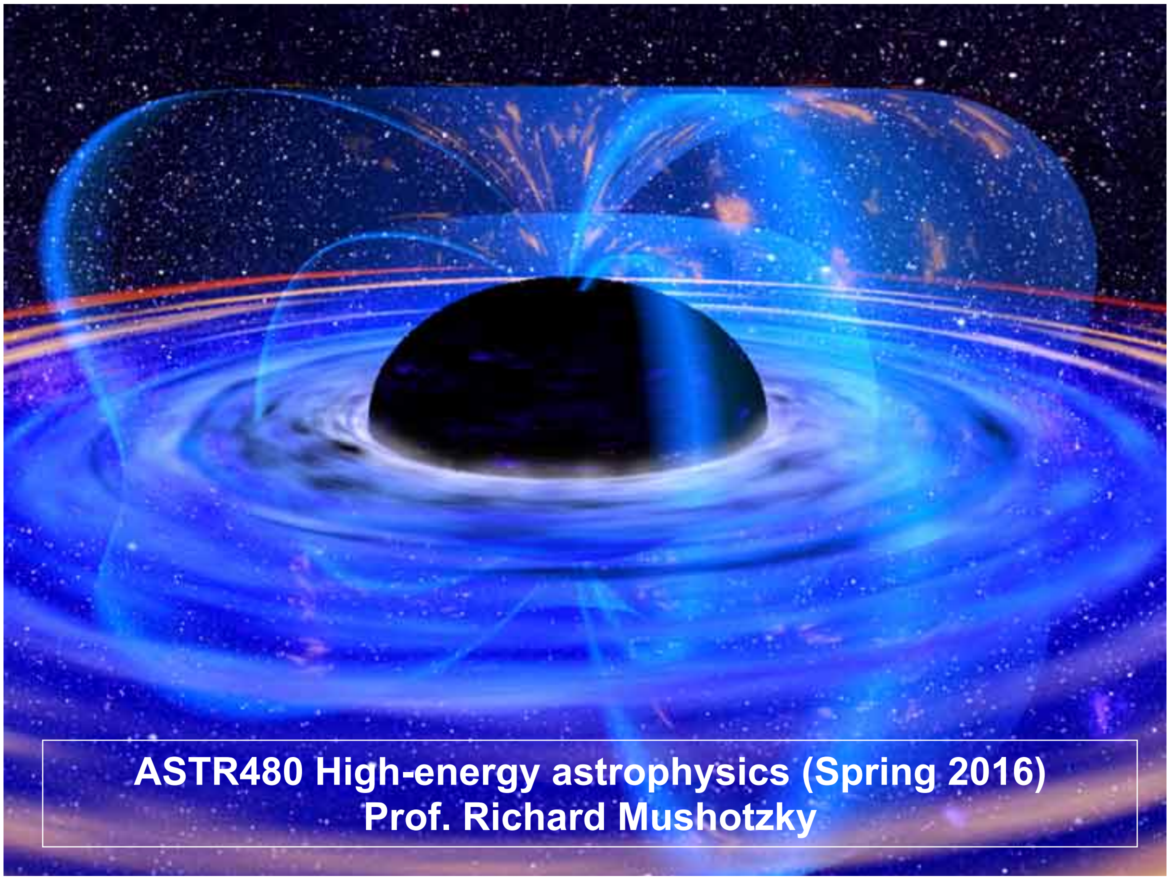


High Energy Astrophysics

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

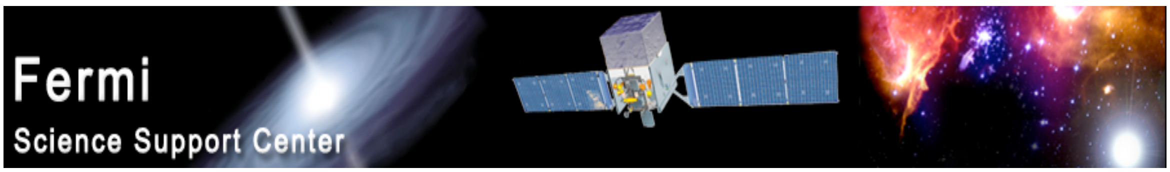
The universe itself (cosmology)

But we may observe high energy phenomena at other energies

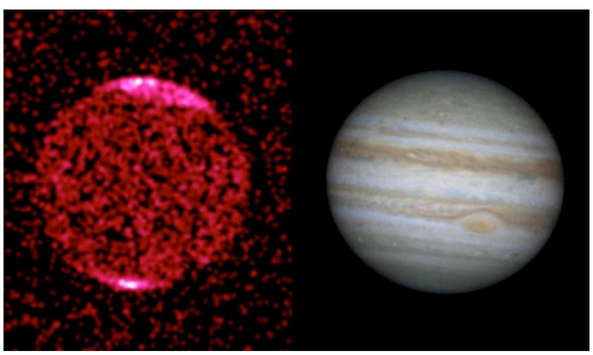
Not only photons and particles !- also gravitational waves

HEA Continued

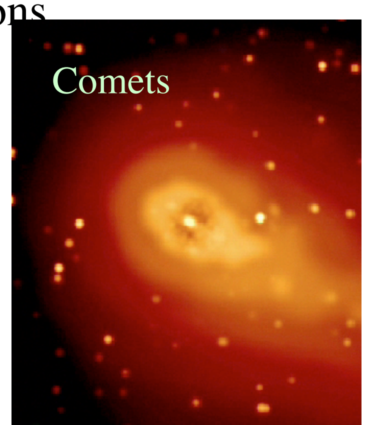
- The study of such objects and processes thus covers a VERY wide range of physics and types of physical objects.
- In order to study x-rays, γ-rays etc from astrophysical objects one needs special techniques and telescopes and the work often must be done in space (I will focus on photons)
- There is 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



Even Objects Not Thought to Be High Energy Can Emit High Energy Photons



- X-rays from Jupiter due to the aurorae and 'precipitating' electrons from Io



Energetic solar wind ions impact the coma, capturing electrons from neutral atoms. As the electrons become attached to their new parent nuclei (the solar wind ion), energy is released in the form of X-rays.
Comets become significant X-ray sources when they interact strongly with solar wind ions.
Read more: http://www.universetoday.com/21826/swift-detectsx-ray-emissions-from-comets

Textbook

- We will be 'using' High Energy Astrophysics' by M. Longair 3rd edition.
- We will cover several chapters in the book, but not in the order in which they appear (chapter numbers in Longair)
  - 1 High energy astrophysics – an introduction
  - 4 Clusters of galaxies
  - 6 Radiation of accelerated charged particles and bremsstrahlung of electrons
  - 8 Synchrotron radiation
  - 9 Interactions of high energy photons
  - 13 Dead stars- including white dwarfs, supernova
  - 14 Accretion power in astrophysics
  - 18 Active galaxies
  - 19 Black holes in the nuclei of galaxies
  - 20 The vicinity of the black hole
  - 22.7 γ-ray bursts
  - 23 Cosmological aspects of high energy astrophysics

Topics to be covered

- Introductory Lecture 1
- Introductory Lecture 2
- X-ray Detectors Lecture 3*
- Radiation Process Lecture 4-5
- Gamma-ray Detectors and X-ray Telescopes Lecture 6
- Clusters of Galaxies 1 Lectures 7-9
- Supernova and Supernova Remnants 10-13
- Neutron Stars Lecture 14-16
- Black Holes Lecture 17-20
- Gamma-ray bursts 21
- AGN 22-26

* I will be away the week of Feb 8-15 attending the Astro-H Launch, Prof. Reynolds will give the lectures on Radiation Processes

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**

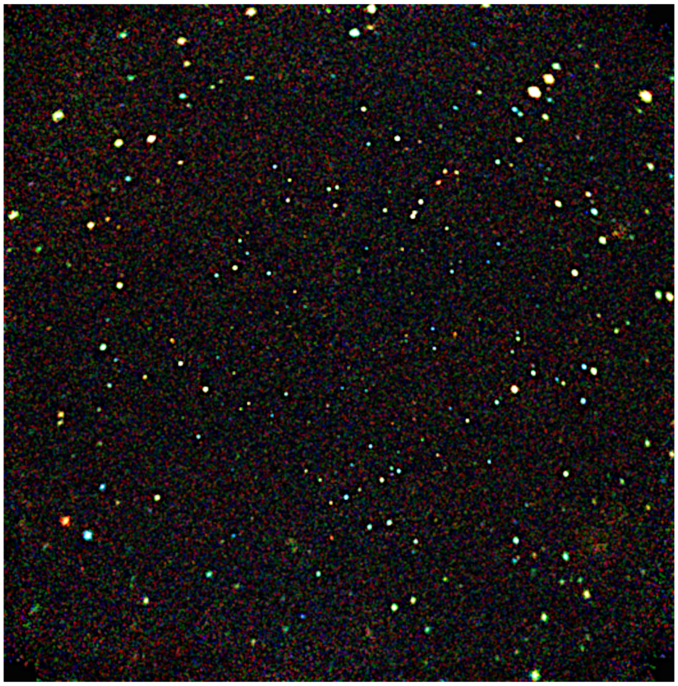
- **Weak radiative transfer difficulties**
- Unique 'penetrating' capabilities (e.g. most of the universe is obscured (AGN and star formation)
- Most of the baryons in the low z universe can only be observed in the x-ray band

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

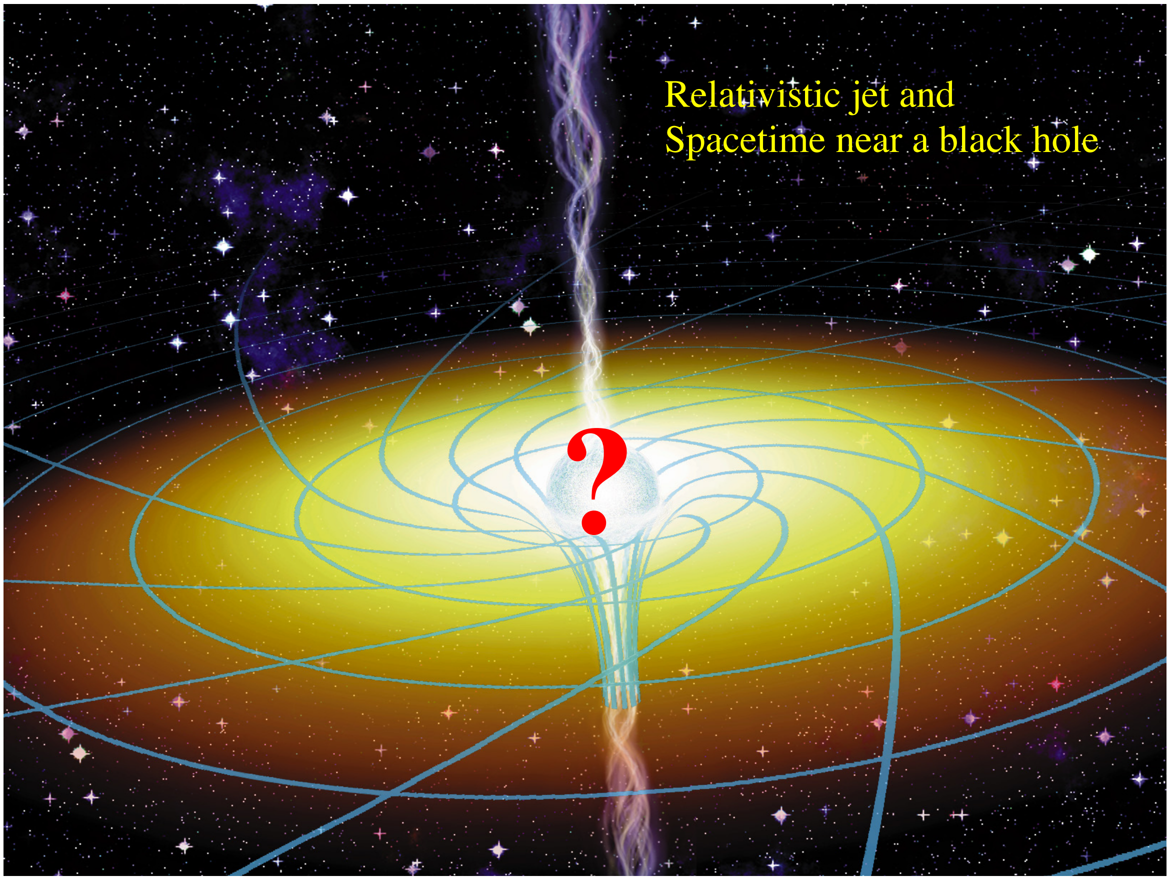
γ-rays are the emitted by radioactive isotopes and thus are a measure of creation of the elements

A small part of the X-ray sky

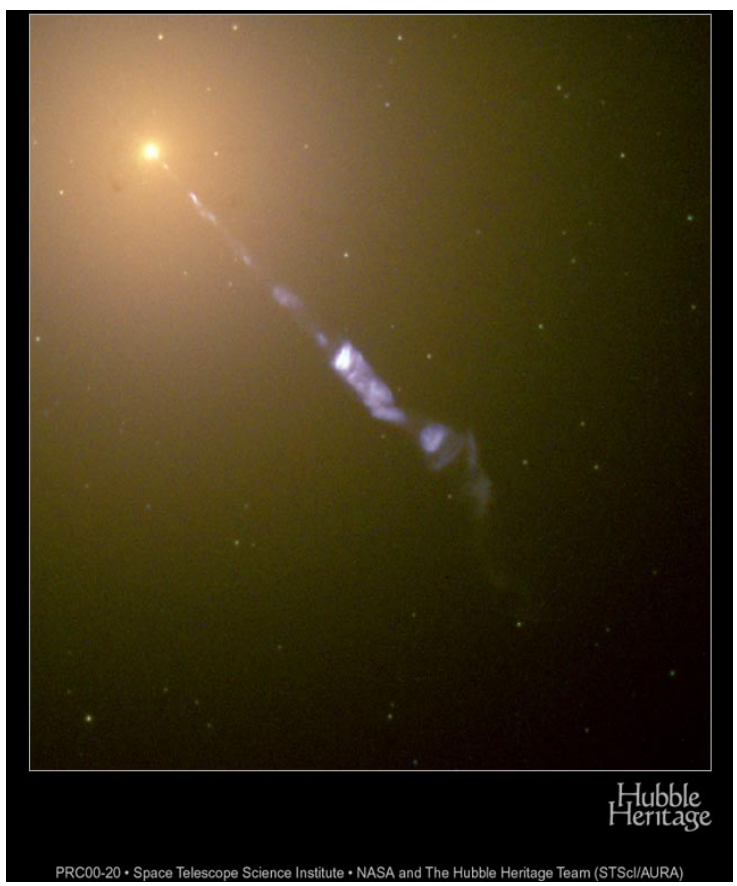


Chandra Deep Field South
(1 million second exposure by the Chandra X-ray Observatory… almost every source is a distant, accreting massive black hole)

(CXC; R. Gioconni et al.)



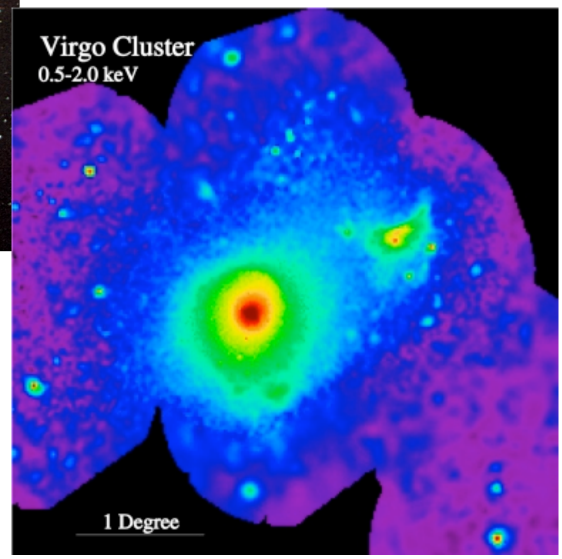
The M87 jet with
HST- Optical Image

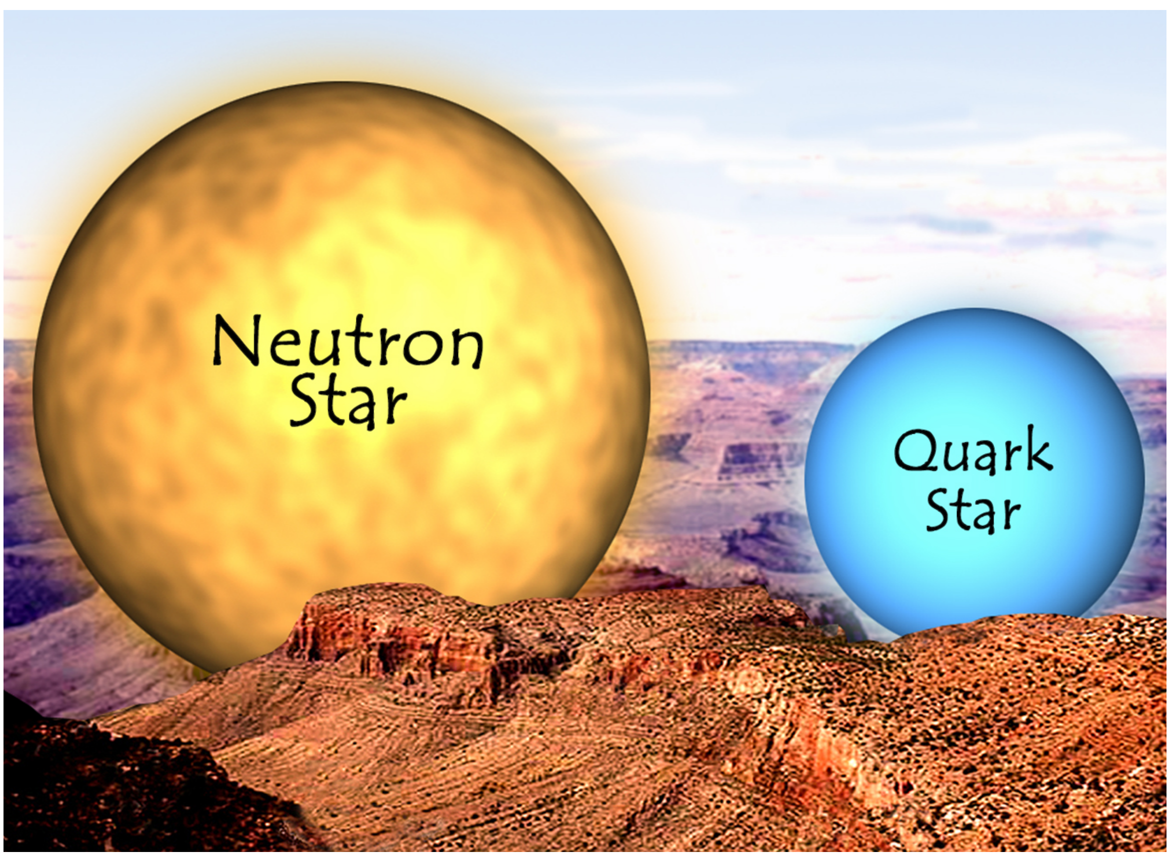


High-energy astrophysics and the formation of galaxies…

X-ray Image

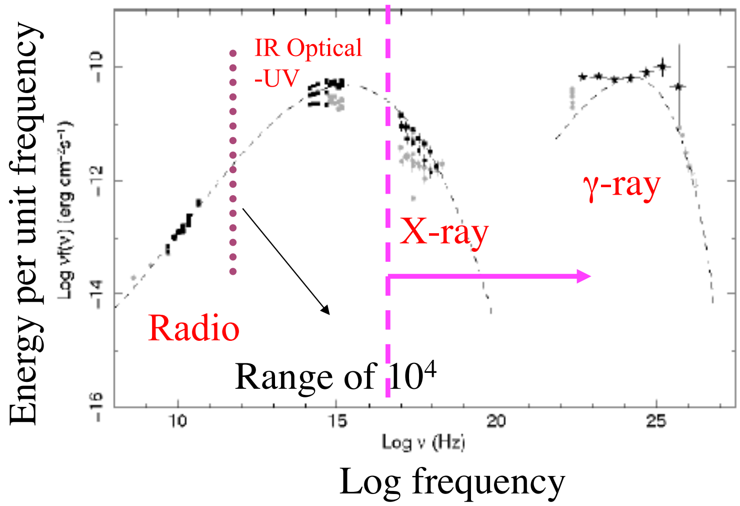
Optical Image





Multi-Wavelength Astronomy

- Astronomy is a multi-wavelength 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)

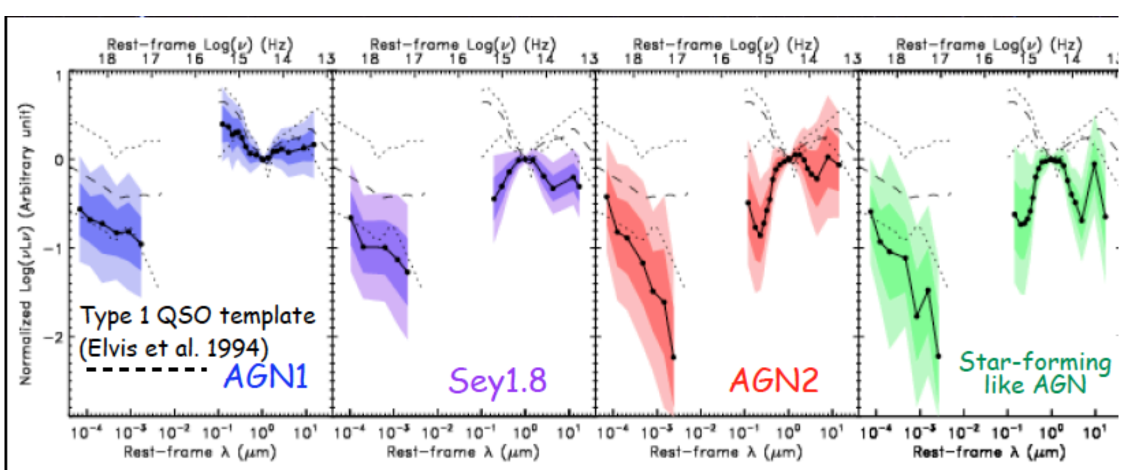


Broad band spectral energy distribution (SED) of a 'blazar' (an active galaxy whose observed radiation is dominated by a relativistic jet 'coming at' us

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

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



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

Basic course logistics

- Pre-requisites
  - Strong background in Physics & Astronomy
  - Will assume knowledge of astronomy at the ASTR120/121 level
  - Will assume proficiency in algebra, and calculus (including vector calculus)
  - Will assume familiarity with Newtonian dynamics and (elementary) quantum mechanics
- Textbook- Longair High Energy Astrophysics 3rd Edition
- Auxiliary Textbooks
  - F Melia **High-Energy Astrophysics**
  - Rosswog and Bruggen **Introduction to High-Energy Astrophysics**

Course structure

- Lectures
  - Attendance is crucial: a major part of this course will be in-class discussions!
  - You must complete any assigned reading before class… you will be lost otherwise!
- Other components
  - Homeworks (1 every two weeks)
  - Midterm exam (10th March 2016)
  - Final exam (18th May 2006; 10.30am)
  - Group project and presentation (more later in the semester)
  - Grading scheme given in Syllabus

Absences, academic dishonesty

- I strictly follow the University policy
- Absences – all must be documented
  - If scheduled (e.g. sports), bring paperwork *as soon as possible*.
  - Illness: contact me *before* missed class or assignment; arrange for make-up (if necessary) within one week
- Academic dishonesty
  - Zero-tolerance policy
  - Absolutely no copying of homeworks or exams!
  - Must list all references used to complete an assignment

Grading scheme

- Distribution
  - HW 30%
  - Midterm 20%
  - Project 30%
  - Final 20%

- Letter grade
  - 90%+ A
  - 80-89% B
  - 70-79% C
  - 60-69% D
  - <59% F

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

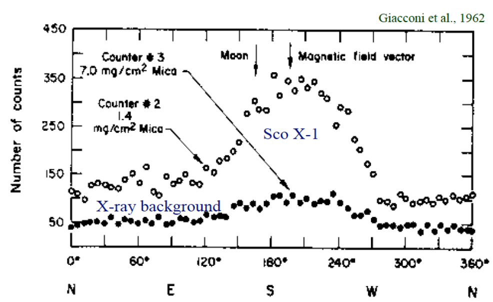
High Energy Astrophysics is 'New'
http://heasarc.gsfc.nasa.gov/docs/history/

- Astronomy is the 1st science- back to Mesopotamia
- High energy astrophysics
  - cosmic rays were discovered in 1912 by Victor Hess (**Nobel prize** 1936),
    - 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



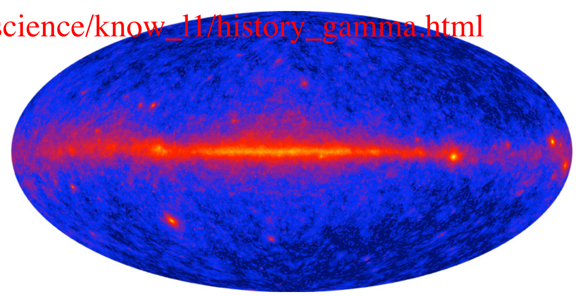
High Energy Astrophysics is 'New'- see heasarc.gsfc.nasa.gov/docs/heasarc/headates/heahistory.html

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

γ-Rays

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

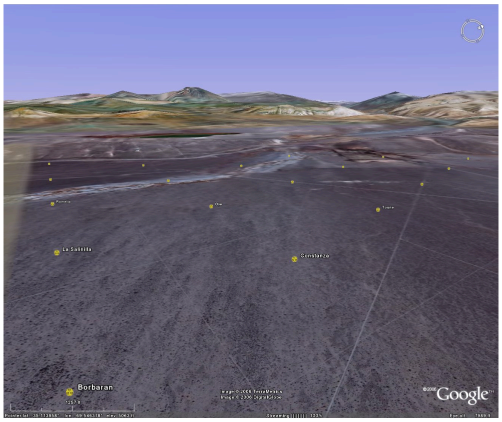


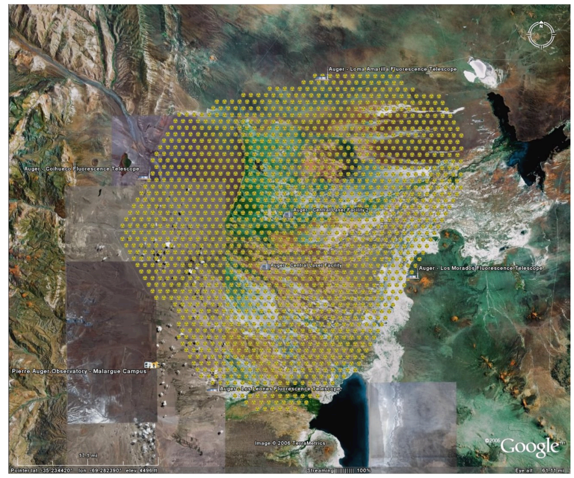
γ-Ray Sky with Fermi Detected >1000 sources in first year of operation (most are blazars and pulsars)- now >3000

Other γ-Ray sources include
Supernova remnants
Unusual binary stars

Notice the introduction of vast amounts of jargon

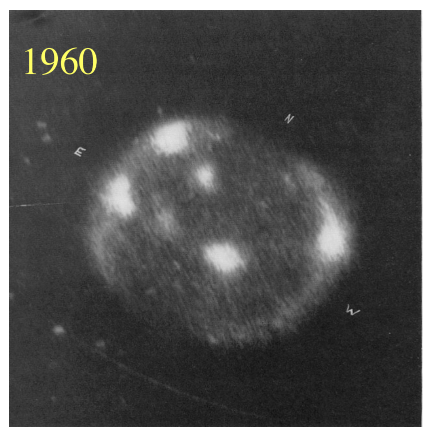
Pierre Auger Observatory-Google Earth

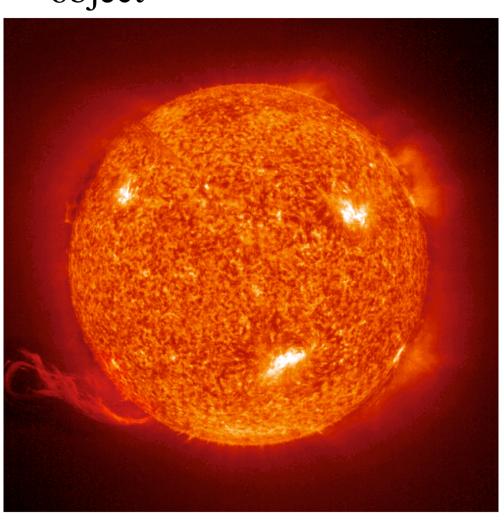




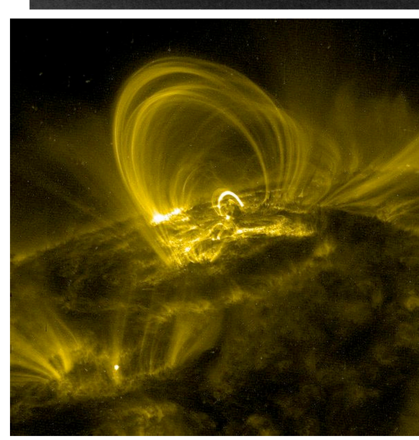
X-ray Images of the Sun

- 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

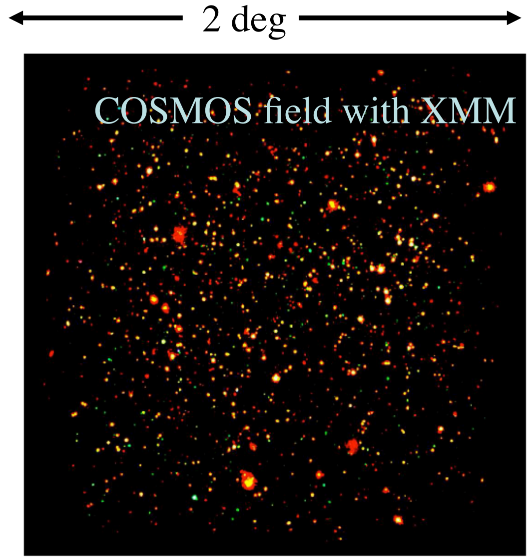




1990's



X-ray Astronomy



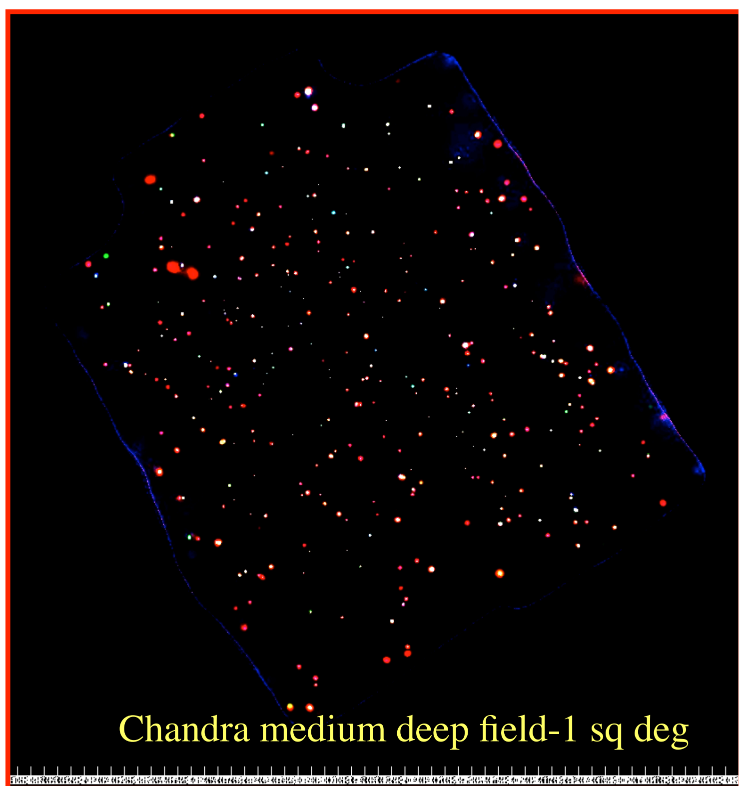
- From its start in 1962
  sensitivity has increased by 10^9

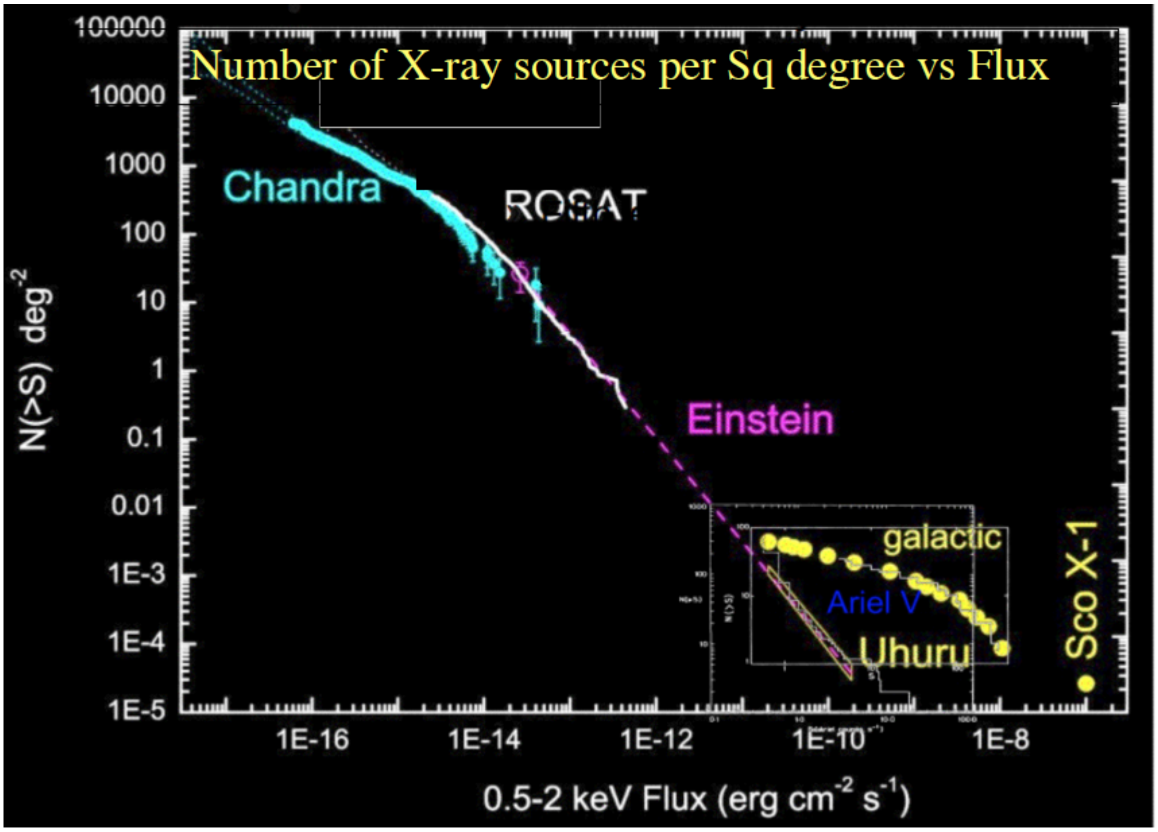
(~5×10^{-17} ergs/cm^{2}sec in the 0.5-2 keV band)

  - angular resolution by 10^5 (10^0-0.5")
  - spectral resolution by 10^4
    now ($E/\Delta E$~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)

Nature of Faint X-ray Sources

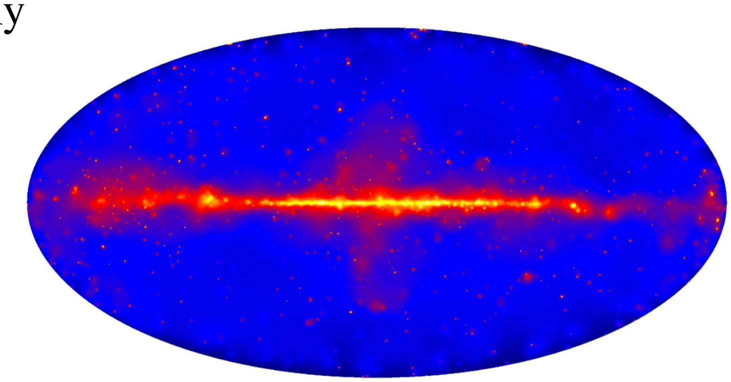
- Most of the faint x-ray sources are active galaxies (AGN, quasars, Seyfert galaxies)
- At a median redshift of 0.7 (D_L=4260 Mpc = 1.31×10^{28} cm)
- median x-ray luminosity ($10^{43.5}$ergs/sec $=8\times10^9 L_\odot$)
  - The red 'blobs' are clusters of galaxies





γ-Ray Astronomy

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



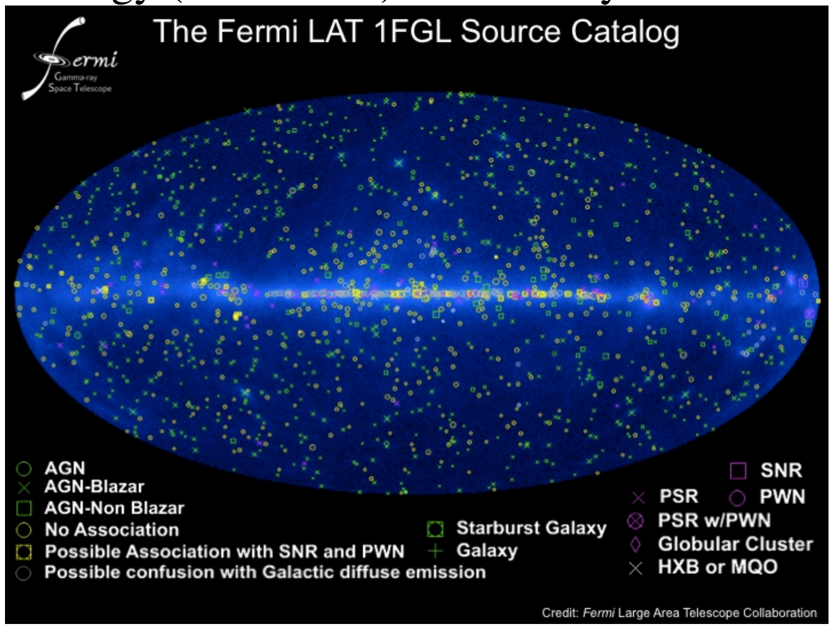
- Fermi launched in 2009 has a sensitivity of ~10^{-9} ph/cm^2/sec and an angular resolution of ~0.1^o
  - ~1600AGNs detected above 100 MeV using 4 years of data.

virtually all the high galactic latitude γ-ray sources are AGN

at low latitude the γ-Ray sky is dominated by diffuse emission due to the interaction of cosmic rays with gas- in addition there are a variety of sources including pulsars, plerions (a certain type of supernova remnant) a few compact binaries and novae

Fermi High Energy (>100 MeV) Gamma-ray Sources

- Many classes
  - Blazars
  - Pulsars
  - Supernova remnants
  - Starburst galaxies
  - Binaries
- 3FGL catalog has 3033 sources of which 1100 are identified



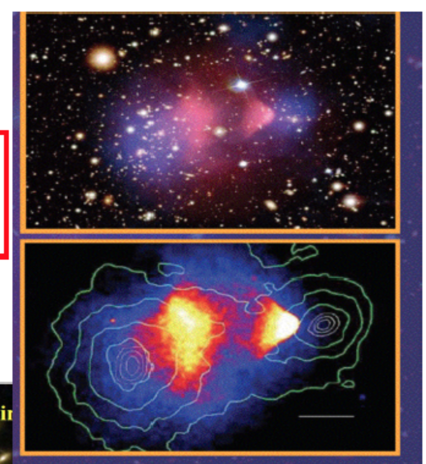
Clusters of Galaxies

Most massive and largest objects in the universe- $M>10^{14}M_{\odot}$ $R\sim3.08\times10^{24}$ cm= 1 Mpc

**the bending of light by strong gravity can act as a lens

Most of the baryons* in clusters are in the hot x-ray emitting gas- most of the mass is **dark matter**

Can act as a gravitational lens**- revealing the amount of and distribution of **dark matter*****.



*Baryon- neutrons protons, nuclei of atoms

Where are we going

- In the class we will discuss
  - The physical mechanisms producing high energy photons – Part II in Longair (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) – Unfortunately Longair does not cover this see 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 14 in Longair; ch 6 (part) +7 of Melia and part of ch 8 of Rosswog and Bruggen)

Clusters of galaxies- Ch 4 in Longair

Supernova remnants

Active galaxies Part IV in Longair.

A 'big' hole is that not all of the material is in one book and in particular supernova remnants are not covered .

A very nice resource is Joern Wilm's website http://pulsar.sternwarte.uni-erlangen.de /wilms/teach/index.html

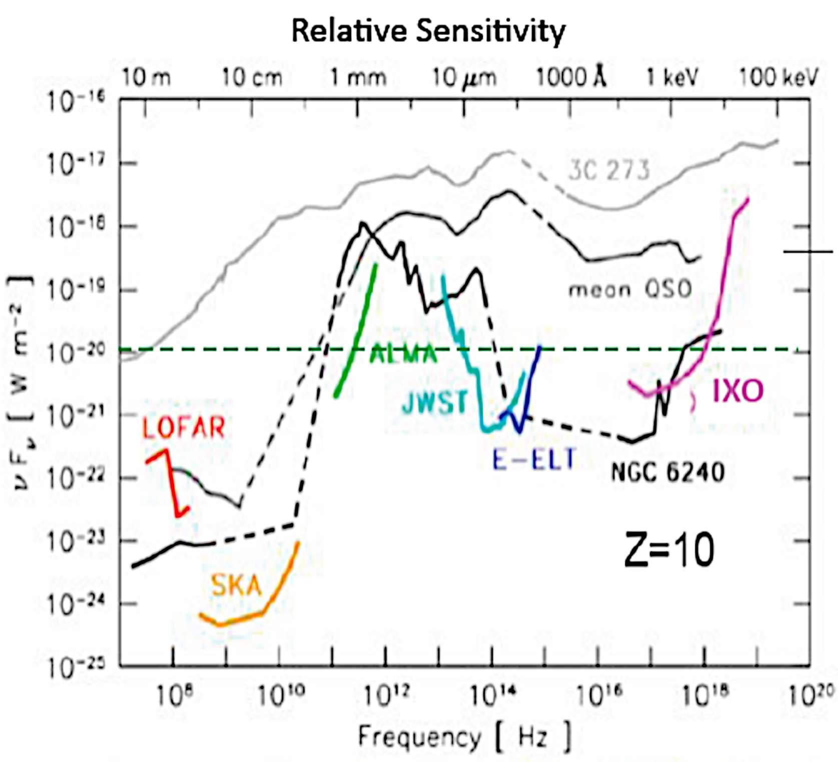
The Next 2-3 Lectures

- 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-Longair parts of sec II 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

Relative Sensitivity Astronomical Observatories



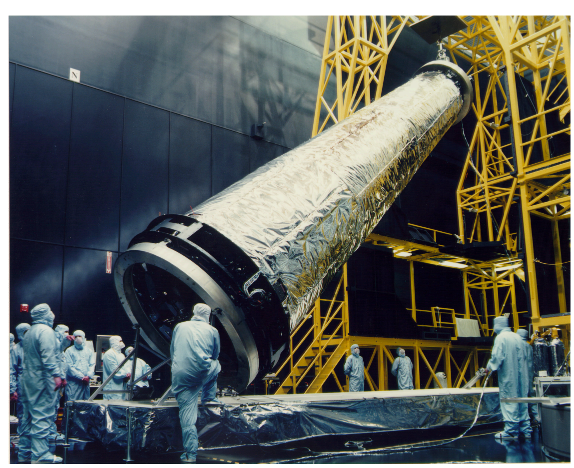
- For study of the faintest known x-ray sources one needs the largest optical and IR telescopes

Space Based High Energy

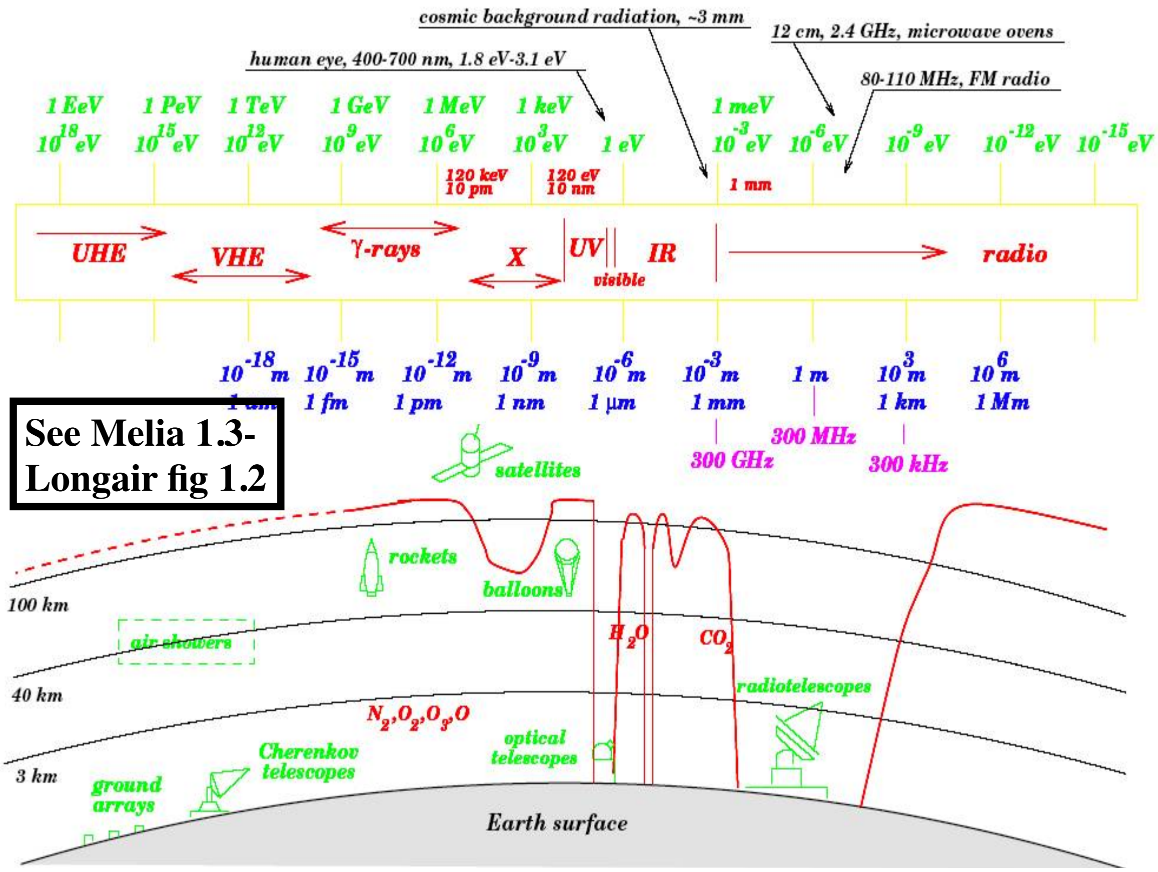
- The atmosphere is opaque (at ground level) to all wavelengths from γ-rays (MeVs) to ultra-violet(10^{11}-10 eV;1eV=1.6×10^{-12} ergs/cm^2/sec)**
- Thus to detect 'high energy' photons need to go to space*
- Space missions are expensive and take a lot of time

*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

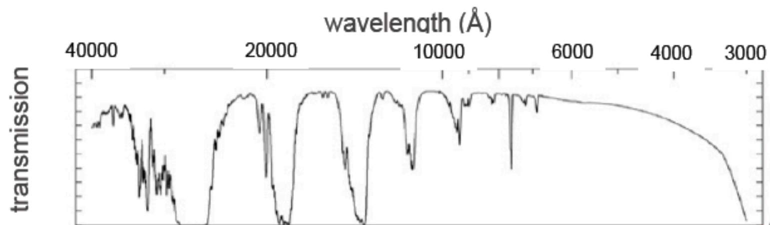


Chandra Optical Bench



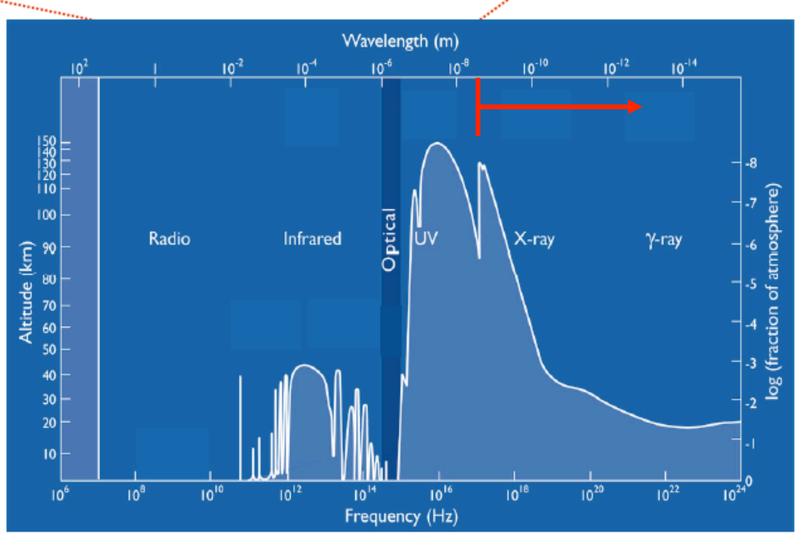
See Melia 1.3- Longair fig 1.2

Atmospheric transmission



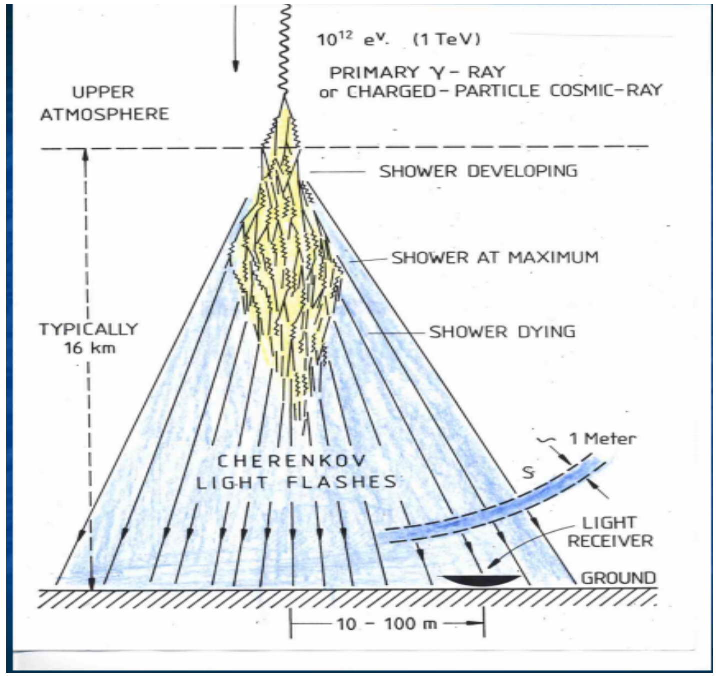
optical-near IR

Why go into space?
High Energy Photons get absorbed in earths atmosphere- graph shows atmospheric height at which 1/2 of photons absorbed



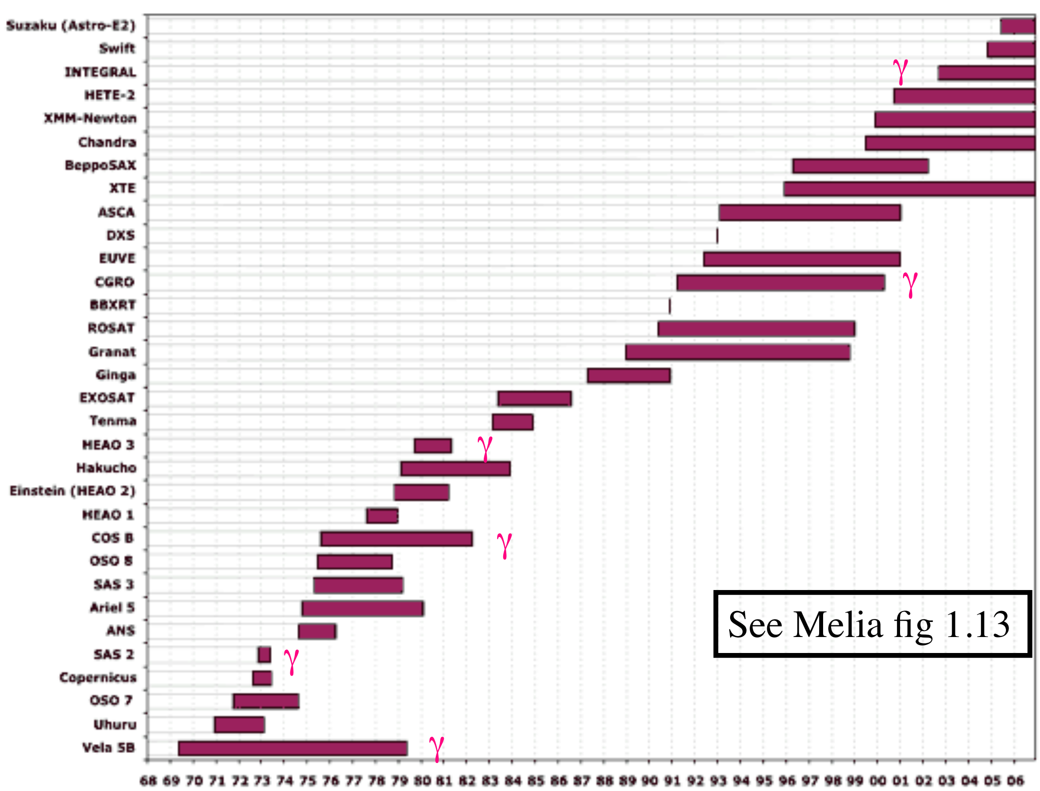
Very High Energy Cosmic Rays and TeV Astronomy

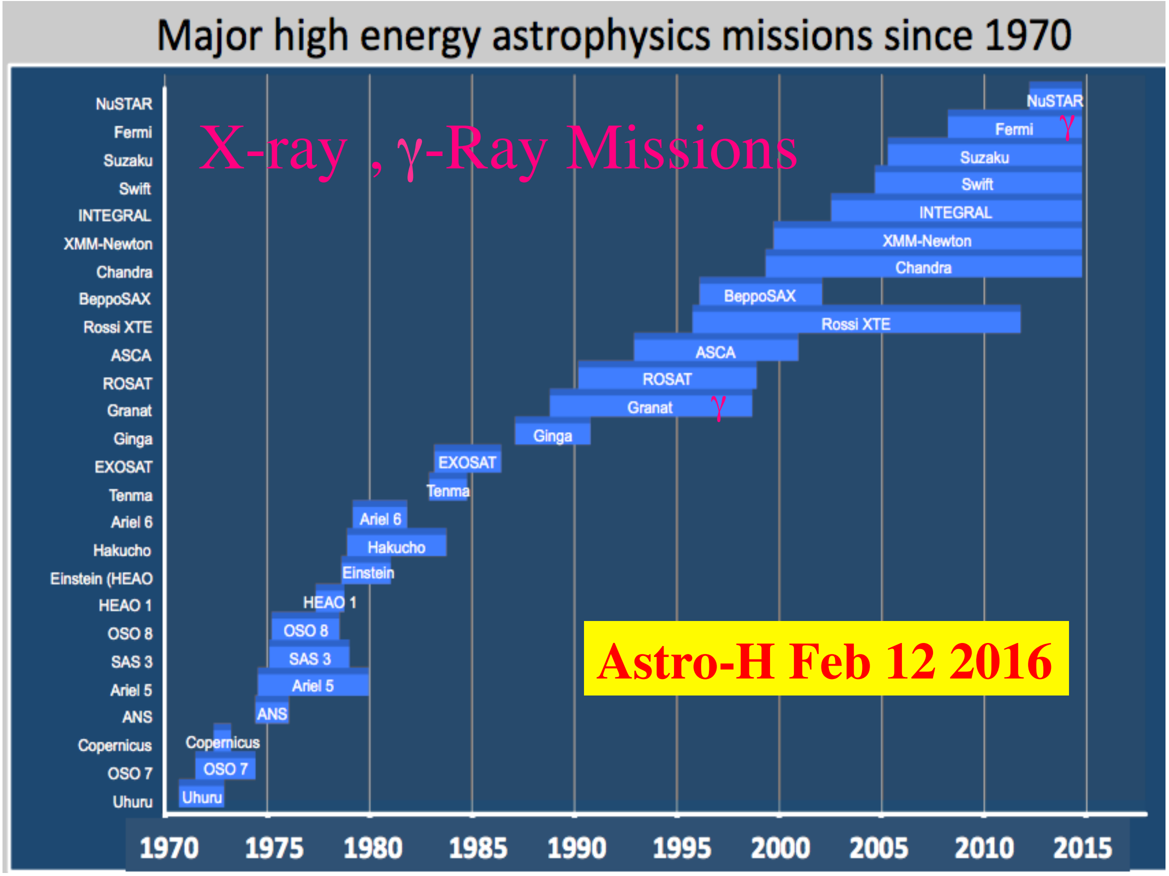
- Very high energy photons and cosmic rays interact in the atmosphere but produce observable effects from the ground



Weekes 2007

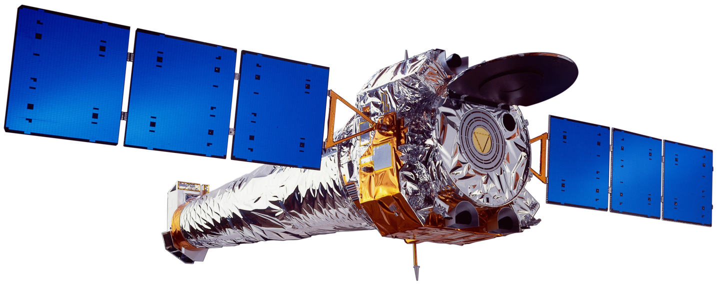
Satellite High Energy Missions 1969-2005

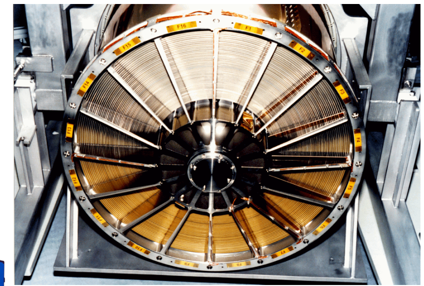



Major high energy astrophysics missions since 1970
X-ray , γ-Ray Missions
Astro-H Feb 12 2016
NuSTAR
Fermi
Suzaku
Swift
INTEGRAL
XMM-Newton
Chandra
BeppoSAX
Rossi XTE
ASCA
ROSAT
Granat
Ginga
EXOSAT
Tenma
Ariel 6
Hakucho
Einstein (HEAO
HEAO 1
OSO 8
SAS 3
Ariel 5
ANS
Copernicus
OSO 7
Uhuru
γ
γ
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015

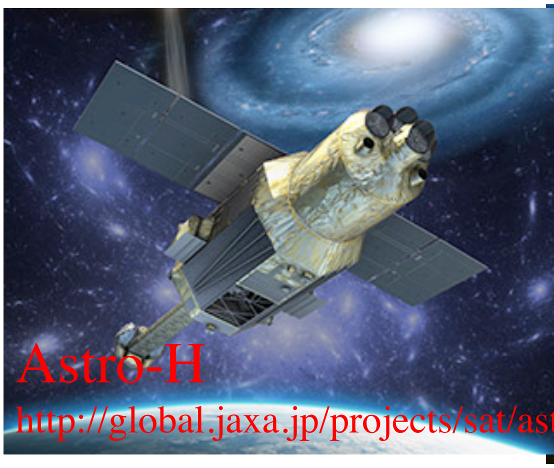

Astro-H at Tsukuba Nov 2015
1-A
1-B
1-C
1-D

Chandra X-ray Observatory



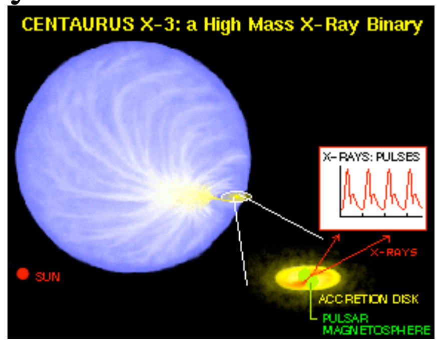


XMM mirror



The Objects of High Energy Astrophysics-Neutron Stars

Longair 13.4 ; 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)

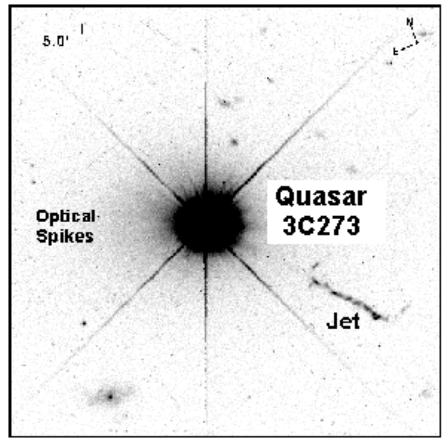
Just 2 yrs after the discovery of the neutron!

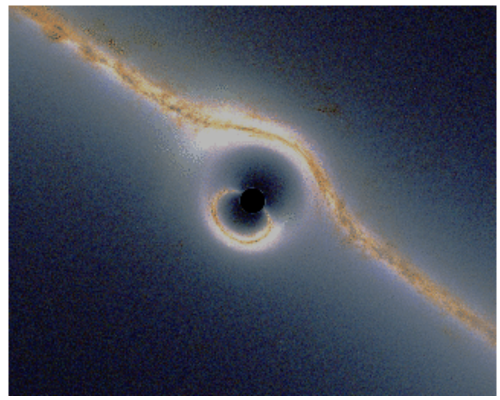
Fritz Zwicky

Black Holes Longair 19 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 (those with accurate masses) and a few in nearby galaxies
- $\sim 10^8$ AGN are 'known'

* $M_{sun=}$ 2×10^{33} gm





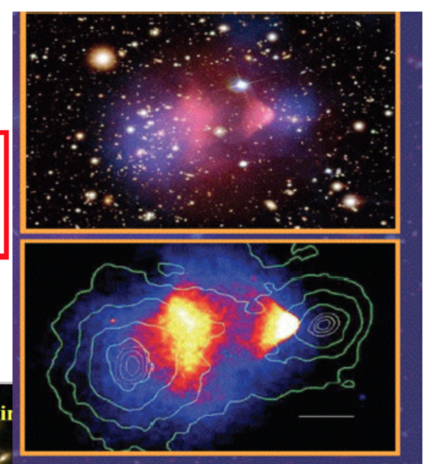
Clusters of Galaxies

Most massive and largest objects in the universe- $M>10^{14} M_{\odot}$ $R \sim 3.08 \times 10^{24}$ cm= 1 Mpc

**the bending of light by strong gravity can act as a lens

Most of the baryons* in clusters are in the hot x-ray emitting gas- most of the mass is **dark matter**

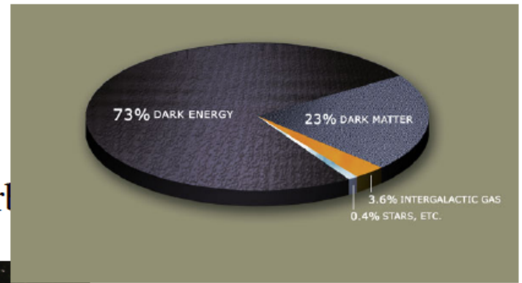
Can act as a gravitational lens**- revealing the amount of and distribution of **dark matter*****.

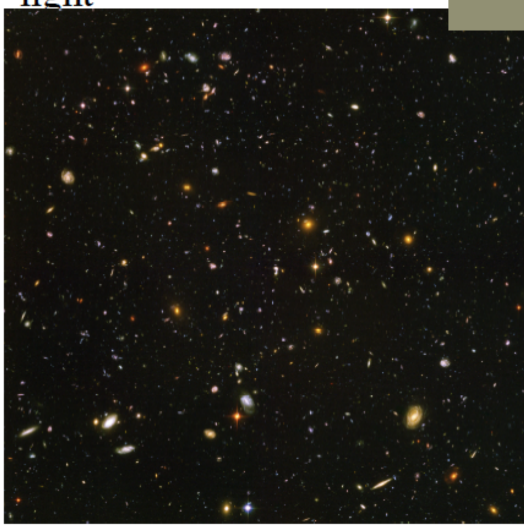


*Baryon- neutrons protons, nuclei of atoms

Dark Matter

- 'Dark' matter is material that interacts via gravity but does not emit or absorb light





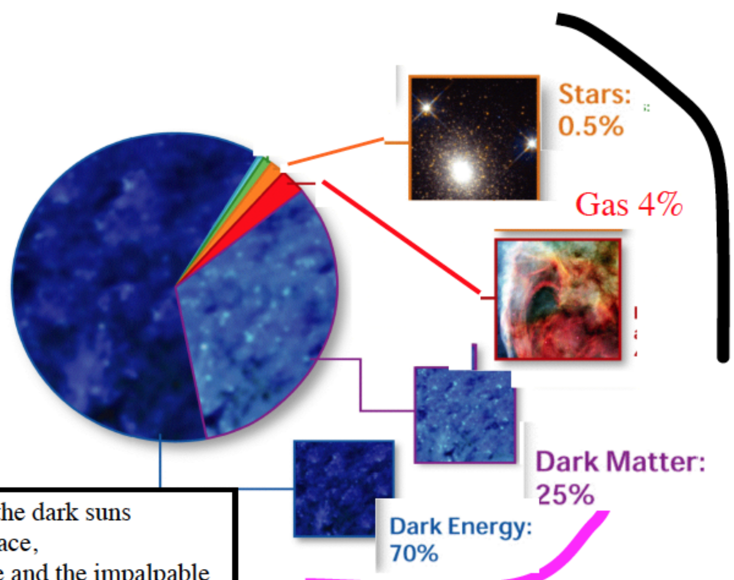
Dark matter has 6x mass of baryons averaged over the entire universe.

Hubble deep field

Dark Matter

- The biggest indication that we do not understand the universe very well
- **95% of the universe consists of stuff that is not understood and can't be 'seen'**
- **The name 'Dark Matter' conveys what we don't know**

Stuff we understand



Stuff we **don't** understand

> The bright suns I see and the dark suns
> I cannot see are in their place,
> The palpable is in its place and the impalpable is in its place
> **Walt Whitman Leaves of Grass**

Physical Processes Over View – More Equations Later

Melia ch 5 and Rosswog and Bruggen ch 3

- How are 'high energy' photons produced
  - Continuum

Thermal emission processes
- Blackbody radiation
- Bremsstrahlung

Non-thermal processes
- Synchrotron radiation
- Inverse Compton emission
- Non-thermal bremms

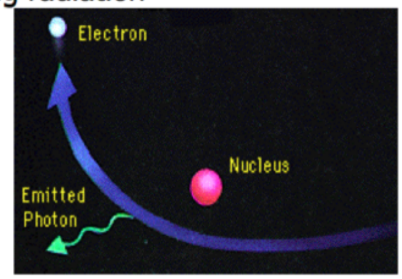
In "thermal" processes the electrons are in a Maxwell-Boltzman distribution- the system has a 'temperature'

In non-thermal the electron distribution is often a power law-no temperature

Longair 6,8,9

BREMSSTRAHLUNG

- "Braking radiation"



Examples: clusters of galaxies, supernova remnants, stellar coronae

Electromagnetic radiation is produced by the acceleration of charged particles (mostly electrons)