INTRODUCCIÓN
A LA
ASTROFÍSICA RELATIVISTA

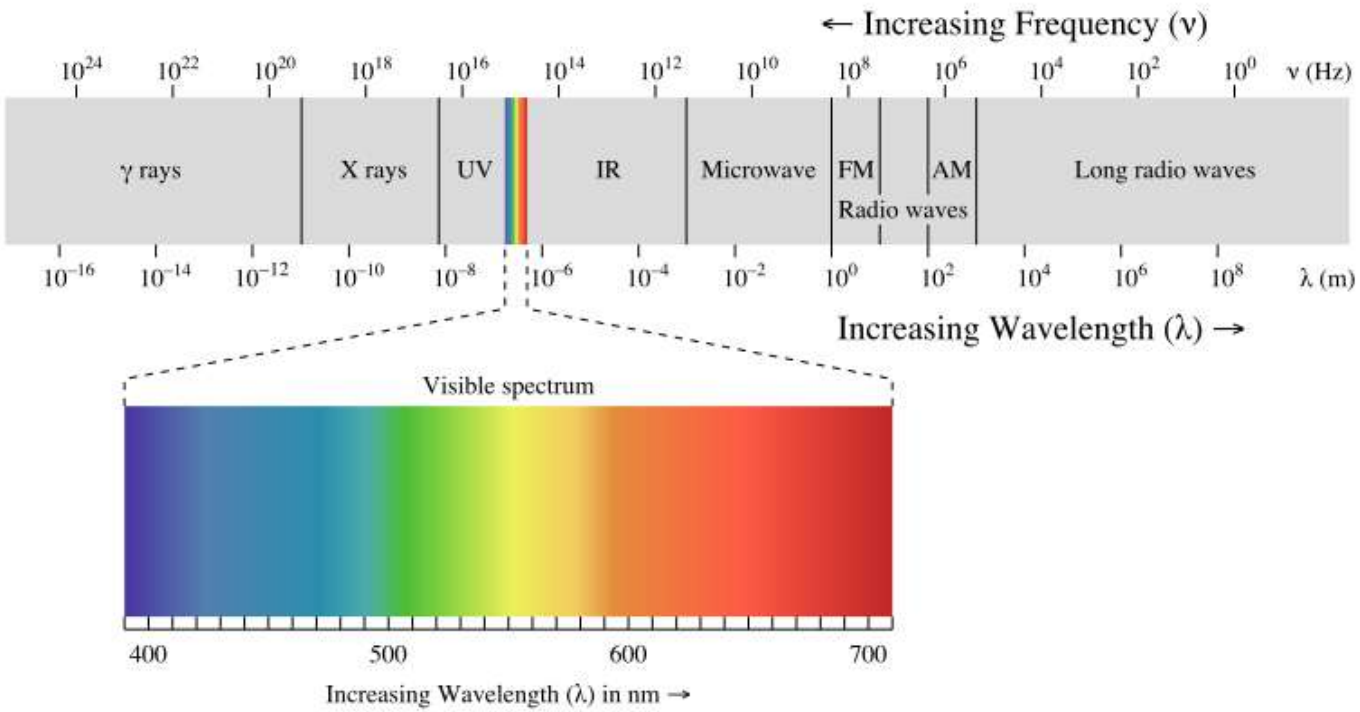
La astronomía es el estudio de
los objetos que forman el Universo
a través de la detección y medición
de las partículas que estos objetos emiten.

La astrofísica es la representación de los procesos físicos que ocurren en los objetos astronómicos.

Durante la mayor parte de su historia,
la Astronomía se ha limitado al estudio de
un tipo muy específico de partículas:
fotones con una longitud de onda en el rango

$$300 \text{ nm} \leq \lambda \leq 1 \ \mu\text{m}$$

lo que corresponde a frecuencias entre
3×10^{14} Hz y 10^{15} Hz.
La radiación formada por estos fotones
es conocida como "luz visible".



FREQUENCY	WAVELENGTH	ENERGY
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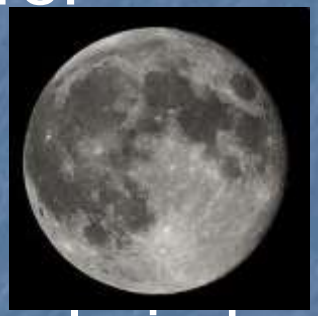
30 THz	10 μm	124 meV
3 THz	100 μm	12.4 meV
300 GHz	1 mm	1.24 meV
30 GHz	1 cm	124 μeV
3 GHz	1 dm	12.4 μeV
300 MHz	1 m	1.24 μeV
30 MHz	10 m	124 neV
3 MHz	100 m	12.4 neV
300 kHz	1 km	1.24 neV
30 kHz	10 km	124 peV
3 kHz	100 km	12.4 peV
300 Hz	1 Mm	1.24 peV
30 Hz	10 Mm	124 feV
3 Hz	100 Mm	12.4 feV

$$300 \text{ nm} \leq \lambda \leq 1\ \mu\text{m}$$

En 1609, Galileo Galilei apuntó por primera vez su telescopio hacia el firmamento realizando descubrimientos asombrosos para la época que cambiaron la percepción del mundo para siempre:

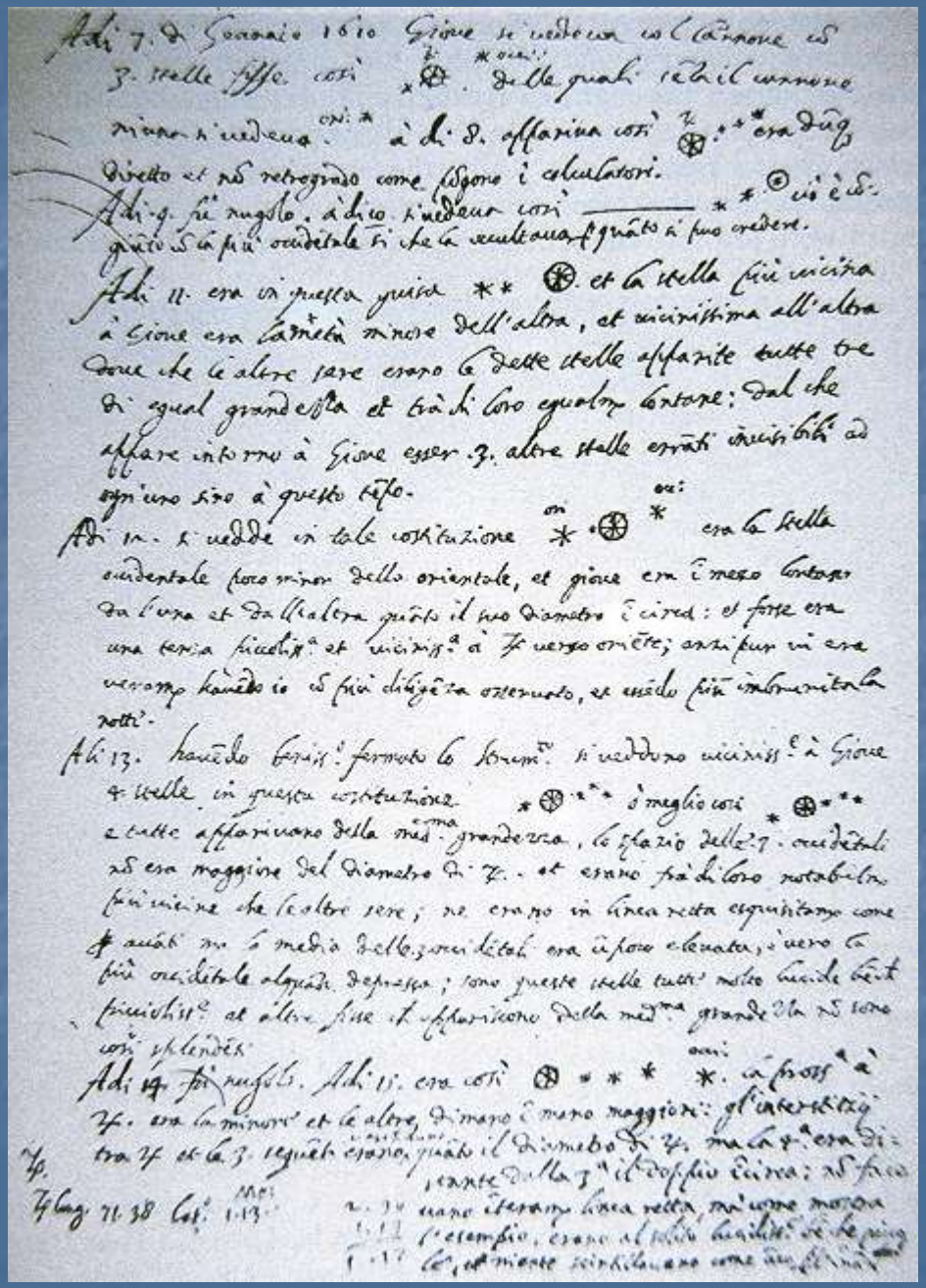
- montañas y cráteres en la Luna,



- una pléyade de estrellas invisibles al ojo humano,
- fases en Venus y

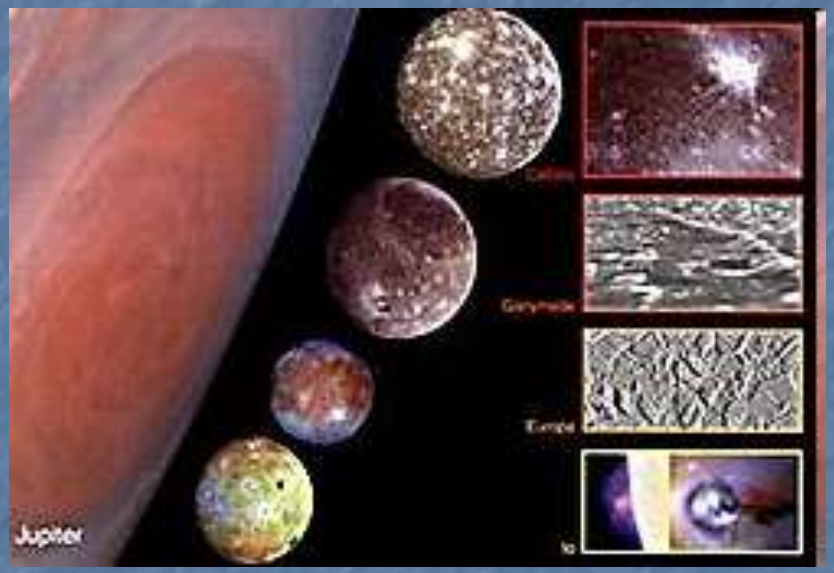
- los cuatro mayores satélites de Júpiter.

January 7th 1610: first observation of Júpiter with a telescope



Sidereus Nuncius (Venice, March 1610)

The discovery of the satellites of Jupiter had a tremendous impact in science, philosophy and religion.



Io, Europa, Calisto and Ganímedes

Deep surveys:

Hubble Deep Field (HDF):
is an image of a small region in the constellation Ursa Major, constructed from a series of observations by the HST.
It covers an area 2.5 arcm across, about one 24-millionth of the whole sky, which is equivalent in angular size to a 65 mm tennis ball at a distance of 100 metres.
The image was assembled from 342 separate exposures taken with the Space Telescope's Wide Field and Planetary Camera 2 over ten consecutive days between December 18 and December 28, 1995.

The field is so small that only a few foreground stars in the Milky Way lie within it; thus, almost all of the 3,000 objects in the image are galaxies, some of which are among the youngest and most distant known.

Deep surveys:

Hubble Ultra-Deep Field (HUDF):

In 2004 a deeper image, known as the Hubble Ultra-Deep Field (HUDF), was constructed from a total of eleven days of observations.

Deep surveys:

On September 25, 2012, NASA released a further refined version of the Ultra-Deep Field dubbed the eXtreme Deep Field(XDF).

The XDF reveals galaxies that span back 13.2 billion years in time, revealing a galaxy theorized to be formed only 450 million years after the big bang event.

On June 3, 2014, NASA released the Hubble Ultra-Deep Field image composed of, for the first time, the full range of ultraviolet to near-infrared light.

HST Frontier Fields

Hubble will undertake a revolutionary three-year deep field observing program to peer deeper into the Universe than ever before.

The Frontier Fields will combine the power of HST with the natural gravitational telescopes of high-magnification clusters of galaxies.

These will be the second deepest observations of blank fields and deepest observations of clusters and their lensed galaxies ever obtained.

Hubble Ultra Deep Field

The metallicities of different structures in the universe and their evolution with redshift are key factors to be considered in our attempts to track the progress of galaxy formation through the cosmic ages.

One of the exciting developments in observational cosmology over the last few years has been the ability to extend studies of element abundances from the local universe to high redshifts:

- Stars
- H II regions
- cool interstellar gas and hot intergalactic medium

all observed when the universe was only
$\sim$ 1/15 of its present age.

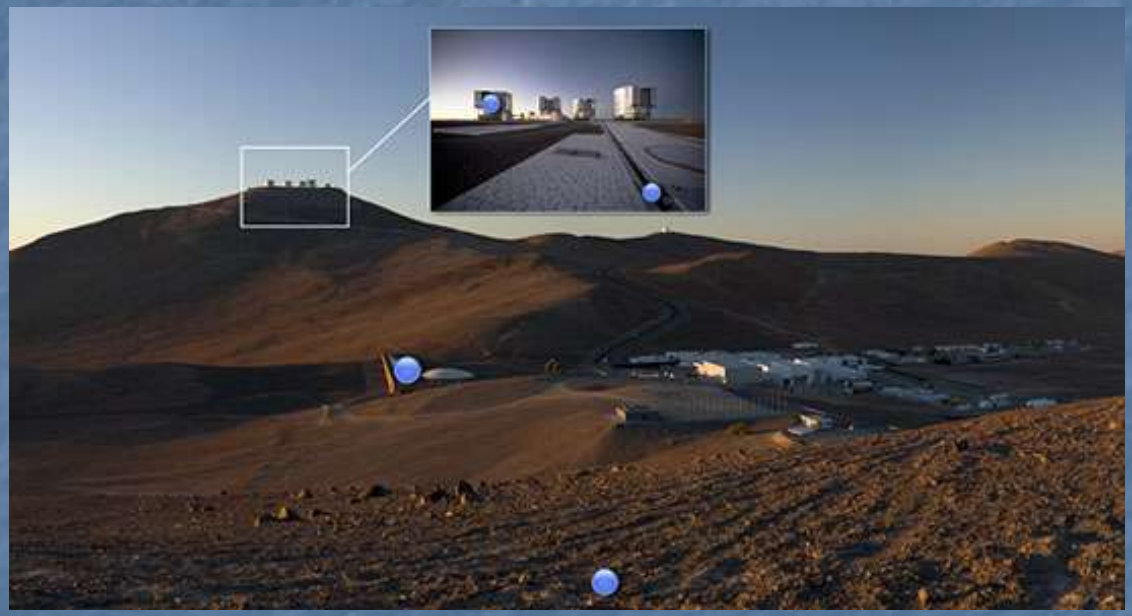
These kind of observations are possible thanks largely to the new opportunities offered by

- Keck telescopes

Two 10-meter telescopes of the W.M. Keck Observatory on Mauna Kea, island of Hawai´i

These kind of observations are possible thanks largely to the new opportunities offered by

- Keck telescopes
- the Very Large Telescope facility at the European Southern Observatory



Consisting of four Unit Telescopes with main mirrors of 8.2m diameter and four movable 1.8m diameter Auxiliary Telescopes, at the Paranal Observatory on Cerro Paranal, Chile.

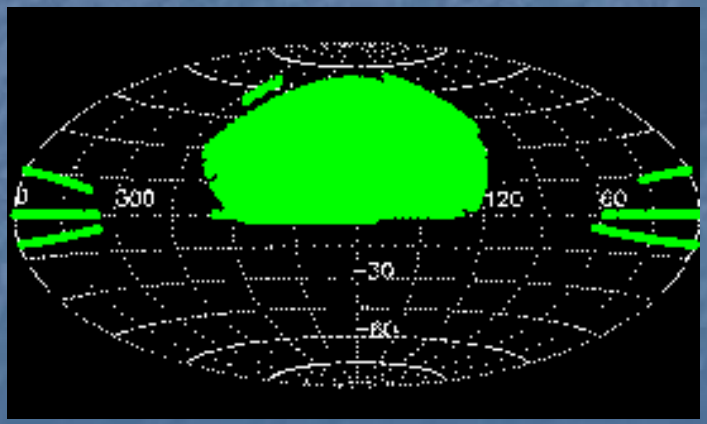
These kind of observations are possible thanks largely to the new opportunities offered by

- Keck telescopes
- the Very Large Telescope facility at the European Southern Observatory
- and most recently the Subaru telescope

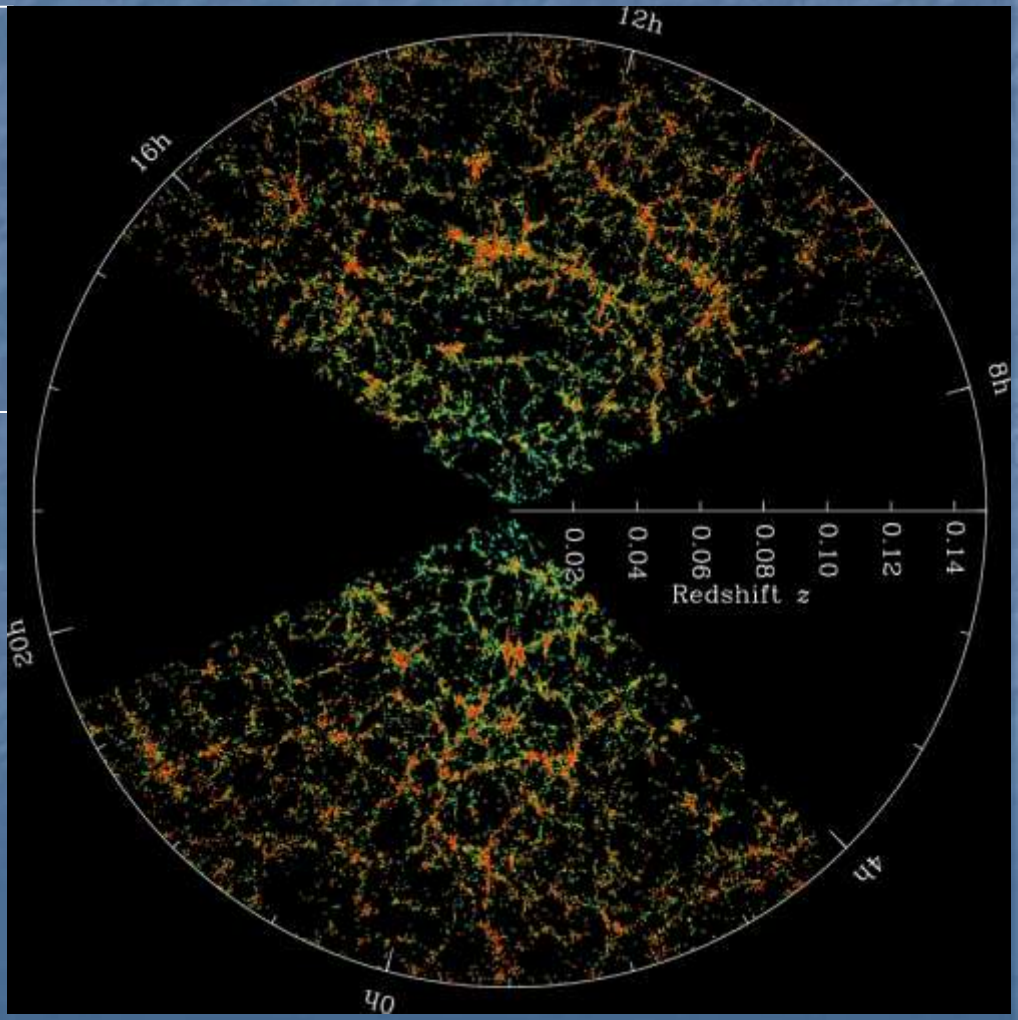
Subaru Telescope is the 8.2 metre telescope of the National Astronomical Observatory of Japan, located at the Mauna Kea Observatory on Hawaii

SDSS: es el survey más grande y sistemático.
Combina relevamientos en 5 bandas ópticas de 25% de la esfera celeste (norte): 8452 grados cuadrados.
Se tienen objetos hasta una magnitud límite M_{lim}=23.1.

SDSS: Large scale structure in the northern equatorial slice of the SDSS main galaxy redshift sample. The slice is 2.5 degrees thick, and galaxies are color-coded by luminosity (DR7)



Region of the sky covered by the SDSS (DR7)

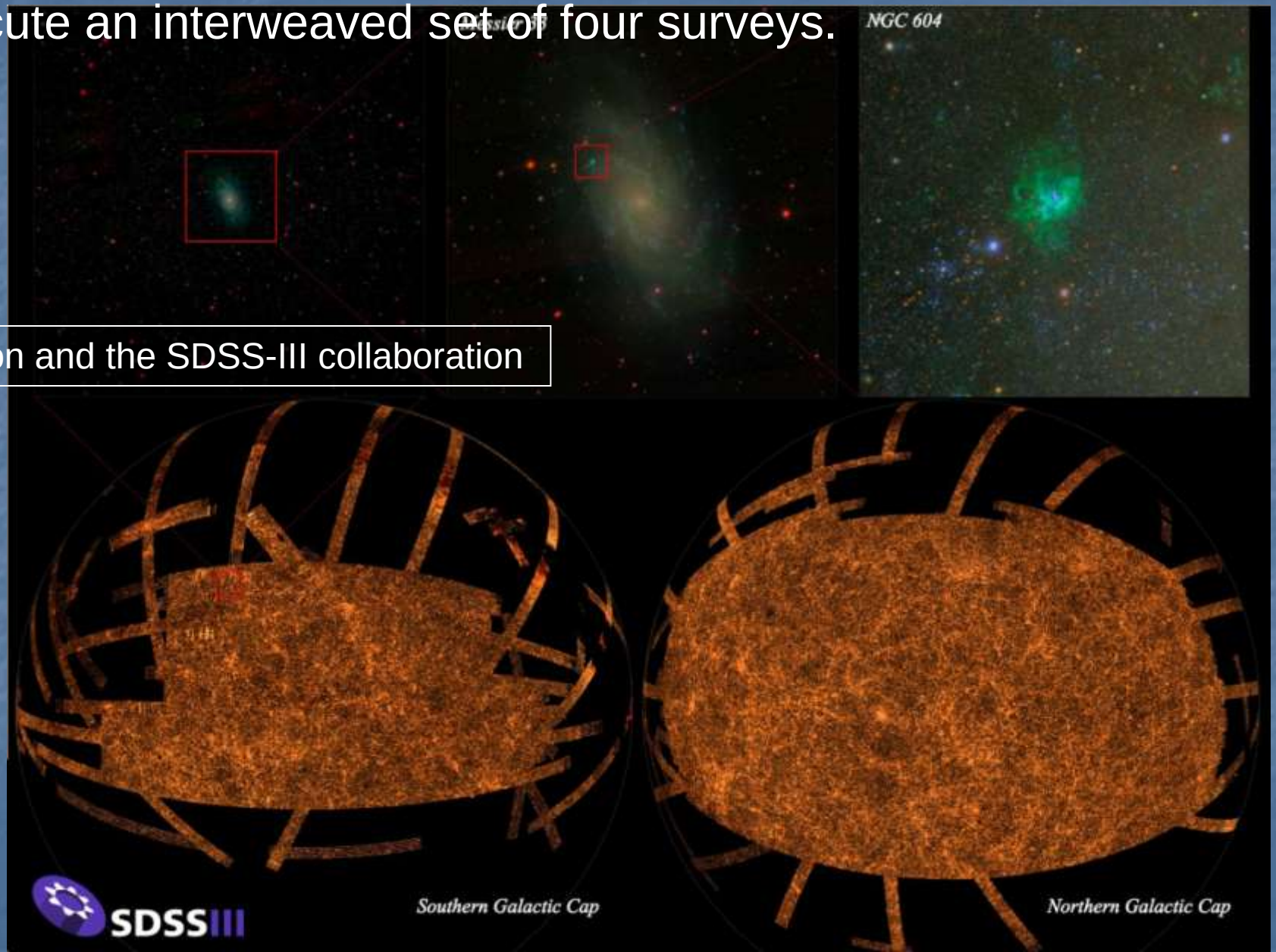


The SDSS is one of the most ambitious and influential surveys in the history of astronomy.

Over eight years of operations (SDSS-I, 2000-2005; SDSS-II, 2005-2008), it obtained deep, multi-color images covering more than a quarter of the sky and created 3-dimensional maps containing more than 930,000 galaxies and more than 120,000 quasars.

The SDSS used a dedicated 2.5-meter telescope at Apache Point Observatory, New Mexico.

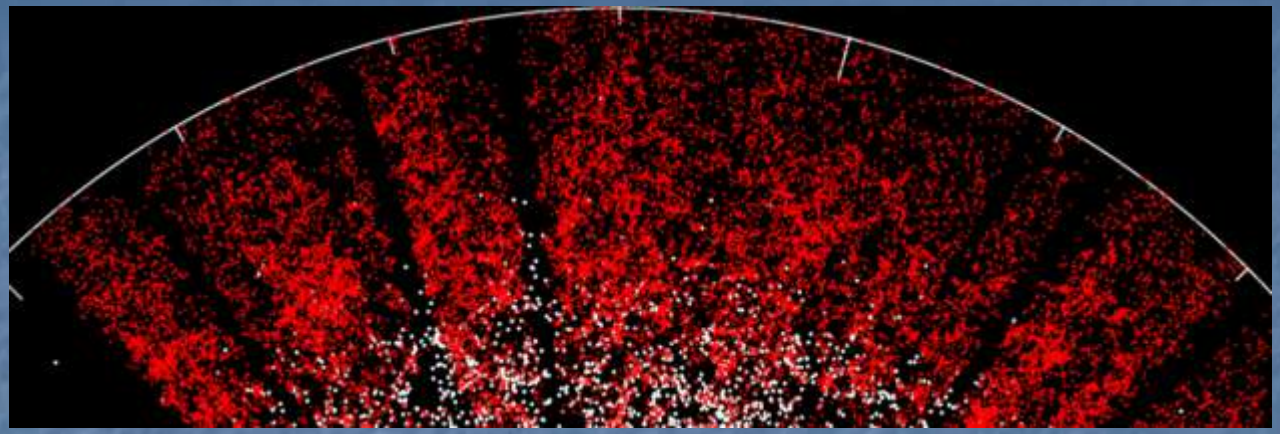
SDSS-III (2008-2014) undertook a major upgrade of the venerable SDSS spectrographs and added two powerful new instruments to execute an interweaved set of four surveys.



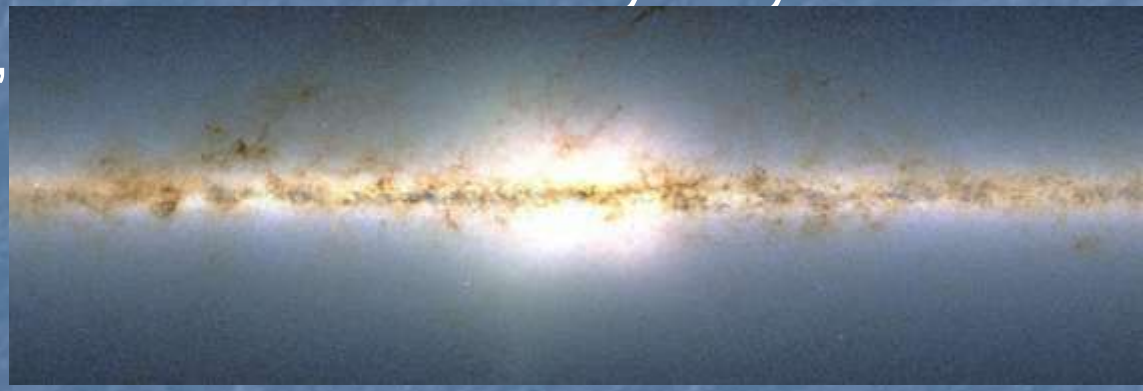
Blanton and the SDSS-III collaboration

SDSS-III (2008-2014) mapped:

- the clustering of galaxies and intergalactic gas in the distant universe (BOSS),

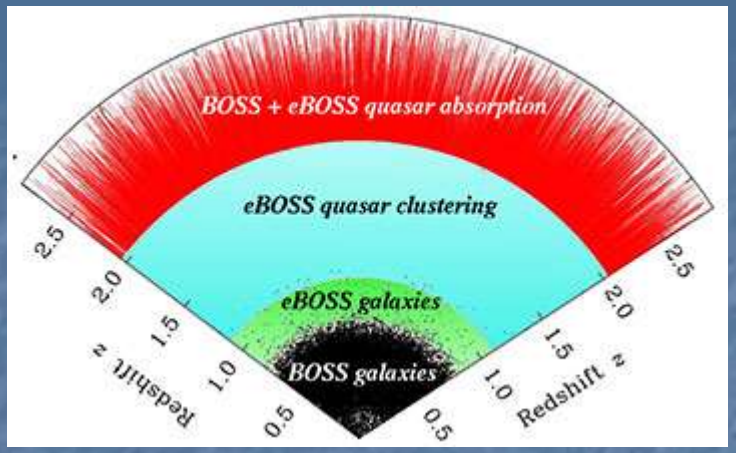


-the dynamics and chemical evolution of the Milky Way (SEGUE-2 and APOGEE),

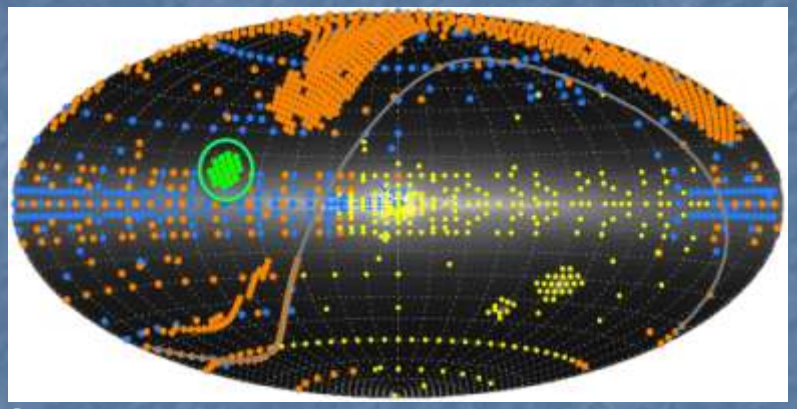


-and the population of extra-solar giant planets (MARVELS).

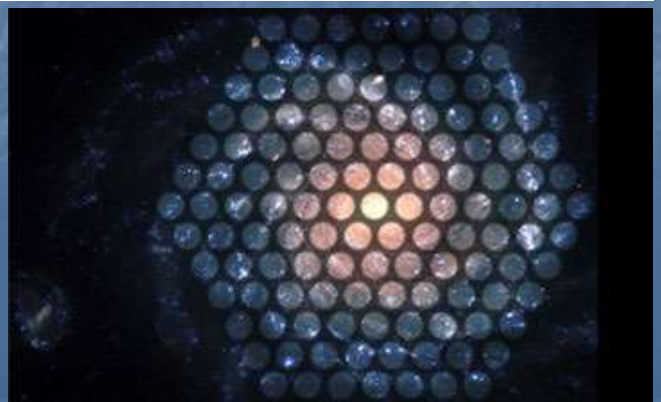
The latest generation of the SDSS (SDSS-IV, 2014-2020) is extending precision cosmological measurements to a critical early phase of cosmic history (eBOSS),



-expanding its revolutionary infrared spectroscopic survey of the Galaxy in the northern and southern hemispheres (APOGEE-2),



- and for the first time using the Sloan spectrographs to make spatially resolved maps of individual galaxies (MaNGA).

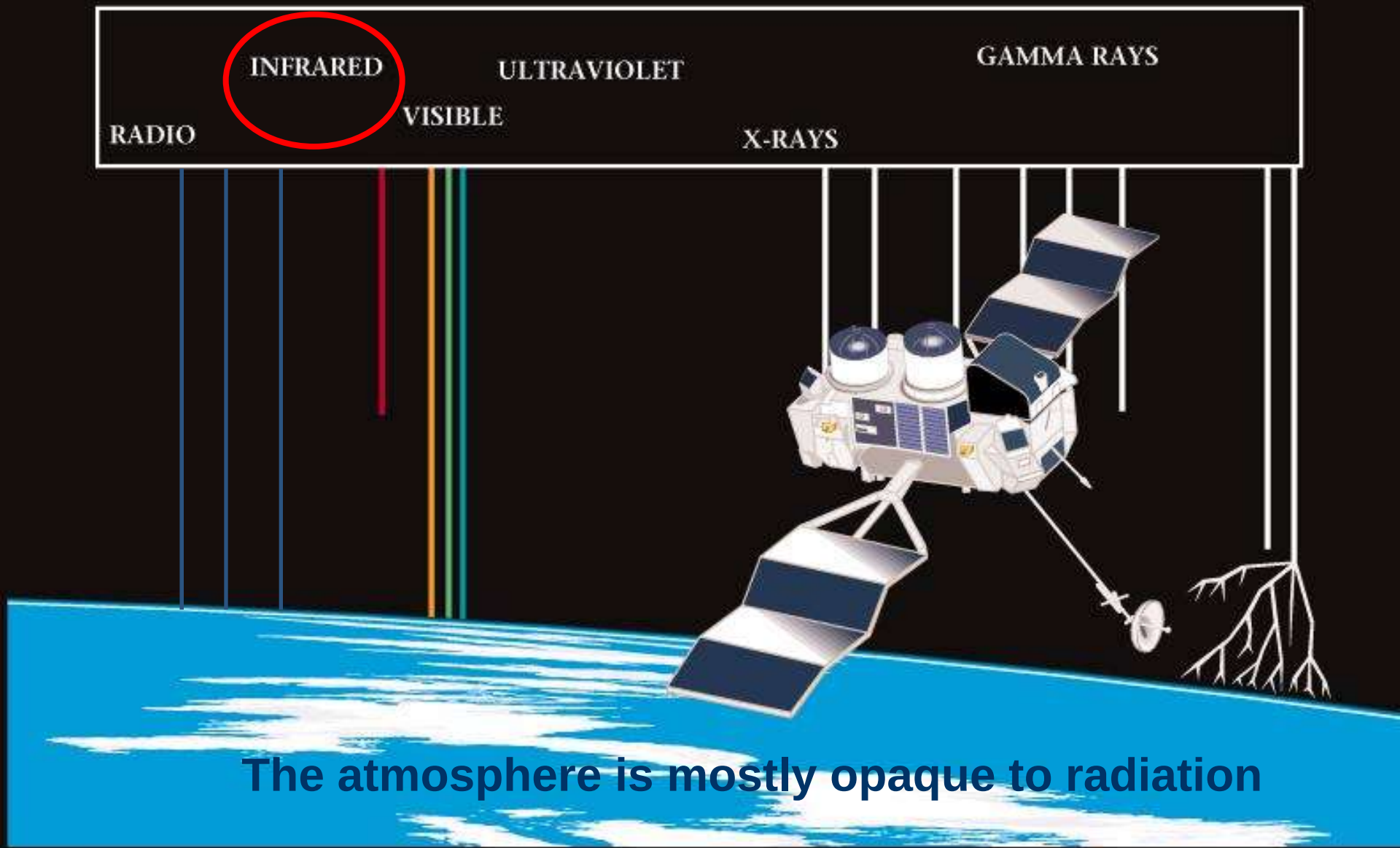


The latest generation of the SDSS (SDSS-IV, 2014-2020)

Two smaller surveys will be executed as subprograms of eBOSS:
- the Time Domain Spectroscopic Survey (TDSS) will be the first large-scale, systematic spectroscopic survey of variable sources;

- while the SPectroscopic IDentification of EROSITA Sources (SPIDERS) will provide an unique census of supermassive black-hole and large scale structure growth, targeting X-ray sources from ROSAT, XMM and eROSITA.

Electromagnetic Spectrum



The atmosphere is mostly opaque to radiation

Astronomía infrarroja

En la década de 1970, los astrónomos de todo el mundo comenzaron a considerar la posibilidad de colocar un telescopio infrarrojo en un satélite en órbita alrededor de la Tierra:

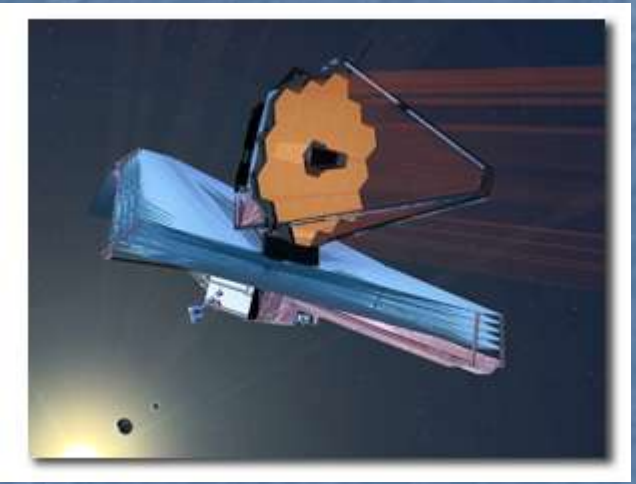
- IRAS fue lanzado con éxito el 25 de enero de 1983:

  IRAS exploró más de 96% del cielo un total de cuatro veces y completó el primer estudio de alta sensibilidad en las longitudes de onda de 12, 25, 60 y 100 micrones. IRAS incrementó en 70% el número de fuentes astronómicas catalogadas detectando cerca de 350.000 fuentes infrarrojas.

- En noviembre de 1989, la NASA lanzó el explorador del fondo cósmico (COBE) para estudiar las características de la radiación de fondo en las bandas infrarroja y de microondas (los ecos del Big Bang), con variaciones en temperatura que podrían haber dado origen a la formación de galaxias.

JWSP

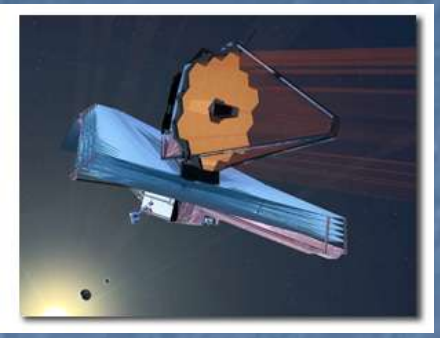
Next Generation Space Telescope renamed as the James Webb Space Telescope (JWST) will be a large infrared telescope with a 6.5-meter primary mirror.
Launch is planned for 2018.



JWST is an international collaboration between NASA, the European Space Agency (ESA), and the Canadian Space Agency (CSA).
The Space Telescope Science Institute will operate JWST after launch.

JWSP

The science goals for the JWST can be grouped into four themes:



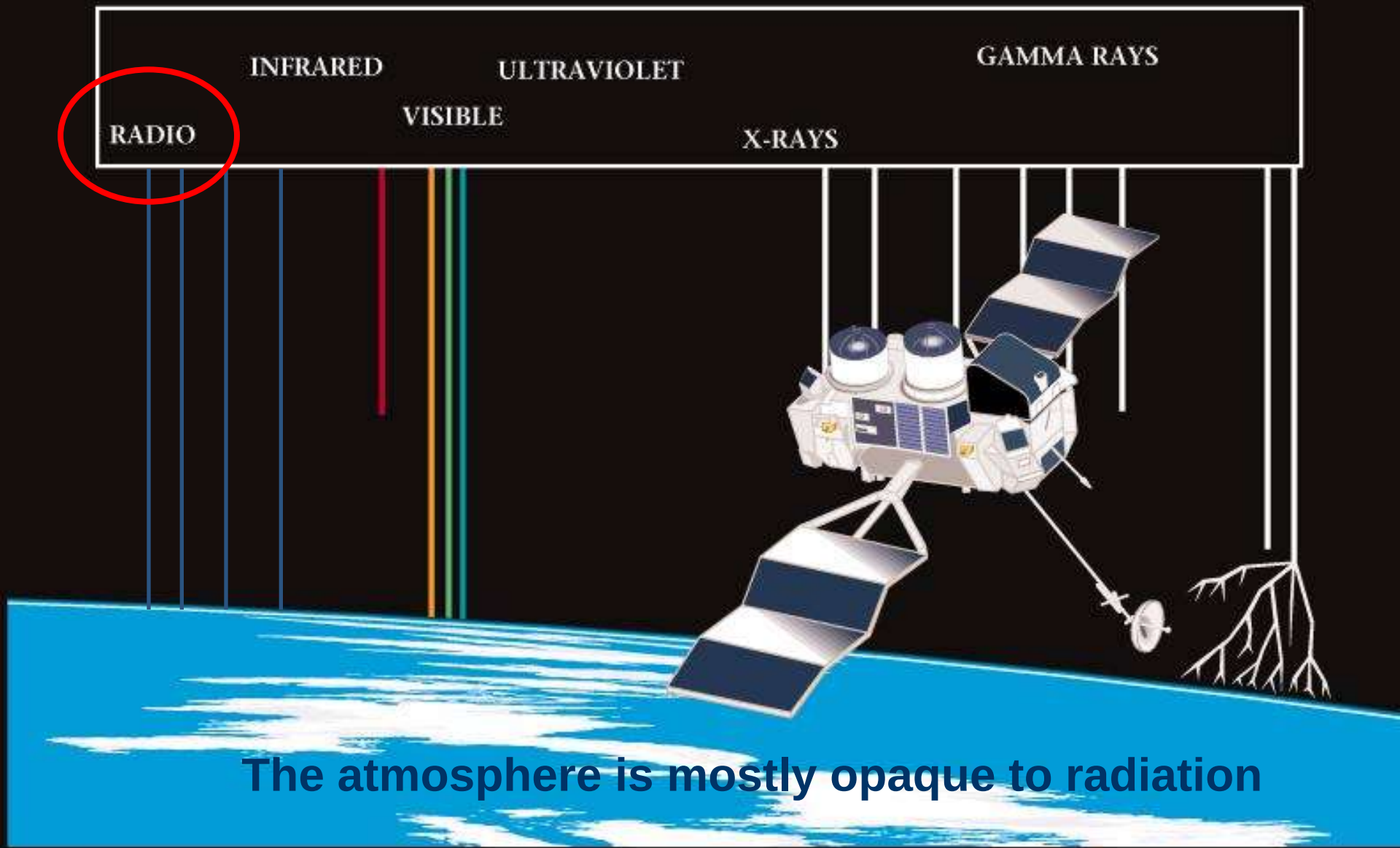
The End of the Dark Ages: First Light and Reionization seeks to identify the first bright objects that formed in the early Universe, and follow the ionization history.

Assembly of Galaxies will determine how galaxies and DM, including gas, stars, metals, physical structures (like spiral arms) and active nuclei evolved to the present day.

The Birth of Stars and Protoplanetary Systems focuses on the birth and early development of stars and the formation of planets.

Planetary Systems and the Origins of Life studies the physical and chemical properties of solar systems (including our own) and where the building blocks of life may be present.

Electromagnetic Spectrum



The atmosphere is mostly opaque to radiation

Recién en la década de 1930,
con la detección de ondas de radio de origen cósmico,
la ventana electromagnética de observación
astronómica se abrió más allá de lo que el ojo
humano es capaz de detectar.

El uso de radiotelescopios como instrumentos
astronómicos no se generalizó y
fue funcional hasta la década de 1950.

Radio Astronomy: A new window for the exploration of the Universe

Karl Jansky frente a su radioantena con la que descubrió la primera fuente radio extraterrestre (el centro de la Vía Láctea), en 1932, mientras hacía un estudio para Bell Telephone sobre las interferencias radio para las comunicaciones.

The technical progress that resulted from WW II provided the crucial impulse for radio astronomy..

Karl Jansky

Jansky detected the first extraterrestrial radio signals in the early 1930s.

Grote Reber

-He built the first radio telescope for astronomical purposes in 1937.

- He published the first radio maps of the sky in 1944.

Radio Astronomy:
A new window for the exploration of the Universe

Primera detección en radio del centro de la Vía Láctea en los Lab. Bell (1931).

Radio Astronomy was accepted as a genuine branch of the astronomical sience only after the amazing discoveries of the 1950s and 1960s:

-HI distribution in the Galaxy
-Molecular clouds
-Supernova remnants
-HII regions
-Radio galaxies and quasars
-Pulsars
-Cosmic microwave background

The 64 meter radio telescope at Parkes Observatory (Australia)

World's largest single-aperture radio telescope at Arecibo Observatory in Puerto Rico (305m de diámetro)

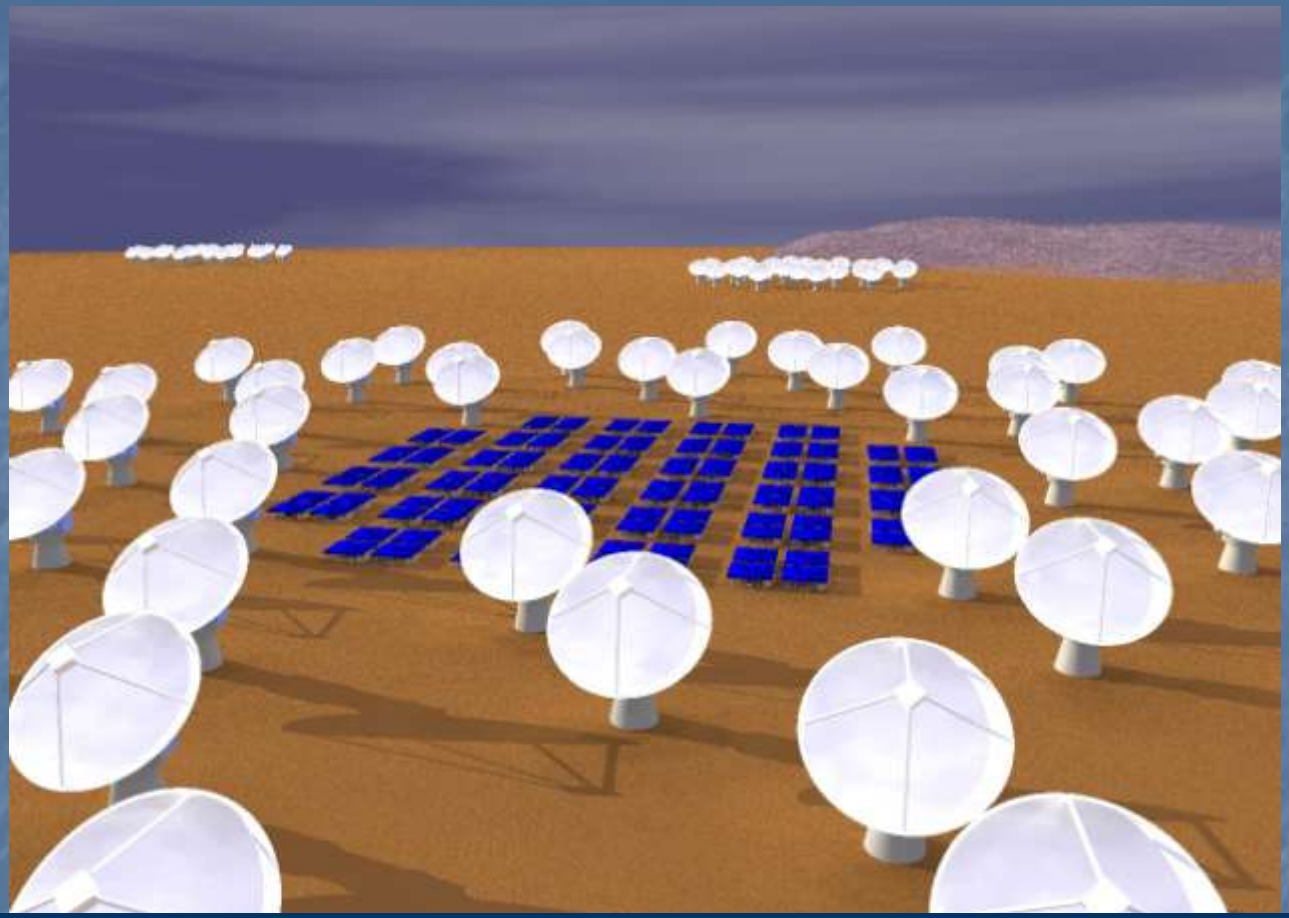
Since the 1970s there was a continuous trend to increase the angular resolution and sensitivity of radiotelescopes using **radio interferometers**

Otro radiotelescopio muy conocido es el Very Large Array (VLA), en Socorro, Nuevo México. Éste telescopio es un array interferométrico compuesto por 27 antenas de 25m de diámetro.

Otro conjunto aún más grande, el 'LOw Frequency ARray' (LOFAR), está en construcción en Europa occidental (Holanda y Alemania), formado por 25000 pequeñas antenas distribuidas en un área de varios cientos de kilómetros de diámetro.

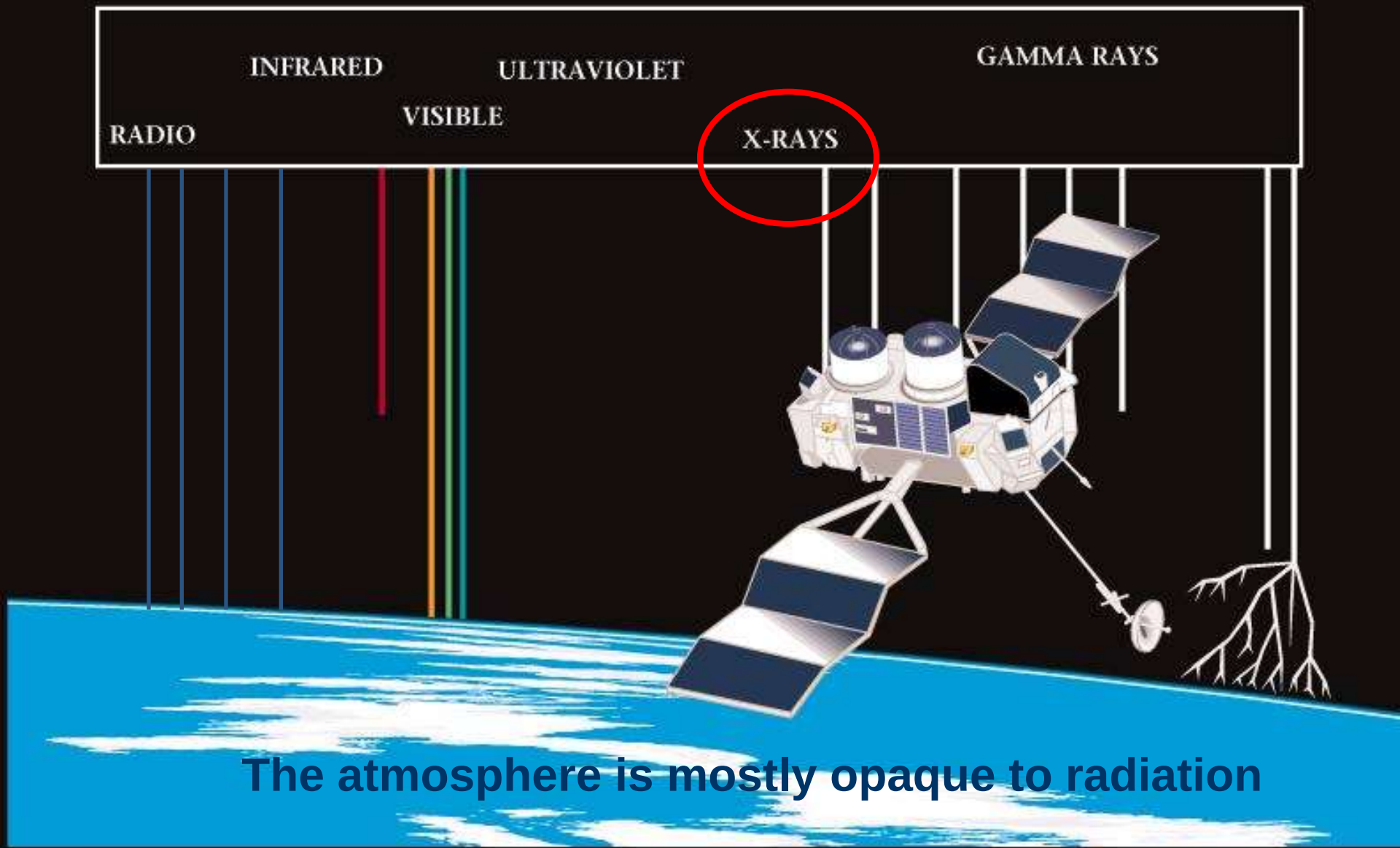
VLT

The Square Kilometre Array (SKA)



The SKA will be built in the southern hemisphere: South Africa and Australia, where the view of our own galaxy, the Milky Way, is best and radio interference least. With a budget of €1.5 billion, construction of the SKA is scheduled to begin in 2013 for initial observations by 2017 and full operation by 2022.

Electromagnetic Spectrum



The atmosphere is mostly opaque to radiation

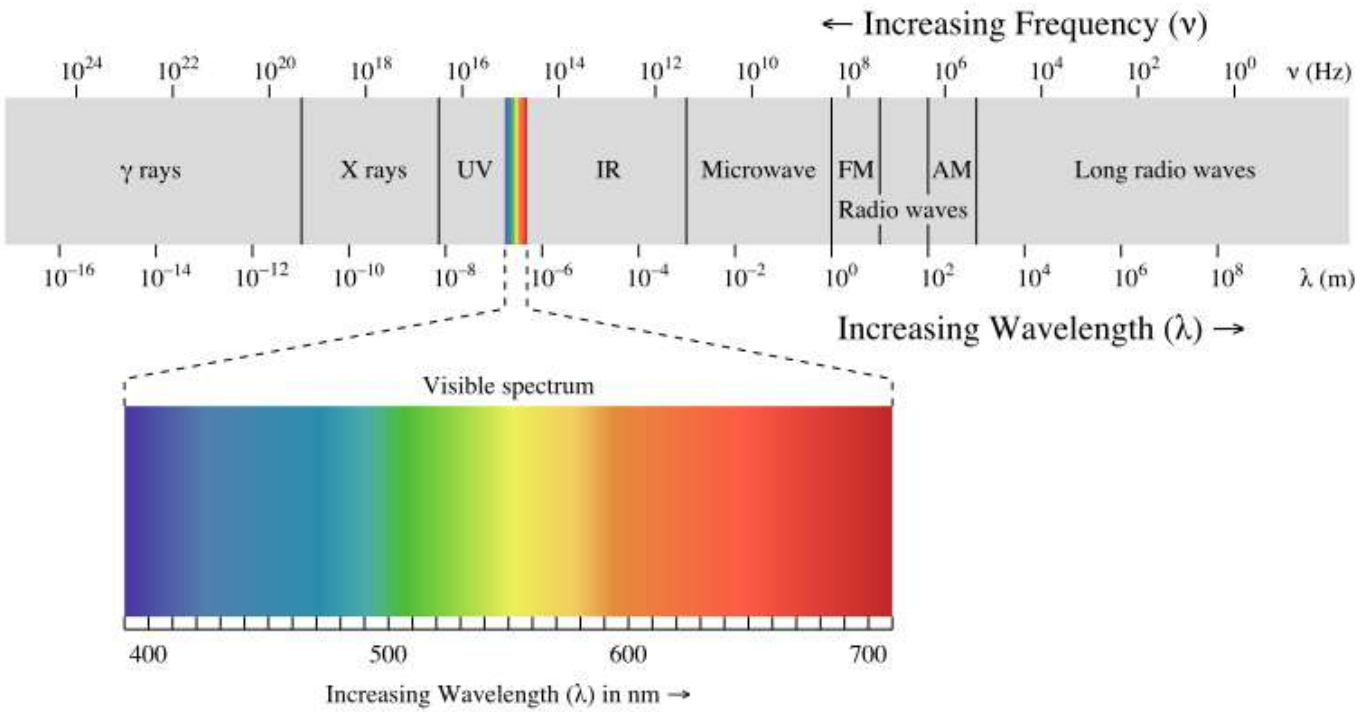
La detección de fotones de energía mayor que los del rango visible debió esperar aún más, ya que la atmósfera terrestre es opaca a la radiación de frecuencias mayores que 10^{15} Hz.

La utilización sucesiva de
- globos estratosféricos,
- cohetes de gran altitud y, finalmente,
- satélites artificiales,

proveyó de plataformas sustentables para albergar detectores de fotones muy energéticos.

Wilhelm Roengten
Discoverer of the X-rays (1895)
First Nobel Prize in Physics (1901)

La denominación **rayos X** designa a una radiación electromagnética, invisible, capaz de atravesar cuerpos opacos y de impresionar las películas fotográficas.
La longitud de onda está entre 10 a 0,1 nm, correspondiendo a frecuencias en el rango de 30 a 3.000 PHz
(PHz: Petahertz=10^{15} Hz)



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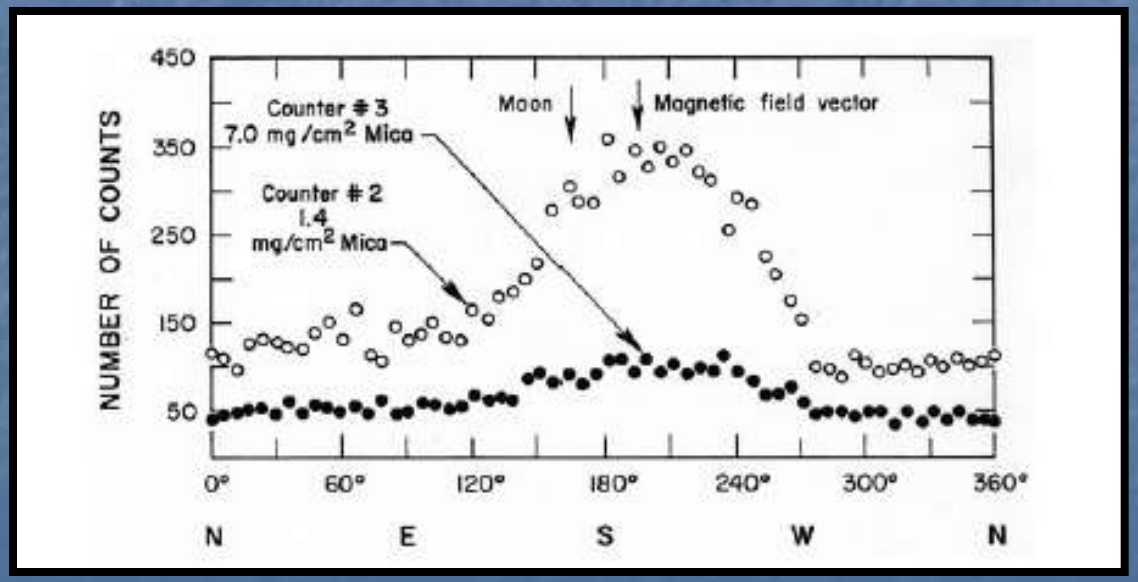
X-ray astronomy

Riccardo Giacconi

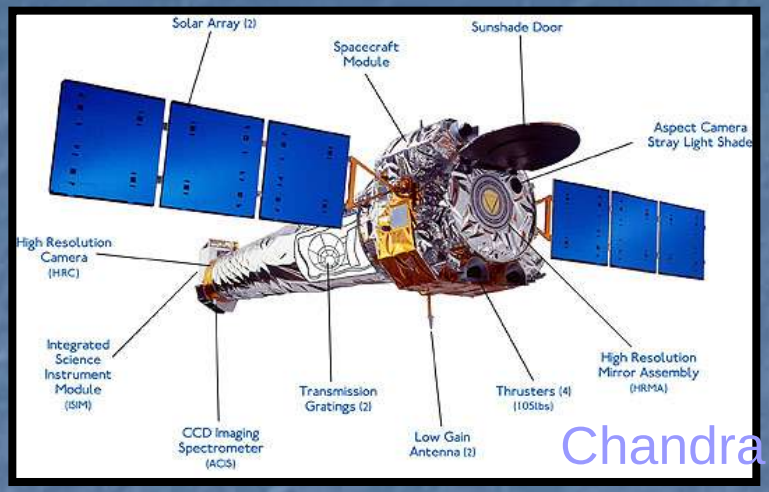
- Riccardo Giacconi was the pioneer of X-ray astronomy (Nobel Prize of Physics 2002).
- He detected in 1962 the first X-ray source outside the Solar System, Scorpius X-1, with a detector onboard a V2 German rocket.



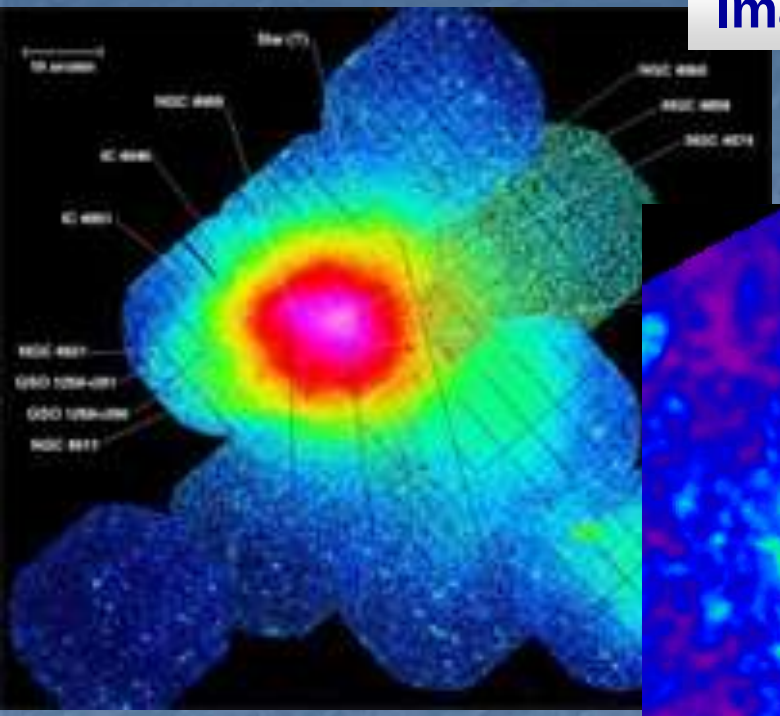
Scorpius X-1: The X-ray flux varies day-to-day, and is associated with an optically visible star, V818 Scorpii.

Some contributions of the X-ray astronomy

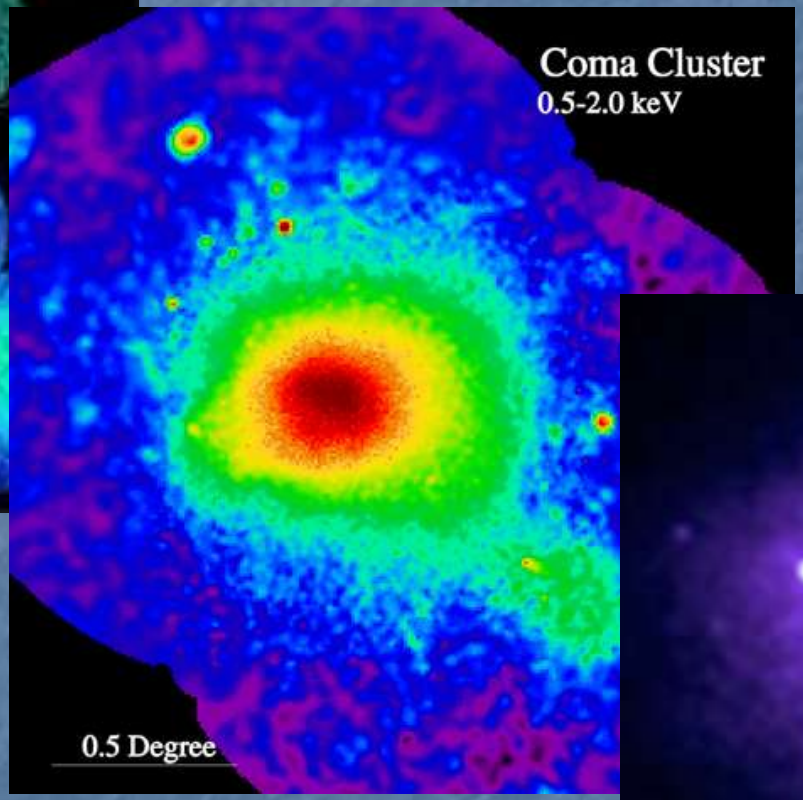
- Discovery of cosmic plasma with temperatures of millons of K.
- Black hole candidates
- X-ray pulsars
- Supernova remnants
- X-ray binaries and Fe Kα lines
- X-rays from the Sun and other stars.
- AGNs



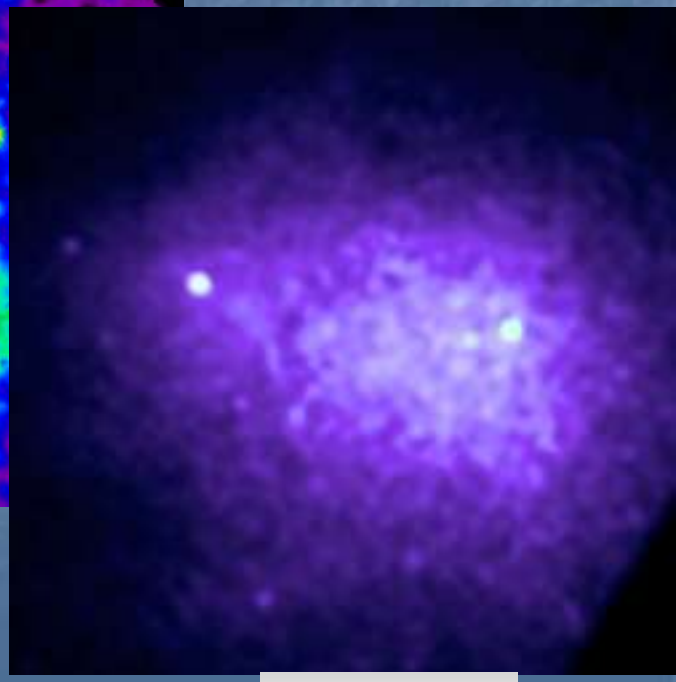
Cúmulo de Coma: Imagen en Rayos X



XMM-Newton



ROSAT



Chandra

La astronomía de rayos X (0.1 keV ≤ E_{ph} ≤ 500 keV) experimentó un rápido desarrollo durante los años 1960 debido a que las facilidades instrumentales estuvieron rápidamente a la altura de los requisitos observacionales primarios.

Por el contrario, el desarrollo de la astronomía de rayos gamma (E_{ph} ≥ 500 KeV) fue un proceso lento que tardó décadas en arrojar resultados significativos.

Esto se debió, en parte,

-a dificultades técnicas específicas y

-al formidable problema de separar las contribuciones producidas en el detector por fuentes legítimas de rayos gamma de aquellas que tienen un origen puramente local y son debidos a la radiación cósmica universal (formada por partículas cargadas y neutrones relativistas).

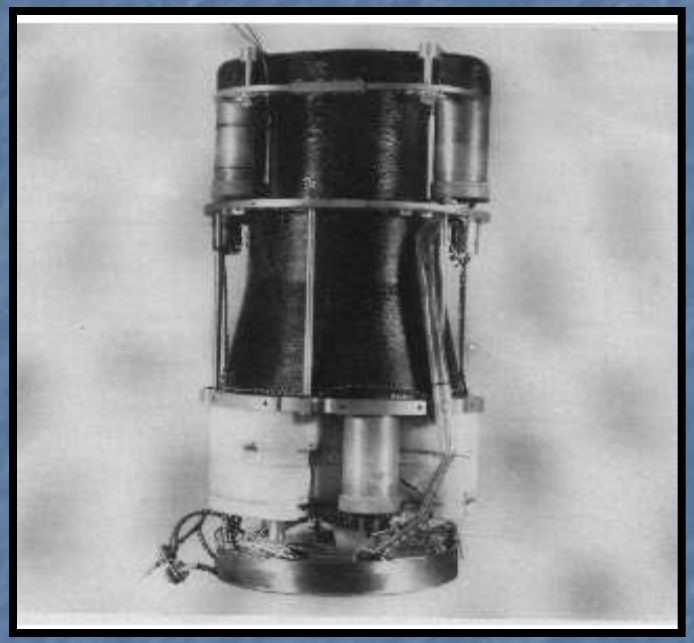
A pesar de las dificultades,
durante la década de 1990,
la astronomía de rayos gamma
se ha consolidado como una herramienta fundamental para el estudio de los procesos no-térmicos en el Universo.

En efecto, este es el único rango del espectro electromagnético libre de contribuciones producidas por plasmas calientes, por lo que **la radiación por encima de 1MeV es debida, casi enteramente, a interacciones de partículas relativistas**.

Gamma-ray astronomy

- Was motivated by the early findings of radio astronomy: Hayakawa (1952), Hutchinson (1952), Morrison (1958).
- Unfortunately, gamma-rays are very difficult to detect: noise generated in the detectors by cosmic rays is ~1000 times stronger than the strongest cosmic signals.
- Spark chambers effectively detected gamma-rays with energies between 100 MeV-10 GeV since the 1970s (SAS-II) till the 1990s (EGRET).

Explorer 11



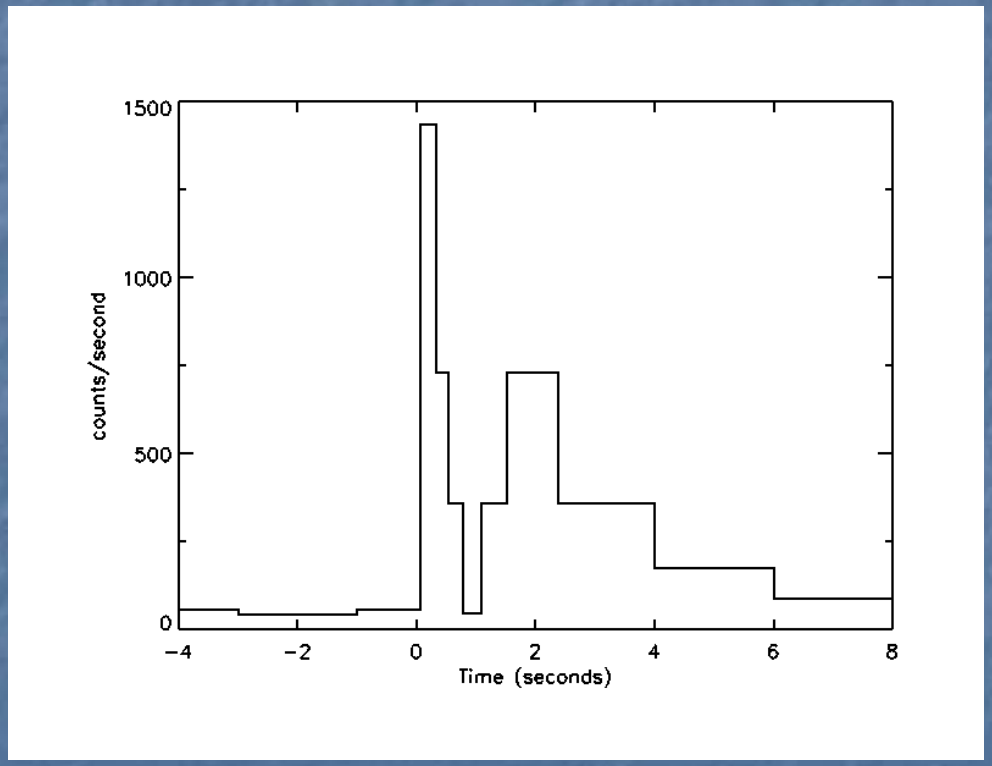
First detection of a cosmic gamma-ray photon

Explorer 11 (also known as S15) was the orbital spacecraft that carried the first gamma ray telescope.
This was the earliest beginnings of gamma-ray astronomy. Launched on April 27, 1961 by a Juno II rocket the satellite returned data until November 17, when power supply problems ended the science mission. During the spacecraft's seven month lifespan it detected twenty-two events from gamma-rays and approximately 22,000 events from cosmic radiation.

Early Gamma-ray Astronomy

- Gamma-ray Bursts
  - Vela Program : A Bomb or Not a Bomb?
  - A few hundred events, a few hundred theories

Vela Program (1967-1979)



Discovery of Gamma-Ray Bursts

GAMMA RAY BURSTS (GRBs)

Las erupciones de rayos γ son un fenómeno astronómico caracterizado por un rápido incremento de la radiación γ que llega a la Tierra desde el espacio.

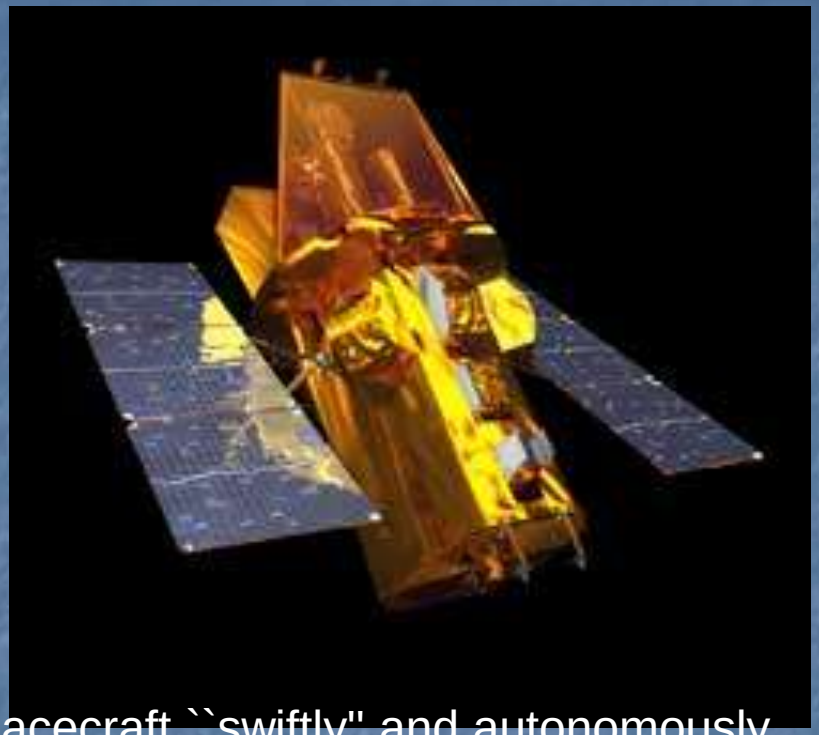
- Este incremento puede ser tal que llegue a superar a toda otra fuente γ del Universo.

- La duración de este fenómeno es muy corta, usualmente yendo de unos pocos segundos a algunas decenas de ellos. Se han observado GRBs con duraciones extremas del orden del ms y de decenas de minutos.
- En promedio ocurren entre 1 y 2 GRBs por día.

- Los GRBs fueron descubiertos por los satélites militares Vela en 1967 y la información sobre su existencia recién se desclasificó en 1973, cuando estuvo claro que se trataba de un fenómeno natural y no del efecto de pruebas nucleares ilegales en el espacio.
- Desde entonces se han detectado más de 3000 de estos eventos.
- Diversas misiones espaciales han llevado a bordo instrumentos dedicados a detectar GRBs. Entre los últimos y más exitosos podemos mencionar a BATSE (en el Copmpton Gamma Ray Observatory) y satélite SWIFT.

Swift Gamma Ray Burst Explorer

- *Swift* (10/11/2004)
  - ~100 GRB/año
  - BAT (Burst alert telescope): detección GRB (2')
  - XRT: afterglow X (3")
  - UVOT: afterglow UV-óptica
  - Posición diseminada en segundos: útil para GRBs cortos



❖ Within seconds of detecting a burst, the spacecraft ``swiftly'' and autonomously repoints itself to aim the XRT and UVOT at the burst to obtain high-precision *X*-ray and optical positions and spectra.

❖ *Swift* provides detailed multi-wavelength light curves for the duration of the afterglow. Key data taken by *Swift* are relayed to the ground in near-real time, allowing the Gamma-Ray Burst Coordinates Network (GCN) to immediately distribute it to the world via the internet for follow-up observations and study.

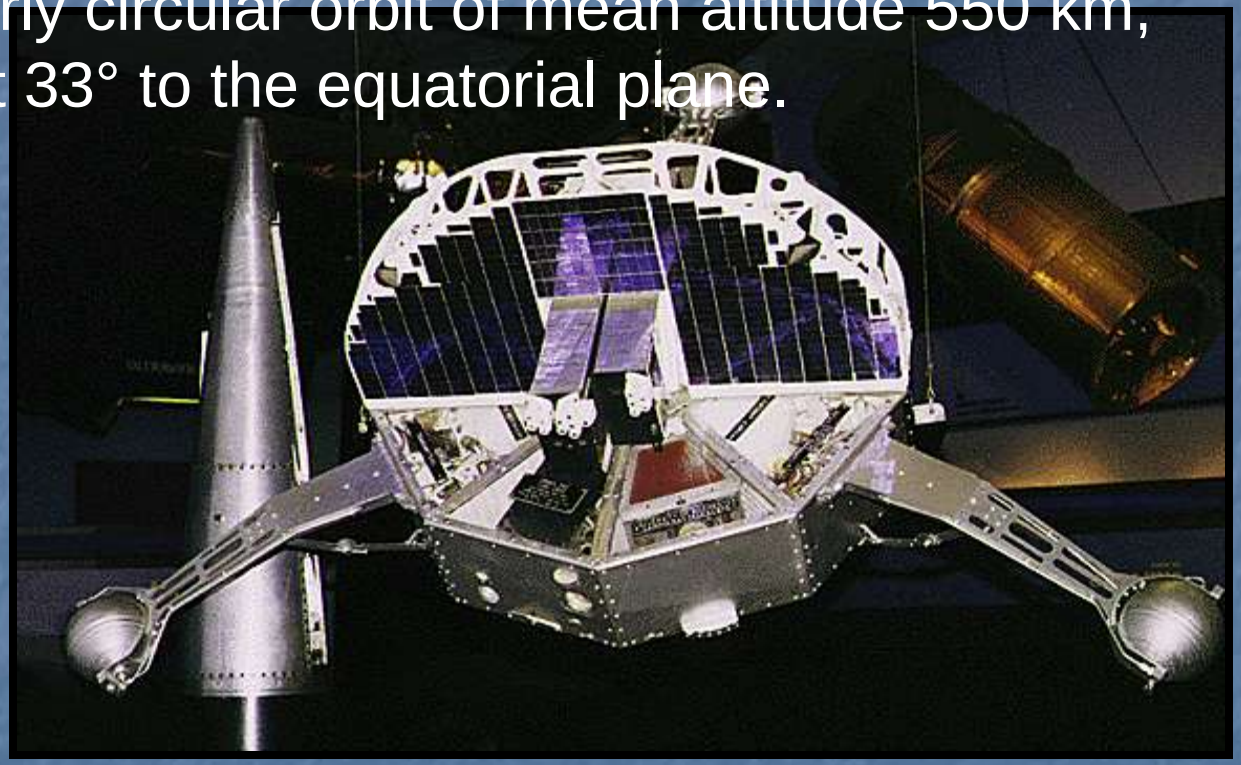
❖*Swift* also uses the BAT to perform an all-sky survey of hard *X*-rays that will be significantly more sensitive than any previous survey.

Early Gamma-ray Astronomy

- Gamma-ray Sources
  - SAS-2 – discovered 2 pulsars (1972)
  - COS-B – about 25 sources (1975-82)
  - Most unidentified, but 1 quasar
  - Diffuse extra-galactic background

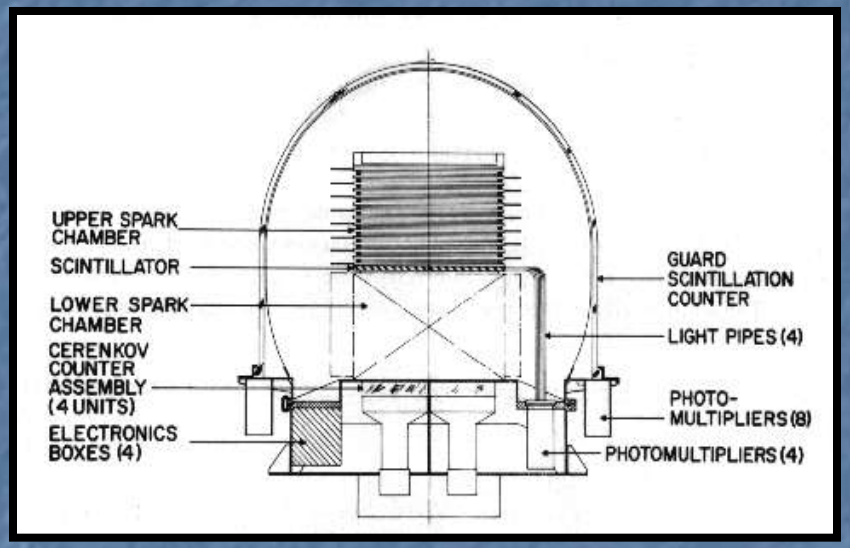
OSO 3

The **Third Orbiting Solar Observatory**
(**OSO 3**, known as OSO C before launch)
was launched on March 8, 1967,
into a nearly circular orbit of mean altitude 550 km,
inclined at 33° to the equatorial plane.



Detected 621 photons with E>100 MeV in 1967
from the general direction of the Galactic Center
(angular resolution ~ 30 degrees).

SAS-II (1972-1973)



Detected ~8000 gamma-ray photons and two pulsars: Crab and Vela

Cos-B (1975-1982)

Detected 25 sources. Among them, the quasar 3C273.

HEAO 3

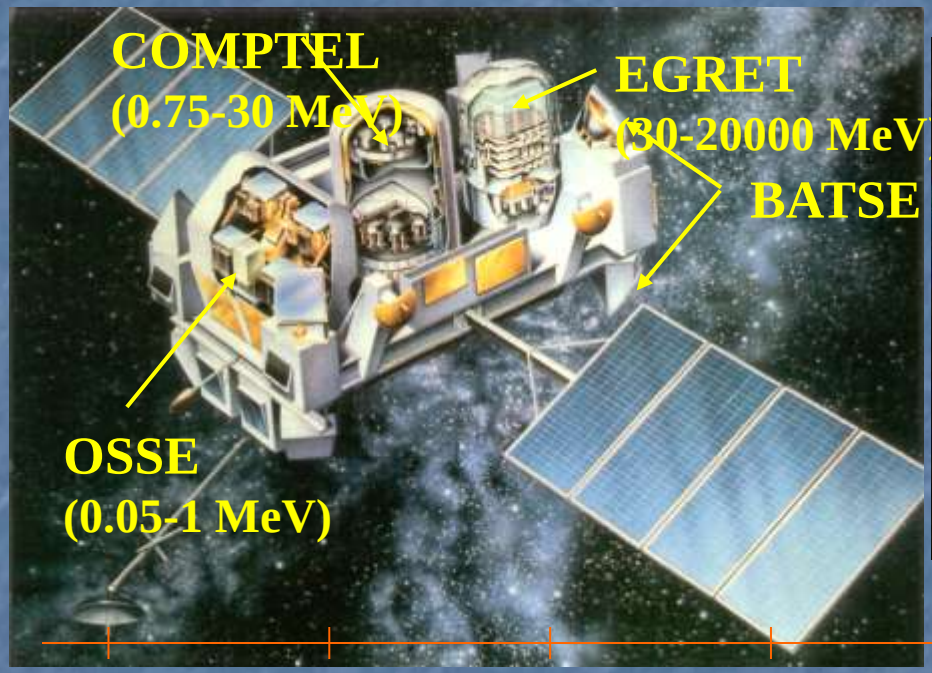
Carried a spectrometer that detected ^{26}Al @ 1809 keV from the Galactic plane in the early 80s.

GRANAT

It was launched on 1 December 1989 aboard a Proton rocket and placed in a highly eccentric four-day orbit, of which three were devoted to observations. It operated for almost nine years.

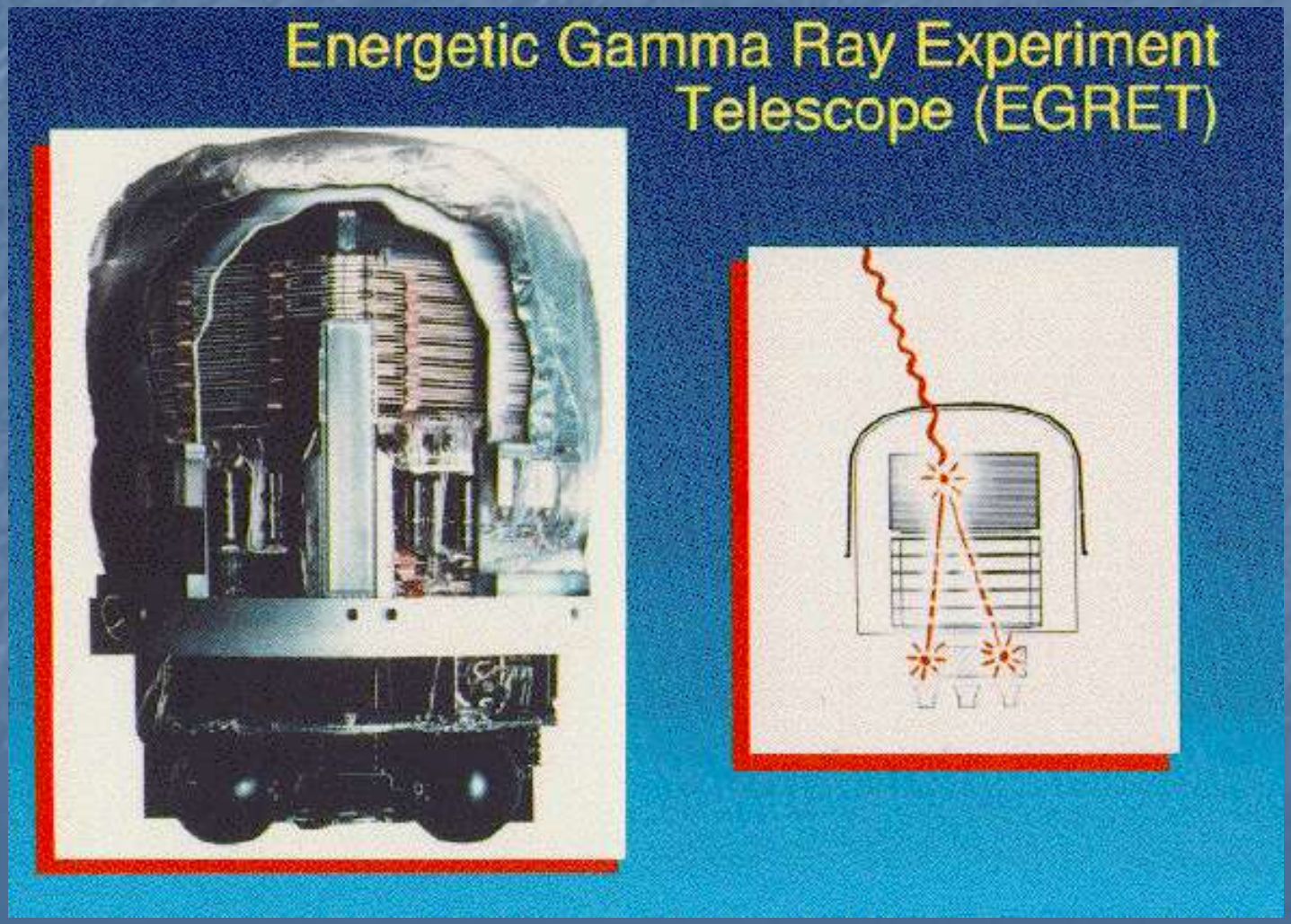
Detection of GRB plus spectroscopy and all-sky monitoring

COMPTON GAMMA RAY OBSERVATORY (CGRO)

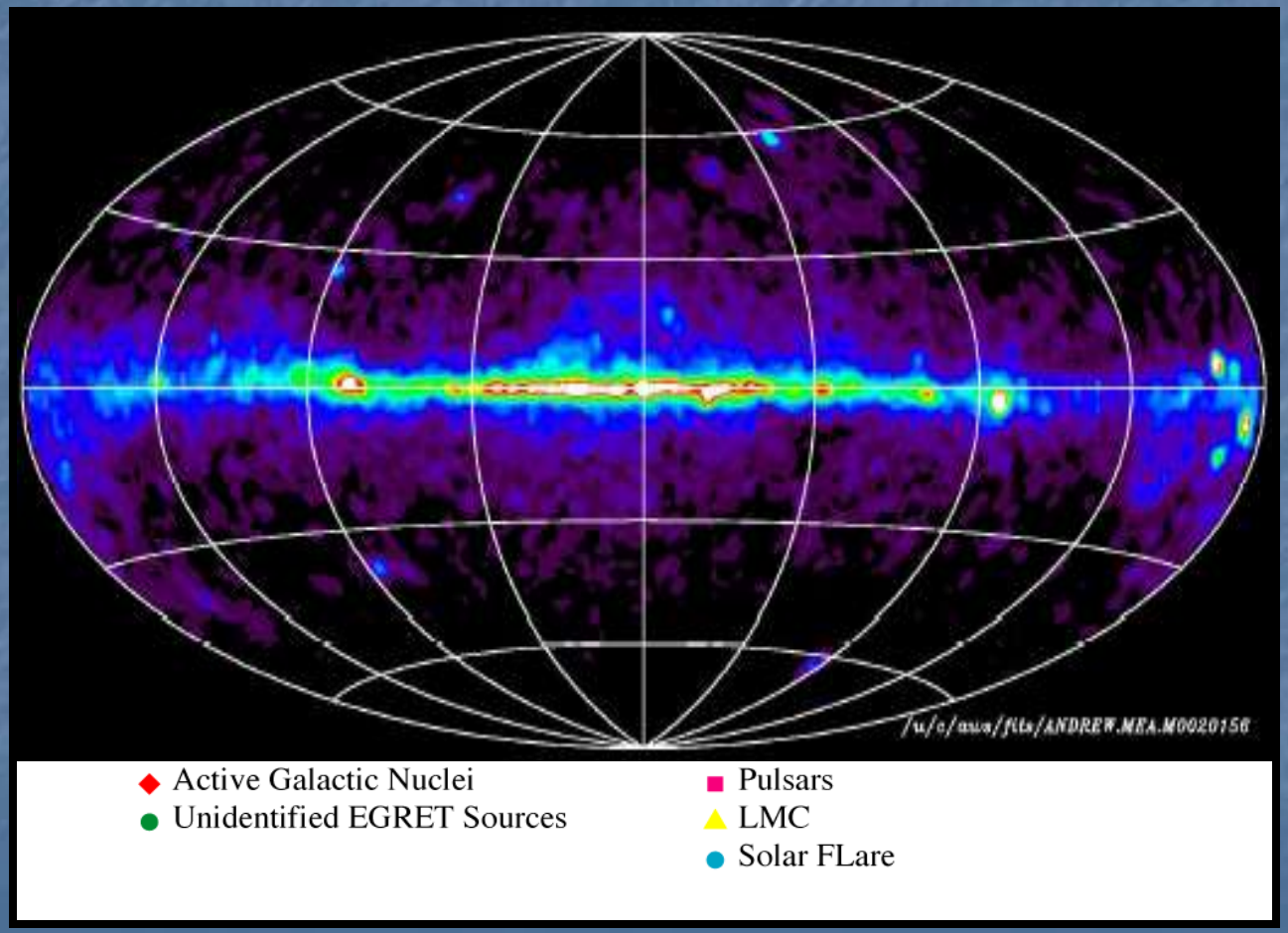


The **Compton Gamma Ray Observatory** (**CGRO**) was the second of the NASA "Great Observatories" to be launched to space, following the HST.
It was launched on the Space Shuttle *Atlantis*, mission STS-37, on 5 April 1991 and operated until its deorbit on 4 June 2000.

EGRET



The Third Egret Catalog E >100 MeV



- EGRET cycles 1-4: 416 gamma-ray excesses above 3 sigma.
- 271 of them included in the 3EG catalog.
- The significance of sources close to the Galactic plane is 5 sigma. Sources off the the plane have 4 sigma.

ASTRONOMÍA GAMMA ESPACIAL:

30 MeV < E < 300 GeV (cont.)

Los satélites GLAST (renombrado como Fermi Gamma Ray Space Telescope) y AGILE incorporan esta tecnología.

LAT, el "LARGE AREA TELESCOPE" de GLAST,
es un telescopio de producción de pares con tecnología de silicio.
El instrumento tiene 16 módulos de conversión/rastreo de pares en una disposición de 4× 4 torres independientes, cada una con su calorímetro.

Las placas (18) de cada torre utilizan tungsteno como elemento de conversión $\gamma \rightarrow e^{\pm}$ y luego tiras de semiconductores de silicio como trazadores. Cada torre mide 87.5 cm.
Los calorímetros están hechos de CsI(Tl) (ioduro de Cesio).

Todos los sistemas están rodeados por un escudo de anticoincidencia construido con un centellador plástico y fototubos en miniatura para las lecturas. No hay elementos consumibles (gas) en el instrumento.
El peso total es de 3 toneladas y sus carácterísticas implican una mejora notable respecto de EGRET.

ASTRONOMÍA GAMMA ESPACIAL:

30 MeV < E < 300 GeV (cont.)

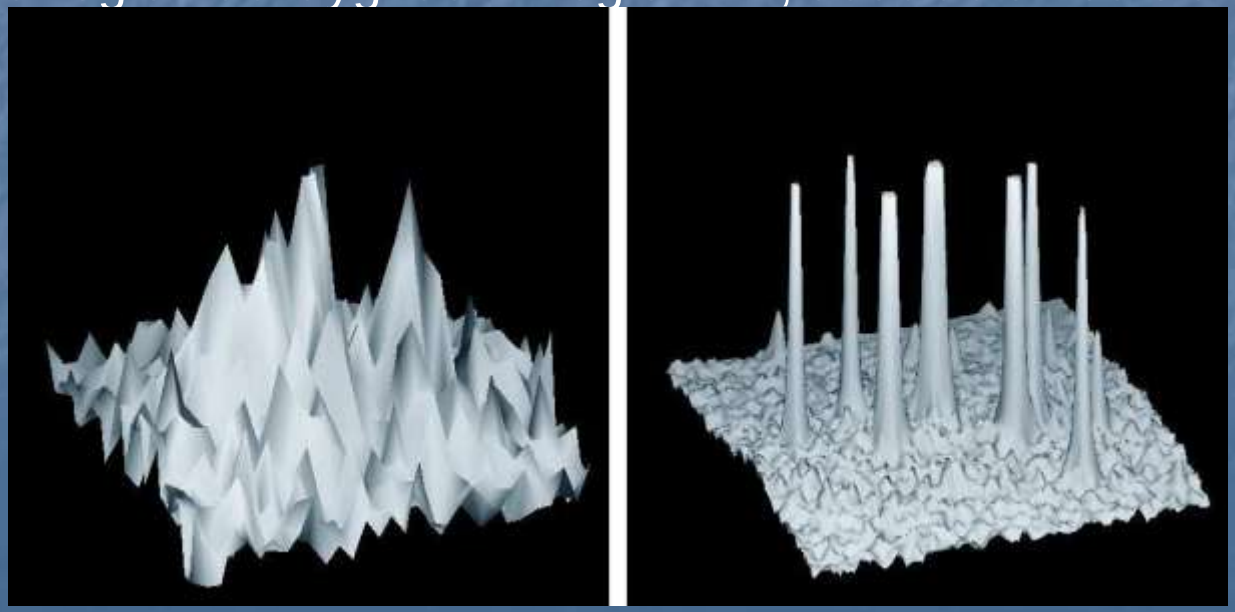
Satélites GLAST (renombrado como Fermi Gamma Ray Space Telescope) fue lanzado el 11 de junio de 2008

LAT, el "LARGE AREA TELESCOPE" de GLAST opera en el rango de energía entre 20 MeV y 300 GeV.

El área efectiva supera los 8000 cm2 con un campo visual de más de 2 sr.

La sensibilidad es 2 órdenes de magnitud mayor que la de EGRET.

Simulaciones de la resolución de EGRET y GLAST
(en la región de Cygnus X: región HII, asociación estelar)



The last frontier: very high-energy gamma-ray astronomy

Astronomy at energies > 10 GeV

The XX Century has been the century of the new astronomies. We are not restricted any more to what we can see through the eyes. Thanks to the new telescopes, radio antennae, and satellite instruments we can detect a huge number of new sources in the Cosmos.

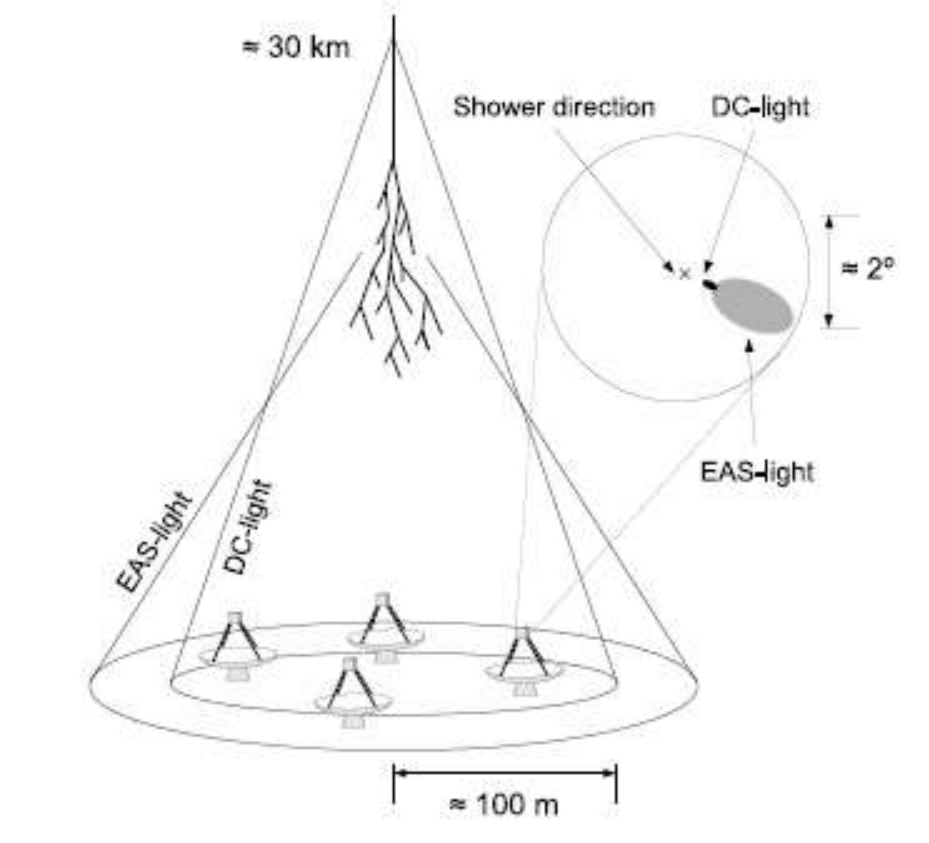
The last frontier in this search for cosmic photons are the gamma-rays of the highest energies. They cannot penetrate the atmosphere, but the initiate showers of particles that shine through Cherenkov pulses during a span of a nanosecond. This light can be detected with Cherenkov telescopes.

ASTRONOMÍA GAMMA DESDE TIERRA: TELESCOPIOS CHERENKOV

Cuando un rayo γ llega a la atmósfera inicia una cascada electromagnética.

Si $E_\gamma > 100\,\mathrm{GeV}$ la cascada se desarrolla hasta una altitud de unos pocos km sobre el nivel del mar y la **luz Cherenkov** producida por los leptones relativistas en la atmósfera puede detectarse en la forma de una columna de luz.

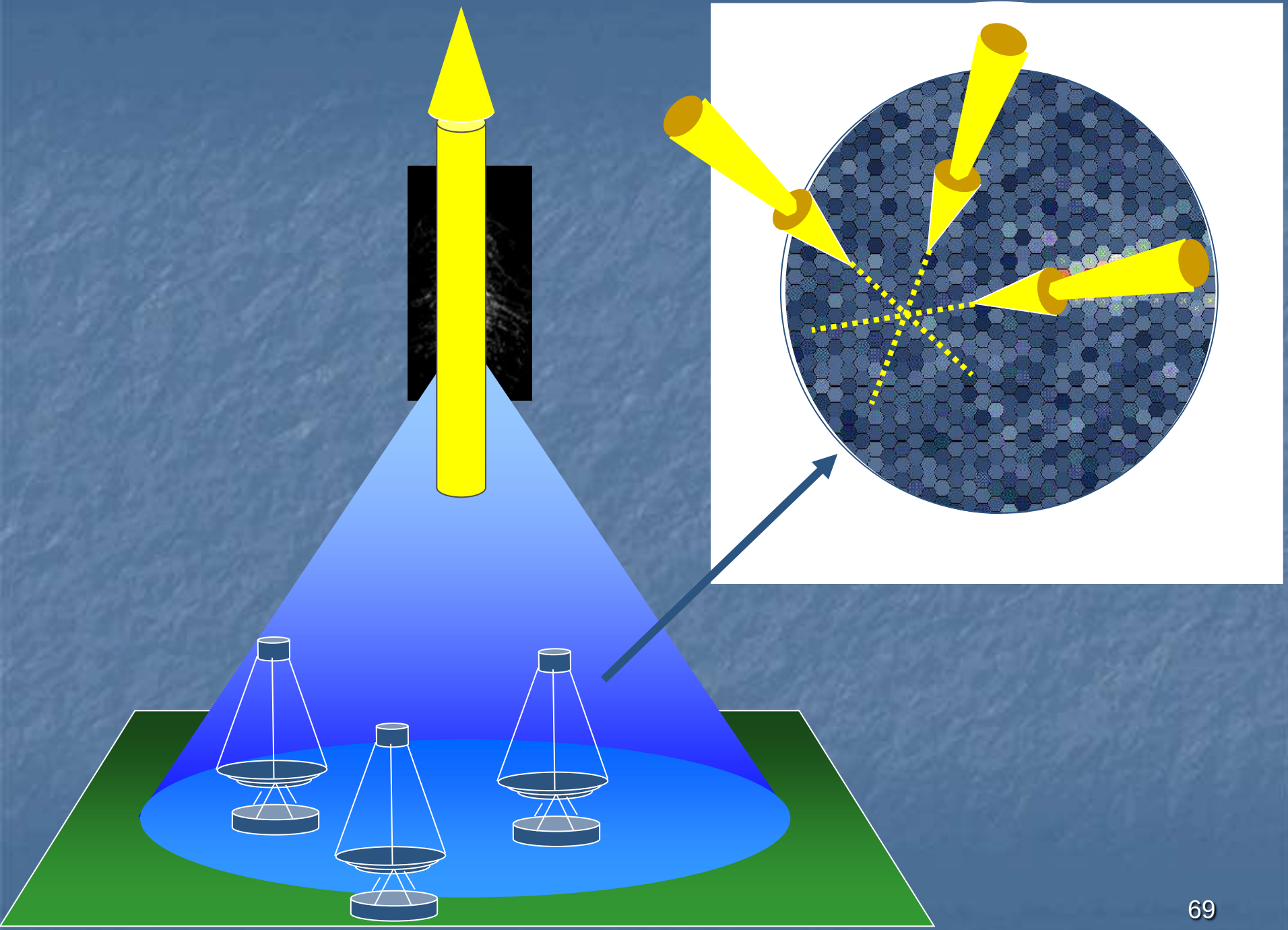
El eje de la columna coincide con la proyección del eje de la cascada y su punto inicial indica el punto del cielo donde el rayo γ interaccionó.



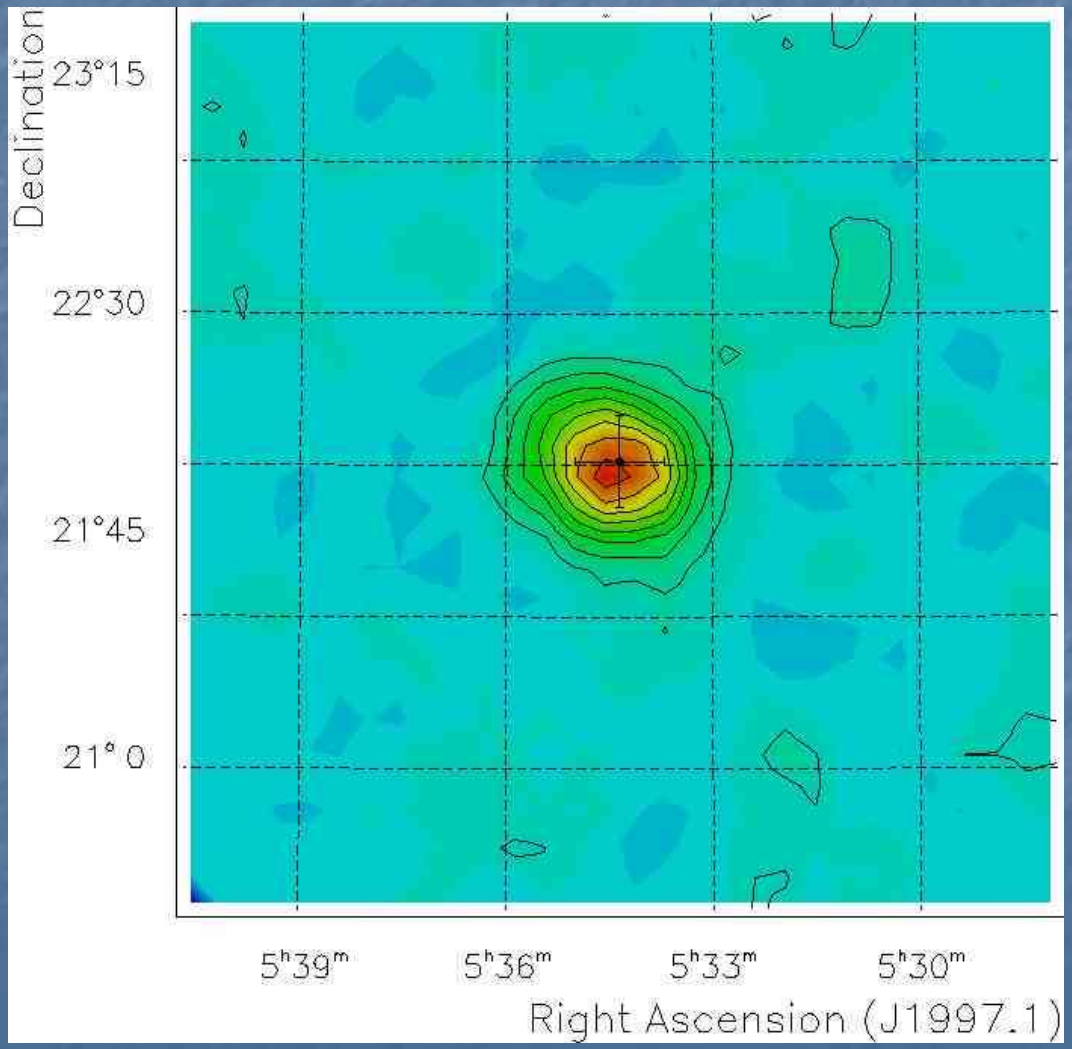
Técnica que empezó a desarrollarse en 1950. Primera detección: 1989.

Ground-based gamma-ray astronomy was slow to develop, because of instrumental problems.

- Cherenkov light by cosmic rays detected in 1953.
- Background contribution by cosmic rays was a serious problem for Cherenkov gamma-ray astronomy since the late 1950s till the late 1980s.
- The problem was solved using imaging techniques based on cameras formed by arrays of PMTs.
- First source detection with a confidence above 5 sigma in 1989, by Whipple telescope.



The Crab Nebula:



Established in 1986
Strongest Steady Source
Standard candle

Supernova explotó en 1054

VHE gamma rays by Compton scattering of relativistic electrons

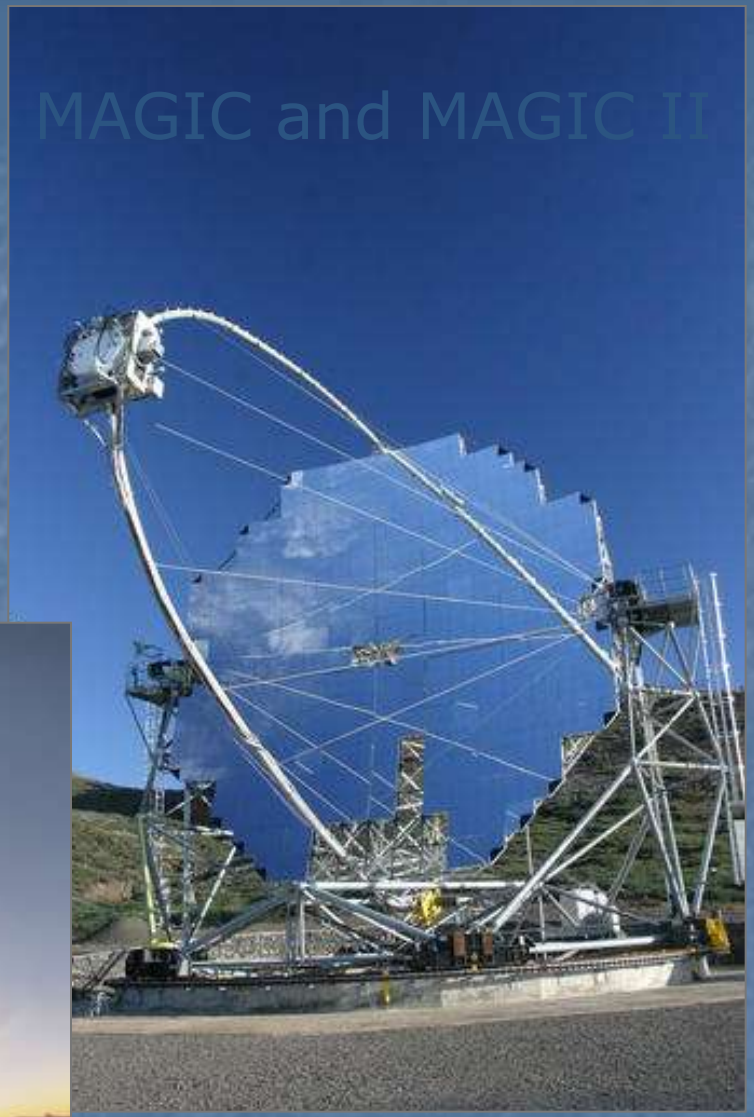
Progress

Detection of TeV gamma rays from the Crab Nebula
Whipple 1989: 50 h observation time

HEGRA 1997 (Canary Islands):
15 min

HESS 2004 (Namibia):
30 sec

New instruments coming online


MAGIC and MAGIC II

VERITAS
(photomontage)

ASTRONOMÍA GAMMA DESDE TIERRA:

Sistemas actuales de telescopios Cherenkov:

2 a 4 telescopios de entre 10 y 17 m de diámetro
Campo visual: 4º
Cámara: 500 – 1000 pixeles
Resolución angular: peor que 0.1º
Rango de energía: 0.1 – 10 TeV

Estos sistemas no producen contaminación alguna para la astronomía

VERITAS (EEUU)

MAGIC (La Palma)

CANGAROO (Australia)

HESS (Namibia)

En este curso estudiaremos:

- cómo partículas materiales pueden ser aceleradas hasta velocidades relativistas ($v \sim c$) en ámbitos astrofísicos,

- qué interacciones pueden sufrir esas partículas,

- qué flujo de radiación gamma resulta de esas interacciones, y

- cómo es posible detectar y medir esa emisión gamma una vez que llega a la vecindad del planeta Tierra.

Nuestro objetivo será presentar las herramientas que nos permitan estudiar y comprender las fuentes cósmicas de rayos gamma

- Review of relativity and particle physics
- Particle acceleration
- Radiative processes I
- Radiative processes II
- Absorption
- Detectors
- Gamma-ray sources

Como la radiación gamma es el resultado de la interacción de partículas relativistas, comenzaremos repasando las propiedades de sistemas que se mueven a velocidades cercanas a la de la luz. Esto es, comenzaremos con un repaso de la Teoría Especial de la Relatividad
y de su concepto central: el espacio-tiempo.