Radio astronomy essentials:
From antennas to interferometry

Cherry
NG-GUIHENEUF

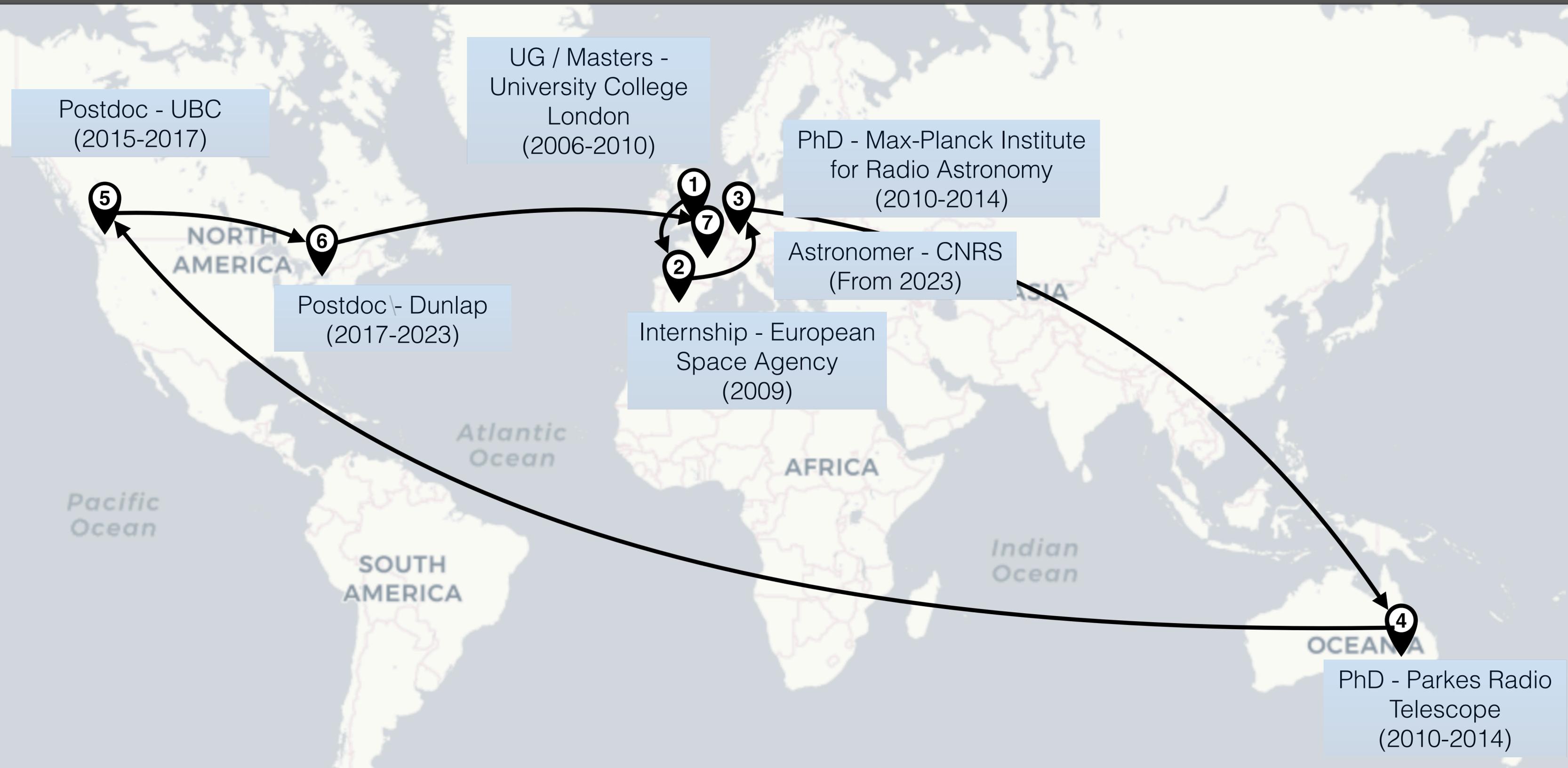CNRS CENTRE NATIONAL DE LA RESEARCHE SCIENTIFIQUE · LPC2E

Lecture planning

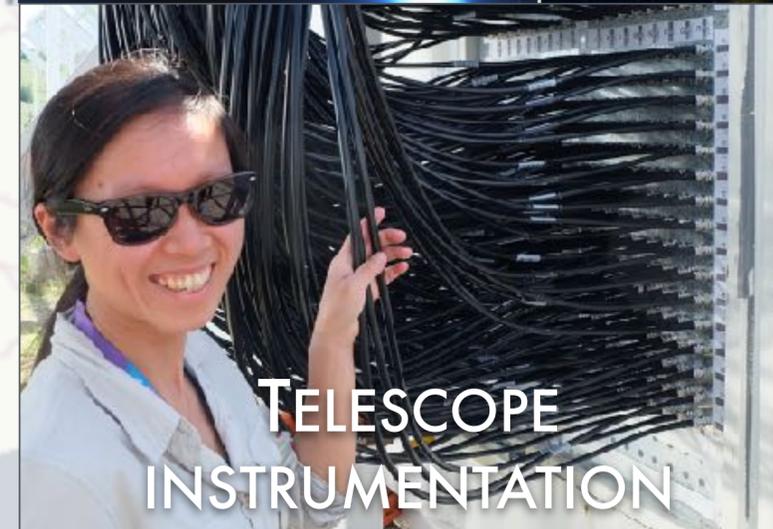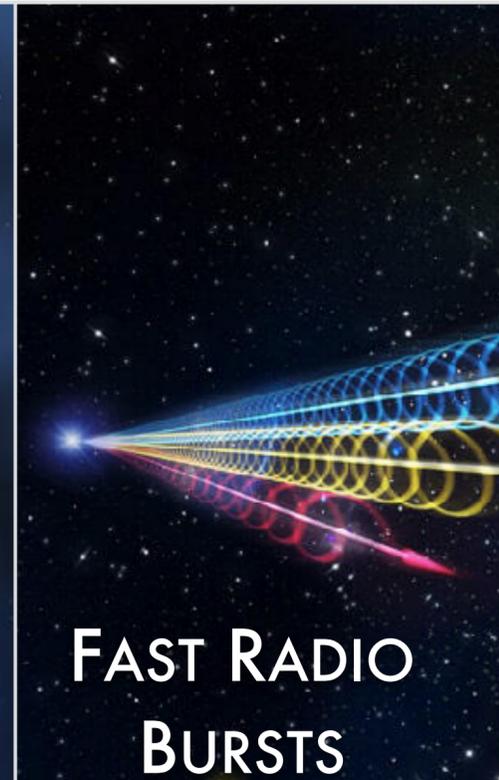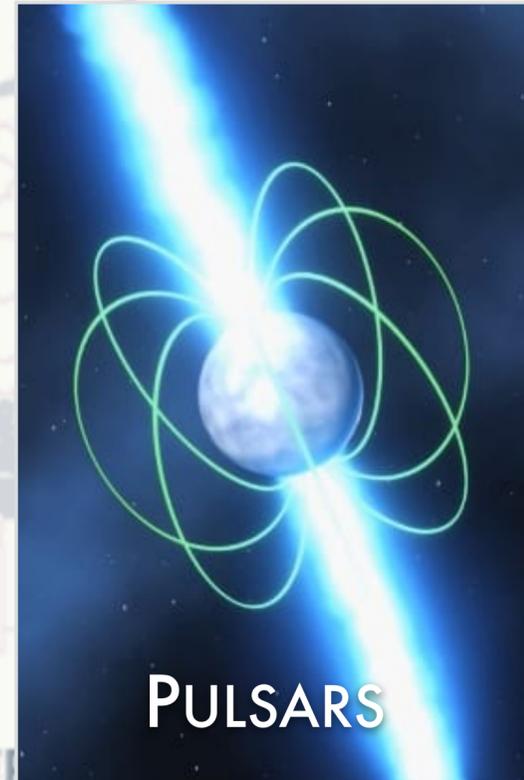## Radio astronomy essentials: From antennas to interferometry

- Class 1 (today 11:20am) - Radio astronomy history, notable observations, single dish and interferometers

- Class 2 (tomorrow 9am) - Pulsars, how to find them and what to do with them

- Class 3 (tomorrow 2pm) - A brief overview of Fast Radio Bursts

- Class 4 (tomorrow 3:30pm) - Hands-on — playing with interferometer imaging + pulsar searching

My career path

Postdoc - UBC
(2015-2017)

UG / Masters - University College London
(2006-2010)

PhD - Max-Planck Institute for Radio Astronomy
(2010-2014)

Astronomer - CNRS
(From 2023)

Postdoc - Dunlap
(2017-2023)

Internship - European Space Agency
(2009)

PhD - Parkes Radio Telescope
(2010-2014)

My career path

LPC2E/CNRS

Nançay Observatory

Radio Astronomy

Pulsars

Fast Radio Bursts

SETI

Telescope Instrumentation

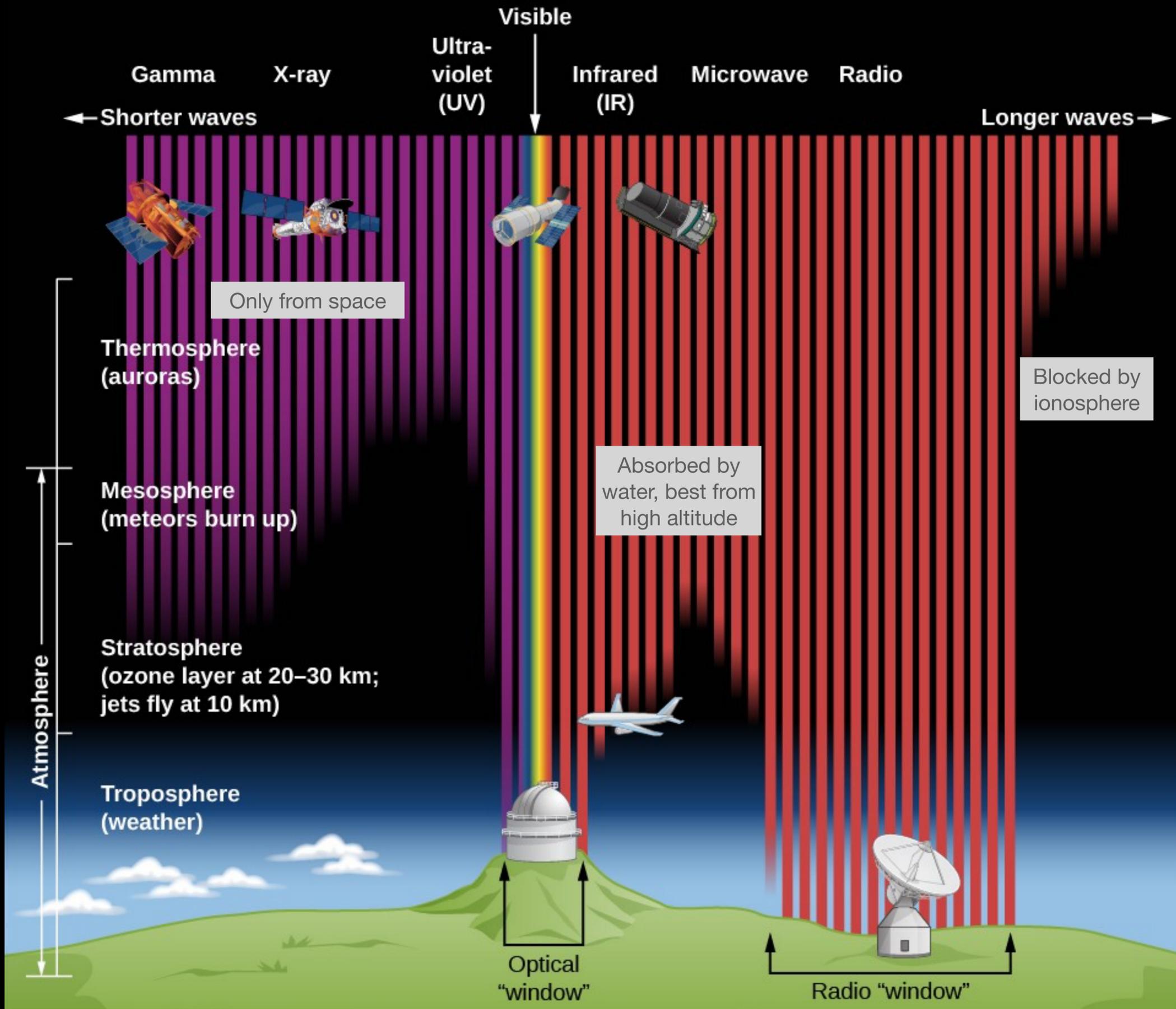Computing

Why radio astronomy?

- Only Radio and Optical are possible from ground base observations (pass though the atmosphere)

- Radio spectrum much wider, lots more information

- Much less affected by dust extinction than optical light, allowing us to observe regions that are obscured in the optical, such as star-forming regions and the Galactic center.

Credit: modification of work by STScI/JHU/NASA
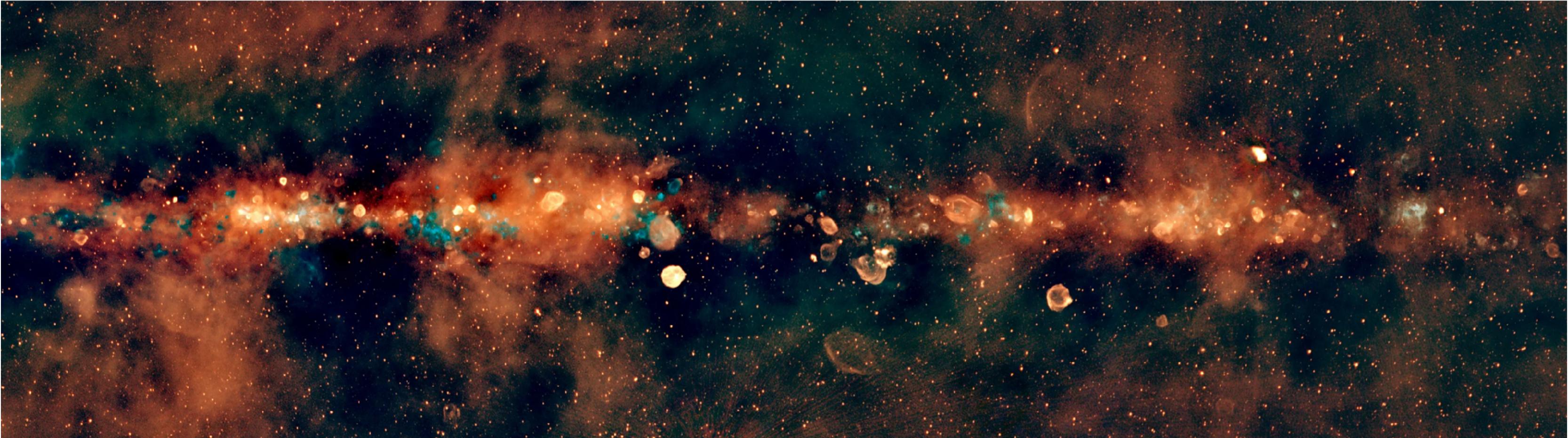
Top image credit: S. Mantovanini & the GLEAM-X team
Bottom image credit: Axel Mellinger, milkywaysky.com

Why radio astronomy came later than optical?

Inside stars:

- Matter is **dense and hot**
- Photons are constantly **absorbed and re-emitted**
- Radiation field reaches **thermal equilibrium**
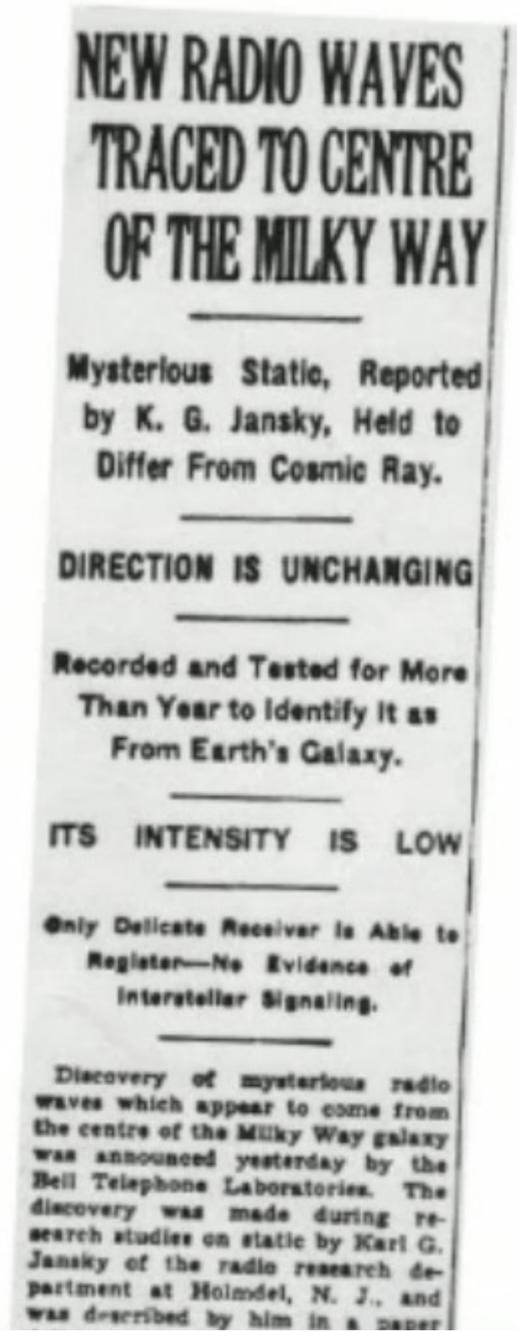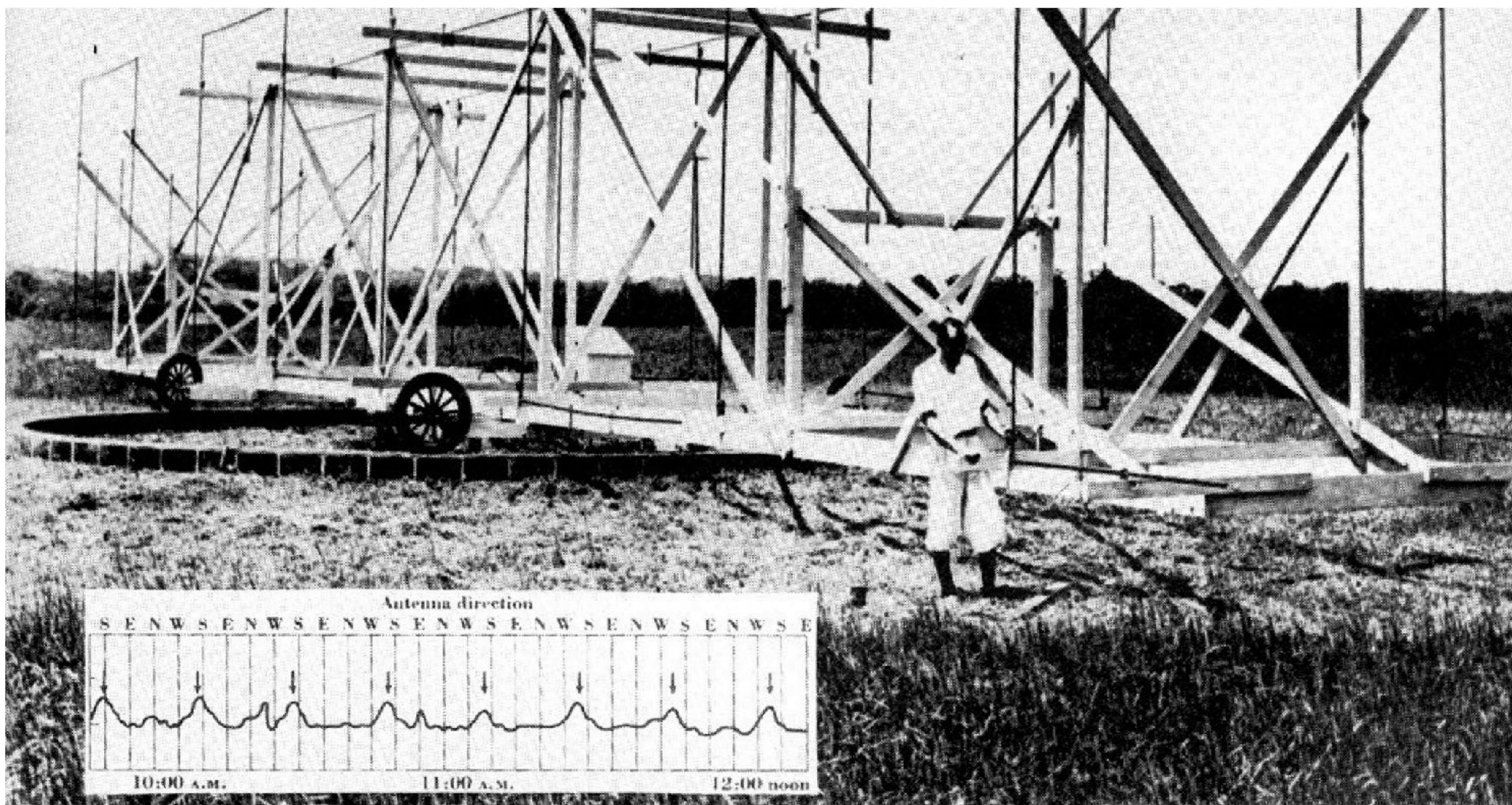- **=> Blackbody**

Blackbody:

- absorbs all incoming radiation
- radiation emitted depends **only on its temperature**
- Hotter objects emit **more energy** and peak at **shorter wavelengths**
- Emitted spectrum follows **Planck's law**:

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

Radio= $10^6 - 10^{14}$ nm
Or $0.1 - 10^7$ cm
Or 300 GHz−3 kHz
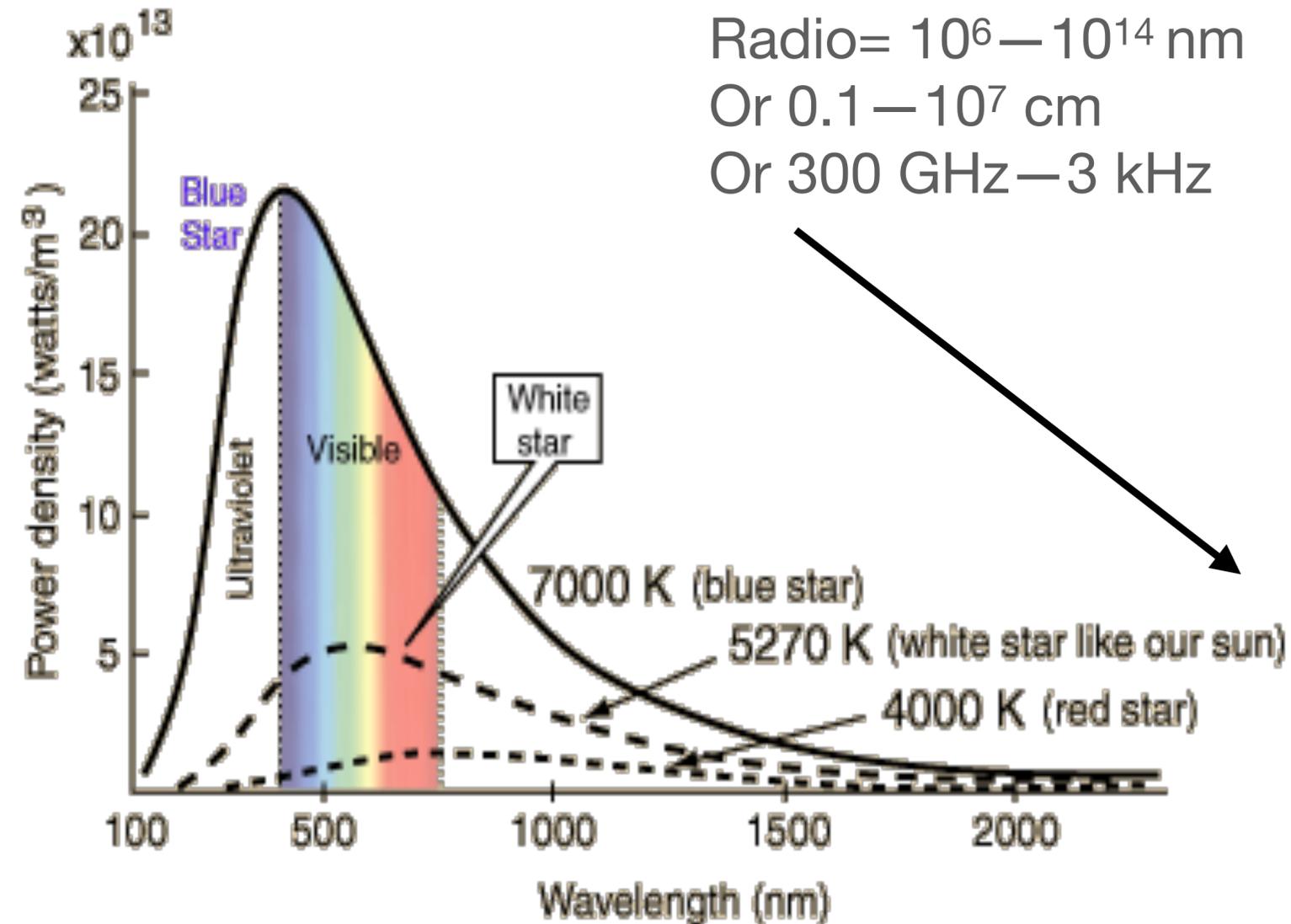
Credit: HyperPhysics

First radio observation

- **Karl Jansky** at Bell Labs discovered cosmic radio emission (1932)
- Photo: Azimuth rotating antenna (20.5 MHz), Holmdel, NJ
- 1 Jy = 10^{-26} W m^{-2} Hz^{-1} (**flux density** = how much radio power from a source reaches a telescope per unit area and per unit freq)

First deliberate radio observation

- 1944 **Grote Reber** an amateur astronomer

- Built 9-m parabolic dish at his parents' backyard, self-funded, designed and constructed by himself

- **First radio map of the Milky Way**
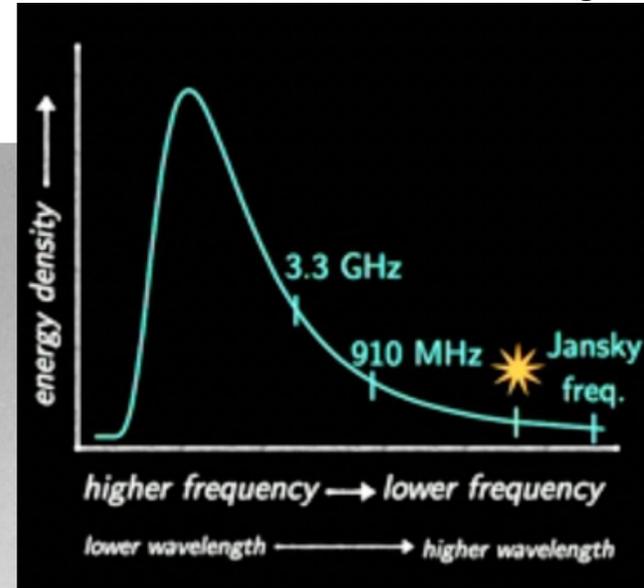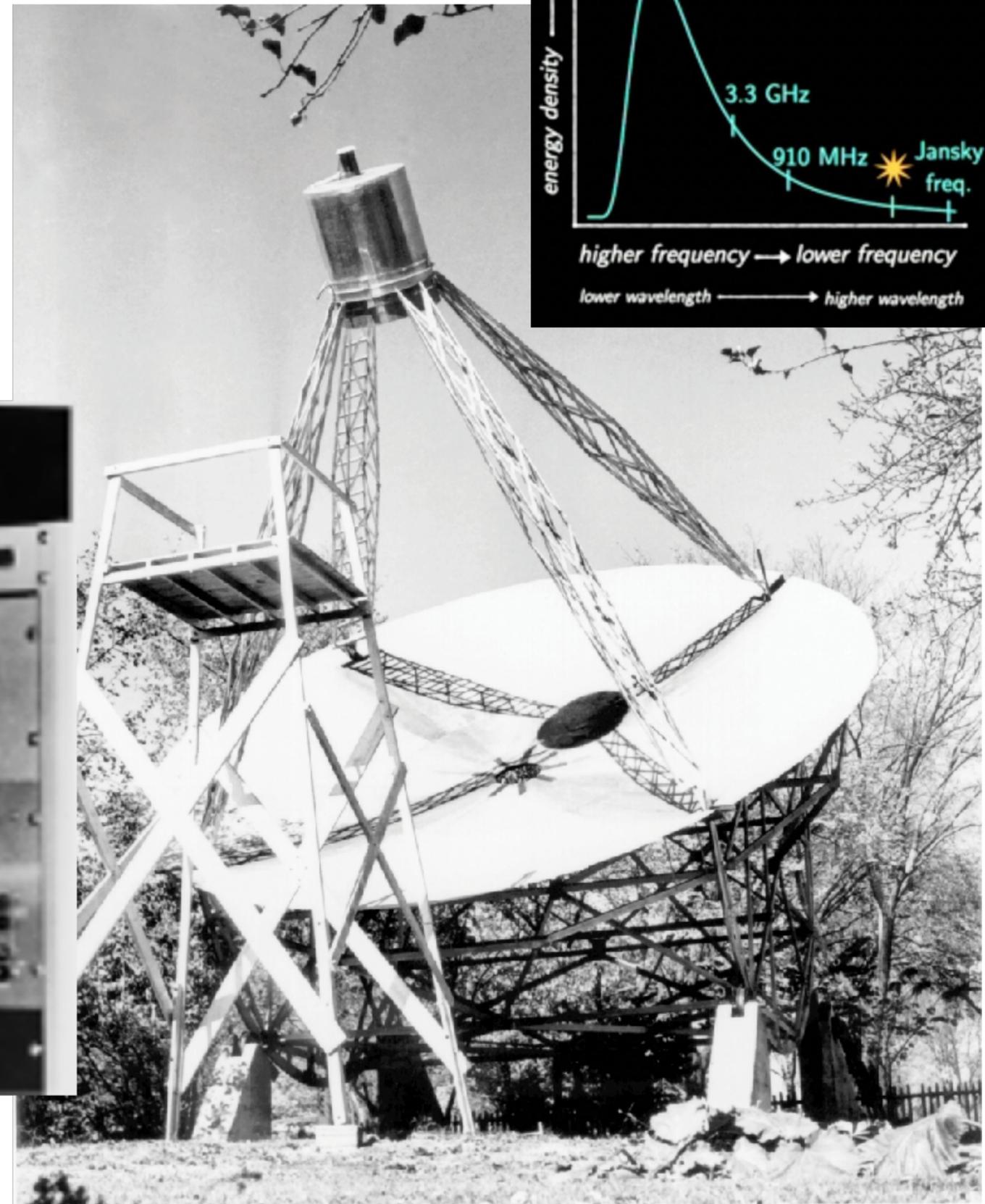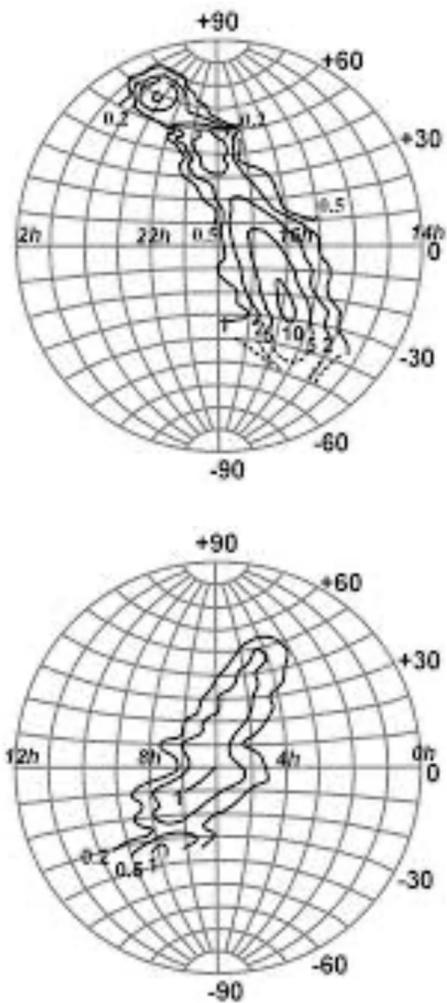
What did Jansky and Reber detect in radio?

Blackbody (stars)

Free-free
(ionized gas)

Dust emission
(molecular clouds)

Thermal radiation

Non-thermal radiation

Synchrotron
(magnetic field)

Coherent radio
(pulsar, FRBs)

Astrophysical
masers
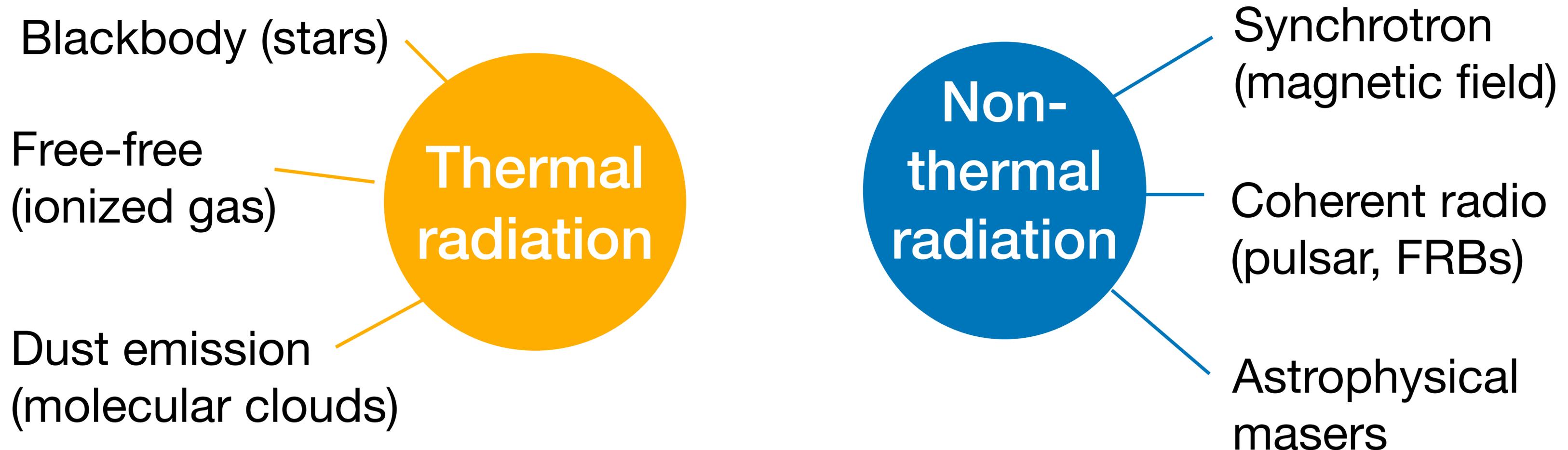
Thermal emission tells us about the **temperature** of matter,
while non-thermal emission reveals particle **acceleration** and **energetic** processes.

Synchrotron radiation
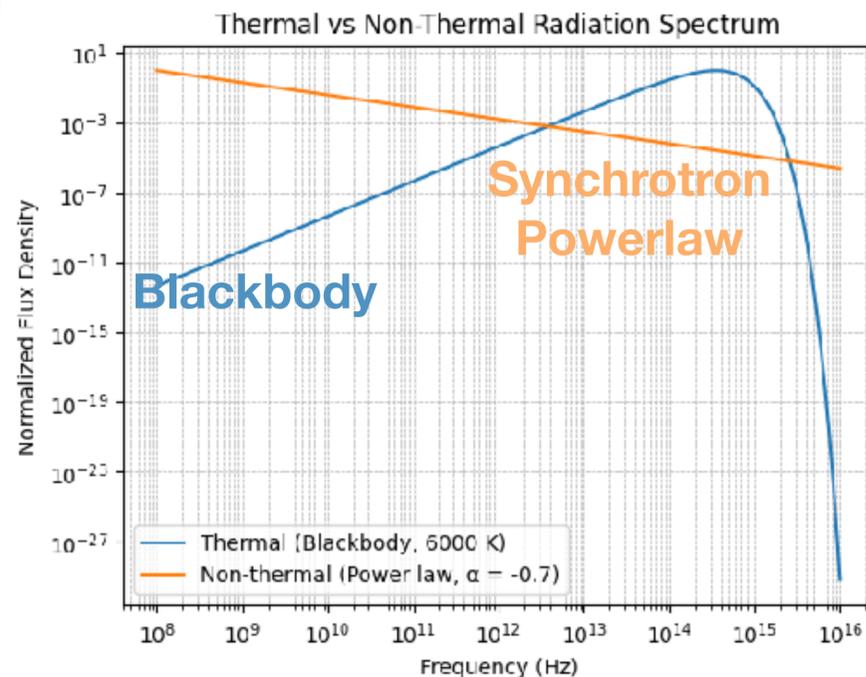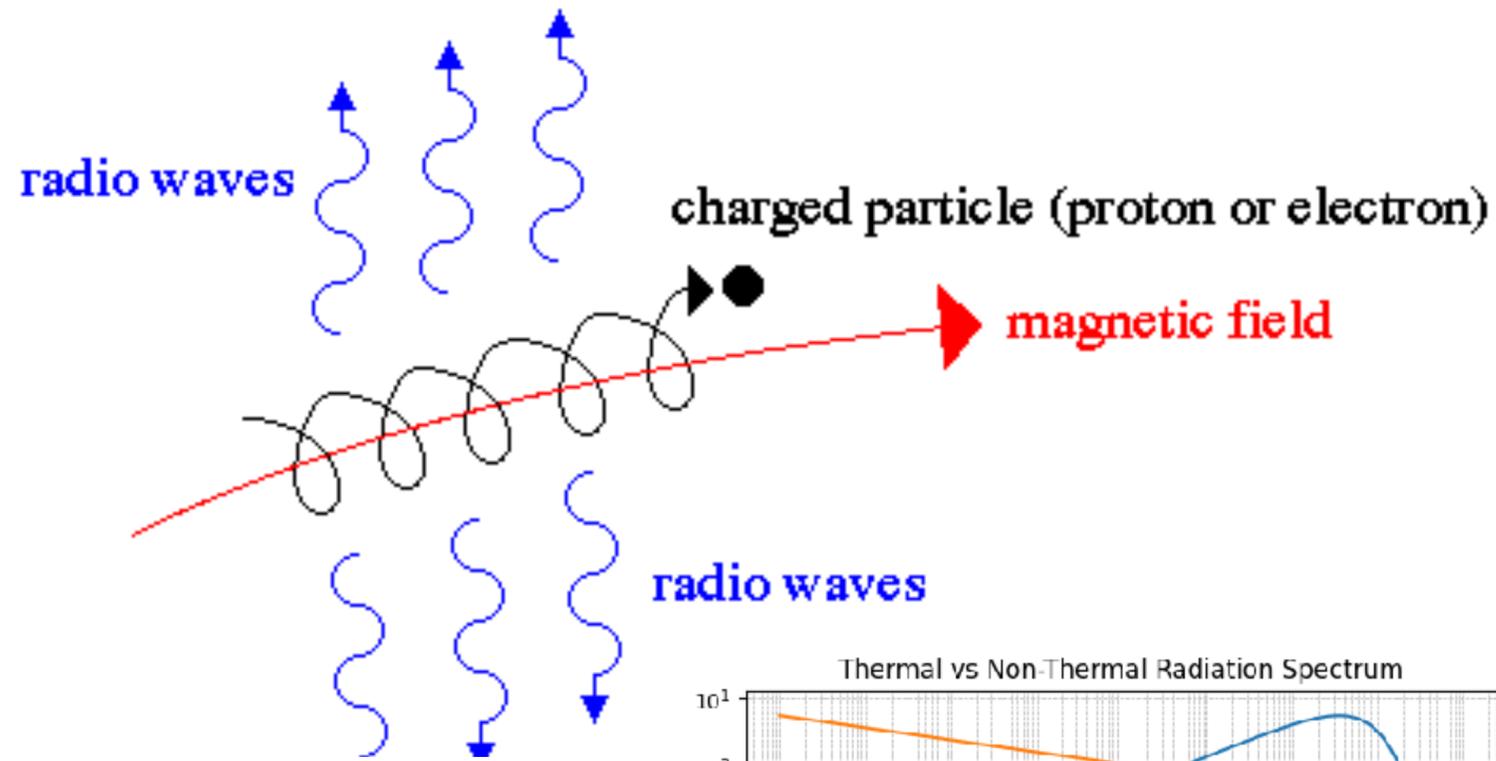
- Relativistic electrons spiral around **magnetic field lines**.

- As the charged particle accelerates in the magnetic field, it emits radiation.

- Electrons move at **relativistic speeds**

- Radiation is beamed along the particle velocity

- Emission freq depends on electron energy and magnetic field

- $S_\nu \propto \nu^\alpha$ where α is negative (-0.5 to -1) so decreases with freq and dominates low-free radio emissions

Free-free (Bremsstrahlung)

- An electron passing near an ion is **accelerated by the Coulomb force**. This acceleration causes the electron to radiate.

- The German name **Bremsstrahlung** means "braking radiation."

- Occurs in ionized plasma

- Electrons are **thermal**

- $S_v \propto v^{-0.1}$ so flat compared to synchrotron

Credit: heliowiki.smce.nasa.gov

Incident Electron
Energy = E_{in}

Scattering Particle - Ze

Bremsstrahlung Photon
Energy = E_{in} - E_{out}

Scattered Electron
Energy = E_{out}
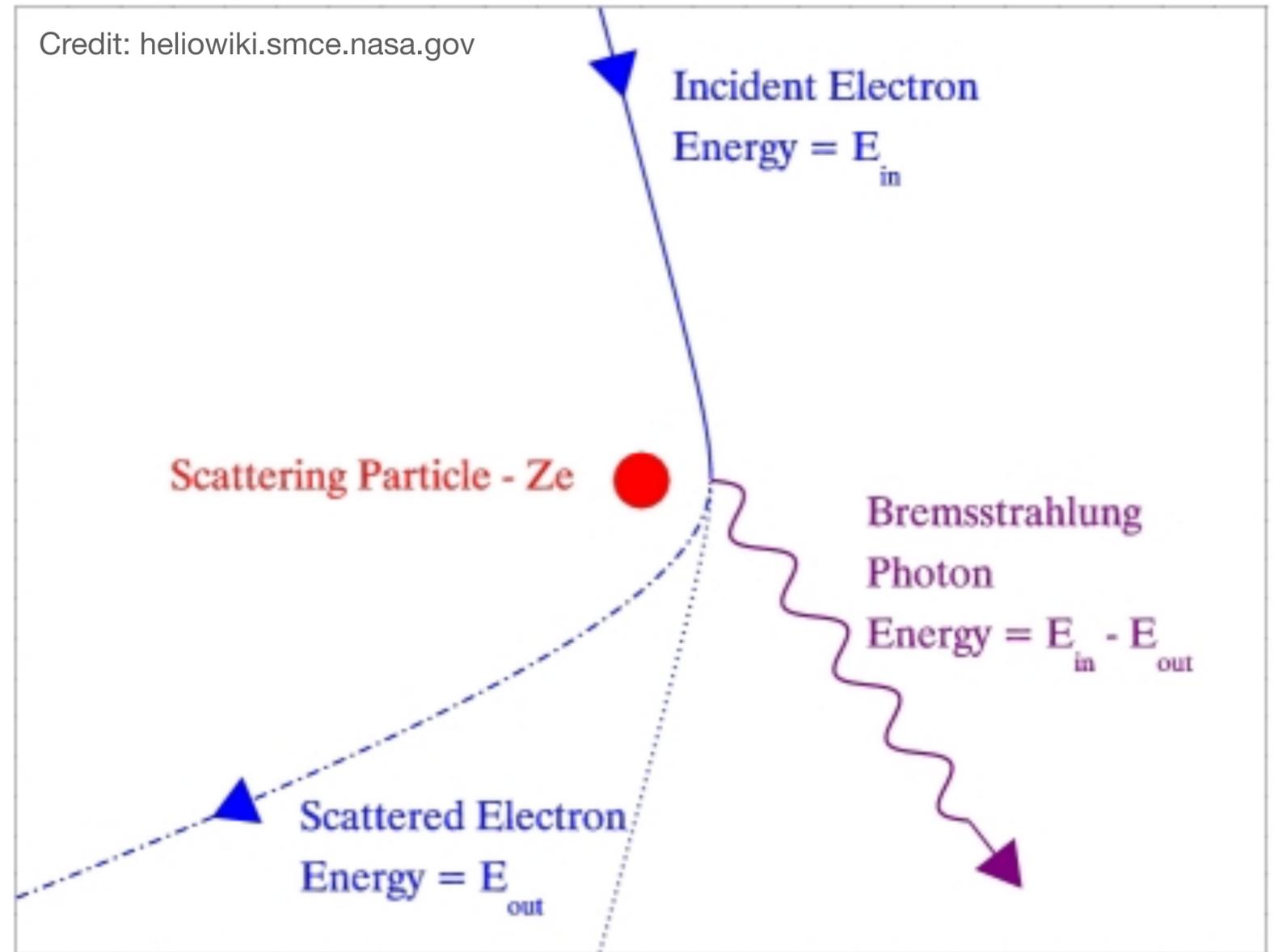
Coherent emission

- Many charged particles radiate EM waves with a fixed phase relationship. Because the waves are **in phase**, they add constructively, producing a much stronger signal than if each particle radiated independently.

- Charge bunching, plasma instability

- Extremely high brightness temperature

- Why in radio?
For coherence to occur, the emitting region must be **smaller than the wavelength** — easier in radio, bunches can be cm long.

- Properties:
Often narrow-band or bursty and highly **polarized**
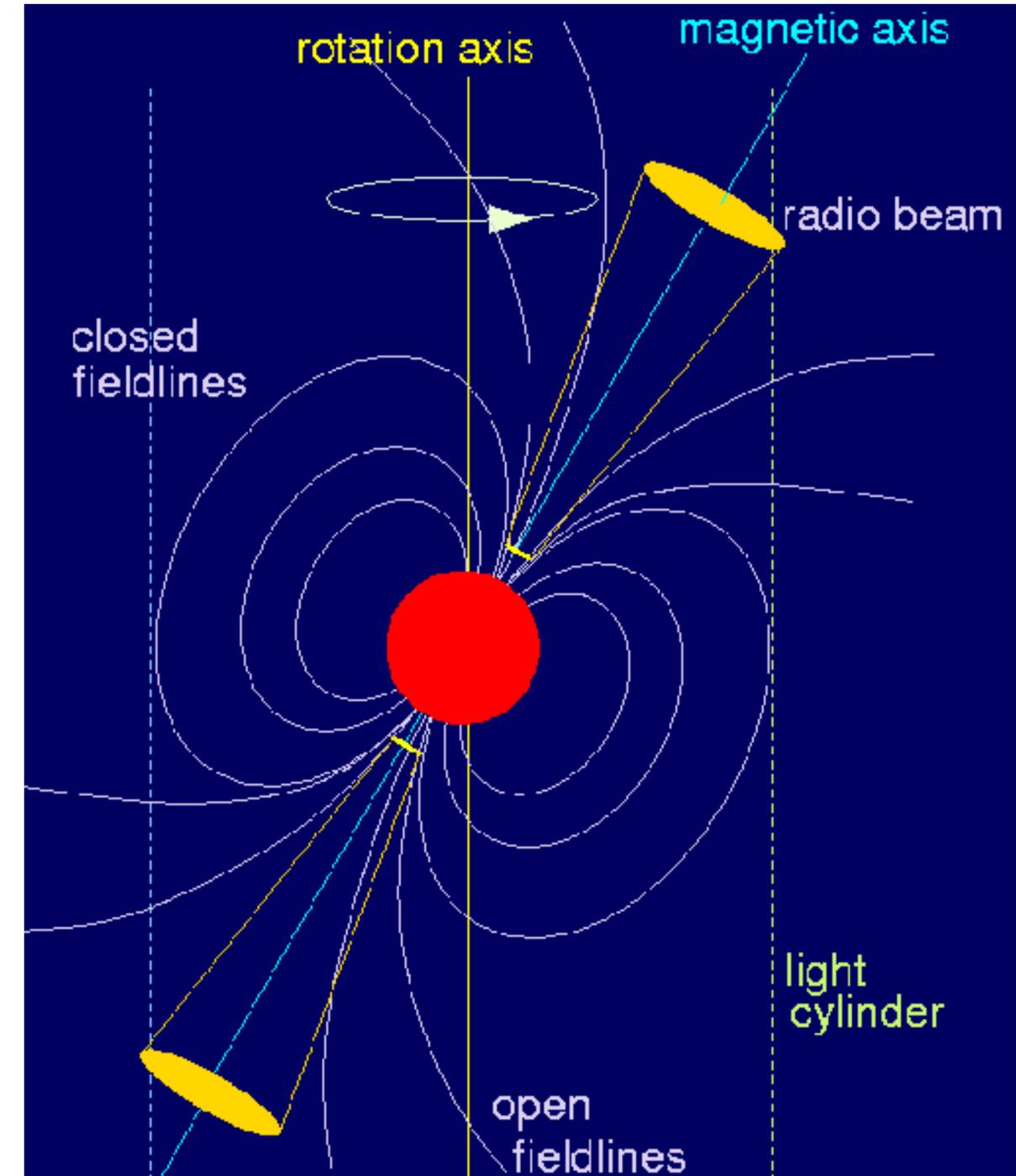
Some good examples of radio observations
Quasars and radio jets from AGN

Synchrotron

Quasar 3C-48 Distance 4 billion light years

40X brighter than the brightest known galaxies
The luminosity was far too high to be explained by stars.
This strongly suggested gravitational energy release.

Strong radio source that appeared star-like in optical cross check
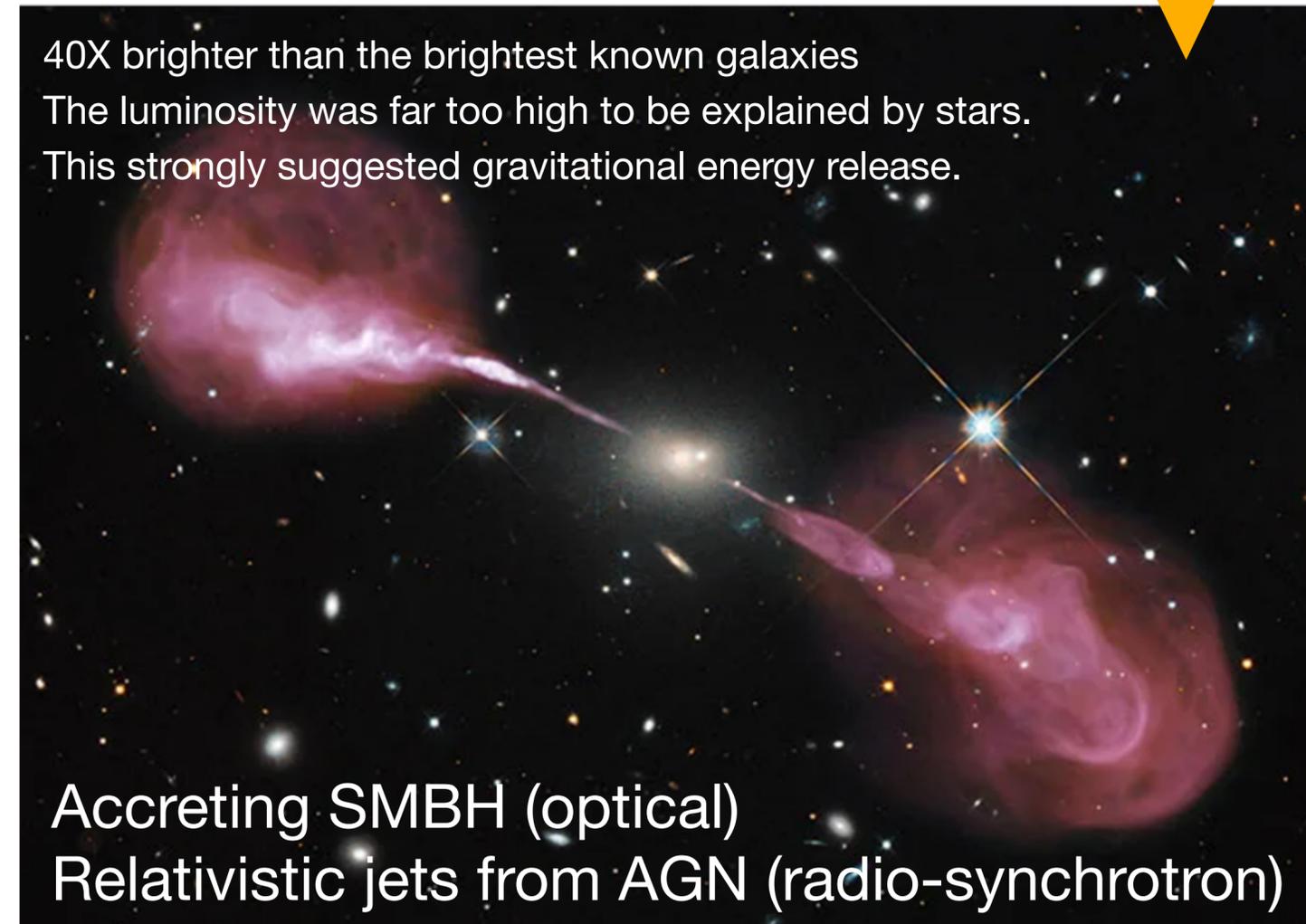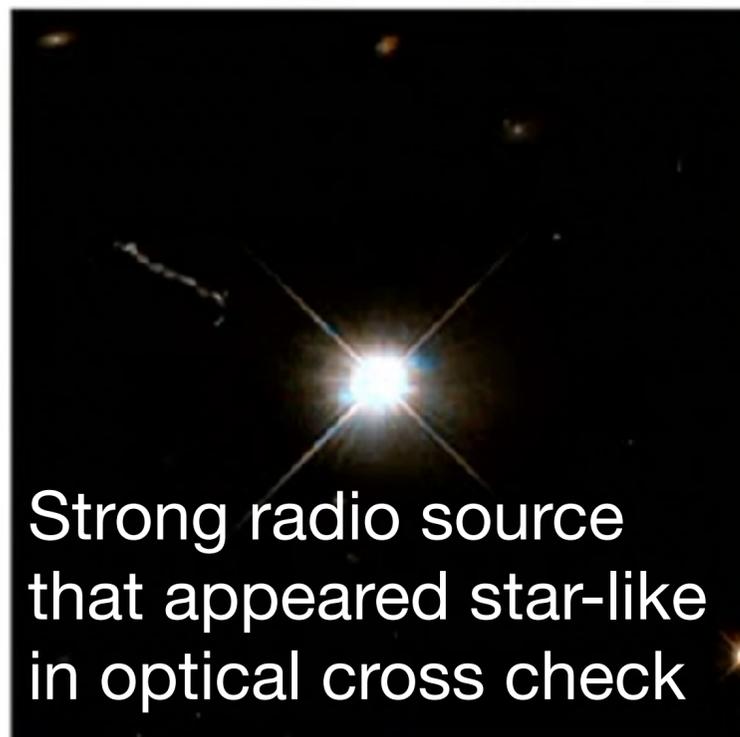
Emission lines have large redshifts

Hδ Hγ Hβ [O III]

3C 273

COMPARISON

4000 Å Hδ Hγ Hβ 5000 Å 6000 Å

Accreting SMBH (optical)
Relativistic jets from AGN (radio-synchrotron)
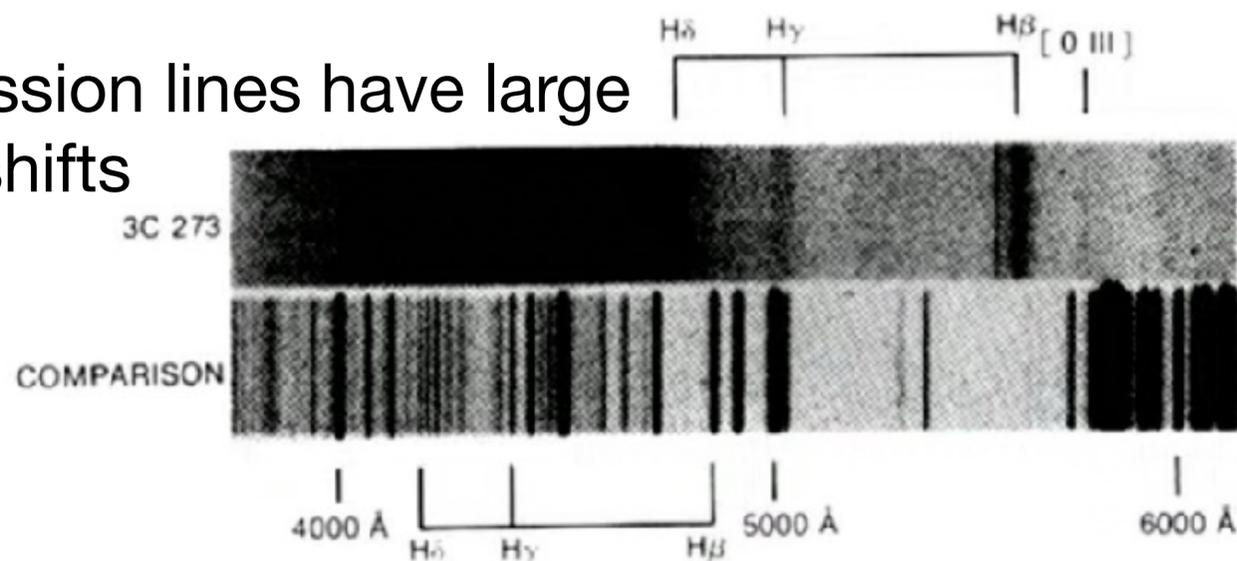
📷 NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)

Some good examples of radio observations
Pulsars (see tomorrow's lecture)
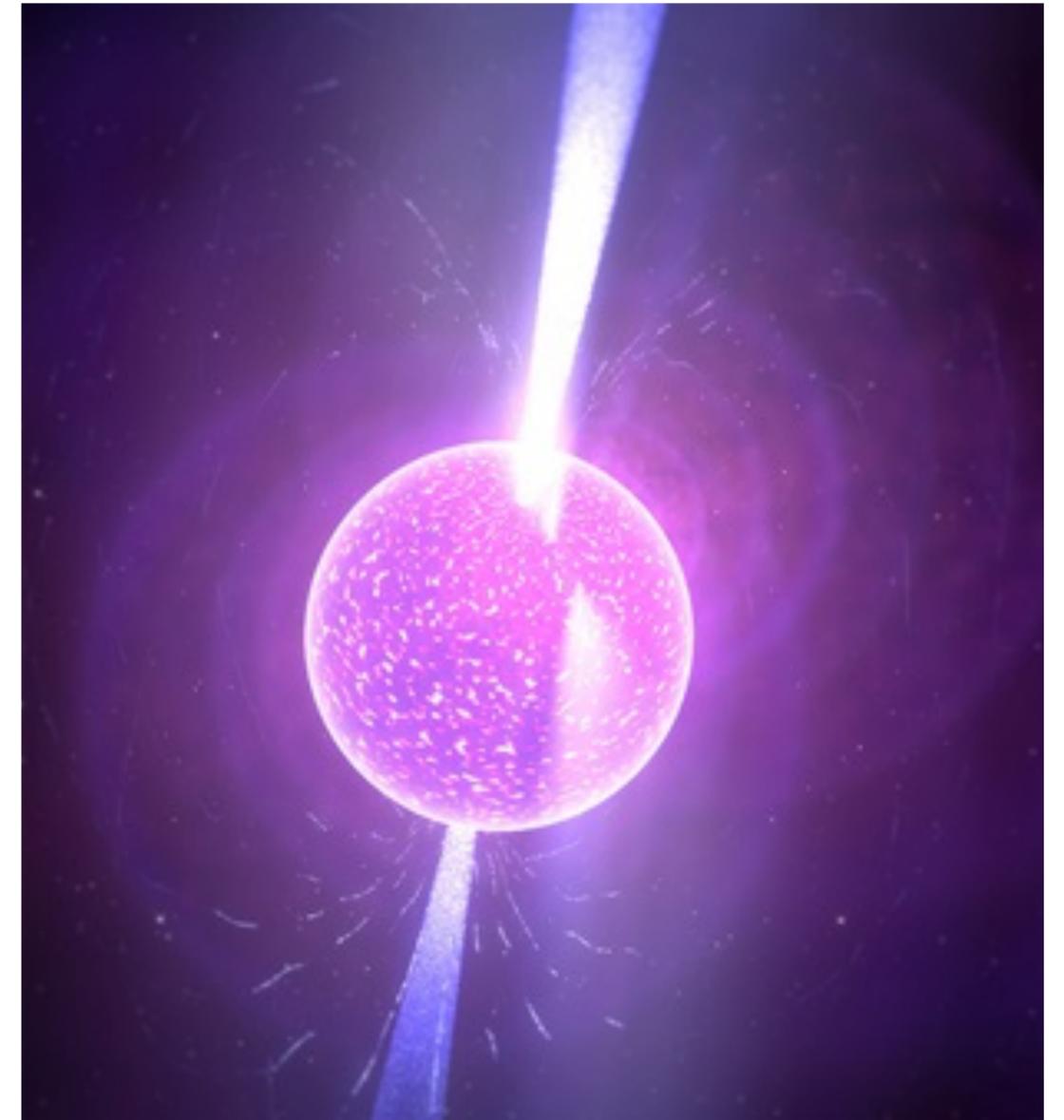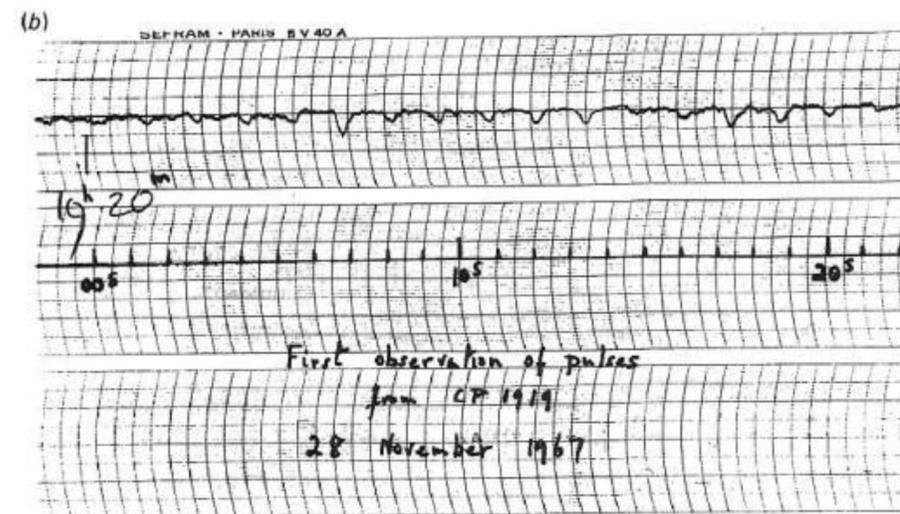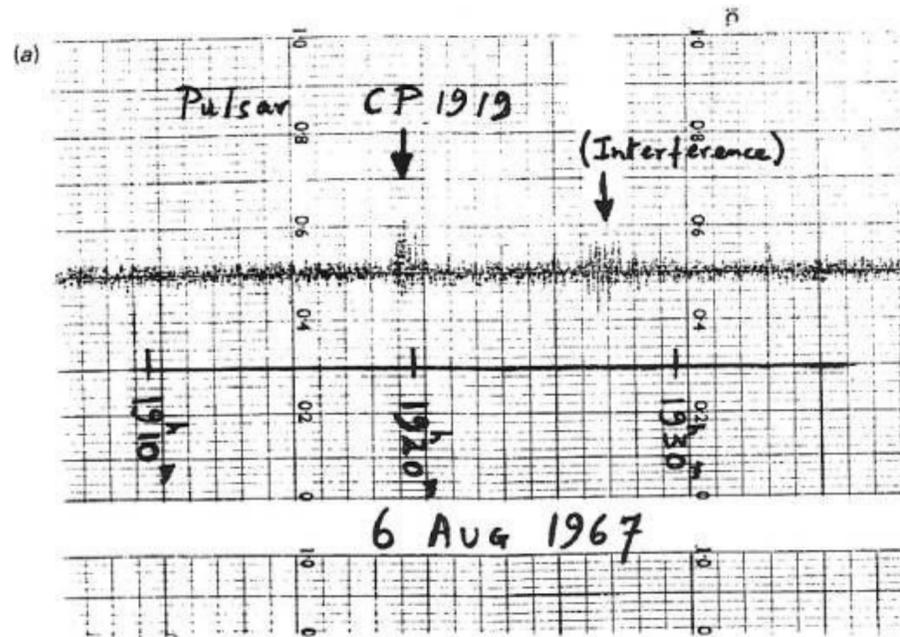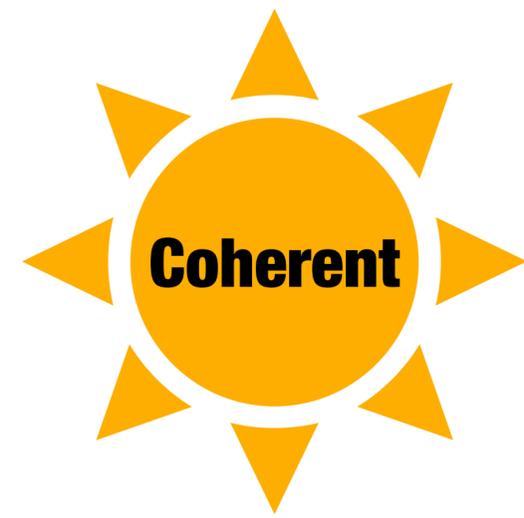
Some good examples of radio observations

Radio observations of the Sun
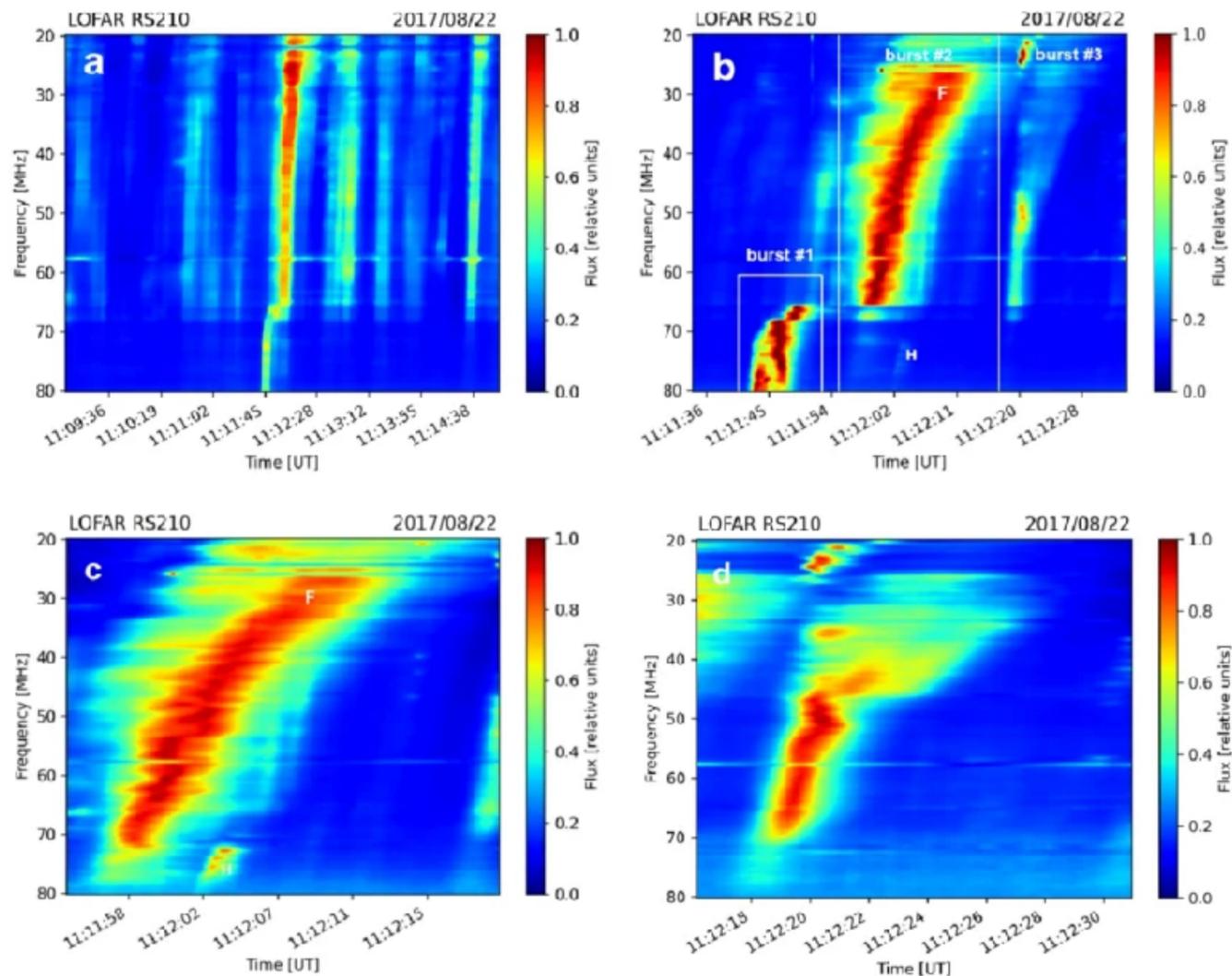
Bright regions (red and yellow) of million-degree gas above sunspots. Credit: Courtesy NRAO / AUI / NSF
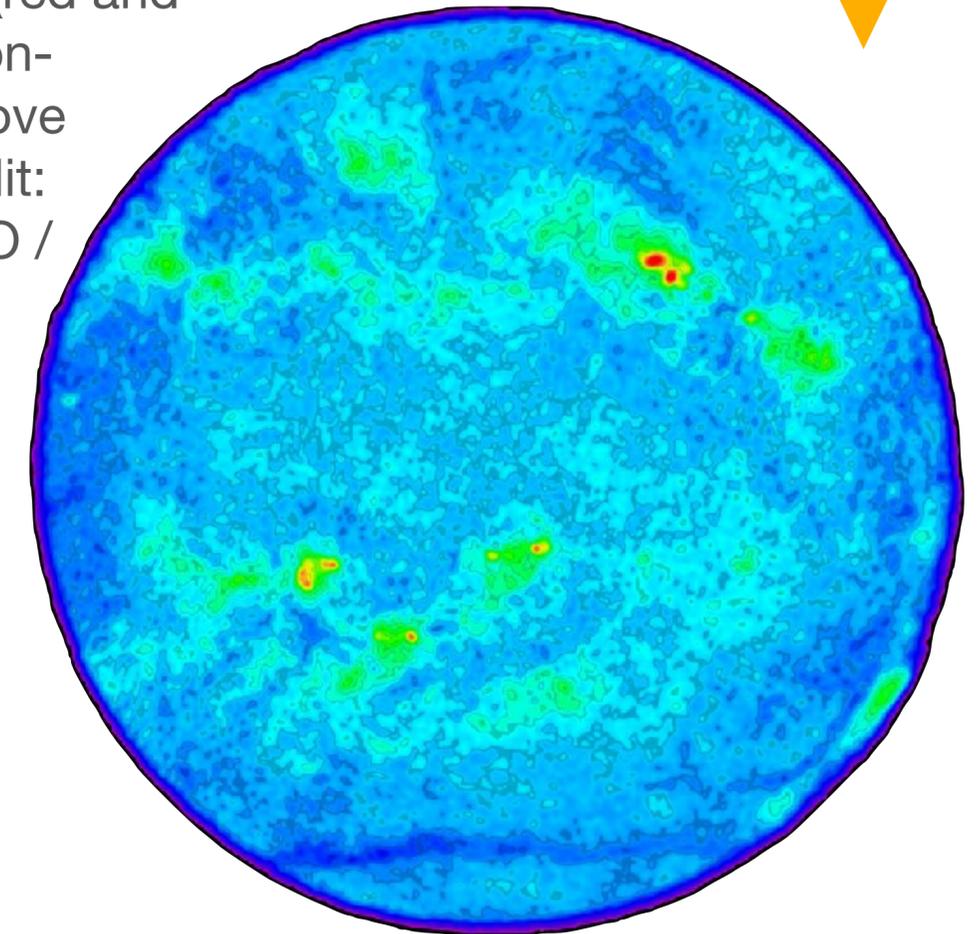
Credit: Dabrowski et al., 2017

Solar bursts — coherent emission due to plasma instabilities in corona

Quiet sun — free-free radiation maps density and temperature of the corona

Some good examples of radio observations
Cosmic Microwave Background

Thermal Blackbody
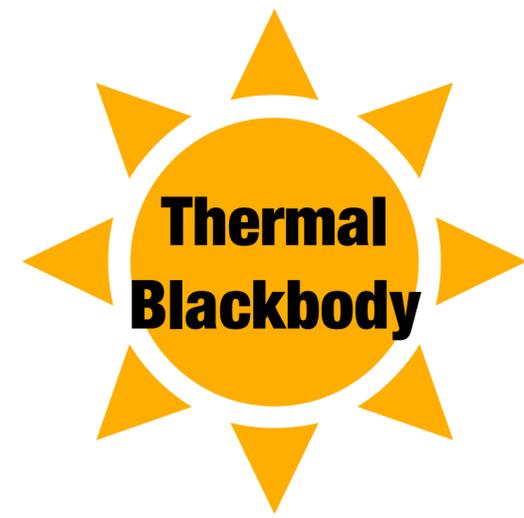
CMB maps show tiny deviations from the mean temperature, not the temperature itself.

Red=slightly hotter =denser regions

Blue=slightly colder =less dense regions
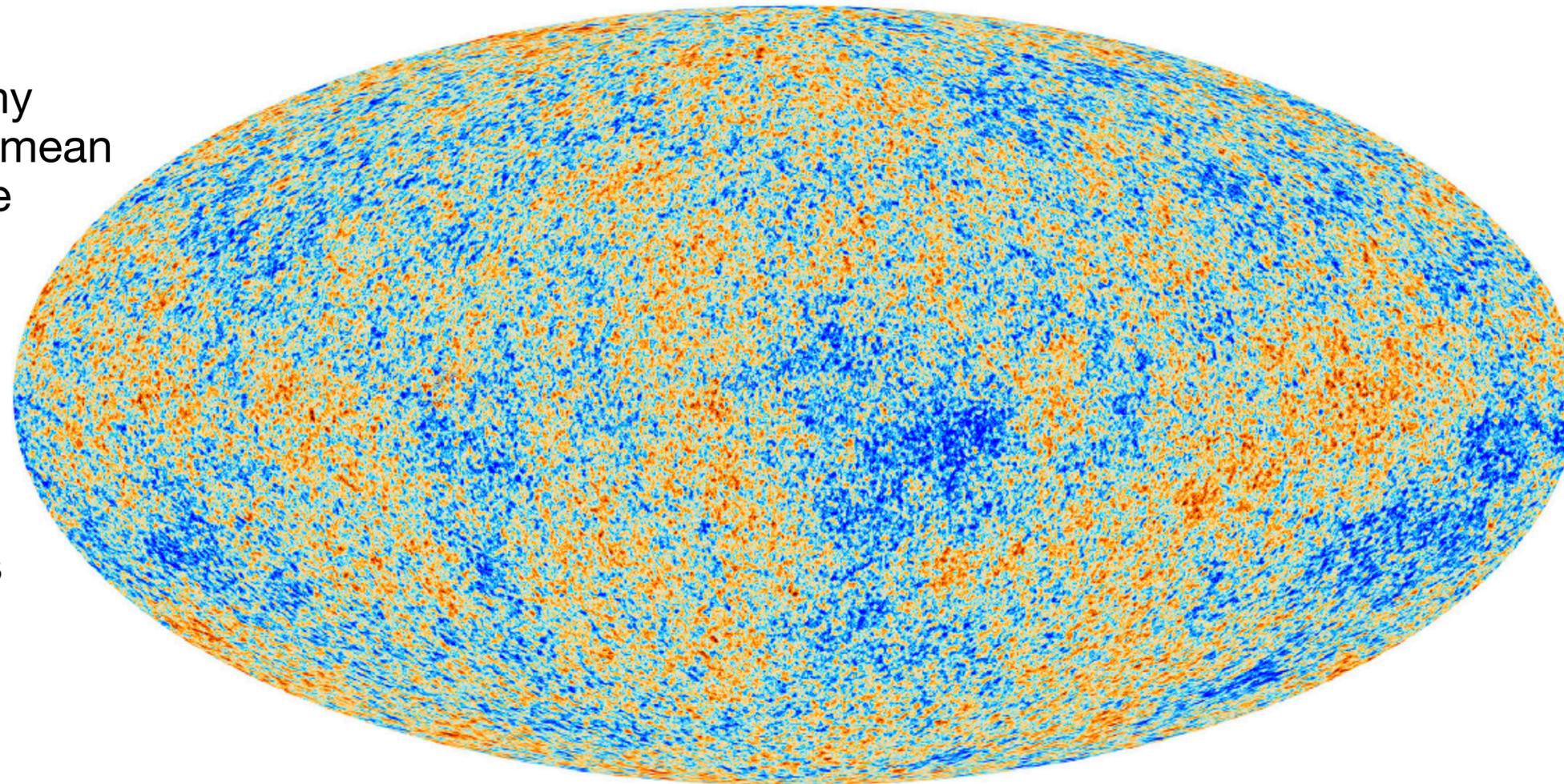
[Stars] Hot but tiny source → weak radio flux

[CMB] Cold but everywhere → strong signal

$$F_v = I_v \times \Omega$$

- Discovered accidentally in 1965 by Arno Penzias and Robert Wilson (Noble prize 1978)

- Afterglow of the early universe (today T≈2.725 K)

- The discovery provided the strongest evidence for the Big Bang (380,000 years ago).

Some good examples of radio observations

Radar mapping of the Moon

Mare Serenitatis / Sea of Serenity. Credit: Bruce Campbell (Smithsonian Institution, National Air and Space Museum); Arecibo/NAIC; NRAO/AUI/NSF

Echo strength and delay
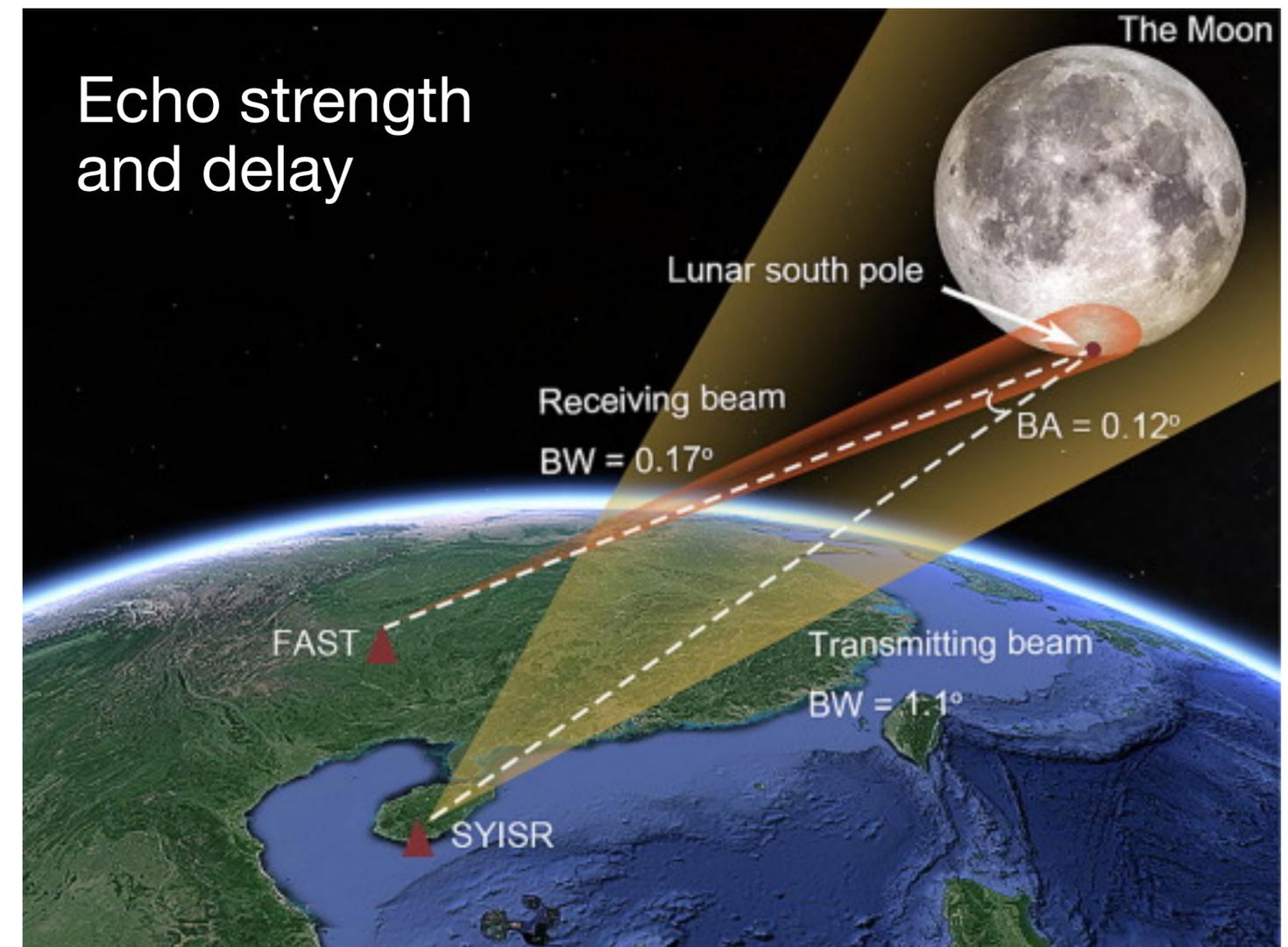
Diagram of the observation geometry for the Sanya incoherent scatter radar (SYISR) and five-hundred-meter aperture spherical radio telescope (FAST) Earth-based bistatic radar lunar imaging experiments. Credit: Li et al (10.1016/j.scib.2025.02.033)

What makes a good radio telescope?

- consider a distant source of emission of intensity I_ν

- power from this emission passes through an (isotropic) sensor

- the increment of power, dP, is

$$dP = I_\nu \, d\nu \, dA \, d\Omega \quad [Watts]$$

- the total power received is a suitable integral over frequency, area, and angle, accounting for variations in the responses

$d\Omega$ solid angle

sensor

filter

power collected

dA

$d\nu$

dP
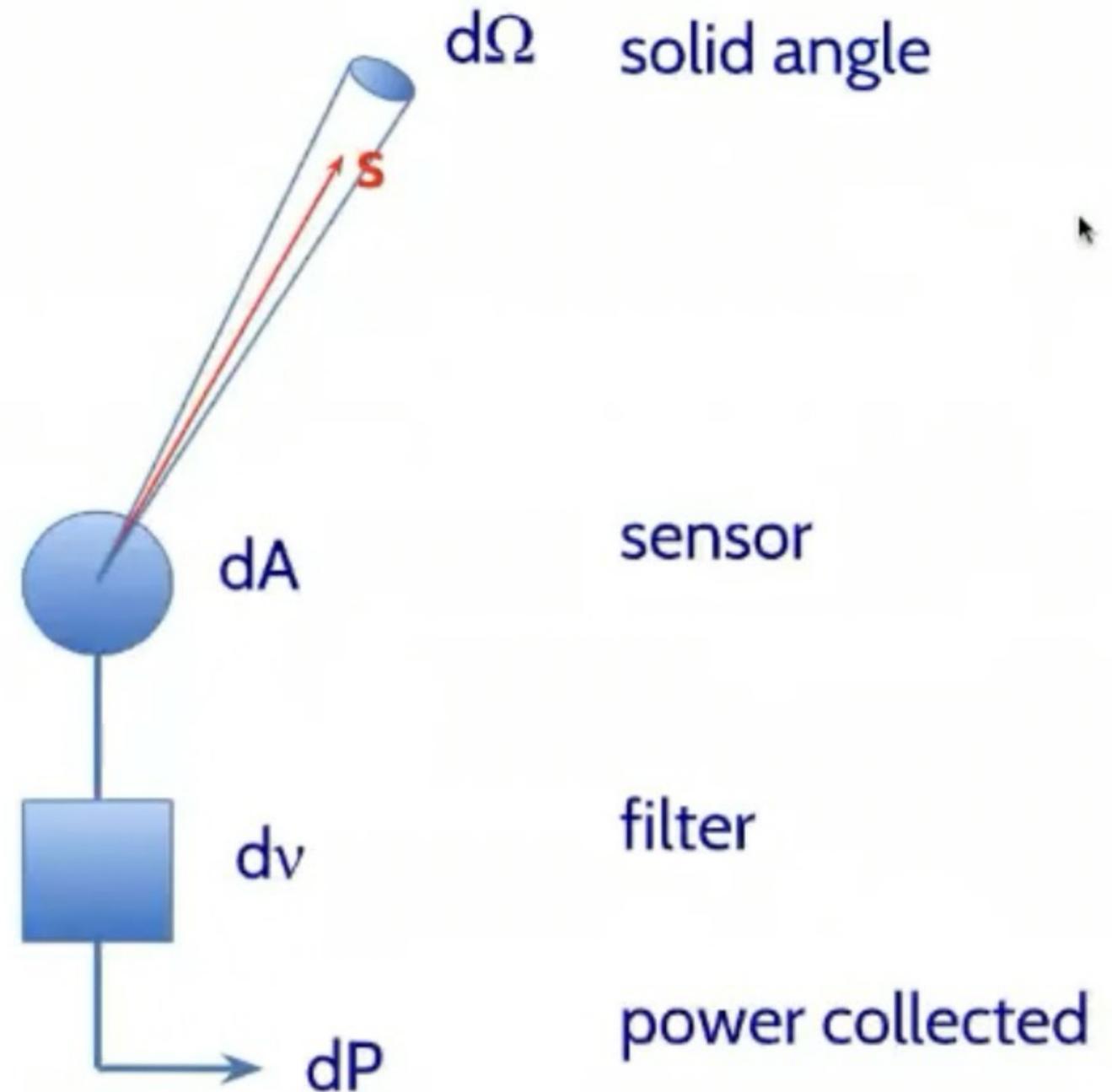
What makes a good radio telescope?

- **parabolic**: primary mirror is a focusing paraboloid with high directional gain
- **steerable**: antenna can move in two angular directions to track sources across the sky
- **cassegrain focus**: secondary mirror (subreflector) in front of focus of primary focuses radio waves to a receiver located behind the primary
- **on-axis**: antenna axis same as optical axis (antennas is symmetric)
- **receiver**: waveguide horn and a cryogenically cooled amplifier
- many variations are possible

Slide from ANITA lecture from David Wilner; Harvard-Smithsonian Center for Astrophysics
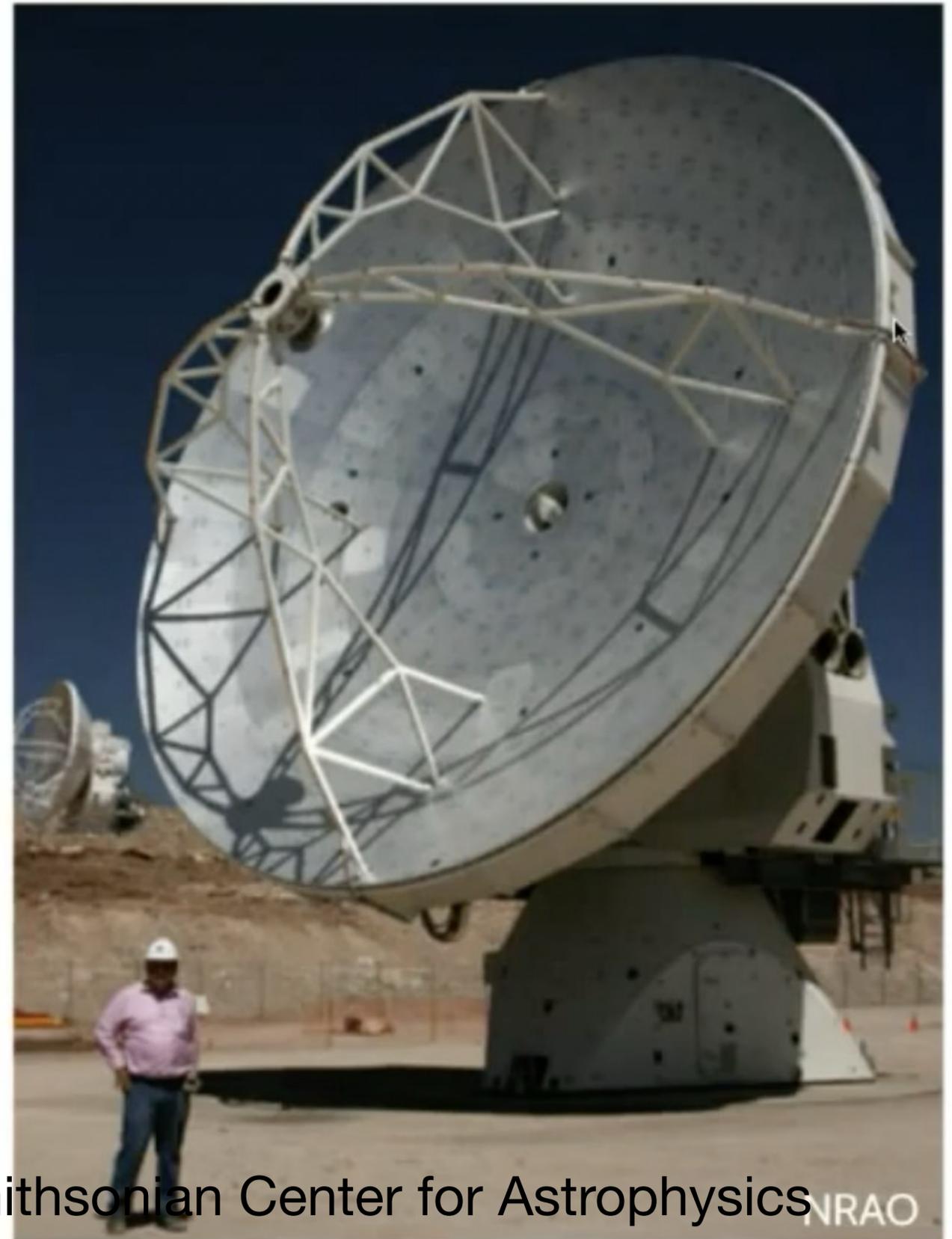
What makes a good radio telescope? —> Diffraction limit & Angular resolution

Approx. 70 metre aperture
- 1.5 arcmin resolution at 3 cm

$$\theta \approx \lambda/D$$

Resolution (radians)

Observing wavelength (m)

Diameter of telescope (m)

Approx. 5 mm aperture
- 3 arcsec resolution at 600 nm

"Just checking."

50 arcsec 0.5 μm/ 2.1 mm	0.05 arcsec 0.5 μm/ 2.4 m	60 arcsec 6 cm/ 200

Image credit: David Wilner; Harvard-Smithsonian Center for Astrophysics

Slide from Joe Callingham (ASTRON/Amsterdam)
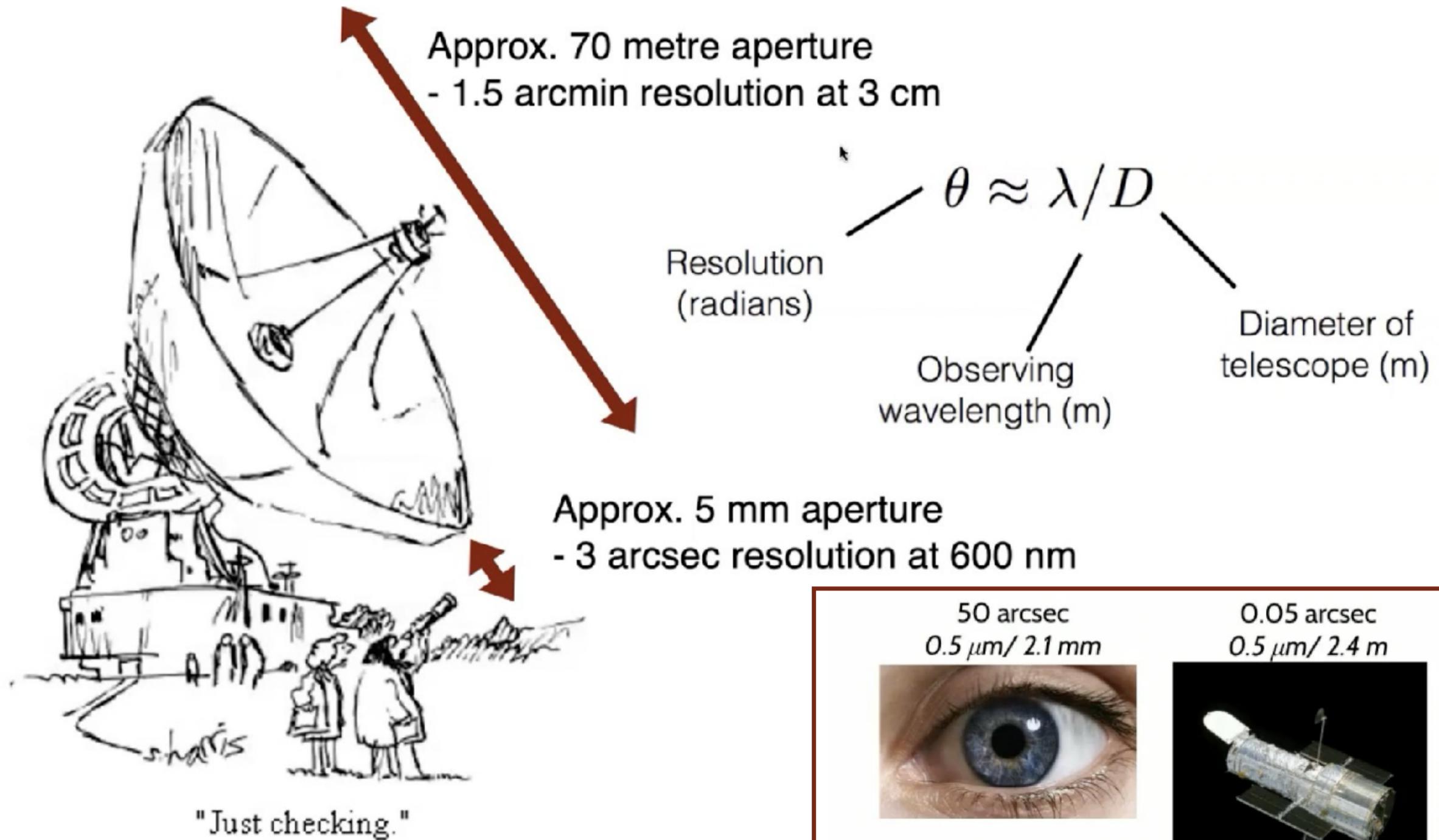
What makes a good radio telescope? —> Sensitivity

$$\text{SEFD} = \frac{2kT_{sys}}{A_e}$$

System equivalent flux density

FAST
China

500m

ARECIBO
Puerto Rico

305m

100m dishes
are the largest
it is possible
to steer

EFFELSBERG
Germany

JODRELL
BANK
UK

100m

76m

25m

13.5m
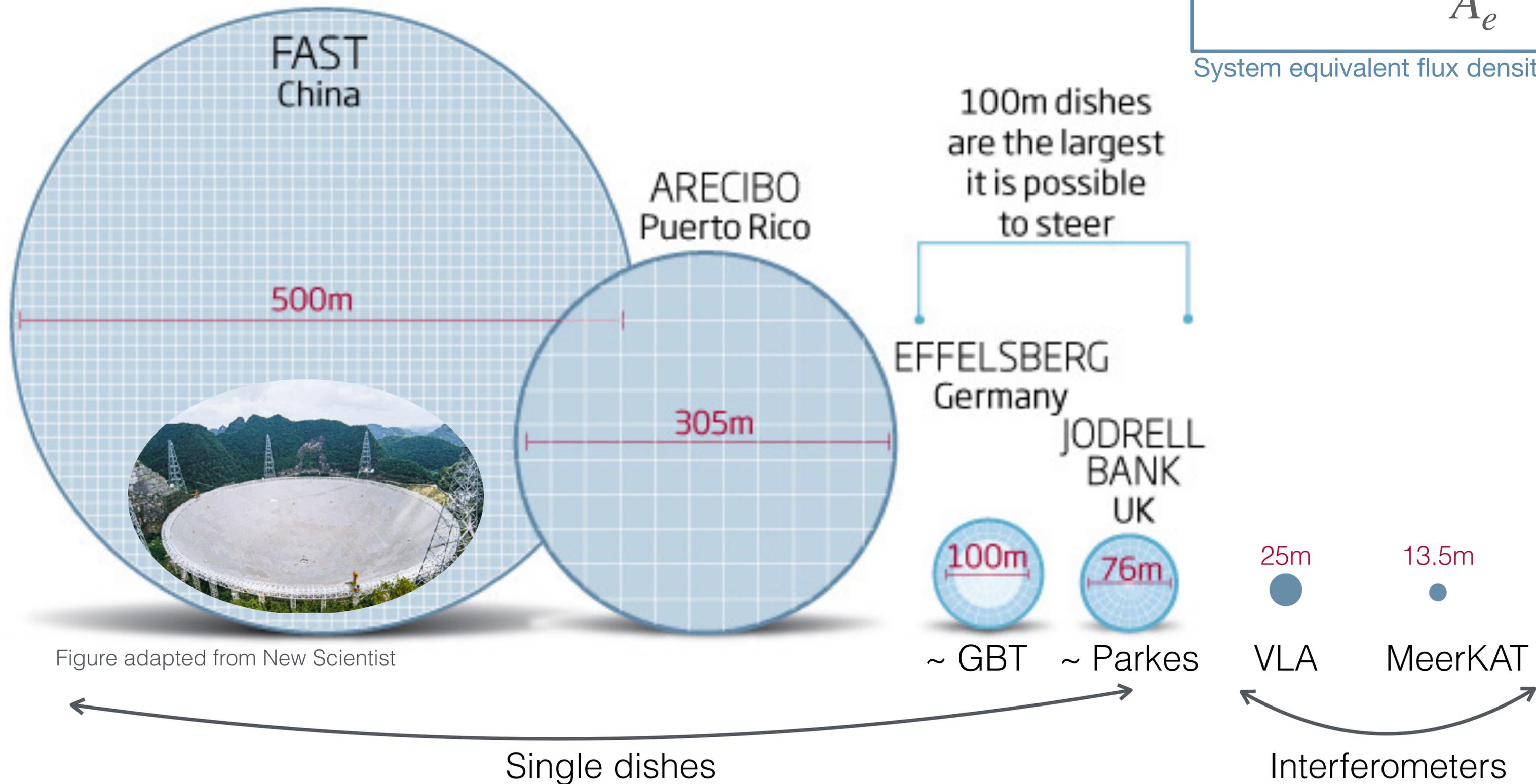
Figure adapted from New Scientist

~ GBT   ~ Parkes

VLA   MeerKAT

Single dishes

Interferometers

Engineering challenge

Tuesday, November 15th, 1988
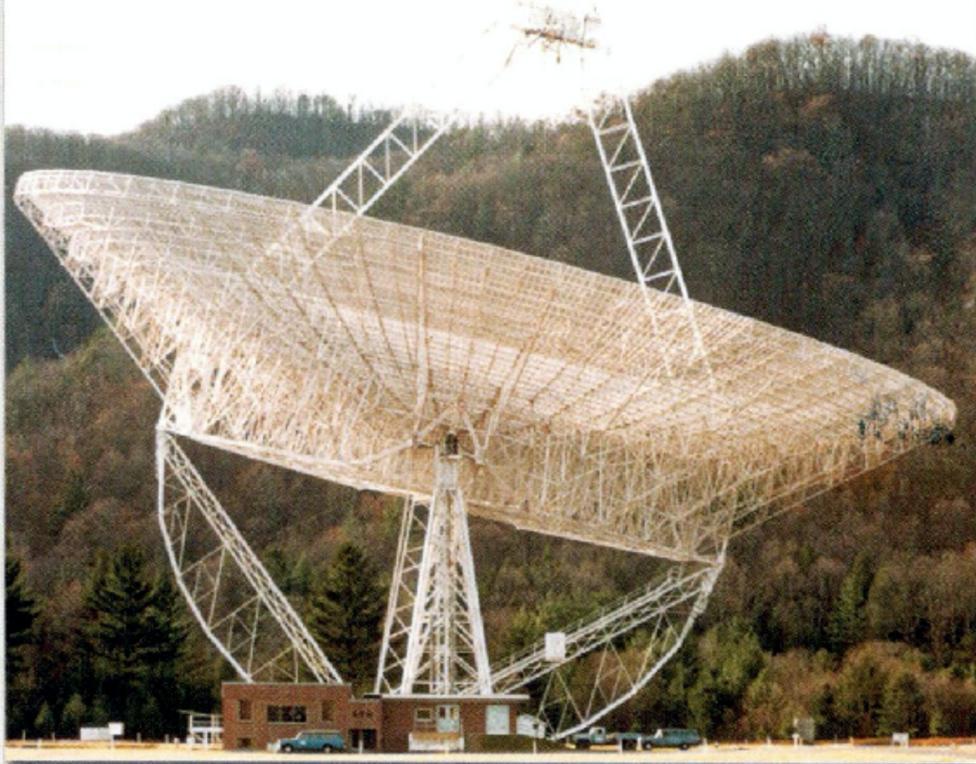
Wednesday, November 16th, 1988

Green Bank 100m

Arecibo 305m

Interferometer

Synthesize a big single dish telescope from lots of small ones.

Radio interferometer

Target wavefront

t_2

t_1

Steering delay stage

t_2

t_1

0

Signal alignment

Σ

Cell phones (Amplifiers)

GPUs (Computations)

Two Recent Technological advancements
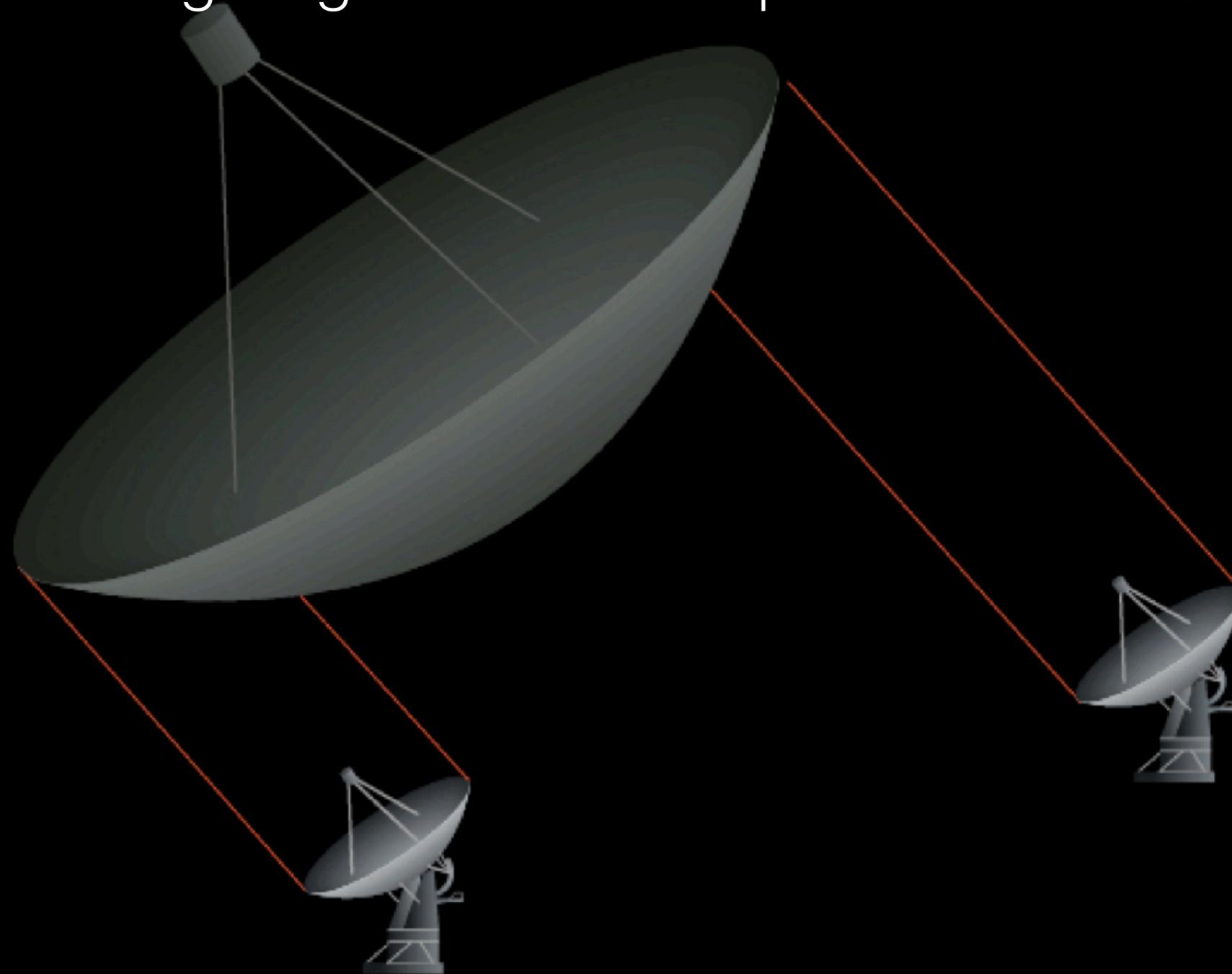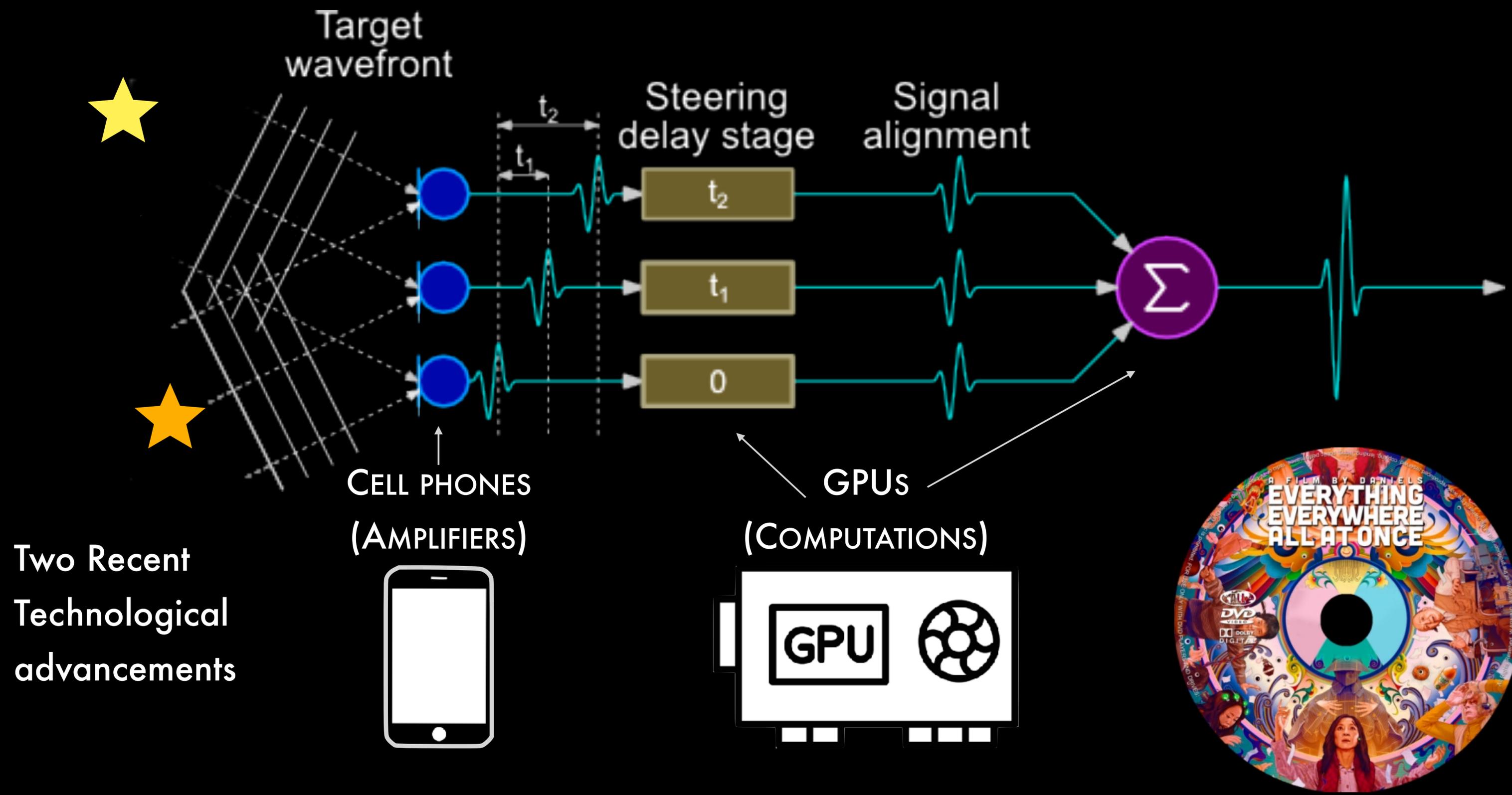
FIELD OF VIEW

$$\text{FWHM} = 1.22 \times \frac{\lambda}{D}$$

← Wavelength

← Dish diameter

	Dish diameter (m)	FWHM at 1GHz (deg)
Green Bank	105	0,2
Parkes	64	0,3
VLA	25	0,8
MeerKAT	13,5	1,5

Single dish

Interferometers

Interferometers have smaller antennas which also means larger instantaneous field-of-view.

Commensal Interferometric Observation

Primary observer

Instantaneous field-of-view

Commensal beams:
Coherent & Incoherent
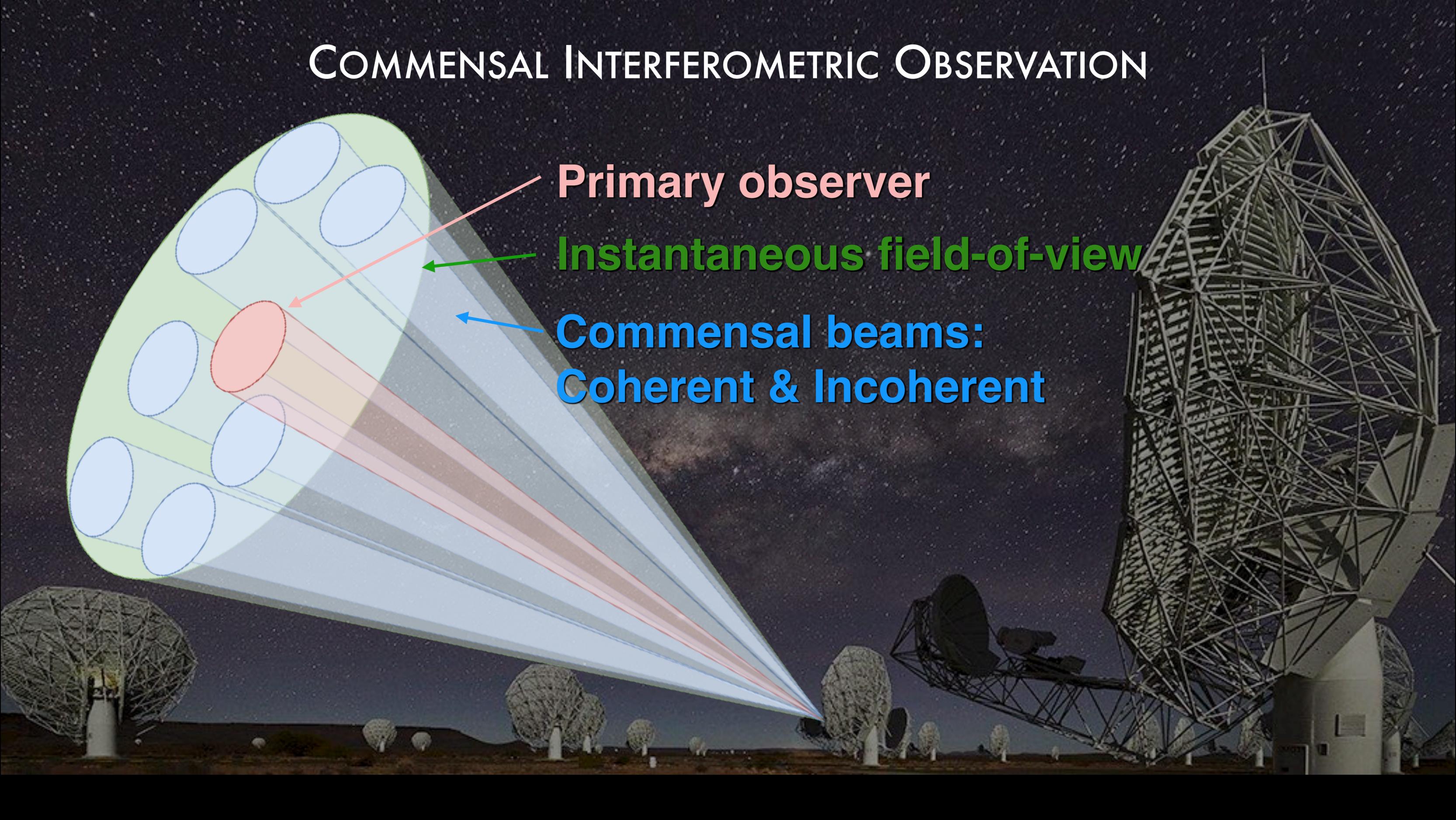
(Reverse of) Young's double slit experiment

Image credit: wikipedia

n=2

n=1

n=0

monochromatic planar wave (e.g. a laser)

screen with two slits

optical screen

optical screen (front view)
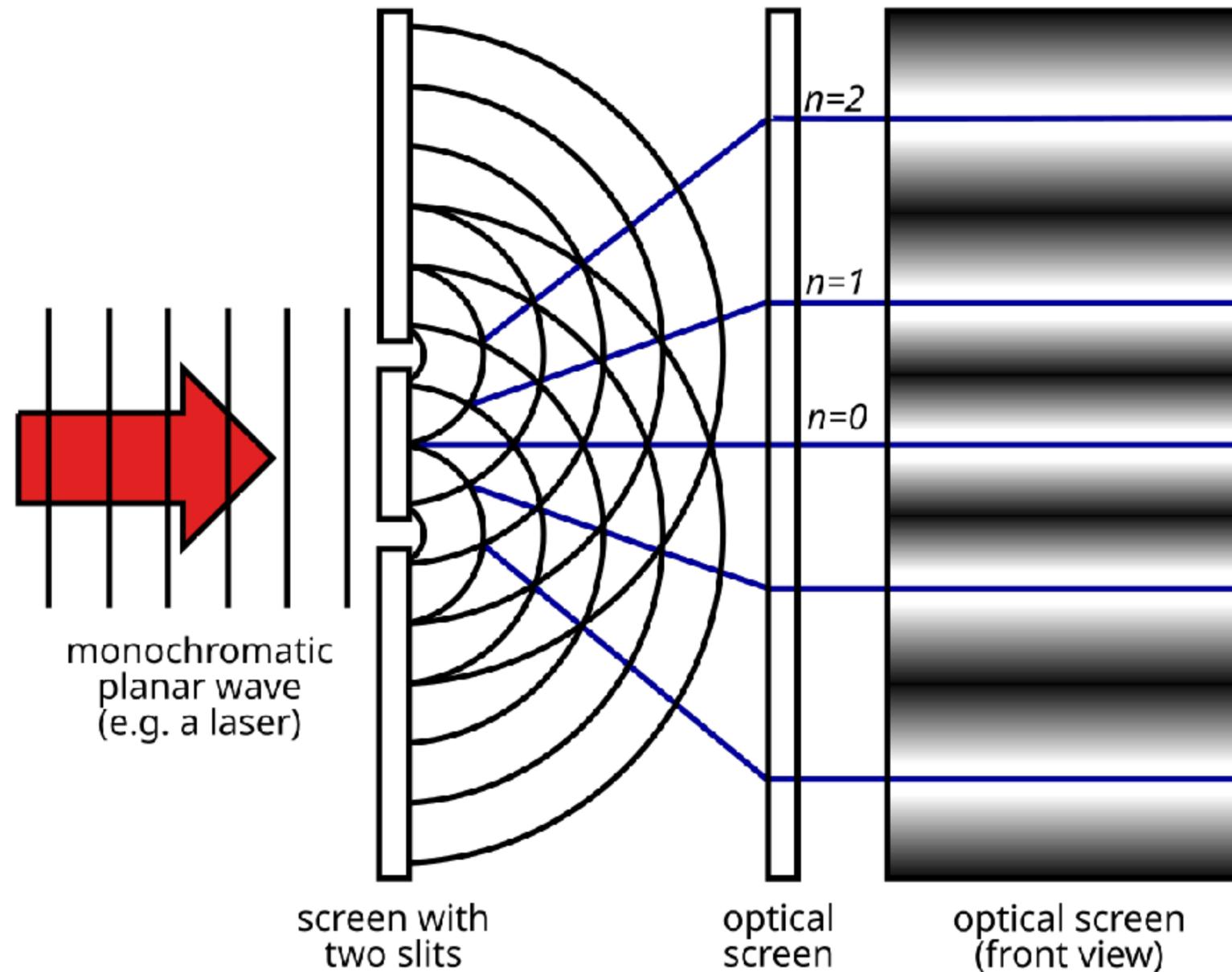
- Two slits = a pair of antennas —> One baseline

- Correlation —> visibility = measures the strength and phase of one sinusoidal spatial pattern on the sky (one Fourier component of the sky brightness)

Fourier transform - mathematical tool to decompose a signal

Square Wave — Four Sinusoids — Sum of 4 Sinusoids
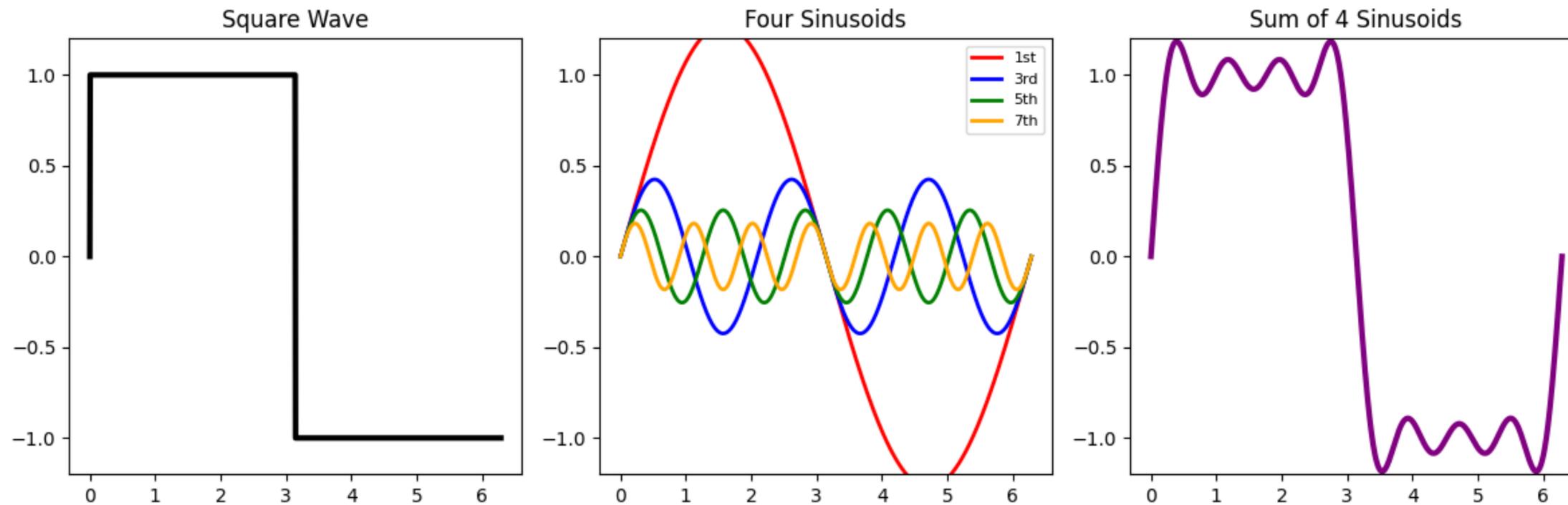
Jean Baptiste Joseph Fourier 1768-1830

- Just like a square wave can be decomposed into a sum of sinusoids, the sky brightness can be decomposed into spatial ripple patterns.

- A specific baseline = a specific sinusoid

  - Short baselines = Low-frequency sinusoids = large-scale structure
    Nearby antennas: see almost the same signal, sensitive only to large structures

  - Long baselines = High-frequency sinusoids = sharp edges
    Far-apart antennas: small shift in angle —> large phase diff, sensitive to very small angular structure

- Inverse Fourier Transform visibilities —> Reconstruct sky image

Conceptualizing radio interferometric imaging with a cat

Filtered Fourier Cat

Remove short baselines

HPF Cat

Missing info on large scale

Slide from DARA school by Joe Callingham (ASTRON/Amsterdam)
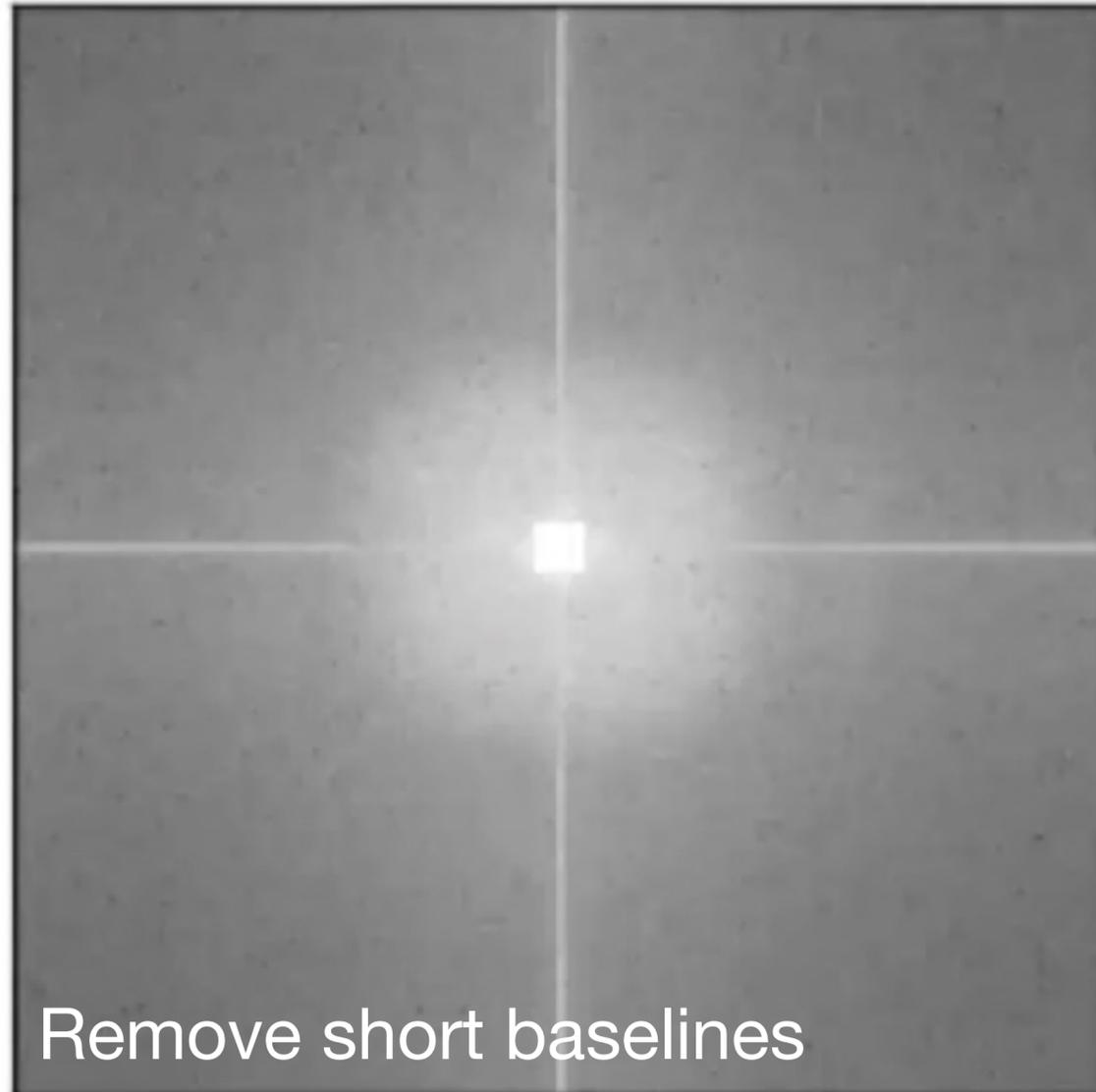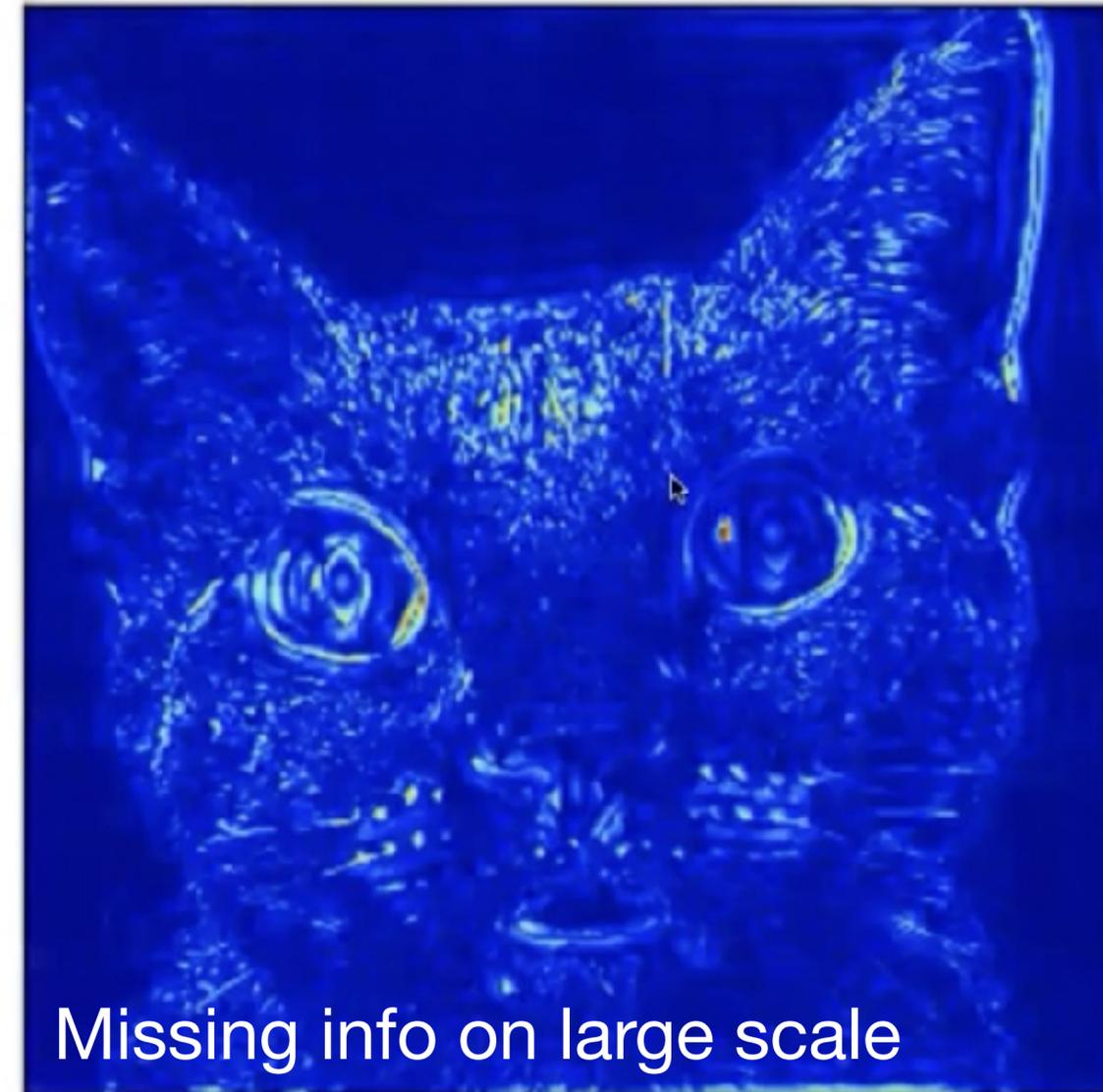
Conceptualizing radio interferometric imaging with a cat

Filtered Fourier Cat
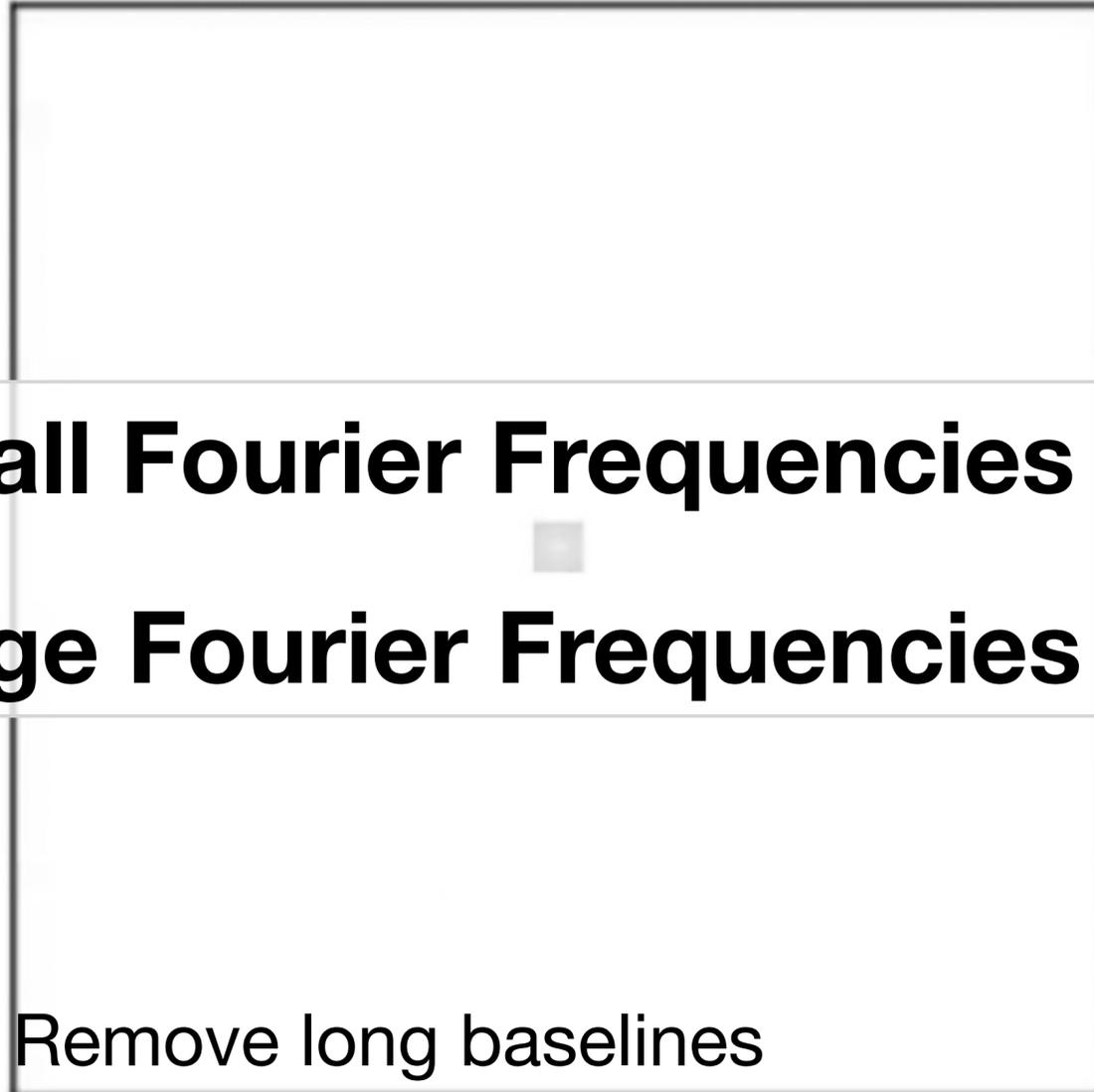
LPF Cat
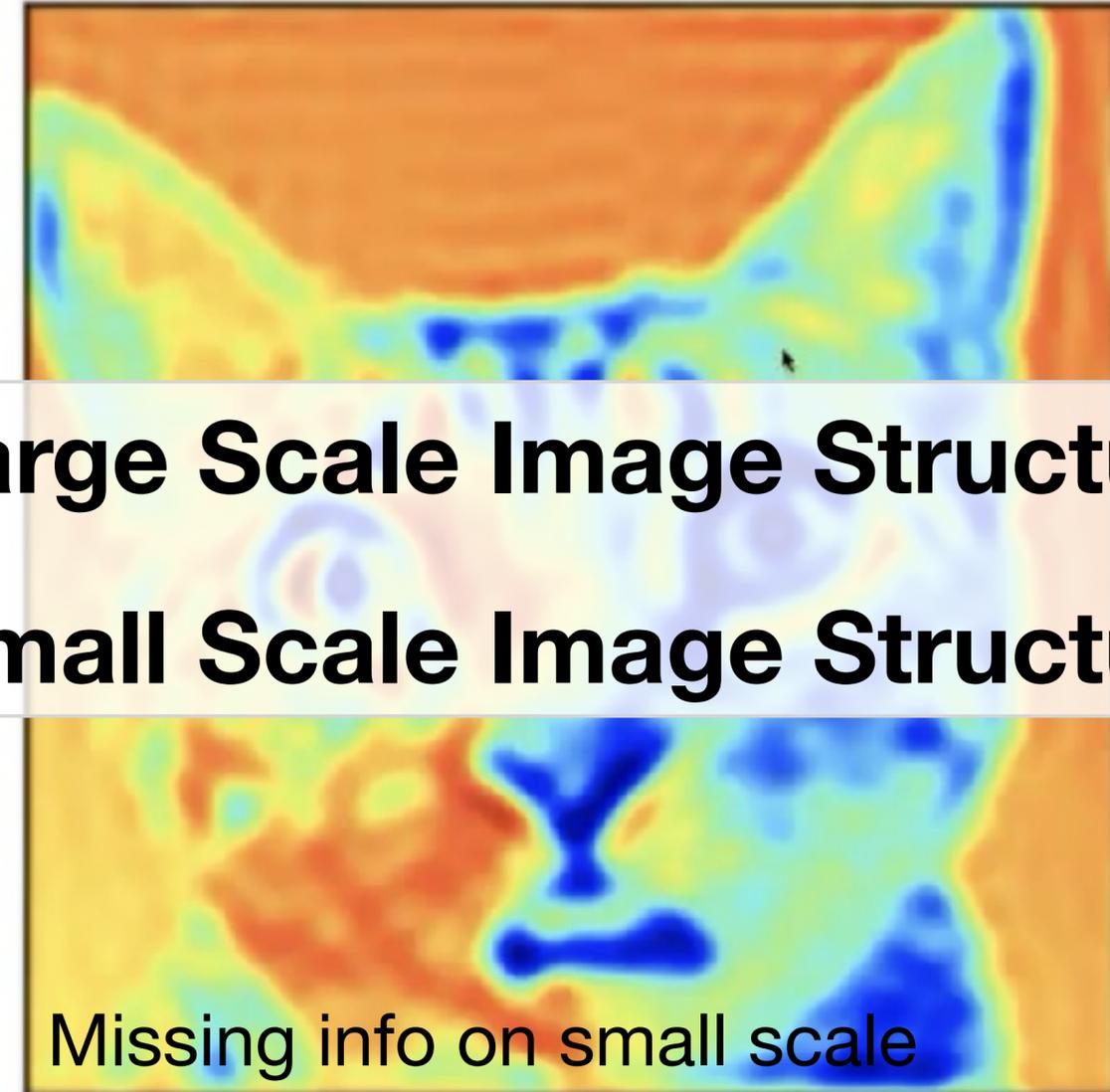
Small Fourier Frequencies = Large Scale Image Structure

Large Fourier Frequencies = Small Scale Image Structure

Remove long baselines

Missing info on small scale

Slide from DARA school by Joe Callingham (ASTRON/Amsterdam)

Some light will fall through
Don't get equal sensitivity
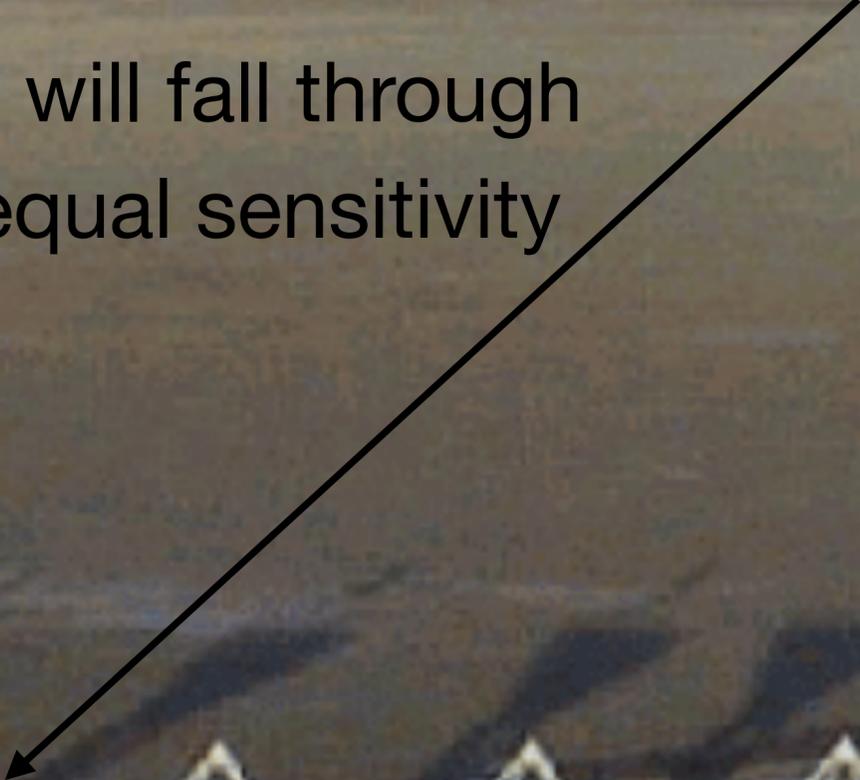
Interferometry recap :

- Each pair of antennas = one **baseline** = one point on the UV plane
  —> measures one Fourier component of the sky brightness

- **Fringe** = the sinusoidal spatial response pattern of a baseline on the sky

- Correlator —> multiplies and averages the signals detected
  —> **visibilities** (phase and amplitude of a Fourier component)
  = Sky x Fringe = how strongly the sky brightness matches that pattern

- **UV plane** = a collection of those spatial frequency measurements
  —> 2D, discrete sample of visibilities

- Collect visibilities and apply an **inverse Fourier transform**, we reconstruct the **sky brightness distribution**.

- Missing baselines = Discrete sampling —> **dirty beam**

Some examples of interferometers

Quelques antennes (IRAM) à quelques dizaines d'antennes (VLA, GMRT, ALMA)

Westerbork (ASTRON, NL)
14 paraboles de 6m
Base max: 2.7 km
$\lambda \sim 10cm - 1m$
A ~ 400 m²

VLA (NRAO, Nouveau Mexique)
27 paraboles de 25 m
Base max: 36 km
$\lambda \sim 1cm - 1m$, f_{min} = 74 MHz
A ~ 14000 m²

SMA (USA – Taïwan) Hawaïi
8 antennes de 6 m
Base max: 0.5 km
$\lambda \sim 0.5mm$, A ~ 220 m²

GMRT (Pune, Inde)
30 paraboles de 45 m
Base max: 25 km
$\lambda \sim 1m$, f_{min} = 153 MHz
A ~ 50000 m²

Plateau de Bure (IRAM, France)
6 antennes de 15m
Base max: ~ 1 km
$\lambda \sim 1mm$
A ~ 1000 m²

ALMA (Chili)
54 antennes de 12m
+ 12 de 7m
Base max: 16 km
$\lambda = 1$ cm-0.3 mm
f = 30-900 GHz
A ~ 6000m²

In the hands-on session tomorrow afternoon, we will see how these different telescope designs affect imaging results.

Slide from Philippe Zarka (LIRA, ORN)

Square Kilometre Array

- Most sensitive radio telescope ever constructed
- 197 steerable dishes in S. Africa + 131,072 tree-like antennas in W. Australia
- $2-billion project, multi-national with IGO status (including France)
- Expected to operate before 2030

SKAO Gloabl partnerships (IGO since 2021)
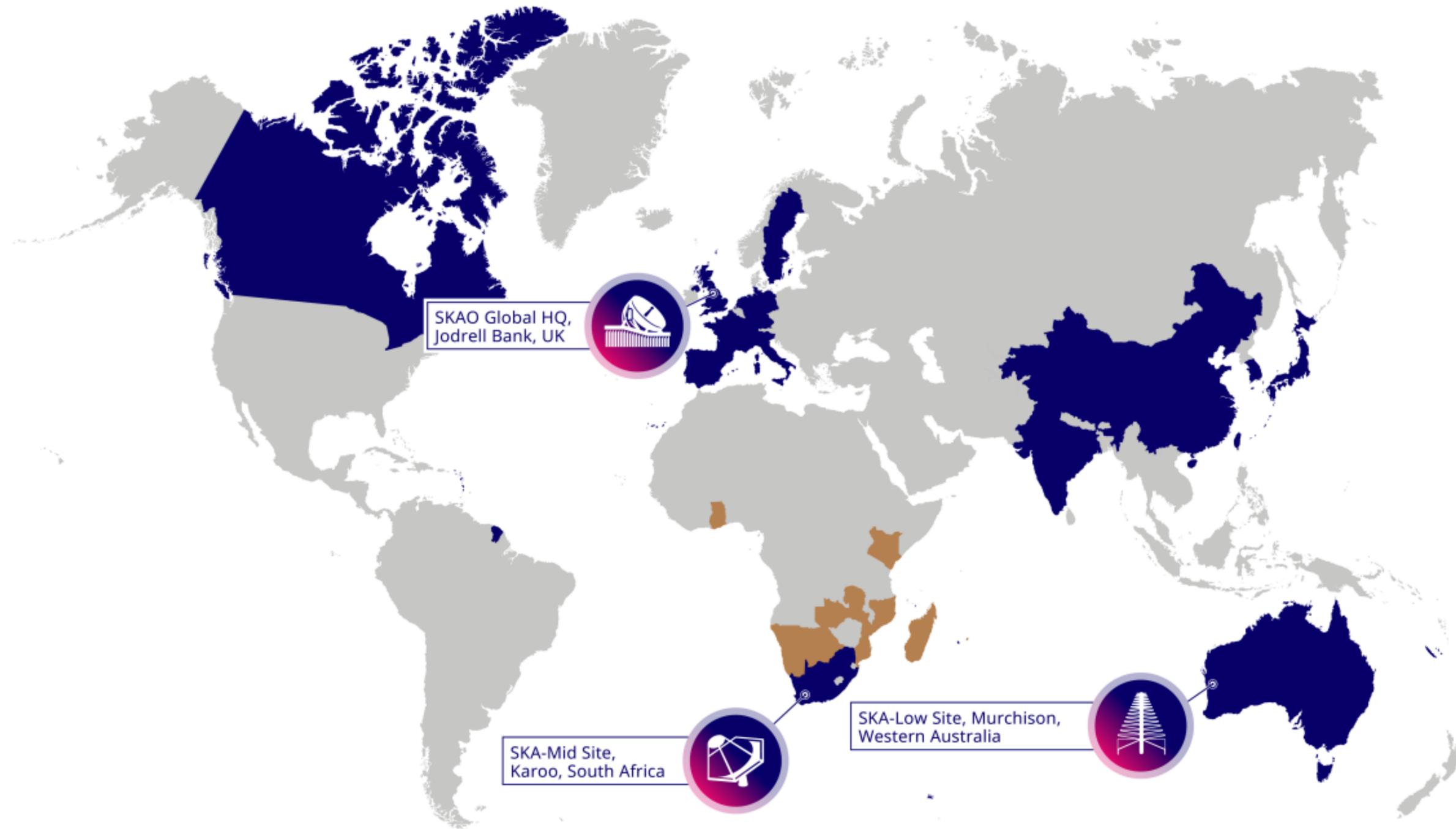
Member countries:
- Australia
- Canada
- China
- **France**
- Germany
- India
- Italy
- The Netherlands
- Portugal
- South Africa
- Spain
- Sweden
- Switzerland
- United Kingdom
- And more…

SKAO Global HQ, Jodrell Bank, UK

SKA-Mid Site, Karoo, South Africa

SKA-Low Site, Murchison, Western Australia

SKAO Partnership - includes SKAO Member States* and SKAO Observers (as of June 2024)

African Partner Countries

How does SKA1 compare with the world's biggest radio telescopes?

SKAO

SKA1 LOW
Australia
419,000m²
~130,000 antennas

SKA1 MID
South Africa
33,000m²
~200 dishes

Lovell
UK
4,500m²
76m dish

Effelsberg
Germany
7,800m²
100m dish

ALMA
Atacama Large Millimetre/
submillimetre Array, Chile
6,500m²
66 dishes

MWA
Murchison Widefield Array, Australia
2,500m²
2048 antennas

ASKAP
Australian SKA Pathfinder, Australia
4,000m²
36 dishes

LOFAR
Low Frequency Array for Radio
astronomy, Netherlands
52,000m²
34,000 antennas

GMRT
Giant Metrewave Radio Telescope, India
48,000m²
30 dishes

MeerKAT
South Africa
9,000m²
64 dishes

Parkes
Australia
3,200m²
64m dish

SRT
Sardinia Radio
Telescope, Italy
3,200m²
64m dish

GBT
Green Bank Telescope, USA
7,800m²
100m dish

IRAM NOEMA
Northern Extended
Millimeter Array, France
2,100m²
12 dishes

JVLA
Karl G. Jansky Very Large Array, USA
13,200m²
27 dishes

NRT
Nancay Radio Telescope, France
7,000m²
300m x 35m
antenna

FAST
Five Hundred Meter Aperture
Spherical Telescope, China
71,000m²
500m dish

Arecibo
Puerto Rico
42,000m²
305m dish

IRAM 30m
Spain
700m²
30m dish

At 110 MHz

ARRAYS

SINGLE DISHES

NON-STEERABLE

**LOW
FREQUENCIES**

**MID
FREQUENCIES**

**HIGH
FREQUENCIES**

The Square Kilometre Array (SKA) will be the world's largest radio telescope, revolutionising our understanding of the Universe. The SKA will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - SKA1 MID and SKA1 LOW - observing the Universe at different frequencies.

A telescope's capacity to receive faint signals - called sensitivity - depends on its collecting area, the bigger the better. But just like you can't compare radio telescopes and optical telescopes, comparison only works between telescopes working in similar frequencies, hence the different categories above.

The collecting area is just one aspect of a telescope's capability though. Arrays like the SKA have an advantage over single dish telescopes: by being spread over long distances, they simulate a virtual dish the size of that distance and so can see smaller details in the sky, this is called resolution.

www.skao.int   @ska   SKA Observatory   SKA Observatory   SKA Observatory   @skaobservatory

How will SKA1 be better than today's best radio telescopes?

Astronomers assess a telescope's performance by looking at three factors - **resolution**, **sensitivity**, and **survey speed**. With its sheer size and large number of antennas, the SKA will provide a giant leap in all three compared to existing radio telescopes, enabling it to revolutionise our understanding of the Universe.
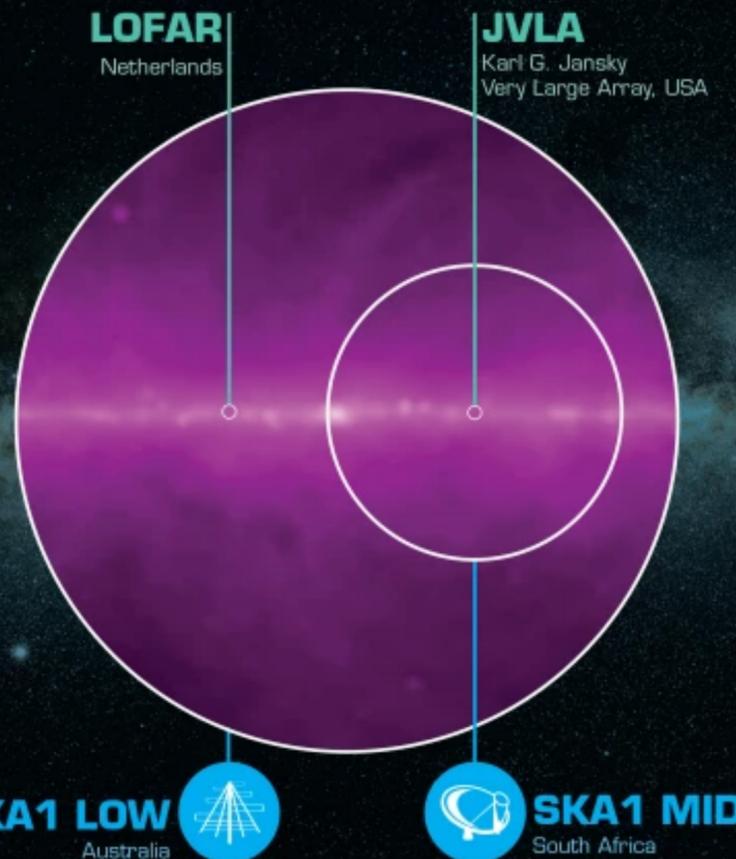
The **Square Kilometre Array** (SKA) will be the world's largest radio telescope. It will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - **SKA1 MID** and **SKA1 LOW** - observing the Universe at different frequencies.

LOFAR
Netherlands

JVLA
Karl G. Jansky
Very Large Array, USA

WITH THE SKA   WITH CURRENT RADIO TELESCOPES

SKA1 LOW
Australia

SKA1 MID
South Africa

WITH THE SKA   WITH CURRENT RADIO TELESCOPES

SKA1 LOW **x1.2** LOFAR NL

SKA1 MID **x4** JVLA

RESOLUTION

Thanks to its size, the SKA will see smaller details, making radio images less blurry, like reading glasses help distinguish smaller letters.

SKA1 LOW **x135** LOFAR NL

SKA1 MID **x60** JVLA

SURVEY SPEED

Thanks to its sensitivity and ability to see a larger area of the sky at once, the SKA will be able to observe more of the sky in a given time and so map the sky faster.

SKA1 LOW **x8** LOFAR NL

SKA1 MID **x5** JVLA

SENSITIVITY

Thanks to its many antennas, the SKA will see fainter details, like a long-exposure photograph at night reveals details the eye can't see.

Challenges in modern radio astronomy

- High data rate
  - SKA: 5 zettabytes per year = more than the worldwide internet traffic today
  - Correlation is computationally intensive — every pair of antennas must be multiplied for each frequency channel.
  - Data storage, transfer, and real-time processing are huge logistical and engineering challenges.
- Radio frequency interferences — 4G, Starlink…

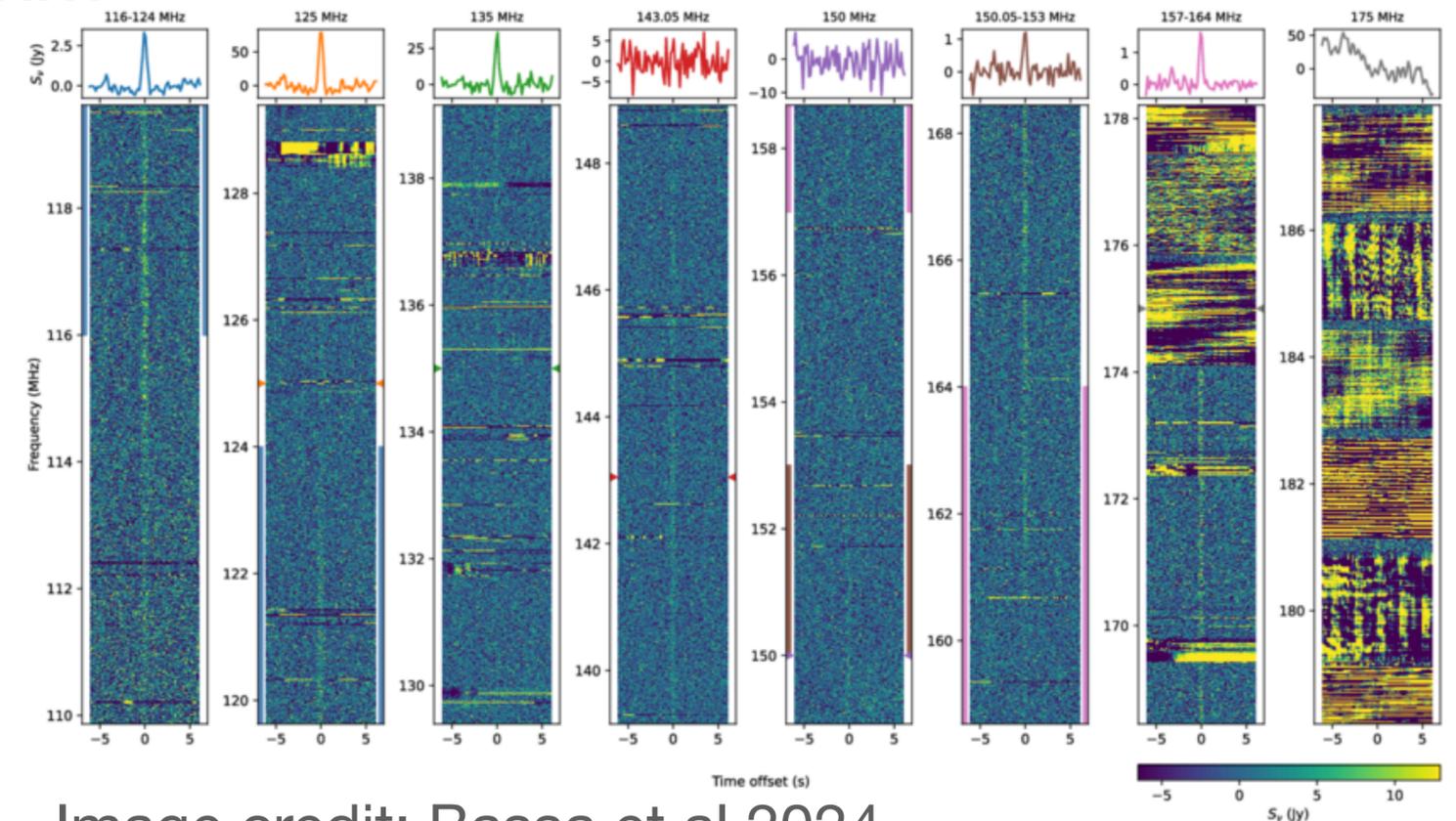Image credit: ALAN DYER/VWPICS VIA REDUX

Image credit: Bassa et al 2024

- Brief History of radio astronomy

- Main types of radiations detected

- Notable examples of radio observations

- Radio telescopes - resolution and sensitivity

- Interfermeter and imaging

- Examples of telescope facilities

- Current challenges

Reminder to self: talk about the hands-on session tomorrow !

Useful materials

- Essentail Radio Astronomy

  - A complete one semester course by J. J. Condon and S. M. Ransom

  - www.cv.nrao.edu/course/astr534/ERA.shtml

- DARA (Development in Africa with Radio Astronomy) Youtube course

  - https://www.youtube.com/@dara-developmentinafricawi1695

- ANITA Lecture on Youtube

  - https://www.youtube.com/@anitachapter5222