Formation of Low-Mass X-ray Binaries in globular clusters

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MODEST14, Bad Honnef, June 5 2014

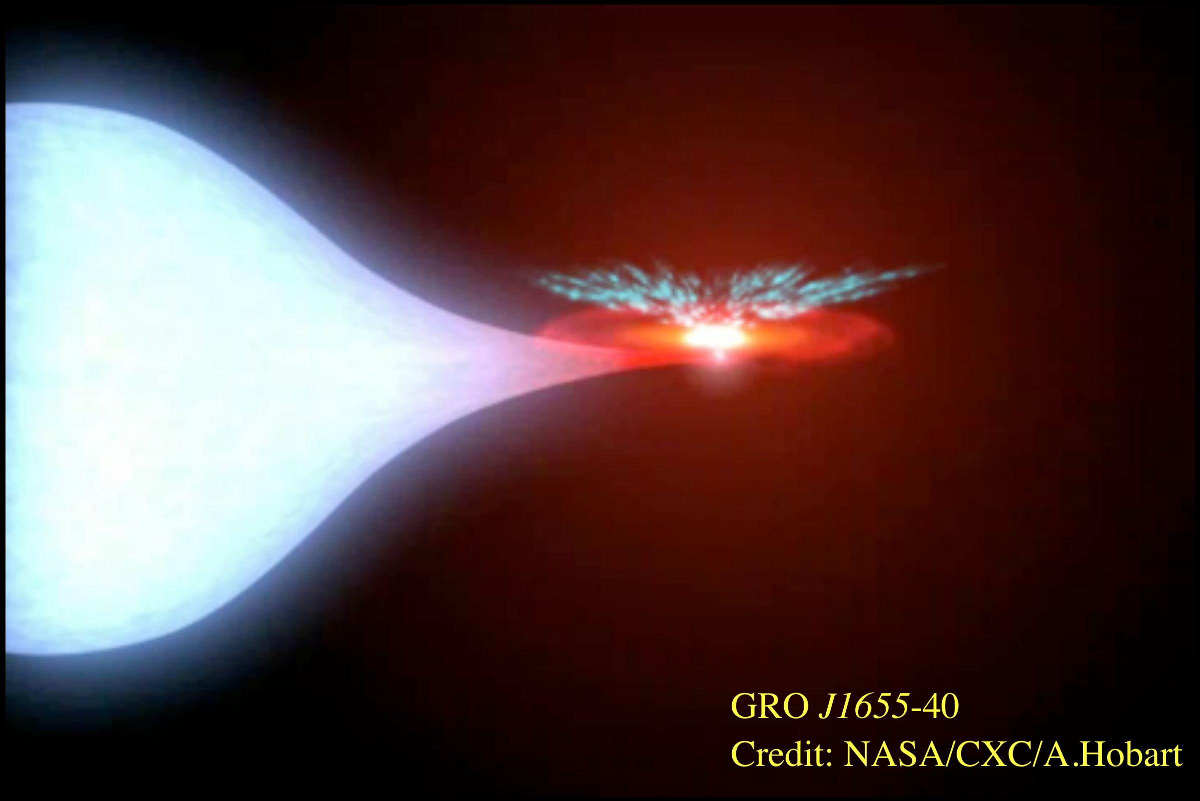
Low-mass X-ray binaries in GCs

Compact accretors - NS or BH

RLOF Donors -
MS, RG, WD/degenerate
low-mass donor

Binary Periods:
10 minutes to ~100 days

Lx: can appear as a persistent or as a transient source.



GRO *J1655*-40
Credit: NASA/CXC/A.Hobart

- Formation rates: exceeds that in the field by about 100 times per stellar mass
- Metallicity: **bright** LMXBs 3 times more likely reside in a metal-rich cluster
- bMSPs: most of known MSPs are located in GCs and 2/3 of them are in binaries. What so UCXBs make?
- Black holes?

field LMXBs: standard scenario

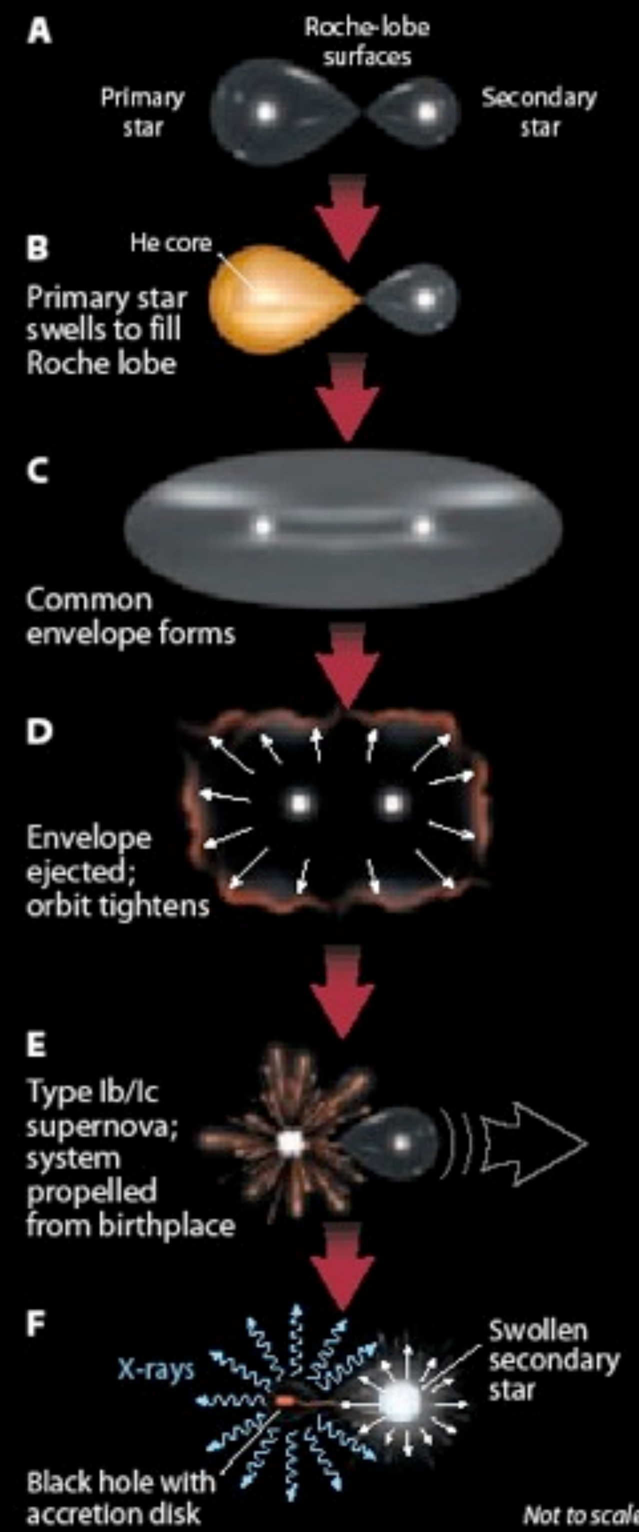
Bhattacharya & van der Heuvel (1991)

common envelope (CE) phase, during which the low-mass star spirals inward through the extended envelope of the massive primary star, and the phase is terminated upon ejection of the common envelope - the ejection uses the orbital energy as an energy source and the final binary is much more compact

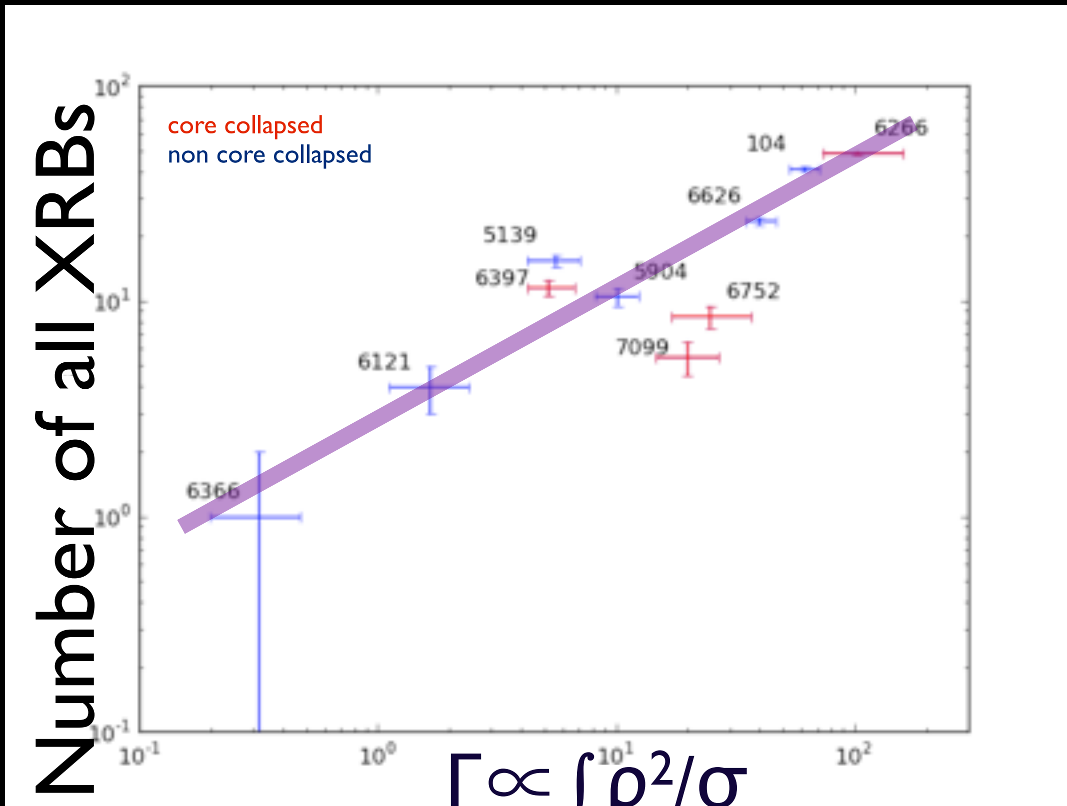
Further orbit shrinkage due to tides, magnetic braking and gravitational waves in, likely, an eccentric binary and may be a second episode of CE event

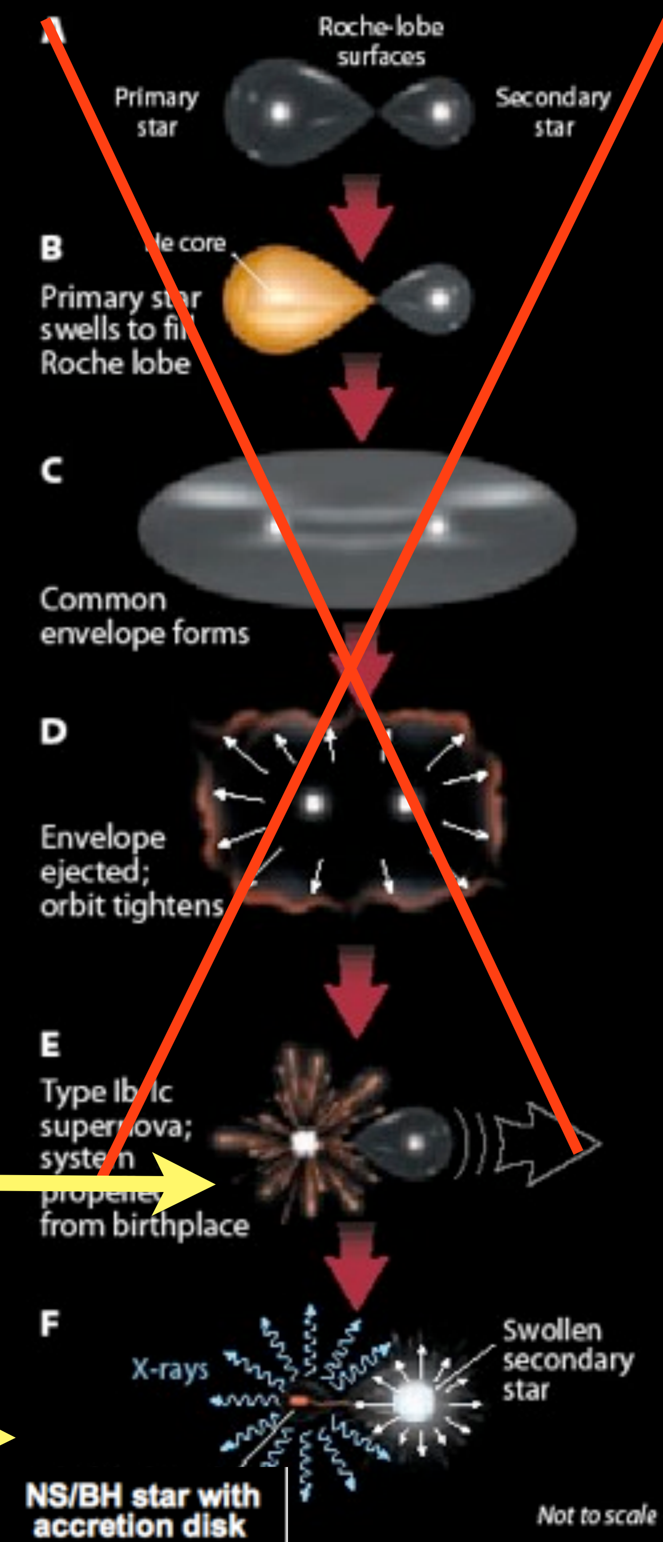
magnetic braking (MB) is the process of the angular momentum loss for late type stars by magnetically coupled wind. The efficiency of the braking is proportional to the mass loss rate with stellar wind and magnetic field strength.

Binary shrinks and mass transfer occurs again. Stable mass transfer reveals the system as an X-ray source.



LMXBs in GCs: cheating





kick is the problem: keep them in!

shortcut:

dynamical binary formation
(BE, TC, PC, triples)

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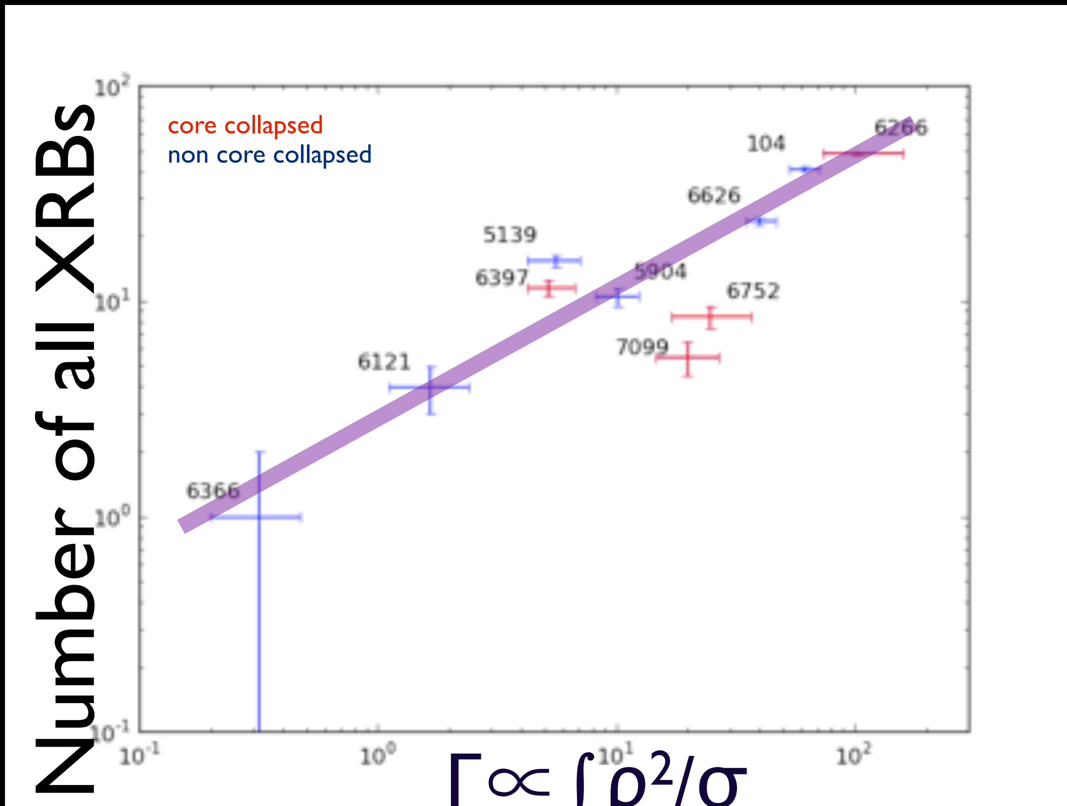

Bahramian et al 2012
(update of Pooley et al 2003 plot)

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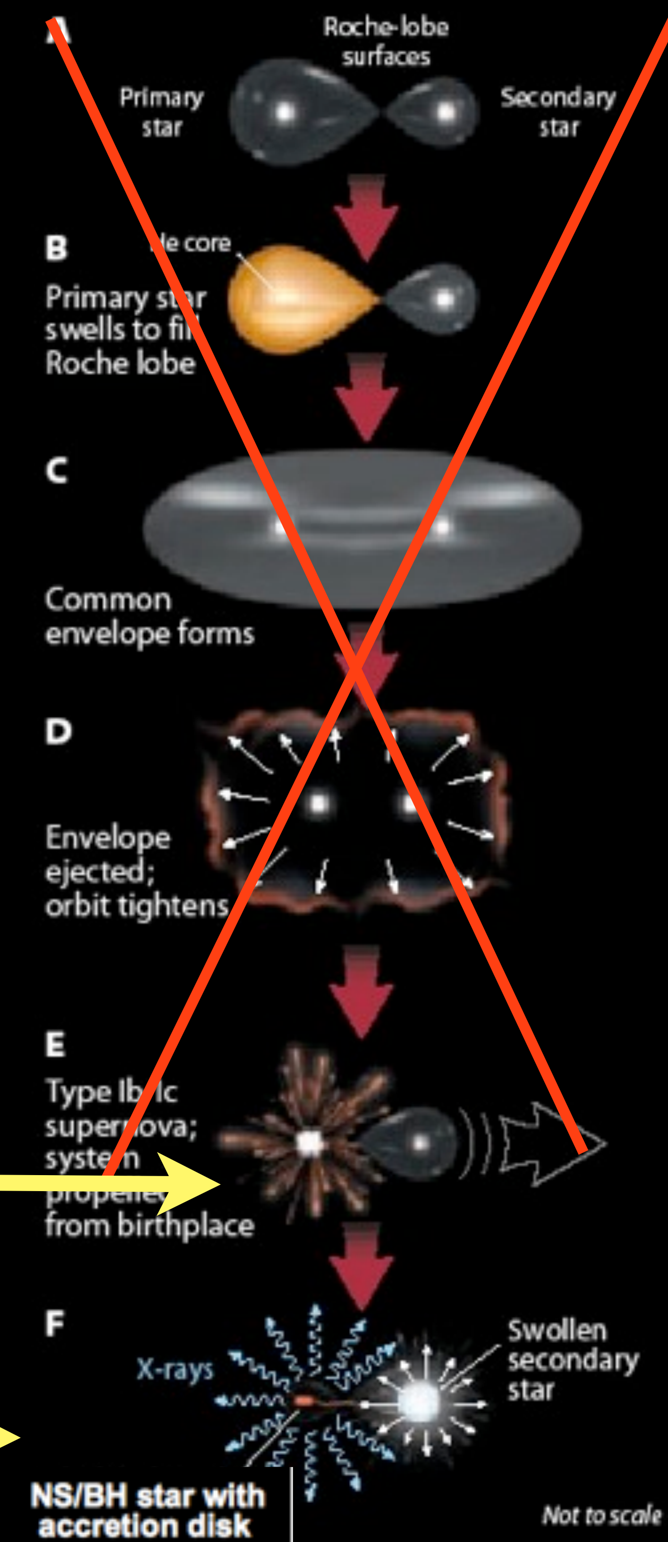

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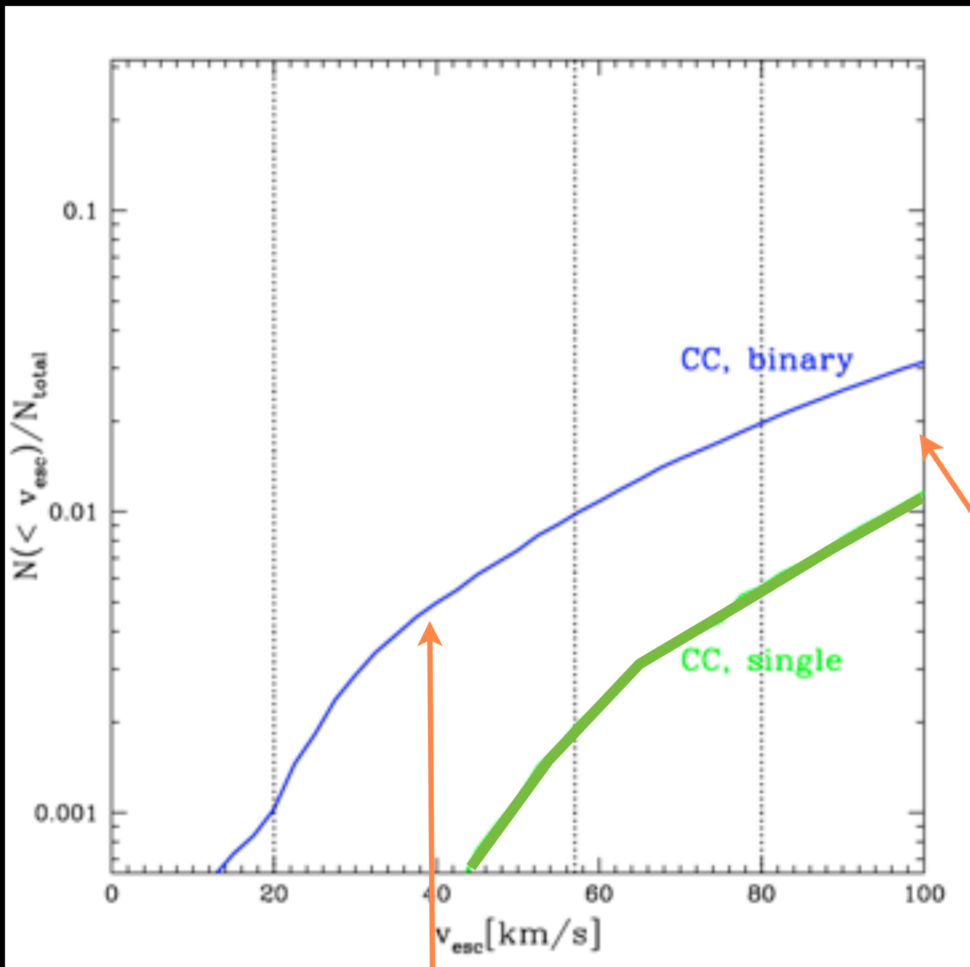
NSs production & retention



Core-collapse SNe:

Single stars mass range ~8-21 M⊙(Z=0.02) and ~7-19 M⊙ (Z=0.001)

Natal kick distribution (Hobbs et al 2005) : mean 3d pulsar birth velocity ~ **400 km/s**

more massive intially?

a typical cluster of 2x10^5 M⊙ : makes ~3000 CC NSs

with v_{esc} ~40km/s: 1 NS will be retained /all single & 15 / all in binaries

NSs production & retention

Electron-capture SNe: **degenerate** ONeMg core reaches 1.38 $M_\odot$

(Miyaji et al. 1980, Nomoto 1984, 1987, Timmes & Woosley 1992,...)

- **Usual stellar evolution**:

  a He core is massive enough to form an ONeMg core, but is less massive than is required to form a non-degenerate ONeMg core:

  - single stars: 7.7-8.3 $M_\odot$ (Z=0.02) and 6.2-6.8 $M_\odot$ (Z=0.0005),
  - in binary stars it can be from 3 to 20 $M_\odot$

- **Accretion induced collapse of a WD**
- **Merger induced collapse.**

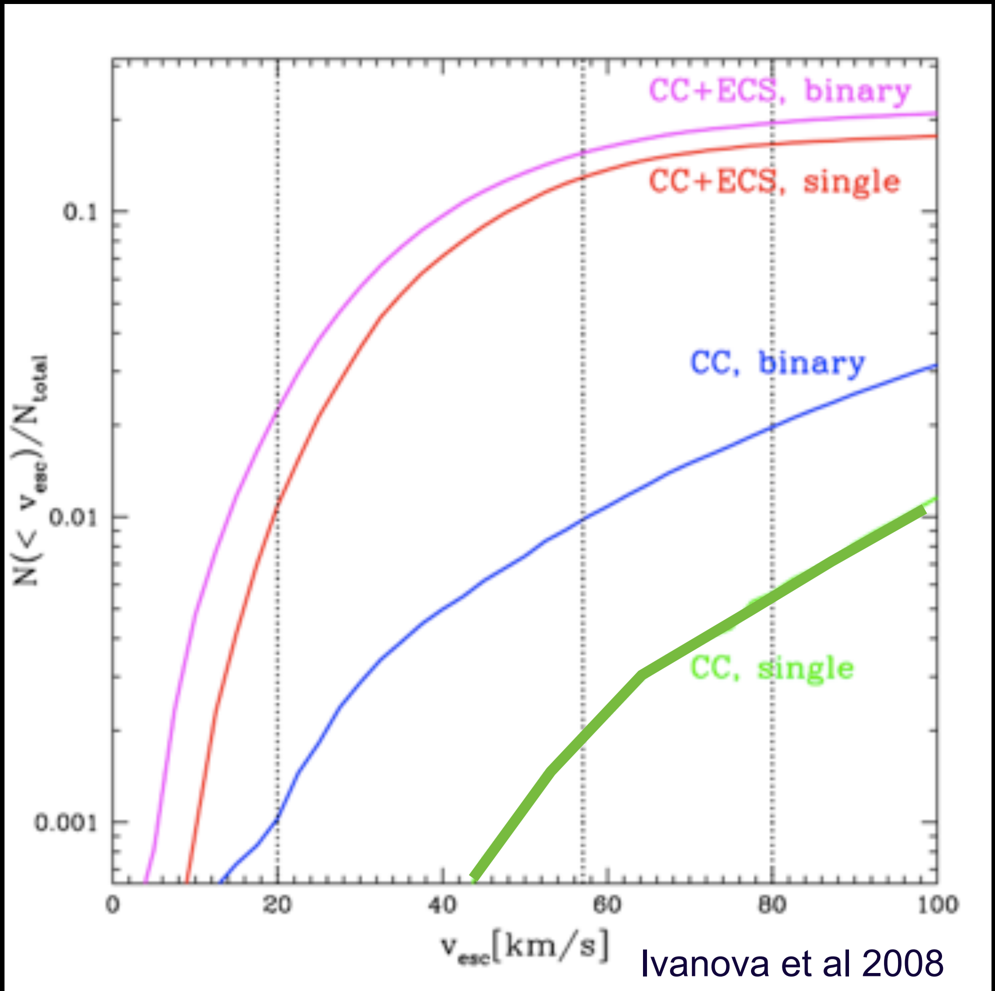
  Might also lead to a formation of a supra-Chandrasekhar WD and accordingly to a heavy and very fast spinning NS (magnetars).

In normal stellar population, only 10-15% of NSs will be formed via ECS

most famous probable example - Crab Supernova (Kitaru et al. 2006)

Kicks do not exceed 100 km/s (Buras et.al. 2005)

NSs production & retention



Most of retained NSs in a GC are from different ECS channels.

Ratio of Core-Collapsed to ECS ~ 1 to 30-200 vs ~10 to 1 in the field.

The typical epoch when ECS NSs are formed is 5×10^7-1.5×10^9 yr vs 2-3×10^7 yr for CC NSs.

Low-mass dominated NSs mass function? (as post-EC NS mass is ~1.22-1.27 M⊙)

with 40 km/s for ECS/AIC:

- a typical cluster of 2×10^5 M⊙ mass can contain as many as 200-300 NSs (even if all stars were single!),
- 47 Tuc type cluster (10^6 M⊙) ~ 1000 NSs.

BHs production & retention

Stellar evolution:

- each 150-200M⊙ “aged” stellar mass produced a BH in the past, ~ half of these BHs have masses above 10M⊙
- retention fraction after SN kicks 30-40% for v_{ecs}=50 km/s (Belczynski et al. 2006)

Dynamics:

- Spitzer instability and quick evaporation...? not working
- Detailed numerical calculations of BH sub-cluster: in massive clusters, up to ~20% of the BHs may remain; and these clusters do not reach equipartition (o'Leary et al. 2006)
- Monte Carlo of a whole GC: up to 25% of initial BHs remained & participated in interaction with other stars (Downing et al. 2009), up to a half and no BHs sub-cluster at all!! (Morscher et al. 2012).

⇒ at least 10-20% of initially formed BHs can remain in a GC

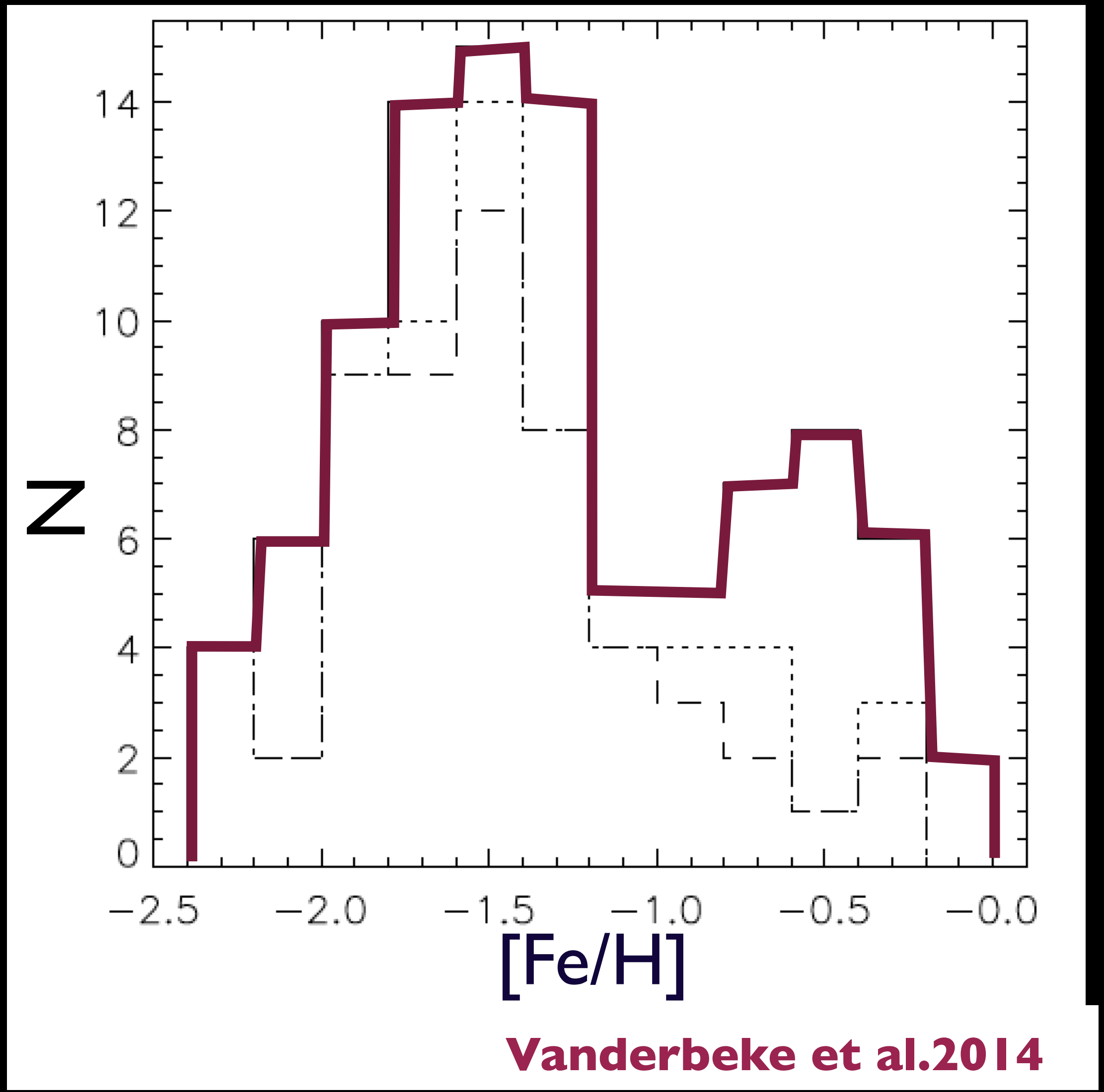
several dozens of BHs per a “typical” GC

1000 BHs per average massive GCs of $6x10^5$M⊙

Milky Way LMXBs: metallicity & bright LMXBs

- persistent
- transient

Bright:
$L_x > 10^{36}$ erg s^{-1}



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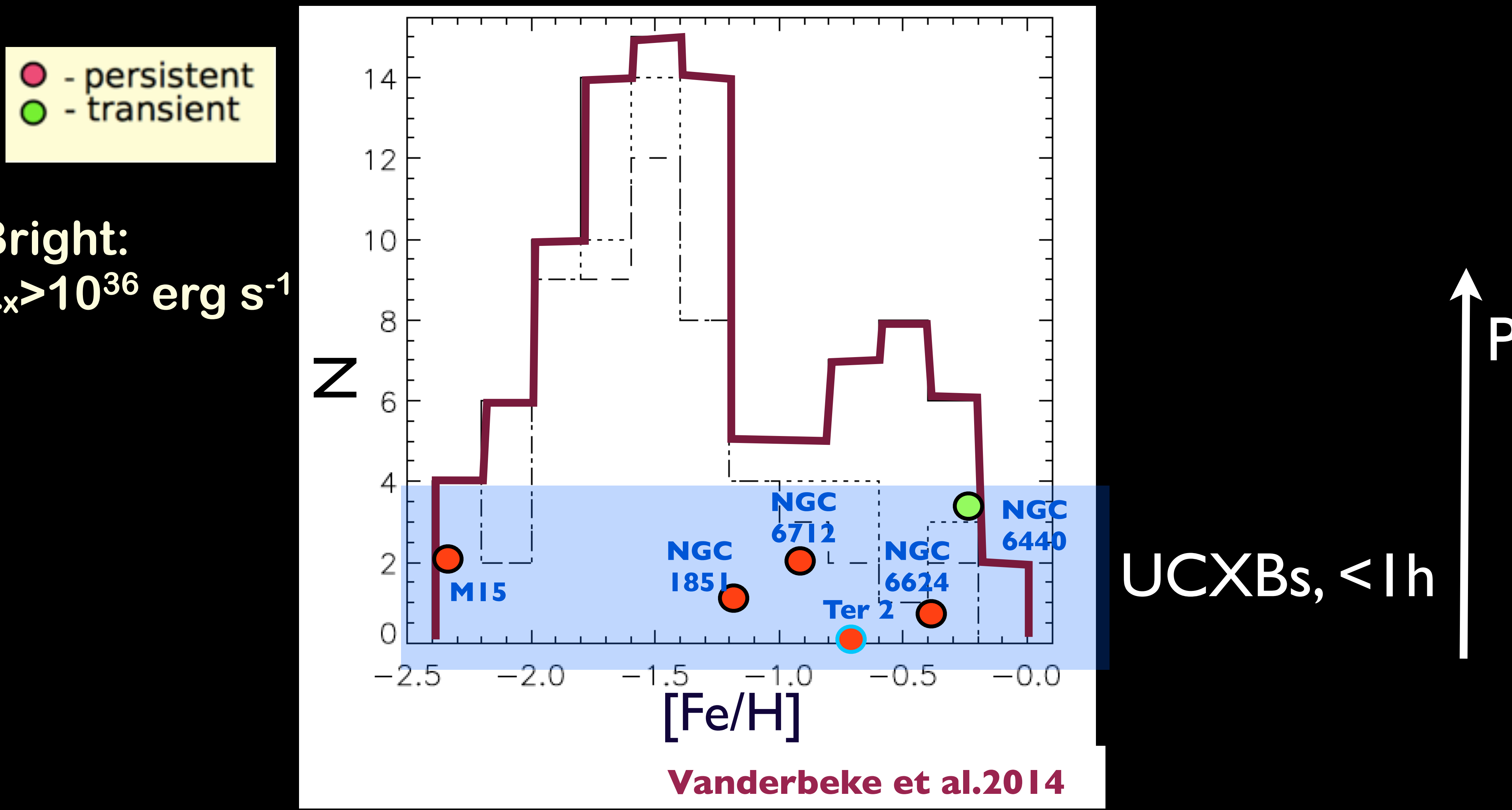

a GC with intermediate metallicity sometime is called as metal-rich…

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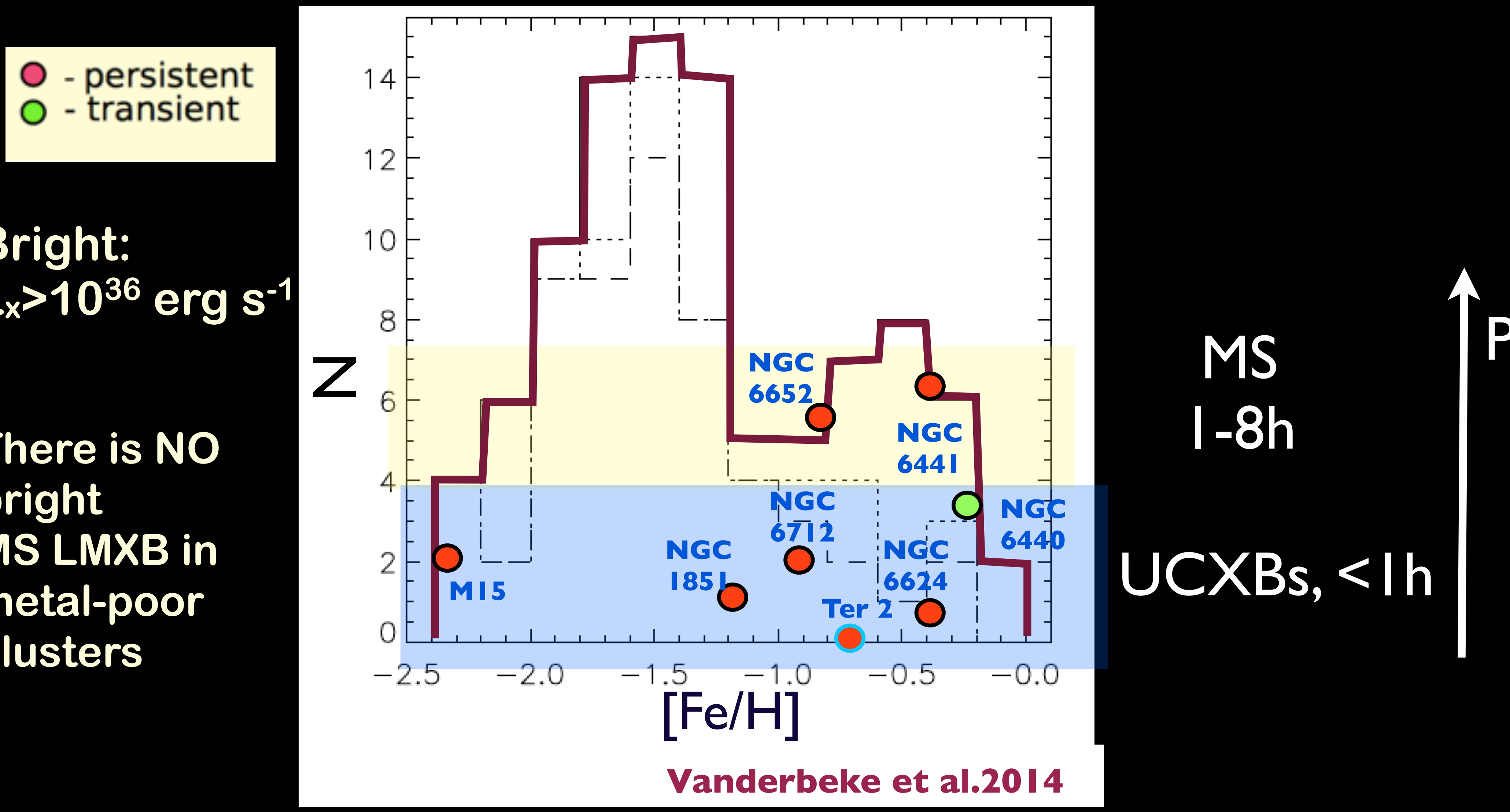

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There is NO bright MS LMXB in metal-poor clusters

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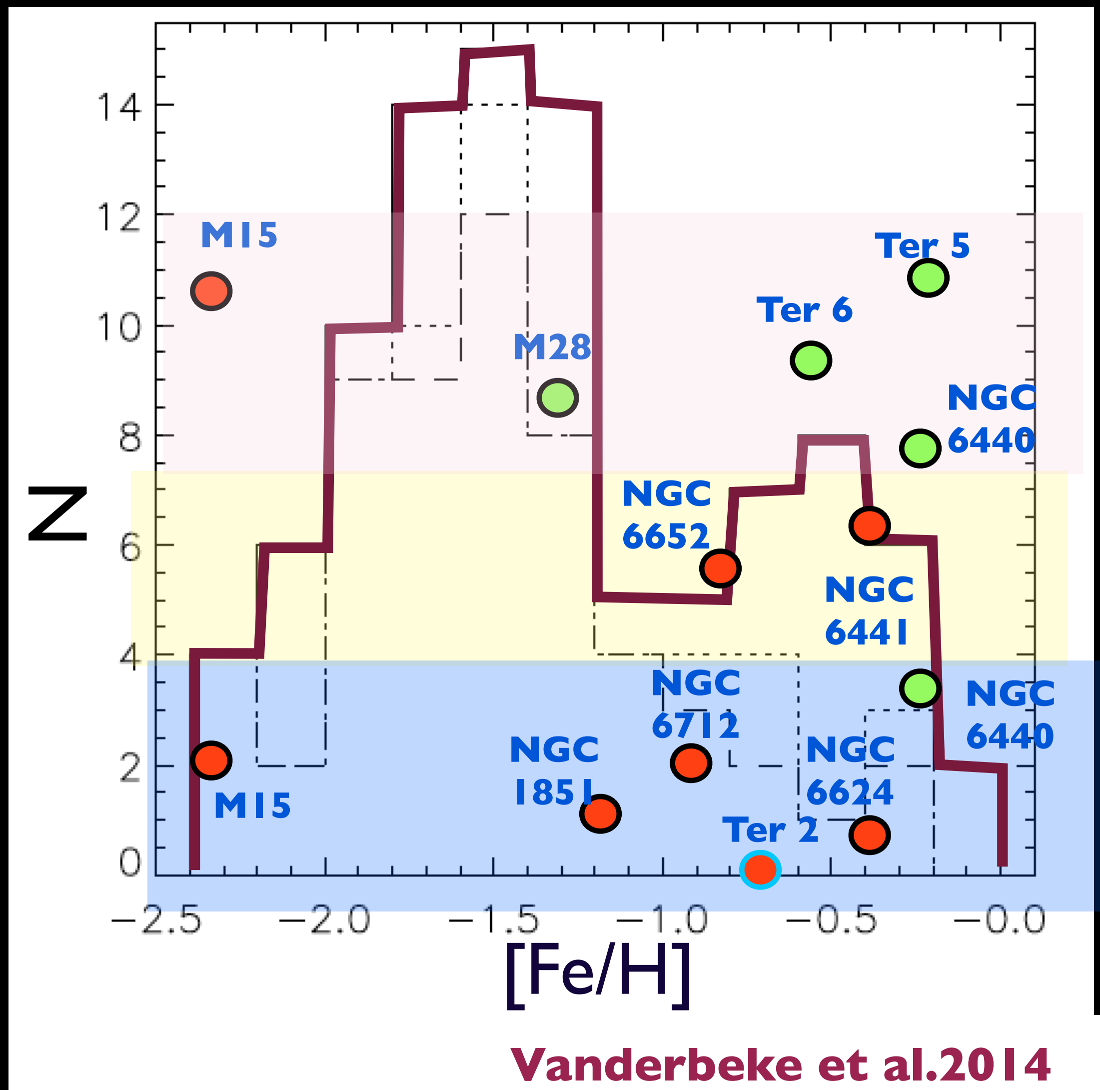

sub-giants, > 8h

MS
1-8h

UCXBs, <1h

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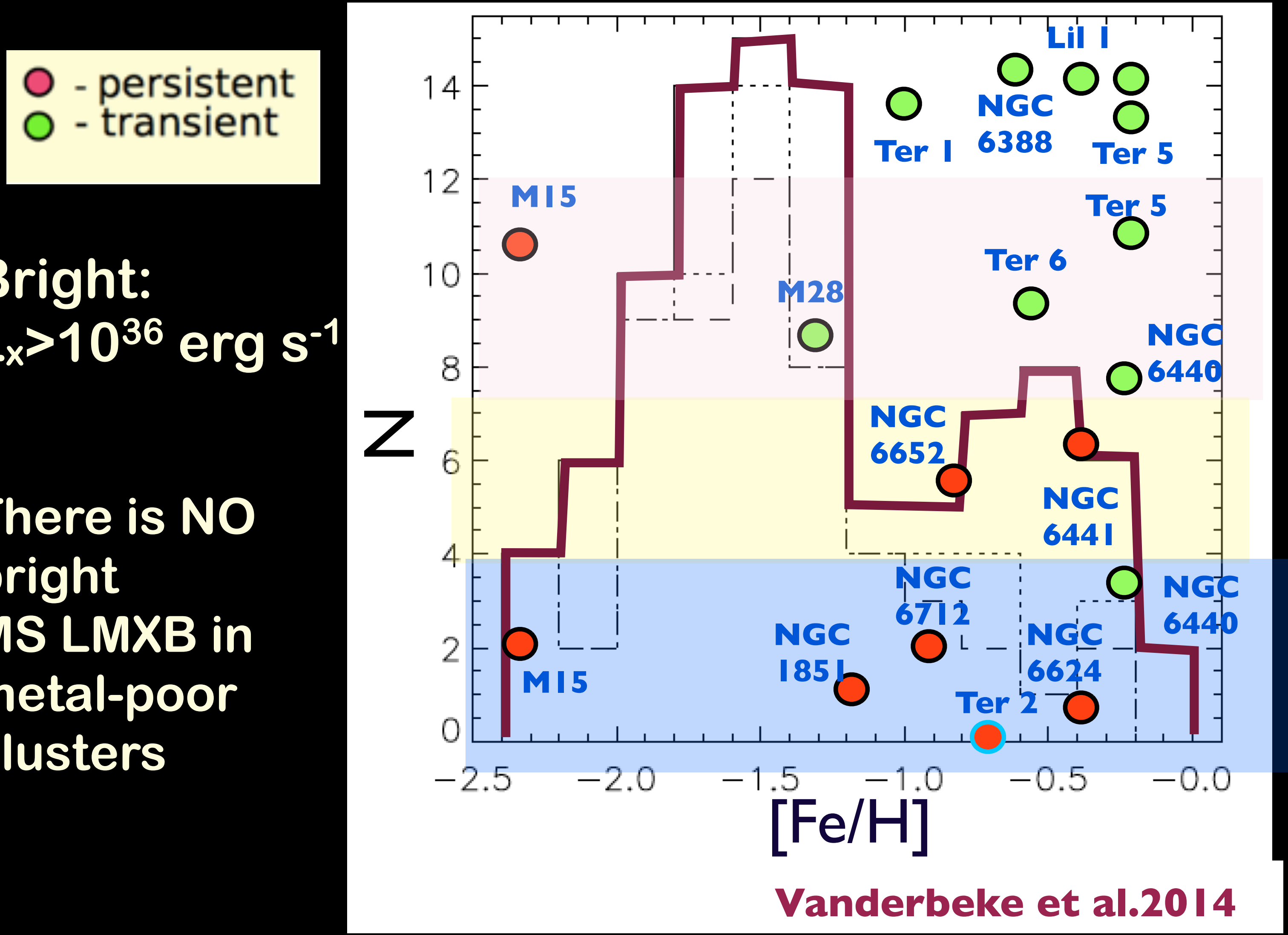


???

Caveat: outbursts; metal rich are better monitored

sub-giants, > 8h

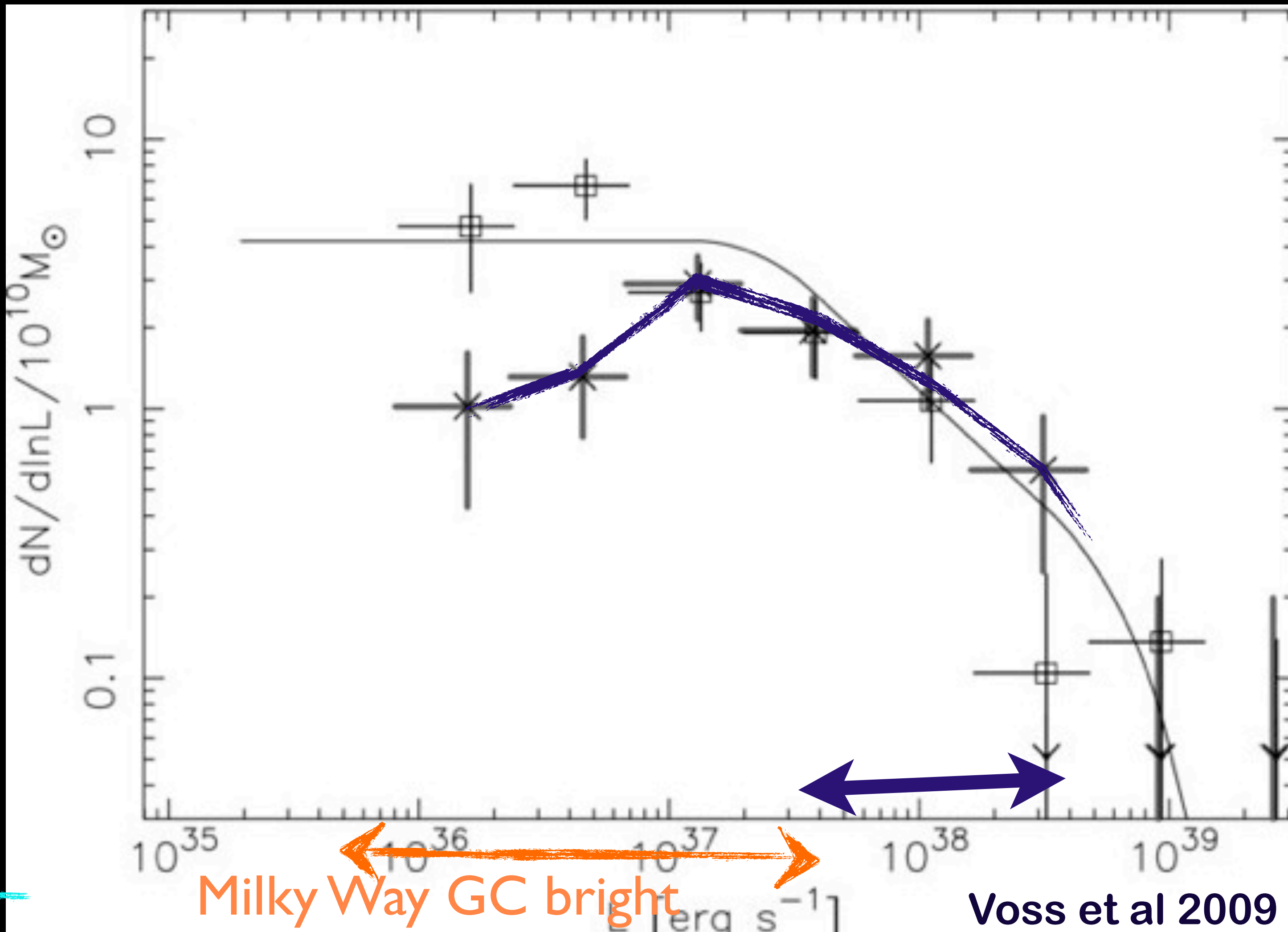
MS
1-8h

UCXBs, <1h

P

a GC with intermediate metallicity sometime is called as metal-rich…

X-ray Luminocity Function of GCs



different L_X implies different donors!!!

Possibly no contribution from MS donors at all

↓ 10^{33} erg/s for qLMXBs

Kim et al 2012: the ratio of ~3 in red/blue GCs is valid for all the bins
Caveat: the exact boundary between blue and red GCs is not same as for MW and is done using g-z, not [Fe/H]

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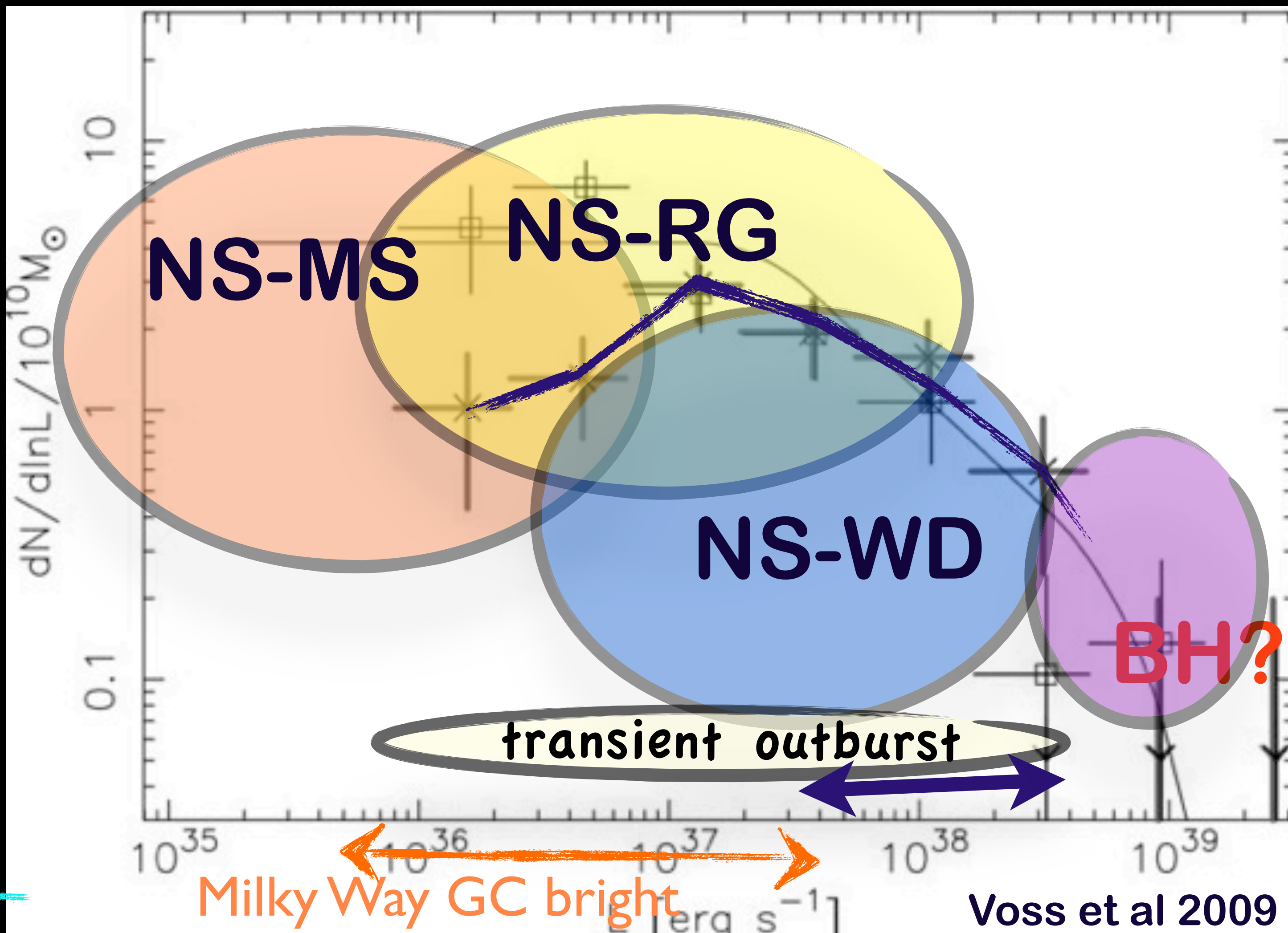

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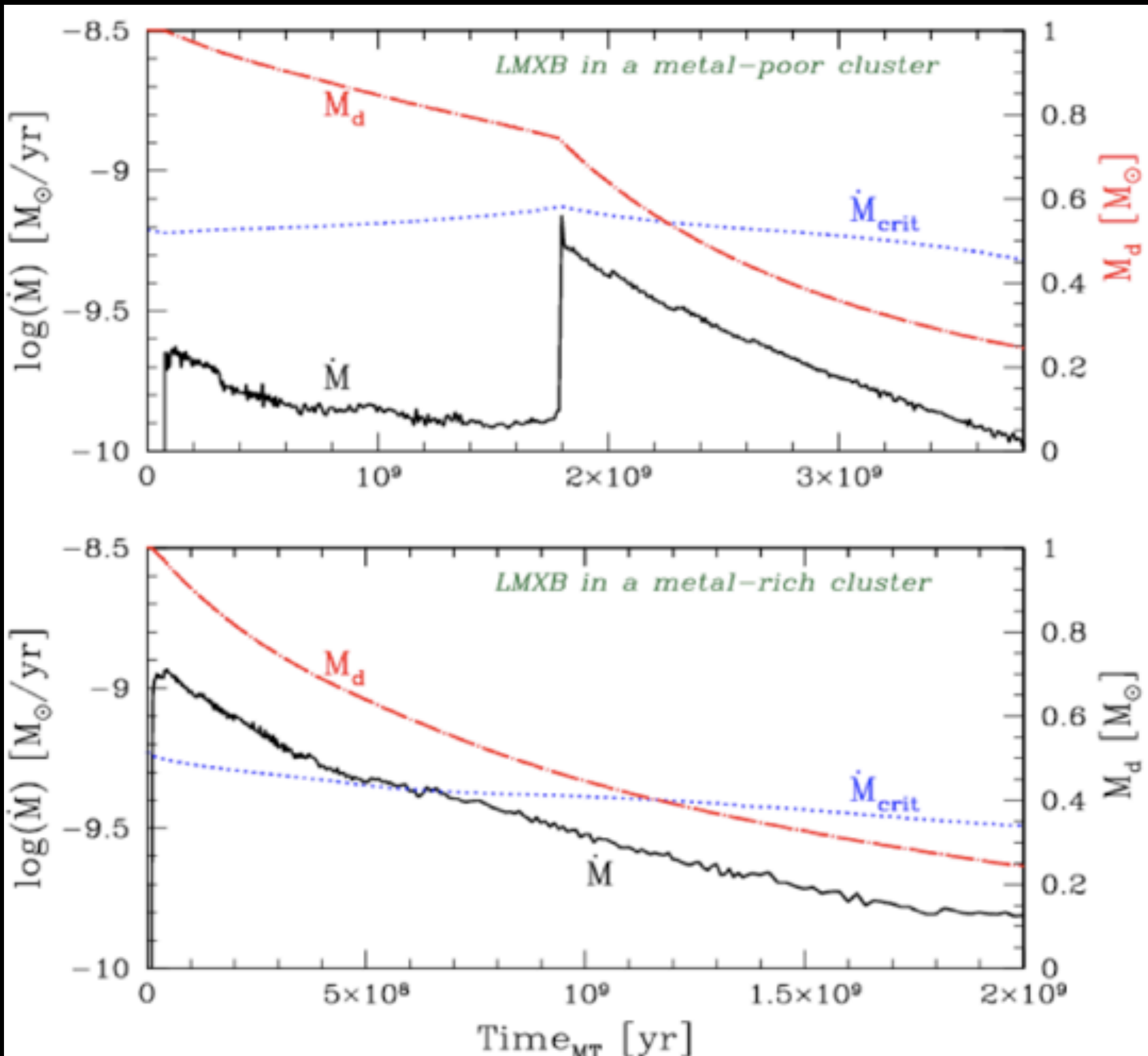
Effect of Metallicity: NS-MS LMXBs Appearance



Formation: BE, TC
Formation has no metallicity dependence

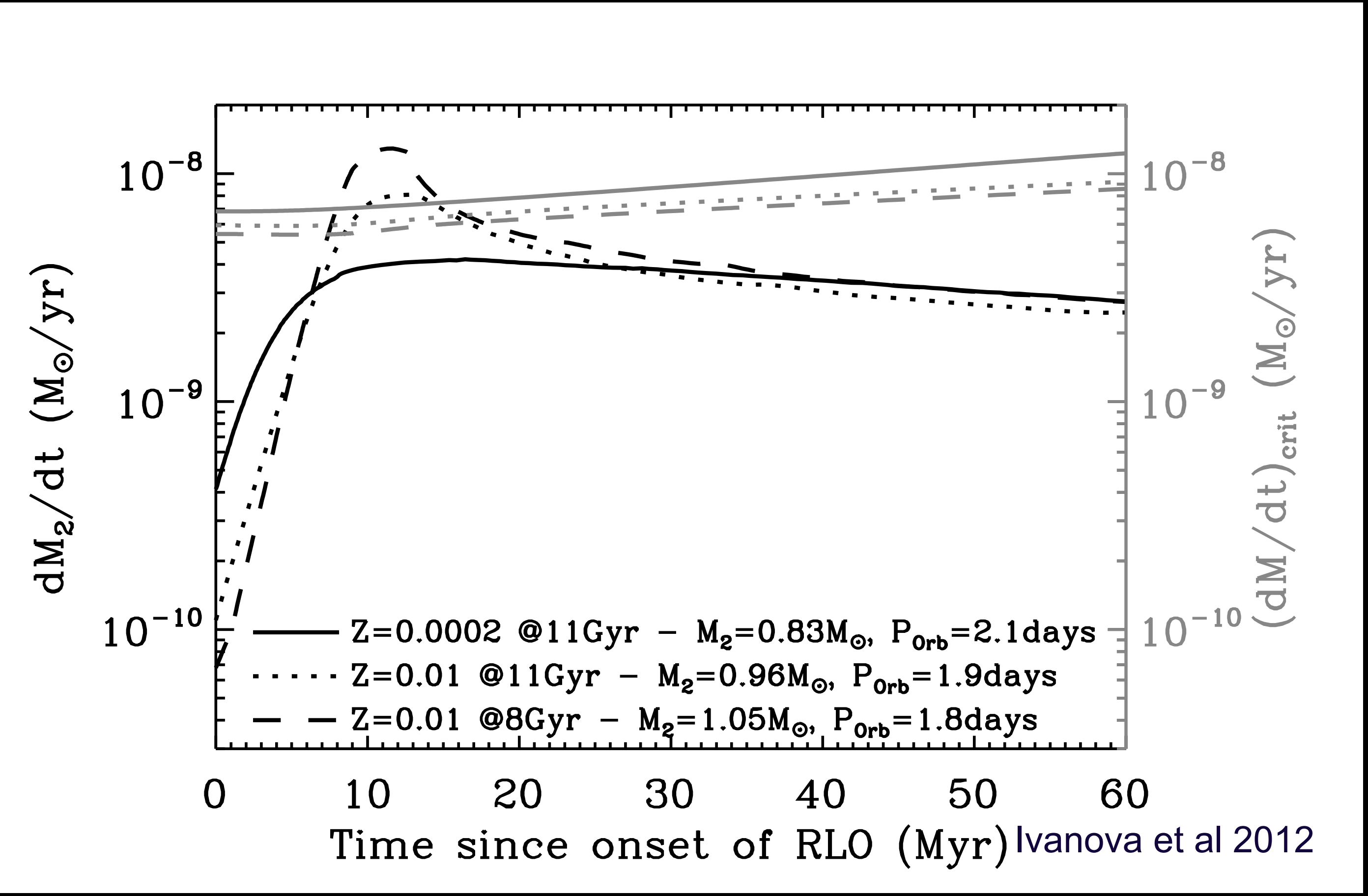
TC: "direct" LMXB formation, some of BE too

Most of time in quiescence

MB :
- persistent stage is expected for metal rich only

- it takes longer for low-metallicity MS-NS binaries to start MT

Effect of Metallicity: NS-RG LMXBs Appearance

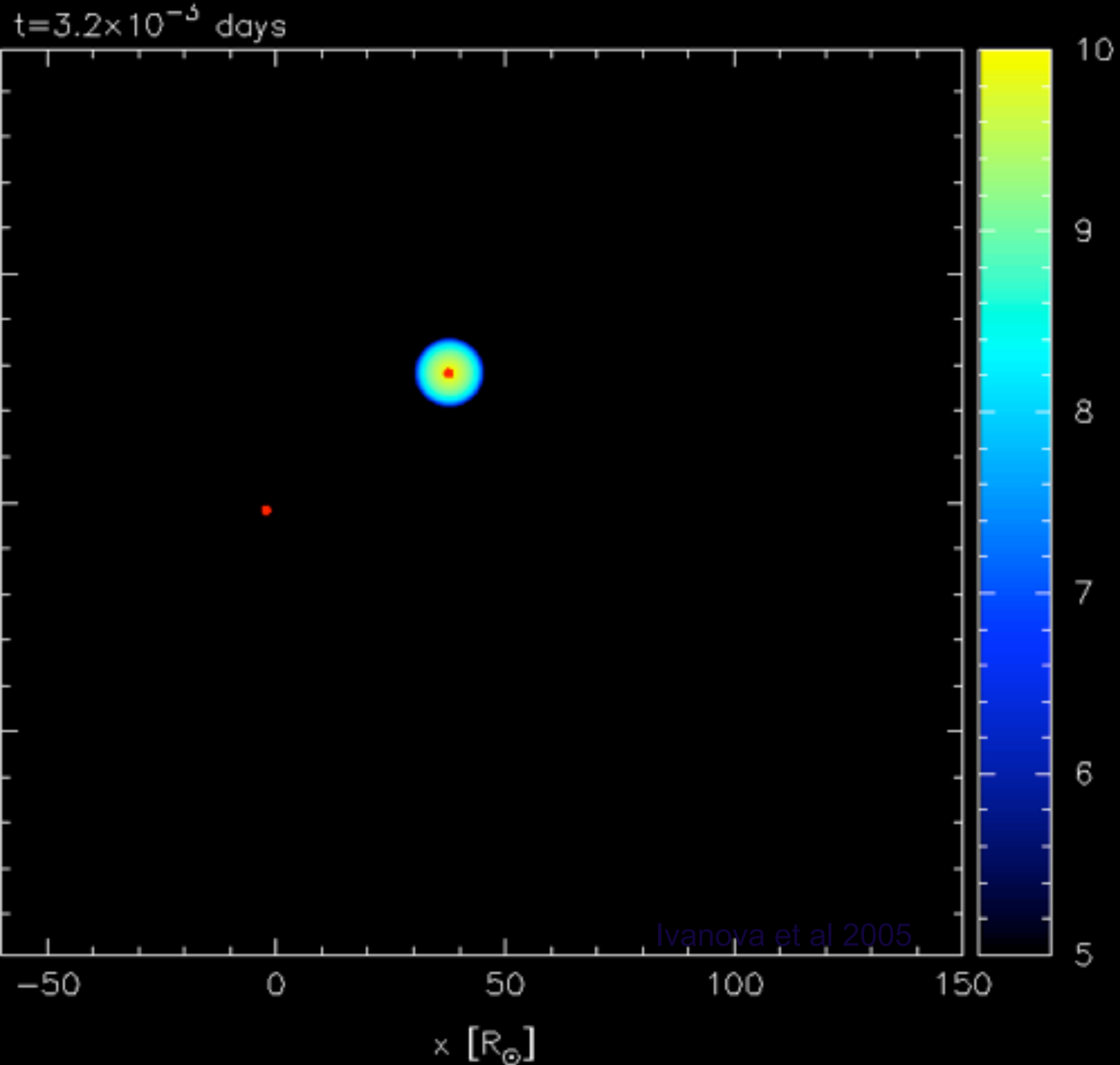


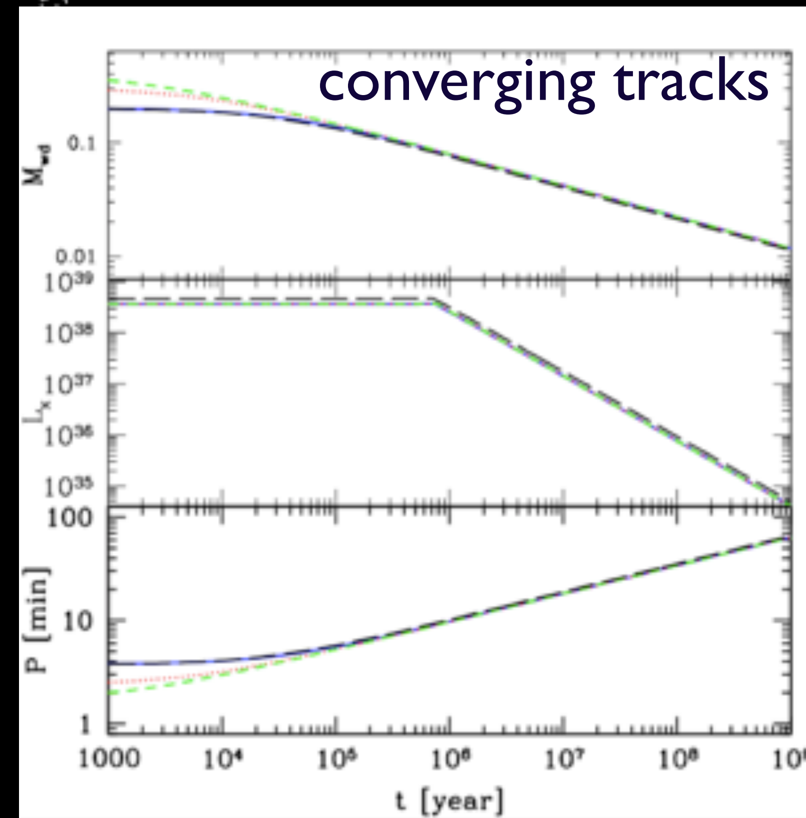
Dynamically: exchanges.

Appearance: slightly favors metal rich, but also a function of age

Caveat: duty cycles are not know well, but can be as long as 30 years

UCXBs formation: physical collisions. Direct LMXB formation.





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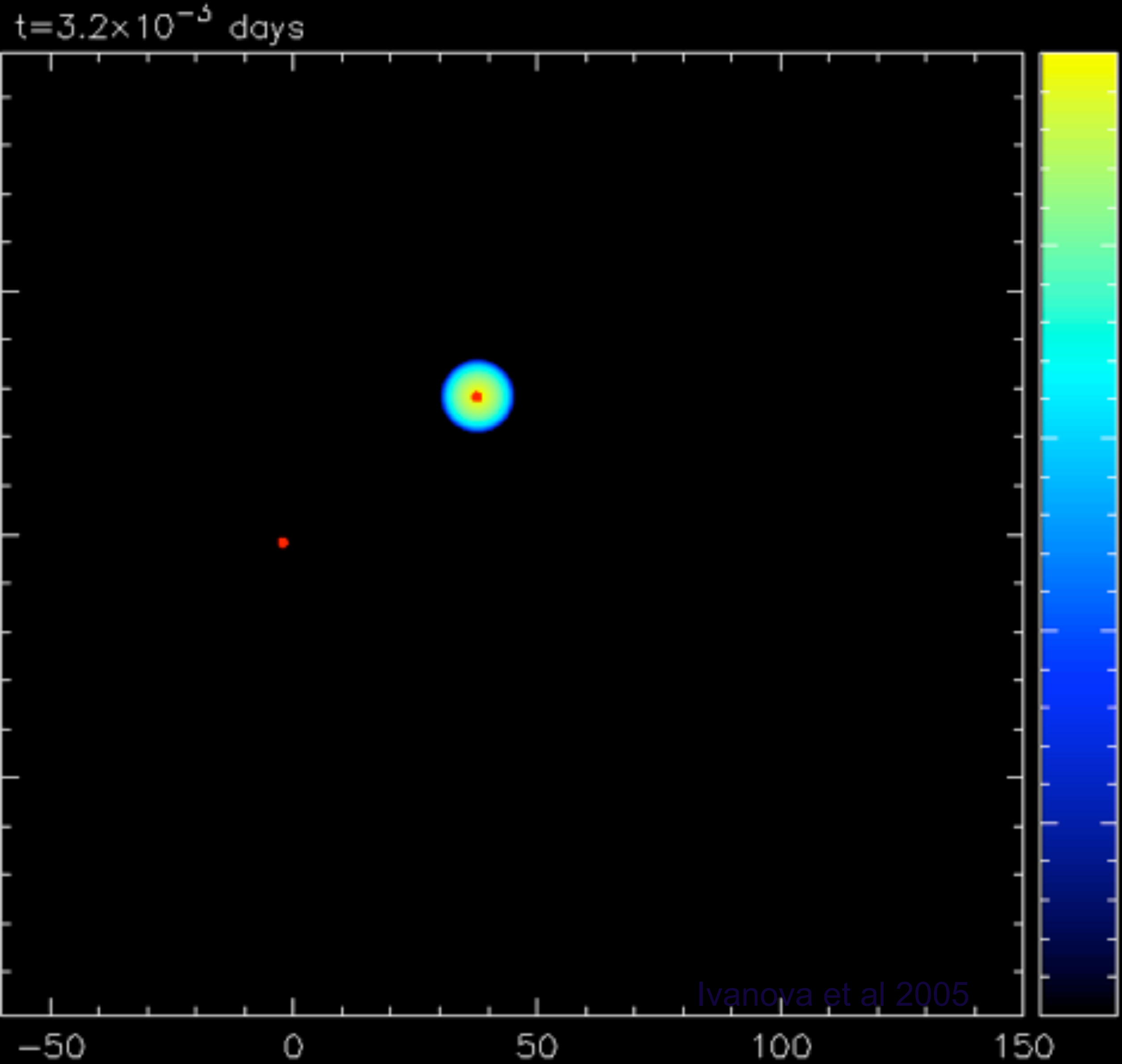
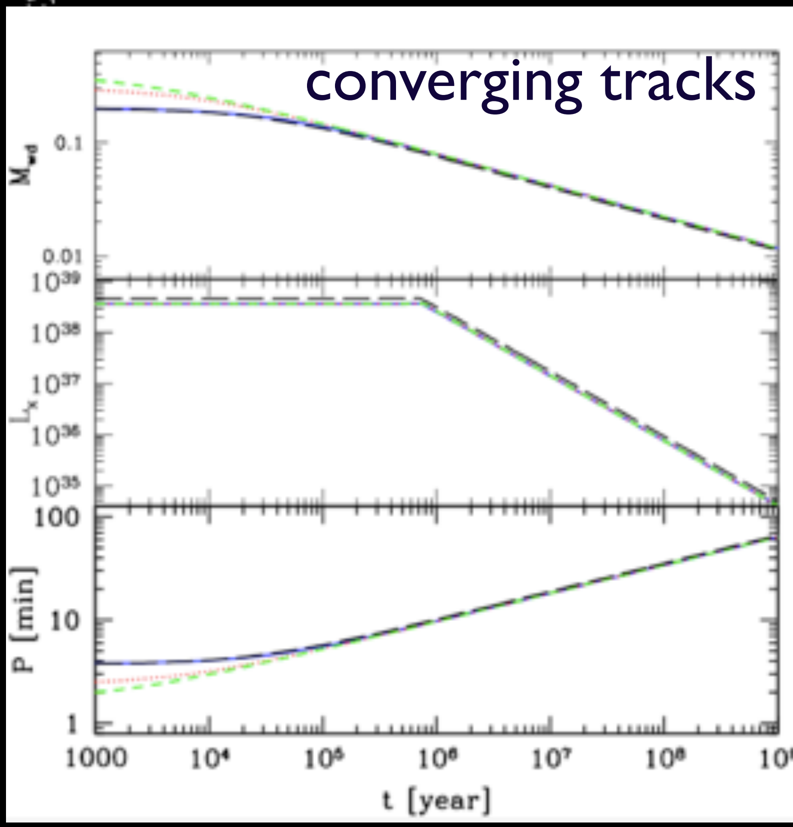




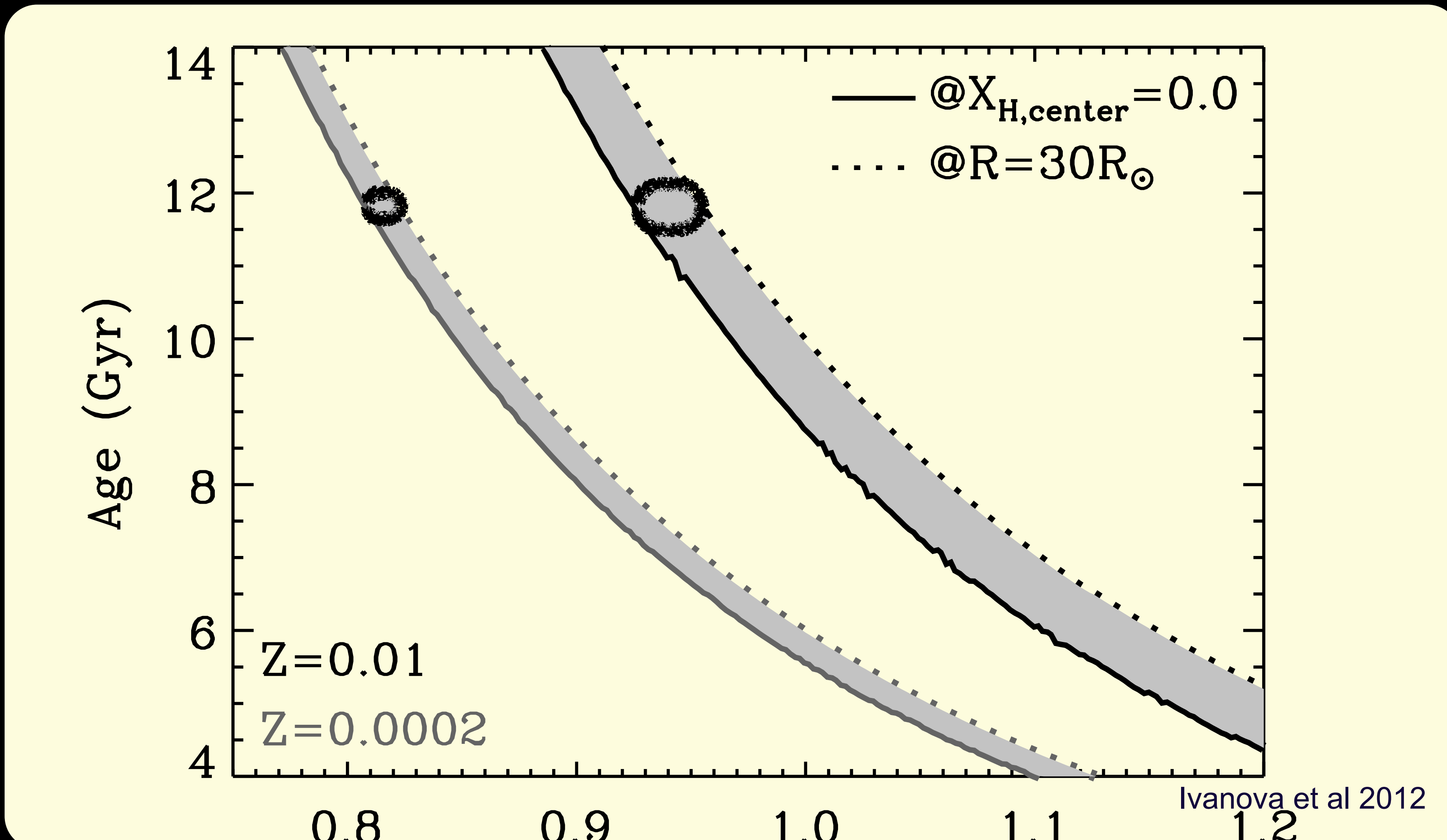
MT in UCBSx: no metallicity effect on *appearance*. Simple.

UXBS in the field are not that nice.

UCXBs numbers are consistent with the observed bright LMXBs in Milky Way GCs ONLY IF several % of NS is retained.

This is possible ONLY if AIC/ECS are at work(?GCs 10 times more massive initially?)

origin of metallicity dependence: RGs lifetimes

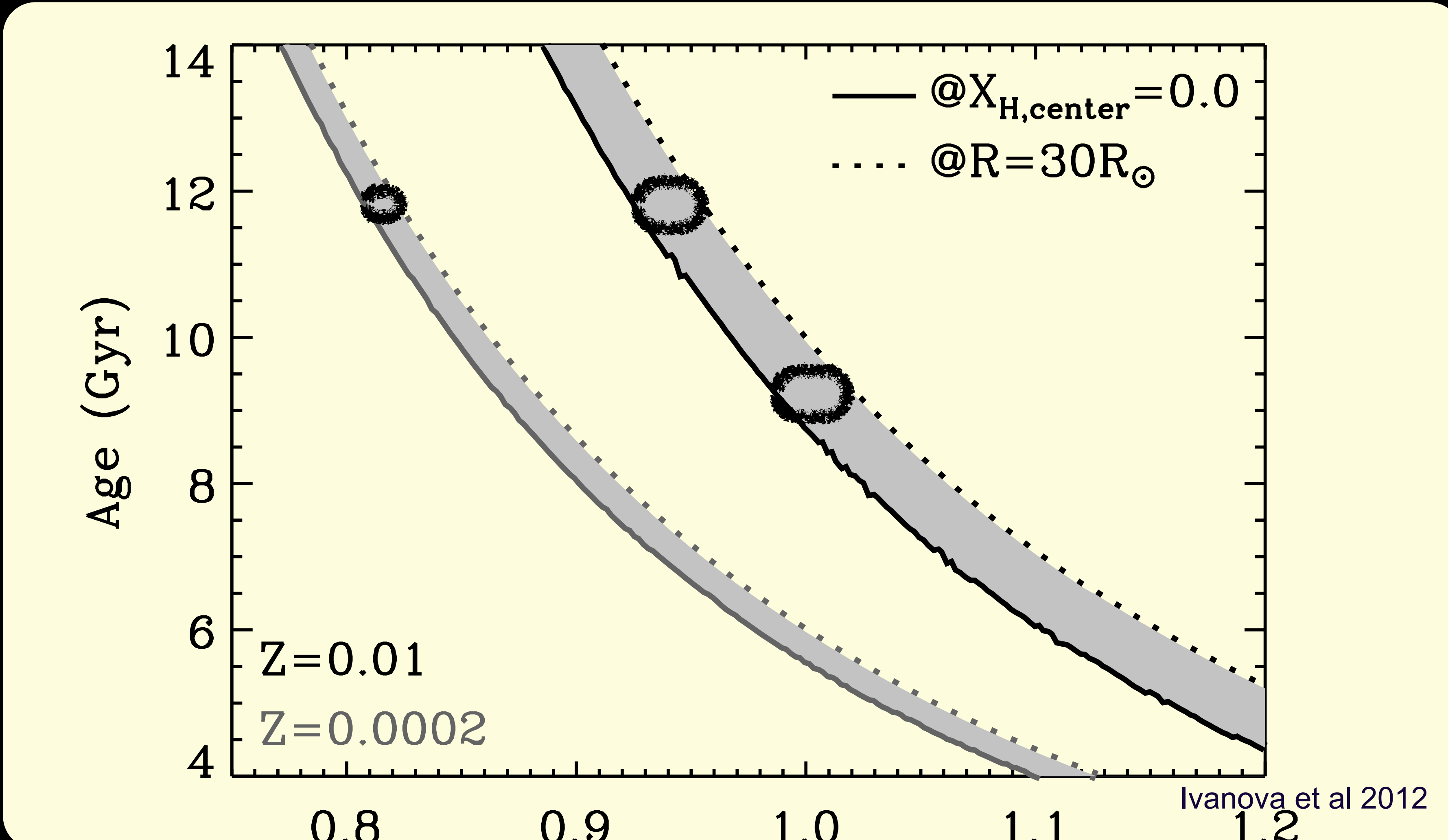


metallicty effect:

- effective cross-section of RGs is higher in metal-rich GCs
- mass of the envelope is larger -> tighter UCXBs

origin of metallicity dependence: RGs lifetimes

and possibly age?...(Hansen et al. 2013)



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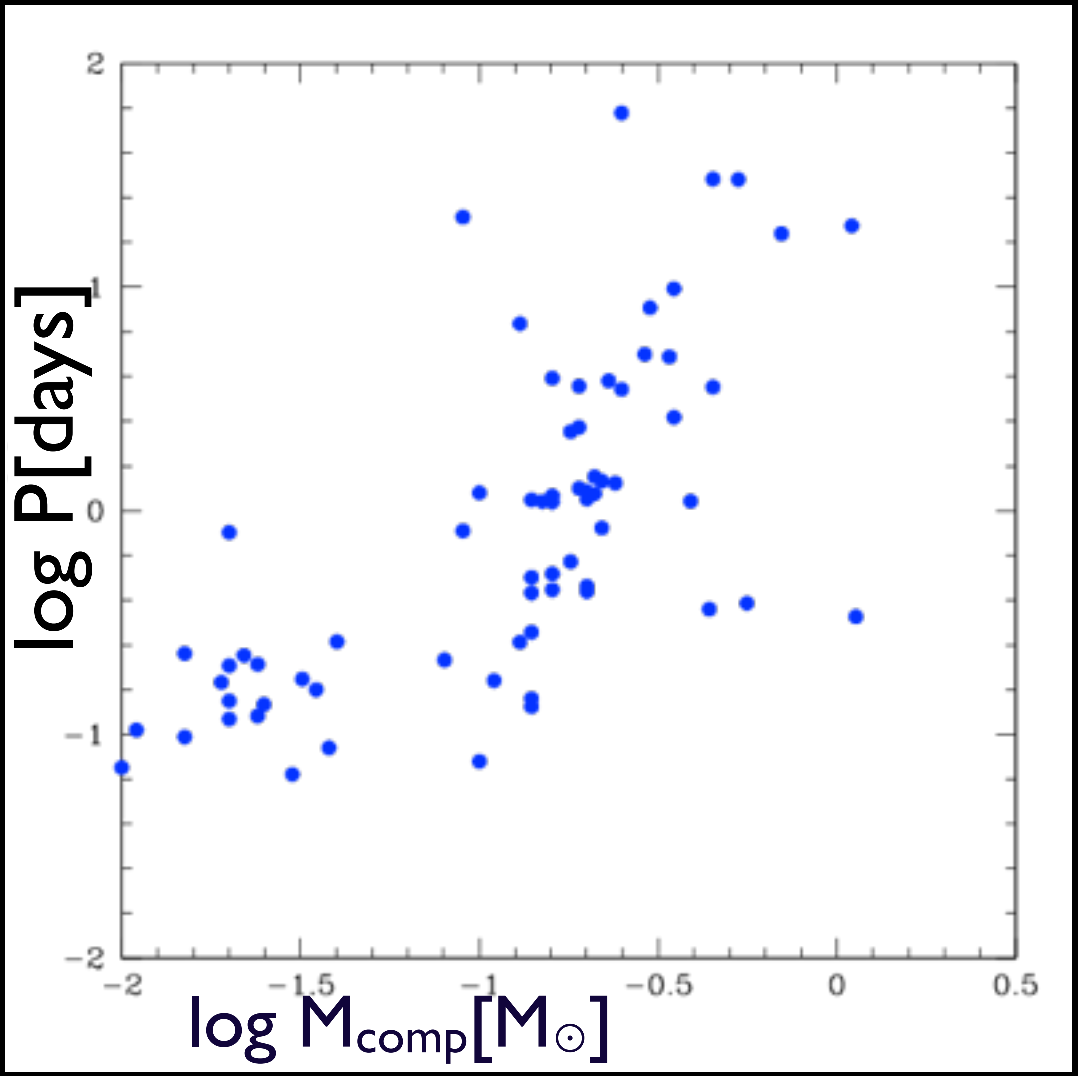
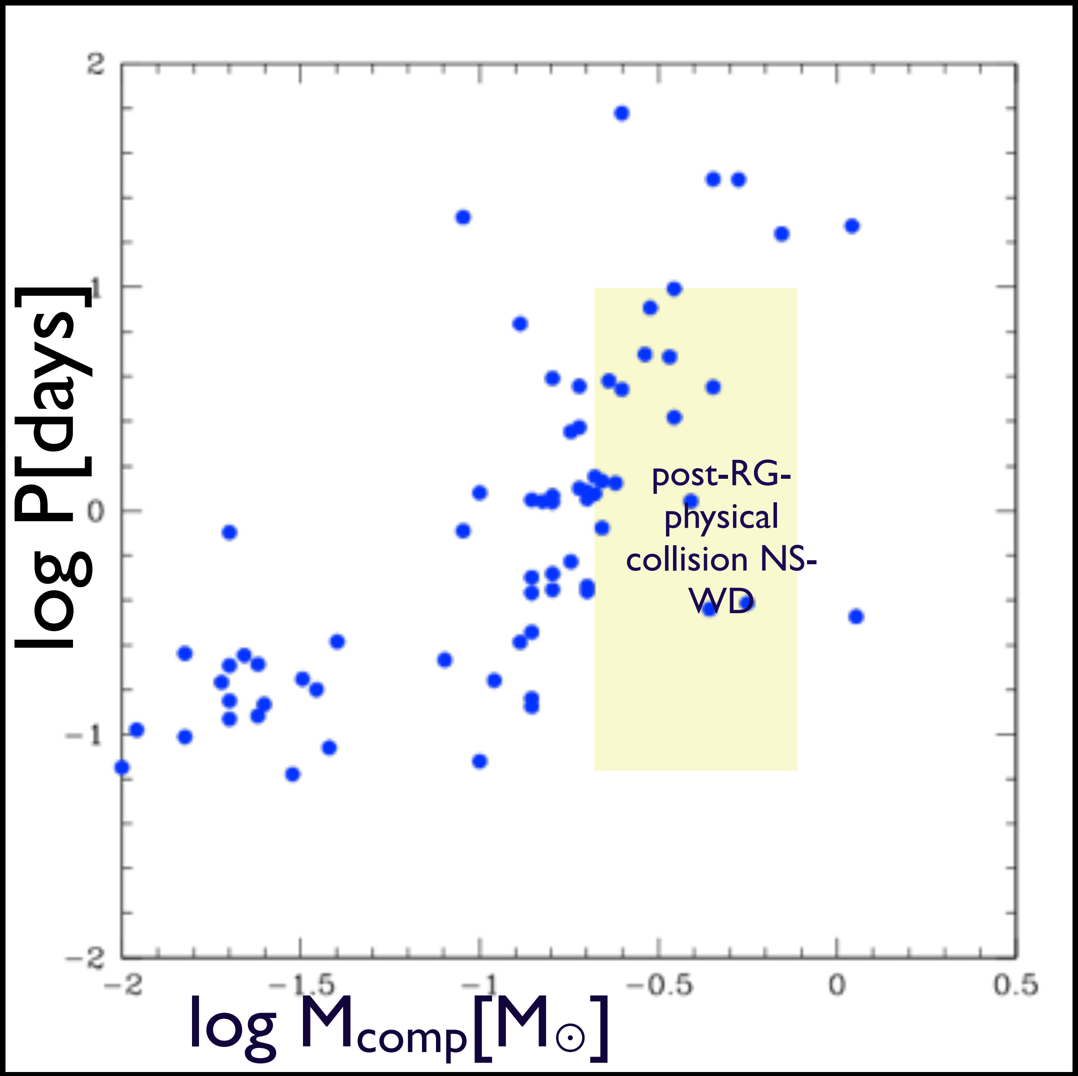
radio bMSPs



Observed radio MSPs

radio bMSPs



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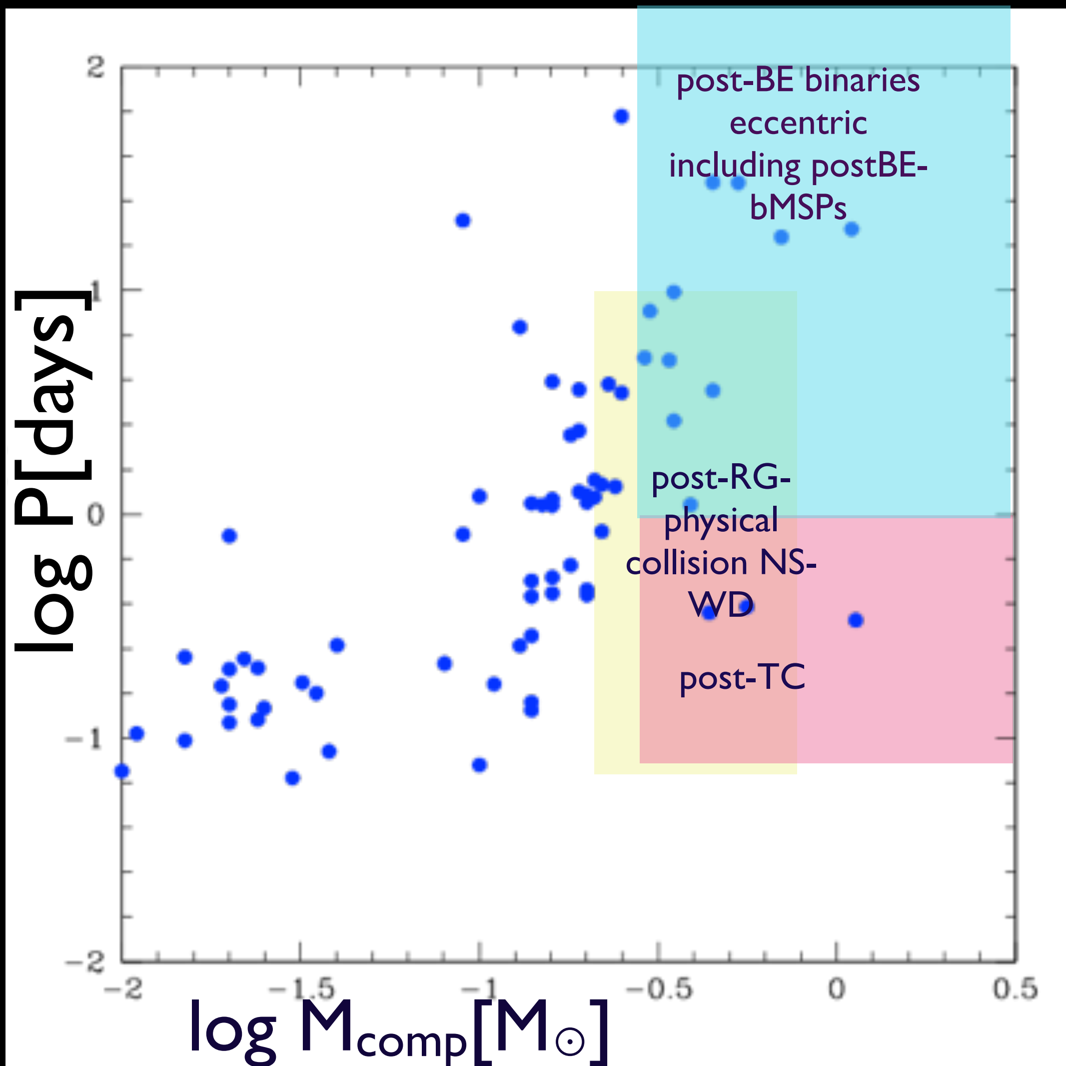

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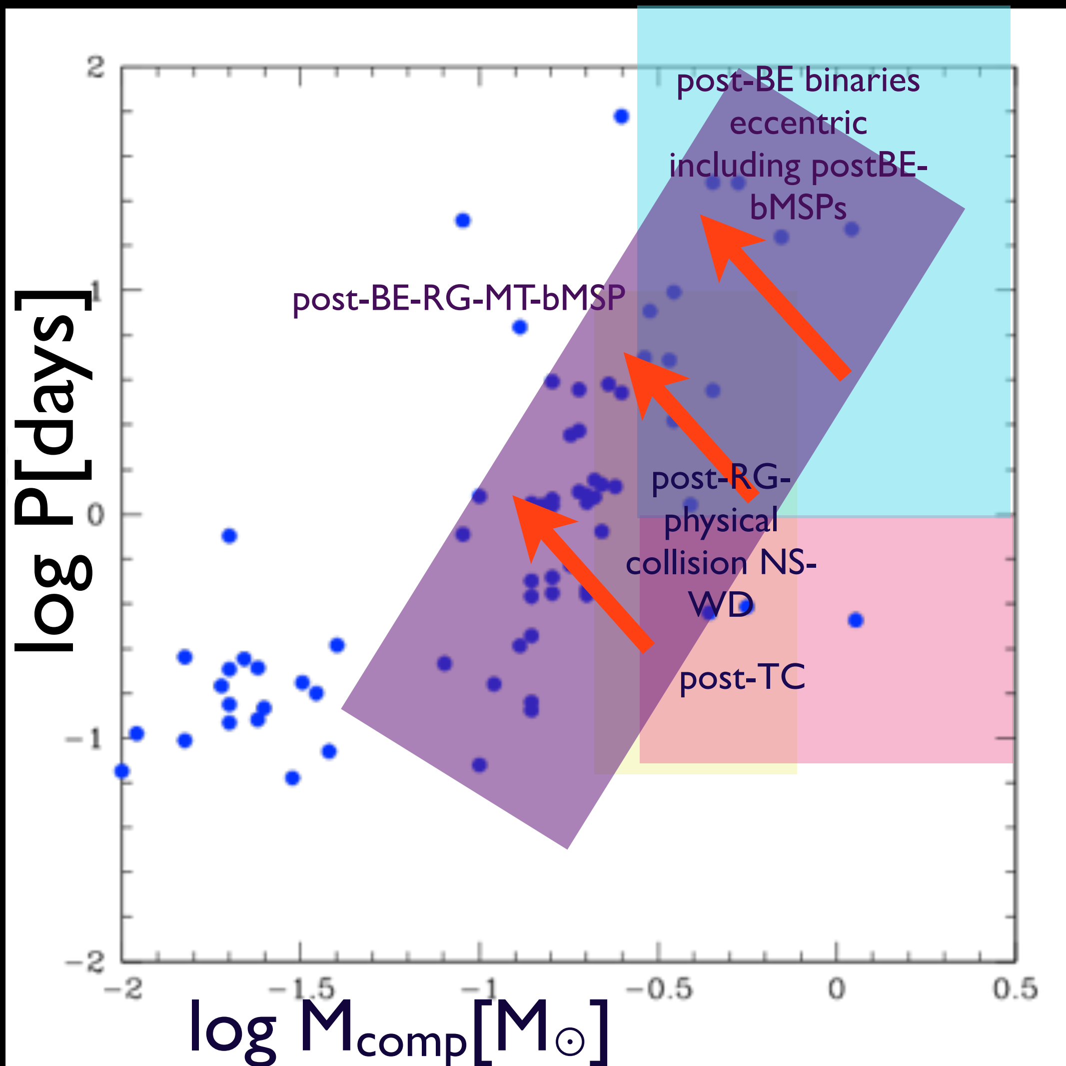

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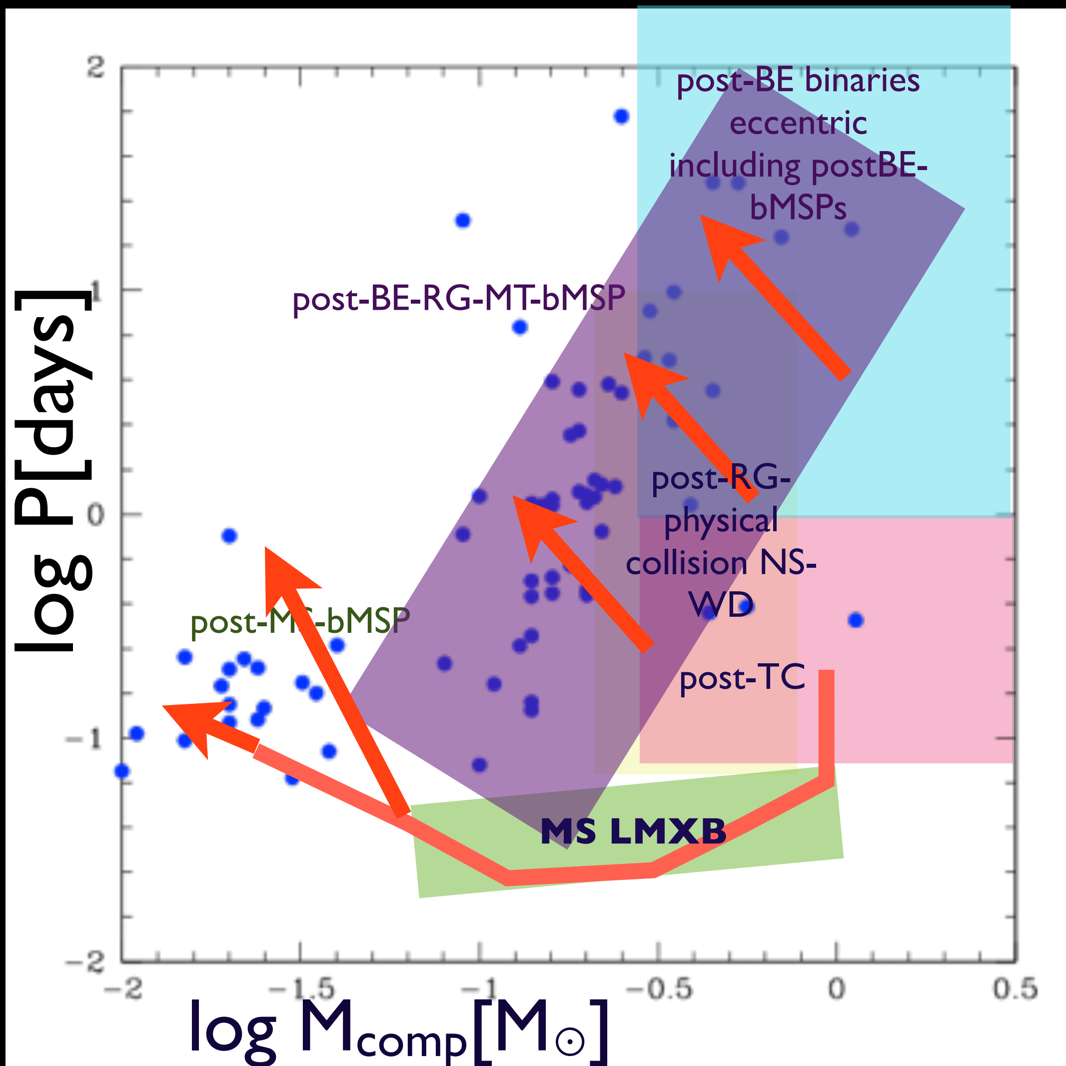

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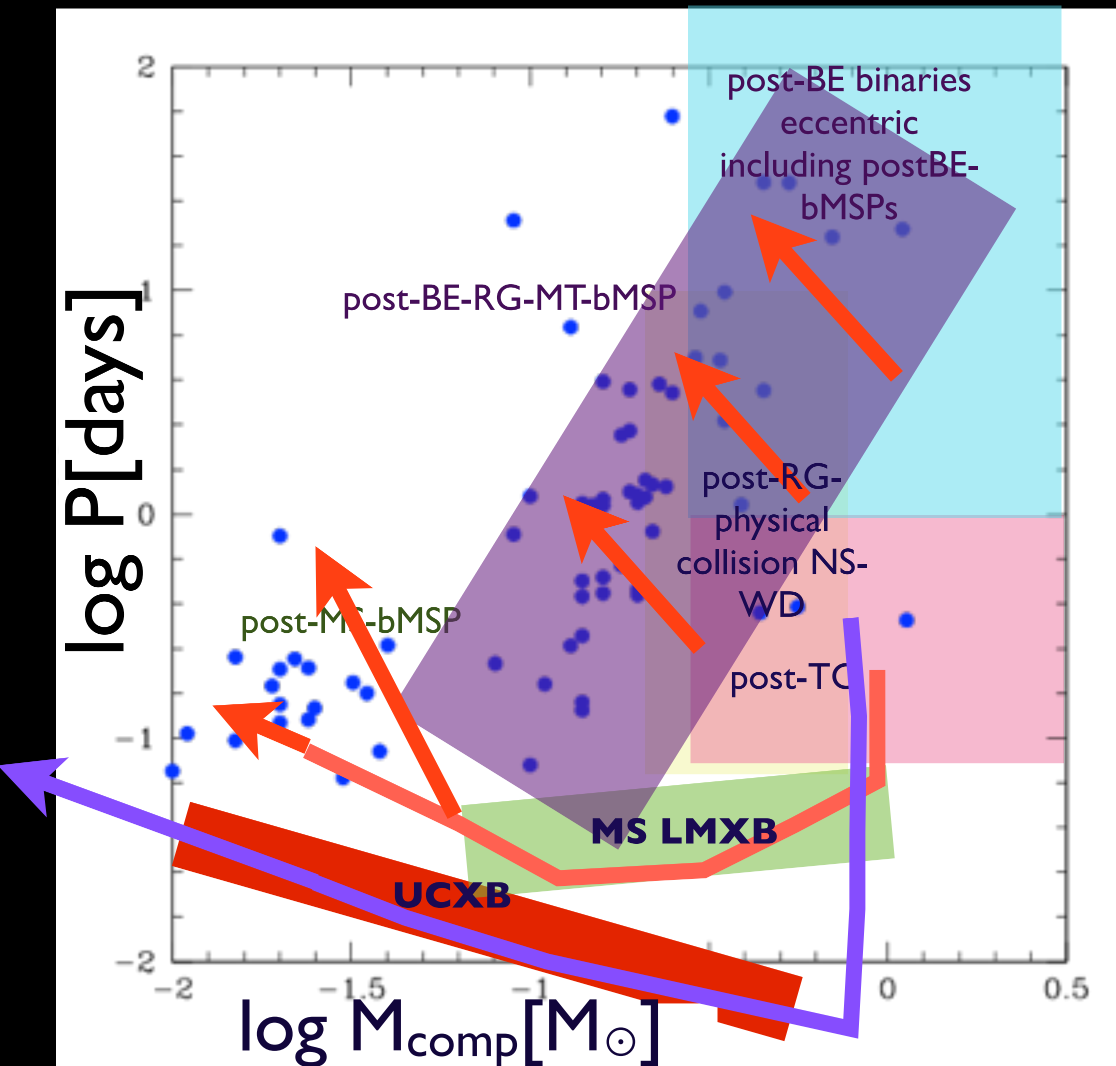

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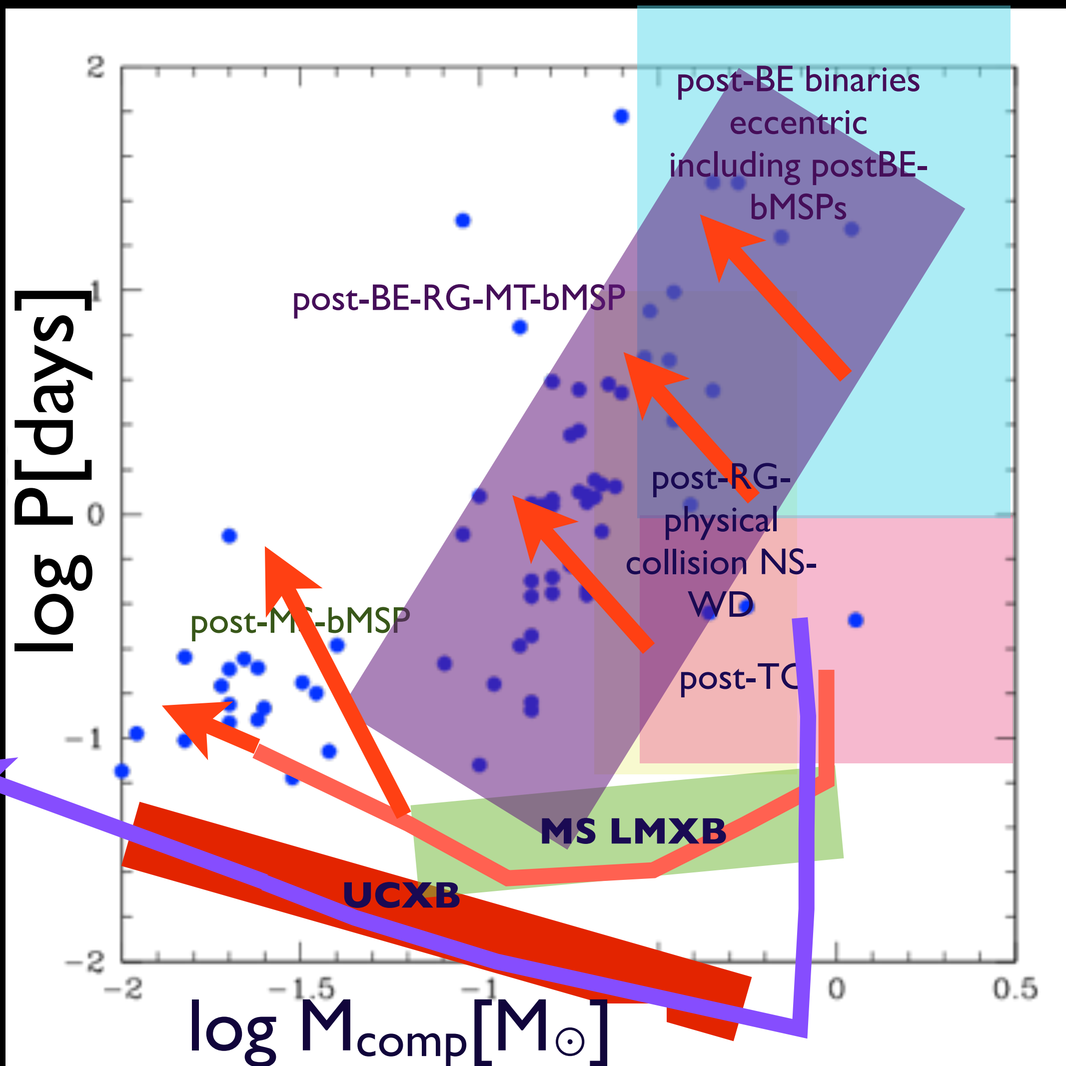
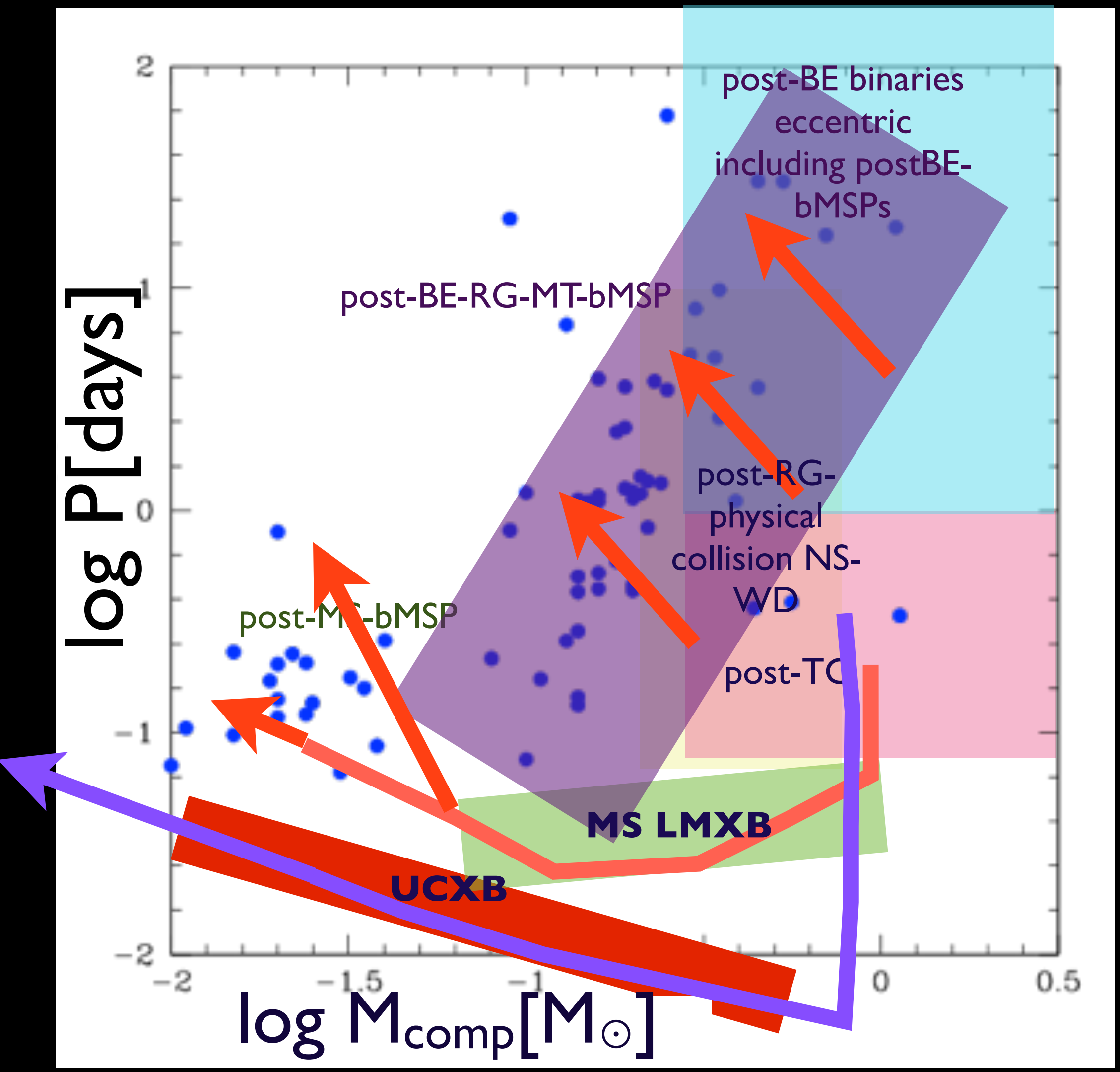


Observed radio MSPs

Excellent match in numbers & period distribution for all theoretically produced radio bMSPs with the exception for made by UCXBs!

radio bMSPs



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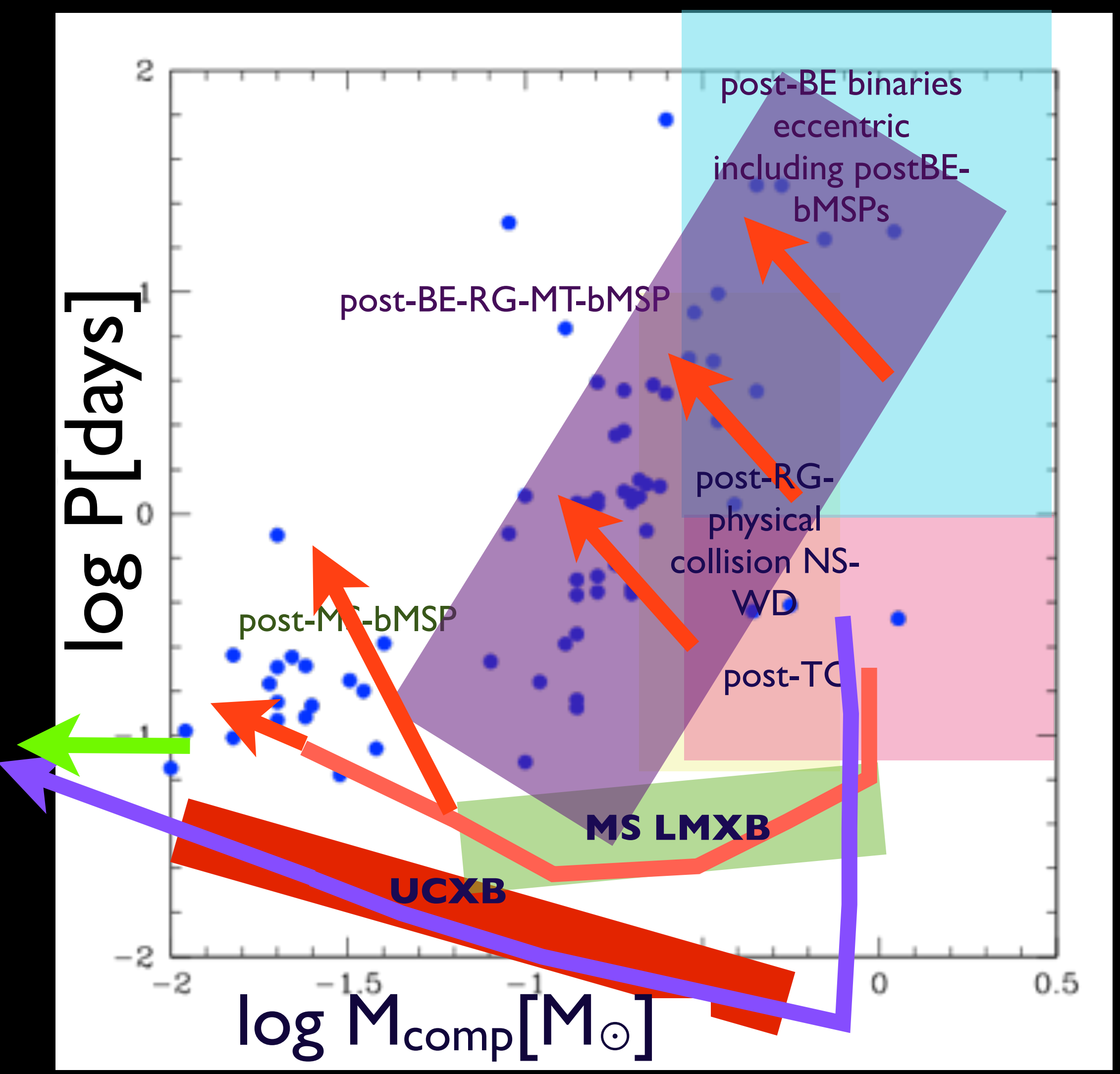
1) Observed numbers of bMSPs do not match numbers of bright UCXBs in Milky Way GCs:
   $\tau \sim 10^8$ yr for $L_x > 10^{36}$ erg/s
   per UCXBs: $N_{bmsp}=100$
2) Periods do not match
3) Same problem in the field: no any bMSPs that comes from UCXBs (deLoye 2008)

radio bMSPs



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PSR J1719-1438 (field): 2.2h + Mjup, minimum density 23 g/cm^3 (Bailies et al 2011)
It takes more than Hubble time to get to this period.
van Haaften et al. 2013: donor wind, irradiation, evaporation?

NS: triples formation rate

$N_{tr,ns}/N_{bin,ns} \sim 0.05$ per Gyr (47 Tuc-type)

$N_{tr,ns}/N_{bin,ns} \sim 0.15$ per Gyr (Ter 5-type)

~1/3 of the formed triples are Kozai triples

~50% of bMSPs were in triples at some point in their past !

In a hierarchical triple, a distant third body exerts tidal forces on the inner binary. As a result, there is a cyclic exchange of the angular momentum between inner binary and third body, causing variations in the eccentricity and inclination of the stars orbits

(Kozai 1962; Ford, Kozinsky & Rasio 2000; Blaes, Lee & Socrates 2001).

Kozai mechanism, if coupled with tidal friction, could drive the inner binary of the triple system to merge or RLOF before next interaction with other stars: KCTF - "Kozai Cycle with Tidal Friction"

(Eggleton & Kiseleva 2006, Fabrycky & Tremain 2007)

NGC 6624: 4U 1820-303

Binary orbital period is ~685s (Stella et al. 1987; Anderson et al. 1997).

Period decreases: $(\dot{P}/P)_{obs}=-(3.5\pm1.5)10^{-8}$ yr^{-1}

vs predicted $\dot{P}/P > 8\times 10^{-8}$ yr^{-1}

4U 1820-303 has the luminosity variation by a factor of ~2 at a super-orbit period P~170d (Chou&Grindlay 2001).

a hierarchical triple? (Chou & Grindlay 2001)

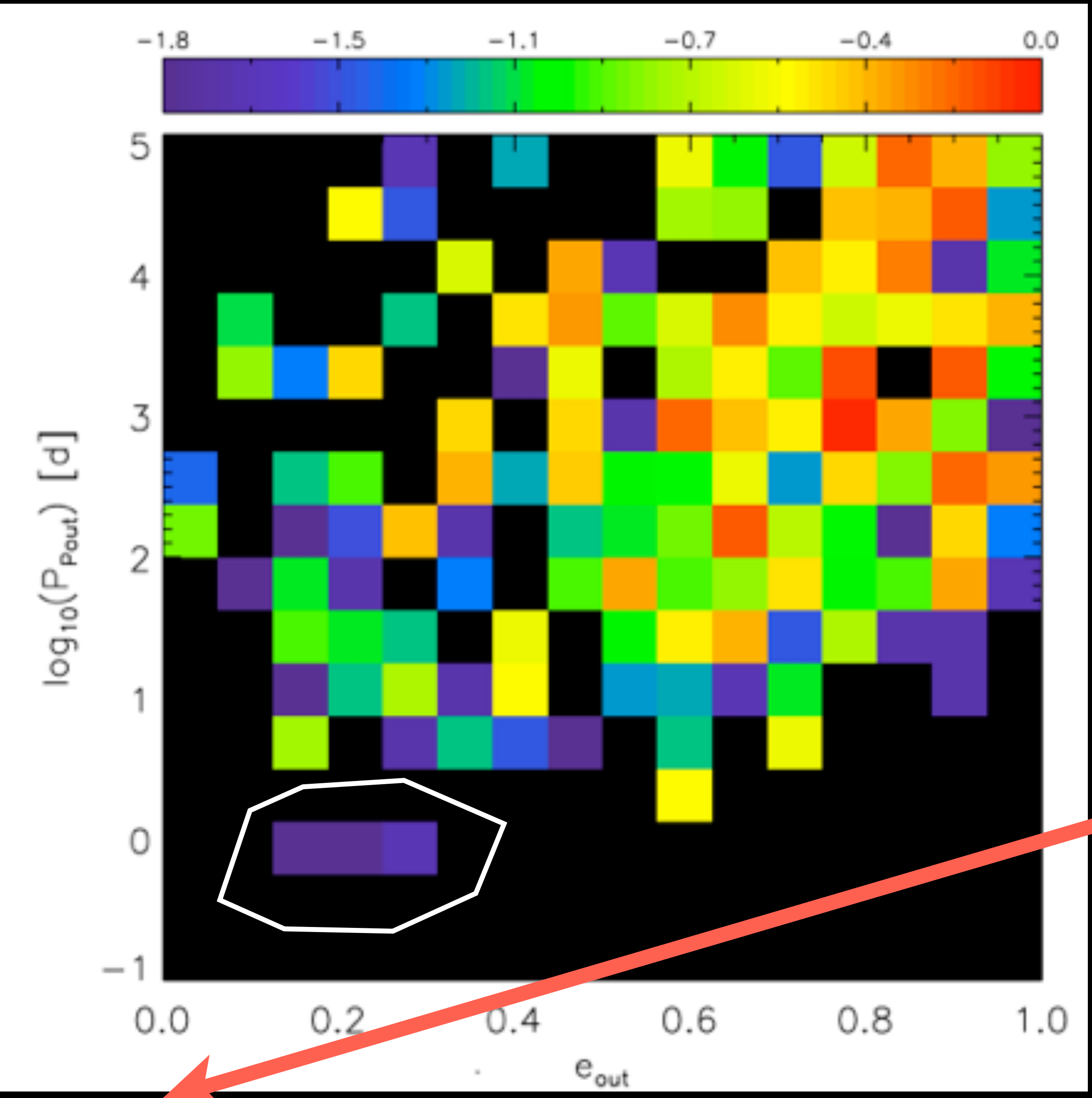
Prodan & Murray 2012:

$M_1=1.4M_\odot$ (primary NS), $M_2=0.067M_\odot$ (secondary WD), $M_3=0.55M_\odot$,

$e_{in}=0.009$, $e_{out}=0.0001$, $i=44^o.715$ (initial mutual inclination),

$a_{out}=1.5\ R_\odot$ (outer binary semi-major axis), $P_{out}=0.15$d

NGC 6623: 4U 1820-303



The observed triple LMXBs s hardest to make via encounters. Double/external CE?

To get to this point, a outer binary has to have some additional a.m. loss

GCs BH XRBs: observations

NGC 4472 (Zepf et al. 2008)

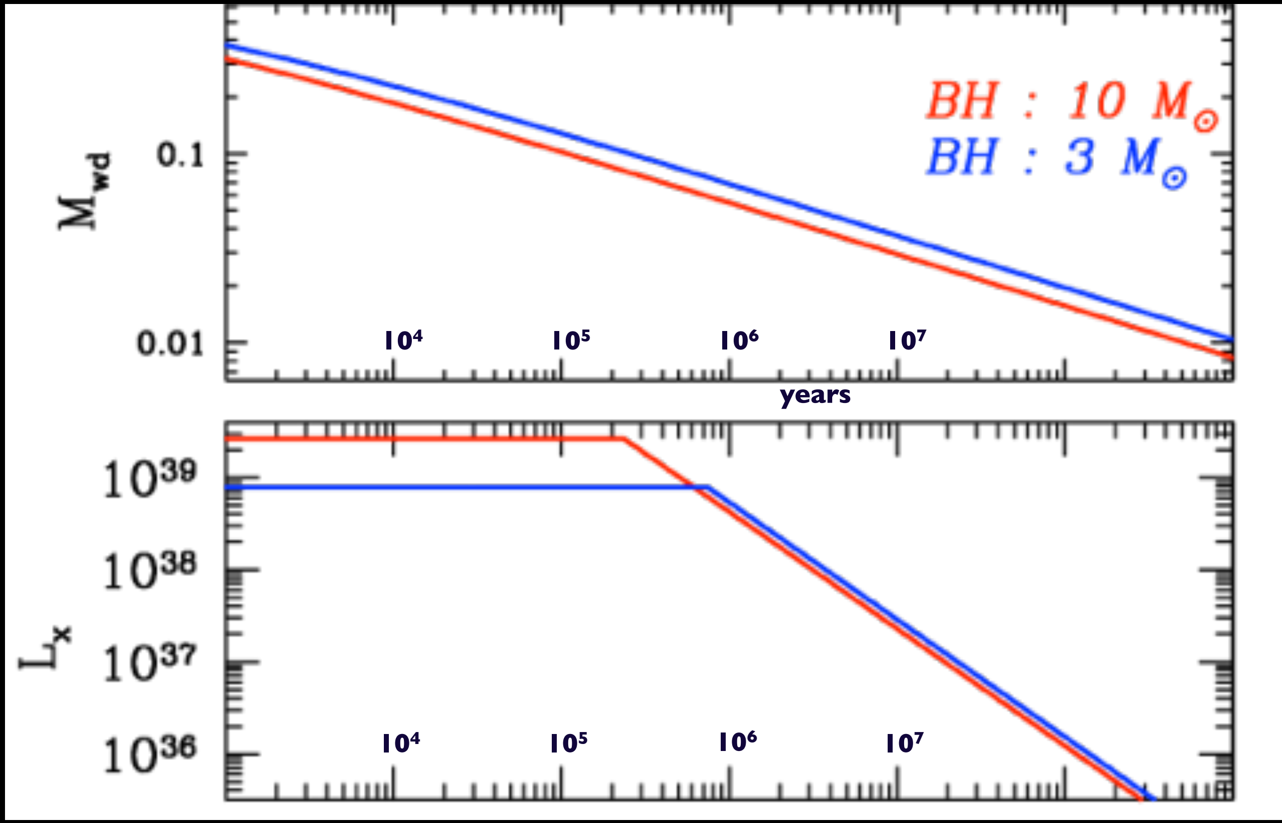
- $L_x \sim 4\times10^{39}$ erg s^{-1}, strong variability
- strong, broad (2000 km/s) O III emission lines and low Hα/[OIII] ratio
- Could be a BH of 5-20 $M_\odot$, most likely 15 $M_\odot$ (Gnedin et al. 2009)

How frequent are ULXs ($L_x > 10^{39}$ ergs/s) in GCs?

- Kim et al. 2006: 8 in 6173 GCs ⇒ 2×10^{-9} per $M_\odot$
- Humphrey&Buote 2008: 2 in 3782 ⇒ 7×10^{-10} per $M_\odot$
- Sivakoff 2010: 7 in 6776 GCs ⇒ 2×10^{-9} per $M_\odot$
- Kim et al. 2012: 24 with $L_x > 5\times10^{38}$ ergs/s erg/s, in 5904 GCs
    - sample is big enough to indicate the metallicity dependence!
    - average Mv≃-9. Only 7 Galactic GCs are in same weight category
- MS companions? 1000 times harder to form than BH-WD in field, however dominate MW field BH XRB populations.

Observationally inferred formation rates

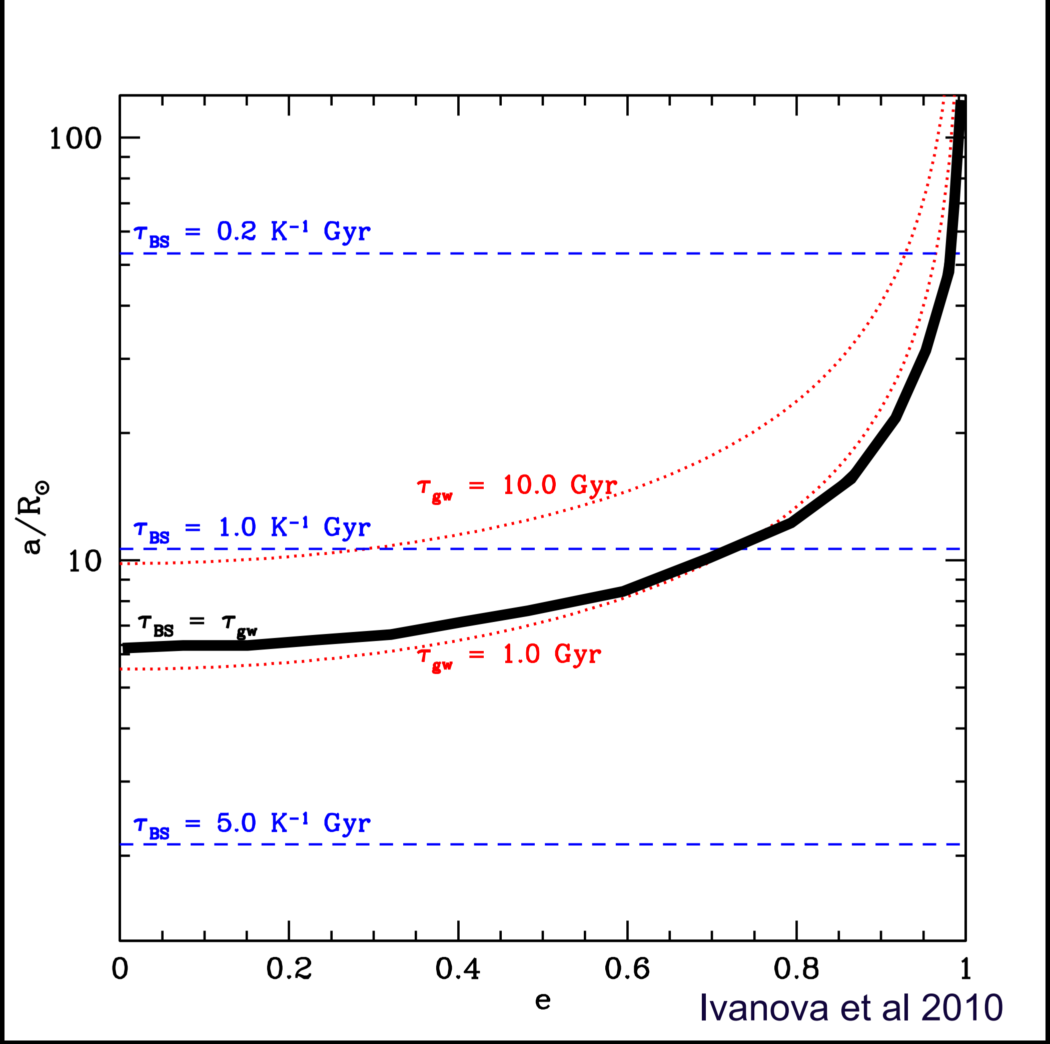
τ~2x10^{5} for Eddington limit
τ~5x10^{5} as for an ULX
($L_x > 10^{39}$ erg/s)



$$R = \tau / N$$

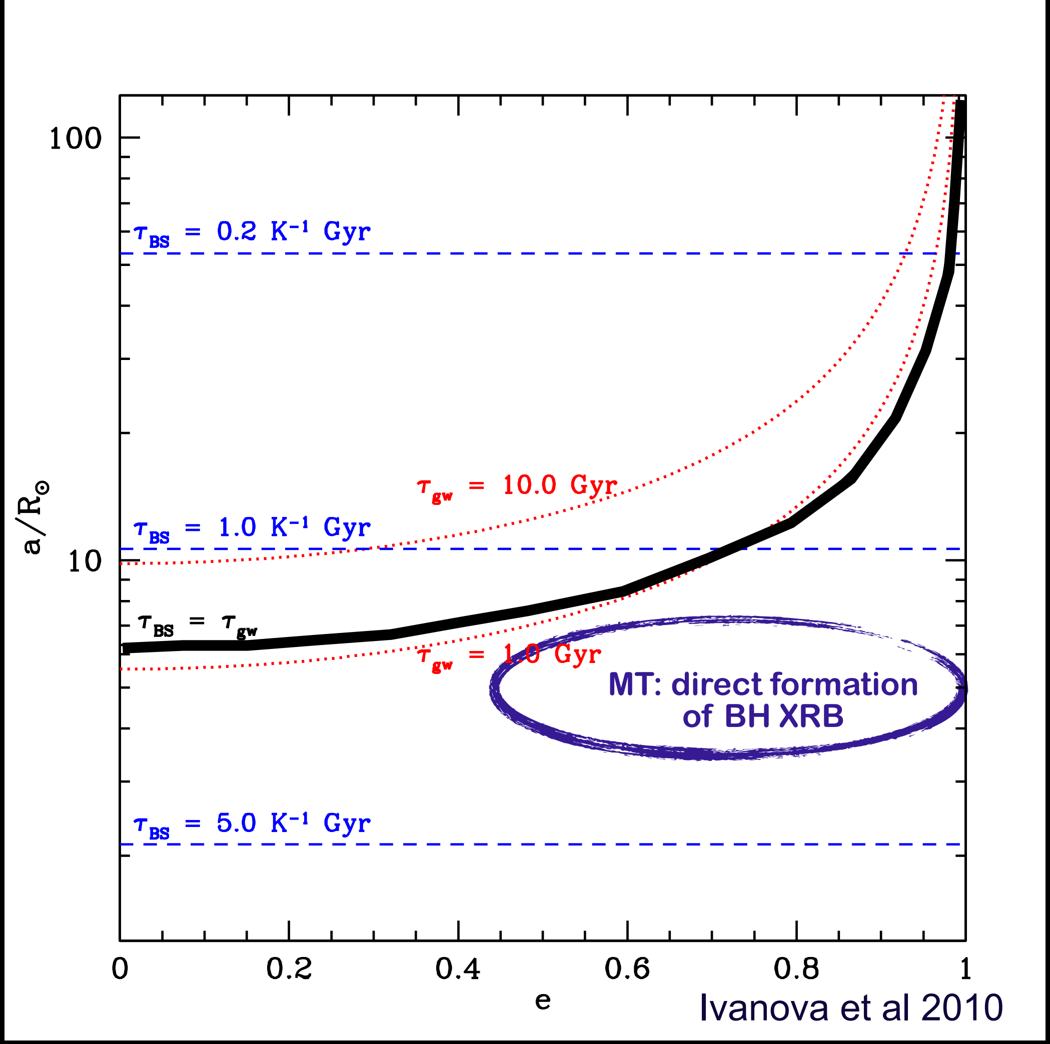
- if only 1 BH remains, R is ~2 LMXB per Gyr per BH
- if 10% remains, R is 4x10^{-3} per Gyr per BH

BH-WD in GCs



100
10
a/R⊙
e
0
0.2
0.4
0.6
0.8
1
τBS = 0.2 K⁻¹ Gyr
τBS = 1.0 K⁻¹ Gyr
τBS = 5.0 K⁻¹ Gyr
τgw = 10.0 Gyr
τgw = 1.0 Gyr
τBS = τgw
Ivanova et al 2010

BH-WD in GCs



100
10
a/R$_\odot$
τ_{BS} = 0.2 K^{-1} Gyr
τ_{BS} = 1.0 K^{-1} Gyr
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τ_{gw} = 10.0 Gyr
τ_{gw} = 1.0 Gyr
τ_{BS} = τ_{gw}
MT: direct formation
of BH XRB
0
0.2
0.4
0.6
0.8
1
e
Ivanova et al 2010

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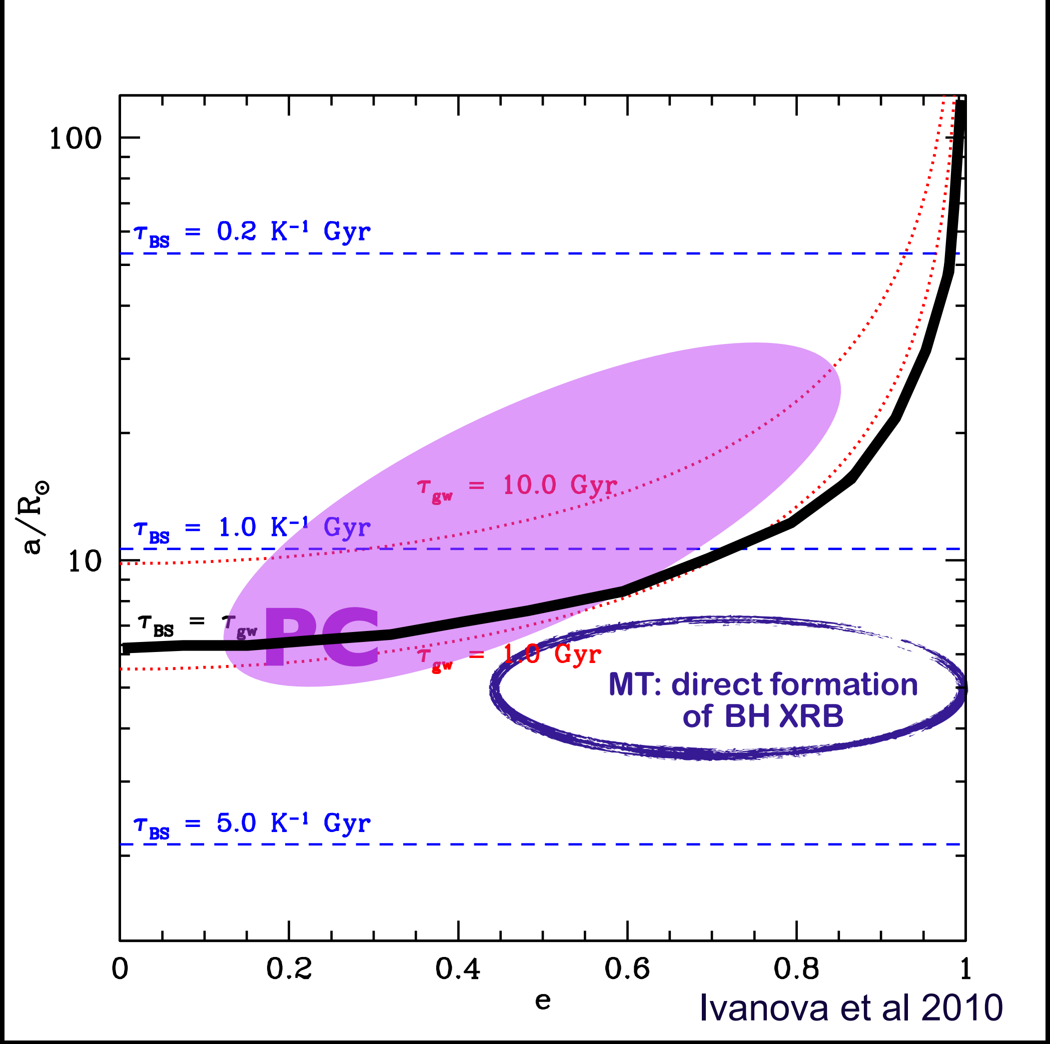

τ_{BS} = 0.2 K⁻¹ Gyr
τ_{gw} = 10.0 Gyr
τ_{BS} = 1.0 K⁻¹ Gyr
$\tau_{BS} = \tau_{gw}$
PC
τ_{gw} = 1.0 Gyr
MT: direct formation
of BH XRB
τ_{BS} = 5.0 K⁻¹ Gyr
a/R⊙
100
10
0
0.2
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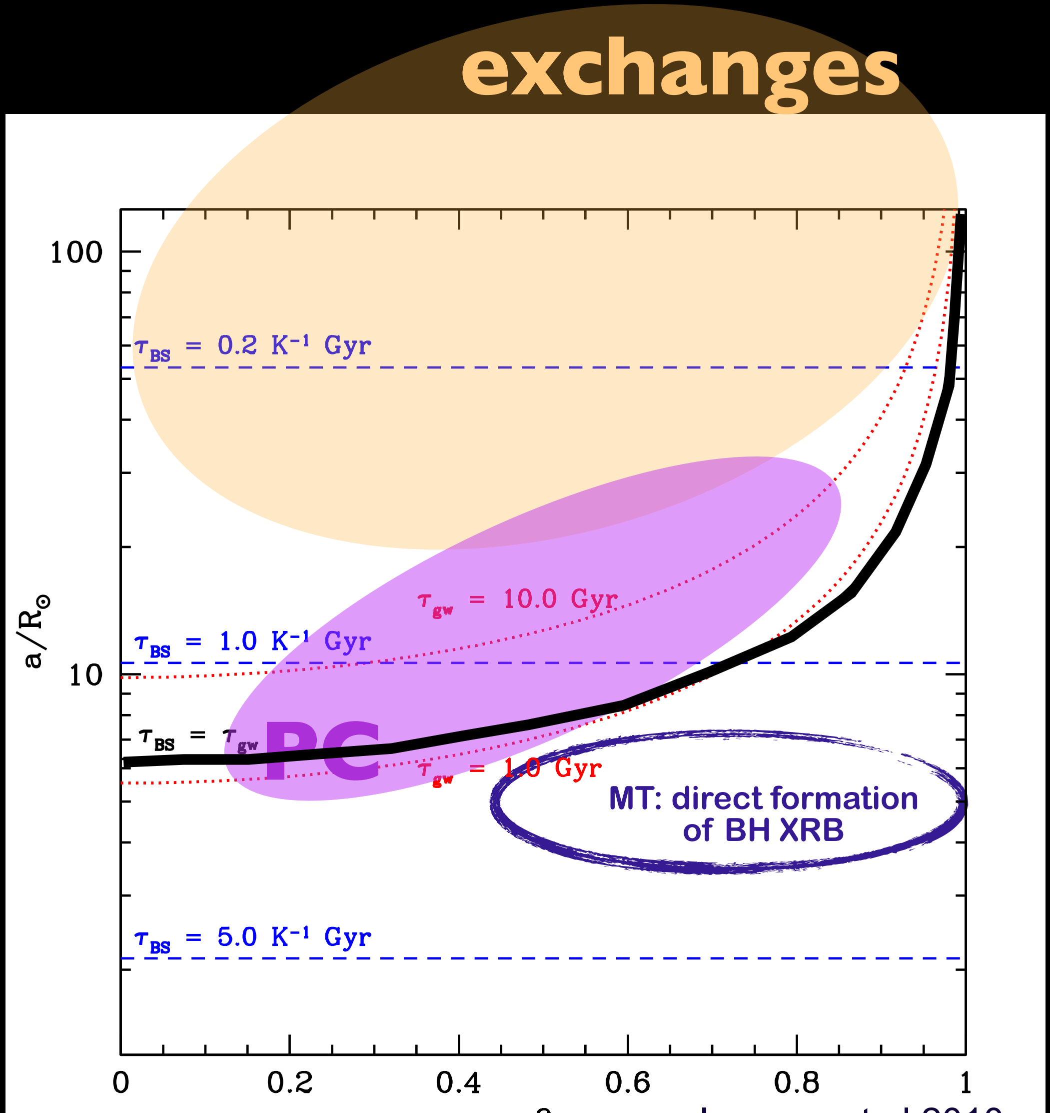
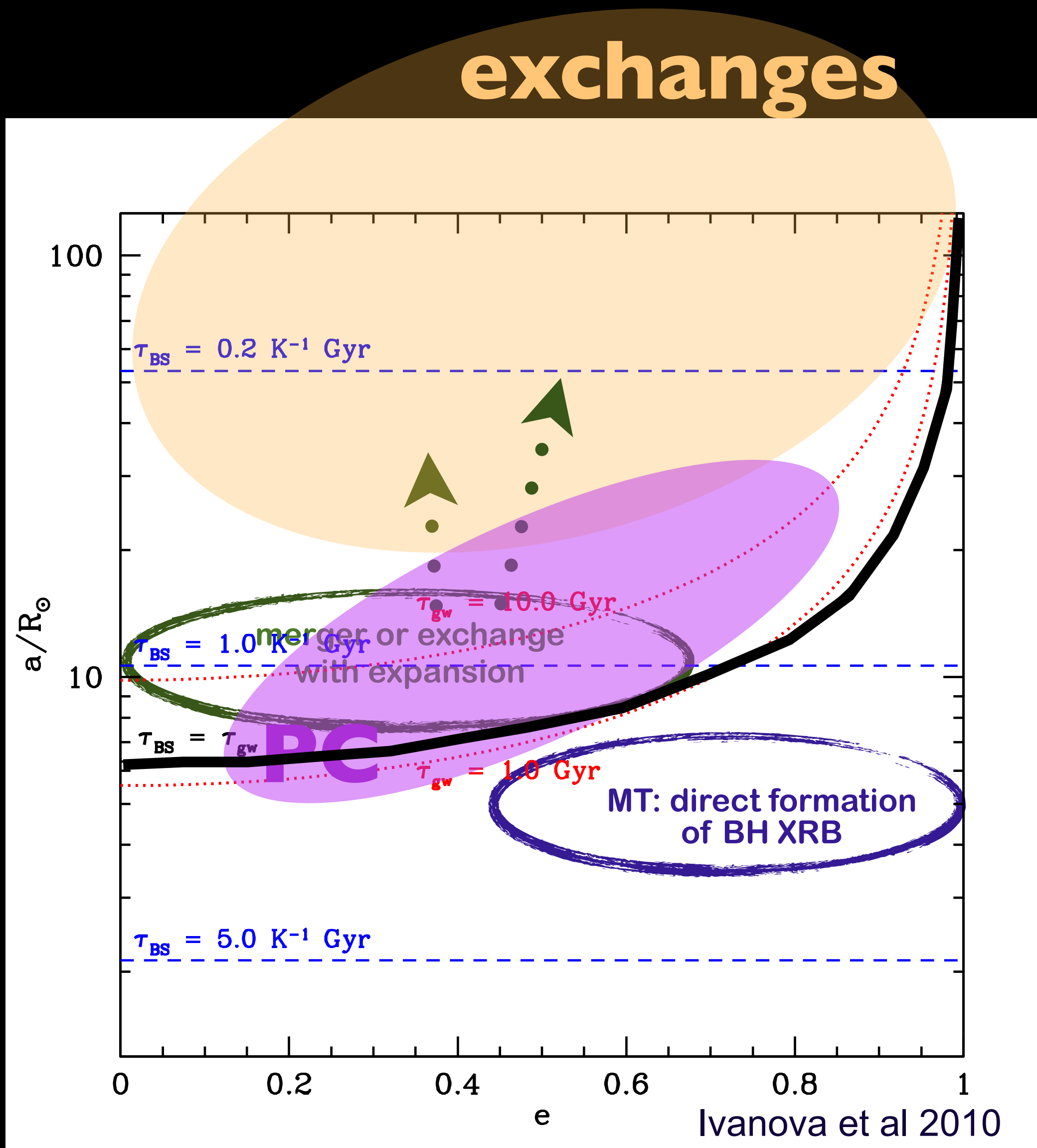
Ivanova et al 2010

BH-WD in GCs



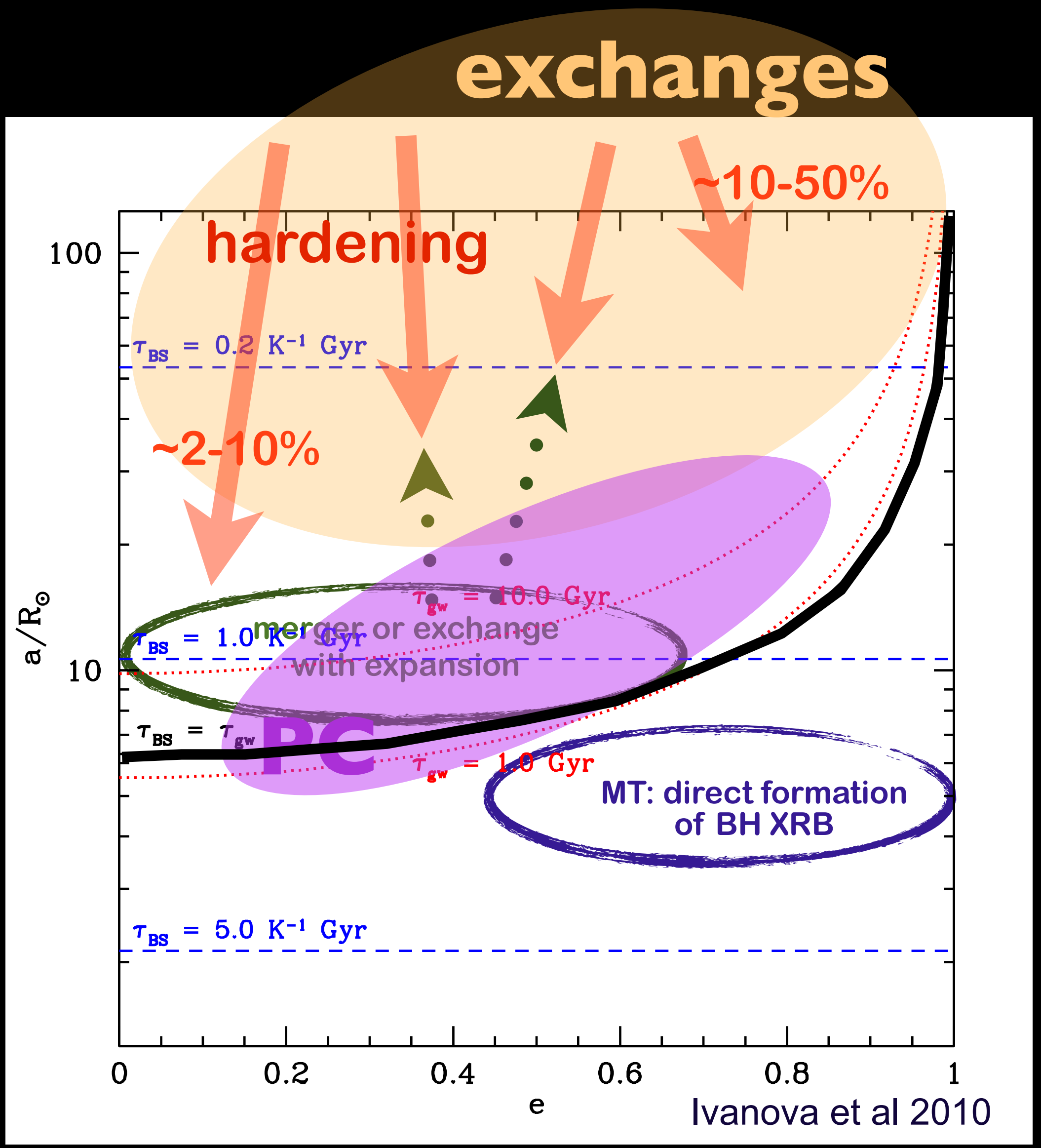
Ivanova et al 2010

BH-WD in GCs



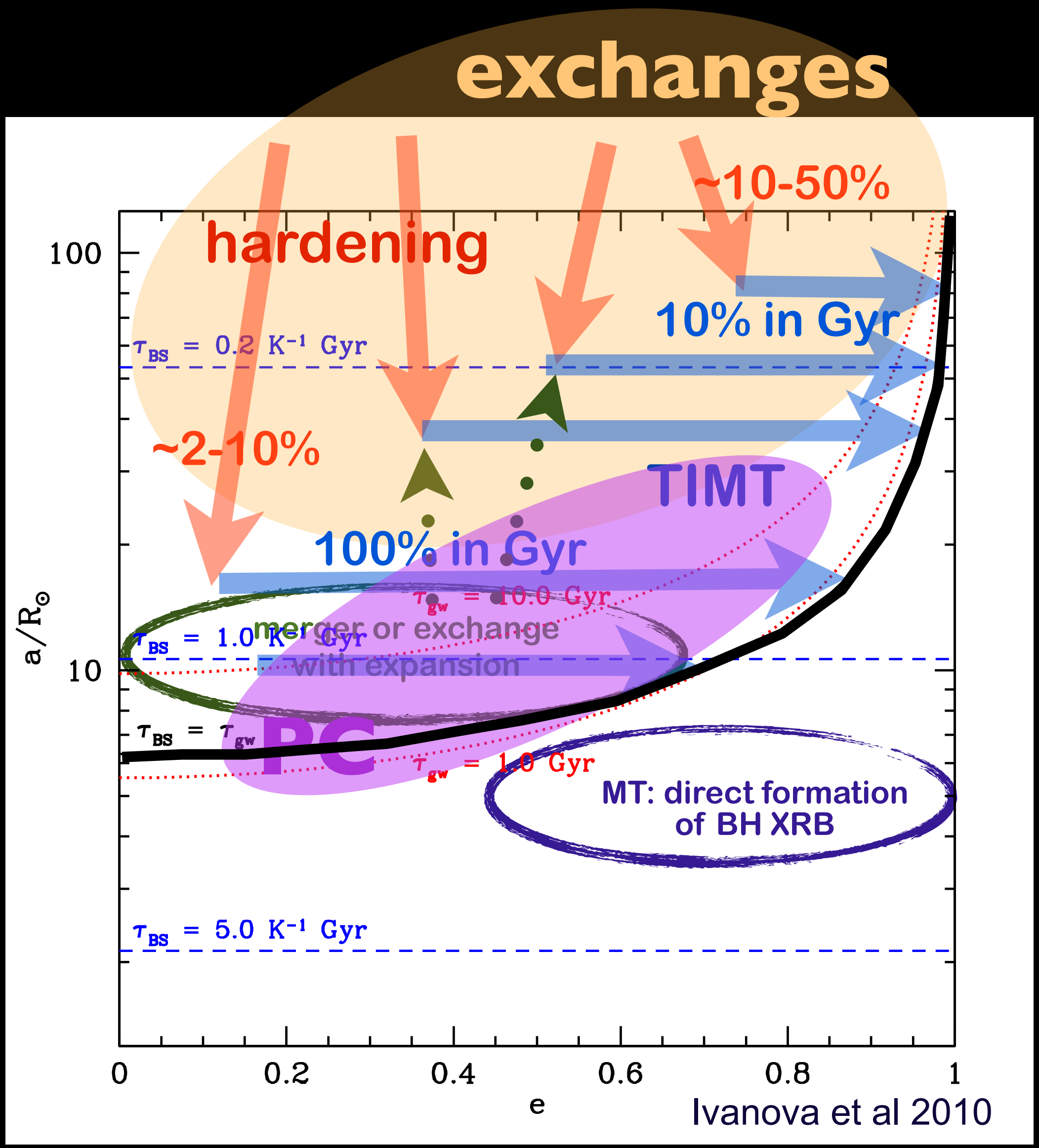
exchanges
100
10
a/R⊙
e
0
0.2
0.4
0.6
0.8
1
τBS = 0.2 K⁻¹ Gyr
τBS = 1.0 K⁻¹ Gyr
τBS = 5.0 K⁻¹ Gyr
τBS = τgw
τgw = 10.0 Gyr
τgw = 1.0 Gyr
merger or exchange
with expansion
PC
MT: direct formation
of BH XRB
Ivanova et al 2010

BH-WD in GCs



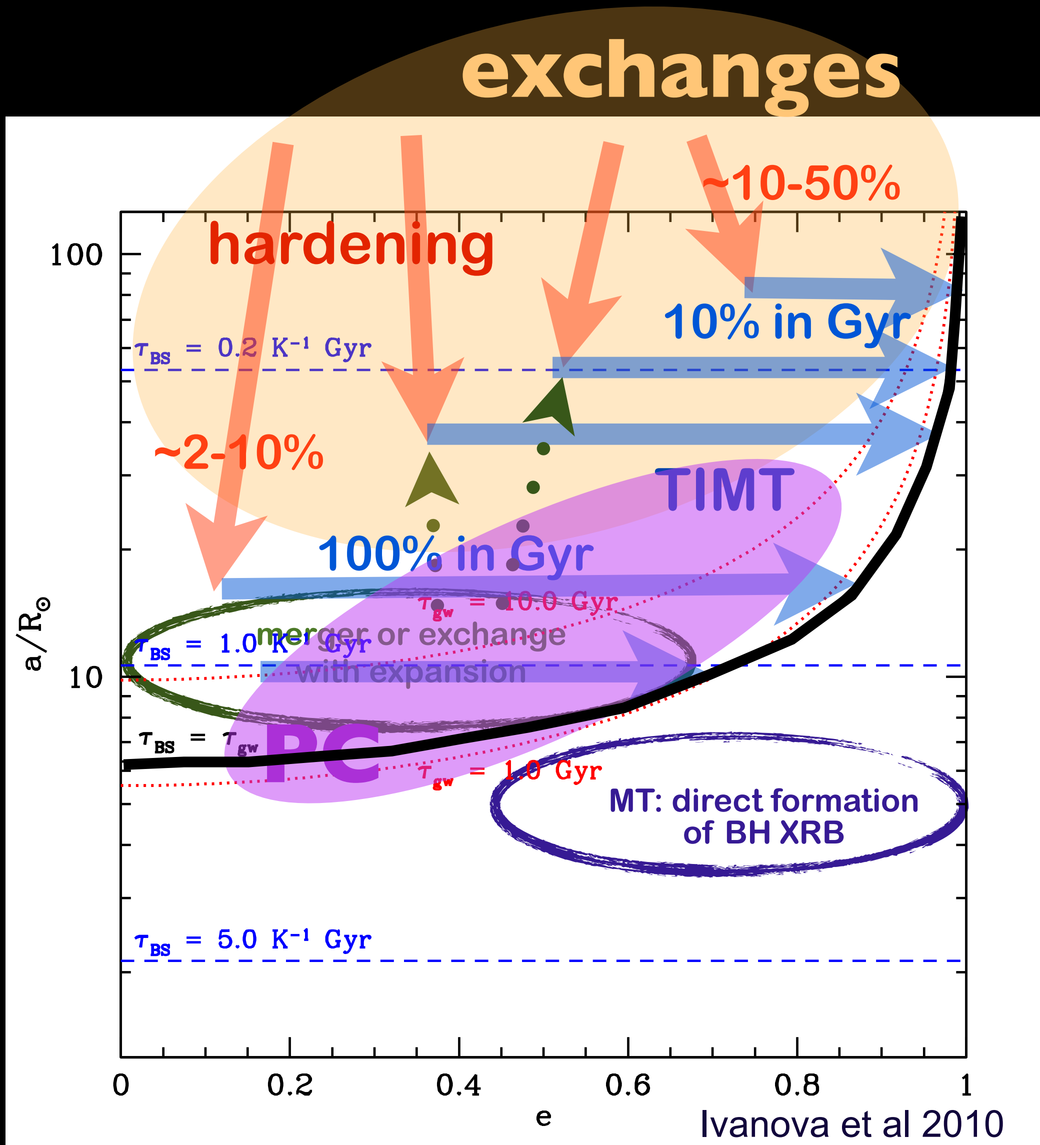
exchanges
~10-50%
hardening
~2-10%
τ_{BS} = 0.2 K⁻¹ Gyr
τ_{gw} = 10.0 Gyr
merger or exchange
with expansion
τ_{BS} = 1.0 K⁻¹ Gyr
$\tau_{BS} = \tau_{gw}$
PC
τ_{gw} = 1.0 Gyr
MT: direct formation
of BH XRB
τ_{BS} = 5.0 K⁻¹ Gyr
100
10
a/R⊙
0
0.2
0.4
0.6
0.8
1
e
Ivanova et al 2010

BH-WD in GCs



exchanges
hardening
~10-50%
~2-10%
10% in Gyr
100% in Gyr
TIMT
PC
merger or exchange
with expansion
MT: direct formation
of BH XRB
τ_{BS} = 0.2 K^{-1} Gyr
τ_{BS} = 1.0 K^{-1} Gyr
τ_{BS} = 5.0 K^{-1} Gyr
τ_{BS} = τ_{gw}
τ_{gw} = 10.0 Gyr
τ_{gw} = 1.0 Gyr
a/R$_\odot$
e
100
10
0
0.2
0.4
0.6
0.8
1
Ivanova et al 2010

BH-WD in GCs

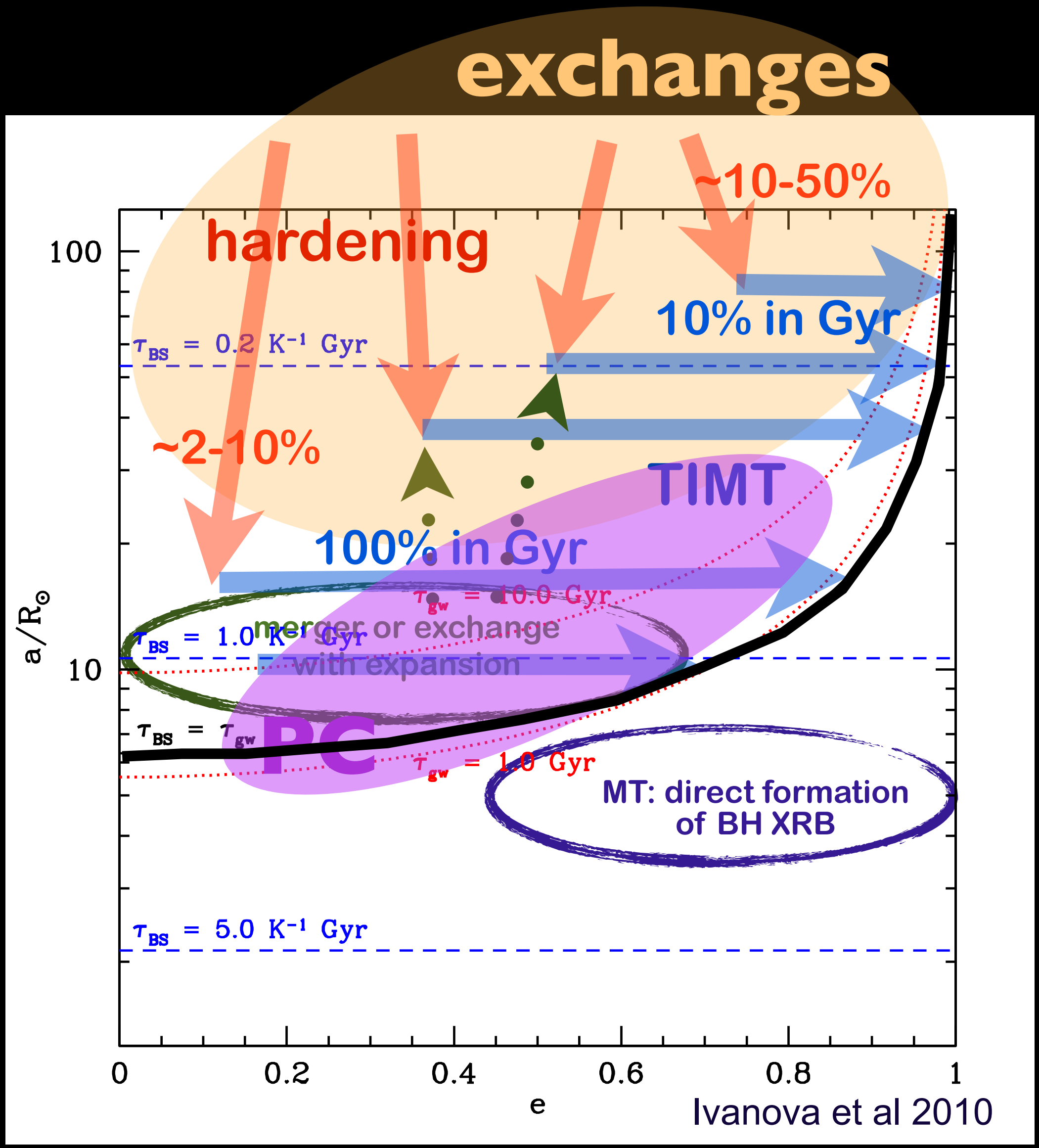


Almost no direct LMXB formation - unlike NS-RG case, BH-RG collision do not make tight enough binaries

Triples induced mass transfer is the most important mechanism.

The combined rate of all the channels is ~4x10^{-2} per BH per Gyr. Retention of 1% of all ever formed BHs is the minimum value to explain the formation rates inferred from the observations.

BH-WD in GCs



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Maccarone et al 2010: large X-ray flux variation consistent with to be in a triple

Final points

- Different formation channels are important at different Lx luminosities. MS&WD for Milky Way, WD&RG for extragalactic.

- ECS/AIC are the must *unless* initially ALL GCs were ~10 more massive or natal kicks were totally different from MW NSs.

- radio bMSPs and UCXBs?

- BH-WD LMXBs give new constraints on the dynamical evolution of BH population in GCs.

- metallicity: lifetime of RGs matters.

- triples are crucial for GC LMXBs, but especially for BH XRBs.

- There is no yet solid scenario to explain faint BH XRBs with non-degenerate donors, especially to catch up with the rate Jay discovers them.