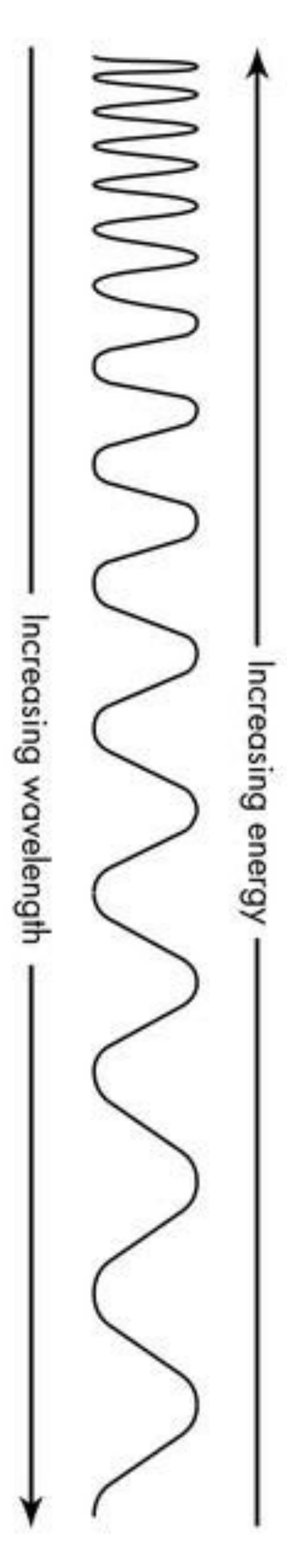
High Energy Astrophysics

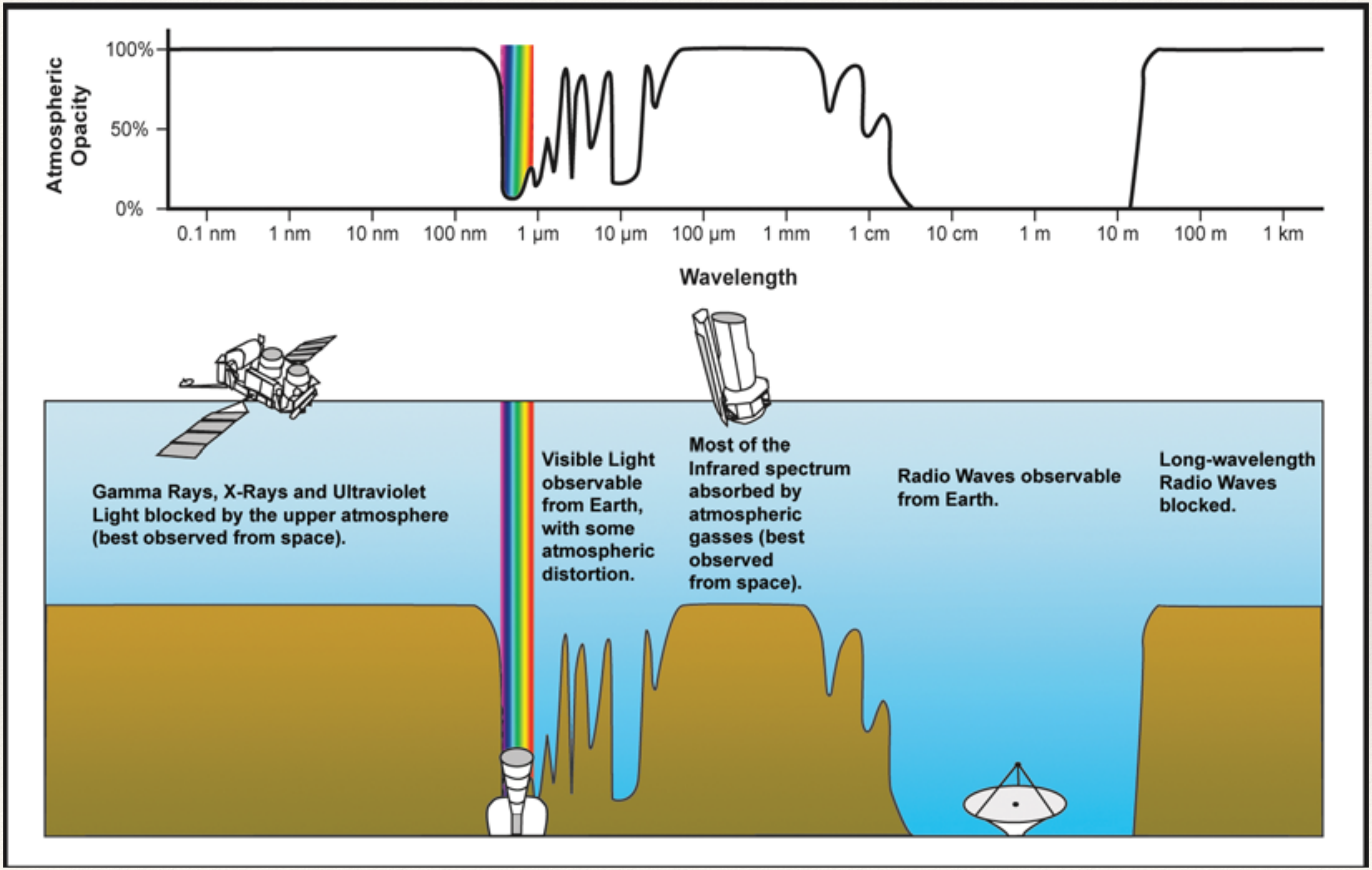
ASTR 5590

Radiation and Objects



Type of Radiation	Characteristic Temperature	Objects Emitting This Type of Radiation
Gamma Rays	More than 10^8 Kelvin (K)	▪ Interstellar clouds where cosmic rays collide with hydrogen nuclei ▪ Disks of material surrounding black holes ▪ Pulsars or neutron stars
X-rays	$10^6 – 10^8$ K	▪ Regions of hot, shocked gas ▪ Gas in clusters of galaxies ▪ Neutron stars ▪ Supernova remnants ▪ The hot outer layers of stars
Ultraviolet	$10^4 – 10^6$ K	▪ Supernova remnants ▪ Very hot stars ▪ Quasars
Visible	$10^3 – 10^4$ K	▪ Planets ▪ Stars ▪ Galaxies ▪ Nebulae
Infrared	$10 – 10^3$ K	▪ Cool stars ▪ Star-forming regions ▪ Interstellar dust warmed by starlight ▪ Planets ▪ Comets ▪ Asteroids
Radio	Less than 10 K	▪ Cosmic background radiation ▪ Scattering of free electrons in interstellar plasmas ▪ Cold gas and dust between the stars ▪ Regions near white dwarfs and neutron stars ▪ Supernova remnants ▪ Dense regions of interstellar space such as the galactic center ▪ Cold molecular clouds

Atmospheric Opacity



Discoveries and New Frontiers

- Subatomic particles
- Cosmic Rays
- Radio Astronomy
- X-ray Astronomy
- Gamma-ray Astronomy
- Ultraviolet Astronomy
- Neutron Stars
- X-ray Binaries and Black Holes
- Supernovae
- Clusters of Galaxies
- Active Galactic Nuclei

Discovery of Subatomic Particles

- The discovery of X-rays (1895) - search for other sources of X-radiation
- Natural radioactivity and sources (Becquerel, 1896)- new types of radiation - α, β, γ
- Discovery of neutron

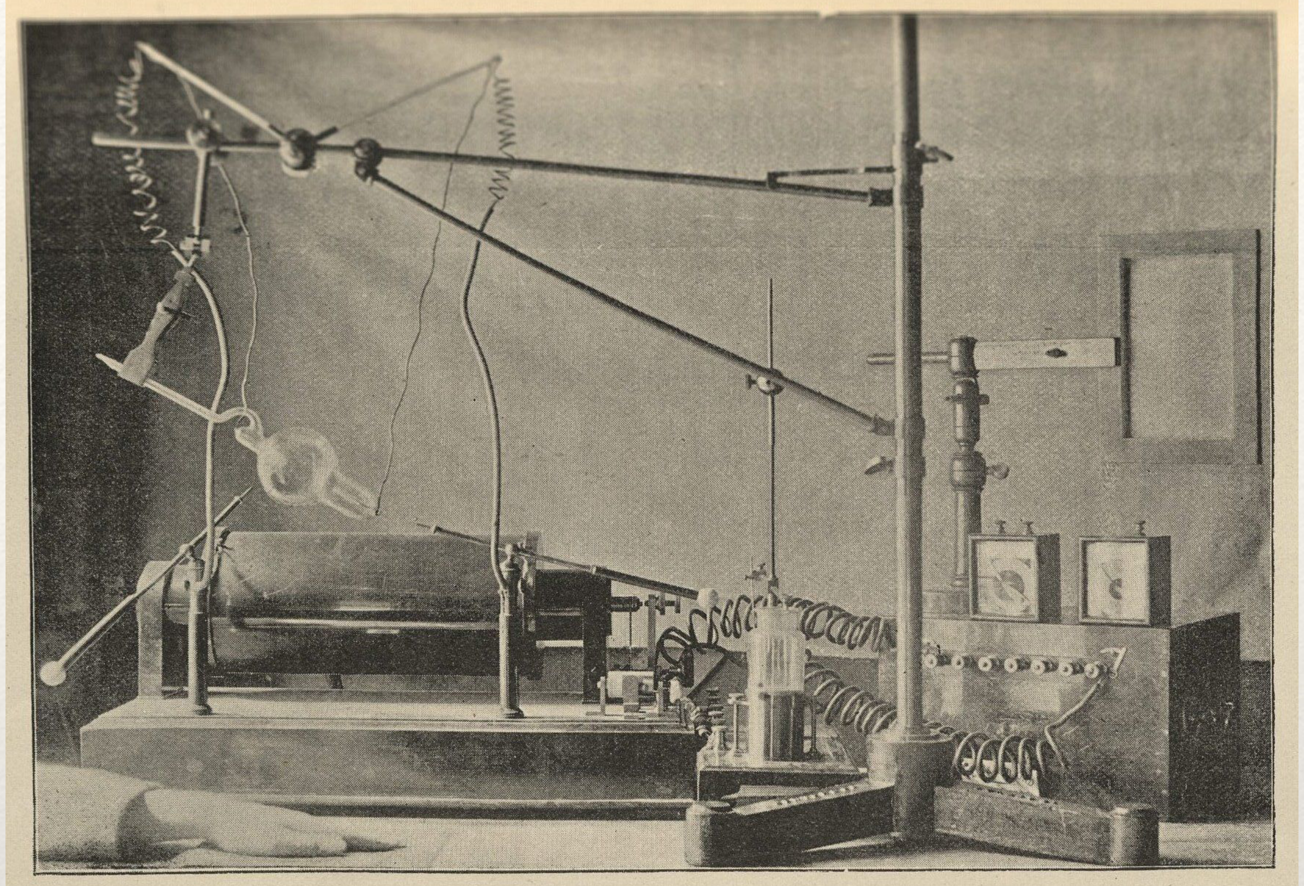


Fig. 17.—Complete Apparatus for Röntgen-Ray Work, consisting of Secondary Battery, Voltmeter, Ammeter, Apps' Induction Coil with Ordinary and Mercurial Break, Rowland's Stand, Focus Tube, Fluorescent Screen on Stand, and Hand in Position upon Photographic Plate.

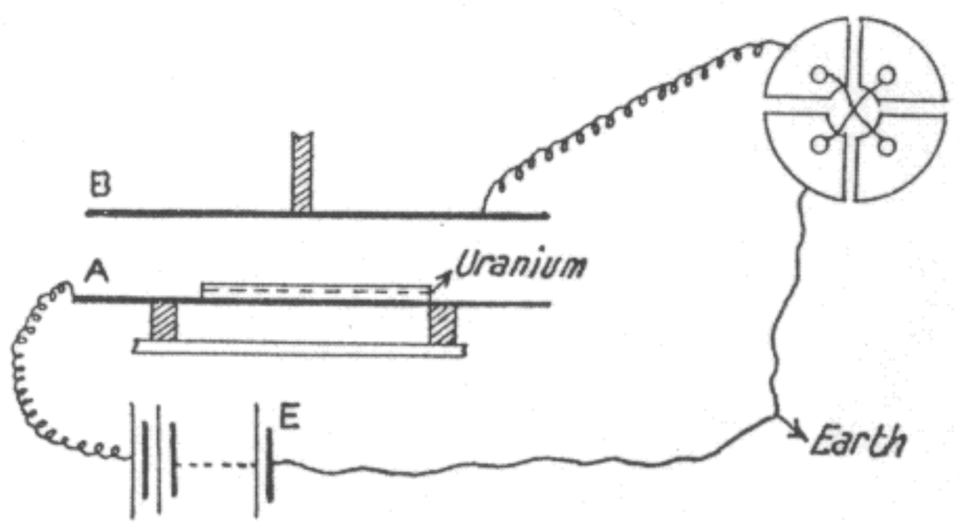


Fig. 1

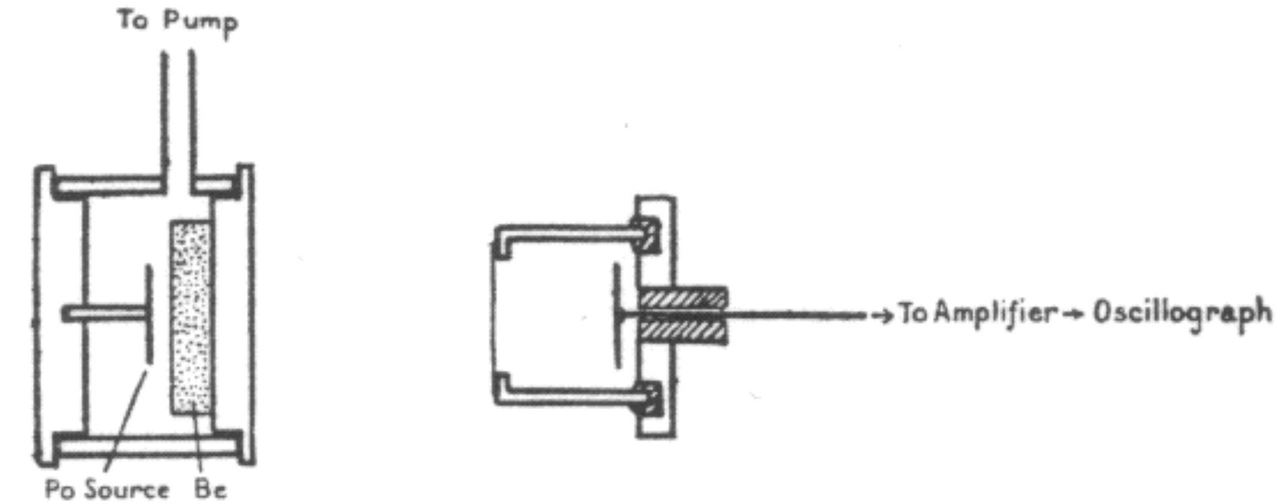
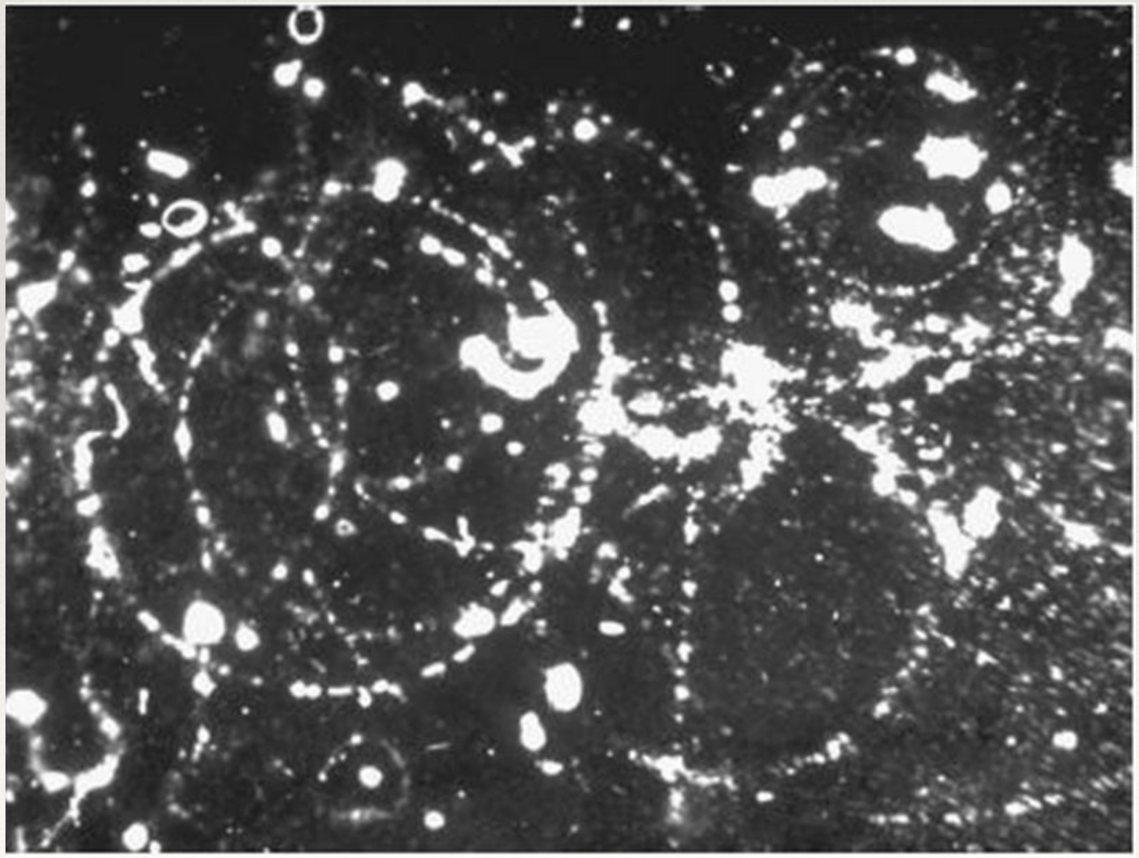


Fig. 1.

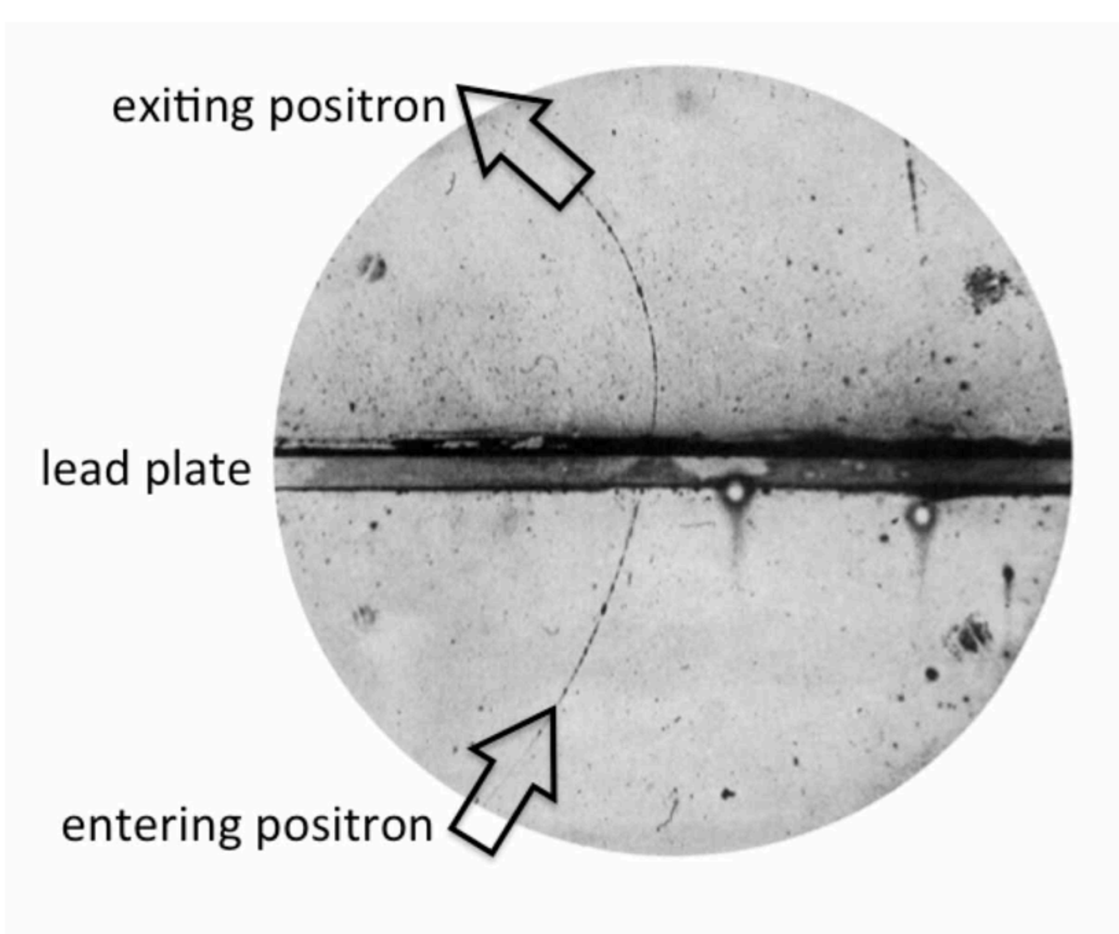
Cosmic Rays

- Viktor Hess (1912) - Intensity of radiation α altitude —> radiation is ET
- The radiation is more penetrating than γ from radioactive decays
- Dmitri Skobeltsyn (1929) - cloud chamber, cosmic ray tracks
- What is observed on Earth were byproducts of very high energy cosmic rays (10^{15} eV)



Cosmic Rays

- Cosmic rays - a natural source of energetic particles which can penetrate into the nucleus.
- Millikan and Anderson (1930) - stronger electromagnet to track particles: discovery of "positively charged" electrons



Just as Dirac (1928) predicted from relativistic wave equation for the electron

- V - tracks (1947) - strange particles (kaons)

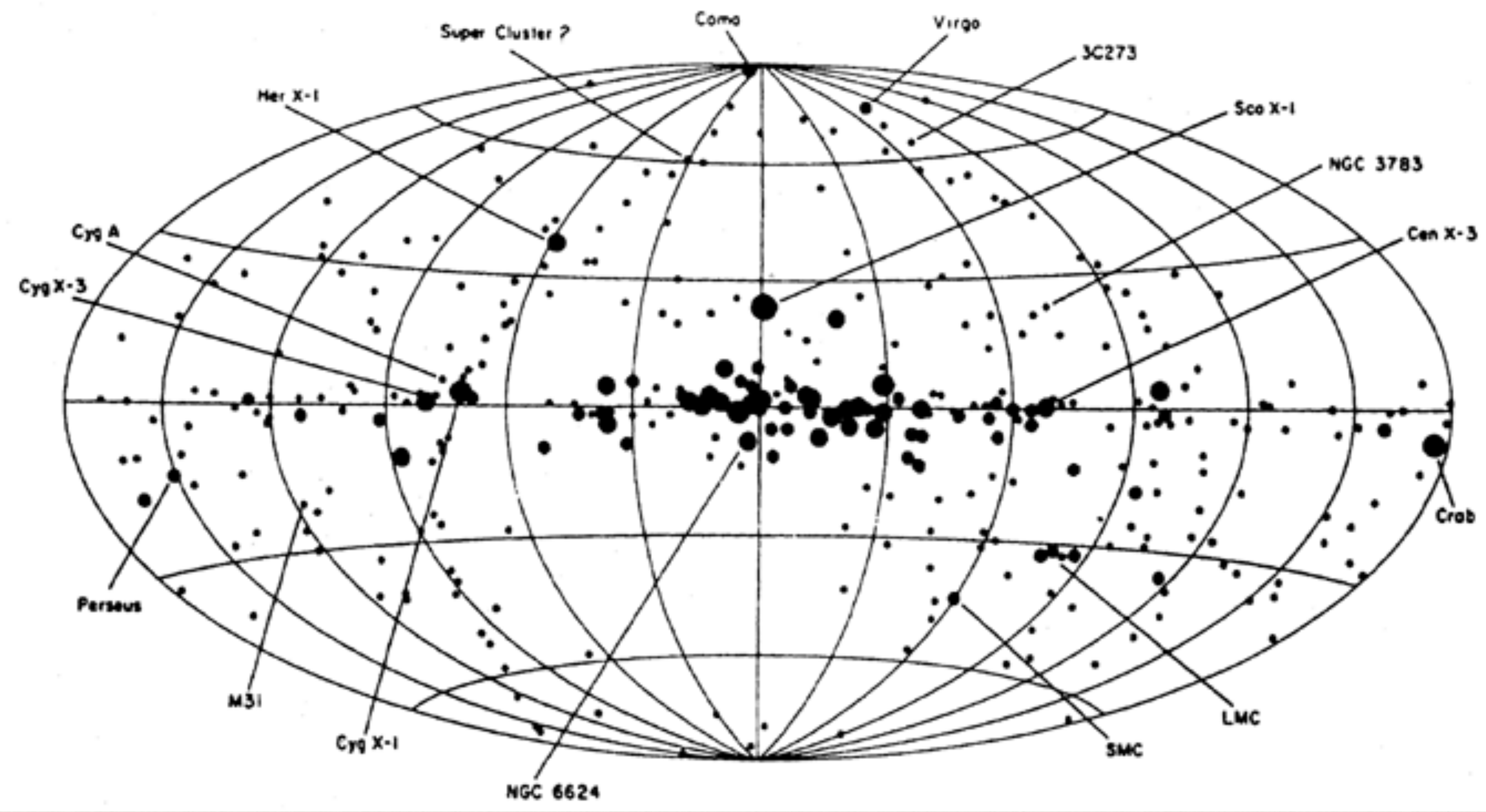
Radio Astronomy

- Karl Jansky (1933) -radio emission from the Galaxy
- James Hey (1942) -intense radio emission from the Sun
- First discrete radio source Cygnus A (1946)
- 3 more- associated with supernova remnant, NGC 5128 and M87
- Advancement of accelerator technology- synchrotron radiation: a broad band continuum and highly polarized.
- Alfven and Herlofson (1950)- Astronomical radio emission is due to the synchrotron radiation of high E electrons gyrating in magnetic fields.
- Radio emission throughout the disk of the Galaxy —> interstellar flux of high energy electrons
- Relativistic plasmas and magnetic fields —> high energy astrophysics

X-ray Astronomy

- Earth's atmosphere is opaque to radiation below 300-310 nm —>UV, X-ray and γ-ray astronomy had to be conducted 150 km above.
- War rockets became science rockets.
- First target: Sun -UV and X-ray emission. Sun has a very hot corona (1951)
- NASA (1958) was founded
- Crab Nebula emitted also in X-rays (1964)
- (1970) UHURU, first satellite dedicated to X-ray astronomy
- Ariel V, X-ray spectrometer: emission line of Fe^{+26} from Perseus.

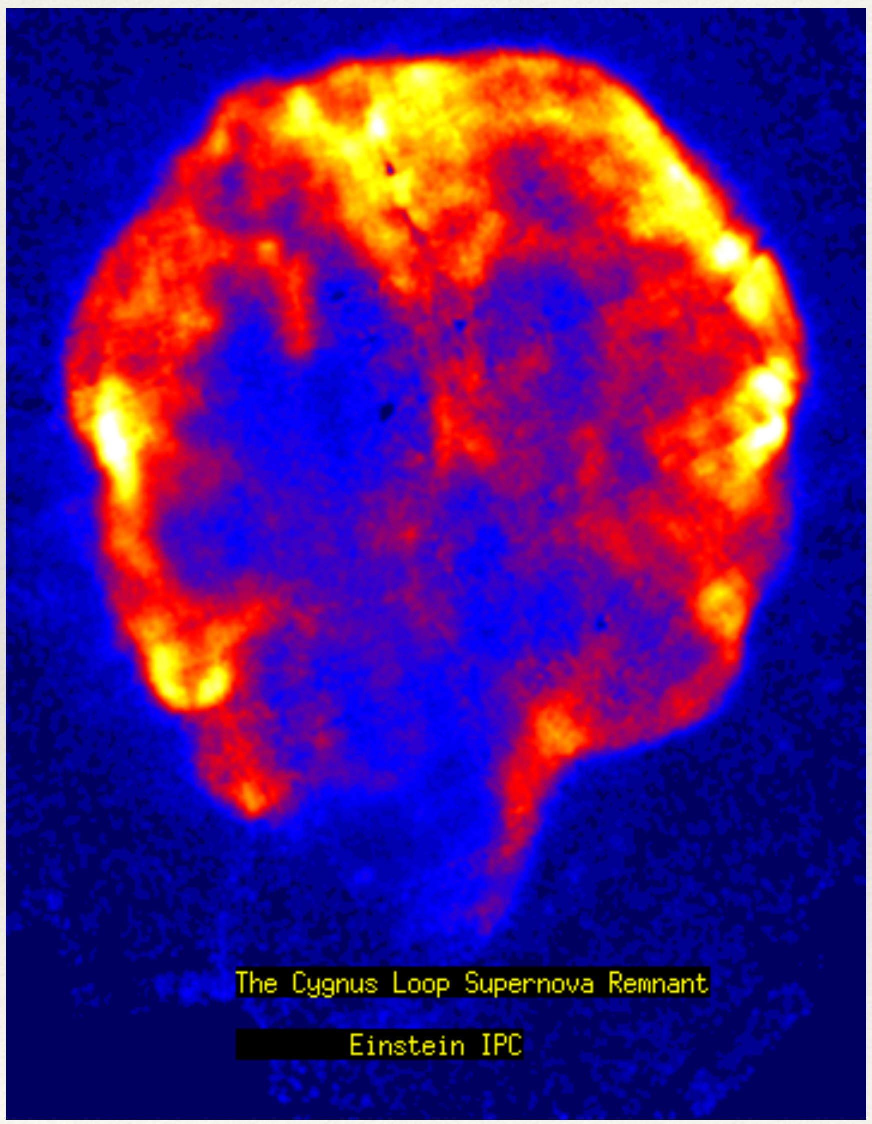
X-ray Astronomy

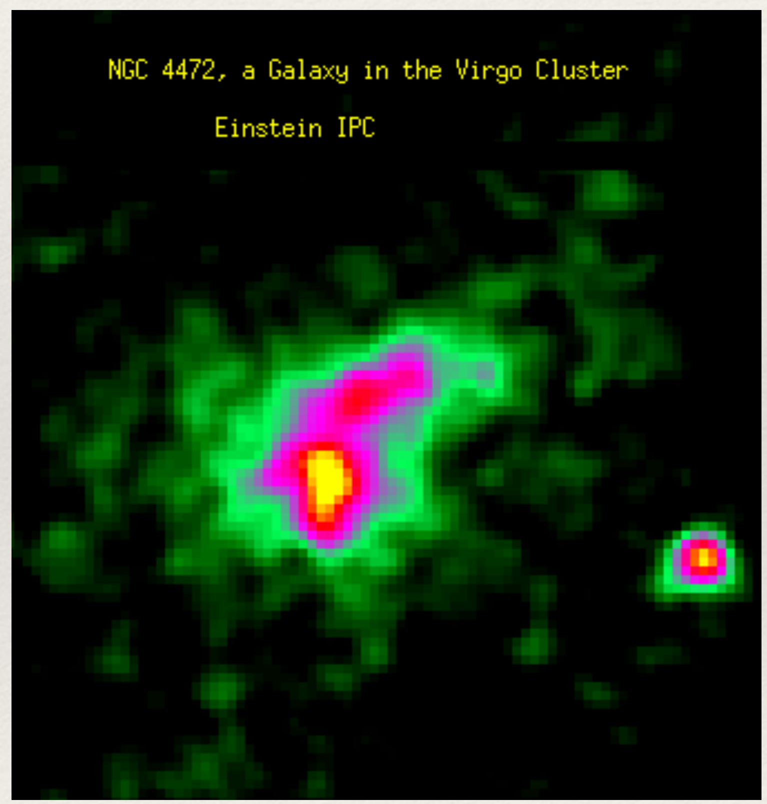


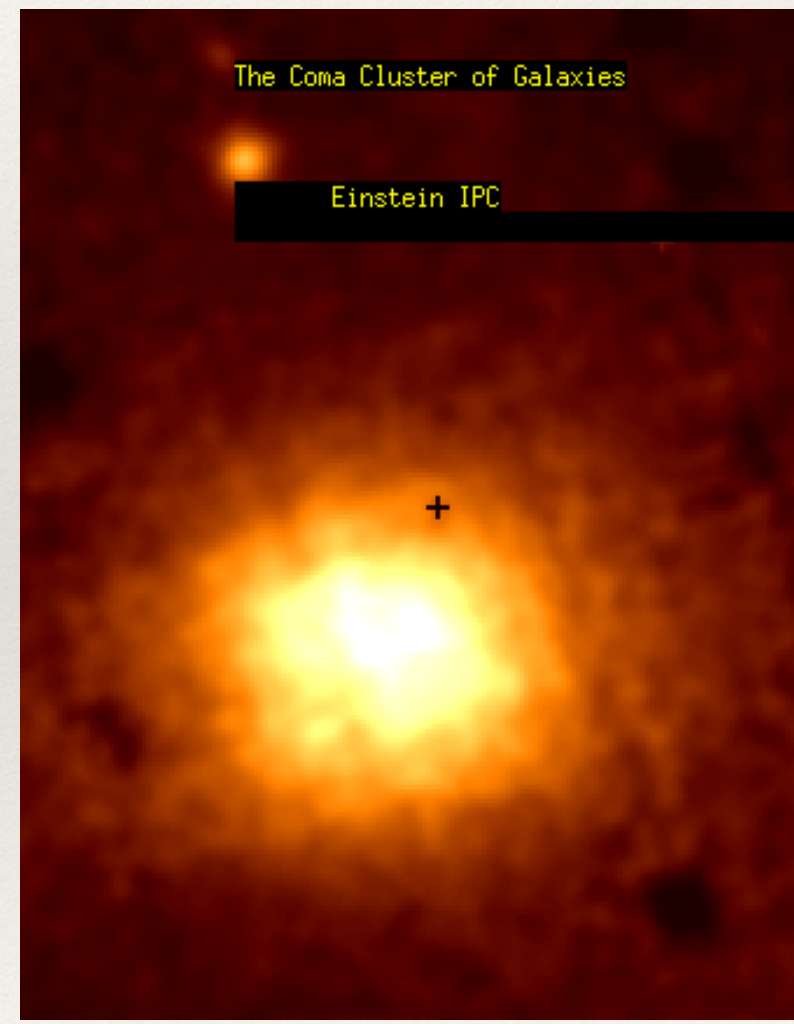
UHURU, 1978

X-ray Astronomy

- X-ray telescopes with imaging capabilities: Einstein X-ray Observatory (1978)

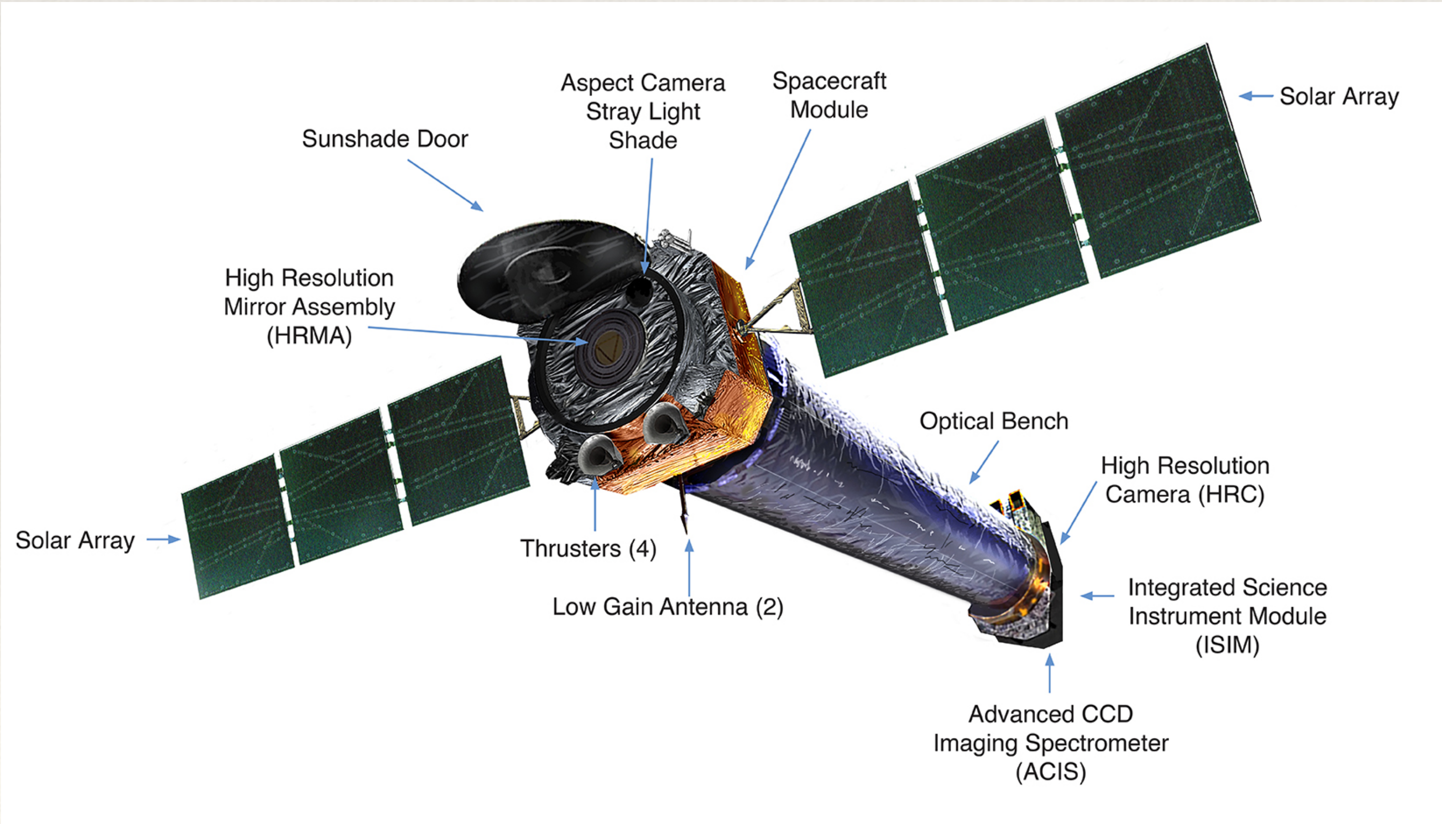


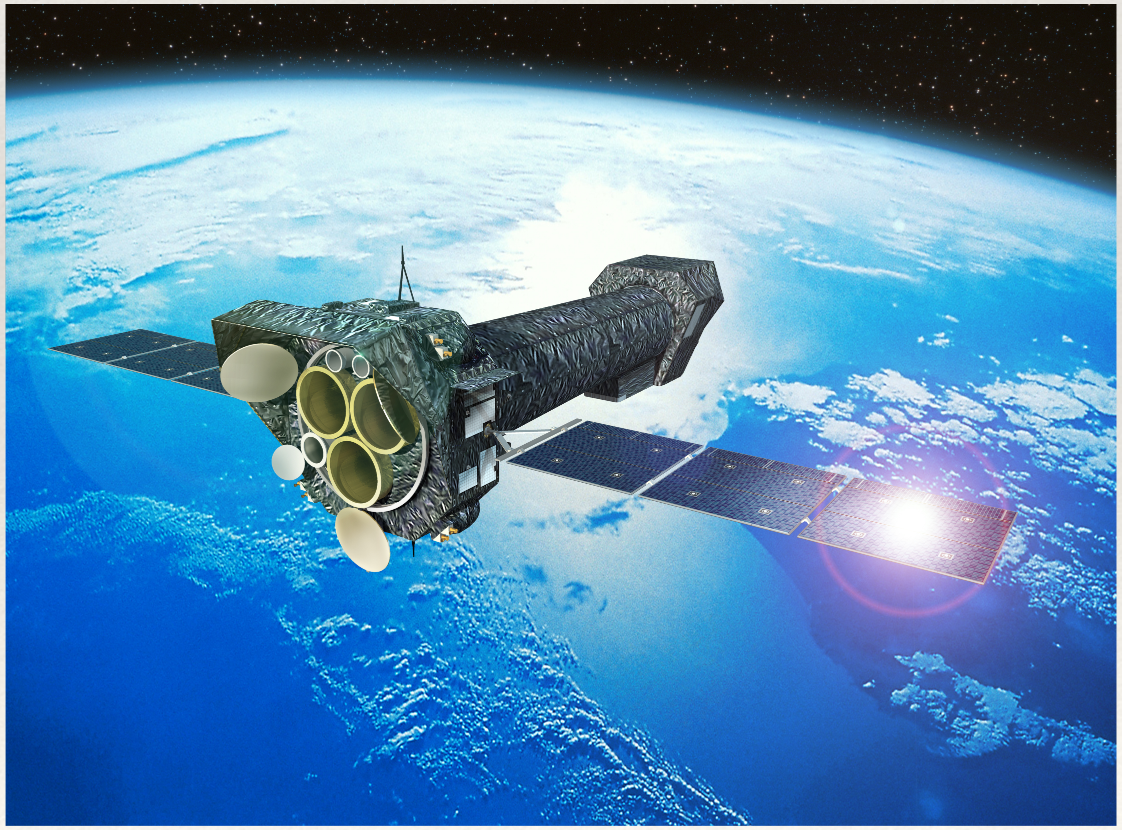




X-ray Astronomy

- NASA Space Transportation System- 'Great Observatories':
  - Hubble Space Telescope
  - Gamma-Ray Observatory
  - Advanced X-ray Astronomy Facility (Chandra)
  - Space Infrared Telescope Facility
- ESA- high sensitivity and high spectral resolution - XMM-Newton

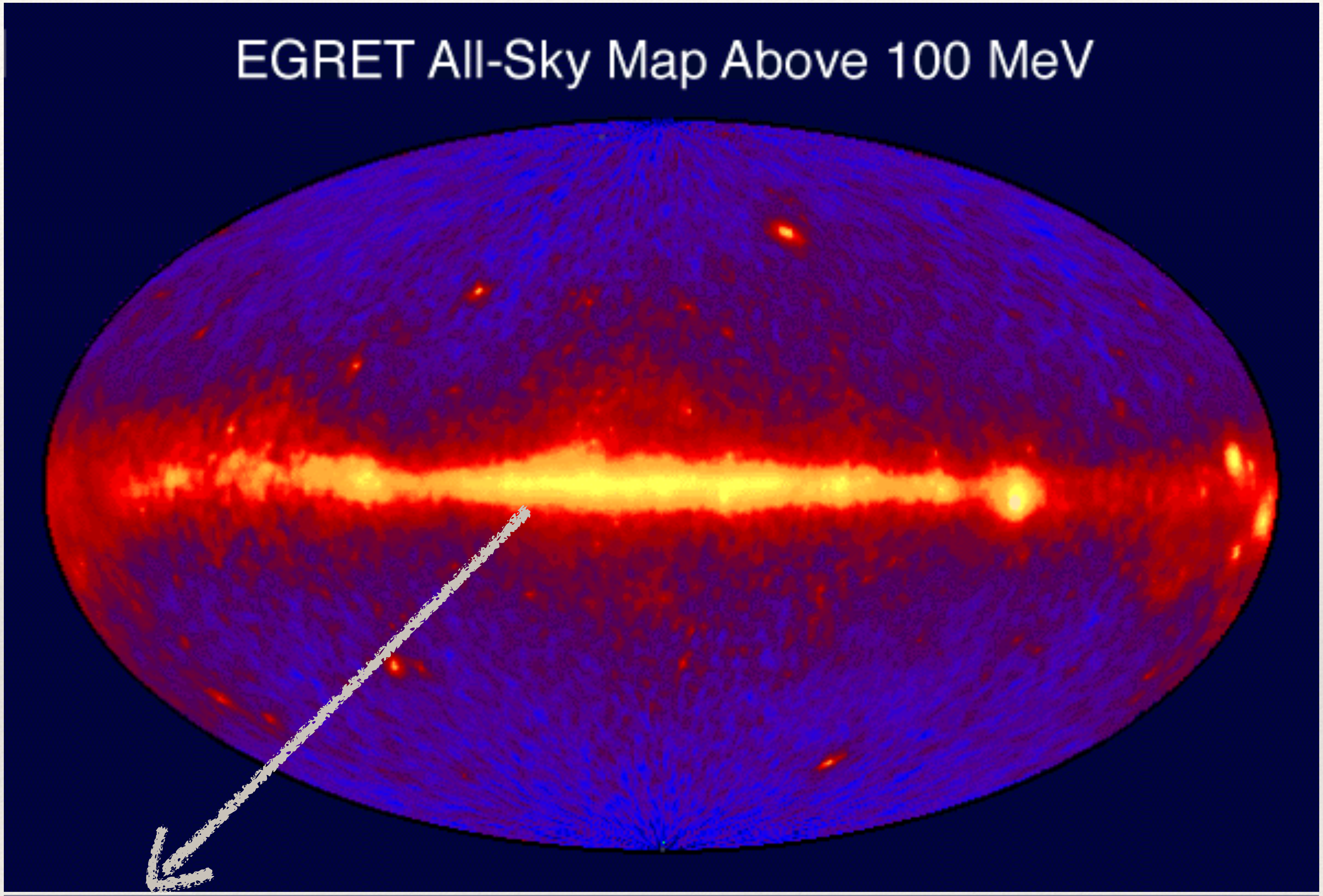




γ-ray Astronomy

- γ-ray emission, $E_\gamma > 100$ MeV, from the Galactic Center with OSO-III (1968): decay of neutral pions from cold plasma (interstellar gas) and relativistic proton collisions.
- SAS-2 discoveries (1978)
  - Concentration of γ-rays at the plane of the Galaxy
  - Discrete γ-ray sources (pulsars in SNRs)
  - Diffuse extragalactic γ-ray background radiation
- First γ-line emission detection: electron-positron annihilation at 511 keV (1977)
- The γ-ray map of the sky…

γ-ray Astronomy

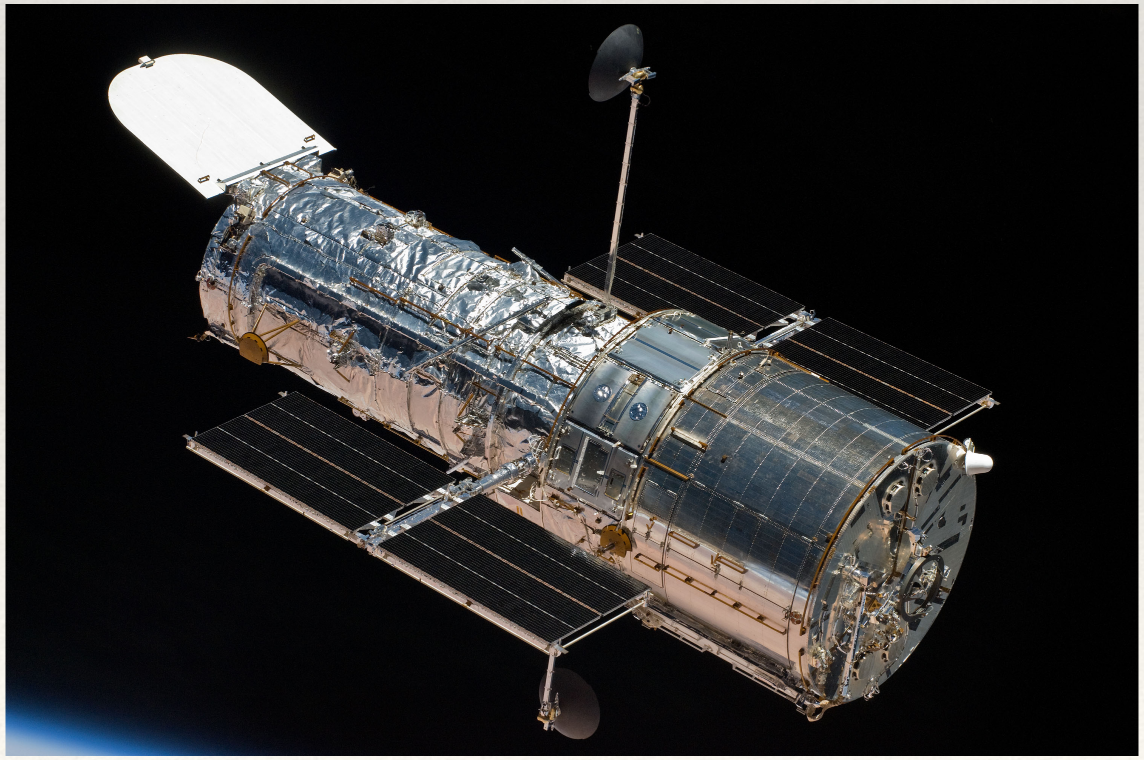


Decay of neutral pions

Discrete sources: pulsars and quasars

UV Astronomy and HST

- Orbiting Astrophysical Observatories 1, 2, 3, 4 (OAO, 90-330 nm)
- Detection of interstellar Lyman-α and Lyman-ε absorption lines of deuterium from blue stars
- Absorption lines of highly ionized O^{5+} —> Interstellar gas has a hot component
- Hubble Space Telescope (1990)- to overcome astronomical "seeing".

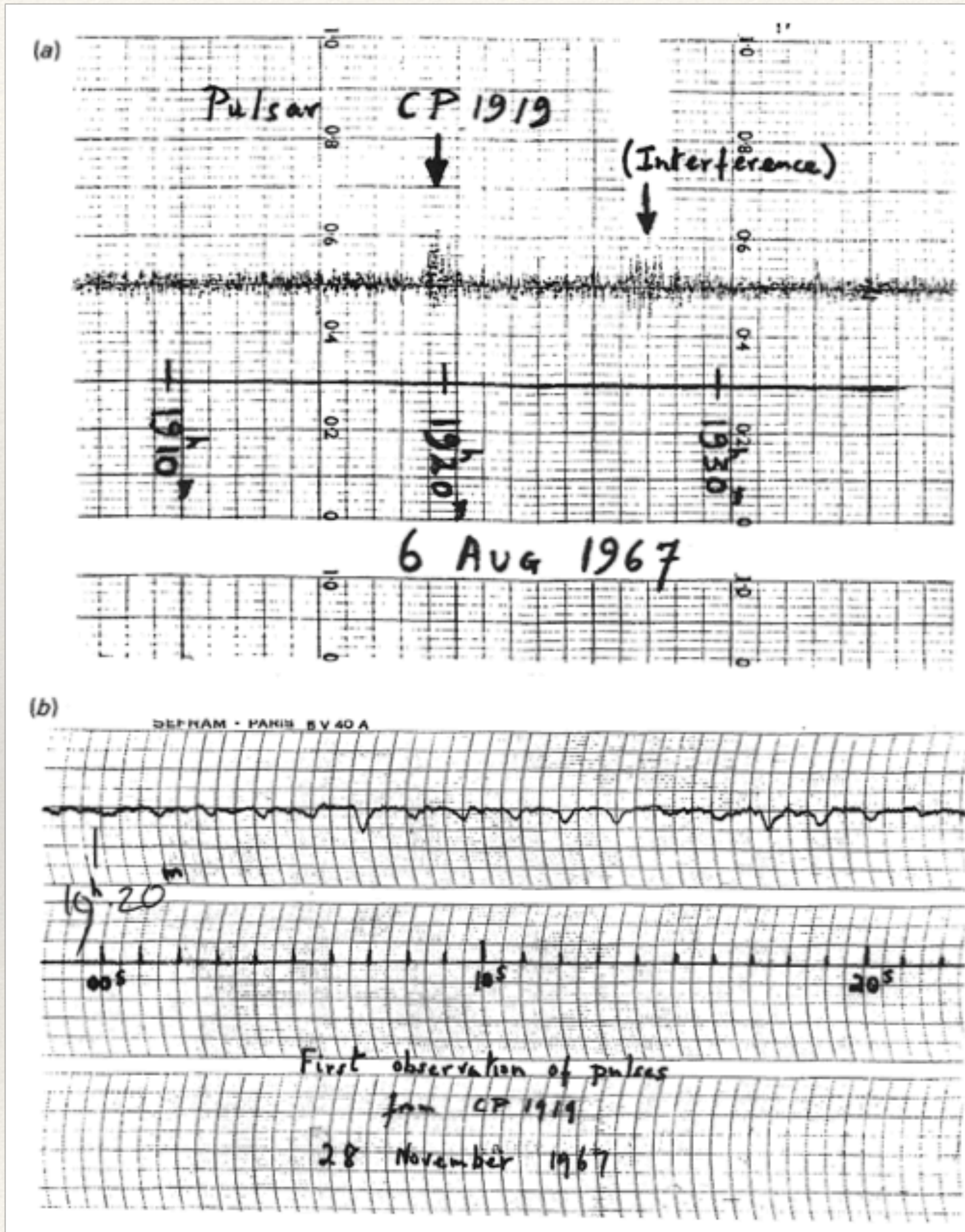


NASA

Neutron Stars

- Predicted in 1934 (Baade and Zwicky) after the discovery of neutron.
- Believed to be detectable through X-ray emissions - hot object, rapid cooling, thermal X-ray radiation.
- Pacini predicts they can be observable at long radio wavelengths, IF, magnetized and oblique rotators.
- Discovered by “chance"as parent bodies of radio pulsars (Hewish and Bell - 1967). By observing the scintillation of radio sources.
- This technique was used to discover radio quasars.
- Discovery of pulsating radio stars; isolated, rotating, magnetized neutron star - pulse due to the misalignment of magnetic and rotation axes. Hundreds of rations in a second!
- Stable stars, formed by stellar collapse.. black hole ‘wannabe's.

Neutron Stars



24-year-old Jocelyn Bell*

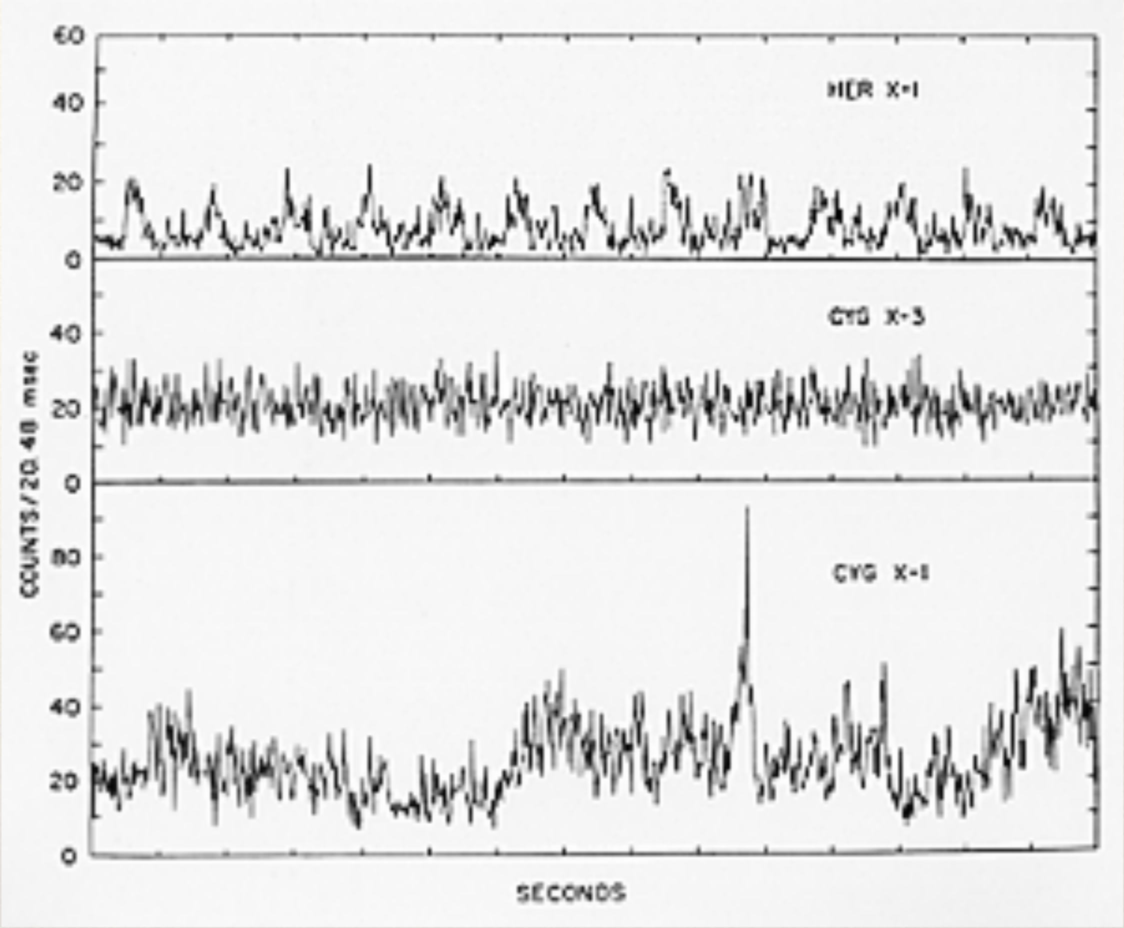
*don't be discouraged!

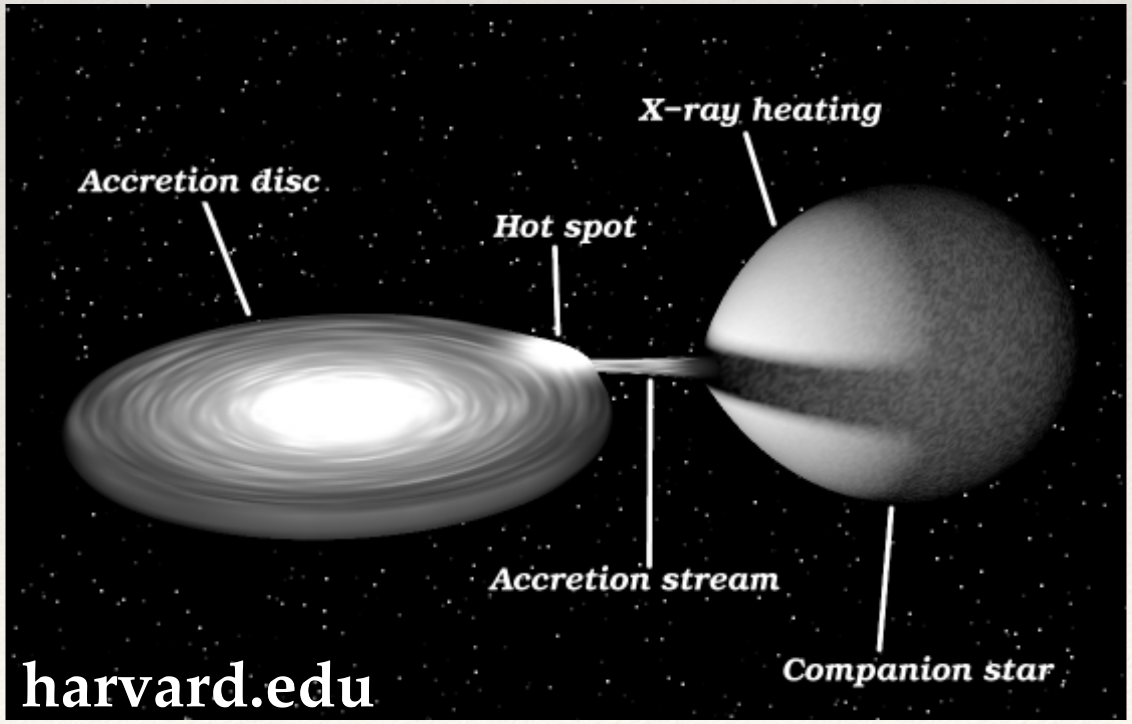
X-ray Binaries and Black Holes

- Discovery of binary X-ray sources, complete X-ray survey of the X-ray sky, UHURU (1971), key objective - variable X-ray sources.
- Observation of Cygnus X-1, variability with 100ms - compact in nature
- Observation of Centaurus X-3
    - (January 1971), unstable pulsation period of 5s - longer than pulsars.
    - (May 1971), sinusoidal pulsations (period of 2.1 days) - Doppler shift of the X-ray pulses in a binary orbit
    - The source is shadowed by a star in the binary system
    - (1973) Star is a massive blue star with the same period

X-ray Binaries and Black Holes

- Observation of Hercules X-1 (1972); X-ray source is a neutron star, accretion is the source of energy.
    - Presence of strong magnetic fields (1978)
- Accreted matter with considerable angular momentum - an accretion disk is formed
- X-ray emission originates from the surface of the neutron star - emitting region has temperature about 10^7 K.





X-ray Binaries and Black Holes

Can there be black holes amongst these X-ray binaries?

How can you look for them?

X-ray Binaries and Black Holes

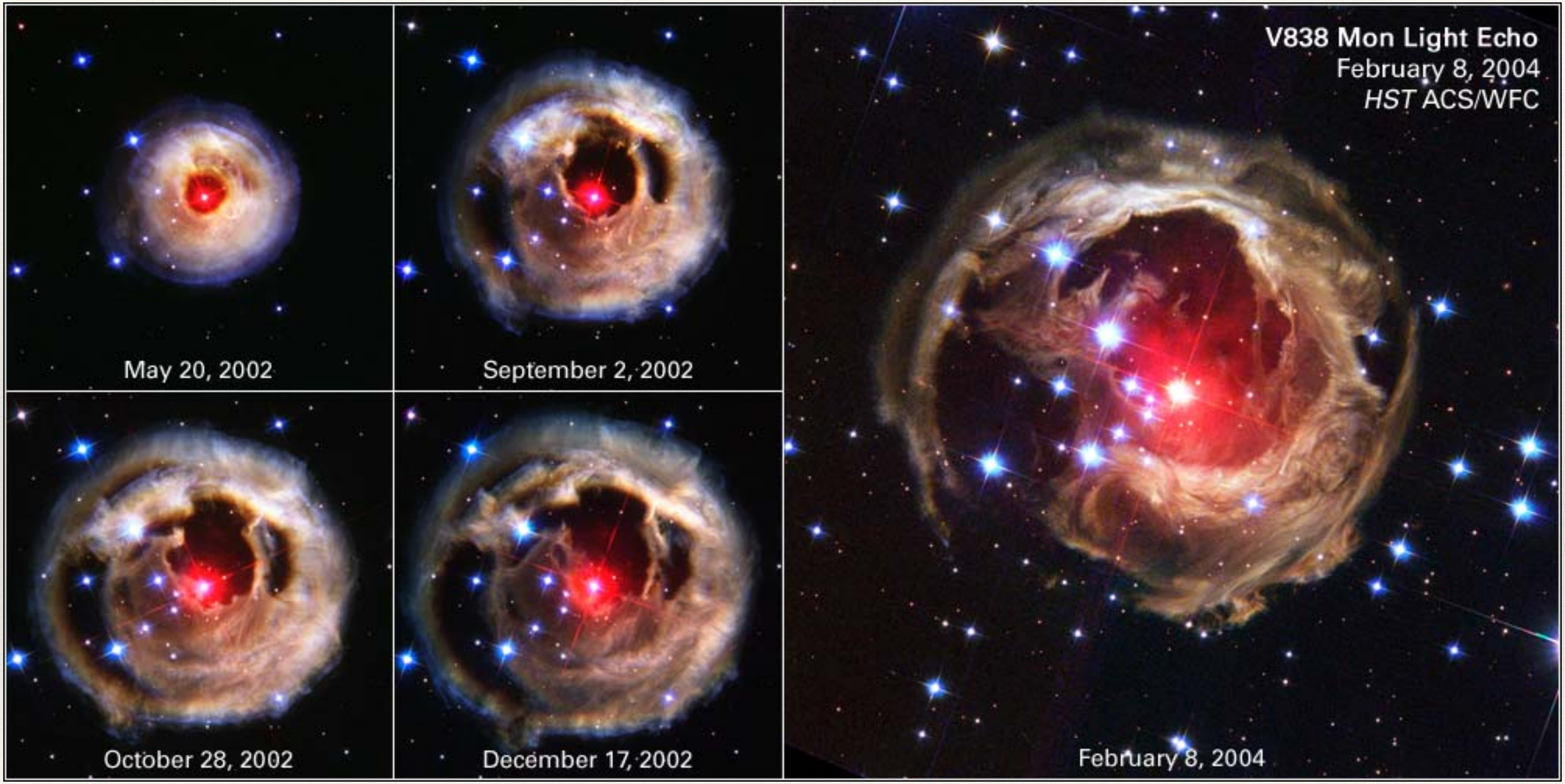
Can there be black holes amongst these X-ray binaries?

How can you look for them?

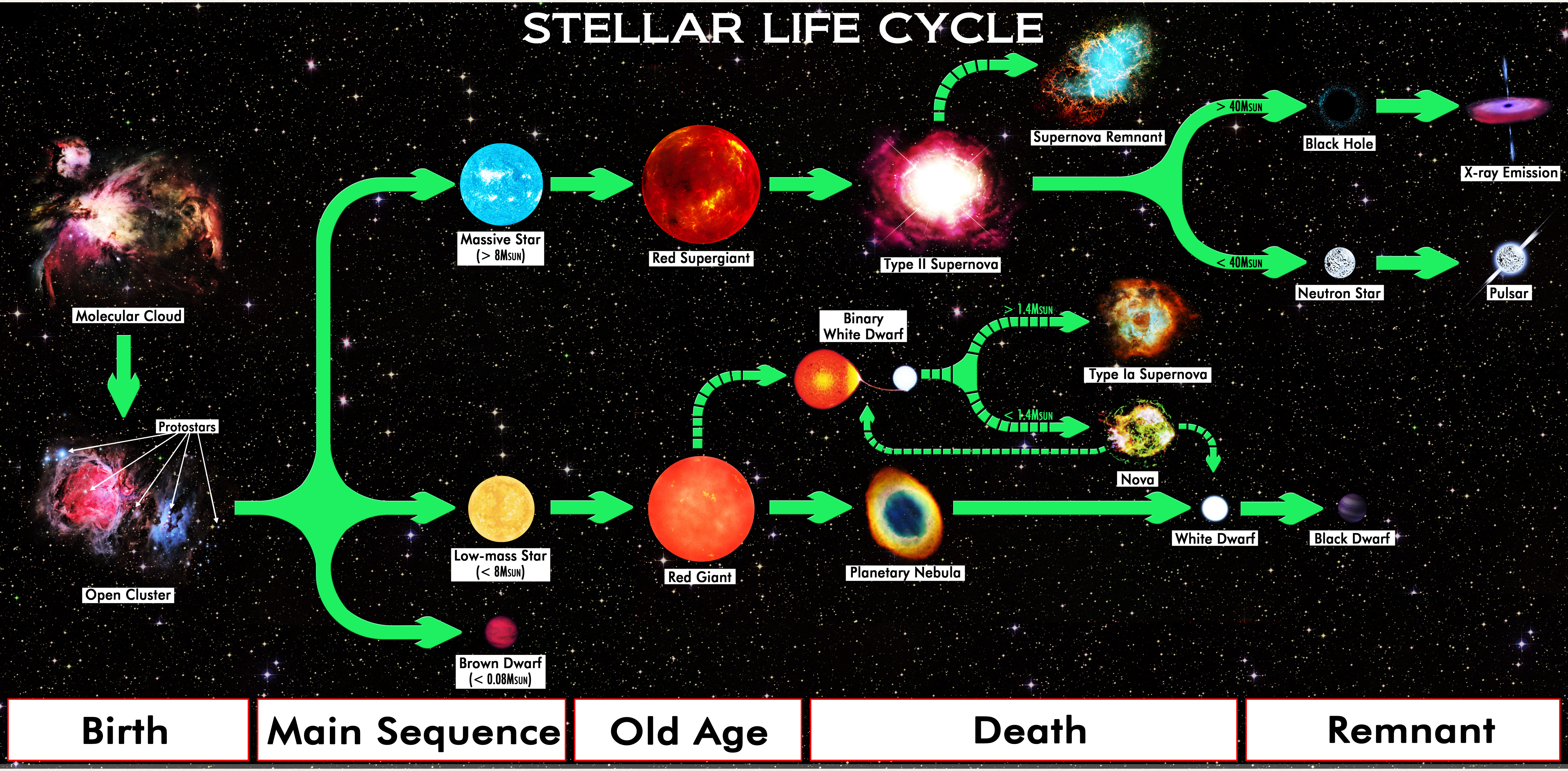
1. **Search for a variable X-ray source**
2. **Find accurate radio position**
3. **Look for a companion star**
4. **Find mass ratios**

- Cyg X-1 was associated with a 20 solar mass blue supergiant star (1971)
- Invisible companion mass was about 10 solar masses: higher than the upper limit for a stable neutron star- must be a black hole (although, Hawking was not convinced until 1990)

Supernovae


V838 Mon Light Echo
February 8, 2004
HST ACS/WFC
May 20, 2002
September 2, 2002
October 28, 2002
December 17, 2002
February 8, 2004

Supernovae


STELLAR LIFE CYCLE
Molecular Cloud
Protostars
Open Cluster
Massive Star
(> 8MSUN)
Low-mass Star
(< 8MSUN)
Brown Dwarf
(< 0.08MSUN)
Red Supergiant
Red Giant
Type II Supernova
Supernova Remnant
> 40MSUN
< 40MSUN
Black Hole
X-ray Emission
Neutron Star
Pulsar
Binary
White Dwarf
> 1.4MSUN
< 1.4MSUN
Type Ia Supernova
Nova
Planetary Nebula
White Dwarf
Black Dwarf
Birth
Main Sequence
Old Age
Death
Remnant

Supernovae

- Baade and Zwicky (1934), existence of super-novae based on 12 supernovae (1900-1930) and historical supernovae (Tycho Brahe, “new star”, 1572)
- Schmidt telescope (1936)
  - First supernova in NGC 4157 (March 1937)
  - Second, in IC 4182 (August 1937), apparent magnitude of 8.4 - 6 magnitudes brighter than the galaxy itself!
- Minkowski proposed two types (1941)
  - Type I
    - broad emission bands: superposition of hundreds of Fe^{+} and Fe^{++} lines
    - Absence of hydrogen lines
    - Found in all types of galaxies
  - Type II
    - Balmer series of hydrogen
    - Only found in spiral galaxies- within the spiral arms
    - More energetic wrt Type I

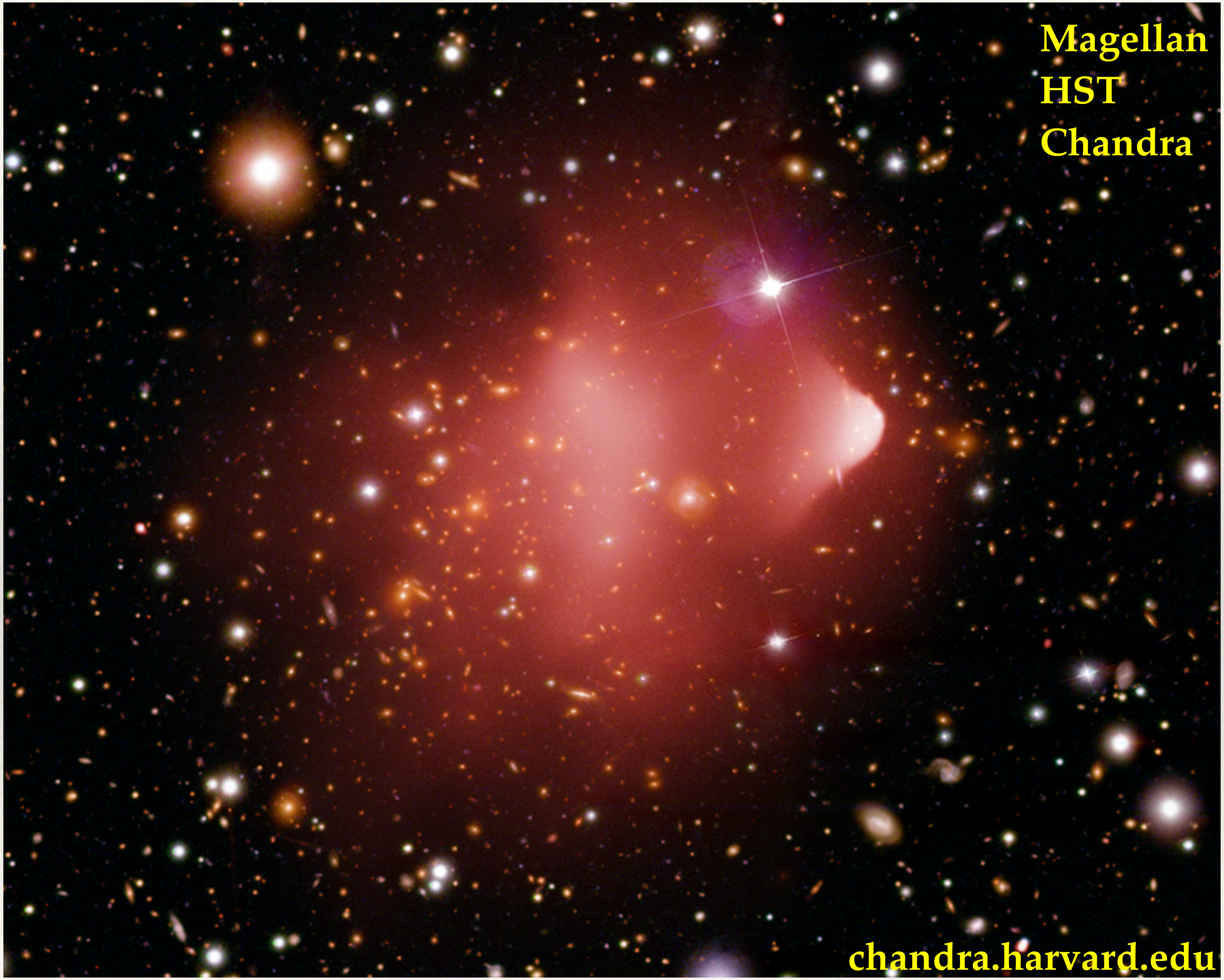
Supernovae

- Both types are quite energetic - collapse of a star to a compact remnant, neutron star or black hole
- Type II: collapse of massive stars $M \geq 8\ M_{sun}$
  - Hydrogen absorption lines: explosion of the core takes place within the red giant
- Type I: accretion of mass onto a white dwarf in a binary system
  - Heating of the surface by the infalling matter
- Initial outburst- long exponential decay of the luminosity
  - Creation of radioactive nickel in the explosion
  - Decay of ^{56}Co - 3.5 MeV γ-rays.

$$^{56}_{28}\mathrm{Ni} \rightarrow\ ^{56}_{27}\mathrm{Co} + e^{+} + \nu_e + \gamma$$

$$^{56}_{27}\mathrm{Co} \rightarrow\ ^{56}_{26}\mathrm{Fe} + e^{+} + \nu_e + \gamma$$

Clusters of Galaxies



Clusters of Galaxies

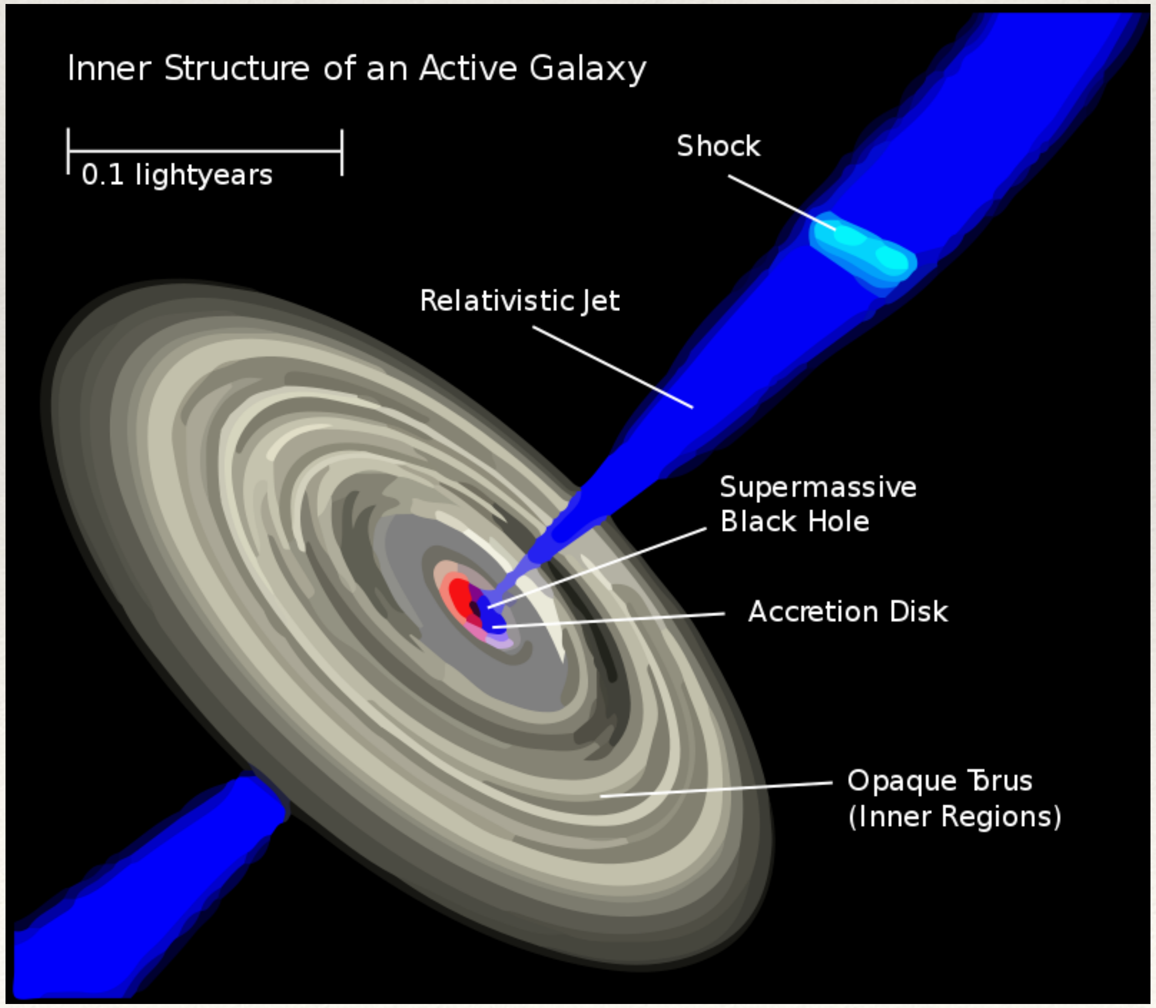
- UHURU - clusters of galaxies are intense X-ray sources
- Emission is diffuse and fills the core (Coma, 1971)
- Bremsstrahlung emission - hot intracluster gas
- Ariel-V discovers emission lines from tightly ionized Fe XXV and Fe XXVI (1976).
- ROSAT- maps of the X-ray surface brightness distribution, and mass distribution in galaxies, in hot gas and dark matter.
- Sunyaev-Zeldovich (1970)- cosmic microwave background photons scattering off of electrons, reach high energies by Compton scattering - pressure of the gas can be inferred.
- Pressure + X-ray temperature and emissivity = physical size of the hot gas, independent of it’s distance —> expansion of the universe (Hubble’s constant)

AGN

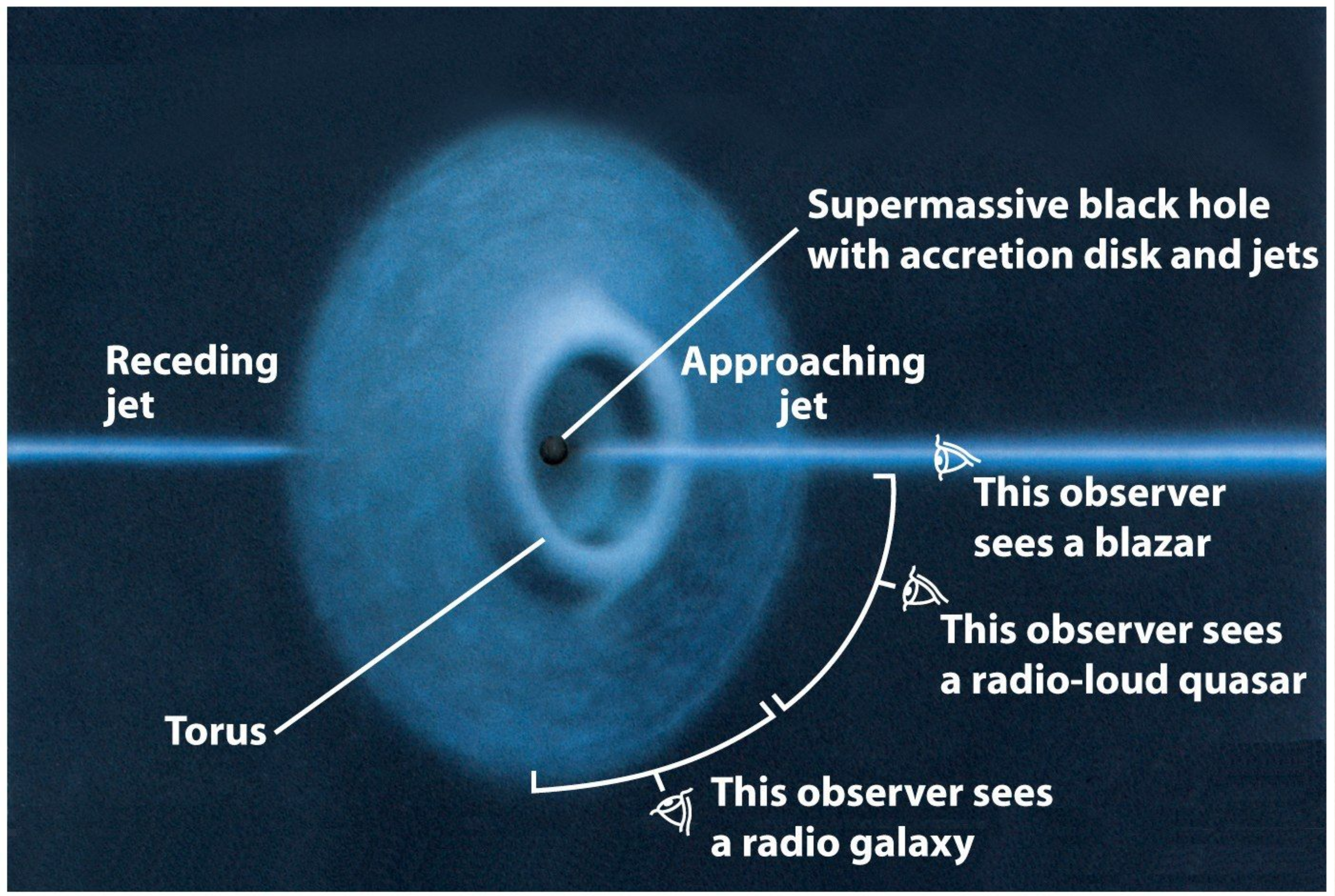
- Identification of the radio galaxy 3C 295 (Minkowski, 1960)
- Optical identifications and redshift of radio sources were studied
  - broad emission lines at unfamiliar wavelengths
  - Variable sources
  - Excess UV emission wrt normal stars
  - Come to known as quasi-stellar radio sources (or quasars)
- 3C 273 A (1963) - a starlike object and a jet pointing away from the star
  - 4 optical emission lines and the redshift was found
  - With the known redshift, a UV line was identified
  - Photoelectric spectrophotometry showed an IR emission line

AGN

- Optical luminosities- 10-30 times brighter than giant ellipticals
- Radio surface brightness- lager than radio galaxies
- Nuclear region- 1 kpc in diameter, the jet- 50 kpc (timescale 10^5 yr)



Unified Model



http://web.physics.ucsb.edu/