Multimessenger Galactic Astronomy

with Double White Dwarfs

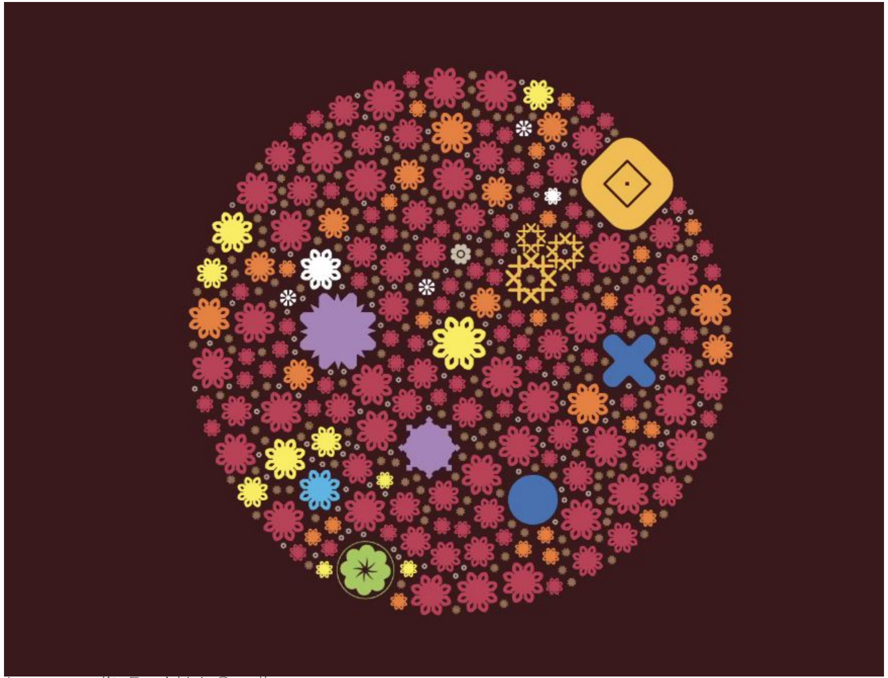

Image credit: David McCandless

Valeriya Korol
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LISA Science Team
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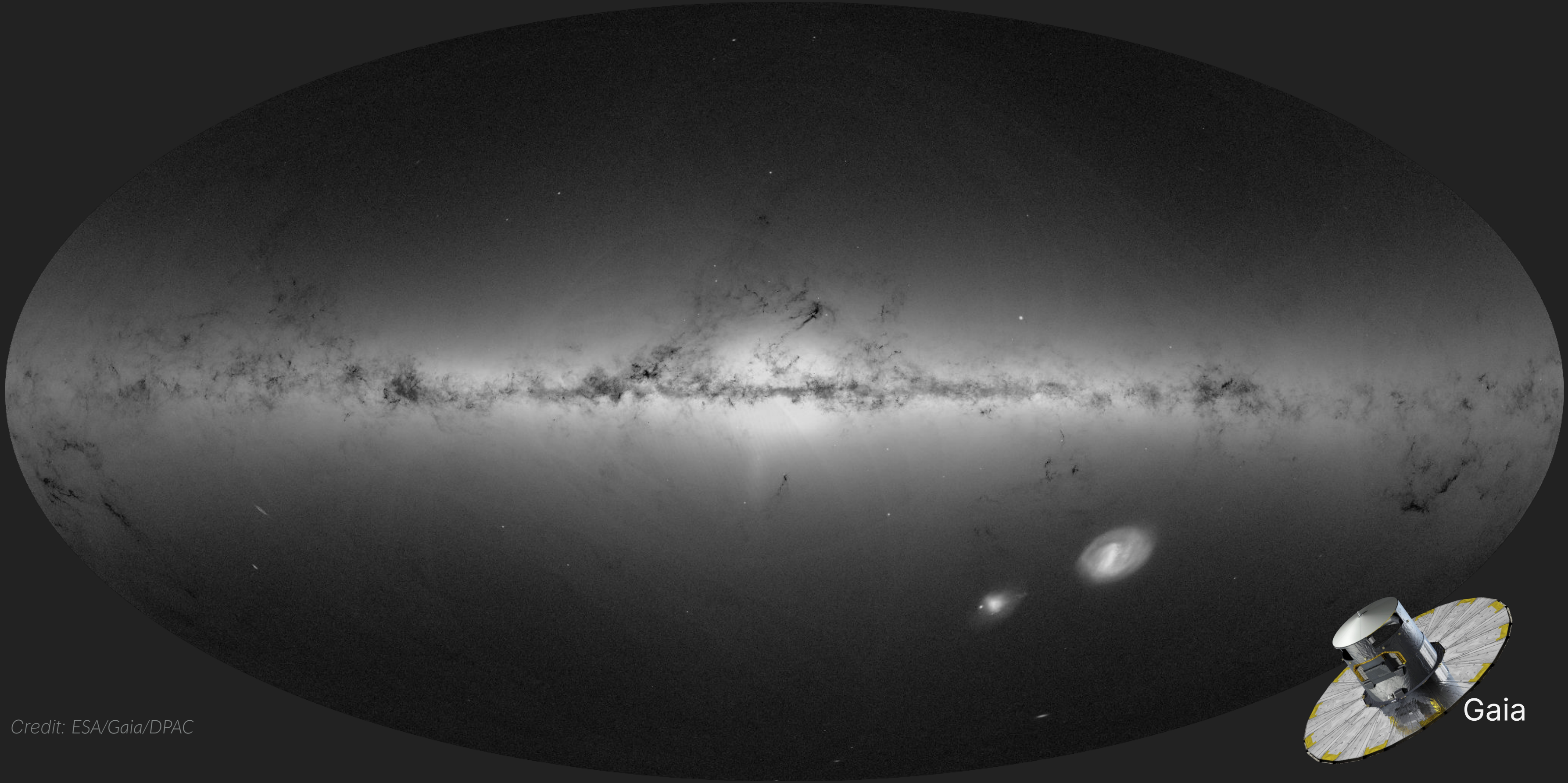
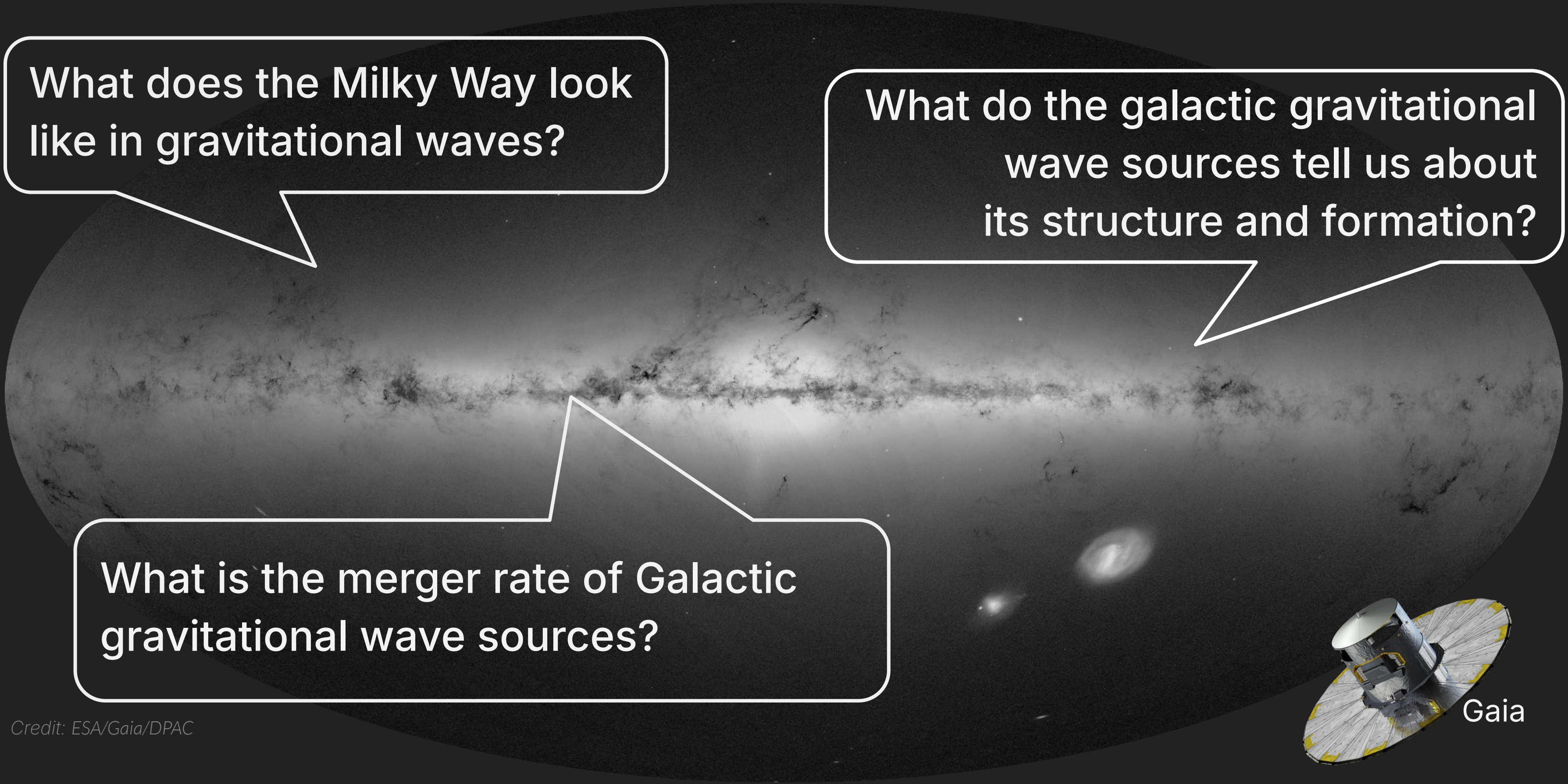
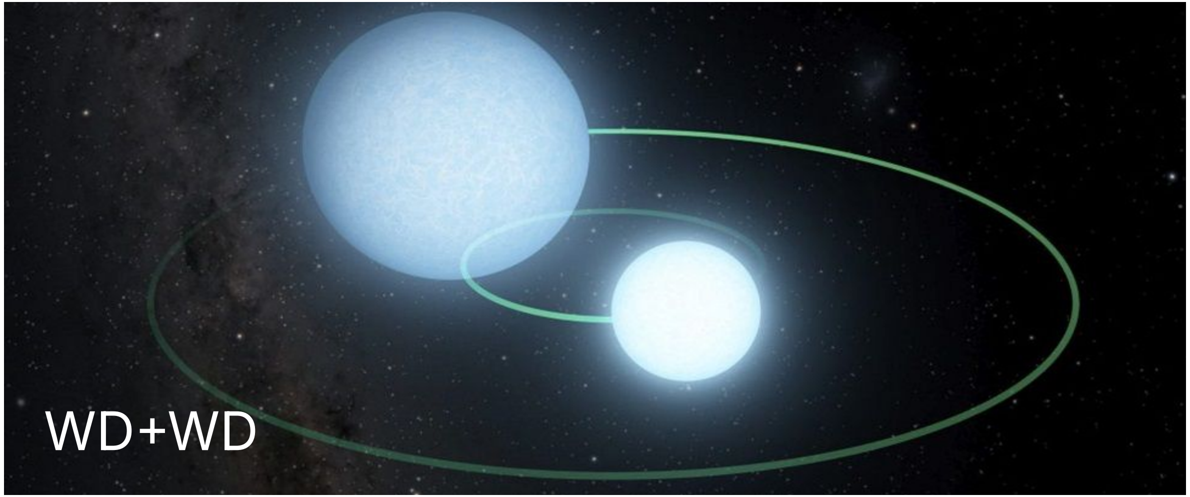
valeriakorol.com

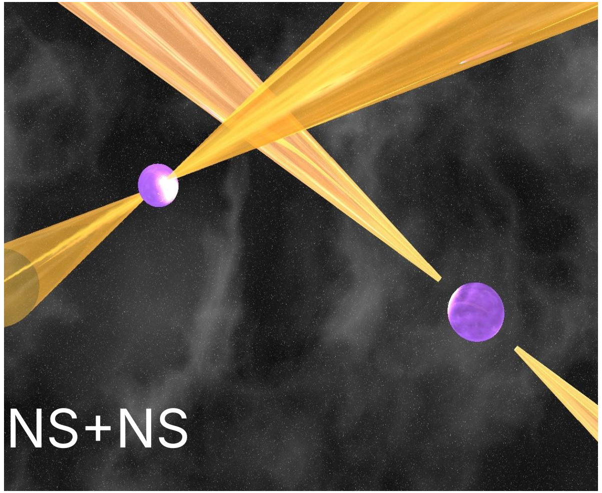


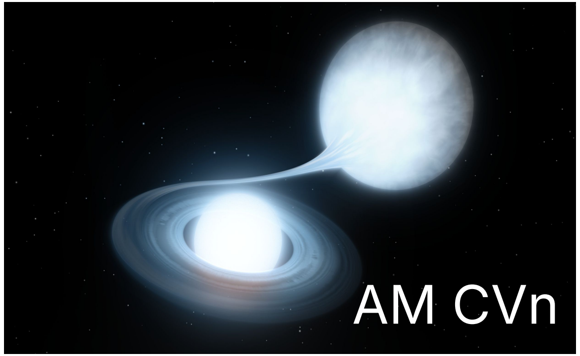
Credit: ESA/Gaia/DPAC

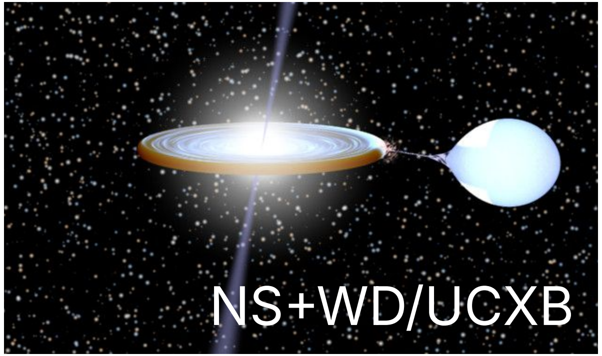

What does the Milky Way look like in gravitational waves?
What do the galactic gravitational wave sources tell us about its structure and formation?
What is the merger rate of Galactic gravitational wave sources?
Credit: ESA/Gaia/DPAC
Gaia

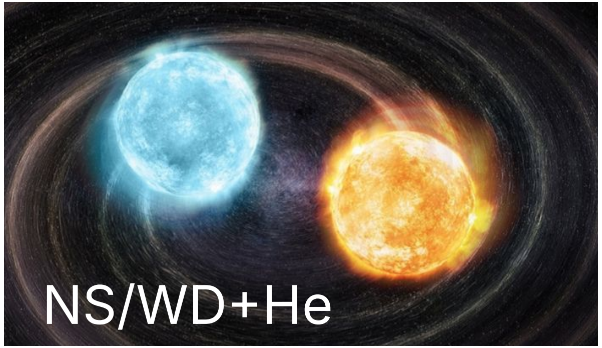
GALACTIC GRAVITATIONAL WAVE SOURCES









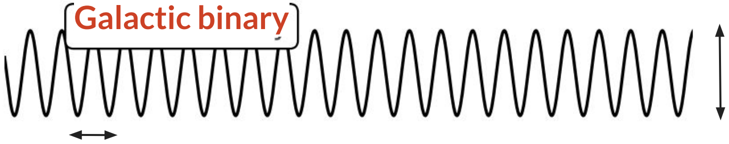


GRAVITATIONAL WAVES FROM **GALACTIC COMPACT BINARIES**

Galactic binaries emit **continuous, nearly sinusoidal** GW signals.

The waveform describing such signals is defined by 8 (up to 11) parameters:

$$\{\mathcal{A}, f, \dot{f}, \lambda, \beta, \iota, \psi, \phi_0\}$$



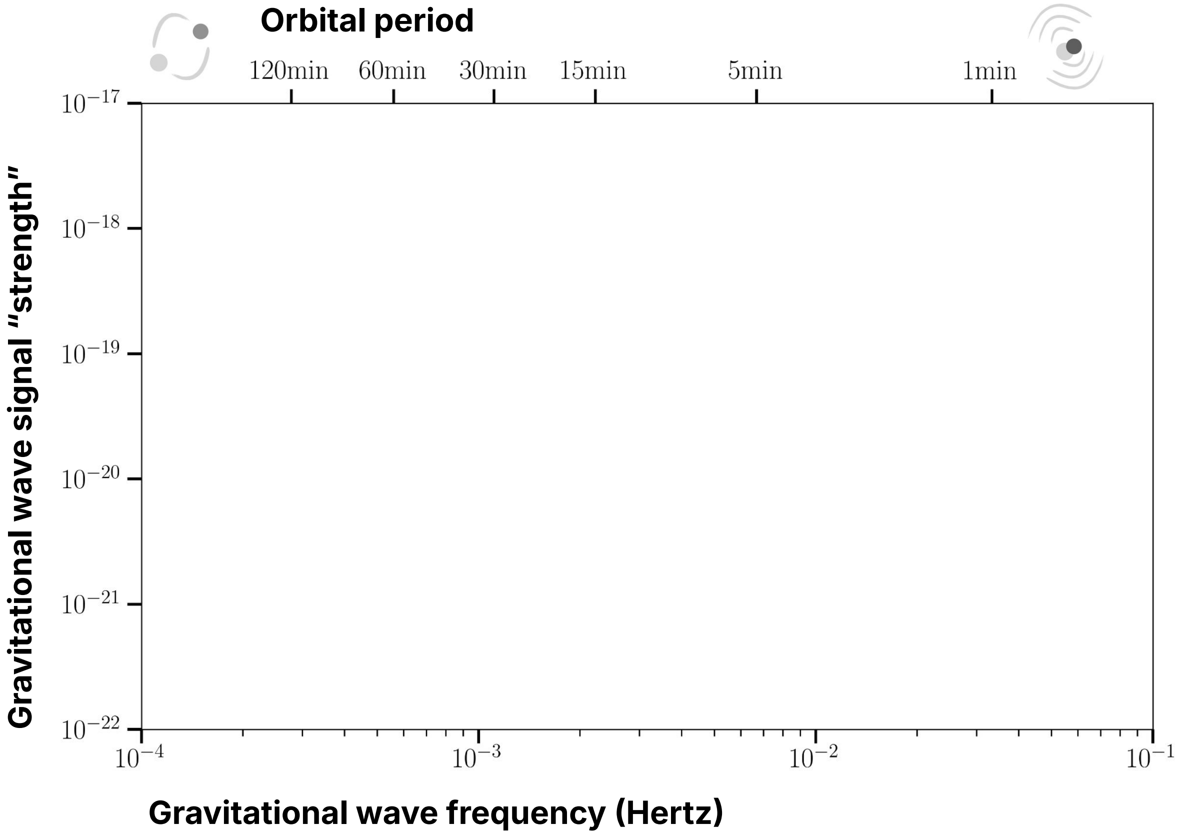
$$h \propto \frac{\mathcal{M}^{5/3} f^{2/3}}{d} \sim 10^{-22}$$

$$f = \frac{2}{P}$$

Change in frequency due to GW radiation $\dot{f} \propto f^{11/3} \mathcal{M}^{5/3} \sim 1\mathrm{nHz\ yr^{-1}}$

LISA WILL REVEAL **UNSEEN COMPACT BINARY** SYSTEMS

Living Review Amaro et al. /w Korol et al. 2023



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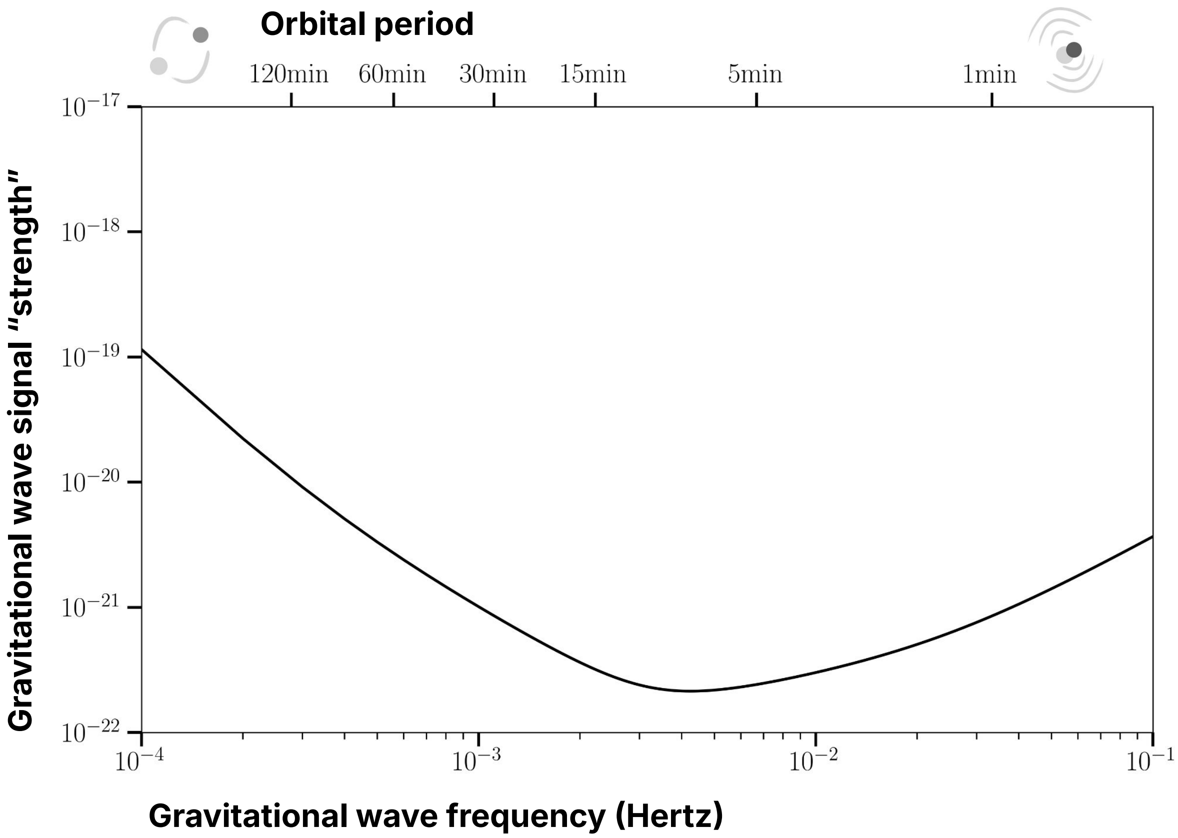

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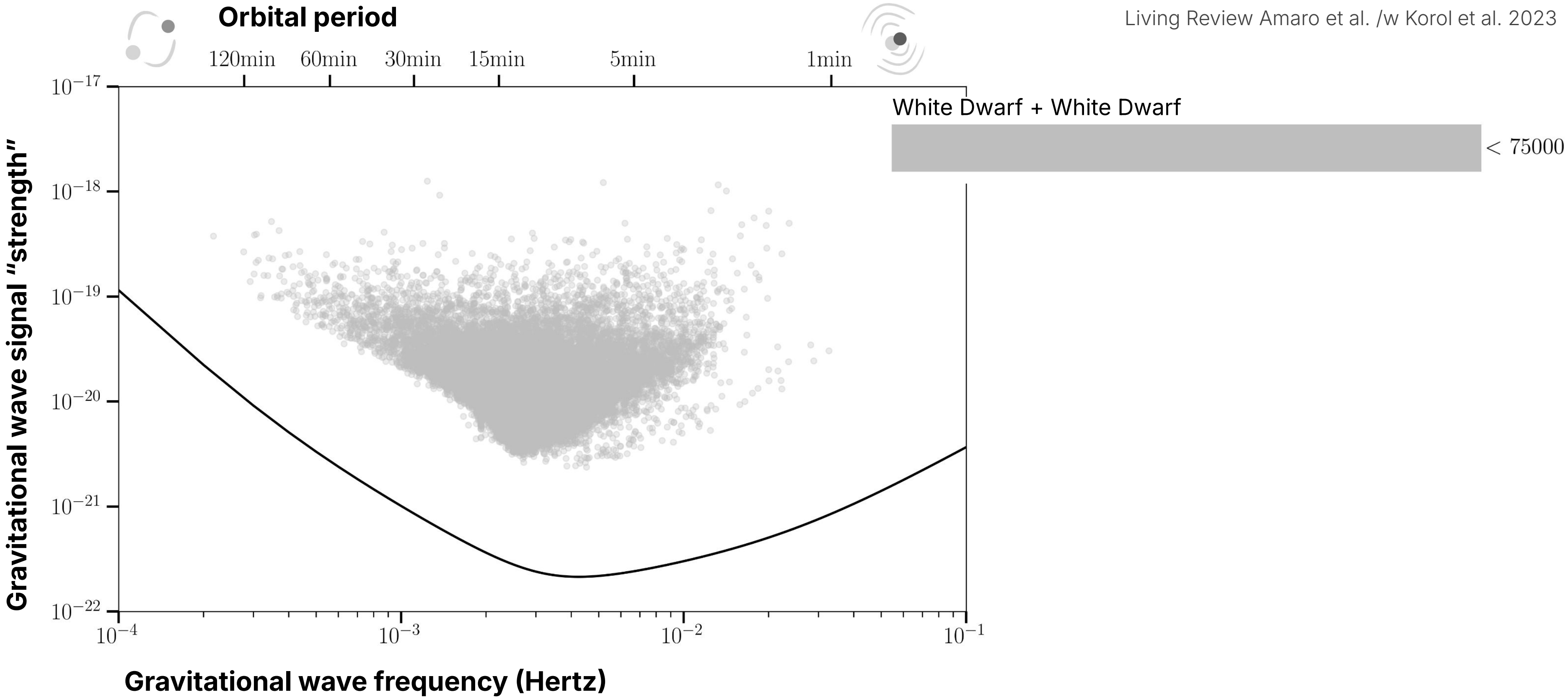

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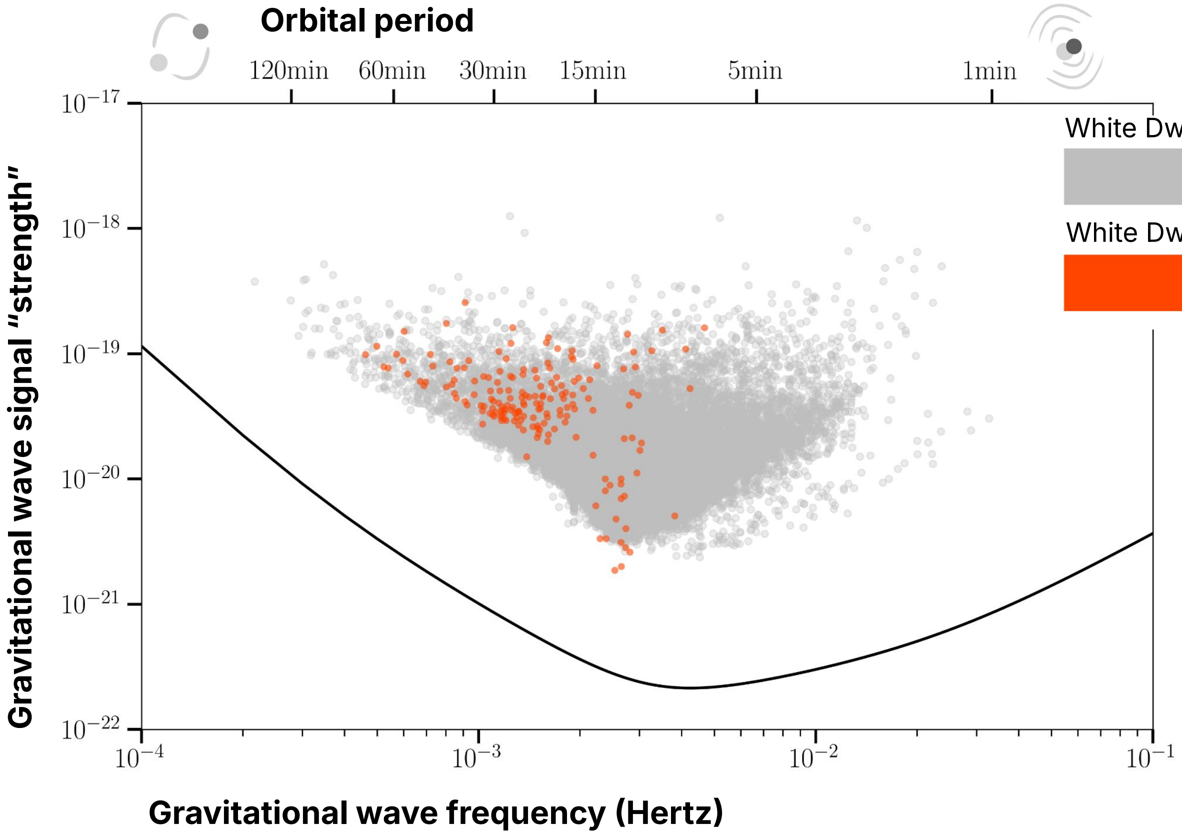

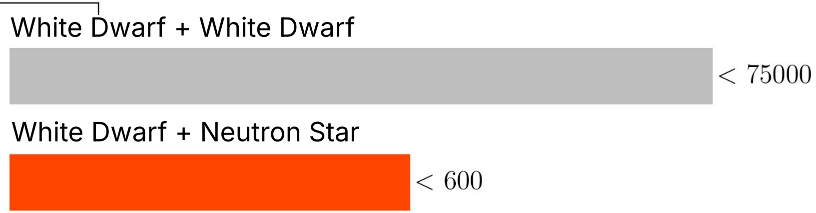

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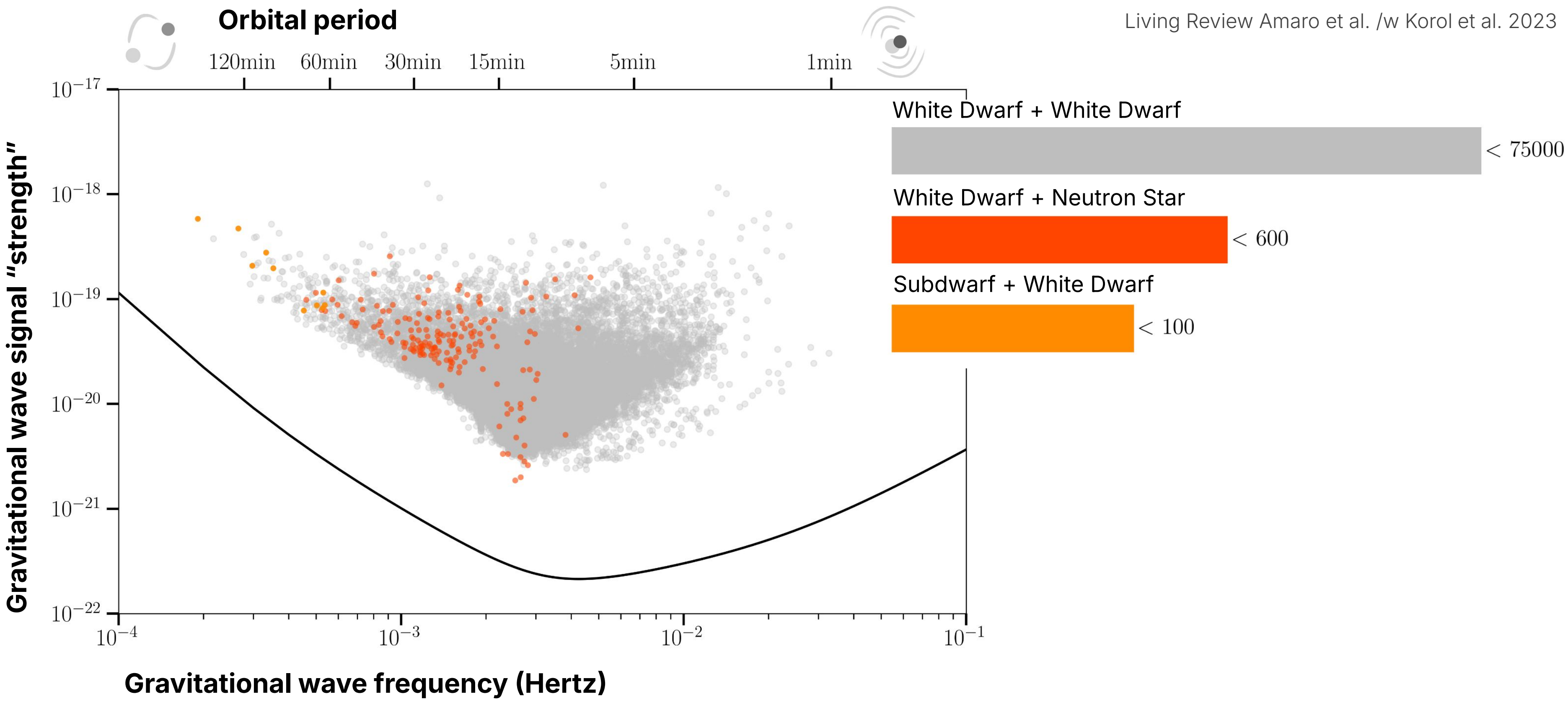

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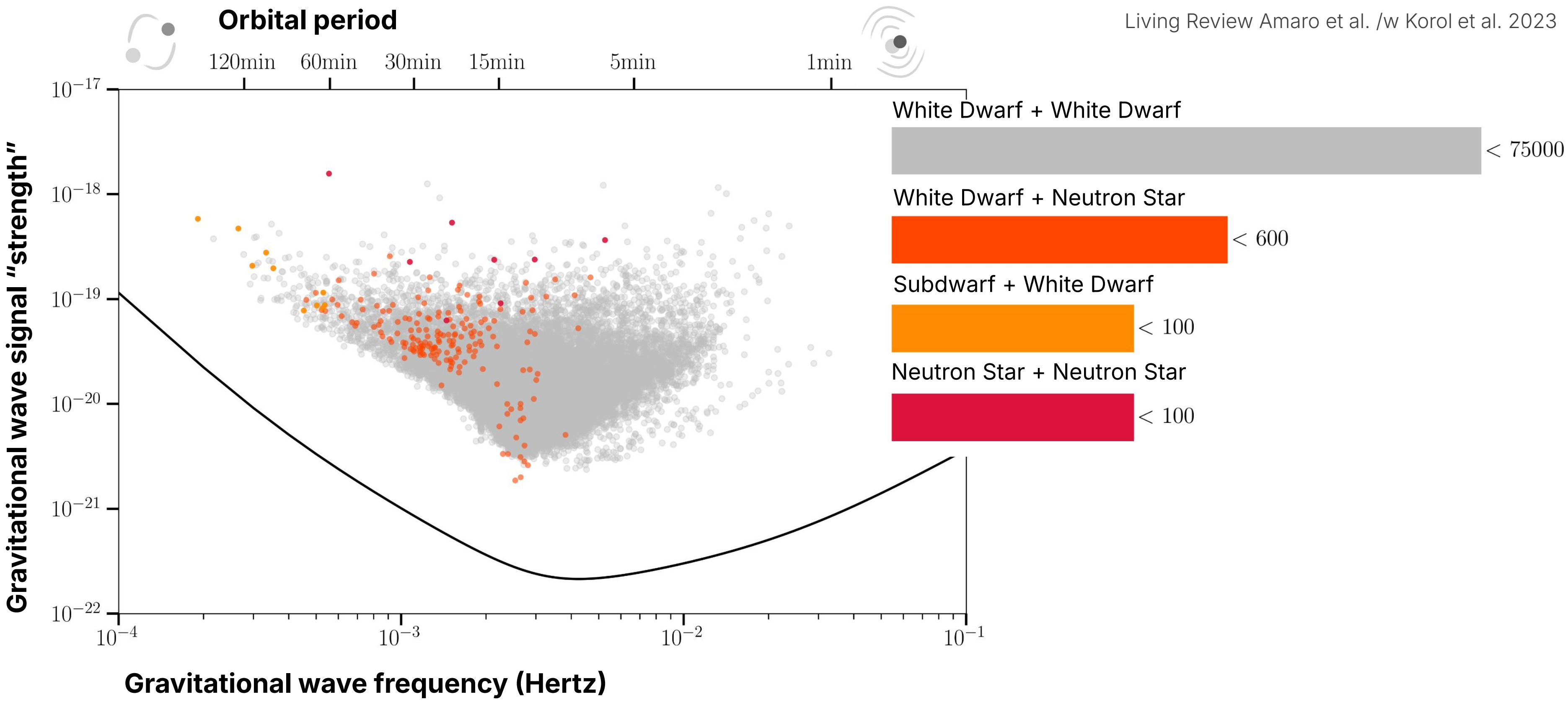

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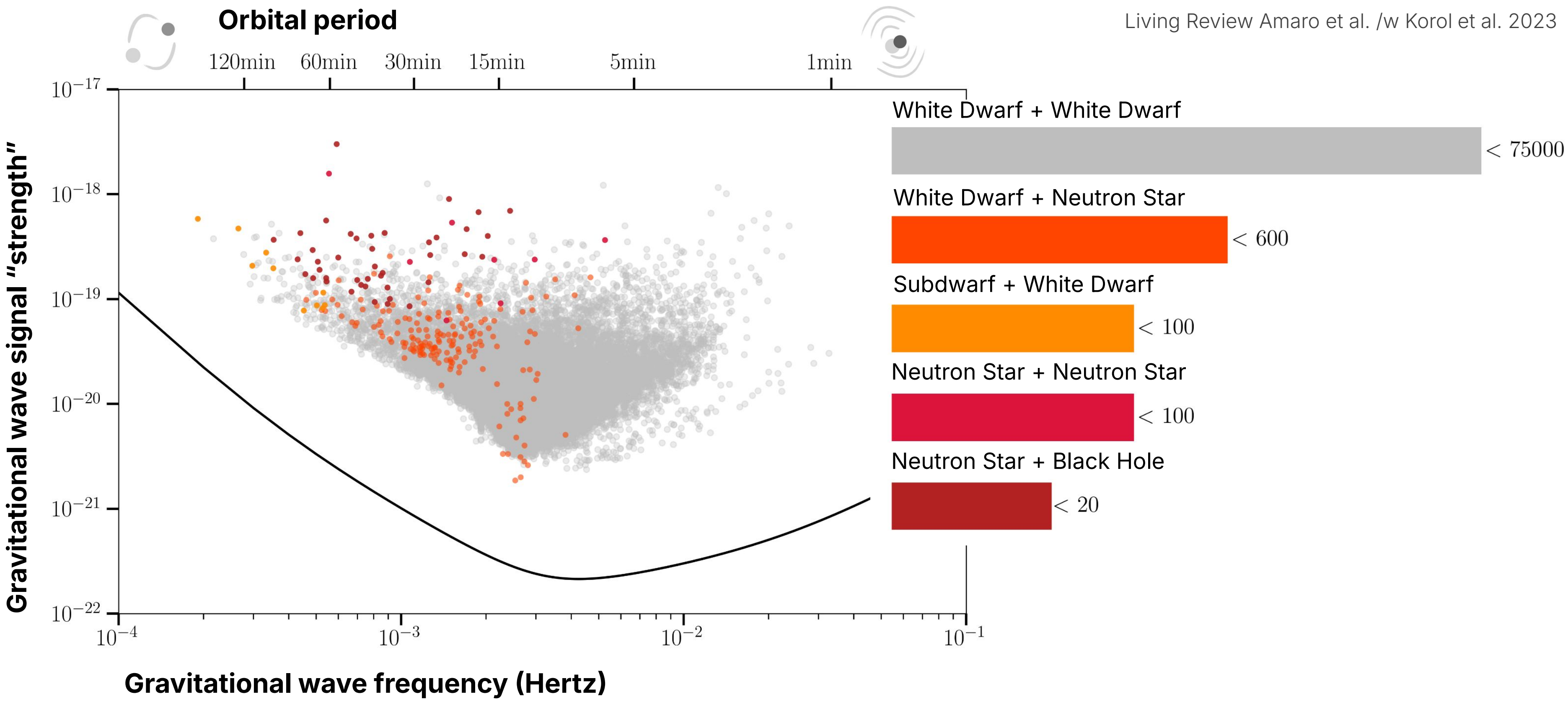

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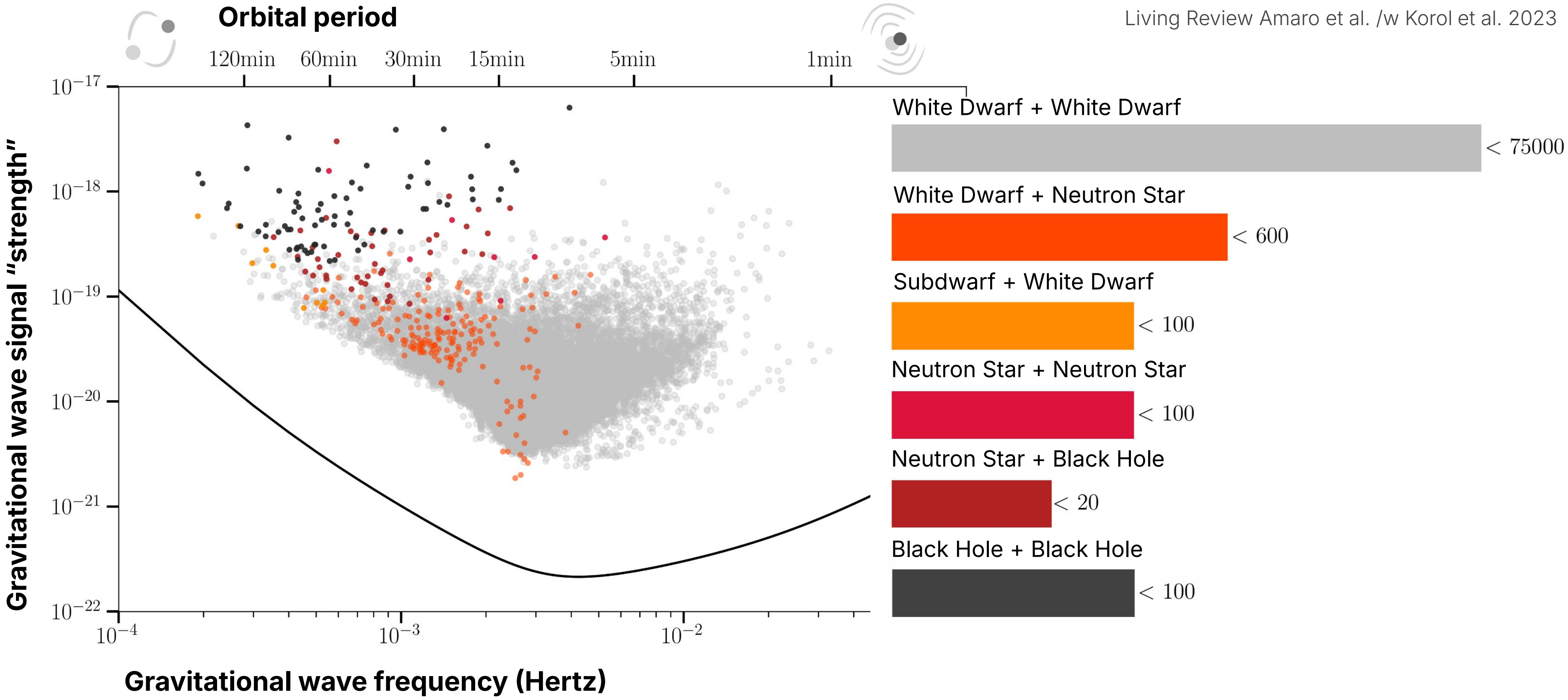

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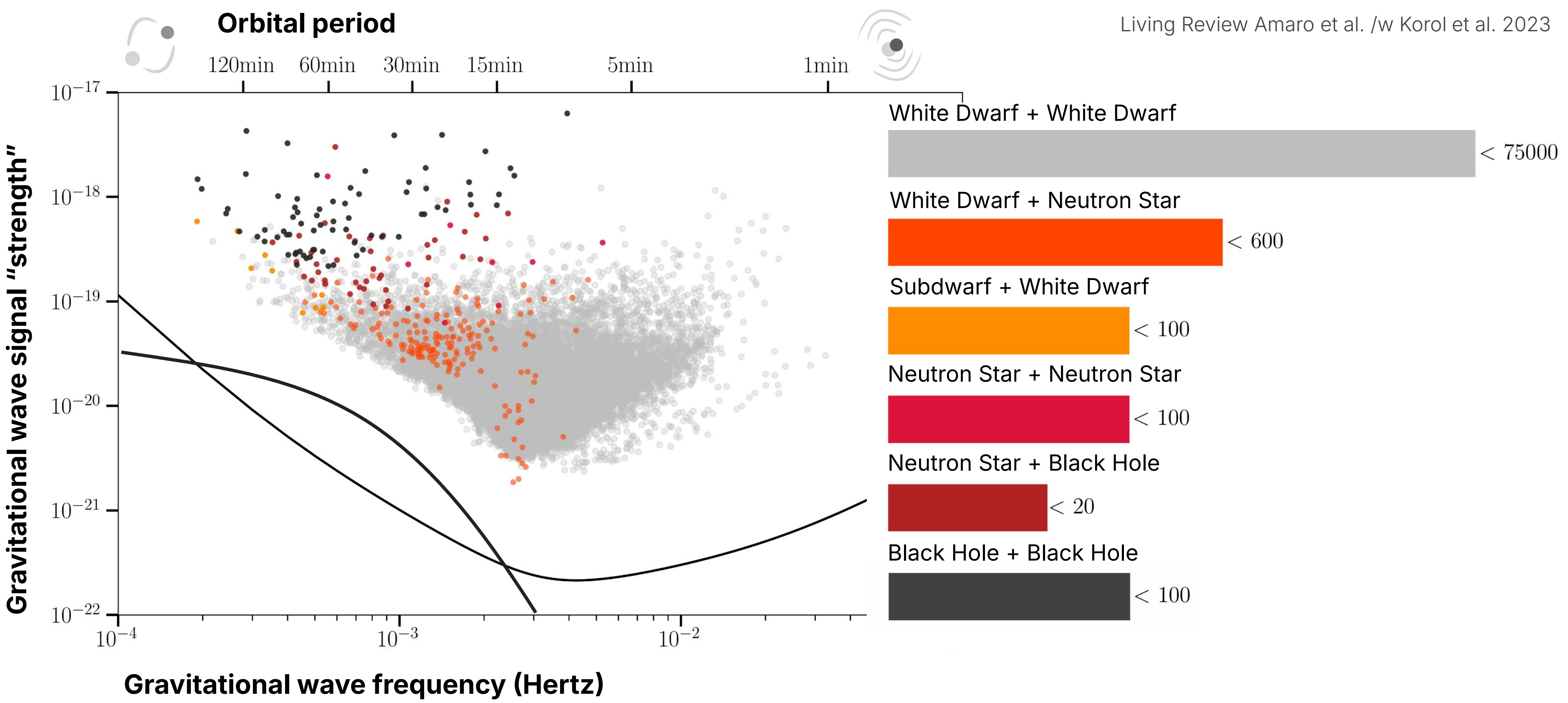
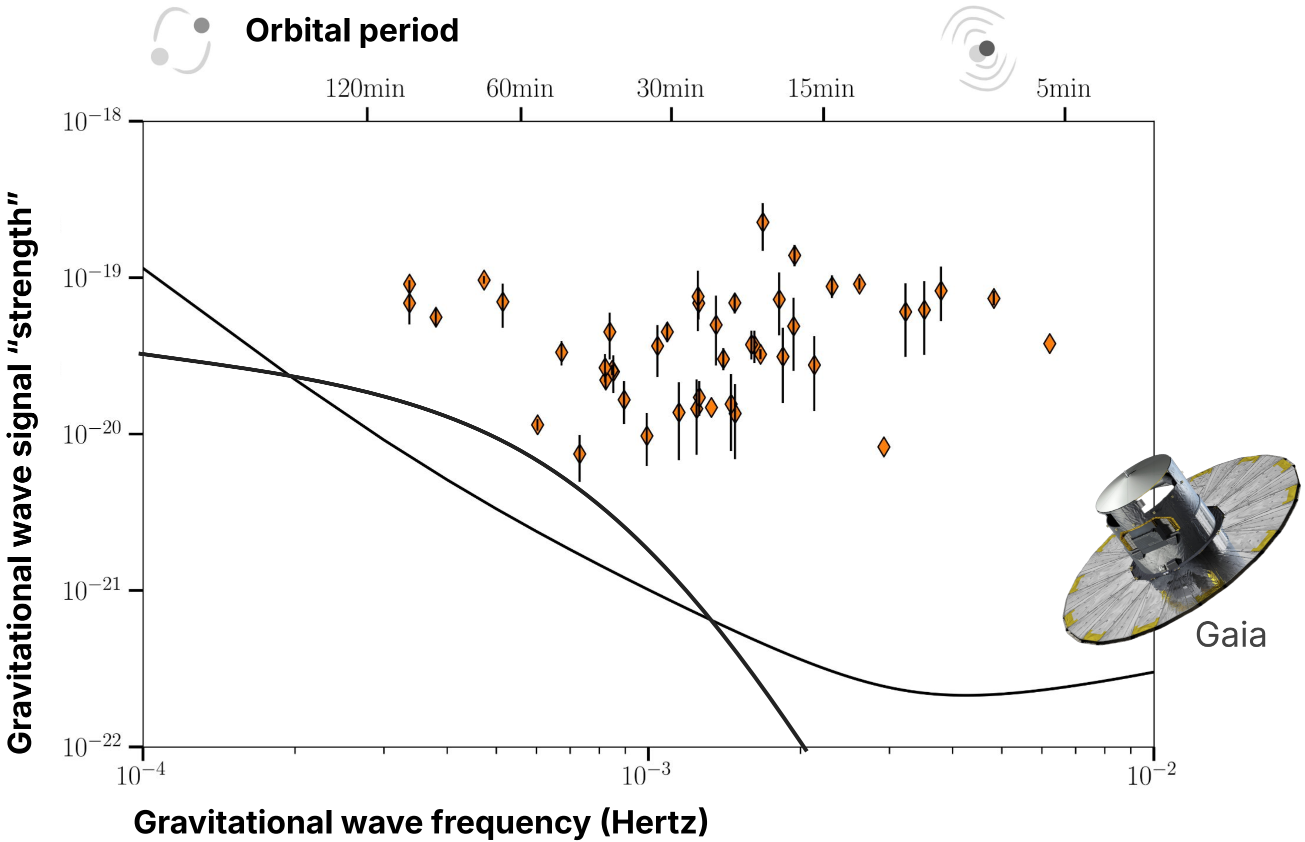


SAMPLE OF **GUARANTEED** LISA SOURCES

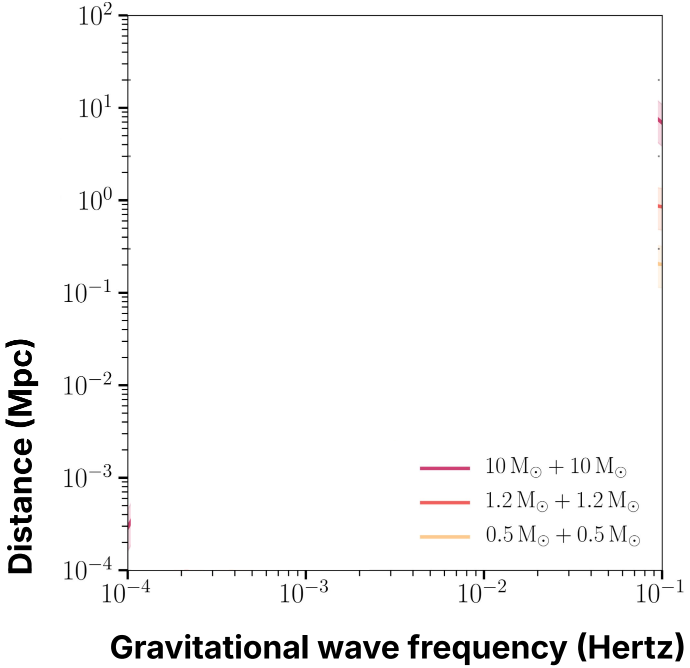
Kupfer, Korol et al. 2018, 2024



LISA WILL REVEAL UNSEEN COMPACT BINARY SYSTEMS

ACROSS THE ENTIRE MILKY WAY

Living Review Amaro et al. /w Korol et al. 2023



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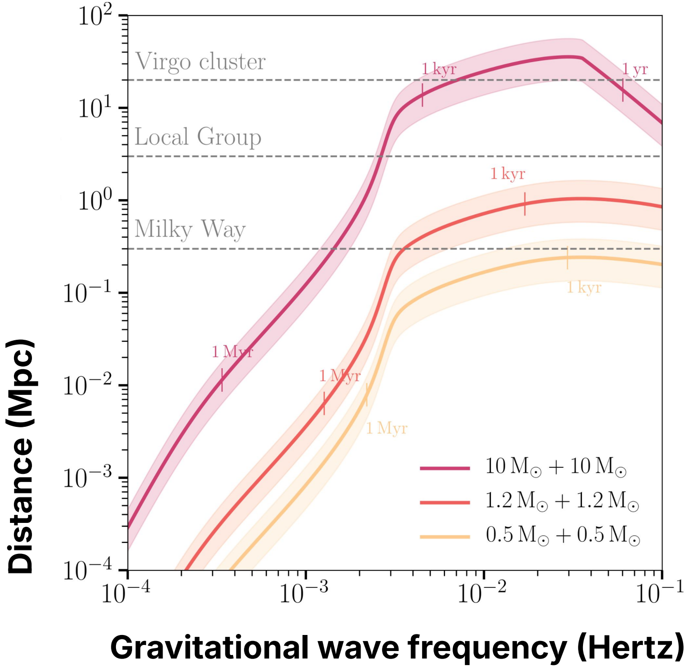

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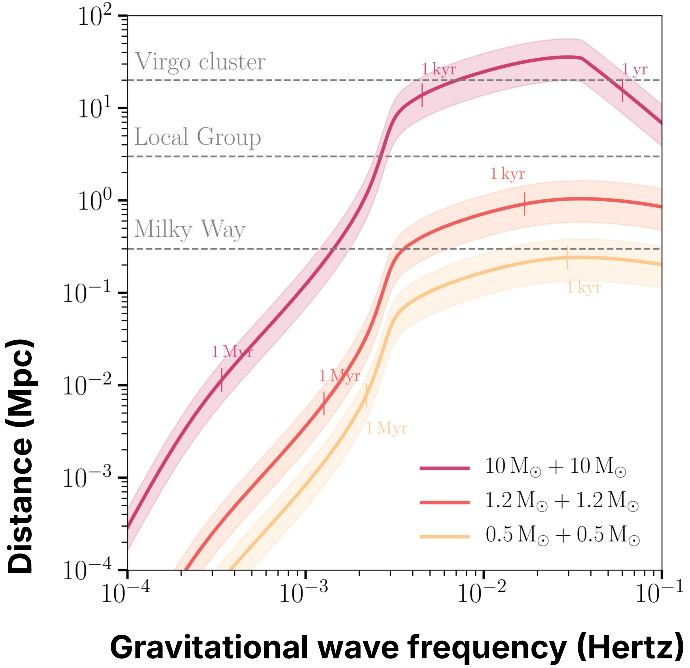

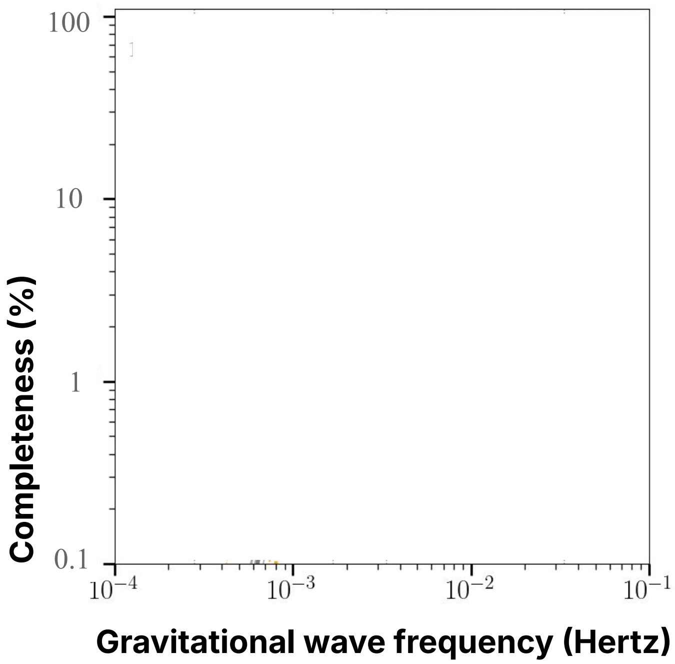

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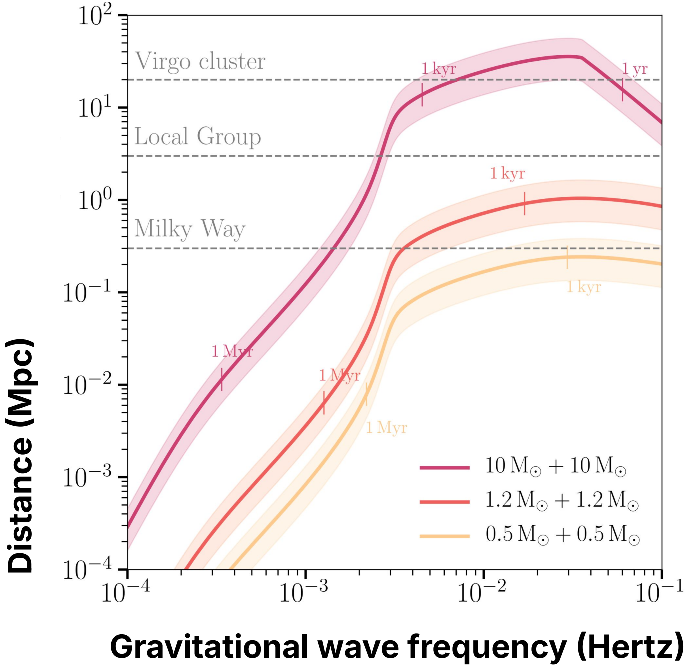
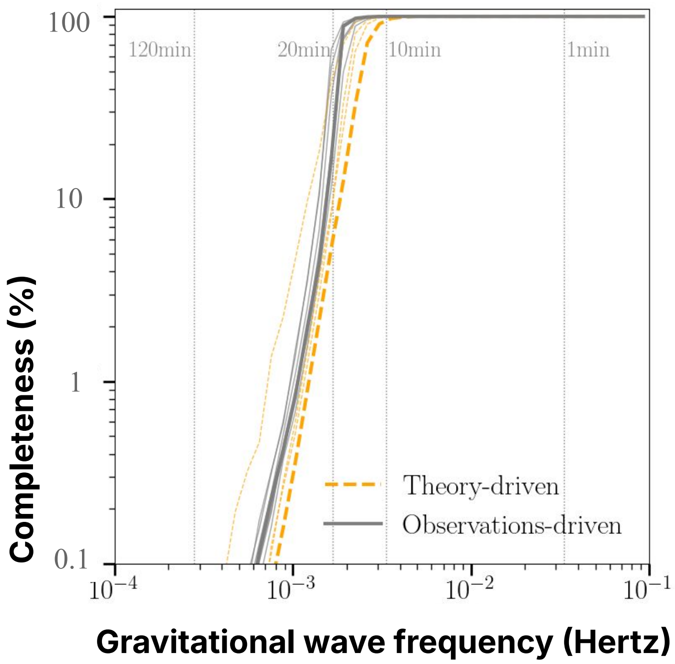


Korol et al. 2024



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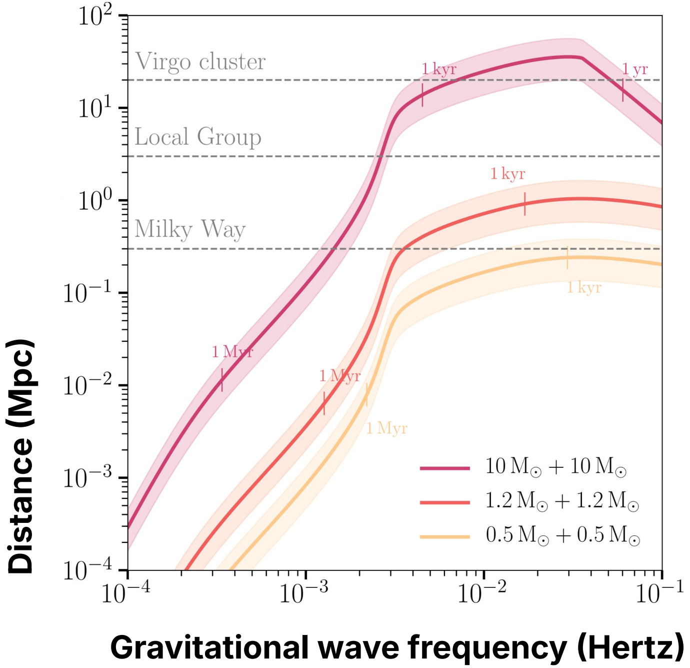

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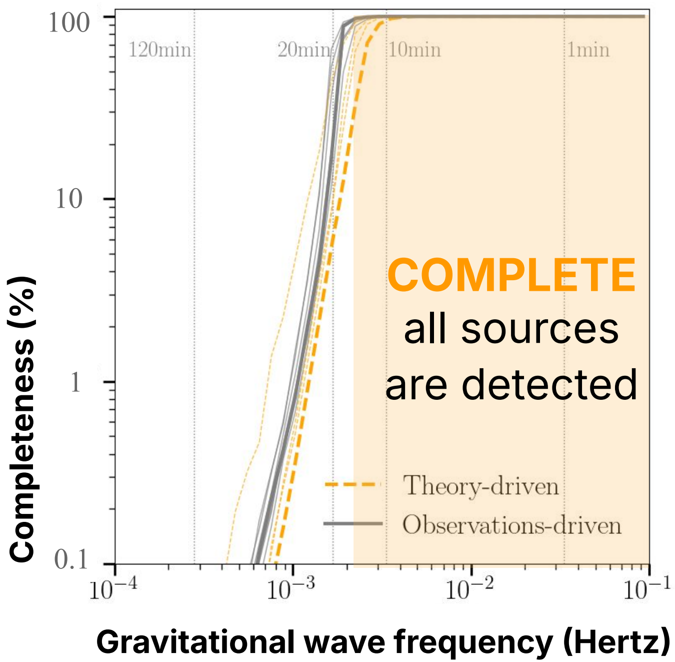
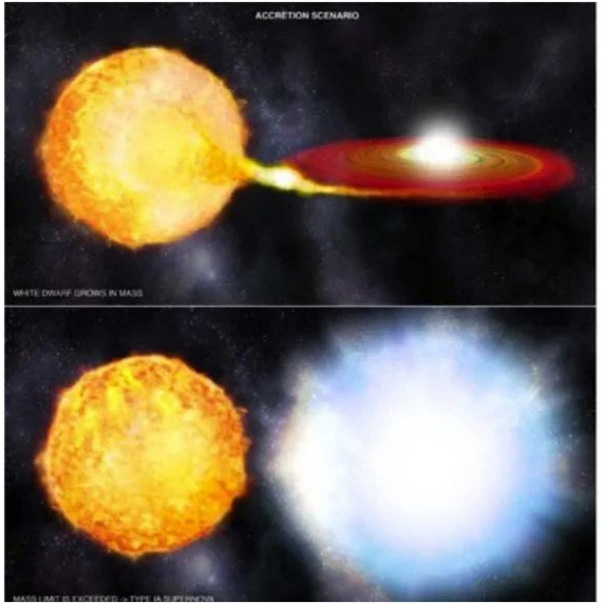


Expected insights on Type Ia supernovae

PROGENITOR DILEMMA: A HISTORICAL PERSPECTIVE

Single-degenerate channel



or

Double-degenerate channel

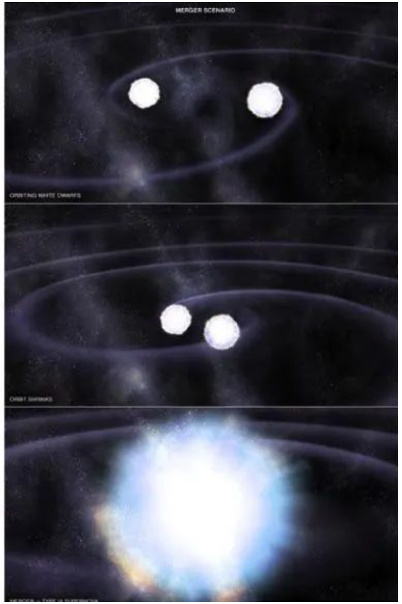
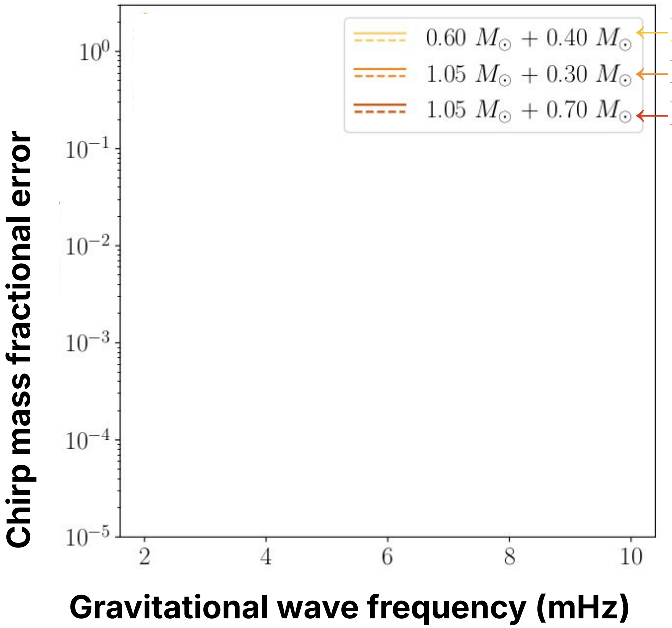


Image credits: NASA / CXC / M. Weiss

This is an oversimplified picture, there are many many nuances to be considered!
Many reviews are published: Livio & Mazzali et al. 2018, Ruiter et al. 2020, Liu et al. 2023 and many others

LISA'S CONSTRAINTS ON THE DOUBLE-DEGENERATE
TYPE IA PROGENITORS



Massive enough to detonate as a low-luminosity thermonuclear transient

Massive enough to result in a "Normal" Type Ia

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Reminder:

$$\dot{f}_{\mathrm{GW}} = \frac{96}{5}\frac{(G\mathcal{M})^{5/3}}{\pi c^5}(\pi f_{\mathrm{GW}})^{11/3}$$

$$\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$$

LISA'S CONSTRAINTS ON DOUBLE-DEGENERATE
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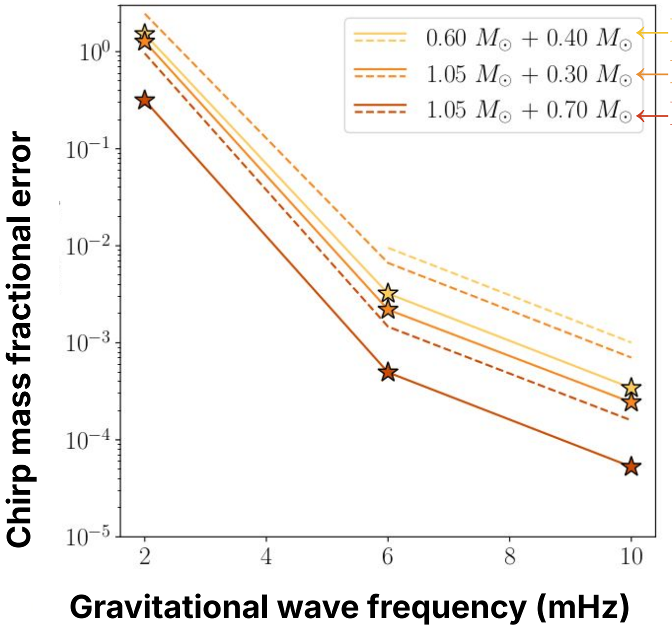
At GW frequencies near to the merger (< 0.01 Hz)

chirp mass constraints at 0.01-0.001%



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Based on the Balrog code (Uni. of Birmingham)

See e.g. Buscicchio et al. 2019, 2021; Roebber et al. 2020; Klein et al. 2022

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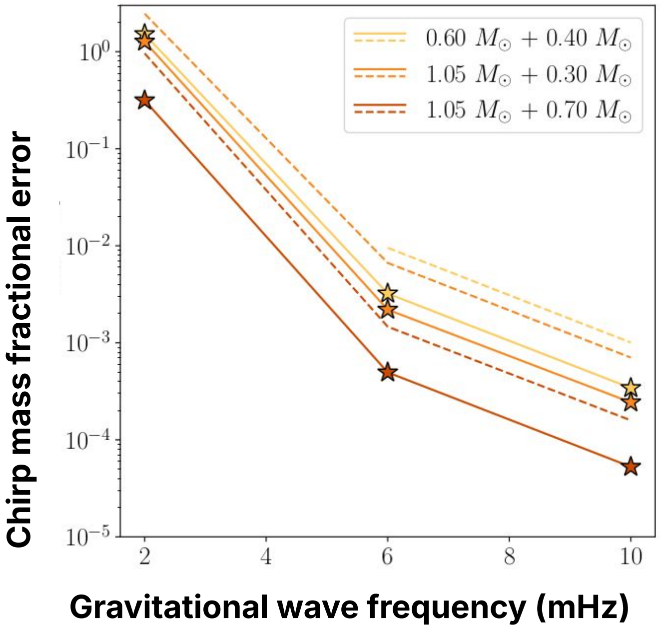
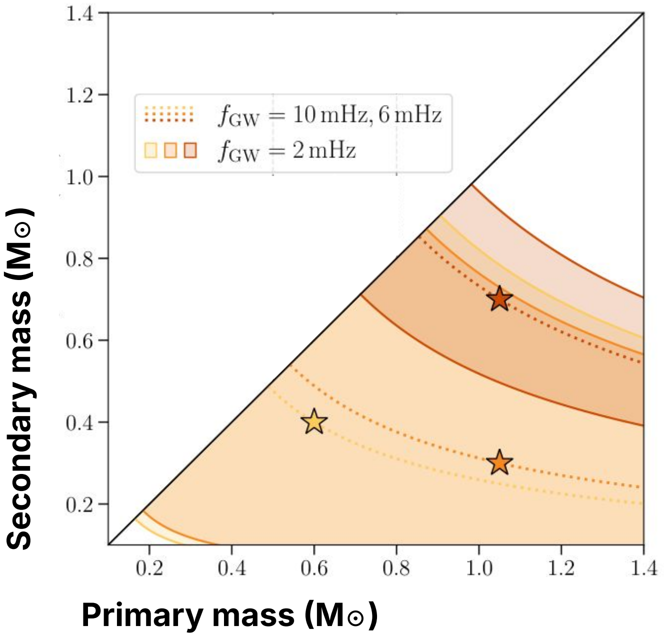


Chirp mass constraint translates into a **lower bound on the primary mass** making it possible to forecast the possibility and the type of thermonuclear transient.



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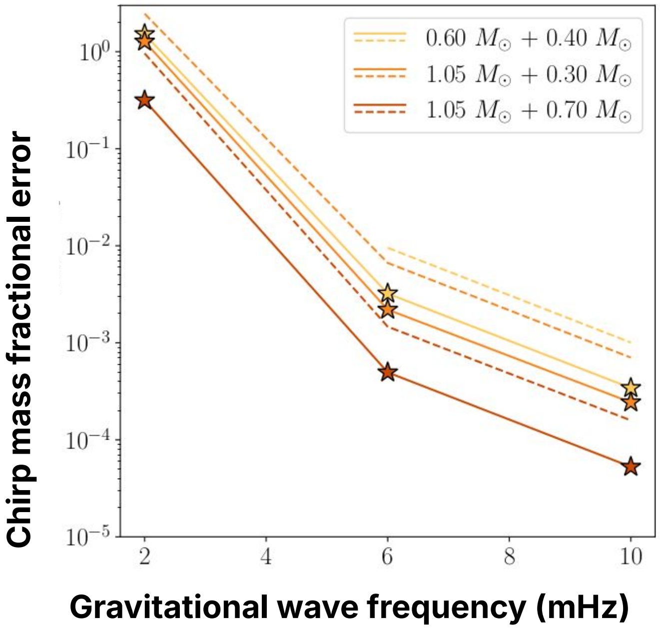

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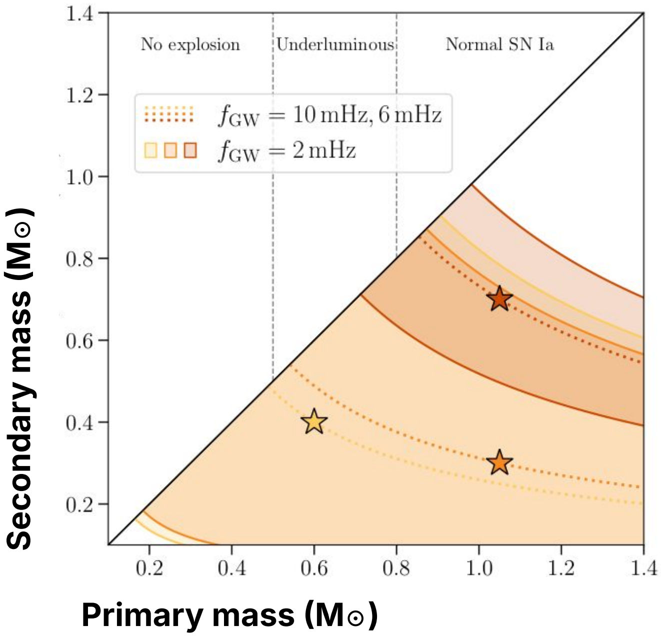


No explosion: $m_1 < 0.5\, M_\odot$

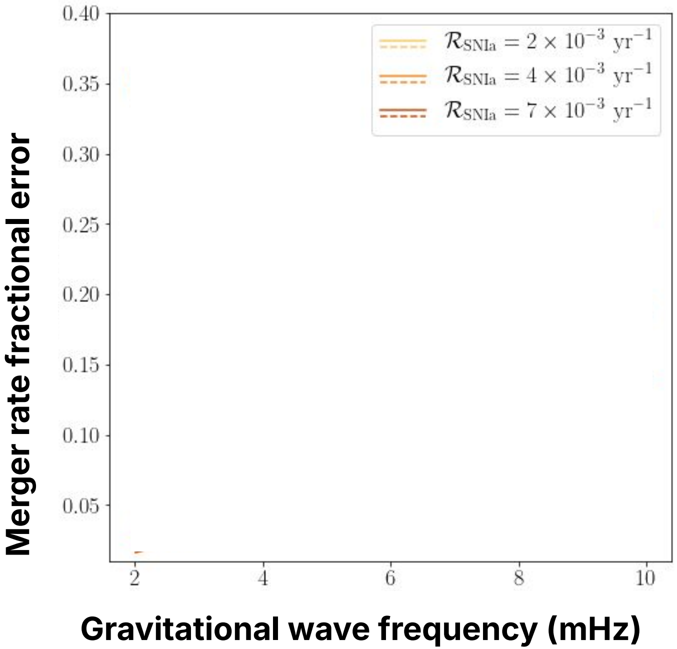
Thermonuclear explosion but **less luminous than a SN Ia**:
$0.5\, M_\odot < m_1 < 0.8\, M_\odot$

"Normal" SN Ia: $m_1 > 0.8\, M_\odot$

(based on 1D and 3D hydro-dynamical simulations: Sim et al. 2010; Shen et al. 2015, 2024; Morean-Fraile et al. 2024)

Based on the Balrog code (Uni. of Birmingham)
See e.g. Buscicchio et al. 2019, 2021; Roebber et al. 2020; Klein et al. 2022

LISA'S CONSTRAINTS ON DOUBLE-DEGENERATE
TYPE IA PROGENITORS

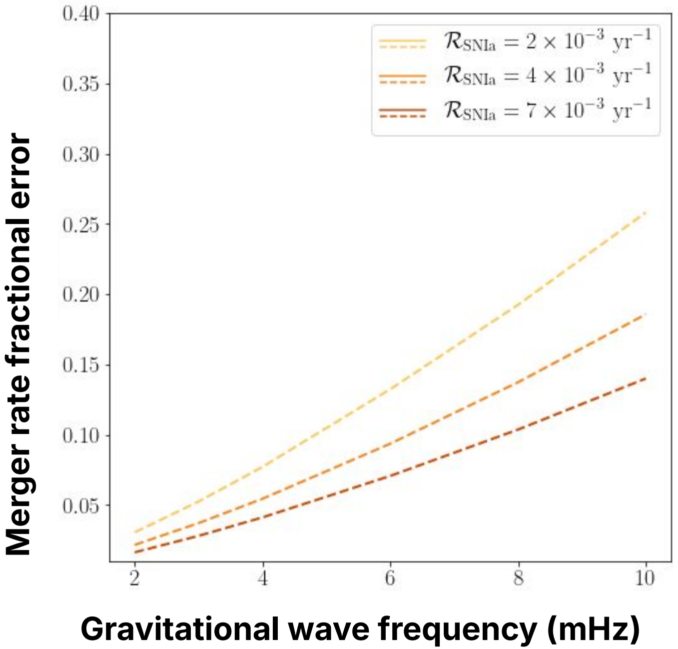


Observed rates in Milky Way-like galaxies

Reminder:

$$\mathcal{R}_{\rm SNIa} = \frac{256(G\mathcal{M})^{5/3}(\pi f_{\rm GW})^{8/3}}{5c^5} N_{\rm SNIa}(> f_{\rm GW}).$$

LISA'S CONSTRAINTS ON DOUBLE-DEGENERATE **TYPE IA PROGENITORS**



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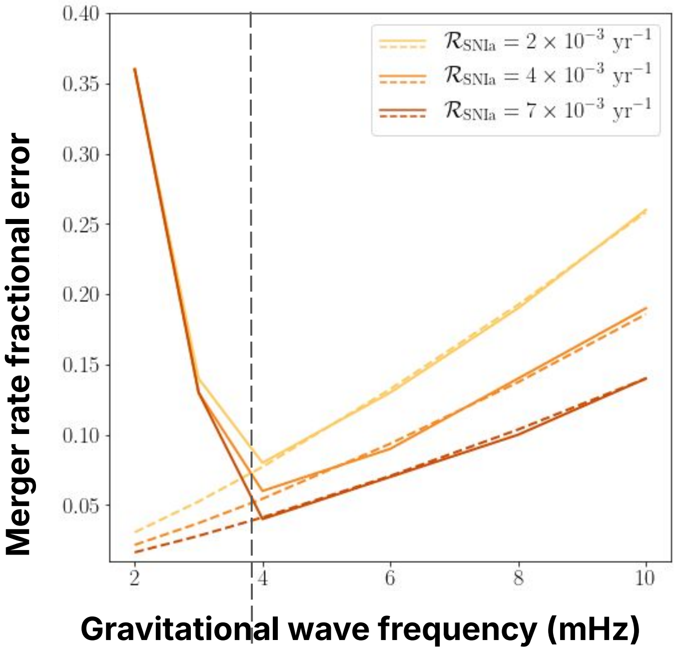

Observed rates in Milky Way-like galaxies

← The error is dominated by the chirp mass error

→ The error is dominated by the Poissonian error

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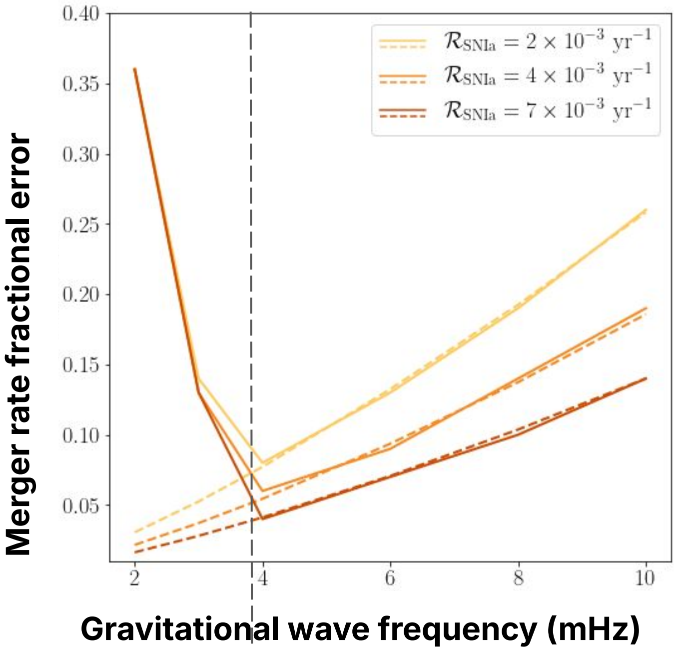
LISA'S CONSTRAINTS ON DOUBLE-DEGENERATE
TYPE IA PROGENITORS

Constraints on the merger rate of WD+WD binaries in the Milky Way to better than 4–9%



← The error is dominated by the chirp mass error

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Observed rates in Milky Way-like galaxies

If the merger rate turns out to be consistent with the SNe Ia rate measured based on EM observations in Milky Way-like galaxies, it would be a strong evidence in favour of the double-degenerate scenario.

Reminder:

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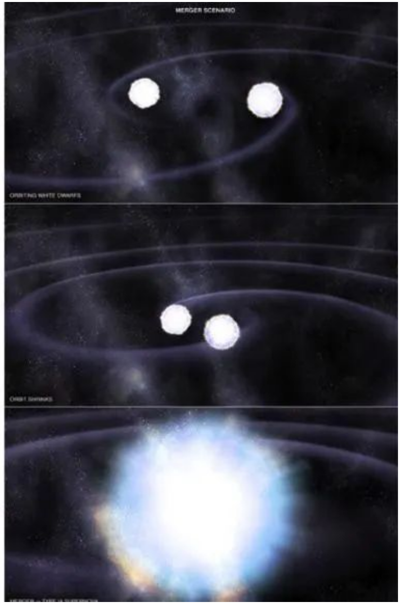
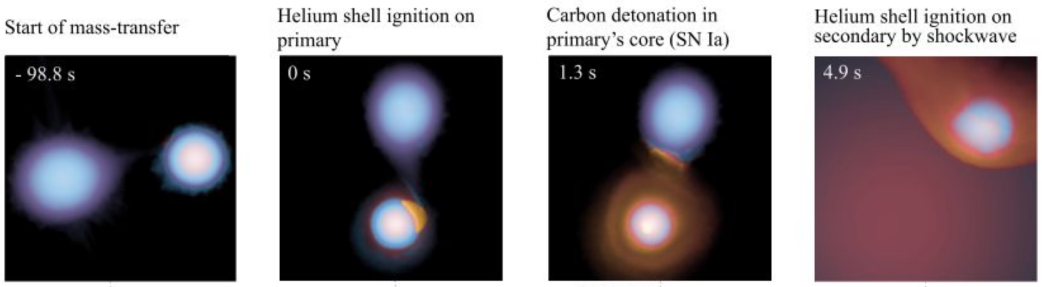


Image credits: NASA / CXC / M. Weiss

There is a 4-7% chance that we will detect a Type Ia supernova with LISA in 10yr

How will it look in gravitational waves?

ASSUMING THAT TYPE IA SUPERNOVAE ARE PRODUCED VIA A **DOUBLE DETONATION** MECHANISM



3D hydrodynamical simulation of a **1.05 M⊙ + 0.7 M⊙ carbon-oxygen white dwarf binary** by Pakmor et al. 2022

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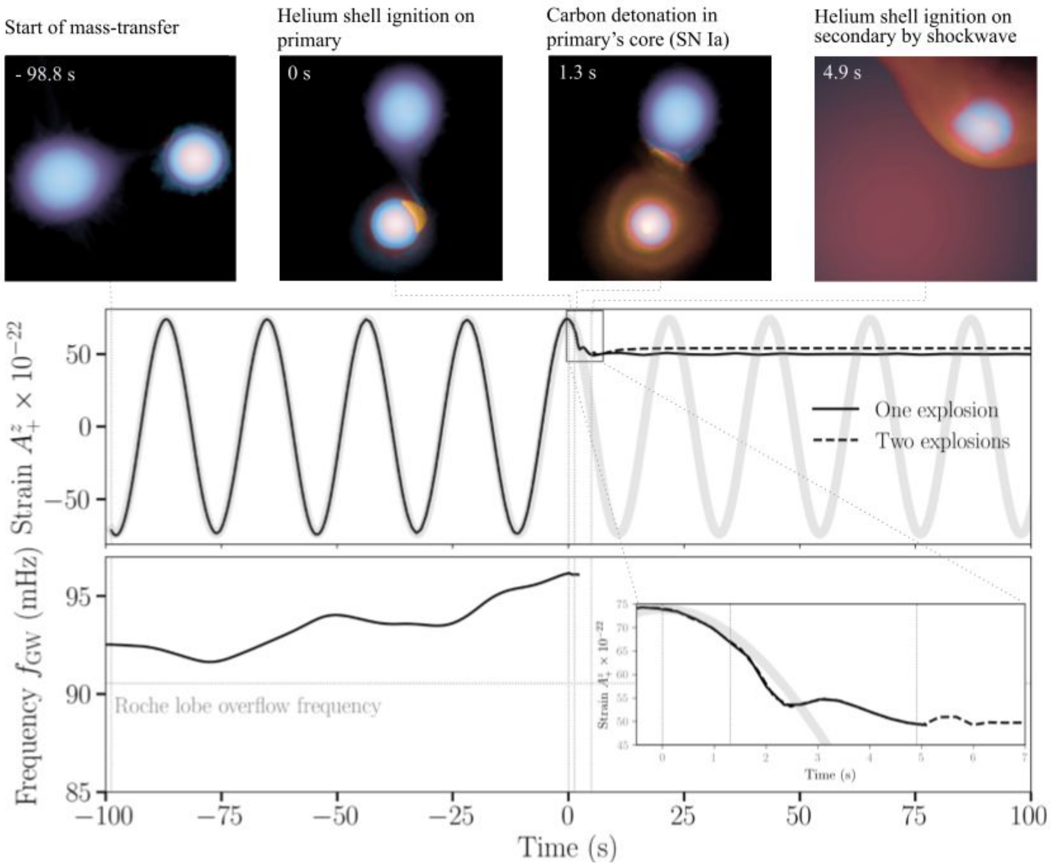
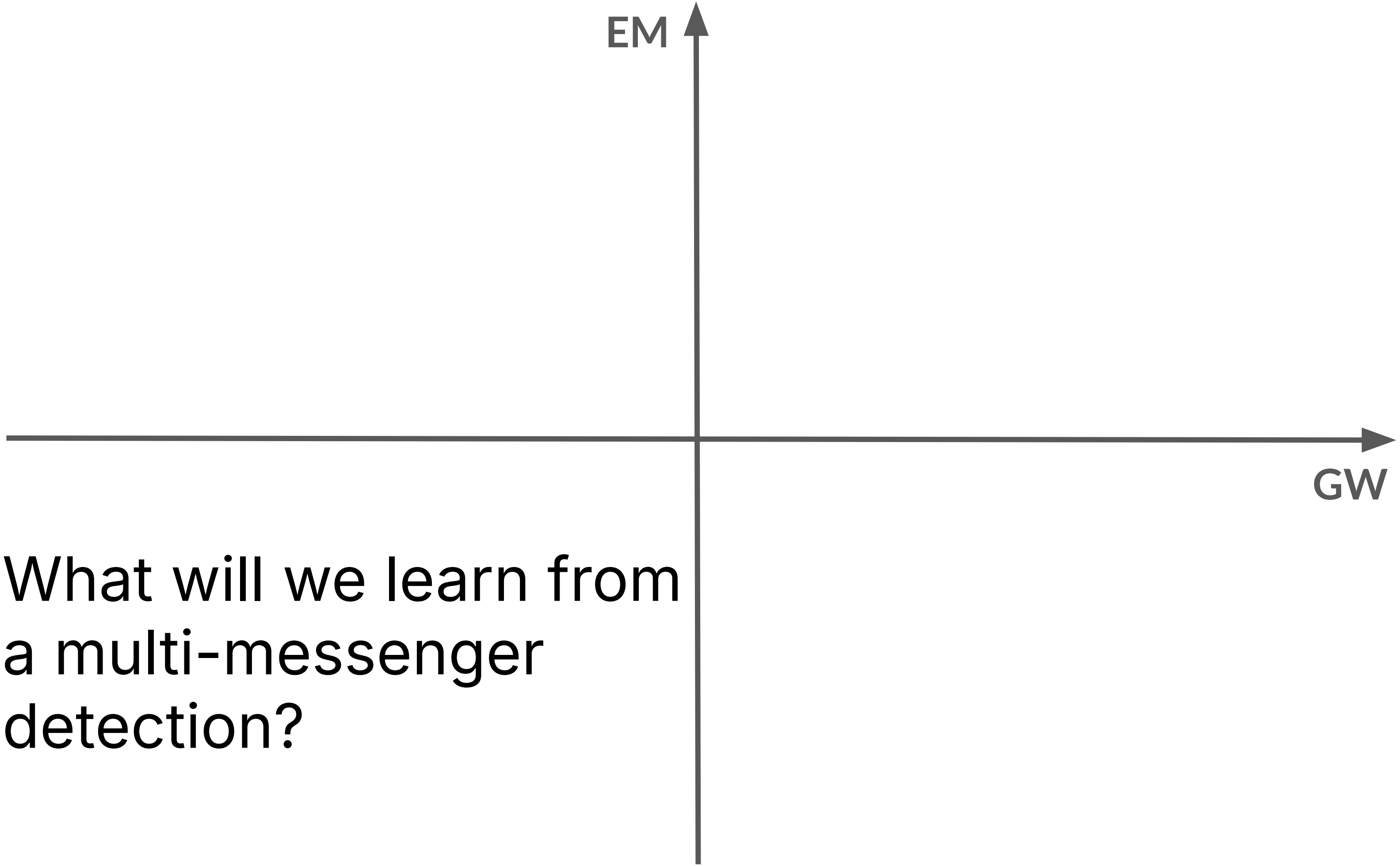


3D hydrodynamical simulation of a **1.05 M⊙ + 0.7 M⊙ carbon-oxygen white dwarf binary** by Pakmor et al. 2022

Korol et al. 2024 arXiv:240703935
based Morán-Fraile el al. 2023



What will we learn from a multi-messenger detection?

EM

GWs → prompt EM (→ no GWs)

Direct confirmation of the **double-degenerate** scenario, Type Ia supernovae produced via dynamical explosions such as **double detonation**.

(Neutrinos detection is unlikely)

GW

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Direct confirmation of the **double-degenerate** scenario, Type Ia supernovae produced via **classical super-Chandrasekhar merger scenario** (delays up to 10^4 yrs).

(Neutrinos detection is possible)

What will we learn from a multi-messenger detection?

EM

Only EM

Indication towards a **single-degenerate** scenario, where GWs signal in the LISA band is not expected or a **double degenerate** merger with a delay time larger than the LISA's mission lifetime.

(Neutrinos detection is possible)

GWs → prompt EM (→ no GWs)

Direct confirmation of the **double-degenerate** scenario, Type Ia supernovae produced via dynamical explosions such as **double detonation**.

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GW

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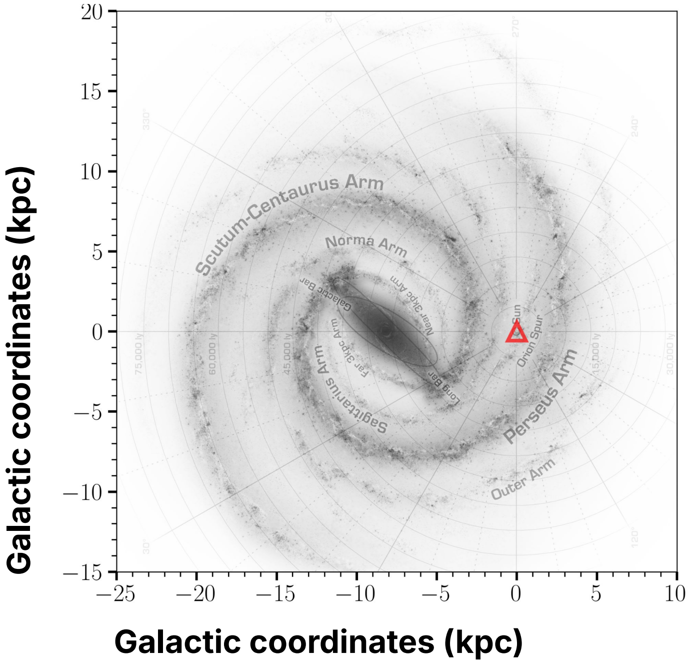
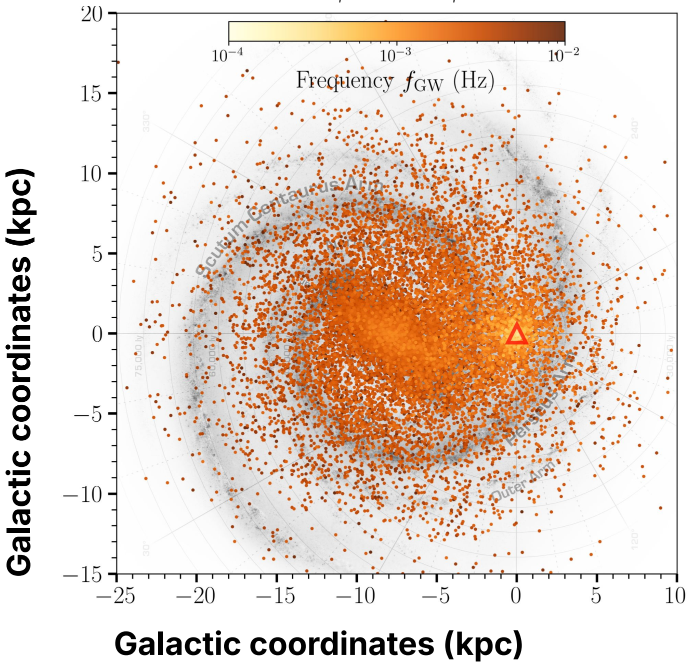
Expected insights on the Milky Way

MAKING A **GRAVITATIONAL WAVE MAP** OF THE MILKY WAY



MAKING A **GRAVITATIONAL WAVE MAP** OF THE MILKY WAY

Korol et al. 2019; Wilhelm, Korol et al. 2021



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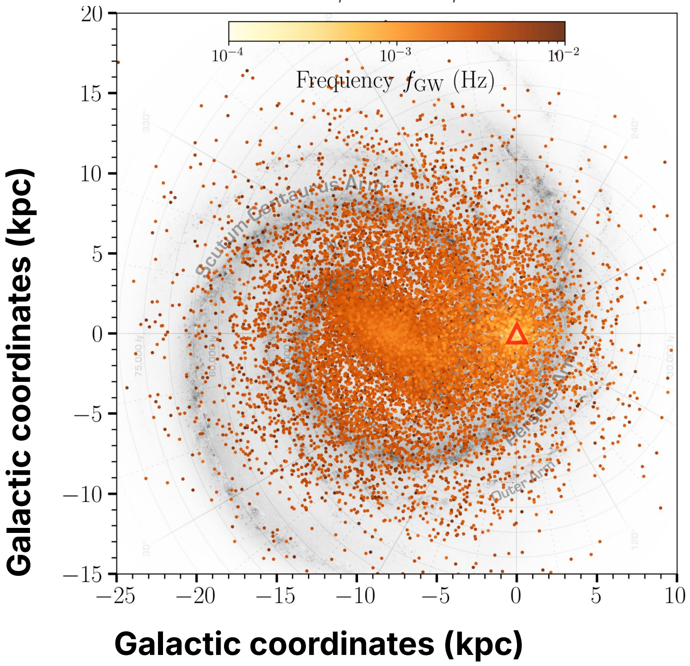


LISA's precision in locating WD+WD binaries will constrain structural parameters of the Milky Way, providing new insights into its shape:

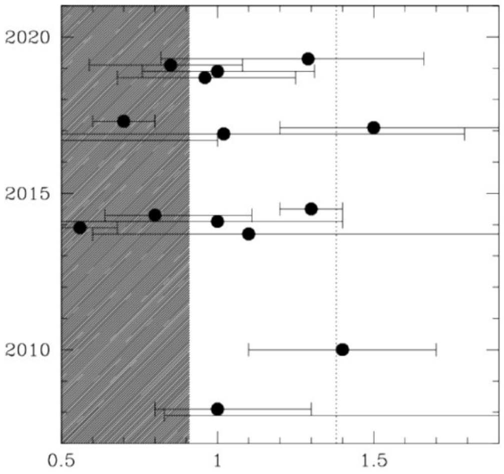
- Bulge Scale Radius: 2% precision
- Disk Scale Radius: 3% precision
- Disk Scale Height: 16% precision
- Bar Axis Ratio: 10% precision
- Bar Length: 1% precision
- Bar Orientation Angle: <1º

Korol et al. 2019; Wilhelm, Korol et al. 2021
See also Adams et al. 2012, Breivik et al. 2021

THE MILKY WAY IS A UNIQUE LABORATORY TO TEST GALAXY FORMATION THEORIES:

current constraints are still poor

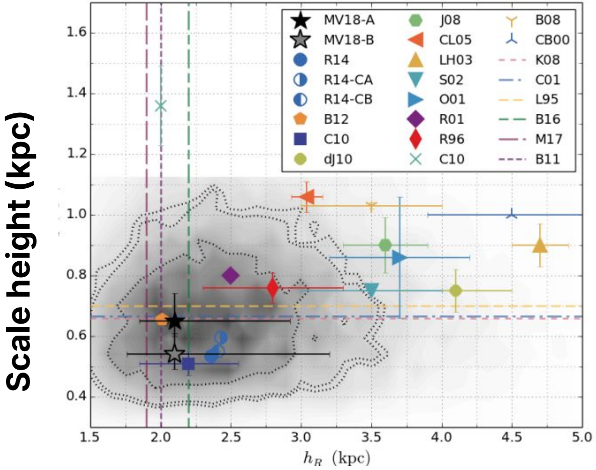
Milky Way's total mass



Total mass x 10[12] (M⊙)

Zaritsky et al. 2019

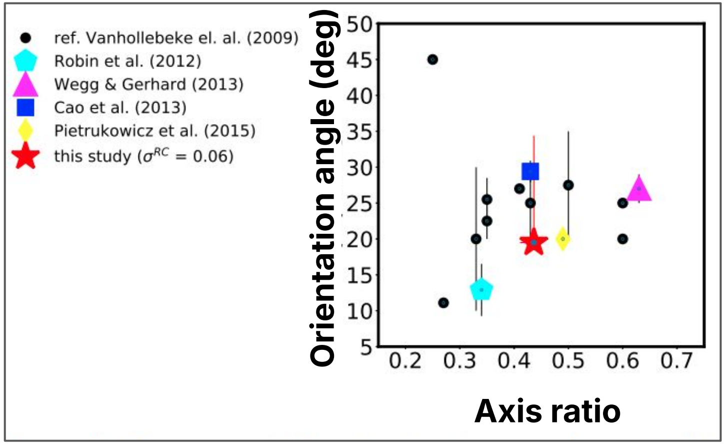
Disc scale parameters



Scale radius (kpc)

Mateu & Vivas 2018

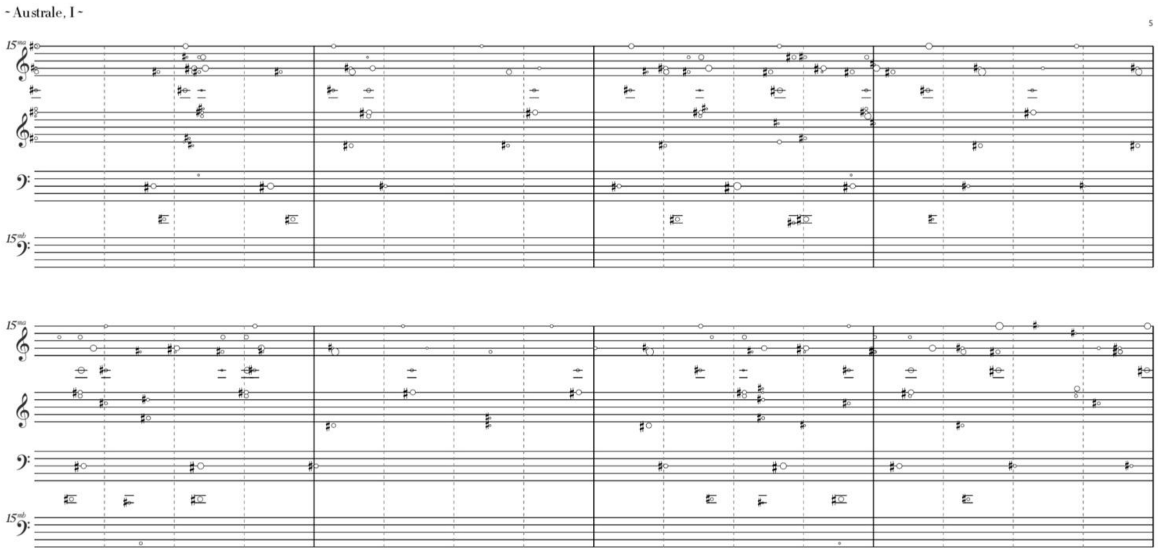
Bar's geometry

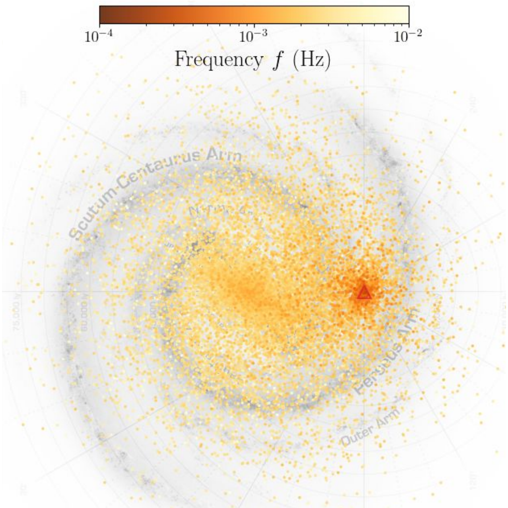


Simion et al. 2017

MAKING A **GRAVITATIONAL WAVE SOUND MAP** OF THE MILKY WAY

In collaboration with ***Andrea Valle*** (composer), ***Luca Ieracitano*** (pianist) and ***Samantha Stella*** (visual artist)
Premiere 29th October 2021, Genoa Science Festival, Genoa, Italy

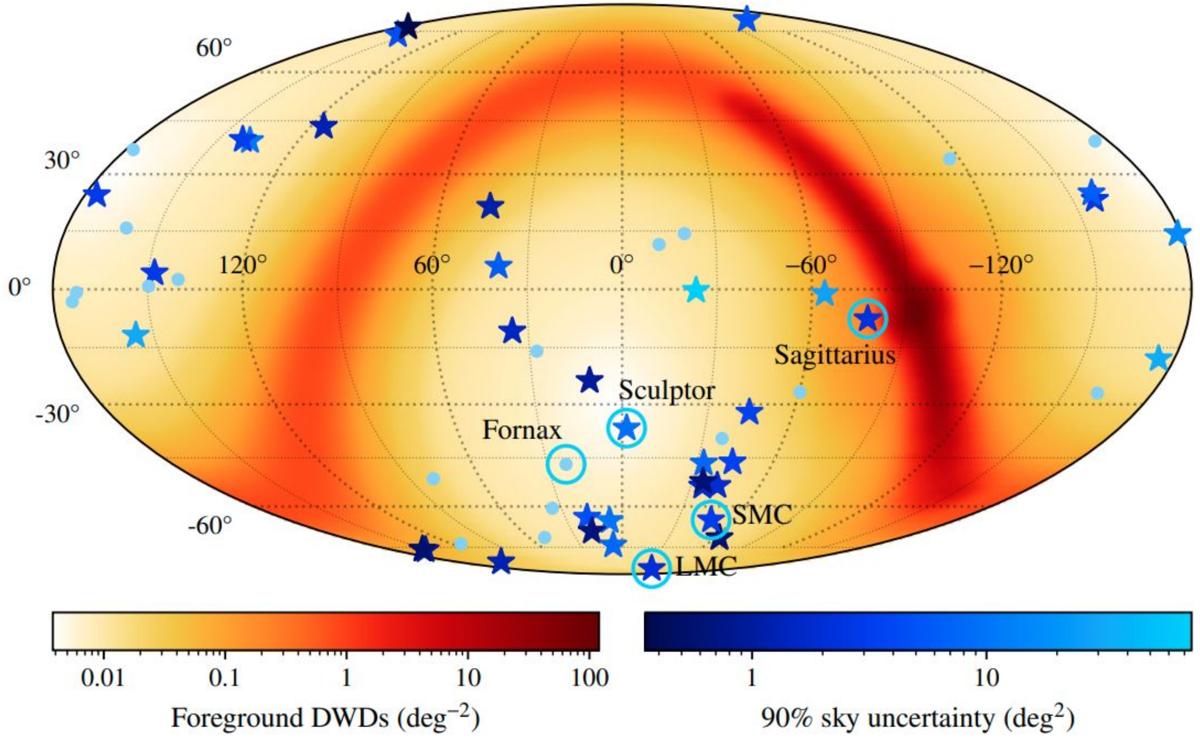




Periplo del latte: bandcamp/andreavalle/periplo-del-latte

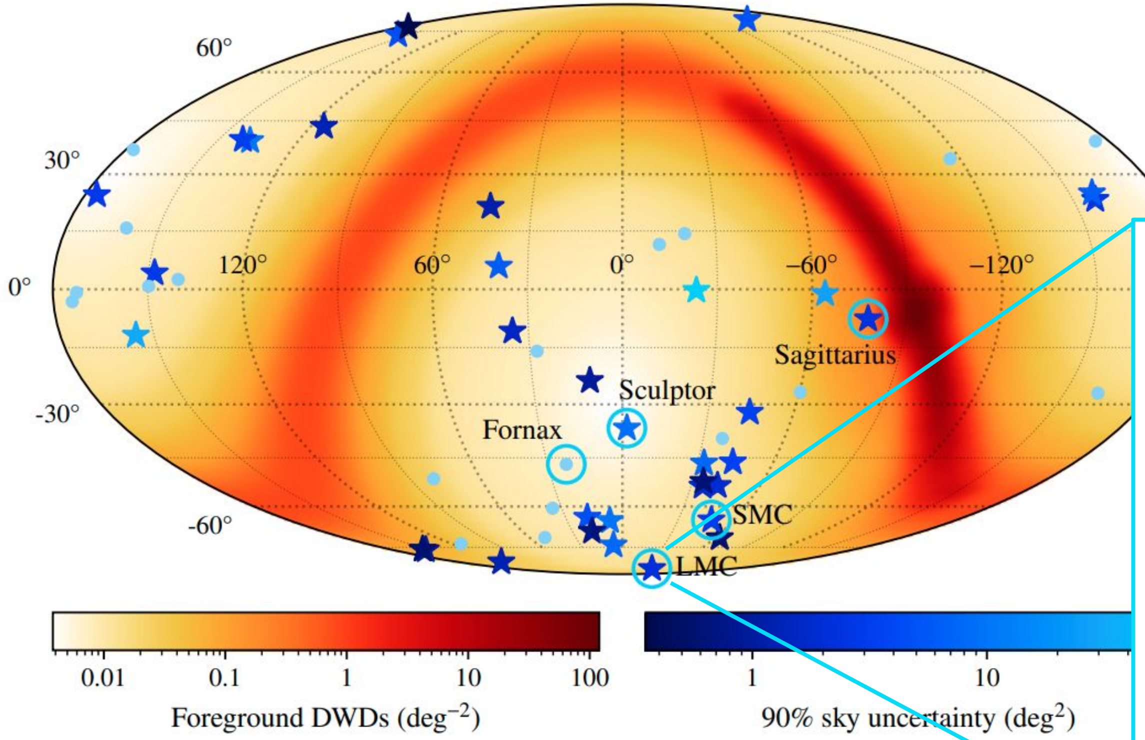
For LISA. Music composition from gravitational waves Valle & Korol 2022, arXiv:2202.04621

(RE-)**DISCOVERING** MILKY WAY **SATELLITES** WITH LISA

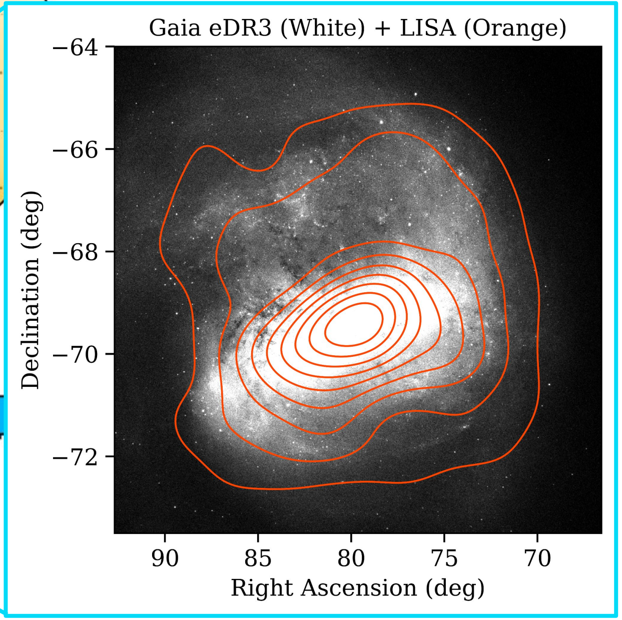


Roebber et al. /w Korol 2020; Korol et al. (2020, 2021); Pozzoli et al. /w Korol (2025)

(RE-)DISCOVERING MILKY WAY SATELLITES WITH LISA



Keim, Korol et al. (2024)

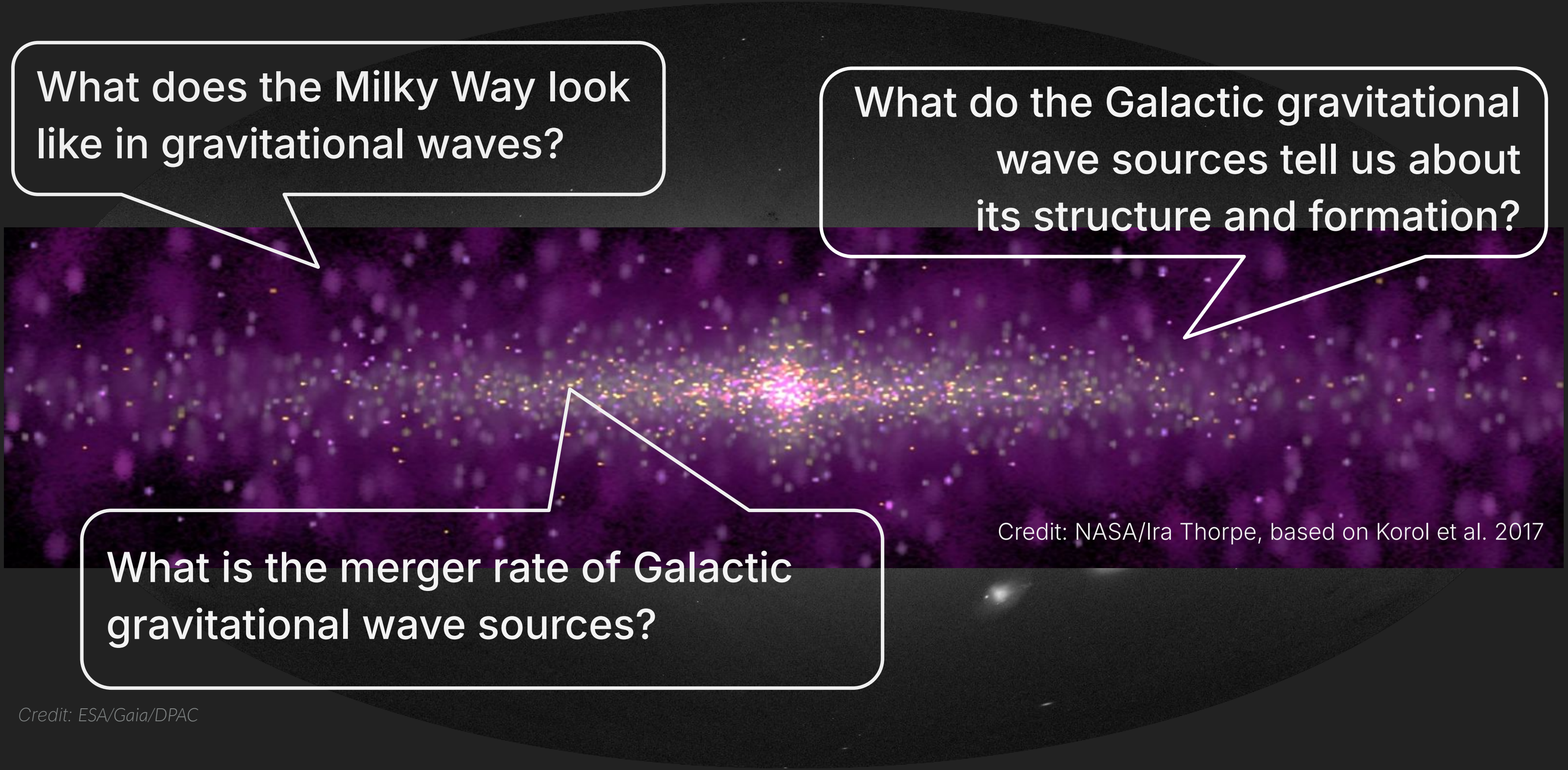


Roebber et al. /w Korol 2020; Korol et al. (2020, 2021); Pozzoli et al. /w Korol (2025)

RECAP

1. Help to unveil Galactic population of stellar “fossils” in binaries
2. Contribute to the solution of the supernova type Ia progenitor problem
3. Map the Milky Way and its satellites

and so much more ...



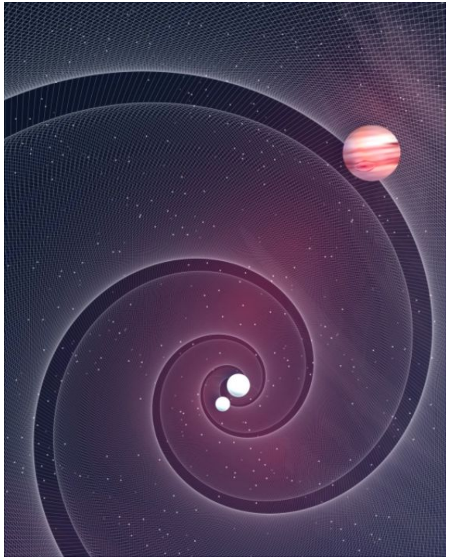
Credit: NASA/Ira Thorpe, based on Korol et al. 2017

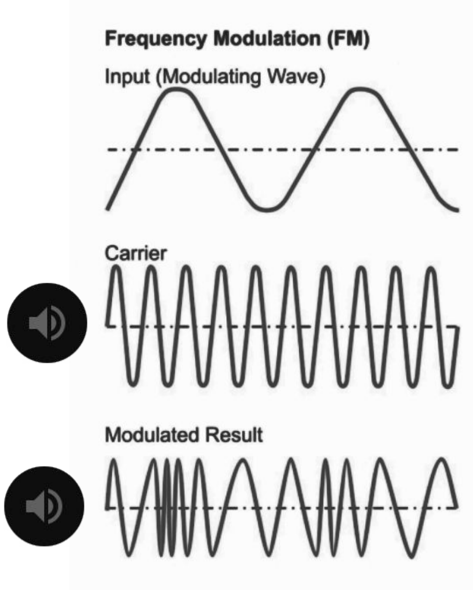
Credit: ESA/Gaia/DPAC

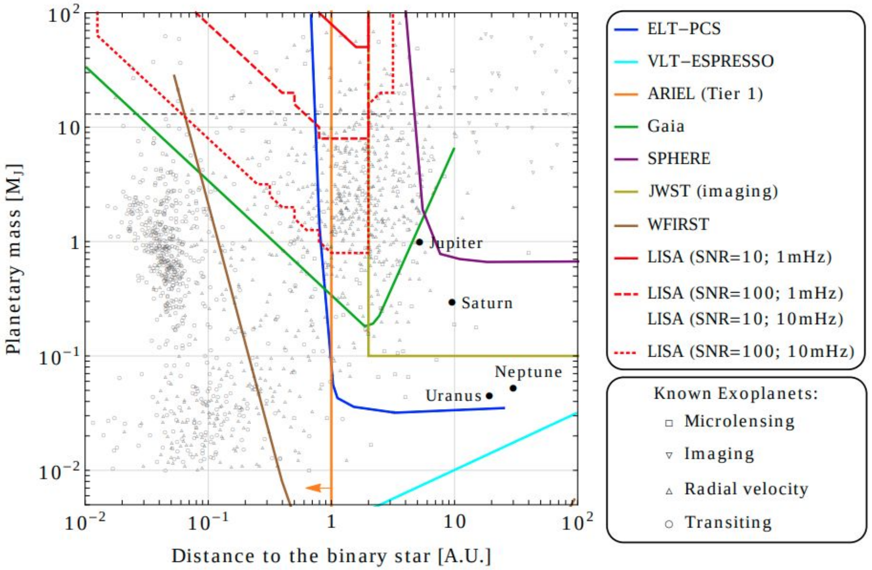
Bonus slides

Expected insights on exoplanets

Detecting a new population of exoplanets with LISA

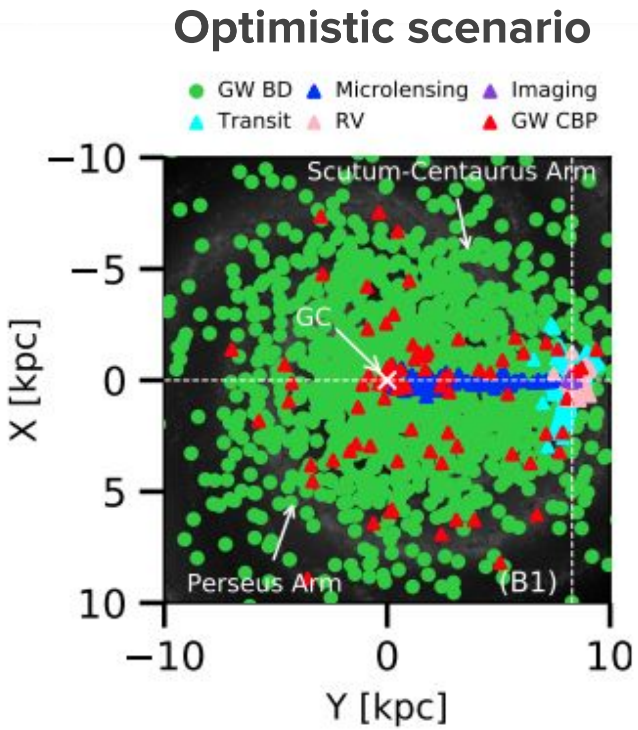


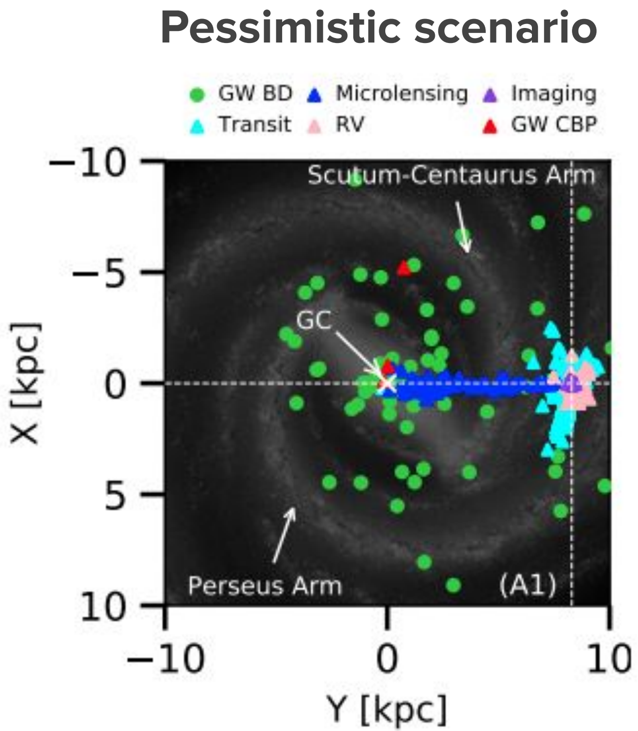




Tamanini & Danielski 2018
See also Seto et al. 2008

Detecting a new population of exoplanets with LISA across the entire Milky Way





Danielski, Korol et al. 2019; Katz et al. /w Korol 2022

Backup slides