

Introduction to Radio Interferometry and ALMA

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EUROPEAN ARC

ALMA Regional Centre || Czech

ALMA School 2026
26-30 January 2026
Leiden, Netherlands



**Astronomical
Institute**

of the Czech Academy
of Sciences

A Little History

Astronomy through History

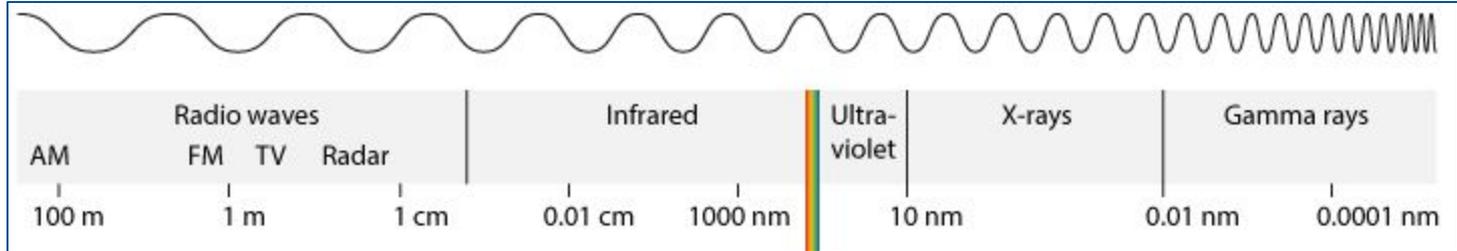


Ancient Human looking at the stars (José A. Peñas/SINC)



Galileo's Telescope (Museo Galileo)

The Wide Electromagnetic Spectrum



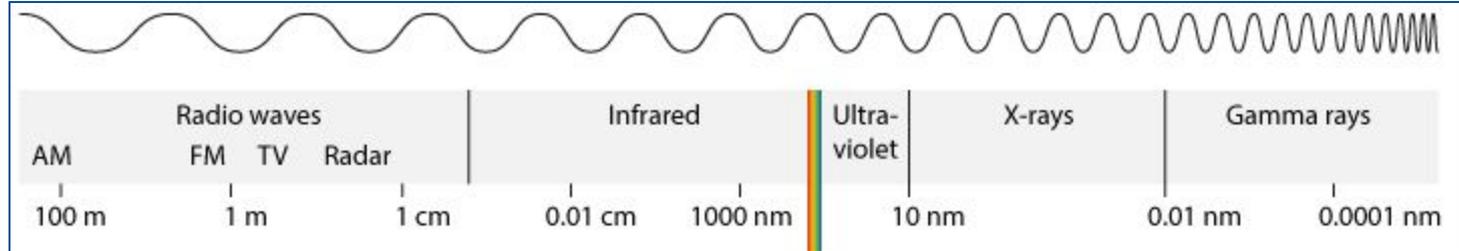
Discovery of light beyond optical

Infrared: Year 1800 by Fredrich William Herschel

Ultraviolet: Year 1801 by Johann Wilhelm Ritter

X-rays: Year 1895 by Wilhelm Röntgen

The Wide Electromagnetic Spectrum



Discovery of light beyond optical

Theory of Electromagnetism: 19th Century (1885 JC Maxwell)

Electromagnetic Waves: Year 1887 by Heinrich Hertz with 5m wavelength radio waves.

Extraterrestrial Radio Detection

- Unsuccessful solar observations in 1890 to 1920s.
- **Karl Jansky**, at Bell Labs, discovered radio emission coming from the center of the Milky Way - 1932, 20.5 MHz, 24° x 35° resolution.
- Birth of Radio Astronomy

“There is no indication of any kind that these radio waves constitute some kind of interstellar signalling or that they are the result of some form of intelligence striving for intra-galactic communication”

NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported
by K. G. Jansky, Held to
Differ From Cosmic Ray.

DIRECTION IS UNCHANGING

Recorded and Tested for More
Than Year to Identify it as
From Earth's Galaxy.

ITS INTENSITY IS LOW

Only Delicate Receiver is Able to
Register—No Evidence of
Interstellar Signaling.

Discovery of mysterious radio waves which appear to come from the centre of the Milky Way galaxy was announced yesterday by the Bell Telephone Laboratories. The discovery was made during research studies on static by Karl G. Jansky of the radio research department at Holmdel, N. J., and was described by him in a paper delivered before the International Scientific Radio Union in Washington.

The galactic radio waves, Mr. Jansky said, differ from the cosmic rays and also from the phenomenon of cosmic radiation, described last week before the American Philosophical Society at Philadelphia by Dr. Vesto M. Slipher, director of the Lowell Observatory at Flagstaff, Ariz.

Unlike the cosmic ray, which comes from all directions in space, does not vary with either the time of day or the time of the year, and may be either a photon or an electron, the galactic waves, Mr. Jansky pointed out, seem to come from a definite source in space, vary in intensity with the time of day and

Dr. Slipher concluded, at some distance above the earth's surface, and possibly produced by the earth's atmosphere.

The galactic radio waves, the announcement says, are short waves, 14.6 meters, at a frequency of about 20,000,000 cycles a second. The intensity of these waves is very low, so that a delicate apparatus is required for their detection.

Unlike most forms of radio disturbances, the report says, these newly found waves do not appear to be due to any terrestrial phenomena, but rather to come from some point far off in space—probably far beyond our solar system.

If these waves came from a terrestrial origin, it was reasoned, then they should have the same intensity all the year around. But their intensity varies regularly with the time of day and with the seasons, and they get much weaker when the earth, moving in its orbit, interposes itself between the radio receiver and the source.

A preliminary report, published in the Proceedings of the Institute of Radio Engineers last December, described studies which showed the presence of three separate groups of static: Static from local thunderstorms, static from distant thunderstorms, and a "steady hiss type static of unknown origin." Further studies this year determine the unknown origin of this third type to be from the direction of the centre of the Milky Way, the earth's own home galaxy.

Direction of Arrival Fixed.

The direction from which these waves arrive, the announcement asserts, has been determined by investigations carried on over a considerable period. Measurements of the horizontal component of the waves were taken on several days of each month for an entire year, and by an analysis of these readings at the end of the year their direction of arrival was disclosed.

"The position indicated," it was explained, "is very near to the point where the plane in which the earth revolves around the sun crosses the centre of the Milky Way, and also to that point toward which the solar system is moving with respect to the other stars."

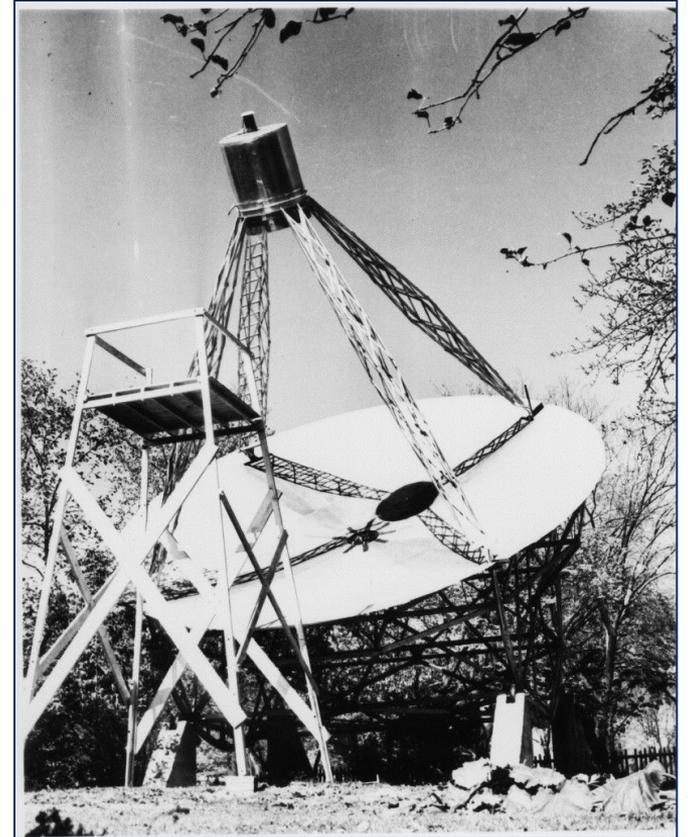
"Further verification of this direction is required, but the discovery, like that of the cosmic rays and of cosmic radiation, raises many cosmological questions of extreme interest."

There is no indication of any kind, Mr. Jansky replied to a ques-

Extraterrestrial Radio Detection

- First radio telescope and receivers built by Grote Reber – 1936-37
- He was the only radio astronomer in the World for a decade.
- Successfully detected radio emission from Milky Way at 160 MHz.
- All Sky Surveys in 1940s.

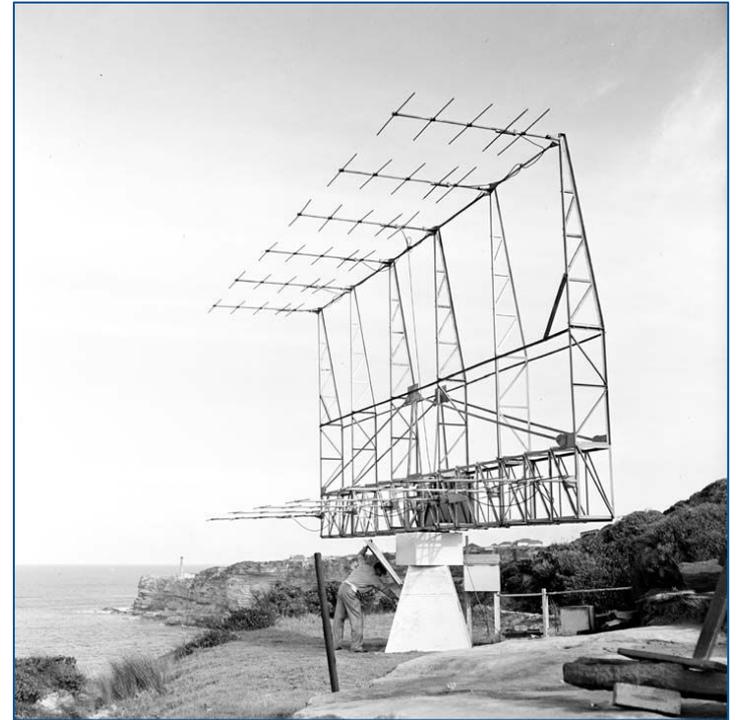
Reber Radio Telescope
in Wheaton, Illinois, 1937



Post WWII Frenzy

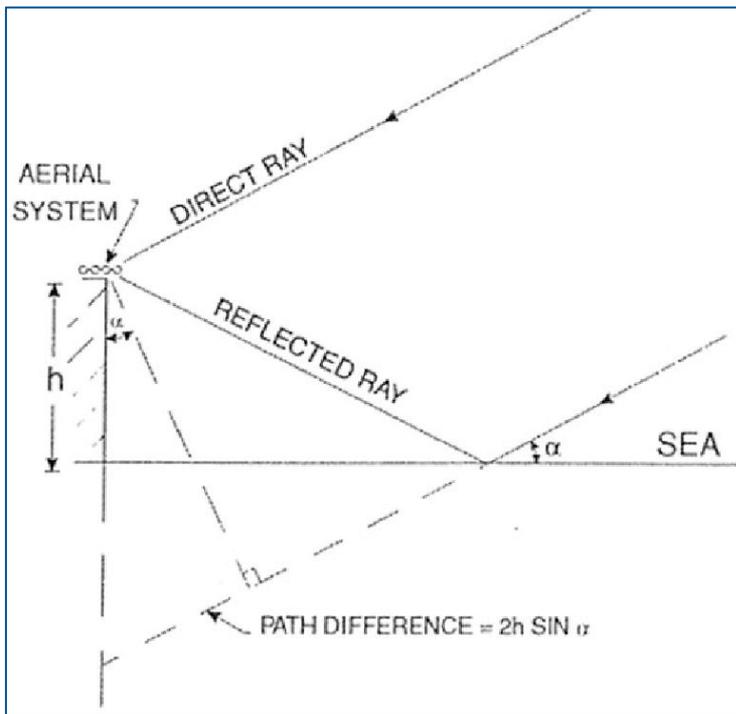


The 80 foot 'hole in the ground' antenna in Australia



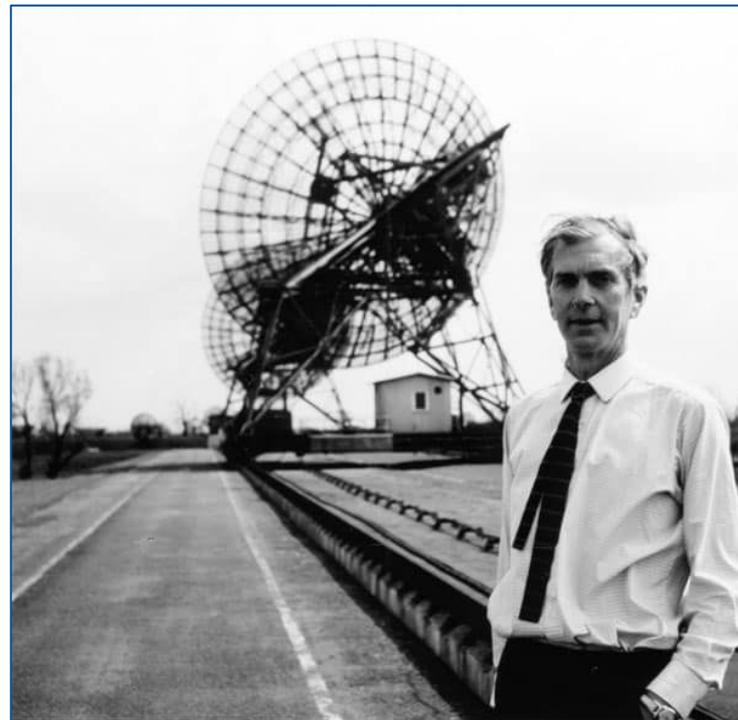
The 12-Yagi array in Australia

Birth of Radio Interferometry



1946: Sea Cliff Interferometer in Australia

Figure from the book "Joe Pawsey and the Founding of Australian Radio Astronomy" by Goss et al.



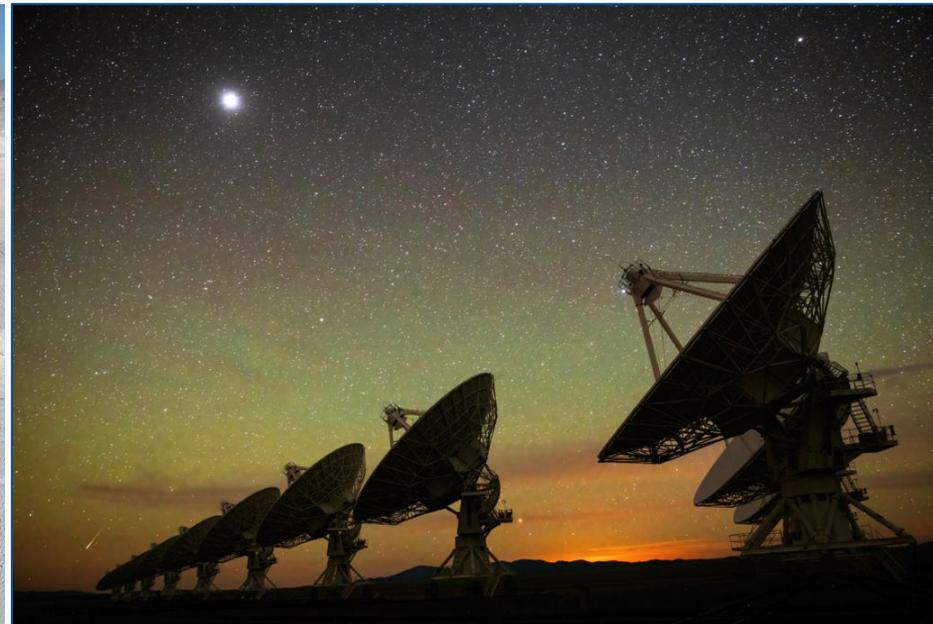
1955: Martin Ryle developed the first radio interferometer

Photograph by John T Scott, AIP Emilio Segrè Visual Archives, Physics Today Collection

Radio Interferometers

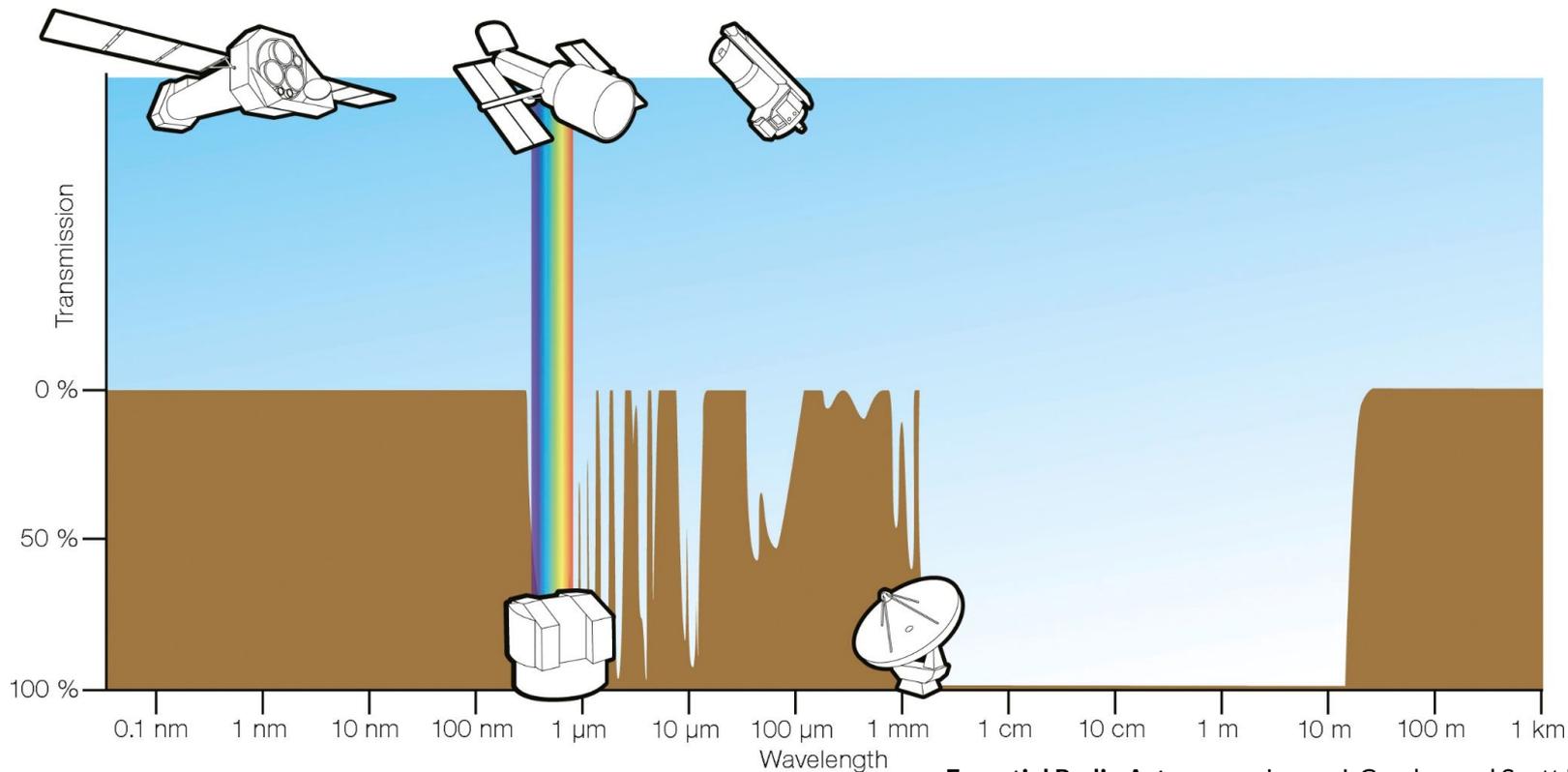


NOEMA (Grenoble, France)
Credit: © IRAM, J. Boissier

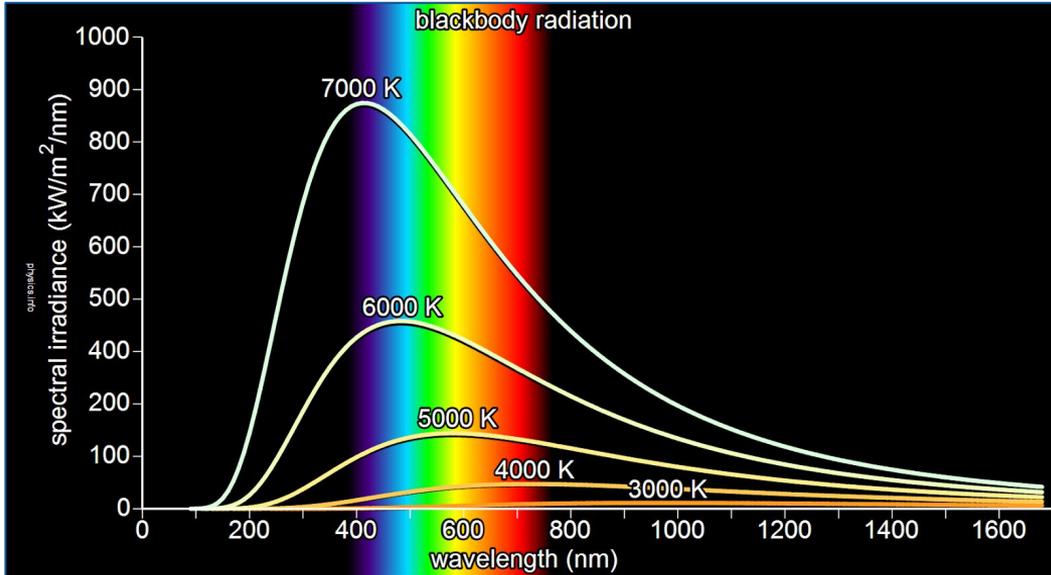


The Very Large Array (New Mexico, USA)
Credit: Bettymaya Foott, NRAO/AUI/NSF

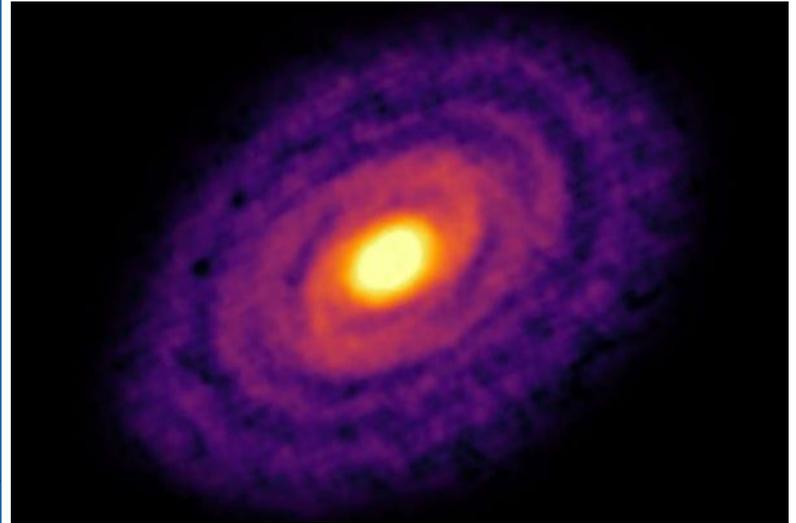
Why do we care about radio?



Thermal Radiation

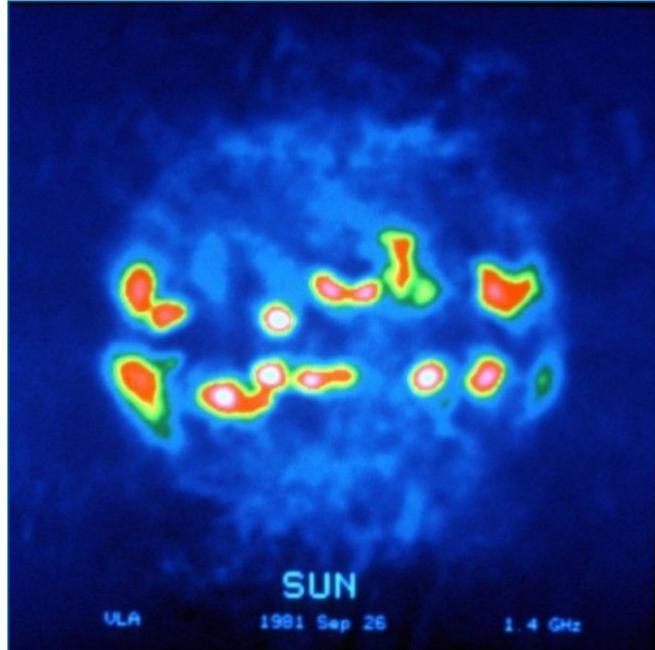


Blackbody emission

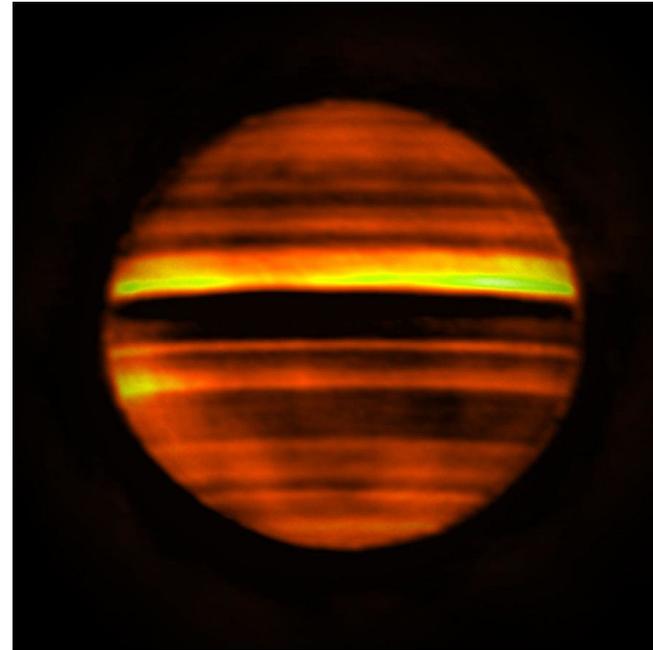


Dust emission

Thermal Blackbody Radiation



The radio Sun: radio image of the Sun recorded by VLA. The brightest regions are part of corona nearby but beyond sunspots. (NRAO/AUI)



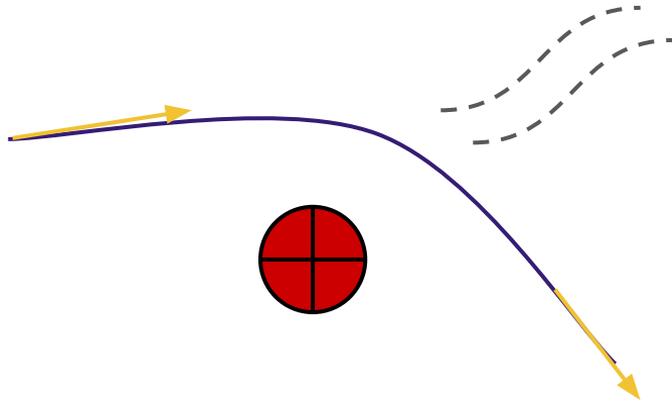
Radio image of Jupiter made with ALMA

de Pater+2019 NRAO/AUI/NSF

Continuum Emission

Interaction of free electrons with photons, or electromagnetic fields

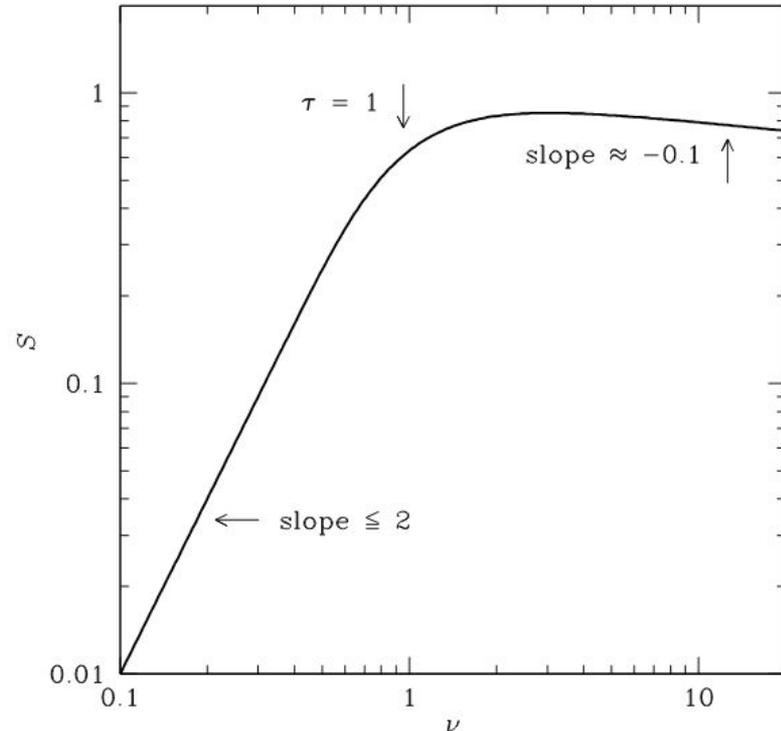
Bremsstrahlung, **Synchrotron**, **Compton**



- **Bremsstrahlung:** HII regions, Star forming nebulae, planetary nebulae, stellar surrounding.
- **Synchrotron emission:** Pulsars, Supernova remnants, AGN and their jets.

Bremsstrahlung

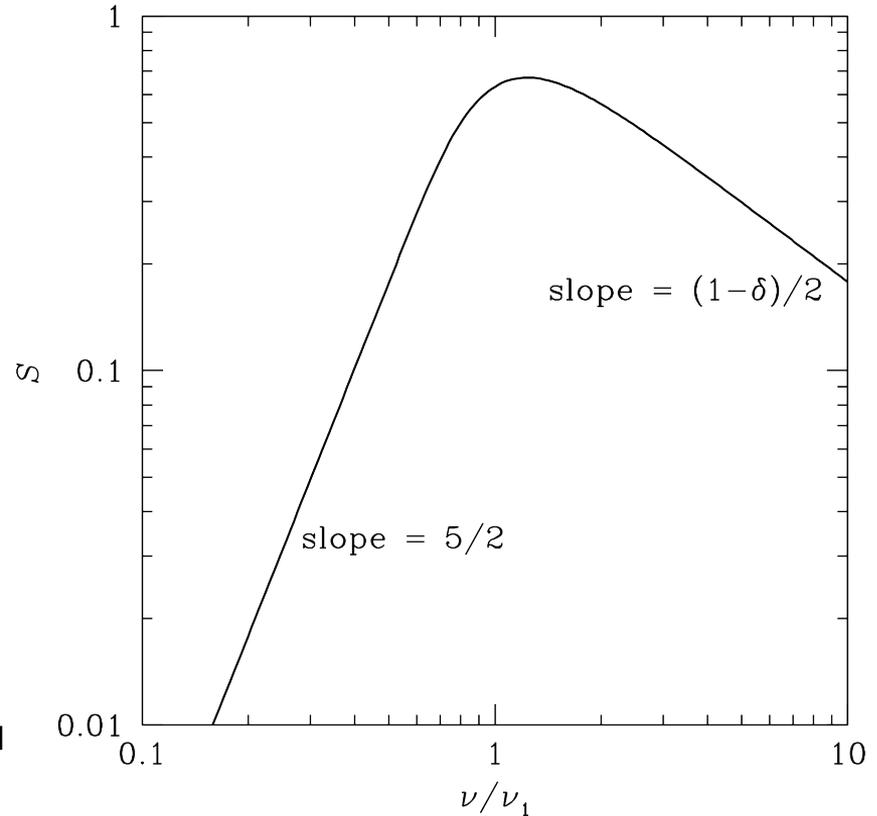
- Free - free emission due to motion of electron in an electrostatic field
- **HII regions:** regions of ISM where hydrogen is ionized
- **Star forming nebulae, planetary nebulae,** regions surrounding stars.



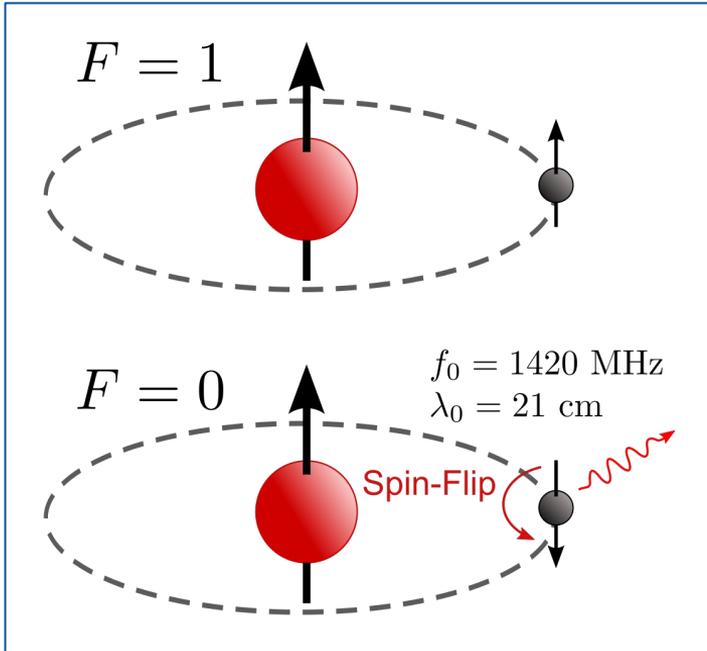
Synchrotron Emission

- Relativistic electrons moving in magnetic field
- Pulsars, Supernova remnants, AGN and their jets.

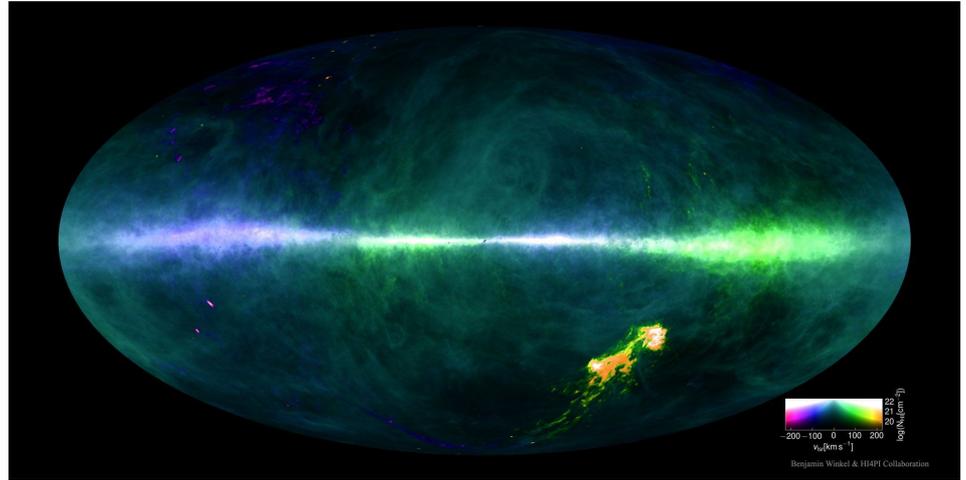
<https://www.cv.nrao.edu/~sransom/web/Ch5.html>



Spectral Line Emission



Electron spin-flip



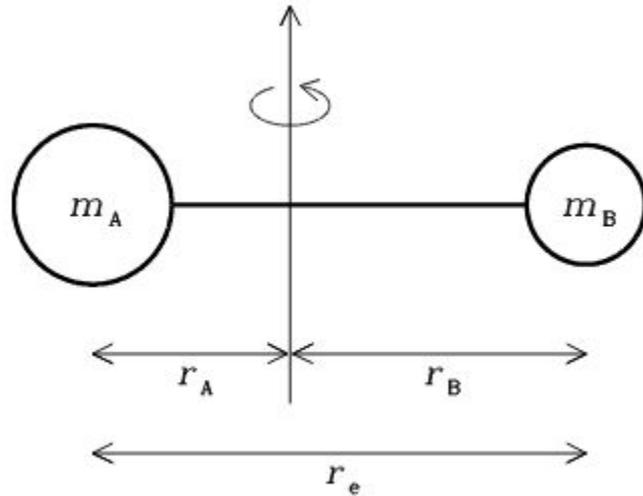
The All-sky map of the 21 cm hydrogen emission
(Benjamin Winkel & the HI4PI Collaboration)

Spectral Line Emission

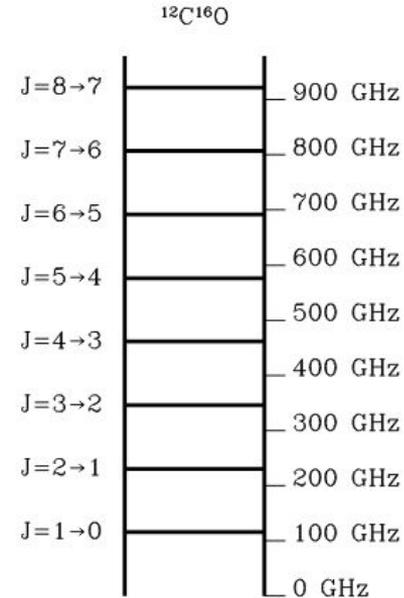
Atomic line emission:

- C II: ionized carbon (158 micron) tracing the warm neutral medium and photodissociation regions.
- O III: 88 micron, often used for measuring accurate redshift of high-z sources

Molecular Line Emission

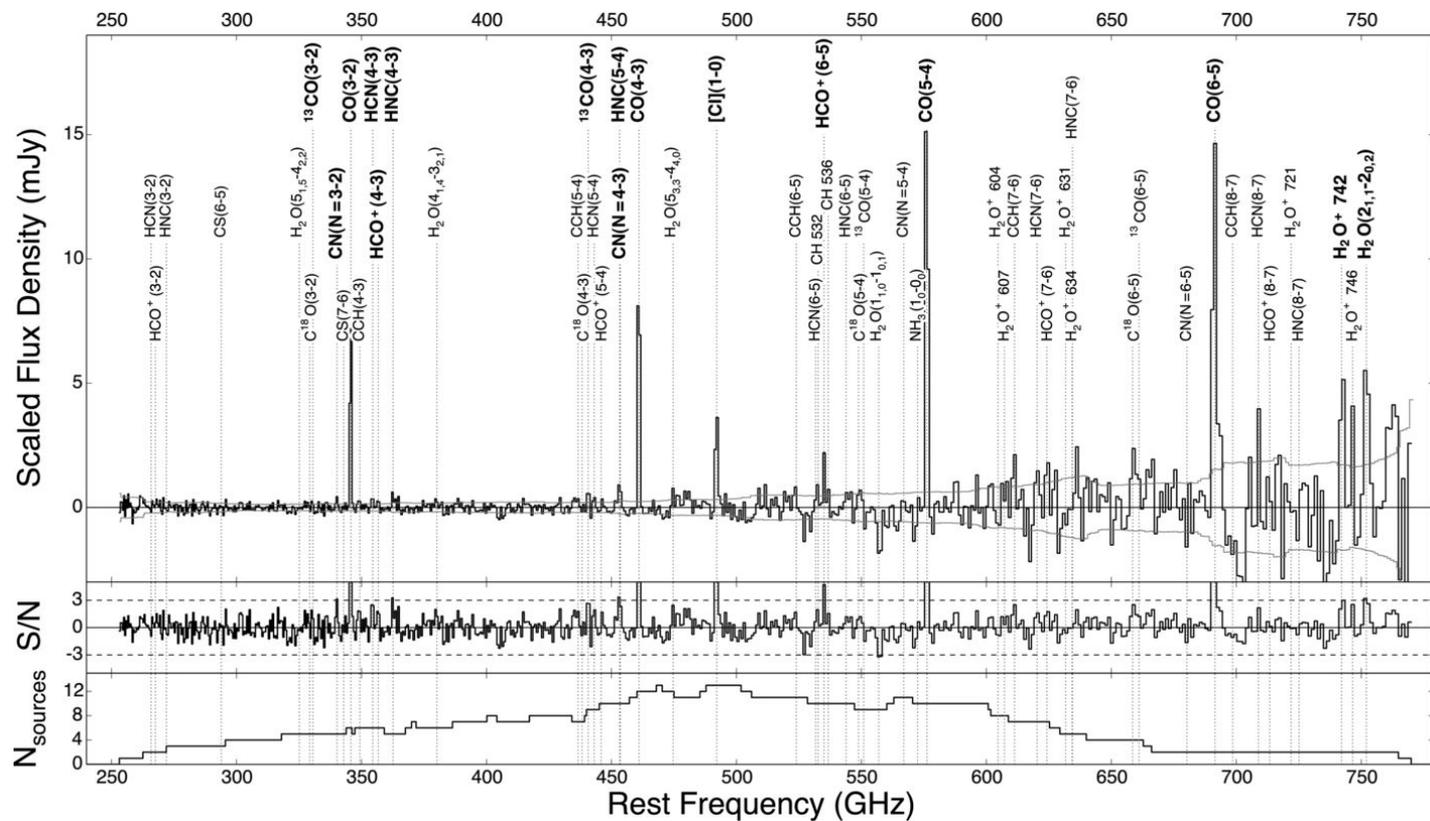


A diatomic molecule rotating about its center of mass.
<https://www.cv.nrao.edu/course/ast534/MolecularSpectra.html>



The spectral lines of the CO molecule
(Benjamin Winkel & the HI4PI Collaboration)

Molecular Line Emission



ALMA Science Capabilities

ALMA works best for:

- Cool Universe
- Cold molecular gas (interstellar medium, galaxies, AGN, Star forming regions etc.)
- Dust (High redshift galaxies, protostars, evolved stars, protoplanetary disks, nebulae etc.)
- Continuum (Synchrotron, free-free emission, SED fitting)
- Sun and the solar system.

ALMA Science Capabilities

ALMA provides:

- Very high angular resolution (the best possible resolution of 15 milliarcsec, better than HST, VLT and comparable with JWST).
- Incredible sensitivity (large collecting area and wide bandwidth).
- High spectral resolution (down to few m/s).
- Full polarization mode.
- Joint proposals with other observatories (VLT, JVLA, JWST).

ALMA Science Capabilities

ALMA Science is broadly divided in these 6 categories

1. [Cosmology and the high redshift universe](#)
2. [Galaxies and galactic nuclei](#)
3. [ISM, star formation and astrochemistry](#)
4. [Planet-forming disks](#)
5. [Stellar evolution](#)
6. [Solar system](#)

ALMA Science Capabilities

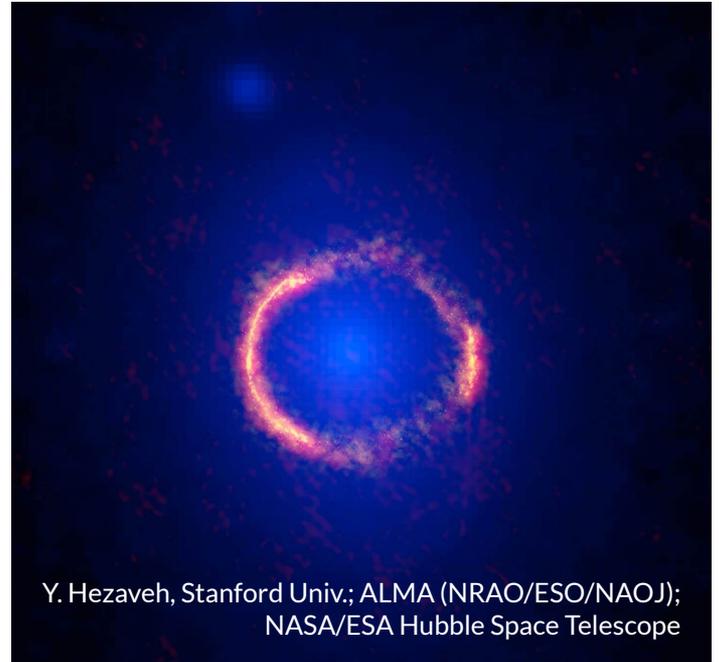
High-z Universe & Cosmology:

Goals:

- Galaxy Mass Assembly & Galaxy Formation.
- Evolution of Galaxies.
- History of Star Formation.

ALMA Capabilities:

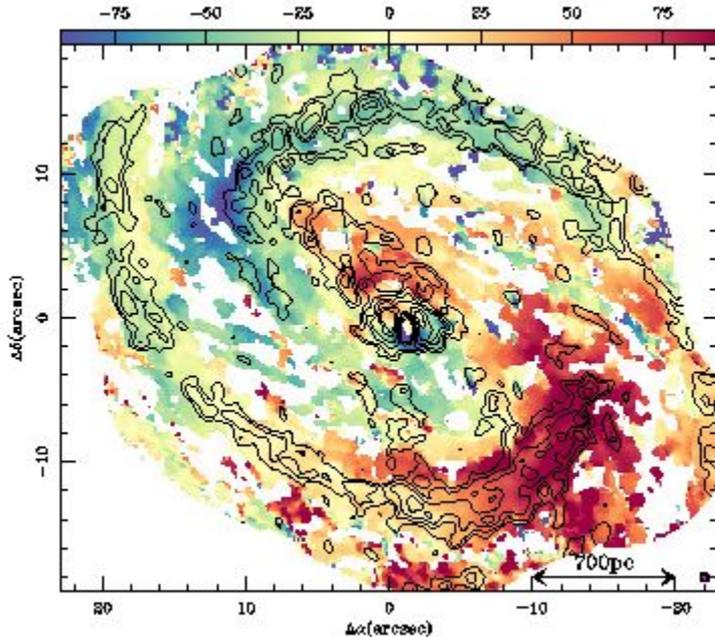
- Detection and imaging of FIR dust emission.
- Molecular line detection and imaging.
- Study molecular gas → Star Formation Reservoir.
- Study dynamical masses.



Y. Hezaveh, Stanford Univ.; ALMA (NRAO/ESO/NAOJ);
NASA/ESA Hubble Space Telescope

Galaxy SDP.81, bright orange part of ring shows glowing dust, diffuse glow is CO emission.

ALMA Science Capabilities



Molecular line emission in NGC 1068 imaged with ALMA: AGN driven outflow in dense molecular gas (Garcia-Burillo+14)

Goals:

- Excitation and dynamics of ISM
- Star Formation in Galaxies.
- Galaxy Mergers.
- Gas Infall & Molecular Outflows around AGN
- Dusty Torus in Galactic Nuclei

ALMA Capabilities:

- High Spatial Resolution (\sim parsec scale).
- High Sensitivity Molecular Line Observations.
- Trace Gas Kinematics with High Spatial and Spectral resolution.

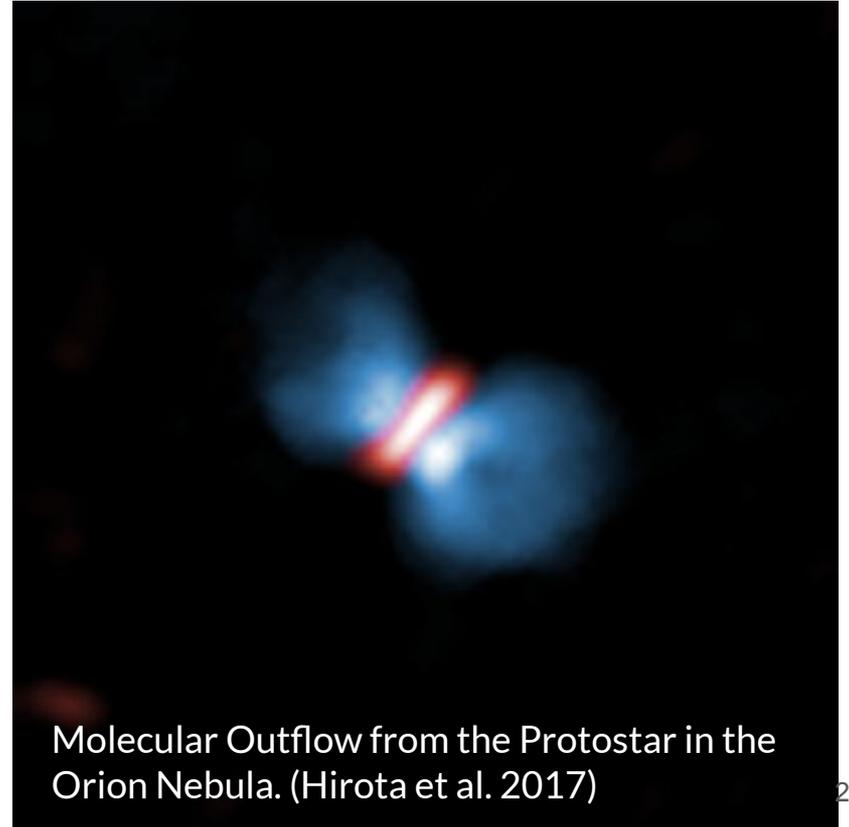
ALMA Science Capabilities

Goals:

- Study of Structure of Giant Molecular Clouds & Initial conditions of Star Formation.
- Observations of Young Stellar Objects.
- Dense Pre-stellar Cores that form Protostars.
- Magnetic Fields in Star Forming Clouds.

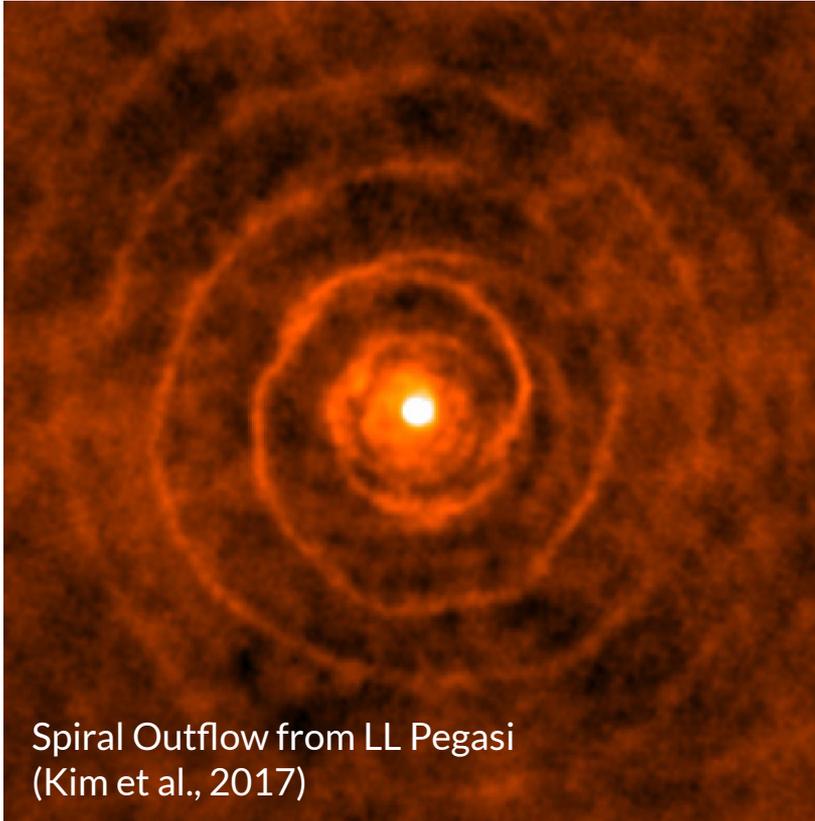
ALMA Capabilities:

- High Spatial Resolution ($\sim 1 - 100$ AU).
- High Sensitivity Molecular Line Observations with access to High Excitation Transitions.
- Millimeter Absorption Spectroscopy.
- Full Polarization.



Molecular Outflow from the Protostar in the Orion Nebula. (Hirota et al. 2017)

ALMA Science Capabilities



Spiral Outflow from LL Pegasi
(Kim et al., 2017)

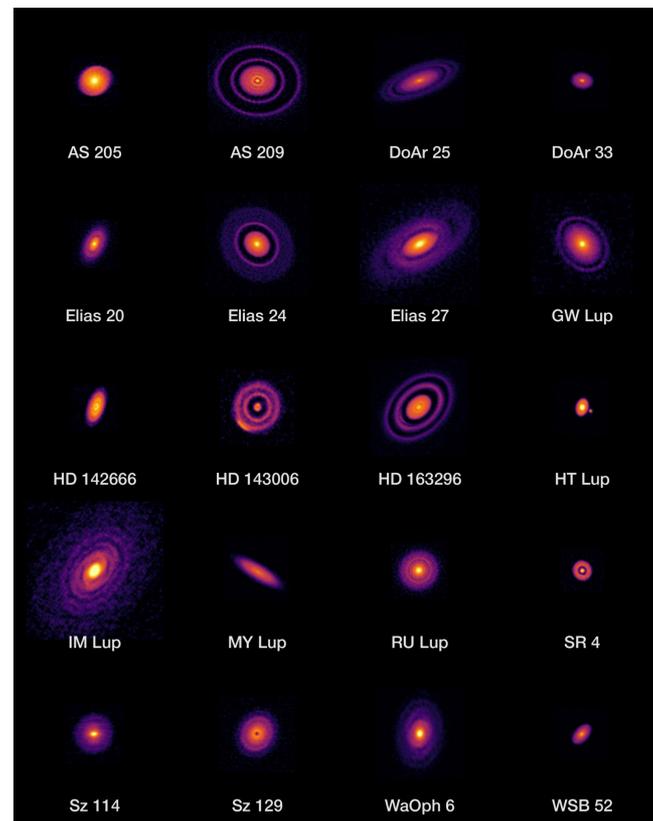
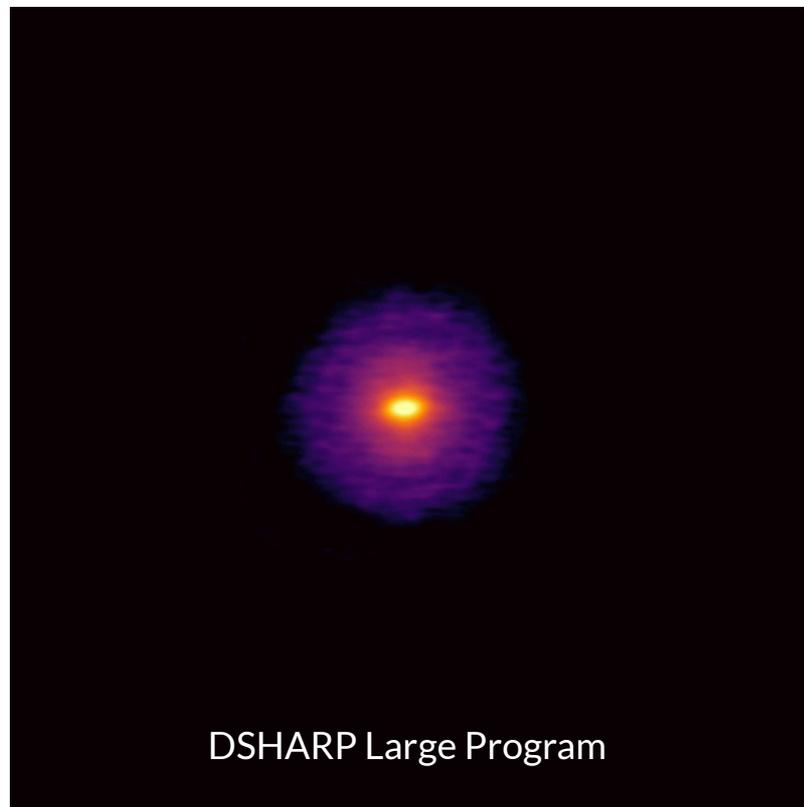
Goals:

- Wind Acceleration of Hot Stars, Be stars and other hot stars with shells
- Stellar Chromospheres of late type giants, supergiants and cool stars.
- Circumstellar envelopes and outflows
- Supernova Remnants & GRBs.
- Stellar Collisions.

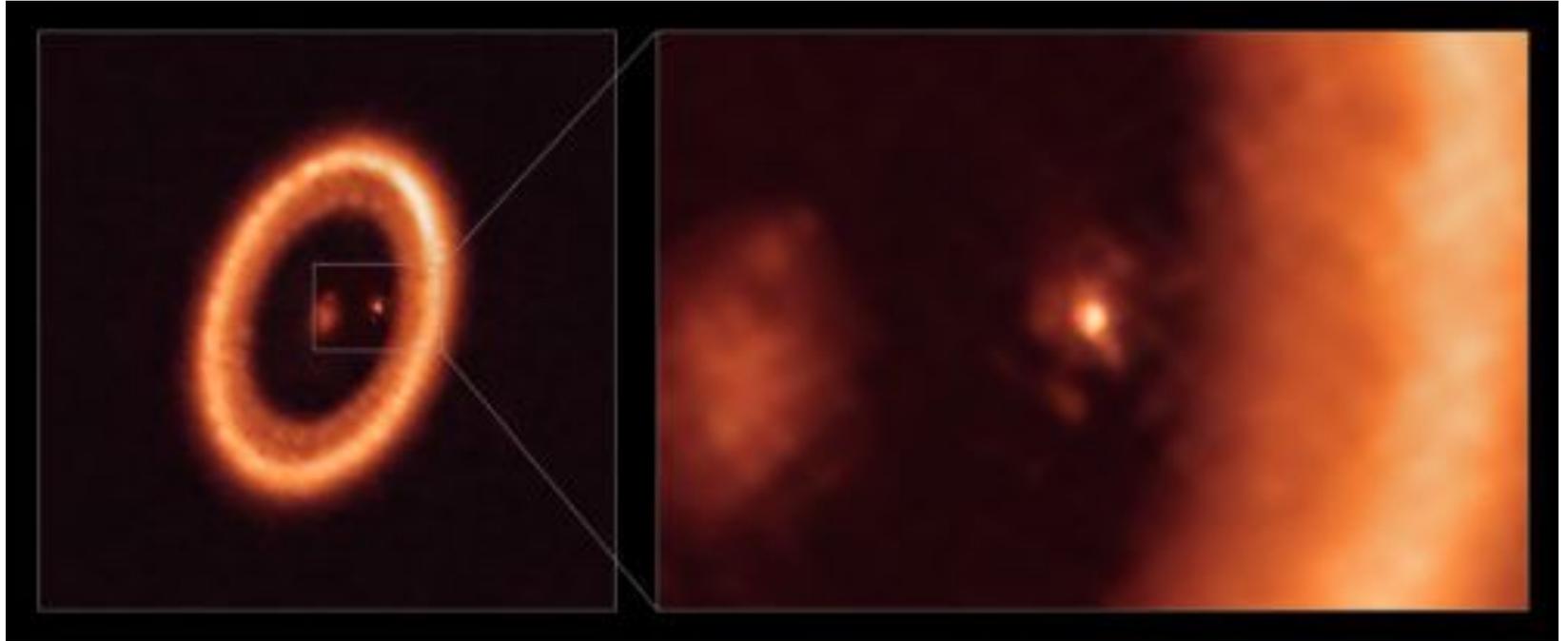
ALMA Capabilities:

- Resolve (sub)millimeter photospheres of red giants.
- Sample regions close to the stellar surface.
- Study outflow & wind nebulae from red giants.

ALMA Science Capabilities

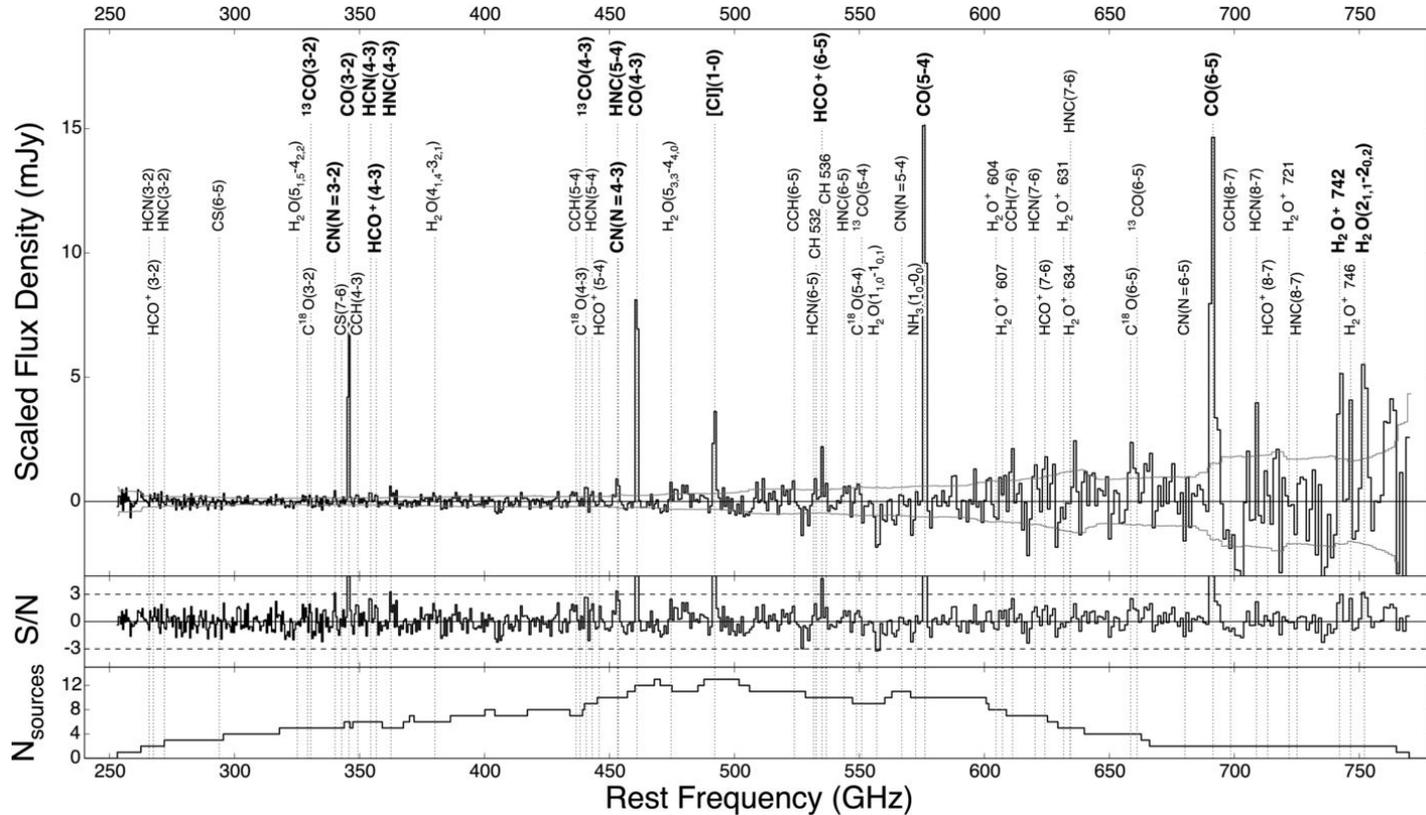


ALMA Science Capabilities

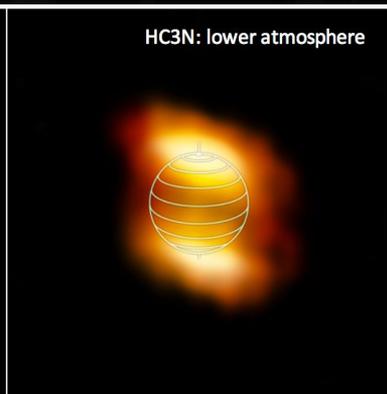
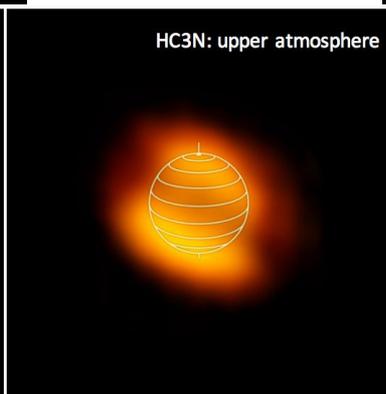
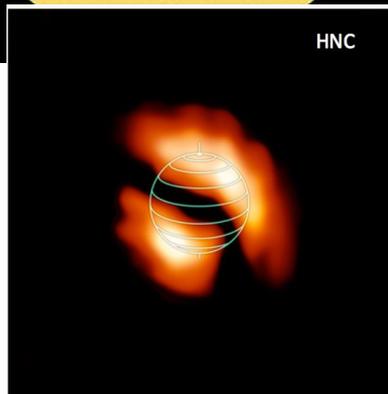
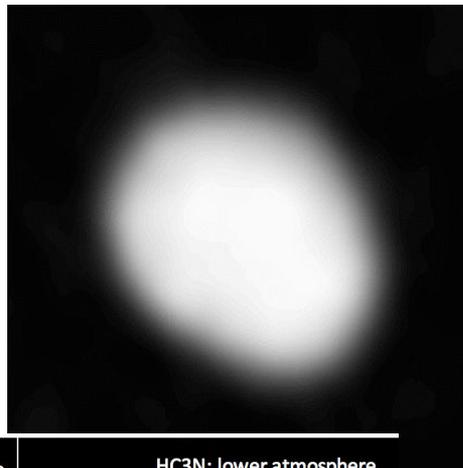
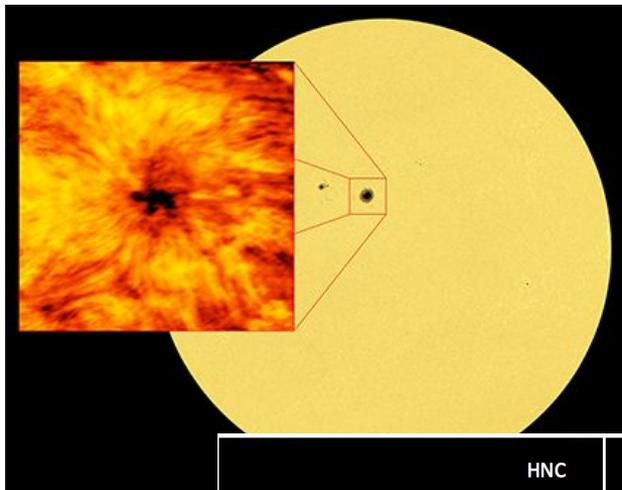


The moon-forming disc surrounding PDS 70c, a young Jupiter-like planet nearly 400 light-years away.
(Benisty et al. 2021)

ALMA Science Capabilities



ALMA Science Capabilities



What is ALMA?



~~Amazingly Large Manufacturer of Acronyms~~

Atacama Large Millimeter/submillimeter Array

- 3 different arrays together:
 - 12-m Main array - 50 antennas
 - 7-m Compact array (ACA) - 12 antennas
 - 12-m Total Power (TP) - 4 antennas
- Operating Frequencies:
 - Bands 1 - 10
 - 35 - 950 GHz

ALMA: An Organization



A Global collaboration between Europe, North America, East Asia and Chile

ALMA: An O

European ARC Network



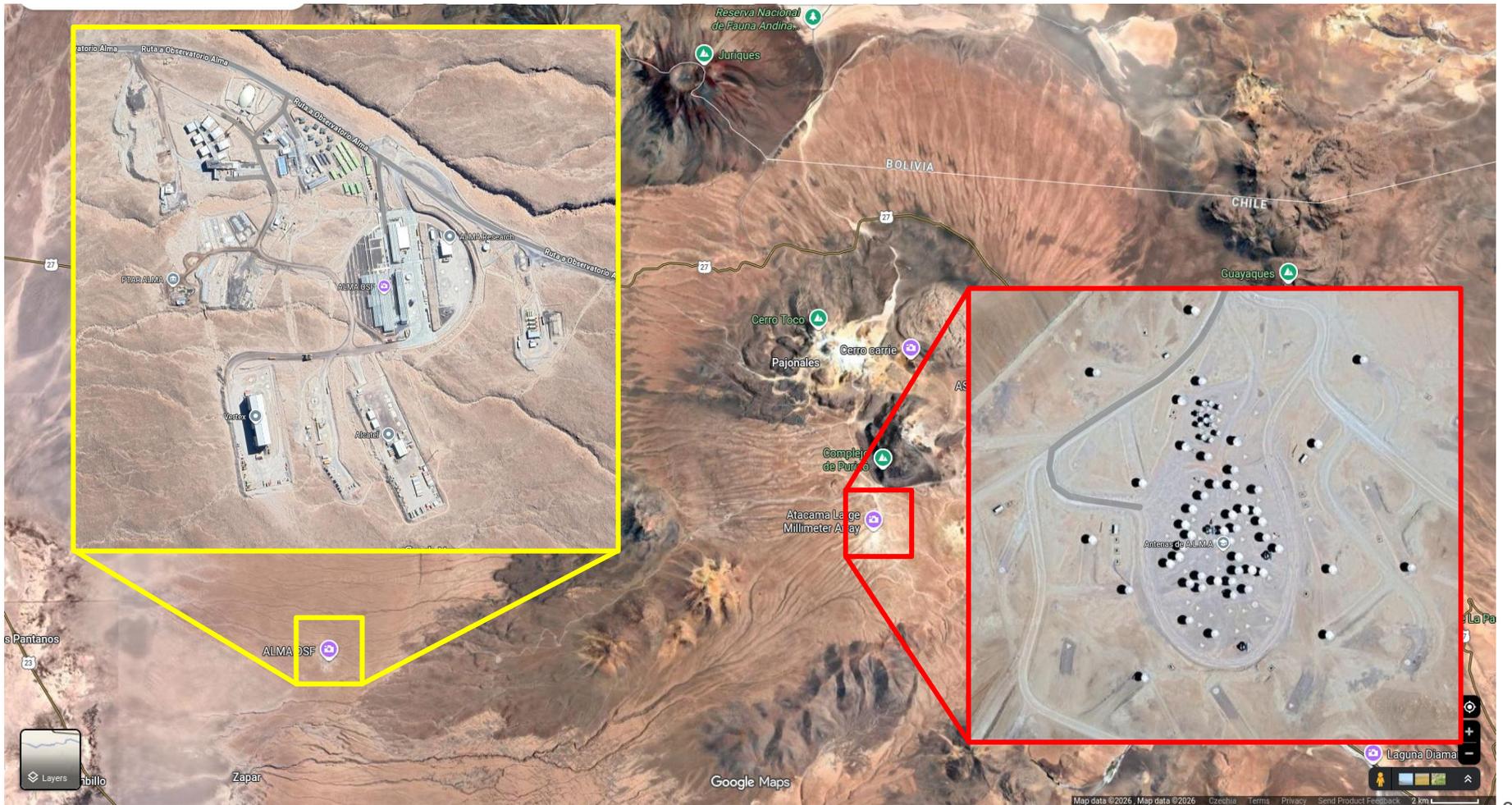
A Globa

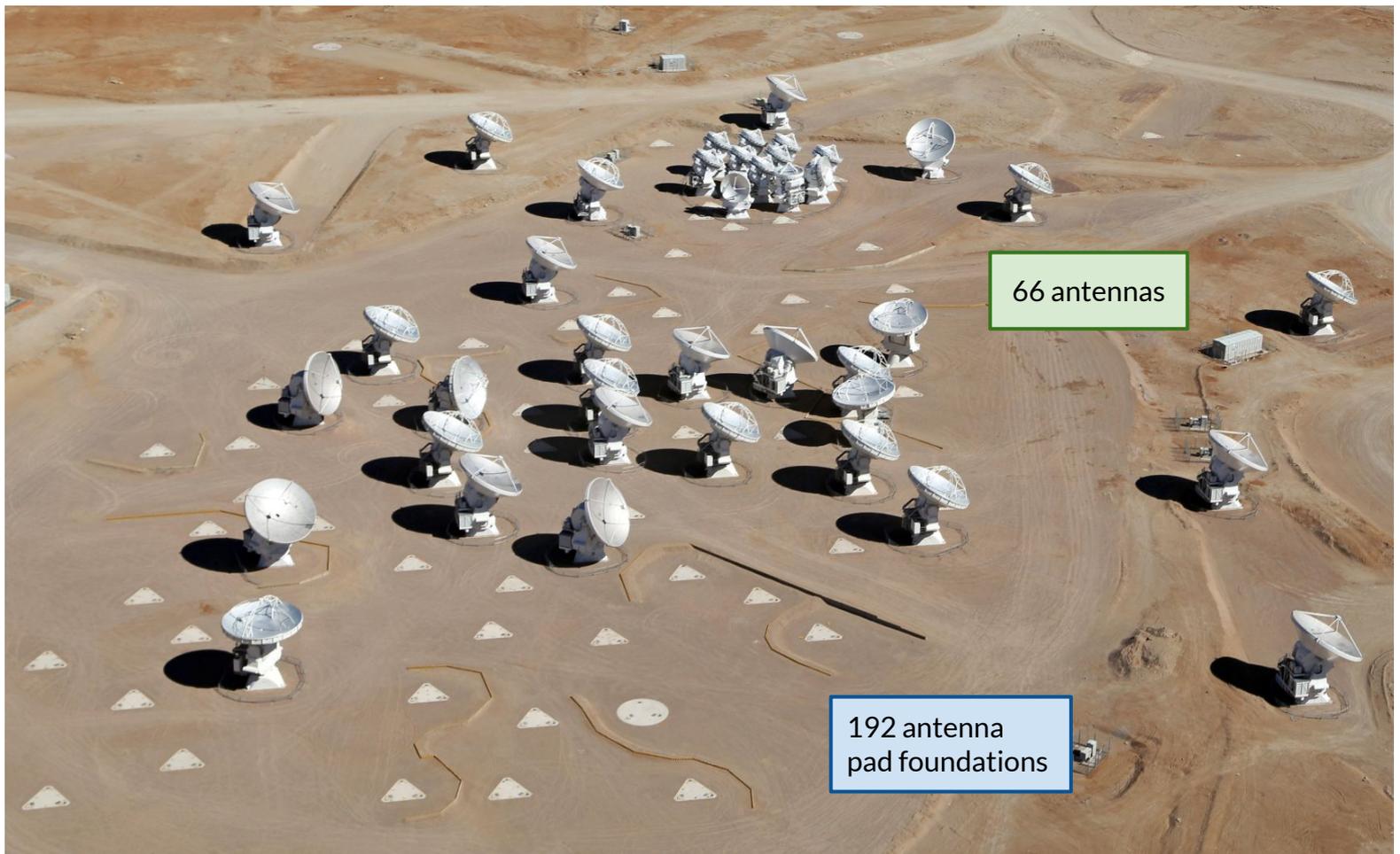
and Chile



Edinburgh of the Seven Seas

Sandwich Islands





66 antennas

192 antenna
pad foundations



The Array Operations Site



D. Schreiner and S. Degezelle (ESO)

The ALMA Correlator

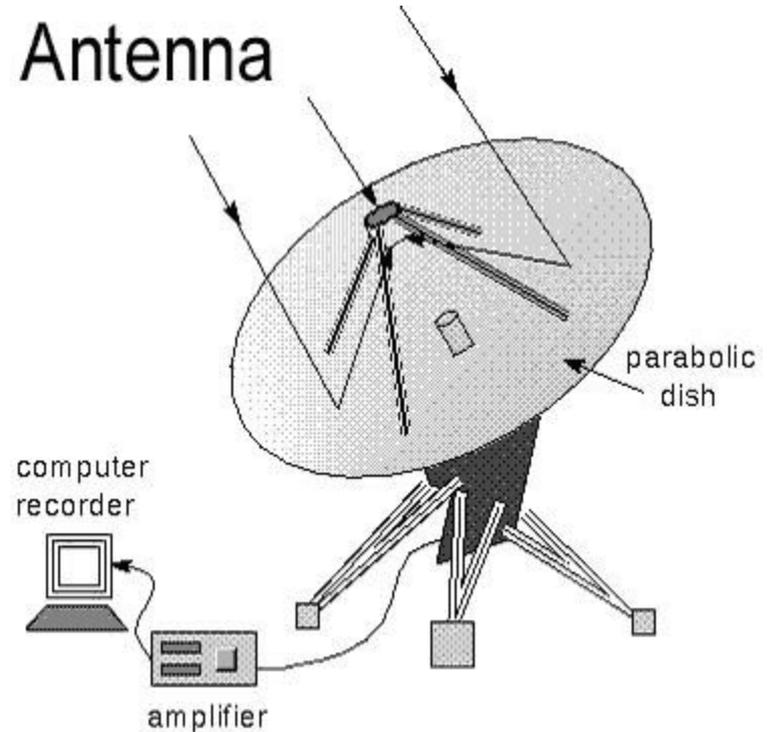


How does *ALMA* work?

A simple radio antenna

The resolution of a single dish radio telescope is given by

$$\theta = 1.22 \lambda/D \text{ (radian)}$$
$$= 2.52 \times 10^5 \lambda/D \text{ (arcsec)}$$

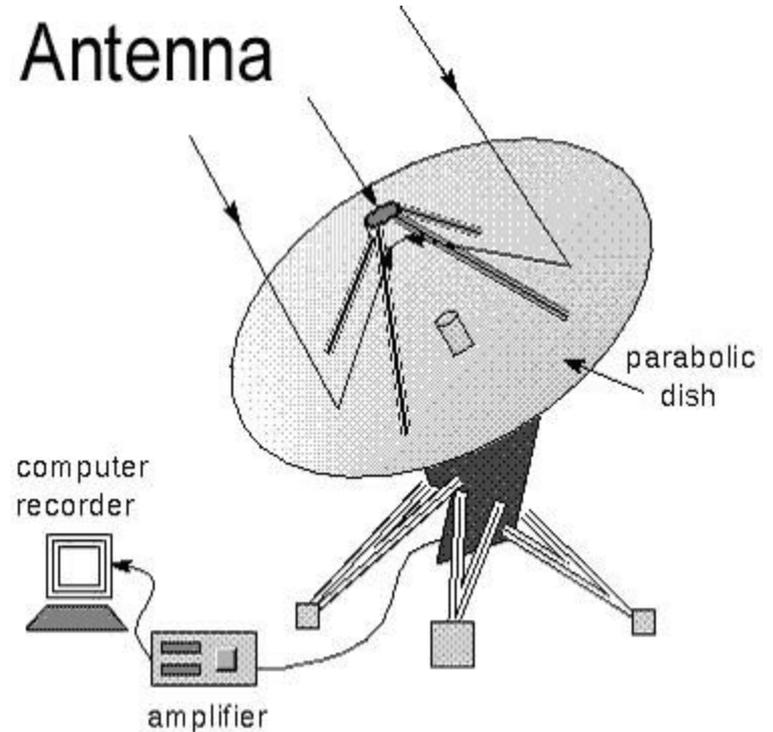


A radio telescope reflects radio waves to a focus at the antenna.

A simple radio antenna

Limitations of single dish radio telescopes:

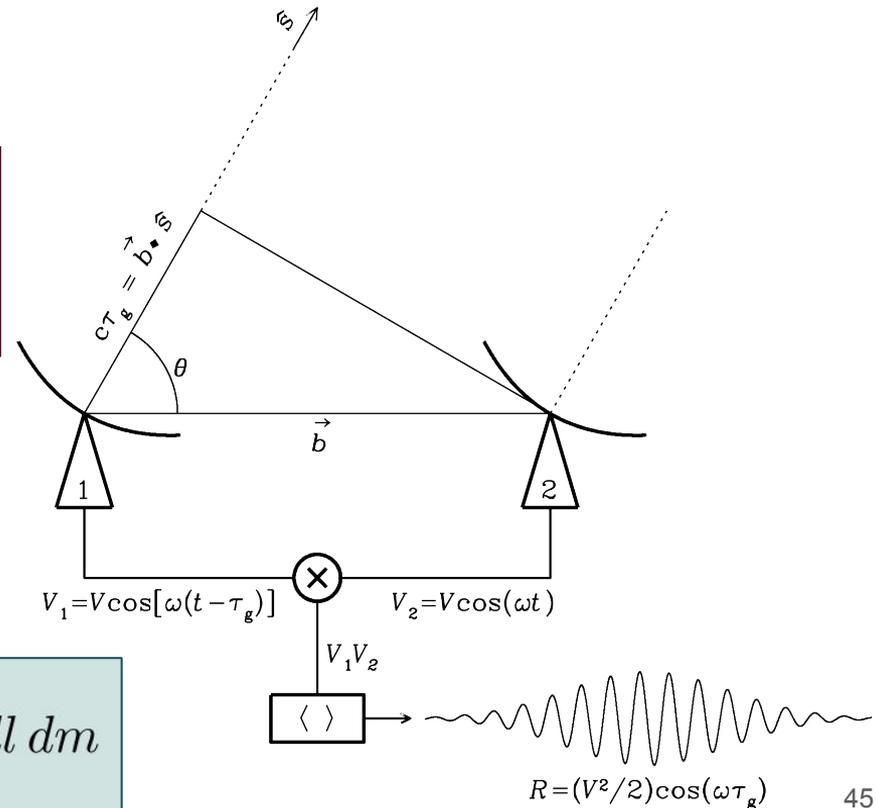
- Low angular resolution
- Larger antennas face major issues:
 - Tracking accuracy problem,
 - gravitational distortion,
 - solar heating



Interferometry

Magic and wizardry of maths and technology

$$\mathcal{V}(u, v) \approx \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I_{\nu}(l, m) e^{-2i\pi(ul+vm)} dl dm$$

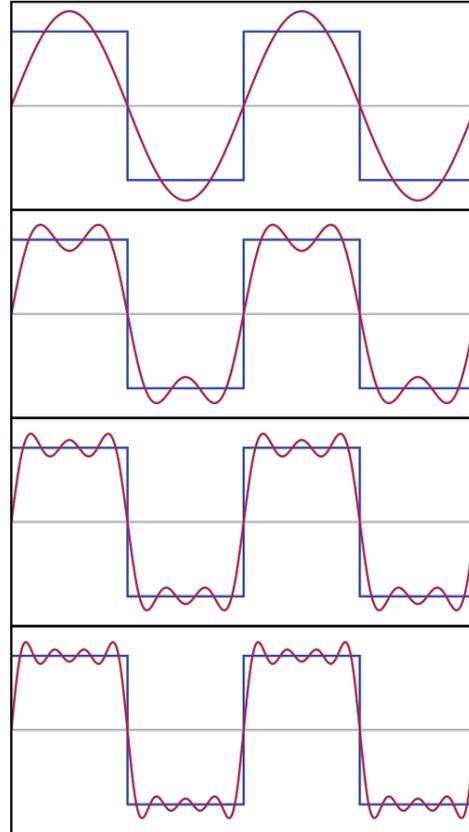


Interferometry

Fourier series

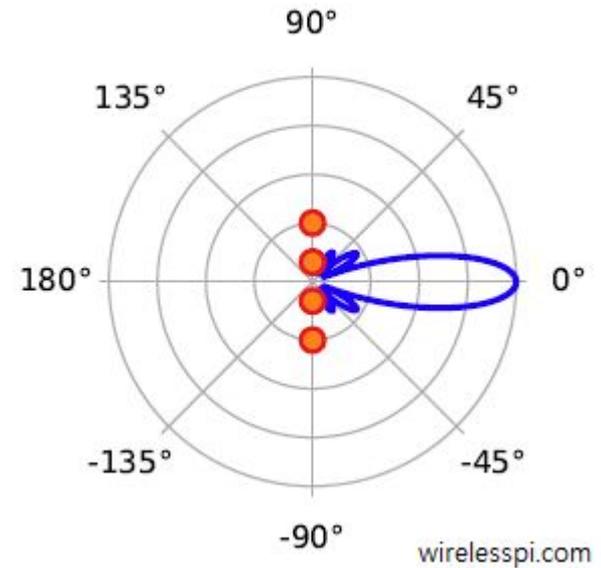
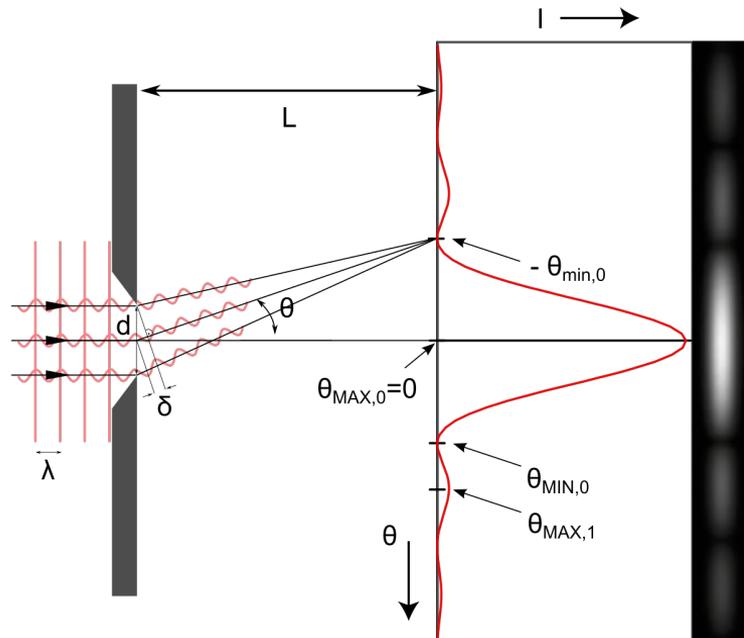
$$f(x) \sim \sum_{n=-\infty}^{\infty} c_n e^{-in\pi x/L},$$

Any well-behaved function
can be written as an
(infinite) sum of sines and
cosines

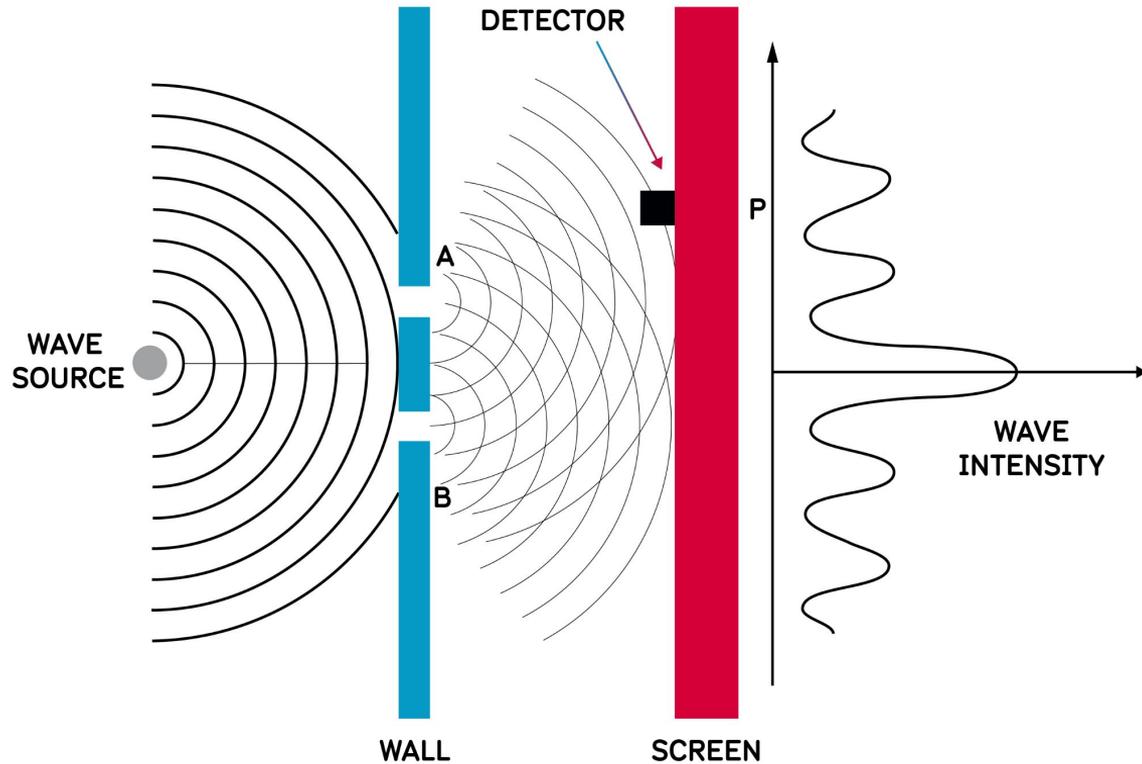


Interferometry

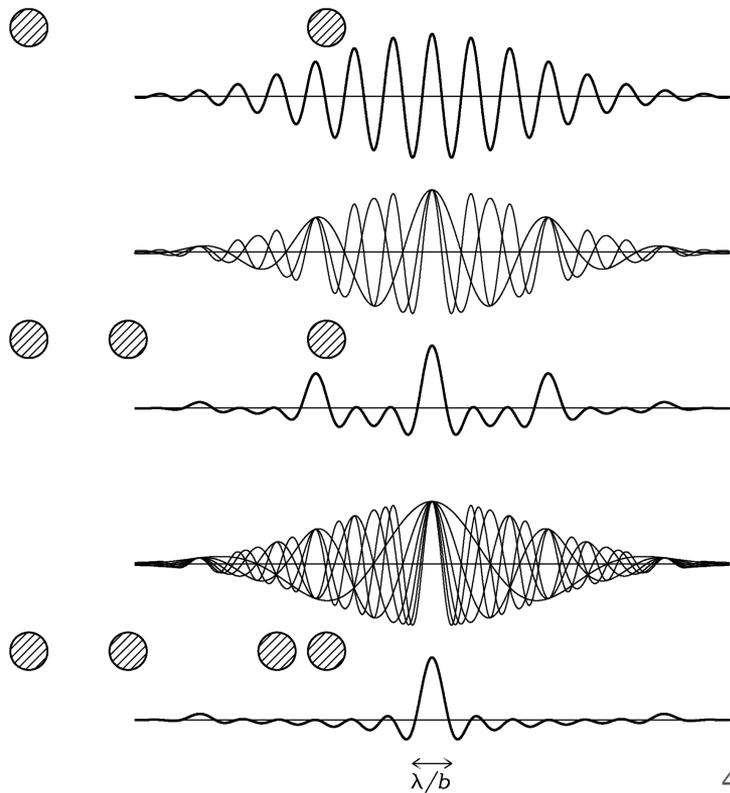
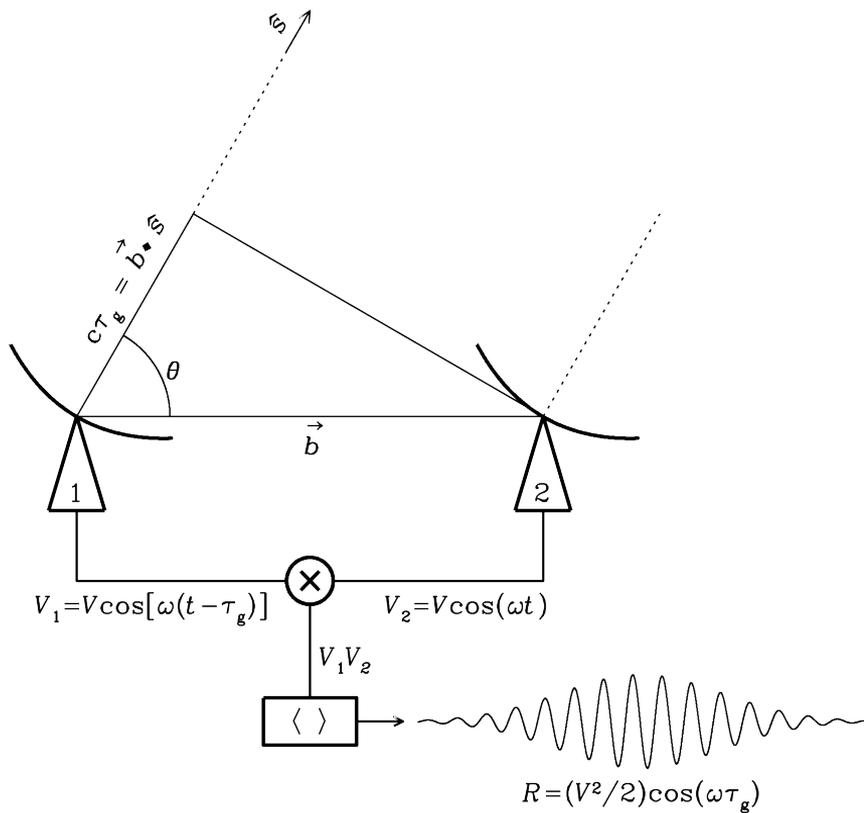
Single antenna response function



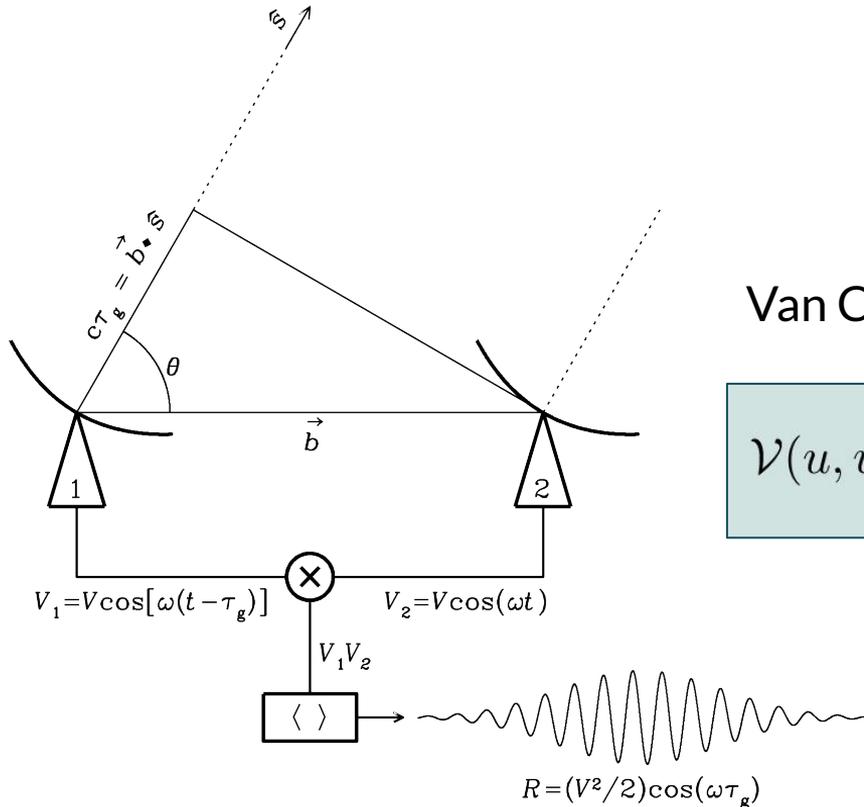
Interferometry



Interferometry



Interferometry



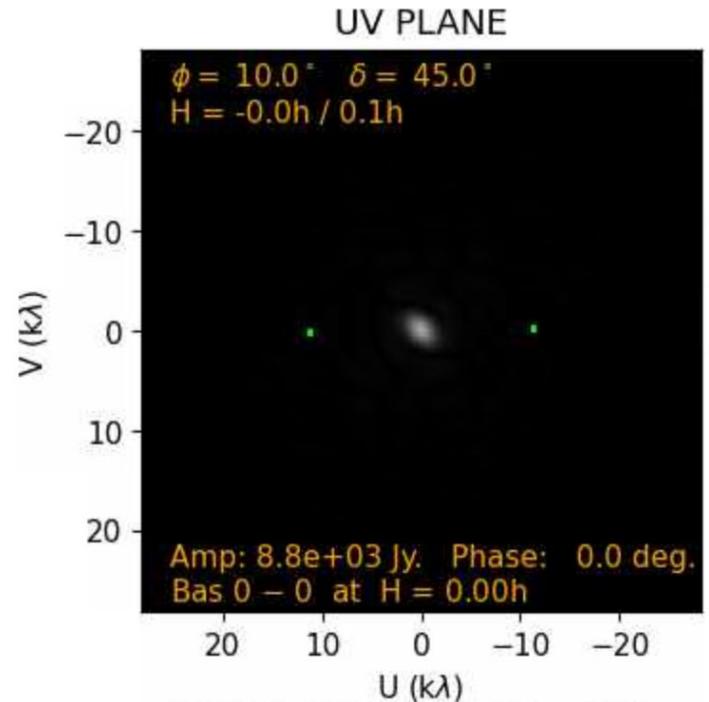
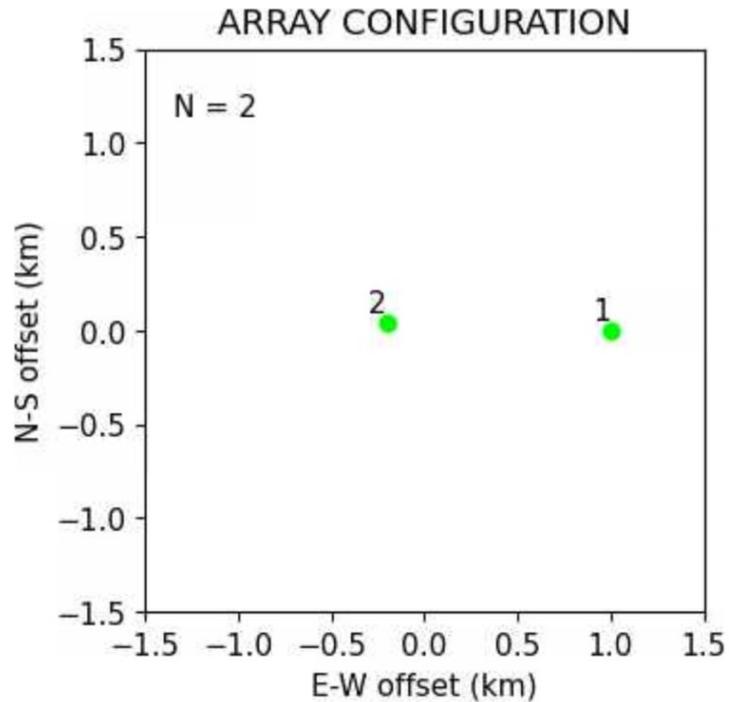
Van Cittert Zernike Theorem

$$\mathcal{V}(u, v) \approx \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I_{\nu}(l, m) e^{-2i\pi(ul+vm)} dl dm$$

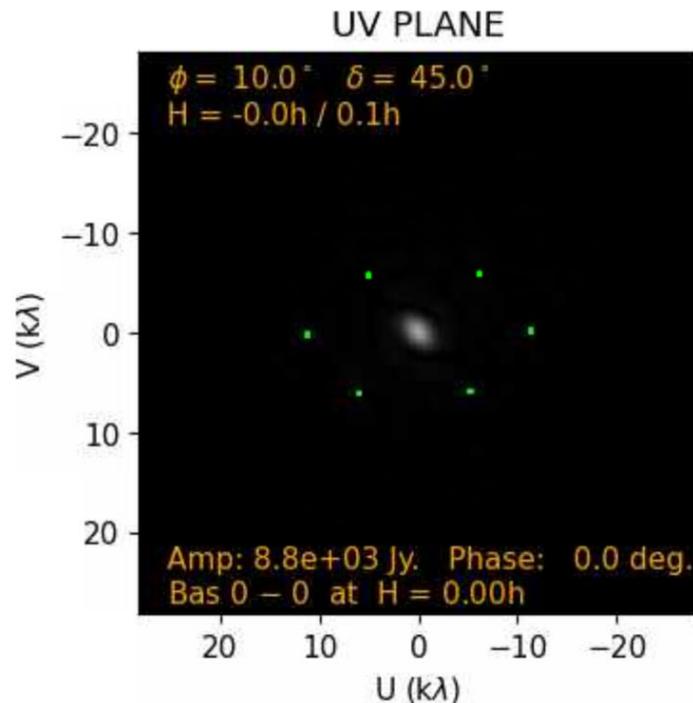
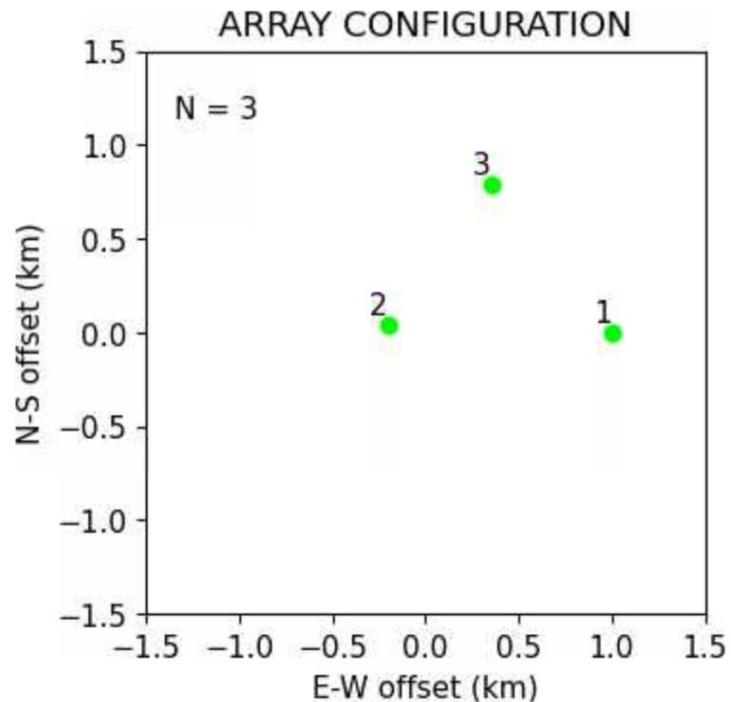
Aperture Synthesis

- Use a distribution of antennas to synthesize a telescope of a large aperture.
- The size of the synthesized aperture is determined by the largest separation between antennas.
- Earth rotation synthesis: source moves across the sky as the earth rotates. Each measurement adds to the UV-plane.
- Multi-frequency synthesis: u - and v - are measured in units of wavelengths. Observe in a broad frequency (wavelength) range to fill the UV-plane.

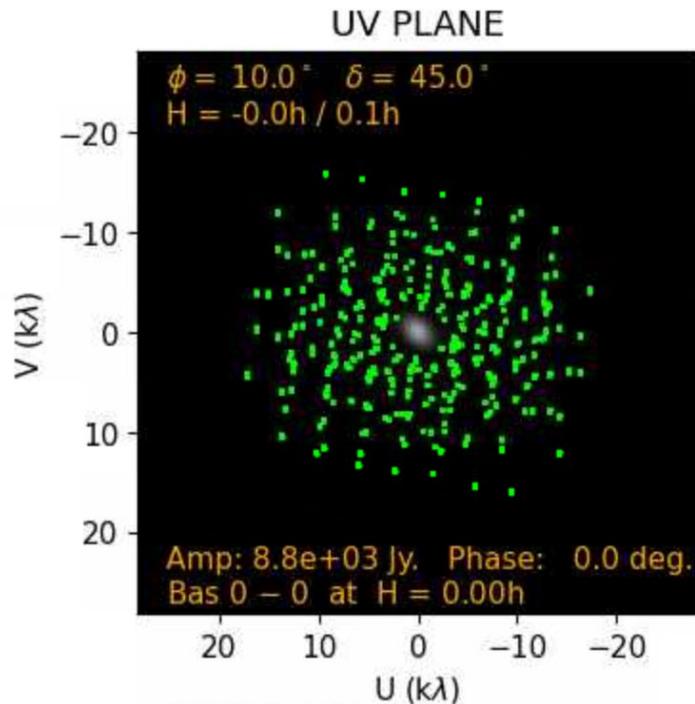
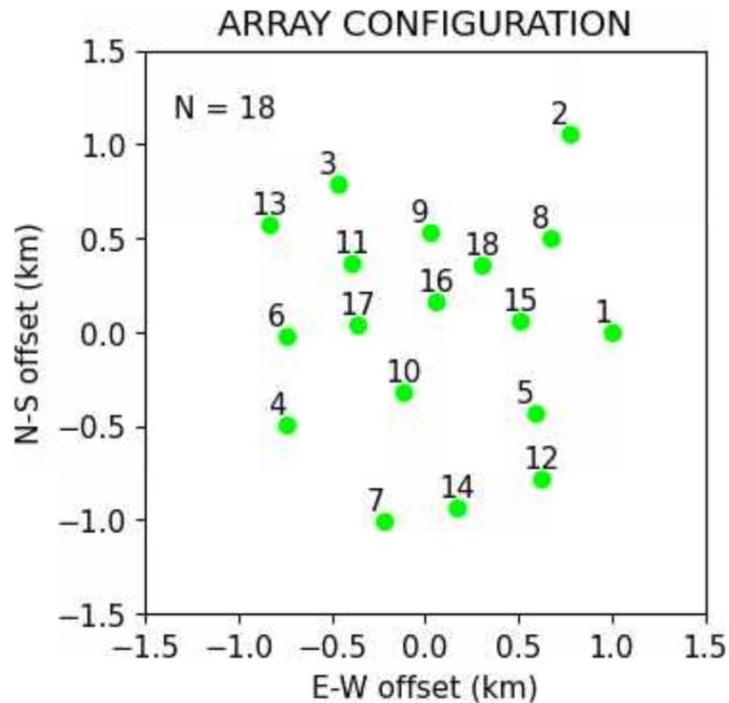
The UV-plane



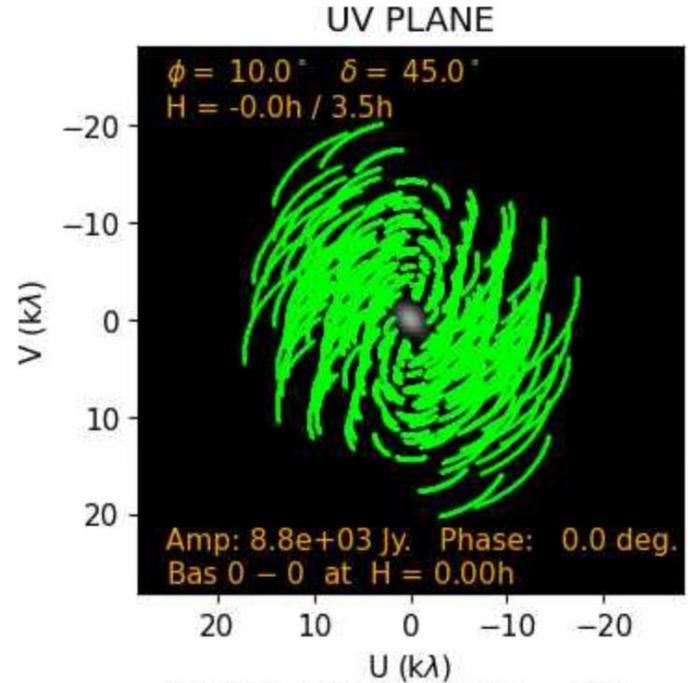
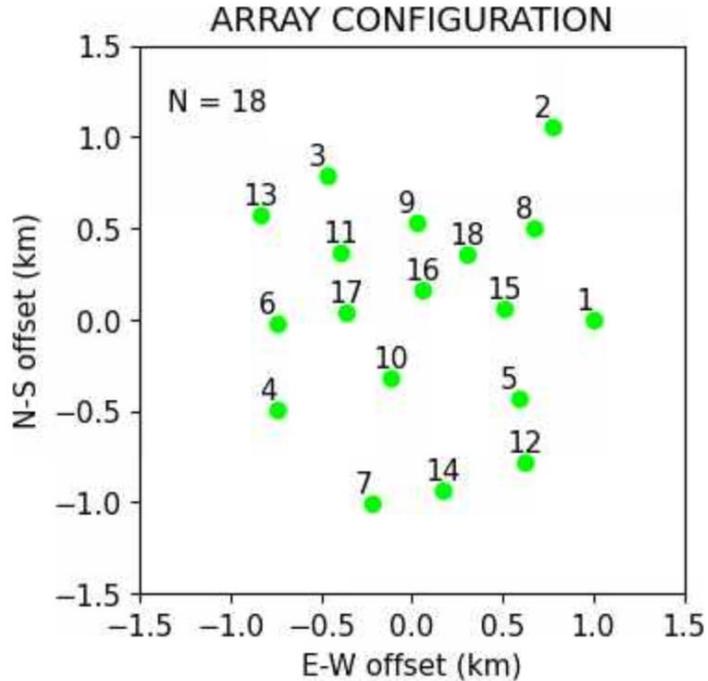
The UV-plane



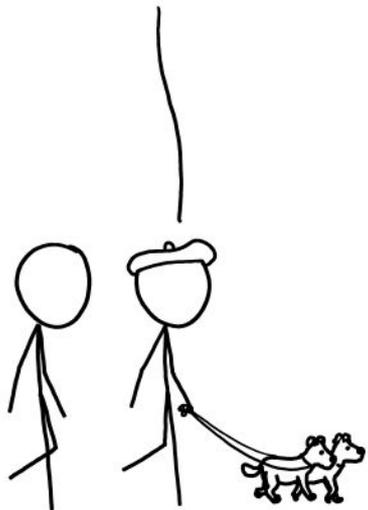
The UV-plane



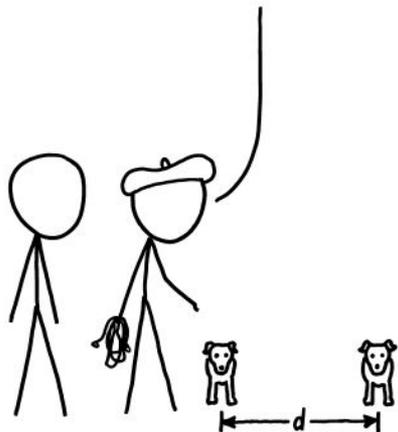
Aperture Synthesis



INTERFEROMETRY.
IS SO COOL!



IF YOU PUT TWO SMALL
DOGS A LARGE DISTANCE
APART, THEY CAN FUNCTION
AS A SINGLE GIANT DOG.



I'M NOT SURE THAT'S-

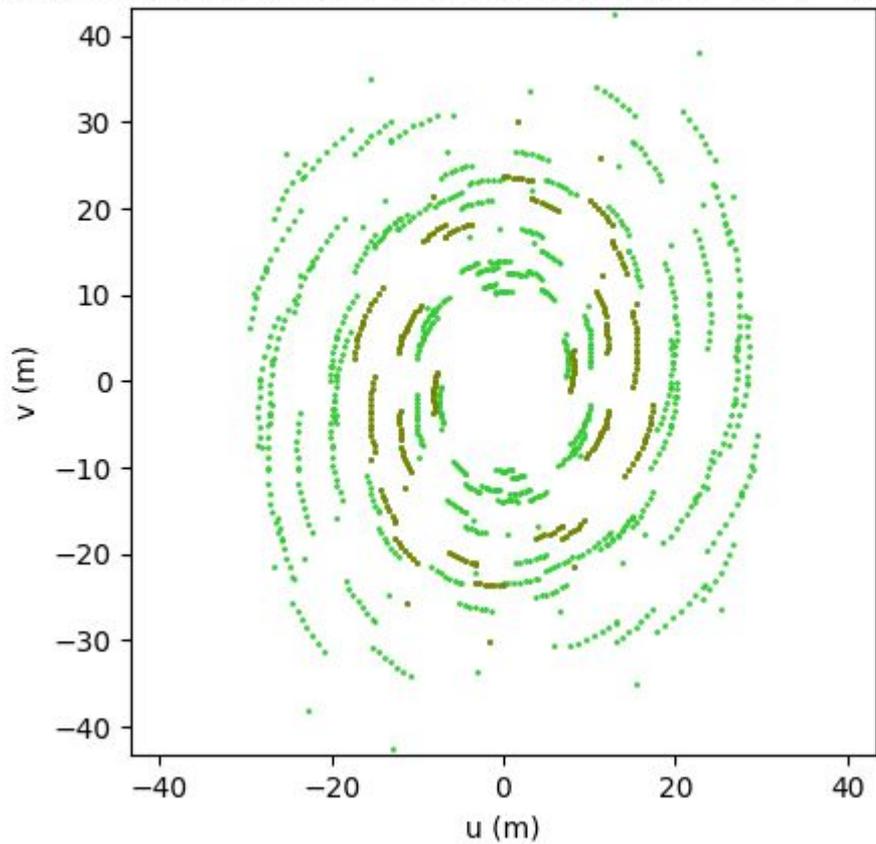
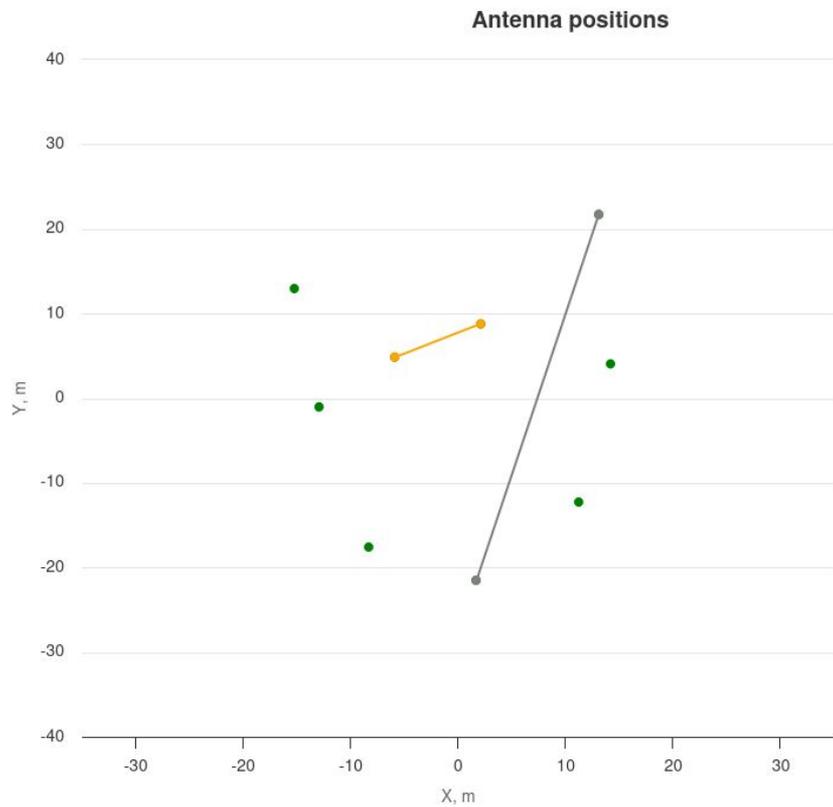


WOOF

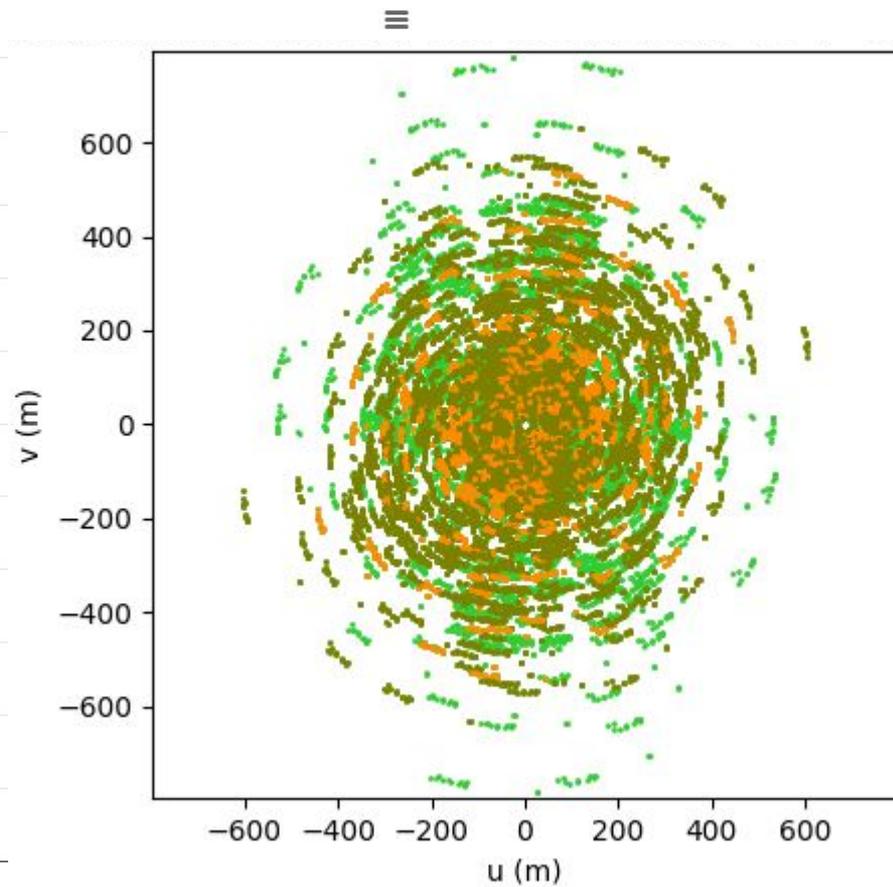
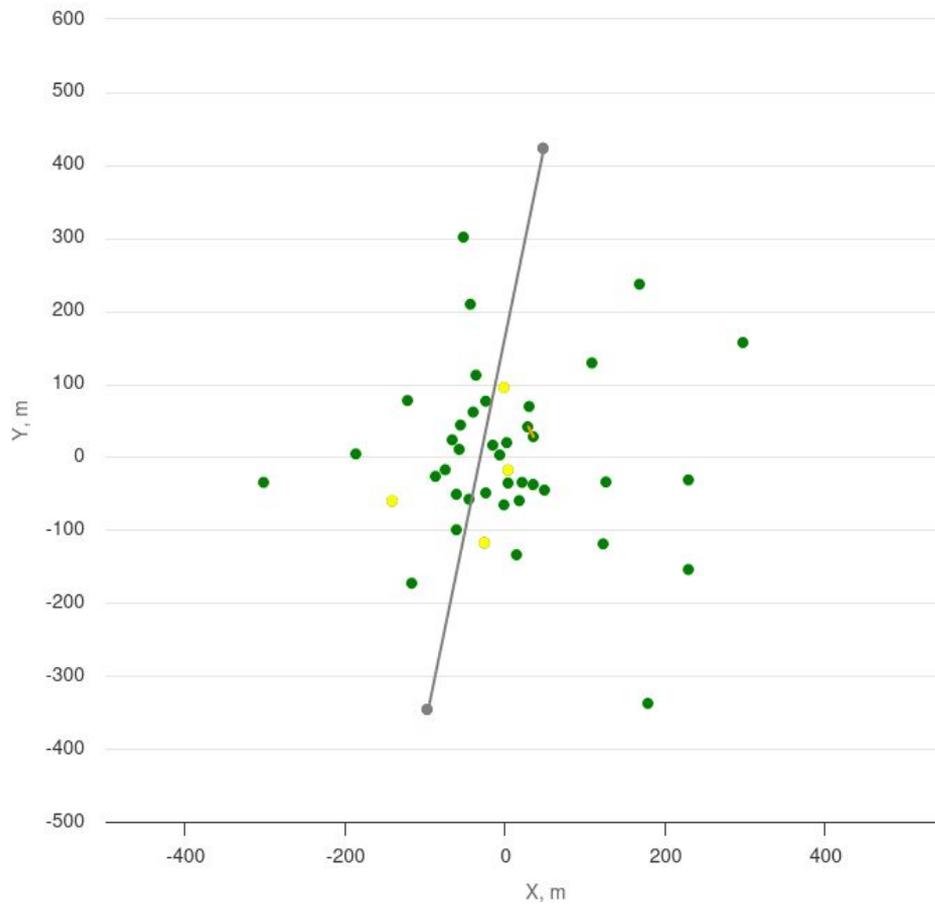
AWAY!



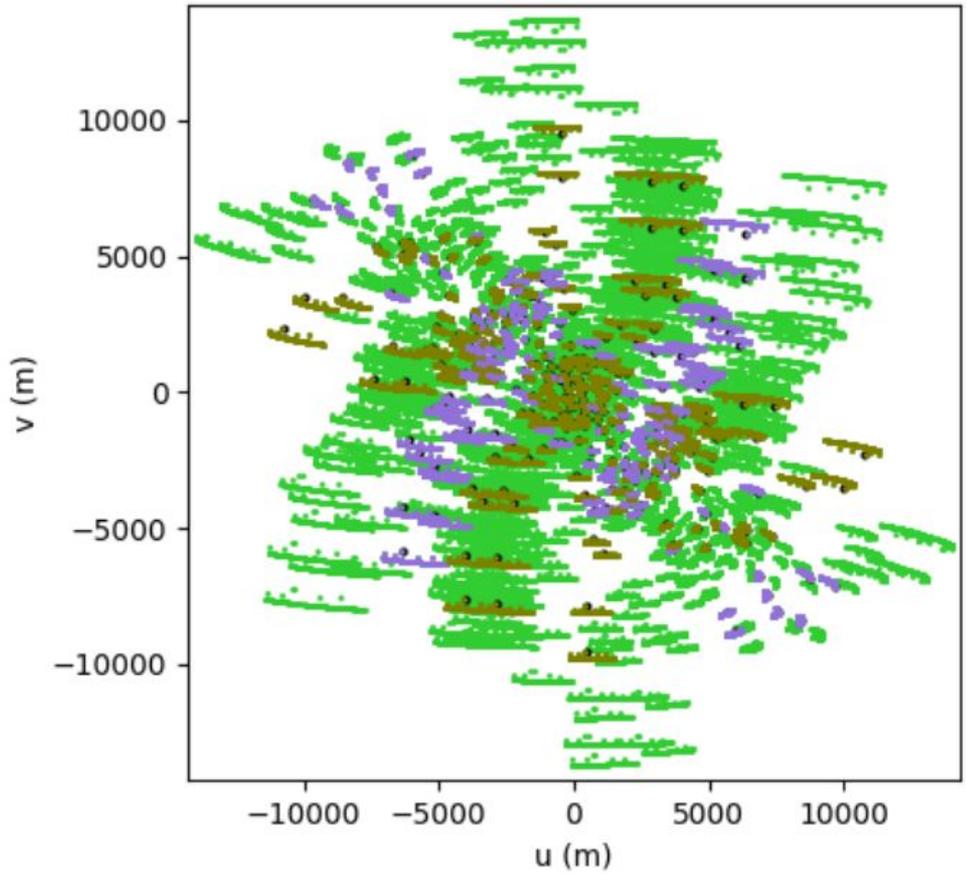
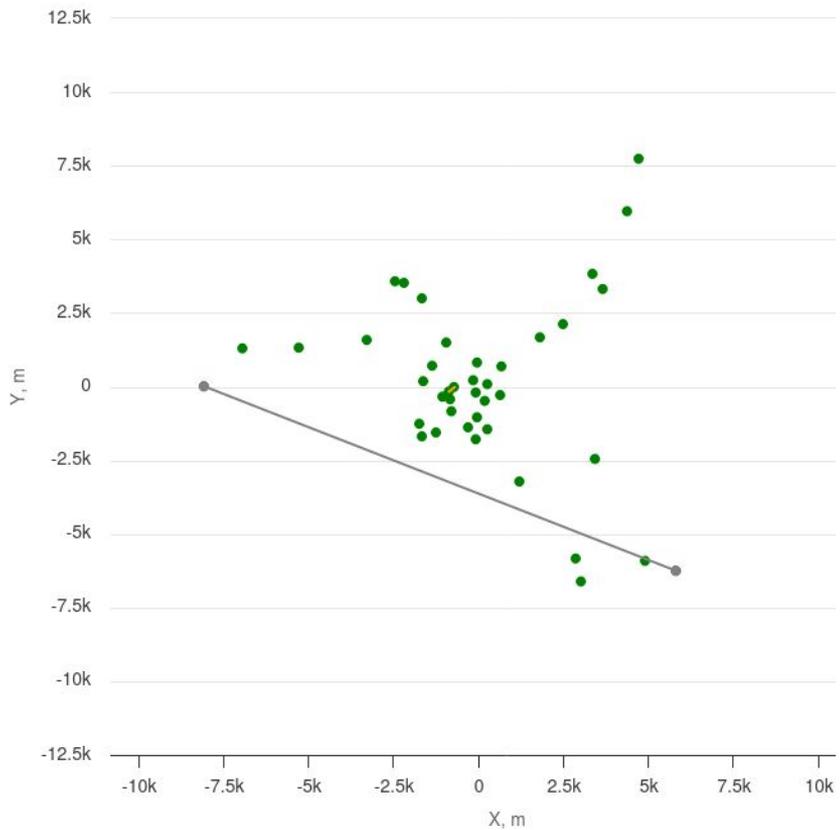
<https://xkcd.com/1922/>



Antenna positions



Antenna positions



Interferometry basics

Interferometry:

- Aperture synthesis: Combine antennas together to create a larger telescope.
- Collect EM Waves, not photons.
- Work in Fourier Space (complex visibility function is a Fourier transform of Sky Brightness).
- Complex calibration and imaging procedure, which can feel intimidating to new users.

Interferometry basics

Angular resolution (aka synthesized beam):

- The effective resolving power of the telescope, equivalent of a point spread function of an optical telescope.

$$\theta \approx 1.22 \frac{\lambda}{D}$$

Interferometry basics

Field of view (aka Primary beam):

- Angular sensitivity pattern of a radio antenna, which defines the field of view.
- Depends on the diameter of the antenna and the observing frequency.
- Few arcsec to arcmin.

Interferometry basics

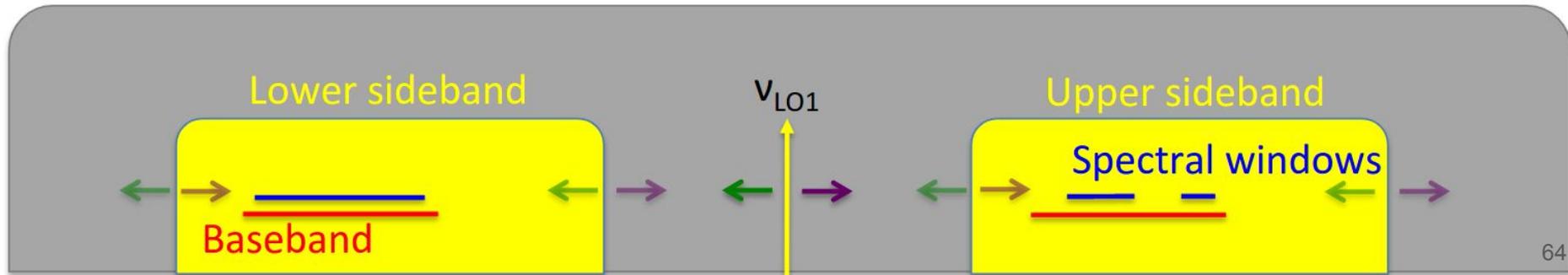
Maximum Recoverable Scale and Largest Angular Structure:

- The largest scale structures you can detect with a radio interferometer.
- Depends on the array and shortest distance between the antennas.
- Shortest baselines are sensitive to the largest structure on the sky, while long baselines “resolve out” the large scale structure and are sensitive to small scales and point sources.
- Small and large scale information can be extracted by combining arrays with different short and long baselines.

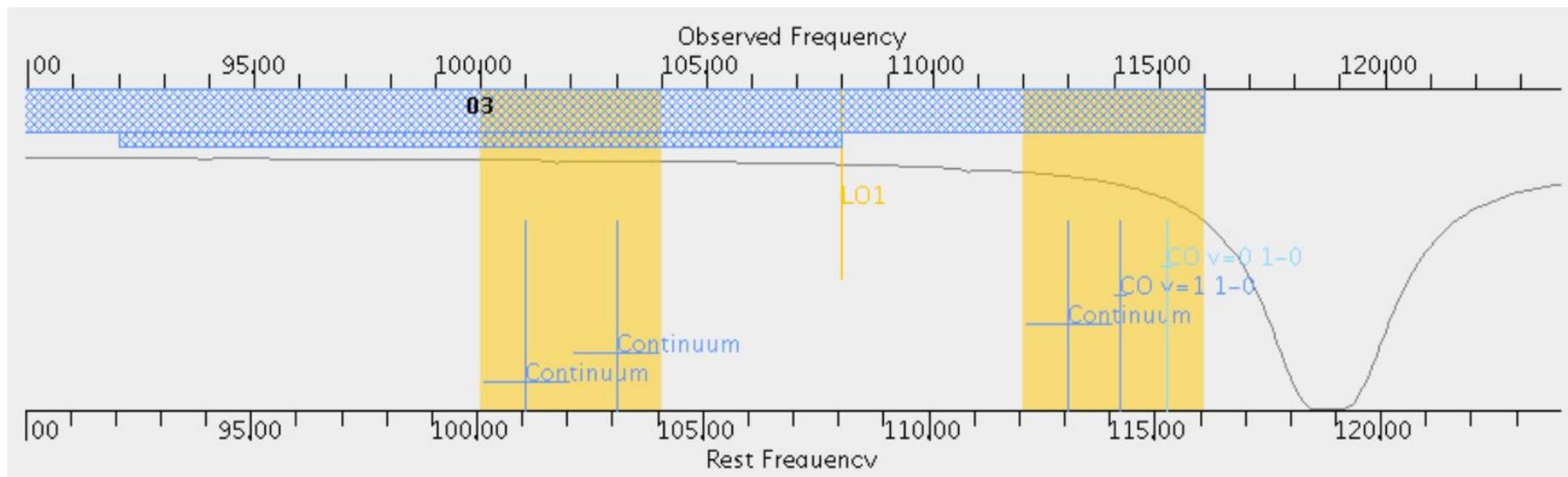
Interferometry basics

Spectral window

- User defined Central frequency, bandwidth, spectral resolution
- Can have variable width, can be placed anywhere within the baseband, and can overlap & be split.



Interferometry basics



Interferometry basics

Sensitivity:

- A measure of noise in the image.
- Relation between sensitivity & observation time depends on many factors (esp. Atmospheric conditions).
- Some observatories offer specific observation time (that you request), while others (like ALMA) guarantee a sensitivity limit (of your choice).

Useful Links

Radio Astronomy and Interferometry

- Essential Radio Astronomy by James J. Condon and Scott M. Ransom
<https://www.cv.nrao.edu/~sransom/web/xxx.html>
- Low Frequency Radio Astronomy (GMRT-TIFR)
<https://www.gmrt.ncra.tifr.res.in/doc/WEBLF/LFRA/index.html>
- Interferometry and Synthesis in radio astronomy by Thompson et al.

ALMA Help

- European ALMA Regional Center Nodes <https://www.eso.org/sci/facilities/alma/arc.html>
- ALMA Helpdesk <https://help.almascience.org/>
- ALMA Primer <https://almascience.nrao.edu/proposing/alma-science-primer>
- I-TRAIN with the EU-ARC Network <https://almascience.eso.org/tools/eu-arc-network/i-train>