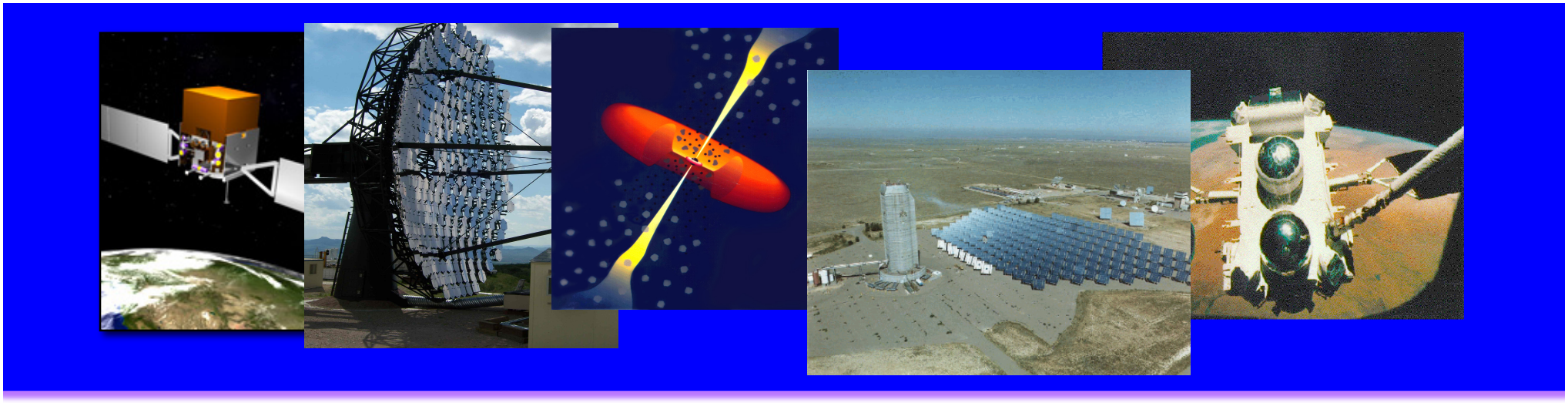

Exploring the Extreme Universe with Gamma-ray Observatories

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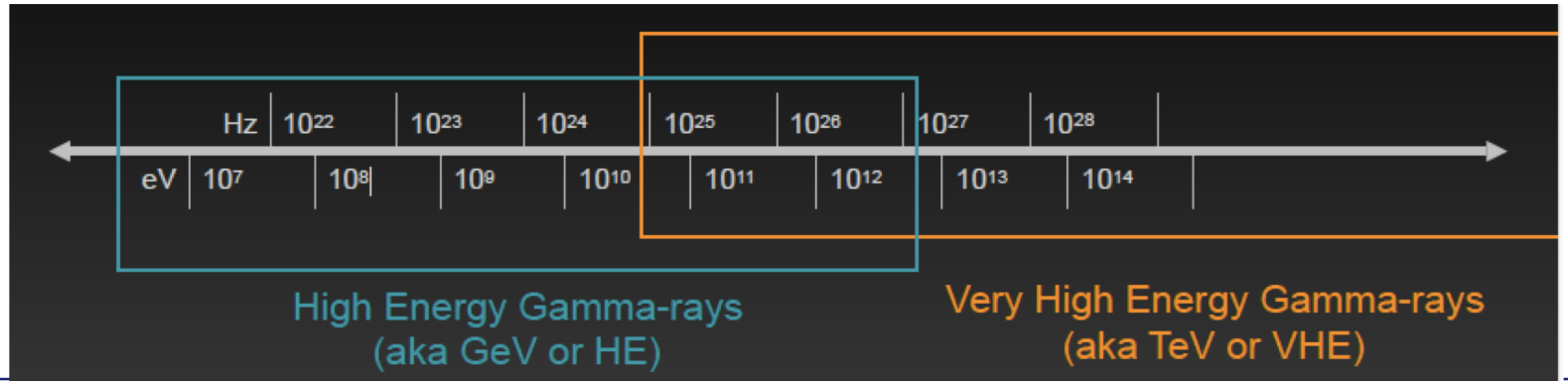
Summer 2020 Colloquium, Series, 16 June 2020

Outline

- Motivation and broad science goals
  - Cosmic ray and astrophysical accelerators
- Techniques in high energy gamma-ray astronomy
  - satellite, ground-based
- Science highlights
  - Open questions in Particle Astrophysics
  - What are the most energetic events in the universe?
- Future – new telescopes



Some Basics & Terminologies …

The electron Volt (eV) unit of energy …….

- Unit of energy: eV (electron Volt) = 1.6×10^{-19} Joules

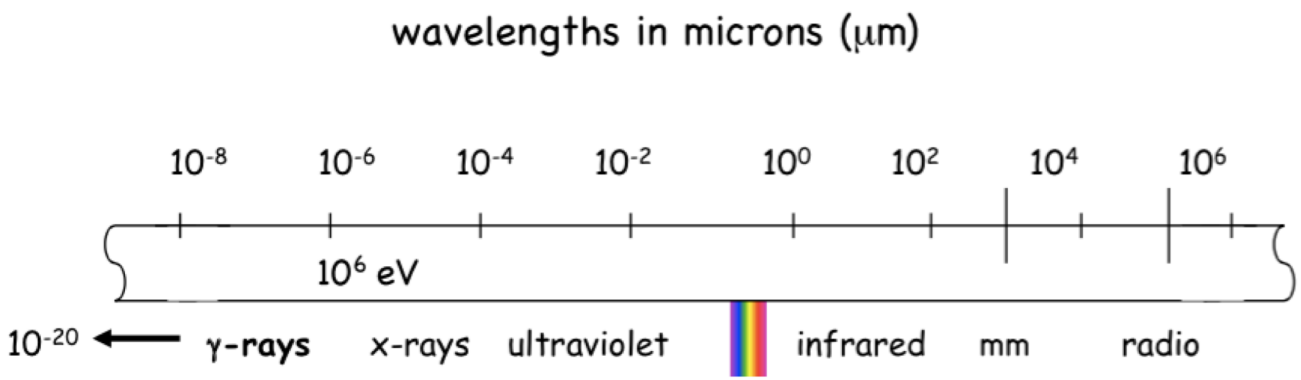
200 MeV: the average energy released in nuclear fission of one U-235 atom

1 TeV: a trillion eV = 1 million MeV

- Photon: "packet" of light (c = speed of light 300,000,000 meters/second)

Why Gamma-Ray Astronomy?

- Provides crucial window in the cosmic E-M spectrum
- Exploration of non-thermal phenomena in the Universe of the most energetic and violent forms
- The "last window" in the cosmic EM spectrum covers 8+ decades



- LE or MeV : 0.1 -100 MeV
- HE or GeV : 0.1 -100 GeV
- VHE or TeV : 0.1 -100 TeV

domain of space-based astronomy

domain of ground-based astronomy

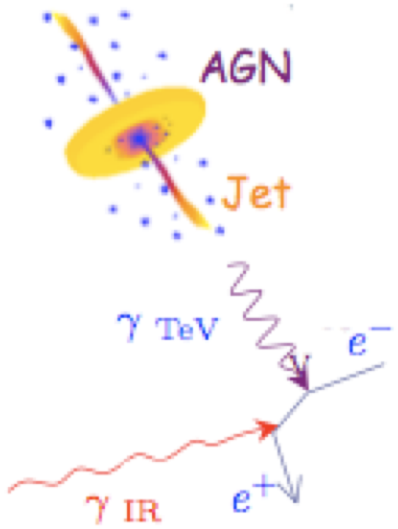
Potential & Uniqueness

- Unique for specific topics
  - e.g. for the solution of the origin of Galactic and Extragalactic Cosmic Rays

- May provide key insight into a number of astrophysics questions
  - physics and astrophysics of relativistic outflows (jets and winds)
  - HE processes at extreme conditions (e.g. close to Black Holes)
  - Physics and astrophysics of Supermassive Black Holes

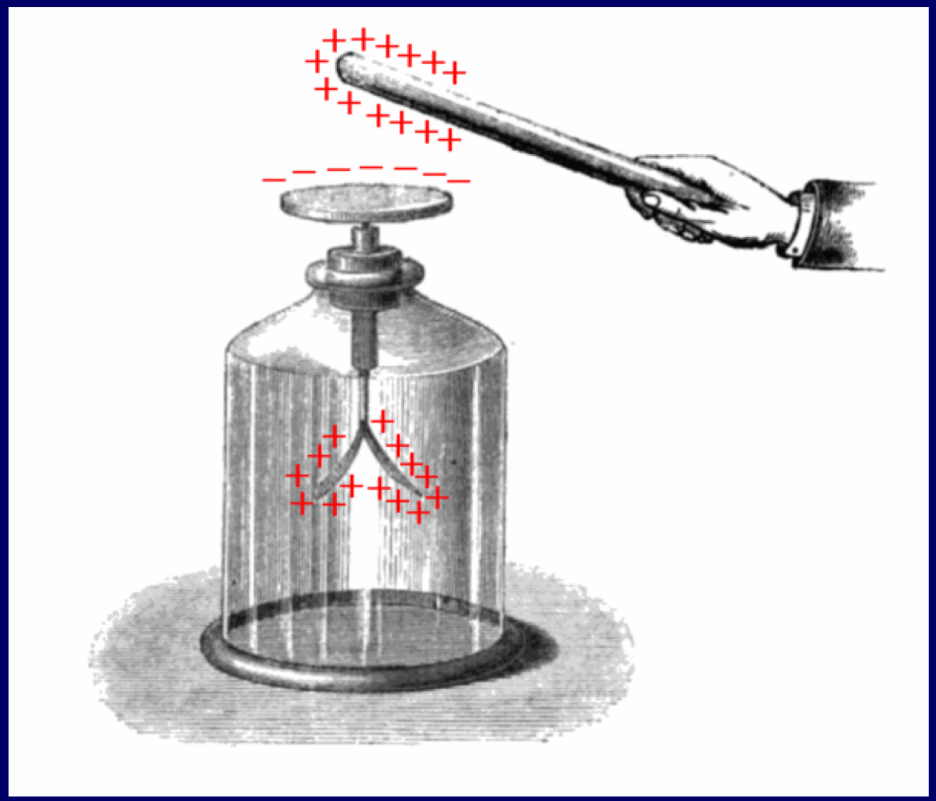
- Using γ rays to probe intergalactic space
  - Diffuse radiation fields.

- Contribution to fundamental physics topics
  - violation of Lorentz invariance
  - search for Dark Matter



Cosmic Rays

- More than 200 years ago, in 1785 Charles de Coulomb in France showed that charged metallic bodies lose charge when placed in air .



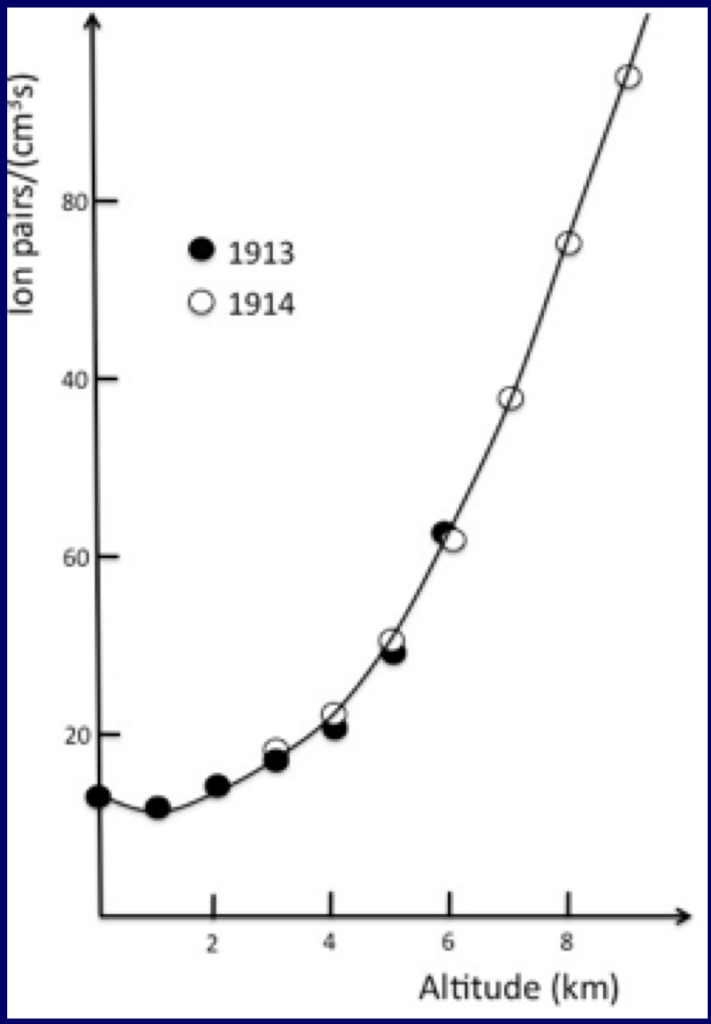
Gold-leaf electroscope, *Elementary Lessons in Electricity & Magnetism*, Thompson (1881)

Portrait of Coulomb by Hippolyte Lecomte (1781)

Origin of Cosmic Rays remains a mystery

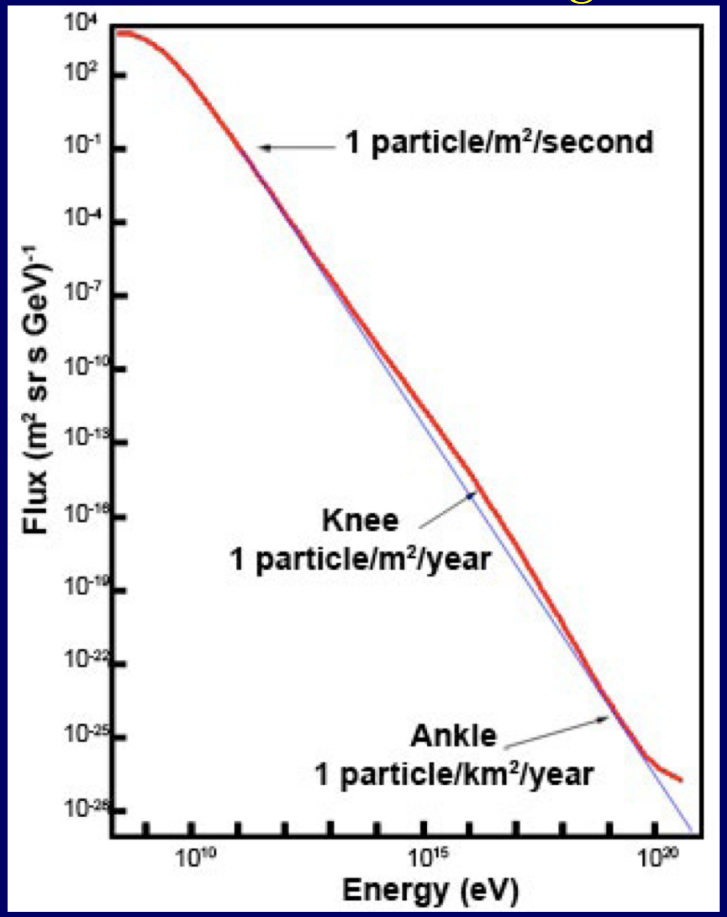
- Cosmic rays, first discovered by Victor Hess on a 17,000 ft balloon flight in 1912, while investigating the source of background radiation.

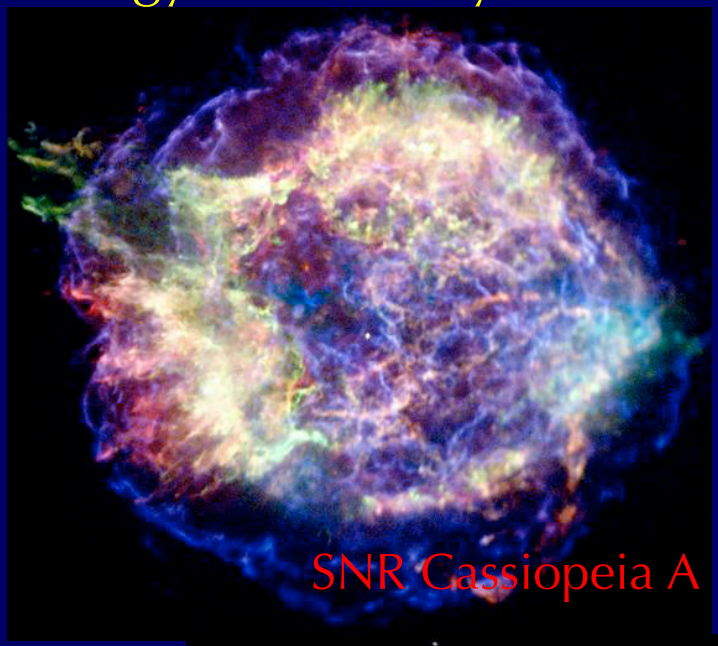

NY Times



Cosmic Ray Energy Spectrum

What is the origin of the highest energy cosmic rays?





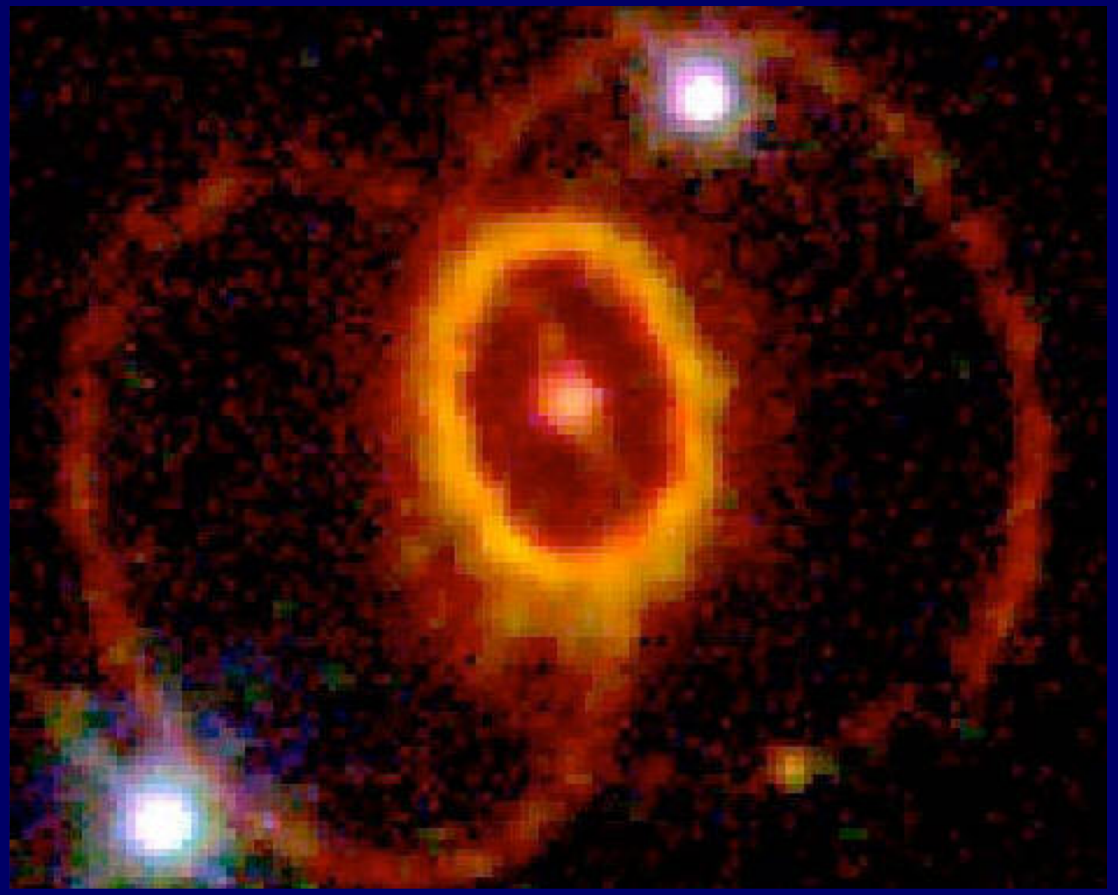
- The magnetic field in our galaxy is approximately 3G, radius ~ 15 kpc
- Protons with $E < 10^{18}$ eV are trapped in our galaxy by the magnetic field

How do you get 10^{20} eV energy?

Particle acceleration in the cosmos…

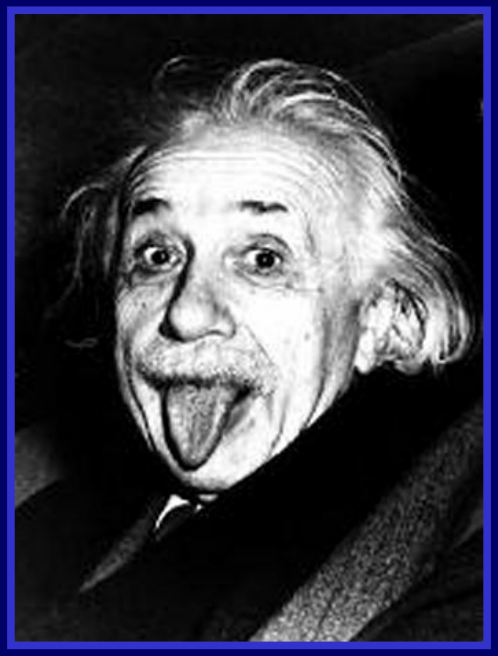
Explosions in Space

- Energy is created from mass when stars explode
- Supernovae herald the deaths of stars
- Gamma-ray Bursts signal the deaths of even more massive stars
- Active galaxies



Mass & Energy

$$E = mc^2$$



Mass and energy

- Einstein's most famous equation
- Einstein realized that mass and energy were equivalent and interchangeable
- This interchange is commonly observed in high-energy astronomy

Creating Energy from Mass

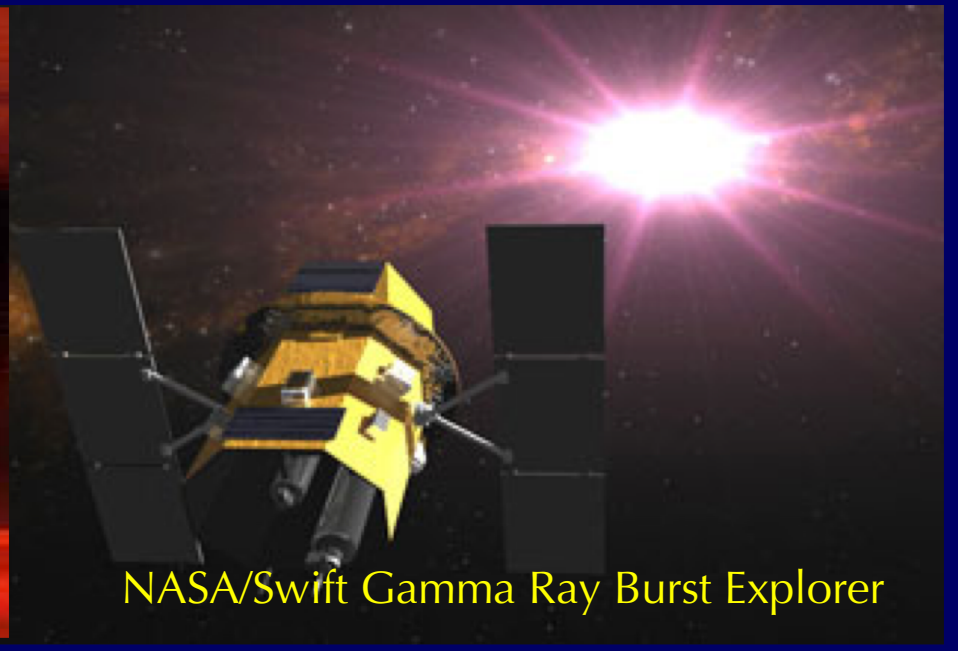
- When two oppositely charged particles meet in flight, they can annihilate to create two gamma-ray photons traveling in opposite directions

- The rest mass of an electron or its anti-particle, the positron, is 511 keV/c^2
- Annihilating of particles creates energy of E= 1.012 MeV

Gamma Ray Burst

$$E = mc^2$$

U.S. Department of Energy-Nevada/Corbis

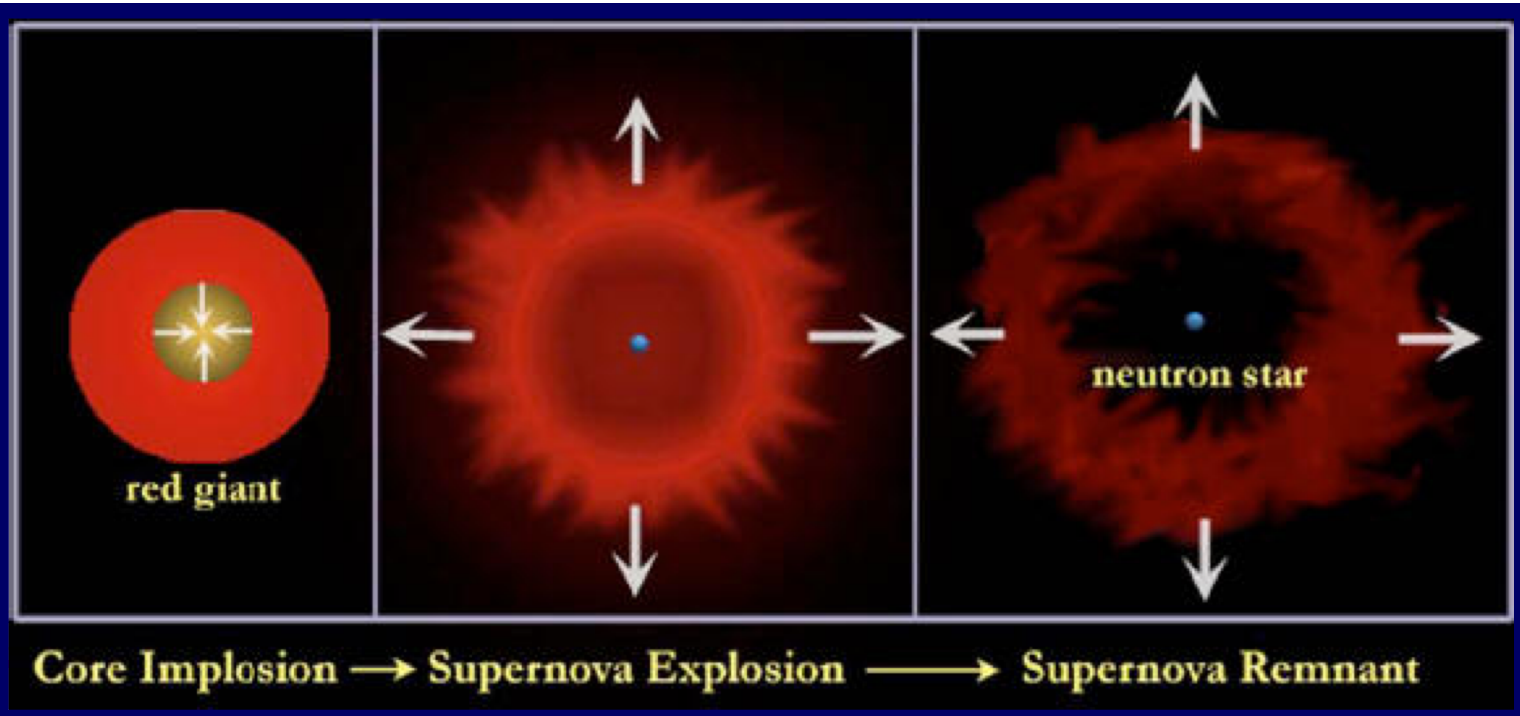


NASA/Swift Gamma Ray Burst Explorer

1 raisin * c^2 = nuclear explosion energy

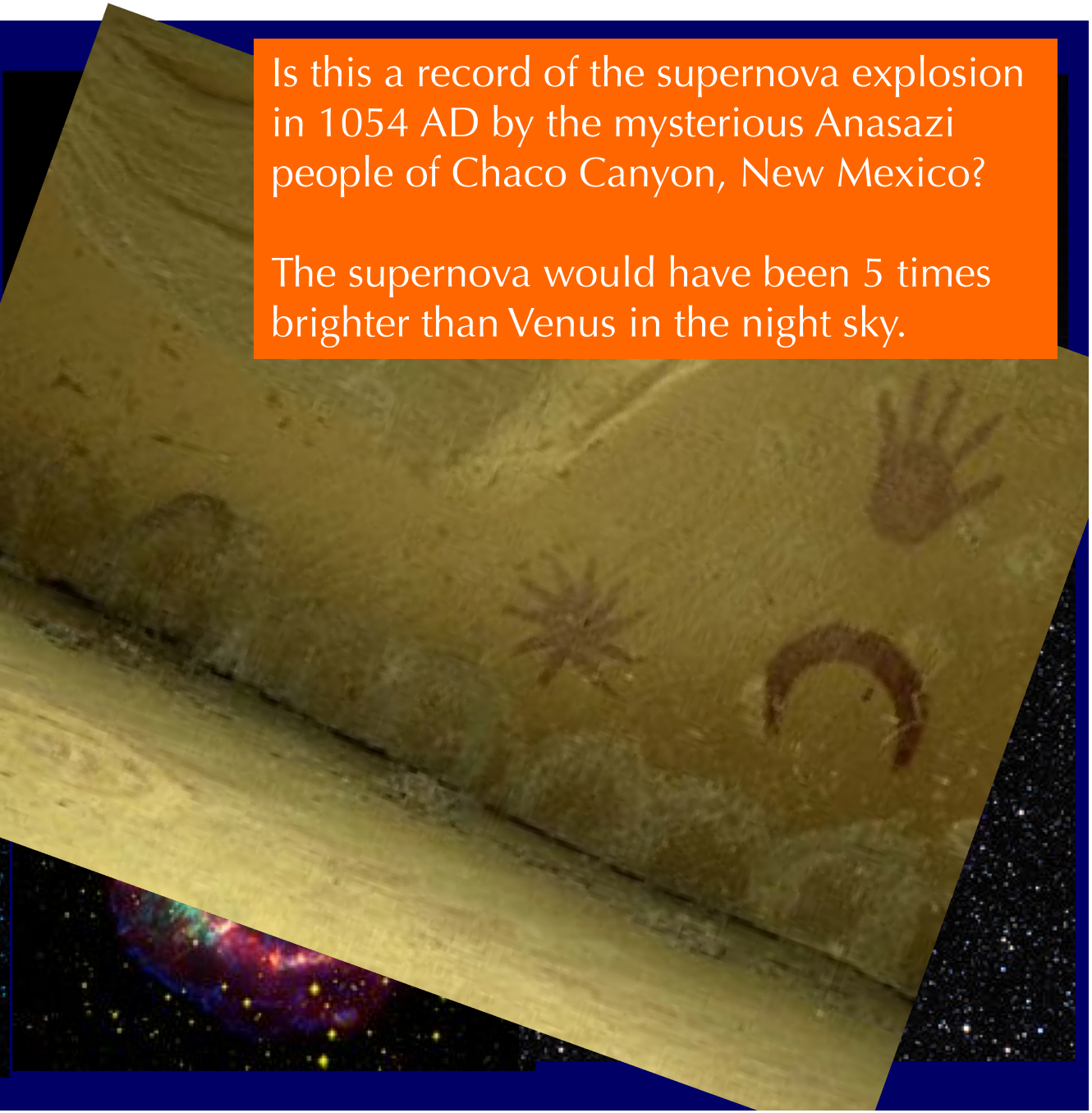
400,000 Earths * c^2 = GRB Energy

Particle Acceleration



- Shock fronts and magnetic fields can accelerate protons to CR energies over time
- Particle's perspective: crossing the shock => head-on collision with magnetic domains

Supernova Explosion

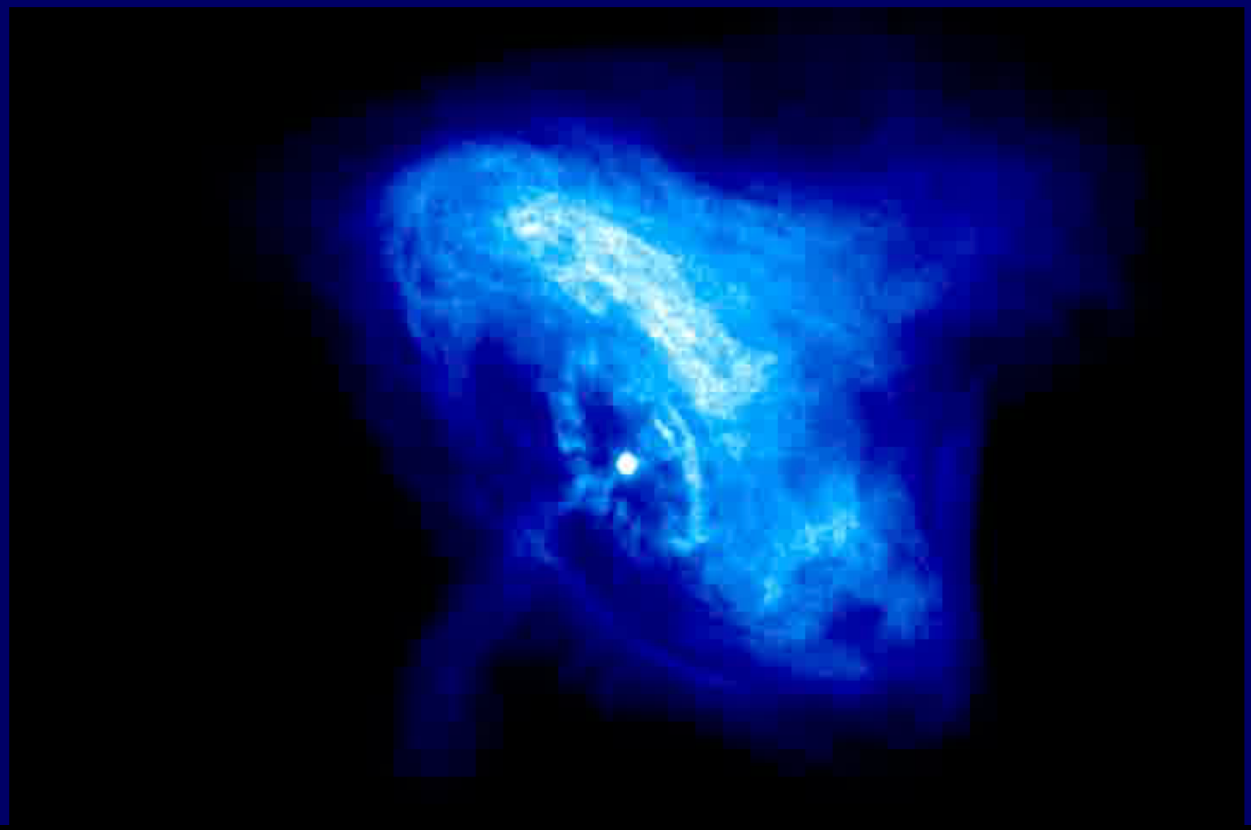


Is this a record of the supernova explosion in 1054 AD by the mysterious Anasazi people of Chaco Canyon, New Mexico?

The supernova would have been 5 times brighter than Venus in the night sky.

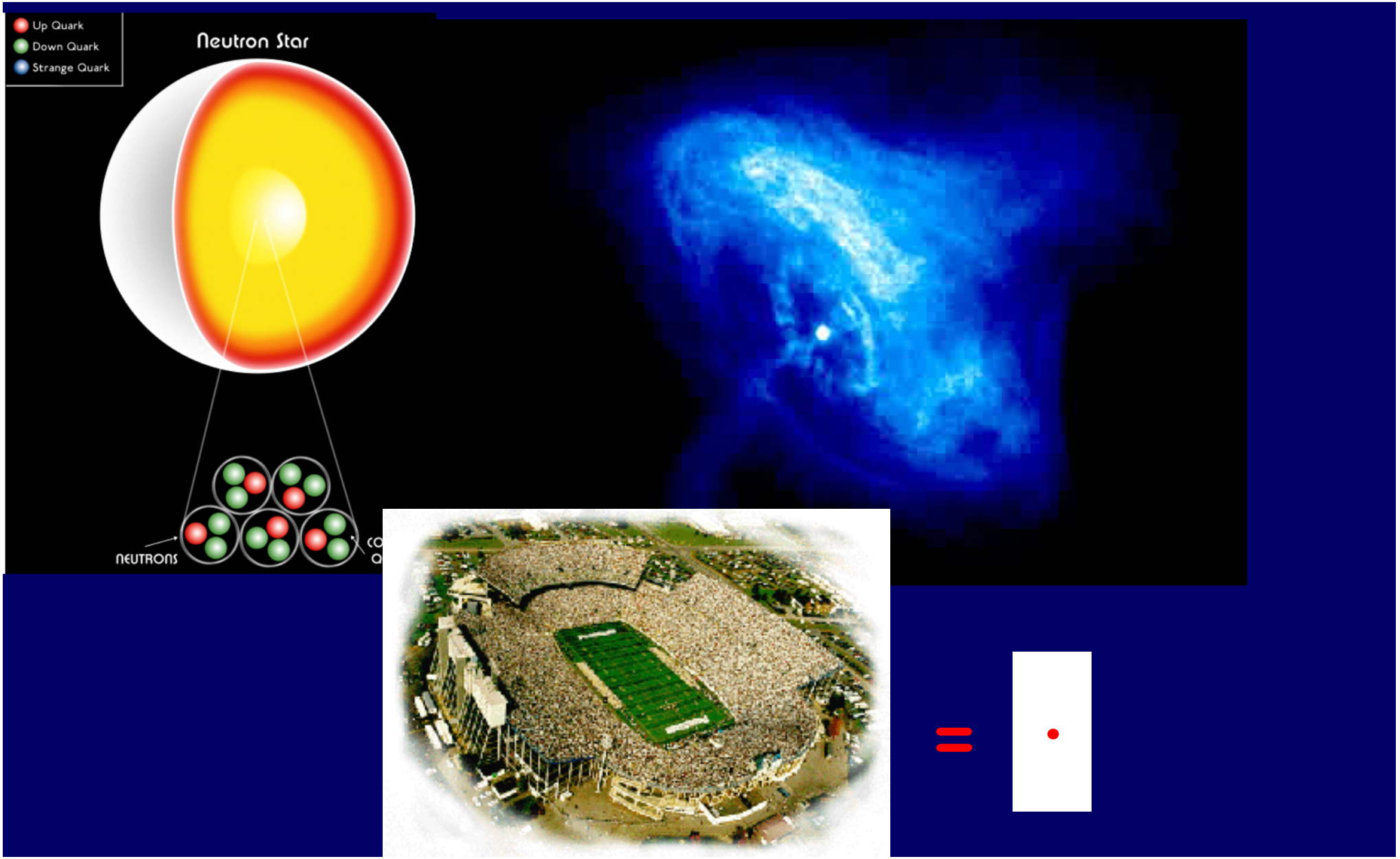
The Crab Pulsar – a rapidly rotating Neutron Star

A rapidly rotating neutron star (30 times per sec).

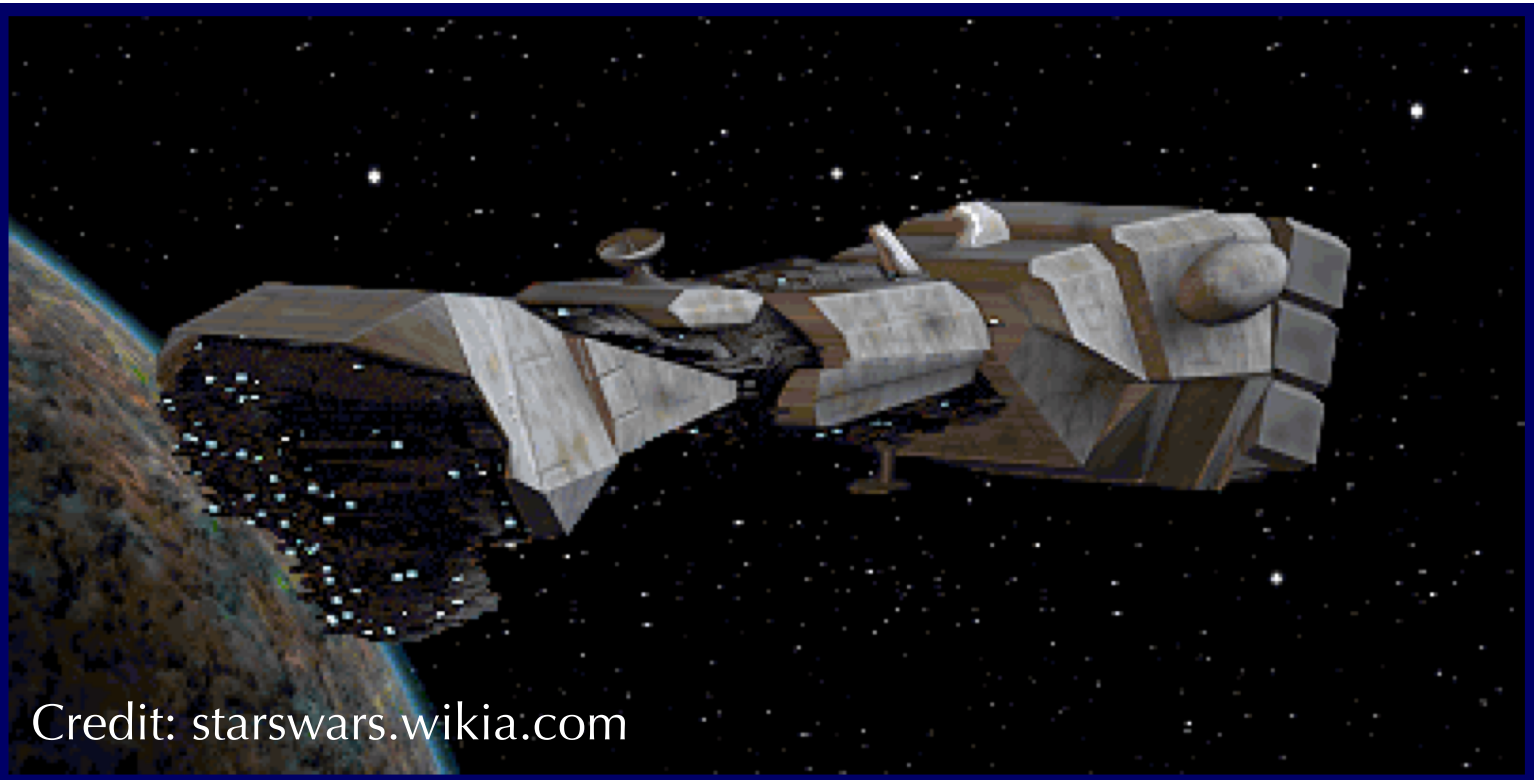


Electric potential differences of quadrillions of volts. Such voltages, which are 30 million times greater than those of lightning bolts, create deadly blizzards of high-energy particles.

Neutron Star ??

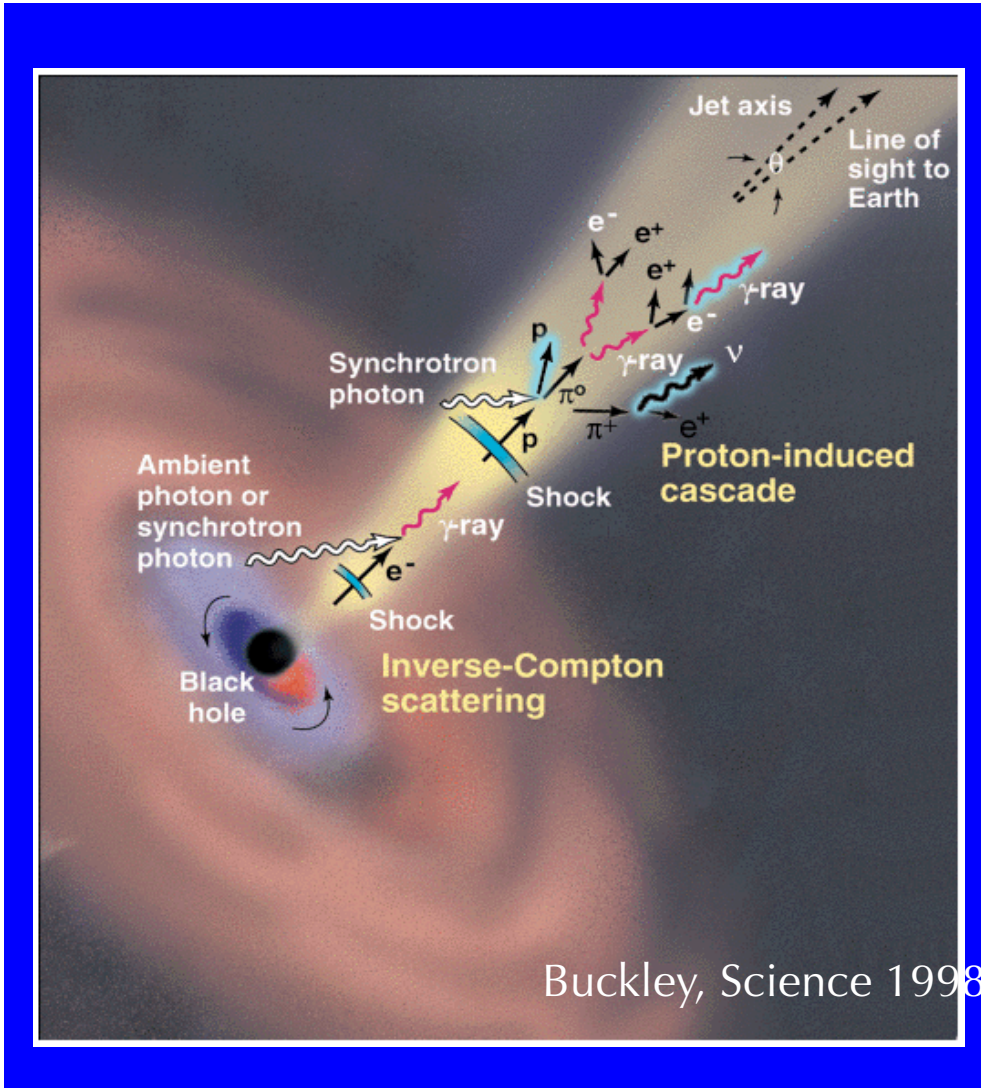


Neutron Star Power



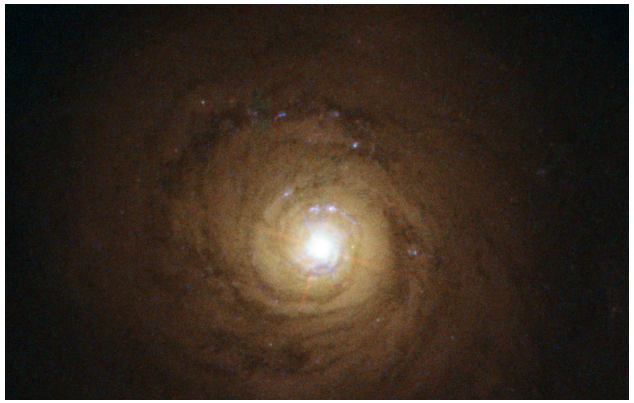
The Neutron Star-class bulk cruiser was a class of capital ship used by the Galactic Empire and Rebel Alliance. They were designed during the Clone Wars to serve as second-line ships.

Physics of Compact Objects: AGN



AGN scales

- Active galactic nuclei occupy a tiny fraction of a galaxy.
- $R_G \sim 10^4$ pc
- $R_{tor} \sim 1$ pc
- $R_{BH} \sim 10^{-5}$ pc

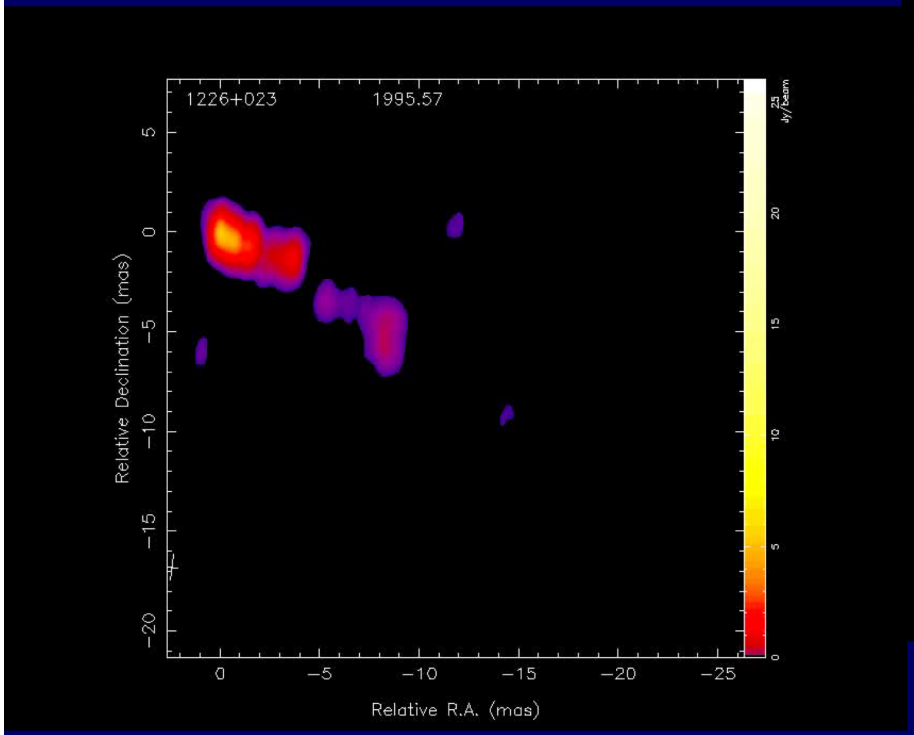


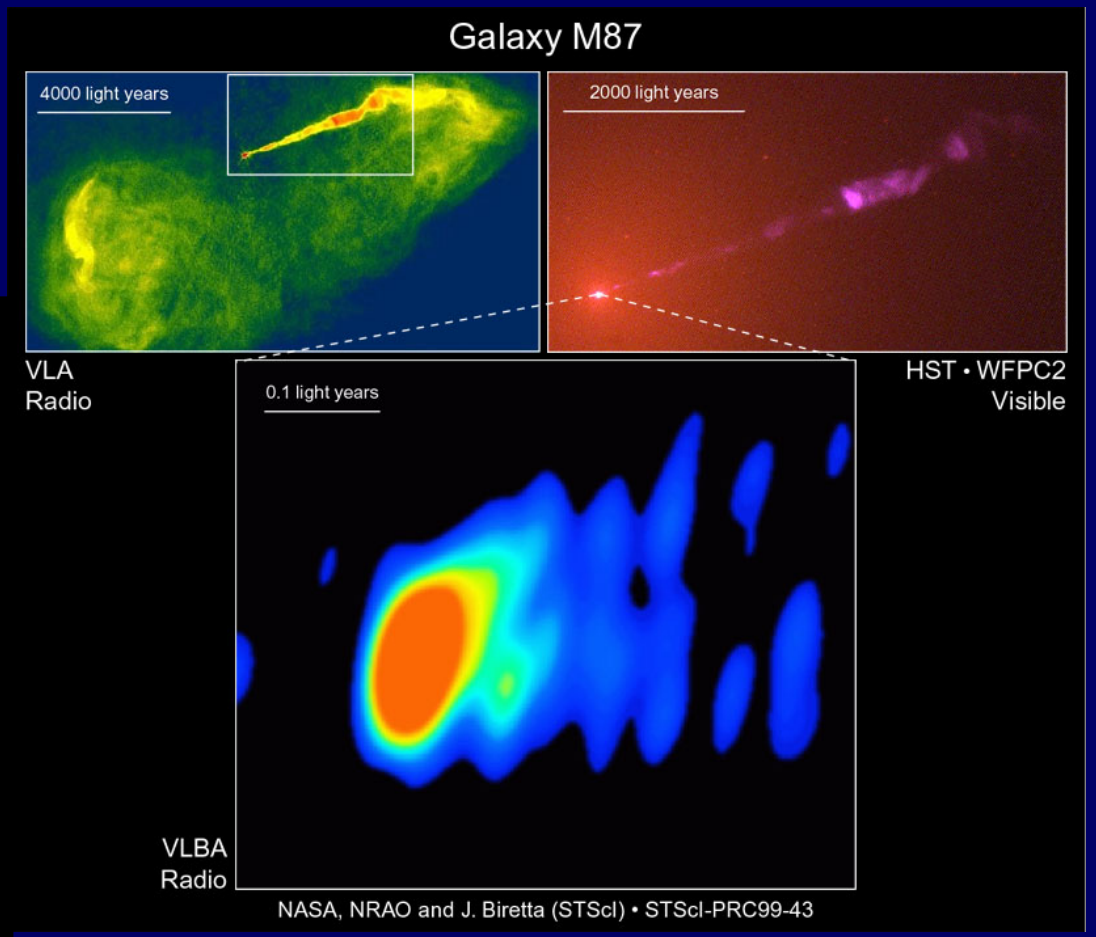
Hubble image of NGC 5548

Extragalactic Sources of Energy

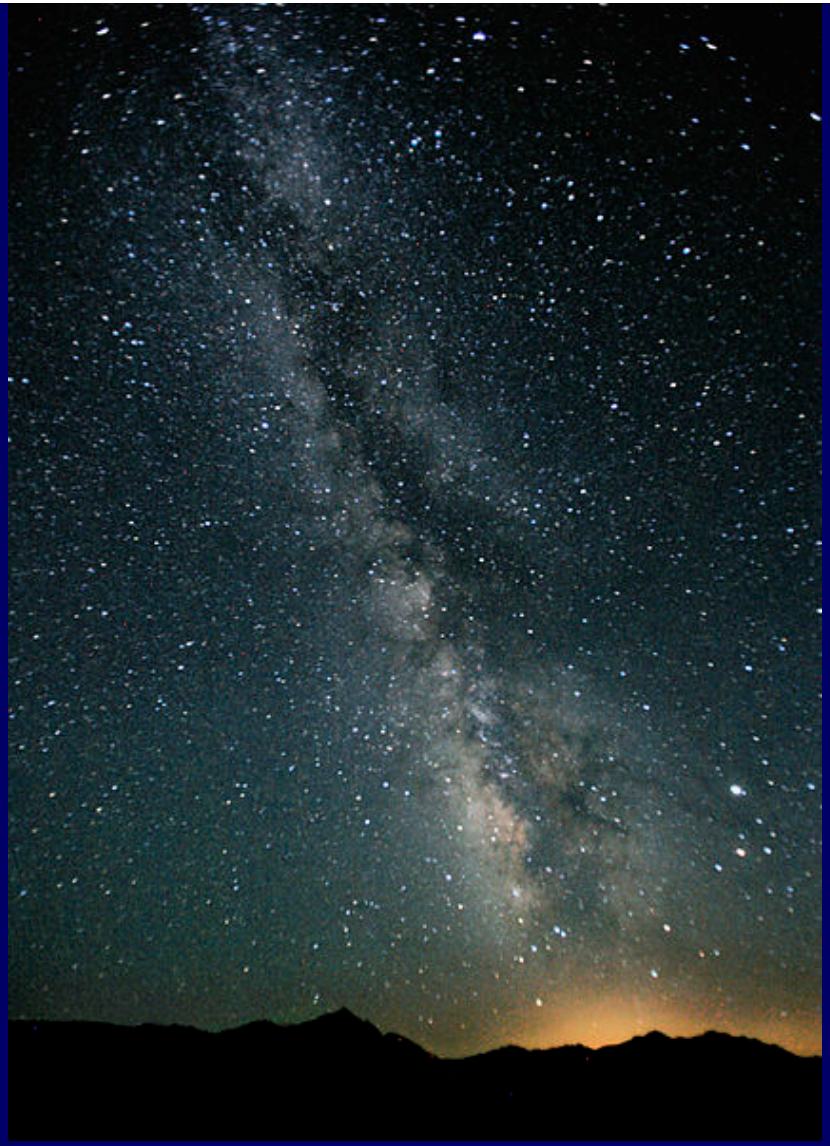
Extragalactic Relativistic Jets in Active Galaxies

- Key quesions: acceleration, collimation and stability/propagation of observed jets.





As opposed to "normal" galaxies …

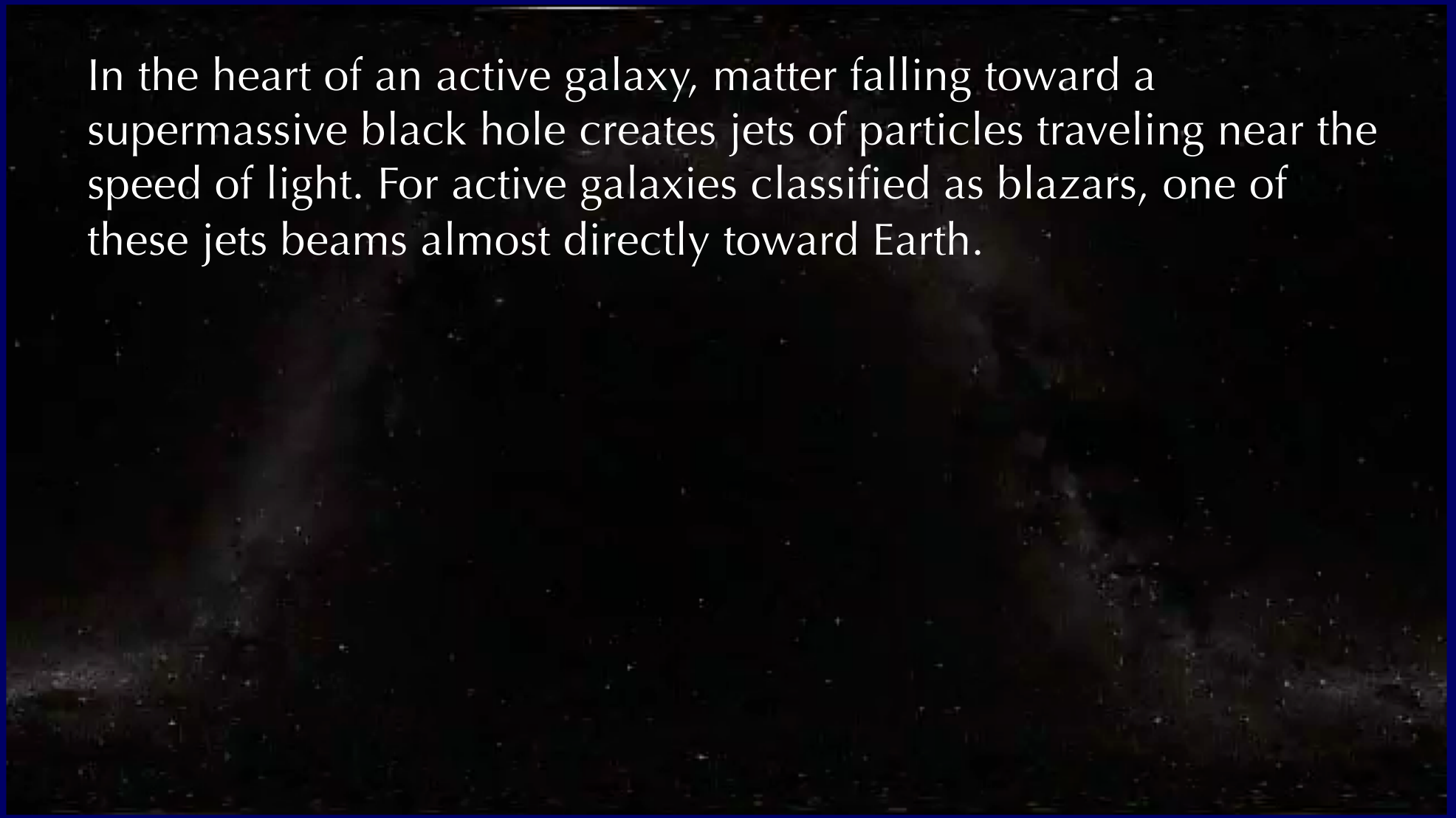


- The Milky Way galaxy is a barred spiral galaxy 100,000–120,000 light-years in diameter containing 200–400 billion stars.

- An active galaxy ~ thousands of Milky Way galaxies.

A view of the Milky Way towards the Constellation Sagittarius (including the Galactic Center) as seen from a non-light polluted area (the Black Rock Desert, Nevada).

Active Galaxies are Powered by Super-Massive Black Holes

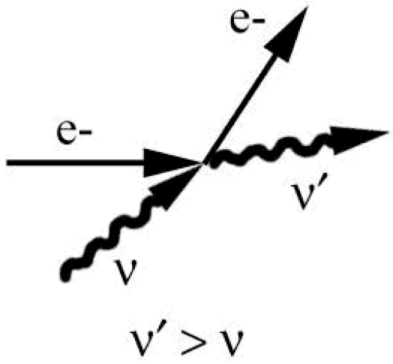


Gamma-Ray Production

In astrophysics, non-thermal processes lead to power-law spectra (Longair 1992)

- electrons
  - synchrotron radiation (X-rays)

  - inverse Compton scattering

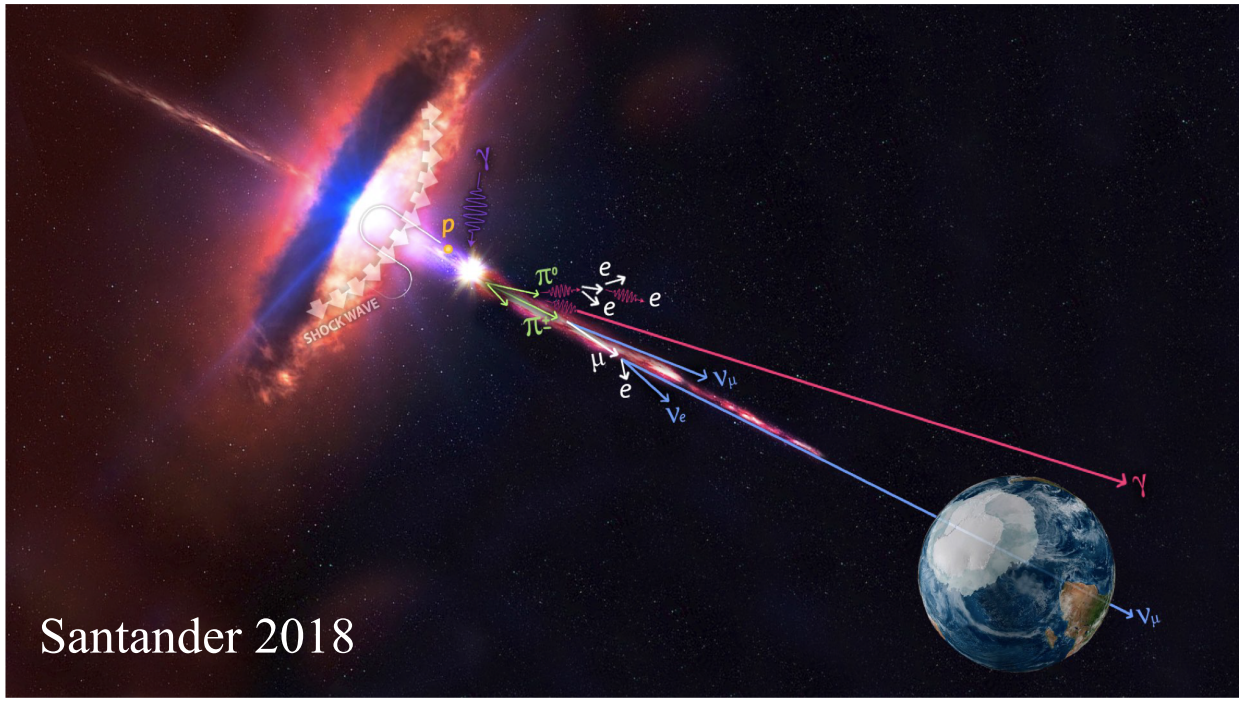


- protons
  - collide with ambient gas (beam dumps)
  - π^0 --> $\gamma\gamma$

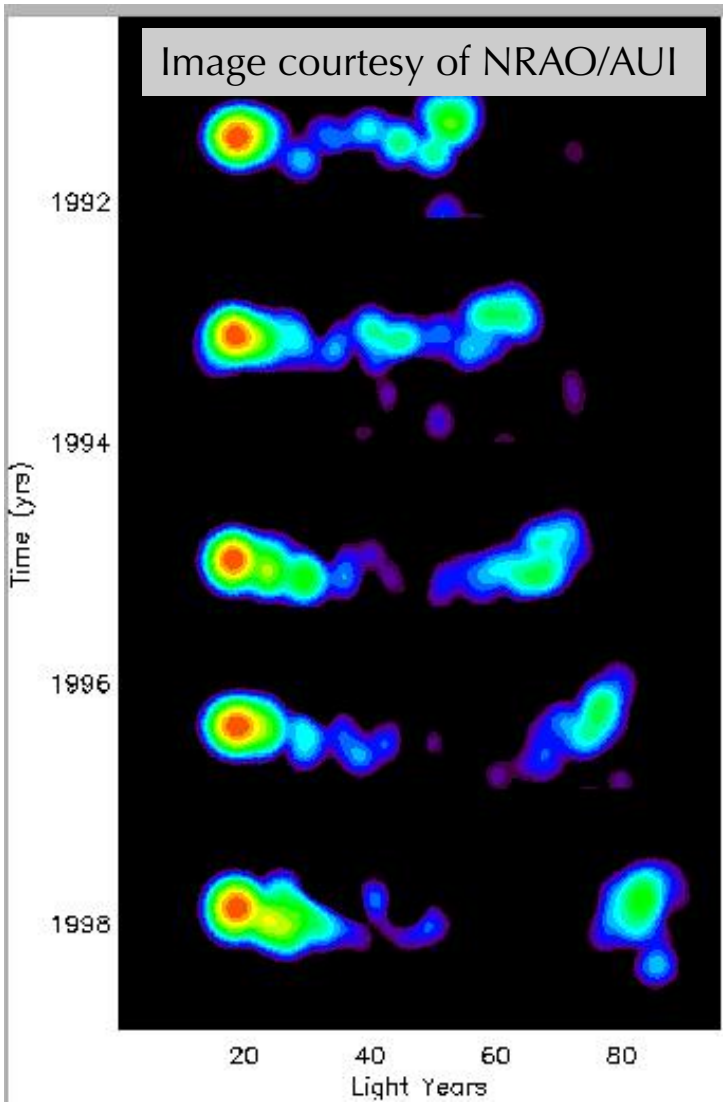
$$p + p \rightarrow \pi^{\pm,0} \rightarrow \nu, e^{\pm}, \gamma$$
$$p+\gamma \rightarrow p+\pi^0, \quad \pi^0 \rightarrow 2\gamma,$$
$$p+\gamma \rightarrow n+\pi^+, \quad \pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu$$
$$\rightarrow e^{\pm} + 2\nu_\mu + \nu_e.$$

Origin of Cosmic Rays?

- **Cosmic rays:**
  - *Origin of CRs cannot be addressed by observations of charged CRs*
  - In order to identify CR accelerators, need to observe neutral stable messengers: **γ rays and neutrinos**

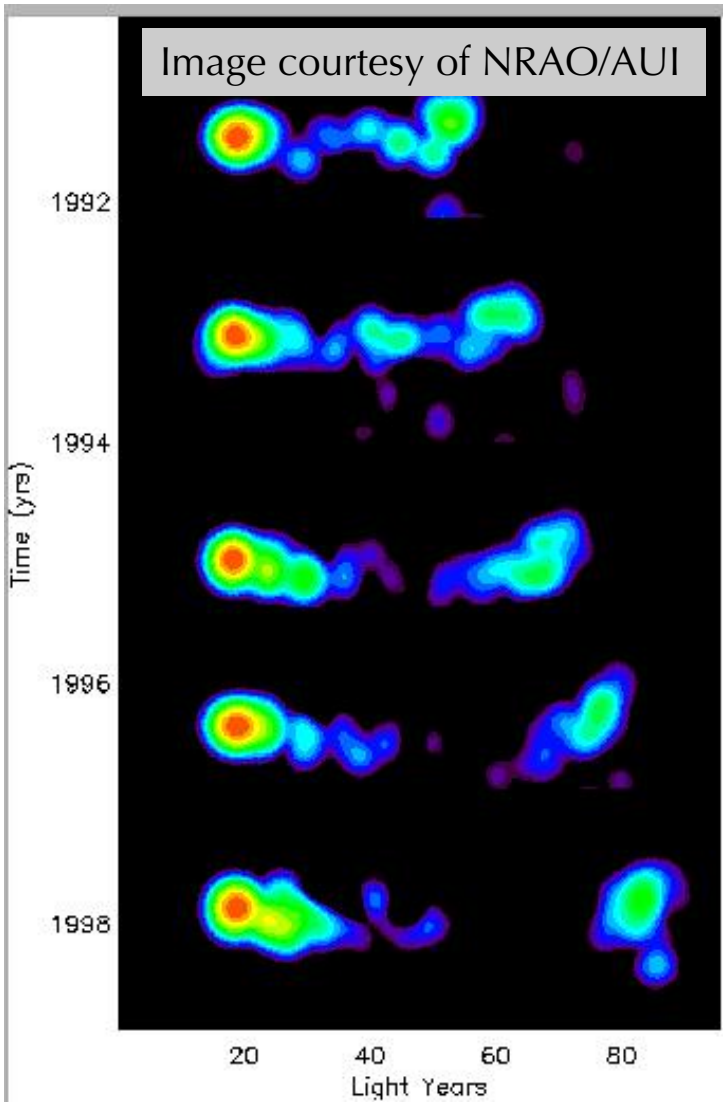


Superluminal Motion Blazar



- Relativistic jet in 3C 279 at 22 GHz.
- 1991 – 1997 (18 epochs)
- Bright, compact VLBI core and jet components.
- Apparent speeds: 4.8 to 7.5 times the speed of light!

Blazar Characteristics



Doppler boosting: Relate observed (*) and intrinsic physical quantities (e.g. Rybicki & Lightman, 1979)

$$L^*_{\rm app} = \delta^n L,\ 3 \leq n \leq 4$$

$$\delta = [\Gamma(1 - \beta \cos\theta^*]^{-1}$$

$$\beta = V_{\rm jet}/c$$

$$\Gamma = (1 - \beta^2)^{-1/2}$$

For blazars, $\theta \sim 1/\Gamma$, $\delta \sim 1/2\Gamma$

About the VLBI ....

Incidentally ...

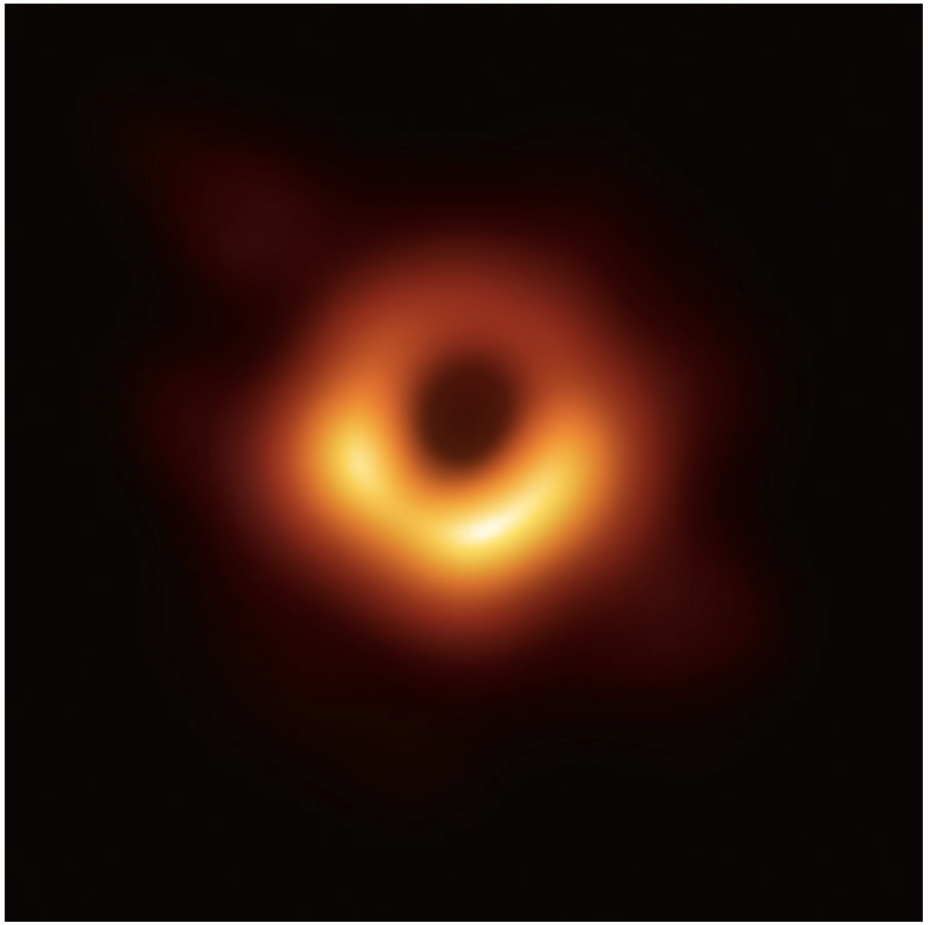
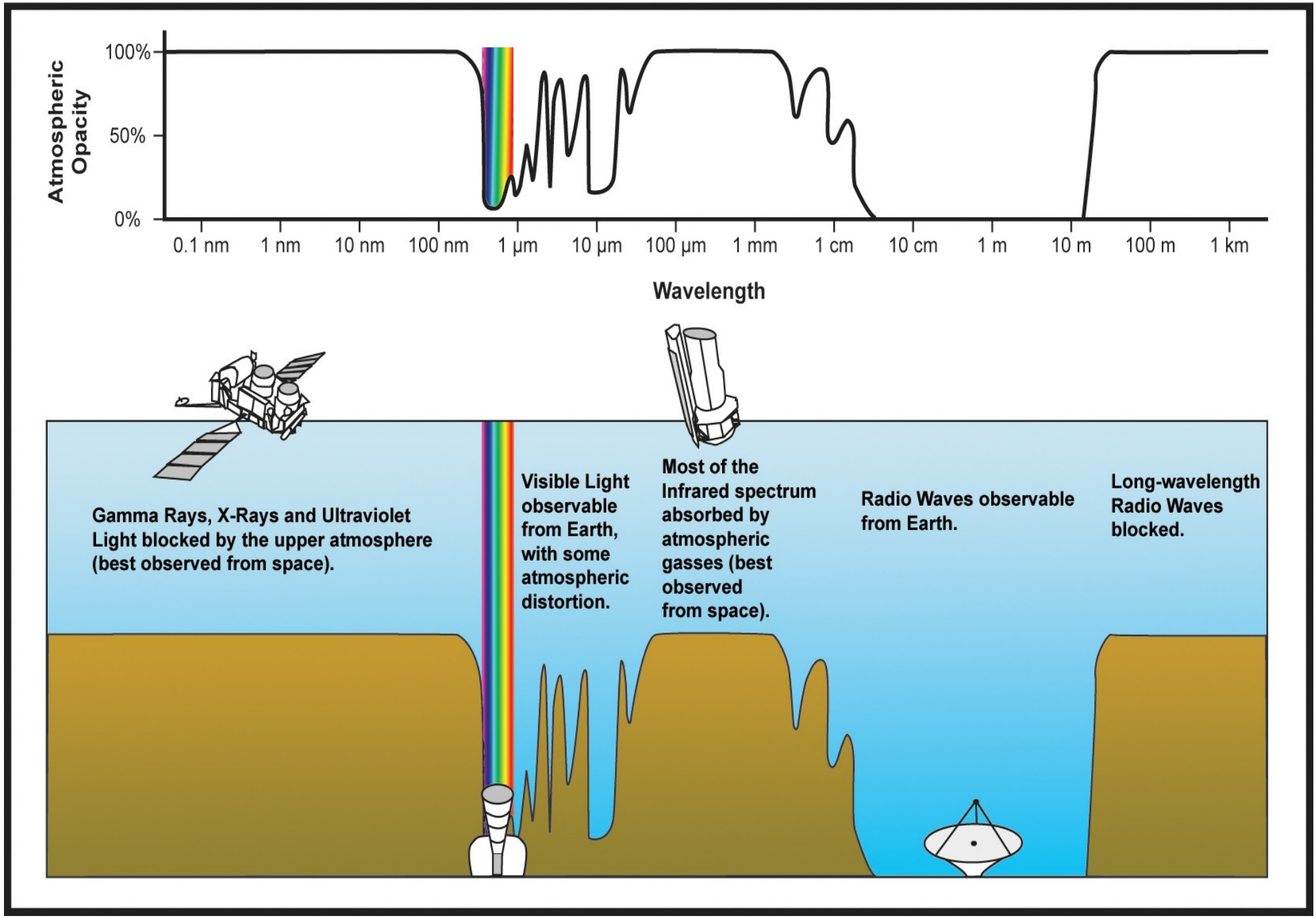


Image courtesy of NRAO/AUI

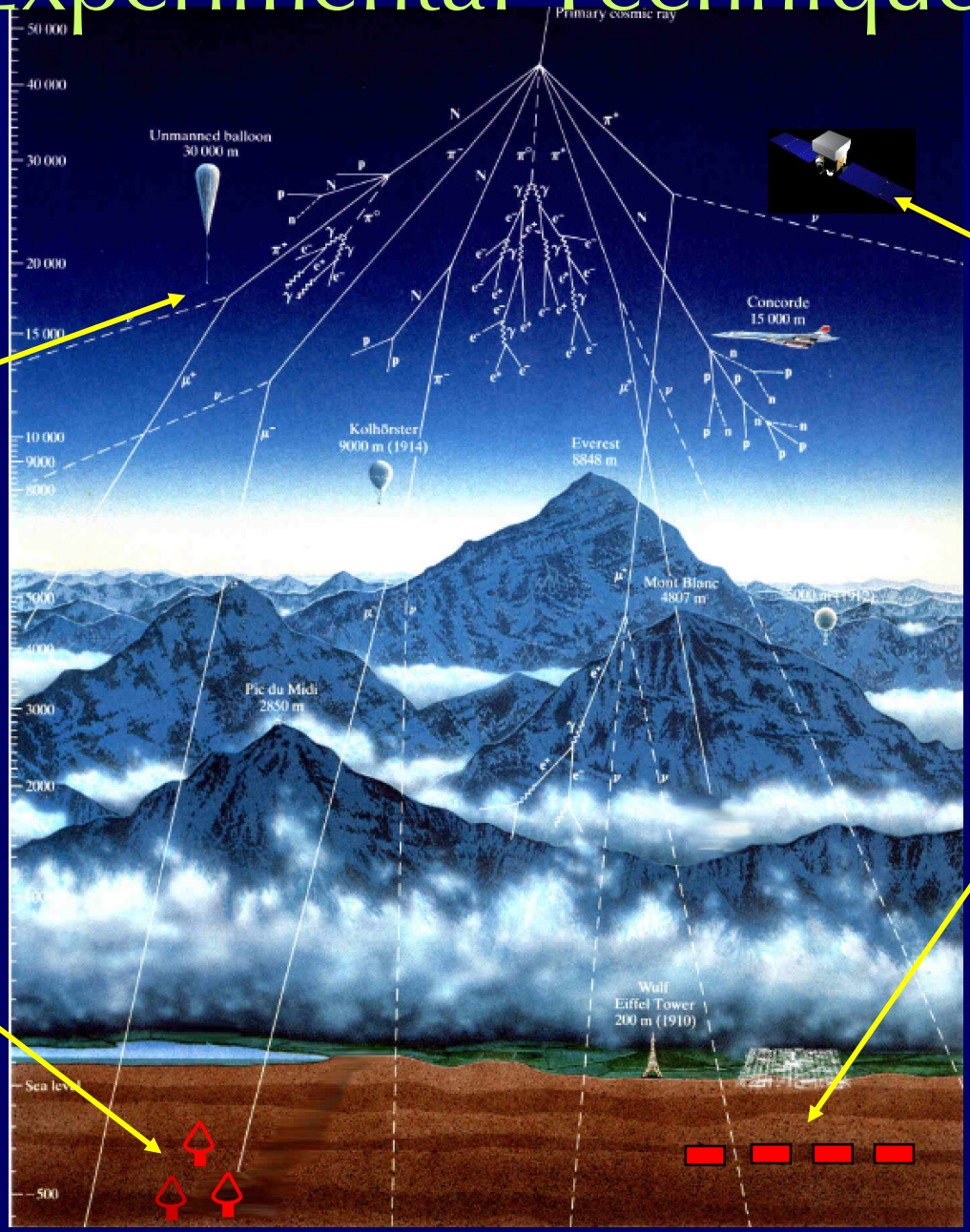
VLBI was used to create the first image of a black hole, imaged by the Event Horizon Telescope and published in April 2019.

Image of Messier 87:
First direct visual evidence of the supermassive black hole in the center of Messier 87 and its shadow.

The instruments at VHE energies


Atmospheric Opacity
100%
50%
0%
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength
Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).
Visible Light observable from Earth, with some atmospheric distortion.
Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).
Radio Waves observable from Earth.
Long-wavelength Radio Waves blocked.

Experimental Techniques



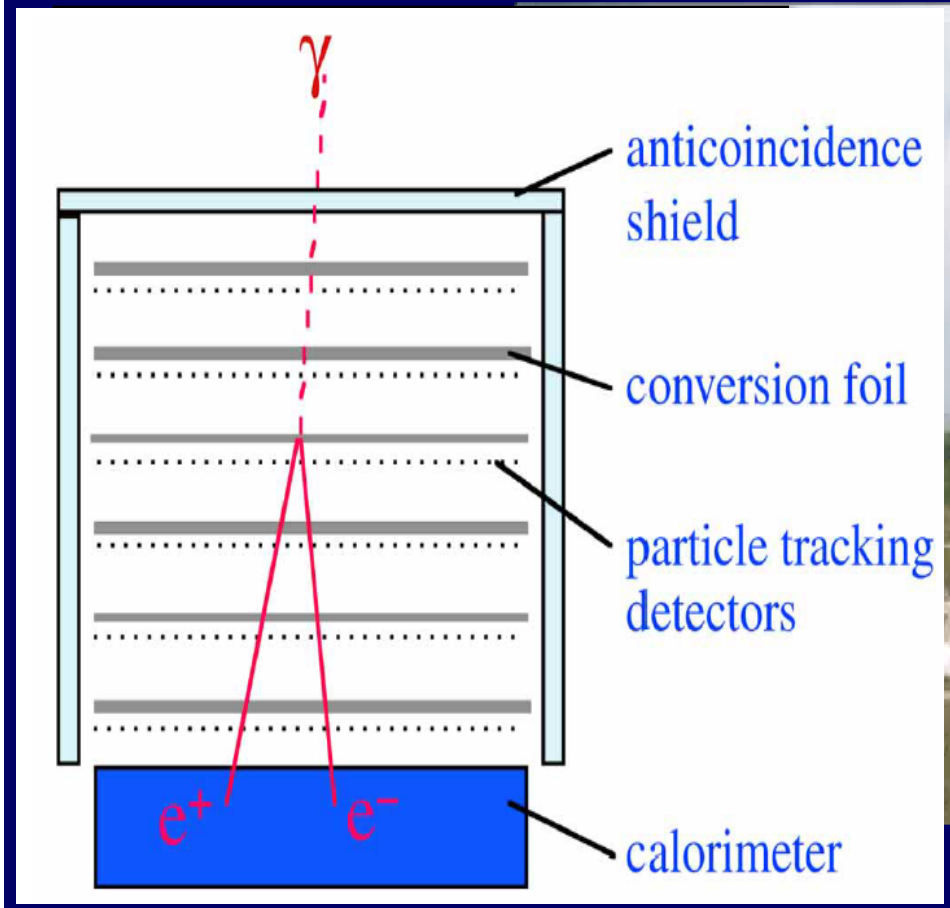
Balloon

Satellite
(Fermi/GLAST)

Cherenkov
Telescopes
(VERITAS)

Air shower array
(Milagro)

NASA's Fermi Gamma Ray Space Telescope



Launch vehicle: Delta II Heavy, June 2008

$>100 M US

To explore the ultimate limits of gravity and energy in the Universe ranging from the closest stars to the most distant quasars.