

The gravitational universe: from stellar couples to merging

S. Chaty

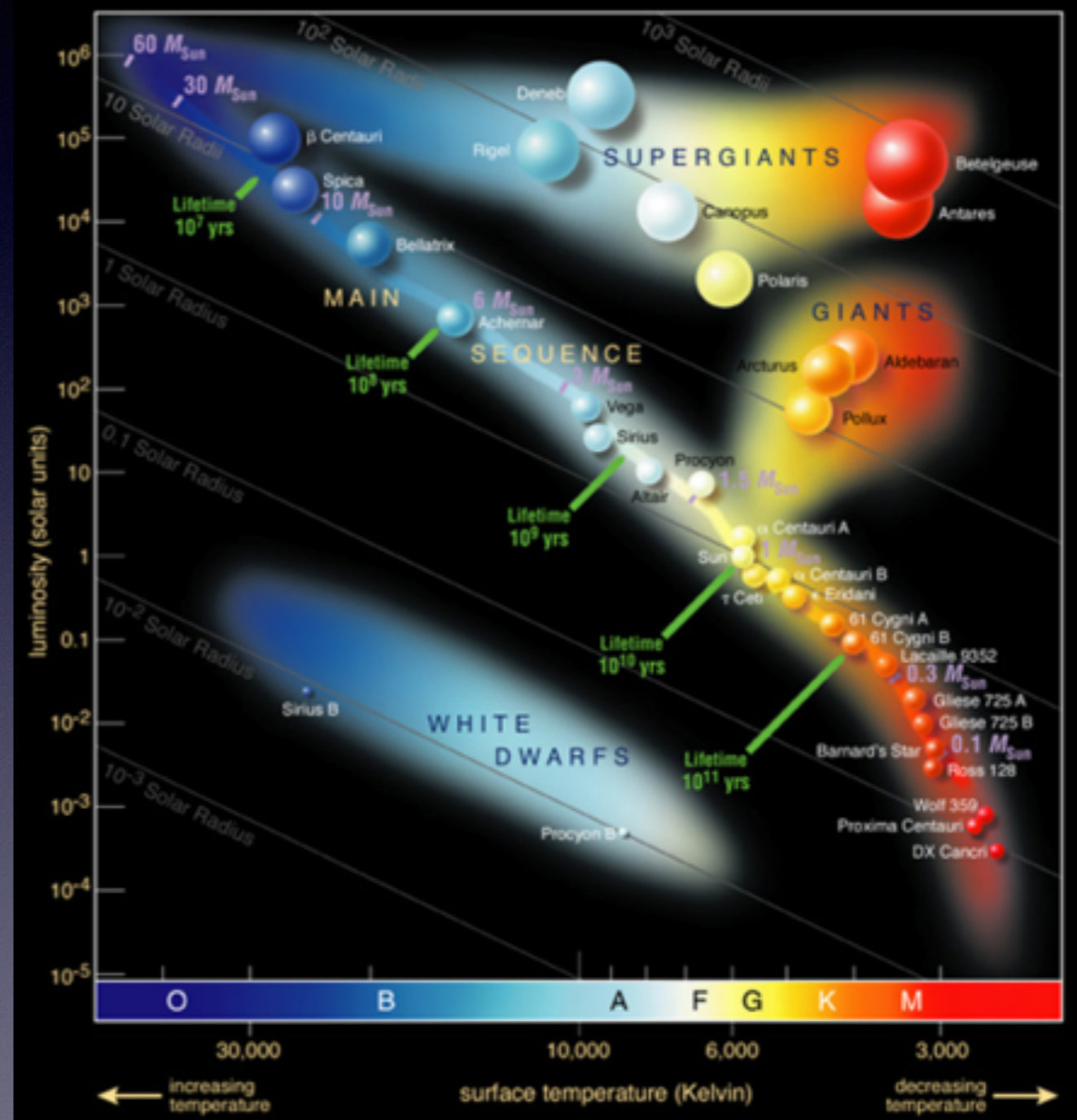
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Purple Mountain Observatory, 2018

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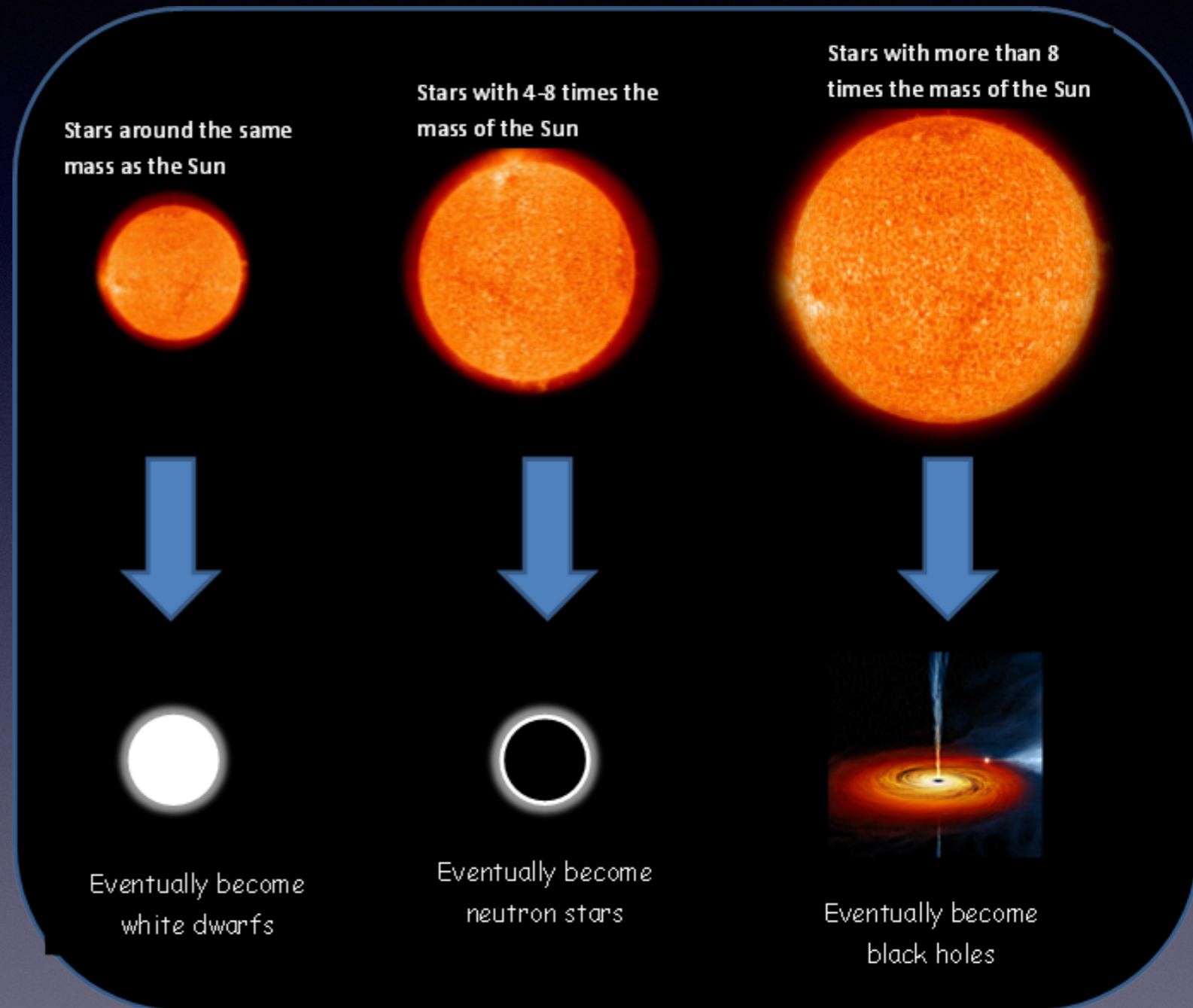
Stellar evolution

- HR diagram describes the evolution of a single, isolated star...
- ...however, most stars belong to multiple systems: +70% of massive (OB) stars experience a binary interaction during their evolution (Sana+2012)
- Transfer of matter/angular momentum has a huge impact on binary evolution



Stellar evolution

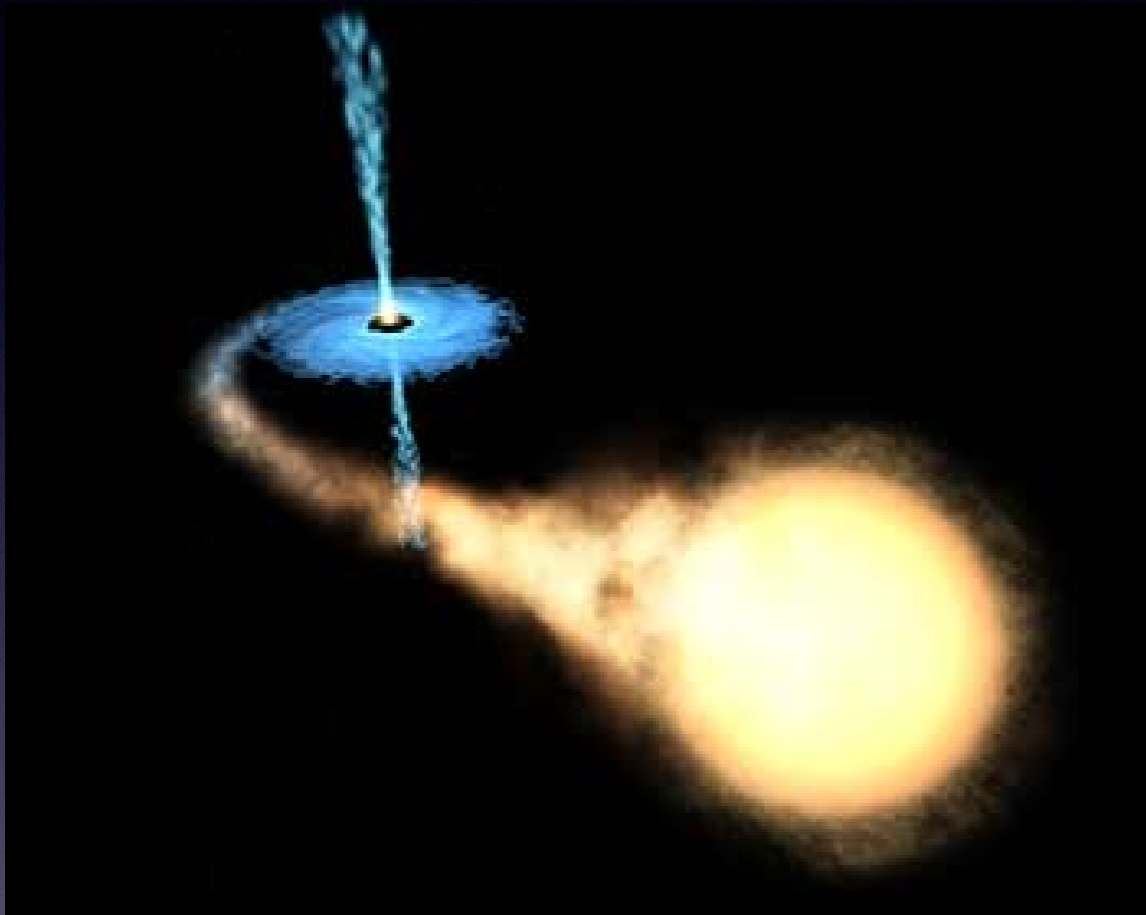
- White dwarf
- Neutron star
- Black hole



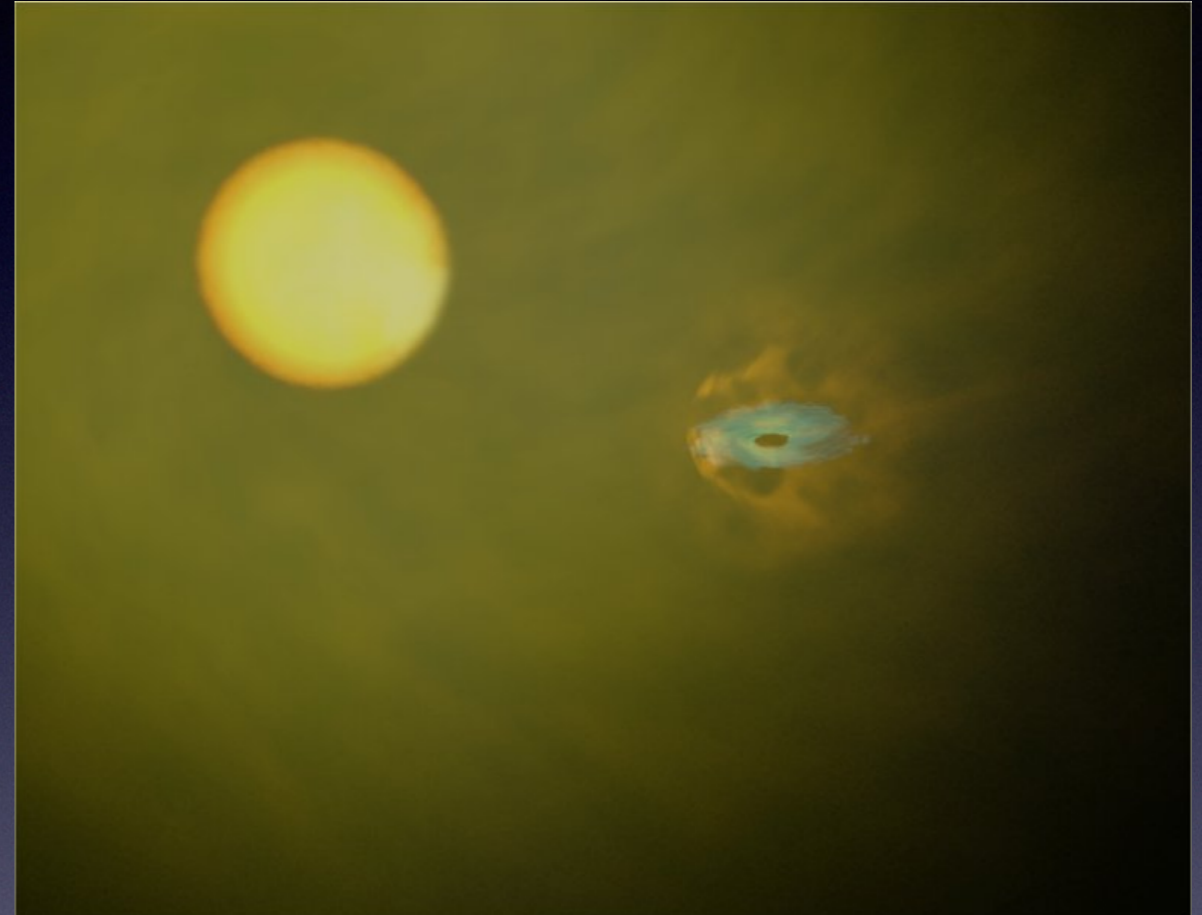
Plan

- I. Introduction: *accreting binaries*
- II. Evolution of accreting binaries
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- IV. *INTEGRAL* binaries
- V. Galactic distribution of HMXB
- VI. Conclusions

Accreting binaries



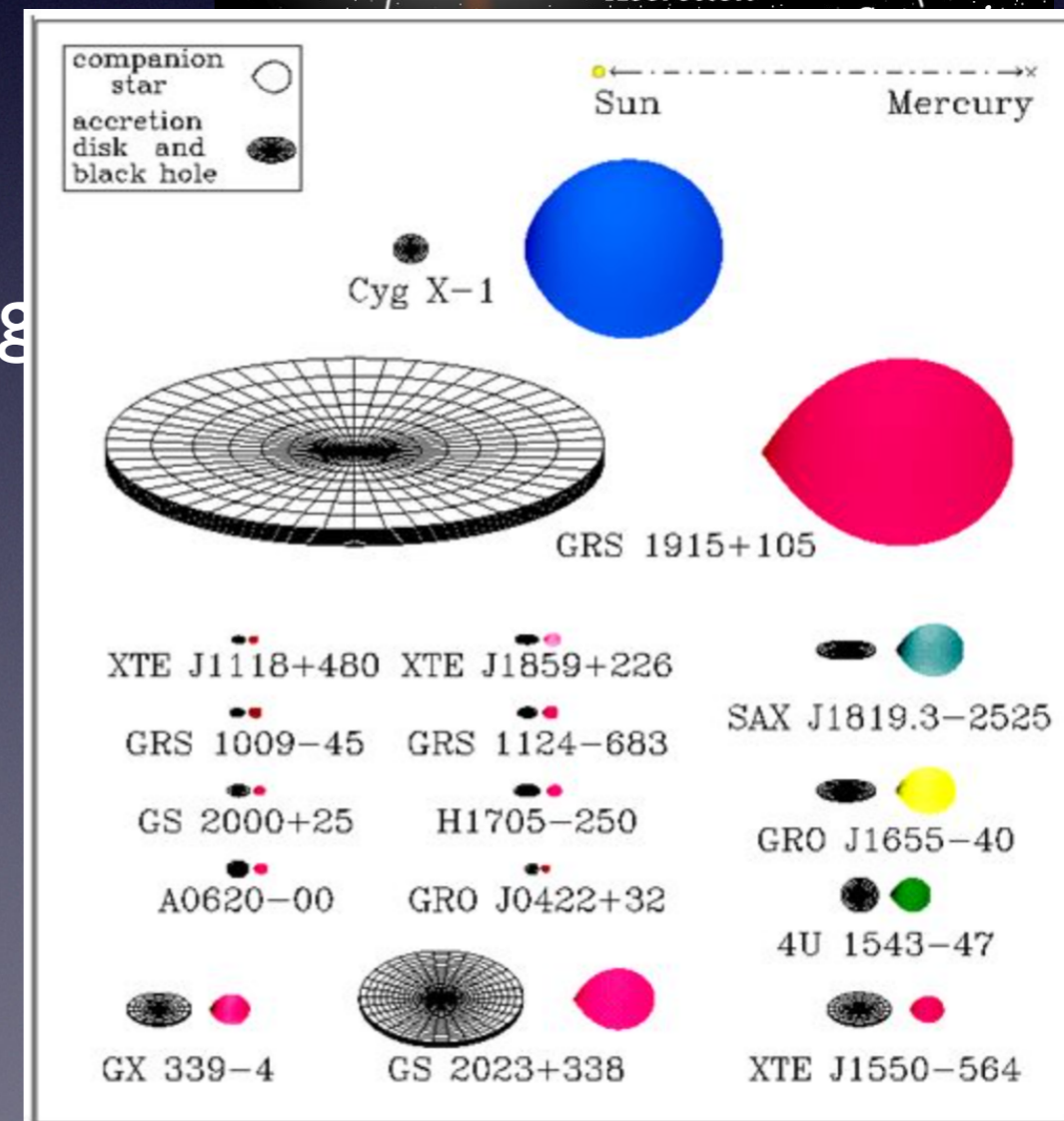
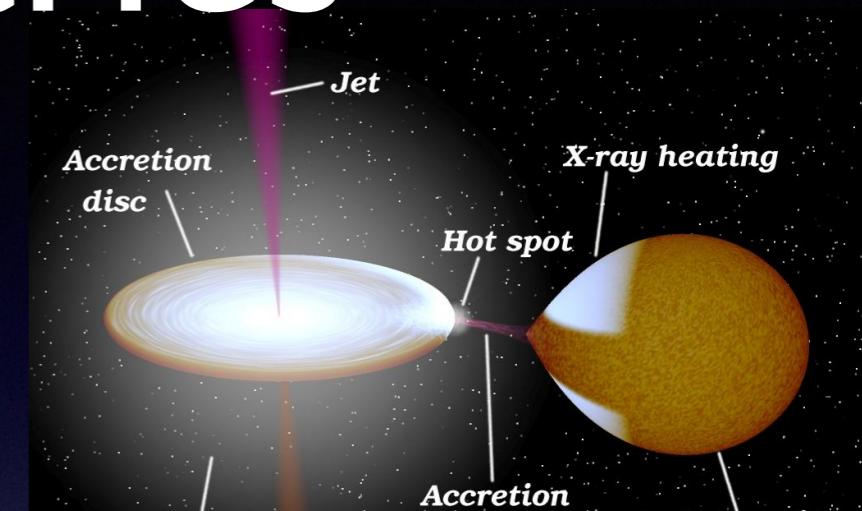
Low-mass X-ray Binaries
(~250 LMXB):
Roche lobe overflow



High-mass X-ray Binaries
(~167 HMXB):
Stellar wind accretion

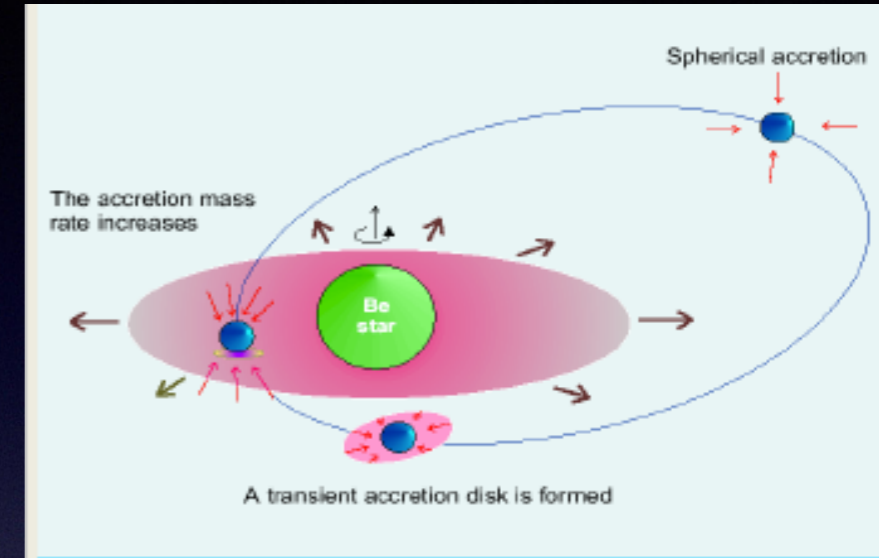
Accreting binaries

- 250 LMXB (60%):
 - Companion star later than B ($M < 1 M_{\odot}$)
 - Mass transfer: Roche lobe filling (accretion disk)
 - BH/NS LMXBs (Sco X-1 ...)
 - Microquasars: jet sources

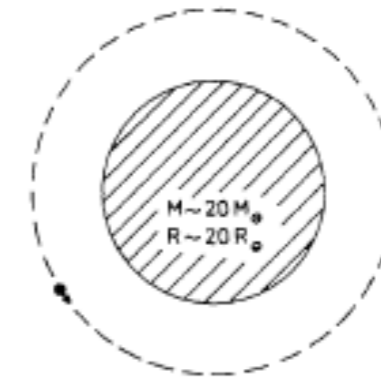


Accreting binaries

- 167 HMXB (40%):
 - Donor: Luminous early-type OB companion star ($M > 10 M_{\odot}$)
 - 3 types depending on mass transfer:
 - **BeXB** (40): direct accretion from Be III-V star decretion disk
 - **sgXB** (36): spherical accretion from sg I/II stellar wind (500-1000 km/s) with CO in circular orbit, $L_X \sim 10^{35-40}$ erg/s (Vela X-1, GX 301-2, 4U 1700-37...)
 - **RLO** (5): Beginning Atmospheric Roche Lobe Overflow

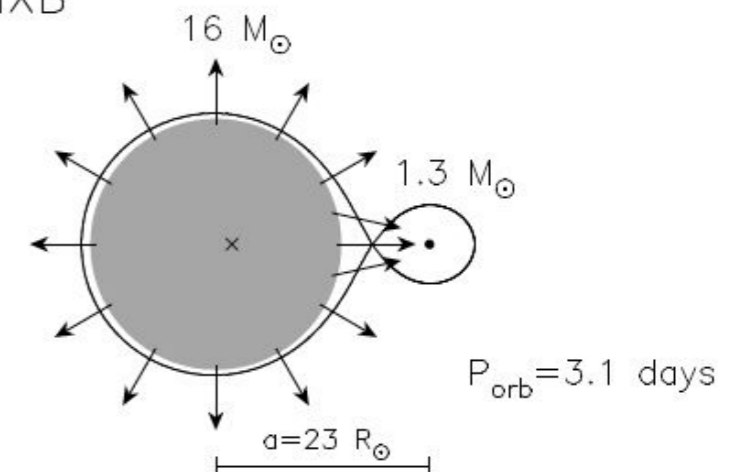


STANDARD MASSIVE X-RAY BINARY

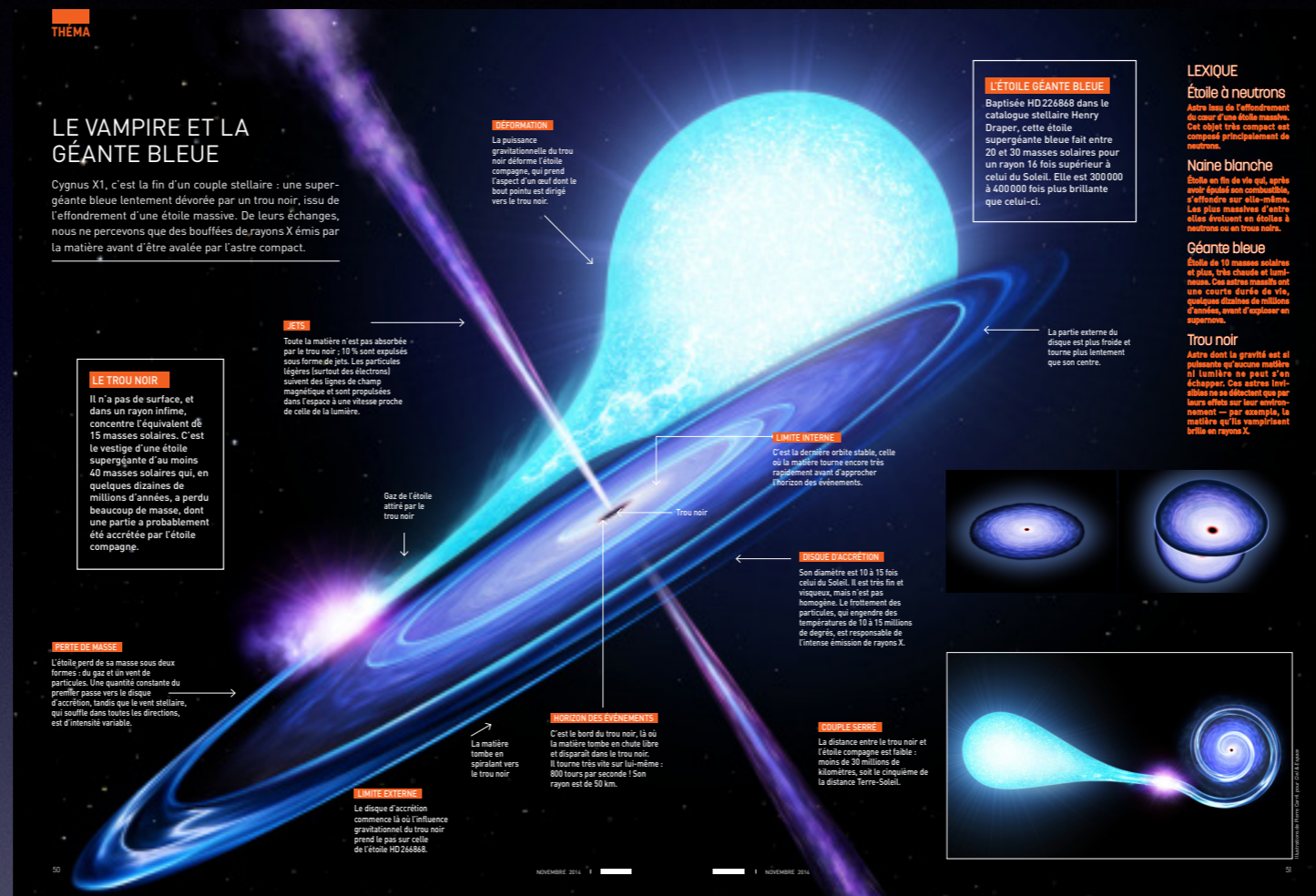


- Companion evolved to fill critical potential lobe
- $Z^d \lesssim P_{\text{orb}} \lesssim 10^d$
- Circular Orbit
- Eclipses likely
- "Steady" X-ray emission
- Mass transfer ($10^{-10} - 10^{-8} M_{\odot} \text{yr}^{-1}$) by Roche lobe overflow, stellar wind or both

HMXB

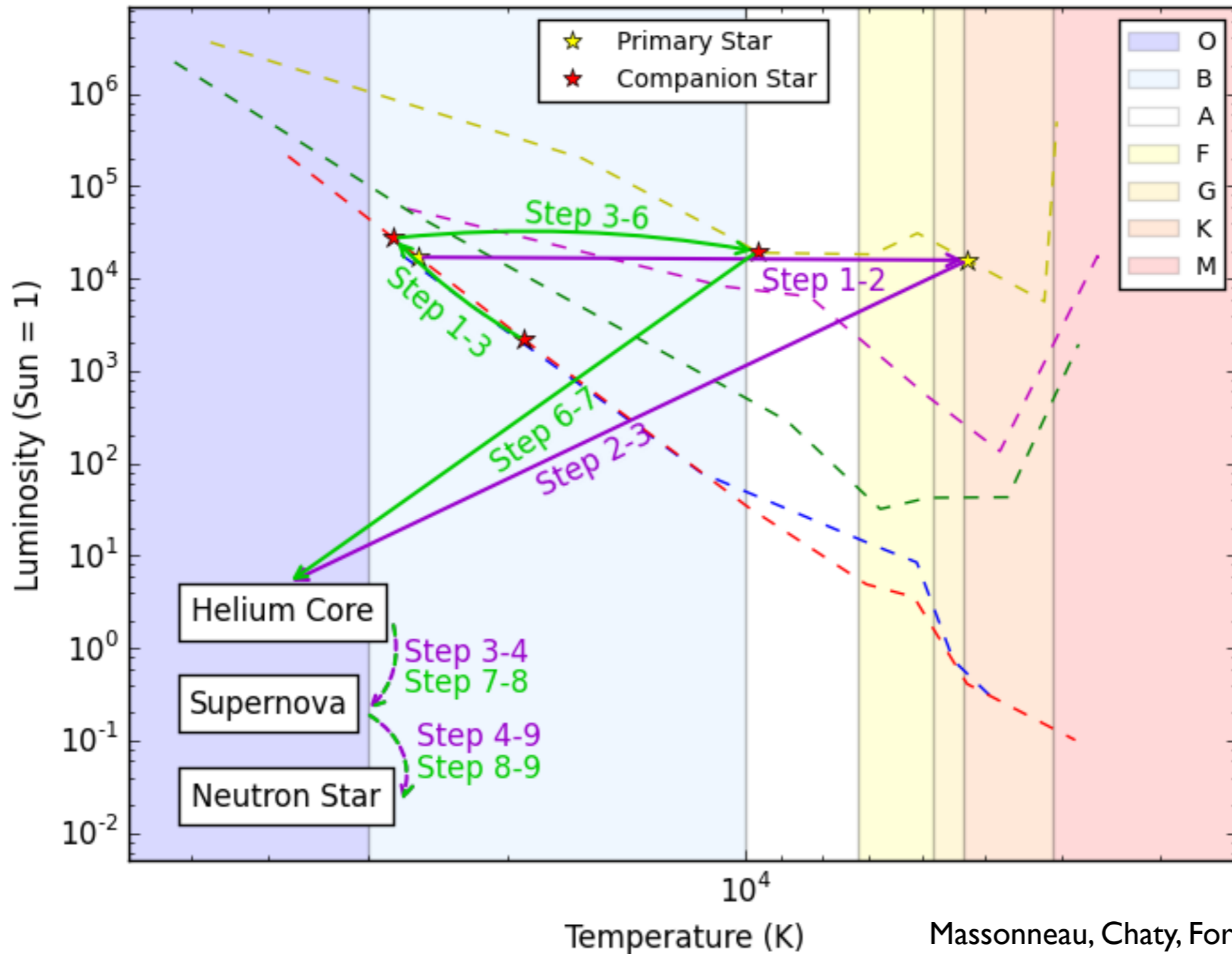


Roche-lobe overflow HMXB: Microquasars



- Classical «bright» sources, CO on circular orbit, accretion disc: high X-ray luminosity ($L_x \sim 10^{38}$ erg/s) during outbursts
- Cyg X-1: the only HMXB with RLO+stellar wind accretion hosting a confirmed BH!

Stellar evolution



Plan

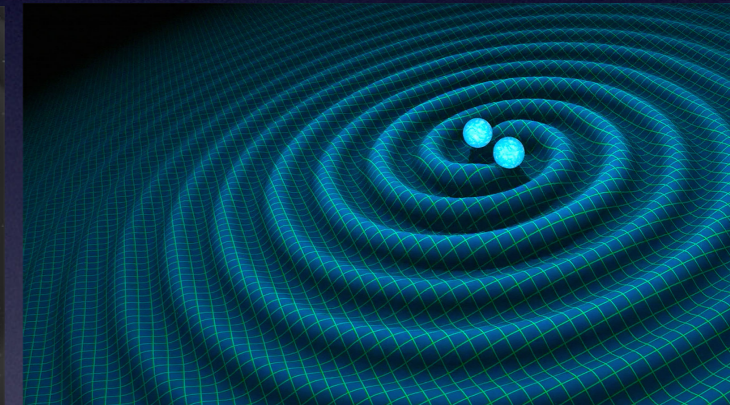
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Binary evolution

- Binaries evolve and eventually merge...
- leading to gravitational wave (GW) emission, such as the events detected by LIGO/Virgo collaboration (Abbott+2016ab)
- The tip of the iceberg!
- « Today's binaries are tomorrow's GW! »



• BBH

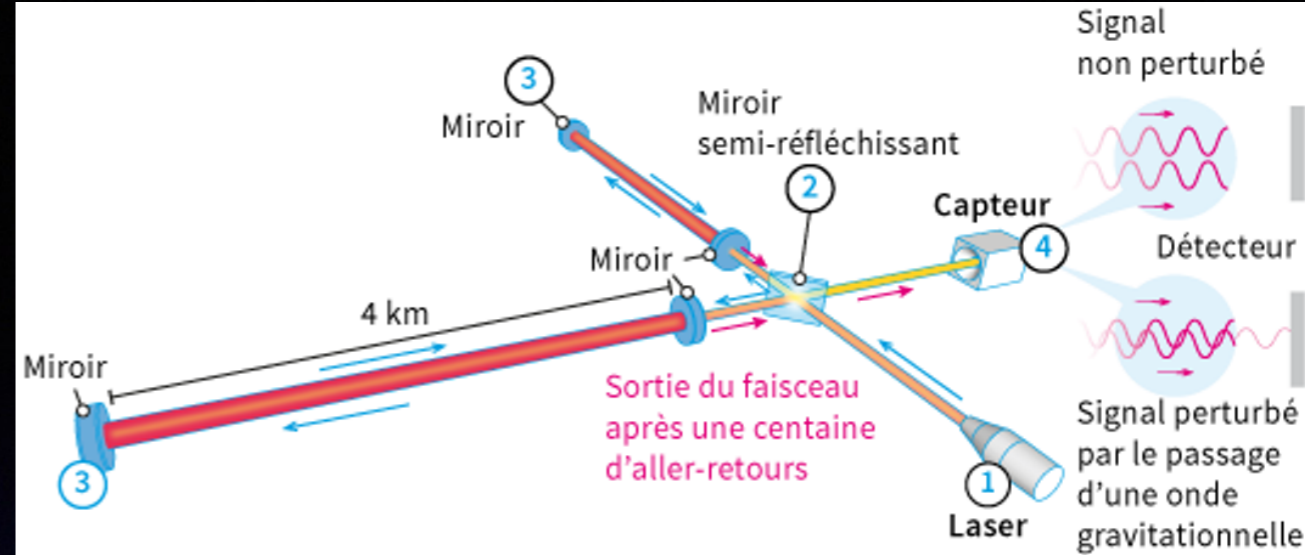


• BNS



Gravitational wave detectors

- LIGO (US): 4 km-arms
- Virgo (EU): 3 km-arms



Un jeu de miroirs

L'interférométrie laser consiste à détecter d'infimes variations de distance engendrées par la déformation de la Terre au passage d'une onde gravitationnelle. Le laser (1), séparé en deux branches (2), est piégé entre des miroirs (3), puis reconcentré vers un capteur (4). Si les longs bras de l'instrument sont déformés (de seulement 10^{-19} m), des interférences apparaissent.

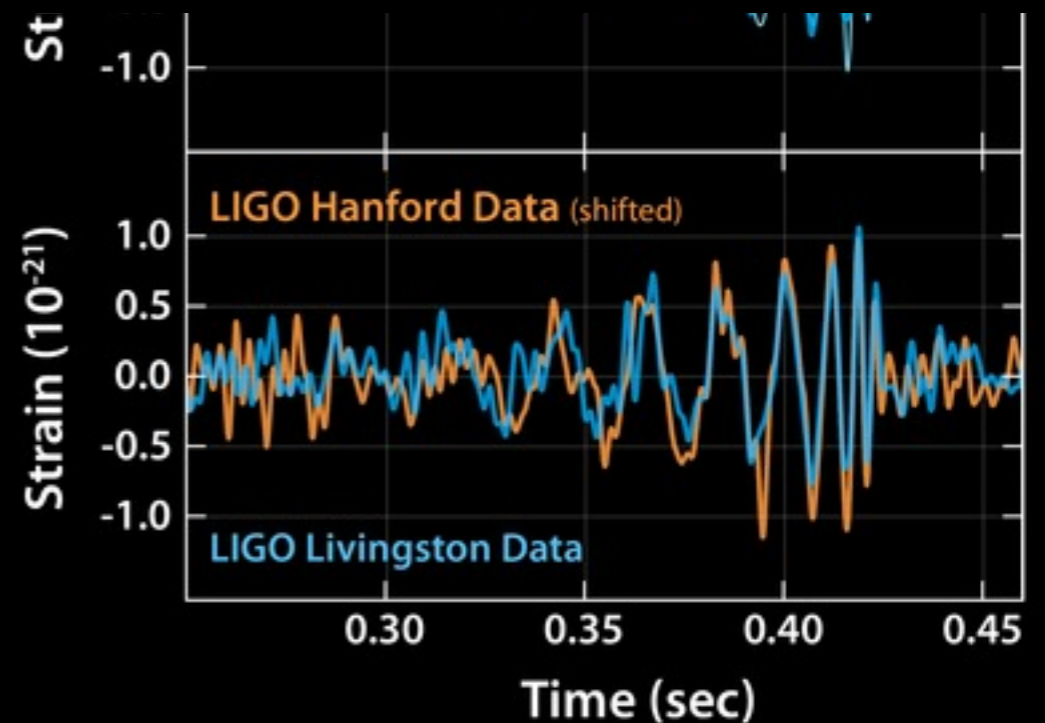
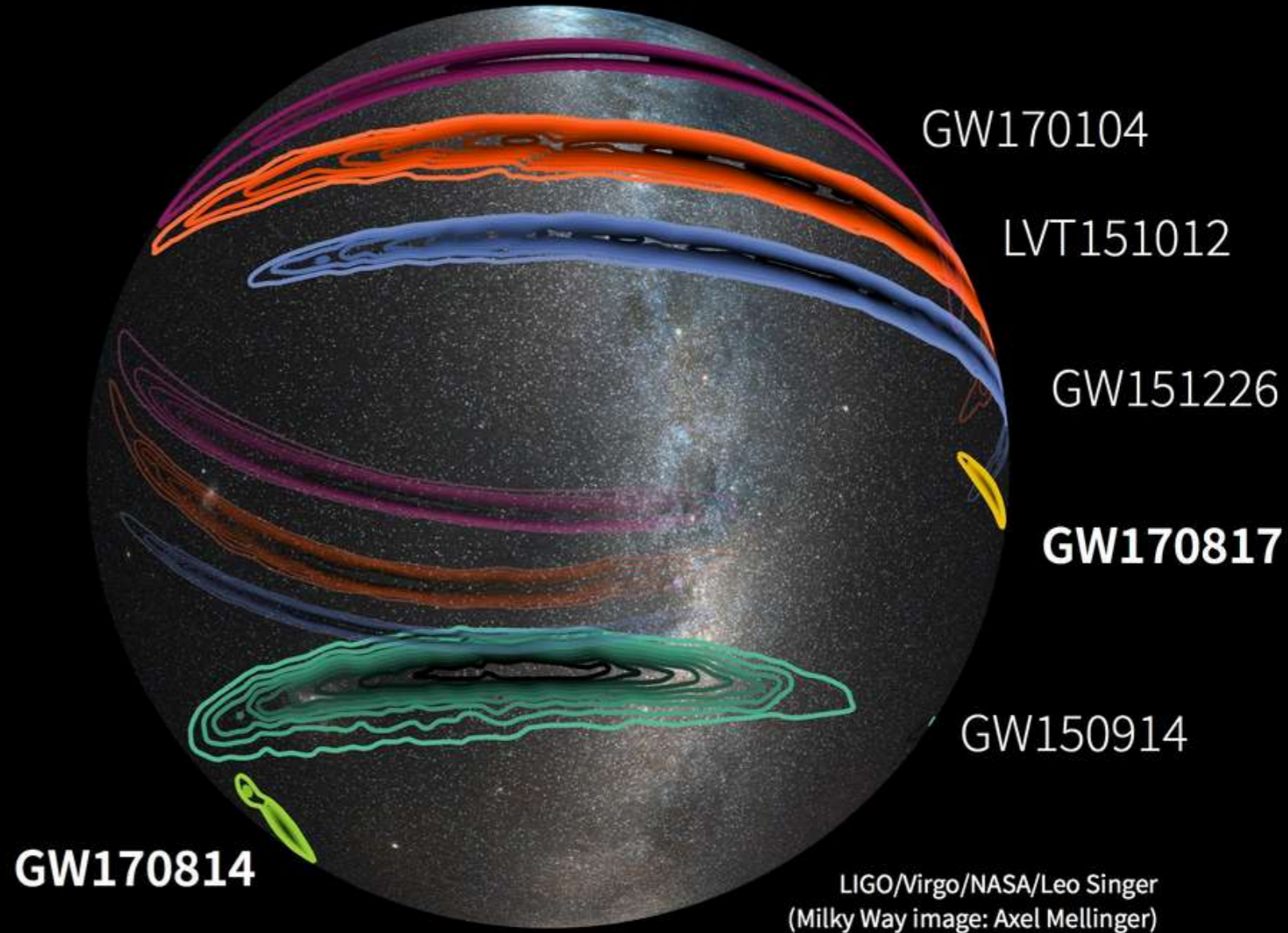
INFOGRAPHIE : HENRI-OLIVIER

SOURCE : LIGO VIRGO



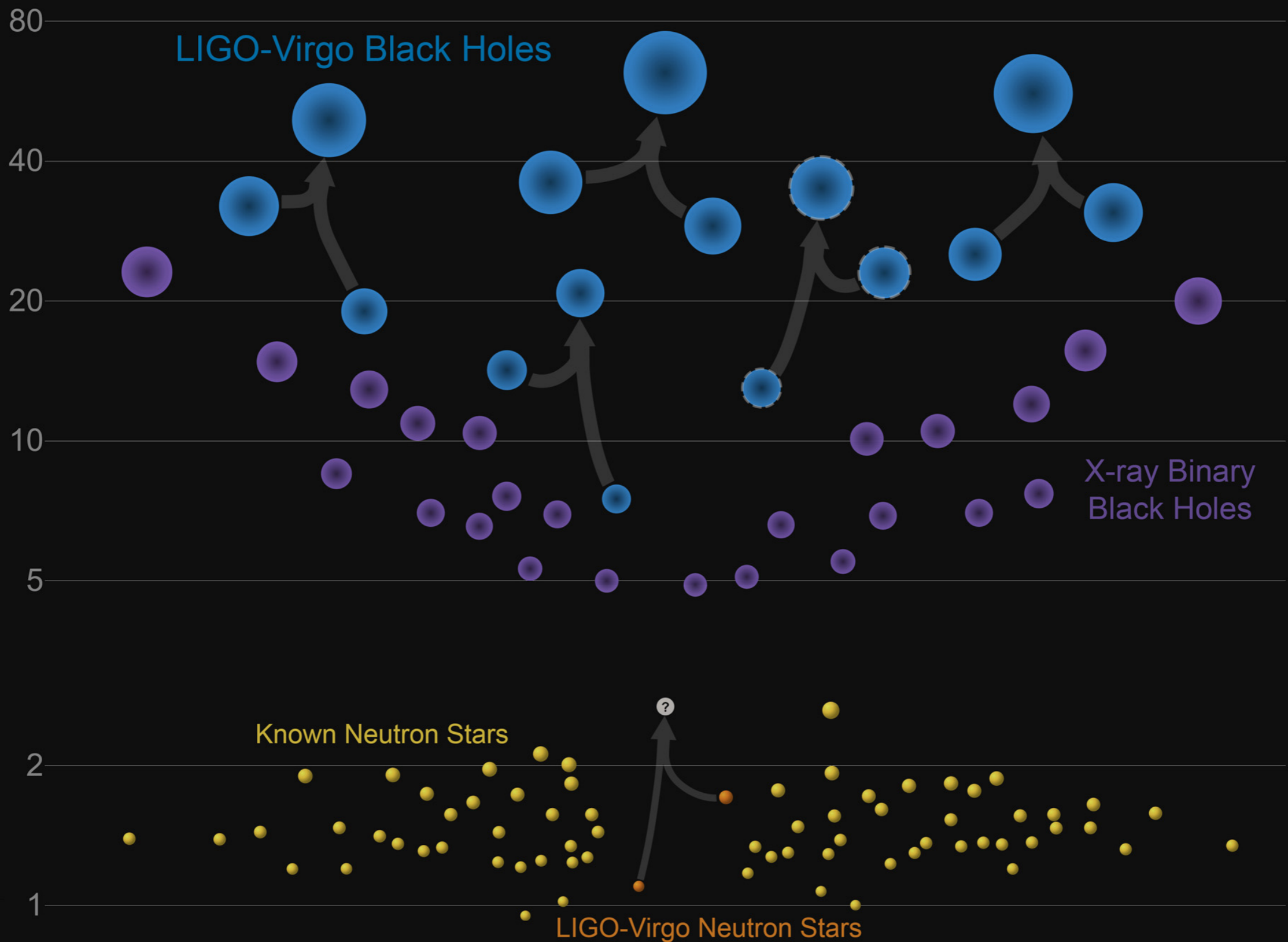
A serie of GW events

- GW150914: BBH 36
- LVT151012: BBH 23
- GW151226: BBH 14
- GW170104: BBH 31
- GW170608: BBH 7+12 Ms @307M
- GW170814: BBH 31+25 Ms @552M
- GW 170817: BNS 1.36-2.26 + 0.86 of 2.82Ms?



Masses in the Stellar Graveyard

in Solar Masses

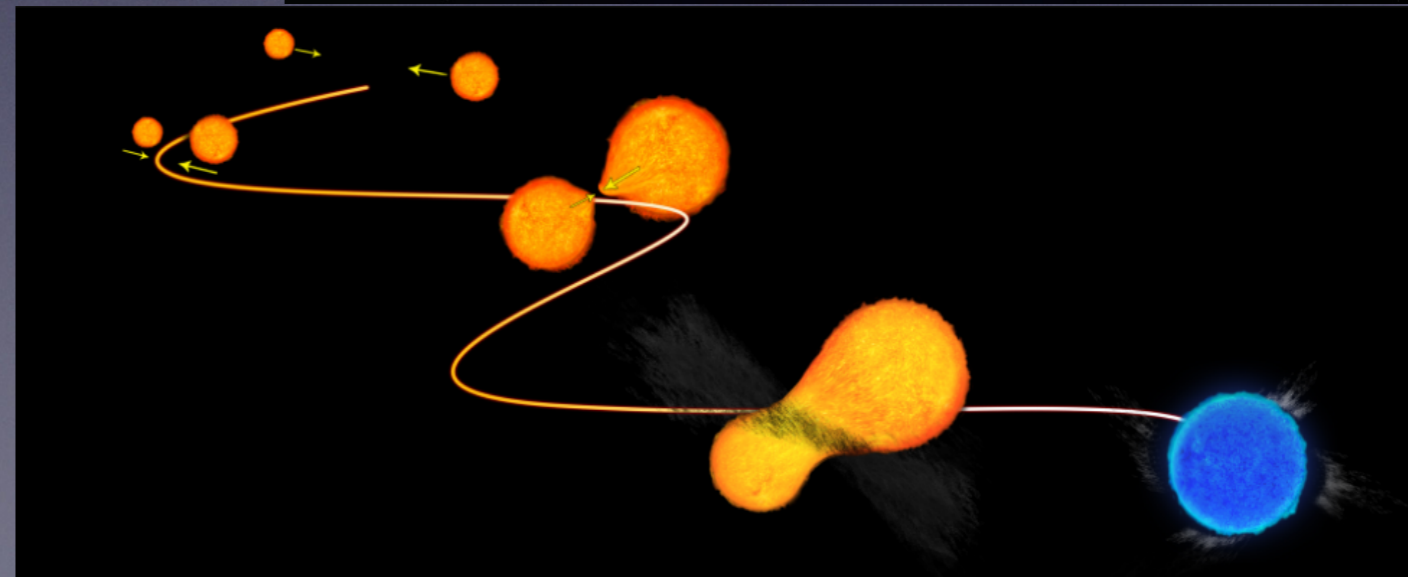
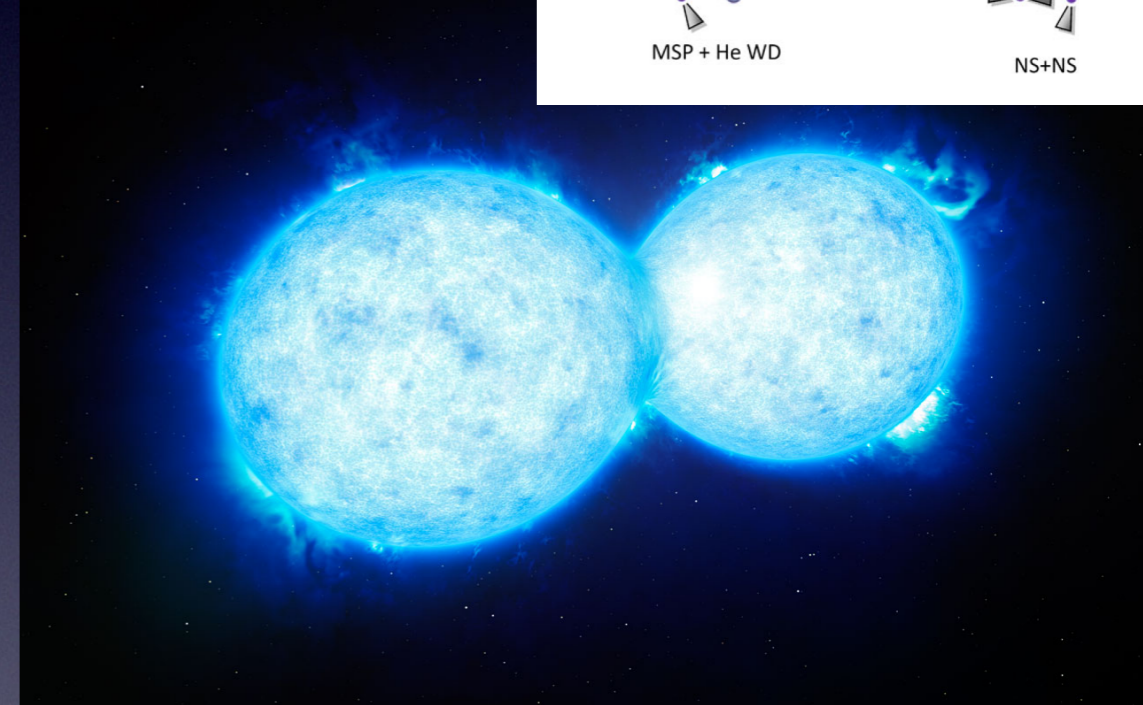
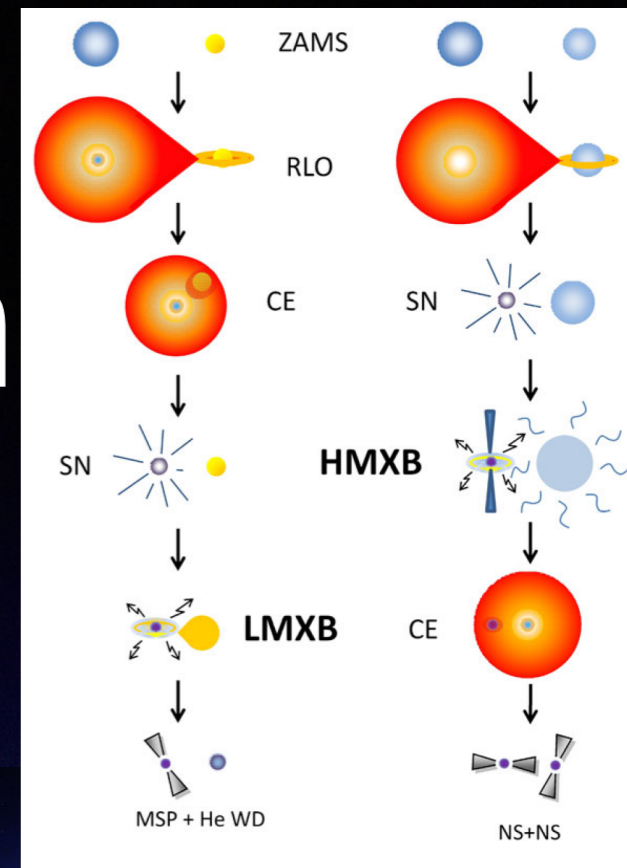


Fundamental questions

- How do binaries evolve from formation to merging?
- How to estimate the rate of mergers?
- How to identify the progenitors of the merger?
- What are the properties (mass ratio, total mass, orbital separation, spin) of binaries before merging?

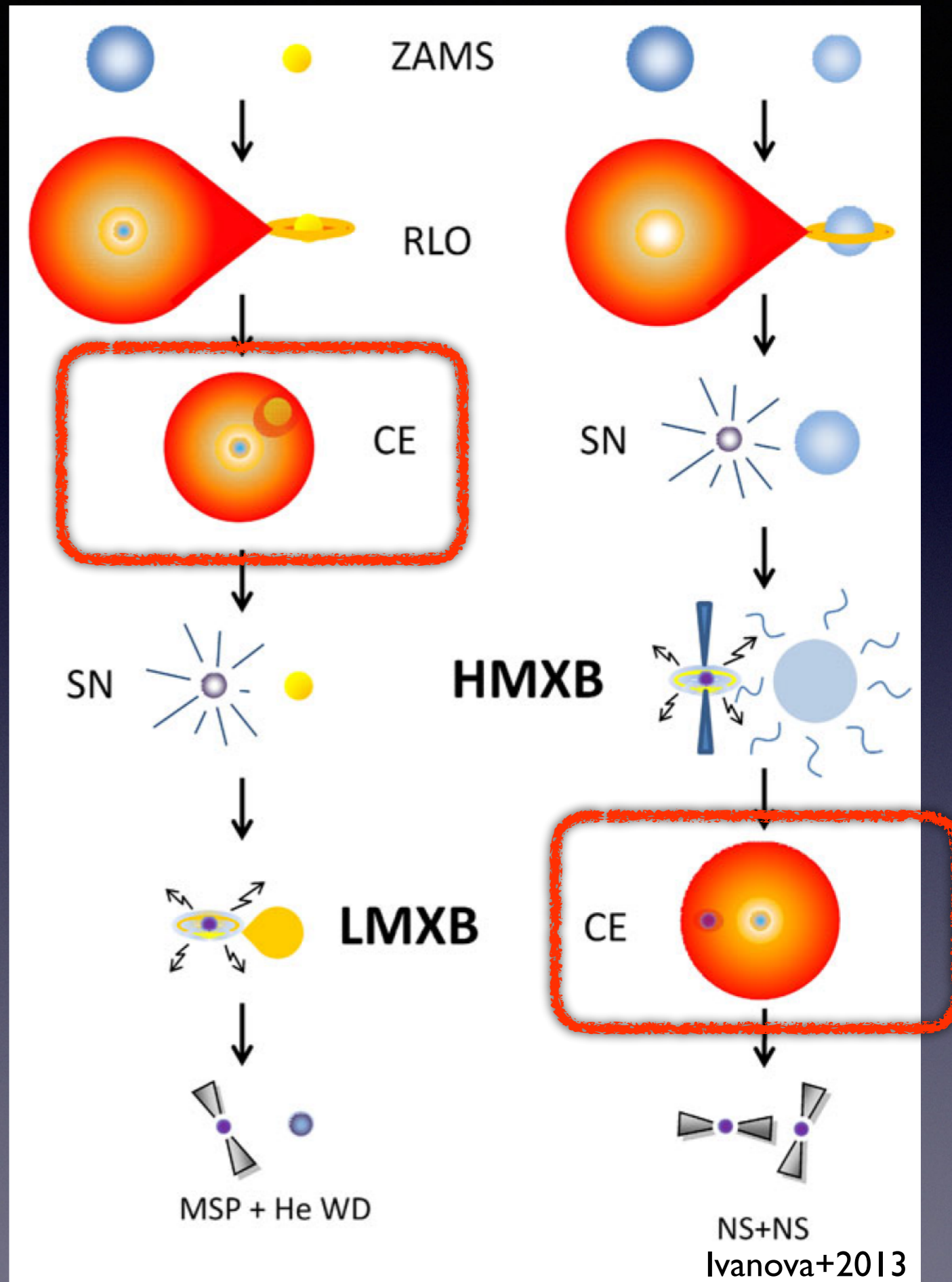
Binary evolution

- 3 different possible channels:
- 1. Classical isolated (90%)
- 2. Homogeneous mixing of over-contact stars, simultaneous evolution (10%)
- 3. Tidal capture in dense clusters (0.1%)



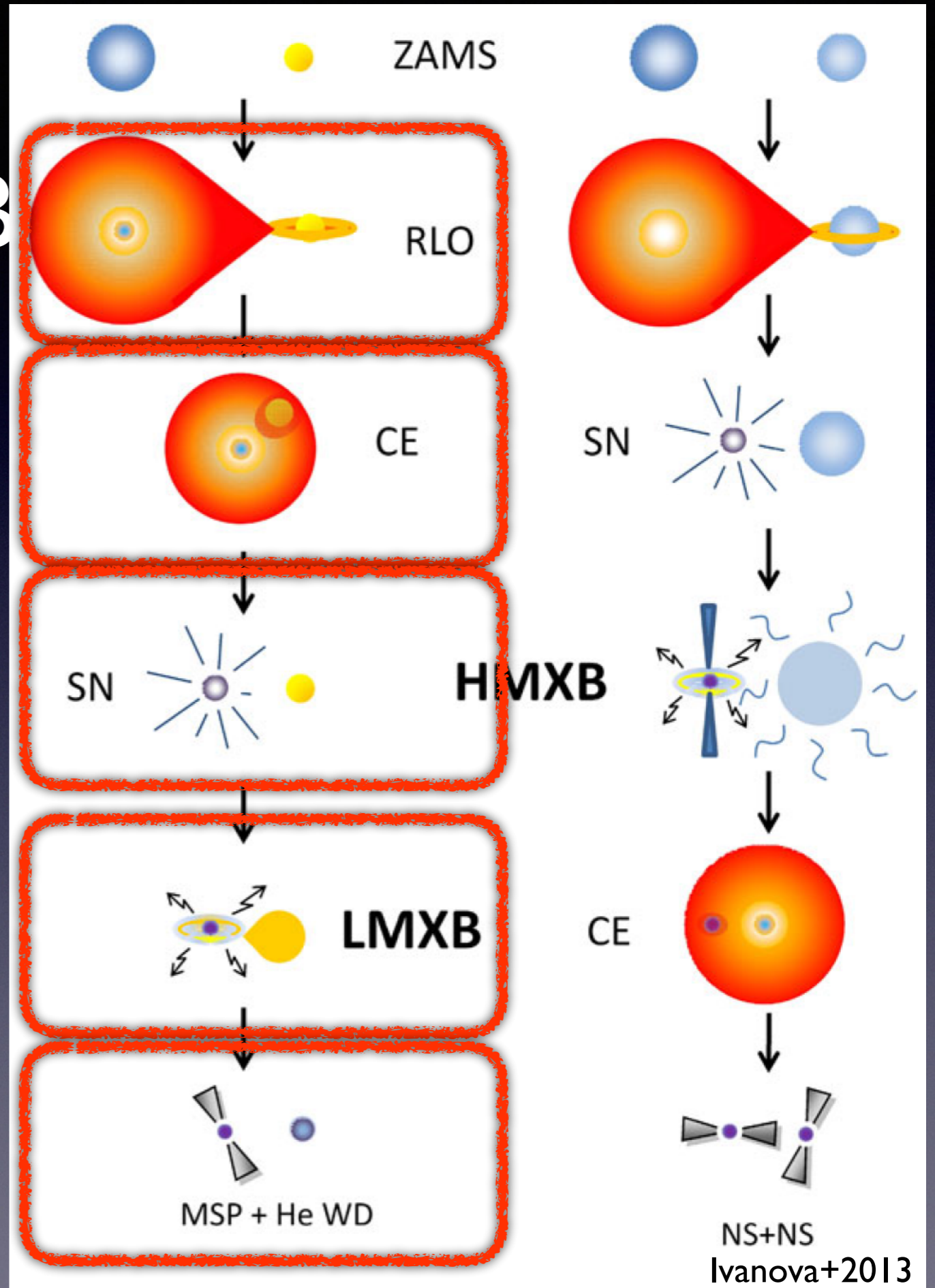
Binary evolution

- Main channel to coalesce within Hubble time (classical isolated, Tauris+2006)
- Evolution: mass ratio, orbital separation, stellar wind... Begin with: stars of mass < 1 or $> 10 M_{\odot}$
- Common Envelope Phase occurs after HMXB / before LMXB
- End up: binaries WD+NS, NS+BH, BNS, BBH



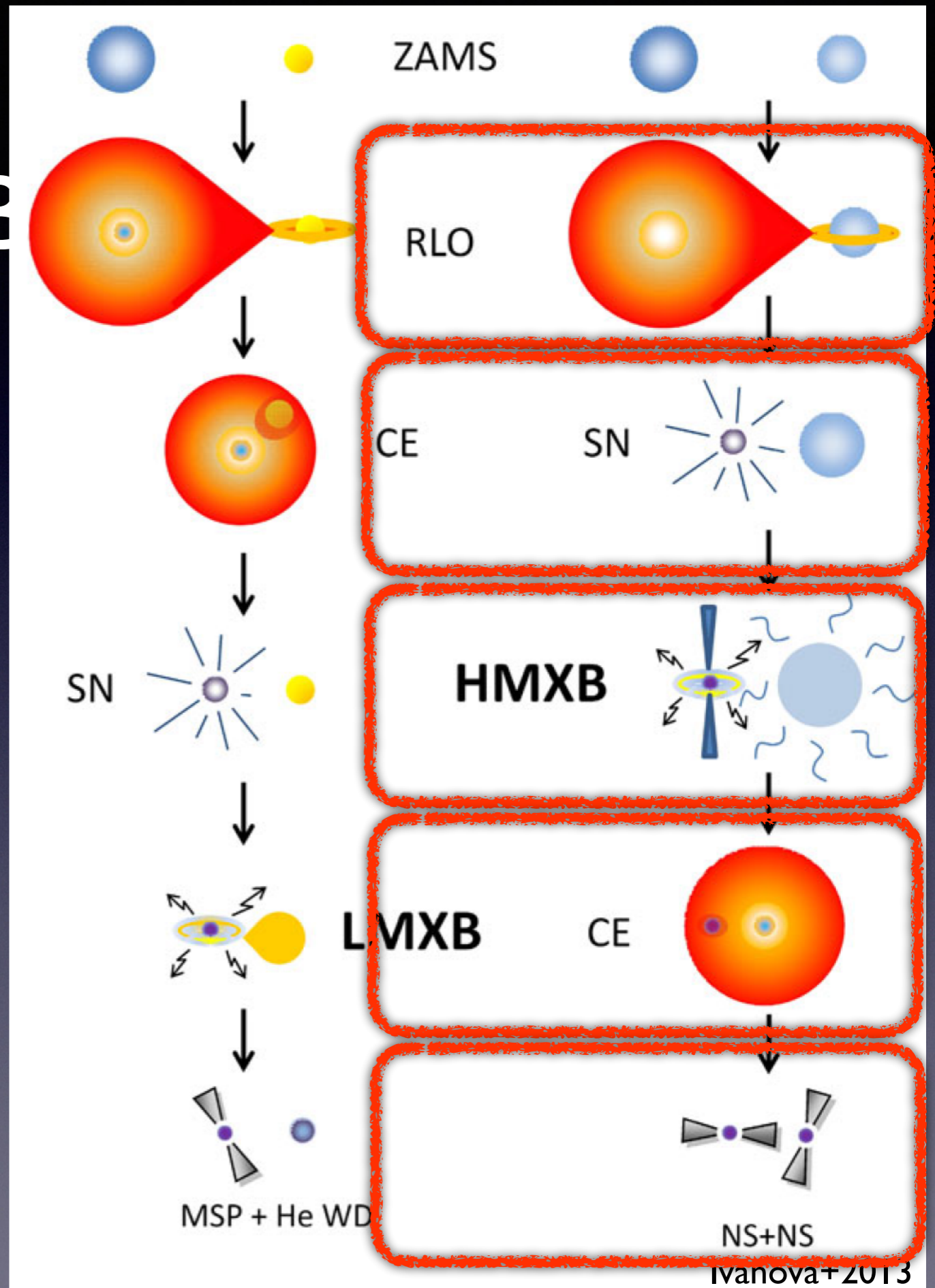
Binary evolution: LMXB

- Formation with stars of mass $< 1 M_{\odot}$ \rightarrow Roche lobe overflow
- It goes through and survives (?) common envelope phase
- After SN, the 2nd star evolves
- Short $P_{\text{orb}} \sim 1 \text{d}$ LMXB (while initial systems have long P_{orb} !)
- they end up as binary systems NS+WD



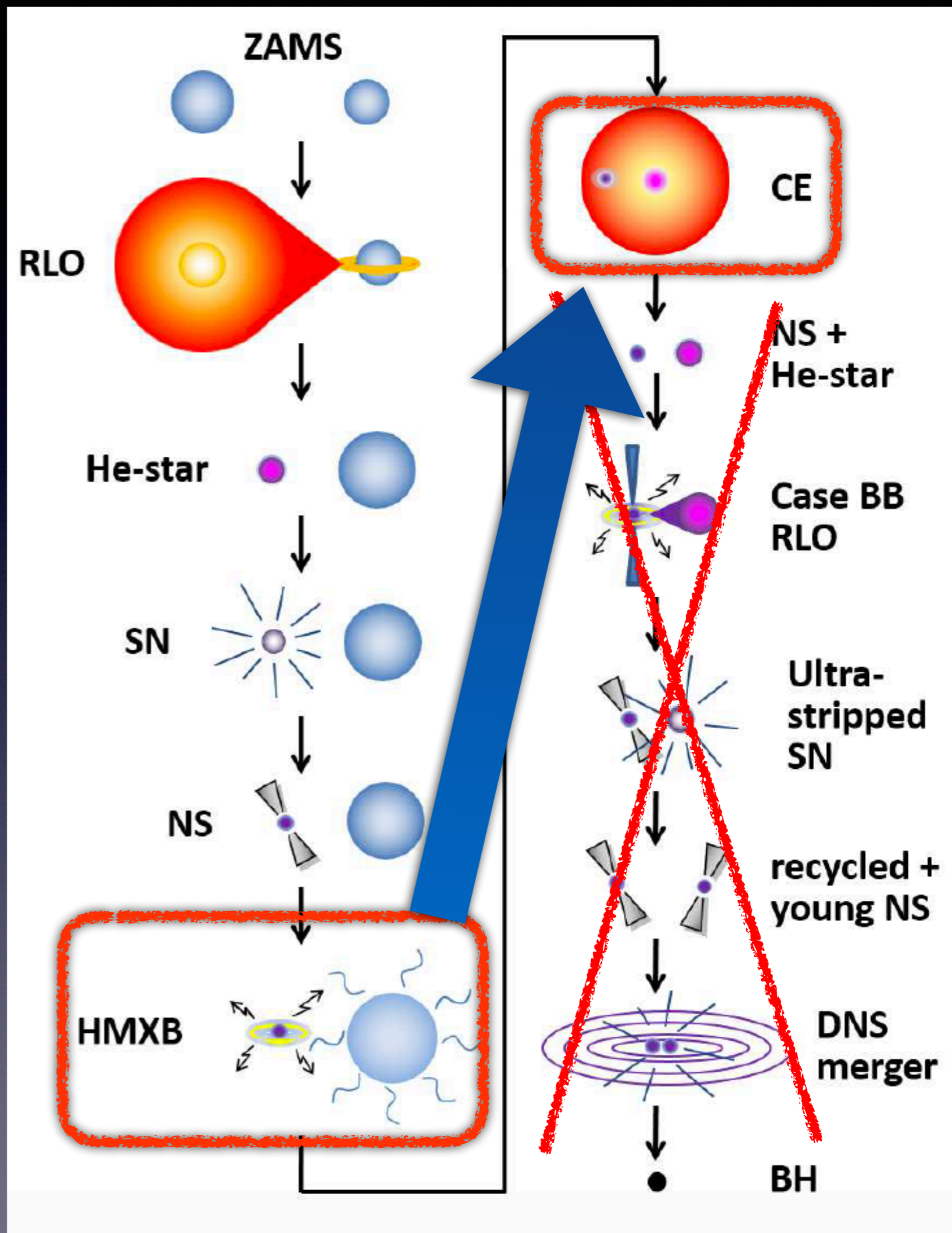
Binary evolution: HMXB

- Formation with stars of mass $> 1 M_{\odot}$ \rightarrow Roche lobe overflow
- After first SN, the second star evolves
- Long $P_{\text{orb}} \sim 100\text{d}$ HMXB requires initial systems with short $P_{\text{orb}} \sim 10\text{d}$
- It goes through and survives (?) common envelope phase
- After 2nd SN, it ends up as close eccentric binaries (BNS, BBH or NS/BH)



Evolution

- « Classical isolated binary evolution »
- Common Enveloppe Phase occurs **after HMXB!** (but before LMXB)
- Long $P_{\text{orb}} (> 1 \text{ yr})$ HMXB will go through, survive CE, later double NS merging in BH
- But short $P_{\text{orb}} (< 1 \text{ yr})$ HMXB will not go through, not survive CE! (Tauris+2017 ApJ)

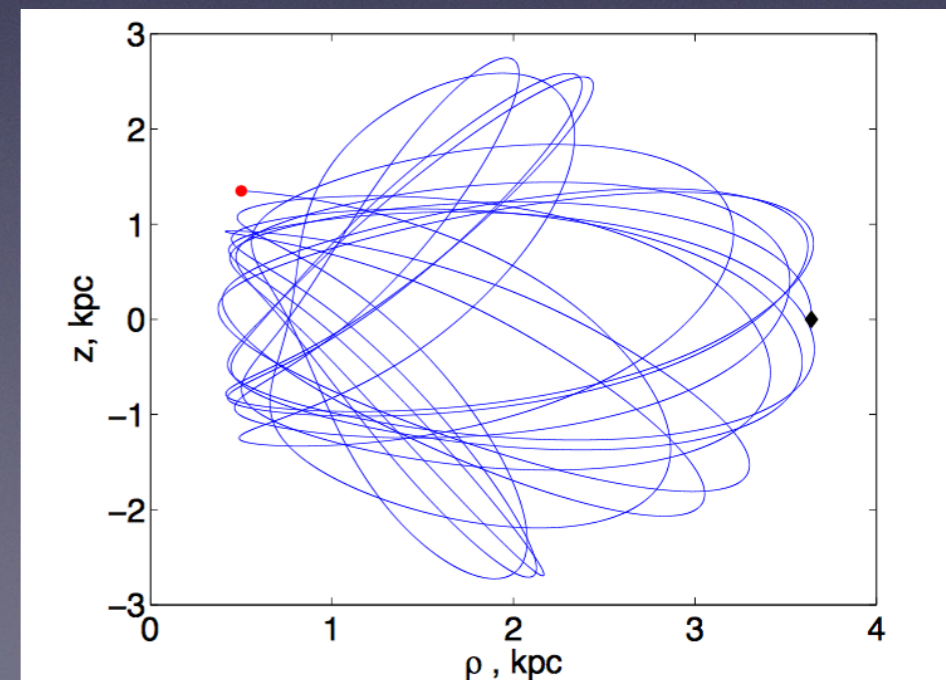
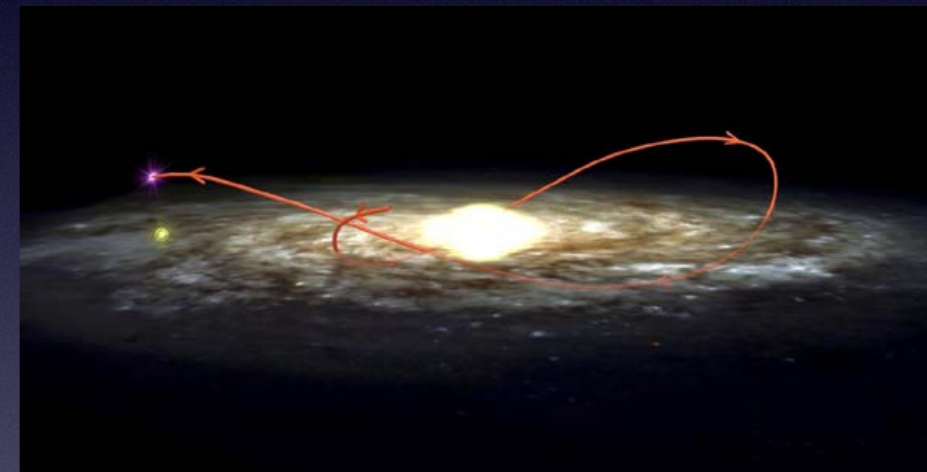


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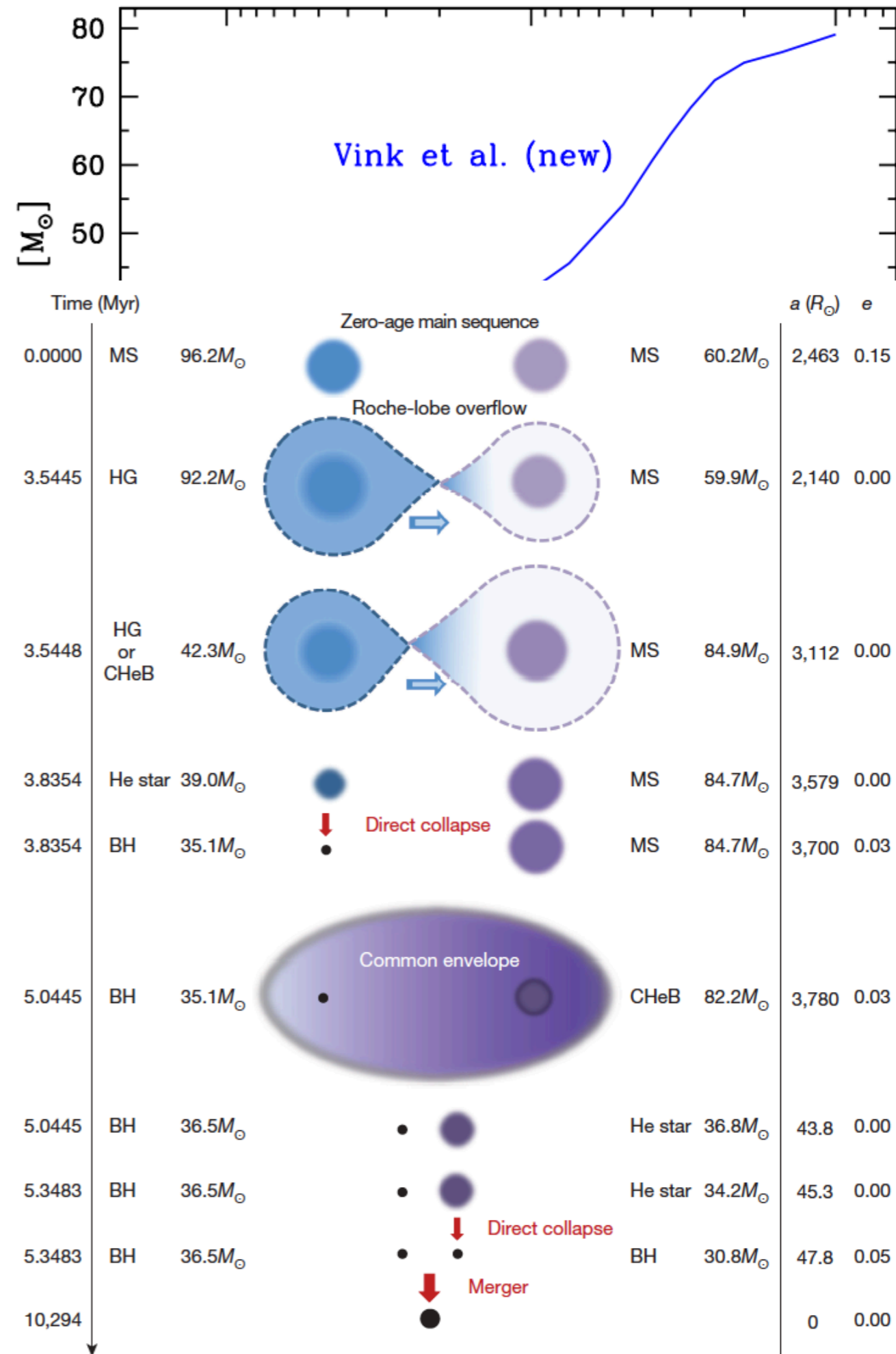
3 uncertain steps in binary evolution

- I. Natal kick (systemic velocity at SN)
(Mandel+2016)
- Leading to: disruption or gravitationally bound binary system?
(Mirabel+2001)

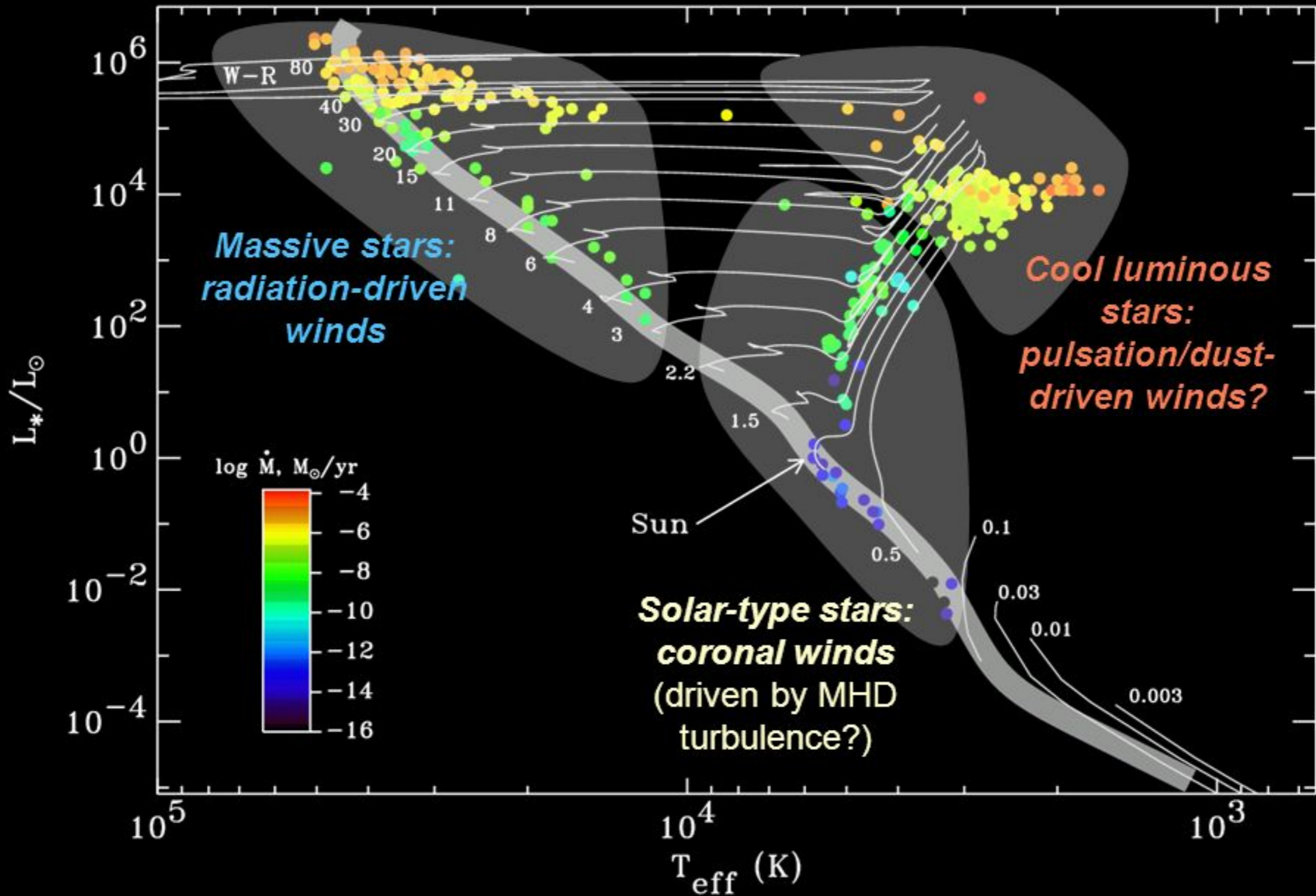


3 uncertain stellar binary evolution

- 2. Stellar wind strength vs metallicity (Kudritzki+2000)
- Massive stars losing most of their mass!
- Extrapolate to low-metallicity galactic environments => Leading to merging! (Belczynski+2016)



Stellar winds across the H-R Diagram



3 uncertain step binary evolution

- 3. Common Envelope (CE) Phase
- Star evolves in red giant, radius increases, Roche lobe overflow (RLOF), envelope engulfs companion star, drastic tightening of binary orbit, by viscous dissipation of angular momentum
- Leading to: ejection of envelope or merging of both components? (Paczynski+1976; Webbink 2008, Ivanova+2002)
- How many systems do survive?

stable RLOF + CE (mass ratio < 1.2 - 1.5)

stable RLOF

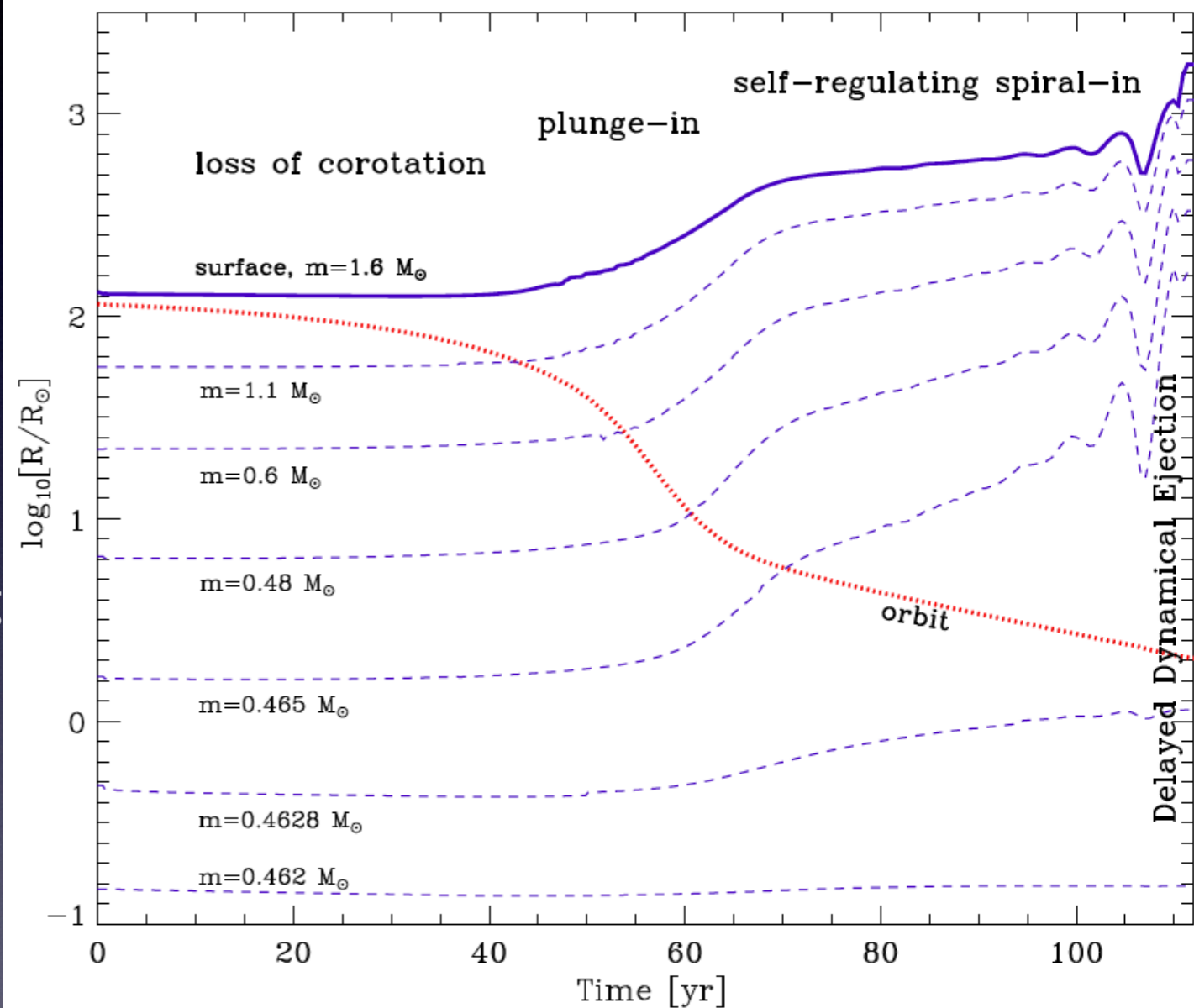
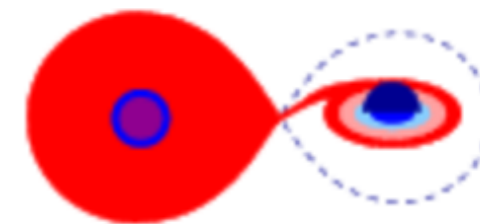


Fig. 2 The main potential phases of a CE event prior to the envelope ejection or the merger. This example is for a $1.6M_{\odot}$ red giant and a $0.3M_{\odot}$ WD, using data from one-dimensional hydrodynamical simulations in Ivanova (2002). Not all phases are expected to happen during all CE events. The dashed lines represent locations at fixed mass coordinates, and the dotted line shows the location of the in-spiralling secondary

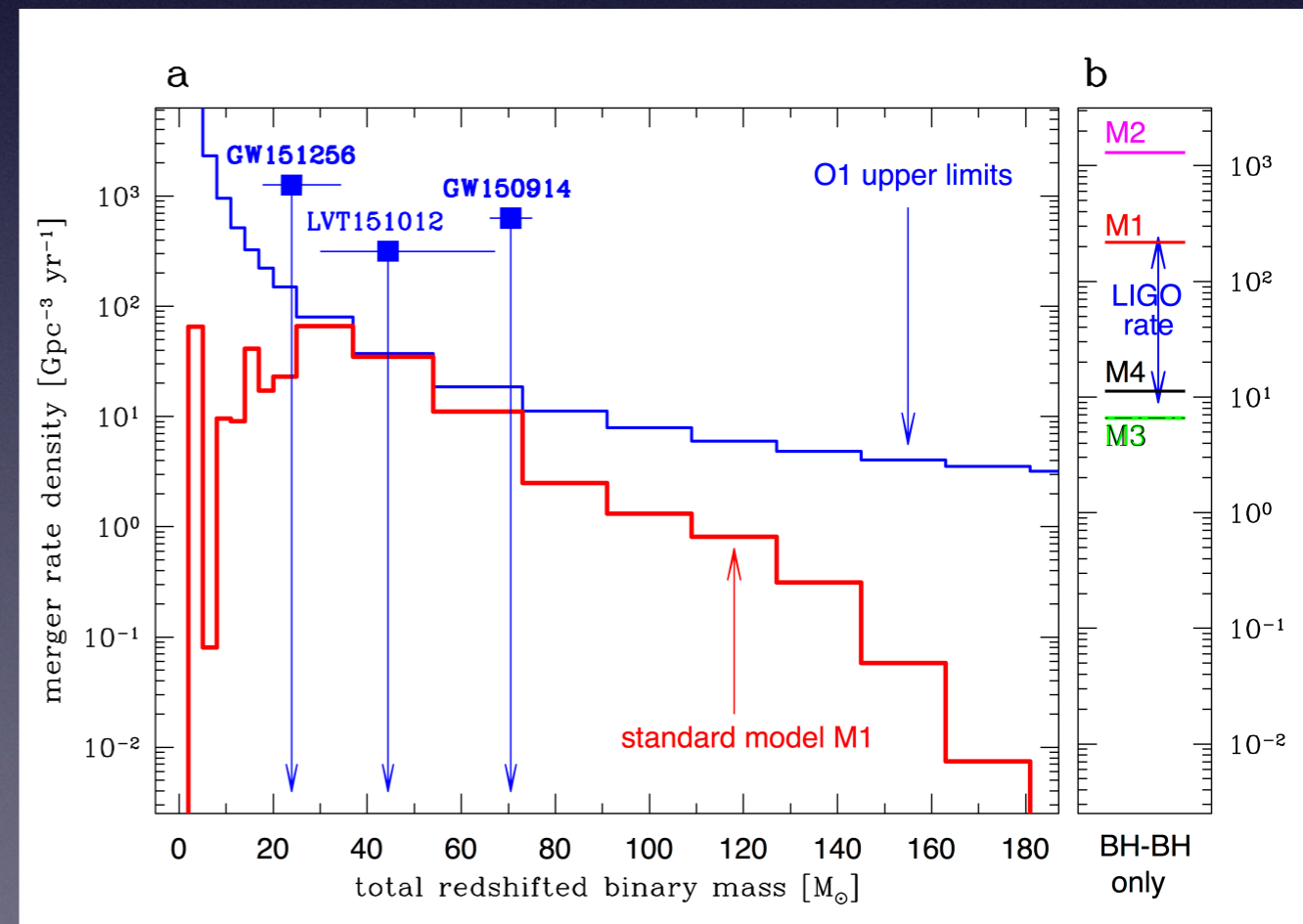
short-period sdB binary with He WD companion



$P_{orb} =$

Rate of mergers

- Using sensitivity curve from LIGO/Virgo:
- constrain mass/spin of binary components
- estimate rate of compact object mergers (BBH, BNS, NS/BH) leading to GW detections: MW-like, rate $\sim 1-20$ fusions/Myr! (Belczynski/2016)

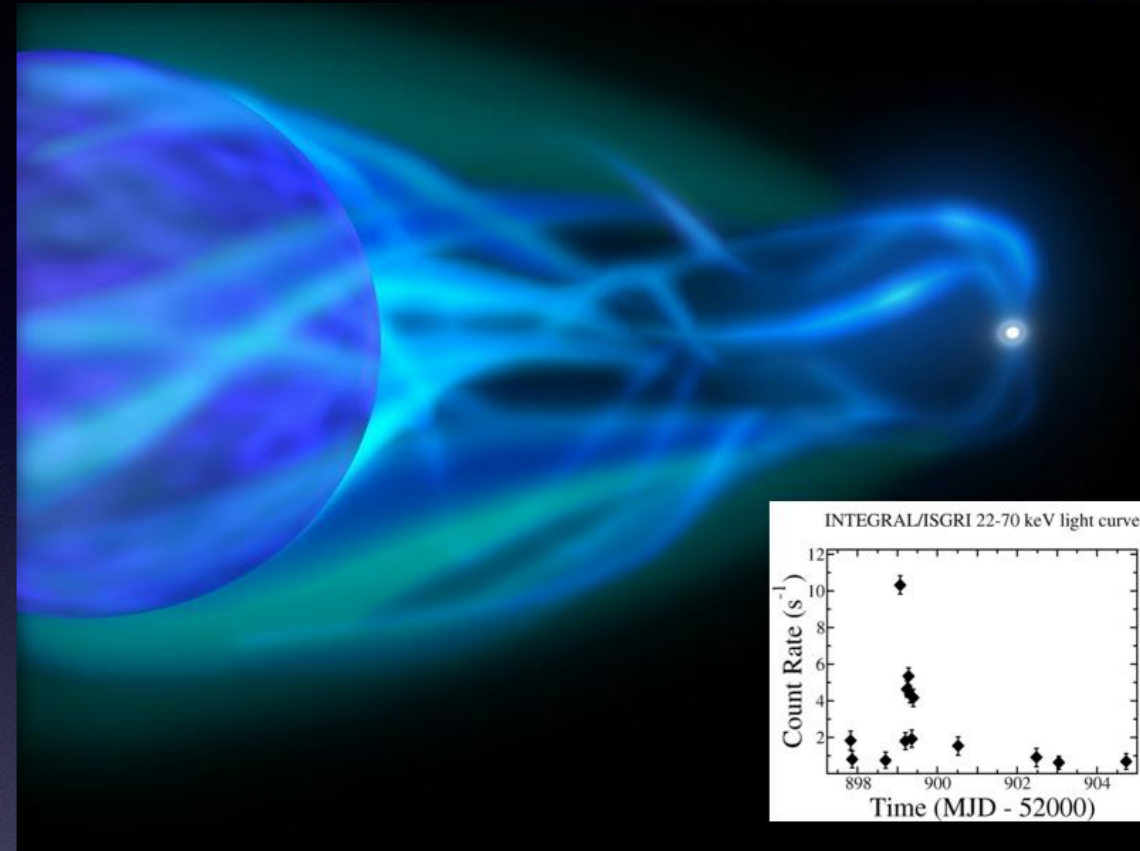
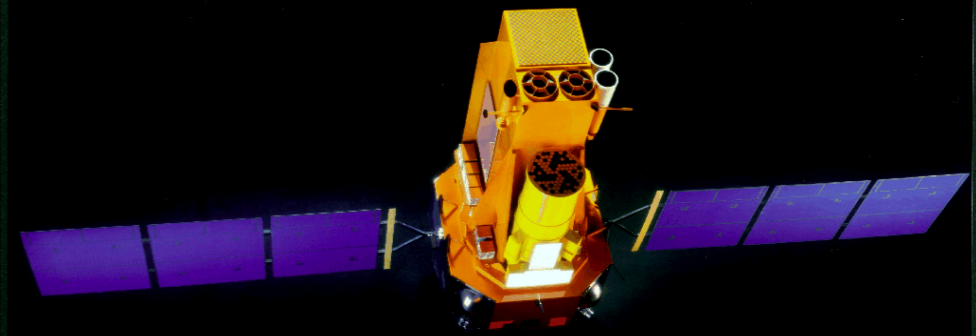


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The *INTEGRAL* legacy (I)

- *INTEGRAL* revealed 2 new categories of HMXBs:
 - Obscured (persistent) sgHMXBs: $N_{\text{H}} > 10^{23} \text{ cm}^{-2}$; short $P_{\text{orb}} = 3.7\text{-}9.7\text{d}$; $L_{\text{X}} = 10^{36}$ to 10^{38} erg/s ; O8-B1 companions
 - Supergiant Fast X-ray Transients (SFXTs): fast and intense flares



The *INTEGRAL* legacy (II)

- *INTEGRAL* (ESA satellite) quintupled the population of known sgHMXB (7 → 36)

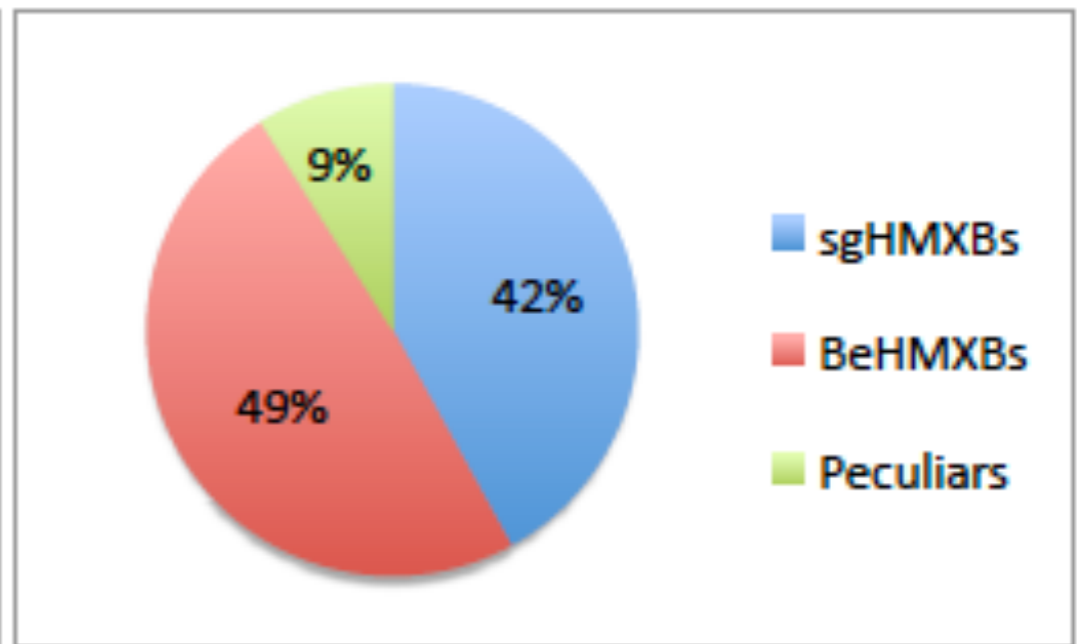
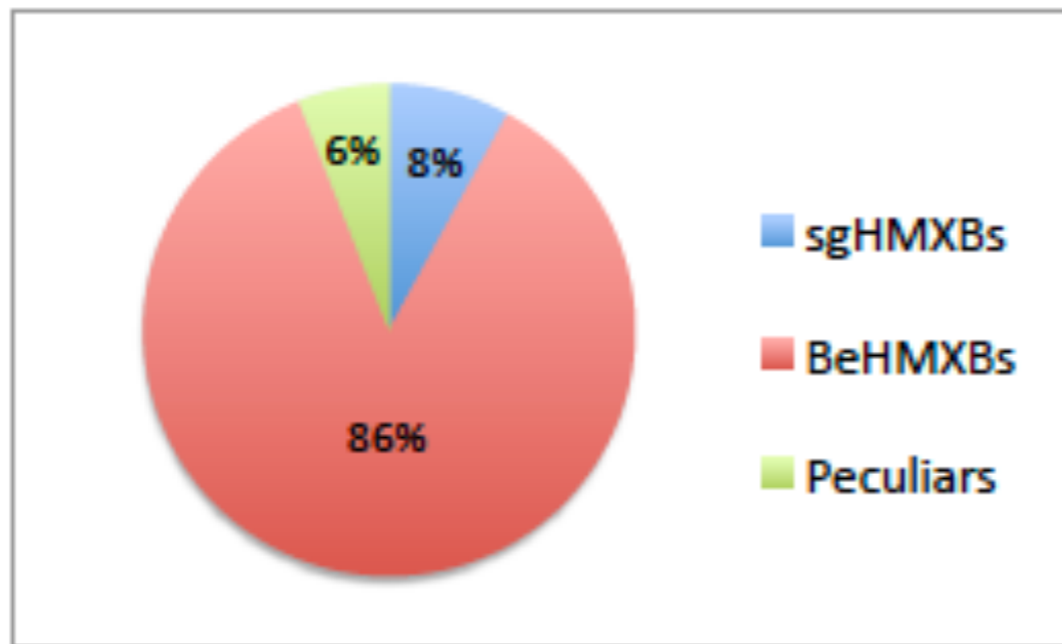
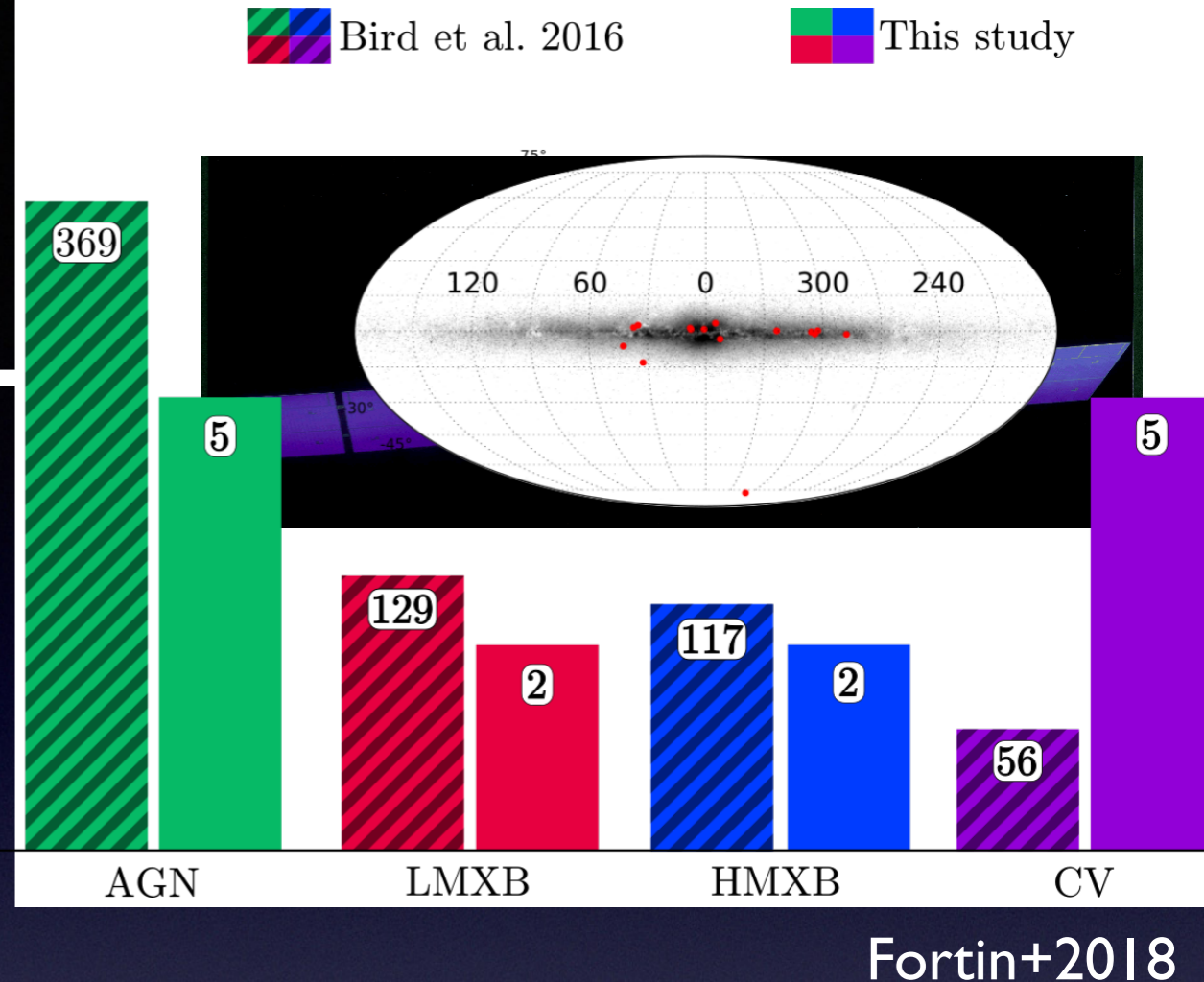
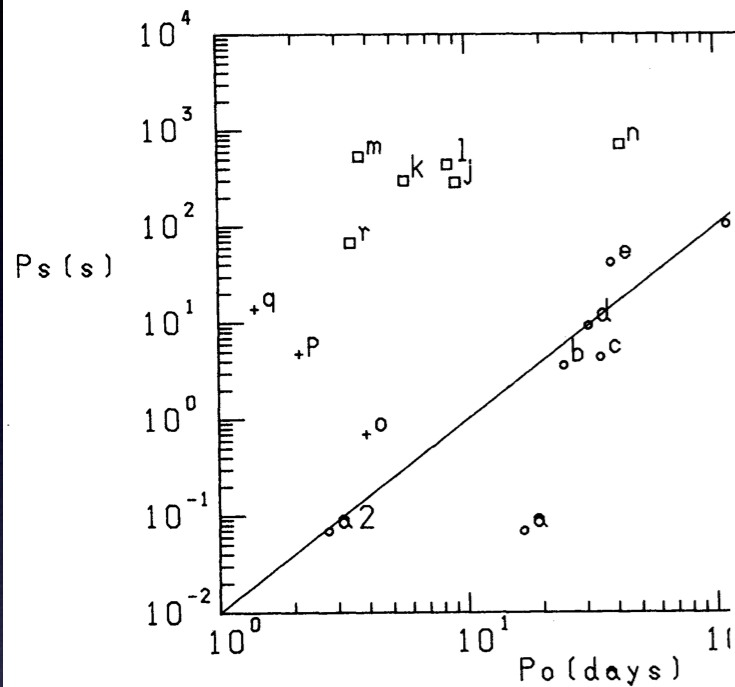


Fig. 8. Left panel: fraction (in percents) of confirmed (with spectral type) sgHMXB, BeHMXB and peculiar HMXB (such as B[e]HMXB) in Liu et al. (2000) catalog. Right panel: fraction (in percents) of confirmed (with spectral type) sgHMXB, BeHMXB and peculiar HMXB (such as B[e]HMXB) to date.

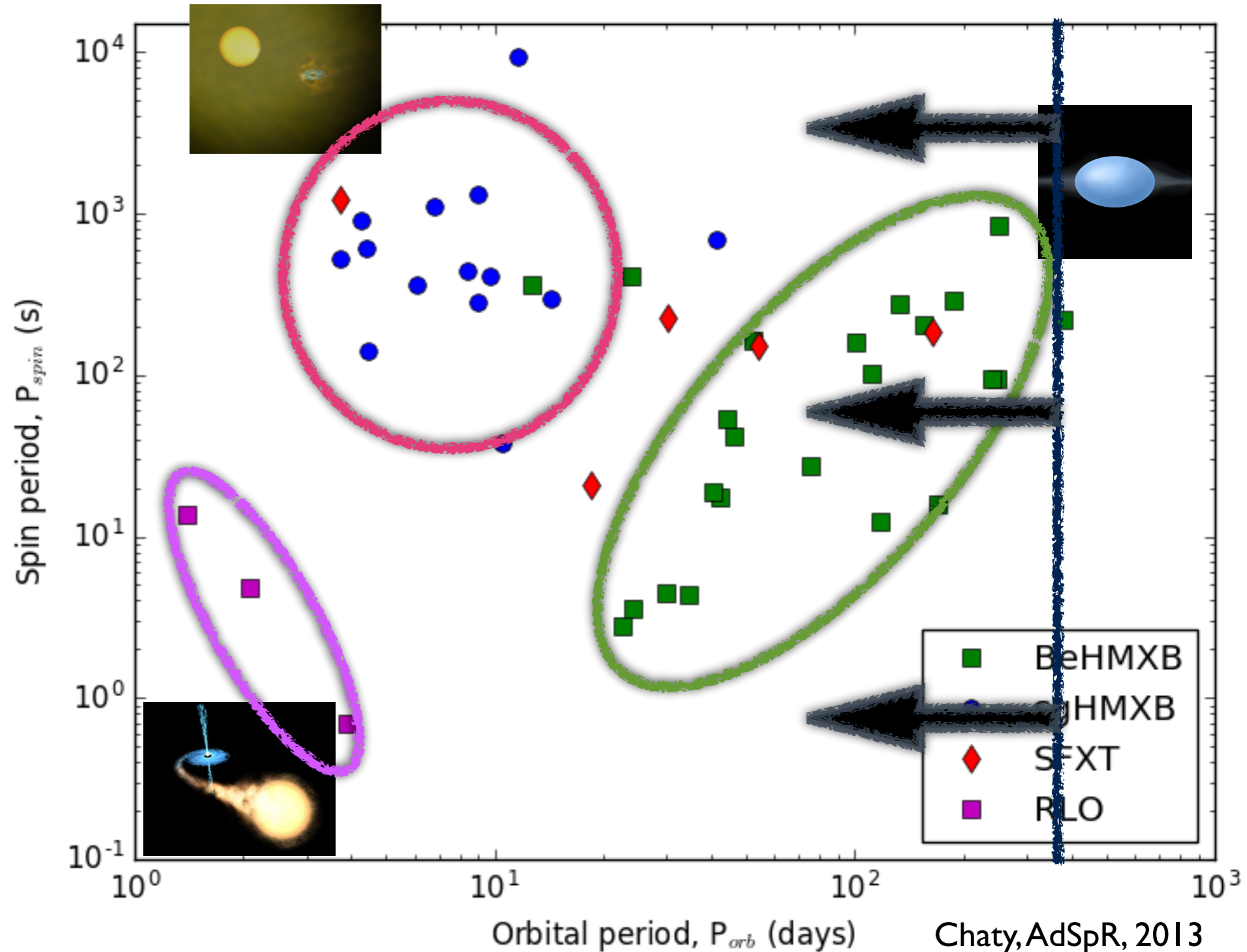
The Corbet Diagramme revisited by *INTEGRAL*



Corbet 1986

NS-HMXB systems!

- Be: correlation NS $P_{spin} \propto (P_{orb})^2$
- Roche-lobe overflow
- sgXBs: no transfer of ang mom
- $P_{orb} < 1yr$ do not survive CE!



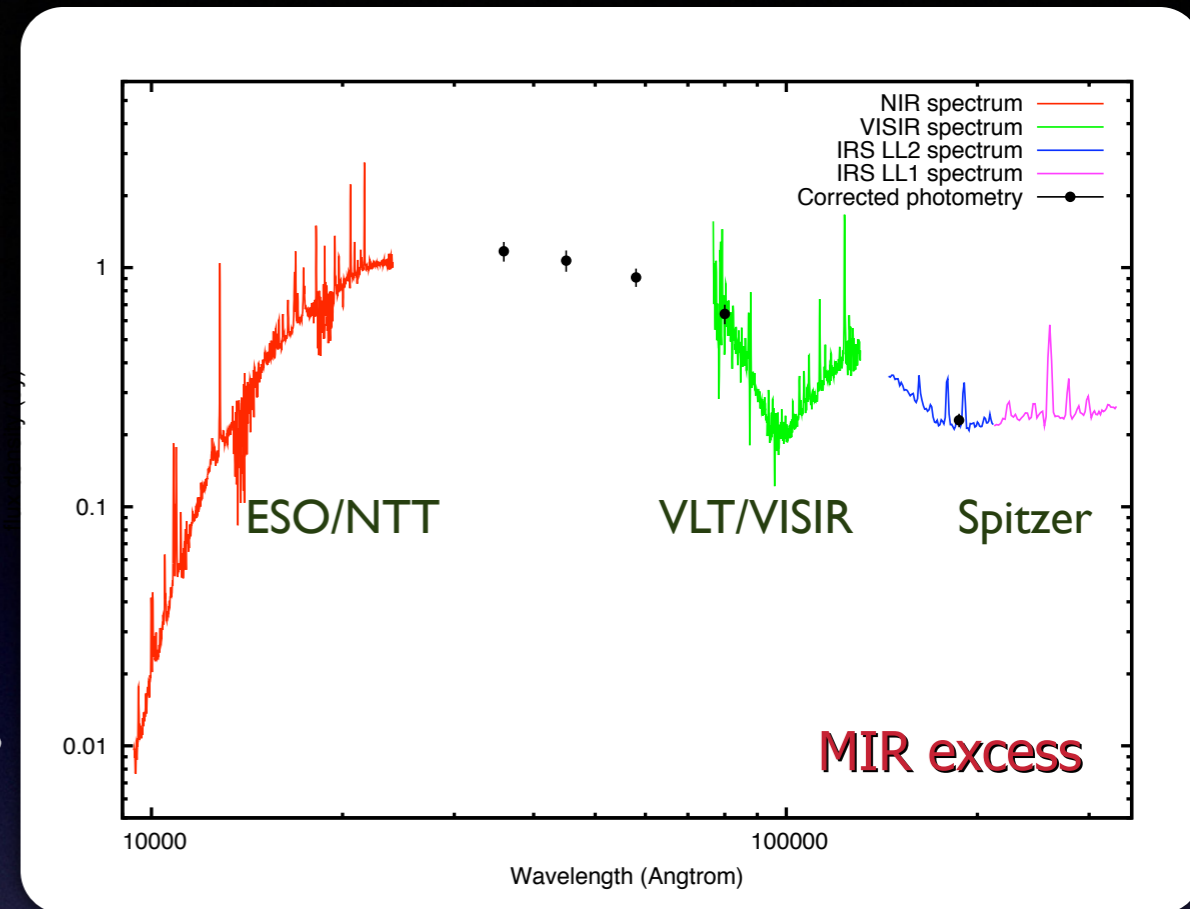
■	BeHMXB
●	HMXB
◆	SEXT
■	RLO

Chaty, AdSpR, 2013

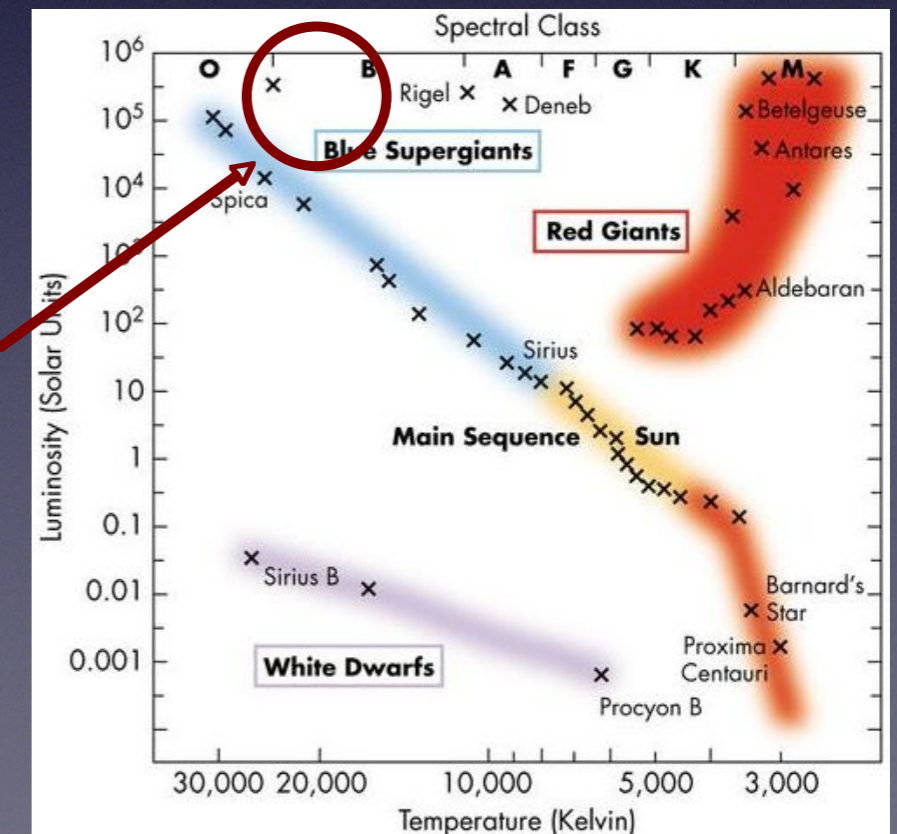
S. Chaty

Obscured sgHMXB: IGR J16318-4848

- HMXB: strong emission lines, MIR excess
- Very absorbed: $N_H > 10^{24} \text{ cm}^{-2}$
- Ionised (H/He) wind 400 km/s
- Shocked [FeII] and dense ($> 10^{5-6} \text{ cm}^{-3}$) regions: NaI, Ne, Si...
- Luminous sgB[e] star with stratified circumstellar envelope:
 $10^6 L_{\odot}$, $30 M_{\odot}$, 22 000 K, $20 R_{\odot} = 0.1 \text{ au}$



Chaty & Rahoui 2012 ApJ



Filiatre & Chaty 2004 ApJ

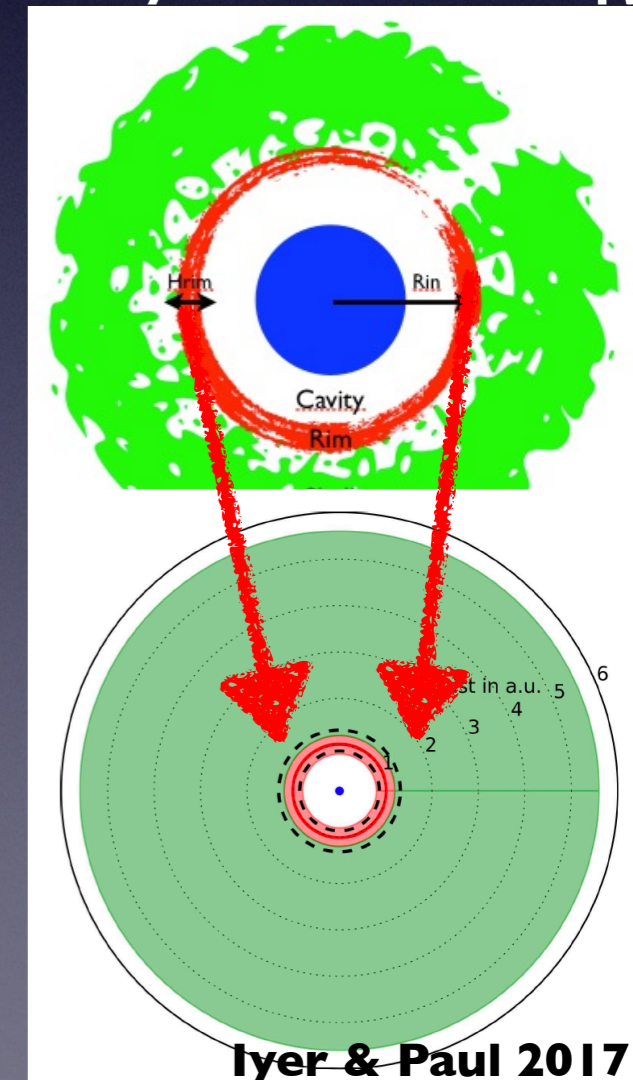
Obscured sgHMXB: IGR J16318-4848



Chaty/ESA

- Herbig Ae/Be models: torus geometry (VLT)
 - Disk rim: $T = 5\ 500\text{K}$, Thickness: $\sim 0.7 R_*$
 - Warm dust shell at 900 K , $R_d = 12 R_*$
- CO orbits within dense disk rim ($P_{\text{orb}} 80\text{d?}$)
- Evolution: transiting to RLO \rightarrow deep spiral-in: pre-CE phase
 - If CO=NS : short P_{orb} HMXB will not survive CE \Rightarrow ideal Thorne-Zytkow candidate! (Tauris+2017 ApJ)
 - If CO=BH with $q < 3.5$: HMXB survives spiral-in \Rightarrow WR-XRB, $P_{\text{orb}} \sim \text{days}$ (van den Heuvel+2017)
- BH/NS binary \rightarrow Ideal candidate merging progenitor?

Chaty & Rahoui 2012 ApJ

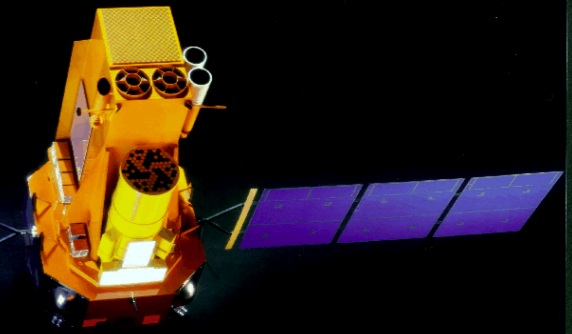


Iyer & Paul 2017

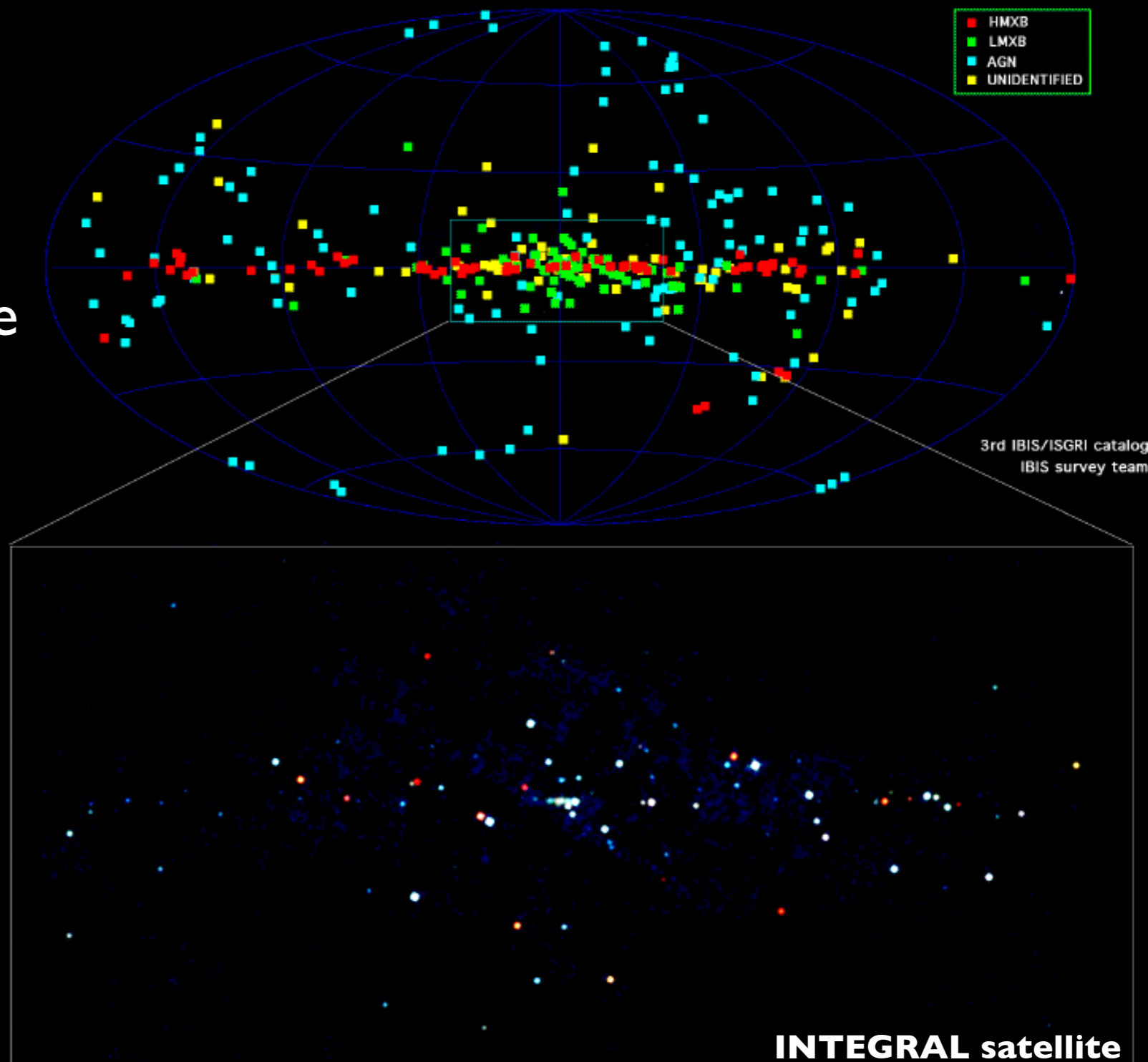
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The Milky Way

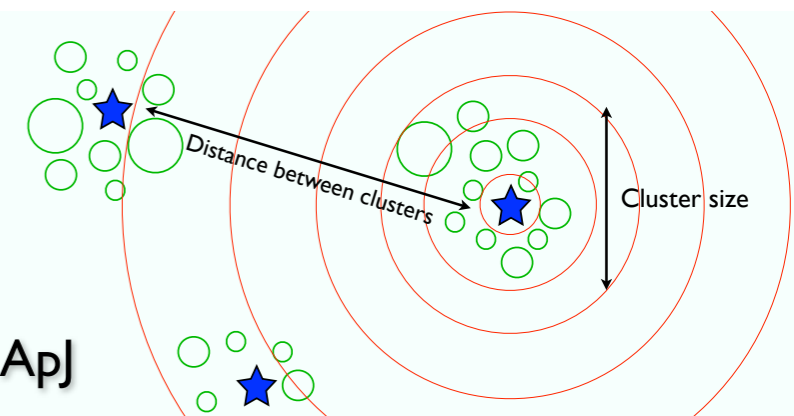
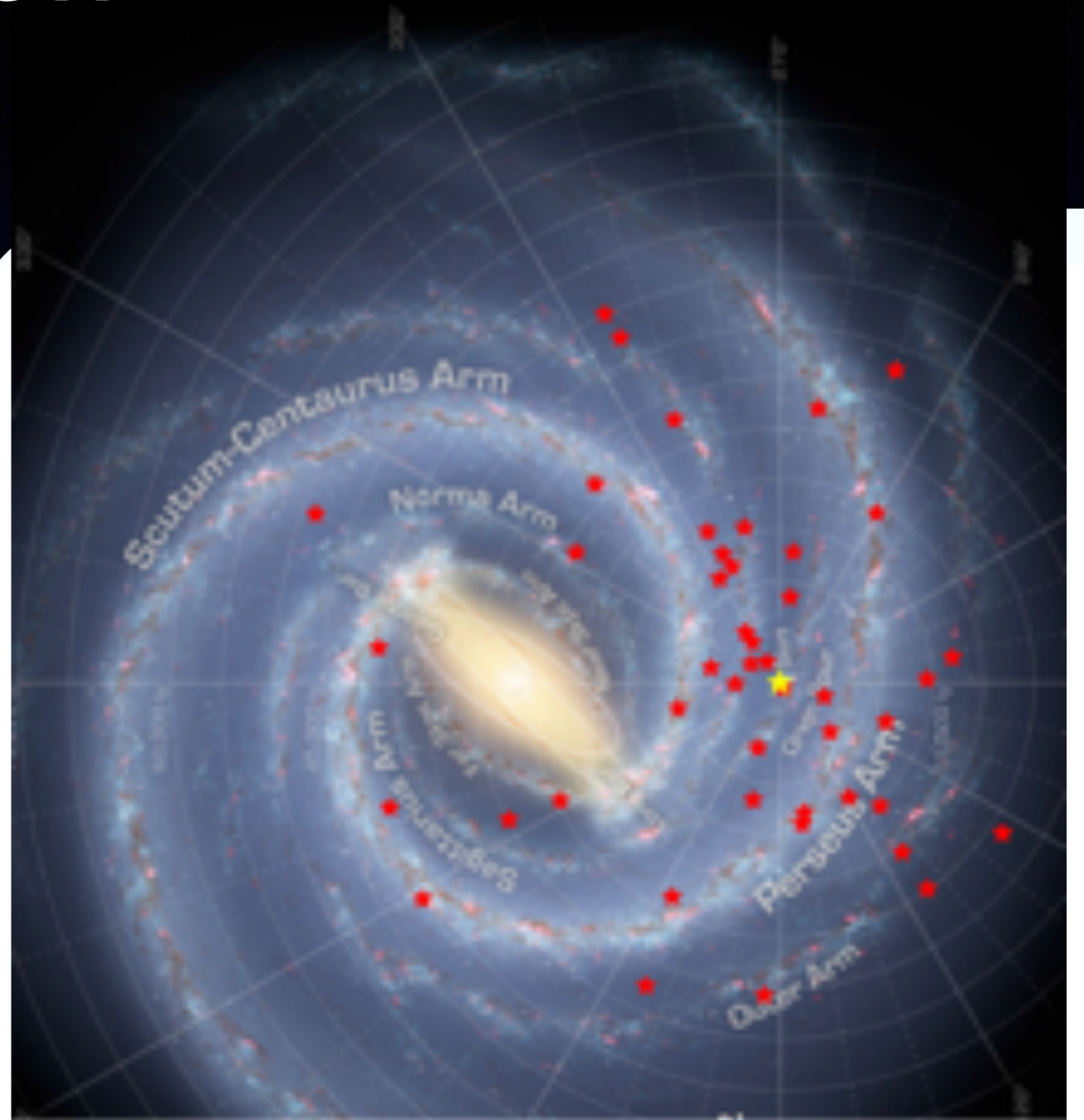


- LMXB (old stars) in Galactic bulge, migration off the plane ($|b| > 3-5^\circ$)
- HMXB (young stars): on Galactic plane, towards tangential directions of spiral arms



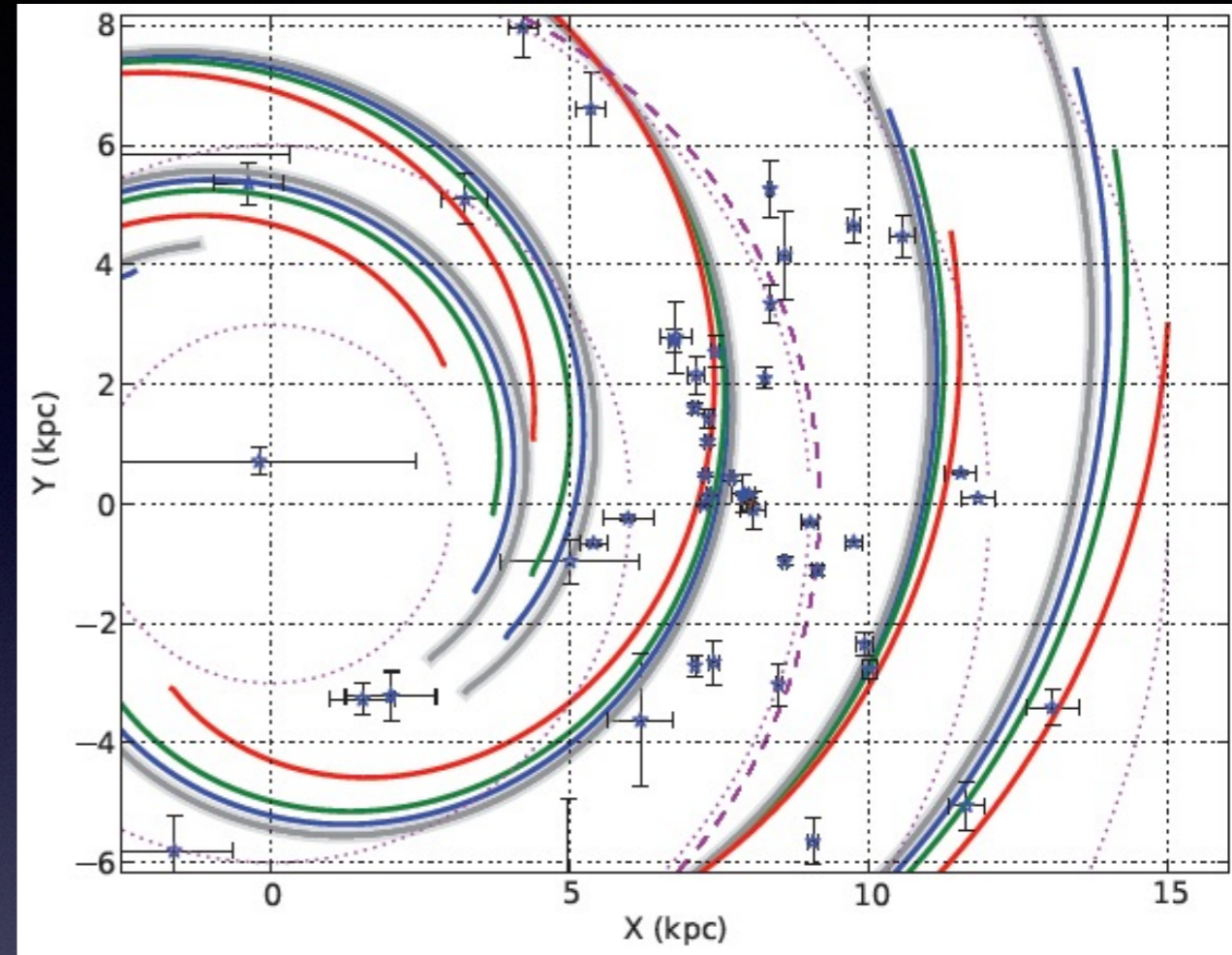
Galactic distribution of HMXB

- Fit (distance, A_v) of 46 HMXB on 4-spiral arm Galactic model
- HMXB clustered with Star Forming Complexes (Russeil 2003)
- $\langle \text{size} \rangle = 0.3 \text{ kpc}$
 $\langle \text{distance} \rangle = 1.7 \text{ kpc}$
- HMXB remain close to their birthplace!



Galactic distribution of HMXB

- Taking into account the Galactic arm rotation
- => HMXB distribution offset by $\sim 10^7$ yrs wrt spiral arms (delay between massive star birth & HMXB phase -10^5 yr-)
- => migration distance & kick (50-90 km/s)
- New stellar parameters with *Gaia*!

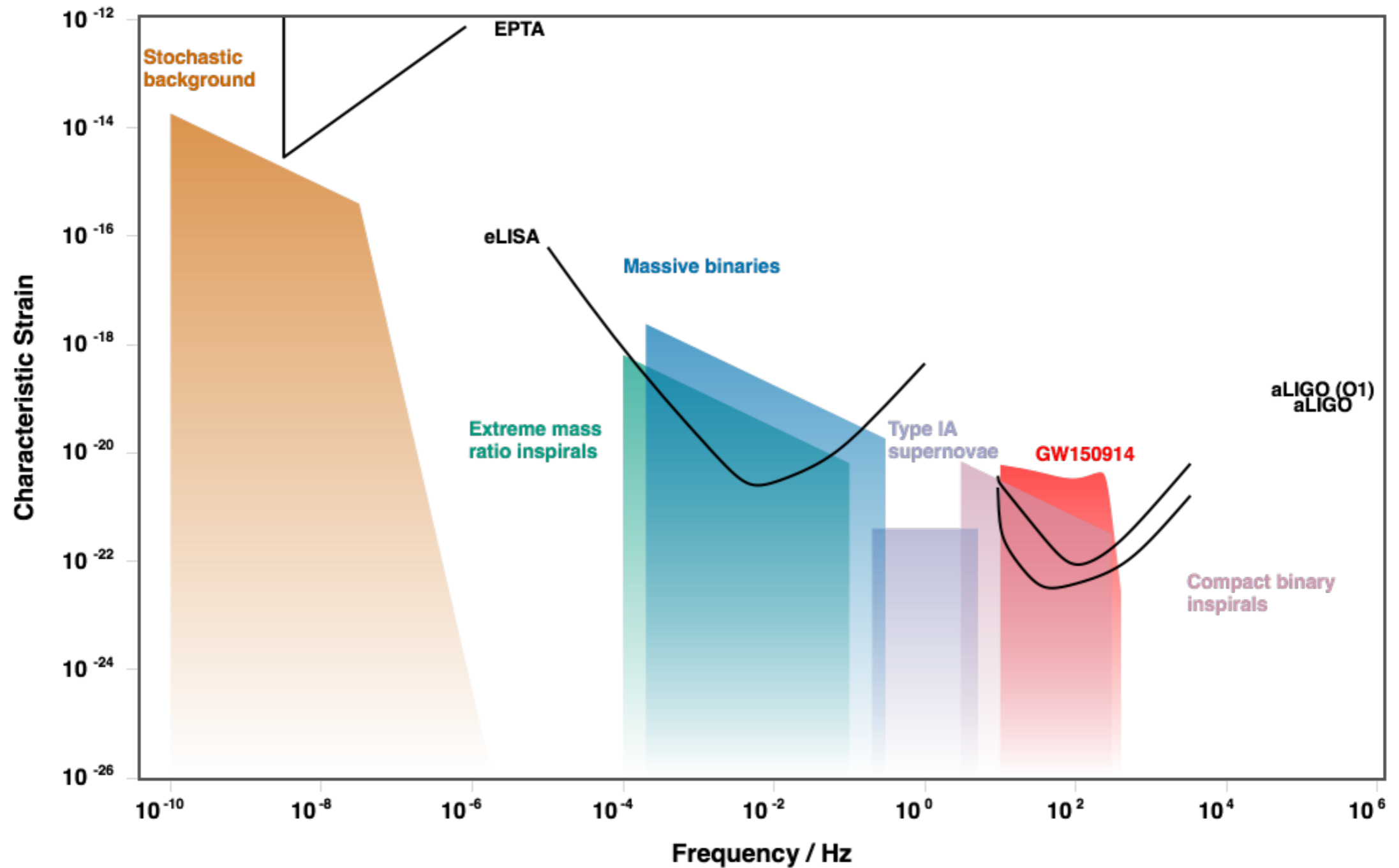


SOURCE NAME	AGE (Myr)	MIGRATION DISTANCE (kpc)	UNCERTAINTY
Be			
1A 0535+262	80	0.10	0.30
1A 1118-615	80	0.088	0.56
EXO 0331+530	60	0.25	0.080
GRO J1008-57	40	0.074	0.15
GX 304-1	40	0.048	0.59
H 1417-624	20	0.20	0.39
PSR B1259-63	60	0.037	0.51
RX J0440.9+4431	20	0.011	0.17
RX J1744.7-2713	60	0.10	1.0
Supergiants			
4U 1700-377	80	0.15	0.28
IGR J16465-4507	20	0.087	0.052
IGR J18410-0535	60	0.013	0.11
H 1538-522	20	0.14	0.52

Statistics

- ~20 000 O stars in Galaxy, 33% within double systems evolving through envelope stripping (Sana+2012)
- Assuming 50% of these systems (~1500) survive natal kicks (close orbits) and massive star last for $\sim 10^7$ yr
=> 1 HMXB forms every ~ 7000 yr, lasting for $\sim 10^5$ yr
- Short P_{orb} NS-HMXB will not survive CE -> TZ objects
- Long P_{orb} NS-HMXB -> DNS and merge after $\sim 10^{10}$ yr
- Short P_{orb} BH-HMXB will survive spiral-in -> WR-XRB, merge

The future of gravitational waves



#3

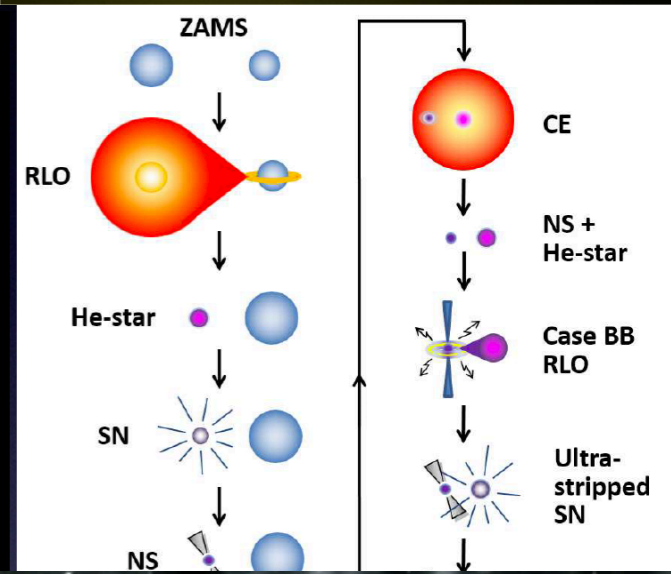
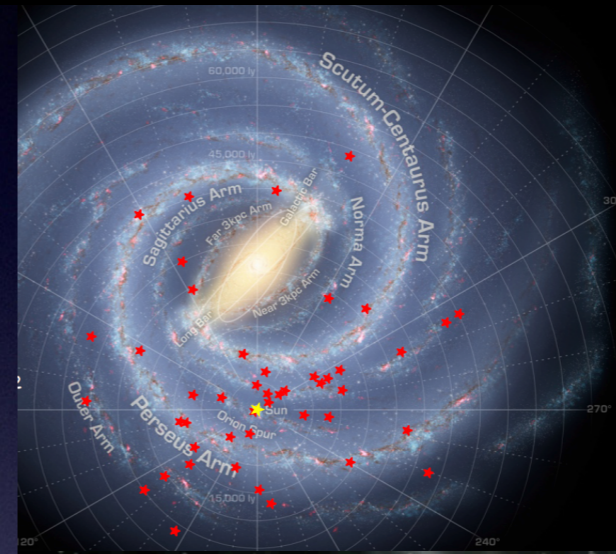
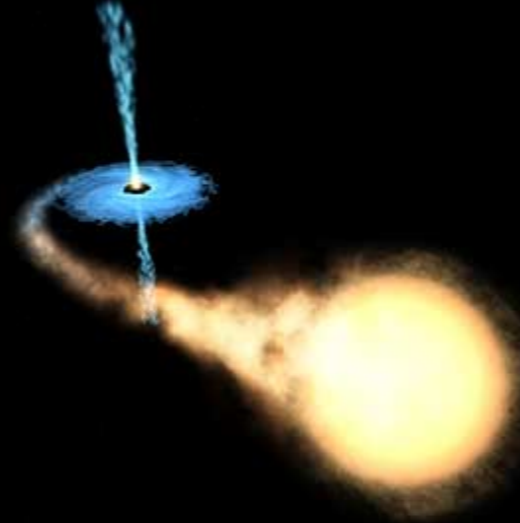
orbit
craft

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Conclusions

- Binaries: LMXB & HMXB
- Evolution: HMXB are the best candidates for TZO or, if they survive the CE phase, DNS and merging
- The *INTEGRAL* revolution: quintupled the number of sgXB
- Galactic distribution: HMXB correlated with SFC => age, migration, kick...



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