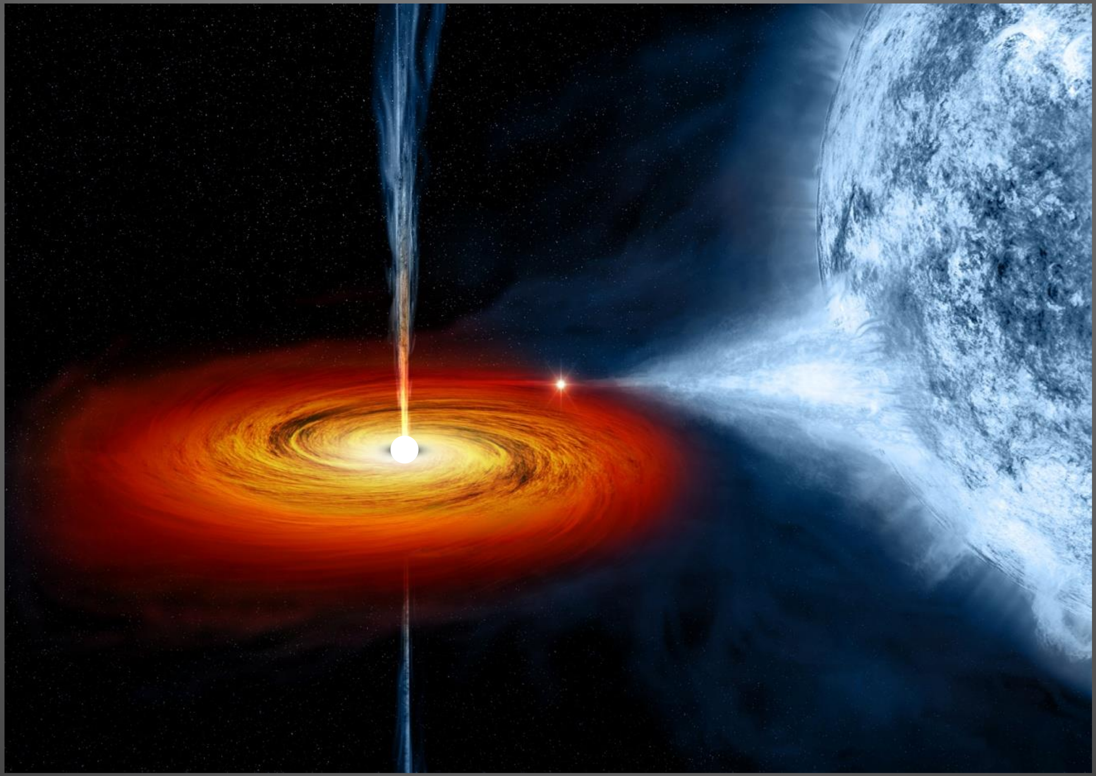
X-RAY BINARIES
AND
RECYCLING OF MILLISECOND PULSARS

AEI IMPRS GW LECTURES 1+2



Thomas Tauris – IFA, Aarhus University

Note: These lectures will be recorded and posted onto the IMPRS website

Dear participants,

We will record all lectures on “The Astrophysics of Compact Objects”, including possible Q&A after the presentation, and we will make the recordings publicly available on the IMPRS lecture website at:

https://imprs-gw-lectures.aei.mpg.de

By participating in this Zoom meeting, you are giving your explicit consent to the recording of the lecture and the publication of the recording on the course website.

Albert-Einstein Institute Lectures 2021

Thomas Tauris @ Aarhus University

- Lectures 1+2: Wednesday May 12, 10:00 – 12:00
  X-ray Binaries and Recycling Millisecond Pulsars

Lectures 3+4: Friday May 14, 10:00 – 12:00
Spin and B-field Evolution of Neutron Stars (+ Black Hole Spins)

Lectures 5+6: Wednesday May 19, 10:00 – 12:00
Formation of Binary Neutron Stars/Black Holes

Lectures 7+8: Friday May 21, 10:00 – 12:00
Binary Neutron Stars and Gravitational Waves at Low and High Frequencies

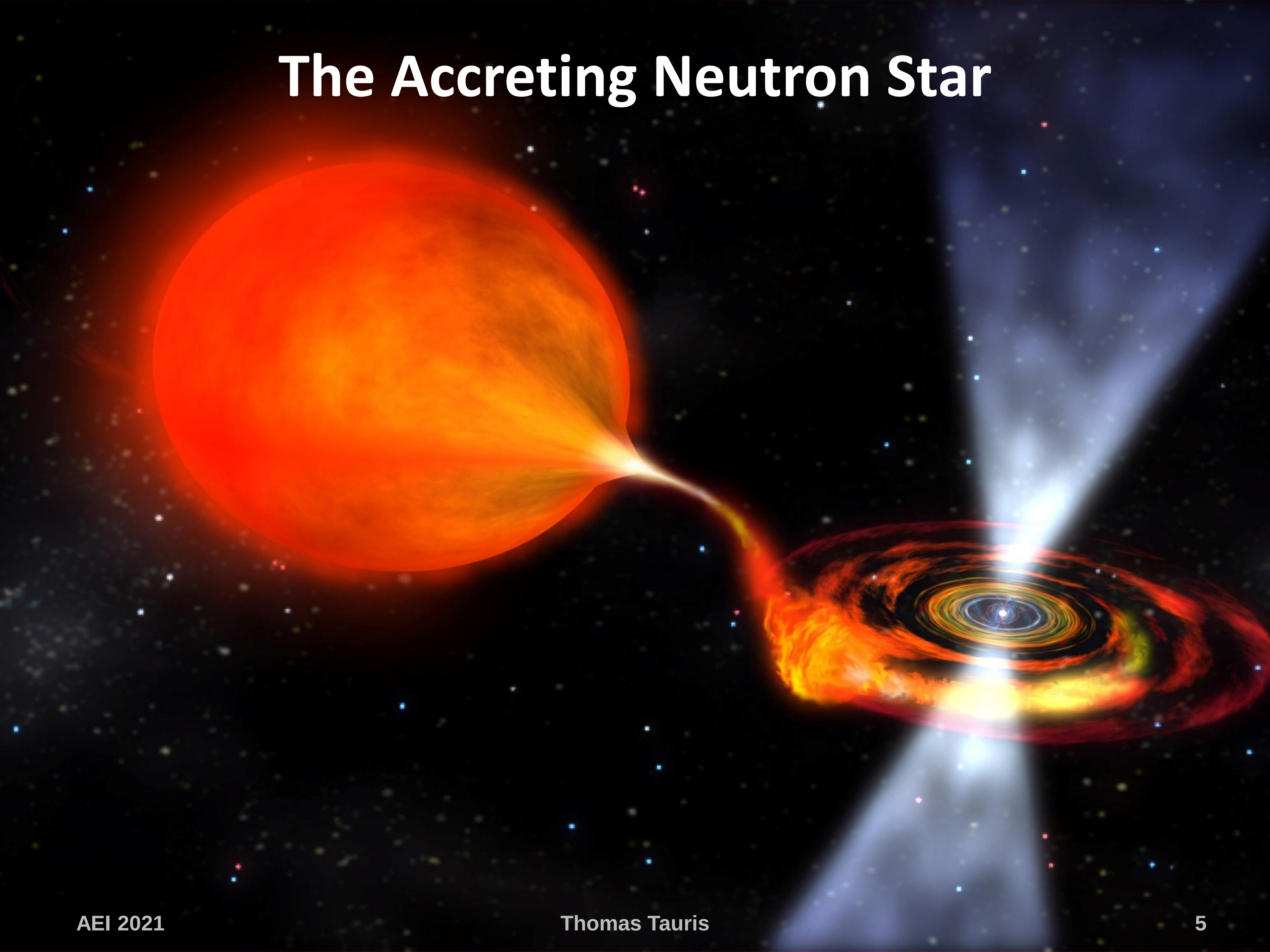
You are most welcome to ask questions any time ☺

X-RAY BINARIES AND
RECYCLING OF MILLISECOND PULSARS
AEI LECTURES 1+2

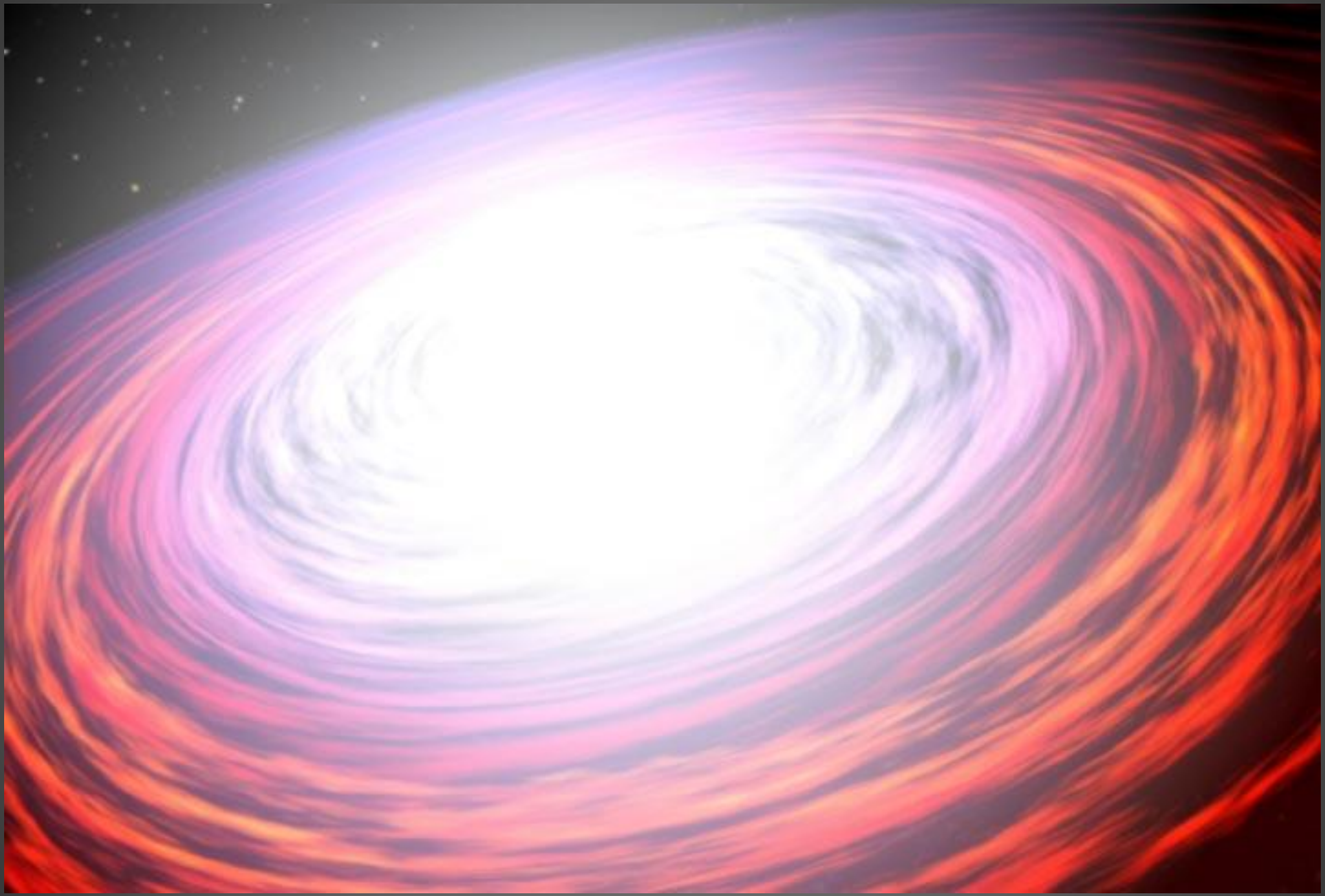
- Introduction to X-ray binaries/Accretion
  - HMXBs and LMXBs
  - Roche-lobe overflow - Cases A, B and C
  - Stability criteria for mass transfer / stellar evolution
  - Orbital angular momentum balance equation
- Common envelope and spiral-in evolution
- Equilibrium spin period and spin-up line in P-P_{dot} diagram
- Accretion physics
  - Accretion disks
  - B-field decay
  - Four phases of accretion (self study)

For a review: Tauris & van den Heuvel (2006)
Tauris & van den Heuvel (2022)
New textbook from Princeton Uni. Press

The Accreting Neutron Star



Energetics of Accretion



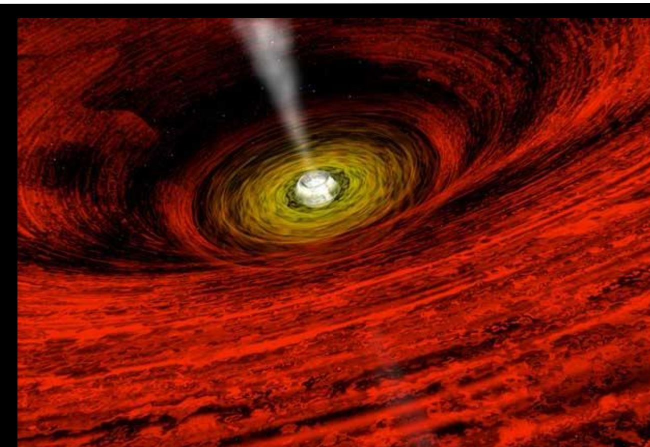
DISCOVERY OF BLACK HOLES AND NEUTRON STARS

1962. Sco X-1: neutron star LMXB
(Giacconi, Aerobee 150 rocket)

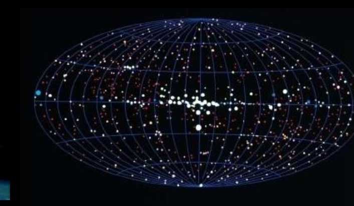
1967. PSR B1919+21

1971. Cen X-3: pulses (P=4.84 sec)

1971. Cyg X-1: black hole HMXB



$$1M_\odot \text{ accretor} \quad \text{and} \quad \mathrm{L_X} = 10^{37}\, erg\ s^{-1}$$



Stellar object	Radius (km)	$\Delta U/mc^2$	$\Delta U/m$ (erg g^{-1})	dM/dt (M_{sun} yr^{-1})	Column density (g cm^{-2})
Sun / star	7×10^5	2×10^{-6}	2×10^{15}	1×10^{-4}	140 *
White dwarf	10000	2×10^{-4}	1×10^{17}	1×10^{-6}	16 *
Neutron star	10	0.15	1×10^{20}	1×10^{-9}	0.5 *
Black hole	3	0.1–0.4	4×10^{20}	4×10^{-10}	0.3 *

* Note: X-rays are stopped at column densities larger than a few g cm^{-2}

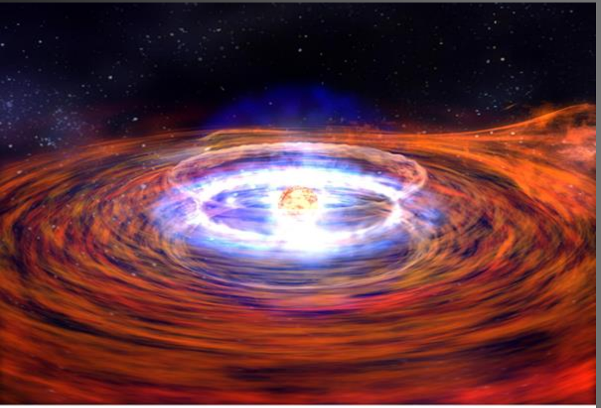
Accretion Luminosity

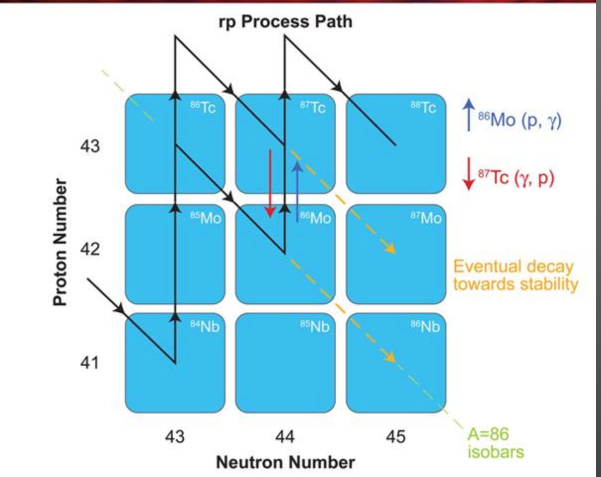
$$L_X = (\varepsilon_{nuc} + \varepsilon_{grav})\,\dot{M}_{acc}$$

Nuclear burning at surface of compact object

$$H \to He \to C \to O \to Si \to Fe \to \ldots$$

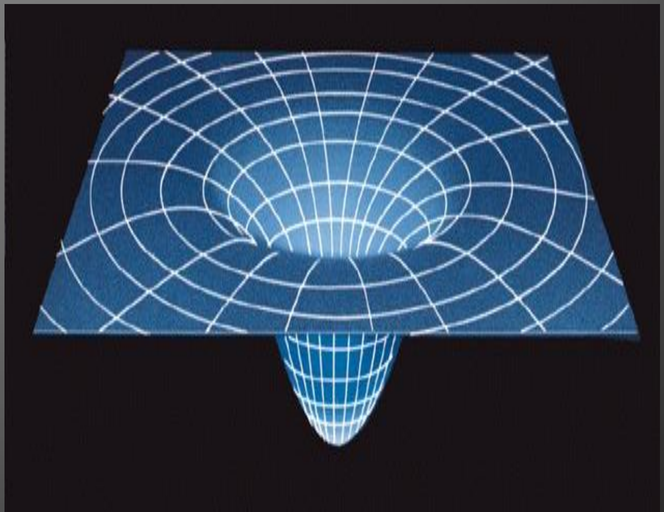
Dominate in accreting WD
(not relevant for BH)



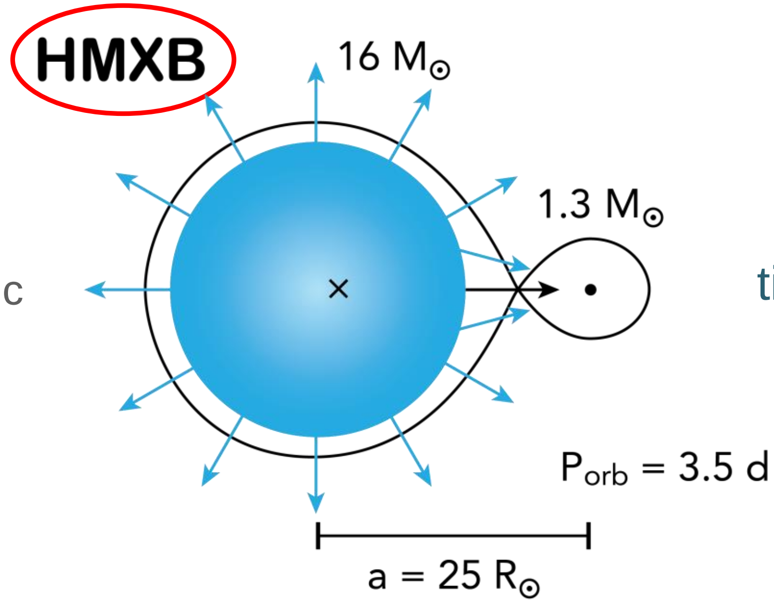


Dominate in NS and BH

Release of gravitational binding energy



High-Mass X-ray Binaries

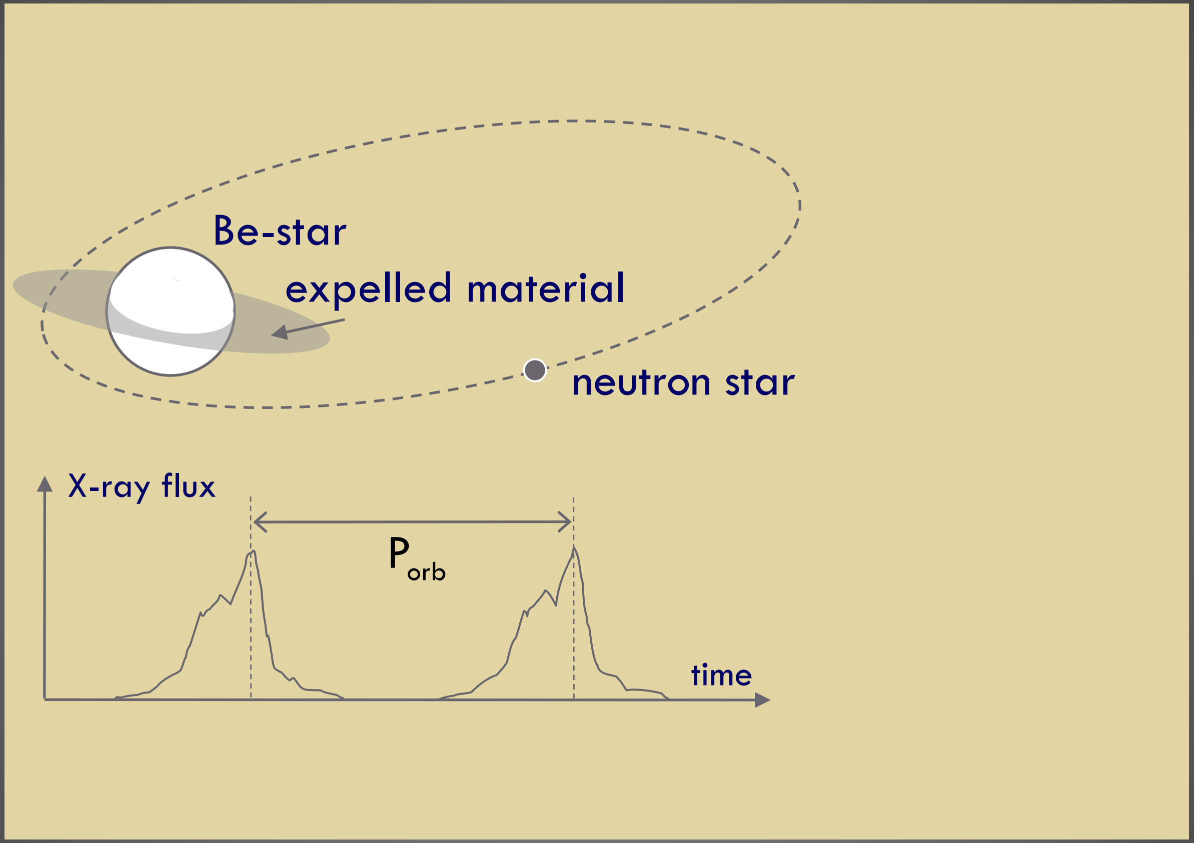


- wind accretion
- beginning atmospheric Roche-lobe overflow

timescale: $10^5 - 10^6$ yr

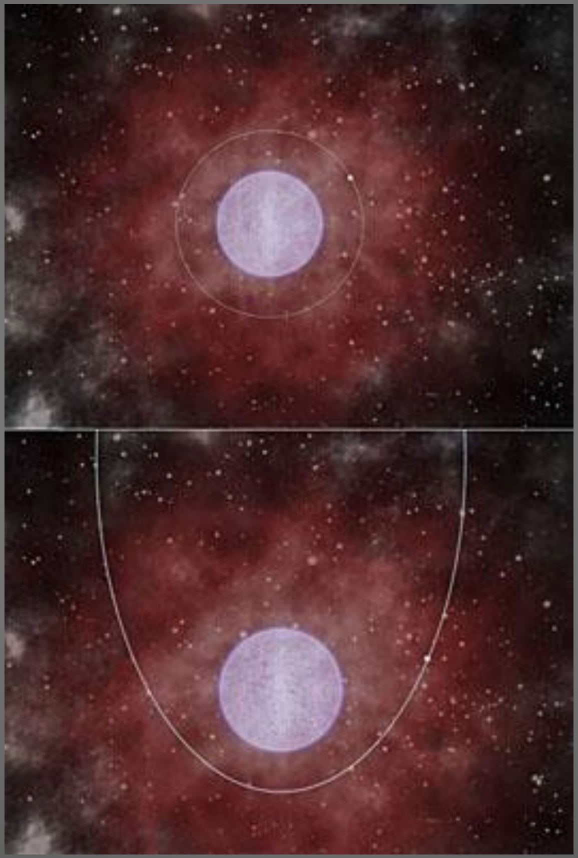
Donor star masses $M_2 > 10\ M_{sun}$
114 systems known in our Galaxy:
- 50 systems with measured P_{orb} = 0.2 – 262 days (median 23 days)
- 66 systems with measured P_{spin} = 33 ms – 4 hours (median 3 min)

Be-star X-ray Binaries
(subclass of HMXBs)



Supergiant Fast X-ray Transients (SFXTs)

(subclass of HMXBs – many discovered with INTEGRAL)



HMXBs with BH accretors

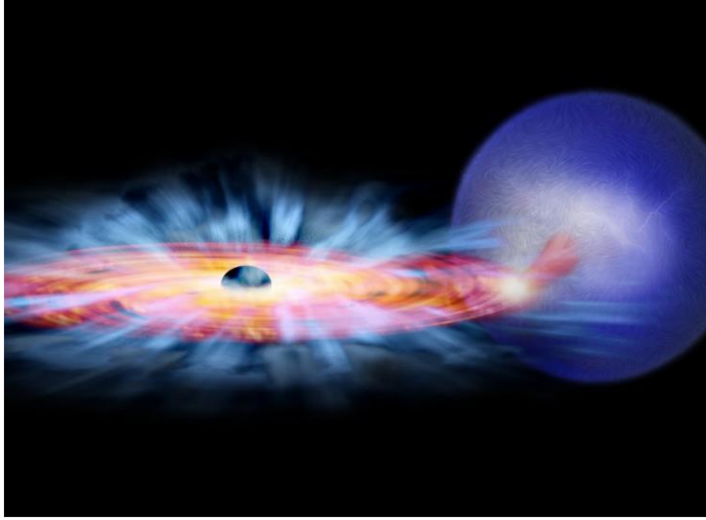


Table 6.6: The five known BH HMXBs. (Updated after van den Heuvel, 2019).

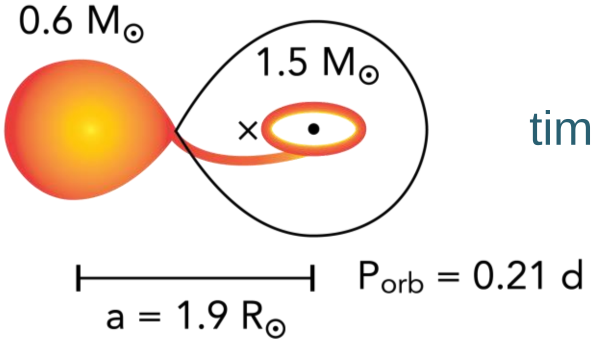
Source	$P_{\rm orb}$ (d)	$M_{\rm donor}$ ($M_\odot$)	$M_{\rm BH}$ ($M_\odot$)	Reference
Cyg X-1	5.6	41 ($\pm$7)	21.2 ($\pm$2.2)	Miller-Jones et al. (2021)
LMC X-1	3.9	31.8 ($\pm$3.5)	10.9 ($\pm$1.4)	Orosz et al. (2009)
LMC X-3	1.7	3.6 ($\pm$0.6)	7.0 ($\pm$0.6)	Orosz et al. (2014)
MCW 656	$\sim$ 60	$\sim$ 13	4.7 ($\pm$0.9)	Casares et al. (2014)
M33 X-7	3.45	70 ($\pm$7)	15.7 ($\pm$1.5)	Orosz et al. (2007)

Tauris & van den Heuvel (2022)

Low-Mass X-ray Binaries

LMXB

- Roche-lobe overflow



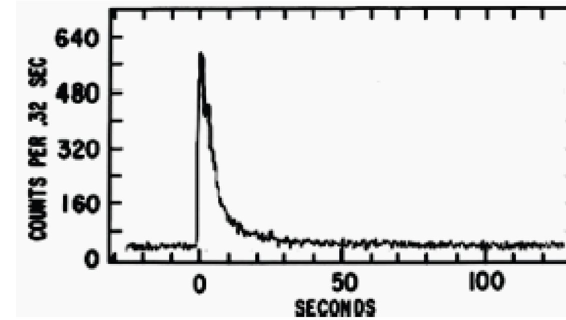
timescale: 10^8 – 10^9 yr

Donor star masses $M_2 < 1\ M_{sun}$
187 candidate systems in our Galaxy:
- 74 systems with measured P_{orb} = 11 min – 1160 days (median: 8 hours)
- 26 systems with measured P_{spin} = 1.6 ms – 7.7 sec (median: 3 ms)

Most systems are **transients** and **X-ray bursters** (thermonuclear explosions)
About 20 **black hole** systems **(soft X-ray transients)**

X-ray Bursts

Burst light curve



Rise time ≈ 0.5 - 5 seconds
Decay time ≈ 10 - 100 seconds
Recurrence time ≈ hours to day
Energy release ≈ 10^{39} erg

Accretion of H-rich matter piles up on the NS. Gravity compresses matter and the temperature rises at the base of this accumulated envelope leading to ignition under degenerate conditions resulting in a thermonuclear explosion and a rapid photospheric expansion.
The burst lasts for some 10-100 sec.
Burst oscillations reveal the spin period of the NS.

HARDY

LMXBs with BH accretors

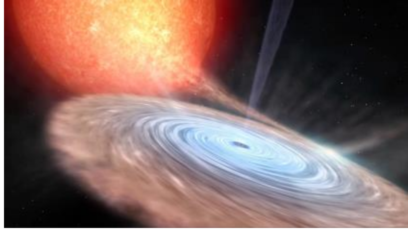
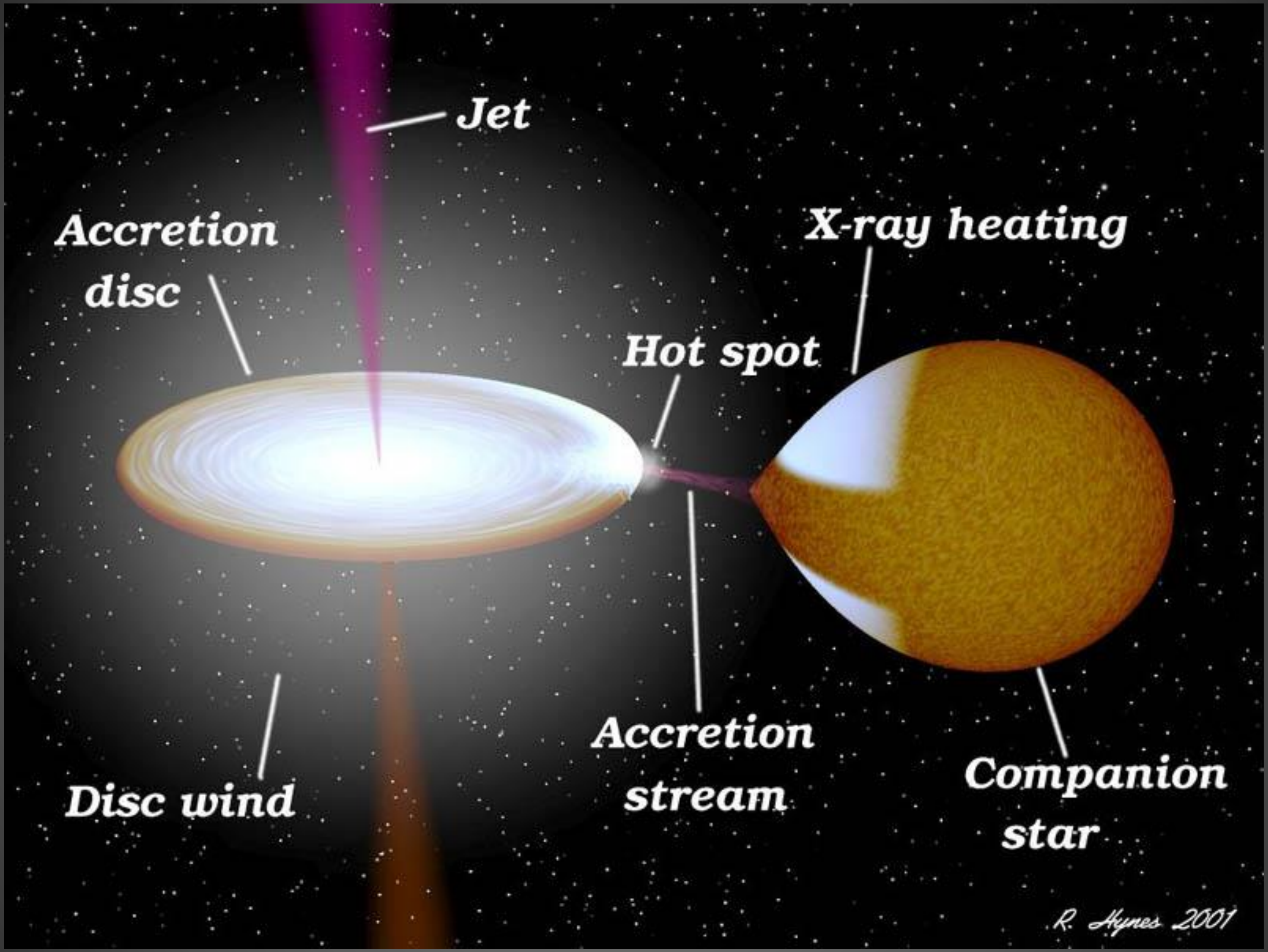


Table 6.5: Examples BH LMXBs. (After McClintock & Remillard, 2006).

Source	Alternative name	P_{orb} (hr)	Spectrum	BH mass ($M_\odot$)
0422+32	V518 Per	5.1	M2V	3.2 – 13.2
0620–003	V616 Mon	7.8	K4V	3.3 – 12.9
1009–45	MM Vel	6.8	K7/M0V	6.3 – 8.0
1118+480	KV UMa	4.1	K5/M0V	6.5 – 7.2
1124–684	GU Mus	10.4	K3/K5V	6.5 – 8.2
1543–475	IL Lupi	26.8	A2V	7.4 – 11.4
1550–564	V381 Nor	37.0	G8–K8IV	8.4 – 10.8
1655–40	V1033 Sco	62.9	F3–F5IV	6.0 – 6.6
1659–487	V821 Ara	42.1	—	—
1705–250	V2107 Oph	12.5	K3/7V	5.6 – 8.3
1819.3–2525	V4641 Sgr	67.6	B9III	6.8 – 7.4
1859+226	V406 Vul	9.2	—	7.6 – 12.0
1915+105	V1487 Aql	804.0	K/MIII	10.0 – 18.0
2000+251	QZ Vul	8.3	K3/K7V	7.1 – 7.8
2023+338	V404 Cyg	155.3	K0III	10.1 – 13.4

Tauris & van den Heuvel (2022)


Jet
Accretion disc
X-ray heating
Hot spot
Disc wind
Accretion stream
Companion star
R. Hynes 2001

Equipotential Surfaces and RLO

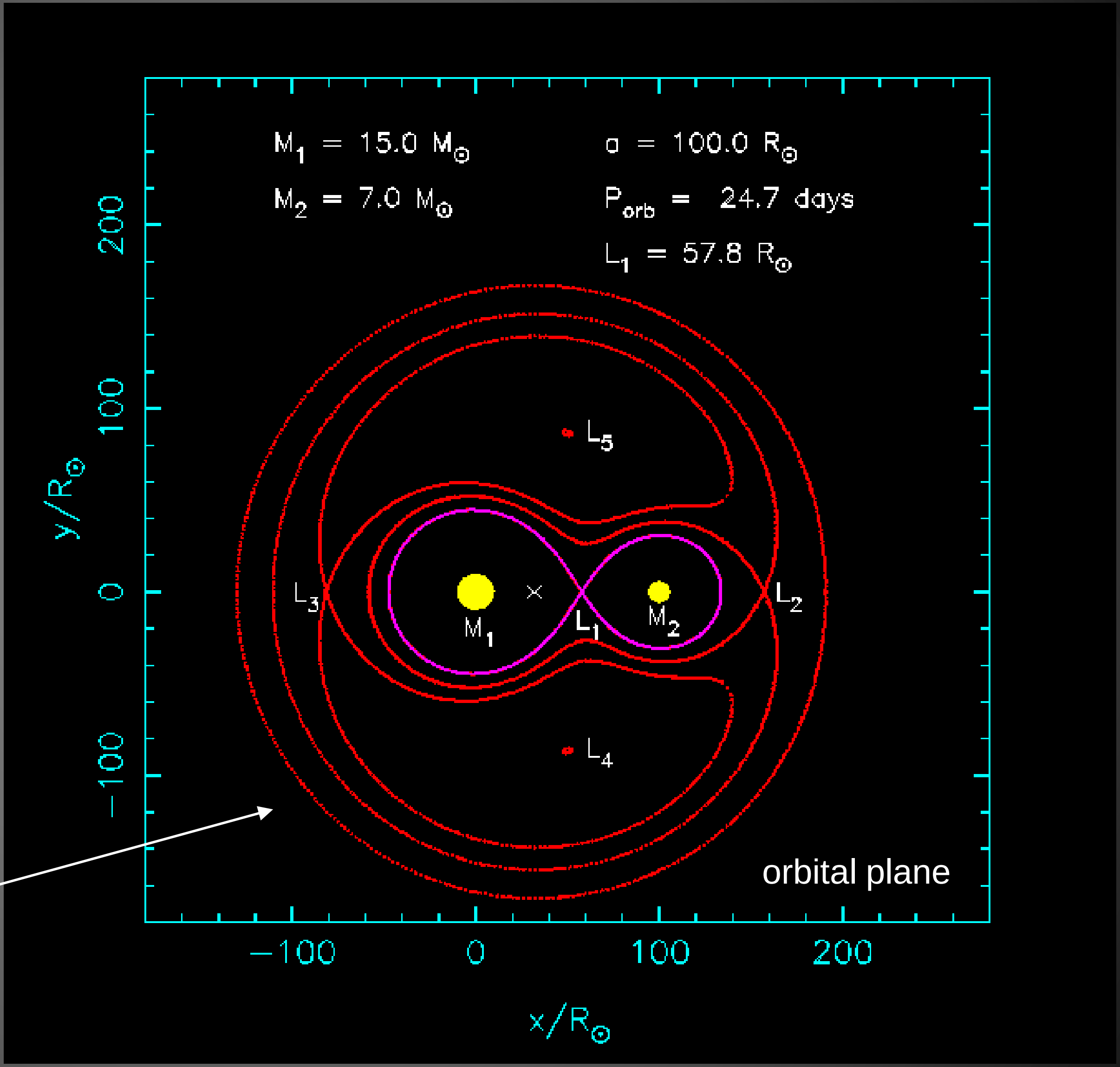
Effective gravitational potential:

$$\Phi = -\frac{GM_1}{r_1} - \frac{GM_2}{r_2} - \frac{\Omega^2 r_3^2}{2}$$

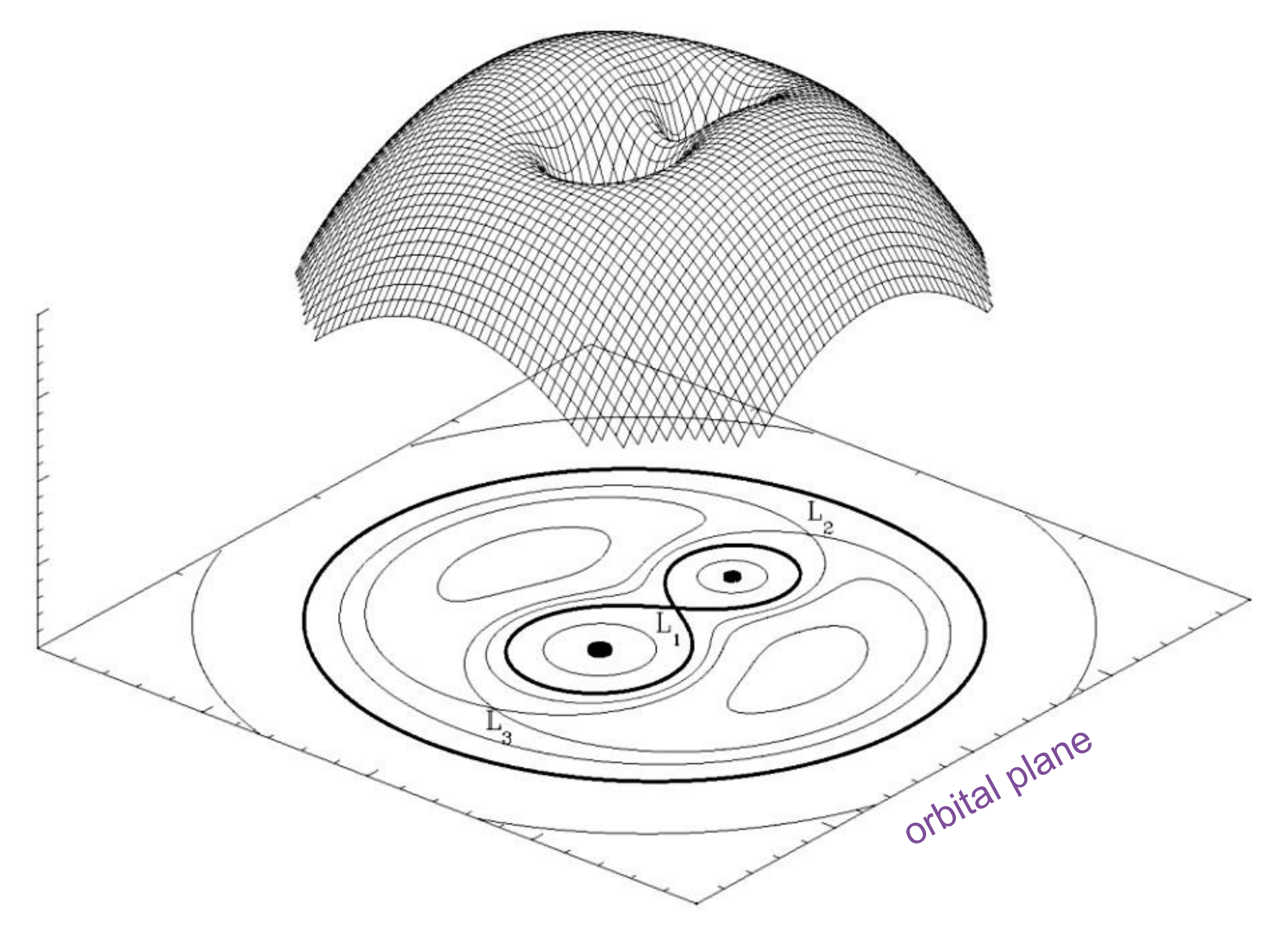
Roche-lobe radius:

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

co-moving frame



Equipotential Surfaces and RLO



X-ray binaries Roche-lobe overflow Cases A, B and C:

(the evolutionary stage of the donor star at onset of RLO is quite important …)

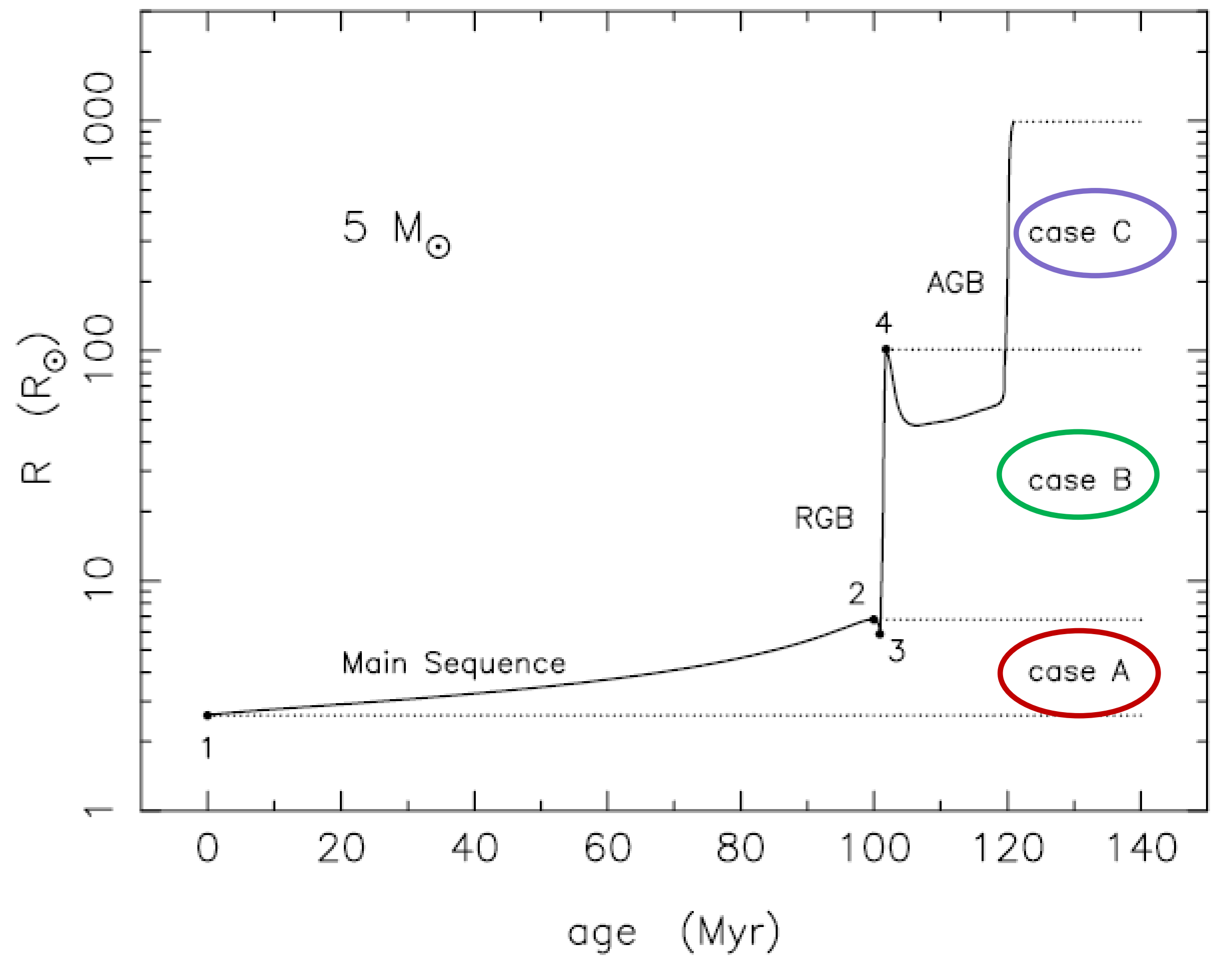


Fig. 16.6. Evolutionary change of the radius of the 5 $M_{\odot}$ star plotted in Fig. 16.5. The ranges of radii for mass transfer to a companion star in a binary system according to RLO cases A, B and C are indicated – see Section 16.4 for an explanation.

The evolution of compact binaries

Stability ?

response of donor star ?

response of Roche-lobe ?

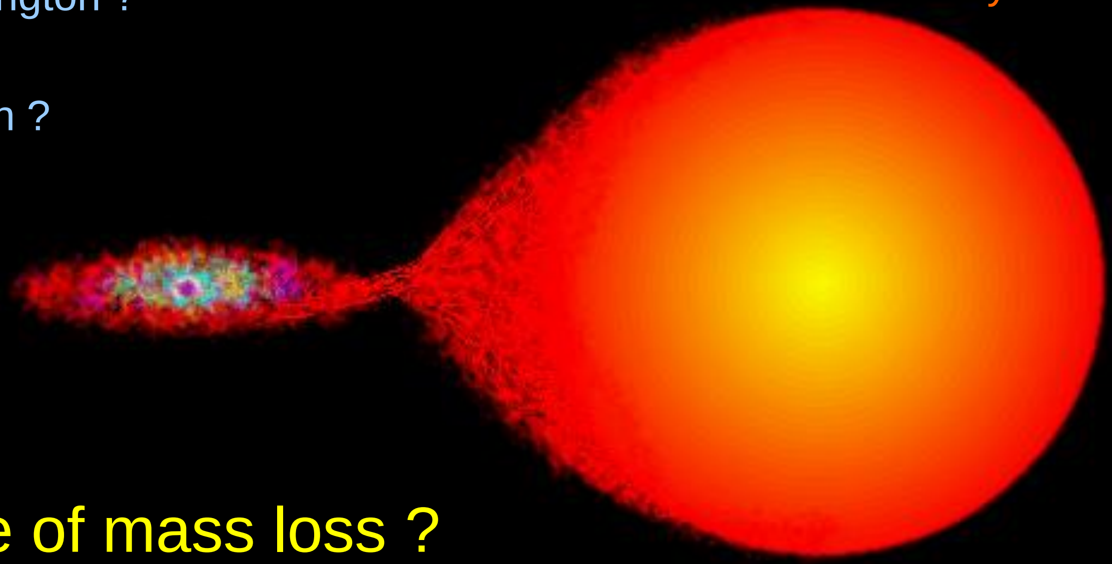
dynamically stable ?

Accretion ?

super-Eddington ?

jet ?

B-field, spin ?



Mode of mass loss ?

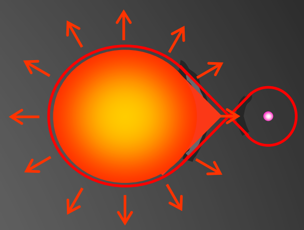
specific orbital angular momentum ?

magnetic braking / tidal interactions

gravitational wave radiation

Stability Criteria for Mass Transfer

exponents of radius to mass: $R \propto M^{\zeta}$



$$\zeta_{donor} \equiv \frac{\partial \ln R_2}{\partial \ln M_2} \quad \wedge \quad \zeta_L \equiv \frac{\partial \ln R_L}{\partial \ln M_2}$$

adiabatic or thermal response of the donor star to mass loss

initial stability criteria: $\zeta_L \leq \zeta_{donor}$

$$\dot{R}_2 = \left.\frac{\partial R_2}{\partial t}\right|_{M_2} + R_2\, \zeta_{donor} \frac{\dot{M}_2}{M_2}$$

$$\dot{R}_L = \left.\frac{\partial R_L}{\partial t}\right|_{M_2} + R_L\, \zeta_L \frac{\dot{M}_2}{M_2}$$

nuclear burning

tidal spin-orbit couplings
gravitational wave radiation

$\dot{R}_2 = \dot{R}_L$ yields mass loss rate!

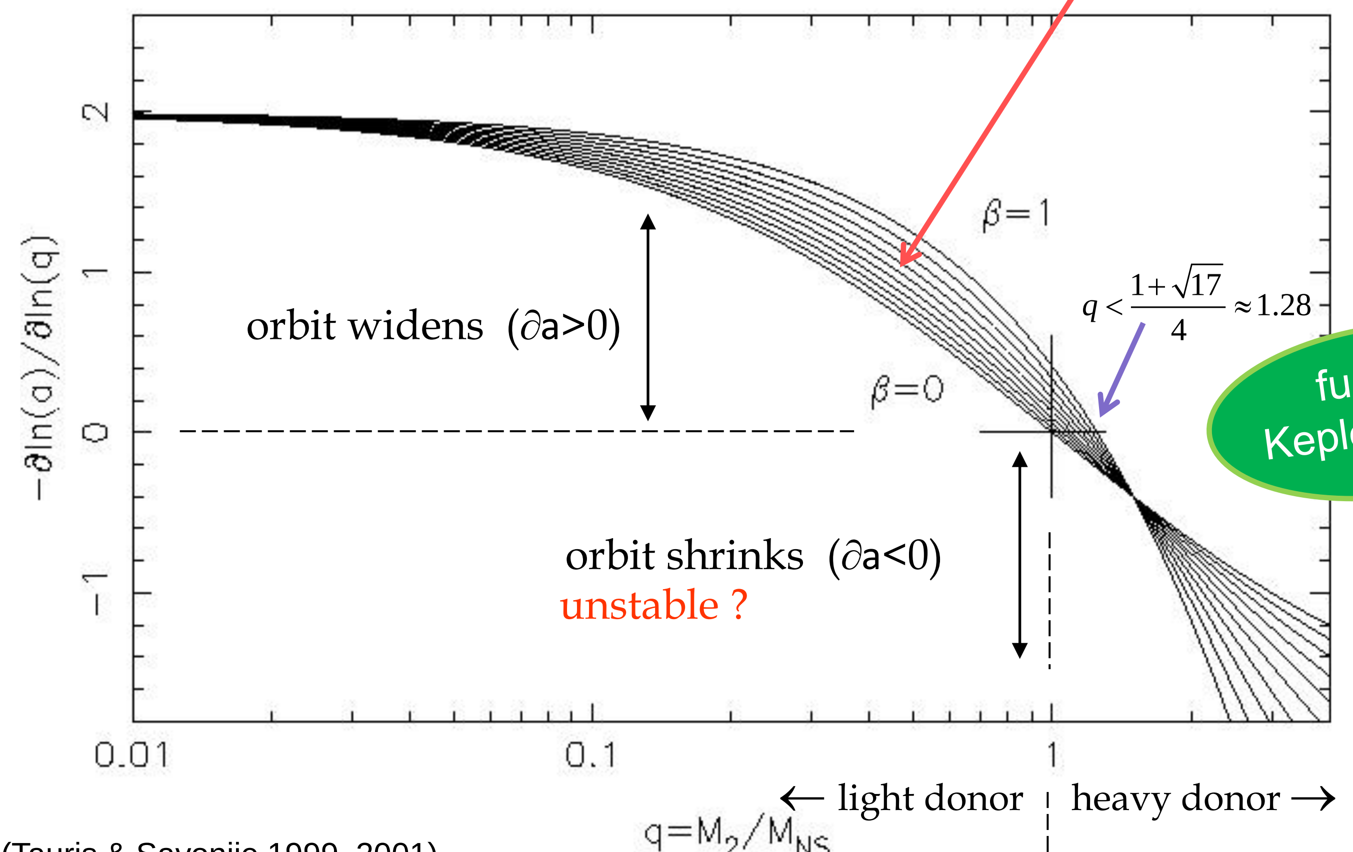
Stability Criteria for Mass Transfer. II

Isotropic Re-emission Model

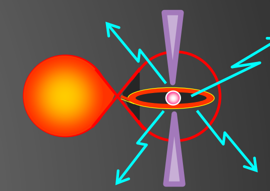
(Bhattacharya & van den Heuvel 1991)
(Soberman, Phinney & van den Heuvel 1997)

Orbital evolution: $-\dfrac{\partial \ln a}{\partial \ln q} \quad \wedge \quad q = \dfrac{M_2}{M_{NS}} \quad (\partial q < 0)$

$$\beta = \max\left(\frac{|\dot{M}_2| - \dot{M}_{Edd}}{|\dot{M}_2|}, 0\right) \quad \alpha = 0 \quad \delta = 0$$



(Tauris & Savonije 1999, 2001)

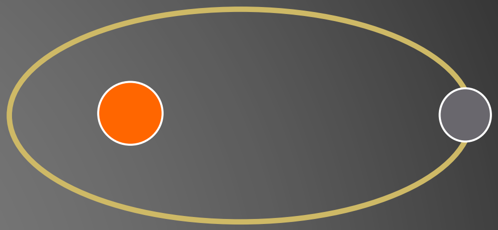


fun with Kepler's 3.law

Orbital Angular Momentum Balance (OAMB) Eqn.

$$J_{orb} = \frac{M_1 M_2}{M}\,\Omega\, a^2 \sqrt{1-e^2}$$

orbital angular momentum



$$J_{orb} = |\vec{r} \times \vec{p}|$$

$$\Omega = \sqrt{GM / a^3}$$

logarithmic differentiation

(e=0, tidal circularization)

$\Downarrow$

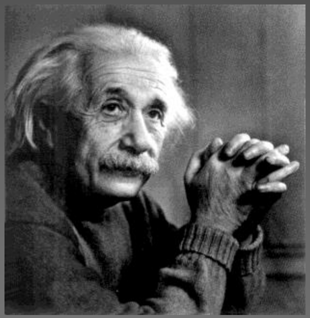
$$\frac{\dot{a}}{a} = 2\,\frac{\dot{J}_{orb}}{J_{orb}} - 2\,\frac{\dot{M}_1}{M_1} - 2\,\frac{\dot{M}_2}{M_2} + \frac{\dot{M}_1 + \dot{M}_2}{M}$$

$$\frac{\dot{J}_{orb}}{J_{orb}} = \frac{\dot{J}_{gwr}}{J_{orb}} + \frac{\dot{J}_{mb}}{J_{orb}} + \frac{\dot{J}_{ls}}{J_{orb}} + \frac{\dot{J}_{ml}}{J_{orb}}$$

See next two slides

Gravitational Wave Radiation:

$$\frac{\dot{J}_{gwr}}{J_{orb}} = -\frac{32}{5}\frac{G^3}{c^5}\frac{M_1 M_2 M}{a^4}$$



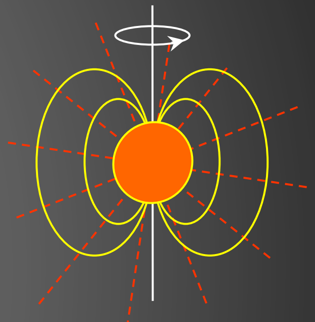
Magnetic braking:

$$\frac{\dot{J}_{mb}}{J_{orb}} \propto -\frac{k^2 R^4}{a^5}\frac{GM^3}{M_1 M_2}$$

(uncertain)

Low-mass stars: magnetic wind!
$\Rightarrow$ loss of spin angular momentum

In tight binaries the system is tidally locked (synchronized) and spin-orbit couplings operate
$\Rightarrow$ loss of orbital angular momentum



$M_2 < 1.5\ M_{sun}$

$P_{orb} < 2$ days

Spin-orbit couplings:

$$\frac{\dot{J}_{ls}}{J_{orb}}$$

- fx change in stellar moment of inertia
(as a result of nuclear burning or mass loss)

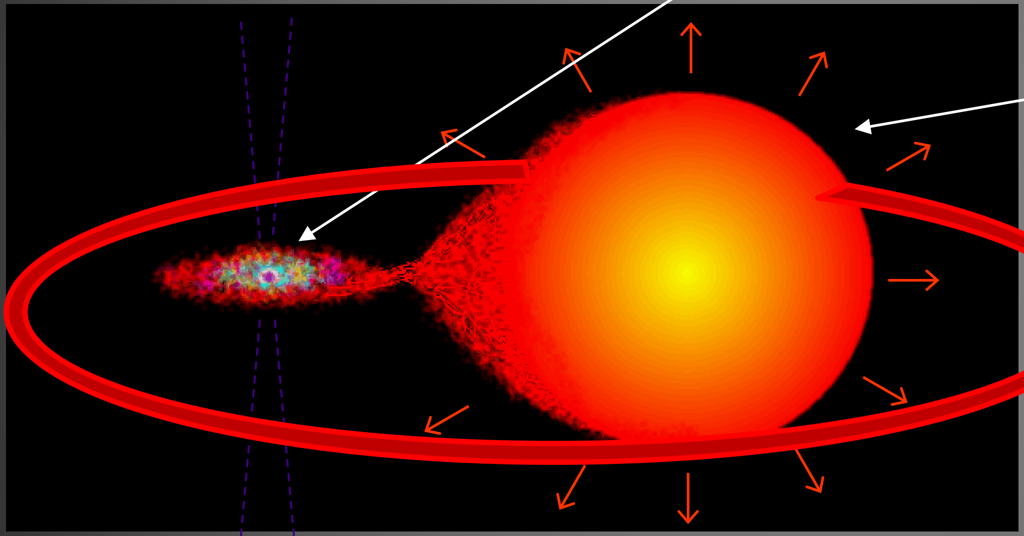
Mass loss: (isotropic re-emission model)

$$\beta = \max\left(\frac{|\dot{M}_2| - \dot{M}_{Edd}}{|\dot{M}_2|}, 0 \right)$$

$$\frac{\dot{J}_{ml}}{J_{orb}} = \frac{\alpha + \beta q^2 + \delta \gamma (1+q)^2}{1+q} \frac{\dot{M}_2}{M_2}$$

β: mass ejected from accretor

- fx. in a relativistic jet (isotropic re-emission)



α: direct fast wind

δ: mass loss via circumbinary coplanar toroid with radius: $\gamma^2 a$

Accretion efficiency: $\varepsilon = 1 - \alpha - \beta - \delta$ $\quad (\partial M_{NS} = -\varepsilon\, \partial M_2)$

Bhattacharya & van den Heuvel (1991)
Tauris (1996)
Soberman, Phinney & van den Heuvel (1997)
Tauris & van den Heuvel (2006)
Tauris & van den Heuvel (2022)

Solution……….

Integration of the OAMB eq. for mass transfer/loss:

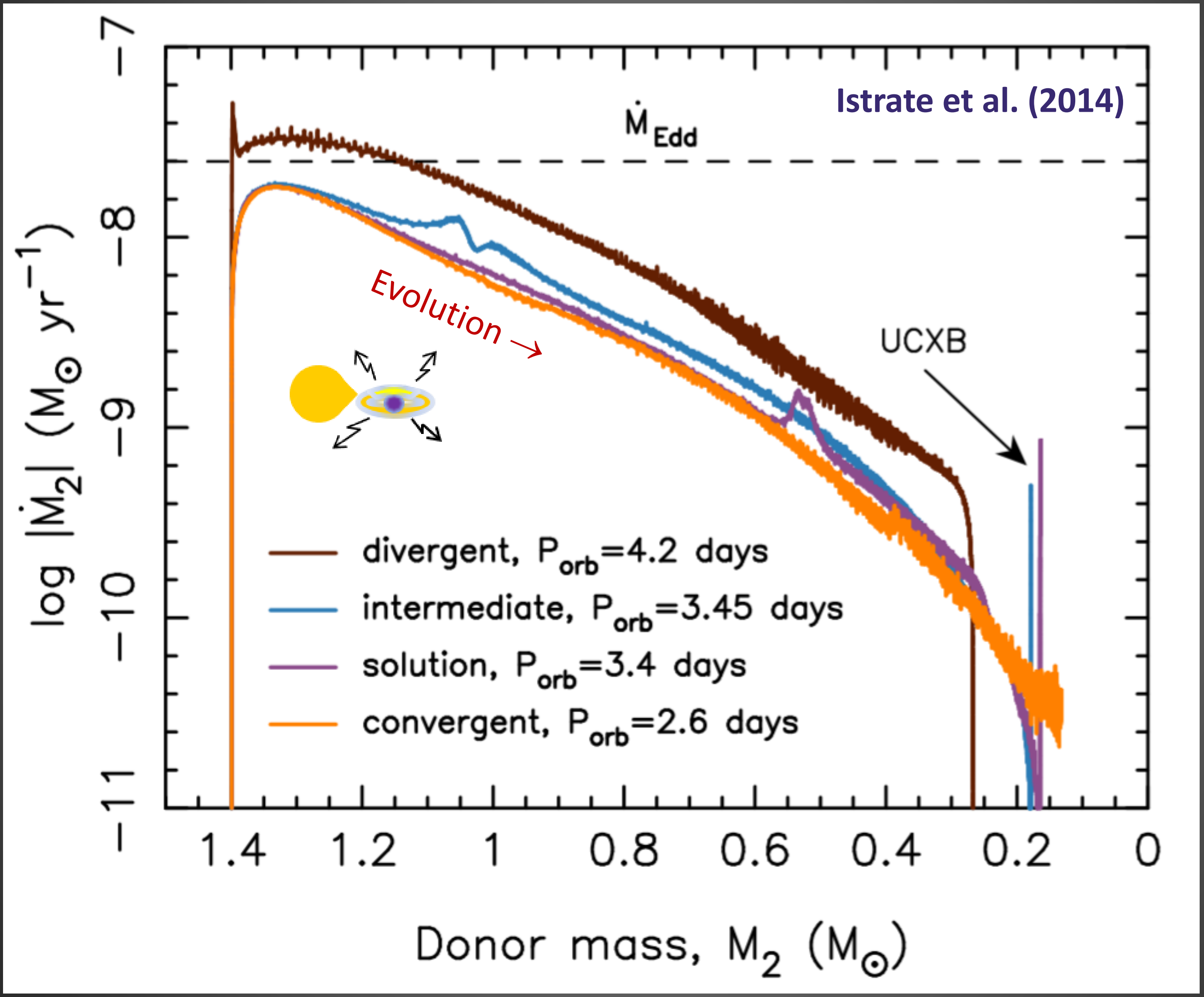
$$\frac{a}{a_0} = \Gamma_{ls}\left(\frac{q}{q_0}\right)^{2(\alpha+\gamma\delta-1)}\left(\frac{q+1}{q_0+1}\right)^{\frac{-\alpha-\beta+\delta}{1-\varepsilon}}\left(\frac{\varepsilon q+1}{\varepsilon q_0+1}\right)^{3+2\frac{\alpha\varepsilon^2+\beta+\gamma\delta(1-\varepsilon)^2}{\varepsilon(1-\varepsilon)}}$$

Tauris & van den Heuvel (2006)

mass ratio

final separation (after RLO)

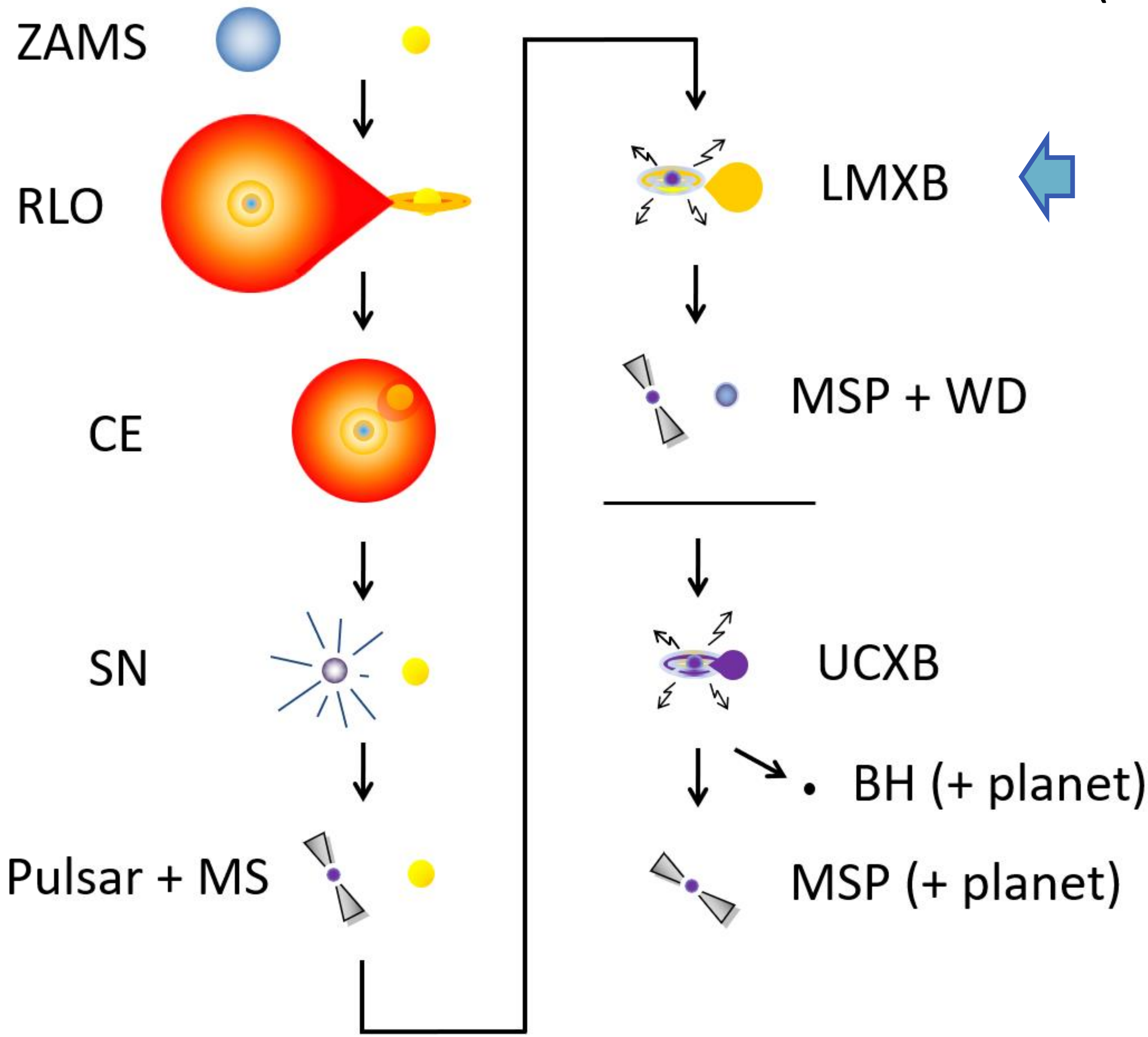
Example of numerical LMXB calculation……….



LMXB

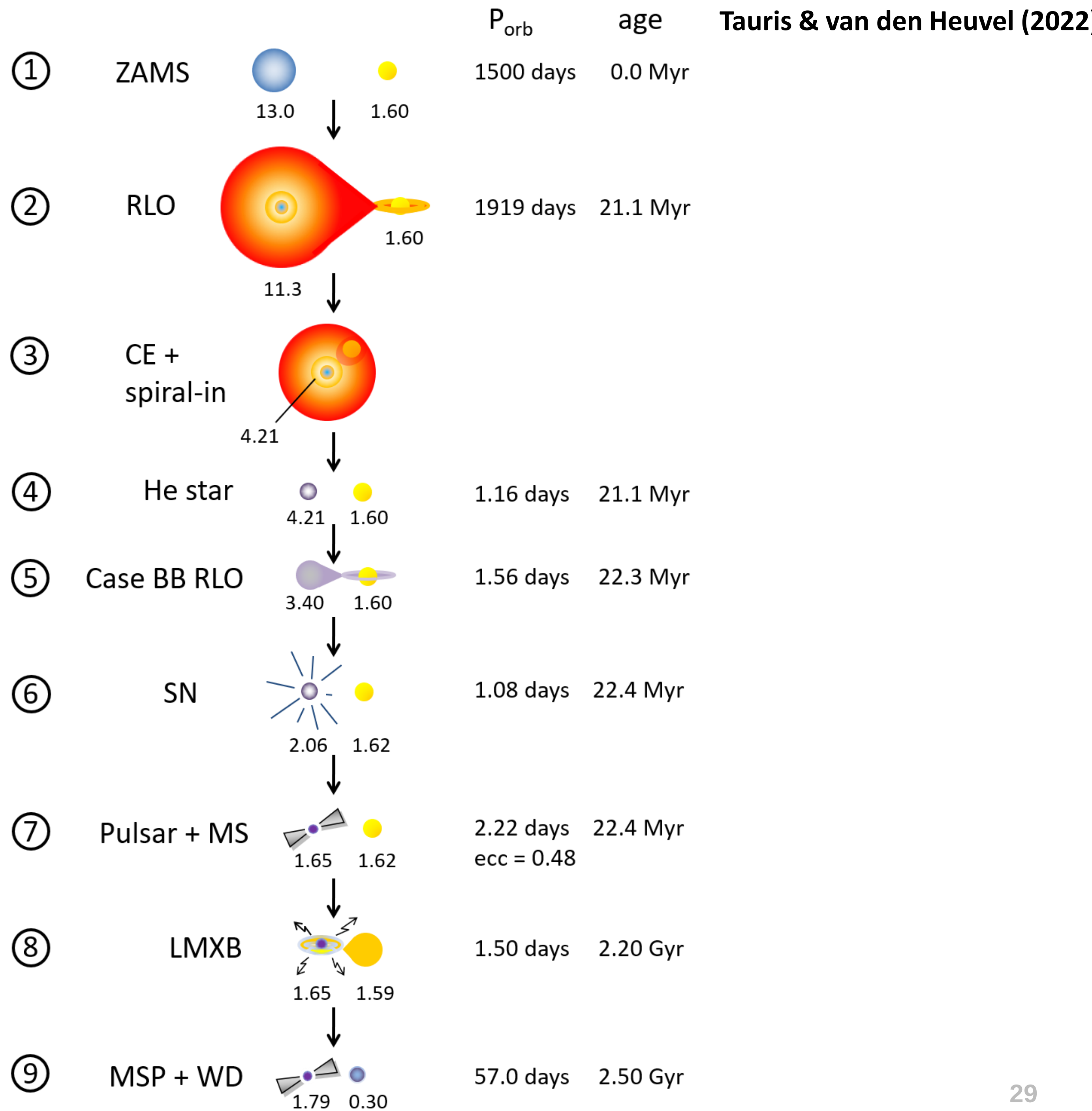
Formation & Evolution

Tauris & van den Heuvel (2022)



LMXB

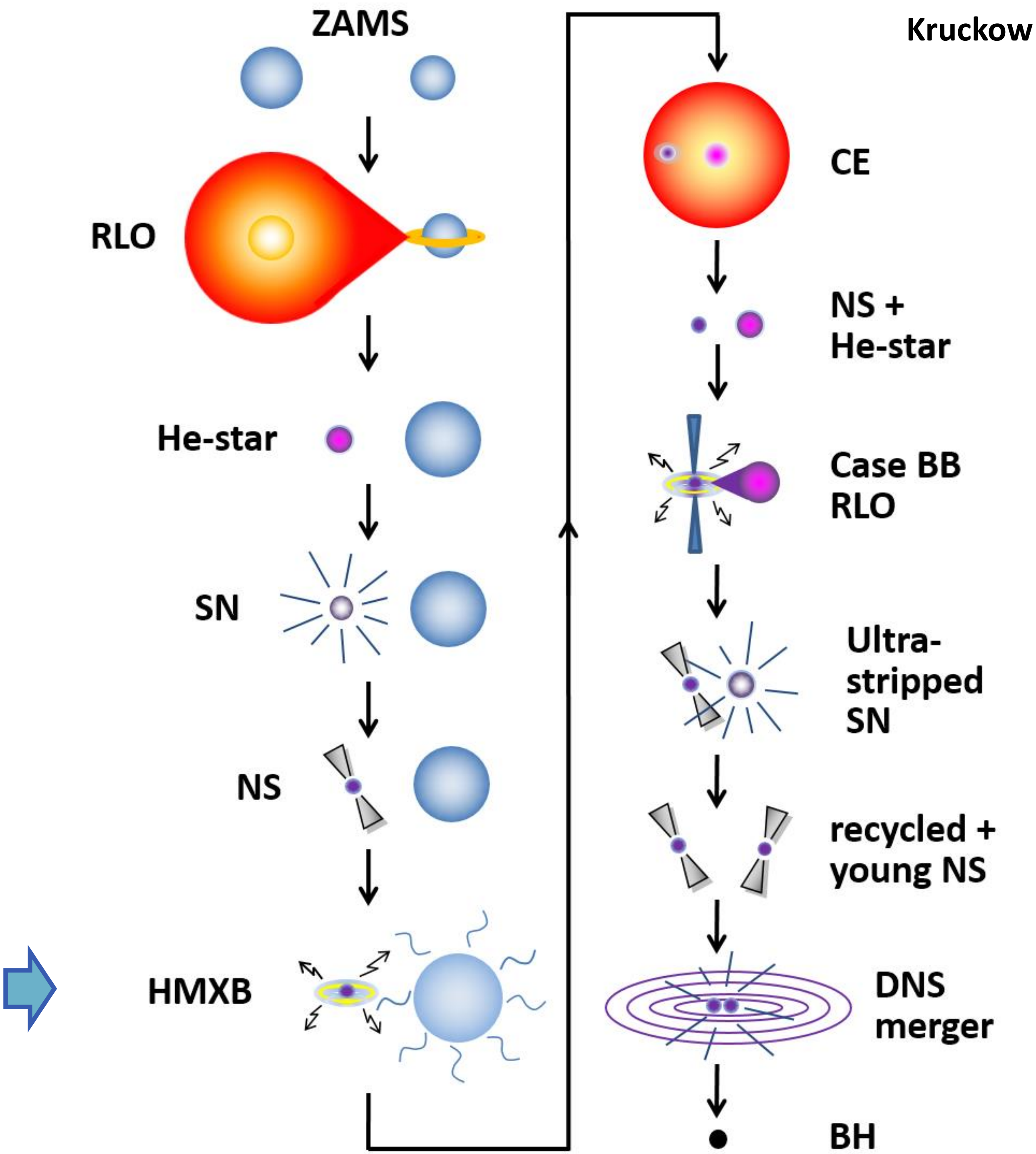
Formation & Evolution in detail



HMXB

Formation & Evolution

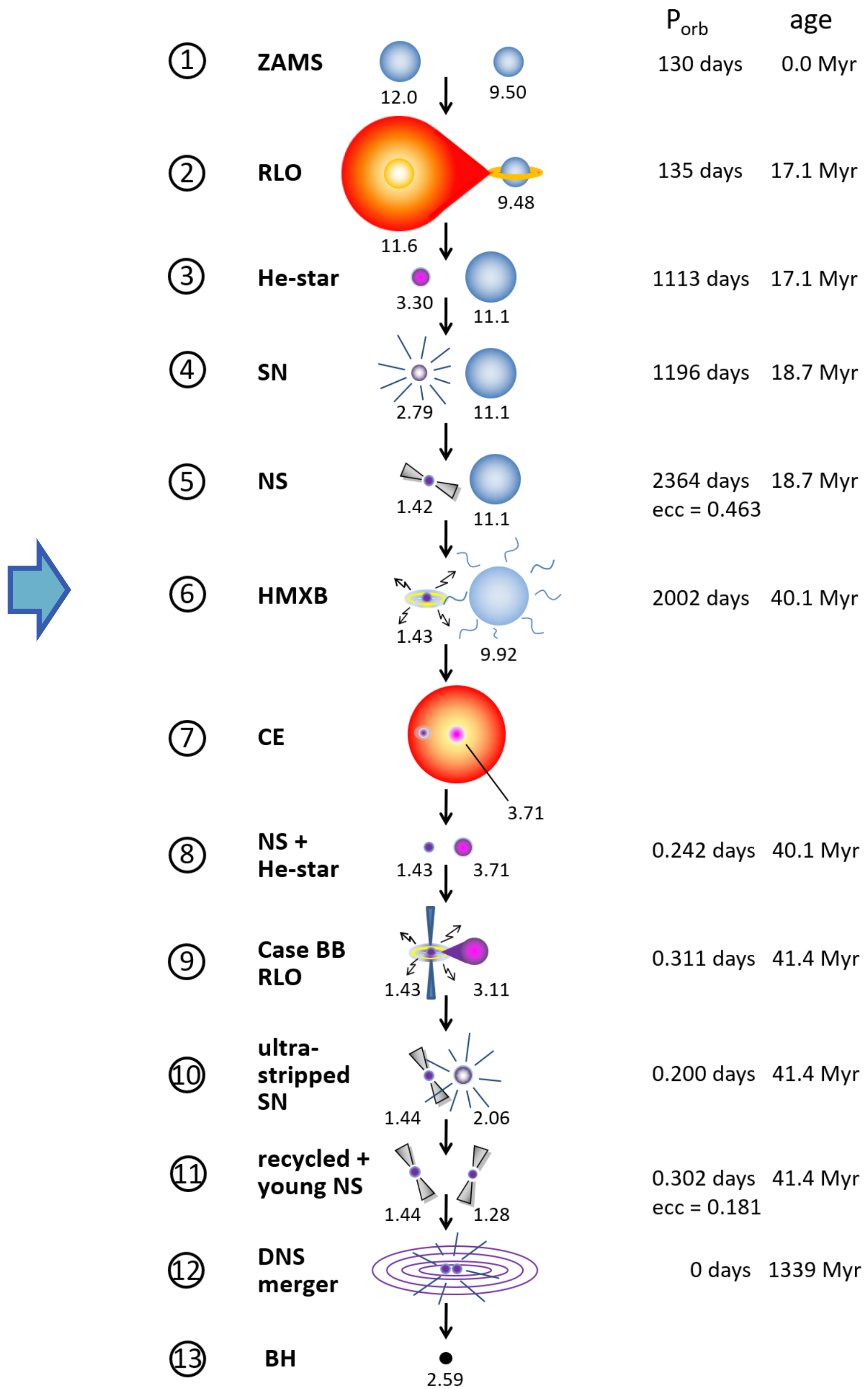
Kruckow et al. (2018)



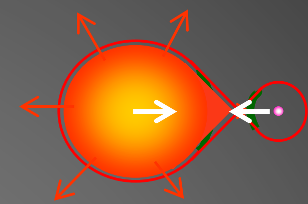
HMXB

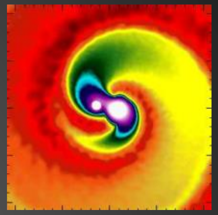
Formation & Evolution in detail

Tauris & van den Heuvel (2022)



Common-Envelope + Spiral-in Evolution





Dynamically <u>un</u>stable mass transfer:

- deep convective envelope of donor star

  (rapid expasion in response to mass loss)

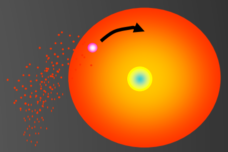
- $M_{donor} > M_{accretor}$

  (orbit shrinks in response to mass loss)

Run-away process!!

$\Downarrow$

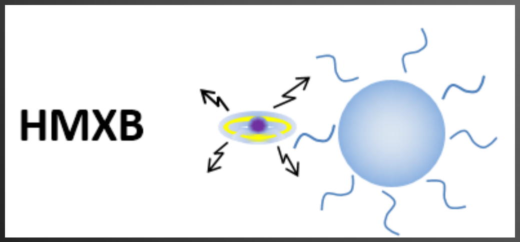
common envelope



drag force $\rightarrow$ dissipation of orb. ang. mom. + deposition of E_{orb} in the envelope

Outcome HMXBs $\rightarrow$ CE:

- CE: huge reduction of orbital separation



rejection of stellar envelope

(NS/BH orbiting a naked helium star)

merging of NS/BH + core

(Thorne-Zytkow object / BH)

COMMON-ENVELOPE EVOLUTION

$$\dot{E}_{orb} = -\frac{GM_{donor}M_{NS}}{2a^2}\frac{da}{dt} = \xi(\mu)\pi R_{acc}^2 \rho_{donor} v^3$$

Dissipation of E_{orb} by drag force (Bondi & Hoyle 1944)

$$E_{\rm env} \equiv \alpha_{\rm CE}\,\Delta E_{\rm orb}$$

Webbink (1984)

$$\alpha_{\rm CE} = 0.3 \sim 1$$

efficiency parameter

!

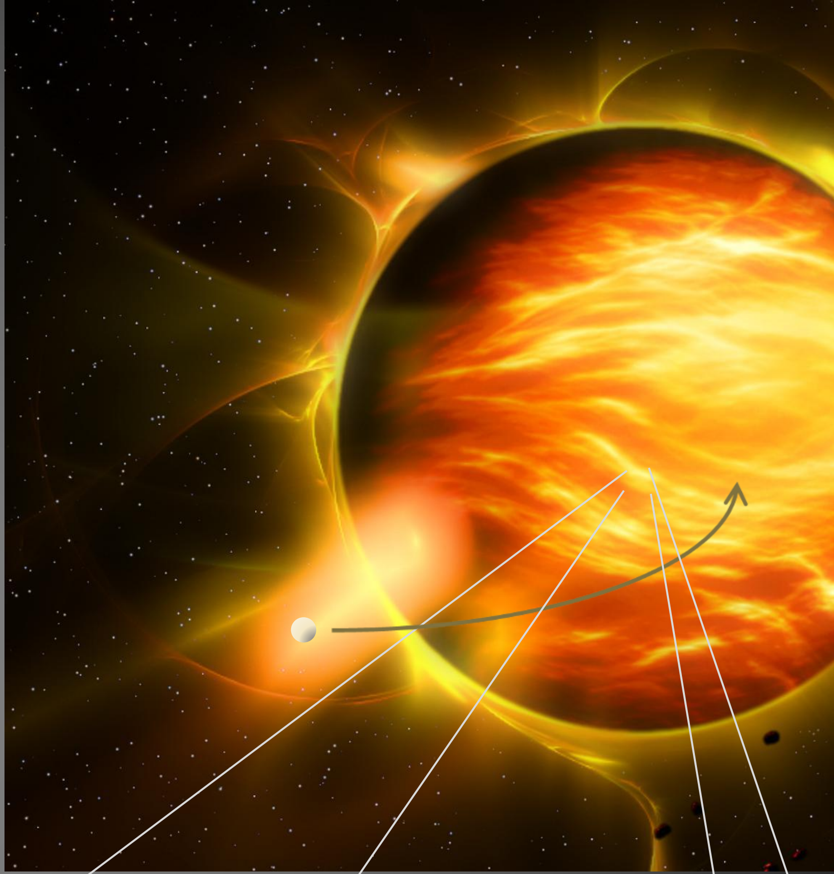
$$E_{env} = -\int_{M_{core}}^{M_{donor}} \frac{GM(r)}{r}\,dm \quad + \quad \alpha_{th}\int_{M_{core}}^{M_{donor}} U\,dm$$

gravitational binding energy

internal thermodynamic energy

Han et al. (1994, 1995)

- thermal energy
- energy of radiation
- ionization energy
- Fermi energy of e^--gas



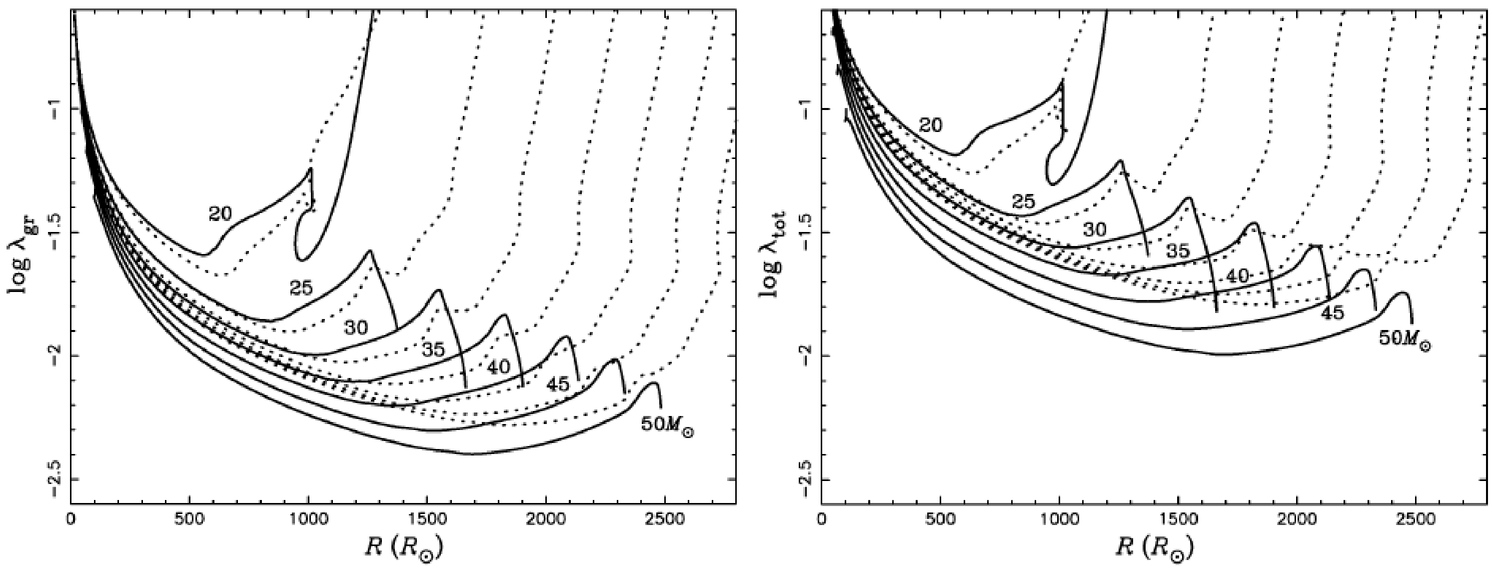


Figure 1. The envelope structure parameter λ as a function of stellar radius for different masses as indicated after hydrogen has been exhausted in the core. In the panels on the left, λ only includes the gravitational binding energy, while on the right λ includes both the gravitati energy (similar to Dewi & Tauris (2000)). The dotted curves are calculated without inclusion of a stellar wind. Note that in this cas largest radii attained by the models.

$$E_{env} \equiv -\frac{G M_{donor} M_{env}}{\lambda R_L}$$

de Kool (1990)

$$\lambda = 0.01 \sim 100$$

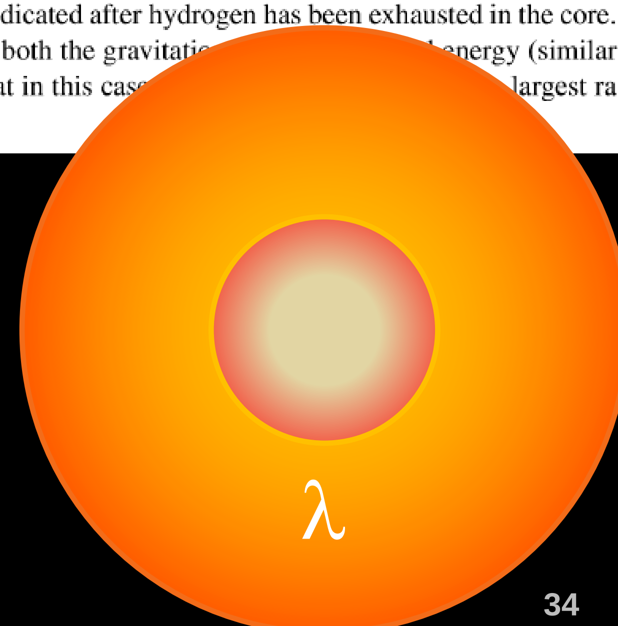
Dewi & Tauris (2000, 2001)

Podsiadlowski et al. (2003)

Xu & Li (2010)

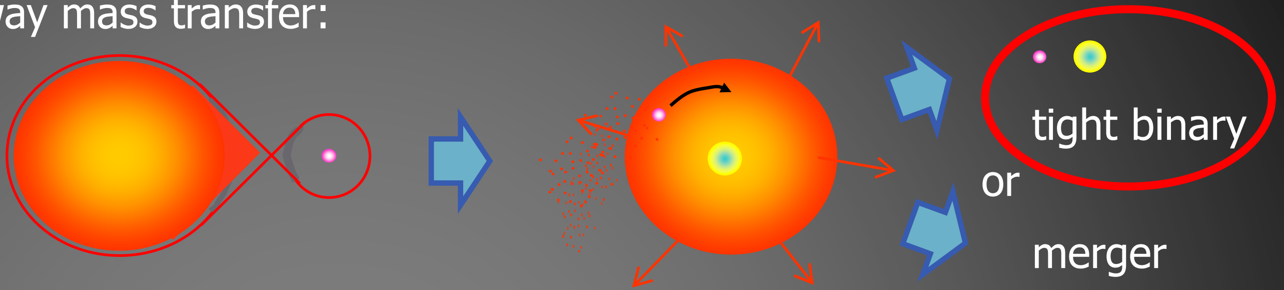
Loveridge et al. (2011)

Kruckow et al. (2016)



Common-Envelope + Spiral-in Evolution

Dynamically <u>un</u>stable run-away mass transfer:



$$E_{\mathrm{env}} \equiv \alpha_{\mathrm{CE}}\ \Delta E_{\mathrm{orb}}$$

$$\alpha_{\mathrm{CE}} = 0.3 \sim 1$$

$$E_{env} \equiv -\frac{GM_{donor}\,M_{env}}{\lambda\,R_L}$$

$$\Delta E_{orb} = -\frac{GM_{core}\,M_{NS}}{2a_f} + \frac{GM_{donor}\,M_{NS}}{2a_i}$$

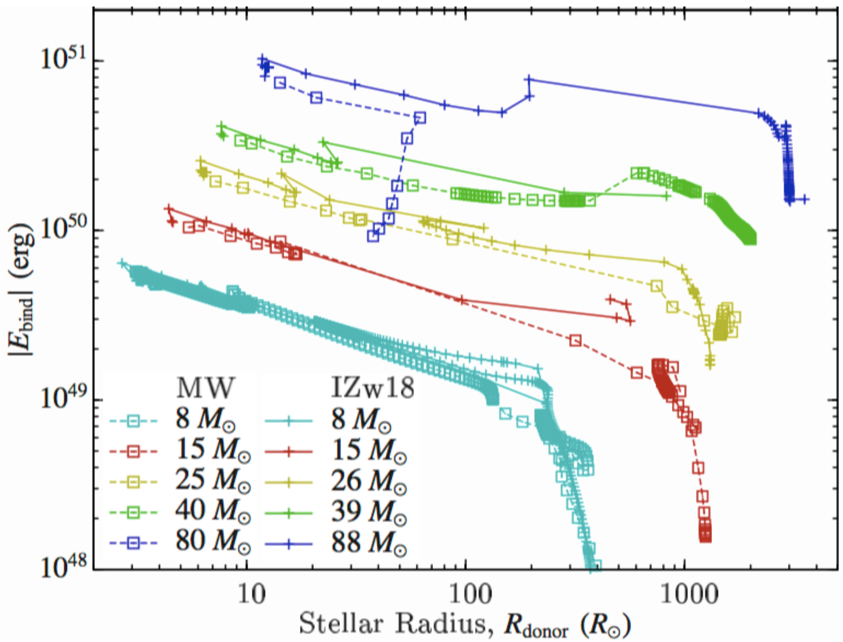
$$\lambda = 0.01 \sim 100$$

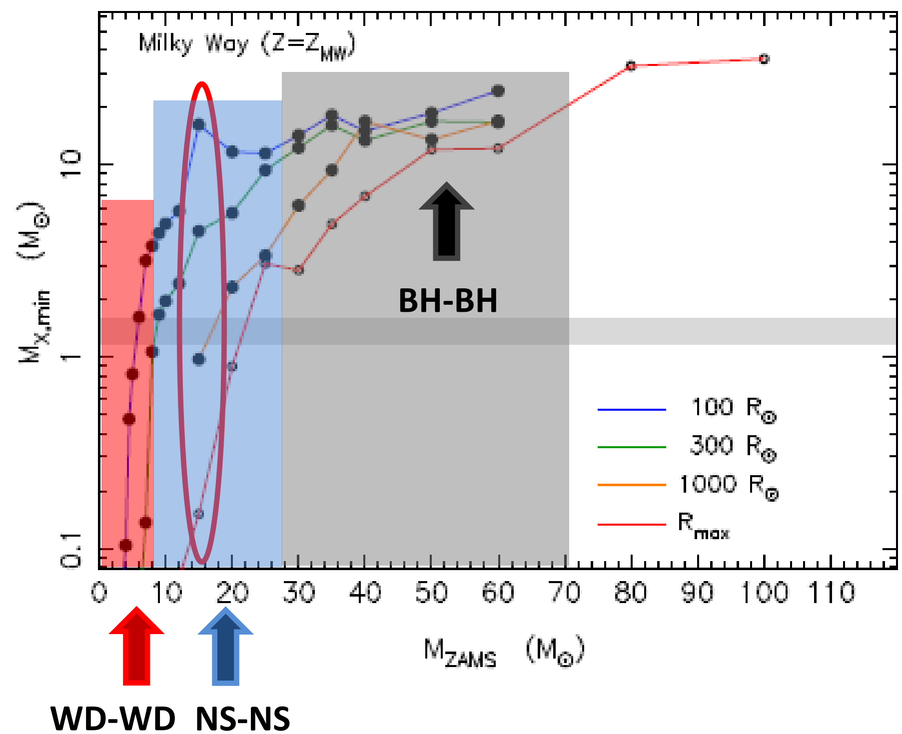
$$\frac{a_f}{a_i} = \frac{M_{core}M_2}{M_{donor}}\,\frac{1}{M_2 + 2M_{env}/(\eta_{CE}\lambda r_L)} \Rightarrow \frac{a_f}{a_i} \approx 10^{-3} - 10^{-2}$$

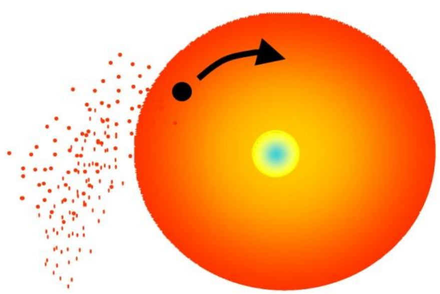
Can an in-spiralling BH or NS eject the envelope of a massive star?

Minimum mass of in-spiralling star to successfully eject the envelope?

Kruckow, Tauris, Langer, Szecsi, Marchant & Podsiadlowski (2016), A&A
Common-envelope ejection in massive binary stars
– Implications for the progenitors of GW150914 and GW151226







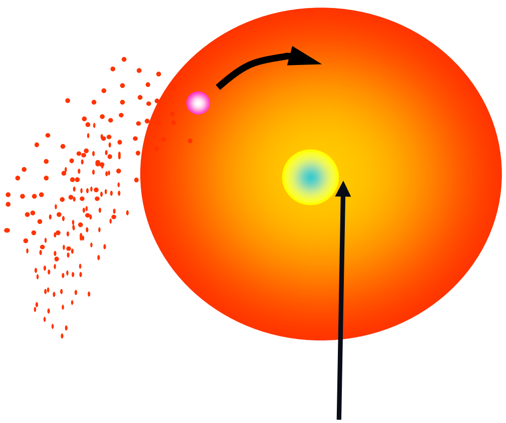
Example:

M = 15 $M_\odot$: R < 500 $R_\odot$ no CE ejection → coalescence

M = 15 $M_\odot$: R > 500 $R_\odot$ succesful CE ejection

CE EJECTION

Bifurcation point ?



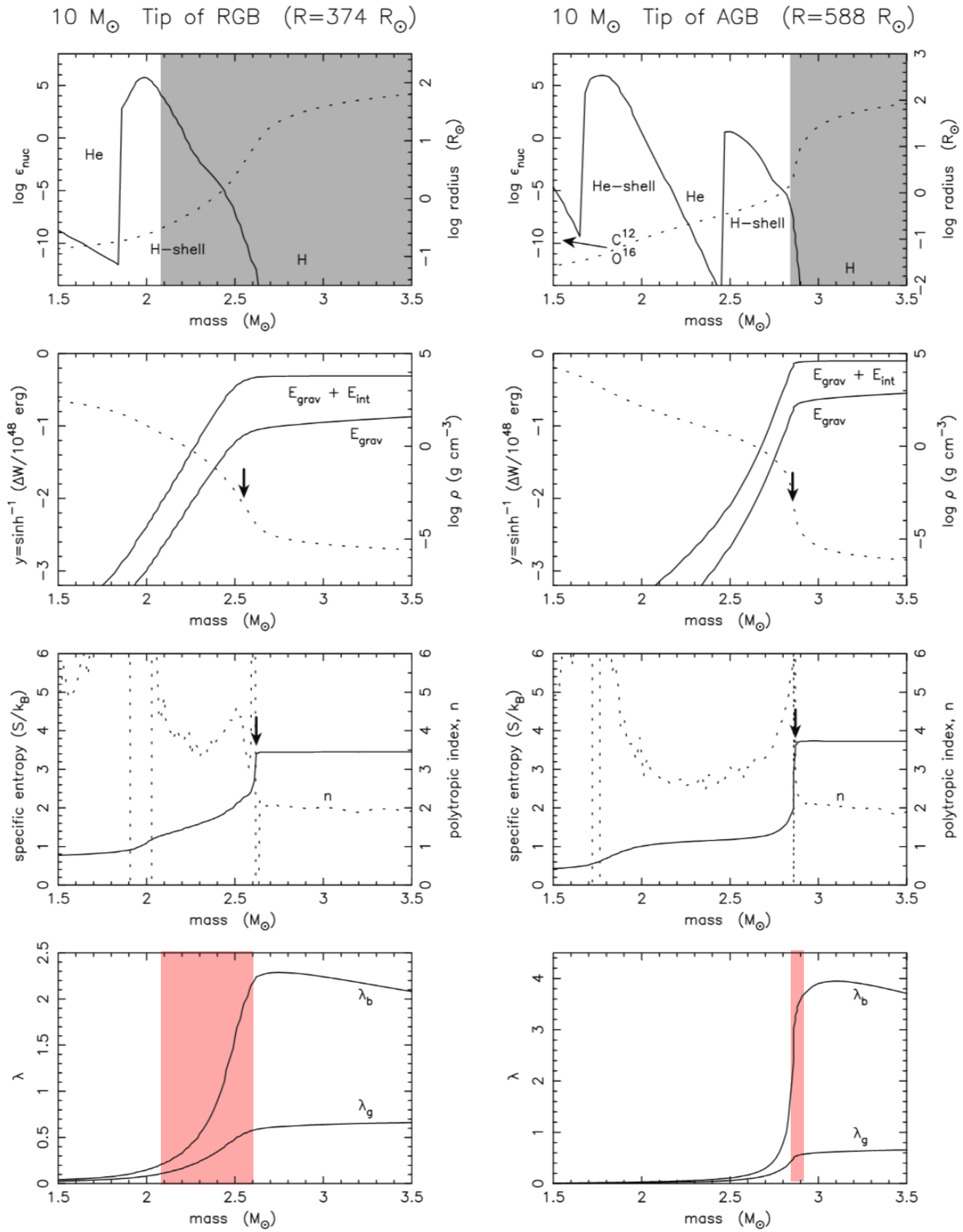
Bifurcation point ?

Tauris & Dewi (2001)

Ivanova (2011)

Kruckow et al. (2016)

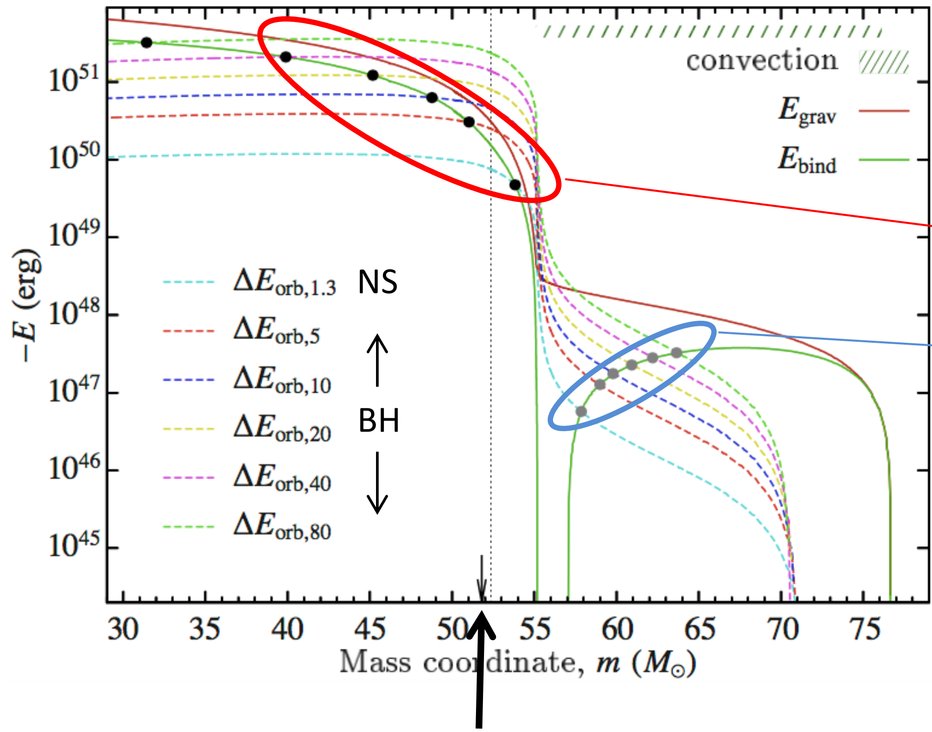
Marchant et al. (2021)



Tauris & Dewi (2001)

Where does the envelope ejection terminate?

Kruckow et al. (2016), A&A



$88\ M_\odot$ star @ $Z = Z_\odot/50$

$R = 3530\ R_\odot$

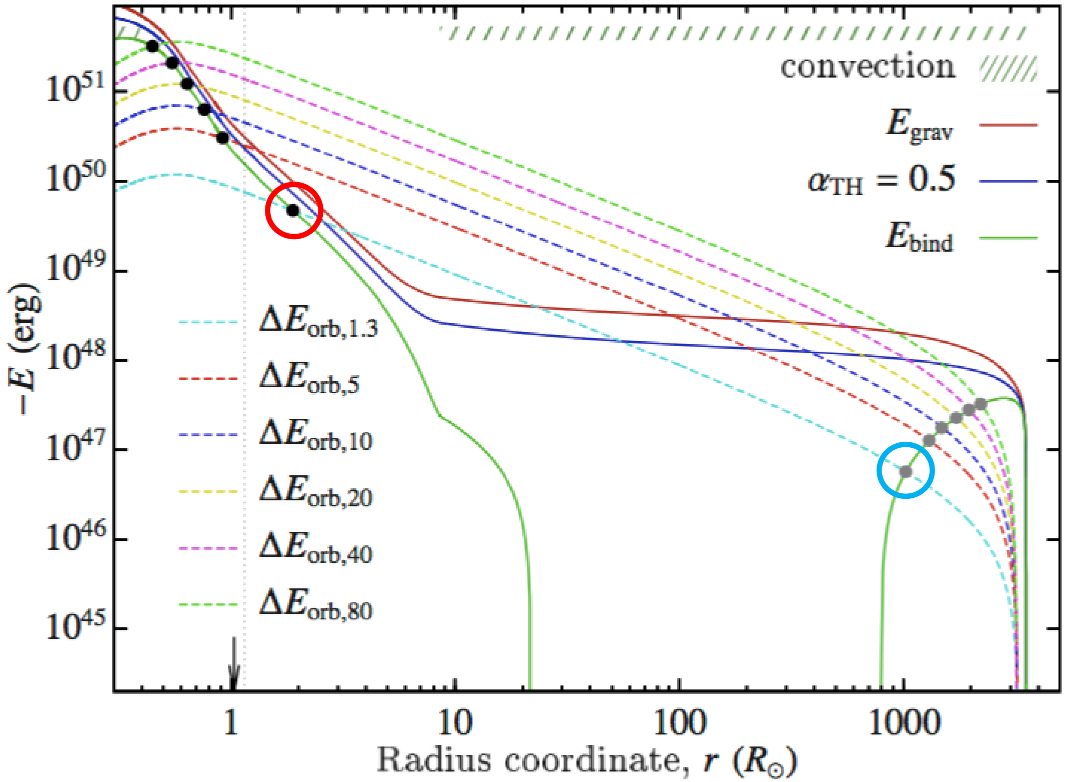
Point of no return

Minimum in-spiral

Core boundary: X_H=0.10

(close to local max. sonic velocity)

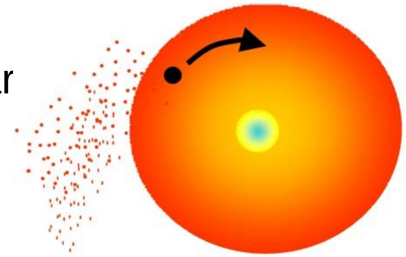
Kruckow et al. (2016), A&A



Difference in mass coordinate of about 4 $M_\odot$
corresponds to a **radius difference** by a **factor 500!**
Extremely important for the final orbital separation.

Additional **energy sources** to help envelope ejection:

- **Recombination energy** from outer (cold) layers of donor star (from H, He, H_2)



- Released **accretion energy** from BH during in-spiral

$$\Delta E_{\rm acc} = \eta\, \dot{M}_{\rm Edd} c^2\, \tau_{\rm CE}$$

$$\dot{M}_{\rm Edd} = 4.4 \times 10^{-9}\ M_\odot\, {\rm yr}^{-1} \left(\frac{M_{\rm BH}}{M_\odot}\right) \frac{r_*}{(1+X_H)}$$

$$\boxed{\Delta E_{\rm acc} = 1.6 \times 10^{48}\ {\rm erg} \left(\frac{M_{\rm BH}}{M_\odot}\right) \left(\frac{\tau_{\rm CE}}{1000\ {\rm yr}}\right) \left(\frac{\eta}{0.20}\right) \frac{r_*}{(1+X_H)}}$$

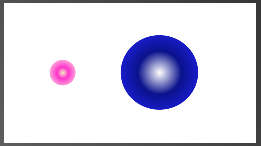
Kruckow et al. (2016)

$$r_* = R_{\rm ISCO}/(GM_{\rm BH}/c^2)$$

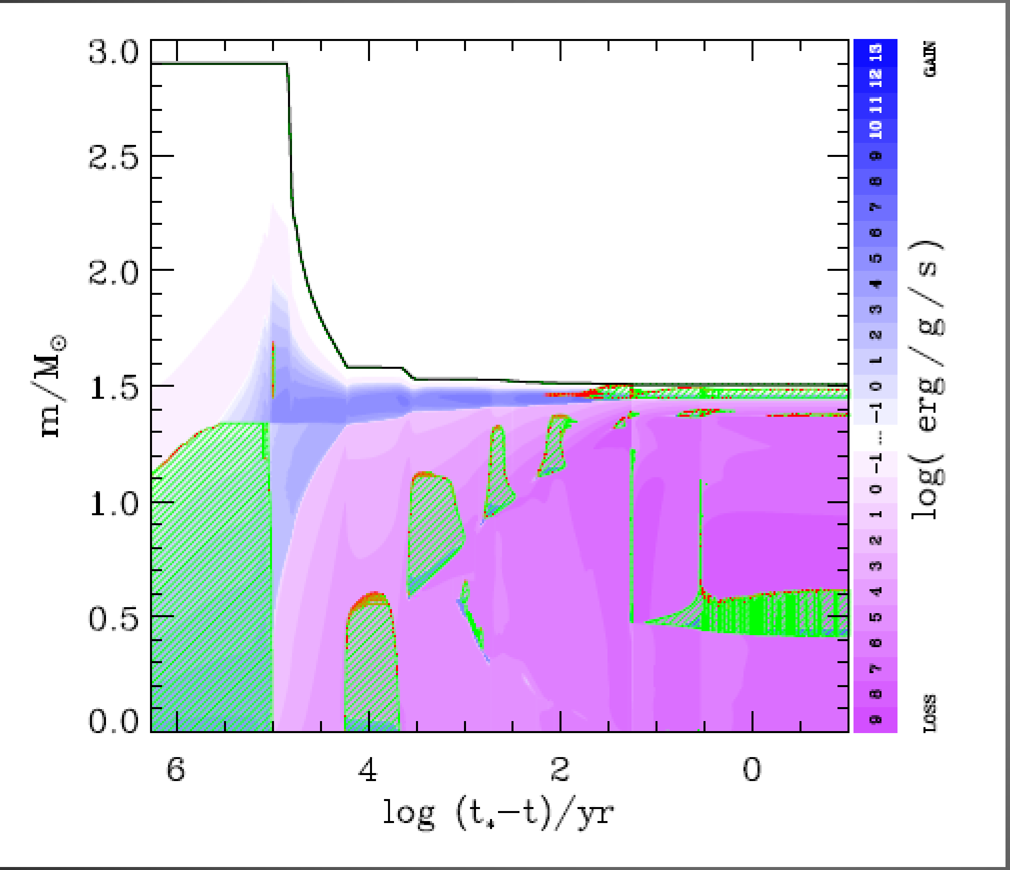
More to learn from ongoing and future hydrodynamical simulations

Ultra-stripped pre-SN metal core

post-CE
Case BB RLO



Tauris et al. (2013)



Post-CE evolution of He-star + NS in close orbit
⇒ bare, pre-SN core just above Chandrasekhar mass

⇒ Iron core-collapse SN with very little ejecta
+ formation of low-mass NSs in NS+NS system

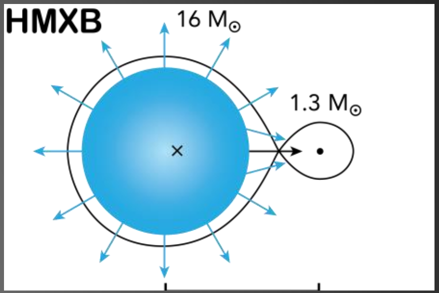
Intermediate-Mass X-ray Binaries

Why are so few IMXBs observed ?

HMXB: wind accretion (beginning atmospheric RLO)

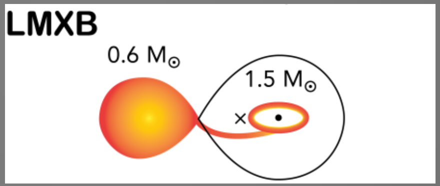
RLO is dynamically unstable and a CE forms

$$M_2 > 10\,M_\odot$$



LMXB: stable RLO

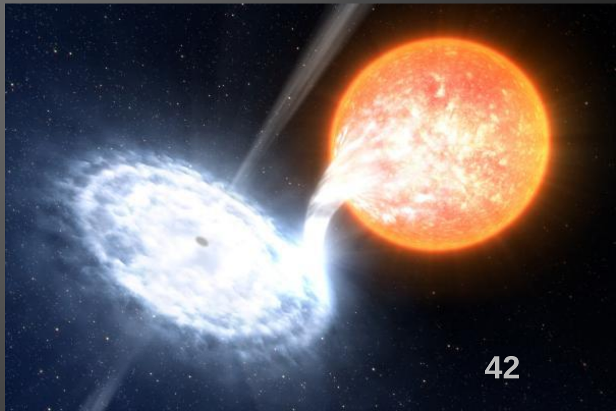
$$M_2 \leq 1.5\,M_\odot$$



IMXB: wind accretion is too weak, and

RLO is often unstable (or very short)

But evidence of post-IMXBs from pulsar+CO WD binaries



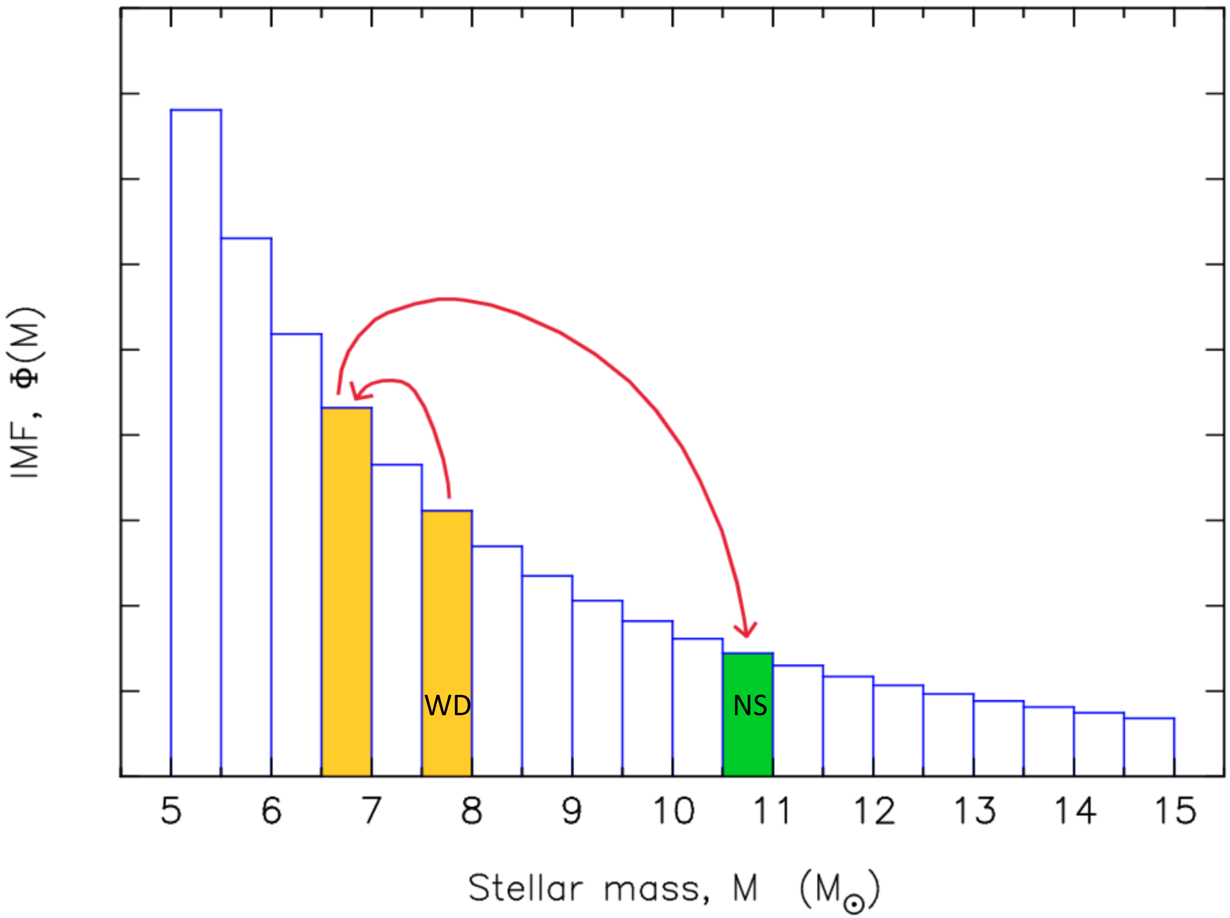
Binaries undergoing mass reversal

producing (WD-NS) systems

first formed

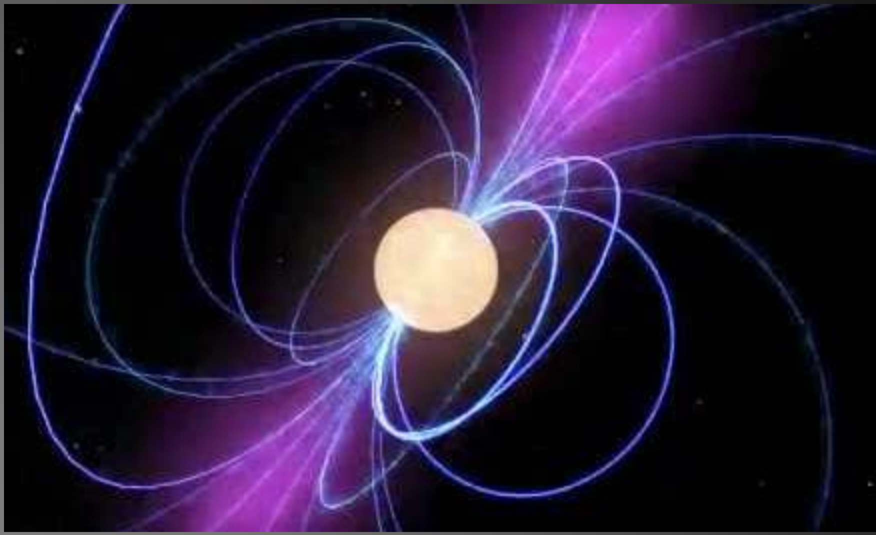
second formed
(non-recycled, young,
eccentric orbit from SN)

Tauris & van den Heuvel (2021)



LECTURE 2

Recycling and Millisecond Pulsars



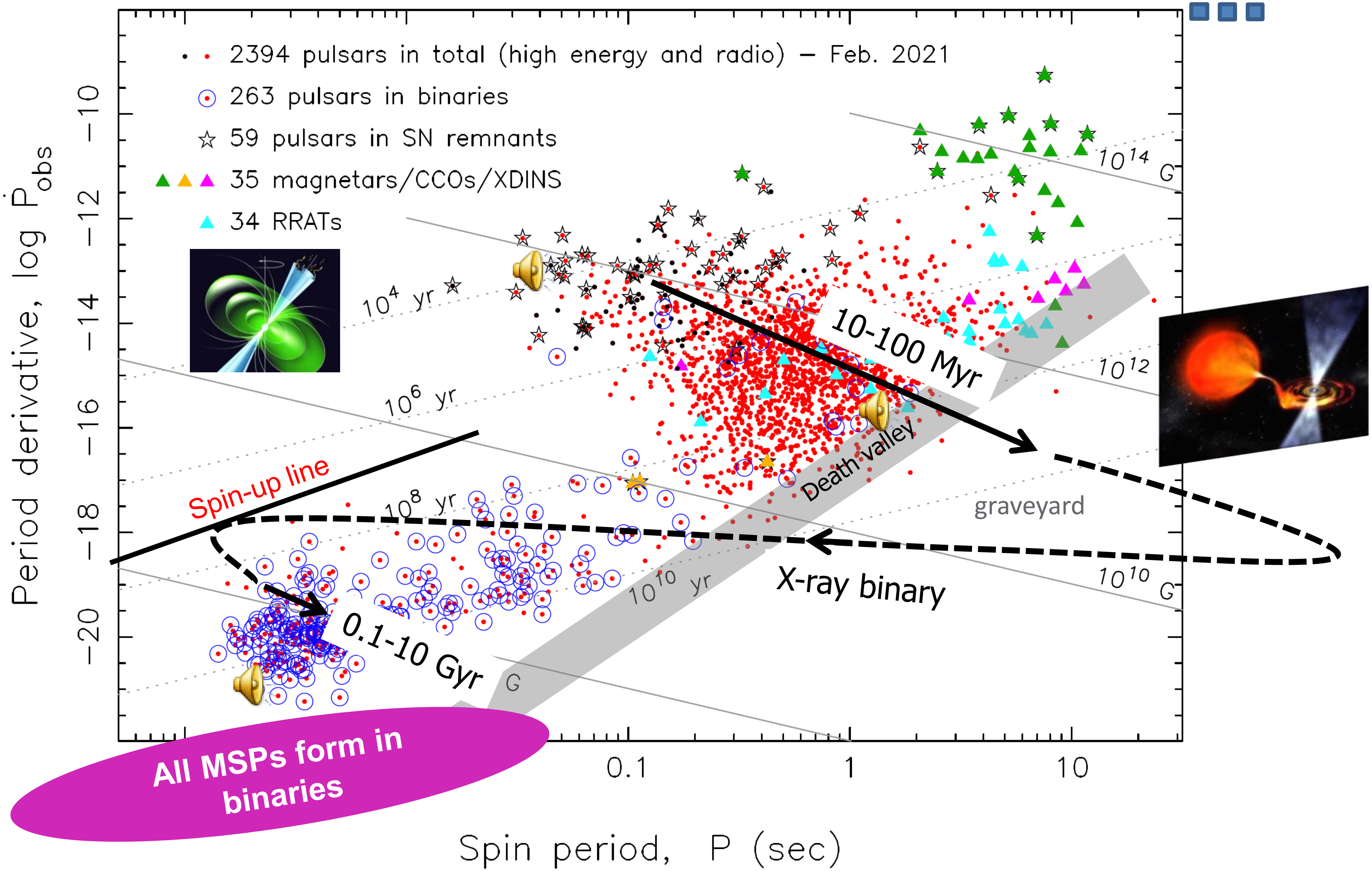
MSPs

- How fast can they spin?
- Why are their B-field strenghts weak?
- How much mass do they need to accrete?
- What are their orbital periods?
- How old are they?
- Where are they located (+ kinematics)?
- What is the nature of their companion stars?

➡ How do MSPs form?

Recycling pulsars - A detour in the P-Pdot diagram

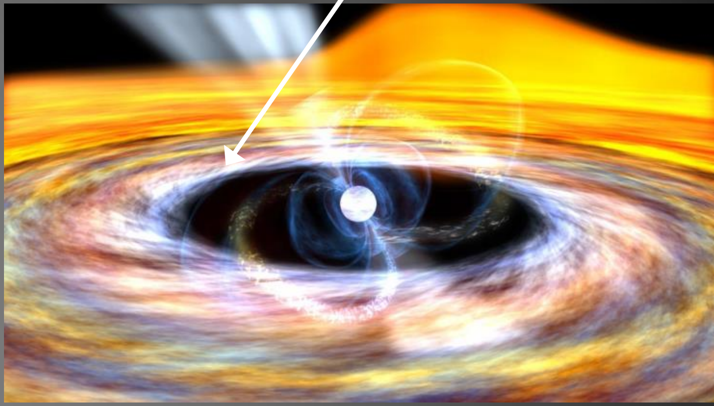
Tauris & van den Heuvel (2022)



Millisecond pulsars - a binary formation scenario

- Rapid spin: $P < 30\ ms$
- Small period derivative: $\dot{P} < 10^{-17}\ s\,s^{-1}$

$$\dot{J} = \frac{d}{dt}|\vec{r} \times \vec{p}|$$



Solution:

- Accretion of mass

$$N = \dot{J}_* \equiv \frac{d}{dt}\left(I\Omega_*\right) = \dot{M}_*\sqrt{GM_* r_A}\ \xi$$

Lamb, Pethick & Pines (1973)
Ghosh & Lamb (1979, 1992)

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{v} \times \vec{B}\right) - \frac{c^2}{4\pi}\nabla \times \left(\frac{1}{\sigma} \times \nabla \times \vec{B}\right)$$

Geppert & Urpin (1994); Konar & Bhattacharya (1997)

$$B = \sqrt{\frac{3c^3 I_{NS}}{8\pi^2 R_{NS}^6} P\dot{P}}$$

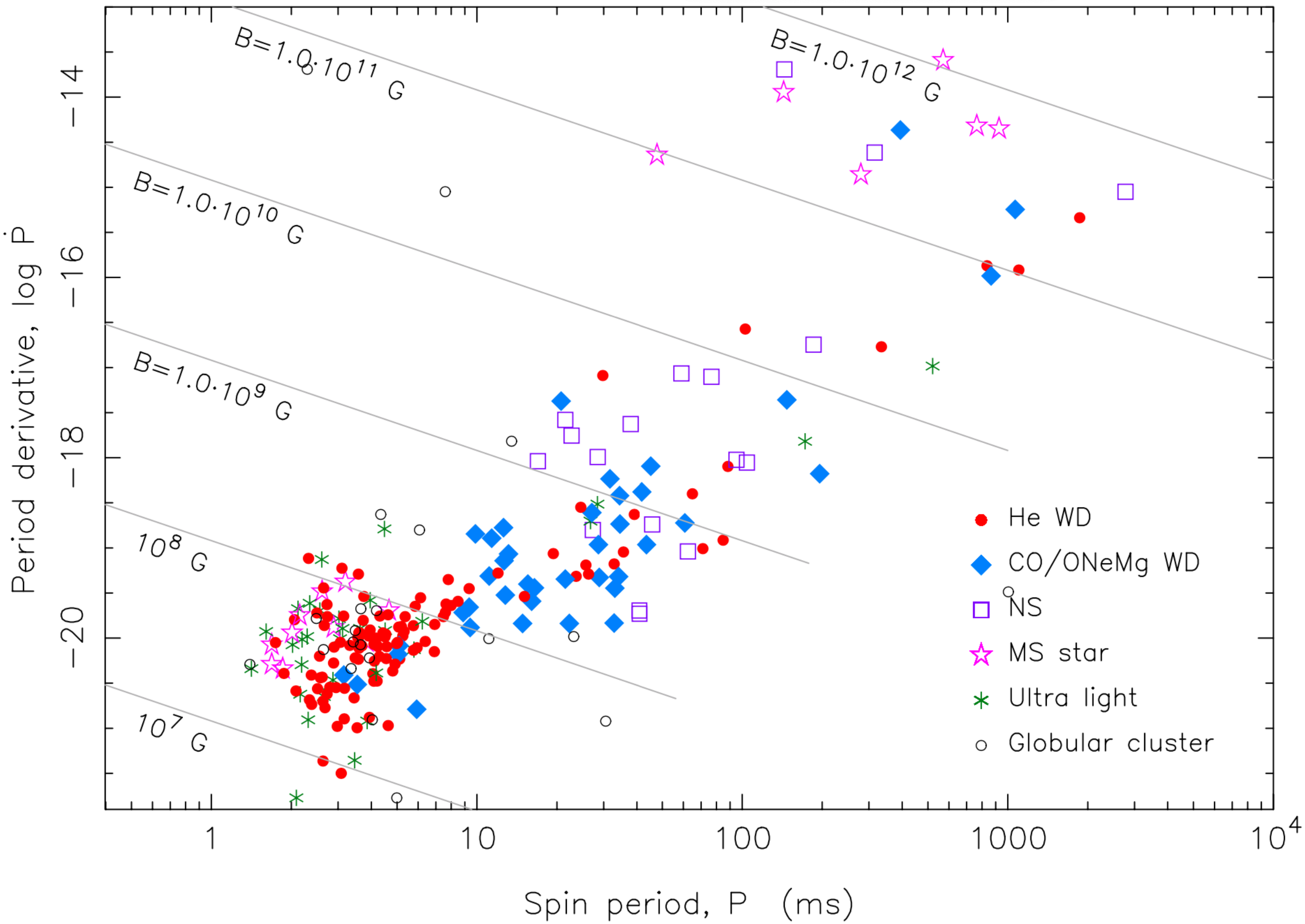
Magnetic-dipole model

Accretion induced B-field decay
– Ohmic dissipation/diffusion
– Flux tube expulsion via spin-down
– B-field burial (screening)

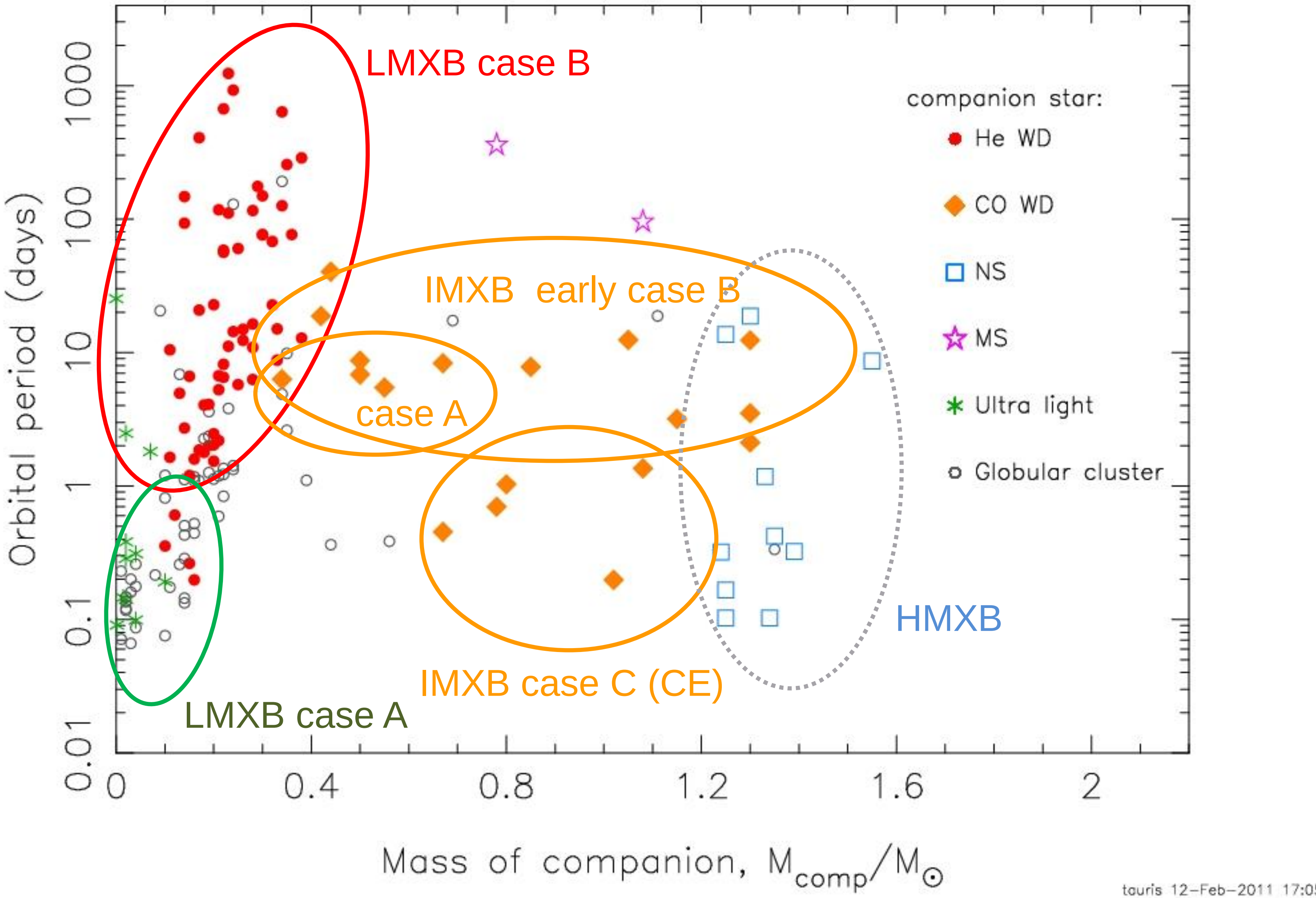
Pulsar companion stars

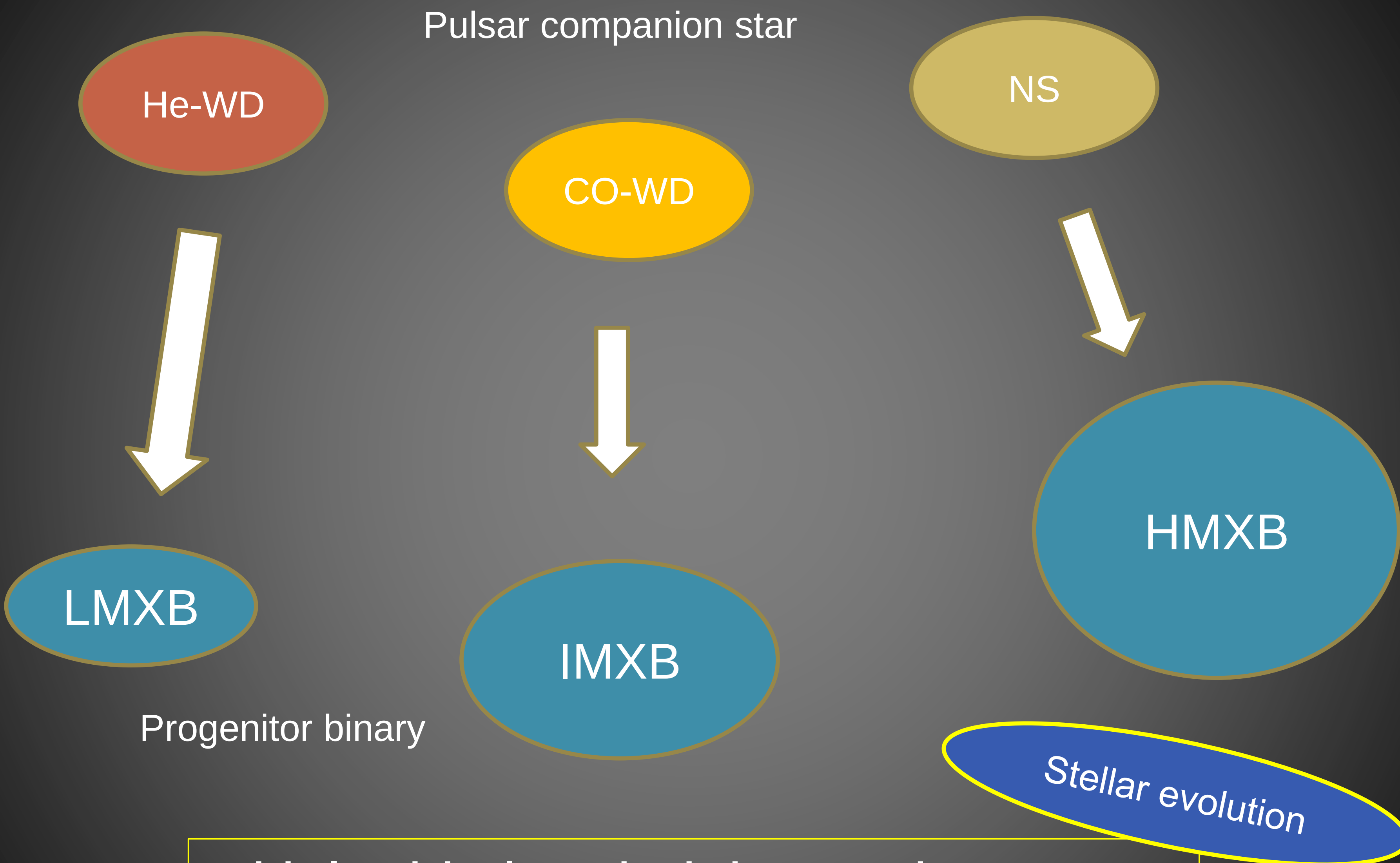
245 binary pulsars with measured P_{dot}

Tauris & van den Heuvel (2022)

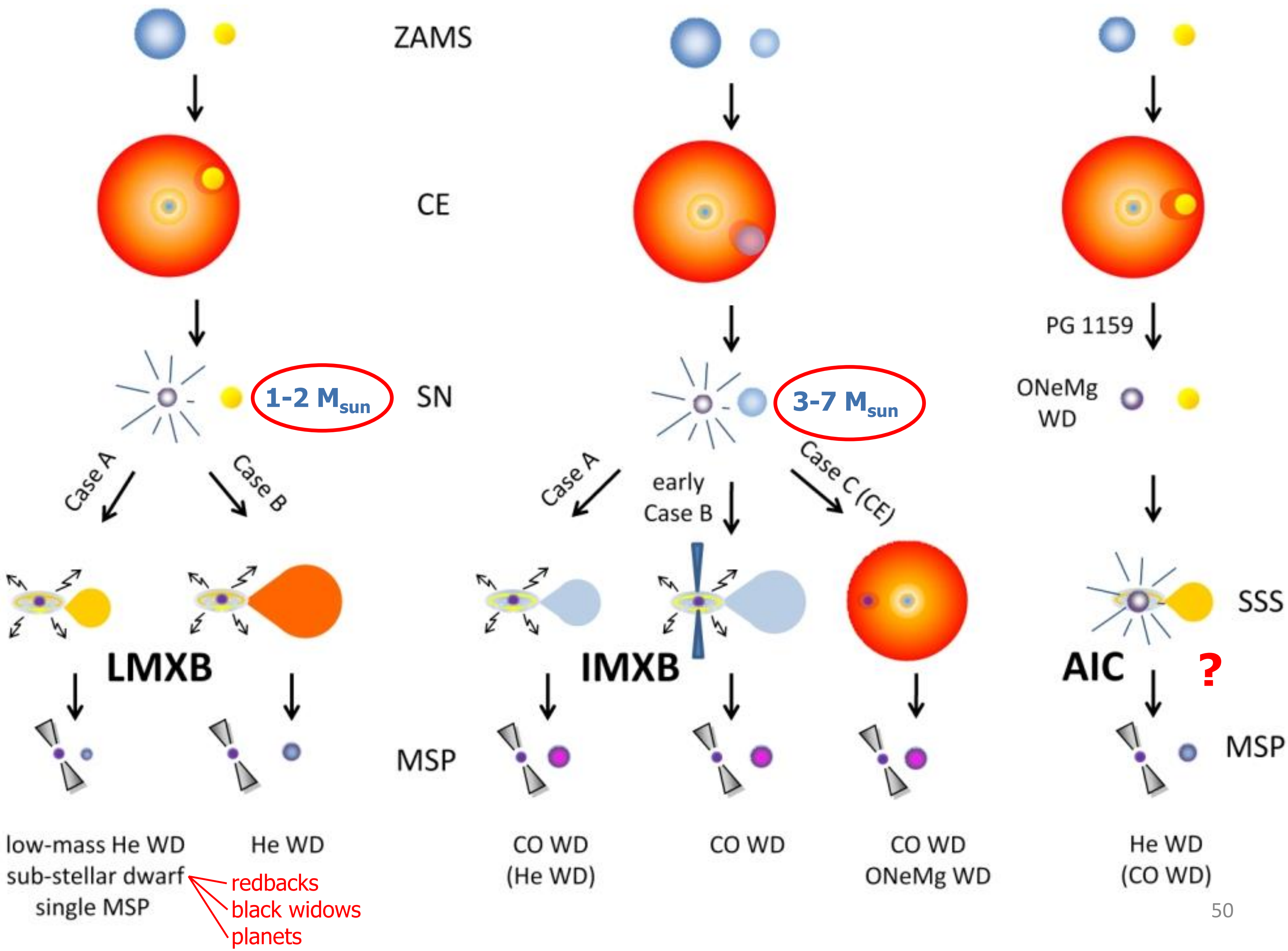


Origin of binary radio pulsars - Which X-ray Binaries?

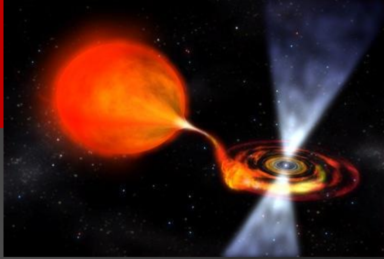




Initial orbital period is very important!


ZAMS
CE
PG 1159
SN
1-2 M_{sun}
3-7 M_{sun}
ONeMg
WD
Case A
Case B
Case A
early
Case B
Case C (CE)
SSS
LMXB
IMXB
AIC
?
MSP
MSP
low-mass He WD
sub-stellar dwarf
single MSP
redbacks
black widows
planets
He WD
CO WD
(He WD)
CO WD
CO WD
ONeMg WD
He WD
(CO WD)

LMXB bifurcation period



$P_{orb} < P_{bif}$: Converging

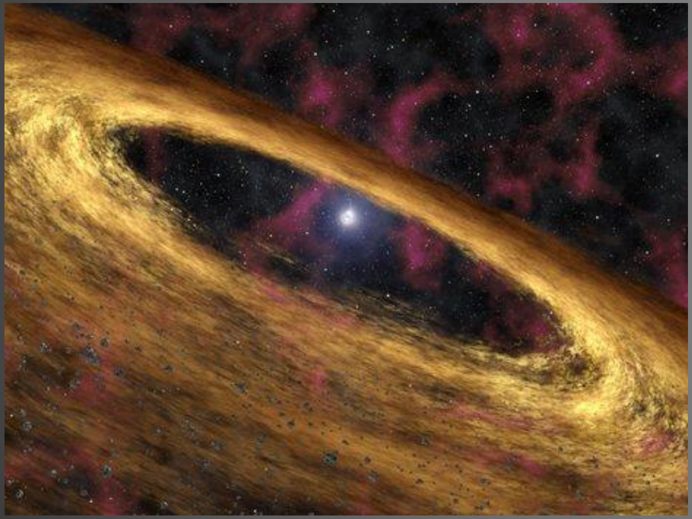
→ LMXB **shorten** their orbital period

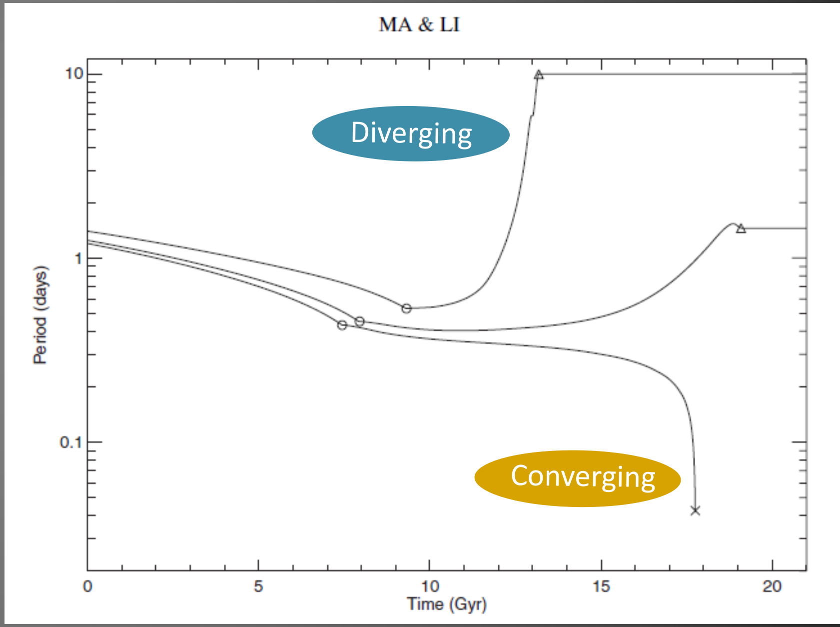
Donor star still on main sequence

RLO driven by loss of J_{orb} (MB, GWs)

Tutukov et al. (1985)
Pylyser & Savonije (1988, 1989)
Ma & Li (2009)
Istrate et al. (2014)
Chen et al. (2021)

$P_{bif} \approx 1\,day$





"Black widow" millisecond pulsars:

$P_{orb} < 10\,hrs \qquad M_{comp.} < 0.1\,M_\odot$

EoS?

Evaporation → single millisecond pulsars ?

Roberts (2012)
Breton et al. (2013)
Chen et al. (2013)

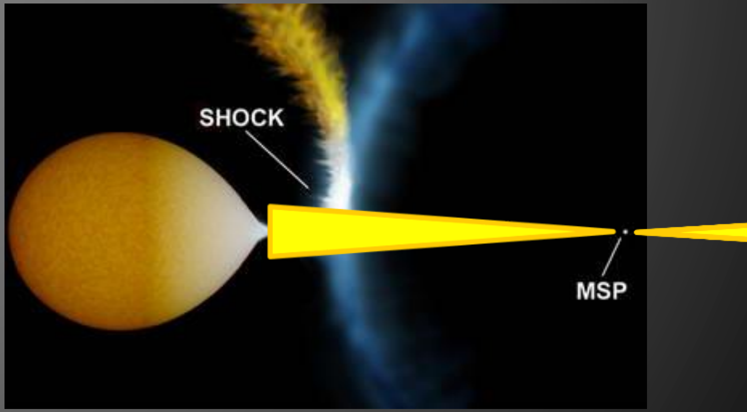
Single Millisecond Pulsars

All single millisecond pulsars are born in a binary system.

Once a recycled millisecond pulsar turns on its emission of ultra-relativistic particles, it is often able to completely evaporate its companion and thus end up as an isolated millisecond pulsar.

Observational evidence:

- ✓ eclipsing MSPs with 0.02 M_{sun} companions
- ✓ the ”planetary pulsar”, PSR 1257+12

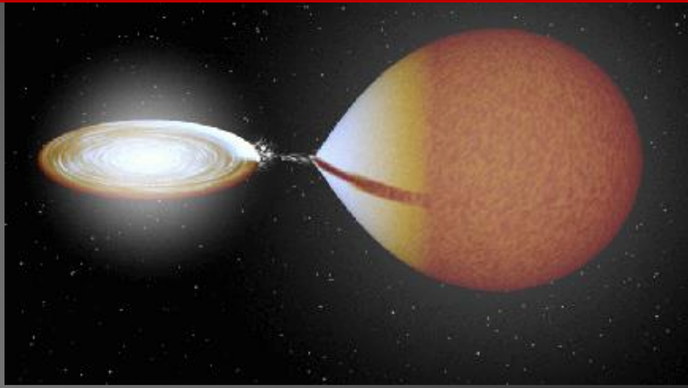


$$\frac{1}{2}\dot{M}_2 v_{esc}^2 = f\,\dot{E}_{psr}\left(\pi R_2^2 / 4\pi a^2\right)$$

$$\tau \sim \frac{M_2}{\dot{M}_2}$$

evaporation timescale

LMXB diverging systems



$P_{orb} > P_{bif}$: Diverging

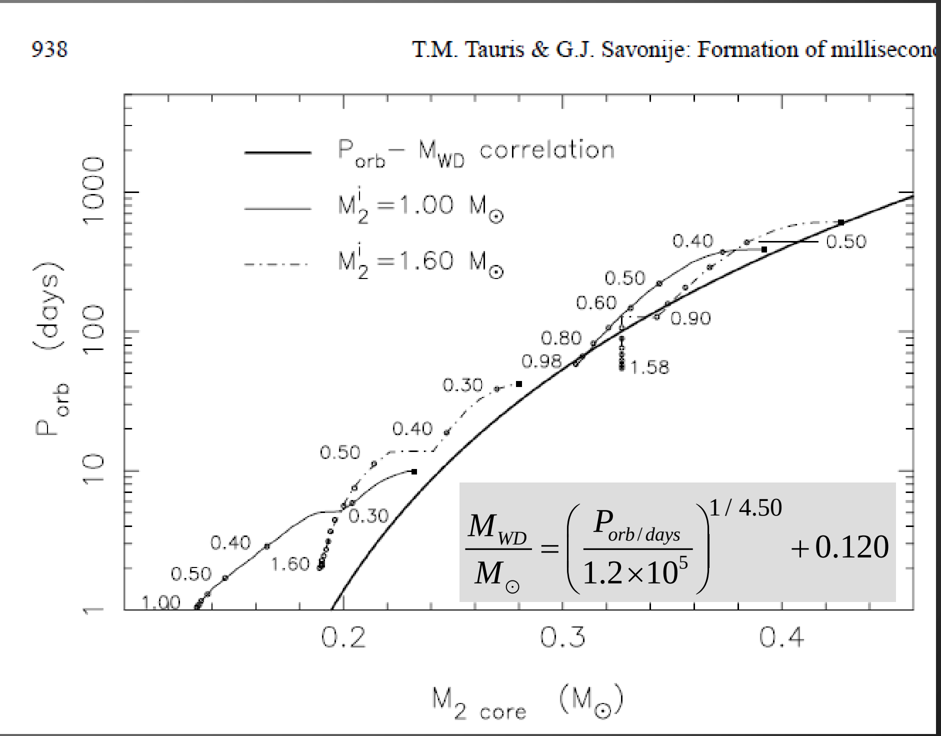
→ LMXB **widen** their orbital period

Donor star is a (sub)giant

RLO driven by nuclear expansion

Formation of BMSPs with He-WD:

$$P_{orb} > 1\ day$$
$$0.18 < M_{WD} < 0.46\ M_{\odot}$$



Unique relation between P_{orb} and M_{WD}

Savonije (1987)

Joss, Rappaport & Lewis (1987)

Rappaport et al. (1995)

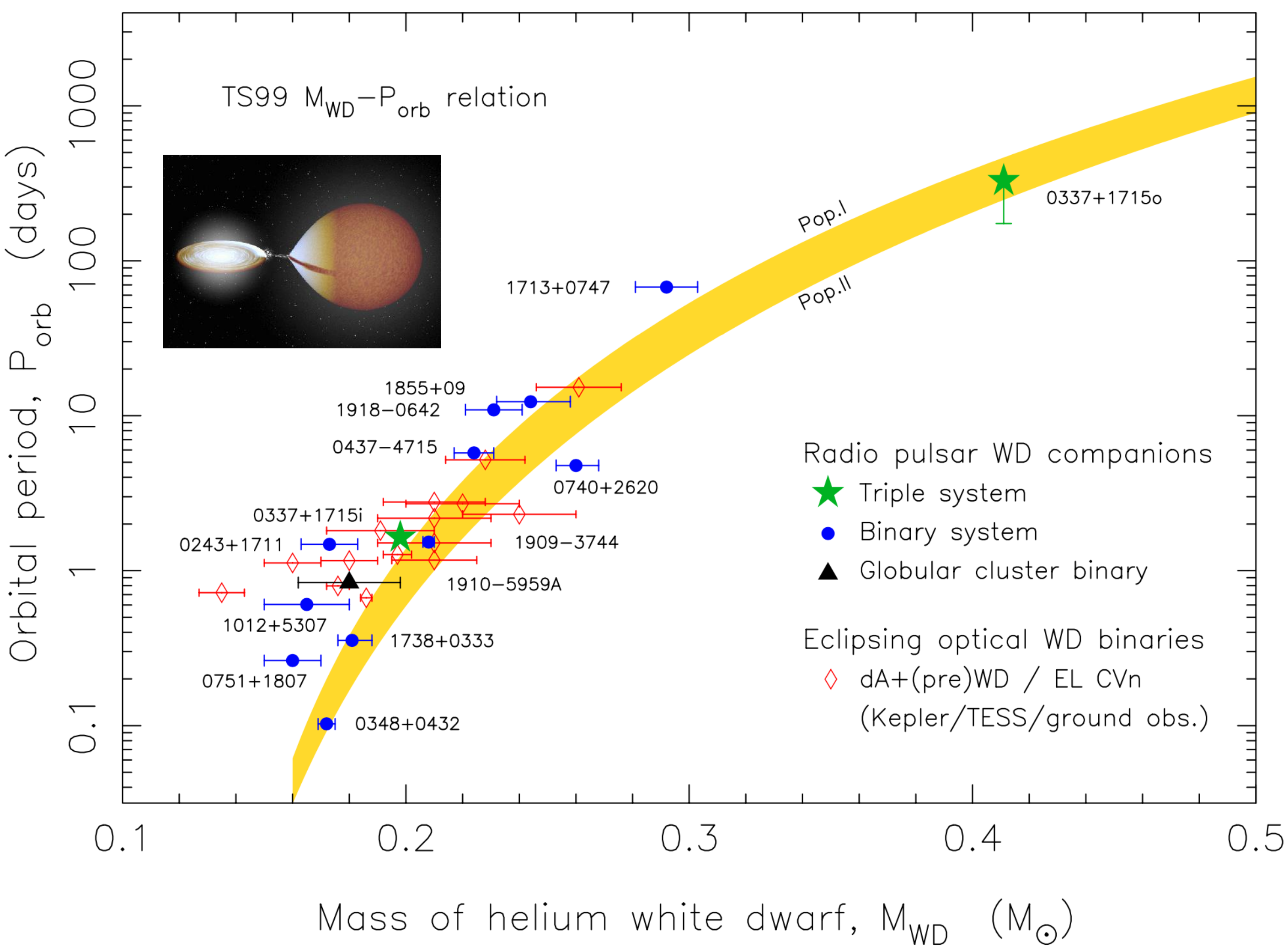
Tauris & Savonije (1999)

Istrate et al. (2016)

match observations well

P_{orb} – M_{WD} correlation for He-WDs

Tauris & van den Heuvel (2022)

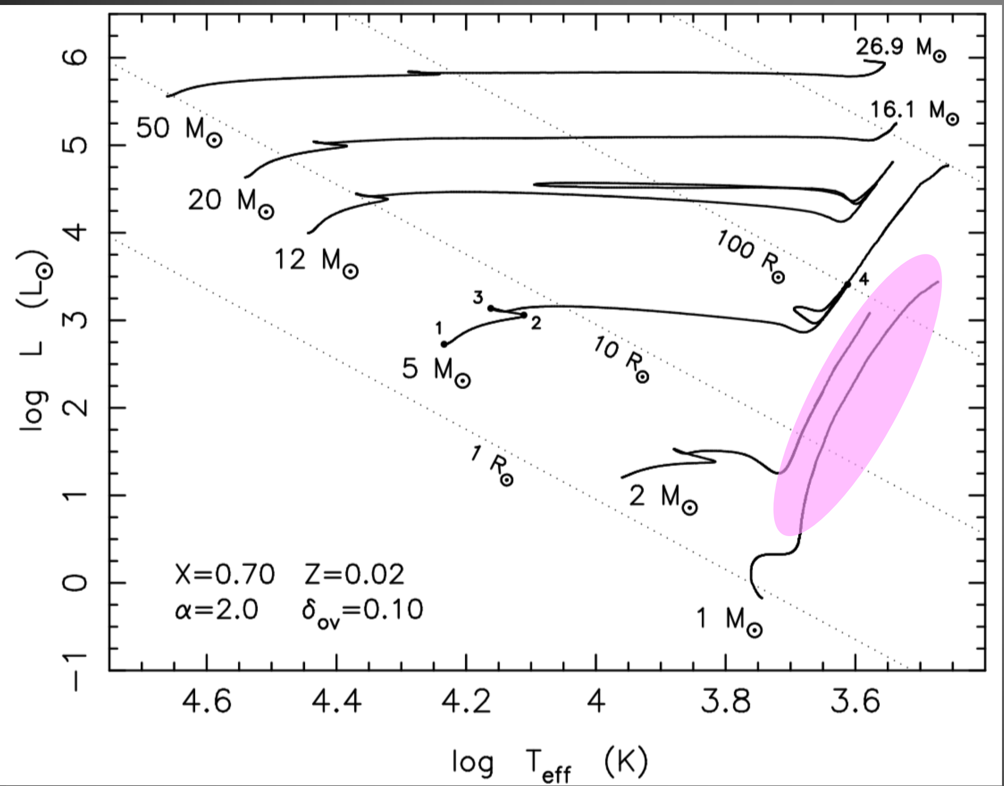


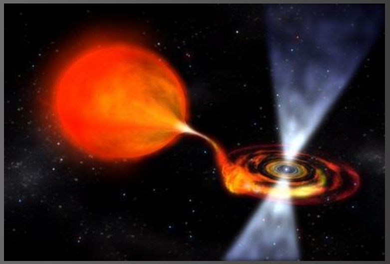
P_{orb} – M_{WD} correlation for He-WDs

- On the red giant branch (hydrogen shell burning), the growth of the degenerate He core mass is directly related to the luminosity of the star
- Temperature is almost constant on the Hyashi track $\Rightarrow$ $L \propto R^2$

$$L = 4\pi R^2 \sigma T_{eff}^4$$

- Hence there is a relation between M_{core} and R (Thomas 1967) independent of M_{env}
- The donor star fills its Roche-lobe during the mass transfer $\Rightarrow$ R is correlated with P_{orb}





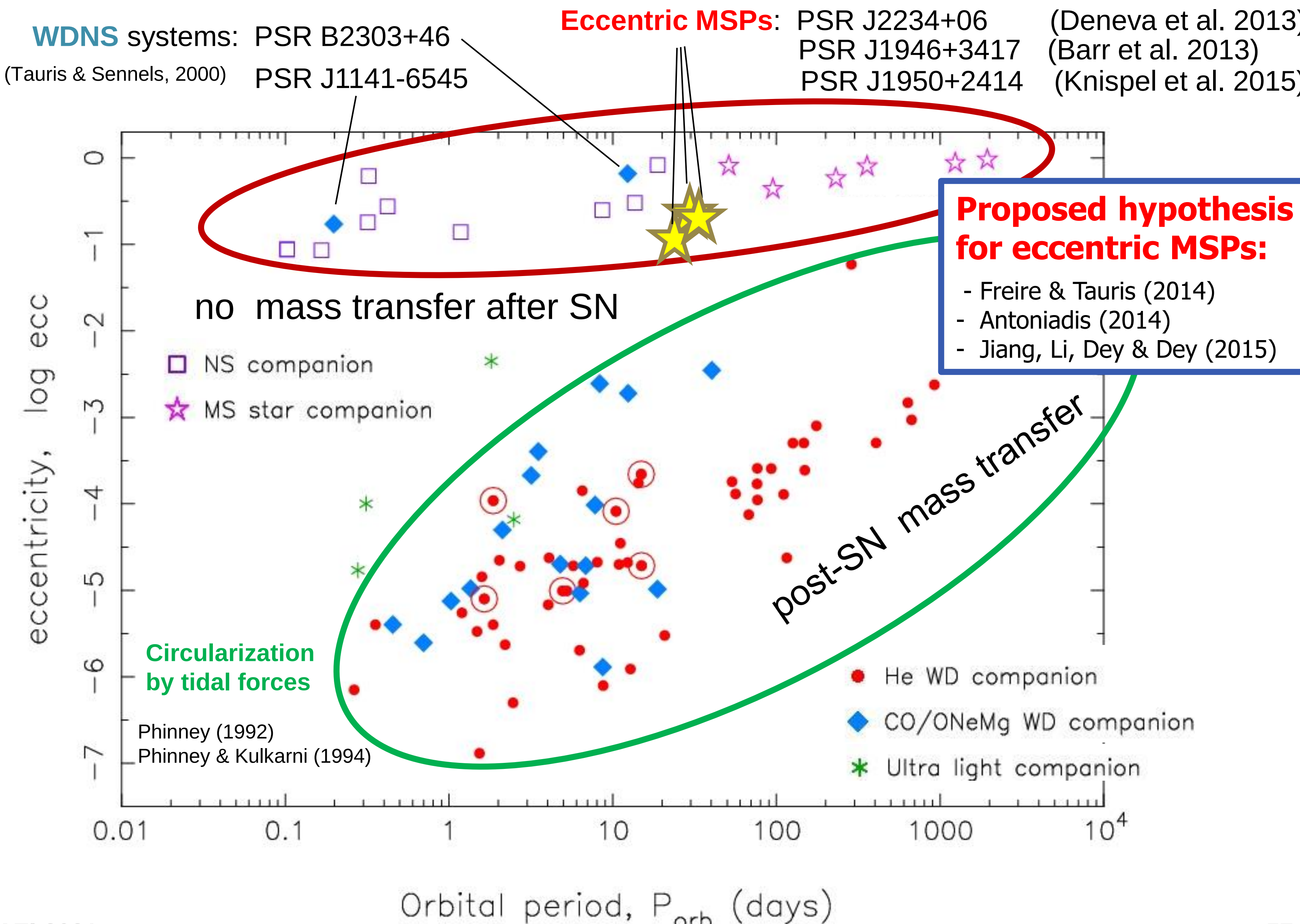
correlation between (P_{orb} , M_{WD})

Table 1. Stellar parameters for a star with $R_2 = 50.0\,R_\odot$ – see text.

$M_2/M_\odot$	1.0**	1.6**	1.0*	1.6*
$\log L/L_\odot$	2.566	2.624	2.644	2.723
$\log T_{\rm eff}$	3.554	3.569	3.573	3.593
$M_{2\rm core}/M_\odot$	0.336	0.345	0.342	0.354
$M_{2\rm env}/M_\odot$	0.215	0.514	0.615	1.217

* Single star (X=0.70, Z=0.02 and α=2.0).
** Binary donor ($P_{\rm orb}^{\rm ZAMS} = 60.0$ days and $M_{\rm NS} = 1.3\,M_\odot$)

Eccentricities



Proposed hypothesis for eccentric MSPs:

- Freire & Tauris (2014)
- Antoniadis (2014)
- Jiang, Li, Dey & Dey (2015)

Dynamical Effects of Asymmetric SNe

As a consequence of **sudden mass loss** and **imparted kicks in SNe**, radio pulsars have large velocities (0-1000 km s^{-1}) and a wide scatter in their Galactic height distribution.

- Most (90%) of all potential LMXB systems are disrupted because of the SN.

- If SNe were purely symmetric then binary systems would be disrupted if $\Delta M/M > ½$ (as a consequence of the virial theorem). Thus a kick can also help to keep systems bound if the direction of the kick is towards the companion star.

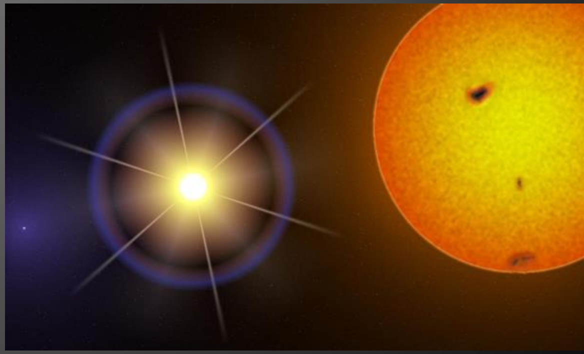
As a result of non-radial hydrodynamical instabilities newborn NSs receive a momentum kick at birth (resulting in a kick velocity of ~ 500 km s^{-1}).

The exact origin is still uncertain but is probably related to neutrino-driven convection bubbles, standing accretion shock instabilities (SASI) in the proto NS or other anisotropies in the ejecta which accelerate the proto-NS via the gravitational tug-boat mechanism, or simiply an asymmetric neutrino outflow (see Janka 2012 for a review).

Analytical equations for calculating dynamical effects of SNe:

- Hills (1983) for binaries

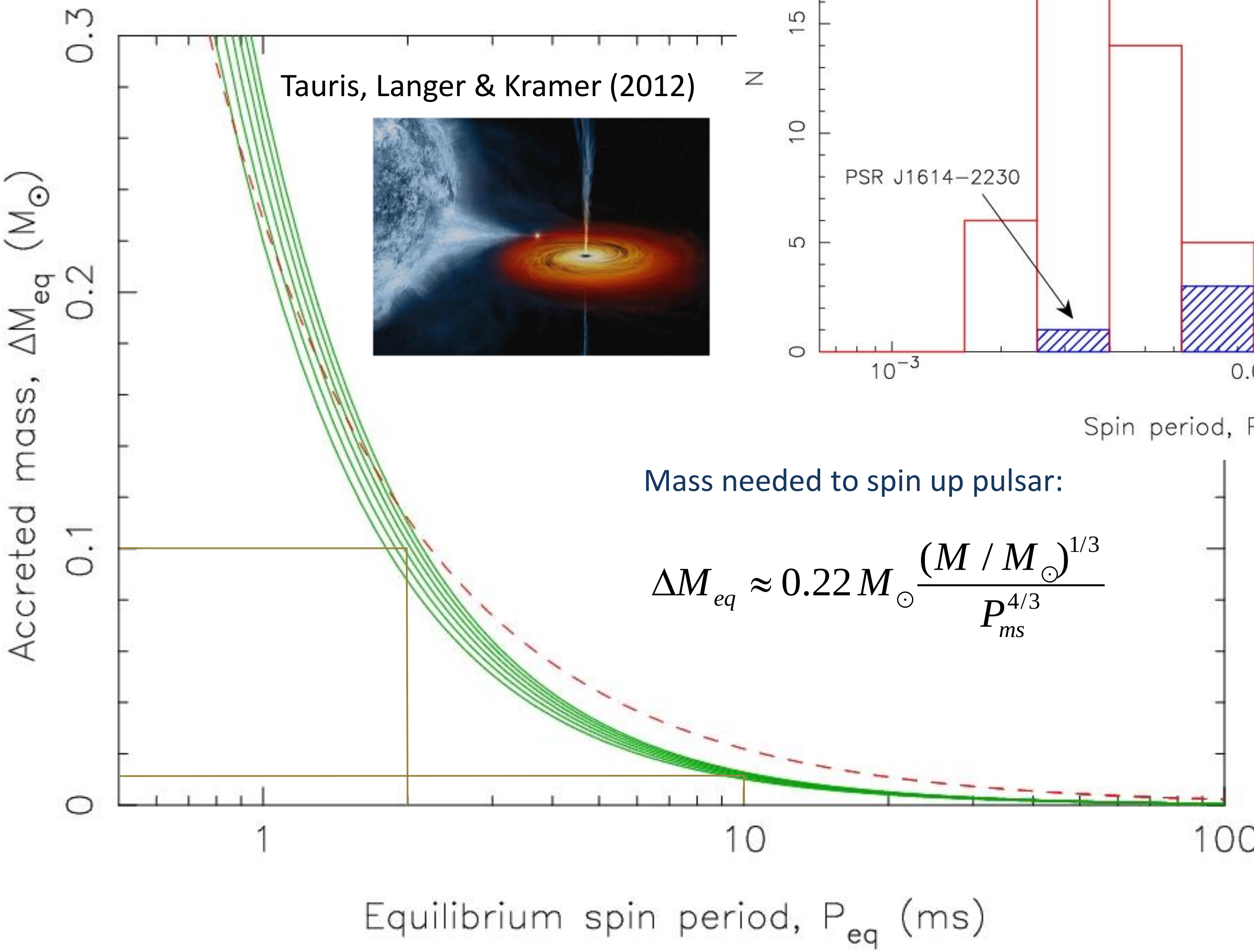
- Tauris & Takens (1998) for the full general case
(disrupted and bound binaries, incl. SN shell impact)

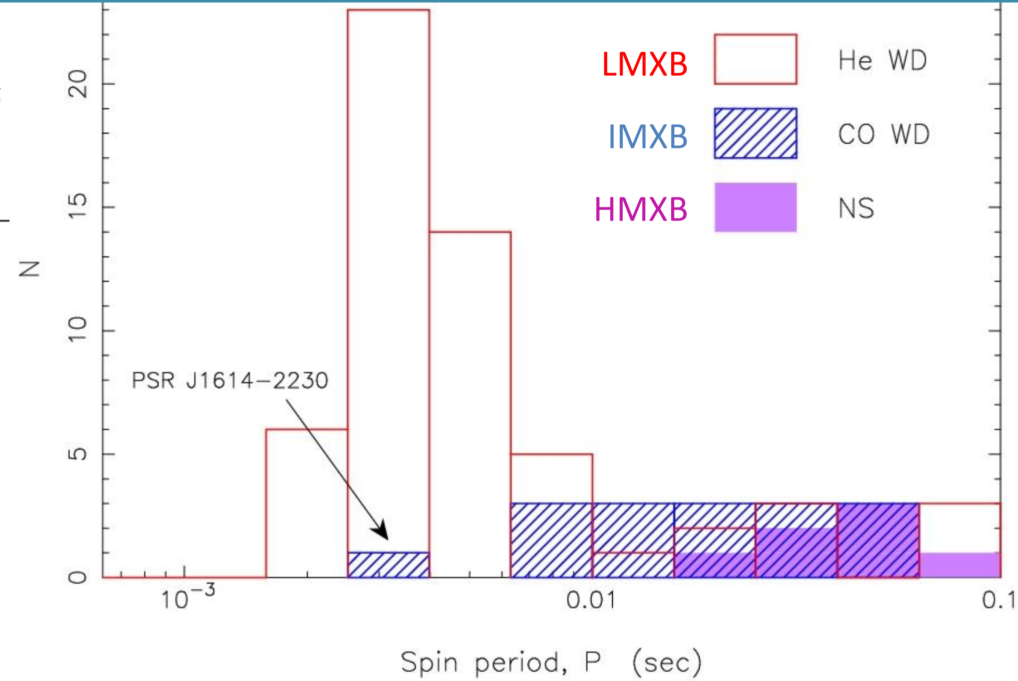


Accreted mass to spin up pulsar

stellar evolution code

$$\Delta J_\star = \int n(\omega,t)\,\dot{M}(t)\,\sqrt{GM(t)r_{\rm mag}(t)}\,\xi(t)\,dt$$





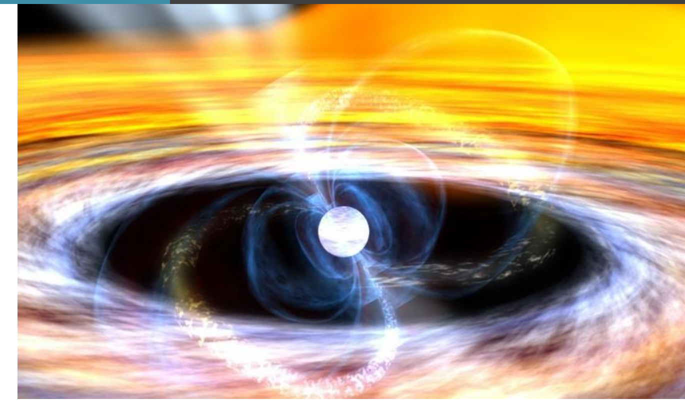
Mass needed to spin up pulsar:

$$\Delta M_{eq} \approx 0.22\,M_\odot \frac{(M/M_\odot)^{1/3}}{P_{ms}^{4/3}}$$

P (ms)	M (M_{sun})
0.7	0.40
2	0.10
5	0.03
10	0.01
50	0.001

Spin-up line in the PṖ-diagram

Tauris, Langer & Kramer (2012)
MNRAS, 425, 1601



$\Omega_{NS} = \Omega_K(r_{mag})$ spin equilibrium

$$P_{eq} = 2\pi\sqrt{\frac{r_{mag}^3}{GM}}\,\frac{1}{\omega_c} \quad \wedge \quad r_{mag}(\dot{M},B) \quad \wedge \quad B(P,\dot{P})$$

$$\dot{P} = \frac{2^{1/6}\,G^{5/3}}{\pi^{1/3}c^3}\,\frac{\dot{M}M^{5/3}P_{eq}^{4/3}}{I}\cdot(1+\sin^2\alpha)\cdot\varphi^{-7/2}\cdot\omega_c^{7/3}$$

spin-up line in $P\dot{P}$ – diagram

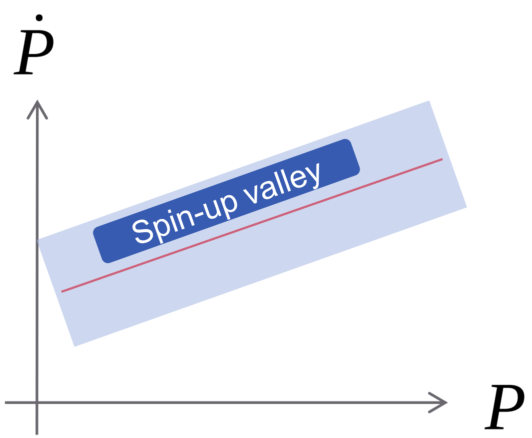
Tauris, Langer & Kramer (2012)

Important!

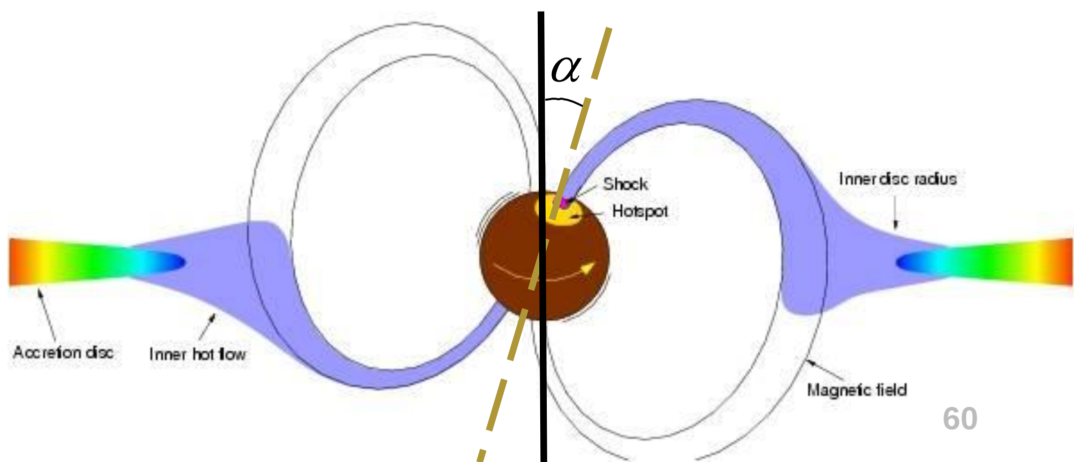
disk –magnetosphere parameters:

$$R_{mag} = \varphi\, R_{Alfven}$$

$$\Omega_{NS} = \omega_c\,\Omega_{mag}^{Kep.}$$

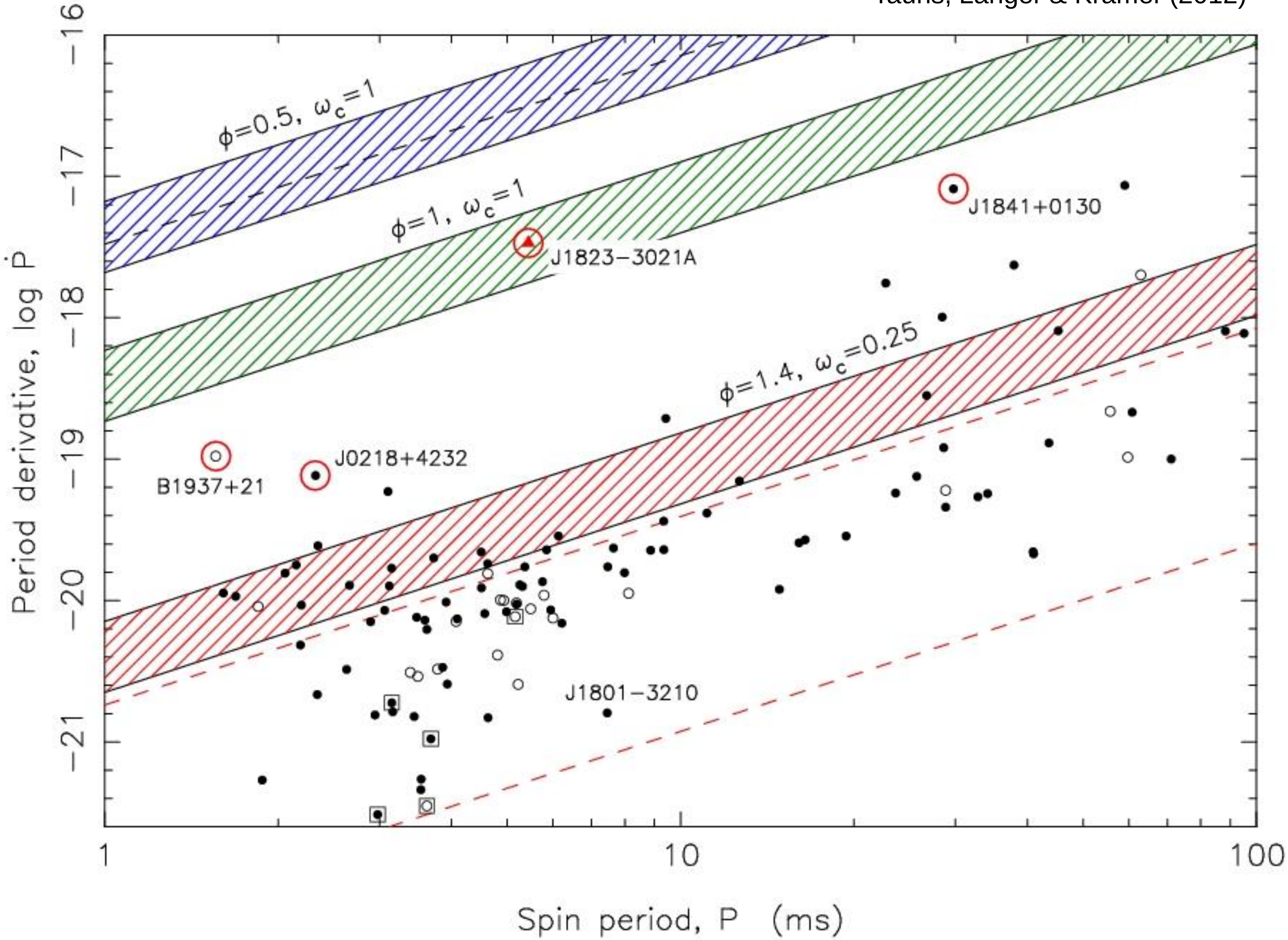


Classical spin-up line
e.g. Bhattacharya & van den Heuvel (1991)

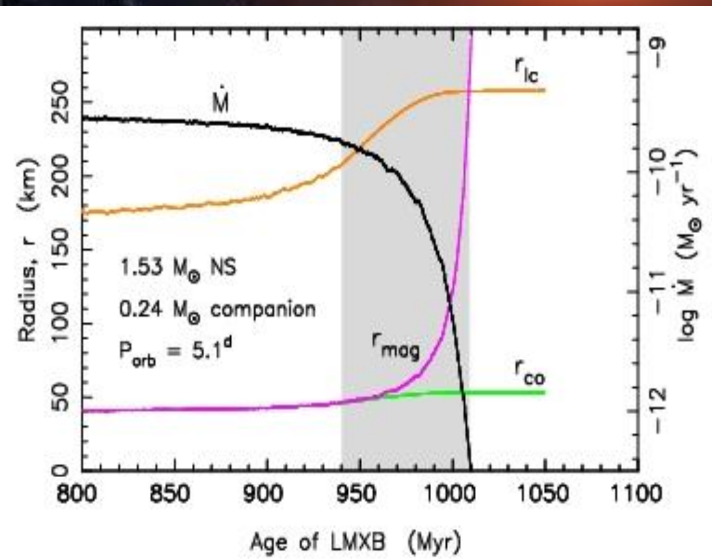


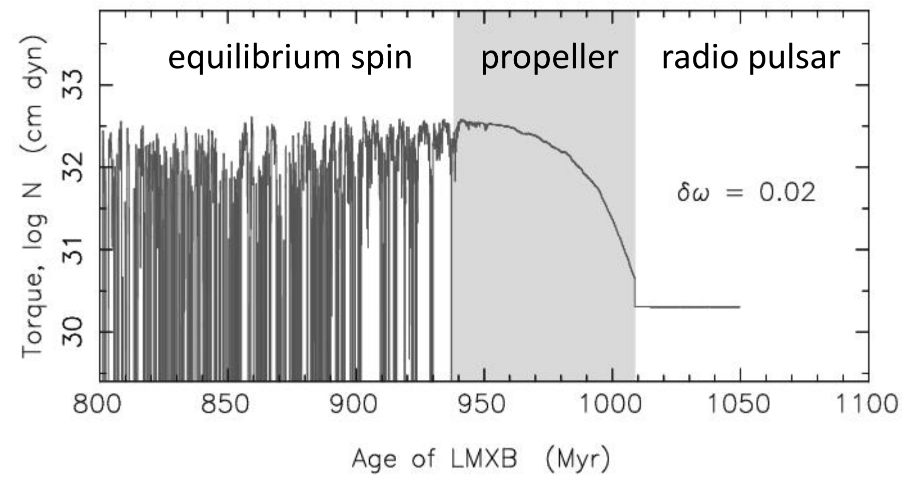
Spin-up line

Tauris, Langer & Kramer (2012)



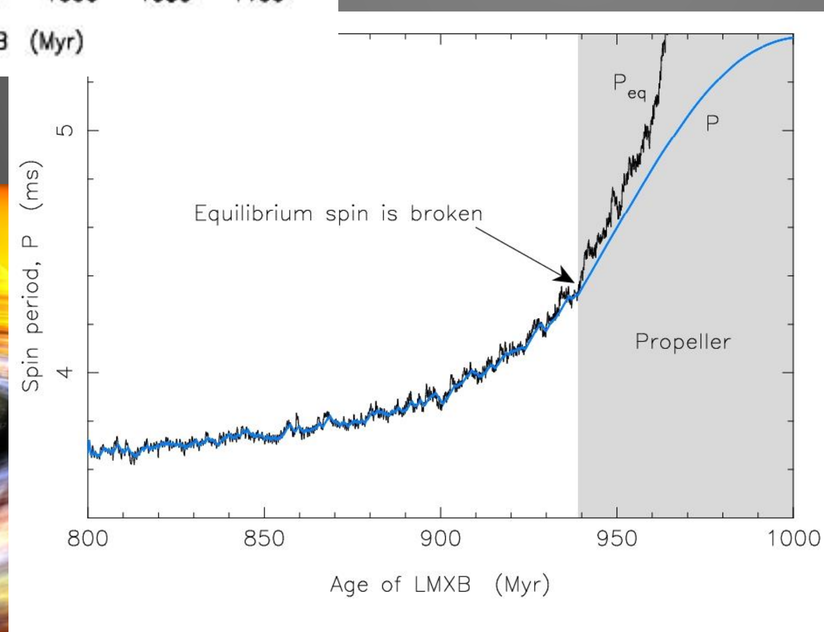
Roche-lobe decoupling phase

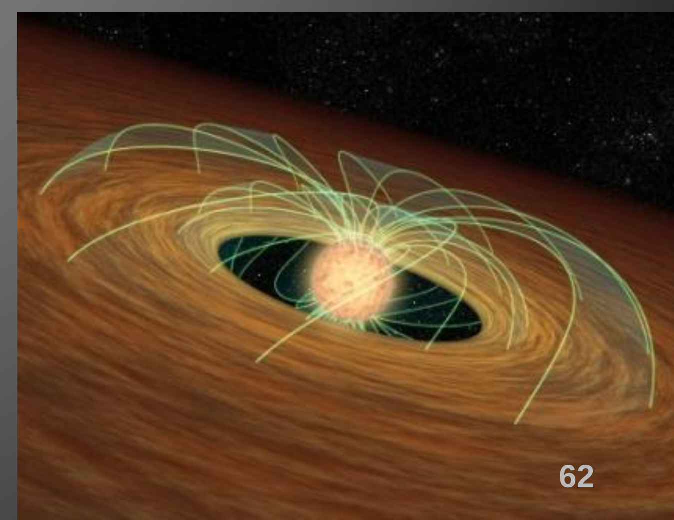




$$N(t) = n(\omega)\left[\dot{M}(t)\sqrt{GM\, r_{mag}(t)}\,\xi + \frac{\mu^2}{9r_{mag}^3(t)}\right] - \frac{\dot{E}_{dipole}(t)}{\Omega(t)}$$

Tauris (2012), Science 335, 561





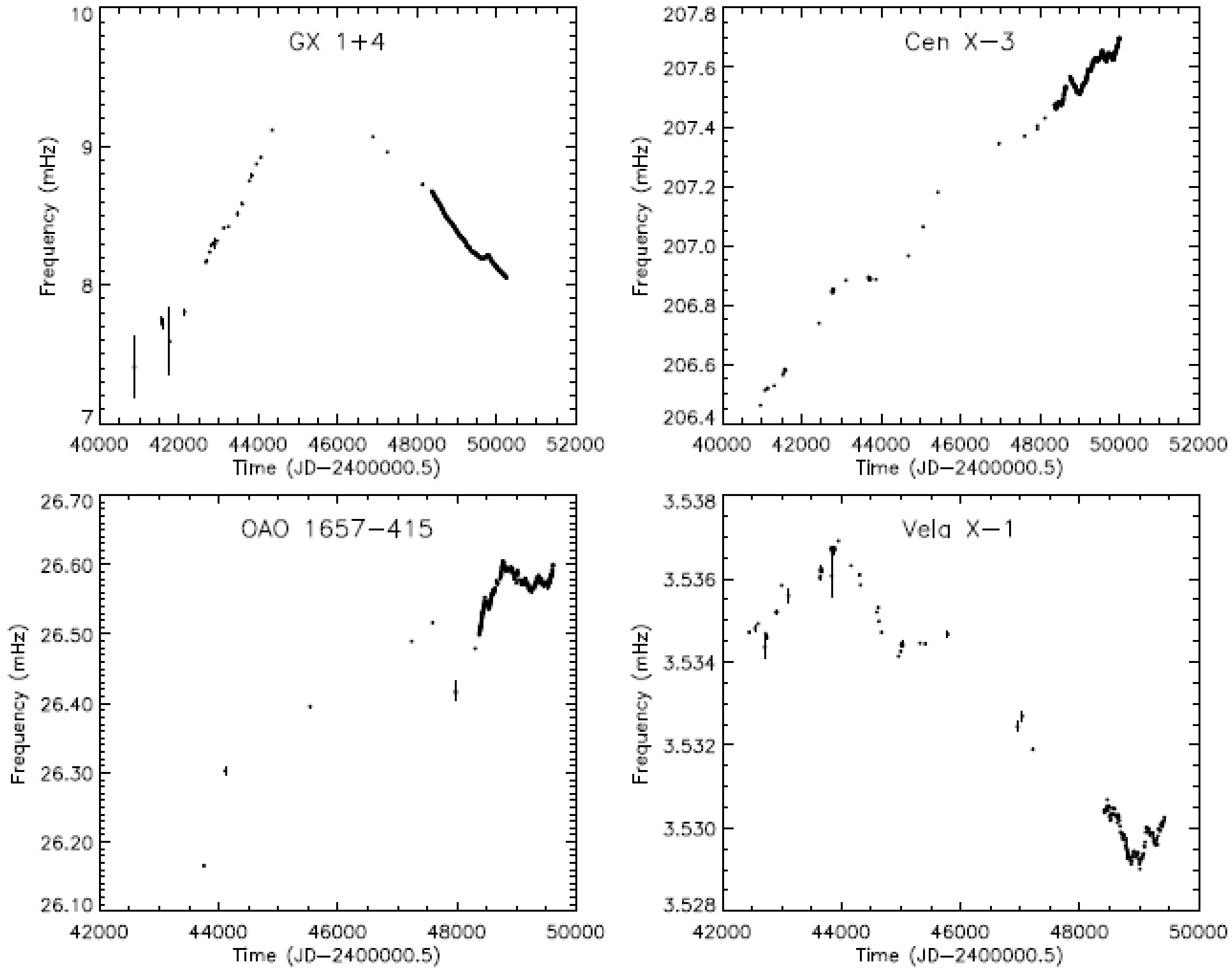
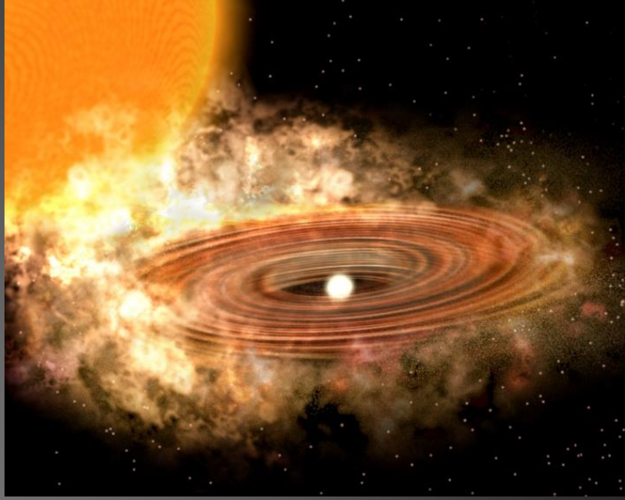


FIG. 6.—Long-term frequency history for all pulsars detected by BATSE that were previously known. The squares show the pre-BATSE data taken from Nagase (1989) and additional references. The line is the BATSE data, which we discuss later in great detail. The long-term frequency history for X-ray pulsars observed by BATSE that were known prior to the *Compton Observatory* launch commences 1991 April. For Her X-1, Cen X-3, Vela X-1, 4U 1538−52, GX 301−2, 4U 0115+634, and EXO 2030+375, all frequencies have been orbitally corrected. For OAO 1657−415, GS 0834−430, 2S 1417−62, and A0535+262, orbital corrections have been applied only to the BATSE observations. No orbital corrections have been applied for 4U 1626−67, GX 1+4, 4U 1145−619, or A1118−615, which have unknown, or incompletely known, orbital elements. The BATSE frequencies for OAO 1657−415, GS 0834−430,

Nagase (1989), Bildsten et al. (1997)

Accretion Disks

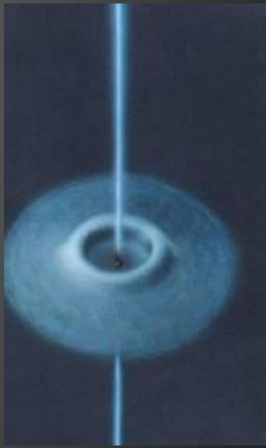


High specific ang.mom. of accreted gas in binary

→ formation of accretion disk
(ang.mom. is transported outward via viscous stresses)

Turbulent-enhanced viscosity models (e.g. α-model by Shakura & Sunyaev (1973))

- If accretion rate is < 0.01 $\dot{M}_{Edd}$: thin disk (high opacity) or ADAF (low opacity)
- If accretion rate is about $\dot{M}_{Edd}$: slim disks
- If accretion rate is > $\dot{M}_{Edd}$: torus (with collimated beam of radiation)

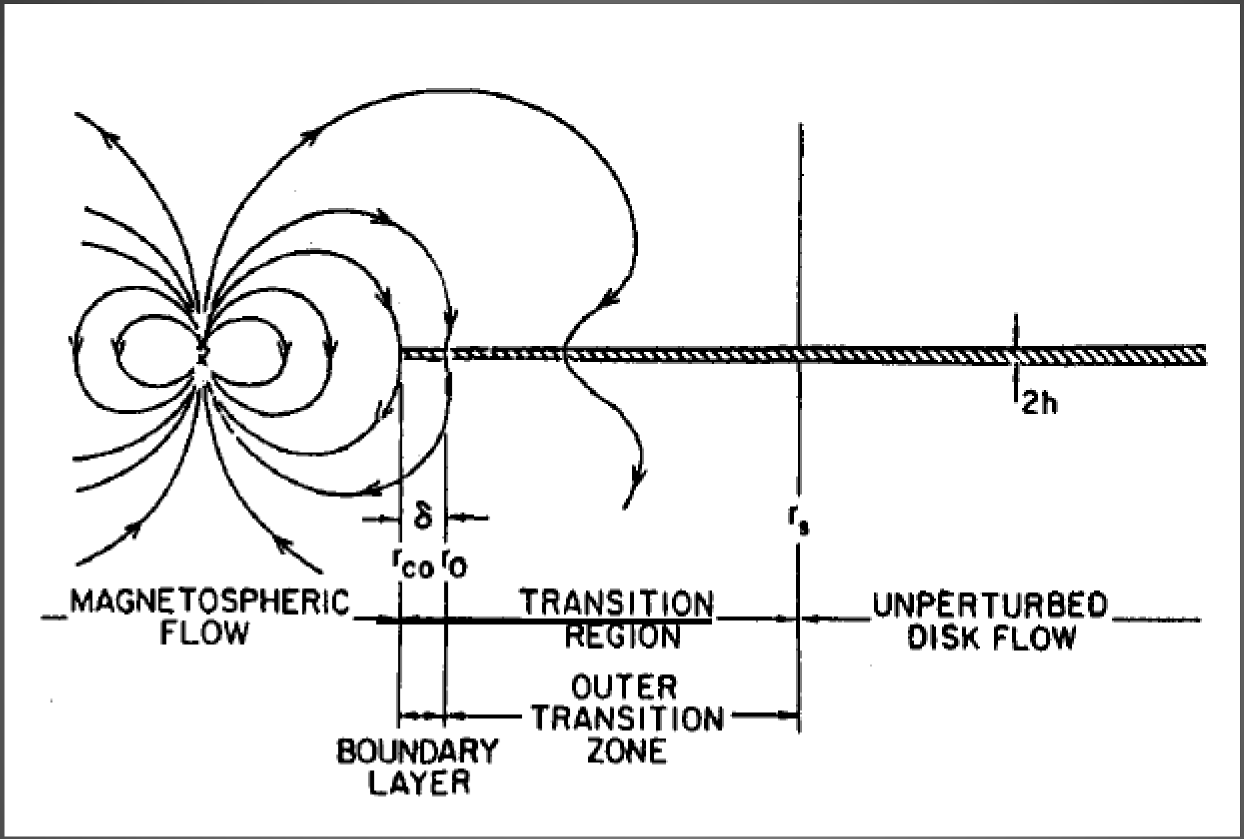


Magnetic stresses truncate the Keplerian disk flow:
- transition zone between disk and magnetosphere

$$R_{magnetosphere} \propto R_{inner\ disk}$$

Spin-up lines in P-P_{dot} diagram depend on nature of accretion disk model (optically thick/thin and gas/radiation pressure dominated)

$$R_{inner\ disk} \propto \dot{M}^a \mu^b M^c$$



Ghosh & Lamb (1979)

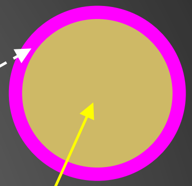
Accretion-Induced Magnetic Field Decay

induction equation:

$$\frac{\partial B}{\partial t} = \underbrace{-\frac{c^2}{4\pi}\vec{\nabla}\times\left(\frac{1}{\sigma_{el}}\times\vec{\nabla}\times\vec{B}\right)} + \underbrace{\vec{\nabla}\times(\vec{v}\times\vec{B})}$$

ohmic dissipation (diffusion)

convective transport of accreted material (Hall term)



Bad approximation!

$$\frac{\partial B}{\partial t} = -\frac{c^2}{4\pi\sigma_{el}}\nabla^2\vec{B} \quad\Leftrightarrow\quad B = B_0 e^{-t/\tau_D} \quad (\tau_D \approx \mu_0\sigma_{el}L^2)$$

$$\boxed{\sigma_{el} = \sigma_{el}(T,\rho,A,Z,Q)}$$

<u>Note:</u> residual B-field ~10^8 G (observed in millisecond pulsars) due to superconducting interior

Summary

- Introduction to X-ray binaries/Accretion
  - HMXBs and LMXBs
  - Roche-lobe overflow - Cases A, B and C
  - Stability criteria for mass transfer / stellar evolution
  - Orbital angular momentum balance equation
- Common envelope and spiral-in evolution
- Equilibrium spin period and spin-up line in P-P_{dot} diagram
- Accretion physics
  - Accretion disks
  - B-field decay
  - Four phases of accretion (self study)

For a review: Tauris & van den Heuvel (2006)
Tauris & van den Heuvel (2022)
New textbook from Princeton Uni. Press

Albert-Einstein Institute Lectures 2021
Thomas Tauris @ Aarhus University

Lectures 1+2: Wednesday May 12, 10:00 – 12:00
X-ray Binaries and Recycling Millisecond Pulsars

Lectures 3+4: Friday May 14, 10:00 – 12:00
Spin and B-field Evolution of Neutron Stars (+ Black Hole Spins)

Lectures 5+6: Wednesday May 19, 10:00 – 12:00
Formation of Binary Neutron Stars/Black Holes

Lectures 7+8: Friday May 21, 10:00 – 12:00
Binary Neutron Stars and Gravitational Waves at Low and High Frequencies

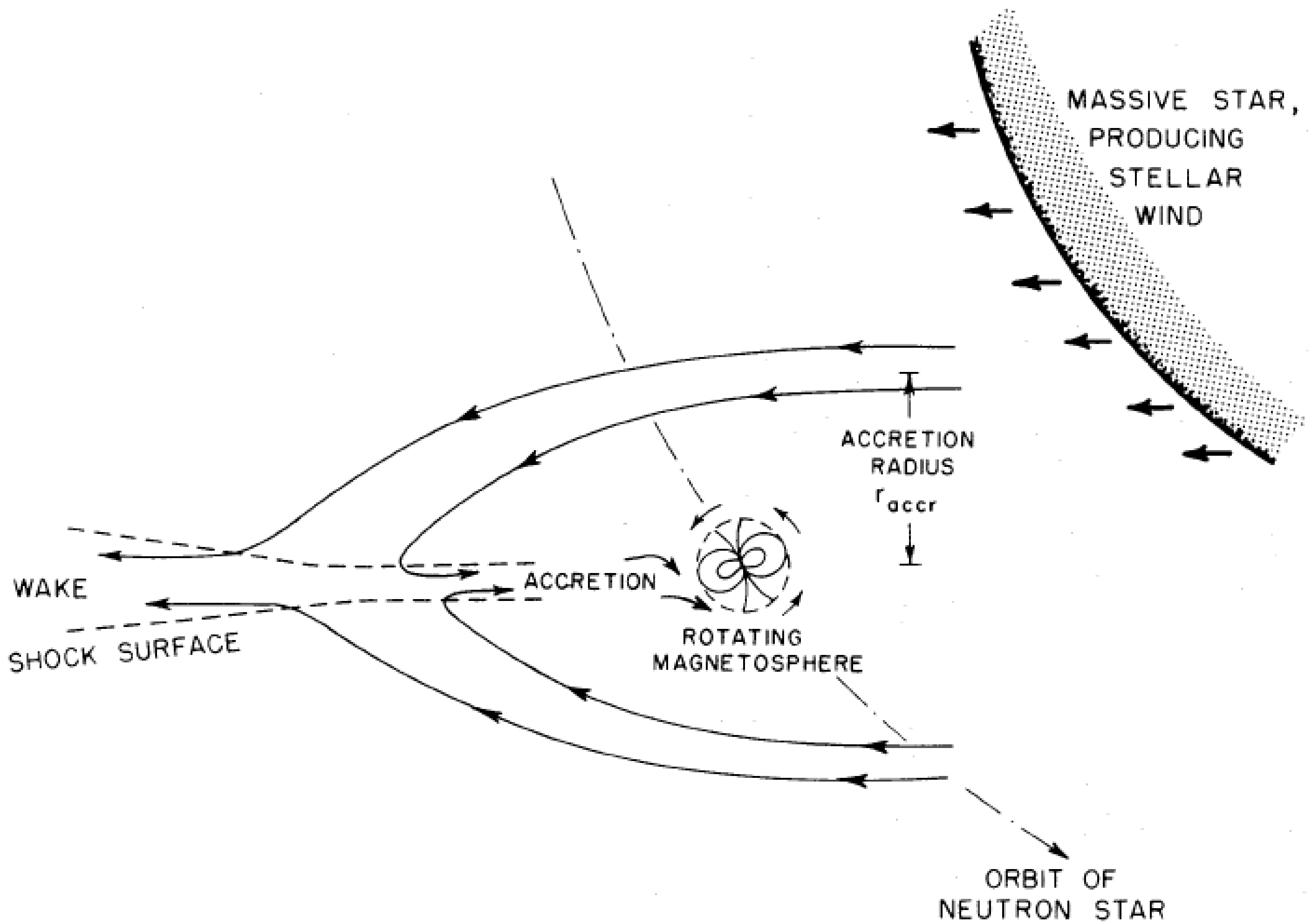
You are most welcome to ask questions any time ☺

Accretion Physics

Self study!

- Introducing the physics of an accreting neutron star
  - Spherical wind accretion
  - Effect of accretion disk

NEUTRON-STAR ACCRETION

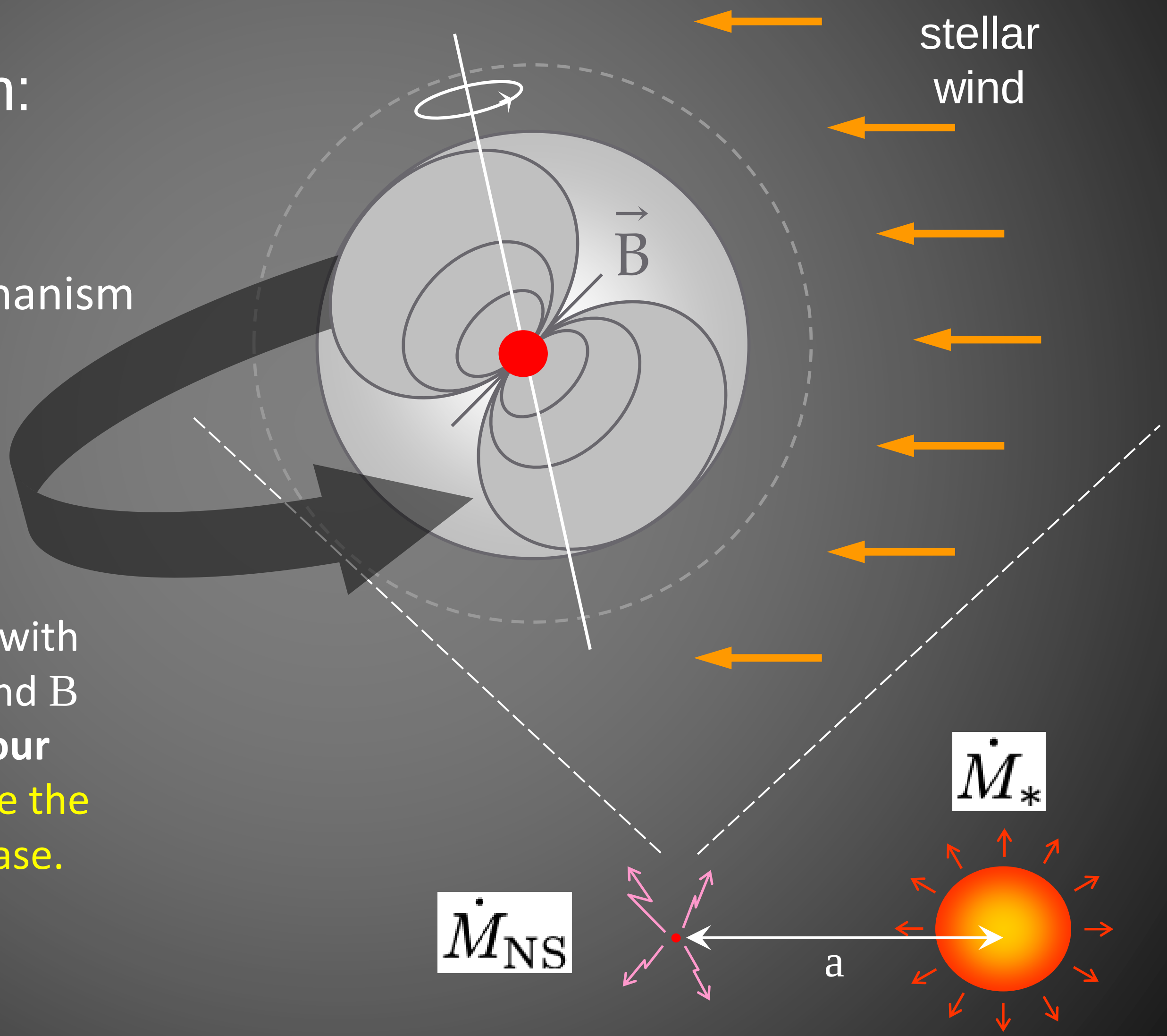


Davidson & Ostriker (1973)

Neutron star accretion

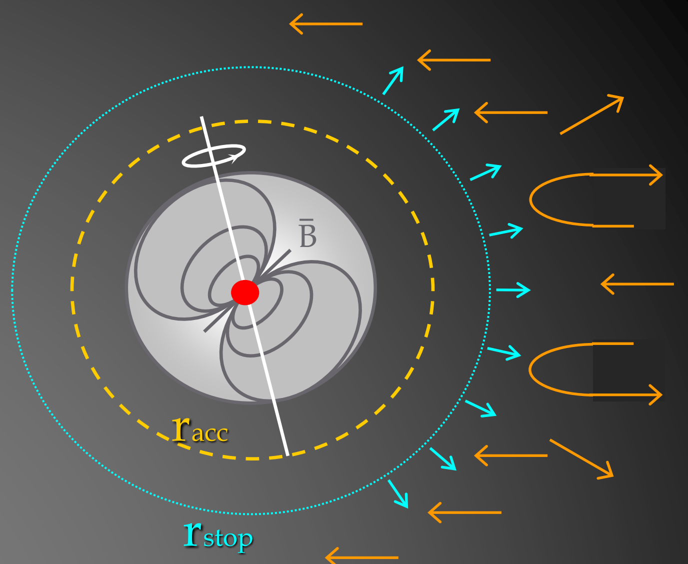
Phases of accretion:

- I. Isolated pulsar
- II. Gunn-Ostriker mechanism
- III. Propeller phase
- IV. Rapid accretion



Consider a young pulsar with initial high values of Ω and B which evolves through **four phases of accretion** while the values of Ω and B decrease.

Phase I



Isolated pulsar: $r_{stop} > r_{acc}$

Wind plasma is stopped by pressure of magneto-dipole radiation outside the radius of gravitational capture. The pulsar evolves as an isolated pulsar.

$$P_{dipole} \approx P_{ram}$$

$$\dot{E}_{dipole} = -\frac{2}{3c^3}|\ddot{m}|^2 \quad \wedge \quad |\ddot{m}| \sim BR^3\Omega^2$$

continuity equation

$$\frac{\dot{E}_{dipole}}{4\pi r_{stop}^2 c} = \frac{2B^2R_{NS}^6\Omega^4/3c^3}{4\pi r_{stop}^2 c} \approx \frac{1}{2}\rho_w v_w^2 = \frac{1}{2}\left(\frac{\dot{M}_*}{4\pi a^2 v_w}\right)v_w^2$$

pressure = $\frac{\text{energy}}{\text{volume}}$

$\Downarrow$

ram pressure of wind

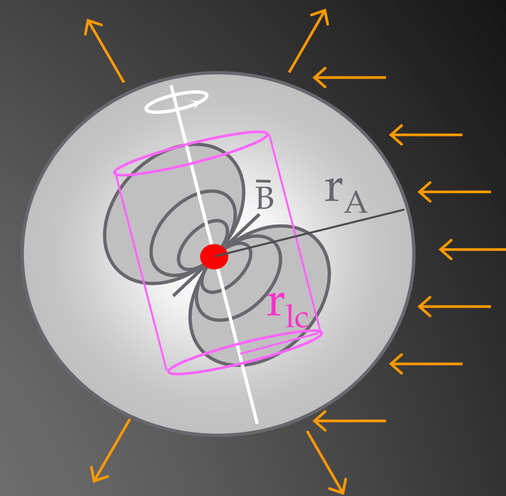
$$r_{stop} = \sqrt{\frac{4B^2R_{NS}^6\Omega^4a^2}{3c^4v_w\dot{M}_*}}$$

$$r_{acc} \sim \frac{2GM_{NS}}{v_w^2}$$

$$r_{stop} \propto B\,\Omega^2$$

Over time, the pulsar loses rotational energy and Ω decreases, causing r_{stop} to decrease… → Phase II

Phase II



Gunn-Ostriker mechanism: r_{acc}, r_A > r_{stop}, r_{lc}

Now r_{stop} < r_{acc}. However, the Alfven radius is located outside the light cylinder and matter cannot couple to the magnetosphere with $v > c$. Therefore, matter is accelerated to relativistic energies by magnetodipole waves.

$$\frac{B(r_A)^2}{8\pi} \approx \frac{1}{2}\rho_w\, v_{ff}^2$$

location of Alfven radius

$$B(r_A) = B\left(\frac{R_{\rm NS}}{r_A}\right)^3$$

perfect dipole

$$v_{ff} = \sqrt{\frac{2GM_{\rm NS}}{r_A}}$$

approx. radial velocity

$$\rho_w = \frac{\dot{M}_*}{4\pi a^2\, v_{ff}}$$

continuity equation

$$\dot{M}_{NS} = \frac{\pi r_A^2}{4\pi a^2}\dot{M}_*$$

accretion rate (solid angle accretion)

$$\Rightarrow \boxed{r_A = \left(\frac{1}{32}\frac{B^4 R_{\rm NS}^{12}}{GM_{\rm NS}\dot{M}_{\rm NS}^2}\right)^{1/7}}$$

$$r_A \propto B^{4/7}\,\dot{M}_{\rm NS}^{-2/7}$$

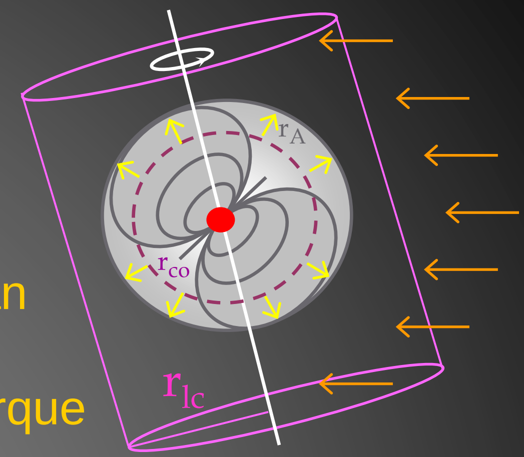
$$r_{lc} \equiv \frac{c}{\Omega}$$

location of light cylinder (distance from spin axis)

$$r_{lc} \propto \Omega^{-1}$$

Over time, Ω decreases, causing r_{lc} to increase… → Phase III

Phase III



Propeller effect: $r_{lc} > r_A > r_{co}$

Accreted matter couples to magnetosphere in super-Keplerian orbits ($F_{centrifugal} > F_{gravitational}$) and thus material piles up near magnetospheric boundary, which creates a strong braking torque (wind carries off ang. mom.)

$$r_{co} = \left(\frac{GM_{NS}}{\Omega^2}\right)^{1/3}$$

co-rotation radius (Keplerian velocity)

$$N = \dot{J}_{spin} \approx \frac{\partial}{\partial t}\left(mr_A^2\Omega_K\right) = \dot{M}_{NS}\sqrt{GM_{NS}r_A}$$

braking torque

$$\vec{J} = |\vec{r} \times \vec{p}|$$

$$\dot{\Omega} = \frac{\dot{J}_{spin}}{I_{NS}} \quad \wedge \quad \Omega = \frac{2\pi}{P} \quad \Rightarrow \quad \dot{P} \approx \frac{\dot{J}_{spin}P^2}{-2\pi I_{NS}} \propto L_X^{6/7}$$

$$L_X = \frac{dE_{acc}}{dt} = \frac{GM_{NS}}{R}\dot{M}_{NS} \propto \dot{M}_{NS}$$

spin-down rate

$$r_A^{1/2} \propto \dot{M}_{\mathrm{NS}}^{-1/7}$$

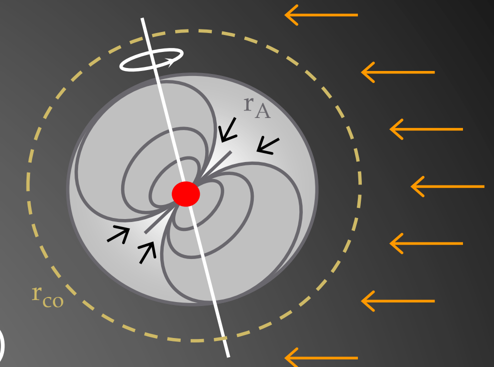
X-ray luminosity

$$r_{co} \propto \Omega^{-2/3}$$

Braking torque causes Ω to decrease… $\rightarrow$ Phase IV

Phase IV

Neutron star accretion: $r_A < r_{co}$



$$\dot{J}_{spin} = \dot{M}_{NS}\sqrt{GM_{NS}\,r_A}\;\xi$$

$\xi = 0.01\sim0.1,$ if no disk is formed (wind)

$\xi = 1,$ if accretion disk is formed (RLO)

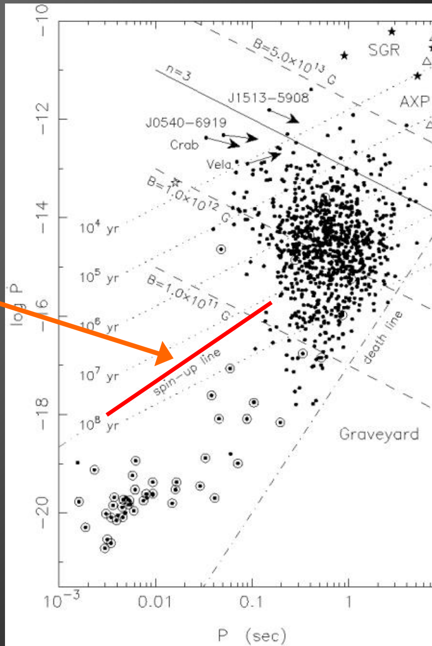
$$\Omega_{NS} = \Omega_K(r = r_A) \quad \Leftrightarrow \quad \frac{2\pi}{P_{eq}} \equiv \sqrt{\frac{GM_{NS}}{r_A^3}}$$

equilibrium spin period!

$$\boxed{P_{eq} \propto \dot{M}_{NS}^{-3/7} B^{6/7} R_{NS}^{18/7} M_{NS}^{-5/7}}$$

See eq. for r_A

see spin-up line in $(P,\dot{P})$ diagram



Accretion is possible if $P > P_{eq}$

In equllibrium r_{co} moves alternately inside and outside r_A.