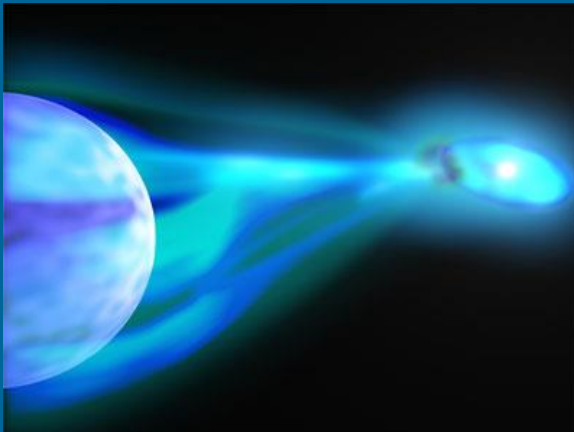
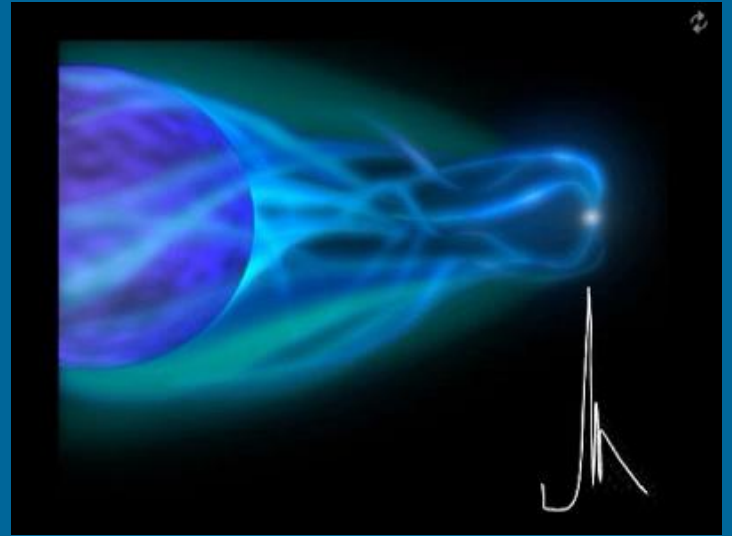


X-ray binaries

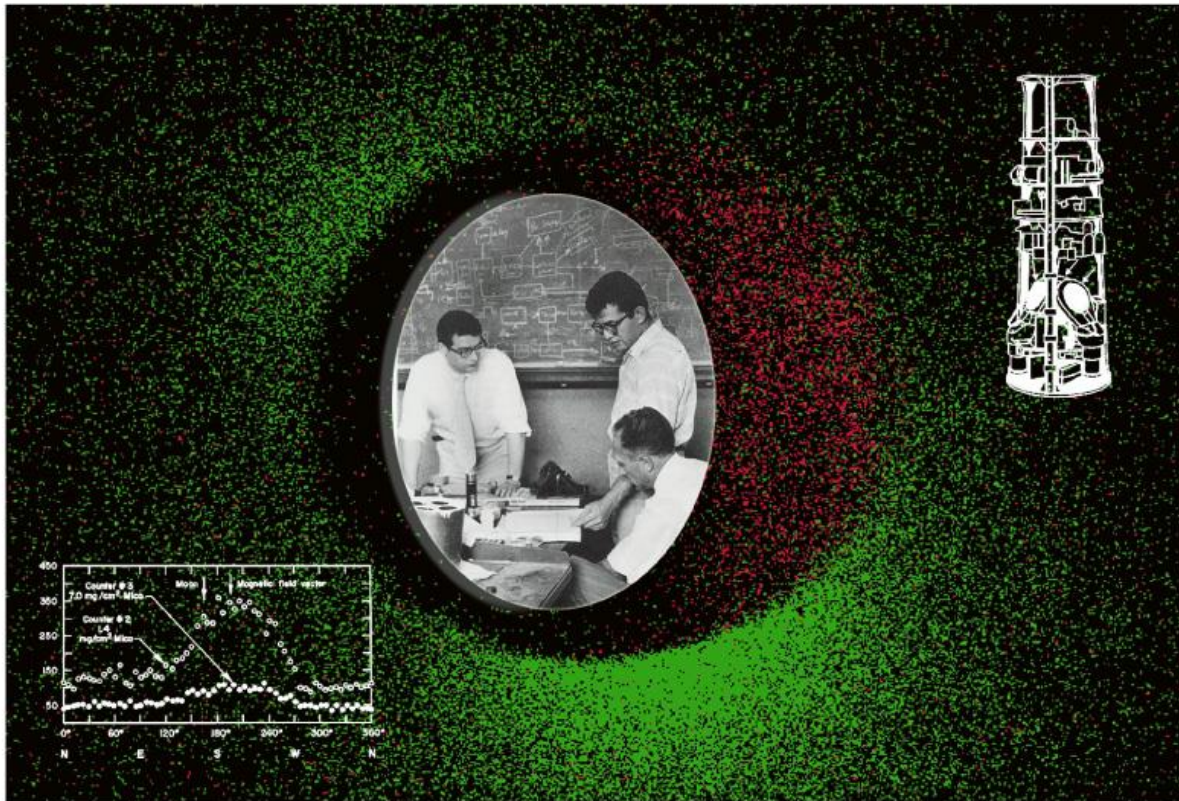


Rocket experiments. Sco X-1

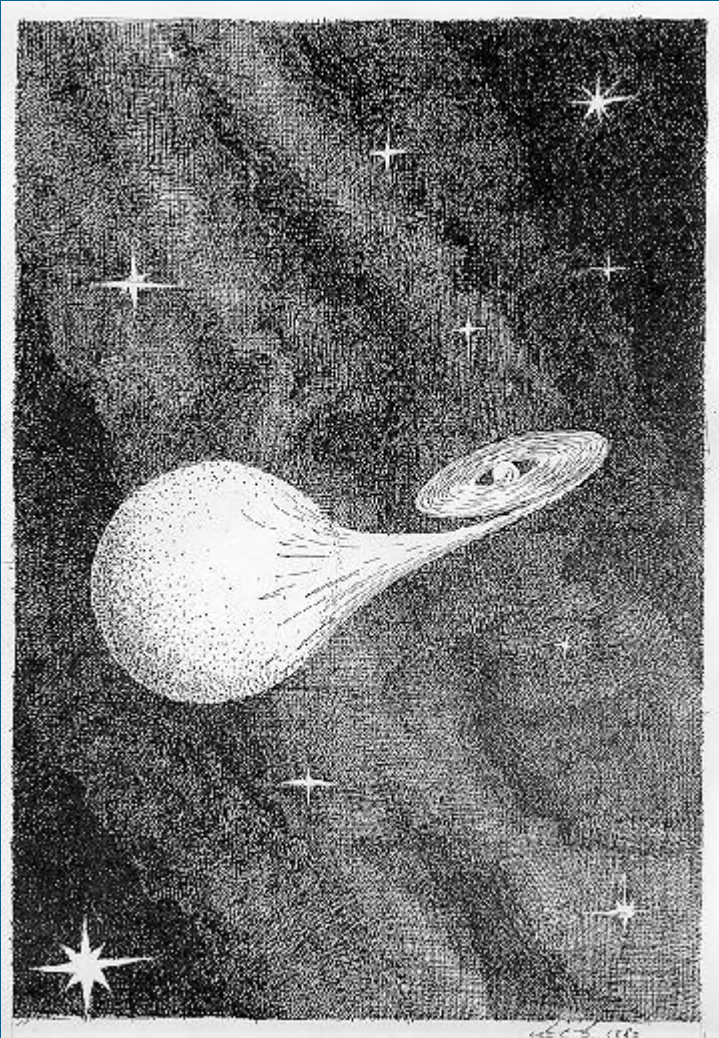
Giacconi et al. 1962

ROSAT Januar 2003

Max-Planck-Institut für
extraterrestrische Physik



Binaries are important and different!



Wealth of observational manifestations:

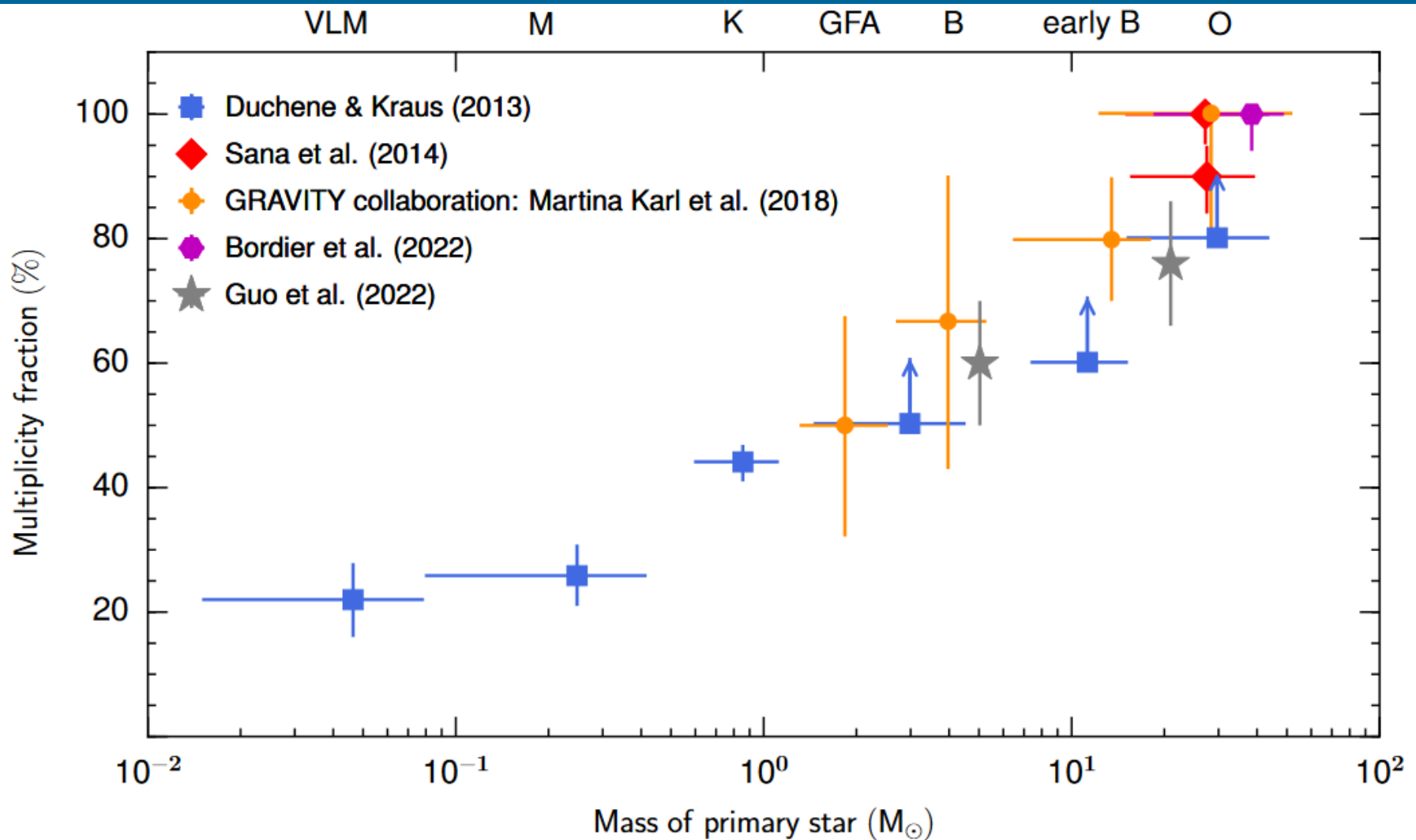
Visual binaries → orbits, masses

Close binaries → effects of mass transfer

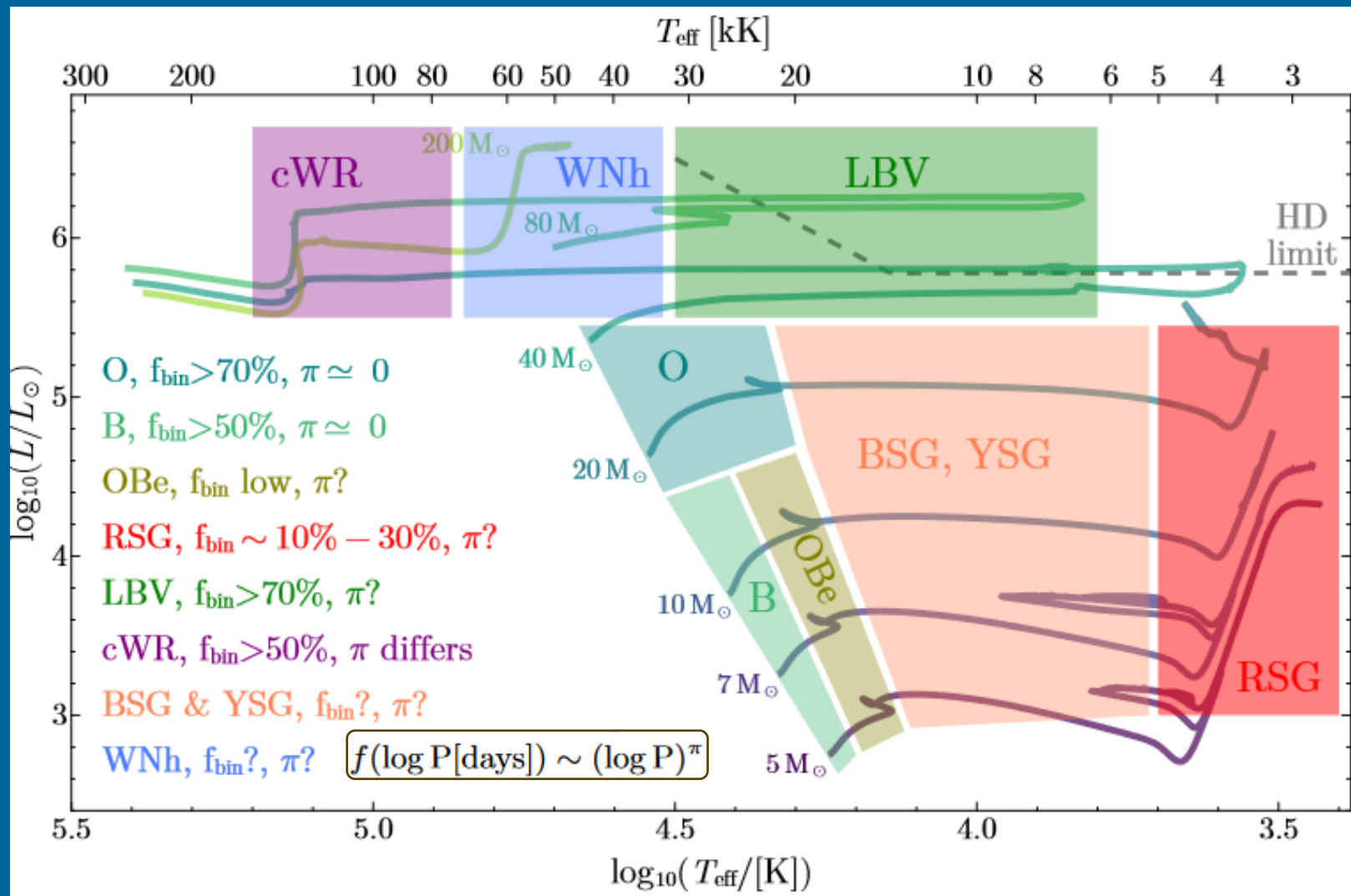
Binaries with compact stars →

X-ray binaries, X-ray transients,
cataclysmic variables, binary pulsars,
black hole candidates, microquasars...

Fraction of binaries



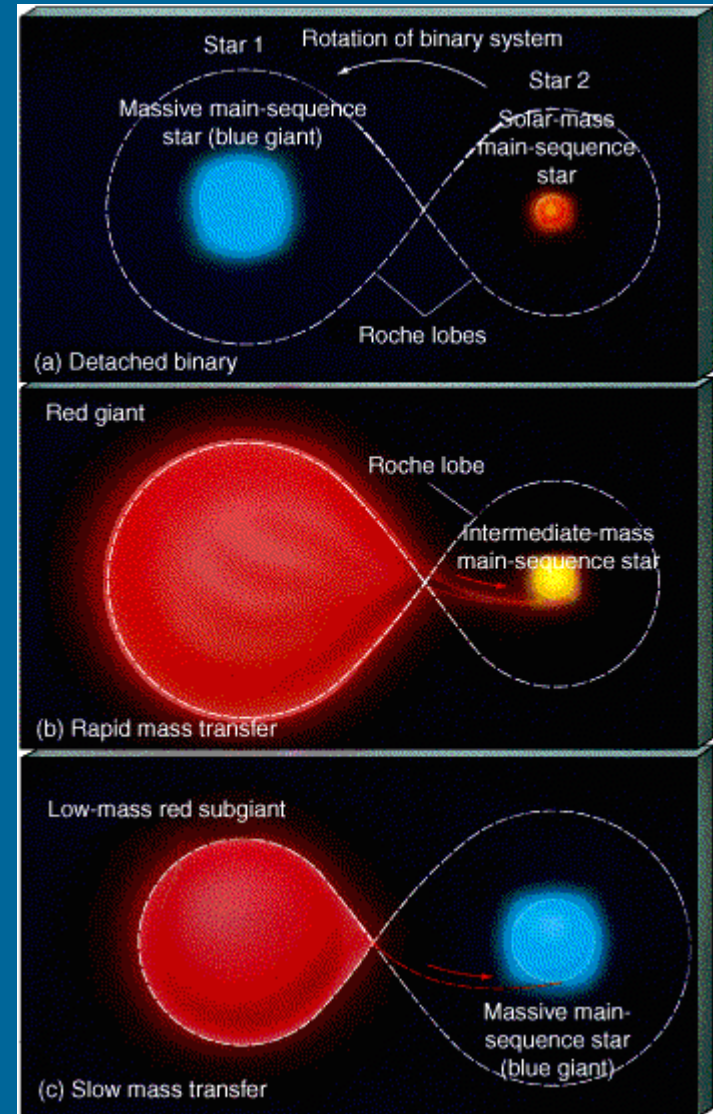
Fraction of binaries



Algol paradox

Algol (β Per) paradox:
late-type (lighter) component
is at a more advanced
evolutionary stage
than the early-type (heavier) one!

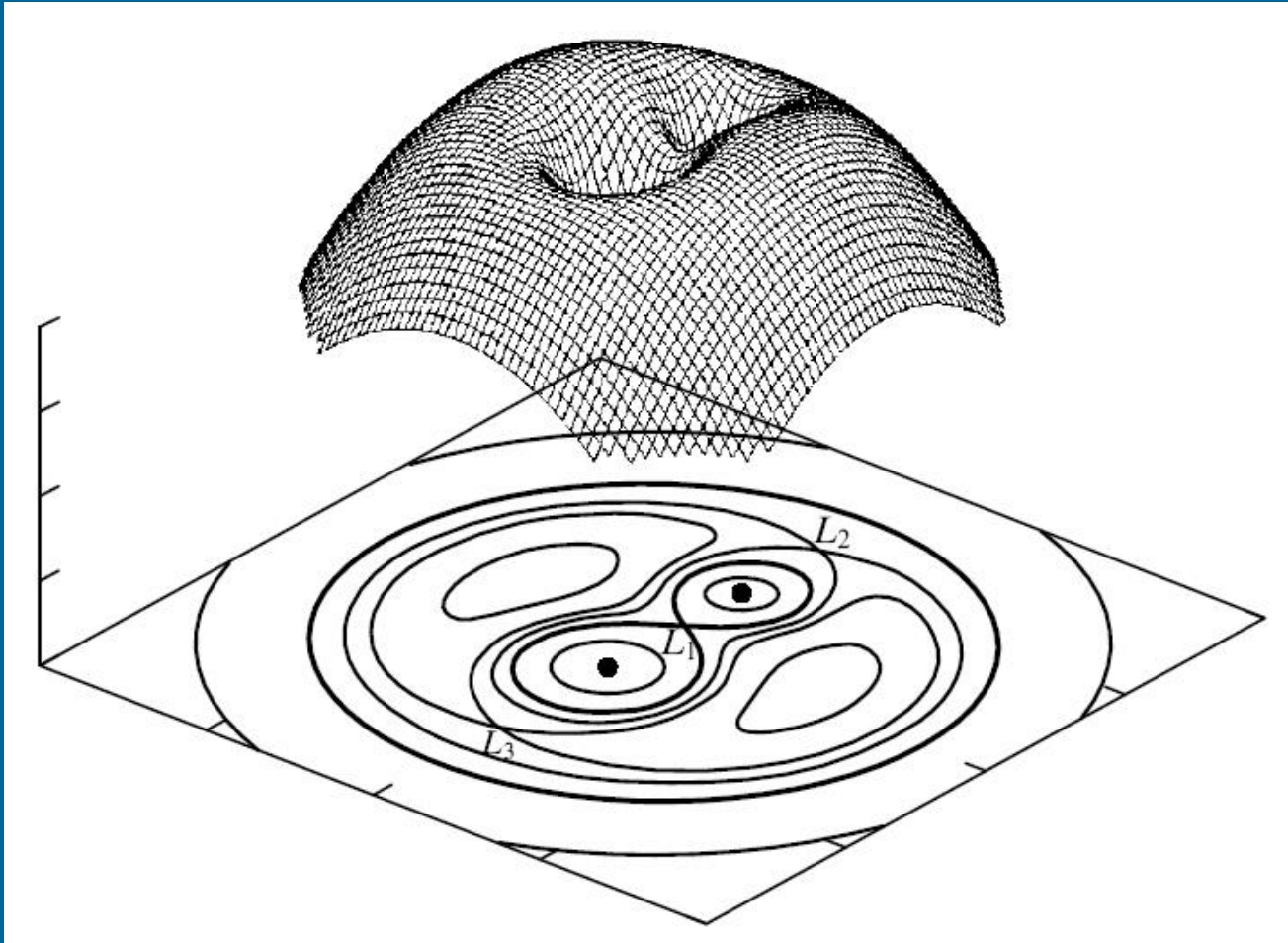
The key to the solution:
component mass reversal due to
mass transfer at earlier stages!



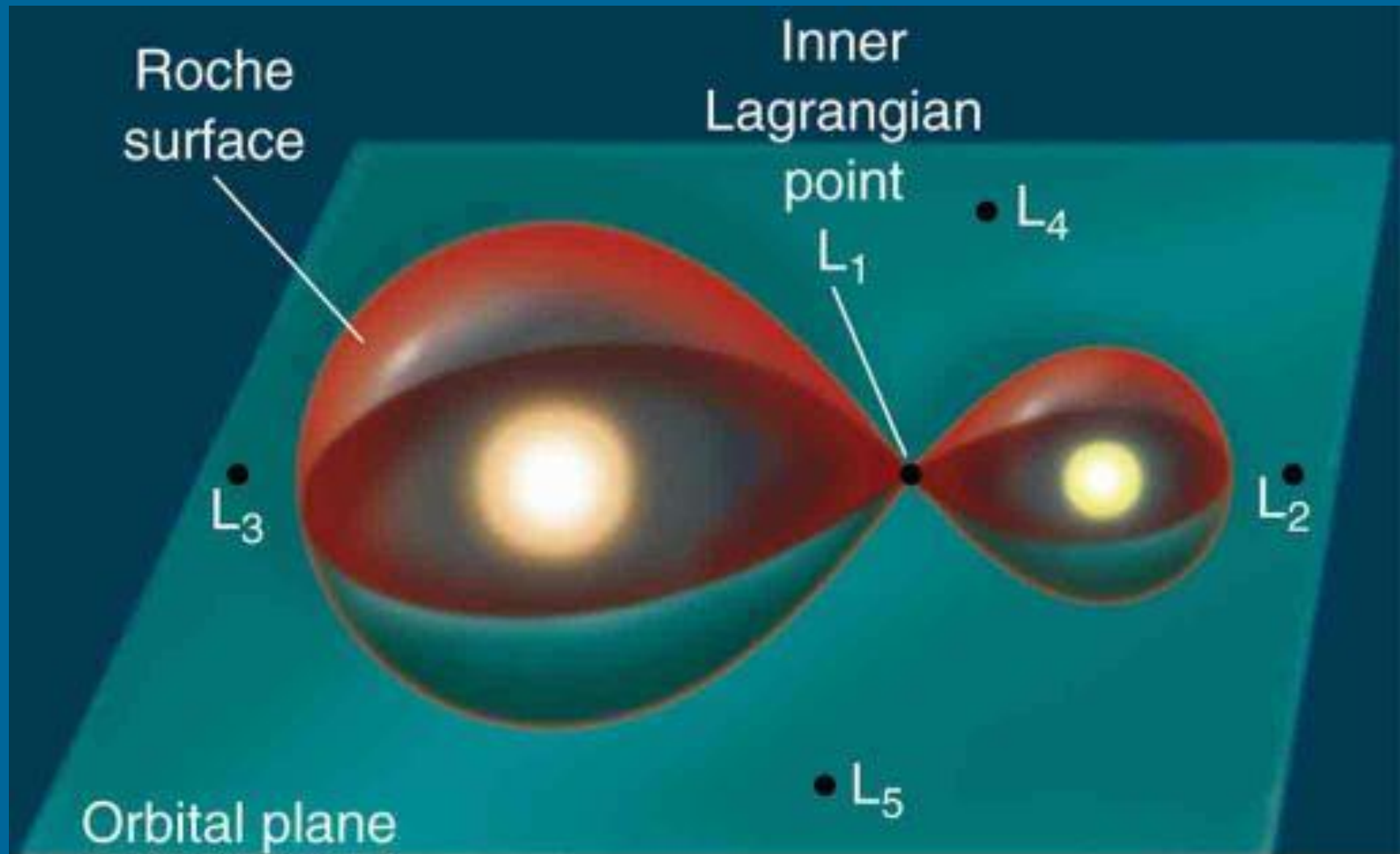
0.8 M_{\odot} G5IV

3.7 B8 V

Roche lobes and Lagrange points



Three-dimensional representation of the gravitational potential of a binary star (in a corotating frame) and several cross sections of the equipotential surfaces by the orbital plane. The Roche lobe is shown by the thick line



Roche Potential

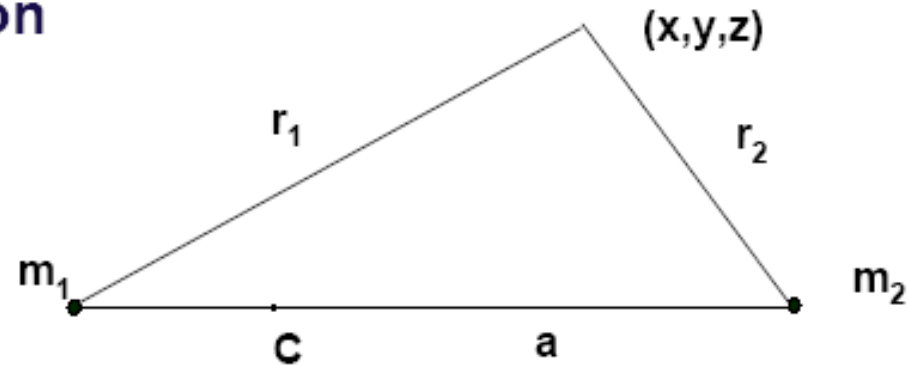
Assumes:

synchronous rotation

circular orbit

2 point masses

rotating frame



$$\omega^2 = \left(\frac{2\pi}{P} \right)^2 = \frac{G M}{a^3}$$

$$r_1^2 = x^2 + y^2 + z^2 \quad r_2^2 = (x - a)^2 + y^2 + z^2$$

$$\frac{x_c}{a} = \frac{m_2}{M} = \frac{q}{1+q} \quad q \equiv \frac{m_2}{m_1} \leq 1$$

$$\Phi = -\frac{G m_1}{r_1} - \frac{G m_2}{r_2} - \frac{\omega^2}{2} \left[(x - x_c)^2 + y^2 \right]$$

Dimensionless Roche Potential

factor out $-\frac{\omega^2}{2} = -\frac{GM}{2a^3}$ and $x \rightarrow \frac{x}{a}$, etc.

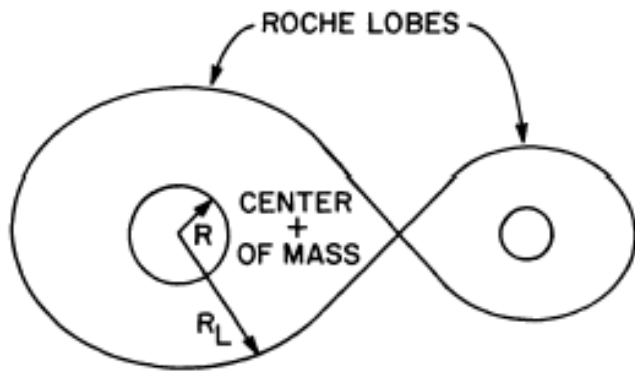
$$\Phi(x, y, z) = -\frac{\omega^2}{2} \Phi_N\left(\frac{x}{a}, \frac{y}{a}, \frac{z}{a}\right)$$

dimensionless Roche Potential:

$$\Phi_N(x, y, z) = \frac{2}{(1+q)} \frac{1}{r_1} + \frac{2q}{(1+q)} \frac{1}{r_2} + \left(x - \frac{q}{(1+q)}\right)^2 + y^2$$

Describes shape of potential surfaces independently of the mass and size of the system.

single parameter : q



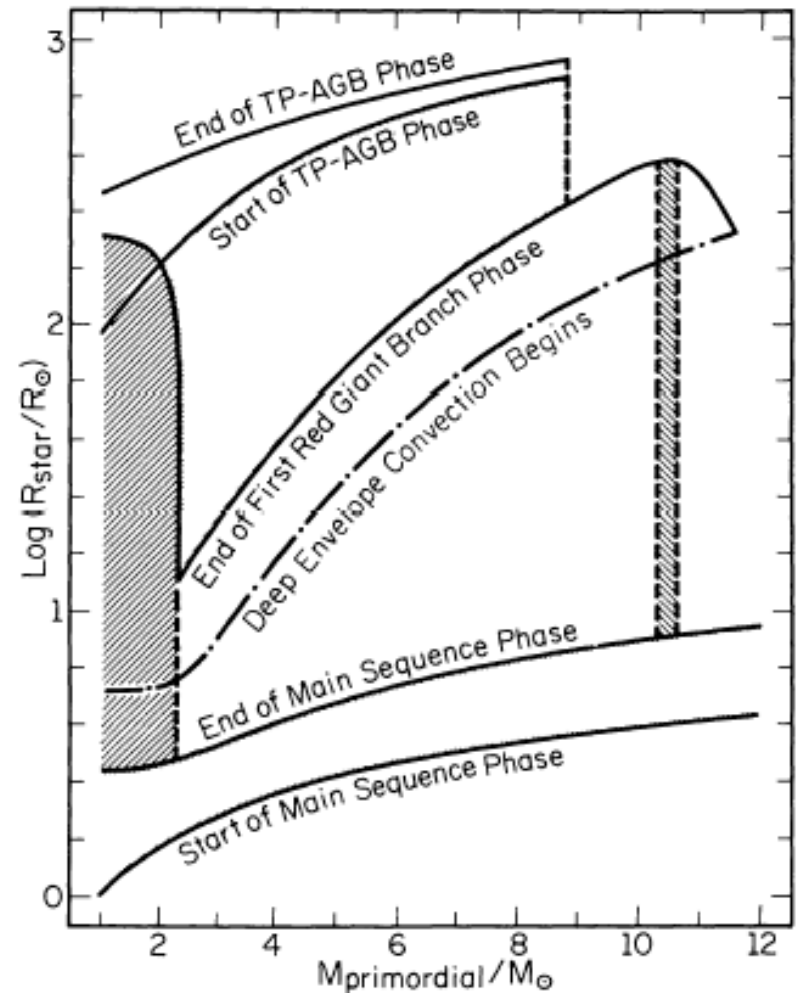
$\longleftrightarrow A$

$$R_{iL} \sim 0.52 \left(\frac{m_i}{m_{\text{tot}}} \right)^{0.44} A$$

WHEN $R_i > R_{iL}$

\Rightarrow ROCHE-LOBE OVERFLOW

$$\frac{R_L}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}$$

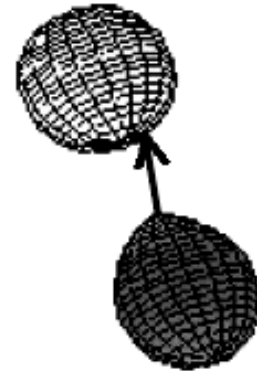


Binaries in Roche-Lobes

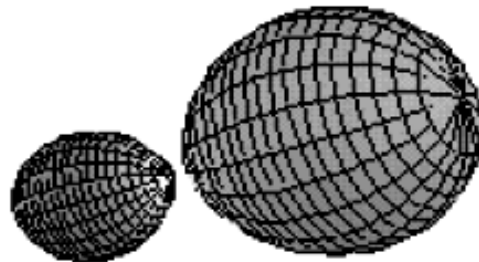
detached



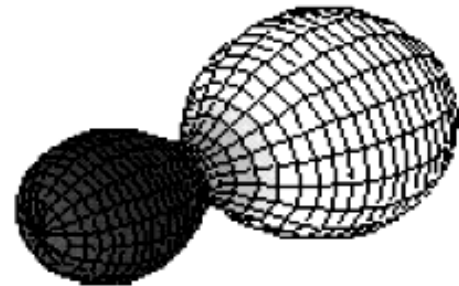
**semi-detached
(Algol)**



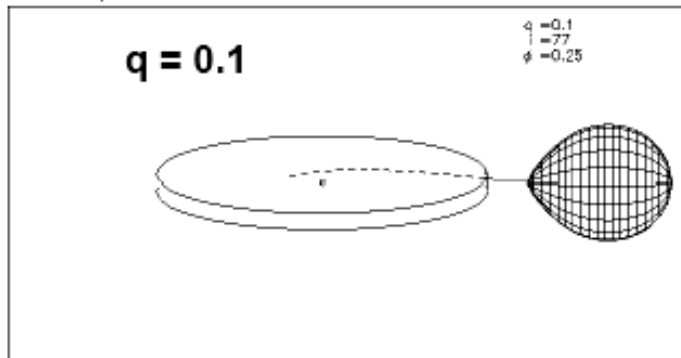
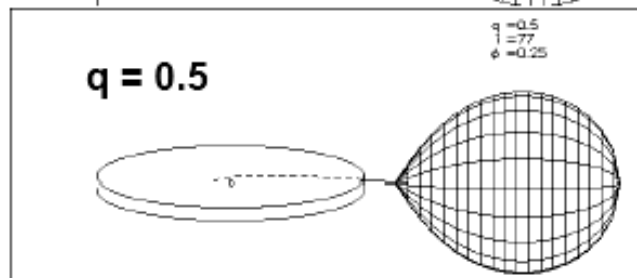
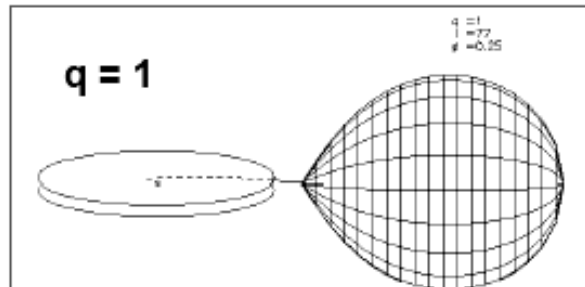
close to contact



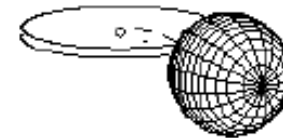
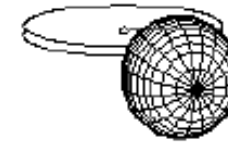
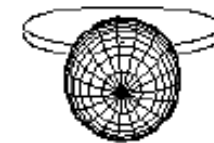
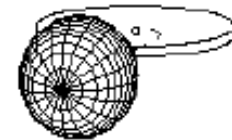
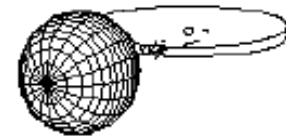
contact (W UMa)



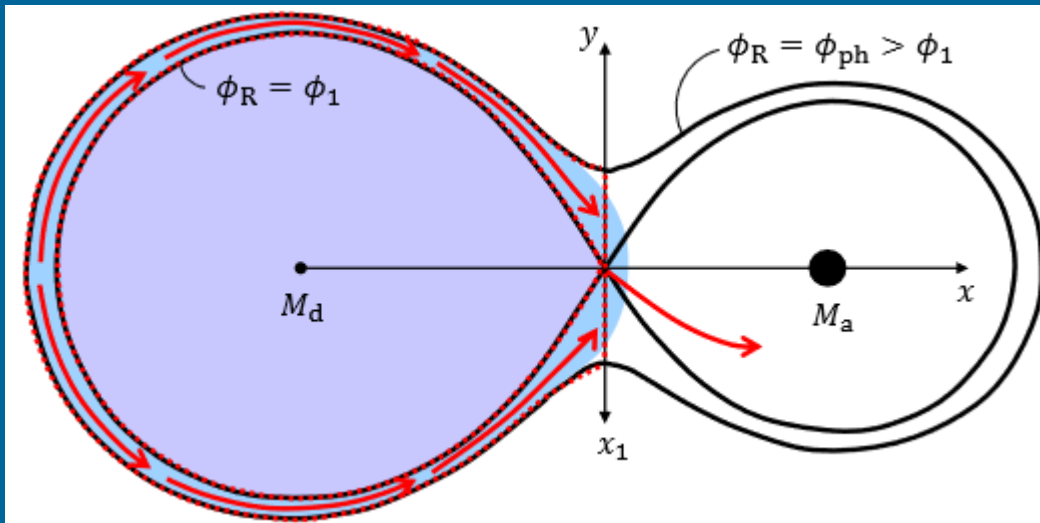
Roche Lobes



eclipses



Mass transfer models

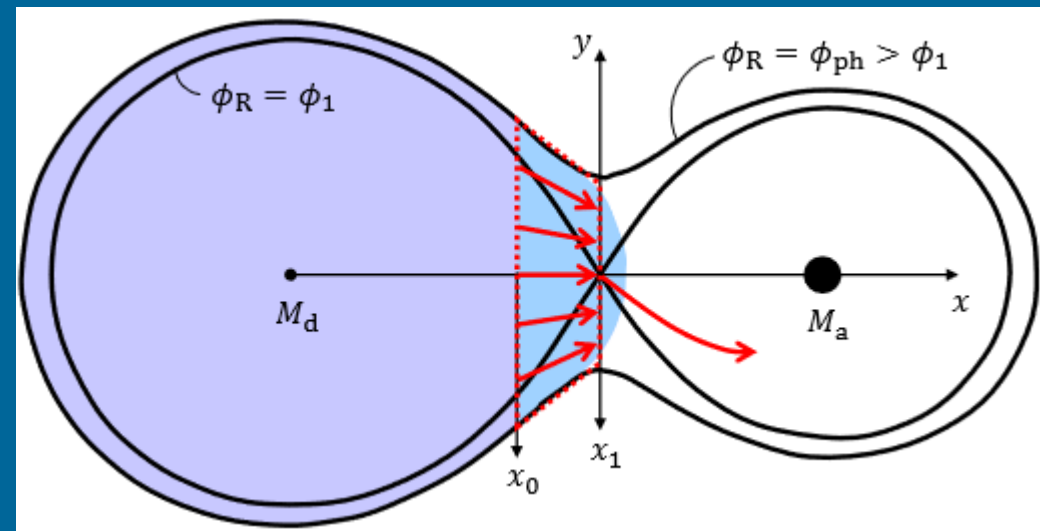


Kolb & Ritter (1990)

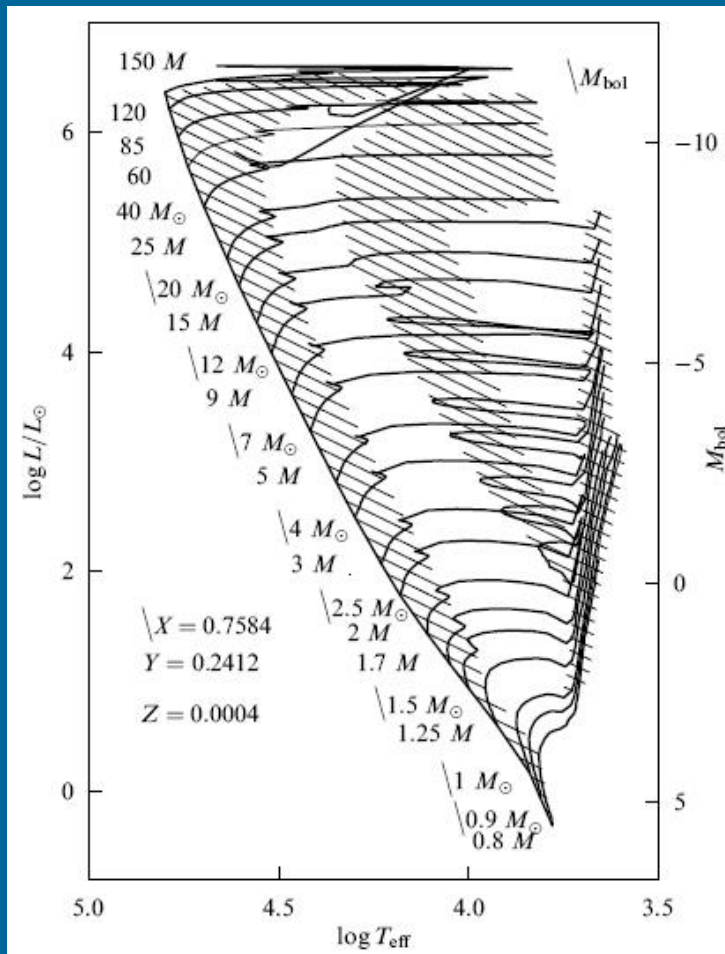
Gas with potential $\phi < \phi_1$ remains in hydrostatic equilibrium whereas the gas with higher potential, flows toward L1 along streamlines that lie nearly on equipotential surfaces.

Chehula & Pejcha (2023)

MT flow is a special case of a non-spherical stellar wind in a 3D potential.



Evolution of normal stars



Evolutionary tracks of single stars with masses from 0.8 to 150 M_{\odot} . The slowest evolution is in the hatched regions (Lejeune T, Schaerer D *Astron. Astrophys.* 366 538 (2001))

A track for a normal 5 solar mass star

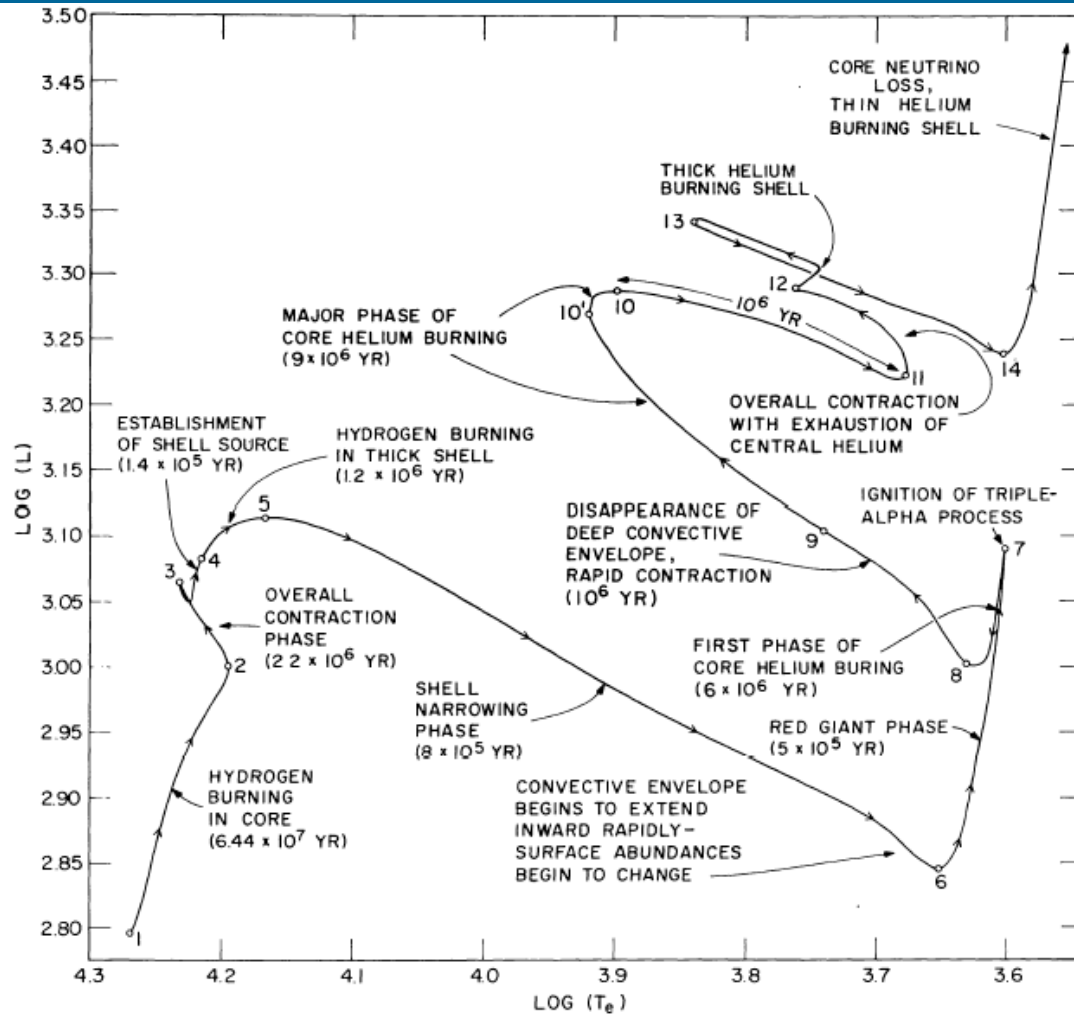
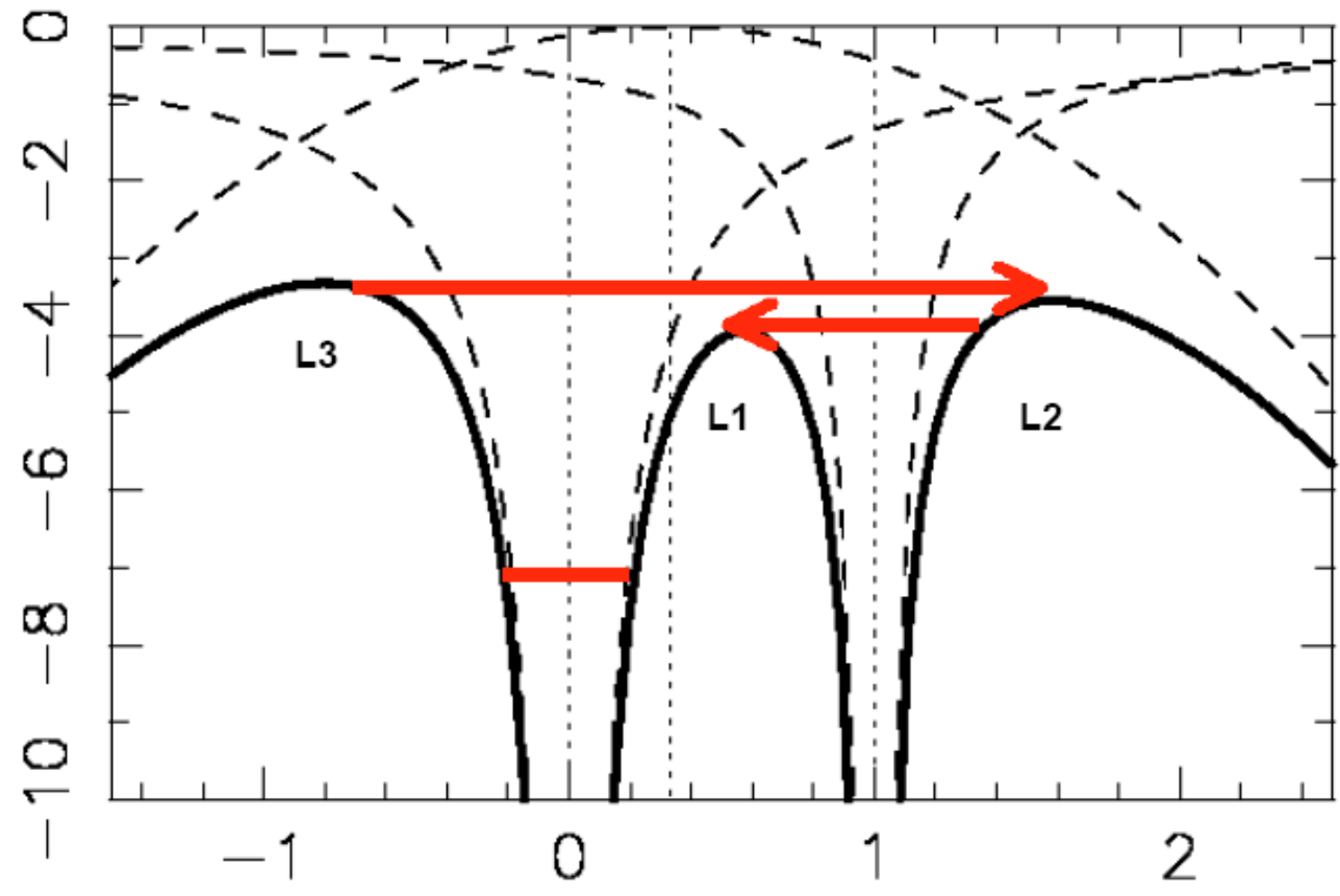
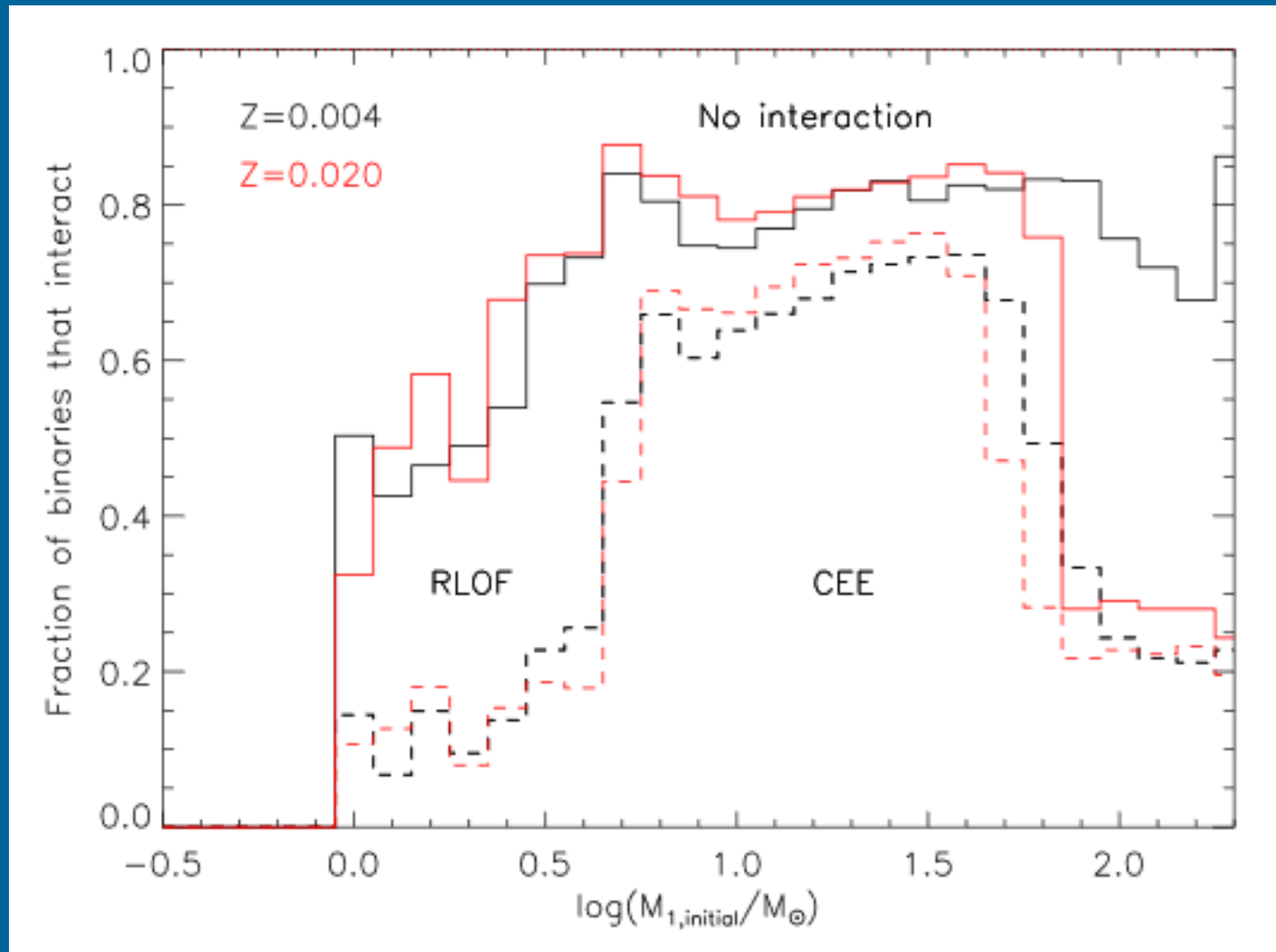


FIG. 2.—The track in the H-R diagram of a theoretical model star of mass $5 M_{\odot}$ and of Population I composition. Text beside various portions of the track describe an important physical process occurring within the star at the indicated position. From Iben (1967c).

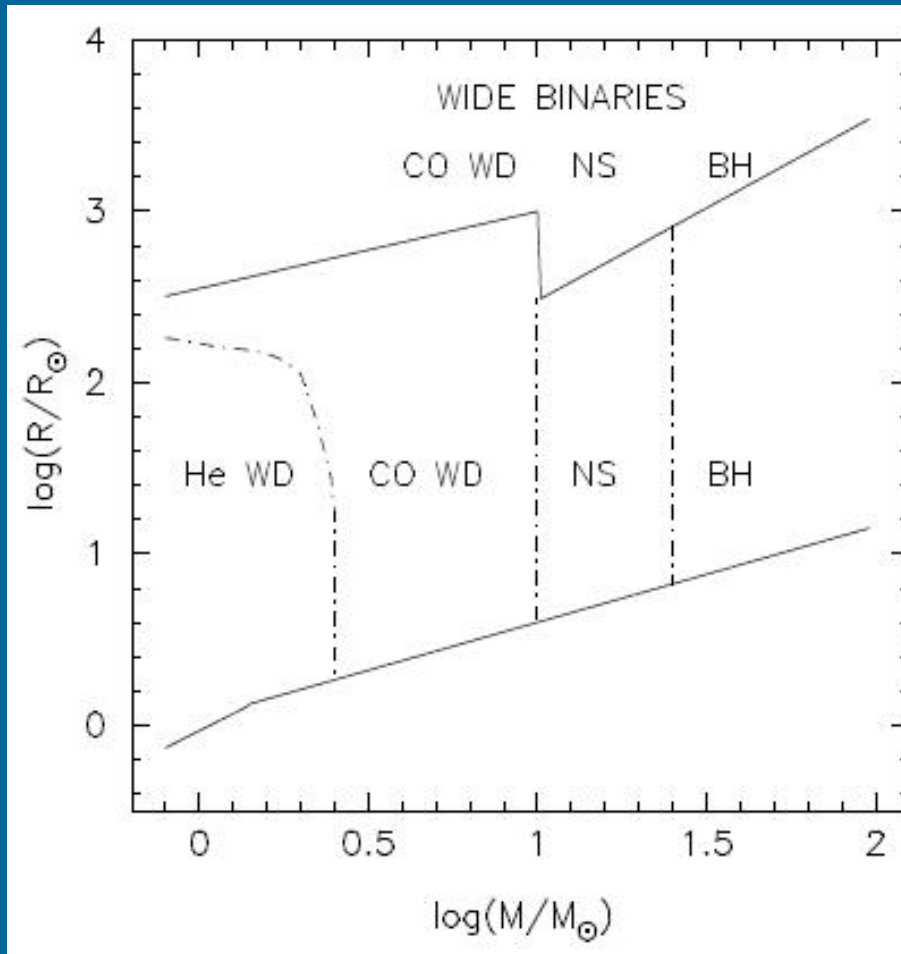
Mass transfer and loss



How often do binaries interact?



Progenitors and descendants



Descendants of components of close binaries depending on the radius of the star at RLOF.

The boundary between progenitors of He and CO-WDs is uncertain by several $0.1M_{\odot}$.

The boundary between WDs and NSs by $\sim 1M_{\odot}$, while for the formation of BHs the lower mass limit may be even by $\sim 10M_{\odot}$ higher than indicated.

[Postnov, Yungelson 2007]

Mass loss and evolution

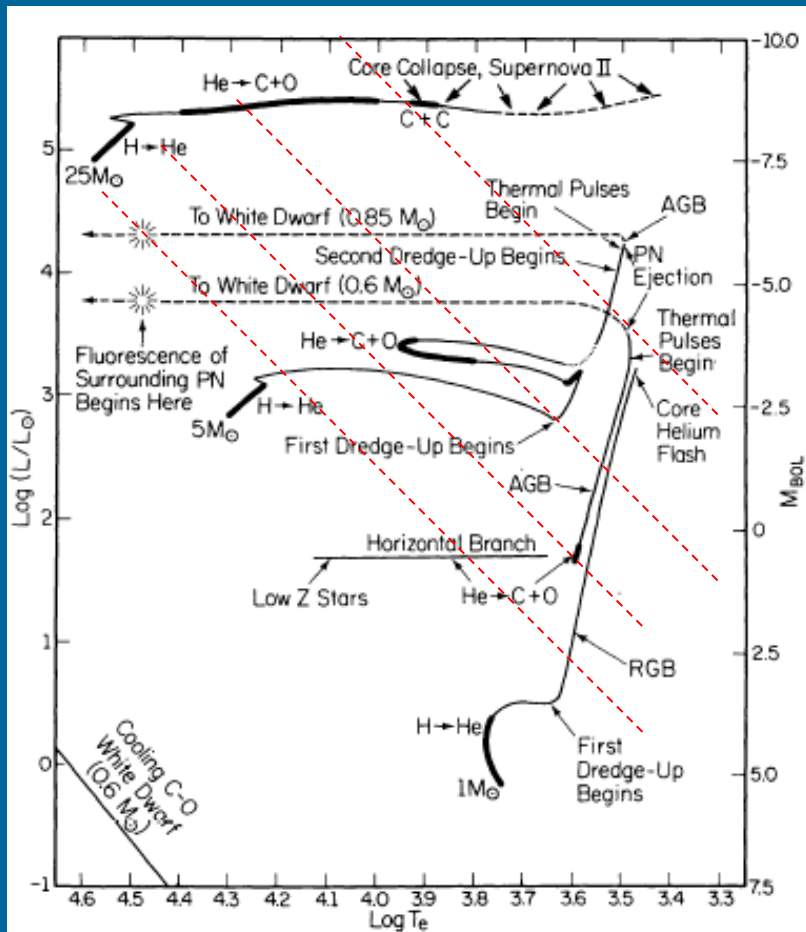


FIG. 5.—Tracks in the H-R diagram of theoretical model stars of low ($1 M_{\odot}$), intermediate ($5 M_{\odot}$), and high ($25 M_{\odot}$) mass. Nuclear burning on a long time scale occurs along the heavy portions of each track. The places

Mass loss depends on which stage of evolution the star fills its Roche lobe

If a star is isentropic (e.g. deep convective envelope - RG stage), mass loss tends to increase R with decreasing M which generally leads to unstable mass transfer.

Evolution of a 5M star in a close binary

Mass loss stages

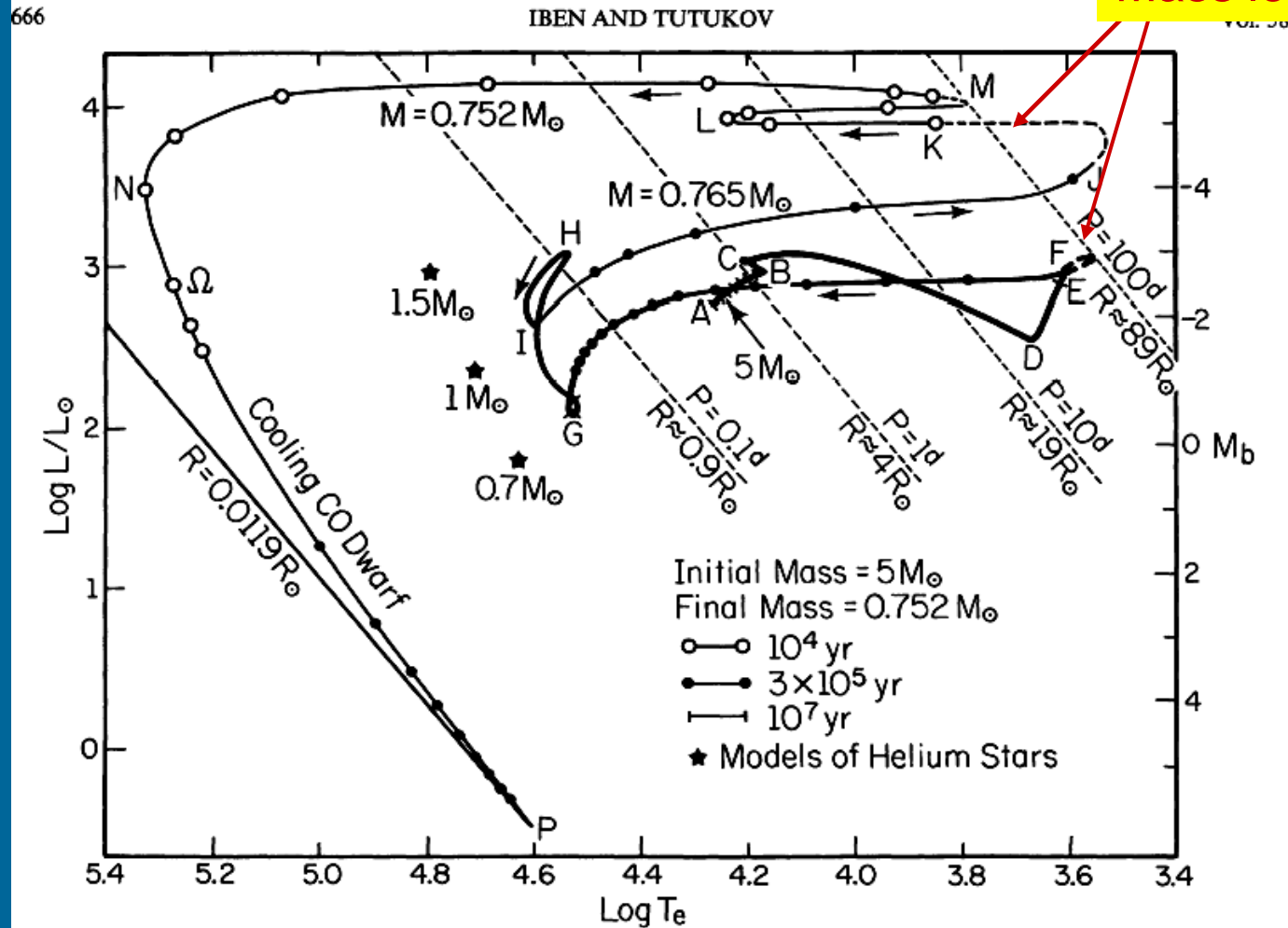


FIG. 1.—Evolution in the H-R diagram of a binary component of initial mass $5M_{\odot}$. Initial composition parameters are $X=0.7$, $Z=0.02$. The positions of helium model stars are given by the filled, five-pointed “stars” (Paczynski 1971). Lines of constant orbital period and Roche-lobe radius for a system consisting of two $5M_{\odot}$ unevolved stars are also shown. The temperature of the CO shell reaches a maximum at the point Ω along the track. The main parameters of the stellar model at other labeled points (A, B, ...) are presented in Table 1. Mass loss occurs along dashed portions of the track (E to F; J to K). Time evolution is measured by tick marks (10^7 yr), filled circles (3×10^5 yr), and open circles (10^4 yr).

Different cases for Roche lobe overflow

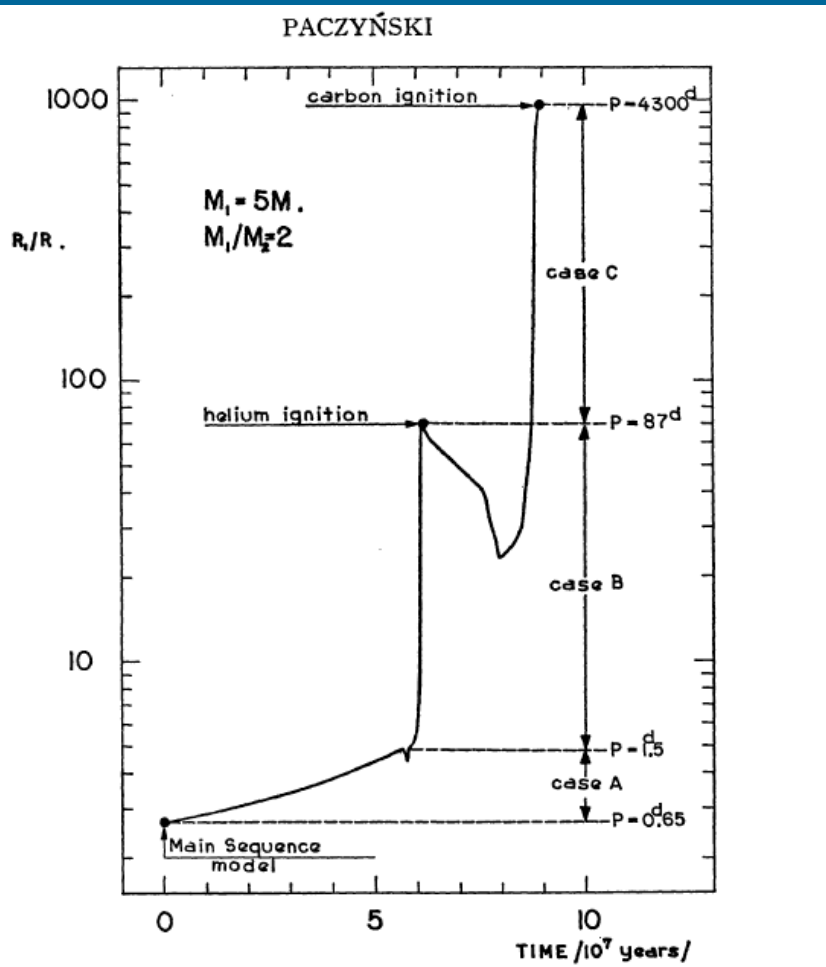


FIGURE 1. The time variation of the radius of a $5 M_\odot$ star. The ranges of orbital corresponding to the evolution with mass exchange in cases A, B, and C are indicated. A mass ratio of $M_1/M_2 = 2$ is adopted.

Three cases of mass transfer loss by the primary star (after R. Kippenhahn)

In the most important case B, mass transfer occurs on the thermal time scale:

$$dM/dt \sim M/T_{KH}, \quad T_{KH} = GM^2/RL$$

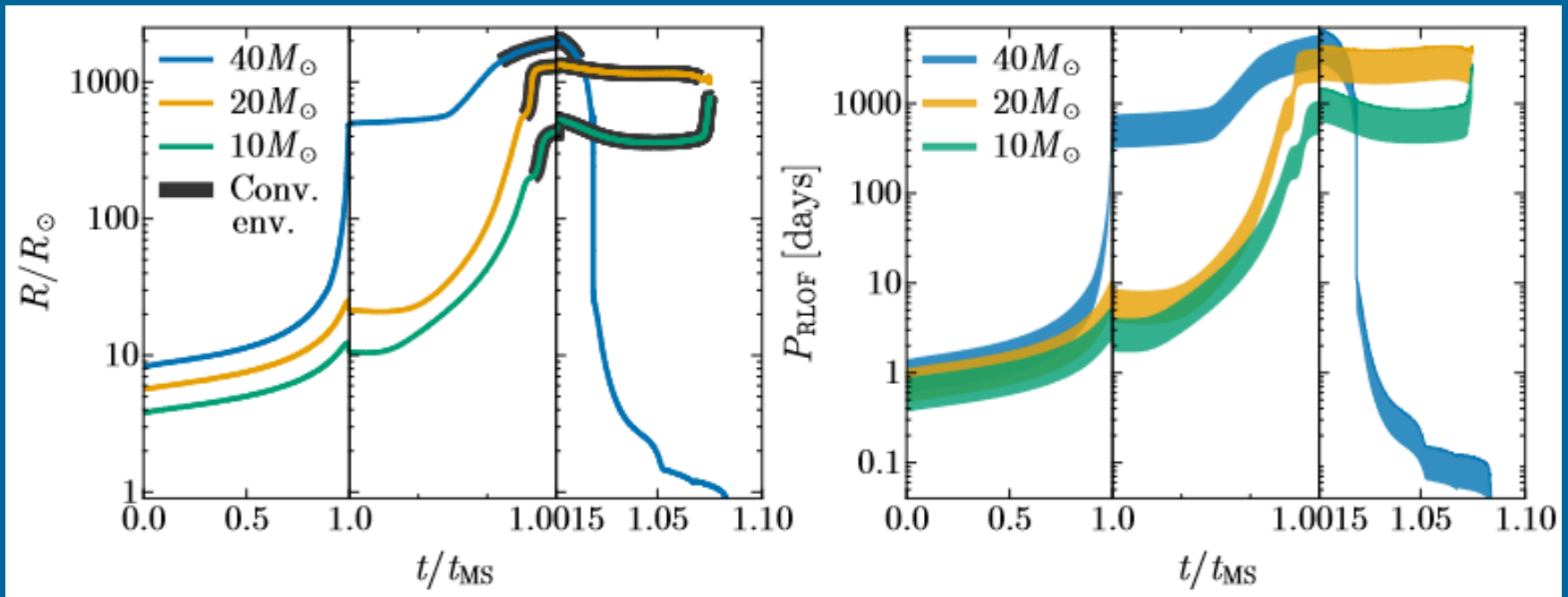
In case A: on the nuclear time scale:

$$dM/dt \sim M/t_{nuc}$$

$$t_{nuc} \sim 1/M^2$$

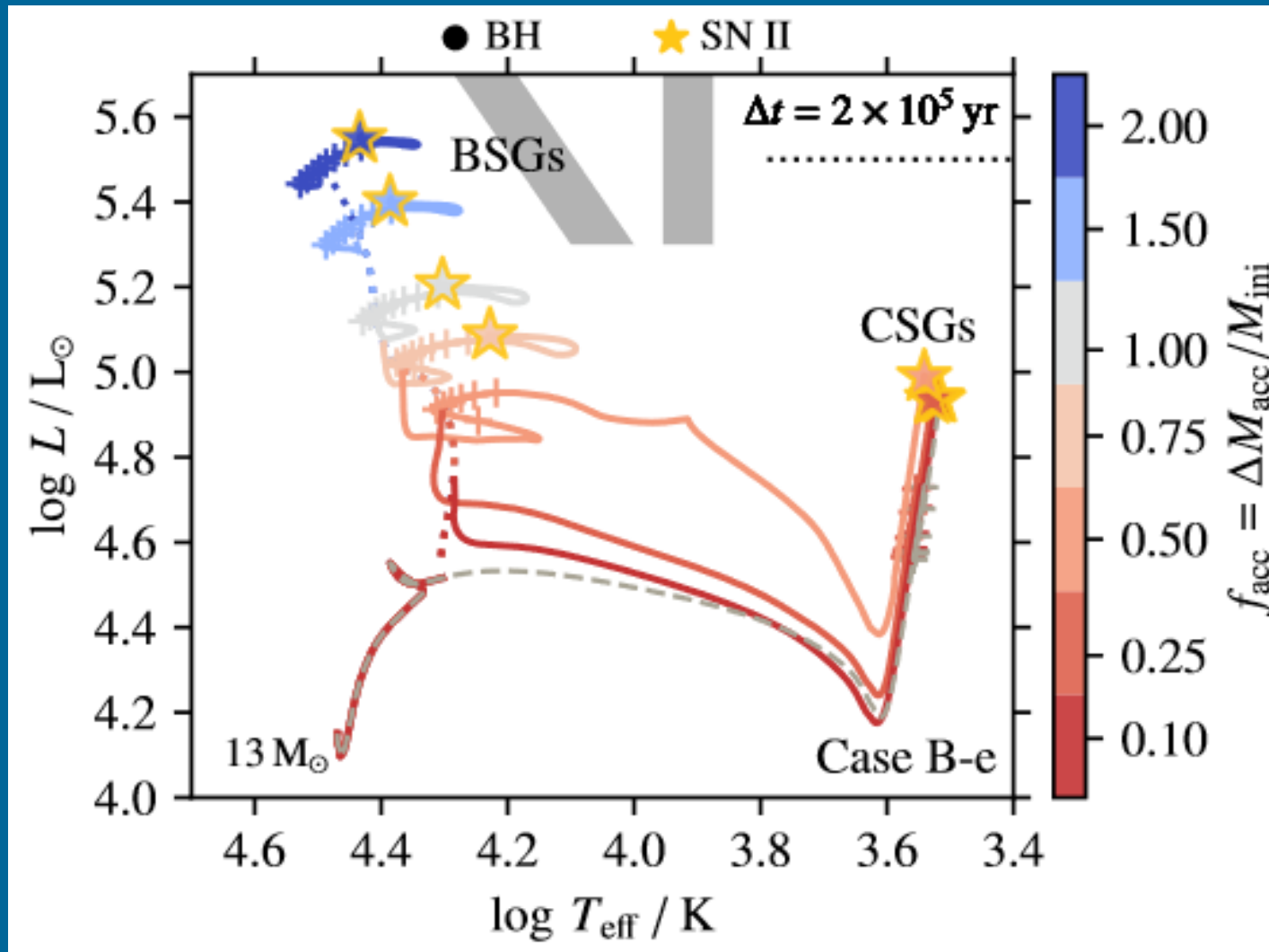
Roche lobe overflow at various stages

HMXBs – High-mass X-ray binaries



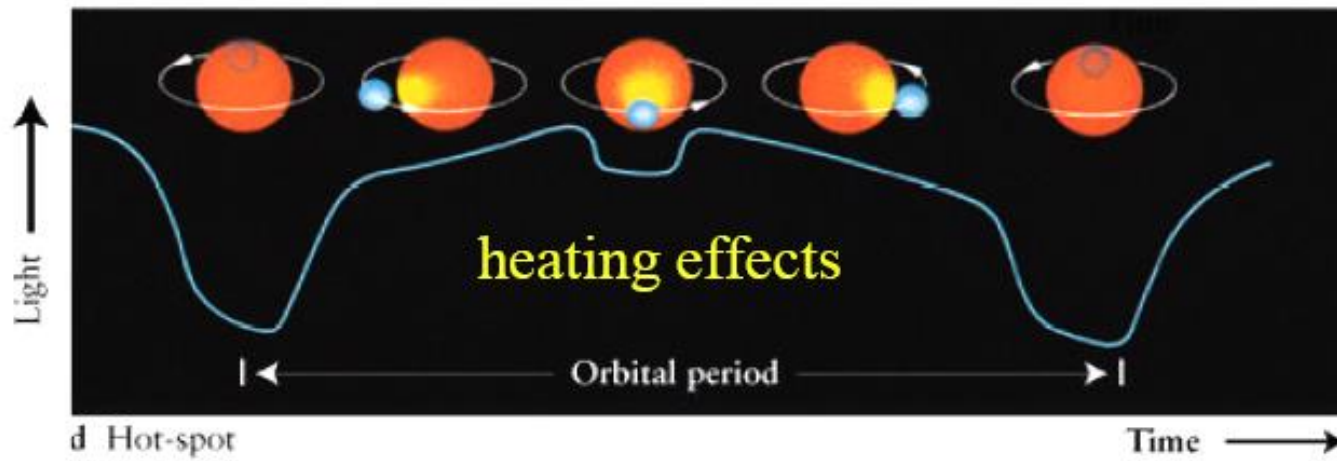
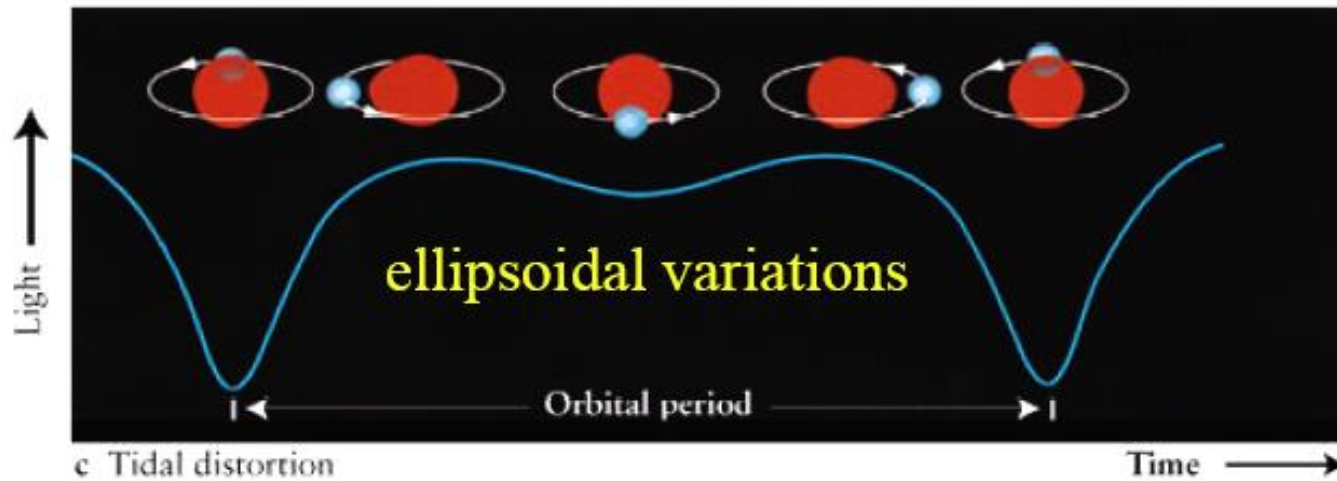
$$P_{\text{RLOF}} = R_1^{3/2} \left(\frac{4\pi^2}{Gm_1} \right)^{1/2} g(q), \quad g(q) \equiv (f(q))^{-3/2} \left(\frac{q}{1+q} \right)^{1/2}$$

Accretion in a binary and pre-SN state

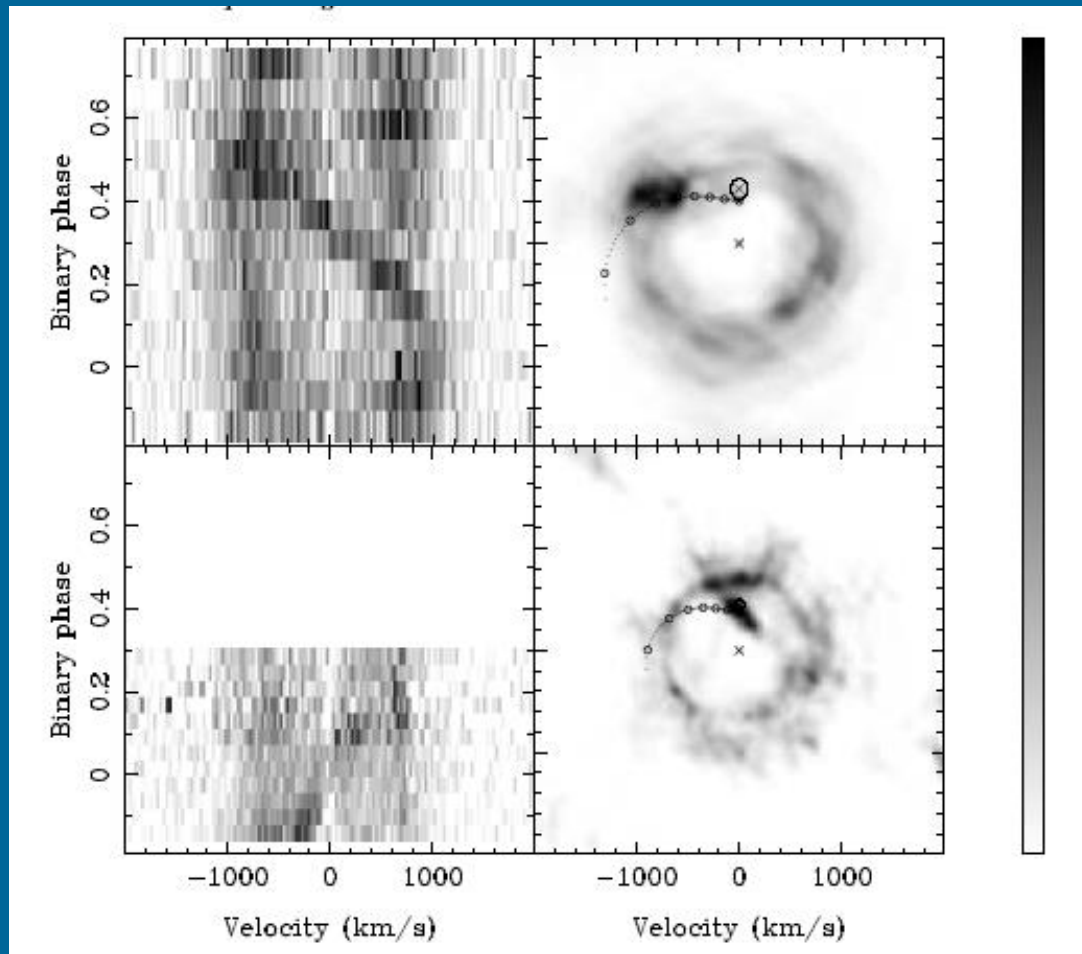


Accretion in a binary system can change the type of the pre-SN.

Proximity Effects



GS 2000+25 and Nova Oph 1997



On the left – H α spectrum,
On the right – the Doppler image

← GS 2000+25

← Nova Oph 1997

See a review in Harlaftis 2001
(astro-ph/0012513)

(Psaltis astro-ph/0410536)

There are eclipse mapping, doppler tomography (shown in the figure),
and echo tomography (see 0709.3500).

Models for the XRB structure

Sco X-1



Heating of the donor star and irradiation.

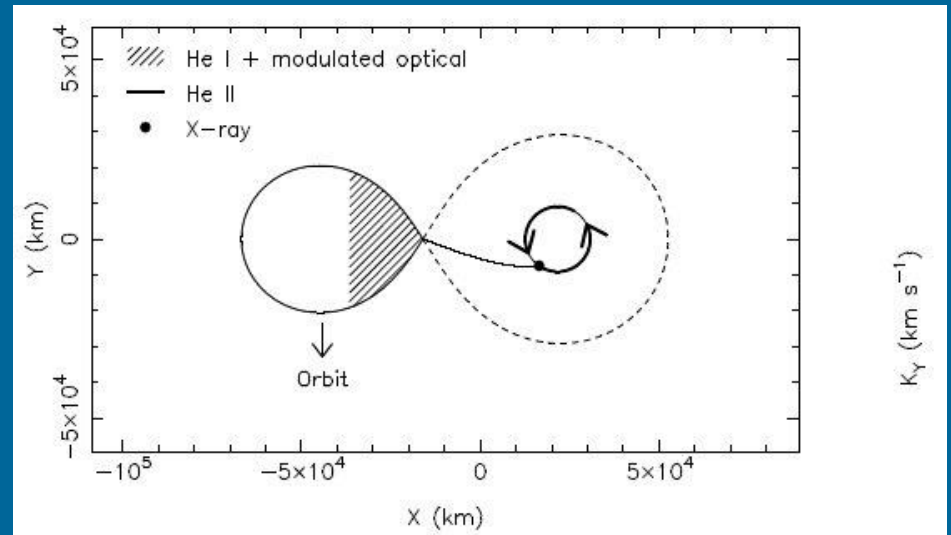
Analysis of time delays between X-ray and optics allows to derive the structure of the system.

The tightest binary

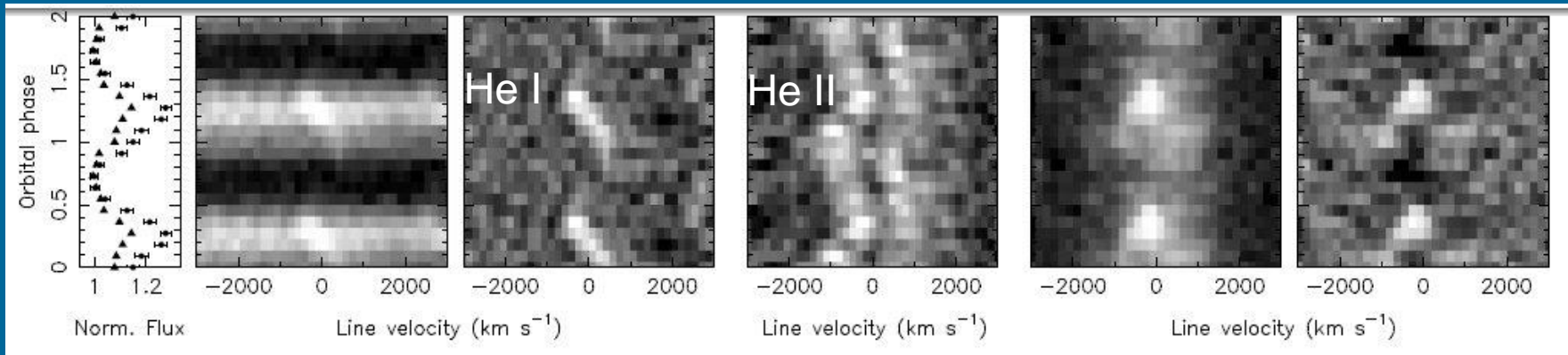


HM Cancri

Two white dwarfs.
Orbital period 321 seconds!
Distance between stars: <100 000 km.
Orbital velocity > 1 000 000 km per hour!
Masses: 0.27 and 0.55 solar
Gravitational wave emission



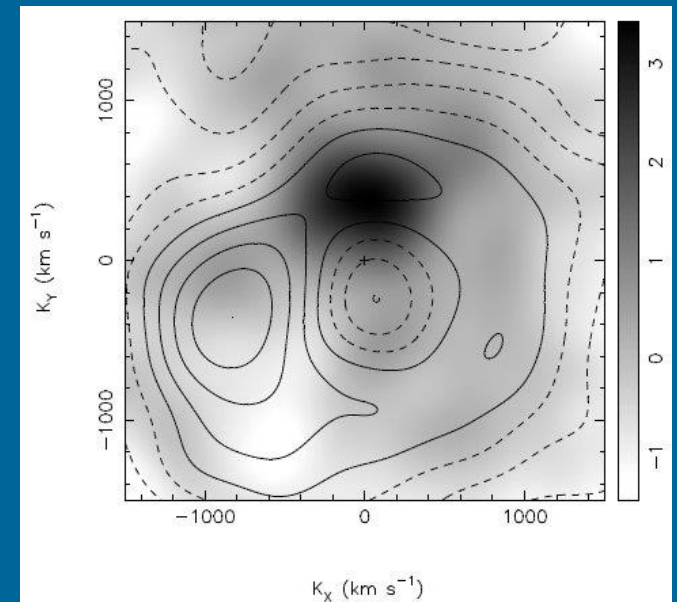
How is it measured?



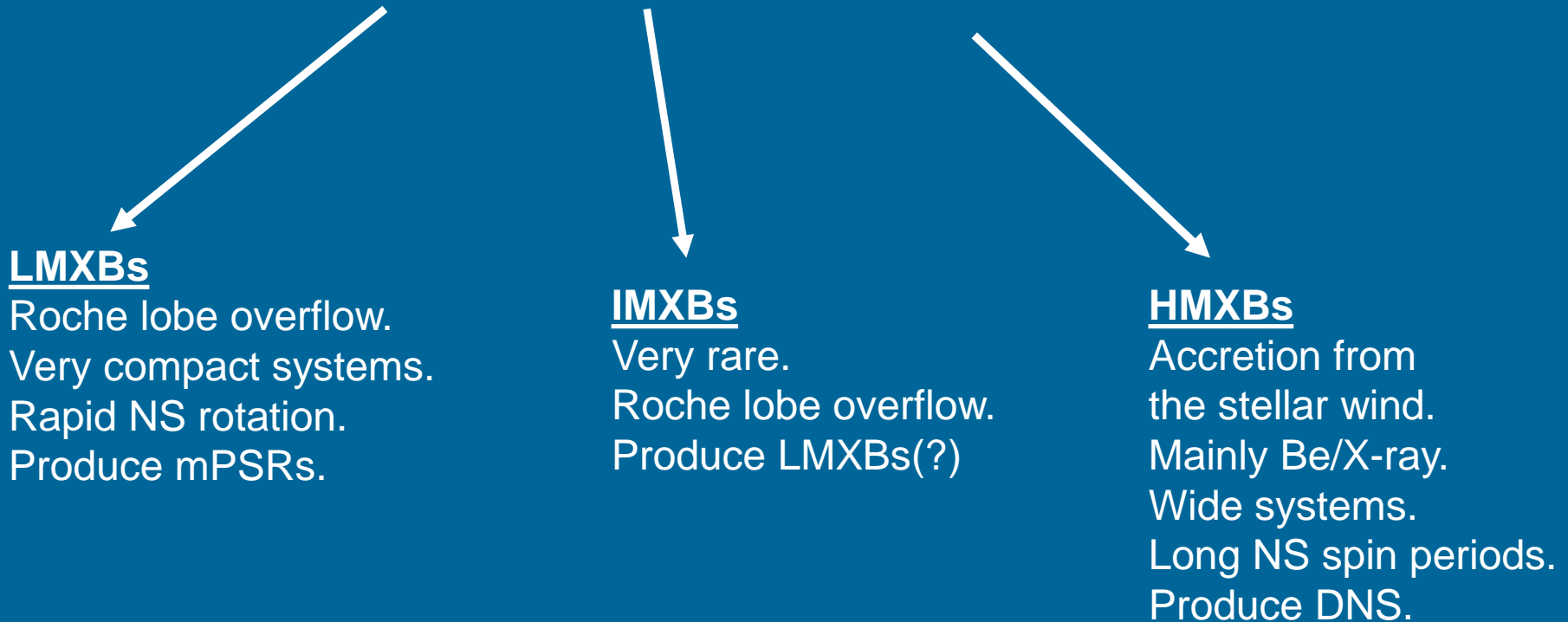
Spectra obtained by the Keck telescope.
Due to orbital motion spectral lines are shifted:
one star – blueshifted, another – redshifted.
The effect is periodic with the orbital period.

Doppler tomograms of He I 4471 (gray-scale) and
He II 4686 (contours).

The (assumed) irradiation-induced He I 4471
emission from the secondary star has been aligned
with the positive K_Y -axis.

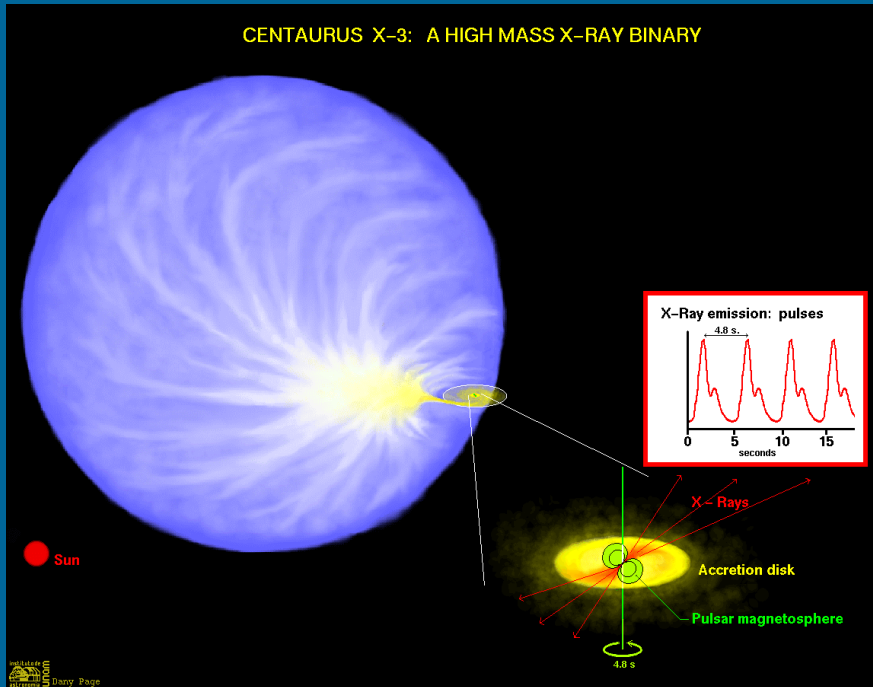


Close binaries with accreting compact objects



Among binaries ~ 40% are close and ~96% are low and intermediate mass ones.

HMXBs

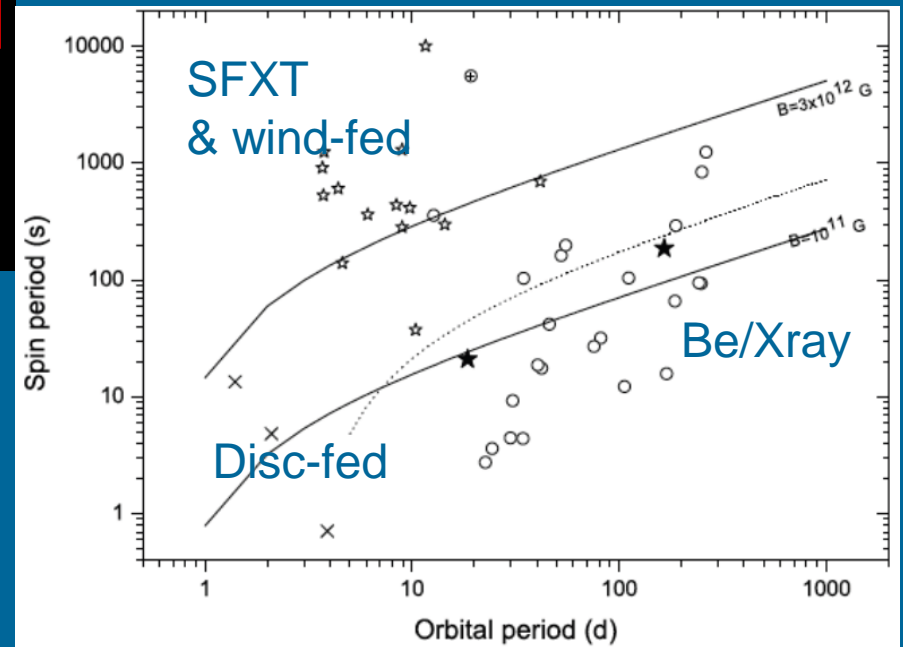


>100 in the Galaxy and >100 in MC.

See catalogs in 2303.16137 and 2302.02656 and a review 2308.02645.

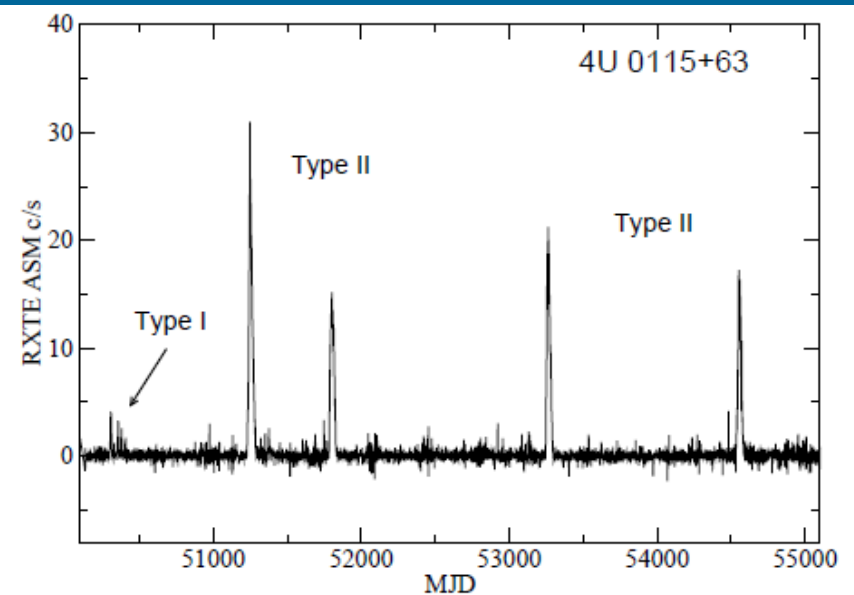
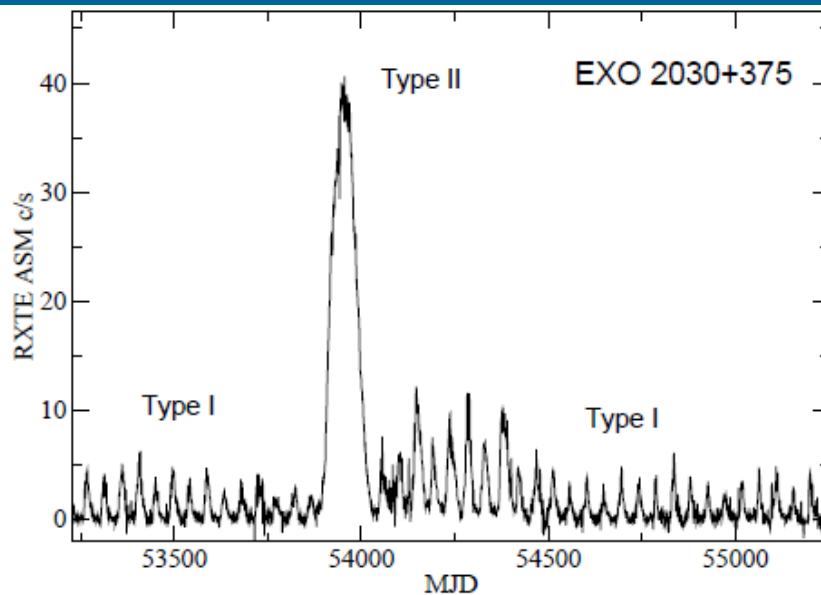
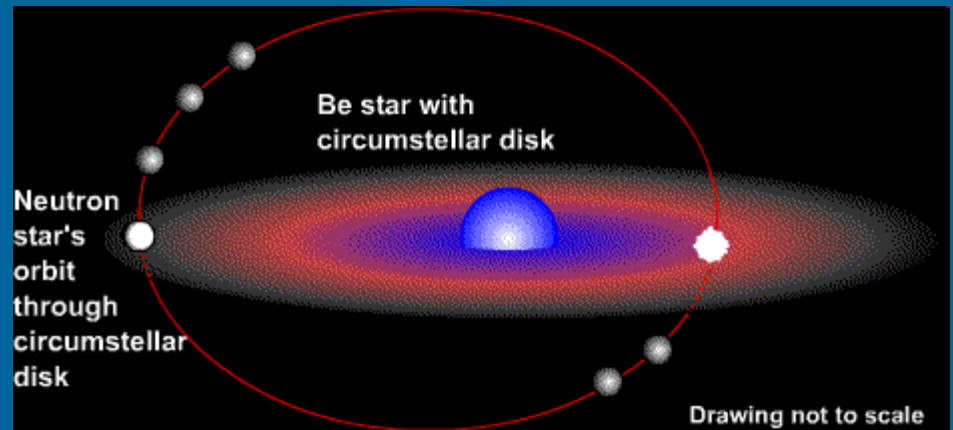
Different types:

- Be/Xray binaries
- SFXT
- “Normal” supergiants
 - disc-fed
 - wind-fed

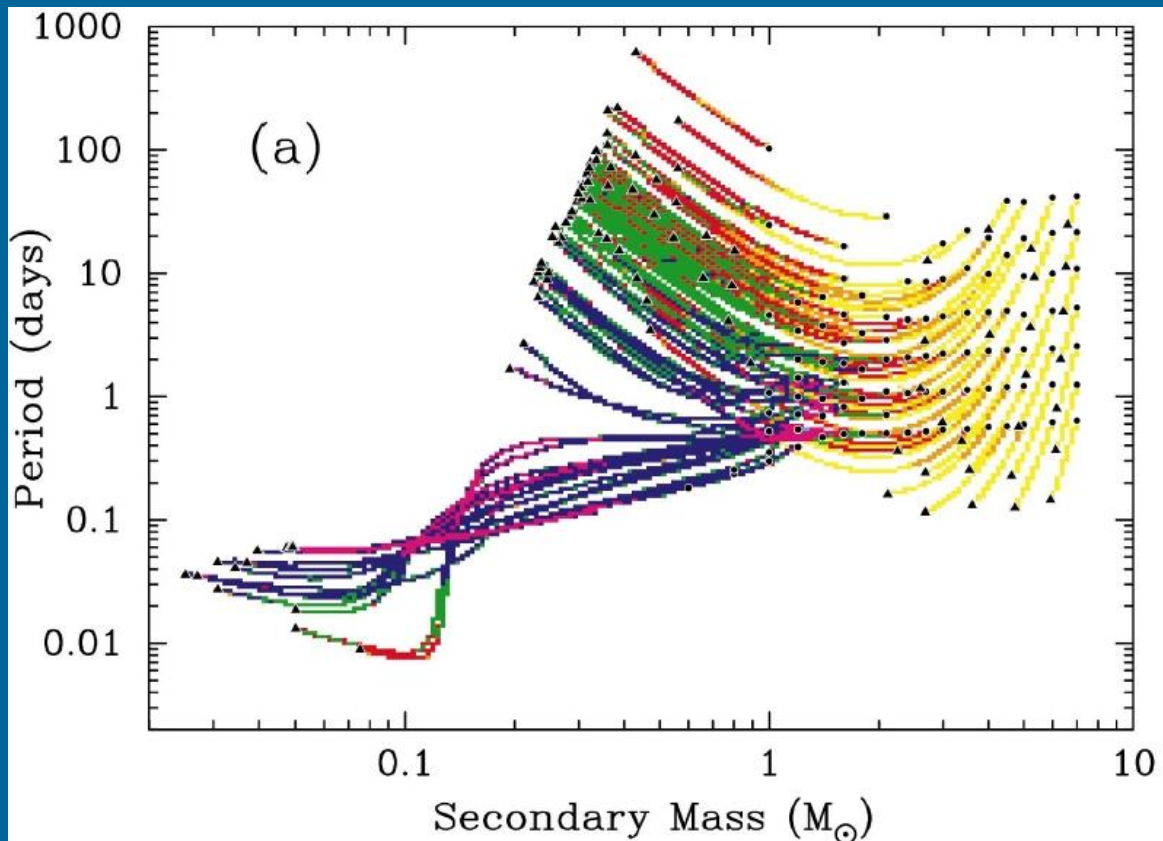


Be/X-ray binaries

Very numerous.
Mostly transient.
Eccentric orbits.



Intermediate mass X-ray binaries



Most of the evolution time systems spend as an X-ray binary occurs after the mass of the donor star has been reduced to $<1M_{\odot}$

Otherwise, more massive systems experiencing dynamical mass transfer and spiral-in.

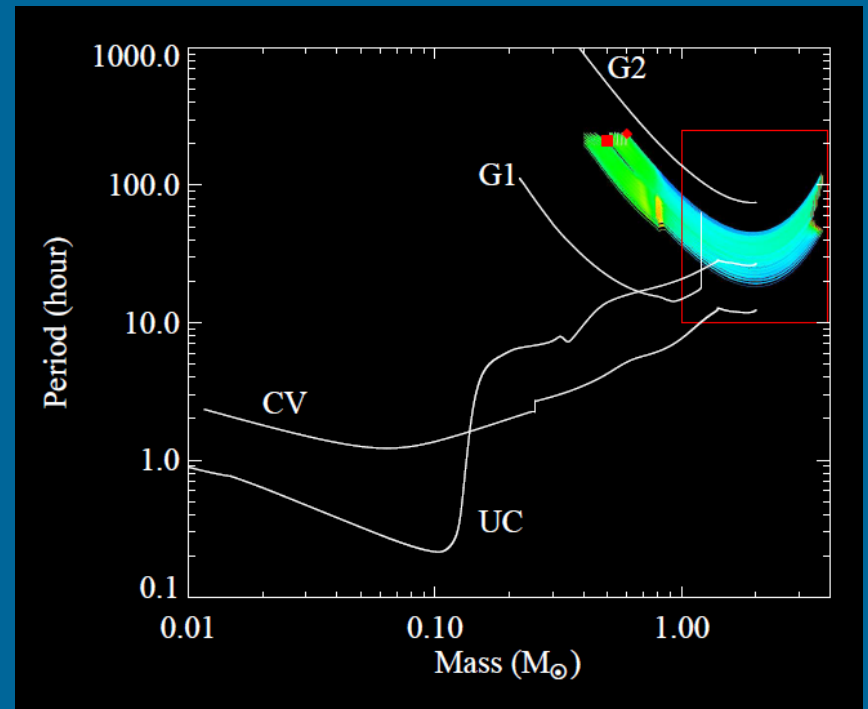
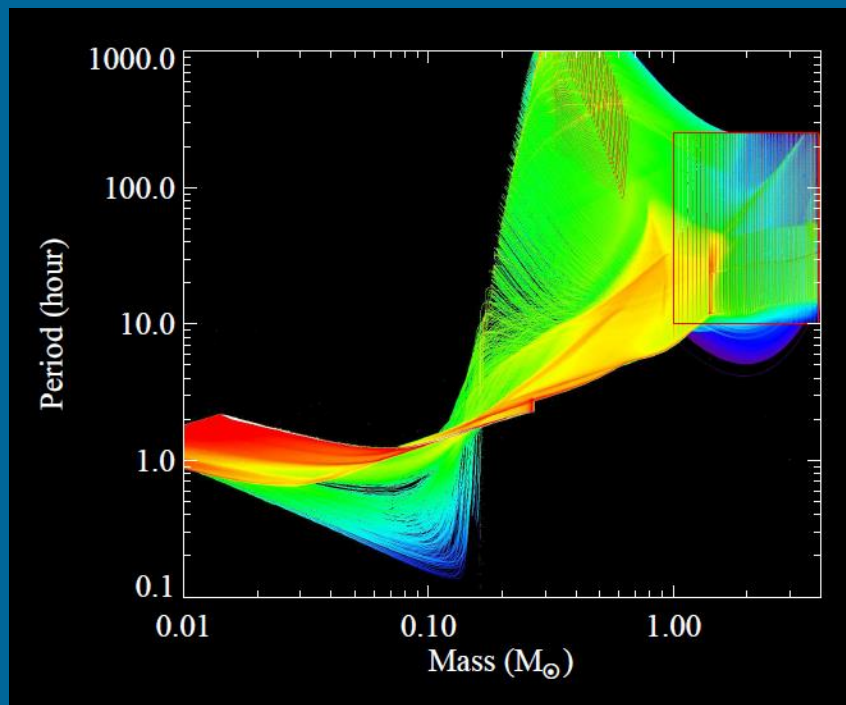
The color of the tracks indicates how much time systems spend in a particular rectangular pixel in the diagrams (from short to long: yellow, orange, red, green, blue, magenta, cyan).

New calculations and specific systems

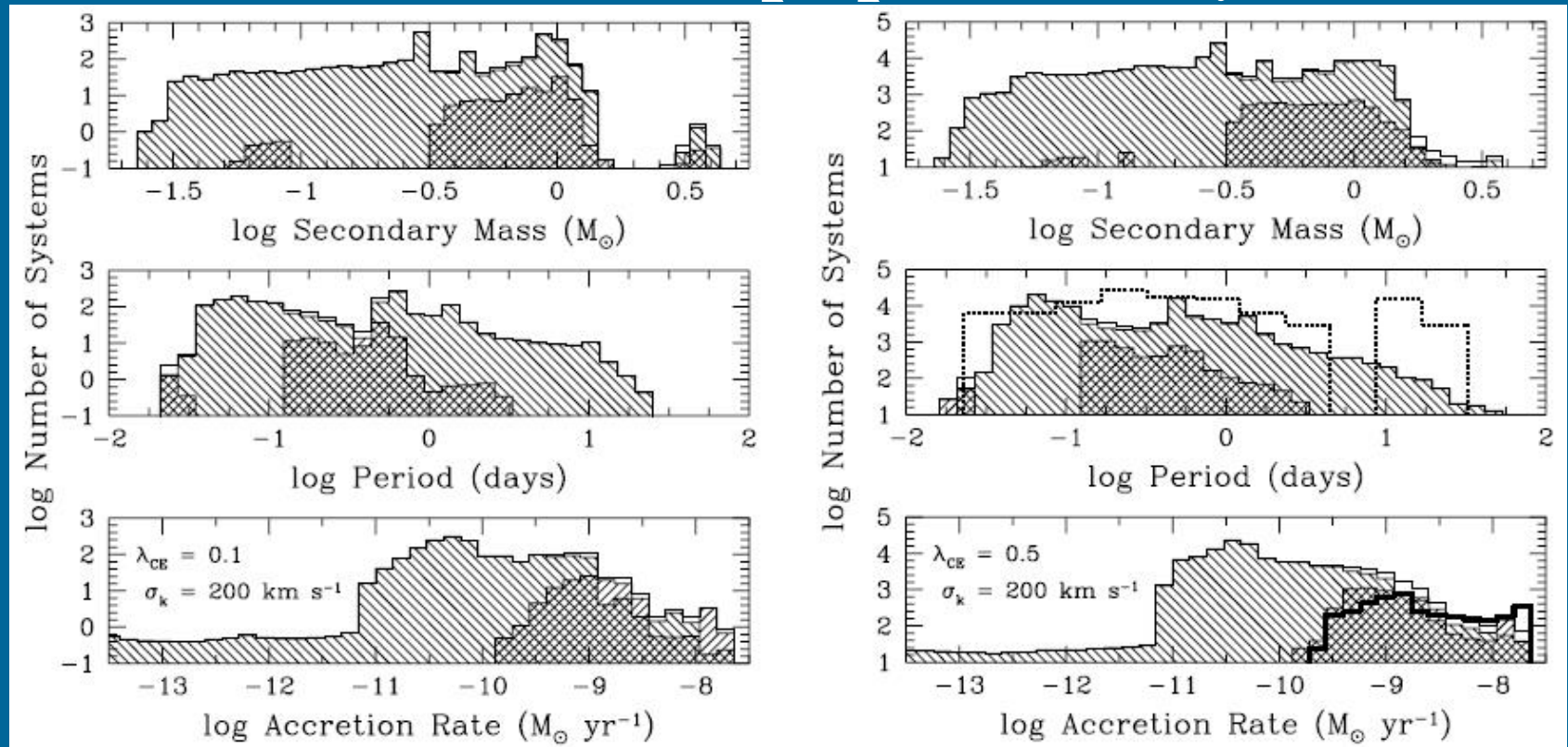
The task: to reproduce with a new code PSR J1614-2230 (red square below)

Red box shows the initial grid of models

The PSR is a “relative” of Cyg X-2 (red diamond)



IMXBs and LMXBs population synthesis



The hatched regions indicate persistent (+45) and transient (-45) X-ray sources, and the enclosing solid histogram gives the sum of these two populations. Overlaid (dotted histogram) on the theoretical period distribution in the figure on the right is the rescaled distribution of 37 measured periods (Liu et al. 2001) among 140 observed LMXBs in the Galactic plane.

Low mass X-ray binaries



NSs as accretors

X-ray pulsars
Millisecond X-ray pulsars
Bursters
Atoll sources
Z-type sources

WDs as accretors

Cataclysmic variables

- Novae
- Dwarf novae
- Polars
- Intermediate polars

Supersoft sources (SSS)

BHs as accretors

X-ray novae
Microquasars
Massive X-ray binaries

LMXBs with NSs or BHs

The latest large catalogue (Avakyan et al. arXiv: 2303.16168) includes 349 galactic LMXBs with NSs and BHs as accreting components.

Donors can be WDs, or normal low-mass stars (main sequence or sub-giants).

Many sources are found in globular clusters.

Also there are more and more LMXBs found in more distant galaxies.

In optics, the emission is dominated by an accretion disc around a compact object.

Clear classification is based on optical data

or on the mass function derived from X-ray observations.

If a source is unidentified in optics, but exhibits Type I X-ray bursts, or just has a small (<0.5 days) orbital period, then it can be classified as a LMXB with a NS.

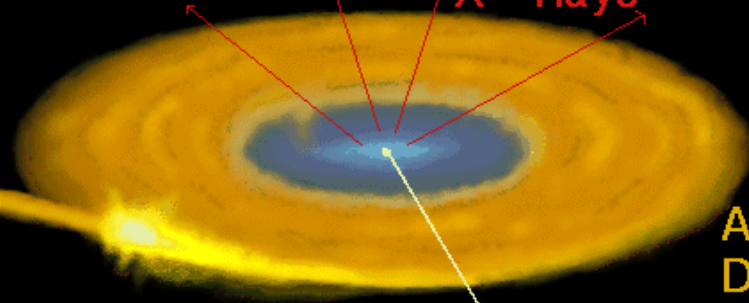
In addition, spectral similarities with known LMXBs can result in classification.

A Low Mass X-Ray Binary: 4U 1820-30



130,000 km

White Dwarf

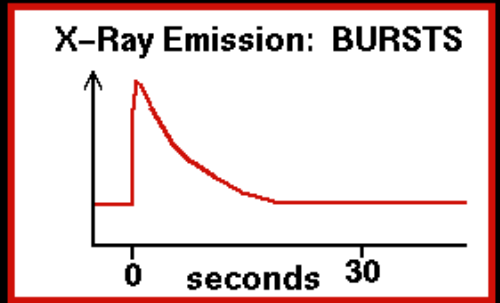


X - Rays

Accretion Disk

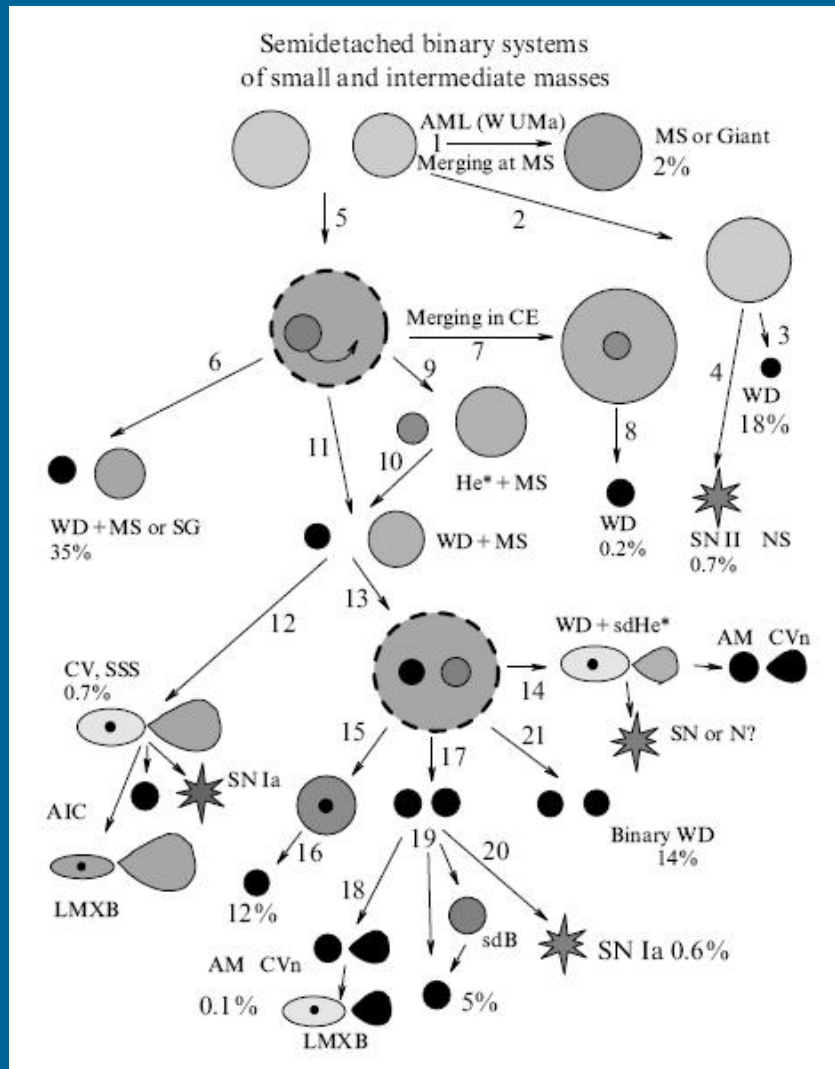
Neutron Star

1,200 km/sec



SUN

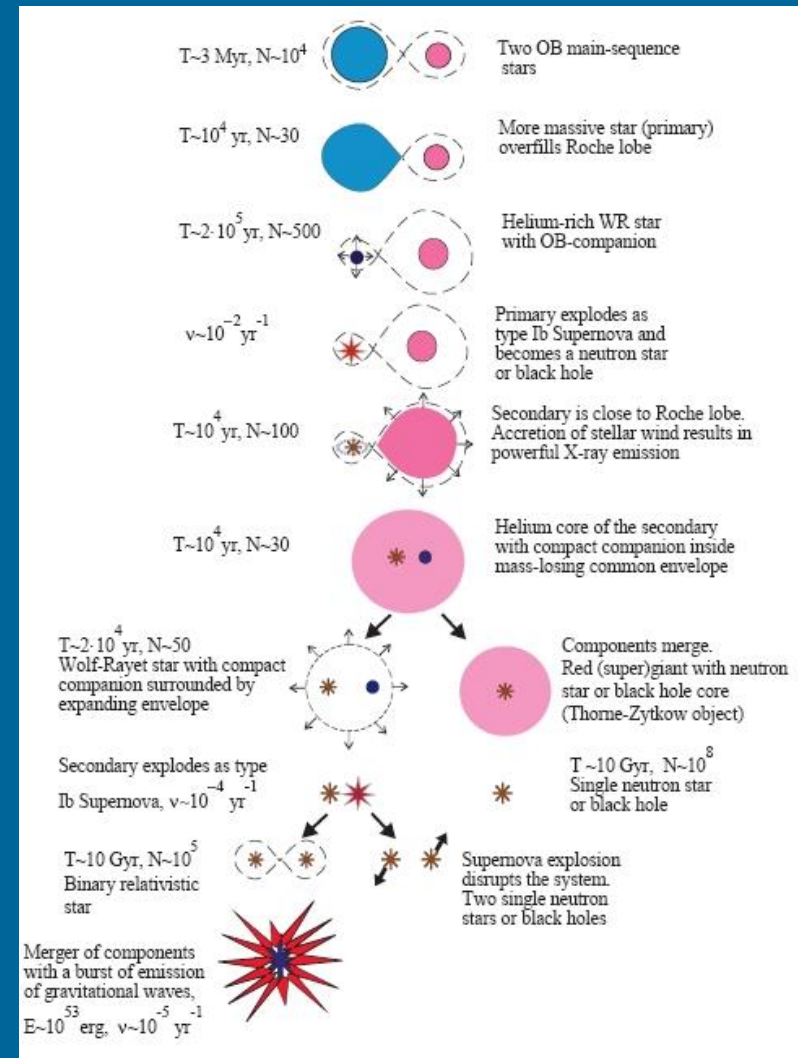
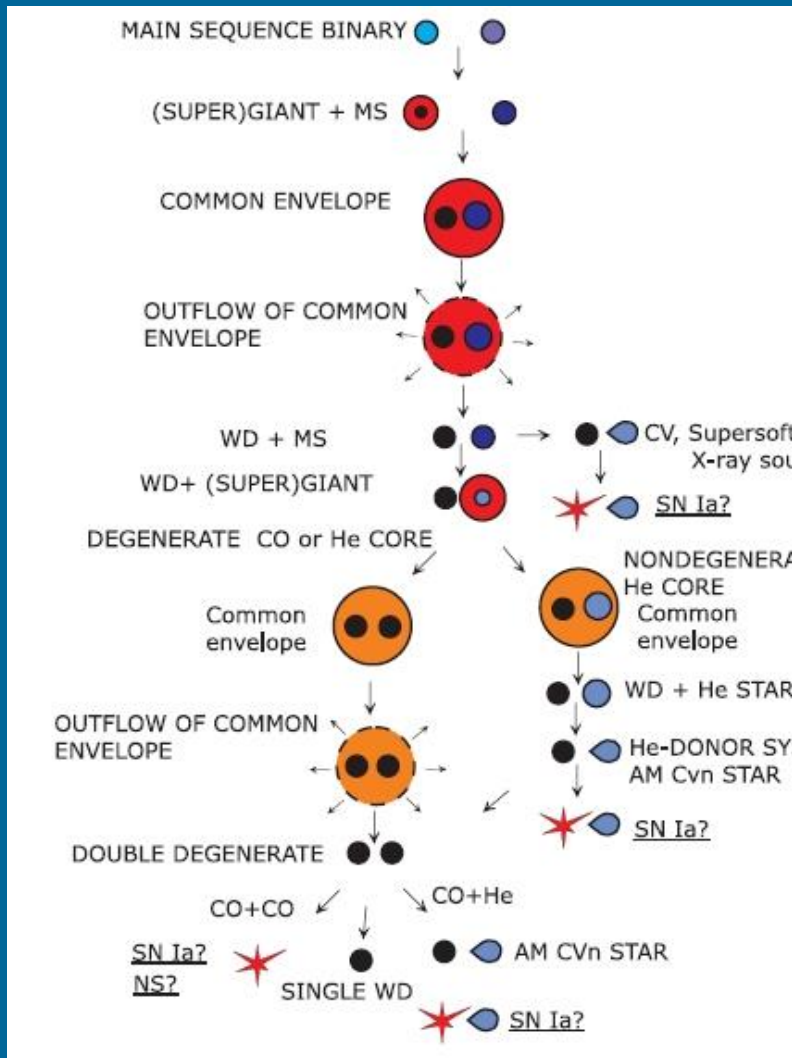
Evolution of low-mass systems



A small part of the evolutionary scenario of close binary systems

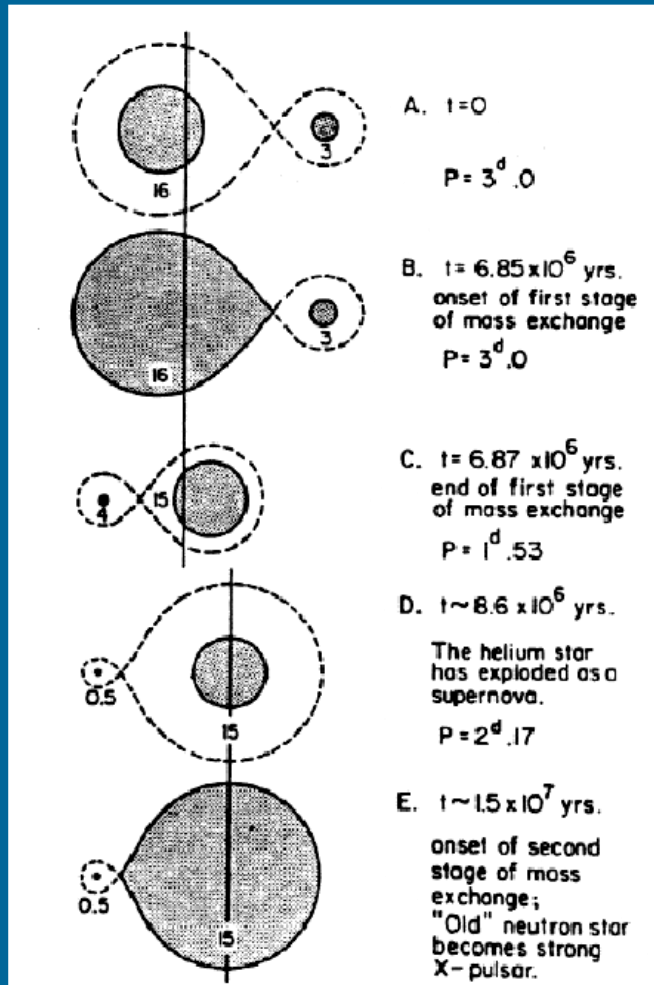
[Yungelson L R, in Interacting Binaries: Accretion, Evolution, Out-Comes 2005]

Evolution of close binaries



(Postnov, Yungelson 2007)

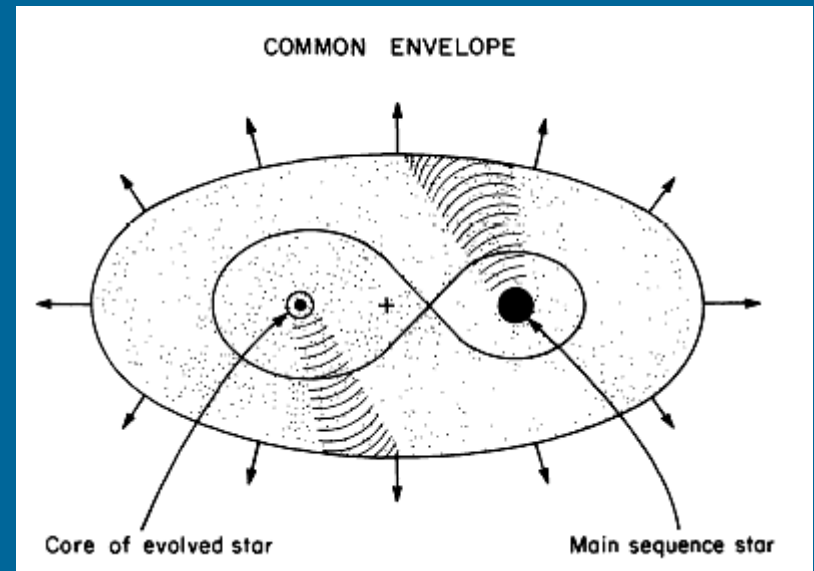
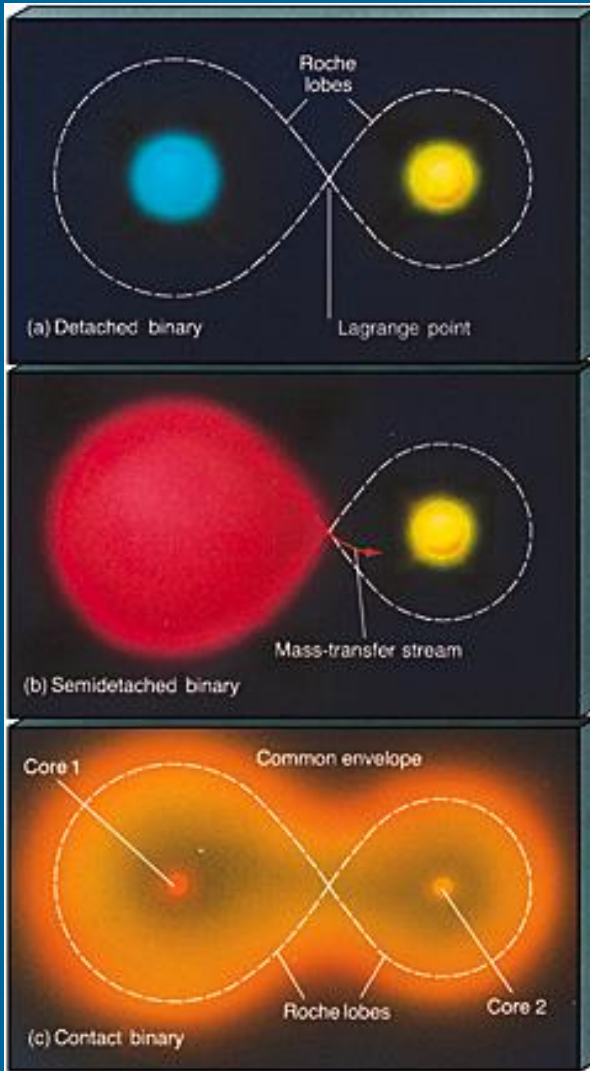
First evolutionary “scenario” for the formation of X-ray binary pulsar



Common envelope

**Problem: How to make close binaries with compact stars (CVs, XRBs)?
Most angular momentum from the system should be lost.**

**Non-conservative evolution:
Common envelope stage
(B.Paczynski, 1976)**



Dynamical friction is important

Tidal effects on the orbit (Zahn, 1977)

1. Circularization

$$\begin{aligned} t_{\text{circ}} &\sim (q(1+q)/2)^{-1} (a/R)^8 \\ &\sim 10^6 q^{-1} ((1+q)/2)^{5/3} P^{16/3} \text{ years} \end{aligned}$$

2. Synchronization of component's rotation

$$t_{\text{sync}} \sim q^{-2} (a/R)^6 \sim 10^4 ((1+q)/2q)^2 P^4 \text{ years}$$

Both occur on a much shorter timescale than stellar evolution!

Conservative mass transfer

$$M = M_1 + M_2 = \text{const}$$

$$\text{Assuming (B.Paczynski): } J_{orb} = \frac{M_1 M_2}{M} \sqrt{aM} = \text{const}$$

⇒ Change of orbital parameters after mass transfer:

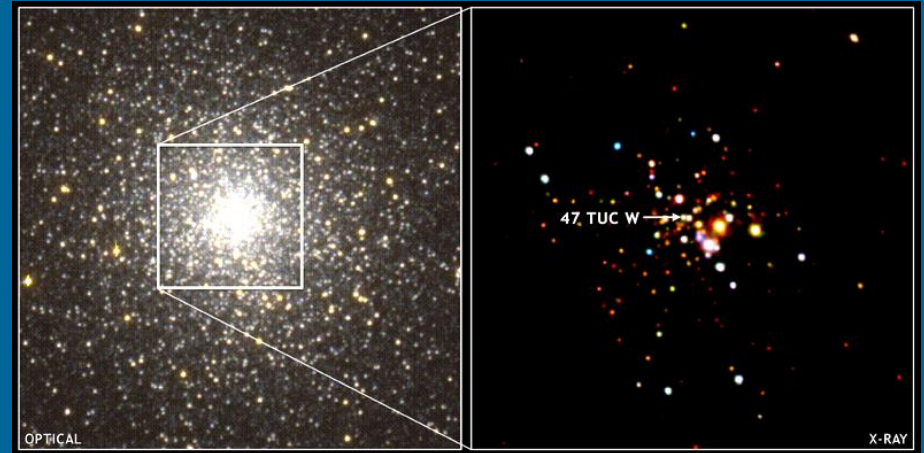
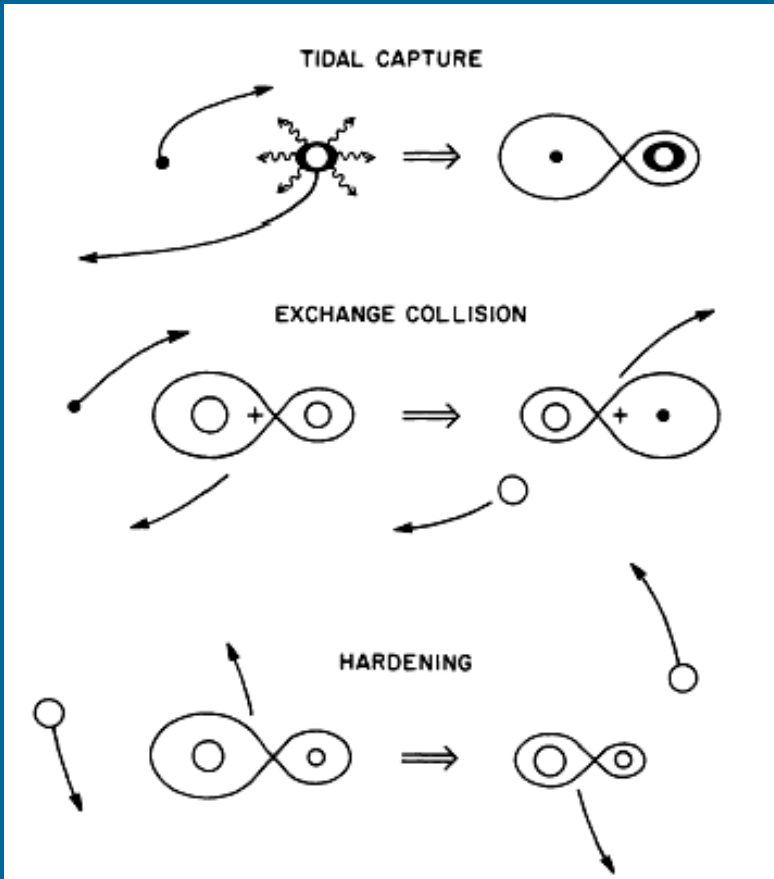
$$M_1' = M_1 - \Delta M, \quad M_2' = M_2 + \Delta M,$$

$$\frac{\Delta a}{a} = 2\Delta M \frac{M_2 - M_1}{M_1 M_2} \begin{cases} > 0, & \text{if } M_2 > M_1 \\ < 0, & \text{if } M_2 < M_1 \end{cases}$$

Non-conservative evolution

- *Massive binaries: stellar wind, supernova explosions, common envelopes*
- *Low-massive binaries: common envelopes, magnetic stellar winds, gravitational wave emission (CVs, LMXBs)*
- *Stellar captures in dense clusters (LMXBs, millisecond pulsars)*

Binaries in globular clusters



Hundreds close XRB and millisecond pulsars are found in globular clusters

Formation of close low-mass binaries is favored in dense stellar systems due to various dynamical processes

Isotropic wind mass loss

- Effective for massive early-type stars on main sequence or WR-stars
- Assuming the wind carrying out specific orbital angular momentum yields:

$$a(M_1+M_2)=\text{const} \rightarrow$$

$$\Delta a/a = -\Delta M/M > 0$$

The orbit always gets wider!

Supernova explosion

- First SN in a close binary occurs in almost circular orbit $\rightarrow \Delta M = M_1 - M_c$, M_c is the mass of compact remnant
- Assume SN to be instantaneous and symmetric

Energy-momentum conservation \Rightarrow

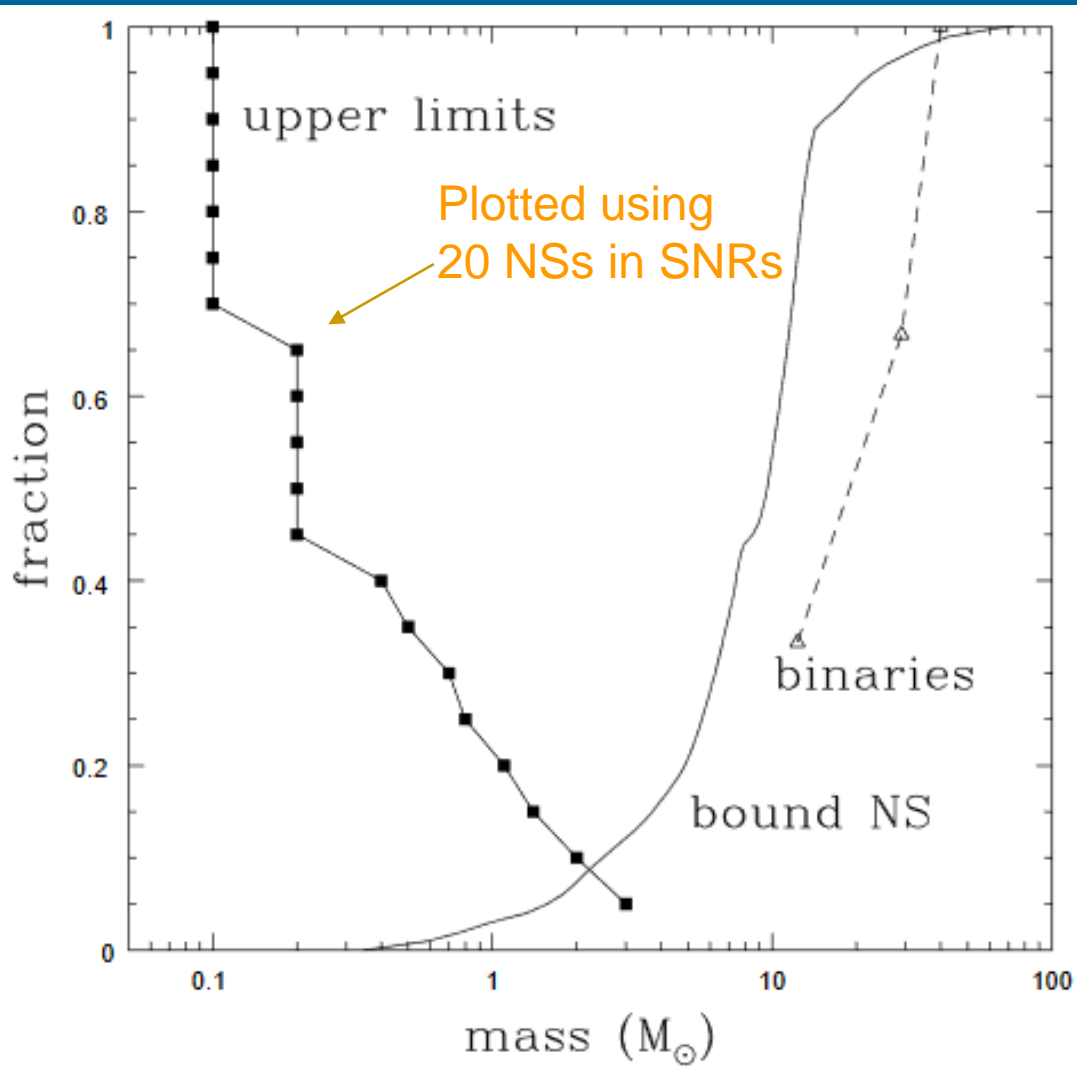
$$\frac{a_f}{a_i} = \left[2 - \frac{M_1 + M_2}{M_c + M_2} \right]^{-1}$$

$$e = \frac{\Delta M}{M_c + M_2}$$

\rightarrow If more than half of the total mass is lost, the system becomes unbound

BUT: Strong complication and uncertainty: Kick velocities of NS!

Survived binaries in SNR



It is expected that ~50% of SNe happen in binaries.

It is expected that 93% of companions of exploding stars have $M > 1 M_{\odot}$.

The authors looked for normal stars (companions) in 49 SNRs.

3 HMXBs were already known. No new candidates found.

It gives the following estimates:

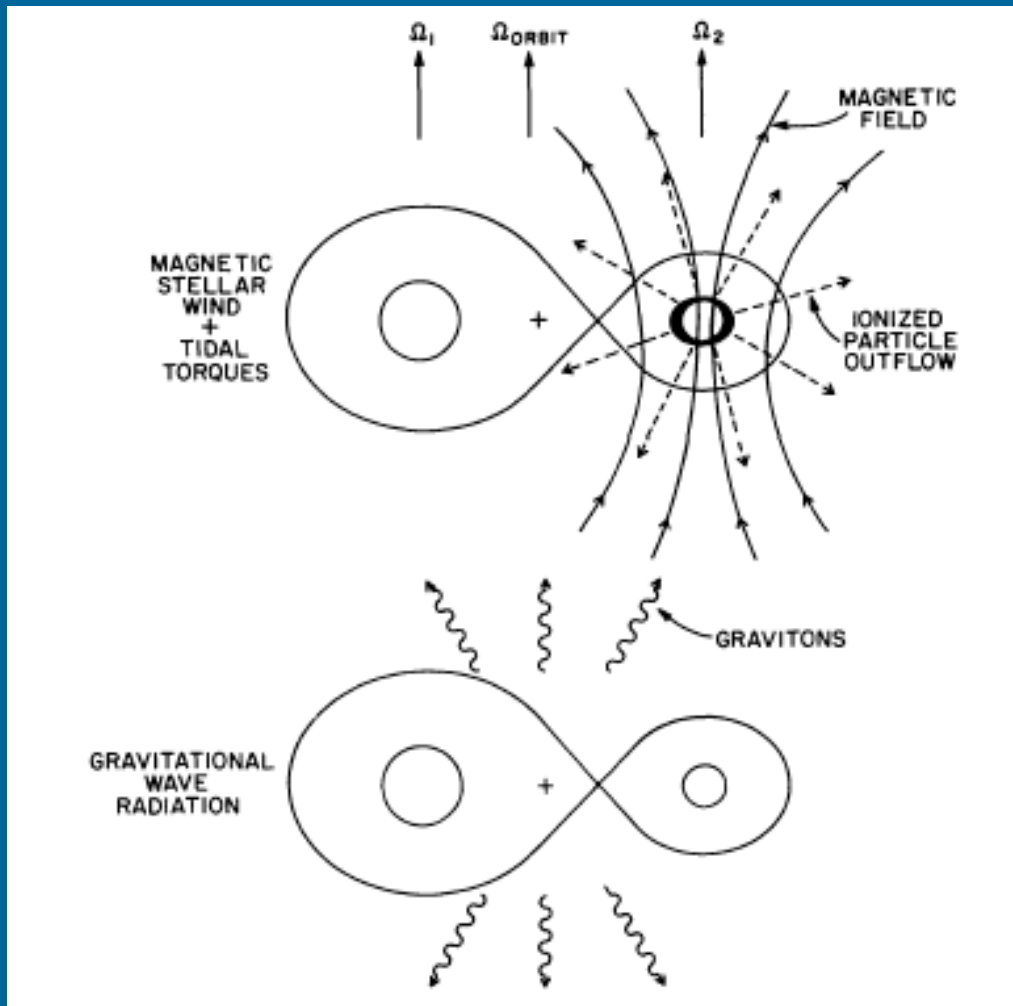
1. $f < 0.1$ of non-interacting binaries with companions $> (1-3)M_{\odot}$
 2. $f \sim 0.08$ for interacting NS or BH
- These estimates are for survivals. In general, ~5% of ccSN might result in survived binaries.

Binaries and supernovae

Case	Non-Interacting Incomplete		Non-Interacting Complete	
	Median	90% Confidence	Median	90% Confidence
Not Binary at Death	72.0%	52.2%-86.4%	76.0%	56.0%-89.2%
Bound Binary	13.9%	5.4%-27.2%	9.5%	3.6%-19.7%
Interacting Binary	10.2%	3.2%-22.3%	5.8%	1.8%-13.1%
Non-Interacting Binary		<8.5%		<8.9%
Unbound Binary	12.5%	2.8%-31.3%	13.2%	3.0%-32.8%

Statistics are still relatively low.
In 2107.13559 the author studied:
7 non-binary neutron stars,
two binary neutron stars and
one binary black hole system
that are both associated with SNRs and have proper motions.
One candidate (HD 37424 in G180.0-01.7) is known.

Angular momentum loss



- **Magnetic stellar wind.**

Effective for main sequence stars with convective envelopes
 $0.3 < M < 1.5 M_{\odot}$

- **Gravitational radiation.**

Drives evolution of binaries with $P < 15$ hrs

Especially important for evolution of low-mass close binaries!

Mass loss due to MSW and GW

Axial rotation braking of single G-dwarfs (Skumanich, 1972)

$$V \sim t^{-1/2}, \text{ where } t \text{ is the age}$$

Physics: stellar wind plasma "streams" along magnetic field lines until $\rho v^2 \sim B^2(r)/4\pi$, so carries away much larger specific angular momentum (Mestel).

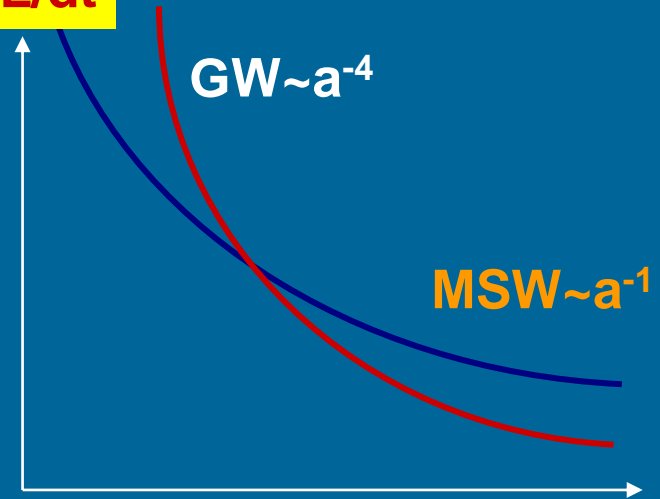
Assume the secondary star in a low-mass binary ($0.4 \leq M_2 \leq 1.5 M_\odot$) experiences m.s.w. Tidal forces tend to keep the star in corotation with orbital revolution: $\omega_2 = \omega$. Angular momentum conservation then leads to:

$$\frac{dL_{orb}}{dt} = \frac{dJ_2}{dt}$$

Recalling that: $L_{orb} = \mu \omega a^2$ and using Kepler's 3d law we get

$$\frac{d \ln L_{orb}}{dt} \sim - \frac{R_2^4}{M_1} \frac{GM^2}{a^5} \Rightarrow$$

dL/dt

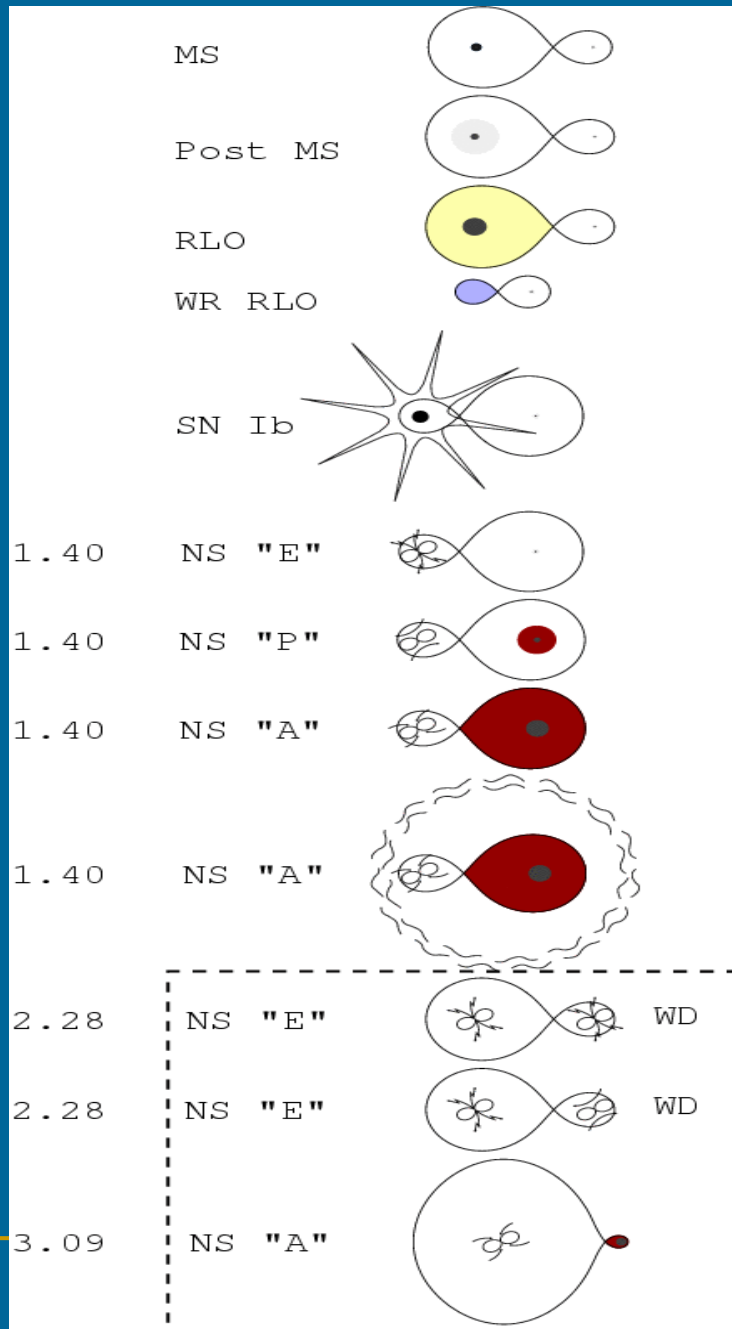


MSW is more effective at larger orbital periods, but GW always wins at shorter periods! Moreover, MSW stops when $M_2 \sim 0.3-0.4 M_\odot$ where star becomes fully convective and dynamo switches off.

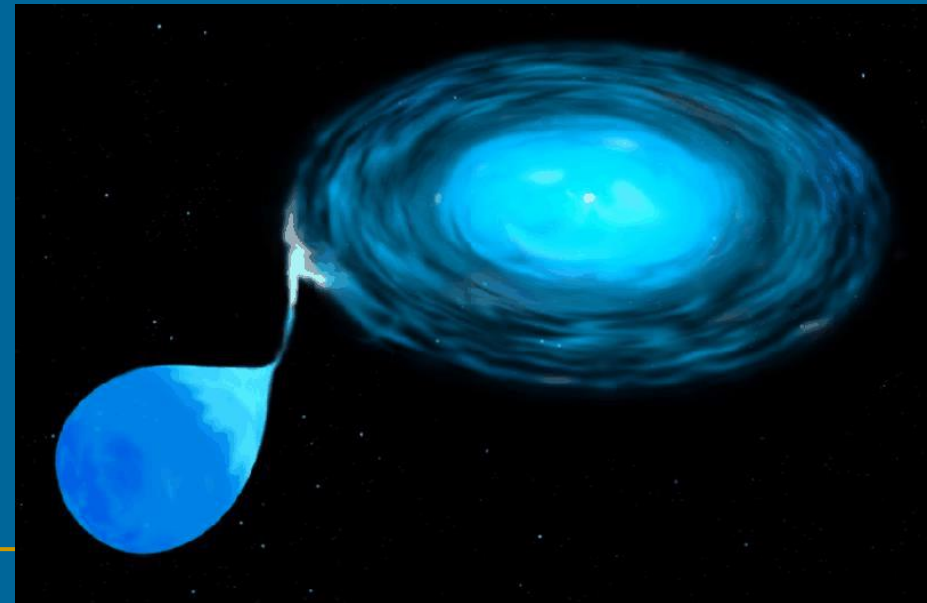
Binary evolution: Major uncertainties

- All uncertainties in stellar evolution (convection treatment, rotation, magnetic fields...)
- Limitations of the Roche approximation (synchronous rotation, central density concentration, orbital circularity)
- Non-conservative evolution (stellar winds, common envelope treatment, magnetic braking...)
- For binaries with NS (and probably BH): effects of supernova asymmetry (natal kicks of compact objects), rotational evolution of magnetized compact stars (WD, NS)

E v o l u t i o n



NSs can become very massive during their evolution due to accretion.



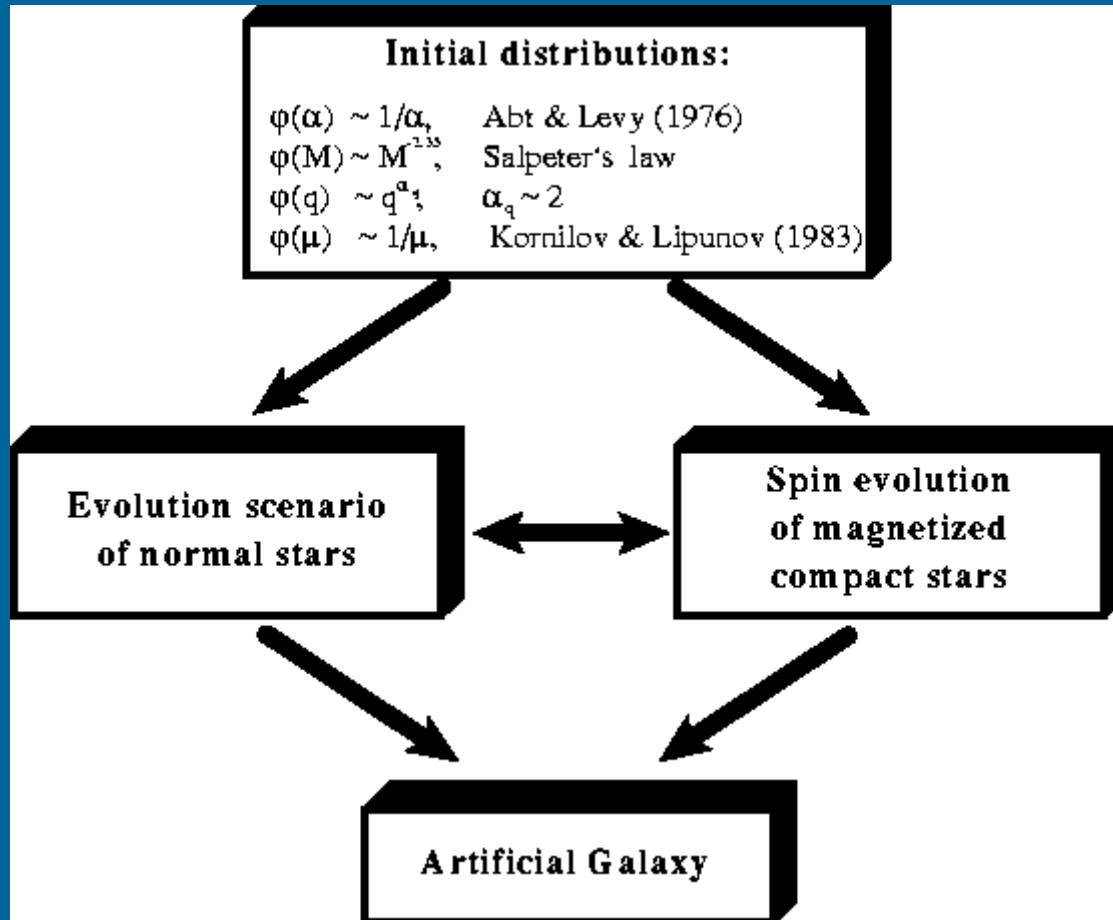
Population synthesis of binary systems

Interacting binaries are ideal subject for population synthesis studies:

- There are many of them observed
- Observed sources are very different
- However, they come from the same population of progenitors...
- ... whose evolution is non-trivial, but not too complicated.
- There are many uncertainties in evolution ...
- ... and in initial parameter
- We expect to discover more systems
- ... and more types of systems
- With new satellites it really happens!

See a review on binary population synthesis in [1808.06883](#)

Scenario machine

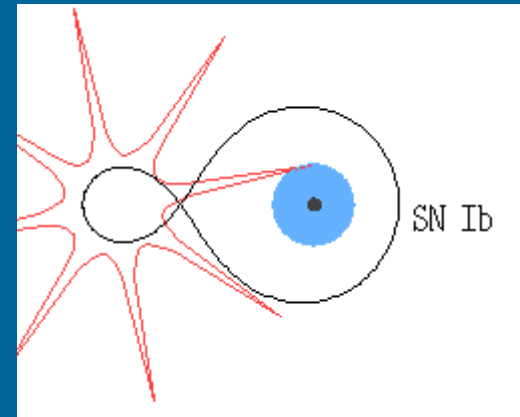
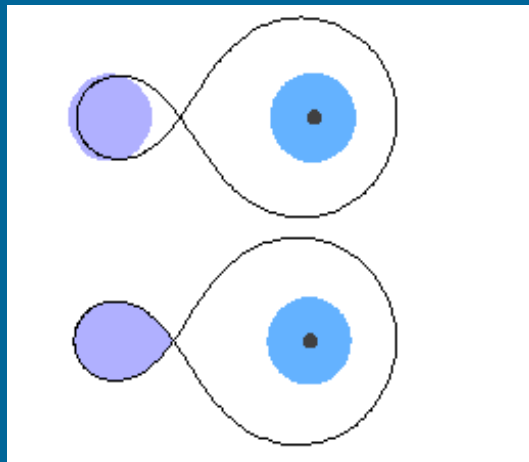
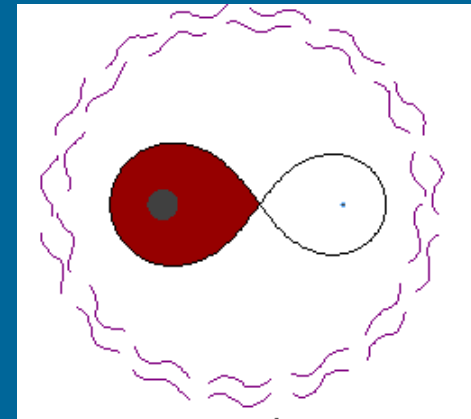
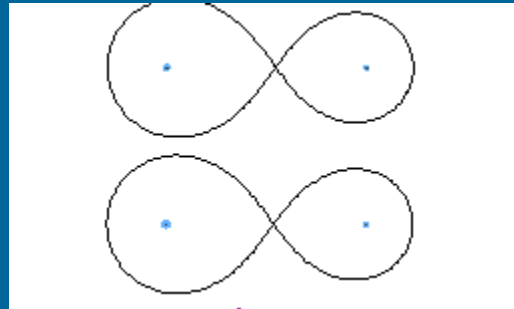
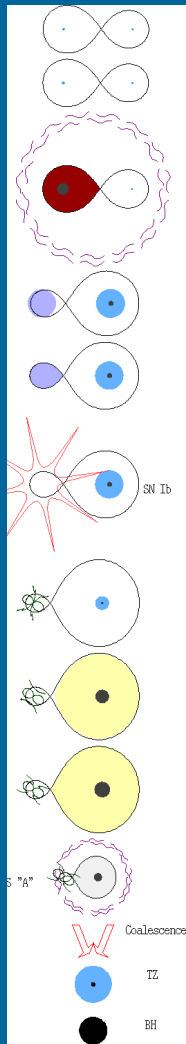


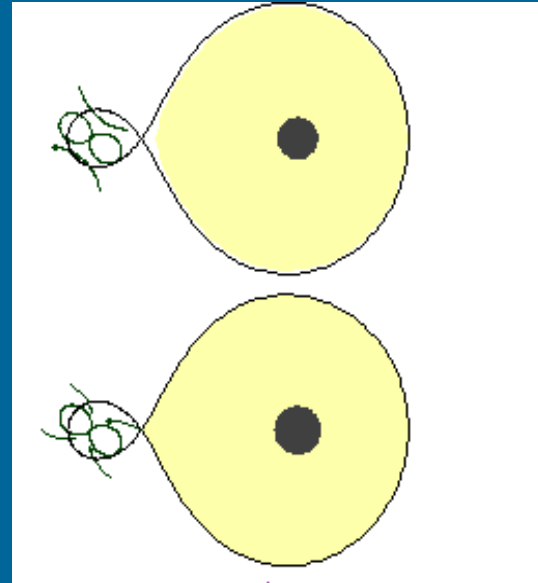
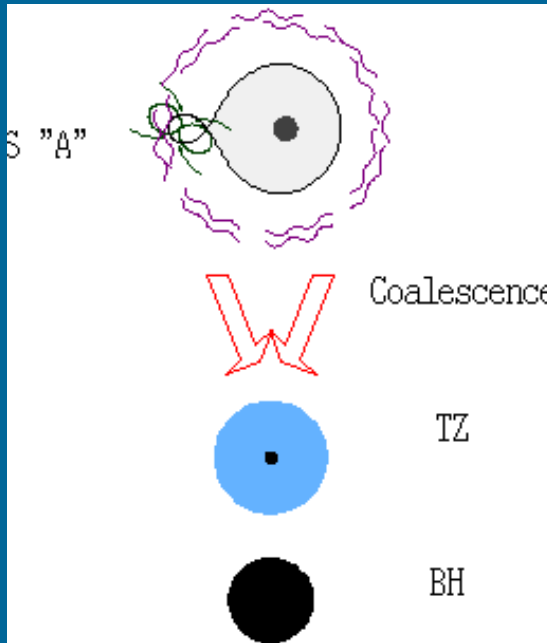
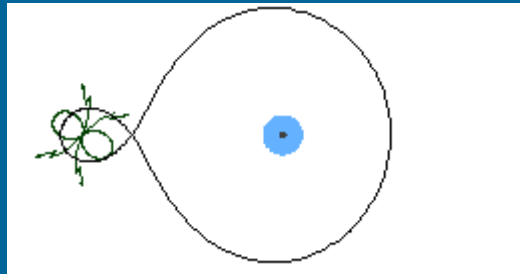
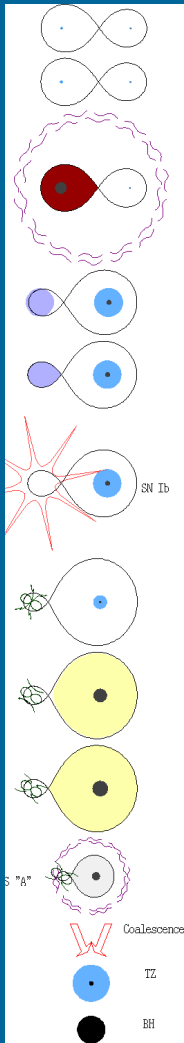
There are several groups in the world which study evolution of close binaries using population synthesis approach.

Examples of topics

- Estimates of the rate of coalescence of NSs and BHs
- X-ray luminosities of galaxies
- Calculation of mass spectra of NSs in binaries
- Calculations of SN rates
- Calculations of the rate of short GRBs

Evolution of close binaries



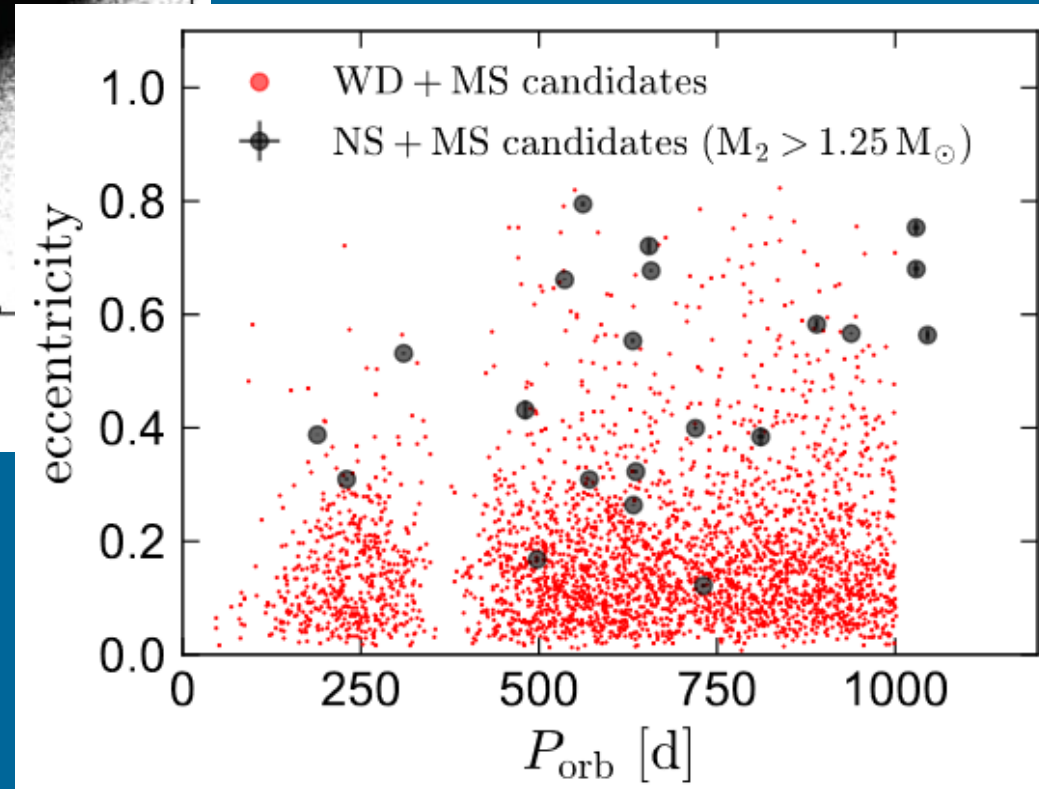
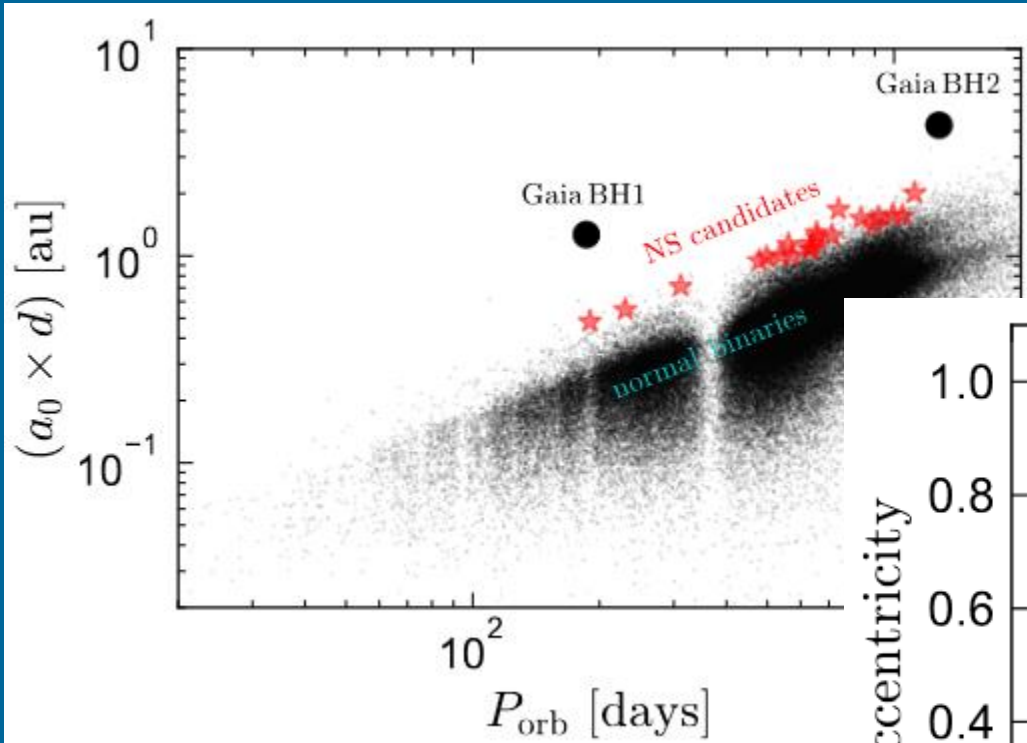


("Scenario Machine" calculations)

<http://xray.sai.msu.ru/sciwork/>

About Thorne-Zytkow objects see 2311.06741, 2311.07278

Wide Gaia binaries with compact objects



A binary with massive BH (33 Msun) was recently discovered with Gaia (2404.10486).

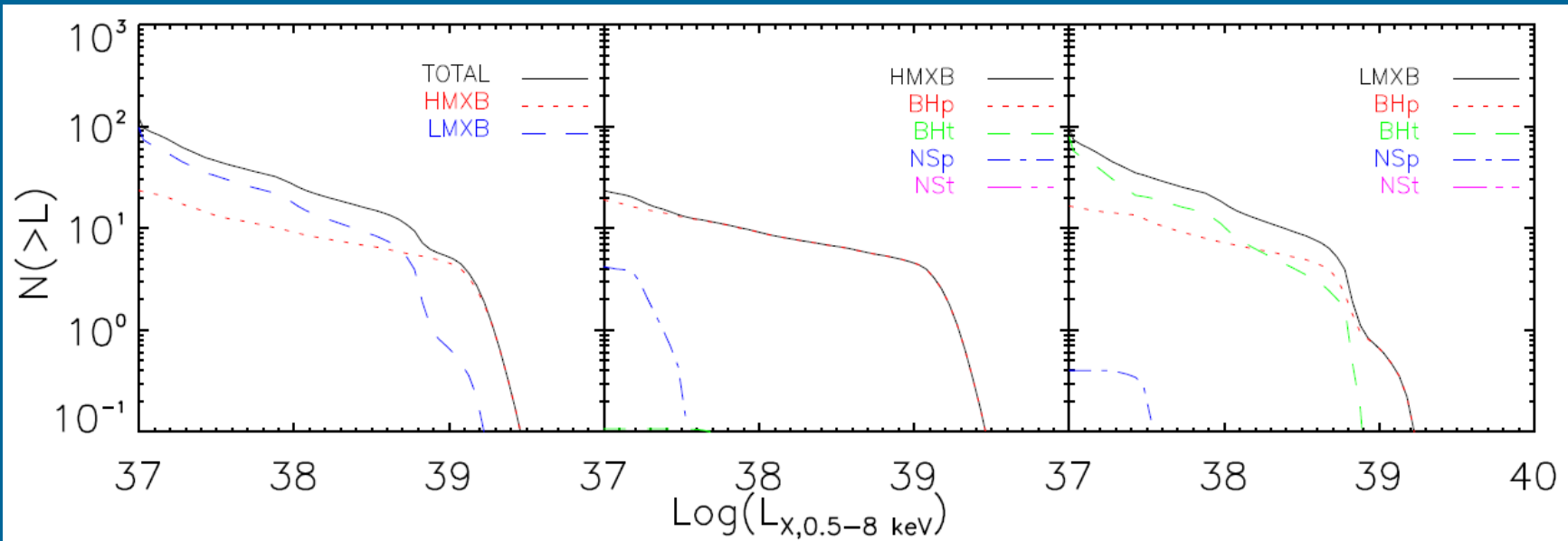
2405.00089

Much more NS and BH binaries are expected in the DR4 in 2026.

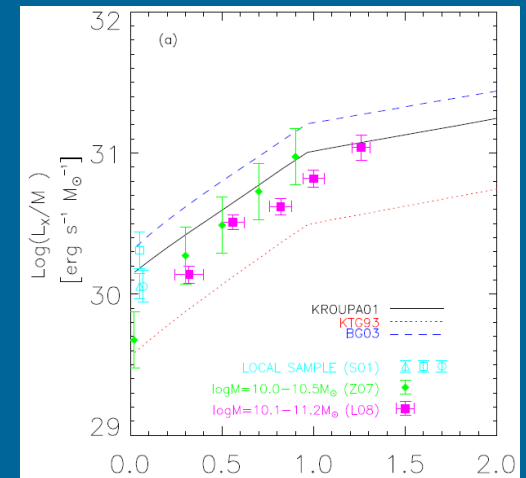
The role of binaries in the properties of galaxies

The authors use the code by Hurley et al. (BSE) to model X-ray luminosity of a late-type galaxy.

Cumulative X-ray luminosity function

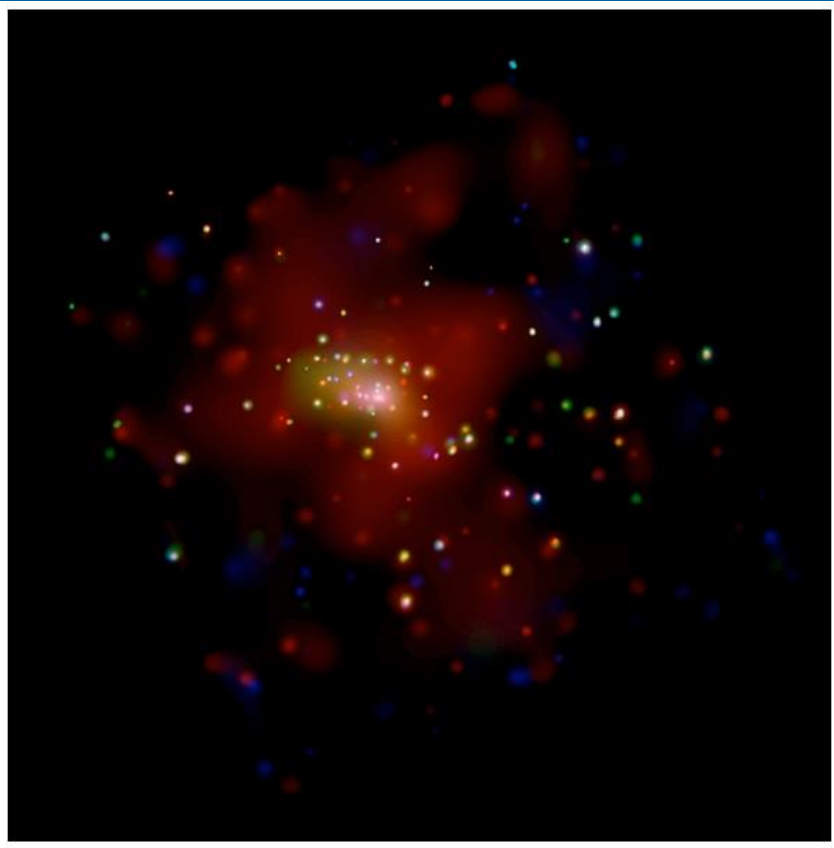


Evolution of L_x with z

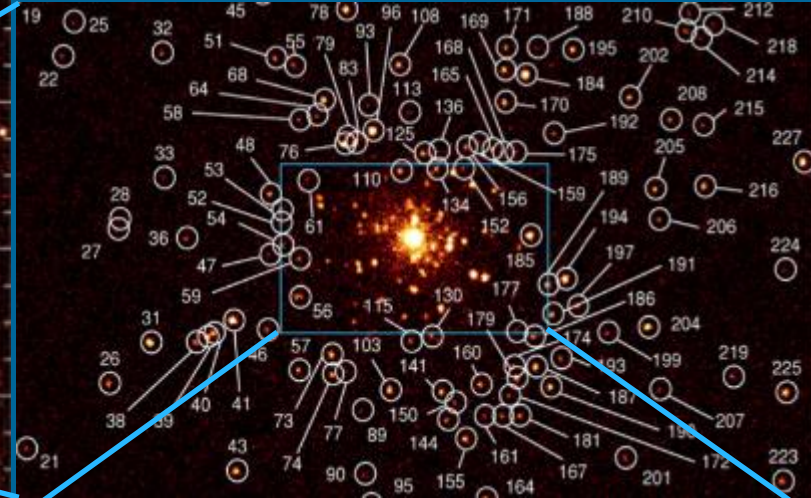
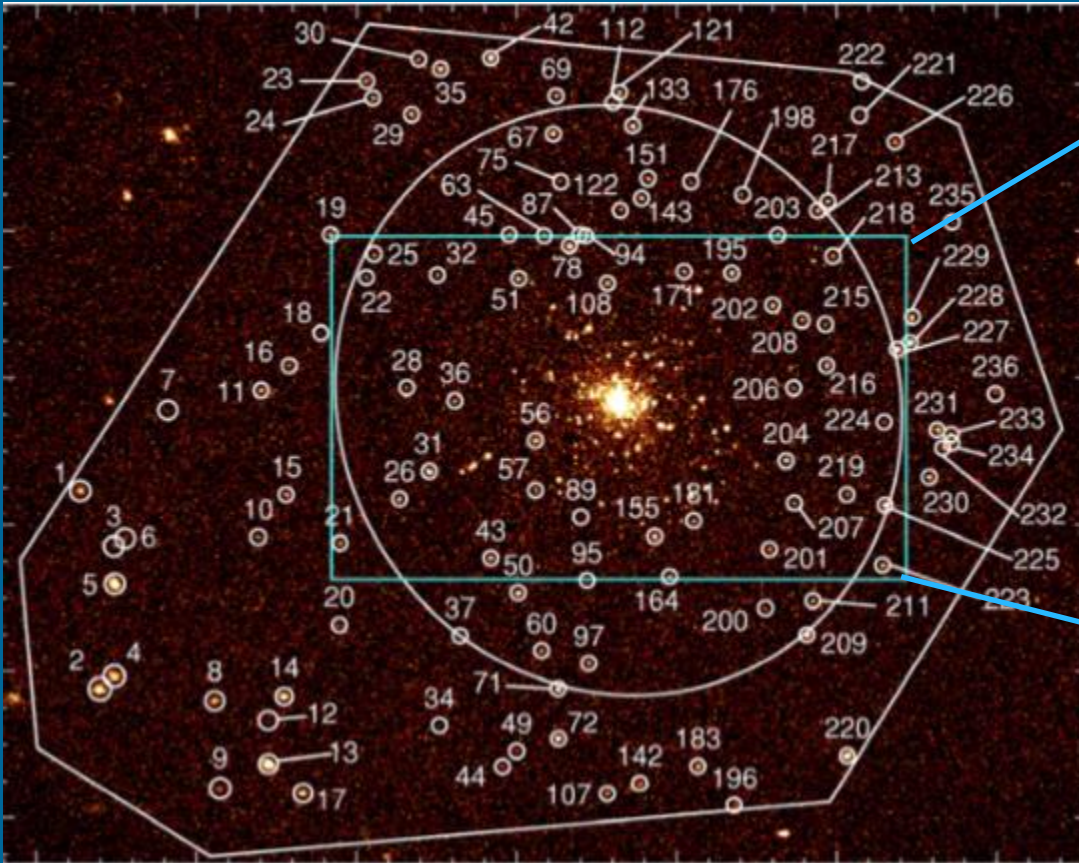


Extragalactic binaries

It is possible to study galactic-like binaries up to 20-30 Mpc.
For example, in NGC 4697 80 sources are known thanks to *Chandra*
(this is an early type galaxy, so most of the sources are LMXBs).



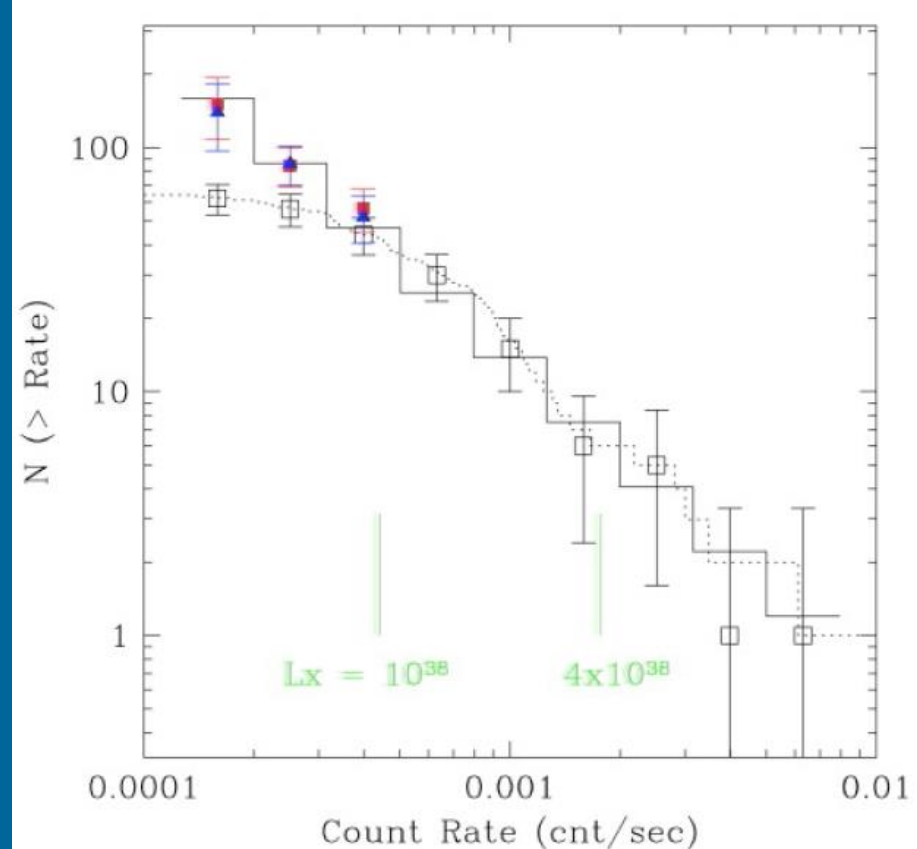
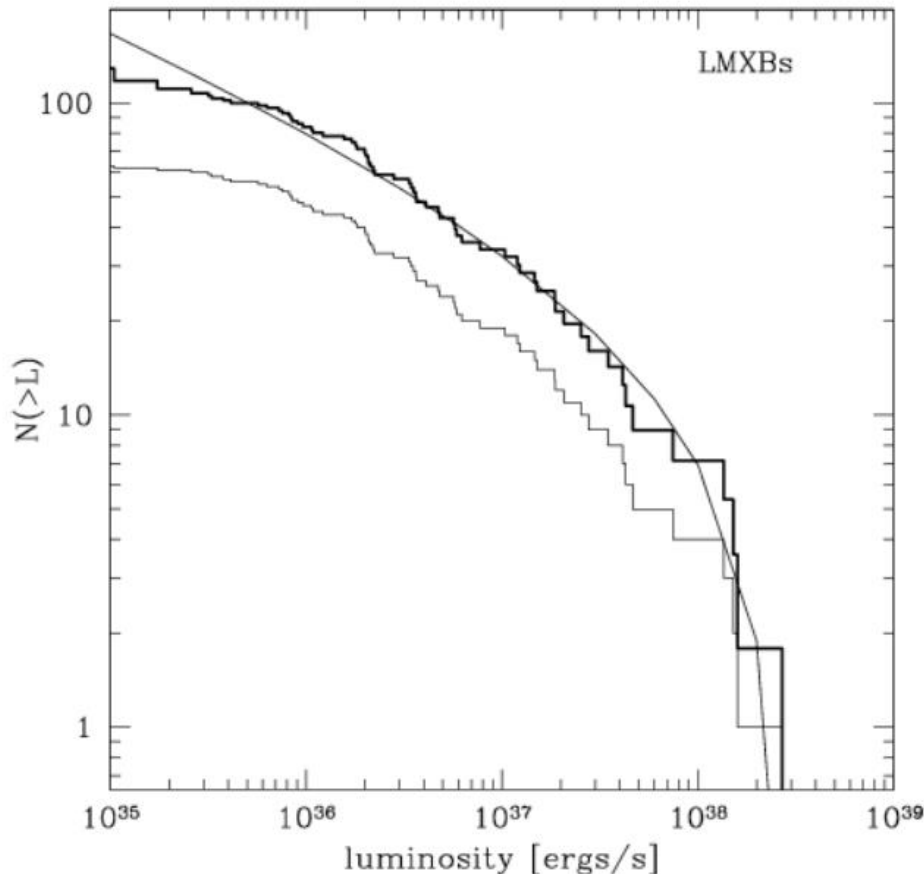
NGC 4278



Chandra data

1903.01970

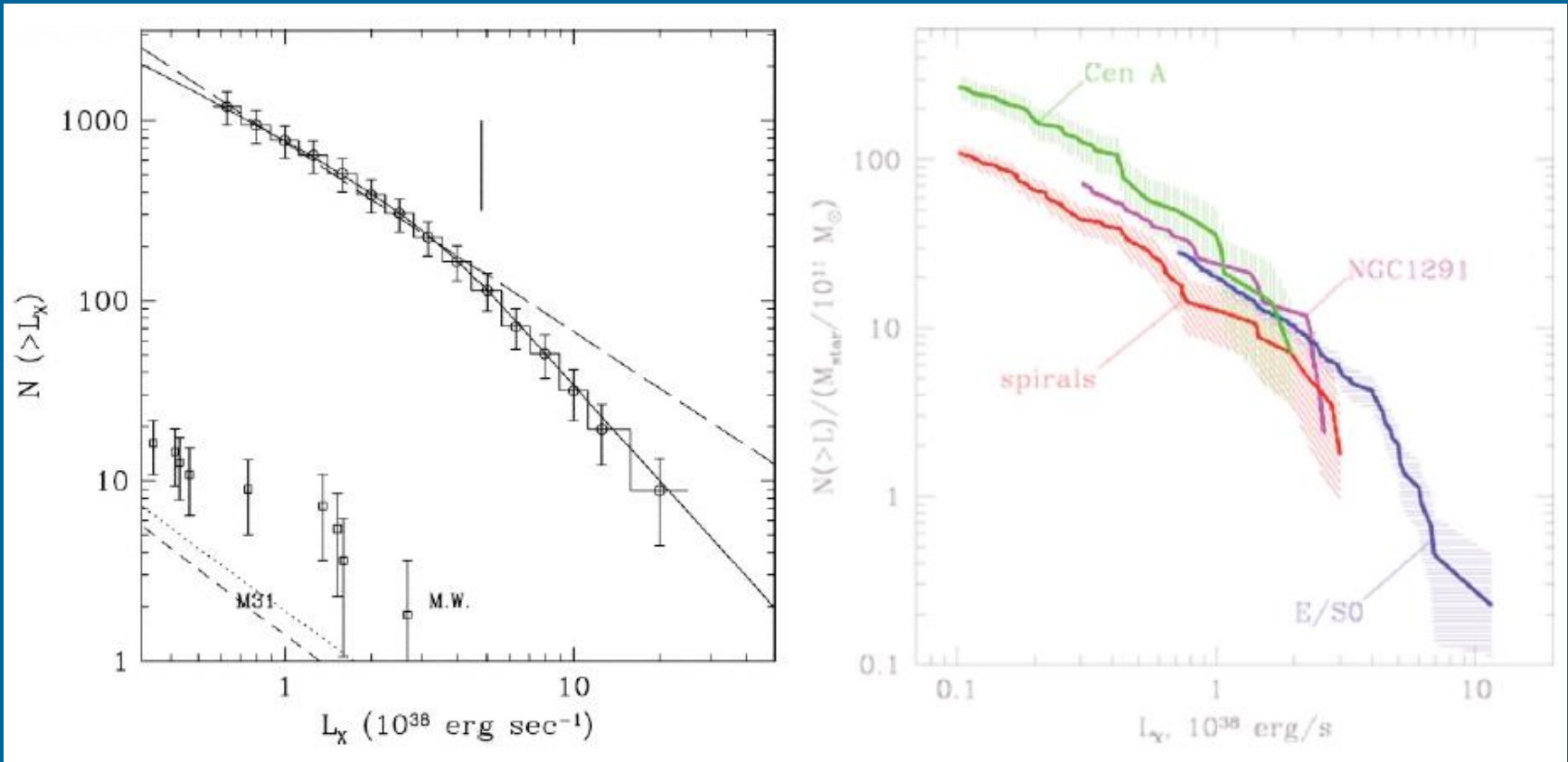
LMXBs luminosity function



LMXB Galactic luminosity function
(Grimm et al. 2002)

LMXB luminosity function for NGC 1316
(Kim and Fabbiano 2003)

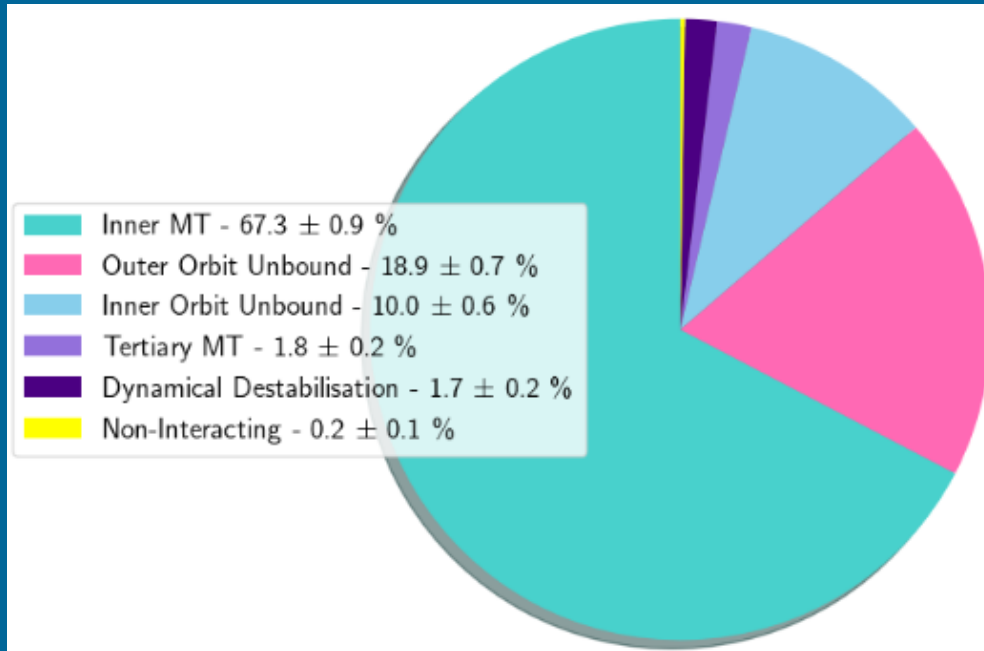
LMXBs luminosity function



Cumulated XLF for 14 early-type galaxies.

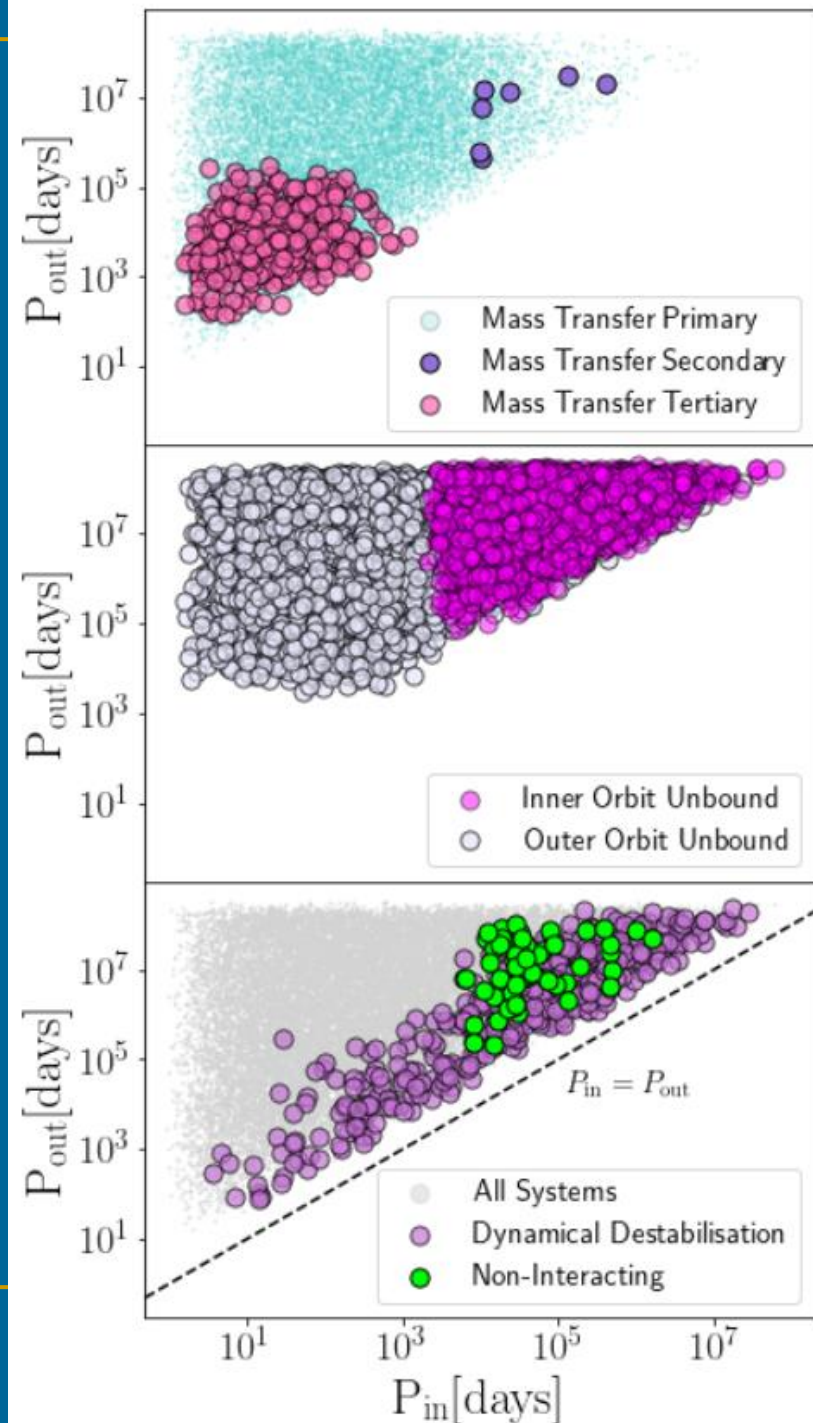
(see Fabbiano astro-ph/0511481)

Triples!



Among O-, B-stars ~30% are triples.

Only systems with massive primaries ($>10M_{\text{sun}}$) are considered. M_2 and M_3 are derived from flat distributions of q_{in} and q_{out} .



Searching for unbound triples

SNR	Center	R_{SNR} ($^{\circ}$)	d (kpc)	$N(H)$ (cm^{-2})	G_{lim} (mag)	Remnant
G065.7 + 01.2	19:52:10 +29:26:00	11	3.0 ± 2.0	$(2 - 7) \times 10^{21}$	15.5	PSR J1952.2 + 2925
G078.2 + 02.1	20:20:50 +40:26:00	30	1.5 ± 0.5	$6.4^{+0.8}_{-1.8} \times 10^{21}$	15	PSR J2021 + 4026
G106.3 + 02.7	22:27:30 +60:50:00	19	3.0	$6.3 \pm 1.3 \times 10^{21}$	16	PSR J2229 + 6114
G114.3 + 00.3	23:37:00 +61:55:00	35	3.2 ± 1.7	$(0.26 - 1.0) \times 10^{22}$	17	PSR B2334 + 61
G119.5 + 10.2	00:06:40 +72:45:00	45	1.4 ± 0.3	$2.8^{+0.6}_{-0.5} \times 10^{21}$	12	RX J0007.0 + 7303
G189.1 + 03.0	06:17:00 +22:34:00	23	1.7 ± 0.3	$(7.2 \pm 0.6) \times 10^{21}$	14.5	PWN G189.22 + 2.90
G266.2 - 01.2	08:52:00 -46:20:00	60	0.7 ± 0.2	$(3.0 \pm 1.0) \times 10^{21}$	11	CXOU J085201.4 - 461753
G291.0 - 00.1	11:11:54 -60:38:00	7	3.5 - 5.0	$(6.7 \pm 0.7) \times 10^{21}$	16.5	CXOU J111148.6 - 603926

8 SNR searched.

No candidates for unbound triples.

<11% of SN leave behind unbound triples.

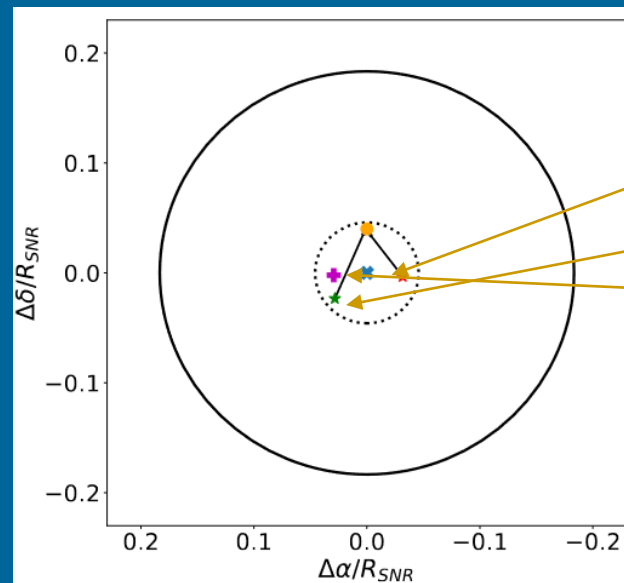


Illustration of a good candidate

Stars

Pulsar

List of reviews

- General review of binaries (including wide systems). arXiv: 2311.11454
- Catalogue of LMXBs. Avakyan et al. arXiv: 2303.16168
- Catalogs of HMXBs: Neumann et al. arXiv: 2303.16137
Fortin et al. arXiv:2302.02656
- Catalog of X-ray pulsars. Kim et al. arXiv: 2308.09295
- Evolution of binaries:
Postnov & Yungelson. astro-ph/0701059
Belloni & Schreiber. arXiv:2303.08997
Marchant et al. arXiv: 2311.01865 (HMXB evolution)
- Extragalactic XRBs. Fabbiano. astro-ph/0511481, 1903.01970
- CVs
 - Evolution. Ritter. arXiv:0809.1800
 - General features. Smith. astro-ph/0701564
- Be/X-ray binaries: Pablo Reig arXiv: 1101.5036
- X-ray emission from black-hole and neutron-star binaries Belloni 1803.03641
- WD binaries. Webb. arXiv: 2303.10055
- HMXBs. Fornasini et al. arXiv: 2308.02645
- X-ray pulsars. Mushtukov, Tsygankov. arXiv: 2204.14185