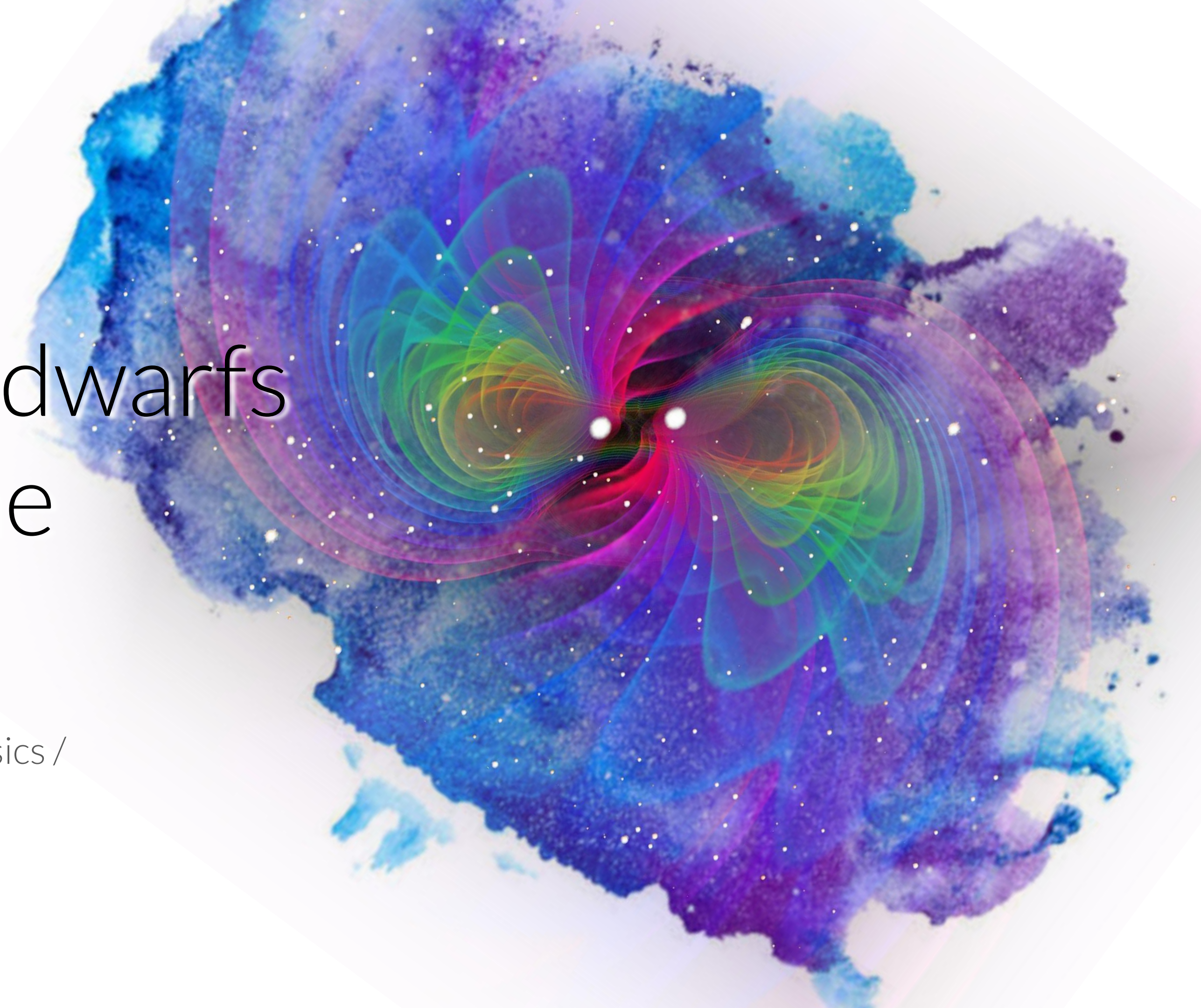
22nd August 2022
TianQin Astronomy Workshop

Binary white dwarfs in mHz regime



Valeriya Korol

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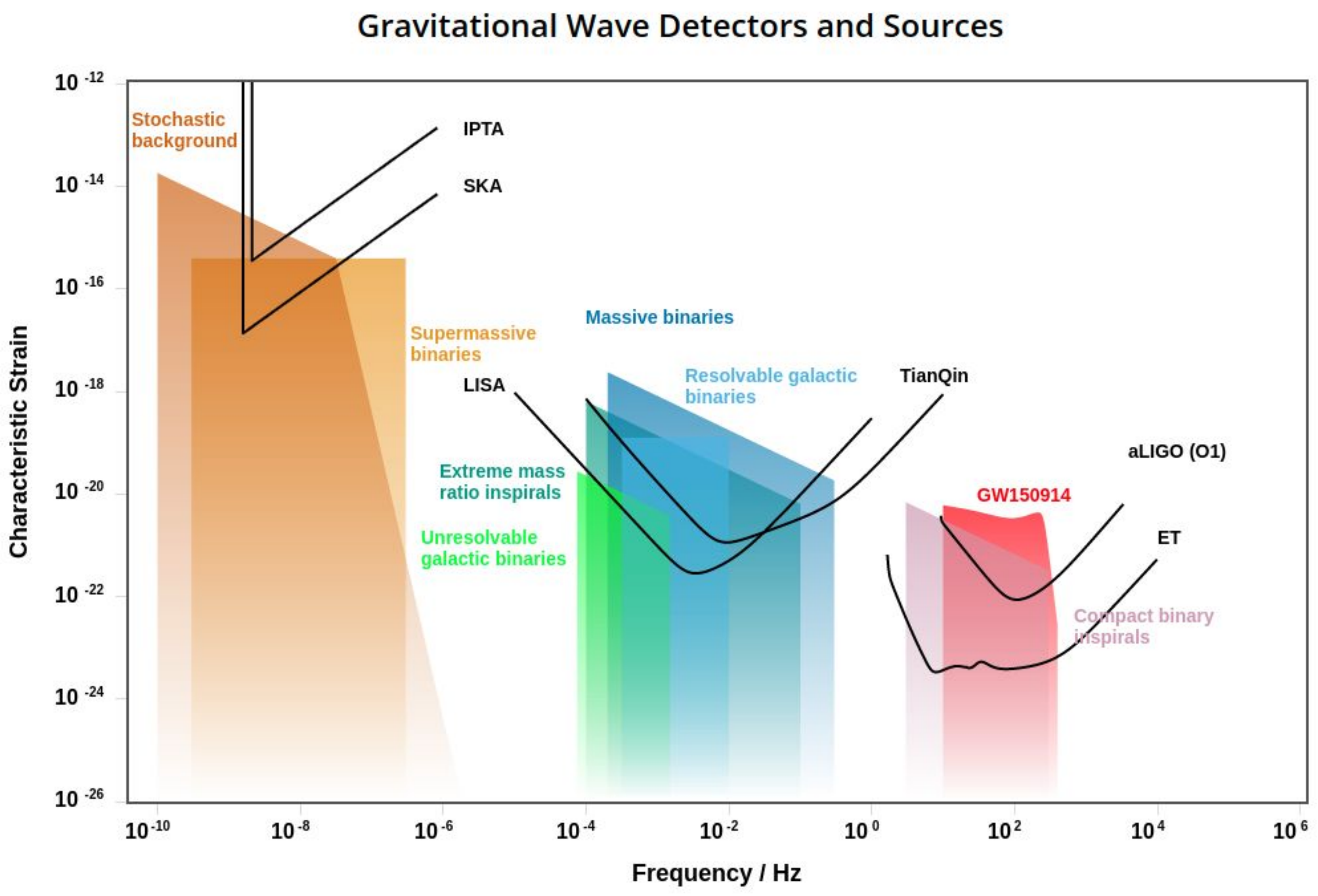
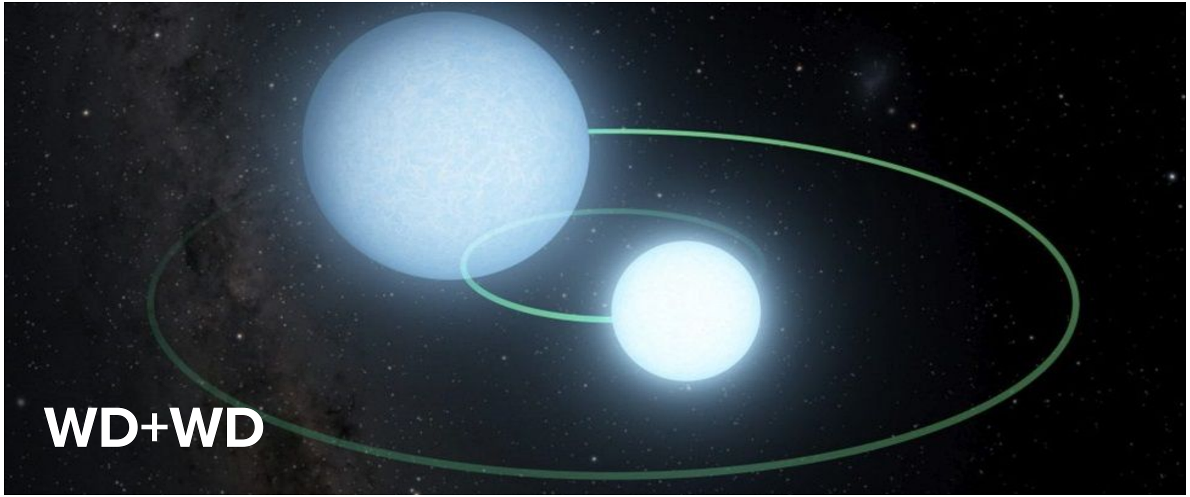
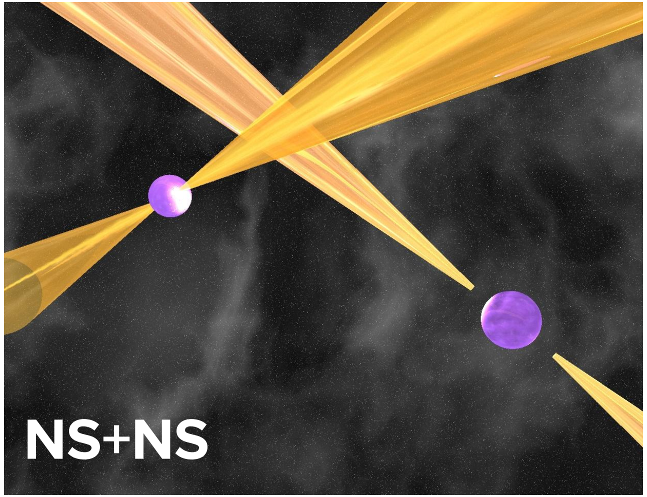
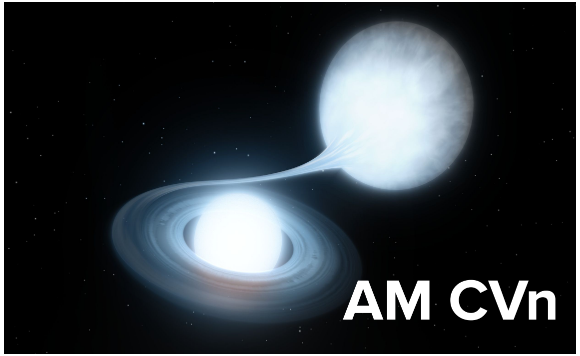


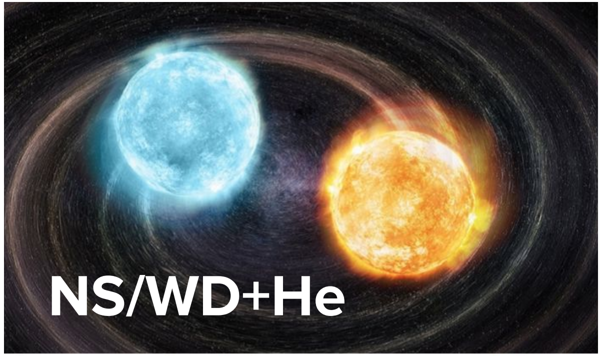
http://gwplotter.com/

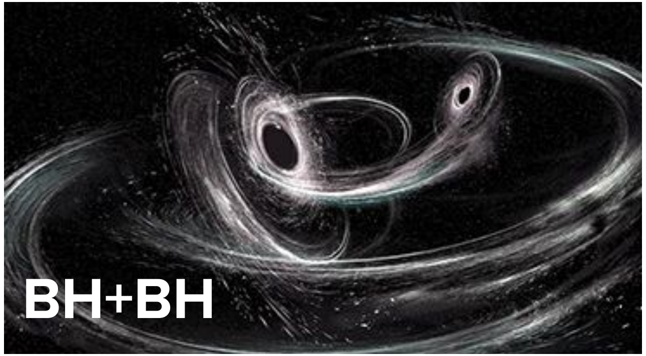
Zoo of Galactic GW sources







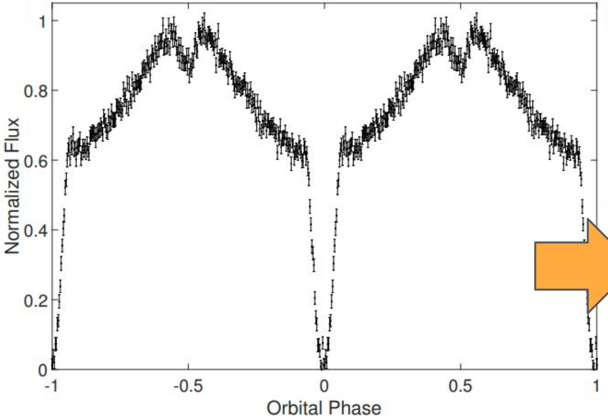


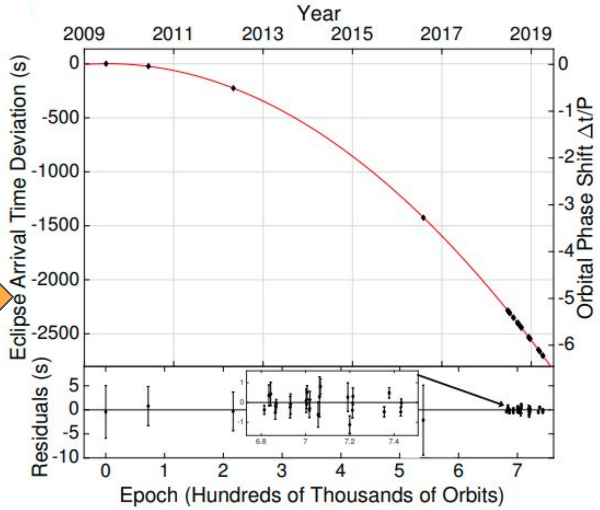


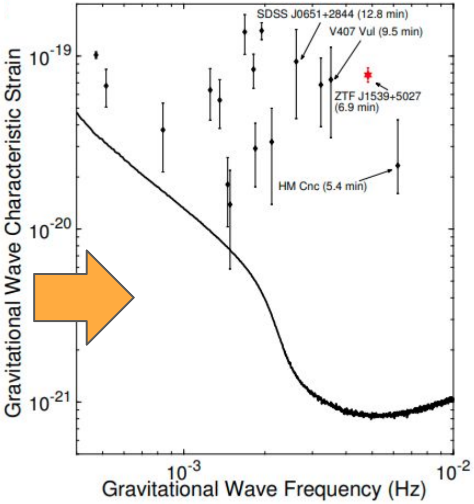
Galactic binaries are #1 science objective for space-based GW observatories

A few reasons why

- Guaranteed mHz GW sources

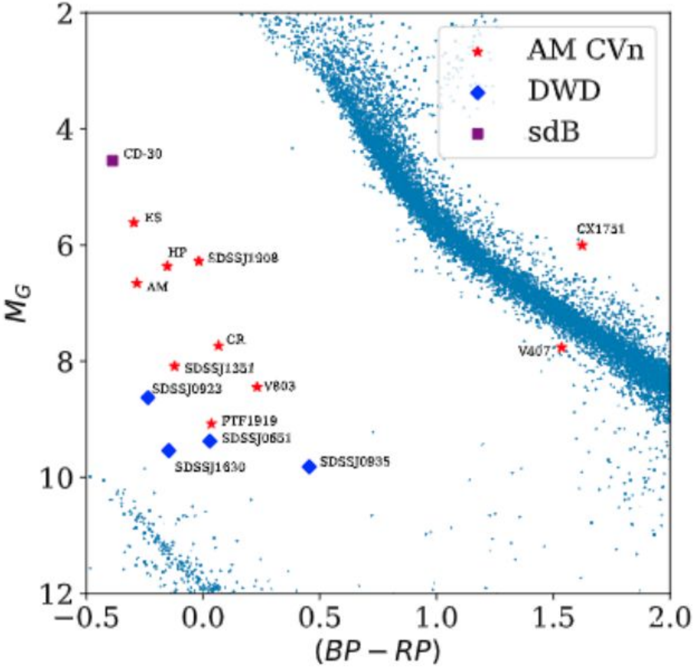


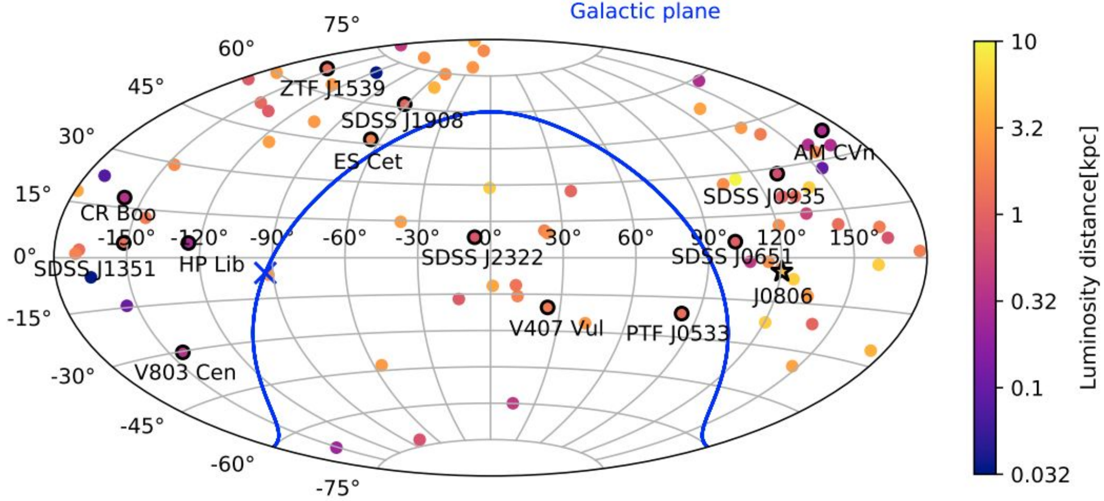




Burdge et al. 2019

About 30 of known binaries can be detectable by TianQin





Courtesy of Thomas Kupfer

Huang, Hu, Korol et al. (2020), arXiv:2005.07889

A few reasons why

- Guaranteed mHz GW sources
- Can be used as verification sources

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- The most numerous amongst mHz GW sources

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- Guaranteed mHz GW sources
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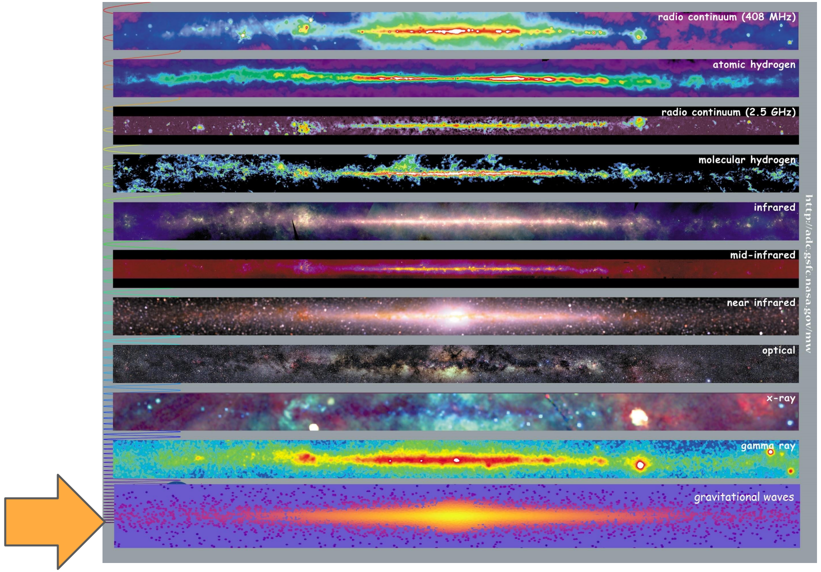
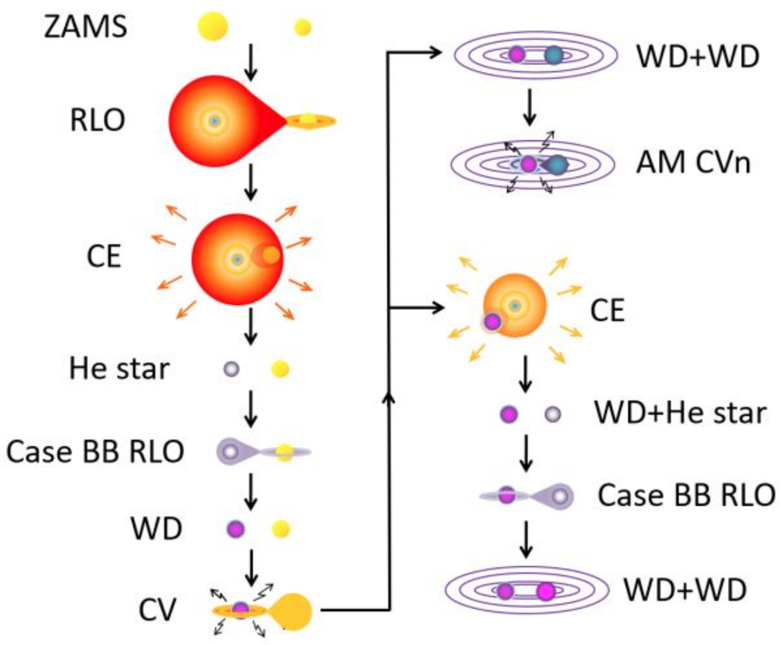
- The most numerous amongst mHz GW sources
- Will effectively make space-based GW observatories all-sky Galactic surveys for compact objects with capabilities complementary to electromagnetic space- and ground-based observatories



How do these binaries form?

A typical formation scenario for a WD+WD

M1, M2 < 8-10 Msun

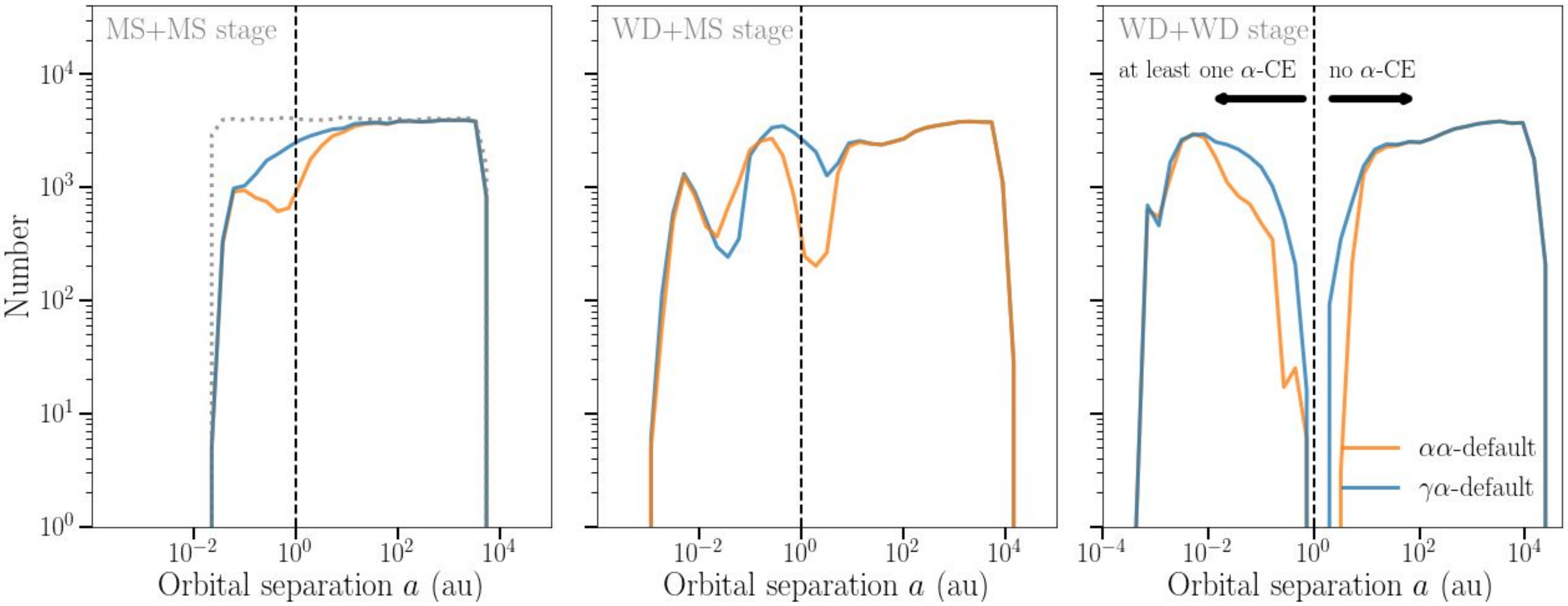


Major uncertainties

- Mass transfer stability
- Accretion efficiency
- Common envelope

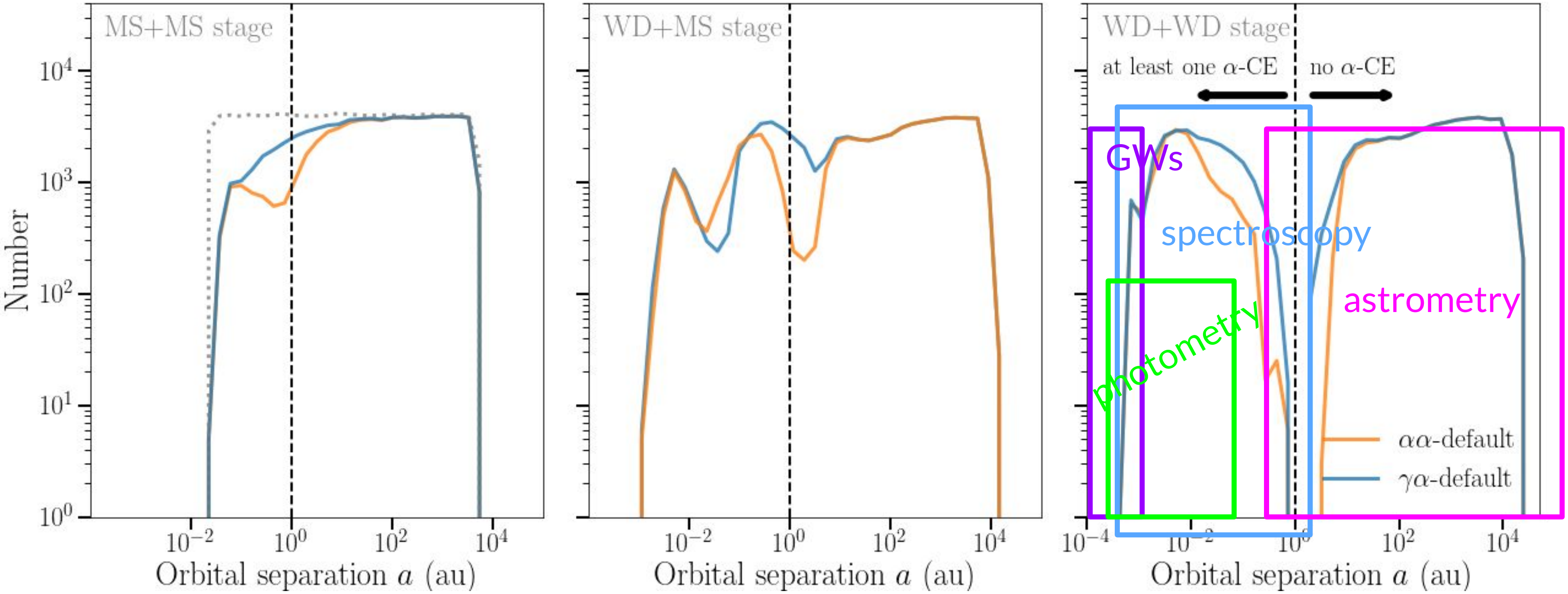
Tauris and van den Heuvel (2022), Amaro-Seoane et al. (2022)

Space-based observatories will provide a large homogeneous sample of WD+WD at shortest orbital periods



Korol, Belokurov, Toonen 2022, [arXiv:2203.03659](https://arxiv.org/abs/2203.03659)

Space-based observatories will provide a large homogeneous sample of WD+WD at shortest orbital periods



Korol, Belokurov, Toonen 2022, arXiv:2203.03659

Major objectives for GW observatories

- Retrieve progenitor evolution and formation pathways
- Reveil the demographics of WD+WD binaries at shortest orbital periods
- Direct measurement of Galactic merger rates and masses of merging WD+WD

  (links to EM transient astronomy)
- Discovering the population of super-chandrasekhar WD+WD

  (potential supernova type Ia progenitors and important cosmological probes)

How many WD+WD space-based GW observatories will detect?

How many DWDs will LISA detect?

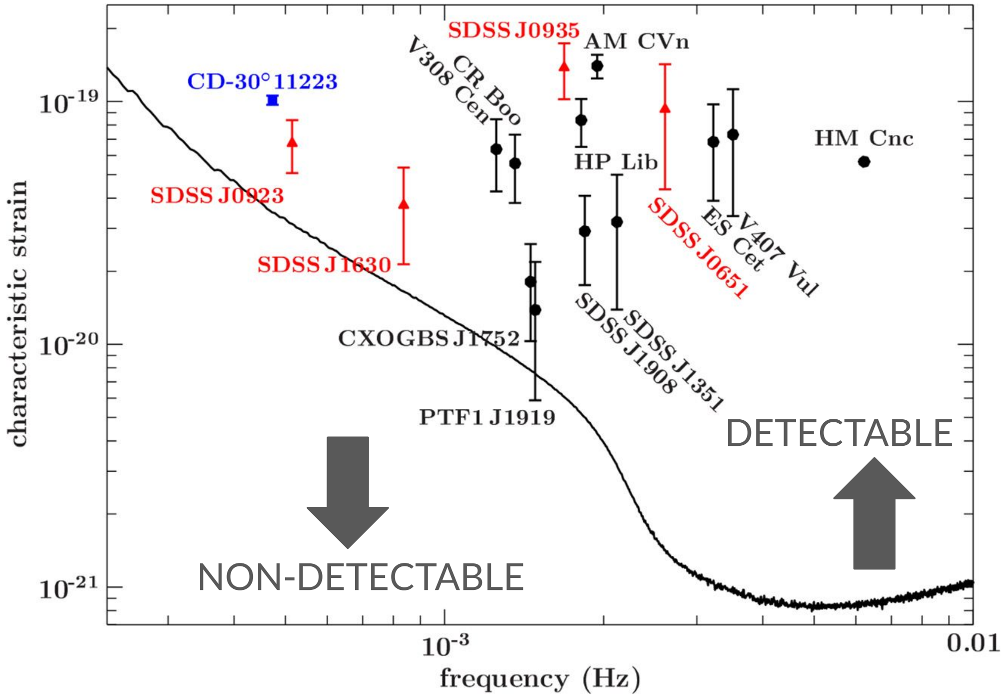
The detectability of Galactic stellar binaries with LISA primarily depends on the parameters involved in the GW amplitude

$$\mathcal{A} = \frac{2(G\mathcal{M})^{5/3}(\pi f)^{2/3}}{c^4 d}$$

- GW frequency $f = \frac{2}{P}$
- Chirp mass $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$

that defines binary's frequency evolution

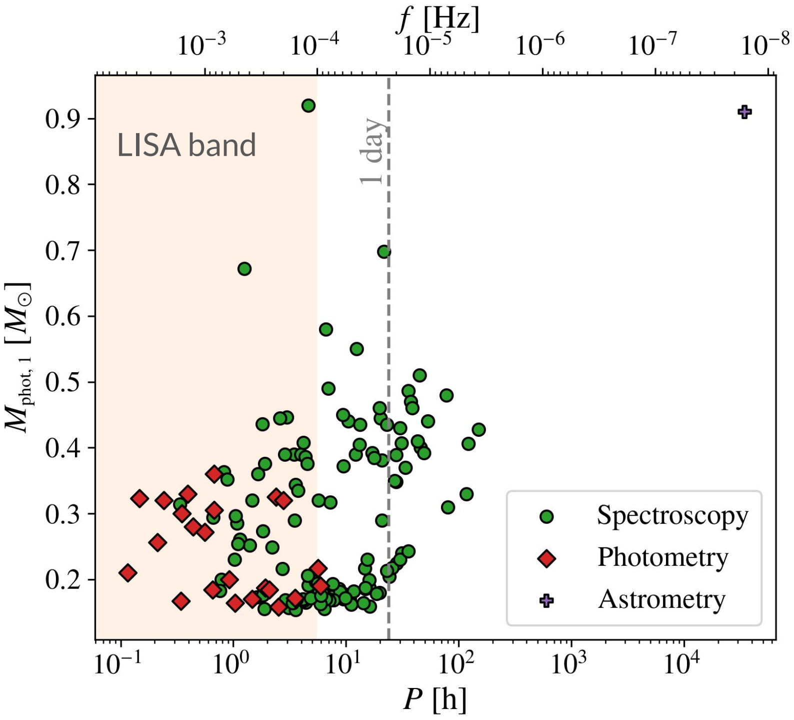
$$\dot{f} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}$$

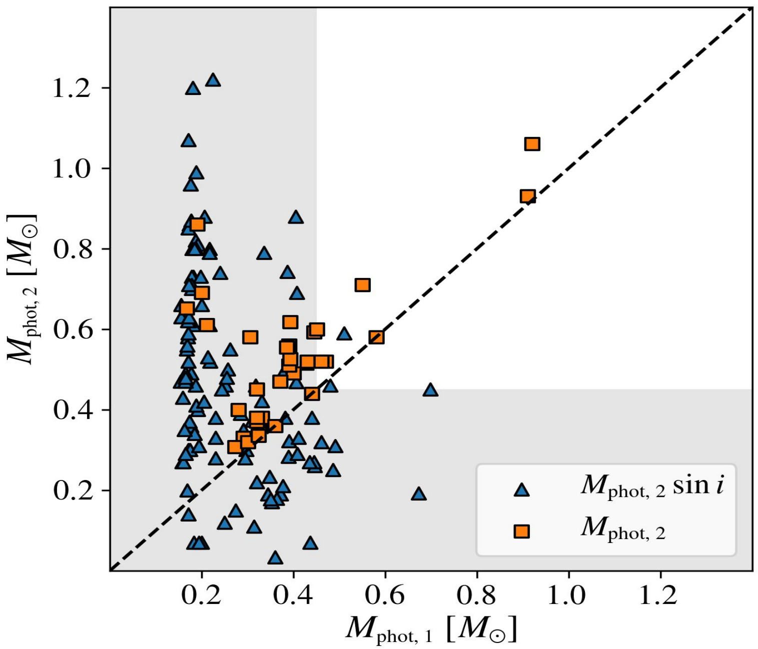


Kupfer, Korol et al. (2018), arXiv:1805.00482
See also Huang, Hu, Korol et al. (2020), arXiv:2005.07889

How many DWDs will LISA detect?

To date we know of ~150 detached DWDs. Our current knowledge the population characteristics such the incidence of DWDs per single WD, their orbital period and component mass distributions is incomplete and biased.

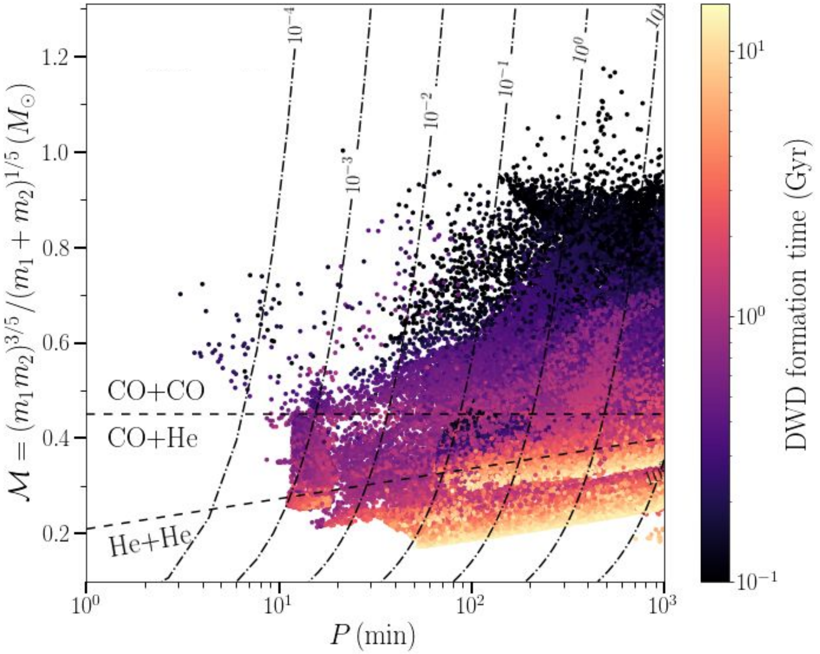




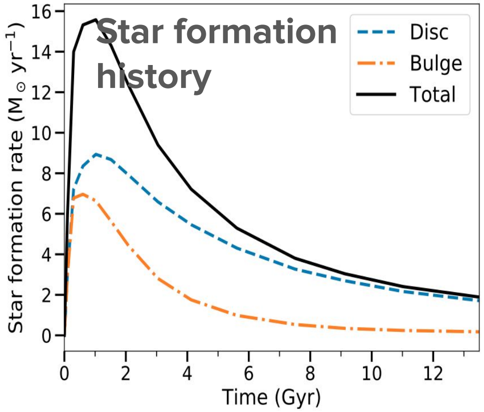
Korol, Hallkoun et al. (2022)

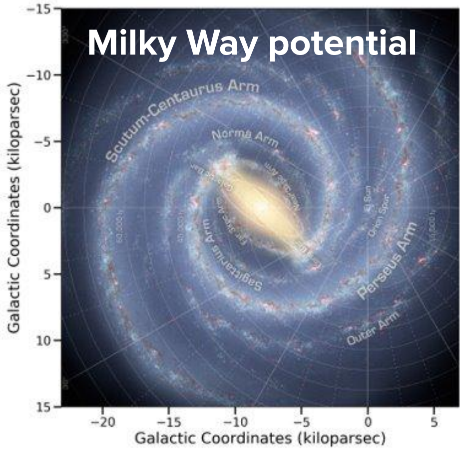
How many DWDs will LISA detect?

When forecasting LISA observations, we mainly rely on the binary population synthesis (BPS) technique.



Toonen et al. 2012, based on SeBa BPS 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





How many DWDs will LISA detect?

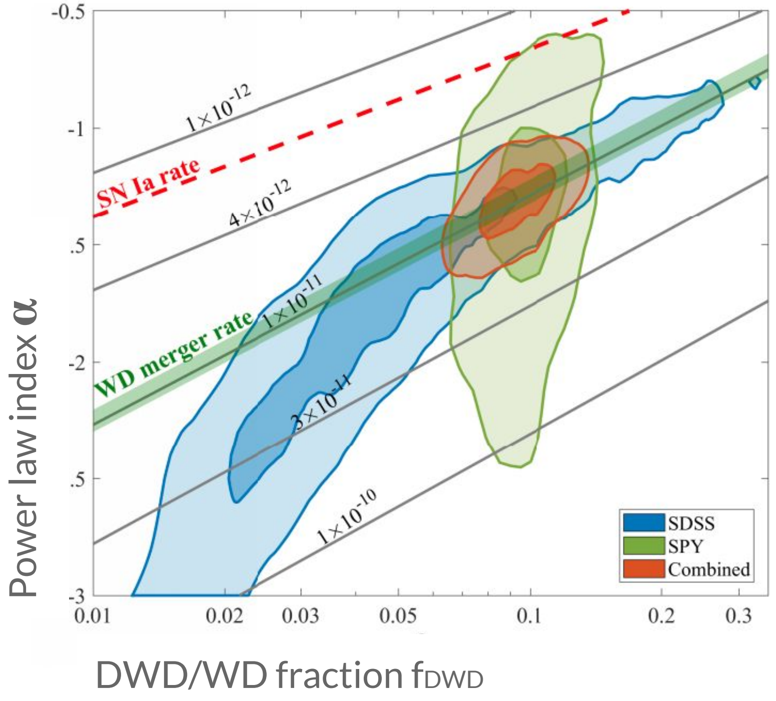
Alternatively, we can construct a representative DWD population based on constraints on the separation distribution and binary fraction of DWDs in SDSS and SPY spectroscopic samples (Maoz, Hallkoun et al. 2018)

Model assumptions:

- The primary WD mass follows the same distribution as dingle WDs
- Mass ratio follows a flat distribution
- The distribution of DWD separations at formation follows a power-law with index α
- Constant star formation over the last 10 Gyr

Fit to SDSS+SPY sample:

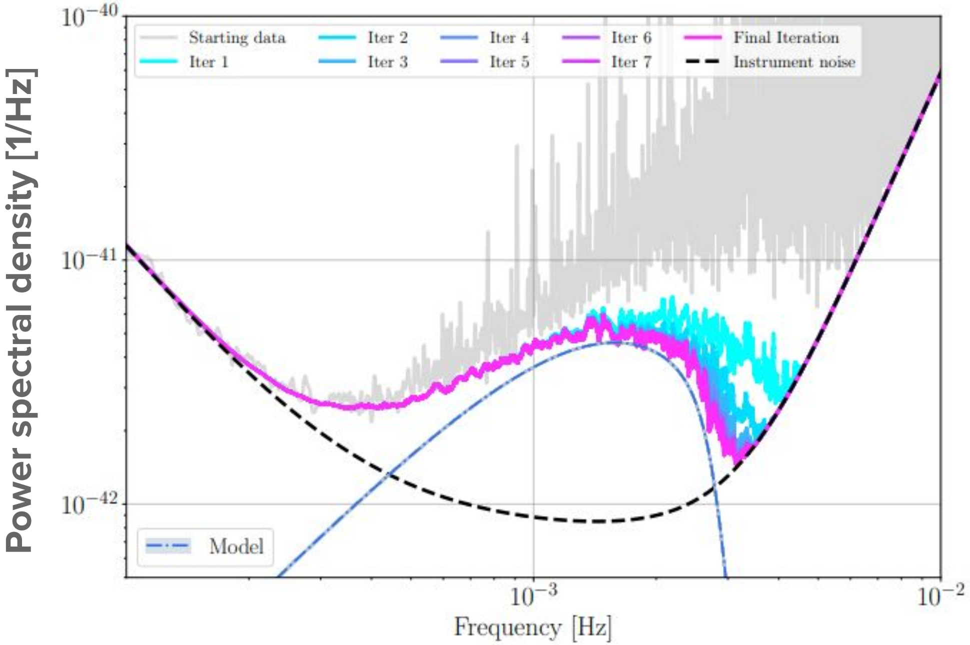
- Power-law index α= -1.3
- DWD fraction = 9.5 % for separations of < 4 au



Maoz, Hallkoun et al. (2018)

Data analysis will be one of the biggest challenges for LISA

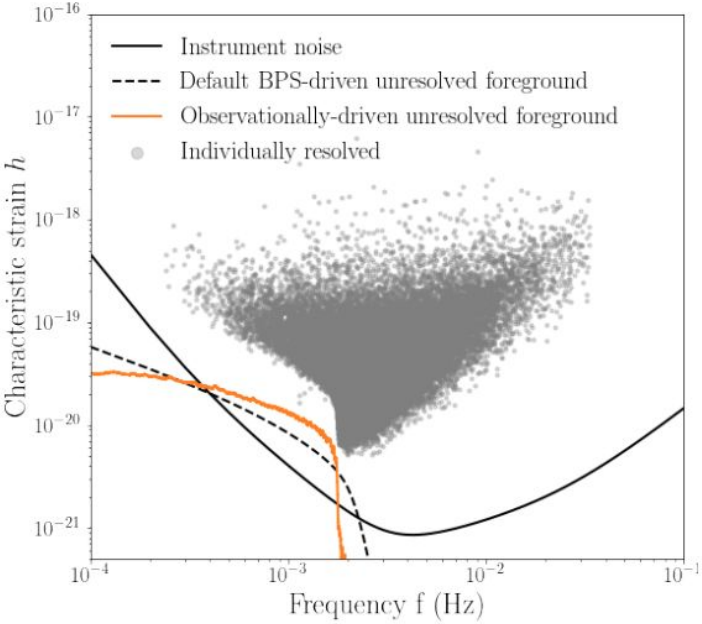
As the result of either BPS- or observation-driven models we have ~10 million DWDs emitting in the LISA frequency band. This represents a significant challenge from the data analysis point of view because all signal will be simultaneously present in the data overlapping with each other and other LISA sources

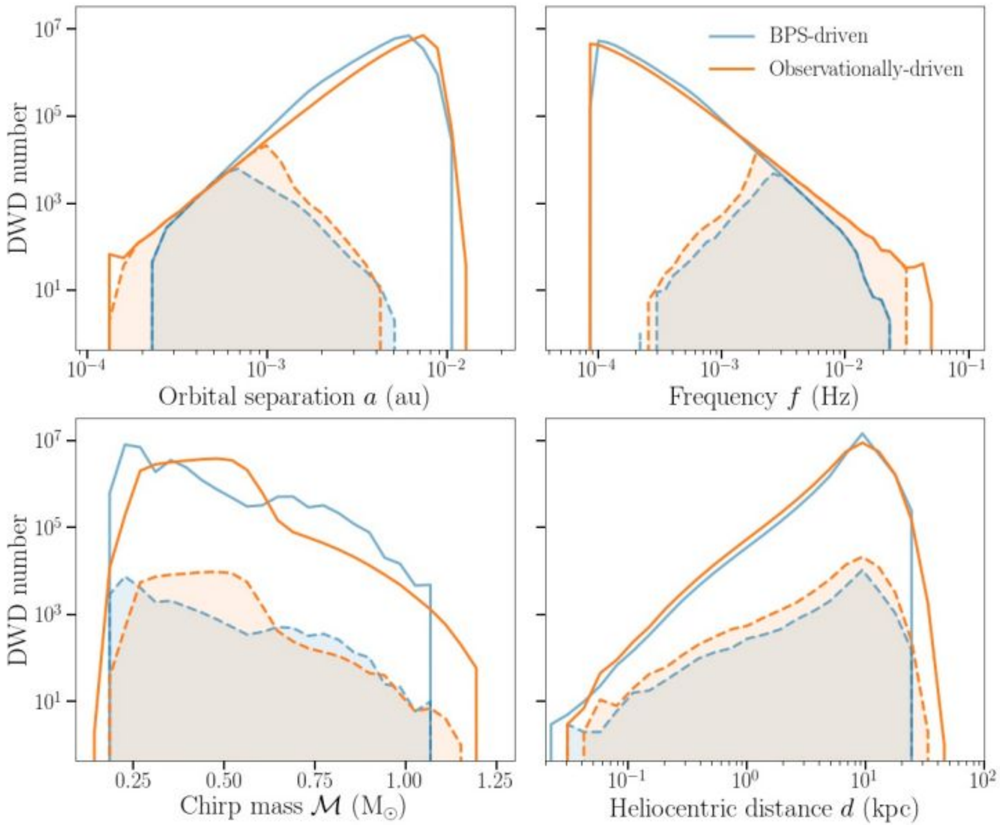


Karnesis et al. (2021)
See also Littenberg et al. (2020) for the global fit data analysis approach.

How many DWDs will LISA detect?

BPS models predict 6k-25k of individually resolved DWD signals vs 60k predicted by the observationally motivated model. Note that the shape of the unresolved signal is also different.

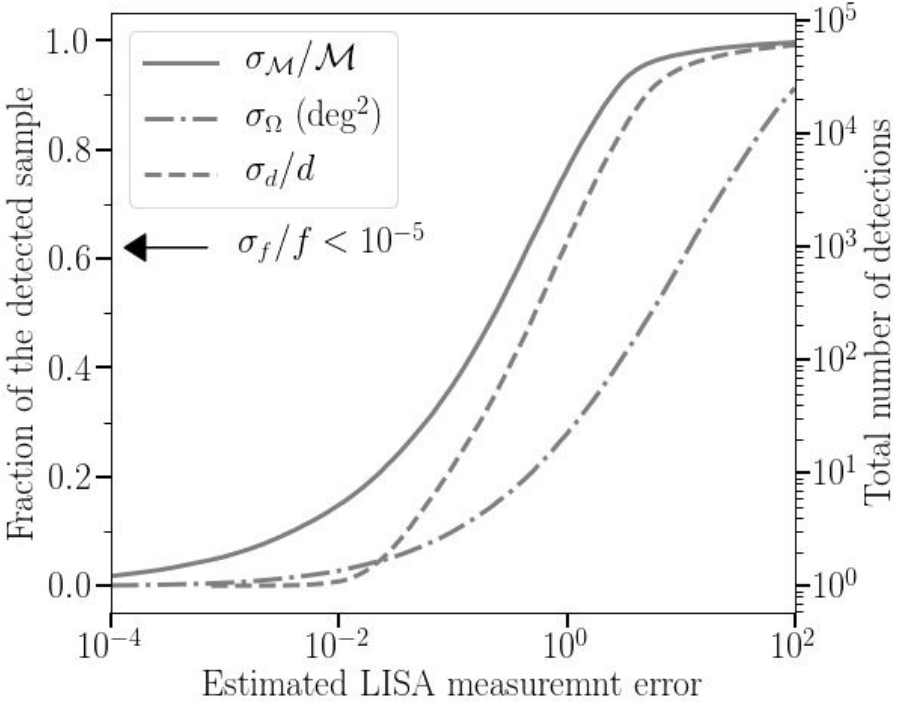




Korol, Hallkoun et al. (2022)

What we will learn from the GW selected sample of WD+WD?

What we will learn from resolved DWD signals?

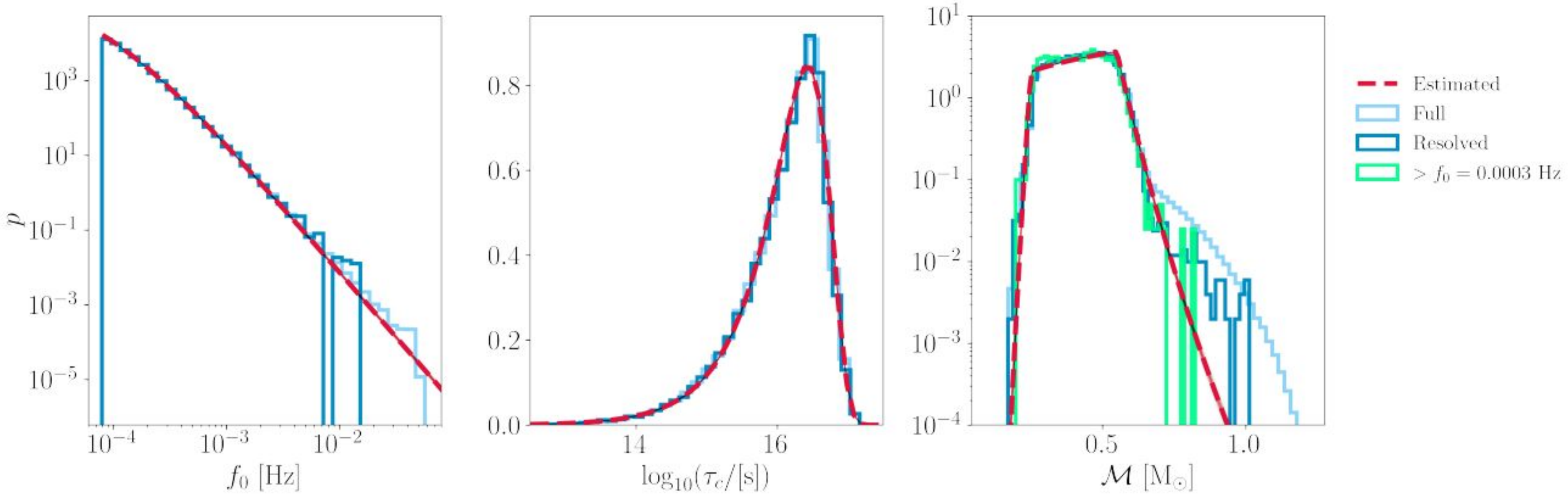


- Frequency σf/f << 10^{-5}
- Frequency derivative for WD+WD with f≳3 mHz
- Measurement of the chirp mass and distance for several thousands WD+WD with measured frequency derivative
- Average sky location $\Delta\Omega$ ~ deg^2

Korol, Hallkoun et al. (2022)
see also Karnesis et al. (2021) and Huang, Hu, Korol et al. (2020), arXiv:2005.07889 for TianQin estimates

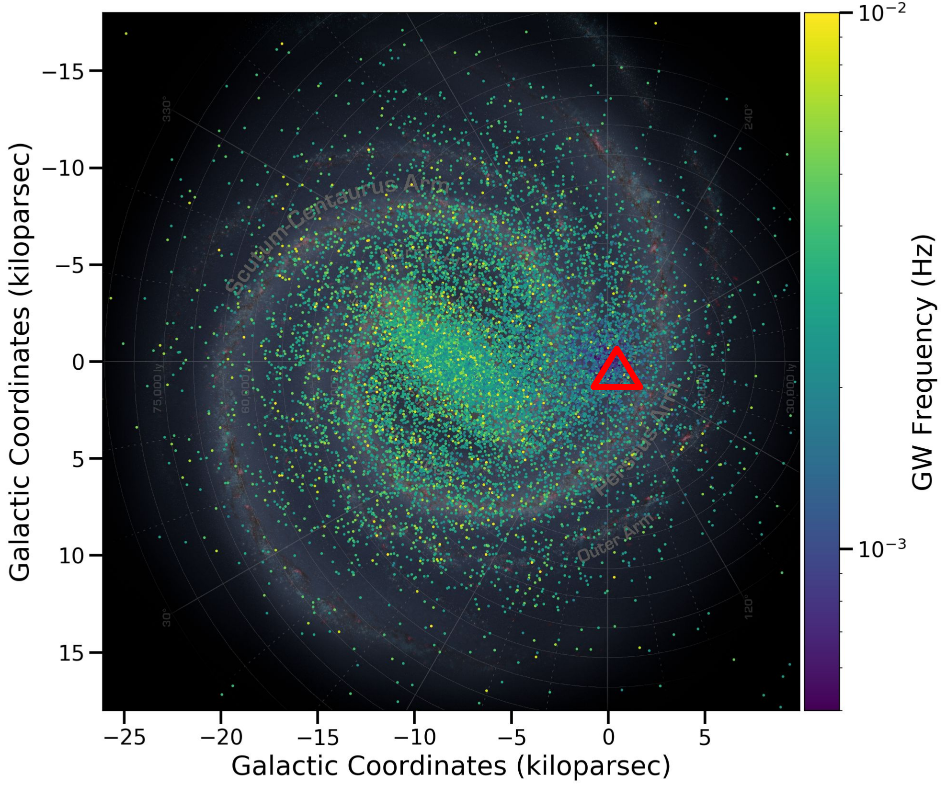
Properties of the underlying DWD population

Based on a few 10k resolved DWDs we can construct a hierarchical Bayesian model to infer the properties of the underlying unresolved population: frequency, merger time and chirp mass distributions. As a proof-of-concept we chose priors based on a fiducial BPS model and we test how well we reconstruct back the respective distributions.



Georgousi et al. (incl. Korol) 2022, arXiv:2204.07349

Shape of the Milky Way



LISA Astrophysics white paper arXiv:2203.06016, based on Wilhelm, Korol et al. 2021 arXiv:2003.11074

The shape of the Milky Way's baryonic components

The spatial distribution of DWDs with measured distances (several thousand) constrains:

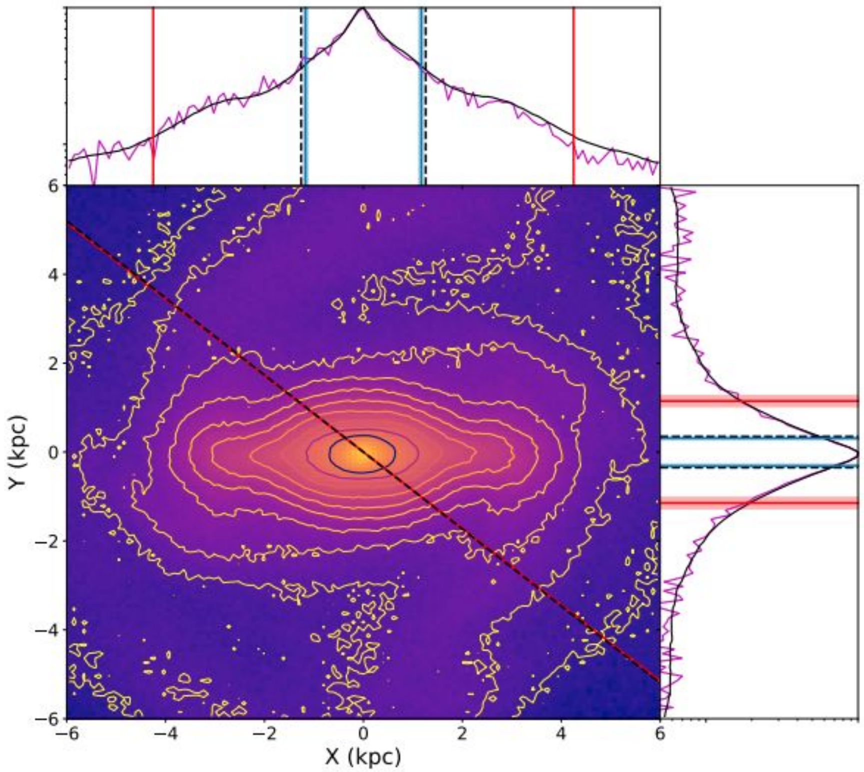
- Bulge scale radius to 2%
- Disc scale radius to 3%
- Disc scale height to 16%

as shown by Korol et al. 2019 using an analytical bulge+disc Milky Way model, and

- Bar's axis ratio to 10%
- Bar's length to 1%
- Bar's orientation angle to 1°

as shown by Wilhelm, Korol et al. 2020 using a high resolution hidro simulation of a Milky Way-like galaxy.

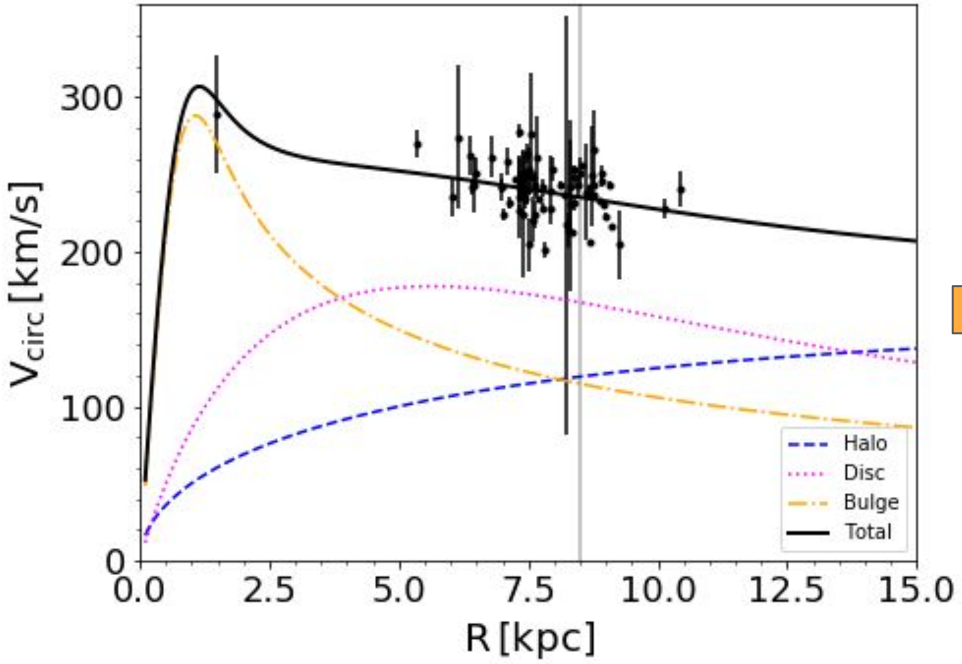
See also Adams et al. 2012; and Benaquista & Holley-Bockelmann 2006, Breivik et al. 2020 for constraints on the disc scale height from galactic foreground



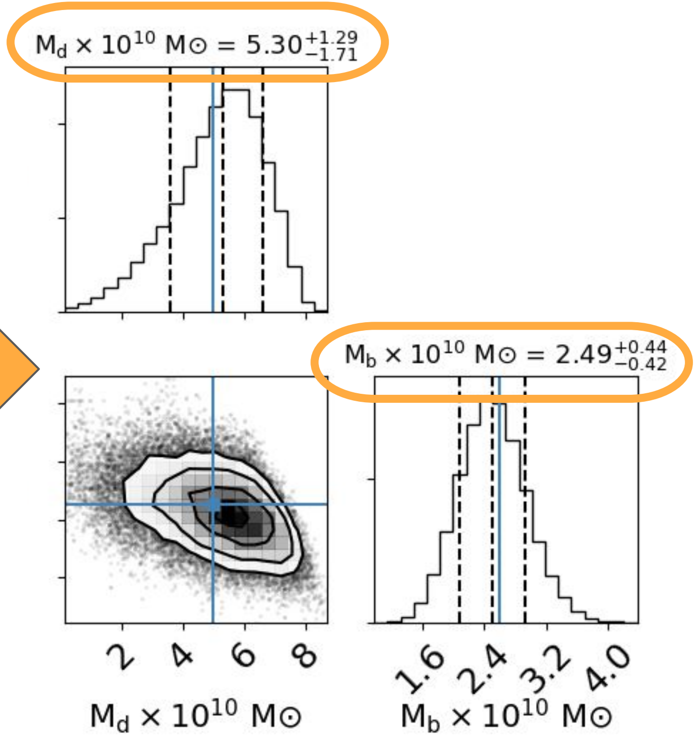
Wilhelm, Korol et al. 2021

Combining GW and EM data into rotation curve

EM proper motions

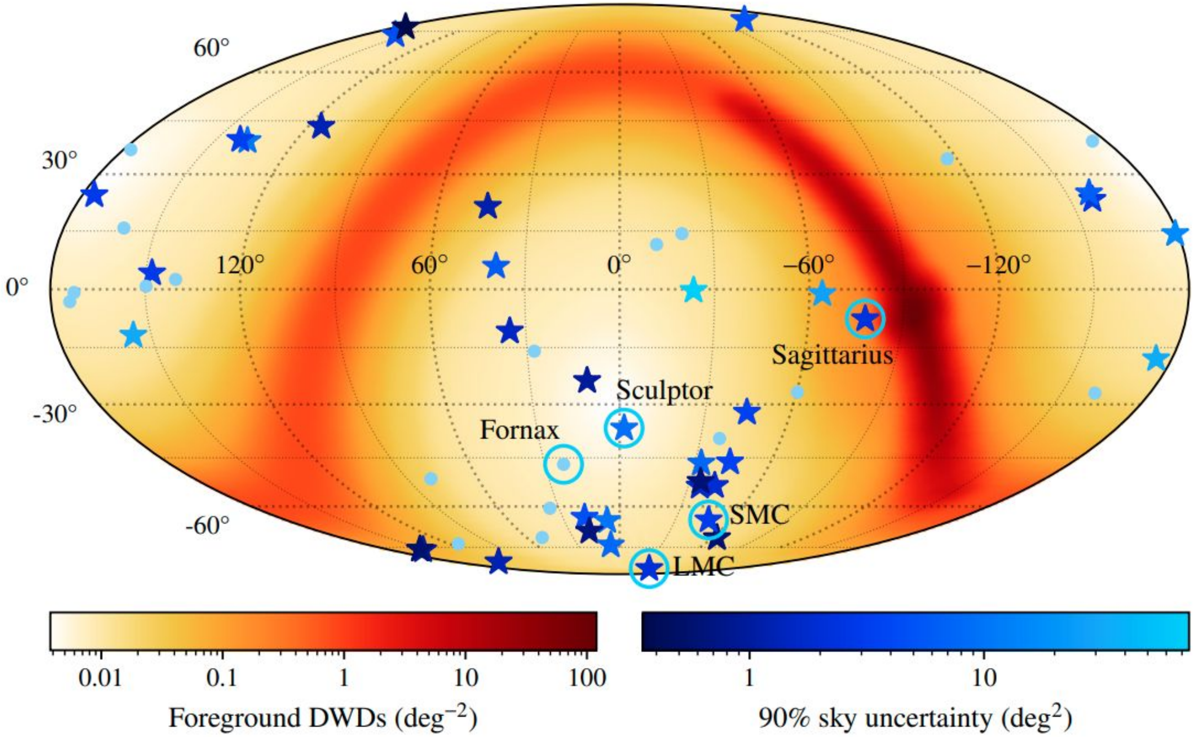


GWs distances +EM parallaxes



Korol, Rossi & Barausse 2019

Discovering Milky Way satellites in gravitational waves



Roebber et al. (incl.Korol) 2020; Korol et al. 2020, 2021; Keim, Korol et al. 2022

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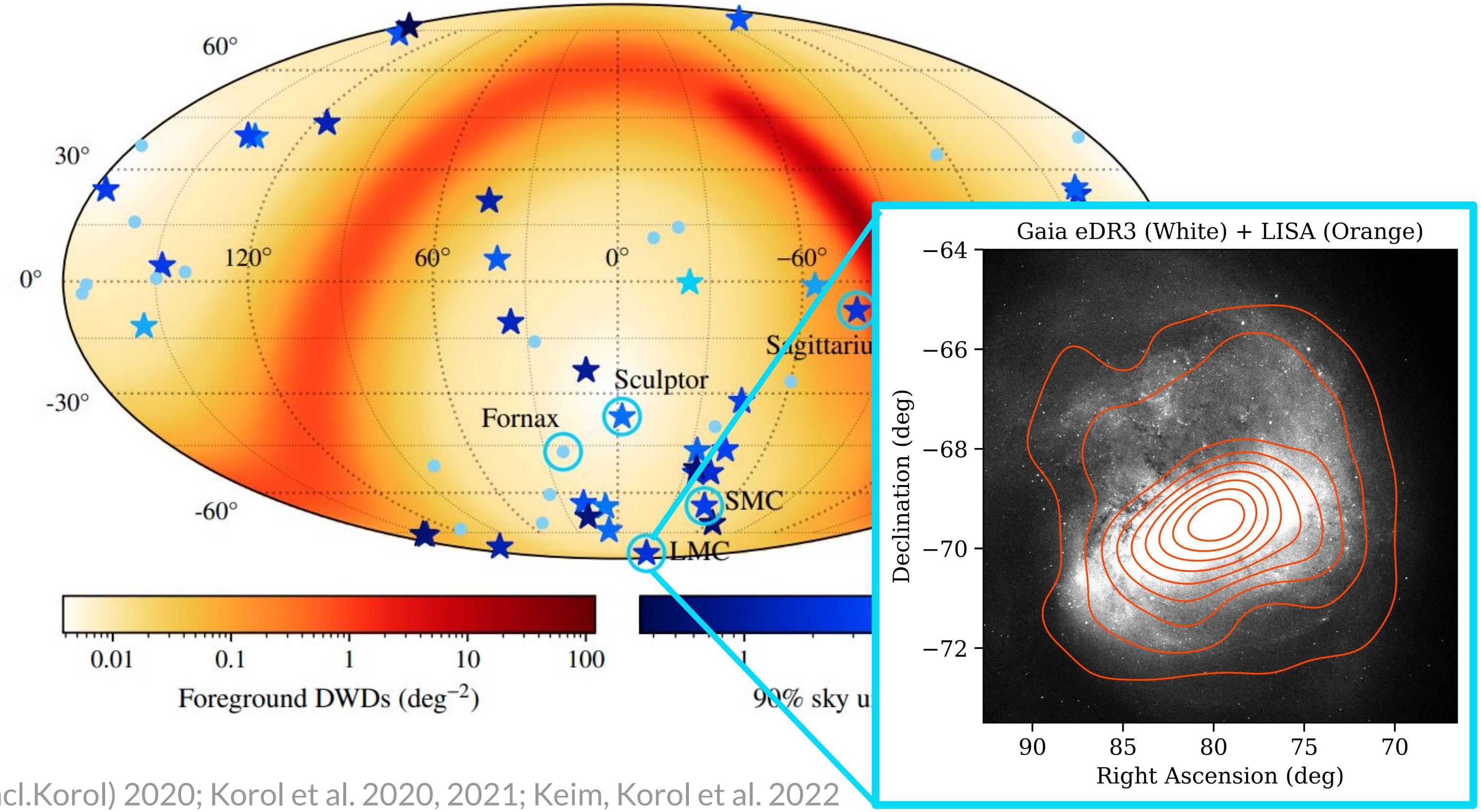

Roebber et al. (incl.Korol) 2020; Korol et al. 2020, 2021; Keim, Korol et al. 2022

Conclusions

1. LISA will detect Galactic DWDs in two ways: as resolved GW signals (up to several tens of thousand) and as unresolved confusion foreground signal. While TianQin will see resolved signals only. Synergies can be envisioned between the two missions.

2. Resolved signals will allow the reconstruction of the underlying Galactic DWD population. The frequency and merger time distributions can be inferred with no bias, while for the chirp mass distribution selection effects has to be taken into account.

3. LISA can be used as an all-sky Galactic GW survey that can map with DWDs the entire Milky Way and its satellites.

4. The unresolved confusion foreground will set the overall normalisation of the DWD population and can be connect to the total stellar mass of the Galaxy