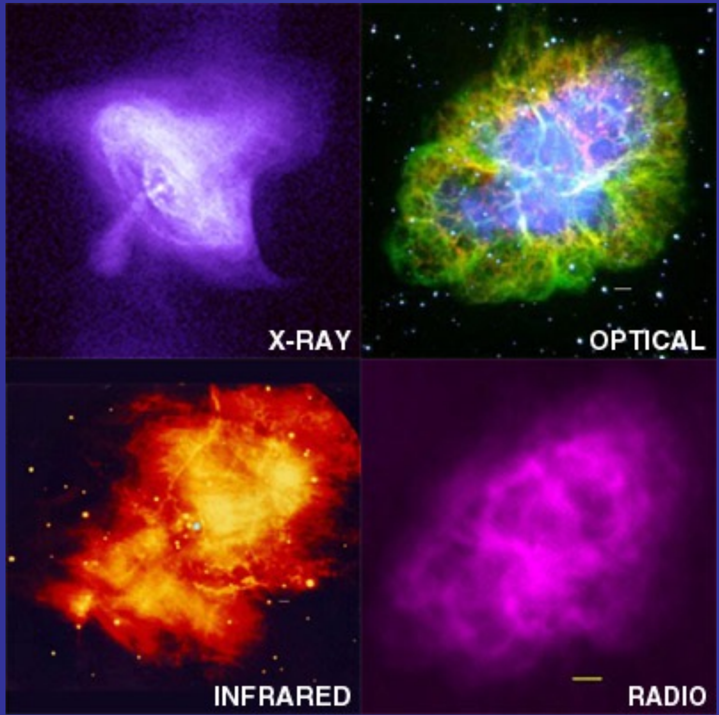
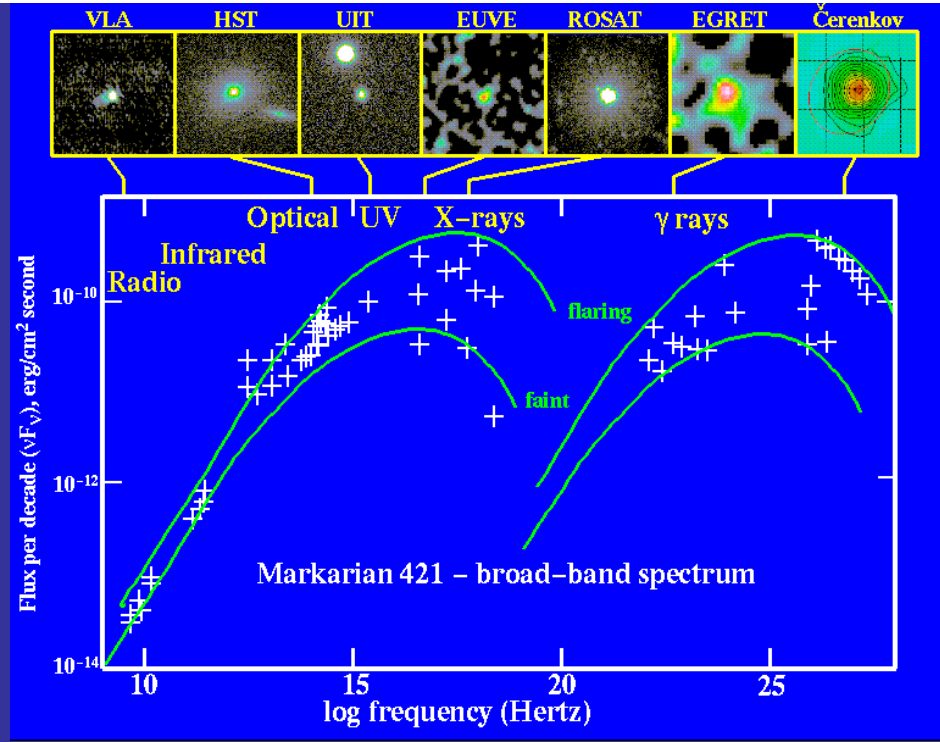




RADIATIVE PROCESSES in ASTROPHYSICS

1. Introduction
2. Basics of radiative transfer
3. Radiation fields
4. Radiation from moving charges
5. Relativistic covariance and kinematics
6. Bremsstrahlung
7. Synchrotron radiation
8. Compton scattering
9. Pair production
10. Cherenkov radiation

TURKU 2026

RADIATIVE PROCESSES in ASTROPHYSICS
Basics

Teacher: Prof. Juri Poutanen; room Quantum 251; e-mail: juri.poutanen@utu.fi

Web site of the course:
https://intranet.utu.fi/fi/yksikot/fysiikka/TAHT7010/Sivut/home.aspx

Schedule: about 18 lectures on Tuesdays (12-14 in QM4) and Wednesdays (10-12 in QM4) and 8-9 exercises on Fridays (12-14 in XVI).

The course finishes by the end of April, but there will be a few breaks (Feb 9-20, March 2-6 if you need it, March 23 - April 3).

Requirements:

1. Home exercises (30%) of the final grade. You cannot take the exam unless you get more than 1/2 of the points for the exercises.

2. Final exam (70%) of the grade. Exam will consist of two theoretical questions and two exercises.

RADIATIVE PROCESSES in ASTROPHYSICS
Literature

Lecture notes: Poutanen J.: Radiative processes in astrophysics

Rybicki G.B., Lightman A.P., 1979, Radiative processes in astrophysics (New York, Wiley)

Ghisellini G. 2013, Radiative processes in high-energy astrophysics, Springer (arxiv:1202.5949)

Shu F.H., The physics of Astrophysics, Vol. 1, Radiation (Mill Valey, Univ. Science Books)

Padmanabhan T., 2000, Theoretical Astrophysics, Vol. 1, Astrophysical Processes, Cambridge: Cambridge Univ. Press

Jackson J.D., Classical Electrodynamics (New York,Wiley)

Arfken G.B., Weber H.J., Mathematical methods for physicists

RADIATIVE PROCESSES in ASTROPHYSICS
Aim

(1) Using classical theory of electrodynamics to go from Maxwell equations to emissivities for the main continuum processes in astrophysics.
(Also useful in Material science, Biophysics, Radiation biology/medicine, Experimental particle physics, etc.)

(2) Develop the ability to deduce the physical conditions in astrophysical objects from the observed spectra.
Problem sets are on the level of research problems.
Most of interesting astrophysics is coming in form of the problems and is discussed during the exercise sessions.

Physical Units

Use Gauss system of units (CGS):

Physics:

$c = 2.9979 \times 10^{10}$ cm/s = speed of light

$e = 4.8032 \times 10^{-10}$ CGS $= 1.6022 \times 10^{-19}$ Coulomb = elementary charge

$\hbar = 1.0546 \times 10^{-27}$ erg s = Planck constant

$m_u = 1.66055 \times 10^{-24}$ g = atomic mass unit

$m_e = 0.91095 \times 10^{-27}$ g = 511 keV = electron mass

$m_p = 1.67265 \times 10^{-24}$ g = 938.28 MeV = proton mass

$m_n = 1.67495 \times 10^{-24}$ g = 939.57 MeV = neutron mass

$G = 6.6720 \times 10^{-8}$ dyn cm^2/g^2 = gravitational constant

$k = 1.3807 \times 10^{-16}$ erg/K = Boltzmann constant

$\sigma = 5.670 \times 10^{-5}$ erg s^{-1} cm^{-2} K^{-4} = Stefan-Boltzmann constant

$a_B = \hbar^2/(m_e e^2) = 0.52918 \times 10^{-8}$ cm = Bohr radius

Ry$= e^2/(2a_B) = 13.6$ eV = Rydberg (atomic energy unit)

RADIATIVE PROCESSES in ASTROPHYSICS
Astrophysical Units

Astrophysics

1 pc $= 3.0857 \times 10^{18}$ cm = distance unit

1 light year $= 9.4605 \times 10^{17}$ cm

1 AU $= 149.598 \times 10^{6}$ km

$M_\odot = 1.989 \times 10^{33}$ g = Sun's mass

$R_\odot = 6.9599 \times 10^{5}$ km = Sun's radius

$L_\odot = 3.826 \times 10^{33}$ erg/s = Sun's luminosity

1 year $= 3.156 \times 10^{7}$ s

1 day = $8.64\text{x}10^{4}$ s

Comments:

1 eV $= 1.6022 \times 10^{-12}$ erg $= 1.6022 \times 10^{-19}$ Joule

1 atm $= 10^{6}$ dyn/cm^2

$q_1 q_2 / r$ = Coulomb interaction potential

INTRODUCTION
Why to study?

Most of the information about the Universe comes to us via electro-magnetic (EM) radiation.

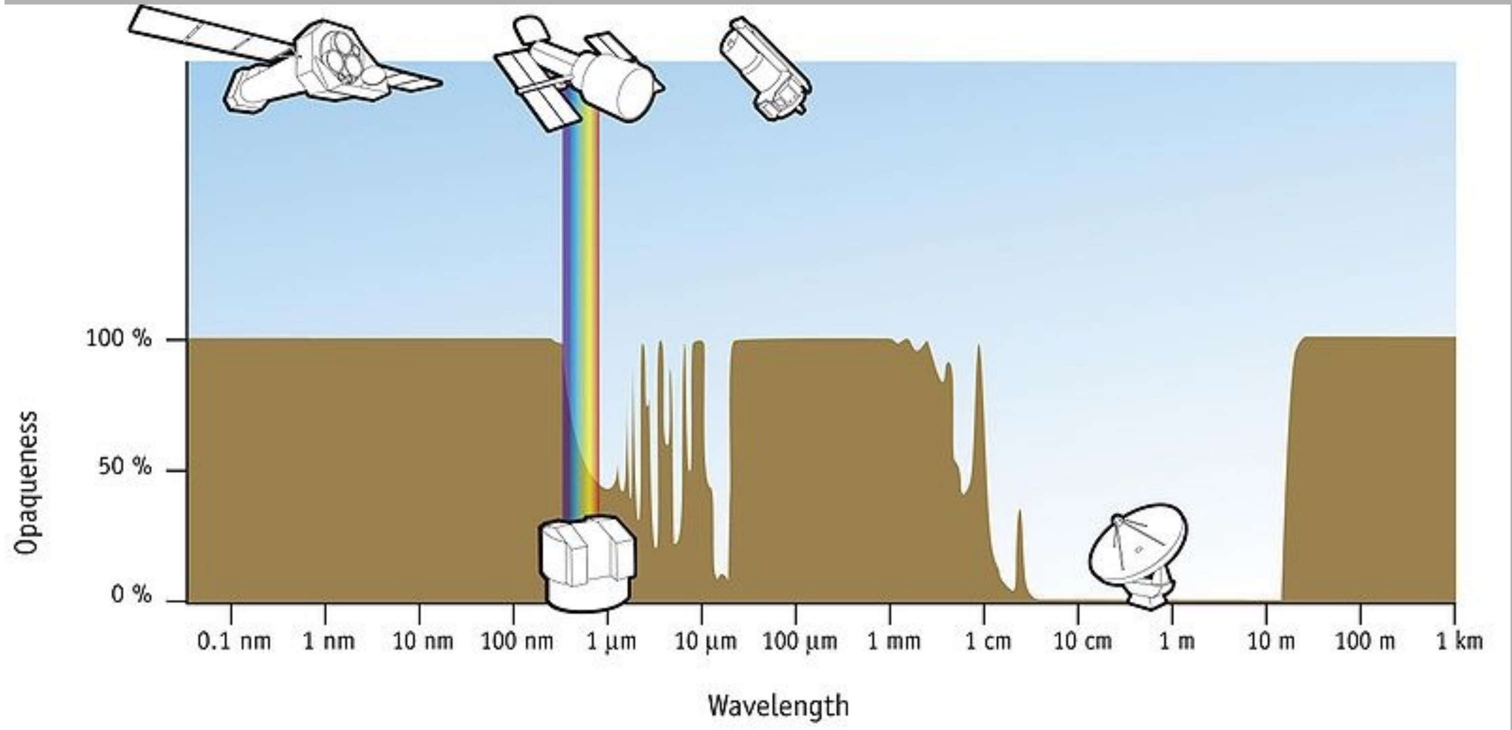
Exceptions:

1. measurements in situ at the surfaces of a few planets and their satellites (e.g. Earth and Moon, Mars, Venus, Saturn's rings and moons Enceladus and Titan)
2. measurements of the particles in the interplanetary space
3. cosmic rays (from 1912)
4. neutrinos (from 1968 – Sun, 1987 – supernova, 2018 – high-energy neutrinos possibly from blazar TXS 0506 +056, plus a few possible sources)
5. gravitational waves (from 2015)

INTRODUCTION
EM radiation

EM radiation:

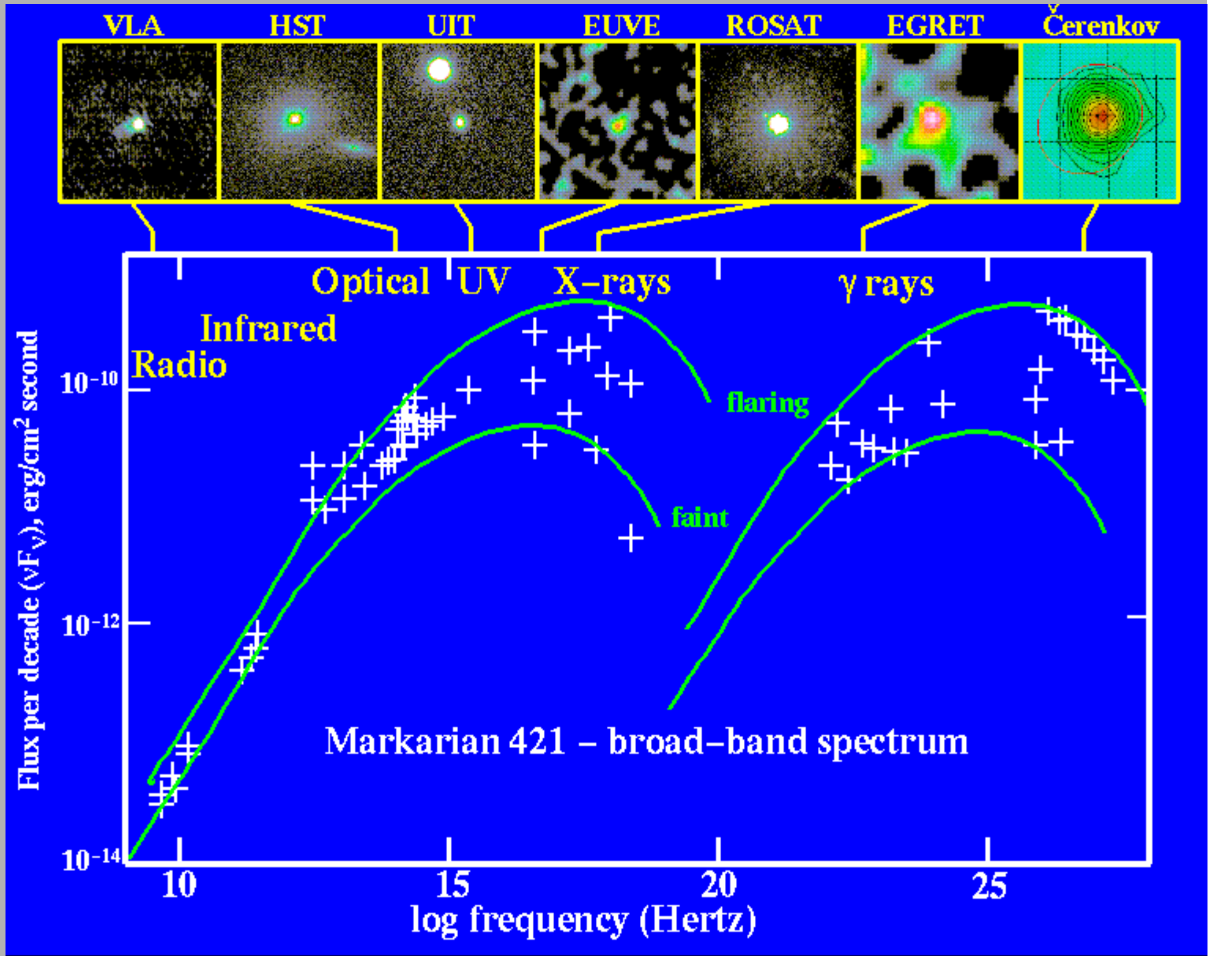
1. Optical - was used for thousands of years.
2. Radio - radars from 1940s
3. IR - observations already in 19th century, but IR telescopes in 1969
4. UV - observations of the Sun in 1946 from rockets
5. X-rays from the Sun in 1949, first X-ray source in 1962.
6. Gamma-rays, cosmic background discovered in 1961



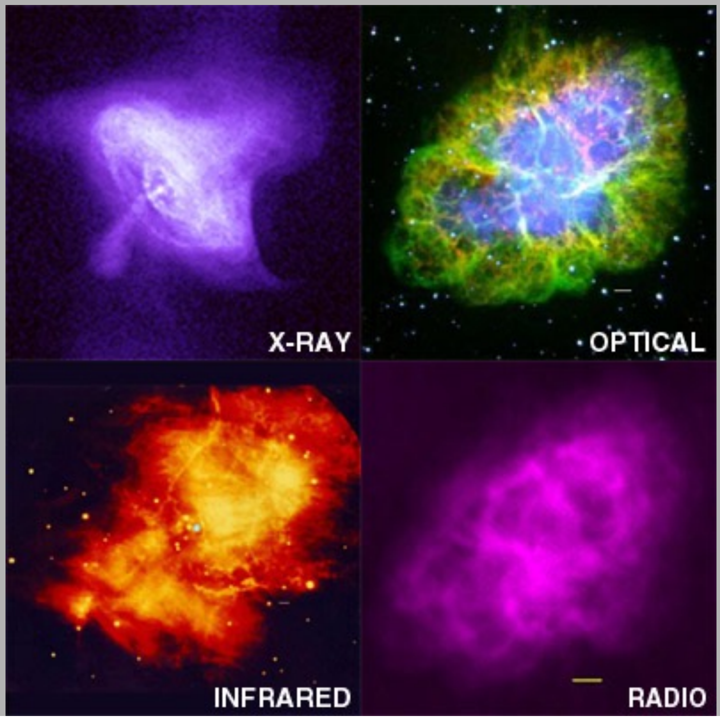
Riccardo Giacconi
(1931-2018)
Nobel prize in 2002

INTRODUCTION
Multiwavelength Universe

Many sources emit EM radiation over many different wavelengths.

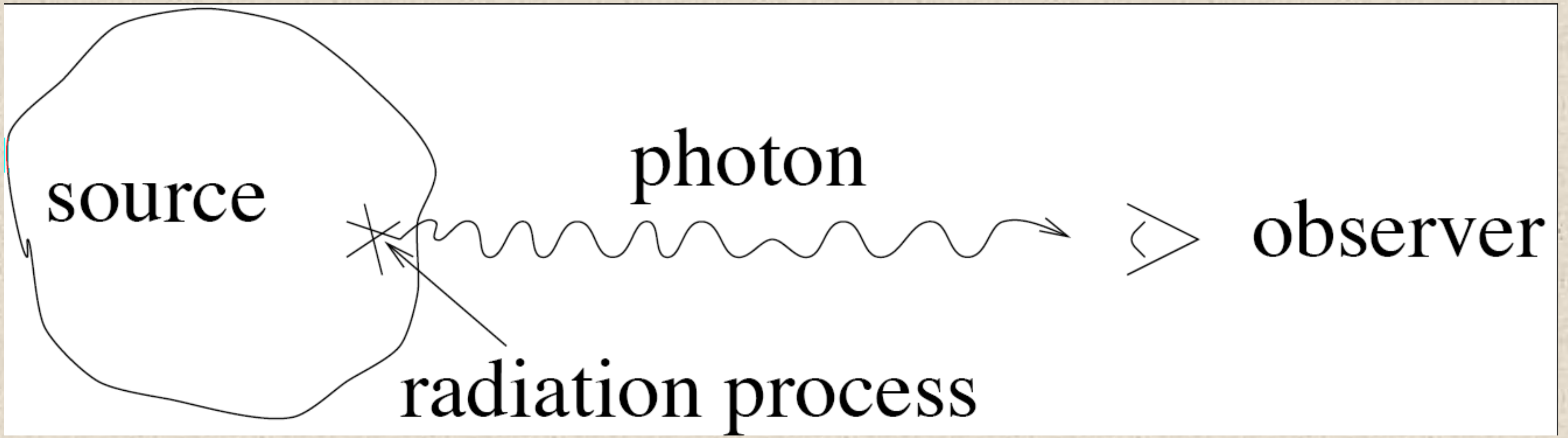


Crab nebula emits radiation over many decades in energy.



Blazars - active galaxies with relativistic jets - shine from radio up to TeV energies.

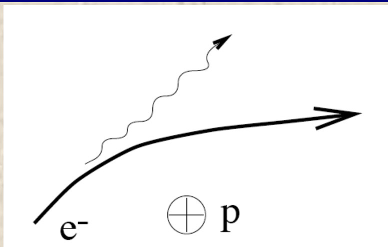
INTRODUCTION
Main continuum radiative processes



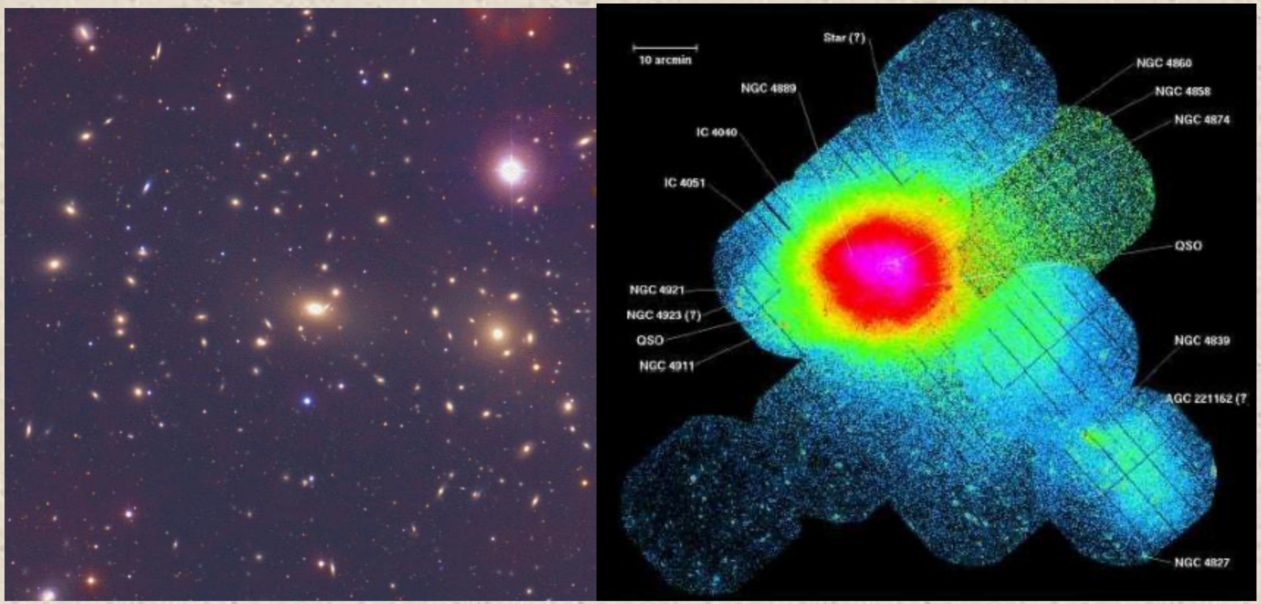
Understanding the microphysics of the radiative processes giving rise to the observed radiation allows to relate the observed properties to the physical parameters in a source using physical models.

INTRODUCTION
Main continuum radiative processes

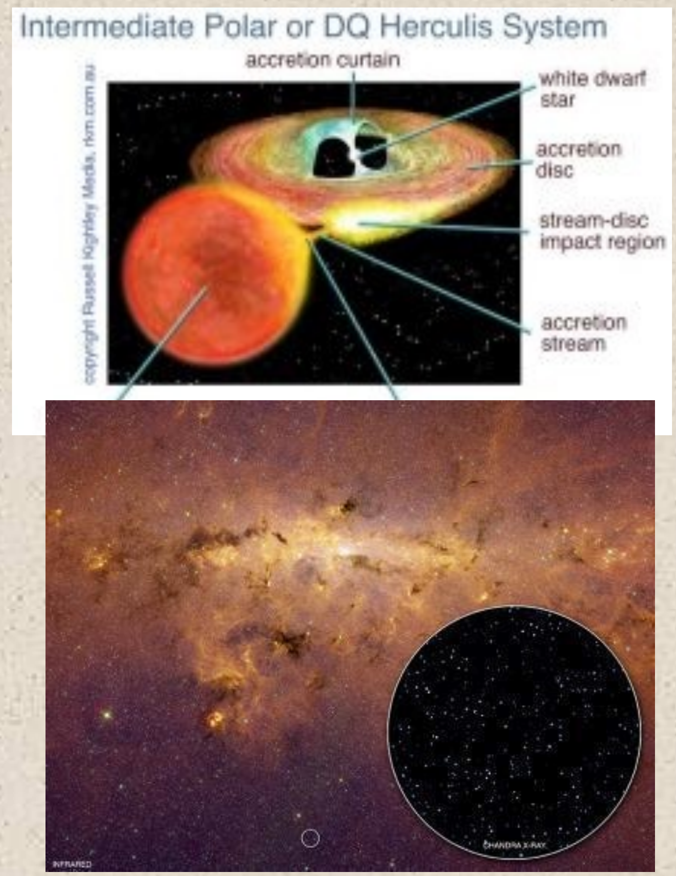
1. **<u>Bremsstrahlung</u> - breaking radiation - free-free radiation: involves interactions between charged particles, e.g. electron and proton.**



Among the astrophysical sources where bremsstrahlung is important are HII regions, clusters of galaxies, accreting white dwarfs



Coma cluster in the optical (left) and X-rays (right)

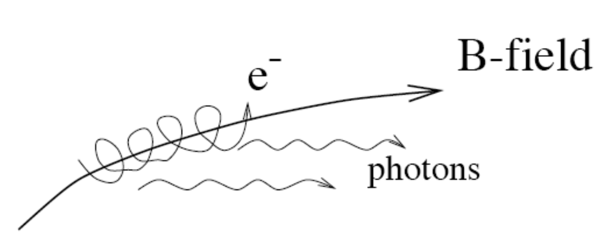


Intermediate polars (upper) as sources of the Galactic ridge emission (lower)

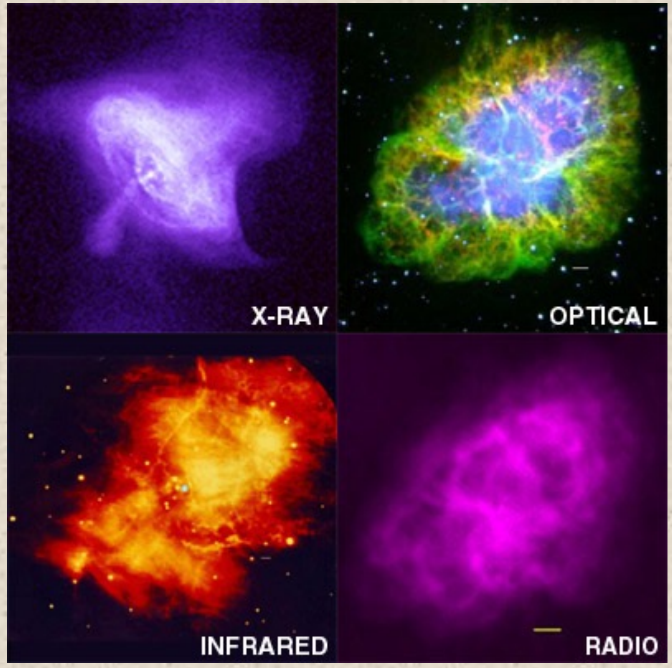
INTRODUCTION
Main continuum radiative processes

2. <u>Synchrotron radiation</u>: emission of charged particles spiraling in the magnetic field.

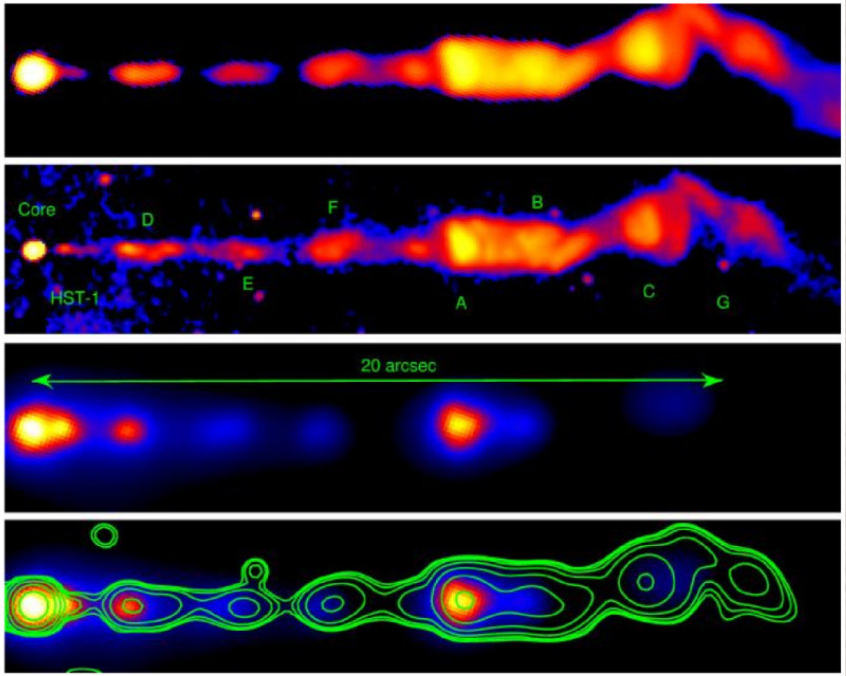
Astrophysical application started after realizing that polarized radiation from the Crab nebula is produced by synchrotron process.



Theory was developed mostly in the 2nd half of the 20th century (Ginzburg, Syrovatsky), while some important papers have already appeared in the 1910s (Schott 1912).



Crab nebula



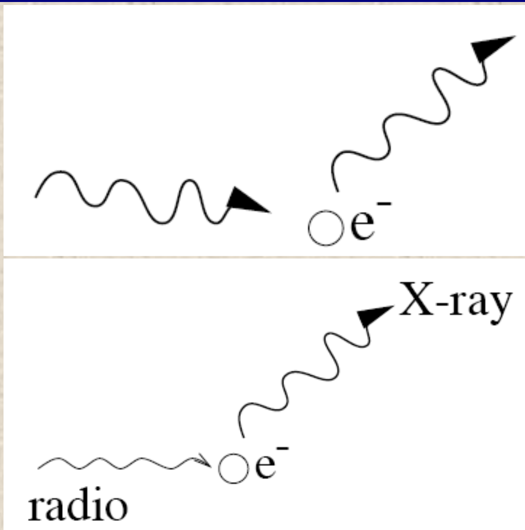
Jets from active galaxies also emit synchrotron radiation

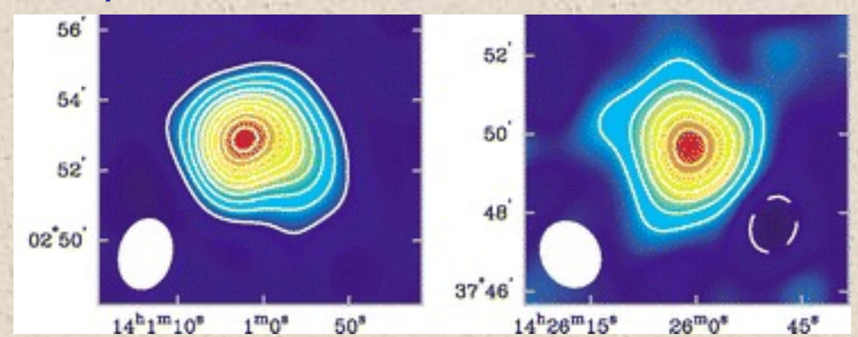
INTRODUCTION
Main continuum radiative processes

3. Electron scattering: involves interactions between photons and charged particles.

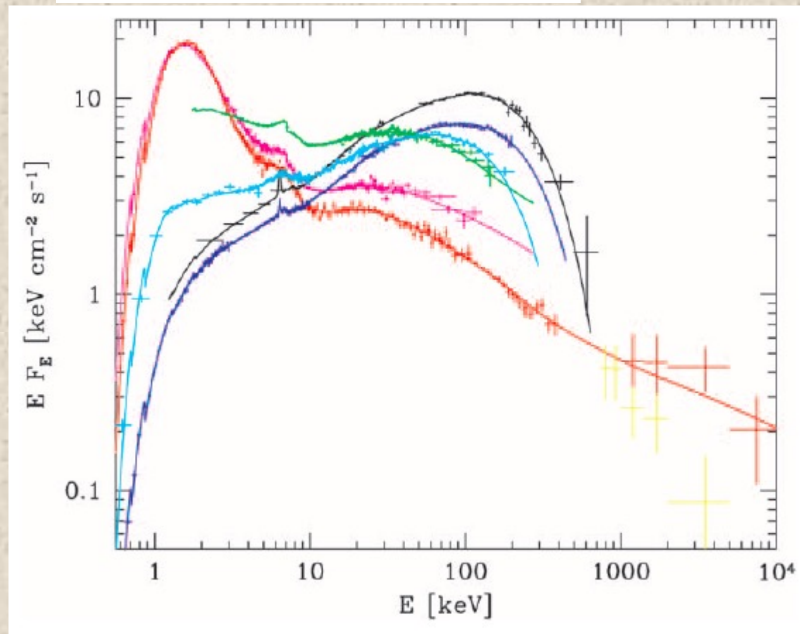
Thomson scattering is important in atmospheres of hot stars.

Among the astrophysical sources where (inverse) Compton scattering is important are compact sources: such as accreting black holes, neutron stars, jets from active galaxies as well as in the Universe and cluster of galaxies (Sunyaev-Zeldovich effect).





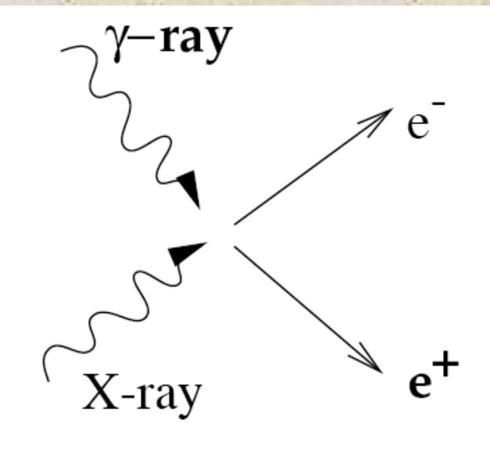
Sunyaev-Zeldovich effect (deviation of CMB from a black body) in clusters of galaxies.



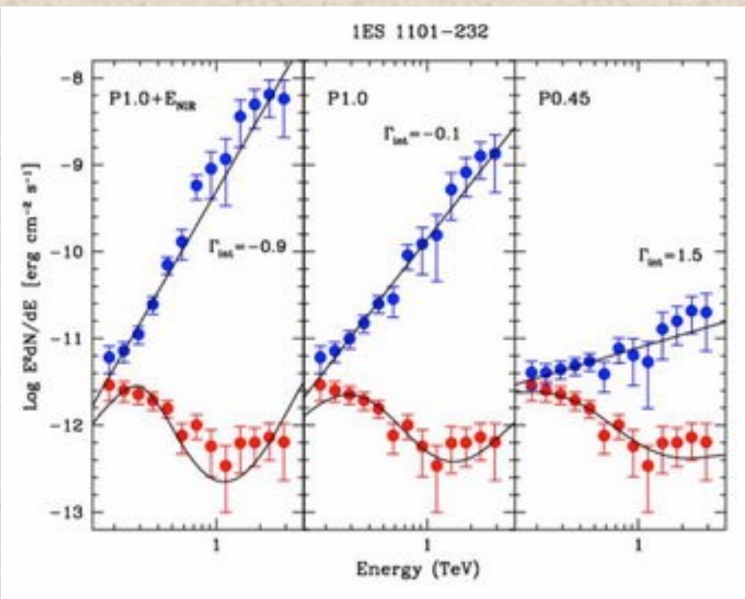
Galactic black hole Cyg X-1. Photons above few keV are produced by Compton up-scattering (or inverse Compton).

INTRODUCTION
Main continuum radiative processes

4. <u>Photon-photon pair production</u> : **involves interactions between high-energy photons.**



Among the astrophysical sources where it is important are compact sources: pulsars, jets from active galaxies and gamma-ray bursts.



Observed TeV spectrum of a blazar (lower red points) and the reconstructed intrinsic spectrum (upper blue points). The difference is caused by absorption of TeV photons on extragalactic IR light.

INTRODUCTION
Plan of the lectures

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