

High Energy Astrophysics

What is 'High Energy Astrophysics'?

Wikipedia 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 (intergalactic medium)

But we may observe high energy phenomena at other energies

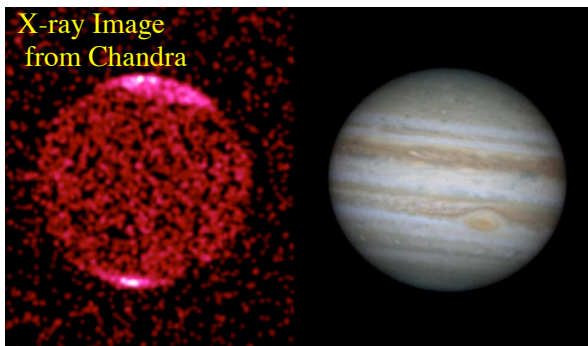
Not only photons and particles !- also gravitational waves

HEA Continued

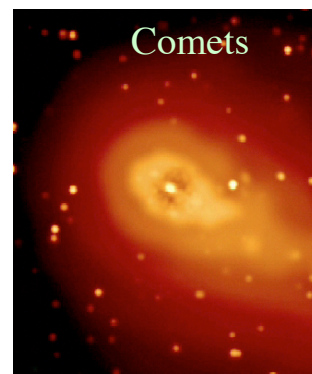
- The study of such objects and processes thus covers a VERY wide range of physics and types of physical objects.
- In order to study x-rays, γ -rays etc from astrophysical objects one needs special techniques and telescopes and the work often must be done in space (**I will focus on photons**)
- There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



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



Comets become significant X-ray sources when they interact strongly with solar wind ions.

Energetic solar wind ions hit the coma, capturing electrons from neutral atoms. The electrons become attached to their new nuclei (the solar wind ion), energy is released in the form of X-rays.

Read more: <http://www.universetoday.com/21826/swift-detectsx-ray-emissions-from-comets>

Textbook

- We will 'use' High Energy Astrophysics' by **M. Longair 3rd edition** as a **resource** as well as **2 other books**
- 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

Topics to be covered-Number of Lectures is Approximate

- Introductory Lecture 1-2
- Radiation Process Lecture 3-4
- X-ray Detectors Lecture 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

Unfortunately I will not have time to cover cosmic rays, gravitational waves, most of gamma-ray astronomy a lot of the fascinating phenomena of x-ray binaries and will only cover in passing the Event Horizon Telescope results.

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.**

For which the ab initio 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. Cl) 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**

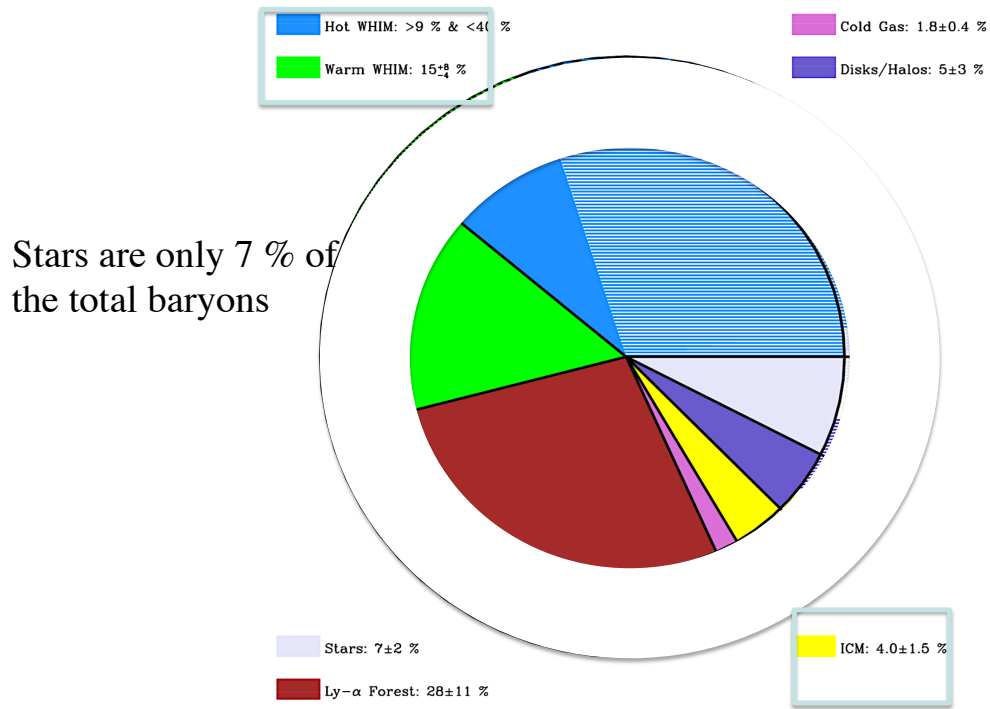
For certain classes of objects (AGN, x-ray binaries, clusters of galaxies) a large fraction of the emitted energy is in the high energy band

In the 0.6-1000MeV γ -ray band most of the universe is transparent

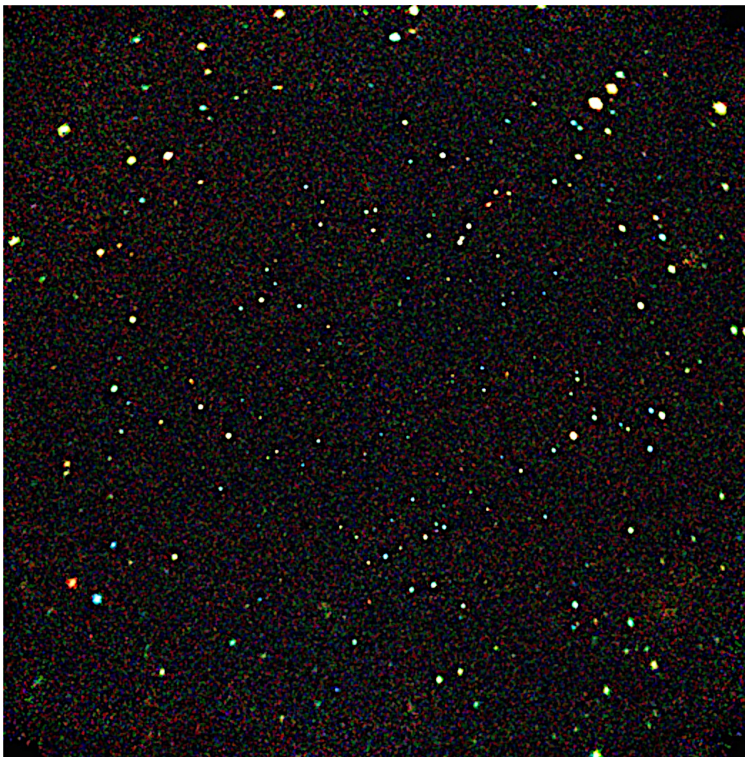
However at higher energies γ -rays are 'absorbed' by photons and thus the opacity at very high energies is a measure of the photon density of the universe

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

~40% of the baryons in the low redshift universe are only visible with high energy data

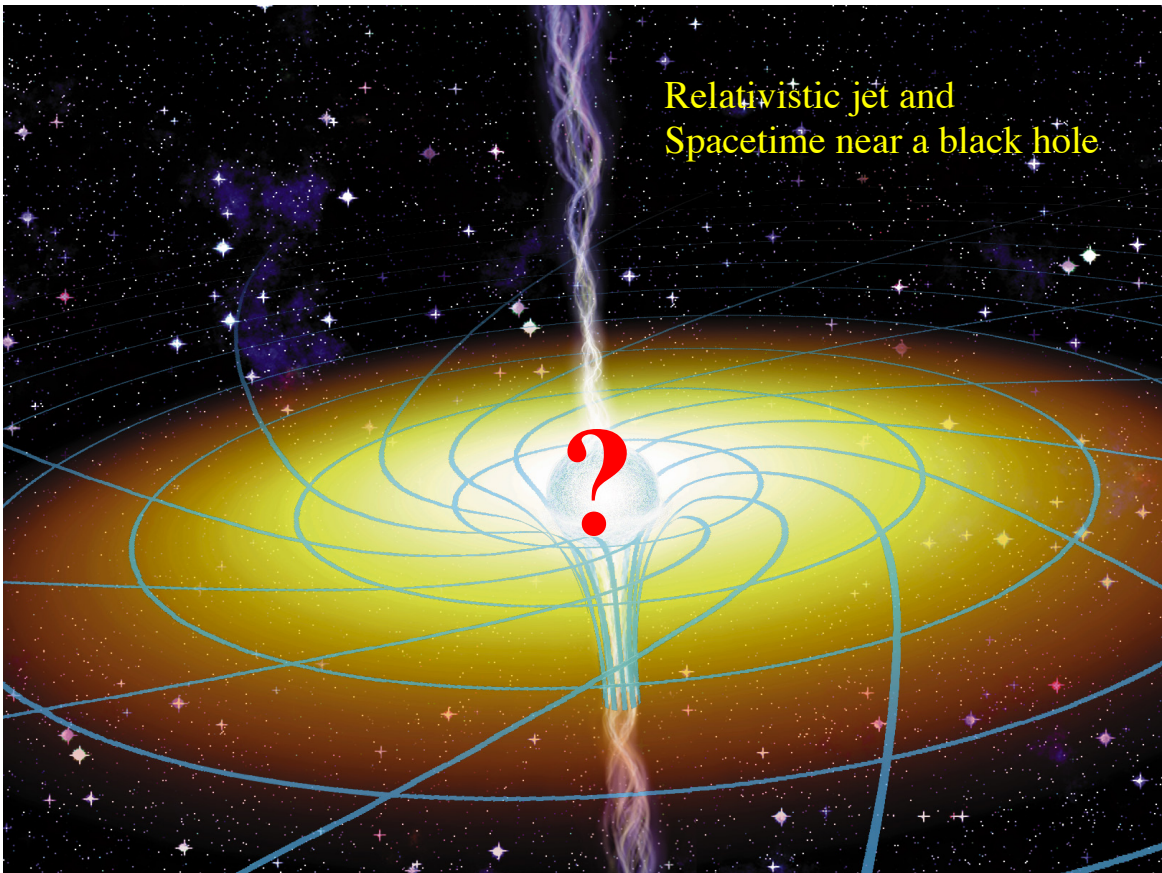


A small part of the X-ray sky



Chandra Deep Field South ~0.1 sq degree
 (1 million second exposure by the Chandra X-ray Observatory... almost every source is a distant, accreting massive black hole)

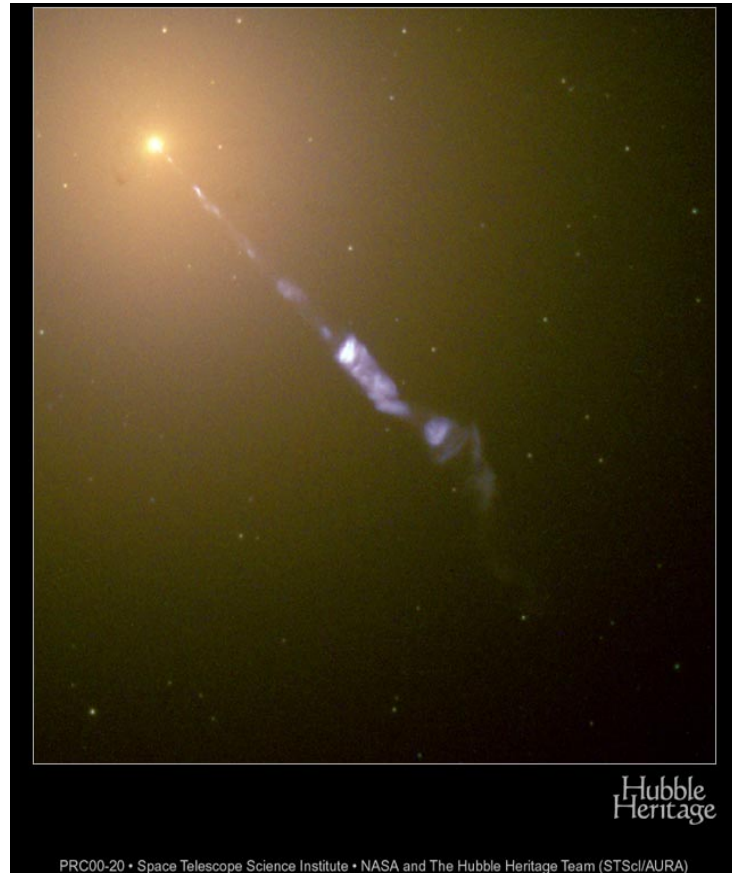
(CXC; R. Giacconi et al.)



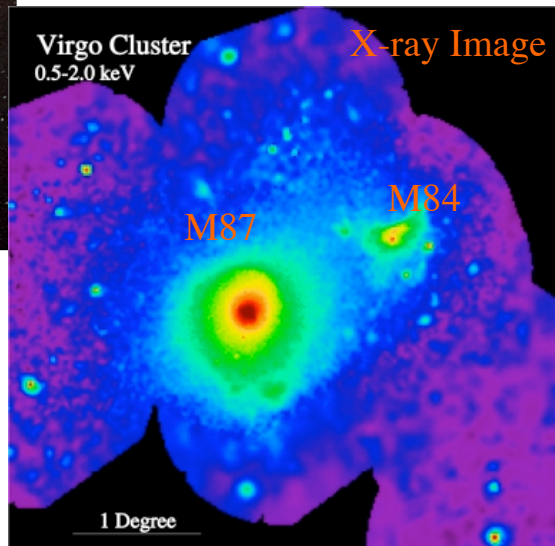
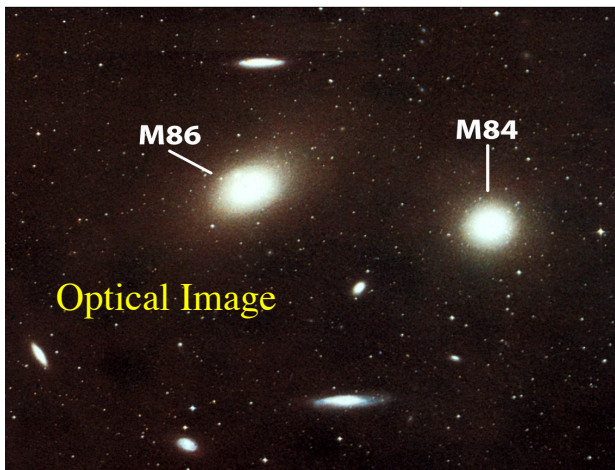
The M87 jet HST- Optical Image

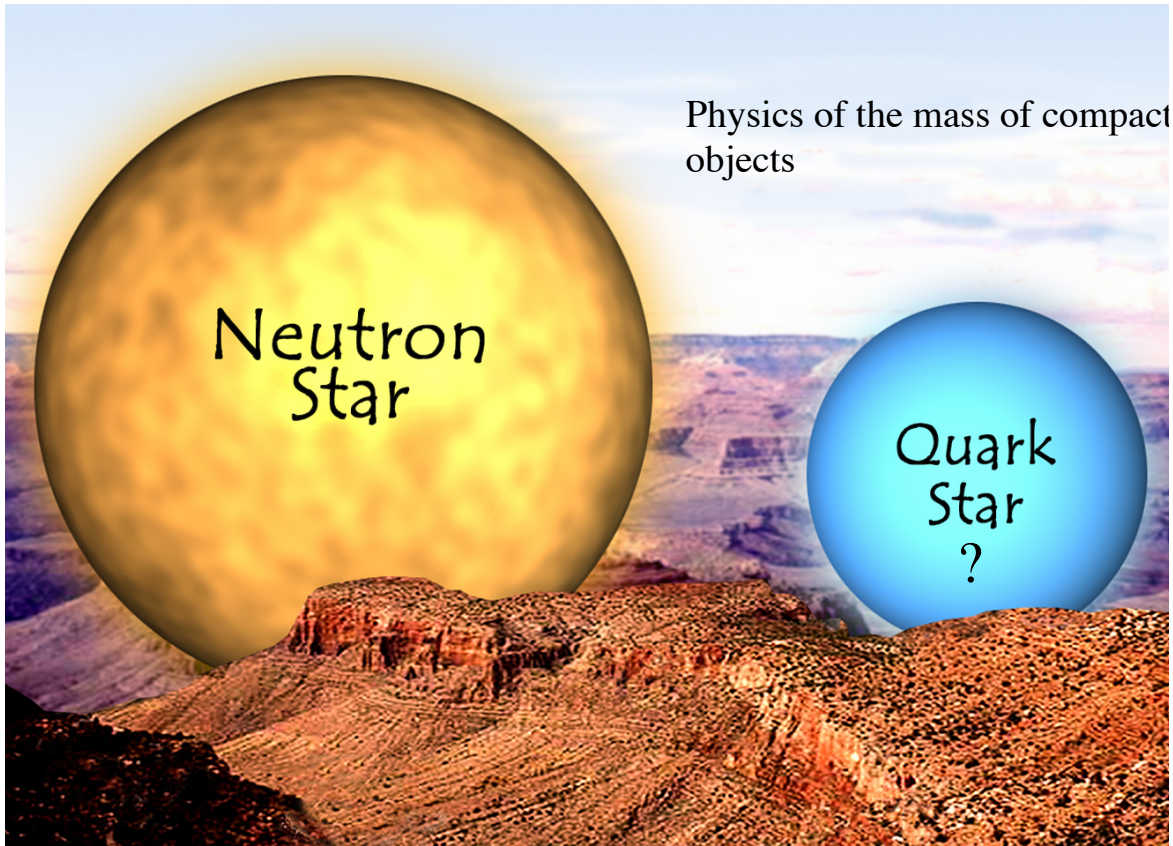
Jargon interrupt
M87 is the 'name' of a
galaxy ~ 16 Mpc distant
which hosts a $\sim 4 \times 10^9 M_{\odot}$
supermassive black hole

HST= Hubble Space
Telescope



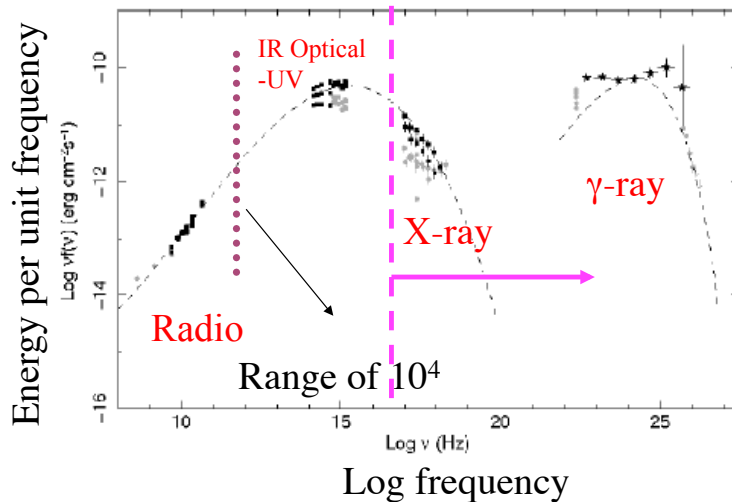
High-energy astrophysics and the formation of galaxies...





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 waves to γ -rays (17 orders of magnitude in frequency)

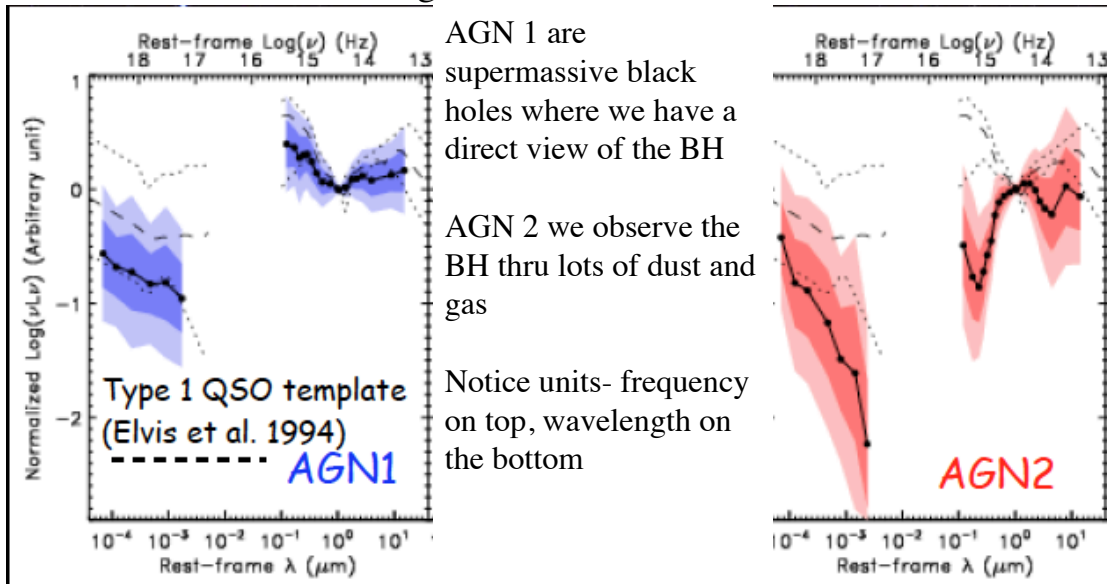


Broad band *spectral energy distribution* (SED) of a '**blazar**' (an active galaxy whose observed radiation is dominated by a relativistic jet 'coming at' us)

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

Different Types of Objects Have Different Spectral Energy Distributions

- 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
 - The universe is a very big, complex and exciting place
- One does **observations not experiments**
 - Most of what we have learned in the last 50 years have come from unexpected discoveries
- This gives a very different flavor to the field
 - Much of this has been driven by new instrumentation and the opening up of new observing windows and the rapid advance of computing
- Of course 'physics' thinking is crucial- we try to understand, not just categorize, catalog and count.
 - 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
- **Reference 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 Oct 2019)
 - Final exam (17th Dec 2019; 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 | | • Letter grade | |
| – HW | 30% | – 90%+ | A |
| – Midterm | 20% | – 80-89% | B |
| – Project | 30% | – 70-79% | C |
| – Final | 20% | – 60-69% | D |
| | | – <59% | F |

From the National Academy of Sciences
Report issued 8-13-2010



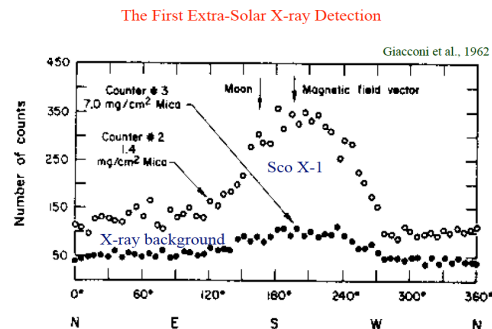
In order to carry out astronomical research, there are increasing demands for detailed knowledge across many sub-fields of physics, statistics, and computational methods. In addition, as astronomy and astrophysics projects have become more complex, both in space and on the ground, there has been a greater 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/>

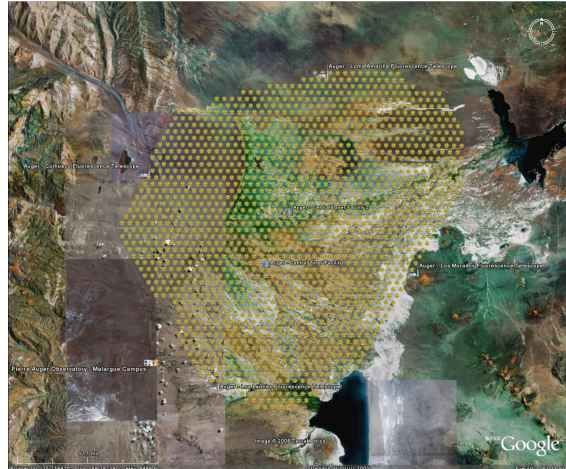
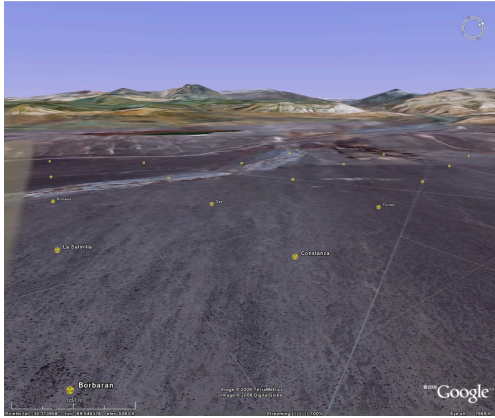
- Astronomy is the 1st science-back to Mesopotamia
- High energy astrophysics
 - cosmic rays were discovered in 1912 by Victor Hess (**Nobel prize** 1936),
 - he found that an electroscope discharged more rapidly as he ascended in a balloon.
 - source of radiation entering the atmosphere from above
 - 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)

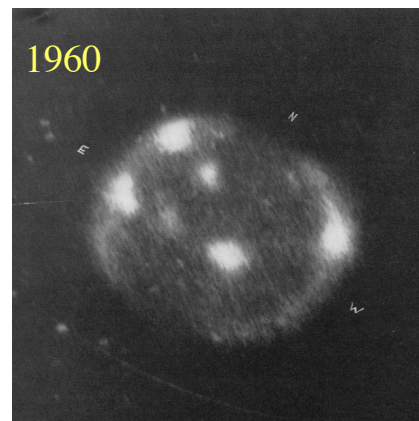
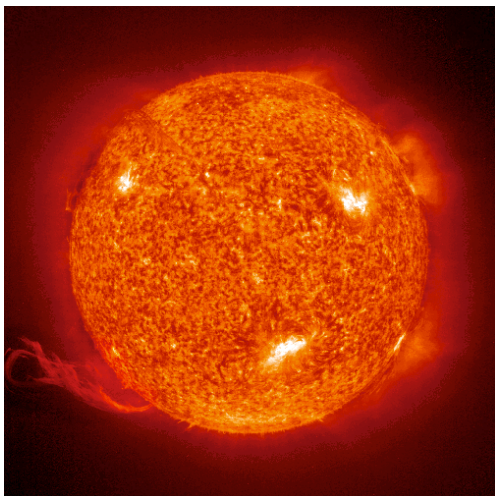


Pierre Auger Observatory-Google Earth

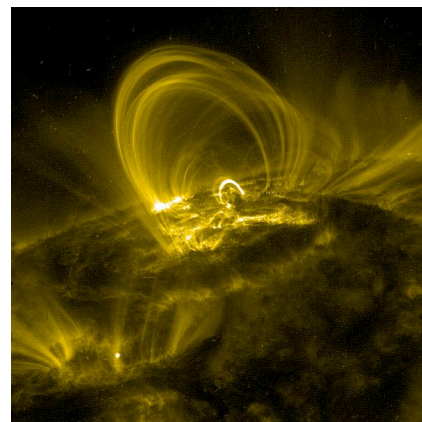


X-ray Images of the Sun

- 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



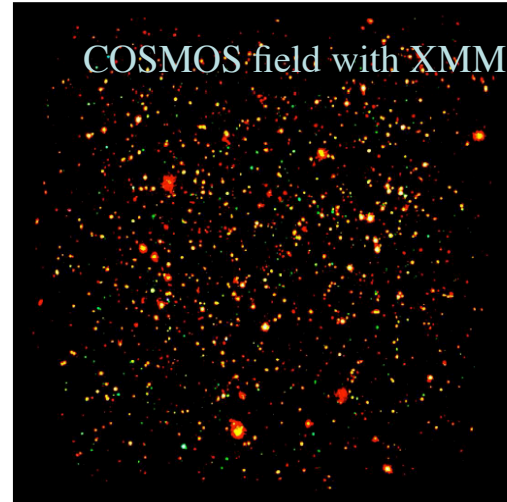
1990's



X-ray Astronomy

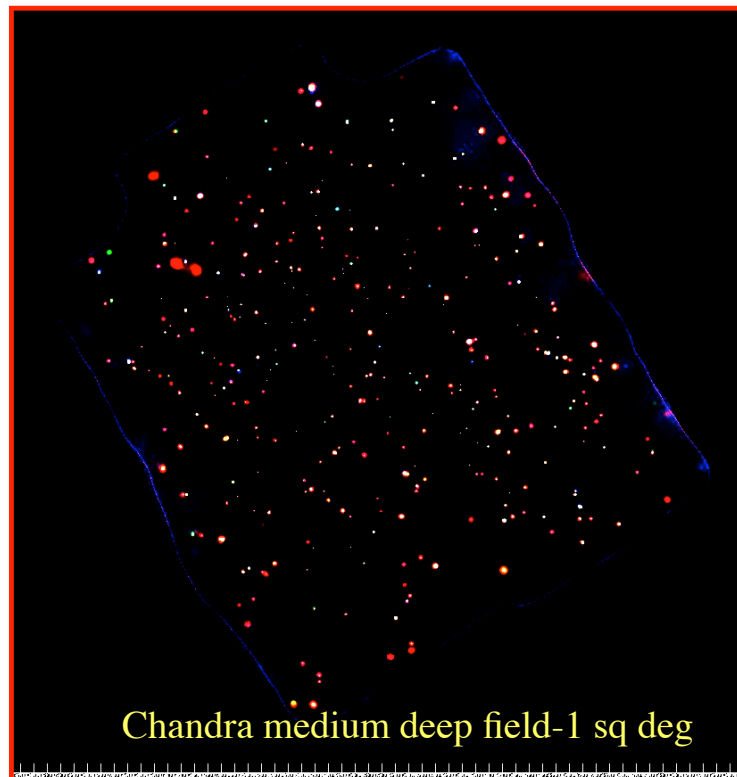
- Start in 1962 with a rocket flight
 - sensitivity has increased by 10^9
($\sim 5 \times 10^{-17}$ ergs/cm²sec in the 0.5-2 keV band)
 - angular resolution by 10^5
($10^0 \rightarrow 0.5''$)
 - spectral resolution by 10^4
now ($E/\Delta E \sim 1000$)
- There are now >500,000 known x-ray sources
- At the faintest levels probed by Chandra there are >2000 x-ray sources/deg² (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 cm² compared to 10^6 cm² for the largest optical telescopes)

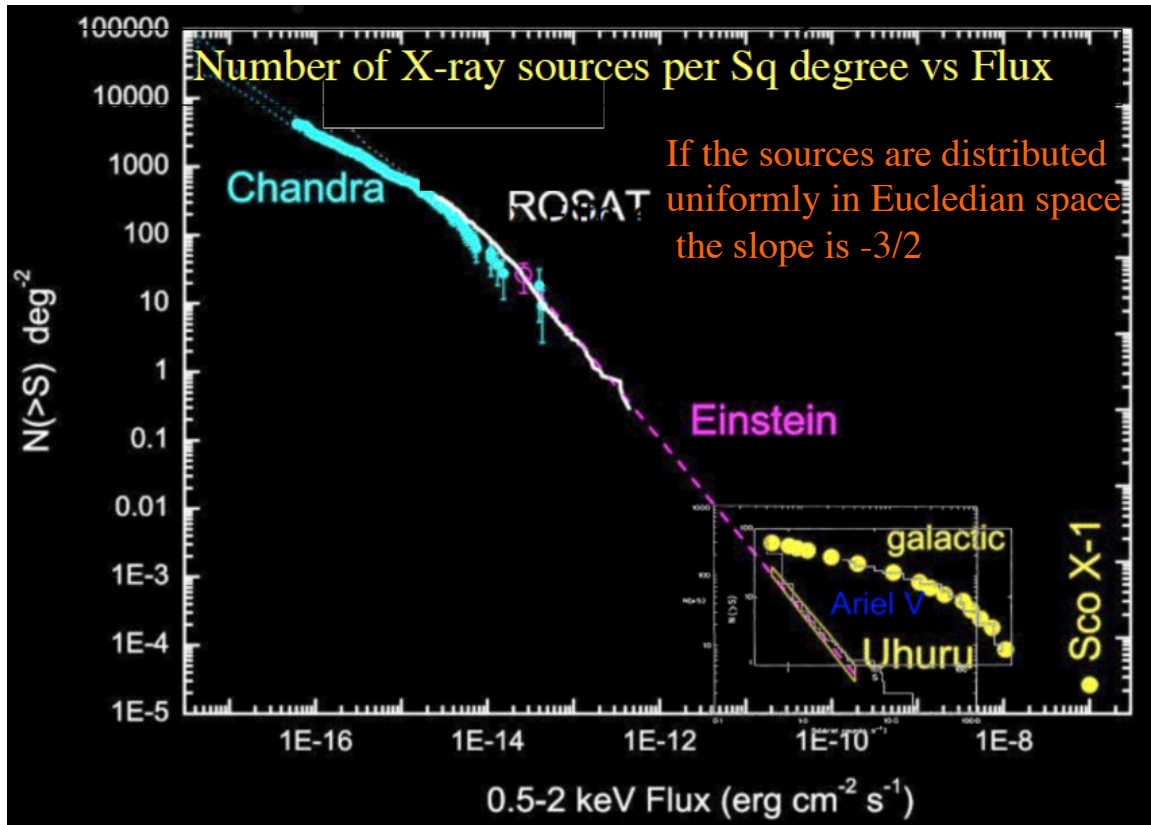
← 2 deg →



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





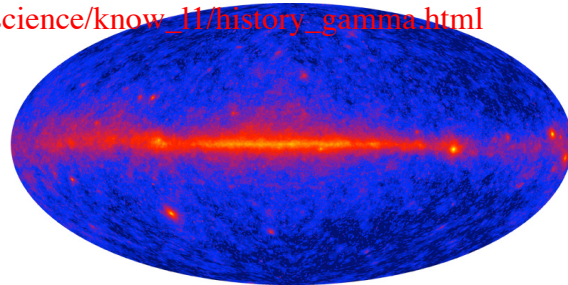
High Energy Astrophysics is 'New'- see heasarc.gsfc.nasa.gov/docs/heasarc/headates/heahistory.html

http://imagine.gsfc.nasa.gov/docs/science/know_11/history_gamma.html

γ -Rays

are emitted by a 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

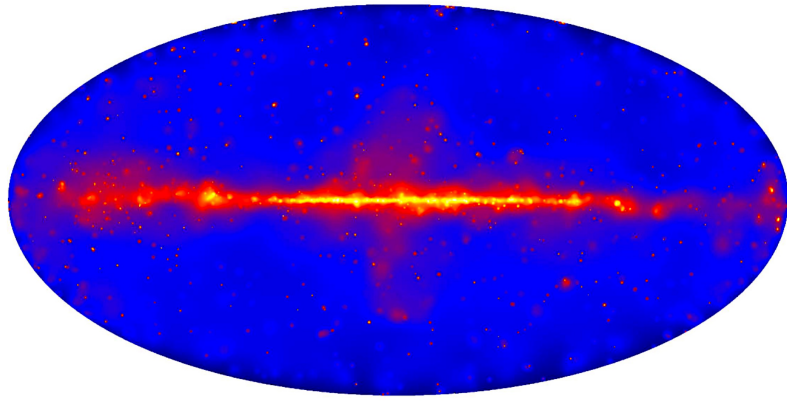
Unusual binary stars

Gravitational Wave Events

*Notice the introduction of vast amounts of jargon**

γ -Ray Astronomy

- First satellite (SAS-2) $E > 35$ MeV in 1972
 - Sensitivity $\sim 10^{-6}$ ph/cm²/sec, 2° angular resolution
 - ~ 30 sources
- Fermi launched in 2009 has a sensitivity of $\sim 10^{-9}$ ph/cm²/sec and an angular resolution of $\sim 0.1^\circ$
 - ~ 500 AGNs detected above 100 MeV using 8 years of data, ~ 220 pulsars

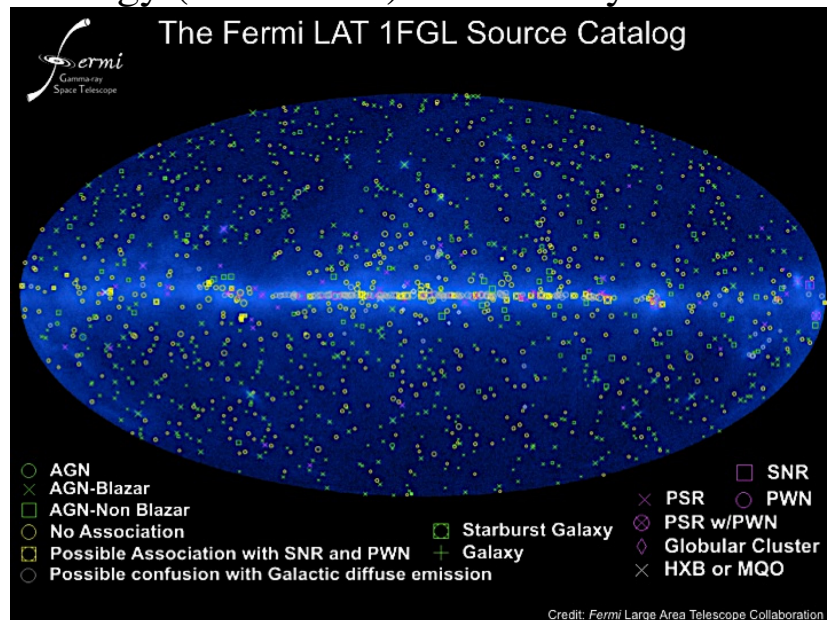


virtually all the high galactic latitude γ -ray sources are AGN

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
- FL8y catalog has 5524 sources of which 2900 are identified



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

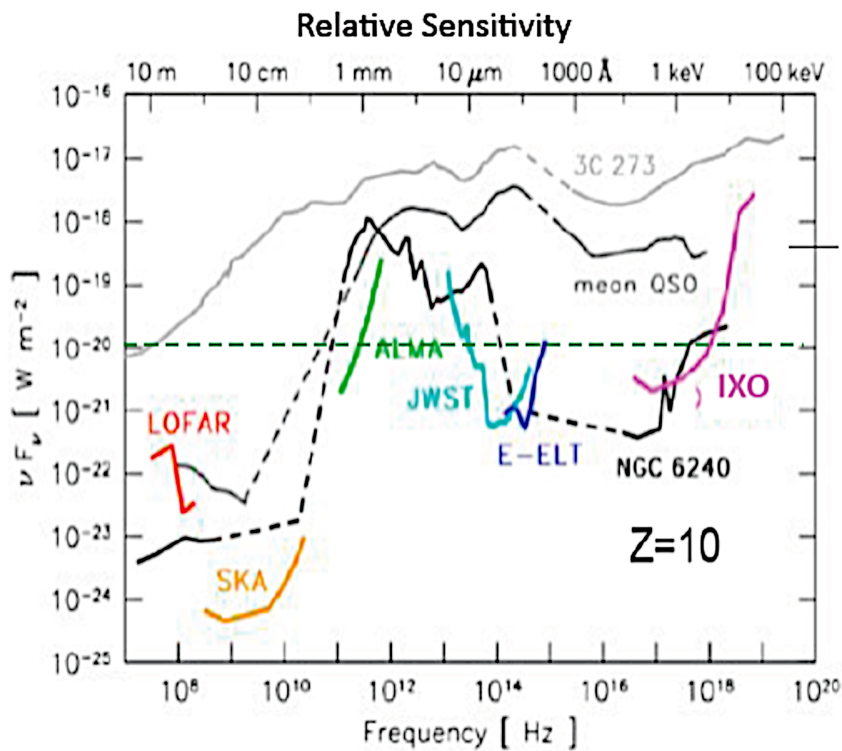
Synchrotron Radiation

Compton Scattering

Line emission and absorption

Absorption (not in the recommended texts- see

Relative Sensitivity of Astronomical Observatories



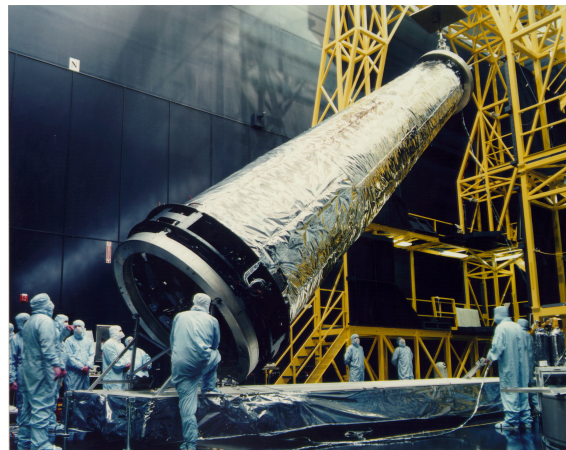
- For study of the faintest known x-ray sources one needs the largest optical and IR telescopes

Space Based High Energy

- The atmosphere is opaque (at ground level) to all wavelengths from γ -rays (GeV) to ultra-violet (10^{11} -10 eV; $1\text{eV}=1.6 \times 10^{-19}\text{J}$)
- 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 (see later)

** 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/cm²/sec/energy bin



Chandra Optical Bench

Why All this Emphasis on Space Observatories ?

The history of the field is thus tied to the opening up of the space age

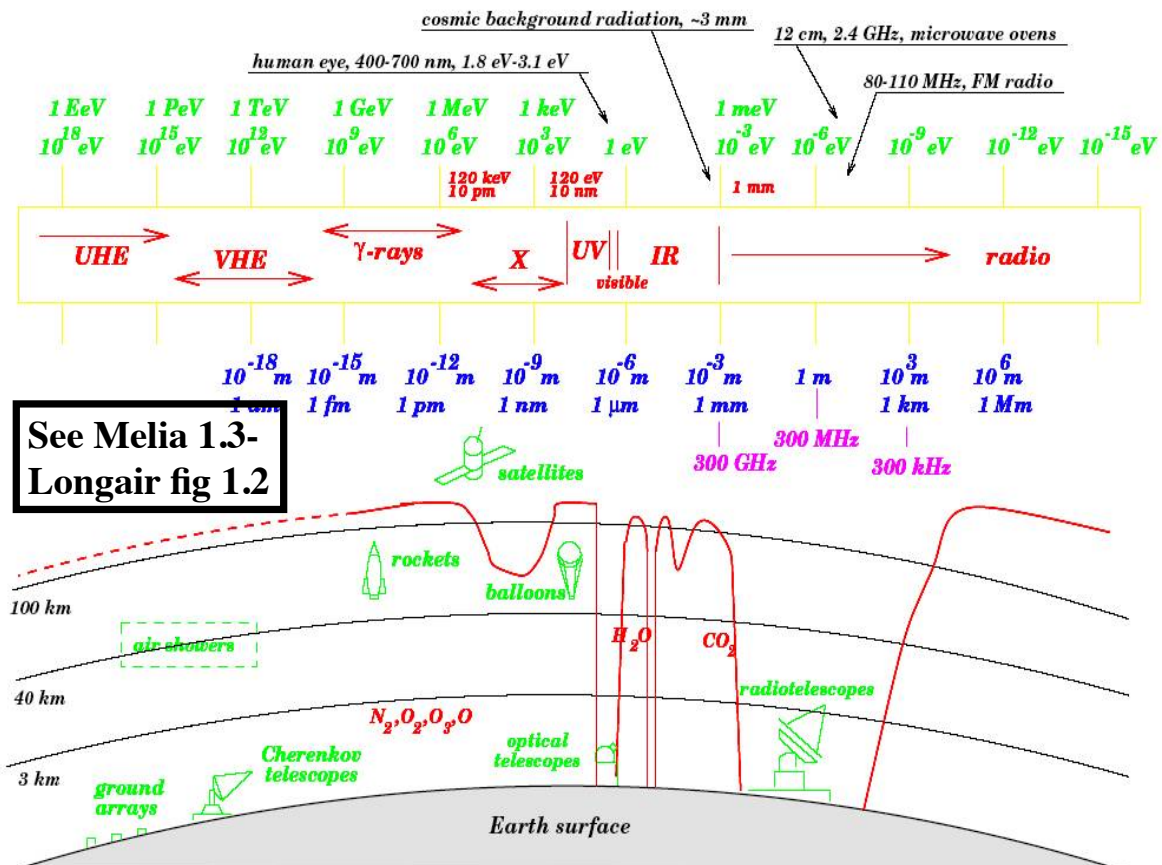
The sociology is thus very different,

space observatories have a finite lifetime
 strong mass limits into how big something
 can be and still be affordable. (Chandra is 5,860 kg,

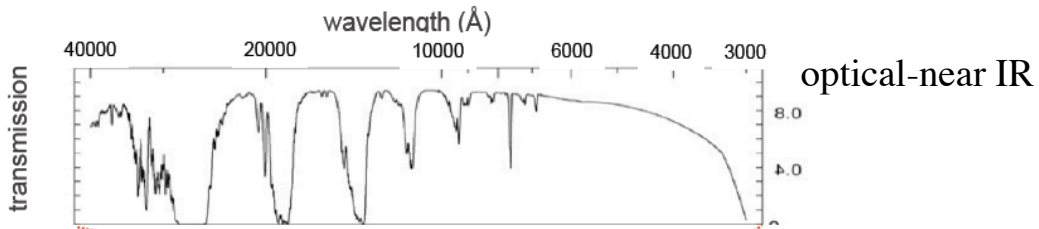
HST 10,863 kg

Fermi 4,303 kg

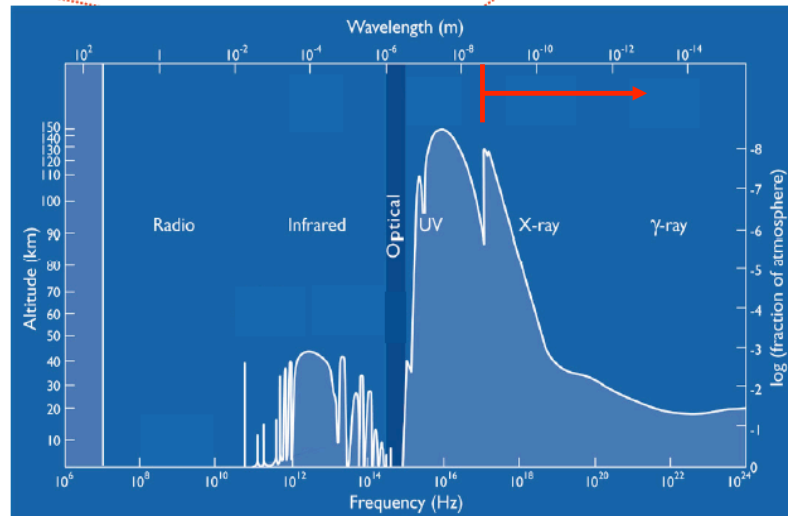
JWST 6200 kg)



Atmospheric transmission

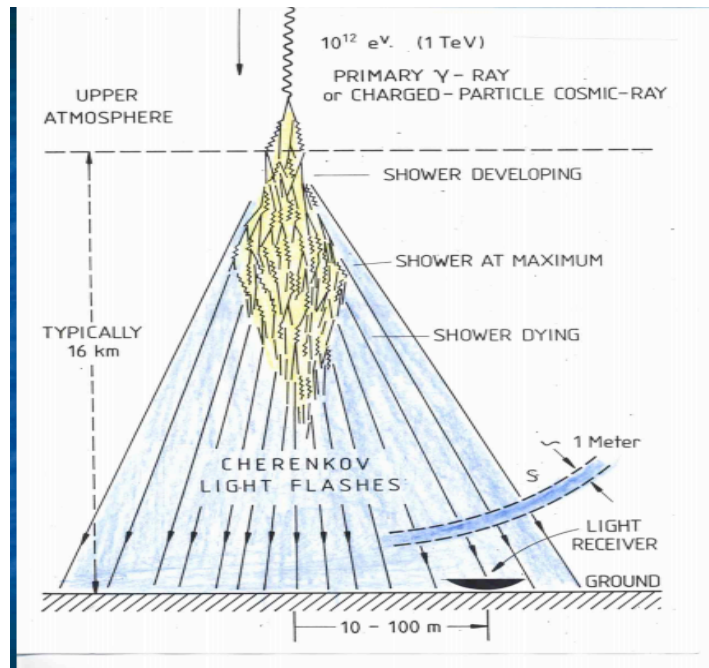


Why go into space?
 High Energy Photons
 get absorbed in earth's atmosphere—
 graph shows atmospheric height at which 1/2 of photons absorbed

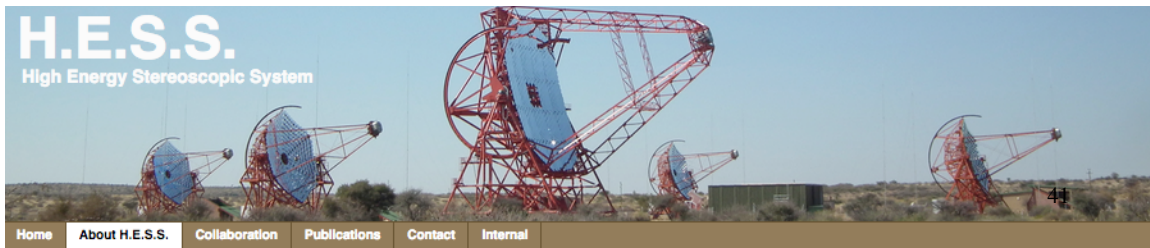


Very High Energy Cosmic Rays and TeV Astronomy

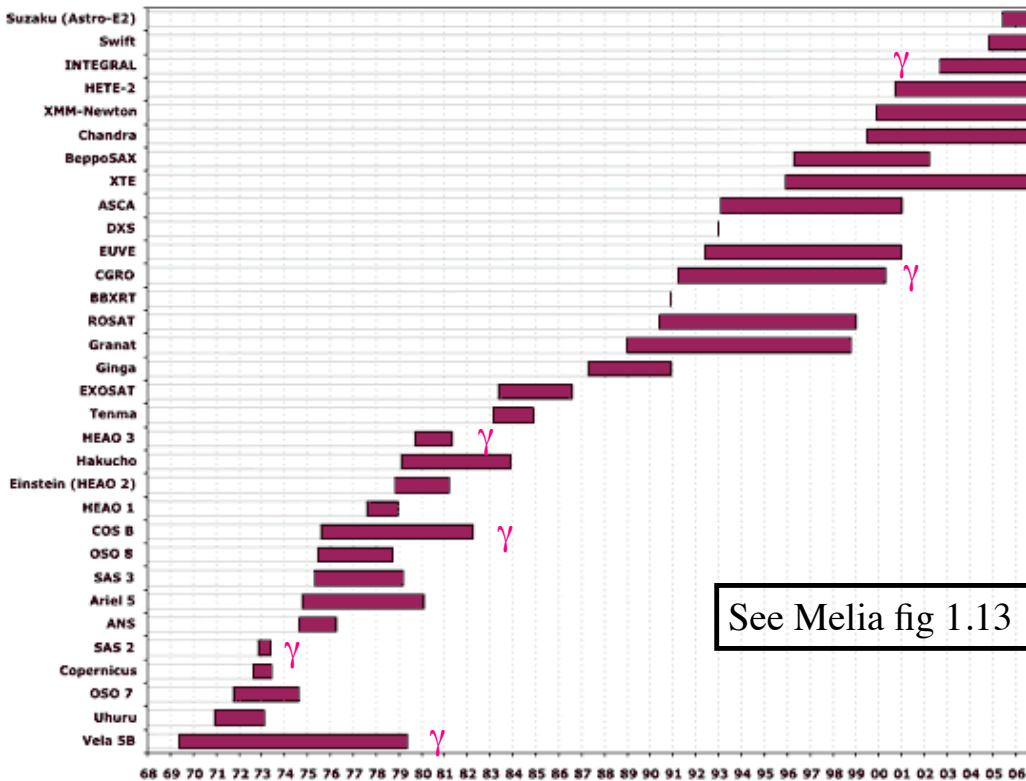
- Very high energy photons and cosmic rays interact in the atmosphere **but** produce observable effects from the ground



- While HAWC and HESS both are ground based very high energy γ -ray detectors they use VERY different technologies

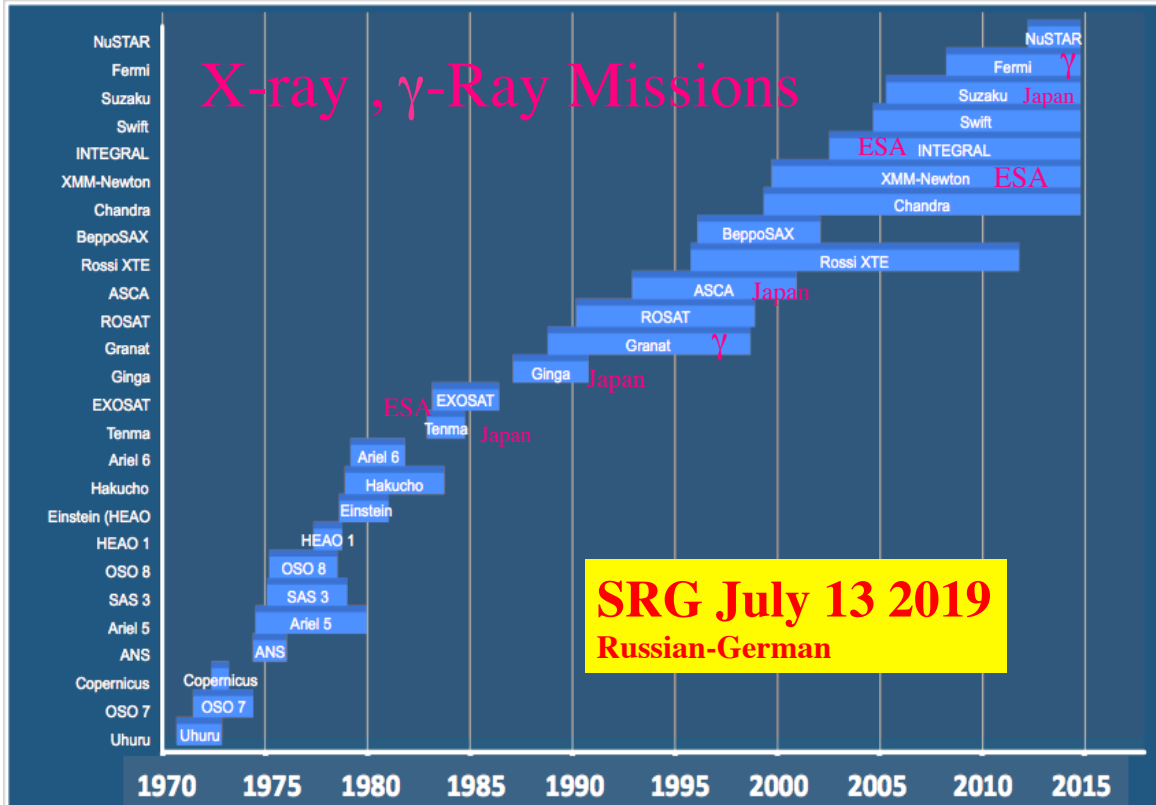


Satellite High Energy Missions 1969-2005



See Melia fig 1.13

Major high energy astrophysics missions since 1970

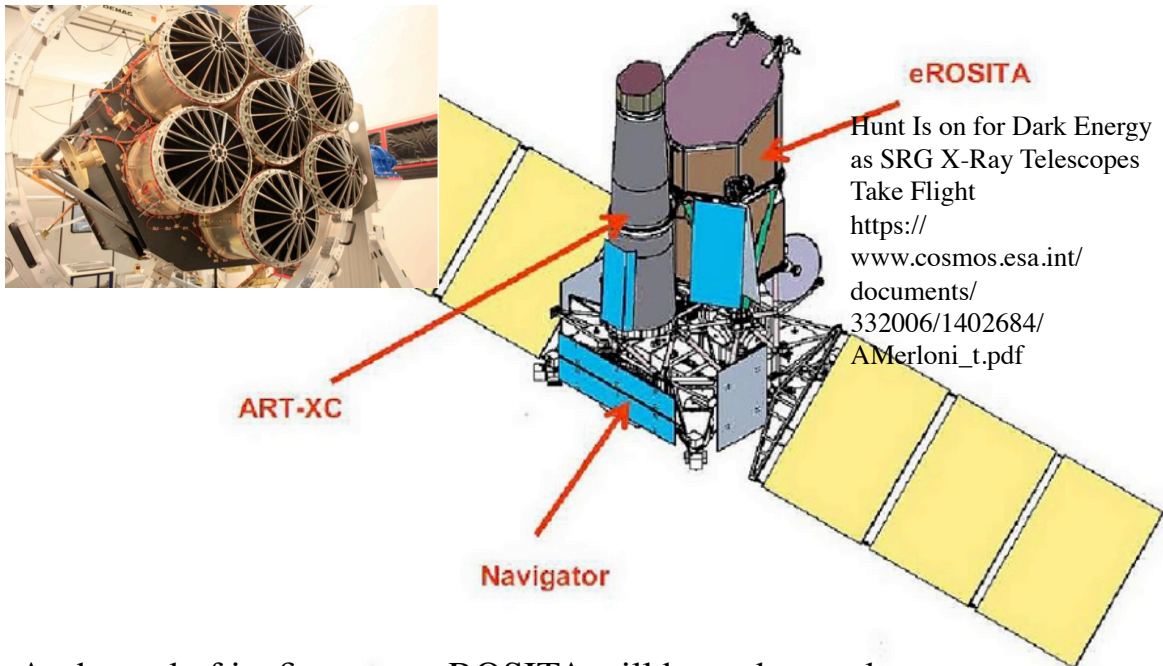


Operating Satellites

- Chandra 1999
- XMM-Newton (ESA) 1999
- INTEGRAL 2002
- Swift 2004
- Agile (γ) 2007
- Fermi (γ) 2008
- Nustar 2012
- AstroSat (Indian) 2015
- NICER (ISS) 2017
- HMXT China 2017

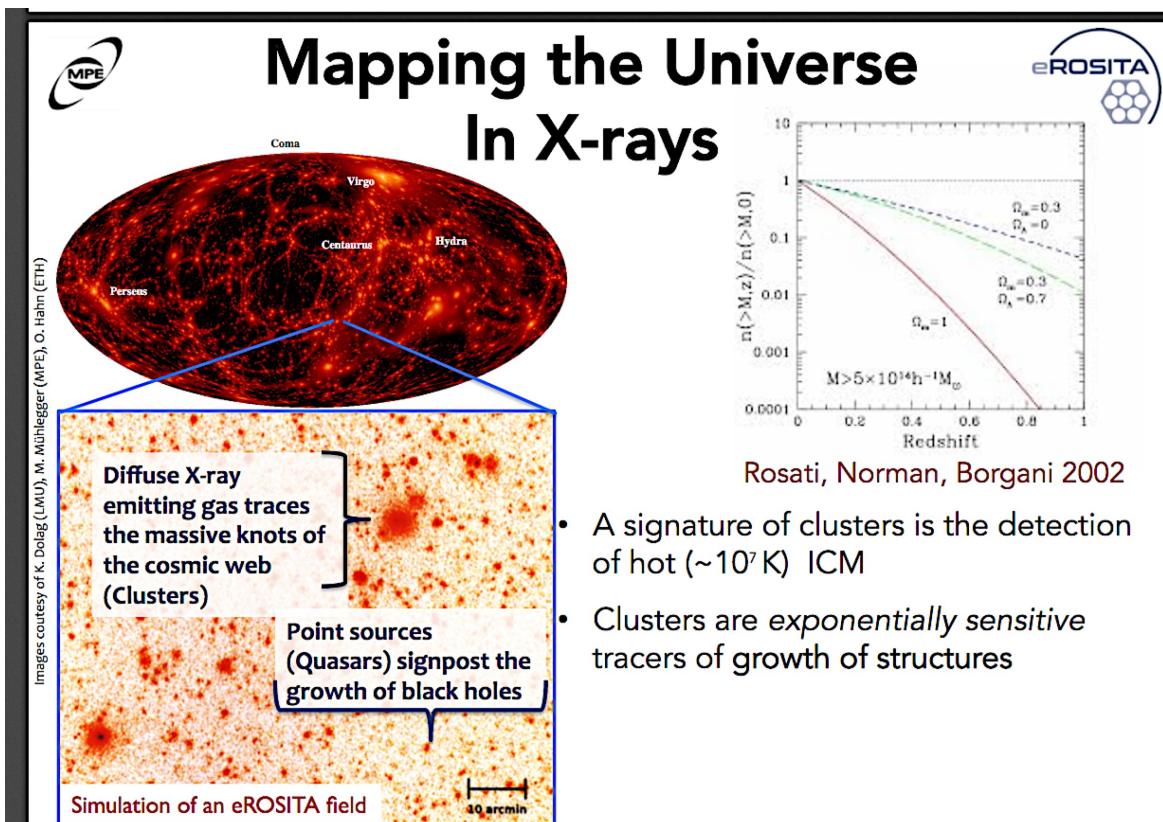
eRosita (Russia/Germany) 2019

Each has a different set of instruments and capabilities <https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/comparison.html>



At the end of its first year, eROSITA will have detected as many new sources as have been catalogued in the first 50 years of X-ray astronomy

All sky survey 50x more sensitive than Rosat



First Light From SRG

- A bright x-ray binary, Cen X-3 seen with the 7 telescopes of ART-XC

