Double white dwarf populations in the era of GW astronomy

Silvia Toonen

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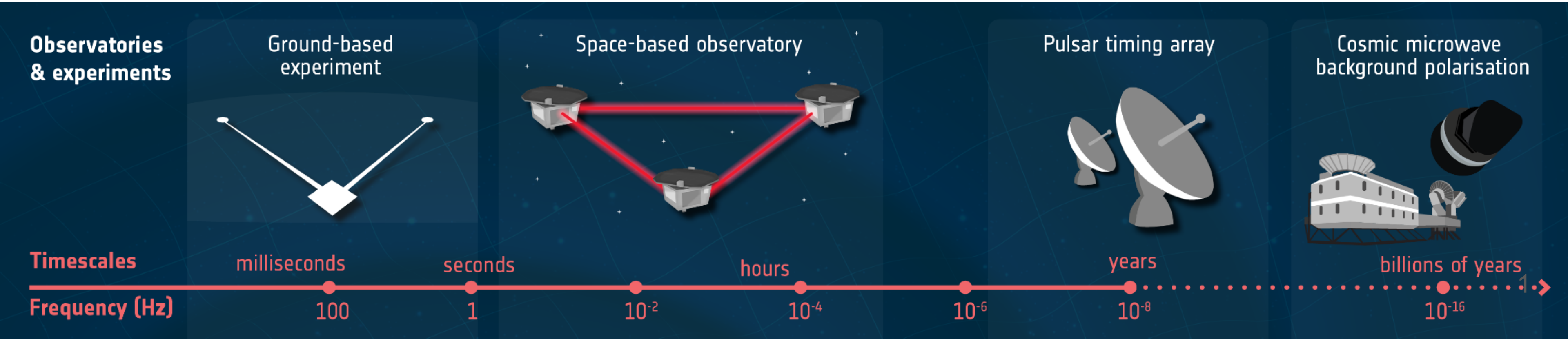
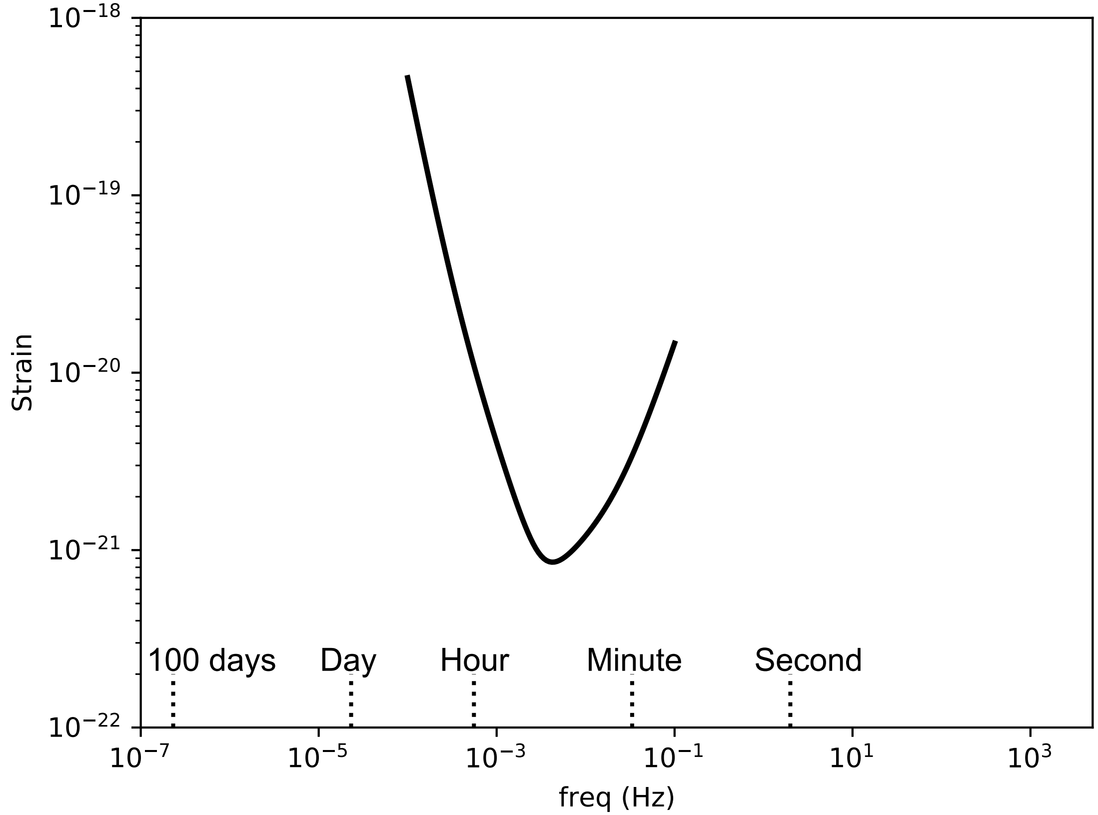
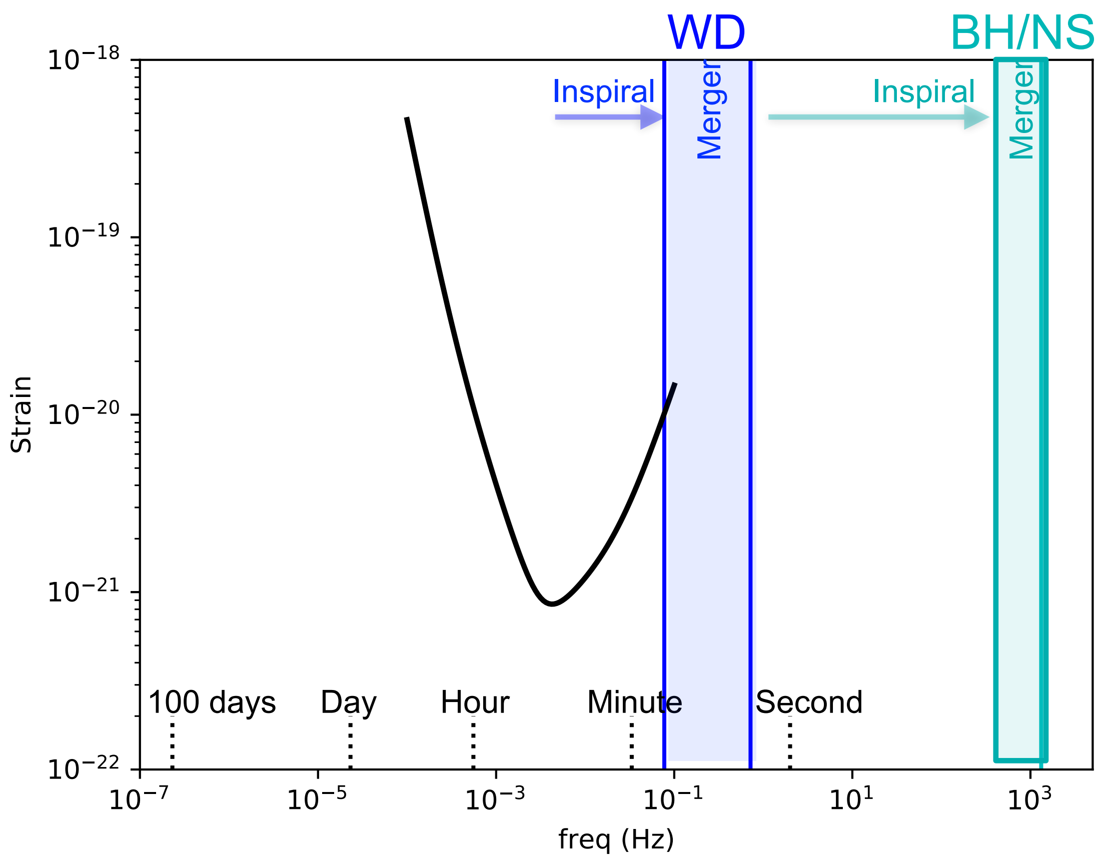


Galactic compact binaries: from micro- to deci-Hz



LISA sensitivity curve
From Robson+ 2019

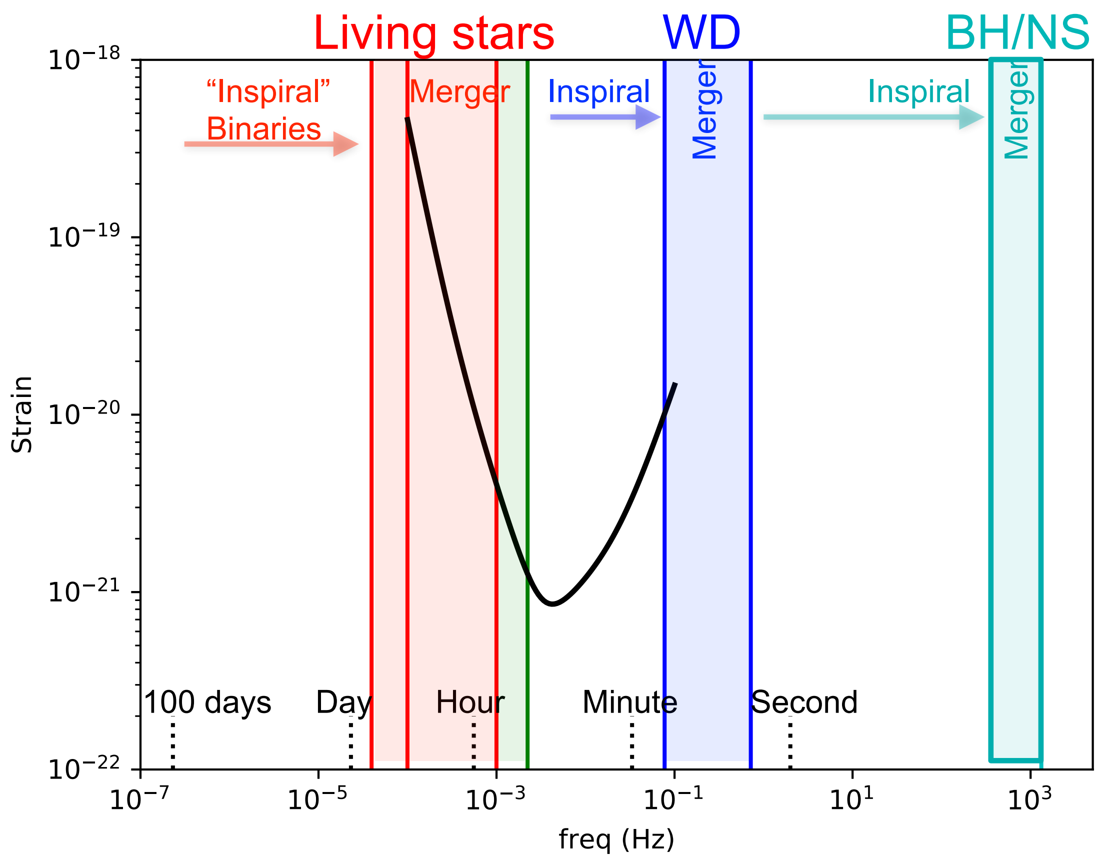
Galactic compact binaries: from micro- to deci-Hz



LISA sensitivity curve
From Robson+ 2019

Galactic compact binaries: from micro- to deci-Hz

“living” stars:
- ‘Main-sequence stars’ Normal hydrogen-burning
- ‘Stripped stars’ Helium rich, SdB



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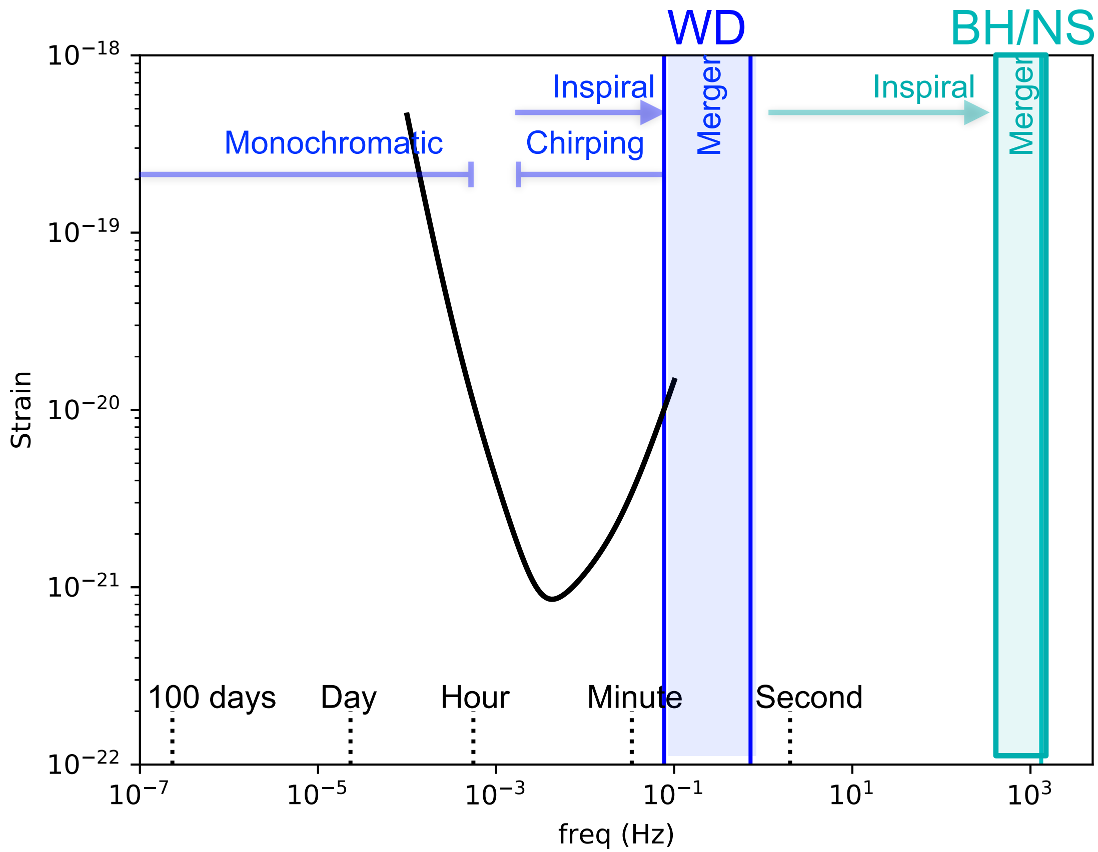
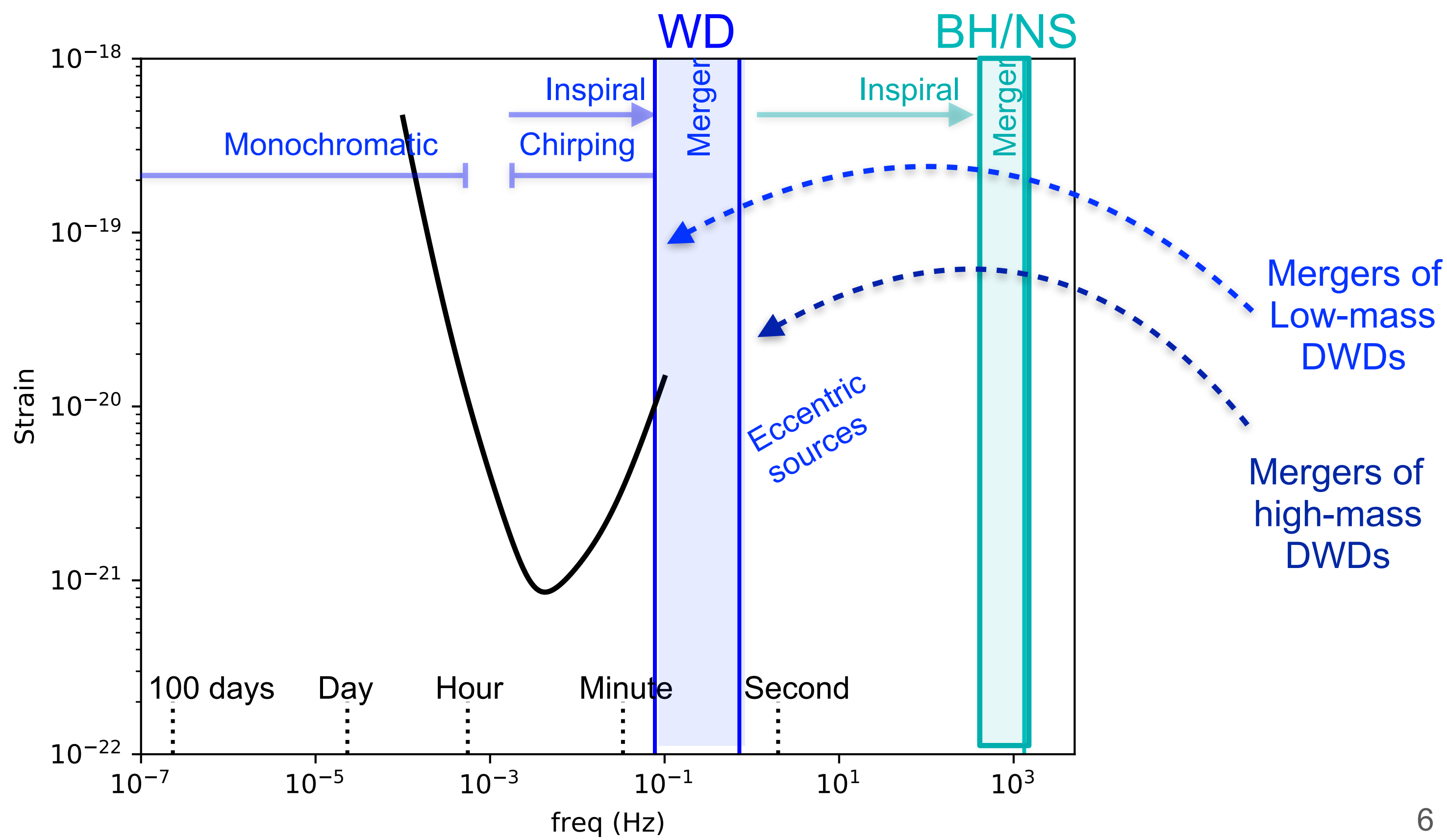


"Chirping" sources with a measurable df/dt (possible d^2f/dt^2)
Break the degeneracy between distance and chirp mass

LISA sensitivity curve
From Robson+ 2019

Galactic compact binaries: from micro- to deci-Hz



LISA sensitivity curve
From Robson+ 2019

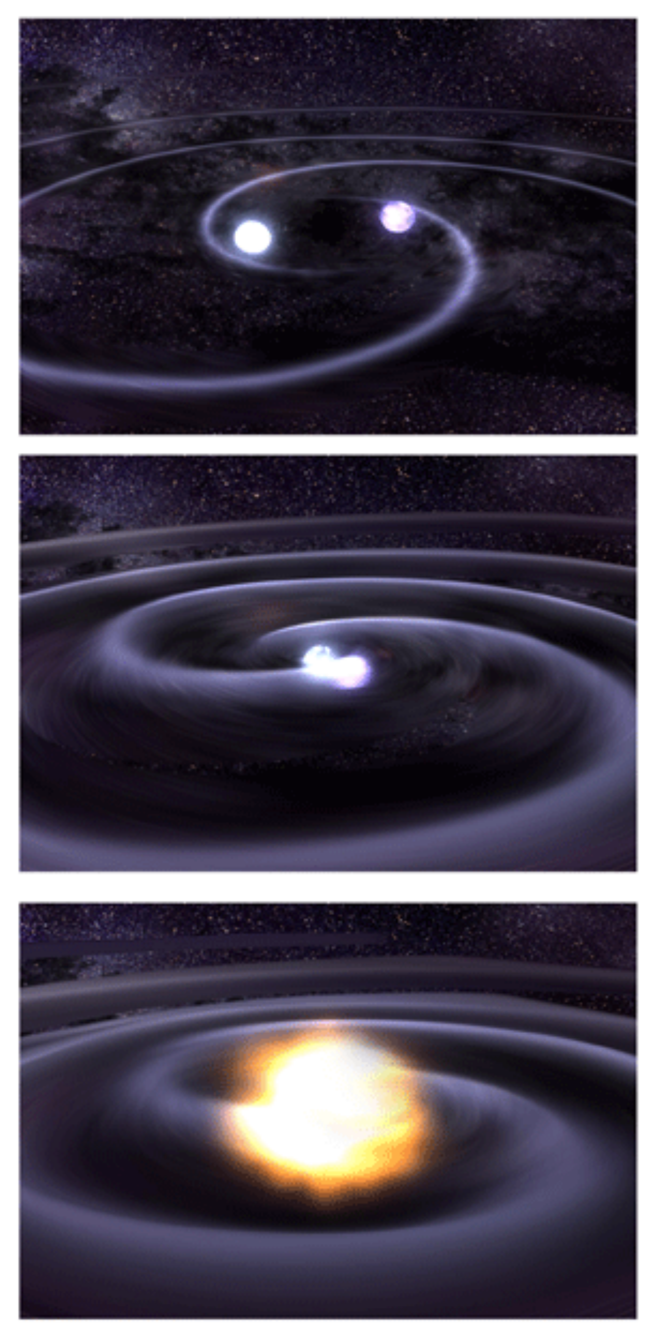
Mergers with WDs

Transient events:

- Supernova type Ia
- Calcium-rich transients
- & other thermonuclear transients

Major quests for the origins of these transients

- Simultaneous GW observations would be ground-breaking, but distance horizon problematic



Why study double white dwarfs?

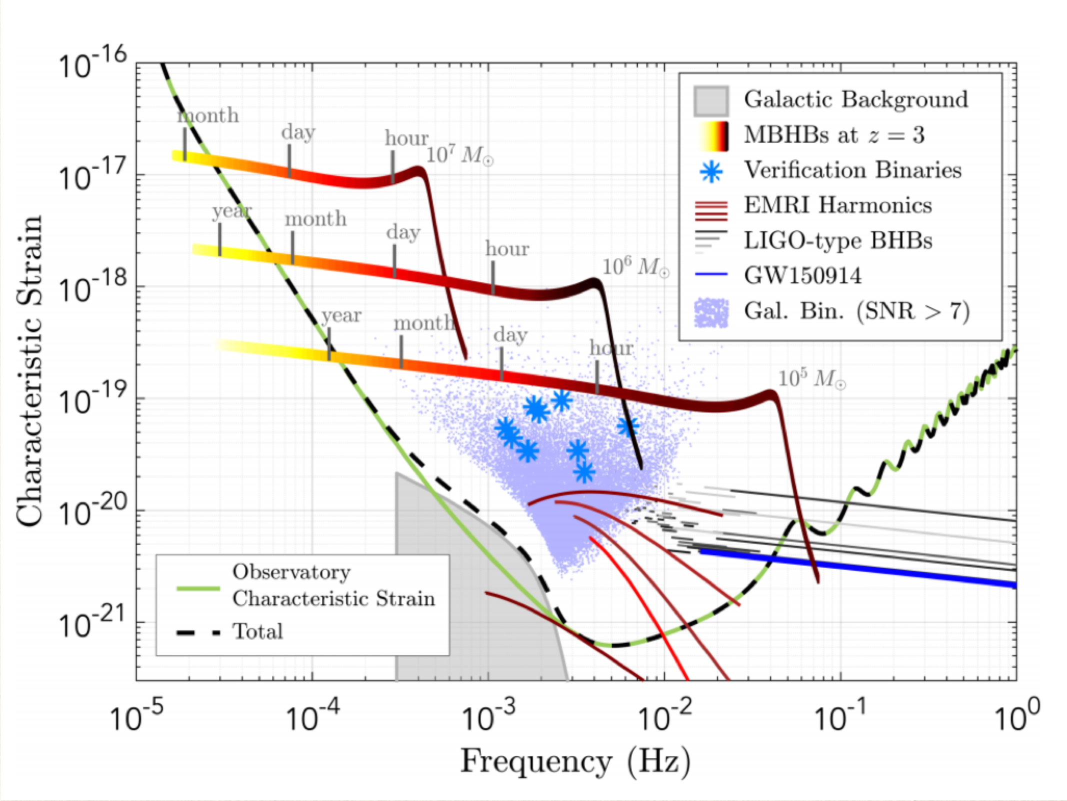
Largest population of ultracompact binaries in the Milky Way

Gravitational waves:
Dominant sources at milli- and decihertz frequencies, leading to GW foreground

Progenitors of supernova Type Ia:
Expansion of universe, dark energy

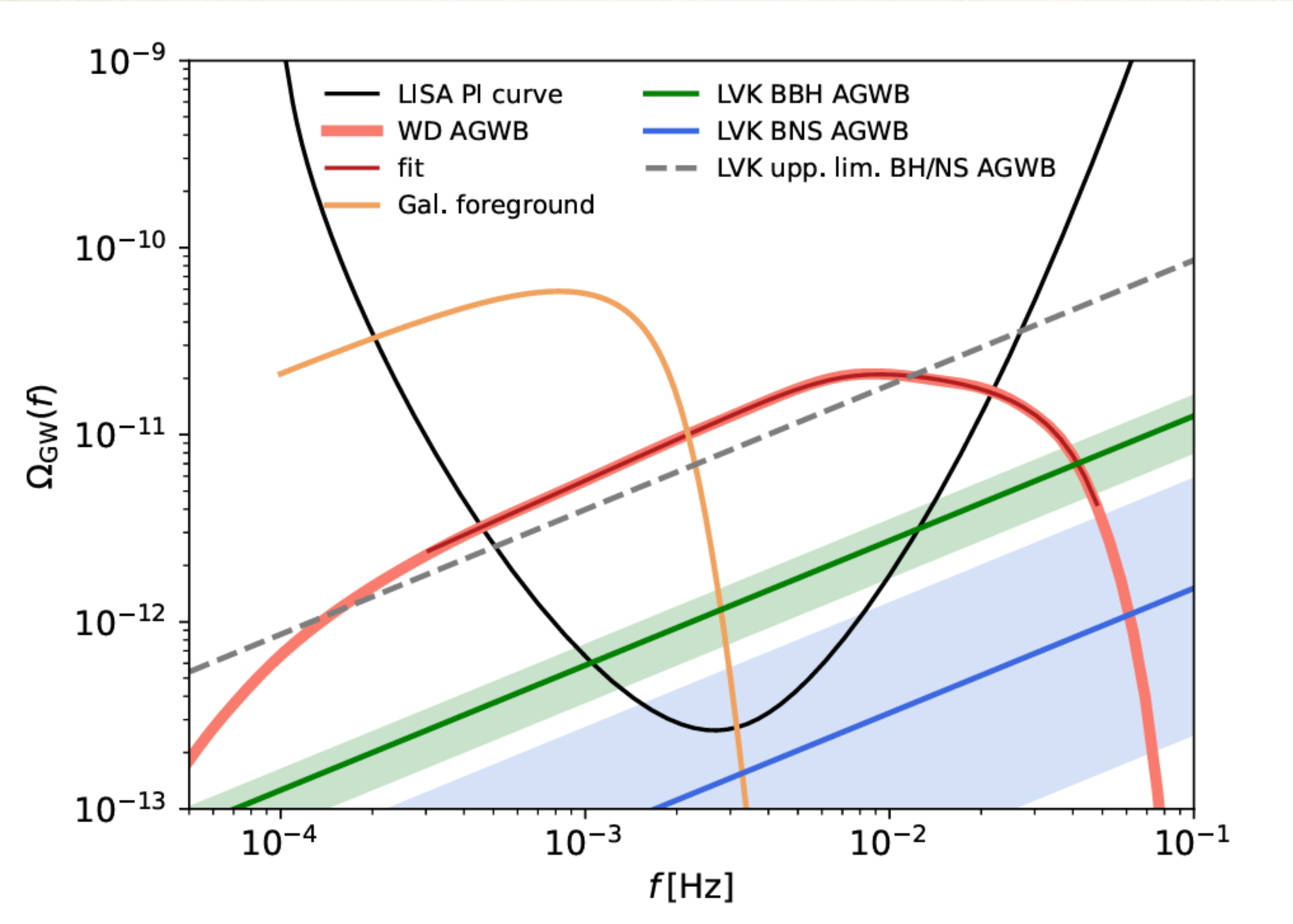
Stellar interaction:
Stellar and binary evolution
Mass transfer

GW foreground

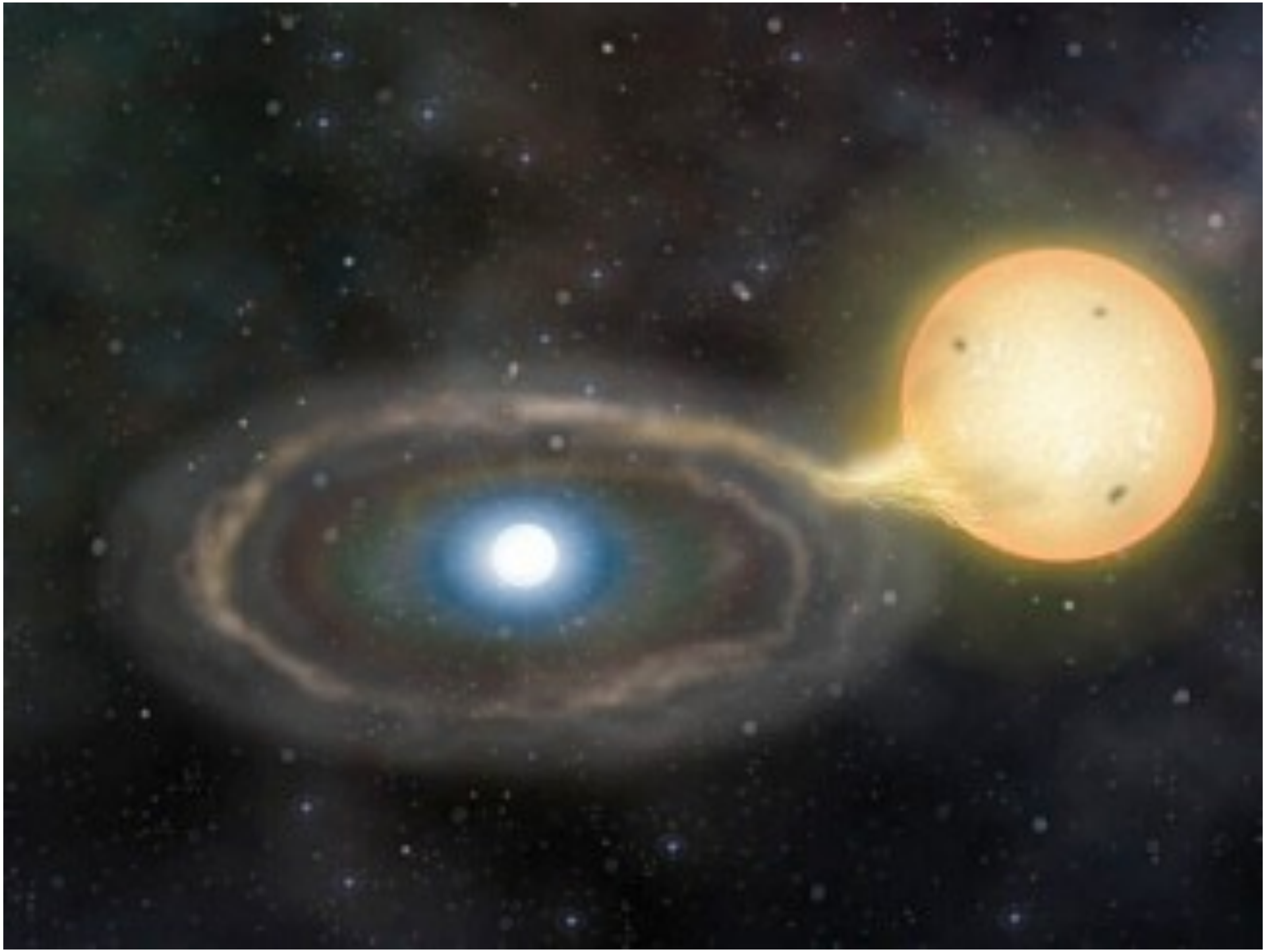


- Resolved vs unresolved
- $\Delta f_{lisa} = 1/T_{obs}$ ~8e-9Hz

GW background from extragalactic sources

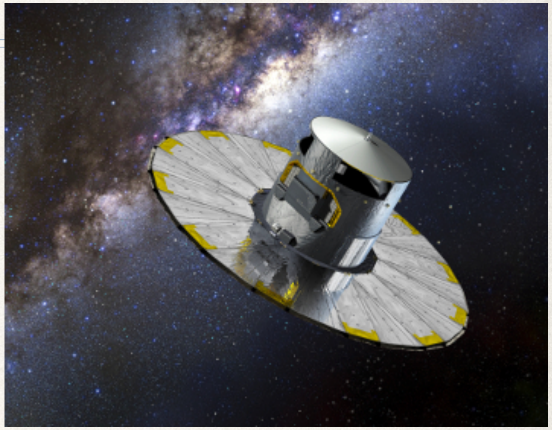


- Farmer & Phinney 03, Schneider 01, Staelens & Nelemans 24
- DWDs dominating the deciHz regime



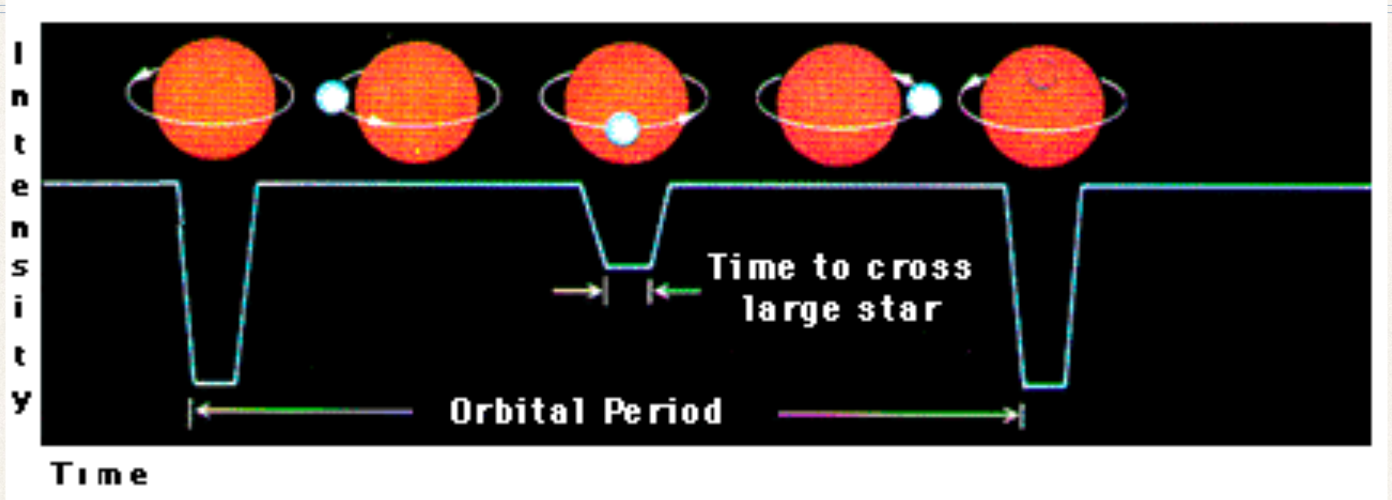
EM observations of double WDs

Observations so far



- ~10 yrs ago : ~50 double WDs known
  - detected with variety of methods
- Now: ~150 double WDs
  - SDSS ELM survey: Extremely-Low Mass WDs
  - ZTF: ~30 eclipsing double WDs (also mostly low mass)
- Next few years:
  - Gaia: 5-10% double WDs in several 100,000 WDs… needs follow-up for confirmation of binarity

Eclipsing binaries



- Expectations:
  - ZTF: ~30 DWDS
  - Vera Rubin Observatory: ~1000 DWDs
  - Gaia satellite: ~200 DWDs

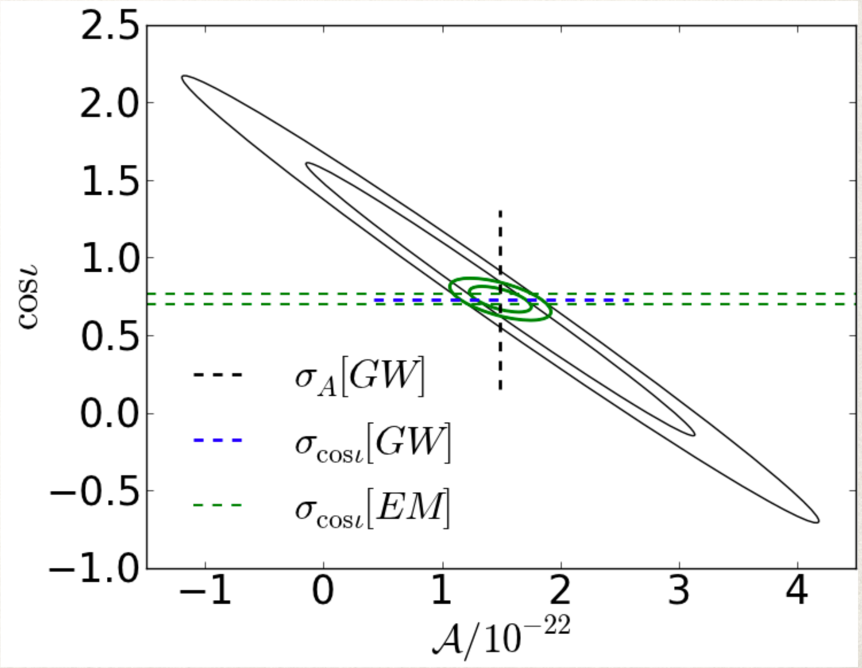
Van Roestel in prep.

Korol+ 17

Multimessenger binaries

- EM can provide: inclination, sky position, distance
- Combining GW & EM observations can improve parameter estimations

- Apriori knowledge of sky position and inclination can improve GW amplitude measurement up to a factor of 60 (Shah+ 13).
- Errors in the GW inclination may indicate an eclipsing system, that can be followed by EM (Shah+ 12)



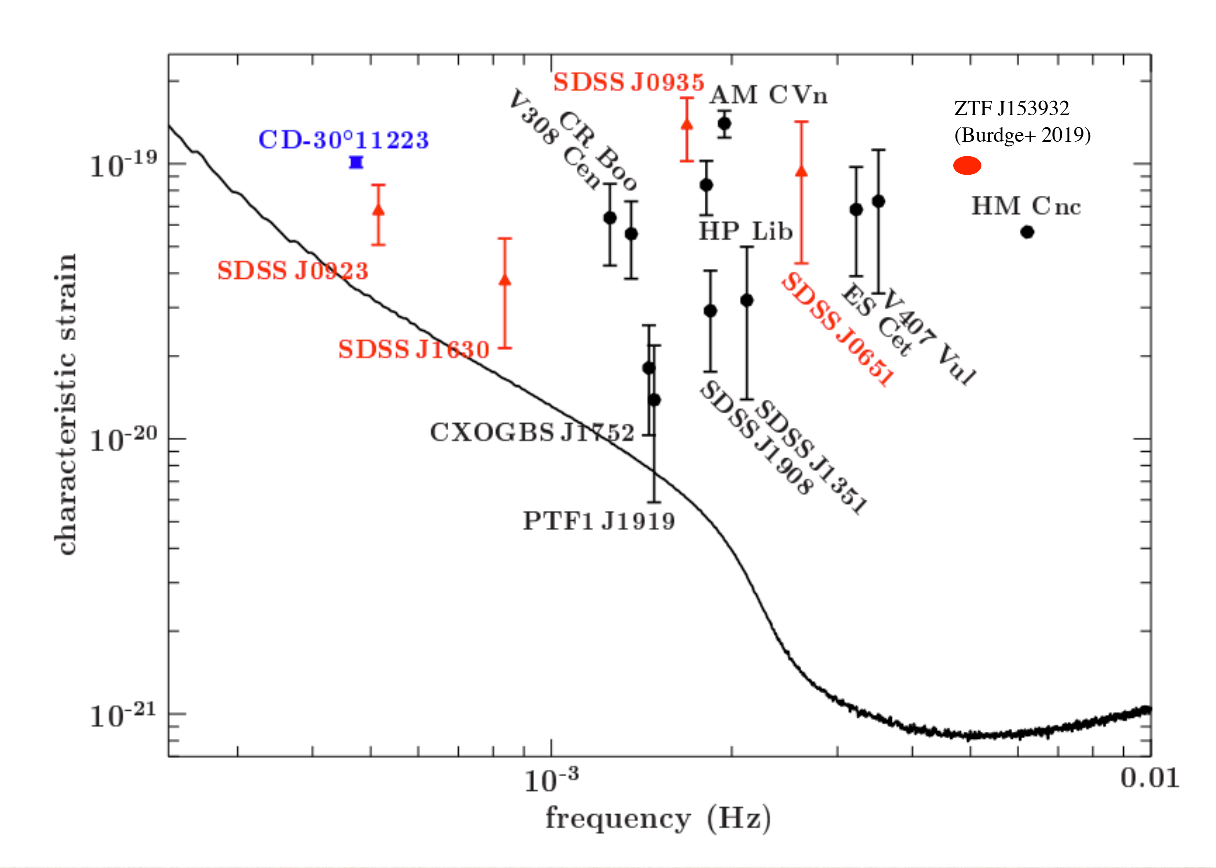
Verification binaries

Detached DWDs

DWDs undergoing mass transfer (AM CVn)

WD + stripped-envelope star

- 'Easily detectable in GWs'
- 18 sources after 3 months, +22 sources after 48 months (Kupfer+ 24)
- Crucial for testing of space-based GW interferometers (but see Littenberg & Lali '24)

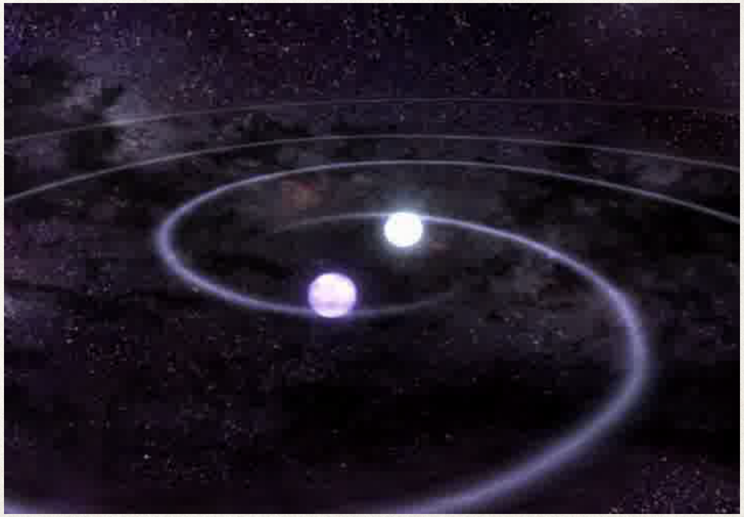


Kupfer+ 15, 24 -> See Thomas Kupfer's talk later today

Optical observations

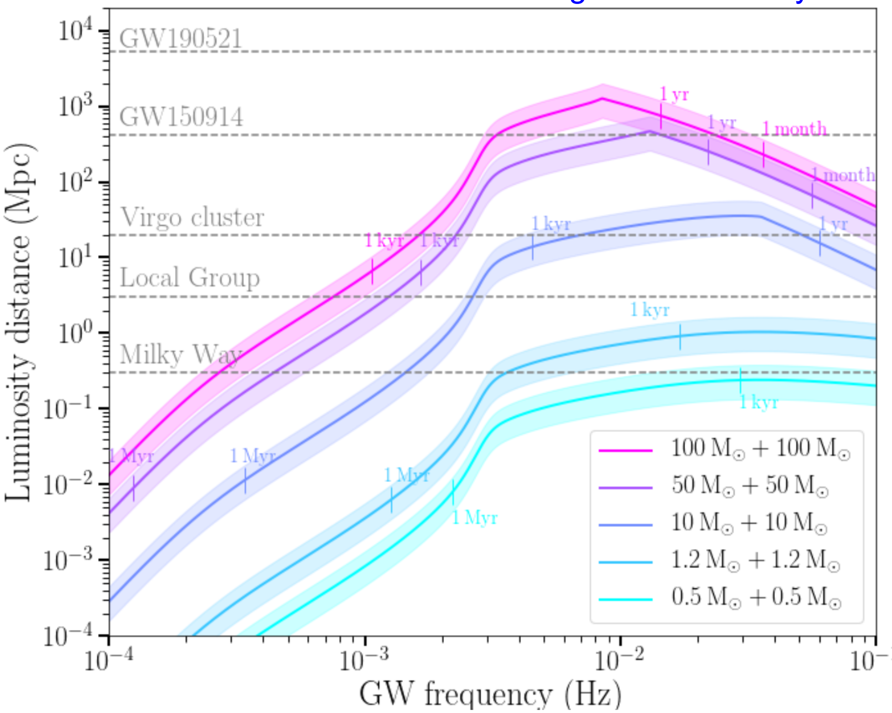
- WDs are dim objects (<300 pc)
- Sensitive to cooling physics & dust extinction
- Selection effects hard to model

Gravitational waves can be a game changer!



Max distance to observe Expected GW sources

Figure credit: Antoine Klein & Valeriya Korol
Assuming SNR>7 & T=4yr



- WD+WD binaries

- NS+WD binaries

evidence: millisecond radio pulsars

- BH+WD binaries

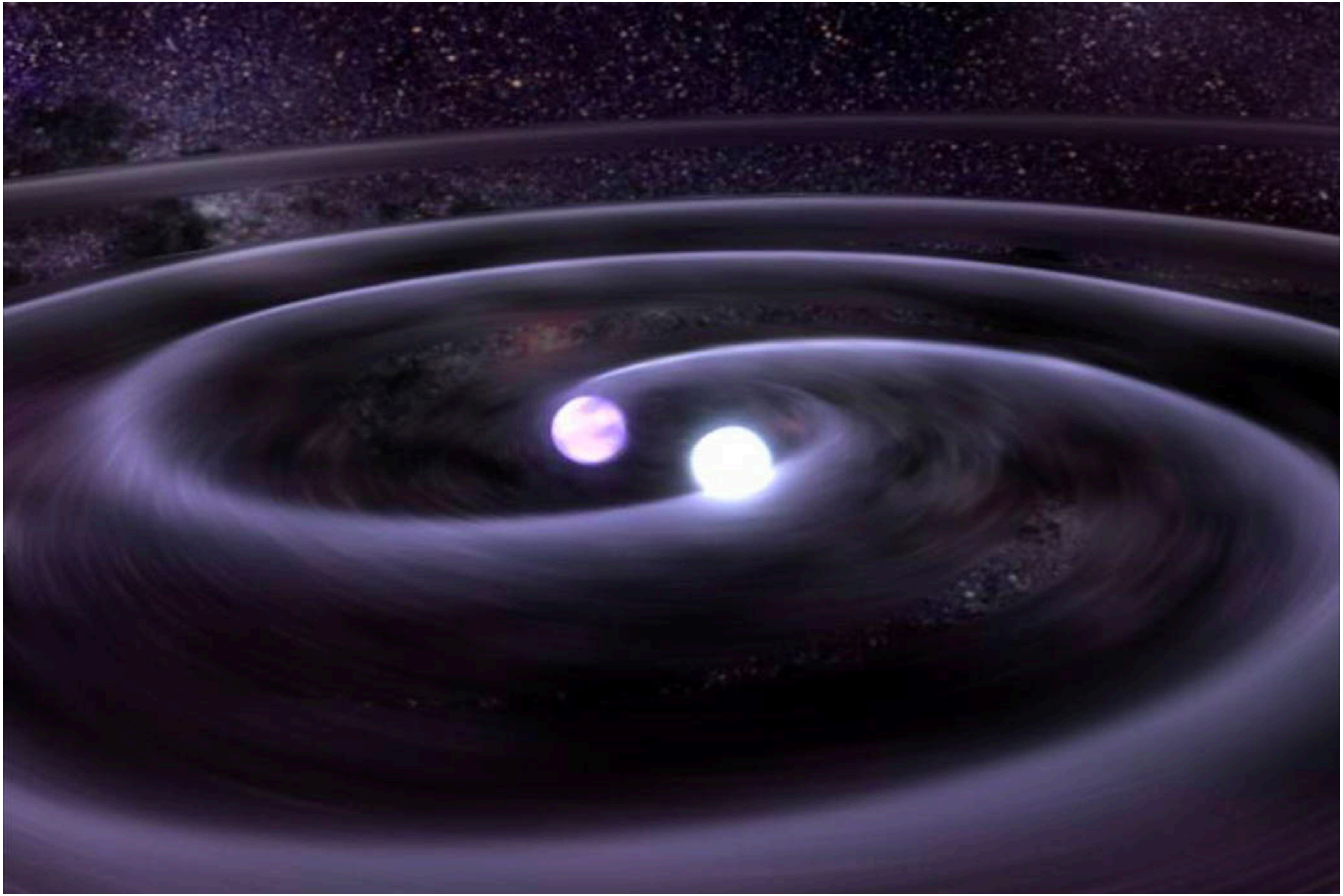
selection effects against detection
expected from population synthesis

- NS+NS binaries

evidence: radio pulsar binaries: 10 out of ~20 known NS+NS will merge

- BH+NS and BH+BH binaries

selection effects against detection - expected from population synthesis
We also anticipate detection of **extragalactic** BH+BH binaries ~few to 10 yr before merger (Sesana 2016)



Double white dwarfs as GW sources: numbers

Many references! See LISA white book, section 1.4

Expected number of sources

	Population synthesis studies			Empirical rate estimates from observed populations	
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BH+NS	$\sim 10^4 - 10^5$	0–20		–	
BH+BH	$\sim 10^6$	0–70		up to ~50	(Sesana '16)
	Total # in the Galaxy	Total # expected by LISA		Total # expected by LISA	

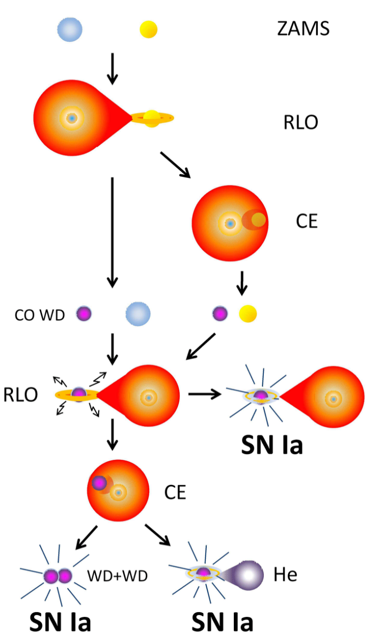
- Several thousand WD binaries
- A few hundred with NS / BH companions
- Lots of potential to combine data from different resources

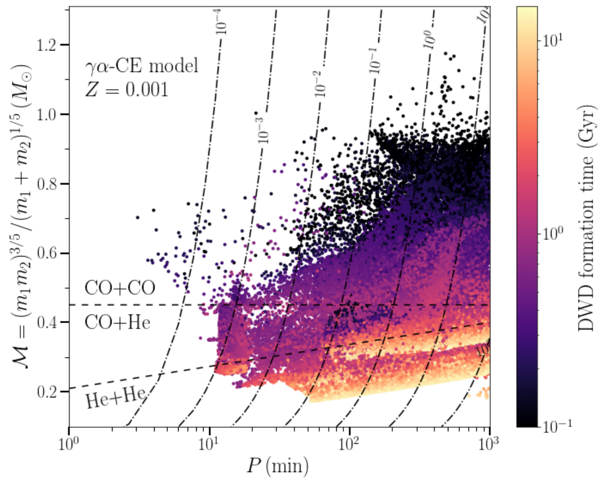
Assembling a mock population with Binary Population Synthesis

Step 1

Model Binary evolution

Binary population





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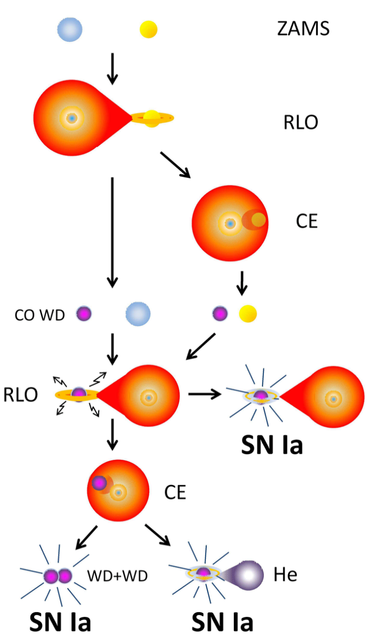
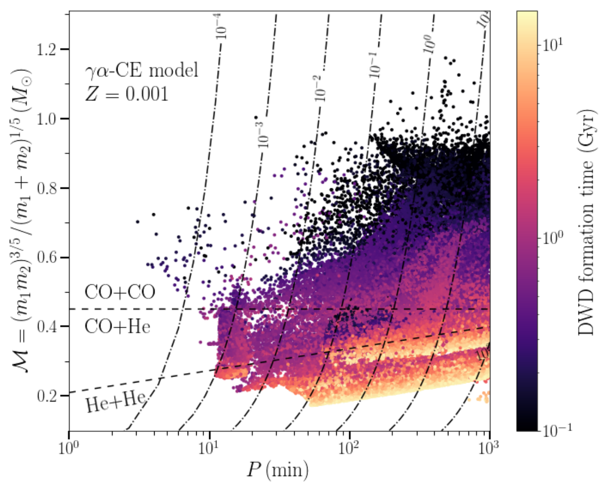


Step 1

Binary population



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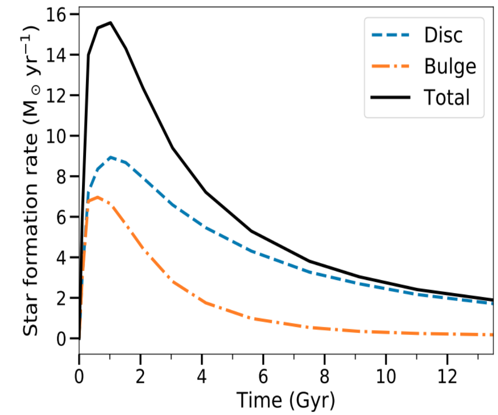
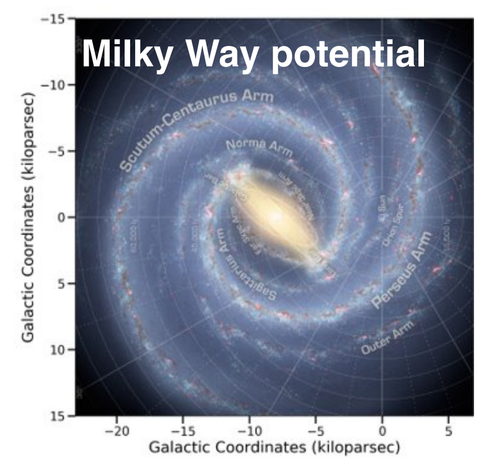
Step 2

Milky Way population

Star formation history





Assembling a mock population with Binary Population Synthesis

How (un)certain are step 1 & 2?

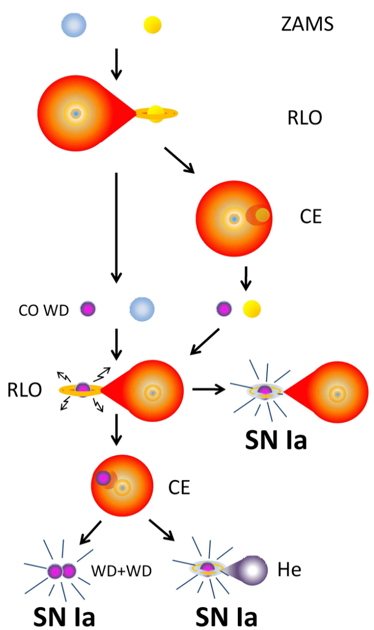
Model Binary evolution

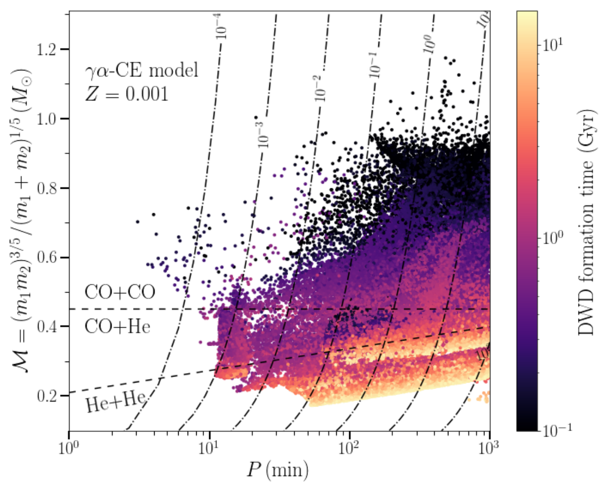
Step 1

Binary population

Step 2

Milky Way population





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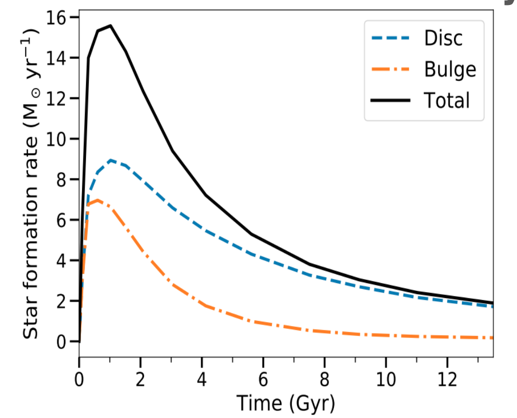
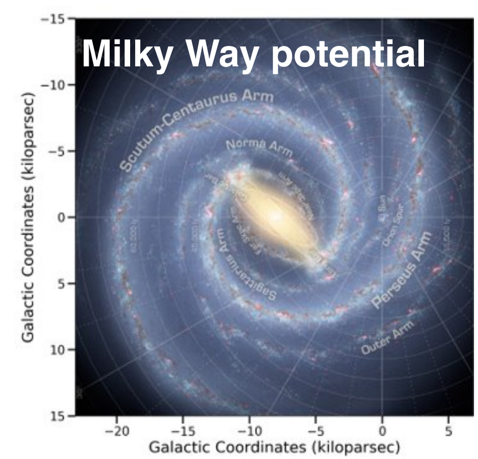
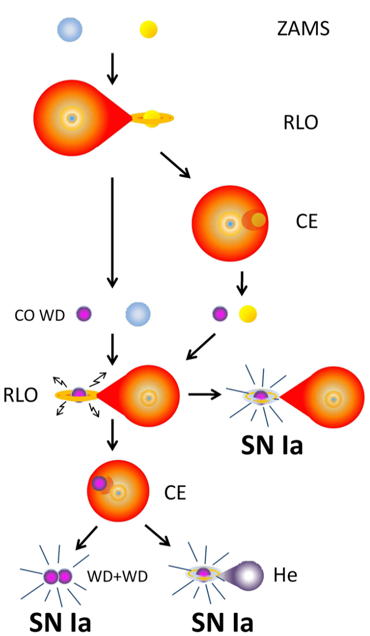


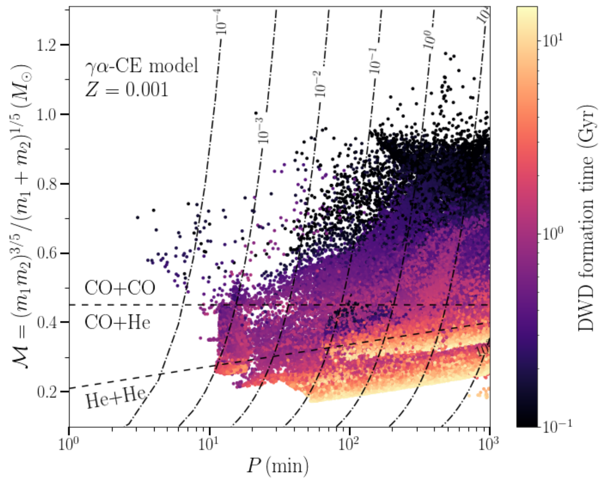


Assembling a mock population with Binary Population Synthesis

How (un)certain are step 1 & 2?
- PopCORN project: when we make the same assumptions, we get the same binary populations (Toonen+ 14)
- Currently on the way: Compact binary collab, lead by Alexey Bobrick & Katie Breivik

Model Binary evolution → Step 1 → Binary population → Step 2 → Milky Way population





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+

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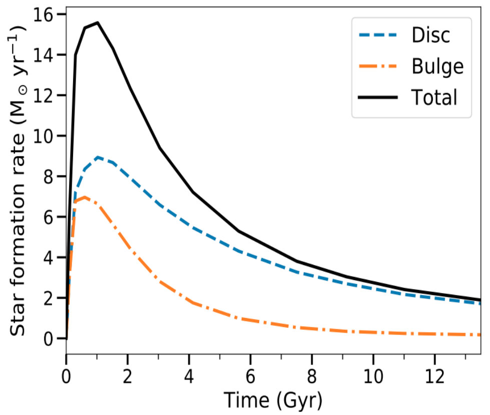
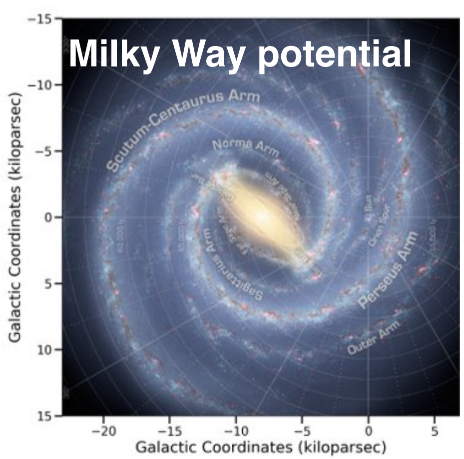
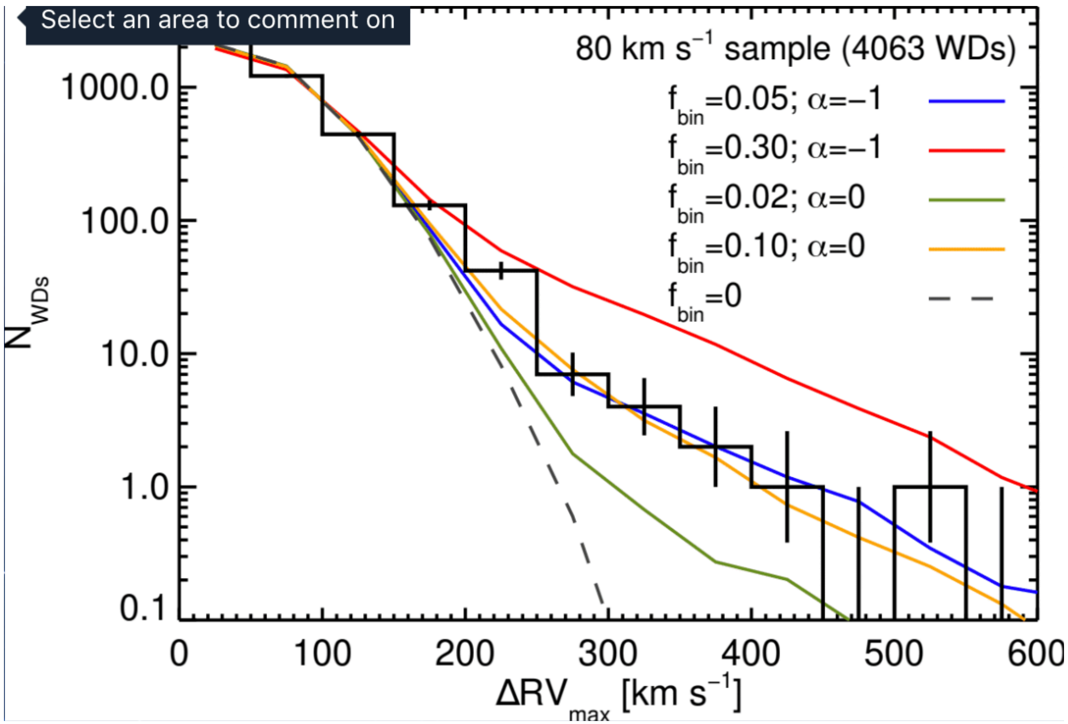




Expected number of sources

Empirical studies

- For example WD+WD (Korol, Hallakoun, Toonen, Karnesis 2022)
  - Using radial velocities from the SDSS & SPY surveys (Maoz, Hallakoun, Badenes 2012,2017,2018)



Depends mostly on:

- Binary fraction f_{bin} & power (α) of separation distribution (a^{α})

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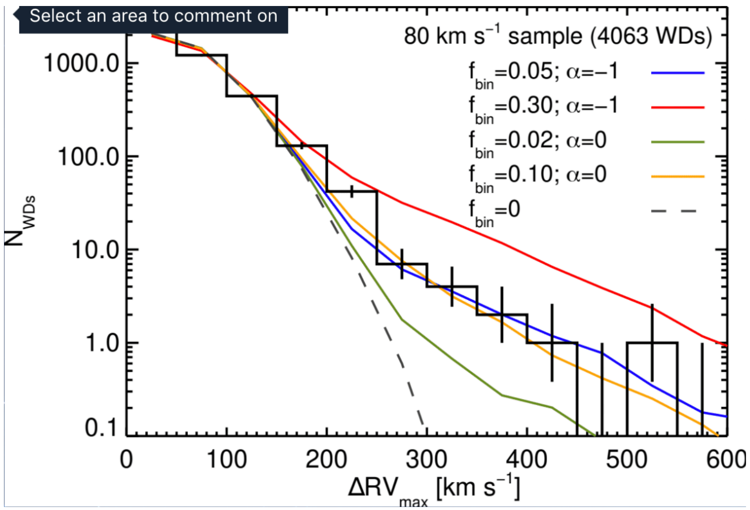

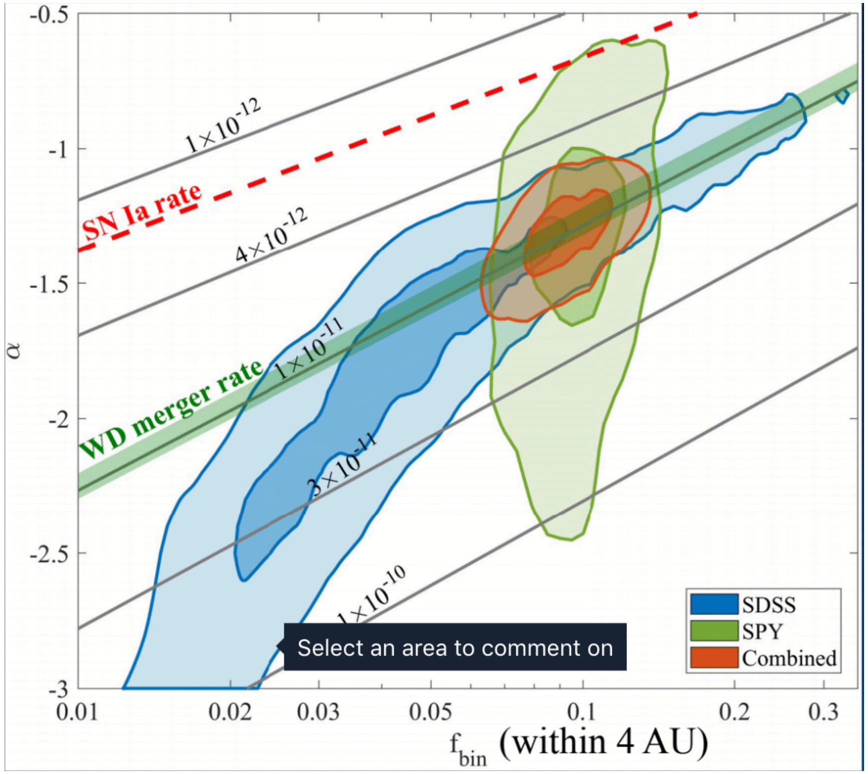

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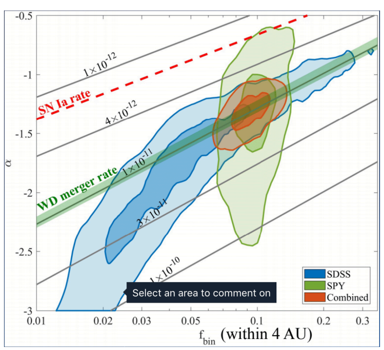
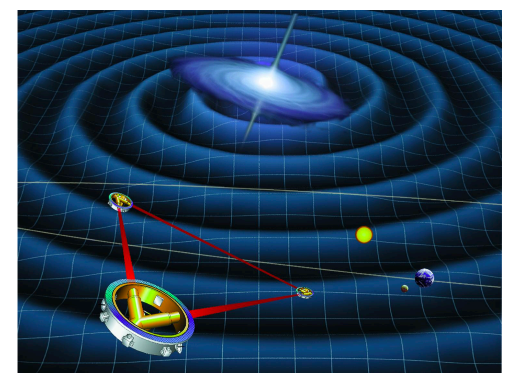
➡ Observations suggest larger DWD space density (Toonen+ ’18)
➡ Effect for LISA (Korol, Hallakoun, Toonen & Karnesis 2022)



Observationally based model of DWD population

Distances as our previous BPS studies (Toonen & Nelemans 2013, Korol+ ‘2017)



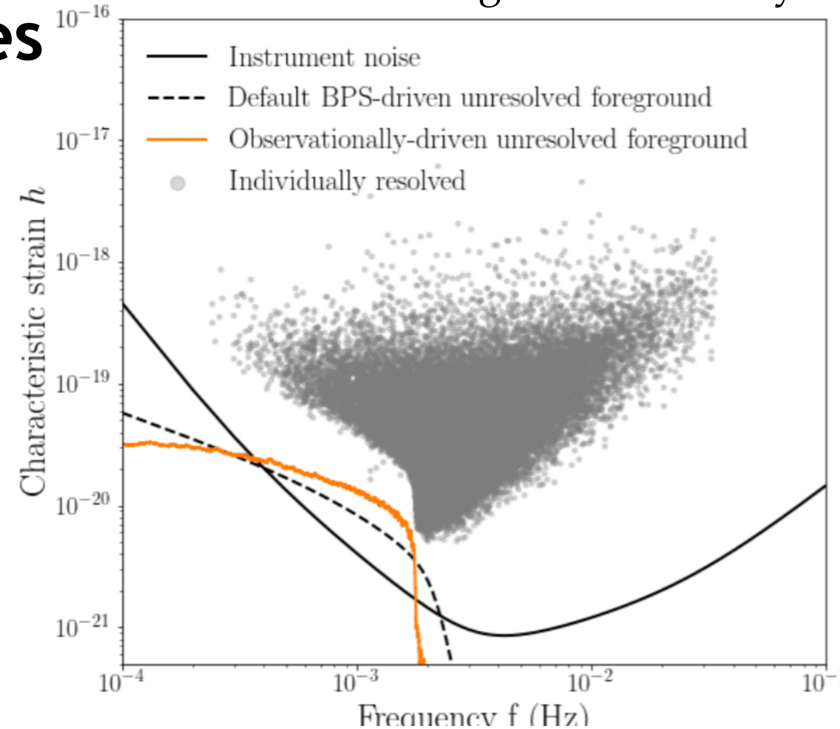
What can LISA see: following Karnesis+ 21

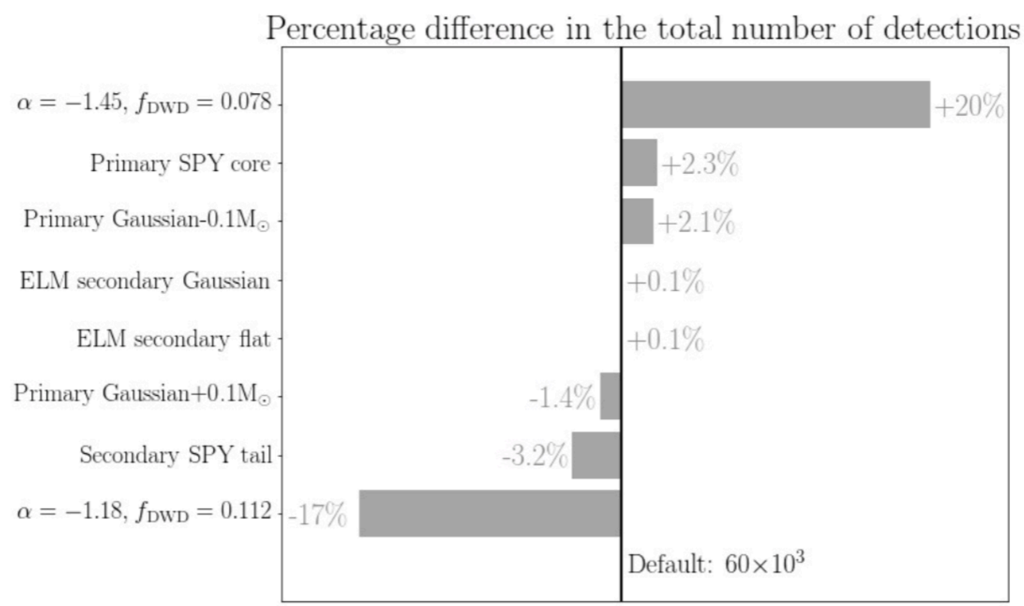
Expected number of sources

Empirical studies

- **~60,000 resolved sources**
  - 2-5x more compared to BPS studies (Korol+ '17, Lamberts+ '19, Breivik+ '20, Wilhelm+ '21)
- a significantly different shape of the DWD confusion foreground.

Assuming SNR>7 & T=4yr





Korol, Hallakoun, Toonen, Karnesis 2022

Expected number of sources

Many references! See LISA white book, section 1.4

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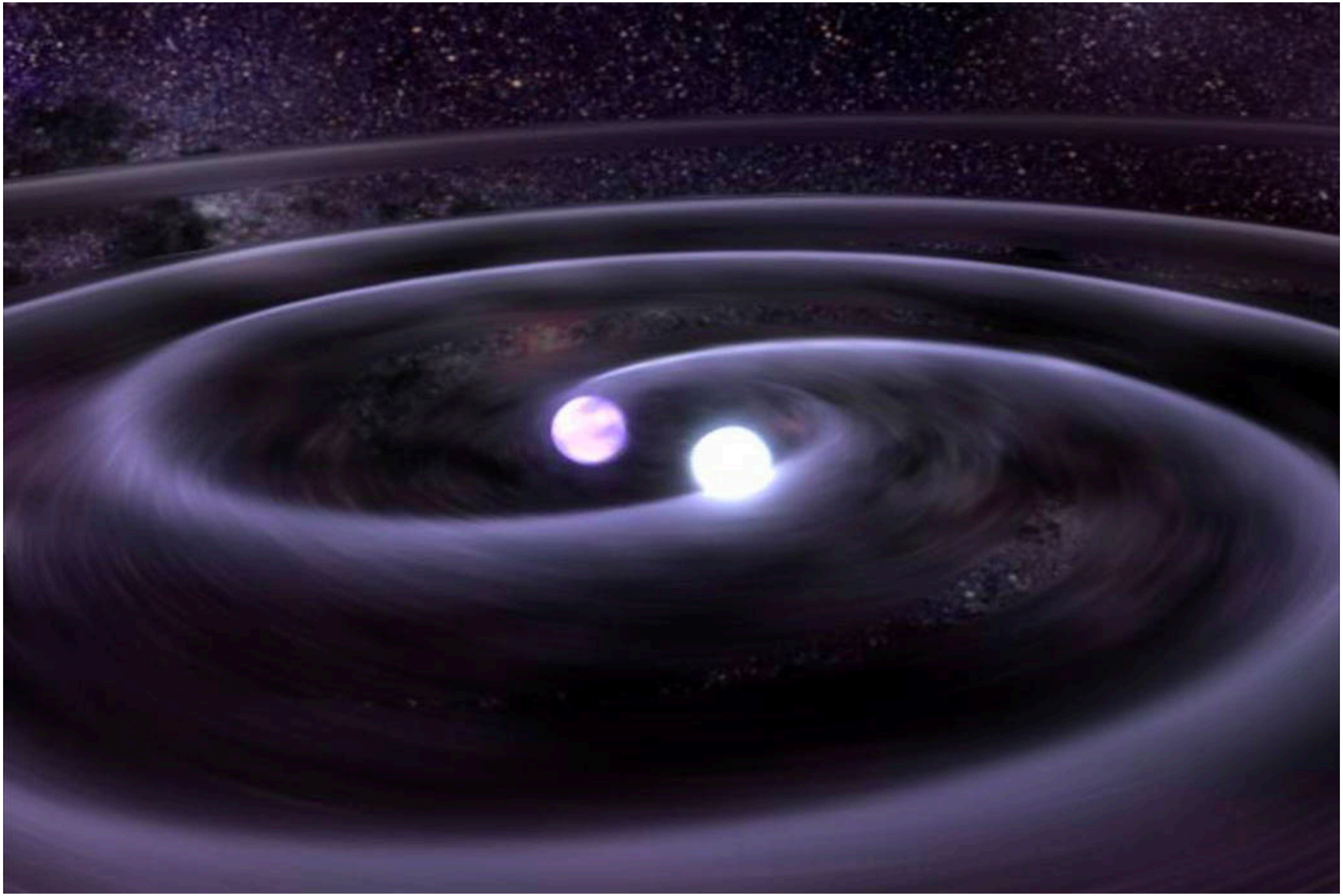
	Total # in the Galaxy	Total # expected by LISA		Total # expected by LISA	

- EM DWD observations help to constrain both methods
- Currently most systems at orbits outside the milliHz & deciHz regime.



Double white dwarfs as GW sources: constraints

Expected number of sources

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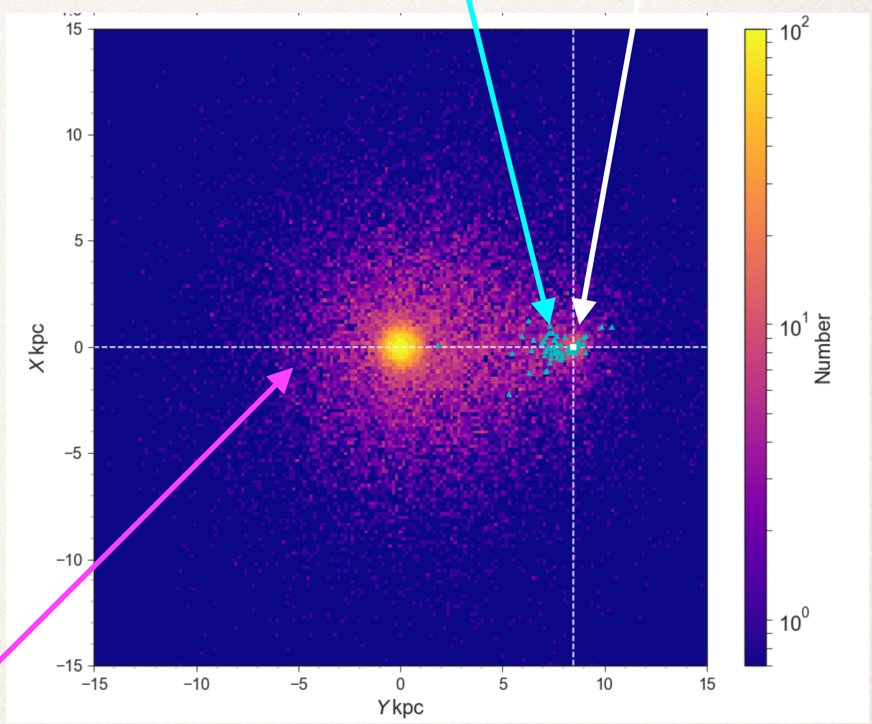
GW observations

- New era for double WDs:
  - LISA: ~6k-30k DWDs
  - Tracer of Galactic structure (Korol +18, Wilhelm+ 21)
  - Even the Local group (Korol +18, Keim+ 23, van Zeist+ 24)

Optical Dwds

Sun



Opposite side of Milky Way!

Korol+ 19

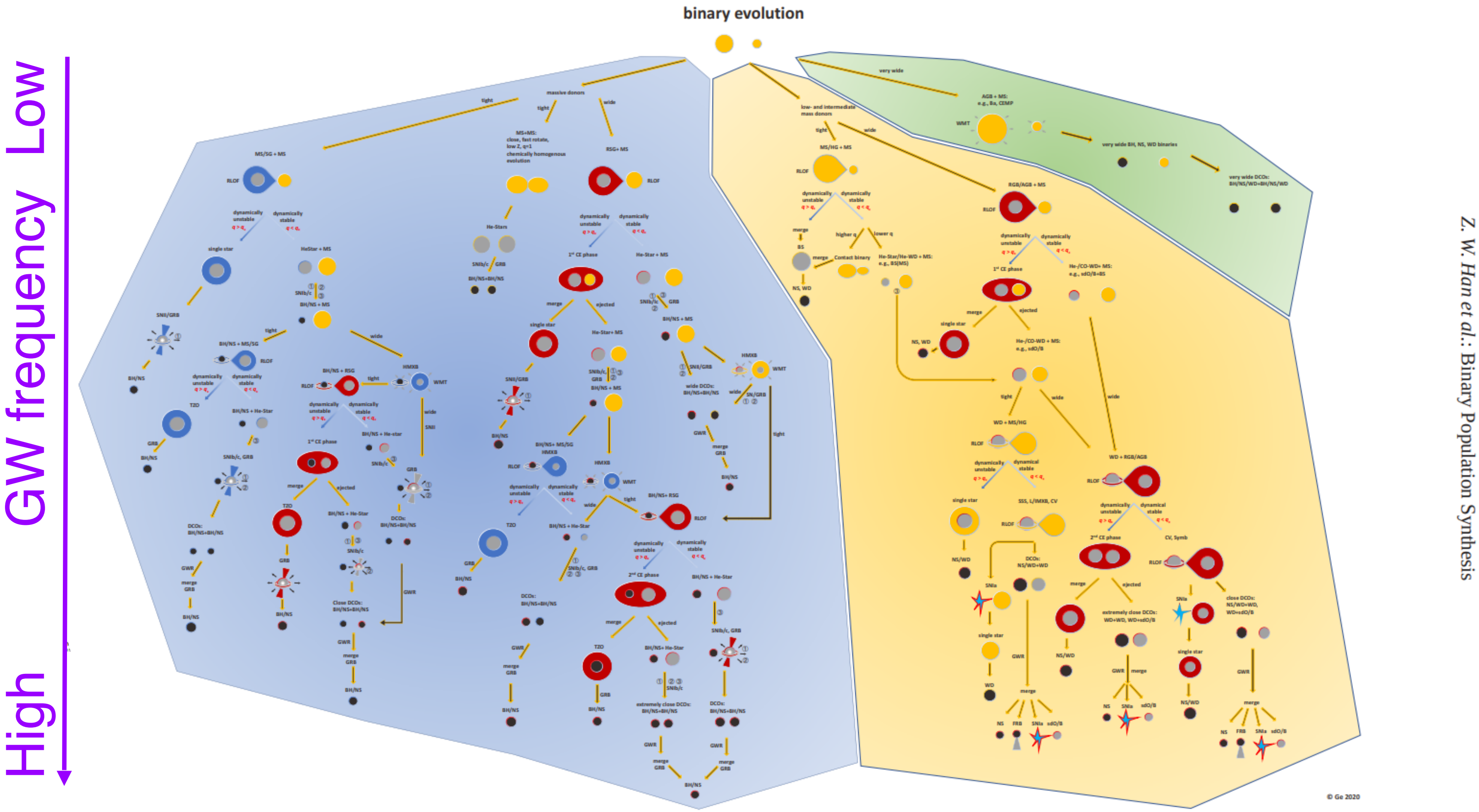
LISA sources as Galactic probes

LISA: several 1000s DWD with sky position & distance to map

- Scale length of disk, bulge (halo) to few 10% accuracy (Adams+ ’12, Korol+ ’19, Wilhelm+ ’20). Crude (~300 pc) but independent measurement from foreground (Benacquista+ ’06, Breivik+ ’20)
- Disk density profile & bar’ axis length ratio & orientation angle. Spiral arms remain elusive (Wilhelm+ ’20)

- Universal IMF? (Rebassa-Mansergas ’19, Korol+ ’20)
- (Local) star formation histories (Yu+ ‘10, Lamberts+ ‘ 19, Korol+ ’20)
- (Satellite) Masses (Korol+ ’21) from # of WD+WD
- Galactic mass from rotation curve with EM proper motion (Korol+ ’17, Breivik+ ’18, Korol+ ’19)

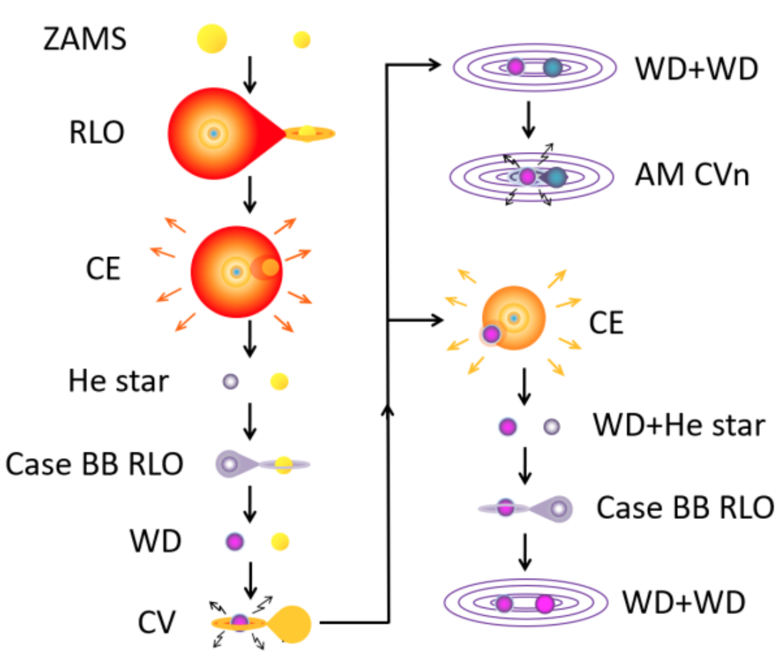
Constraints on Binary evolution



- Demographics of LISA sources sculpted by multiple phases of mass transfer

Evolution in characteristic strain-frequency parameter space

An example of the evolutionary process leading to the formation of the most common double compact objects in the Milky Way: **detached double white dwarfs** (WD+WD) and **interacting double white dwarfs** (AM CVns).



Tauris and van den Heuvel (2022), Amaro-Seoane et al. (2023)

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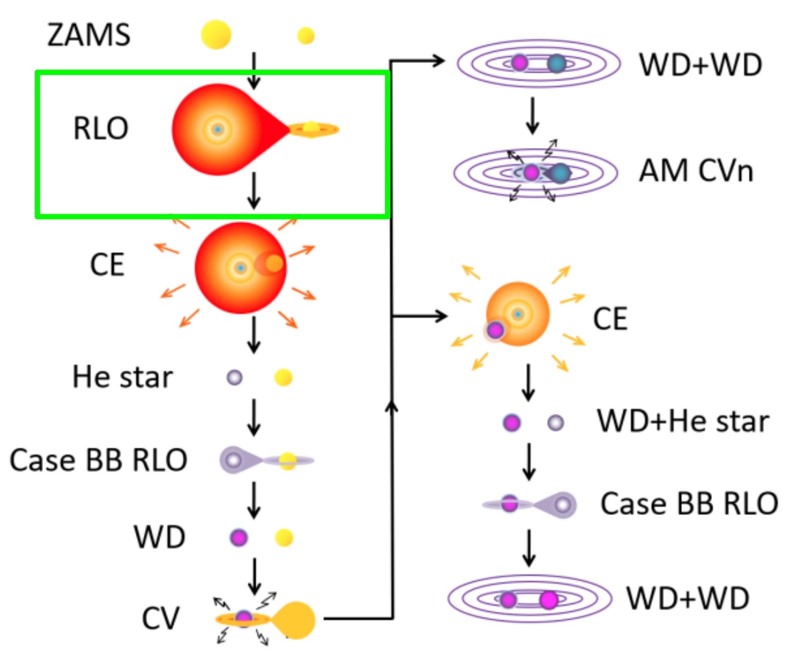


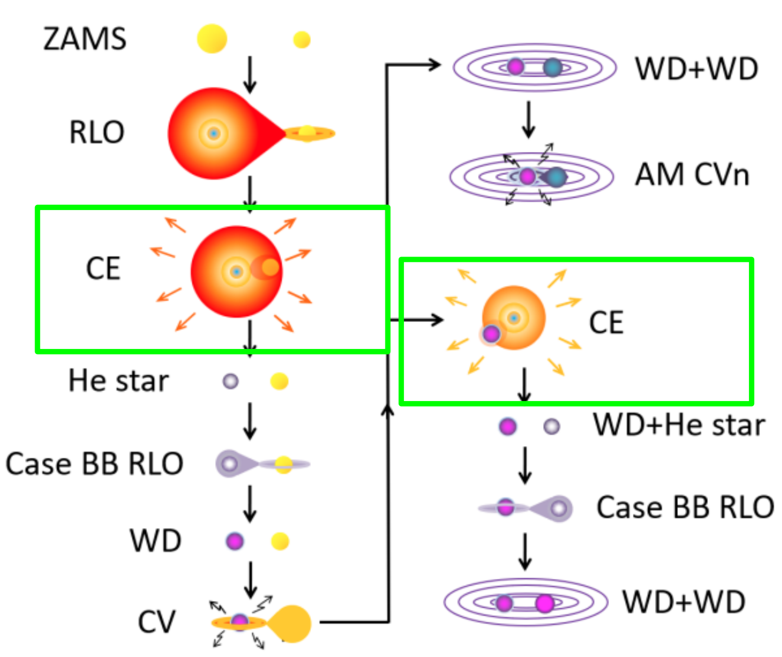
Tauris and van den Heuvel (2022), Amaro-Seoane et al. (2023)

- Stability of mass transfer, accretion efficiency during mass transfer
- Determines DWD mass ratios & chirp masses
- Recent work favours stable mass transfer (RLO) (Nelemans+ 01, Woods+ 12, Passy+ 12, Ge+ 15, Temmink+ 23, Li+ 23)

Evolution in characteristic strain-frequency parameter space

Common envelope ejection (major uncertainty; Which systems eject the CE? What is the final orbital separation?)

- Indirect information from the LISA population
- Binaries 'born' in the LISA band
- Direct observations related to CE interaction



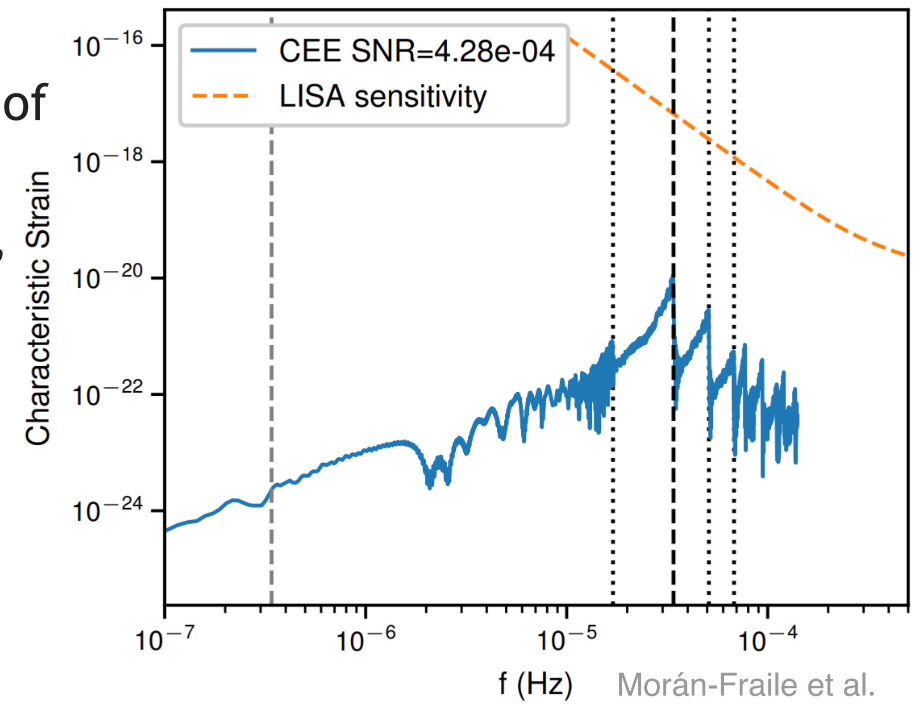
Tauris and van den Heuvel (2022), Amaro-Seoane et al. (2023)

Evolution in characteristic strain-frequency parameter space

Common envelope ejection (major uncertainty; Which systems eject the CE? What is the final orbital separation?)

- Indirect information from the LISA population
- Binaries 'born' in the LISA band
- Direct observations related to CE interaction

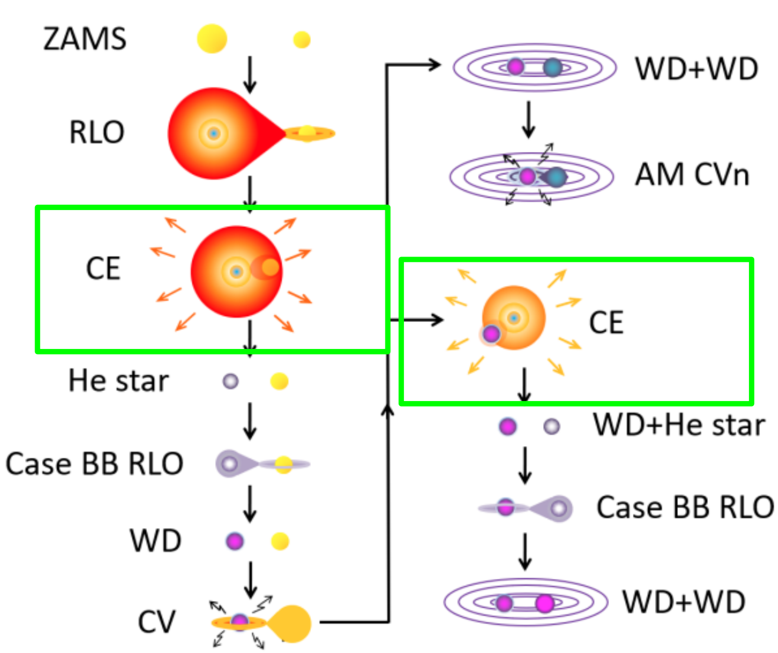
  - Typically: compact object spiralling in deeply in envelope of giant with compact core
  - Unlikely to see initial plunge-in, at most 1 per few centuries (Ohlmann+ '16, Ginat+ '20)
  - Better chances for the slow thermal phase: ~0.1-100 in MW during LISA mission (Renzo+ '21)



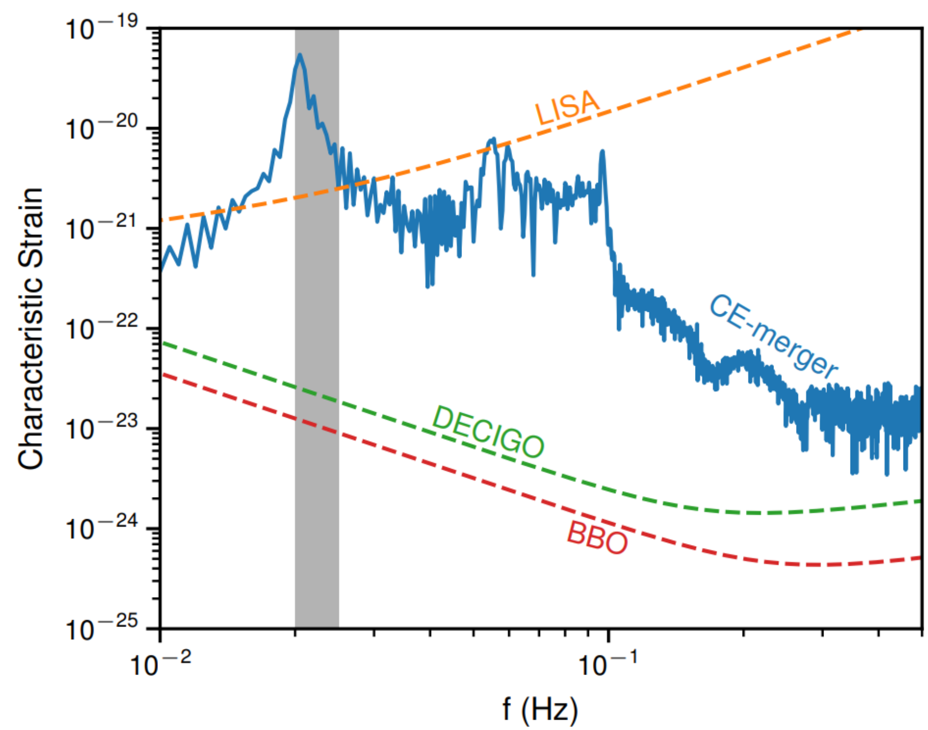
Morán-Fraile et al. (2023)

Evolution in characteristic strain-frequency parameter space

A non-successful common-envelope ejection leads to a merger in the deci-Hz band



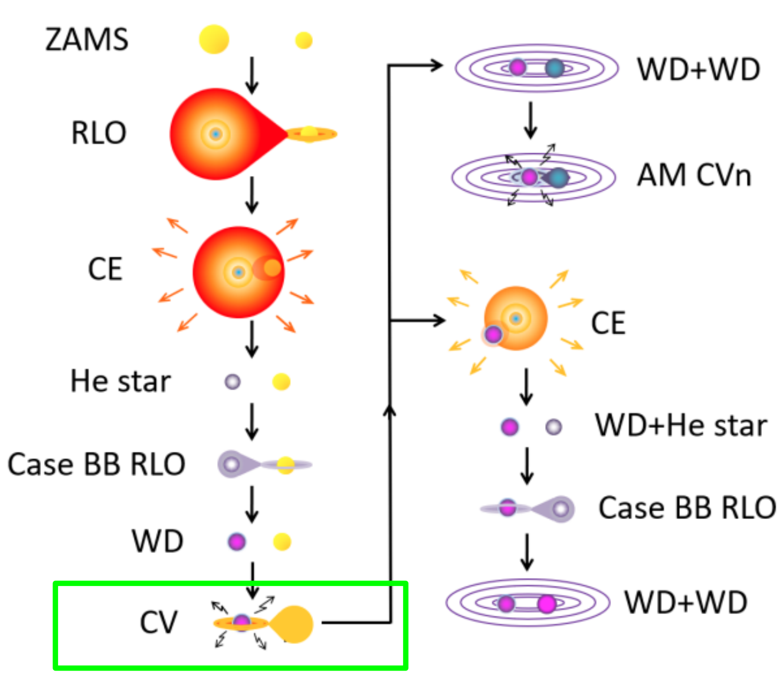
Tauris and van den Heuvel (2022), Amaro-Seoane et al. (20

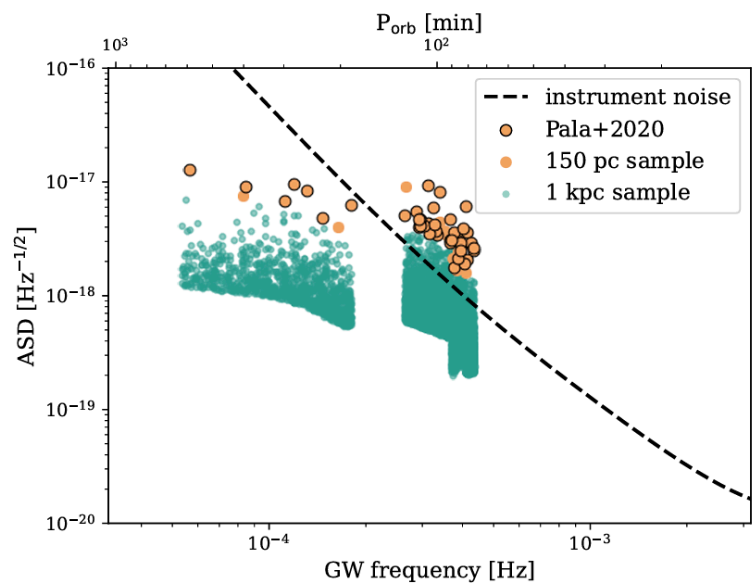


Morán-Fraile et al. (2023)
Signal last ~few 1000s sec

Evolution in characteristic strain-frequency parameter space

Scaringi et al. (2023) have recently shown that known Cataclysmic Variables (CVs) may be detectable by LISA. CVs pile up at ~ 0.3 milli-Hz (reaching their orbital period minimum) to produce a spike in the Galactic foreground.



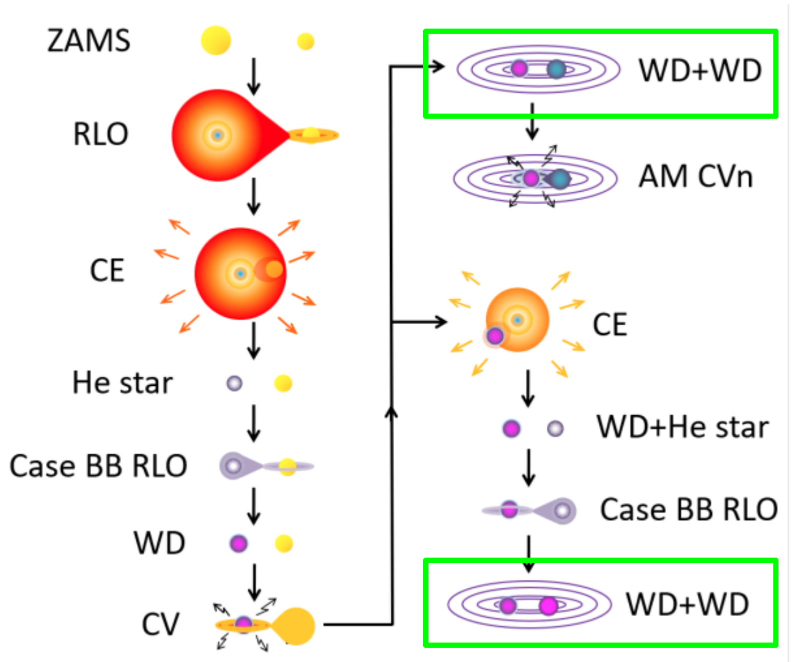


Tauris and van den Heuvel (2022), Amaro-Seoane et al. (2023)

Evolution in characteristic strain-frequency parameter space

- WD+WDs are the predominant GW emitters in the milli-Hertz regime. Other phases capable of producing detectable GW signals, such as CE, CV, etc., are significantly rarer, by orders of magnitude.

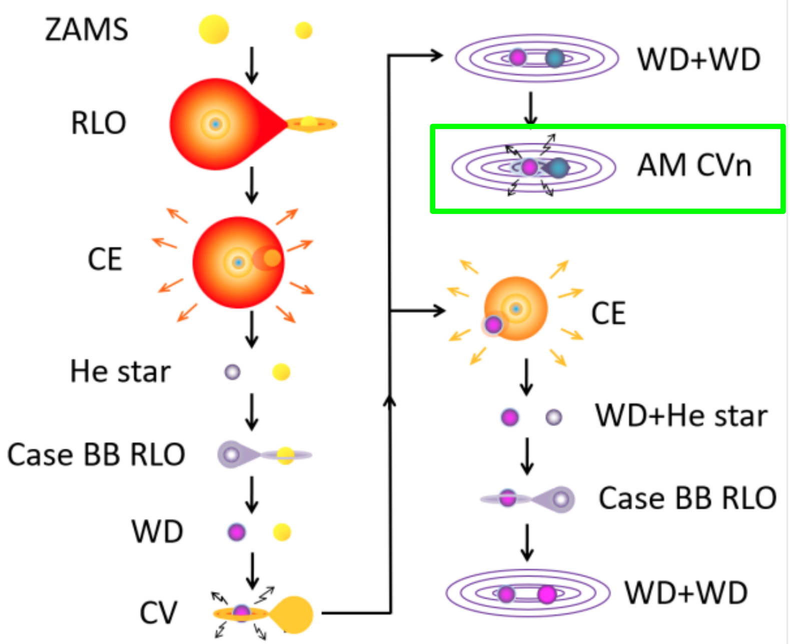
- In fact, according to our current understanding of WD+WDs, evolution through a common envelope phase—bypassing the cataclysmic variable stage—is more likely.

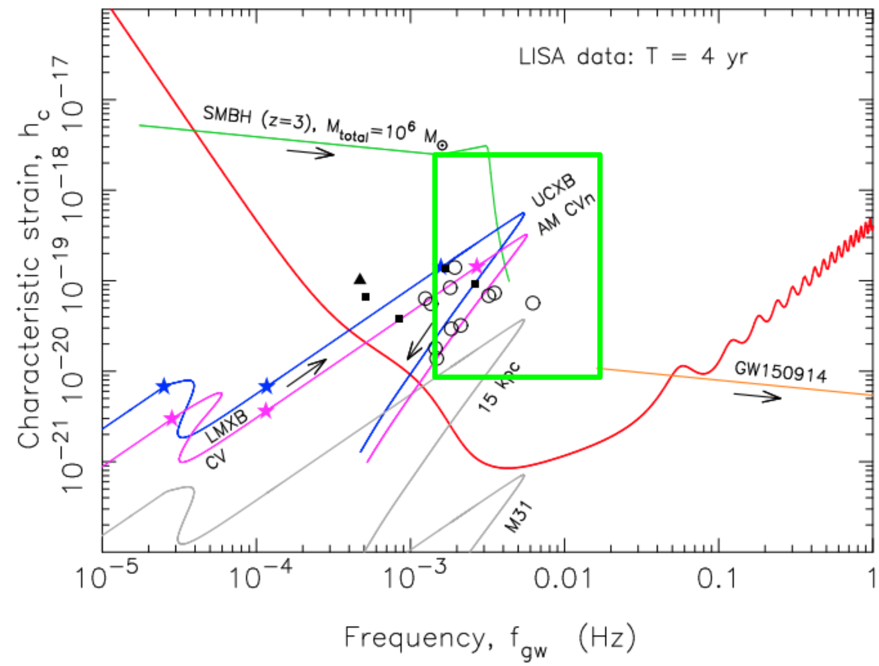


Tauris and van den Heuvel (2022), Amaro-Seoane et al. (2023)

Evolution in characteristic strain-frequency parameter space

AM CVns are amongst the shortest period binaries that we know of from electromagnetic observations. Can be distinguished from detached (non-interacting) WD+WD because of the negative chirp.

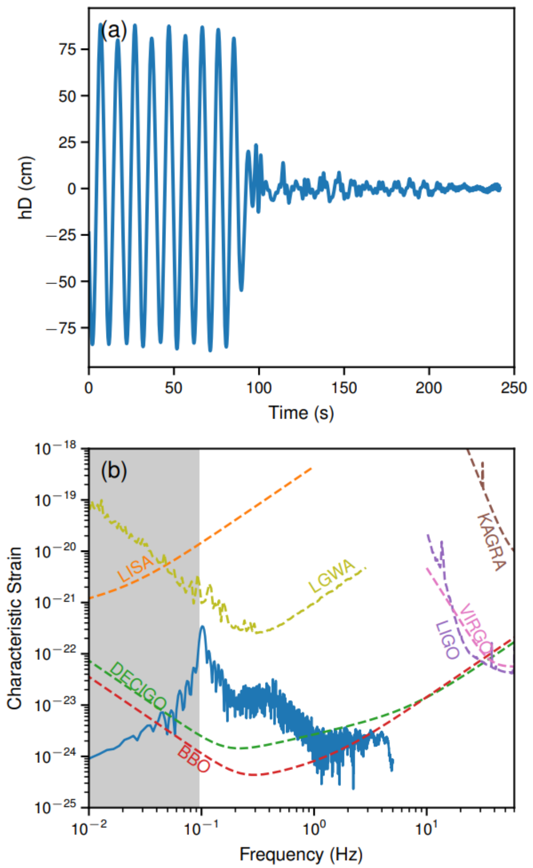




Tauris and van den Heuvel (2022), Amaro-Seoane et al. (2023)

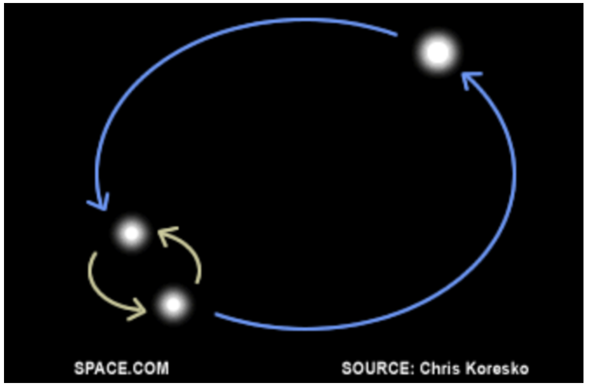
Evolution in characteristic strain-frequency parameter space

- Binaries without extreme mass ratios fail to establish stable accretion, resulting in mergers
- Mergers of WD+WD may result in thermonuclear transients, and mergers of massive WD+WD may result in bright Type Ia supernovae
- Indirect GW constraints on Galactic merger rates
  - ~500 compact superchandrasekhar DWDs (Ruiter+ '10, Rebassa-Mansergas+ '19)



An example of a NS + WD merger from Morán-Fraile et al. (2023)

Triples and other multiples



- Common: For every 3 binaries, there is at least 1 triple (Tokovinin+ ’08, Moe+ ’17)

Visible in LISA through:

- Eccentricity variations from three-body dynamics (Hoang+ ’19)
- Doppler frequency modulation (Robson+ ’18, Tamanini & Danielski ’19, Tamanini+ ’20)

➡ The sensitivity of LISA will be able to detect DWDs companions with masses down to ~ M_J (Danielski+ ’19)

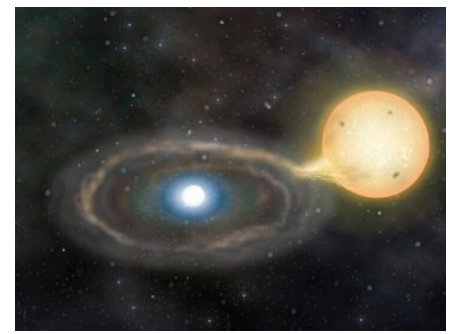
- Detectable out to LMC! (Danielski & Tamanini ’20)

- Early estimates: 3-83 circumbinary exoplanets, and 14-2218 circumbinary brown dwarfs (Danielski+ ’19)
- Preliminary results with full triple calculations with TRES (Toonen+ 16, 20), ~20% of DWDs manage to retain their planets (Columba, Danielski, Toonen, Dorozsmai in prep.)

Detecting stellar binaries and multiples with GWs

A key science objective and most abundant observable sources for current & planned GW detectors. The only guaranteed sources!

- Primary population: Galactic compact binaries with $P_{orb} \lesssim 60$ mins
  Not all of them will be resolved.



- Rich physics constraints to
  Stellar & binary evolution theories

- Strong synergies with: -> See Thomas Kupfer's talk
  - Electromagnetic observatories
    to enhance measurement precision
  - Among GW detectors
    for multiband observations (primarily binary black holes)

Scientific return is immense

Unprecedented Survey of Galactic Stellar Content

- Nearly half of all stars in the Milky Way are in binaries. GWs offer a unique, independent messenger to explore the Milky Way's stellar content.

Direct Access to Electromagnetically Dark Companions

- GWs grant direct insight into binaries consisting of electromagnetically dark companions, such as white dwarfs, neutron stars, and black holes, which are often challenging to detect through traditional electromagnetic methods.

Enhancing Understanding of Binary Evolution

- Significantly advances in our knowledge of binary evolution are anticipated from GW astronomy, shedding light on critical processes such as mass transfer, loss of mass and angular momentum, and the outcomes of mergers.

A Guaranteed Multi-Messenger Link

- Inspiralling and merging Galactic compact binaries guarantee a multi-messenger connection from micro-Hz to deci-Hz frequencies, bridging the gap between mergers and their progenitors.