Formation and Evolution of Compact Objects in Dense Clusters

A Theory Overview

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12 Jan 2009

NSs in GCs

- *LMXBs's formation rate in GCs vastly exceeds that in the field (about 100 times more)*
- *most of known MSPs are located in GCs*

Outline

NS

making them and keeping them in

LMXB

the standard formation scenario

dynamical formation

MSPs

the standard formation paradigm

formation in globular clusters and the consequence for the standard paradigm

Red & Blue GCs

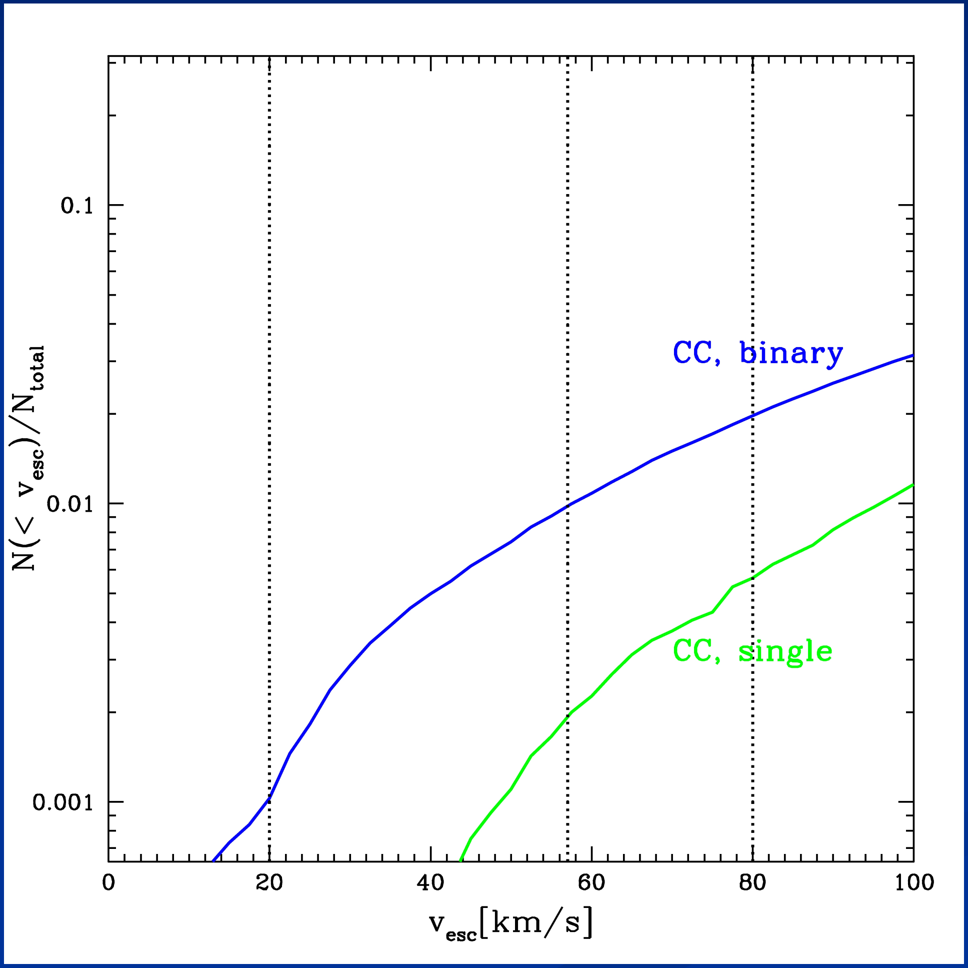
Triples

NS production

- Core-collapse SNe:

Single stars mass range ~8-21 $M_\odot$(Z=0.02) and ~7-19 $M_\odot$ (Z=0.001)

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



a typical cluster of $2x10^5$ M⊙

would have produced ~3000 CC NSs (by present 10-11 Gyr, assuming the only mass loss from a GC through a stellar wind)

if the escape velocity ~40km/s, then 1 NS will be retained if all stars were initially single and 15 if all stars were initially in binaries

NS production

- Electron-capture SNe: ***degenerate*** ONeMg core reaches 1.38 $M_\odot$ *no iron core !*

(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*).

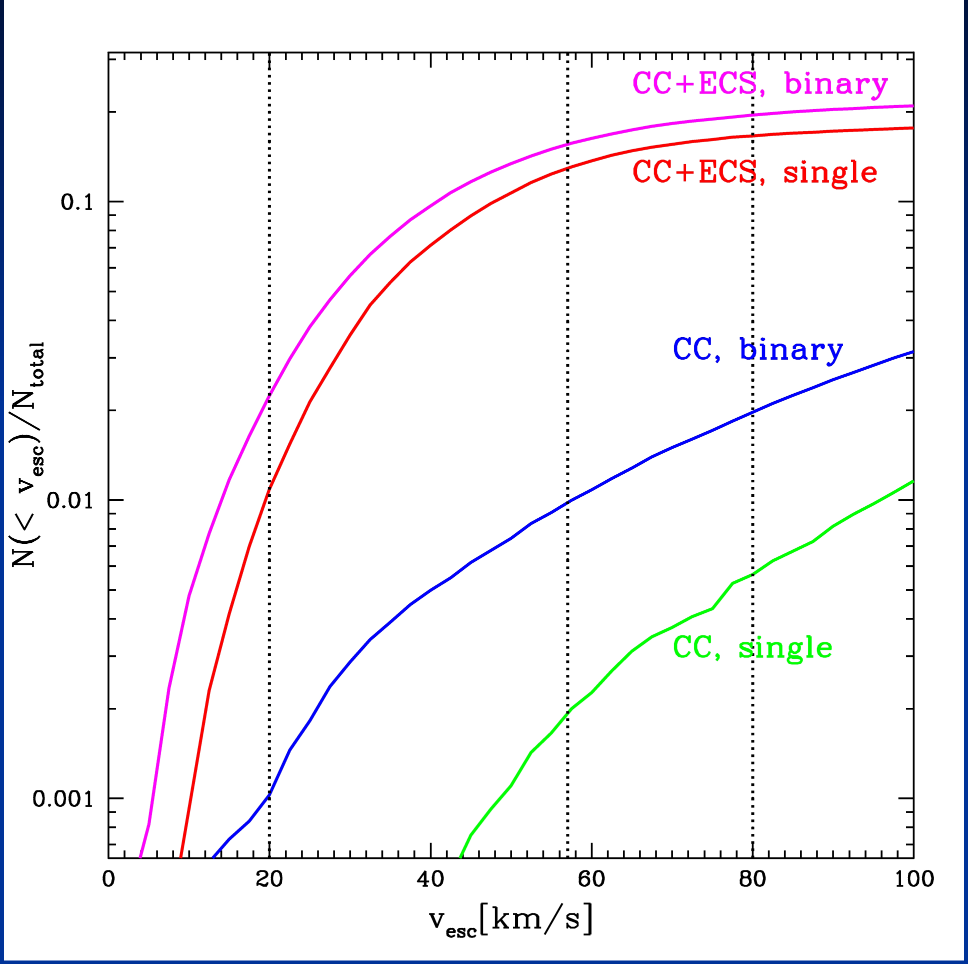
In normal stellar population, only small fraction of normal stars will experience ECS

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

Kicks are smaller than in the case of CC Sne and do not exceed 100 km/s

(Buras et.al. 2005)

NS retention



assuming 40 km/s kick,

a typical cluster of 2x10^5 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.

So, it is possible to form and keep NSs in GCs, BUT:

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 5x10^7-1.5x10^9 yr vs 2-3x10^{7}yr for CC Nss.

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

Low-Mass X-ray Binaries

Compact accretors - NS or BH

RLOF Donors -

MS, RG, WD/degenerate

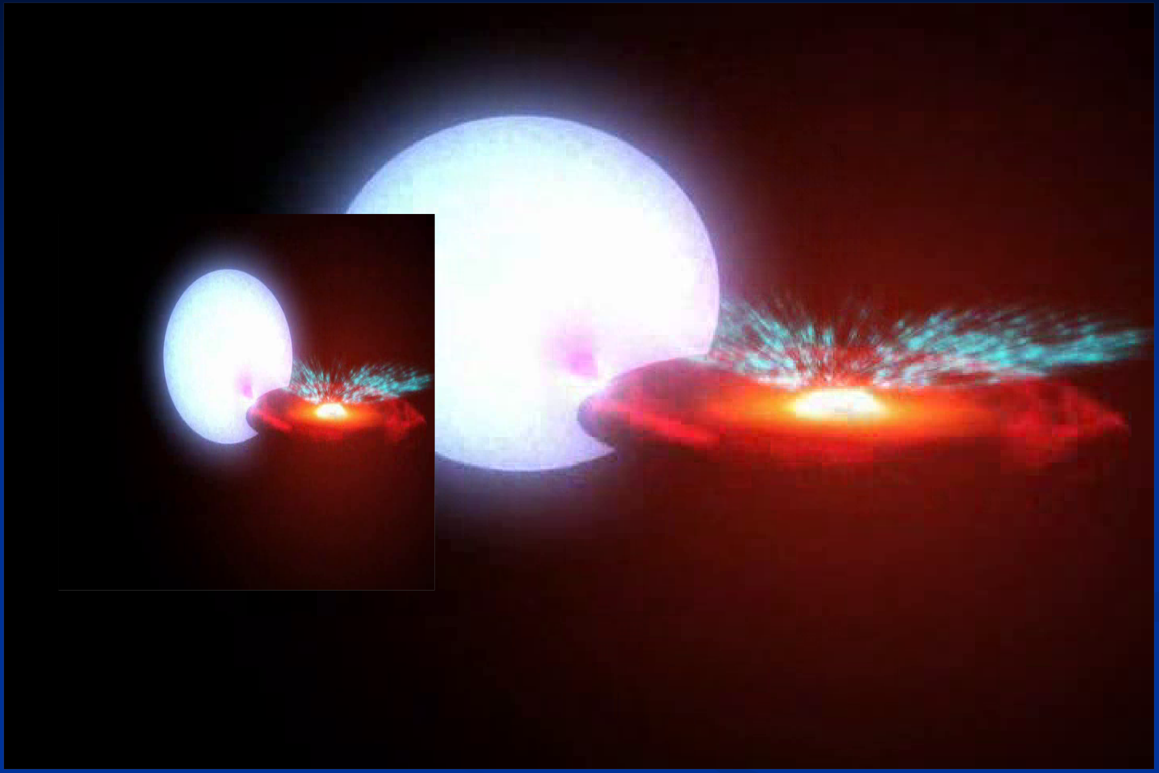
low-mass, < 1M⊙

Binary Periods:

10 minutes to ~100 days

Ages: ~ 0.1 - 10 Gyr

MT timescale 10^7-10^9 yr



Credit: NASA/CXC/A.Hobart

Lx: can appear as

a persistent or as a transient source.

~10^{32} erg/s(in quiescence, qLMXB)

to ~10^{39} erg/s (and may be more in outbursts)

Can be detected in distant Galaxies in X-ray.

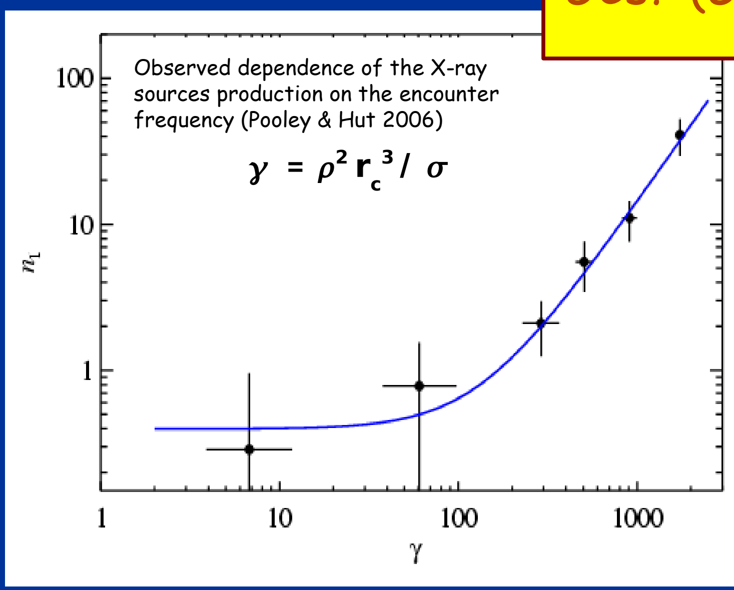
LMXBs in GCs

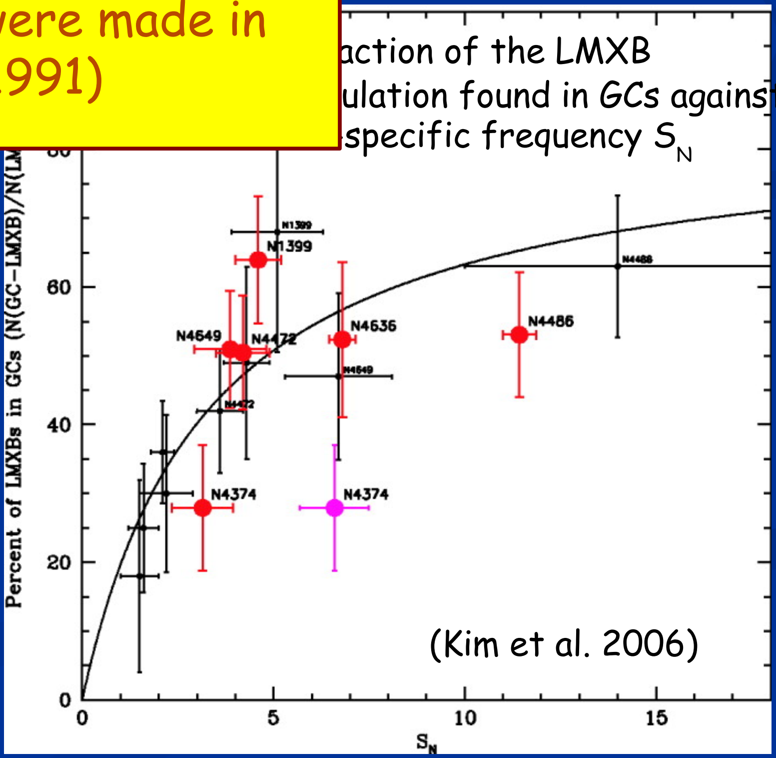
- LMXBs are dynamically formed in GCs, as their formation rate in clusters vastly exceeds that in the field (about 100 times more), 13 bright LMXBs, several quiescent LMXBs (qLMXBs) in 47 Tuc, several in other clusters (wCen, M80, NGC6440, NGC 6397,...).

- number of qLMXBs has very strong dependence upon the cluster density (Heinke et al. 2004).

- bright LMXBs preferentially reside in metal-rich cluster (3 times more likely). It was noted for our galaxy on the set of 13 LMXBs in GCs, M31 - 19 LMXBs, NGC4472 - 30 LMXBs, M82 - 58 LMXBs (Grindlay 1993, Belazzini et al. 1995, Kundu et al. 2003, Jordan et al. 2004).

All NS LMXBs were made in GCs? (Grindlay 1991)



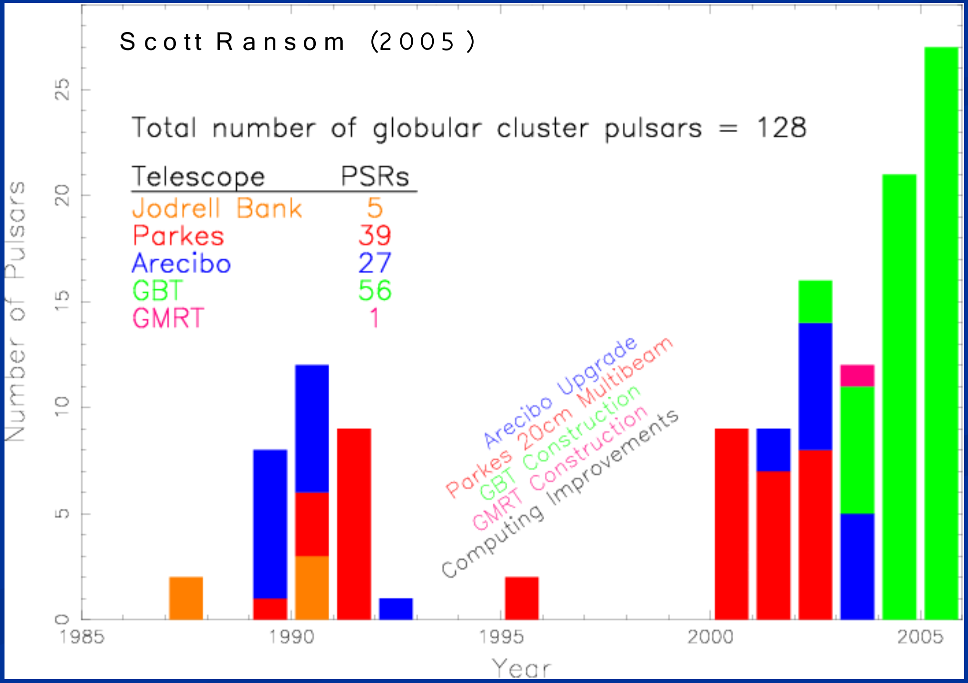


LMXBs & MSPs in GCs

~140 MSPs are currently known in GCs,
~83 in the rest of the Milky Way,
~1000 estimated to be present in the Galactic GC system

Do all NSs that were LMXBs become MSPs??

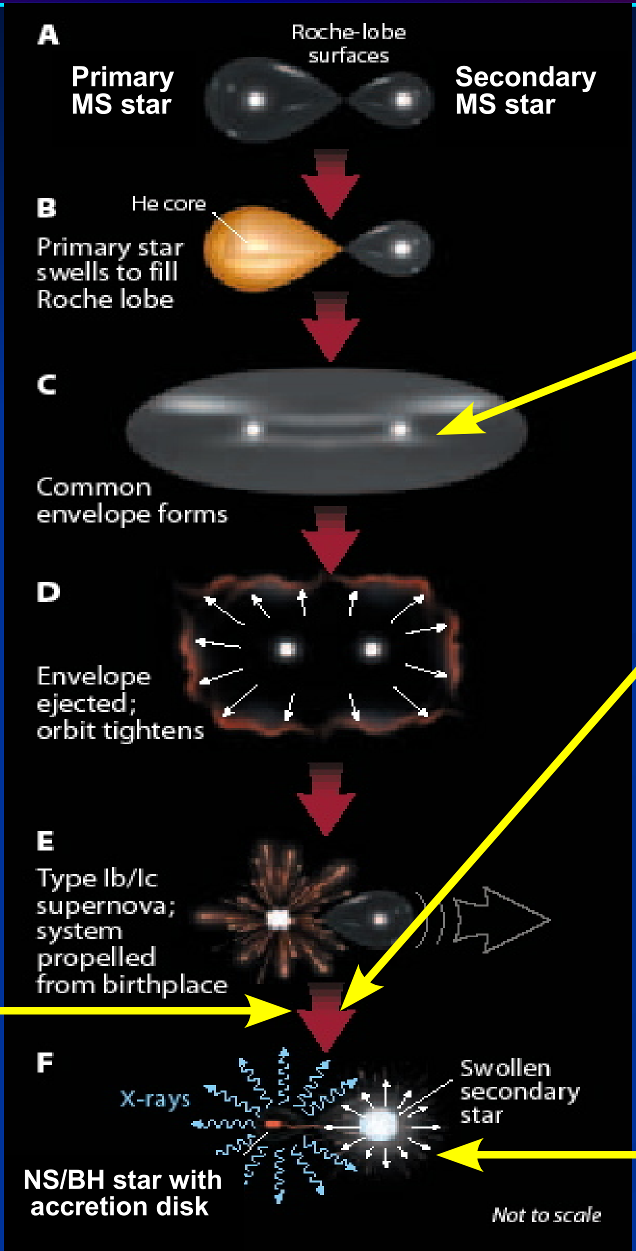
A millisecond pulsar (MSP), "recycled pulsar", is a pulsar with a rotational period in the range of about 1-10 milliseconds.
MSPs are believed to be spun up through a disk accretion in Roche lobe overflowing binaries.
Compared to young pulsars, they have low B and long spin-down times.



LMXBs: standard paradigm

Bhattacharya & van den Heuvel (1991)

artist impression, Sky&Telescope



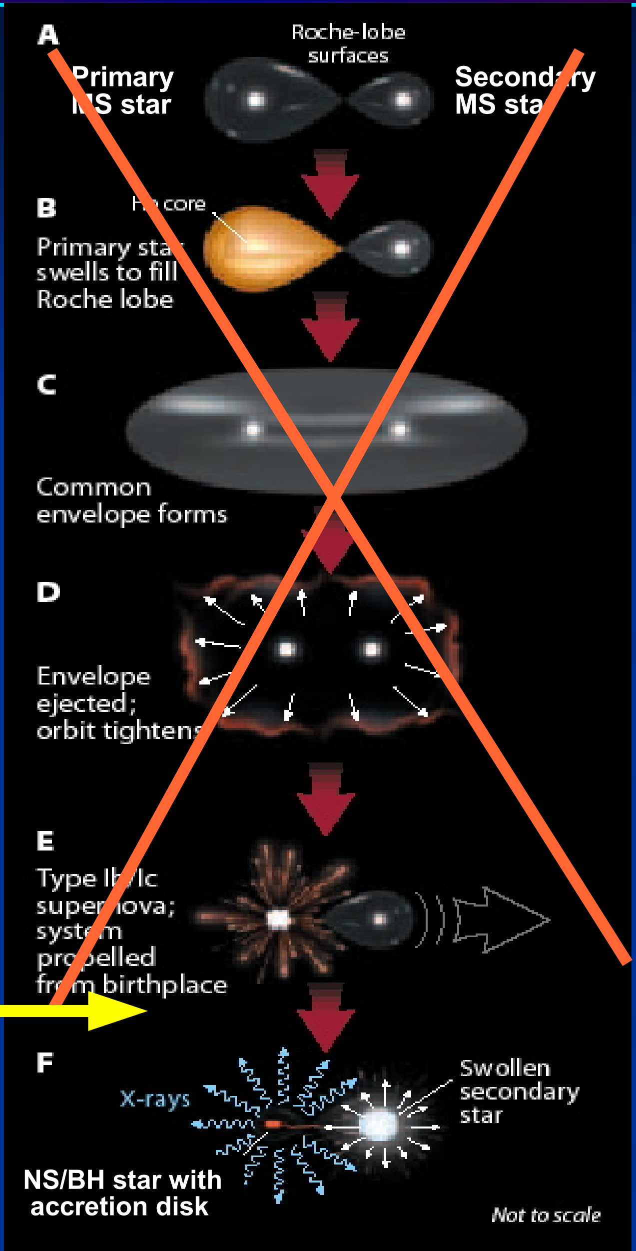
a **common envelope** (CE) phase, during which the low-mass star spirals inward through the extended envelope of the massive primary star, and the phase is terminated upon ejection of the common envelope – the ejection uses the orbital energy as an energy source (**Paczyński 1976)**

The **magnetic braking** is the process of the angular momentum loss for late type stars by magnetically coupled wind. The efficiency of the braking is to the density of the stellar wind, and therefore to the mass loss rate. 2 different prescriptions (Skumanich 1972, Ivanova & Taam 2003)

Further orbit shrinkage due to tides, magnetic braking and gravitational waves in, likely, an eccentric binary

During MT, an LMXB can radiate in X-ray as a persistent source or as a transient source. A transient spends most of the time in quiescence. During "quiescence" mass is accumulating to the accretion disk, and during outburst most of disk falls on the compact object.

LMXBs in GCs: cheating!

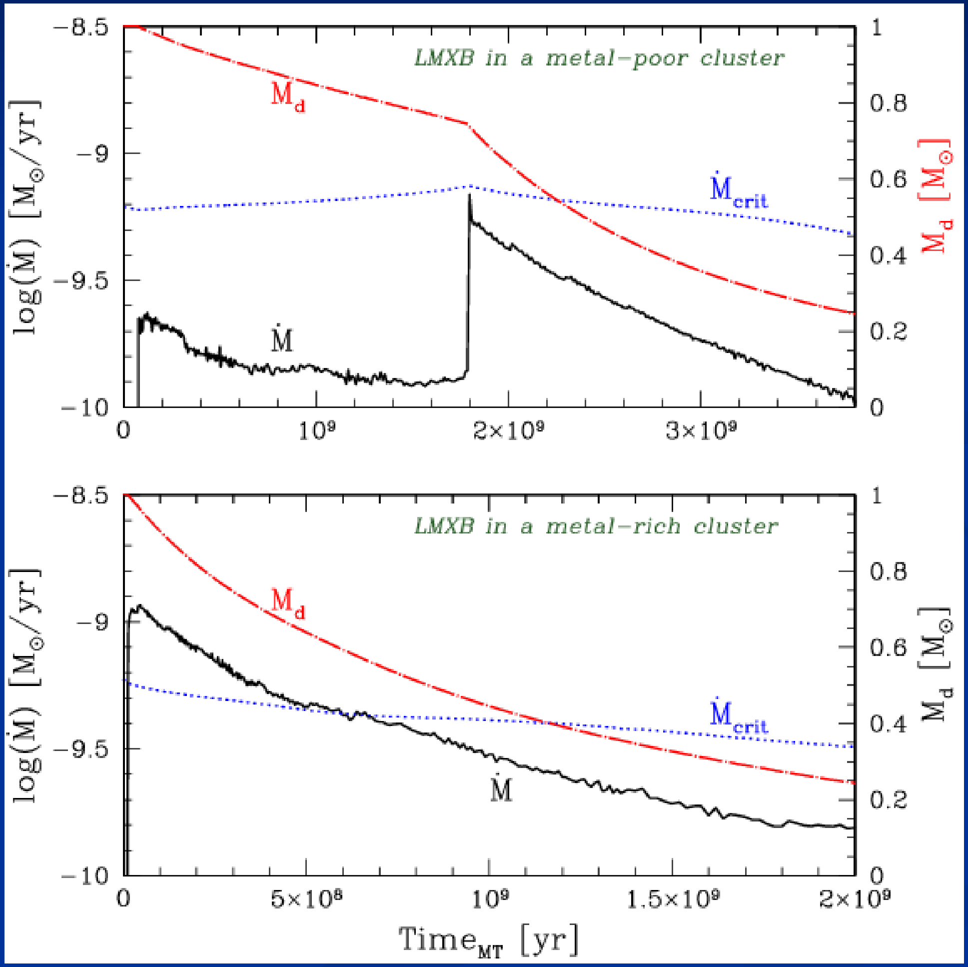


SHORTCUT:
dynamical binary formation

NS-MS LMXBs: life-time

NS-MS

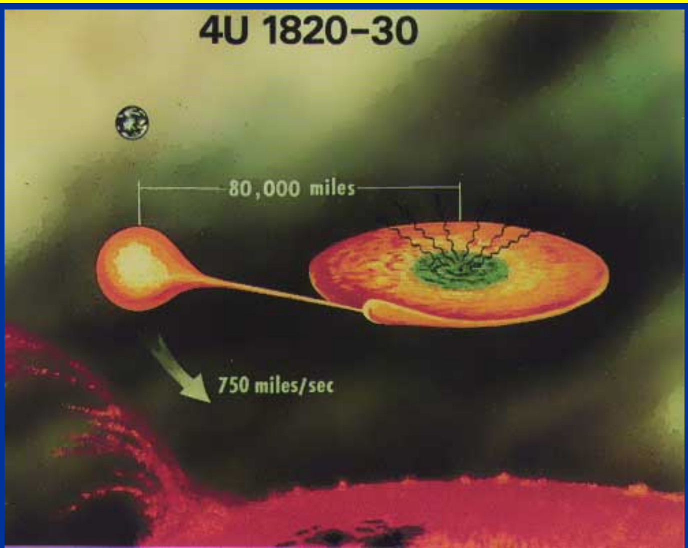
Bright & persistent for only $t_{lmxb} \sim \frac{1}{2}\,10^9$ yr

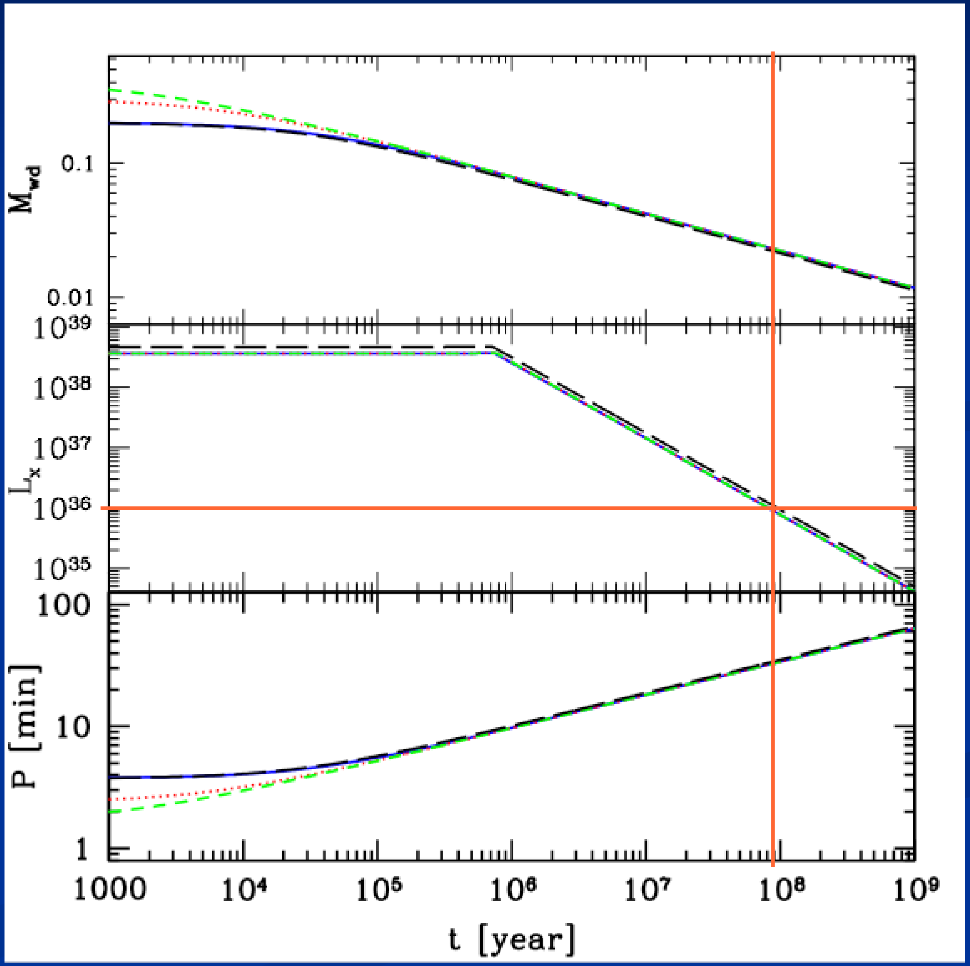


NS-WD LMXBs: UCXBs

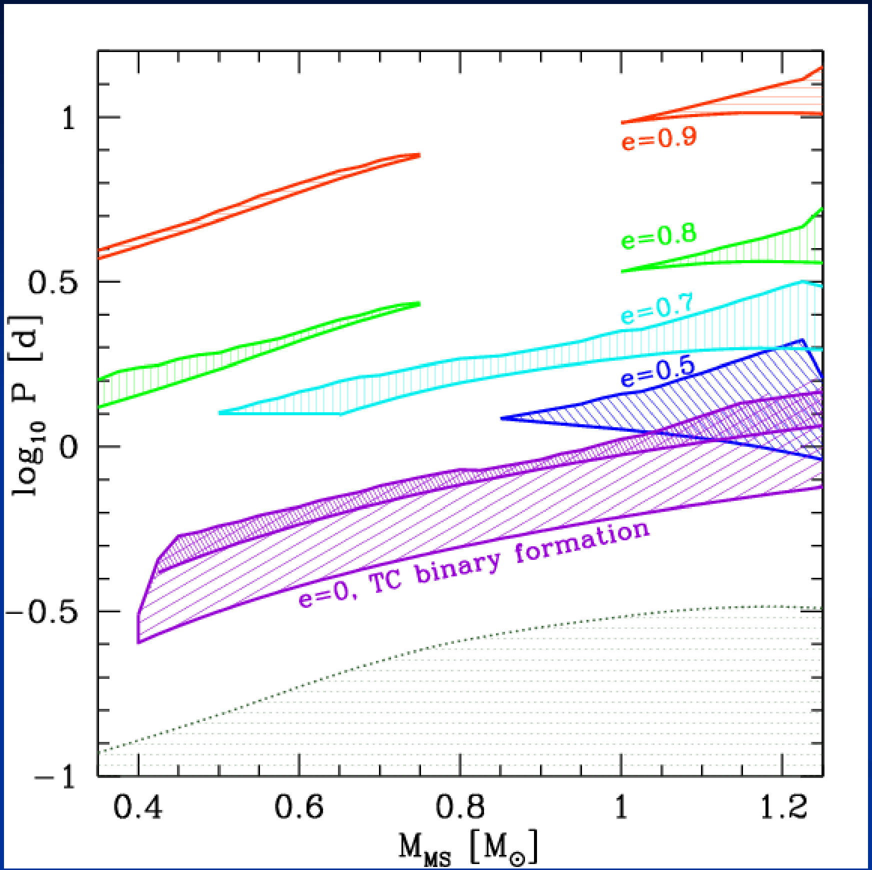
- subset of low-mass X-ray binaries (LMXBs) and have periods P <1 h – have a compact donor
- persistent
- believed to be related to NS recycling: half of Galactic accretion-powered millisecond X-ray pulsars are UCXBs and may be the progenitors of eclipsing binary radio pulsars with very low-mass companions
- Their relative fraction in the field is **much** smaller than in GCs

“Bright” ($L_x>10^{36}$ erg/s) for only $t_{ucxb}\sim10^8$ yr





Prospective NS-MS LMXBs

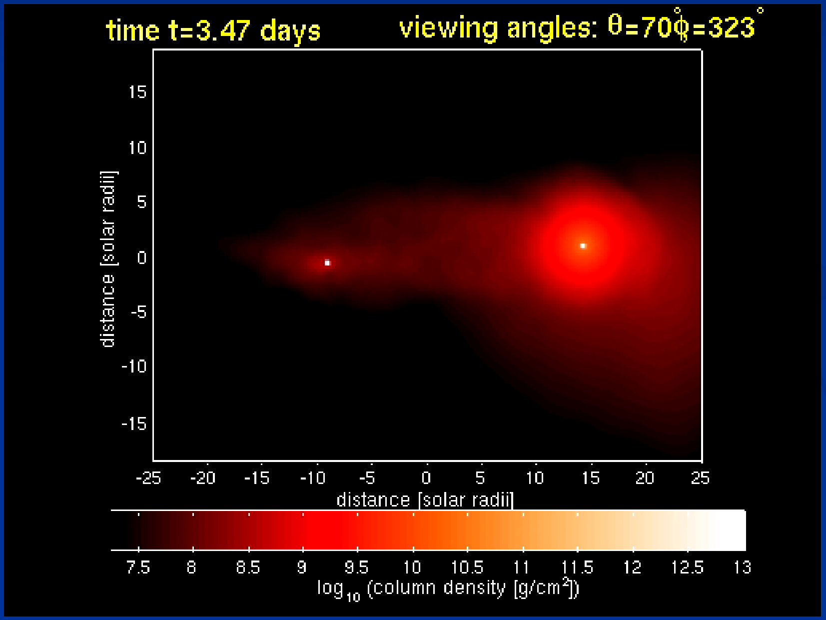


There is a very narrow post-encounter parameters space that a binary can have in order to become an LMXB within the Hubble time.
Almost NONE for NS-WD LMXBs...unless eccentricity pumping...

NS+RG collisions-"dynamical CE"

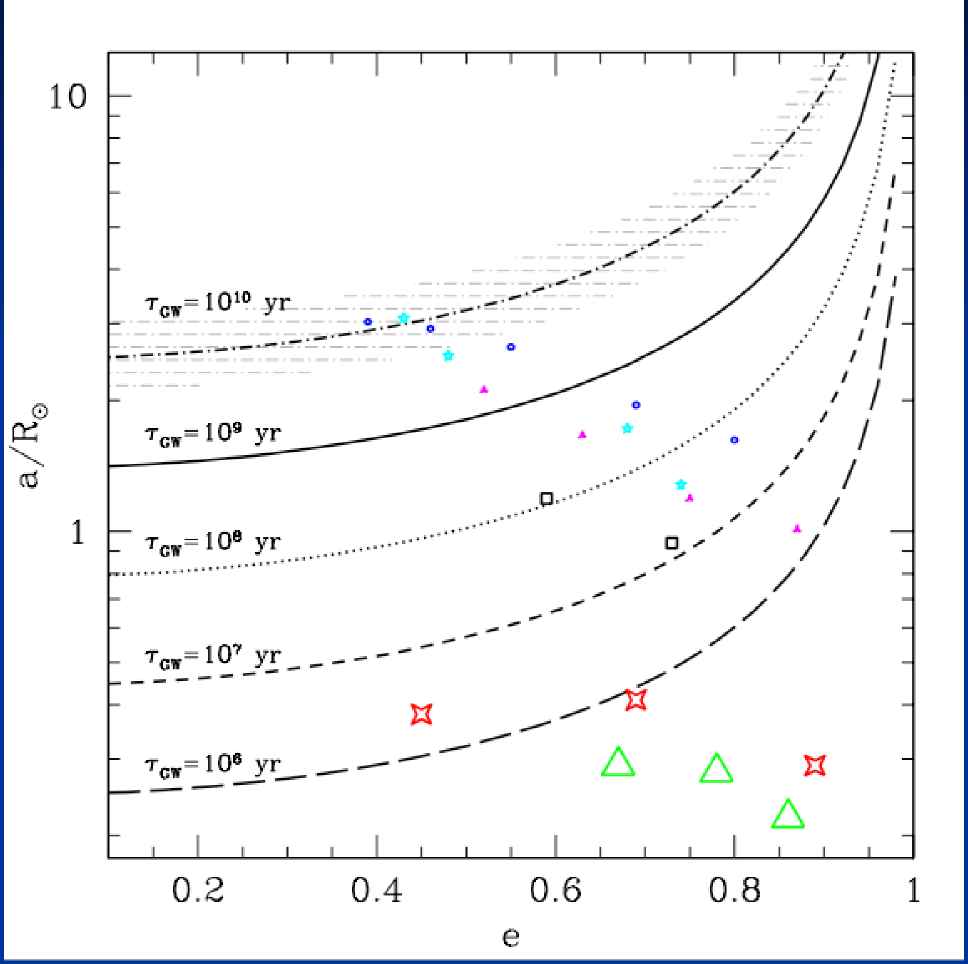
SPH simulations using "realistic" RG structure

Collision: NS of 1.4 $M_\odot$ NS and RG of 0.9 $M_\odot$ (core 0.23 $M_\odot$) at 3.8 $R_\odot$



Lombardi et al. (2006)

Physical collisions of NS and RG



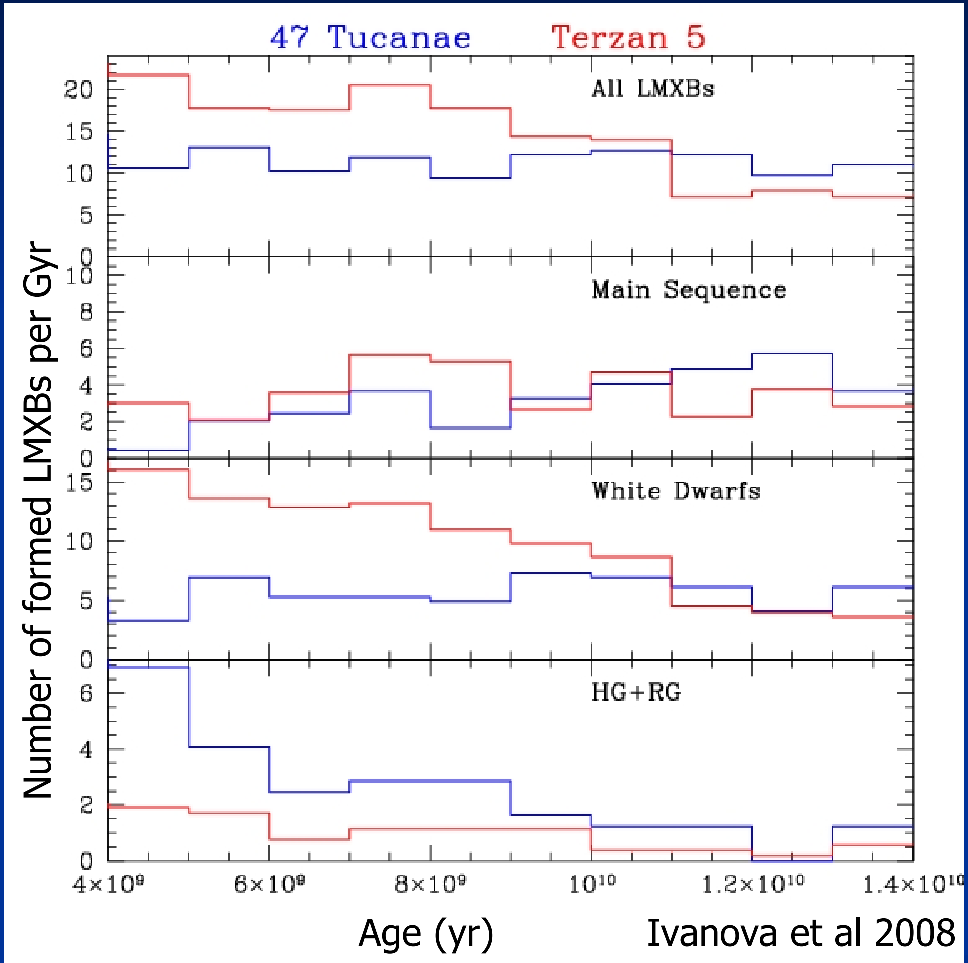
- constant merger time for a 1.4 $M_\odot$ NS and a 0.25 $M_\odot$ WD, as function of post-collision eccentricity e and a.
- Data points from SPH results.
- Data point size indicates likelihood of collision (symbols for less evolved RGs are larger).
- The hatched area shows how the merger time changes for slightly different binary masses: the upper boundary corresponds to a 1.5 $M_\odot$ NS with a 0.45 $M_\odot$ WD, and the lower boundary corresponds to a 1.3 $M_\odot$ NS with a 0.15 $M_\odot$ WD.

set of SPH numerical simulations

$$e_f = 0.88 - p \,/\, (3\, R_{RG})$$

$$a_f = p \,/\, (3.3\,(1 - e_f^{\,2}))$$

LMXBs: formation rates



Terzan 5

NS-MS: ~ 2-4/Gyr now

~50 in 11 Gyr

NS-WD: ~ 10/Gyr

~ 150 till 11 Gyr

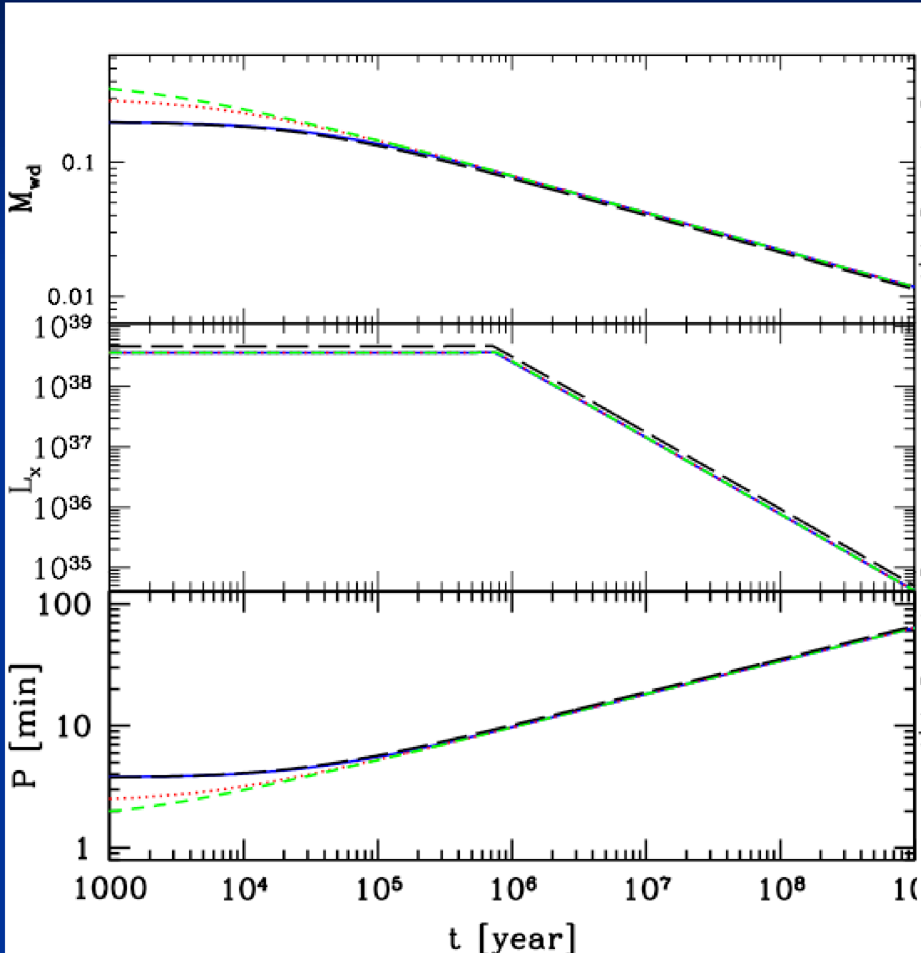
To predict the observed numbers, one needs not only the formation rates, but also the lifetimes!

million-body runs

LMXBs life-times

UCXBs (NS-WD)

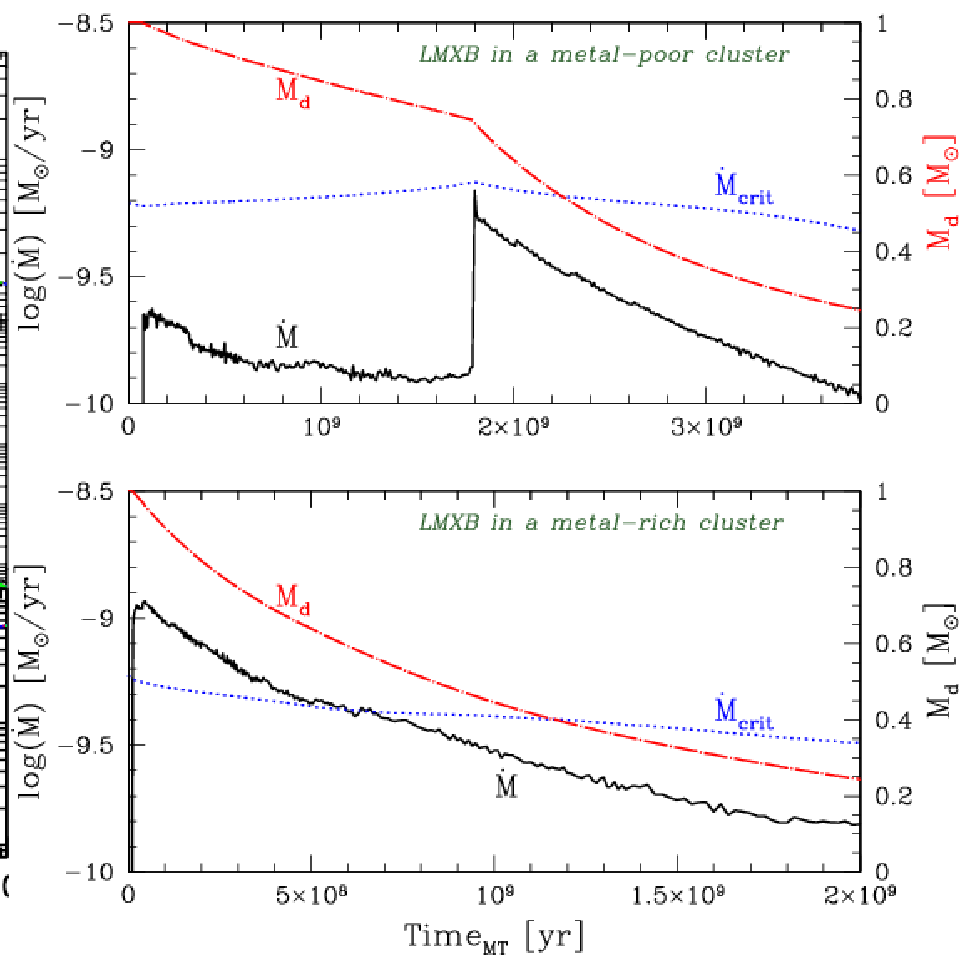
"Bright" (L_x>10^{36} erg/s) for only t_{ucxb}~10^8 yr



Top: WD masses; middle: X-ray luminosity
bottom: binary period [minutes]

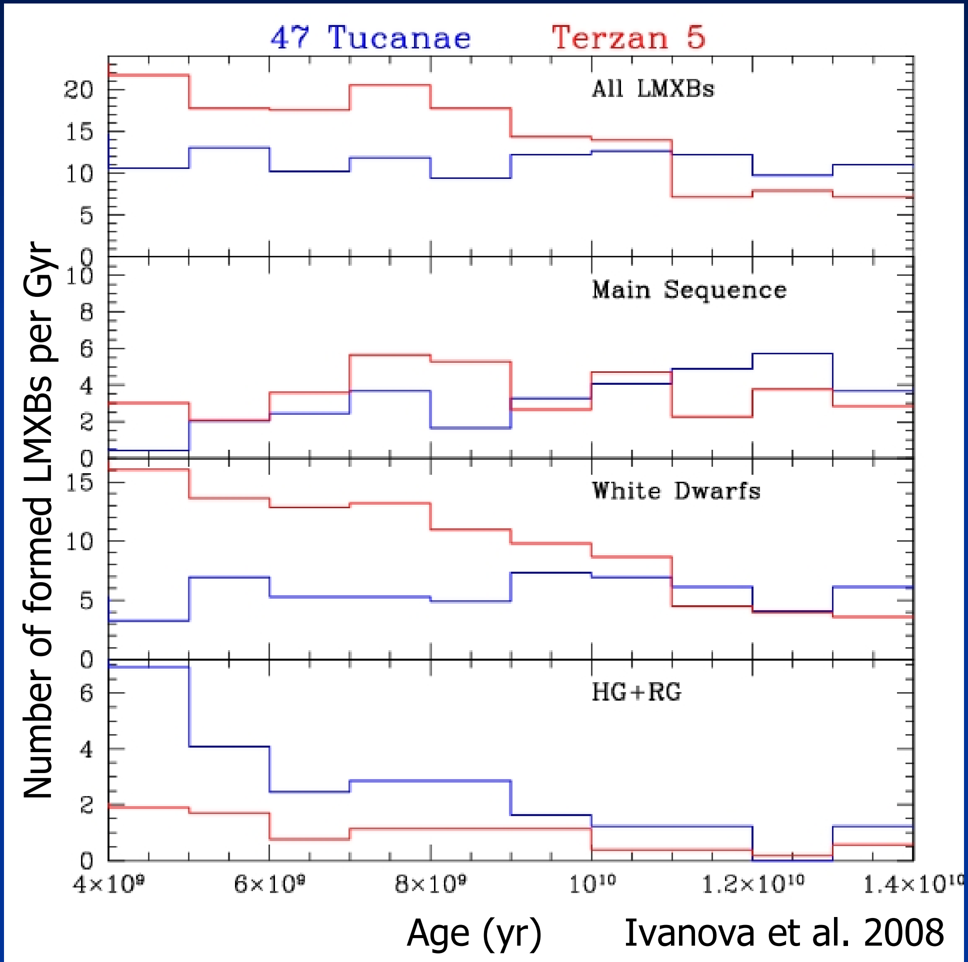
NS-MS

Bright & persistent for only t_{ucxb}~ ½ 10^9 yr



most time in quiescence

LMXBs: rates



Terzan 5

NS-MS: ~ 2-4/Gyr now,

τ_p ~0.2-0.5 Gyr, τ_{Tot} ~2-3 Gyr

~50 in 11 Gyr

can have 4-12 qLMXBs

NS-WD: ~ 10/Gyr; τ_p ~0.1 Gyr

~ 150 till 11 Gyr

1 bright UCXBs is observed

can have several very faint qLMXBs

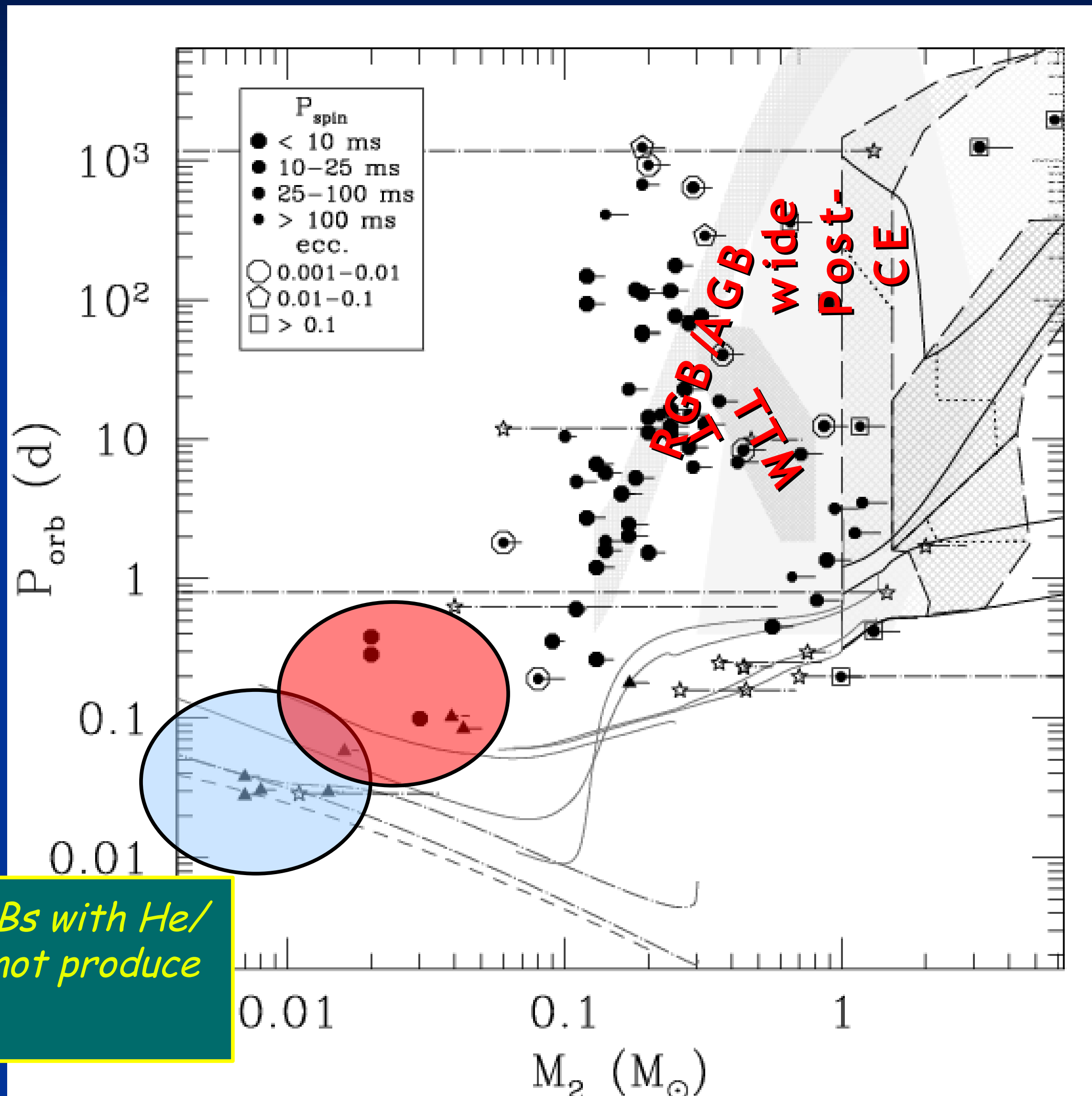
observed: 13 qLMXBs candidates

33 MSPs is observed, maximum 60 is estimated by LF (Ransom et al. 2007)

UCXBs do NOT produce radio MSPs!

bMSPs in field

LMXBs – triangle symbols (accreting MSPs) and star symbols



Deloye (2008)

It seems that UCXBs with He/CO rich donors do not produce bMSPs.

Accretion powered bMSP SWIFT J1756.9-2508

Krimm et al. 2007:

- 5.5 ms
- orbital period 54.7m
- minimum mass companion 0.0067-0.0086 $M_\odot$
- maximum mass companion 0.03 $M_\odot$
- 13 days outburst, no earlier outbursts found in archival data

was NOT detected in radio neither during the outburst, or later (Possenti et al 2007, Hessels et al 2007)

It is likely that dozens of MSPs, that did not turn on yet in radio, sit in GCs and could be detected only in outbursts OR as single MSPs if their binary was destroyed

Red & Blue

LMXBs preferentially reside in metal-rich cluster (3 times more likely). Was noted for our galaxy on the set of 13 LMXBs in GCs, M31 - 19 LMXBs, NGC4472 - 30 LMXBs, M82 - 58 LMXBs, … (Grindlay 1993, Belazzini et al. 1995, Kundu et al. 2003, Jordan et al. 2004, Kim et al. 2006, Kundu et al. 2007).

In NGC 1399, LMXBs are preferentially in the reddest clusters of the metal rich GCs.

- IMF is different? (Grindlay 1993)

  No, IMF is fairly universal (Kroupa 2002). In fact, metal-poor cluster produce MORE NSs.

- Stellar radii are different -> affect encounters rate? (Belazzini et al. 1995)

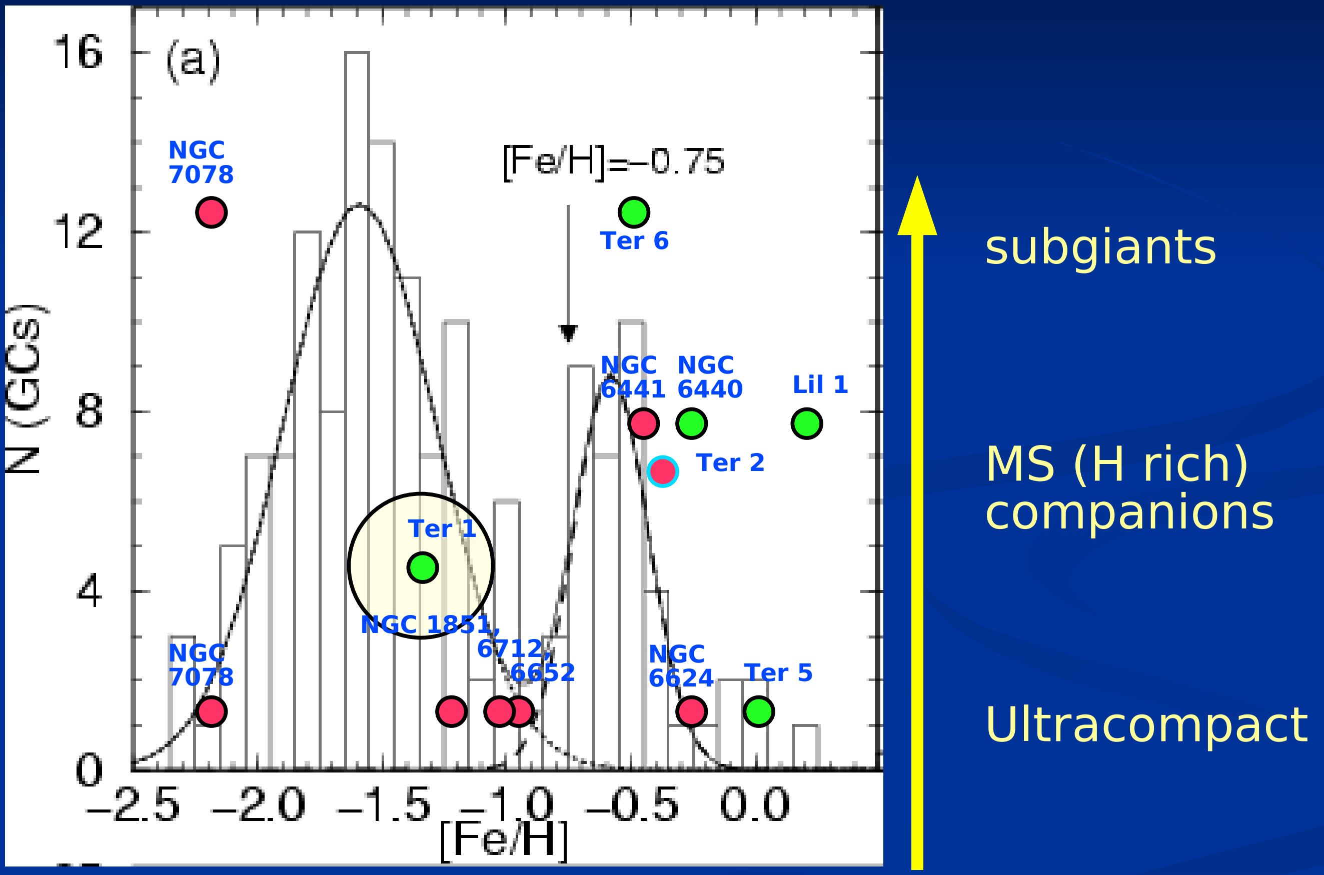
  Gives only about 30% increase, far from 3 fold…(Maccarone et al. 2004)

- Lifetimes of LMXBs are shortened due to irradiation induced winds? (Maccarone et al. 2004)

  This model predicts harder X-ray spectra in BGC LMXBs than RGC LMXBs, because of the extra absorption by accreting materials in BGC LMXBs. However the comparison the X-ray spectral hardness/absorption of LMXBs in red and blue clusters reveals no difference (Kim et al. 2006).

Red & Blue LMXBs

- persistent
- transient



Bica et al. 2006

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  Observations in metal-poor GCs are required to find out whether they have NS-MS qLMXBs

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- IMF **IS** different!?

  Dense metal-rich proto-GC, due to larger optical thickness, might have higher Jeans mass (Murray08)

Red & Blue LMXBs

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In NGC 1399 LMXBs are preferentially in the reddest clusters of the metal rich GCs.

Ivanova et al. 2008 suggested diagnostics:

II Winds (Maccarone) favor the same number of MSPs formation but no qLMXBs

Failed MB (Ivanova) favors the same MSPs & qLMXB formation rates

If no MSPs & no qLMXBs are present, IMF (Murray)

BFs measurements in halos could also provide a key

• IMF

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• IMF **IS** different!?

Dense metal-rich proto-GC, due to larger optical thickness, might have higher Jeans mass (Murray08)

• Primordial binary fraction is different???

At least some metal-poor GCs seem to have extremely low primordial BF, lower than in metal-rich GC

Red & Blue

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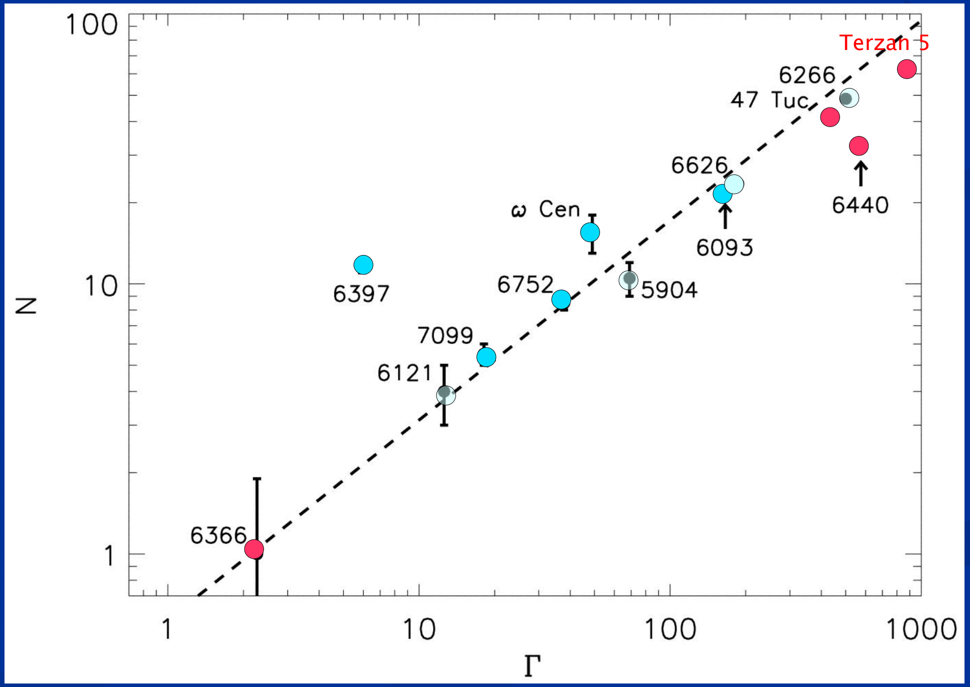
If no MSPs & no qLMXBs are present, IMF (Murray)

- Terzan 5: [Fe/H]=0, $\Gamma \sim 3\ \Gamma_{47\ Tuc}$:33 MSPs, LMXB + 12 qLMXB
- 47 Tuc: [Fe/H]=-0.76 :23 MSPs, 5 qLMXB

- M28 (NGC 6626) :
  - *moderately metal-poor* [Fe/H]=-1.45, $\Gamma_{M15} \sim 0.25\ \Gamma_{47\ Tuc}$
  - 12 MSPs - *third largest population*
  - qLMXB
- NGC 6397:
  - [Fe/H]=-1.95, $\Gamma_{6397} \sim 0.01\ \Gamma_{47\ Tuc}$
  - qLMXB (Heinke at al. 2003)
- M30 (NGC 7099):
  - [Fe/H]=-2.12, $\Gamma_{M30} \sim 0.04\ \Gamma_{47\ Tuc}$
  - qLMXB Lugger at al. 2007
- M15 (NGC 7078):
  - [Fe/H]=-2.26, $\Gamma_{M15} \sim 0.3\ \Gamma_{47\ Tuc}$
  - qLMXB with a MS companion 0.65 M⊙ (Heinke et al. 2008)
  - 8 MSPs



Pooley et al 2003

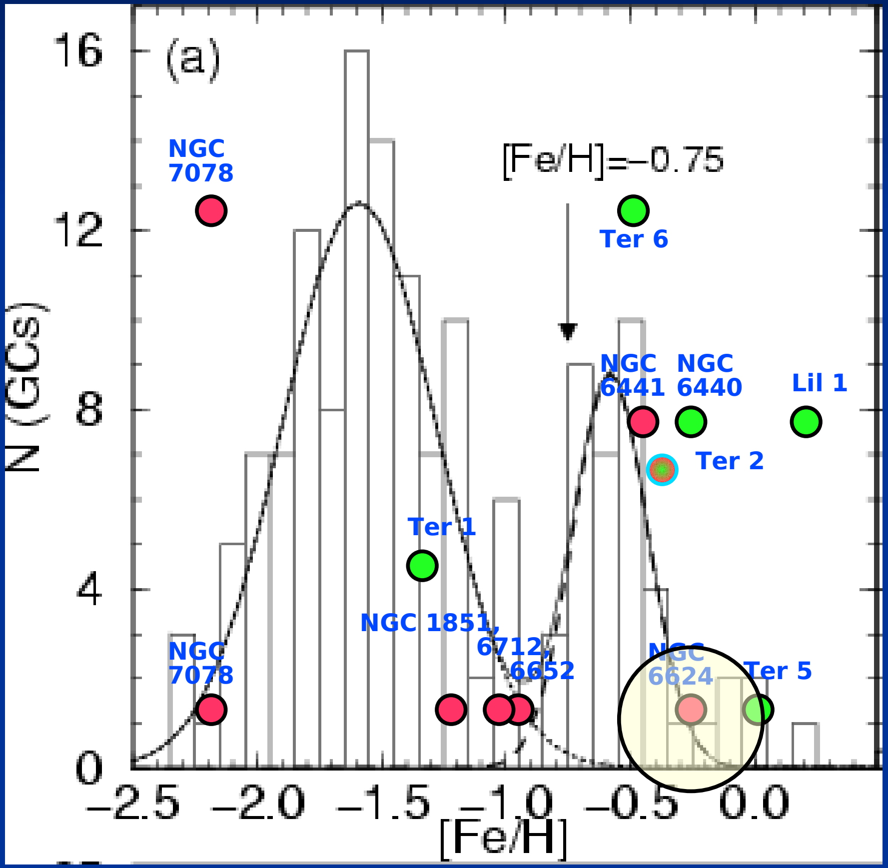
Red & Blue: qLMXBs & MSPs

[Fe/H]				$\Gamma/\Gamma_{47\ Tuc}$	
0.00	Terzan 5	12 qLMXB candidates (1 br trans)	33 MSPs	~2.5	Wijnands et al. 2005, Heinke et al. 2006.
-0.34	NGC 6440	8 qLMXB candidates, 1bright	6 MSPs	~2	Pooley et al. 2002, Heinke et al. 2003.
-0.59	NGC 6304	3 qLMXB candidates		~0.1	Guillot et al. 2009.
-0.60	NGC 6388	5 qLMXB candidates		~3	Maxwell et al. 2008, BAAS proceeding
-0.76	47 Tuc (NGC 104)	5 qLMXBs (2 are likely MS)	23 MSPs	1	Grindlay et al. 2001a, Heinke et al. 2003, 2005a,b.
-0.96	NGC 6652	1 qLMXB, 1 bright		0.1	Heinke et al. 2001.
-1.15	NGC 2808	1 qLMXB		~1	Servillat et al. 2008.
-1.29	NGC 6266	5 qLMXB candidates	5MSPs	~1.4(CC)	Pooley et al. 2003.
-1.45	M28 (NGC 6626)	1 qLMXB	12 MSPs	~0.25	Becker et al. 2003
-1.54	M13 (NGC 6205)	1 qLMXB	5 MSPs	~0.1	Gendre et al. 2003b.
-1.61	GLIMPSE-C01	1 qLMXB candidate			Pooley et al. 2007.
-1.62	omega Cen (NGC 5139)	1 qLMXB (likely MS)		~0.1	Rutledge et al. 2003, Gendre et al. 2003, Haggard et al. 2004.
-1.75	M80 (NGC 6093)	2 qLMXB candidates		~0.6	Heinke et al. 2003b.
-1.95	NGC 6397	1 qLMXB (ultracompact?)	1 MSPs	~0.01(CC)	Grindlay et al. 2001b.
-2.12	M30 (NGC 7099)	1 qLMXB	2 MSPs	~0.04(CC)	Lugger et al. 2007.
-2.26	M15 (NGC 7078)	1 qLMXB (very faint) (2 bright)	8 MSPs	~0.3(CC)	Heinke et al. 2009.

Tests of the metallicity dependence of cluster qLMXBs are inconclusive at this time (Heinke)

Red & Blue LMXBs

- persistent
- transient



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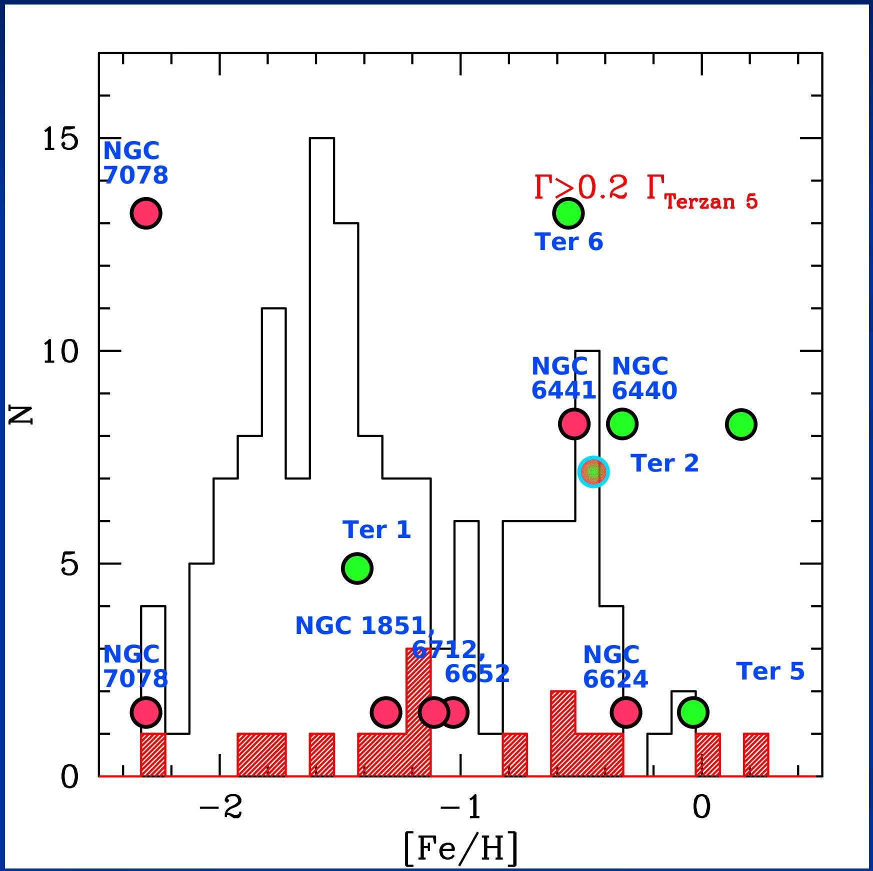


NGC 6623: 4U 1820-303

- Binary orbital period is ~685s (Stella, Priedhorsky & White 1987; Anderson et al. 1997).
- Secondary star is a He WD 0.06-0.08 M⊙ (Rappaport 1987).
- Stability of the period of Pdot/P=(3.5+-1.5)10^{-8} yr^{-1} makes certain that 685s period is the orbital period (Chou & Grindlay 2001).
- Formation scenario of 4U 1820-303 is a direct collision of a neutron star and a giant (Verbunt 1987; Ivanova et al. 2005).

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

- X-ray busts take place only at the flux minima ⇒ the observed variability is due to intrinsic luminosity/accretion rate changes and not obscuration or changes of the projected area of the source due to precession.
- Ratio between superorbital and orbital periods (~22000) is too high for any kind of the disk precession at the mass ration of the system (Larwood 1998; Wijers & Pringle 1999).

a hierarchical triple?

(Chou & Grindlay 2001)

- The third body mass < 0.5M⊙, based on the lack of its optical detection.
- The third body orbital period P_{out}~1.1d .

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).

NGC 6623: 4U 1820-303

Prodan & Murray 2008:

- perturbation from a third body on a longer period orbit
- the quadrupolar distortion of stars due to their intrinsic spins
- the further quadrupolar distortion due to their mutual gravity
- tidal friction in the equilibrium tide approximation
- General Relativity
- mass transfer
- gravitational radiation

Initial parameters are: M_1=1.29M☉ (primary NS), M_2=0.07M☉ (secondary WD), M_3=0.5M☉,

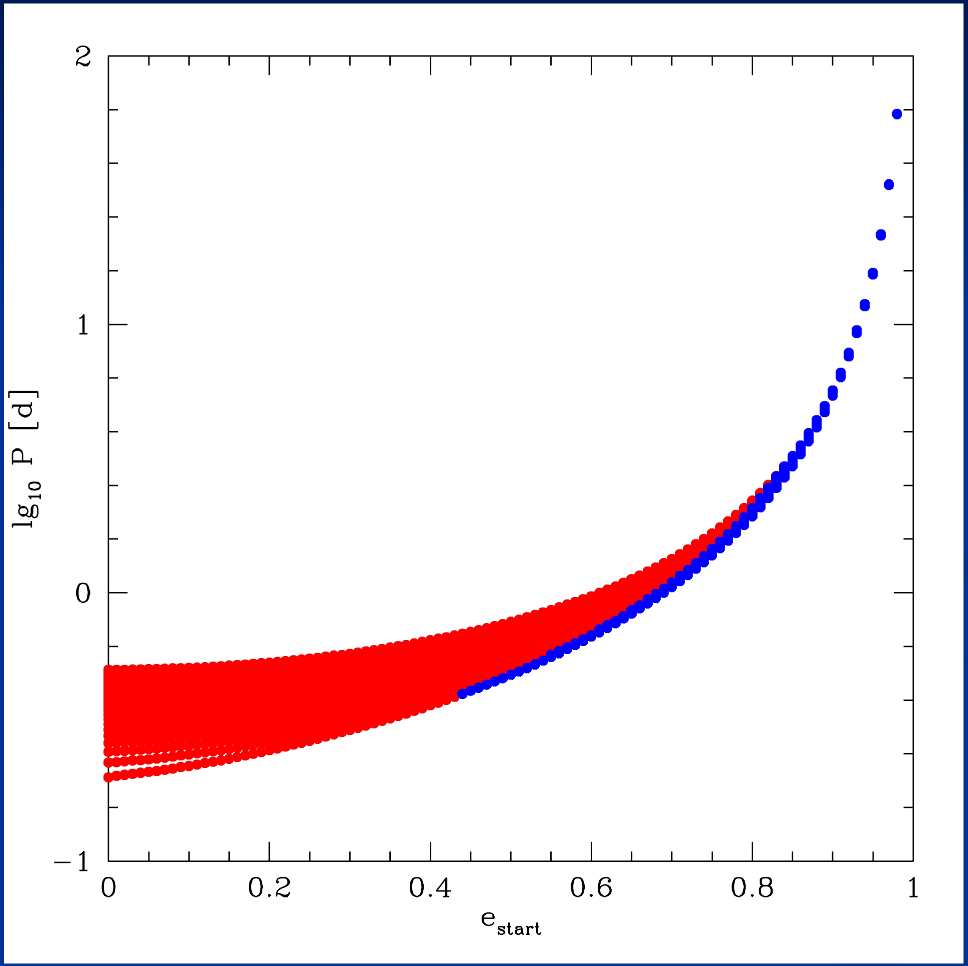
e_{in}=0.0001, e_{out}=0.0001, i=40°.044 (initial mutual inclination),

a_{out}=8.66a_{in} = 1.6 R☉ (outer binary semi-major axis), P_{out}=4.1h

a companion is not a MS star

This model reproduces observed P_{super}=170d and e_{max}=0.004.

NGC 6623: 4U 1820-303



dynamical tides are mandatory to bring e_{out} down!

P_{out}<1.6 d

e_{out}<0.8

Triples: formation rate

A typical cluster has about 5000 hier. stable triples formed throughout its evolution

$$\Delta N_{tr}/N_{bin} \approx 0.05\ f_b\ \langle m_b\rangle\ \langle a\rangle \text{ per Gyr}$$

At 10 Gyr : $\langle m_b\rangle \approx 1.0 M_\odot$, $\langle a\rangle \approx 10 R_\odot$, $f_b \approx 10\%$

$$\Delta N_{tr}/N_{bin} \approx 5\% \text{ per Gyr}$$

$$\Delta N_{tr} \approx 600/t_9^{1/3} \text{ per Gyr, at ages} > 1 \text{ Gyr}$$

(for fixed n_c and σ)

Triples: formation rate for NS triples

$\Delta N_{tr,ns} / N_{bin,ns} \approx 0.05$ per Gyr (47 Tuc–type)

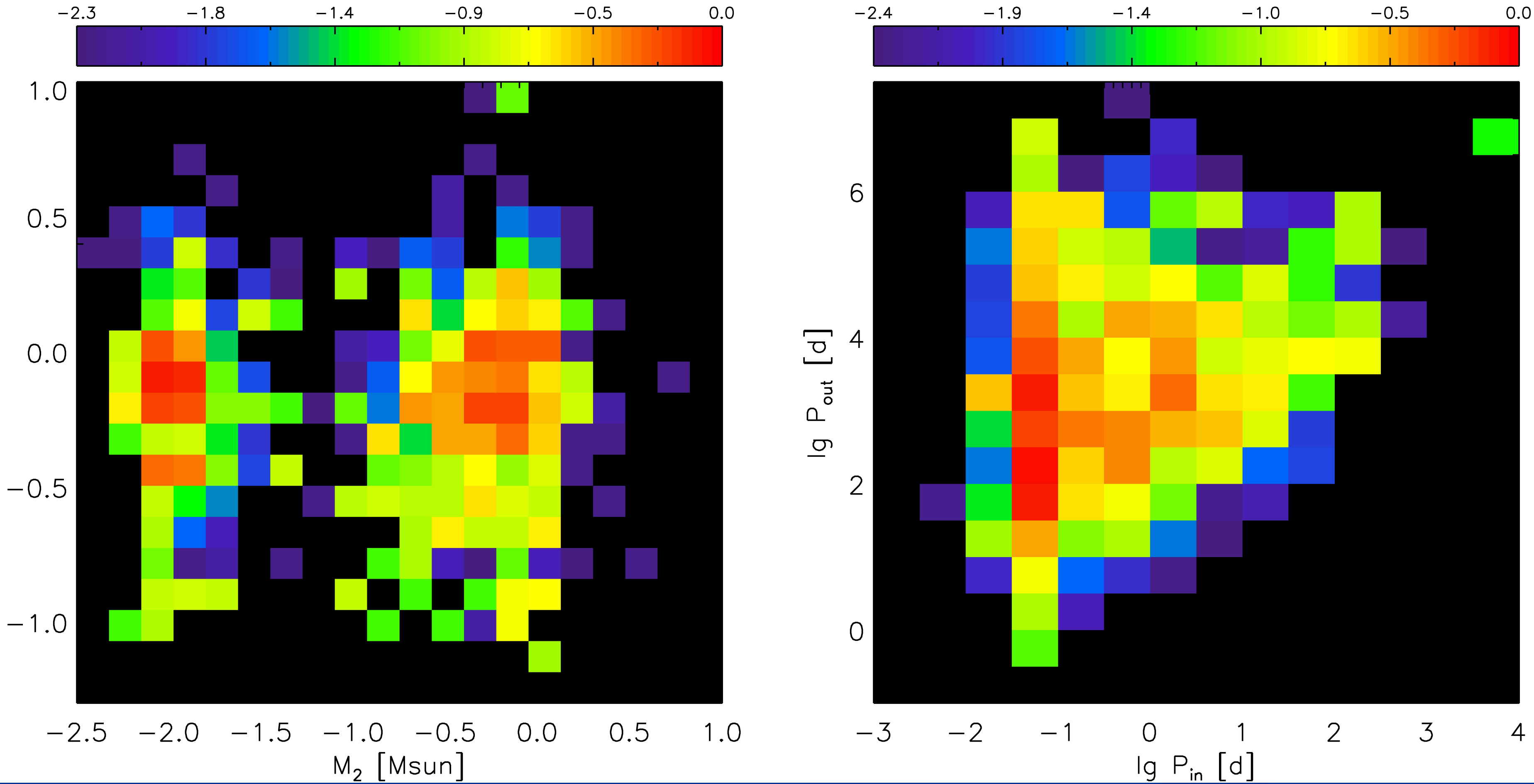
$\Delta N_{tr,ns} / N_{bin,ns} \approx 0.15$ per Gyr (Ter 5–type)

~1/3 of the are Kozai triples: $\tau_{koz} < \tau_{coll}$

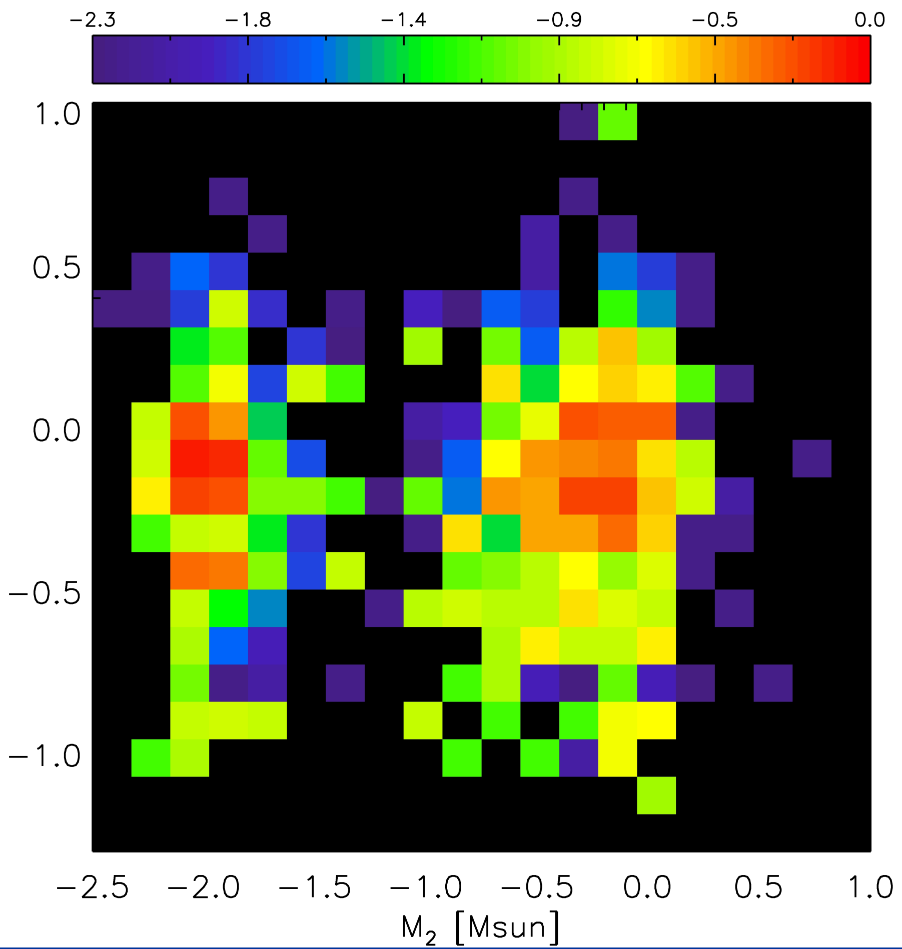
Kozai mechanism causes large variations in the eccentricity and inclination of the stars orbits and could drive the inner binary of the triple system to merge before next interaction with other stars.

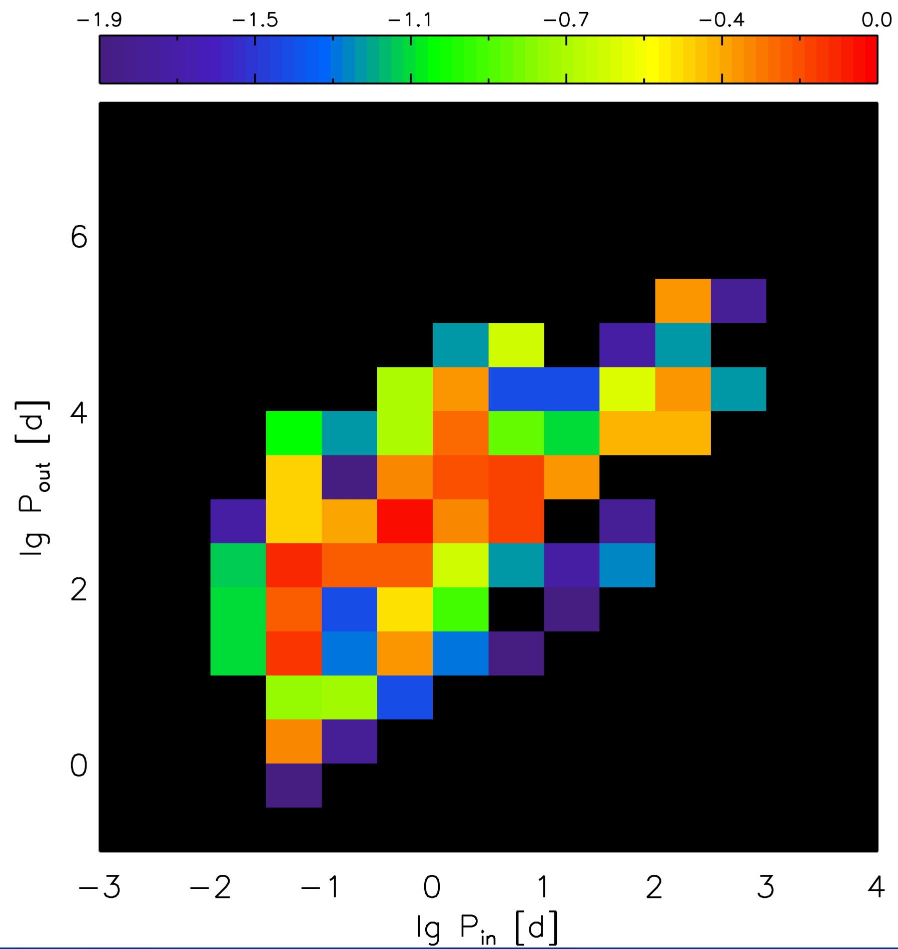
Kozai time-scale τ_{koz} as in Innanen et al. (1997)

NS-Triples: properties



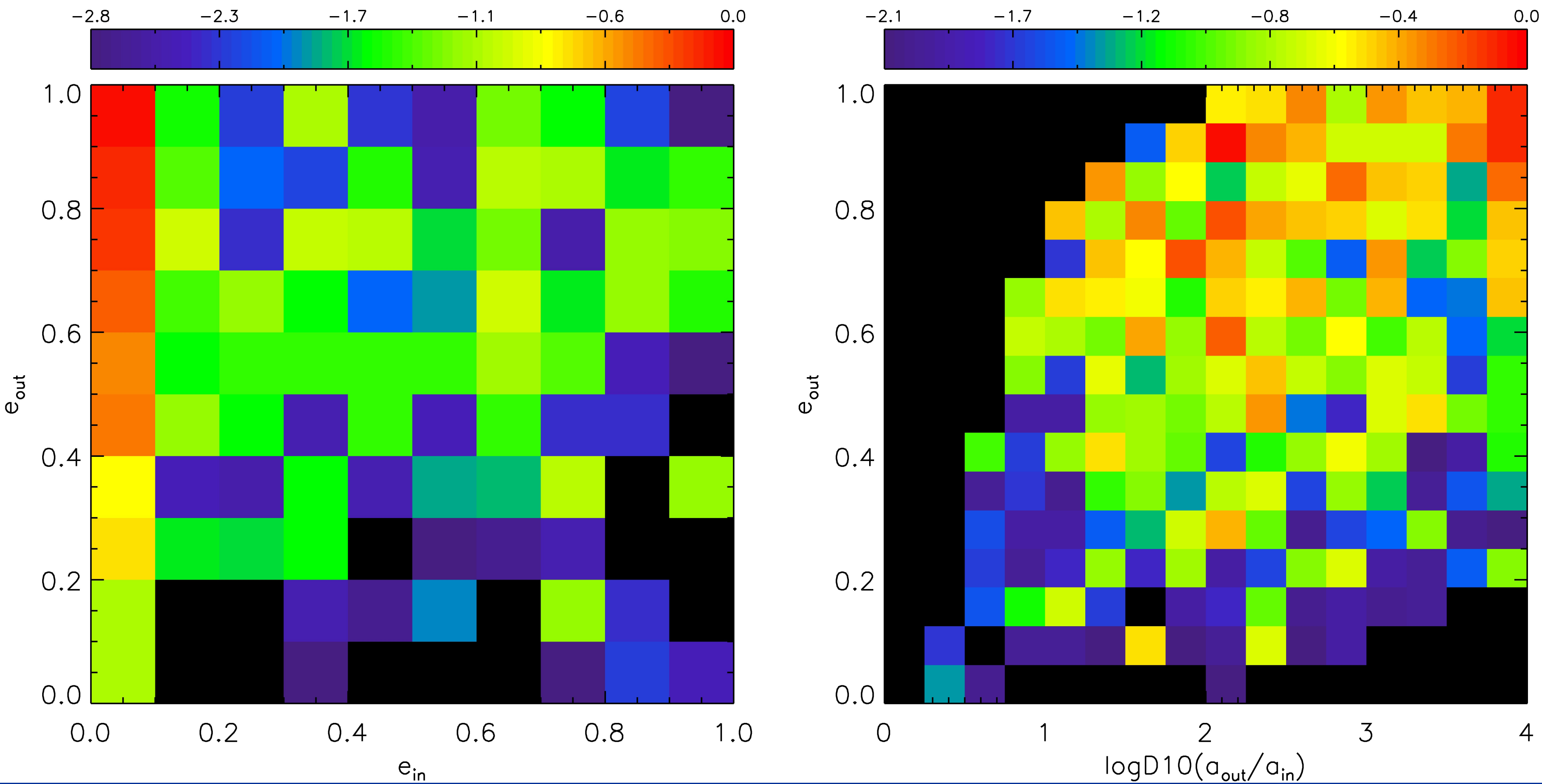
NS-Triples: properties



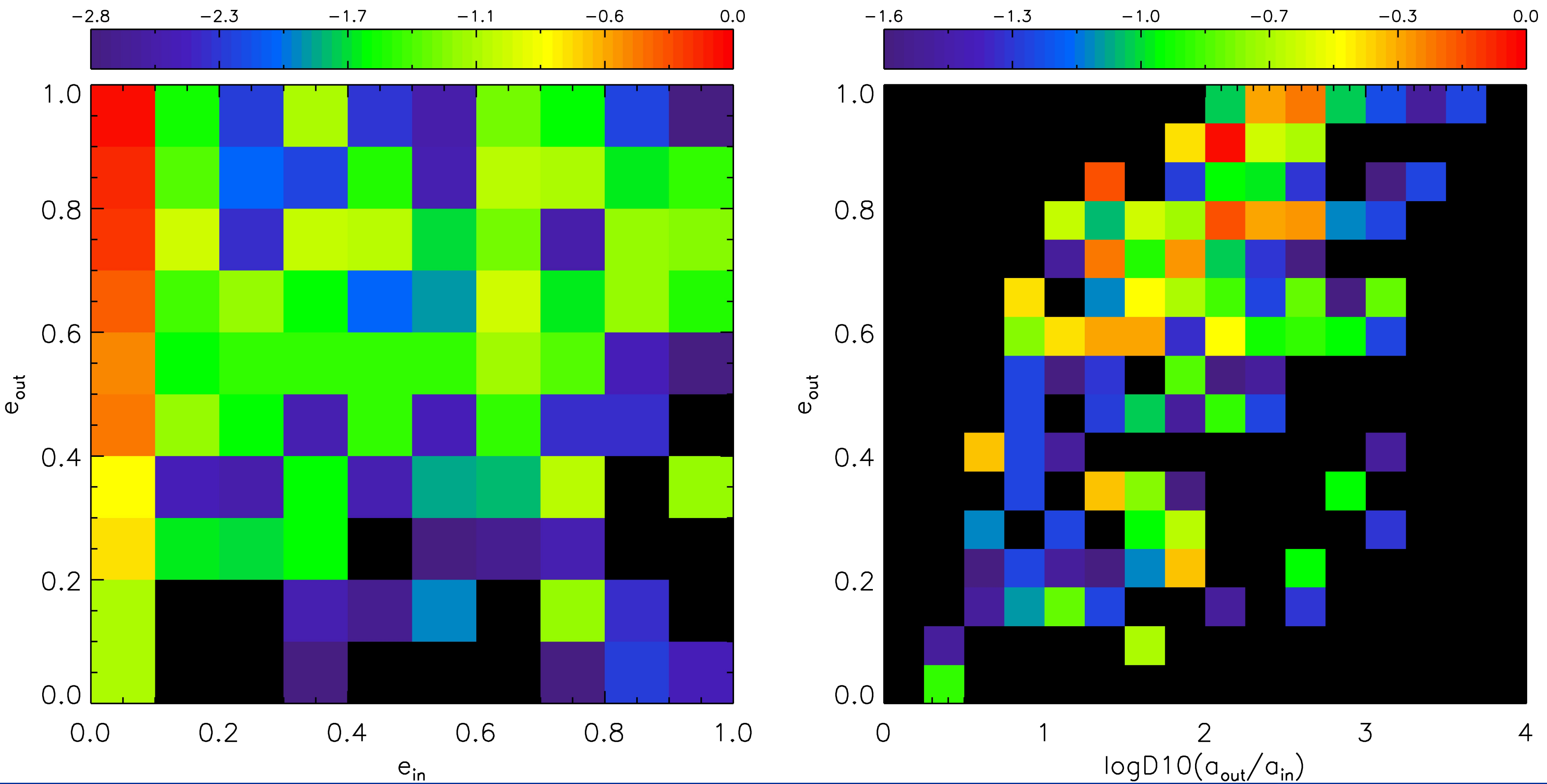


Kozai triples only

NS-Triples: properties

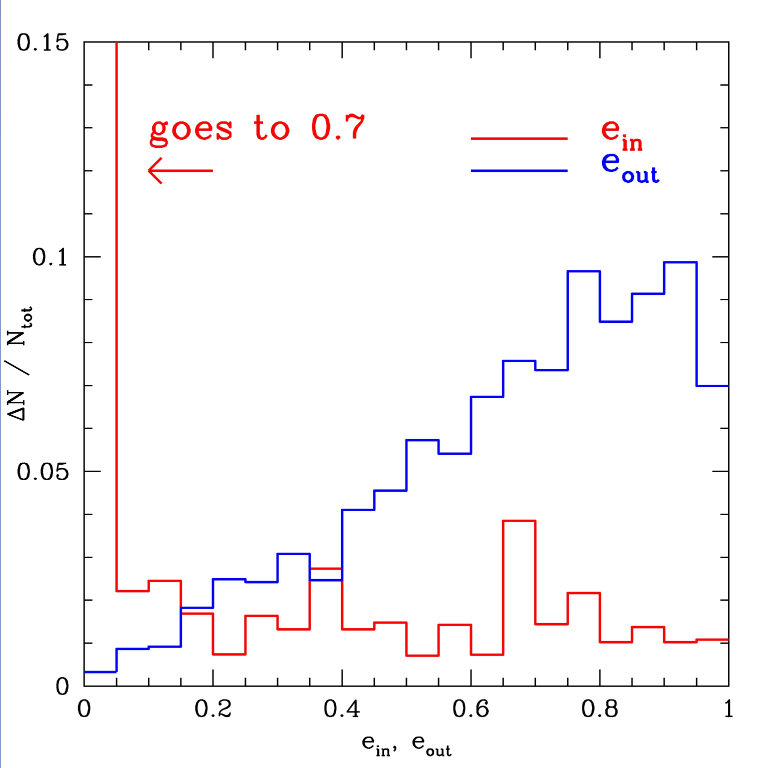


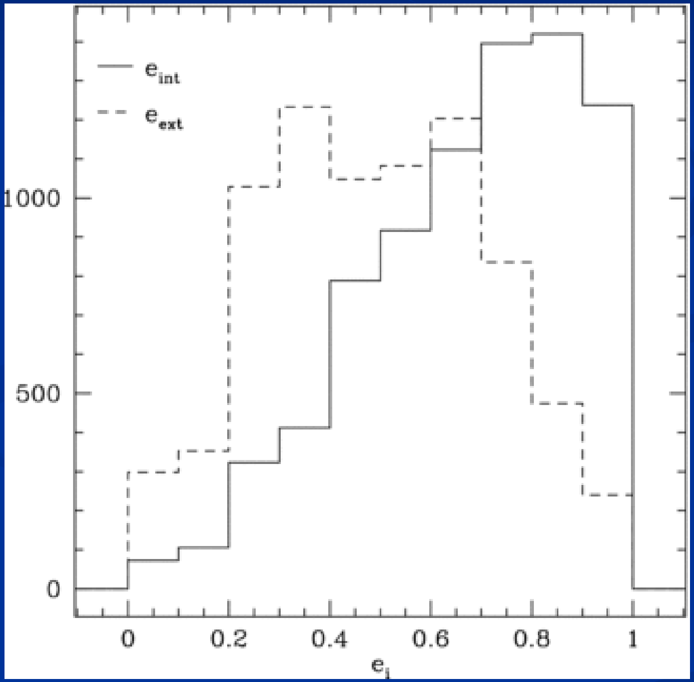
NS-Triples: properties



Kozai triples only

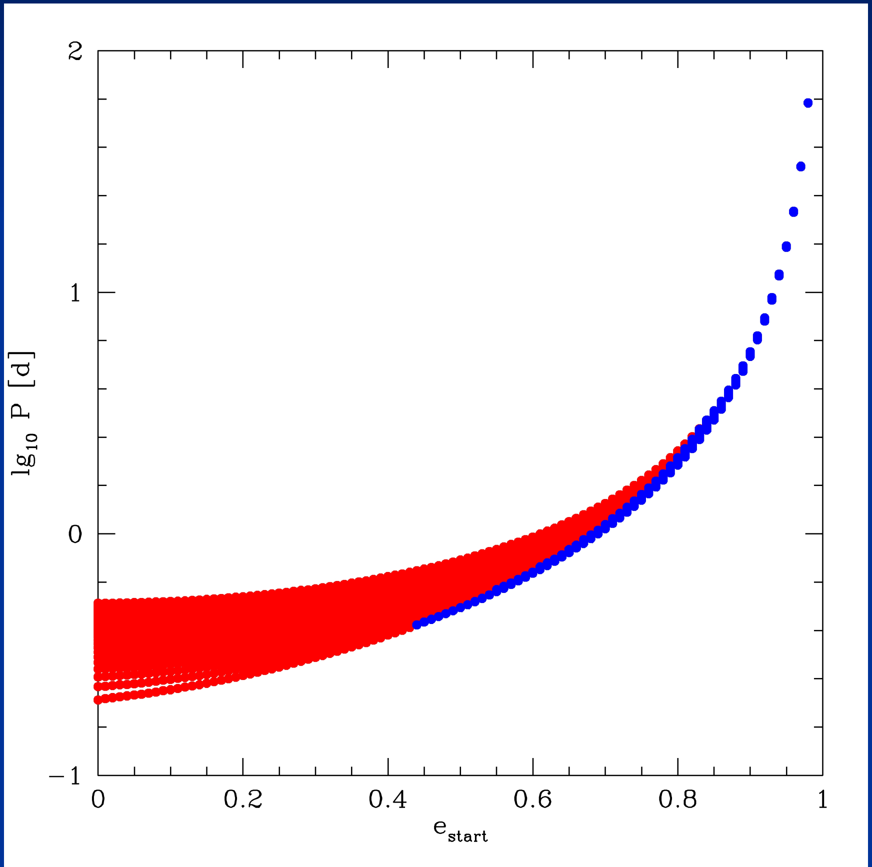
NS-Triples: properties

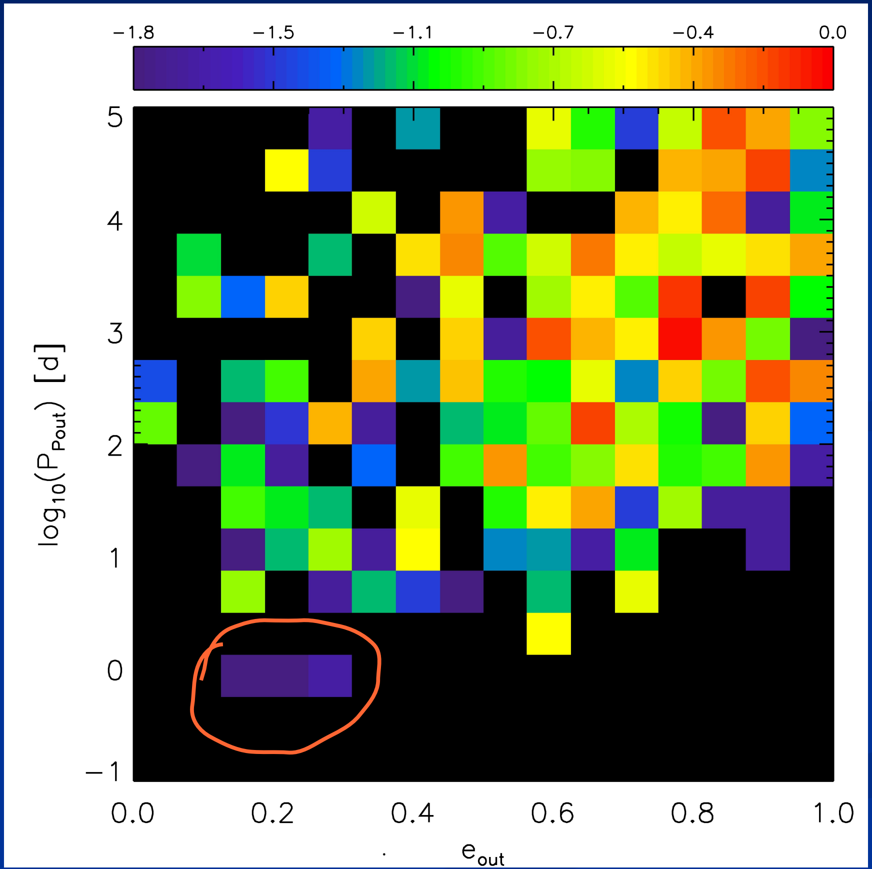




Trenti et al 2008

NGC 6623: 4U 1820-303





Summary

- Formation rates and the population of LMXBs and MSPs in GCs are consistent with the observations. Dynamical formation of LMXBs is understood better (as it has less degrees of freedom) than the formation of LMXBs in the field
- There is no obvious red-blue dependence for the formation rates of qLMXBs
- no *radio* MSP is formed during UCXB evolution with a He/CO donor. An accretion-powered X-ray millisecond pulsar, for some reason, will never turn on in radio
- Triple systems with a NS are expected to be formed, though the only observed likely triple LMXB 4U 1820-303 is one of the hardest to make theoretically. Half of LMXBs were members of some hierarchically stable triples in the past
- Deep observations of metal-poor clusters, both for X-ray sources and for MSPs, are on a high demand.