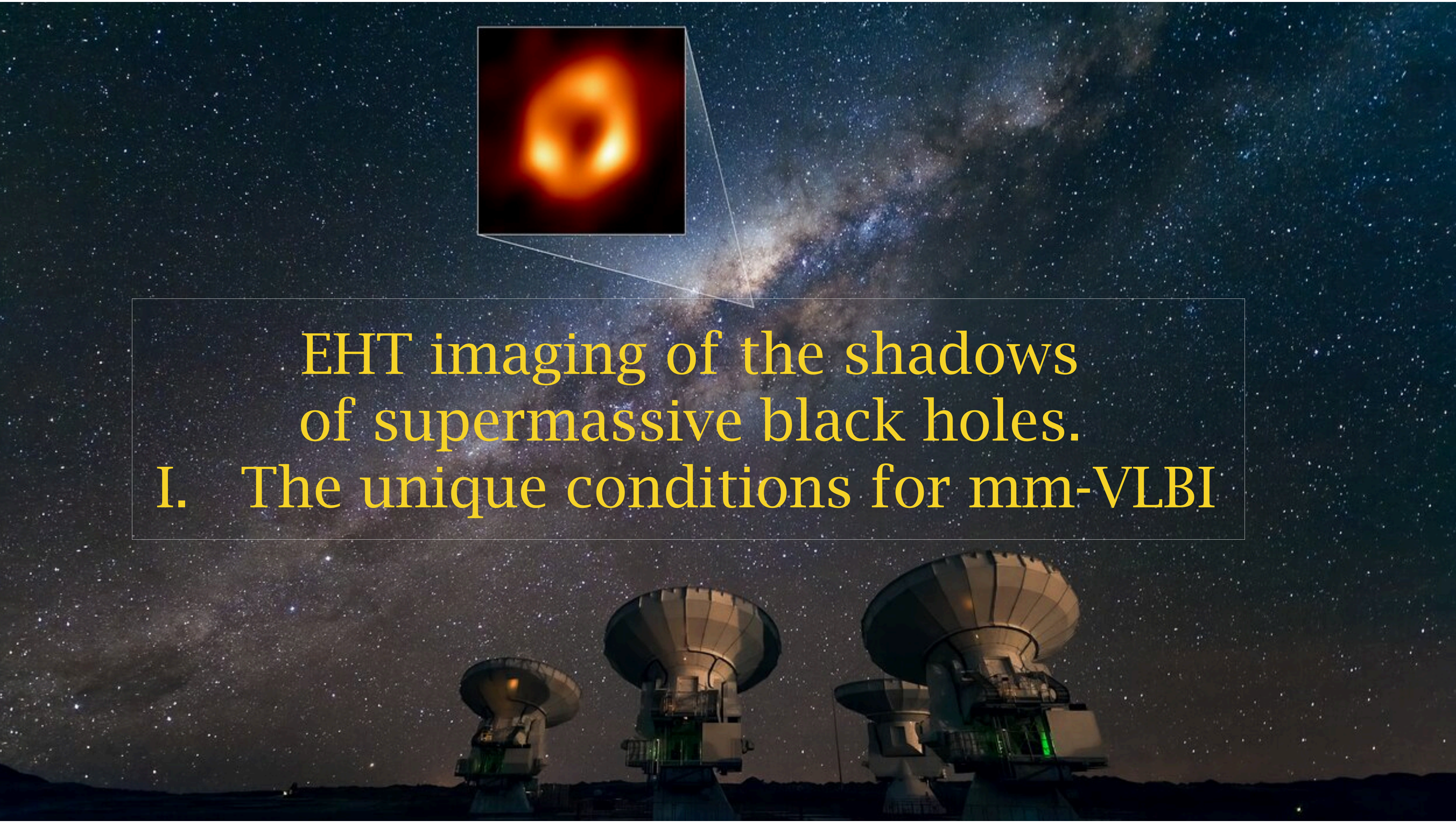


# EHT imaging of the shadows of supermassive black holes.

## I. The unique conditions for mm-VLBI

# Introducing

- Chief Scientist at JIVE:
  Joint Institute for VLBI ERIC
  - EVN: European VLBI Network
    - Consortium of (European) Telescopes operators
- Professor Galactic Radio Astronomy
  Sterrewacht Leiden, Leiden University
  - Oldest astronomy department in the world
- Affiliated staff
  University of New Mexico, Albuquerque
- Project Director Event Horizon Telescope

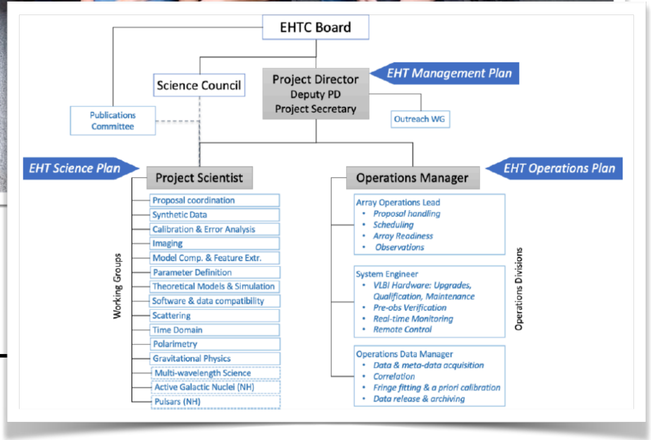
# Career path…

- 1981 study astronomy at Leiden
  - Computer science, experimental physics
- 1987 PhD project on OH maser stars in the Galactic centre
  - Field around SgrA*, VLA monitoring, VLBI measuring interstellar scattering
  - Algorithm research, visibility based continuum subtraction, MC radiative transfer masers
- 1992 postdoc on astrochemistry
  - Using the Owens Valley millimeter telescope
- 1994 postdoc/support at VLBA, New Mexico
  - Start interest on astrometry of masers
  - Developed VLBI scheduling software used for VSOP mission (still being used)
- 1997–2007 at JIVE, head of software, operations, user tools
- 2007–2017 JIVE director
  - Heading a small-sized observatory, now a European entity
- 2013– today Professor Galactic Radio astronomy at Leiden
  - teaching radio astronomy and practical astronomy
- 2020 – today EHT project director

# What is the EHT?

Event Horizon Telescope

- 400+ scientists in 19 countries
    - Consortium of 13 stakeholders
        - Associated with correlators and telescopes
        - but not ALMA
    - Run VLBI telescope 2 weeks/year
    - But also organise the science process
- Complex project
    - Internal structure
        - Board
        - Management Team
        - Science Council
        - Working Groups
            - Including the Publication WG
            - Deciding on papers scope, authorship, status
    - Many cultures and ambition levels
        - Mixed funding arrangements
        - Many time zones



EHTC Board

Science Council

Project Director
Deputy PD
Project Secretary

EHT Management Plan

Publications Committee

Outreach WG

EHT Science Plan

Project Scientist

Operations Manager

EHT Operations Plan

Working Groups

- Proposal coordination
- Synthetic Data
- Calibration & Error Analysis
- Imaging
- Model Comp. & Feature Extr.
- Parameter Definition
- Theoretical Models & Simulation
- Software & data compatibility
- Scattering
- Time Domain
- Polarimetry
- Gravitational Physics
- Multi-wavelength Science
- Active Galactic Nuclei (NH)
- Pulsars (NH)

Operations Divisions

Array Operations Lead
- *Proposal handling*
- *Scheduling*
- *Array Readiness*
- *Observations*

System Engineer
- *VLBI Hardware: Upgrades, Qualification, Maintenance*
- *Pre-obs Verification*
- *Real-time Monitoring*
- *Remote Control*

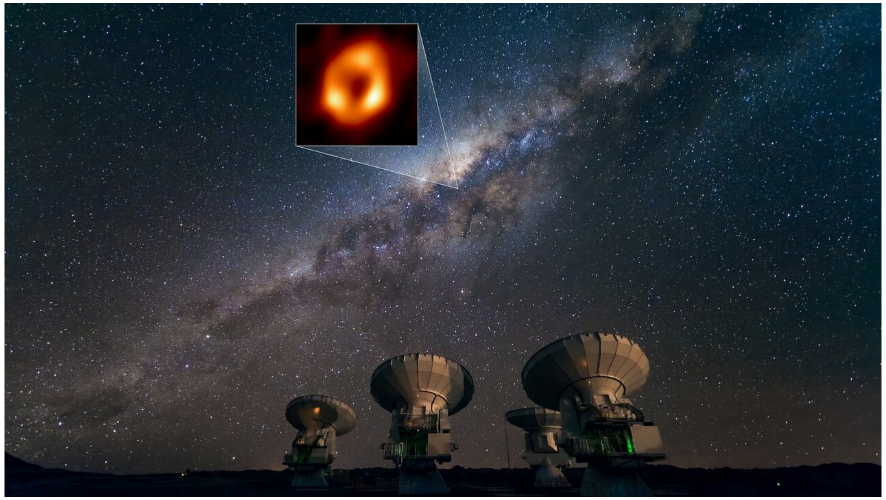
Operations Data Manager
- *Data & meta-data acquisition*
- *Correlation*
- *Fringe fitting & a priori calibration*
- *Data release & archiving*

# Outline

- Overall Objective
  - Introduce the practices of the EHT:
  - facilitating a critical look what it takes to measure the shadow of supermassive black holes

- Today: Understanding the special astronomical circumstances that allow us to resolve 2 black hole shadows
  - History, the central engine puzzle
  - Optically thin view of centers of AGN
  - Synchrotron emission is bright enough for VLBI
  - The earth can support mm-VLBI at sufficient resolution
  - Results so far, variability differences

- Later lectures
  - Synthesis imaging, understanding the visibility data
  - Instrument implementation, calibration, polarisation
  - Interpretation, calibrating gravity



# Who are you?

- Assume you are physics students with basic knowledge of astronomy
  - Yes?: Galaxies, Fourier transforms, kpc
  - No?: Radiative processess, Radio loud Active Galactic Nuclei, VLBI telescopes

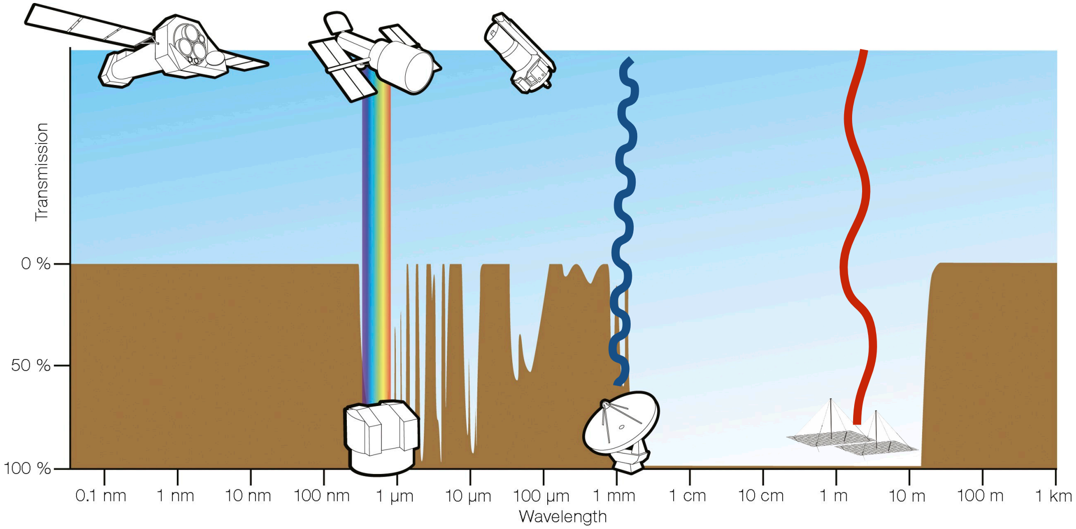
- Must communicate:

QUESTIONS PLEASE!

  - Type 1: Can you explain more?
  - Type 2: That is interesting, does it imply that…?

# Radio Astronomy - Unobscured

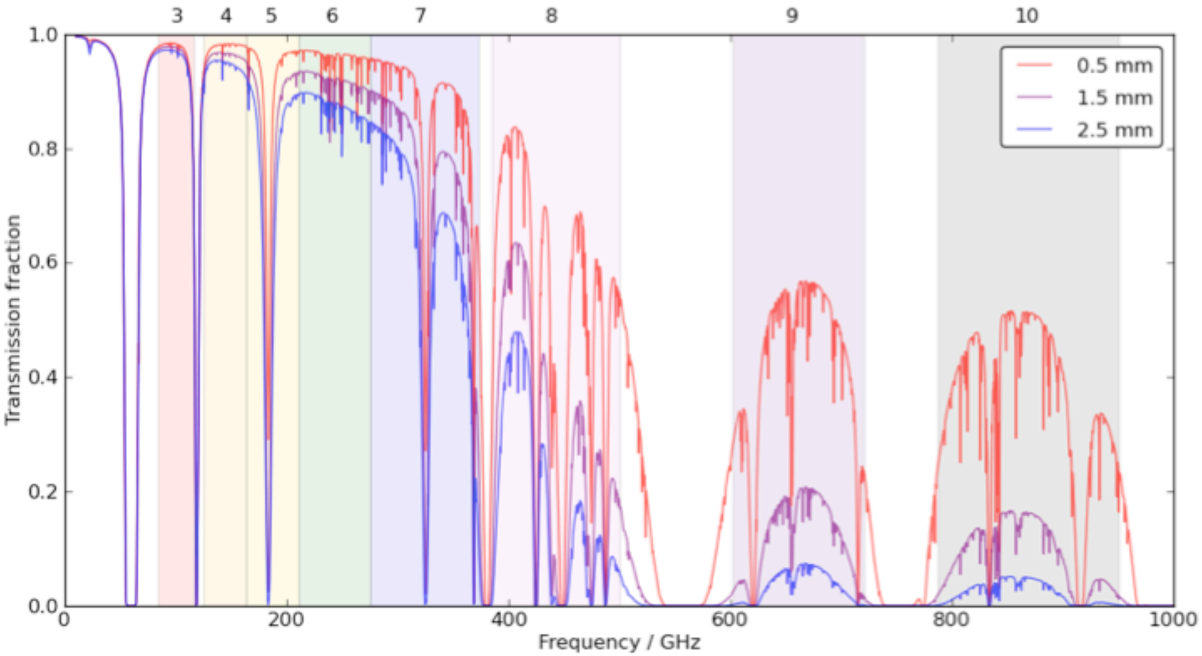
- Radio waves travel freely through space
    - Not affected by “dust”
        - As dust is much smaller than radio waves
    - Molecules come in at FIR
    - But radio affected by free electrons
        - When $\nu$ goes below plasma frequency, typically $n_e=0.03\ \mathrm{cm}^{-3} \Rightarrow 0.3\mathrm{kHz}$
- And through a large window in the atmosphere
    - Except in ionosphere the electron are more abundant
        - $n_e=10^6\ \mathrm{cm}^{-3} \Rightarrow \nu = 10\mathrm{Mhz}$
    - High end cut-off by molecules
        - Go to high sites, like ALMA
- But low frequency, long wavelengths
        - Factor $10^6$ longer waves compared to optical
    - Carry little energy, not much signal
        - For small, thermally emitting objects like stars
    - Low resolution even with big telescopes



But, at least they can be treated as waves..

# Shortest wavelengths

- Must go to very high dry sites
  - ALMA is “half way space”
- Can do 1mm or even sub-mm
- ALMA was a game changer!
  - But was not obvious it would do VLBI…



# Early days of radio astronomy

- James Clerk Maxwell develops the laws of electro-magnetism (Maxwell's laws) that show that radiation can span a wide-range of frequency (1865)

Heinrich Hertz became the first person to artificially generate waves of a different wavelength from those of NIR/ visible light (1886).

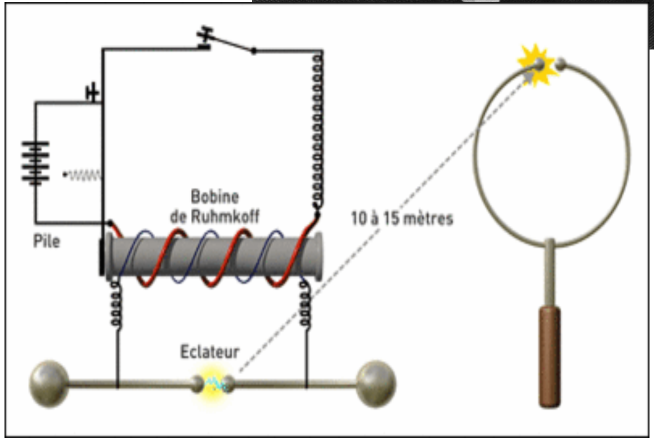
$$\nabla \cdot D = \rho$$

$$\nabla \cdot B = 0$$

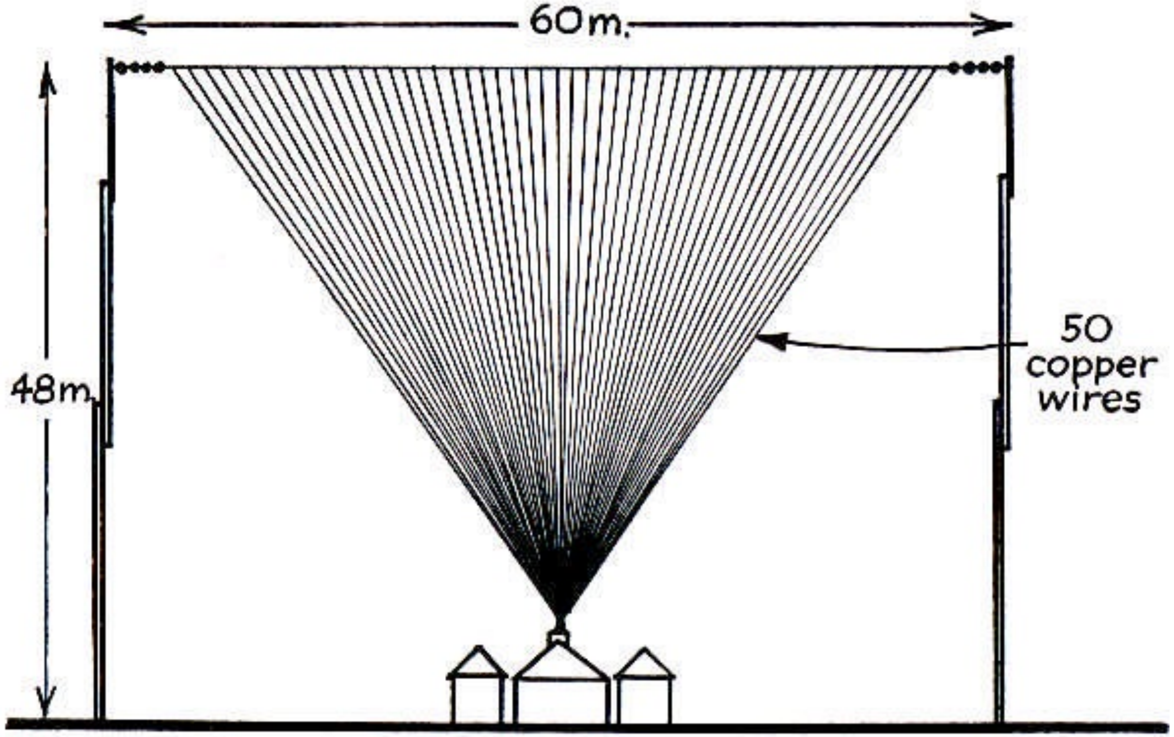
$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

*James Clerk Maxwell*



# Early Antenna Arrays (1900)

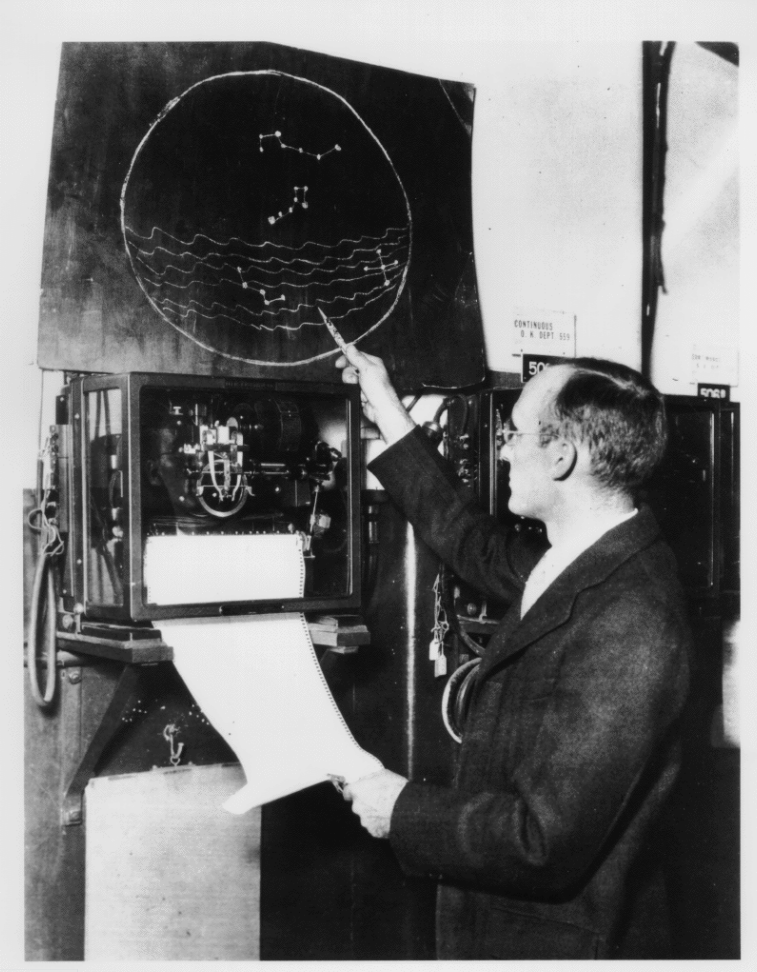


Centrally fed ground antennas - G. Marconi (1901)

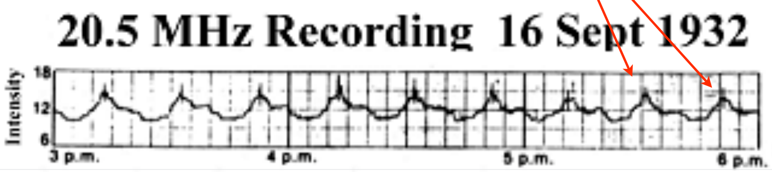
Marconi testing the new and exclusive microwave system from Sant Margerita to Levanto (photo: L'illustazione Italiana 1929)

# Early days of radio astronomy

1932 Discovery of cosmic radio waves
Karl Jansky:



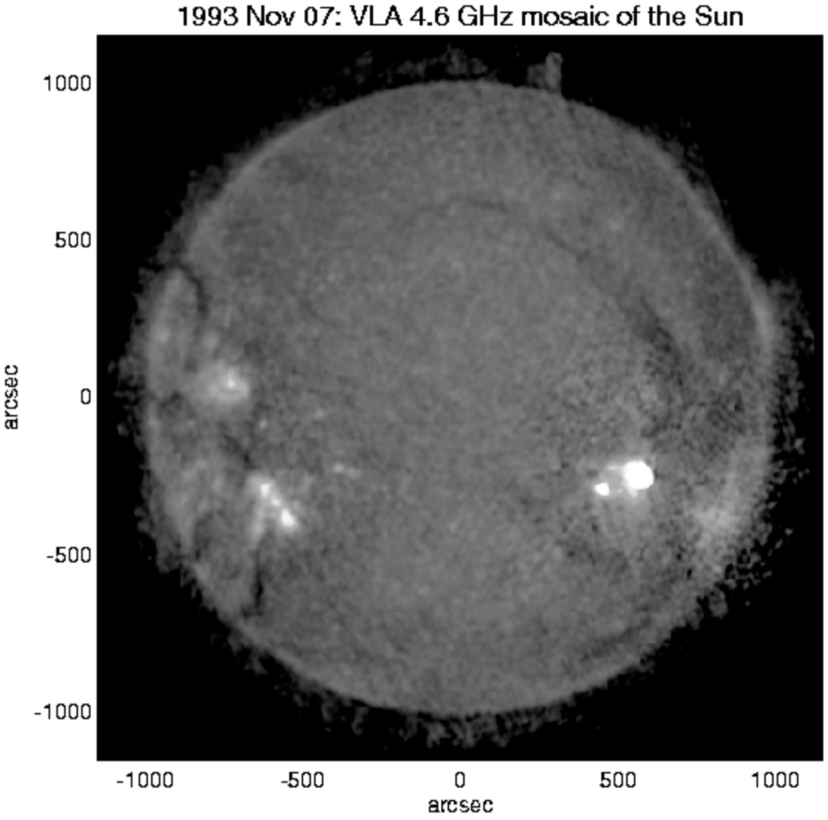
Galactic centre



Skepsis: requires something of $2\ 10^5$ K covering many square degrees in the sky

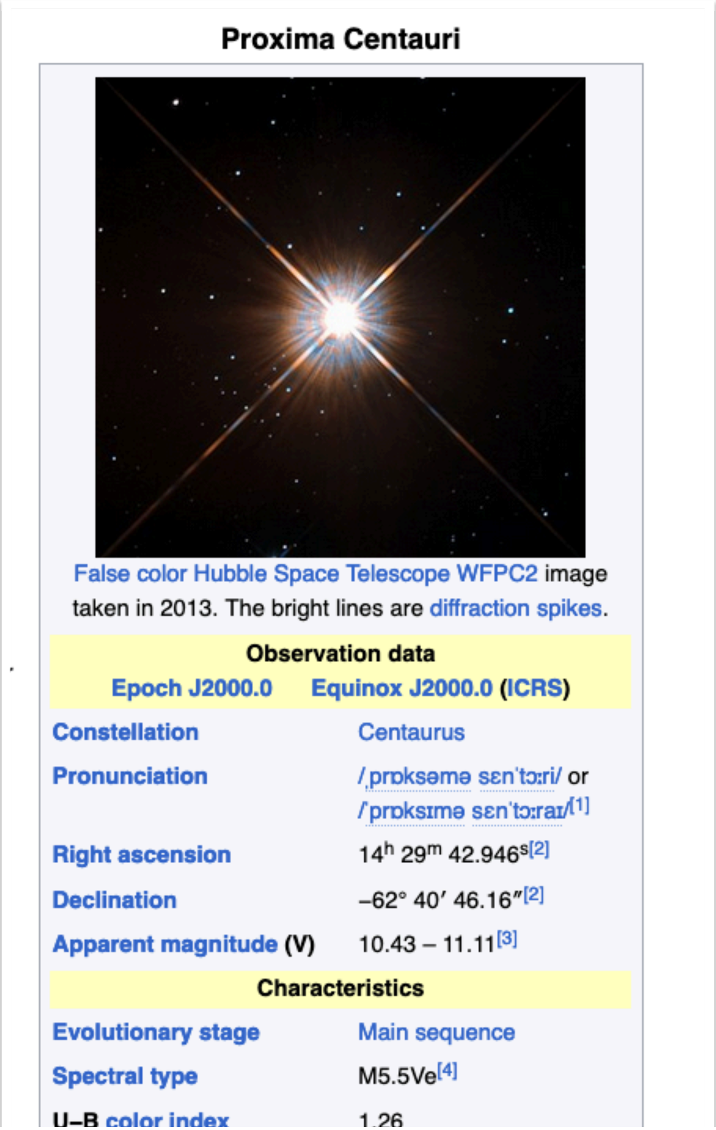
# Radio astronomy was a surprise

- As almost all we see shine in optical are stars
  - Close nebulas are in fact heated by stars
  - Other galaxies? Only established after ‘Great debate” in 1920
- Do some numbers with that knowledge
  - Observe at 1GHz = 30cm
  - Assume the Sun is a black-body at 5770K
  - Observe it with the Dwingeloo telescope
    - Note: its beam at 1 GHz = $0.8^0$
  - Yields 12000Jy = 12,000 $10^{-26}$ W $m^{-2}$ $Hz^{-1}$
  - Power received: 5 $10^{-14}$W for bandwidth of 1MHz
- The current in antenna receiver:
  - approximately 0.03μA
  - But at a frequency where you can operate an amplifier
    - Like in your mobile phone, 50dB does the trick



# But this was at 8 light-min, next star…

- Put the sun at 1pc
  - Same calculation, now with much smaller beam
  - Or simply divide everything by (1 pc/1 AU)$^2$
- Normal, thermally emitting star: $0.3\mu\mathrm{Jy}$
  - Very hard to do, even nowadays
  - Bit better if you go up the Planck curve
- So (normal) stars are not (yet) the favourite targets
- Need something that is a bit bigger on the sky
  - Example: interstellar clouds
- Or something that appears to be a lot hotter
  - Non-thermal emission from “exotic” processes
- Or move up the RJ law by going to (sub)mm
    - Clouds the size of planetary systems can be detected at 10 - 100 K



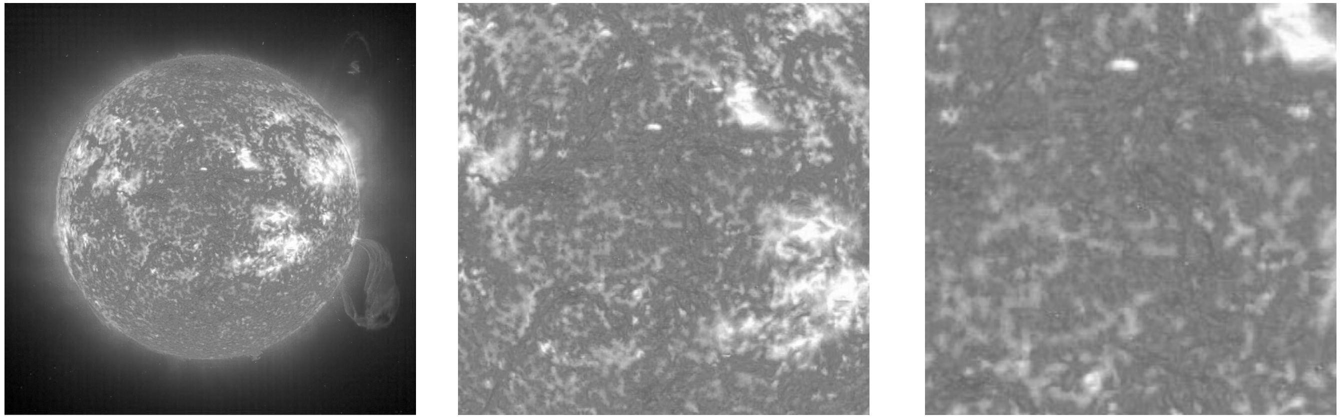
**Proxima Centauri**

False color Hubble Space Telescope WFPC2 image taken in 2013. The bright lines are diffraction spikes.

| Observation data | |
|---|---|
| Epoch J2000.0 | Equinox J2000.0 (ICRS) |
| **Constellation** | Centaurus |
| **Pronunciation** | /ˌprɒksəmə sɛnˈtɔːri/ or /ˈprɒksɪmə sɛnˈtɔːraɪ/[1] |
| **Right ascension** | $14^{h}\ 29^{m}\ 42.946^{s}$[2] |
| **Declination** | −62° 40′ 46.16″[2] |
| **Apparent magnitude (V)** | 10.43 – 11.11[3] |
| **Characteristics** | |
| **Evolutionary stage** | Main sequence |
| **Spectral type** | M5.5Ve[4] |
| **U−B color index** | 1.26 |

# Flux vs Intensity

- Specific Intensity is an intrinsic property of the source,
- Flux density depends on the distance
  - As the solid angle of the source decreases
  - If it is smaller than the telescope beam: “beam dilution”



- Specific intensity can be measured on earth
  - Relates to the radiation physics
  - If the radiation reaches us without absorption, scattering
- Brightness temperature + LTE + optically thick = $T_{kin}$
  - Assumption of optically thin necessary to measure column density

# From intensity to detected energy

- Accumulate specific intensity (for up to 2 polarisation components) over time, frequency, solid angle

$$dE = I_\nu \cos\theta \, d\sigma \, d\Omega \, dt \, d\nu$$

- Integrate Specific Intensity to get Flux density
  - Express Flux density as Jy (not to be called flux)
  - 1 Jy = $10^{-26}$ W $m^{-2}$ $Hz^{-1}$
  - Specific Intensity as Jy/beam (also spectral intensity, spectral brightness)

$$S_\nu = \int I_\nu \, d\Omega$$

- Difference is the beam solid angle
  - Set by the telescope (i.e. unresolved object)
  - Or by the astronomical body (resolved object)
- Relates in turn to receiver temperature of telescope

| | | radians | steradian |
|---:|---|---:|---:|
| 1 | deg | 1.75E-02 | 2.39E-04 |
| 1 | arcmin | 2.91E-04 | 6.65E-08 |
| 1 | arcsec | 4.85E-06 | 1.85E-11 |
| 1 | mas | 4.85E-09 | 1.85E-17 |

# Radiative transfer and brightness temperature

- Basic equation defines absorption and source

$$\frac{dI_\nu}{ds} = -\kappa I_\nu + j_\nu$$

- Defining optical depth:

$$\frac{dI_\nu}{d\tau_\nu} = I_\nu - B_\nu(T)$$

  - Note that optical depth has only meaning at specific frequency
- In Rayleigh Jeans approximation:
  - Remember: $h\nu/kT << 1$ $e^{h\nu/kT} \sim 1 + h\nu/kT + ...$ $B_\nu = \frac{2h\nu^3/c^2}{e^{h\nu/kT}-1} \Rightarrow B_\nu \approx \frac{2kT\nu^2}{c^2}$

-

$$\frac{dT_b}{d\tau_\nu} = -T_b + T$$

# Simple solution

- Which has the formal solution

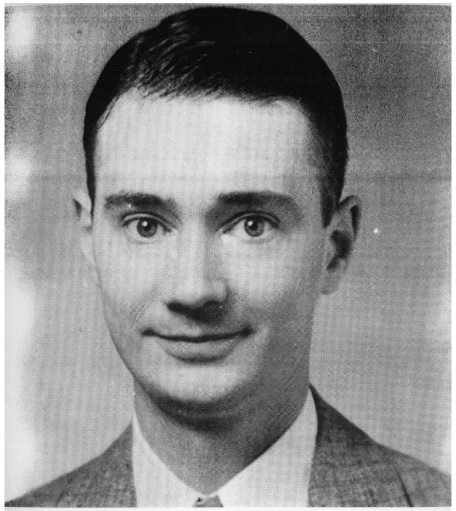
$$T_b = T_{ex}(1 - e^{-\tau_\nu}) + T_{bg} e^{-\tau_\nu}$$

  - So, the brightness temperature starts ($\tau$=0) at some background $T_{bg}$
  - And approaches the (excitation) temperature ($\tau$=∞)
  - This in turn is the kinetic temperature when LTE can be assumed

$$T_{ex} \approx T_{kin}$$

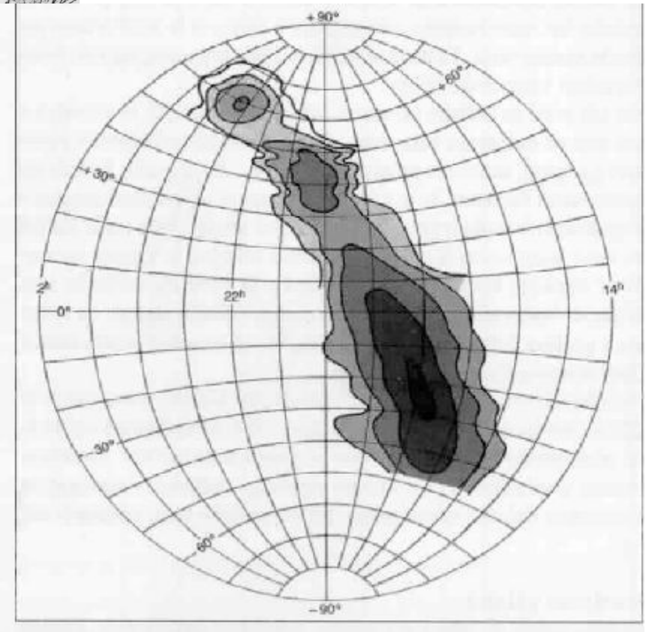
- Lot of detailed physics hidden in $\tau_\nu$
  - But when $\tau$=0 the brightness is constant
    - Brightness is an observable that is distance independent
    - Can be measured (and interferometers are good at that)
  - When optically thick: measure Temperature at $\tau$=1
    - Spectrum depends on $\tau(\nu)$
    - And $T(\tau)$: the temperature structure along line of sight

# Grote Reber (1911-2002); the first radio astronomer



–Grote Reber, about 1937.

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



Built the first parabolic radio telescope:
- "Good" angular resolution
- Good visibility of the sky
- Published his results in ApJ
- Multi-frequency observations

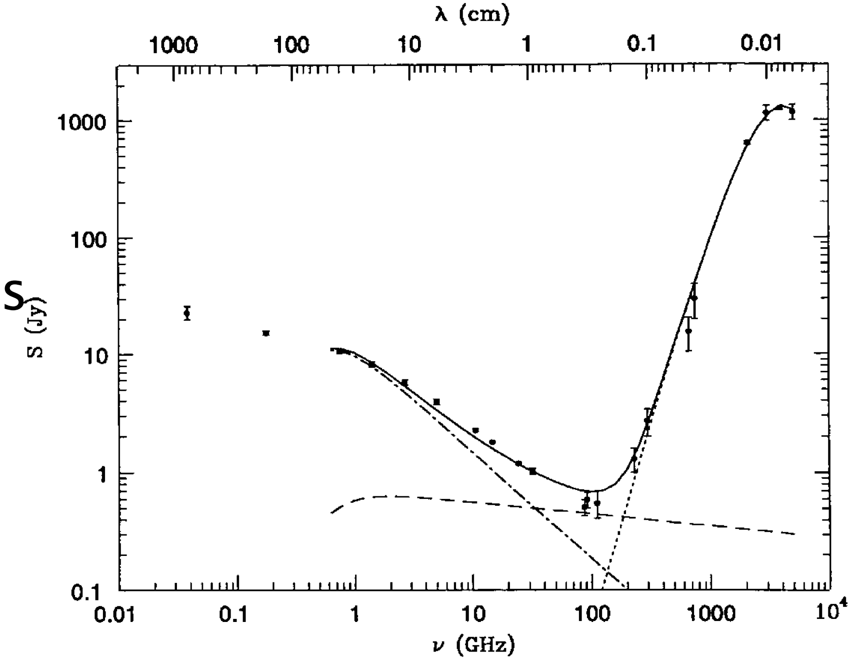
# Emission mechanism

$$B_\nu = \frac{2kT}{\lambda^2} = \frac{2kT\nu^2}{c^2}$$

- Thermal emission: radio is in the Rayleigh Jeans tail
  - Example: Sun = 5600K, and $6\ 10^5$km at 1 pc: 1μJy at 1 GHz
  - Need much brighter/much larger objects

- RJ tail of galaxy dominated by dust:
  - Very small particles, large areas
    - Such that high frequency heating must be re-emitted in the IR
- Flattens at millimeter:
  Large scale ionised medium: free-free emiss
    - HII regions
- Then taken over by synchrotron
    - Relativistic electrons accelerated in large scale magnetic field
    - Originating from non-equilibrium events
    - Reach equivalent (RJ) temperatures of $10^9$K…
    - (Self-) absorbed at lowest frequencies

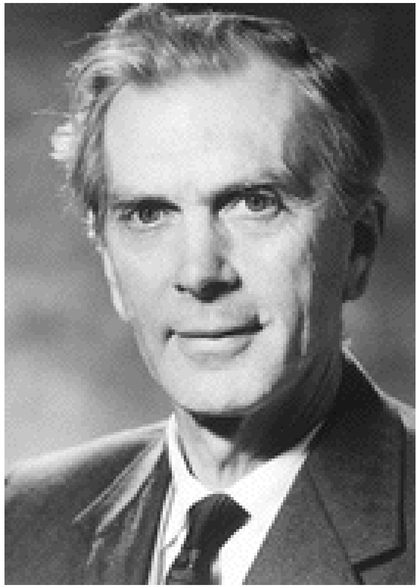
- Dominating the radio sky!



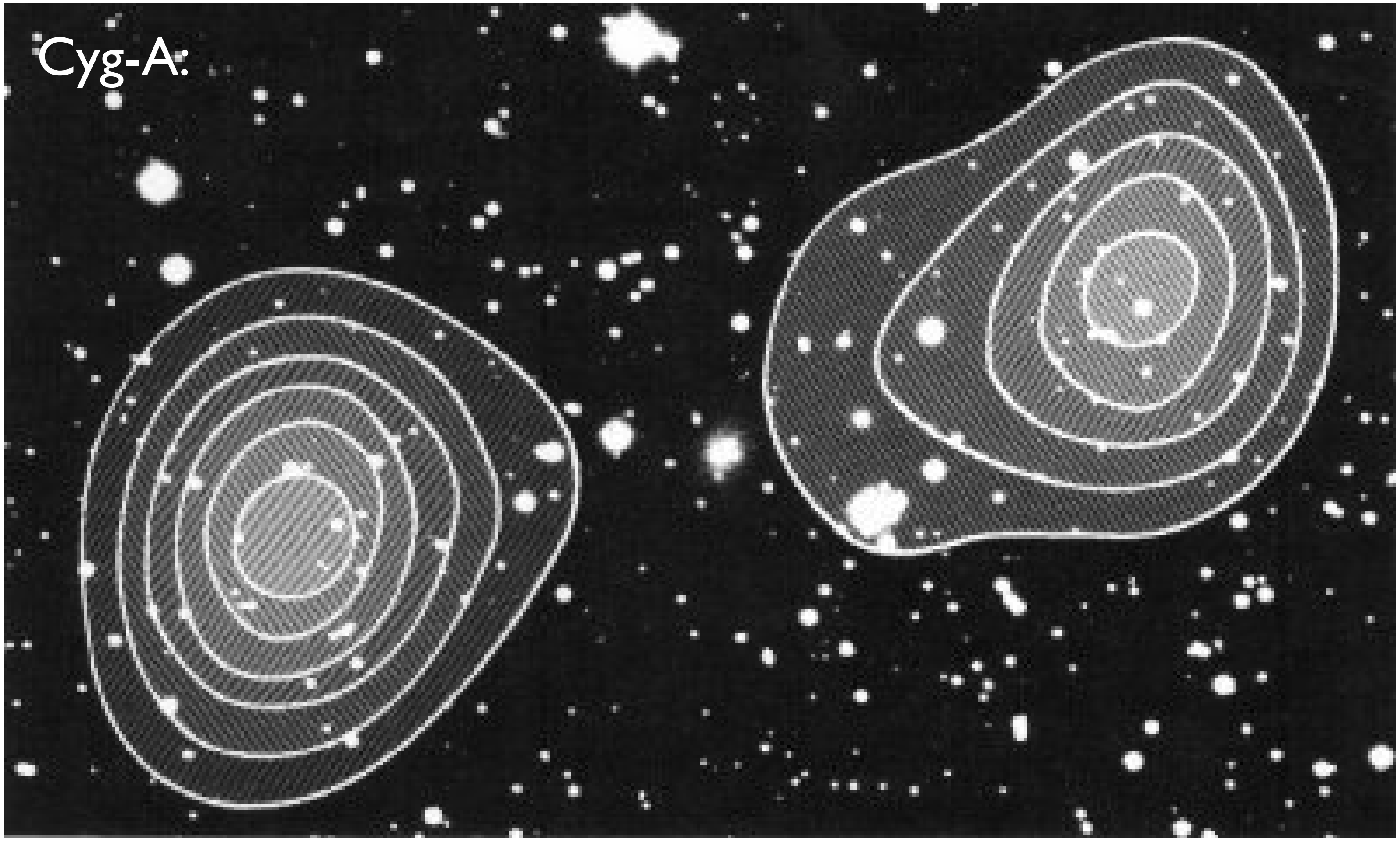
The radio and far-infrared spectrum of the nearby starburst galaxy M82: dust, free-free and synchrotron

# Radio interferometers

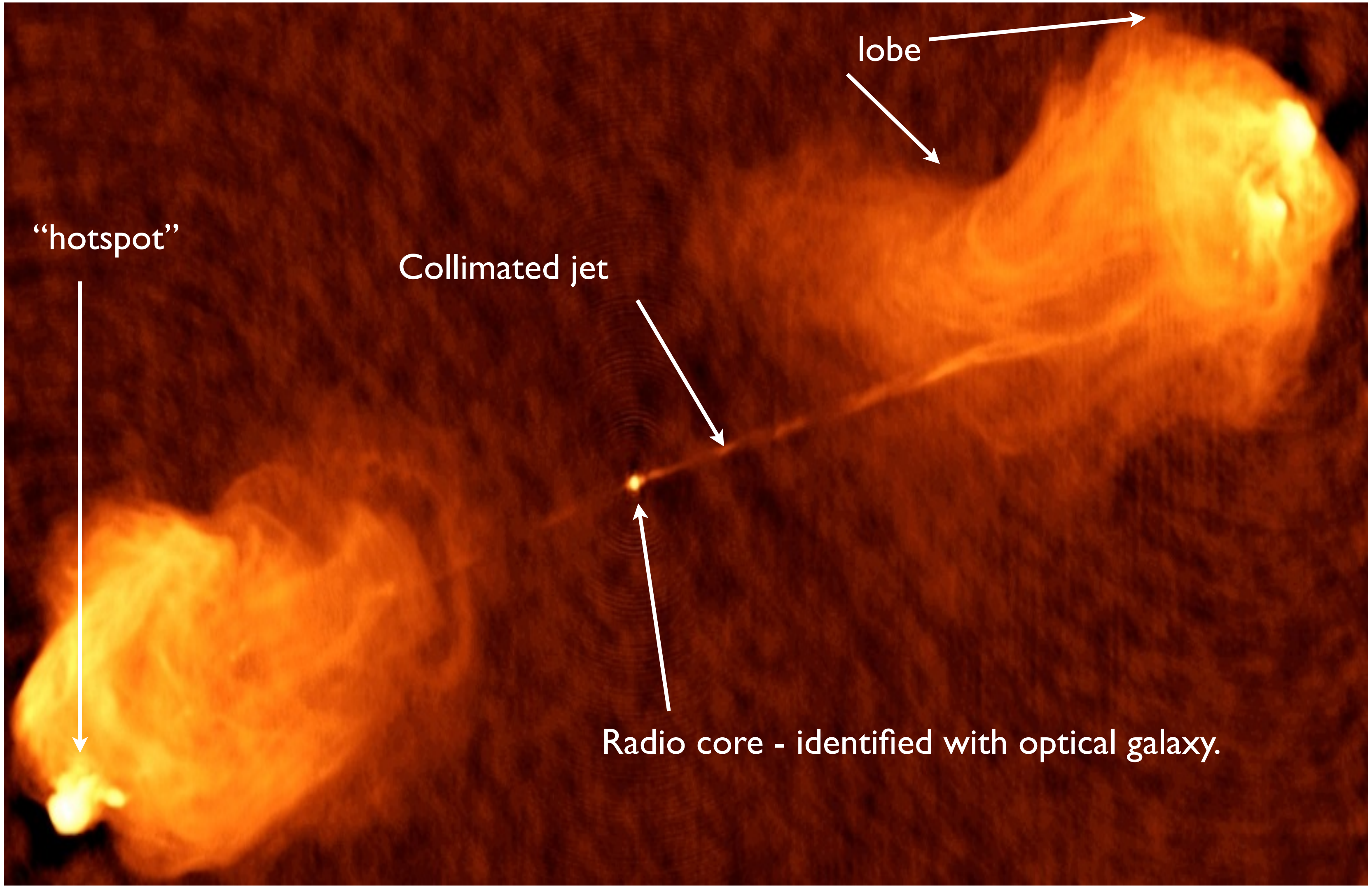
In the 1950's the first radio arrays (interferometers) were constructed. People like Martin Ryle (pictured) pioneered the the interferometry technique, receiving the Noble Prize in 1974 for developing the concept of aperture synthesis (see lecture 4).



In 1954 interferometer measurements showed that the radio emission from one of the brightest sources in the sky, Cyg-A came from bright regions on either side of a host galaxy.



As interferometers began to survey hundreds of bright radio sources, many of them exhibited this "classical double-structure".



“Modern” (1990!) VLA image of the radio galaxy Cyg-A

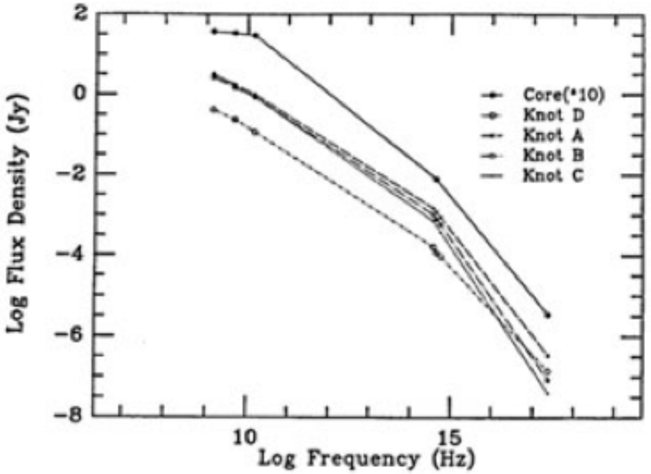
# AGN Energy crisis

- Cygnus A is blowing radio lobes
  - Distance of CygA = 230Mpc (cosmological scale)
  - Radio lobes are at 30kpc radius ⇒ this has lasted at least 30,000 yr!
- Synchrotron radiation: relativistic electrons in magnetic fields
  - Flux of CygA is $S_\nu = 3000\mathrm{Jy}(\frac{\nu}{1\mathrm{GHz}})^{-0.8}$, where 1 Jy = $10^{-26}$ W $m^{-2}$ $Hz^{-1}$
  - Very little energy reaches our telescopes, but the total energy is enormous
  - Integrate from 10MHz to 100GHz, and use $L = 4\pi d^2 \int S_\nu d\nu$
  - 3.5 $10^{11}$ $L_\odot$ ! same as entire Galaxy (and this is only radio)
- This requires converting 0.5 $M_\odot$/yr into energy at 5% efficiency…
  - For direct conversion $E=mc^2$
- And if it comes from single object, stationary, we need to worry about Eddington limit:
    - There is a minimum mass for certain energy production
    - Or it will be blown apart
  - At least $10^7$ $M_\odot$ object required to gravitationally balance radiation pressure

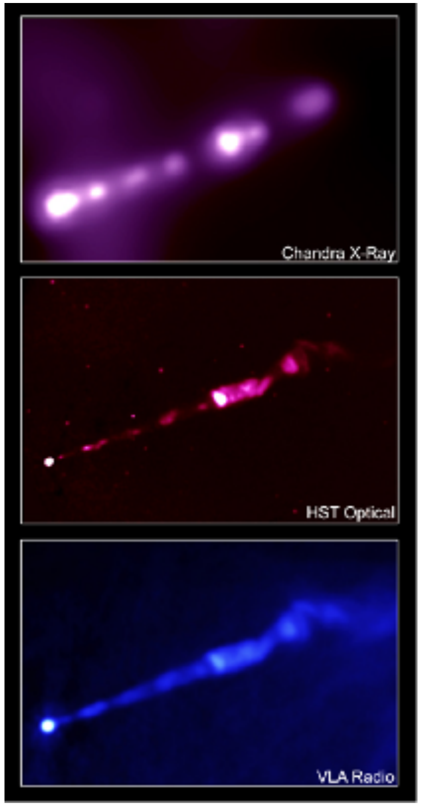
$$(\frac{L_E}{L_\odot}) \approx 3.310^4(\frac{M}{M_\odot})$$

# Non-thermal synchrotron emission

- Synchrotron emission is associated with the acceleration of (ultra-)relativistic electrons in magnetic fields
  - Energy emitted depends on magnetic field and electron energies
- Synchrotron emission is observed in AGN at radio, IR, optical, UV and even X-ray wavelengths



The spectrum of the source across these wavelengths is a steep power-law and reflects the power-law that describes the energy distribution of the electrons

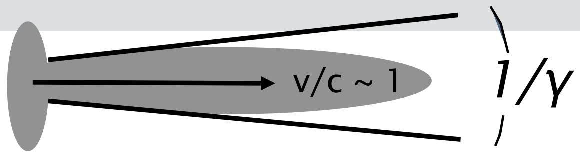


Synchrotron emission observed in Virgo-A (M87)

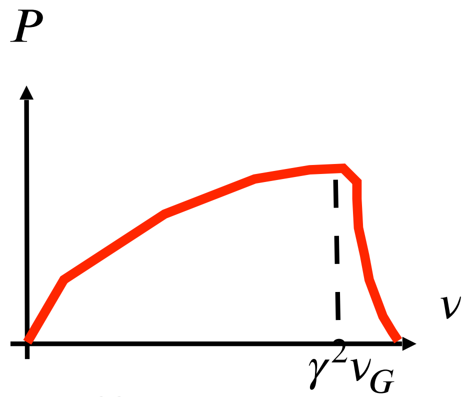
# Synchrotron particularities

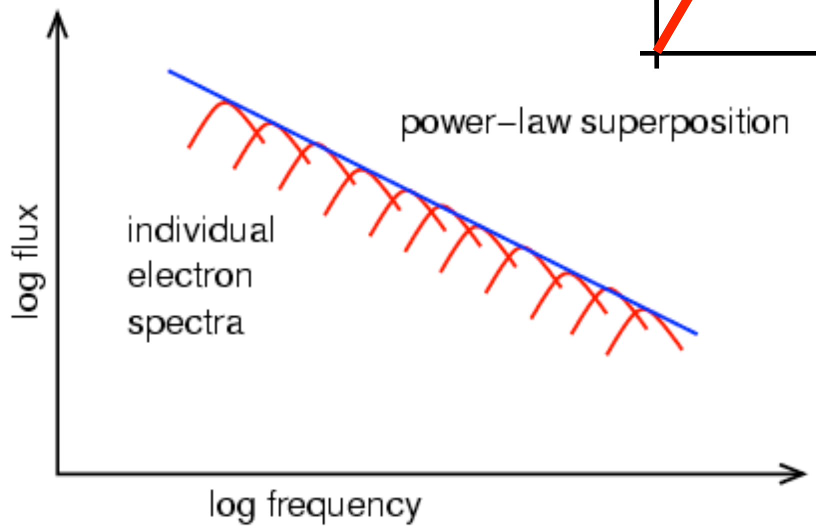
- Relativistic effects: $m = \gamma m_e$ and $E = \gamma m_e c^2$
  - power pattern of the electron beamed ≈ 1/γ
  - Frequency pattern electron depend on E
  - In practice power spectrum of energies

- Large scale magnetic fields are involved
  - Source will polarised
  - Beam depolarisation can occur when small scale



*relativistic electron dipole pattern*
$(\gamma \gg 1)$





after Shu, Fig. 18.4

# Common radio emission processes

| λ | Spectral line | Continuum |
|---|---|---|
| m, cm and mm | Neutral Hydrogen (HI) 21cm fine structure line: neutral gas<br>Hydrogen recombination lines: ionized gas<br>OH, $H_20$, SiO Masers: dense, warm molecular gas<br>Molecular rotation lines: cold molecular gas | Thermal Bremsstrahlung (free-free emission): HII regions<br>Synchrotron Radiation: Jets in radio galaxies, pulsars, shocks in supernovae, cosmic ray electrons in the magnetic fields of normal galaxies etc., acceleration of electrons in stellar and planetary systems<br>Thermal emission from dust: cold, dense gas |
| sub-mm (and FIR) | Molecular Rotation Lines: warm, dense gas<br>Solid State features (silicates): dust<br>Hydrogen recombination lines: ionized HII regions | Thermal emission - warm dust |

# The radio sky is dominated by bright radio galaxies in far universe

Radio sky over Green Bank radio telescopes

Moon to scale on LOFAR field

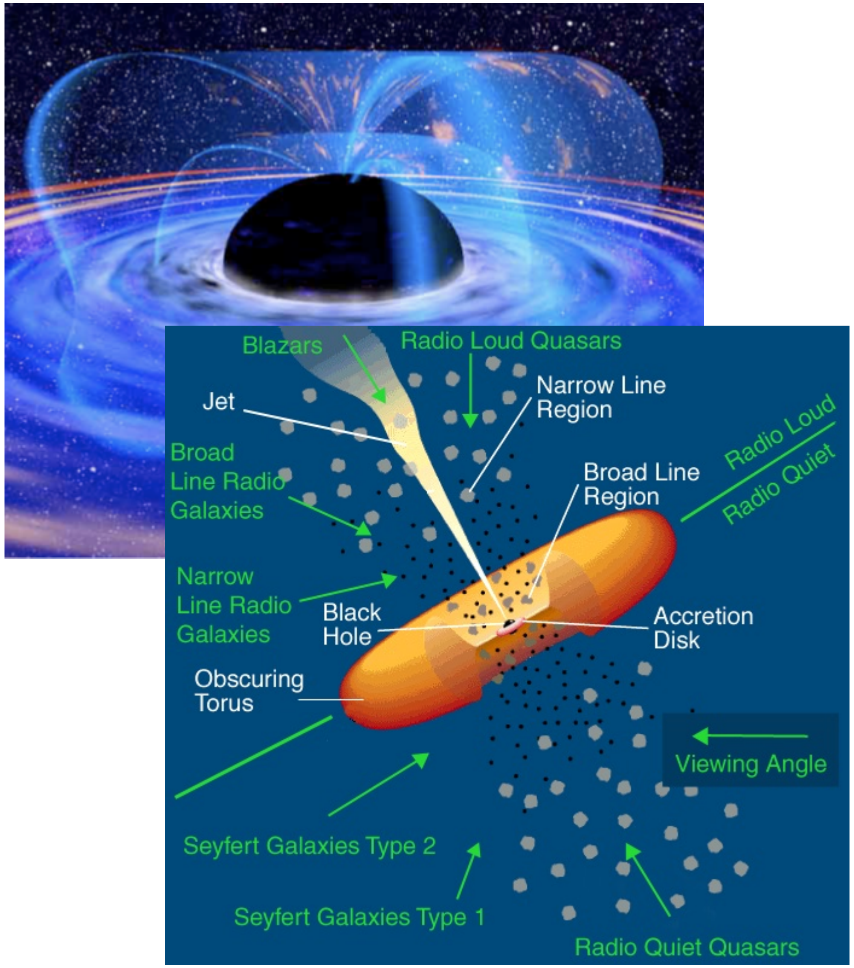
# Active Galactic Nuclei come in varieties

- Low activity AGN (radio quiet)
  - Mainly spirals (Sa-c)
  - Some disturbed morphology E/S0 galaxies

- High activity AGN (radio quiet)
  - Mainly E/S0 galaxies
  - Some spirals

- Radio loud AGN
  - Massive ellipticals

- Likely due to a difference in black hole mass
- Unified by orientation?



**The standard representation of the unified model of AGN**

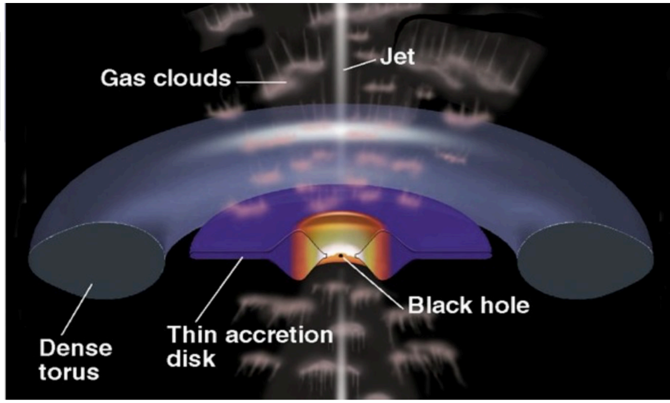
# Types of radio-loud AGN

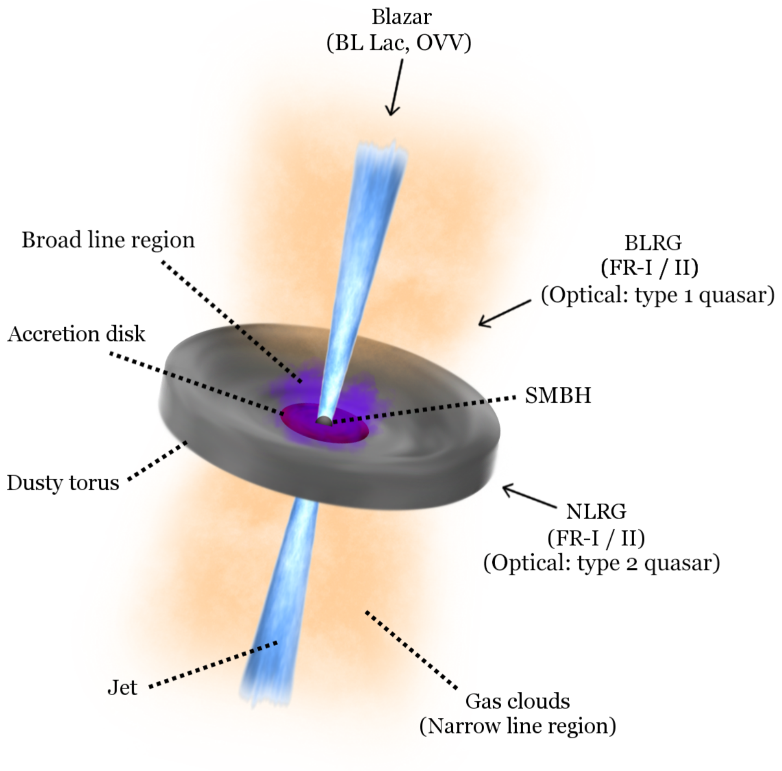
- Looking down the barrel of the jet (θ = few degrees) we see spectral continuum over all wavelengths e.g. no spectral lines in BL Lacs

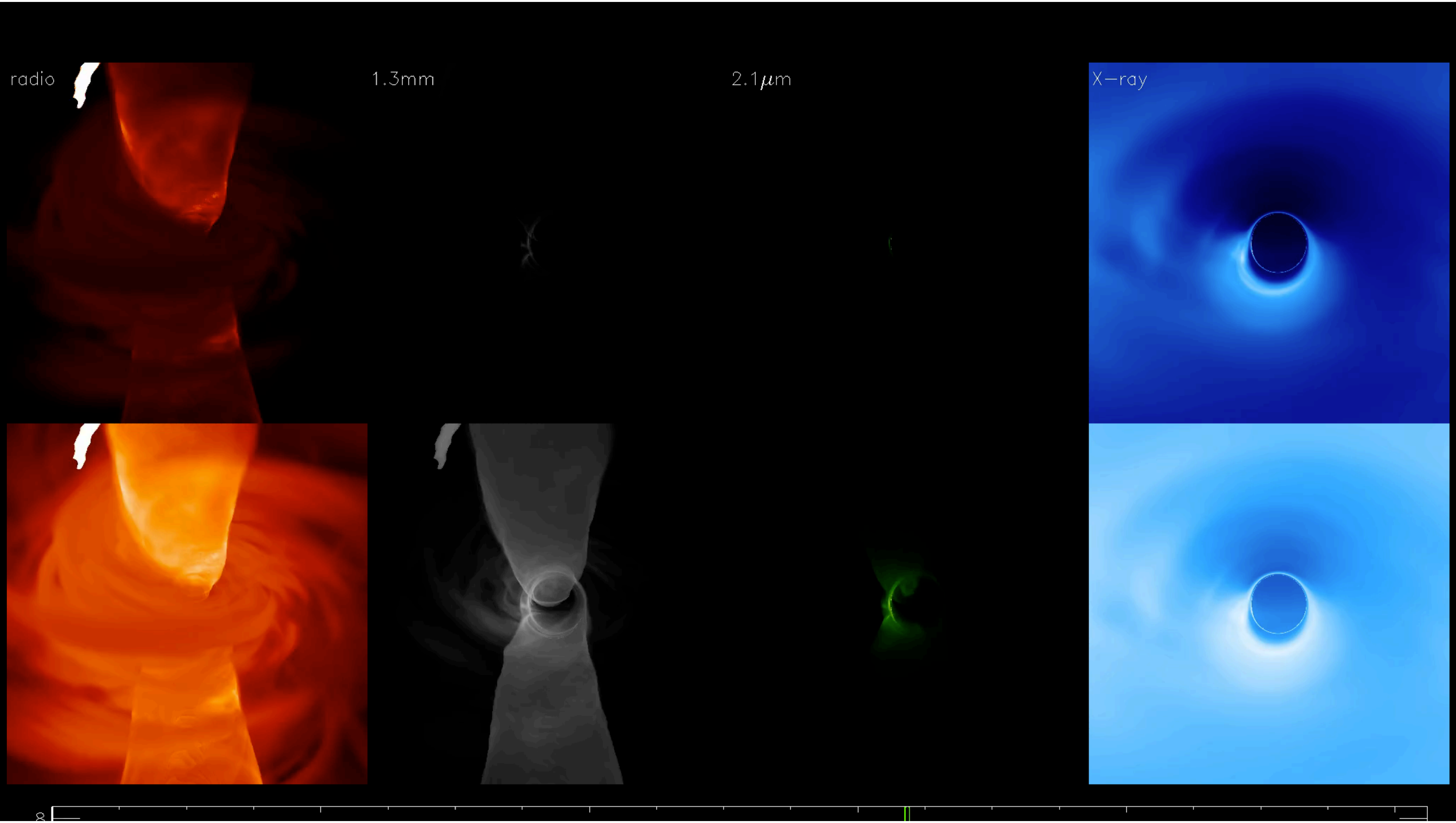
- At small angles (~15 degrees), a one sided jet is observed. Broad and narrow line emission may also be seen in the optical

- When the jet is close to the plane of the sky (~75 – 90 degrees) we see a two sided radio galaxy

- When viewed in the plane of the sky they take two (morphological) forms, FR I and FR II





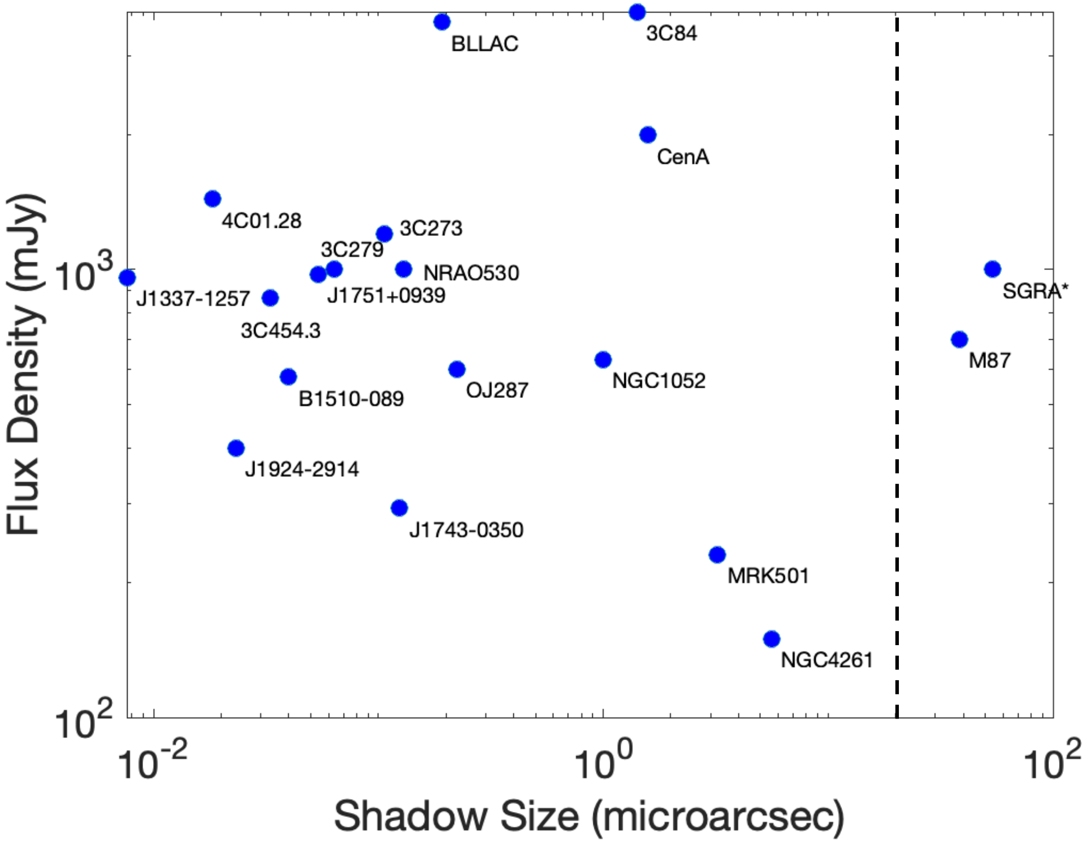

radio
1.3mm
2.1μm
X−ray

# The Largest Black Holes on the Sky

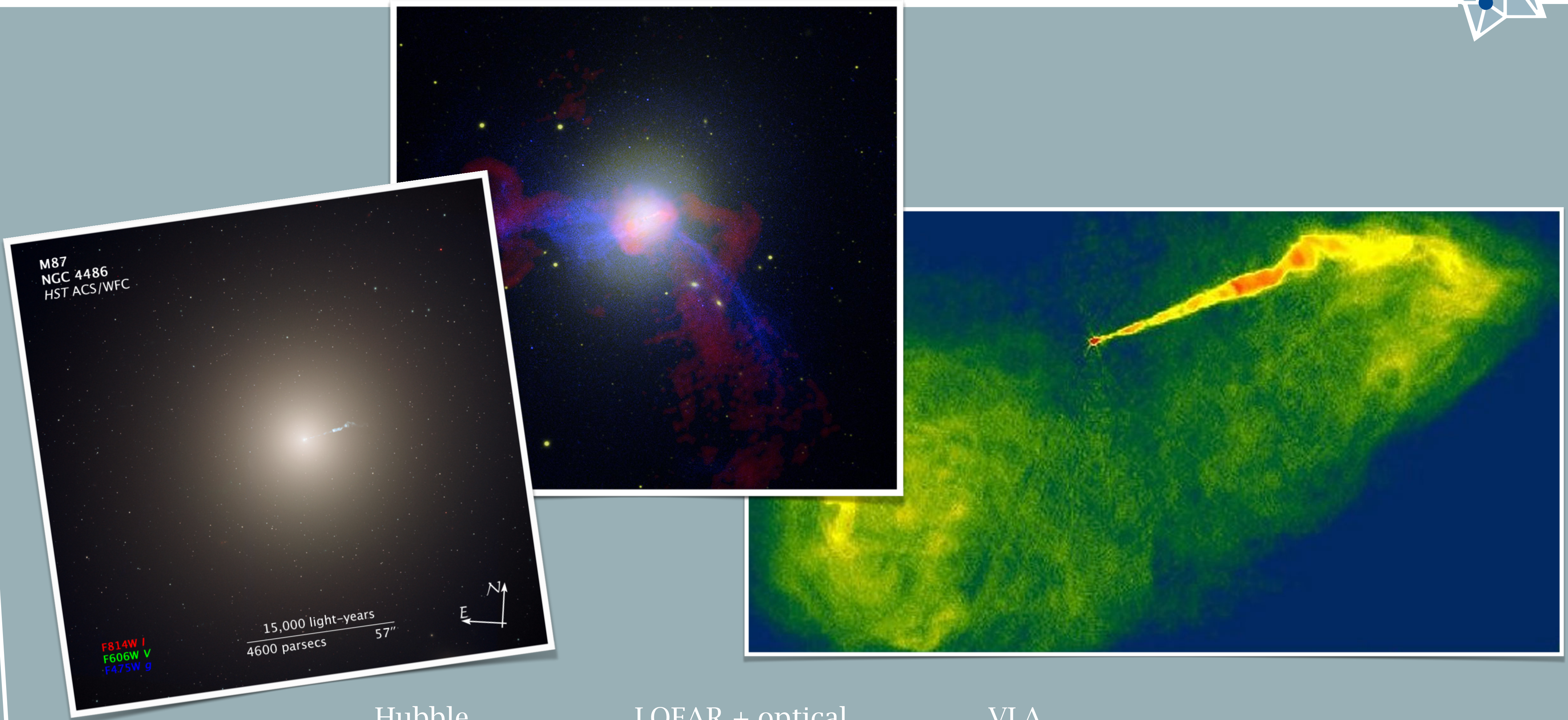
- Depends on knowing:
  - Distances (not so easy)
  - BH mass estimates (no easy at all)
    - Interesting stuff with last stable orbit
    - Or photon ring

$$\theta_{\text{shadow}} \approx 10\frac{GM}{Dc^2}$$

- M87 ≈ 20 - 40 µas
  - Depending on mass determination
- SgrA* ≈ 50 µas
  - very well determined

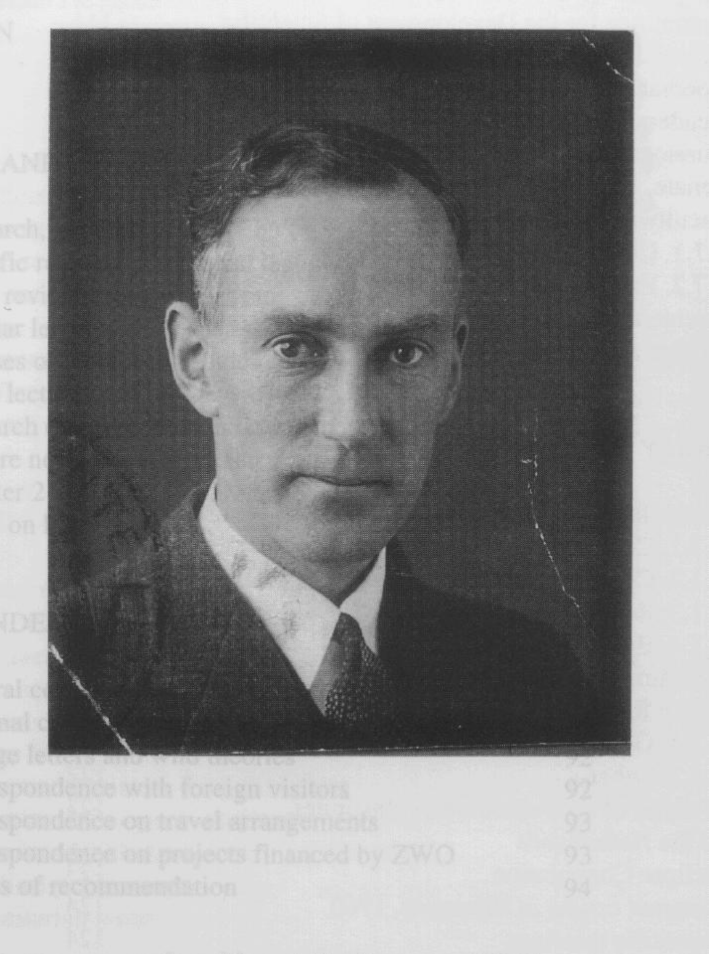


# Messier 87 = Virgo A



Hubble LOFAR + optical VLA

# Jan Oort

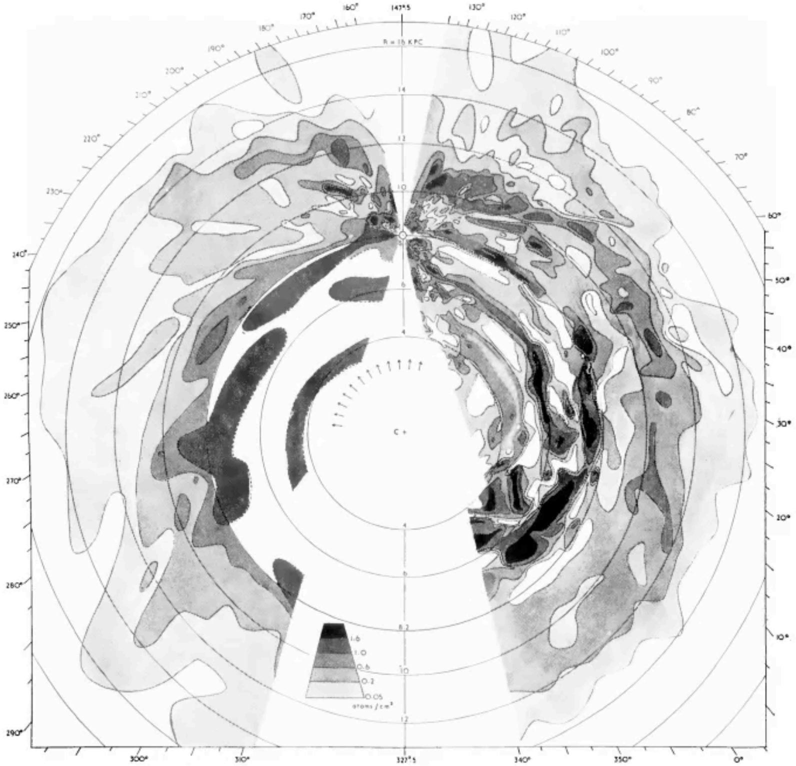


*Jan Hendrik Oort, c. 1935*

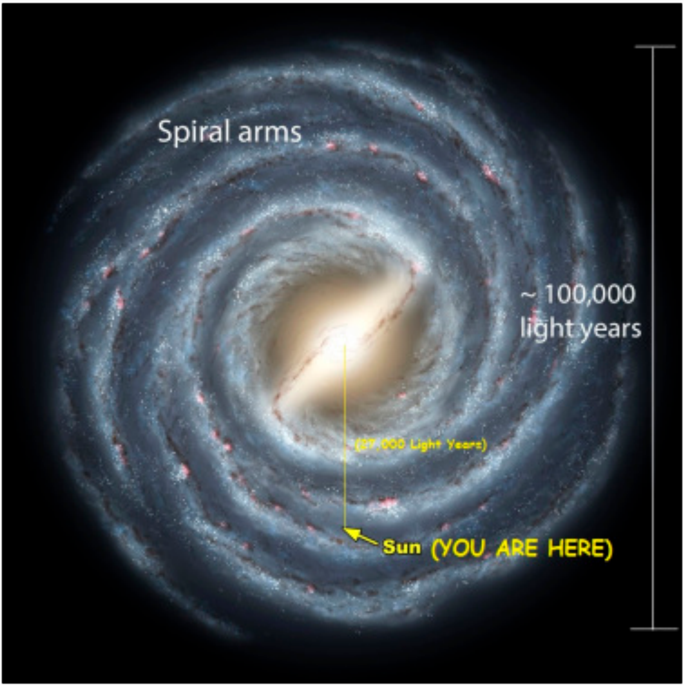
Oort had shown that the Milky Way rotated around its nucleus in Sagittarius.

First heard of Reber's work in 1944.

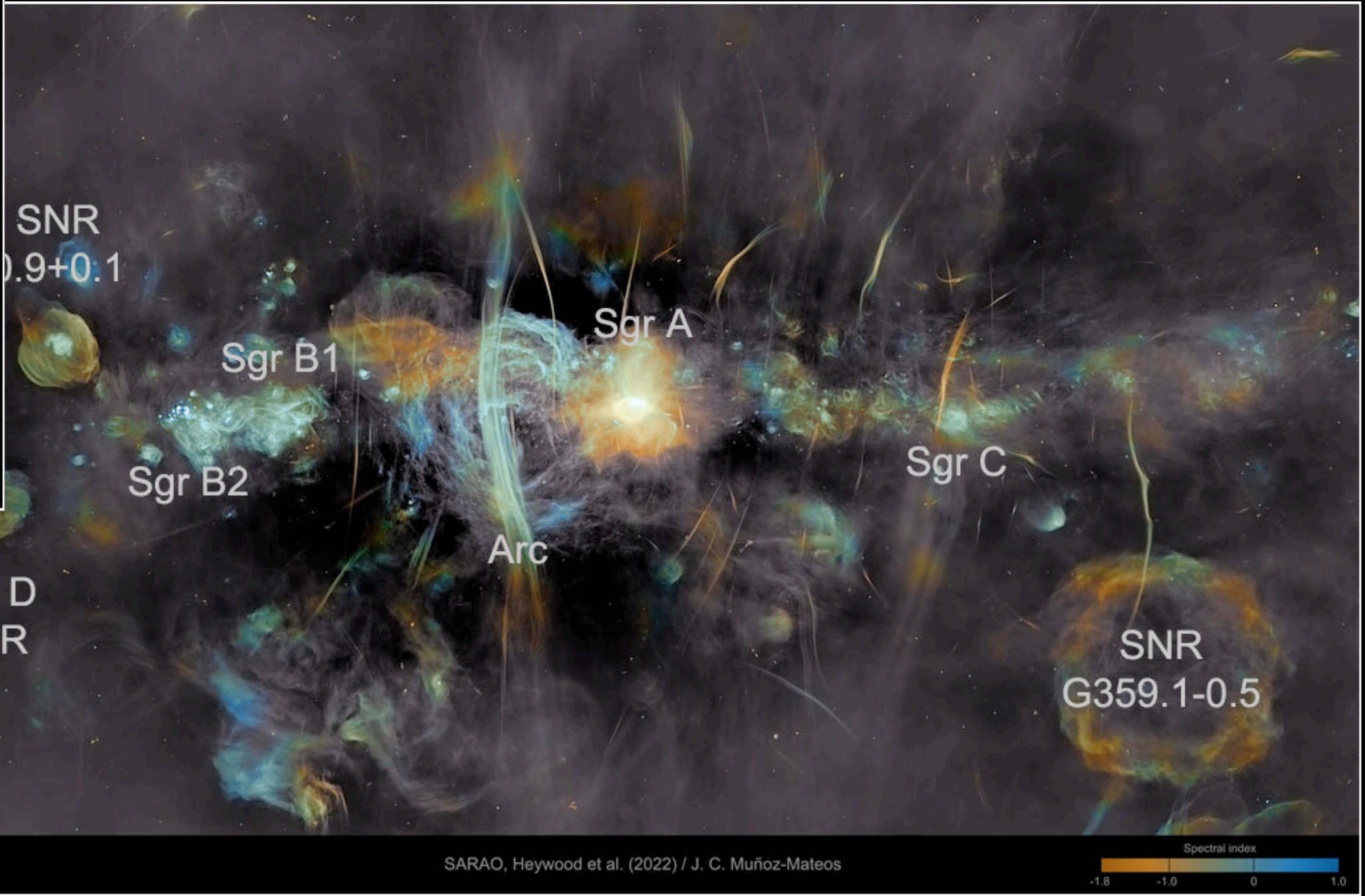
He was greatly interested in studying the central part of the Milky Way but was unable to make progress due to dust obscuration...



# The Milky Way, our Galaxy



MeerKat image of inner Galaxy



SARAO, Heywood et al. (2022) / J. C. Muñoz-Mateos

# Interstellar scattering

- Limits view on SgrA* at longer wavelengths
  - Where it is optically thick anyway
- Becomes sub-dominant at 1mm
  - Where it is optically thin
  - And global VLBI reaches 20µas

van Langevelde, Frail, Cordes & Diamond 1992

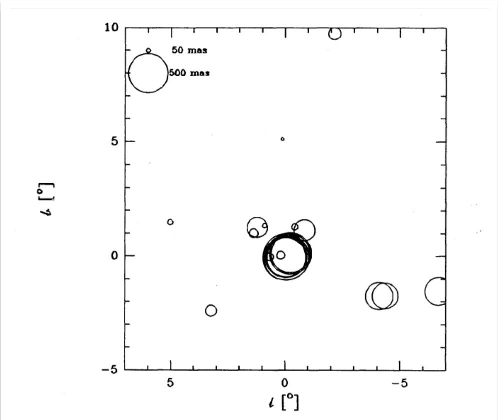
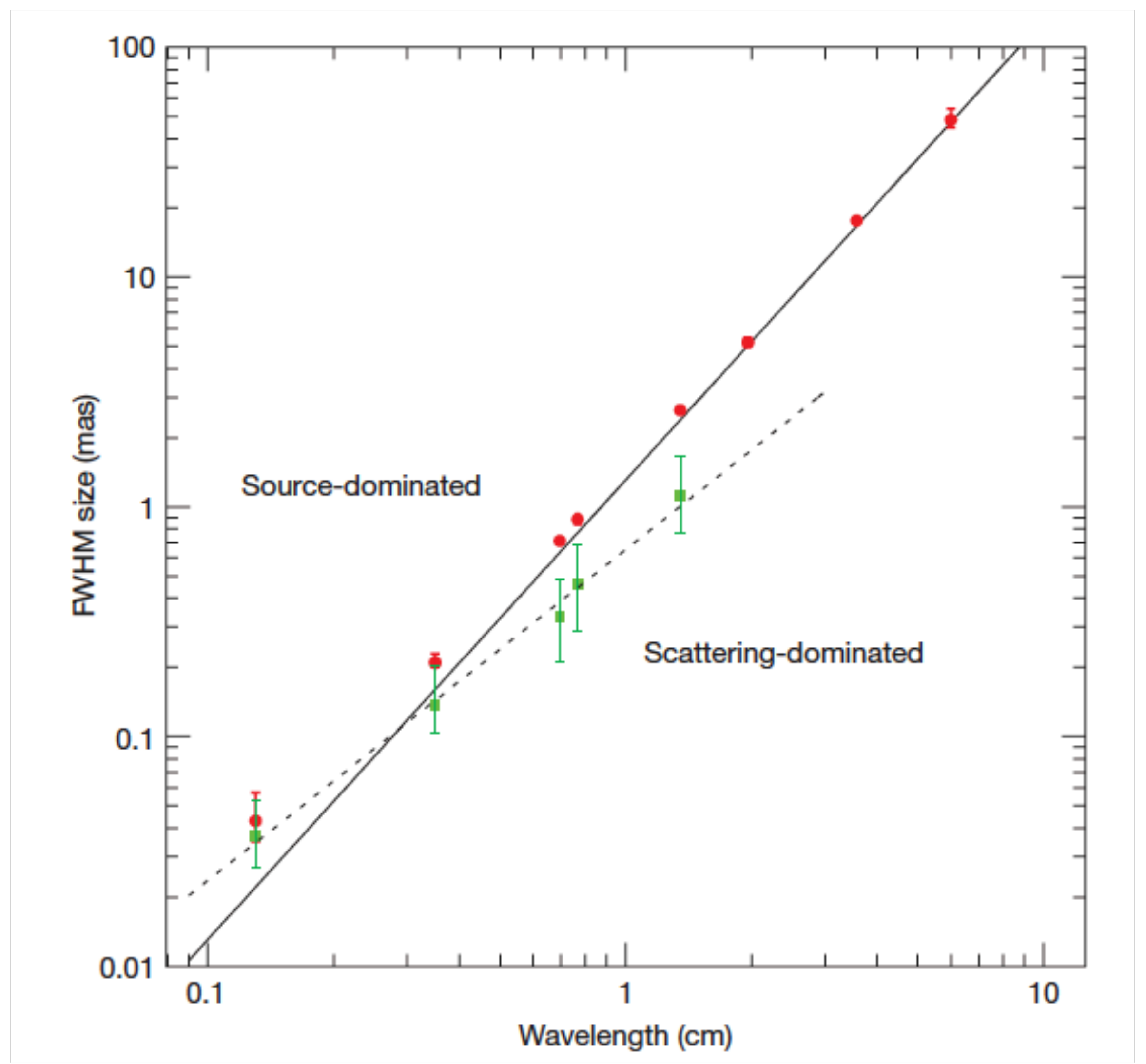


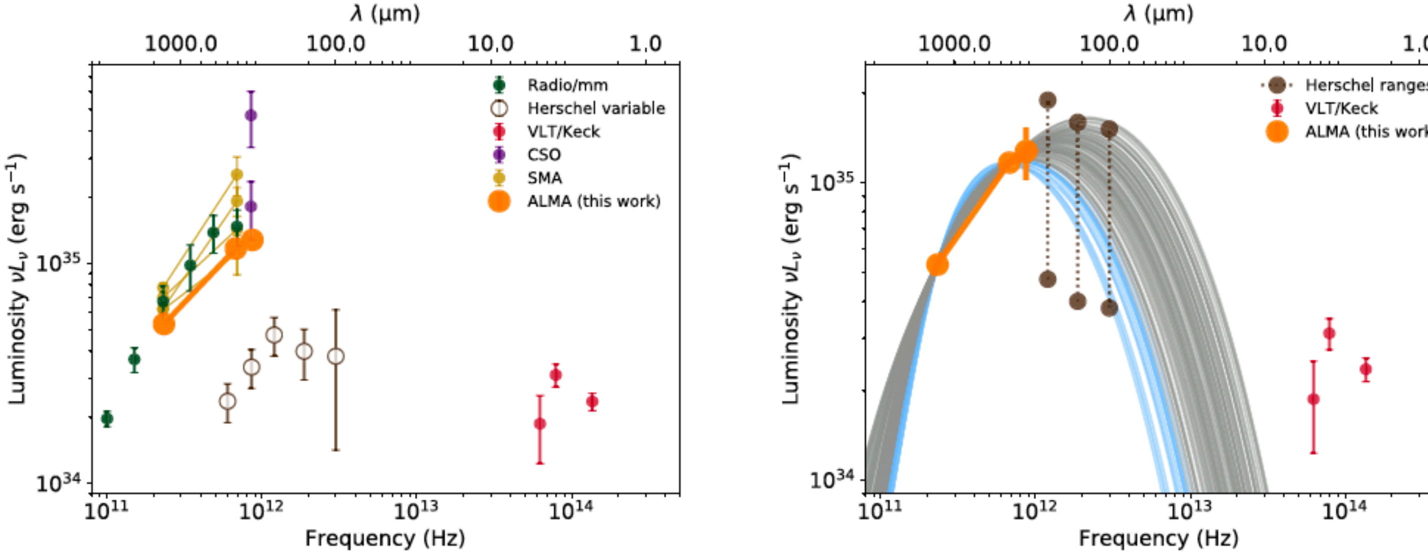
FIG. 2.—Scattering sizes for all the lines of sight near the Galactic center. The sizes of the circles indicate the amount of observed angular broadening.



Doeleman et al. 2008

# Optically thin?

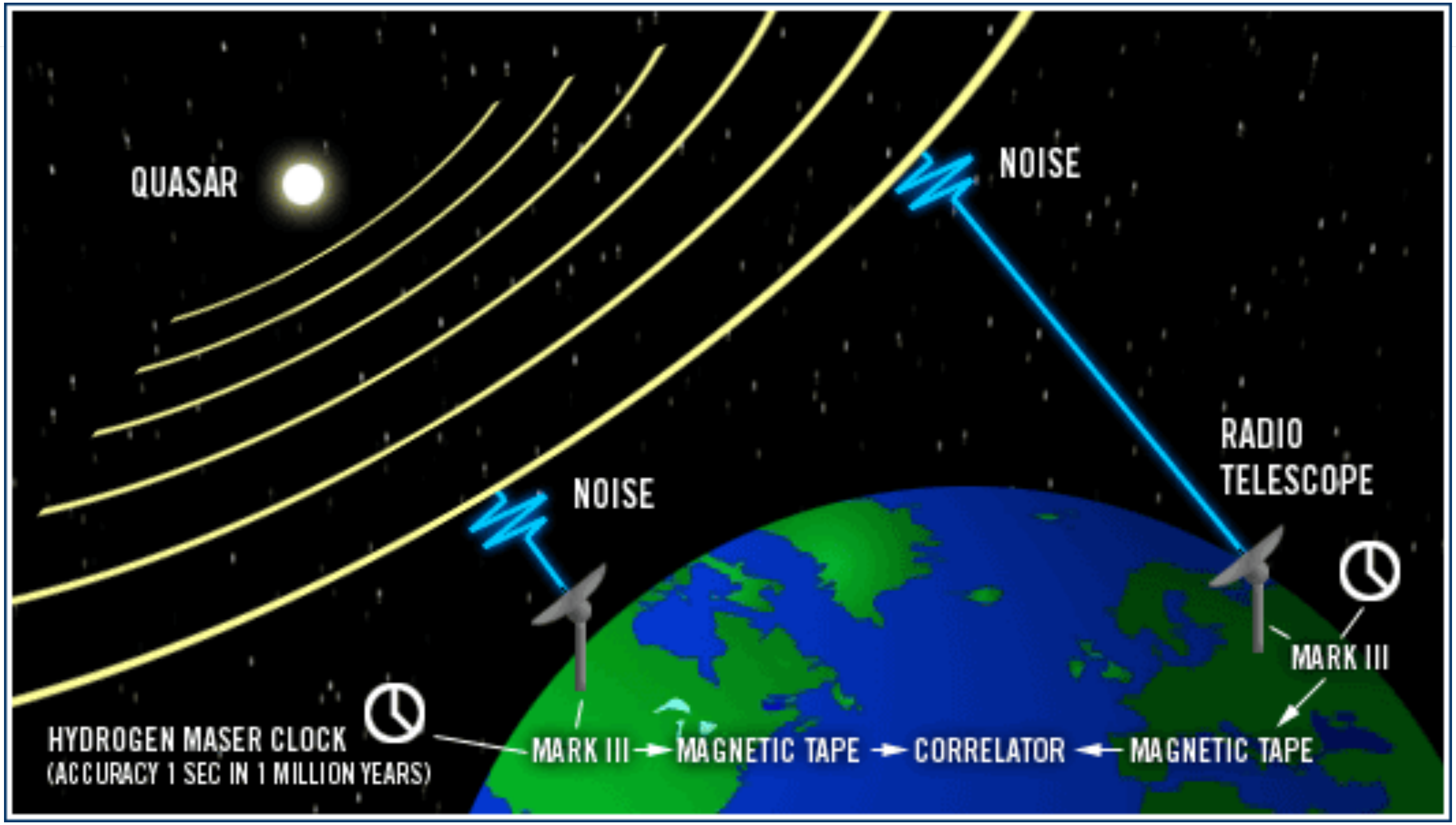
- Can be determined from overall spectrum
  - But must be taken with similar aperture across frequency range
  - ALMA result for SgrA*

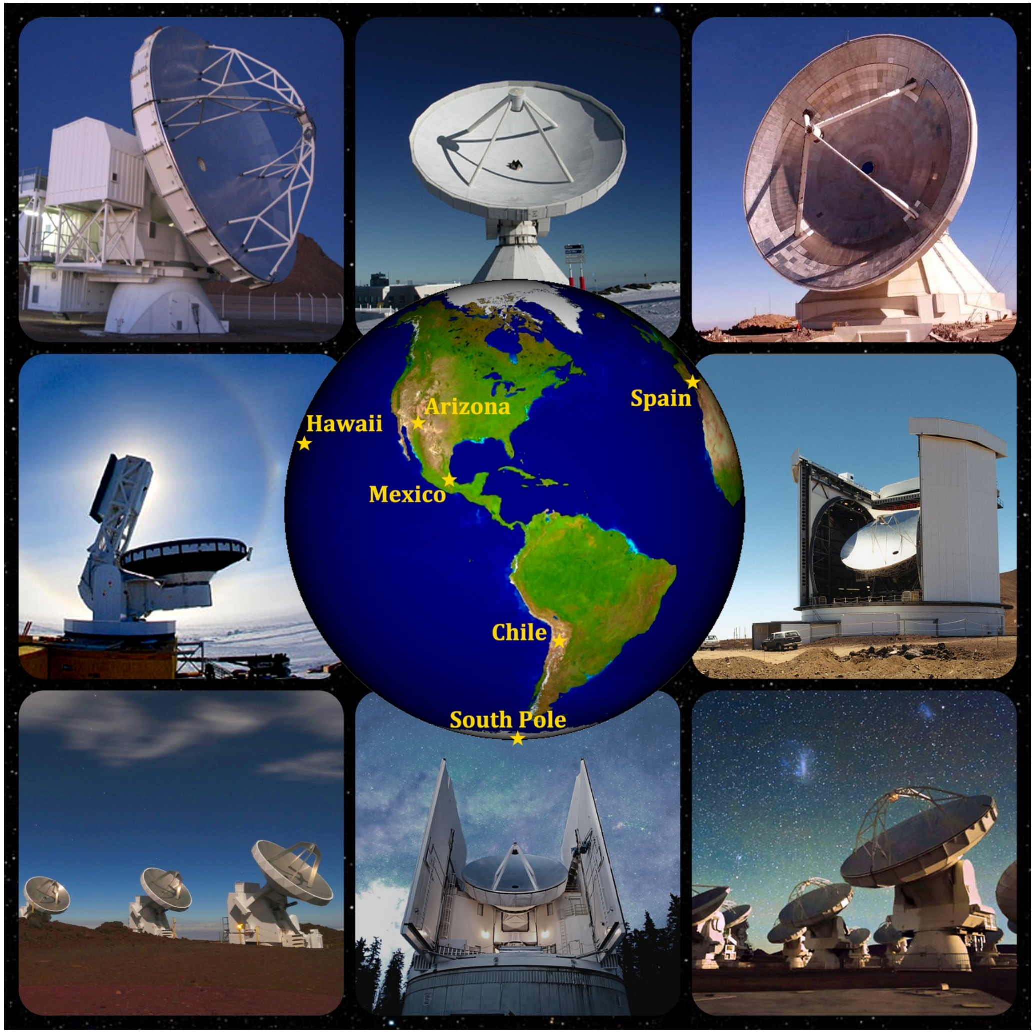


- AGN often show core-shift across frequencies
  - BH surrounding optically thick except for highest frequencies

# Very Long Baseline Interferometry

In 1967 the first transatlantic baselines (USA-Sweden) detected very compact radio sources.
B ~ 8000km: milli-arcsecond resolution, very small sources.





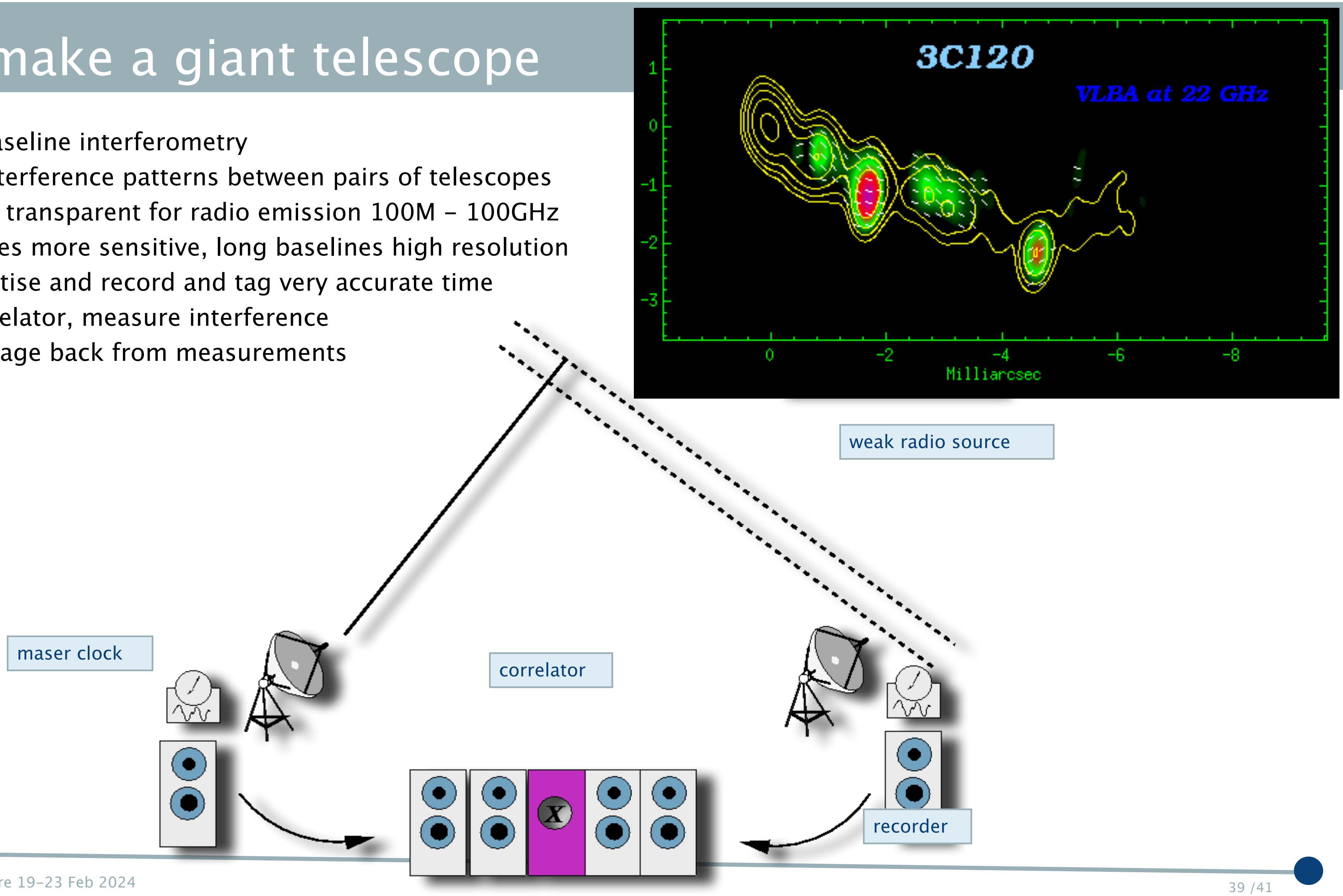
- Atacama Large Millimeter Array (ALMA), Chile
- ALMA Pathfinder Experiment (APEX), Chile
- James Clerk Maxwell Telescope (JCMT), Hawaii
- Large Millimeter Telescope (LMT), Mexico
- IRAM 30-meter Telescope, Spain
- South Pole Telescope (SPT), South Pole
- Submillimeter Array (SMA), Hawaii
- Submillimeter Telescope (SMT), Arizona

$$\theta_r \approx \frac{\lambda}{B}$$

- EHT λ/B
  - 1.3 mm/13000 km = 1E−10 = 20.6 μas
- Hair in New York
  - 75 μm / 1700 km = 4E−11
- Donut on the moon
  - 8cm / 384400 km = 2E−10
- GPS on Mars
  - 15m / 225E6 km = 6.7E−11

# VLBI: make a giant telescope

- Very long baseline interferometry
- Measures interference patterns between pairs of telescopes
- Atmosphere transparent for radio emission 100M – 100GHz
- Big telescopes more sensitive, long baselines high resolution
- Sample, digitise and record and tag very accurate time
- Send to correlator, measure interference
- Compute image back from measurements



weak radio source

maser clock

correlator

recorder

# Fantastic resolution⇔ high brightness

- Express the sensitivity of VLBI in terms of Tb
  - The sensitivity of an array with N identical dishes of size A is given by:

$$\boxed{\Delta S_v = \frac{\sqrt{2}\, k_b T_{\mathrm{sys}}}{\eta_a \eta_c A \sqrt{\Delta t\, \Delta v}\sqrt{\frac{1}{2} N(N-1)}}}$$

  - Convert to Intensity $\Delta I = \Delta S/\Delta\Omega$
  - Approximate the resolution as $\Delta\Omega = \pi\theta^2 \approx (\lambda/L)^2$
- An use the Rayleigh-Jeans approximation:
    - Not really valid in mm regime…

$$\boxed{T_b = \frac{c^2}{2\upsilon^2 k} I_\upsilon}$$

# Brightness sensitivity of an array:

- So one can derive:

$$\boxed{\Delta T_\nu \approx \frac{A_{synth} T_{sys}}{\sum A_{tel} \eta_a \eta_c \sqrt{\Delta t \Delta \nu}}}$$

- Which expresses the brightness sensitivity in terms of the aperture filling factor ($A_{synt}/\Sigma A_{tel}$)
  - Typically we have:

$$\boxed{\sqrt{\Delta t \Delta \nu} \leq 10^3}$$

  - And:

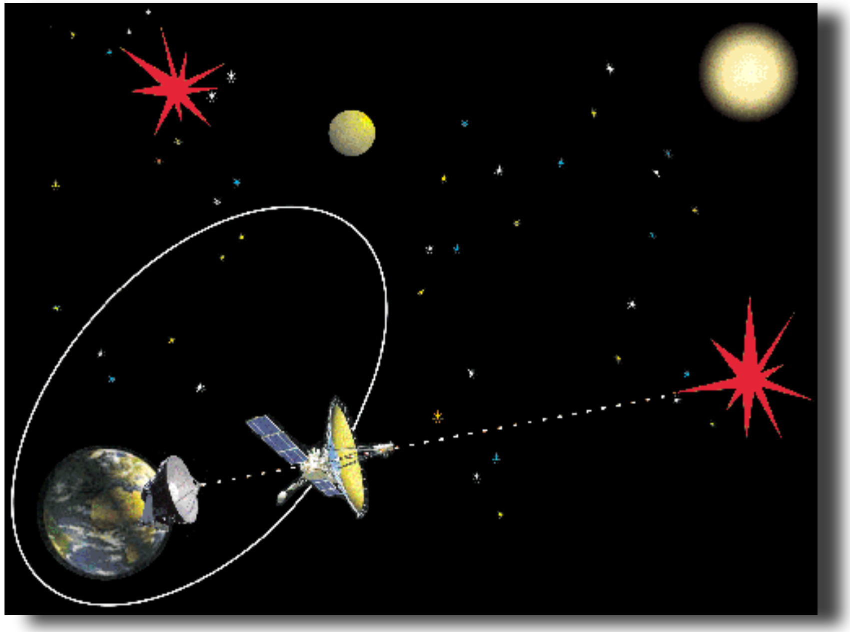
$$\boxed{A_{synth} / A_{tel} = 1000^2\, km^2 / 30^2\, m^2 \approx 10^9.}$$

- So we can only detect very high brightness emission
  - ie lots of flux coming from a very small region
  - Only interesting (resolved) when matching the beam

# Brightness sensitivity

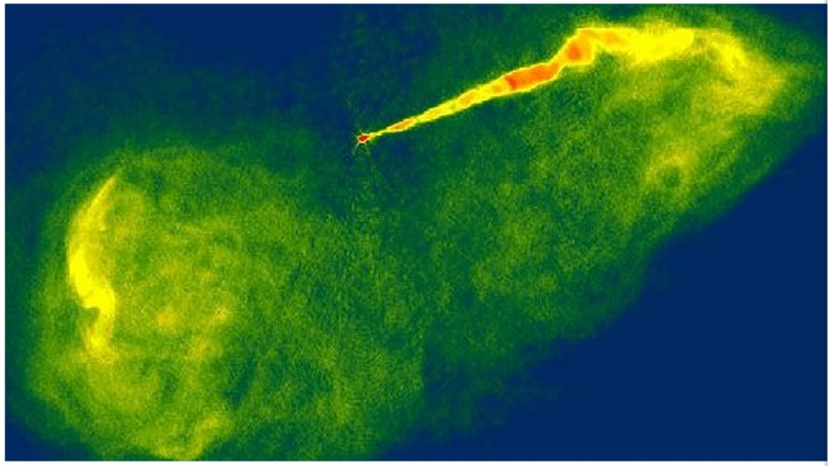
- Sub-arcsec resolution requires 200000 λ baseline
  - Brightness sensitivity requires filled aperture
    - Thermal emission can be reached with ALMA
    - Highest possible brightness temperatures with RadioAstron

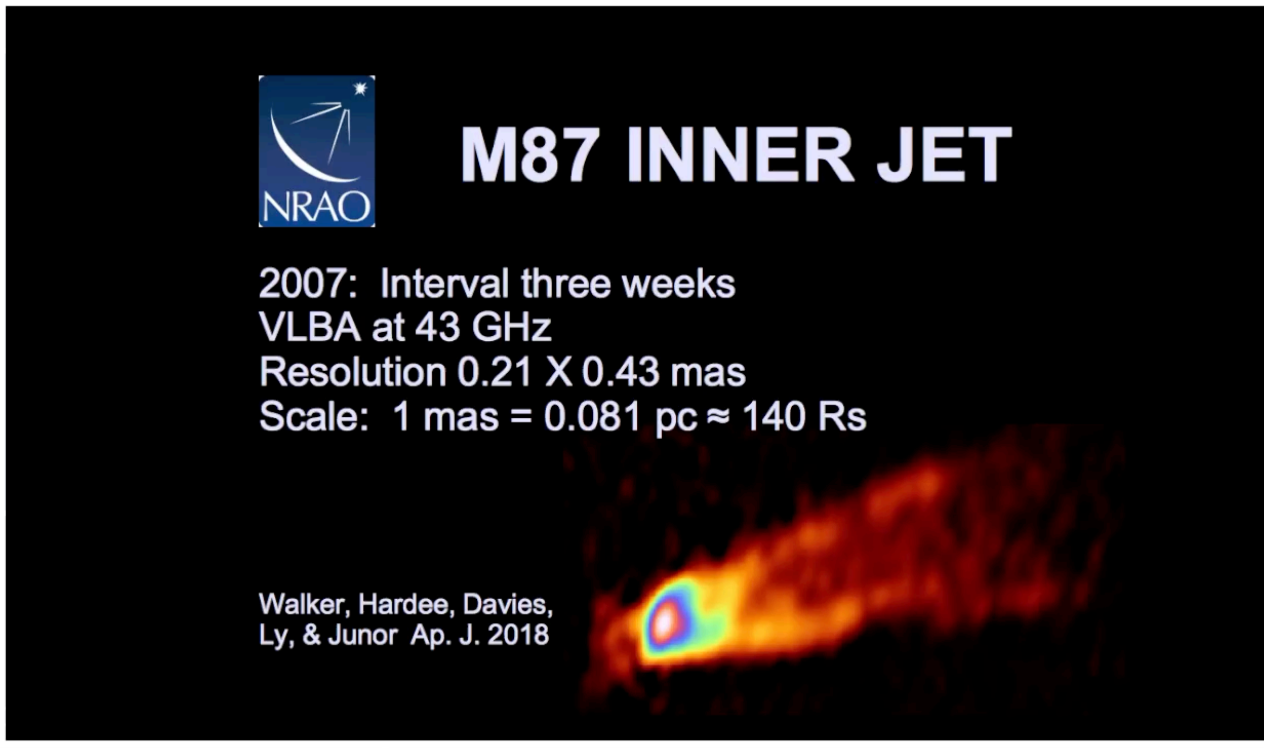
ALMA



RadioAstron

# Let’s zoom in on M87

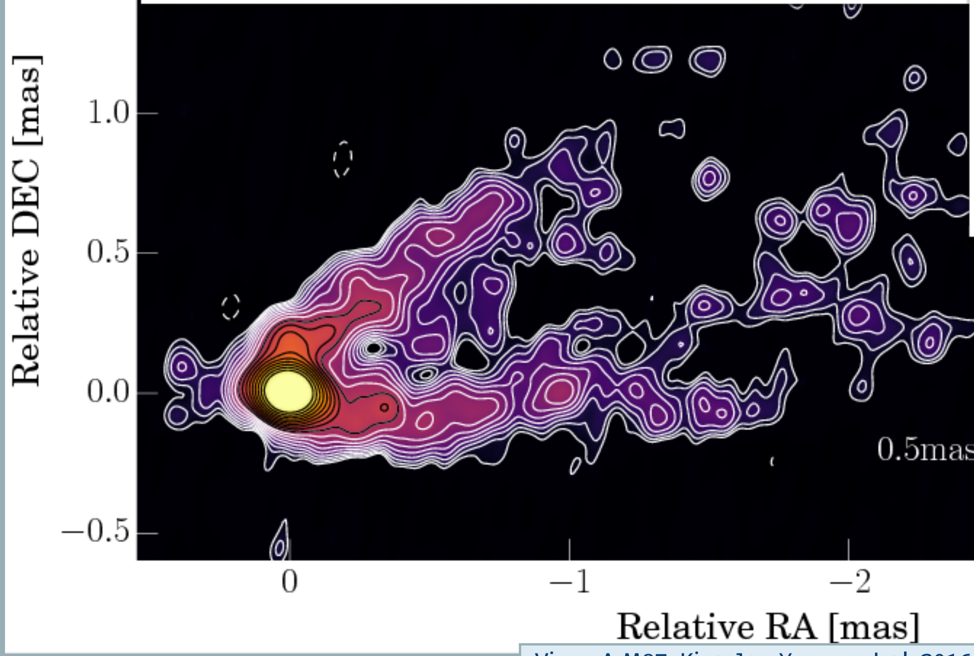




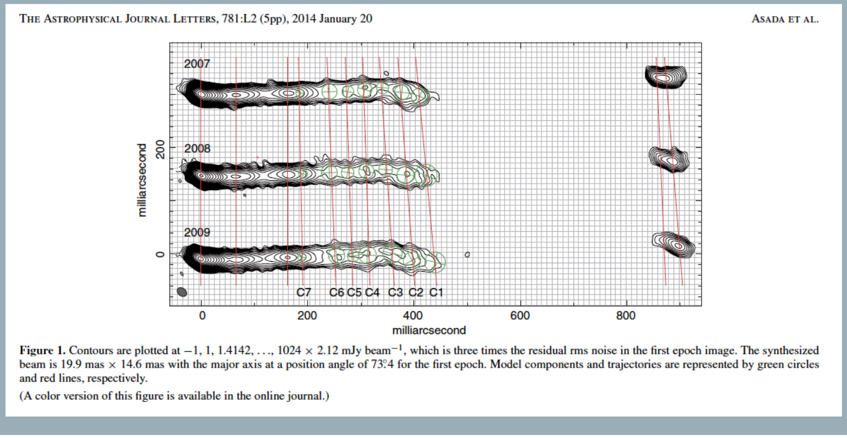
## M87 INNER JET

2007: Interval three weeks
VLBA at 43 GHz
Resolution 0.21 X 0.43 mas
Scale: 1 mas = 0.081 pc ≈ 140 Rs

Walker, Hardee, Davies,
Ly, & Junor Ap. J. 2018



Virgo A M87, Kim, Jae-Young et al. 2016



THE ASTROPHYSICAL JOURNAL LETTERS, 781:L2 (5pp), 2014 January 20 ASADA ET AL.

**Figure 1.** Contours are plotted at −1, 1, 1.4142, . . ., 1024 × 2.12 mJy $\mathrm{beam}^{-1}$, which is three times the residual rms noise in the first epoch image. The synthesized beam is 19.9 mas × 14.6 mas with the major axis at a position angle of 73°.4 for the first epoch. Model components and trajectories are represented by green circles and red lines, respectively.

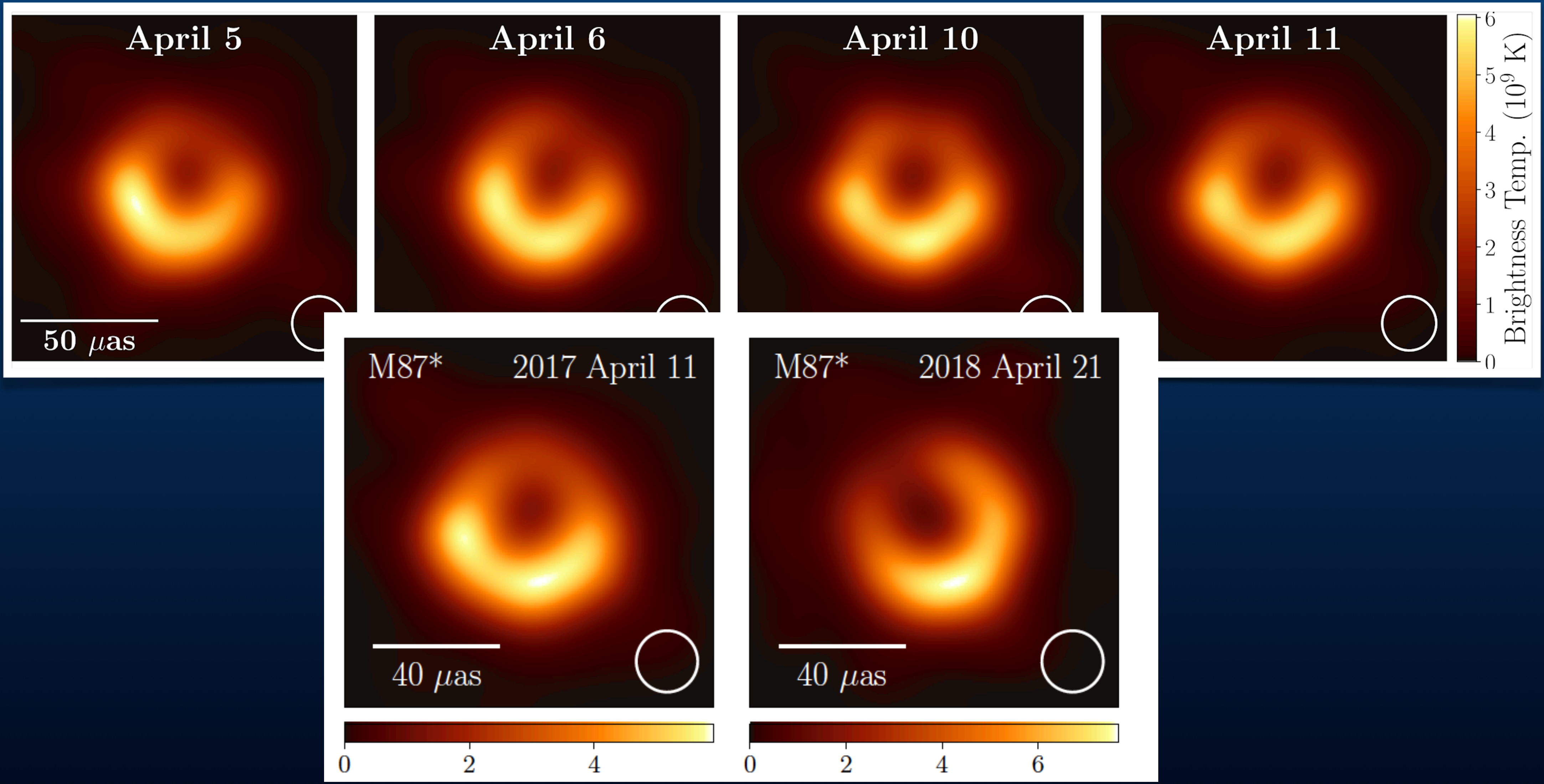
(A color version of this figure is available in the online journal.)

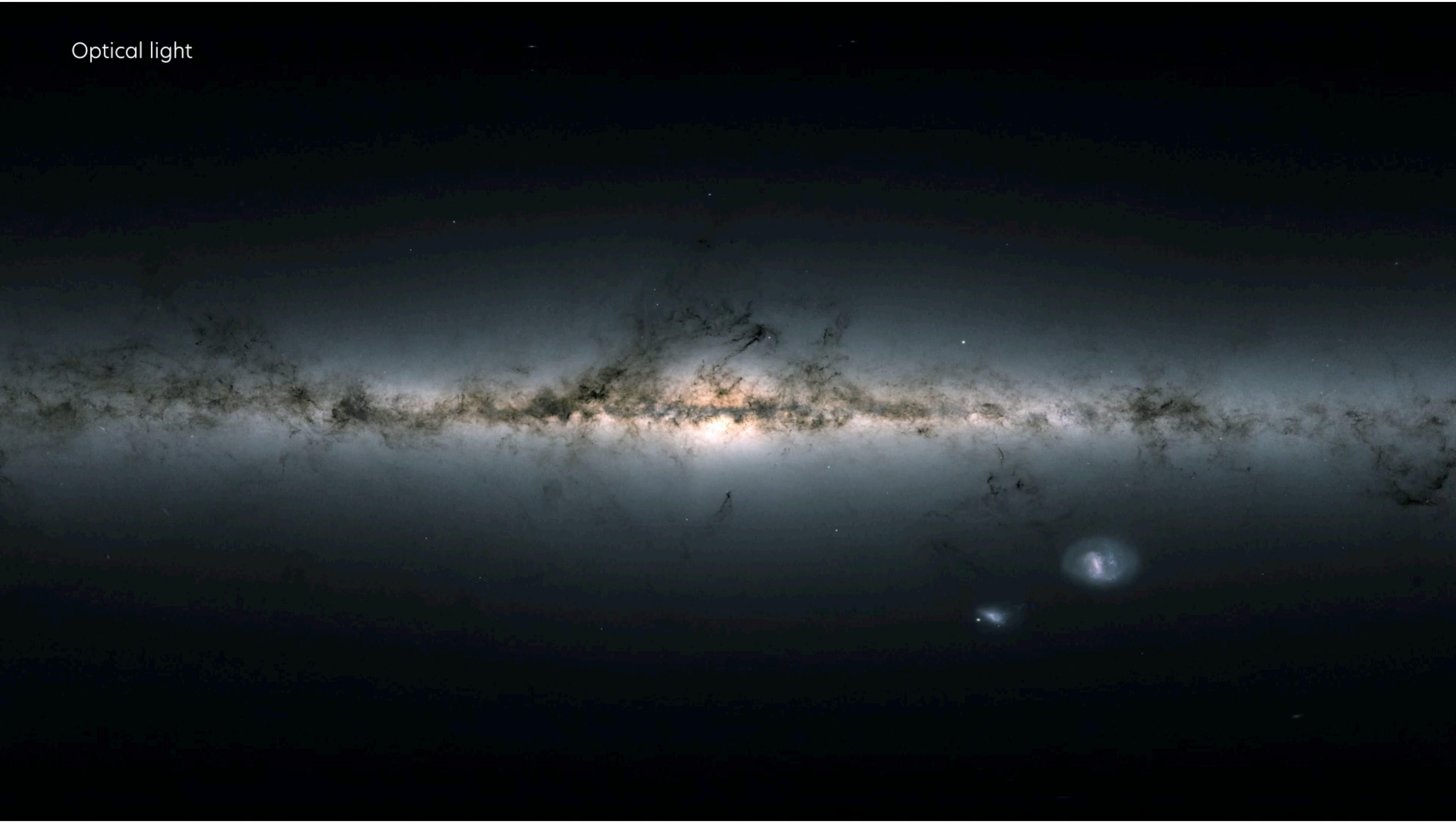
# First M87 Event Horizon Telescope Results I. The Shadow of the Supermassive Black Hole

Distance to M87: 54 million lyr
Black Hole mass: $6.5\ 10^9\ M_\odot$

42 μas
≈ 700 au
= 98 lh

Observations at 1.3 mm ≈ 230 GHz
Brightness temperature: $6\ 10^9$K

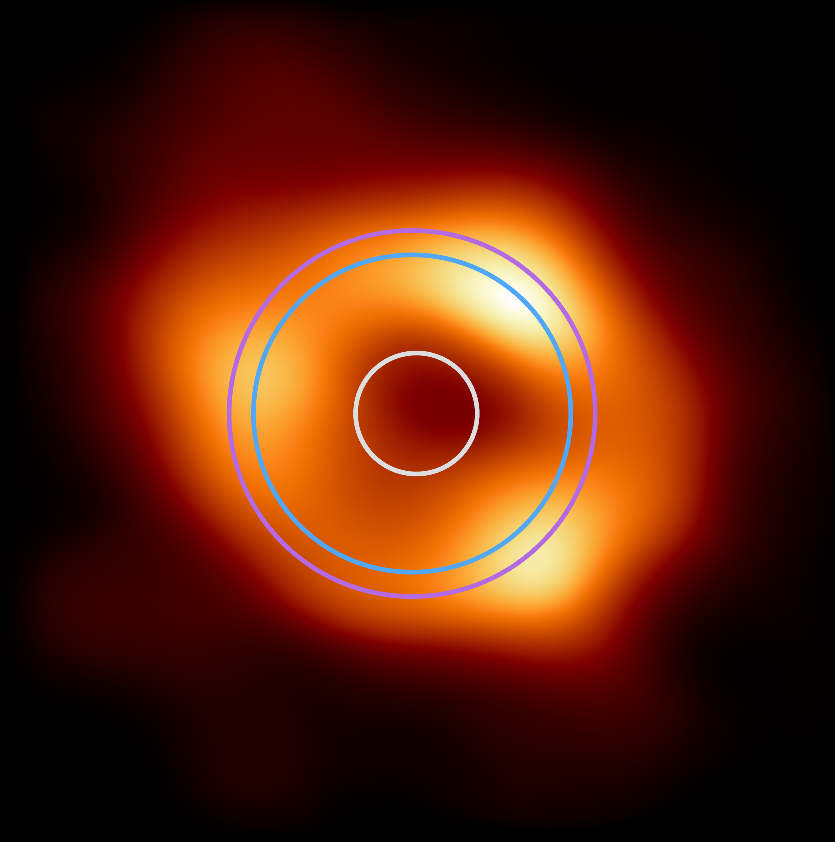

April 5
April 6
April 10
April 11
50 μas
Brightness Temp. ($10^9$ K)
0
1
2
3
4
5
6
M87*
2017 April 11
40 μas
0
2
4
M87*
2018 April 21
40 μas
0
2
4
6



Optical light

# Astrophysics with the SgrA* Black Hole

we know quite precisely it is at a distance of 26 thousand lightyear…



last stable orbit
of gas in orbit around
Black Hole —

Event Horizon,
radius of the Black Hole,
no return from here —

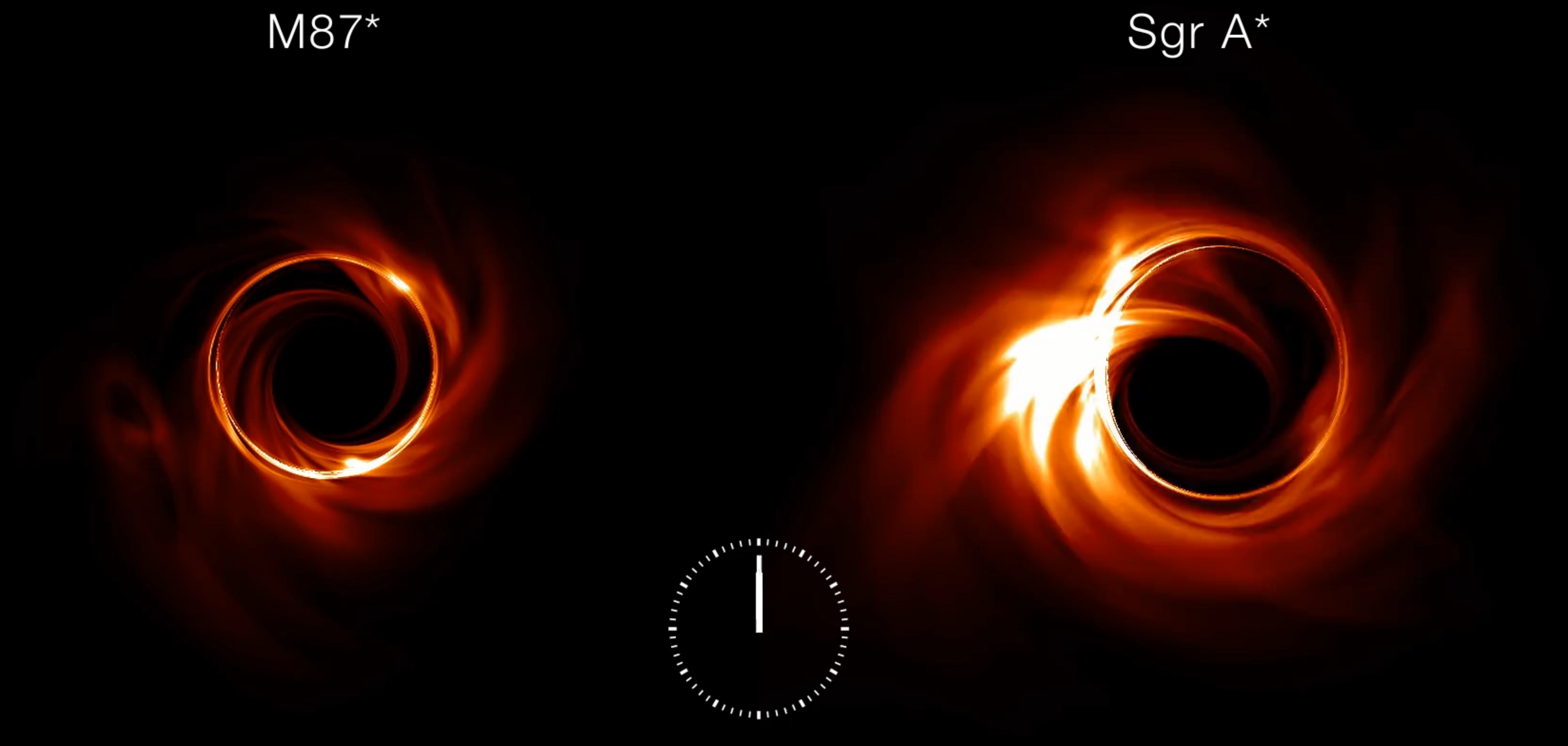
Photon Ring,
where we see the
photons that have gone
round the Black Hole
once or multiple times —

image follows circle,
as predicted by General
Relativity

diameter equals 51 μas,
because we know the
mass and distance, this
is precisely correct!

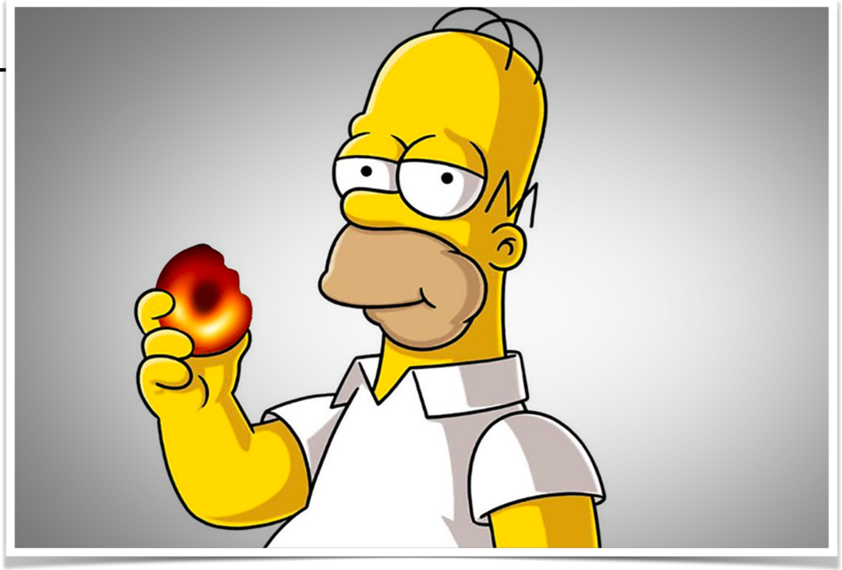
Source is variable,
azimuthal structure
uncertain;
almost face on?

● resolution of the EHT, we cannot
resolve smaller details



Simulation

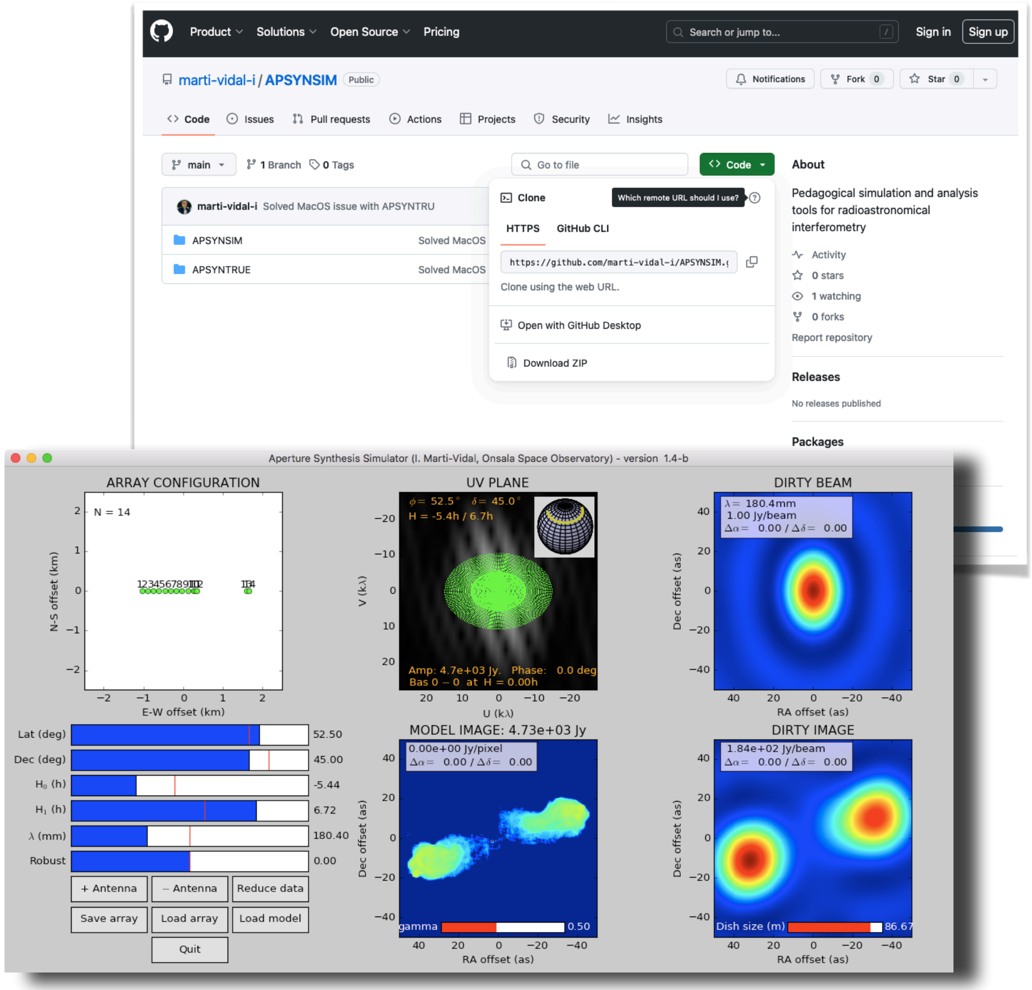
# We are “lucky”



- 2 Black Holes big enough on the sky
    - For VLBI baselines across the entire planet
    - At the edge of the radio window (≤ 1mm)
- Optically thin
    - At the edge frequency
- Just not obscured by interstellar scattering
- Bright enough to be observable
    - With current size telescopes
    - And bandwidth
    - To track variability

# Next:

- Later lectures
  - Synthesis imaging, understanding the visibility data, deconvolution
  - Instrument implementation, correlator, calibration, polarisation
  - Interpretation, calibrating gravity, future projects



marti-vidal-i Solved MacOS issue with APSYNTRU

https://github.com/marti-vidal-i/APSYNSIM.g

Clone using the web URL.

Pedagogical simulation and analysis tools for radioastronomical interferometry

No releases published

Aperture Synthesis Simulator (I. Marti-Vidal, Onsala Space Observatory) - version 1.4-b

$\phi$ = 52.5° $\delta$ = 45.0°
H = -5.4h / 6.7h

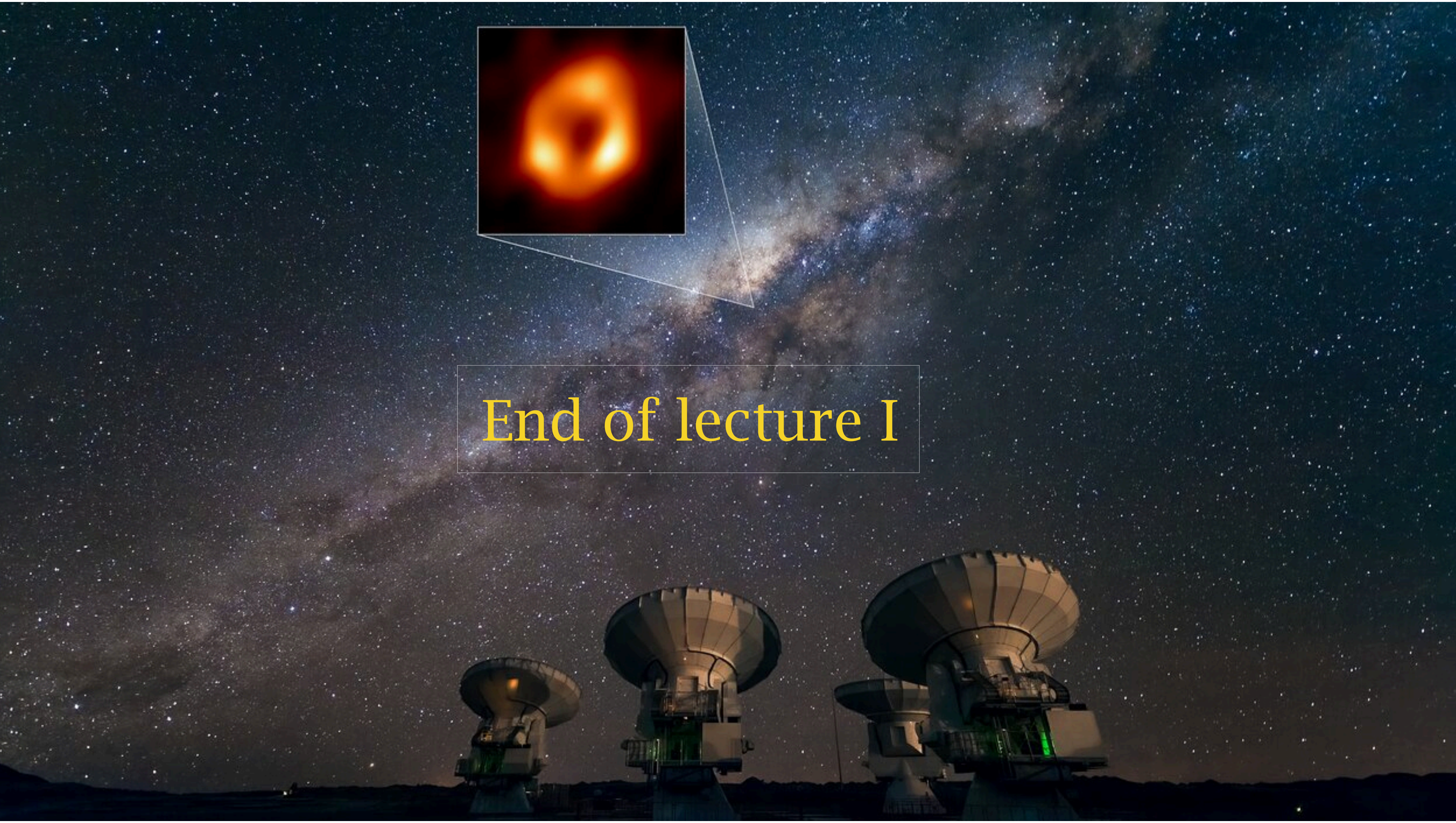
Amp: 4.7e+03 Jy. Phase: 0.0 deg
Bas 0 – 0 at H = 0.00h

λ = 180.4mm
1.00 Jy/beam
$\Delta\alpha$ = 0.00 / $\Delta\delta$ = 0.00

0.00e+00 Jy/pixel
$\Delta\alpha$ = 0.00 / $\Delta\delta$ = 0.00

1.84e+02 Jy/beam
$\Delta\alpha$ = 0.00 / $\Delta\delta$ = 0.00

- We can play with
  - Ivan Marti-Vidal’s APSYNSIM, APSYNTRUE
  - https://github.com/marti-vidal-i/APSYNSIM



# End of lecture I