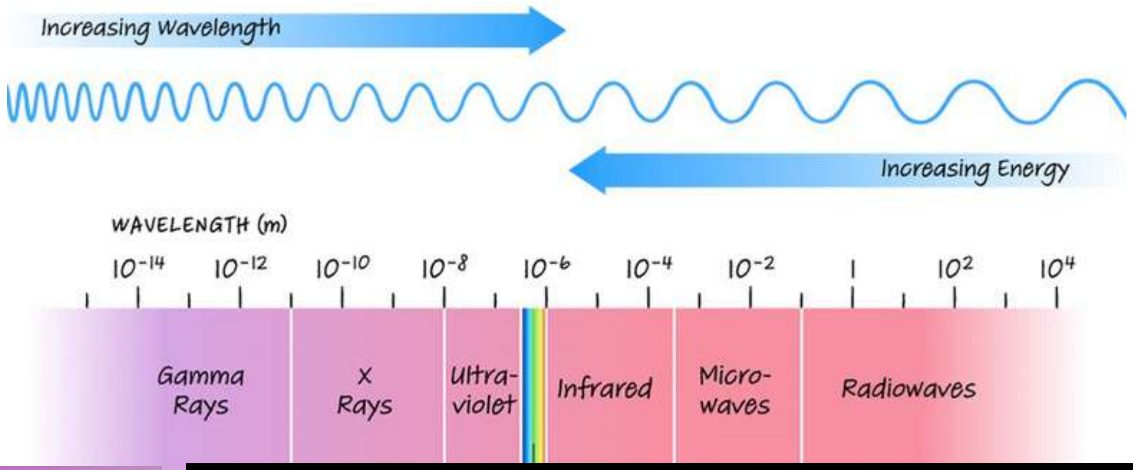
Introduction to interferometry and VLBI

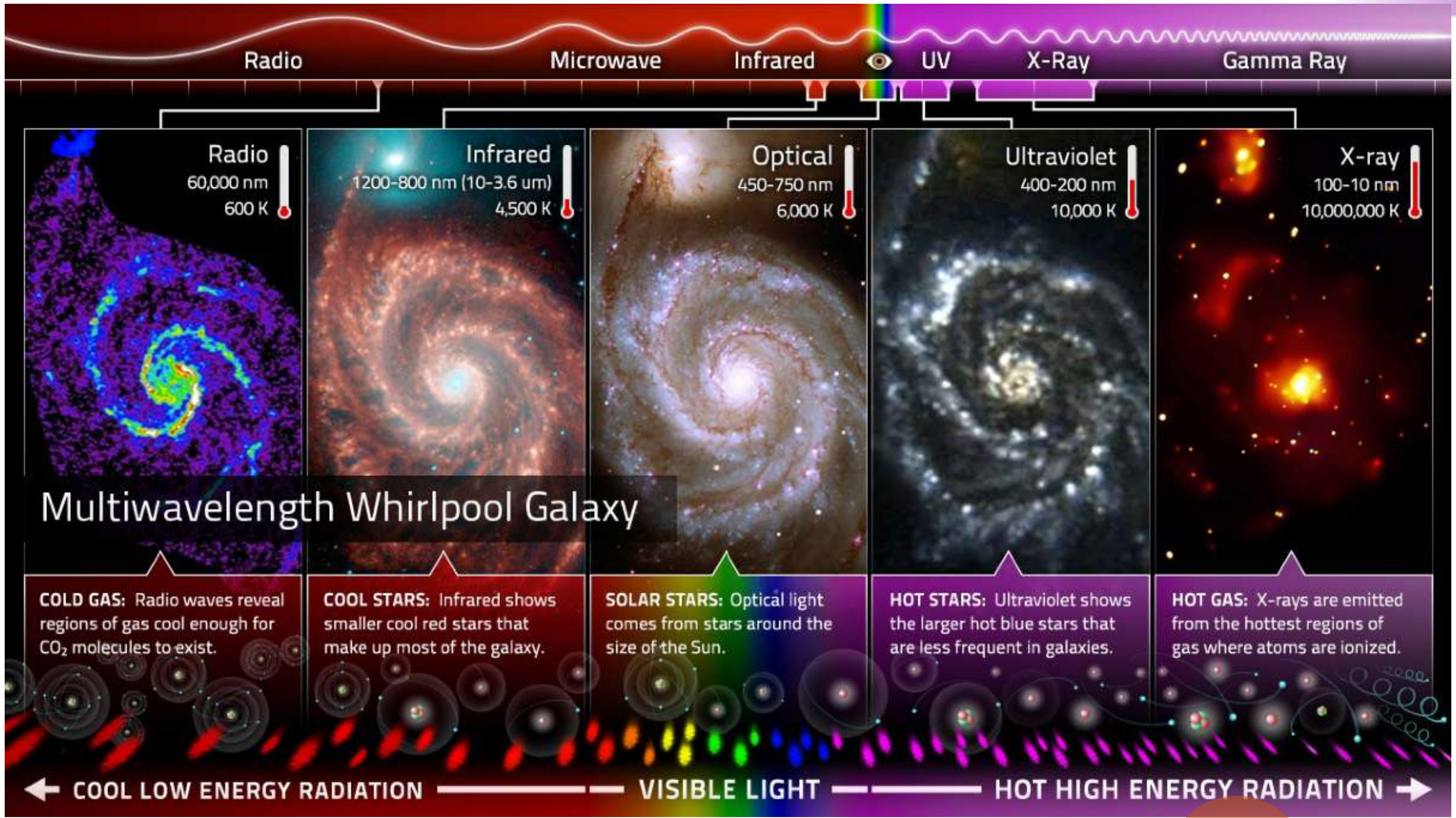
Laurent Loinard
BHI and DRCLAS, Harvard University
Instituto de Radioastronomía y Astrofísica, UNAM
(ng-)Event Horizon Telescope Collaboration

BLACK HOLE INITIATIVE
DAVID ROCKEFELLER CENTER FOR LATIN AMERICAN STUDIES
HARVARD UNIVERSITY

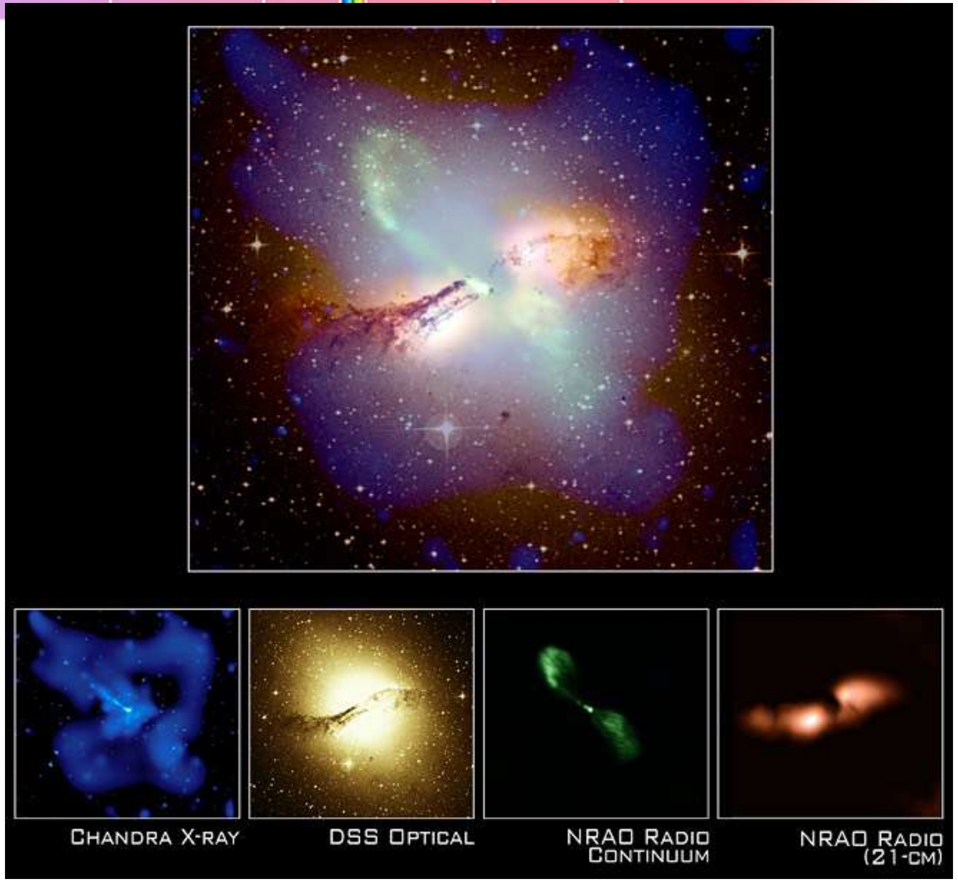
Part 1: Radioastronomy and Interferometry in a Nutshell

Multi-wavelength Astronomy



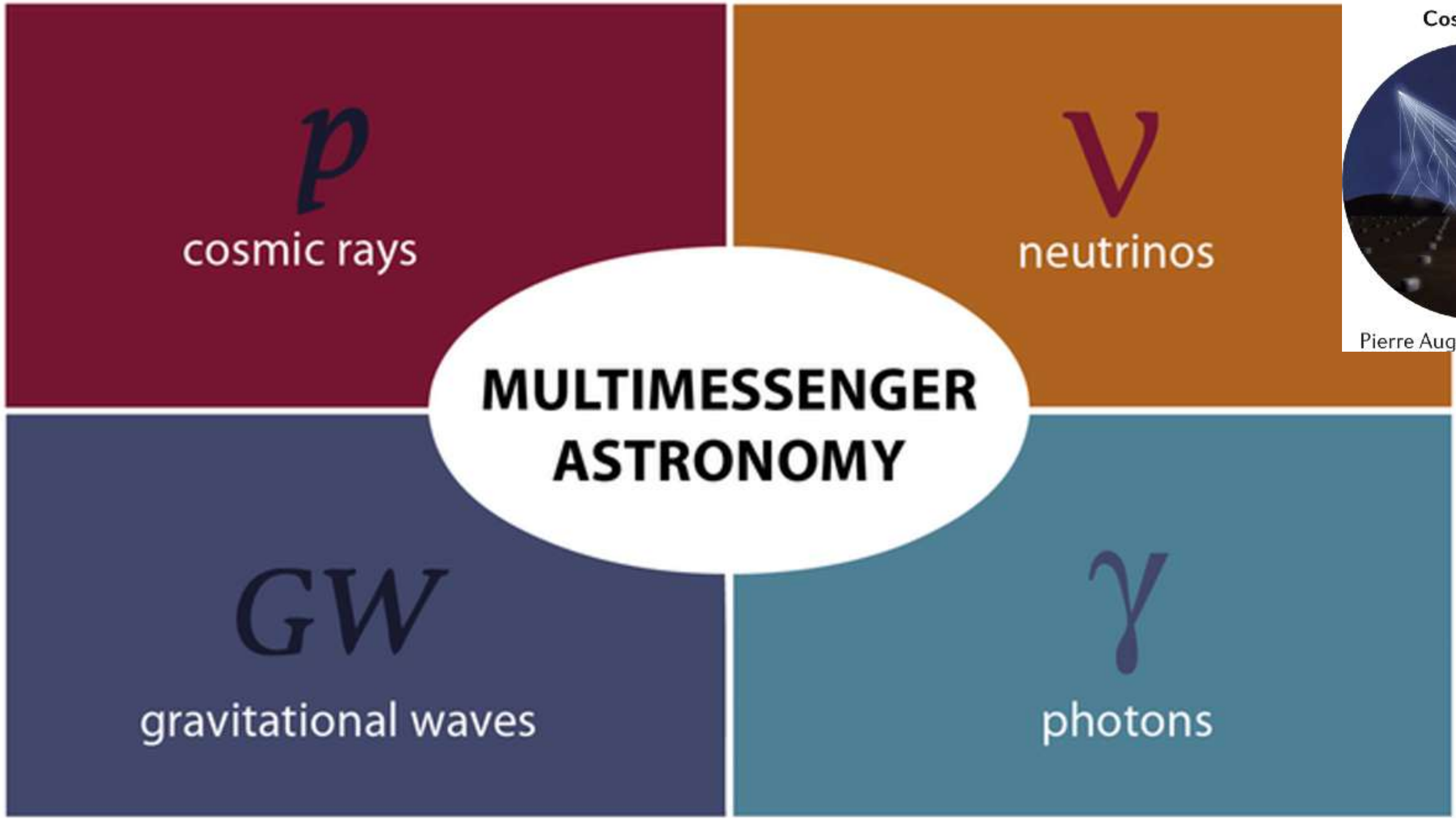


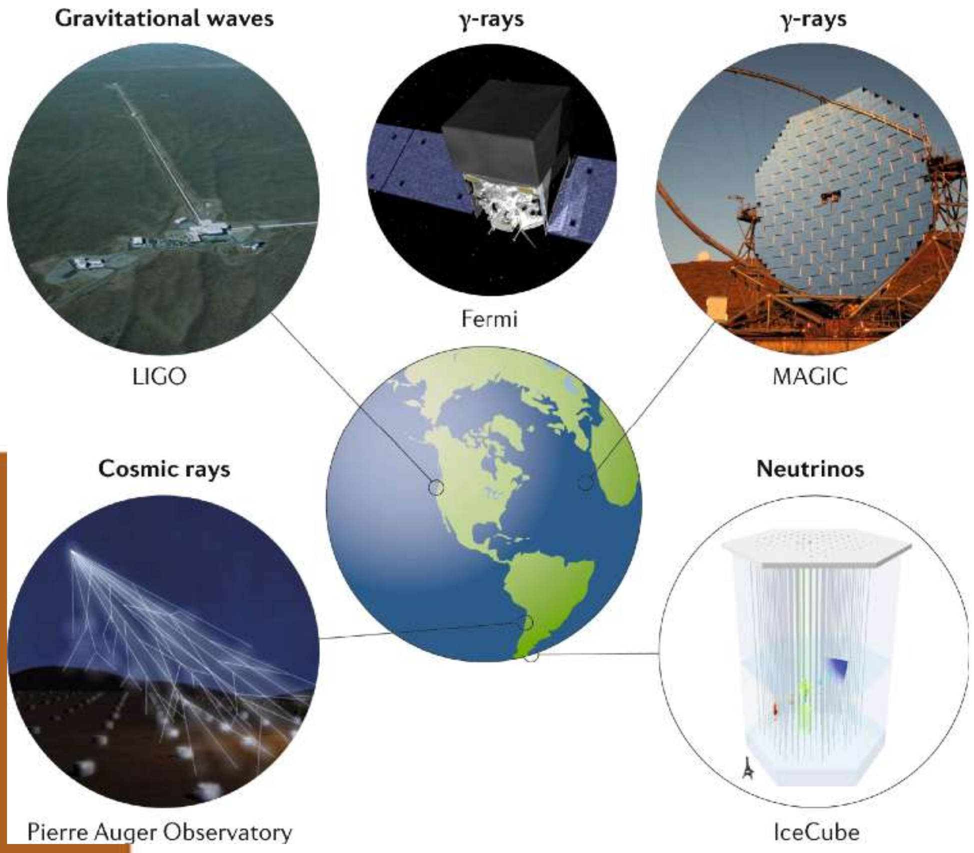
Spiral Galaxy M51



Active galaxy Centaurus A

Multi-messenger Astronomy





Astronomy Nobel Prizes

1974: M. Ryle & A. Hewish (J. Bell)

Imaging synthesis; pulsar

1978: A. Penzias & R. Wilson

Cosmic Microwave Background

1993: R. Hulse & J. Taylor

Double pulsar

2002: R. Giacconi, M. Koshiba & R. Davis Jr.

Cosmic X-ray and neutrino sources

2006: J. Mather & G. Smoot

Cosmic Microwave Background

2011: S. Perlmutter, B.Schmidt & A. Riess

Dark energy (Cosmic expansion)

2017: R. Weiss, B. Barrish & K. Thorne

Gravitational wave detection

2019: M. Mayor & D. Queloz

Extrasolar planets

2020: R. Genzel & A. Ghez

Black hole @ Galactic center

Astronomy Nobel Prizes

R R R

R R

R R

X ν ν

R R

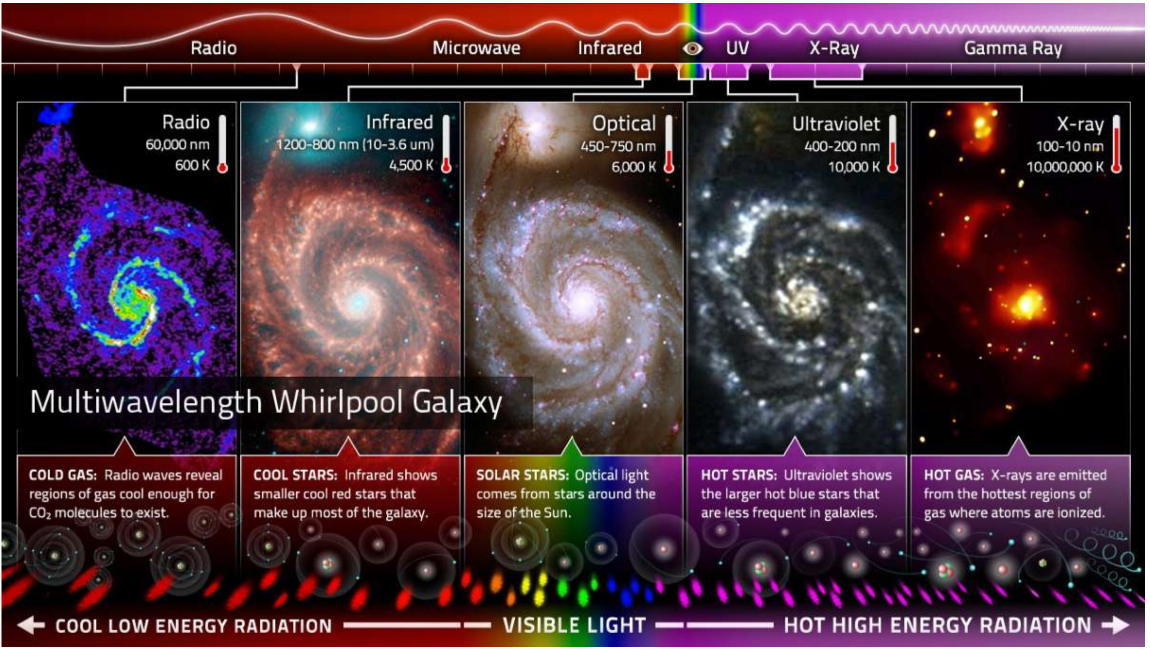
O O O

G G G

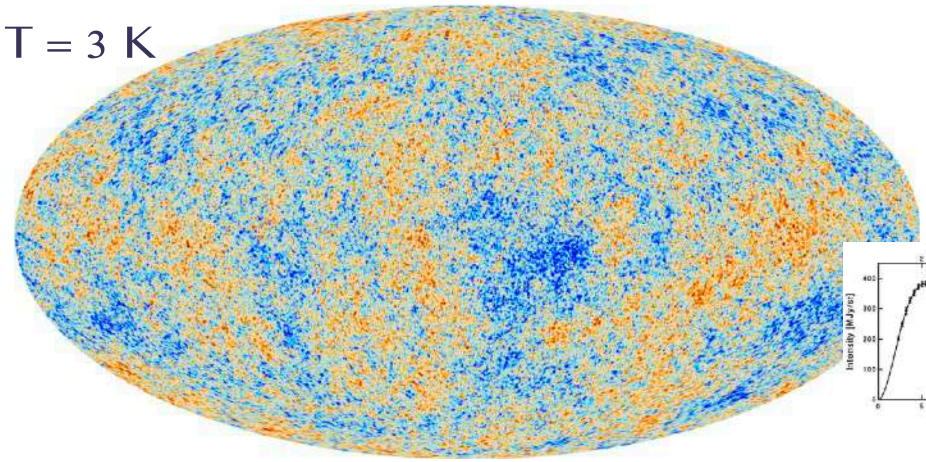
O O

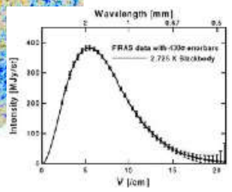
IR IR

Emission processes: thermal (blackbody)

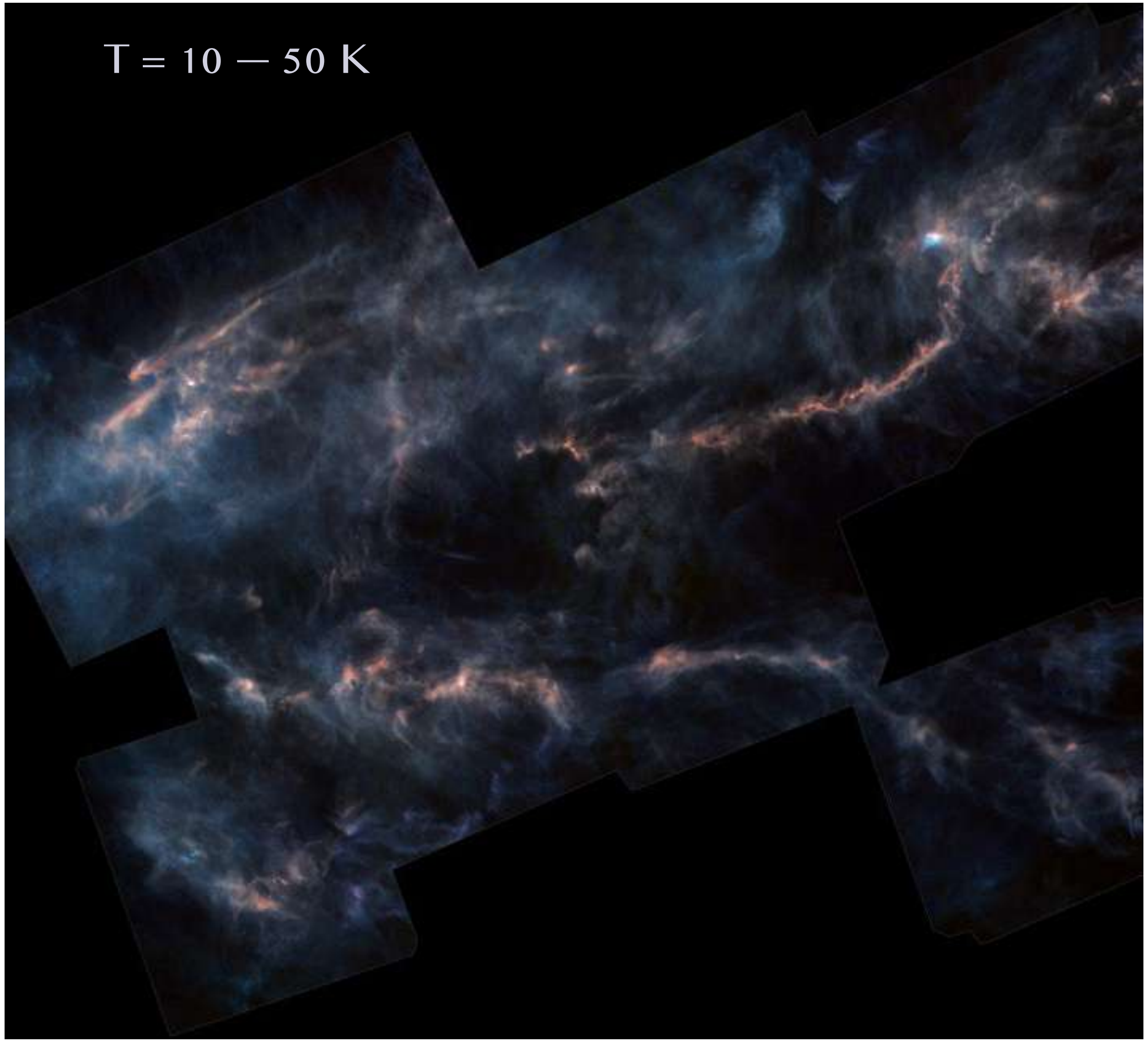


T = 3 K



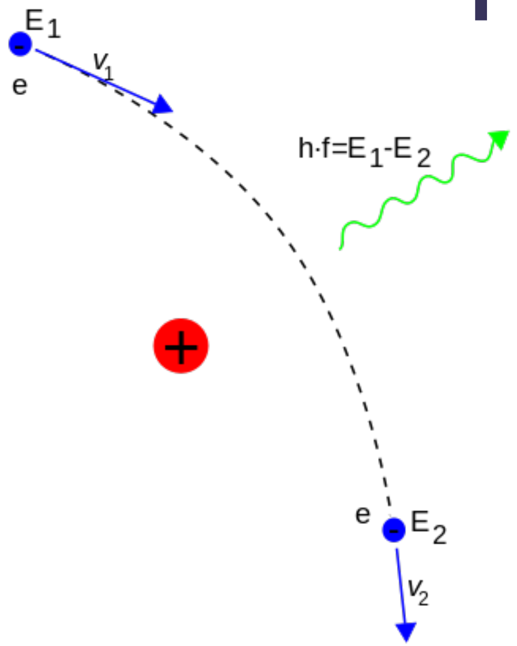


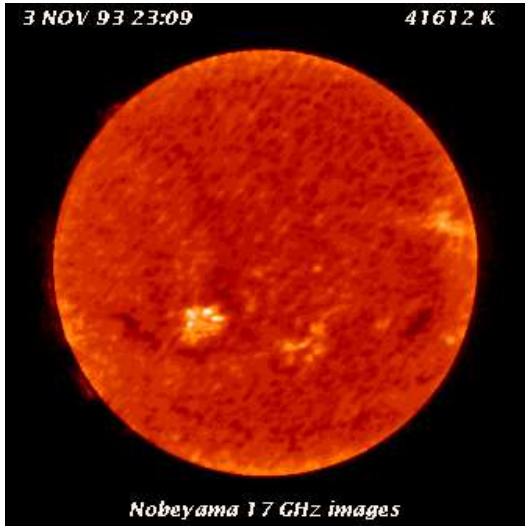
The cosmological microwave background

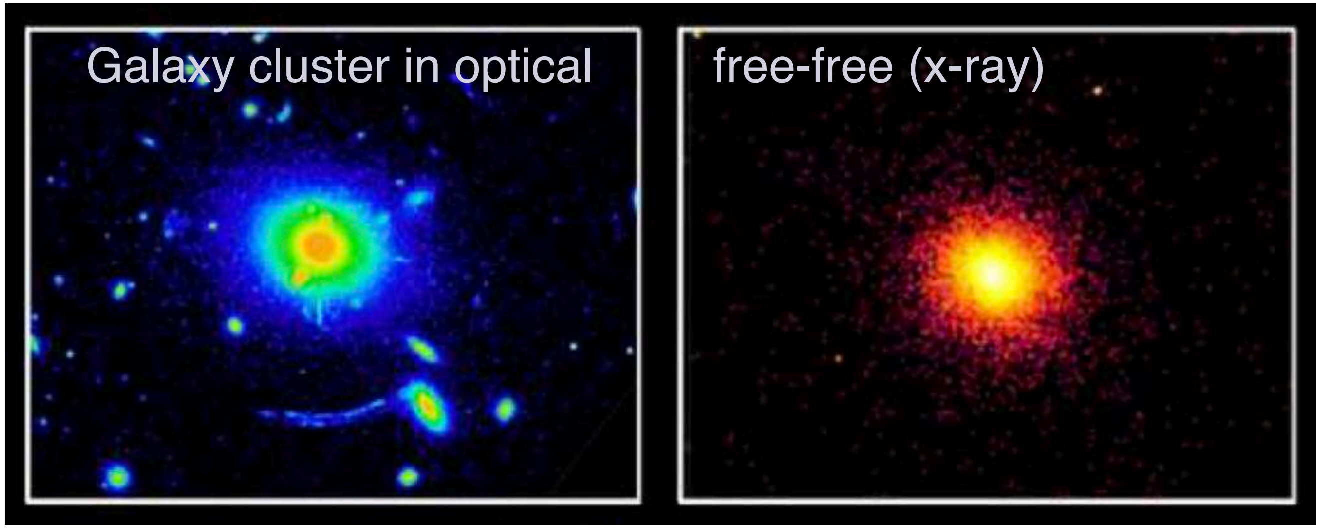


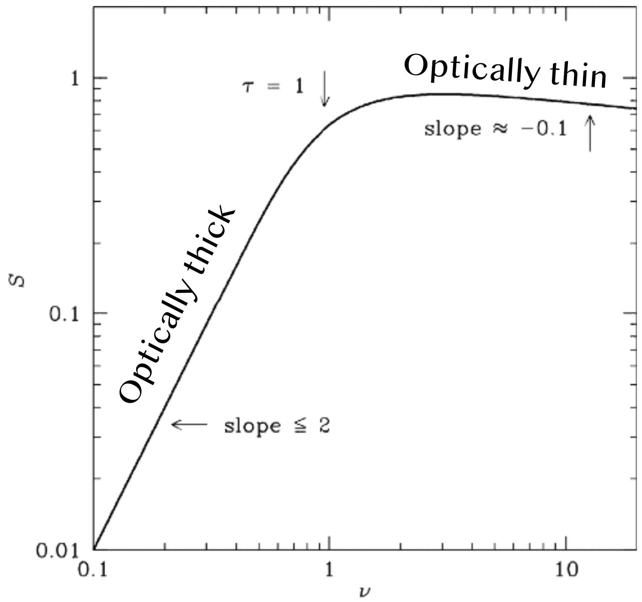
Taurus clouds with the Herschel satellite (150, 250, 350, 500 μm)

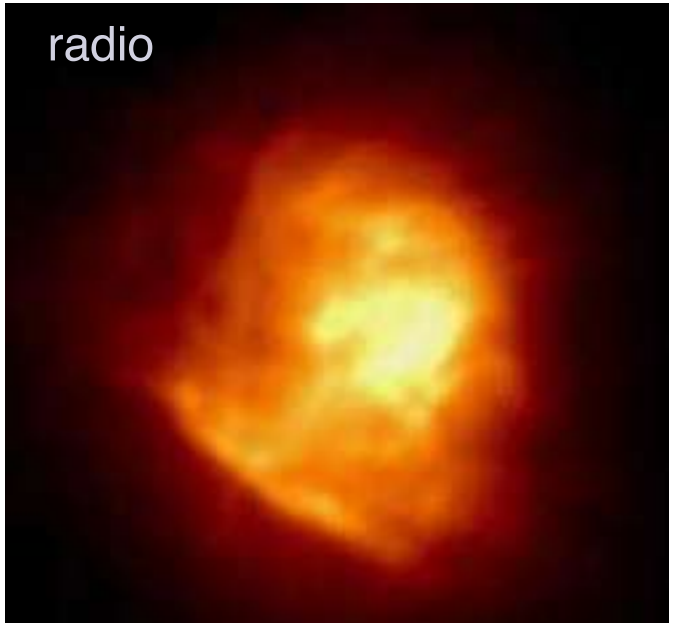
Emission processes: free-free (thermal)





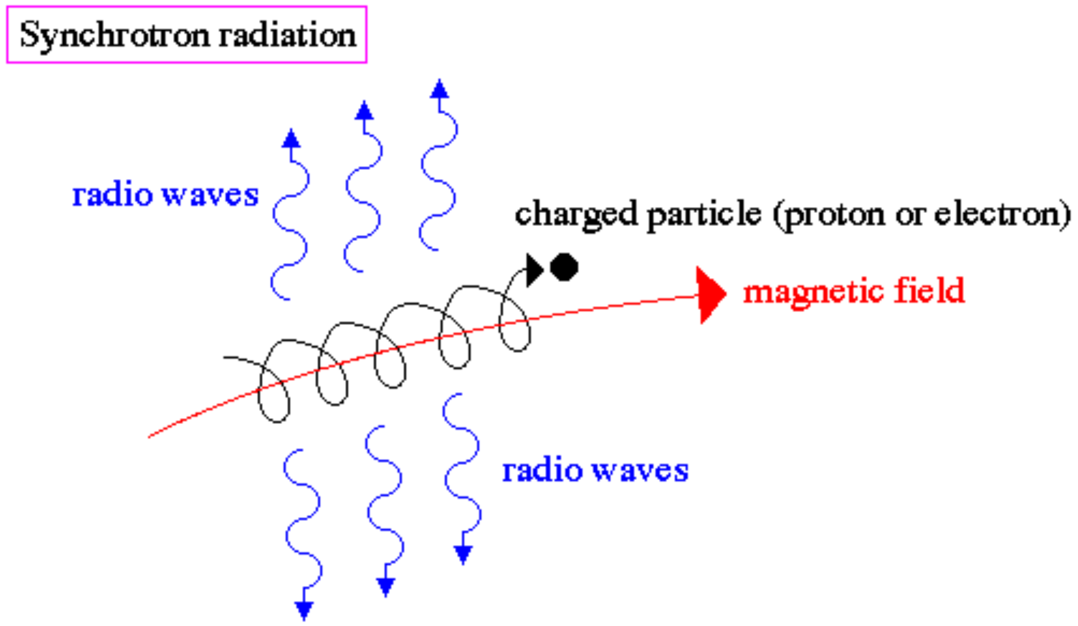


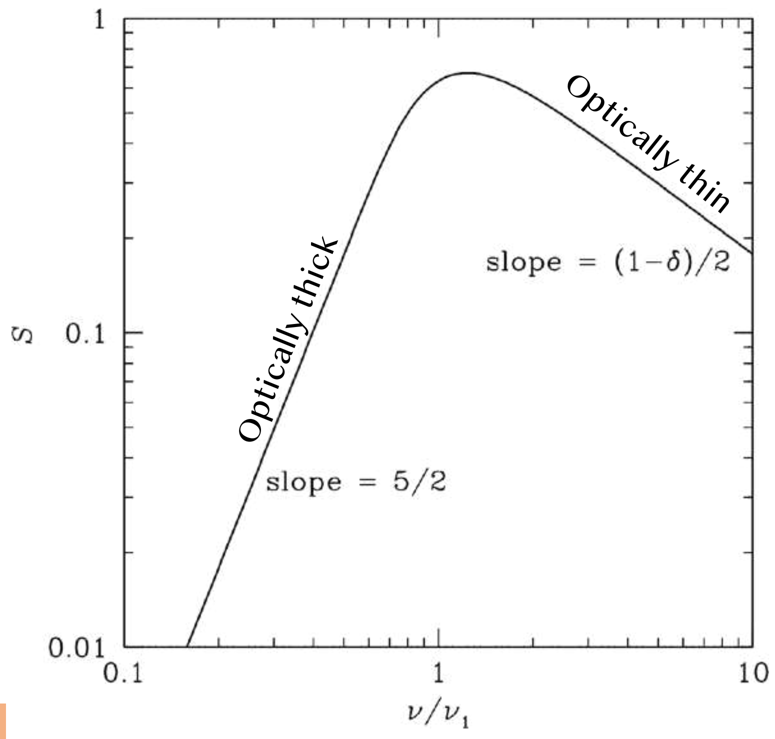




Emission processes: synchrotron (non-thermal)

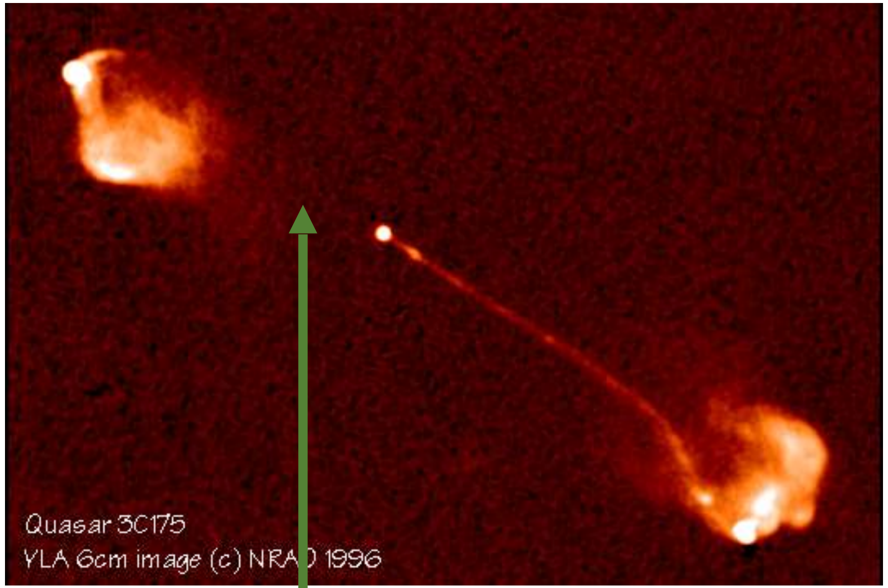
Radioastronomy (and, as we will see, particularly VLBI) is the realm of non-thermal processes

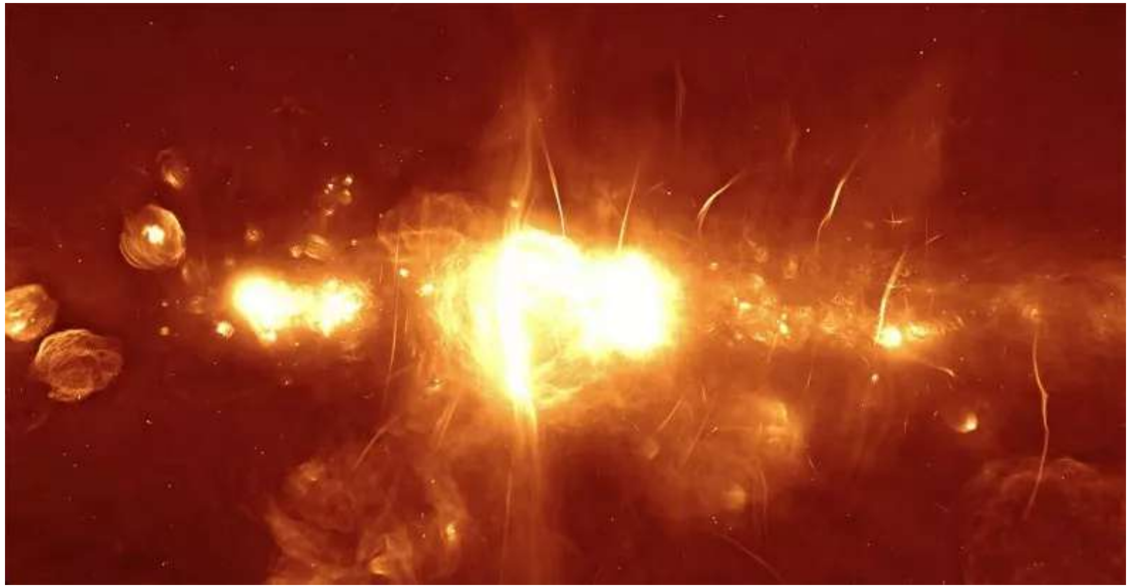


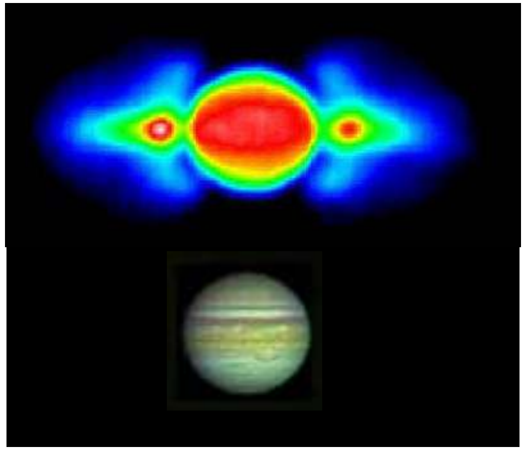


Relativistic electrons needed (acceleration mechanism)

Emission processes: synchrotron (non-thermal)

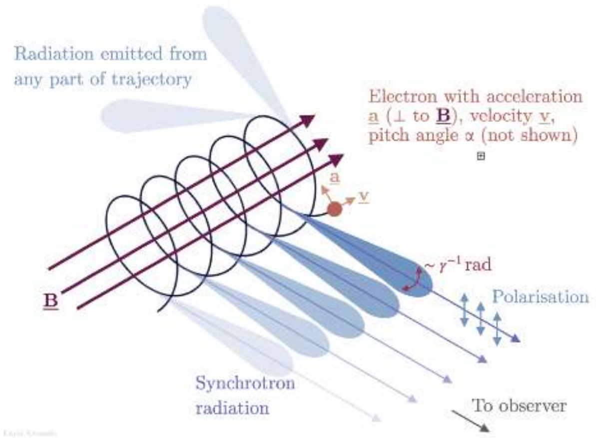


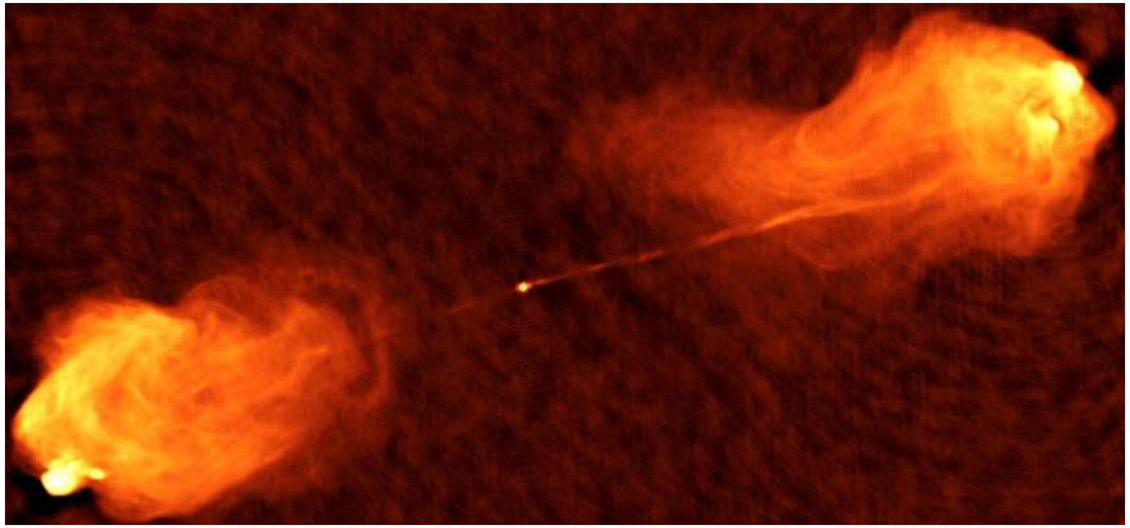




Quiz: why isn't there a counterjet?

The Galactic center in radio waves

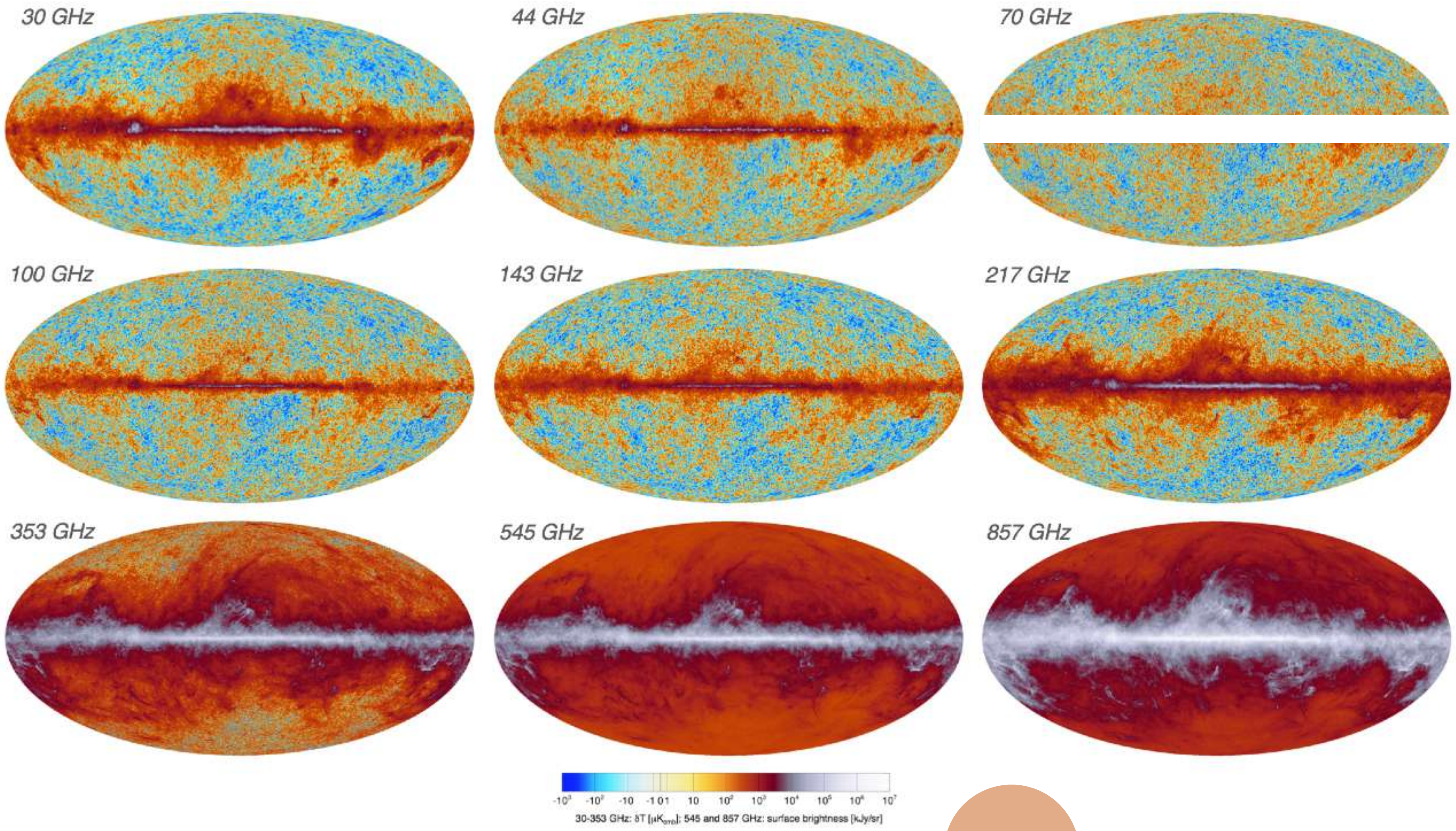


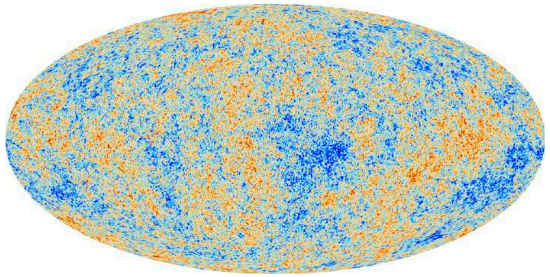


All-sky Planck microwave maps

At low frequencies, strong contamination by foreground free-free and synchrotron

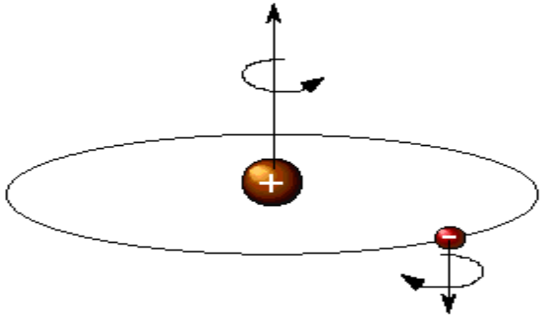
The sweet spot for cosmological microwave background

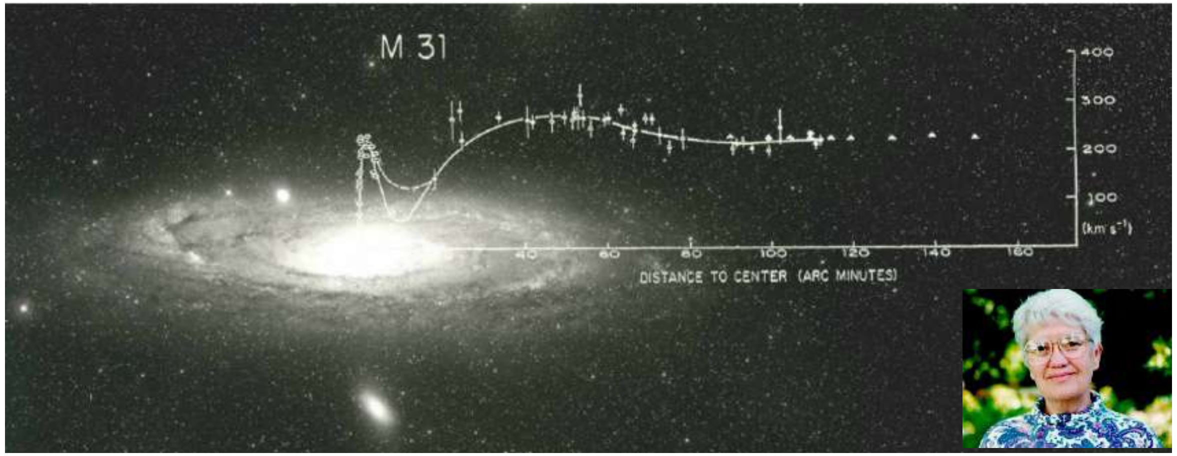




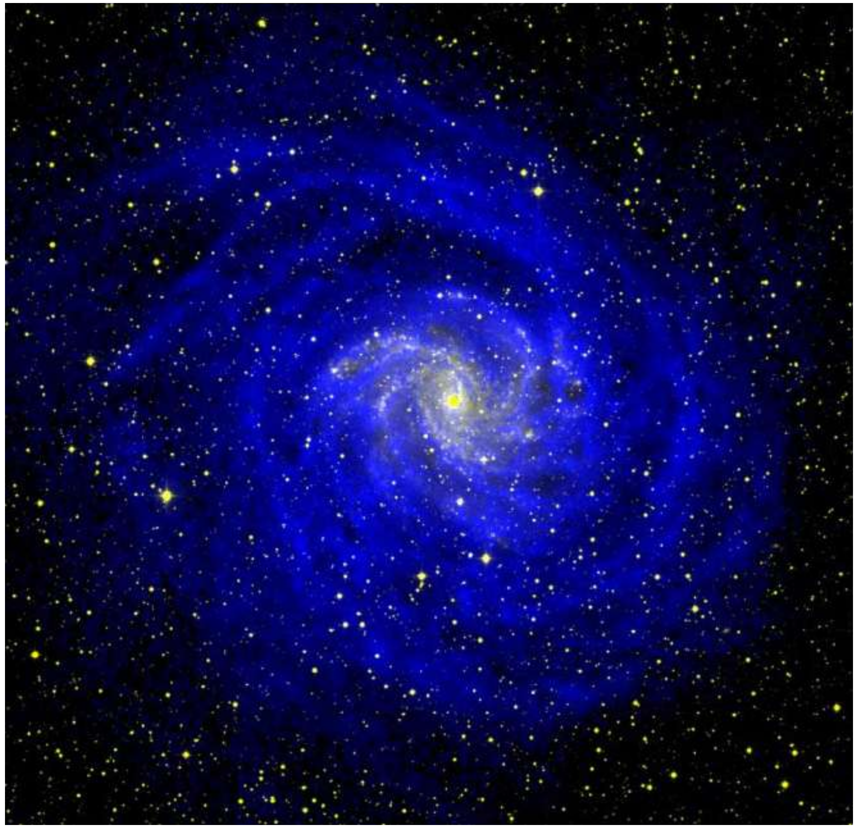
At high frequencies, strong contamination by foreground dust

Line emission: 21-cm hydrogen line



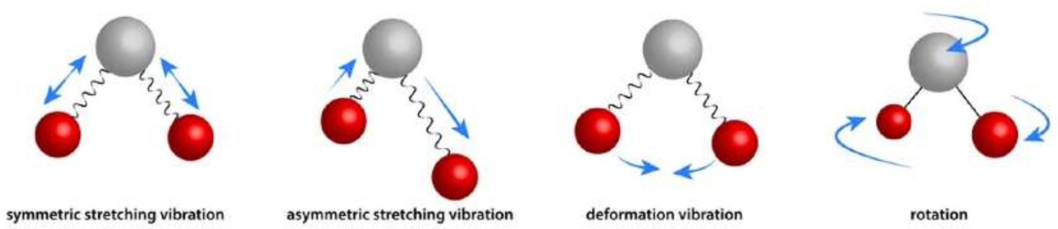


Vera Rubin

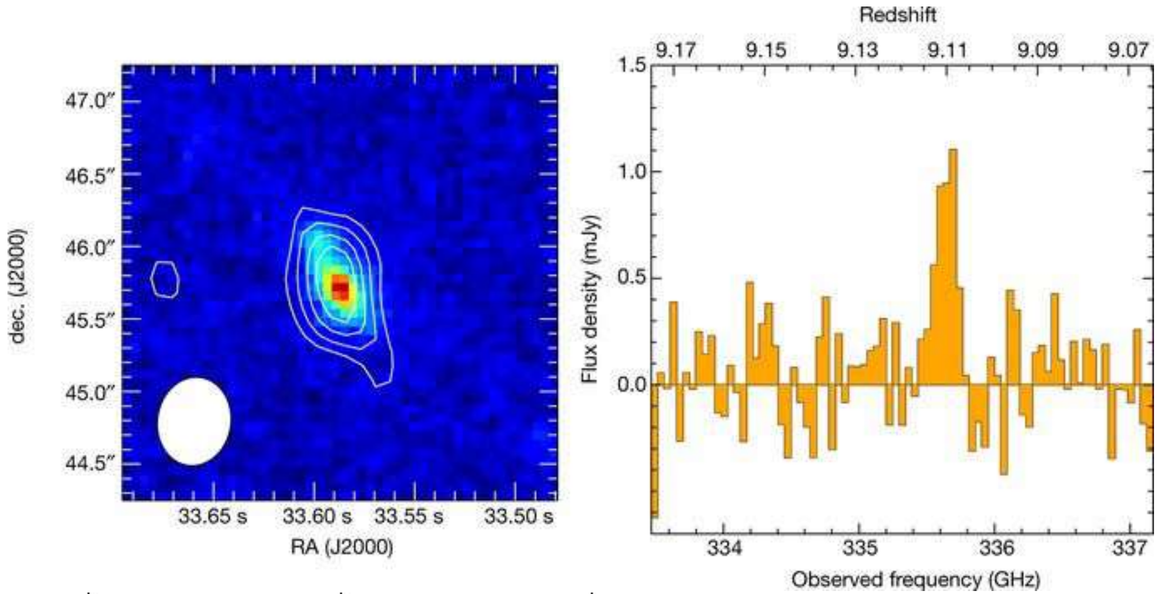


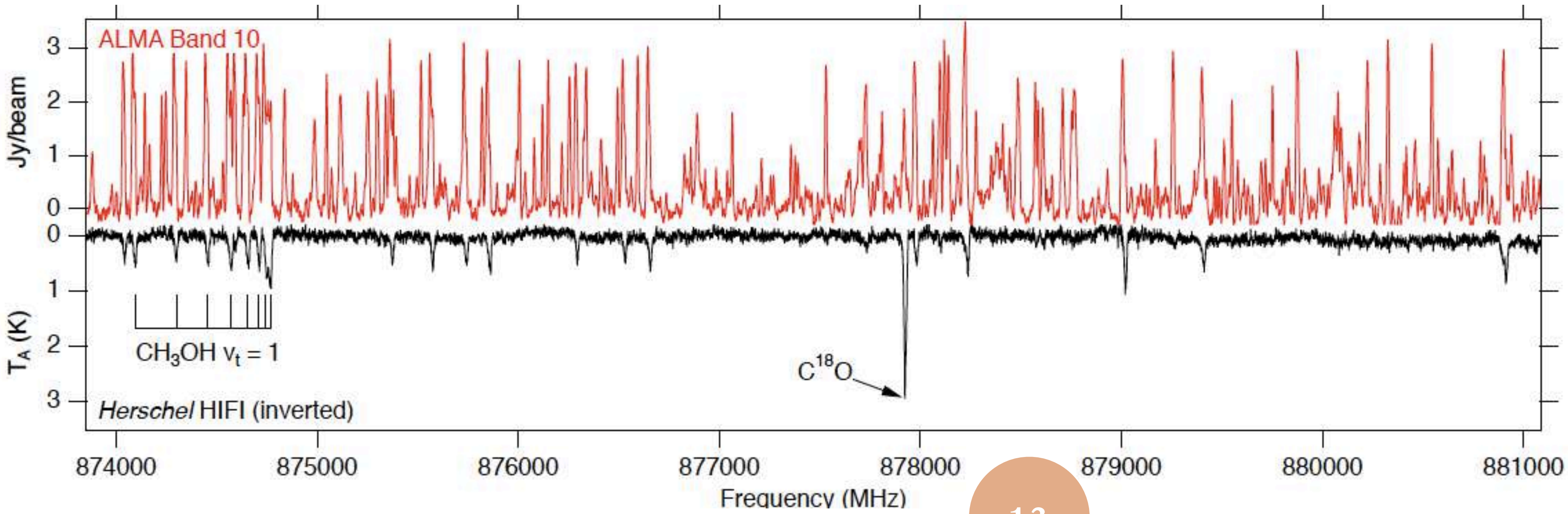
Optical image 21-cm map

Molecular emission lines

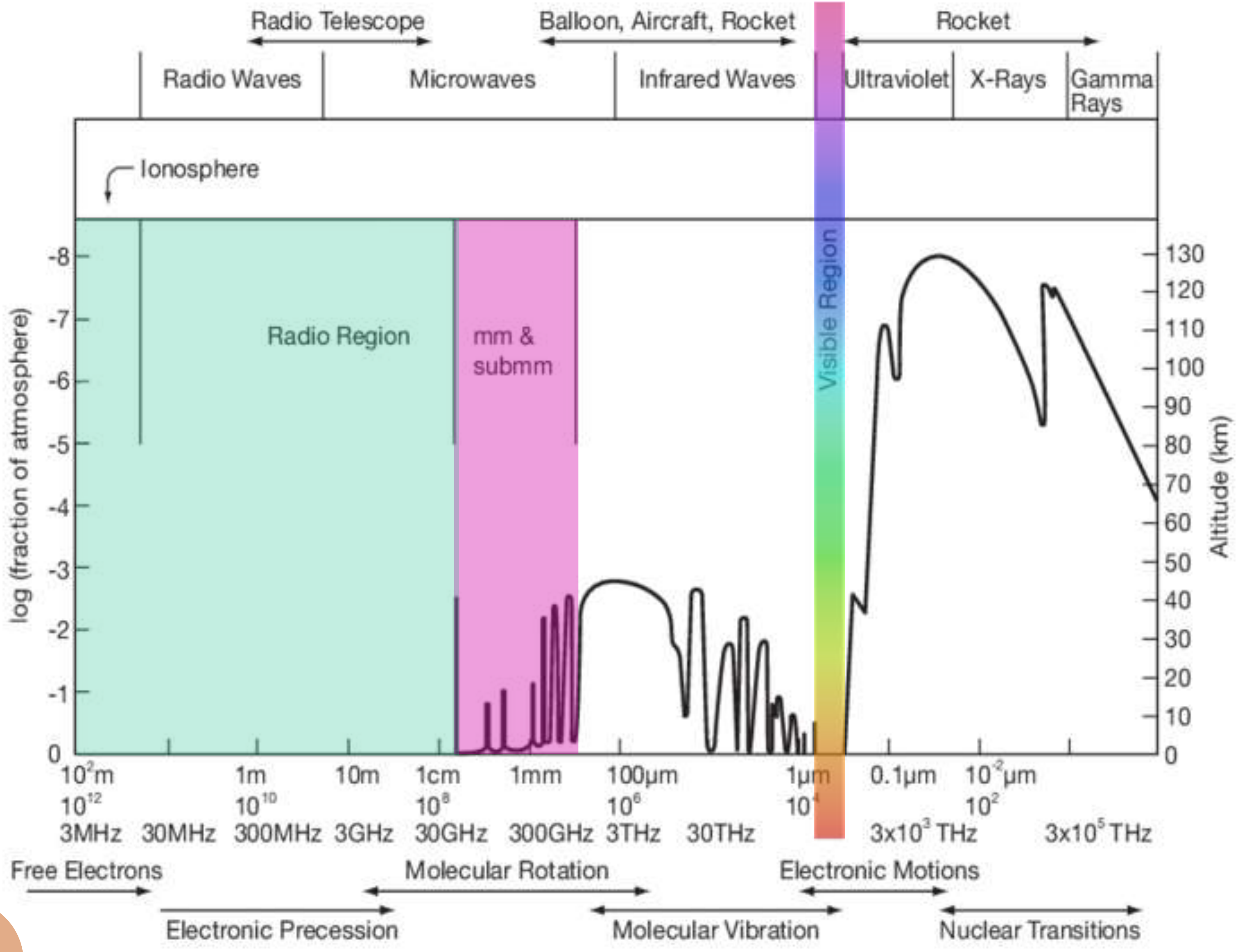


Oxygen at z = 9 with ALMA

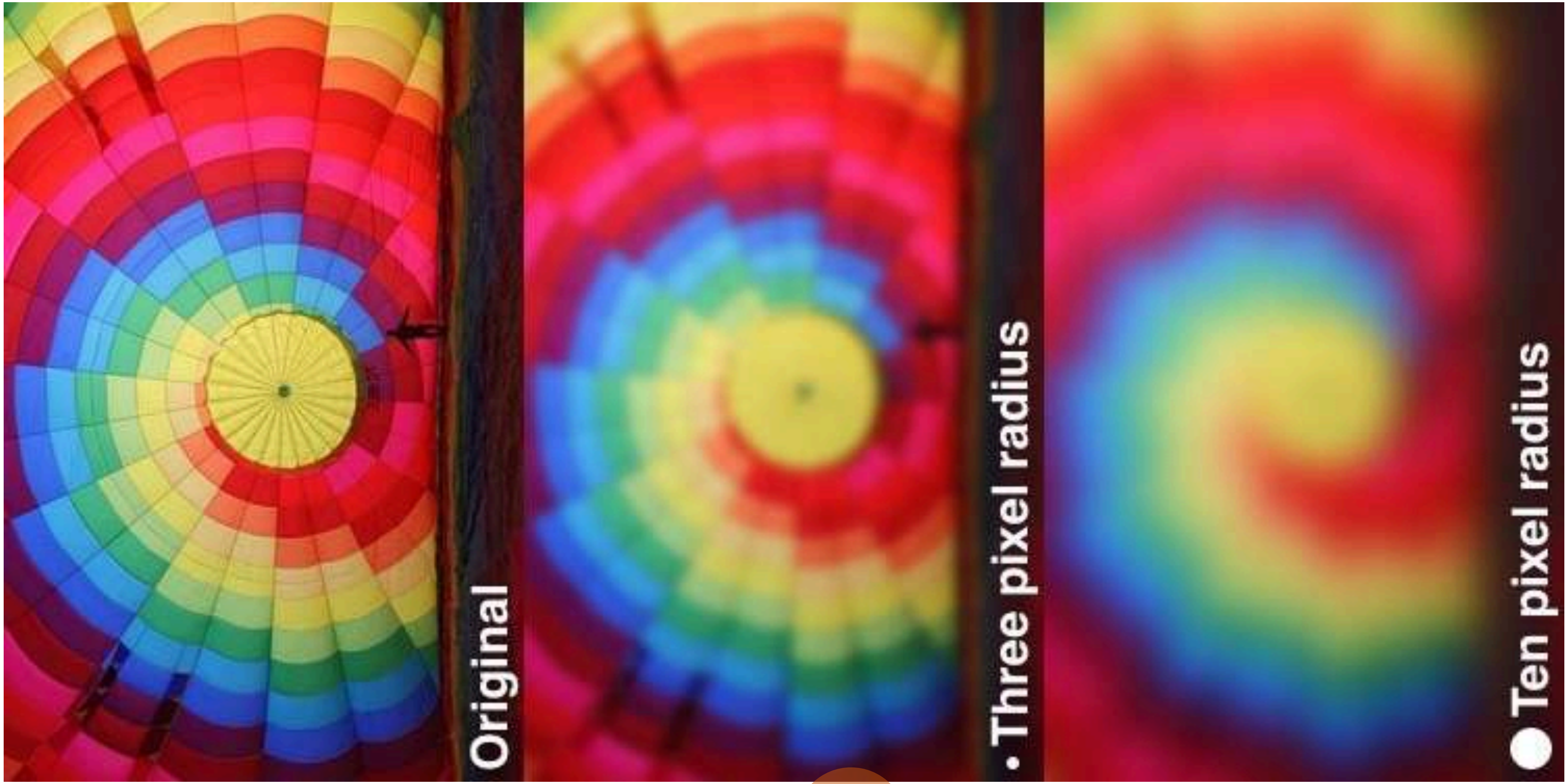




Atmospheric transparency/opacity



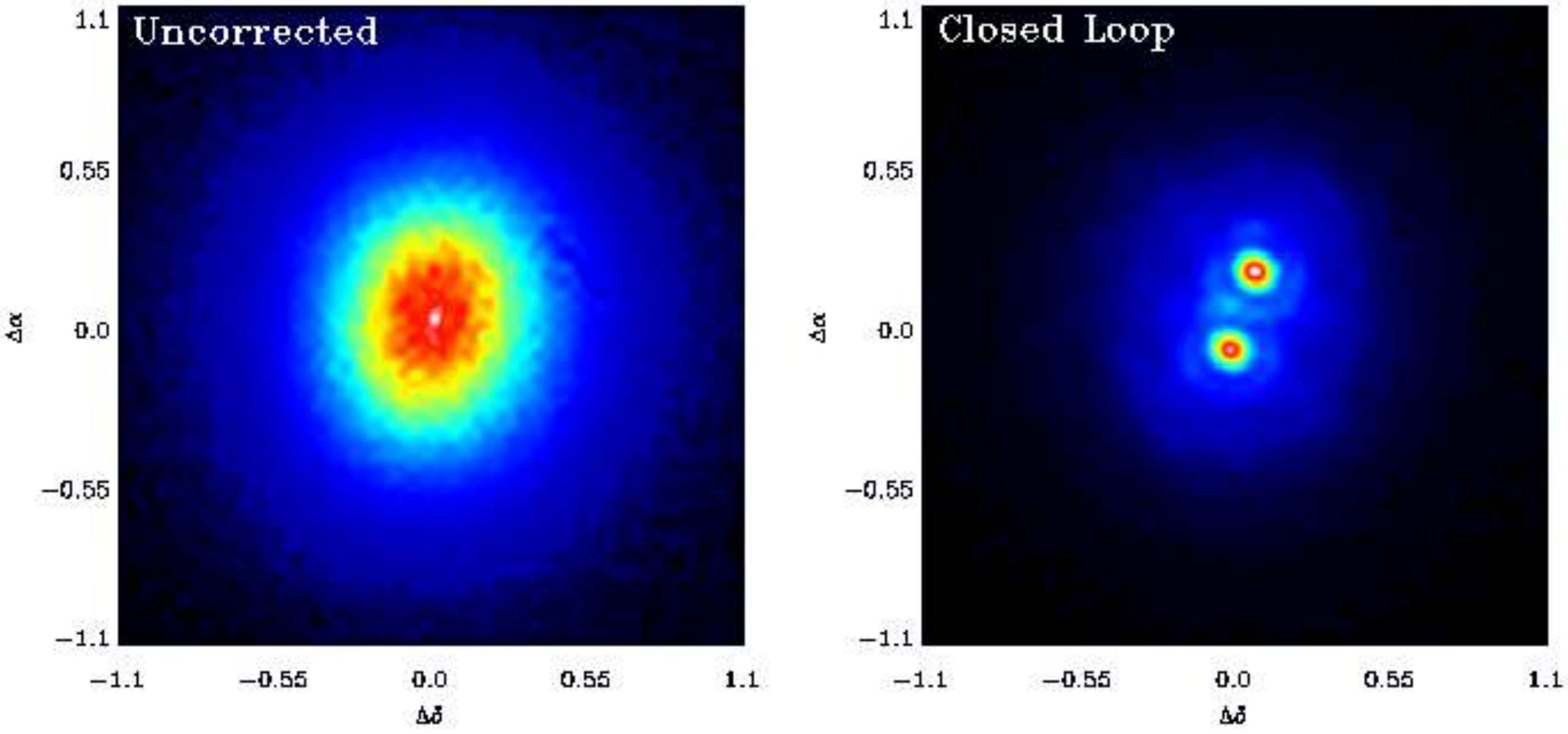
Angular resolution (image sharpness)



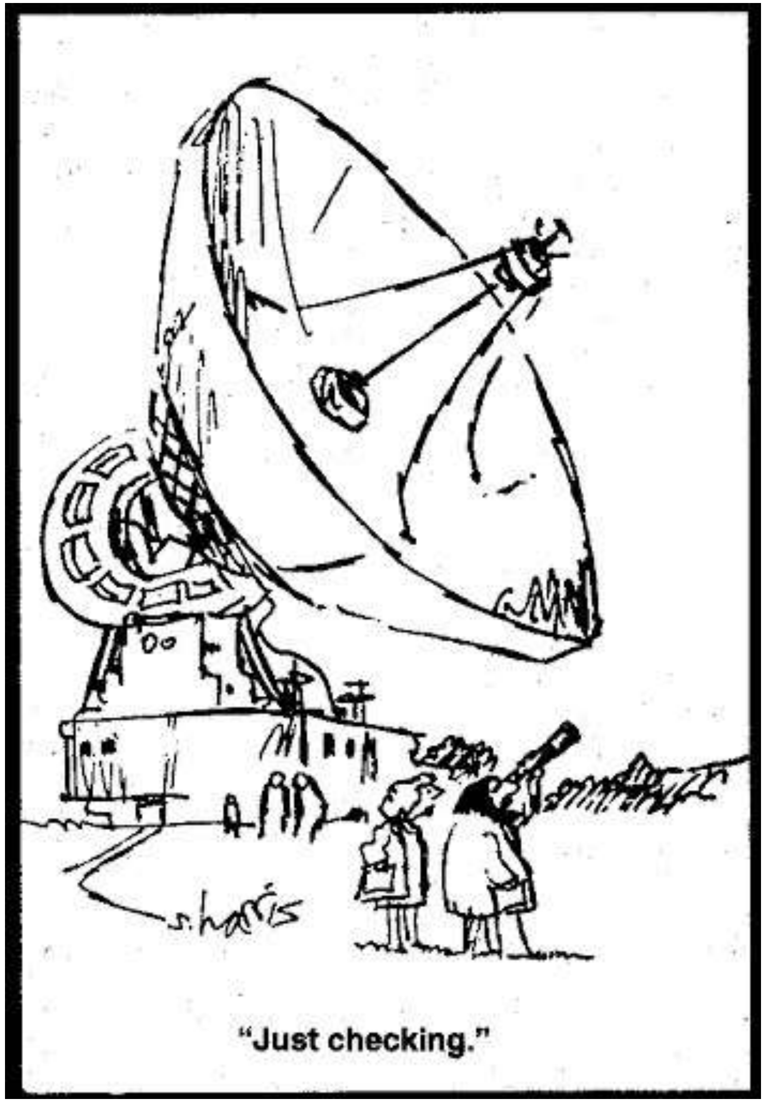
Angular resolution definition

The angular resolution is the minimum separation that an optical instrument can resolve:

$$\theta \approx \frac{\lambda}{D}$$



The angular resolution **problem** in radioastronomy



$$\theta \approx \frac{\lambda}{D}$$

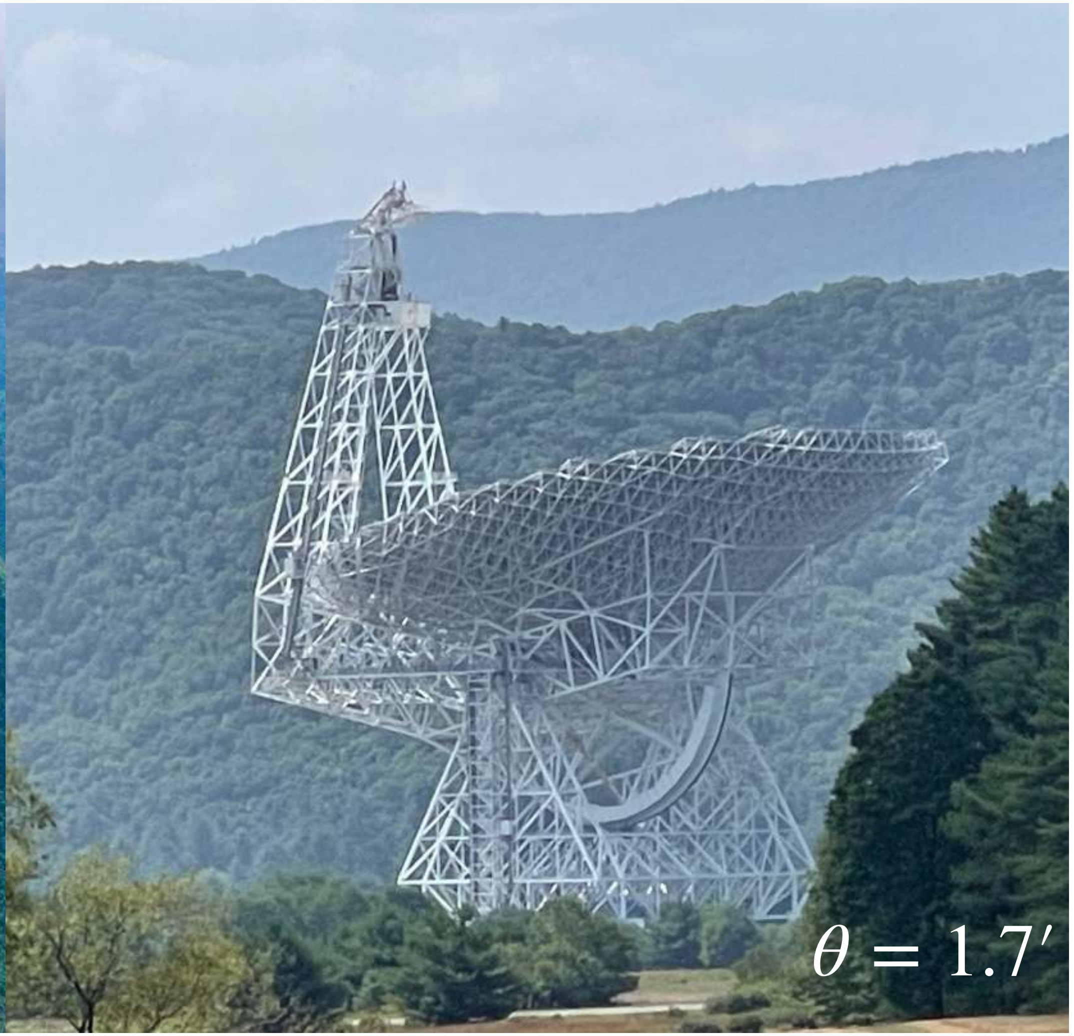
$\lambda = 5$ cm & $D = 160$ m $\longrightarrow \theta = 1'$

$\lambda = 0.5$ μm & $D = 1.6$ mm $\longrightarrow \theta = 1'$

Radio-astronomers need to build **BIG** telescopes

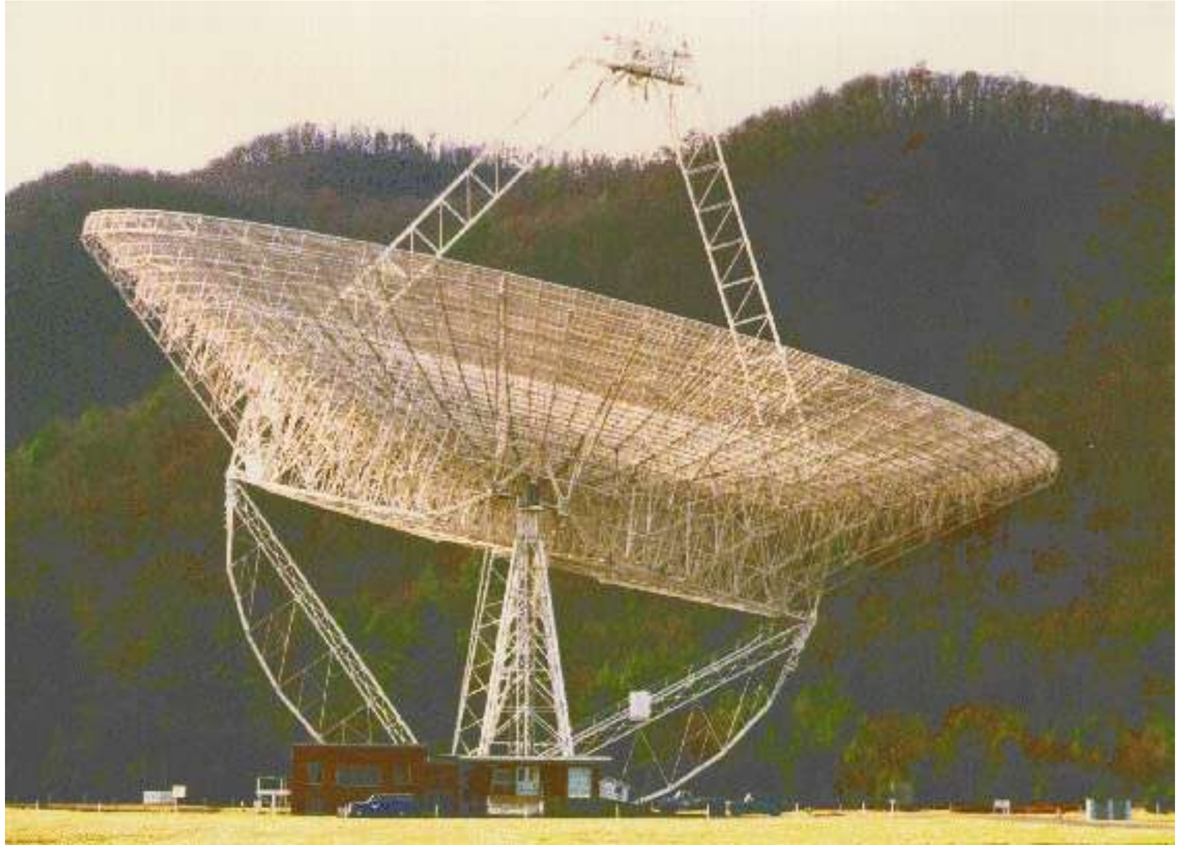
That's hard and expensive…

Five Hundred Meter Aperture Spherical Telescope (China)



Green Bank Telescope (100m, USA)

… and potentially risky

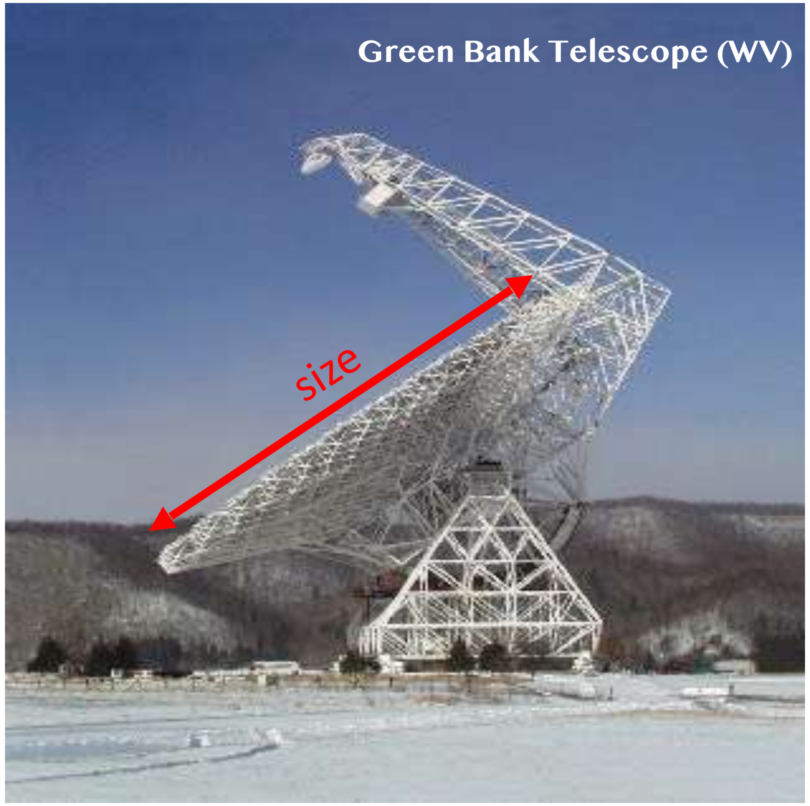


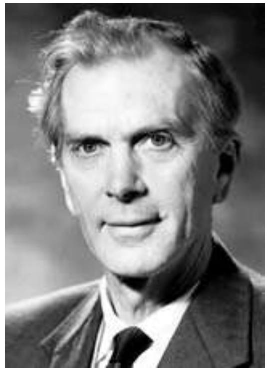
300 foot telescope in Green Bank (November 15, 1988)

300 foot telescope in Green Bank (November 16, 1988)

Credit to Joe Callingham for the idea for the slide

Two kinds of radio telescopes





Sir Martin Ryle (Nobel 1974)

Imaging synthesis

Single-dish

$$\theta \approx \frac{\lambda}{D}$$

Interferometers

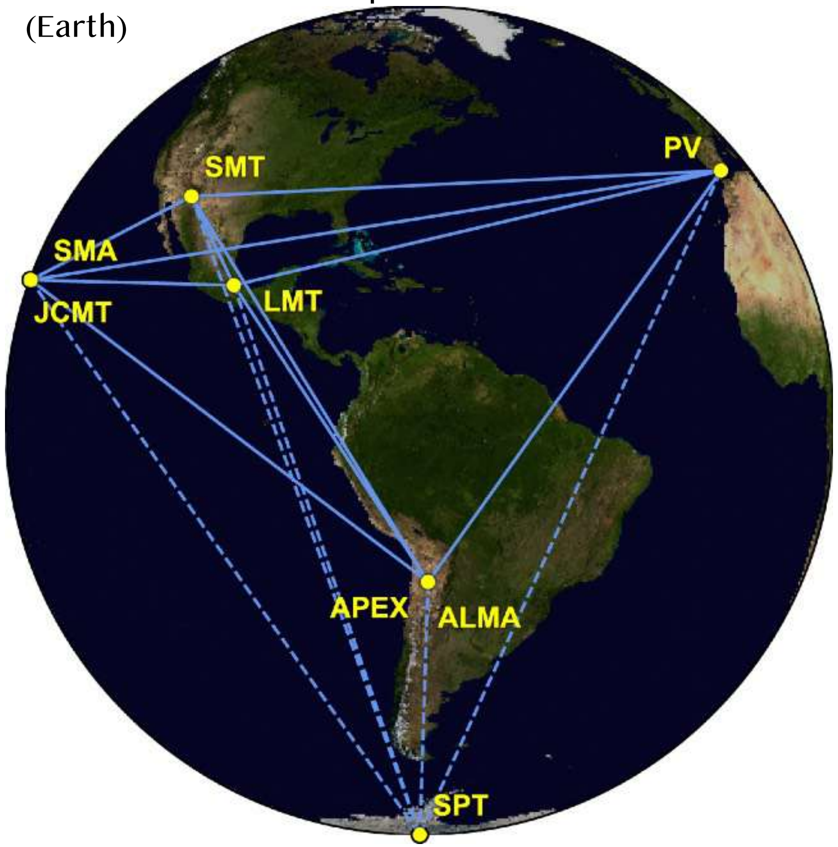
$$\theta \approx \frac{\lambda}{B_{max}}$$

Maximum "baseline"

Very Long Baseline Interferometry (VLBI)

1 milli-arcsecond resolution

Event Horizon Telescope
(Earth)



25 microarcsecond resolution

The angular resolution **solution** in radioastronomy

Biggest single-dish

Same resolution as human eye
(~ one arcminute)

“conventional” interferometers

Same resolution as large optical telescope
(~ 0.1 arcsecond)

VLBI arrays

Highest resolution in astronomy
(~ 1 milli-arcsecond down to 10 micro-arcsecond)

This is the highest angular resolution achievable in all of astronomy


VLA (NM, USA)


ALMA (Chile)


ASKAP (Australia)

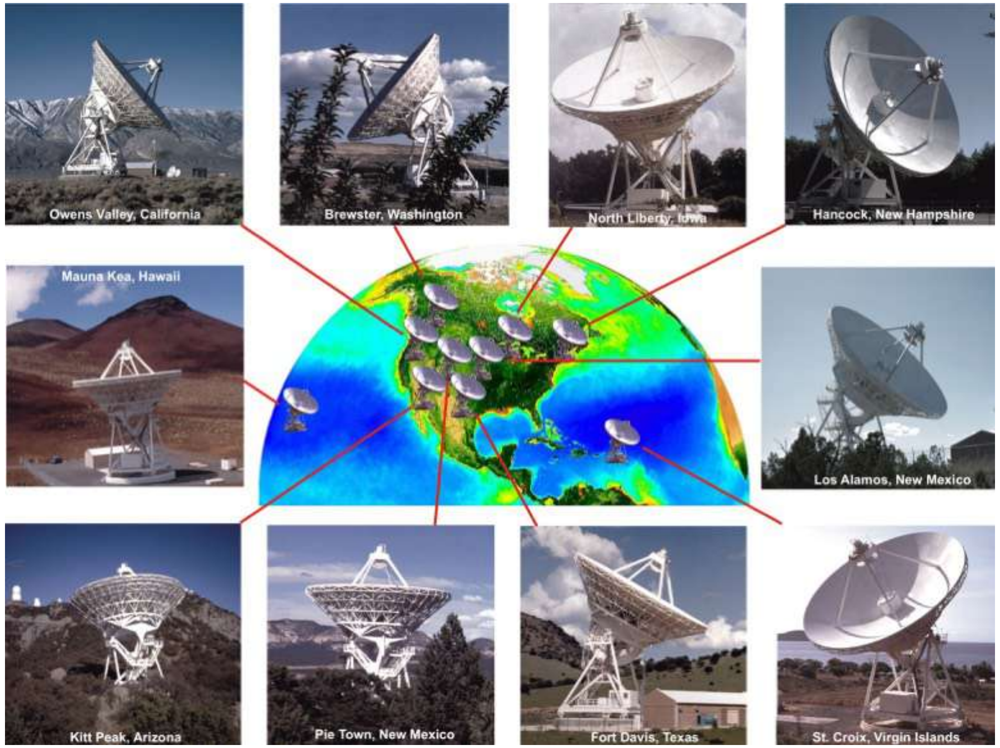

Keercat (South-Africa)


Lower (Europe)

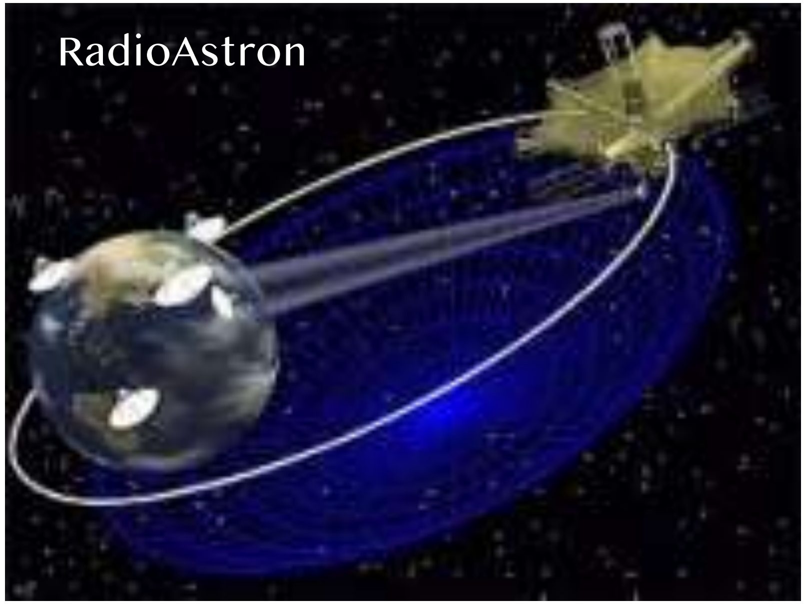
EHT


Hawaii
Arizona
Spain
Mexico
Chile
South Pole

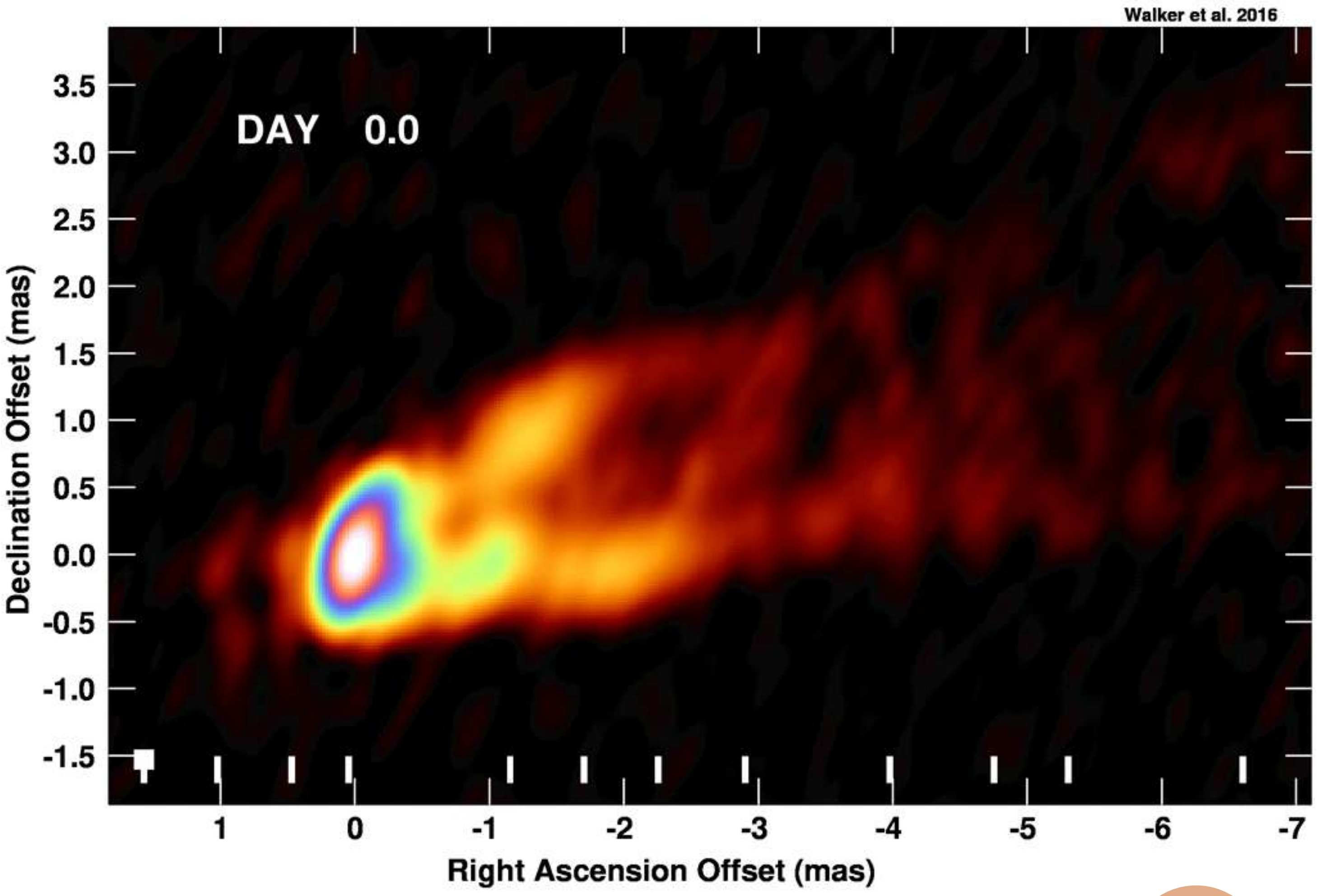
VLBA

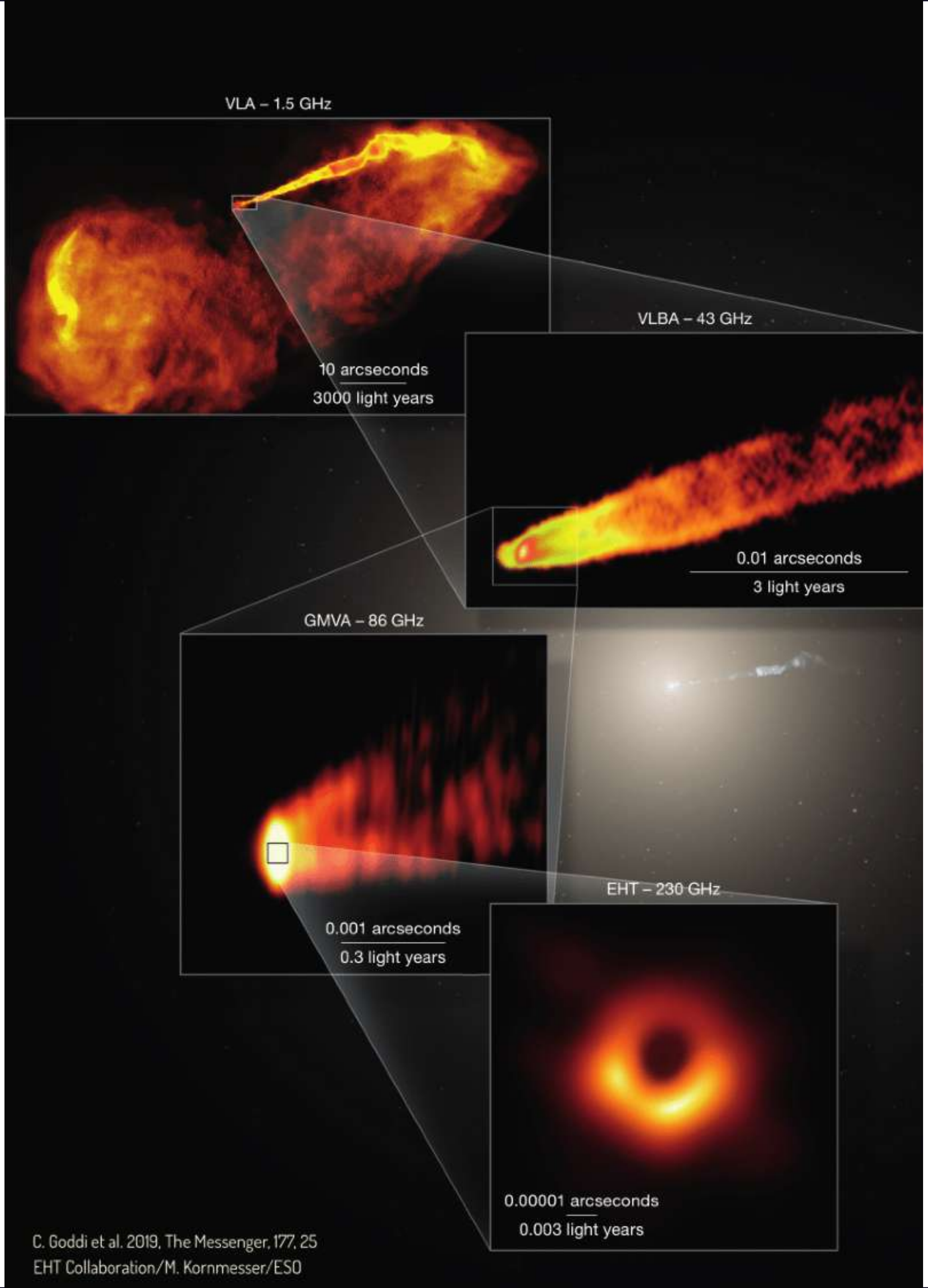

Owens Valley, California
Brewster, Washington
North Liberty, Iowa
Hancock, New Hampshire
Mauna Kea, Hawaii
Los Alamos, New Mexico
Kitt Peak, Arizona
Pie Town, New Mexico
Fort Davis, Texas
St. Croix, Virgin Islands


VLBA – Pie Town
VLBA – Los Alamos
Greenland Telescope
VLBA – North Liberty
NRAO – GBT 100m
Metsähovi 14m
VLBA – Brewster
Onsala 20m
VLBA – Mauna Kea
MPIfR – Effelsberg 100m
VLBA – Owens Valley
GMVA
GLOBAL MILLIMETER VLBI ARRAY
M87 2018 Array
VLBA – Kitt Peak
VLBA – Fort Davis
Phased-ALMA
IRAM – Pico Veleta 30m
OAN – Yebes 40m


RadioAstron

VLBI highlights



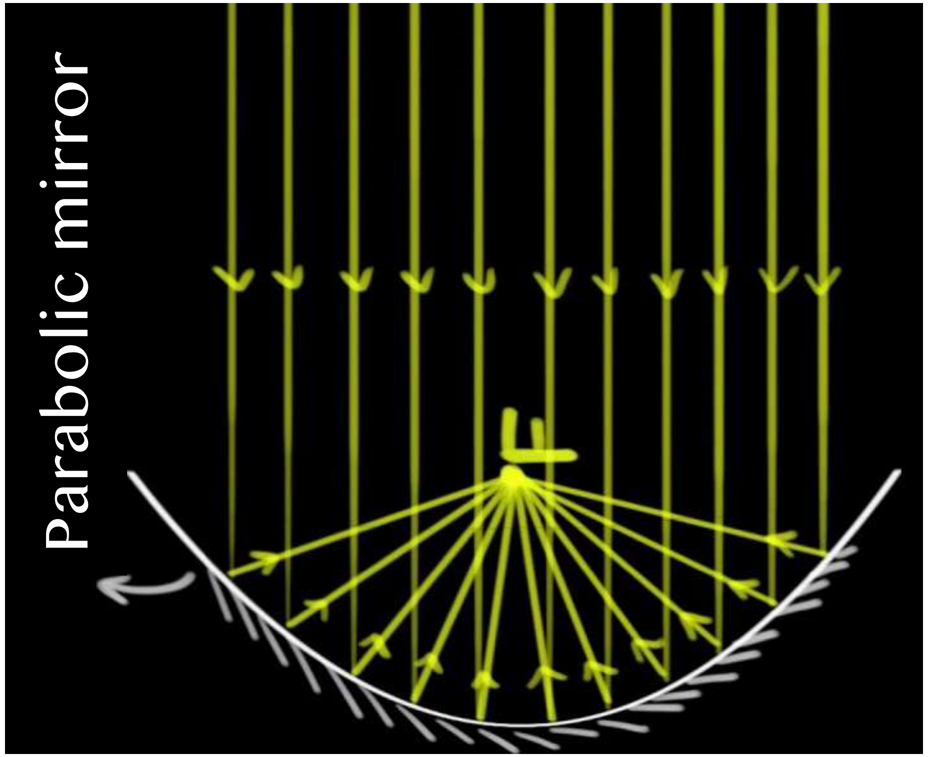


Part 2: Fundamentals of Interferometry

Fair warning: interferometry is more work than single-dish…

- Observing with $N \gg 1$ antennas, is N times more work than observing with one antenna (or maybe even N^2 times more work…)
- As we will see in details later, interferometers do not provide directly an image. Rather they deliver complex quantities ($\in \mathbb{C}$) that need to be manipulated mathematically to computationally reconstruct an image
- The resulting images contain artifacts caused by the geometry of the array
- Sensitivity is limited
- Calibration is more work than for single-dish telescopes

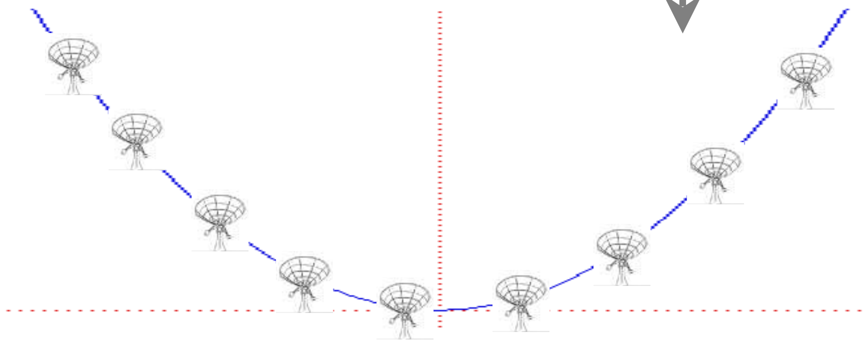
Pictorial principle of interferometry



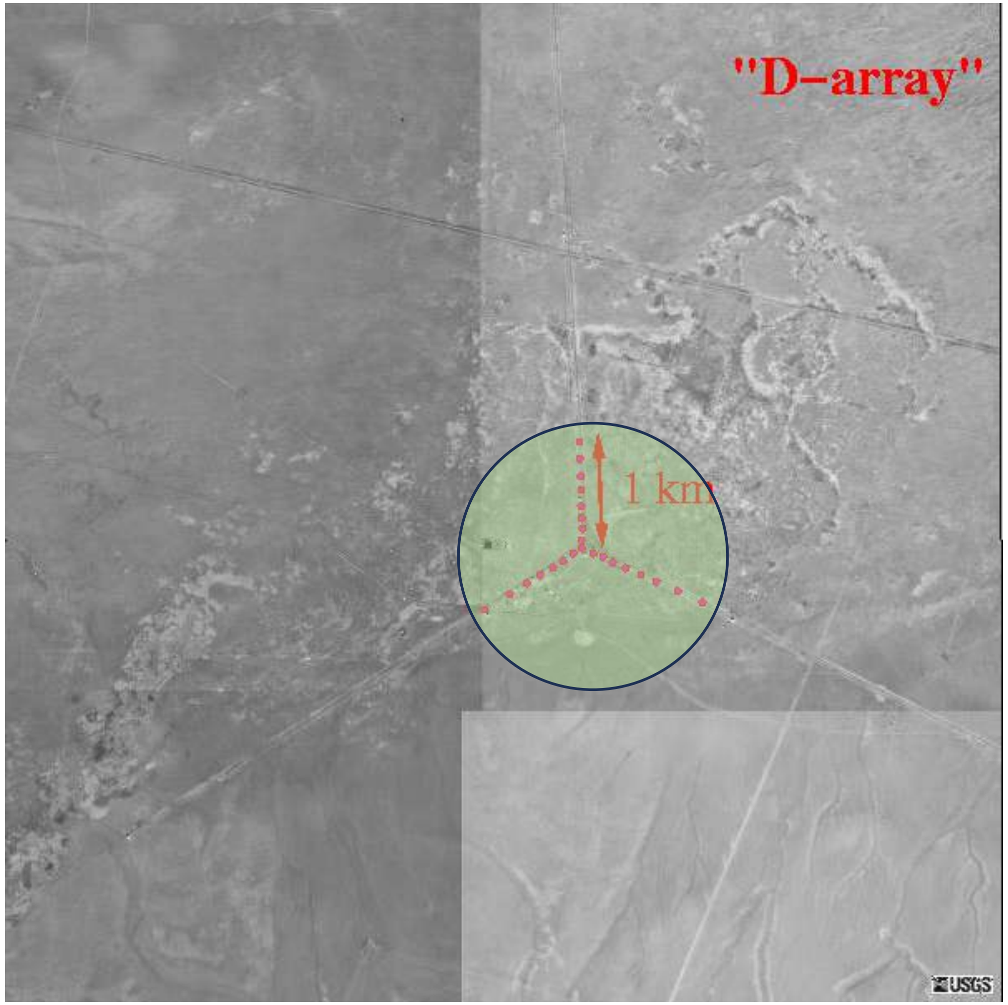
Reflector telescope

Replace with

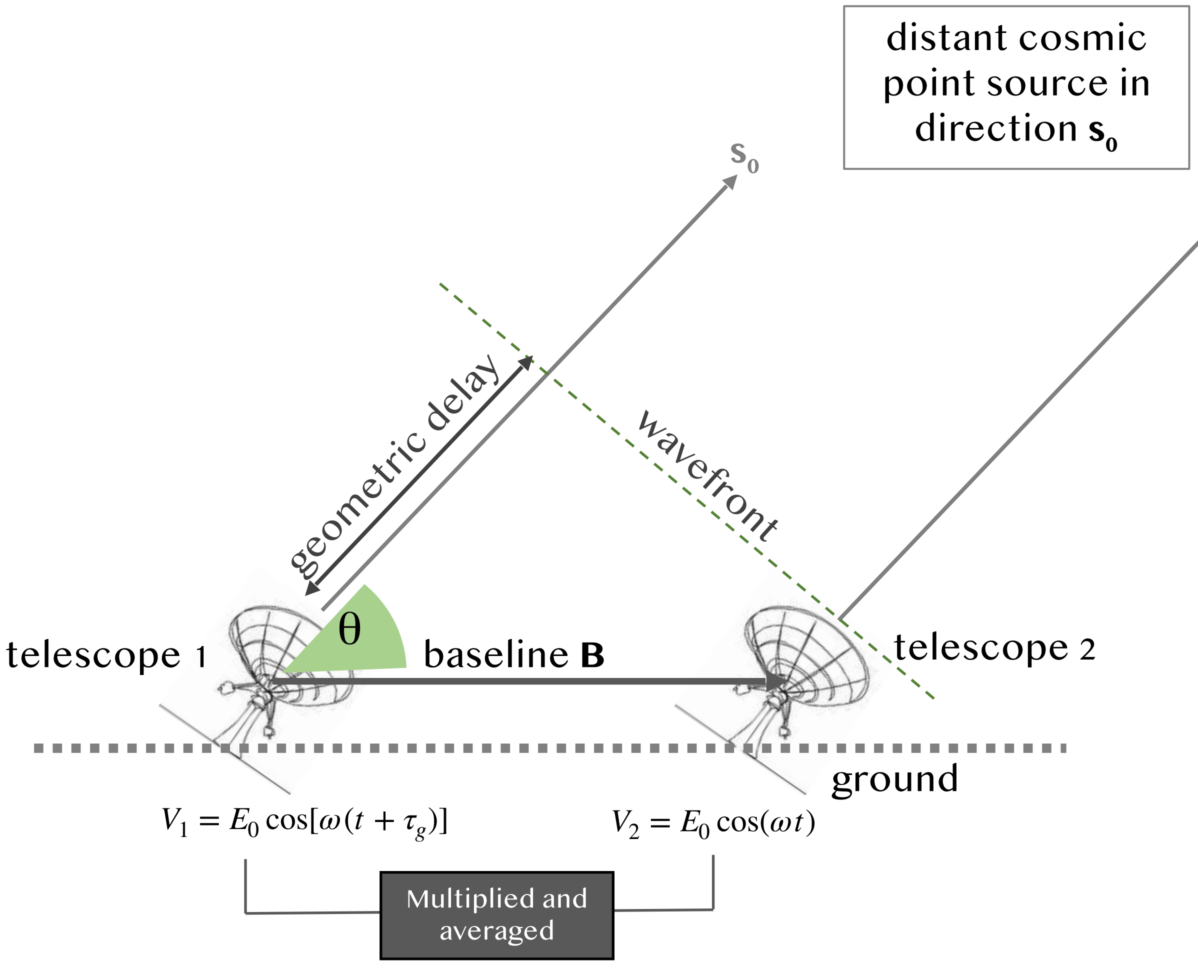
Combination (to form the image at the focus) is done electronically



Interferometers as fragmented mirrors



How it really works…



- Each telescope of the array acts as a **coherent sensor** of the incoming electric field **E**

- The **geometric delay** , τ_g , is:

$$\tau_g = \frac{\mathbf{B} \, . \, \hat{\mathbf{s}}_0}{c}$$

- The output of the interferometer is:

$$R_c = P_0 \cos(\omega \tau_g)$$

$P_0 = E_0^2/2$ is the received power in the EM wave

How it really works…

- If the source is not point-like,

$$R_c = \iint I(\hat{\mathbf{s}})\cos(\omega\tau_g)d\Omega$$

$I(\hat{\mathbf{s}})$ is the sky brightness

- By adding a $\pi/2$ phase delay to the output of telescope 2 before multiplying, we can get a complementary interferometer response:

$$R_s = \iint I(\hat{\mathbf{s}})\sin(\omega\tau_g)d\Omega$$

- The specialized hardware that produces R_c and R_s from the output of the telescopes is called a "correlator"

How it really works…

- We now **define** a new **complex** function R , by combining R_c and R_s :

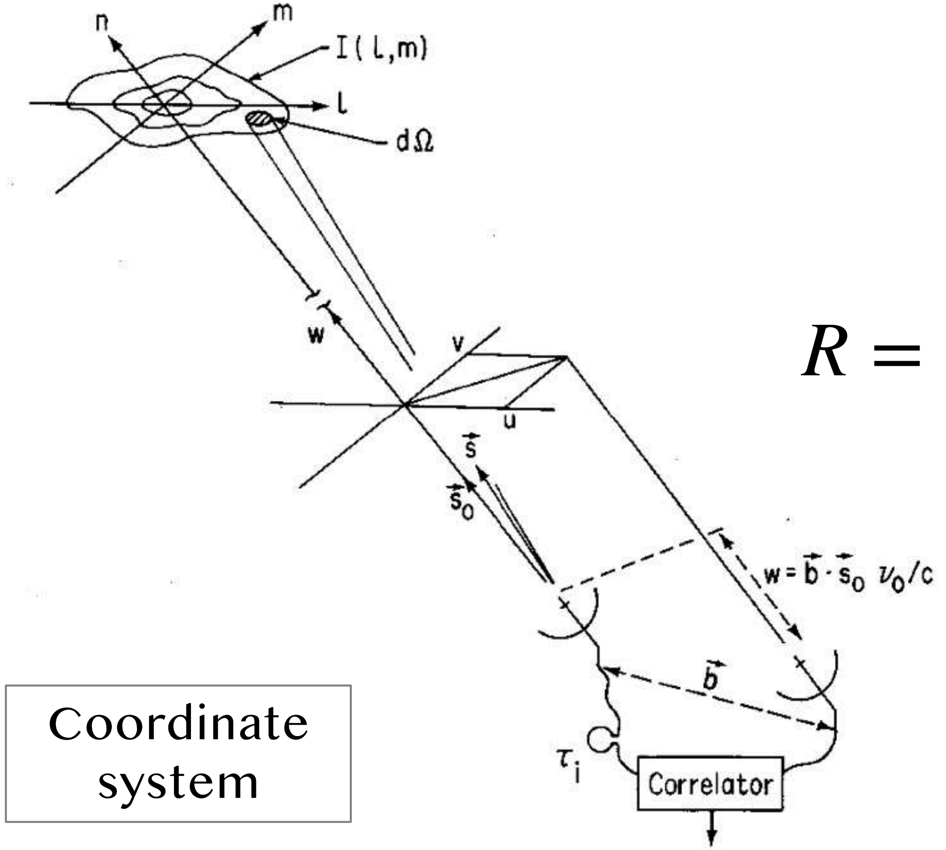
$$R = R_c - iR_s$$

- From the formulae of R_c and R_s , we see that:

$$R = \iint I(\hat{\mathbf{s}}) e^{-i\omega\tau_g} d\Omega = \iint I(\hat{\mathbf{s}}) e^{-2\pi i \mathbf{B}.\hat{\mathbf{s}}/\lambda} d\Omega$$

- Because R is a complex number, the specialized hardware that produces R (i.e. R_c and R_s) from the output of the telescopes is called a “complex correlator”

How it really works…



Coordinate system

$$e^{-2\pi i \mathbf{B}.\hat{\mathbf{s}}/\lambda} = e^{-2\pi i \mathbf{B}.\hat{\mathbf{s}}_0/\lambda} \,.\, e^{-2\pi i (ul+vm)}$$

$$R = e^{-2\pi i \mathbf{B}.\hat{\mathbf{s}}_0/\lambda} \iint I(l,m) e^{-2\pi i (ul+vm)} \frac{dldm}{\sqrt{1-l^2-m^2}}$$

Complex visibility function

Fundamental result

$$R = e^{-2\pi i \mathbf{B}.\hat{\mathbf{s}}_0/\lambda} \iint I(l,m) e^{-2\pi i (ul+vm)} \frac{dldm}{\sqrt{1-l^2-m^2}}$$

Response of the interferometer

$$V(u,v) = \iint I(l,m) e^{-2\pi i (ul+vm)} \frac{dldm}{\sqrt{1-l^2-m^2}}$$

Complex visibility function

Van Cittert-Zernike Theorem

Fourier Transform

$$I(l,m) = \sqrt{1-l^2-m^2} \iint V(u,v) e^{2\pi i (lu+mv)} dudv$$

Sky brightness

But, careful…

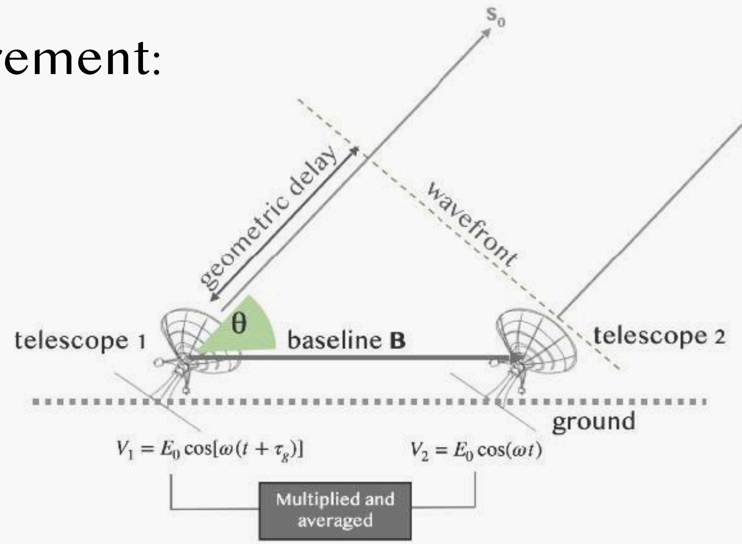
$$V(u,v) = \iint I(l,m) e^{-2\pi i(ul+vm)} \frac{dldm}{\sqrt{1-l^2-m^2}}$$

This is a **function** of (u, v)

$$I(l,m) = \sqrt{1-l^2-m^2} \iint V(u,v) e^{2\pi i(lu+mv)} dudv$$

This is a **function** of (l, m)

One measurement:



corresponds to one baseline : $\mathbf{B}$,

and therefore also to one value of (u_i, v_i)

(actually two points: also $(-u_i, -v_i)$ Including both baselines from telescope 1 to telescope 2 and from telescope 2 to telescope 1)

Summary

- The complex visibility function, $V(u, v)$, and the sky brightness, $I(l, m)$, are Fourier conjugates (van Cittert-Zernike Theorem).
- Measuring the visibility function and taking the inverse Fourier transform enables us to obtain the sky brightness.
- This is the (electronic and computational) process by which radio interferometers re-construct an image “in the focal plane” of the telescope they simulate.
- For each observation with two antennas, one only gets one the values of the complex visibility at two points (u_i, v_i) and $(-u_i, -v_i)$.