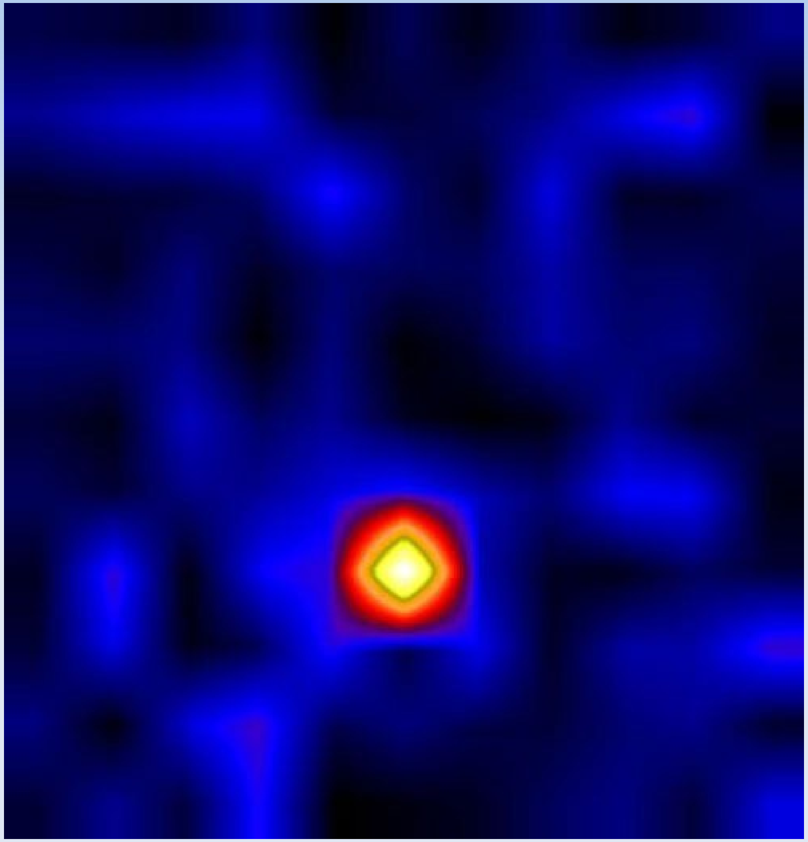
Compact Stars



Lecture 4

Summary of the previous lecture

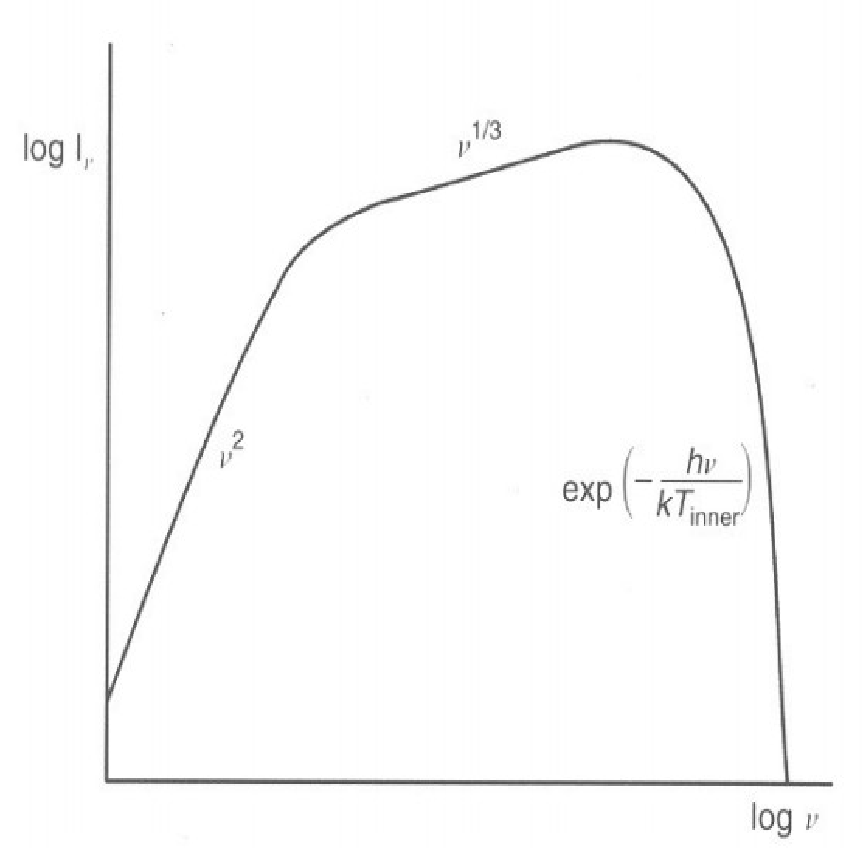
- We have talked about the basic structure of accretion disks in X-ray binaries, process of disk formation by viscous diffusion and angular momentum transport thorugh the turbulence
- I presented the fundamental equations of hydrodynamics, the mass and angular momentum conservation, and energy equation
- 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 greater than for the nuclear fusion
- I also presented the classification of X-ray binaries

Alpha-disks in X-ray binaries

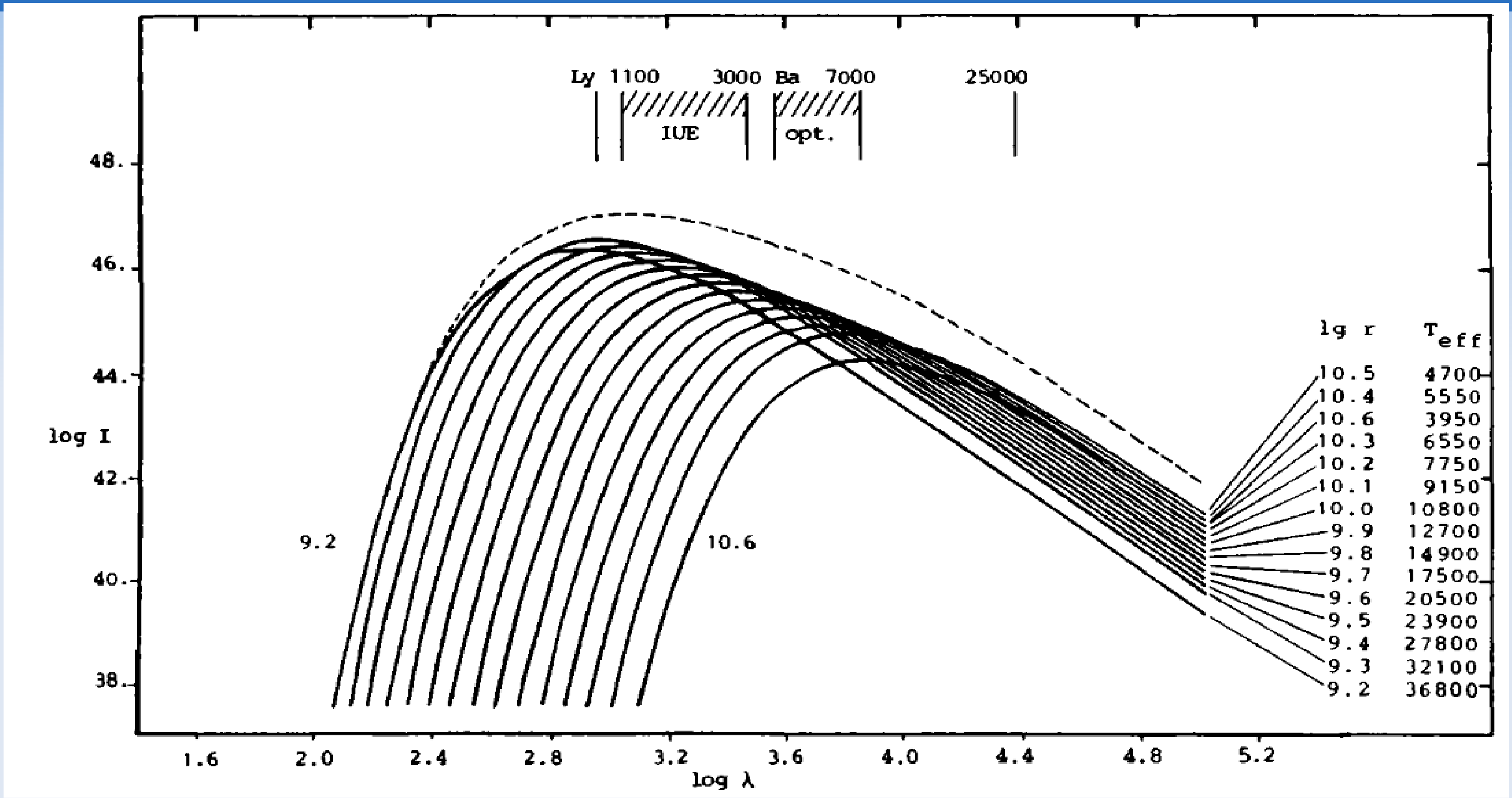
- I will show the observational properties of accreting compact stars in various sources
- The history of X-ray astronomy will be briefly described
- I will present also the basic evolutionary scenarios of low mass and high mass XRBs
- The theory of the disk will be continued, with focus on the specific aspects of the alpha-disks theory.

Shape of the spectrum

- From the outer parts, we'll see the Rayleigh-Jeans tail of the spectrum
- From the inner edge, we'll see the exponential cut-off

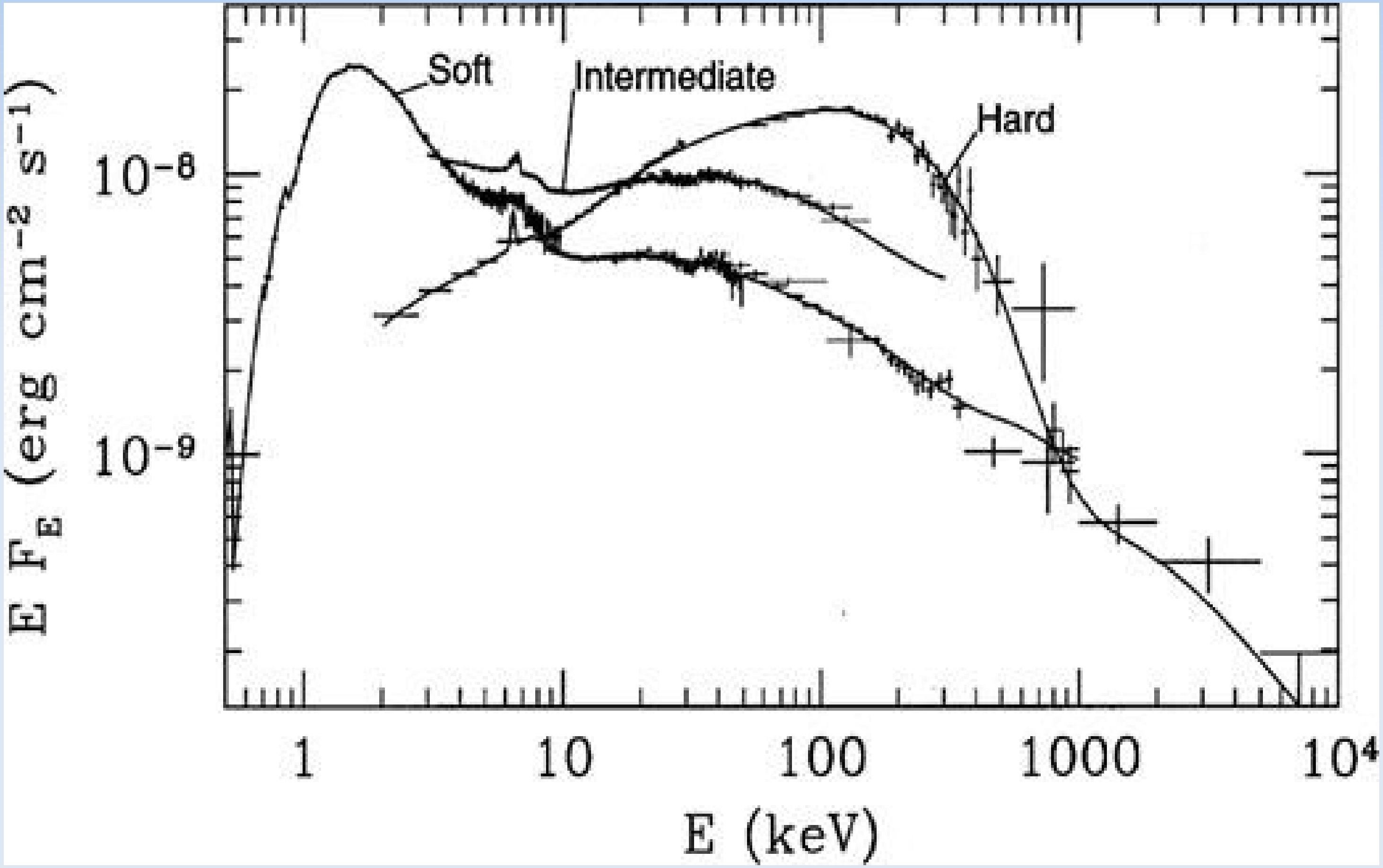


Disk black body



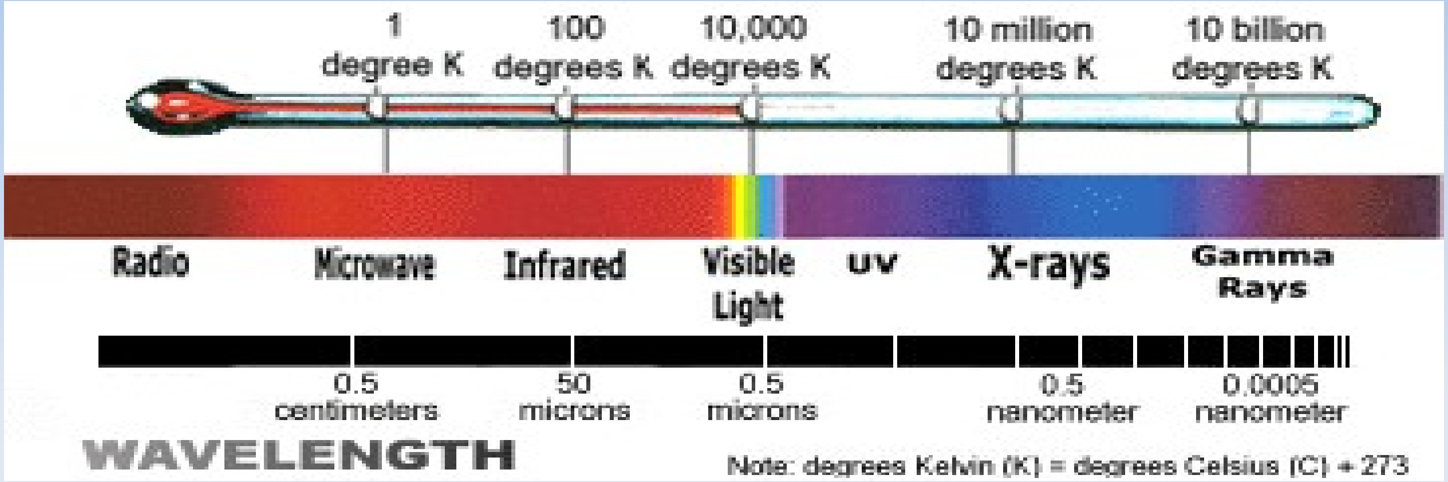
- Contributions from different annuli of the disk to its thermal spectrum

Spectral States of Cygnus X-1



- Gierliński et al. 1997

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

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

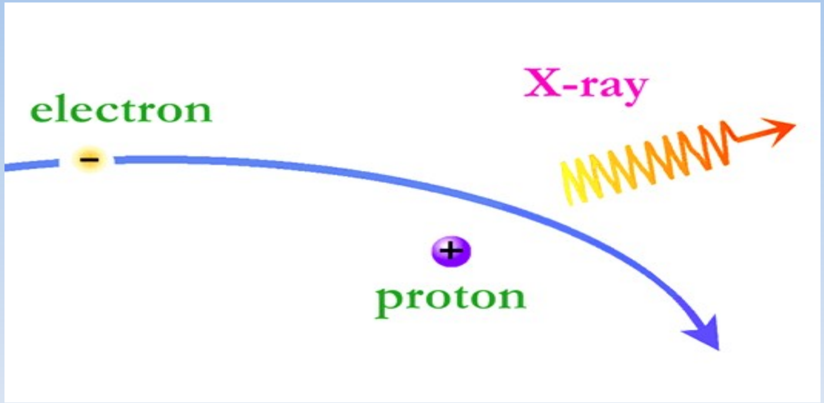
- Optically thin case: gravitational potential enegy is turned into thermal energy

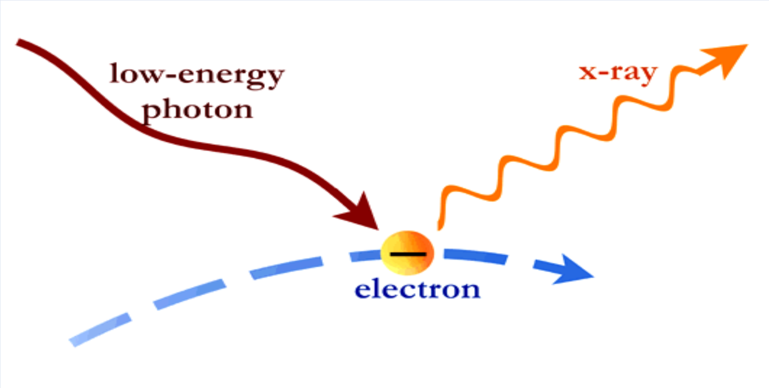
$$\frac{GM\left(m_{p}+m_{e}\right)}{R}=\frac{3}{2}kT_{th}$$

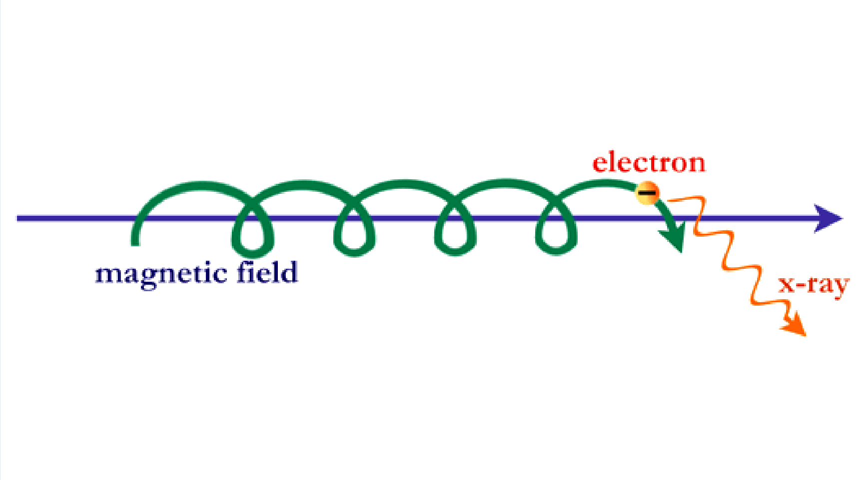
- For accreting binaries, L~10^{36} – 10^{38} erg/s, R~10^{6} cm. $T_{bb}<T_{rad}<T_{th\,.}$. 1 keV < T_{rad} < 50 MeV . Therefore the photon frequency hν is in X-rays.

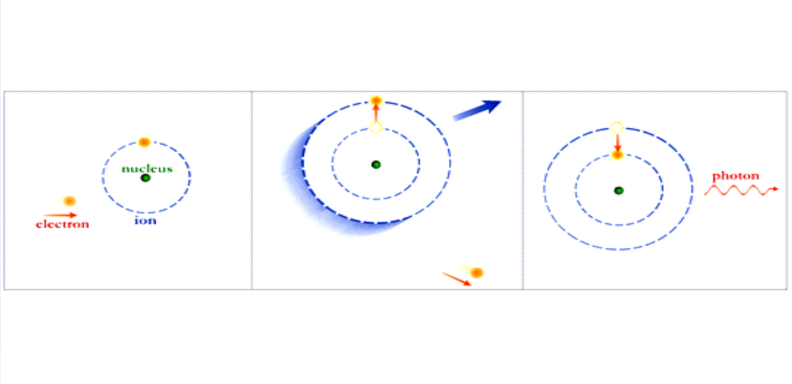
Mechanisms of X-ray emission

- Bremsstrahlung
- Compton upscattering
- Synchrotron
- Atomic emission





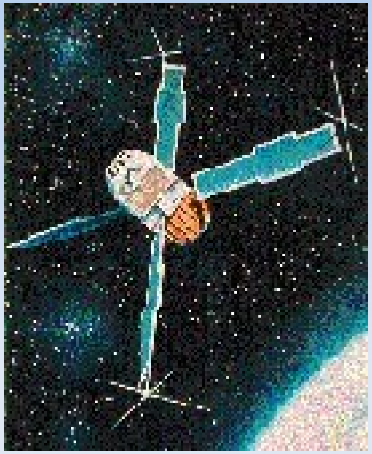




History of X-ray astronomy

- 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, Cyg X-1
- 2002: Nobel prize for Riccardo Giacconi, for his pioneering contributions to X-ray instrumentation

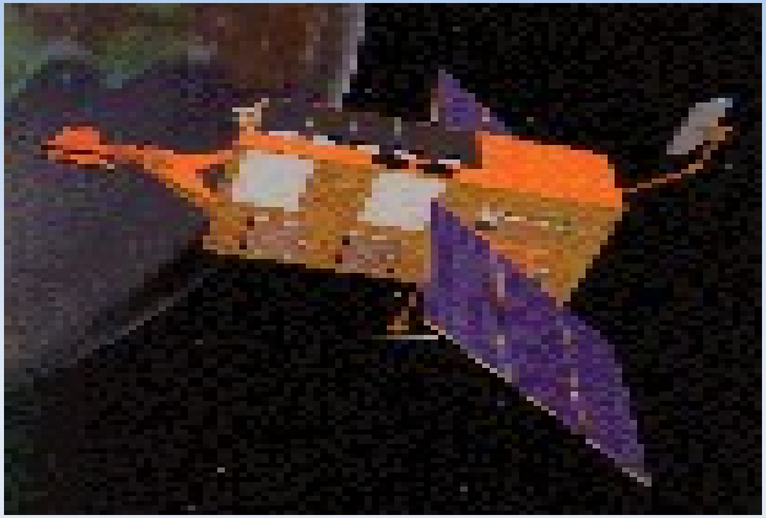
Important X-ray observatories

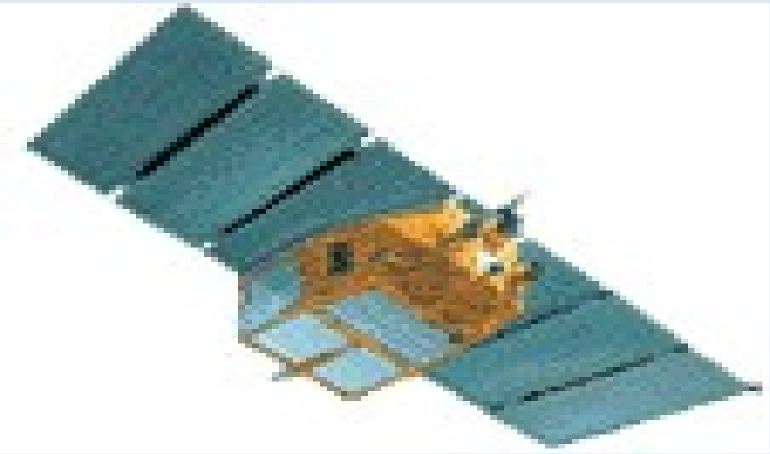


- **Uhuru**. Worked from 1970 to 1973, first mission dedicated to X-ray astronomy. The X-ray sources are collected in the ”4U” Catalog
- **Einstein** (HEAO-2). Worked from 1978 to 1981. First X-ray imaging telescope in space
- **ROSAT**. 1990-1999. Collected over 150,000 sources in the All-sky survey catalog. Detected isolated neutron stars and showed morphology of supernova remnants.

X-ray observatories

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





Future observatories

- Athena+ planned by NASA/ESA (2028)

Athena – Advanced Telescope for High-ENergy Astrophysics – will be an X-ray telescope designed to address the Cosmic Vision science theme 'The Hot and Energetic Universe'. The theme poses two key astrophysical questions:

How does ordinary matter assemble into the large-scale structures we see today? and

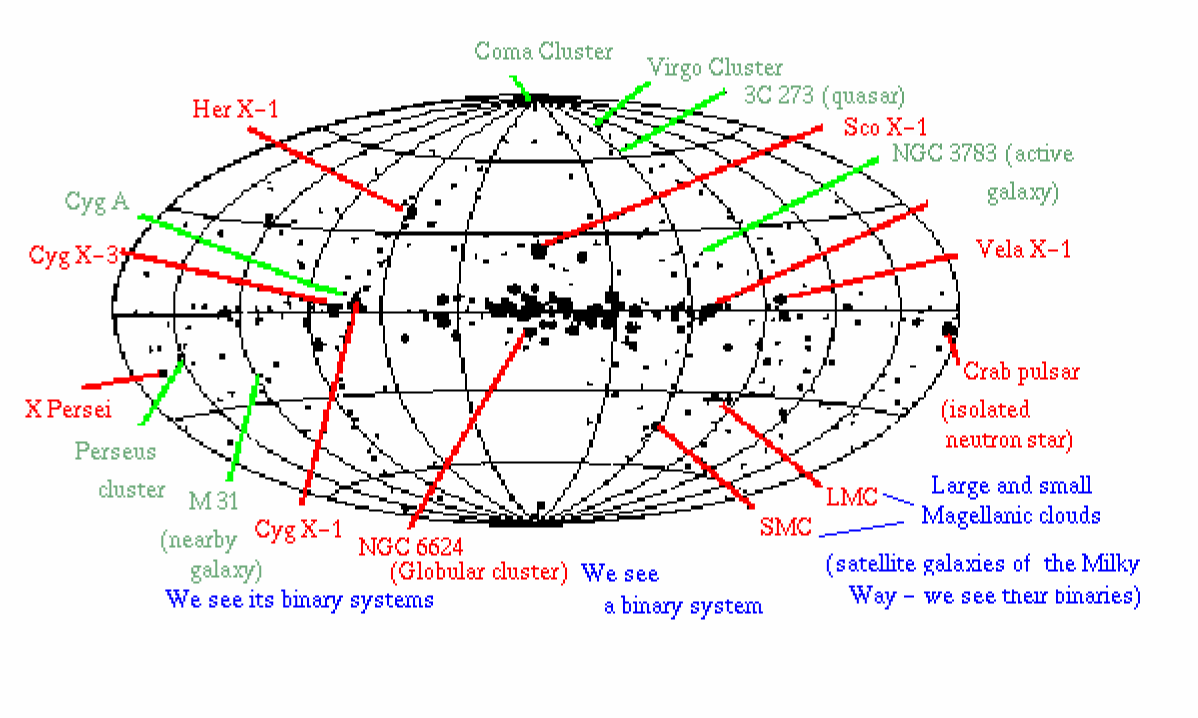
How do black holes grow and shape the Universe?

To address the first question, it will be necessary to map hot gas structures in the Universe – specifically the gas in clusters and groups of galaxies, and the intergalactic medium – determine their physical properties and track their evolution through cosmic time.

To answer the second question, supermassive black holes (SMBH) must be revealed, even in obscured environments, out into the early Universe, and both the inflows and outflows of matter and energy as the black holes grow must be understood.

On 27 June 2014, Athena was selected as the second L-class mission in ESA's Cosmic Vision 2015–25 plan, with a launch foreseen in 2028. The mission has now entered the study phase; once the mission design and costing have been completed, it will eventually be proposed for 'adoption' around 2019, before the start of the construction phase.

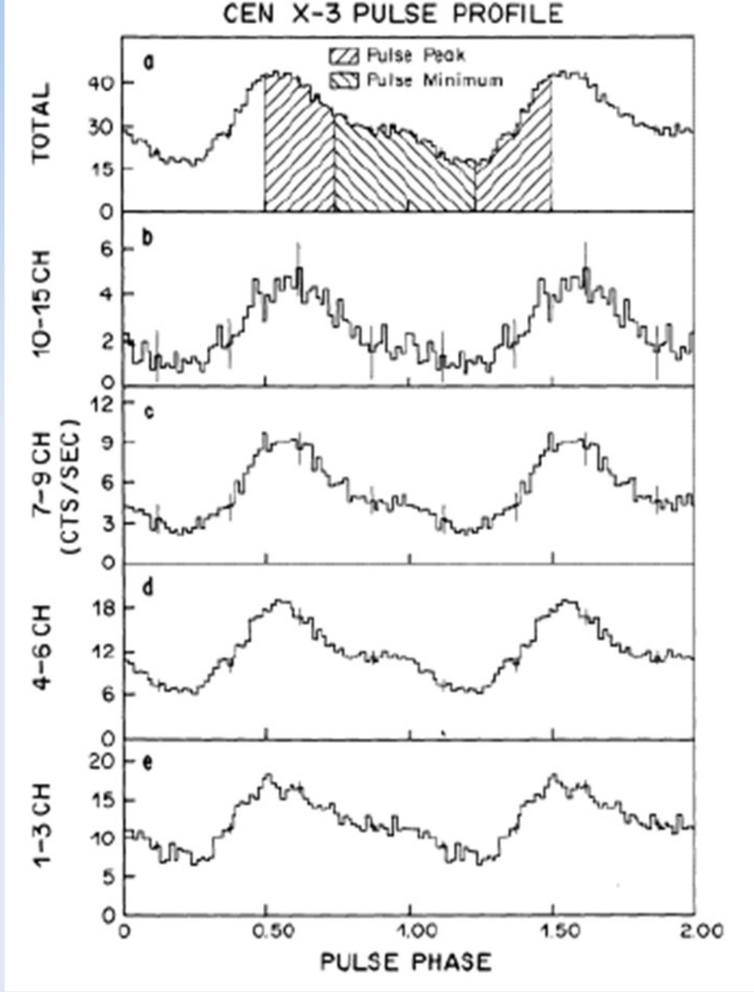
Observational characteristics



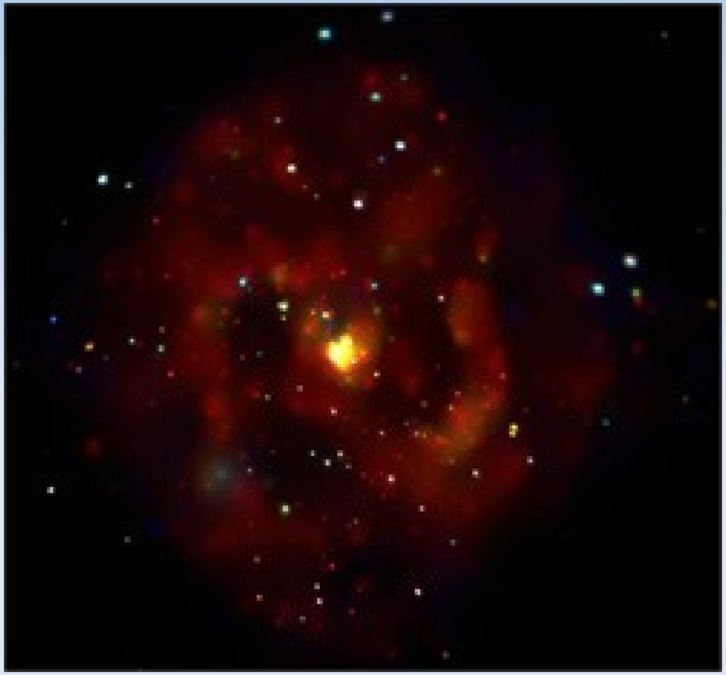
All sky map from Uhuru

- 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



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



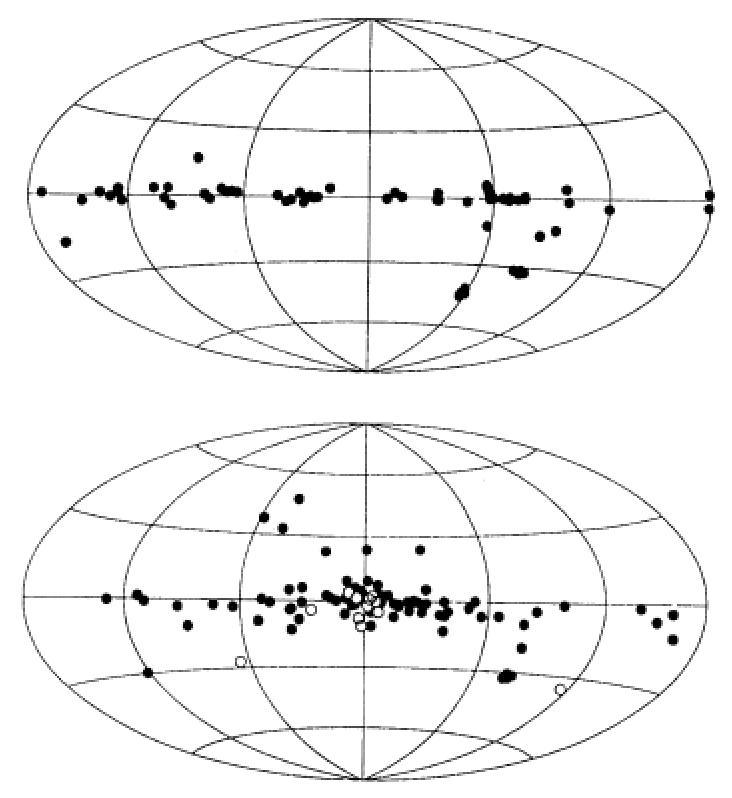
Chandra image of M83 with point-like NS and BH X-ray sources

Break

Neutron star LMXB

- 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

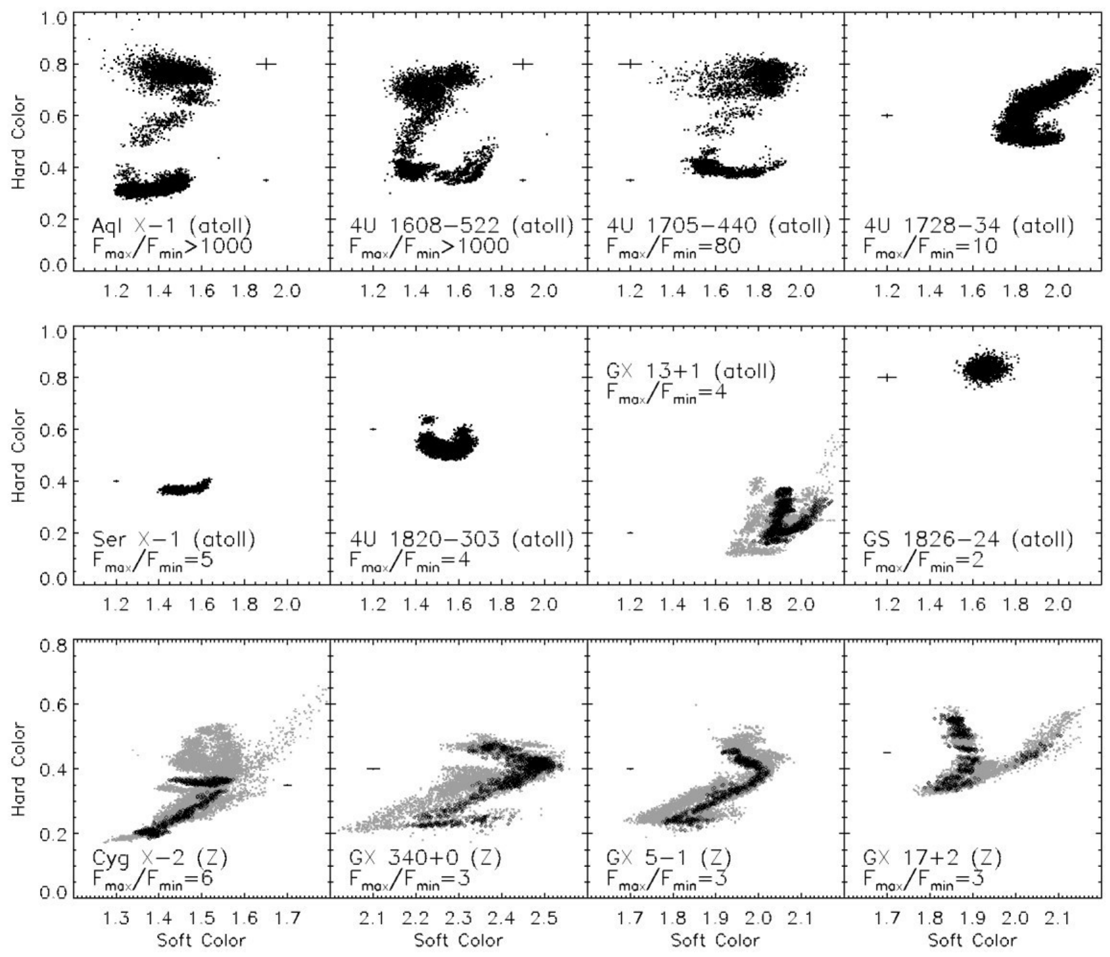
HMXBs



LMXBs

Spectral variability

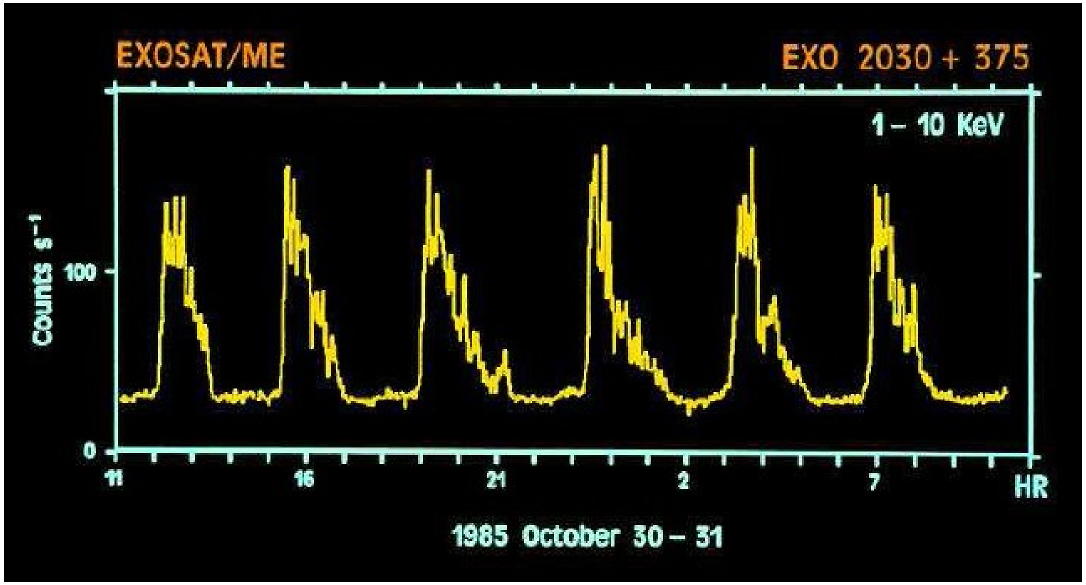
- NS LMXBs are divided into ”Atoll” and ”Z”-sources, based on color-color diagram
- Atolls have lower luminosities, power-law spectra; Z's have thermal spectra
- Soft: log $F_{(3.5\text{-}6.4\ \mathrm{keV})}/F_{(2.0\text{-}3.5\ \mathrm{keV})}$
- Hard: log $F_{(9.7\text{-}16\ \mathrm{keV})}/F_{(6.4\text{-}9.7\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



Muno et al. 2001

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

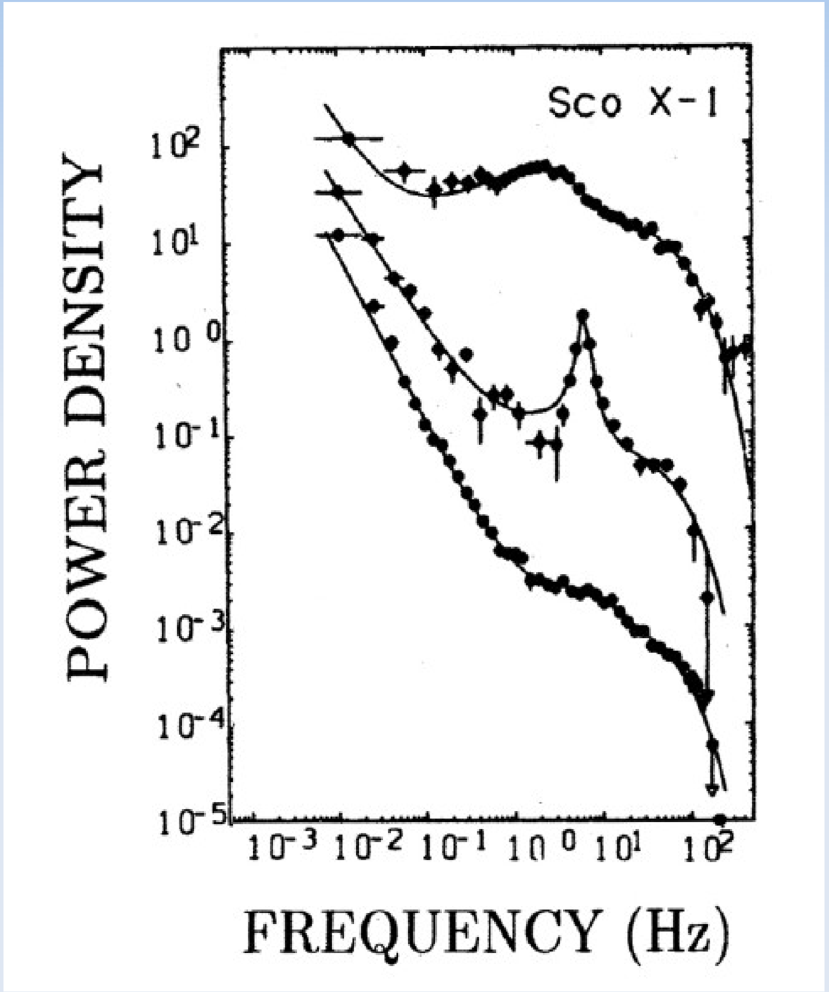


NASA GSFC

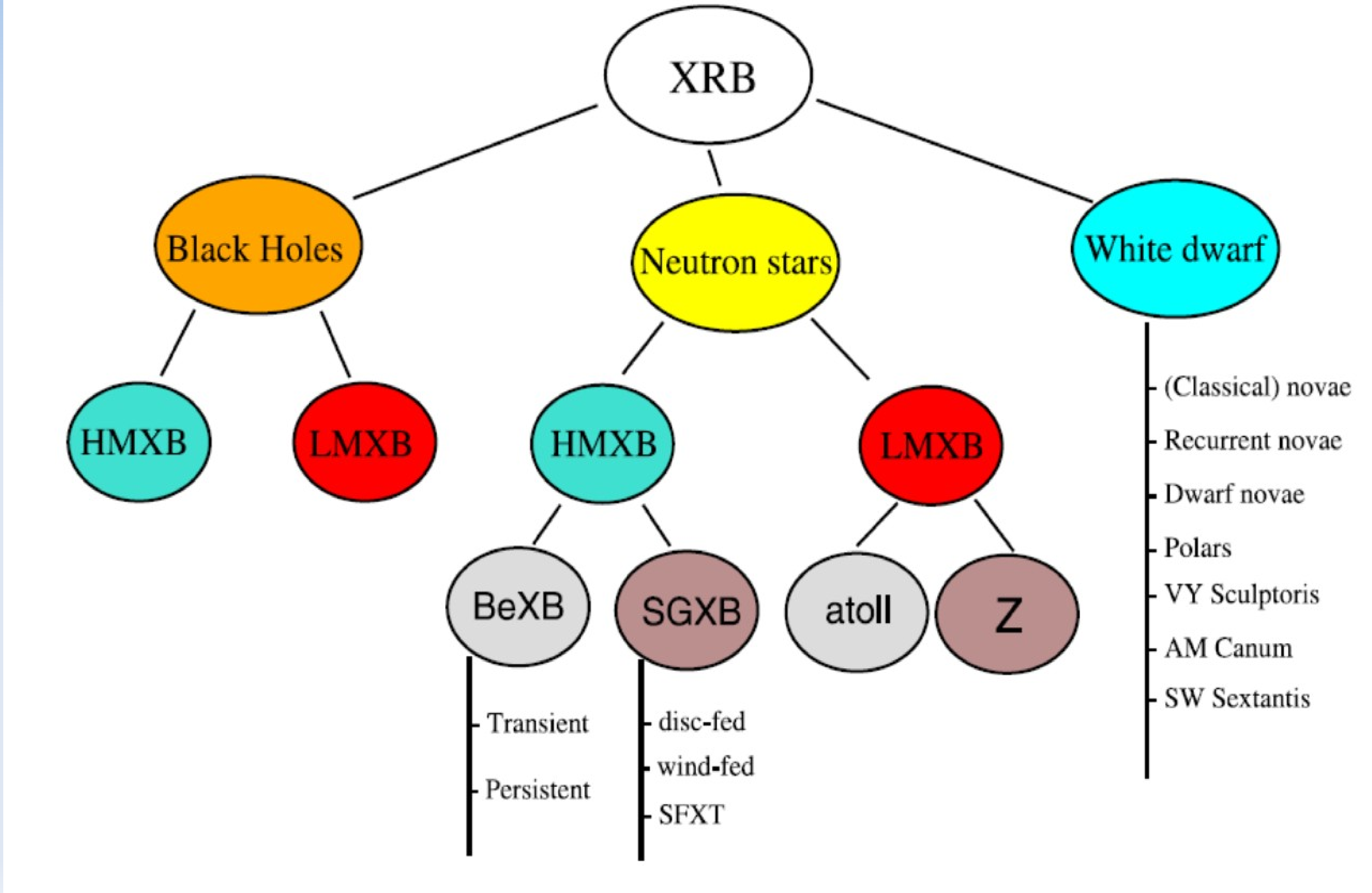
X-ray bursts from EXO 2030+375 as seen with EXOSAT.

Quasi-periodic oscillations

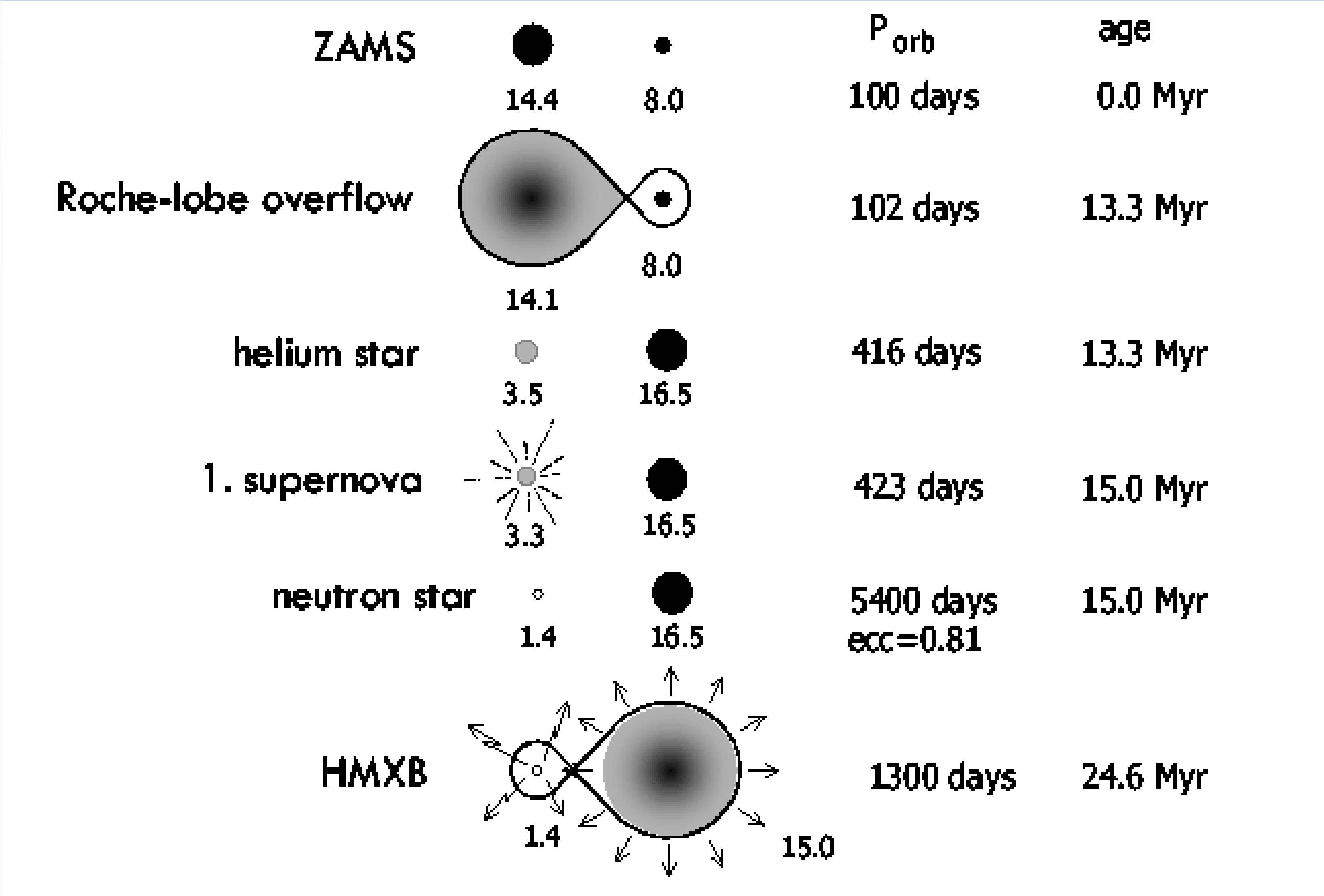
- QPOs are intensity fluctuations with a preferred frequency
- HOBs (Horizontal branch QPOs): 5-60 Hz, correlating with X-ray intensity
- Burst oscillations: represent spin frequency of NS



Classification of X-ray binaries



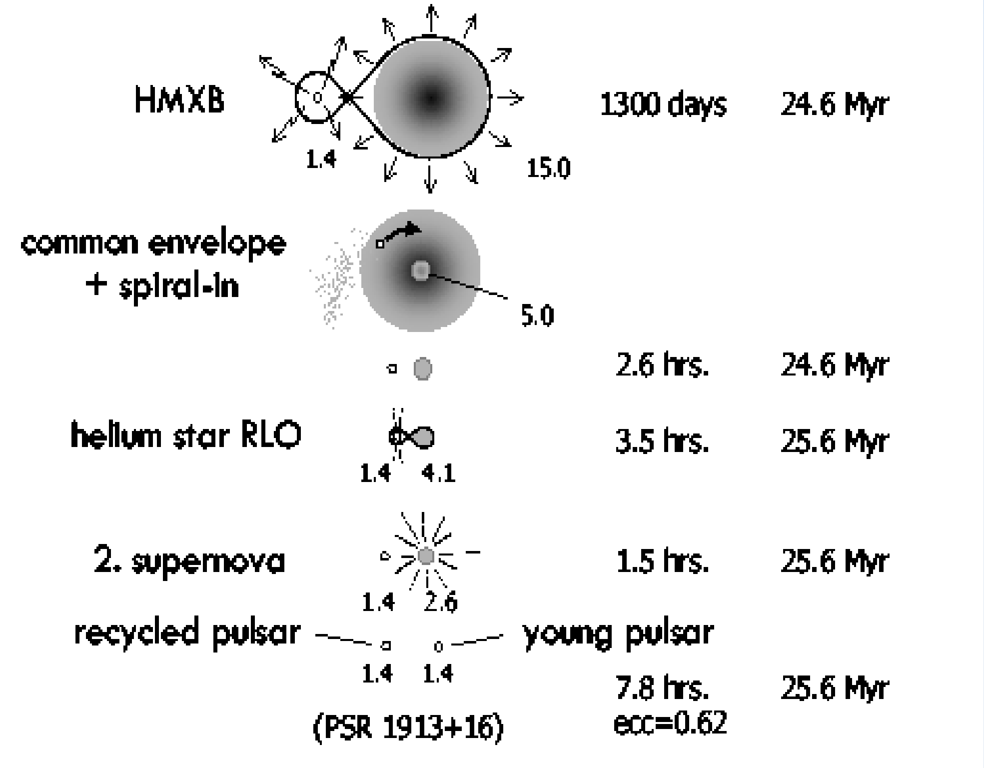
Evolution history of HMXB



			P_{orb}	age
ZAMS	14.4	8.0	100 days	0.0 Myr
Roche-lobe overflow	14.1	8.0	102 days	13.3 Myr
helium star	3.5	16.5	416 days	13.3 Myr
1. supernova	3.3	16.5	423 days	15.0 Myr
neutron star	1.4	16.5	5400 days ecc=0.81	15.0 Myr
HMXB	1.4	15.0	1300 days	24.6 Myr

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)

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

$$\boxed{a_i = a_f (1 - e)}$$

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

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

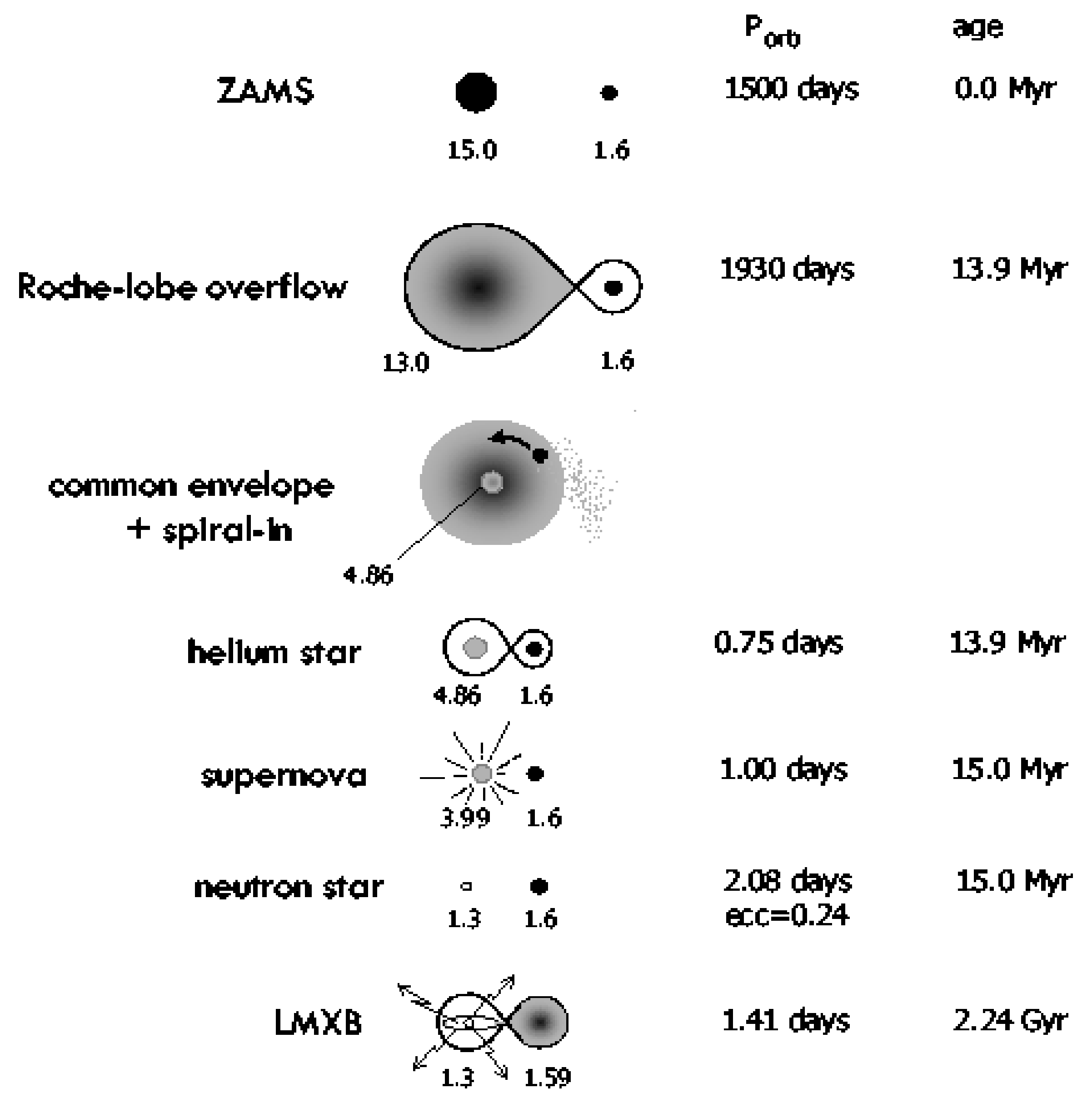
How to survive SN explosion

- 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

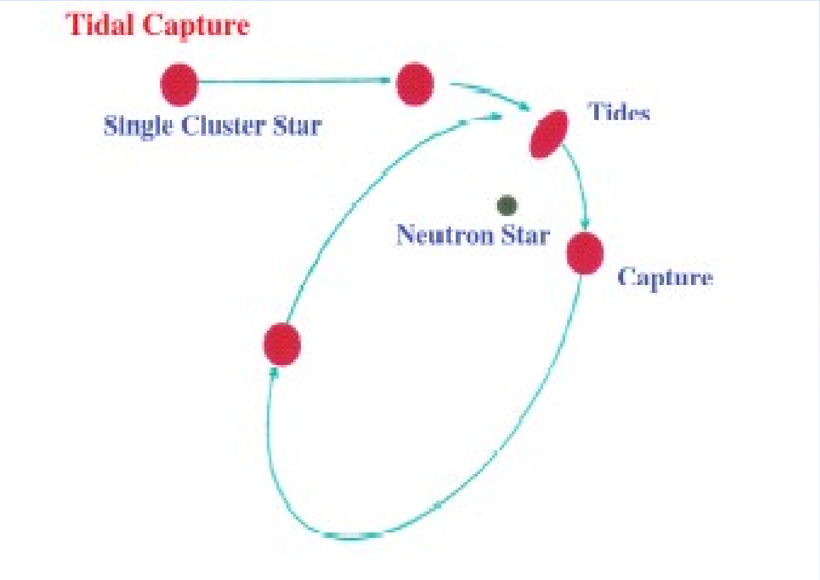
Evolution history of LMXB



		P_{orb}	age
ZAMS	15.0 1.6	1500 days	0.0 Myr
Roche-lobe overflow	13.0 1.6	1930 days	13.9 Myr
common envelope + spiral-in	4.86		
helium star	4.86 1.6	0.75 days	13.9 Myr
supernova	3.99 1.6	1.00 days	15.0 Myr
neutron star	1.3 1.6	2.08 days ecc=0.24	15.0 Myr
LMXB	1.3 1.59	1.41 days	2.24 Gyr

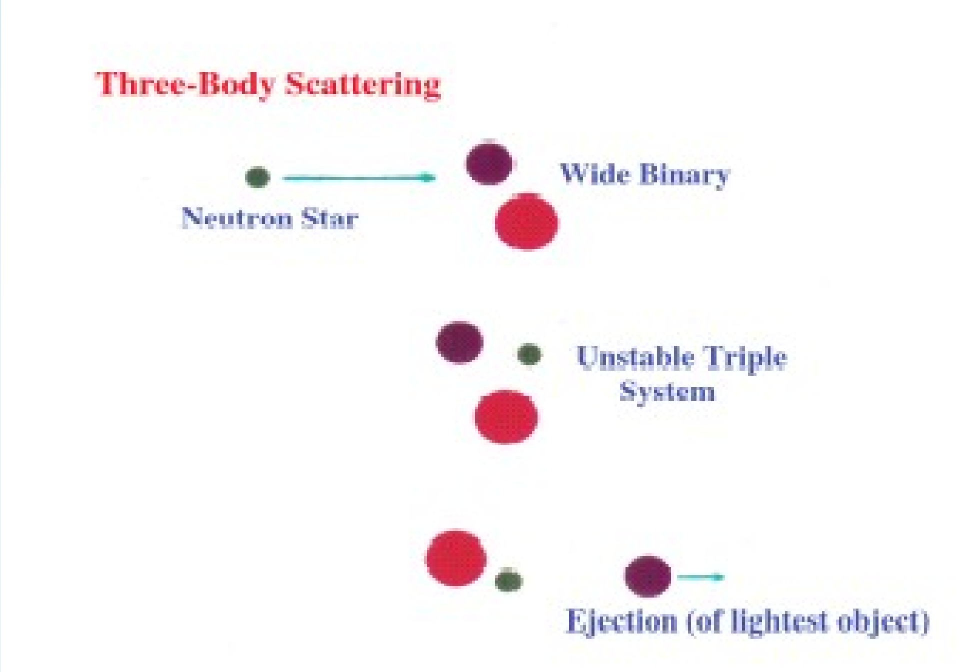
Formation of LMXBs in clusters

- 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

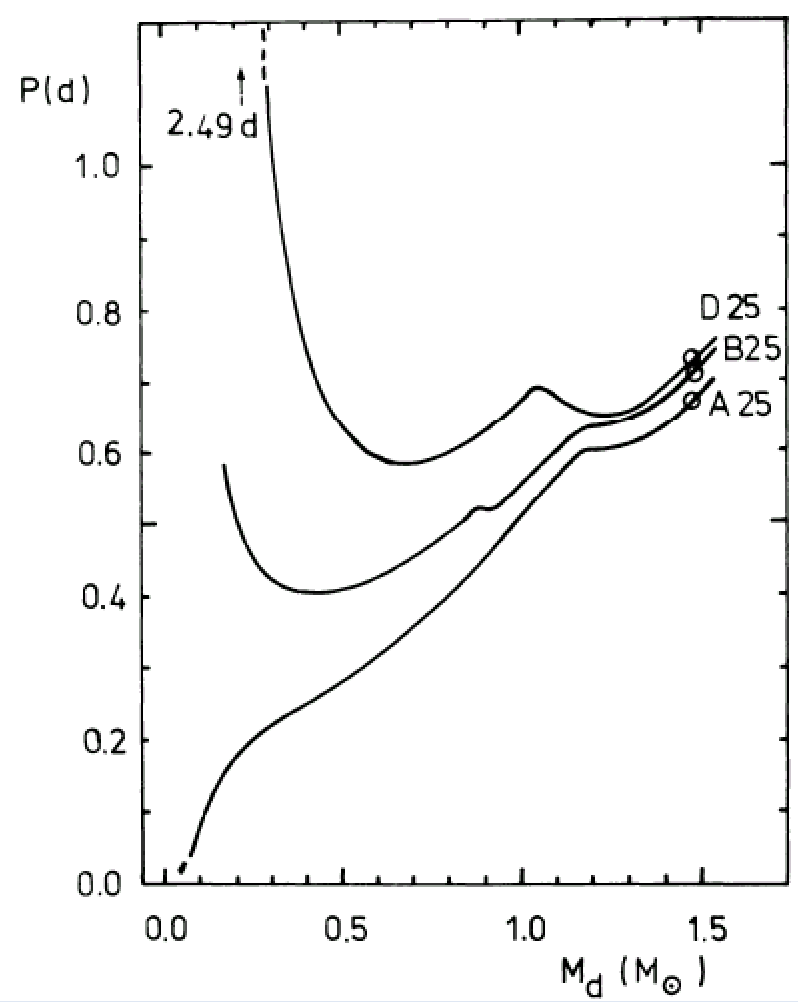
- Compact star interacts with a binary and replaces one of its components
- Ratio of tidal captures to exchange encounter rates: Nt/Ne ~ R/a n/nb



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

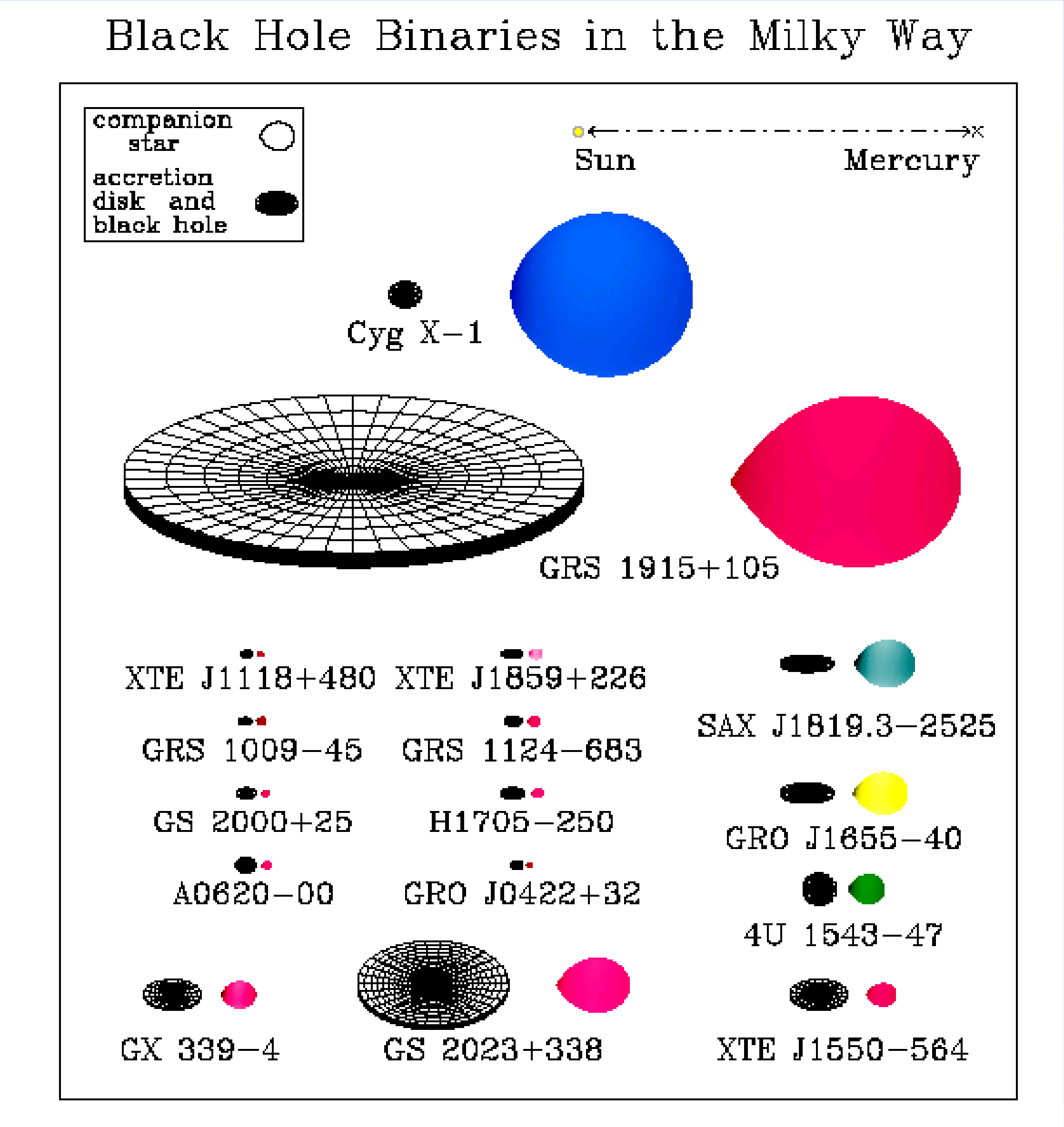
Further evolution of LMXBs

- 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 meatlicity, the star's radius is determined only by the mass of its helium core. System evolves to longer periods.



Black hole binaries

- Classified to both LMXBs or HMXBs
- Can be transient or persistent sources
- About 30 are known, in our Galaxy and Magellanic Clouds



Next week

- More about X-ray sources. Spectral states, state transitions.
- X-ray nova outbursts
- Black hole spectra and indirect BH diagnostics
- Theory of accretion; tbc. Eddington limit. Viscosity
- 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