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

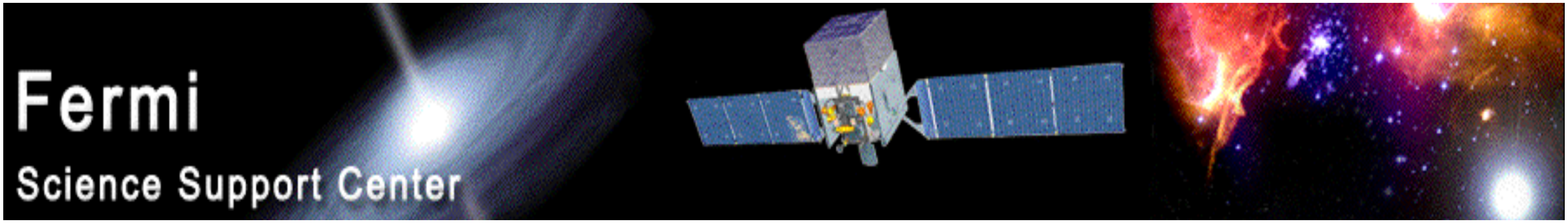
The universe itself (cosmology)

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

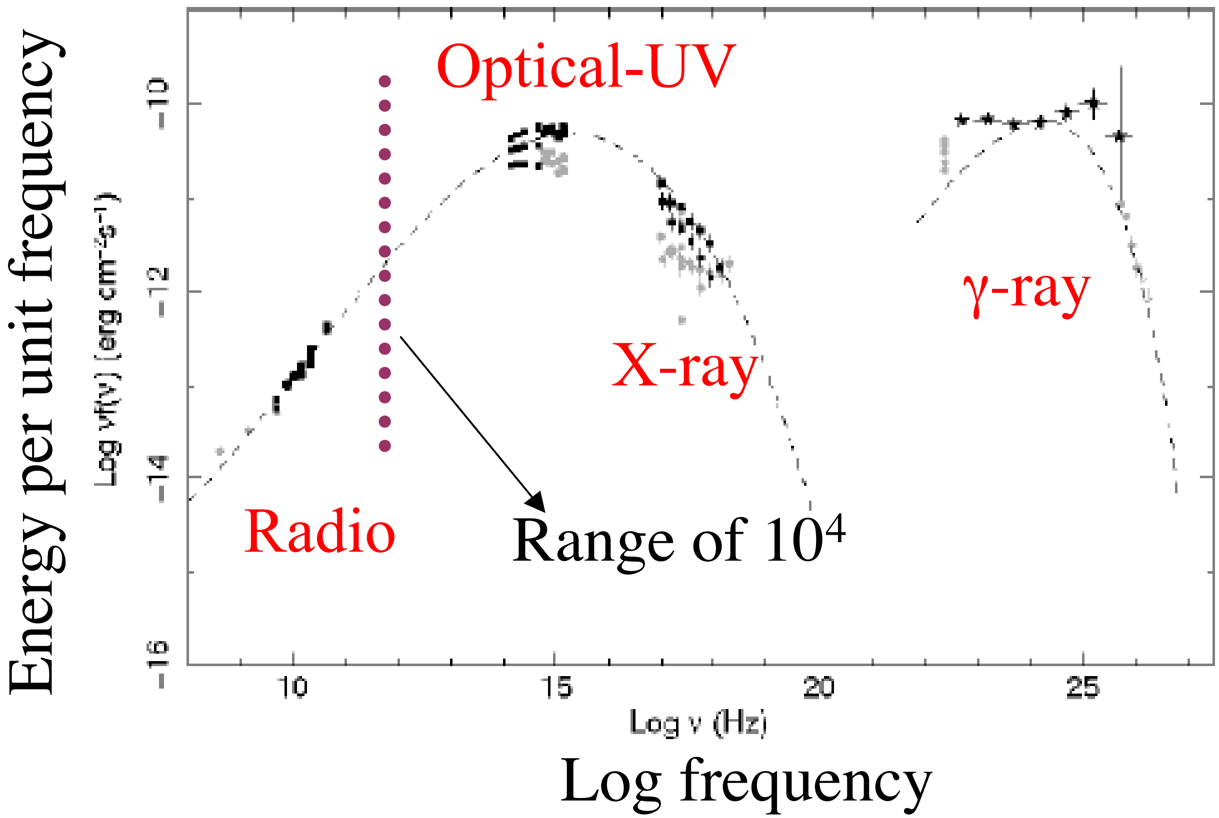
For certain classes of objects (AGN, x-ray binaries,clusters of galaxies) a large fraction of the emitted energy is in the high energy band

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

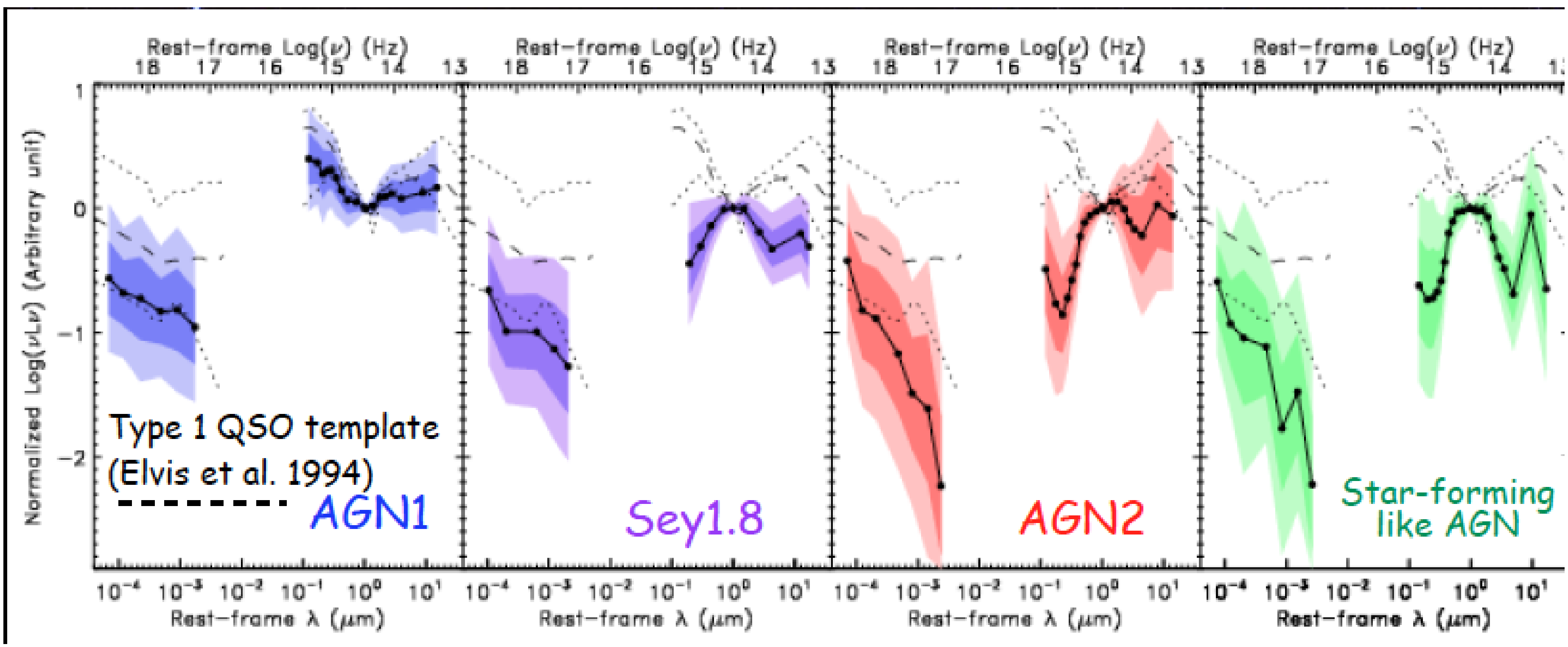
Most of what we have learned in the last 50 years have come from unexpected discoveries

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

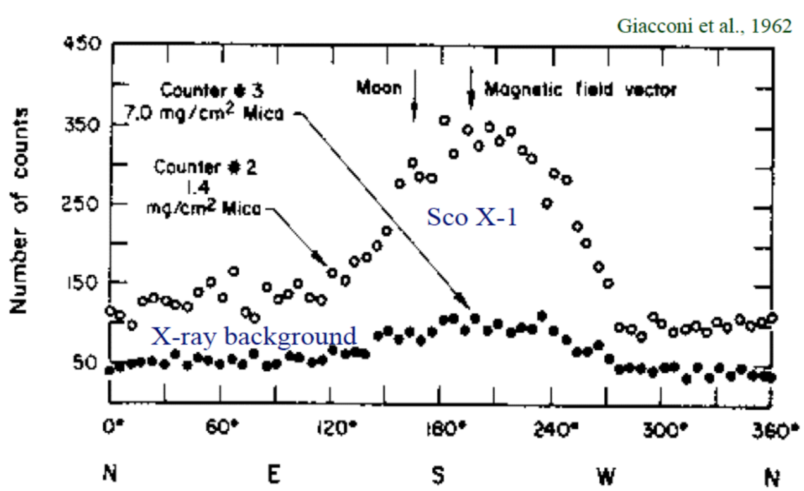
High Energy Astrophysics is 'New'
http://heasarc.gsfc.nasa.gov/docs/history/

- 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- 1936 Nobel prize
    - Cosmic' rays' are electrically charged particles
  - The latest project is the Pierre Auger in Argentina-A Detector 30 Times the Size of Paris

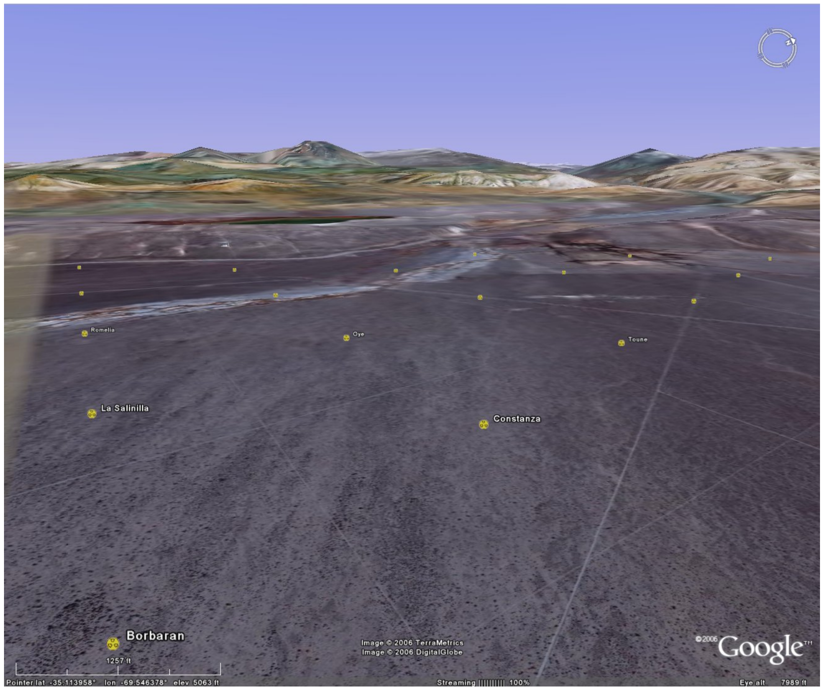
The first astronomical X-ray source- the sun (1948) using captured WWII V2 rockets. Herb Friedman and collaborators at the US Naval Research Lab (in Washington DC).

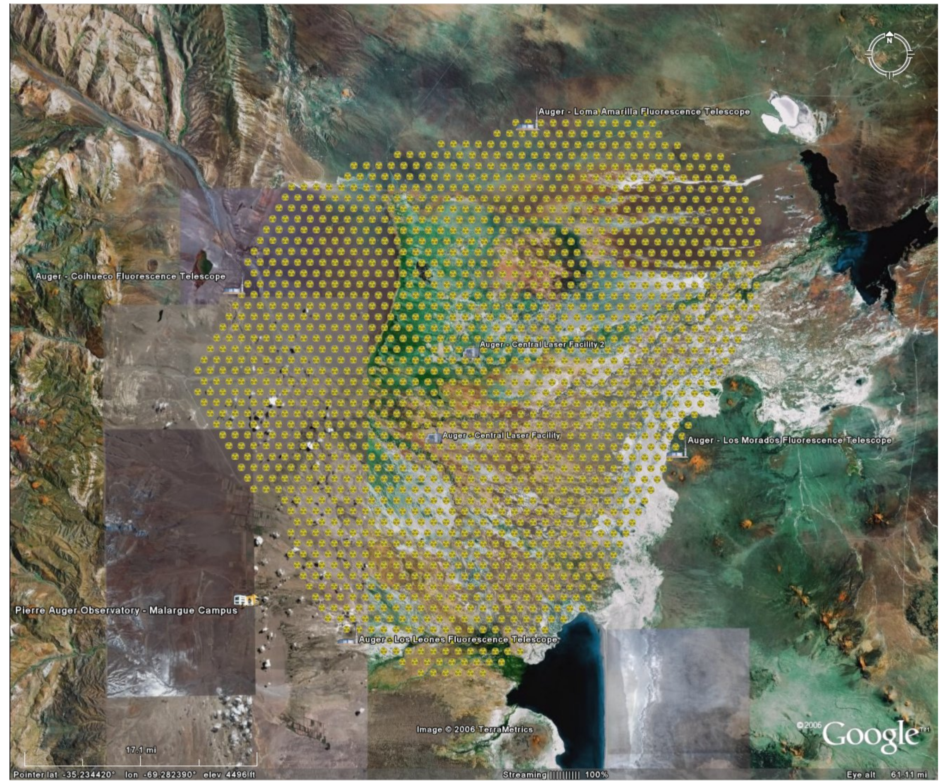
First non-solar x-ray source Sco X-1 rocket (Giacconi et al **Nobel prize** 2002)

The First Extra-Solar X-ray Detection



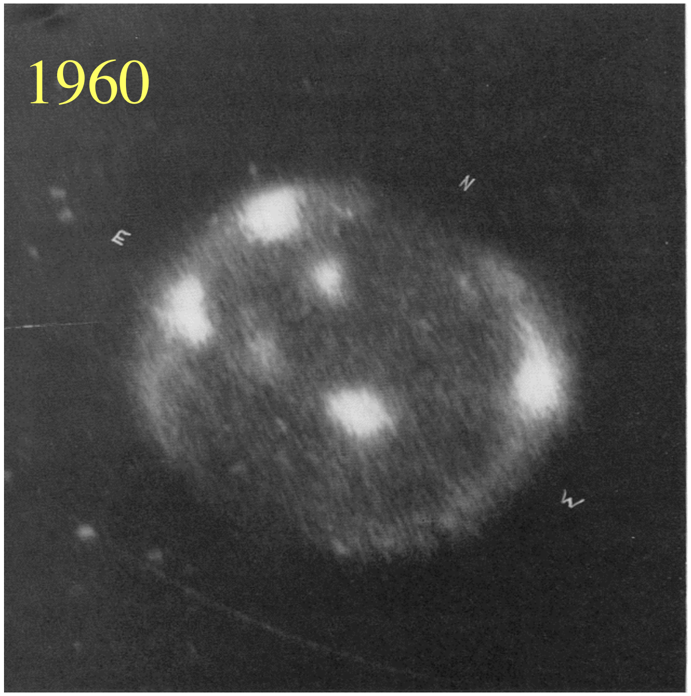
Pierre Auger Observatory-Google Earth

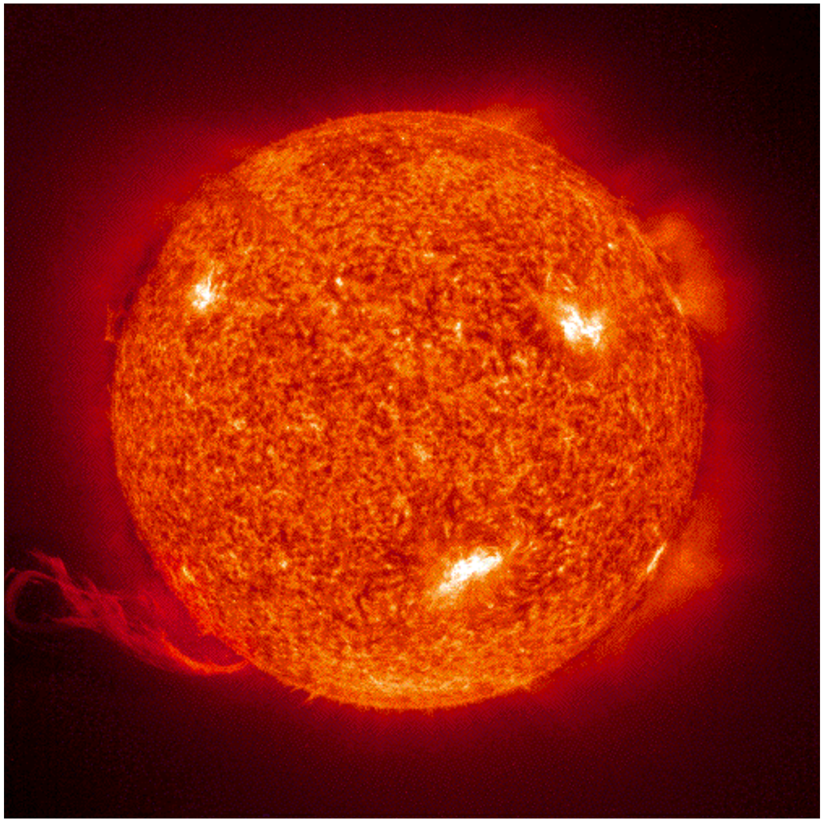




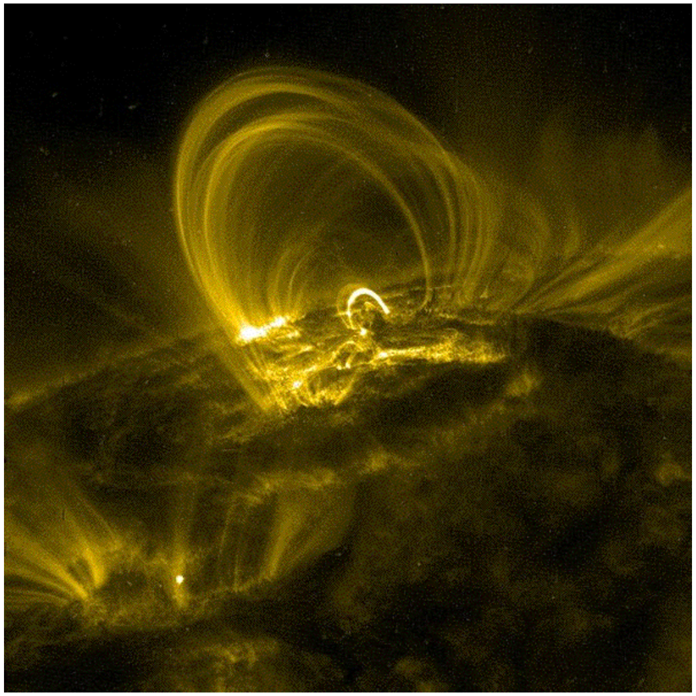
X-ray Images of the Sun

- 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



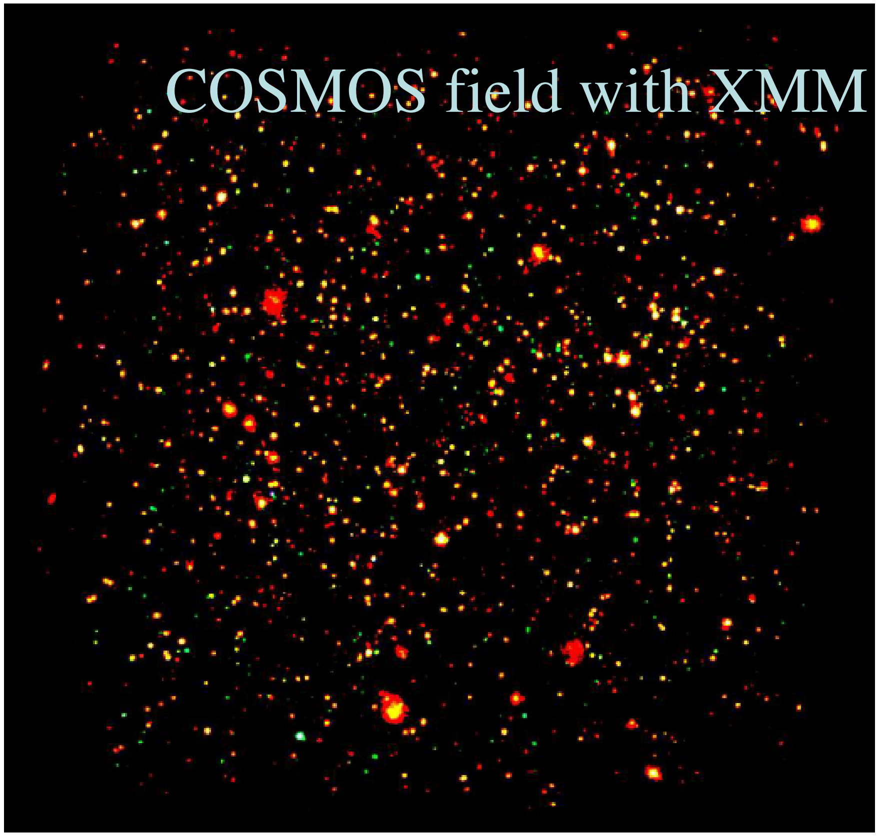
X-ray Astronomy

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

(~5×10^{-17} ergscm2sec in the 0.5-2 keV band)

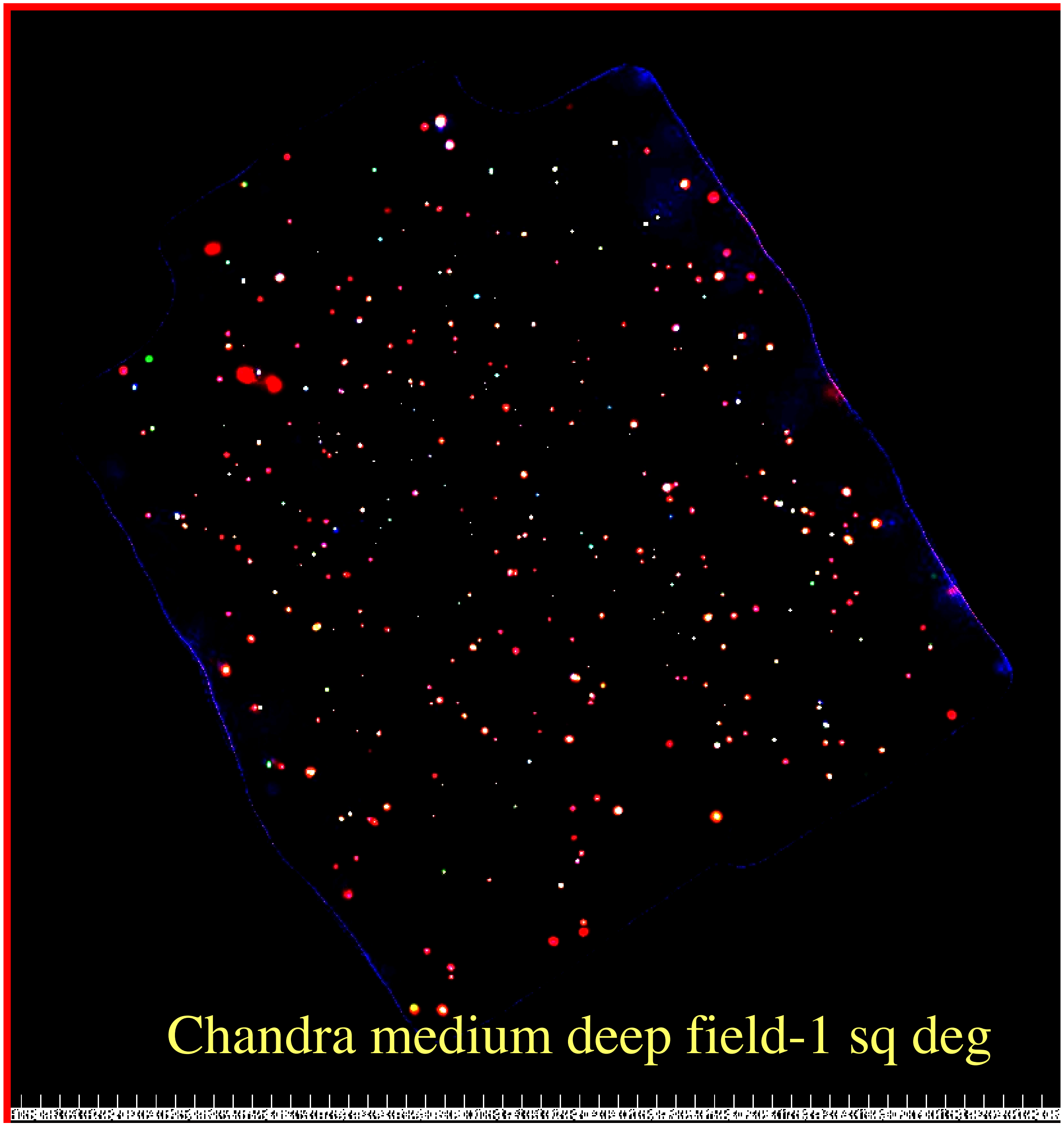
  - angular resolution by 10^5 (0.5")
  - spectral resolution by 10^4 ($E/\Delta E$~1000)
- There are now >300,000 known x-ray sources
- At the faintest levels probed by Chandra there are >2000 x-ray sources/deg^2 (e.g. 10^8 all sky)
- Despite these spectacular advances x-ray astronomy is photon limited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

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 = 1.312×10^{28} cm)
- median x-ray luminosity $10^{43.5}$ergs/sec $= 8 \times 10^9 L_{sun}$)
- The red 'blobs' are clusters of galaxies



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 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 - I will find an appropriate source material for this in time for the next class

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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).

I am working on the web page
But it is not ready yet… probably end of next week (Unless someone wants to help me ….)
Another book with relevant material is **Advanced Astrophysics byNeb Duric Cambridge Univ Press**

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

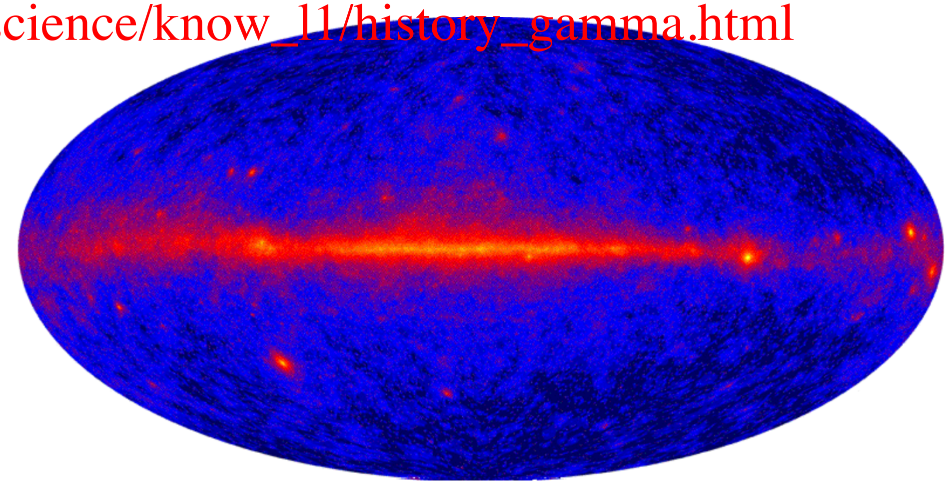
High Energy Astrophysics is 'New'- see

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)

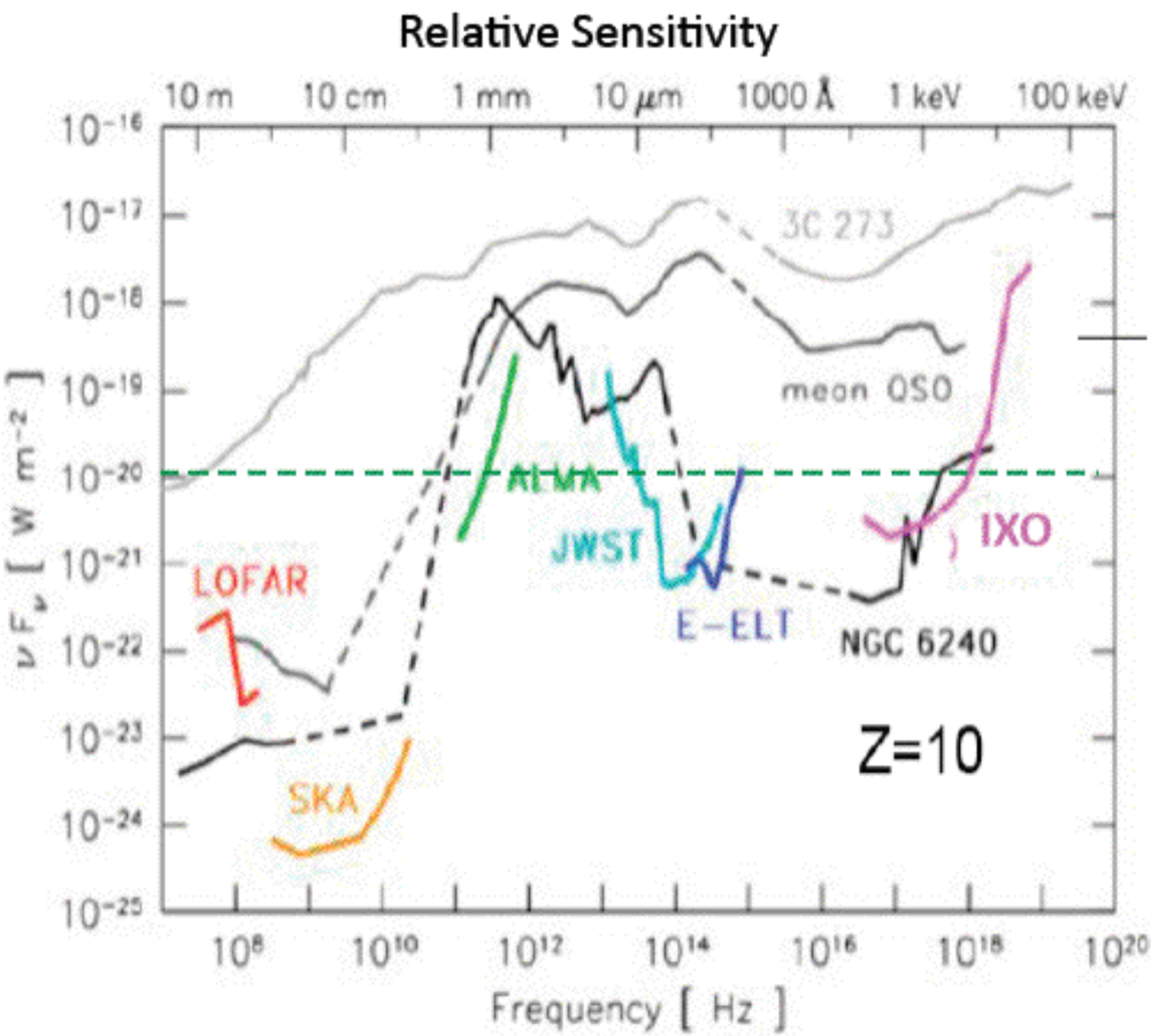
Other γ-Ray sources include

Supernova remnants

Unusual binary stars

Notice the introduction of vast amounts of jargon

Relative Sensitivity Astronomical Observatories



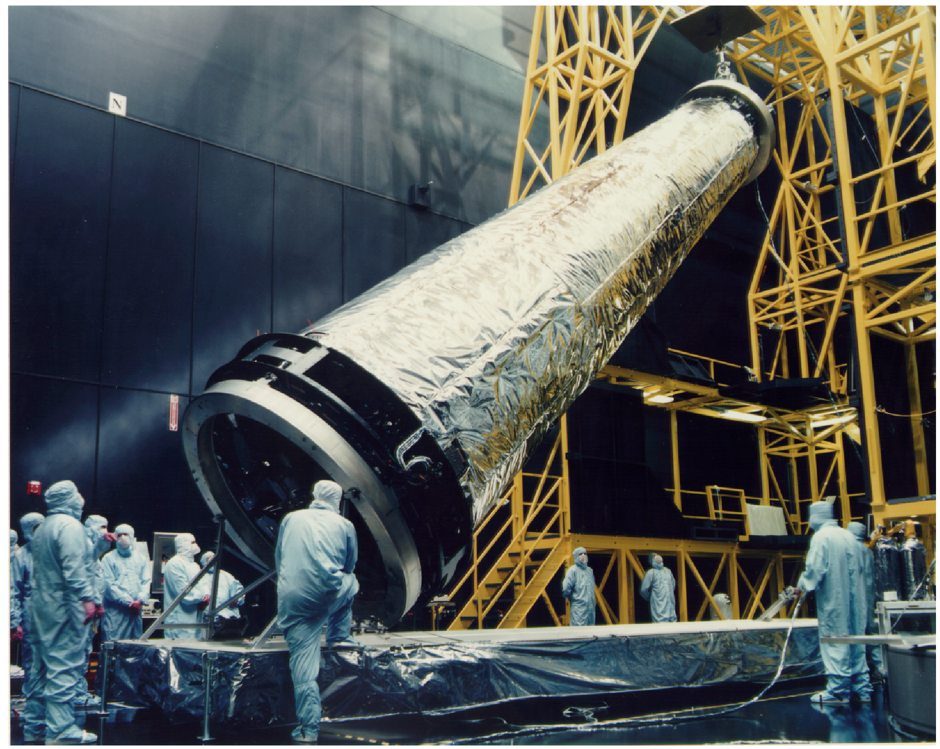
- For study of the ‍aintest known ‍-ray sources ‍ne needs the ‍argest optical ‍nd IR ‍elescopes

Space Based High Energy

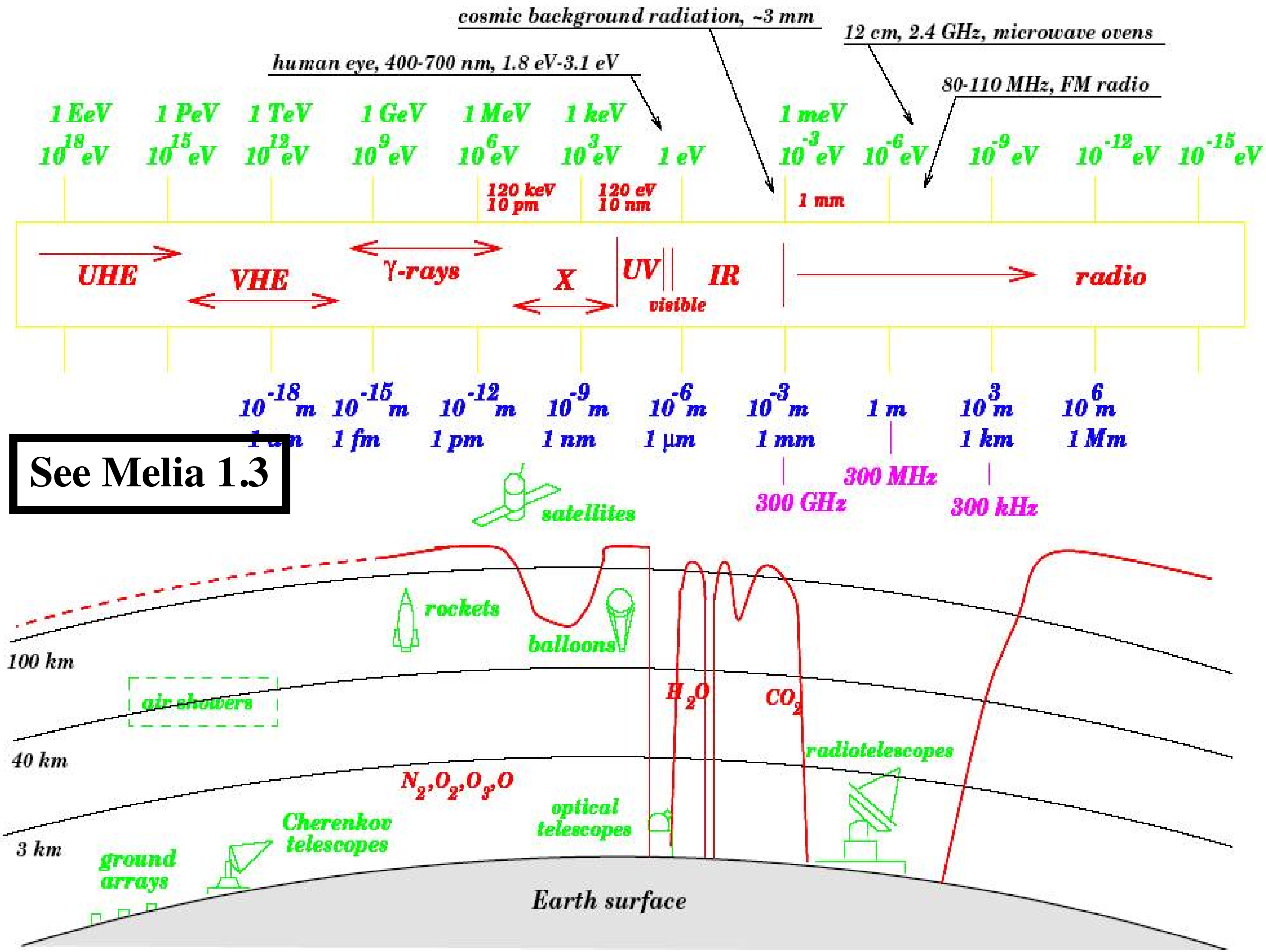
- The atmosphere is opaque (at ground level) to all wavelengths from γ-rays (GeVs) to ultra-violet(10^{11}-10 eV;1eV=1.6×10^{-12} ergs/cm^2/sec)**
- Thus to detect 'high energy' photons need to go to space*
- Space missions are expensive and take a lot of time

*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

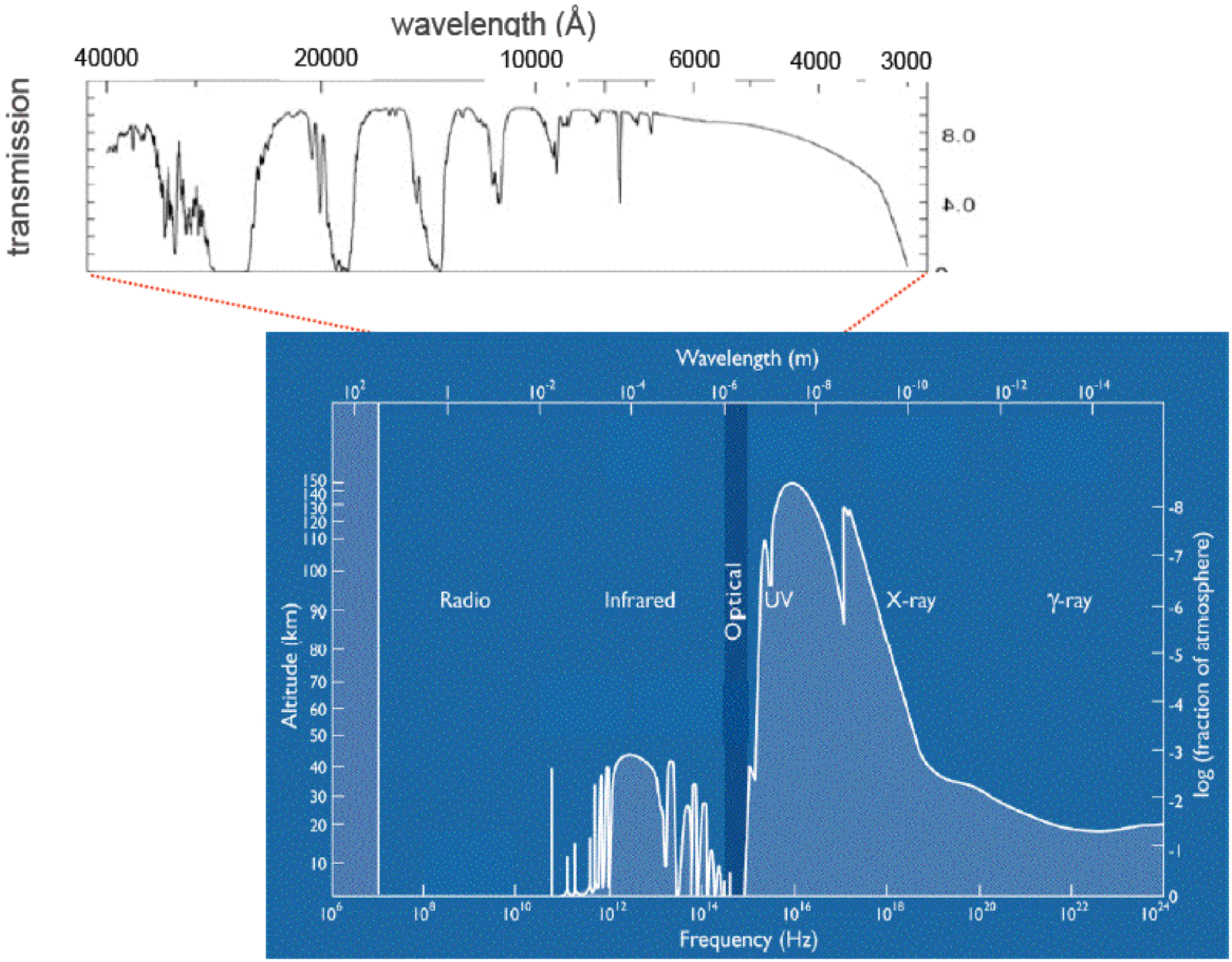


Chandra Optical Bench

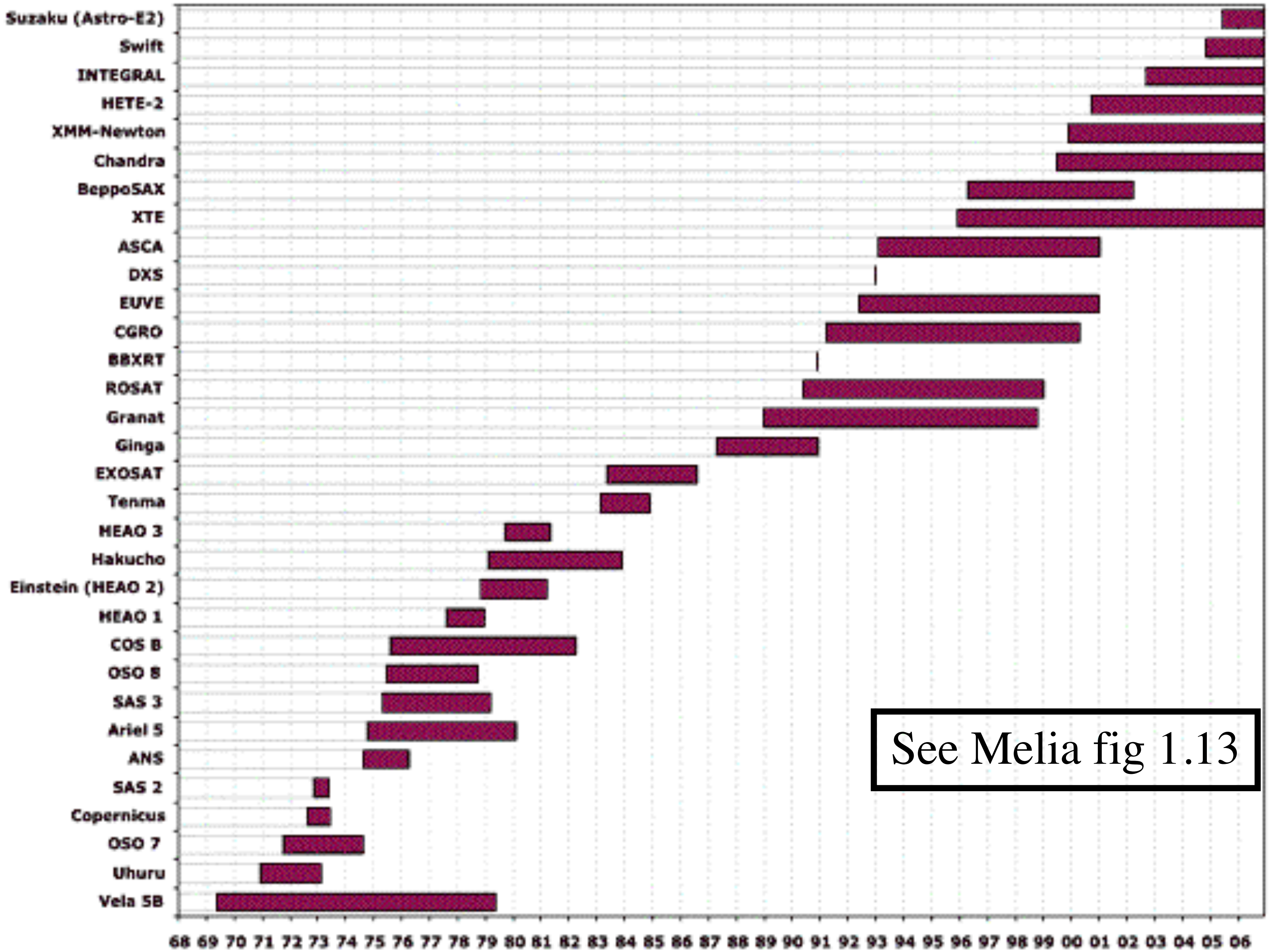

cosmic background radiation, ~3 mm
12 cm, 2.4 GHz, microwave ovens
human eye, 400-700 nm, 1.8 eV-3.1 eV
80-110 MHz, FM radio
1 EeV
1 PeV
1 TeV
1 GeV
1 MeV
1 keV
1 meV
10^18 eV
10^15 eV
10^12 eV
10^9 eV
10^6 eV
10^3 eV
1 eV
10^-3 eV
10^-6 eV
10^-9 eV
10^-12 eV
10^-15 eV
120 keV
10 pm
120 eV
10 nm
1 mm
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
H2O
CO2
40 km
radiotelescopes
N2,O2,O3,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

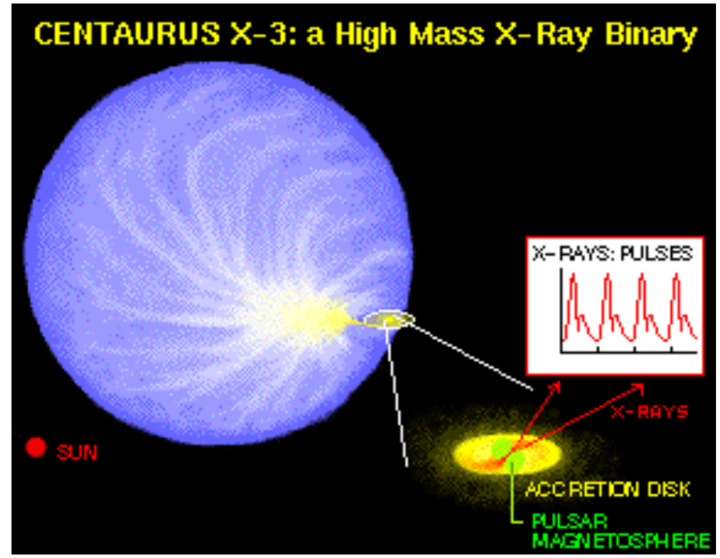
R+B pg 161 sec 5.1

- 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

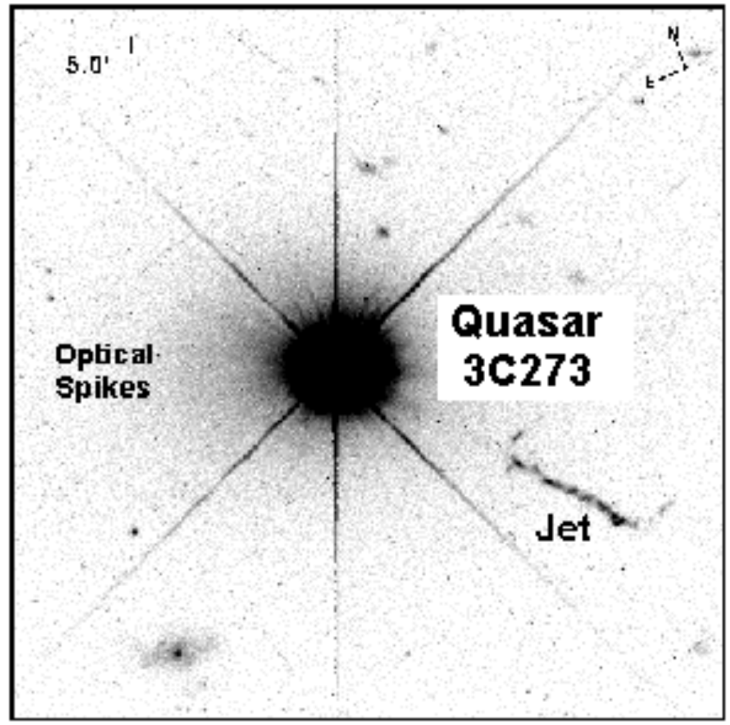
"With all reserve, we advance the view that a *supernova* represents the transition of an ordinary star into a *neutron star* consisting mainly of neutrons…

Baade & Zwicky (1934)

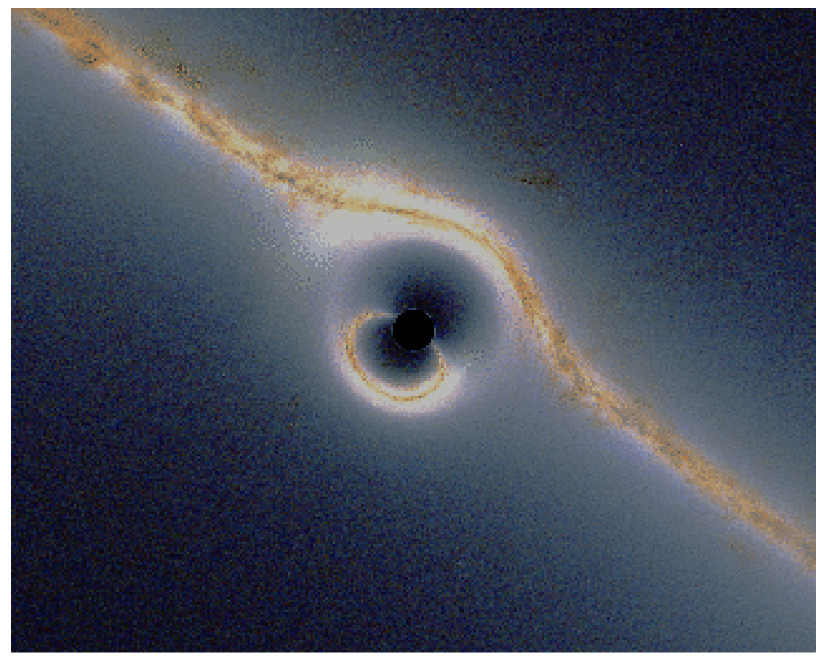
Fritz Zwicky

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

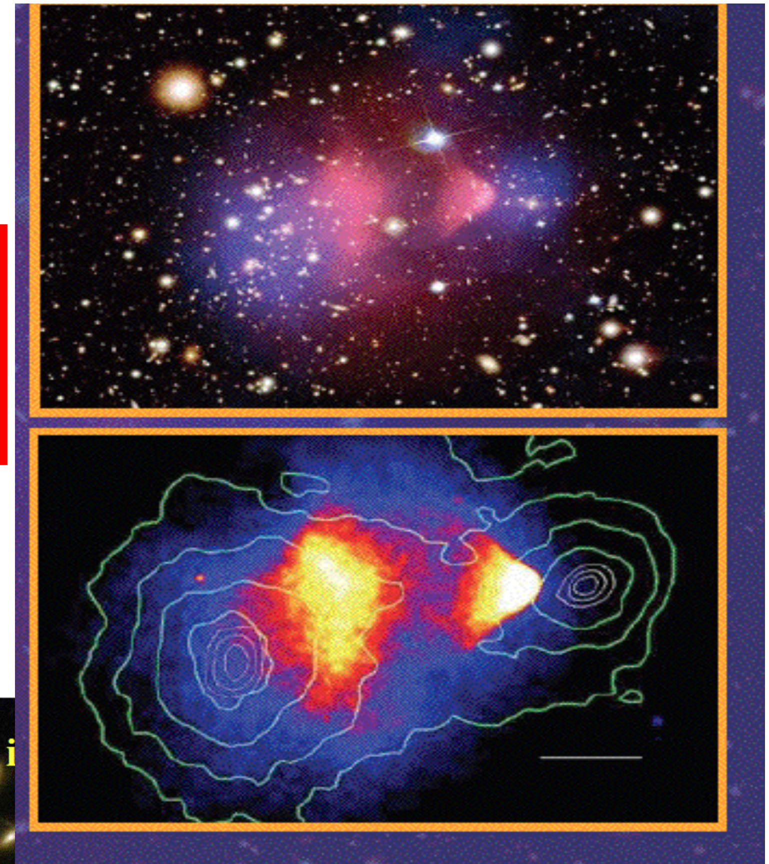


* $M_{sun=}$ $2\text{x}10^{33}$ gm

Clusters of Galaxies

Most massive and largest objects in the universe- $M>10^{14}M_{sun}$; $R\sim 3\times10^{24}$ cm= 1 Mpc

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



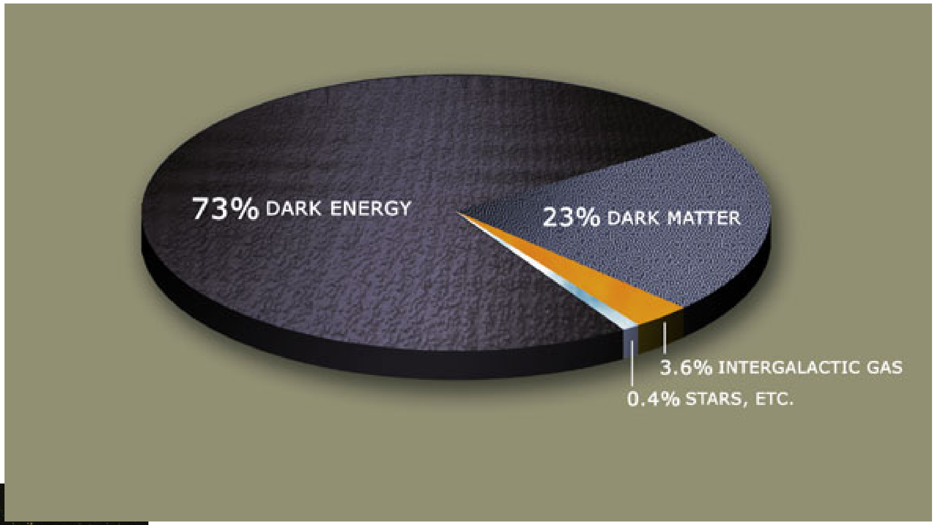
Most of the baryons* are in the hot x-ray emitting gas- most of the mass is dark matter

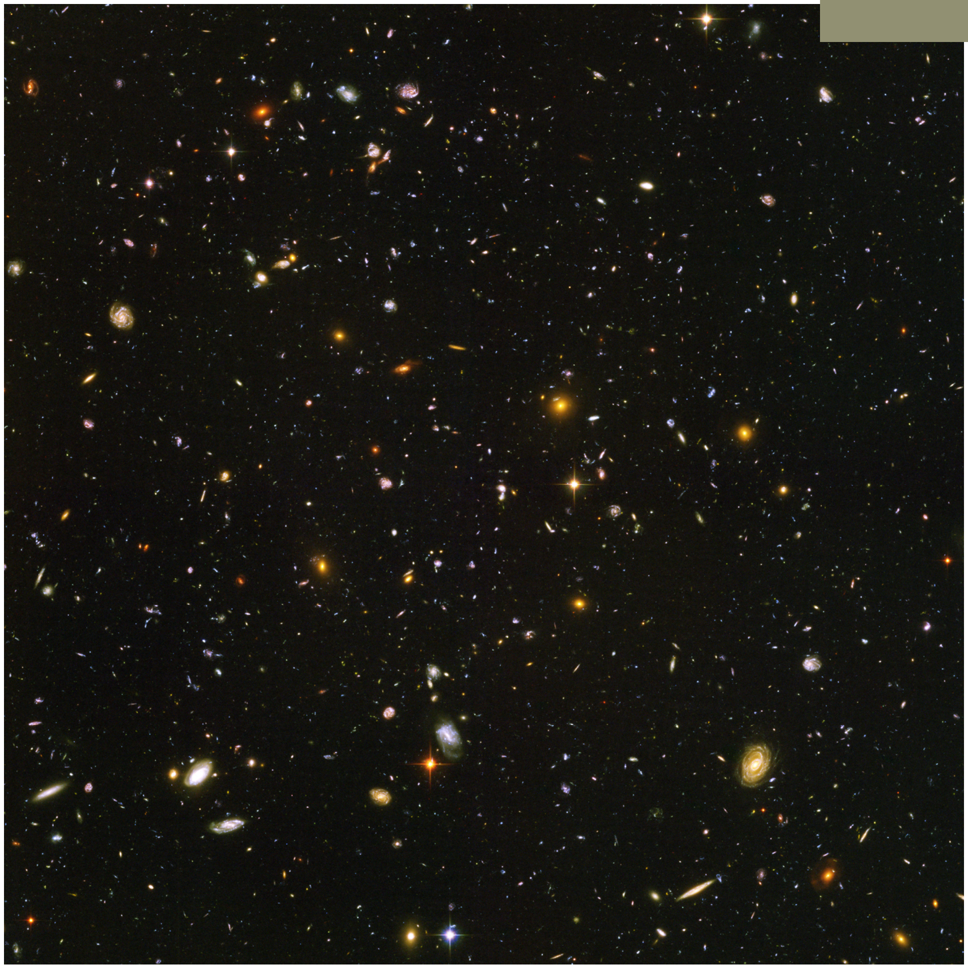
Can act as a gravitational lens**- revealing the amount of and distribution of **dark matter*****.

*Baryon- neutrons protons, nuclei of atoms

Dark Matter

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

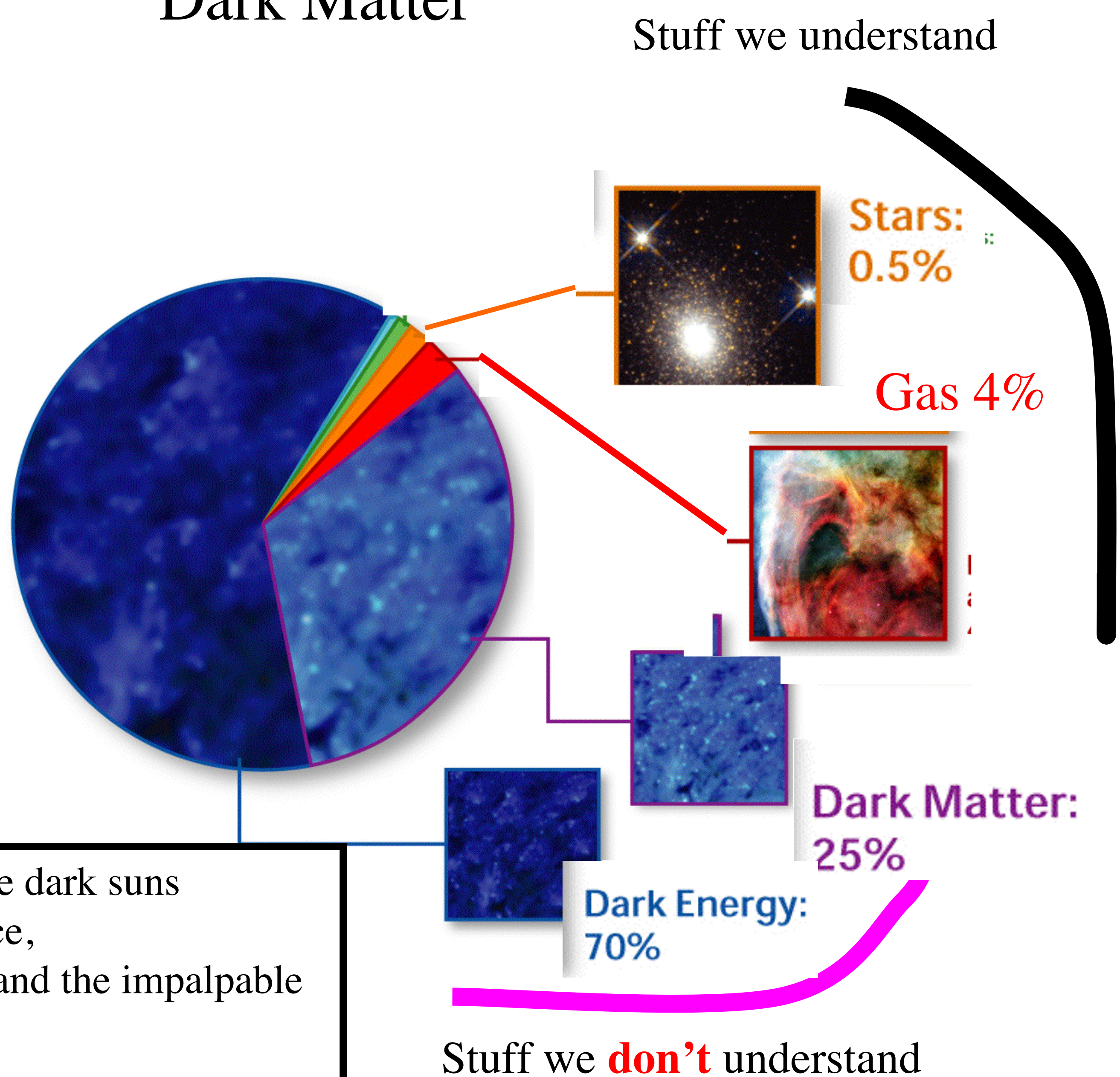




Dark matter has 6x mass of baryons averaged over the entire universe.

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**



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

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
  - Let me know if you have a religious observance that will effect your attendance
- Academic dishonesty
  - Zero-tolerance policy
  - Absolutely no copying of homeworks or exams!
  - Must list all references used to complete an assignment
- Students with a documented disability should contact me.

Course structure

- Lectures
  - Attendance is crucial: a major part of this course will be in-class discussions!

- Other components
  - Homeworks (roughly 1 every two weeks) 1/4
  - Midterm exam 1/4
  - Final exam 1/3
  - Group project and presentation (more later in the semester) 1/5
  - Class participation

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

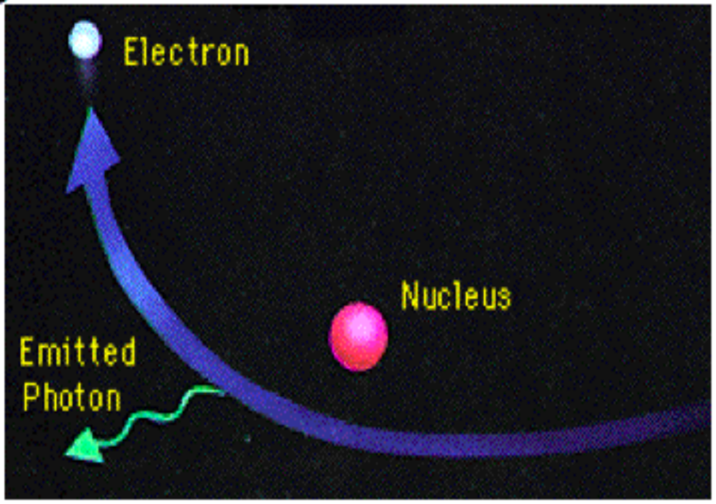
Non-thermal bremms

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

BREMSSTRAHLUNG

- "Braking radiation"



Examples: clusters of galaxies, supernova remnants, stellar coronae

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

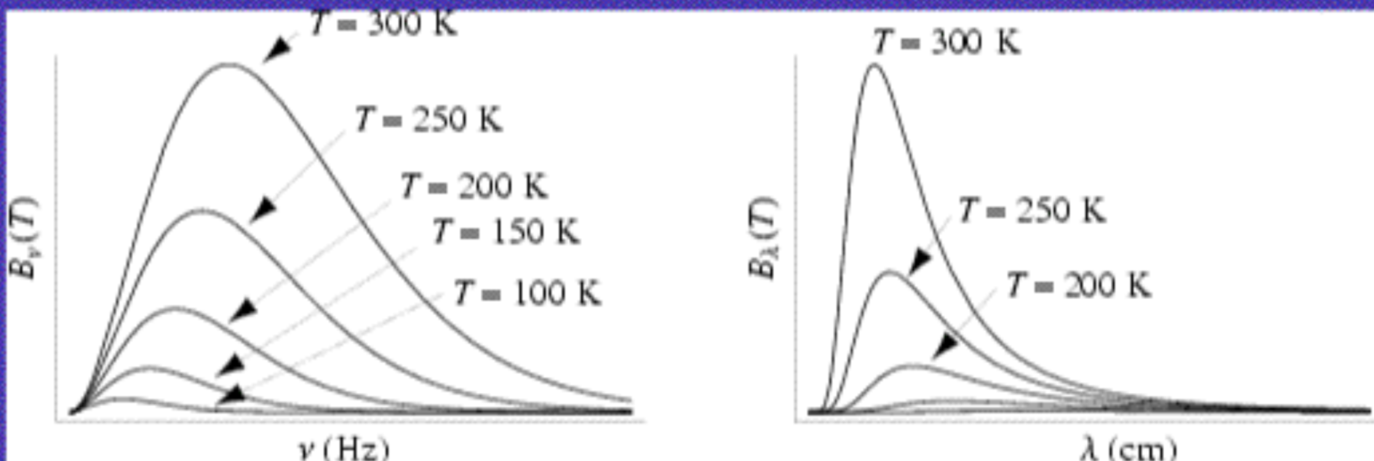
Black Body

An accelerated charge can produce EM radiation over a continuous range of frequencies (energies).

Black Body: An ensemble of charges which absorbs all radiation incident. The absorbed energy raises the temperature of the body, which radiates some of this energy. The radiation has a characteristic brightness distribution ($B_\nu(T)$), called the Planck curve:

$$B_\nu(T) = \frac{2h}{c^2}\frac{\nu^3}{e^{h\nu/kT} - 1}$$ ergs s^{-1} cm^{-2} Hz^{-1} $steradian^{-1}$

$L \sim A\sigma T^4$



Other Continuum Sources

Synchrotron radiation: a moving electron in the presence of a magnetic field *B* feels an acceleration *a* given by

$$a = \frac{e\,v}{m\,c} \times B$$

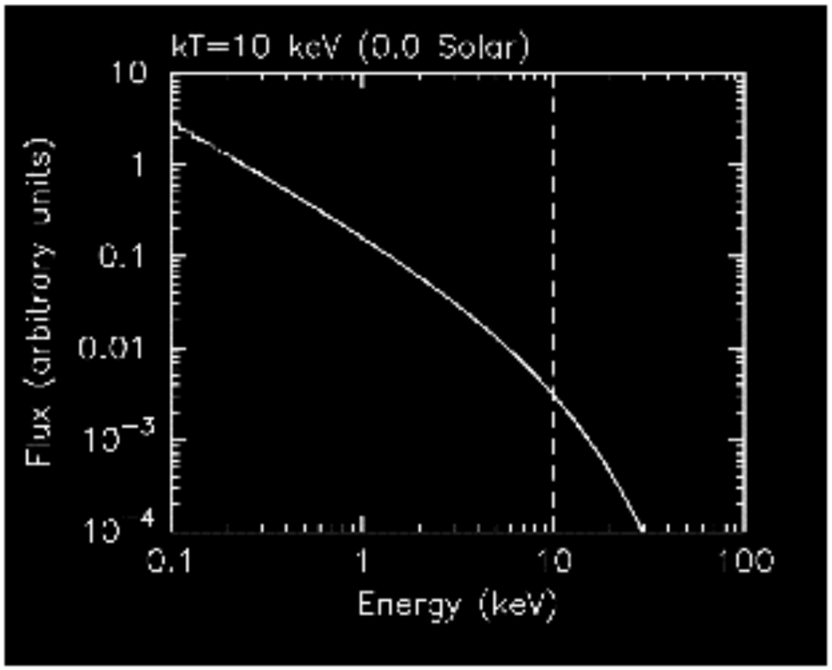
which causes the electron to spiral around the B field. The acceleration of the electron produces synchrotron radiation

Bremsstrahlung radiation: "braking" radiation, occurs in ionized gases (plasmas) when thermal electrons are accelerated by passing near another electron or an ion.

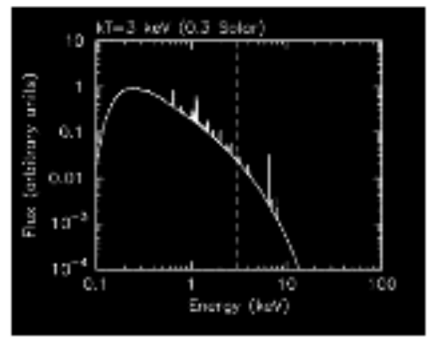
Black body emission and Bremsstrahlung are sometimes called thermal emission (because the statistical motion of the charged particles depends on temperature). Synchrotron emission is an example of non-thermal emission since the statistical motion of the charged particle depends on the magnetic field strength.

BREMSSTRAHLUNG SPECTRUM

$$I(E) = AG(E,T)Z^2 n_e n_i (kT)^{-1/2} e^{-E/kT}$$



A = normalization, G = Gaunt factor,
Z = charge of positive ions
n_e and n_i electron and ion densities
for $E \ll kT$ the spectrum is approximately a power law
for $h\nu \gg kT$ there is an exponential cutoff



[In reality accompanied by recombination line emission]

Luminosity $L = 2.4 \times 10^{-28} T^{1/2} n_e^{1/2} V$ (W) T = temperature, V = volume

Todays Lecture- How are Photons Generated/Absorbed

- Physical processes (Melia ch 5,RB ch 3)
  - **Black body radiation-** system is in equilibrium and all electromagnetic radiation falling on it is absorbed. At a particular temperature a black body emits the maximum amount of energy possible for that temperature.
  - **Synchrotron radiation**

    High energy (relativistic) particles 'spiraling' in a magnetic field (accelerated electrons)

Compton scattering
Electrons scattering of photons/photons scattering off electrons
Line Emission and absorption
Atomic transitions in atoms- x-rays mostly from K, L shell transitions
Photoelectric Absorption
Photons are absorbed by atomic transitions

There is a good 'on-line' text book Elements of Astrophysics; N. Kaiser http://www.ifa.hawaii.edu/~kaiser/lectures/content.html
Or
http://www.ebooksdirectory.com/details.php?ebook=2399

Thursdays Lecture

- How are high energy photons detected?
  - X-ray imaging and spectroscopic detectors
  - □ γ-ray detectors
- X-ray telescopes

Black Body- RB Ch 3.5

$$I(\nu,T)d\nu=(2h\nu^3/c^2)(1/(e^{h\nu/kT}-1))$$

$I(\nu,T)d\nu$ is the amount of energy per surface area per unit time per solid angle emitted in the frequency range between ν and $d\nu$ by a black body at temperature T

h is Planck's constant, c is the speed of light , k is Boltzman's constant

The wavelength of maximum intensity λ_m is b/T (b is Wiens constant)

The energy of maximum intensity $\nu_m=0.245T_6$ keV

$L= A\sigma T^4$;

σ is Stefan-Boltman's constant 5.67×10^{-8} $W/m^{-2}K^{-4}$

A is the collecting area

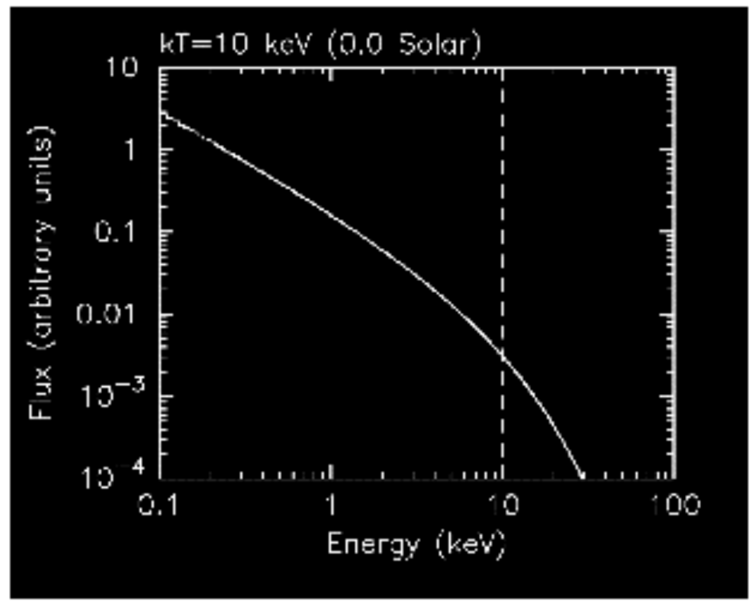
$\sigma=2\pi^5k^4/15c^2h^3$

Bremmstrahlung

- RB pg 97 (sec 3.8.1)Melia ch 5.3 point out that a proper derivation requires QED (quantum electrodynamics)
- Summary
  - Produced by charged particle collisions in ionized plasmas
  - Spectrum is flat at low energies (roughly a power law of $I(E) \sim E^{-0.4}$) with a characteristic exponential turnoff at high energies related to the temperature of the electrons
  - Total emission/unit volume ~ $n_e ni_{on} T^{1/2}$

BREMSSTRAHLUNG

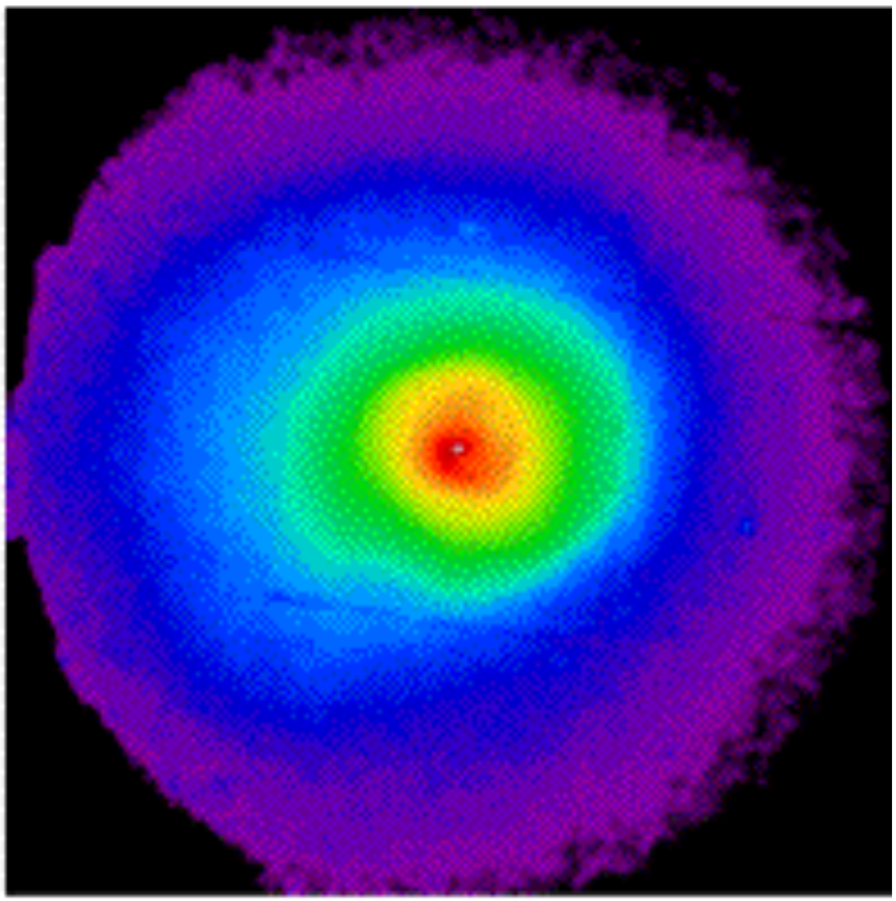
$$I(E) = A\boxed{G(E,T)}Z^2 n_e n_i (kT)^{-1/2} e^{-E/kT}$$



Bremsstrahlung Observed

Coma cluster in X-ray and optical light

x-ray emission is due to thermal bremsstrahlung +line emission



SYNCHROTRON RADIATION

Nice summary at http://www.cv.nrao.edu/course/astr534

- Electrons spiralling in magnetic field

Spectrum for power-law electron distribution:

$$I(\nu) = A(KB^{1+\alpha})\nu^{-\alpha}$$

A = constant, K = total energy of electrons,
B = magnetic field, α = spectral index

Examples: pulsar synchrotron nebulae, jets, most extragalactic radio sources

Rather complex derivation Ginzburg, V. L., Syrovatskii, S. I., ARAA, 1965

Synchrotron Radiation (Melia Ch 5.4 RB sec 3.8)

- For a single electron the characteristic frequency $\omega_{sync} = 3/2\gamma^2 B/m_e c$
- $dE/dt = P \sim \gamma^2 B/m^2{}_*$

$\nu_c = 6.3\times 10^{12}$Hz $(B(E/m_e c^2)/10^3))$

To get x-ray photons $v \sim 10^{18}$ Hz need very high energies or very strong magnetic field

$t_{\,cool} \sim m_e c^2/4/3 u_B c \sigma_T \gamma \sim 16 \mathrm{yr} B^{-2}\,\gamma^{-1}$

The most energetic particles have the shortest lifetimes

Field strengths vary enormously from 10^{-6} G in radio galaxies to 10^{13}G in pulsars

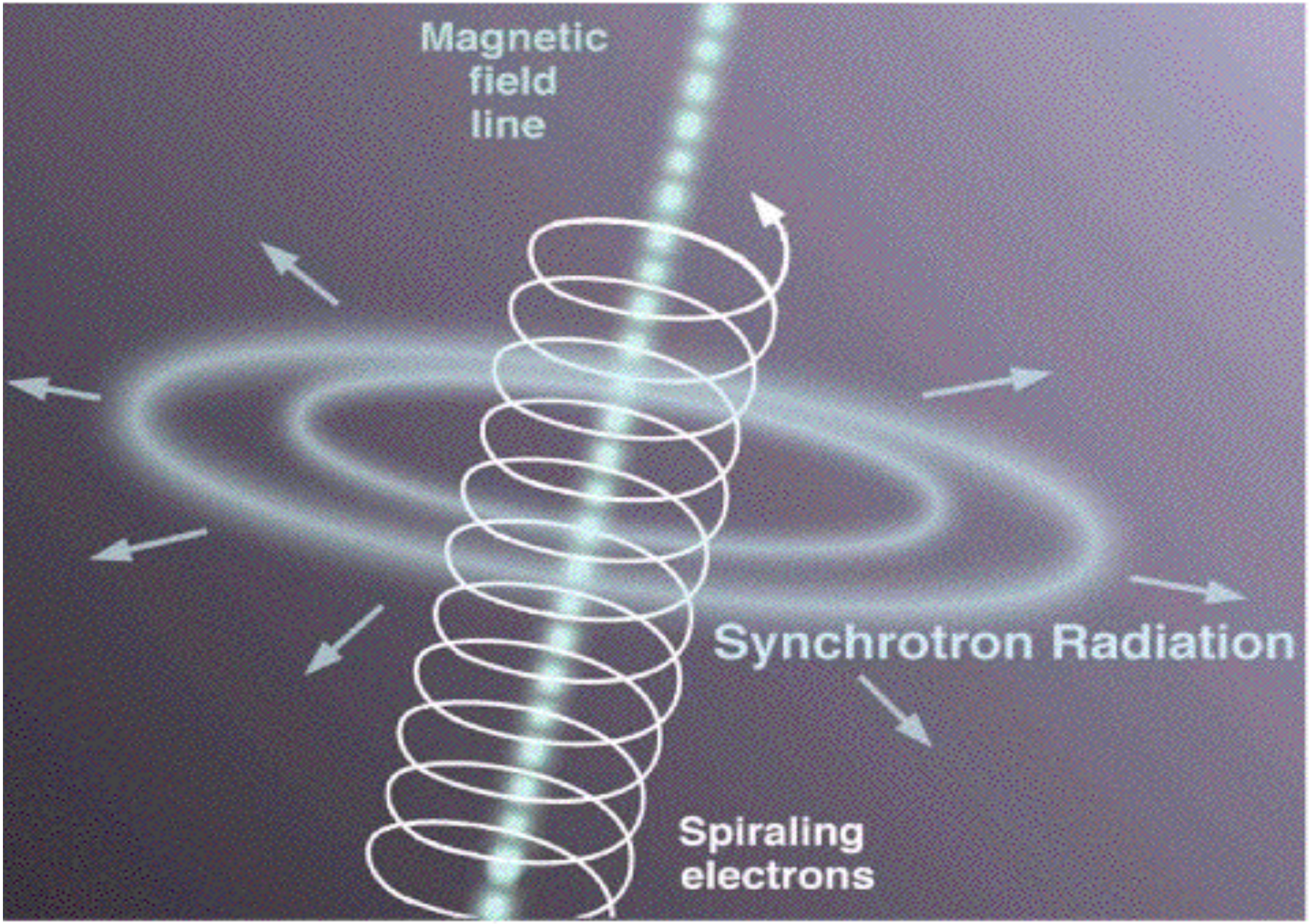
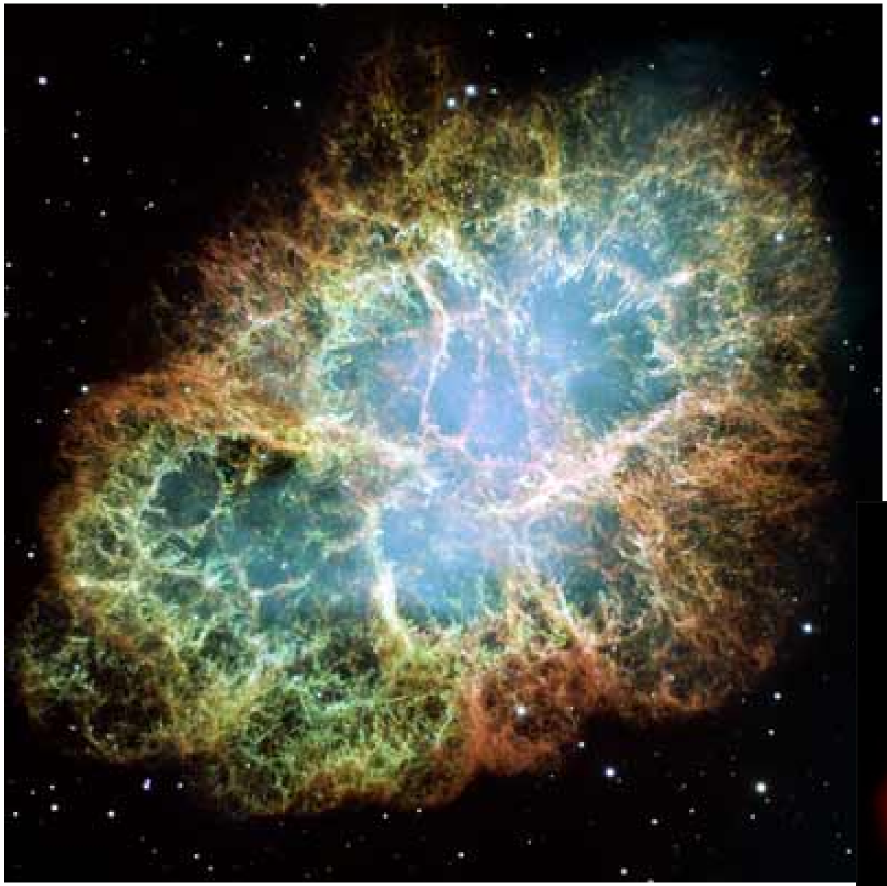


Fig. 1.— Artist's conception of synchrotron radiation. Cool figure from http://www.gemini.edu/gallery/science/m87/Synchrotron_Radiation_med.jpg

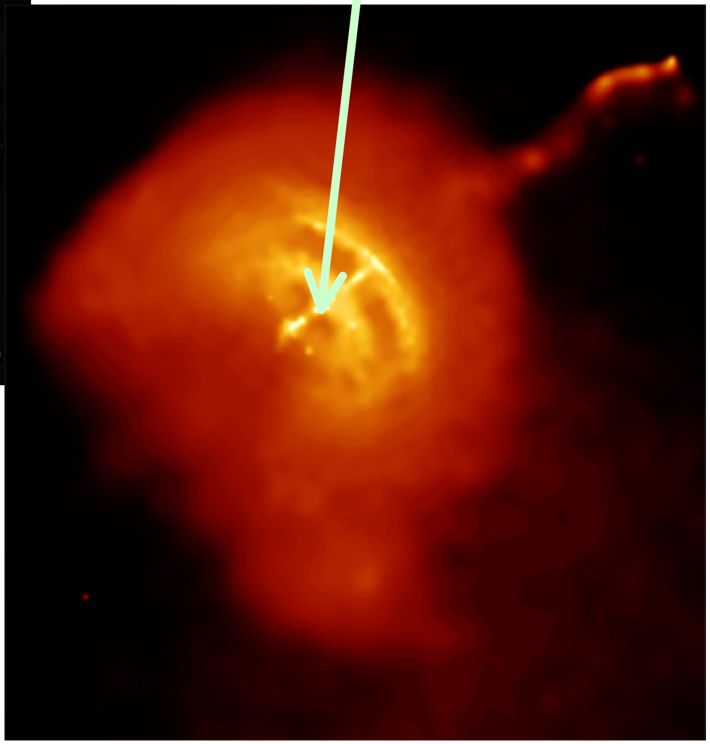
Synchrotron radiation-lit nebulae

Crab Nebula- optical IR and X-ray image

Supernova in 1054 AD



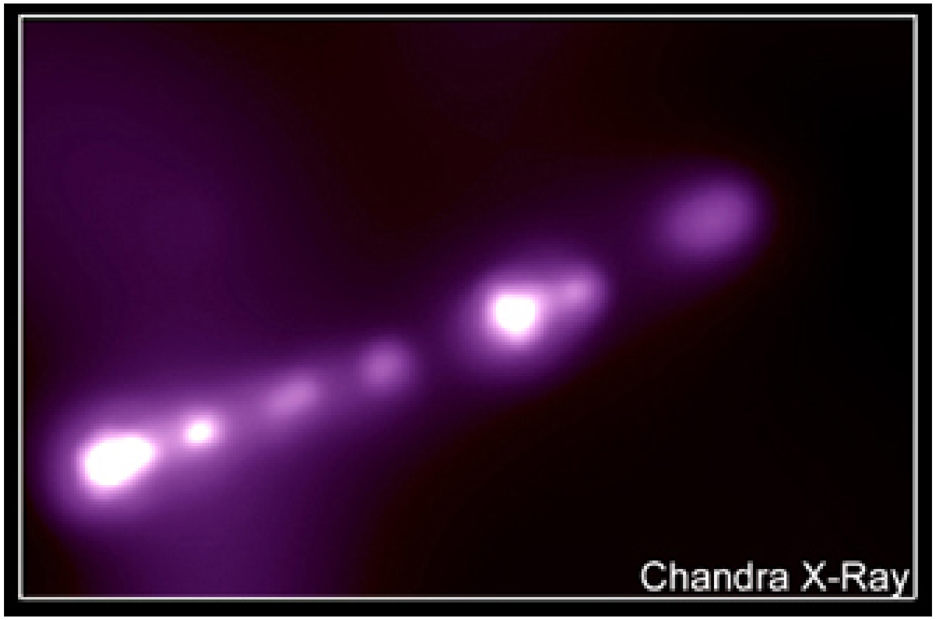
Pulsar-rotating, non-accreting Neutron star



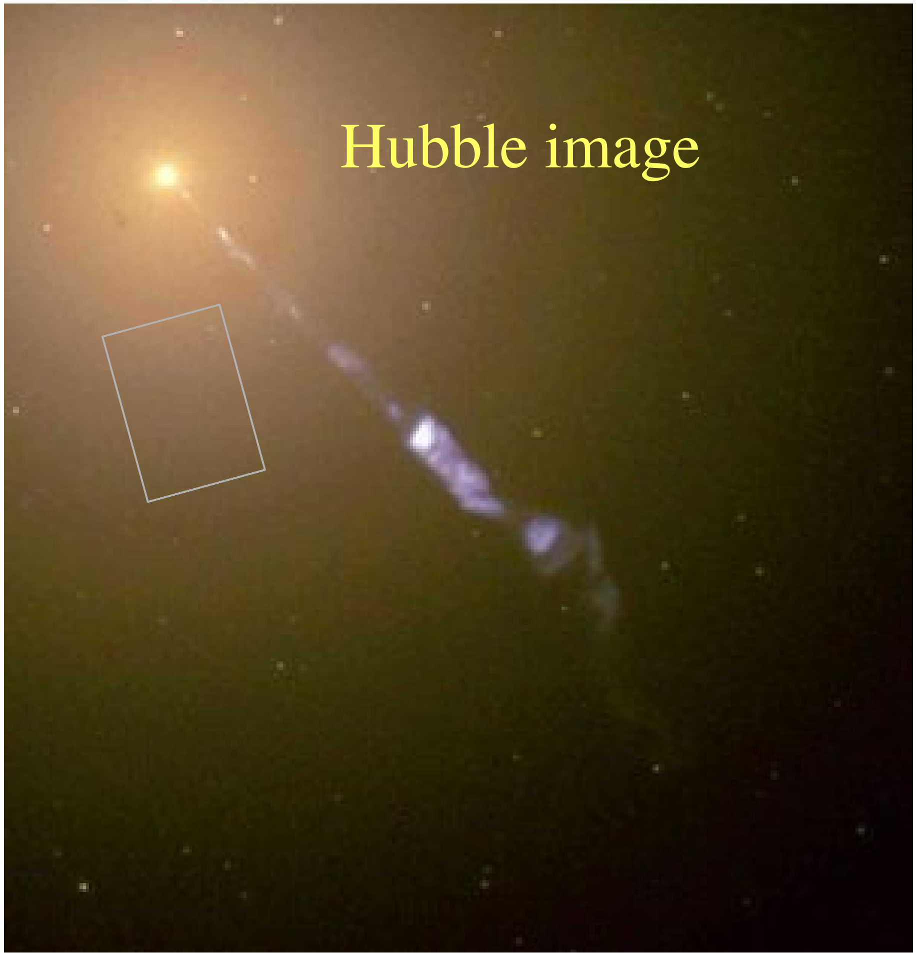
X-ray image of Vela pulsar

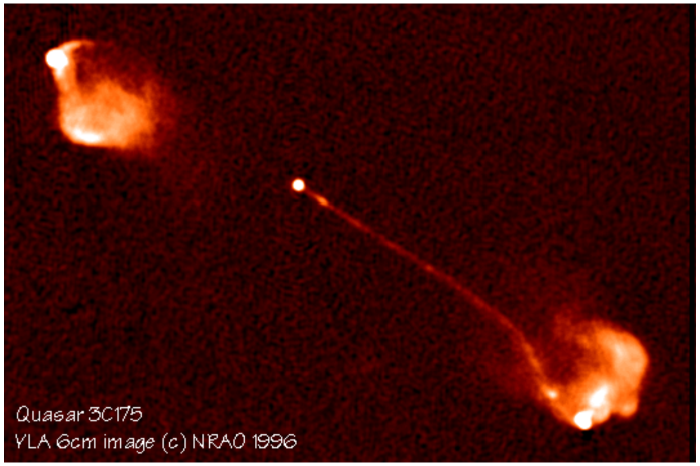
Synchrotron Radiation Examples

Image of M87 Synchrotron X-ray Radiation in jet



~1.5kpc=5×10^{21}cm long

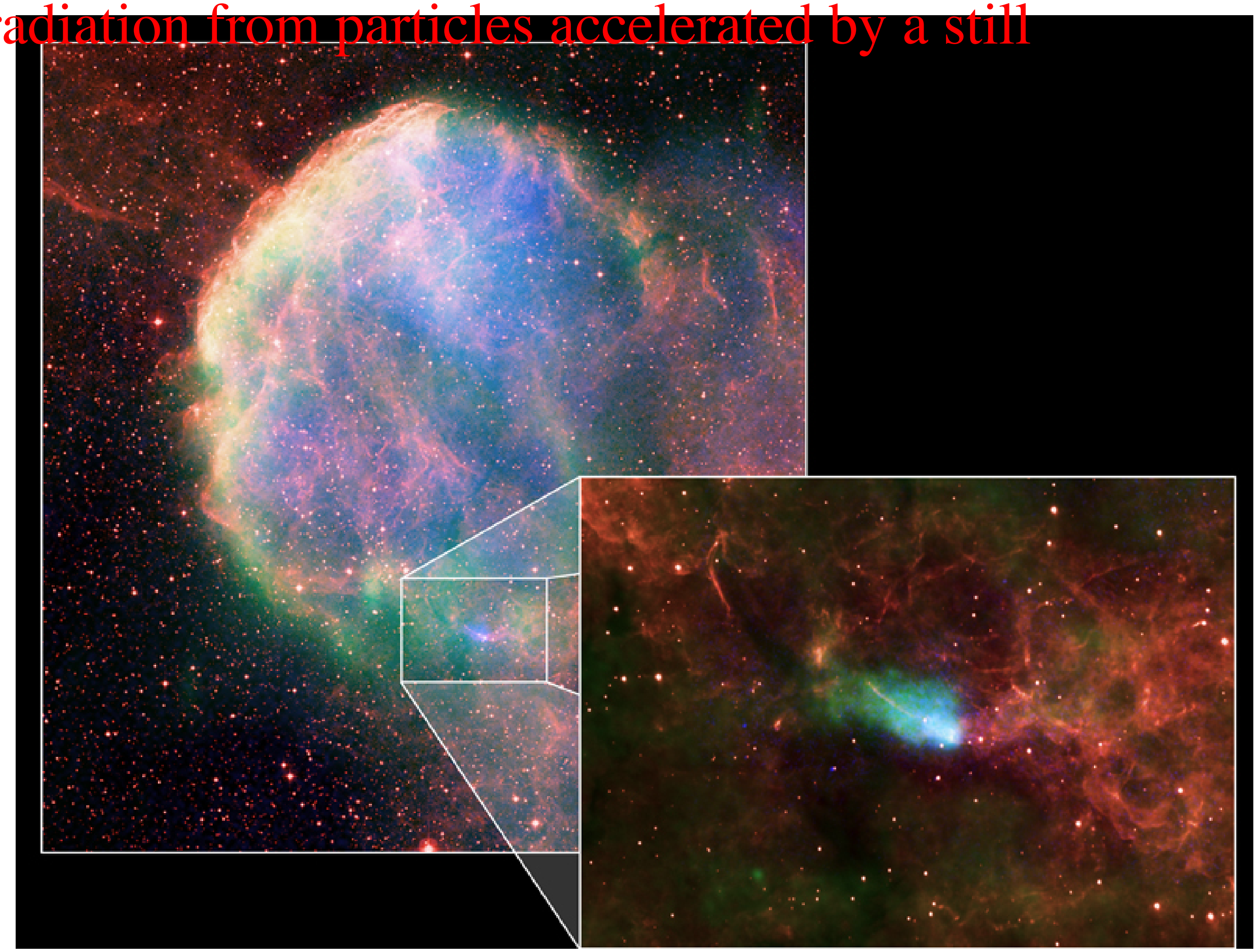




Radio image of a quasar

Combining Bremmstrahlung and Synchrotron Radiation

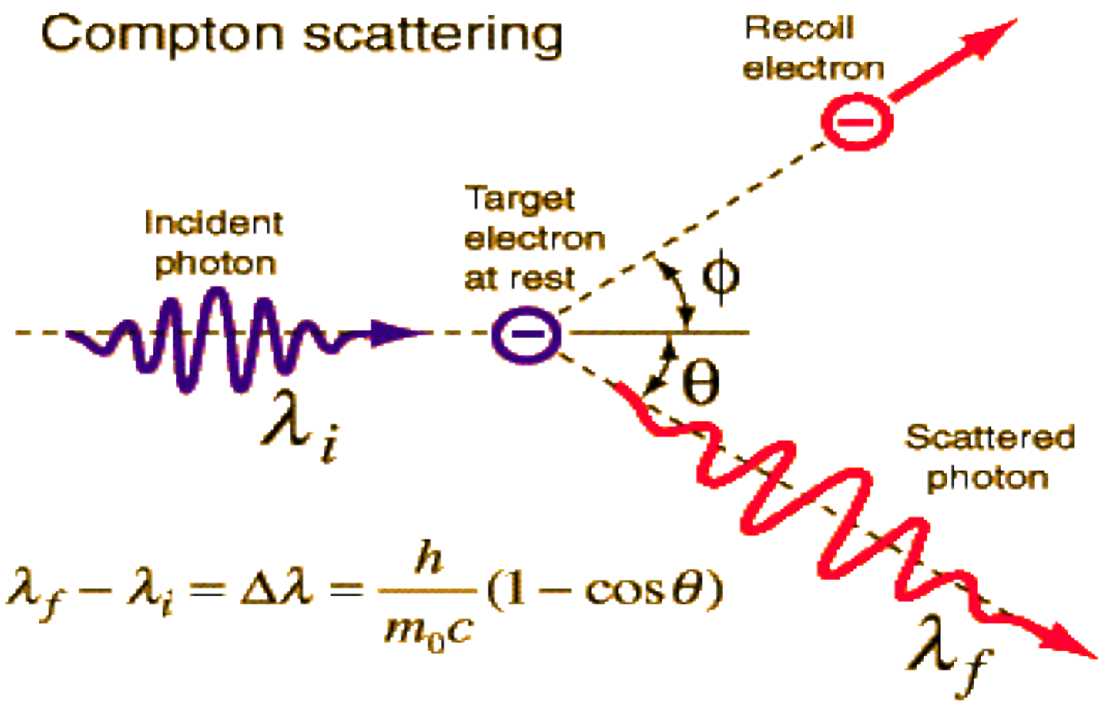
- In some supernova remants one sees both processes at work
  - Bremmstrahlung from electrons that are shock heated by the SN blast wave
  - Synchrotron radiation from particles accelerated by a still active pulsar



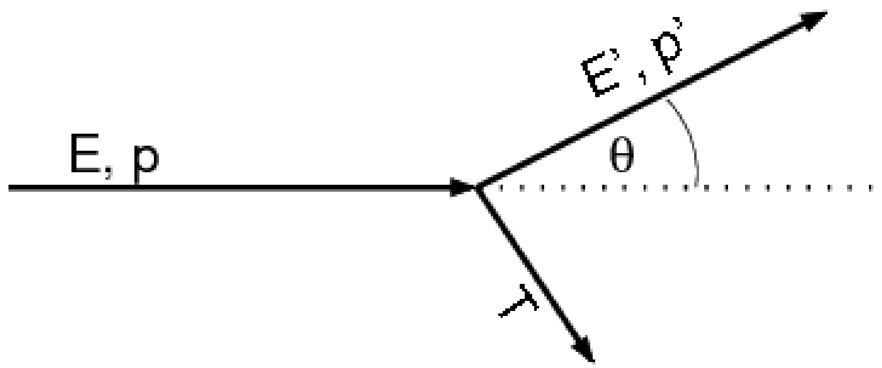
Compton Effect(s) RB Ch 3.8

Compton Wavelength=h/mc=0.00243 nm for an electron

Whether the photon gives energy to the electron of vice versa



http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/compton.html



Thomson scattering: initial and final wavelength are identical.

But: in reality: light consists of photons

$\Longrightarrow$ Scattering: photon changes direction

$\Longrightarrow$ Momentum change

$\Longrightarrow$ Energy change!

This is a quantum picture

$\Longrightarrow$ Compton scattering.

Dynamics of scattering gives energy/wavelength change:

$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)} \sim E\left(1 - \frac{E}{m_e c^2}(1 - \cos\theta)\right) \tag{7.14}$$

and

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta) \tag{7.15}$$

where $h/m_e c = 2.426 \times 10^{-10}$ cm (Compton wavelength).

Averaging over θ, for $E \ll m_e c^2$:

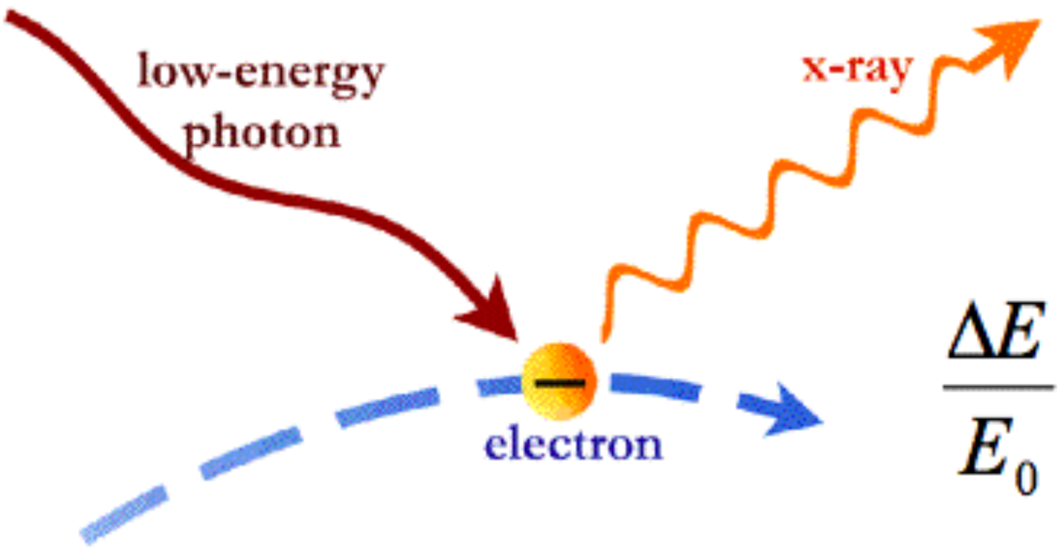
$$\frac{\Delta E}{E} \approx -\frac{E}{m_e c^2} \tag{7.16}$$

- http://pulsar.sternwarte.uni-erlangen.de/wilms/teach/radproc/radproc0177.html

INVERSE COMPTON EMISSION

Compton scattering

- Photon $E_0 = h\nu$ boosted in energy by hot e^- at kT to e.g. X-rays



$$\frac{\Delta E}{E_0} = \frac{1}{m_e c^2}(4kT - E_0)$$

Examples in X-ray astronomy: active galactic nuclei (AGN), X-ray binaries

INVERSE COMPTON EMISSION

- Results depend on source geometry

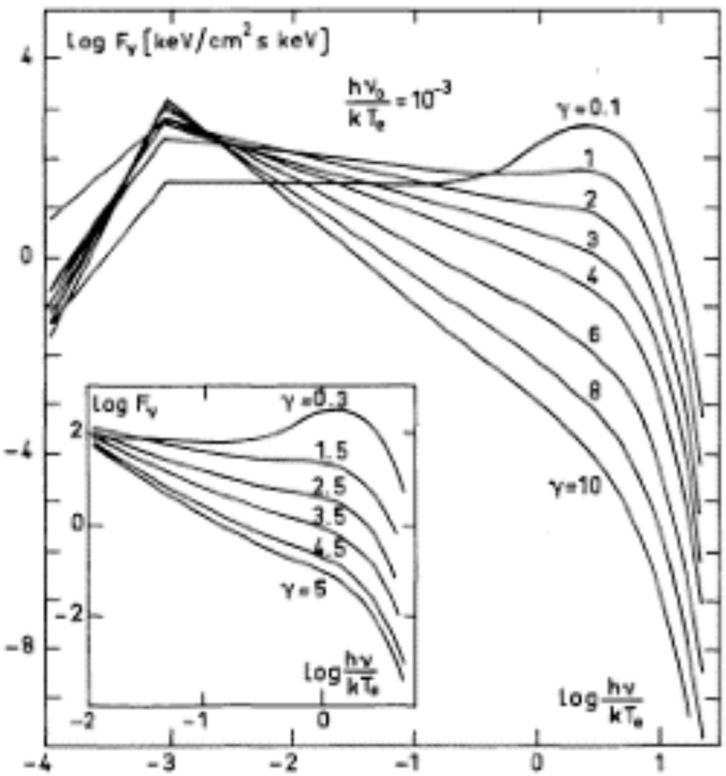


Fig. 5. The spectrum resulting from comptonization of low-frequency photons ($h\nu_0 = 10^{-3}$ kT$_e$) in a high temperature plasma clouds with different parameters γ (14)

- ***Power law***

$$F(E) = AE^{-\Gamma} e^{-E/E_c}$$

$$I(E) = BE^{-\alpha} e^{-E/E_c}$$

A,B normalizations

F,Γ ***photon*** flux photon index

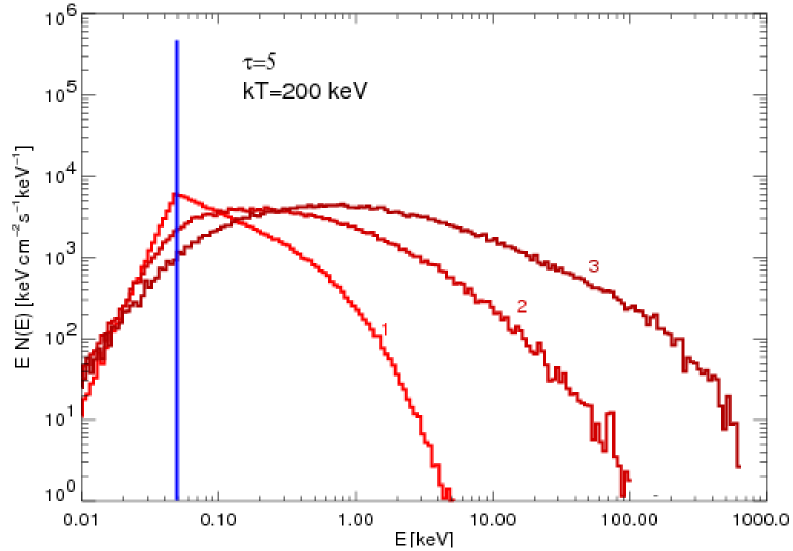
I,α ***energy*** flux, index (α=Γ-1)

E_c=*kT*=cutoff energy

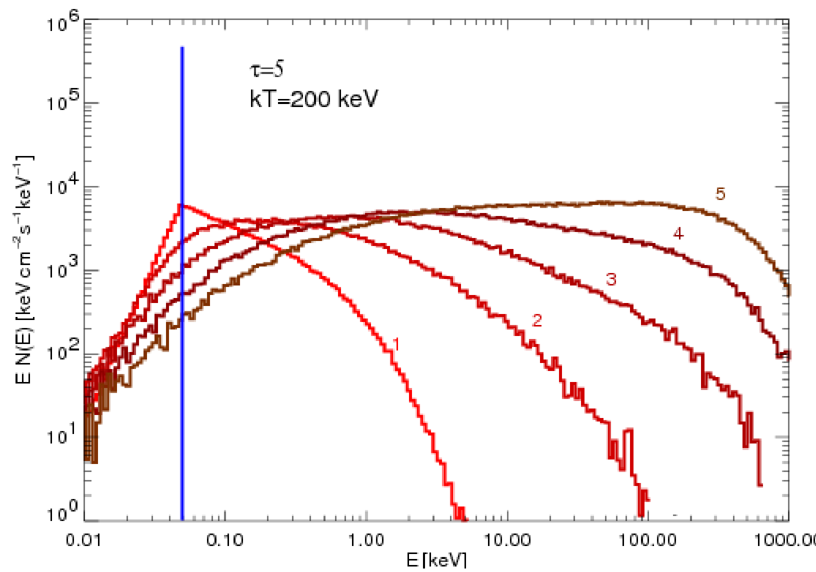
Sunyaev & Titarchuk 1980

Compton scattering

- Each scattering tends to produce a broad distribution of photons and the sum tends to a power law shape
- X-ray spectra of galactic and extragalactic black holes can be well explained by a comtptonized spectrum with kT_e~150 kev, y~1 ($y=4kT_e/m_ec^2(\max(\tau,\tau^2))$)

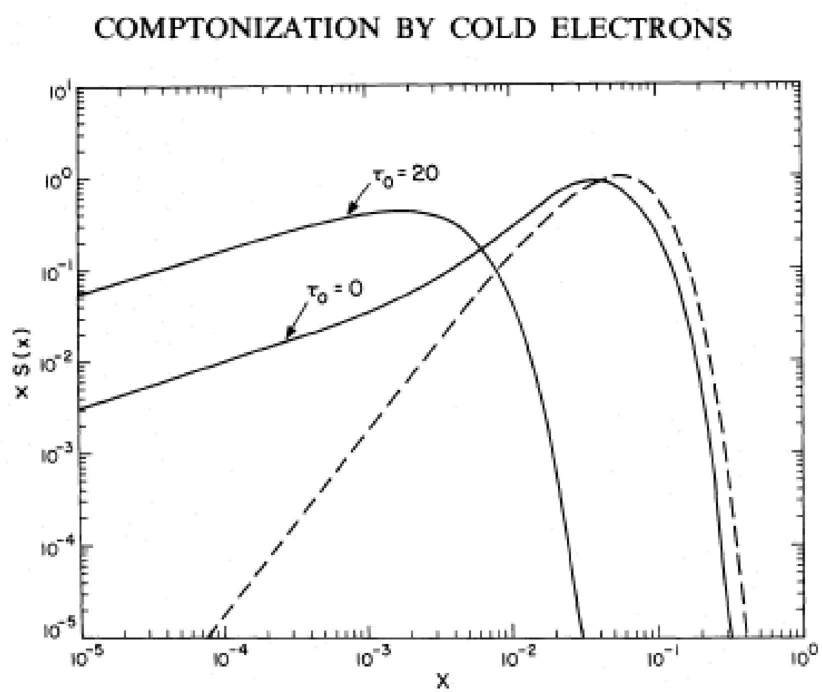


- http://pulsar.sternwarte.uni-erlangen.de/wilms/teach/radproc/radproc0201.html



Comptonization

- The output spectrum depends on the distribution function of both the electrons and photons
- If the electrons are 'cooler' than the photons the spectrum is 'down scattered' if the electrons are hotter it is up scattered.
- If $E_{photon} < 4kT_e$ photons gain energy gas cools
- If $E_{photon} > 4kT_e$ electrons gain energy gas heats
- Up scattering tends to produce a power law distribution



Relative Power in Compton and Synchrotron Radiation

$P_{IC}=4/3\sigma_T c^2 U_{rad}\beta^2\gamma^2$
net inverse-Compton power gained by the radiation field and lost by the electron.

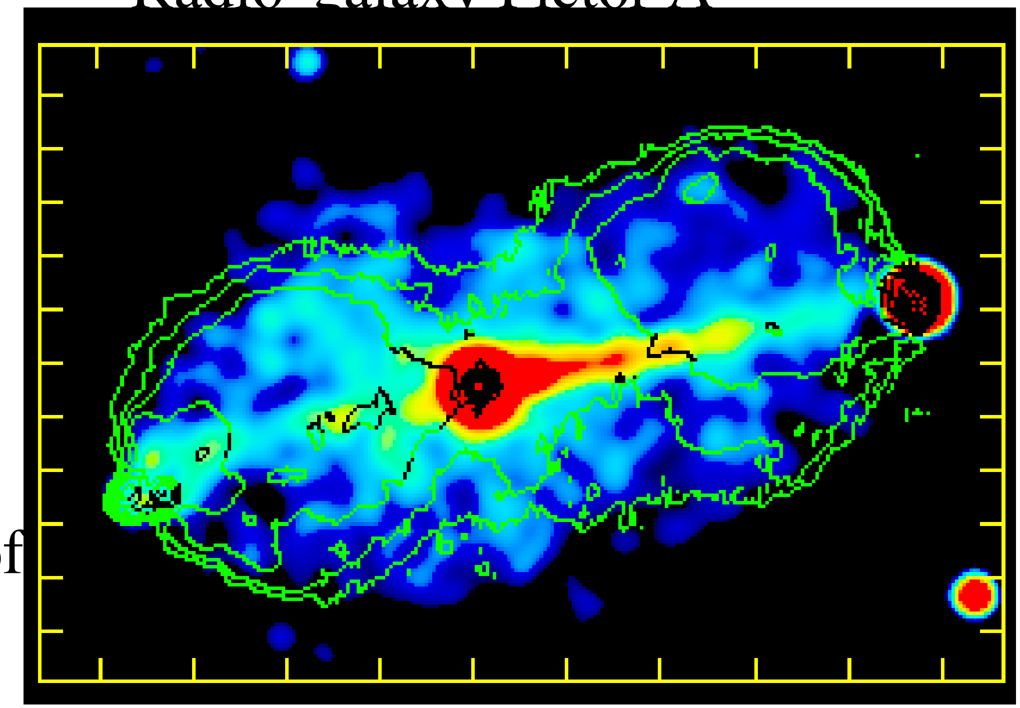
Synchrotron power
$P_{synch}=4/3\sigma_T c^2 U_B\beta^2\gamma^2$

Where $U_B=B^2/8\pi$ is the energy density of the magnetic field
And U_{rad} is the energy density of the photon field

$\beta=v/c$; $\gamma=(1-\beta^2)^{-1/2}$

Ratio of Synchrotron to Compton is U_B/U_{rad}

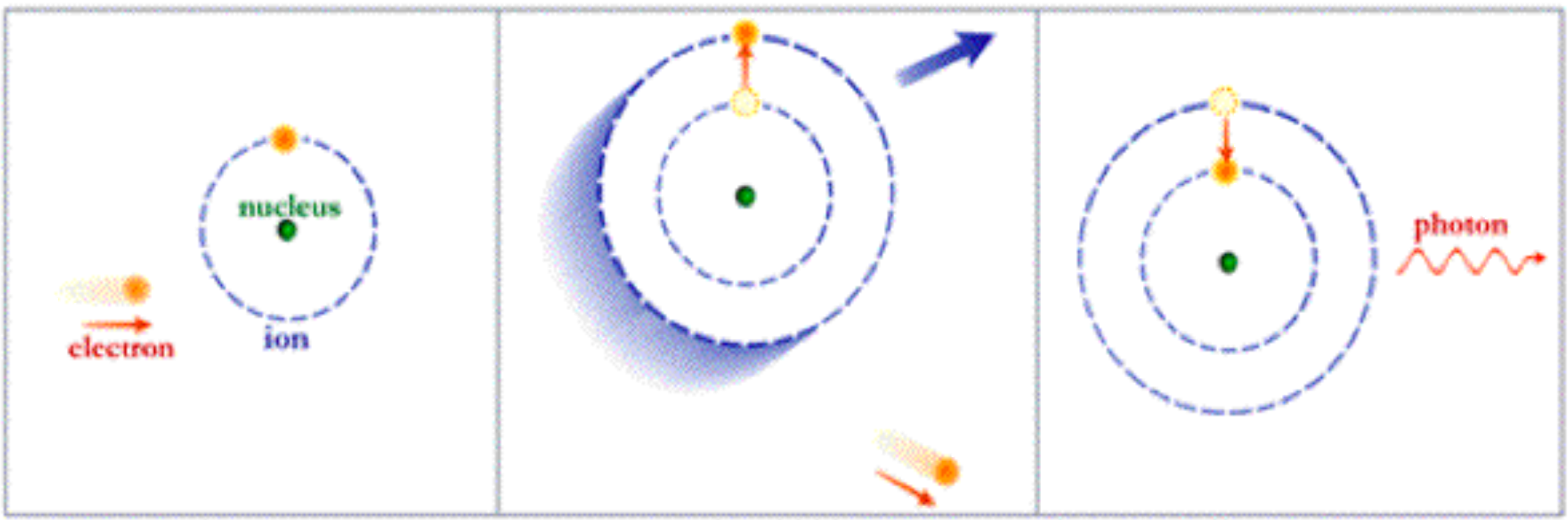
'Radio' galaxy Pictor A



Radio image (synchrotron) green contours
IC image (x-rays, color) Hardcastle and Birkinshaw 2004

LINE EMISSION

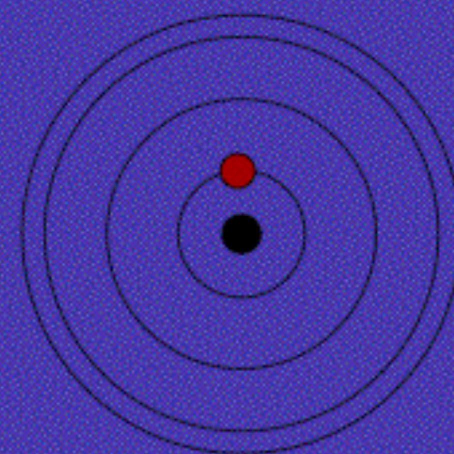
- Excitation of atoms by:
  - Thermal collisions
  - Radiative excitation
- Then radiative de-excitation



Specific Emission

Electron in bound orbitals around an atomic nucleus of nuclear charge Z can produce radiation at specific frequencies or energies, since electrons can only orbit the atomic nucleus in a well-defined set of allowed orbits.

Each orbit is associated with an electron energy, so are sometimes called energy levels. An electron has to gain energy to move from an inner to an outer energy level. An electron loses energy when moving from an outer to an inner energy level.

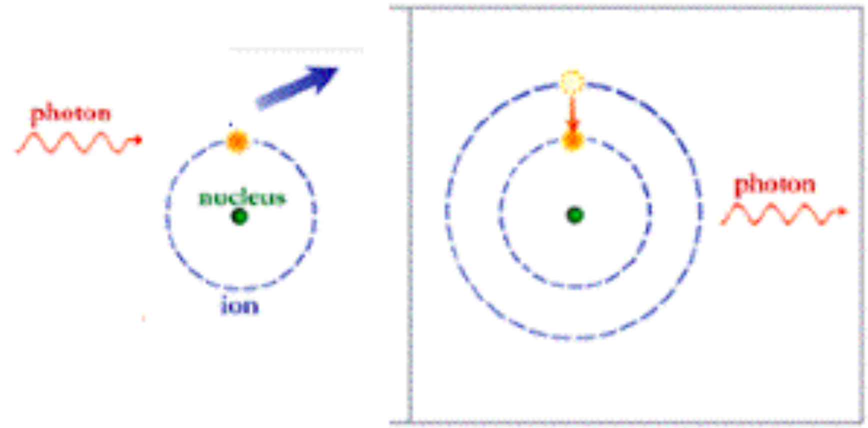


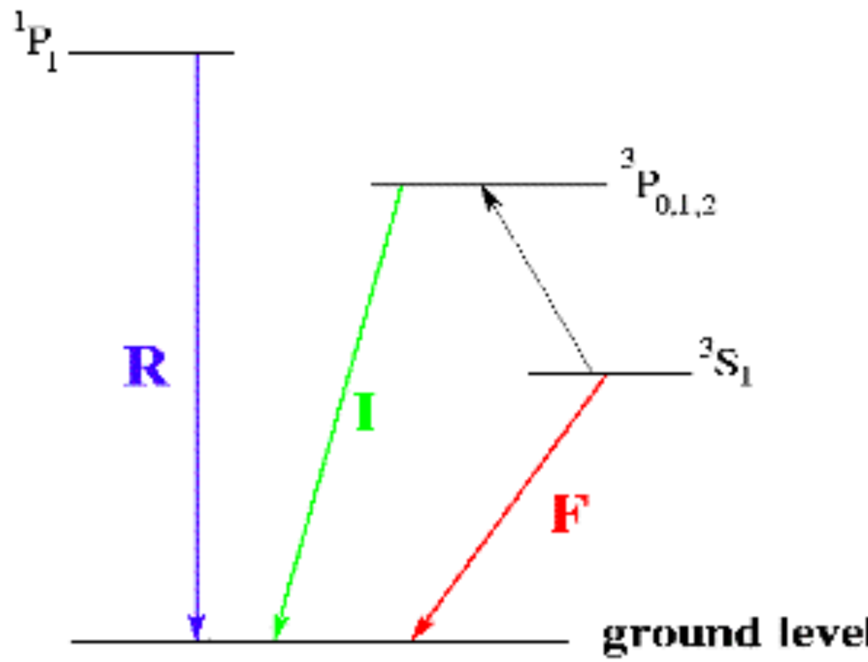
Each element has its own unique set of energy levels:

$$E_N = -\frac{13.58Z^2}{N^2}\text{electron volts (eV)}$$

TYPES OF LINE EMISSION

- Fluorescence:
  - Needs L-shell electrons
  - Photoionization, then either:
  - 2p->1s radiative transition
  - *or* Auger ionization
  - **Fluorescence yield** measures ratio
- Recombination (ionized)
  - He and H-like are most important
  - Triplet: forbidden, resonance, intercombination

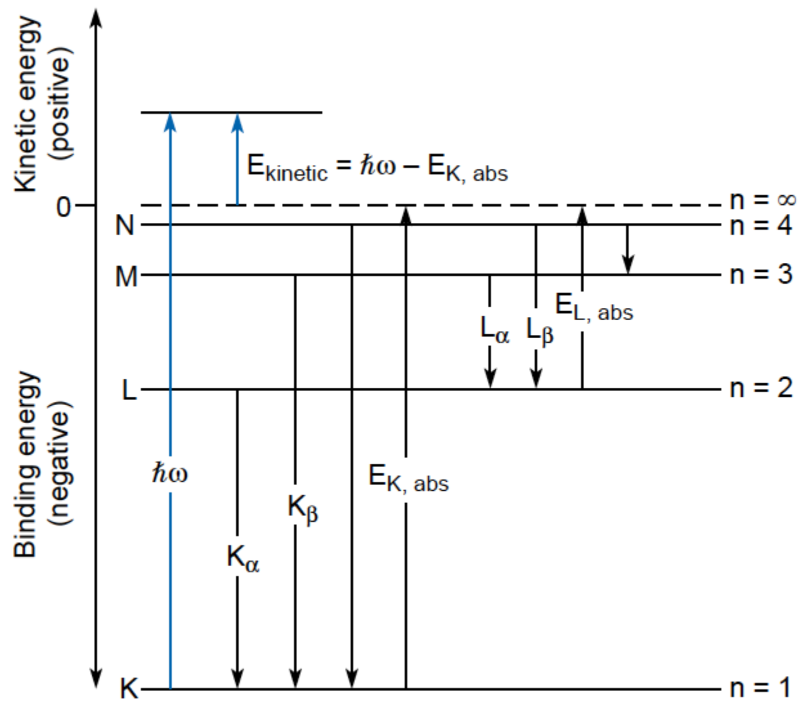




From R. Smith

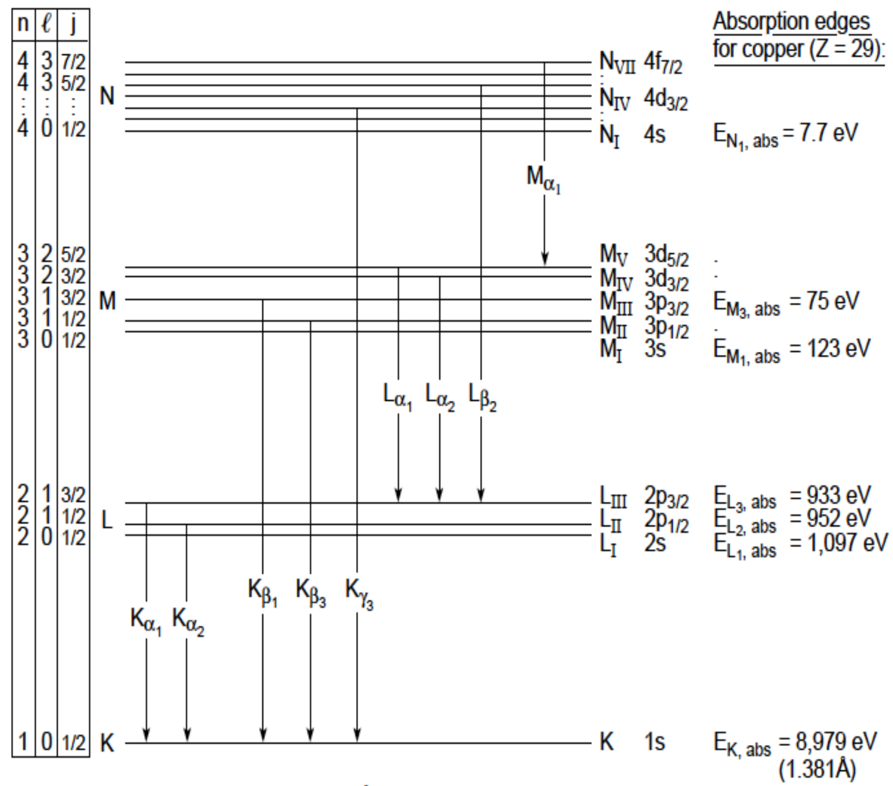
- **Generic Atom**

Energy Levels, Absorption Edges, and Character Line Emissions for a Multi-Electron Atom



wood

Energy Levels, Quantum Numbers, and Allowed Transitions for the Copper Atom



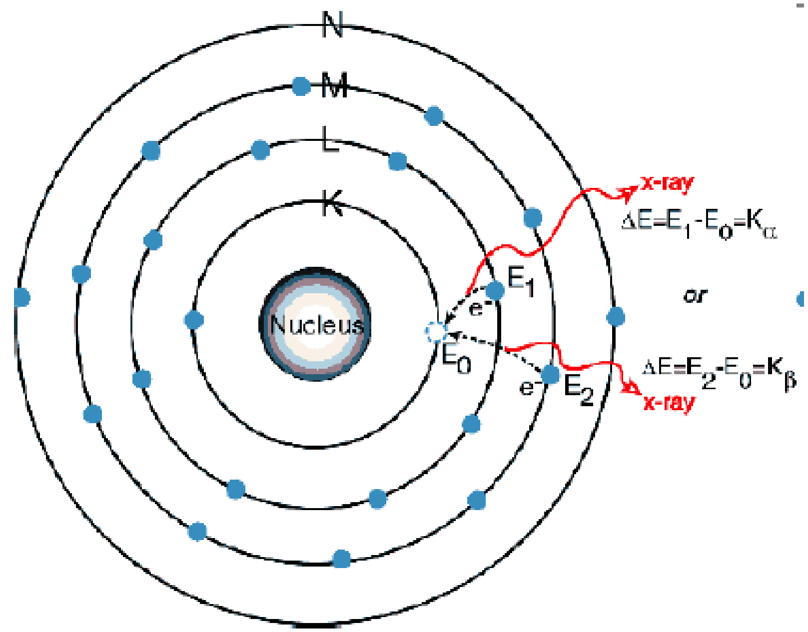
Cu K_{α_1} = 8,048 eV (1.541Å) Cu L_{α_1} = 930 eV
Cu K_{α_2} = 8,028 eV (1.544Å) Cu L_{α_2} = 930 eV
Cu K_{β_1} = 8,905 eV Cu L_{β_1} = 950 eV

ood

- **Copper Atom**

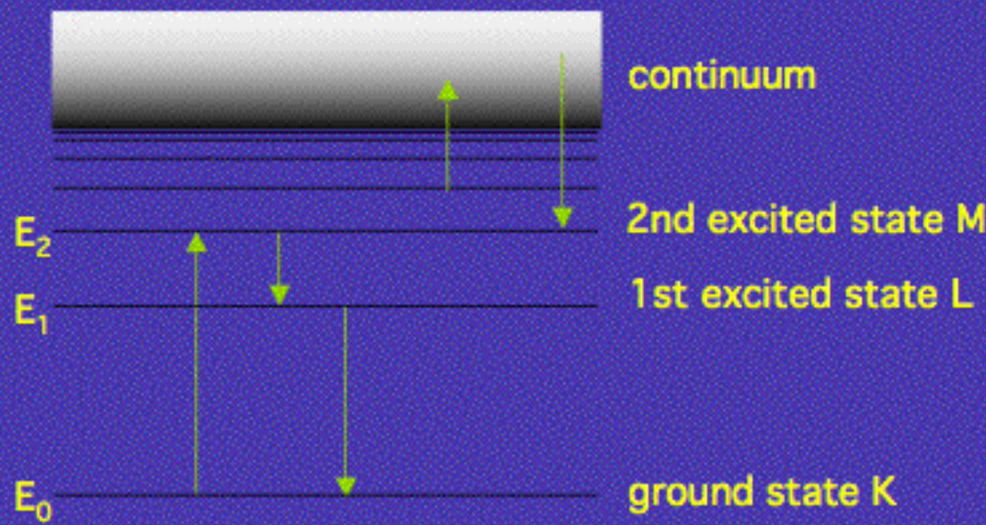
Flourescence

- X-ray fluorescence



  - discrete lines!

Electronic Processes



$E_0 < E_1 < E_2$ (it takes energy to move the electron away from the positively charged nucleus)

Atomic Energy Level Diagram (Schematic)

Excitation: an electron absorbs radiation of energy $E = E_N - E_M$ and jumps from energy level M to level N (M<N)

De-excitation: an electron jumps from level N to level M (M<N) and emits a quantum of radiation (a photon) of energy $E = E_N - E_M$

Ionization: an electron jumps from level N to the continuum (E_∞) after absorbing a photon of energy $E > E_N$. The energy required to ionize an atom from its ground state is called the **Ionization Potential**.

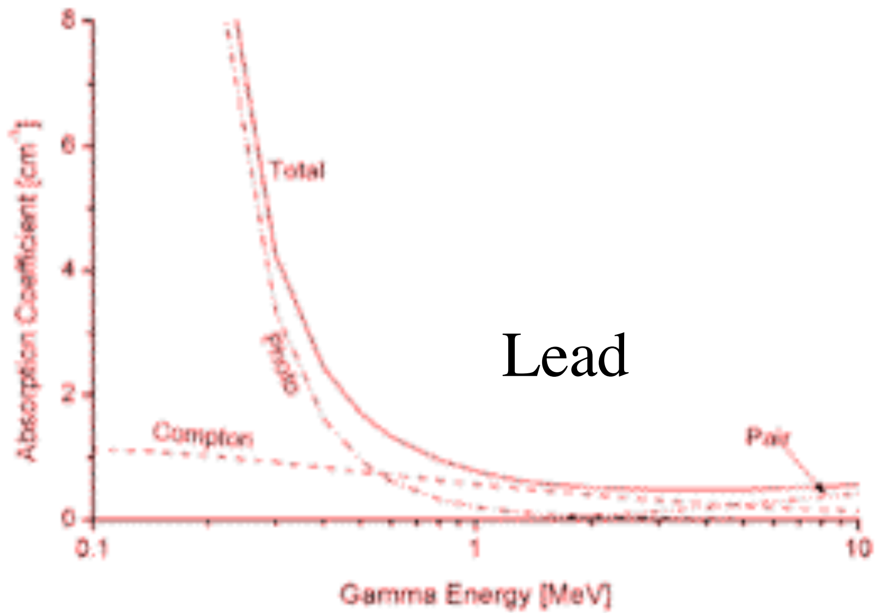
Recombination: A free electron is captured by an atom into some energy level N.

Absorption of X and γ-ray Photons

- Absorption processes
  - Photoelectric absorption
  - Ionized gas: warm absorbers
  - Absorption lines

absorption of γ-rays via pair creation, photoelectric effect, Compton scattering (photons reduced in energy, not absorbed).

X-ray and γ-rays are very penetrating radiation -but A 1 keV x-ray is totally absorbed by ~0.01gm of material (~10^{22} atms/cm^2)



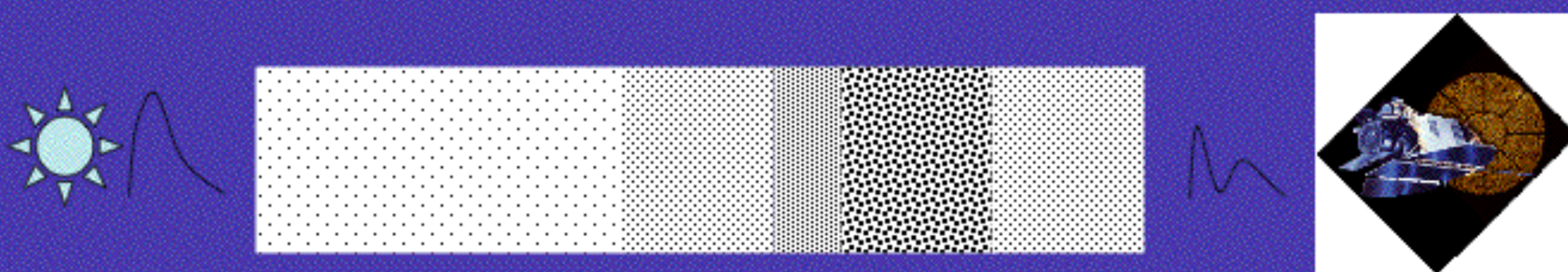
Absorption

As radiation passes through a medium, in general the medium will absorb some of the radiation, and emit some radiation. Thus the radiation received at a detector will be different from that emitted by the source. For a source of intensity I_0 whose light passes through an absorbing medium, the observed intensity I is

$$I = I_0 \exp^{-\tau}$$

where τ is the optical depth of the medium. τ is sometimes expressed in terms of an absorption cross-section σ and a column density N (the number of particles in a cylindrical column of unit area in the medium)

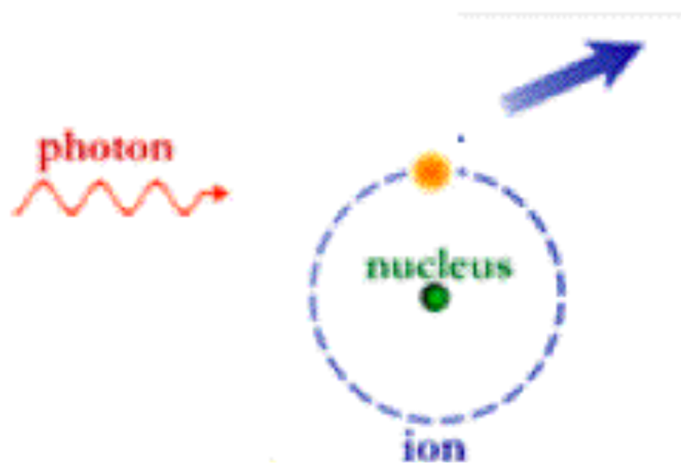
$$\tau = N\sigma$$



PHOTOELECTRIC ABSORPTION

- Bound-free ionization of e^- by photon
- Threshold energy $E_{th}=h\nu$ depending on ionziation potential of atom (i.e. on Z)
- Abundant elements (C,N,O) are light: absorption dominant at soft (<1 keV) X-rays

Continuum ⇒



⇐ Observer

PHOTOELECTRIC ABSORPTION

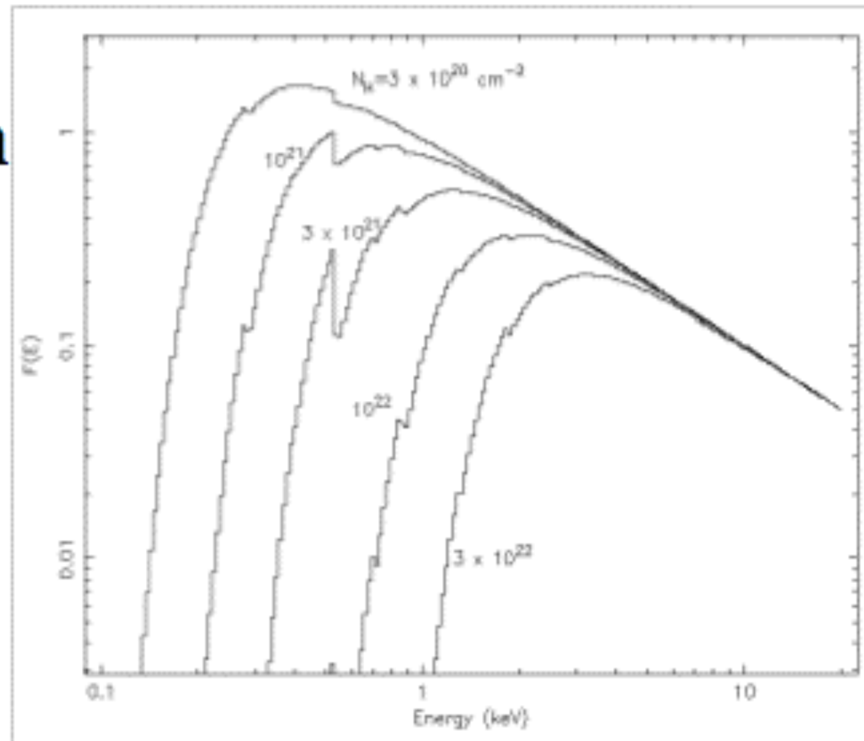
$N_H =$ Equivalent hydrogen column density (cm^{-2})

$\sigma(E) =$ cross section (cm^2)

$\tau = \sigma(E) N_H =$ optical depth

$$F(E) = A E^{-\Gamma} e^{-\sigma(E) N_H}$$

$$\sigma(E) \approx E^{-3}$$



Profile dominated by bound-free edges of abundant elements

IONIZED ABSORBERS

- In practice gas may be hot (collisionally ionized) or, more importantly, photoionized
- Ionization parameter (flux/density):

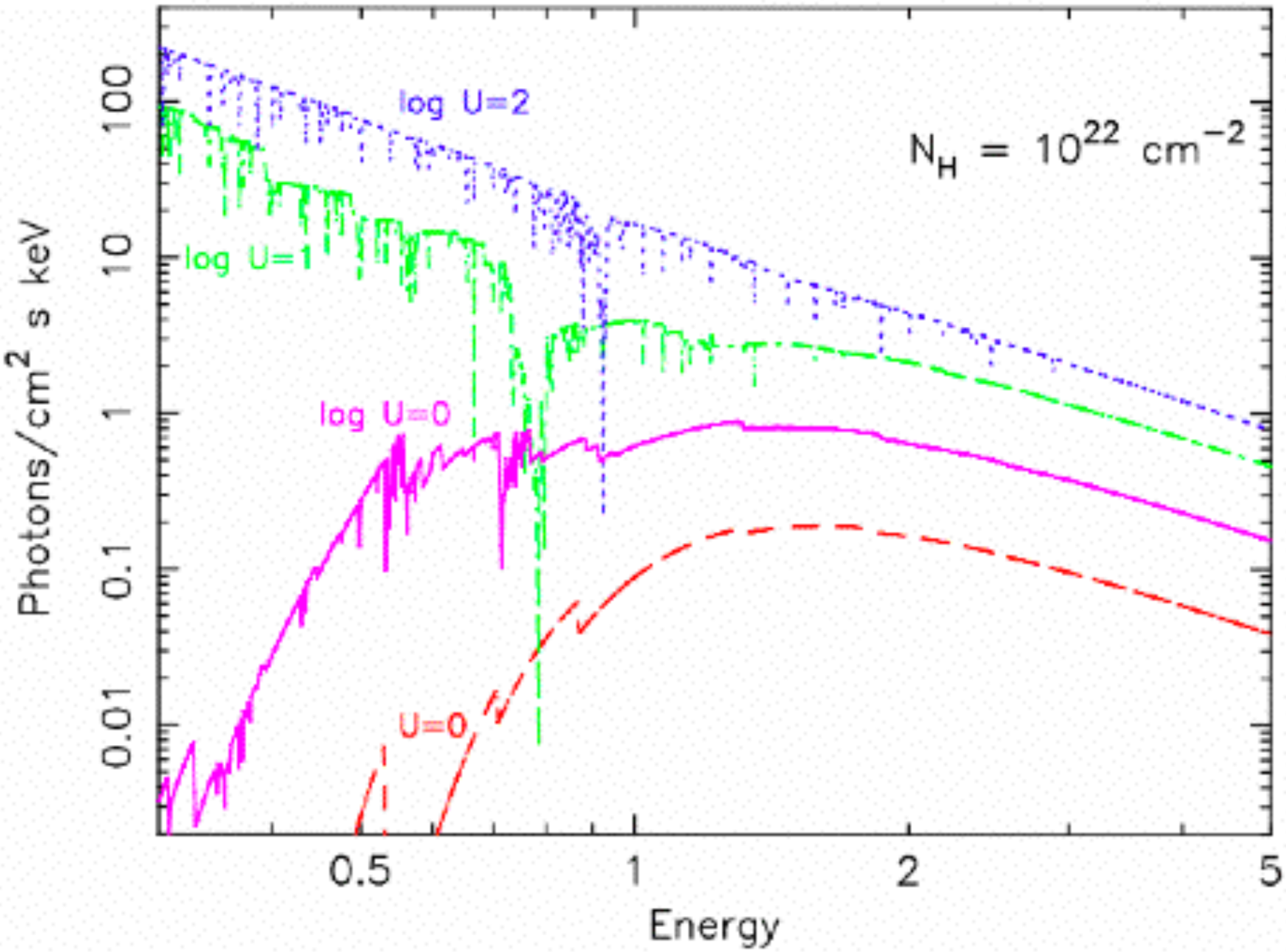
$$\xi \equiv \frac{L_X}{n_e R^2} \quad \text{Tarter, Tucker \& Salpeter (1969)}$$

$$U_X \equiv \frac{N_X}{4\pi R^2 n_e c} \qquad \text{Davidson (1974)}$$

$$L_X \equiv \int_{E_{\min}}^{\infty} L(E)\,dE \qquad N_X \equiv \int_{E_{\min}}^{\infty} \frac{L(E)}{E}\,dE$$

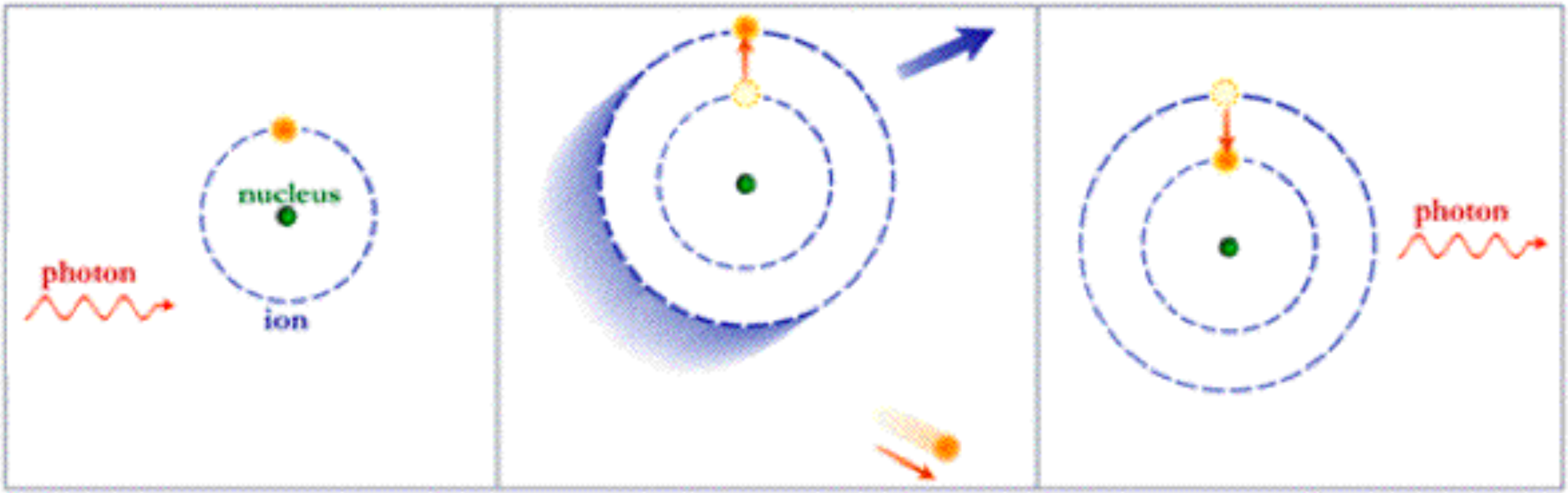
$$E_{\min} = 13.6\text{eV, } 0.1\text{ keV, } 0.7\text{ keV (Davidson, Netzer, George)}$$

IONIZED ABSORPTION



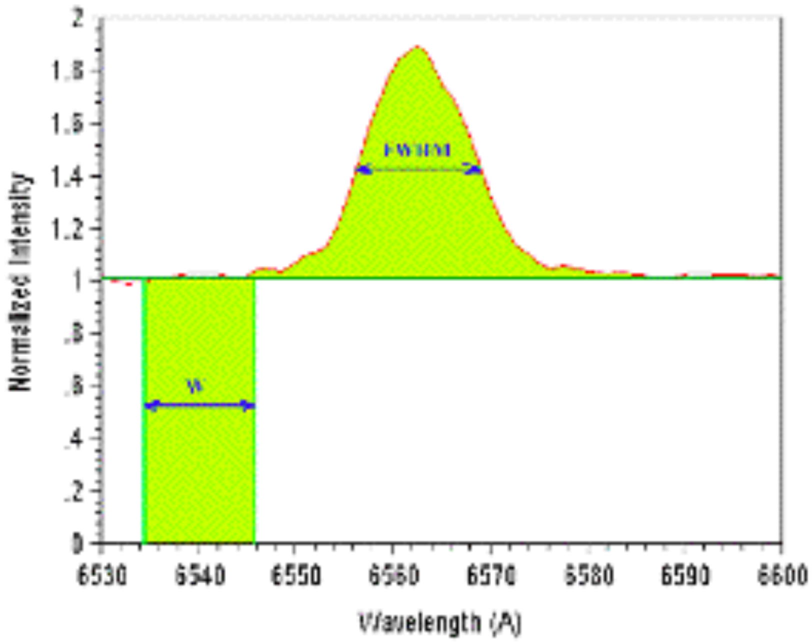
Continuum absorption profile still can be dominated by bound-free edges of abundant elements but….

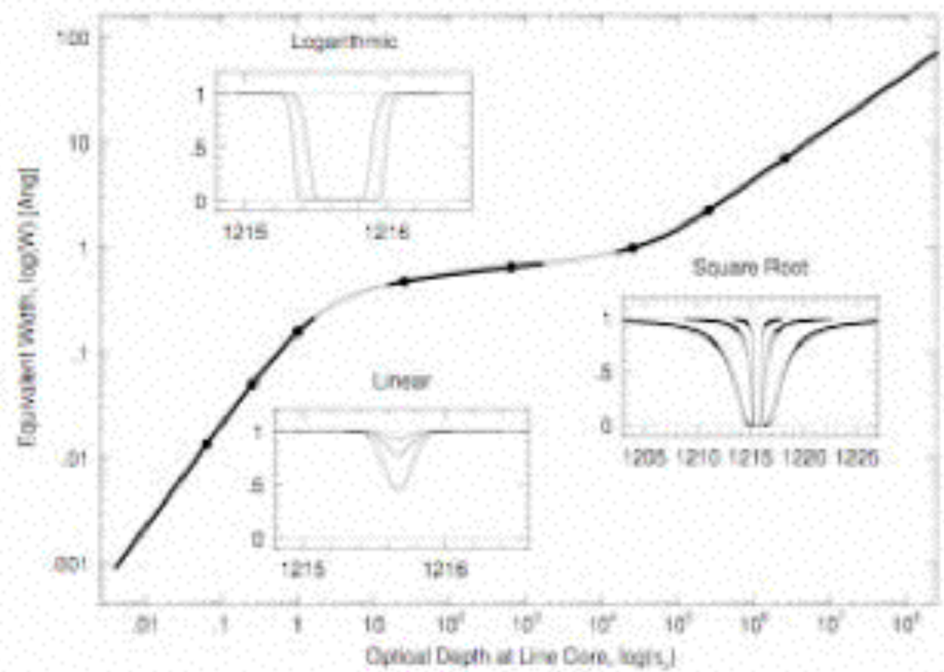
ABSORPTION LINES



- Absorption by a specific transition in atom
- Cross-sections larger than photoelectric
- But only over a small wavelength range
- Strength depends on Doppler parameter *b*
- Can measure N_H, U, velocity etc.

ABSORPTION LINES





Equivalent width:

$$EW = \frac{\int_{-\infty}^{\infty} F_l(E)dE}{F_c(E_l)}$$

$F_l =$ line flux, $F_c =$ continuum flux,

$E_l =$ line energy

Curve of growth:

$\tau < 1 \quad EW \propto N$ (linear)

$10 < \tau < 10^3 \quad EW \approx const$ (saturated)

$\tau >> 10^4 \quad EW \propto \sqrt{N}$ (damping wings)

Examples of Emission and Absorption Lines

- Mkn509 - section of the x-ray spectrum
- Notice the wide range of ionization