Stellar-mass Black Holes

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TianQin Astrophysics Workshop 22/08/2022

Outline

1. Formation of black hole (BH) binaries as gravitational wave sources

2. Overview of LISA BH binaries

3. Detection of TianQin BH binaries (for the white paper)

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A brief history for gravitational waves (GWs)

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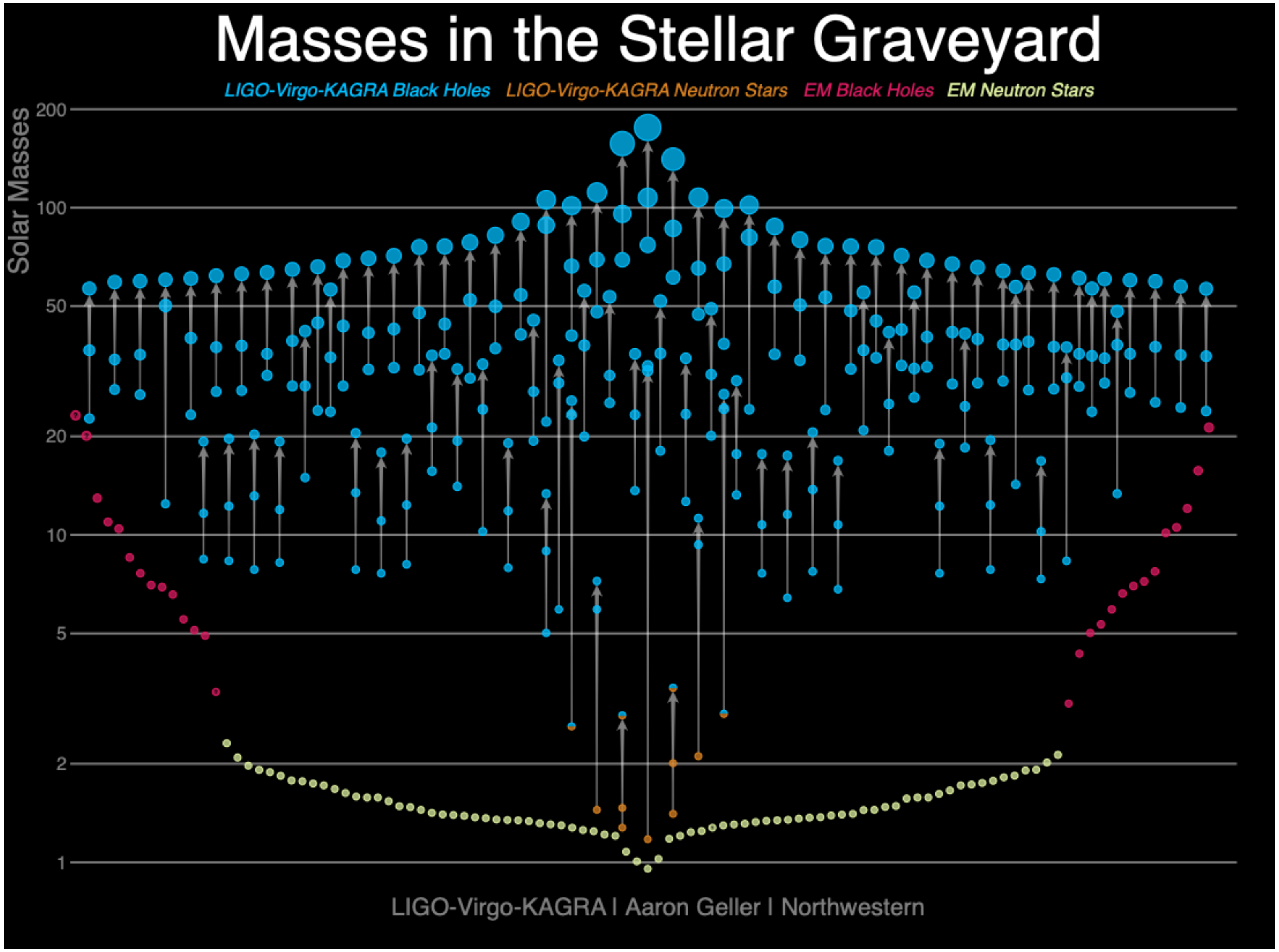
> In 2017, **Rainer Weiss**, **Barry Barish** and **Kip Thorne** shared the Nobel Prize in Physics "for decisive contributions to the LIGO detector and the observation of gravitational waves." (detection of the first BHBH merger GW150914)

Detection of GW transients

> over **80** BHBH mergers

> **a few** BHNS mergers

> **2** NSNS mergers



(The LIGO Scientific Collaboration et al. 2021)

Formation channels of GW transients

> Isolated binary evolution

> Chemically homogeneous evolution

> Population III stars

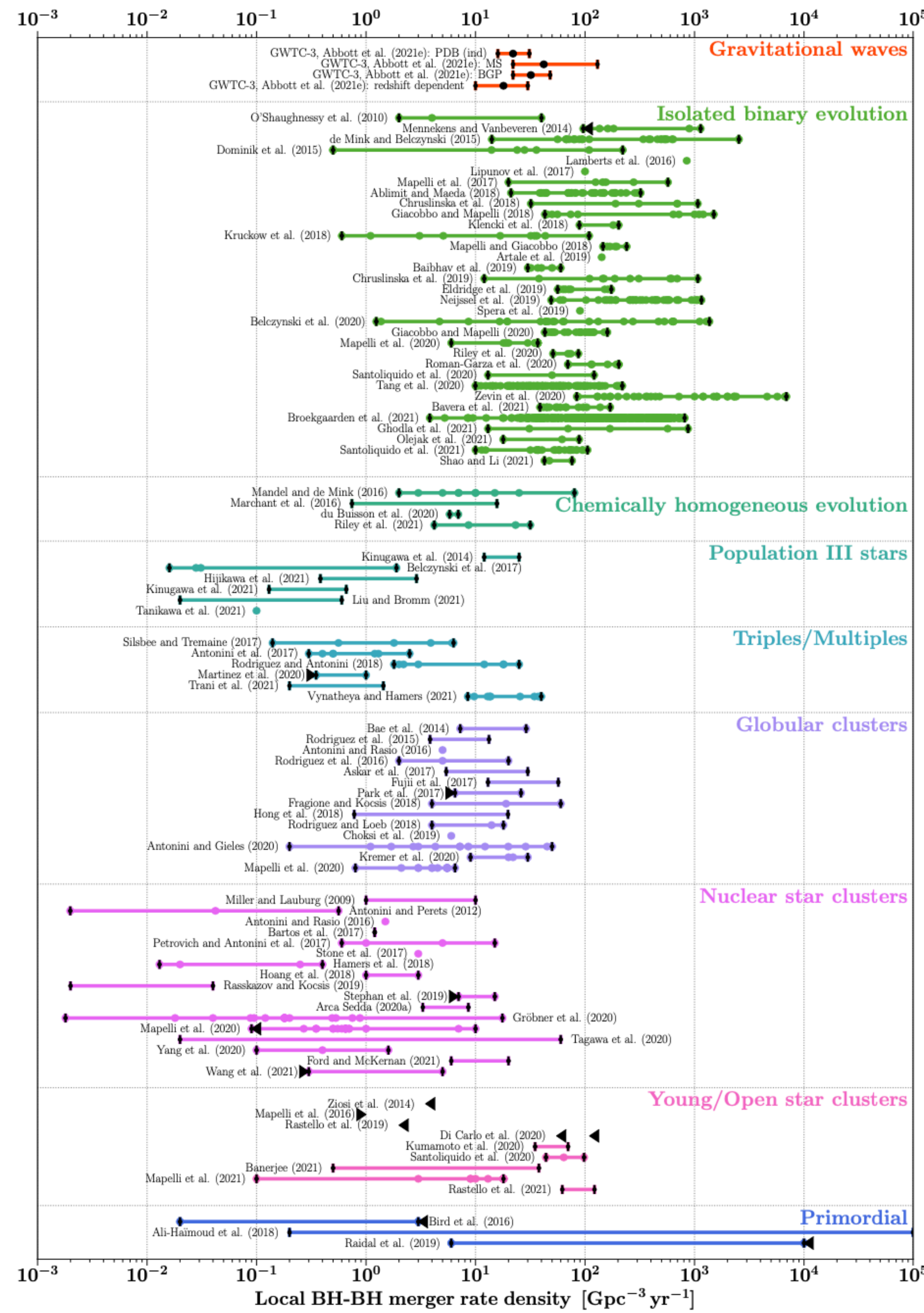
> Triples/Multiples

> Globular clusters

> Nuclear star clusters

> Young/Open star clusters

> Primordial BHs



(Mandel & Broekgaarden 2022)

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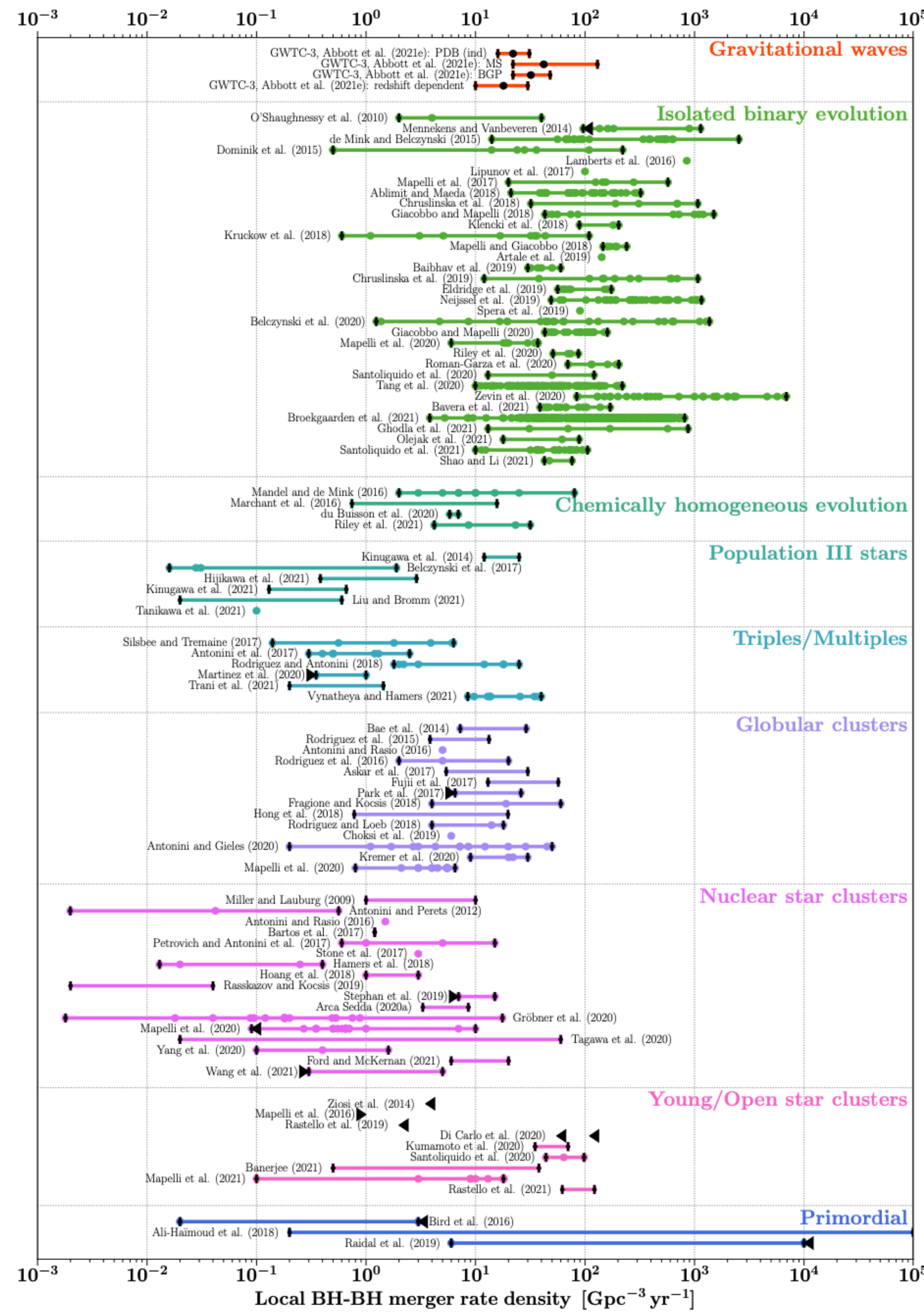
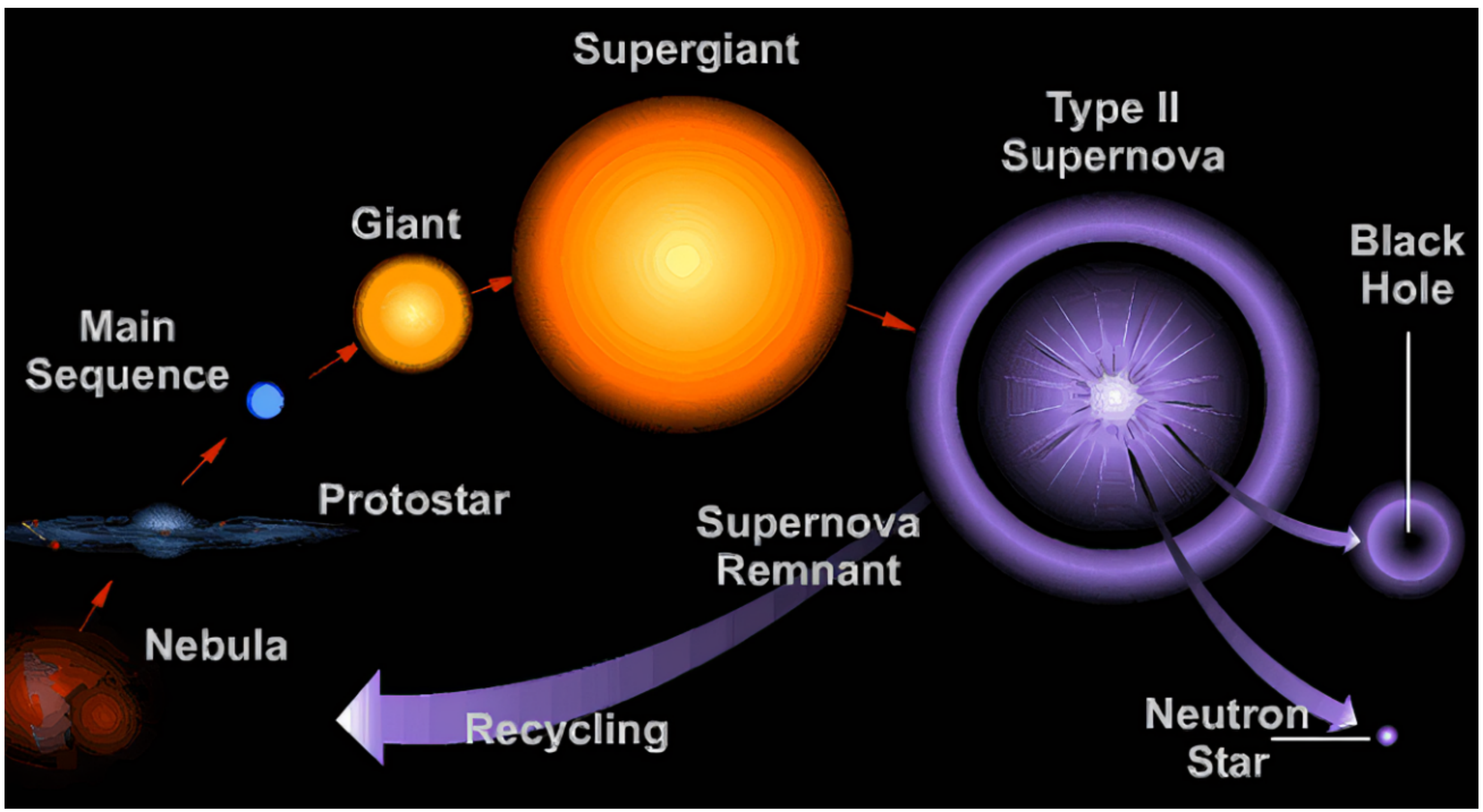


Evolution of massive stars

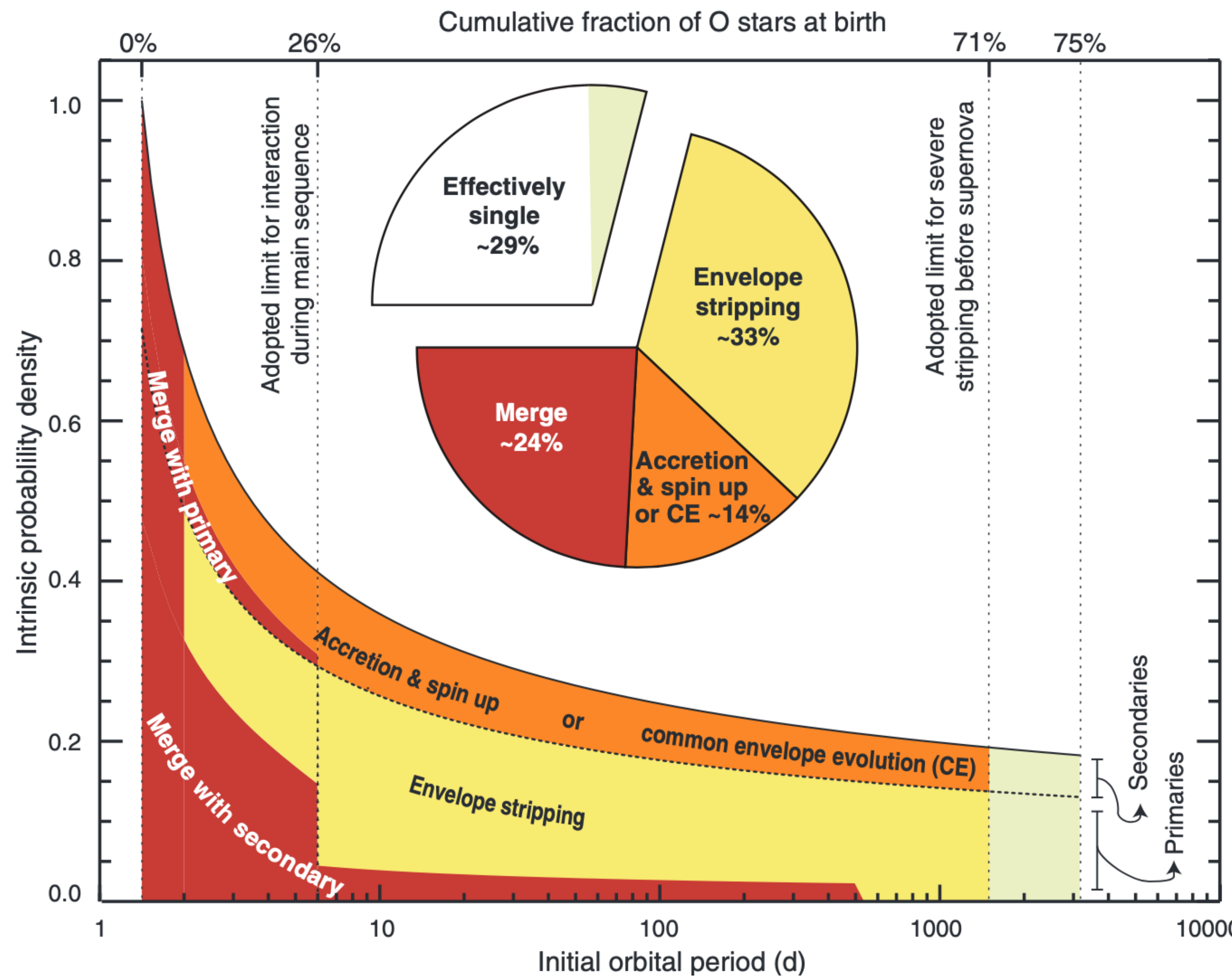
> BHs: remnants of massive stars experienced a supernova explosion



Binarity of massive stars

> Observations show that about ***70%* of O-type stars** are born in binary and multiple systems

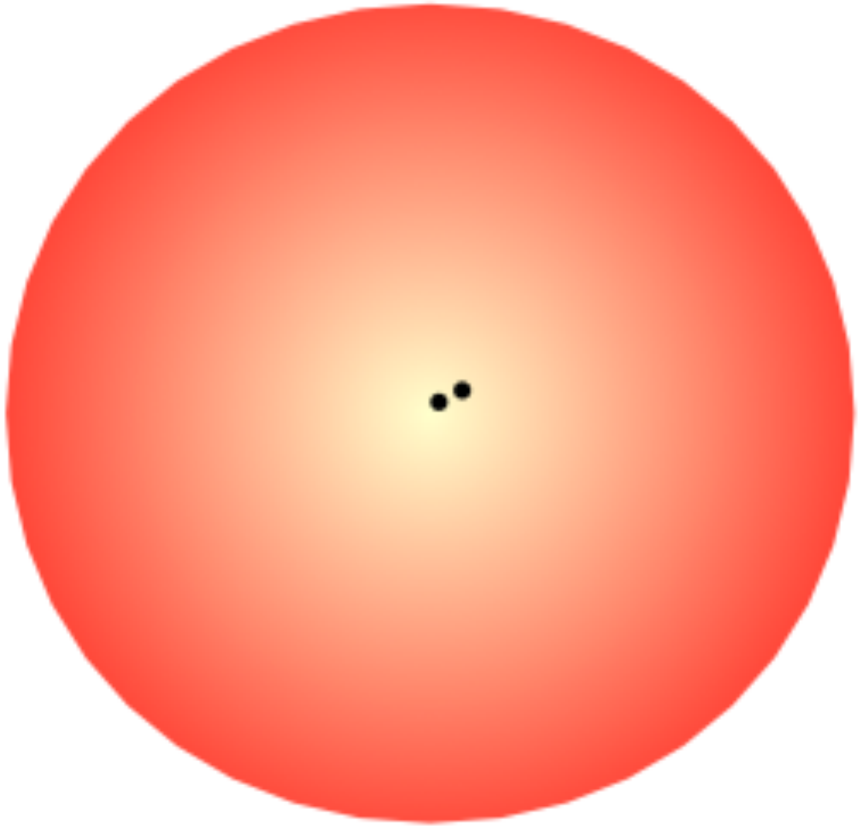
> **GW sources of merging BH binaries**



(Sana et al. 2012)

However

> Only tight BH binaries can appear as GW sources if their orbital separations are $\lesssim 10R_{\odot}$



> BH's progenitors can extend to $\sim 10^3 R_{\odot}$ in the supergiant phases

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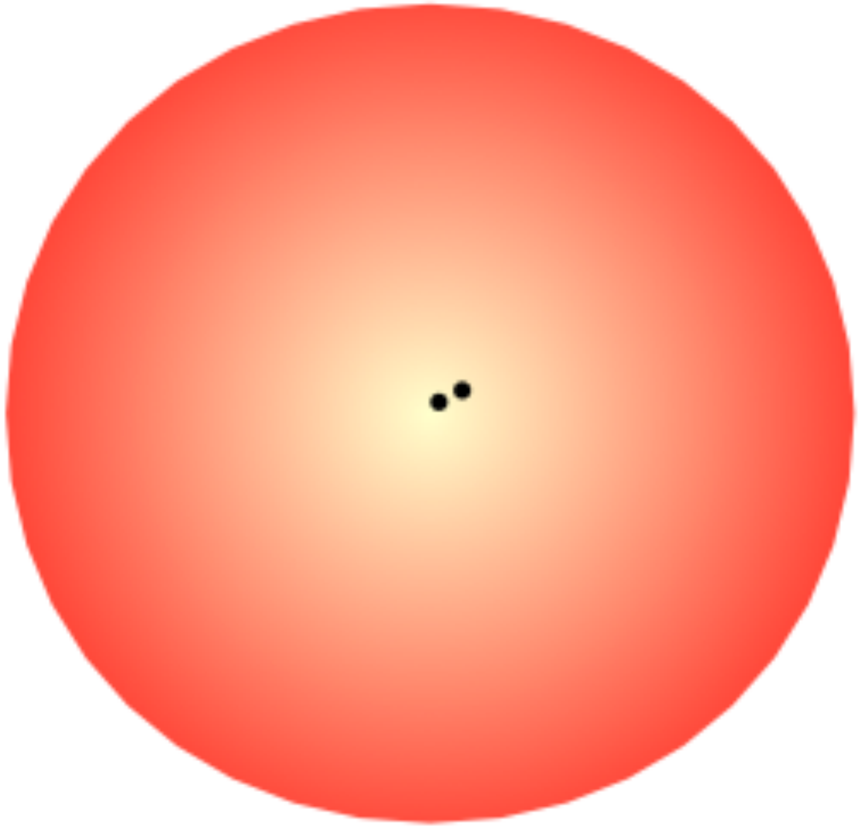


> BH's progenitors can extend to $\sim 10^3 R_{\odot}$ in the supergiant phases

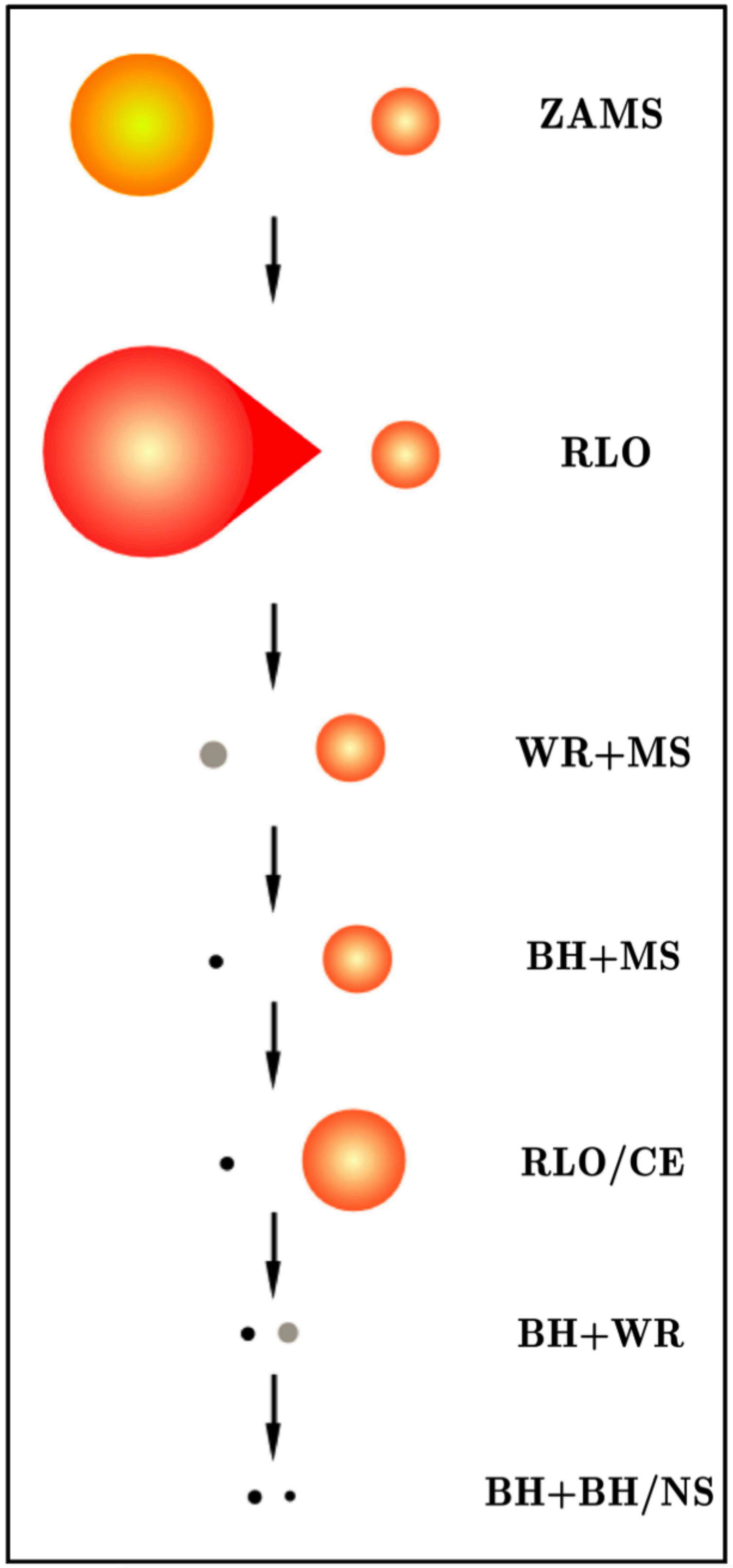
Binary interactions must happen before the formation of merging BH systems

Formation of merging BH binaries

Two major uncertainties:

I) **Mass transfer processes** from a massive donor to a BH

II) **Supernova explosions** that form BHs/NSs



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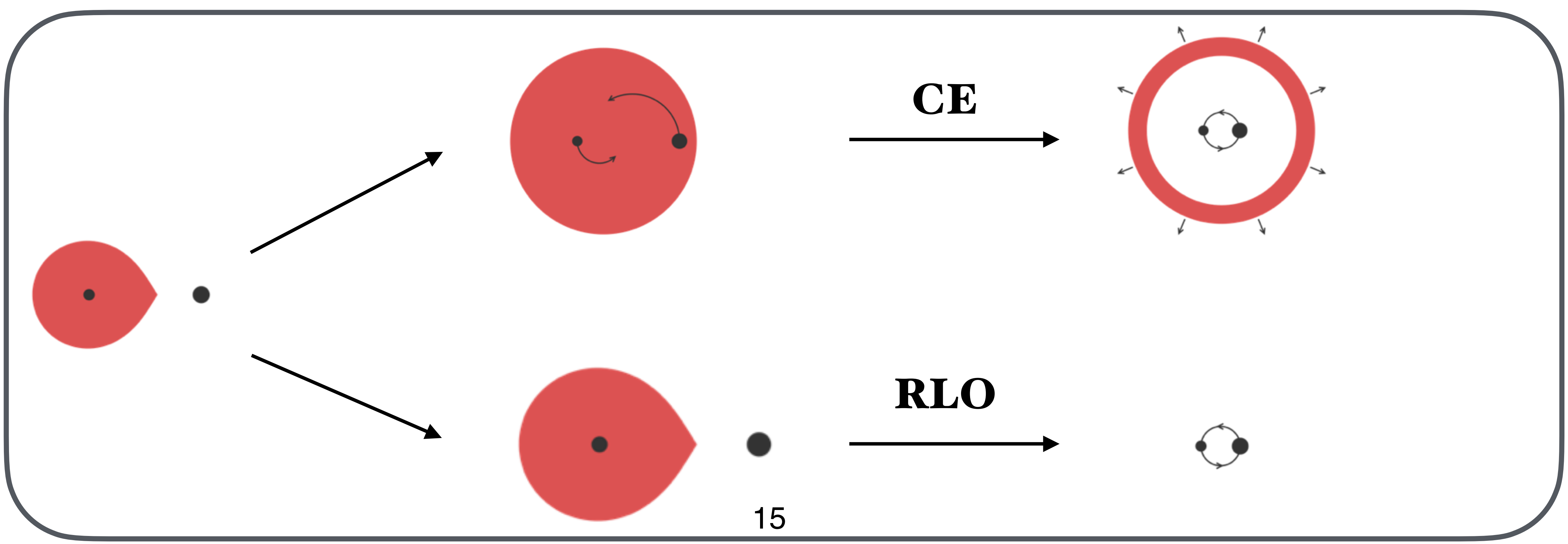
Mass transfer between binary components can occur via either

> a dynamically unstable phase that followed by common envelope **(CE)** evolution

or

> a **stable** Roche-lobe overflow **(RLO)** phase



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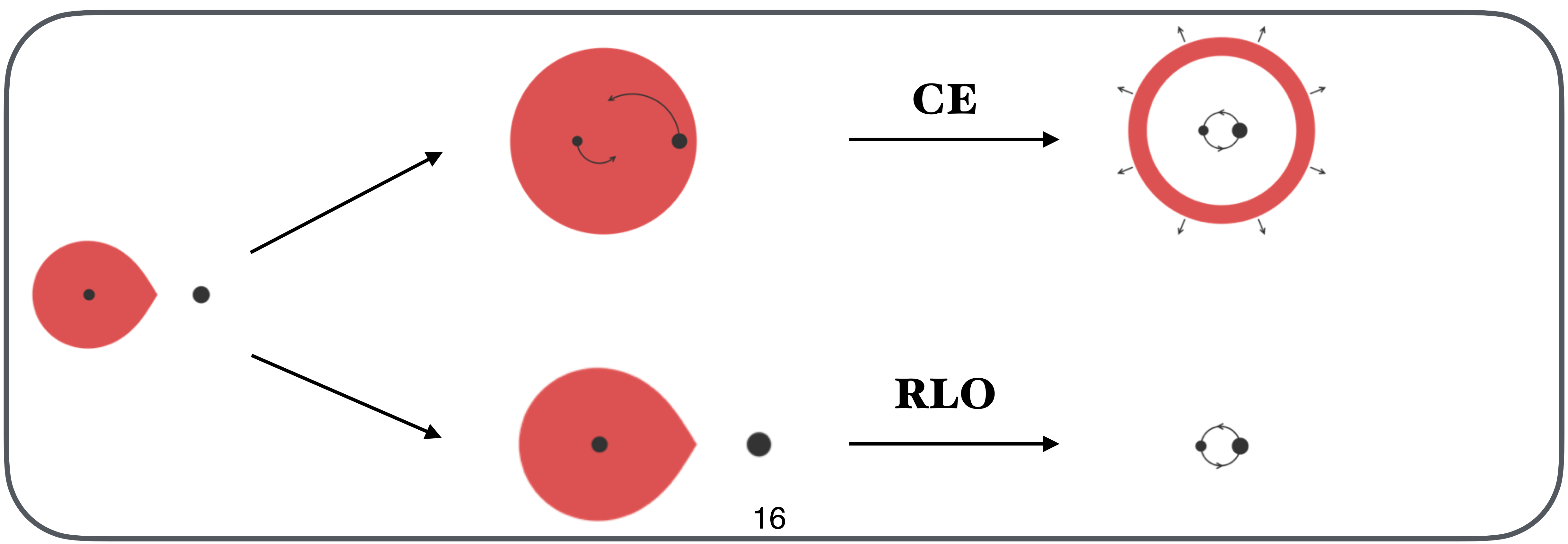

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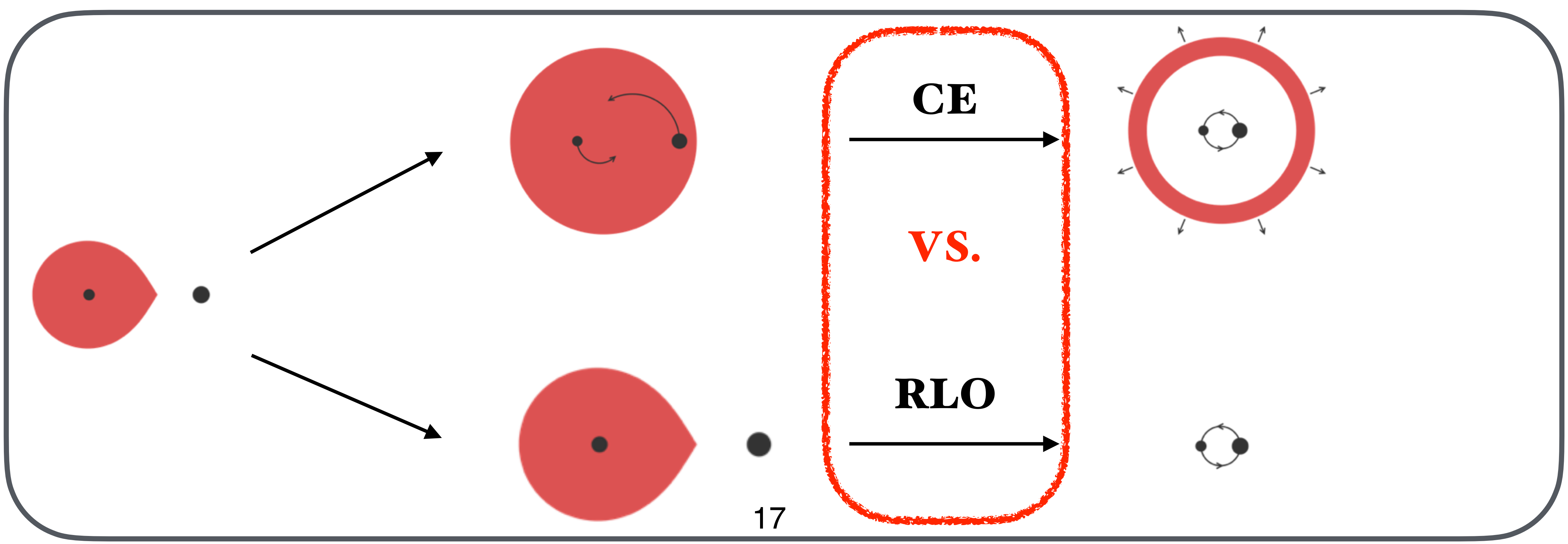
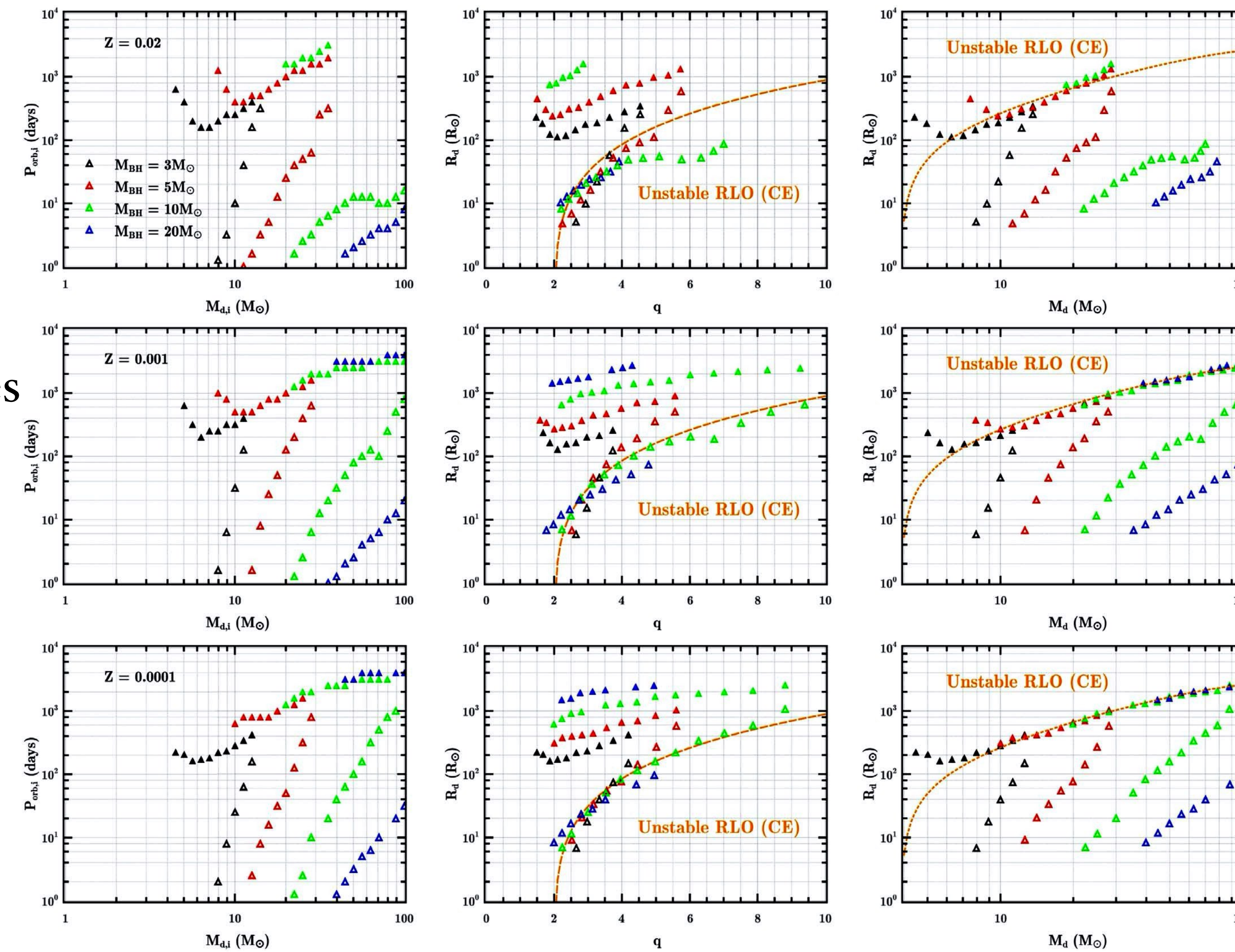
1) Which one of these two pathways is dominant for the formation of GW sources



1) **Mass transfer processes** from a massive donor to a BH

> Stellar evolution code **Mesa** (Paxton et al. 2011)

> **easy-to-use criteria** to distinguish CE and stable RLO phases for BH binaries



I) $q < q_{\min} \sim 1.5 - 2.0$

II) $q > q_{\max} \sim 2.1 + 0.8M_{\rm BH}$

III) $R_{\rm d} < R_{\rm U} \sim 6.6 - 26.1q + 11.4q^2$

IV) $R_{\rm d} > R_{\rm U} \sim -173.8 + 45.5M_{\rm d} - 0.18M_{\rm d}^2$

(Shao & Li 2021)

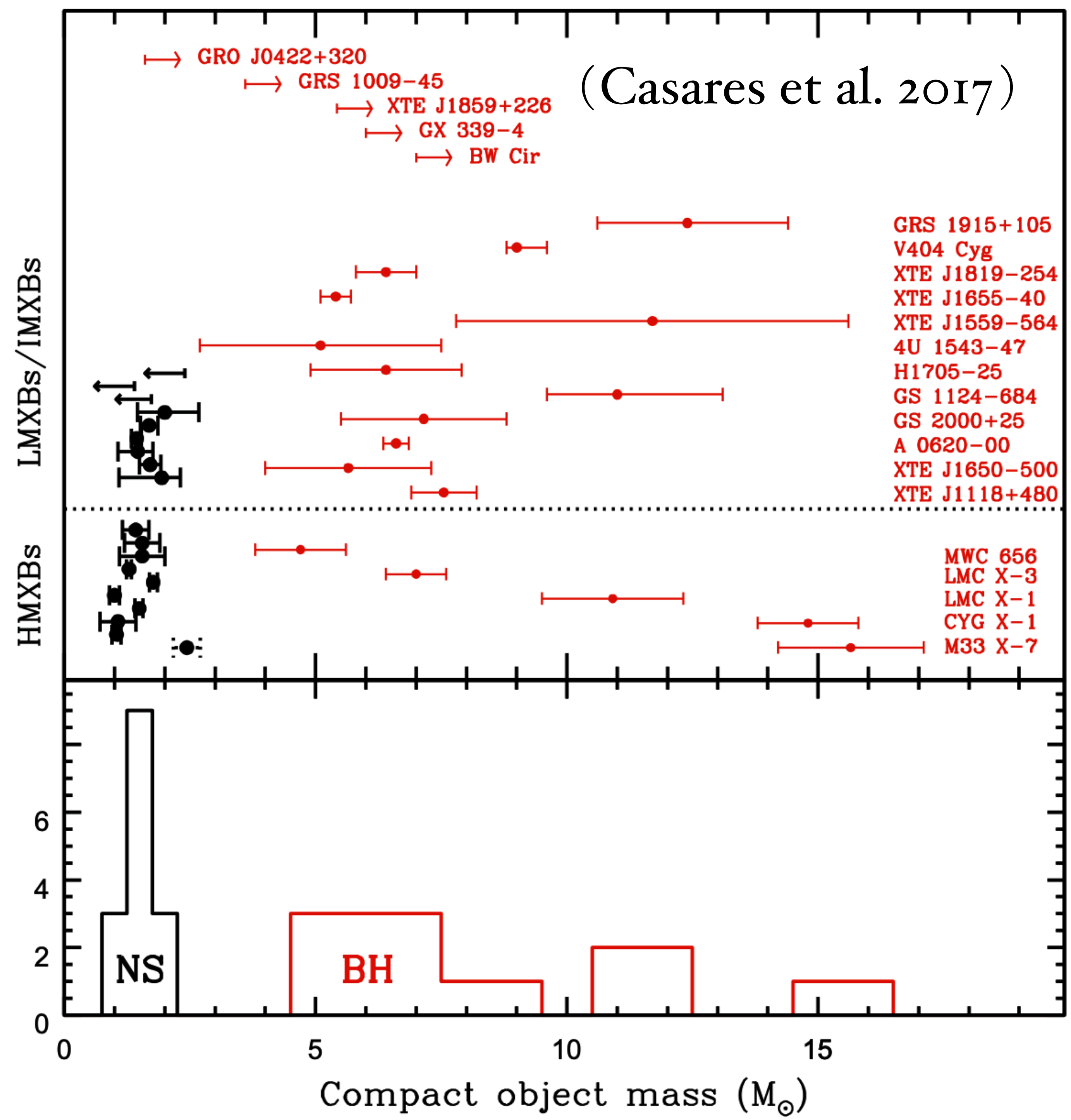
II) **Supernova explosions** that form BHs/NSs

> X-ray binary observations indicate a minimal mass of $\sim 5M_{\odot}$ for BHs (e.g., Ozel et al. 2010)

> BH/NS "**mass gap**" ($\sim 2-5M_{\odot}$)

> **Supernova-explosion mechanisms** may be responsible for this gap (Fryer et al. 2012; Ugliano et al. 2012; Kochanek 2014; Liu et al. 2021)

> See however GW190814 ($M \sim 2.6M_{\odot}$)



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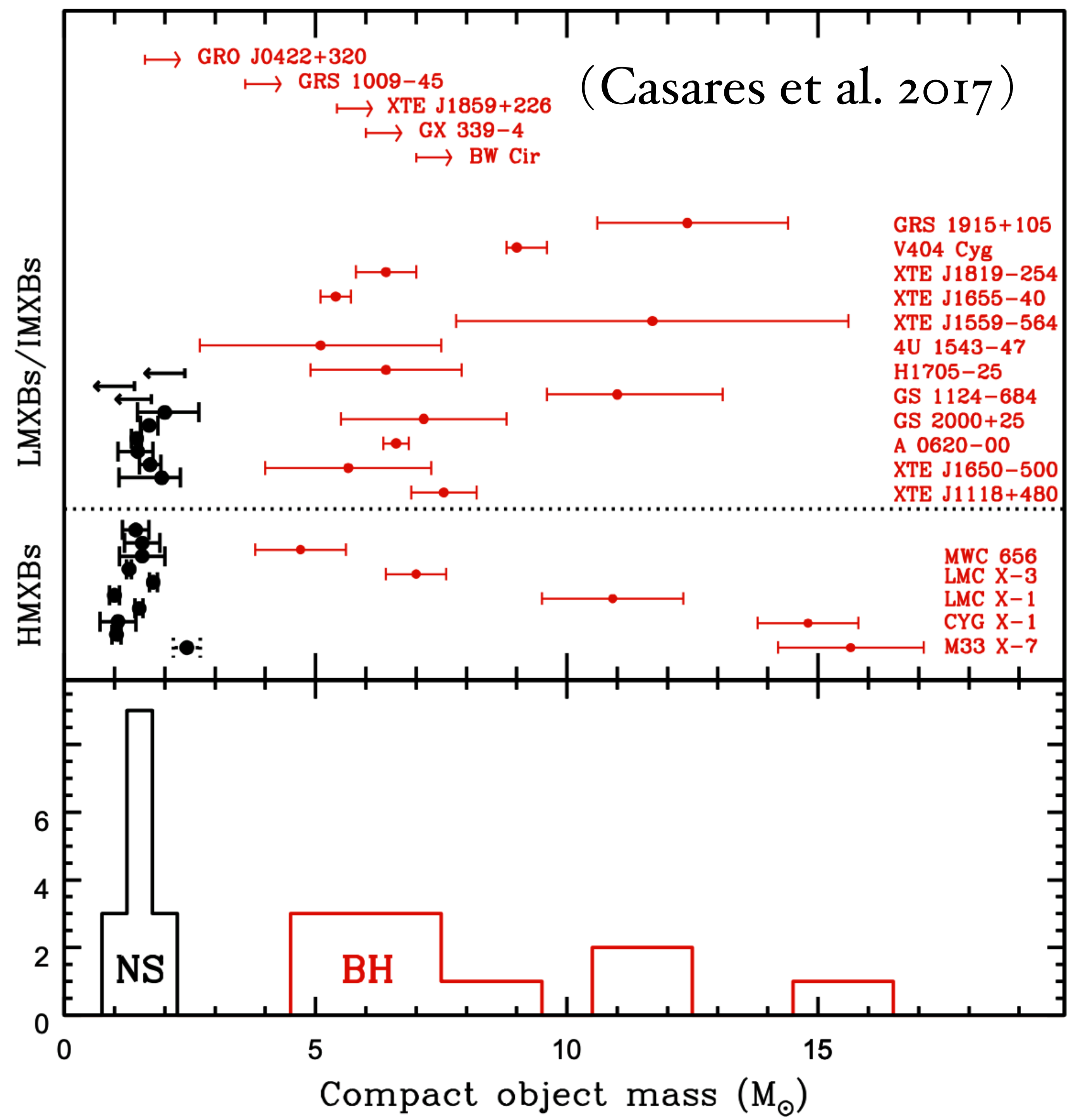
II) Whether or not this mass gap exists



II) **Supernova explosions** that form BHs/NSs

> **Rapid** explosion mechanism

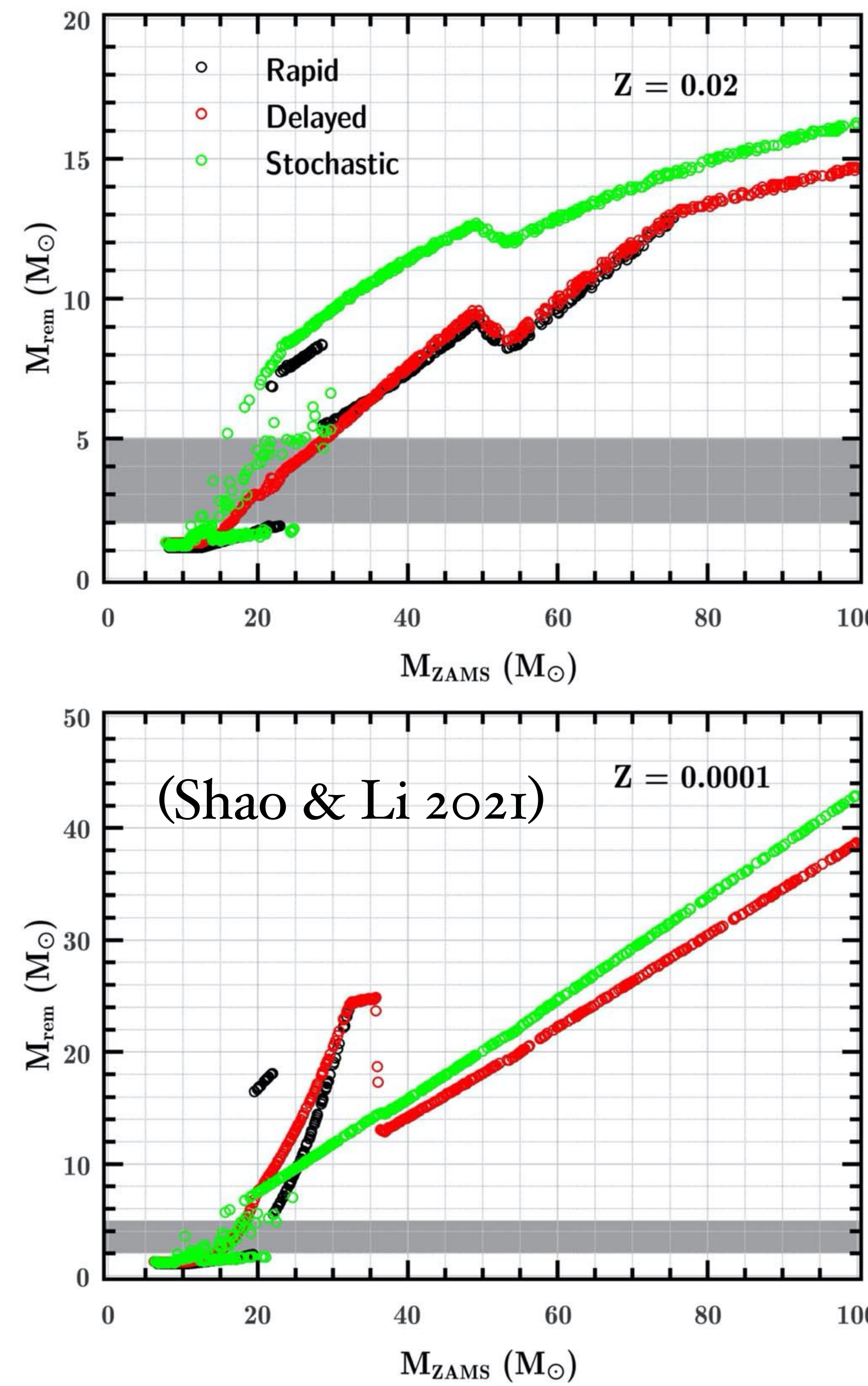
(Fryer+2012)

> **Delayed** explosion mechanism

(Fryer+2012)

> **Stochastic** explosion mechanism

(Mandel & Müller 2020)



Results

Two major uncertainties:

1) **Mass transfer processes** from a massive donor to a BH

II) **Supernova explosions** that form BHs/NSs

> Binary population synthesis code **BSE** (Hurley et al. 2002)

A) GW sources of merging BH binaries in the Milky Way

B) GW sources of merging BH binaries in the local universe

A) GW sources of merging BH binaries in the Milky Way

> LISA can detect **dozens** of merging BH binaries with SNR>5

> **Fraction** of sources hosting mass-gap BHs among a specific population (f_{MG}):

Rapid

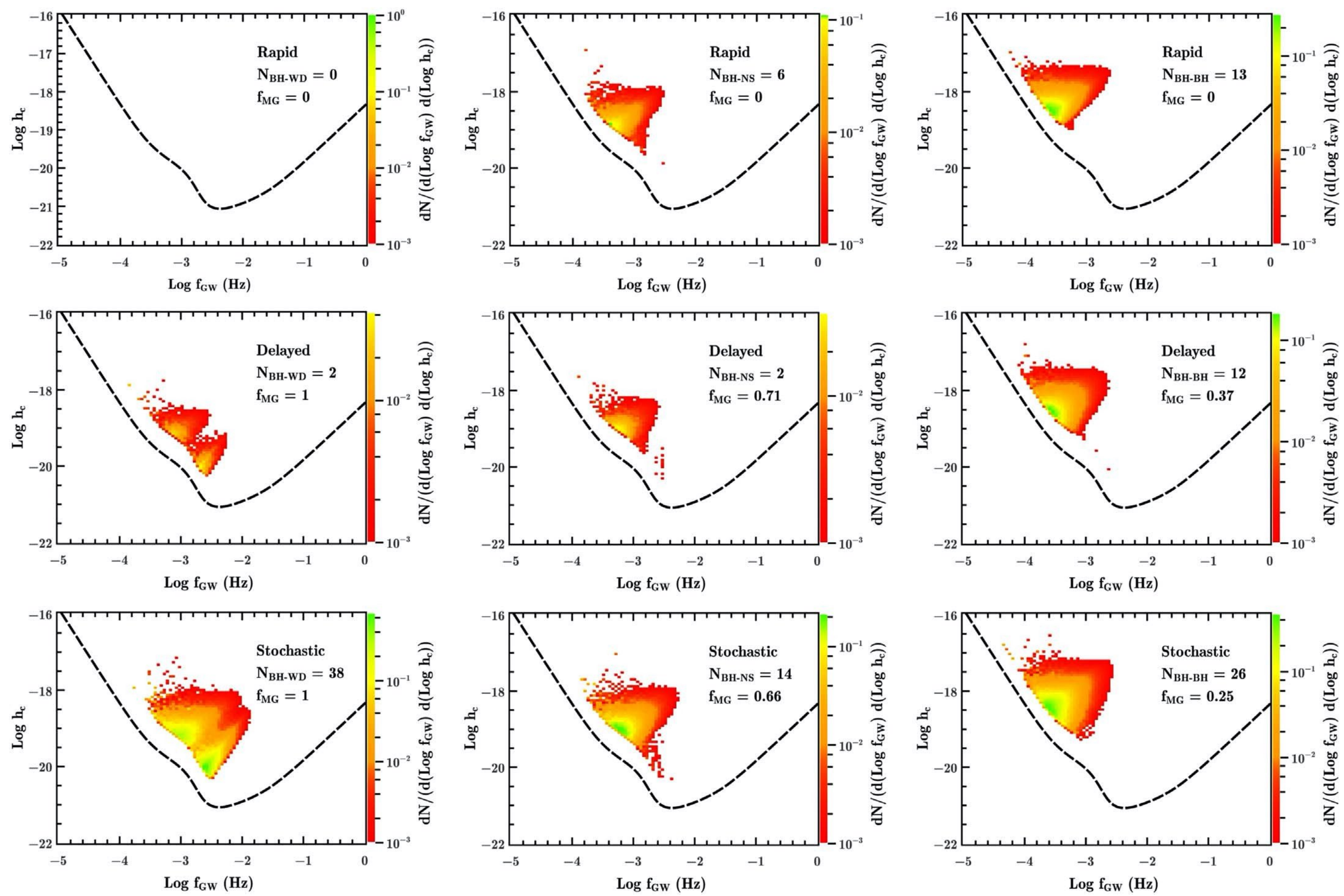
$f_{MG} = 0$

Delayed and **Stochastic**

$f_{MG} \sim 1$ for BHWD systems

$f_{MG} \sim 0.7$ for BHNS systems

$f_{MG} \sim 0.3$ for BHBH systems



A) GW sources of merging BH binaries in the Milky Way

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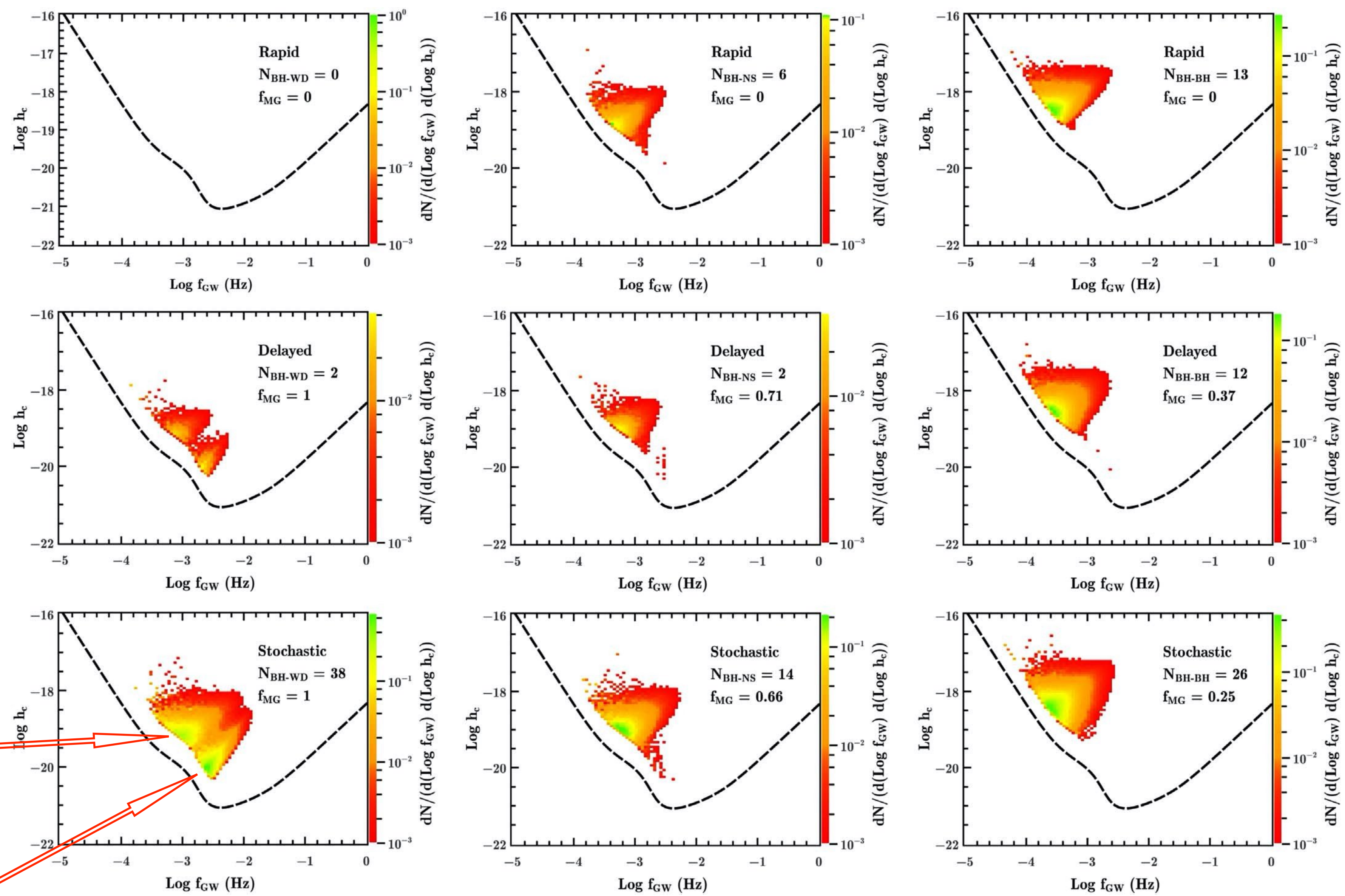


detached systems

mass-transferring systems

> Mass-transferring BHWD systems

> Since (Sberna et al. 2021)

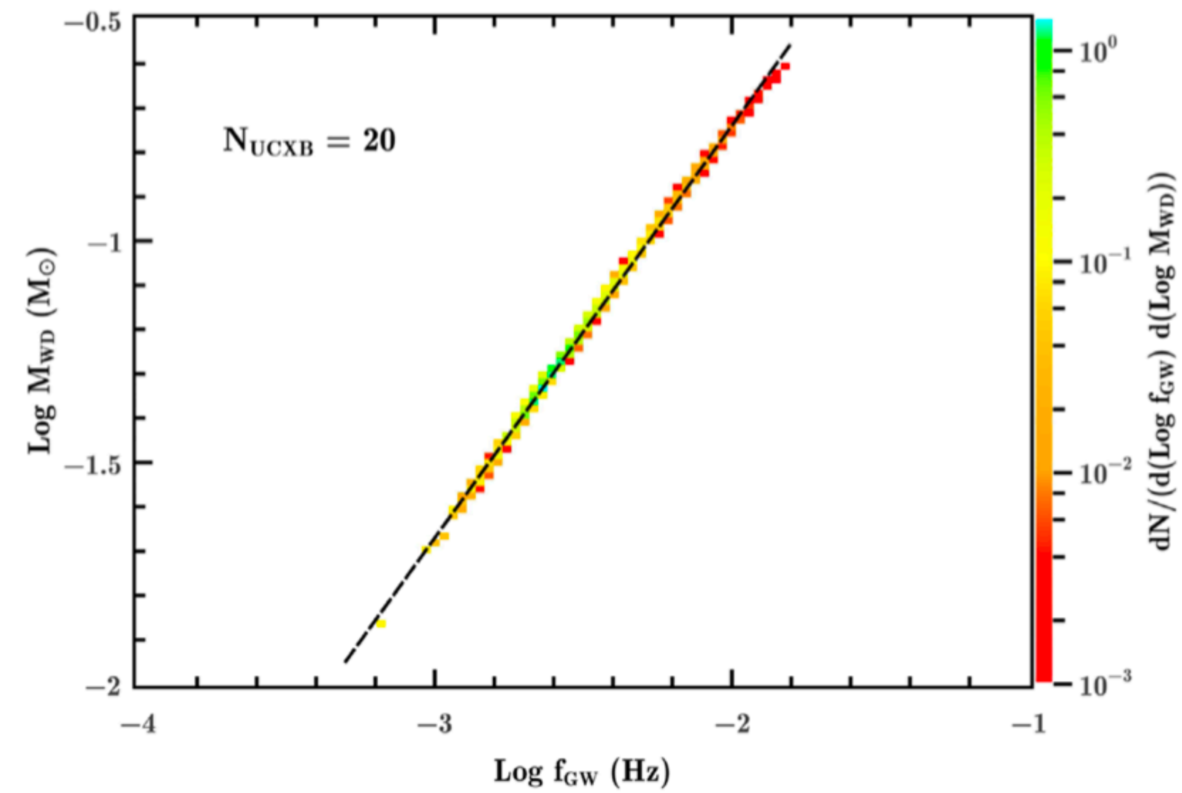
1) $M_{\rm BH} \gg M_{\rm WD}$

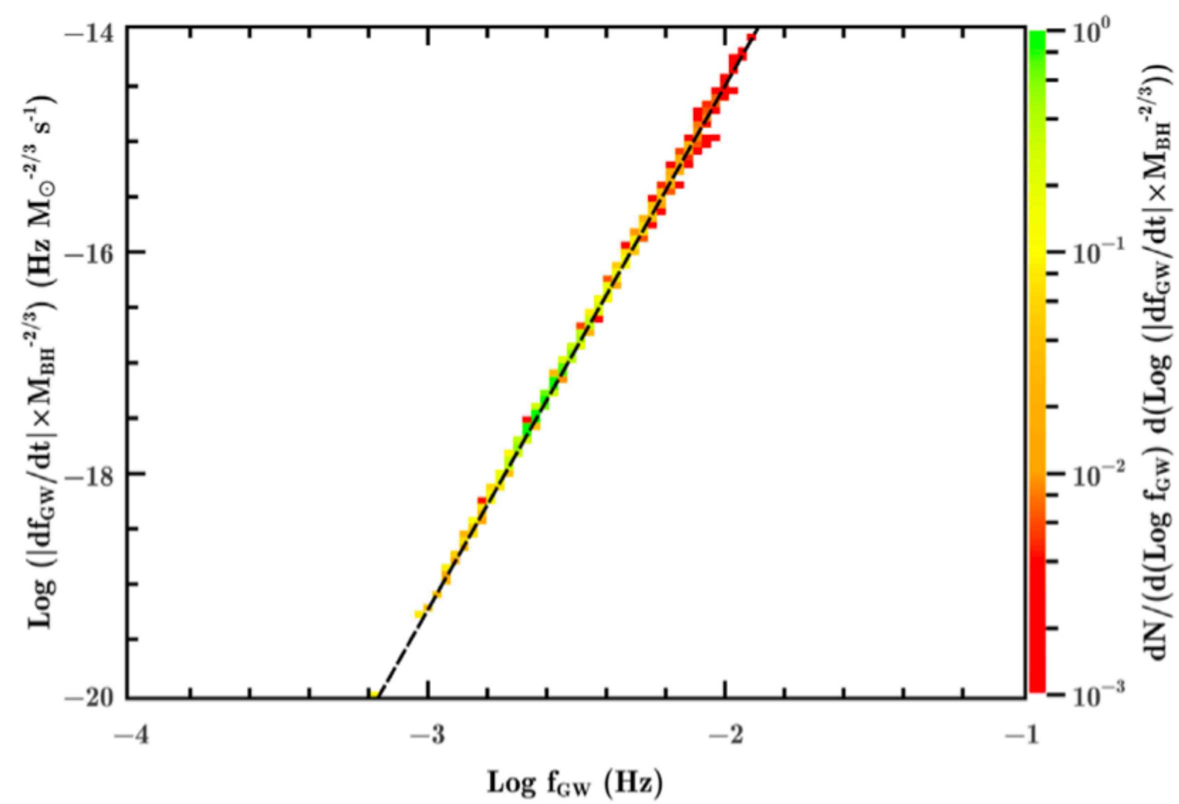
2) Relation between $R_{\rm WD}$ and $M_{\rm WD}$

> Two linear relationships:

$$\log M_{\rm WD} = 1.12 + 0.93 \log f_{\rm GW}$$

$$\log(|\dot{f}_{\rm GW}| M_{\rm BH}^{-2/3}) = -5.04 + 4.73 \log f_{\rm GW}$$





B) GW sources of merging BH binaries in the local universe (LIGO/Virgo)

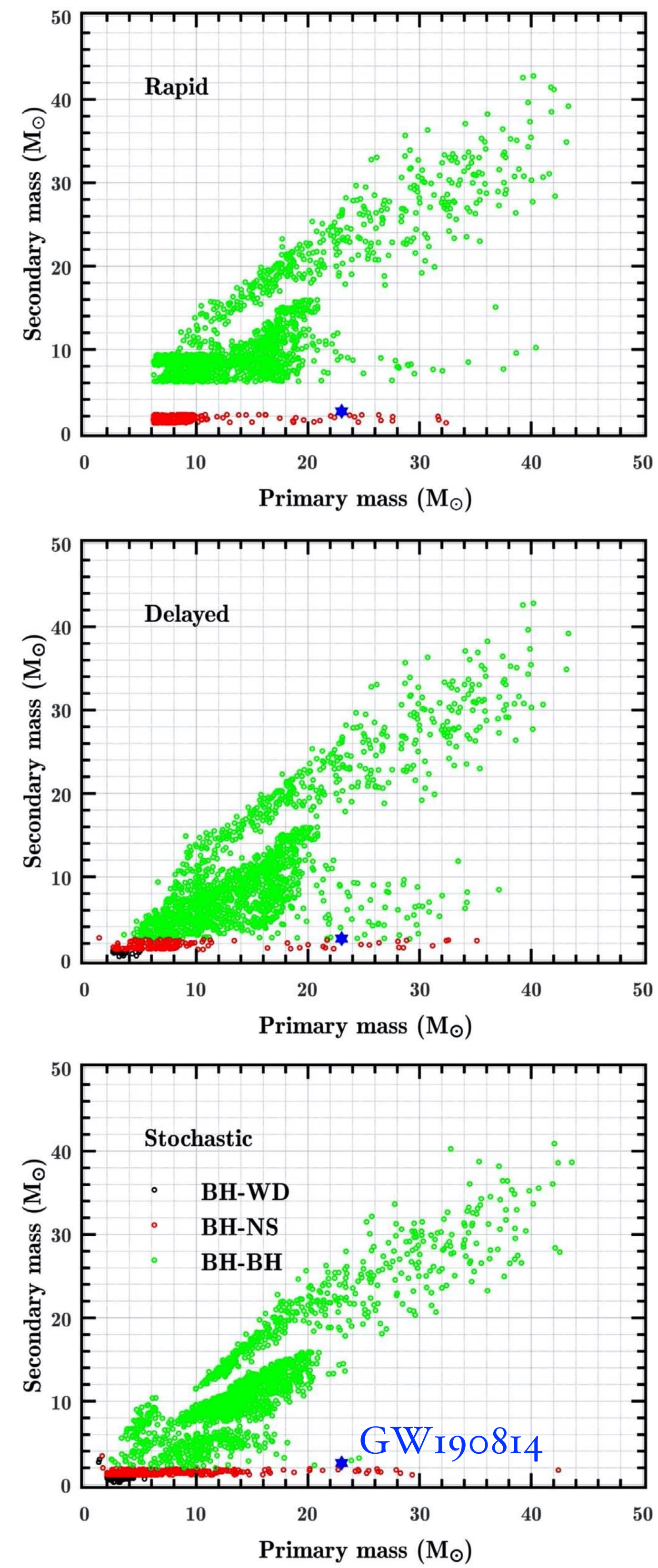
> Local merger rate densities

$\mathscr{R}_{\mathrm{BHWD}} \sim 0 - 59\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

$\mathscr{R}_{\mathrm{BHNS}} \sim 10 - 72\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

$\mathscr{R}_{\mathrm{BHBH}} \sim 43 - 76\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

> GW190814 can be formed in both the delayed and the stochastic mechanisms



> Fraction of mergers with mass-gap BHs (f_{MG})

Rapid

$f_{MG} = 0$

Delayed and **Stochastic**

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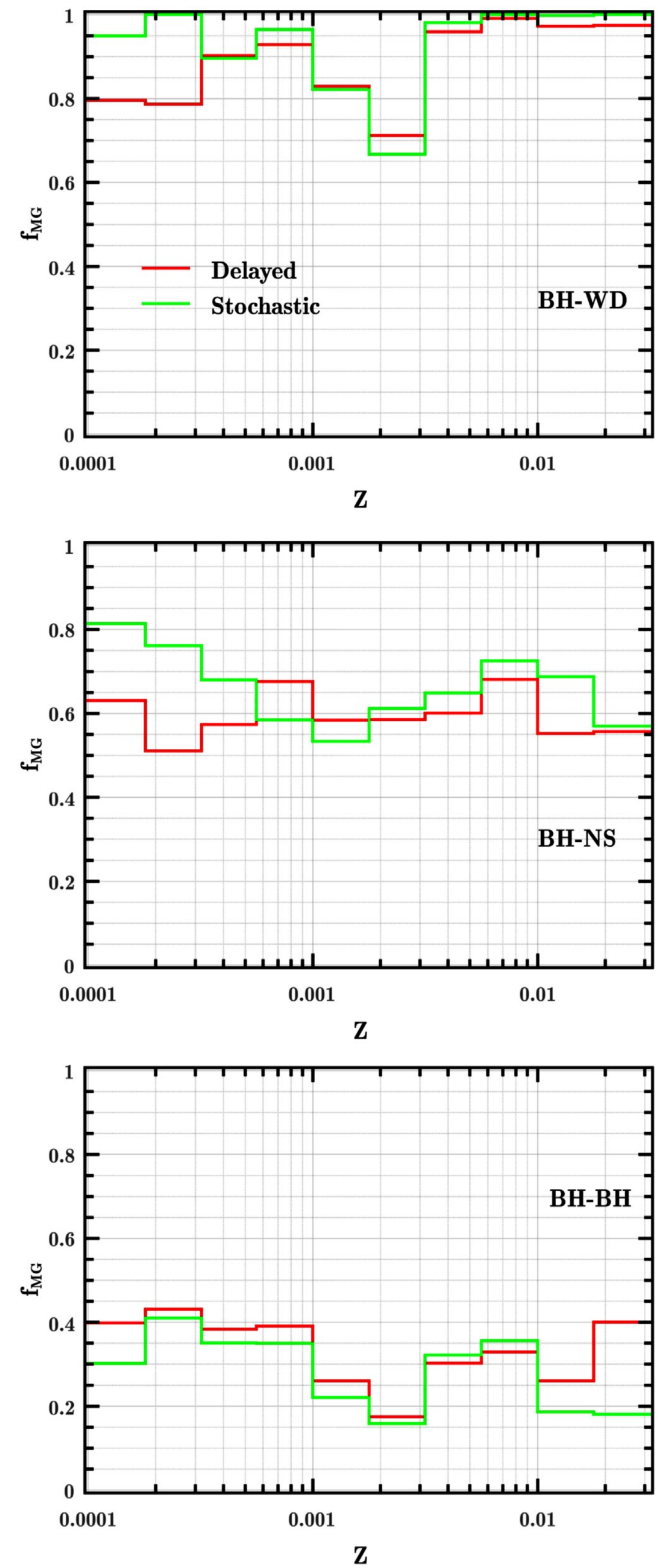


> Formation pathways

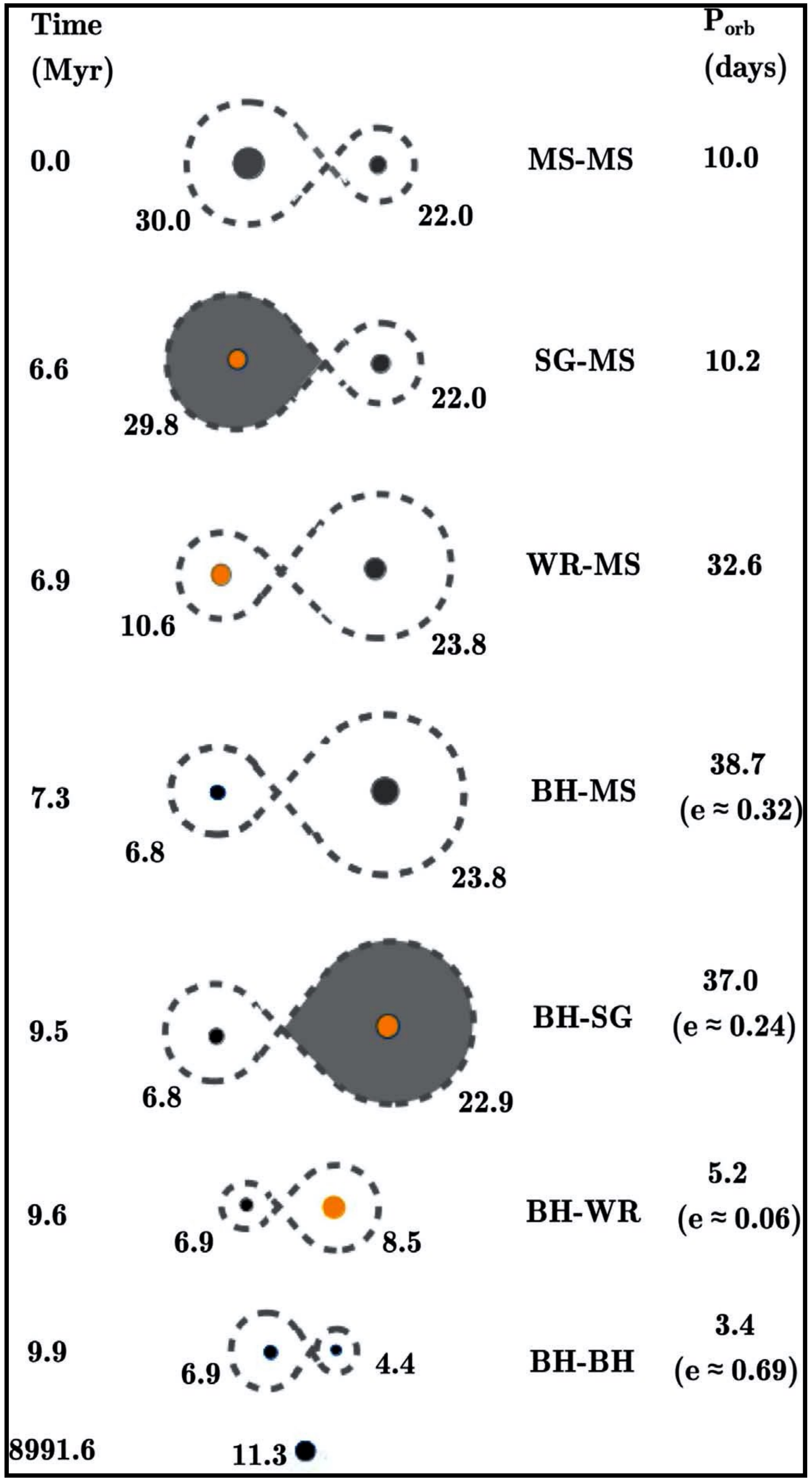
Stable RLO and CE pathways

> Only **stable RLO** pathway can produce

$\sim 10\% - 40\,\%$ **of local BHNS mergers**

and

$\sim 30\% - 70\,\%$ **of local BHBH mergers**



Summary

(1) **Dozens** of LISA systems in the Milky Way

(2) Merger rate densities in the local universe

$\mathscr{R}_{\rm BHWD} \sim 0 - 59\,{\rm Gpc^{-3}yr^{-1}}$

$\mathscr{R}_{\rm BHNS} \sim 10 - 72\,{\rm Gpc^{-3}yr^{-1}}$

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(3) **Fractions** of systems with mass-gap BHs

Rapid explosion mechanism

$f_{\rm MG} = 0$

Delayed and **Stochastic** mechanisms

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Outline

1. Formation of black hole (BH) binaries as gravitational wave sources

2. Overview of LISA BH binaries (arXiv:2203.06016)

3. Detection of TianQin BH binaries (for the white paper)

> Distance to which LISA binaries can be detected as a function of GW frequency

> Milky Way (1 – 10 kpc)

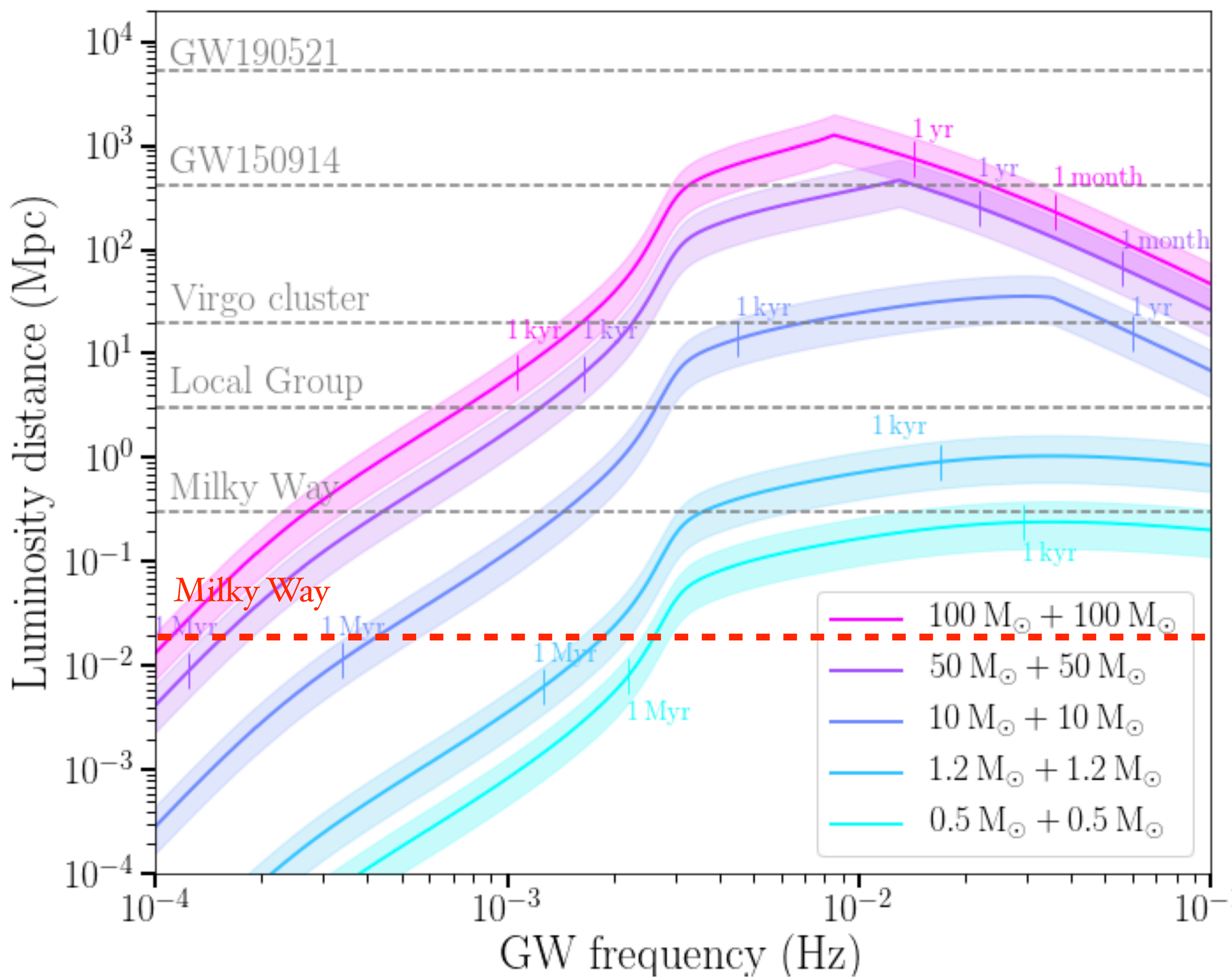
GW sources last ~ 1 Myr

> Local group (1 – 10 Mpc)

GW sources last ~ 1 kyr

> Local universe (1 – 10 Gpc)

GW sources last ~ 1 yr



> Distance to which LISA binaries can be detected as a function of GW frequency

> Milky Way (1 – 10 kpc)

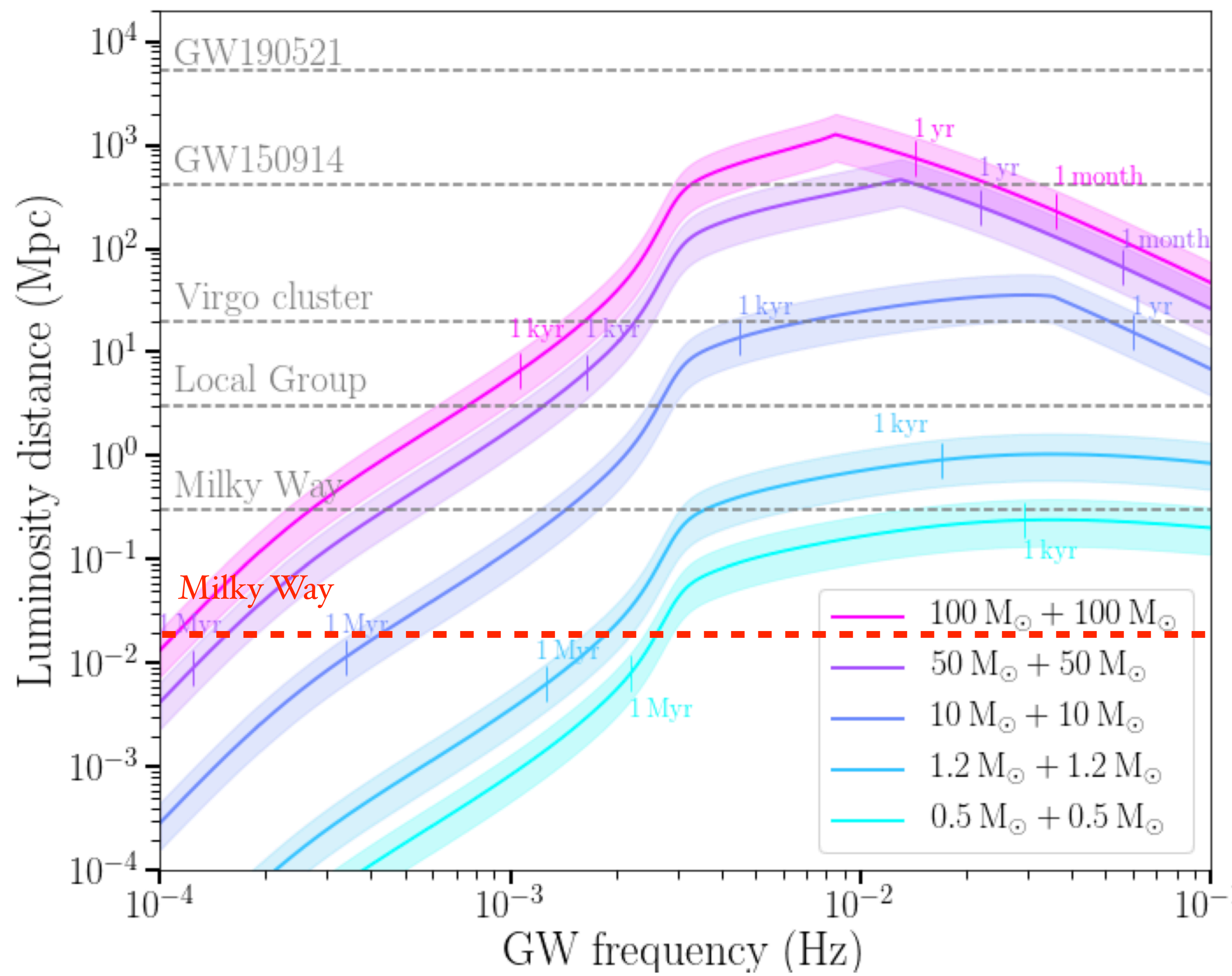
all types of GW binaries

> Local group (1 – 10 Mpc)

typical BHBH binaries

> Local universe (1 – 10 Gpc)

massive BHBH binaries



> Estimated absolute number of compact binaries from isolated binary evolution in the Milky Way

> **dozens** of systems containing BHs in the LISA band

Source	N	N^{detected}
WD+WD	$\sim 10^8$	6,000–10,000
NS+WD	$\sim 10^7$	100–300
BH+WD	$\sim 10^6$	0–3
NS+NS	$\sim 10^5$	2–100
BH+NS	$\sim 10^4 - 10^5$	0–20
BH+BH	$\sim 10^6$	0–70

Outline

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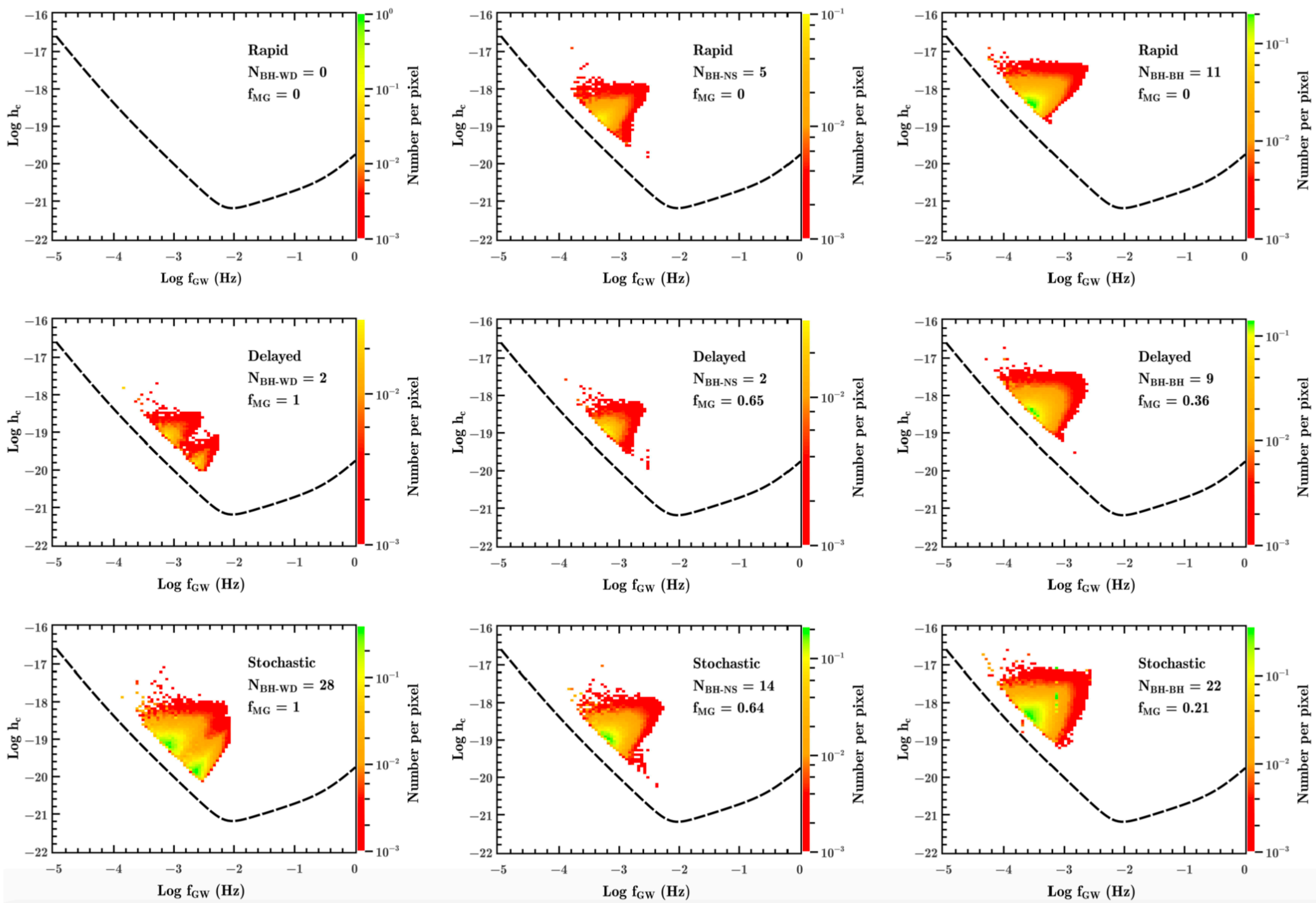
In the Milky Way:

> TianQin can detect **dozens** of merging BH binaries ($T_{\rm obs}$ = 5yr & SNR > 5)

> Assuming a constant star formation rate of $3M_\odot\,{\rm yr}^{-1}$ over the past 10 Gyr

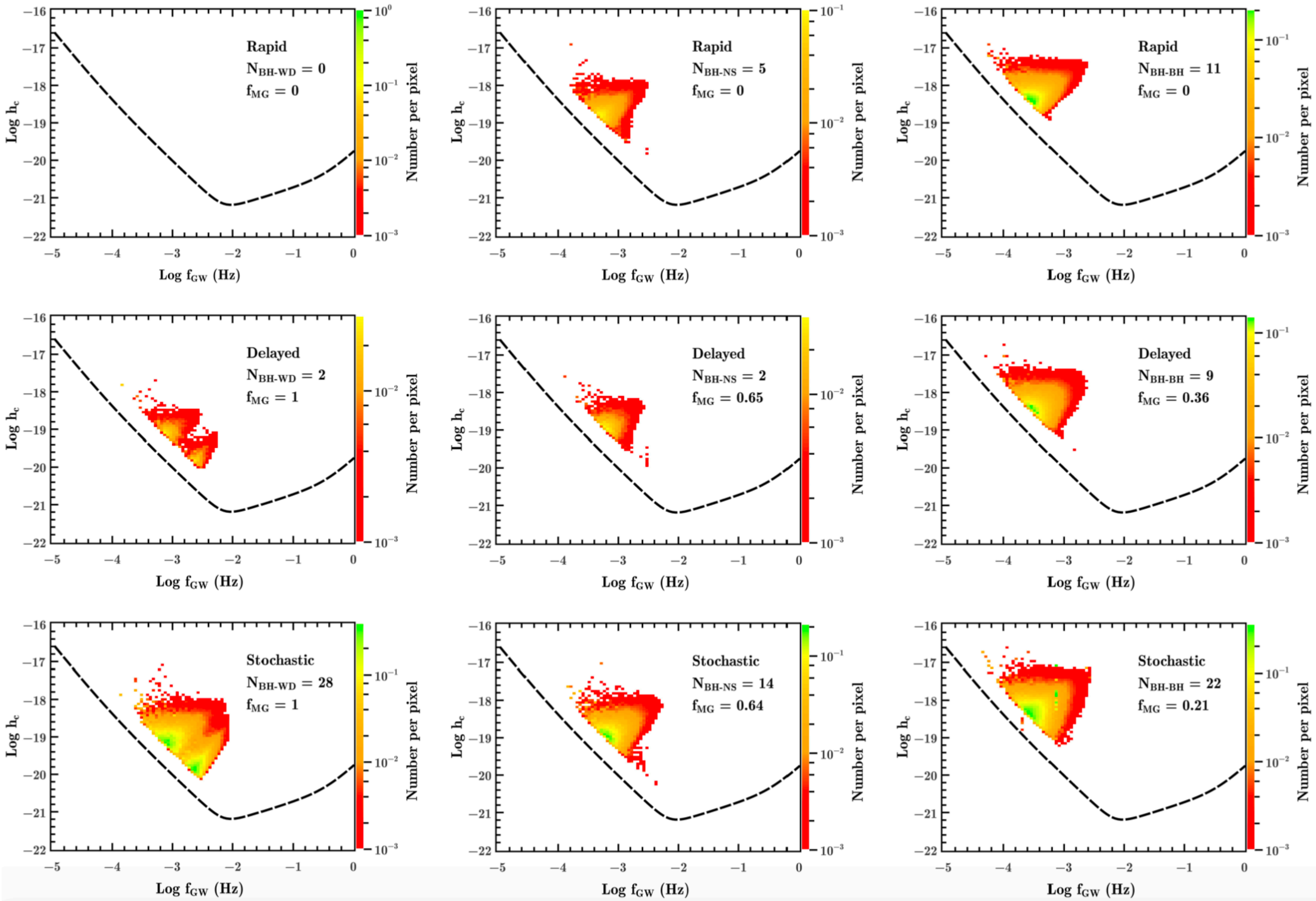
> Not involving dynamical formation in globular clusters



In the Milky Way:

> TianQin can detect dozens of merging BH binaries($T_{\rm obs}$ = 5yr & SNR > 5)

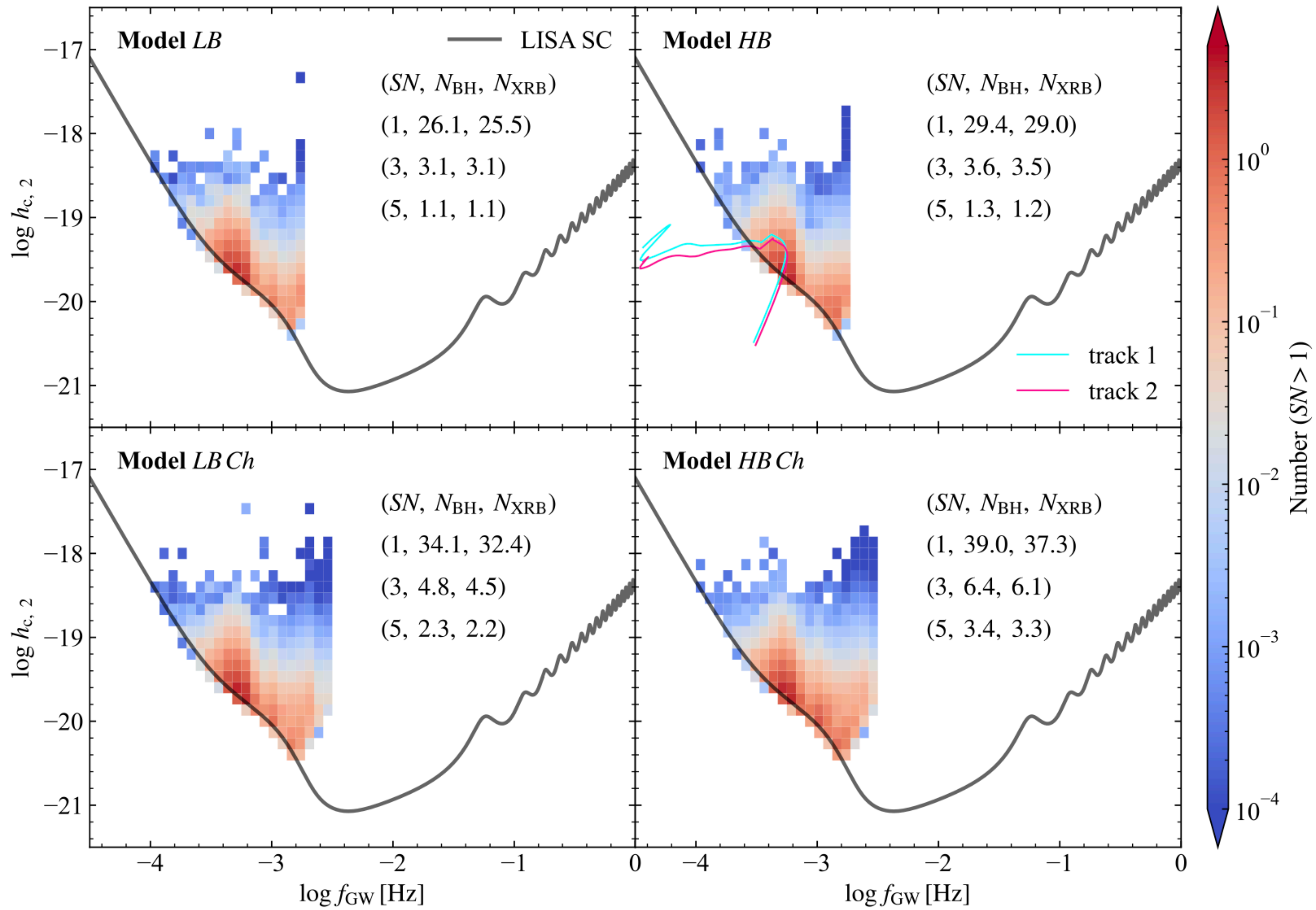
> Over half of them have mass-gap BHs (delayed and stochastic)



In the Milky Way:

> Formation of Mass-gap BHs via accretion-induced collapse of NSs in X-ray binaries

> LISA may detect a few ultracompact X-ray binaries hosting a mass-gap BH



(Gao, Li & Shao 2022)

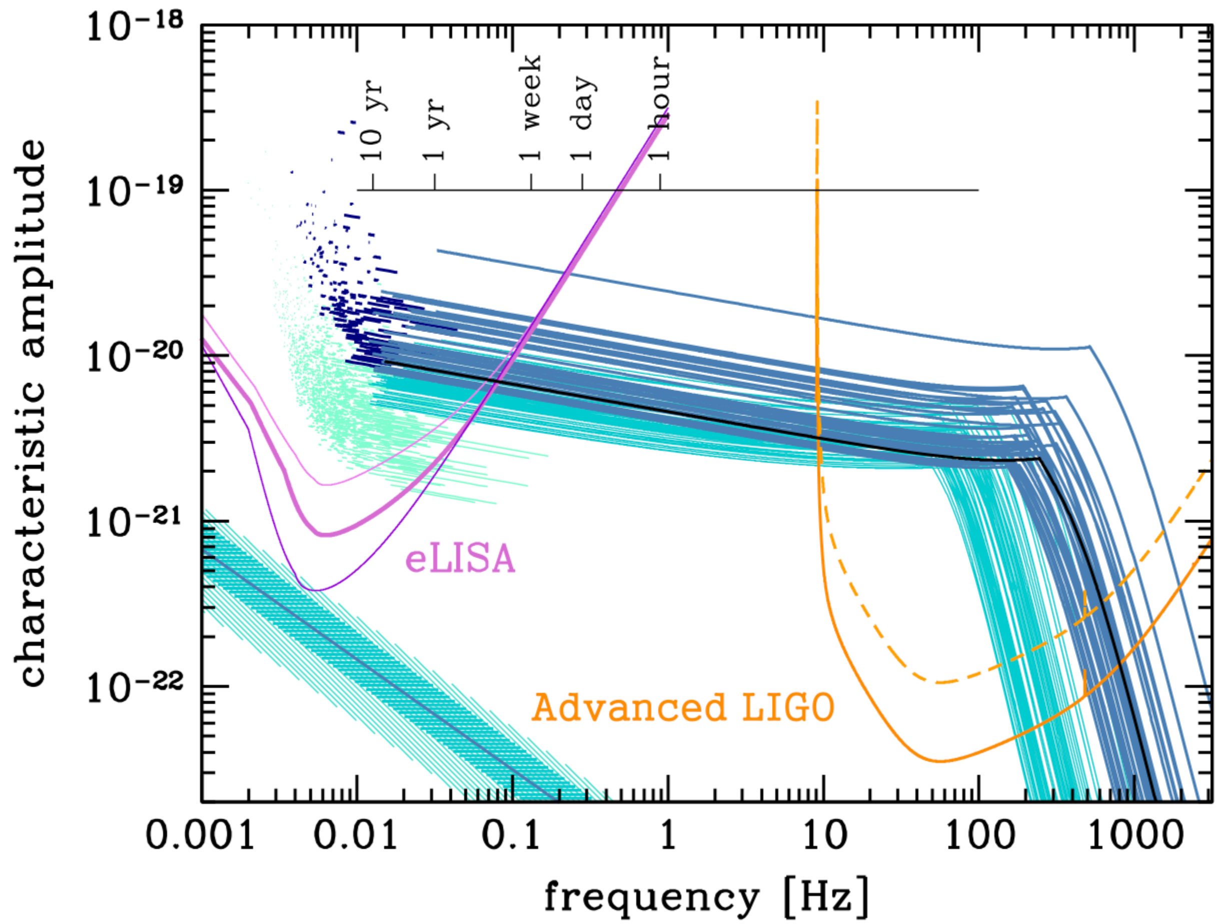
In the local group:

1) For a Milky Way-like galaxy, the merger rate of BH-WD/BH-NS/BH-BH binaries $\sim 10^{-5}\,\mathrm{yr}^{-1}$
2) GW sources can last $\sim 10^3 - 10^4$ yr in the TianQin and LISA band
3) More than 50 galaxies exist

TianQin can potentially detect a few merging BH systems

In the local universe:

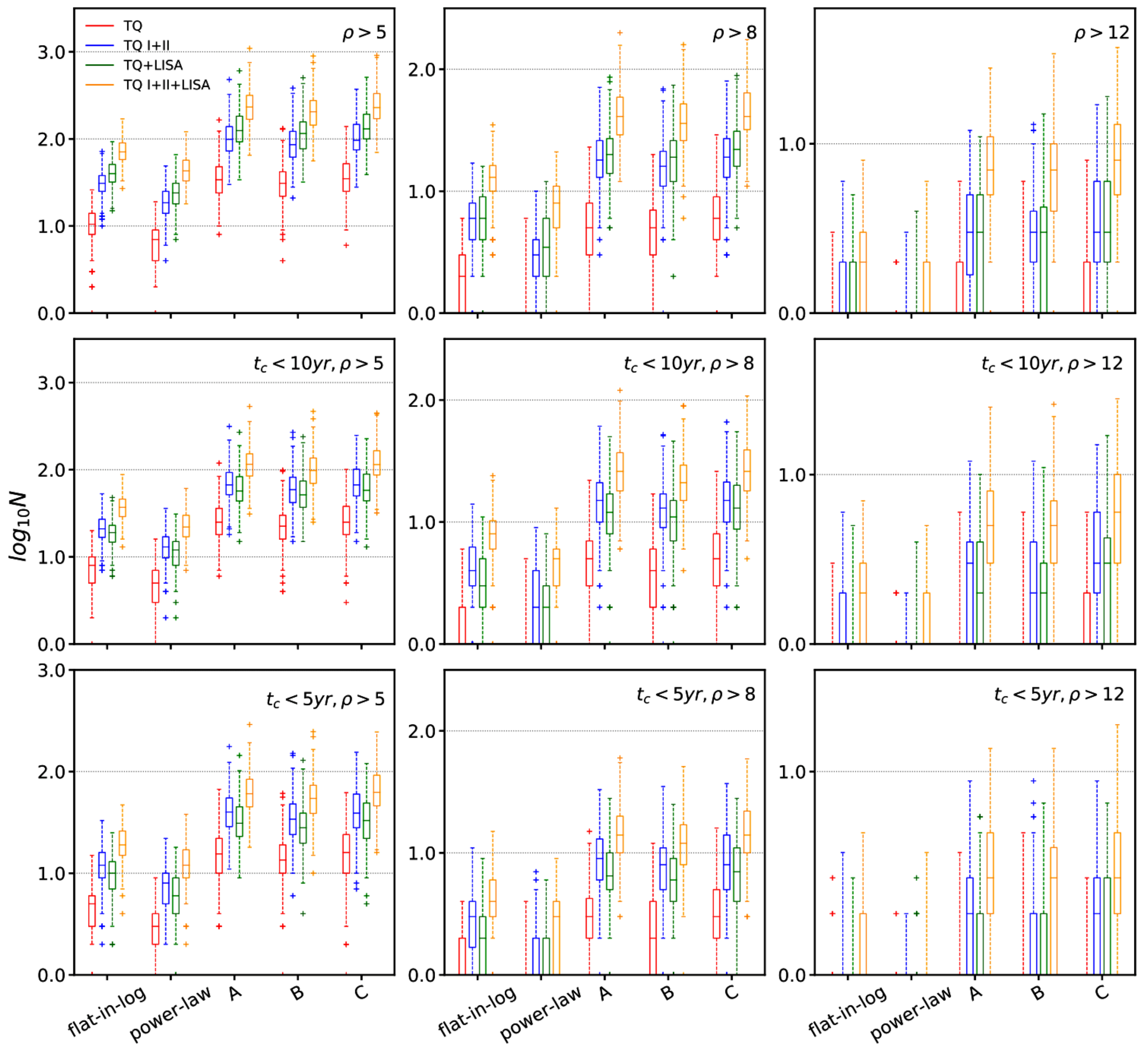
> Both **TianQin** and LISA can detect **massive BHBH binaries**



(Sesana 2016)

In the local universe:

> TianQin can detect over a few such massive BHBH systems



(Liu et al. 2020)

For the part of stellar-mass BHs in the white paper

Suggestions:

> a general picture for the formation of merging BH binaries

> detection of merging BH binaries in the TianQin band

Thanks