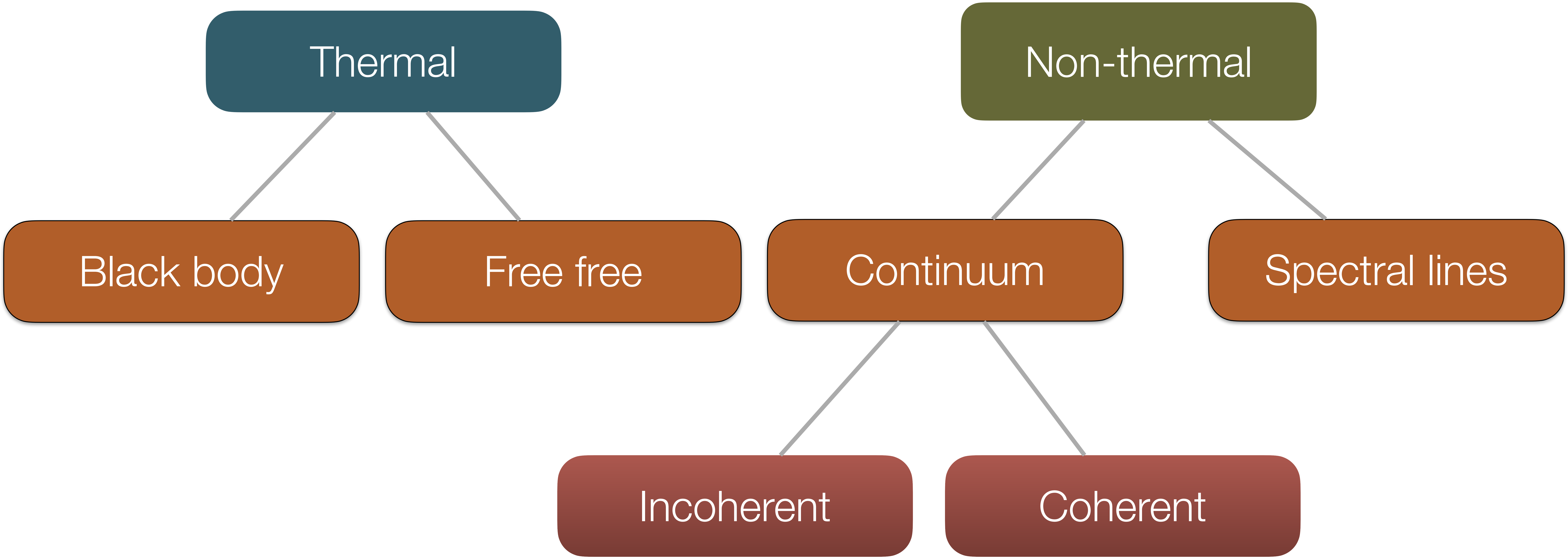
Free free absorption

- Below a critical frequency (ν_c), the electrons absorb radio emission
- Frequency where the optical depth (τ_ν) → 1
- $\tau_\nu \propto T_e^{-1.35} \nu^{-2.1} \mathrm{EM}$
  - EM = "emission measure"
  - $\mathrm{EM} = \int_0^S \mathrm{N_e^2 ds}$
- Important to consider when interpreting radio spectra



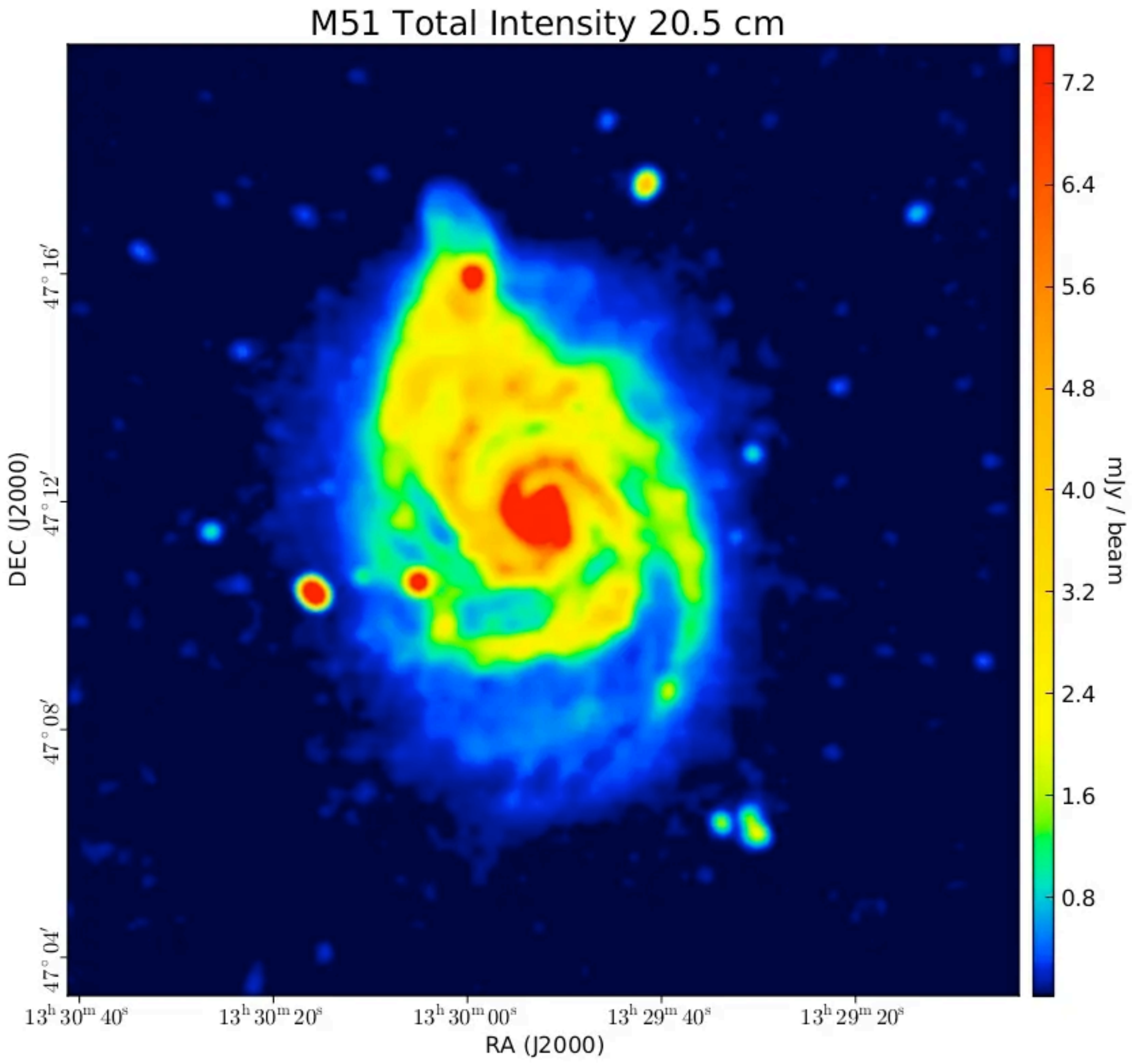
Credit: *Tools of Radio Astronomy*

Emission mechanisms



Particle in magnetic fields: synchrotron radiation

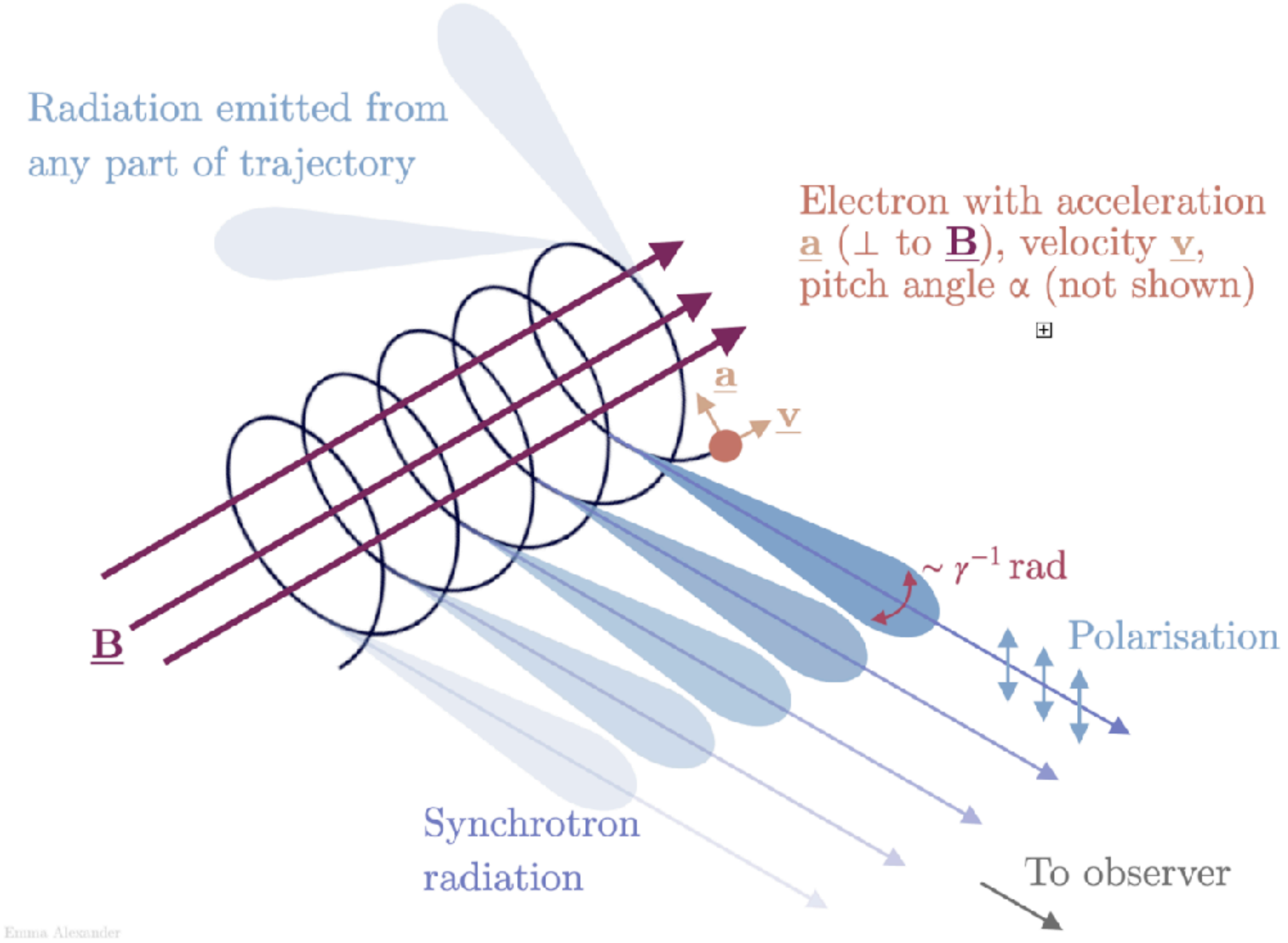
- Incoherent, non-thermal process
- Ubiquitous continuous radio emission process
- Origin: cosmic rays accelerated in the galaxy's magnetic fields
    - Cosmic rays likely accelerated at shock fronts around supernovae (SNe)
    - Rate of SNe correlated with rate of star formation
    - **Galactic synchrotron emission correlates with star formation rate within a galaxy**



Credit: Fletcher et al 2011

Particle in magnetic fields: synchrotron radiation

- Relativistic extension to cyclotron radiation
  - Emitted radiation is relativistically beamed
  - Angular beaming drives the observed spectrum (not the gyration frequency)
  - Spectral index of radiation related to the distribution of particle energies (power law is generally assumed)
  - Intrinsically highly polarized



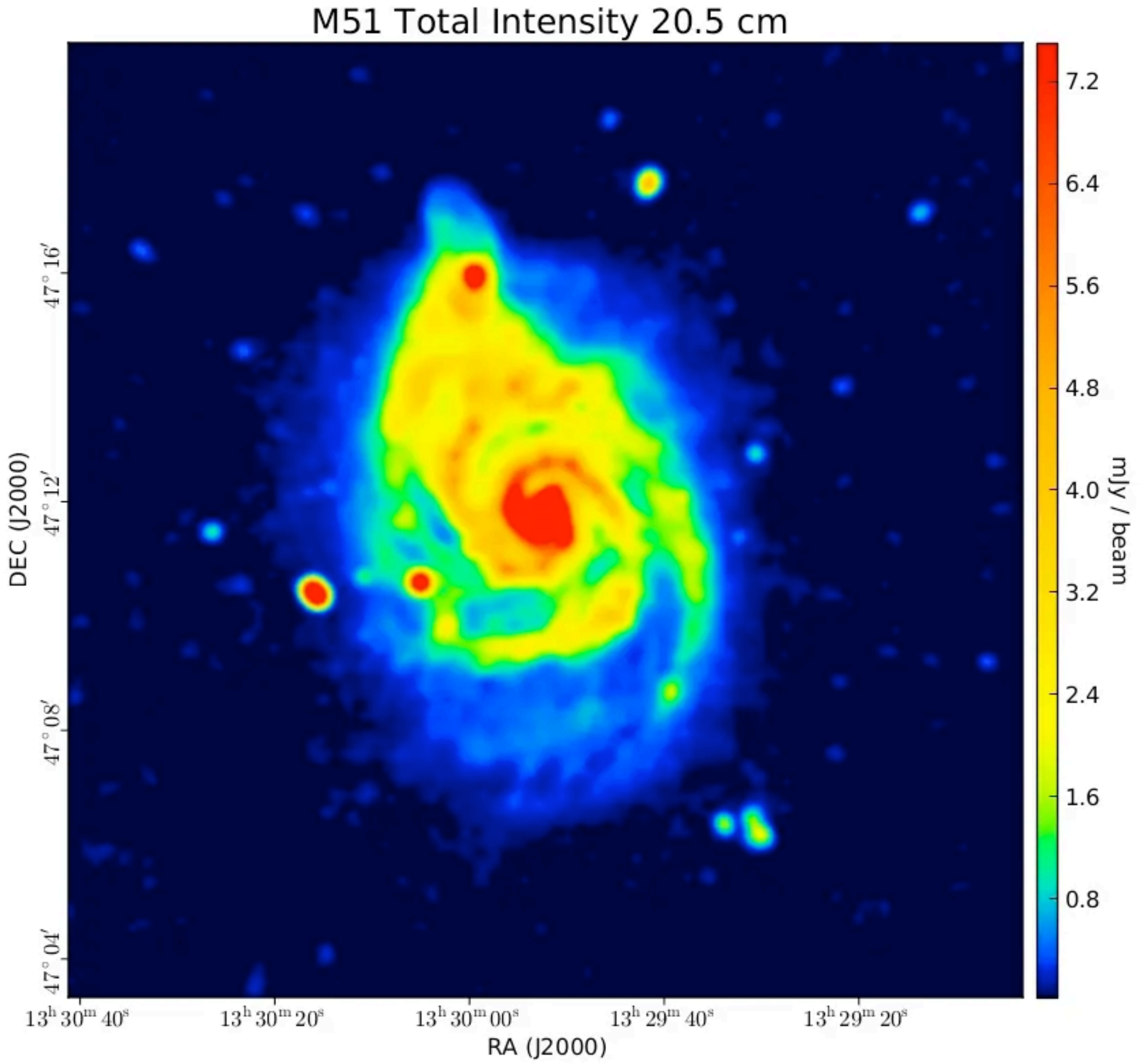
Particle in magnetic fields: synchrotron radiation

Spectral index:

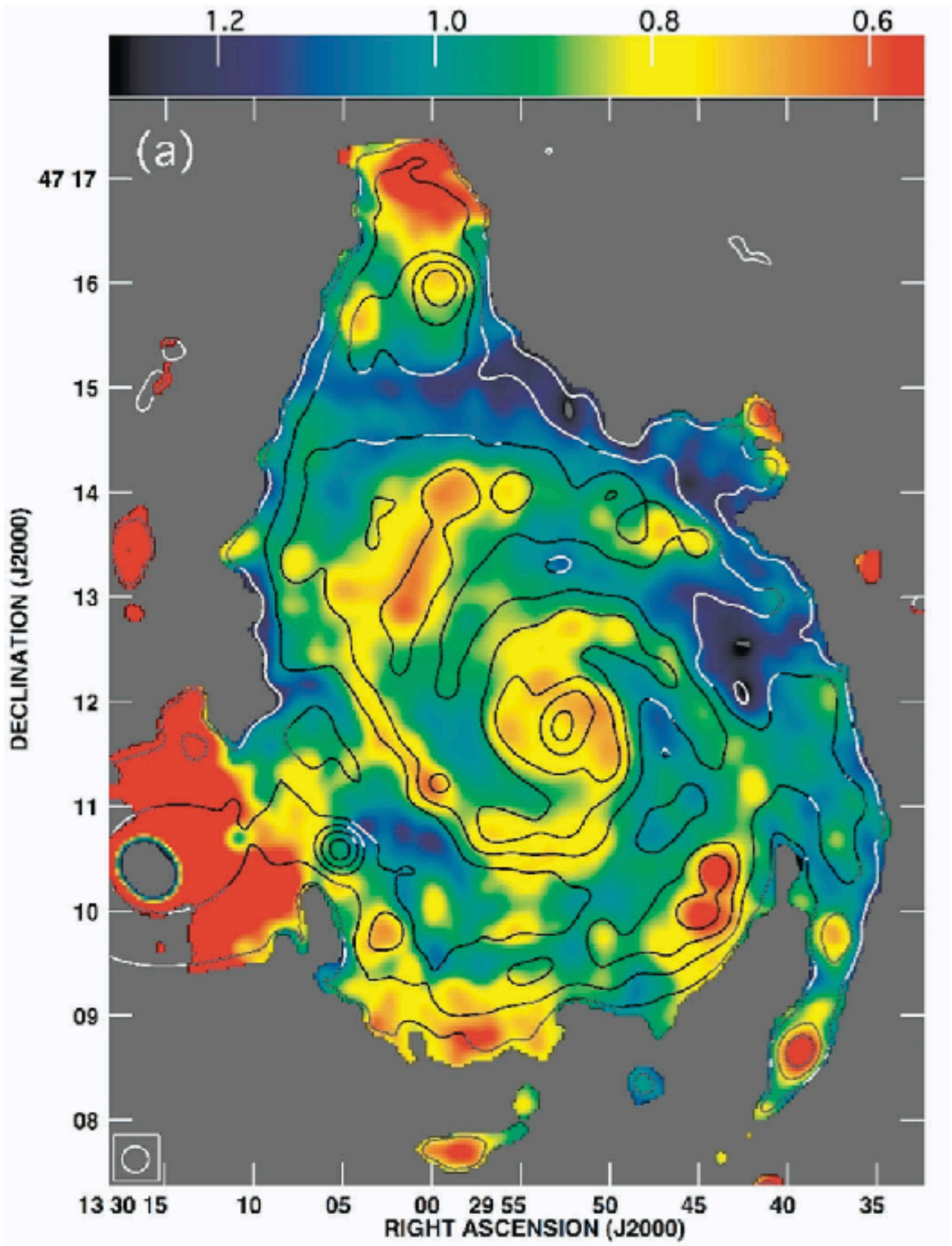
$$S_\nu \propto \nu^{-\alpha}$$

Synchrotron emission:

$$\alpha \sim 0.8$$



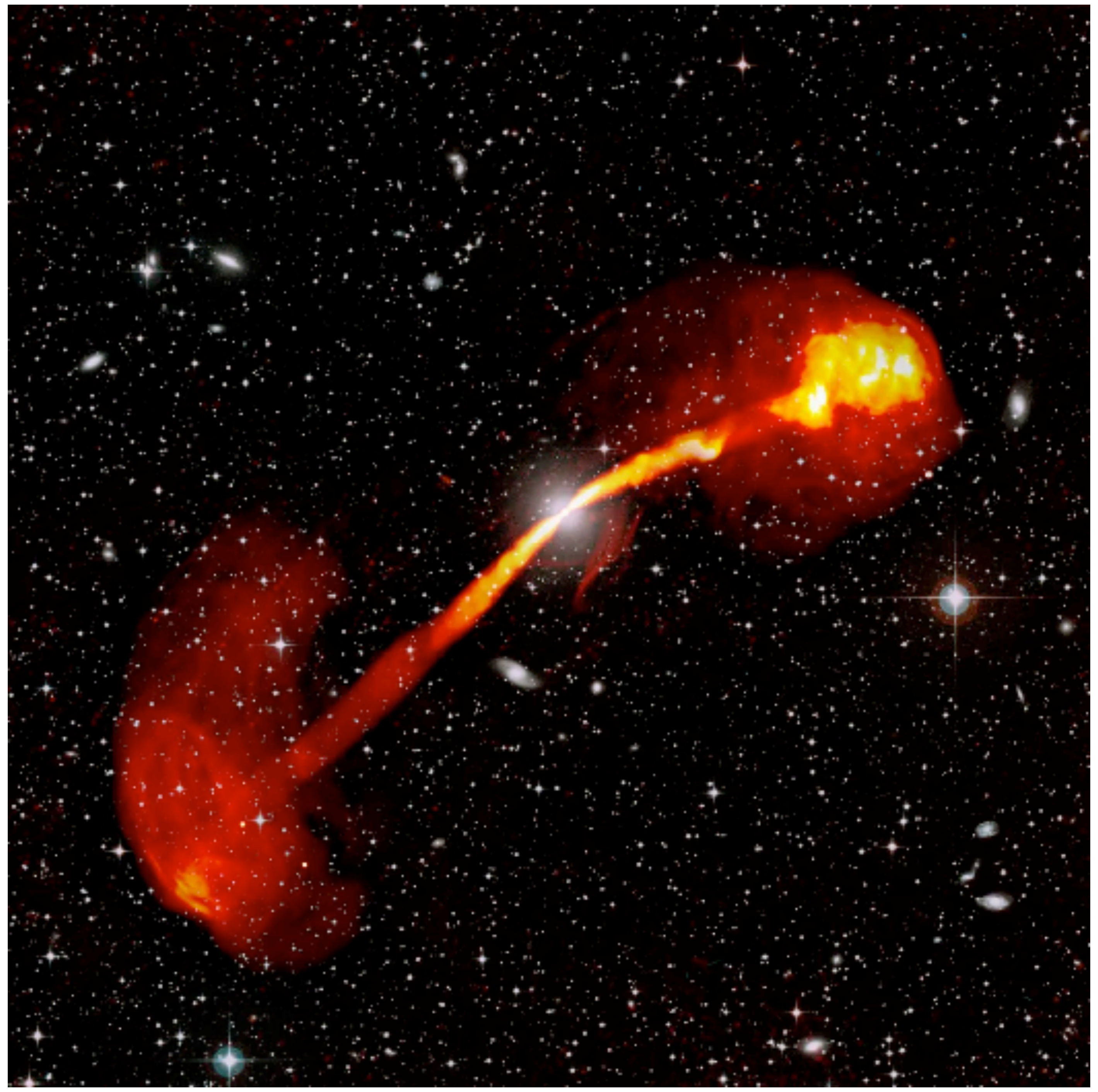
Spectral index map



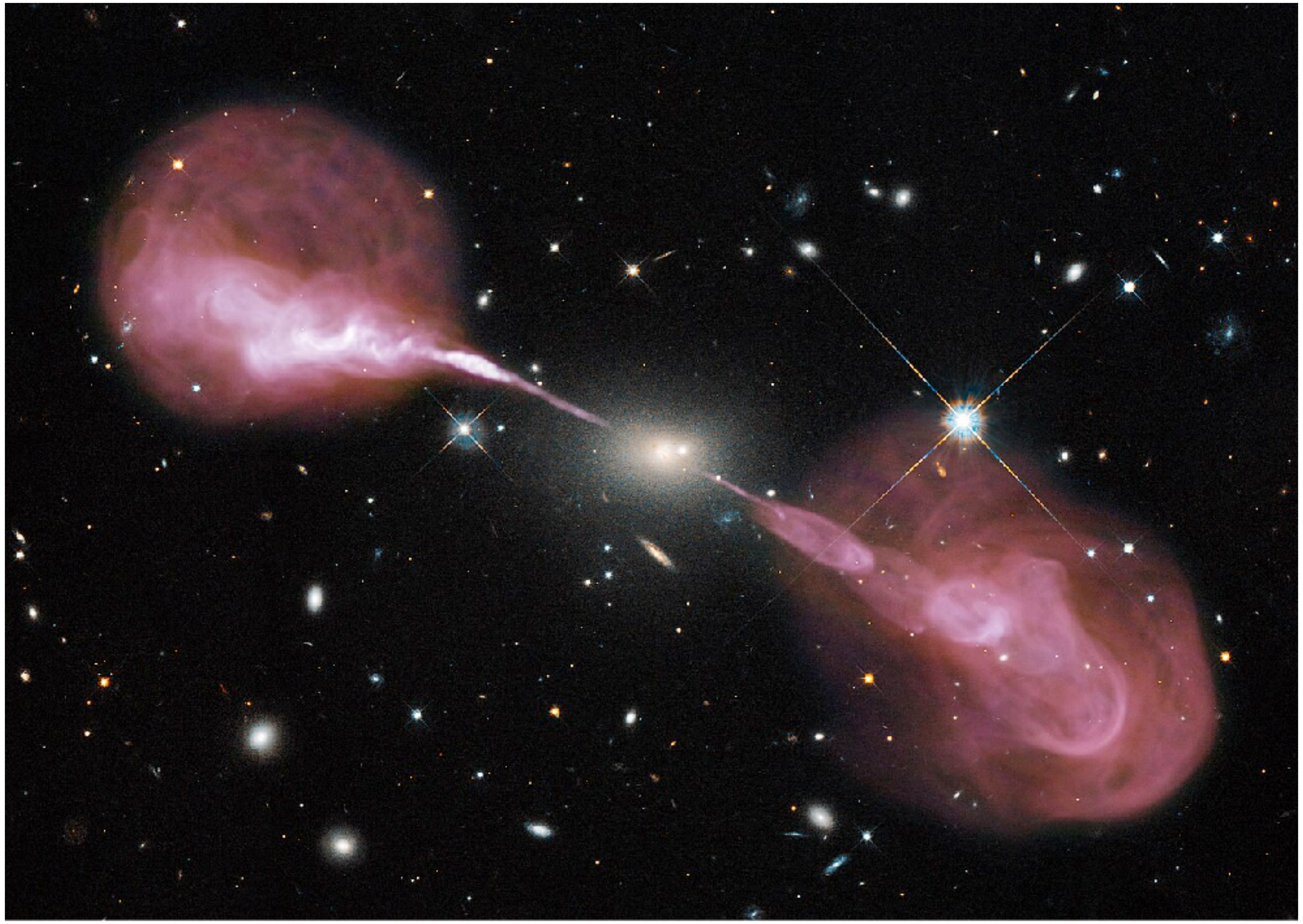
Credit: Fletcher et al 2011

Synchrotron radiation: galactic jets

- Particles accelerated by a supermassive black hole in the galaxy's center interacting with magnetic fields in the intergalactic medium



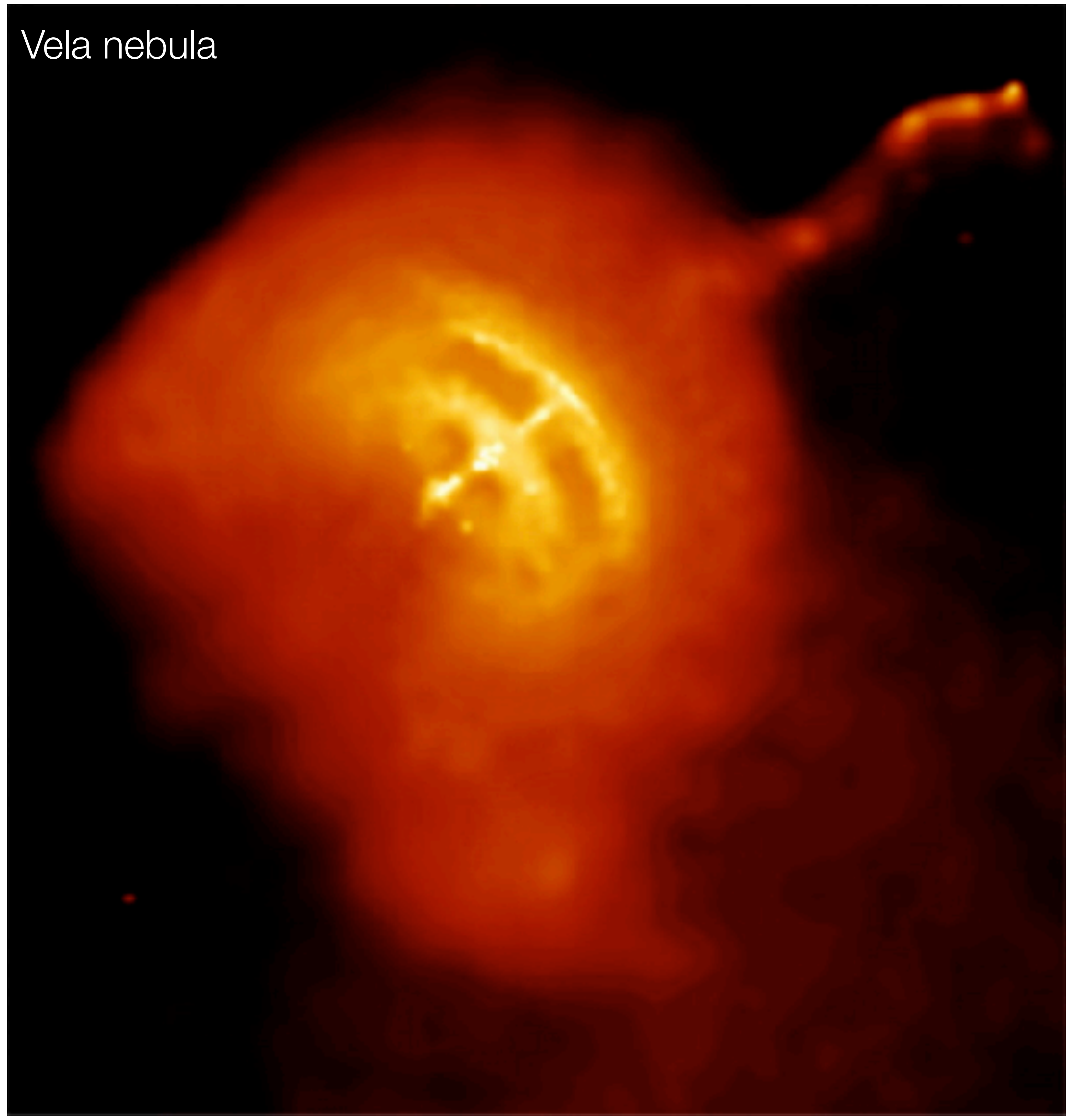
Credit: SARAO, SSS, S. Dagnello and W. Cotton (NRAO/AUI/NSF)



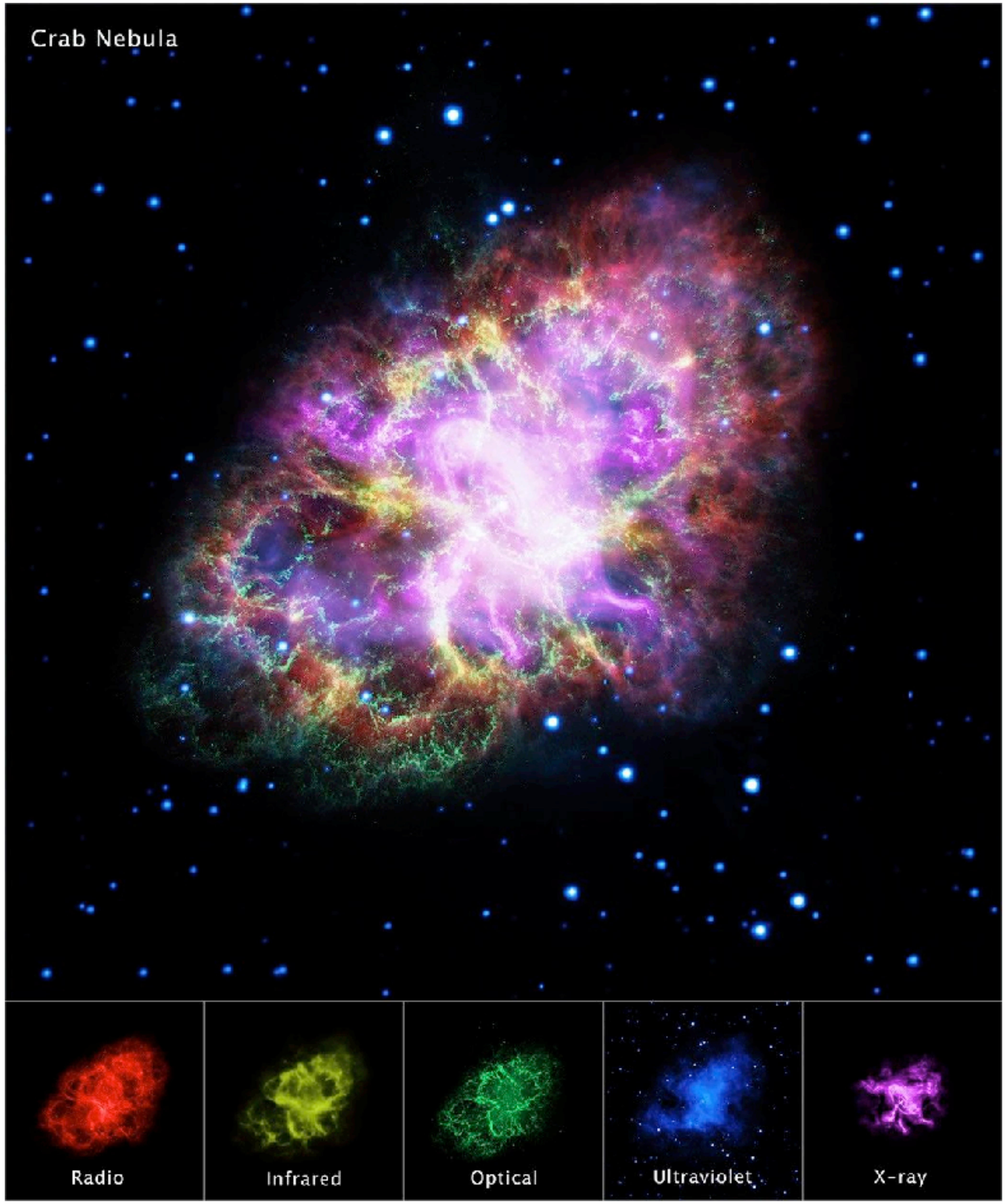
Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)

Synchrotron radiation: pulsar wind nebulae

- Particles accelerated by the magnetic field of the young neutron star interact with magnetic fields in supernovae ejecta



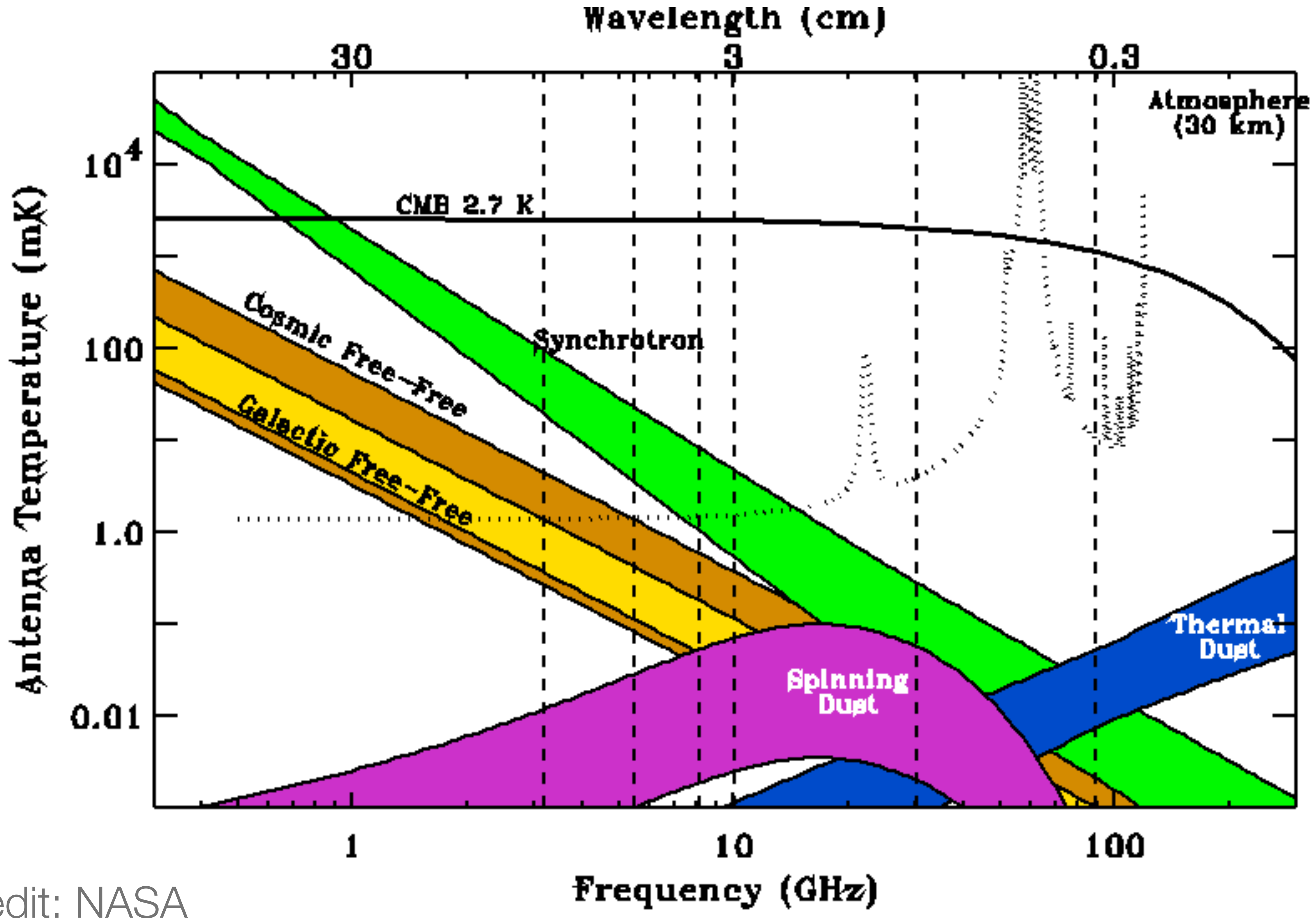
Credit: NASA/CXC/PSU/G.Pavlov et al.



Credit: NASA, ESA, G. Dubner (IAFE, CONICET-University of Buenos Aires) et al.; A. Loll et al.; T. Temim et al.; F. Seward et al.; VLA/NRAO/AUI/NSF; Chandra/CXC; Spitzer/JPL-Caltech; XMM-Newton/ESA; and Hubble/STScI

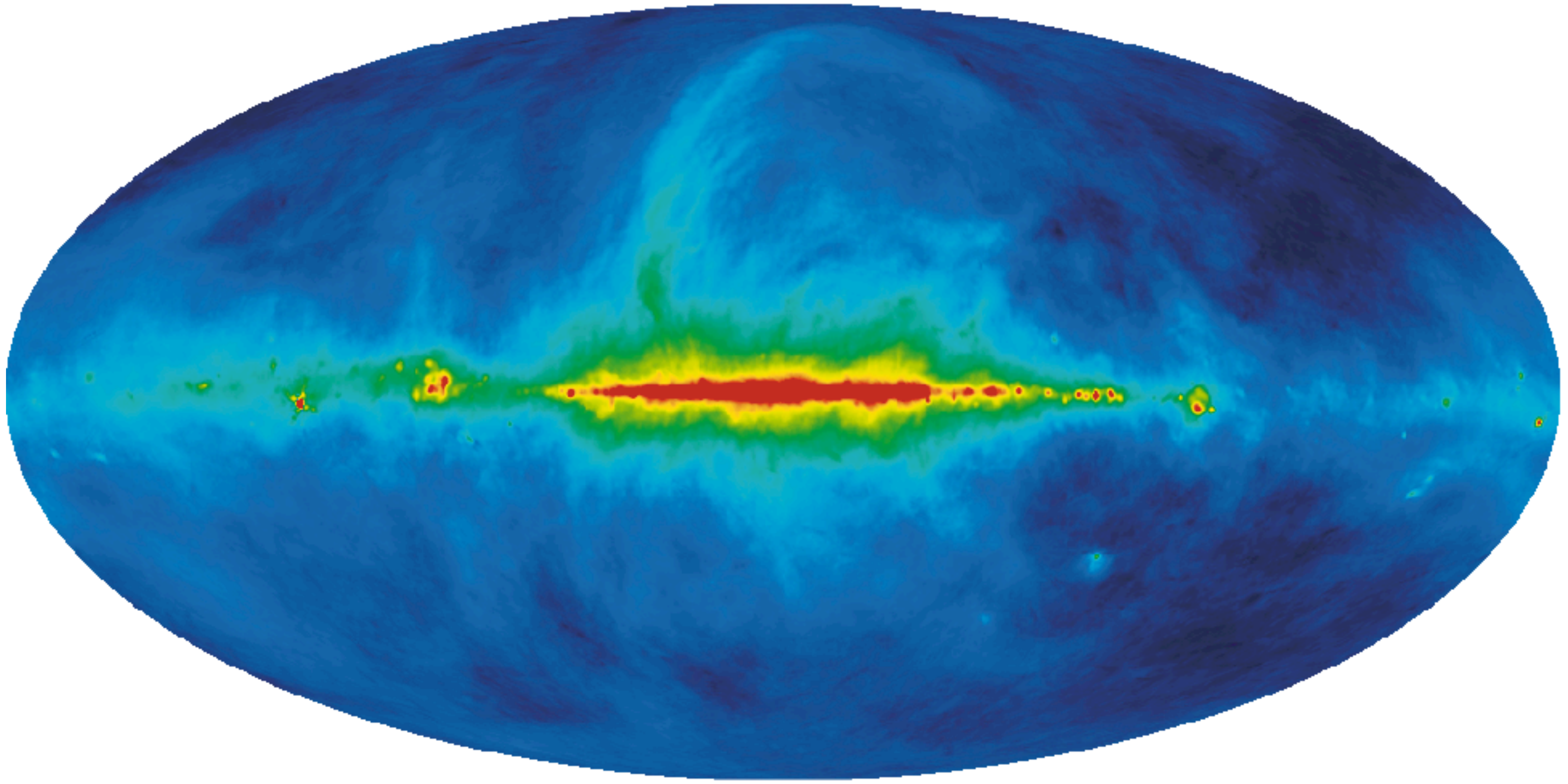
Synchrotron radiation: Milky Way

- At ~1 GHz the cosmic microwave background dominates the background (T = 3 K)
- At ~100 MHz synchrotron dominates the background (T ~ 100 K)



Credit: NASA

Synchrotron emission at 408 MHz



Credit: Haslam / NASA / LAMBDA Archive Team

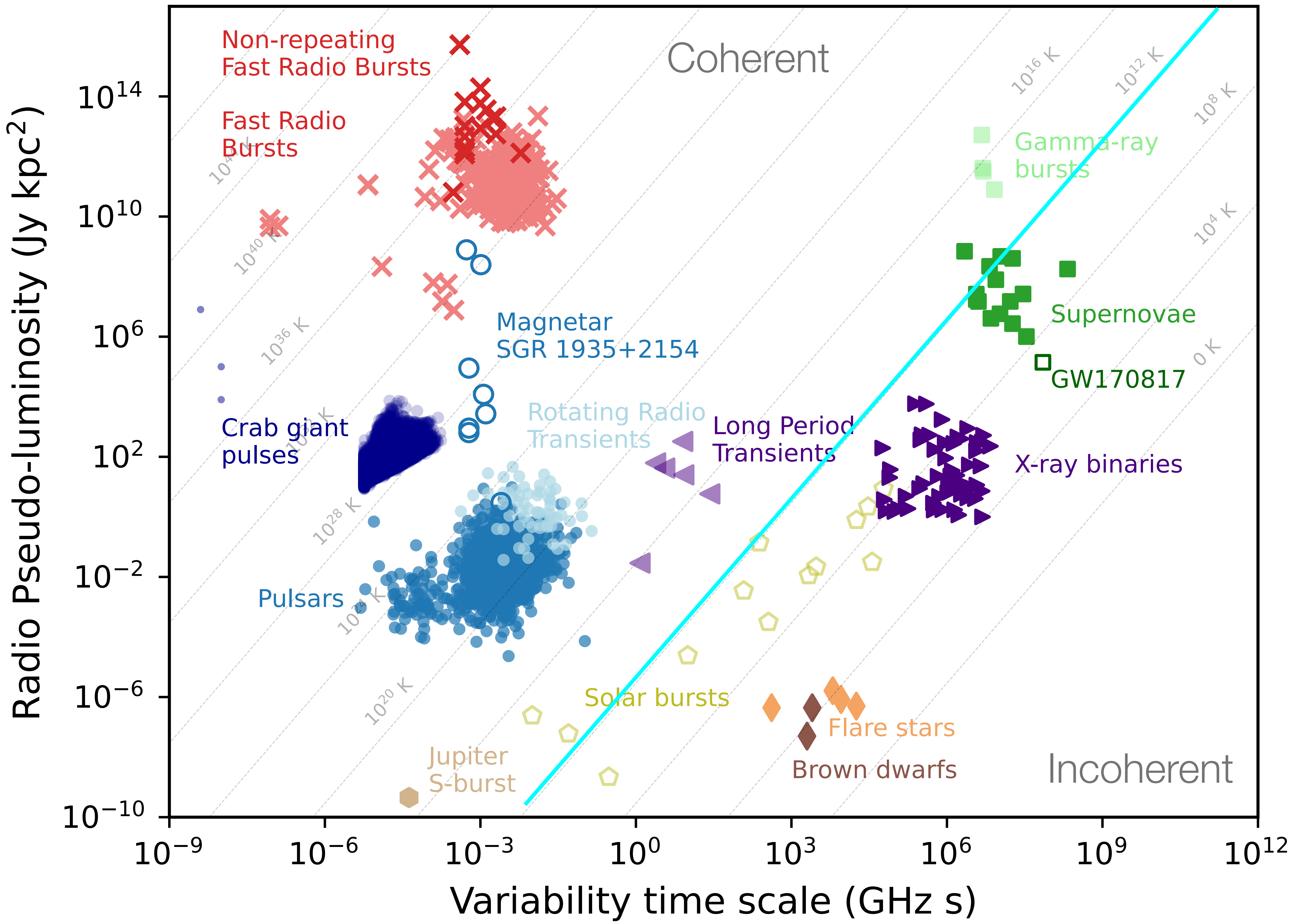
Particle in magnetic fields: coherent processes

- Particles emit coherently
  - $P_{\text{emit}} \propto N_p^2$
- Examples:
  - Lasers
  - Microwave ~~(L)~~asers (masers)
  - Coherent curvature (pulsars)
  - Electron cyclotron maser instability (planets)

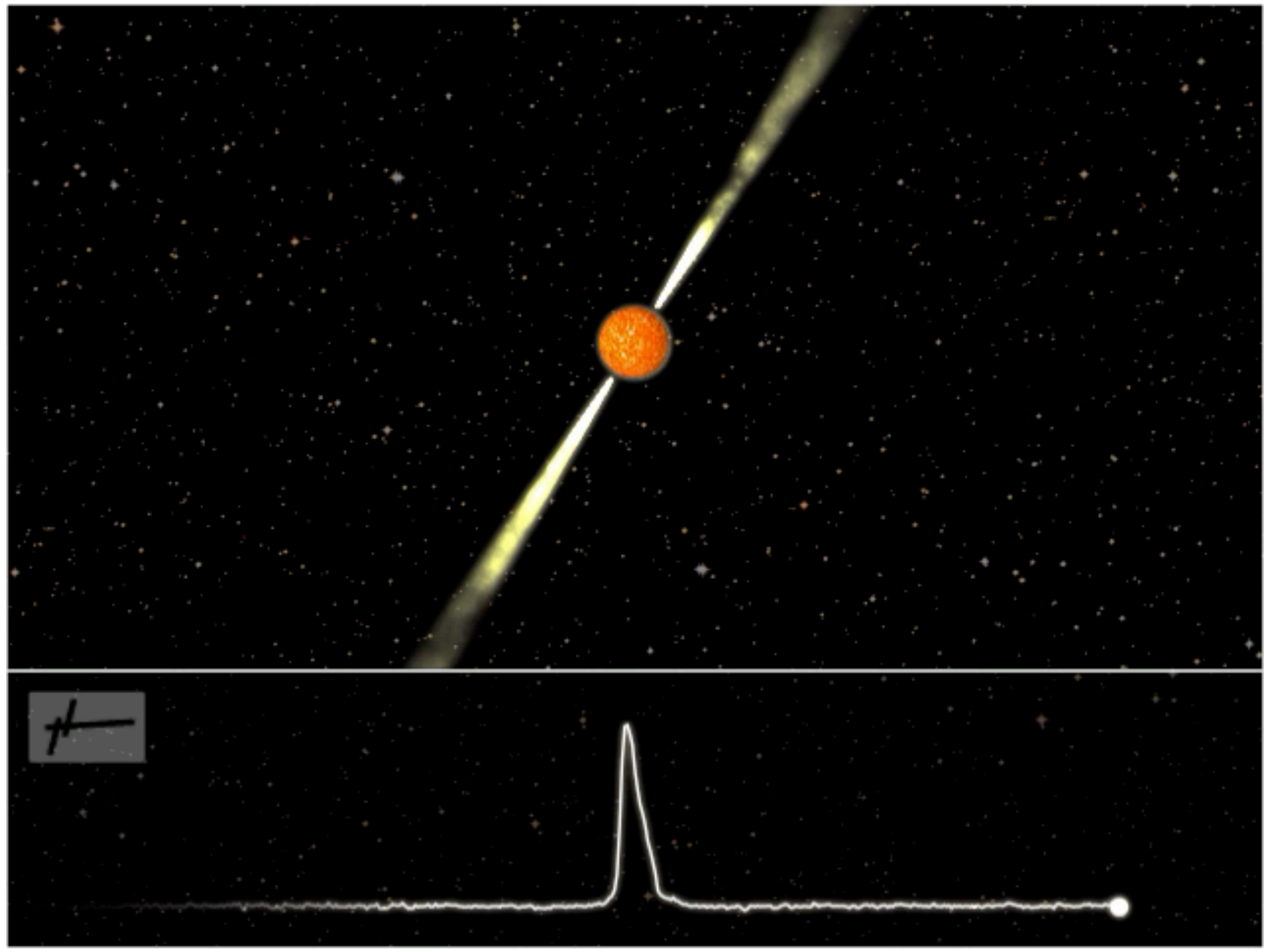
Credit: ESO/A. Ghizzi Panizza

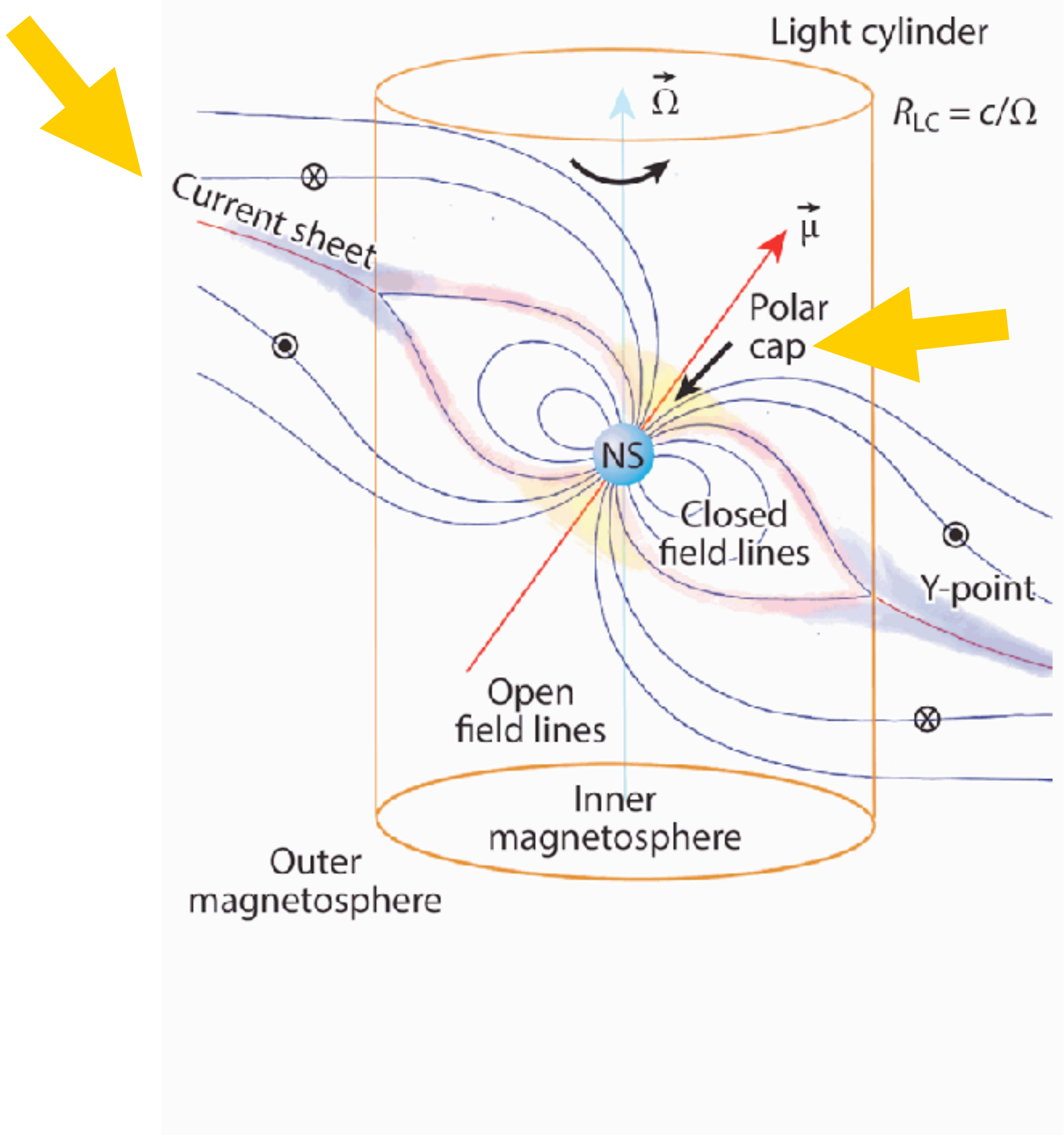
Particle in magnetic fields: coherent processes

- Coherent emission processes have $T_b >> 10^{12}$ K
- Typically observed from stellar or planet-sized objects



Coherent emission process: radio pulsars

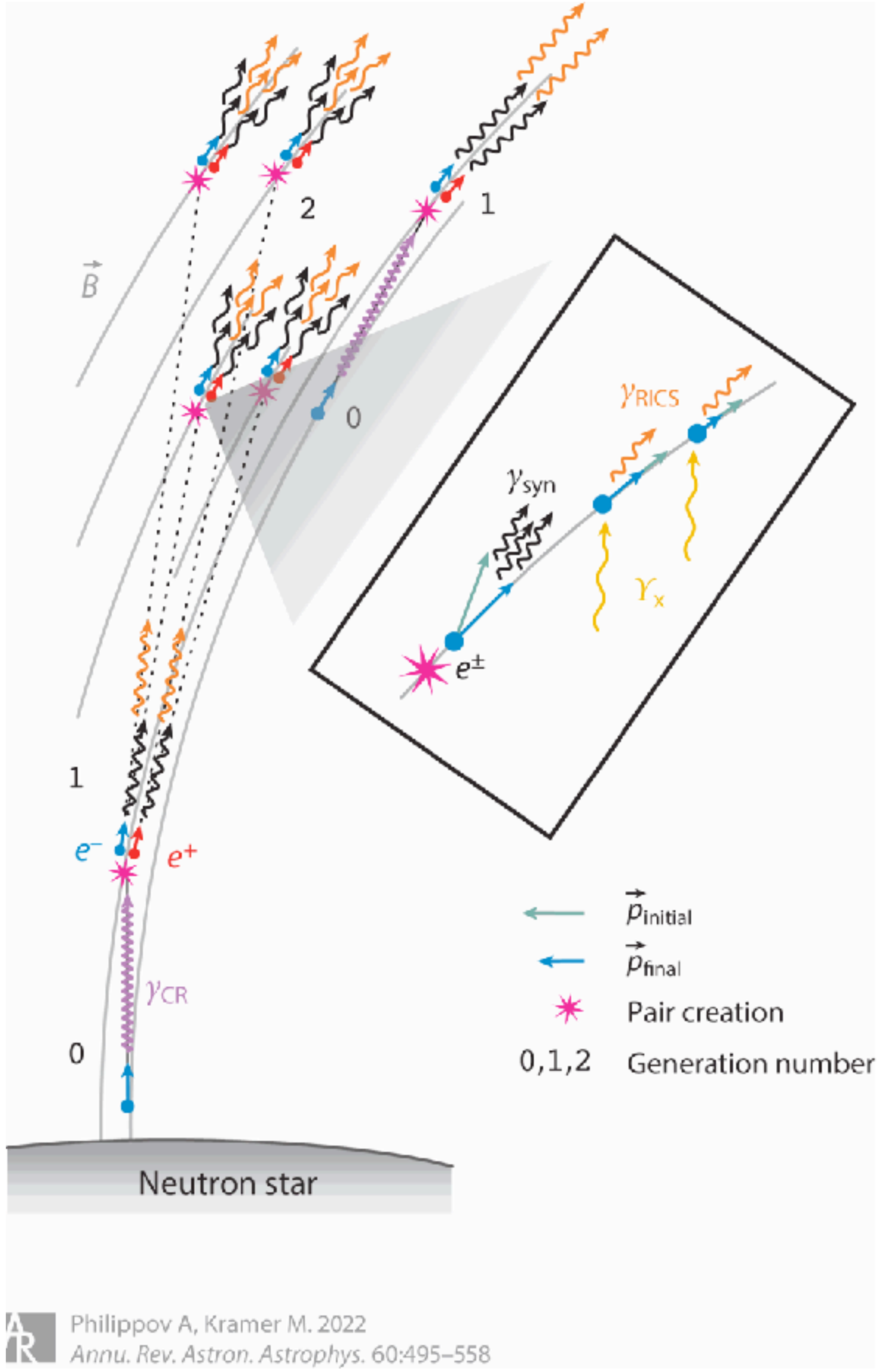




Philippov A, Kramer M. 2022
Annu. Rev. Astron. Astrophys. 60:495–558

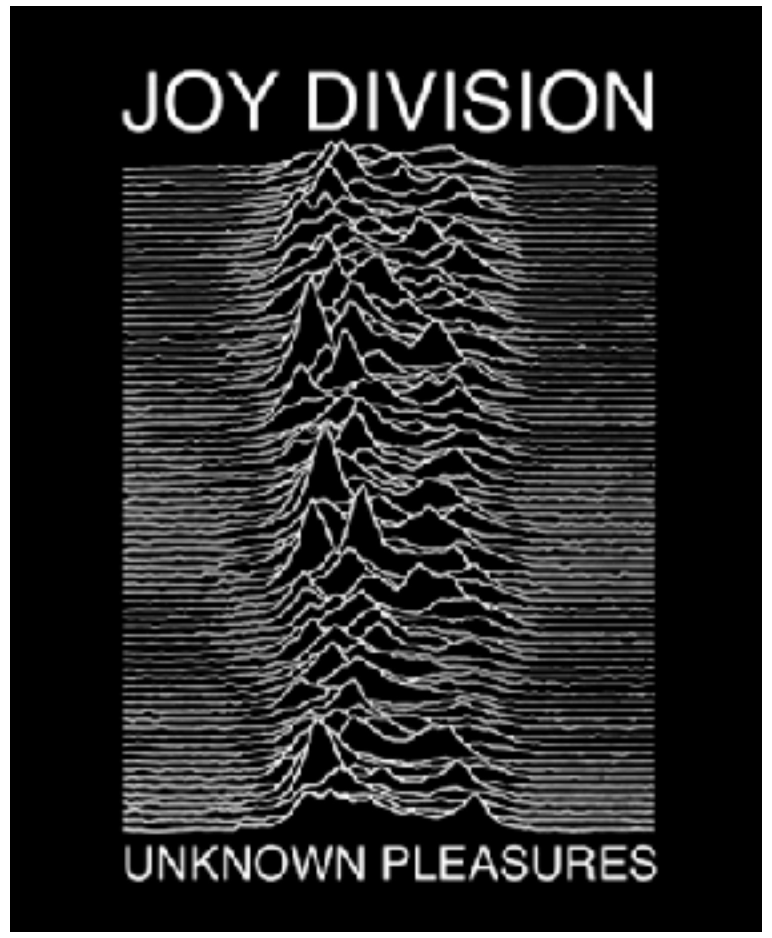
Coherent emission process: polar cap

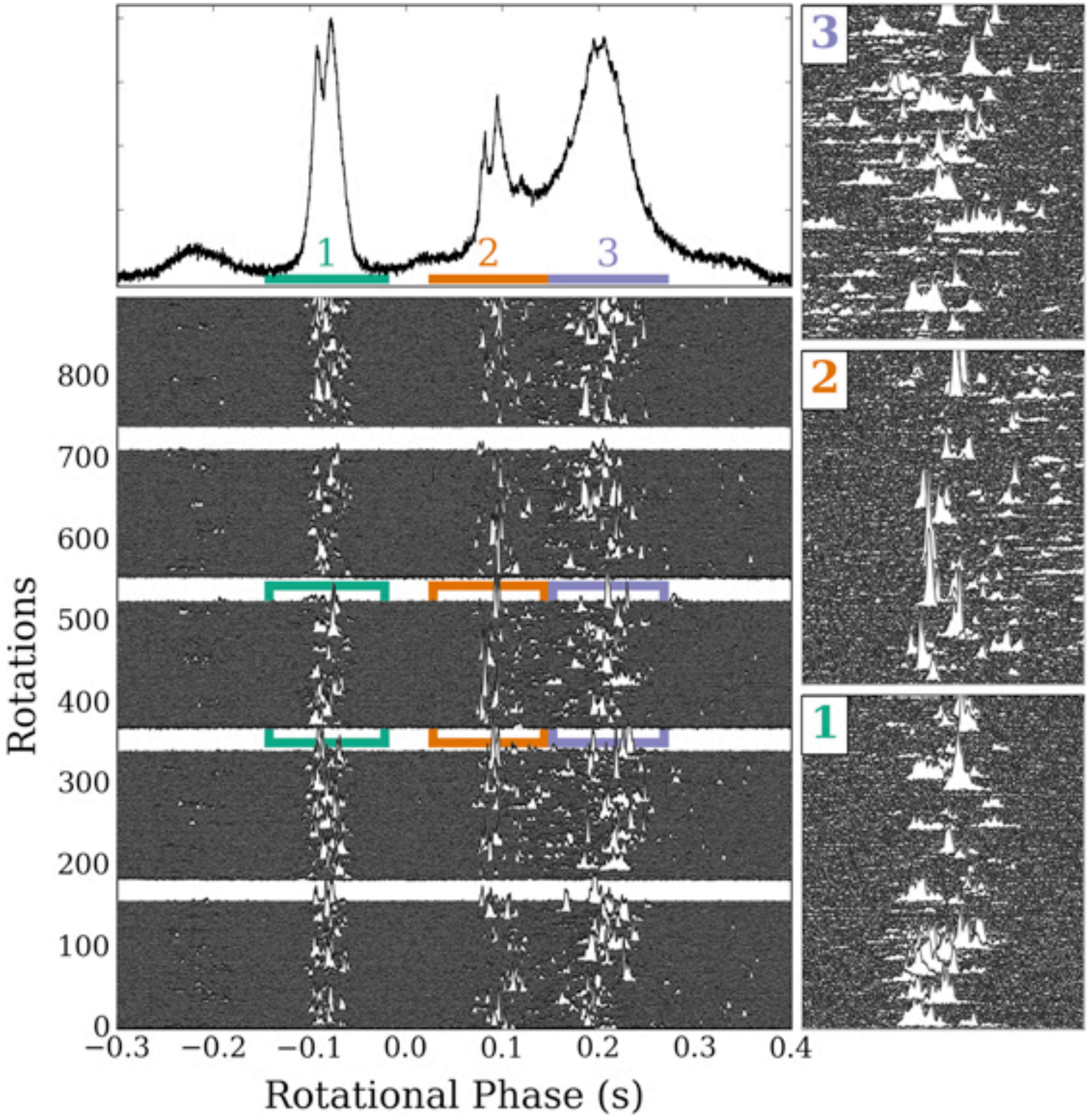
- Dipolar magnetic field strengths: 10^{11} - 10^{15} G
- Rotation-powered emission
- Pair cascade:
  - Large voltage induced by strong rotating magnetic field accelerates particles along field lines, which emit gamma-ray photons through curvature radiation.
  - Electron-positron pairs produced from the gamma-ray photons, which in turn produce more gamma-ray photons
- Method of conversion of this kinetic energy into radio emission is still not established (curvature, synchrotron, or inverse Compton)



J1745-2900

- Radio loud magnetar in the Galactic center
- Magnetars are a sub-class of neutron star with particularly strong magnetic fields
- Only 6 of the ~30 known magnetars show radio emission
- Magnetars exhibit rapid changes in pulsed profile and spectrum





Credit: Wharton et al. 2019

Coherent emission process: beyond the light cylinder

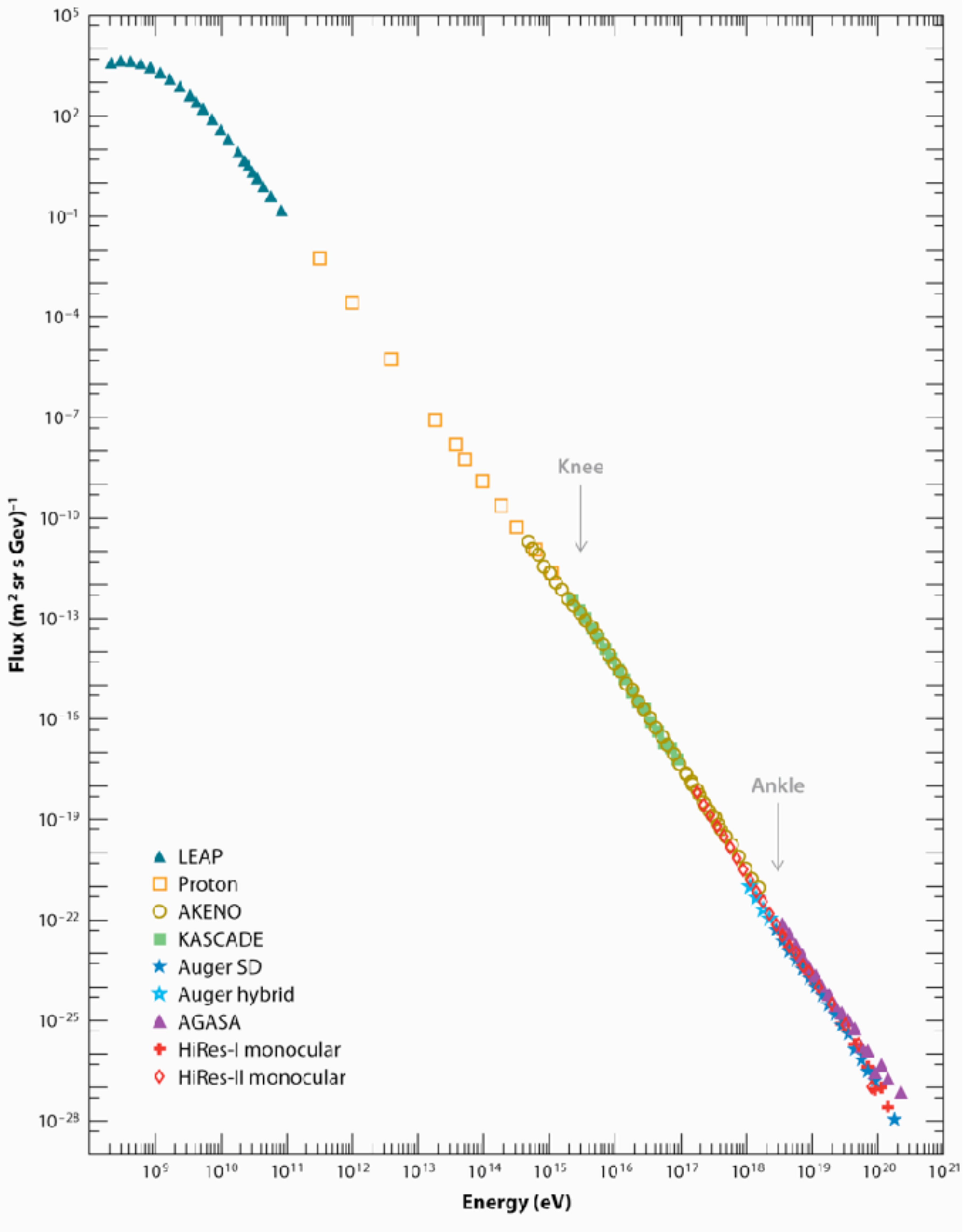
- Magnetic reconnection in the current sheet
- Origin of gamma-ray emission in pulsars

b) magnetic reconnection in the plasmoid

Credit: Philippov et al

Astroparticle physics: cosmic rays

- High-energy particles accelerated extreme energies
- Origin is unknown
- Detection through various methods:
  - Optical air showers
  - Florescence



Beatty JJ, Westerhoff S. 2009.
Annu. Rev. Nucl. Part. Sci. 59:319–45

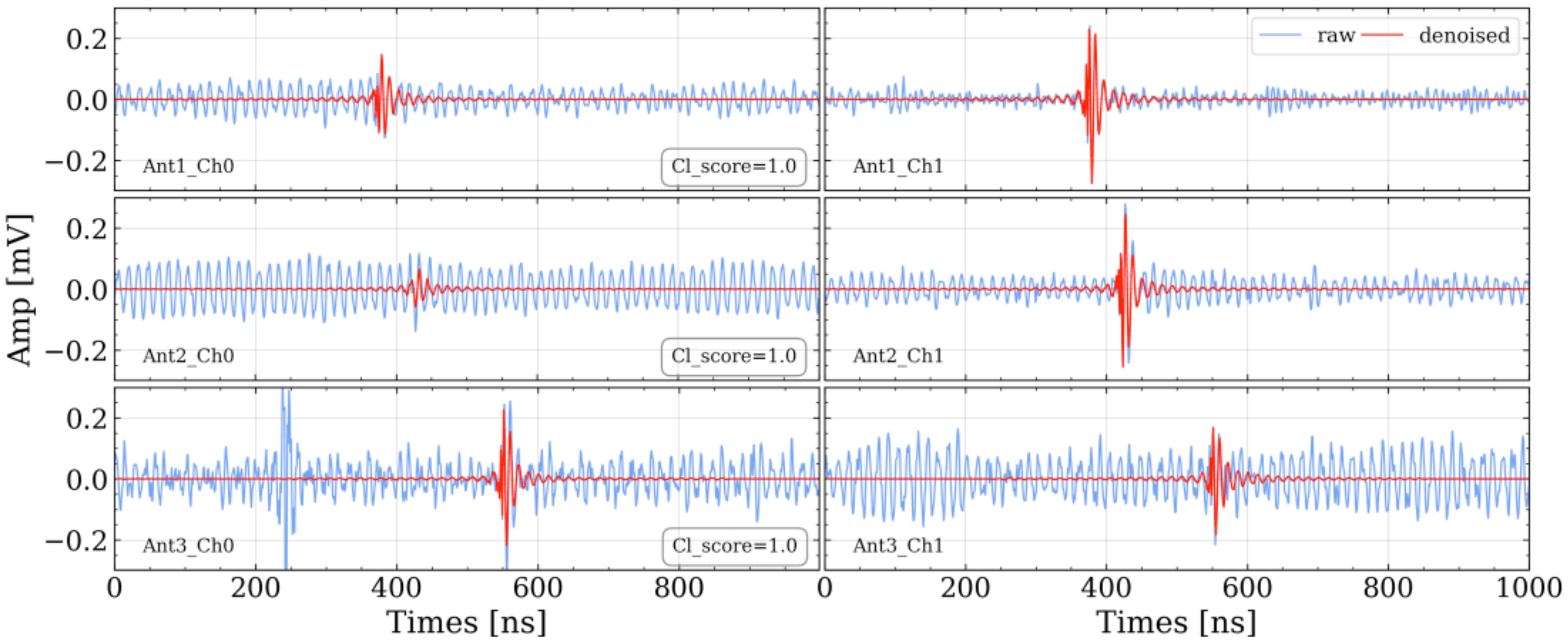
Astroparticle physics: cosmic rays

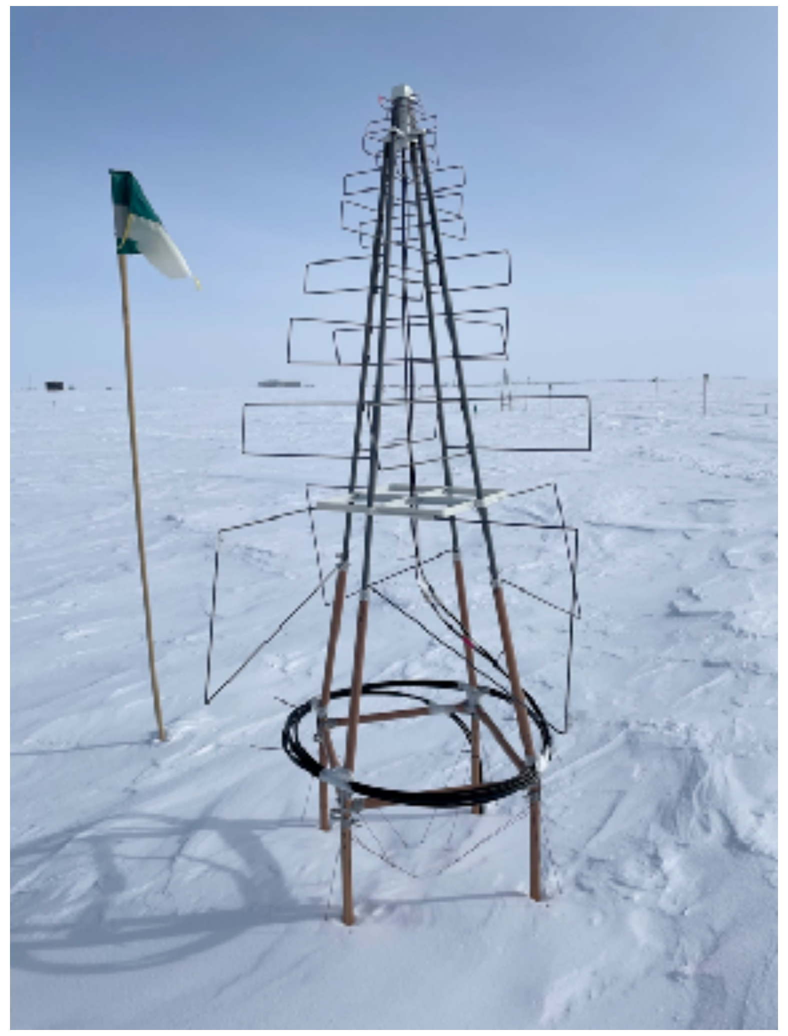
- Cosmic ray creates a pair cascade in the Earth's atmosphere
- Charged particles accelerated in the Earth's magnetic field
- Produce short-duration pulsed radio emission

Credit: ASTRON/KIT/Radboud

Astroparticle physics: cosmic rays

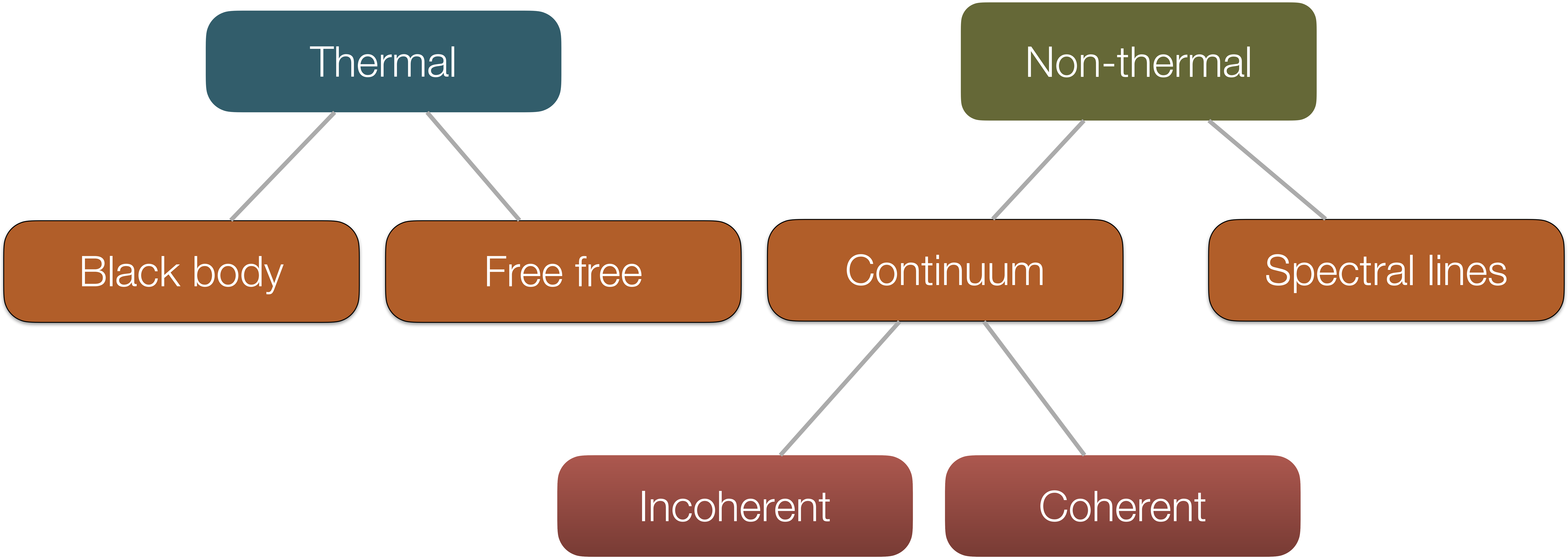
- Duration: 10 - 100 ns
- Spectrum: 30 MHz - a few GHz
- Coherent
- High linear polarization
- Strongly beamed





Credit: IceCube collaboration

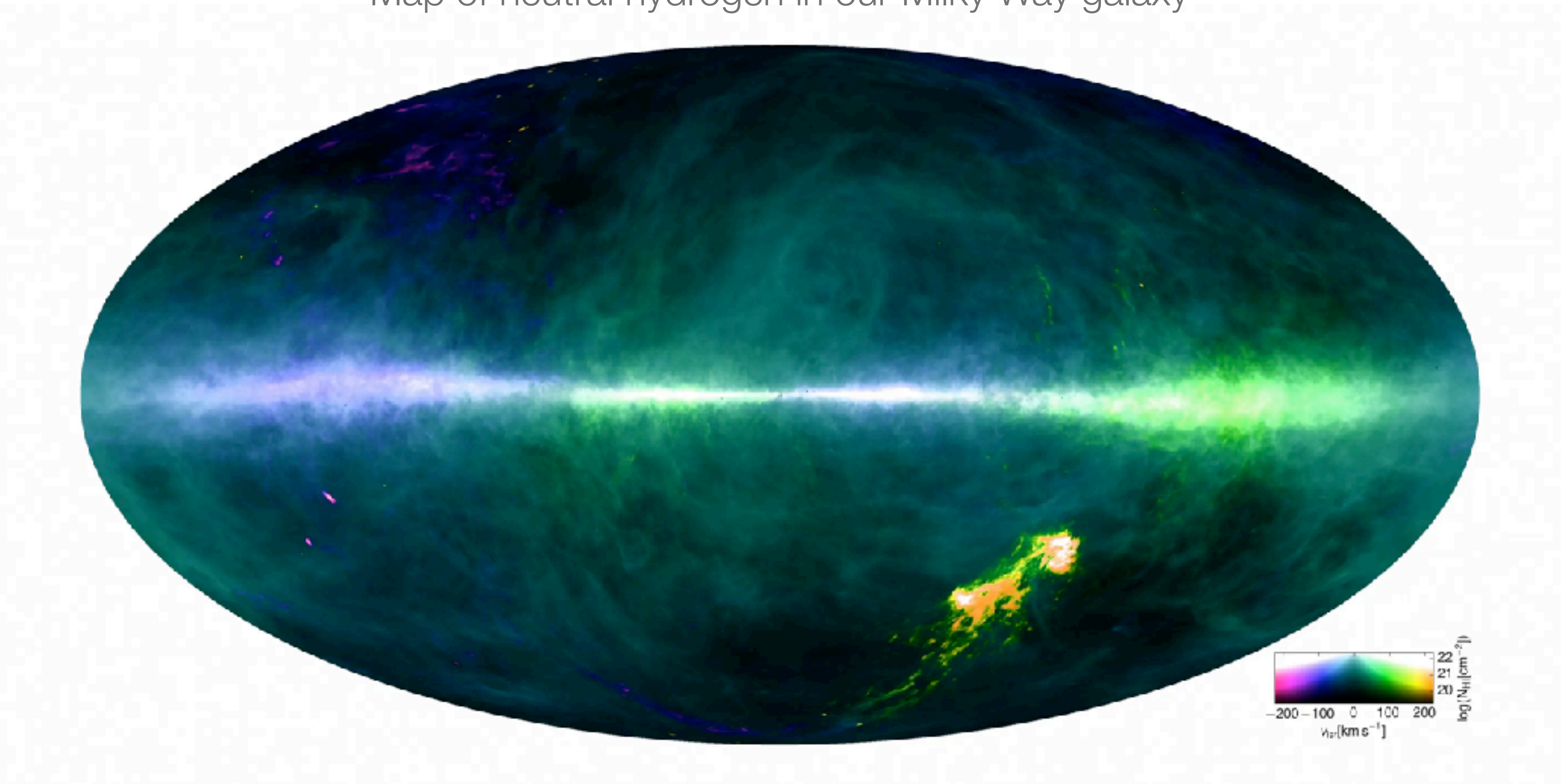
Emission mechanisms



Spectroscopy

- Spin flip transition of neutral hydrogen (HI)
  - ν = 1,420.405751786 MHz
  - λ = 21.106114054160 cm
  - So-called “21-cm line”
- Sets the most common radio astronomy frequency

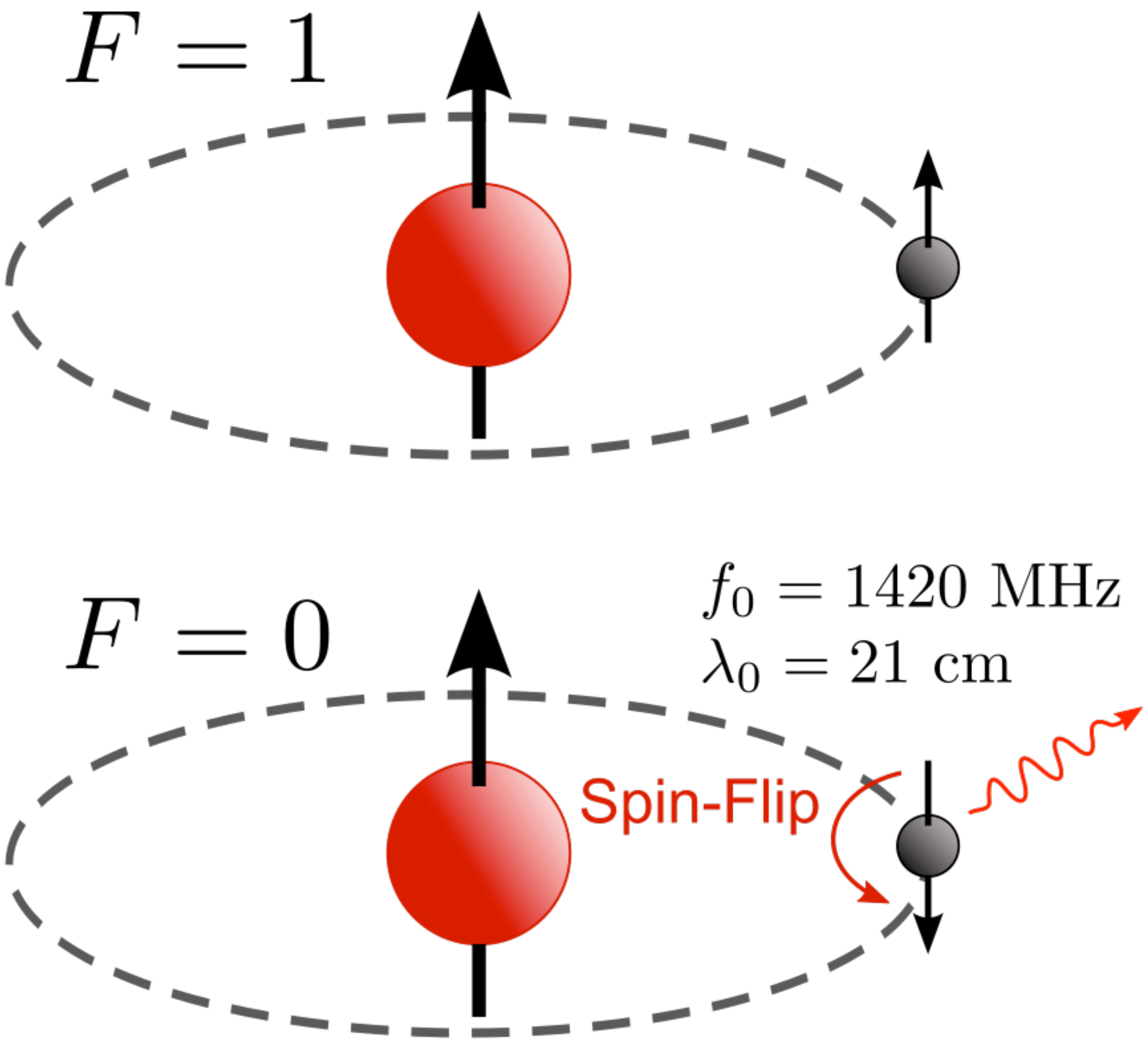
Map of neutral hydrogen in our Milky Way galaxy



Credit: HI4PI Collaboration

Spectroscopy: physics

- Quantum mechanical spin of the electron and proton split into hyperfine levels with aligned or mis-aligned spins
- A photon with energy 5.8 μeV is emitted when an aligned hydrogen atom transitions to a mis-aligned atom.
  - ν = 1,420.405751786 MHz
  - λ = 21.106114054160 cm

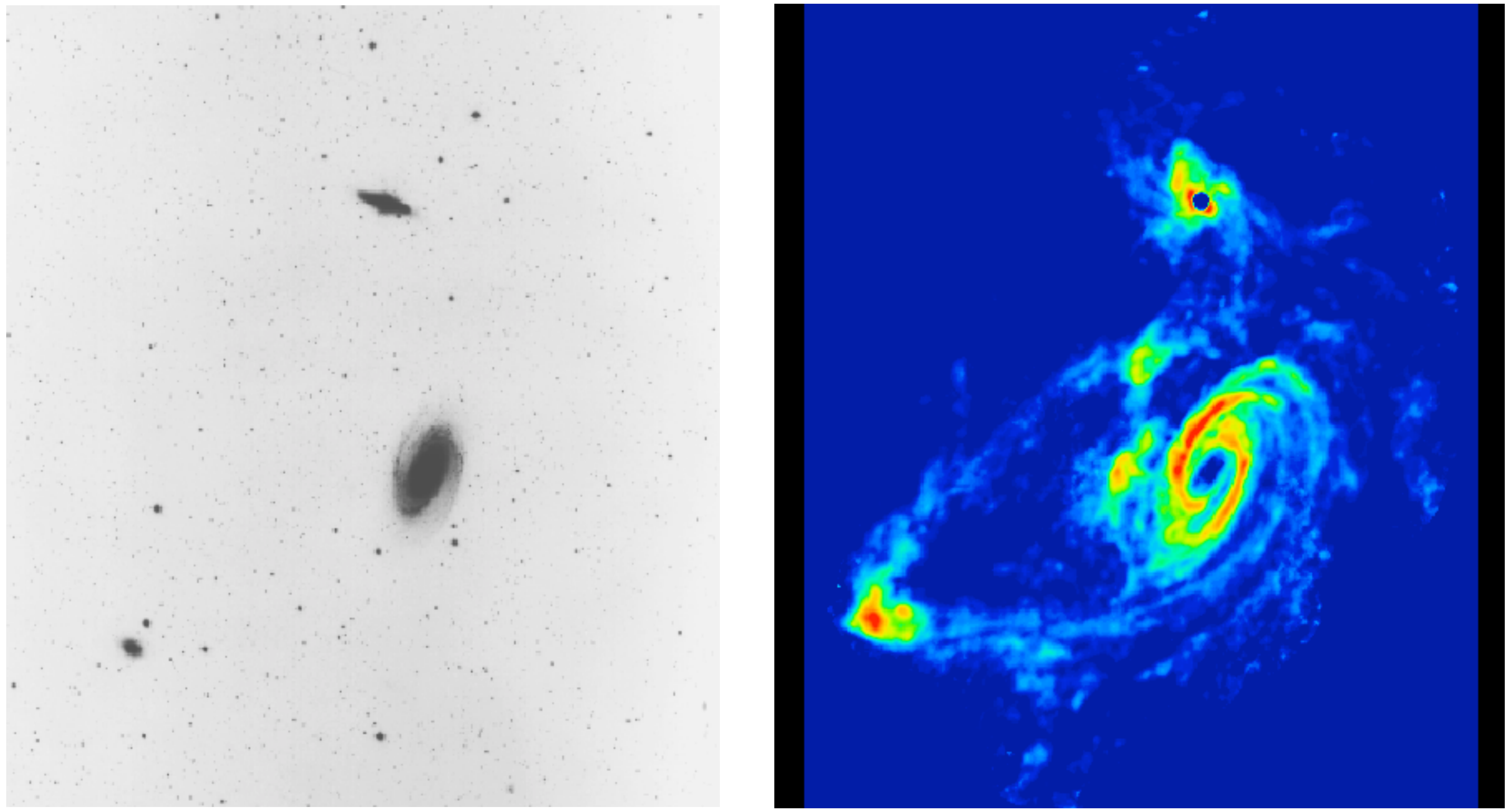


Credit: Wikipedia

Spectroscopy: HI science

- HI often extends beyond stellar disk and can reveal evidence for tidal interactions
- Fuel for star formation
- Doppler-shifted frequency can reveal rotation of galactic disk
- Key tracer of the epoch of reionization
    - Redshifted to $\nu = 200$ MHz at $z = 6$

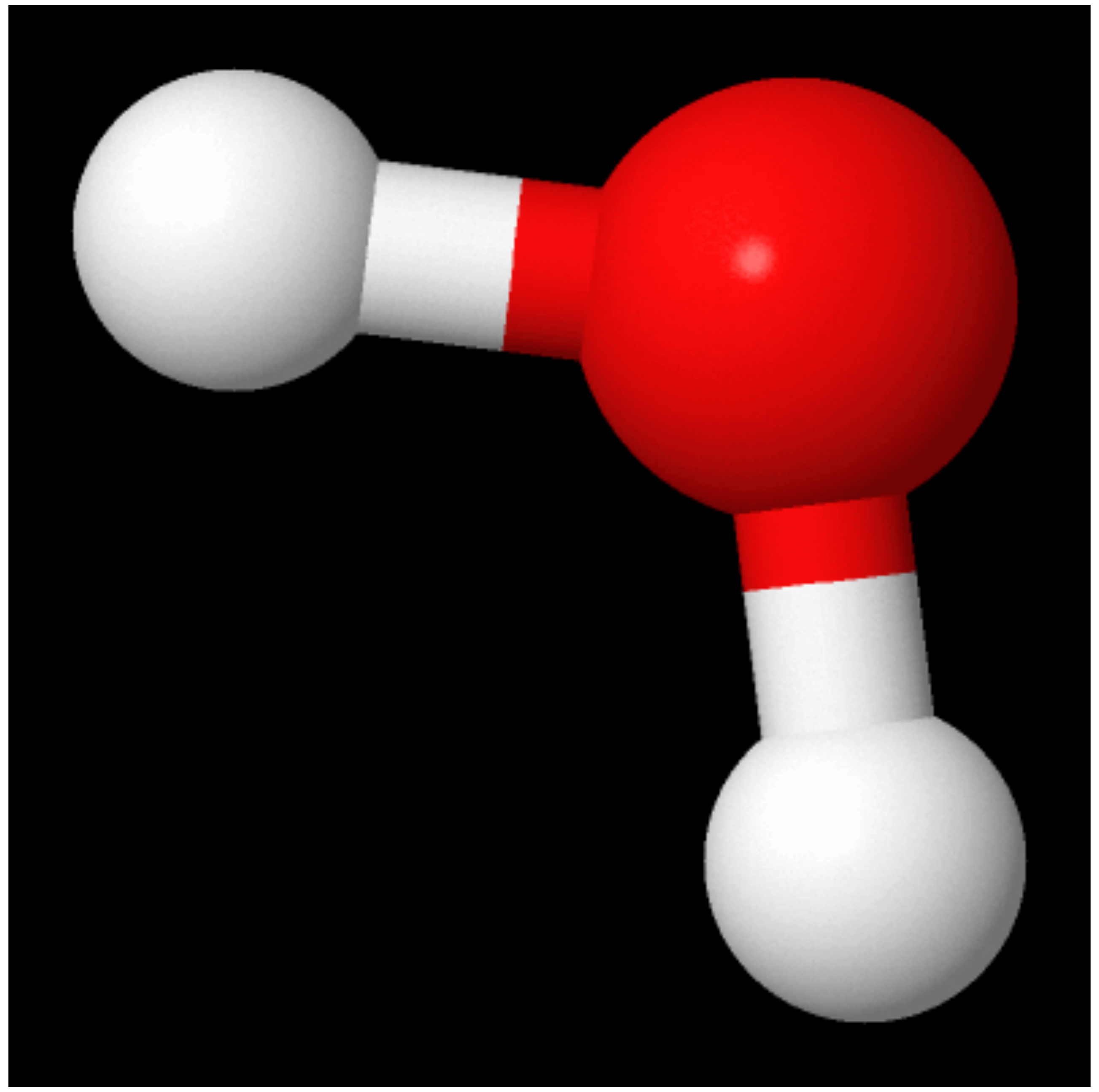
Tidal interactions in the M81 galaxy group

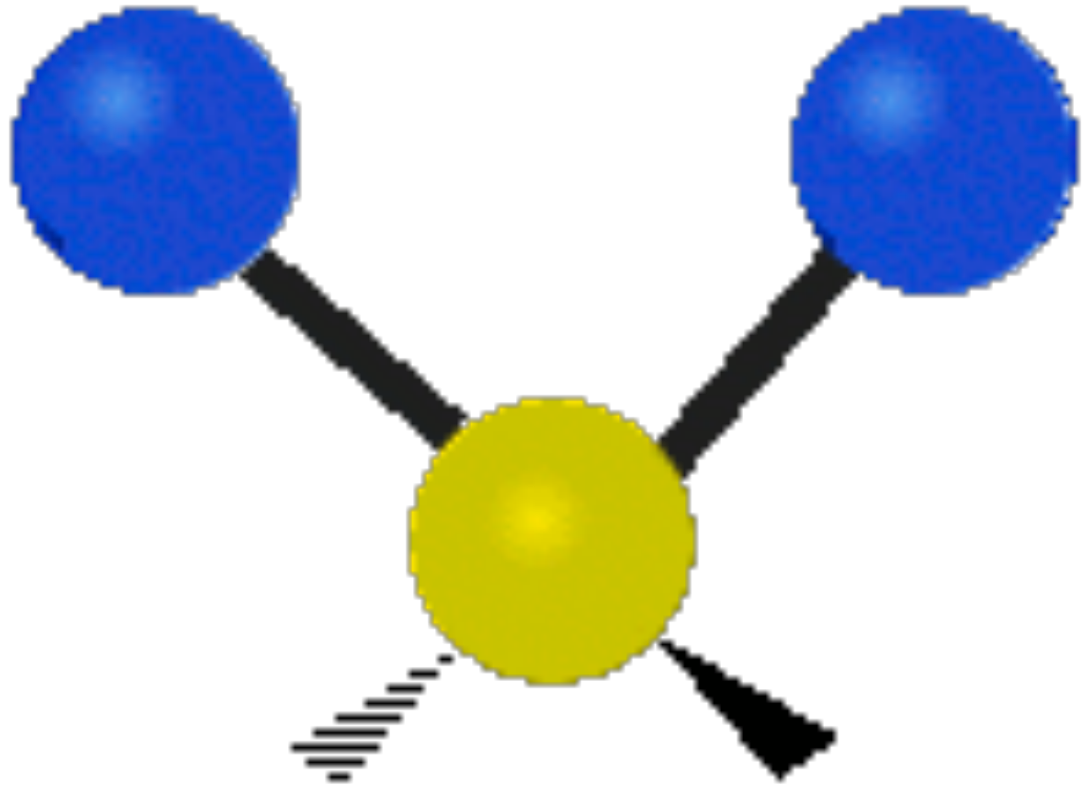


Credit: Yun, Ho, Lo, *Nature*, 1994

Spectroscopy: molecular vibrations or rotations

- Spectral lines predominately from molecular transitions
- Particularly abundant in observations at millimeter and sub-millimeter wavelengths





Credit: Wikipedia

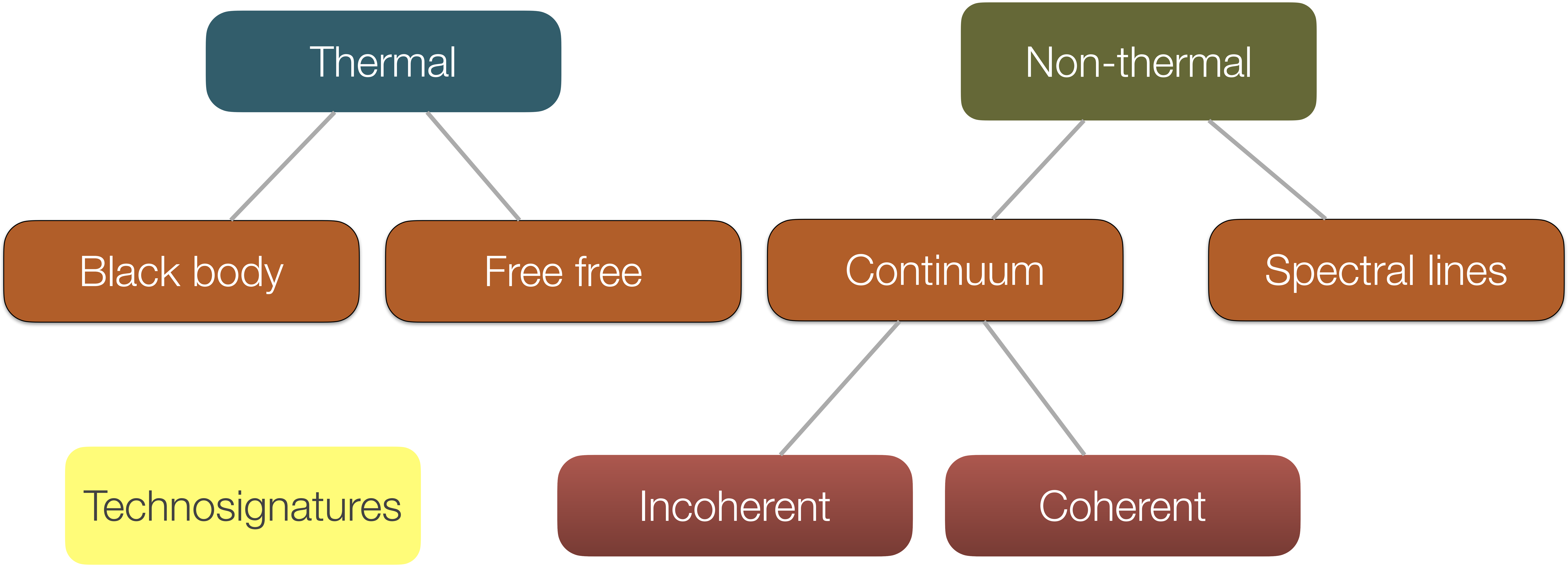
Additional molecular lines

Atom/Molecule	Line Name	Rest frequency (GHz)
HI	neutral hydrogen	1.420405752
OH	hydroxyl radical	1.612231
OH	hydroxyl radical	1.6654018
OH	hydroxyl radical	1.667359
OH	hydroxyl radical	1.72053
H_2CO	ortho-formaldehyde	4.82966
CH_3OH	methanol	6.668518
HC_3N	cyanoacetylene	9.098332
CH_30H	methanol	12.178593
H_2CO	ortho-formaldehyde	14.48849
C_3H_2	ortho-cyclopropenylidene	18.343145
H_20	ortho-water	22.23507985
NH_3	para-ammonia	23.694506
NH_3	para-ammonia	23.722634
NH_3	ortho-ammonnia	23.87013
SiO	silicon monoxide	42.82057

Atom/Molecule	Line Name	Rest frequency (GHz)
SiO	silicon monoxide	43.12209
SiO	silicon monoxide	43.423853
CS	carbon monosulfide	48.990964
DCO^+	deuterated formylium	72.039331
SiO	silicon monoxide	85.640456
SiO	silicon monoxide	86.243442
$H^{13}CO^+$	formylium	86.754294
SiO	silicon monoxide	86.846998
HCN	hydrogen cyanide	88.631847
HCO^+	formylium	89.188518
HNC	hydrogen isocyanide	90.663574
N_2H^+	diazenylium	93.173809
CS	carbon monosulfide	97.980968
$C^{18}O$	carbon monoxide	109.782182
^{13}CO	carbon monoxide	110.20137
CO	carbon monoxide	115.271203

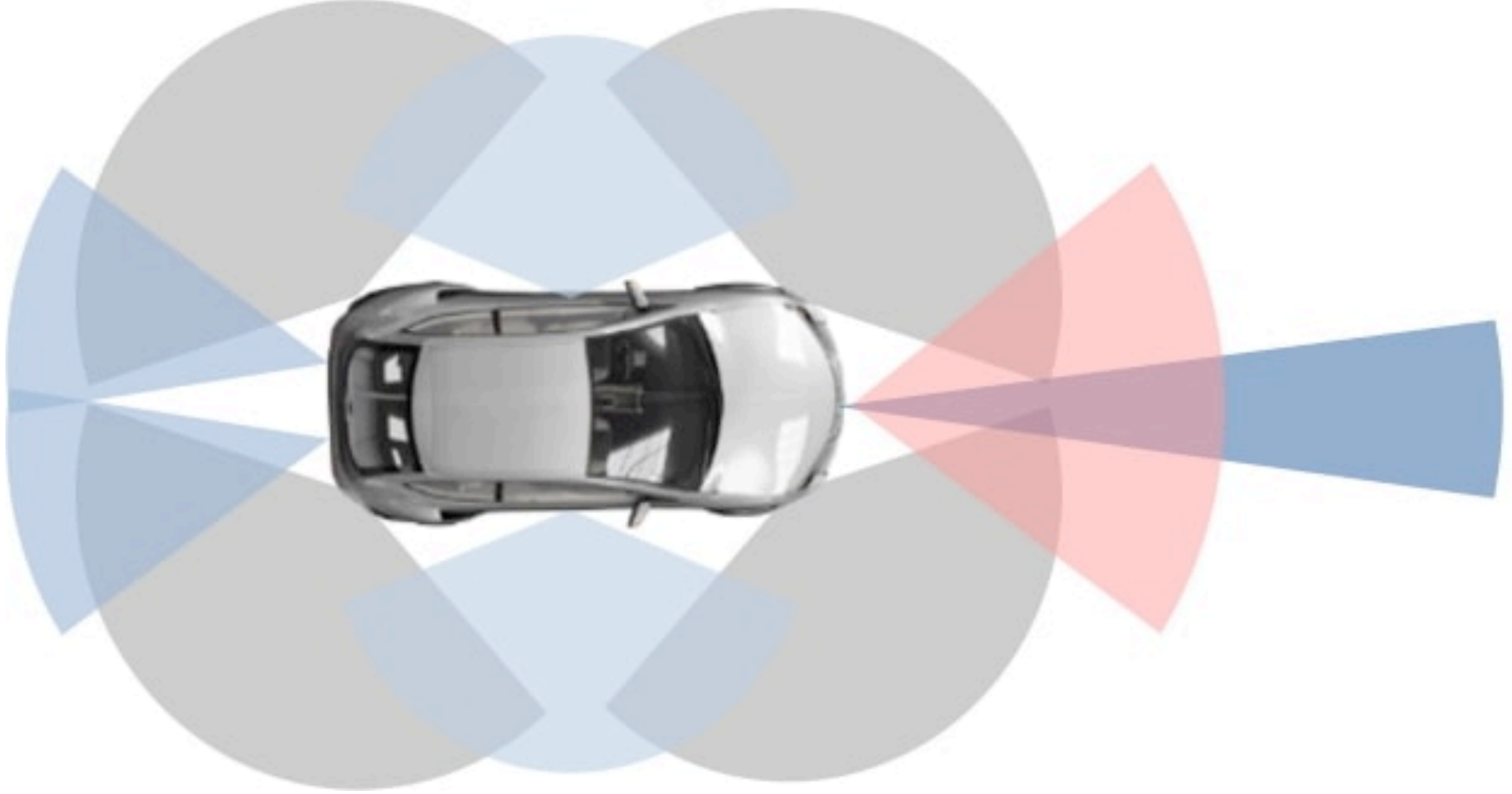
Credit: Karen Lee-Waddell

Emission mechanisms



Techno-signatures:
radio frequency interference

- Radio transmission from human-generated communication
- Generally brighter than the astrophysical signals
- More on this later…

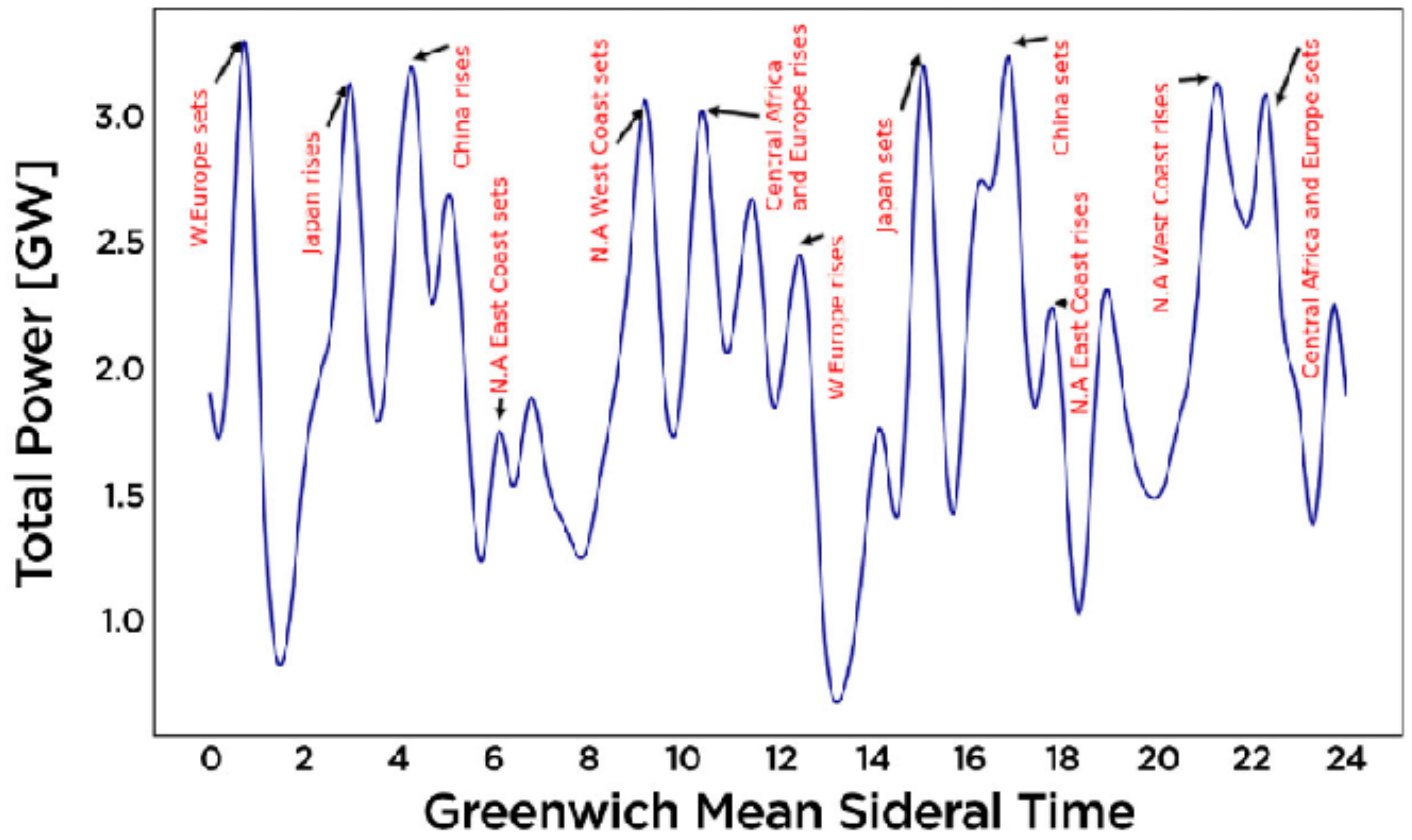


Credit: Wikipedia
https://semiengineering.com/RADAR-for-automotive-why-do-we-need-RADAR/

Techno-signatures: extraterrestrial

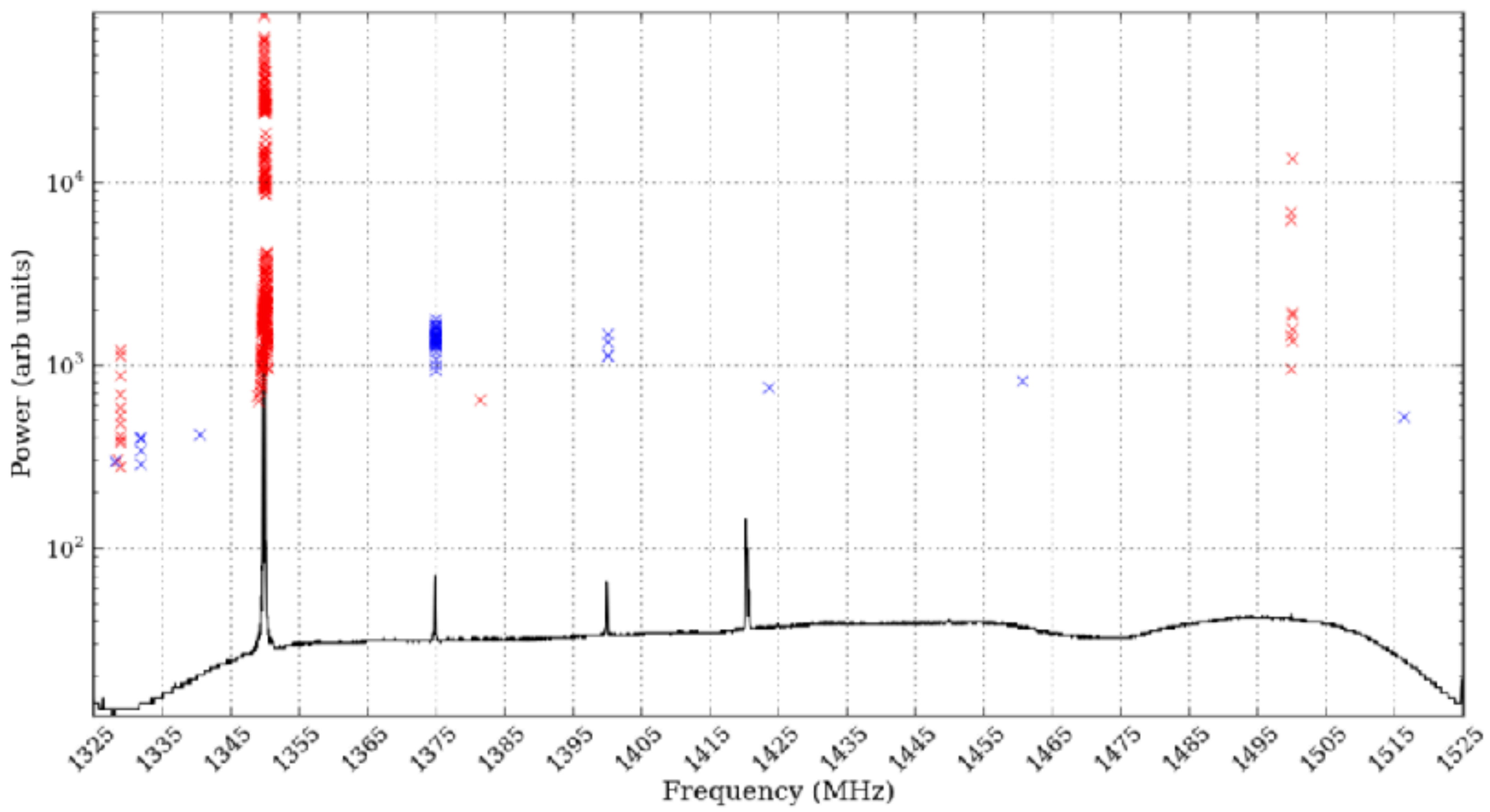
- Search for signals that are "unnatural"
  - Extremely narrow spectral lines (~Hz)
  - Planetary "leakage" radiation
- Searches often done commensually on other observations

Barnard star: RA = 17.9636^h, Dec = 4.693391°



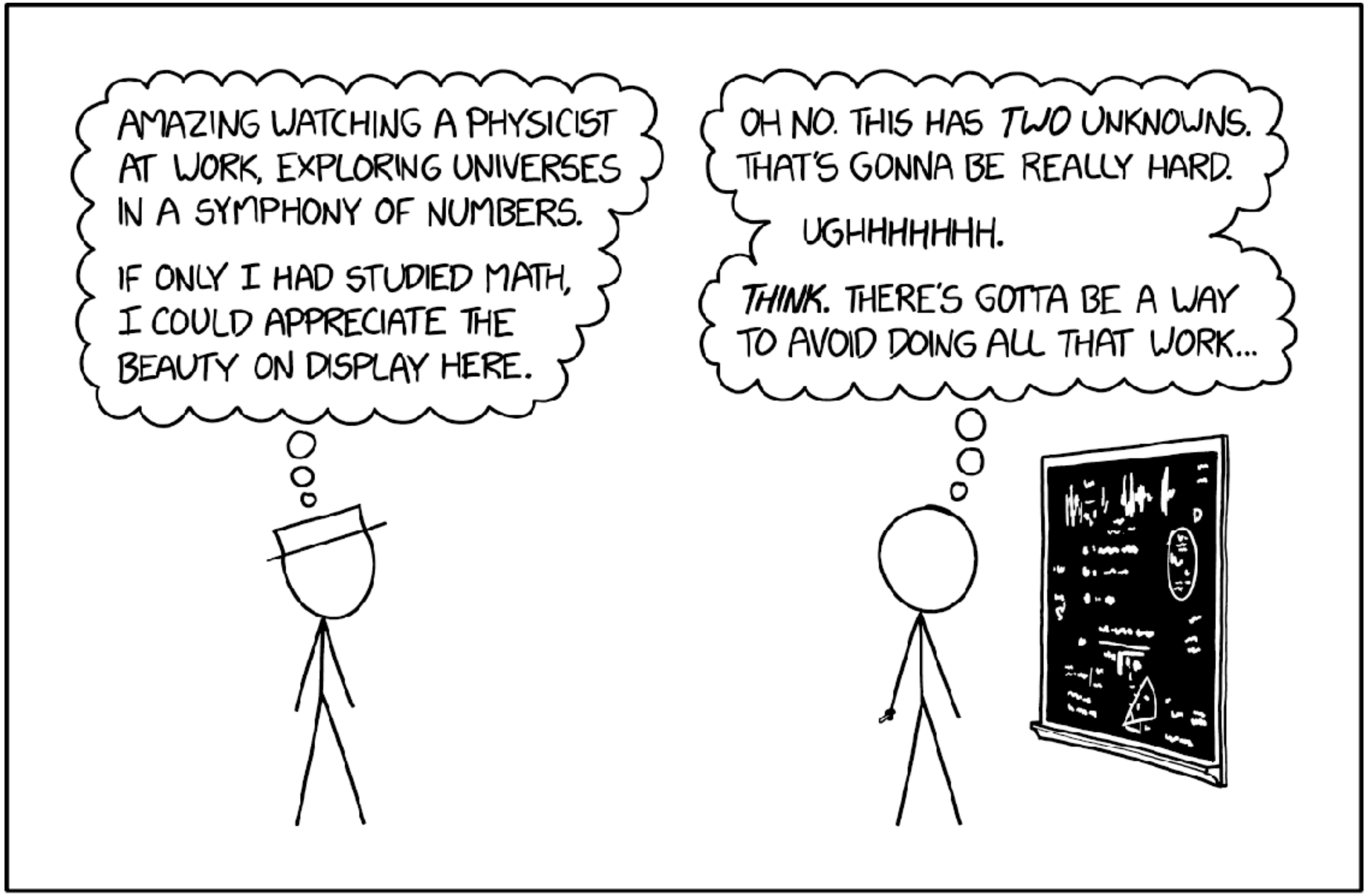
Credit: Saide et al 2023

SERENDIP V survey



Discussion and Question break

xkcd: 2207



Hover over text: “I could type this into a solver, which MIGHT help, but then I have to get all the parentheses right.”

Type of radio telescopes

Single dish

Effelsberg 100-m radio telescope

Interferometer

MeerKAT radio interferometer

Image credits:
(left): MPIfR
(right): SARAO

Single dishes

- Single antenna observing independently
- Strengths
  - High sensitivity
  - Wider frequency coverage
- Weaknesses
  - Angular resolution
  - Small number of beams
  - Robustness to RFI

Image credits:
Top (L. Spitler)
Bottom (SCJiang/Wikipedia)

Interferometers

- Several smaller antennas observing together
- Strengths
  - High spatial resolution
  - Imaging capabilities
  - More robust to RFI
- Weaknesses
  - Lower sensitivity
  - Narrower bandwidths

Image credits:
Top: NRAO
Bottom: ASTRON

Radiometer Equation

Observed signal-to-noise ratio

System temperature

Observed flux density: $$S_\nu = \left(\frac{S}{N}\right)\frac{2kT_{\rm sys}}{A_e\sqrt{n_p \Delta\nu_{\rm BW} t_{\rm int}}}$$

Integration time

Effective area

Integrated bandwidth

Number of summed polarizations

System equivalent flux density: $S_{\rm sys} = \dfrac{2kT_{\rm sys}}{A_e}$

System sensitivity

- Thermal noise of a receiving system can be quantified by an effective temperature

e.g. CMB, MW synchrotron

System temperature: $T_{\text{sys}} = T_{\text{RX}} + T_{\text{sky}}$

System equivalent flux density: $S_{\text{sys}} = \dfrac{2kT_{\text{sys}}}{A_e}$

Diffraction-limited optics (SD)

- $\theta_{\mathrm{beam}} \approx 1.2\frac{\lambda}{D}$

  where D is the diameter of the single dish antenna

- A radio telescope can only spatially distinguish between points on the sky separated by more than θ_{beam}

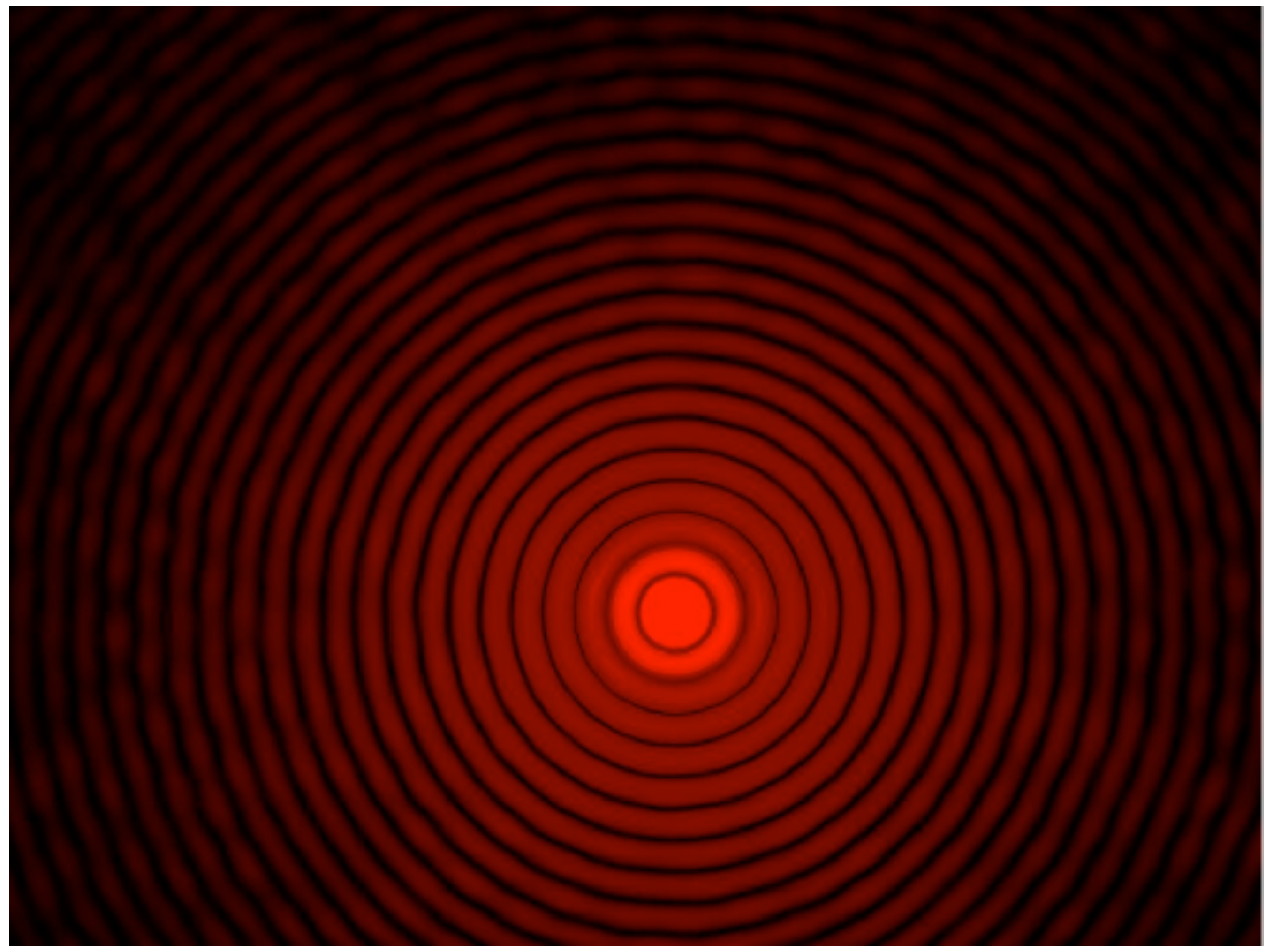
- Main lobe well-approximated with a Gaussian

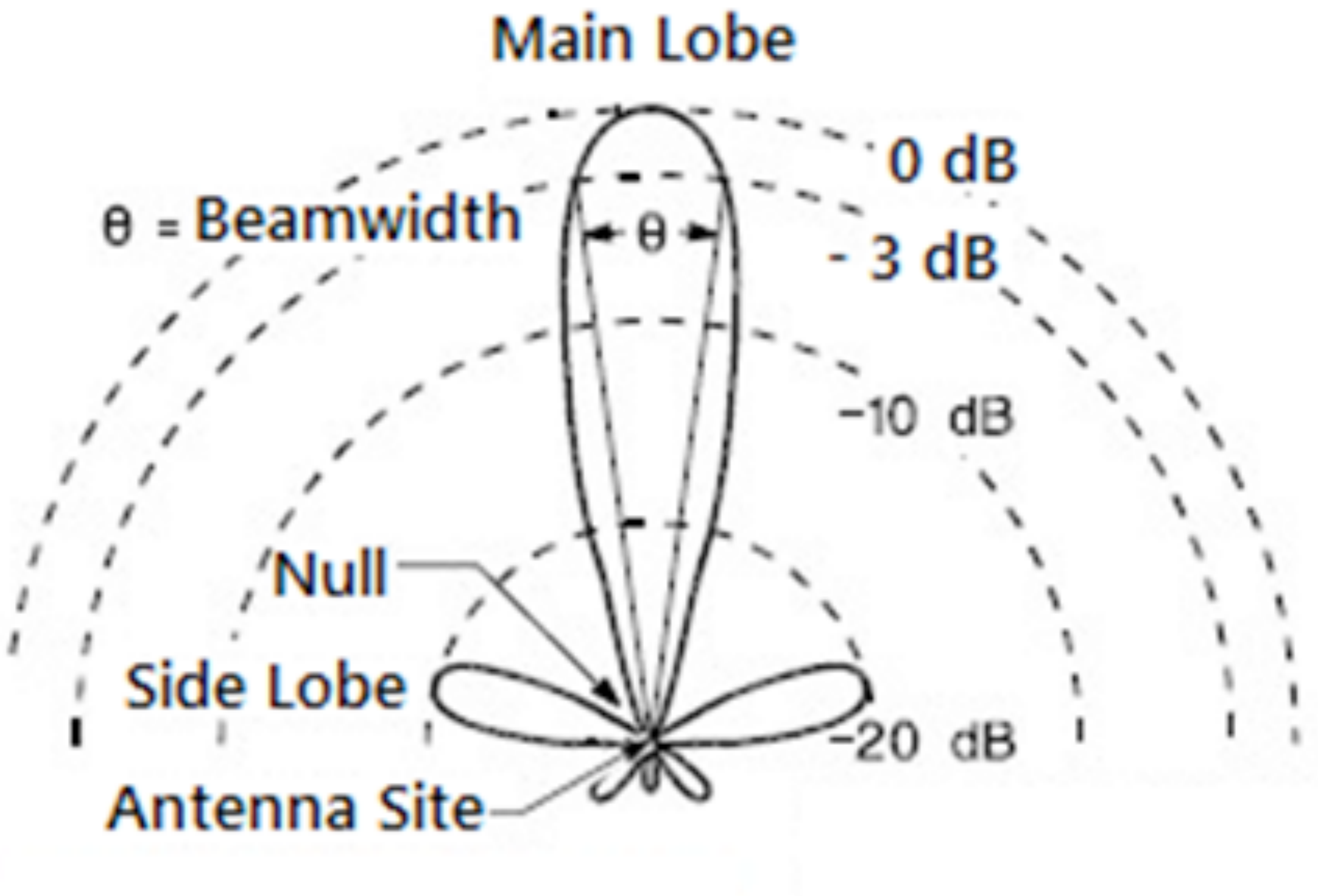
- θ_{beam} is quantified by the “full-width at half maximum (FWHM)”

  - Reference value (Effelsberg):

    - D = 100 m, λ = 21 cm -> θ = 10 arcmin

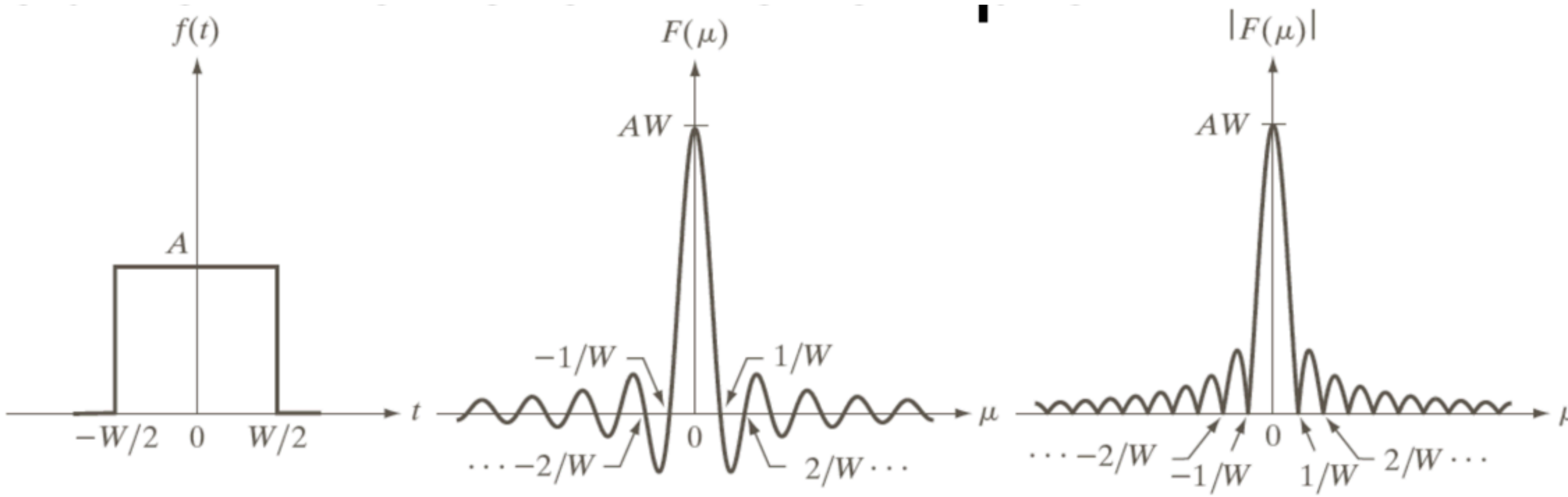
Airy disk



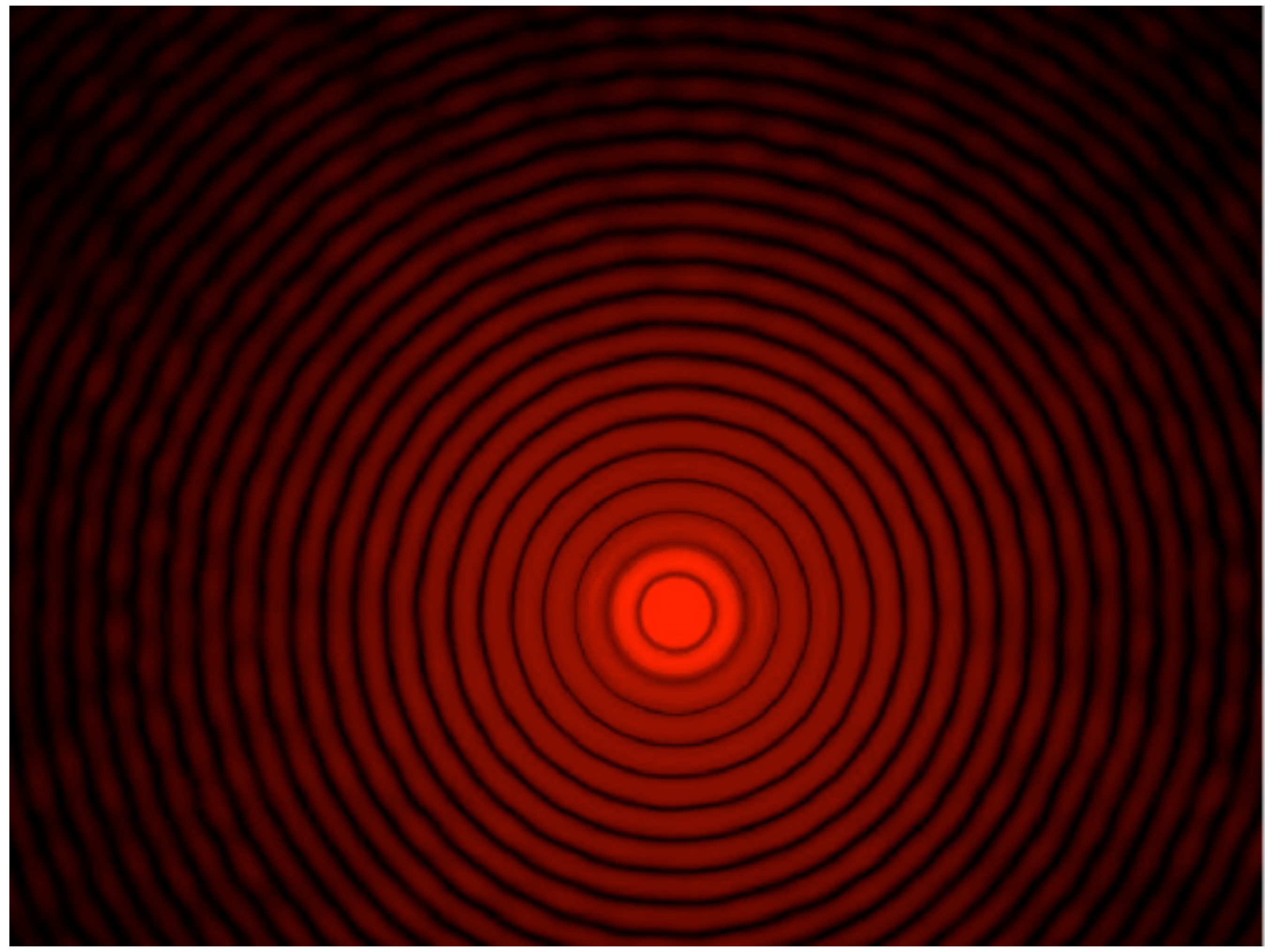


Diffraction-limited optics (SD)

- Fourier transform view:
    - FT(top-hat function) is a sinc function

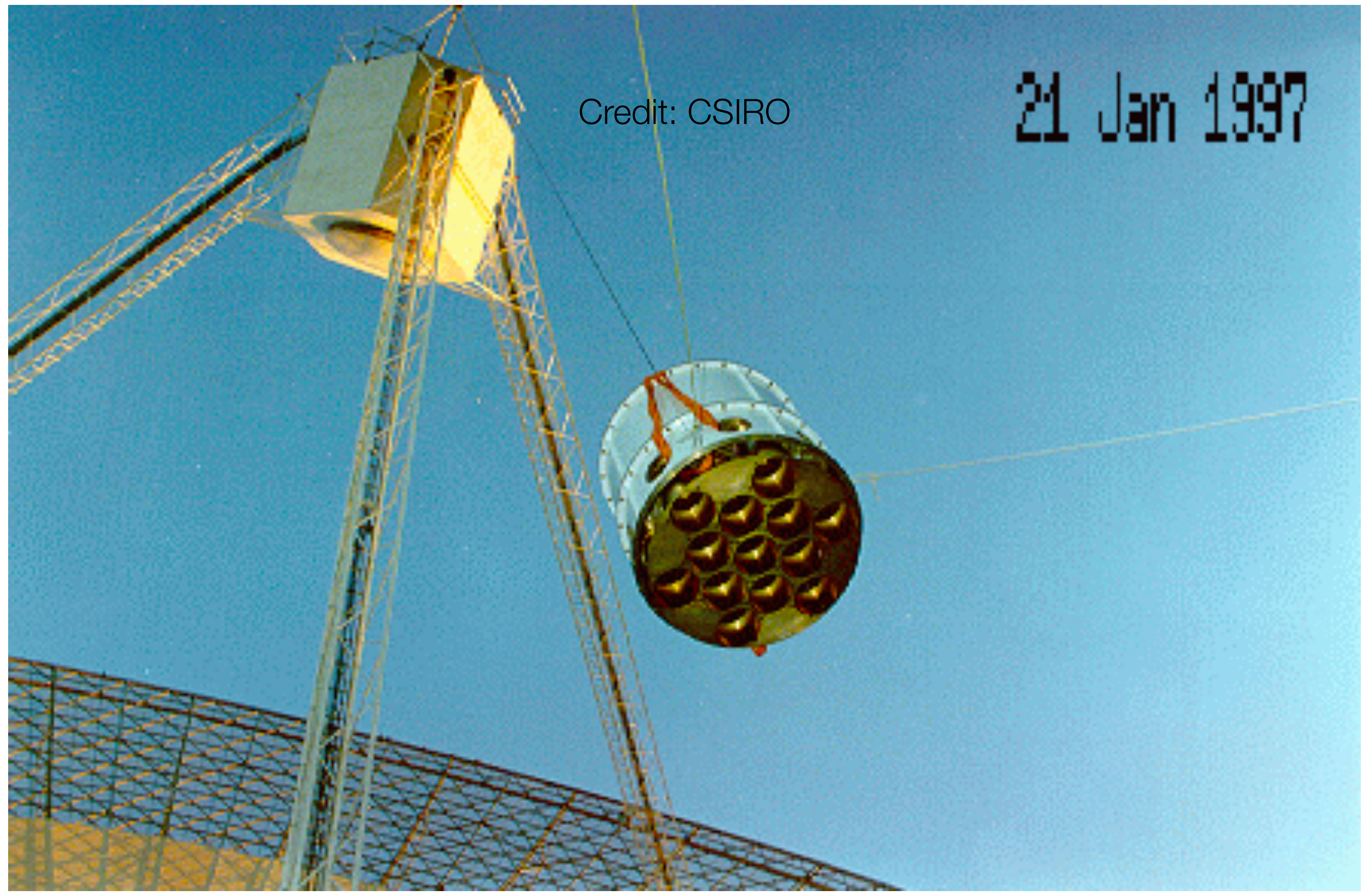


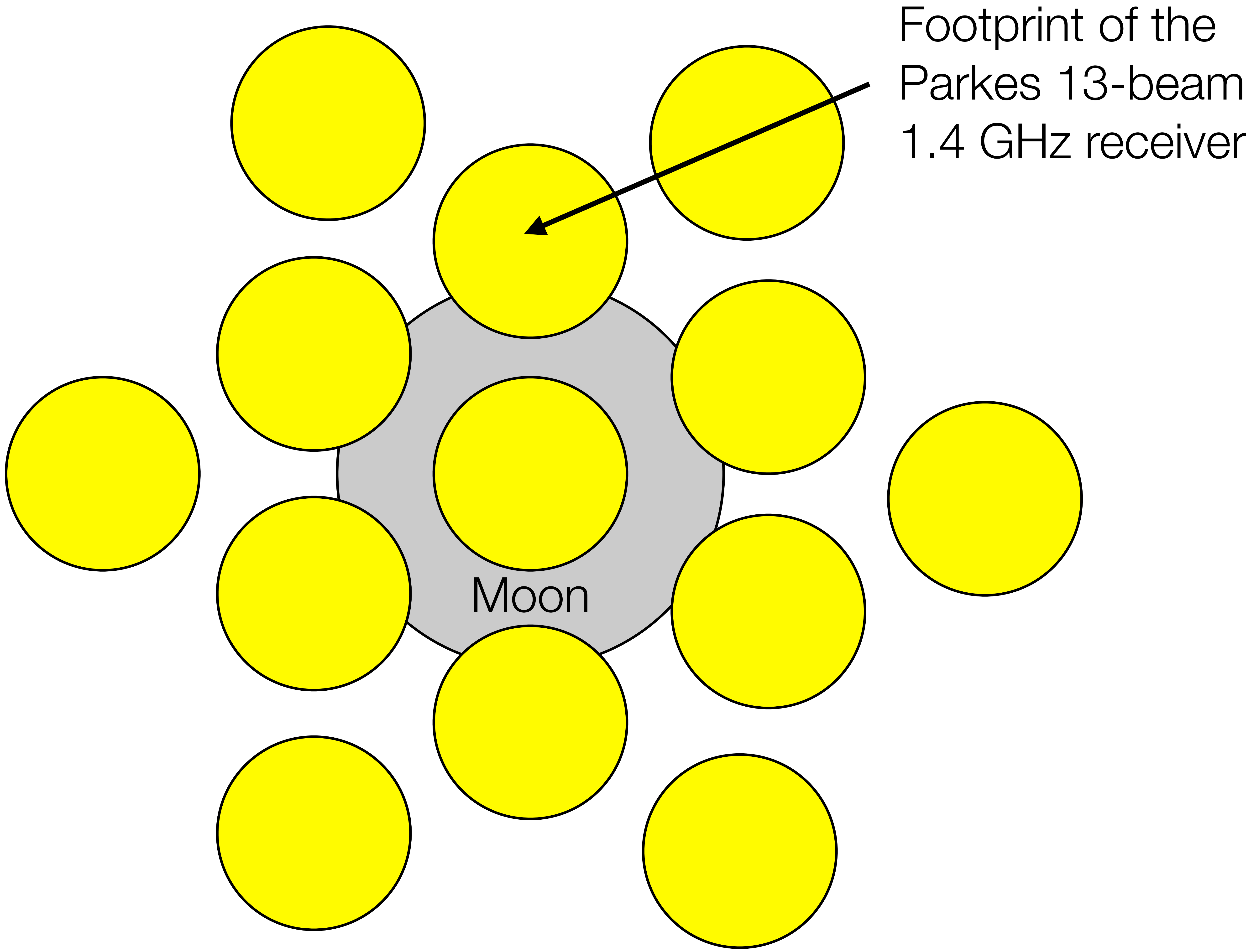
- Diffractive optics view:
    - Airy disk produced by the diffraction through a circular aperture



Single dish spatial resolution

Parkes 13-beam,1.4 GHz receiver

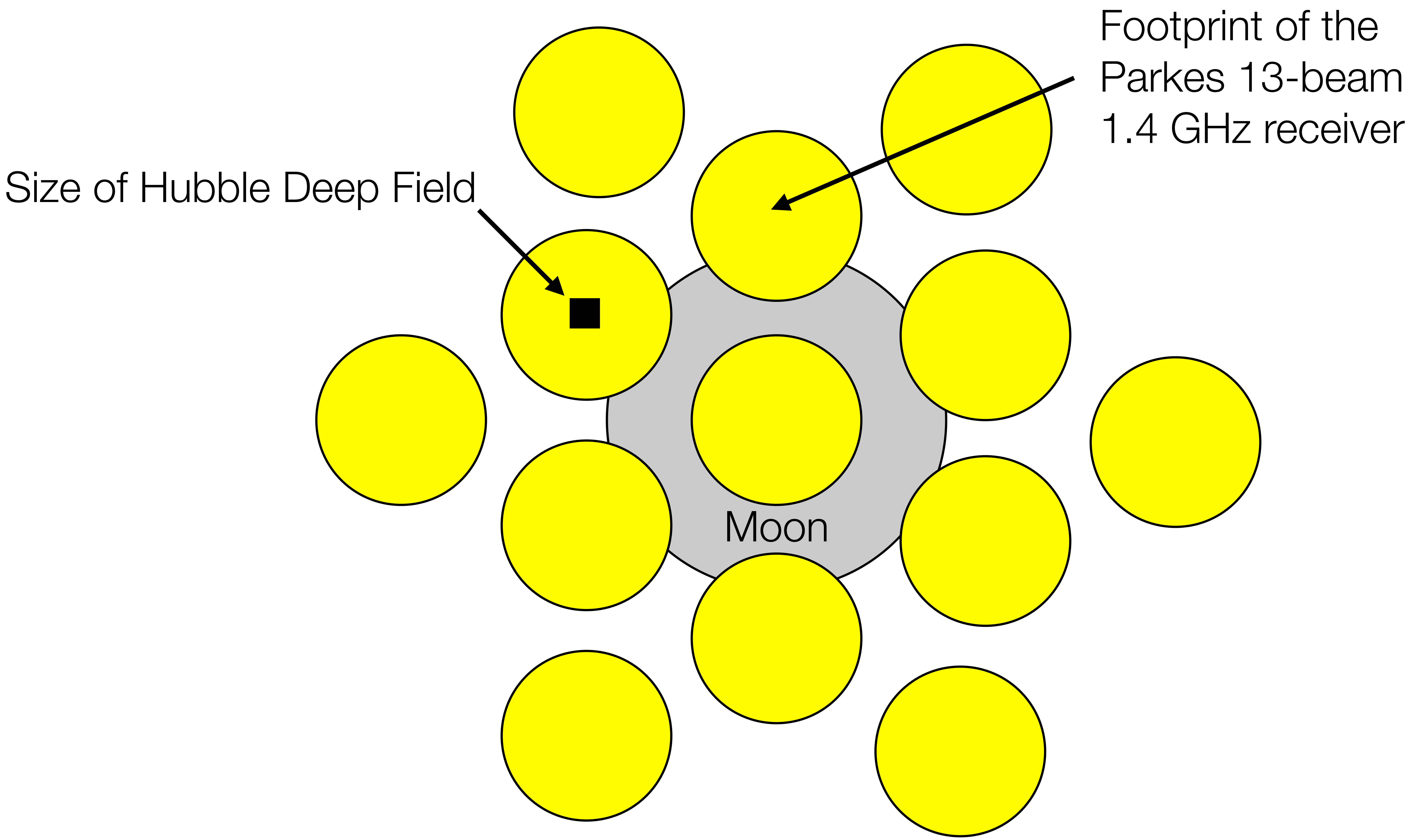




Single dish spatial resolution

Hubble Deep Field

Image Credit: NASA

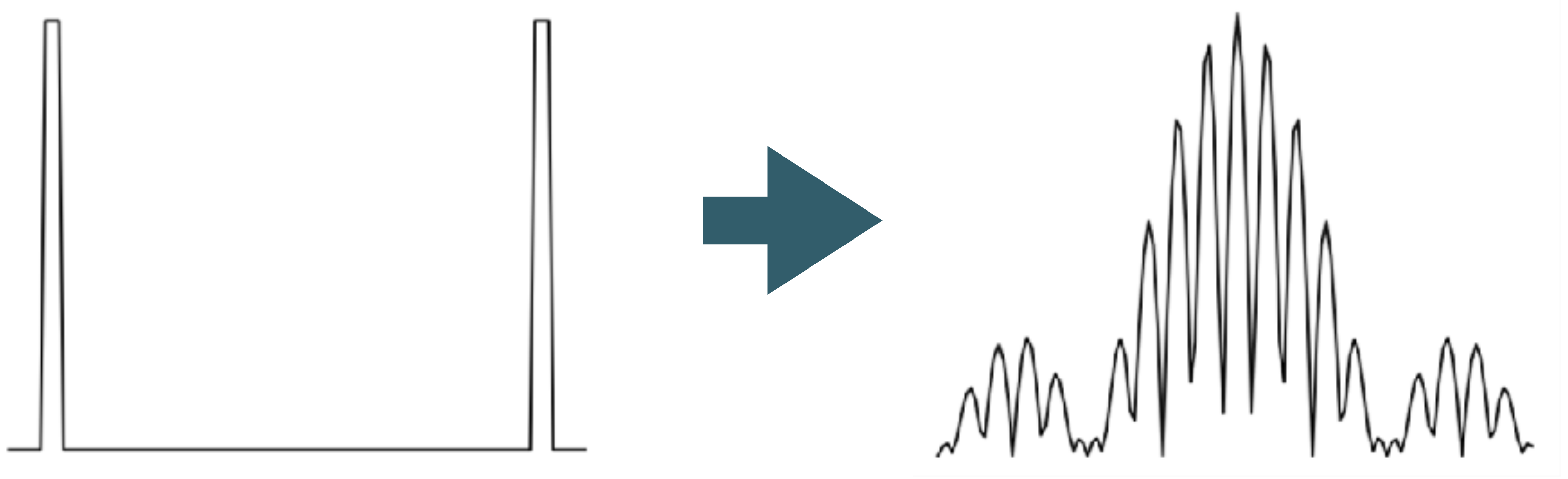


Diffraction-limited optics (Interferometer)

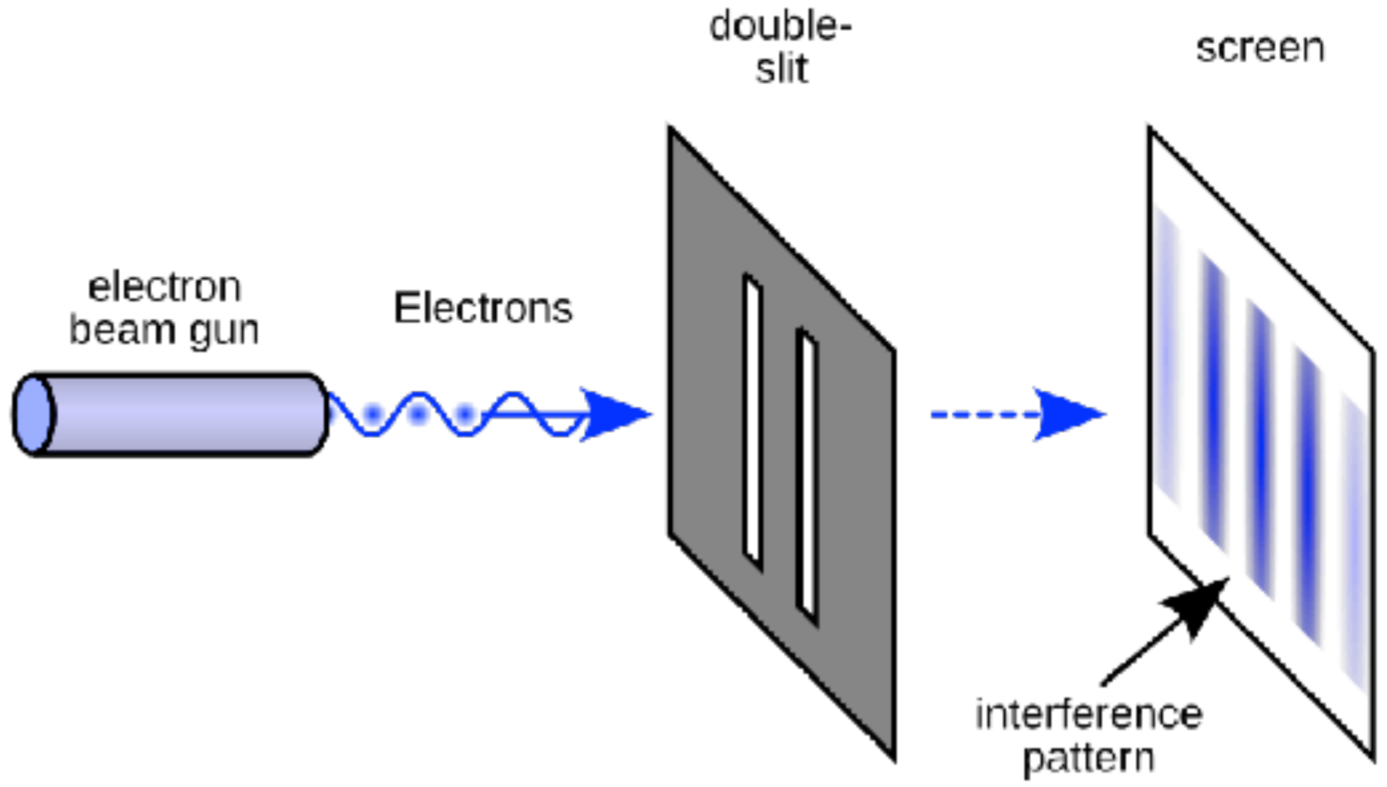
- $\theta_{\text{beam}} \approx 1.2\frac{\lambda}{B}$

  where B is the distance between two antennae ("baseline")

- Fourier transform view (top)



- Diffractive optics view:
  - Double-slit experiment



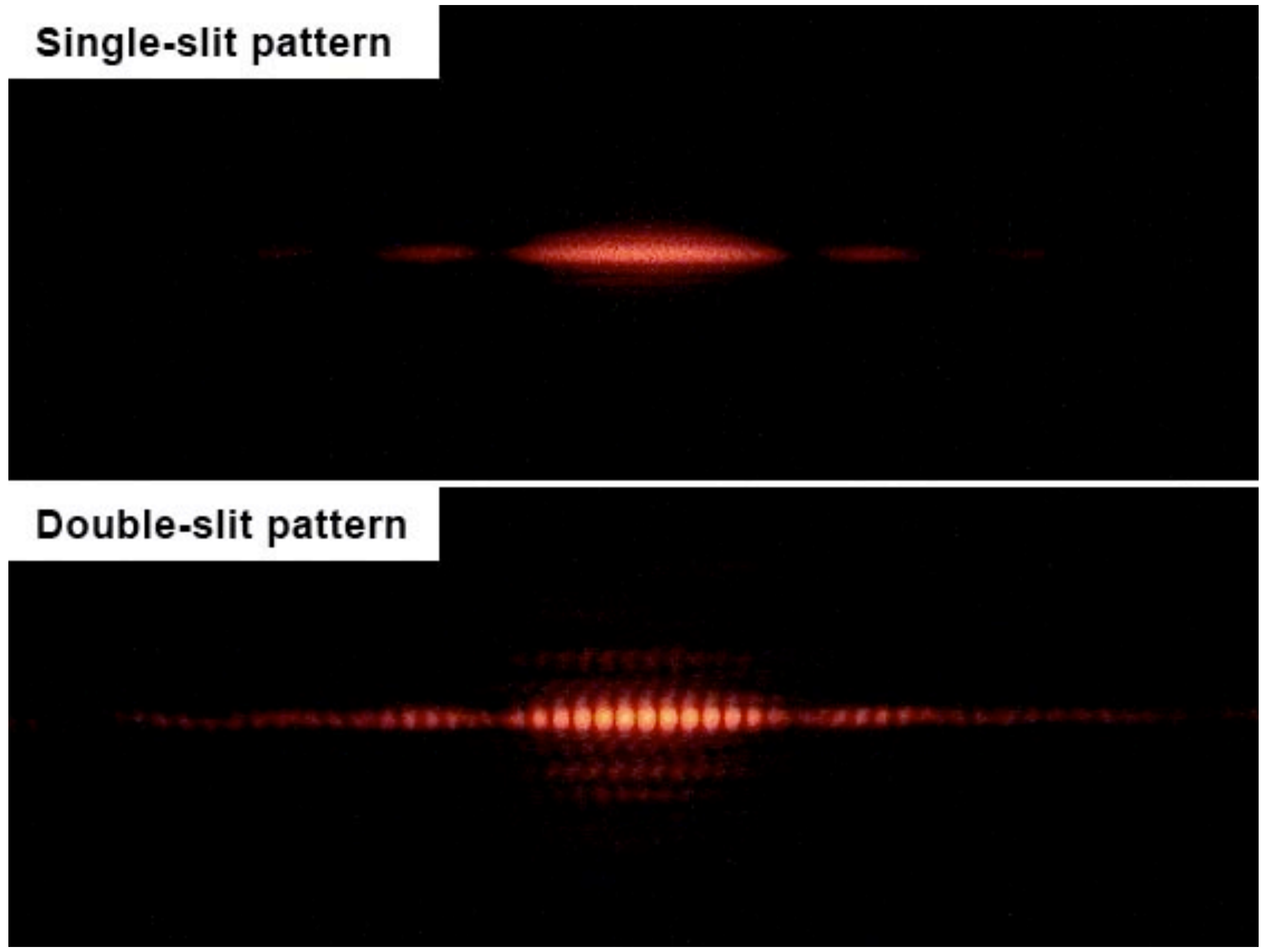


Image Credit: Wikipedia

Interferometer spatial resolution

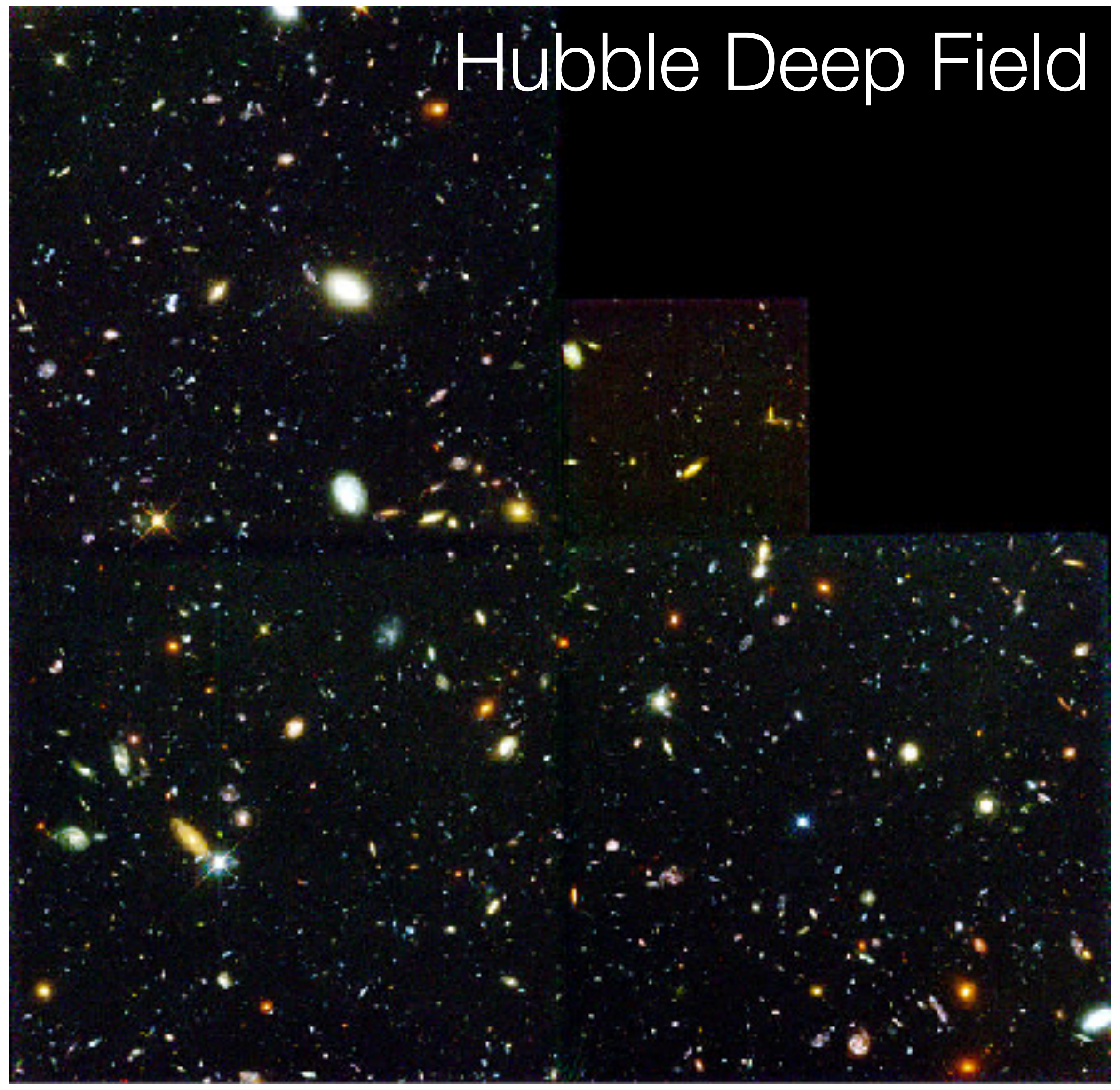
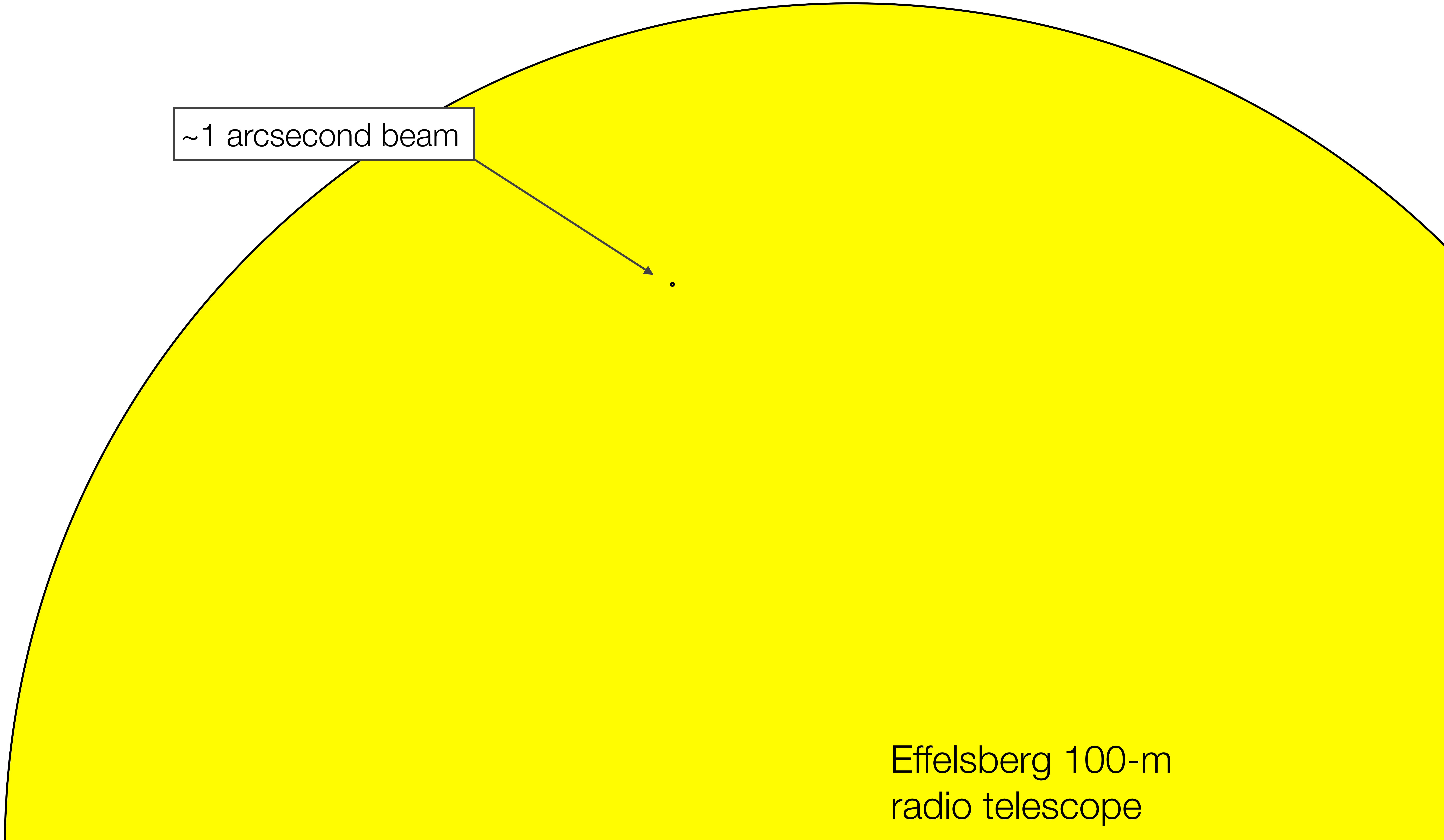
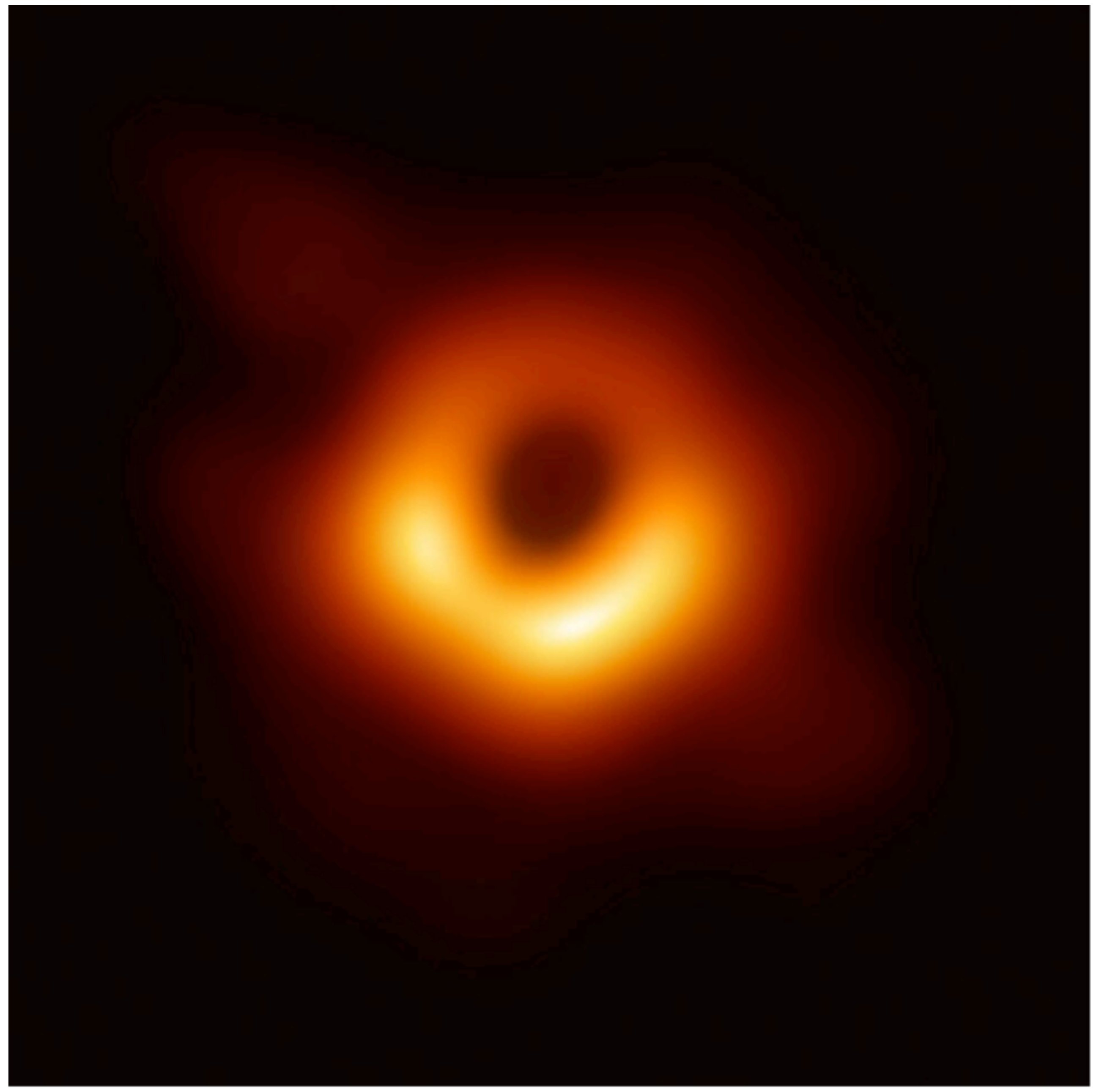


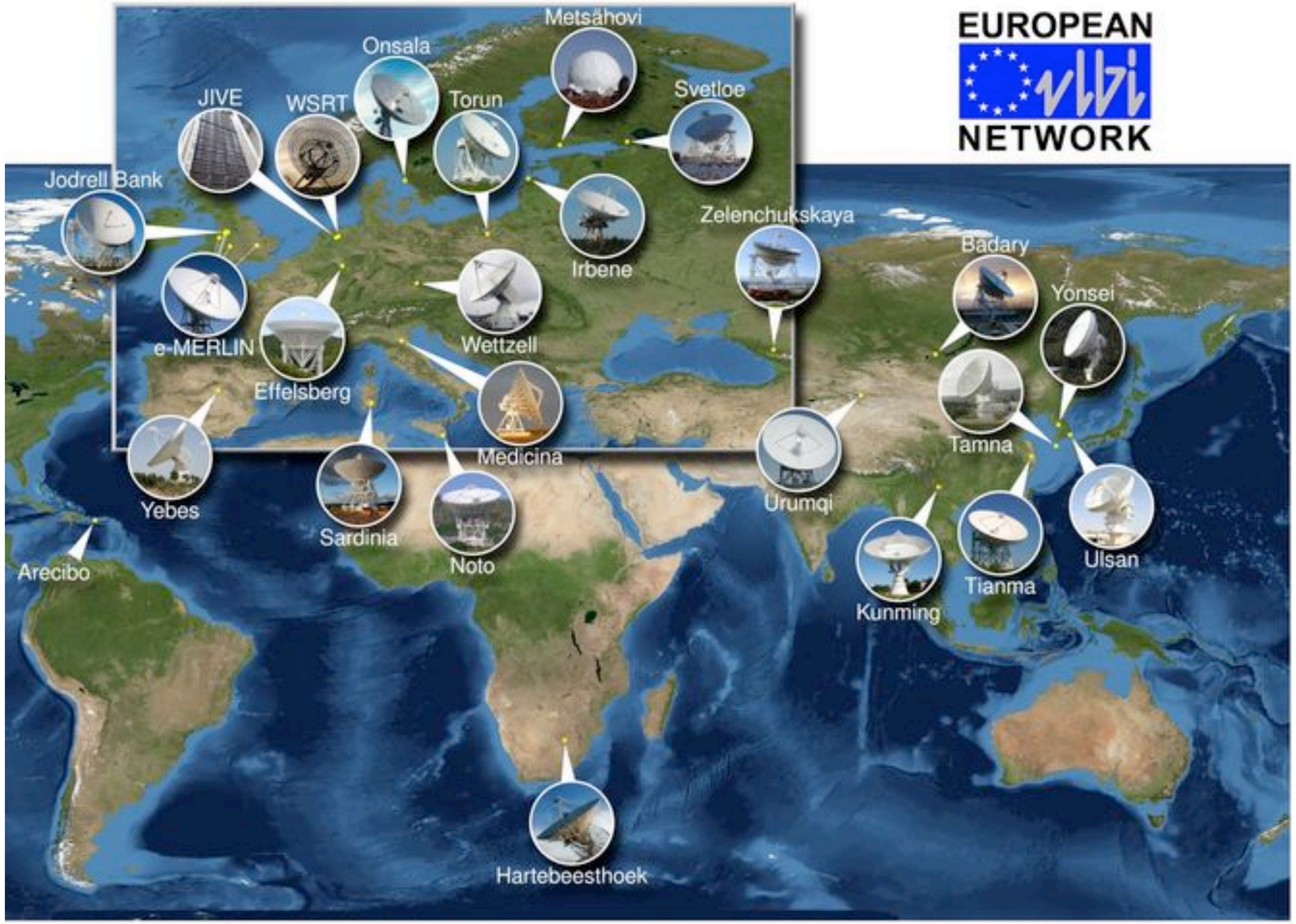
Image Credit: NASA



Very Long Baseline Interferometry

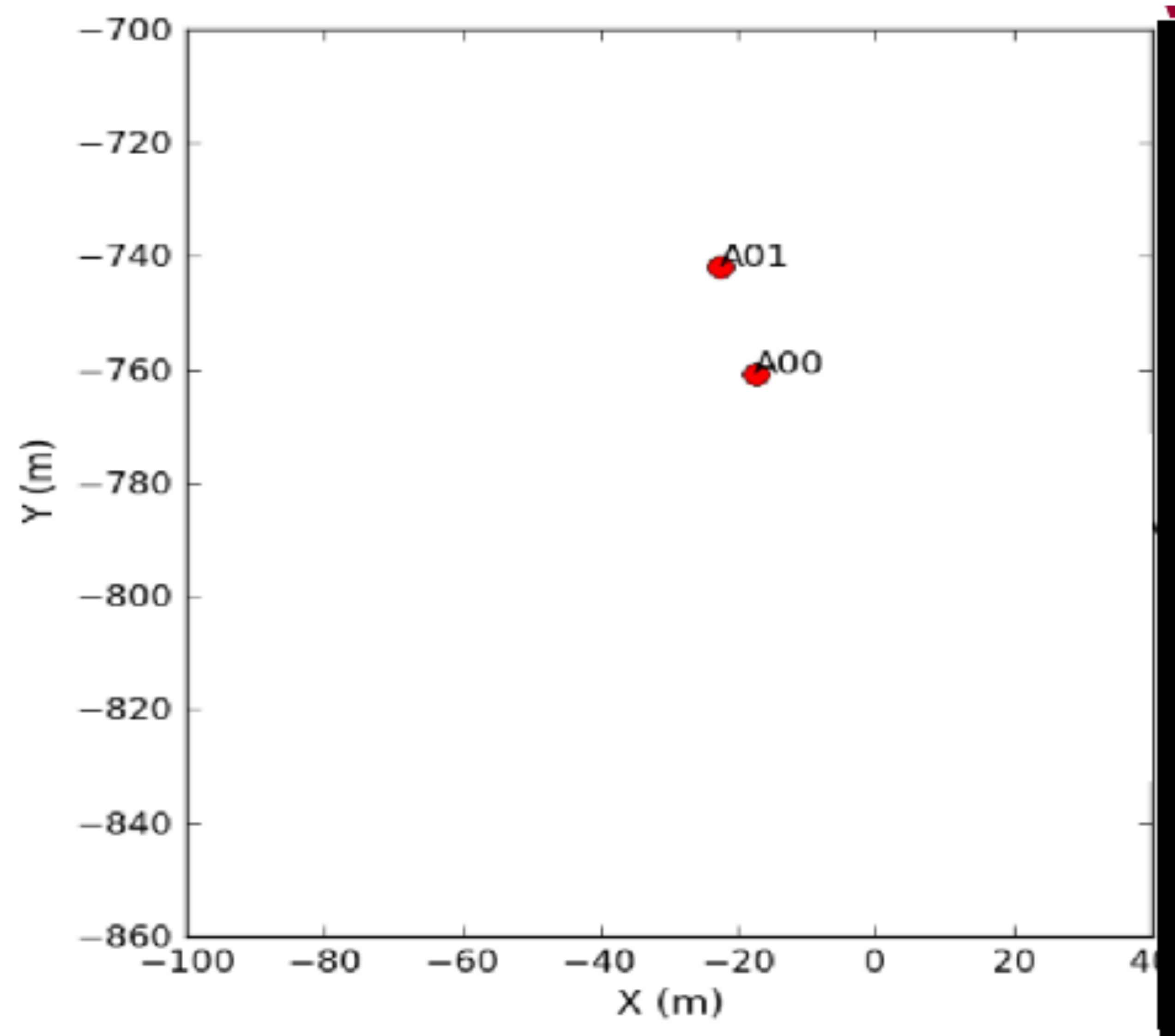
- High spatial resolution → milliarcseconds
- Also important for geodesy

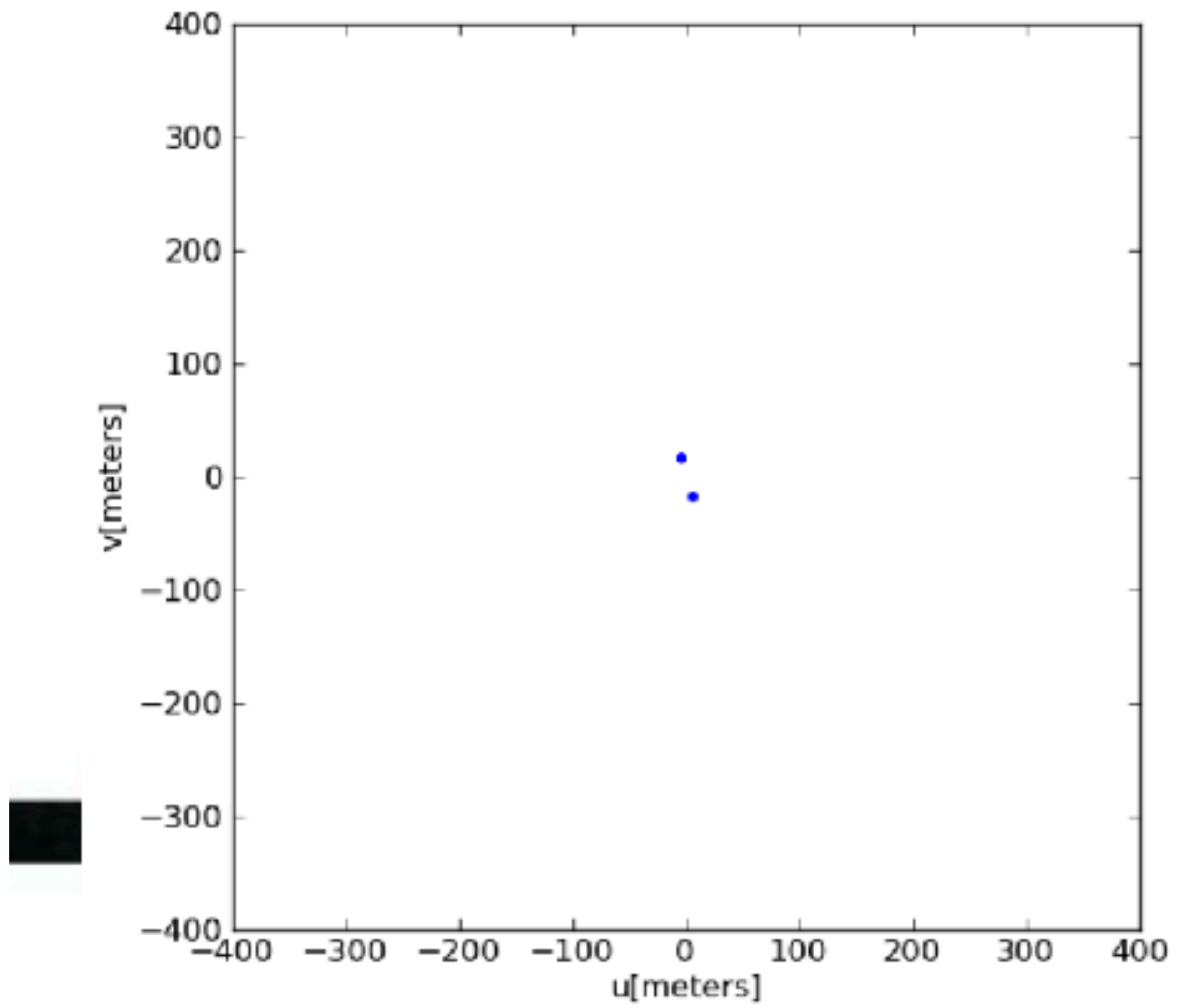


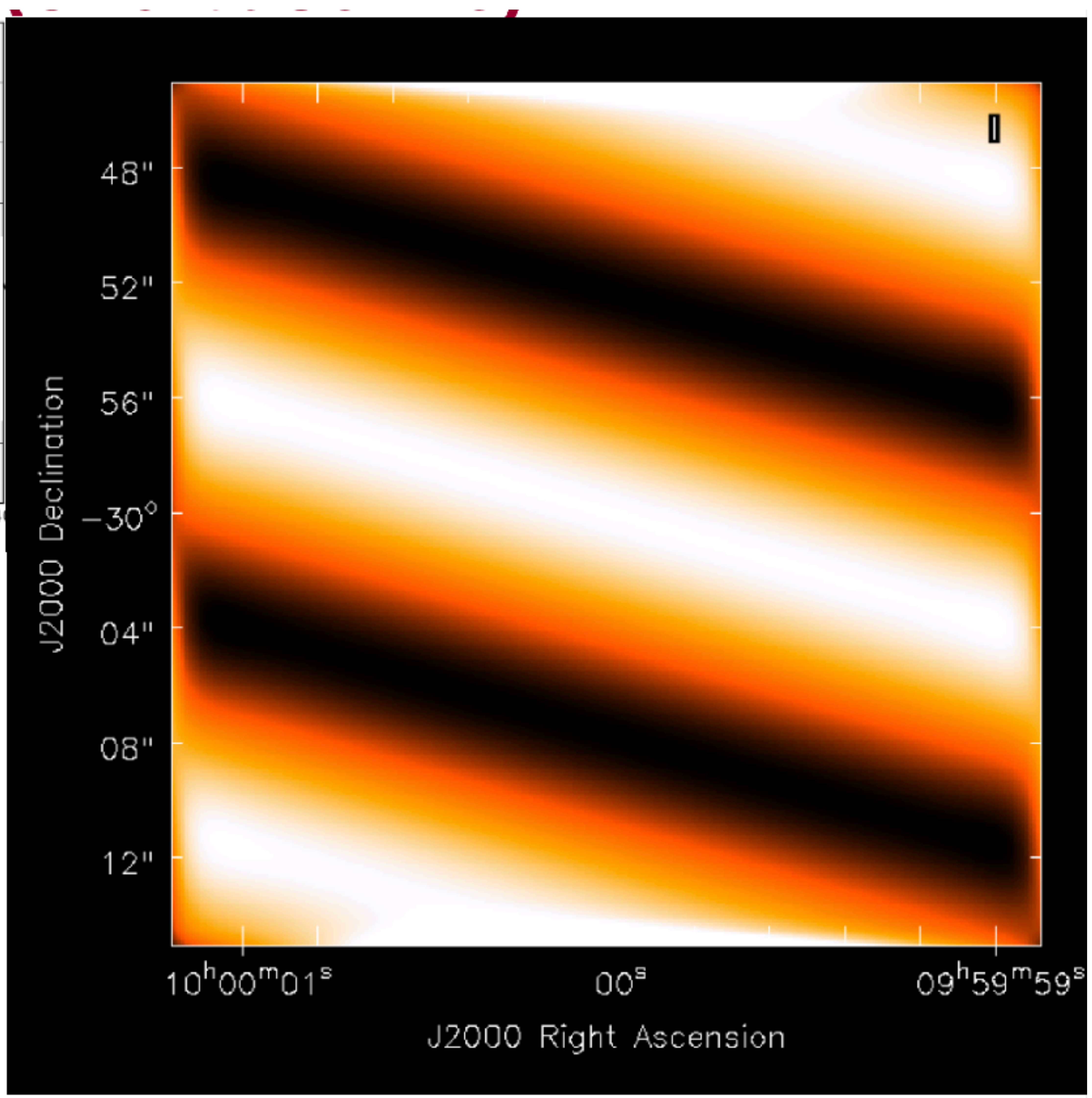


Interferometers sample a set of spatial wavelengths

- Two antennas
- One baseline



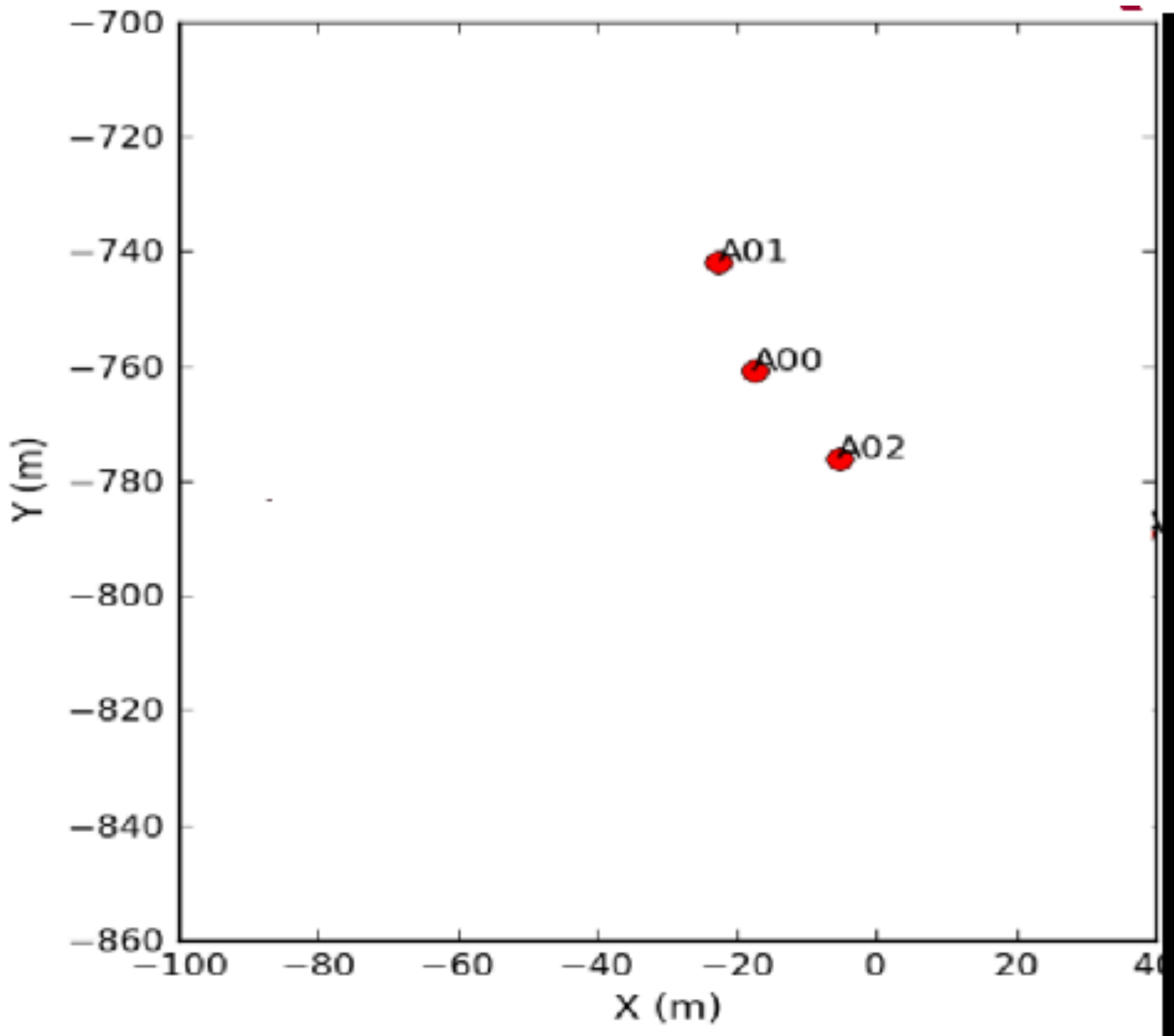


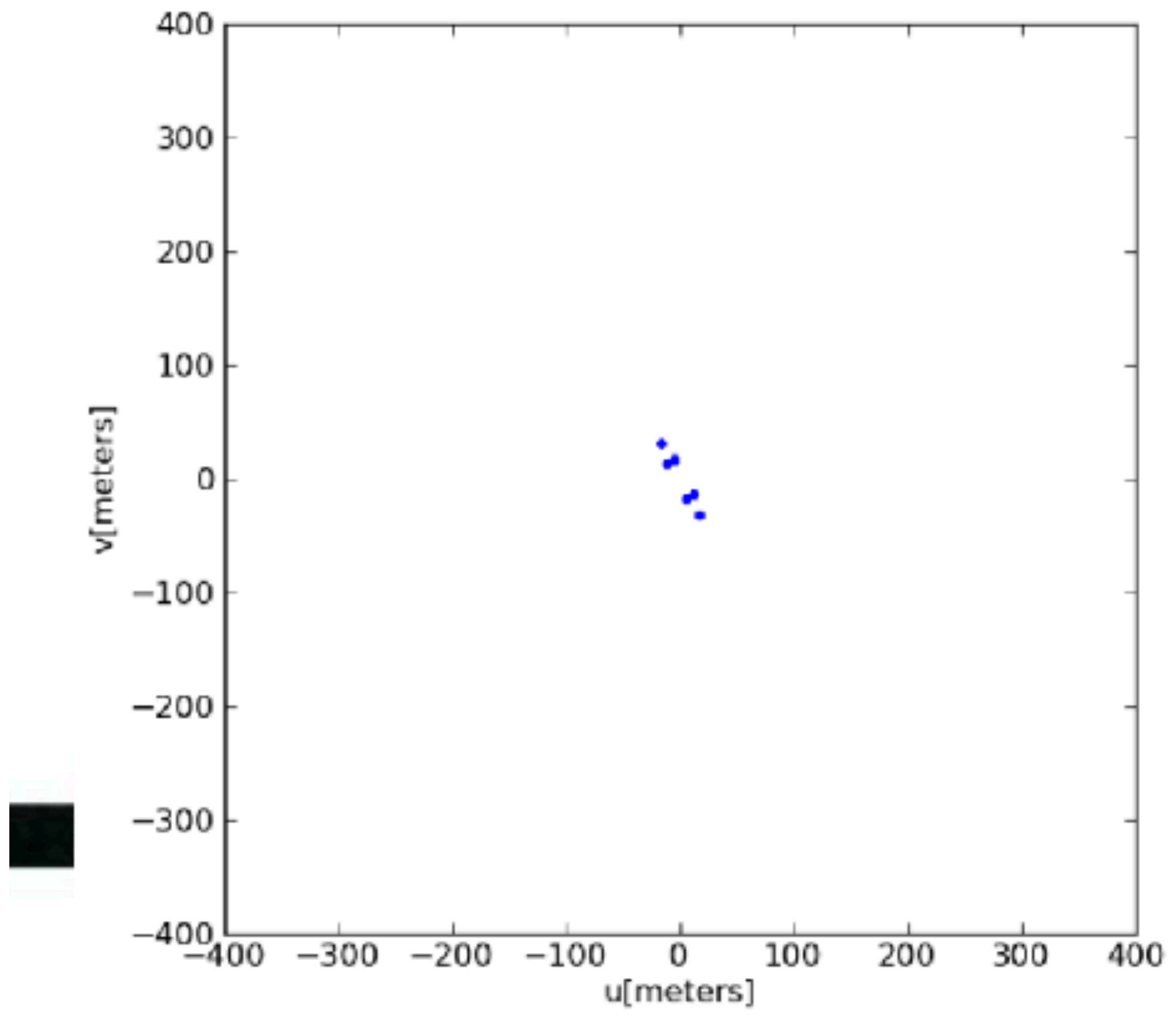


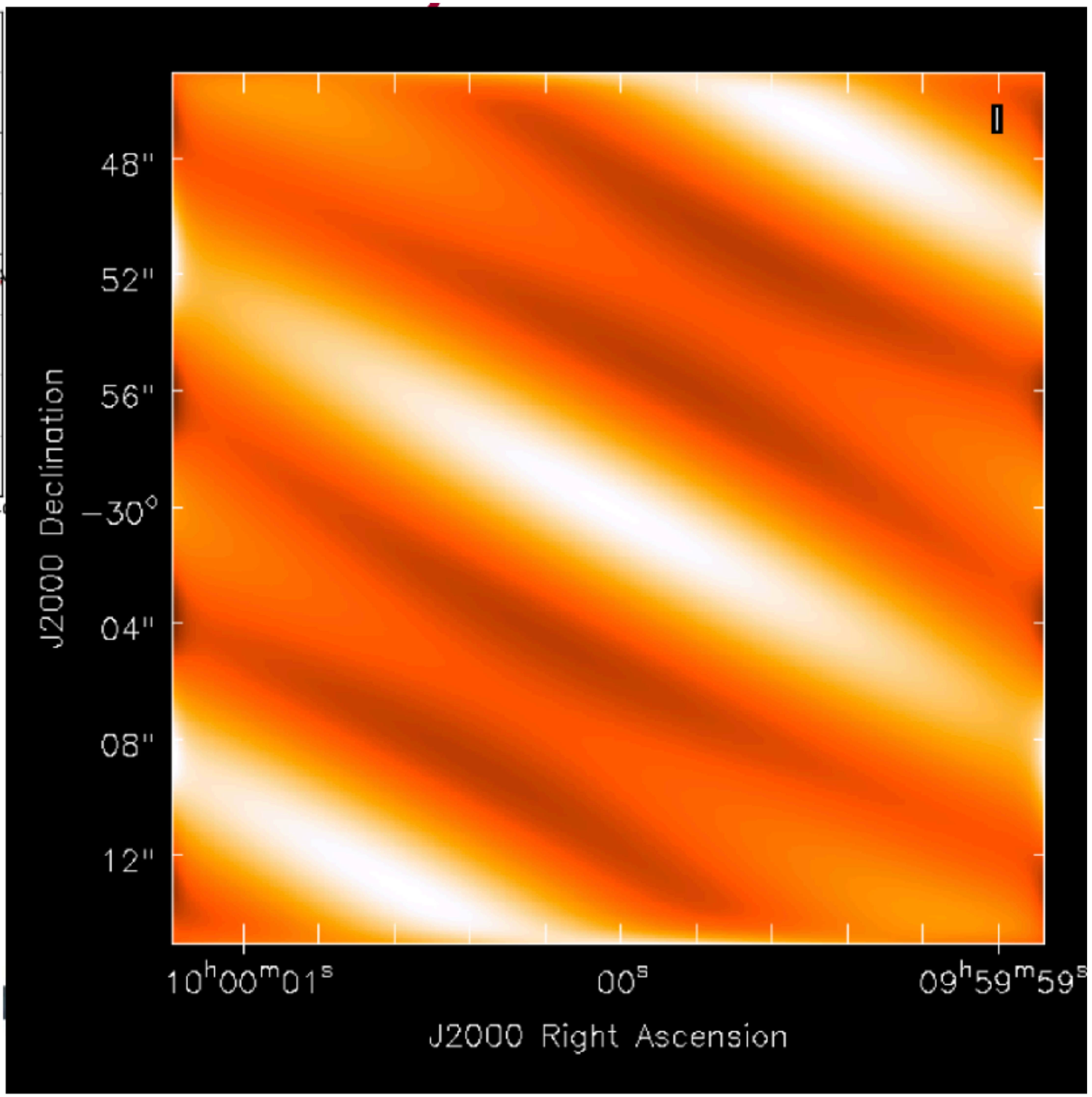
Credit: Cassie Reuter - “Introduction to Radio Interferometry

Interferometers sample a set of spatial wavelengths

- Three antennas
- Three baselines



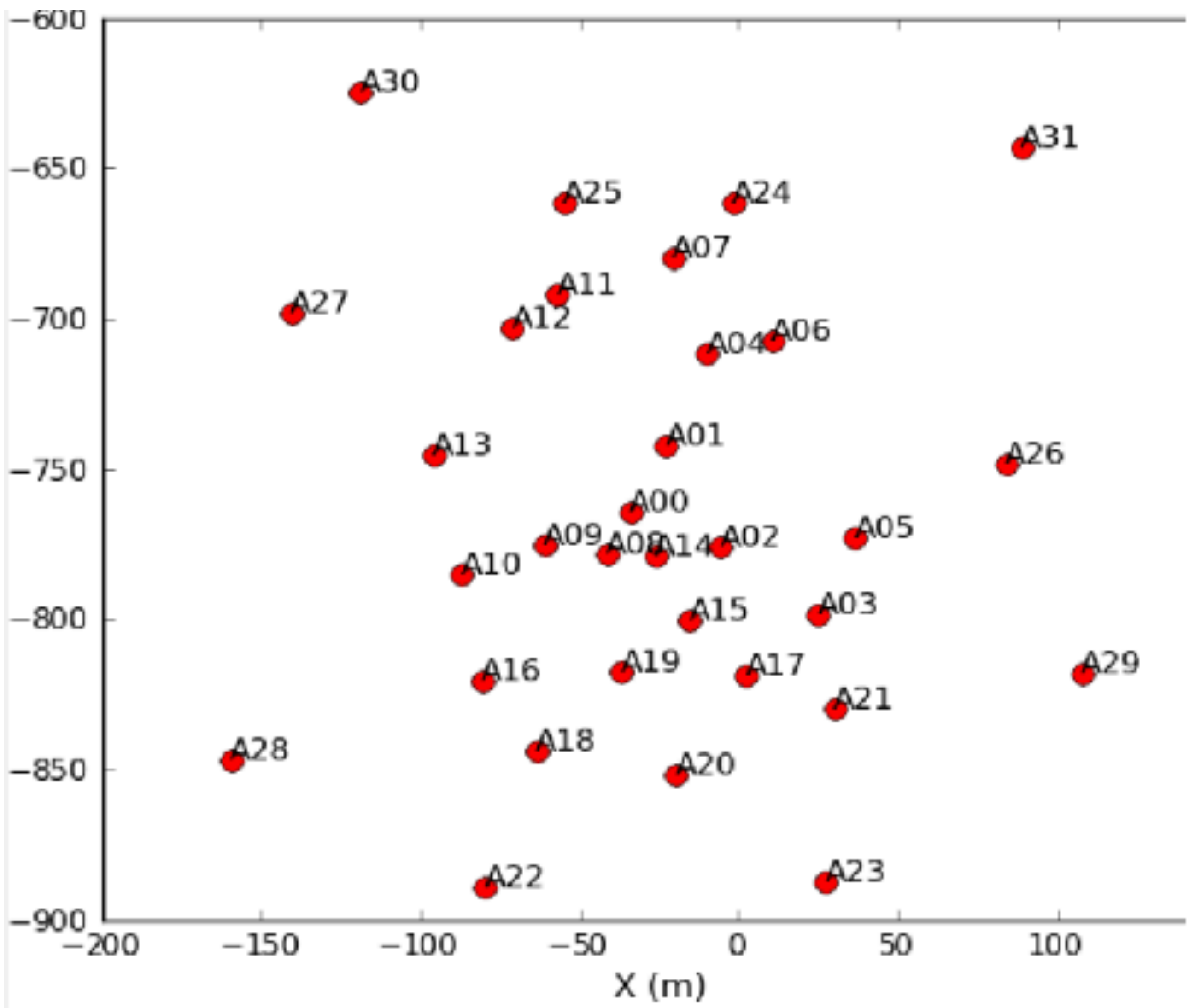


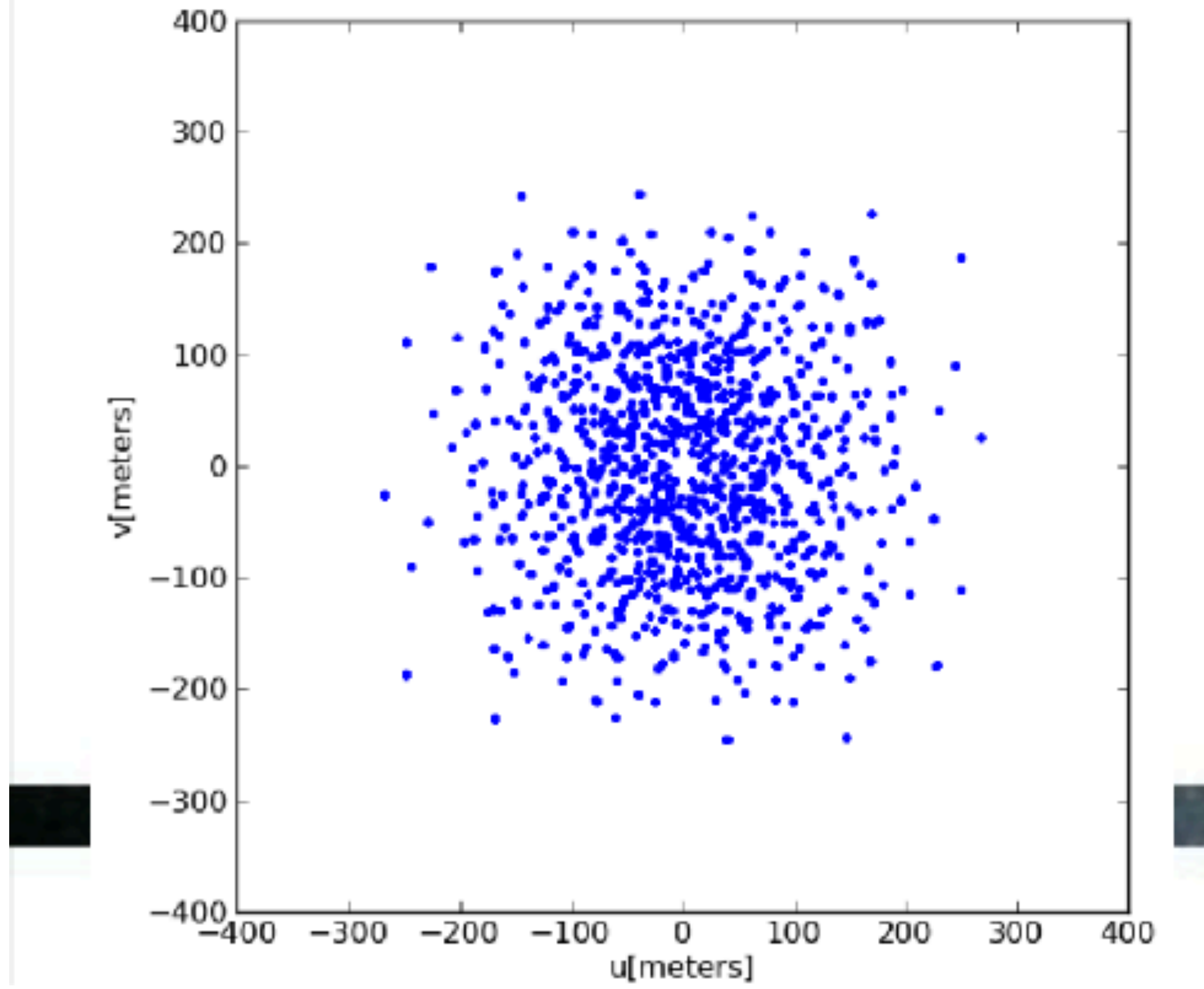


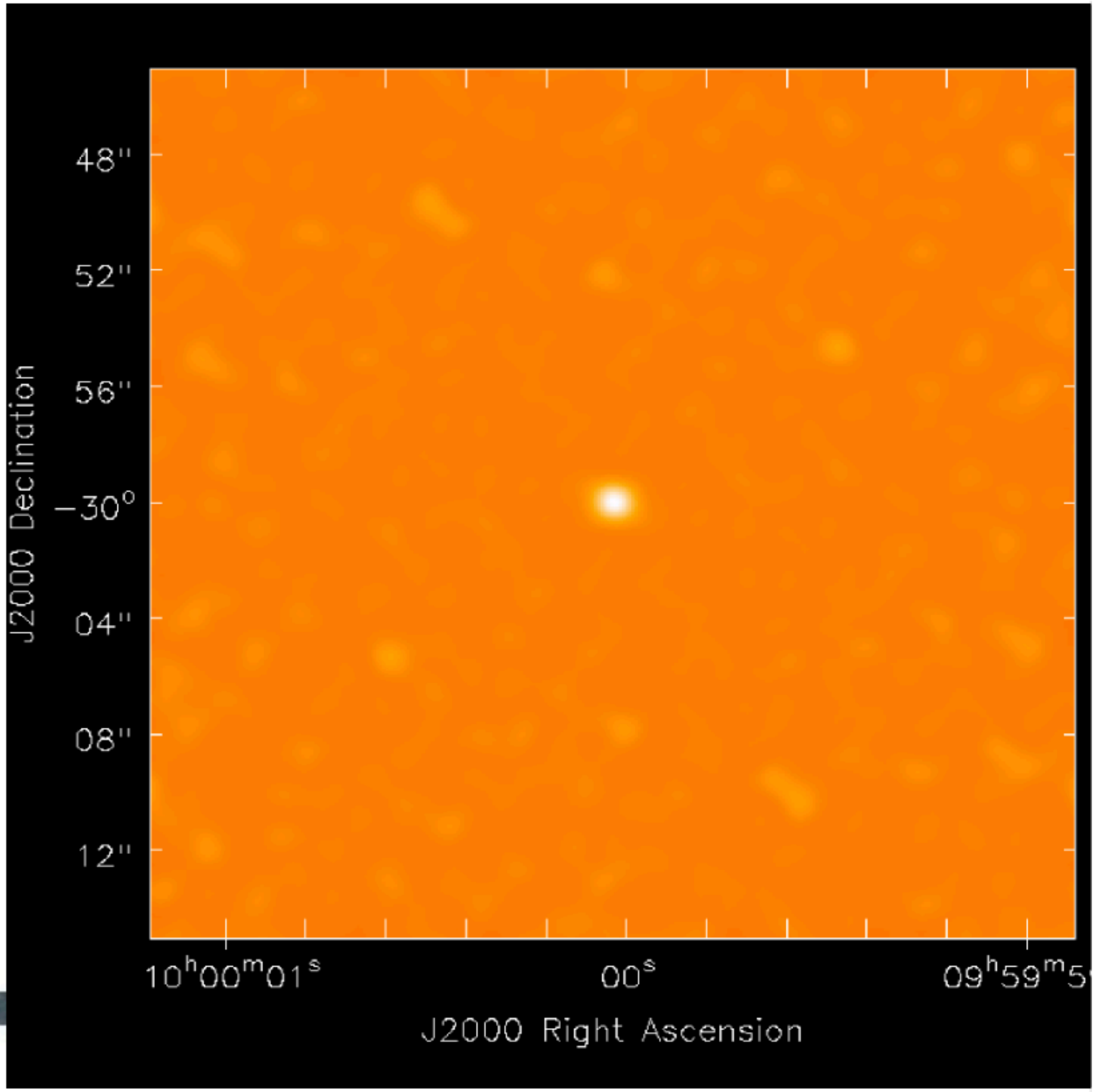
Credit: Cassie Reuter - "Introduction to Radio Interferometry

Interferometers sample a set of spatial wavelengths

- 32 antennas
- ~500 baselines



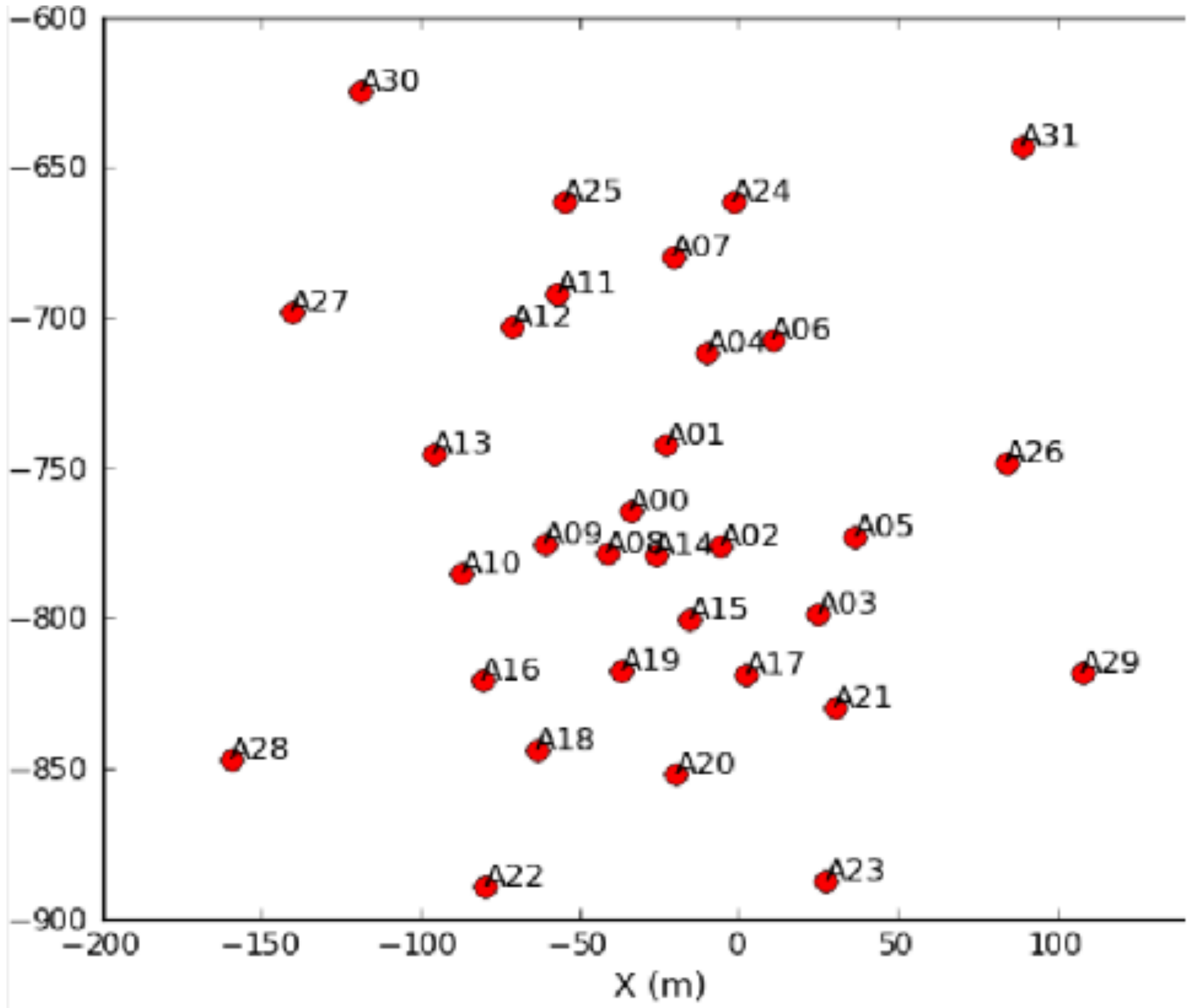


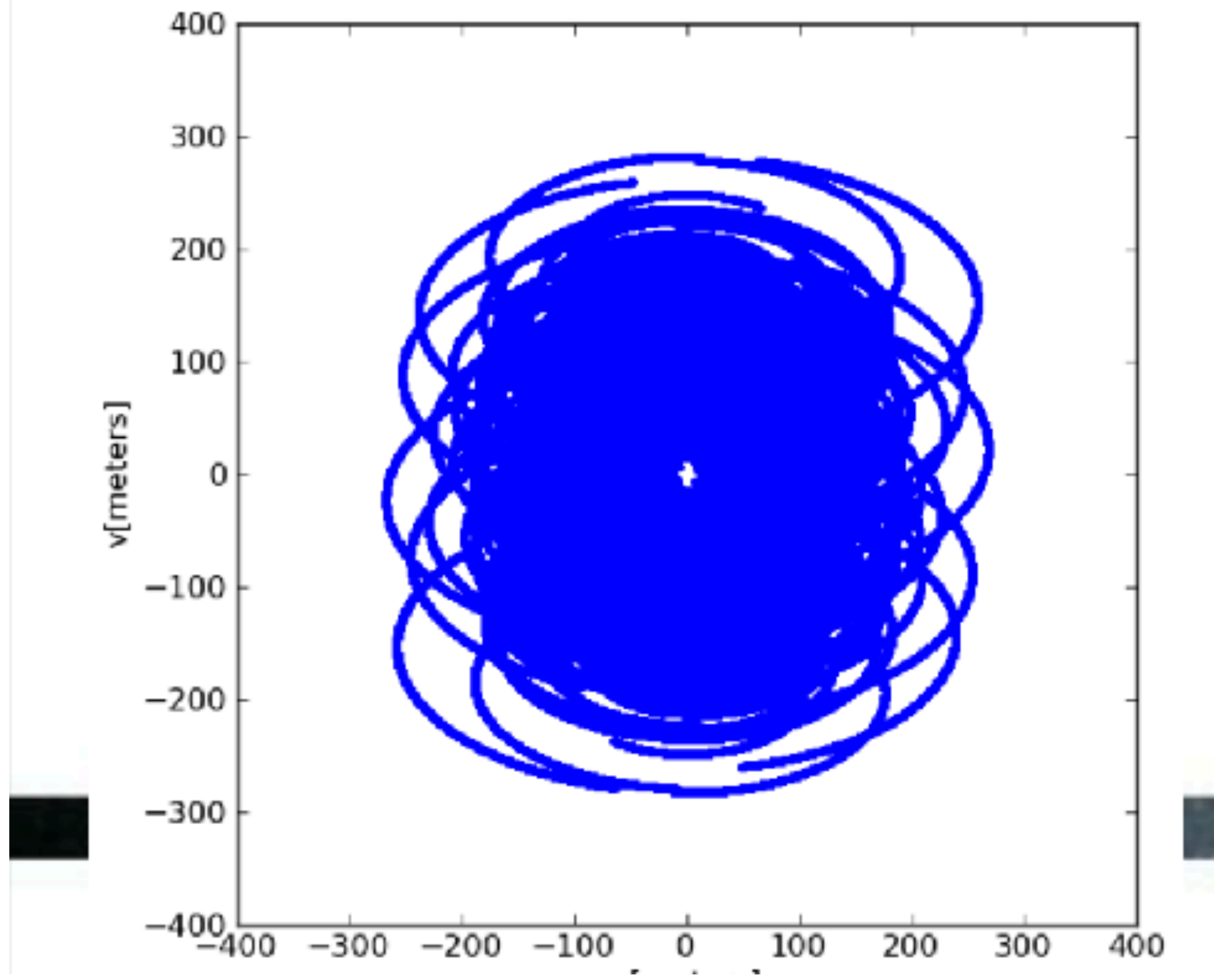


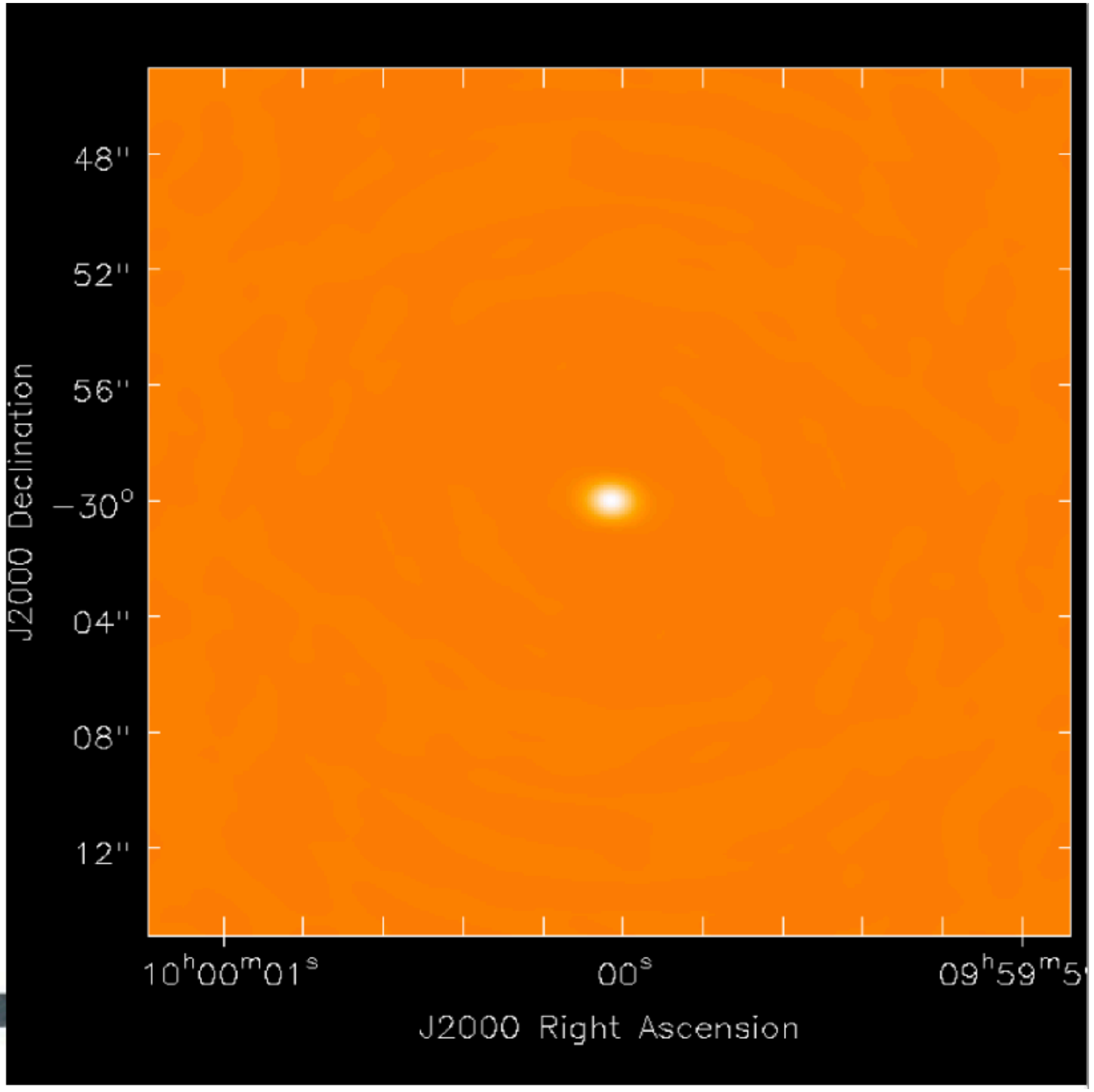
Credit: Cassie Reuter - “Introduction to Radio Interferometry

Interferometers sample a set of spatial wavelengths

- 32 antennas
- ~500 baselines
- 8 hours integration
  - "Aperture synthesis"

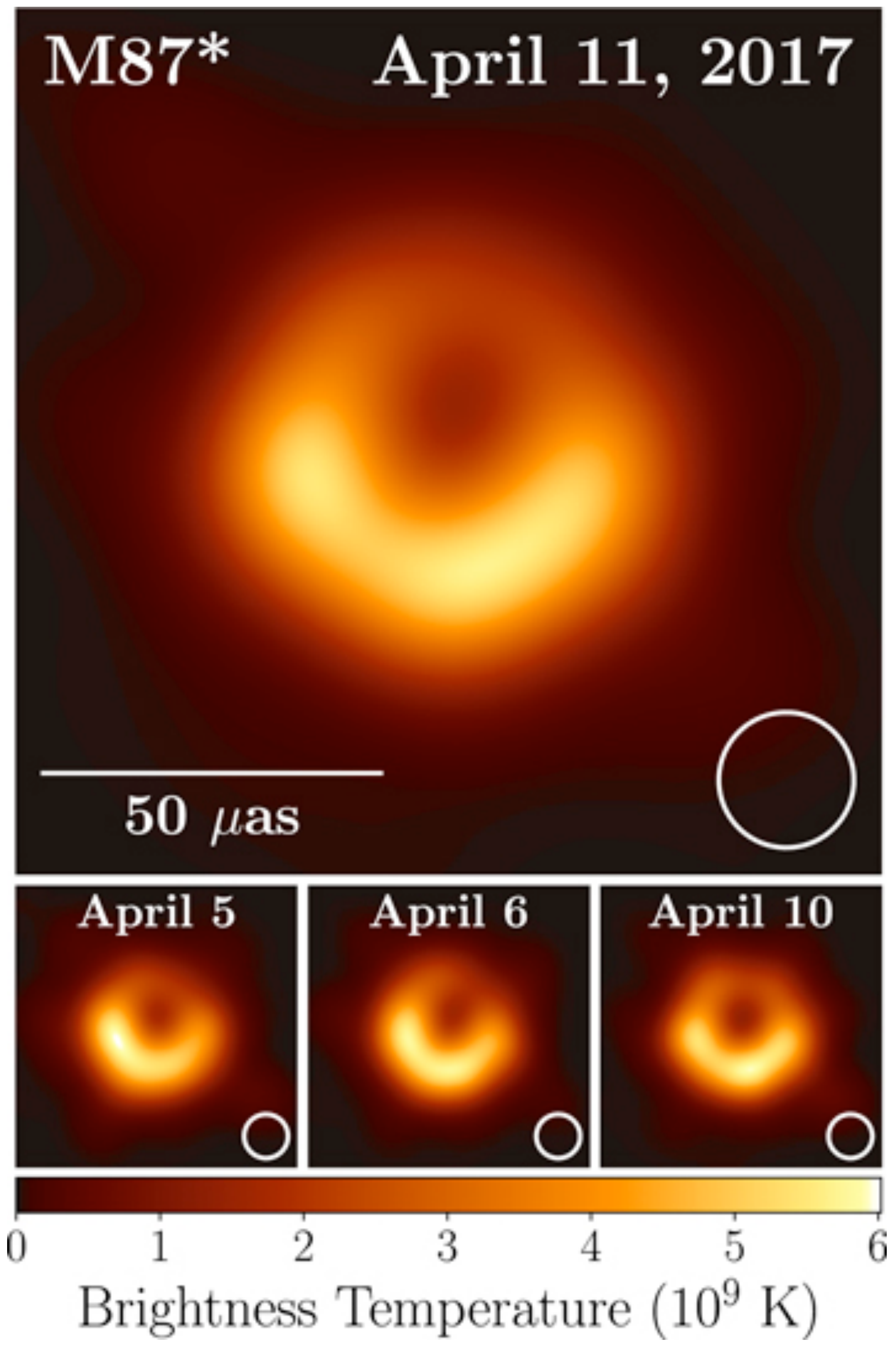


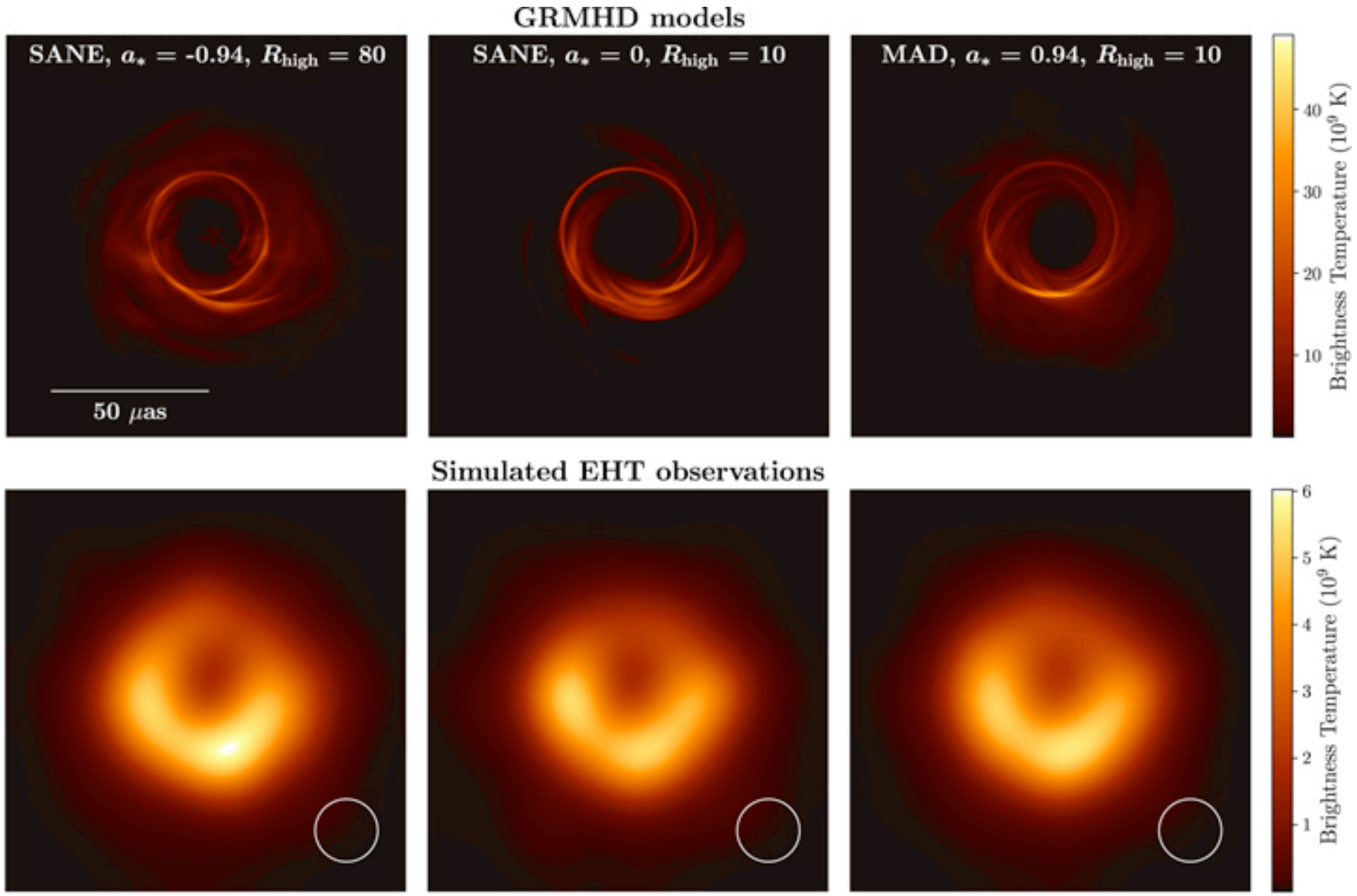




Credit: Cassie Reuter - "Introduction to Radio Interferometry

Sky convolved with the beam defined by baselines





Credit: EHT collaboration, ApJL, 875:L1, 2019

Basics of radio telescope signal chain

Analog receiver

Feed
Amplifiers
Filters

Digitization

Analog-to-digital converter (ADC)

Disk

01001101 01111001
01000100 01100001
01110100 01100001

Signal is sampled coherently,
i.e. amplitude and phase
of the radio waves is measured.

UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

Radio Services

- Aeronautical Mobile
- Inter-Satellite
- Radio Astronomy
- Aeronautical Mobile - Satellite
- Land Mobile
- Radiodetermination - Satellite
- Aeronautical Radionavigation
- Land Mobile - Satellite
- Radiolocation
- Amateur
- Maritime Mobile
- Radiolocation - Satellite
- Amateur Satellite
- Maritime Mobile - Satellite
- Radionavigation
- Broadcasting
- Maritime Radionavigation
- Radionavigation - Satellite
- Broadcasting - Satellite
- Meteorological
- Space Operation
- Earth Exploration - Satellite
- Meteorological - Satellite
- Space Research
- Fixed
- Mobile
- Standard Frequency and Time Signal
- Fixed - Satellite
- Mobile - Satellite
- Standard Frequency and Time Signal - Satellite

Federal/Non-Federal Rights

- Federal Exclusive
- Non-Federal Exclusive
- Federal/Non-Federal Shared

Key Wi-Fi Bands

Allocation Usage Designation

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital letters
Secondary	Mobile	Initial capital followed by lowercase letters

U.S. DEPARTMENT OF COMMERCE

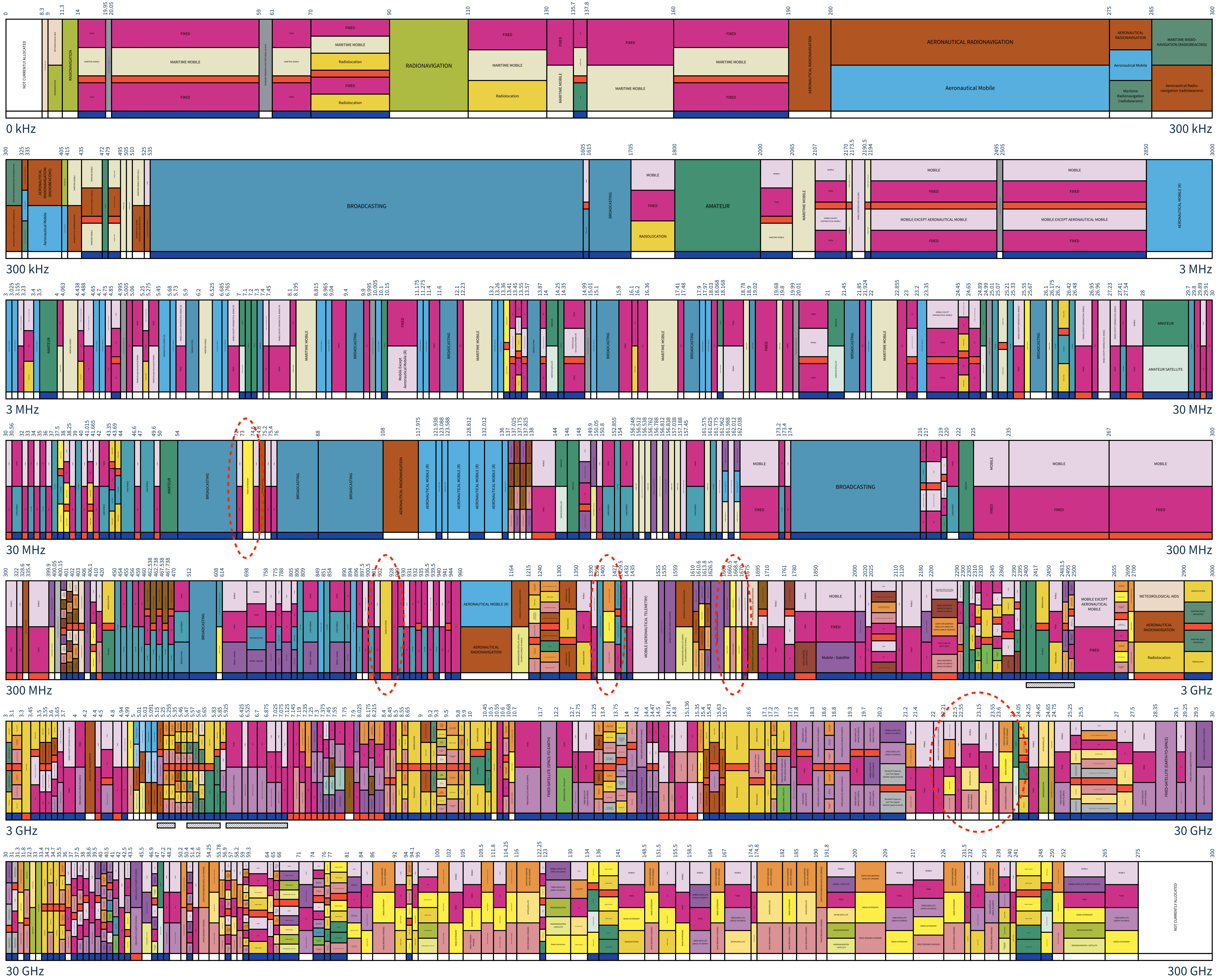
National Telecommunications and Information Administration

Office of Spectrum Management

September 2025

Arielle Roth, Assistant Secretary of Commerce for Communications and Information

This chart is a visual representation of the Table of Frequency Allocations published by the Federal Communications Commission (FCC) as of 31 March 2025. It does not contain all the information published in the Table, such as international allocations or footnotes.



Build your telescope in some remote region (+ radio quiet zone)

SKA-Low prototype:
Murchison Observatory in Australia

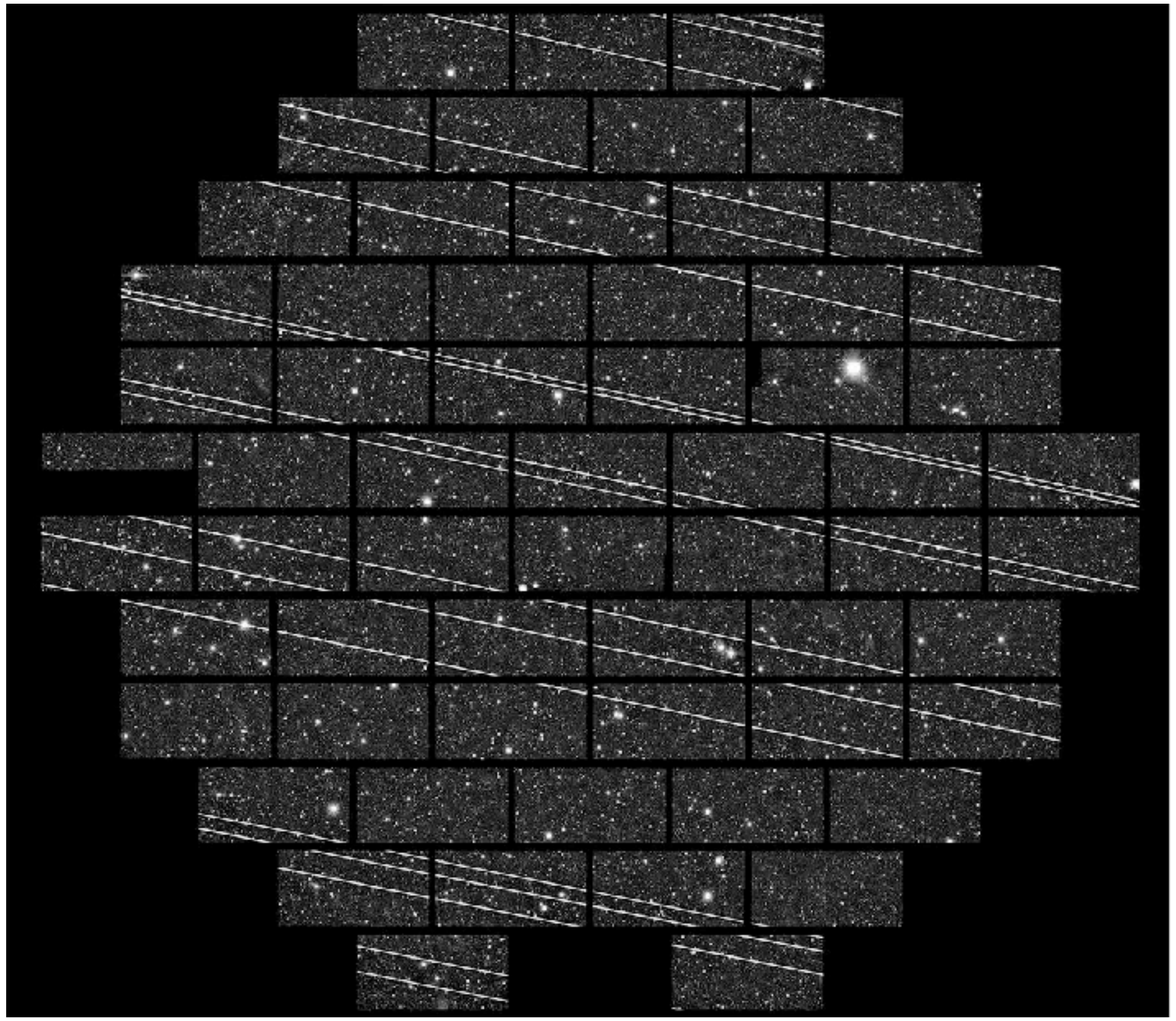
MeerKAT: Karoo desert of South Africa

Credit: CSIRO

Credit: SARAO

Latest threat: satellite constellations

Optical light pollution from Starlink satellites



Credit: NSF's National Optical-Infrared Astronomy Research Laboratory/CTIO/AURA/DELVE

Constellation	Number of Satellites	Downlink Frequencies	Altitude [km]
Starlink Phase 1	4,400	Ku, Ka	550
OneWeb Phase 1	648	Ku, Ka	1200
Amazon Phase 1	3,200	Ka	~600
Guo Wang (GW)	13,000	Ku, Ka	590 – 1145
Starlink VLEO	7600	V	340
Telesat	1,700	Ka	
Starlink Phase 2	30,000	Ku, Ka, E	328 – 614
OneWeb Phase 2	6,372	Ku, Ka, V	1200
Boeing	5,789		
Astra	13,620		
Amazon Phase 2	7,774		
Cinnamon-937	300,000	???	???

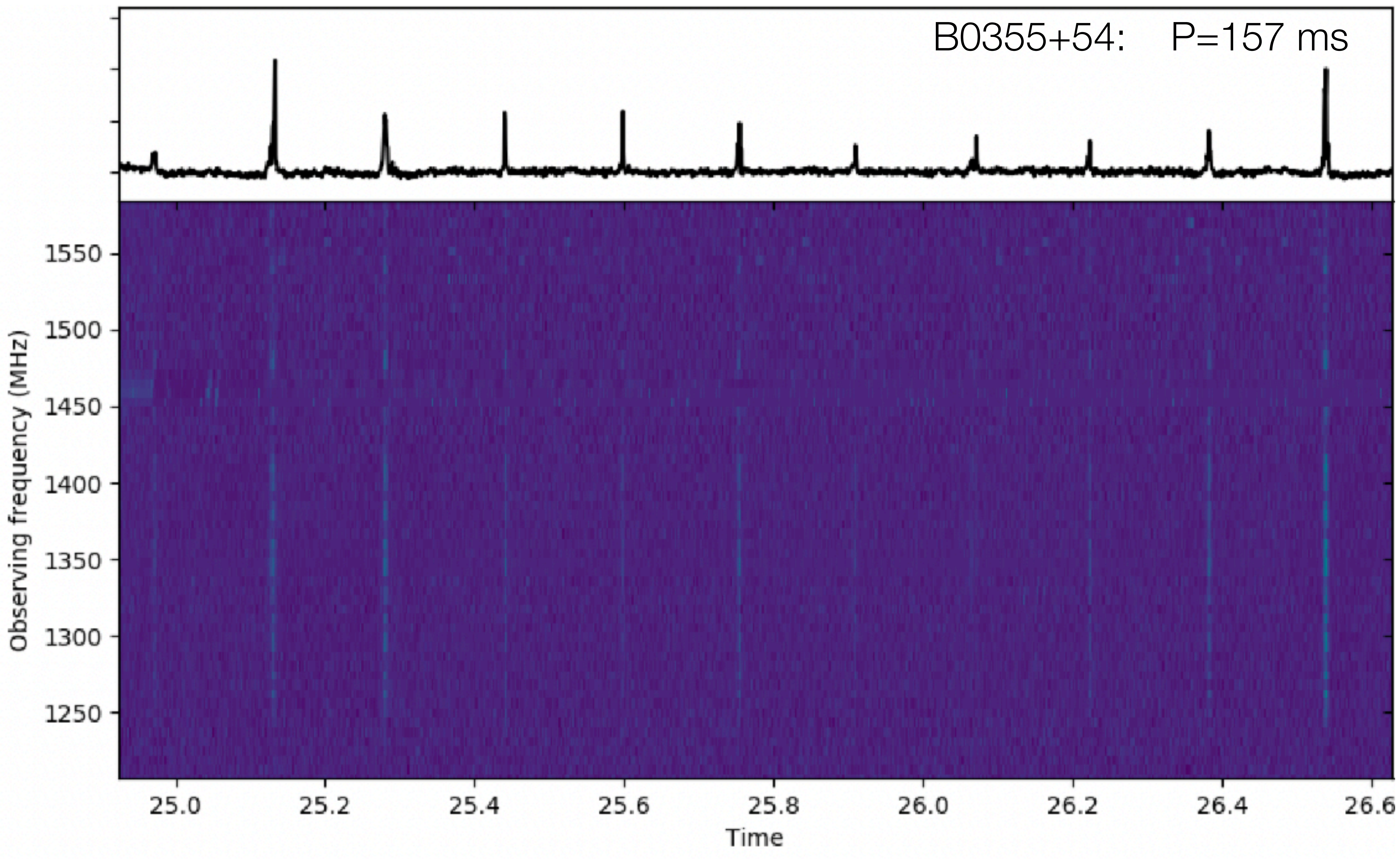
Credit: Di Vruno - RFI 2022

Latest threat: satellite constellations

Credit: Daniëlle Futselaar (artsource.nl) & IAU / CPS

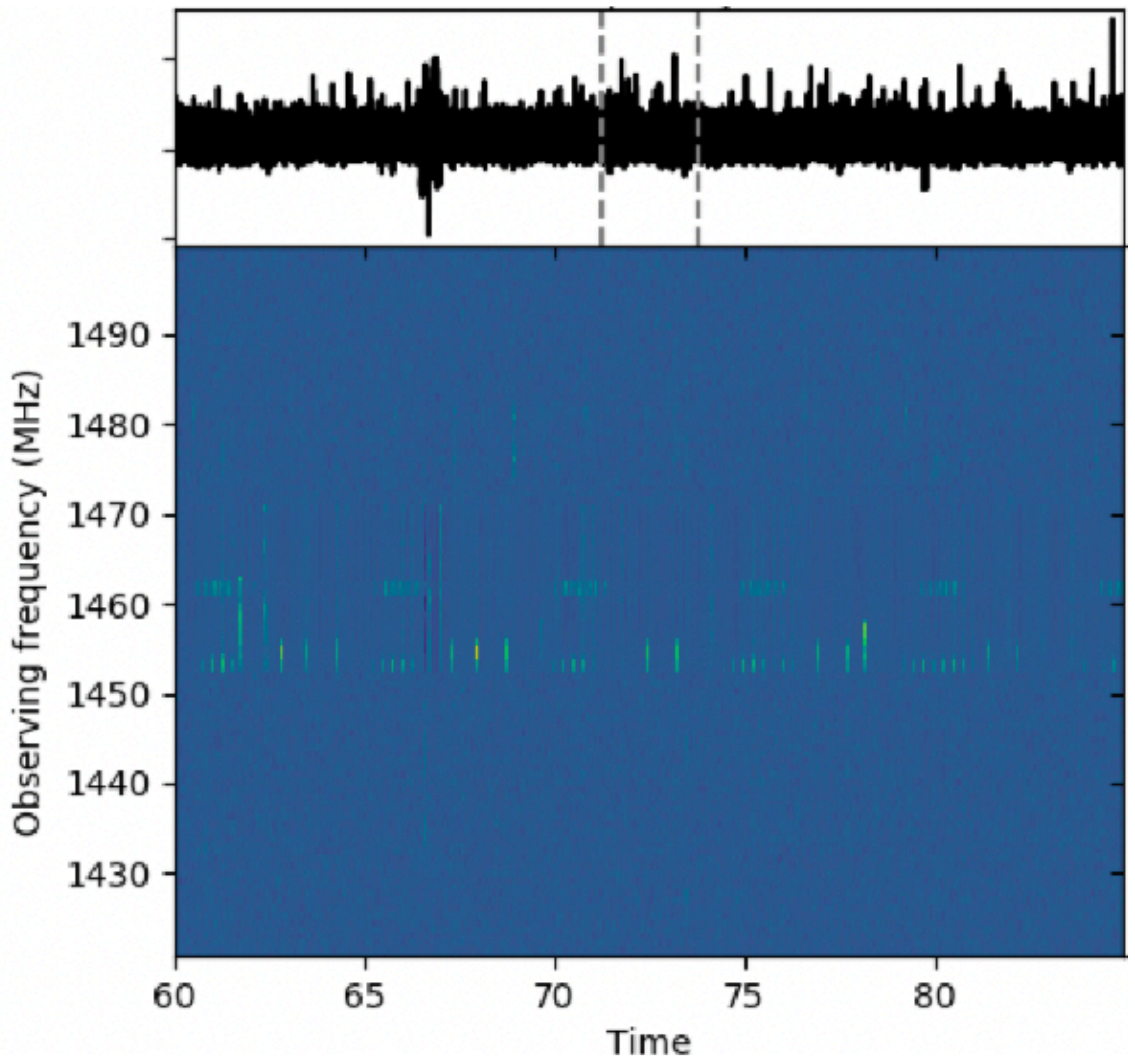
Example data from a bright pulsar

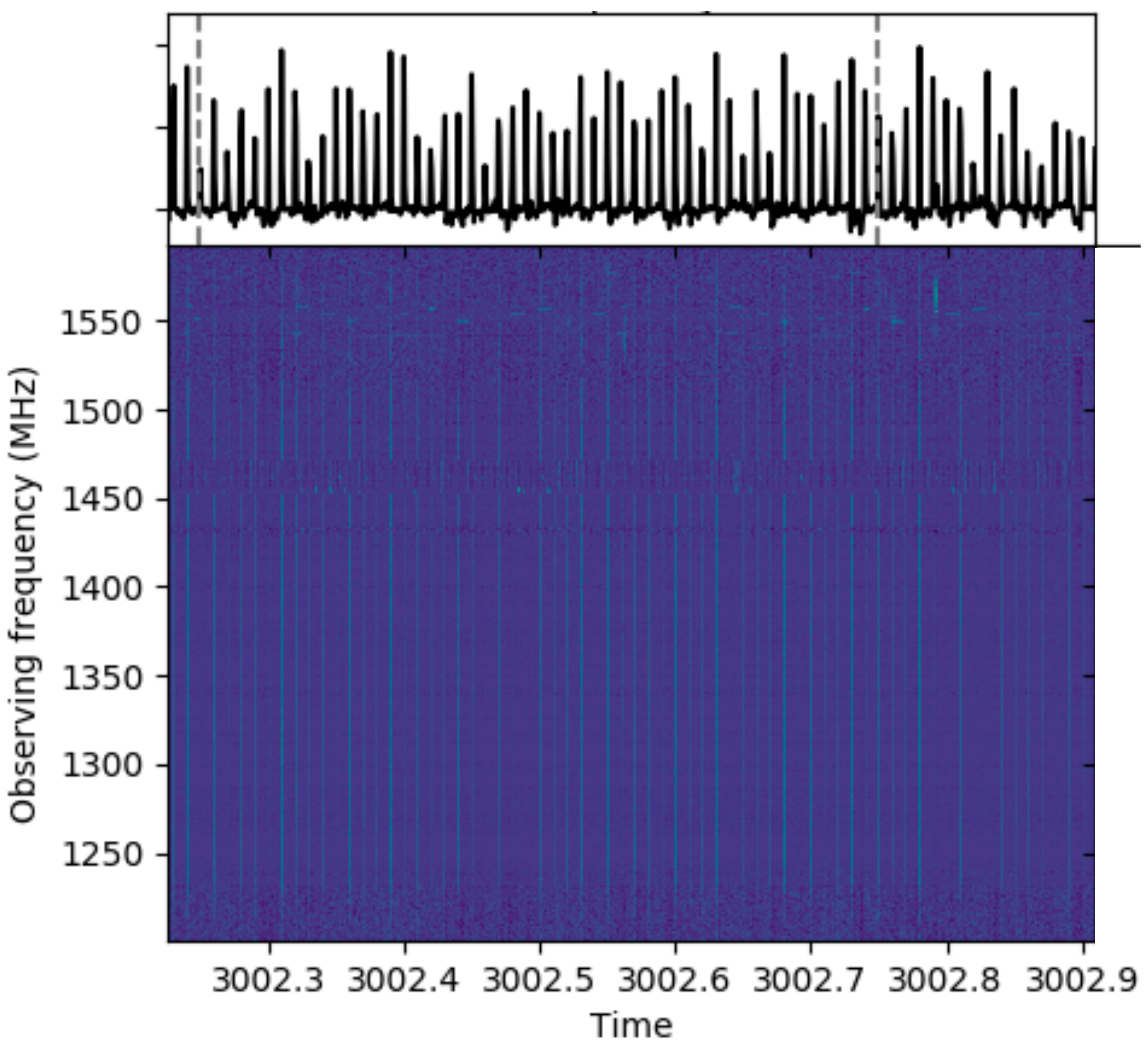
- Instrumental noise in radio data is distributed according to Gaussian statistics
- In theory, source detection is just applying a S/N threshold guided by the expected false alarm probability

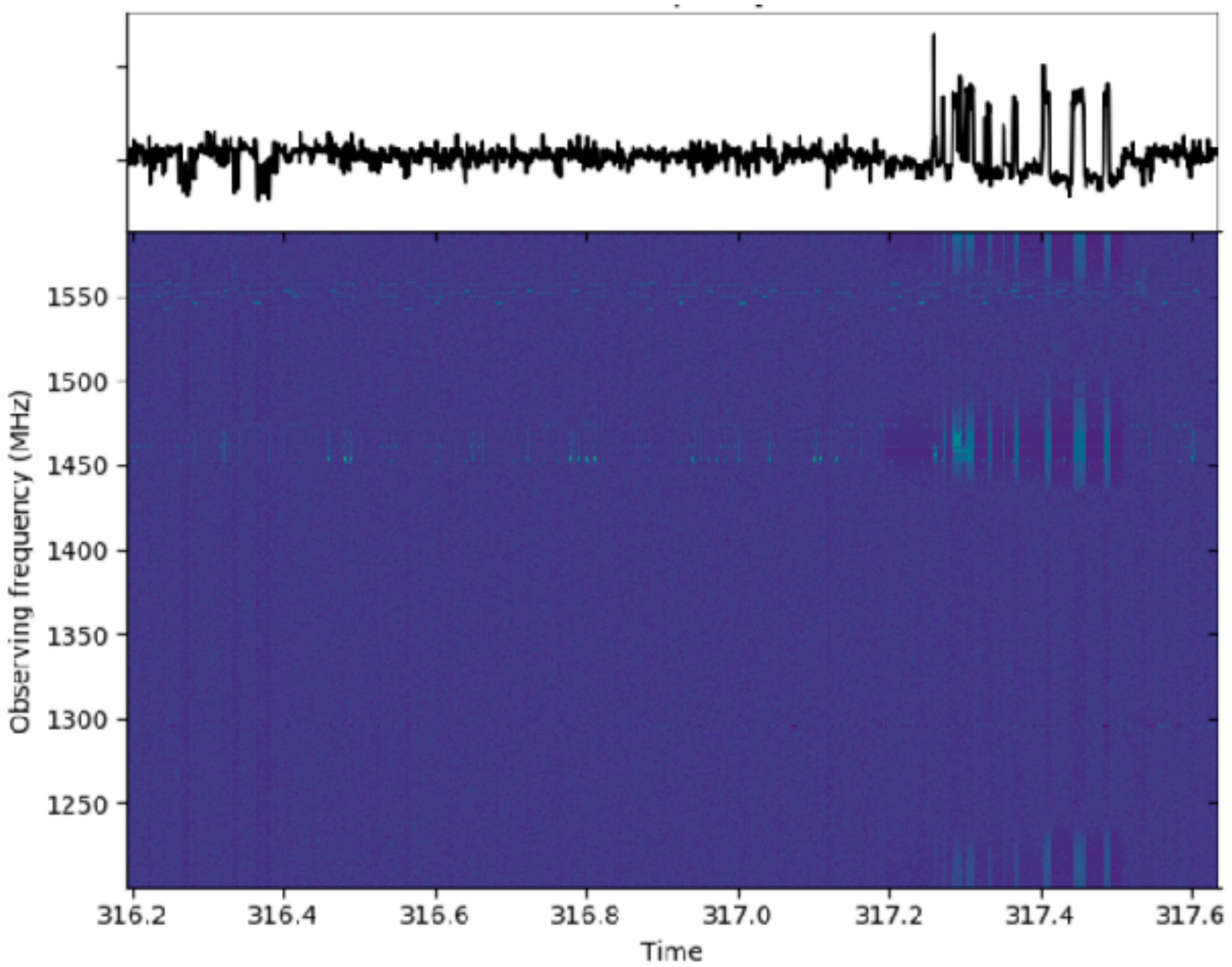


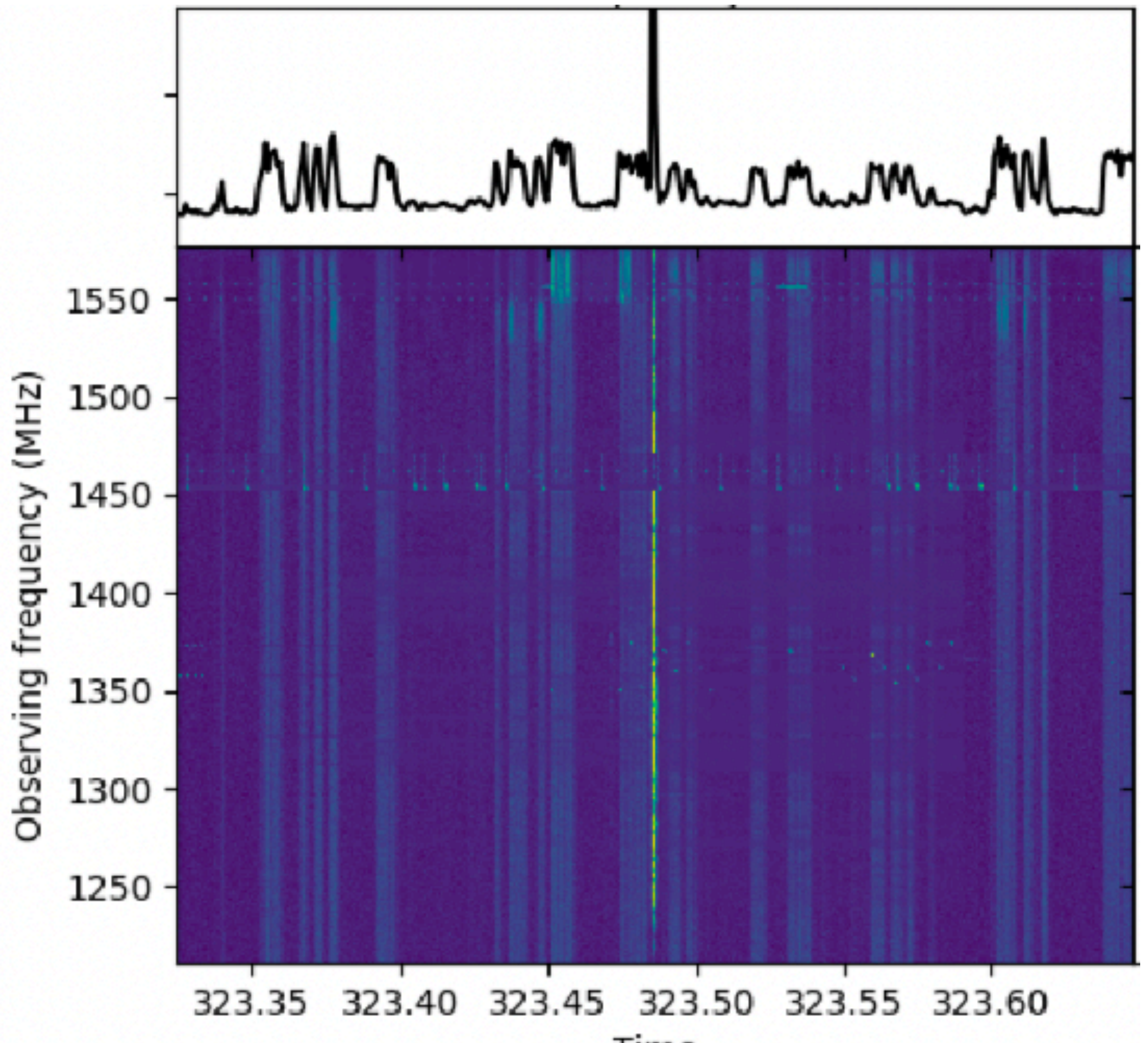
What we actually see…

… on short time scales



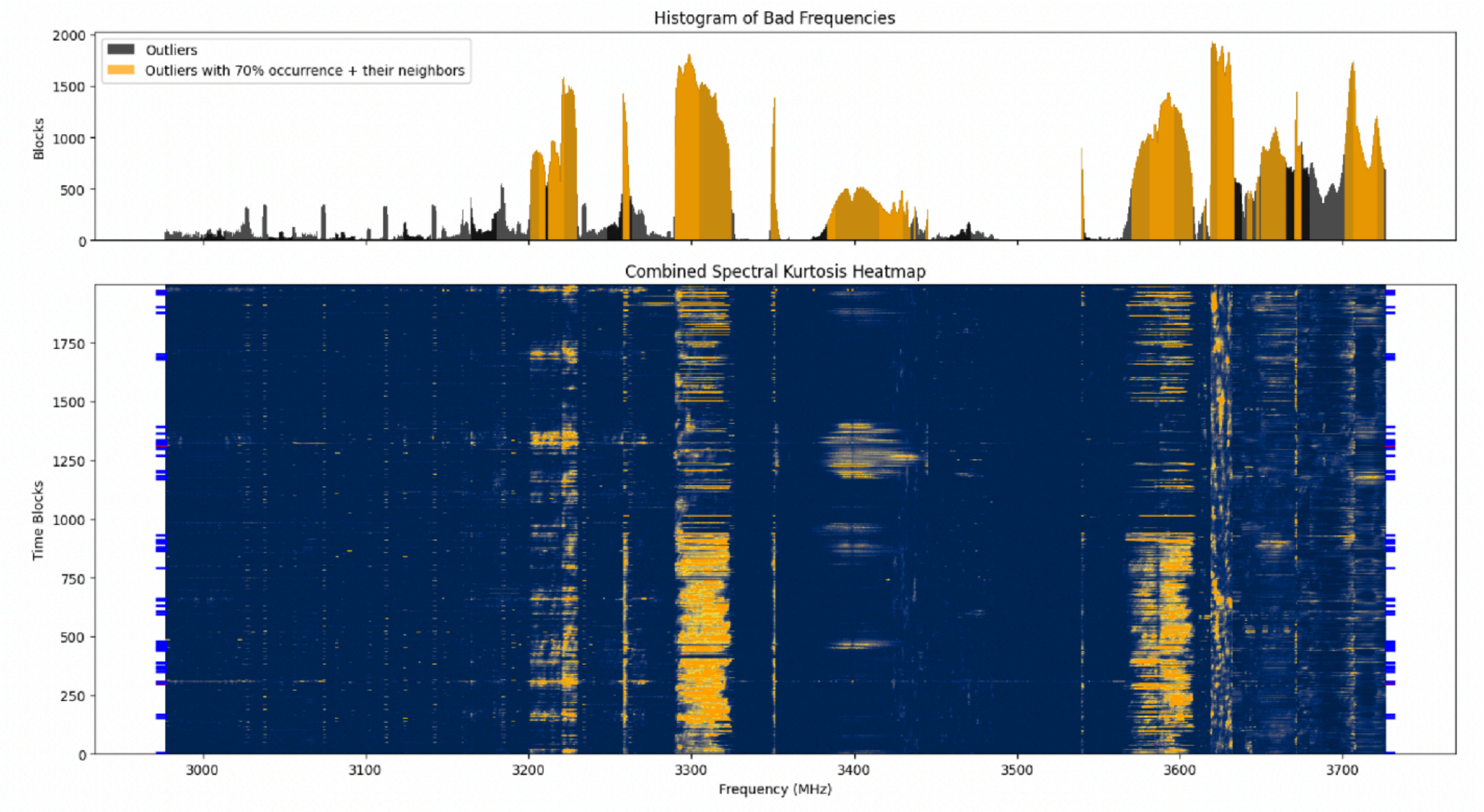






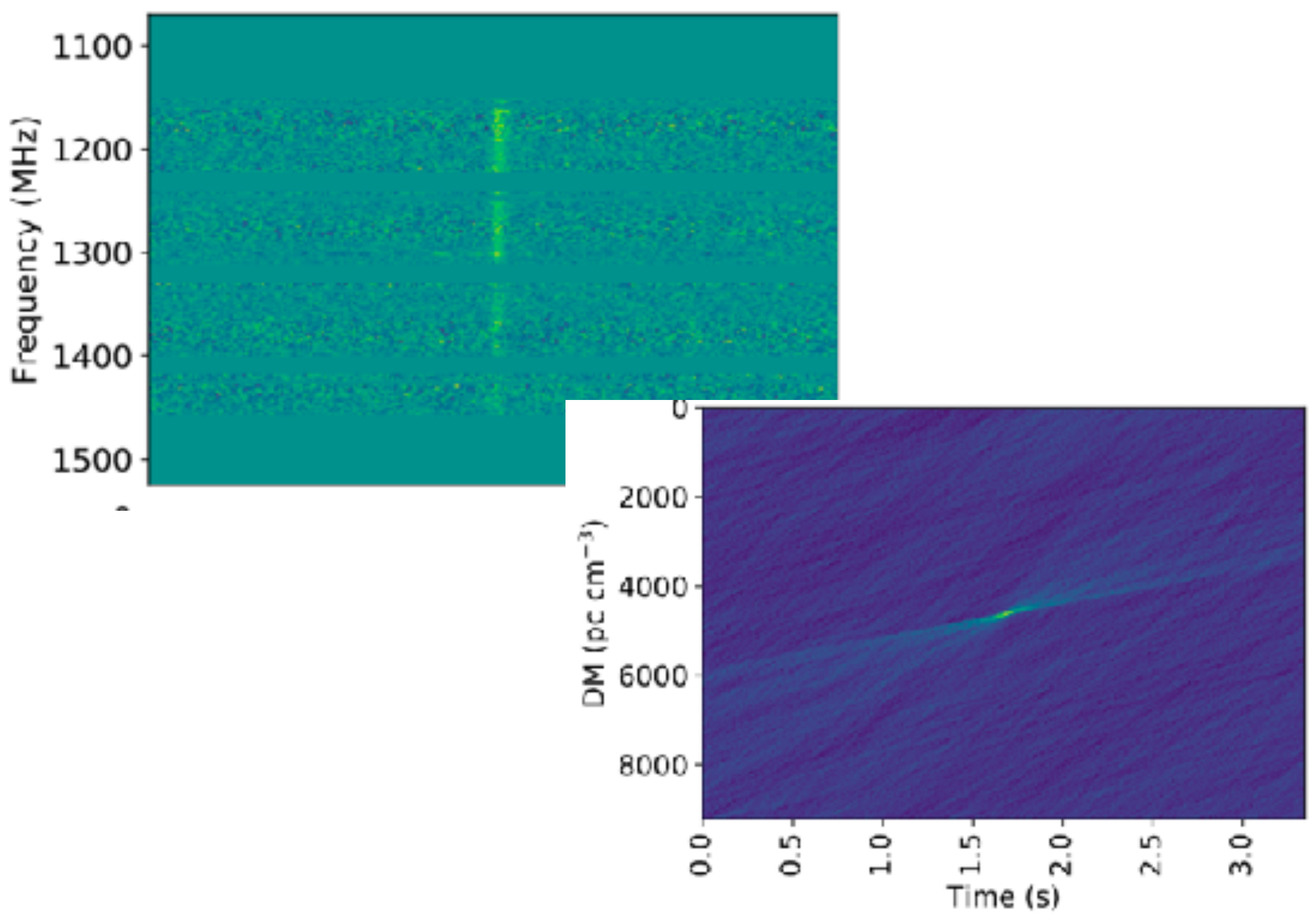
What we actually see…

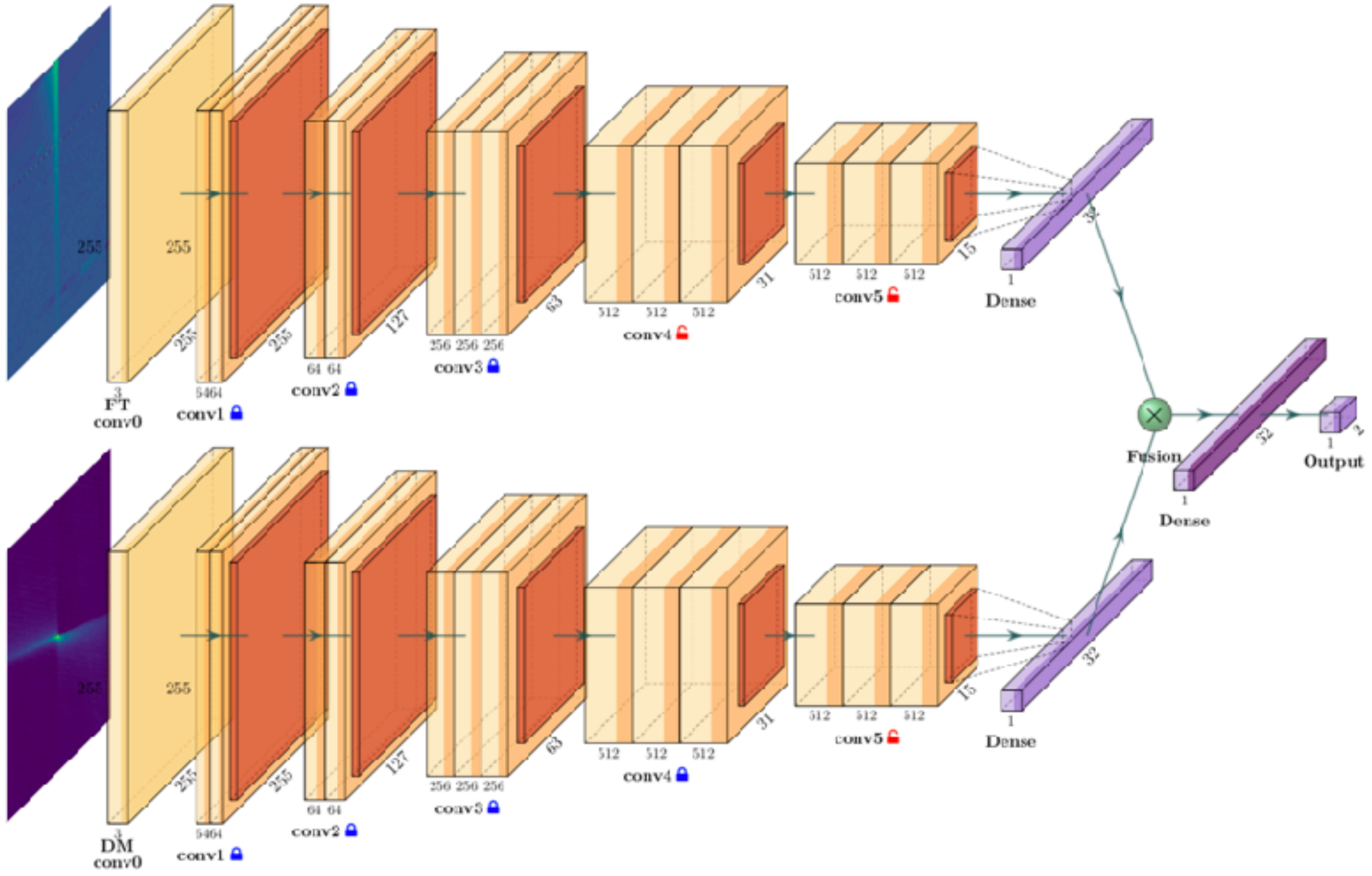
… over 30 minutes



ML to the rescue

- Blind searches can yields many 1000s of candidates, most of which are caused by RFI
- Train convolutional neural networks (CNNs) to distinguish between real, astrophysical signals and RFI
- Mitigating RFI is an enormous time sink

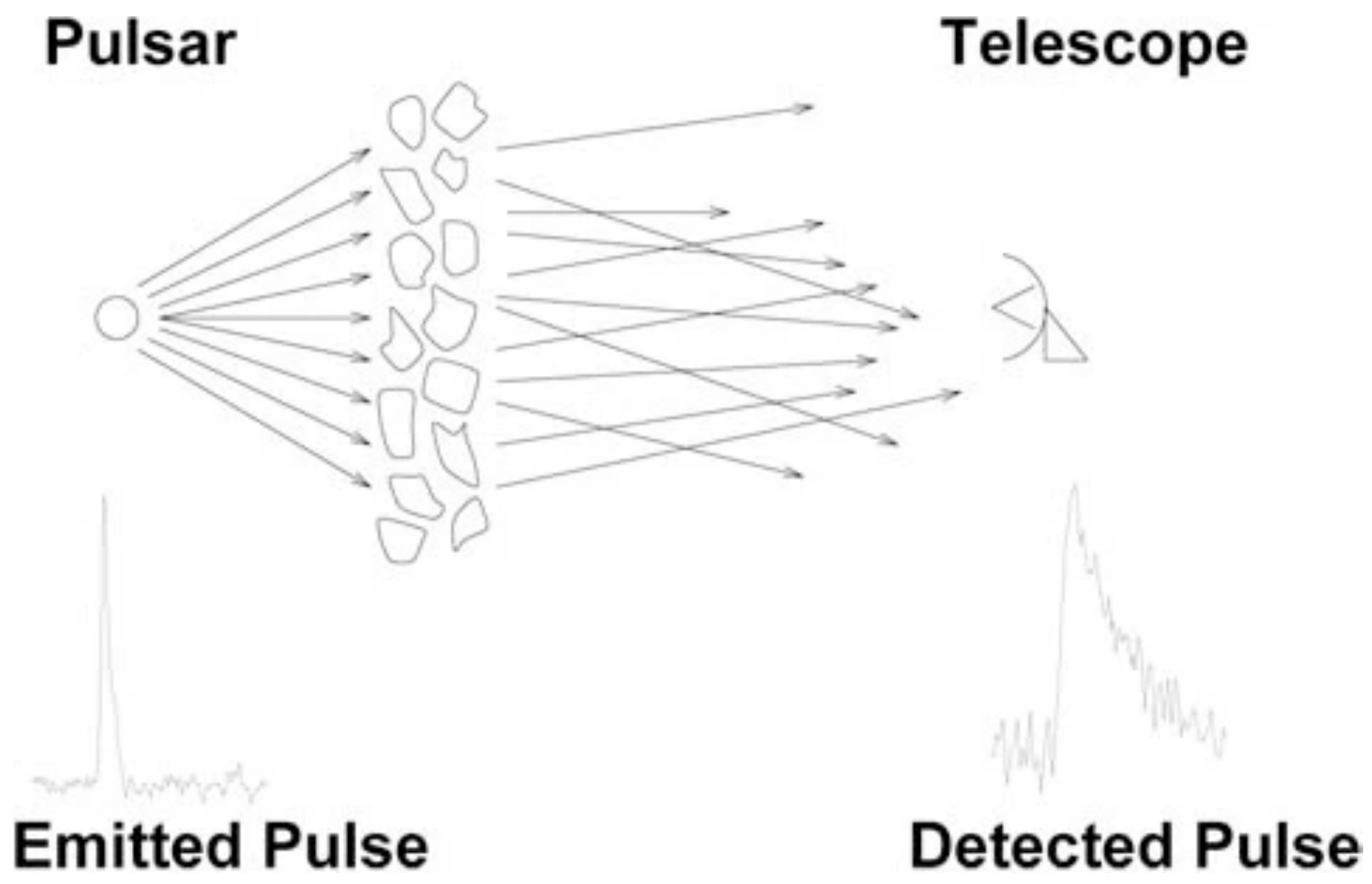




Agarwal et al., MNRAS, 497, 2020

Throwback to Monday…
Kolmogorov turbulence

- "All astrophysical plasmas are turbulent"
- Use pulsars to study the turbulence (or structures) in the **interstellar medium (ISM)**
- **Multi-path propagation through "scattering screens"**
  - Astrophysical origin of these screens is unknown
  - Observables
    - Pulse broadening or "scattering"
    - Scintillation in intensity and frequency

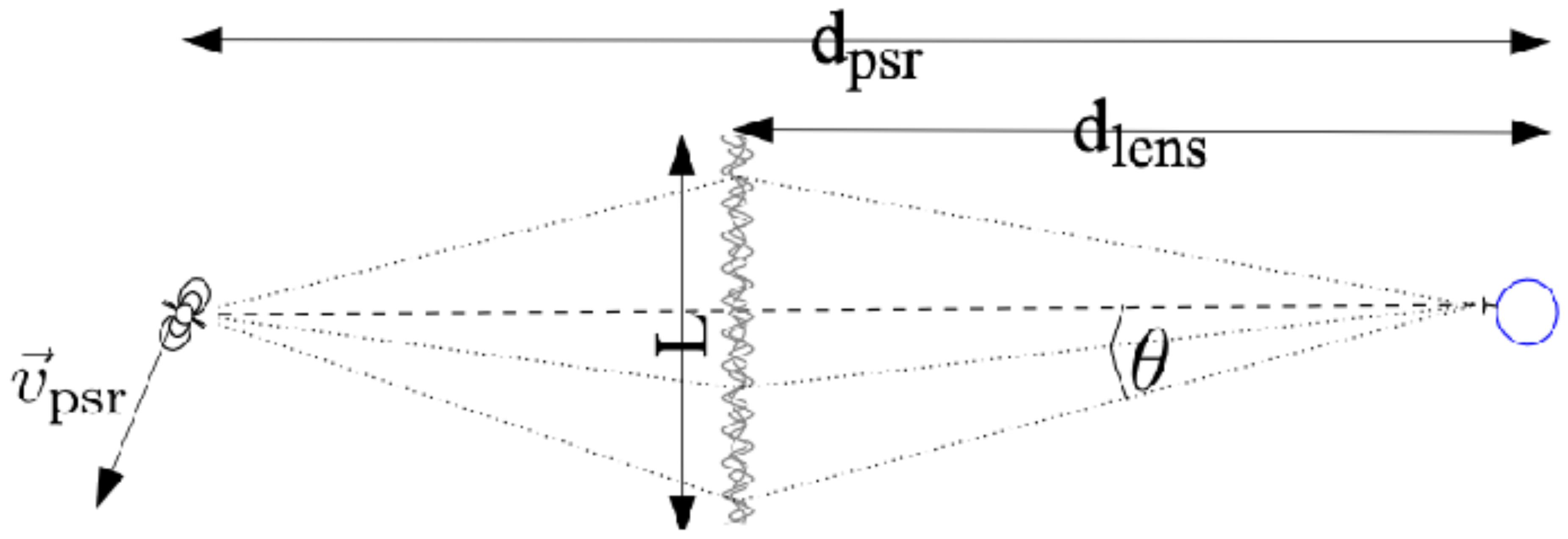


Credit: Duncan Lorimer, 2001

Two models for scattering

- **Model 1: Kolmogorov turbulence**
- Scattering accumulates over line-of-sight
  - $P_{\delta n_e}(q) = C_n^2 q^{-\beta}$
    - Spatial wavenumber: $q = 2\pi / l$
    - Power law index: $\beta = 11/3$
    - $\tau_s \propto \nu^{-4.4}$

- **Model 2: thin screen**
- Scattering dominated by one (or more) small-scale structures ($L << d_{\mathrm{psr}}$)



- $\tau_s \propto \nu^{-4}$

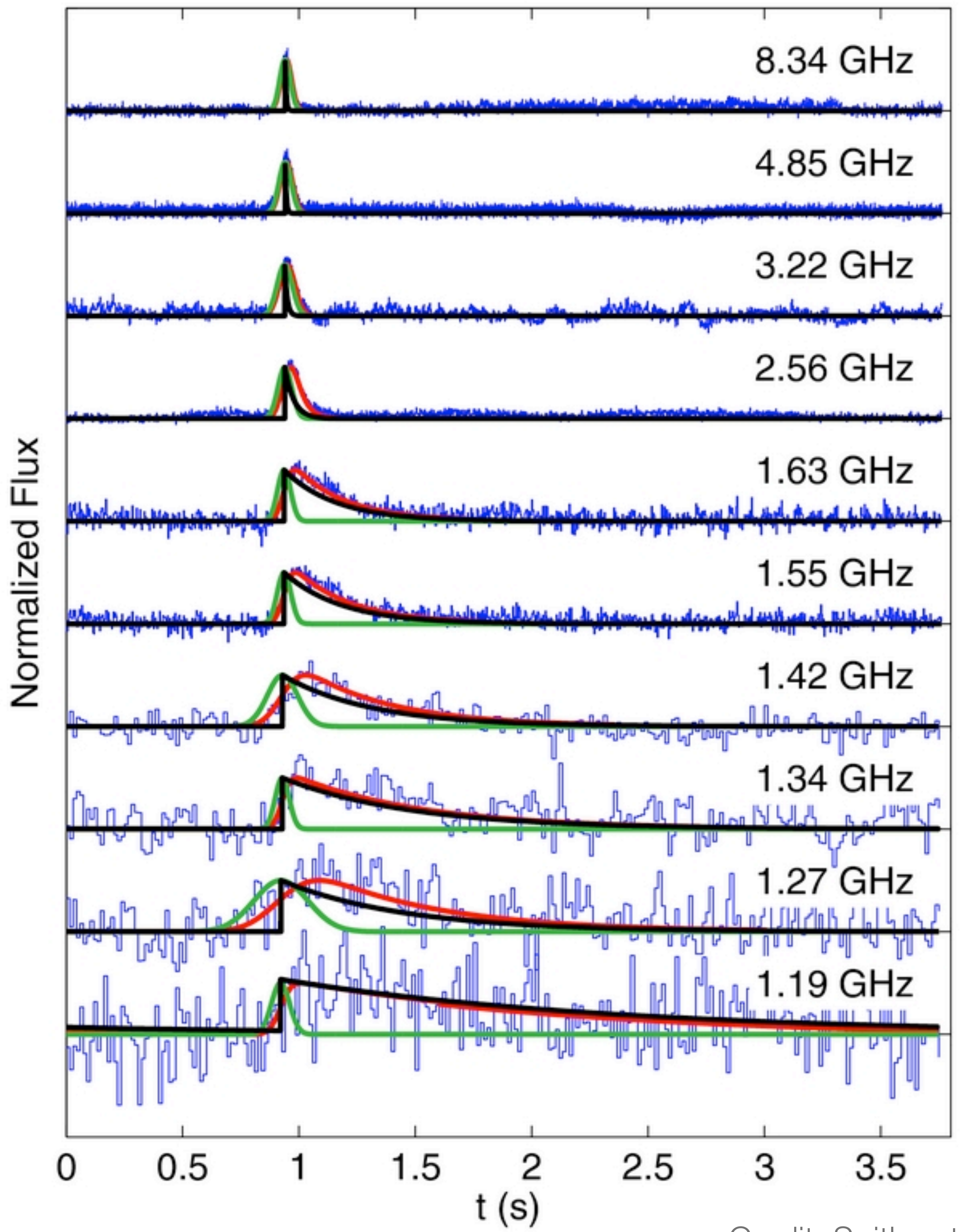
Credit: Robert Main

Scattering screens in the ISM

- Measure the pulse broadening (scattering) as a function of observing frequency

- J1745-2900 (magnetar at the center of the Milky Way)

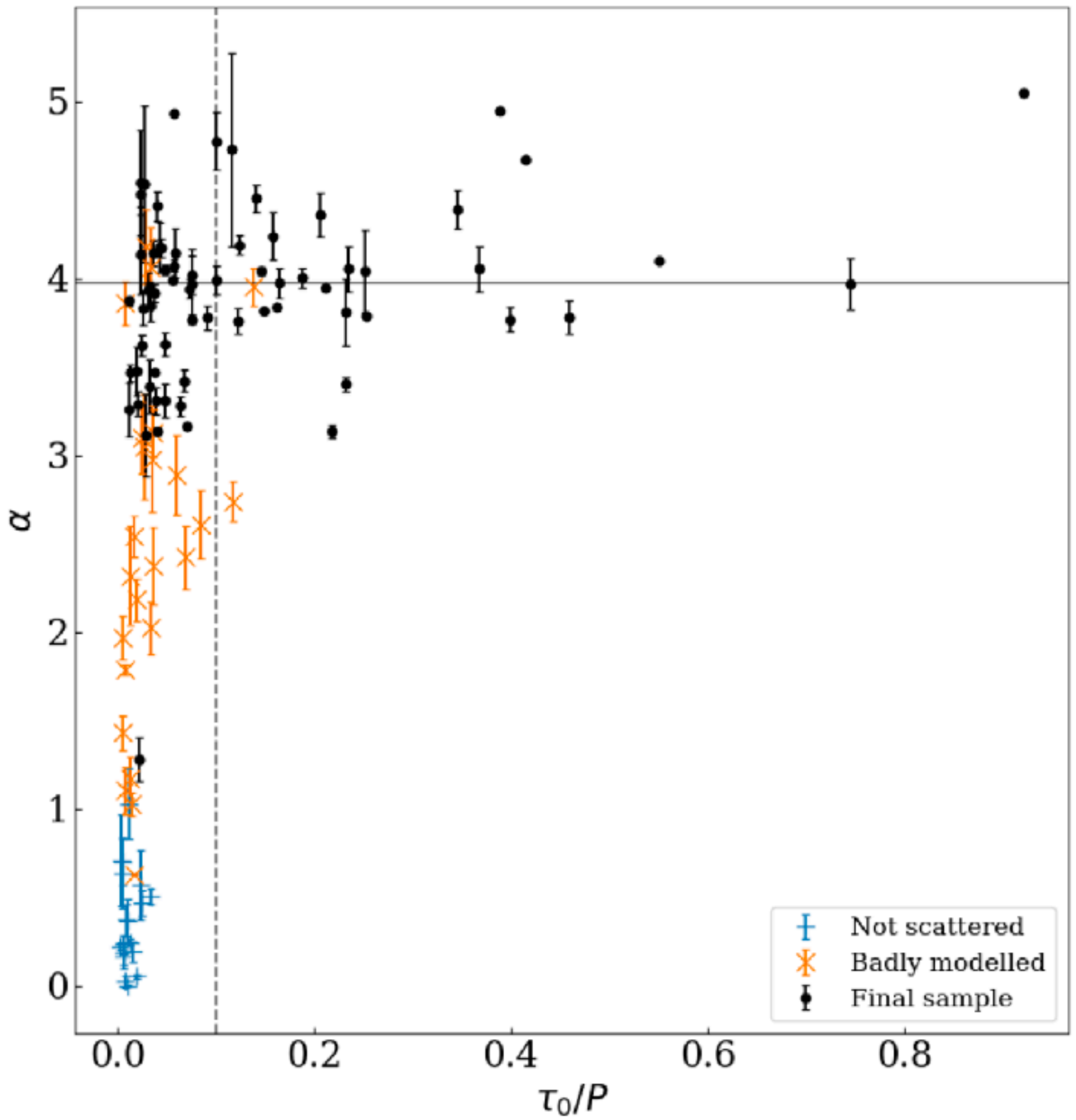
  - $\tau \propto \nu^{-3.8 \pm 0.2}$



Credit: Spitler et al 2014

Scattering screens in the ISM

- Measure the pulse broadening (scattering) as a function of observing frequency
- J1745-2900 (magnetar at the center of the Milky Way)
  - $\tau \propto \nu^{-3.8\pm0.2}$
- Large sample of pulsars:
  - $<\alpha> = 4.0 \pm 0.6$



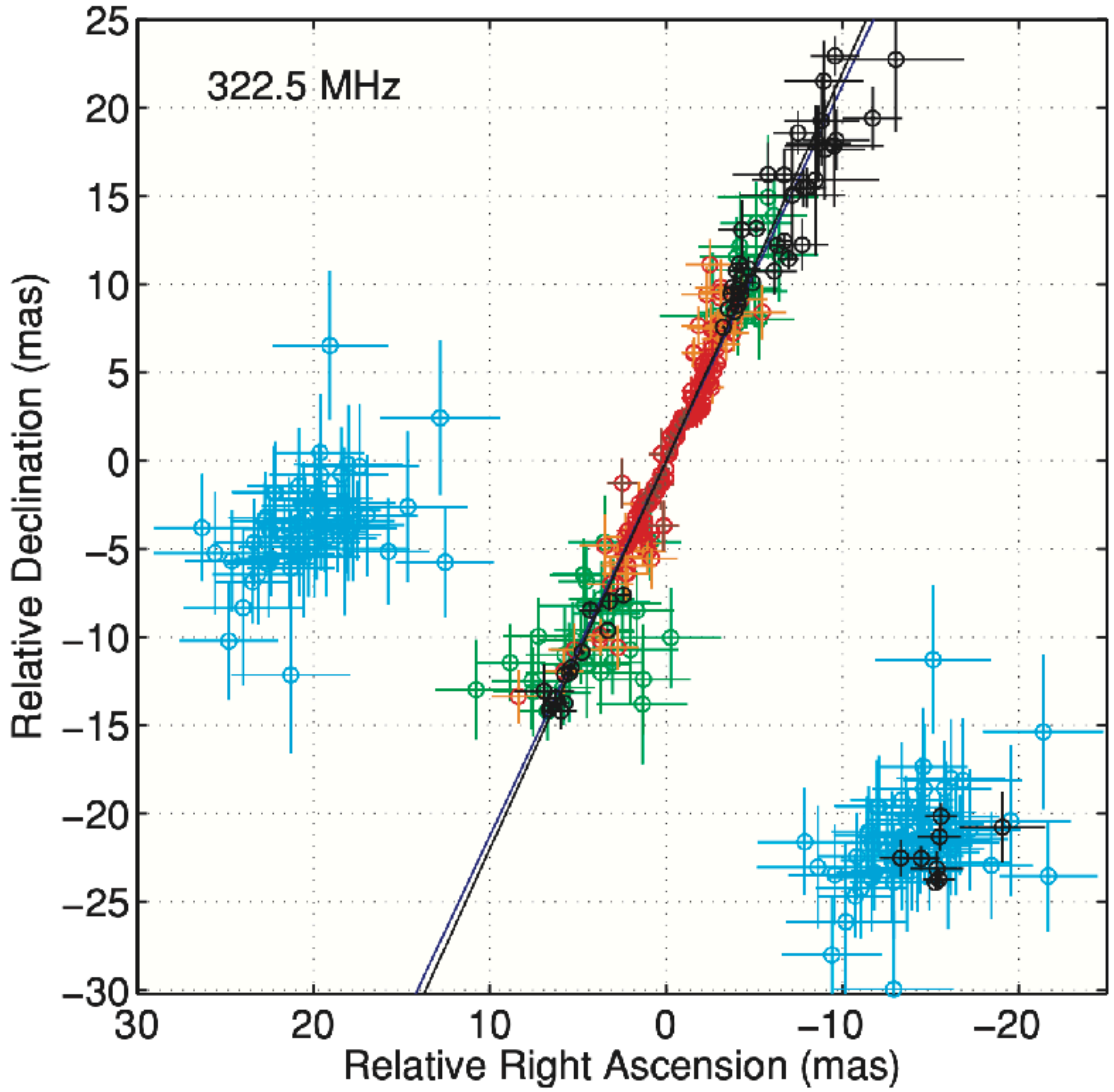
Credit: Oswald et al, MNRAS, 2021

Imaging the scattering

- Imaging the scattering screen using VLBI data also suggests highly elongated scattering screens

- Theoretical models suggest corrugated sheets:

Credit: Pen & Levin 2014



Credit: Brisken et al. 2010

Radio astronomy is…

lowest energies of the electromagnetic spetrum

Fourier transforms

Thermal noise

particles in magnetic fields

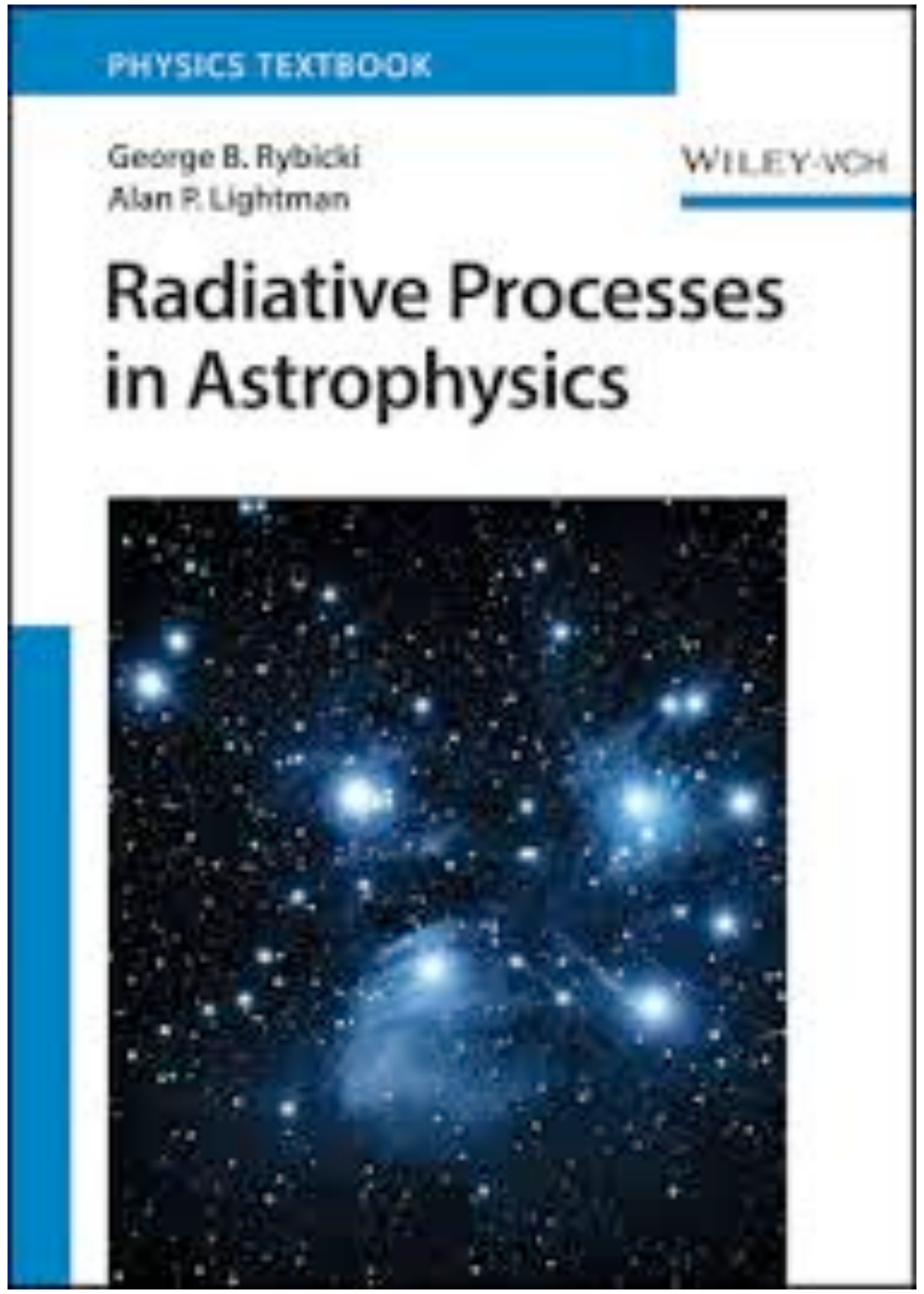
Atomic hydrogen and molecules

Power laws

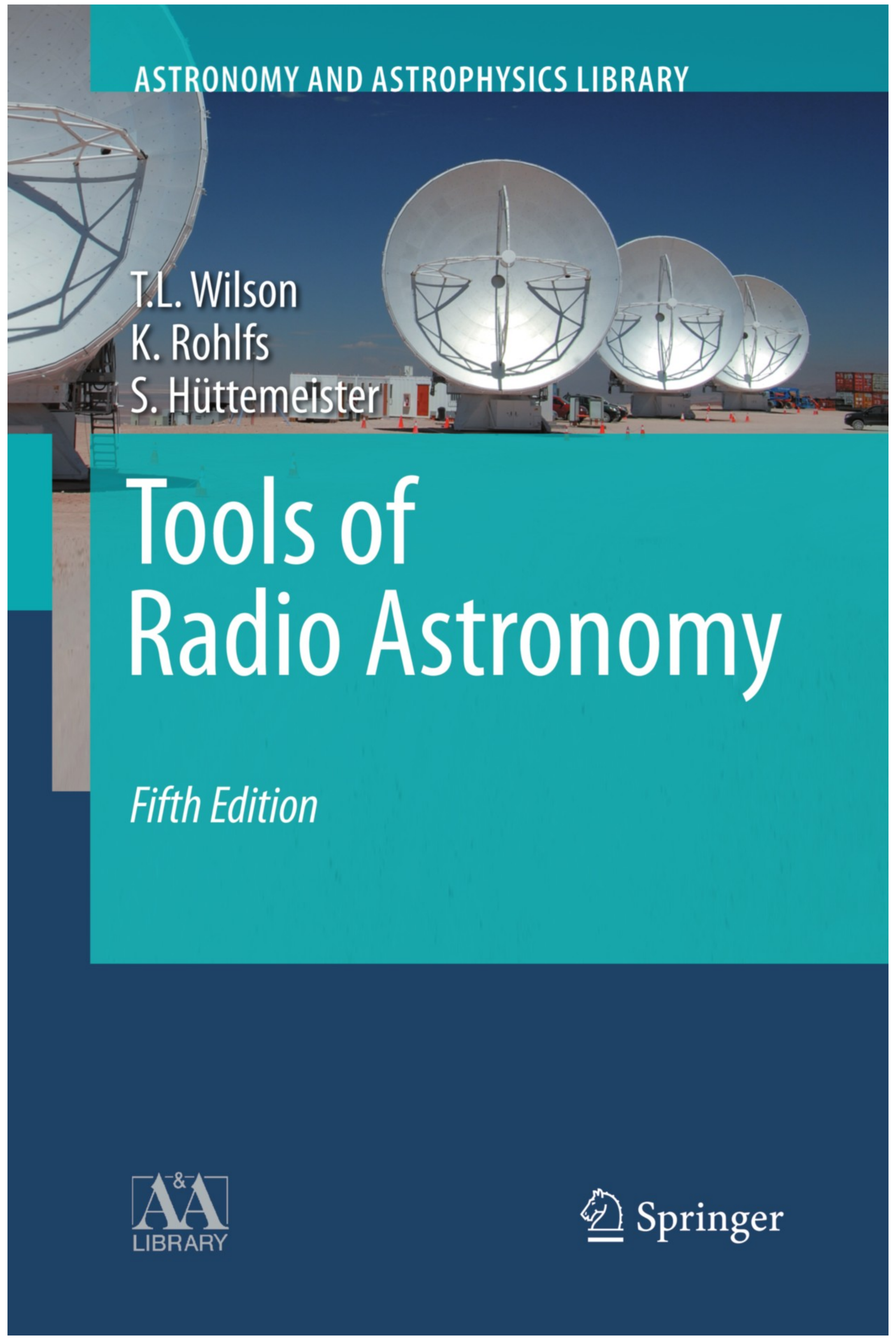
A few things I didn't mention

- Polarimetry
- Technology of "frontends" and "backends"
- Did not do mm- and sub-mm radio astronomy justice

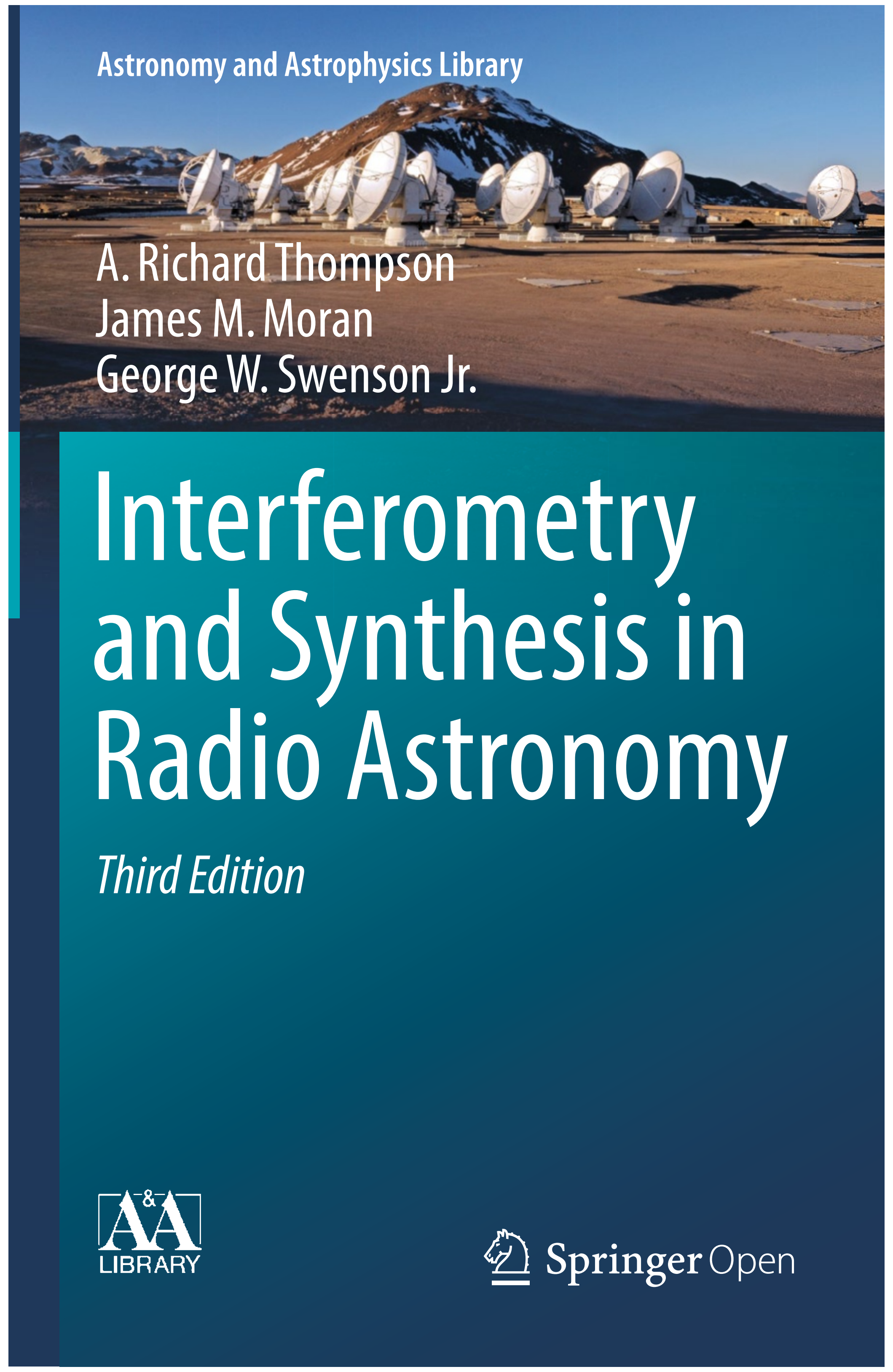
References



Rybicky & Lightman



Wilson, Rohlfs, Hüttemeister



Questions and Discussion