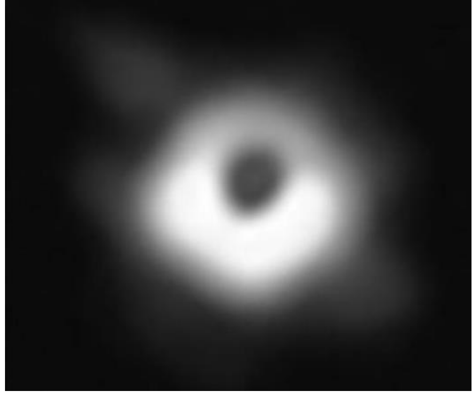
Radio Astronomy
ALMA -- Atacama Large Terahertz(mm) Array



Prof. Dr. Mehdi Khan, MEE, MD (Cont), PhD

Professor: Hunan university of Arts and Science

Senior consultant: Total Artificial Heart Transplant- United Christian Hospital, Peking Union Medical University

Senior consultant: RFIC, MMIC, ASIC, MCU, Nanotechnology, submm/mm for Radio Astronomy - Upplysning Robotics -- Chile (Claudio- **Professor** Universidad de Andes)

CTO & Co-Founder: Upplysning Robotics → Biomedical devices & Radio Astronomy devices.

CEO & Co-Founder: Aitemad Advanced Cardiovascular R&D Hospital → Total Heart transplant, LVAD & Cardiac Robotics surgery (Under Construction and Fund Raising)

Patron: Journal of Medical, Electronics & Mechanical circulatory support.

Patron: International society of Medical, Electronics & Mechanical circulatory support.

Radio Astronomy
ALMA -- Atacama Large Terahertz(mm) Array

- Background
- Apply Proposals Band 6,3 to study Jet structure black hole
- THz Advantage , Constraints, Applications
- THz Atmospheric, Sensors, Galactic, Benefit
- Types of Telescope
- Radio Astronomy, Interferometry, System
- Why Radio Astronomy
- ALMA
- Aperture synthesis , Frequency Synthesis, Rotation, Correlation
- Black hole, Black Hole in Galaxies

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Radio Astronomy

ALMA -- Atacama Large Terahertz(mm) Array

- Hawking Radiation
- Einstein’s Theories of Relativity
- Quantum loop theory, String theory overcome singularity
- Special Relativity
- Space Travel Near Black Holes
- Observational Evidence for Black Holes
- Test of General Relativity
- Roy Kerr Black Hole Equation for BH Model for image
- M87 → Video →VLBI Array
- Black Hole Sgr A*→ Kerr matrix BH, Cluster/average Image
- Polarization
- Summary , References

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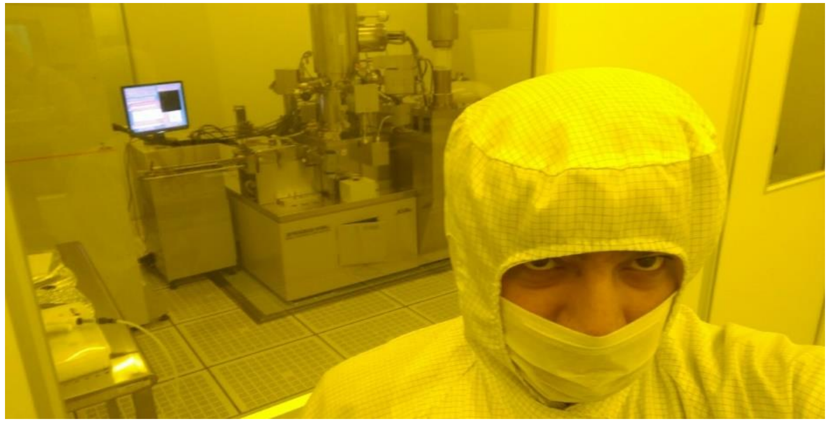
Worked THz ALMA→ joined Chalmers Lab JPL & OSL



JPL
Jet Propulsion Laboratory
California Institute of Technology

ALMA

Research paper on THz for ALMA

Quadrature Waveguide Coupler with H-plane Horn Antenna at 2.5 THz

Mehdi Khan[1],

[1] University of science and technology of China, [1] Upplysning Robotics SMC PVT LTD

The Atacama Large Millimetre/Submillimeter Array (ALMA), the most extensive astronomical undertaking to date, is a visionary telescope comprised of 66 high-precision antennas. Situated at an elevation of 5000 metres in northern Chile, the Chajnantor Plateau houses this revolutionary telescope. ALMA is a single telescope of revolutionary design, composed initially of 66 high-precision antennas and operating at wavelengths of 0.32 to 3.6 mm. Its main 12-metre array has fifty antennas, each measuring 12 metres in diameter, which together act as a single telescope—an interferometer. An additional compact array of four 12-metre and twelve 7-metre antennas complements this.

This paper talks about a waveguide structure that has a 450 µm × 90 µm quadrature waveguide coupler and a 2.5 THz H-plane Horn antenna. The coupler has a bandwidth of 3 dB. Analyse the quadrature waveguide losses while integrating the H-plane horn antenna and manipulating the skin depth thickness. It is applicable to balanced amplifiers, sideband-separating mixers, THz-balanced heterodyne receivers, power combiners, and dividers. By employing the FEM method and HFSS simulation, the design was optimised.

Radio astronomy receiver for 70-90 GHz HEMT amplifier vs. SIS mixer frontend

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Abstract:-
In this paper I compare performance of HEMTs amplifier and SIS Mixer for Radio Astronomy receiver at 70 to 90 GHz. The mixer noise temperature when using SSB, DSB, 2SSB, (Side-band) Modulation Technique and also compare Orthogonal mode for Dual Polarization

Introduction:-

HEMT:-
High electron mobility transistor (HEMT) was invented in 1980 by Mimura et al [1]. The Narrow bandgap HEMT is mainly utilized in low noise and low power applications. The most distinctive properties of HEMTs are their maximum frequency of oscillation Fmax and noise figure. The highest ever achieved Fmax among all types of transistors is based on 35 nm InGaAs/InAlAs/InP HEMT, and it is above 1 THz [2]. It also provides very high cutoff frequency and cutoff frequency more that 560 GHz is reported [3]. The noise figure provided by HEMTs is the lowest in microwave and millimeter-wave region with respect to other transistors. For instance minimum noise figure of 1.2-1.3 dB at 90 GHz can be obtained based on 150 nm InAlAs/InGaAs HEMT [4], which is excellent for radio space astronomy as amplifiers [5].

SIS:-
SIS (Superconductor-insulator-superconductor) a theory of superconductivity developed by Bardeen, Cooper, and Schrieffer in 1957. A SIS junction consists of two superconductors separated by a very thin (only several atoms thick) layer of insulator, typically an oxide. The three layers combination is referred to as a trilayer because they are usually made without breaking the vacuum [6]. The SIS junctions is limited to the high frequency sidb by gap frequency[7]. The sensitivity of SIS mixers is excellent among all type of submm mixers in their frequency range. The extensivly used superconducting material in SIS juncctions is Nb and aluminum oxides, e.g. *Al2O3*, AlO etc. [6] for inssulator. *Nb* has a transition temperature of about 9.6 K, and SIS devices based on it must be used at temperatures below 5 K. SIS junctions that are made of these materials are said to as Nb-AlOx-Nb junctions. The performance of an SIS mixer is limited by the gap frequency $F = 4\Delta/h$ which is about 1200 GHz for Nb-AlOx-Nb junctions. More than 1200 GHz, the conversion efficiency of SIS mixers degrades rapidly and other mixing principles or superconducting materials with higher energy gaps must be used. There is one more frequency limitations comes from the RF loss in superconducting microstrip lines above a frequency limit of $F = 2\Delta/h$. Above that frequency it becomes more difficult to compensate for the SIS junctions' geometric capacitance by using superconducting microstrip lines. The way to reduce the influence of the junction's capacitance is to use higher current densities. This would require a very small area junctions in order to keep reasonable value of *RN*. Electron beam pattern definition can than be used to make an efficient SIS mixer for frequencies above 1 THz.

Sideband:-

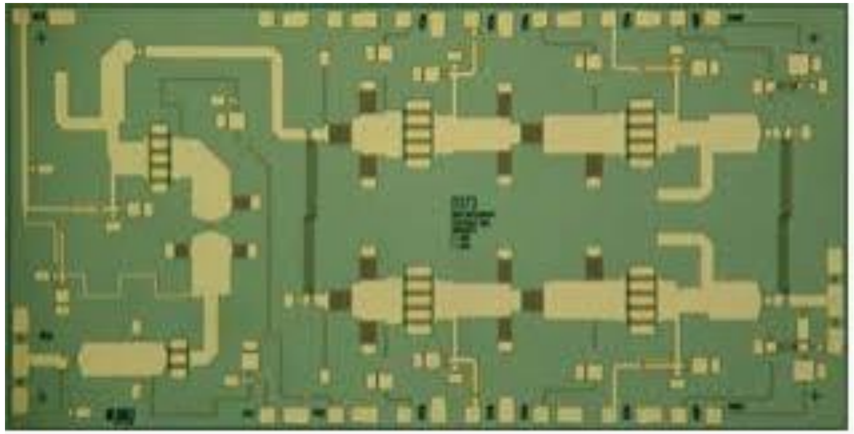
1.SSB:-
The concept of single side-band (SSB) that if you don't need two side-bands (LSB,USB) and get rid of one. To make that happen, you need to add a component to your system that removes the extra side-band. That component is called a band pass filter. Band pass filter remove the lower side-band (LSB) and the carrier from the spectrum. The remainder is transmitted. The receiver in a SSB system has its own carrier signal (from a local oscillator) that is puts back in. By eliminating the duplicated side-band and carrier from transmission, the bandwidth has been reduced by half. The formula for predicting bandwidth in a SSB system is $BW = f_m$, where f_m is the maximum modulating frequency used. By reducing the bandwidth transmitted, you may put double the number of channels (or stations) in the same frequency band.
SSB cuts the bandwidth in half and improves the efficiency to nearly 100% .You must add a band pass filter to the transmitter and a local oscillator to the receiver to make a conventional system into SSB.

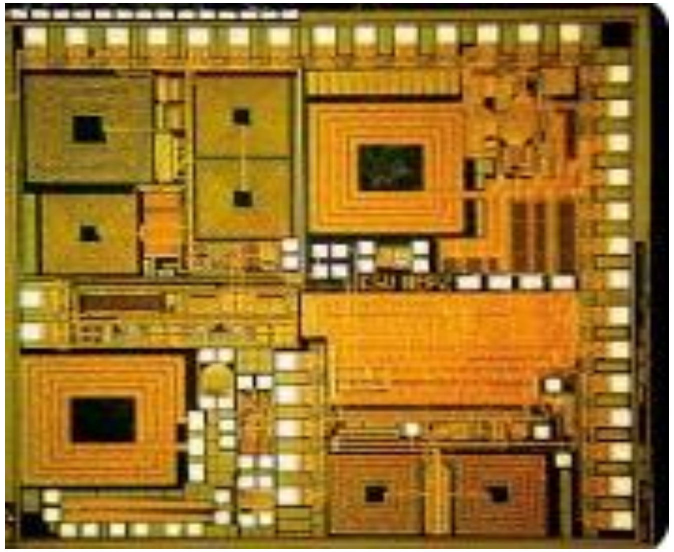
2.DSB:-
In Double Sideband communication both sidebands are transmitted. This requires twice the bandwidth $BW = 2f_m$ and power of transmitting just one of the sidebands , but involves less complex transmitters and receivers.

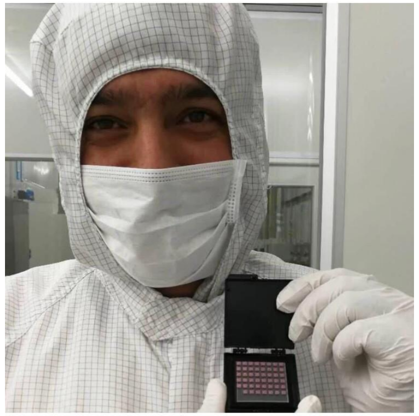
Background Silicon Valley

CTO: Chinese silicon valley → Hengtong 7th largest company
Project: MCU, ASIC, RFIC, MMIC, NANOTECHNOLOGY for Radio Astronomy & mems bio sensor

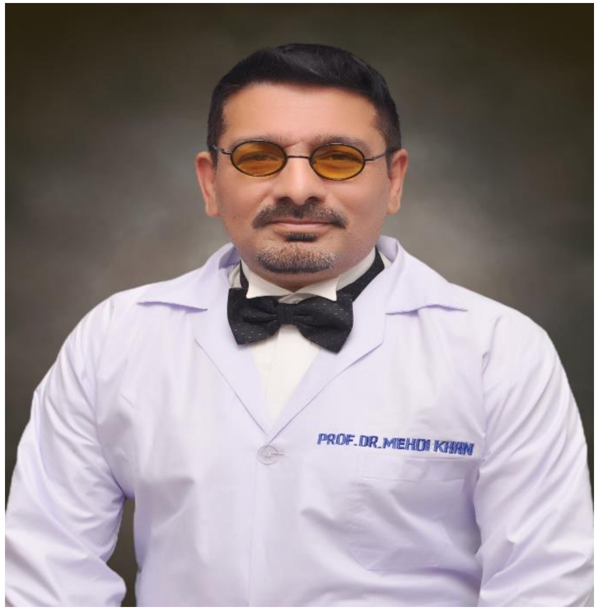
HTGD
HENGTONG
GROUP

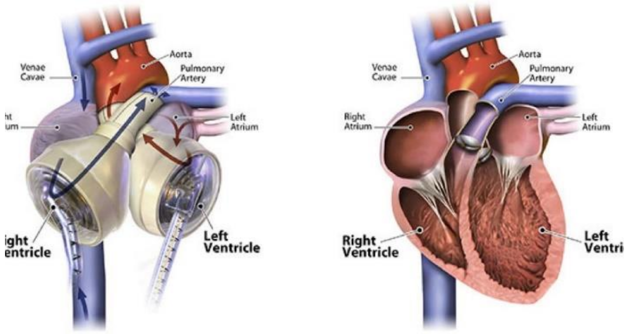


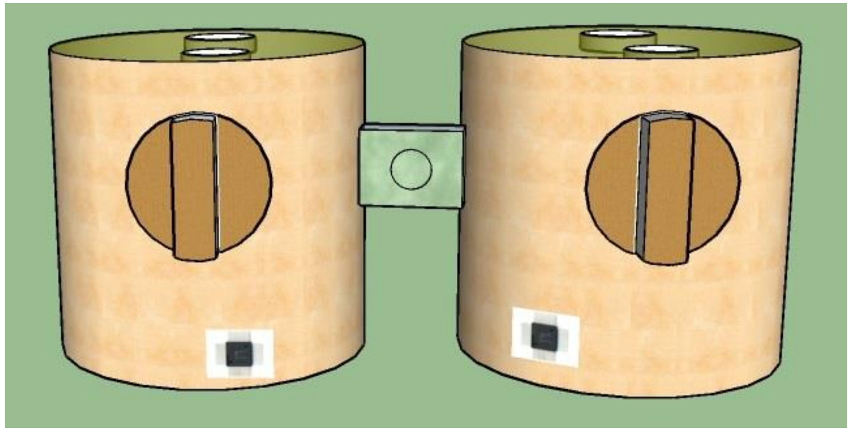




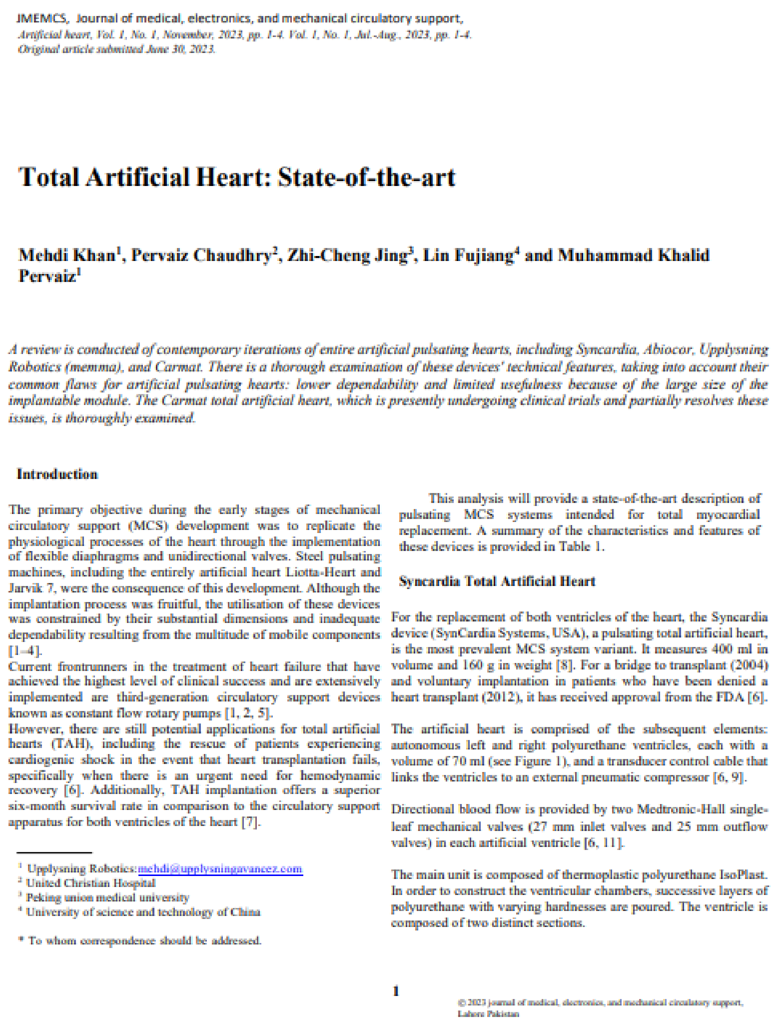
Total Artificial Heart







Total Artificial Heart



JMEMCS, Journal of medical, electronics, and mechanical circulatory support,
Artificial heart, Vol. 1, No. 1, November, 2023, pp. 1-4. Vol. 1, No. 1, Jul.-Aug., 2023, pp. 1-4.
Original article submitted June 30, 2023.

Total Artificial Heart: State-of-the-art

Mehdi Khan[1], Pervaiz Chaudhry[2], Zhi-Cheng Jing[3], Lin Fujiang[4] and Muhammad Khalid Pervaiz[1]

A review is conducted of contemporary iterations of entire artificial pulsating hearts, including Syncardia, Abiocor, Upplysning Robotics (memma), and Carmat. There is a thorough examination of these devices' technical features, taking into account their common flaws for artificial pulsating hearts: lower dependability and limited usefulness because of the large size of the implantable module. The Carmat total artificial heart, which is presently undergoing clinical trials and partially resolves these issues, is thoroughly examined.

Introduction

The primary objective during the early stages of mechanical circulatory support (MCS) development was to replicate the physiological processes of the heart through the implementation of flexible diaphragms and unidirectional valves. Steel pulsating machines, including the entirely artificial heart Liotta-Heart and Jarvik 7, were the consequence of this development. Although the implantation process was fruitful, the utilisation of these devices was constrained by their substantial dimensions and inadequate dependability resulting from the multitude of mobile components [1–4].

Current frontrunners in the treatment of heart failure that have achieved the highest level of clinical success and are extensively implemented are third-generation circulatory support devices known as constant flow rotary pumps [1, 2, 5].

However, there are still potential applications for total artificial hearts (TAH), including the rescue of patients experiencing cardiogenic shock in the event that heart transplantation fails, specifically when there is an urgent need for hemodynamic recovery [6]. Additionally, TAH implantation offers a superior six-month survival rate in comparison to the circulatory support apparatus for both ventricles of the heart [7].

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[2] United Christian Hospital
[3] Peking union medical university
[4] University of science and technology of China

* To whom correspondence should be addressed.

This analysis will provide a state-of-the-art description of pulsating MCS systems intended for total myocardial replacement. A summary of the characteristics and features of these devices is provided in Table 1.

Syncardia Total Artificial Heart

For the replacement of both ventricles of the heart, the Syncardia device (SynCardia Systems, USA), a pulsating total artificial heart, is the most prevalent MCS system variant. It measures 400 ml in volume and 160 g in weight [8]. For a bridge to transplant (2004) and voluntary implantation in patients who have been denied a heart transplant (2012), it has received approval from the FDA [6].

The artificial heart is comprised of the subsequent elements: autonomous left and right polyurethane ventricles, each with a volume of 70 ml (see Figure 1), and a transducer control cable that links the ventricles to an external pneumatic compressor [6, 9].

Directional blood flow is provided by two Medtronic-Hall single-leaf mechanical valves (27 mm inlet valves and 25 mm outflow valves) in each artificial ventricle [6, 11].

The main unit is composed of thermoplastic polyurethane IsoPlast. In order to construct the ventricular chambers, successive layers of polyurethane with varying hardnesses are poured. The ventricle is composed of two distinct sections.

American College of Cardiology Foundation
2400 N Street NW
Washington, D.C. 20037

CERTIFICATE OF PARTICIPATION

The American College of Cardiology Foundation (ACCF) certifies that

Dr Mehdi Khan

participated in the Other (Live and Enduring Material) activity titled

New York Cardiovascular Symposium 2022

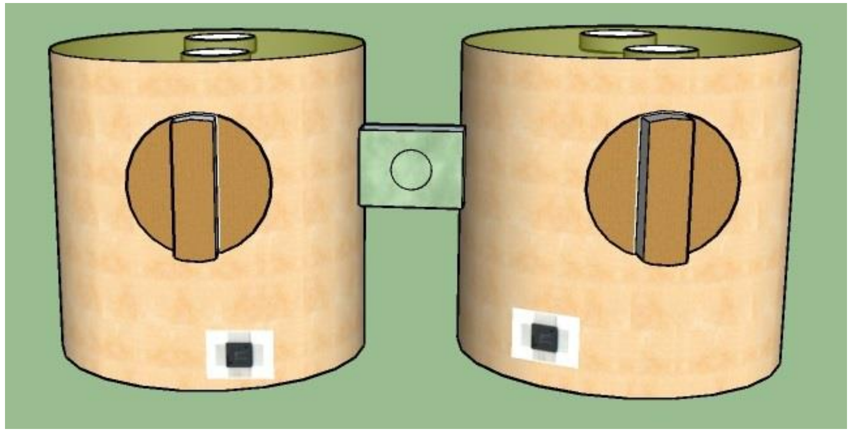
on December 9 - 11 2022.

This activity was designated for a maximum of 15.25 *AMA PRA Category 1 Credits™*.

American College of Healthcare Executives (ACHE)
By attending this program, participants may earn up to 15.25 ACHE Qualified Educational Hours toward initial certification or recertification of the Fellow of the American College of Healthcare executives (FACHE) designation.

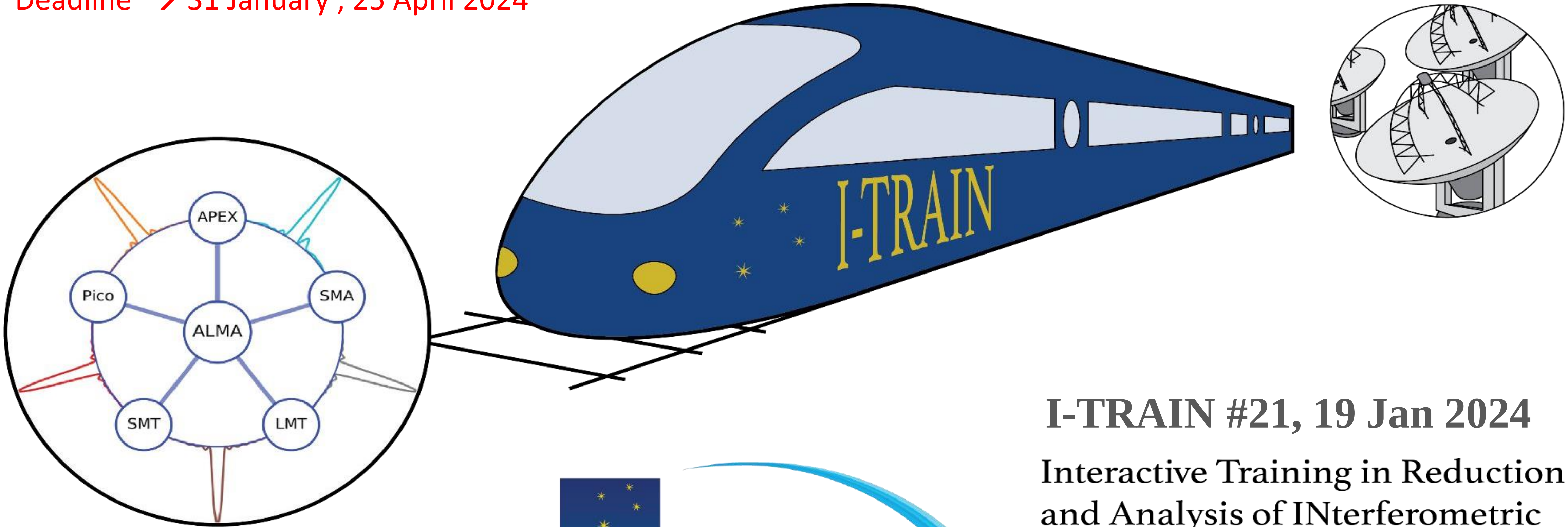
Activity Completion Date: 11/12/2022

In support of improving patient care, the American College of Cardiology Foundation is jointly accredited by the Accreditation Council for Continuing Medical Education (ACCME), the Accreditation Council for Pharmacy Education (ACPE), and the American Nurses Credentialing Center (ANCC), to provide continuing education for the healthcare team.



ALMA Extension VLBI: Science and Proposals

Frequency Band → 6 & 3
Deadline → 31 January , 25 April 2024



Design: Katharina Immer

EUROPEAN ARC
ALMA Regional Centre

I-TRAIN #21, 19 Jan 2024

Interactive Training in Reduction and Analysis of INterferometric data with the European ARC network

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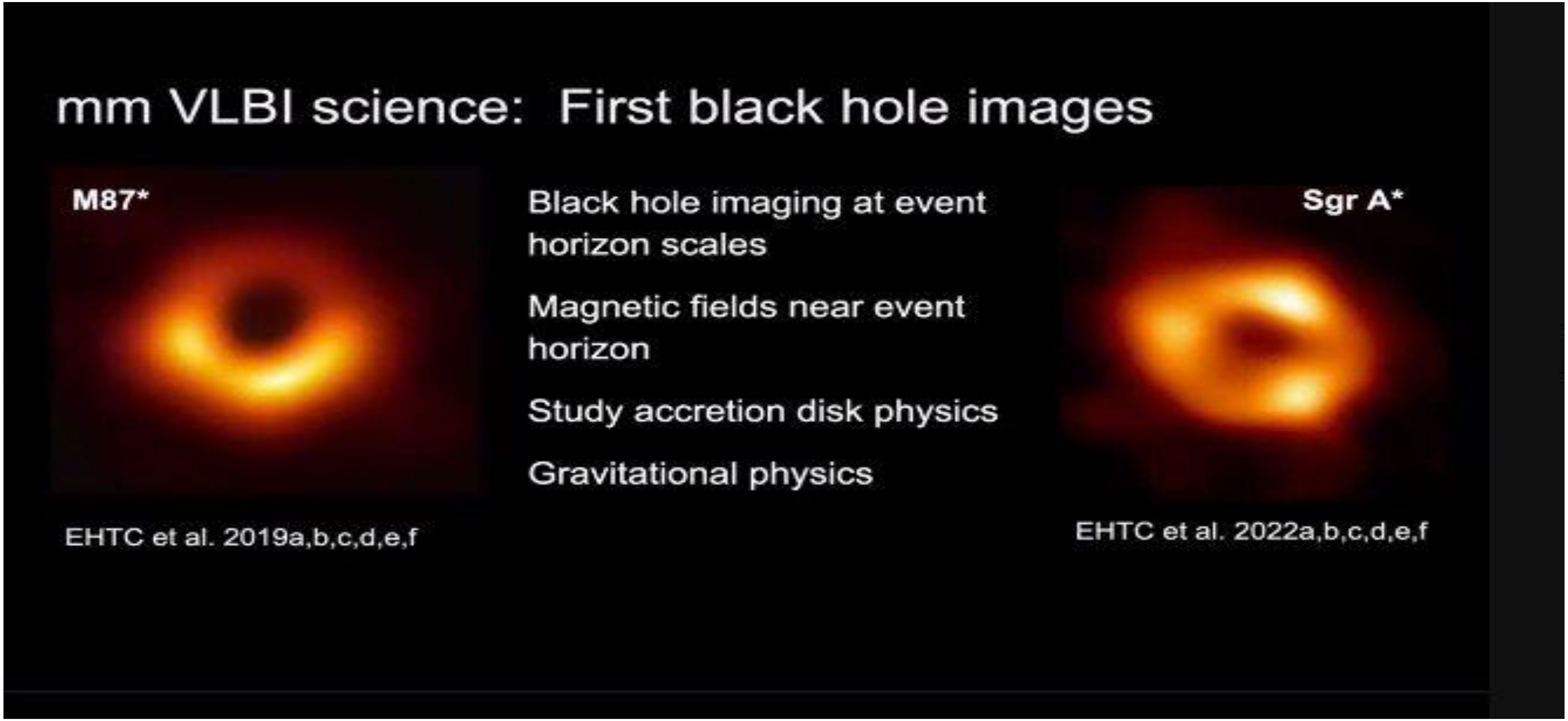
ALMA Extension →Black Hole mmVLBI



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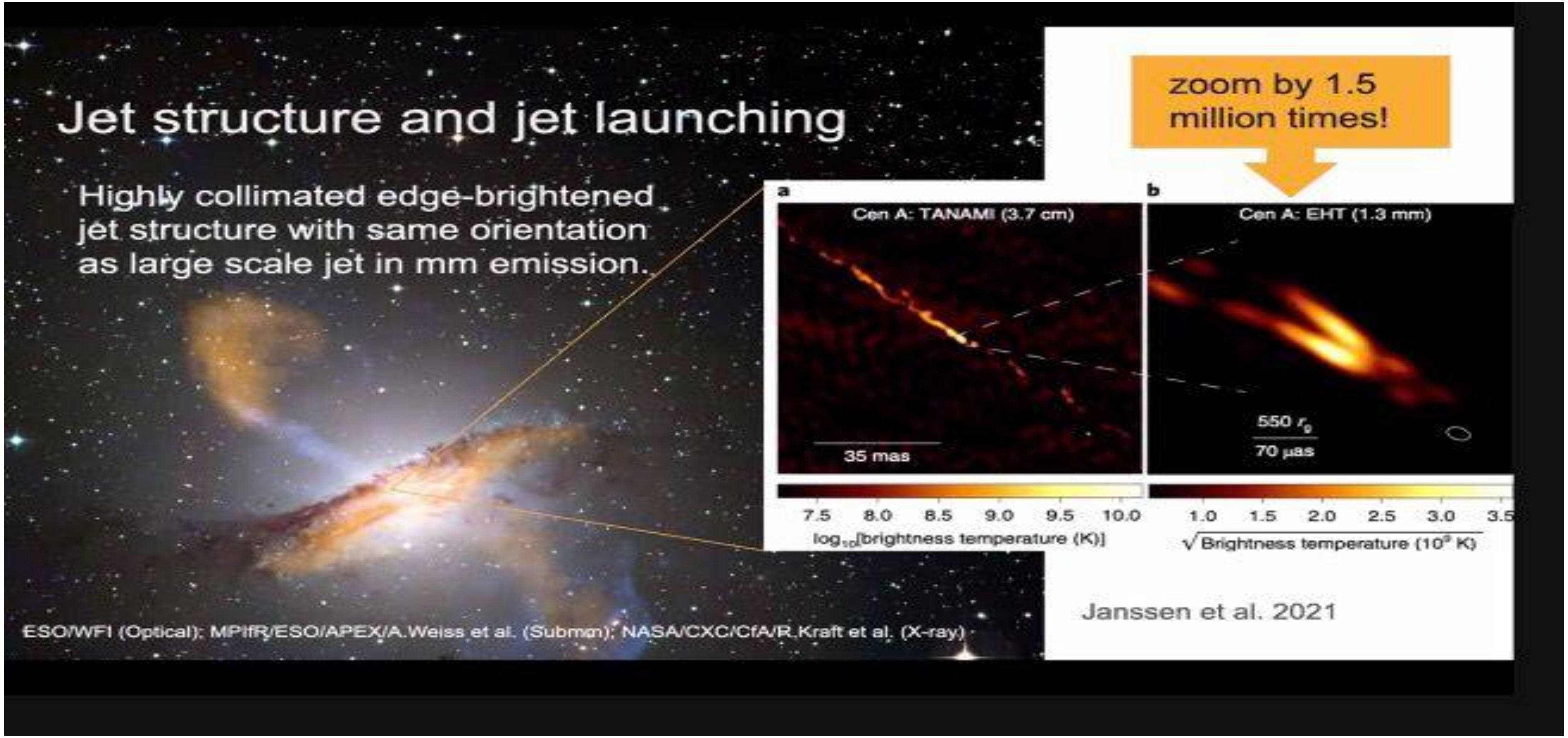
ALMA Extension→Jet structure and jet launching



THz Advantages

1. Strong interactions with Mater – All states
2. Significant Penetration in some materials
3. Naturally occurring spectral signatures
4. Natural Frequency for femtosecond probing
5. Very high sensitivity for signal detector
6. Aperture Advantages over millimeter
7. Non-Inoizing Radiation
8. Low Tolerance Optics
9. Huge Available Bandwidth
10. Untapped Potential

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THz Constraints

1. High Material Losses – Metals and dielectrics
2. Poor Atmospheric Transmission
3. Noise Background Limited Signal Detection
4. Few Natural Resonances except in low pressure gases
5. Poor Contrast/ Huge Speckle Ratio
6. Millimeter-Scale Focus at Best
7. Large Apertures Required
8. Serious Guide Media Dispersion and Losses
9. $$$$$ For Components/Instruments

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Traditional THz Applications

1. Space Science: Astrophysics, Earth, Planets, Comets and Asteroids
2. Plasma Diagnostics
3. Non Destructive Evaluation (Assorted niches)
4. Gas Spectroscopy and Quantum Physics
5. Ultrafast Chemistry and Nonlinear Optoelectronics

(Since Thz Time Domain Systems – Late 1980S

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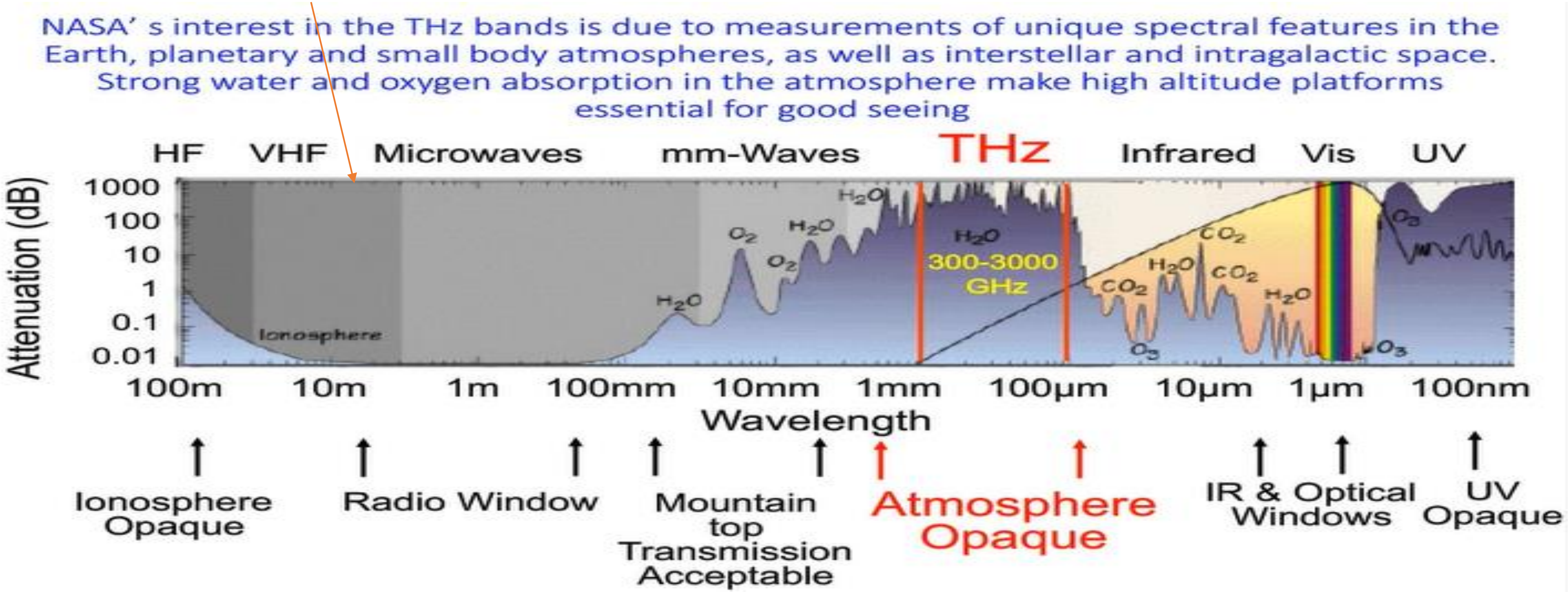
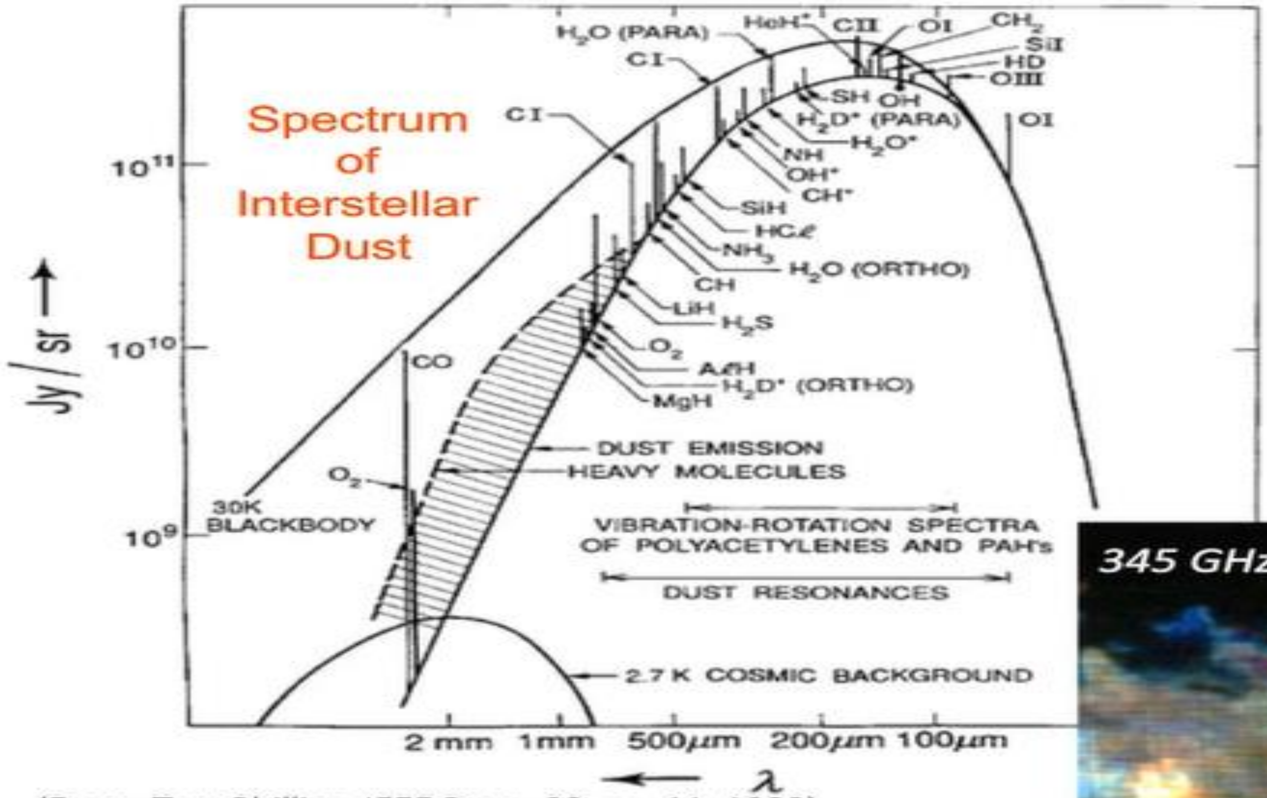
0.3 to 3THz Bands & Atmospheric Transmission

- Gases in the earth's atmosphere absorb electromagnetic radiation to the Most wavelengths from space do not reach the ground.
- Visible light, most radio waves, and some infrared penetrate the atmosphere.
- Through atmospheric windows, wavelength regions of high transparency
- Lack of atmospheric windows at other wavelengths is the reason for astronomers placing telescopes In space



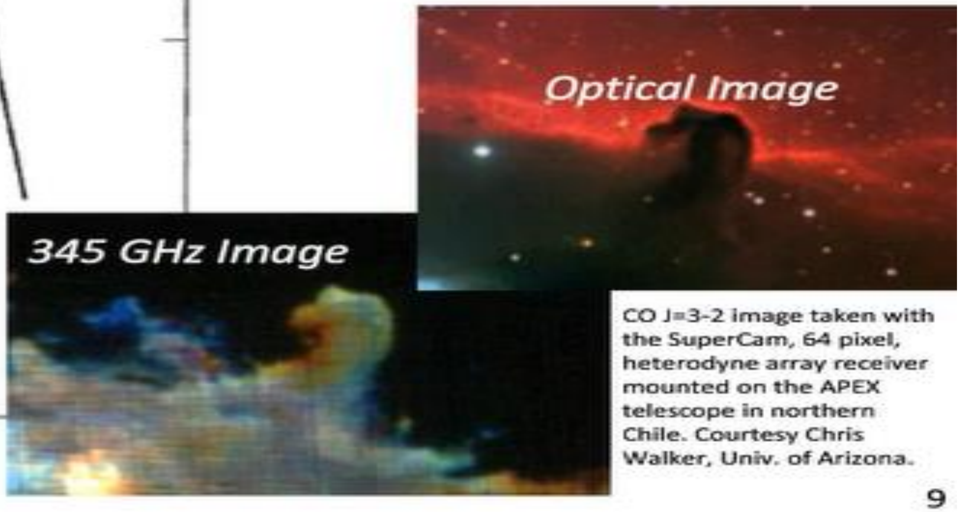
Astrophysics Drivers for THz sensors

THz is the primary freq. for line and continuum radiation from cool (5-100 K) gas (atoms and molecules) and dust.



(From: Tom Phillips, IEEE Proc., 80, no. 11, 1992)

Useful for Studying Stellar and Galactic Constituents and Evolution, Cosmology, Dust & Gas Chemistry, Cosmic Background Physics.



CO J=3-2 image taken with the SuperCam, 64 pixel, heterodyne array receiver mounted on the APEX telescope in northern Chile. Courtesy Chris Walker, Univ. of Arizona.

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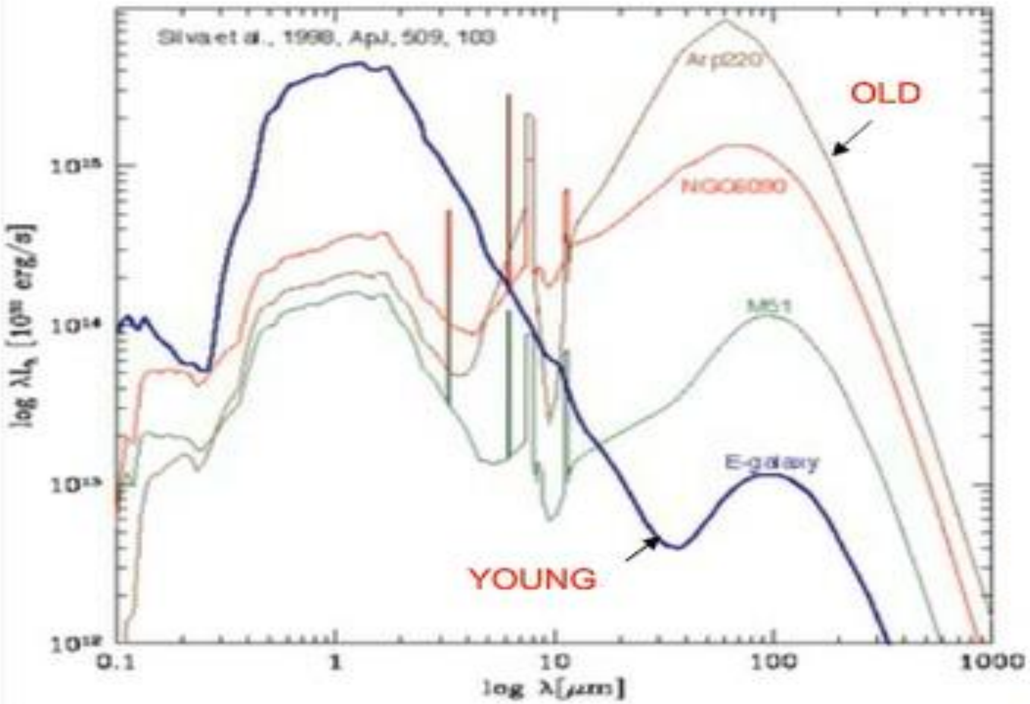
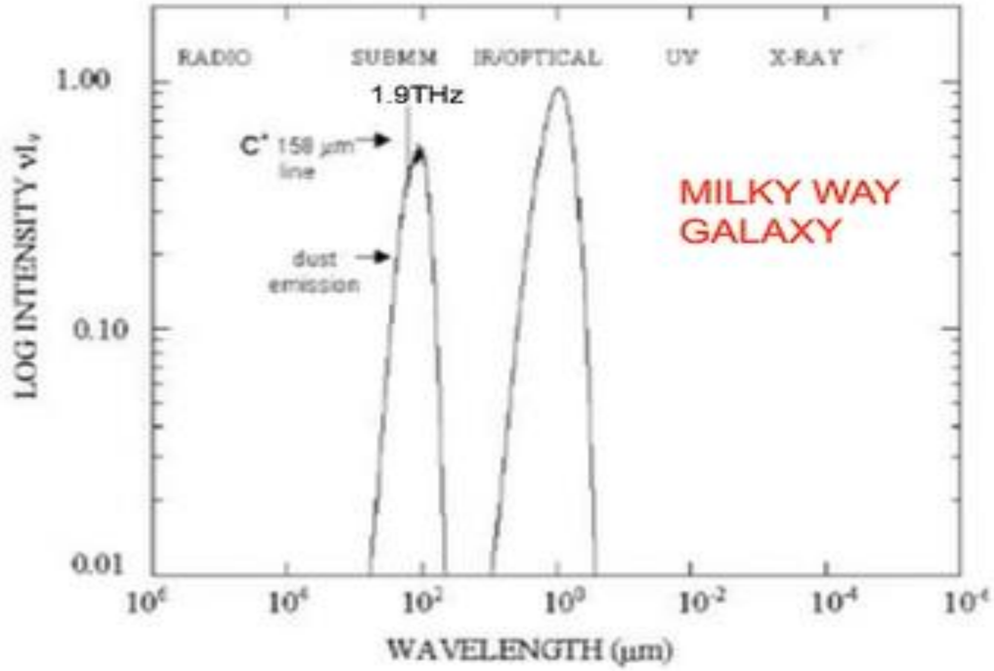
Galactic Emission at THz Frequencies

Half the luminosity and 98% of the photons released since the Big Bang fall into the Submillimeter and Far IR regions!



Energy output vs. wavelength for galaxies of ascending ages showing advantages of THz detection for probing the early universe
(Courtesy Bill Langer – Herschel Sp. Obs.)



Spectrum of Milky Way galaxy showing luminous power output vs. wavelength. Almost 50% of the power is emitted at THz frequencies!
(From Dave Leisawitz, SPIE Proc., 4013, Mar 2000)

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THz Telescope

ASTROPHYSICS

Herschel Space Telescope was launched in May 2009 by the European Space Agency after a 24 year development phase, more than $1.5 Billion dollars, and literally hundreds of astronomers and engineers working around the globe.

Major drivers are cosmic dust, star formation, galactic evolution and cosmology

98% of all photons we measure in the universe fall into the THz regime!

Eleven astrophysics missions with THz sensors have flown since 1978!

11

PLANETS & COMETS

MIRO on Rosetta

Planetary remote sensing (also comets and asteroids), like Earth sensing, is a very strong driver for passive and perhaps even active THz spectroscopy.

Can detect water, CO, methanol, & many other gaseous species…

Only one THz planetary mission has launched to date: MIRO (comet sounder), in 2004, but many more are in current, and will be in future, launch queues.

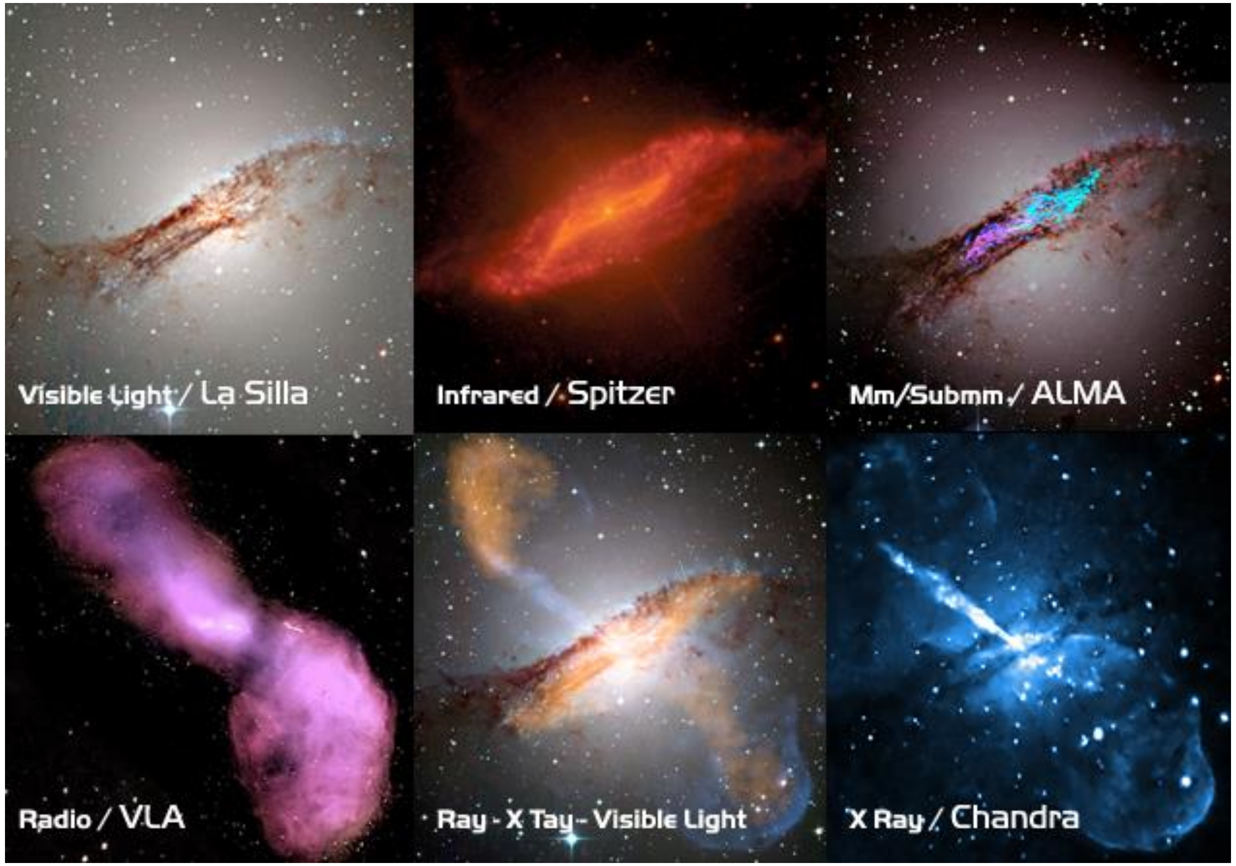
Although space applications are "niche" the funding levels are consistent with the largest worldwide investments in technology and science.

13

Types of Telescopes

- Optical Telescopes
- Ultraviolet and X-Ray
- Space-Based Astronomy → Hubble
- Infrared Telescope
- Radio Astronomy
- Interferometry

→ The Alma Array



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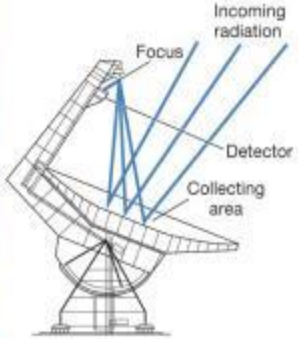
Radio Astronomy

Radio telescopes

- **Similar to optical reflecting telescopes**
- **Prime focus**
- **High sensitive (with shorter wavelength); can be made very large**

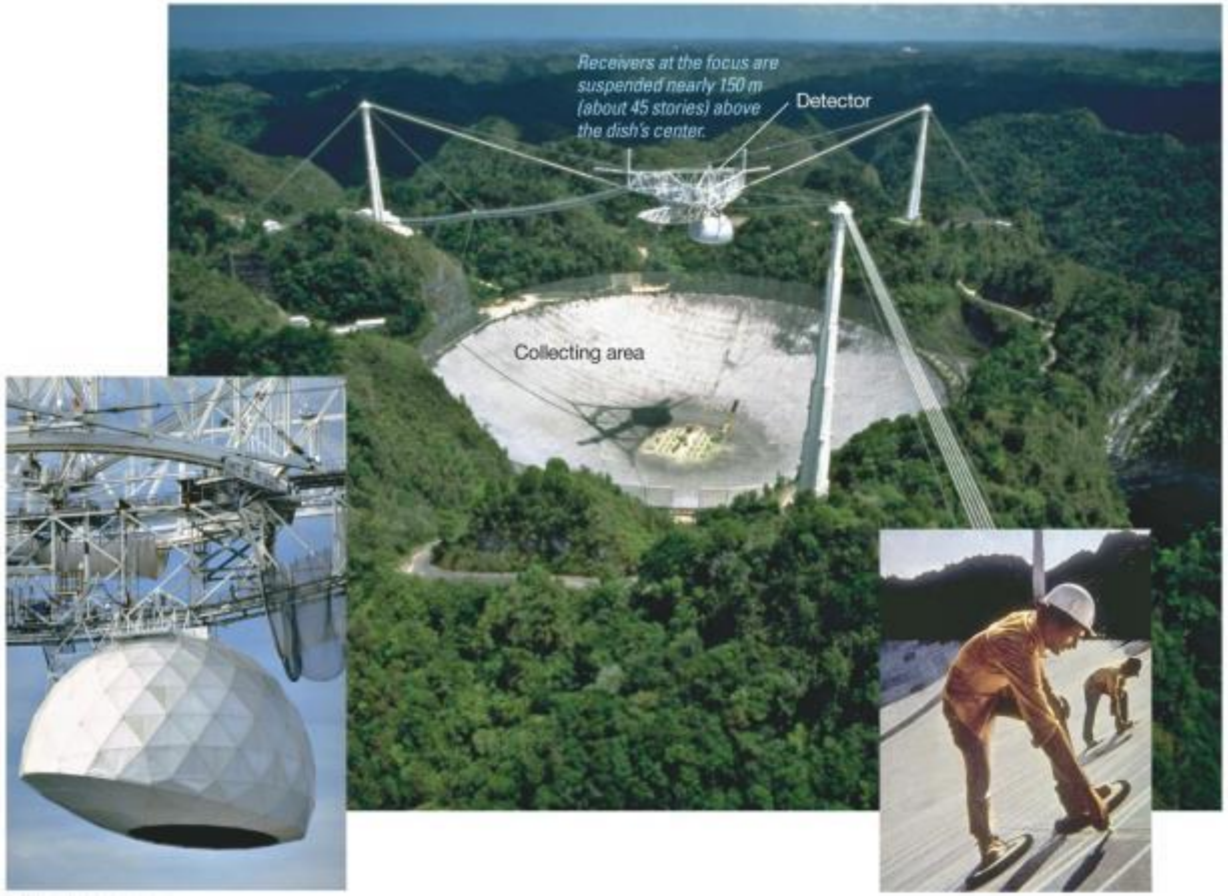
(a)



(b)

Radio Astronomy

Largest radio telescope is the 300-m dish at Arecibo



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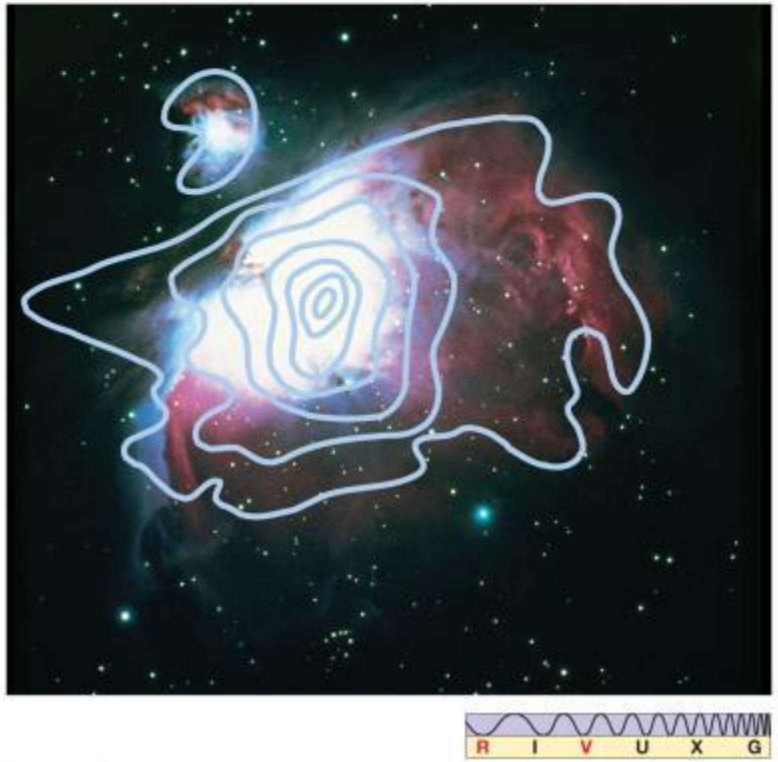
Radio Astronomy

Longer wavelength means poor angular resolution

Advantages of radio astronomy:

- **Can observe 24 hours a day**
- **Clouds, rain, and snow don't interfere**
- **Observations at an entirely different frequency; get totally different information**



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Interferometry

Interferometry:

- **Combines information from several widely spread radio telescopes as if it came from a single dish**
- **Resolution will be that of dish whose diameter = largest separation between dishes**

(a)

(b)

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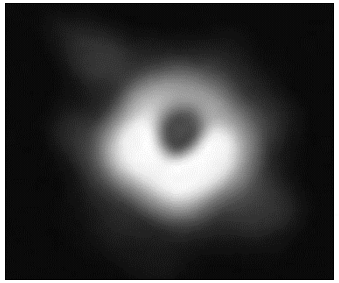
Interferometry

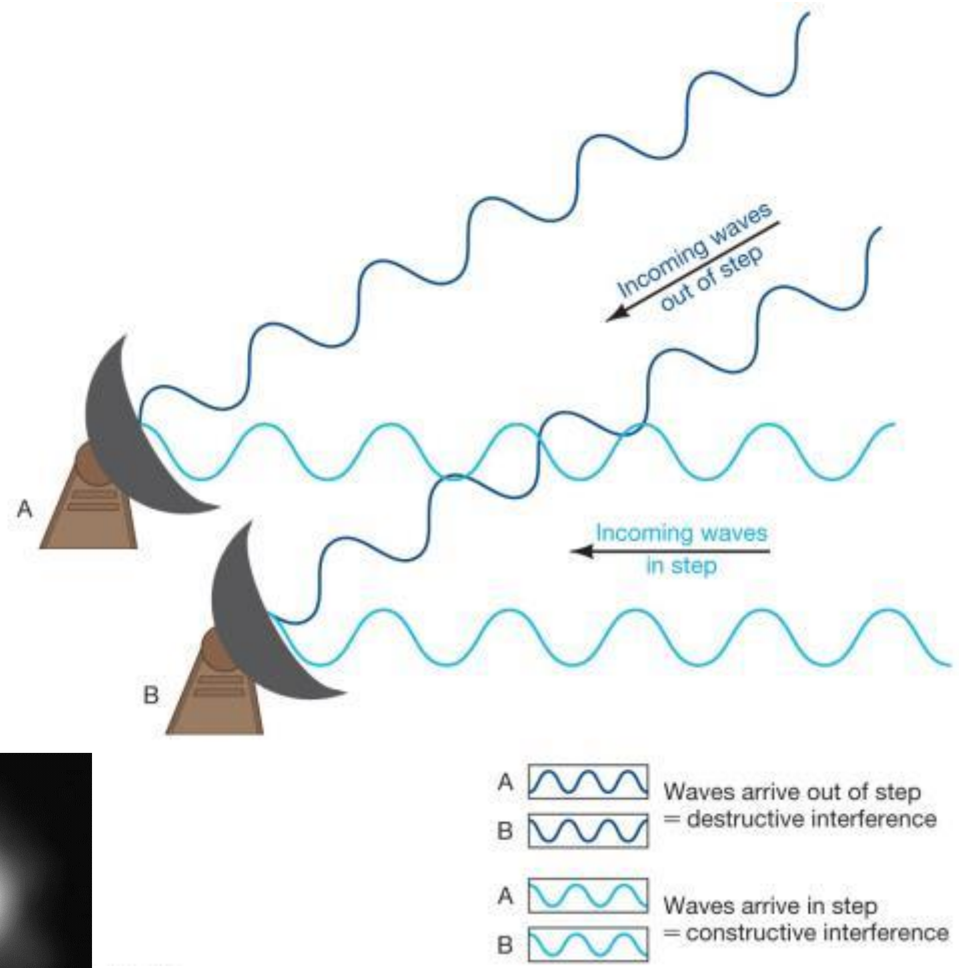
Interferometry involves combining signals from two receivers; the amount of interference depends on the direction of the signal

$$D = \frac{\lambda}{\theta} = \frac{0.877mm}{2 * 10^{-9}} = 30,407\ km$$

M87= $2 * 10^{-9}$ Angular Resolution

$$\theta = \frac{\lambda}{B}$$





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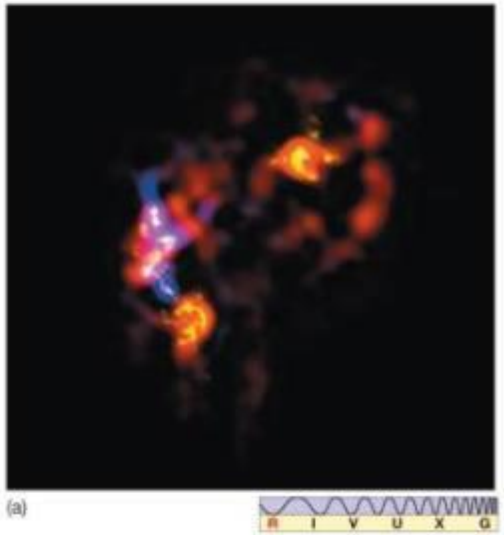
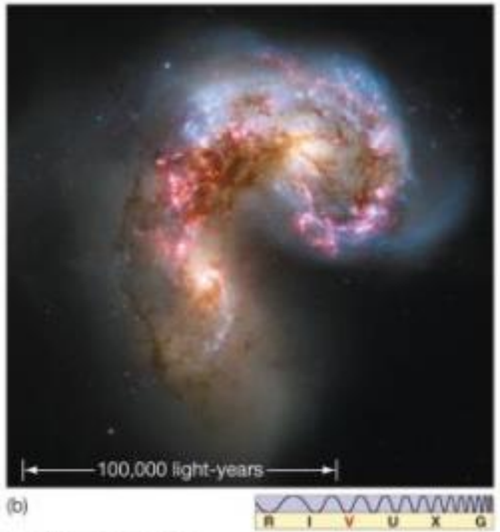
Interferometry

Can get radio images whose resolution is close to optical

Interferometry can also be done with visible light but is much more difficult due to shorter wavelengths



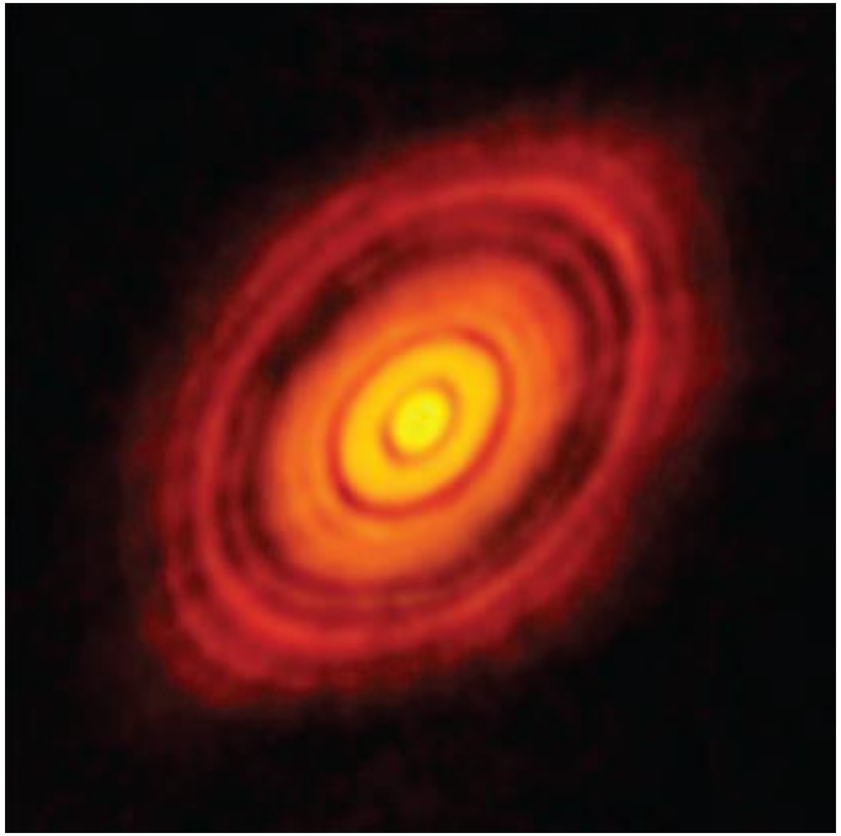
(a)



(b)

The ALMA Array

This image shows a protoplanetary disk surrounding the star HL Tauri.



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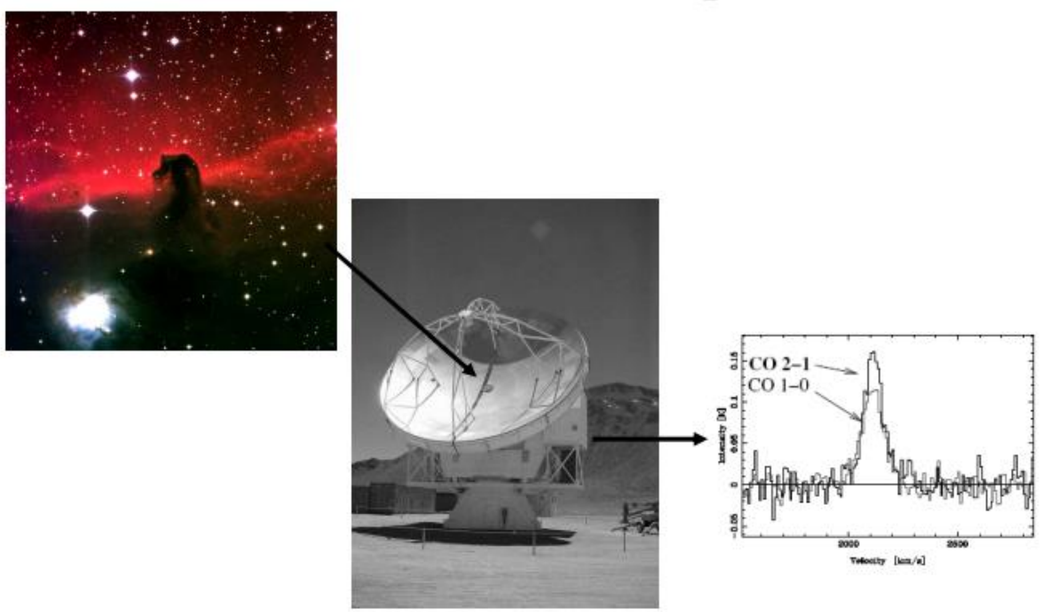
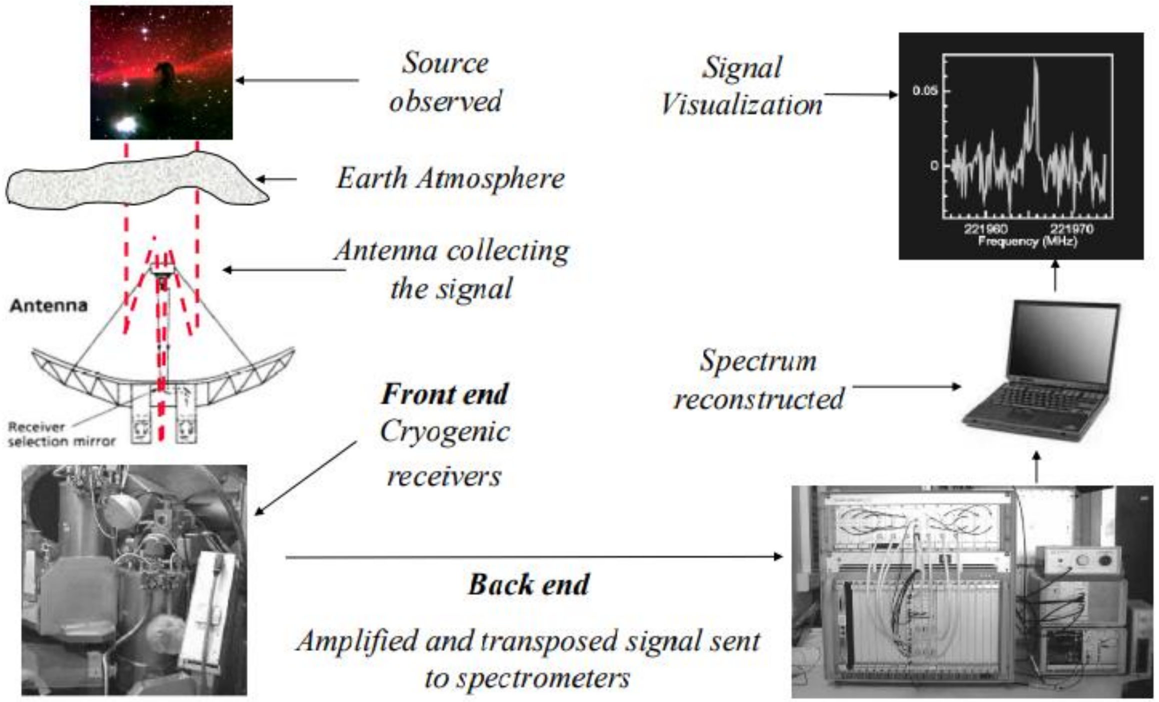
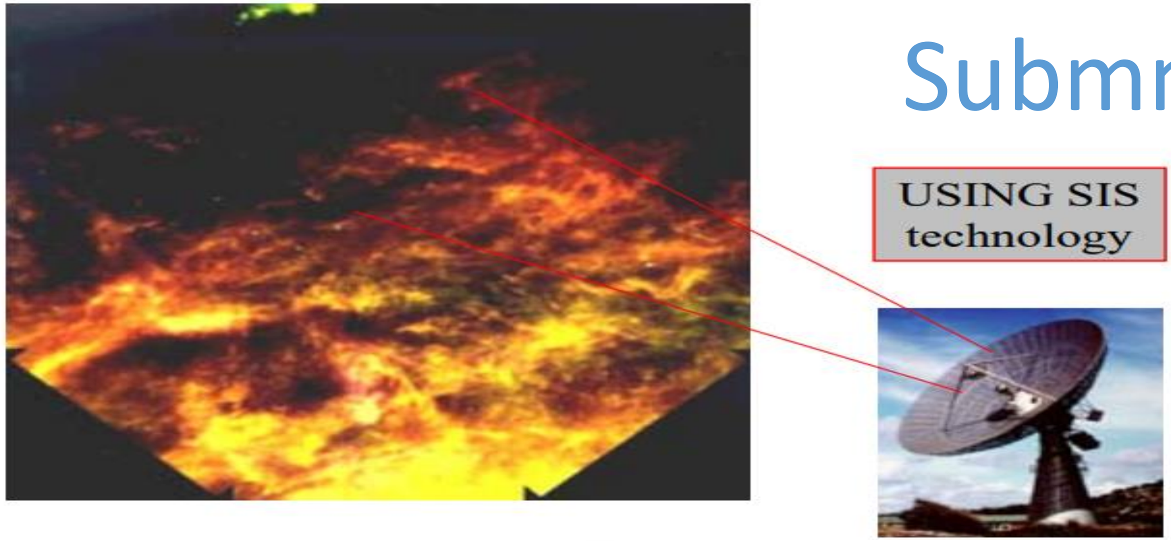
Radio Astronomy System Submm/mm

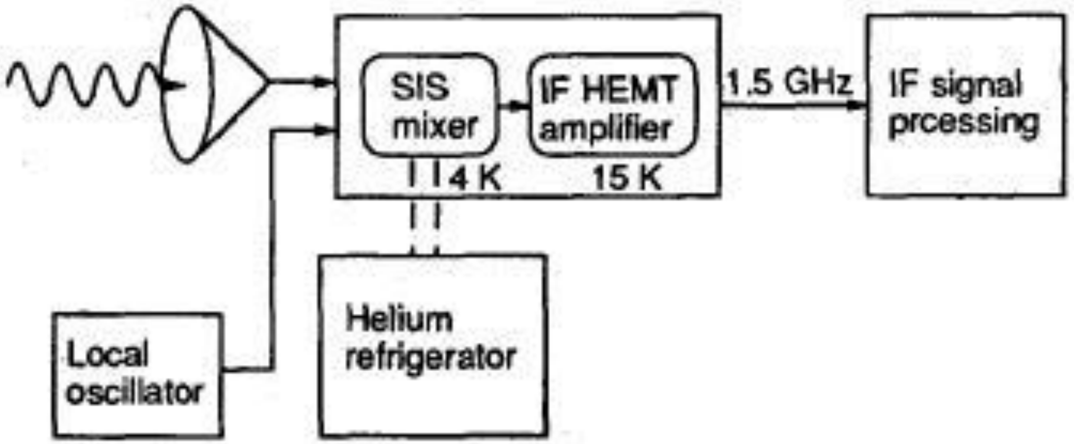
Radio astronomy is a subfield of astronomy that studies celestial objects at radio frequencies. The first detection of radio waves from an astronomical object was in 1933,

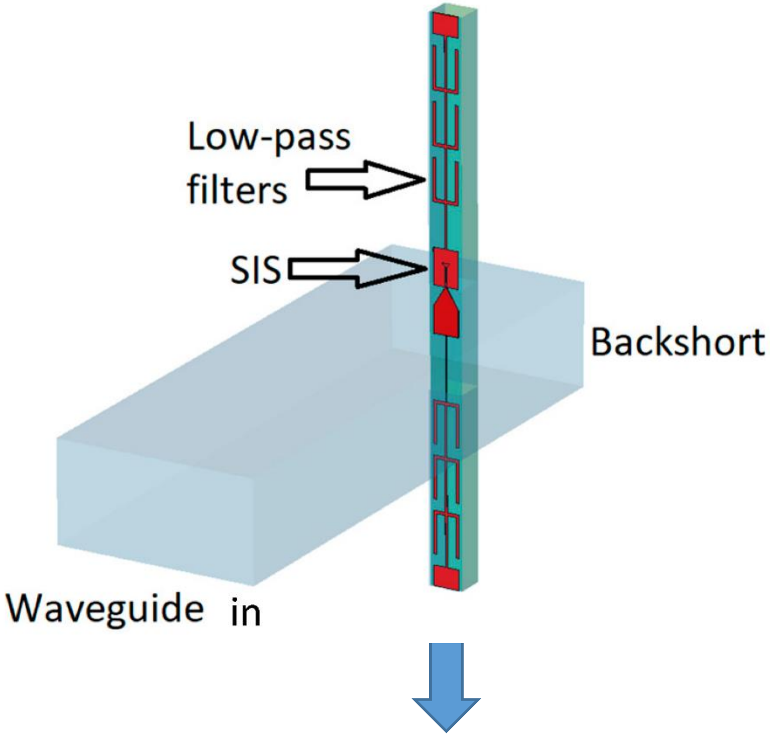


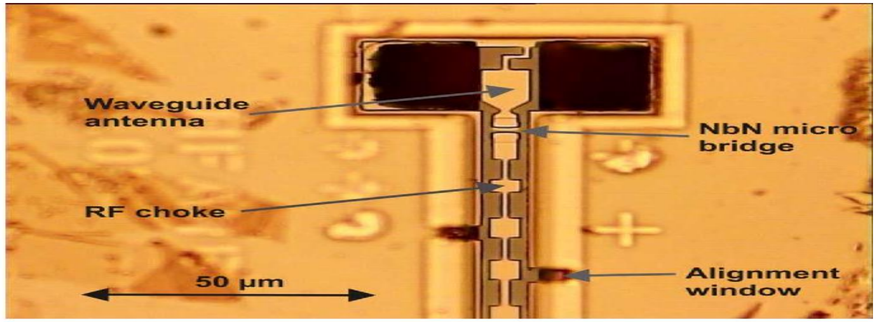


Radio Astronomy System Submm/mm









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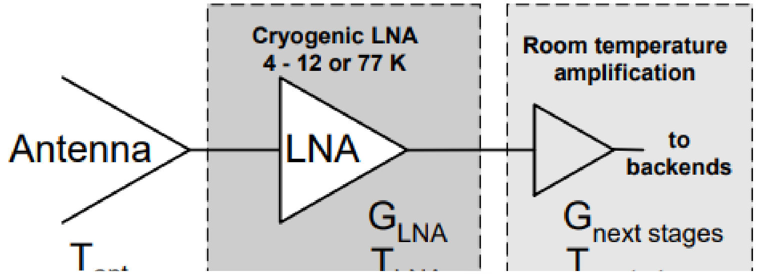
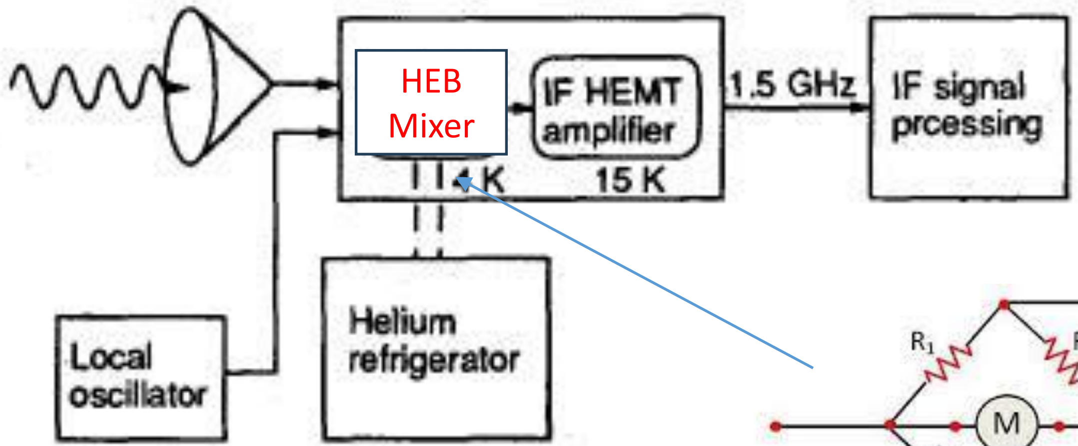
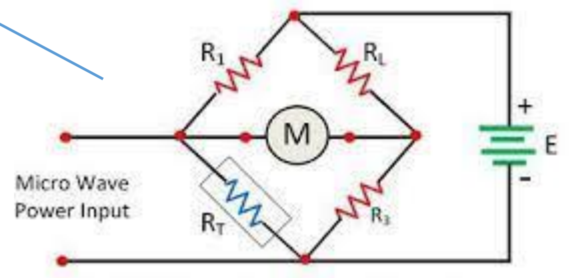
Radio Astronomy System Submm/mm

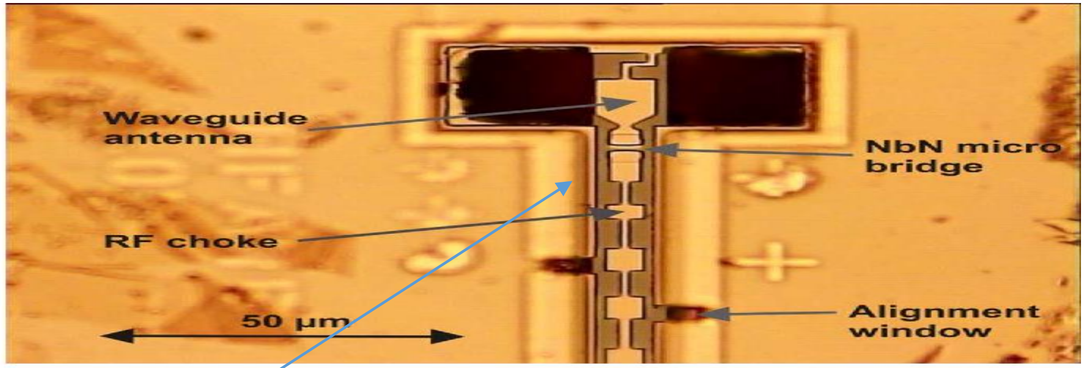
Up to 100 GHz, usual scheme is :



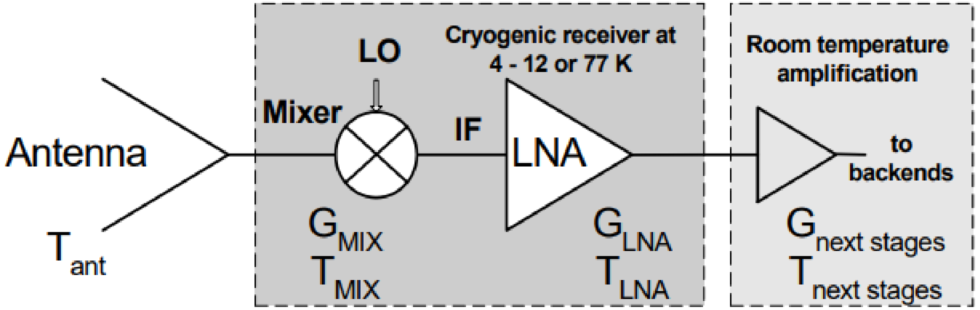




Basic Bolometer Bridge Circuit



> 100 GHz, usual scheme is :



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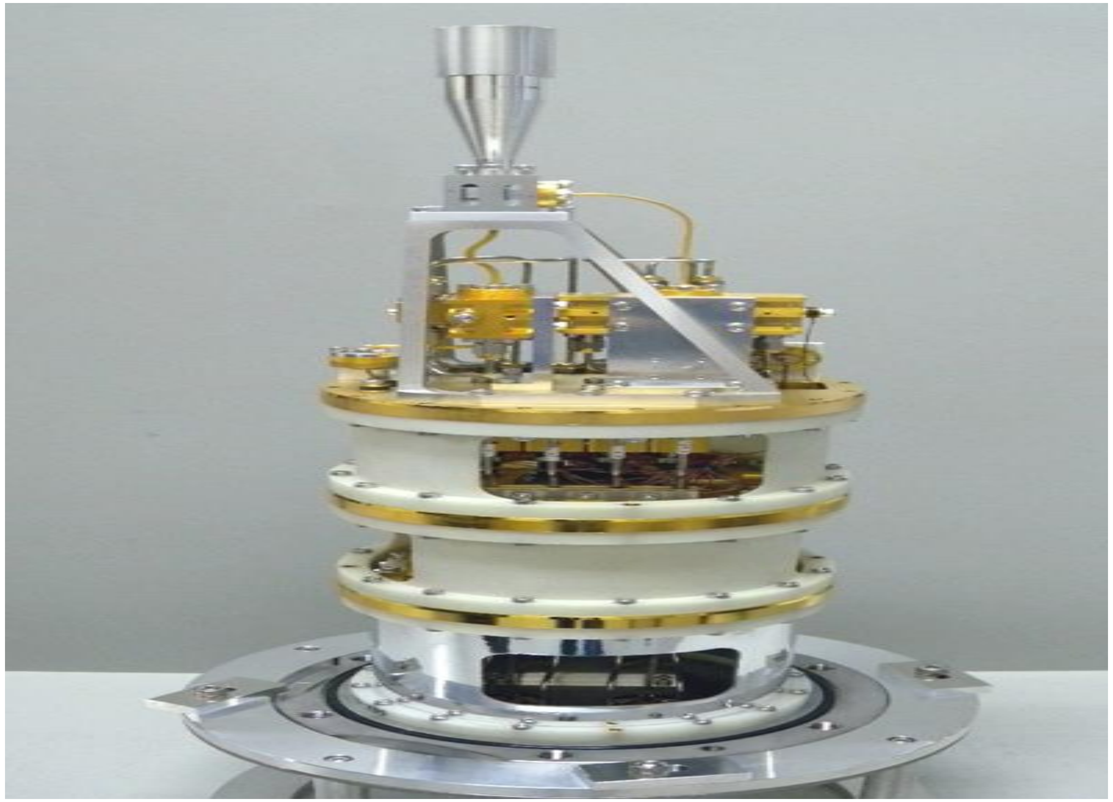
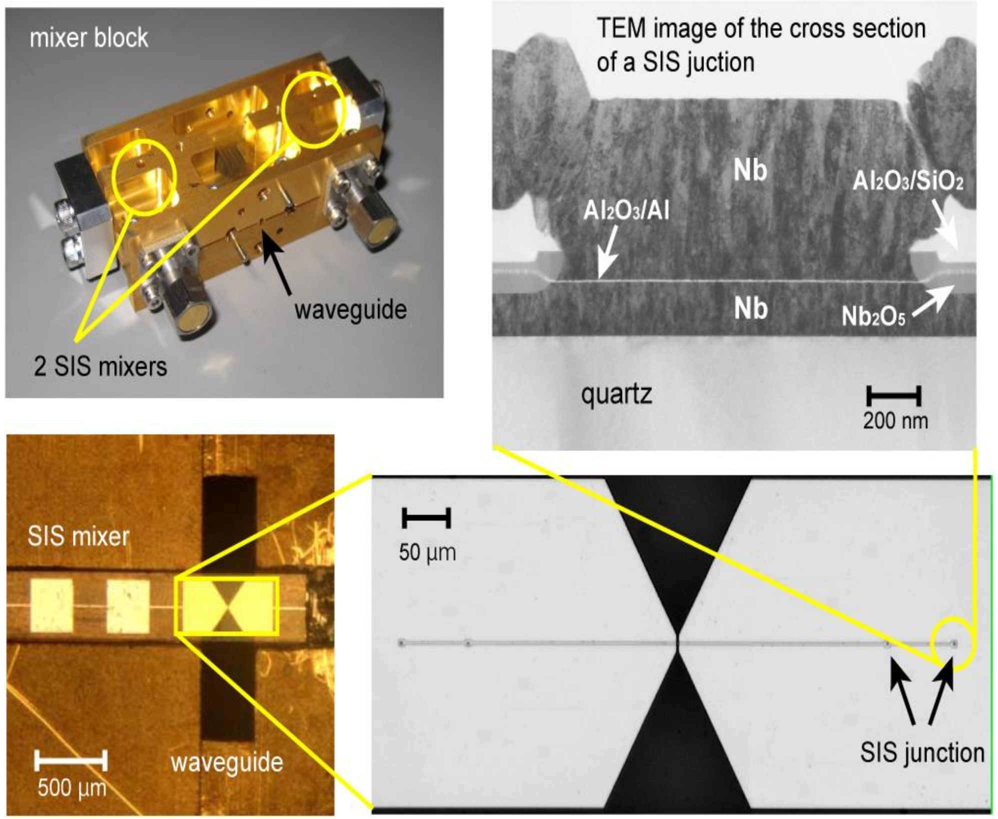
Radio Astronomy System
Submm/mm , Receiver





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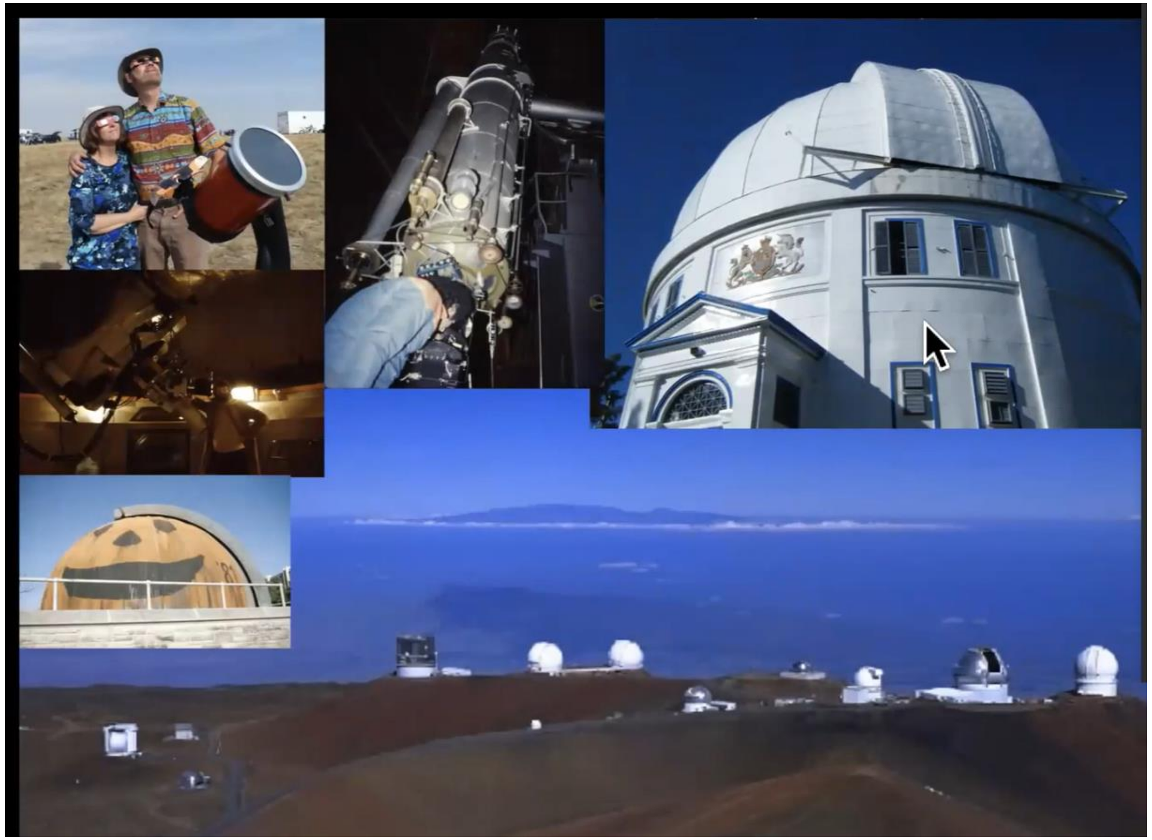
Why we need Radio Astronomy

The stunning images taken by optical instruments like the iconic Hubble Space Telescope are famous the world over, but there are many details they cannot see. Radio astronomy reveals parts of the invisible sky. By detecting radio waves emitted by a wide range of astronomical objects and phenomena, radio telescopes provide a totally different view of our Universe.



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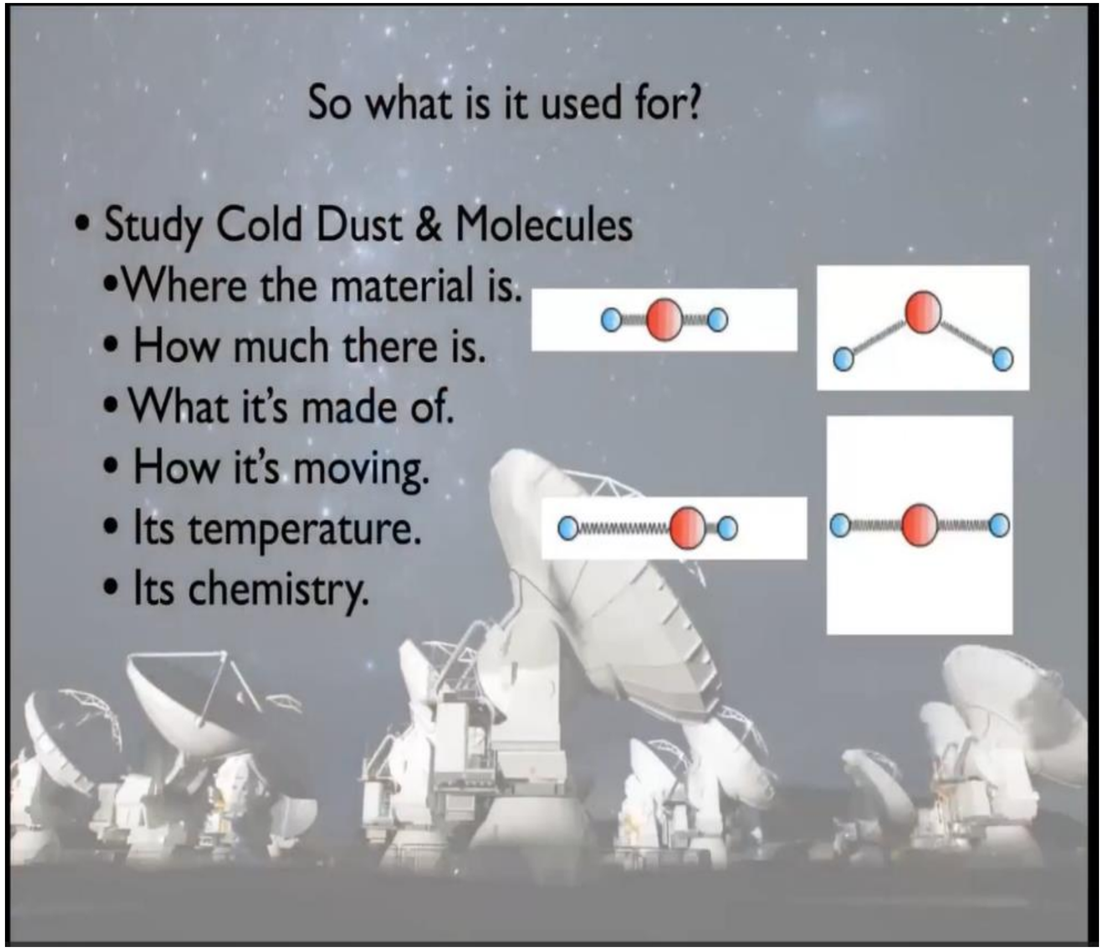
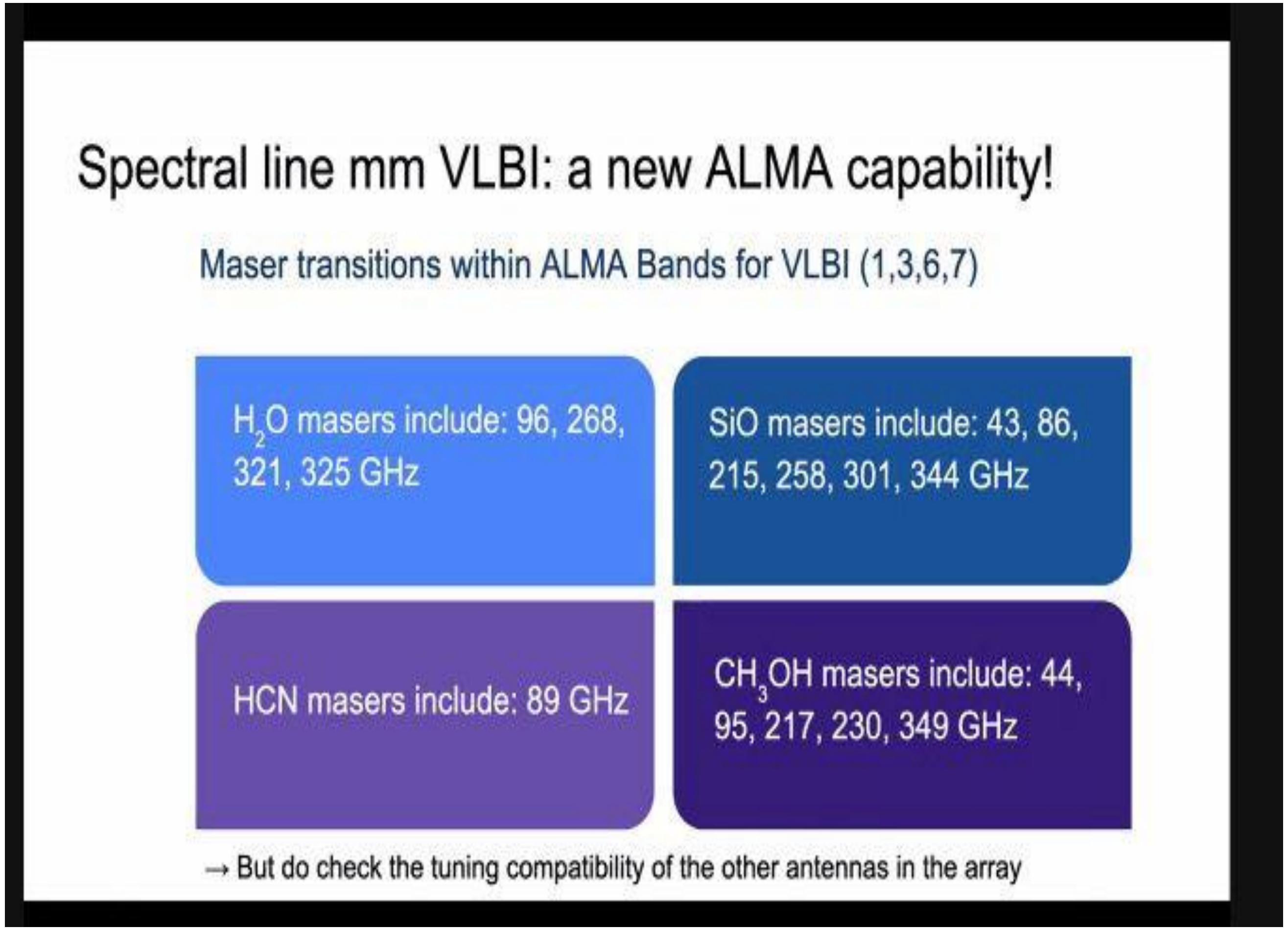
Why we need Radio Astronomy





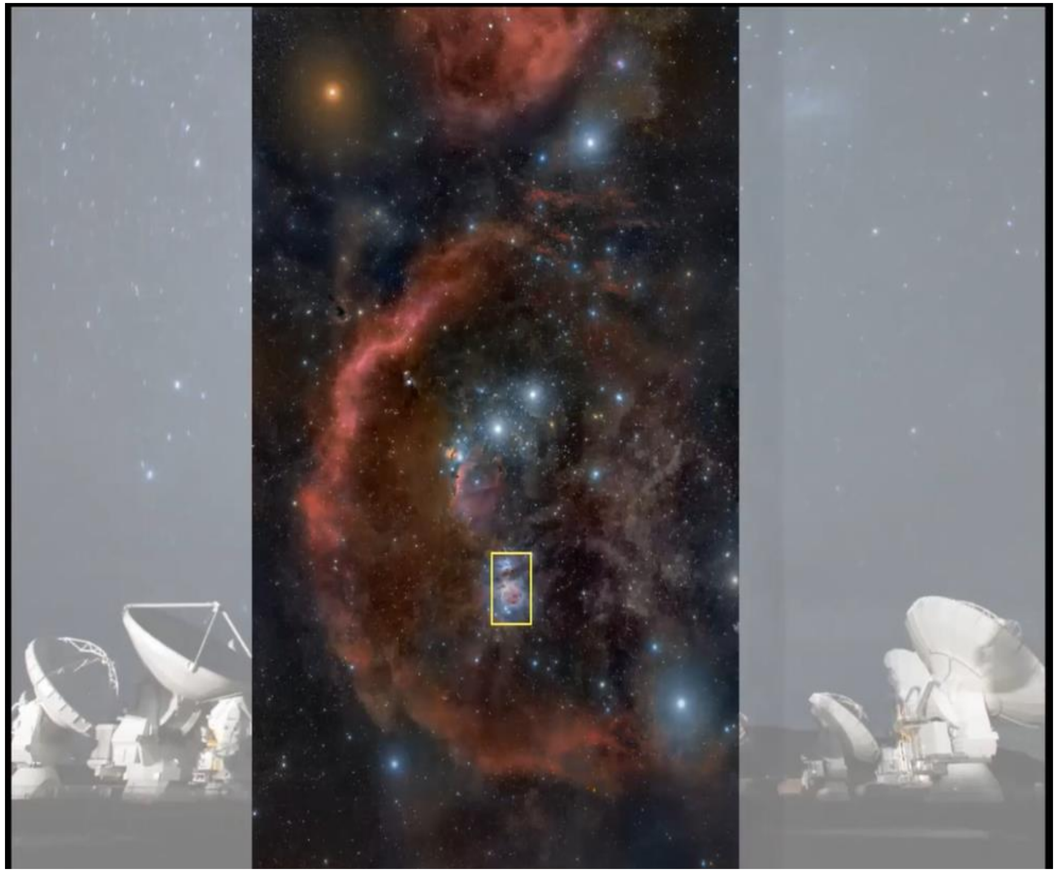
Why we need Radio Astronomy

nebula of orion

Hydrogen gas release by stars by inside region, new star gass

horse head nebula

Orion constellation



Why we need Radio Astronomy

Optical vs infrared

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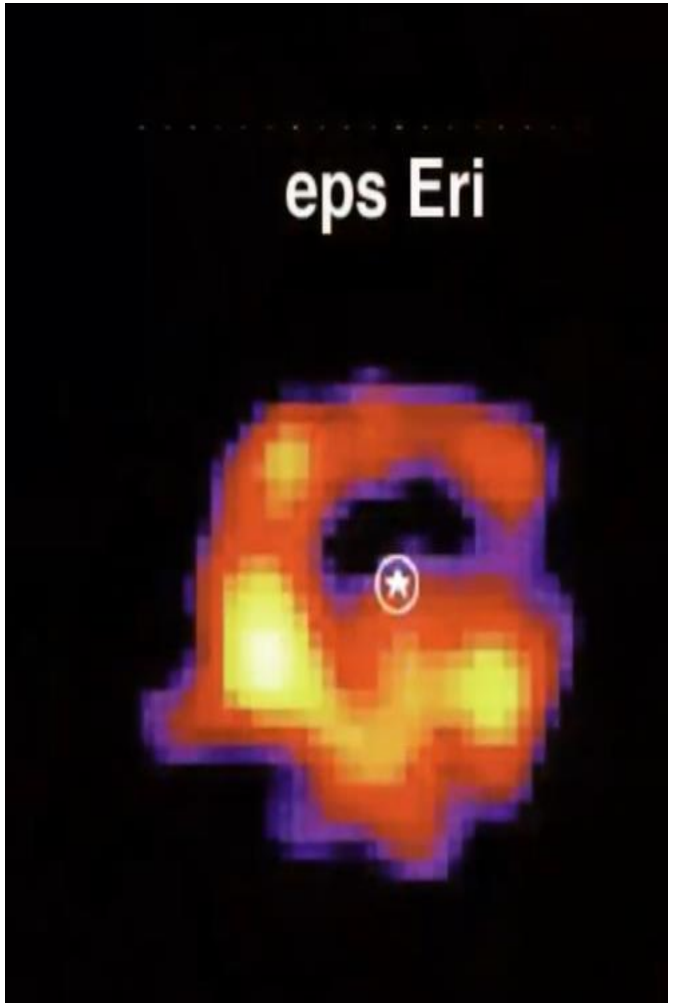
Why we need Radio Astronomy

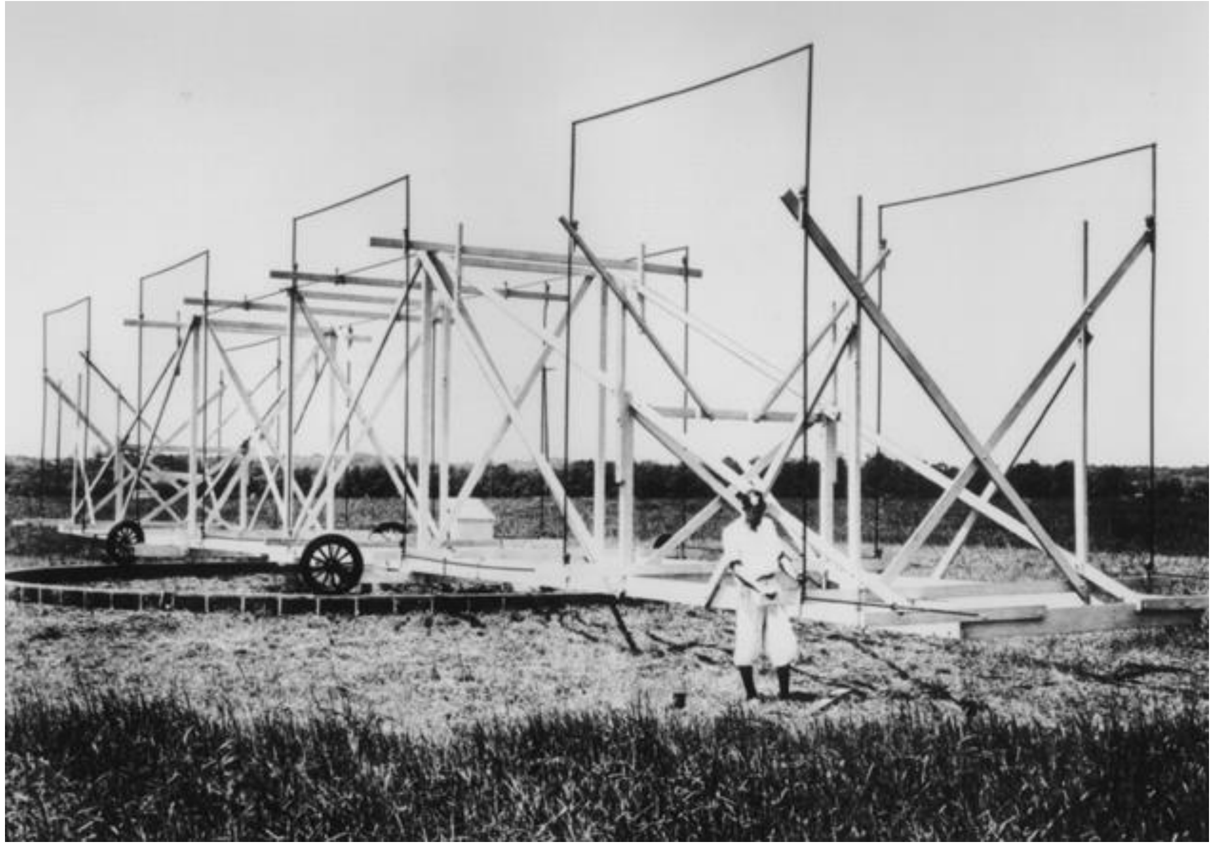
orion nebula

Radio to study cold gas we see gas and dust

10 light year away disk of dust, debre disk comet collision



Radioastronomy: A brief history



In 1933vKarl Guthe Jansky proved it was possible to capture certain bands of electromagnetic radiation coming from the Universe with antennas similar to those used in radio transmission.

Later in 1937, Grote Reber, another American engineer, built the first parabolic radio telescope in order to capture and register radio wave signals originating from the Universe.

In 1938 Reber was able to detect radio wave emissions from the Milky Way.

Jansky antenna carrousel, which he designed to capture 20.5-MHz frequency radio waves (a wave length of around 14.5 meters). The antenna is mounted on a rotating platform allowing it to turn in any direction.
Credit: NRAO-Green Bank

The History of ALMA

In the 1980s the international scientific community developed an interest in creating a radio telescope that could capture, at high resolutions, millimetric and sub-millimetric radio bands.

In 1995 the European Organization for Astronomical Research in the Southern Hemisphere (ESO), the National Radio Astronomy Observatory (NRAO) of the United States and the National Astronomical Observatory of Japan (NAOJ) began to carry out atmospheric trials in the Atacama desert.

Four years later, **in 1999, the three observatories signed a cooperation agreement to install ALMA in Chile**.

Another six years passed and in October **2005, the foundations were laid on the Chajnantor Plateau**, initiating construction of the ALMA observatory.

Testing at the Chajnantor Plateau.

Credit: ALMA (ESO/NAOJ/NRAO), NAOJ.

The soul of ALMA

The people who work at ALMA represent more than **20 nationalities and the most diverse cultures, languages and professions**.

In addition, there are thousands of people from distant universities, institutes, laboratories and companies who collaborate to make the world's largest and most powerful radio astronomy telescope a reality.

Everyone contributes scientific experience, new designs and groundbreaking technological developments.

Working with ALMA components at the Rutherford Appleton Laboratory in the United Kingdom, 2004.

Credit: ALMA (ESO/NAOJ/NRAO), H. Zodet, ESO.

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ALMA operation

In 2013 ALMA’s 66 antennas fully operational.
This mean a huge leap forward in astronomical terms, since **ALMA will have a sensitivity and spectral resolution 100 times greater sensibility than its predecessors** in millimeter and sub-millimeter waves.
As has happened with the great telescopes that have preceded it, **ALMA will allow us to see things in the Universe of which we aren't yet aware**.

Group of antennas at Chajnantor Plateau, 2011.
Credit: ALMA (ESO/NAOJ/NRAO), J. Guarda.

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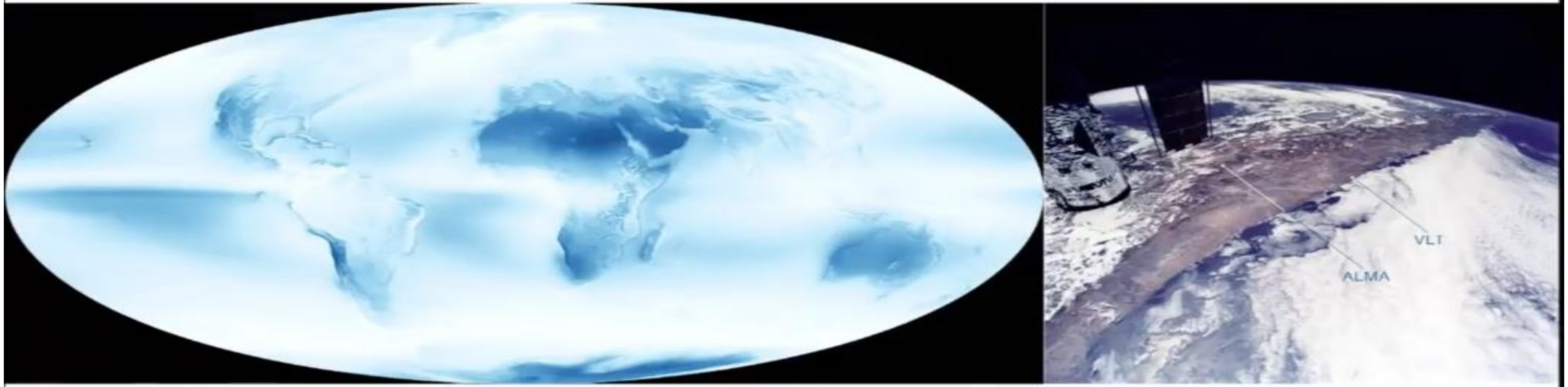
ALMA Receivers Bands

ALMA Band	Wavelength coverage (mm)	Noise Temperature (K) Specification	Frequency (GHz)	Produced by	Receiver Technology	First light
1	6–8.6	32	35 – 50	ASIAA (Taiwan) / NAOJ (Japan)	HEMT	2021
2	2.6–4.5	47	67 – 116	OSO (Sweden) / NOVA (Netherlands) / INAF (Italy) / NAOJ (Japan)	HEMT	TBD
3	2.6–3.6	60	84 – 116	HIA (Canada)	SIS	2009
4	1.8–2.4	82	125 – 163	NAOJ (Japan)	SIS	2013
5	1.4–1.8	105	163 – 211	OSO (Sweden) / NOVA (Netherlands)	SIS	2016
6	1.1–1.4	136	211 – 275	NRAO (US)	SIS	2009
7	0.8–1.1	219	275 – 373	IRAM (France)	SIS	2009
8	0.6–0.8	292	385 – 500	NAOJ (Japan)	SIS	2013
9	0.4–0.5	261	602 – 720	NOVA (Netherlands)	SIS	2011
10	0.3–0.4	344	787 – 950	NAOJ (Japan)	SIS	2012

Why Chile?

- The Earth’s atmosphere and the water vapor it contains absorbs the sub/mm radiation
- Facilities operating at sub/mm wavelengths need to be located at high altitude and in dry places



Aqua Satellite: Observing the Earth’s water cycle;
Cloud coverage averaged over 13 years

The ALMA Array

The ALMA Array is a set of 66 radio antennae located in northern Chile, which detect radiation with wavelengths between 0.3 mm and 10 mm. The antennae are mobile, allowing excellent resolution.

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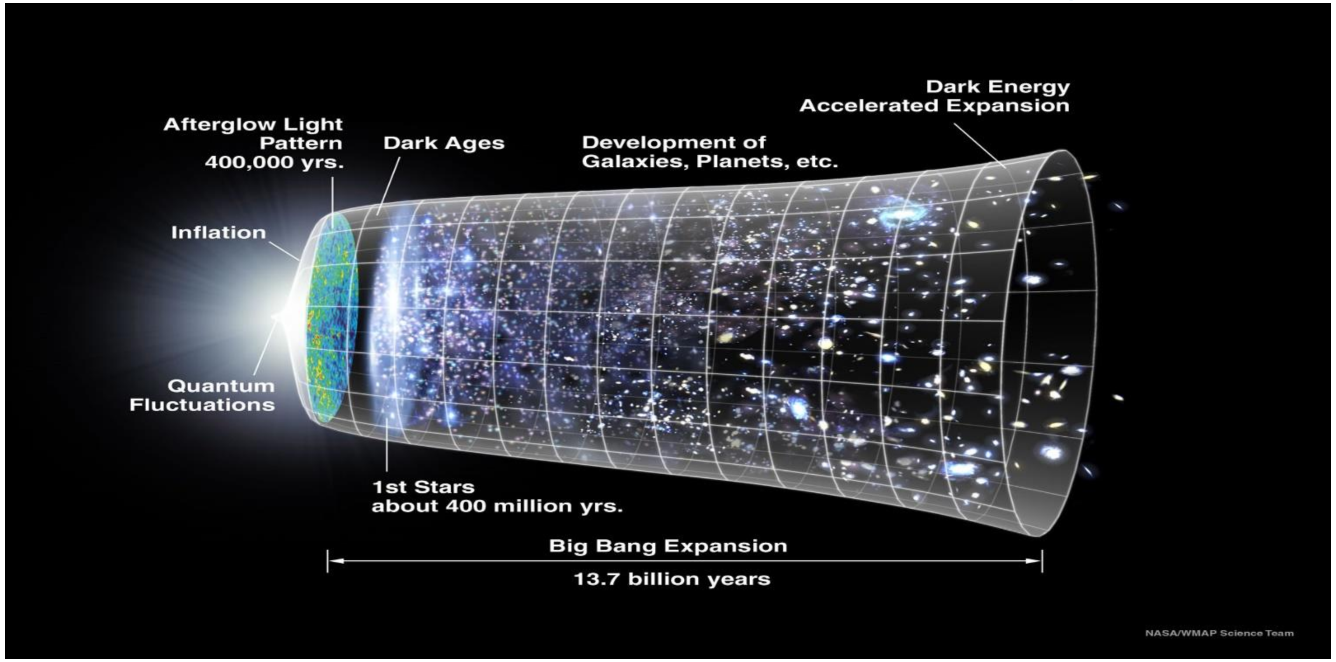
Why is ALMA is so Powerful?

- Because it is located **5,000 meters above sea level** on the **Chajnantor Plateau** in the Atacama Desert.
- The **altitude and aridity** make it an exceptional site for astronomical observation.
- The **minimal amount of water** vapor at the site provides the **transparency needed** for the antennas to capture millimetric radio wavelengths without distortion.

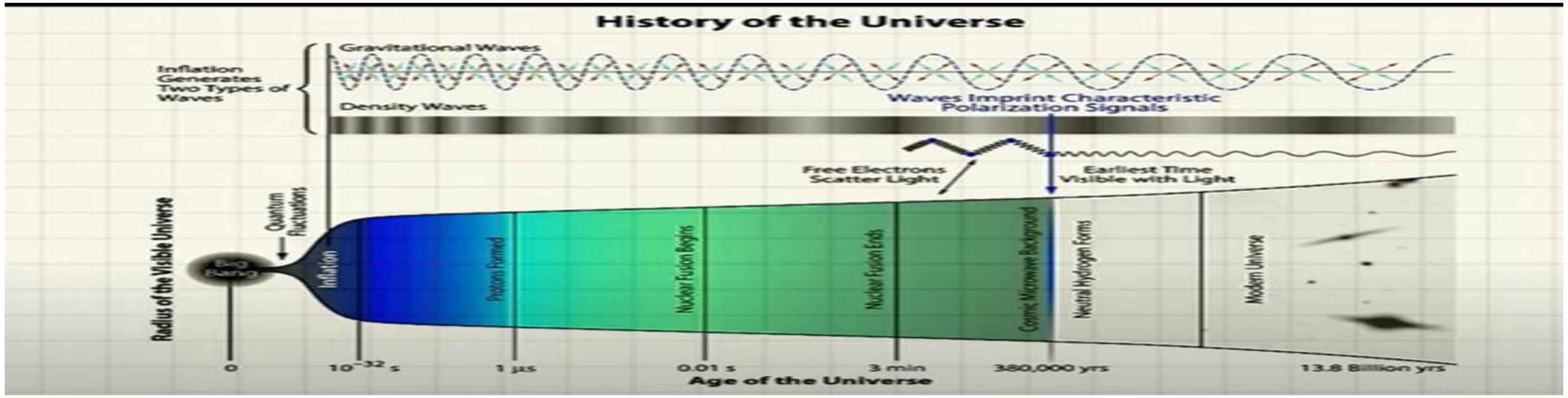
ALMA is the highest-altitude land-based observatory.
Credit: ALMA (ESO/NAOJ/NRAO).

Astronomy: Observation today



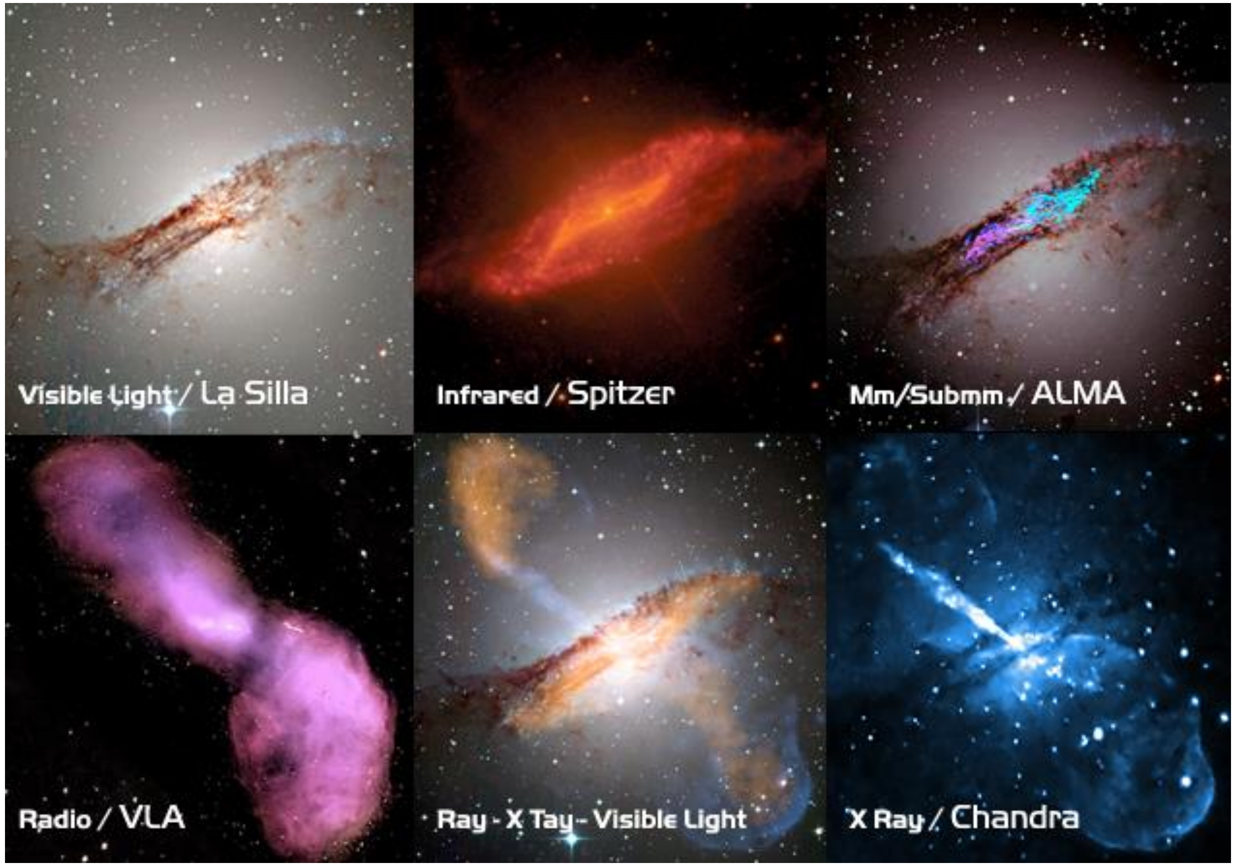
Now **we also know that warm, cold and dark matter exist** thanks to the measurement of a wide range of wavelengths emitted throughout the Universe. Even after centuries of astronomical observation, scientists today know little about what the Universe is made up of.

ALMA's study of cold matter permits the observation of "*old*" planets and galaxies too faint to be detected by optical telescopes, allowing us to learn about the early Universe.



Universe expansion since the Big Bang.
Credit: NASA - WMAP. License: GNU

What we can see in universe today



View of Centaurus A galaxy in radio wavelength from VLA radio telescope.

Credit: VLA radio telescope.

Scientific technological development today allows scientists to design equipment that **can capture a wider range of wavelengths**.

- **Optical telescopes**, which observe the light of the stars and hot gas emission.
- **Ultraviolet and X-Ray** observatories that study very hot gas and ultra energetic emission.
- **Infrared light** observatories that study warm and hot dust.
- **Radio telescopes** that capture radio emissions from warm and cold matter.

ALMA observes millimetric and submillimetric radio wavelengths.

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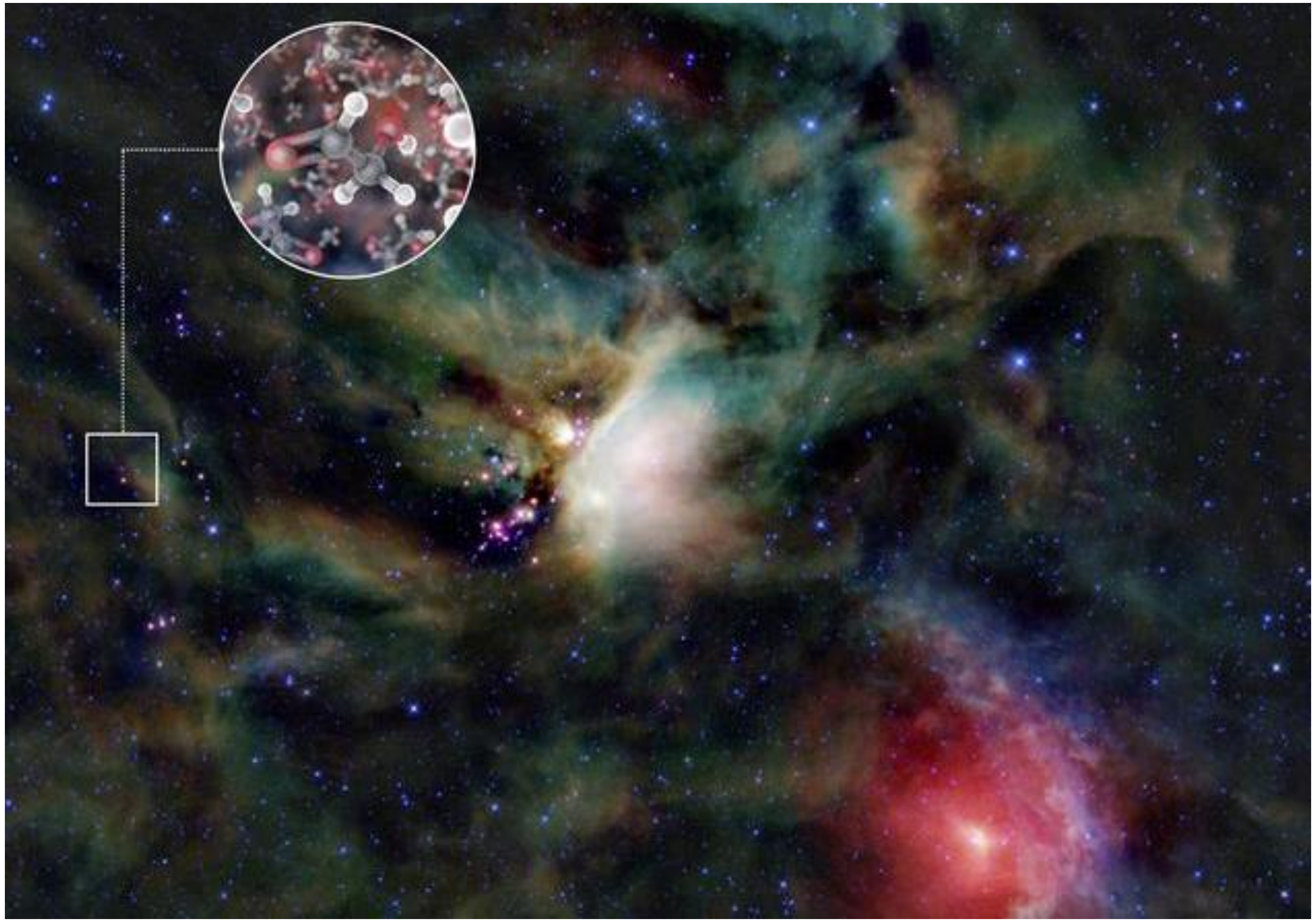
What ALMA can see

By observing millimetric wavelengths, **ALMA can see the so called “*Cold Universe*”**, where plants and galaxies are formed. ALMA has an unprecedented capability for discovering the **presence and distribution of molecules in space** and can observe, with high resolution, masses of cold and warm gas around protoplanets. By observing the "*invisible*" **ALMA can see our sun in detail** and capture light emitted by particles rather than light reflected by them.

Thus, **ALMA opens up innumerable possibilities for astronomical research**, from the discovery of new interstellar molecules to the mysteries of our cosmic origins.



Combined view of the dust ring around the bright star Fomalhaut from the ALMA observatory and Hubble telescope, 2012.

Credit: ALMA (ESO/NAOJ/NRAO) / NASA / ESA.

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How does an ALMA antenna work?

Antenna diagram, 2012.
Credit: ALMA (ESO/NAOJ/NRAO).

Most antennas used in radio astronomy have a **reflective surface that is parabolic in shape**. Because of its geometric characteristics a **parabolic antenna can efficiently capture signals** that reach its surface and direct them to a single point known as the **focal point**.
The **wavelengths** concentrated at the focal point **are channeled to band receptors** located behind the antenna, at the so-called ***front end,*** where **signals are amplified and digitized** so they can be processed.

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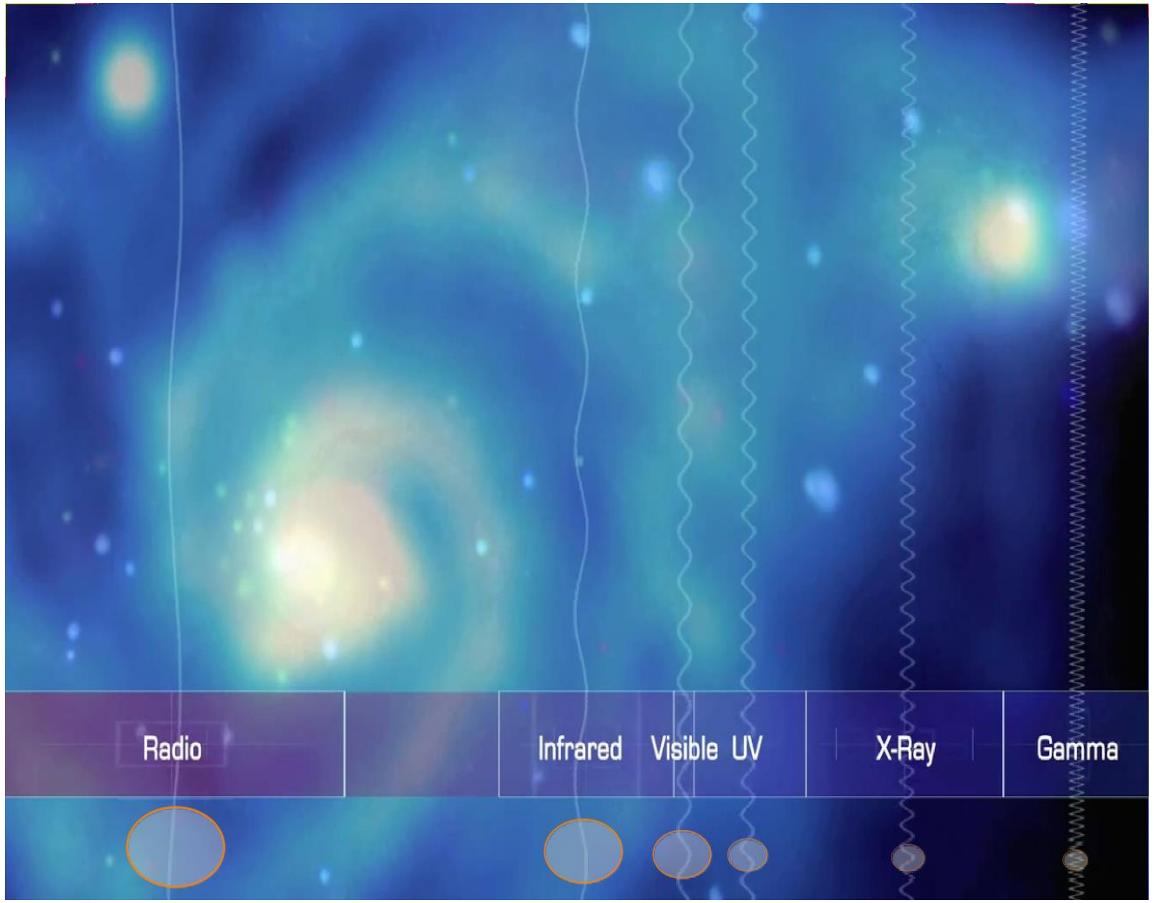
Resolution

A telescope's capacity to capture details depends on two things;

- The **diameter** of the collecting surface.
- The color or **wavelength** of the light it captures.

The greater the wavelength to be captured, the greater the diameter must be.

In order to observe with the sharpness of the human eye, **a radio telescope such as ALMA needs to be at least 500 times wider than the human eye.** The construction of such an enormous antenna, however, is impossible. The scientific community has solved this problem through **Interferometry**.



The resolution depends on the diameter of the collecting surface.

Credit: ALMA (ESO/NAOJ/NRAO).

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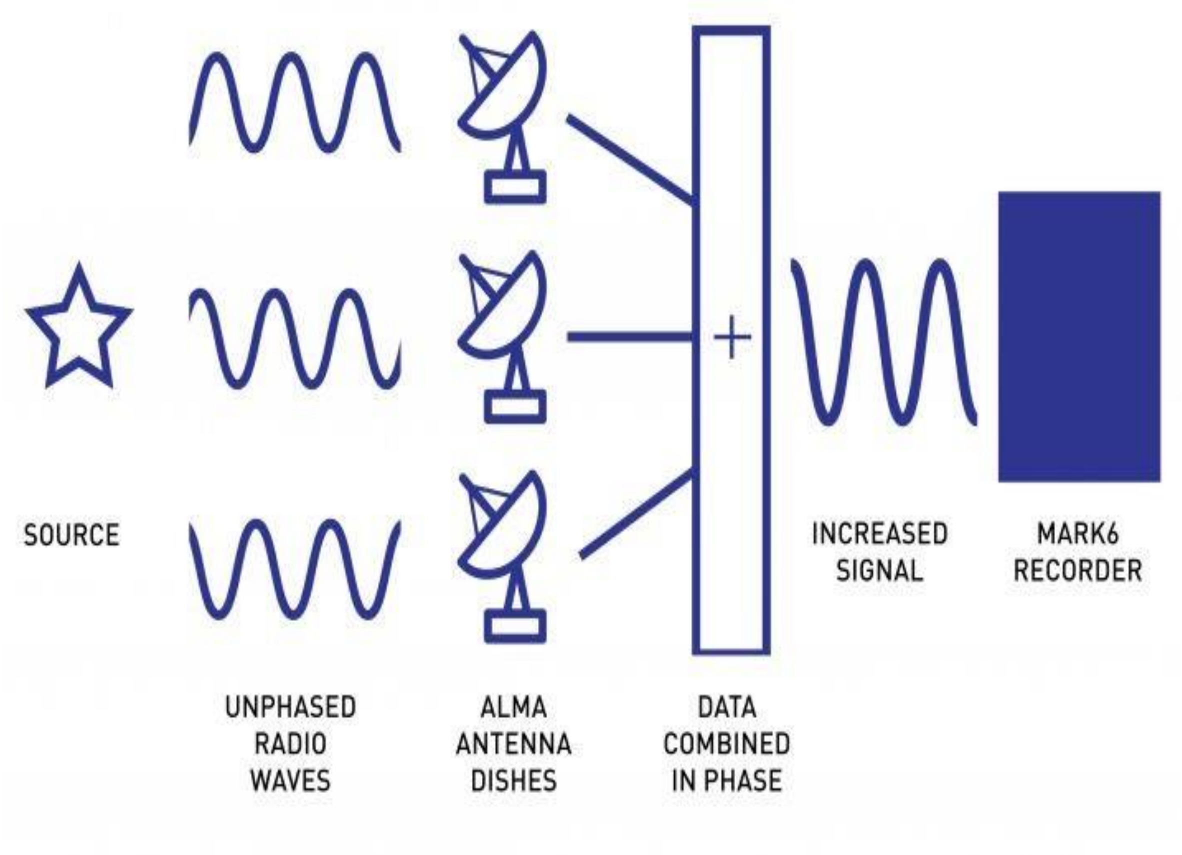
Interferometry



Interferometer diagram, 2012.
Credit: ALMA (ESO/NAOJ/NRAO)

The surface of an antenna is made up of **various panels**, and the antenna would still work if one of the panels were missing.
It is possible to **group together multiple antennas** inside a large, defined surface area, where **each antenna acts as a panel** within this "*virtual antenna*".
When a **group of antennas is synchronized to observe the same object** and the signals captured by each one are then directed, simultaneously, to a single **focal plane**, an image is obtained that is equivalent in resolution to an image obtained by a single antenna equal in diameter to the group of antennas.
The **66 antennas at ALMA**, located on the Chajnantor Plateau**, will form a radio interferometer with a maximum diameter of 16 kilometers**.

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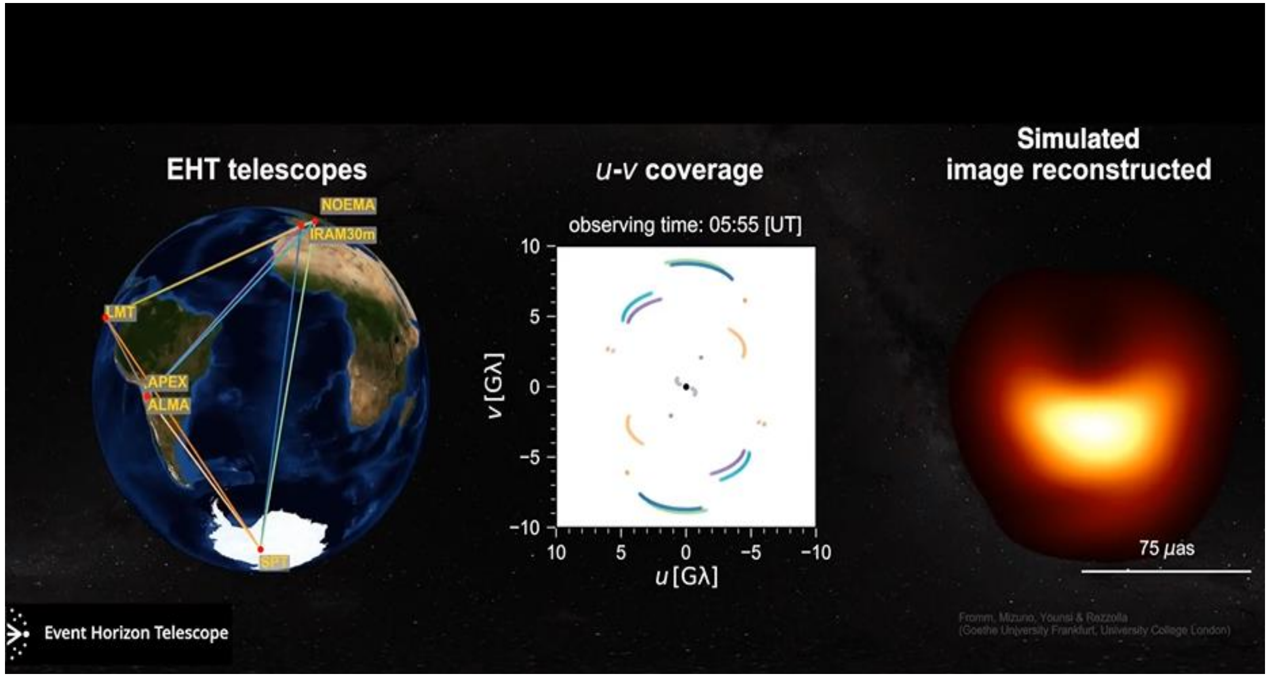
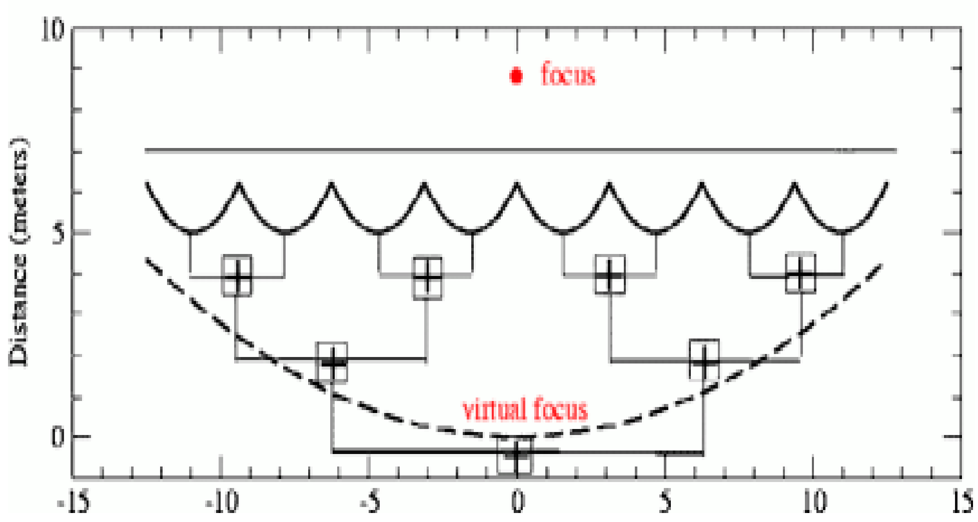
Aperture Synthesis

- If the source emission is unchanging, there is no need to measure all the pairs at one time
- One could imagine sequentially combining pairs of signals. For N sub-apertures there will be N(N-1)/2 pairs to combine
- Adding together all the terms effectively "synthesizes" one measurement taken with a large filled-aperture telescope
- Can synthesize apertures much larger than can be constructed as a filled aperture, giving very good spatial resolution





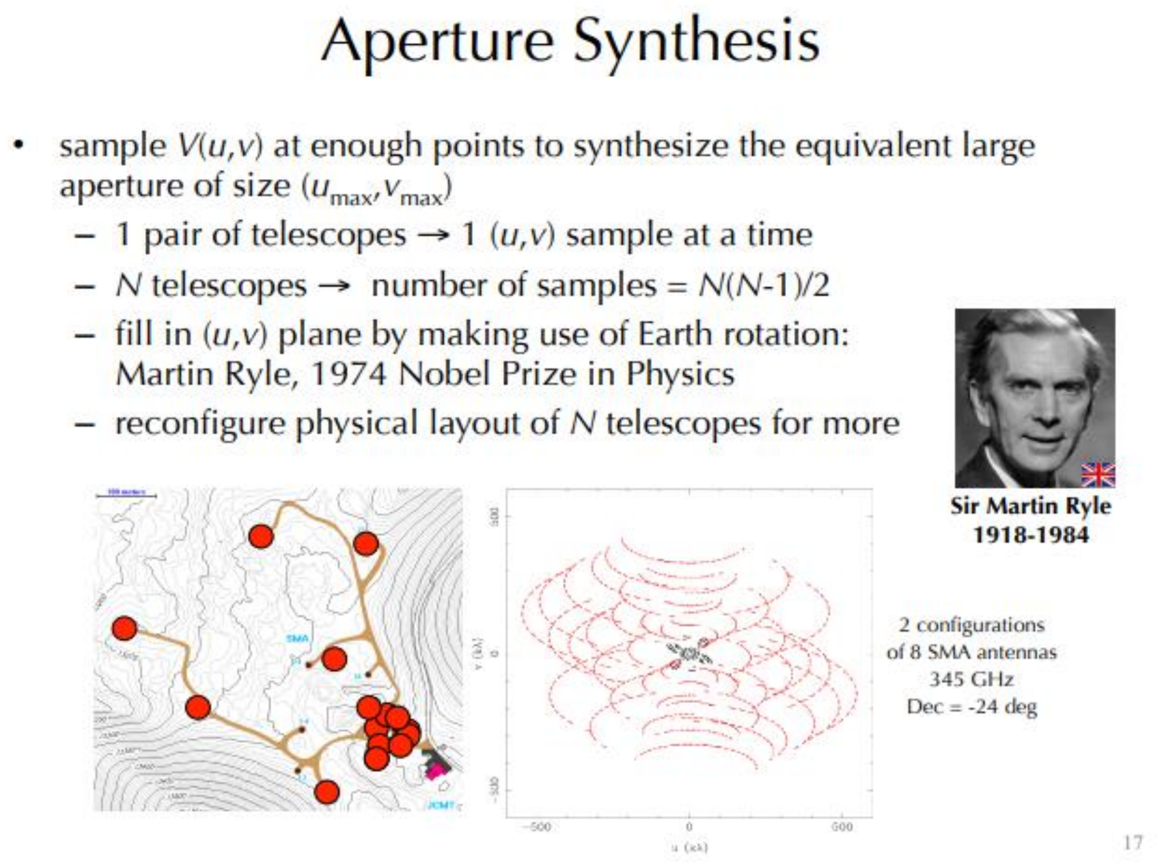
ALMA’s Interferometry by Martin Ryle

The technique of **Interferometry**, invented by the British astronomer Martin Ryle in the 1950s, not only allows for a greater diameter but also **enables redistribution of the antennas depending on the resolution** required for each observation.

✶The **more details** that are needed, the **greater the diameter over which the antennas will be distributed** for greater resolution.

✶If greater **amplitude is needed**, the **antennas will be grouped together in smaller-diameter** groups, in order to cover larger portions of the sky.

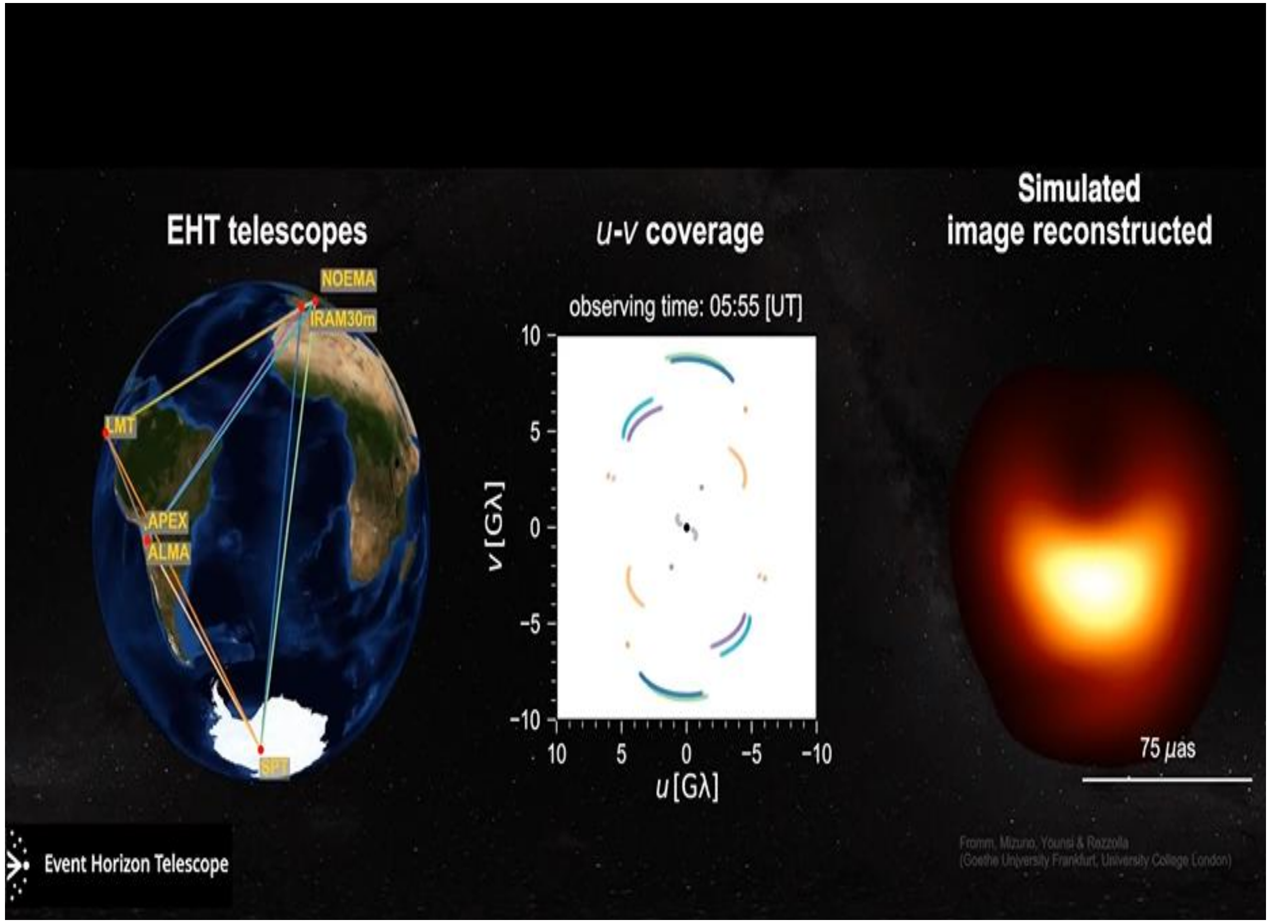
ALMA has two transporters that can move the antennas for the diameter requirements of each observation.

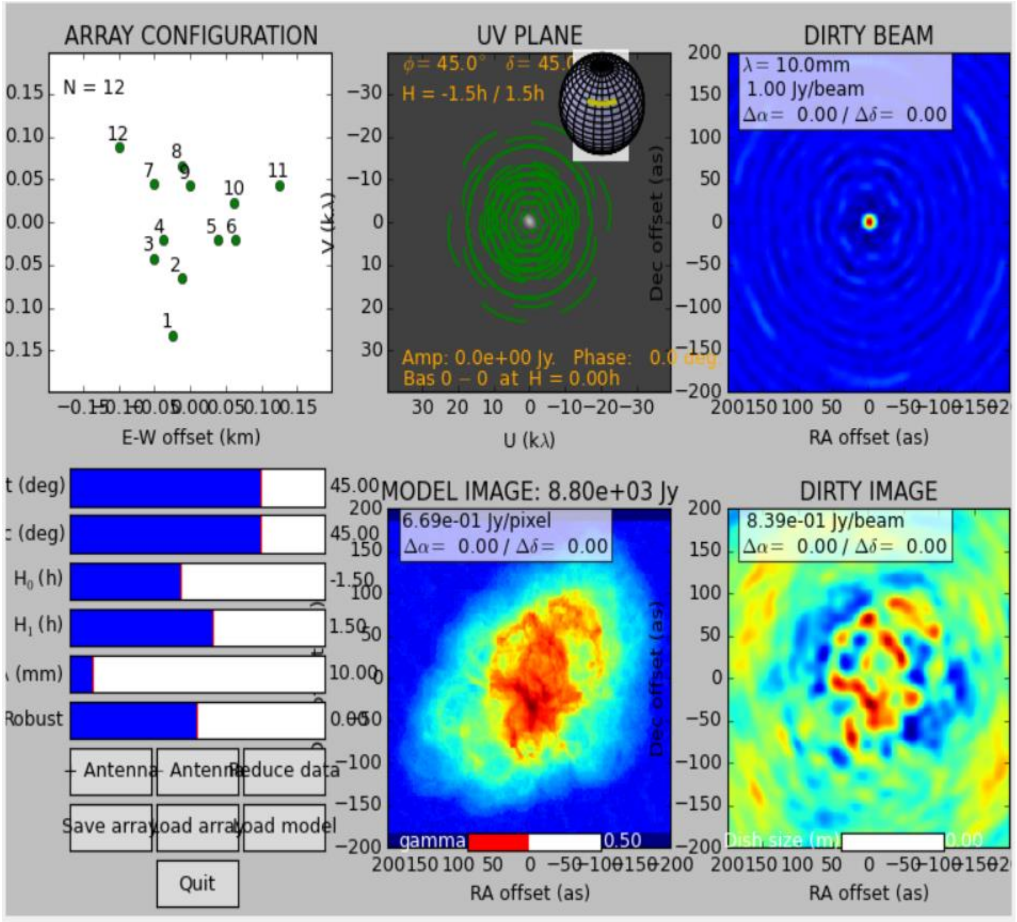


Artist’s conception of the extended array of antennas at ALMA.

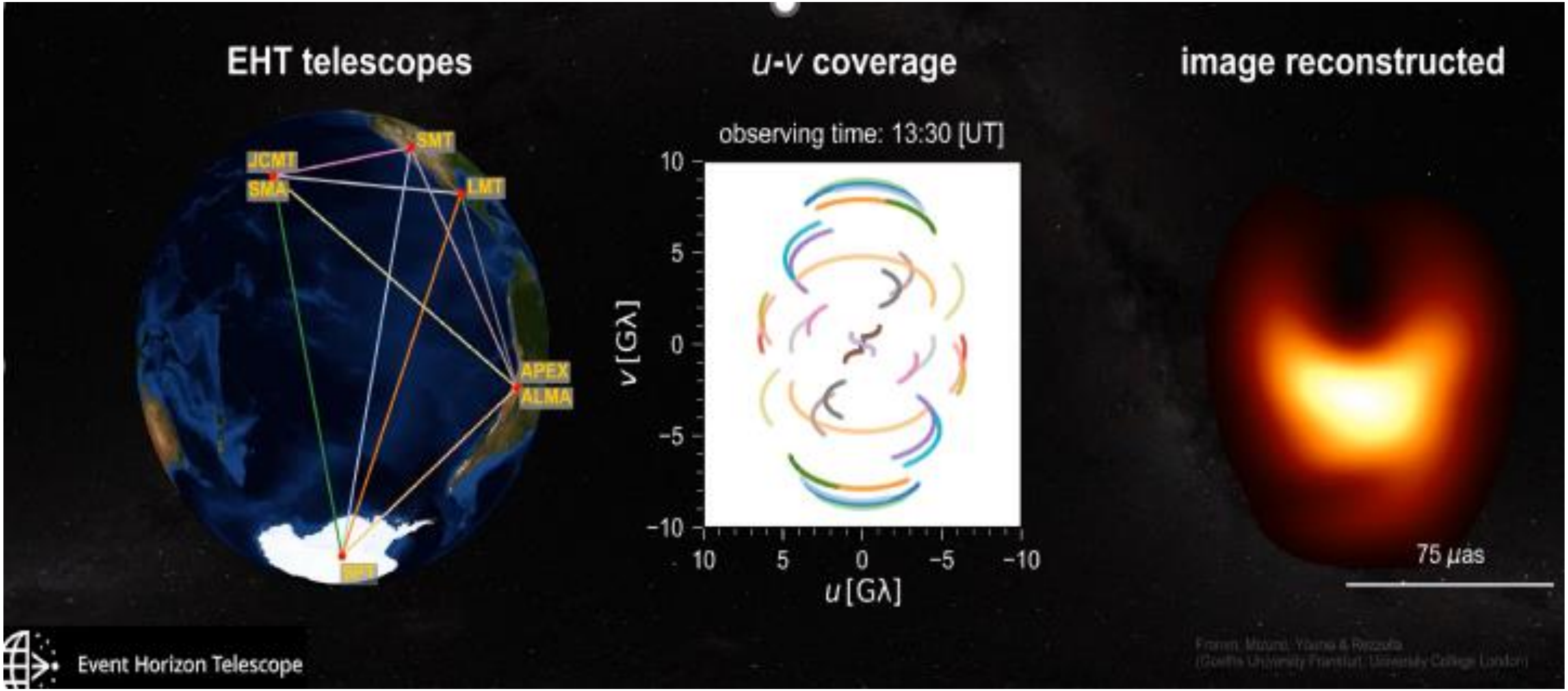
Credit: ALMA (ESO/NAOJ/NRAO).

Aperture Synthesis

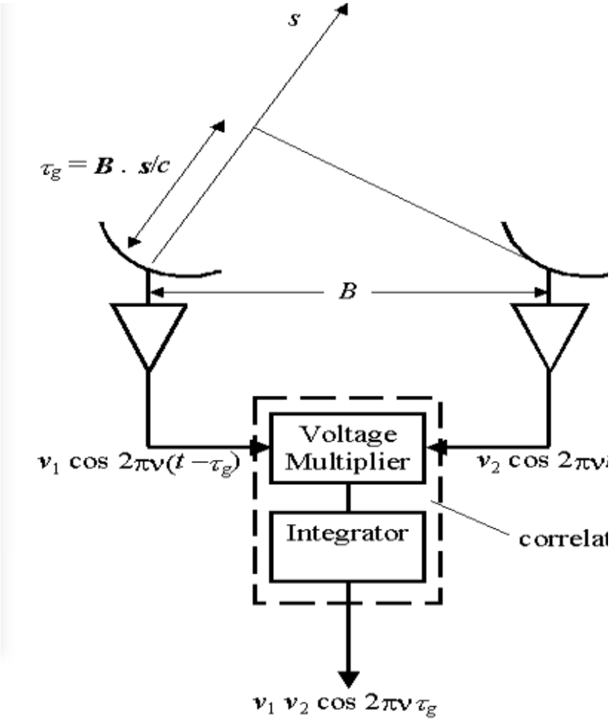


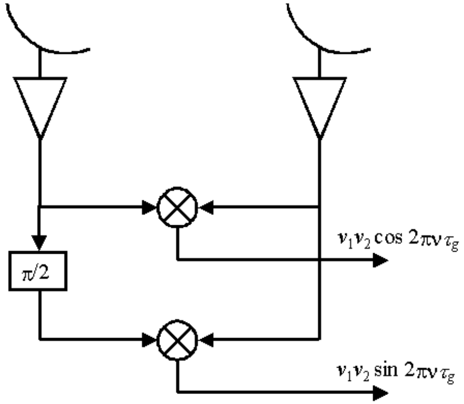


Aperture synthesis



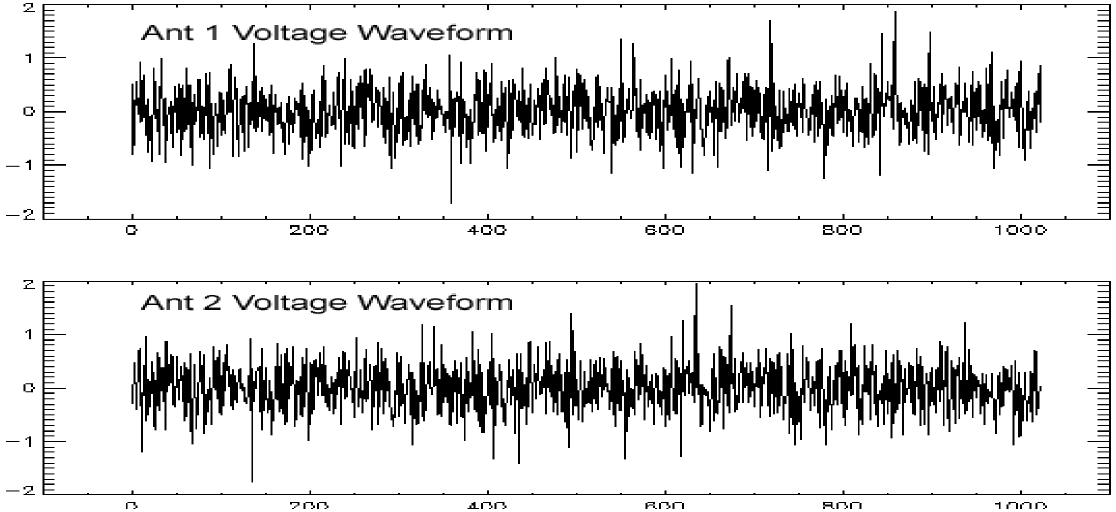
Correlation

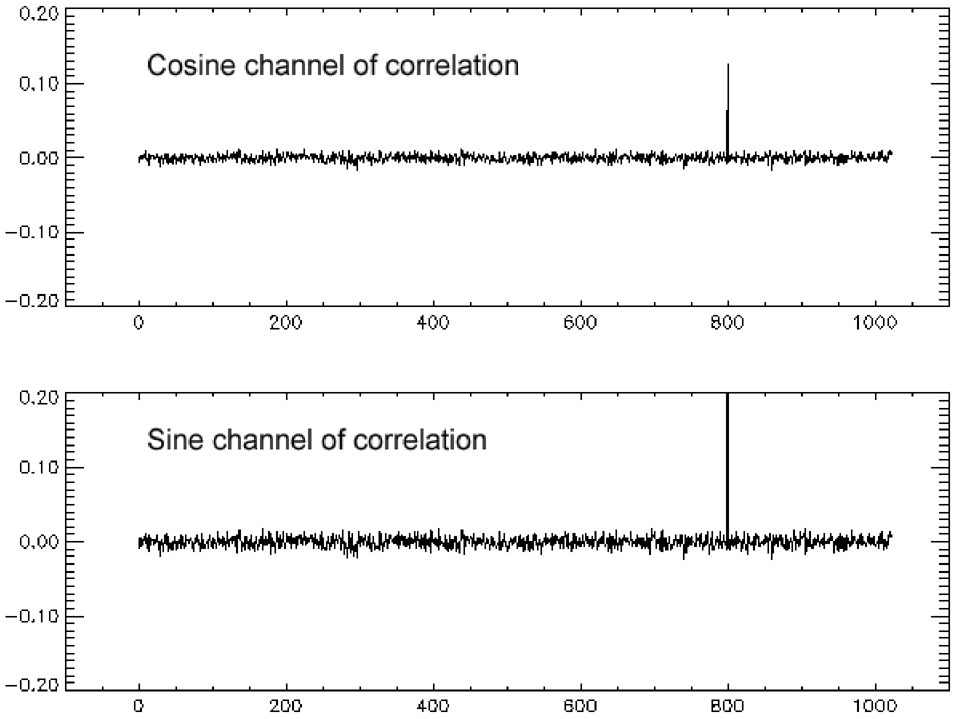




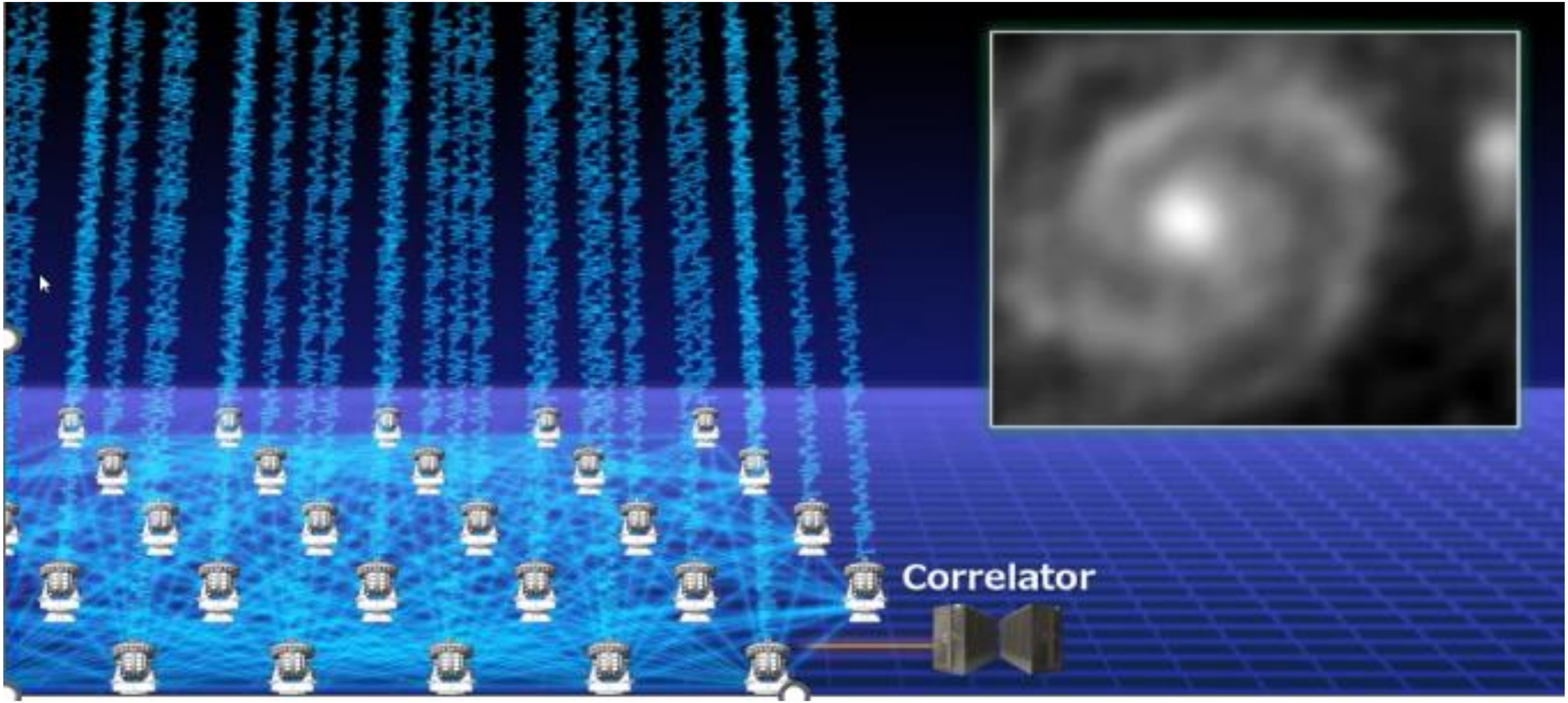
The IF signal from each receiver looks like a noise signal. Part of the waveform is really signal from the source, and part of it (perhaps the largest part) is noise. If both signal and noise look the same, how do we tell the difference? The essential point is that source signal will be correlated between the two antennas, while the (locally generated) noise signal will not. This is illustrated with the simulated waveforms from two antennas, below:

A major refinement is to use a second correlator, and shift one of the signals by $\pi/2$, so that both sine and cosine components are measured simultaneously, as shown below.





ALMA’s Imaging Correlator →Video



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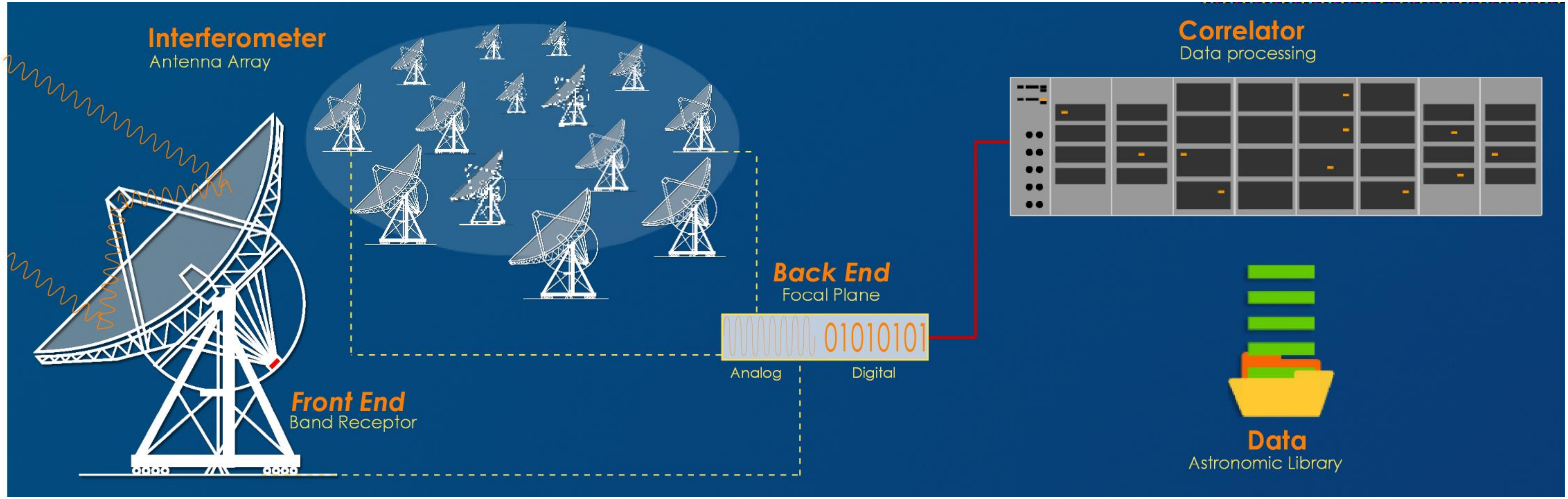
How ALMA translate wavelengths into images?

Each antenna has a ***front end***, where **band receptors convert wavelengths into electrical signals** to be sent to the ***back end***, a complex and accurate electronic system where **the signals are digitized and synchronized** and then sent, via fiber optics, to a central computer known as the **Correlator**.



ALMA operations diagram.
Credit: ALMA (ESO/NAOJ/NRAO).

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How can we observe through ALMA?

Each year s**cientists compete for observation time** by presenting proposals that are evaluated on the basis of scientific merit.

Priority will be given to projects from the countries that finance ALMA: North America (USA and Canada), East Asia (Japan and Taiwan), 14 European countries and Brazil. **Chile, as the host nation, is entitled to 10% of the overall observation time.**

Those **astronomers whose proposals are admitted** don't have to travel to ALMA to carry out observations; instead, they **will have remote and exclusive access to the data gathered**.

ALMA has an exclusive software structure that allows astronomers to do many things, from generating the astronomical project to receiving the data for the observational proposal.

Scientists examining ALMA data.

Credit: NAOJ

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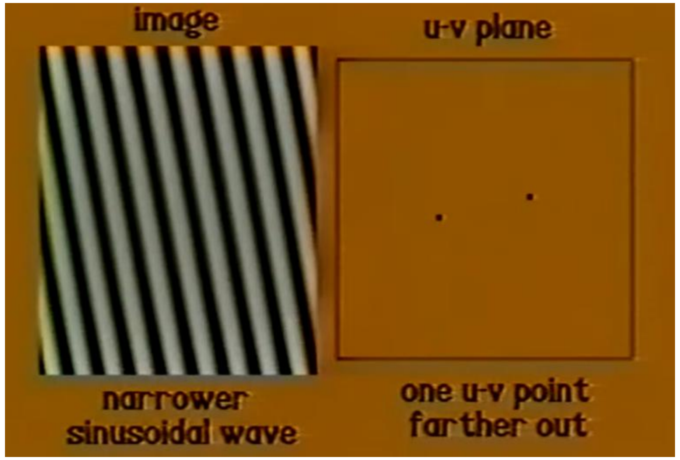
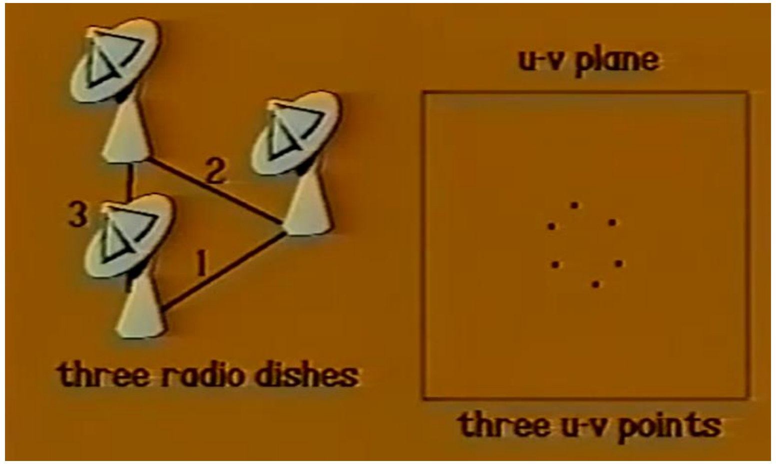
Summary Interferometry

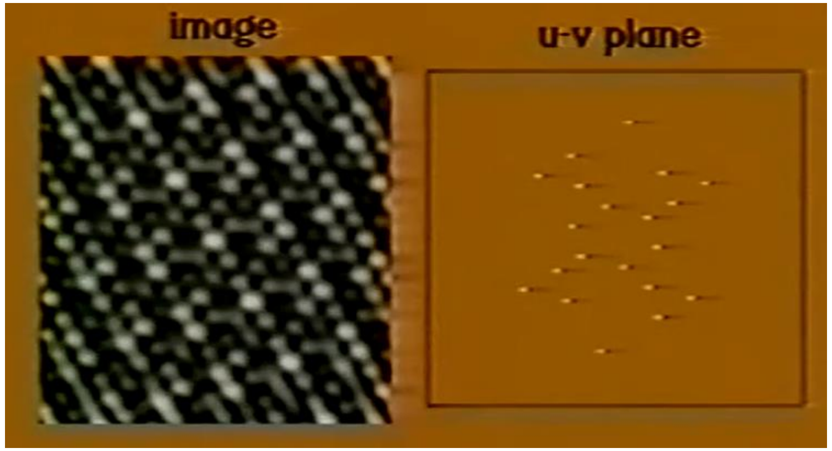
One Antenna FT plan



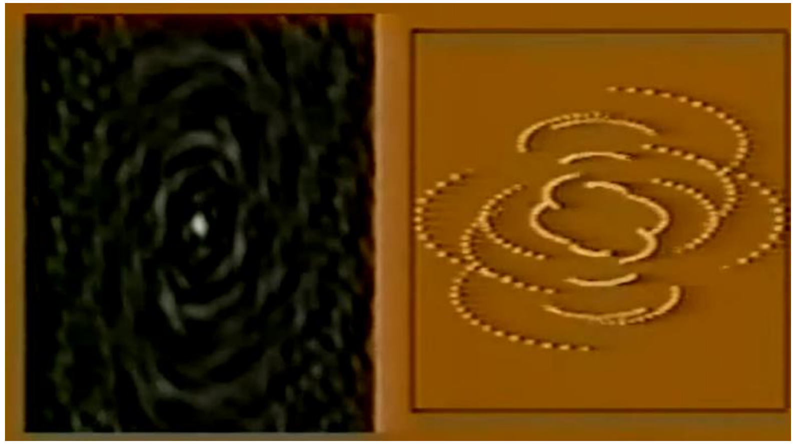
Aperture Synthesis VLBI,
Three antenna 6 Points FT



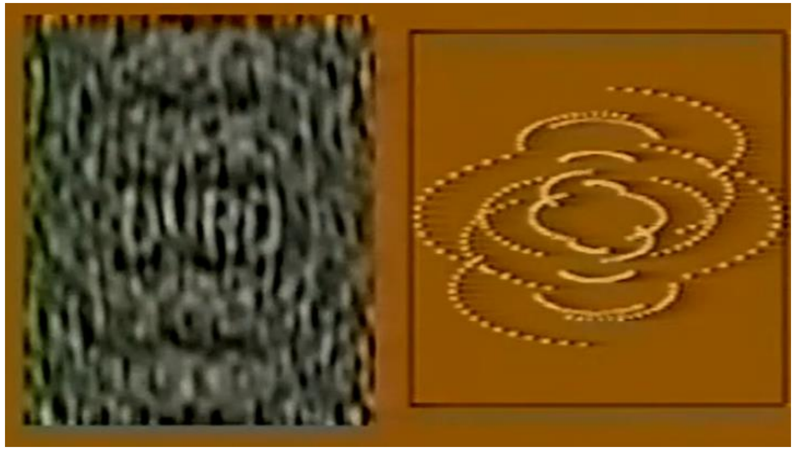
VLBI, many antenna Points FT



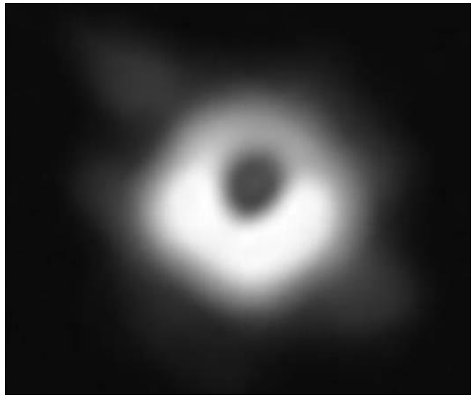
Aperture Synthesis & Rotation



Aperture Synthesis/Fourier Synthesis & Rotation



Black hole M87 Image



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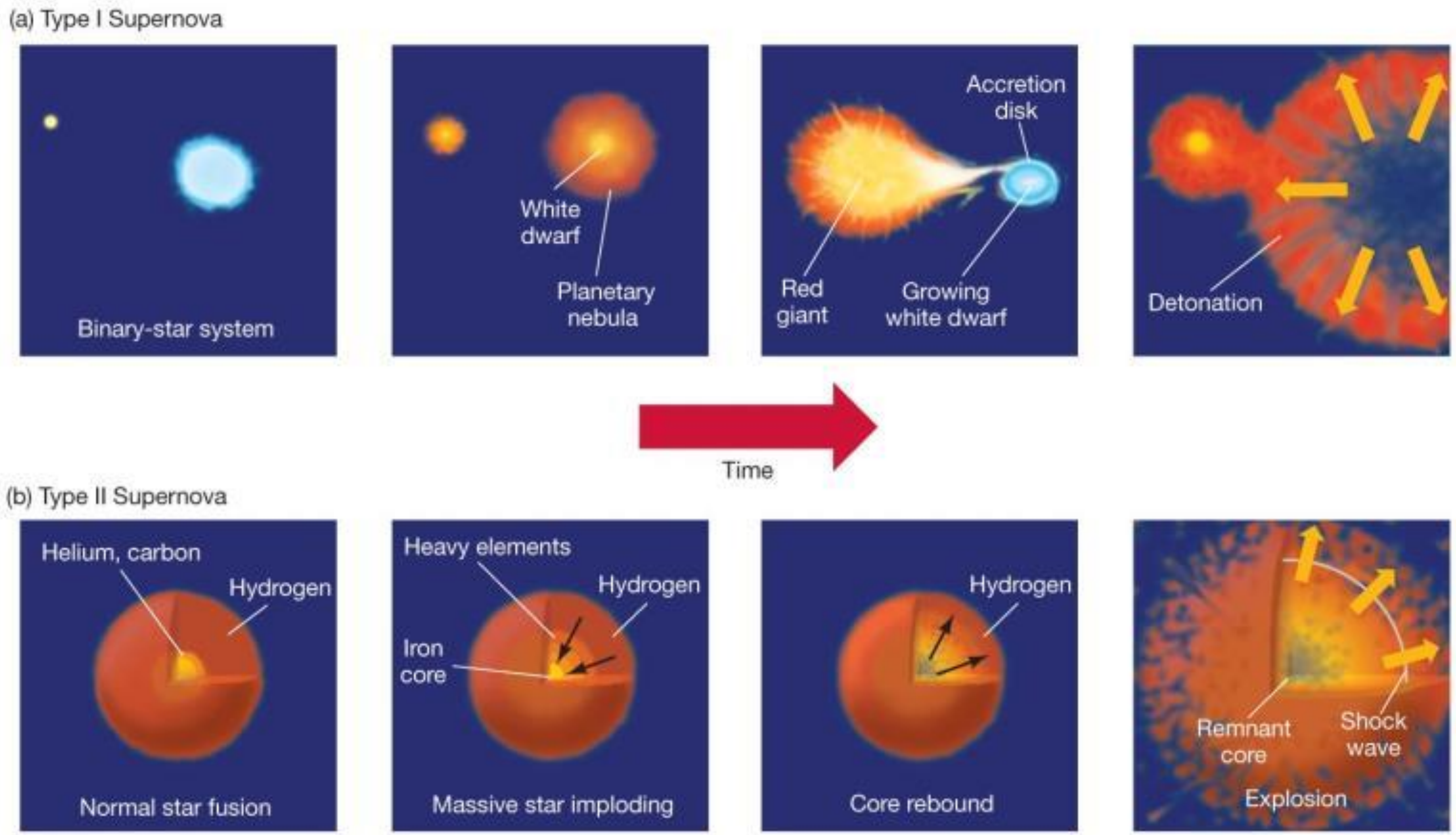
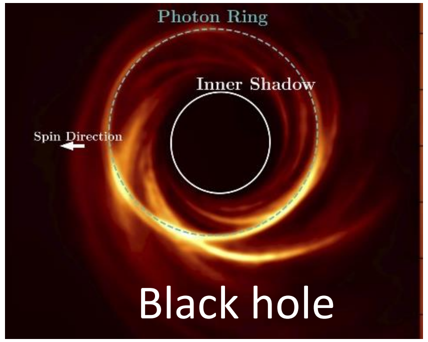
Supernovae Type I , II

This graphic illustrates the two different types of supernovae:

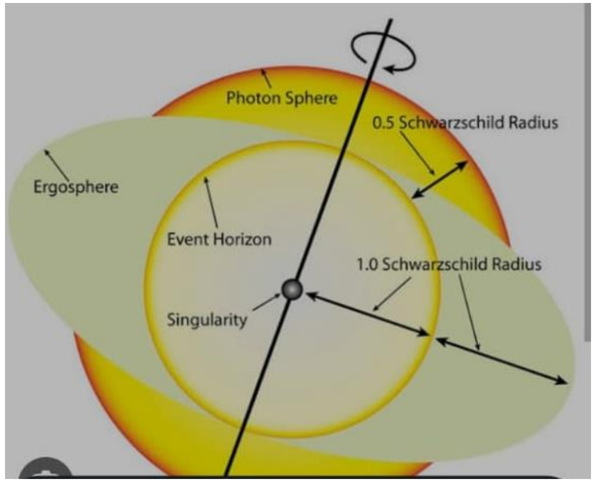




Black Holes

The mass of a neutron star cannot exceed about 3 solar masses. If a core remnant is more massive than that, nothing will stop its collapse, and it will become smaller and smaller and denser and denser.

Eventually, the gravitational force is so intense that even light cannot escape. The remnant has become a black hole.

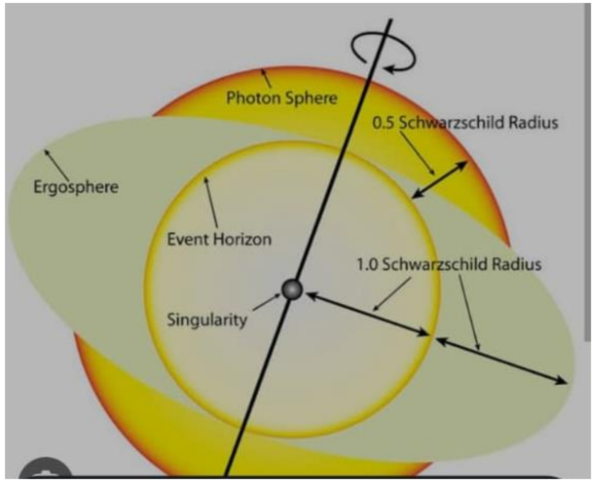


Black Holes

The radius at which the escape speed from the black hole equals the speed of light is called the Schwarzschild radius.

The Earth’s Schwarzschild radius is about a centimeter; the Sun’s is about 3 km.

Once the black hole has collapsed, the Schwarzschild radius takes on another meaning—it is the event horizon. Nothing within the event horizon can escape the black hole.



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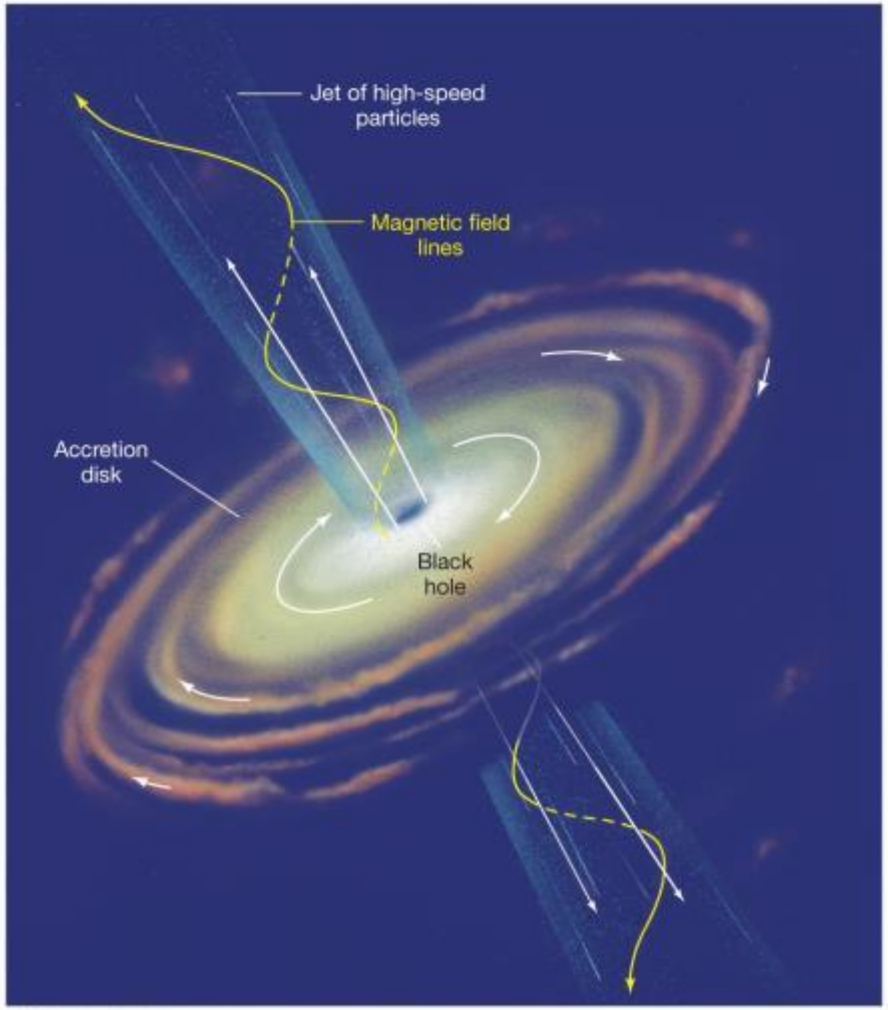
The Central Engine of an Active Galaxy

This is the leading theory for the energy source in an active galactic nucleus: a black hole, surrounded by an accretion disk. The strong magnetic field lines around the black hole channel particles into jets perpendicular to the magnetic axis.



The Central Engine of an Active Galaxy

In an active galaxy, the central black hole may be billions of solar masses.

The accretion disk is whole clouds of interstellar gas and dust; they may radiate away as much as 10–20% of their mass before disappearing.

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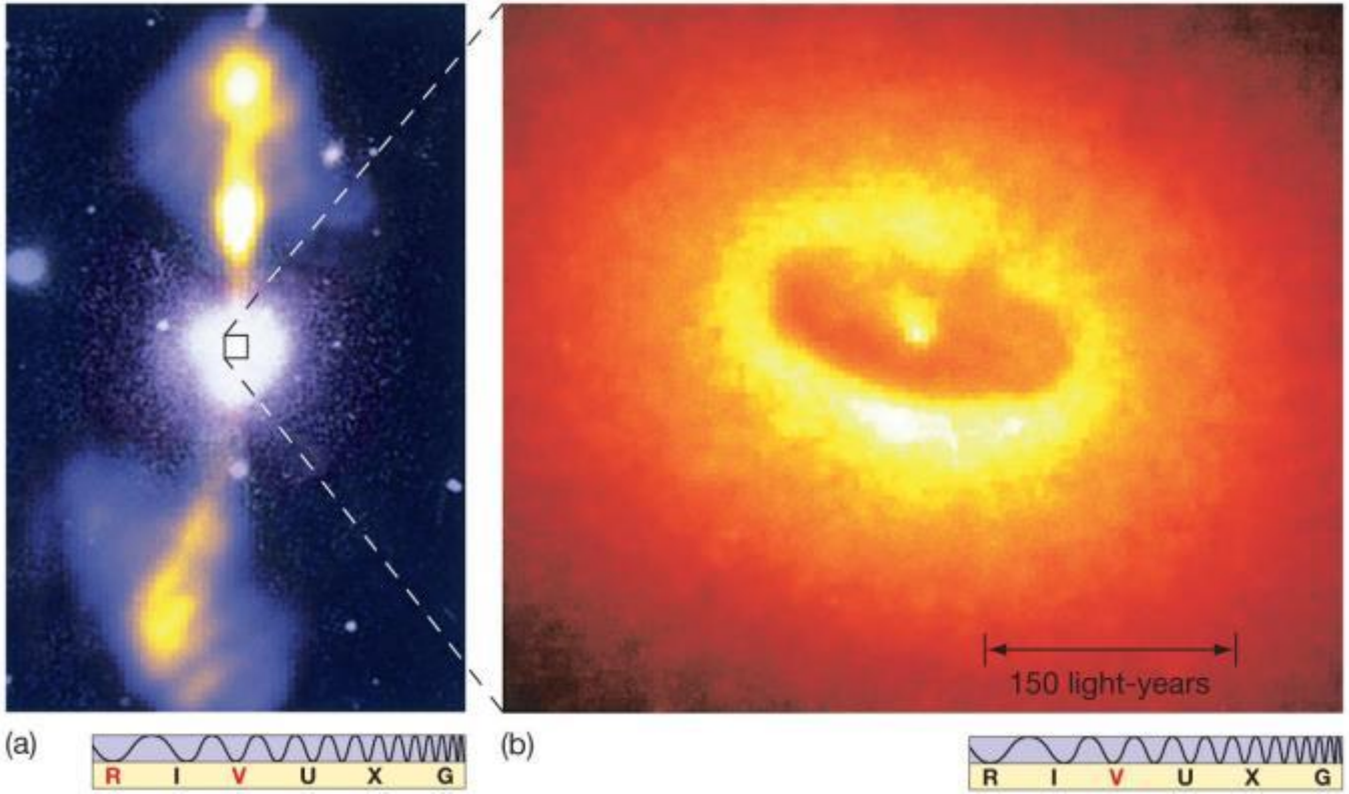
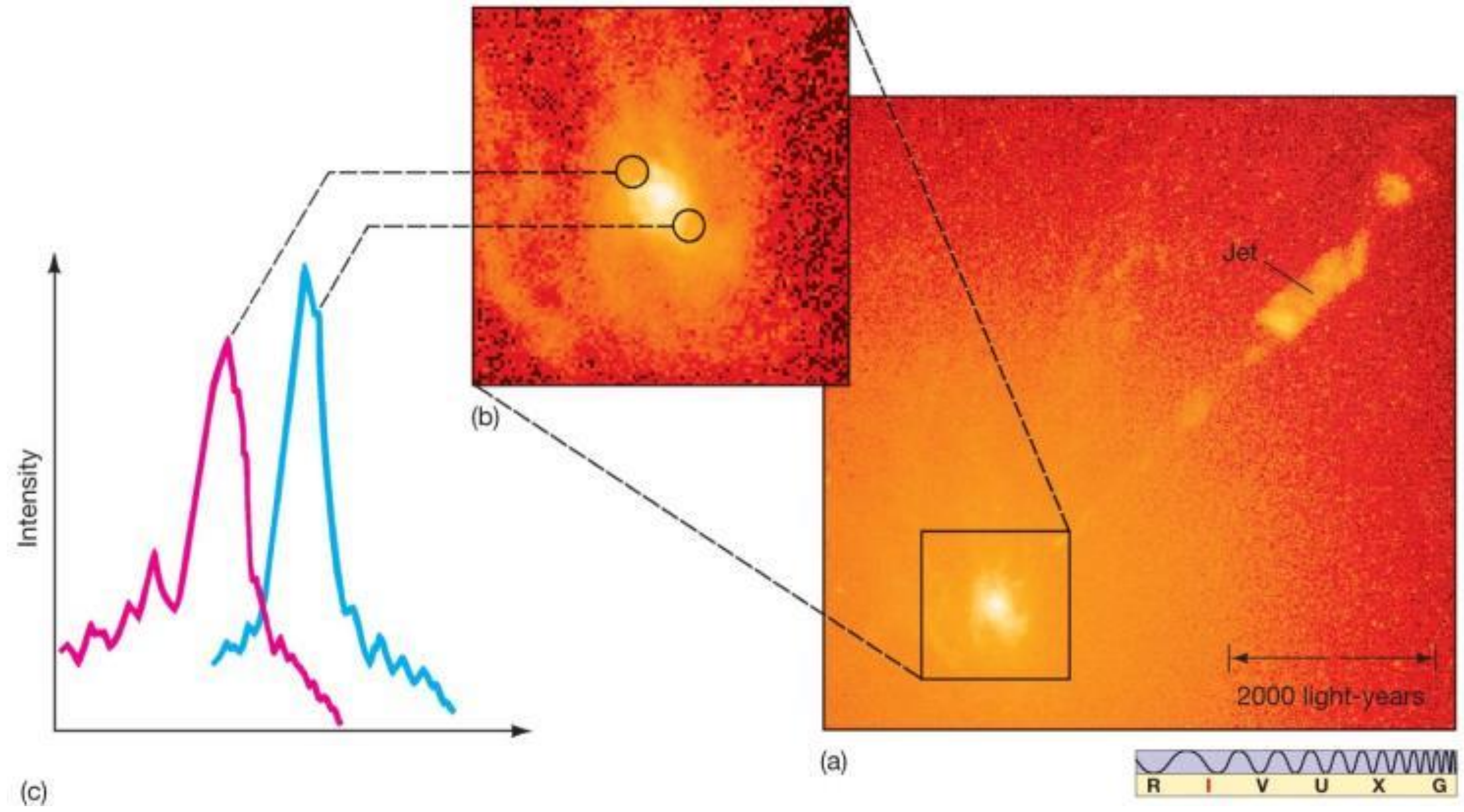
The Central Engine of an Active Galaxy

This pair of images shows evidence for a black hole at the center of NGC 4261.



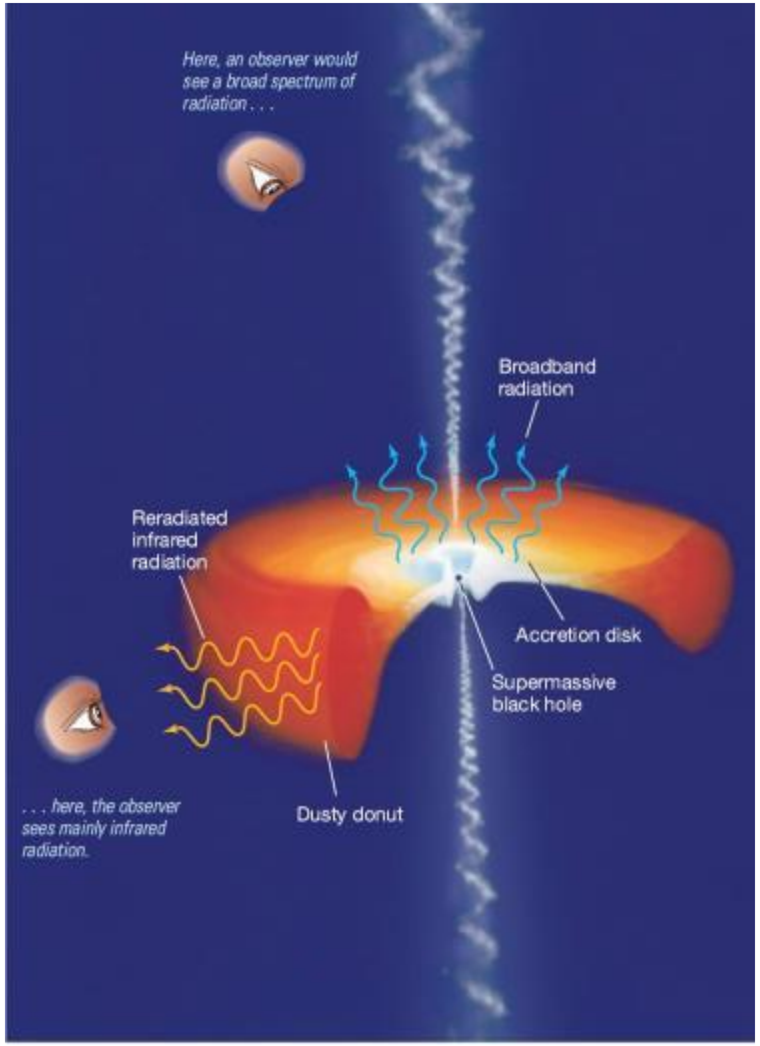
The Central Engine of an Active Galaxy

The central portion of M87 shows rapid motion and jets characteristic of material surrounding a black hole.



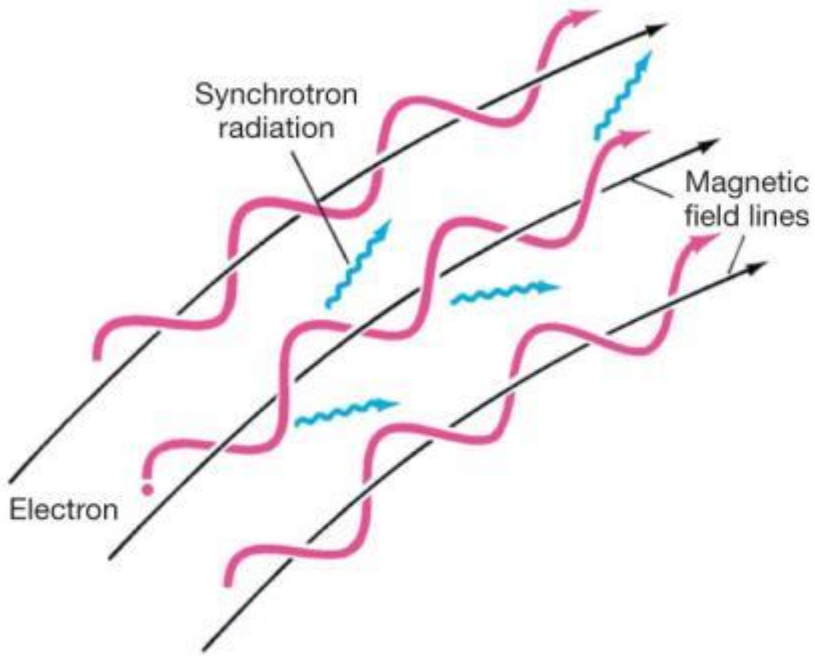
The Central Engine of an Active Galaxy

One might expect the radiation to be mostly X-rays and gamma rays, but apparently it is often “reprocessed” in the dense clouds around the black hole and reemitted at longer wavelengths.

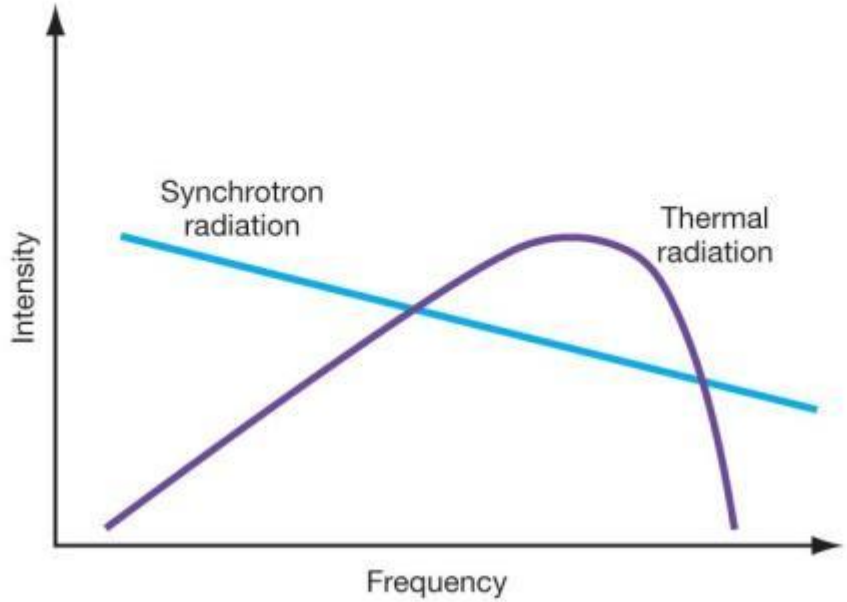


The Central Engine of an Active Galaxy

Particles will emit synchrotron radiation as they spiral along the magnetic field lines; this radiation is decidedly nonstellar.



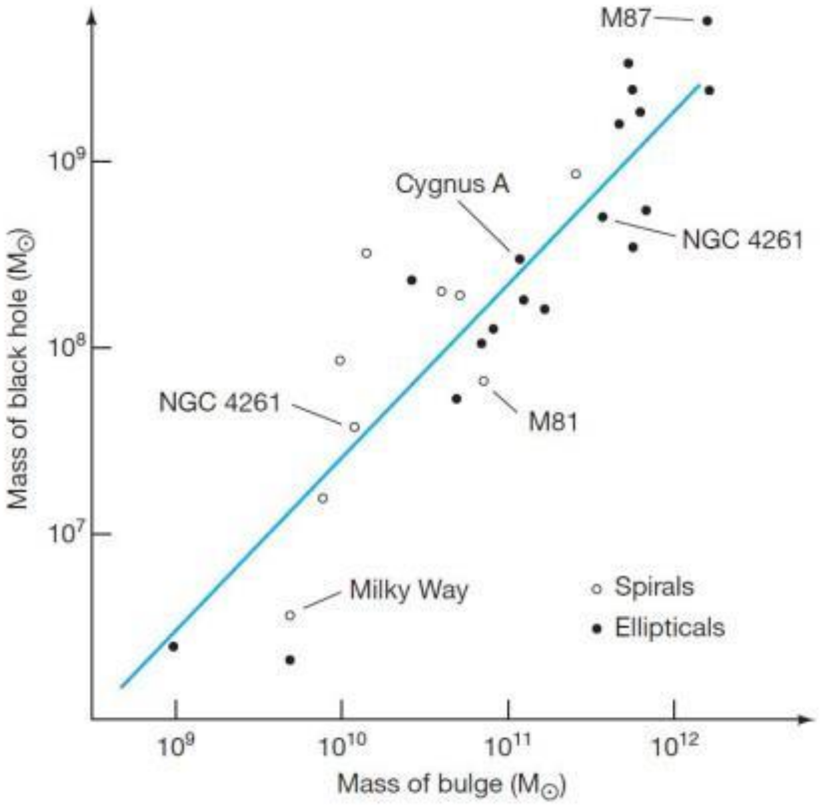
(a)



(b)

Black Holes in Galaxies

The mass of the central black hole is well correlated with the mass of the galactic bulge, for those galaxies where both have been measured.



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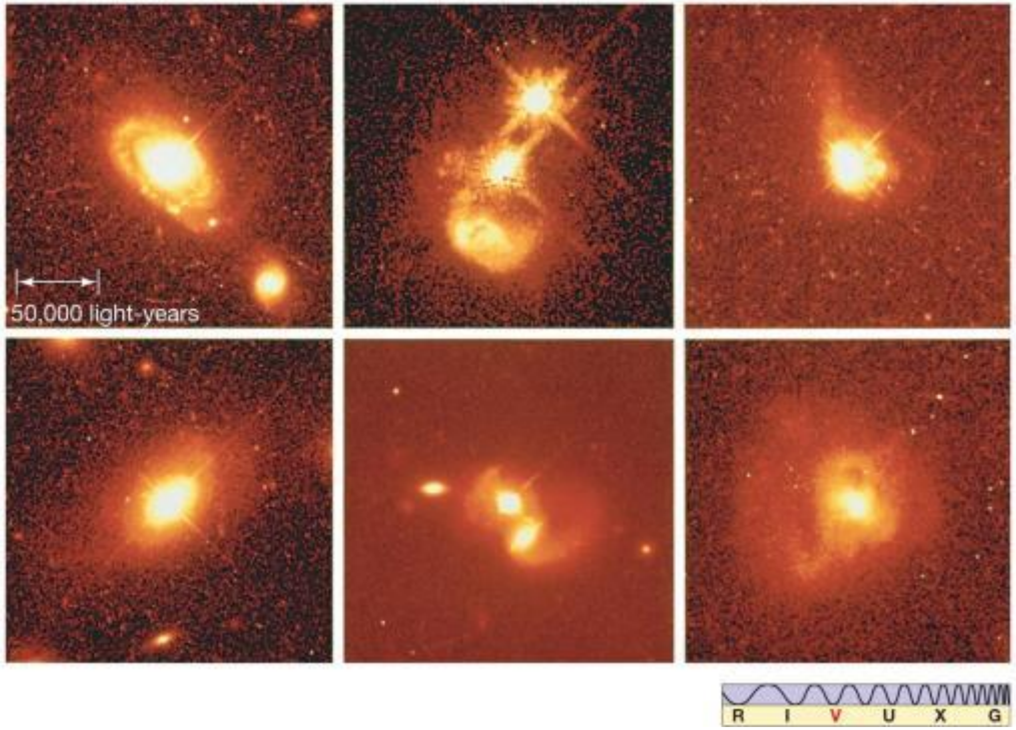
Black Holes in Galaxies

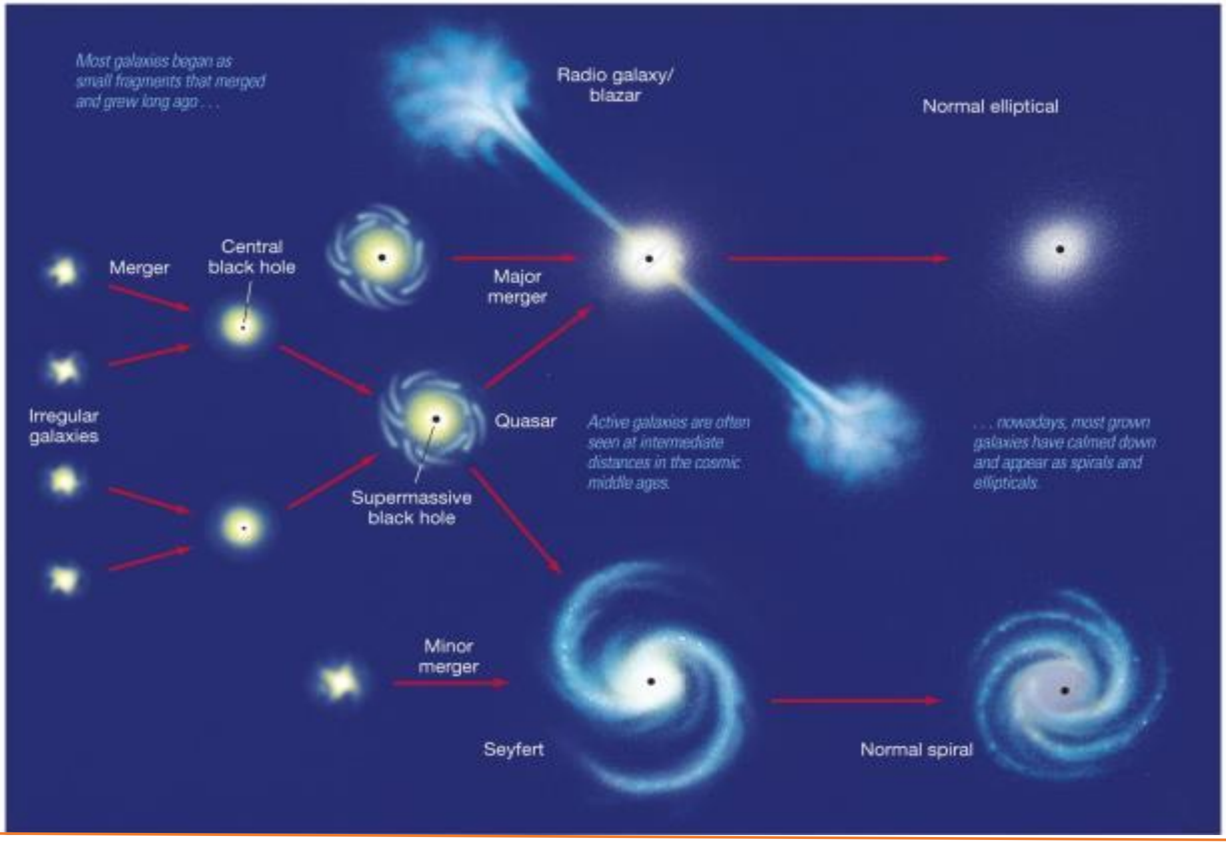
The quasars we see are very distant, meaning they existed a long time ago. Therefore, they may represent an early stage in galaxy development.



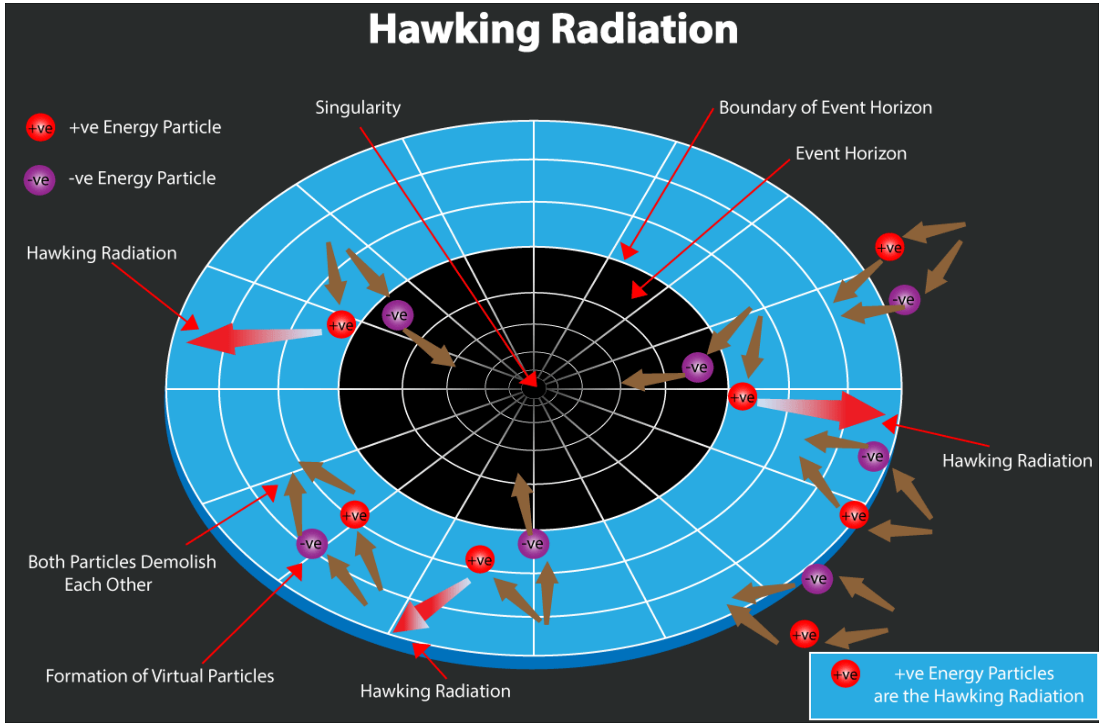
The quasars in this image are shown with their host galaxies; many appear to be involved in collisions.

Black Holes in Galaxies

This figure shows how galaxies may have evolved, from early irregulars through active galaxies to the normal ellipticals and spirals we see today.



No Hair Theorem → Hawking Radiation



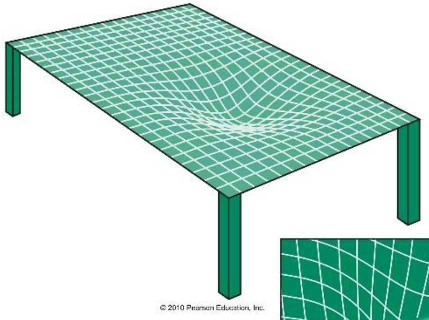
- MASS
- SPIN
- Charge

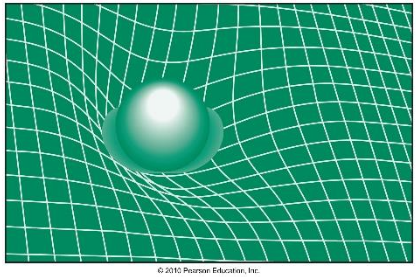
Black Holes ain't so black, They Glow in a sky like coals
In a sky and they radiate. And so overtime, they loose energy
And mass and ultimately disappear over a huge time scales.

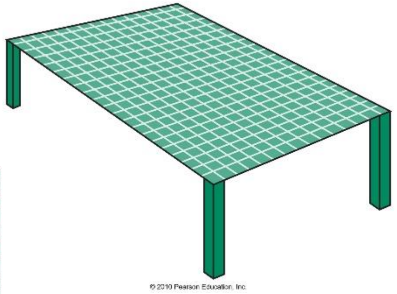
→ By Hawking

$$T_{\mathrm{H}} = \frac{\hbar c^3}{8\pi G k_{\mathrm{B}} M}$$

General theory of relativity formula







Schwarzschild's Solution to Einstein's Equations

Time Dilation

Radial Length Contraction

$$ds^2 = -\left(1-\frac{R_S}{r}\right)c^2dt^2 + \frac{1}{\left(1-\frac{R_S}{r}\right)}dr^2 + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)$$

Invariant Line Element

Schwarzschild Radius

$$R_S = \frac{2GM}{c^2}$$

Time dilation due to gravity is weaker than time dilation due to velocity

Earth's time runs slow from the Perspective of Astronaut

Clocks on international space station run slightly faster compared to clock on earth

He provided the first exact solution to the Einstein field equations of general relativity,----Karl Schwarzschild

Density of matter and energy

$$R_{\mu\nu} - \frac{1}{2}R\,g_{\mu\nu} + \Lambda\,g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

geometry of space and time

"Space-time tells matter how to move.
Matter tell space-time how to curve."
John Wheeler (American physicist)

Riemann Curvature Tensor $R^{\alpha}_{\beta\gamma\delta}$

Ricci Curvature Tensor $R_{\mu\nu}$

Ricci Curvature Scalar R

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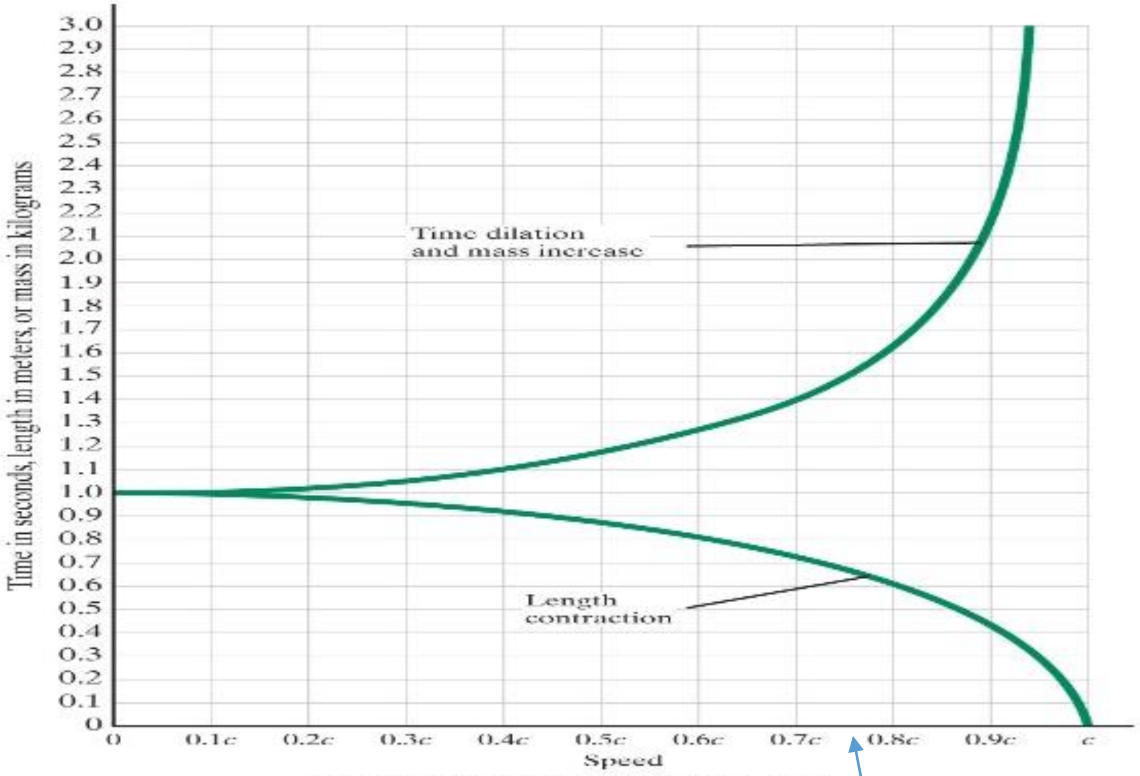
Solve Relativity →Quantum Loop Gravity, String Theory



Special Relativity

Constraints

Black Holes, Wormholes, Dark matter, Singularity
infinity if 1- Rs/r =1 and time stop

Solution

No singularity → Quantum Loop gravity
String Theory→ Define as Surface BH

$$S_{BH} = \frac{1}{4}\frac{\text{Horizon area}}{\text{Planck area}}$$

geometry of space and time

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Density of matter and energy

In physics, string theory is a theoretical framework in which the point-like particles of particle physics are replaced by one-dimensional objects called strings.

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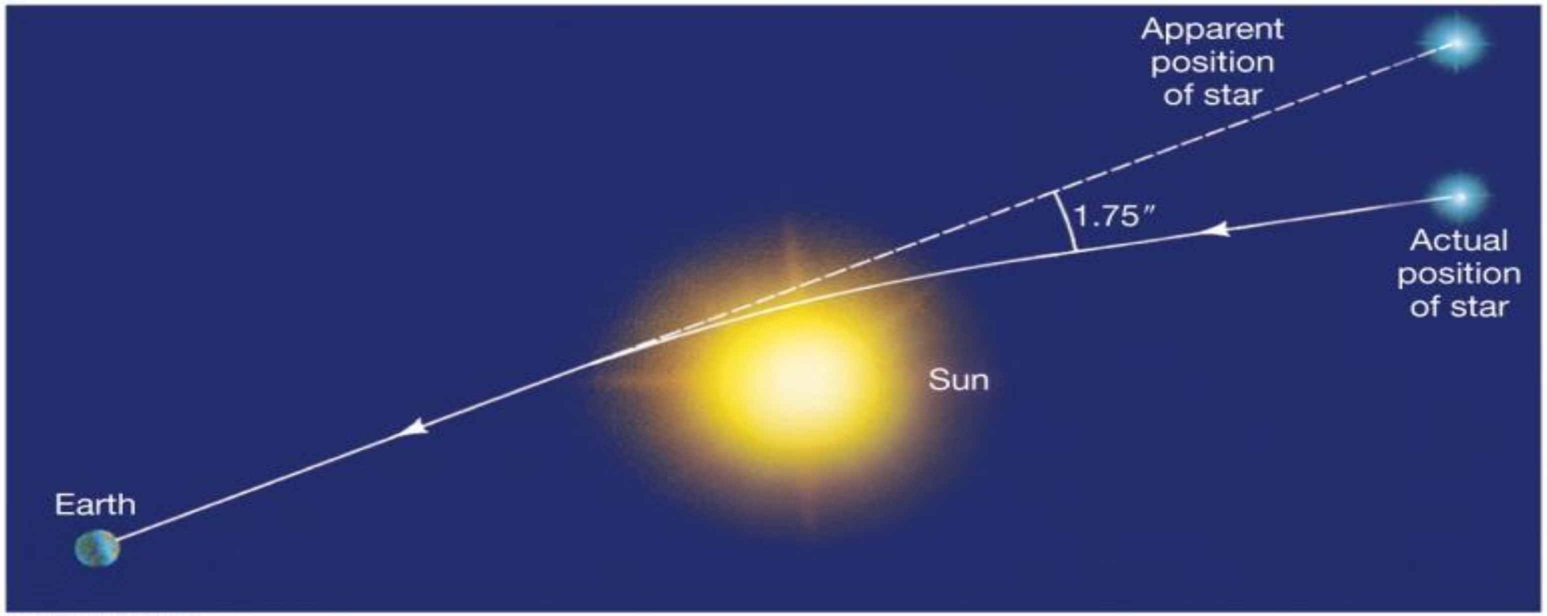
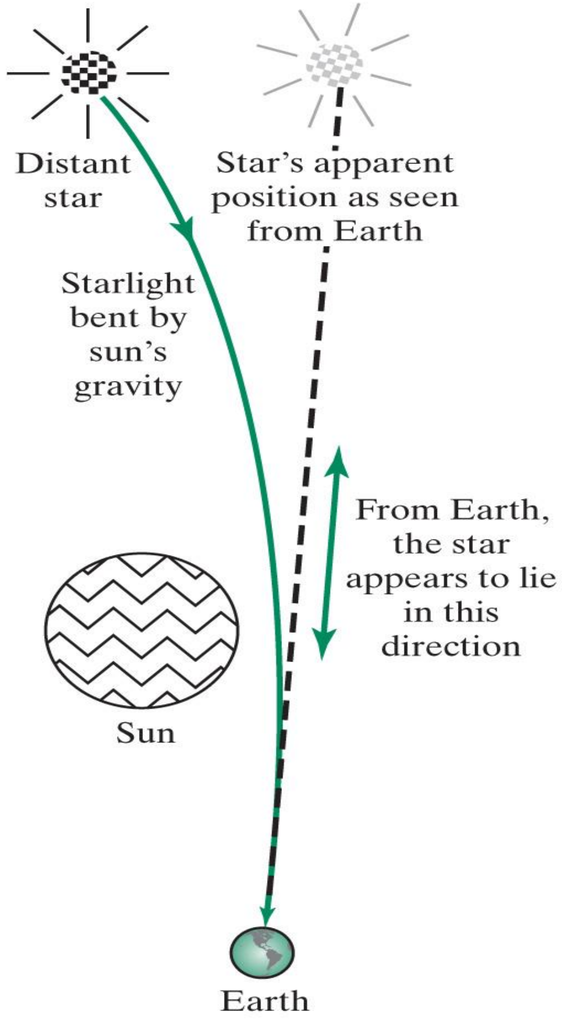
More Precisely
Tests of General Relativity

Deflection of starlight by the Sun's gravity was measured during the solar eclipse of 1919; the results agreed with the predictions of general relativity.

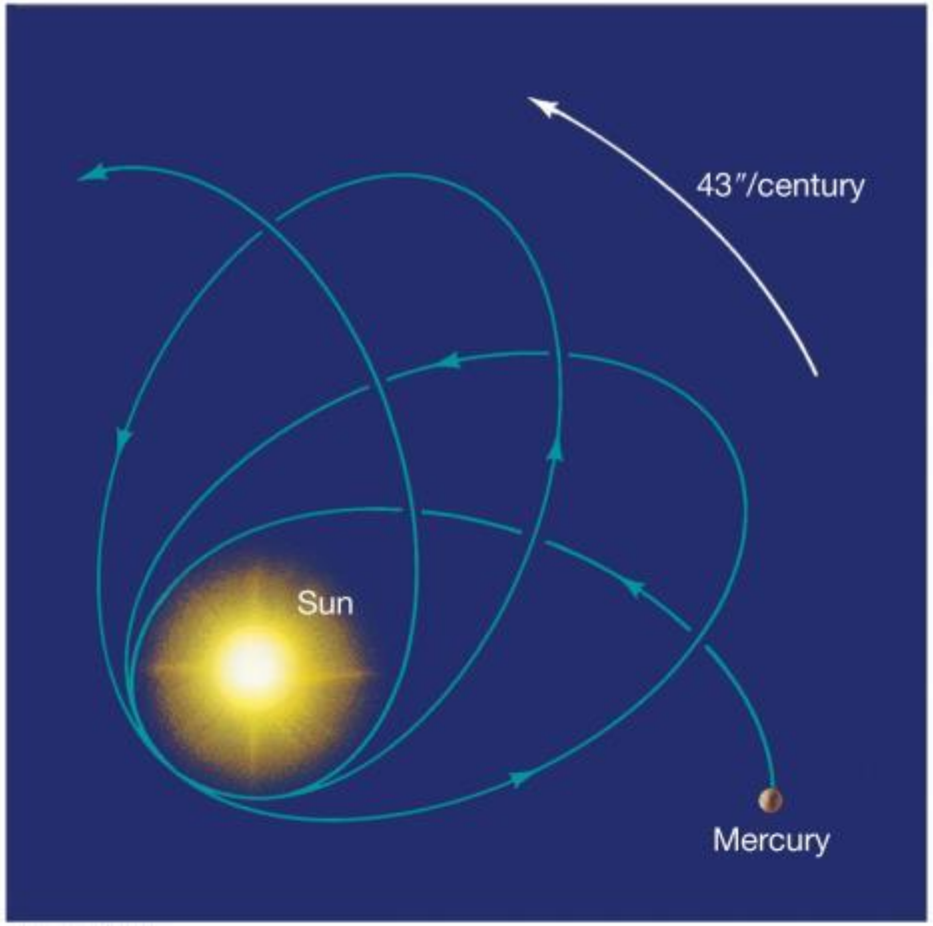




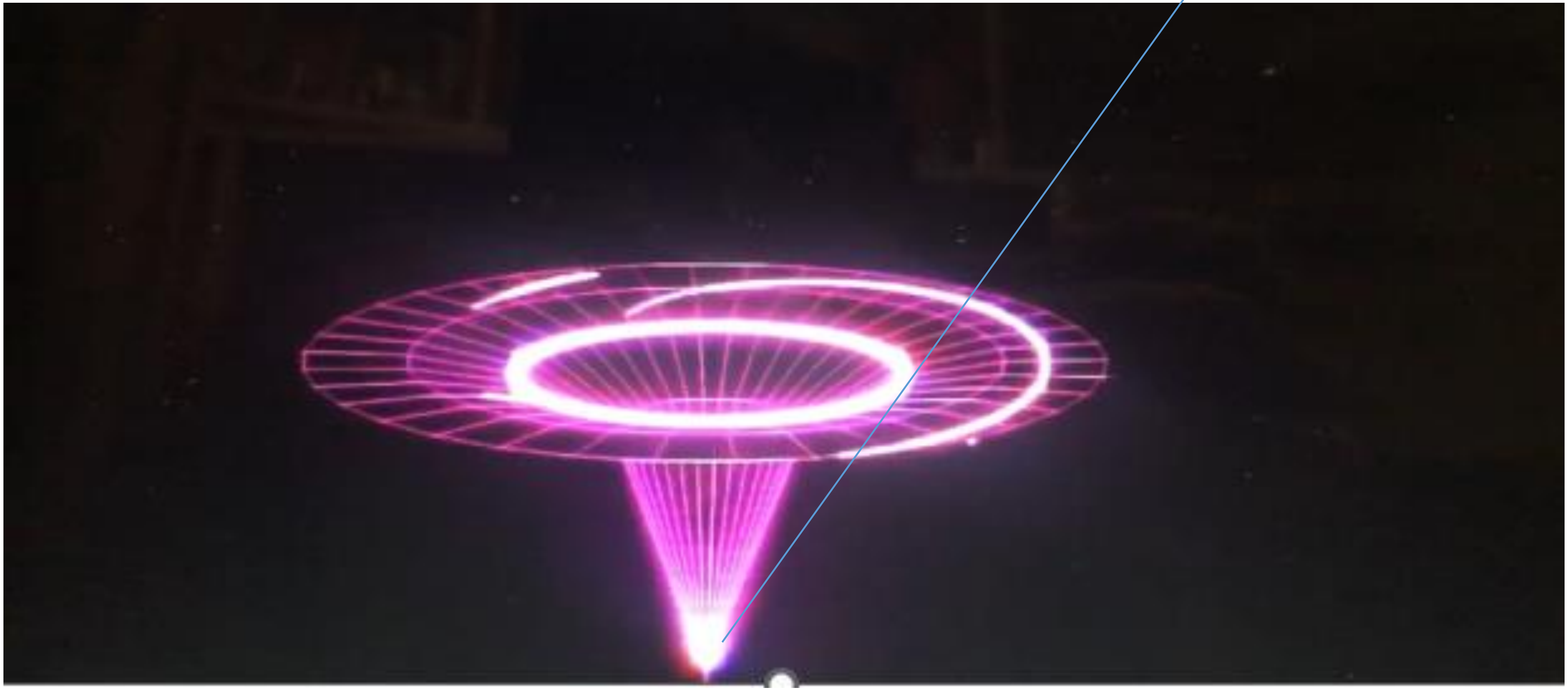
Einstein predicted that light should be bent by gravity. Sir Arthur Eddington lead an expedition to photograph the 1919 Total Eclipse of the Sun. The photographs revealed stars whose light had passed near to the Sun. Their positions showed that the light had been bent exactly as Einstein had predicted.

More Precisely, Tests of General Relativity

Another prediction—the orbit of Mercury should precess due to general relativistic effects near the Sun; again, the measurement agreed with the prediction.



General theory of relativity, Singularity



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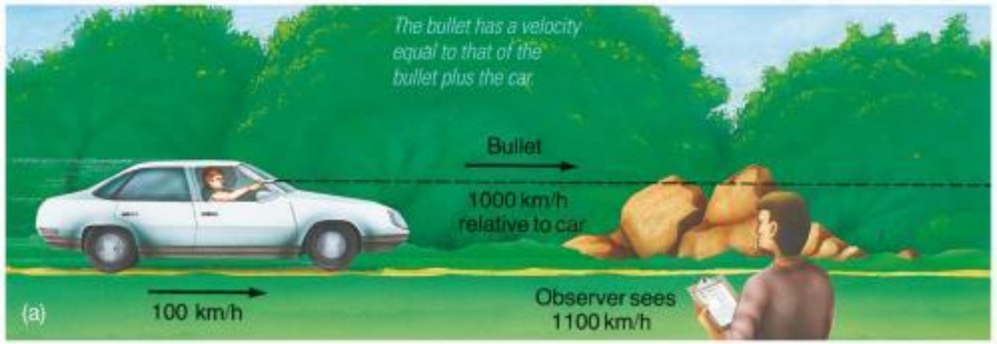
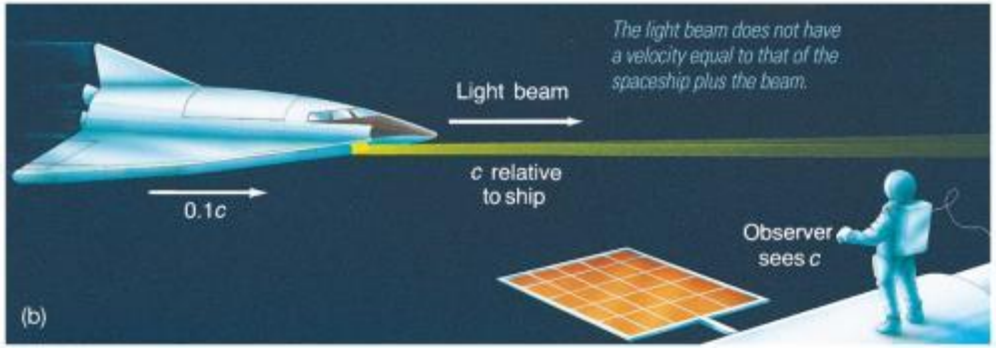
Einstein's Theories of Relativity

Special relativity:

1. The speed of light is the maximum possible speed, and it is always measured to have the same value by all observers:





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Einstein’s Theories of Relativity

Special relativity (cont.):

2. There is no absolute frame of reference, and no absolute state of rest.

3. Space and time are not independent but are unified as spacetime.

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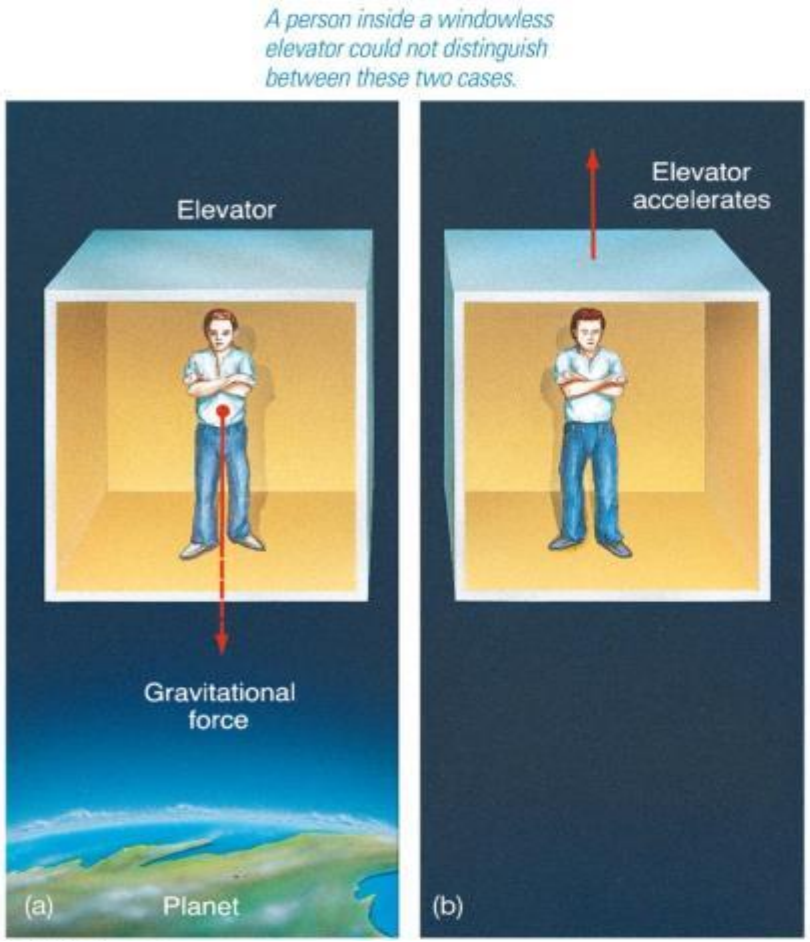
Einstein's Theories of Relativity

General relativity:

It is impossible to tell from within a closed system whether one is in a gravitational field or accelerating.



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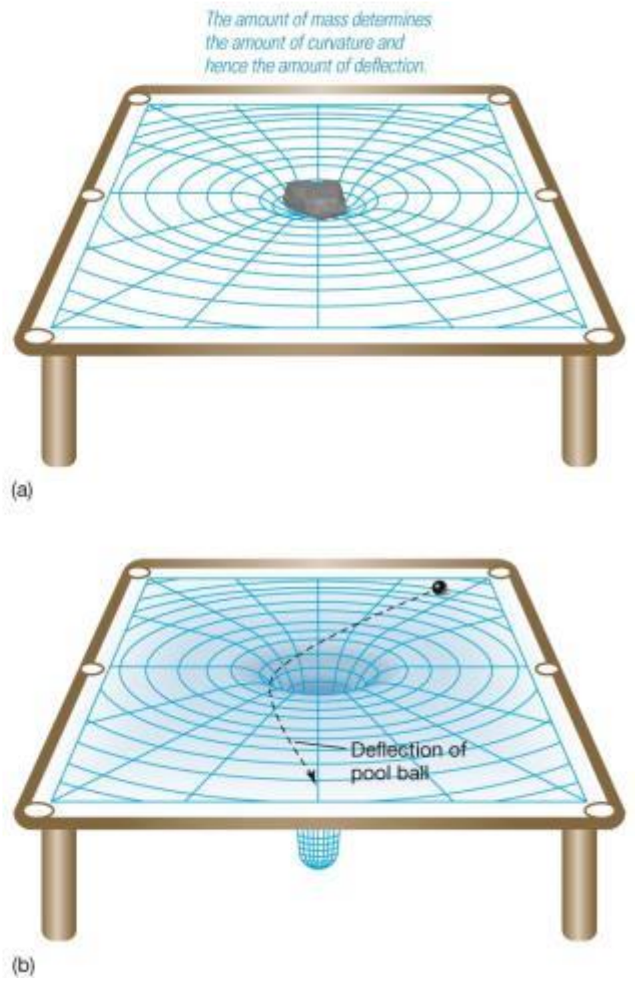
Einstein’s Theories of Relativity

Matter tends to warp spacetime, and in doing so redefines straight lines (the path a light beam would take):

A black hole occurs when the “indentation” caused by the mass of the hole becomes infinitely deep.



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Special Relativity

In the late 19th century, Michelson and Morley did an experiment to measure the variation in the speed of light with respect to the direction of the Earth's motion around the Sun.

They found no variation—light always traveled at the same speed. This later became the foundation of special relativity.

Taking the speed of light to be constant leads to some counterintuitive effects—length contraction, time dilation, the relativity of simultaneity, and the mass equivalent of energy.

Skip if needed

Space Travel Near Black Holes

The gravitational effects of a black hole are unnoticeable outside of a few Schwarzschild radii—black holes do not "suck in" material any more than an extended mass would.

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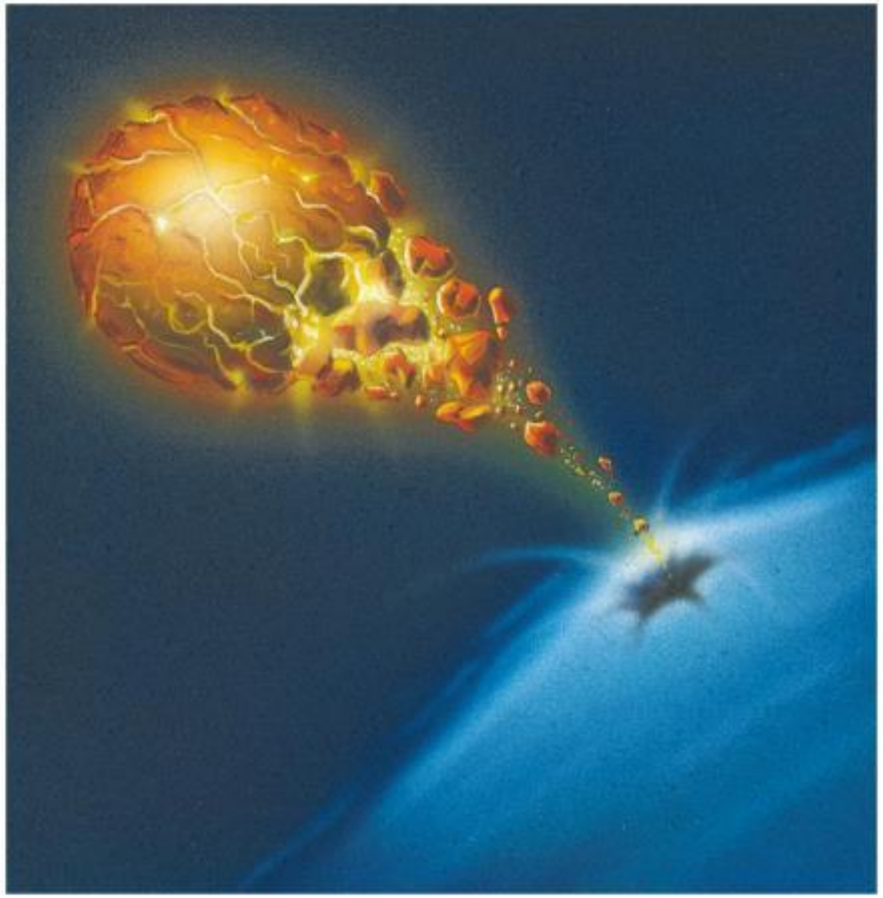
Space Travel Near Black Holes

Matter encountering a black hole will experience enormous tidal forces that will both heat it enough to radiate and tear it apart:



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Skip if needed

Space Travel Near Black Holes

A probe nearing the event horizon of a black hole will be seen by observers as experiencing a dramatic redshift as it gets closer, so that time appears to be going more and more slowly as it approaches the event horizon. This is called a gravitational redshift—it is not due to motion, but to the large gravitational fields present. The probe, however, does not experience any such shifts; time would appear normal to anyone inside.

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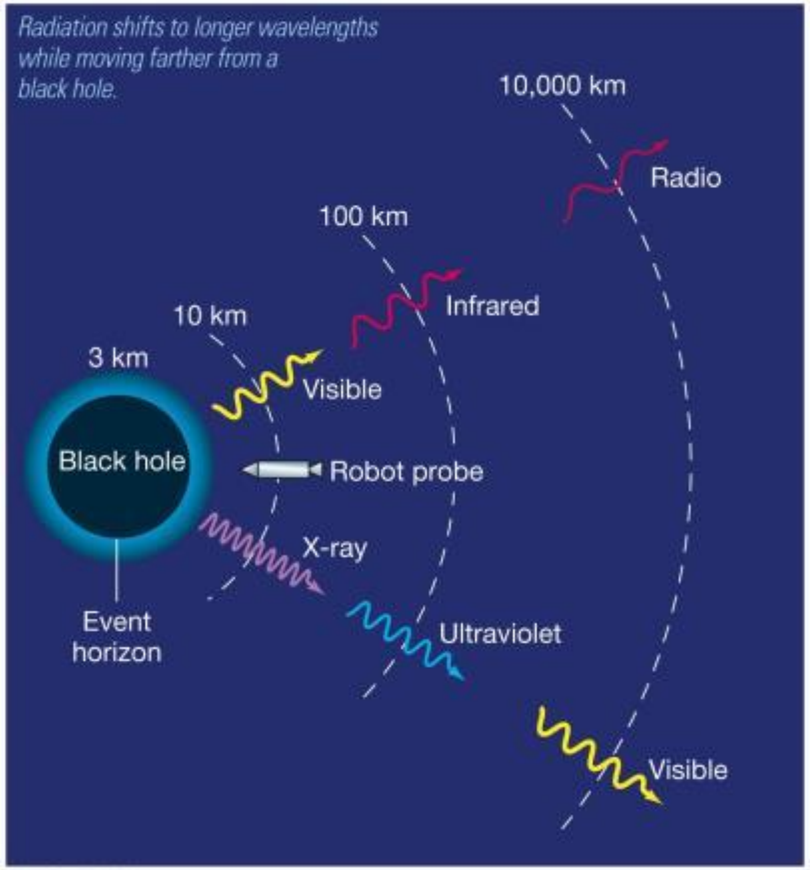
Space Travel Near Black Holes

Similarly, a photon escaping from the vicinity of a black hole will use up a lot of energy doing so; it cannot slow down, but its wavelength gets longer and longer



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Space Travel Near Black Holes

What's inside a black hole?

No one knows, of course; present theory predicts that the mass collapses until its radius is zero and its density is infinite, but it is unlikely that this actually happens.

Until we learn more about what happens in such extreme conditions, the interiors of black holes will remain a mystery.

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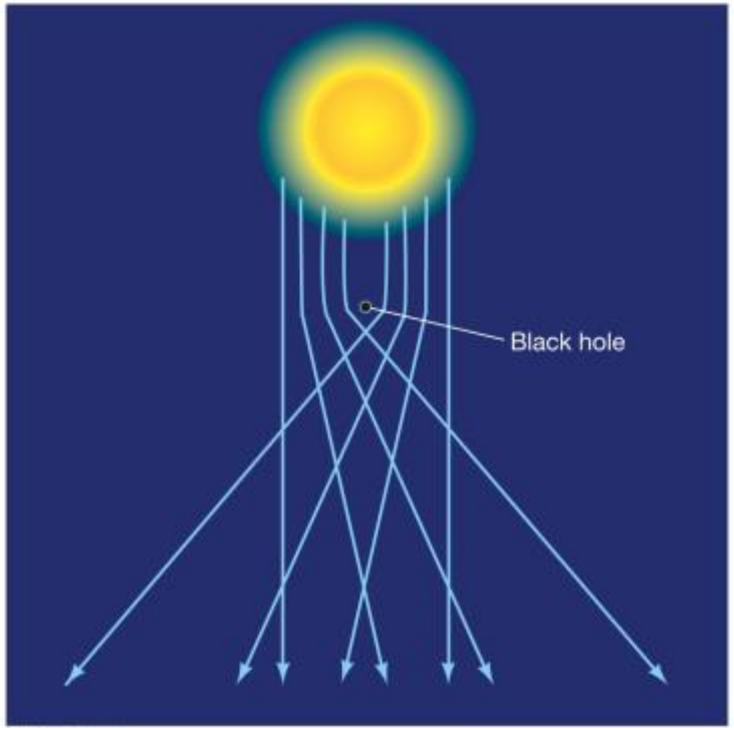
Observational Evidence for Black Holes

Black holes cannot be observed directly, as their gravitational fields will cause light to bend around them.



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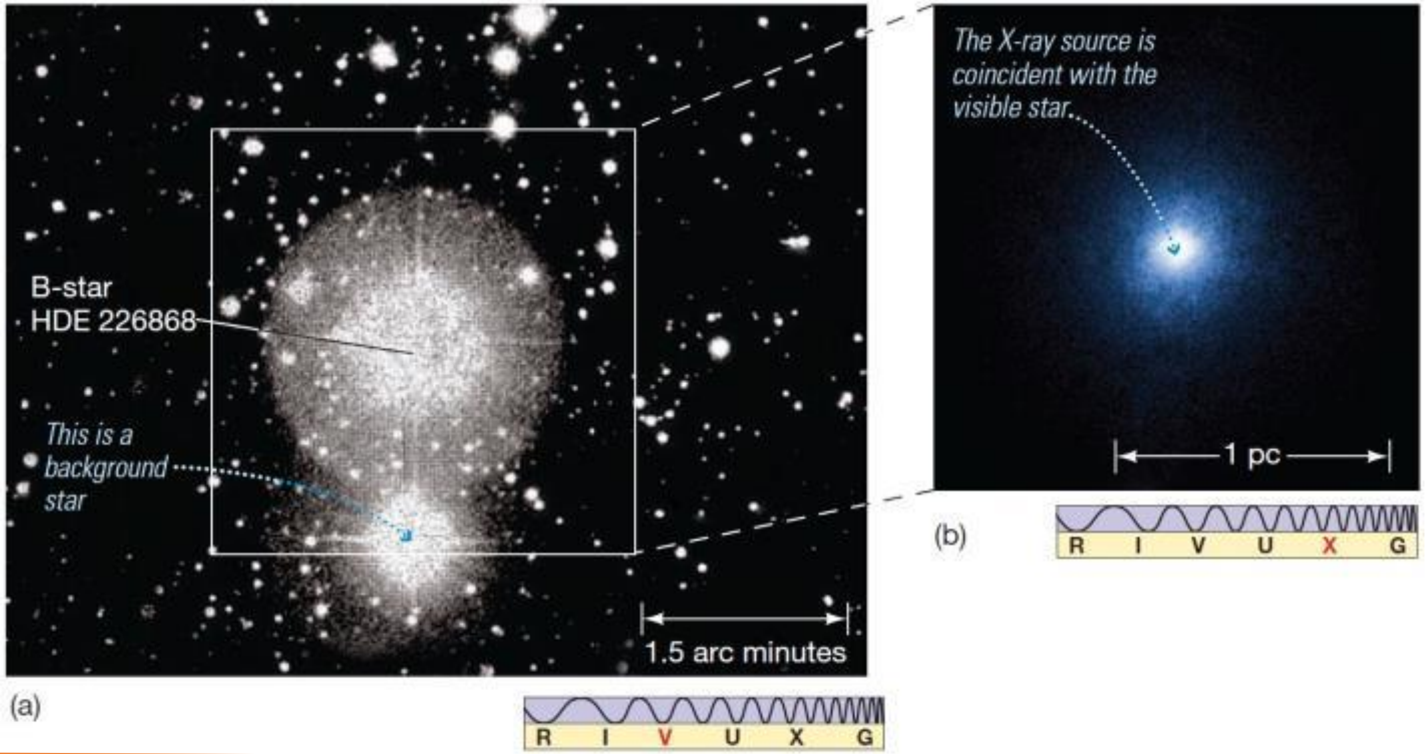
Observational Evidence for Black Holes

This bright star has an unseen companion that is a strong X-ray emitter called Cygnus X-1, which is thought to be a black hole:



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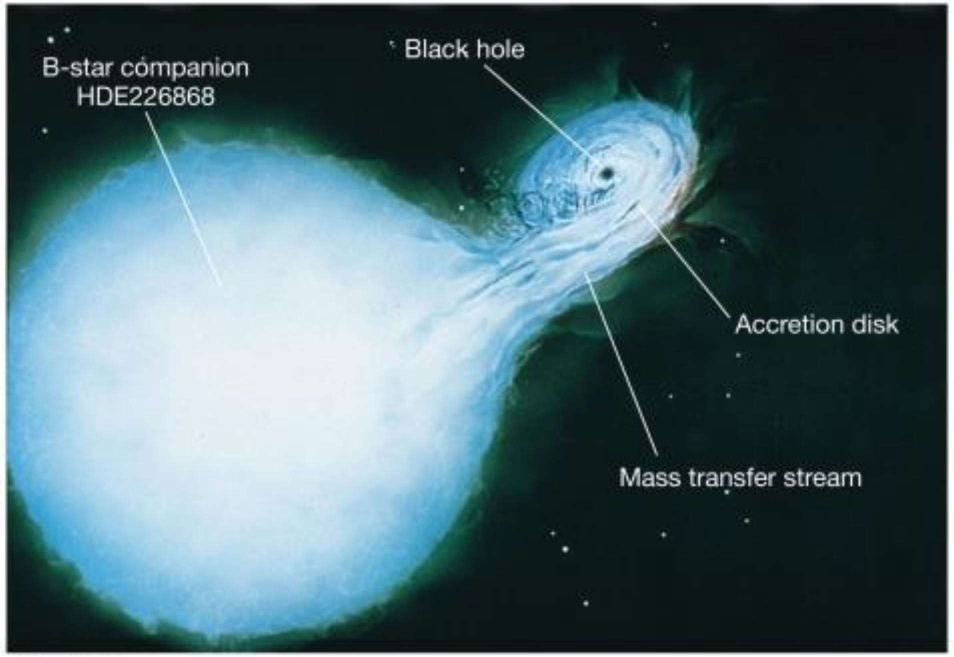
Observational Evidence for Black Holes

The existence of black-hole binary partners for ordinary stars can be inferred by the effect the holes have on the star's orbit, or by radiation from infalling matter.



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Observational Evidence for Black Holes

Cygnus X-1 is a very strong black-hole candidate:

- **Its visible partner is about 25 solar masses.**
- **The system's total mass is about 35 solar masses, so the X-ray source must be about 10 solar masses.**
- **Hot gas appears to be flowing from the visible star to an unseen companion.**
- **Short time-scale variations indicate that the source must be very small.**

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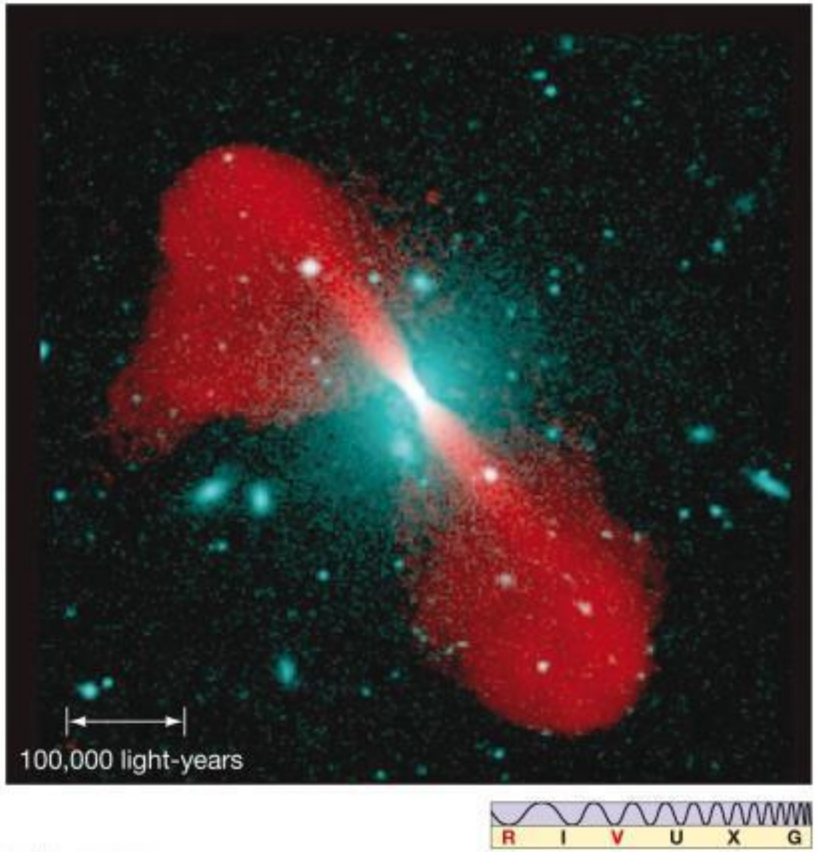
Observational Evidence for Black Holes

There are several other black-hole candidates as well, with characteristics similar to those of Cygnus X-1.

The centers of many galaxies contain supermassive black holes—about 1 million solar masses.



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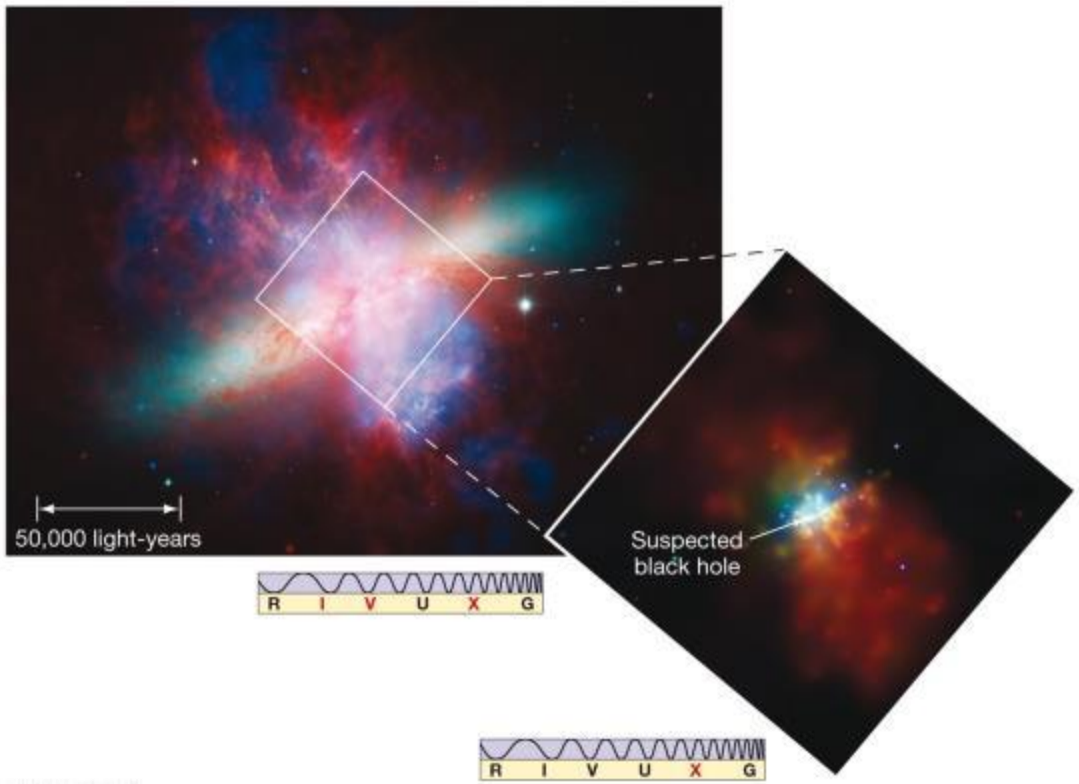
Observational Evidence for Black Holes

Recently, evidence for intermediate-mass black holes has been found; these are about 100–1000 solar masses. Their origin is not well understood.



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Gravitational Waves: A New Window on the Universe

General relativity predicts that orbiting objects should lose energy by emitting gravitational radiation. The amount of energy is tiny, and these waves are very difficult to detect.

A neutron-star binary system has been observed (two neutron stars); the orbits of the stars are slowing at just the rate predicted if gravity waves are carrying off the lost energy.

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Gravitational Waves: A New Window on the Universe

This figure shows part of *LIGO*, the *Laser Interferometric Gravity-wave Observatory*, designed to detect gravitational waves. It has been operating since 2003.

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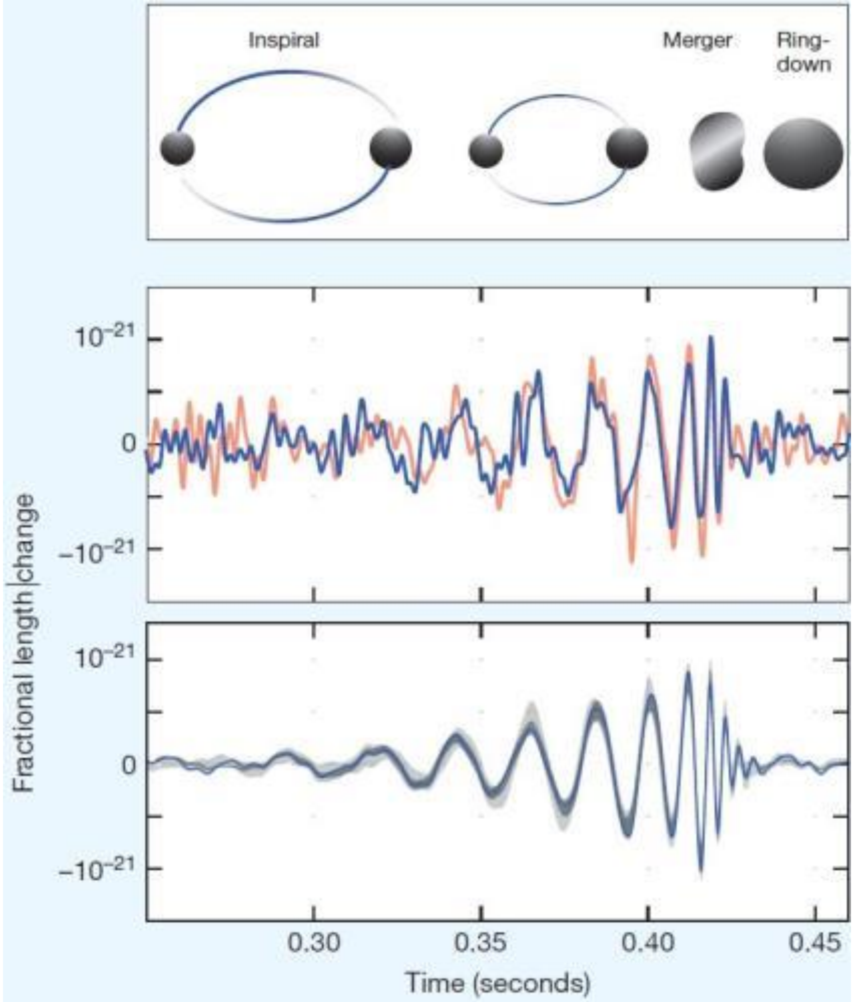
Gravitational Waves: A New Window on the Universe

In September 2015, LIGO first observed gravitational waves from a merger of two black holes.



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Roy Kerr

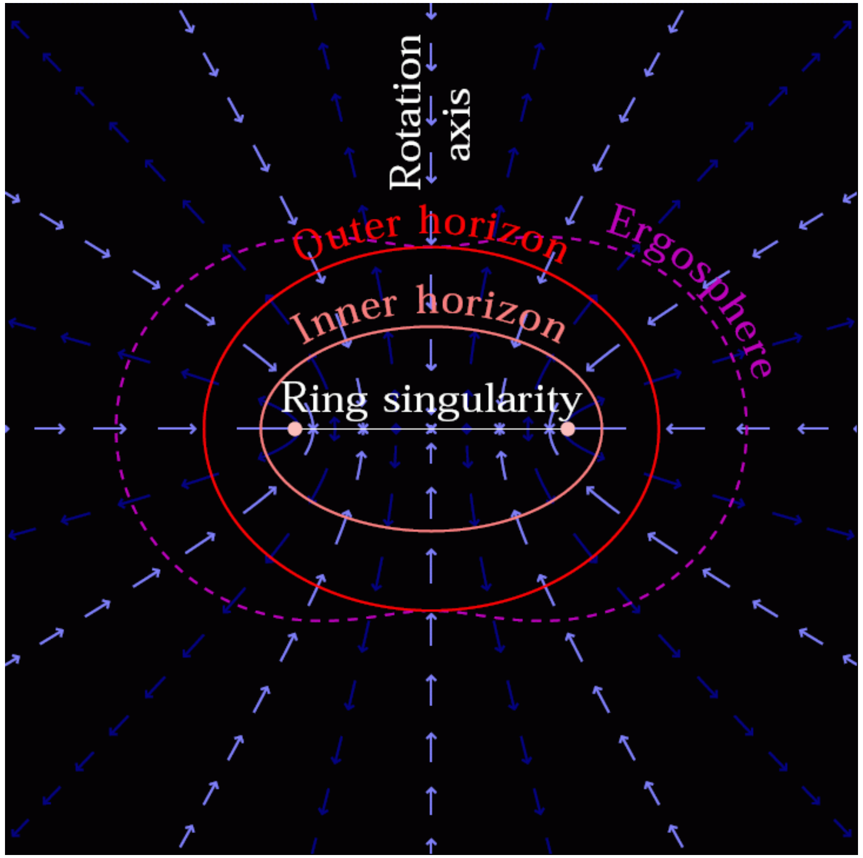
Single point Singularity does not exist

Ring Singularity

Mass does not on single point but Depend on ring motion

Kerr Newman black hole with Spin equation use for imaging

$$ds^2 = -\frac{\Delta_r}{\rho^2}\left[\frac{dt}{I} - \frac{a\sin^2\theta\, d\phi}{I}\right]^2 + \frac{\Delta_\theta \sin^2\theta}{I^2}\left[\frac{a\,dt}{\rho} - \frac{(r^2+a^2)\,d\phi}{\rho}\right]^2 + \rho^2\left(\frac{dr^2}{\Delta_r} + \frac{d\theta^2}{\Delta_\theta}\right)$$



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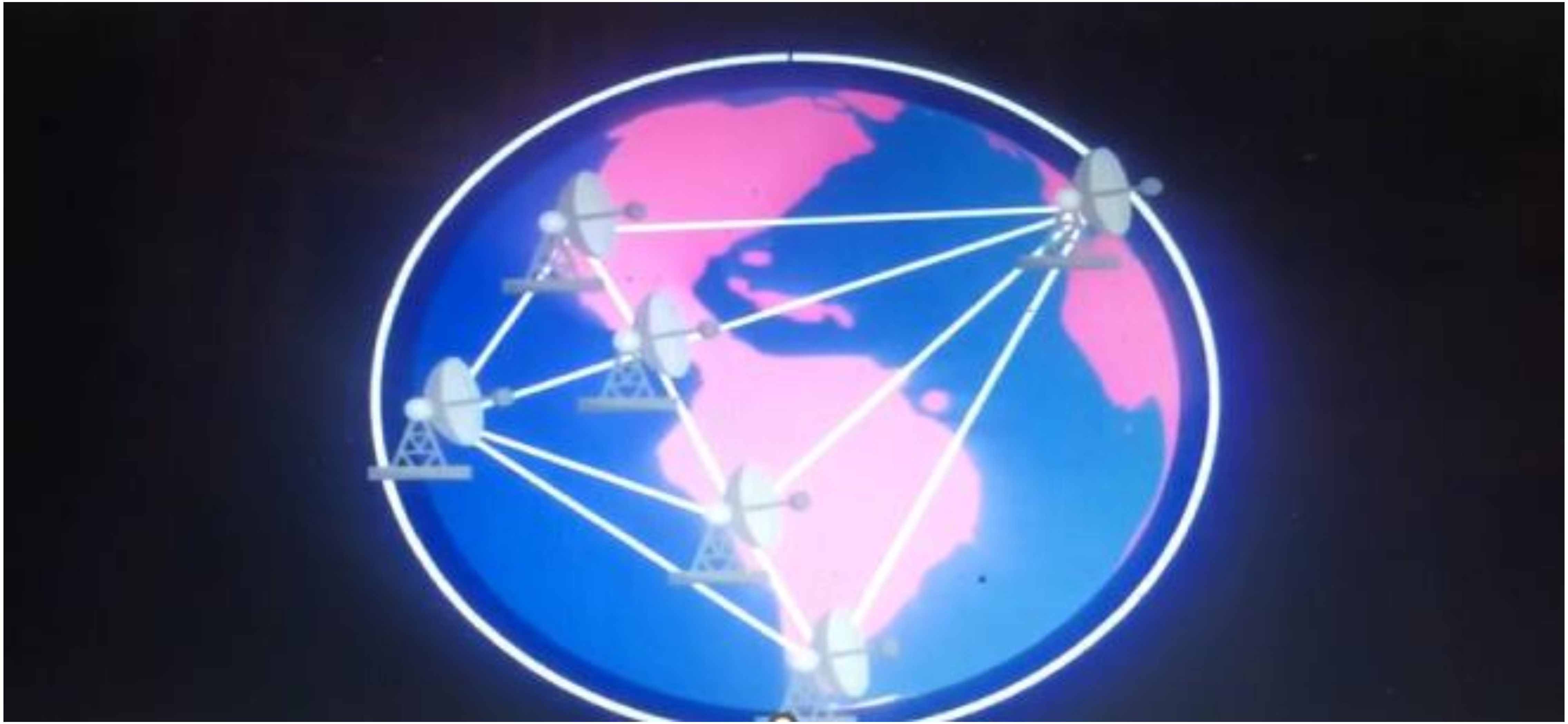
Black hole M87 imaging by Interferometry



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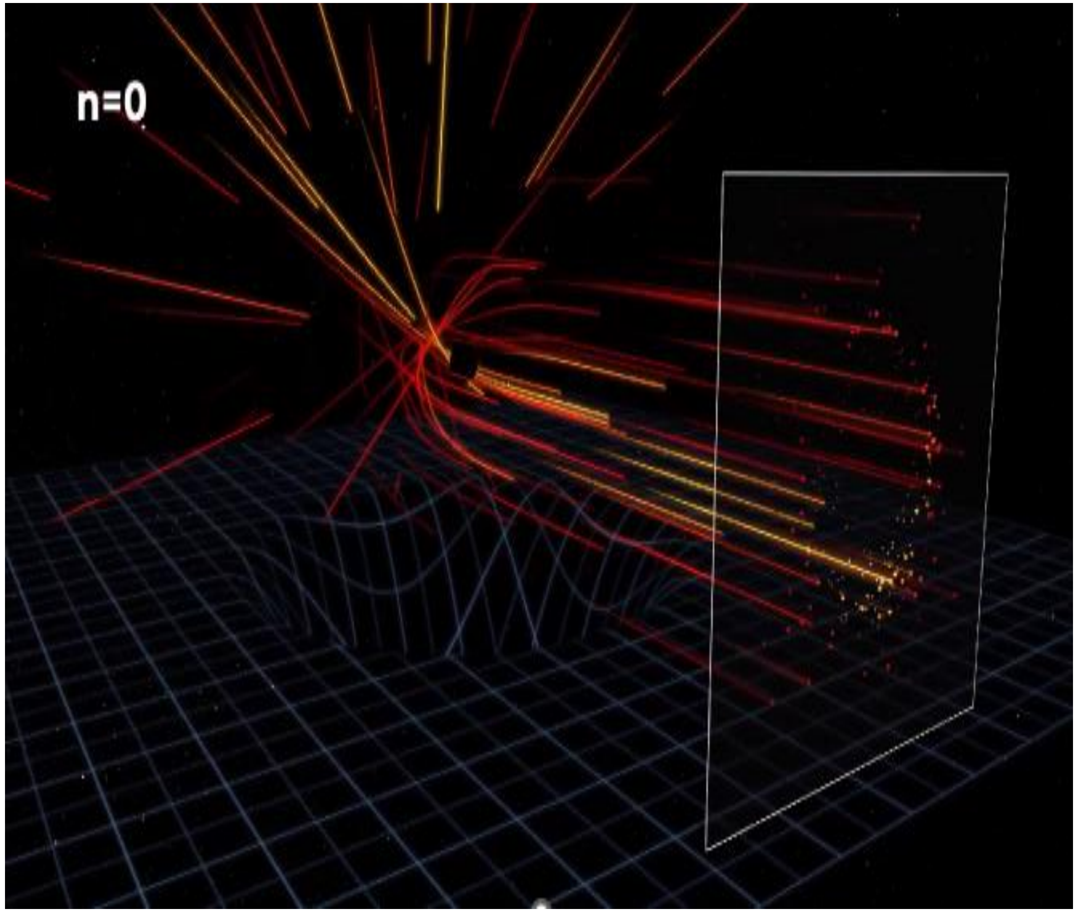
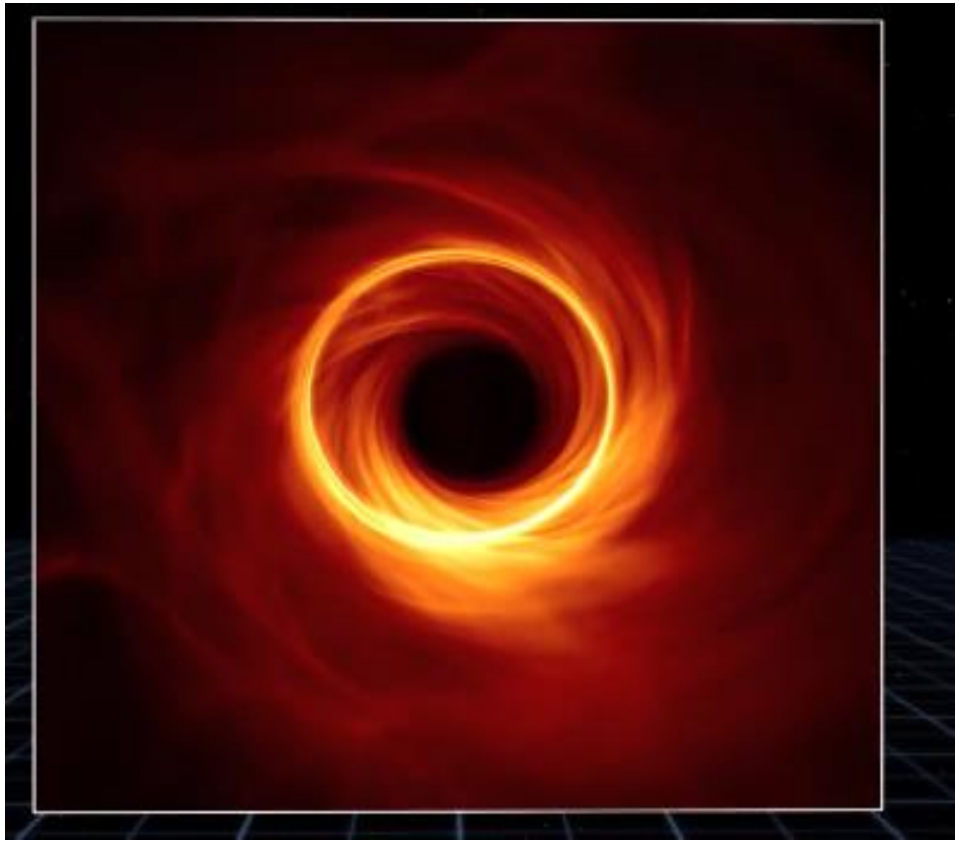
Black hole & General relativity Light bend





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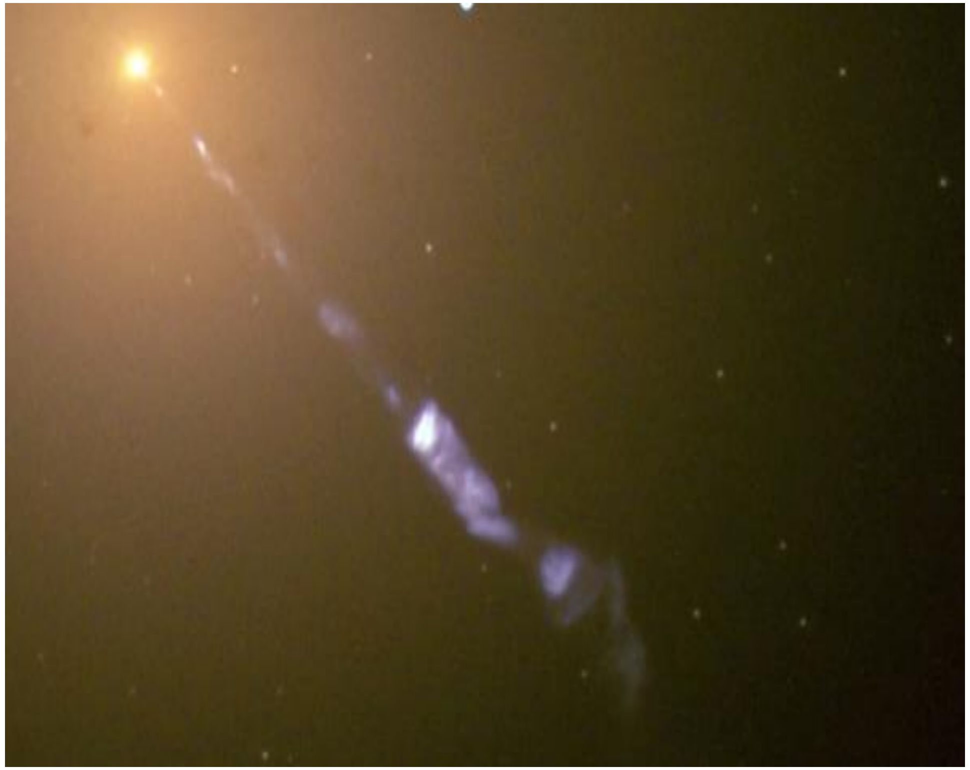
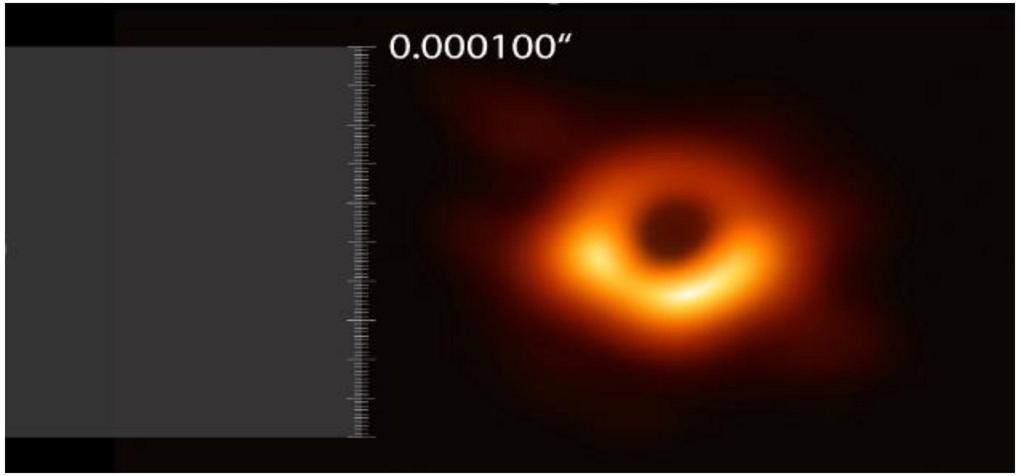
Black hole M87 images with Jet





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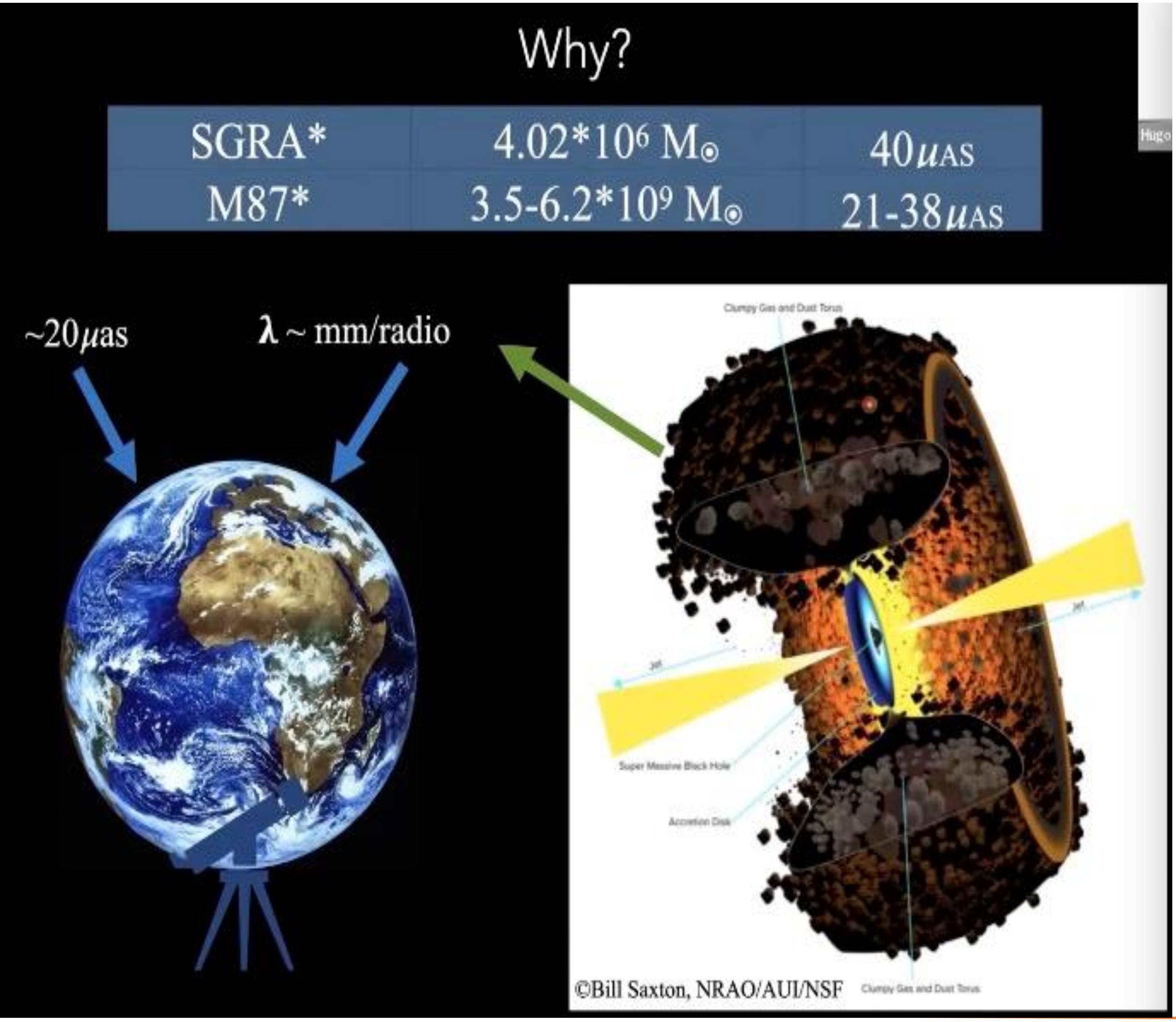
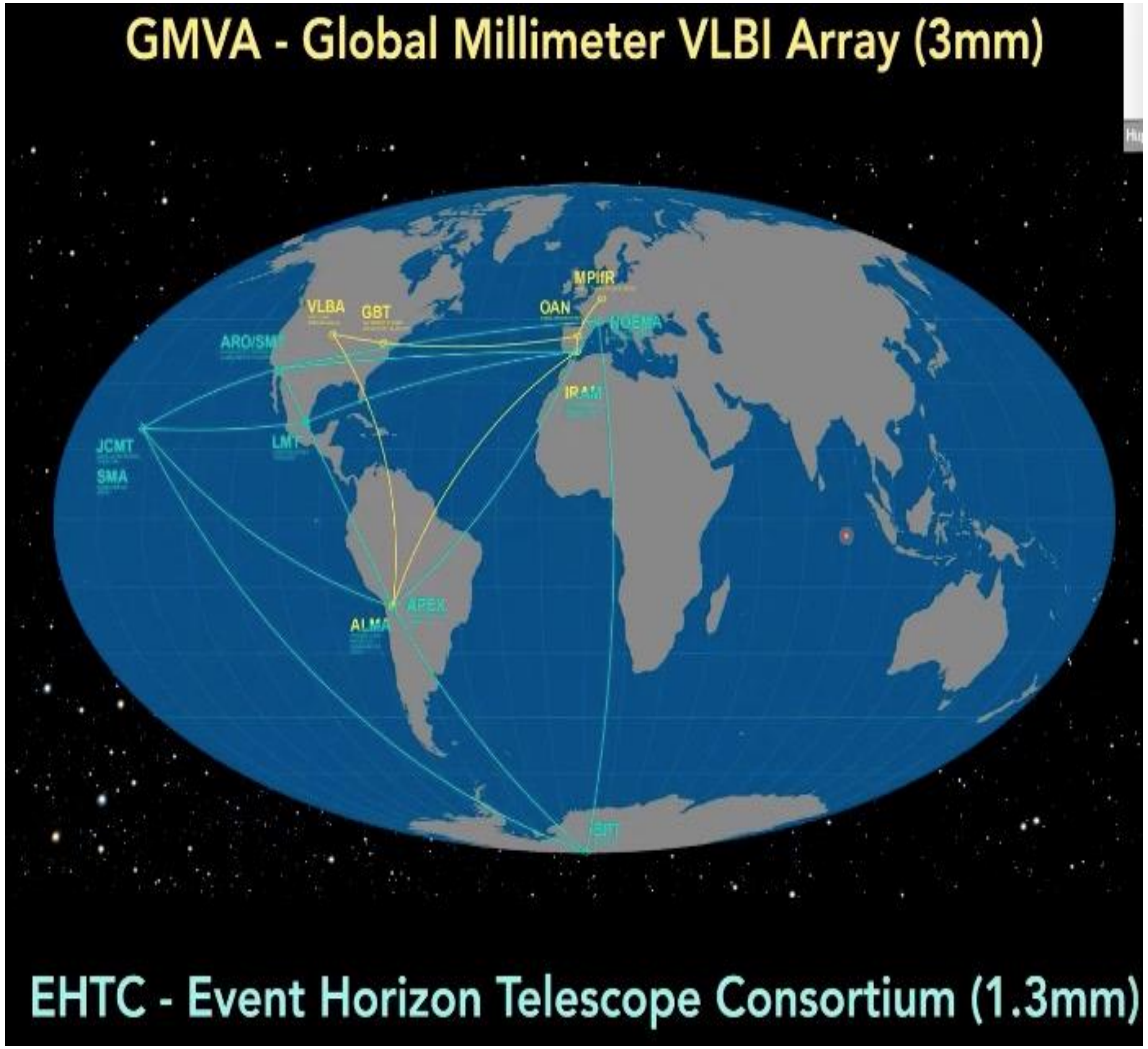
EHTC

Band 3 GMVA, 4 GBPS 1 SPW 128 MHz Dual pol,
band 6 ETH 32 GBPS 2(4) GBPS 2 GHz





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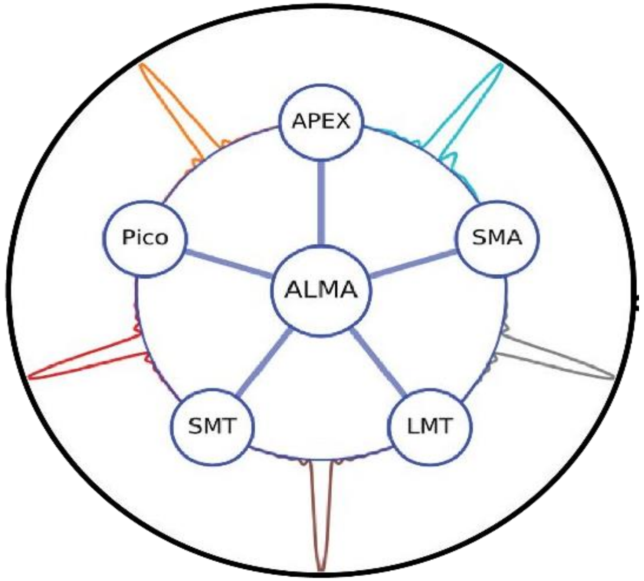
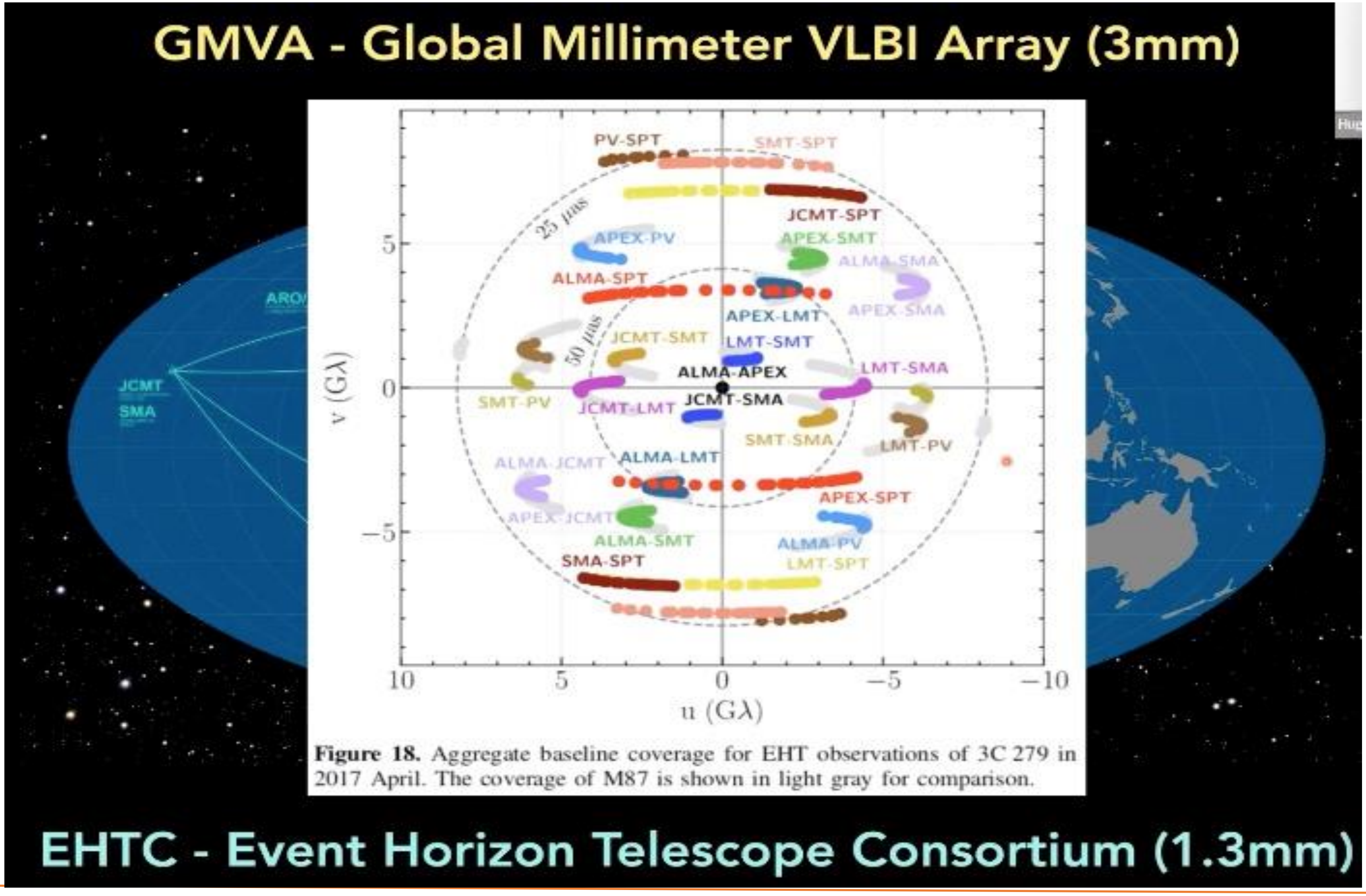
EHTC

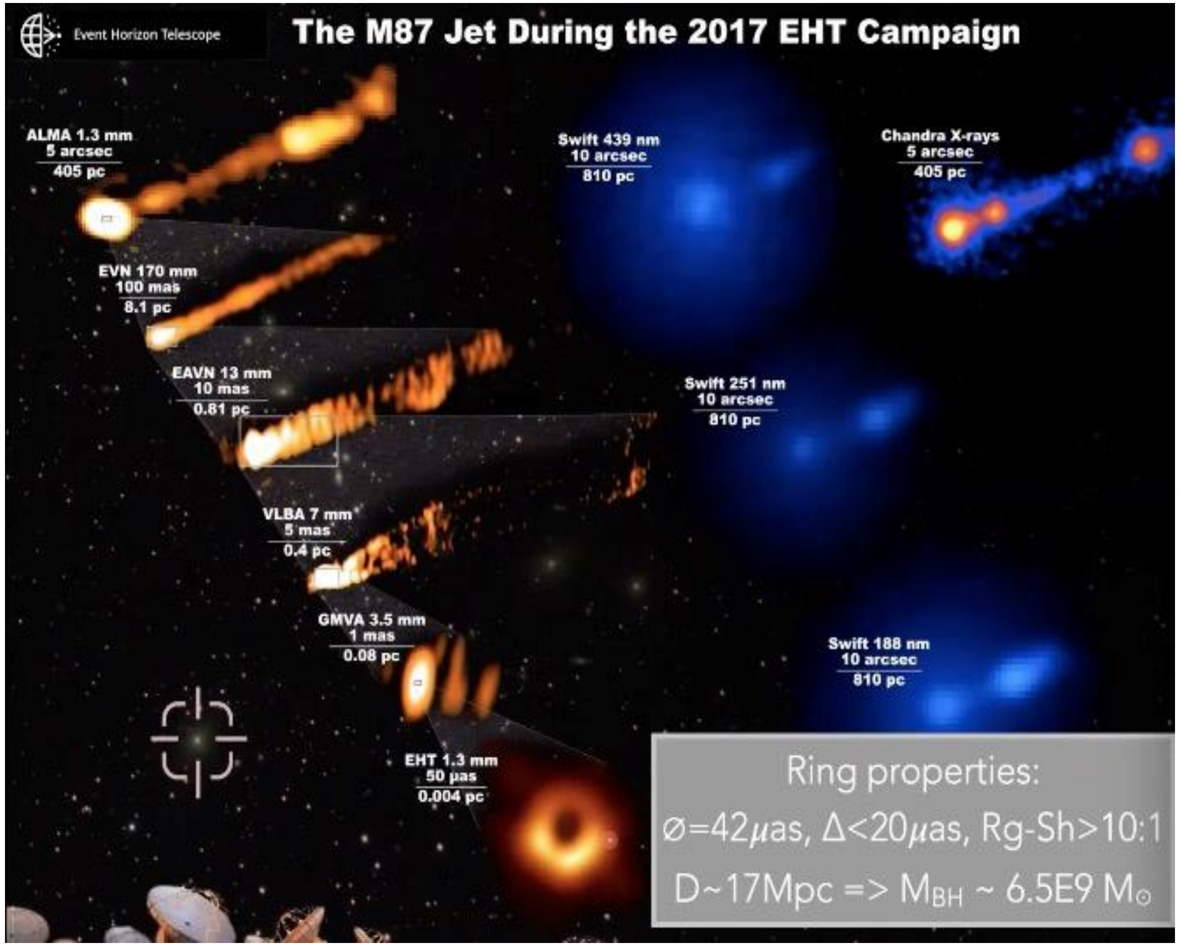


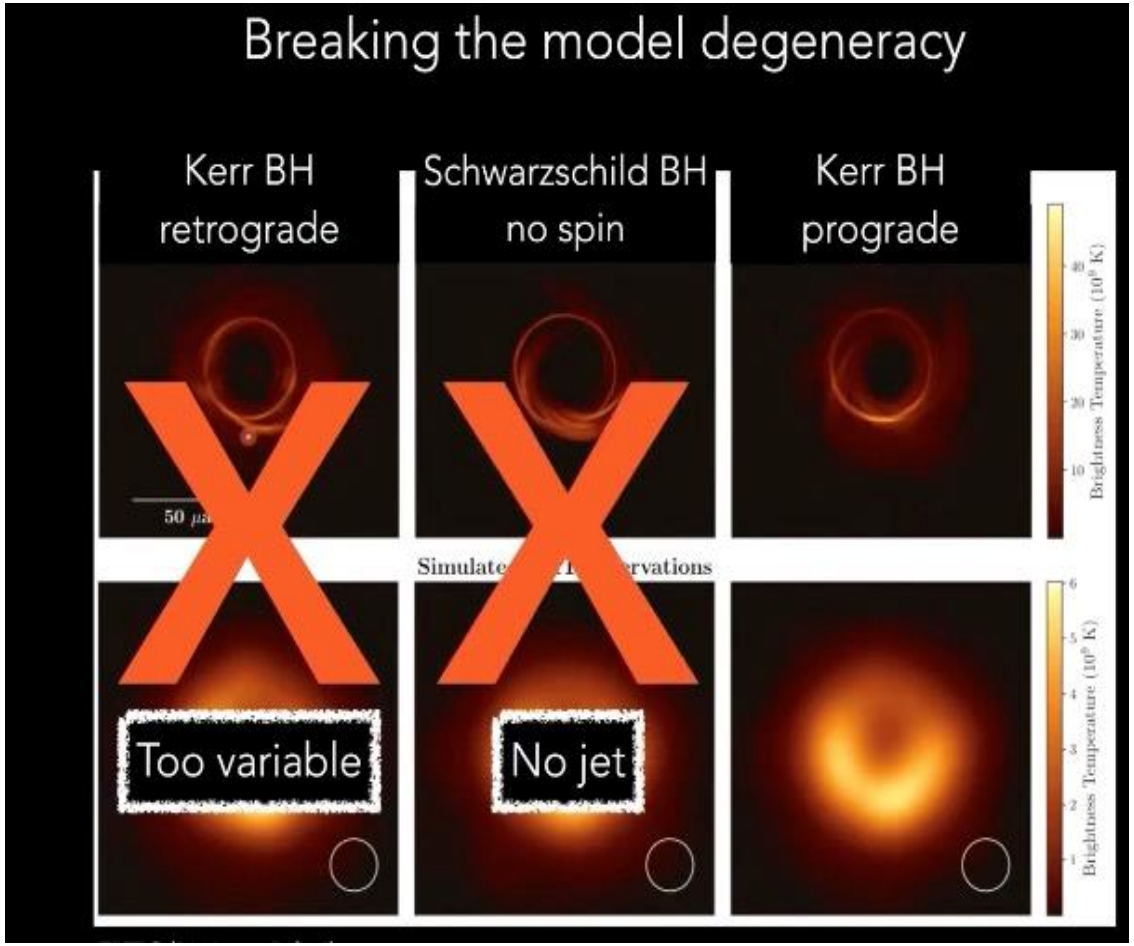
APEX
Pico
SMA
ALMA
SMT
LMT



GMVA - Global Millimeter VLBI Array (3mm)
PV-SPT
SMT-SPT
JCMT-SPT
APEX-PV
APEX-SMT
ALMA-SMA
ALMA-SPT
APEX-SMA
APEX-LMT
JCMT-SMT
LMT-SMT
ALMA-APEX
LMT-SMA
SMT-PV
JCMT-LMT
JCMT-SMA
SMT-SMA
LMT-PV
ALMA-JCMT
ALMA-LMT
APEX-SPT
APEX-JCMT
ALMA-SMT
ALMA-PV
SMA-SPT
LMT-SPT
25 μas
50 μas
v (Gλ)
u (Gλ)
JCMT
SMA
Figure 18. Aggregate baseline coverage for EHT observations of 3C 279 in 2017 April. The coverage of M87 is shown in light gray for comparison.
EHTC - Event Horizon Telescope Consortium (1.3mm)

Black hole M87– breaking the model
Kerr black hole metric →model Spin





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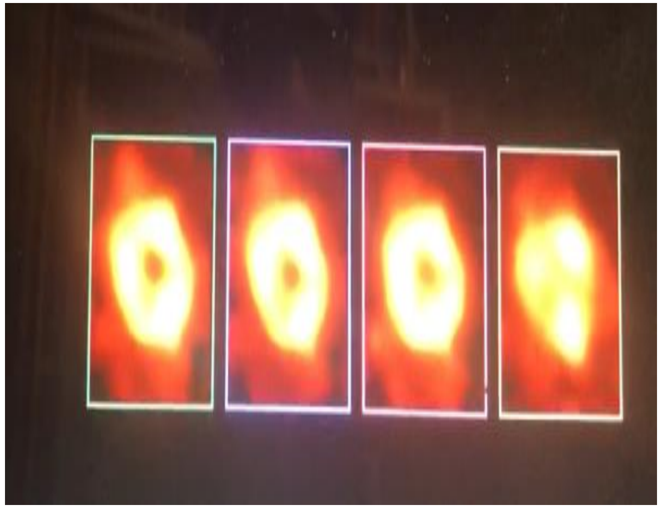
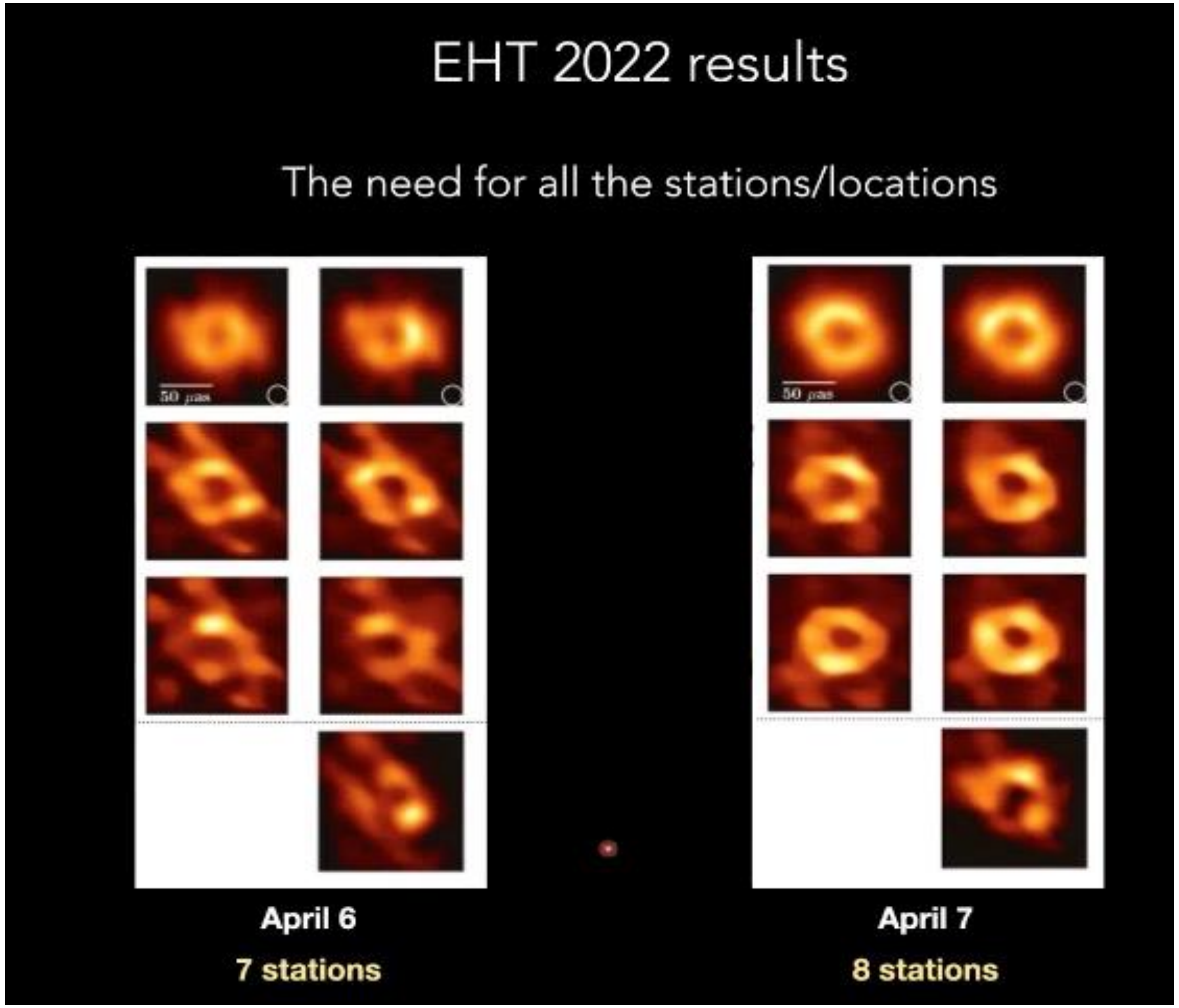
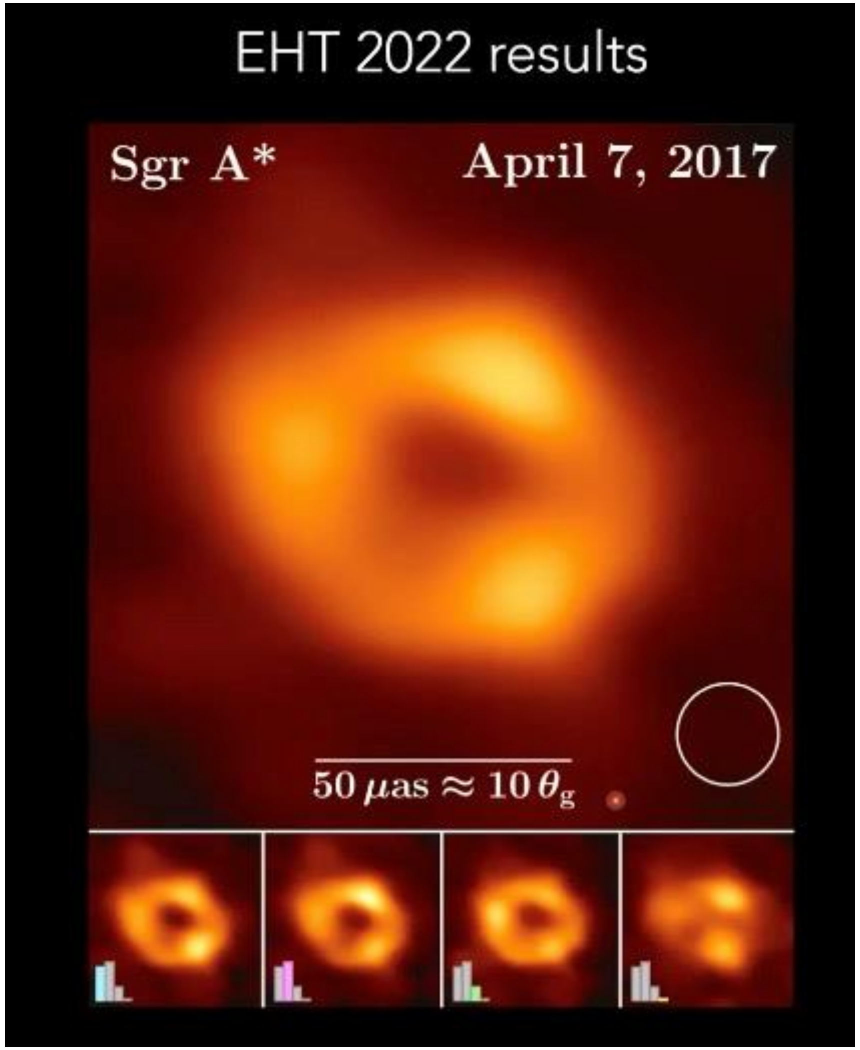
Clustering/Average imaging Black hole Sgr A *



Average image Black hole Sgr A*





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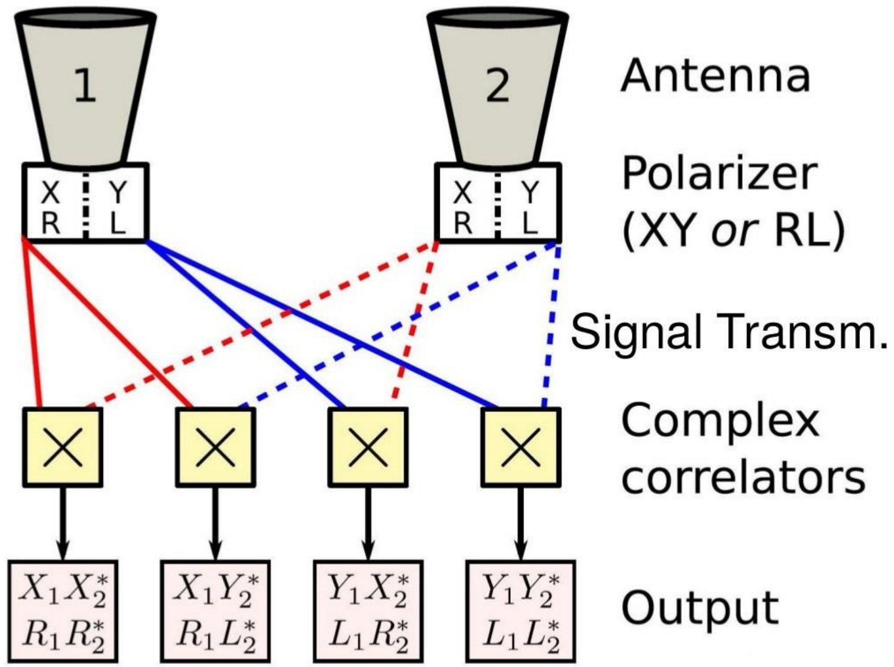
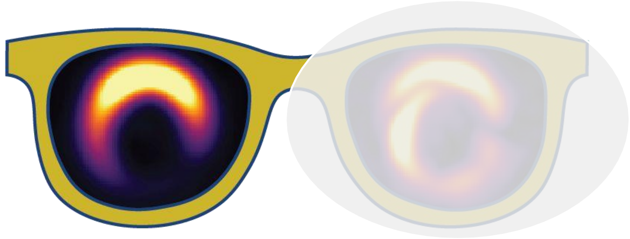
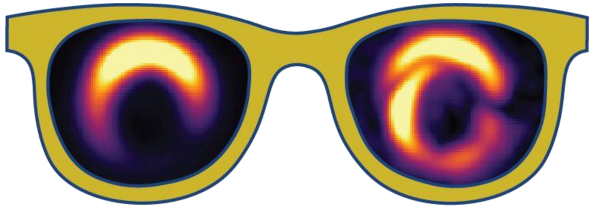
Interferometric polarization observations



- **single mode only XX**
- **dual mode only XX and YY** are registered → Stokes I only



- **full polarization mode** the four correlations
  XX YY YX XY are saved



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Interferometric polarization observations

$$I = \frac{1}{2}(XX + YY)$$

$$Q = \frac{1}{2}(XX - YY)$$

$$U = \frac{1}{2}(XY + YX)$$

$$V = \frac{1}{2}(XY - YX)$$

In an ideal world we would get

- **total intensity ---> Stokes I**
- **circular polarization ---> Stokes V**
- **linear polarization** $PI = \sqrt{Q^2 + U^2}$
- **EVPA→ electric vector polarization angle** $tan2\chi = \frac{U}{Q}$

Imaging & polarization for M87 & Sgr A*
Astrophysical Journal Letters Open Access

The Astrophysical Journal Letters, 910:L12 (48pp), 2021 March 20 https://doi.org/10.3847/2041-8213/abe71d

First M87 Event Horizon Telescope Results. VII. Polarization of the Ring

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)

Received 2020 November 23; revised 2021 February 15; accepted 2021 February 16; published 2021 March 24

Abstract

In 2017 April, the Event Horizon Telescope (EHT) observed the near-horizon region around the supermassive black hole at the core of the M87 galaxy. These 1.3 mm wavelength observations revealed a compact asymmetric ring-like source morphology. This structure originates from synchrotron emission produced by relativistic plasma located in the immediate vicinity of the black hole. Here we present the corresponding linear-polarimetric EHT images of the center of M87. We find that only a part of the ring is significantly polarized. The resolved fractional linear polarization has a maximum located in the southwest part of the ring, where it rises to the level of ~15%. The polarization position angles are arranged in a nearly azimuthal pattern. We perform quantitative measurements of relevant polarimetric properties of the compact emission and find evidence for the temporal evolution of the polarized source structure over one week of EHT observations. The details of the polarimetric data reduction and calibration methodology are provided. We carry out the data analysis using multiple independent imaging and modeling techniques, each of which is validated against a suite of synthetic data sets. The gross polarimetric structure and its apparent evolution with time are insensitive to the method used to reconstruct the image. These polarimetric images carry information about the structure of the magnetic fields responsible for the synchrotron emission. Their physical interpretation is discussed in an accompanying publication.

Unified Astronomy Thesaurus concepts: Polarimetry (1278); Radio interferometry (1346); Very long baseline interferometry (1769); Supermassive black holes (1663); Active galactic nuclei (16); Low-luminosity active galactic nuclei (2033); Astronomy data modeling (1859); Galaxy accretion disks (562); Galaxies: individual: M87

1. Introduction

The Event Horizon Telescope (EHT) Collaboration has recently reported the first images of the event-horizon-scale structure around the supermassive black hole in the core of the massive elliptical galaxy M87, one of its two main targets.[130] The EHT images of M87's core at 230 GHz (1.3 mm wavelength) revealed a ring-like structure whose diameter of 42 μas, brightness temperature, shape, and asymmetry are interpreted as synchrotron emission from relativistic electrons gyrating around magnetic field lines in close vicinity to the event horizon. We have described the details of the EHT's instrumentation, data calibration pipelines, data analyses and imaging procedures, and the theoretical interpretation of these first images in a series of publications (Event Horizon Telescope Collaboration et al. 2019a, 2019b, 2019c, 2019d, 2019e, 2019f, hereafter Papers I, II, III, IV, V, VI, respectively).

In this Letter, we present the first *polarimetric* analysis of the 2017 EHT observations of M87 and the first images of the linearly polarized radiation surrounding the M87 black hole shadow. These polarimetric images provide essential new information about the structure of magnetic field lines near the event horizon of M87's central supermassive black hole, and they put tight constraints on the theoretical interpretations of the nature of the ring and of relativistic jet-launching theories. The theoretical implications of these images and the constraints that they place on the magnetic field structure and accretion state of the black hole are discussed in an accompanying work (Event Horizon Telescope Collaboration et al. 2021, hereafter Paper VIII). Readers interested in the details of the data reduction, methodology, and validation can find a detailed index of this Letter in Section 1.2. Readers primarily interested in the results may skip directly to Section 5 and to subsequent discussion and conclusions in Section 6.

1.1. Previous Polarimetric Observations of the M87 Jet

The giant elliptical galaxy Messier 87 (M87, NGC 4486) is the central member of the Virgo cluster of galaxies and hosts a low-luminosity radio source (Virgo A, 3C 274, B1228+126). M87 is nearby and bright, and at its center is one of the best-studied active galactic nuclei (AGNs). M87 was the first galaxy in which an extragalactic jet (first described as a "narrow ray") extending from the nucleus was discovered (Curtis 1918). This kiloparsec-scale jet is visible, with remarkably similar morphology, at all wavelengths from radio to X-ray. The optical radiation from the jet on kpc scales was found to be linearly polarized by Baade (1956), which was confirmed by Hiltner (1959), suggesting that the emission mechanism is synchrotron radiation.

The central engine that powers the jet contains one of the most massive black holes known, measured from the central stellar velocity dispersion (Gebhardt et al. 2011; $M = (6.6 \pm 0.4) \times 10^9 M_\odot$) and directly from the size of the observed emitting

[127] NASA Hubble Fellowship Program, Einstein Fellow.
[128] EACOA Fellow.
[129] UKRI Stephen Hawking Fellow.
[130] The other primary target being the black hole in Sgr A* in the center of the Milky Way.

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First M87 Event Horizon Telescope Results. VIII. Magnetic Field Structure near The Event Horizon

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)

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Abstract

Event Horizon Telescope (EHT) observations at 230 GHz have now imaged polarized emission around the supermassive black hole in M87 on event-horizon scales. This polarized synchrotron radiation probes the structure of magnetic fields and the plasma properties near the black hole. Here we compare the resolved polarization structure observed by the EHT, along with simultaneous unresolved observations with the Atacama Large Millimeter/submillimeter Array, to expectations from theoretical models. The low fractional linear polarization in the resolved image suggests that the polarization is scrambled on scales smaller than the EHT beam, which we attribute to Faraday rotation internal to the emission region. We estimate the average density $n_e \sim 10^{4-7}\ \mathrm{cm}^{-3}$, magnetic field strength $B \sim 1$–30 G, and electron temperature $T_e \sim (1$–$12) \times 10^{10}$ K of the radiating plasma in a simple one-zone emission model. We show that the net azimuthal linear polarization pattern may result from organized, poloidal magnetic fields in the emission region. In a quantitative comparison with a large library of simulated polarimetric images from general relativistic magnetohydrodynamic (GRMHD) simulations, we identify a subset of physical models that can explain critical features of the polarimetric EHT observations while producing a relativistic jet of sufficient power. The consistent GRMHD models are all of magnetically arrested accretion disks, where near-horizon magnetic fields are dynamically important. We use the models to infer a mass accretion rate onto the black hole in M87 of $(3$–$20) \times 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$.

Unified Astronomy Thesaurus concepts: Accretion (14); Black holes (162); Event horizons (479); Jets (870); Kerr black holes (886); Magnetic fields (994); Magnetohydrodynamics (1964); Plasma astrophysics (1261); Polarimetry (1278); Radiative transfer (1335); Radio jets (1347); Relativistic jets (1390)

1. Introduction

The Event Horizon Telescope (EHT) Collaboration has recently published total intensity images of event-horizon-scale emission around the supermassive black hole in the core of the M87 galaxy (M87*; Event Horizon Telescope Collaboration et al. 2019a, 2019b, 2019c, 2019d, hereafter EHTC I, EHTC II, EHTC III, EHTC IV). The data reveal a 42 ± 3 μas diameter ring-like structure that is broadly consistent with the shadow of a black hole as predicted by Einstein's Theory of General Relativity (Event Horizon Telescope Collaboration et al. 2019e, 2019f; hereafter EHTC V, EHTC VI). The brightness temperature of the ring at 230 GHz ($\gtrsim 10^{10}$ K) is naturally explained by synchrotron emission from relativistic electrons gyrating around magnetic field lines. The ring brightness asymmetry results from light bending and Doppler beaming due to relativistic rotation of the matter around the black hole.

M87* is best known for launching a kpc-scale FR-I type relativistic jet, whose kinetic power is estimated to be $\sim 10^{42-44}\ \mathrm{erg\ s^{-1}}$ (e.g., Stawarz et al. 2006; de Gasperin et al. 2012). The structure of the relativistic jet has been resolved and studied at radio to X-ray wavelengths (e.g., Di Matteo et al. 2003; Harris et al. 2009; Kim et al. 2018; Walker et al. 2018).

The published EHT image of M87* together with multi-wavelength observations are consistent with the picture that the supermassive black hole in M87 is surrounded by a relativistically hot, magnetized plasma (Rees et al. 1982; Narayan & Yi 1995; Narayan et al. 1995; Yuan & Narayan 2014; Reynolds et al. 1996; Yuan et al. 2002; Di Matteo et al. 2003). However, it is not clear whether the compact ring emission is produced by plasma that is inflowing (in a thick accretion flow), outflowing (at the jet base or in a wind), or both. Furthermore, the total intensity EHT observations also could not constrain the structure of magnetic fields in the observed emission region. In order to find out which physical scenario is realized in M87*, additional information is necessary.

Event Horizon Telescope Collaboration et al. (2021, hereafter EHTC VII) reports new results from the polarimetric EHT 2017 observations of M87*. The polarimetric images of M87* are reproduced in Figure 1. These images reveal that a significant fraction of the ring emission is linearly polarized, as expected for synchrotron radiation. The EHT polarimetric measurements are consistent with unresolved observations of the radio core at the same frequency with the Submillimeter Array (SMA; Kuo et al. 2014) and the Atacama Large Millimeter/submillimeter Array (ALMA; Goddi et al. 2021). They also provide a detailed view of the polarized emission region on event-horizon scales near the black hole. Polarized synchrotron radiation traces the underlying magnetic field

[126] NASA Hubble Fellowship Program, Einstein Fellow.
[127] EACOA Fellow.
[128] UKRI Stephen Hawking Fellow.

https://www.eventhorizontelescope.org/science
https://iopscience.iop.org/journal/2041-8205/page/Focus_on_EHT

Summary

- THz Benefit
- Radio Astronomy benefits
- ALMA
- Einstein theory
- Stephen Hawking theory
- Roy Kerr
- Interferometry techniques
- Imaging Polarization
- Black Holes

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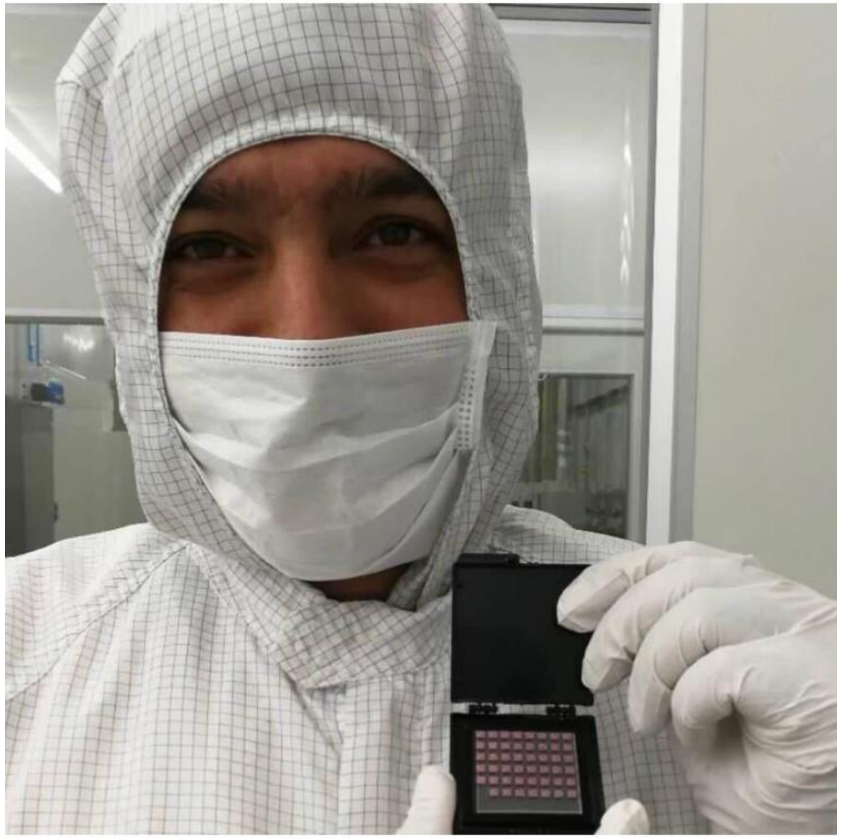
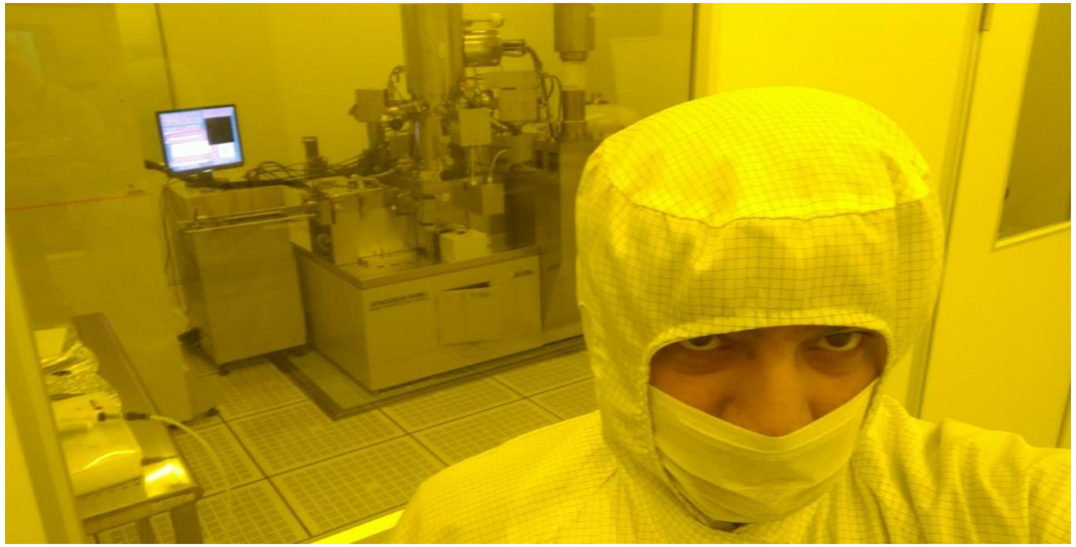
Thank You

Q & A





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