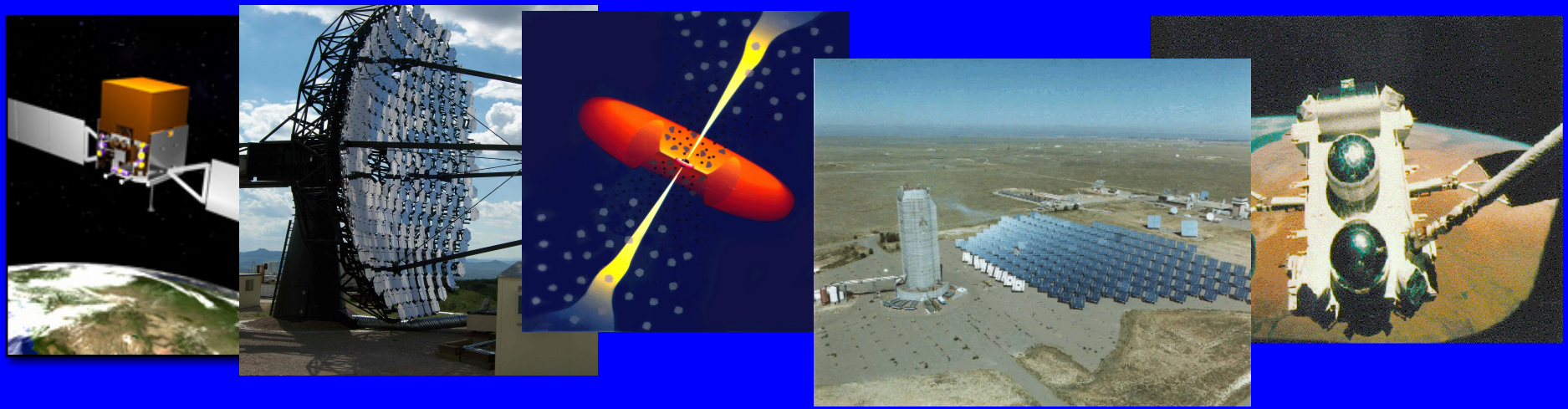


Astroparticle Physics: Cosmic Mysteries
&
Introduction to the Barnard Summer Colloquium Series

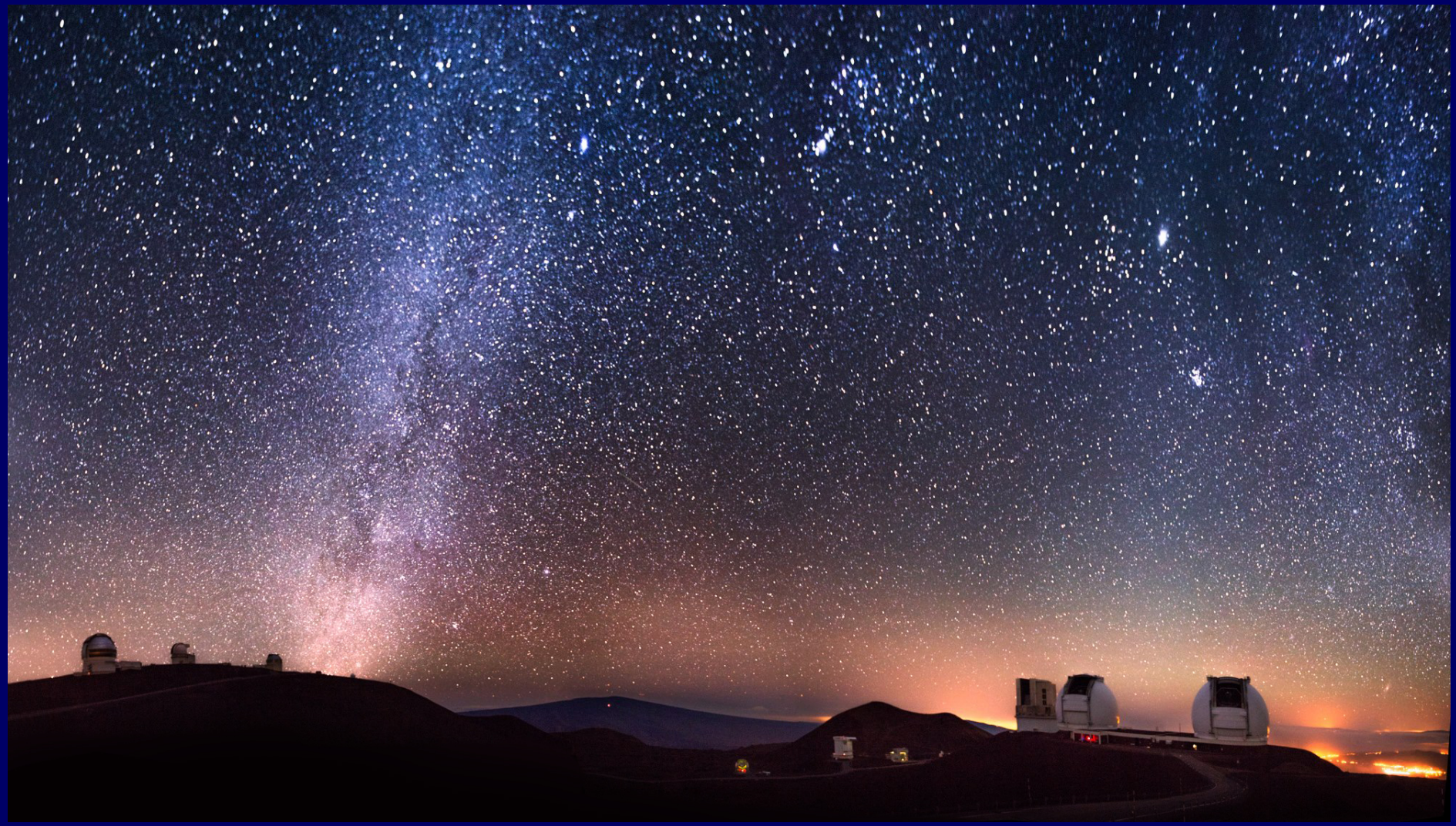
Reshmi Mukherjee[1]
[1]Barnard College, Columbia University, NY

Outline

- Motivation and broad science goals
  - Cosmic ray and astrophysical accelerators
- Techniques in high energy gamma-ray astronomy
  - Satellites, Earth-based
- Open questions in Particle Astrophysics
  - What are the most energetic events in the universe?
  - How do super-massive black holes launch relativistic jets?
  - Do jets in active galaxies accelerate ultra high energy cosmic rays?
  - What are the origins of very high energy neutrinos detected in the cosmos?
  - Is the speed of light really constant?
- Future – new telescopes

The Keck Telescopes (1996)

The Keck Telescopes

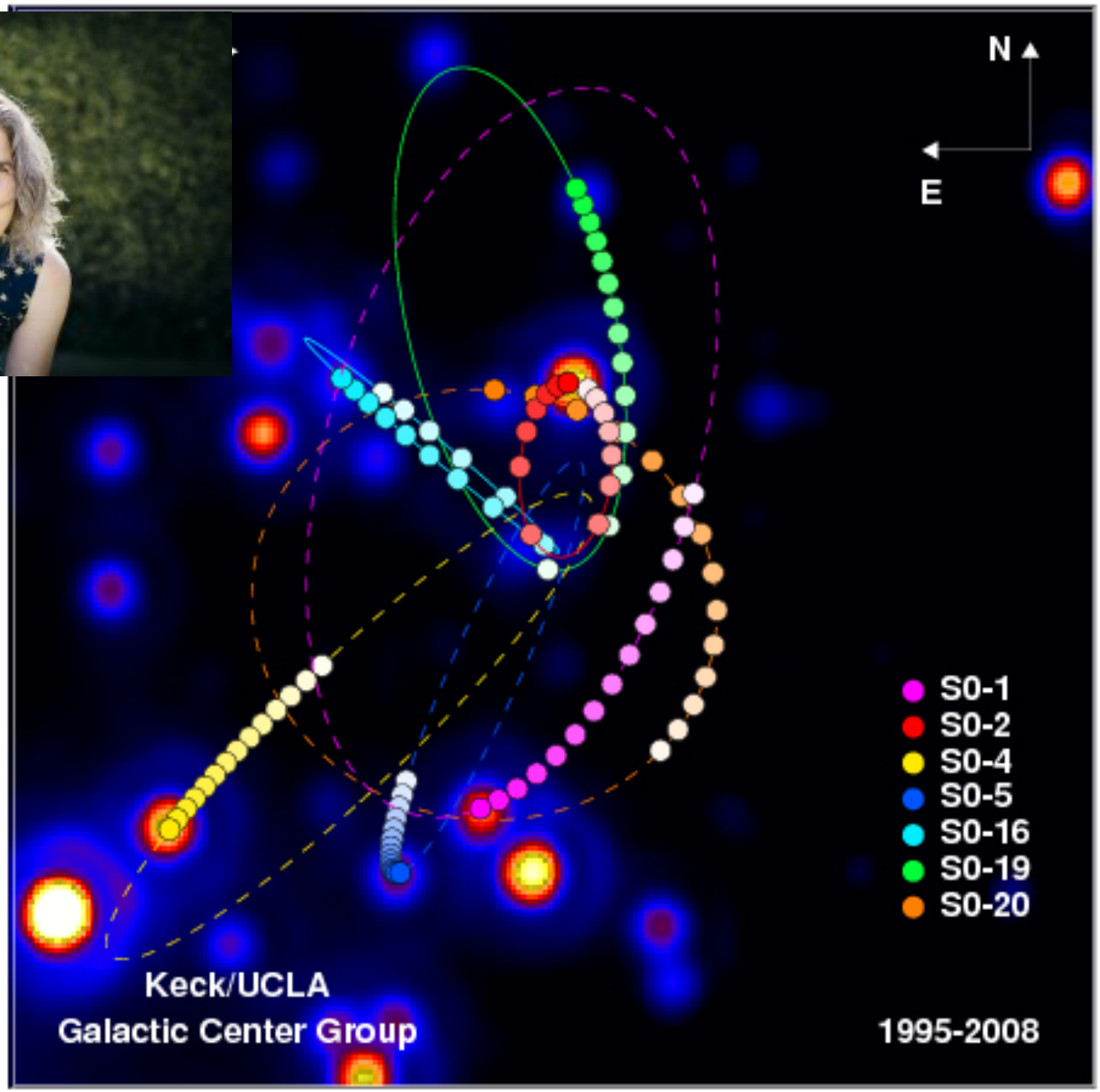


Maunakea Hawaii

Reshmi Mukherjee

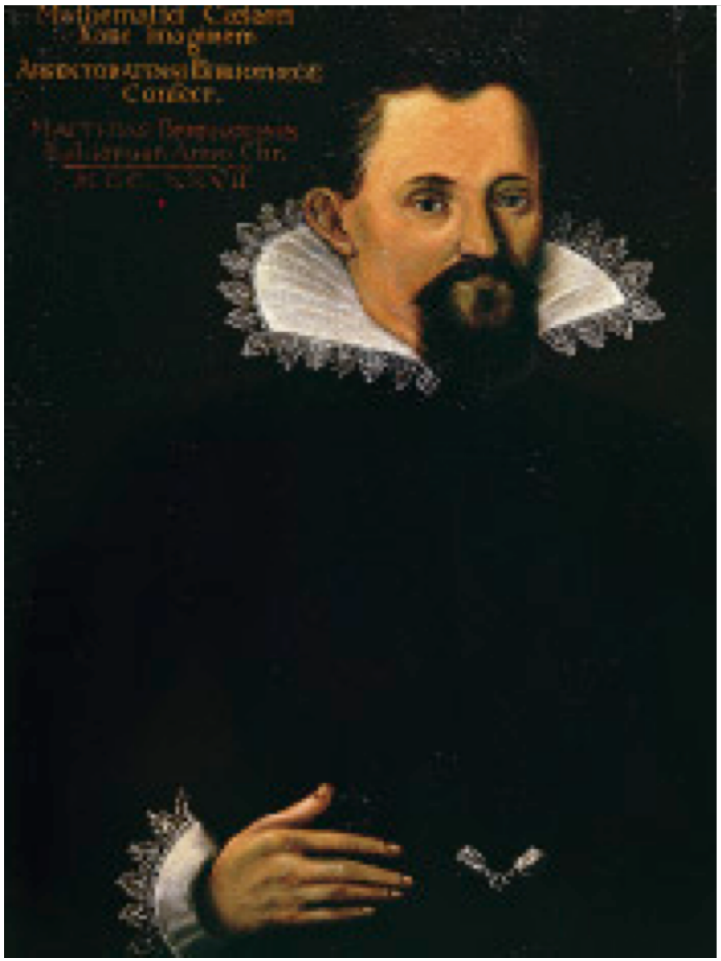
Stellar Orbits in the Central Arcsec

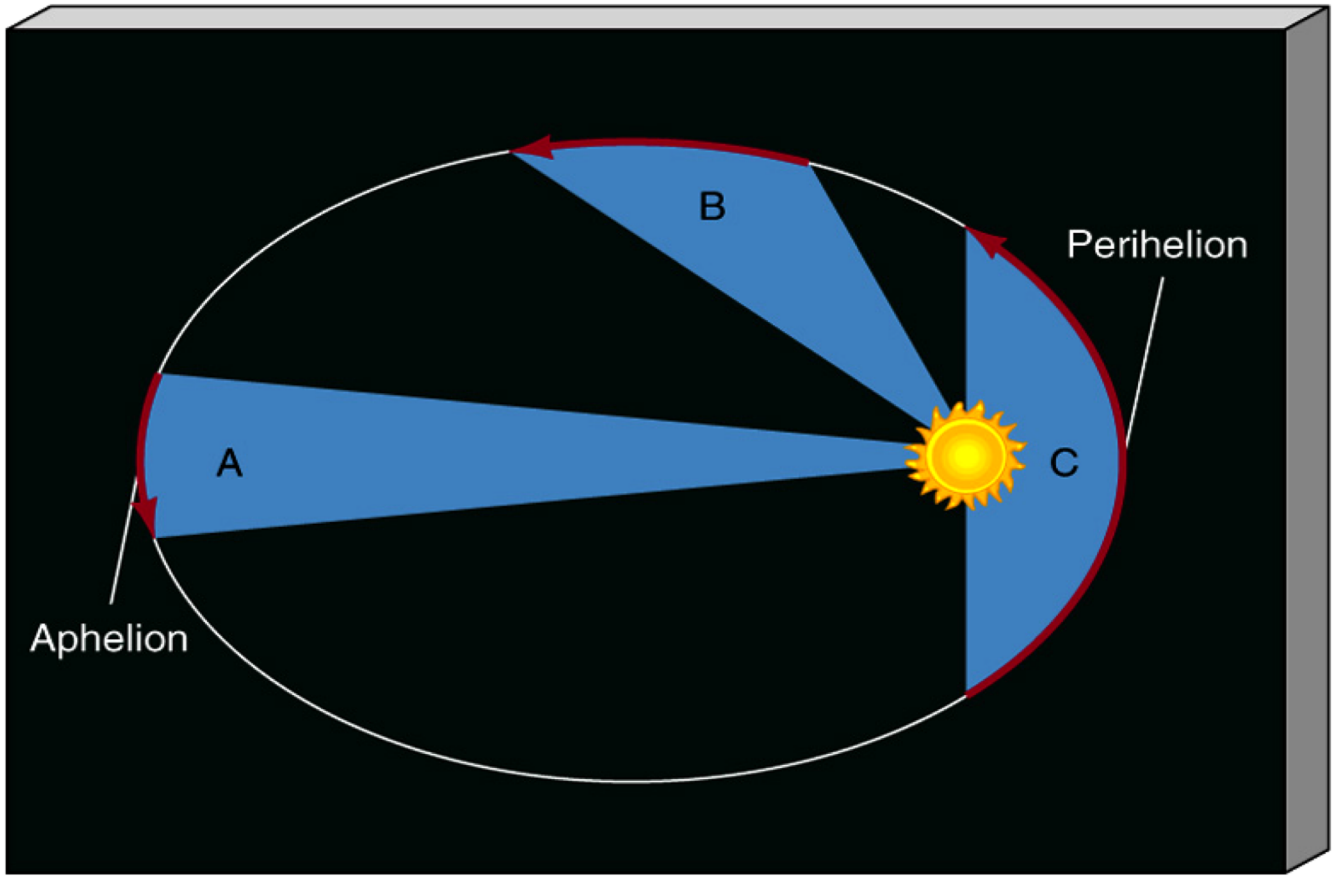
Andrea Ghez, UCLA



Kepler's Laws

- The orbits of the planets are elliptical (not circular) with the Sun at one focus of the ellipse.

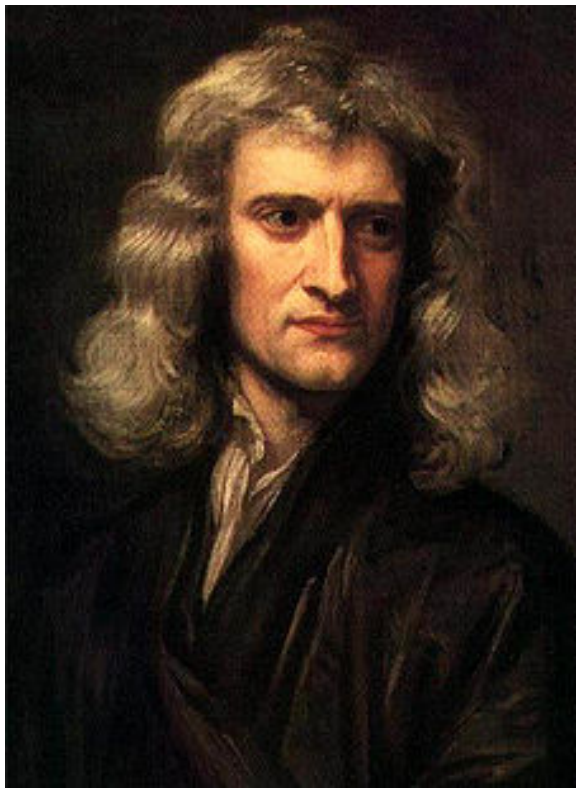


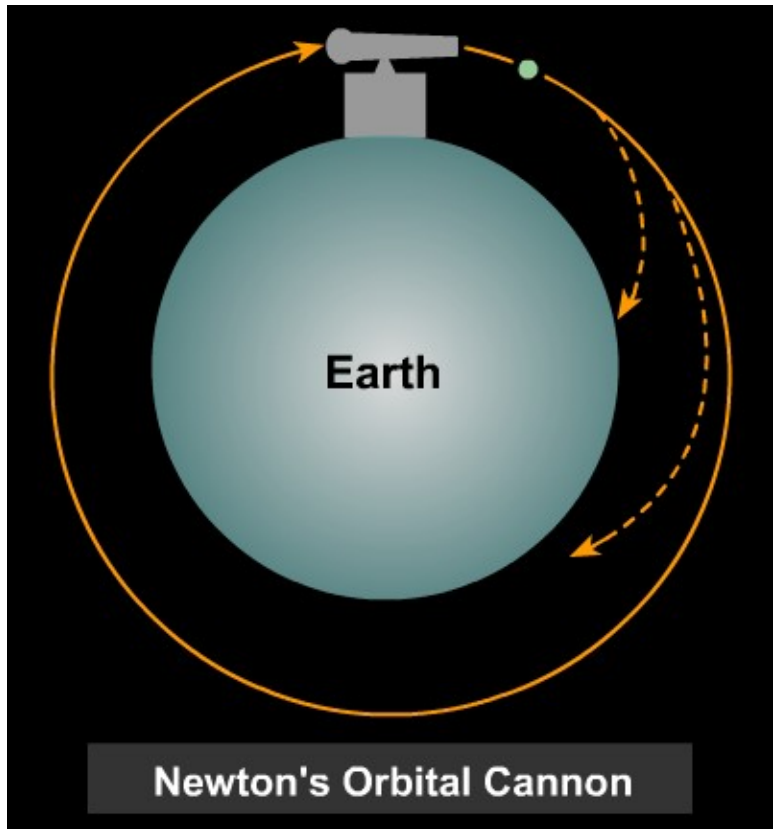


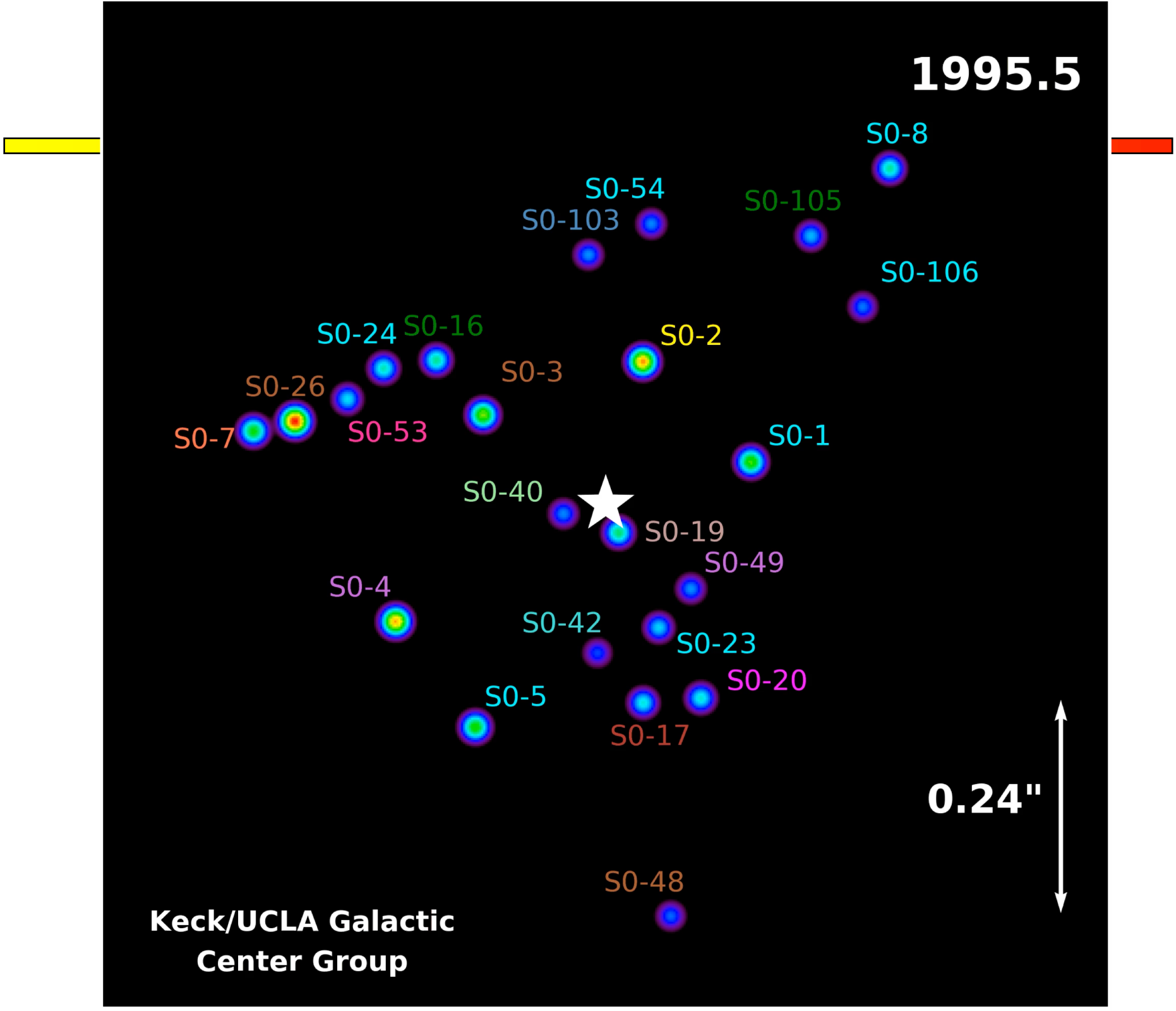
- The further the planet is from the sun, the longer the period.

Sir Isaac Newton: The Universal Law of Gravitation

- Newton was the first to prove Kepler's laws.
- Acceleration of the planets to a force exerted by the Sun on the planets.
- Gravitational attraction exists between all planetary bodies.



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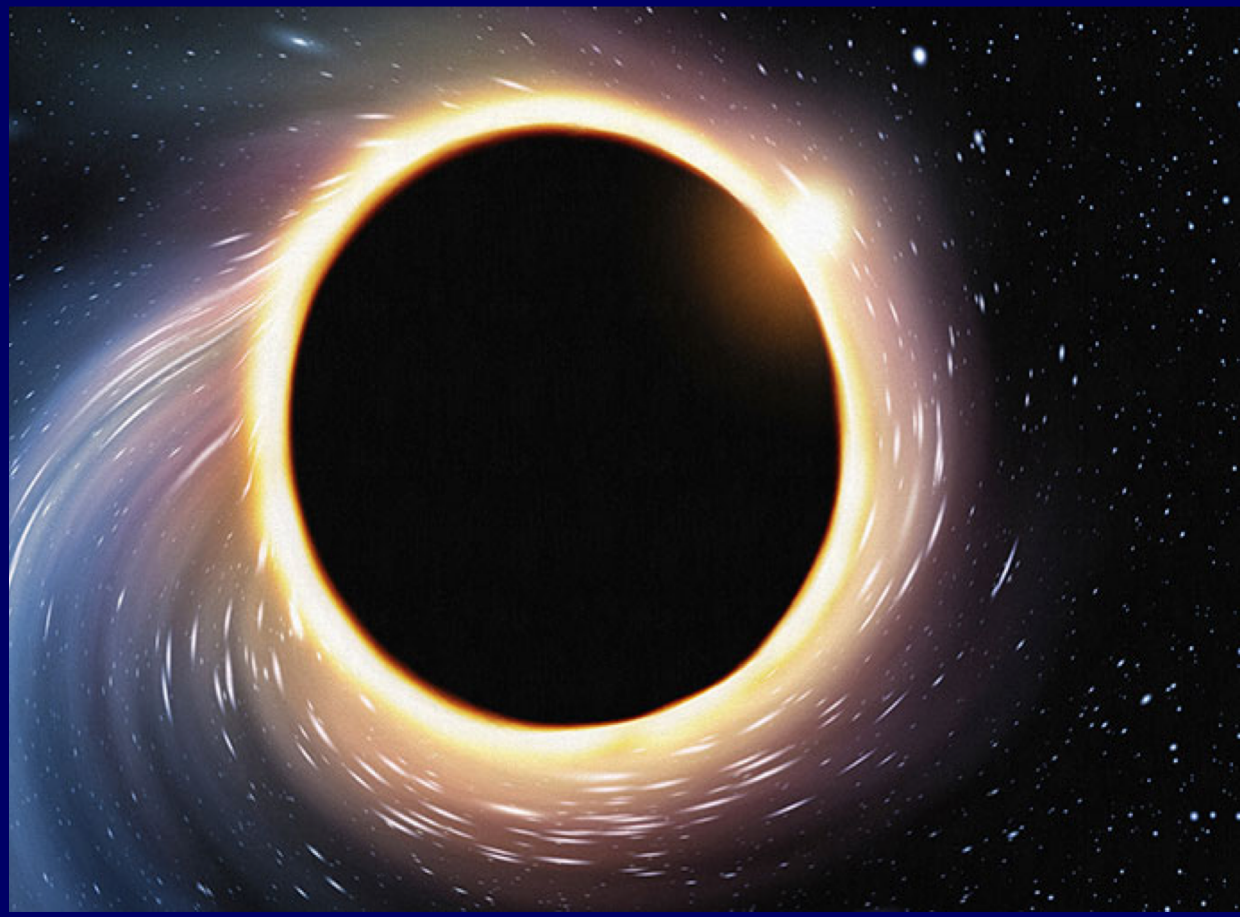
Keck/UCLA Galactic
Center Group

Black Holes

Einstein's General Theory of Relativity

- Compact object with all mass at center point - singularity - No particles or light can escape
- Construct of General Relativity
- Black holes have only 3 observable properties (mass, spin and charge)

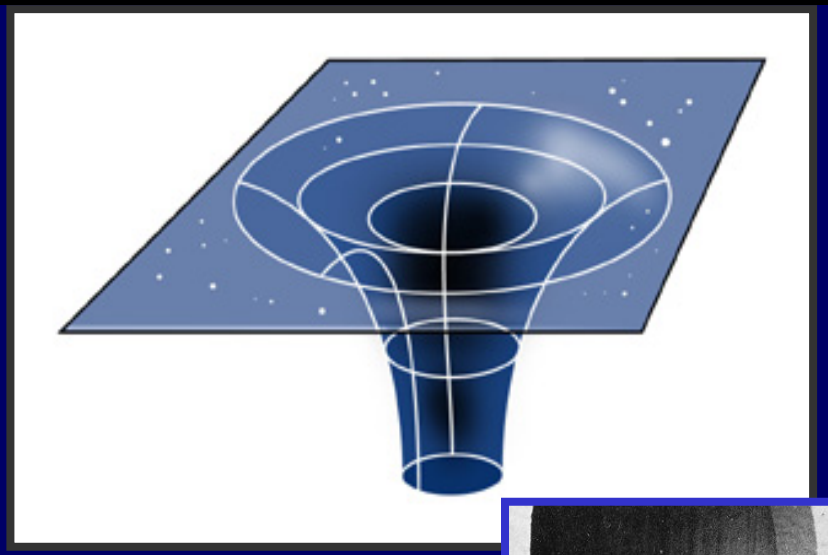


Black Holes

Einstein's General Theory of Relativity

- Event horizon around singularity is defined by radius where escape velocity is equal to the speed of light.

- Not even light can escape, once it has crossed the event horizon.



$$R = 2GM/c^2$$

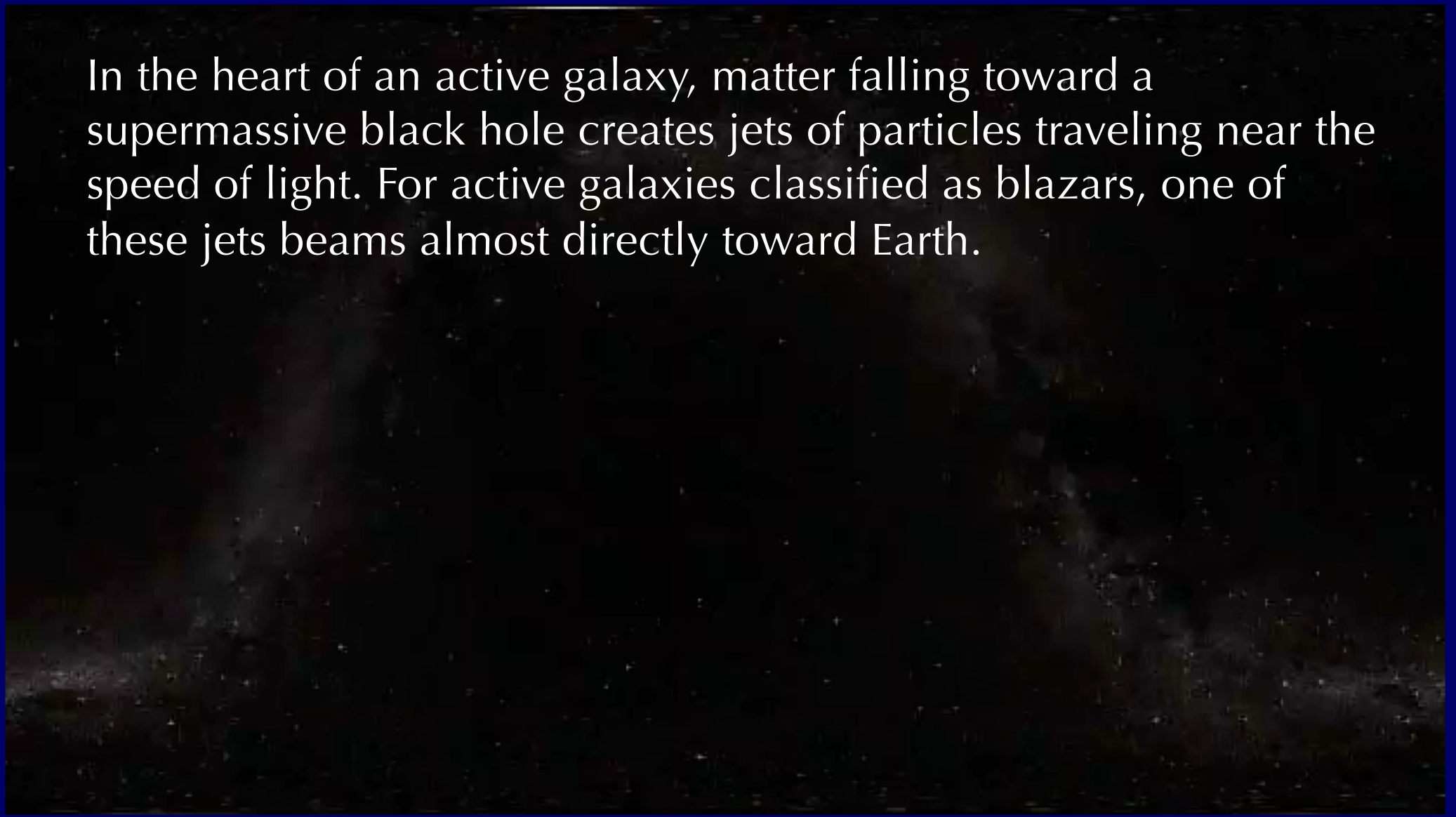
As opposed to "normal" galaxies …

- 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.

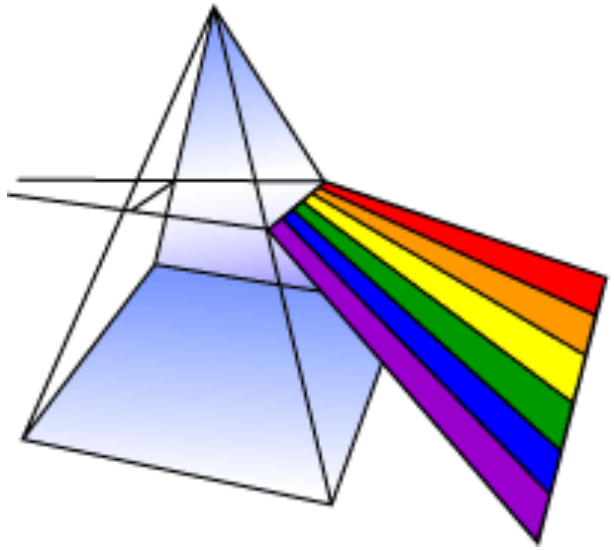
A view of the Milky Way towards the Constellation Sagittarius (including the Galactic Center) as seen from a non-light polluted area (the Black Rock Desert, Nevada).

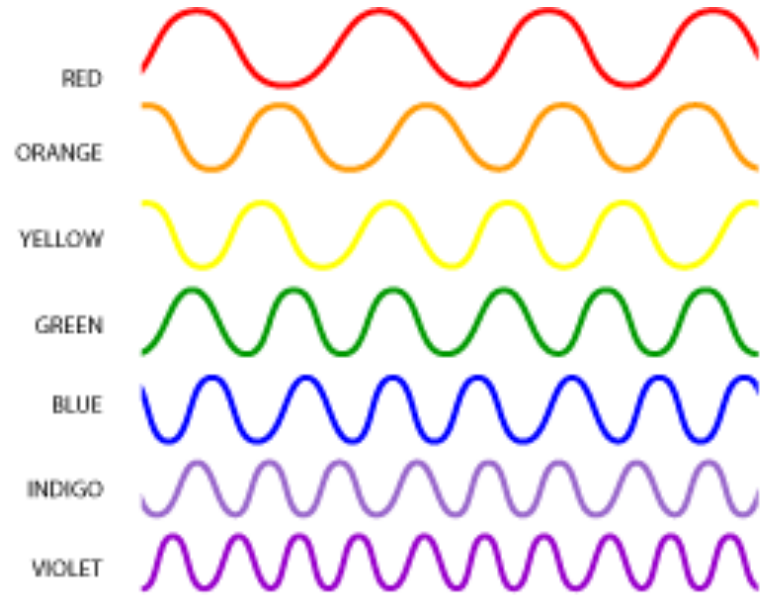
Active Galaxies are Powered by Super-Massive Black Holes

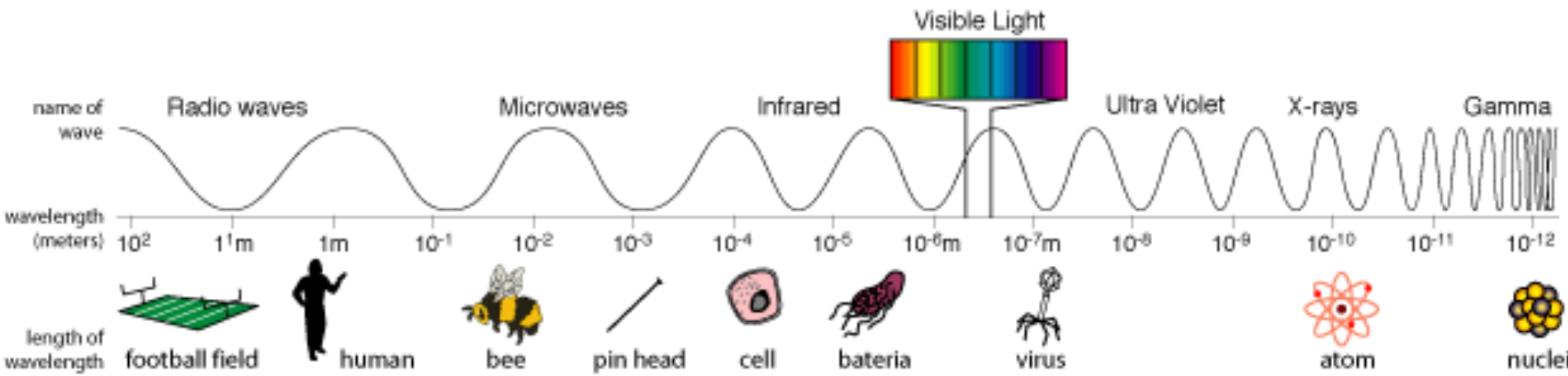


In the heart of an active galaxy, matter falling toward a supermassive black hole creates jets of particles traveling near the speed of light. For active galaxies classified as blazars, one of these jets beams almost directly toward Earth.

The Electromagnetic Spectrum







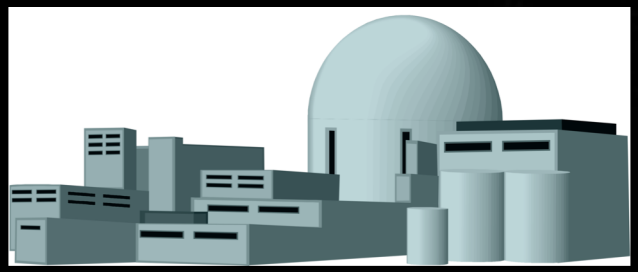
Reshmi Mukherjee

VHE Gamma-Ray Astronomy

VHE =Very High Energy

Optical Light Energy:

VHE gamma-ray Energy:

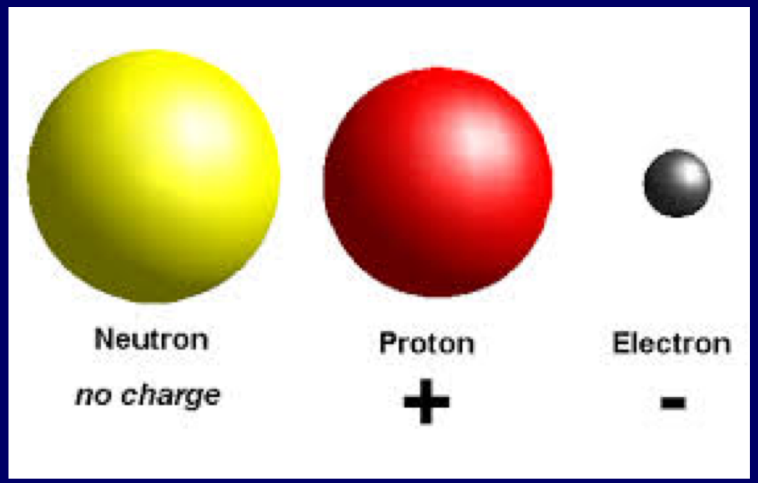


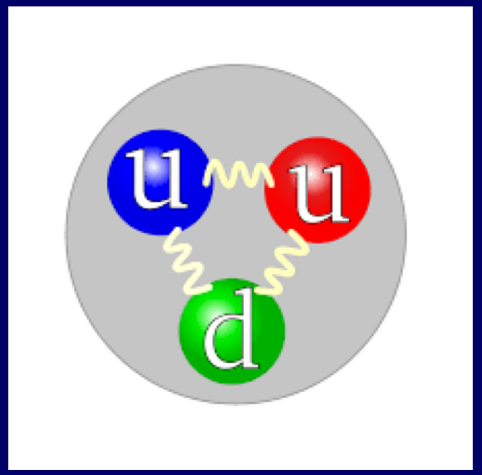
x1000

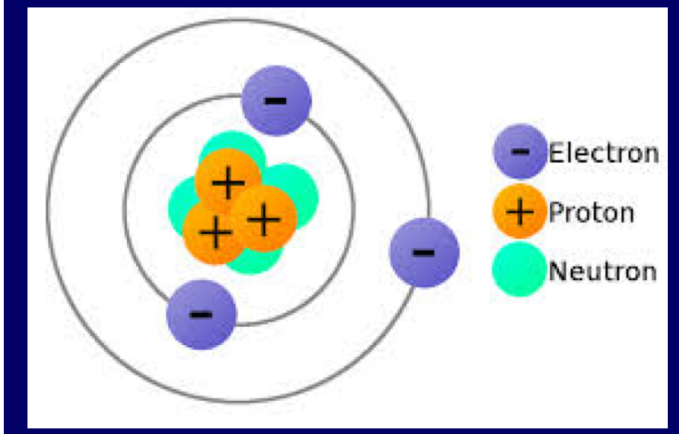
VHE Gamma-Rays

Some Basics & Terminologies …

- Structure of the atom







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

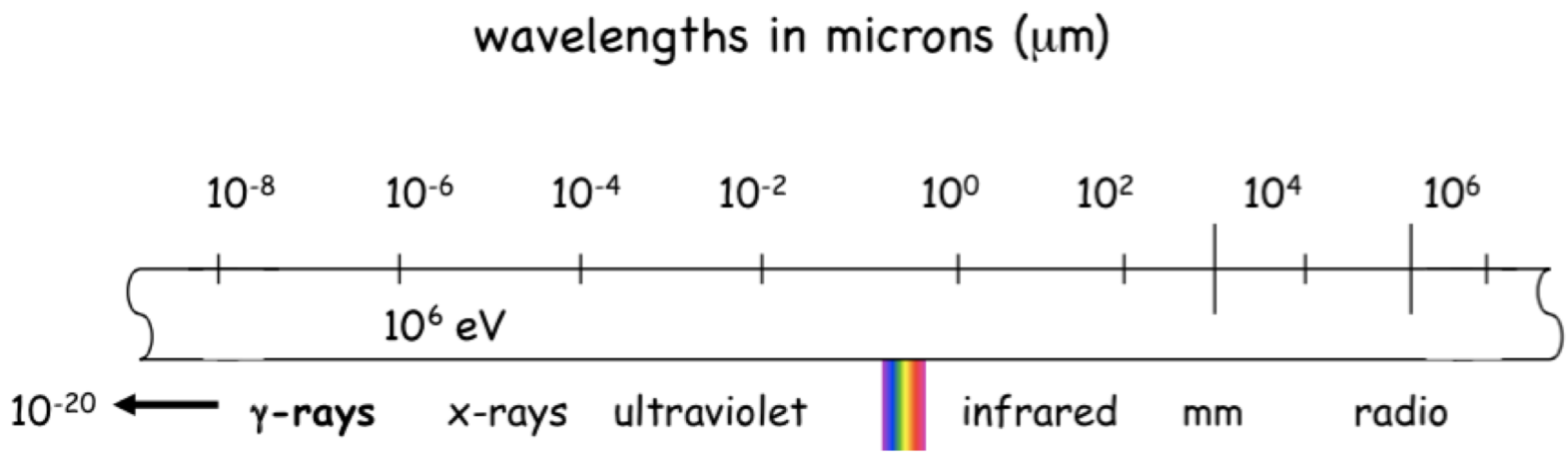
** 200 MeV: the average energy released in nuclear fission of one U-235 atom

** 1 TeV: a trillion electronvolts = 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

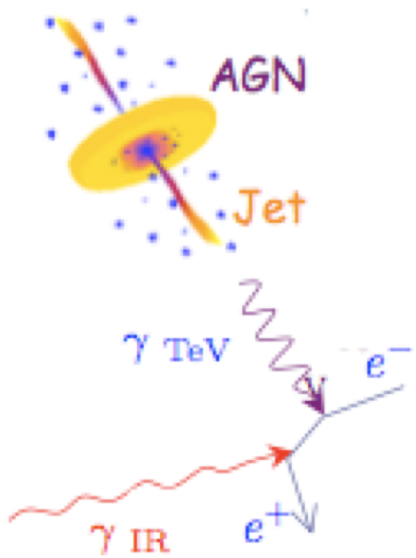
Potential & Uniqueness

- 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

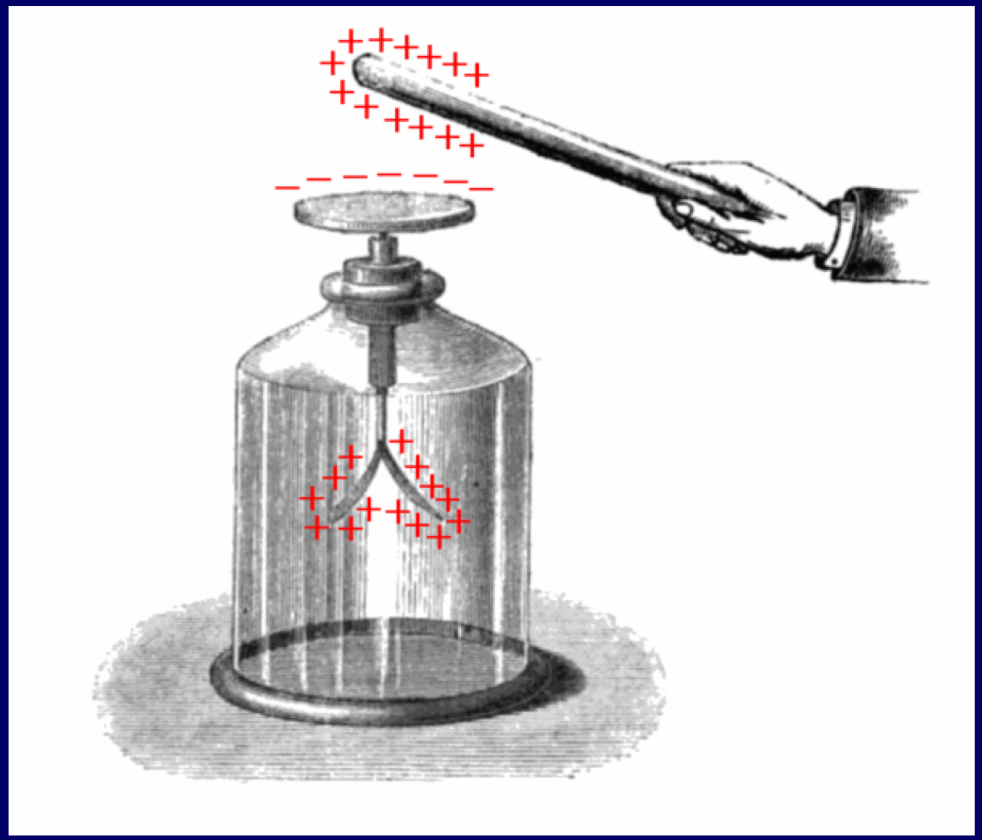
- Using γ rays to probe intergalactic space
  - Diffuse radiation fields.

- 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)

Is Earth the Source of Radiation?

- Should the radiation decrease at higher altitudes?

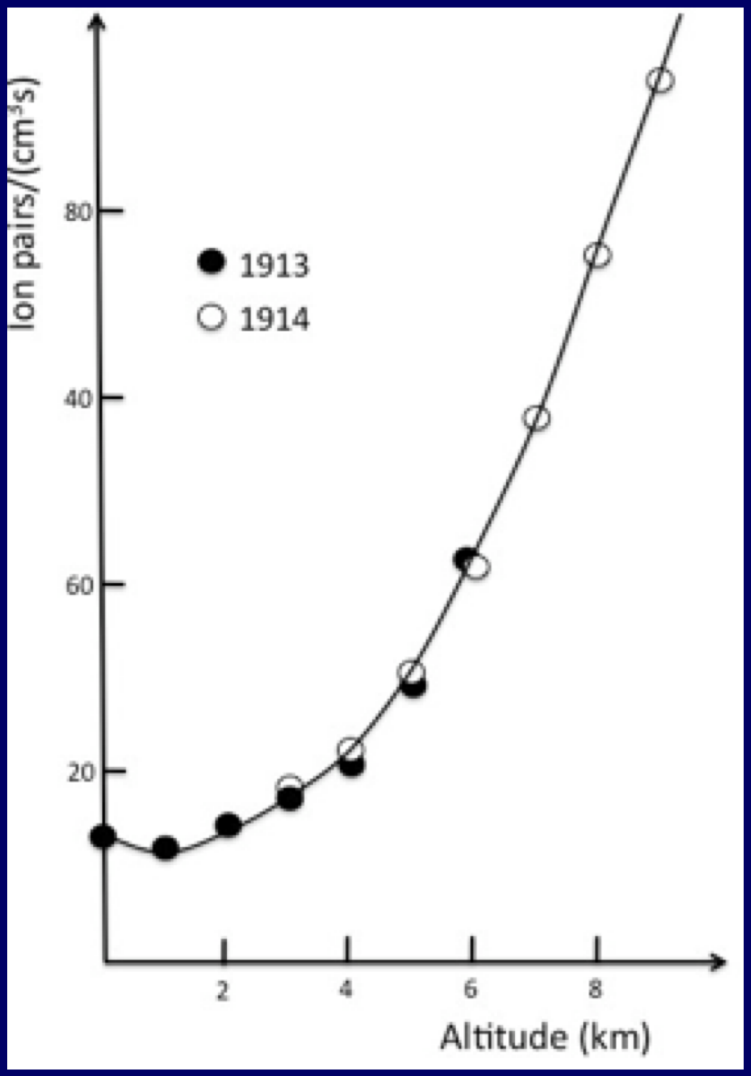
- Experiments performed by Theodor Wulf in 1910. Measured radiation at the base of the Eiffel Tower and at the top.

- Significant radiation measured at the top, but not conclusive.

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



Millikan Rays ?

- Debate on the origin of cosmic rays – what are they? Where do they come from?


The New York Times

MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious'

Headlines, NY Times 1932

- The NY Times claims that Millikan "discovered" them. Millikan names them "cosmic rays."

Cosmic Rays Only Thing Immortal

NEITHER stars nor worlds, sunlight or heavens, can science admit to be eternal. Only one thing known to science can be called immortal—the cosmic rays investigated, among others, by the famous California physicist, Dr. R. A. Millikan. These rays may even be relics of days before there existed any universe as we know it now.

Jan 1932 Issue, Modern Mechanix

What are Cosmic Rays ?

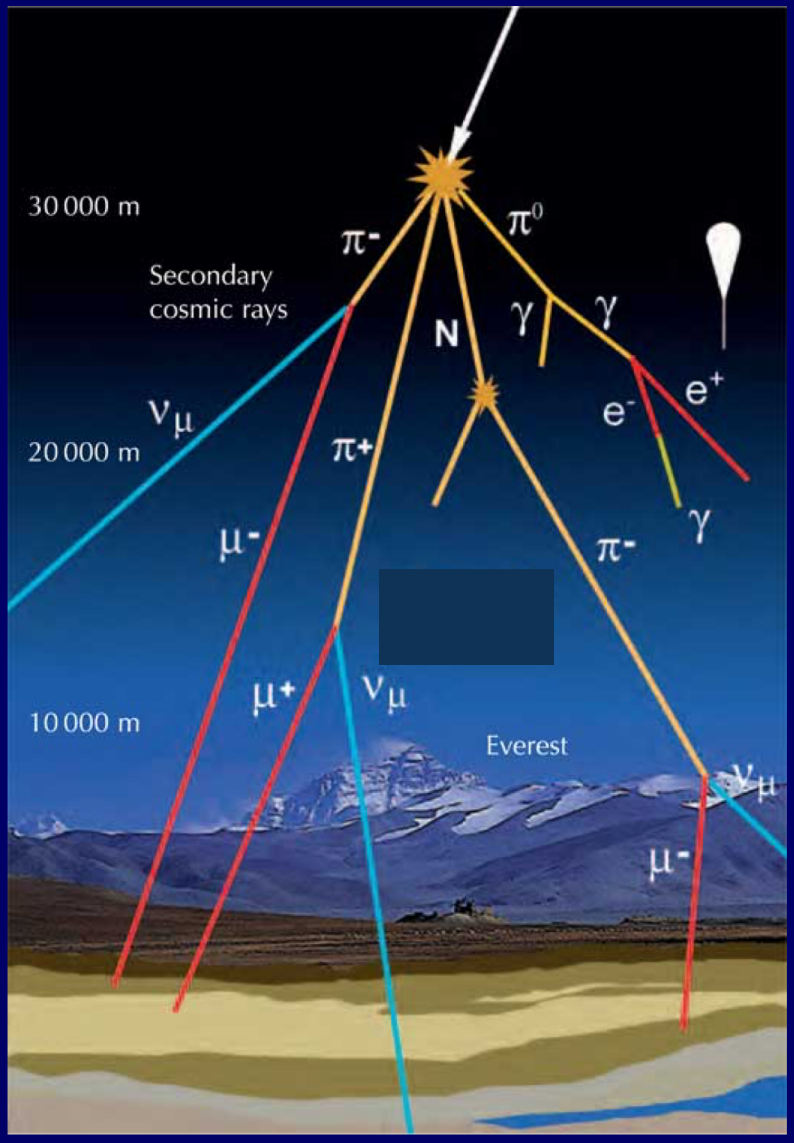
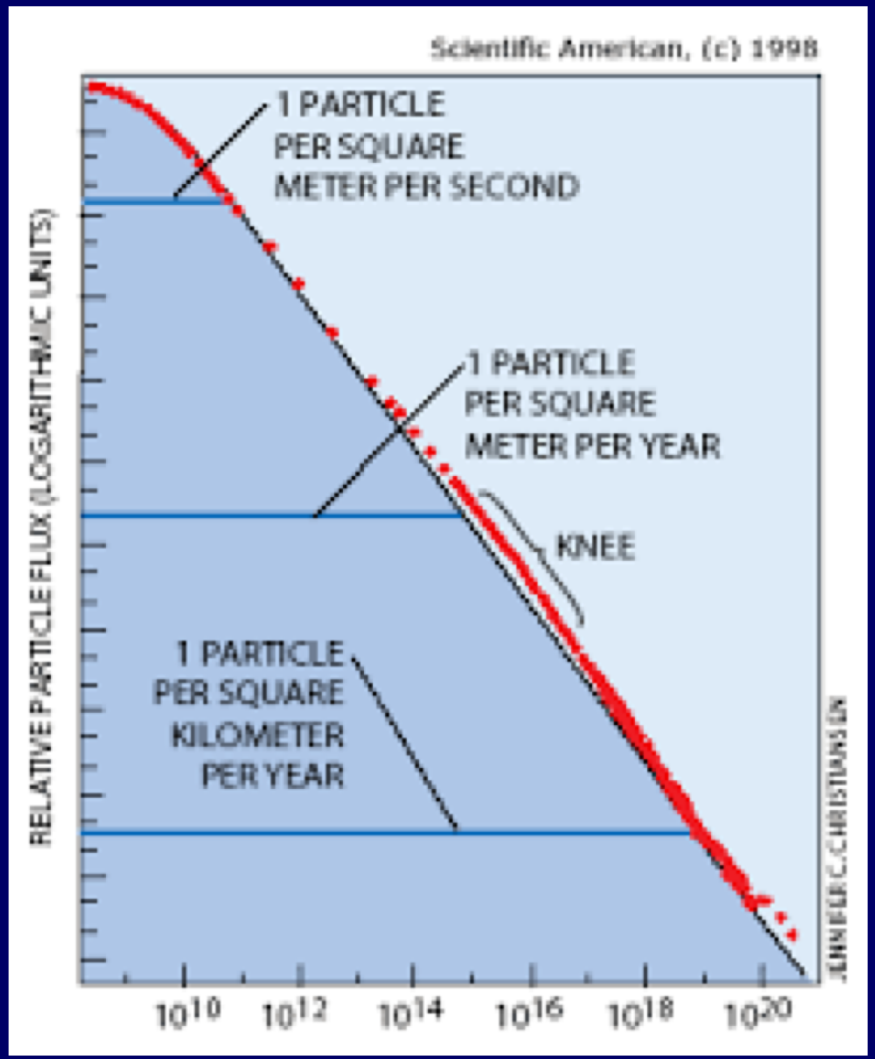


Image from http://www.scienceinschool.org (2010, Issue14)

- On the evening of October 15, 1991, a detector in the Dugway Proving Grounds, Utah, detected the highest energy cosmic ray ever, shocking astrophysicists worldwide.
- This so-called "Oh-My-God" particle was traveling at 0.99999999999999999999951 times the speed of light.
- In scientific notation, energy is 10^{20} eV (~ 50 J)

Cosmic Ray Spectrum



Open questions:

- What is the origin of the highest energy cosmic rays?
- A mystery that has remained unsolved for more than 100 years!

- >100 year old mystery !
- Enormous energy range
- Mostly charged particles
- Energy density ~ 1 eV/cm^3

Citation

COSMIC RAYS

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

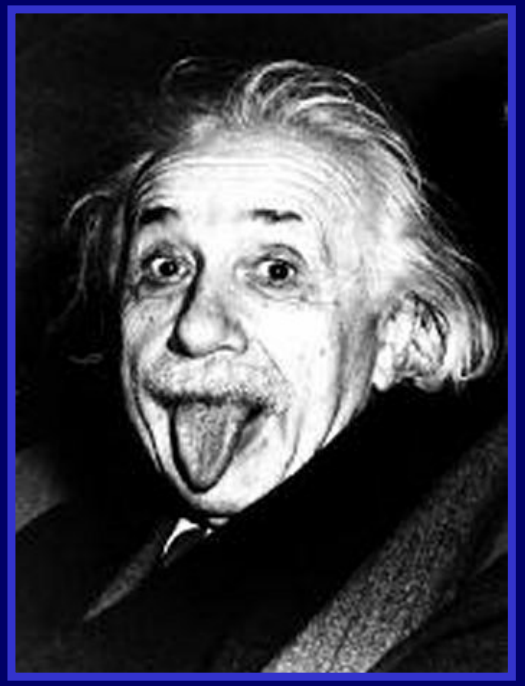
Particle acceleration in the cosmos…

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

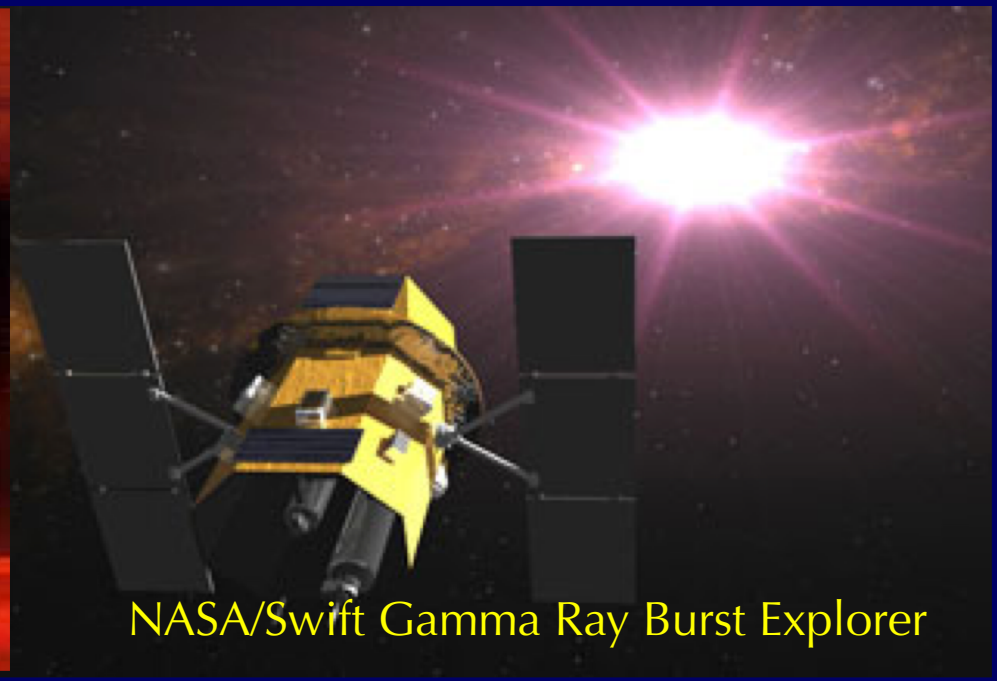
Creating Energy from Mass

- 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

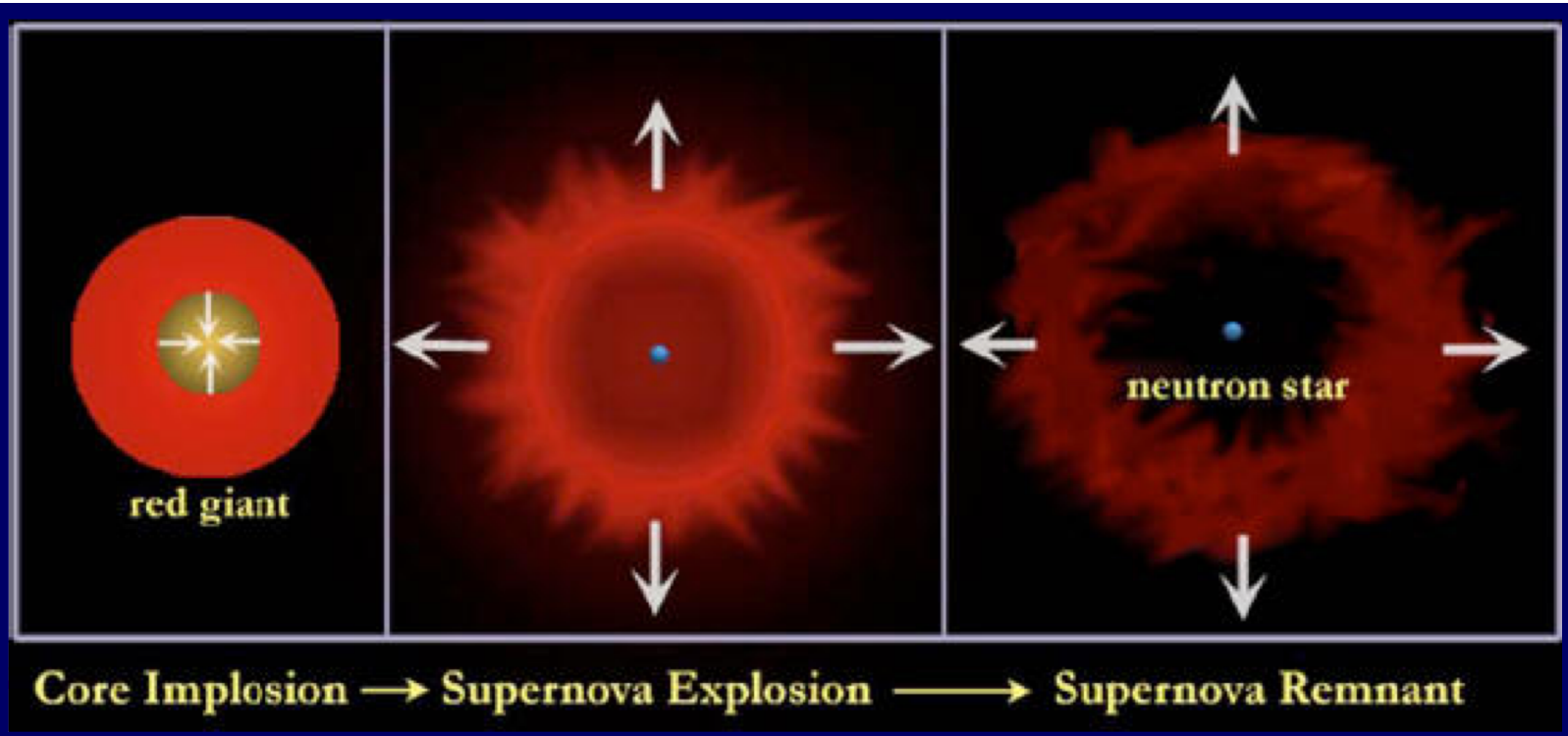
$$E = mc^2$$



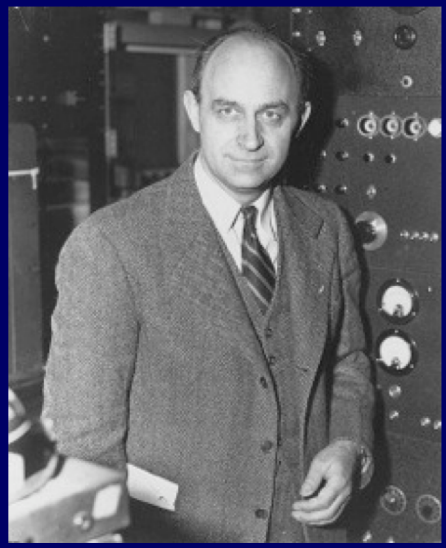
1 raisin * c^2 = nuclear explosion energy

400,000 Earths * c^2 = GRB Energy

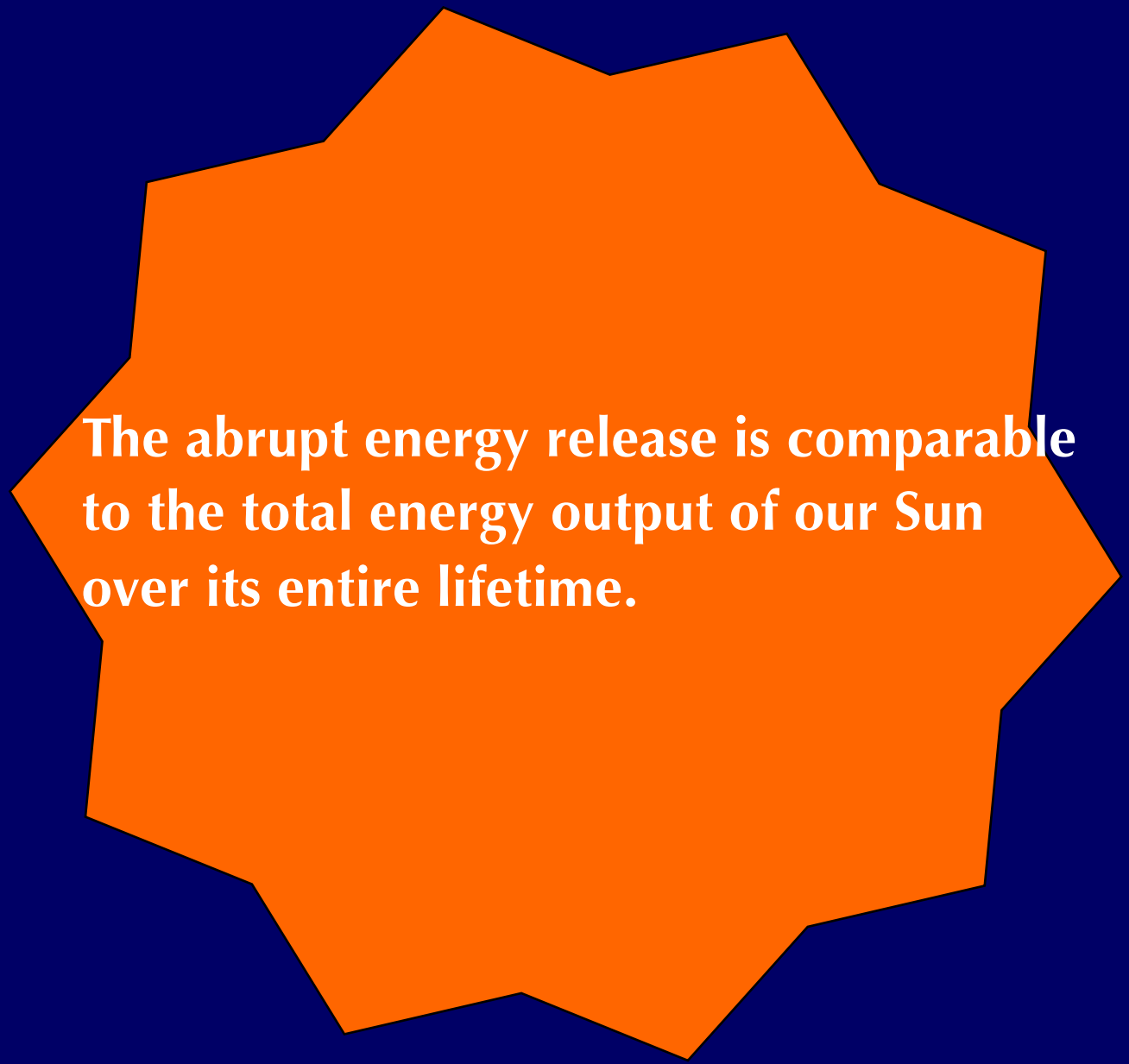
Particle Acceleration



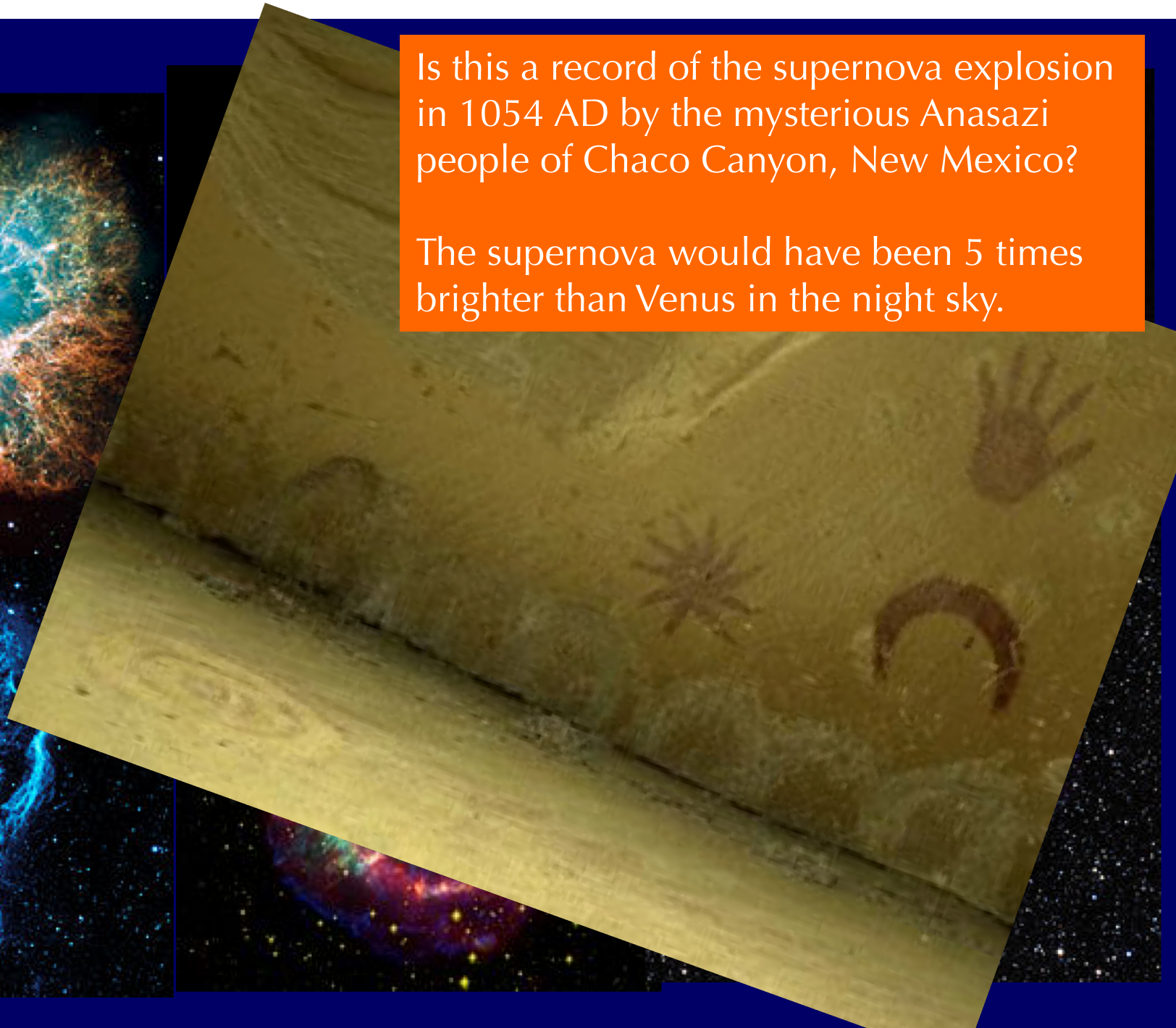
- Shock fronts and magnetic fields can accelerate protons to CR energies over time
- Particle's perspective: crossing the shock => head-on collision with magnetic domains



Particle Acceleration in Supernova Explosions



Supernova Explosion

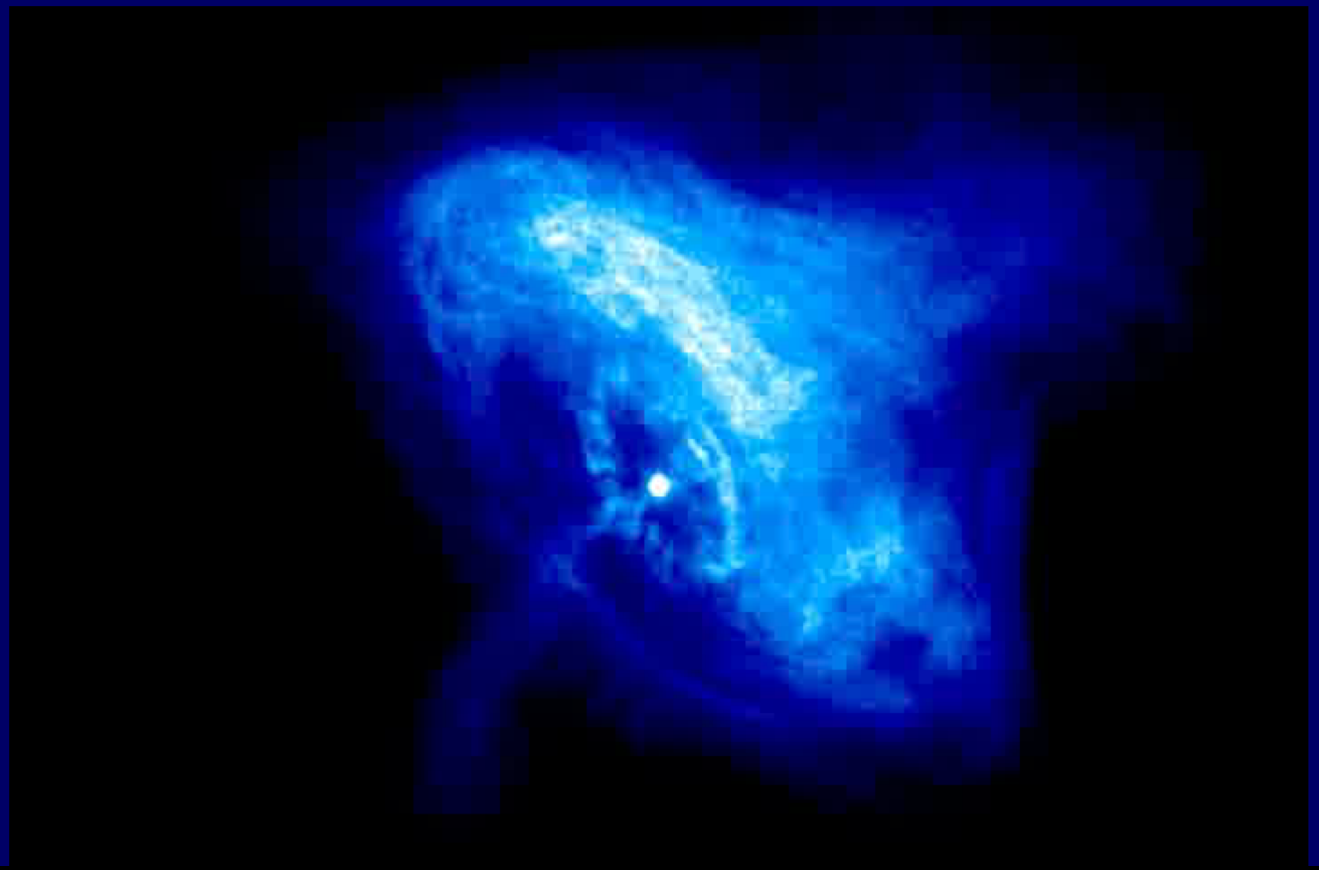


Is this a record of the supernova explosion in 1054 AD by the mysterious Anasazi people of Chaco Canyon, New Mexico?

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

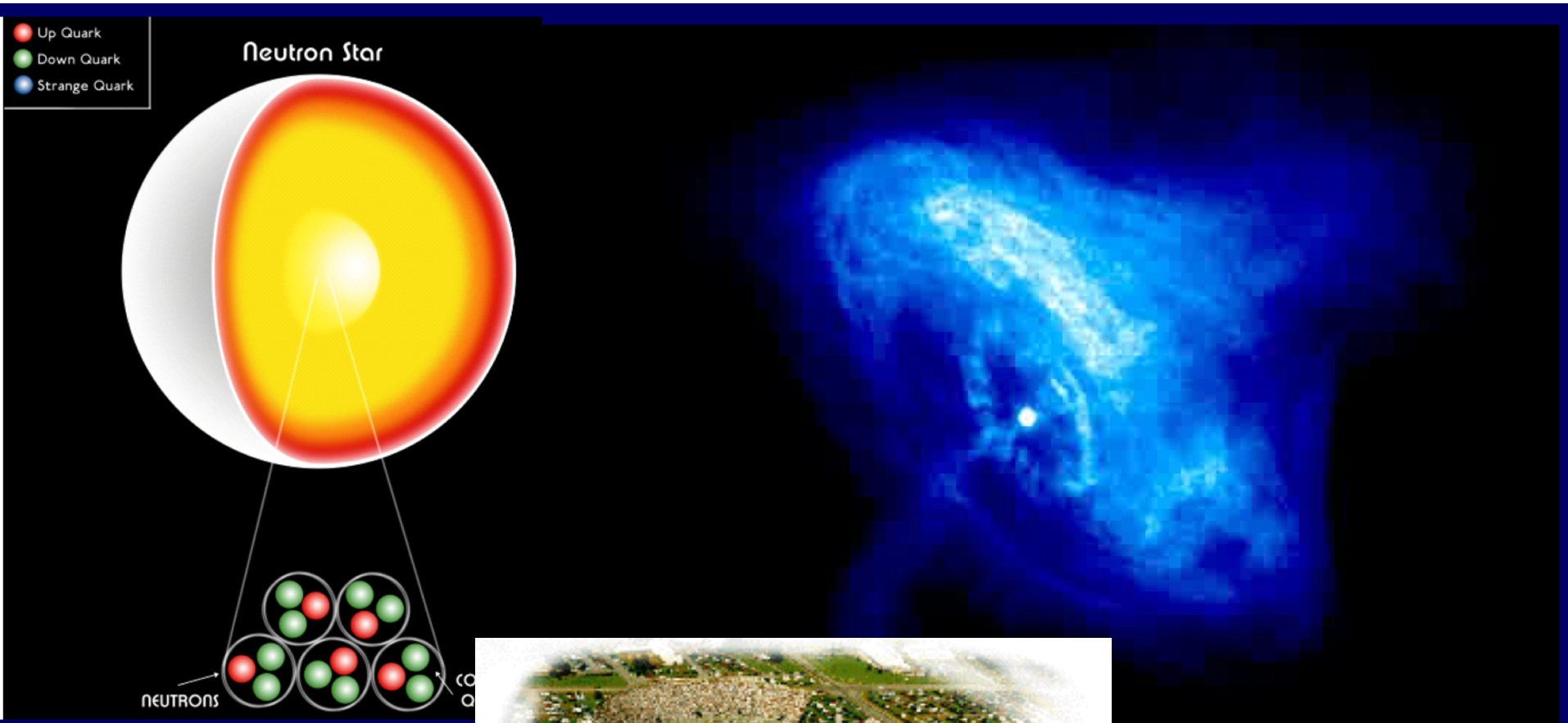
The Crab Pulsar – a rapidly rotating Neutron Star

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 ??



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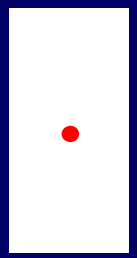
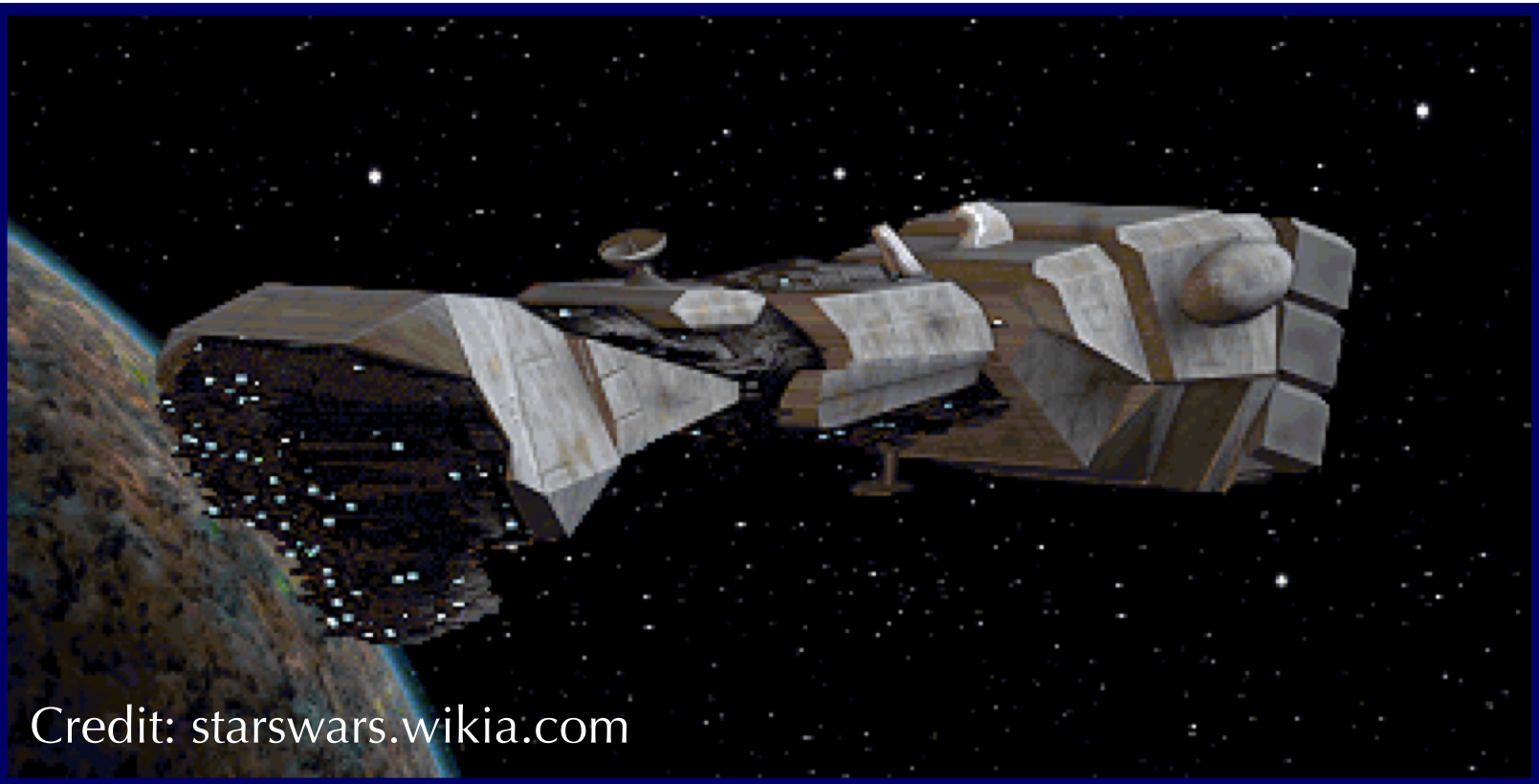
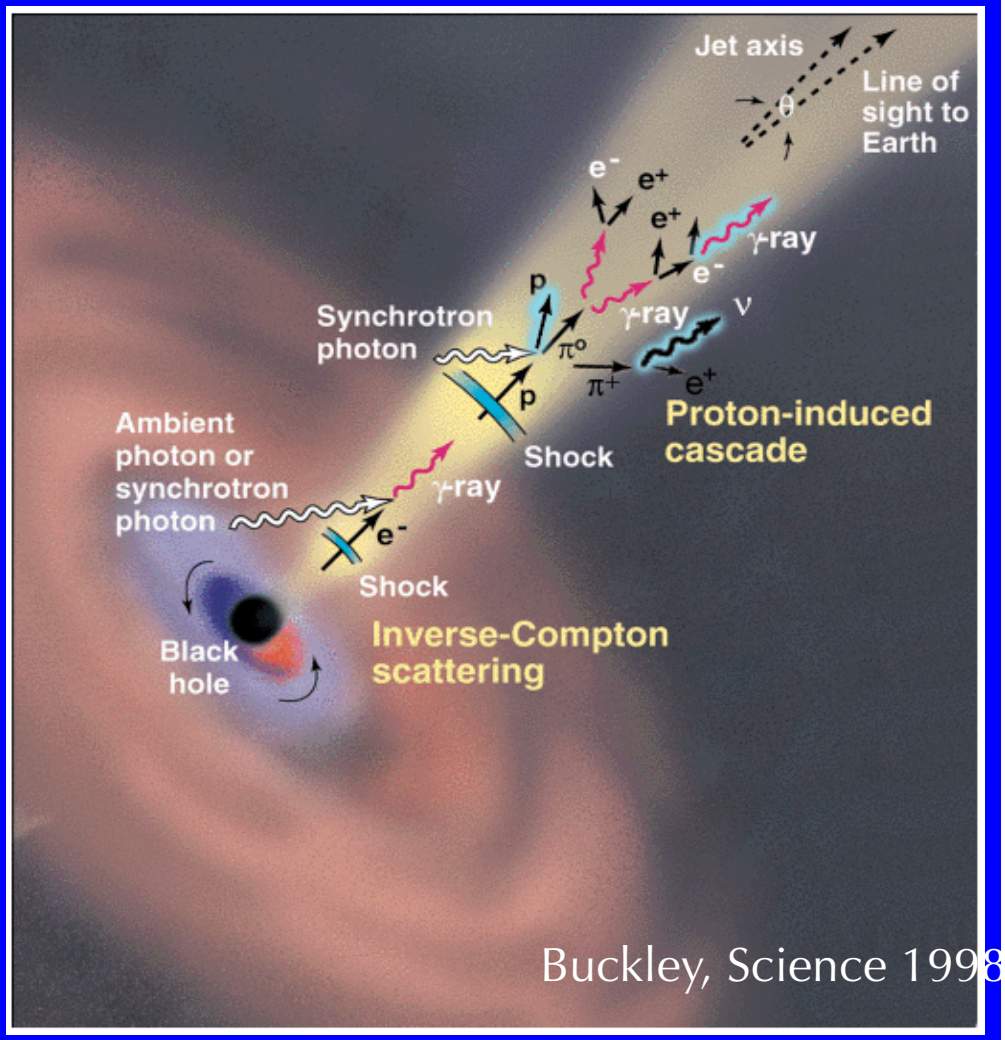


Neutron Star Power



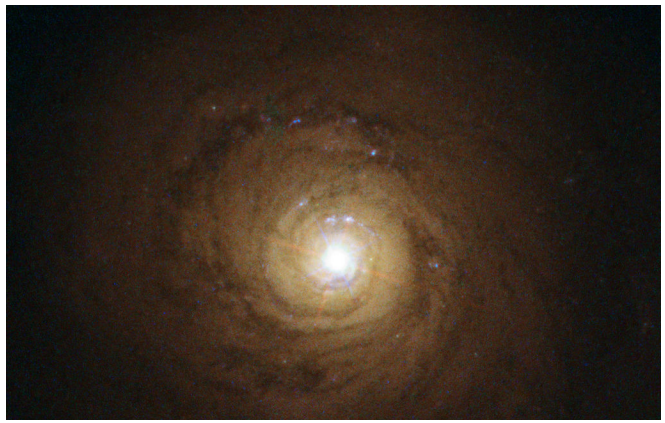
The Neutron Star-class bulk cruiser was a class of capital ship used by the Galactic Empire and Rebel Alliance. They were designed during the Clone Wars to serve as second-line ships.

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

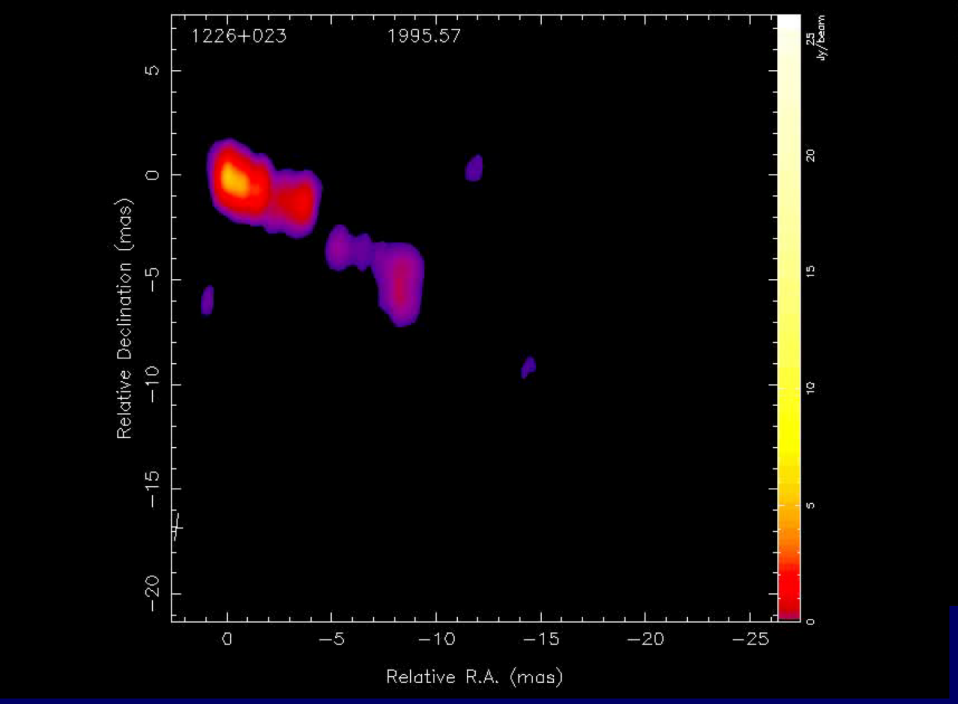


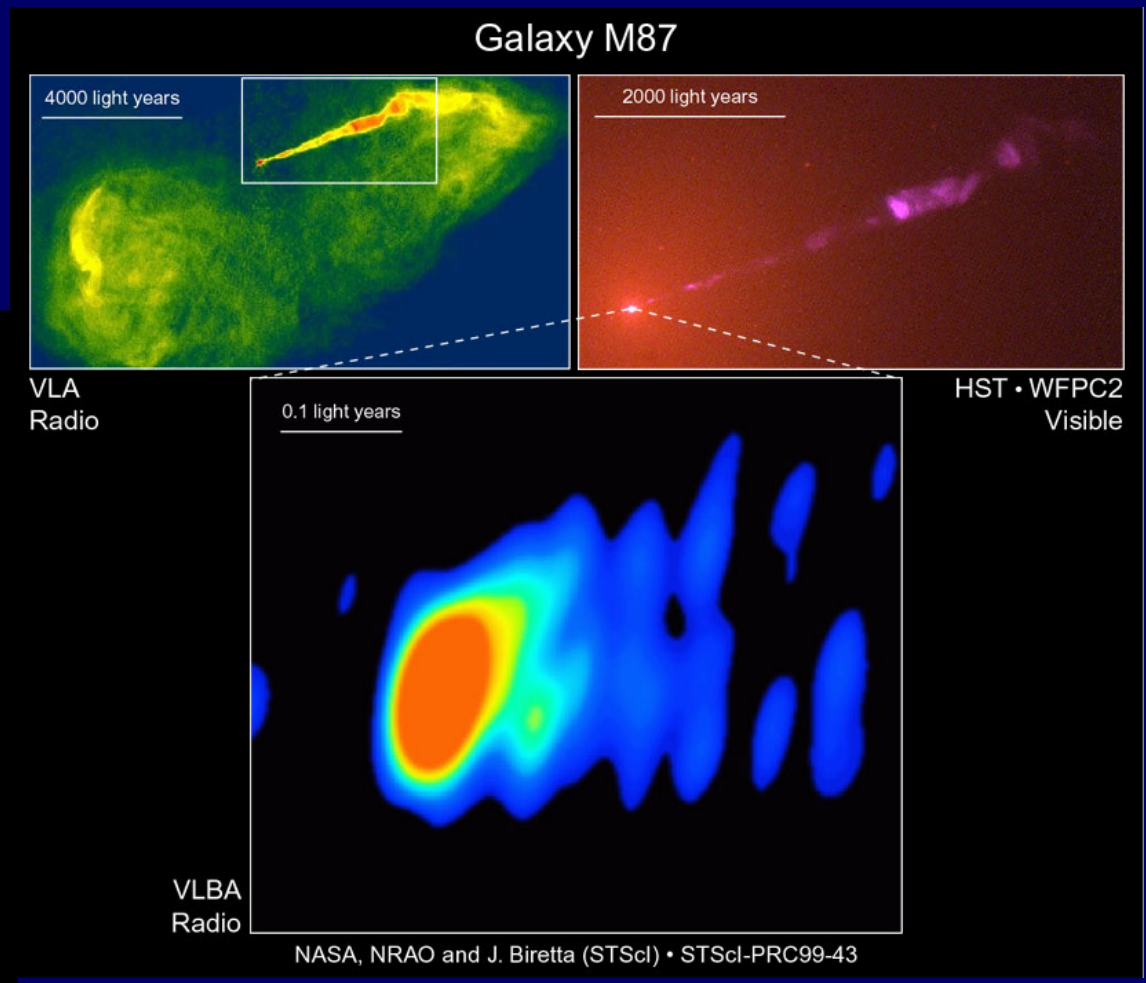
Hubble image of NGC 5548

Extragalactic Sources of Energy

Extragalactic Relativistic Jets in Active Galaxies

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

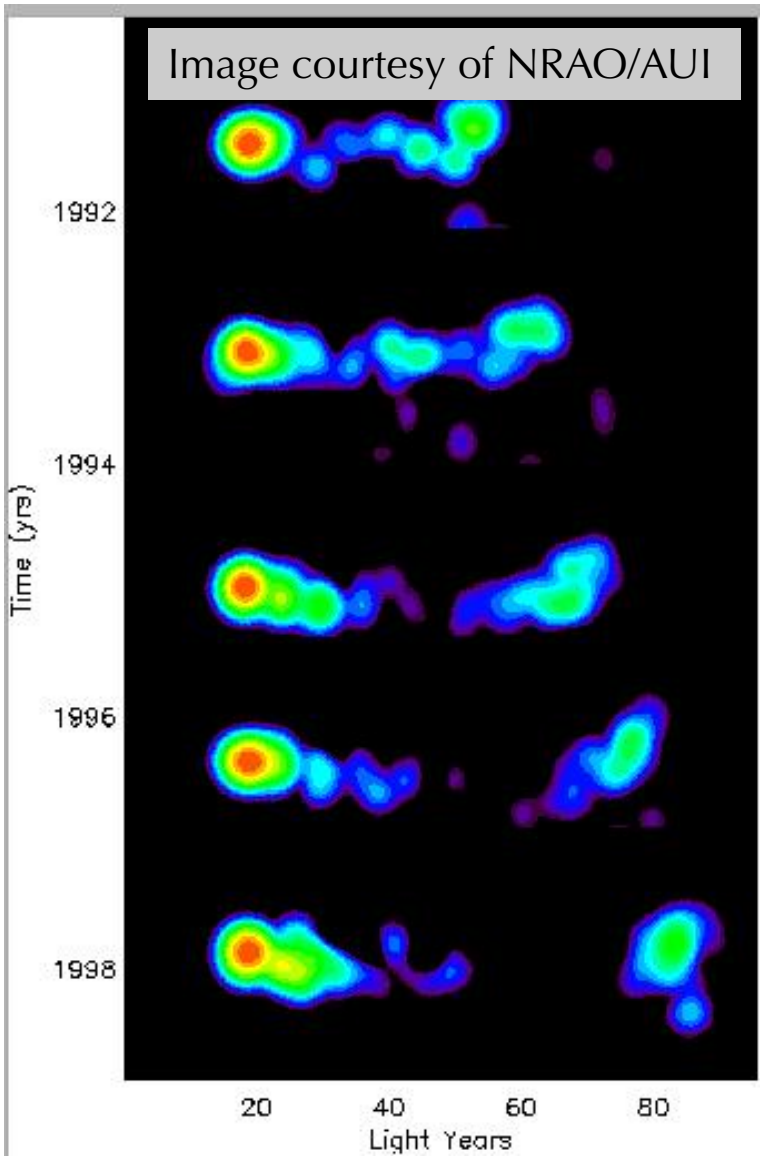




Extragalactic Sources of Energy

See talk: **Story of Escape: A Gamma-ray Photon's Extragalactic Journey**
Speaker: Amy Furniss (Cal State East Bay) July 15

Superluminal Motion Blazar



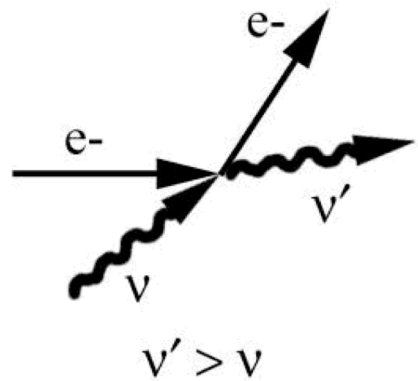
- Relativistic jet in 3C 279 at 22 GHz.
- 1991 – 1997 (18 epochs)
- Bright, compact VLBI core and jet components.
- Apparent speeds: 4.8 to 7.5 times the speed of light!

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*
    of cha
  - In ord
    neutra

See talk **Hunting for ghost particles at the South Pole,** June 24
Speaker: Anna Frankowiak (DESY, Germany)

Icecube Observatory at the South Pole