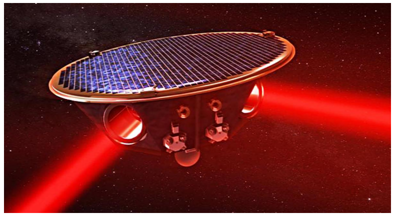
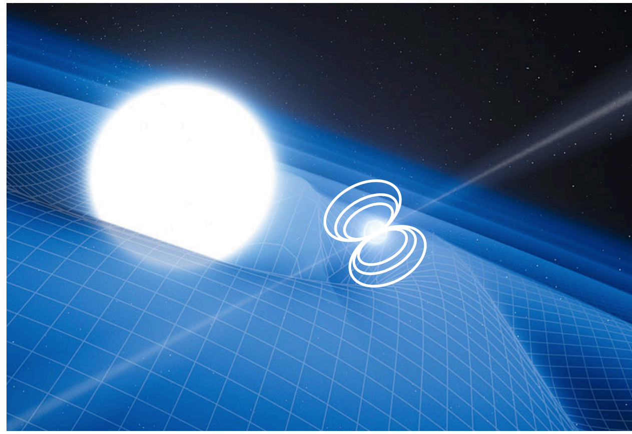
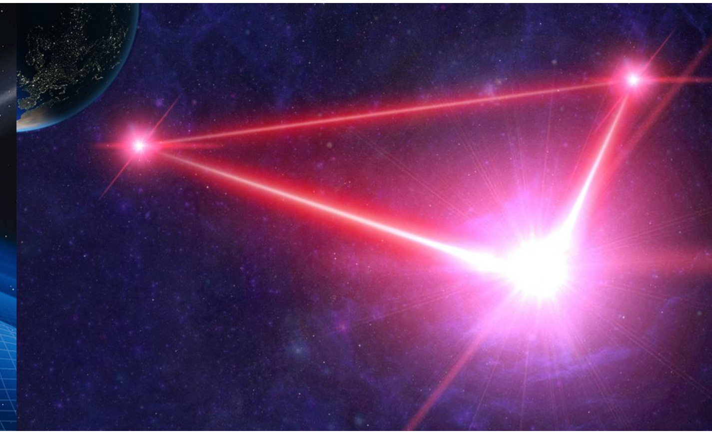
LISA CONSORTIUM







HIGHLIGHTS OF STELLAR BINARIES WITH LISA

by *Silvia Toonen*
toonen@uva.nl
University of Amsterdam

Highlights of stellar binaries with LISA

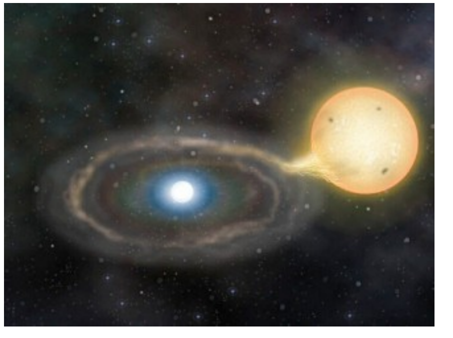
A key science objective and most abundant observable sources

The only guarantied LISA sources!

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

- Not comparable with 2G or even 3G ground-based detectors

- Rich physics constraints to
  Stellar & binary evolution theories

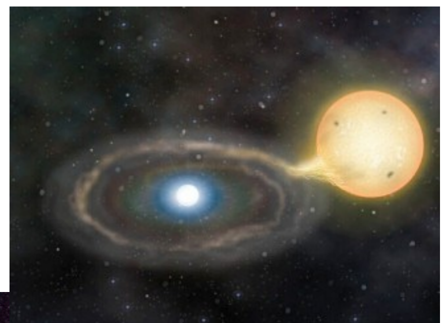


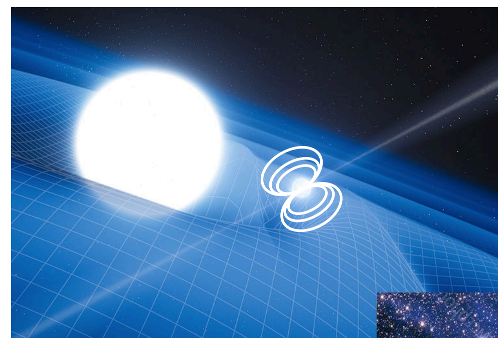
- Strong synergies with:
  - Electromagnetic observatories
    to enhance measurement precision
  - Ground-based GW detectors
    for multiband observations (primarily binary black holes)

Plan for this talk

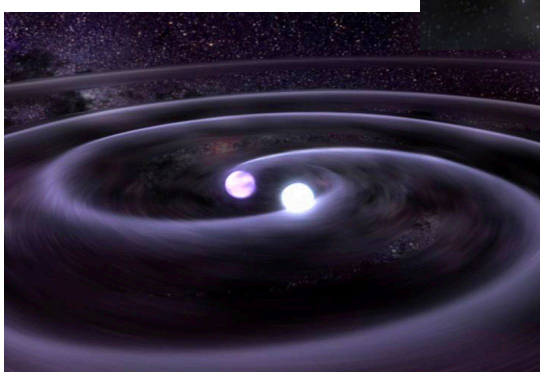
- Known (verification) binaries
- Anticipated sources
  - What are our expectations?
  - What can learn with LISA (objectives) ?

AM CVn

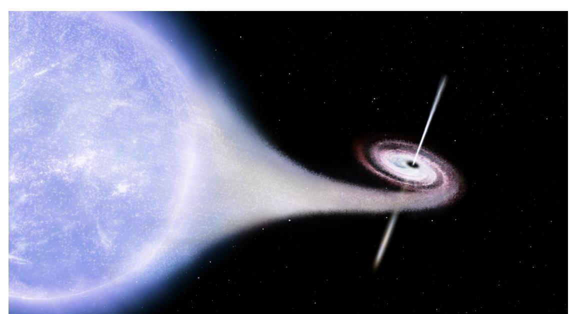




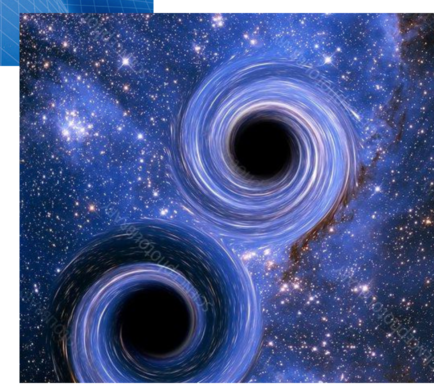
Pulsar binary



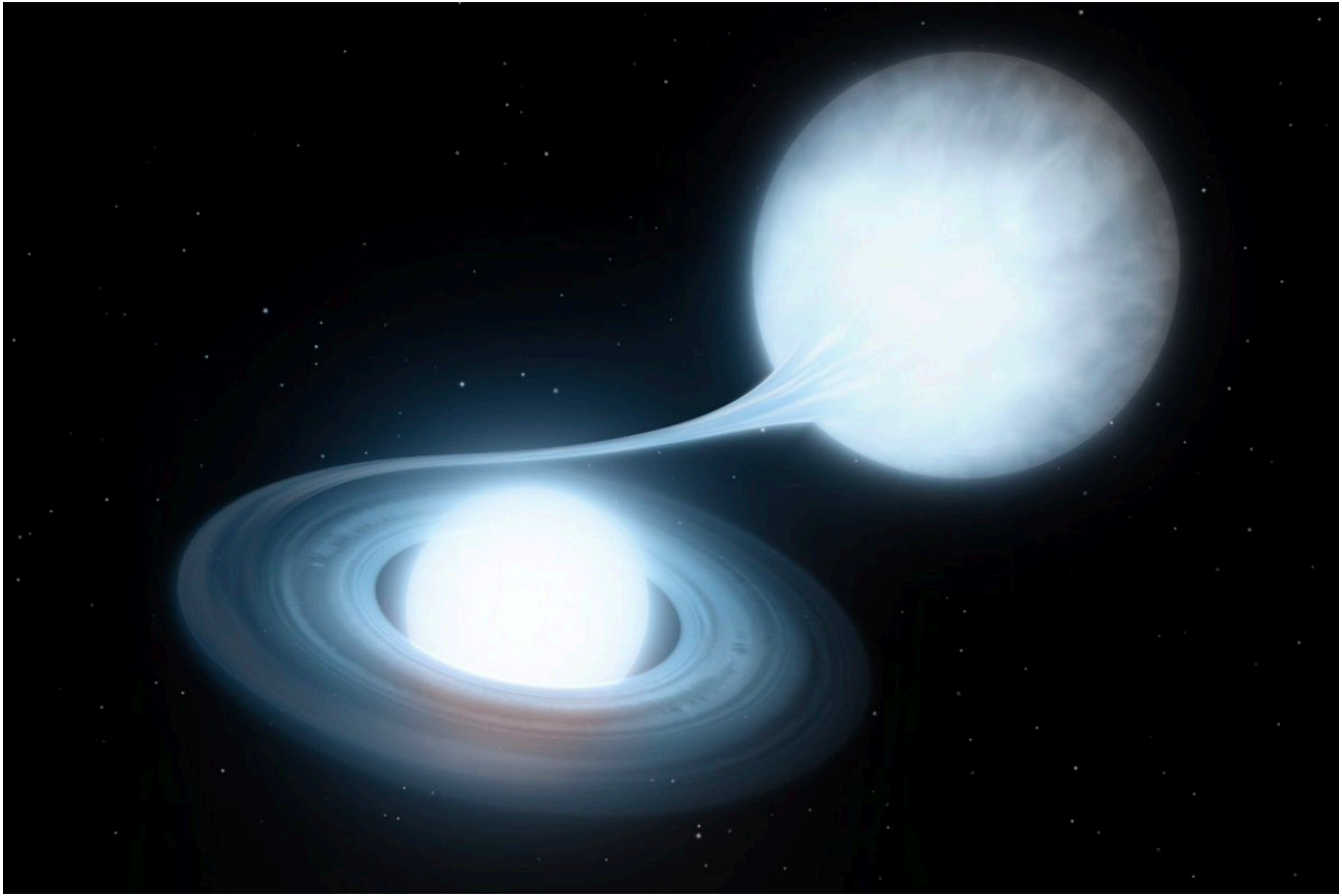
WD+WD



UCXB



BH+BH

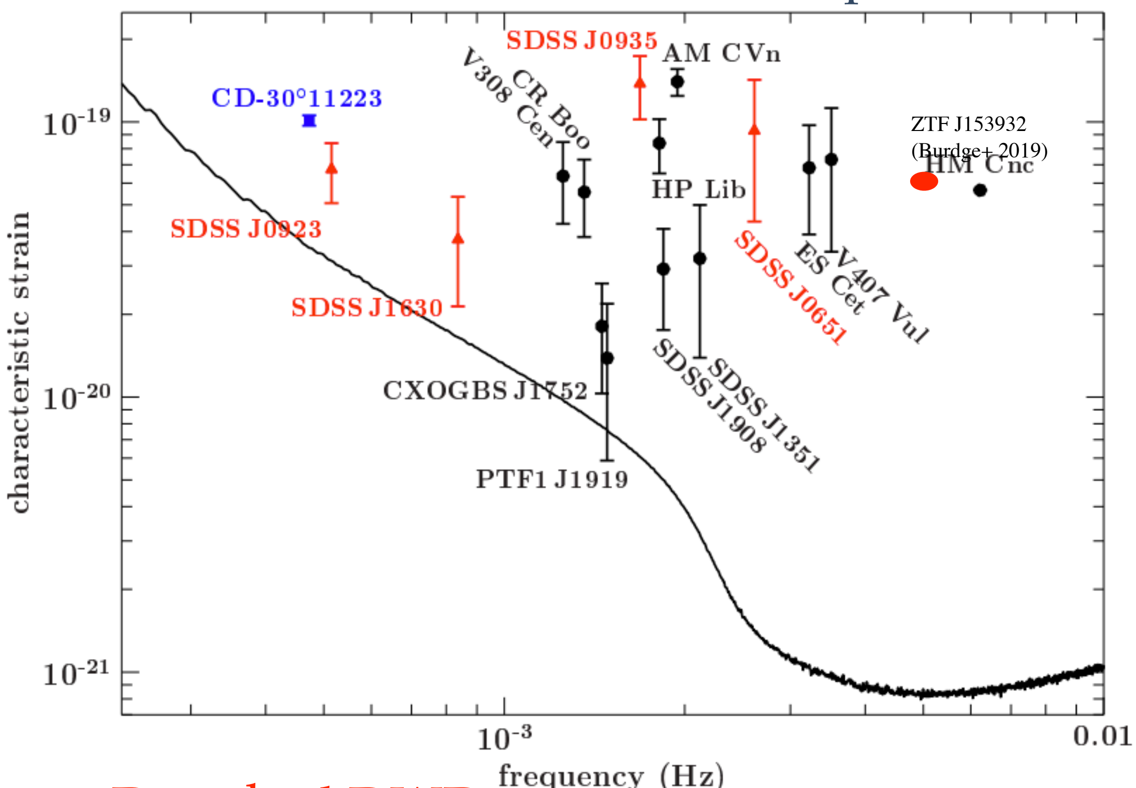


Verification binaries

Verification binaries

- ‘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)
- Bias to northern hemisphere and high Galactic latitude

Kupfer+ 15, 24



Detached DWDs

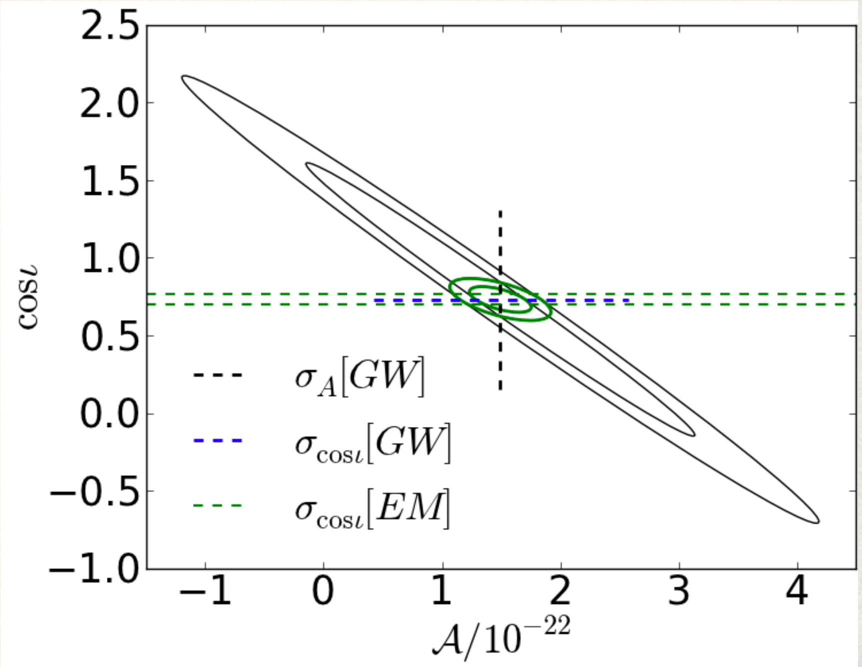
DWDs undergoing mass transfer (AM CVn)

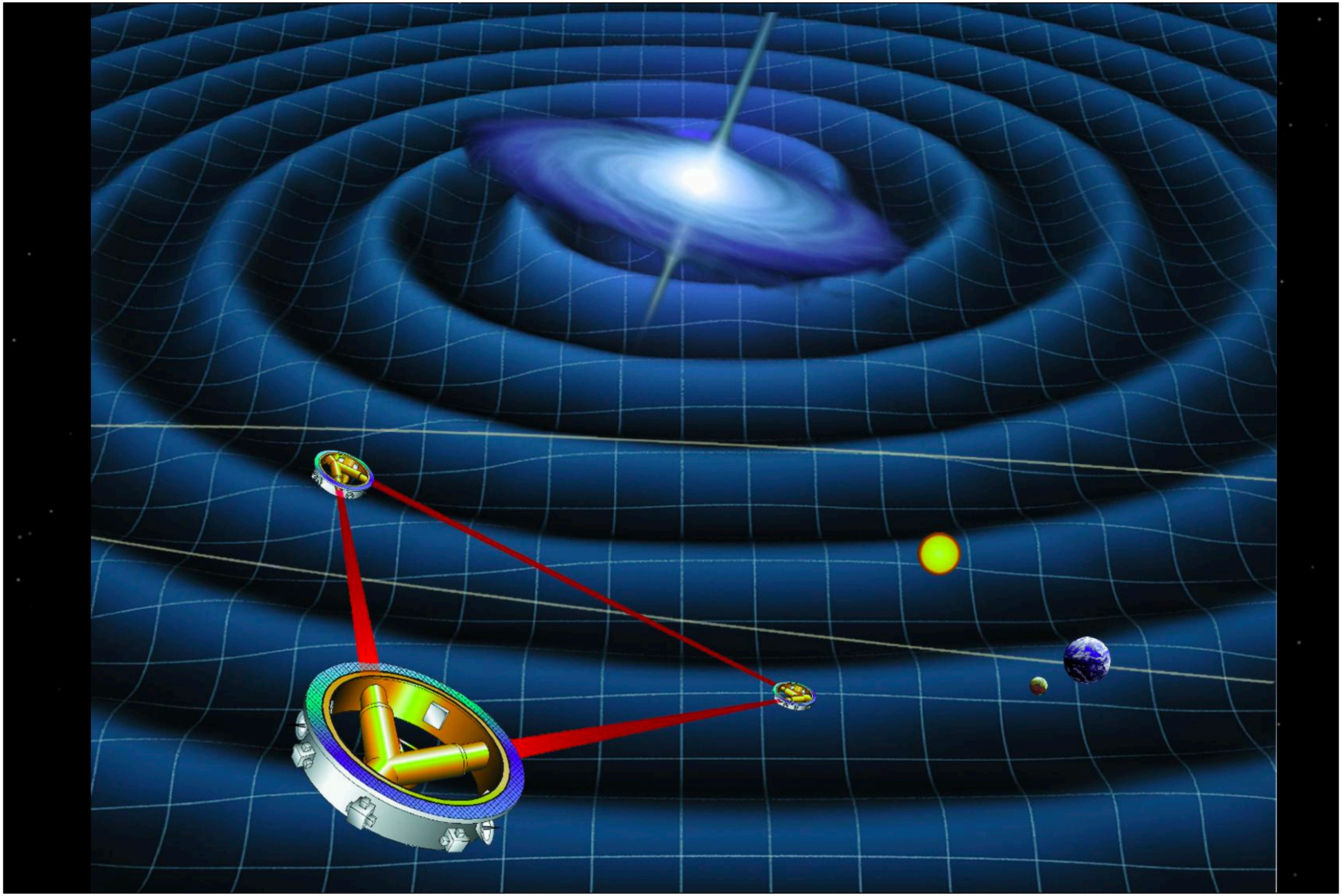
WD + stripped-envelope star

Multimessenger binaries

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

- A priori 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)

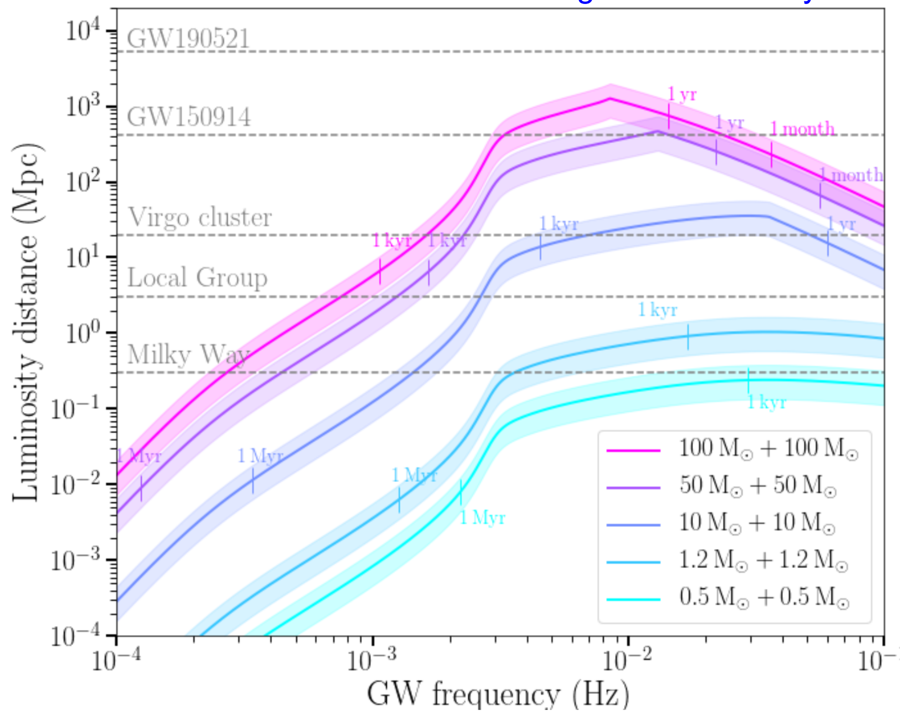




Anticipated LISA binaries

Anticipated Galactic LISA 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)

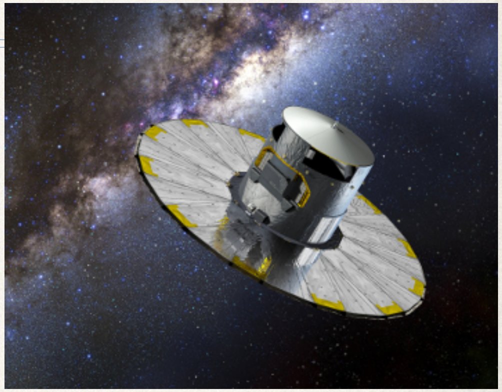
Expected number of sources

Many references! See LISA white book, section 1.4

	Population synthesis studies		Empirical rate estimates from observed populations	
Source	N	N^{detected}		
WD+WD	$\sim 10^8$	6,000–10,000 (- 30,000)	60000	(Korol w/Toonen+ '22)
NS+WD	$\sim 10^7$	100–300	100 – 150	(Tauris '18)
BH+WD	$\sim 10^6$	0–3	–	
NS+NS	$\sim 10^5$	2–100	50 – 300	(Andrews+ '20)
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 thousands of WD binaries
- A few hundred with NS / BH companions
- Lots of potential to combine data from different resources

Observations of double WD so far



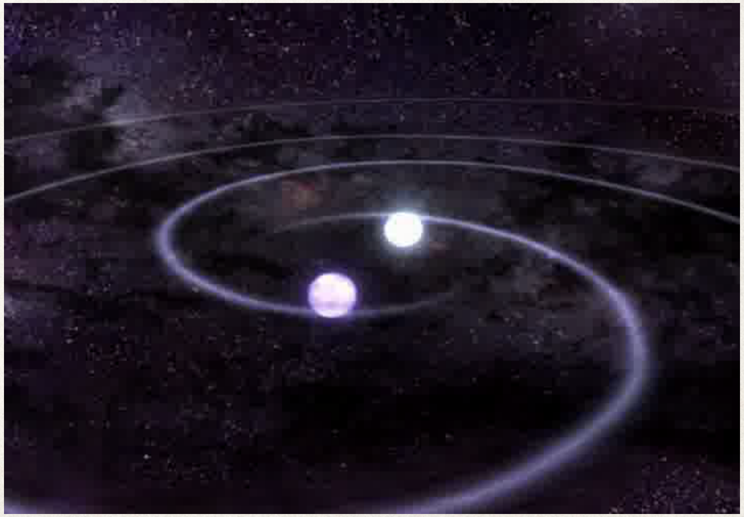
- ~10 yrs ago : ~50 double WDs known
  - detected with variety of methods
- Now: ~200 double WDs
  - SDSS ELM survey: Extremely-Low Mass WDs
  - ZTF: ~30 eclipsing double WDs (also mostly low mass)
- Next few years:
  - Gaia satellite: ~200 eclipsing DWDs (mid 2026), thousands non-eclipsing need EM followup (WEAVE, 4most)
  - Vera Rubin Observatory: ~1000 eclipsing DWDs

Korol+ 17

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!



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- Several thousand WD binaries
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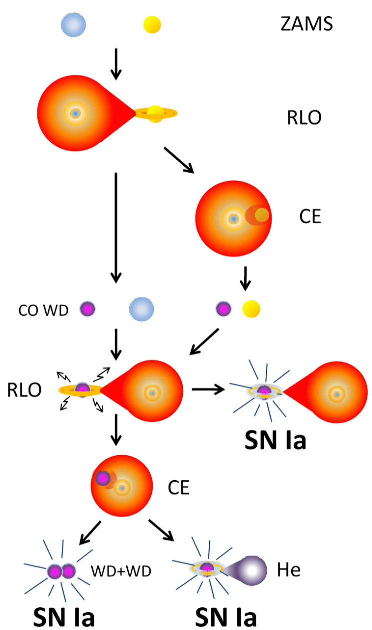
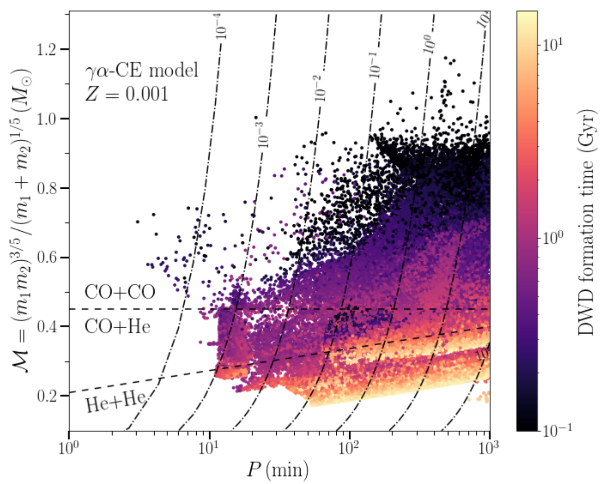
Assembling a mock population with Binary Population Synthesis

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

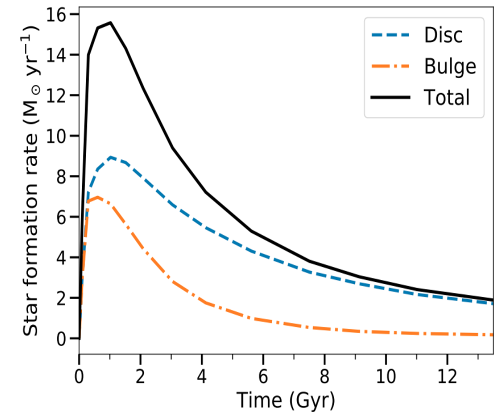


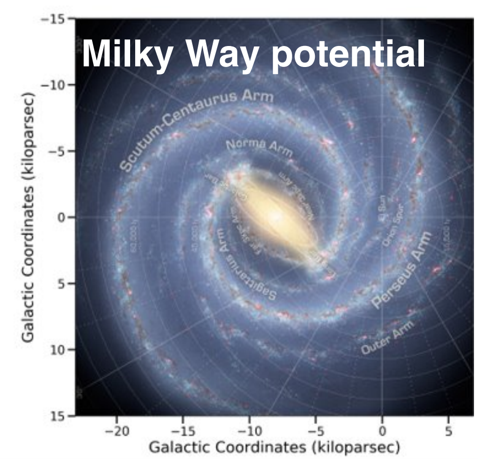


Toonen et al. 2012, 2017, 2018, based on the SeBa code See also: Nelemans et al. (2001), Ruiter et al. (2010), Yu & Jaffery (2010), Lamberts et al. (2018), Breivik et al. (2020), Li et al. (2020) and others

+

Star formation history





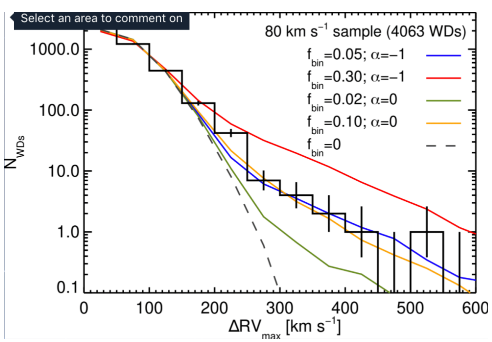
Expected number of sources

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})

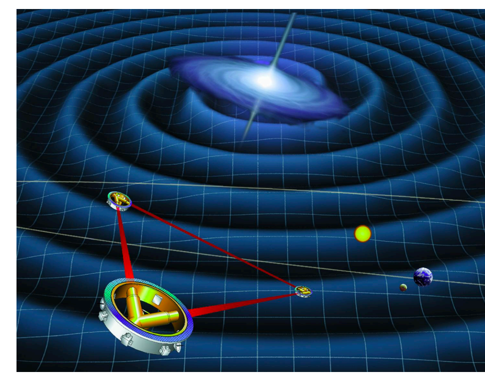
➡ Observations suggest larger DWD space density (Toonen+ '18)

➡ 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

Many references! See LISA white book, section 1.4

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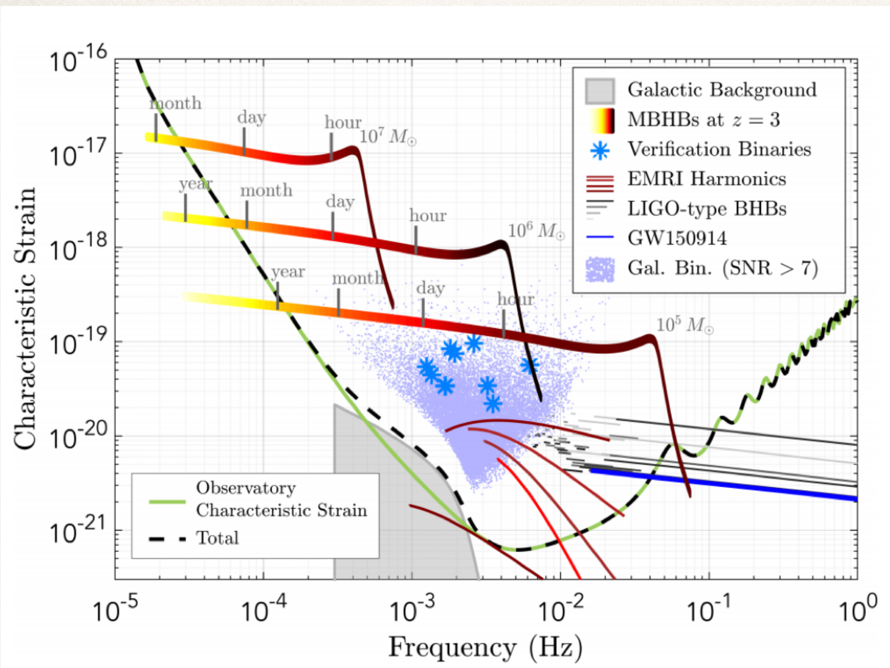
	Total # in the Galaxy	Total # expected by LISA	Total # expected by LISA	

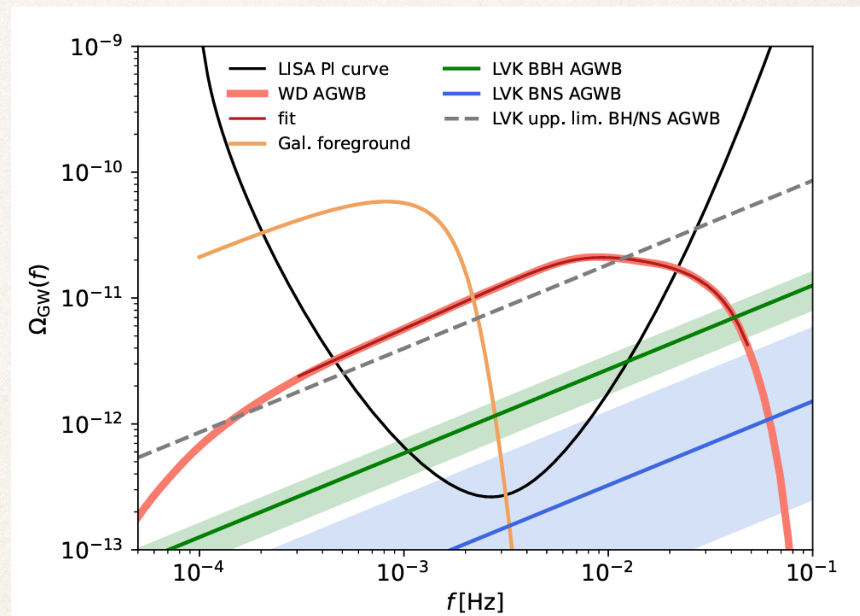
- EM DWD observations help to constrain both methods
- Currently most systems at orbits outside the LISA frequency range

Unresolved sources

Galactic sources



Extra-galactic sources



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

- Farmer & Phinney 03, Schneider 01, Staelens & Nelemans 24

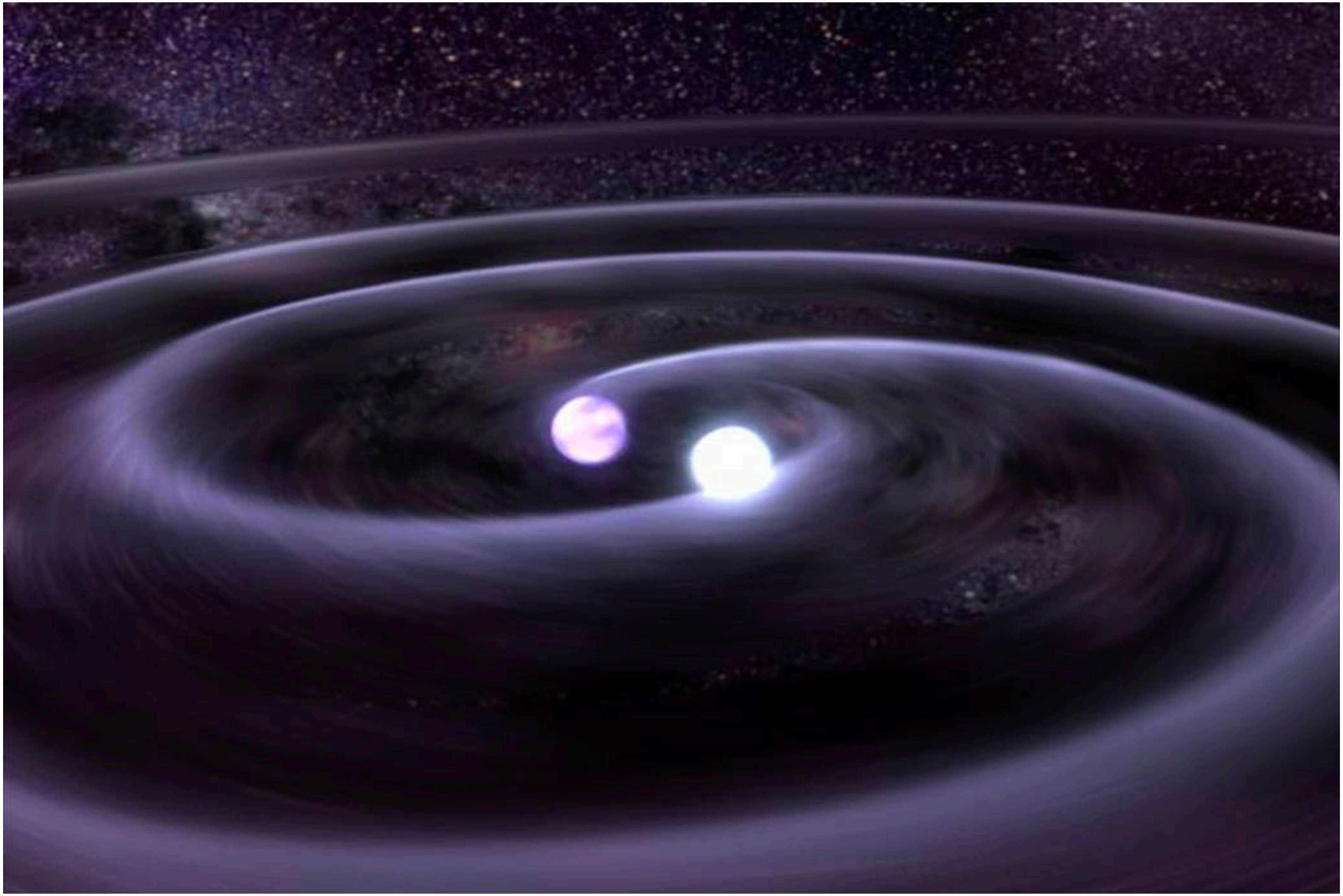
LISA sources as Galactic probes

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

Tracer of Galactic structure, and even the Local Group (Korol +18, Wilhelm+ 2, Keim+ 23, van Zeist+ 24)

- 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)

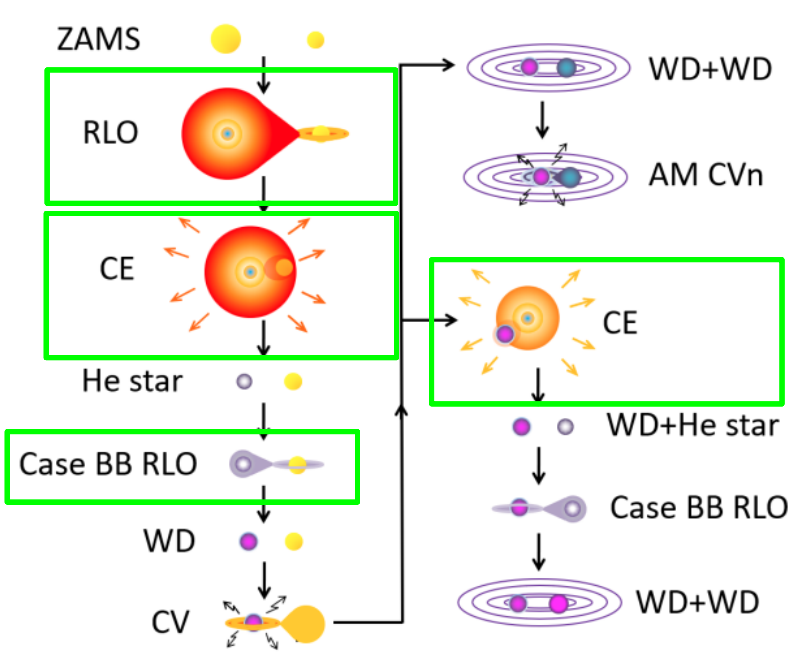
- Universal IMF? (Rebassa-Mansergas ’19, Korol+ ’20)
- (Local) star formation histories (Yu+ ‘10, Lamberts+ ‘ 19, Korol+ ’20)
- (Satellite) Masses (Korol+ ’21) from # of WD+WD
- Galactic mass from rotation curve with EM proper motion (Korol+ ’17, Breivik+ ’18, Korol+ ’19)



What to learn from double white dwarfs?

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).



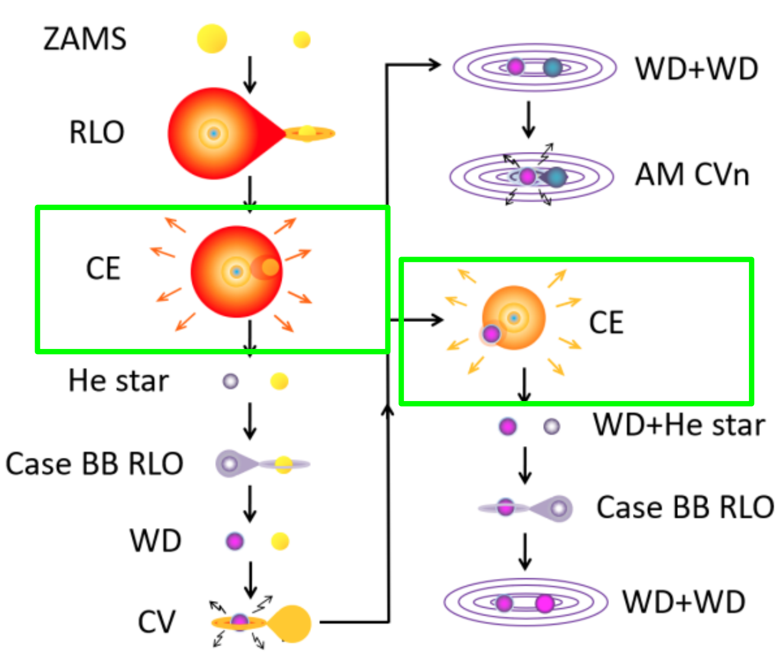
Tauris and van den Heuvel (2022), Amaro-Seoane et al. (2023)

- Demographics of LISA sources sculpted by multiple phases of mass transfer
  - Recent work favours stable mass transfer (RLO) (Nelemans+ 01, Woods+ 12, Passy+ 12, Ge+ 15, Temmink+ 23, Li+ 23)
- Bright explosive end points
  - Discover origin of transients

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



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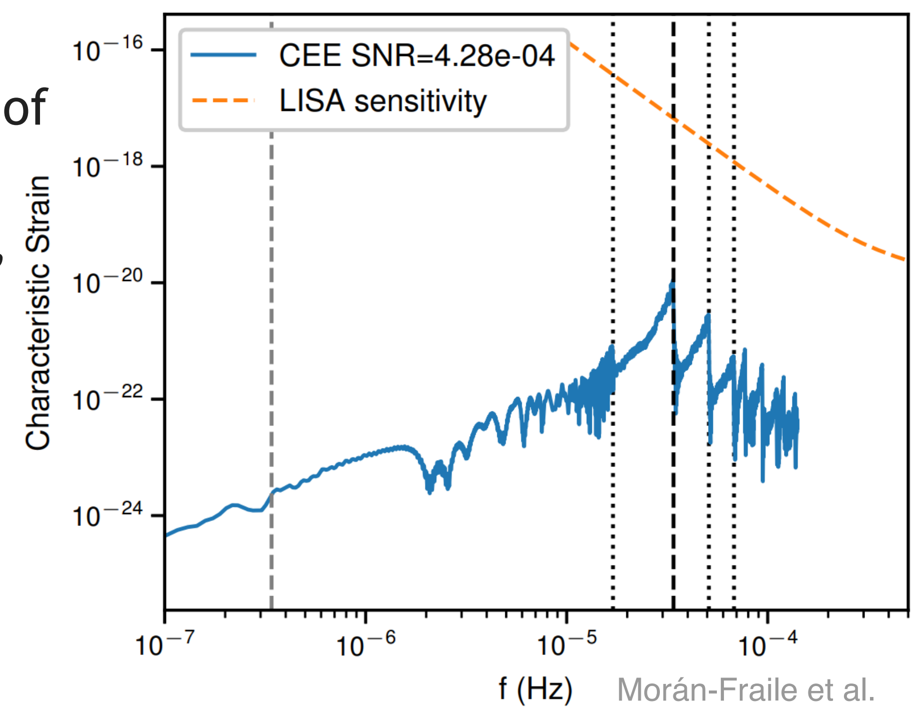
Evolution in characteristic strain-frequency parameter space

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

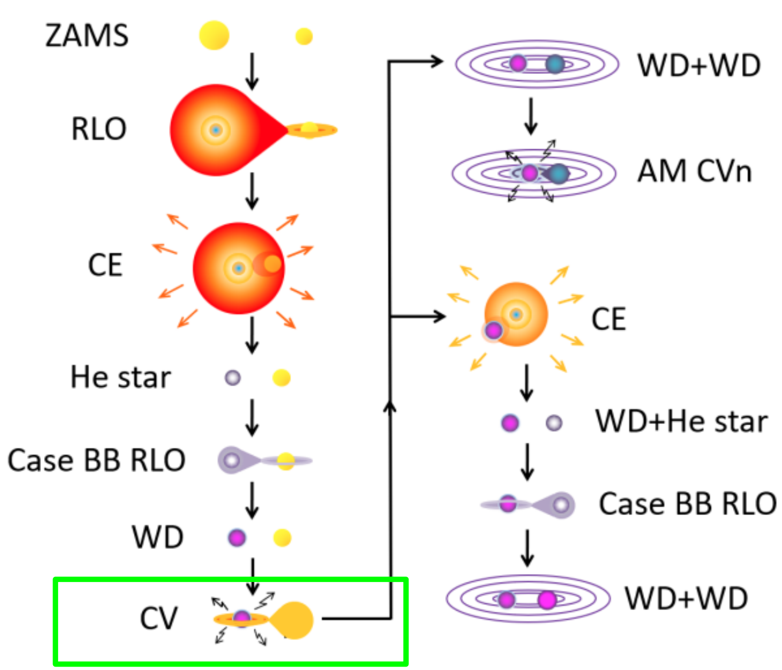
  - Typically: compact object spiralling in deeply in envelope of giant with compact core
  - Unlikely to see initial plunge-in, at most 1 per few centuries (Ohlmann+ '16, Ginat+ '20)
  - Better chances for the slow thermal phase: ~0.1-100 in MW during LISA mission (Renzo+ '21)

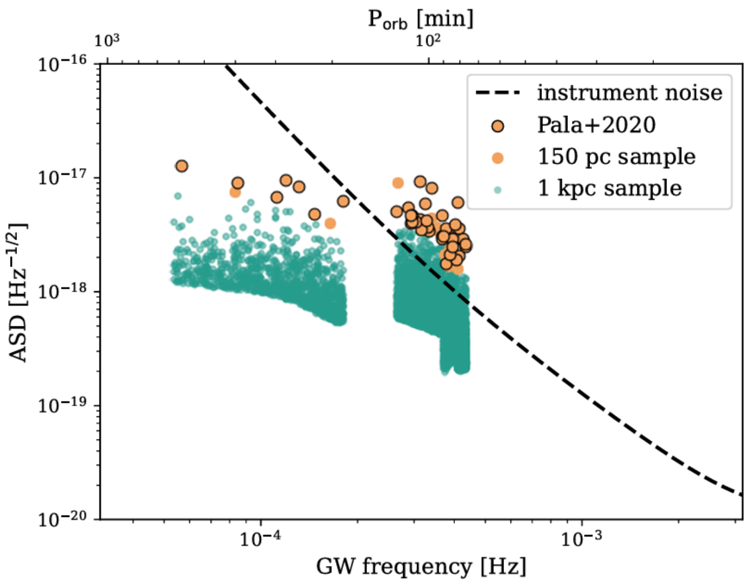


Morán-Fraile et al. (2023)

Evolution in characteristic strain-frequency parameter space

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.

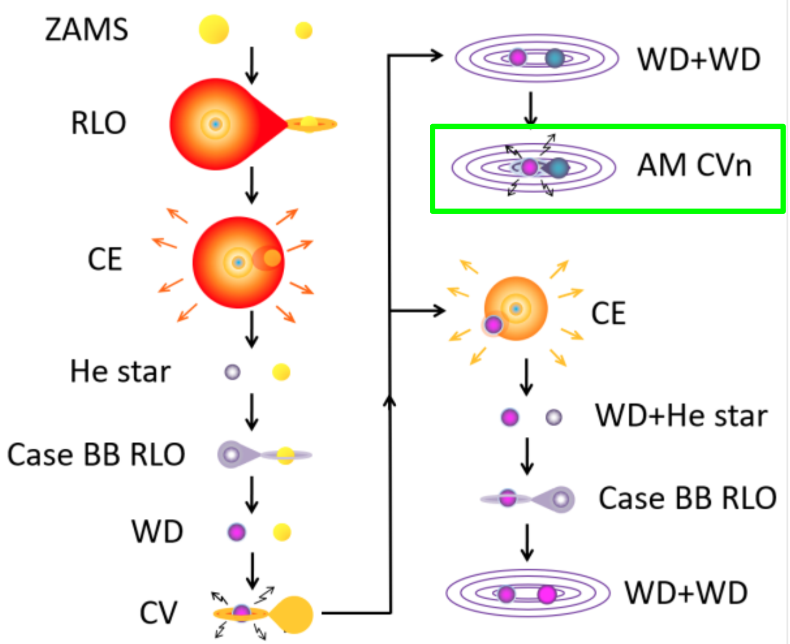


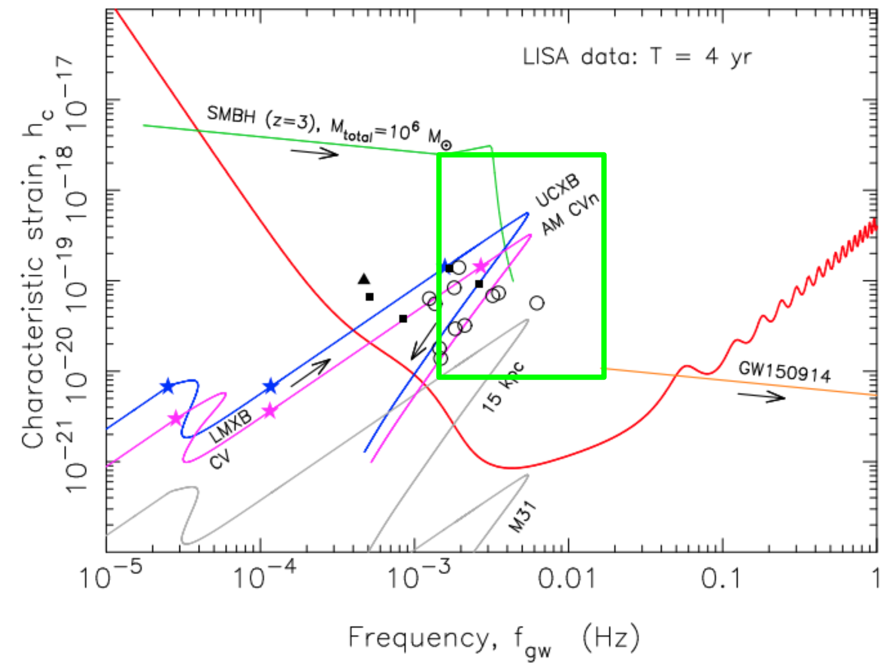


Tauris and van den Heuvel (2022), Amaro-Seoane et al. (2023)

Evolution in characteristic strain-frequency parameter space

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.

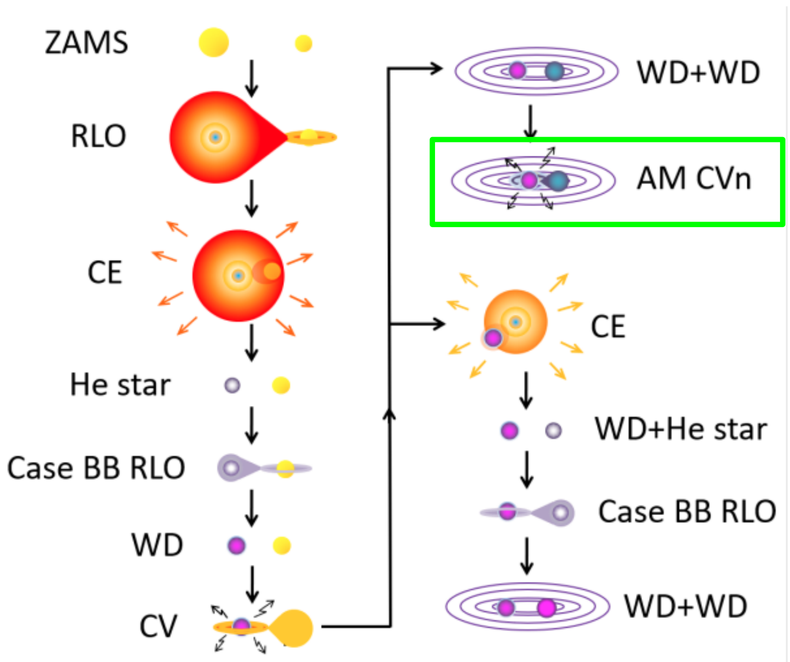




Tauris and van den Heuvel (2022), Amaro-Seoane et al. (2023)

Evolution in characteristic strain-frequency parameter space

- 'Failed AM CVns' would lead to a WD+WD merger likely accompanied by an EM transients. Massive WD mergers are expected to lead to SNIa.
- Indirect GW constraints on Galactic merger rates: ~500 compact superchandrasekhar DWDs (Ruiter+ '10, Rebassa-Mansergas+ '19)



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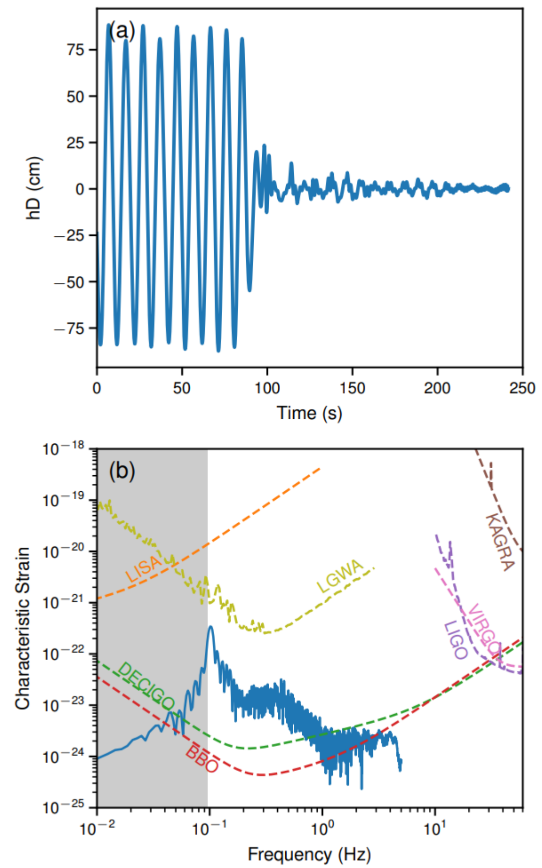

An example of a NS + WD merger from Morán-Fraile et al. (2023)

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.