Understanding the Theory of Mass Transfer: The past and the future

Natasha Ivanova

Accretion in Stellar Systems
Cambridge, Aug 9, 2018

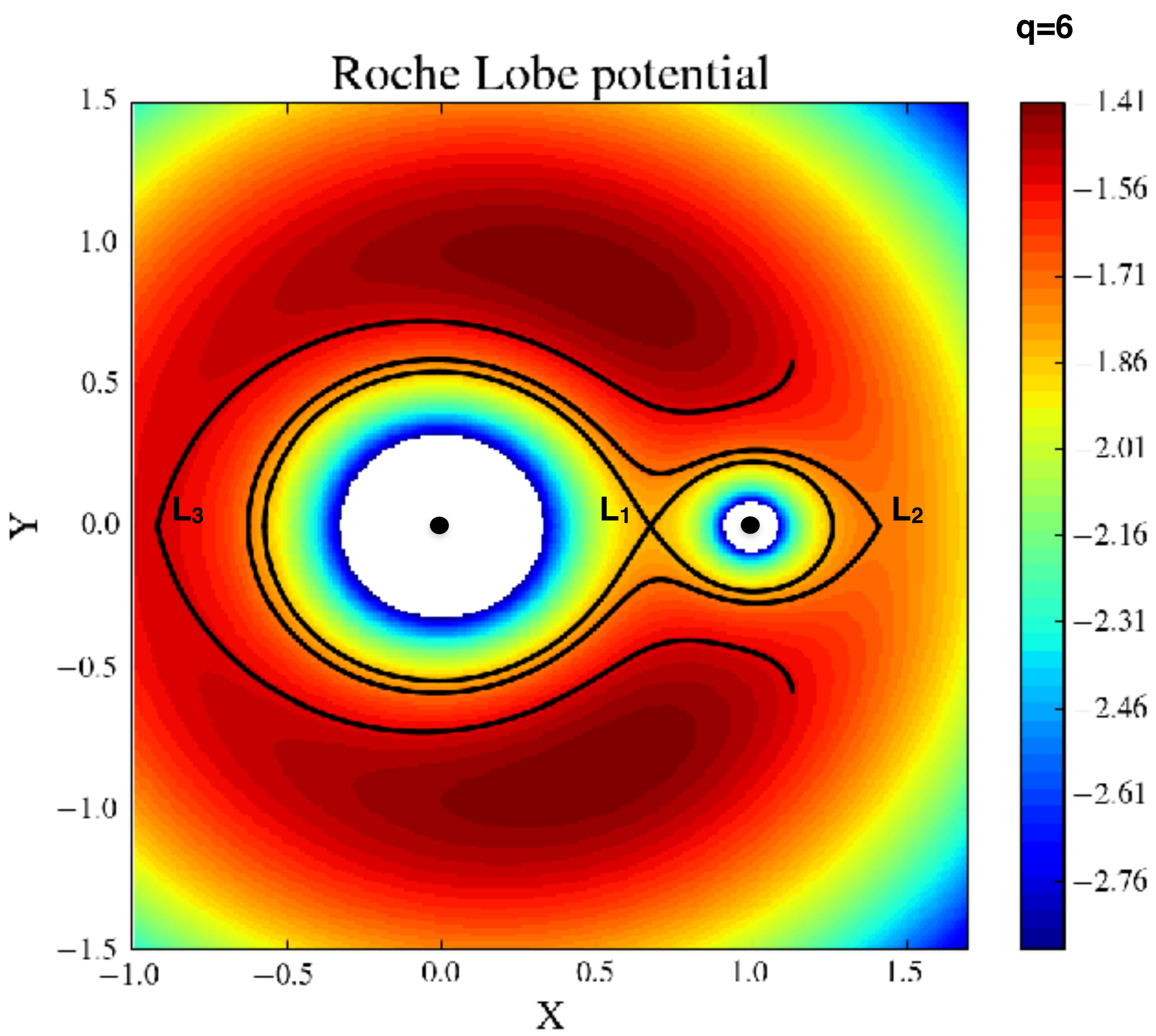
Understanding the Theory of Mass Transfer:
The past and the future

The story of q and ζ,
and, to some extent, of α,β,γ

Natasha Ivanova

Accretion in Stellar Systems
Cambridge, Aug 9, 2018

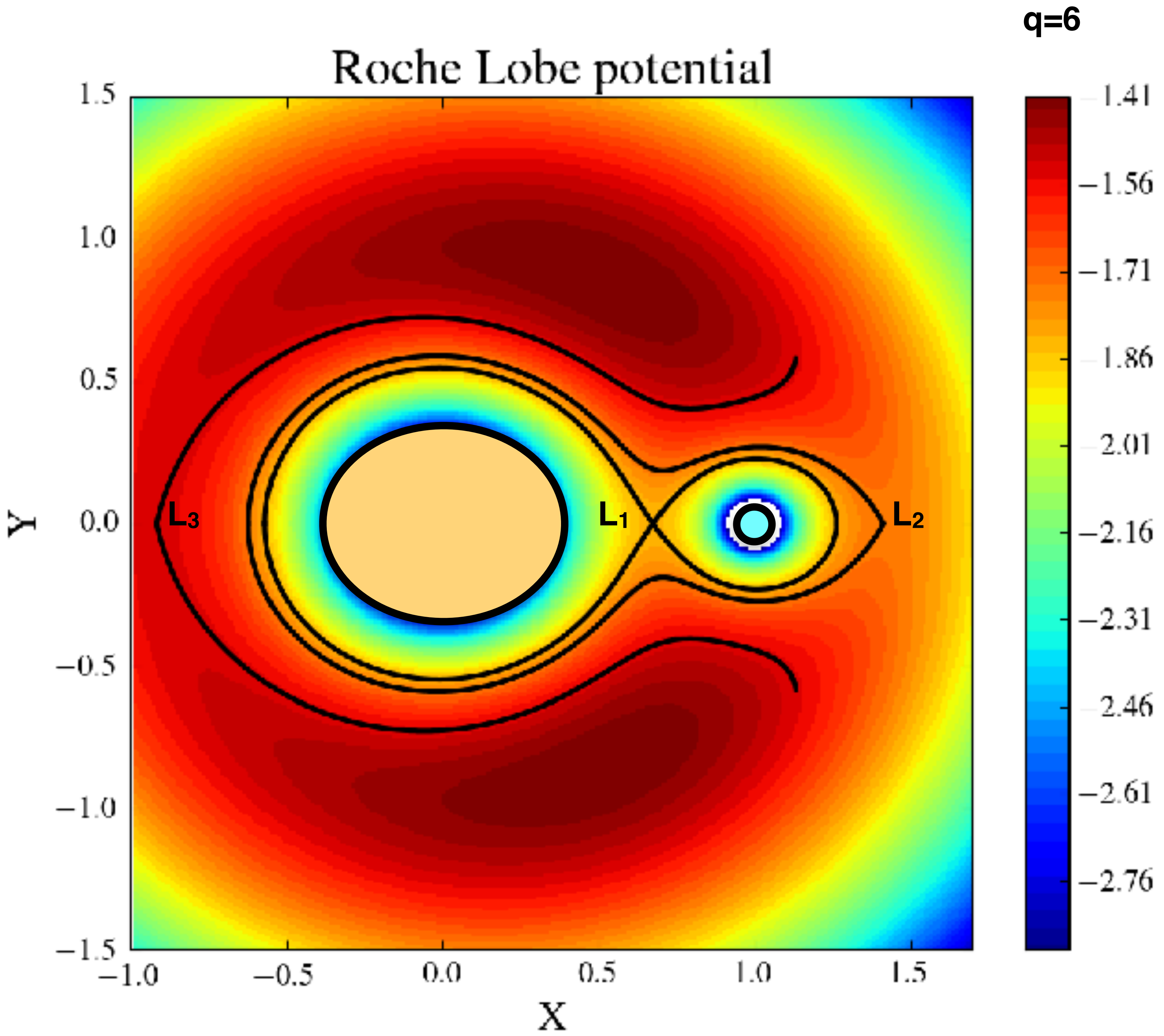
Understanding the start and RLOF: basic picture



Orbital plane, corotation frame

q is the (initial) mass ratio, donor to accretor, $q=M_{donor}/M_{accretor}$

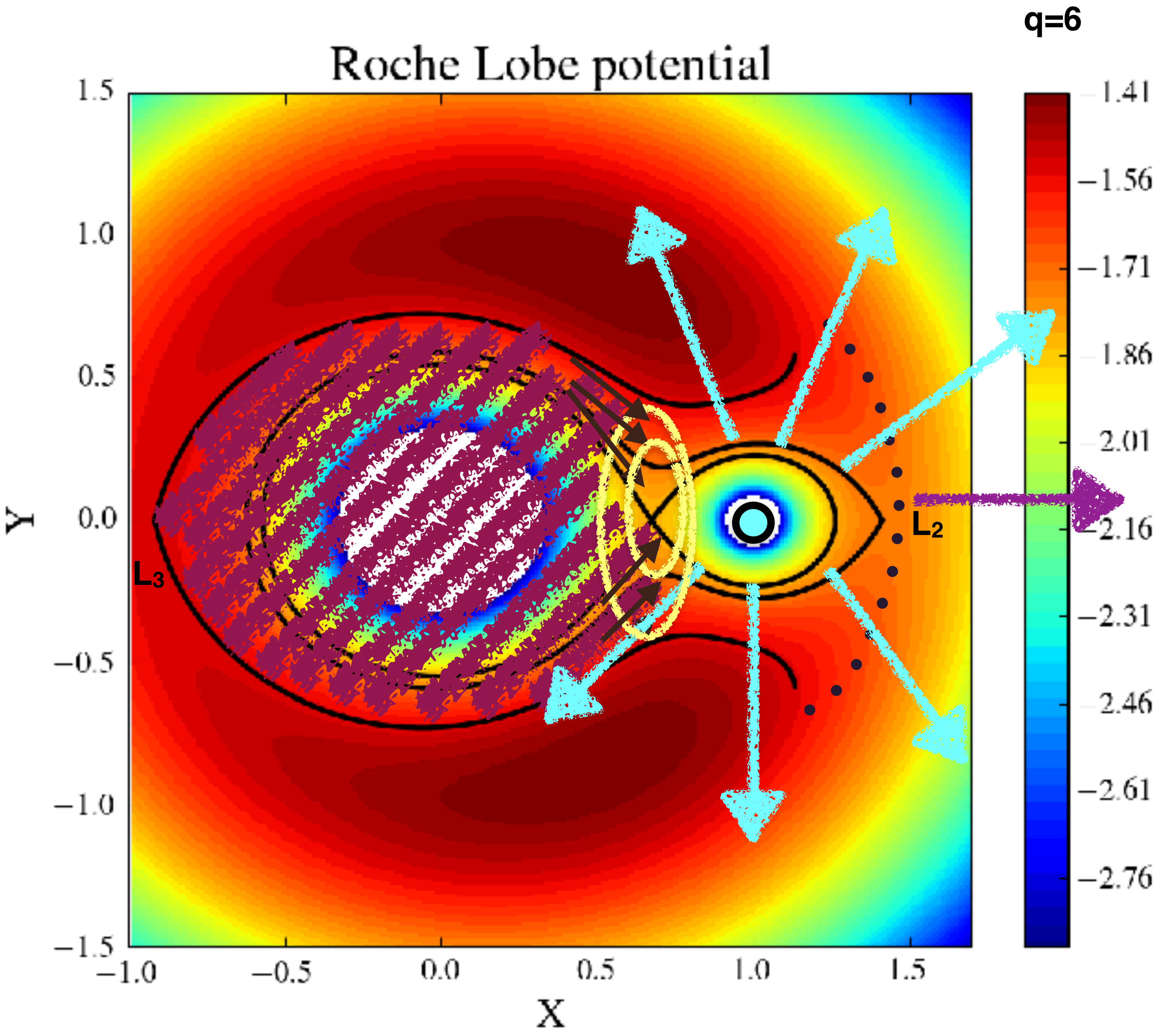
Understanding the start and RLOF: basic picture



Orbital plane, corotation frame

q is the (initial) mass ratio, donor to accretor, $q=M_{donor}/M_{accretor}$

Understanding the start and RLOF: basic picture



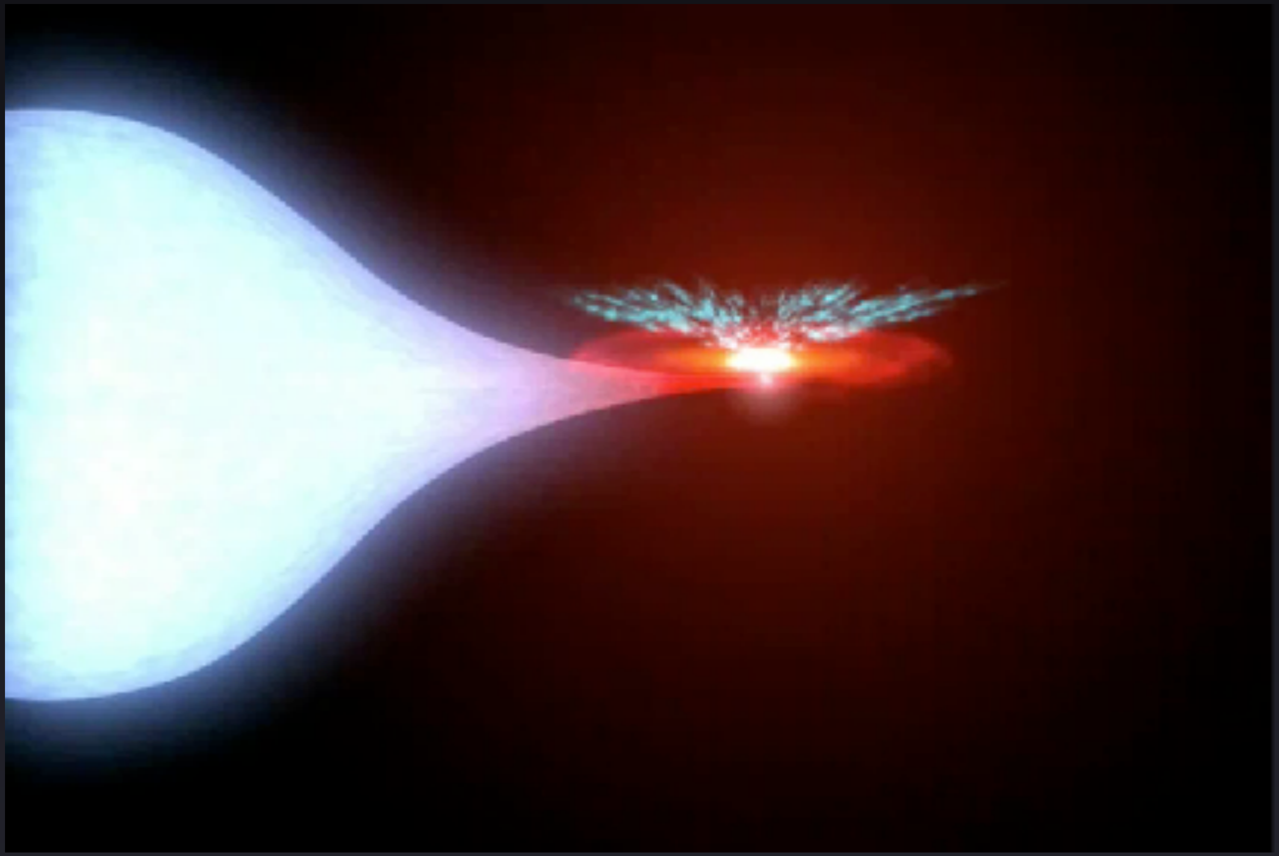
Orbital plane, corotation frame

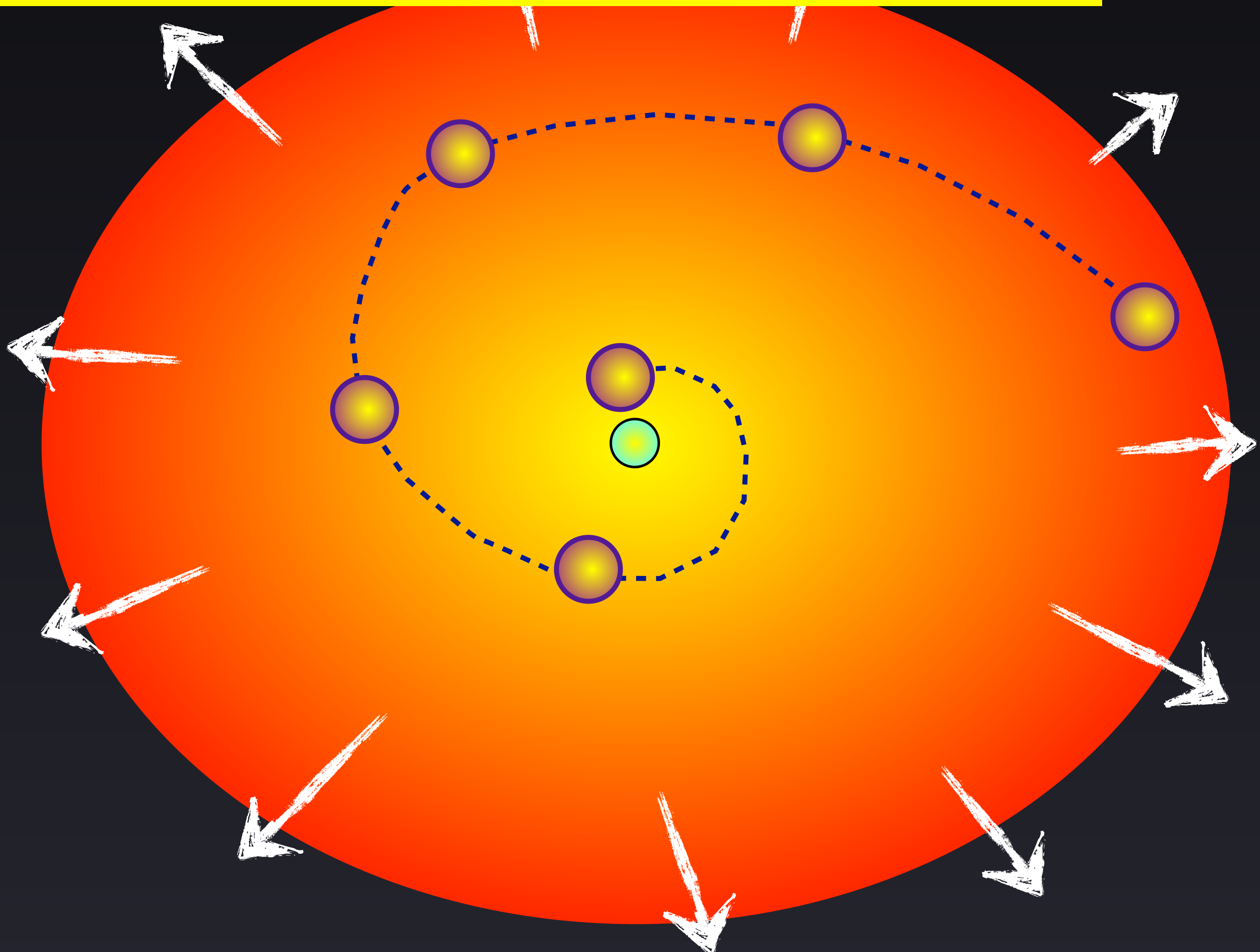
q is the (initial) mass ratio, donor to accretor, $q=M_{donor}/M_{accretor}$

Stability of RLOF MT decides the fate of the binary:

- ➡ Stable, long-term mass transfer (e.g. X-ray binaries)
- ➡ Unstable, AKA Common Envelope event (1976: Webbink, Paczynski, Ostriker).

α - efficiency of the orbital energy re-use, can not be more than 1
For interpretation of existing X-ray binaries with a NS or a BH accretor, **α** is usually used as an argument on whether the current (initially less massive) donor could have survived the preceding CEE.





Which binaries become MT binaries: defined by understanding instability

How long they remain as MT binaries: defined by understanding the stable behaviour

➡ Resulting population of the observed MT binaries

Outline

1. The basics of theory on instability and on stable MT
2. What is a standard treatment
3. What has been recently questioned and revised
4. Scattered here and there: what BPS codes cannot do

Roche Lobe Overflow: (simplified) treatment in stellar codes

Standard assumption:
Donor radius must stay ~ within Roche lobe radius

Compare <u>responses</u> to determine stability:

$$R_{\mathrm{RL}} \propto M_{\mathrm{d}}^{\zeta_{\mathrm{RL}}}$$

$$R_{\mathrm{d}} \propto M_{\mathrm{d}}^{\zeta_{\mathrm{d}}}$$

All we know about how conservative MT is, GW, MB, CB disk, tides...

All we know about a donor's response on ML

Zetas, ζ: mass-radius response exponents

$$\zeta_{\rm d} = \frac{d\log R_{\rm d}}{d\log M_{\rm d}}, \qquad \zeta_{RL} = \frac{d\log R_{RL}}{d\log M_{\rm d}}$$

$\zeta_{\rm d} \geq \zeta_{RL}$ stability

$\zeta_{\rm d} < \zeta_{RL}$ instability

Complication:

stars react to perturbations on two very different timescales, thermal and dynamical, and there is no single $\zeta_{\rm d}$

If a star suddenly loses mass: **both its HE and its TE are disturbed.**

Readjustment of its structure (hence its radius) to recover equilibrium.

Mass-radius response exponents & fate of the system

Hydrostatic Readjustment

$\tau_{\rm dyn} << \tau_{\rm KH}$ ➡ the initial (dynamical) response to mass loss will be **almost (locally) adiabatic**

$$\zeta_{\rm ad} \equiv \left(\frac{d\log R_d}{dM}\right)_{\rm ad} \Rightarrow$$

$\zeta_{\rm RL} \le \zeta_{\rm ad}$ **the criterion for dynamical stability of MT**

if the donor can **shrink** within its Roche lobe on $\tau_{\rm dyn}$ and **is able to recover HE** ➡ Thermal Readjustment

On $\tau_{\rm KH}$ the star will attempt to **recover the TE radius** appropriate for its new mass

$$\zeta_{\rm eq} \equiv \left(\frac{d\log R_d}{dM}\right)_{\rm eq} \Rightarrow$$

$\zeta_{\rm eq} < \zeta_{\rm RL} \le \zeta_{\rm ad}$ **thermal timescale MT**

$\zeta_{\rm RL} \le \min(\zeta_{\rm ad}, \zeta_{\rm eq})$ **secularly stable MT**

Most of observed MT system are in the latter regime

Mass-radius response exponents: Roche lobe response

CONSERVATIVE CASE:

depends primarily on the binary mass ratio $q=M_{donor}/M_{accretor}$.

$$\zeta_{RL}=2.13q-1.67 \text{ for } q=M_d/M_a < 10$$

➠ stability criteria for MT can be rewritten in terms of a **critical mass ratio** q_{crit}: for each ζ_{ad} can be found q_{crit}, such that if $q > q_{crit}$, MT is unstable

➠for $q>1$, ζ_{RL}=>0.46

NONCONSERVATIVE CASE:

ζ_{RL} depends on different values for non-conservative mass transfer:

- β, or how mass in not conserved; β=1 MT is fully conservative
  (mass non conservation decreases ζ_{RL} and helps stability)
- γ, or how angular-momentum is removed from the orbit (GW, MB, CB disk, tide...).

$$h_{\rm loss} \equiv \frac{\dot{j}}{\dot{M}_a+\dot{M}_d} = \gamma \frac{J}{M_a+M_d}$$

Mass-radius response exponents: adiabatic response

Standard conception:

- Hjellming & Webbink 1987 - using hydro and polytropic stars, core mass dependence
- Soberman, Phinney & van den Heuvel 1997 - polytropes, large scale analyzes
- Ge et al 2010 - adiabatic 1D stellar models

- stars with radiative envelopes are expected to shrink rapidly in response to mass loss (i.e. $\zeta_{ad} \gg 0$)

- stars with convective envelopes are expected to expand or keep a roughly constant radius ($\underline{\zeta_{ad} \lesssim \mathbf{0}}$)

Consequence: A fully conservative MT with $q=m_{donor}/m_{accretor} > \underline{\mathbf{q_{crit}=0.78}}$ and a convective donor is deemed to be unstable => Any first episode of conservative MT with a convective donor is unstable. **CEE**.

Radiative donors deem to produce (initially) dynamically stable M,T unless q>10 (Darwin instability).

Mass-radius response exponents: equilibrium response

For **homogeneous** stars: (ZAMS) mass-radius relation:

- for upper ZAMS stars ($M \geq 1\ M_\odot$) $\zeta_{eq} \approx 0.6$
- for low-mass ZAMS stars ($M \lesssim 1\ M_\odot$) $\zeta_{eq} \approx 1.0$.

The effect of a non-homogeneous composition is to make stars expand rather than contract in response to mass loss: stability decreases

- $\zeta_{eq} \lesssim 0$ for fairly evolved MS stars
- $\zeta_{eq} \approx 0$ for post-MS phases (R_{eq} is insensitive to the total stellar mass)
- for low-mass red giants the radius depends strongly on the core mass

<u>**Consequence:**</u> MT from radiative donors can start with a higher value of ζ_{eq} and be stable, but as it decreases, MT can become unstable. This is known as **Delayed Dynamical Instability** and is described by $q_{crit} = 3.5$ (e.g., Ge et al. 2010)

Typical implementations of MT in codes

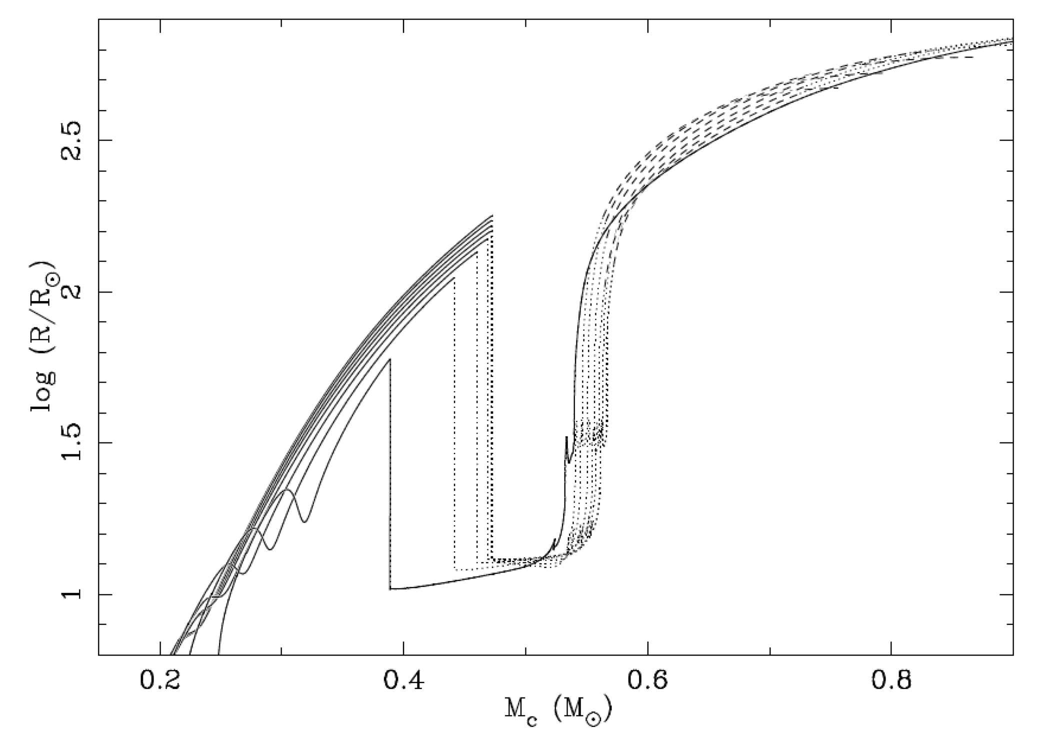
- Parametrized BPS codes and some 1D stellar codes use pre-calculated ζ_{ad} to determine stability, at the moment of the initial RLOF. Parametrized BPS codes use pre-calculated ζ_{eq} to determine their TMMT rate, and remove the envelope down to the “core” (which mass is taken at the start of the MT). Mass ratio-ζ parameter spaces are used to determine binary system fate.
- (many)1D codes that do not use pre-calculated ζ_{ad}:
  - $R_*=R_{RL}$ condition to determine MT rate
  - if MT rate exceeds 10^{-3} M_{sun}/yr (varies on the code, can be even smaller), system is declared to be dynamically unstable
- Mass non-conservation: varied with respect to Eddington limited MT rate.
- AM non conservation: GW, standard Skumanich MB, mass lost from the system carries (isotropic) donor/accretor spec.a.m. (rare: MB variations, circumbinary, triples, L2/L3,...)
- MT is generally assumed to take place in circularized systems (rate: MT in eccentric systems)
- No feedback on the donor from X-ray(rare: an arbitrary implementation of irradiation)

Case: adiabatic response $\zeta_{ad} \lesssim 0$

Consequence of the standard assumption: any MT with $q=m_{donor}/m_{accretor}>0.78$ with conservative MT and a convective donor is deemed to be unstable. **CEE**.

Case study

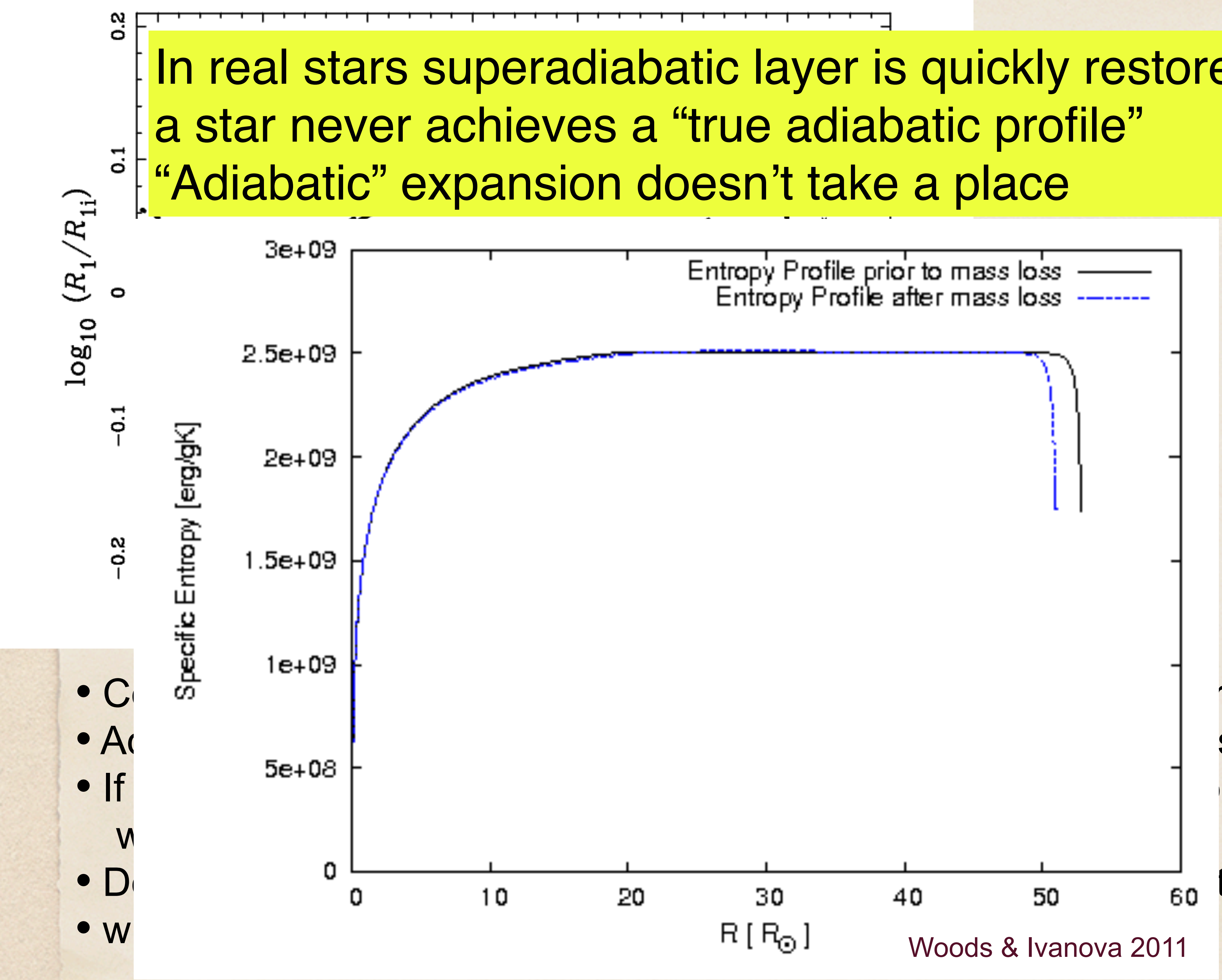
- Double WD formation: first MT has to be a CEE. Reconstruction of the observed DWDs is possible only with unrealistic values of common envelope α (Nelemans et al 2010).



- Why DWDs? Strongest constraints from stellar evolution on pre-MT conditions due core mass- red giant radius relation

The roots of adiabaticity assumption

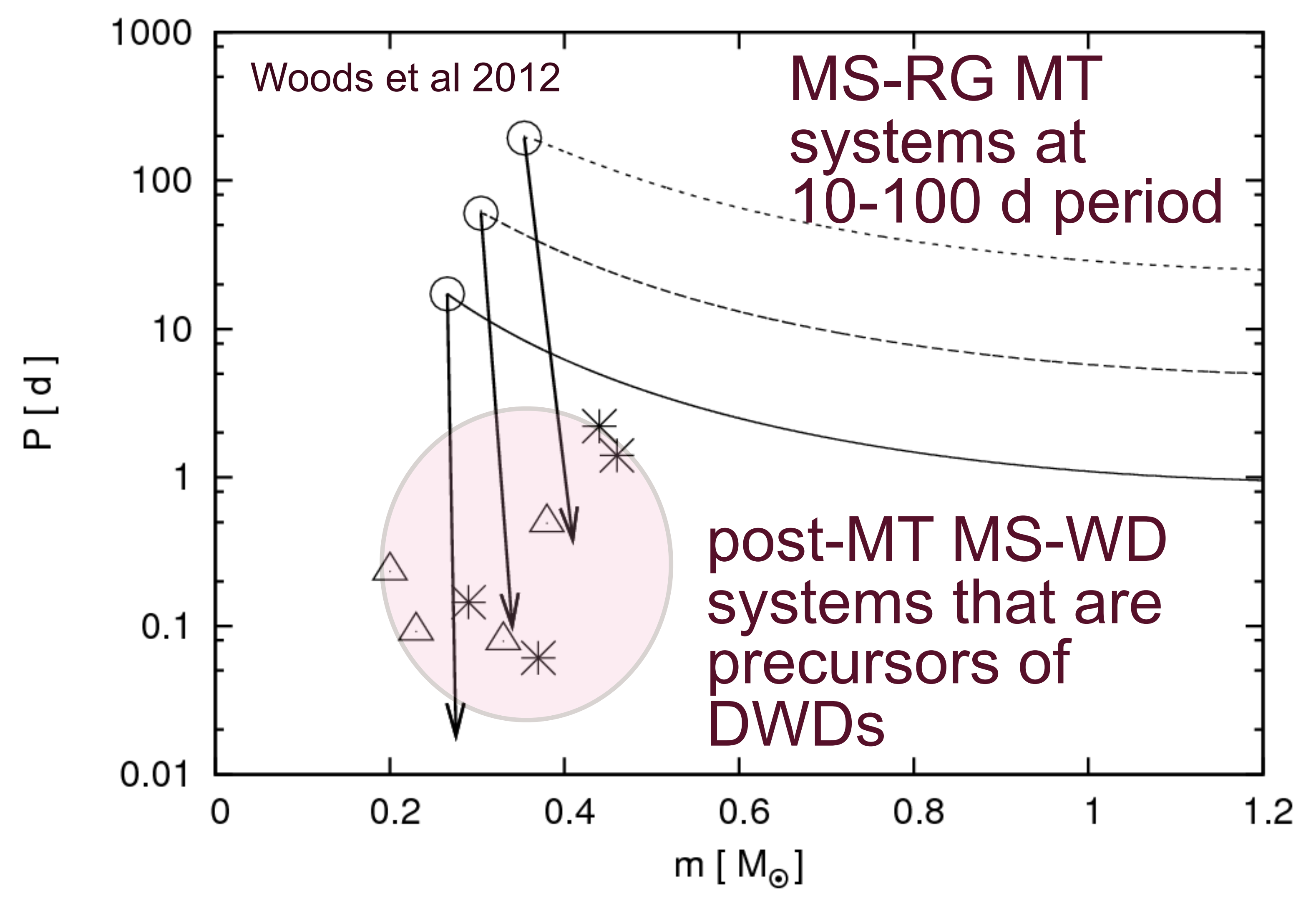
In real stars superadiabatic layer is quickly restored,
a star never achieves a “true adiabatic profile”
“Adiabatic” expansion doesn’t take a place



Woods & Ivanova 2011

- C ropy blanket
- A s removed
- If nor is left
  w
- D tropy profile
- w

Removal of the adiabaticity assumption



- DWD system evolve though stable 1st episode of MT
- Progenitors systems are RG-MS semidetached binaries with periods of few -150 days
- CEE energy budget is not in danger
- q_{crit} has increased from 0.78 to 1.1-1.3, depending on a donor mass

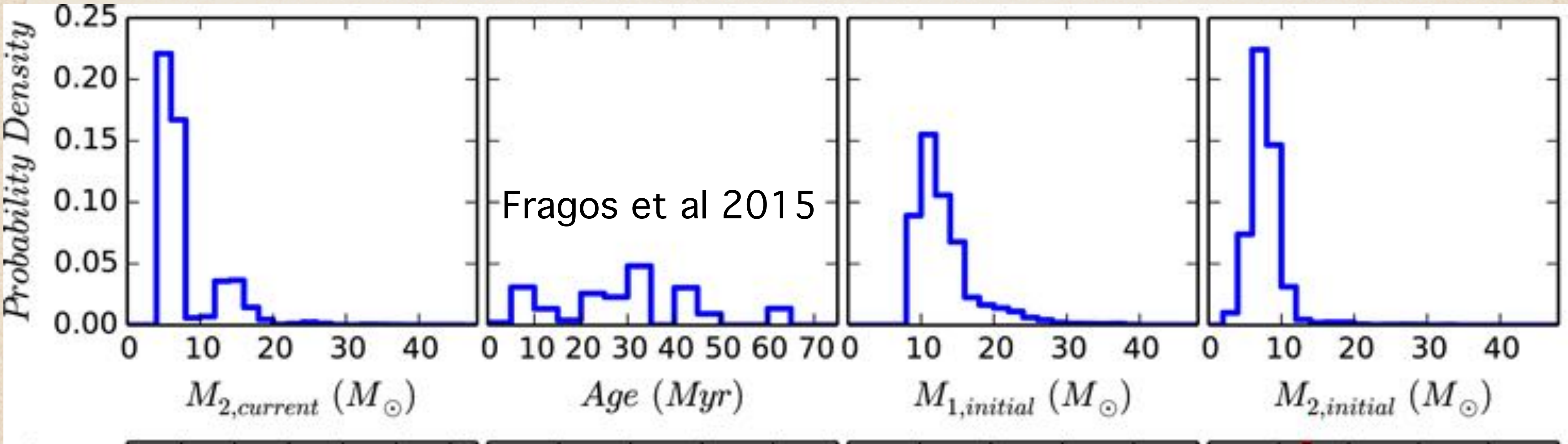
Case: q_{crit} for massive radiative donors

M82 X-2 ULX with a NS (Bachetti et al 2014)

From observations: high MT rate, low accretor mass : TTMT and large $q > q_{crit} = 3.5$ (more ULXs with NS have been discovered)

Note that that there is no parameterized analysis employed by BPSs that could produce ULXs with NS

This system can be explained with the donor that was initially 8-10 $M_\odot$ (Fragos et al 2015): effectively, initial $q_{crit} \Rrightarrow 7$. Non-conservative MT. Caution: lots of lost a.m. carries specific a.m. of the donor, not accretor.



Fragos et al 2015

really hard to make MT been dynamically unstable, presumably till L_2 /L_3 overflow

Stream is very wide

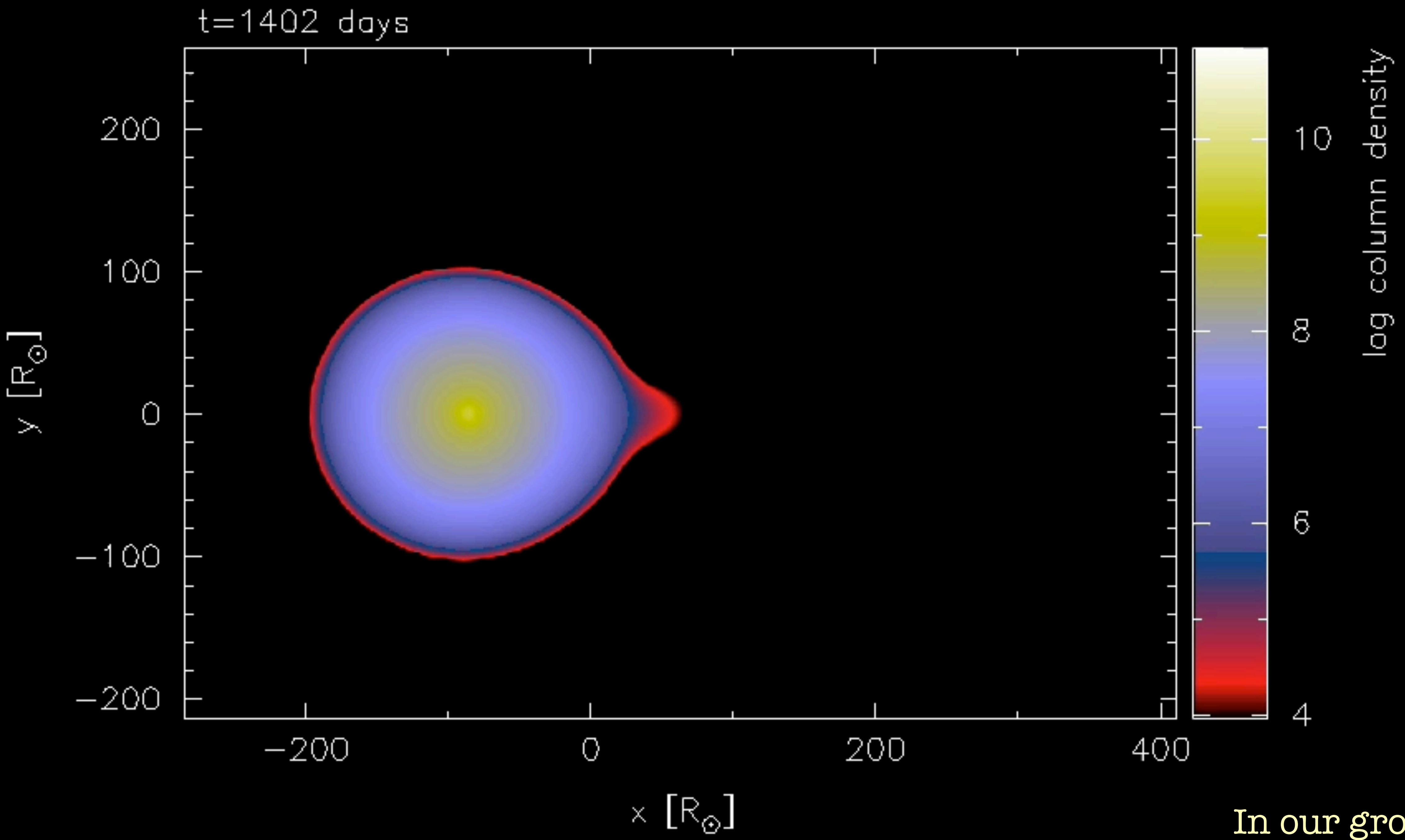
5 $M_\odot$ BH + 8$M_\odot$ RG

q=1.6

in 6 yr: 0.084$M_\odot$ ejected ,

0.025 $M_\odot$ went to circumbinary disk,

Effective ML about 0.02 $M_\odot$/yr



In our group

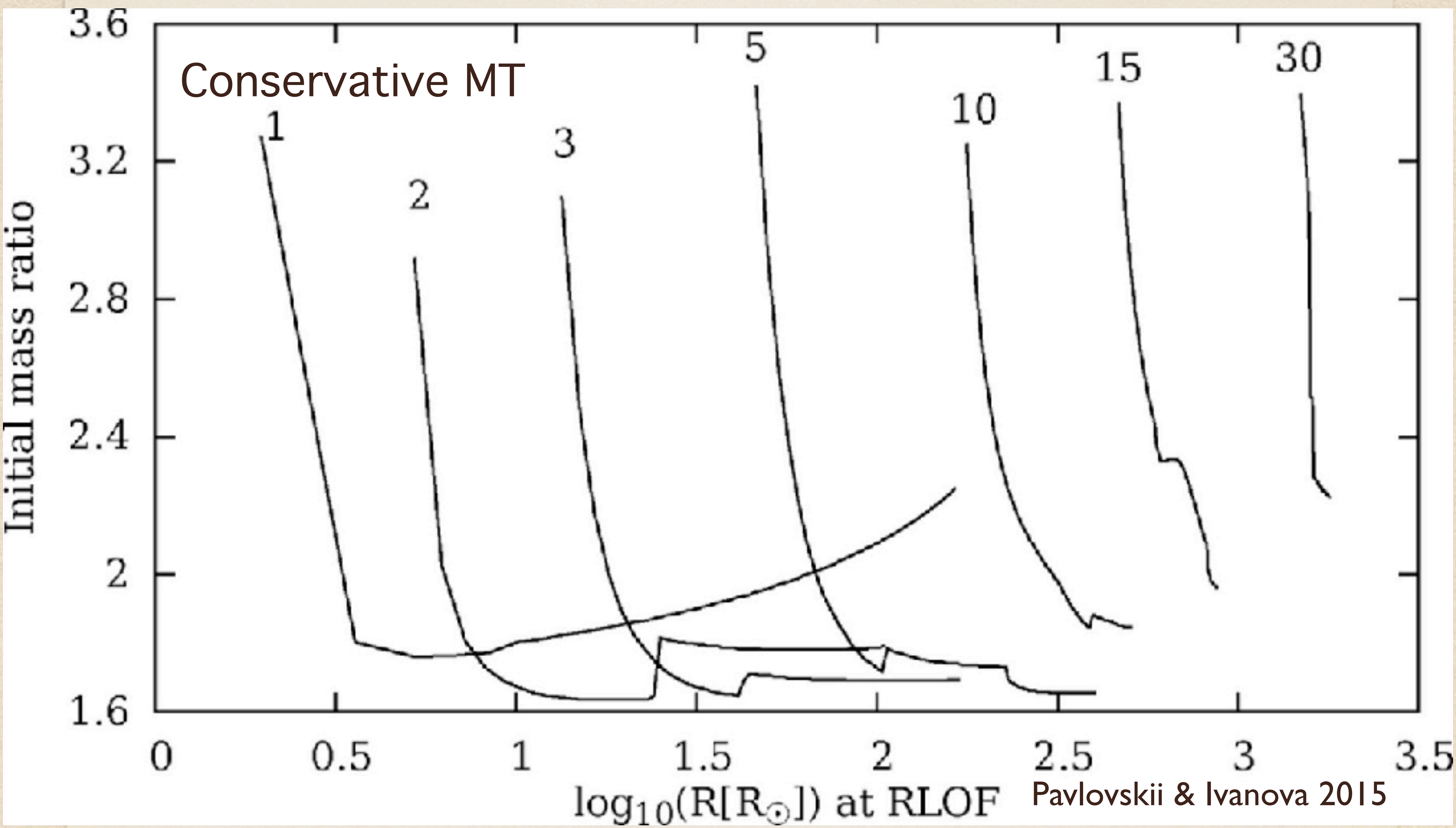
Case: $R_* = R_{RL}$

- The start of RLOF does not have to determine the stability
- The donor does not have to stay within RL
- Lots of mass can be removed via stable MT, even if later a dynamical instability may take place

MT revision for a "true" RLOF:

- Do not keep the donor within its RL: find MT rate depending on actual RLOF and on stream's conditions at L_1
- New condition for MT instability: only when L_2/L_3 equipotential is overfilled, and mass loss via outer Lagrangian point is started, a CEE starts.

New stability: “true” RLOF + MT limited by stream



Pavlovskii & Ivanova 2015

when convective envelope is shallow, critical mass ratio q_{crit} ~3.5 (as for DDI)
while convective envelope develops, q_{crit} is decreasing, saturating at ~1.6

Case: q_{crit} for very massive donors; application of “true” RLOF

(past) LIGO rates predictions for BH-BH binaries formation from BPSs:

Belczynski et al 2007, StarTrack BPS code:
Used standard assumption that massive donors with convective envelope will have unstable MT
Formation rate exceeded vastly those shown recently by LIGO

Pavlovskii et al 2017:
Massive donors are very undense in their outer envelopes
stable conservative MT could take place for a large range of radii and for as large q as 8

Consequence:

- affects the formation of BH-BH, decreasing the formation rates making it more consistent with the the empirical rate obtained by LIGO, 9-240 Gpc^{-3} yr^{-1}
- Produces bright ULXs, in numbers high enough to explain the number of observed bright ultraluminous X-ray sources to have stellar mass BHs accretions

Stable MT: how well do we know it?

$$\frac{\dot{R}_\mathrm{d}}{R_\mathrm{d}} = \left(\frac{\dot{R}_\mathrm{d}}{R_\mathrm{d}}\right)_\mathrm{ev} + \zeta_\mathrm{d,ml}\frac{\dot{M}_\mathrm{d}}{M_\mathrm{d}} \qquad (\zeta_\mathrm{d,ml} = \zeta_\mathrm{eq}\text{for TTMT})$$

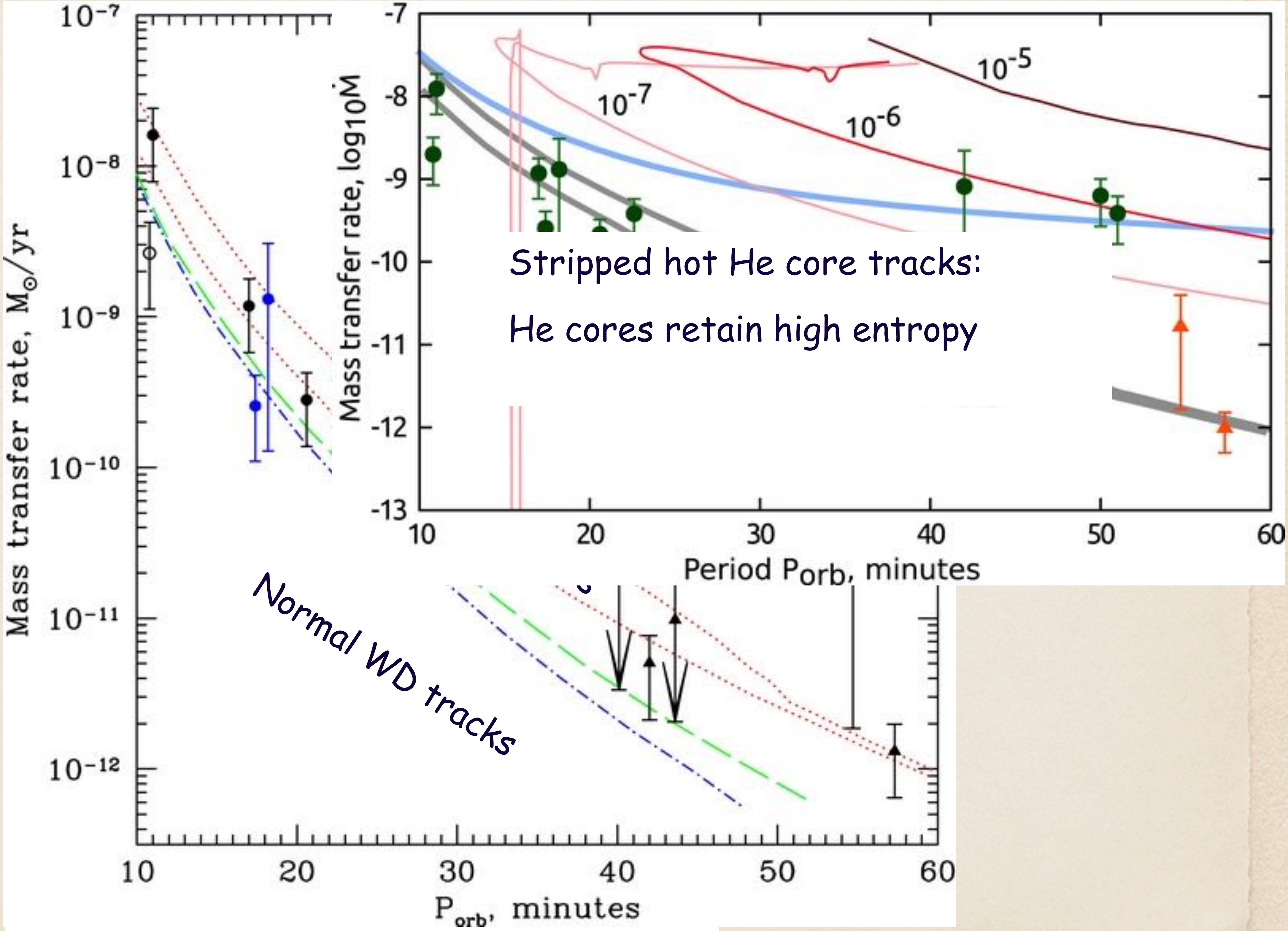
$$\frac{\dot{R}_\mathrm{RL}}{R_\mathrm{RL}} = \left(\frac{\dot{R}_\mathrm{d}}{R_\mathrm{d}}\right)_\mathrm{AML} + \zeta_\mathrm{RL}\frac{\dot{M}_\mathrm{d}}{M_\mathrm{d}}$$

$$-\frac{\dot{M}_\mathrm{d}}{M_\mathrm{d}} = \frac{1}{\zeta_\mathrm{d,ML} - \zeta_\mathrm{RL}}\left[\left(\frac{\dot{R}_\mathrm{d}}{R_\mathrm{d}}\right)_\mathrm{ev} - 2\frac{\dot{J}}{J}\right]$$

For detailed binary codes, uncertainty in a long term stable MT rate comes from uncertainties in AML

In BPS, it also comes from donor’s response on mass loss

Stable MT: NS-LMXBs with degenerate donors, $\zeta_{ad} = \zeta_{eq} = -1/3$



Stripped hot He core tracks:

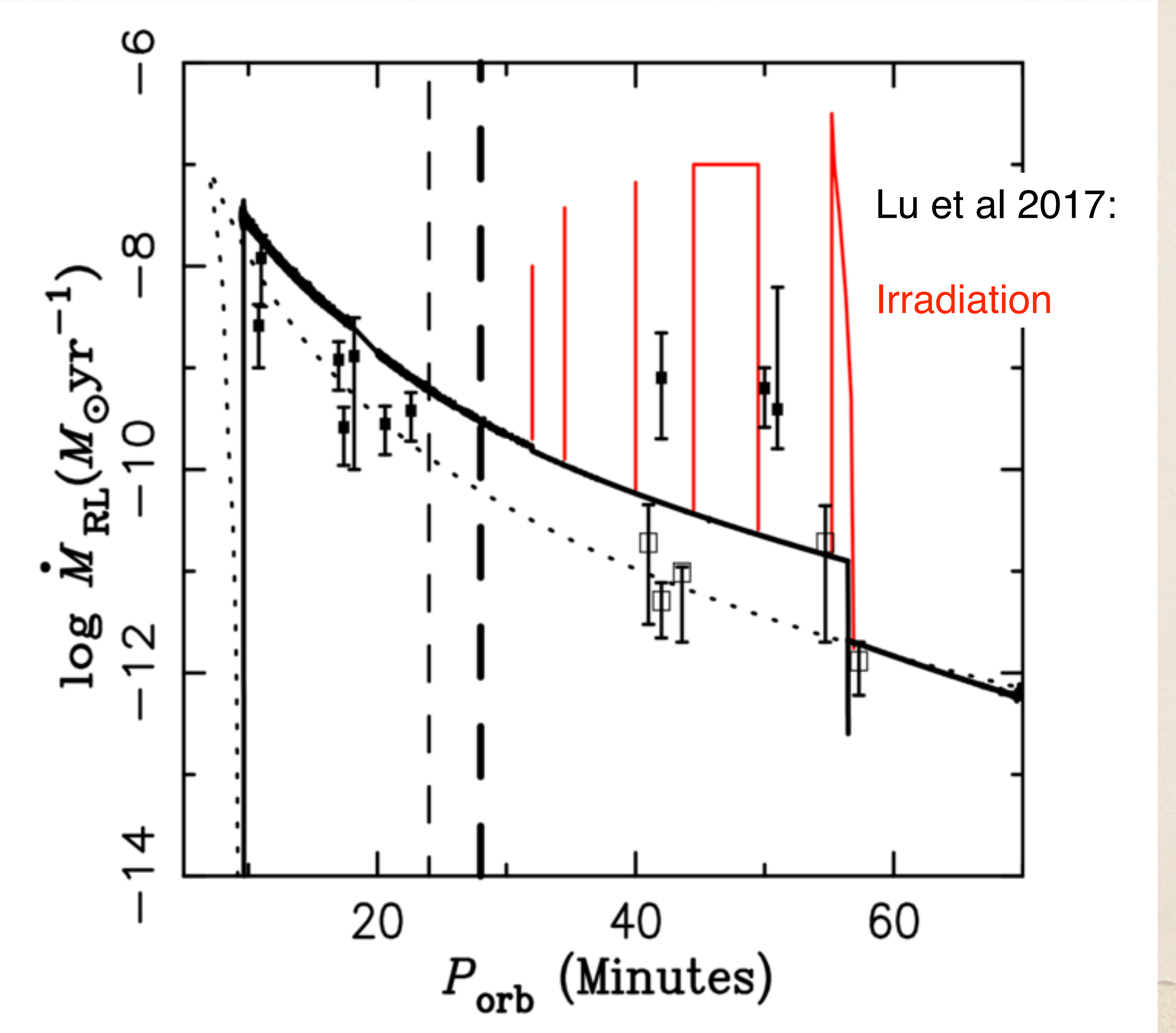
He cores retain high entropy

Normal WD tracks

AM loss via GW is well understood

Heinke et al 2012

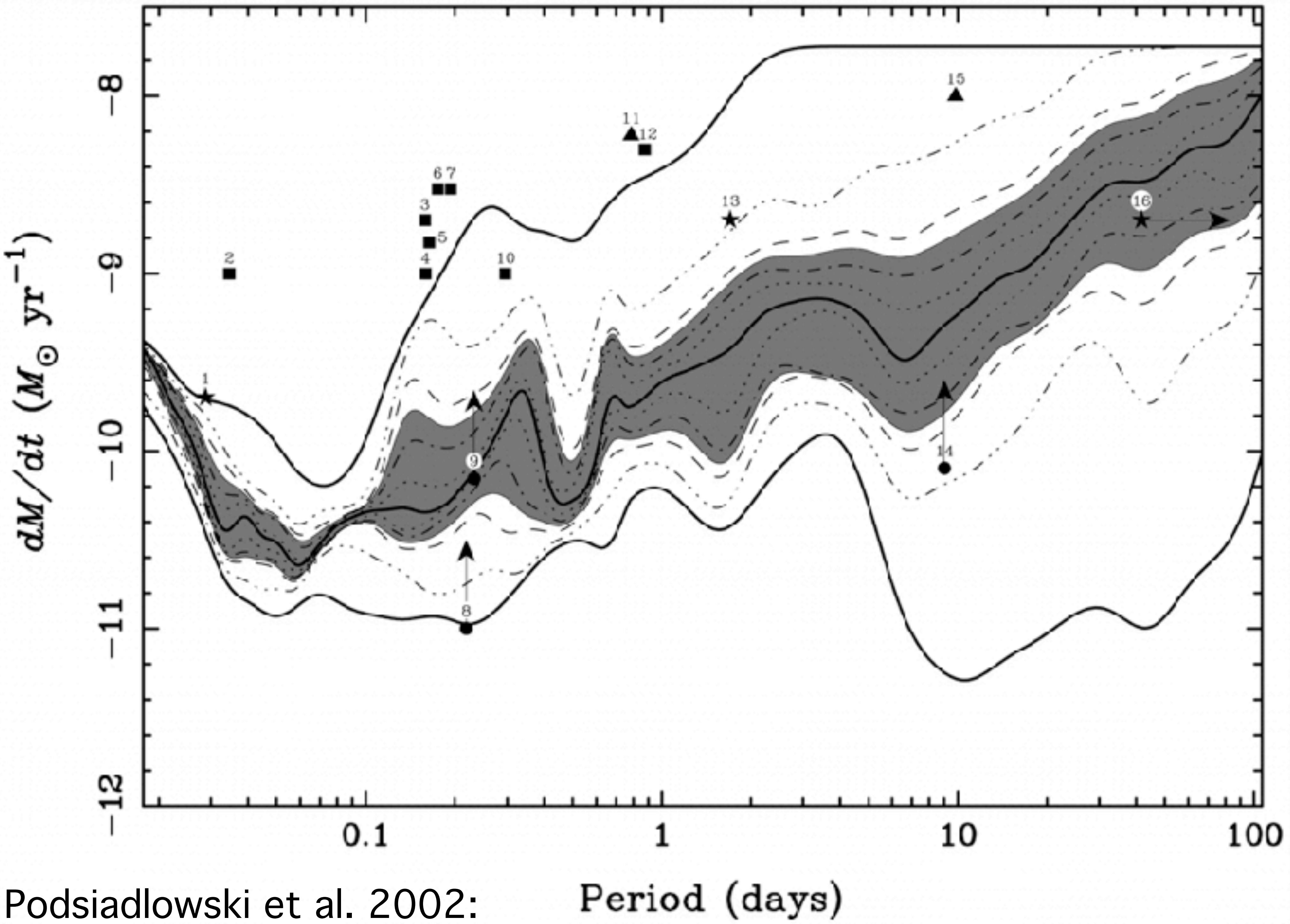
Stable MT: NS-LMXBs with degenerate donors, $\zeta_{ad} = \zeta_{eq} = -1/3$



Lu et al 2017:

Irradiation

Stable MT: NS-LMXBs with non-degenerate donors



Podsiadlowski et al. 2002:

Middle line: medium mass accretion rate, other lines: 20%, 40%, 60%, 80%, and 98%

triangles: Z sources; squares: atoll sources; stars: X-ray pulsars; circles: systems with accretion disk coronae

Standard MB assumptions

Standard MB:

Empirical Skumanich law is derived using Sun-type stars - slow rotating MS stars with a weak wind mass loss, and not too strong MB field

Skumanich functional dependence (Mestel 1968, Mestel & Spruit 1987)

$$\dot{J}_{\rm MB} \propto \Omega B_S^2 R^4$$

It is derived in assumption

- stellar wind isotropic and isothermal
- magnetic field is radial

And additional assumption that surface MF is boosted by rotation, $B_s/B_{s,\odot}=\Omega/\Omega_\odot$ brings it to commonly used prescription (Rappaport et al. 1983)

$$\dot{J}_{\rm MB} \propto \Omega^3 R^\gamma, \ \ \gamma = 4 \text{ for Skumanich}$$

Variations of standard MB: its all about the donor

- Too fast rotating stars may stop to form new spots, MF is saturated (Andronov et al 2003)

- MF of rapidly rotating stars form “dead zone” where stellar wind is trapped - MB is saturated (Mestel & Spruit 1987, Ivanova & Taam 2003)

- Ap/Bp stars - different ML rate, MF strength & shape (Justham et al 2006)

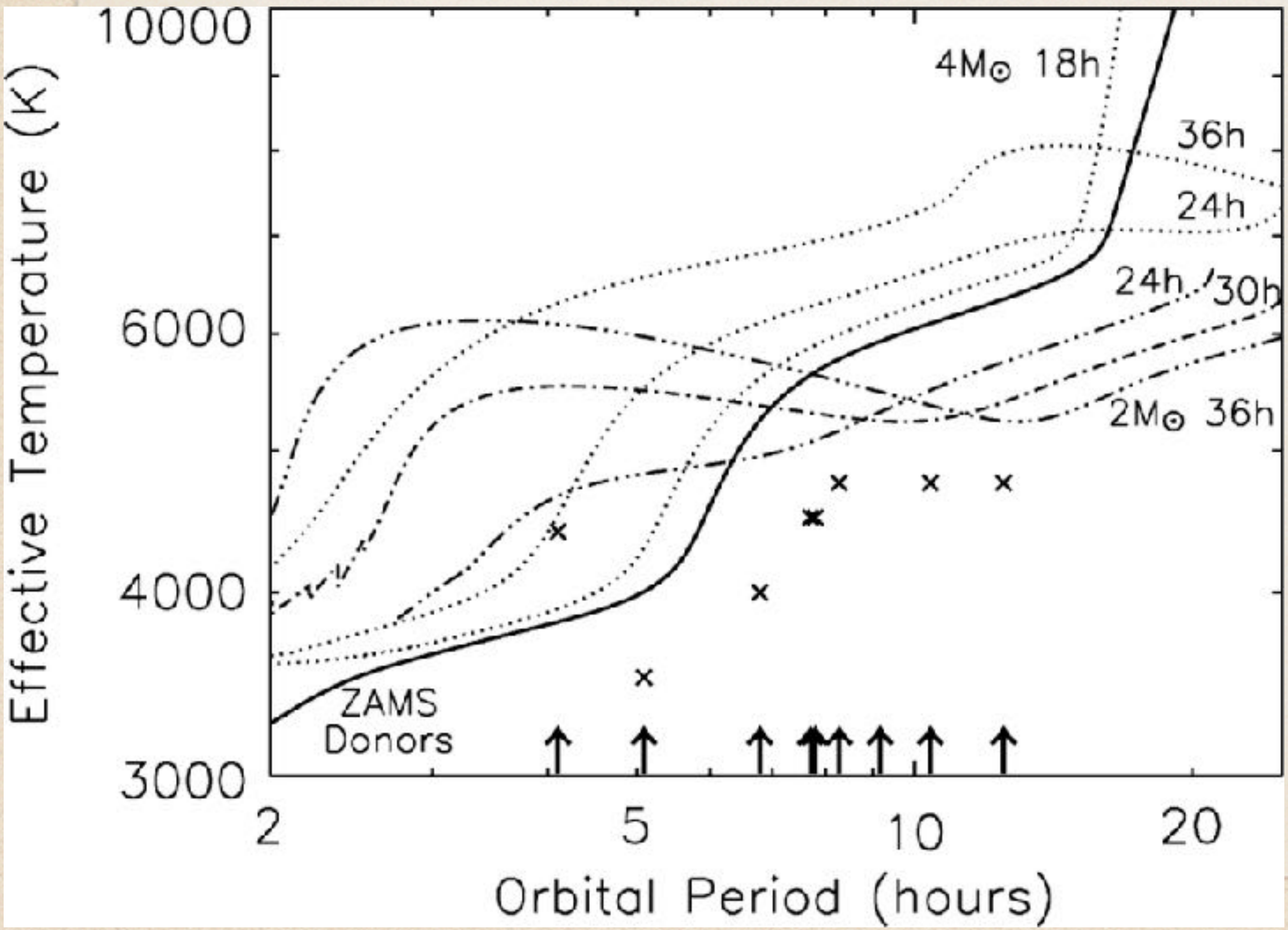
- Pre-MS stars have stronger MF and larger winds ML rate(Ivanova 2006)

- In cold stars/giants, stellar wind is not isothermal - taking this into account brings wind mass loss rate in MB law, and ML rate is drastically higher than in the Sun (Pavlovskii & Ivanova 2016)

- Strength of MF scales with dynamo number and hence has to take into account also convective turnover time, $B_s/B_{s,\odot}=(\tau/\tau_\odot)\ (\Omega/\Omega_\odot)$

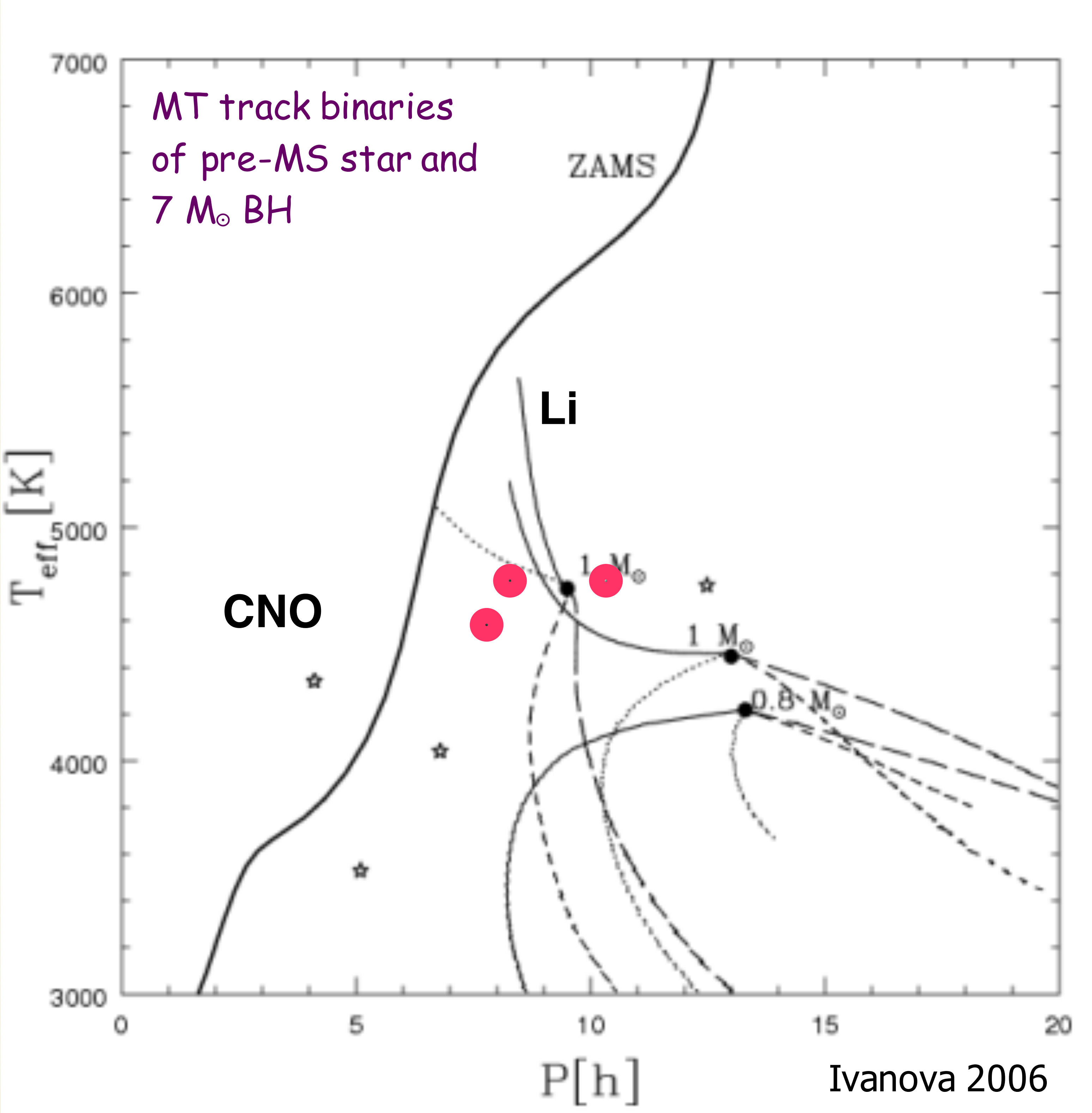
Variations of standard MB & BH LMXBs: intermediate mass donors

Reason: hard to form with low-mass companions (CEE) — the need for higher mass donors, but with higher mass companions standard MB is not working.
Model: assumes Ap/Bp stars, strong irradiation driven winds, dipole MF independent on Ω (Justham et al 2006).



Drawbacks: MF has to be present in the entire envelope; donors too hot at present

Variations of standard MB & BH LMXBs: pre-MS donors



MT track binaries of pre-MS star and 7 $M_\odot$ BH

Ivanova 2006

Observations:
B on the Sun : 2 G
B in T Tauri -> 5 kG

TW Hyd: 2.5 kG, age 2×10^7yr

With a MF that is characteristic of pre-MS stars, MT goes on thermal time-scale

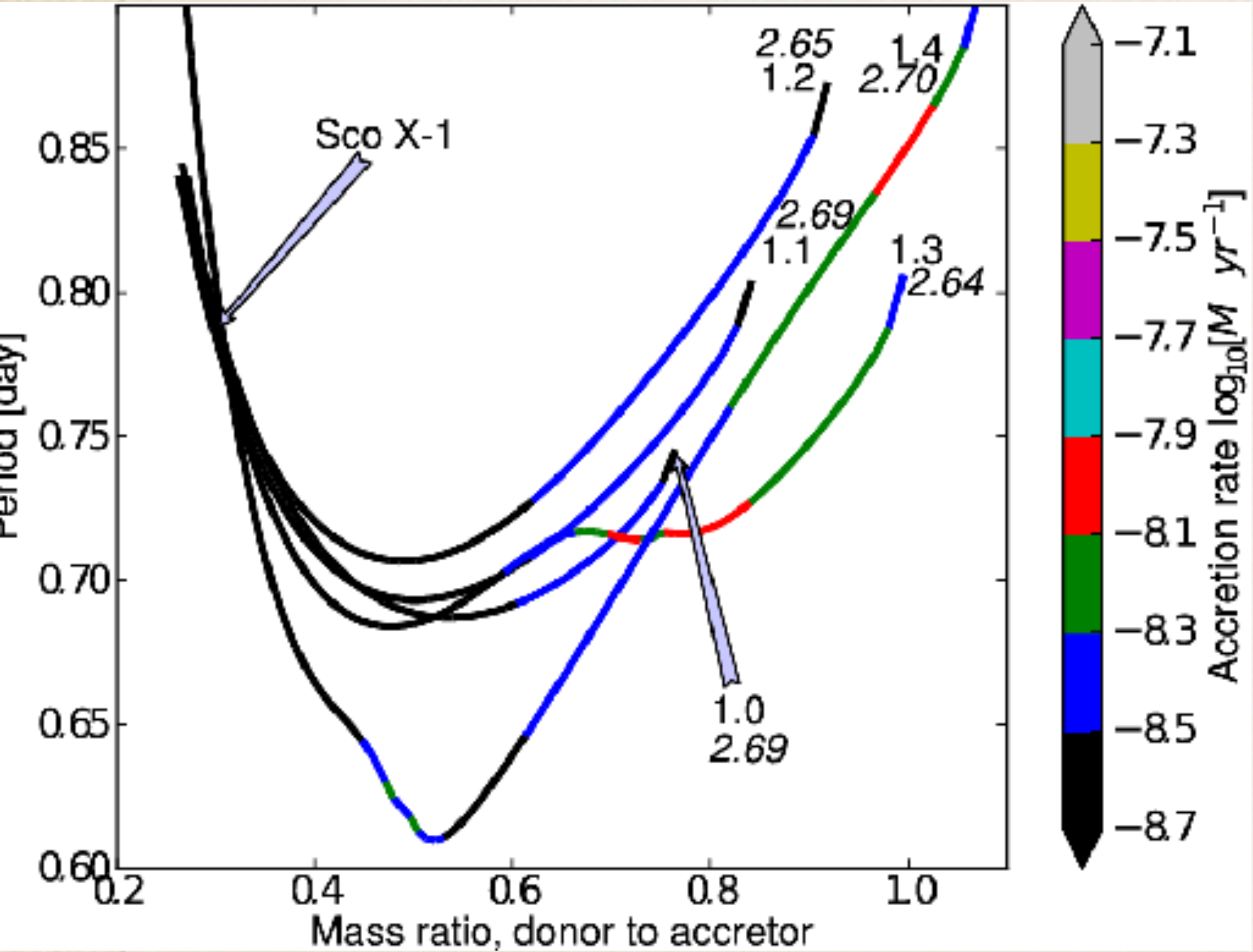
Shown tracks are for different initial MF strength.

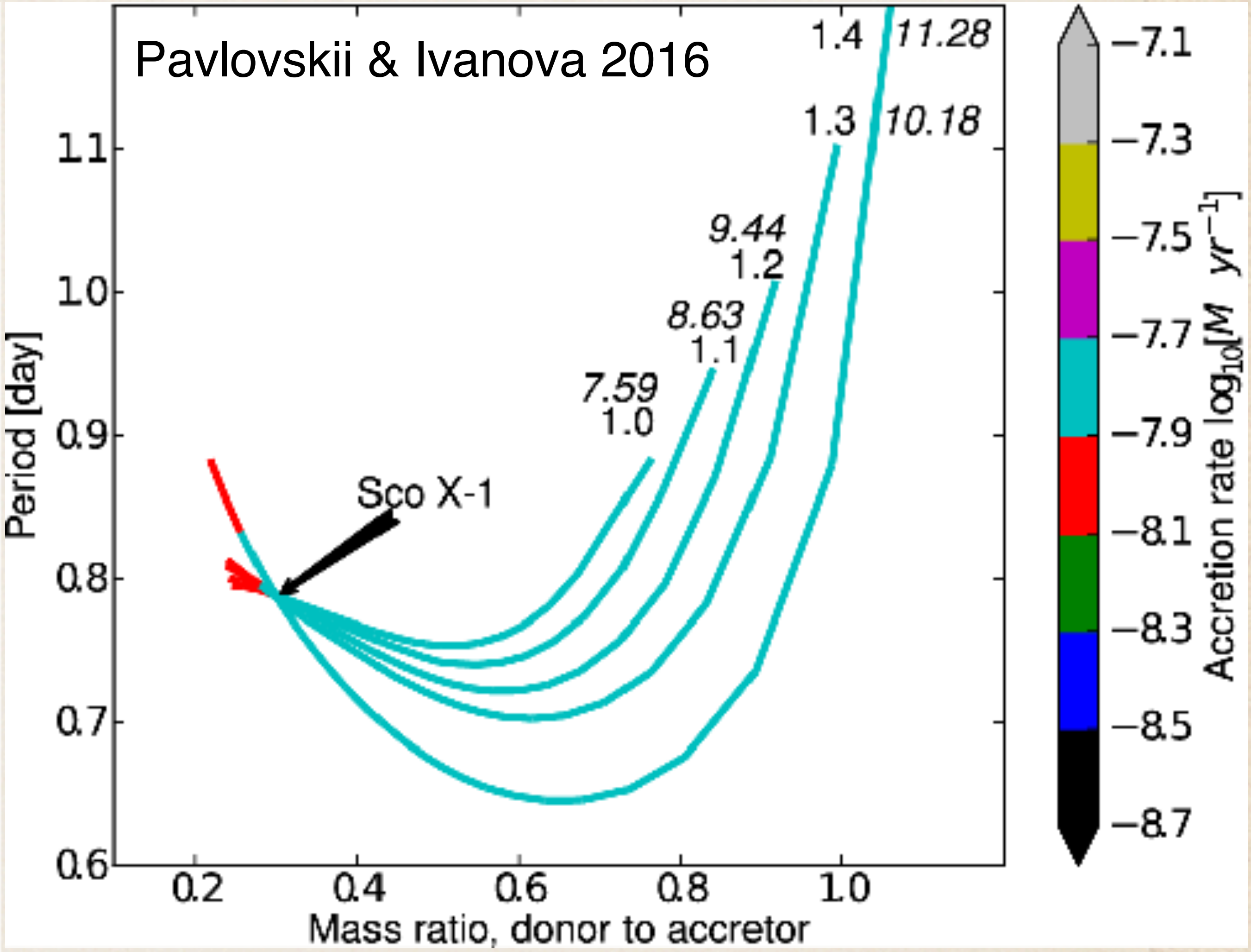
Drawback: have to survive a CEE

Variations of standard MB & NS LMXBs: any donor

<u>Sco X-1</u>: mass ratio 0.3-0.46, P=0.787d, spectral class later than K4,
minimum MT rate ~3.5 10^{-8} Msun/yr

Problem: Skumanich MB law can provide <0.1 of the observed MT rate

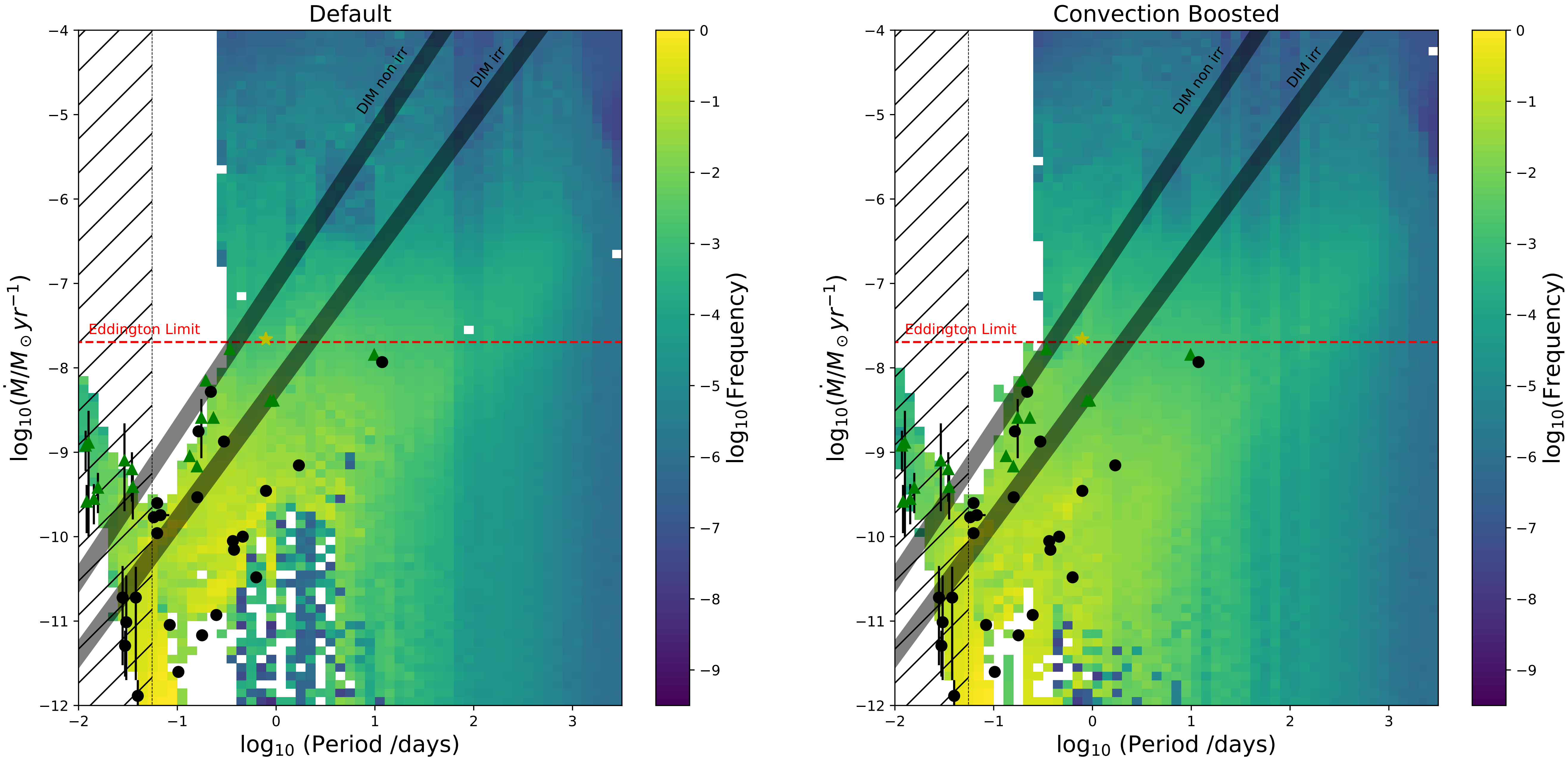



Pavlovskii & Ivanova 2016

<u>MB:</u> non-thermal winds plus the inclusion of ML dependence (wind boosting)

Chen 2017: formation of Sco X-1 from an Ap/Bp donor using MB as in Justham et al 2006

Testing MB laws



Van, Ivanova & Heinke in prep

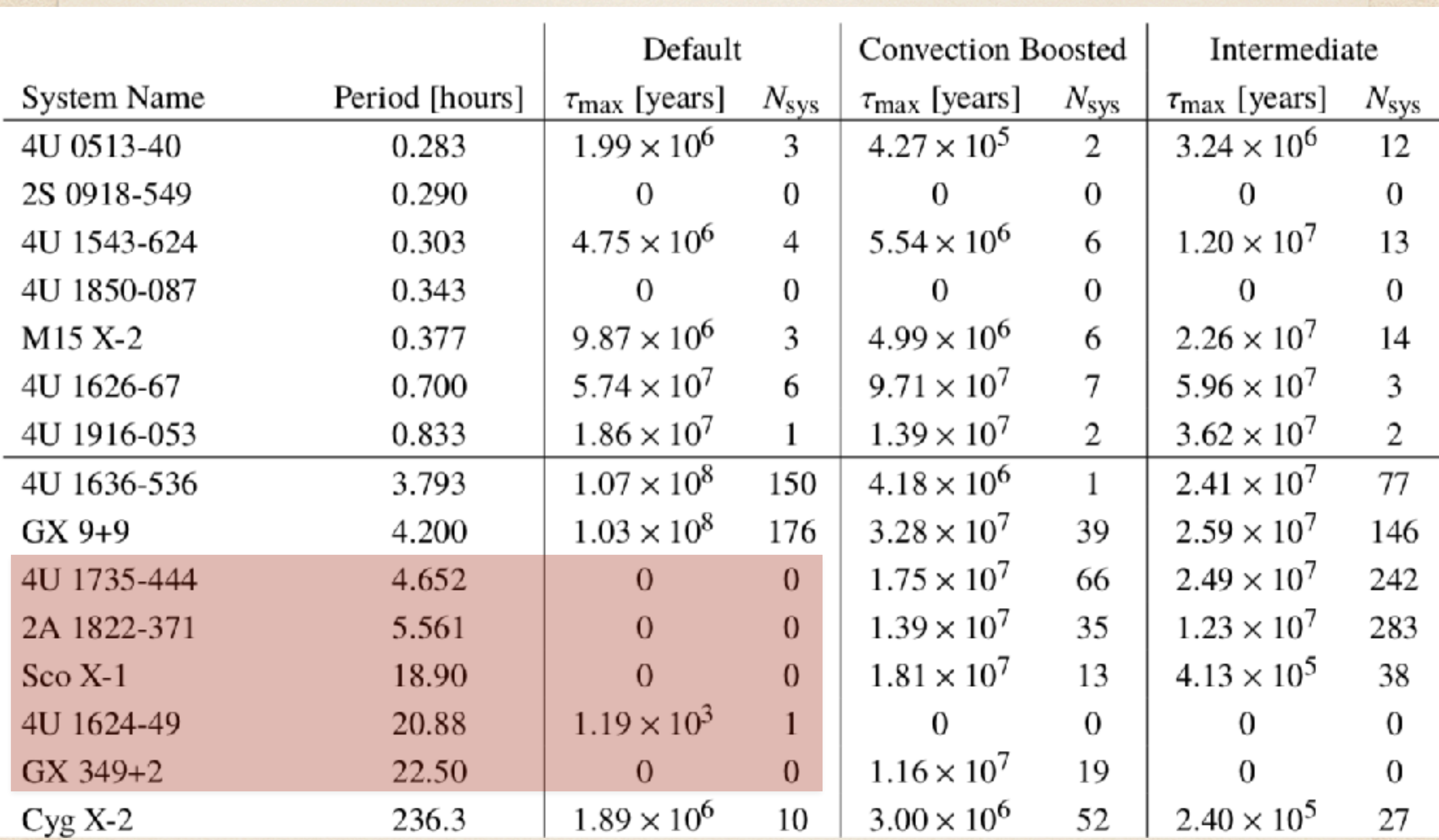
circles are known transient NS LMXBs with P and MT rates

triangles are known persistent NS LMXBs with P and MT rates

The star is the binary Sco X-1

Kenny Van

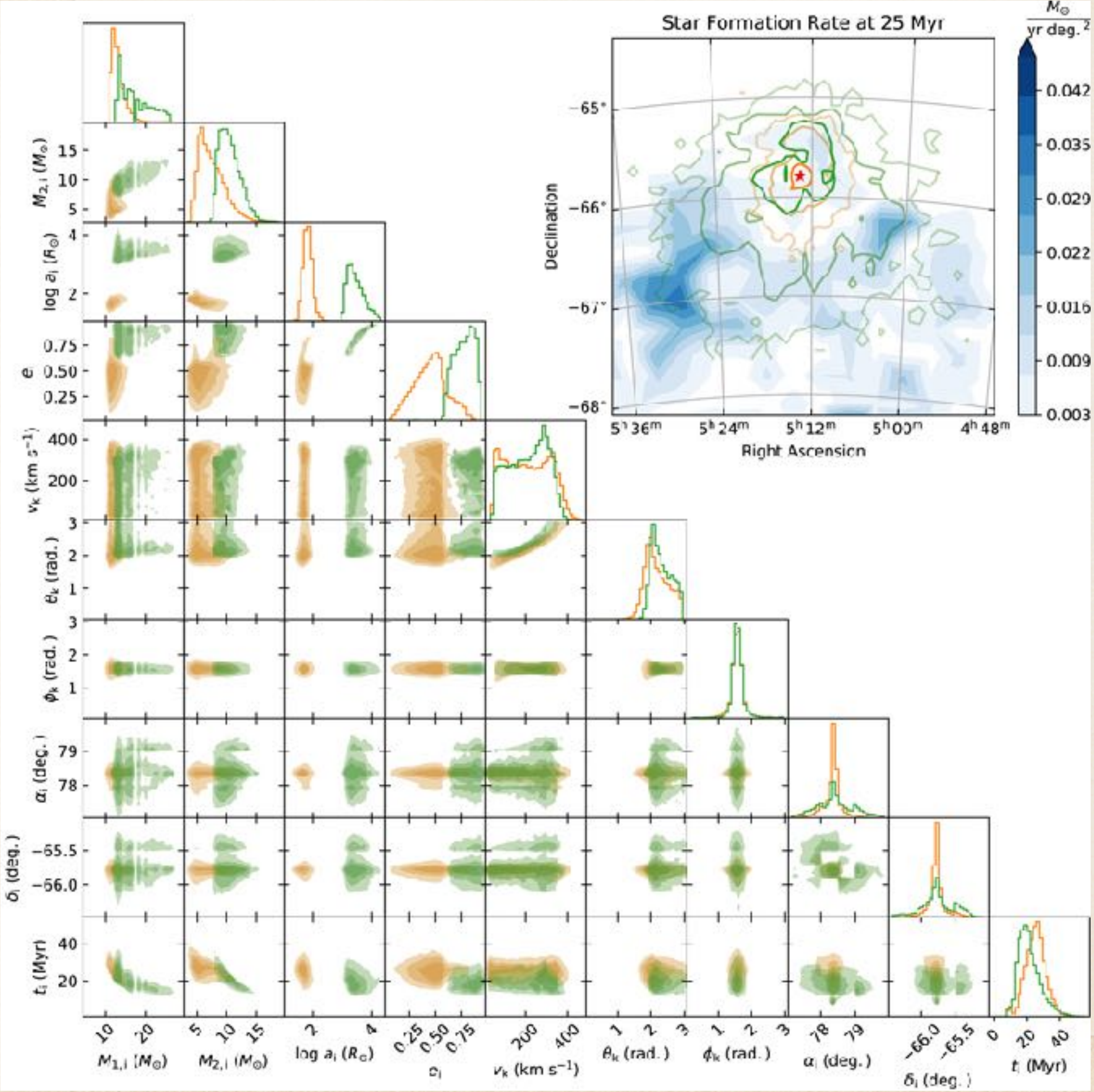
Adding q to P and MT rate



		Default		Convection Boosted		Intermediate	
System Name	Period [hours]	$\tau_{\max}$ [years]	$N_{\rm sys}$	$\tau_{\max}$ [years]	$N_{\rm sys}$	$\tau_{\max}$ [years]	$N_{\rm sys}$
4U 0513-40	0.283	1.99×10^6	3	4.27×10^5	2	3.24×10^6	12
2S 0918-549	0.290	0	0	0	0	0	0
4U 1543-624	0.303	4.75×10^6	4	5.54×10^6	6	1.20×10^7	13
4U 1850-087	0.343	0	0	0	0	0	0
M15 X-2	0.377	9.87×10^6	3	4.99×10^6	6	2.26×10^7	14
4U 1626-67	0.700	5.74×10^7	6	9.71×10^7	7	5.96×10^7	3
4U 1916-053	0.833	1.86×10^7	1	1.39×10^7	2	3.62×10^7	2
4U 1636-536	3.793	1.07×10^8	150	4.18×10^6	1	2.41×10^7	77
GX 9+9	4.200	1.03×10^8	176	3.28×10^7	39	2.59×10^7	146
4U 1735-444	4.652	0	0	1.75×10^7	66	2.49×10^7	242
2A 1822-371	5.561	0	0	1.39×10^7	35	1.23×10^7	283
Sco X-1	18.90	0	0	1.81×10^7	13	4.13×10^5	38
4U 1624-49	20.88	1.19×10^3	1	0	0	0	0
GX 349+2	22.50	0	0	1.16×10^7	19	0	0
Cyg X-2	236.3	1.89×10^6	10	3.00×10^6	52	2.40×10^5	27

Van, Ivanova & Heinke in prep

Modern approaches for BPS: case of HMXBs



Andrews et al 2018:

new: use Markov Chain Monte Carlo to determine progenitors for the population in general, and some specific systems

Underlying code: rapid BPS with simplified RLOF MT

Points to take

Instability:

- Over the last few years, the stability of the MT has been significantly revised for all kinds fo donors (high mass, low mass, radiative, convective,…), with more initial binary systems expected to evolve through stable MT, producing such objects as ULXs, DWDs and more. Recovering of this stability can be expected from most 1D stellar codes; rapid BPS codes status to account for this is unclear. Treating of a ”true” RLOF is rarely implemented in detailed codes.

Stable life:

- Standard Skumanich MB law should not be expected to be used to reproduce mass transferring LMXBs
  - Loss of a.n. with disk outflows?…

Populations:

New statistical approaches are coming into play, to recover progenitors systems and to test MT governing laws. However, given by all uncertainties listed, take the results of populations' studies with a great grain of salt.

Wishes:

observations: please, more, more Lx, P, Pdots, Teff, radii, masses, non-conservation/outflows in understandable for theorists statements
theory/simulations: a.m. loss modes, especially in the presence of M.F.