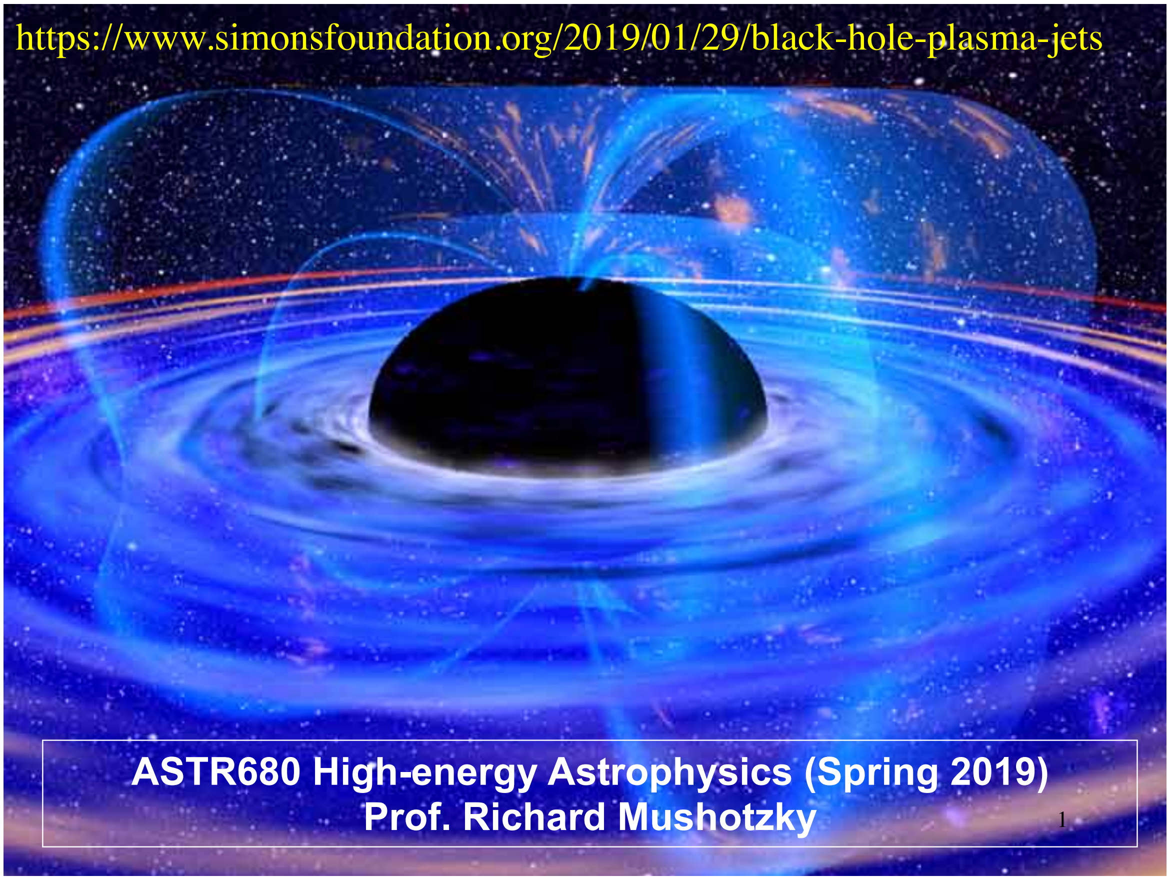


High Energy Astrophysics

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

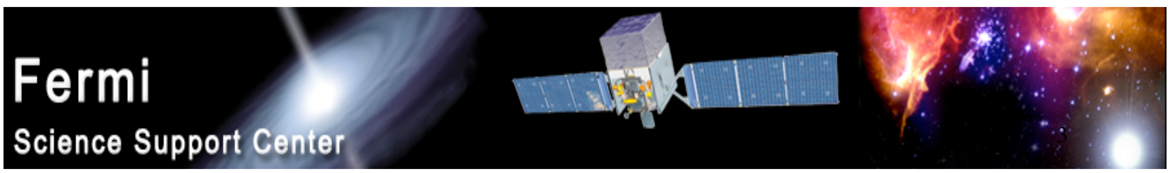
The universe itself (cosmology)

But we also observe high energy phenomena at other energies

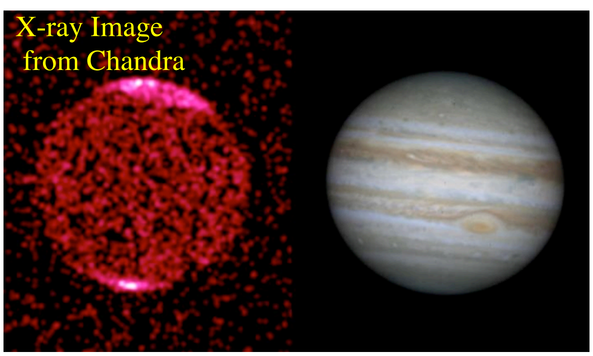
Not only photons and particles !- also gravitational waves

HEA Continued

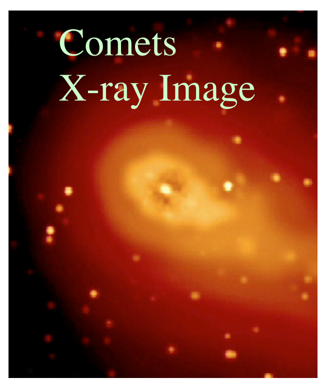
- The study of such objects and processes thus covers a VERY wide range of physics and types of physical objects.
- In order to study x-rays, γ-rays etc from astrophysical objects one needs special techniques and telescopes and the work often must be done in space (I will focus on photons)
- There is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



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

Topics to be covered- Longair Chaps in Red

- Introductory Lecture 1
- Introductory Lecture 2
- Radiation Process Lecture 3-4 Parts of Part II
- X-ray Detectors Lecture 5
- Gamma-ray Detectors and X-ray Telescopes Lecture 6
- Clusters of Galaxies 1 Lectures 7-9 Ch 4
- Supernova and Supernova Remnants 10-13
- Neutron Stars Lecture 14-16 Ch 13/14
- Stellar Mass Black Holes Lecture 17-20 Ch 13/14
- Gamma-ray bursts 21
- AGN 22-26 Ch 18/19/20

Cosmic rays, neutrinos, Grav Waves and radio sources will be mentioned only briefly

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 Neutron stars, 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

Where are we going-other resources

- 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) – 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 6 (part) +7 of Melia and part of ch 8 of Rosswog and Bruggen)

Clusters of galaxies-

Supernova remnants

Active galaxies Ch 12 in Melia

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

Material/Books

- Textbook- Longair High Energy Astrophysics 3rd Edition
- Auxiliary Textbooks
  - F Melia **High-Energy Astrophysics**
  - Rosswog and Bruggen **Introduction to High-Energy Astrophysics**
- **Lots of additional material in class web pages and at Joern Wilms web page**

http://pulsar.sternwarte.uni-erlangen.de/wilms/teach/ xray1/

Reading Assignment

- **Read Ch 1 of Longair**

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

Important dates

-Last day for students to add a course or drop a course without a W: Friday, Feb. 8
-Spring break: Sat, Mar.16−Sun Mar. 24
-Last day for students to drop a course with a W: Friday, Apr. 12
-Last day of classes: Tuesday, May 14
- exam: Monday, May 20 10:30am-12:30pm

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

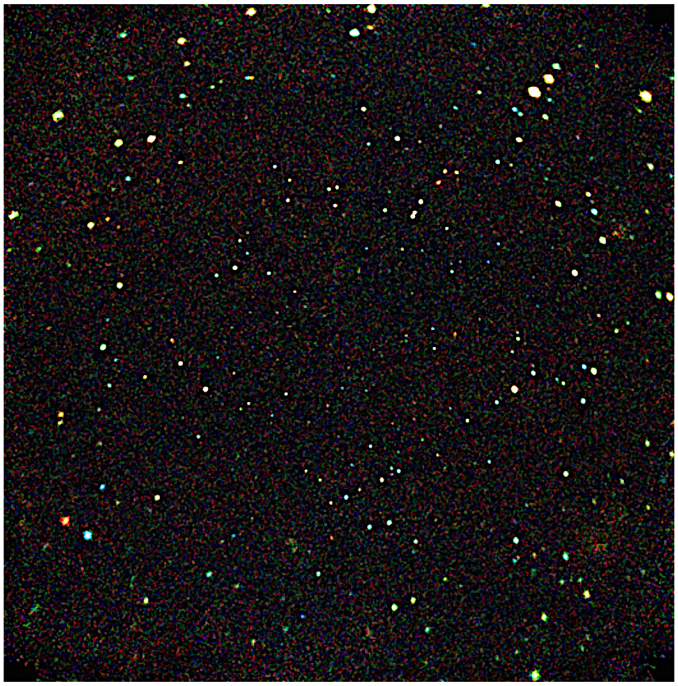
For certain classes of objects (AGN, x-ray binaries, clusters of galaxies, SNR) a large fraction of the emitted energy is in the high energy band

Gamma-Rays

- In the 0.6-1000 Mev 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 (see Science 30 Nov 2018:Vol. 362, pp. 1031-1034 **A gamma-ray determination of the Universe's star formation history**)

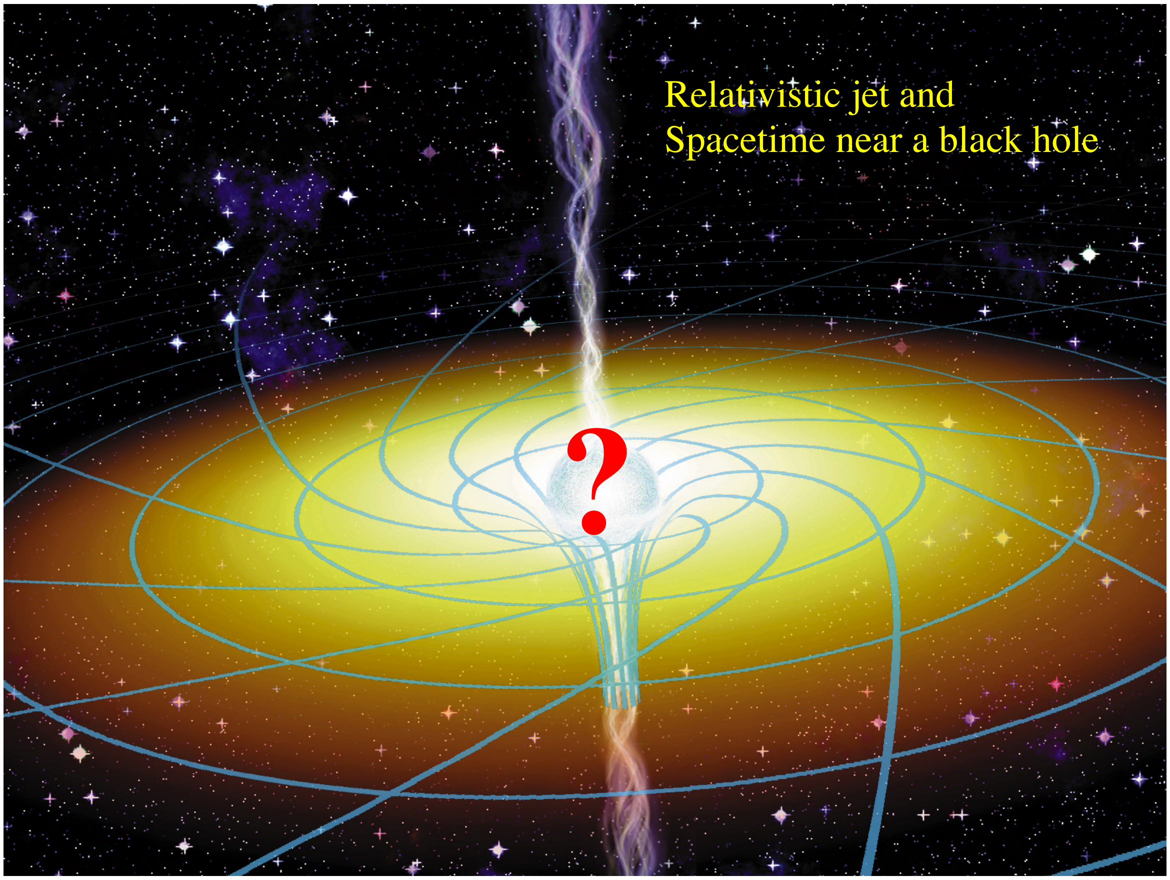
- γ-rays are the emitted by radioactive isotopes and thus are a measure of creation of the elements
- At E> 25 GeV can perform γ-ray observations from the ground (see https://www.mpi-hd.mpg.de/hfm/HESS/pages/about/physics/)

A small part of the X-ray sky

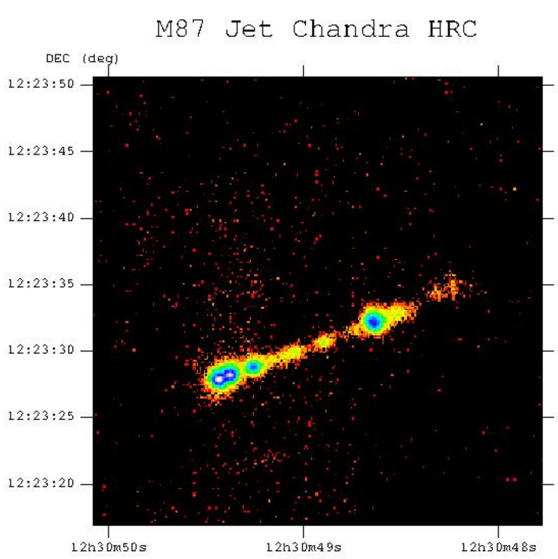


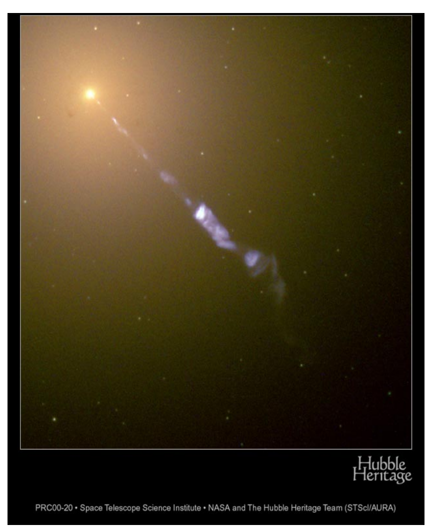
Chandra Deep Field South
(1 million second exposure by the Chandra X-ray Observatory… almost every source is a distant, accreting massive black hole)

(CXC; R. Giaconni et al.)

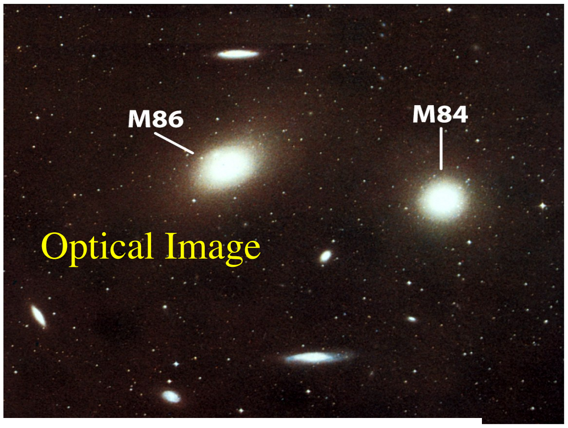


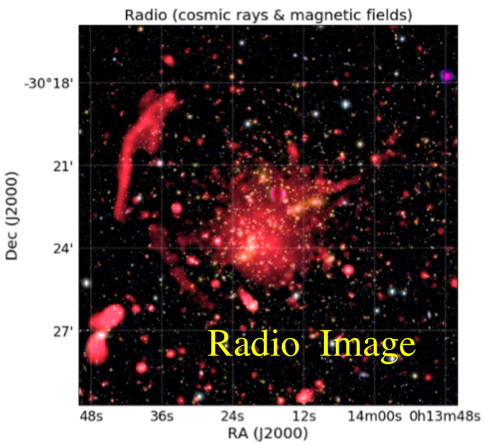
The M87 jet HST- Optical Image
Chandra- Xray

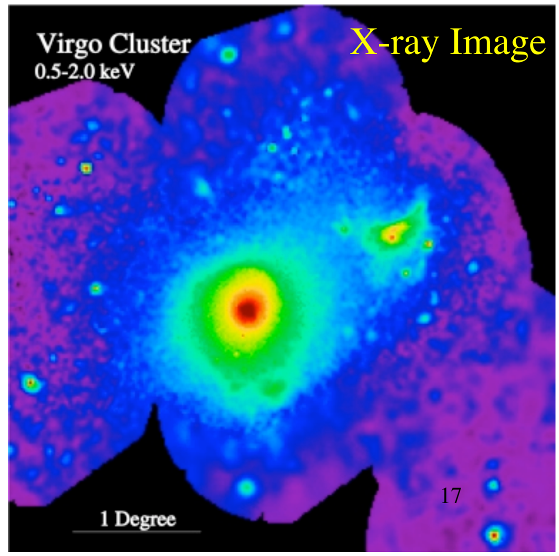




Clusters of galaxies…







Cluster Multi-Wavelength

L. Rudnick 1901.09448.pdf

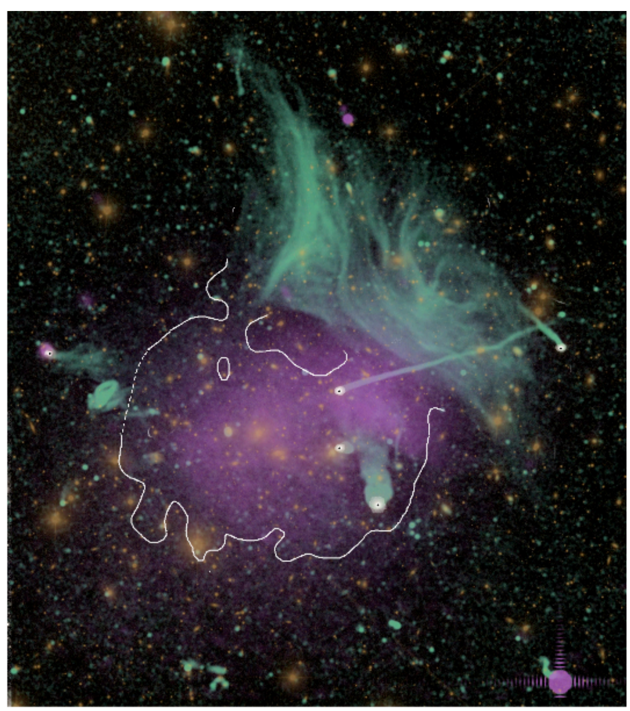
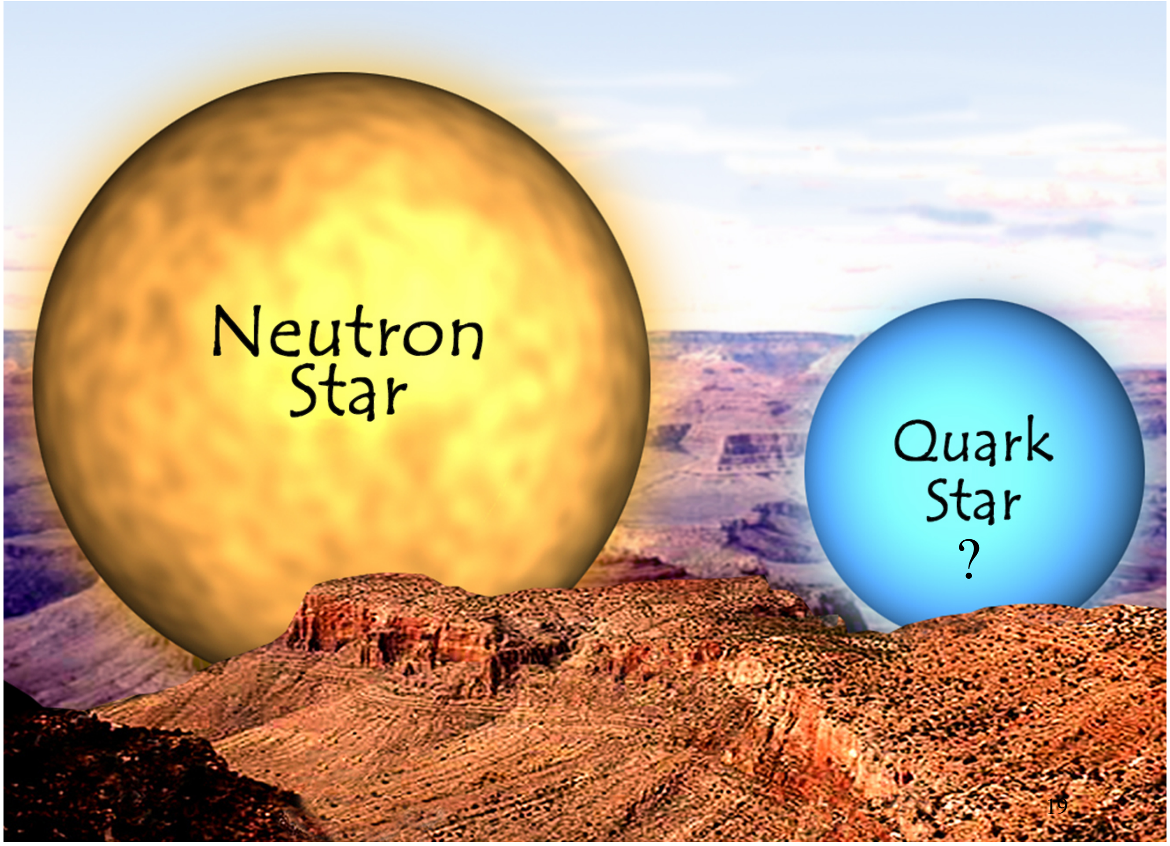
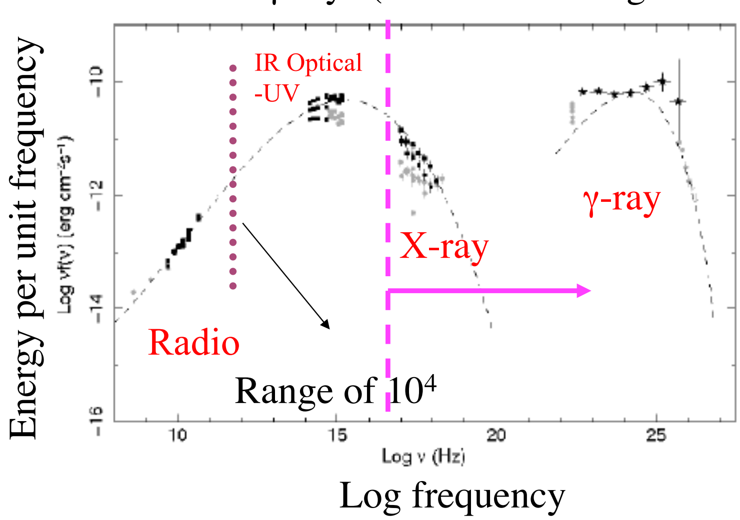


Figure 4. Abell 2256, in the 2-10 keV X-ray band (purple), near infrared band (orange) and ra
synchrotron (green, [6]) The white contour indicates the extent of the diffuse radio "halo". The
patches with dark spots indicate a few of the cluster galaxies that host a radio structure bent b



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)



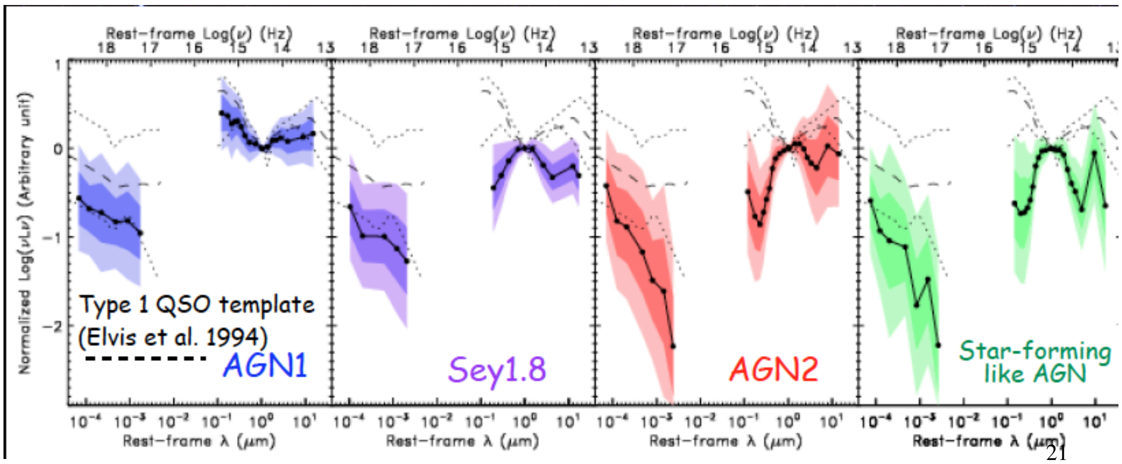
Broad band *spectral energy distribution* (SED) of a '**blazar**' (an active galaxy whose observed radiation is dominated by a relativistic jet 'coming at' us)

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

AGN SEDs



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*

Course structure

- Lectures
  - Attendance is crucial: a major part of this course will be in-class discussions!
- Other components-tentative- due to large class this maybe changed!
  - Homeworks (1 every two weeks)
  - Midterm exam (12th March 2019)
  - Final exam (20th May 2019; 10.30am)
  - Project and presentation (more later in the semester)
  - Grading scheme given in Syllabus

Grading scheme-Tentative

- Distribution

– HW	30%
– Midterm	20%
– Project	30%
– Final	20%

- Letter grade

– 90%+	A
– 80-89%	B
– 70-79%	C

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/

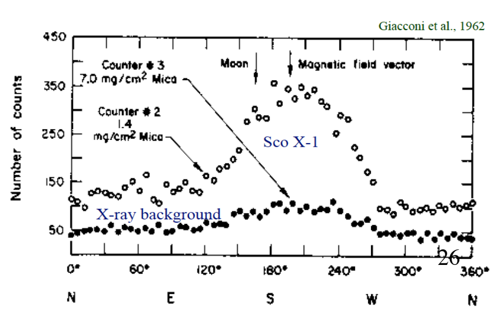
- High energy astrophysics
  - cosmic rays were discovered in 1912 by Victor Hess (**Nobel prize** 1936),
    - he found that an electroscope discharged more rapidly as he ascended in a balloon.
      - source of radiation entering the atmosphere from above
    - Cosmic' rays' are electrically charged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

see https://heasarc.gsfc.nasa.gov/docs/heasarc/headates/heahistory.html

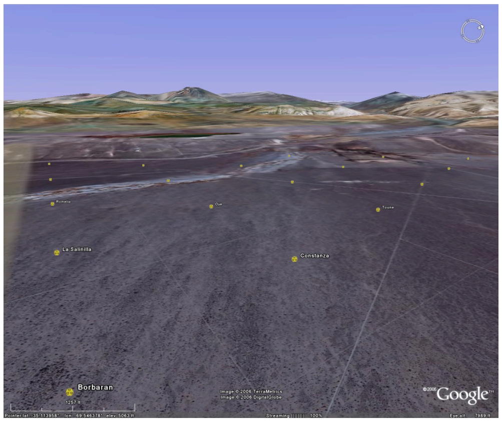
The first astronomical X-ray source- the sun (1949) using captured WWII V2 rockets. Herb Friedman and collaborators at the US Naval Research Lab (in Washington DC). 1951PhRv...83.1025F

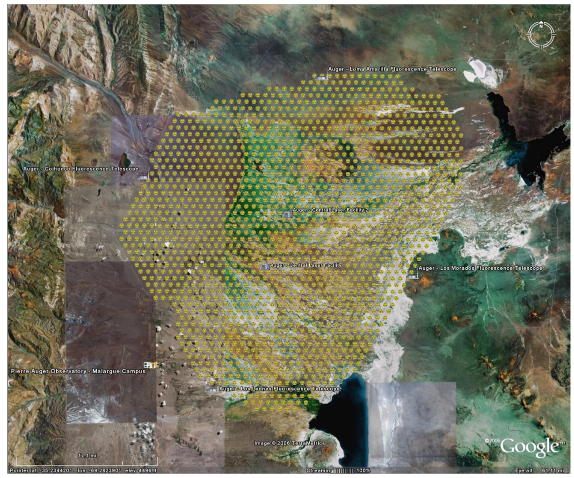
First **non-solar** x-ray source Sco X-1 rocket (Giacconi et al **Nobel prize)**

The First Extra-Solar X-ray Detection

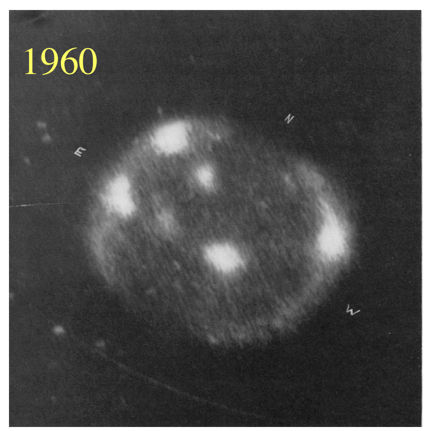


Pierre Auger Observatory-Google Earth

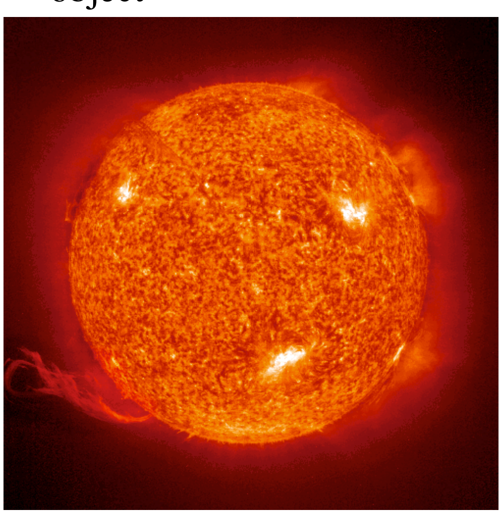




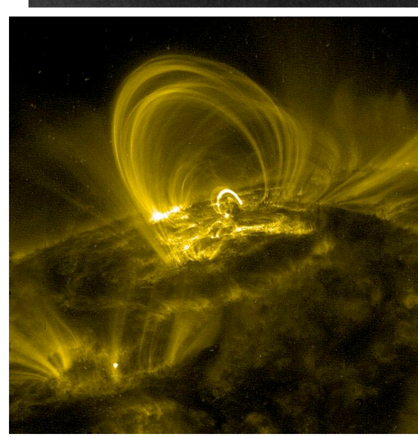
X-ray Images of the Sun



- 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



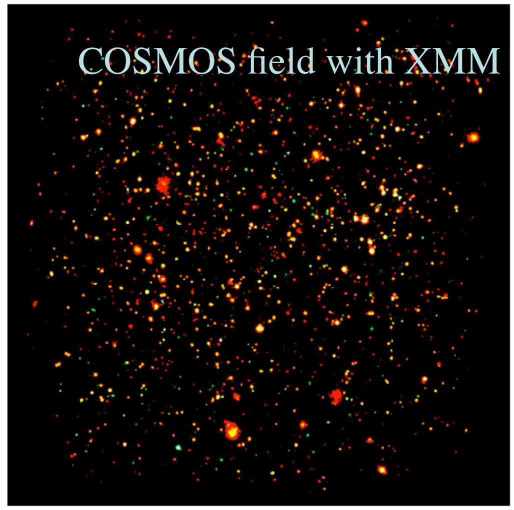
X-ray Astronomy

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

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

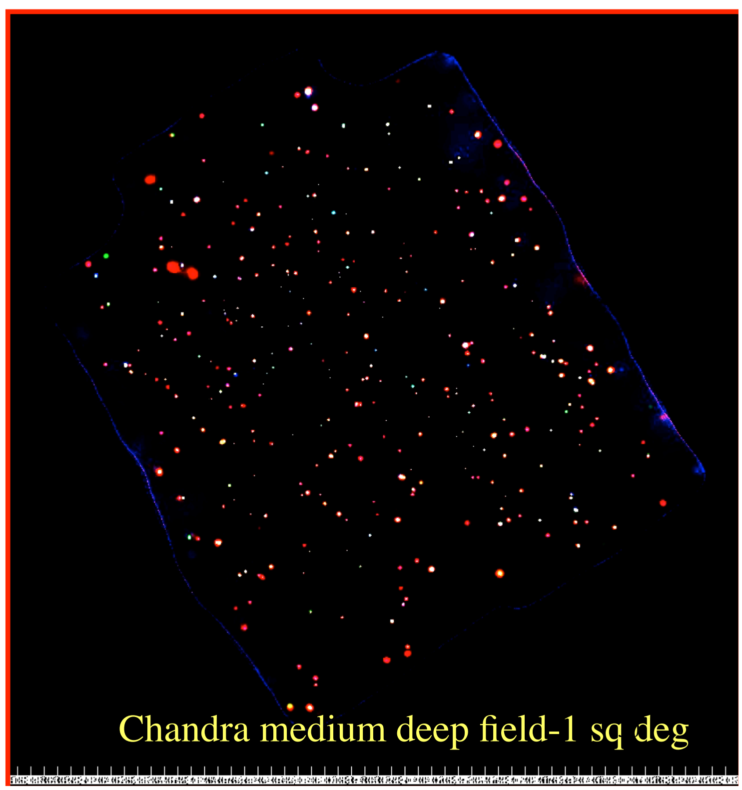
  - angular resolution by 10^5 ($10^0 \rightarrow 0.5''$)
  - spectral resolution by 10^4
    now ($E/\Delta E\sim1000$)
- There are now >300,000 known x-ray sources
- At the faintest levels probed by Chandra there are >2000 x-ray sources/deg^2 (e.g. 10^8 all sky)
- Despite these spectacular advances x-ray 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)

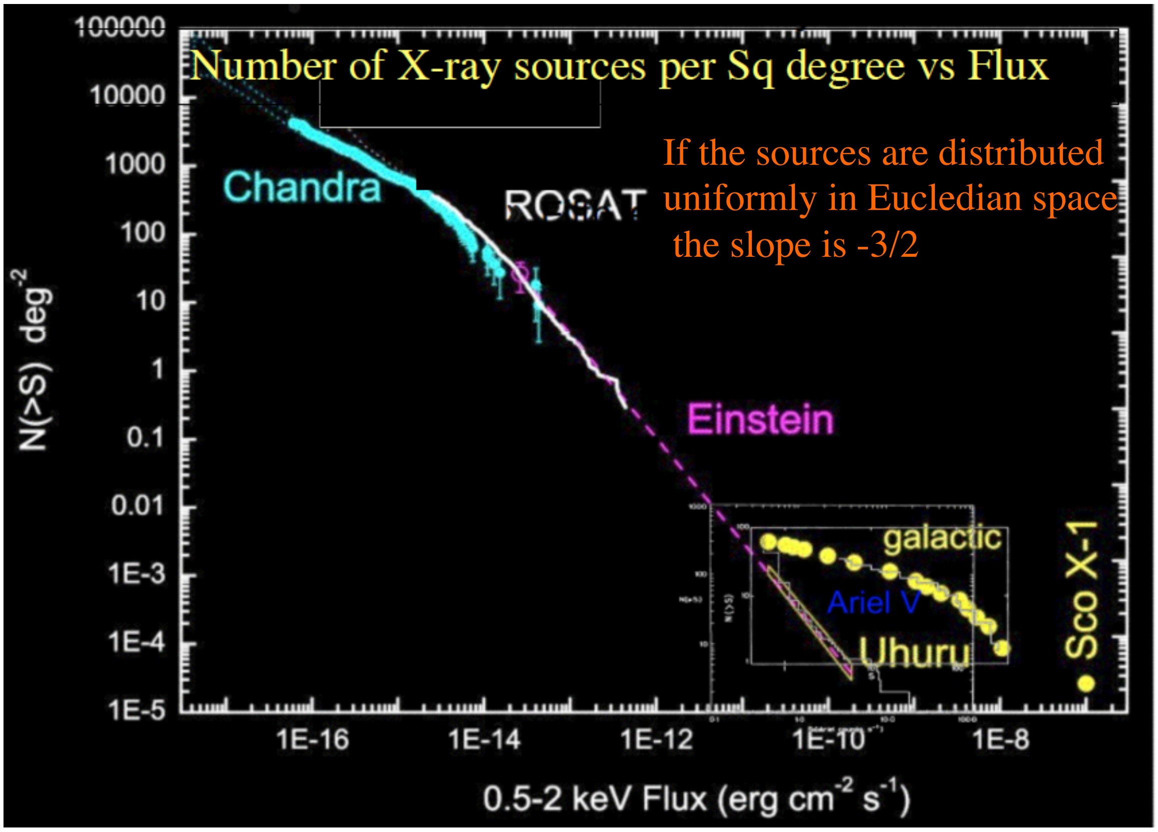
← 2 deg →



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 $=8\times10^9 L_\odot$)
  - The red 'blobs' are clusters of galaxies





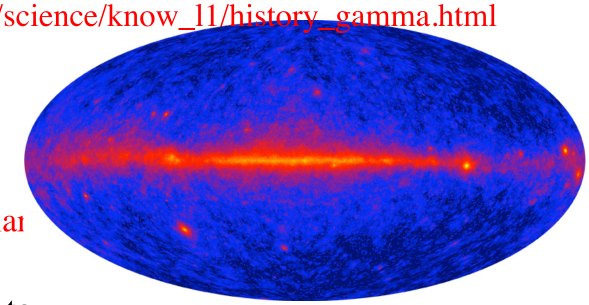
Gamma-Rays

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



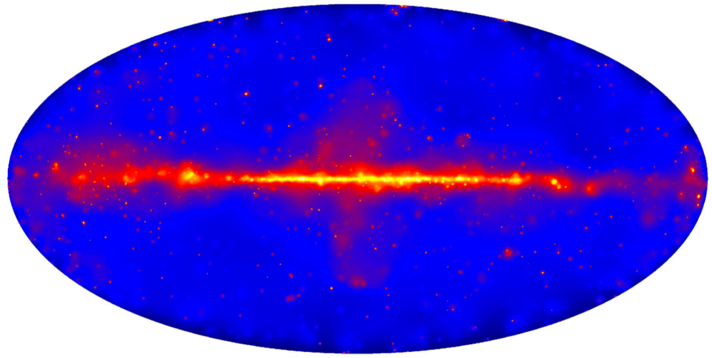
γ-Ray Sky with Fermi
Detected >1000 sources in first year of operation (most are blazars and pulsars)- now >3000 sources

Other γ-Ray sources include
Supernova remnants
Unusual binary stars

Notice the introduction of vast amounts of jargon

γ-Ray Astronomy

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



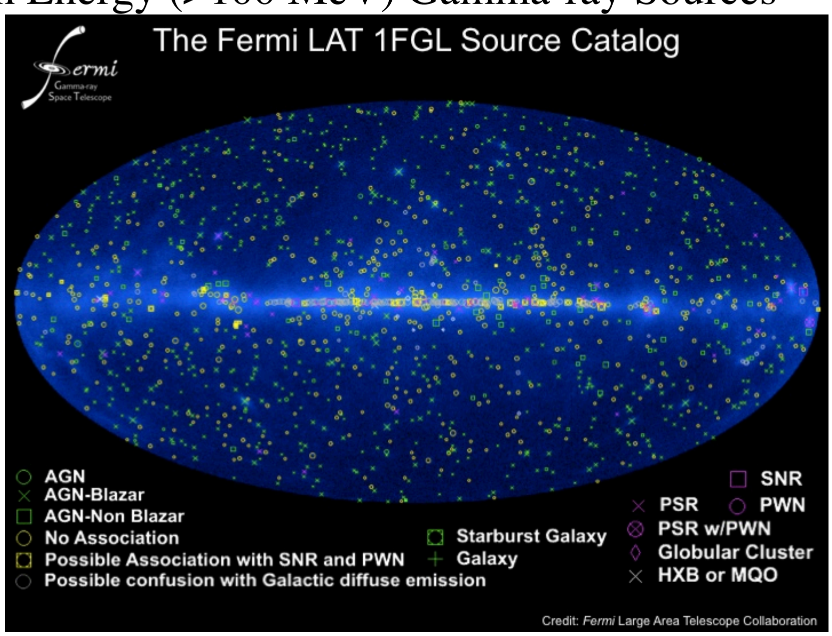
- Fermi launched in 2009 has a sensitivity of **~10^{-9}** ph/cm^2/sec and an angular resolution of ~0.1°

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

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
- FL8Y catalog has ~5500 sources of which ~66% are associated (80% at high b) 2/3 are blazars



Median error radius 4.4'

https://fermi.gsfc.nasa.gov/science/mtgs/symposia/2018/program/mon/Benoit_1.pptx.pdf

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 (Longair fig 1.3, Melia 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 .

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