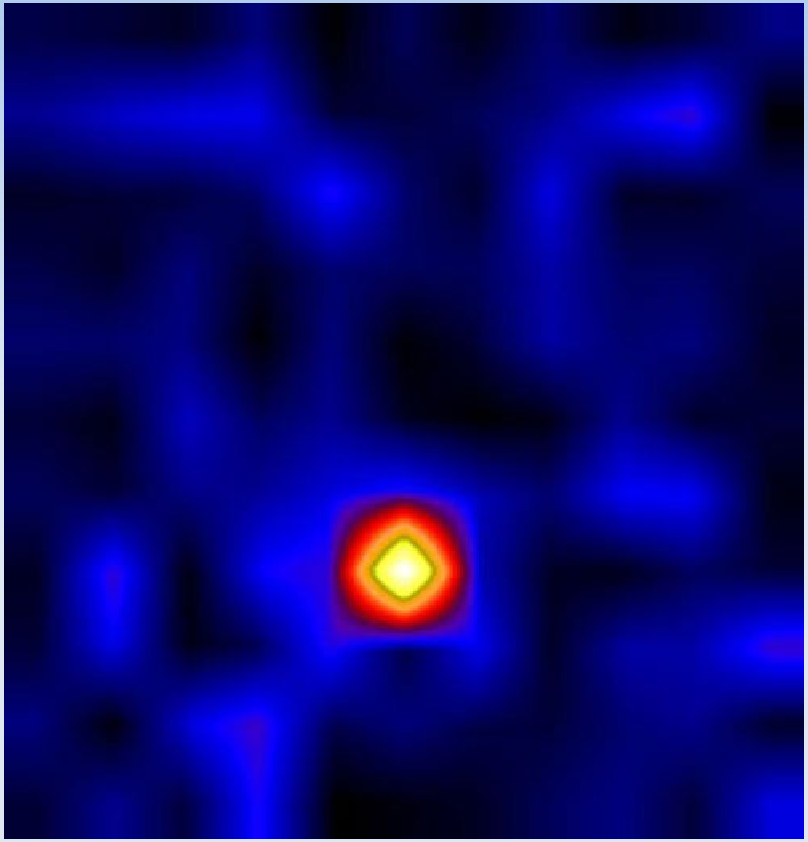
Compact Stars



Lecture 4

Summary of the previous lecture

- We have talked about the physical structure of accretion disks in X-ray binaries, process of disk formation by viscous diffusion and angular momentum transport thorugh the turbulent viscosity
- I presented the fundamental equations of hydrodynamics: the mass and angular momentum conservation.
- For the case of thin, stationary, axisymmetric disk, I derived the rate of local energy dissipation by the viscous stress.
- The radial dependence of black body temperature in the disk gives the characteristic shape of emitted radiation spectrum
- The accretion efficiency is much greater than for the nuclear fusion

Alpha-disks in X-ray binaries

- I will show the observational properties of accreting compact stars in various sources
- The history of X-ray astronomy will be briefly described
- I will present the classification of XRBs, and basic evolutionary scenarios of low mass and high mass XRBs

SS73 paper

- Most known article in high energy astrophysics (11600 citations until 2023)
- 50-years anniversary session at EAS-23 in Kraków

Astron. & Astrophys. 24, 337 – 355 (1973)

Black Holes in Binary Systems. Observational Appearance

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Summary. The outward transfer of the angular momentum of the accreting matter leads to the formation of a disk around the black hole. The structure and radiation spectrum of the disk depend, mainly on the rate of matter inflow $\dot{M}$ into the disk at its external boundary. The dependence on the efficiency of mechanisms of angular momentum transport (connected with the magnetic field and turbulence) is weaker. If $\dot{M} = 10^{-9} - 3 \cdot 10^{-8} \frac{M_\odot}{\text{year}}$ the disk around the black hole is a powerful source of X-ray radiation with $h\nu \sim 1 - 10$ keV and luminosity $L \approx 10^{37} - 10^{38}$ erg/s. If the flux of the accreting matter decreases, the effective temperature of the radiation and the luminosity will drop. On the other hand, when $\dot{M} > 10^{-9} \frac{M_\odot}{\text{year}}$ the optical luminosity of the disk exceeds the solar value. The main contribution to the optical luminosity of the black hole arises from reradiation of that part of the X-ray and ultra-violet energy which is initially produced in the central high temperature regions of the disk and which is then absorbed by the low temperature outer regions. The optical radiation spectrum of such objects must be saturated by broad recombination and resonance emission lines. Variability, connected with the character of the motion of the black hole, with gas flows in a binary system and with eclipses, is possible. Under certain conditions, the hard radiation can evaporate the gas. This can counteract the matter inflow into the disk and lead to autoregulation of the accretion.

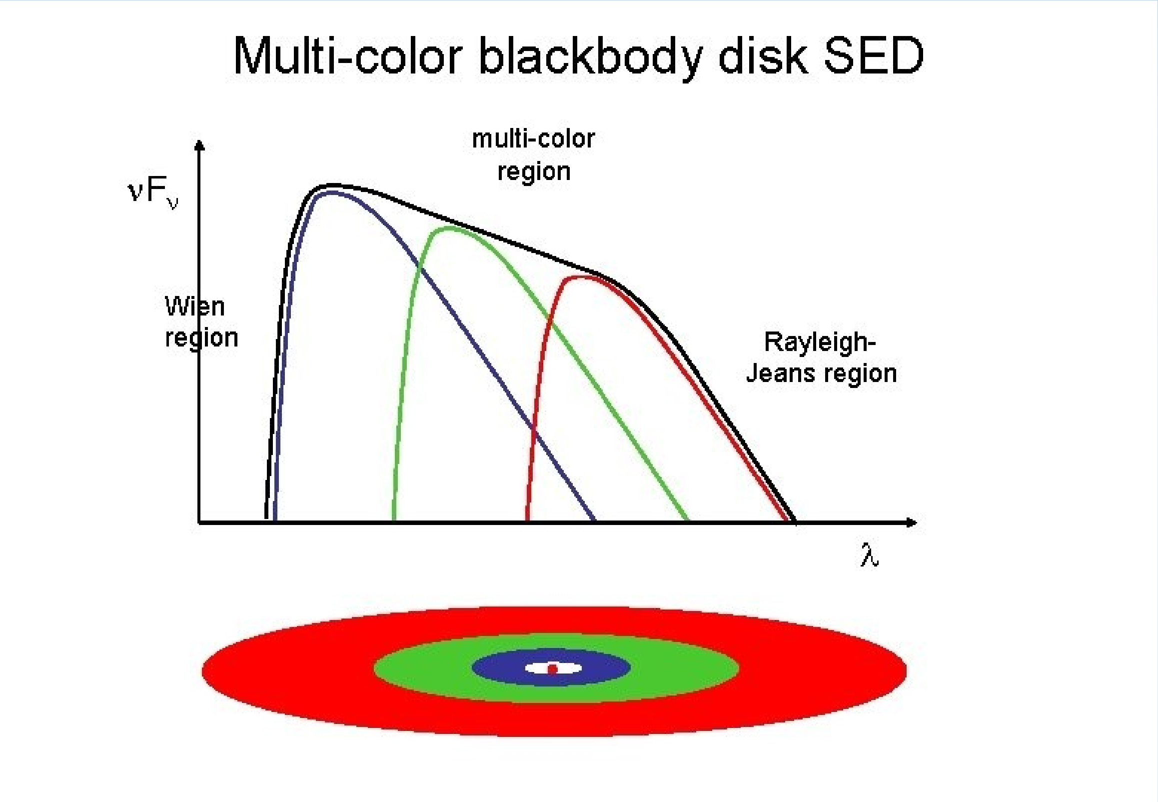
If $\dot{M} \gg 3 \cdot 10^{-8} \frac{M_\odot}{\text{year}}$ the luminosity of the disk around the black hole is stabilized at the critical level of $L \approx 10^{38} \frac{M}{M_\odot} \frac{\text{erg}}{\text{s}}$. A small fraction of the accreting matter falls under the gravitational radius whereas the major part of it flows out with high velocity from the central regions of the disk. The outflowing matter is opaque to the disk radiation and completely transforms its spectrum. In consequence, at the supercritical regime of accretion the black hole may appear as a bright, hot, optical star with a strong outflow of matter.

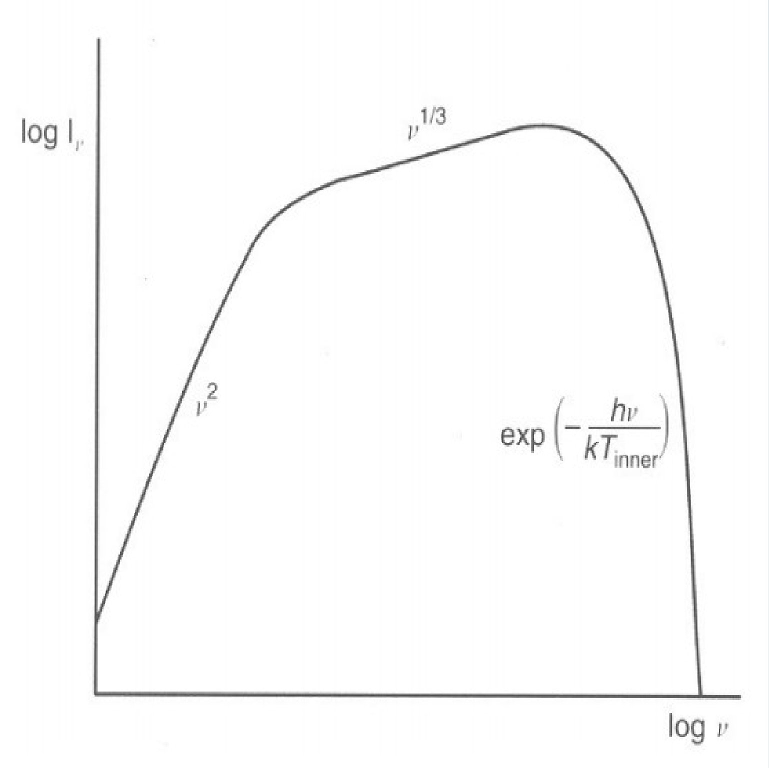
Key words: black holes – binary systems – X-ray sources – accretion

The black hole (collapsar) does not radiate either electromagnetic or gravitational waves (Zeldovich and Novikov, 1971). Therefore, it can be found only due to its gravitational influence on the neighbouring star or on the ambient gas medium (the gas must accrete with the release of large amount of energy (Salpeter, 1964; Zeldovich, 1964)).

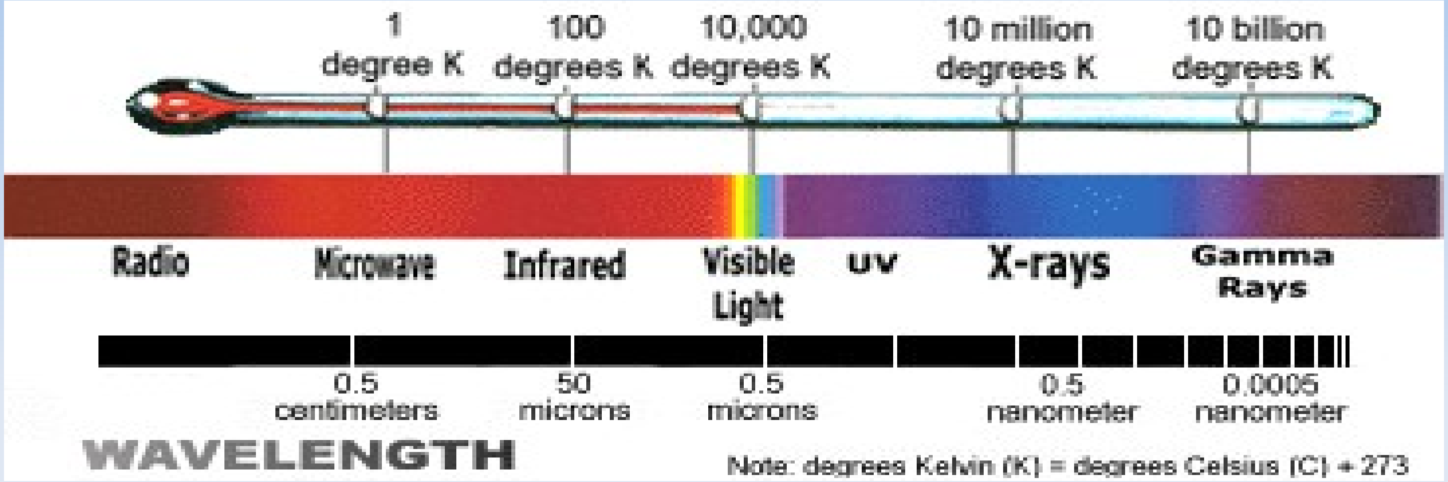
Many papers have suggested searching for collapsars in binary systems. It is often considered that the collapsar should appear as a "black" body which practically does not influence the total radiation of the system. In this paper, the attention of the reader is drawn to the case where the outflow of matter from the surface of the visible component and its accretion by the black hole should lead to an appreciable observational effect. In the system with an outflow of matter $\frac{dM}{dt} = \dot{M} > 10^{-12} \frac{M_\odot}{\text{year}}$, the luminosity of the disk around the black hole formed by the accreting matter can be comparable and even exceed the luminosity of the visible component. In a typical case most of the radiation is emitted in the spectral range of $h\nu \sim 100 - 10^4$ eV. However, as will be shown below, the optical and ultra-violet (responsible for the formation of a Strömgren region) luminosities are also high. Therefore, it is entirely possible that black holes are among the optical objects, soft X-ray sources and the harder X-ray sources now being intensively investigated. The radiation connected with accretion by black holes in binary systems has, in fact, distinctive features. However, they are not as astonishing as is usually assumed; the black holes may be hidden among known objects.

Disk black body





Radiation of the disk



- The temperature profile of the disk scales with radius as $R^{-3/4}$
- Maximum temperature: X-rays
- Wavelength λ=1-25 Å, energy $h\nu$=0.5-15 keV

Why X-rays?

- Optically thick case: the blackbody temperature is

$$T_{bb} = \left(\frac{L}{4\pi R^2 \sigma}\right)^{1/4}$$

- Optically thin case: gravitational potential enegy is turned into thermal energy

$$\frac{GM\left(m_p + m_e\right)}{R} = \frac{3}{2} k T_{th}$$

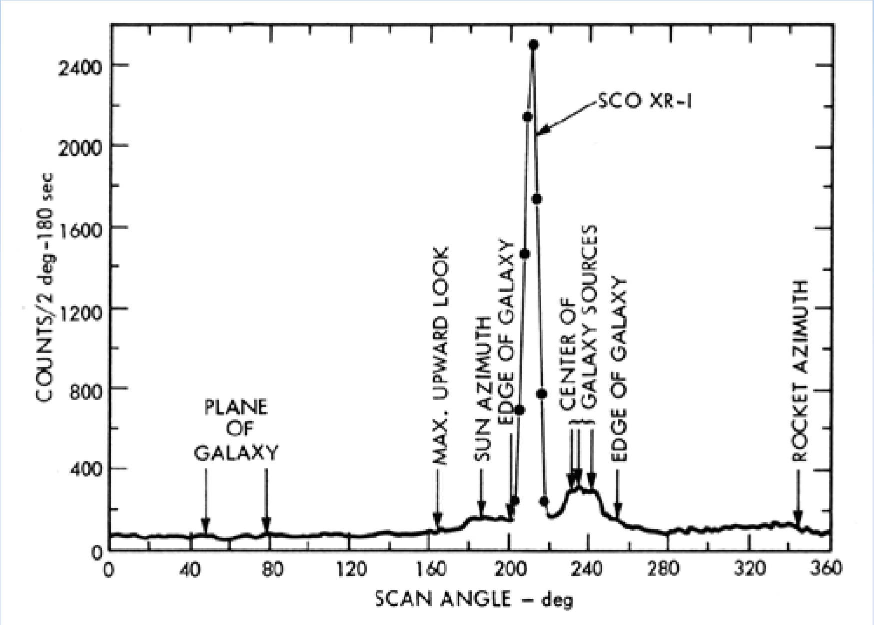
- For accreting binaries, $L \sim 10^{36} - 10^{38}$ erg/s, $R \sim 10^6$ cm. $T_{bb} < T_{rad} < T_{th}$ . . 1 keV < T_{rad} < 50 MeV . Therefore the photon frequency $h\nu$ is in X-rays.

History of X-ray astronomy

- 1054: Crab Supernova, observed by Chinese
- 1572: Supernova in Cassiopeia, observed by Tycho Brahe
- 1895: X-rays discovered by Roentgen
- 1949: detection of X-rays from the Sun
- 1962: detection of first X-ray source outside the Solar system, Scorpius X-1
- 2002: Nobel prize for Riccardo Giacconi, for his pioneering contributions to X-ray instrumentation

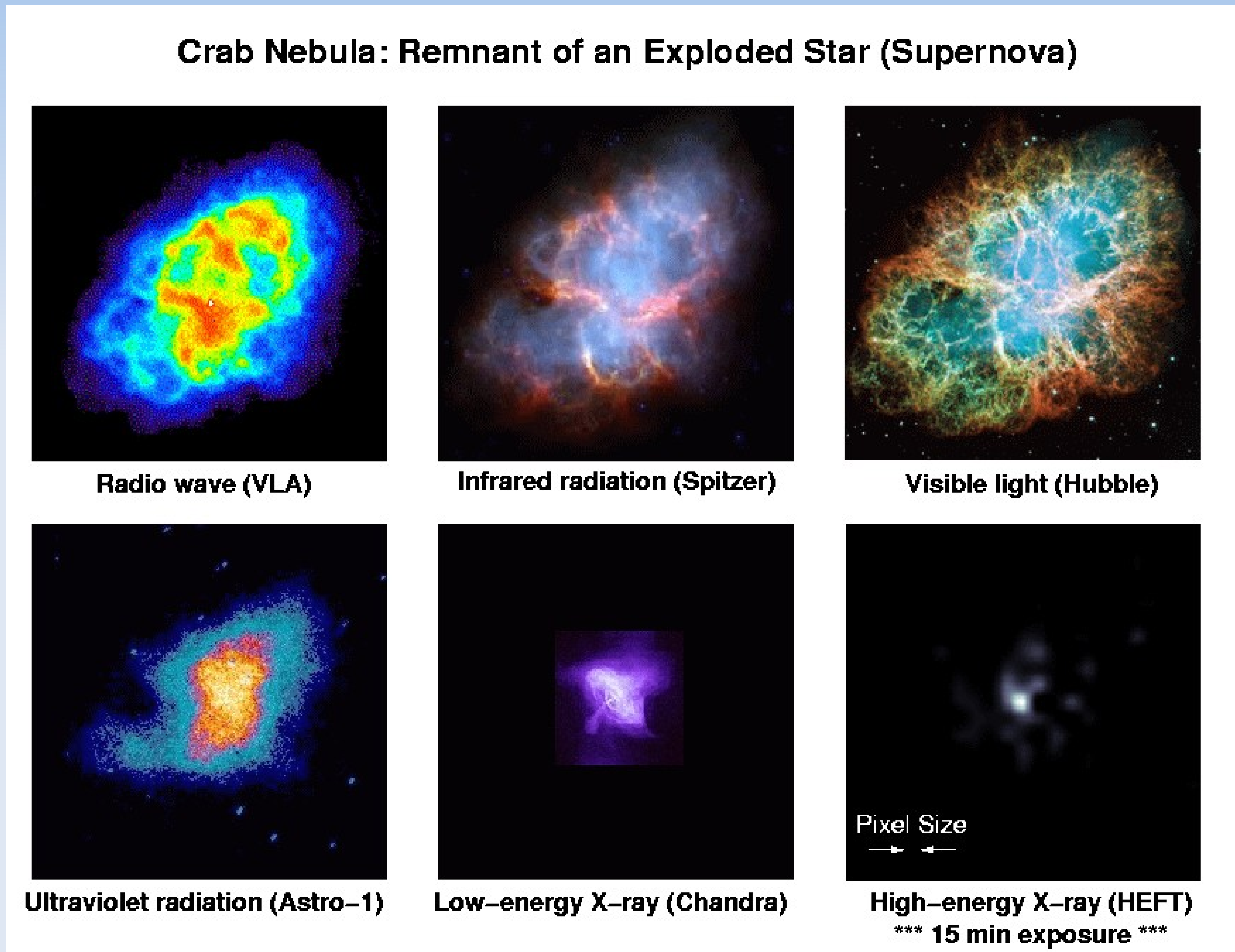
X-ray astronomy

- The first rocket flight to successfully detect a cosmic source of X-ray emission was launched in 1962 by a group at American Science and Engineering (AS&E), including scientists Riccardo Giacconi, Herb Gursky, Frank Paolini, and Bruno Rossi.
- Found a very bright source named Scorpius X-1
- It turned out to be an accreting neutron star. Its ptical counterpart is a faint star V818 Scorpii



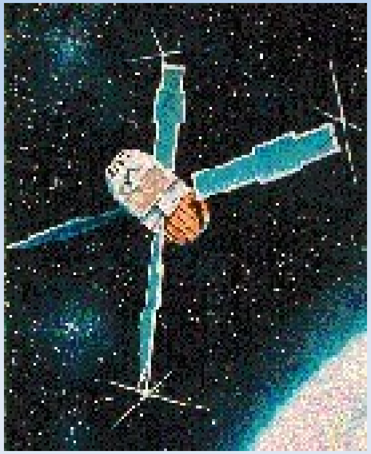
Three minutes of data from a rocket-born X-ray detector flown in October 1967. This shows the counting rate of the detector as it scanned a great circle containing the source Sco X-1 and a cluster of sources in the direction of the galactic center. The detector field of view was 5x30 degrees. The Sun was below the horizon.

Multi band observations

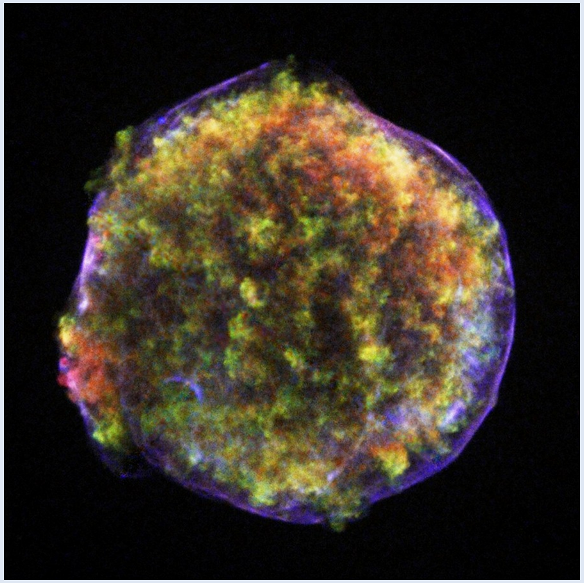


First X-ray observatories

- **Uhuru**. Worked from 1970 to 1973, first mission dedicated to X-ray astronomy. The X-ray sources are collected in the ”4U” Catalog (339 sources)



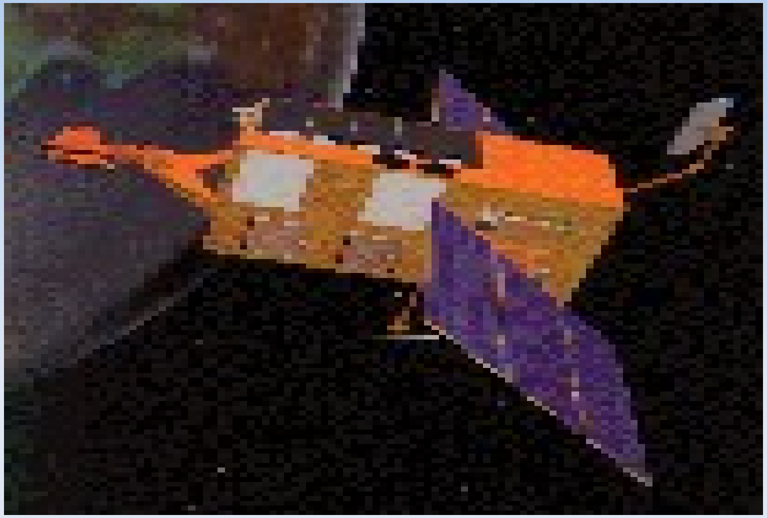
- **Einstein** (HEAO-2). Worked from 1978 to 1981. First X-ray imaging telescope in space, sensitive in 0.2-20 keV. Discovered supernova remnant

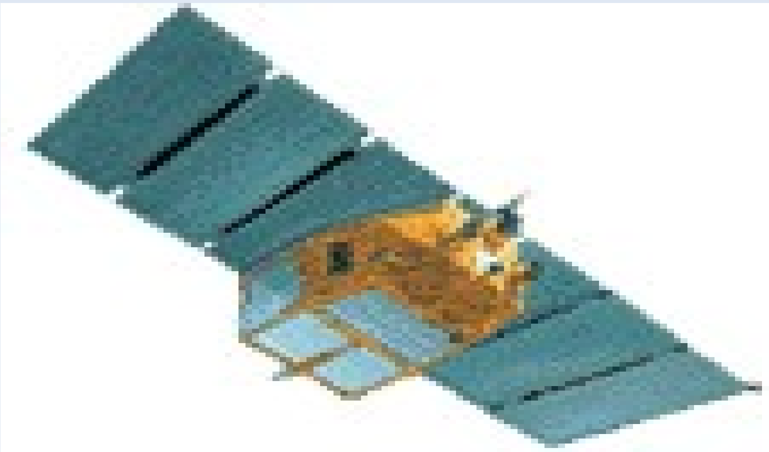


- **ROSAT**. 1990-1999. Collected over 150,000 sources in the All-sky survey catalog. Detected isolated neutron stars and showed morphology of supernova remnants.

X-ray observatories

- **ASCA**. 1993-2001. First used CCD detectors for X-rays
- **Beppo SAX**. 1996-2003. Sensitive from 0.1 to 300 keV. Provided first accurate positions of gamma ray bursts.
- **Chandra**. Launched by NASA in 1999. Studied 100 times fainter sources than other instruments
- **XMM-Newton**. ESA mission, from 1999. Large effective area; the catalog contains over half million sources.



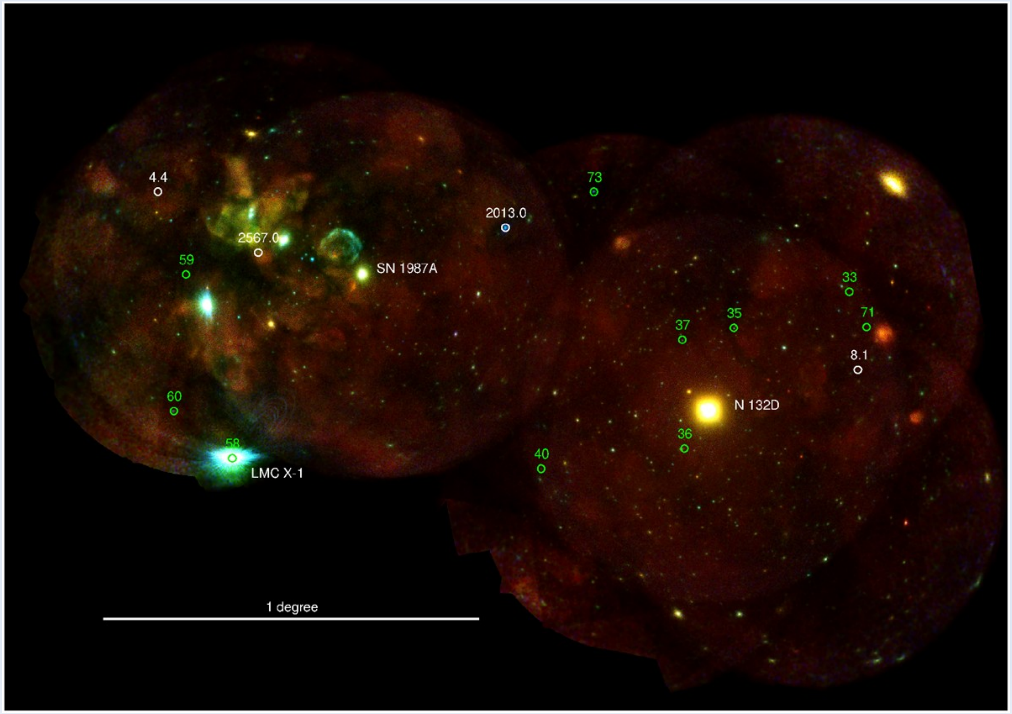


X-ray observatories

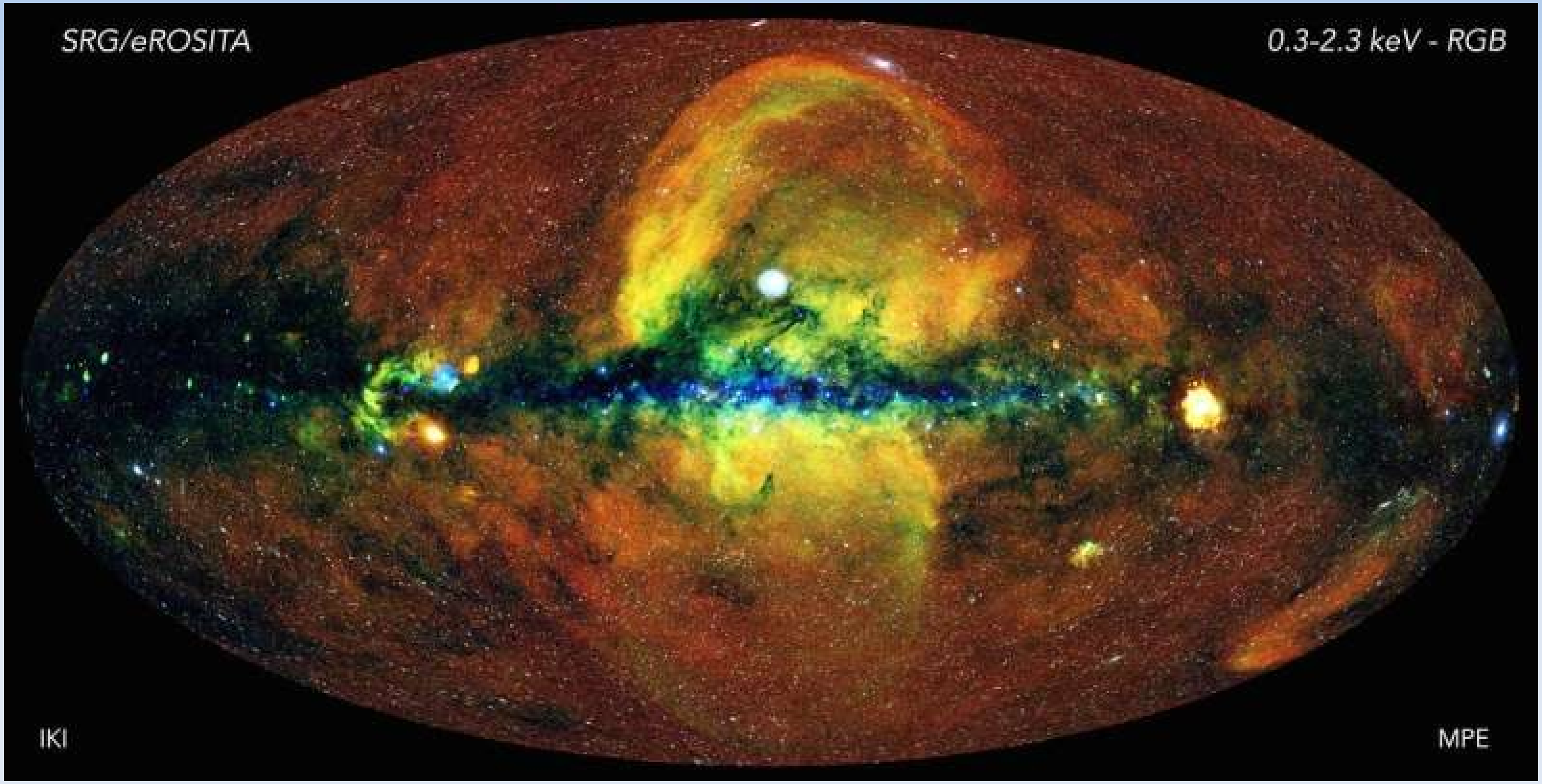
- **CGRO** – Compton Gamma Ray observatory. Sensitive in 30 keV – 30 GeV. Studied gamma ray bursts, Al^{26} map of the Galaxy
- **RXTE** – worked from 1995 to 2012. Observed pulsars and X-ray binaries. Followed by **NICER**
- **Fermi** – gamma ray telescope, launched in 2008. Contains 2 detectors, LAT and GBM, sensitive in 20 MeV – 300 GeV band and down to 10 keV
- **Suzaku** (Astro E2) – JAXA/NASA mission, worked in 2005-2015, deactivated
- **Swift –** dedicated to gamma ray bursts, and their X-ray afterglows

Recent X-ray observatories

- **NuSTAR**, launched in 2013, is dedicated to observing hard X-rays and seeking out black holes and other collapsed stars in our galaxy, mapping material in young supernova remnants, and studying relativistic jets in active galactic nuclei.
- **eROSITA**, the soft X-ray instrument on board the Spektrum-Roentgen-Gamma (SRG) mission, was successfully launched from Baikonur on July 13, 2019.



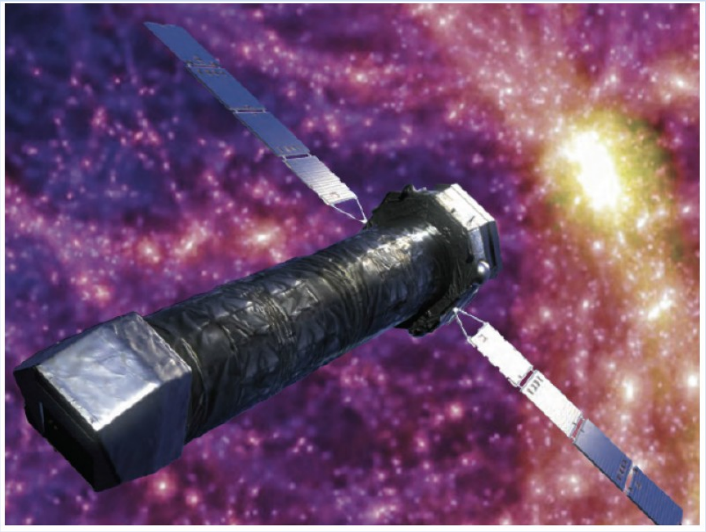
eROSITA survey



This first complete sky image from eROSITA is about four times deeper than the previous all-sky survey by the ROSAT telescope 30 years ago, and has yielded around 10 times more sources: about as many as have been discovered by all past X-ray telescopes combined.

Future observatories

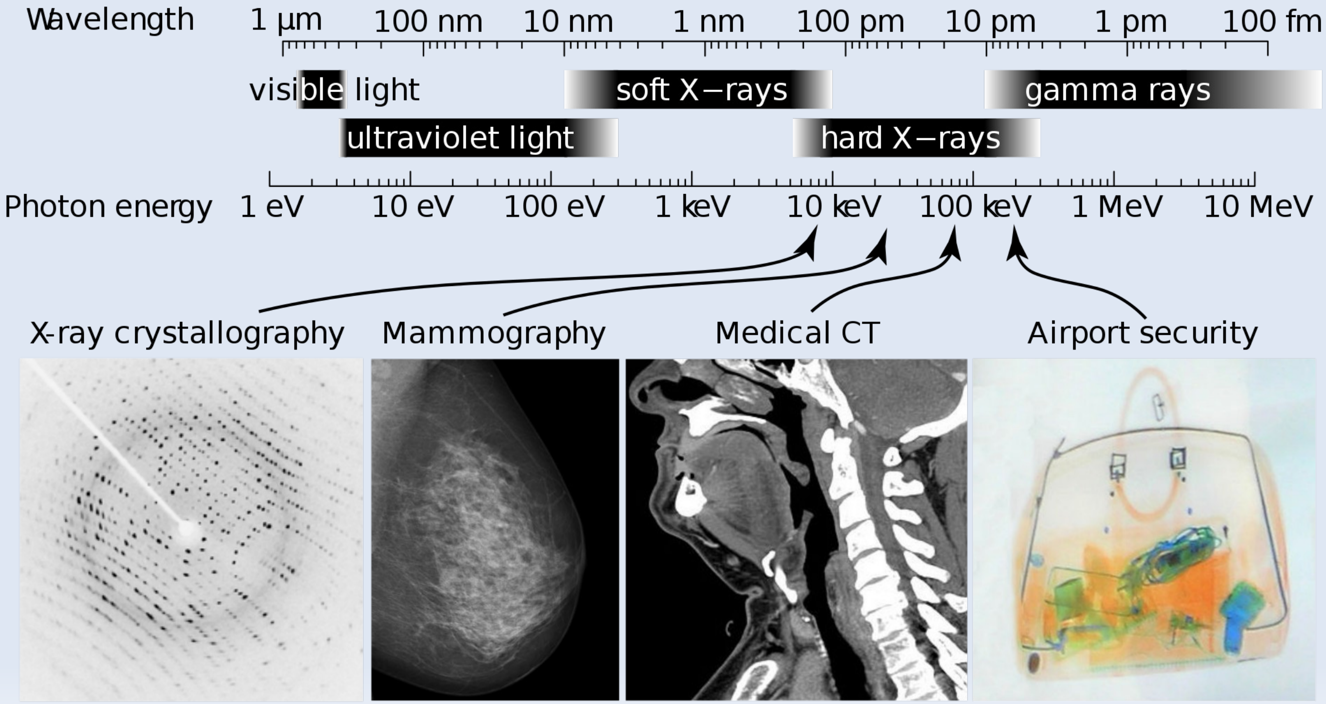
Athena+ planned by NASA/ESA



- Athena has been conceived as a powerful X-ray observatory with an unprecedented combination of collecting area, survey capabilities and energy resolution. It will be operated as an open observatory.
- At the June 2014 meeting of ESA Science Programme Committe, Athena was selected as the mission for the 2nd Large mission opportunity. While Athena was selected to address the Cosmic Vision theme of the "Hot and Energetic Universe", it is posed to have a transformational impact on most areas of modern astrophysics. Its performance well matches those of large ground-based and space-borne observational facilities to be operational in the decade of the 2030s. Athena shall also provide a key contribution to multi-messenger astrophysics, in synergy with gravitational wave arrays and neutrino telescopes.
- After 8 years of Phase A and Phase B1, the meeting of the ESA Science Program Commitee in June 2022 deliberated that Athena will not be adopted, because the estimated Cost-at-Completion to ESA exceeds the budget allocated for an L-class mission. The mission is therefore undergoing a design-to-cost exercise, aiming at defining a profile consistent with a strict cost cap while preserving its flagship nature.

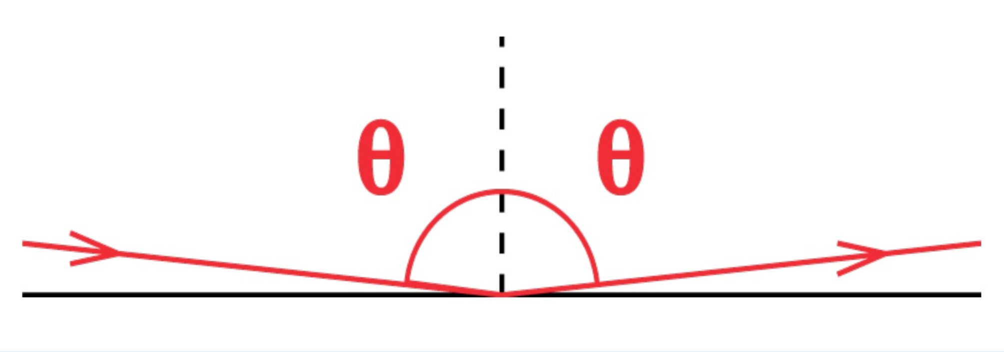
X-ray detection

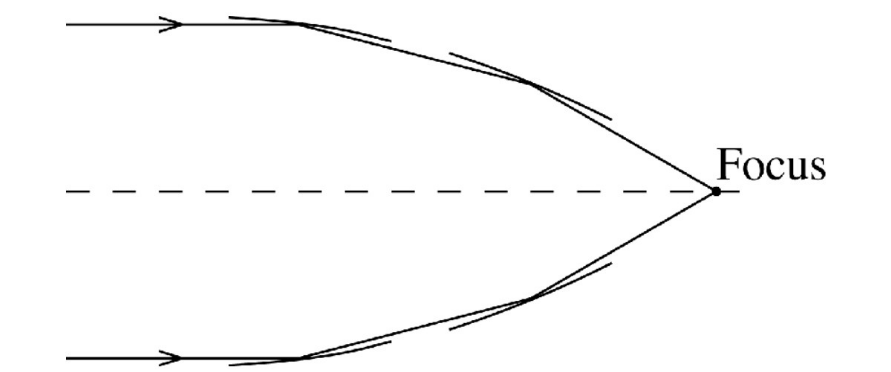
- X-rays span 3 decades in wavelength (~8 nm - 8 pm), frequency (~50 PHz - 50 EHz) and energy (~0.12 - 120 keV). In terms of temperature, 1 eV = 11,604 K. Thus X-rays (0.12 to 120 keV) correspond to range 1.39×10^6 - 1.39×10^9 K.
- From 10 to 0.1 nm (about 0.12 to 12 keV) they are classified as soft X-rays, and from 0.1 nm to 0.01 nm (about 12 to 120 keV) as hard X-rays.

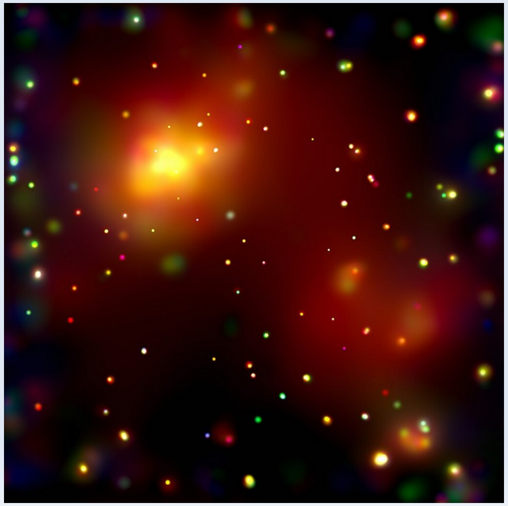


X-ray telescopes

- Hard X-rays are energetic enough to pass through normal mirrors.
- Grazing incidence reflection can be used for soft X-rays. Incident angles very small, $\theta > 89$ deg.
- X-rays are brought to focus, by successive grazing reflection

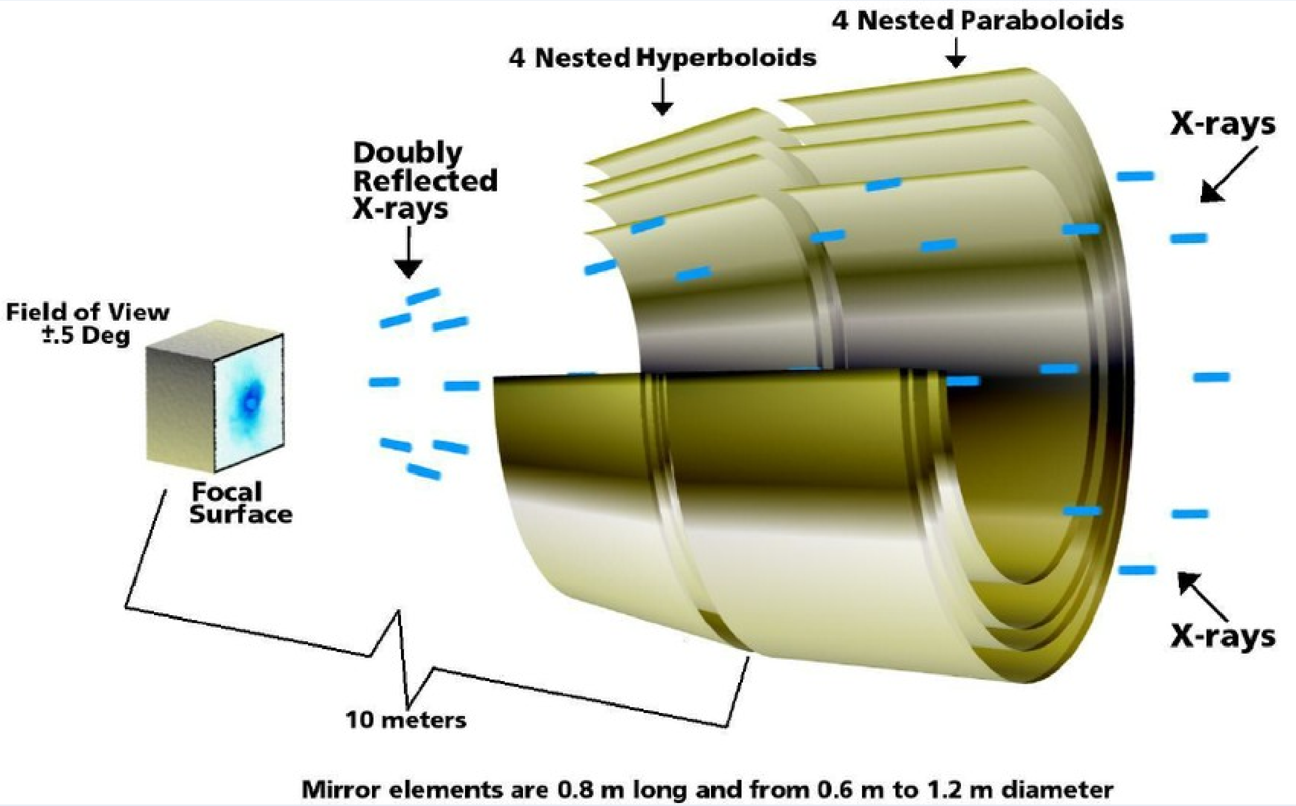






X-ray telescopes

- Effective area of Wolter mirror is small, due to smal incidence angles.
- Several nested mirrors can be used, to improve performance.



Chandra telescope

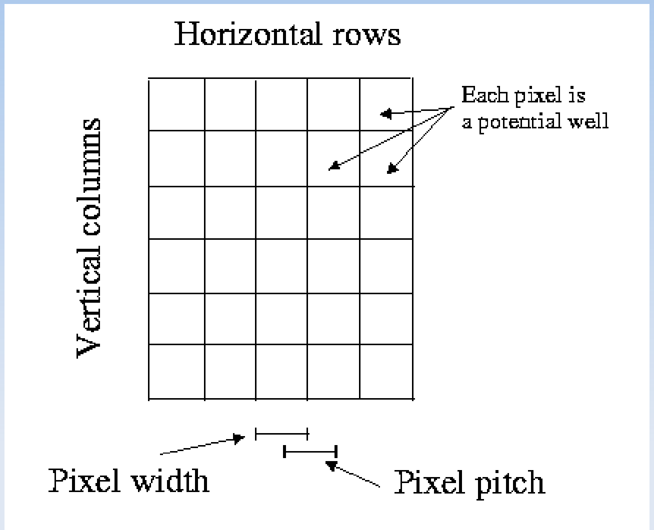
X-ray detectors

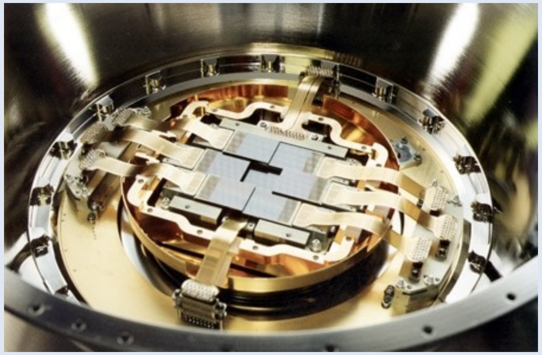
- **Imaging**
  - Used in optical, UV and Soft X. Have spatial resolution. E.g. Charged couple devices (CCDs)

    How images are formed: Wolter telescopes (up to ~15 keV), coded mask telescopes (above that)
- **Non-imaging**
  - Capable of detecting photons from a source but without any spatial resolution. Need collimators to limit their field of view. E.g. Proportional counter arrays, scintillators

CCD camera

- Standard device in astronomy. Consists of semi-conductors, where electrons are excited via photo-electric effect to an upper energy band.
- Electrons are stored near the electrodes, where their charge is added, if more photons arrive. Charges are transferred along a row. This proceeds until readout.
- Device is built from pixels, typically 2048x2048. Their arrays used to record position, energy, and time of each photon.
- In X-ray telescope, every pixel can receive 1 or 0 photons, due to low flux per unit time. Longer exposure is needed, which limits the time resolution

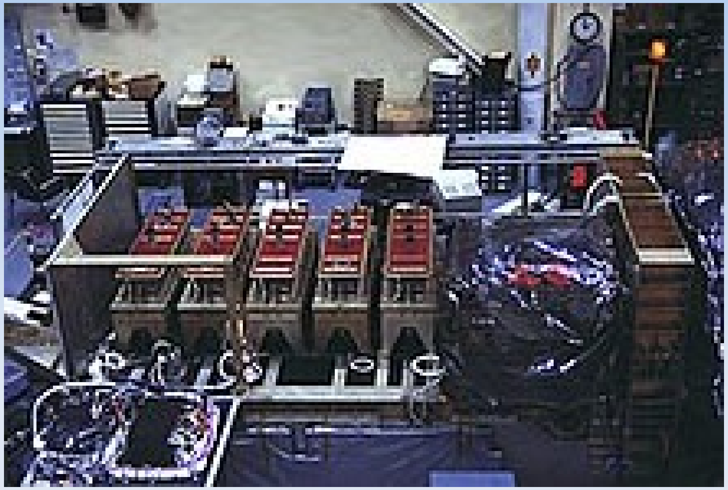




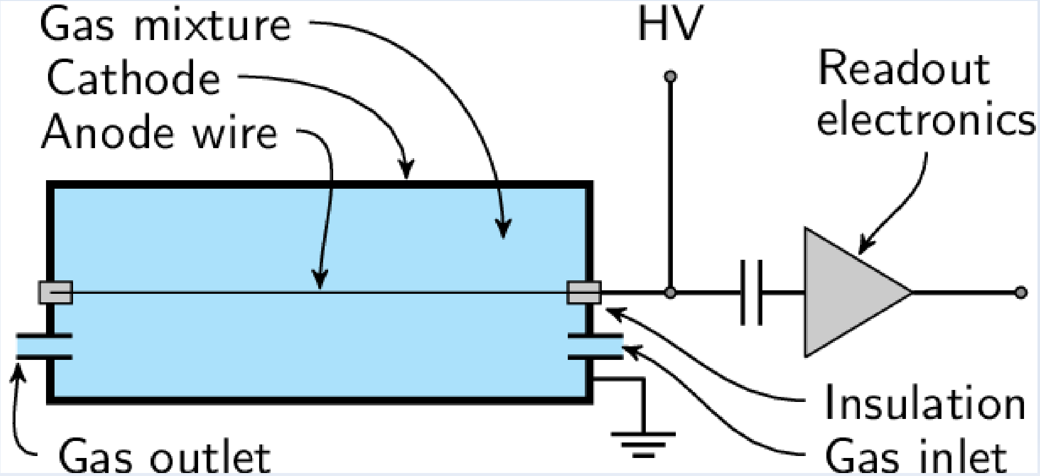
EPIC-MOS array of CCDs on XMM-Newton

Proportional counters

- Proportional counter is a type of gaseous ionization detector used to measure particles of ionizing radiation.
- The key feature is its ability to measure the energy of incident radiation, by producing a detector output pulse that is proportional to the photon energy absorbed by the detector due to an ionizing event.



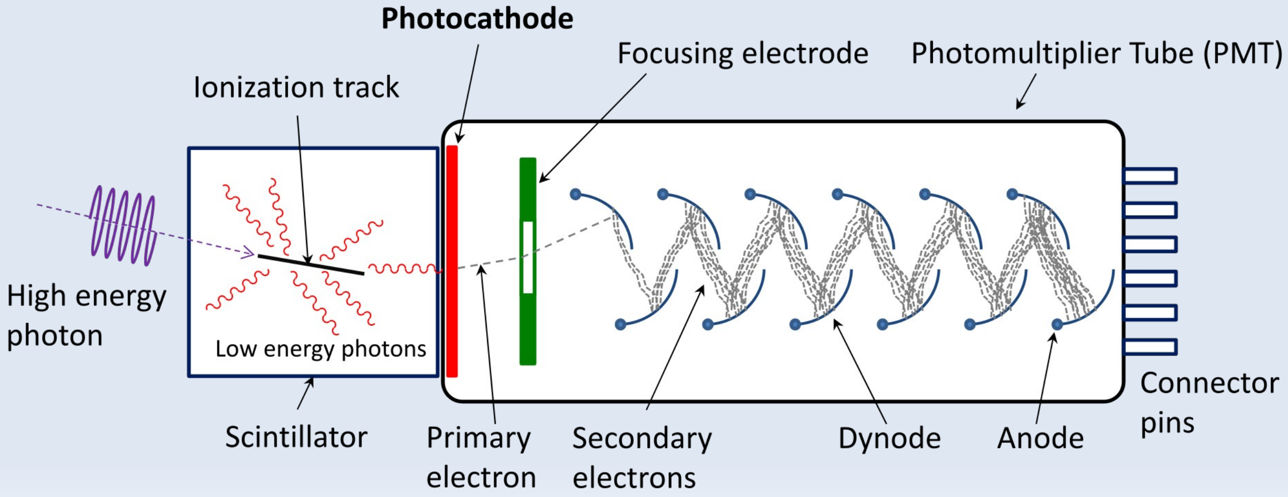
RXTE PCA array



Strong and time-varying background is present in the detector, due to high energy particles in atmosphere (e.g, SAA)

Scintillation detectors

- In scintillators, ionizing particle deposits energy and generates scintillation light
- Light scatters in detector, and is amplifed in the photo-multiplier
- Example materials: NaI, CsI
- Example device: High Energy X-ray Timing Experiment (HEXTE)



Formal data analysis

- Finite resolution of X-ray detector has major implications for data analysis. The measurement process is described as:

$$N_{ph}(c) = \int_0^\infty A(E)\,R(c,E)\,F(E)\,dE$$

  - $N_{ph}(c)$ – source count rate at channel c
  - F(E) – source photon flux density
  - A(E) – effective area
  - R(c,E) – detector response, i.e. probability of detecting photon of energy E in channel c
- To analyze data we need to discretize this over energy, account for background, and uncertainty (Poisson noise)

Formal data analysis

- To get the measurement, we must find F(E)
- The count rate formula is invertible.
- We must use a model of the spectrum, and calculate predicted model counts, via minimizing the Chi-2. This is done by varying x vector of model parameters (like power law index, black body temperature, etc.)

$$\chi^2(x) = \sum_c \frac{\left(S_{ph}(c) - M(x,c)\right)^2}{\sigma^2}$$

where $S_{ph}(c) = N_{ph}(c) - B(c)$ is background subtracted estimated source count rate, M(x,c) is the model spectrum, and $\sigma=(S_{ph}(c)+B(c))^{1/2}$ is the uncertainty

Example fitting

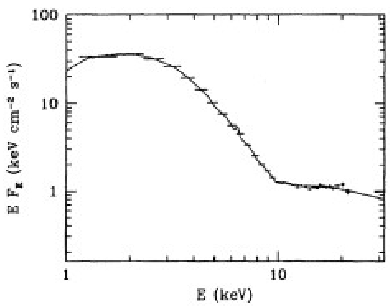


FIGURE 2. Spectrum of Nova Muscae in the high state (14 Feb 1991). The solid curve is the spectrum computed in disc-corona model and data are indicated by crosses.

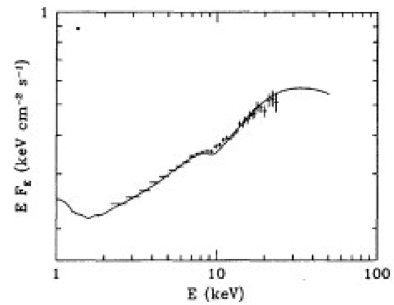
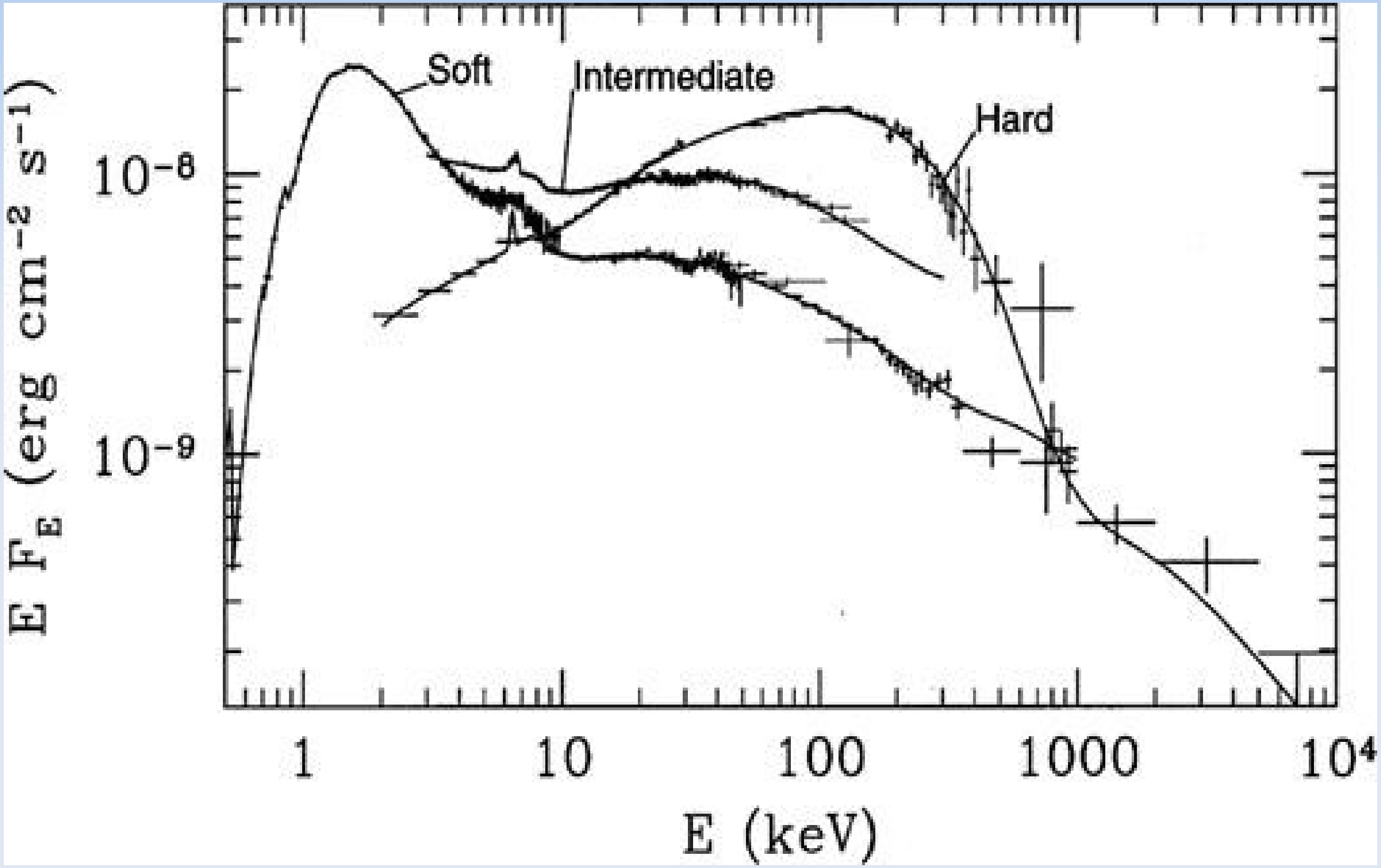


FIGURE 3. Spectrum of Nova Muscae in the low state (21 Jul 1991). The solid curve is the model spectrum and data are indicated by crosses.

Two spectral fits to data of BH X-ray binary, Nova Muscae 1991, observed by ASCA.
Model consists of disk black body spectrum, absorbed partially in the intergalactic medium, plus Comptonized tail, and reflection component. (Janiuk, Czerny, Życki, 1999, ApLC, 38, 277)

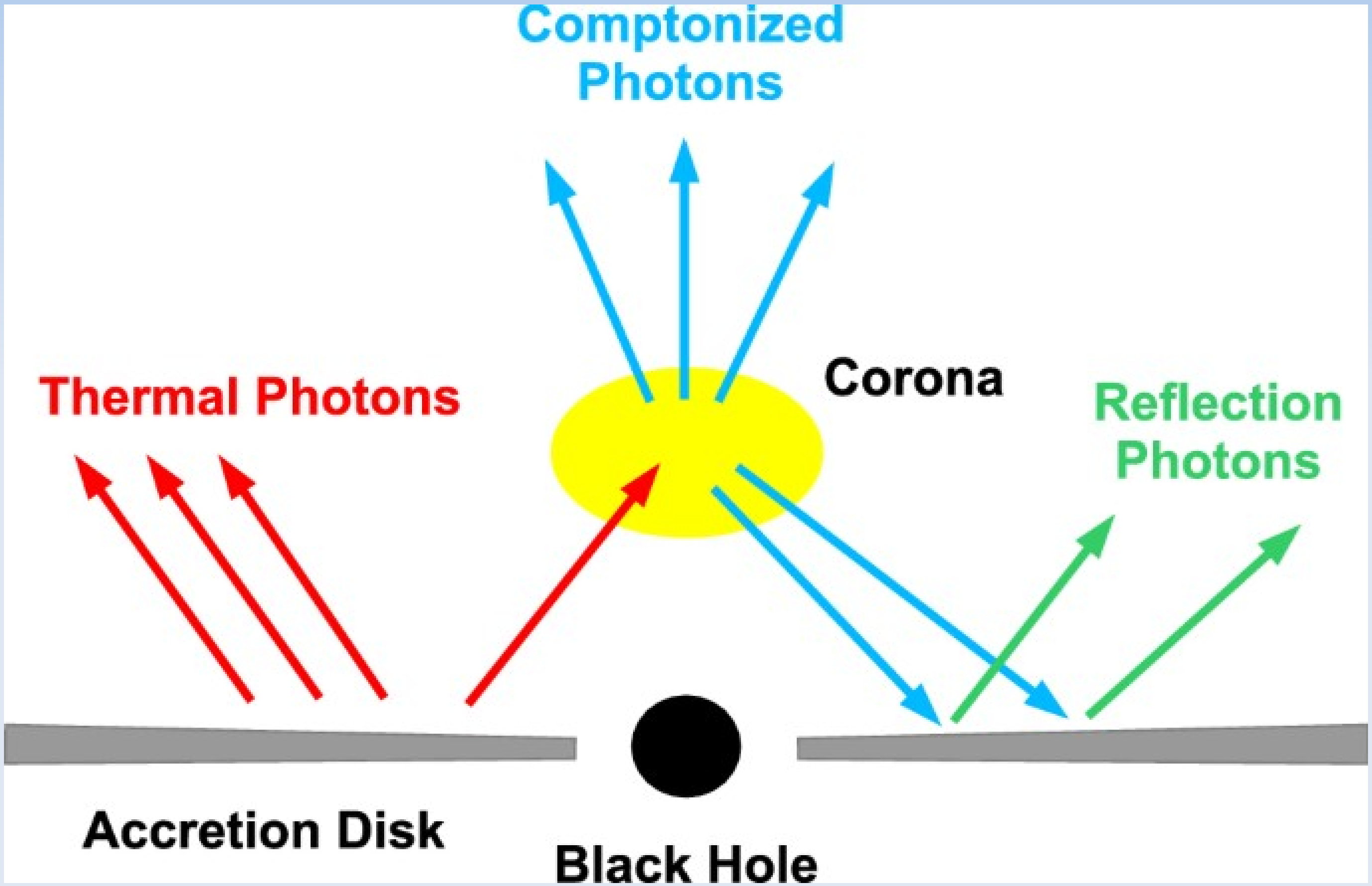
Break

Spectra of Cygnus X-1



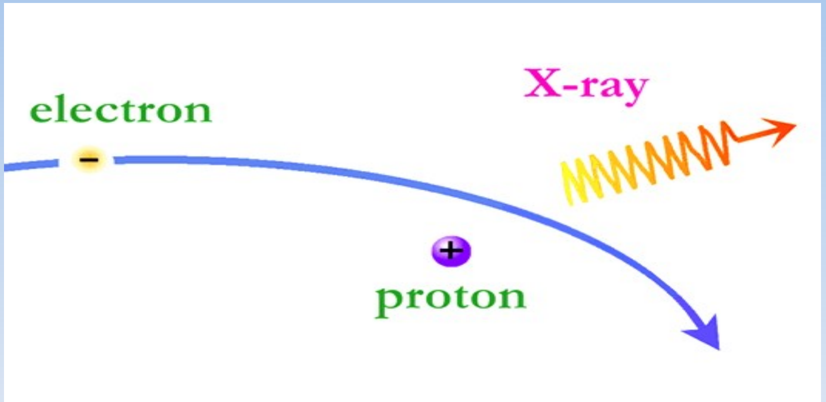
M. Gierliński et al. 1997

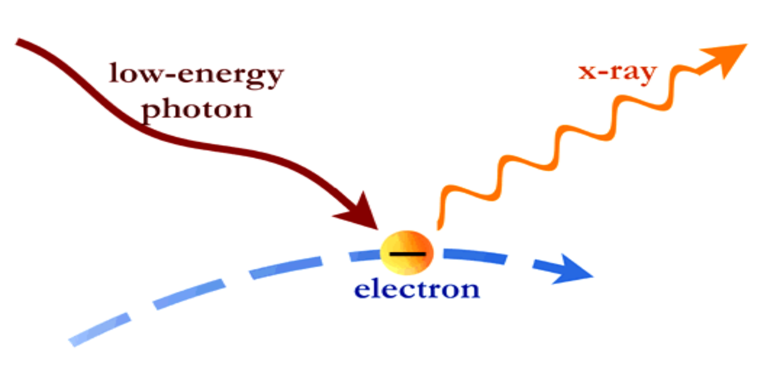
Origin of components in the spectrum

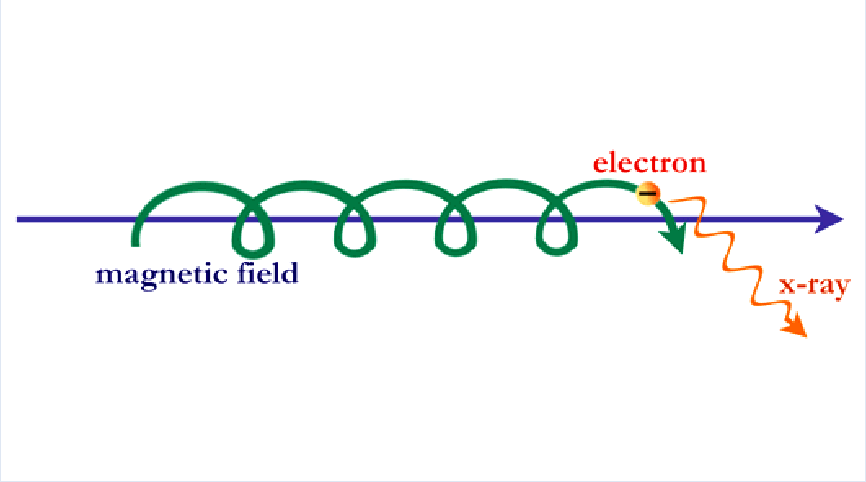


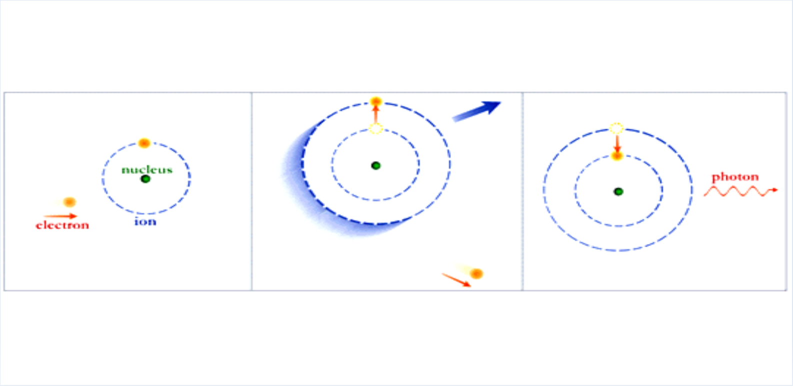
Mechanisms of hard X-ray emission

- Bremsstrahlung
- Compton upscattering
- Synchrotron
- Atomic emission



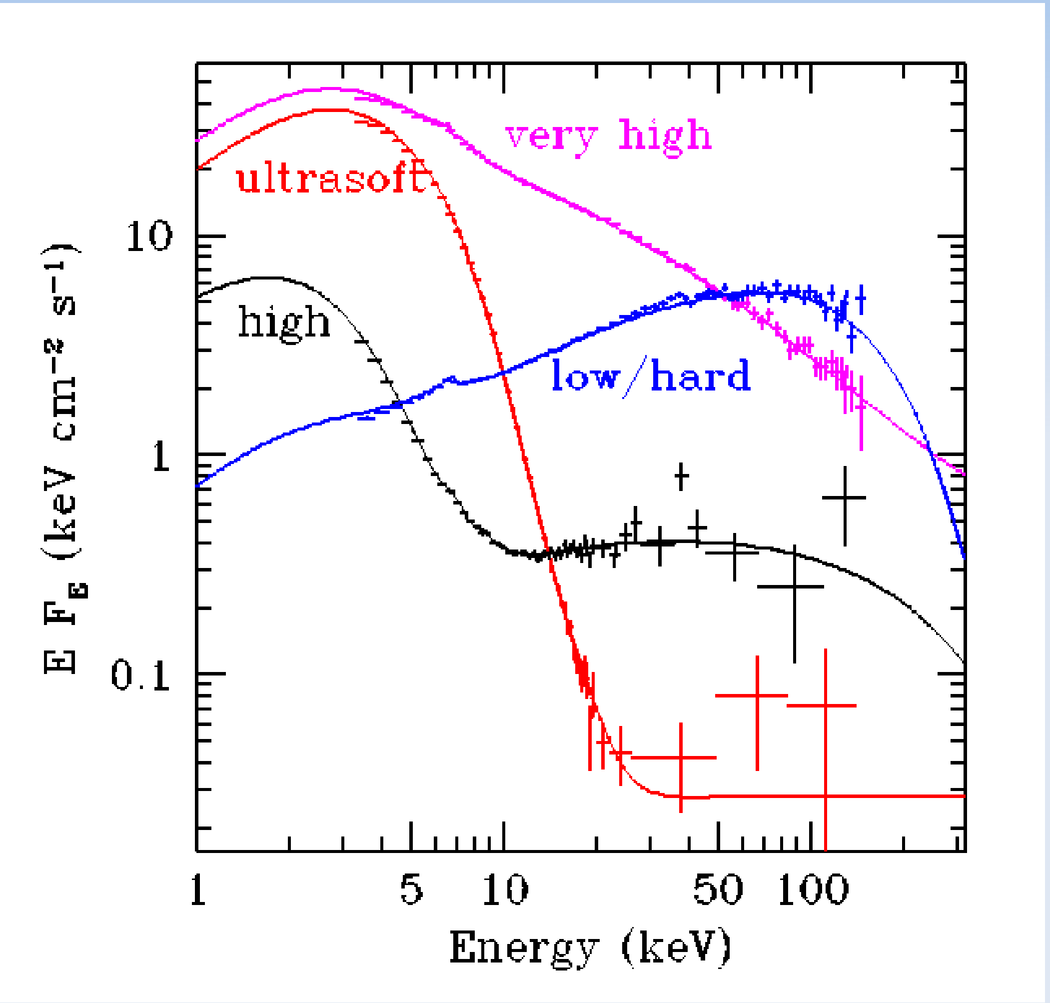




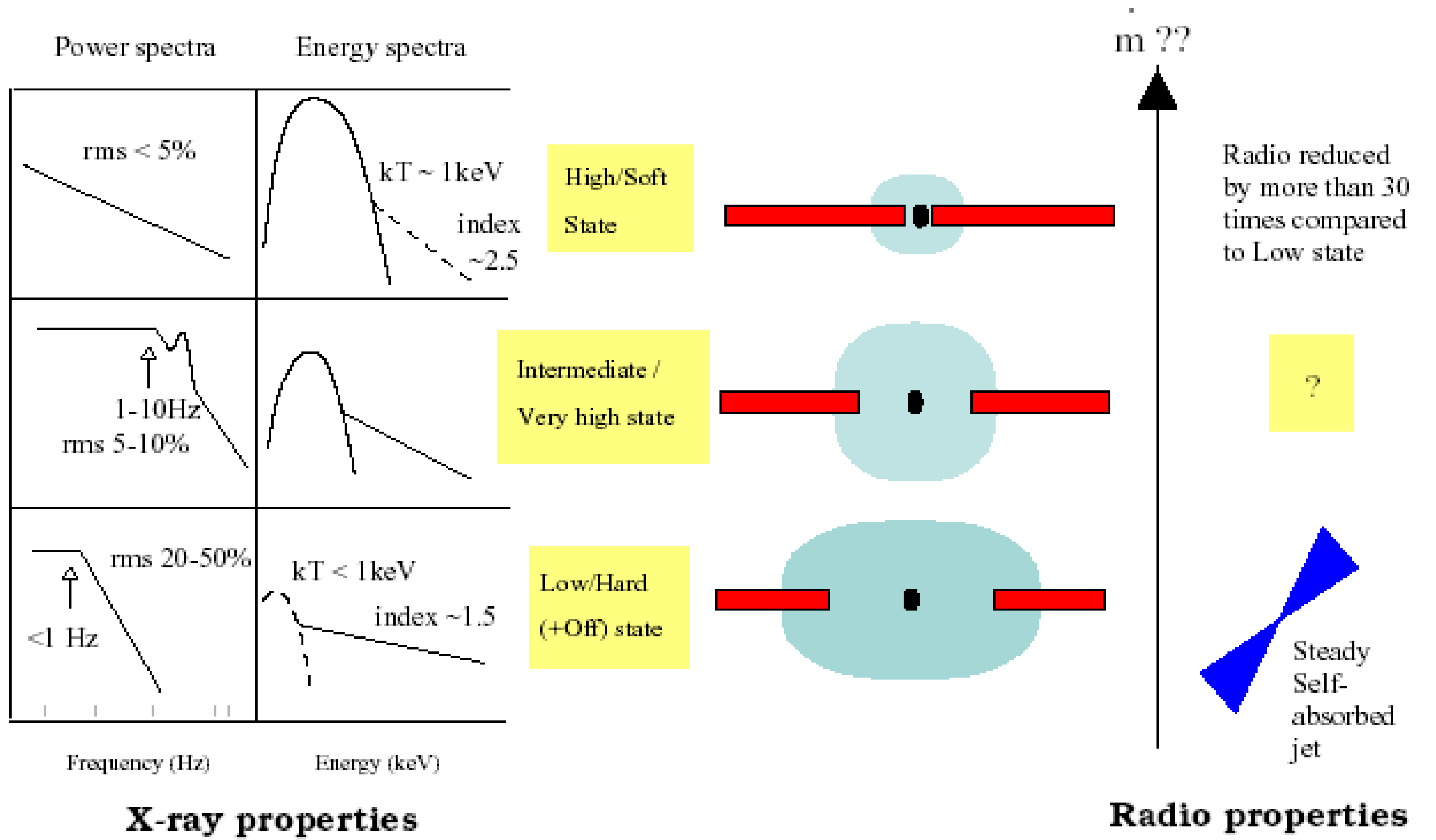


State transitions

- Spectra composed of disk black body component and power-law tail
- Hard X-rays possibly originate in a separate medium, i.e. Corona above the disk

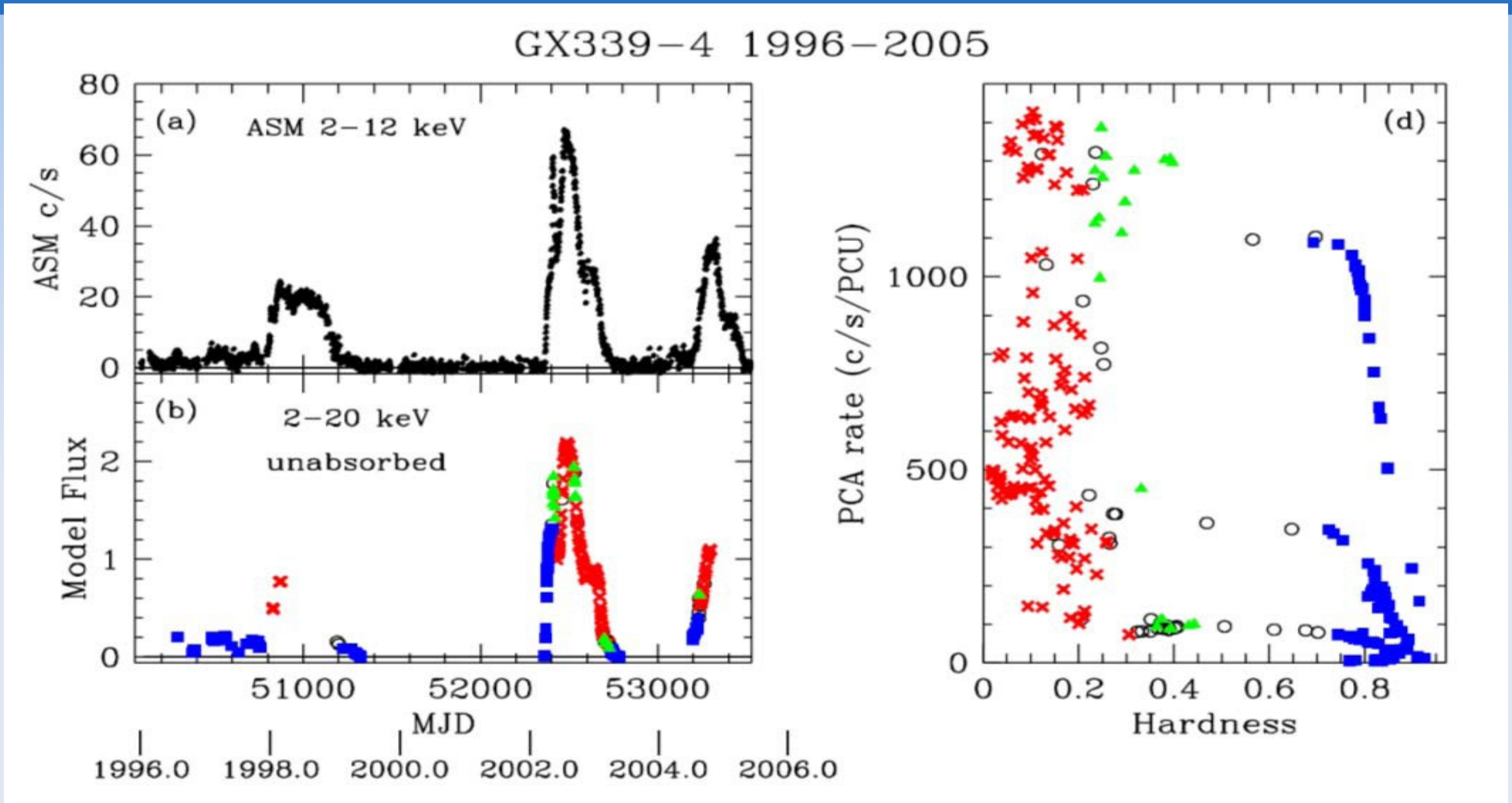


State transitions



Fender 2000

Hysteresis effect

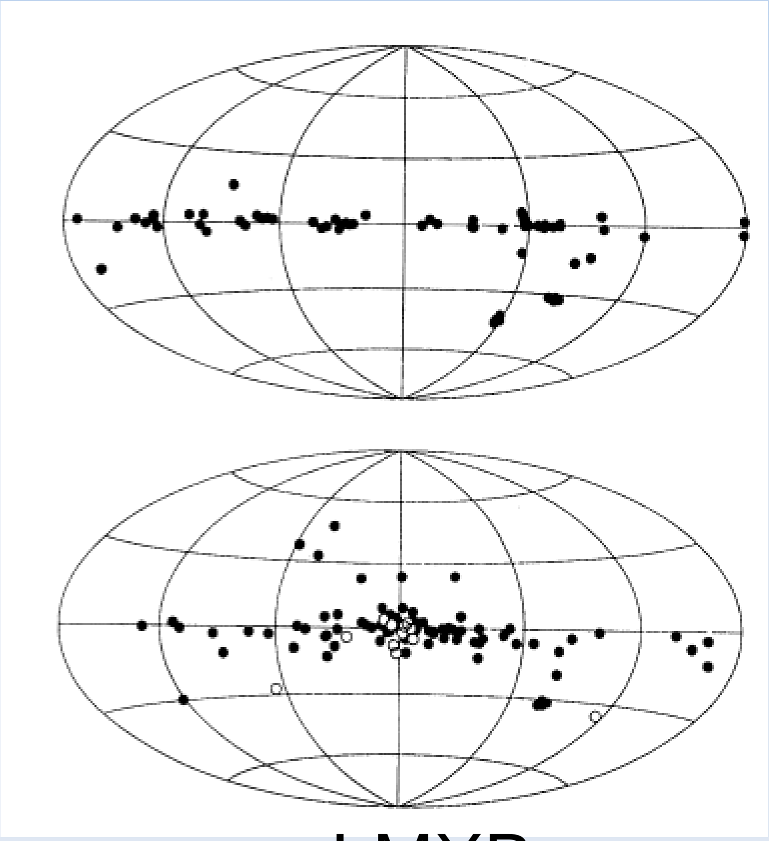


- Hard->soft transition is made at much higher luminosity than soft-> hard

High and Low mass X-ray Binaries

- Contain Galactic bulge X-ray sources, X-ray bursters, soft X-ray transients
- Numerous sources are in globular clusters
- Observed properties may depend on the viewing angle: X-ray dips, eclipses

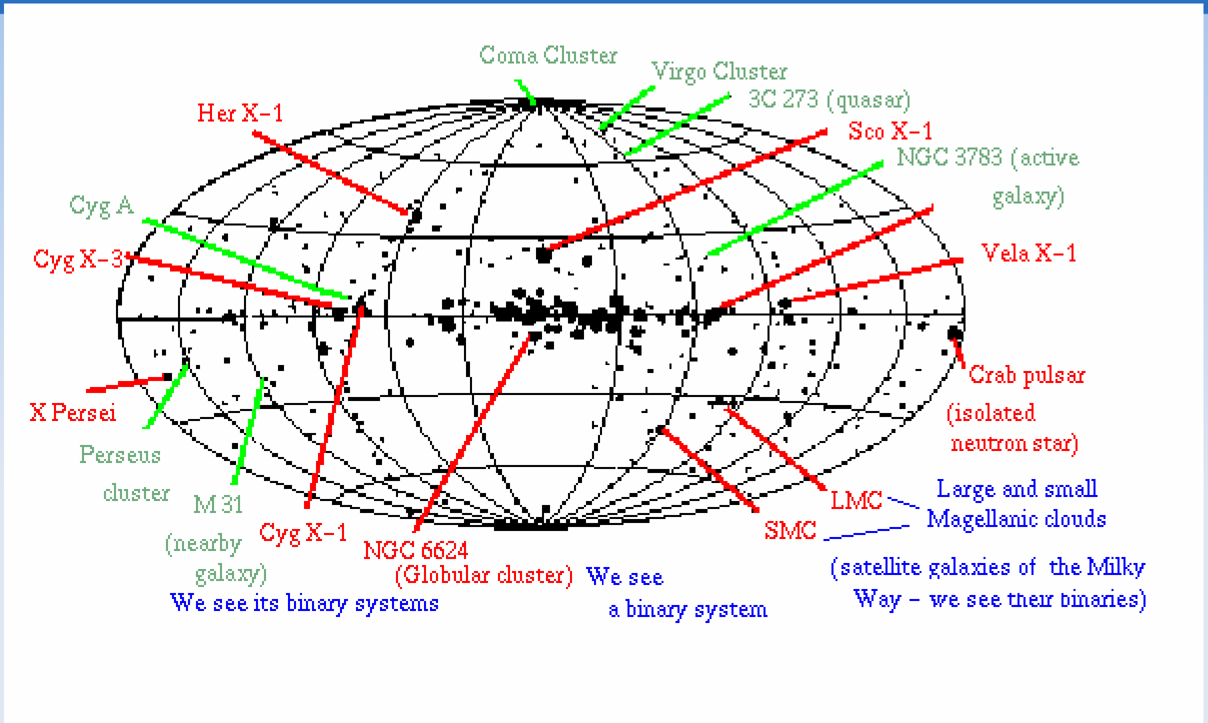
HMXBs



LMXBs

Galactic distribution of HMXBs (top) and LMXBs (bottom). Open circles indicate LMXBs in globular clusters (From van Paradijs 1998)

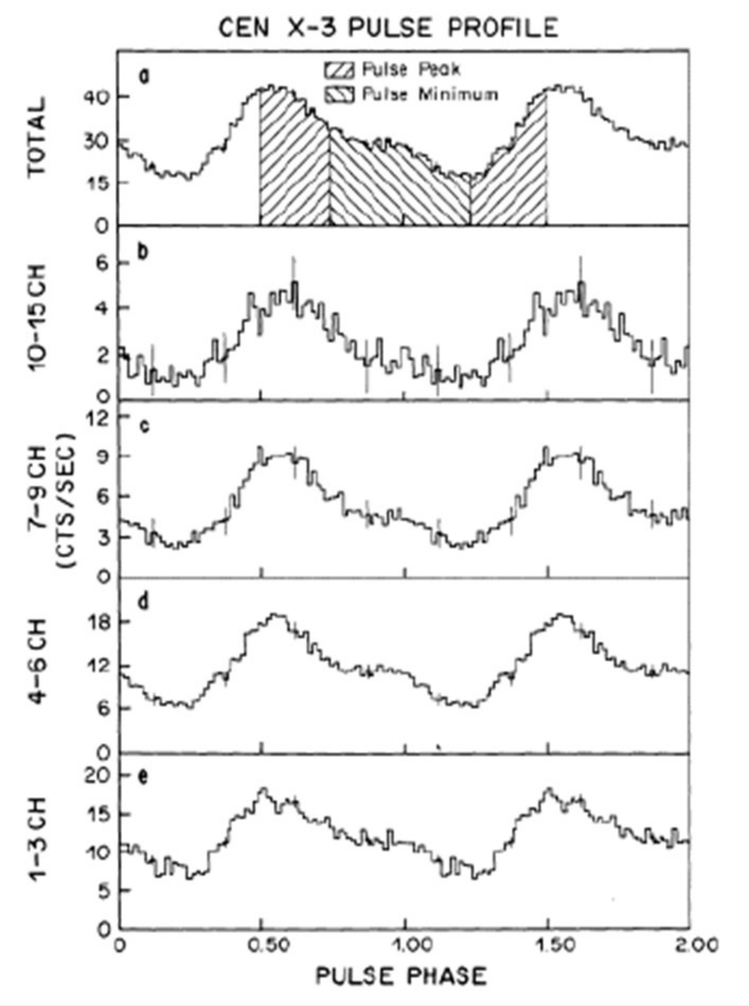
X-ray binaries in the Universe

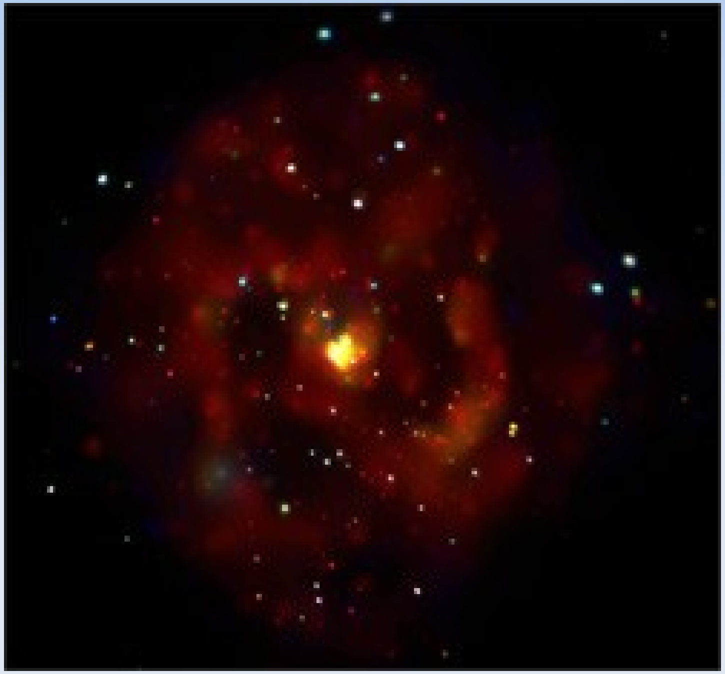


All sky map from Uhuru

- More than 300 X-ray binaries in the Galaxy, with luminosities $10^{34} - 10^{38}$ erg/s
- Galactic plane, center, globular clusters
- Some in other galaxies (LMC, SMC)

Galactic and extragalactic sources



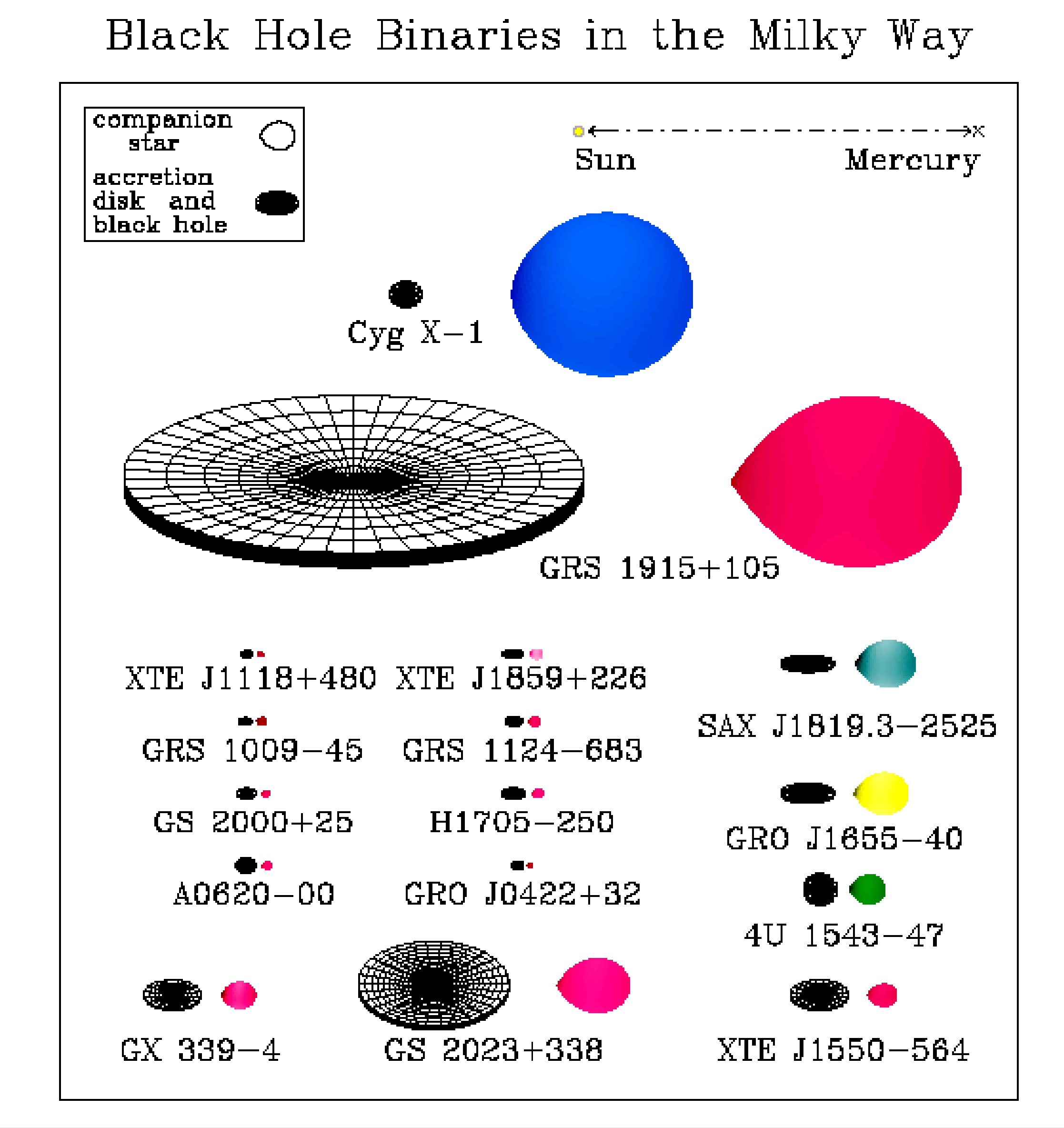


Chandra image of M83 with point-like NS and BH X-ray sources

X-ray binary Cen X-3, discovered in 1971.
Orbital modulation of 2.08 days, neutron star pulsations with 4.84 sec.

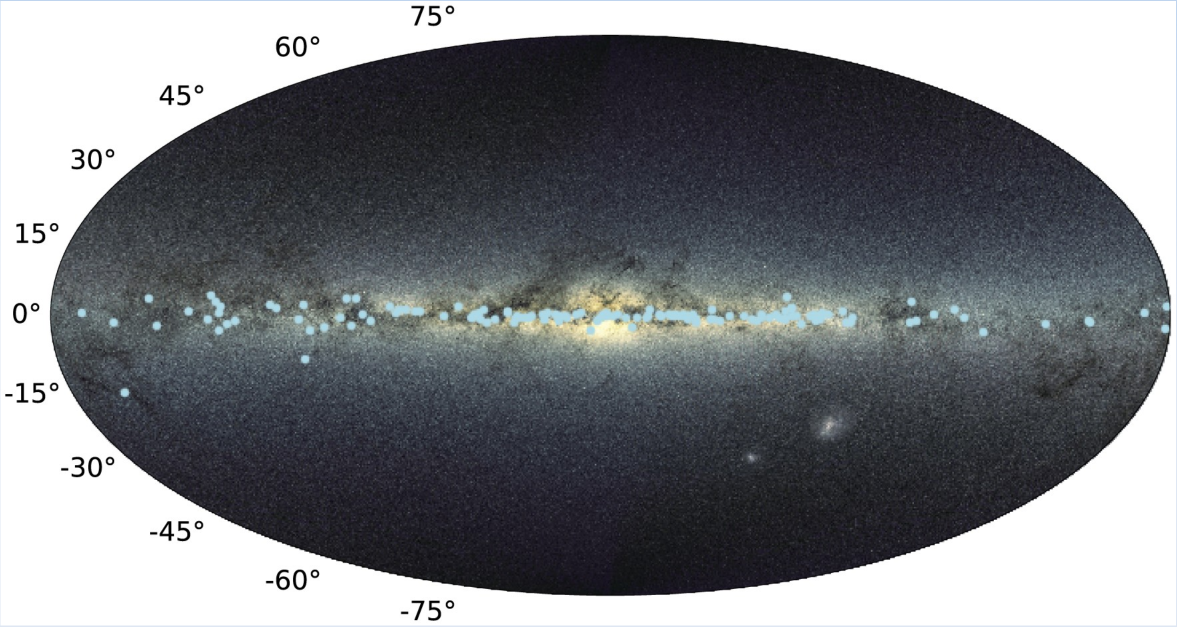
Black hole binaries

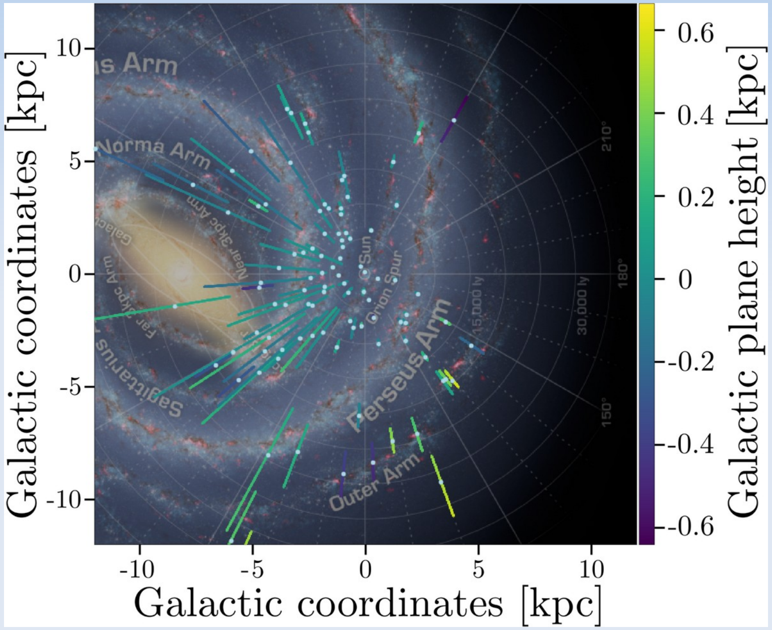
- Classified to both LMXBs or HMXBs
- Can be transient or persistent sources
- About 60 (as of 2021; now ~300?) are known, in our Galaxy and some in Magellanic Clouds



Plot from S. Chaty, J. Orosz (2015)

Galactic HMXBs





Edge-on view of the 152 HMXBs in the Galaxy. Figure from Fortin et al. (2023, A&A, 671, 149)

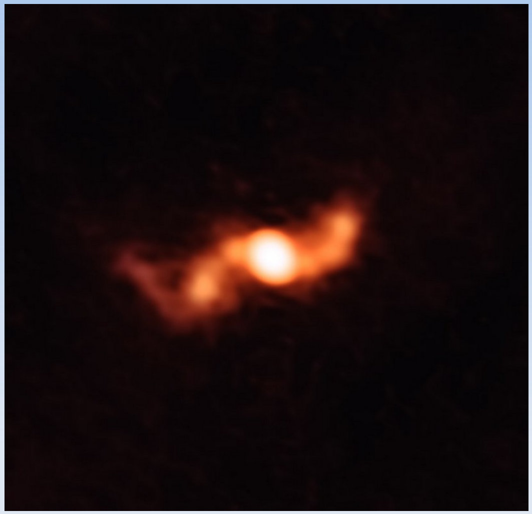
Galactic latitudes are indicated in degrees. Background image credits: ESA/Gaia/DPAC.

Face-on view of the 107 Galactic HMXBs with Gaia parallaxes. Bars indicate the 68% confidence interval in distance.

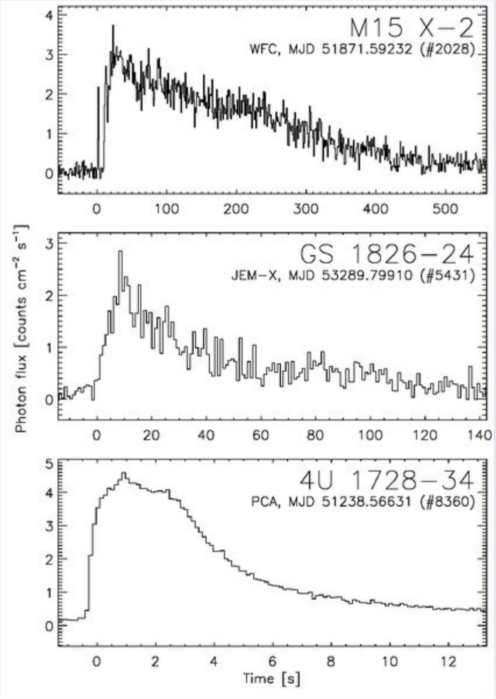
Background image credits: NASA/JPL-Caltech/R. Hurt (SSC/Caltech).

NS X-ray binaries

- Neutron stars can accrete matter from low or high mass companion stars in binary systems
- They belong to LMXBs or HMXBs.
- Some of them show jets, so they are called microquasars. Source 4U 0614+091 is a microquasar with neutron star
- Sometimes, the mass of compact object is poorly constrained, so we do not know if it is neutron star or black hole.
- If the compact object has hard surface then bursts in X-rays can be observed due to thermonuclear burning of accreted material



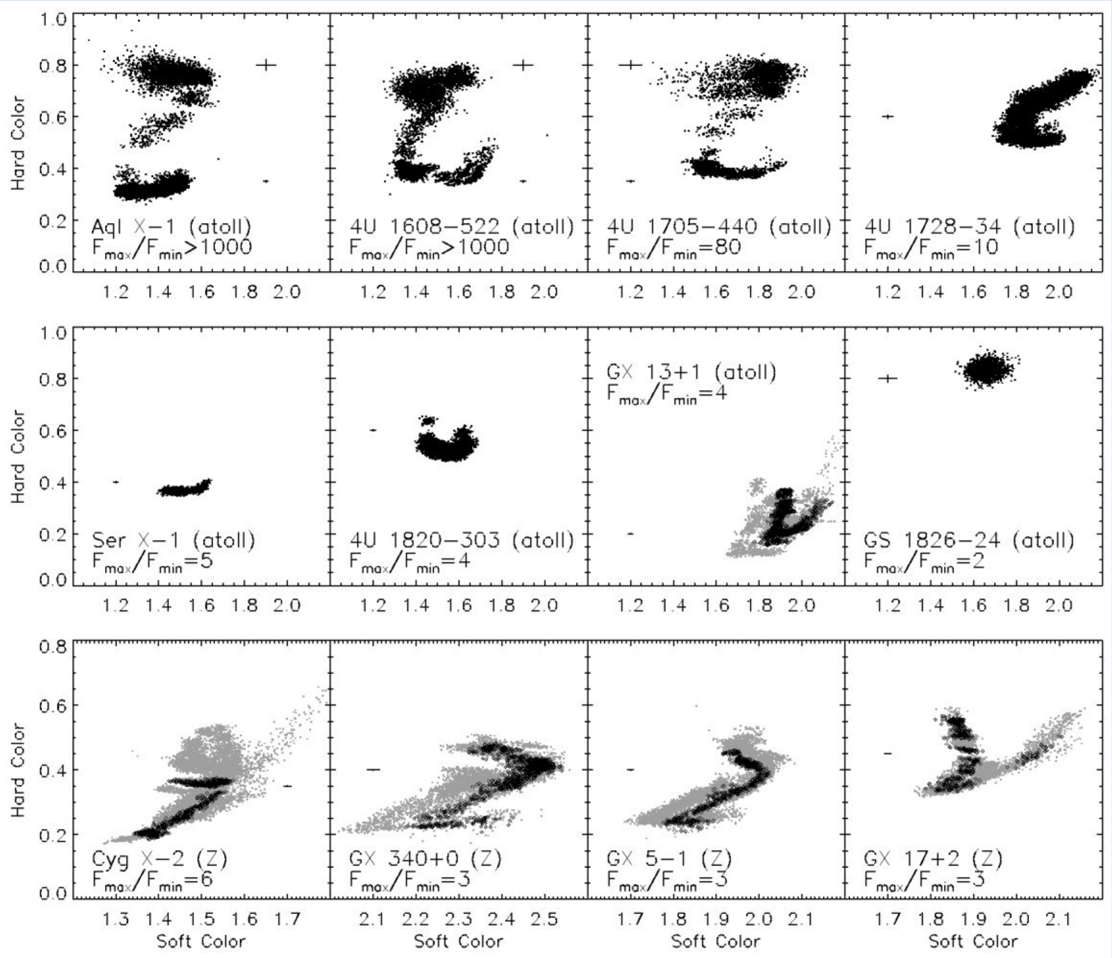
Microquasar SS 433



Sources with main sequence donor star and accreting NS, called X-ray bursters

Spectral variabilityof NS Binaries

- NS LMXBs are divided into ”Atoll” and ”Z”-sources, based on color-color diagram
- Atolls have lower luminosities, power-law spectra; Z's have thermal spectra
- Soft: log $F_{(3.5\text{-}6.4\ \mathrm{keV})}/F_{(2.0\text{-}3.5\ \mathrm{keV})}$
- Hard: log $F_{(9.7\text{-}16\ \mathrm{keV})}/F_{(6.4\text{-}9.7\ \mathrm{keV})}$
- Evolution of a source reflects the changes of mass accretion rate

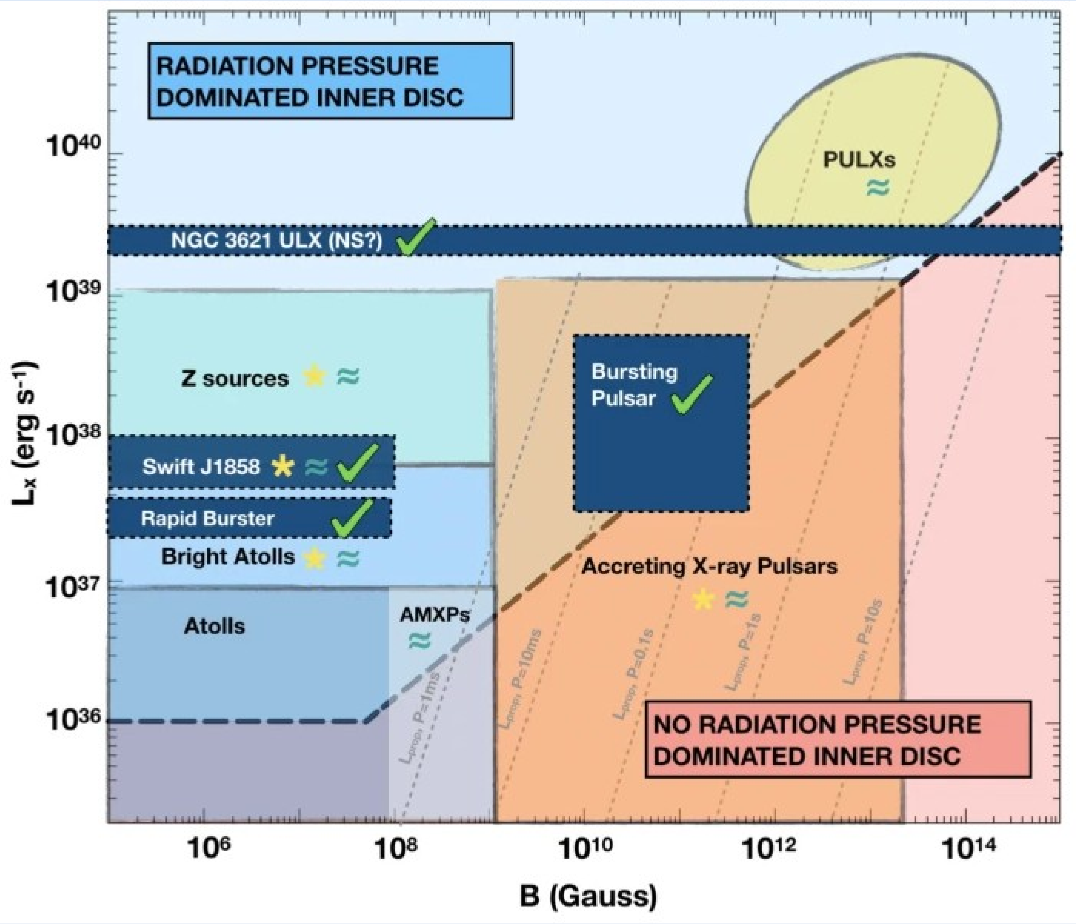


Muno et al. 2001

Accreting neutron stars

Swift J1858.6–0814 is a low-mass X-ray binary with neutron star, discovered in 2018.

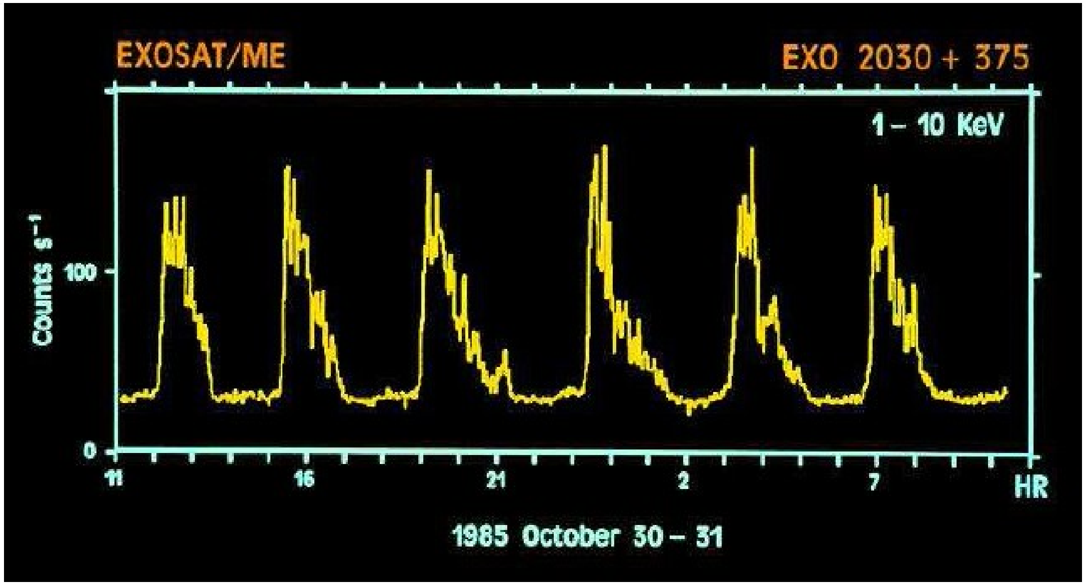
On long timescales, source exhibited alterations between quiet and variable phases. Active phases showed cyclic oscillations on timescales of about 100 s.



Luminosity vs magnetic field diagram for accreting neutron stars (from Vincentelli et al. 2023)

X-ray bursts

- Rise time ~1 s, decay times >~ 10 s; intervals hrs-days
- BB temperature decreases during burst decay
- Bursts are due to thermonuclear explosions of H/He on the NS surface

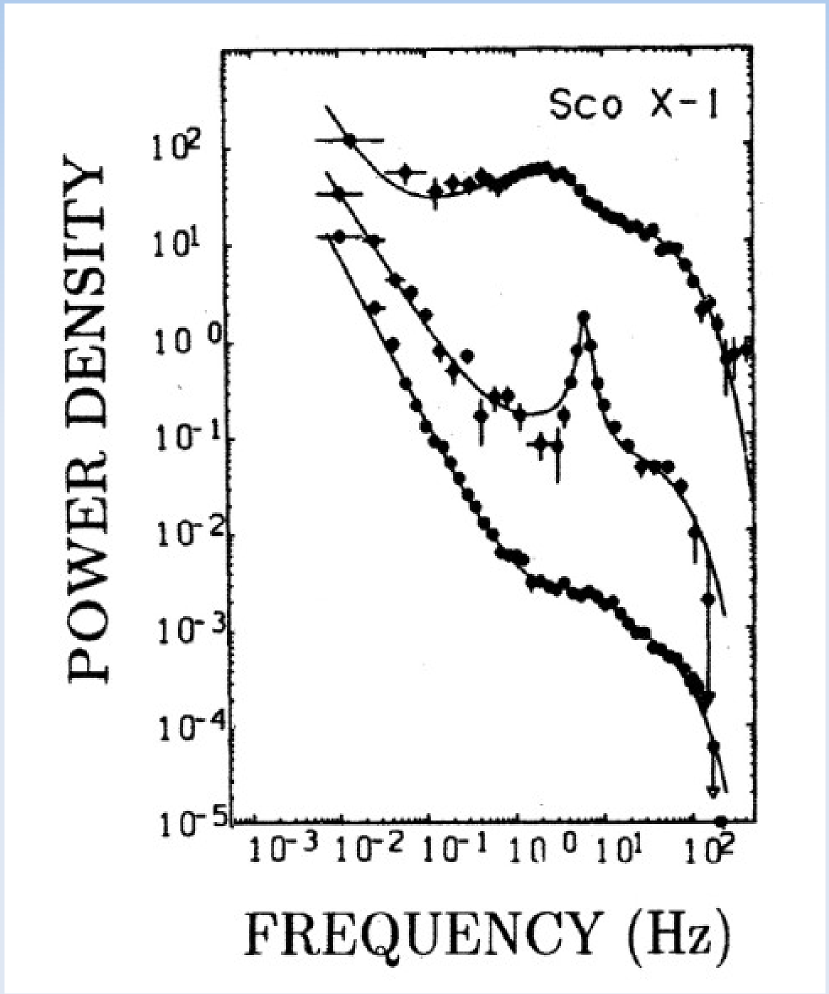


NASA GSFC

X-ray bursts from EXO 2030+375 as seen with EXOSAT.

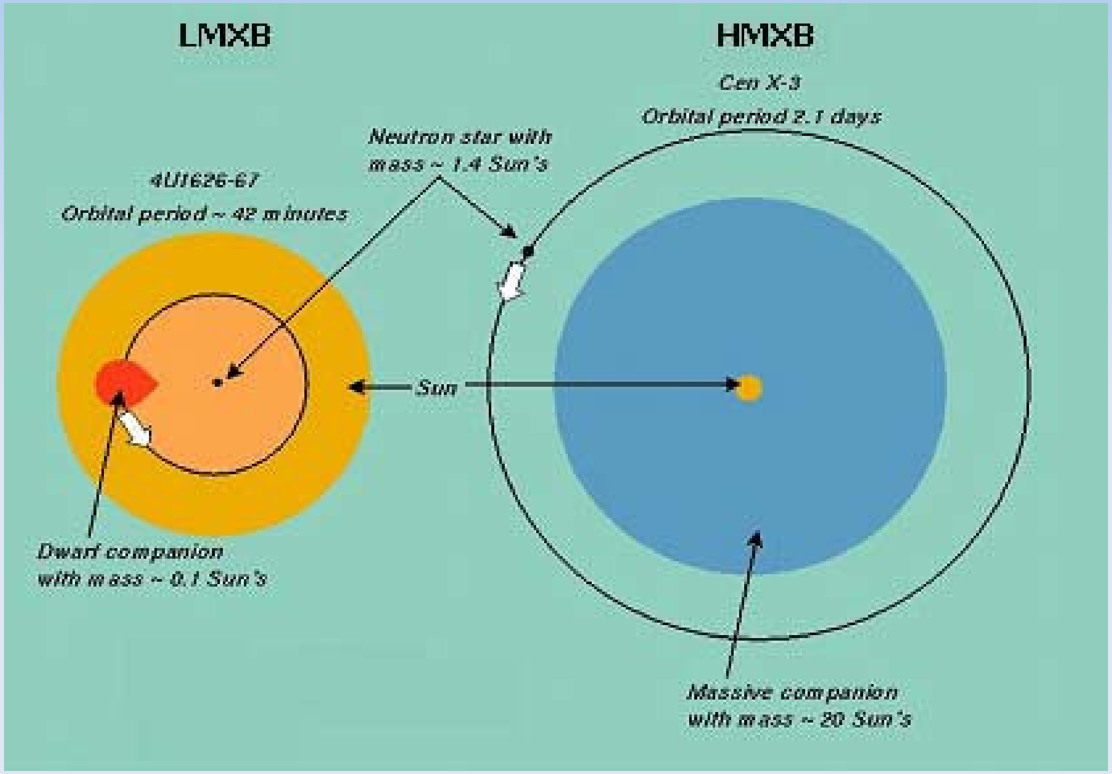
Quasi-periodic oscillations

- QPOs are intensity fluctuations with a preferred frequency
- HOBs (Horizontal branch QPOs): 5-60 Hz, correlating with X-ray intensity
- Burst oscillations: represent spin frequency of NS



NS X-ray binaries

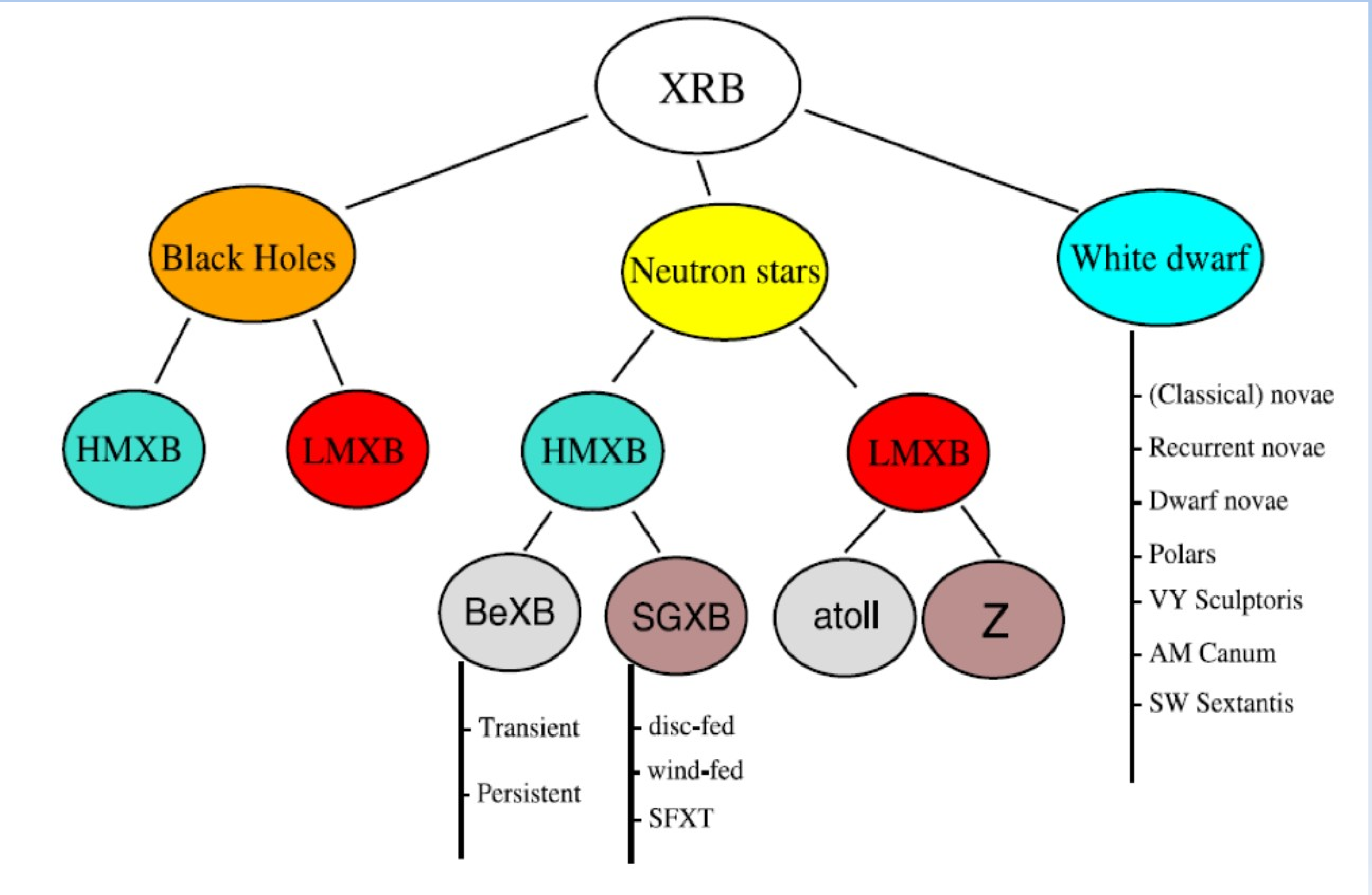
- Low mass
- High mass



This name reflects donor's mass.

Stars orbit around common center of mass.

Classification of X-ray binaries



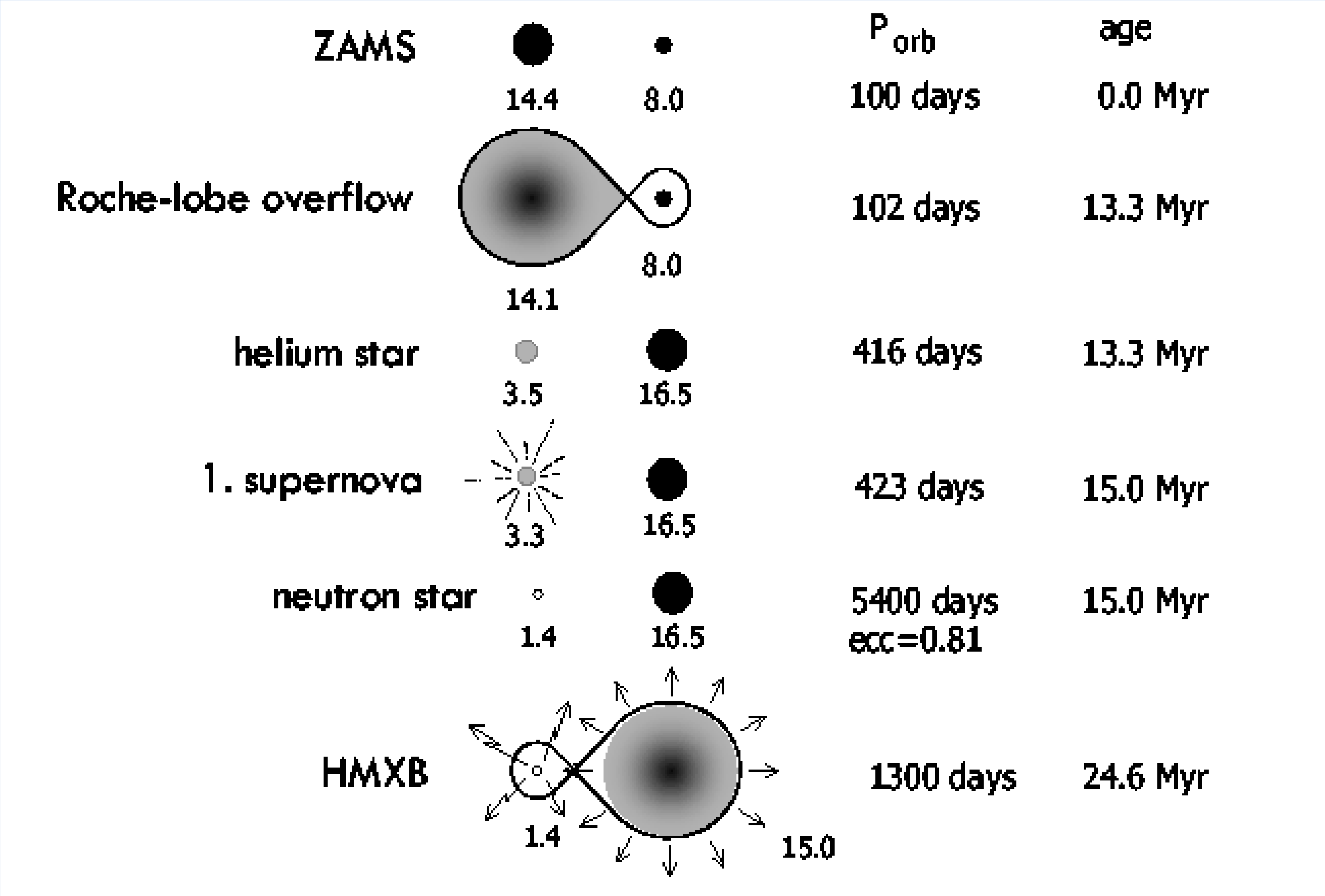
Comparison of X-ray characteristics

Feature	HMXBs	LMXBs
X-ray spectrum	Hard, kT >= 15 keV , or power-law index of 0-1	Soft, kT = 5-10 keV
Time variability	Regular pulsations, no X-ray bursts, often X-ray eclipses	Often X-ray bursts, quasi-periodic oscillations
Optical spectrum	Stellar-like	Reprocessing
Optical counterpart	Massive, early-type star (O, B), L_{opt}/L_x = 0.1-1000	Faint stars, L_{opt}/L_x = 0.001-0.01
Orbital period	1d - 1yr	10 min – 10 d
Distribution	Concentrated towards Galactic plane, age < 10^7 yrs	Concentrated towards Galactic center, age >10^9 yrs

BH diagnostics

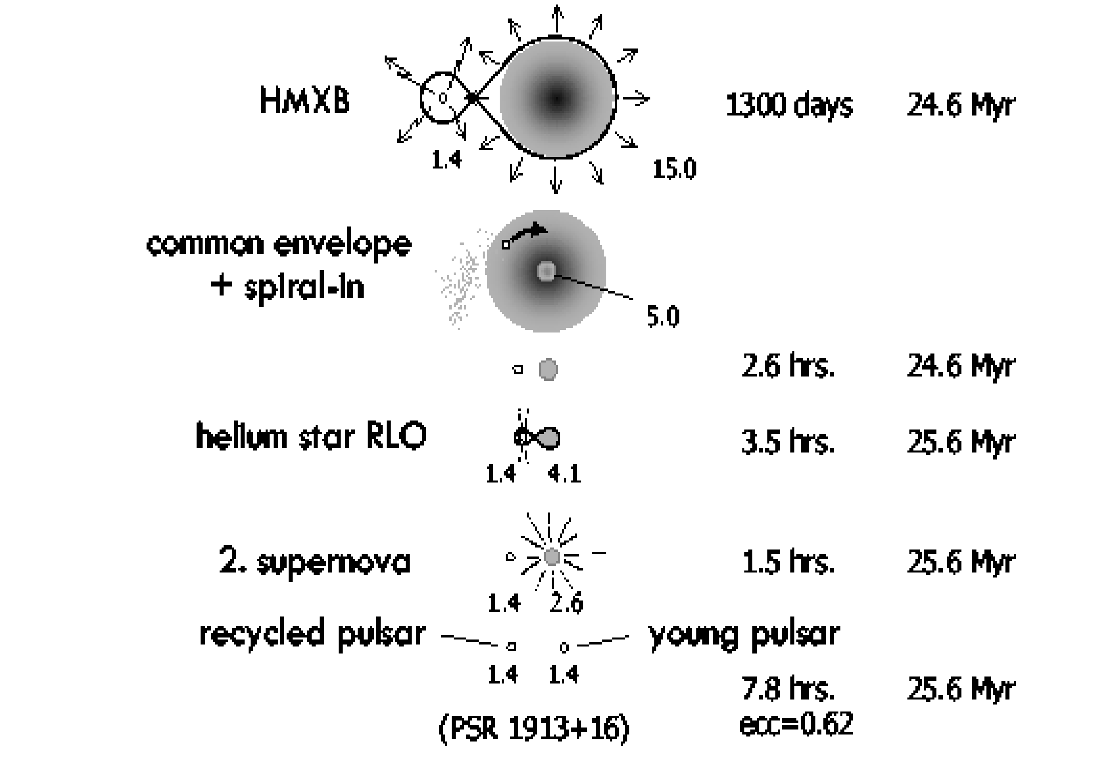
- Lack of type 1 X-ray bursts
- In general, much softer spectra
- High energy power-law tail
- State transitions: high-soft and low-hard
- For a given orbital period, BH sources are ~100 times dimmer than NS sources

Evolution history of HMXB



What next?

- HMXBs will end up in a common envelope
- Spiral in of a NS or BH into the companion's envelope
- Binary pulsar or binary black hole
- Uncertainties: wind mass loss, survival after the SN explosion

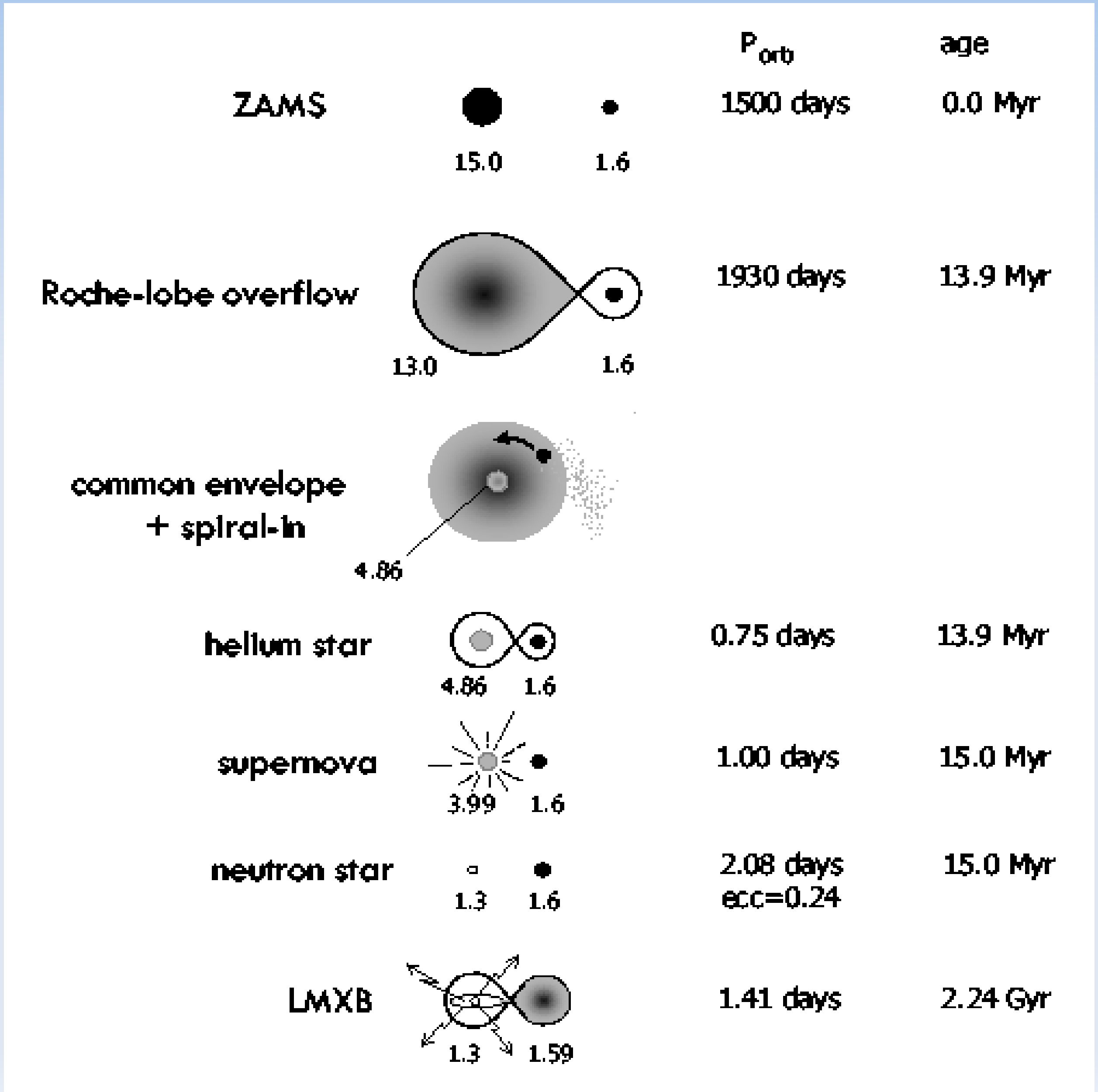


Thorne-Żytkow object

- Final stage of evolution of a close HMXB
- Orbital period of the binary was P<1 yr
- Red supergiant star forms with a neutron core, after spiral in and merging
- Inside supergiant envelope small accretion disk
- Very fast wind mass loss, unstable
- Will leave a single neutron star

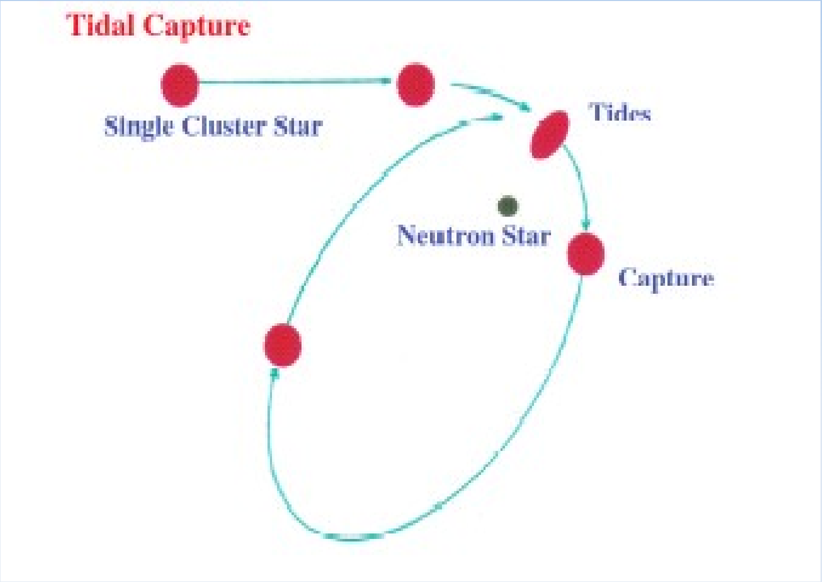
Thorne and Zytkov (1977)

Evolution history of LMXB



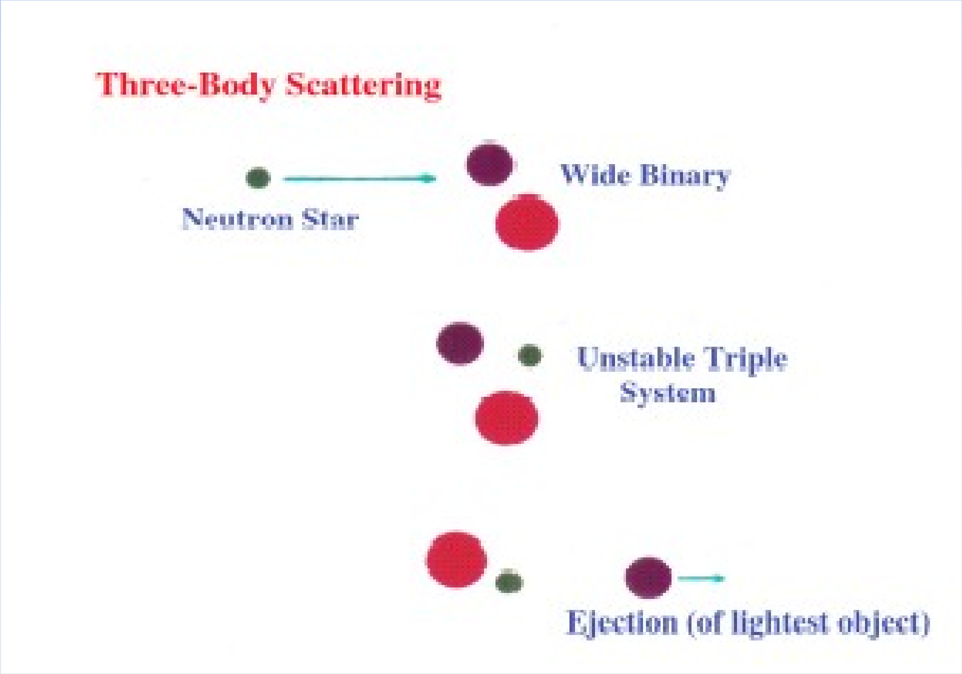
Formation of LMXBs in clusters

- Unbound orbit: positive energy
- Passing star will undergo tidal deformation
- Part of the kinetic energy of the orbit will be dissipated in oscillations and heating
- If the total energy becomes negative, a bound orbit remains



Exchange encounter

- Compact star interacts with a binary and replaces one of its components
- Ratio of tidal captures to exchange encounter rates: Nt/Ne ~ R/a n/nb



where R is radius of the target star, n number density of stars in clusters, - nb – number of binaries per unit volume, a - binary separation

How to survive the SN explosion

- Mass ejection in the SN explosion leads to a decrease of the system's binding energy.
- Orbit becomes eccentric

$$a_i = a_f (1 - e)$$

- The relative velocity at periastron equals to the relative velocity of a circular orbit

$$G \frac{(m+M)}{a_i} = G \frac{(M+m-\Delta M)}{a_f} \frac{1+e}{1-e}$$

How to survive SN explosion

- Eccentricity and semi-axis of the final orbit

$$e = \frac{\Delta M}{m + M - \Delta M} \qquad \frac{a_f}{a_i} = \frac{m + M - \Delta M}{m + M - 2\Delta M}$$

- If more than half of mass is ejected, system will become unbound
- If the explosion is asymmetric, the newborn neutron star will receive a kick velocity. Depending on its magnitude and direction, the orbit may be disrupted

Next week

- Theory of accretion. Eddington limit. Viscosity. Time dependent models of accretion
- Dwarf novae. Recurrent novae, cataclysmic variables.
- Instability of accretion disk due to partial hydrogen ionisation.
- Modeling of instability cycles. Radiation pressure instability.

  Suggested articles:

  - Tauris and Van den Heuvel, ”Formation and evolution of compact stellar X-ray sources” (arXiV:0303456)
  - E. Levesque et al., ”Discovery of a Thorne-Zytkow object candidate in the Small Magellanic Cloud”, arXiV:1406.0001

Further evolution of LMXBs

- P_{orb} < 10 hrs: angular momentum loss due to gravitational radiation or magnetic breaking. Evlution to shorter periods.
- P_{orb} > 1-2 d: nuclear evolution of the donor star. For a given metallicity, the star's radius is determined only by the mass of its helium core. System evolves to longer periods.