High Energy Astrophysics

What is 'High Energy Astrophysics'?

Wikiedia says :

- High energy astronomy is the study of astronomical objects that release EM radiation of highly energetic wavelengths. It includes X-ray astronomy, gamma-ray astronomy, and extreme UV astronomy, as well as studies of neutrinos and cosmic rays. The physical study of these phenomena is referred to as high-energy astrophysics.

Half-true

HEA also studies objects
Where

gravity is very strong (Neutron stars, white dwarfs and black holes)

things are moving very fast ('relativistic')- e.g jets, supernovae

'very hot' or energetic -gas in clusters of galaxies, supernovae remnants, interstellar medium of spiral and elliptical galaxies

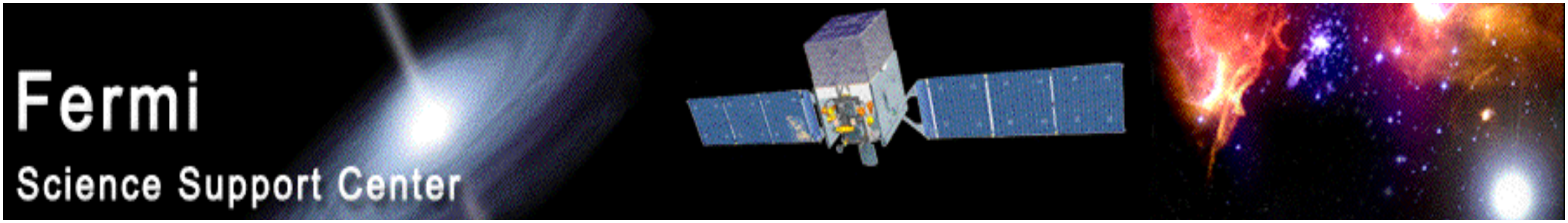
The universe itself (cosmology)

But we may observe high energy phenomena at other energies

Not only photons and particles !- also gravitational waves

HEA Continued

- The study of such objects and processes thus covers a VERY wide range of physics and types of physical objects.
- In order to study x-rays, γ-rays etc from astrophysical objects one needs special techniques and telescopes and the work often must be done in space (I will focus on photons)
- There is a lot of material available (see http://heasarc.gsfc.nasa.gov/docs/heasarc/resources.html) in particular the 'x-ray' schools
- http://heasarc.gsfc.nasa.gov/docs/xrayschool-2007
- And from various 'mission' sites



Conduct of Class

- Ask questions if you do not understand what I am saying or need more explanation-
  - In other words *SLOW ME DOWN*
  - I will be happy to provide additional references and reading material
  - *If I fall into 'jargon' remind me*
- I expect to have a early-term student review of the class- are we heading in the right direction at the right level of detail and the right choice of material

Why Bother with High Energy At All??

The energies covered by high energy astrophysics have 'unique' attributes not available in other energy regimes -e.g. for x-rays

- The Ionization balance, as in all other energy bands is a strong function of temperature and ionization parameter- but can observe most of the ions directly
- The atomic physics is extremely simple (compared to other λ bands) since the strongest lines are H and He-like.

s

For which the ab intitio calculations of cross sections and rates is particularly simple

- 'Relatively' easy to distinguish method of ionization (e.g. collisional, shocks photoionization)
- The x-ray band is sensitive to all stage of ionization from absorption by cold material (e.g. CI) to emission by hot material (e.g. Ni XXVII) and thus provides a wealth of diagnostics

- Weak radiative transfer difficulties
- Unique 'penetrating' capabilities (e.g. most of the universe is obscured (AGN and star formation)
- Most of the baryons in the low z universe can only be observed in the x-ray band

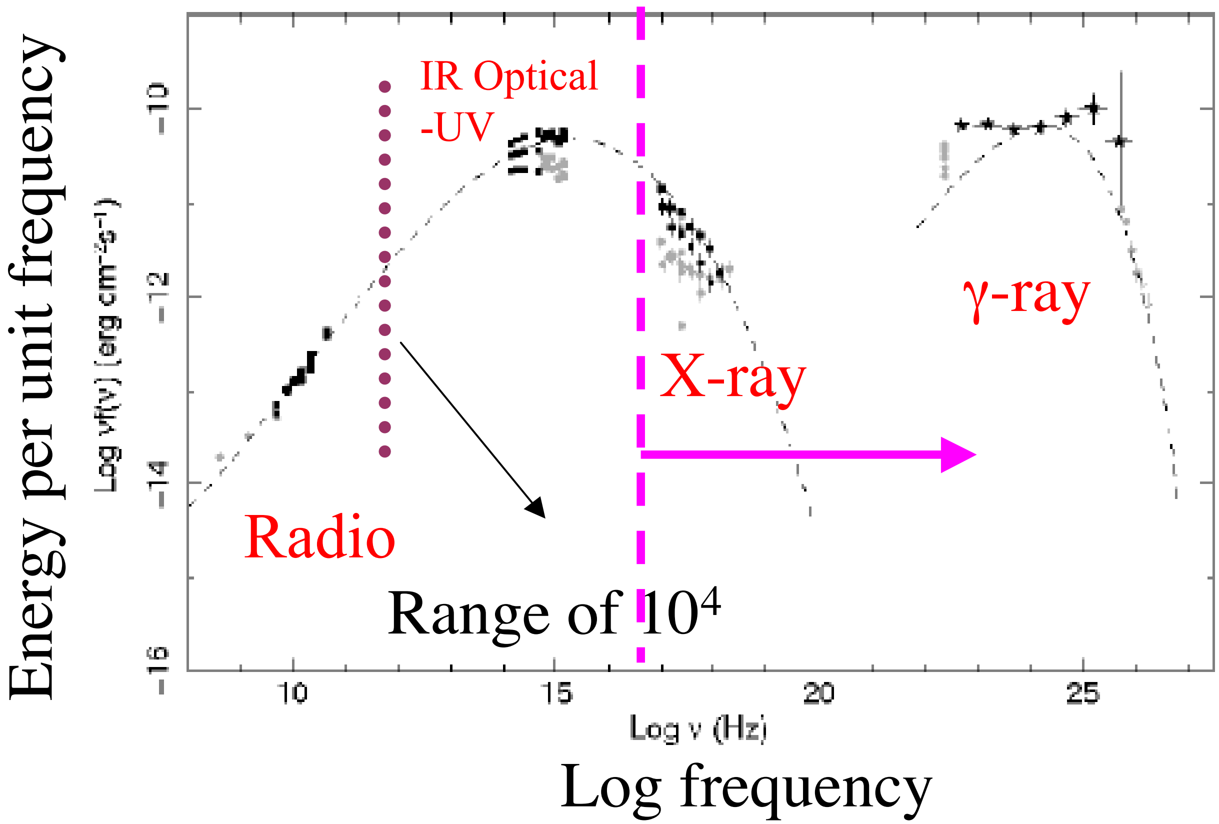
For certain classes of objects (AGN, x-ray binaries,clusters of galaxies) a large fraction of the emitted energy is in the high energy band

In the 0.6-1000Mev γ-ray band most of the universe is transparent
However at higher energies γ-rays are 'absorbed' by photons and thus the opacity at very high energies is a measure of the photon density of the universe

γ-rays are the emitted by radioactive isotopes and thus are a measure of creation of the elements

Multi-Wavelength Astronomy

- Astronomy is a multi-wavelength *observational* science
- Most astronomical objects from the comets to quasars emit radiation across the electromagnetic spectrum
- In order to understand these objects one has to observe them from radio wave to γ-rays (17 orders of magnitude in frequency)



Broad band spectral energy distribution (SED) of a 'blazar' (an active galaxy whose observed radiation is dominated by a relativistic jet 'coming at' us

A large fraction of the total energy appears in the γ-ray band

Astrophysics (Astronomy) and Physics

- Astrophysics is a branch of physics like geophysics and meteorology
- One does observations not experiments
- This gives a very different flavor to the field
- Of course 'physics' thinking is crucial- we try to understand, not just categorize, catalog and count.

The universe is a very big, complex and exciting place

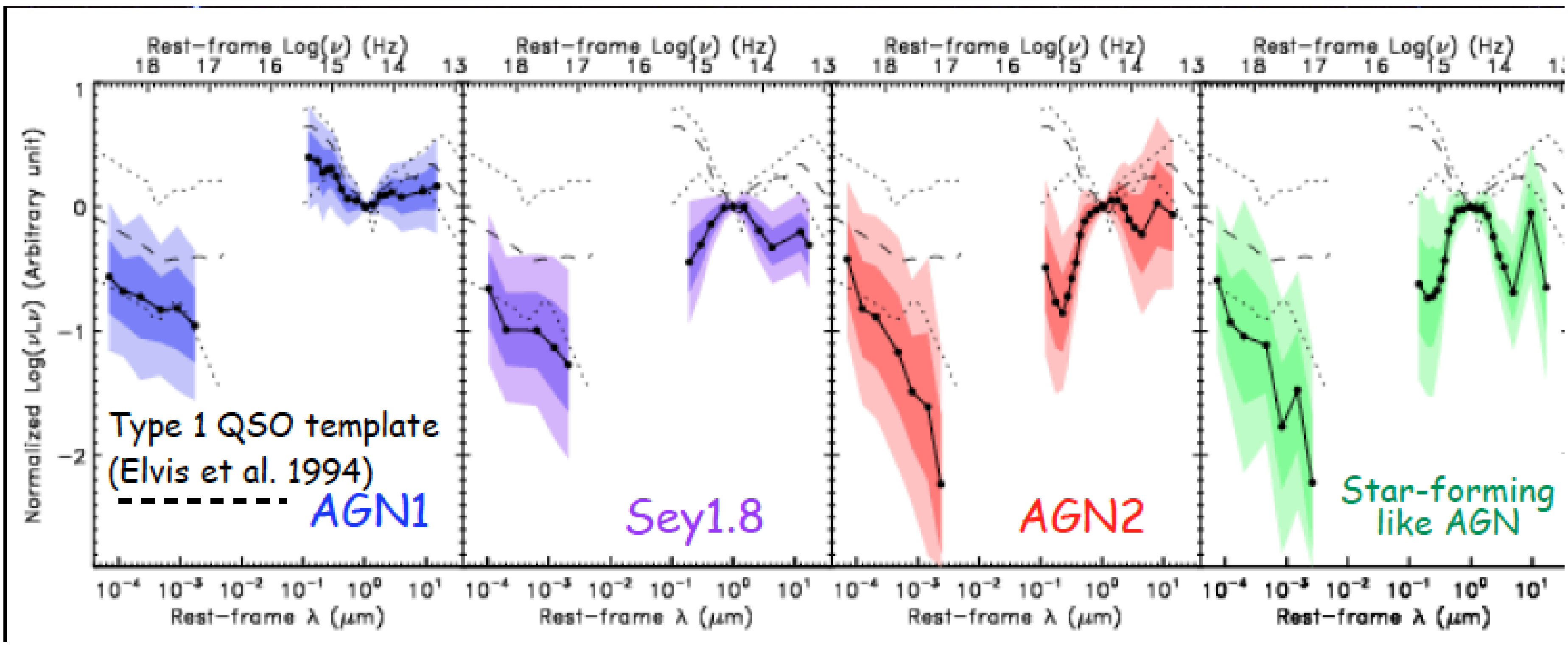
Most of what we have learned in the last 50 years have come from unexpected discoveries

Much of this has been driven by new instrumentation and the opening up of new observing windows and the rapid advance of computing

The wide range of astrophysical conditions involves **virtually all of physics** (plasma, atomic, nuclear, quantum etc) and thus astrophysicists have to be knowledgeable about almost all of physics

Different Types of Objects Have Different SEDS

- The broad band spectrum represents the convolution of the energy generating mechanisms and the radiative transfer of this energy to the observer
- In other words the 'engine' and its environment



From the National Academy of Sciences

Report issued 8-13-2010

In order to carry out astronomical research, there are increasing demands for detailed knowledge across many sub-fields of physics, statistics, and computational methods. In addition, as astronomy and astrophysics projects have become more complex, both in space and on the ground, there has been a greater need for expertise in areas such as instrumentation, project management, data handling and analysis, astronautics, and public communication, These require broader training

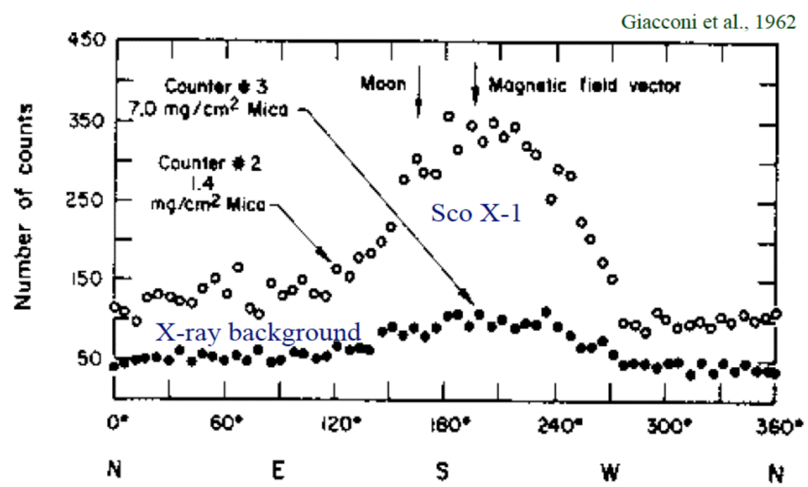
High Energy Astrophysics is 'New' http://heasarc.gsfc.nasa.gov/docs/history/

- Astronomy is the 1st science- back to Mesopotamia
- High energy astrophysics
  - cosmic rays were discovered in 1912 by Victor Hess (**Nobel prize** 1936),
    - when he found that an electroscope discharged more rapidly as he ascended in a balloon.
      - source of radiation entering the atmosphere from above
    - Cosmic' rays' are electrically charged particles
  - The latest project is the Pierre Auger in Argentina-A Detector 30 Times the Size of Paris

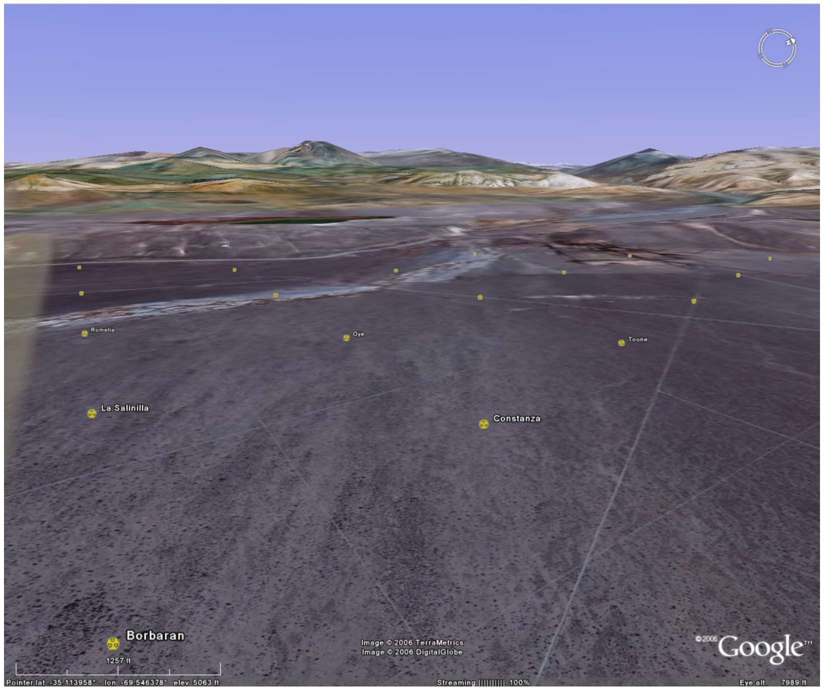
The first astronomical X-ray source- the sun (1948) using captured WWII V2 rockets. Herb Friedman and collaborators at the US Naval Research Lab (in Washington DC).

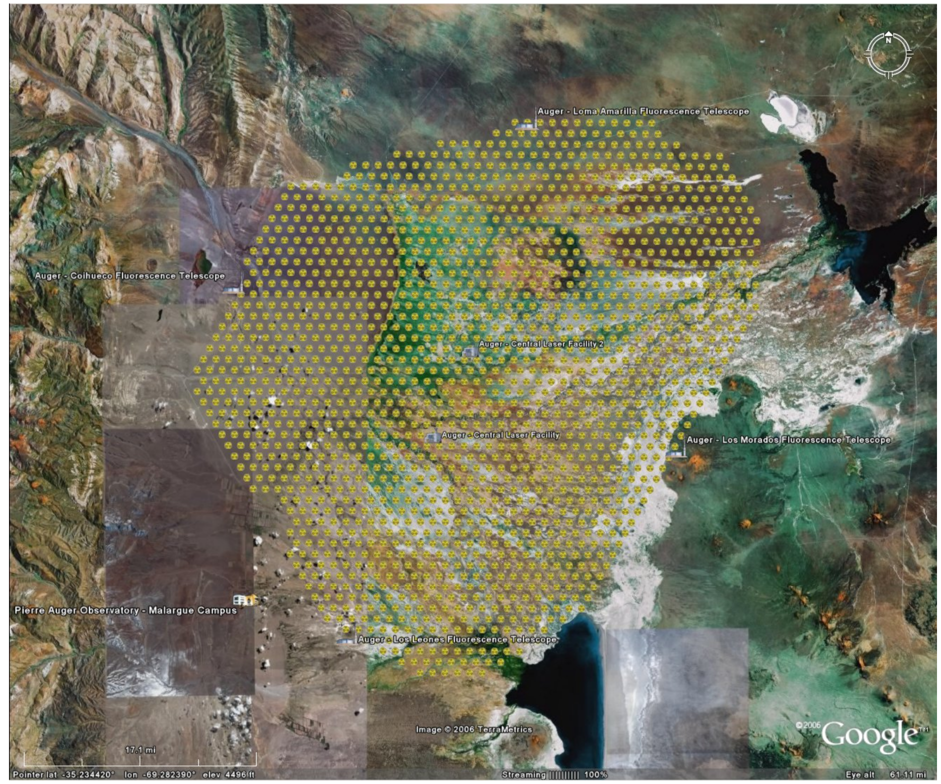
First non-solar x-ray source Sco X-1 rocket (Giacconi et al **Nobel prize** 2002)

The First Extra-Solar X-ray Detection



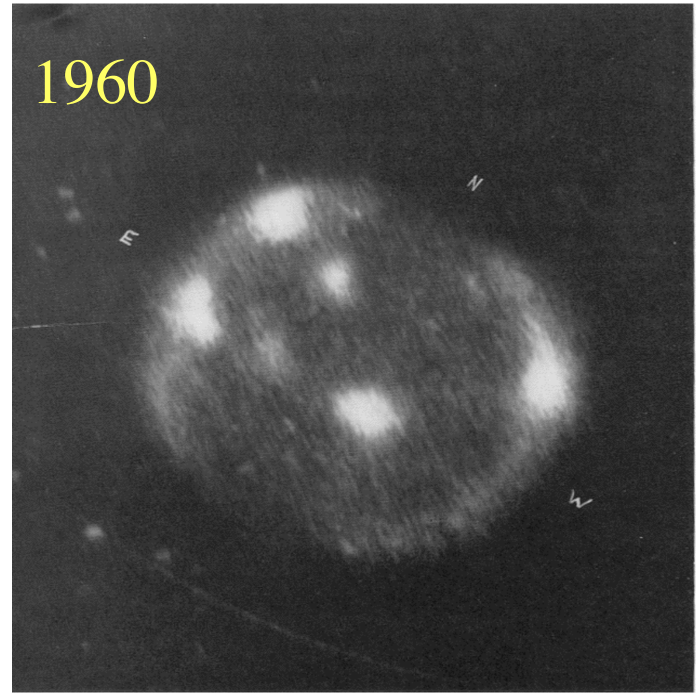
Pierre Auger Observatory-Google Earth

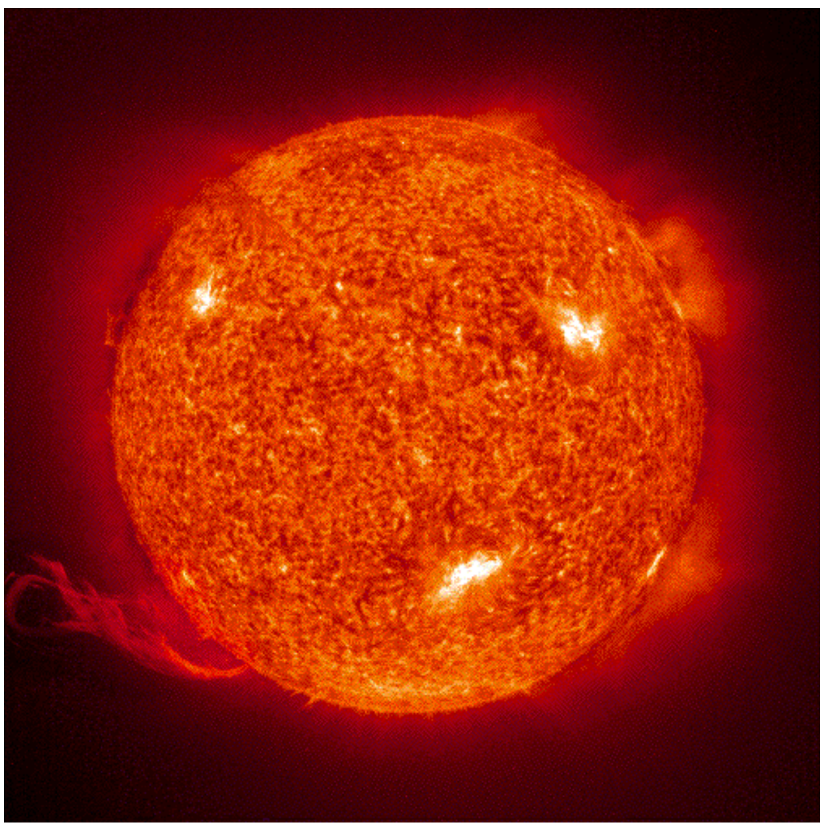




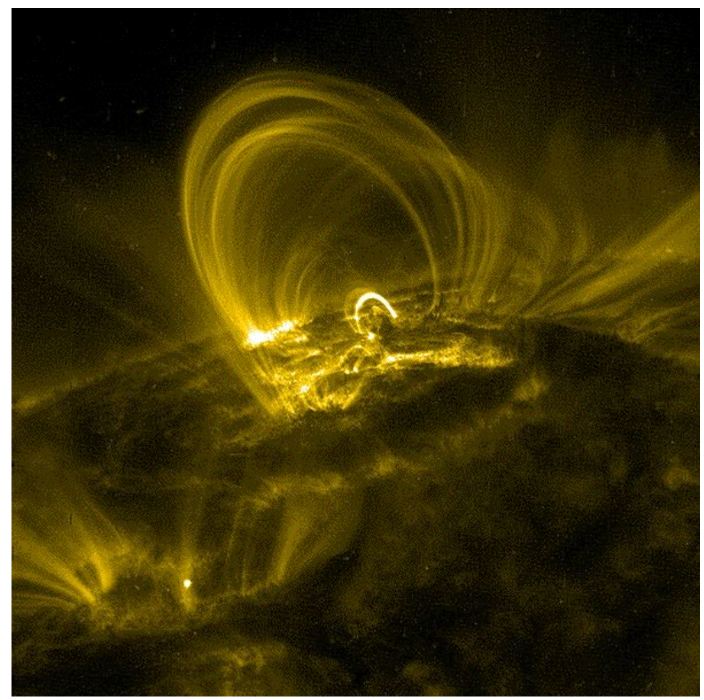
X-ray Images of the Sun

- In addition to being the '1st' x-ray source the sun was the first object imaged in x-rays
- The sun is orders of magnitude brighter than the next brightest object





1990's



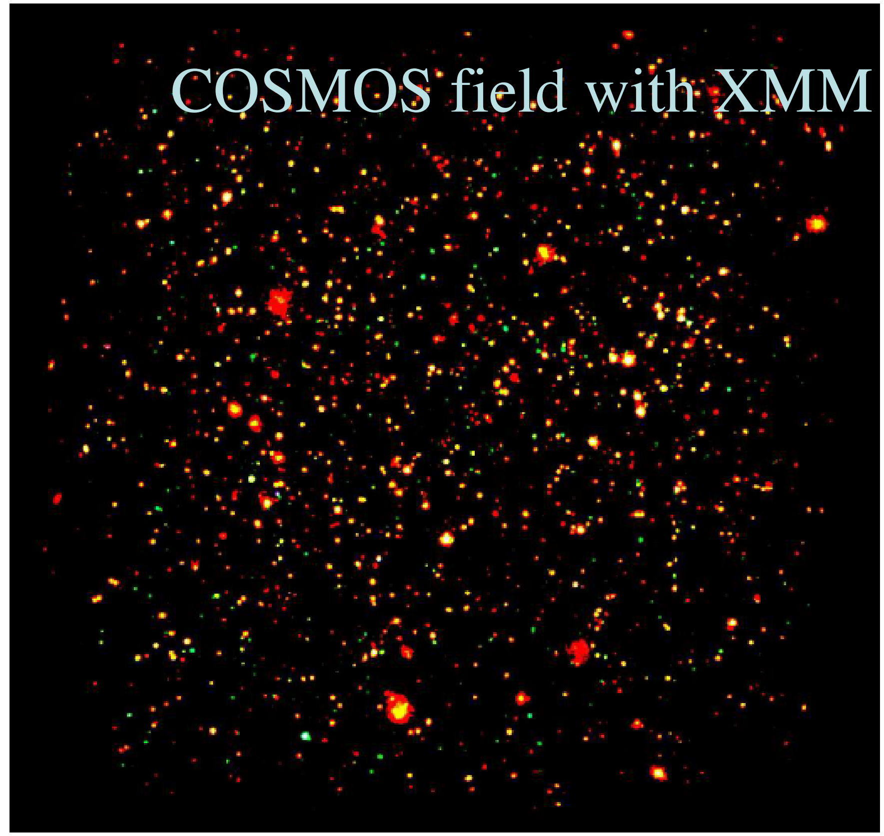
X-ray Astronomy

- From its start in 1962 sensitivity has increased by 10^7

(~5×10^{-17} ergs/cm^{2}sec in the 0.5-2 keV band)

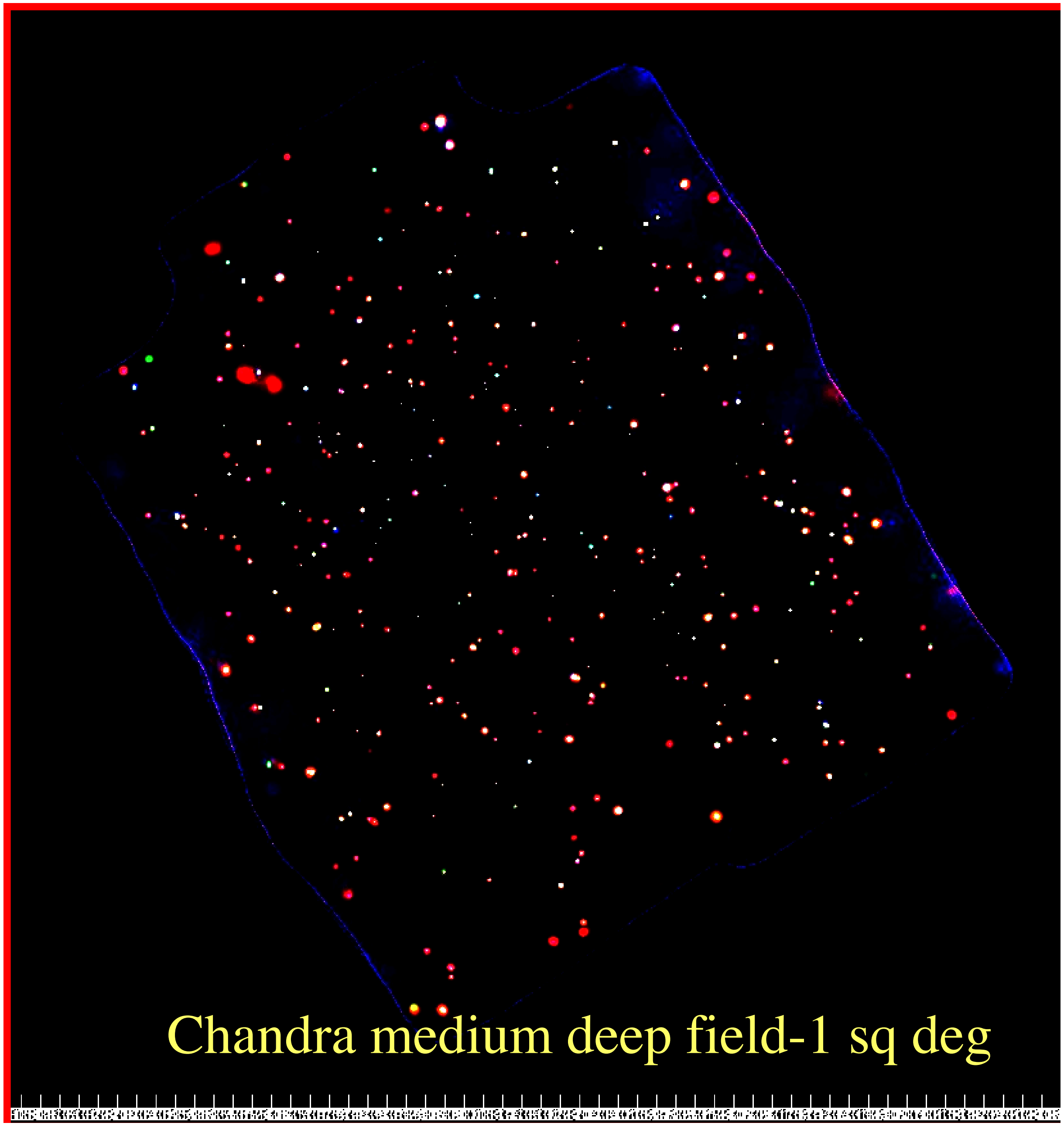
  - angular resolution by 10^5 (10^{0}-0.5")
  - spectral resolution by 10^4 ($E/\Delta E \sim 1000$)
- There are now >300,000 known x-ray sources
- At the faintest levels probed by Chandra there are >2000 x-ray sources/deg^2 (e.g. 10^8 all sky)
- Despite these spectacular advances x-ray astronomy is photon limited (the largest x-ray telescopes have collecting areas of 3000 cm^2 compared to 10^6 cm^2 for the largest optical telescopes)

2 deg



Nature of Faint X-ray Sources

- Most of the faint x-ray sources are active galaxies (AGN, quasars, Seyfert galaxies)
- At a median redshift of 0.7 (D_L=4260 Mpc = 1.31×10^{28} cm)
- median x-ray luminosity $10^{43.5}$ergs/sec =$8 \times 10^9 L_\odot$)
  - The red 'blobs' are clusters of galaxies



γ-Ray Astronomy

- First satellite (SAS-2) E> 35 MeV in 1972
- Sensitivity was ~10^{-6} ph/cm^2/sec , 2^o angular resolution
- ~30 sources

- Fermi launched in 2009 has a sensitivity of ~10^{-9} ph/cm^2/sec and an angular resolution of ~0.1^o
  - >1000 sources

Where are we going

- In the class we will discuss
  - The physical mechanisms producing high energy photons (e.g ch 5 of Melia and ch 3 of Rosswog and Bruggen)
  - The objects 'of' high energy phenomena (e.g. ch 9,10,11,12,13 of Melia and 4,5,6,7,8 of Rosswog and Bruggen)
  - How one obtains the data (e.g. instruments and telescopes) - ch 1.4-1.5 of Melia and Appendix A of Rosswog and Bruggen)- I will go into more detail than Melia on this subject

In order to understand a lot of this we will

discuss accretion disks (ch 6 (part) +7 of Melia and part of ch 8 of Rosswog and Bruggen)

Clusters of galaxies

Supernova remnants

Active galaxies

A 'big' hole in these books is that clusters of galaxies are not discussed -

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In order to understand a lot of this we will also try to

discuss accretion disks (ch 6 (part) +7 of Melia and part of ch 8 of Rosswog and Bruggen)

A 'big' hole in these books is that clusters of galaxies are not discussed -

a comprehensive book is "A pan-chromatic view of clusters of galaxies and the large-scale structure Plionis, López-Cruz, Hughes"- Springer Lecture notes in physics, 740

For Next Week

- For the next class I will have an outline of the material for the first half of the class and the relevant sections of the texts where this material is discussed

- I propose that we have 1 mid-term and a 'project' + a final and 'several' homeworks for the grade.
  - Many of the homework problems will be taken from the two books (but not all).

web page
-end of next week

I have lots of online material available

The Next 2-3 Lectures

- Today we are continuing the intro to the field and will discuss a bit of the history of the field, (see heasarc.gsfc.nasa.gov/docs/heasarc/headates/heahistory.html
- atmospheric transmission (Melia's book sec 1.3) , the objects of high energy astrophysics (e.g. neutron stars, black holes, clusters of galaxies) from a very broad perspective (Rosswog and Bruggen ch 5.1 and Melia sec 10.1) If we have the time I will start on physical process (Melia ch 5 and Rosswog and Bruggen ch 3).

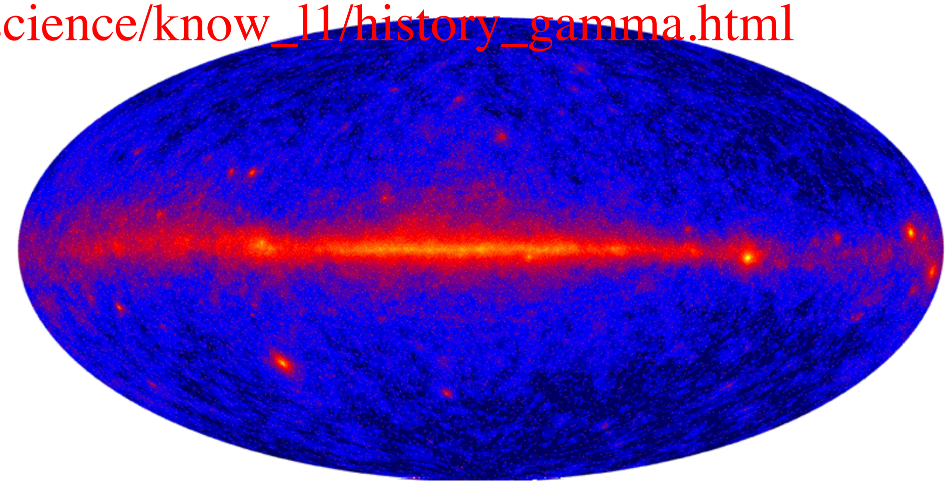
Physical Processes-**Melia ch 5 and Rosswog and Bruggen ch 3**

Black body radiation
Synchrotron Radiation
Compton Scattering
Line emission and absorption
Absorption (not in the recommended texts- see

High Energy Astrophysics is 'New'- see

heasarc.gsfc.nasa.gov/docs/heasarc/headates/heahistory.html

http://imagine.gsfc.nasa.gov/docs/science/know_l1/history_gamma.html



γ-Rays gamma rays are emitted by the nucleus or from other particle decays or annihilation events.

- 1958 a burst of gamma rays from a solar flare
- 1962 diffuse γ-ray background at (0.1 to 3 MeV) - Ranger 3, which flew by the moon.
- 1967 The 1st cosmic γ-Ray Burst (GRB)* via the Vela 4a,b satellites. This discovery was not made public for several years due to military classification.
- 1970 γ-ray emission from the Galactic Center
- 1971 pulsed high-energy γ-ray emission from the Crab Pulsar above 50 MeV

γ-Ray Sky with Fermi
Detected >1000 sources in first year of operation (most are blazars and pulsars)

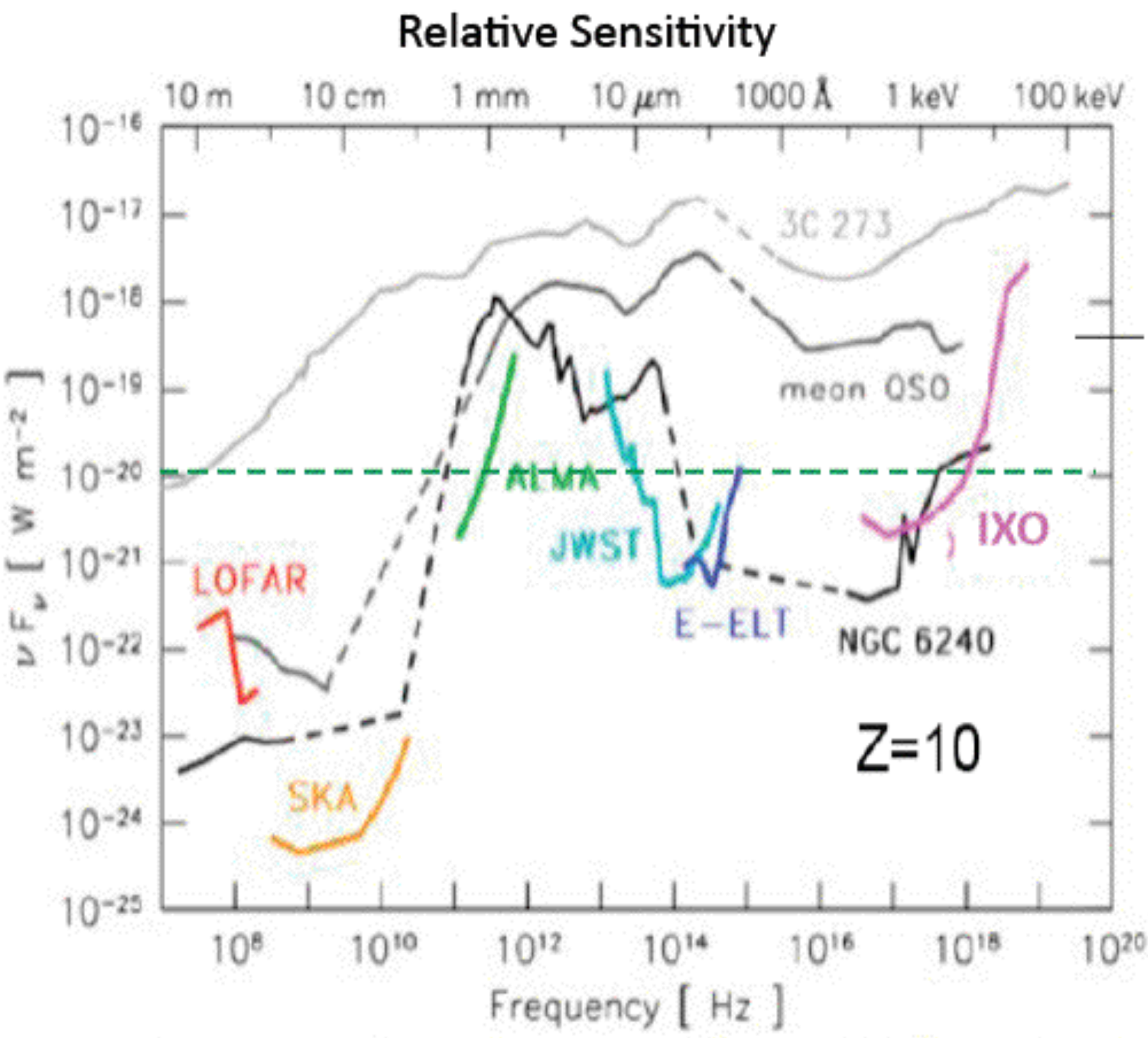
Other γ-Ray sources include

Supernova remnants

Unusual binary stars

Notice the introduction of vast amounts of jargon

Relative Sensitivity Astronomical Observatories



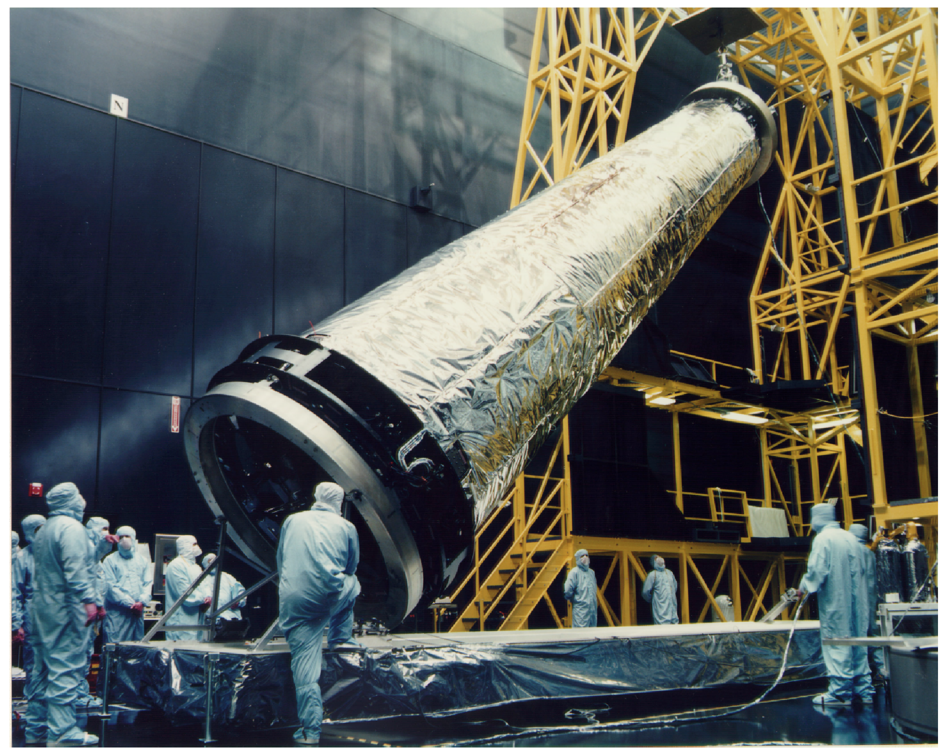
- For study of the faintest known x-ray sources one needs the largest optical and IR telescopes

Space Based High Energy

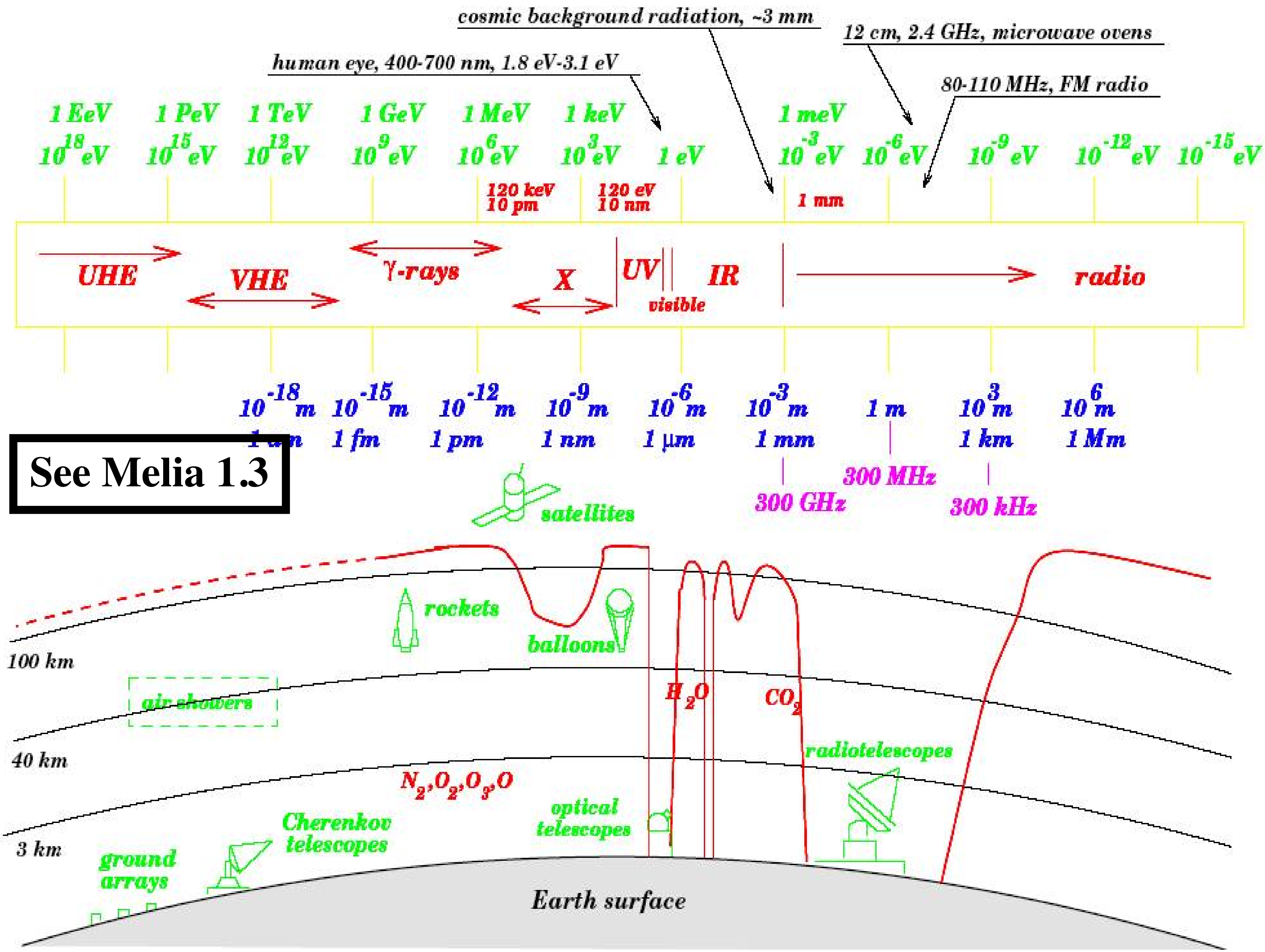
- The atmosphere is opaque (at ground level) to all wavelengths from γ-rays (MeVs) to ultra-violet(10^{11}-10 eV;1eV=1.6×10^{-12} ergs/cm^2/sec)**
- Thus to detect 'high energy' photons need to go to space*
- Space missions are expensive and take a lot of time

*its possible to detect TeV photons from the ground

** I will use CGS rather than MKS- it is traditional in astrophysics- I will also often use eV, keV etc for energy and flux in photons/cm^2/sec/energy bin

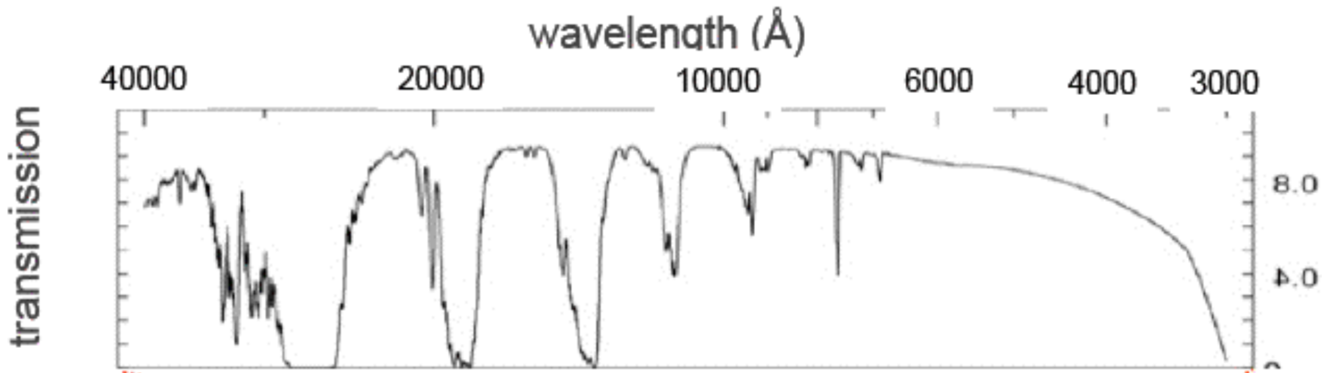


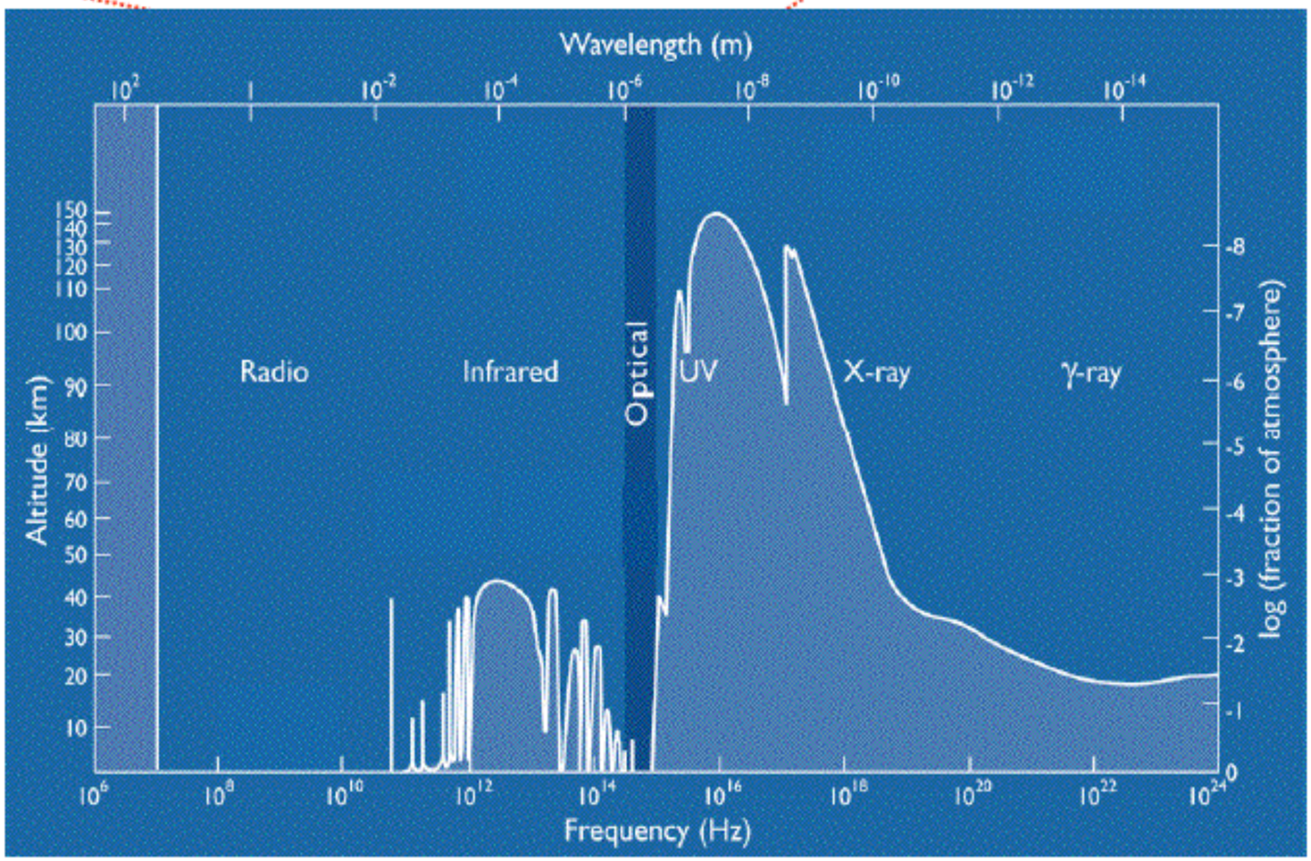
Chandra Optical Bench


cosmic background radiation, ~3 mm
12 cm, 2.4 GHz, microwave ovens
human eye, 400-700 nm, 1.8 eV-3.1 eV
80-110 MHz, FM radio
1 EeV
1 PeV
1 TeV
1 GeV
1 MeV
1 keV
1 meV
10^{18} eV
10^{15} eV
10^{12} eV
10^{9} eV
10^{6} eV
10^{3} eV
1 eV
10^{-3} eV
10^{-6} eV
10^{-9} eV
10^{-12} eV
10^{-15} eV
120 keV 10 pm
120 eV 10 nm
1 mm
UHE
VHE
γ-rays
X
UV
visible
IR
radio
10^{-18} m
10^{-15} m
10^{-12} m
10^{-9} m
10^{-6} m
10^{-3} m
1 m
10^{3} m
10^{6} m
1 am
1 fm
1 pm
1 nm
1 µm
1 mm
1 km
1 Mm
300 MHz
300 GHz
300 kHz
satellites
rockets
balloons
100 km
air showers
H_2O
CO_2
40 km
radiotelescopes
N_2,O_2,O_3,O
optical telescopes
Cherenkov telescopes
3 km
ground arrays
Earth surface

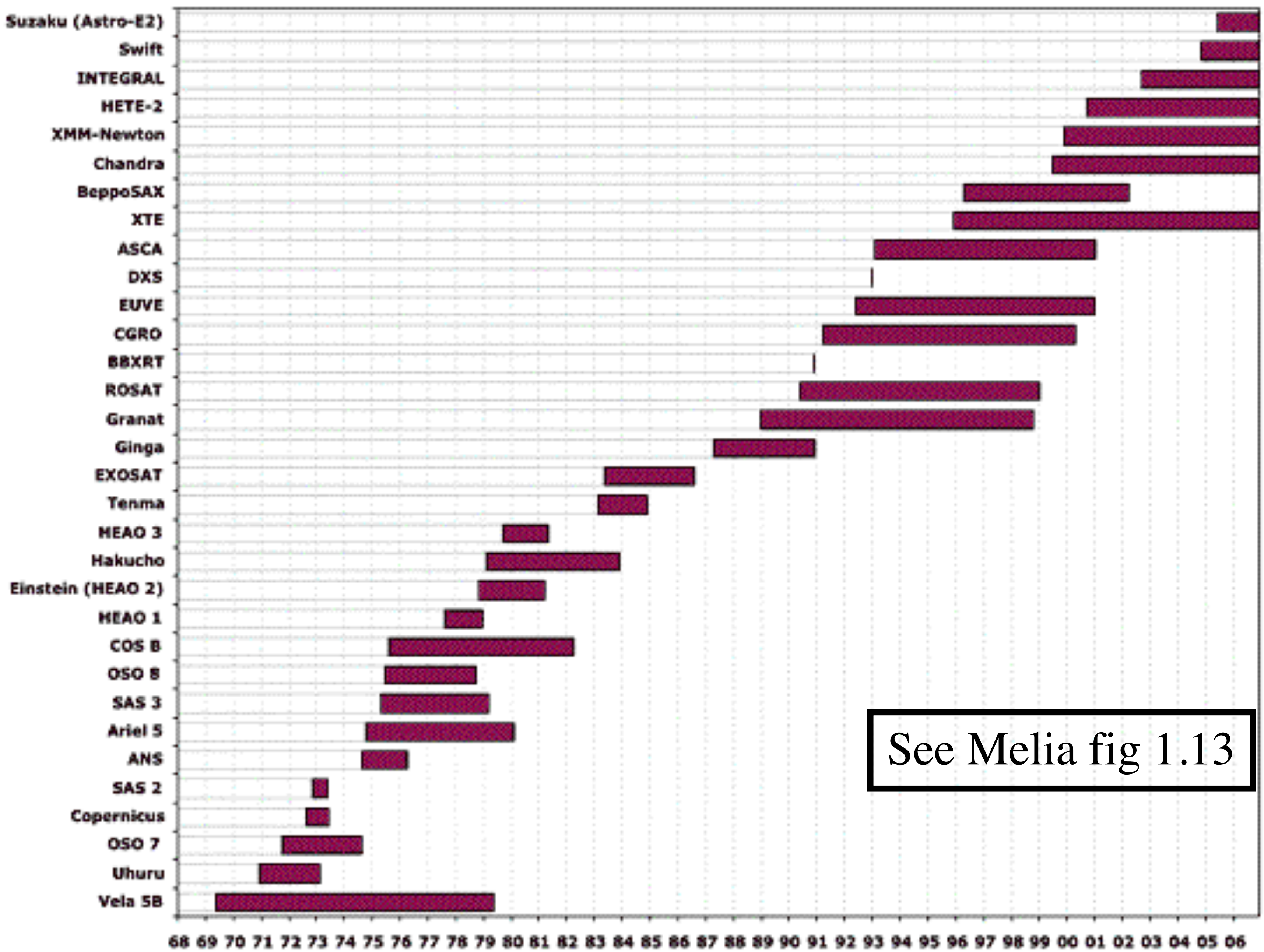
See Melia 1.3

Atmospheric transmission





Satellite High Energy Missions 1969-Now



See Melia fig 1.13

The Objects of High Energy Astrophysics-Neutron Stars

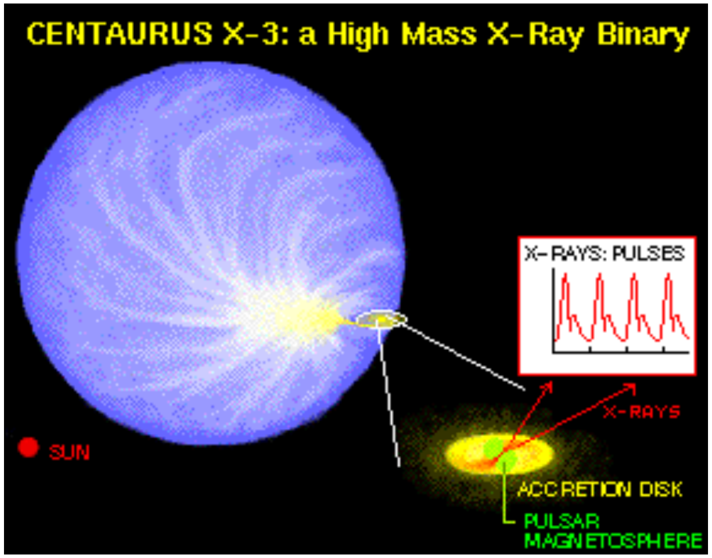
R+B pg 161 sec 5.1

- 1934, Baade and Zwicky proposed the existence of the neutron star a year after Chadwick's* discovery of the neutron - they proposed that the neutron star is formed in a supernova

- 1967, Shklovsky explained the X-ray and optical observations of Scorpius X-1 (the first non-solar) x-ray source as radiation coming from a neutron star via accretion.

- 1967, Jocelyn Bell and Antony Hewish** discovered regular radio pulses from the Crab-radiation from an isolated, rotating neutron star. The energy source of the pulsar is the rotational energy of the neutron star.

- 1971, Giacconi*** et al discovered 4.8 sec pulsations in an X-ray source in the constellation Centaurus, Cen X-3: Emission from a rotating hot neutron star. The energy source is the same as in Sco X-1



*Nobel laureate in physics awarded for his discovery of the neutron.

** Nobel laureate in physics 1974

***Nobel laureate in physics 2002

History: Baade and Zwicky

Walter Baade

"With all reserve, we advance the view that a *supernova* represents the transition of an ordinary star into a *neutron star* consisting mainly of neutrons…

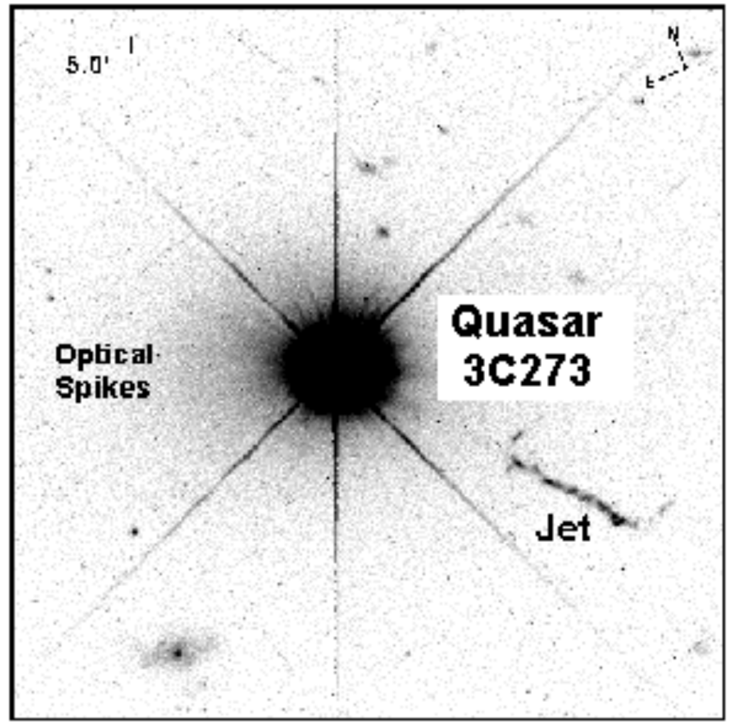
Baade & Zwicky (1934)

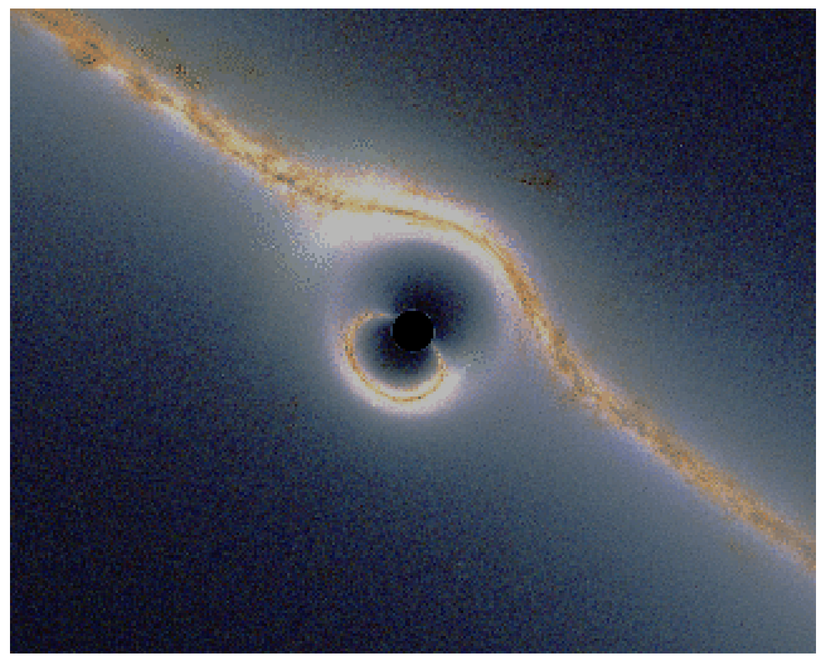
Fritz Zwicky

Just 2 yrs after the discovery of the neutron!

Black Holes Melia ch 10.1

- 1963 Schmidt identified the first quasar, showing that these starlike objects exhibit ordinary hydrogen lines, but at redshifts far greater than those observed in stars.
- Quasars were shown to be powerful x-ray sources in the mid-1970s
- Quasars are accreting supermassive ($M>10^6 M_{sun}$ black holes (*)- how do we know this??
- The first accreting 'stellar mass' black hole Cyg X-1 was identified in 1972 as an x-ray source
- About 20 BHs in the Milky Way are known
- ~10^8 AGN





* $M_{sun=}$ $2x10^{33}$ gm

End of First Lecture