Triple systems and circumbinary exoplanets with LISA

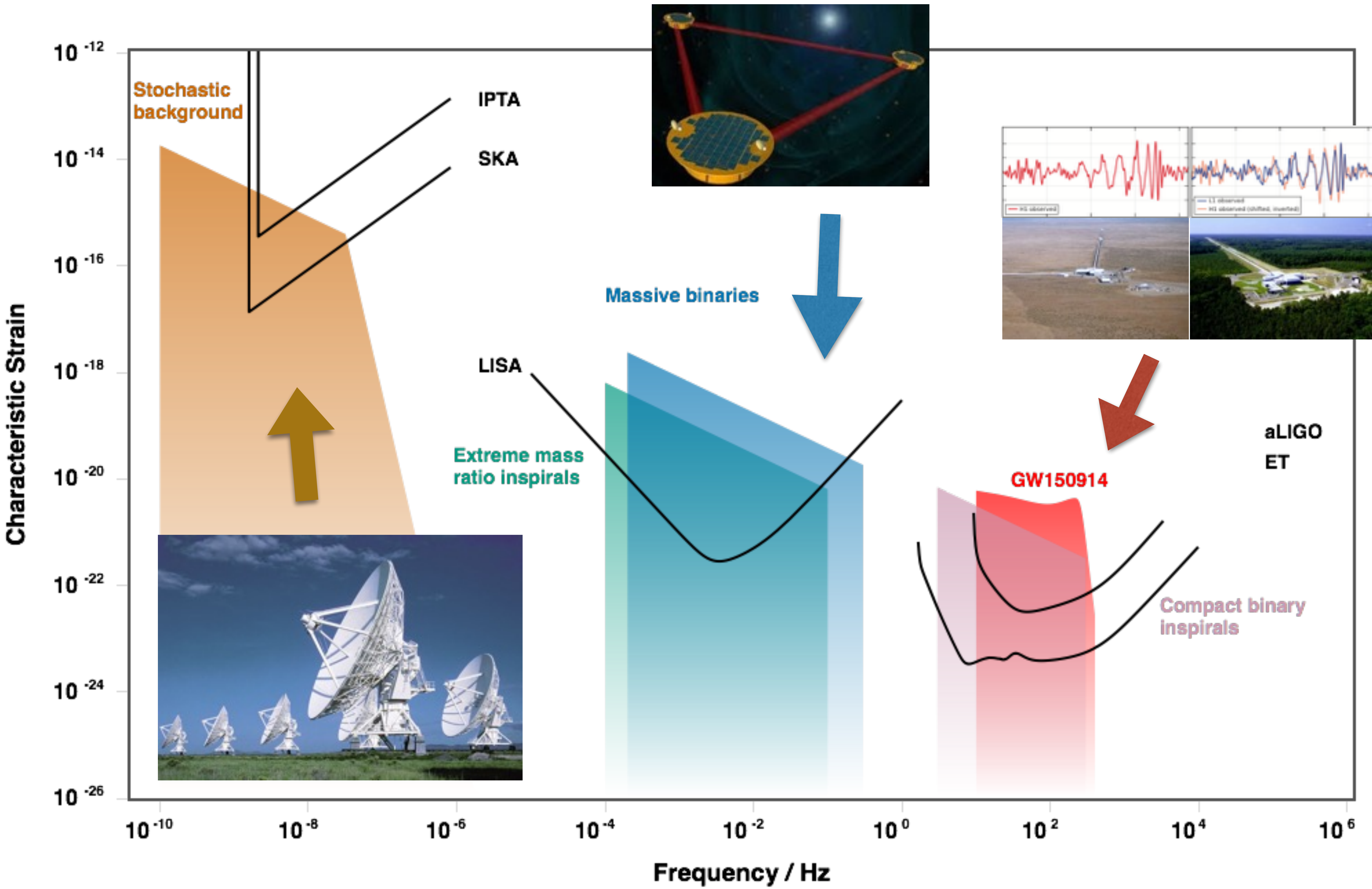
Nicola Tamanini

École MaNiTou
08/07/2022

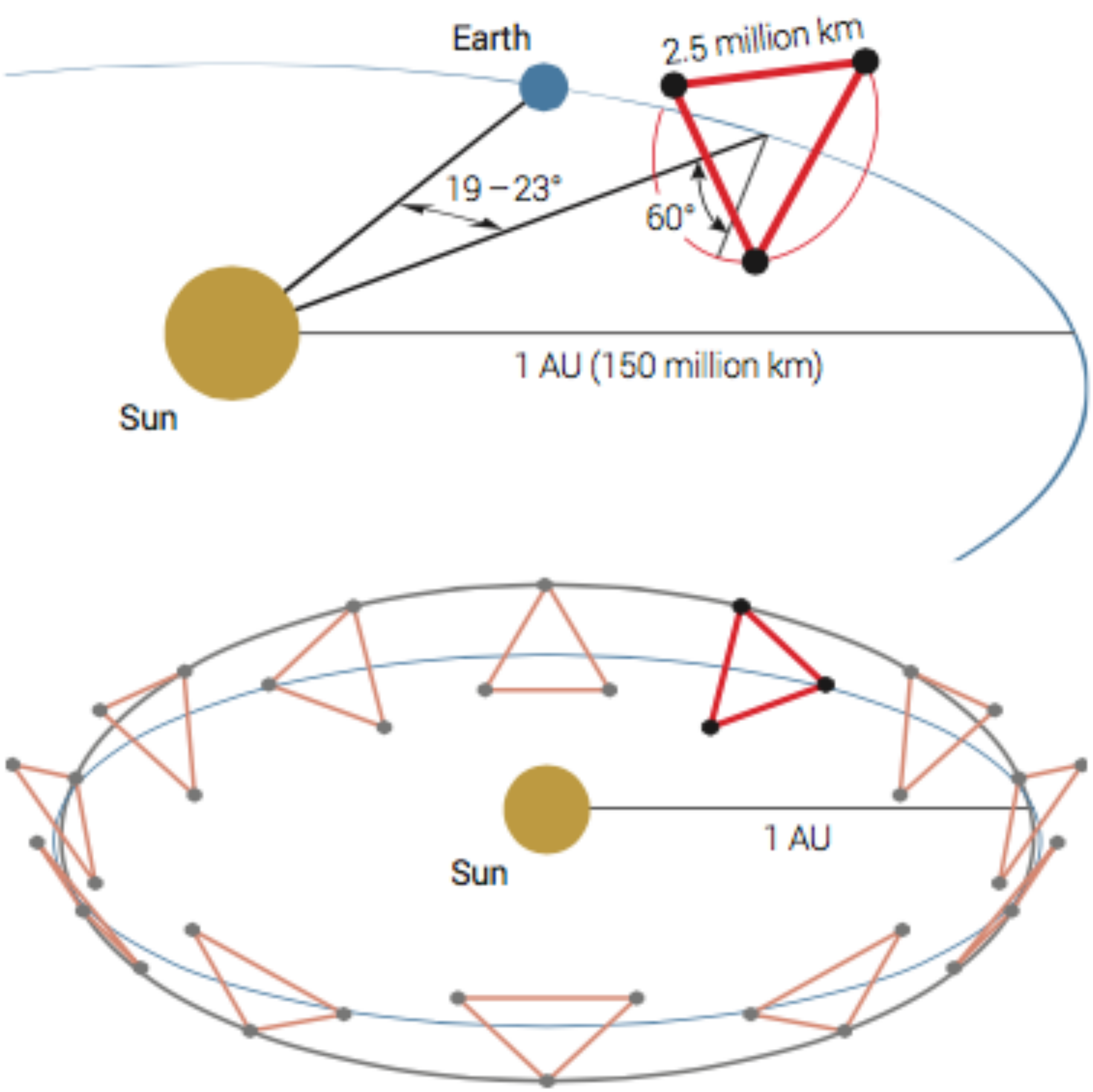
Outline

- Introduction
  - GW astronomy: from the ground into space
- LISA
  - Long-living GW sources in the mHz region
  - Observational effects of the center-of-mass motion on the GW waveform
- Application: stellar-mass BBHs
  - Probing their astrophysical environment
- Application: Galactic double white dwarf binaries
  - Detectability of circumbinary objects
  - Expected detection rates for LISA Implications for exoplanetary searches
- Further prospects and conclusions

Introduction



LISA



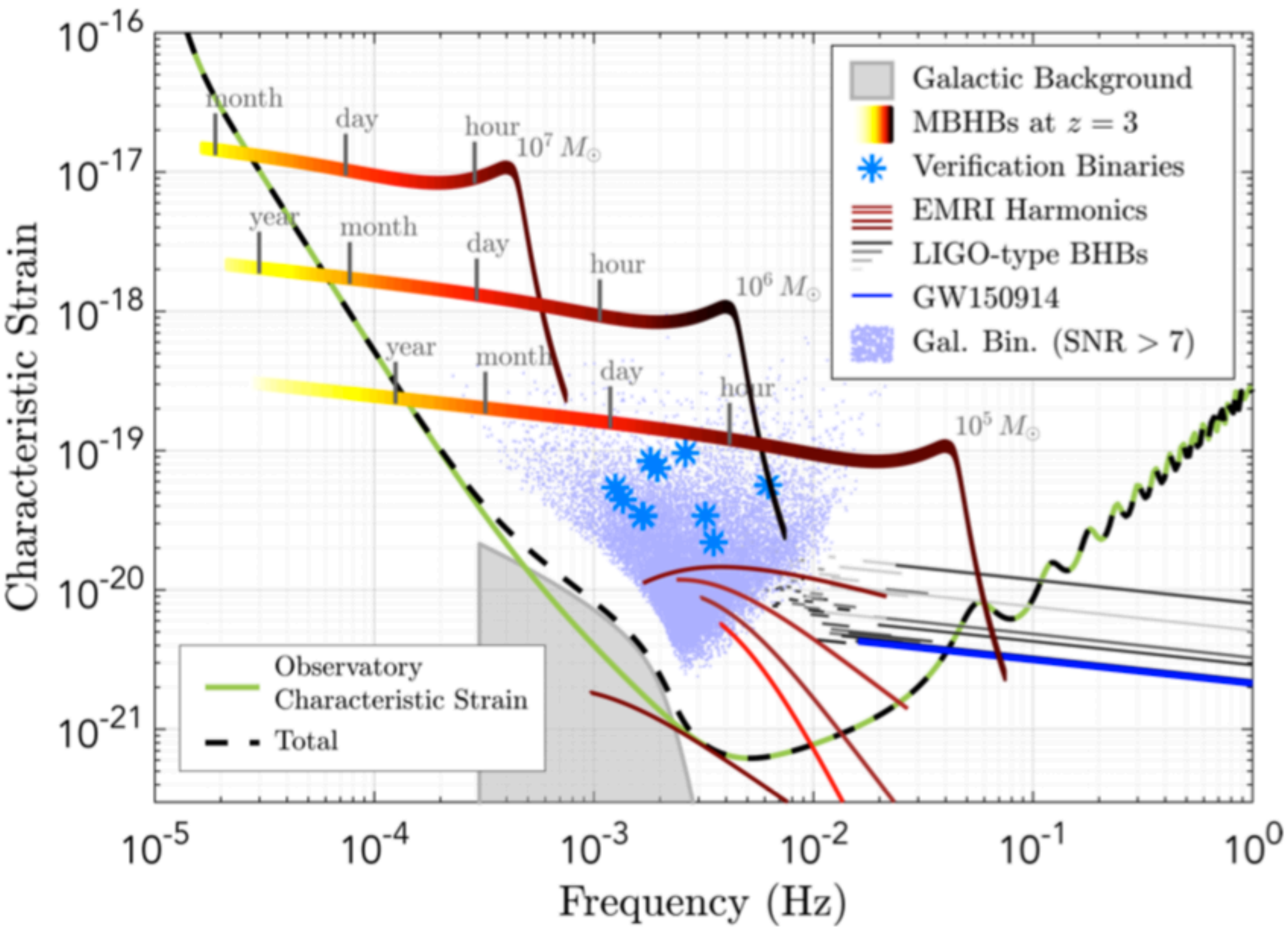
Laser Interferometer Space Antenna

Design:

- **Near equilateral triangular formation in heliocentric orbit (trailing Earth by ~50 million km)**
- **6 laser links (3 active arms)**
- **Arm-length: 2.5 million km**
- **Mission duration: 4 to 10 yrs**
- **Launch: mid-2030s**

[LISA (2017), arXiv:1702.00786]

LISA



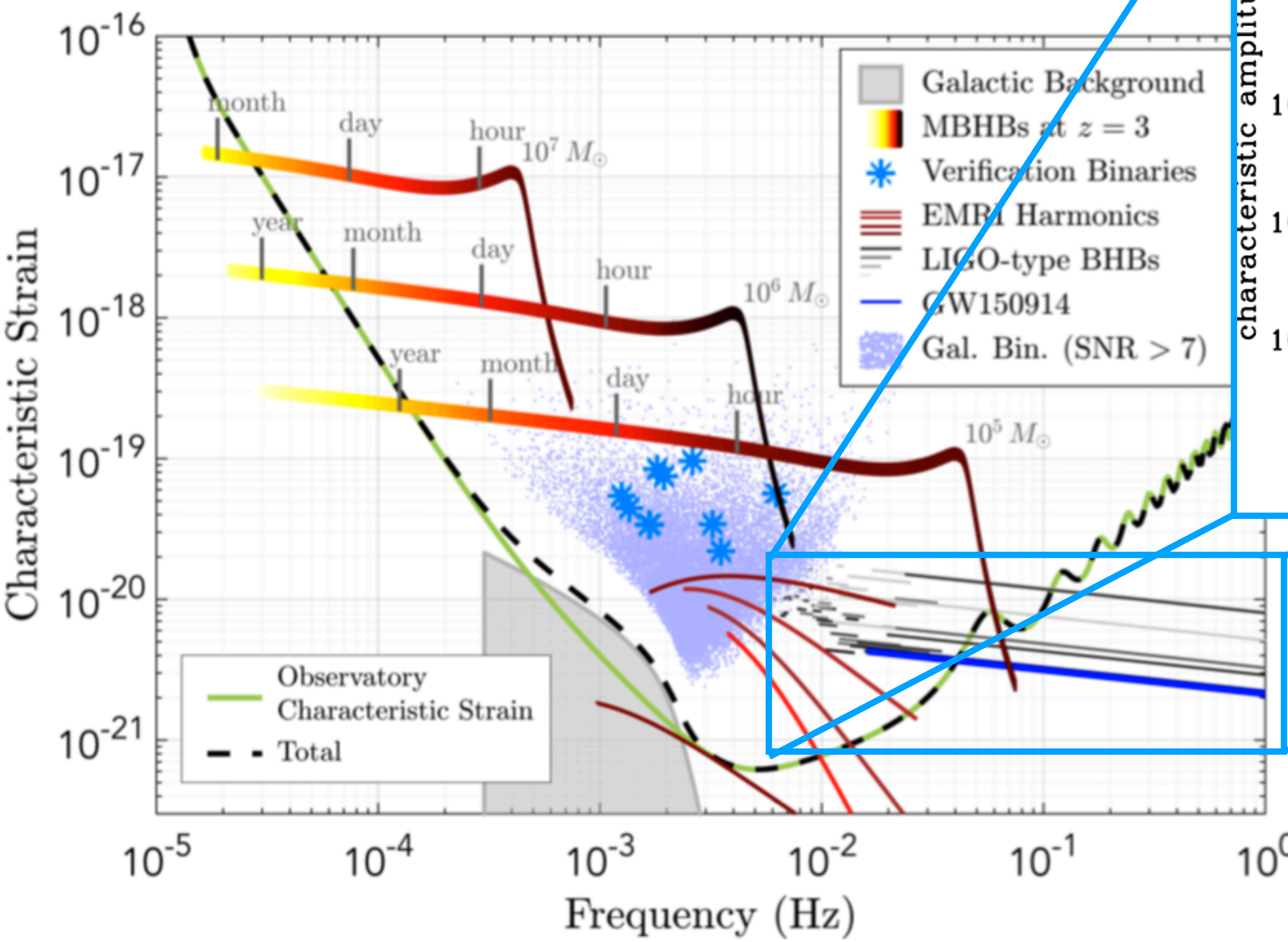
LISA GW target sources:

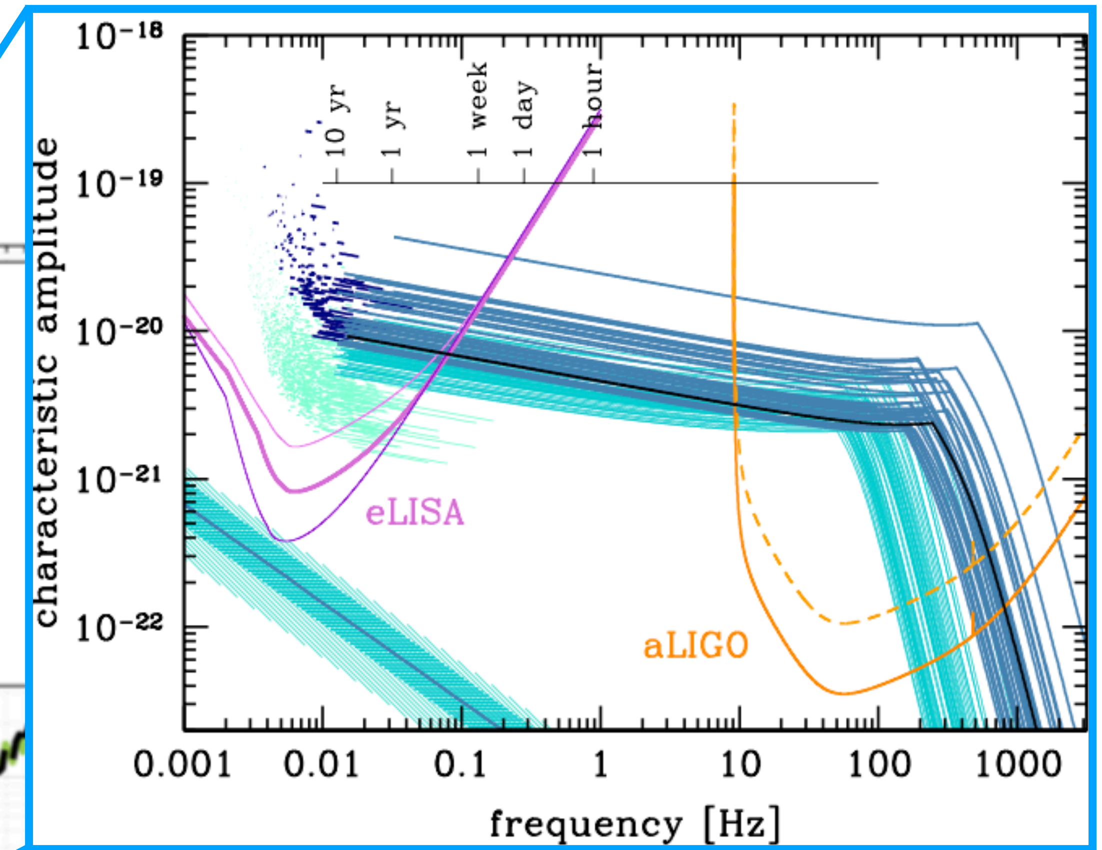
- Massive BBHs
- Galactic binaries
- Extreme mass ratio inspirals
- Stellar-mass BBHs
- Intermediate-mass BBHs
- Stochastic GW backgrounds

[LISA (2017), arXiv:1702.00786]

LISA

LISA will detect the <u>inspiral phase</u>
of stellar-mass multi-band BBHs





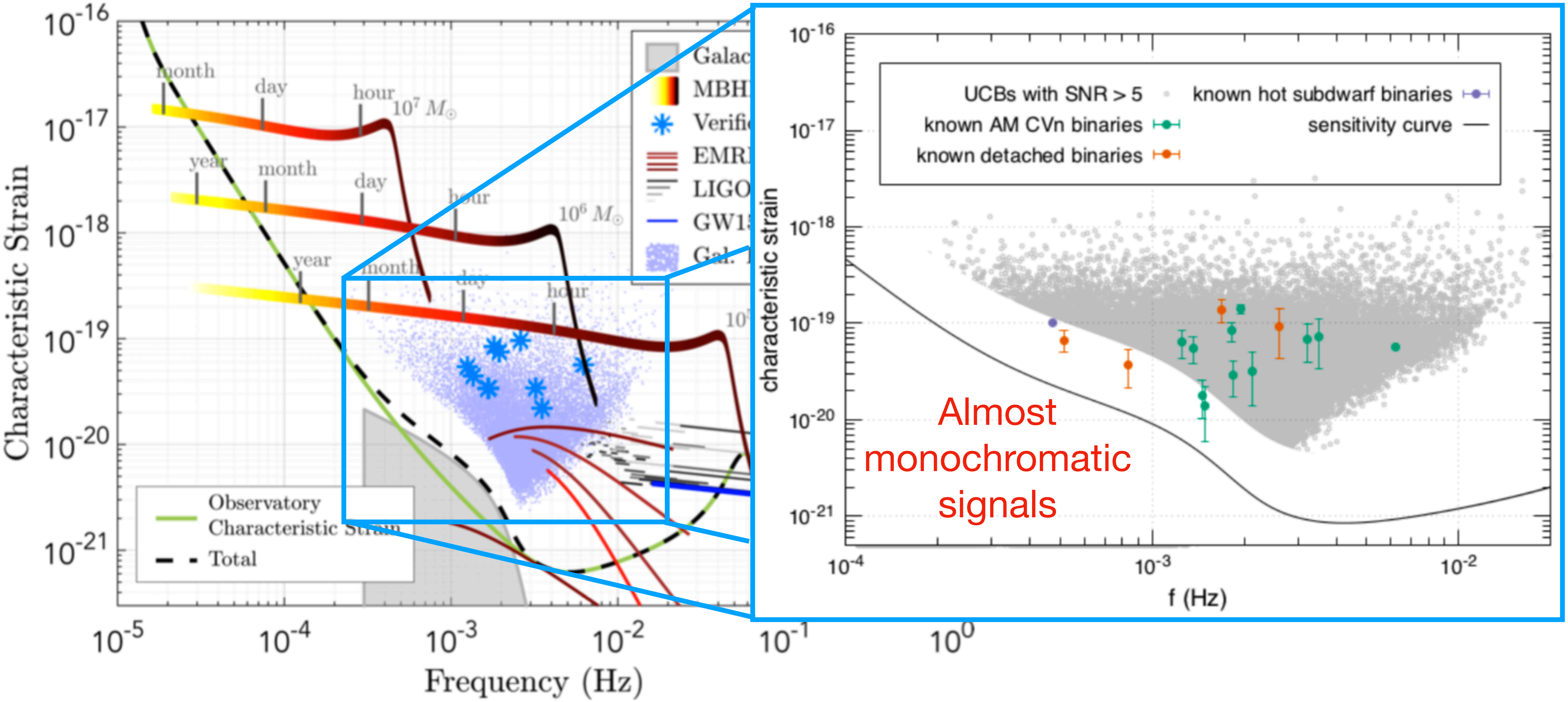
Slow inspiral in the
LISA band

[LISA (2017), arXiv:1702.00786]

[Sesana, *PRL*, 116, 231102 (2016), arXiv:1602.06951]

LISA

LISA will detect tens of thousands of double white dwarf (DWD) binaries all over the Milky Way and beyond



[LISA (2017), arXiv:1702.00786]

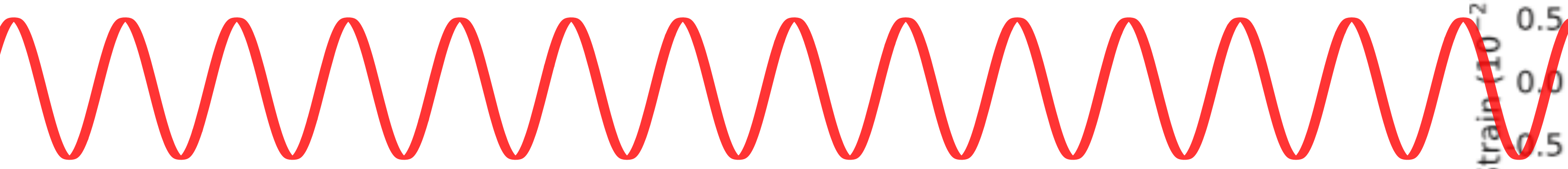
[Littenberg+ (2019), arXiv:1903.05583]
[Kupfer+, *MNRAS*, 480, 302, (2019); arXiv:1805.00482]

Center-of-Mass Effect on GWs

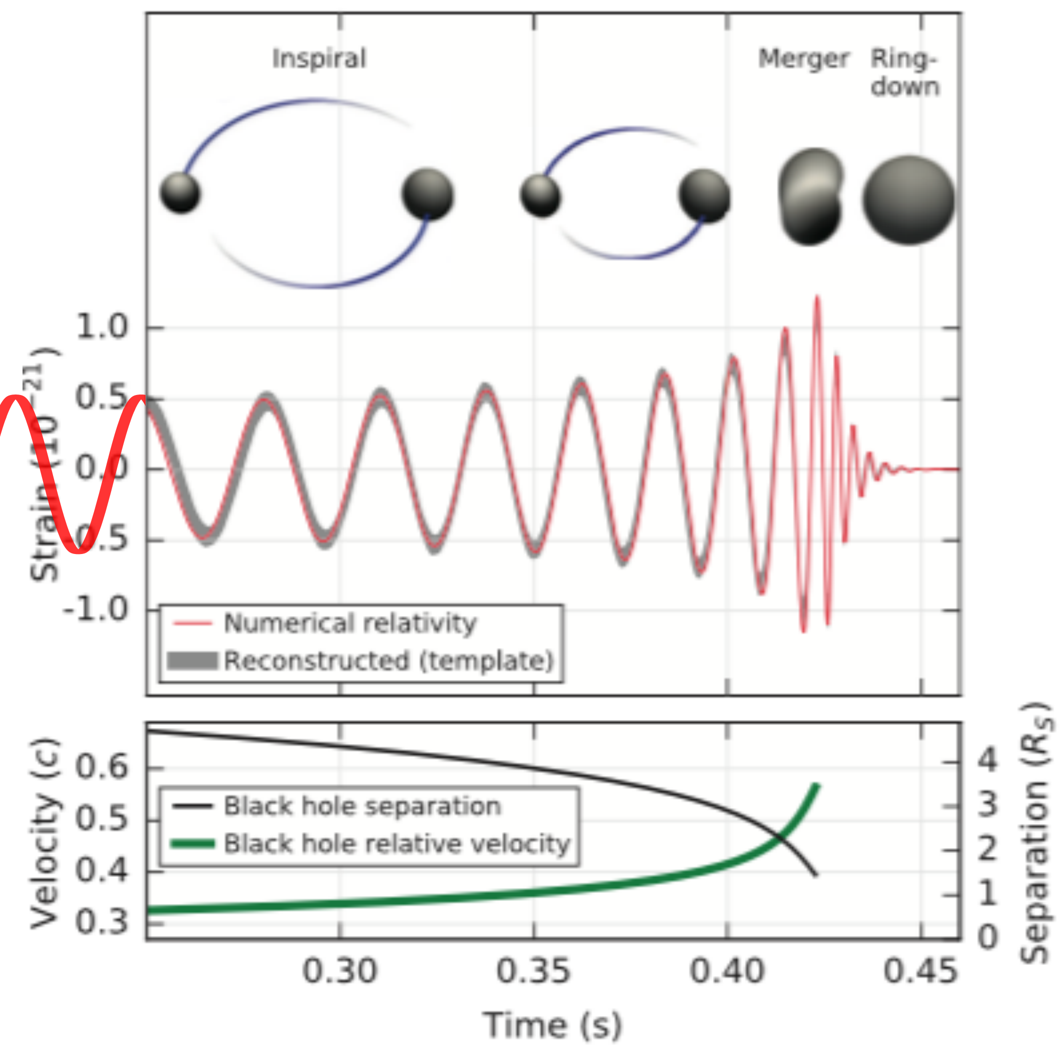
Stellar-mass BBHs and Galactic binaries are <u>long-living GWs sources for LISA</u>:
their GWs signal will be observed for as long as the whole mission duration (years)

LISA

Deep inspiral phase: GW signal varies very slowly during the observational time (~years)



LIGO-Virgo



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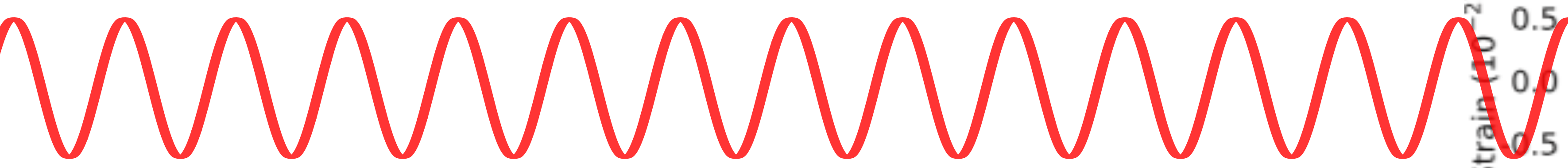

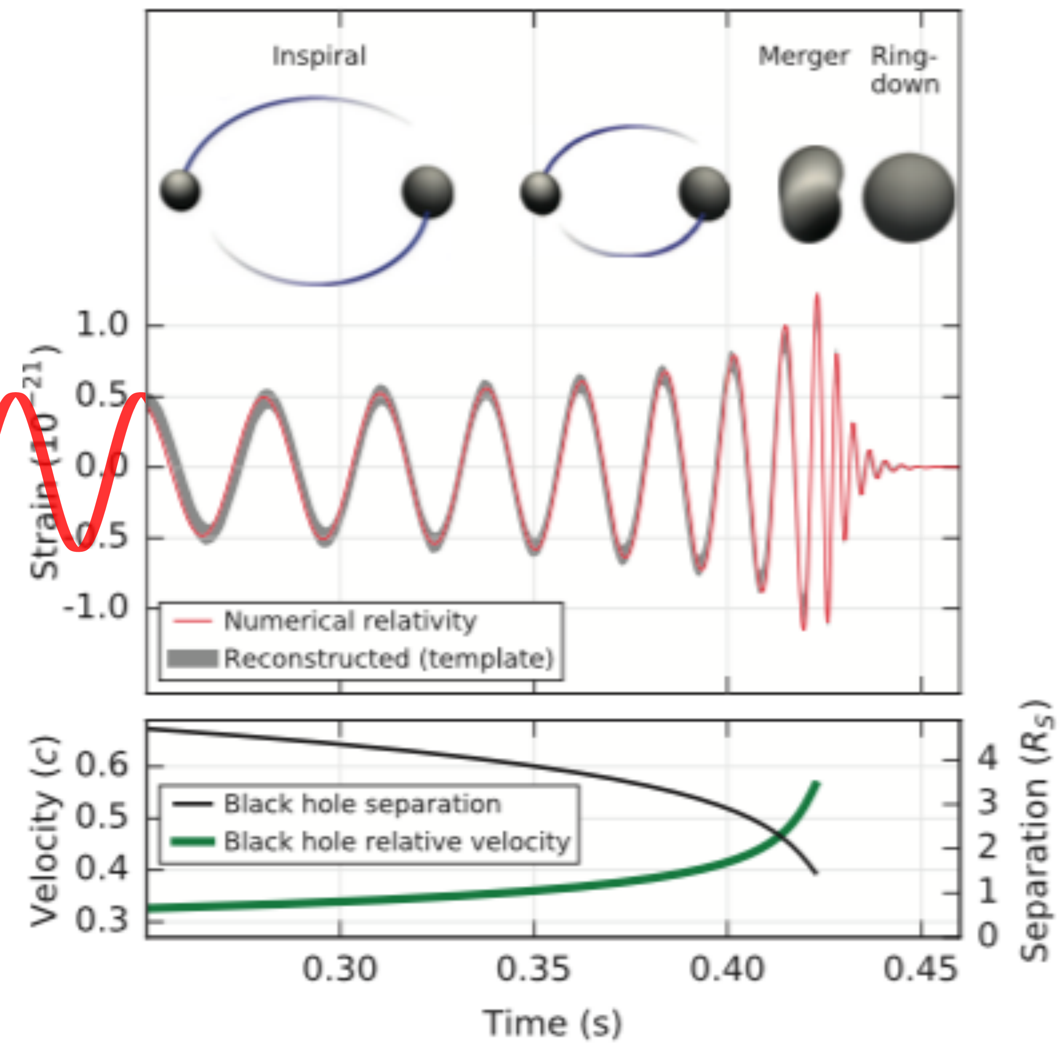

Eppur si muove! (and yet it moves!)

This is the emitted GW signal. If source and observer are in motion relative to each other, the observed GW signal will be different!

Center-of-Mass Effect on GWs

For a constant relative velocity between source and observer, all effects of the relative motion are degenerate with a mass rescaling (similar to the cosmological redshift)

$$M_c \mapsto M_{cz} = (1 + v/c)M_c \qquad \text{and} \qquad d_c \mapsto d_L = (1 + v/c)d_c$$

source-frame chirp mass (M_c) — observed chirp mass (M_{cz}) — comoving distance (d_c) — observed distance (d_L)

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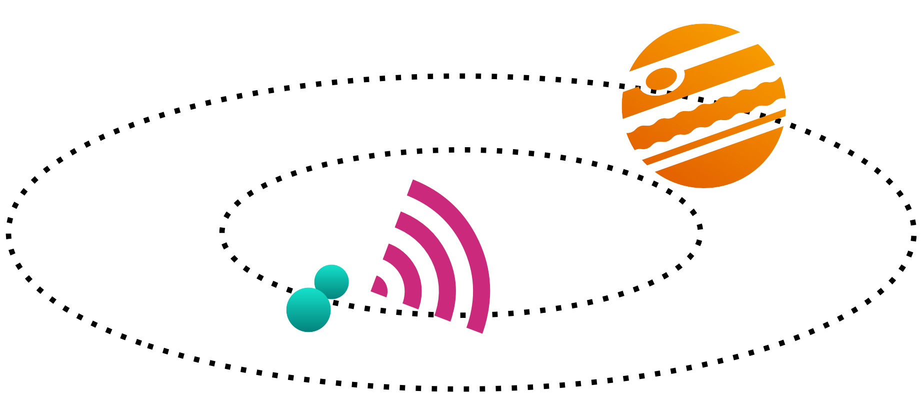
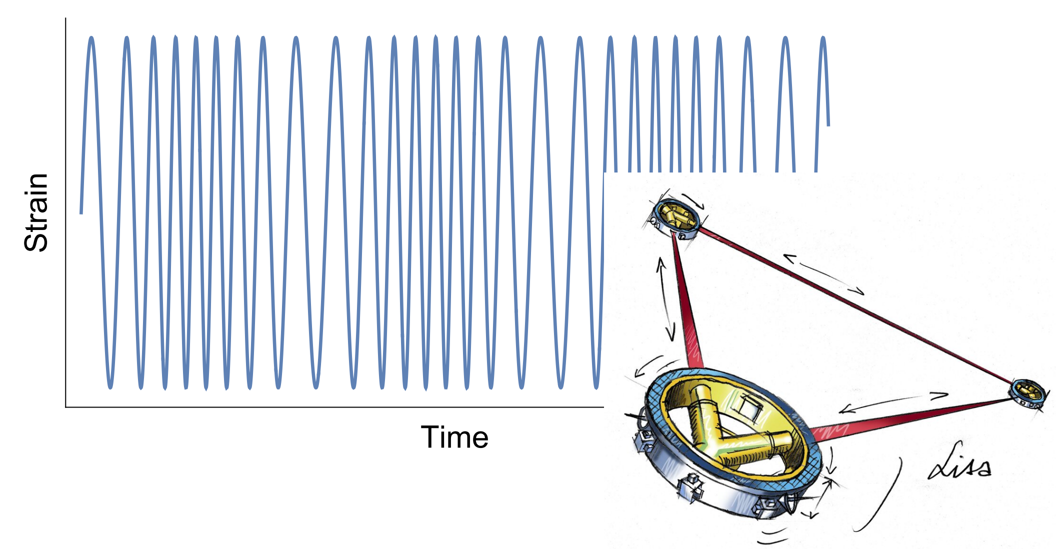
However if the velocity along the line-of-sight between source and observer is changing with time (acceleration!), the GW waveform will be modulated through the Doppler effect:

Continuous GW signal emitted by binary in orbit with a third object



Observed GW waveform Doppler modulated in frequency



Center-of-Mass Effect on GWs

observed frequency — emitted frequency — binary's center-of-mass velocity along the line-of-sight (circular orbit)

$$f_{\rm obs}(t) = \left(1 + \frac{v_{\rm los}(t)}{c}\right) f_{\rm src}(t) \quad \text{with} \quad v_{\rm los} = \left(\frac{2\pi G}{P_3}\right)^{1/3} \frac{M_3 \sin \iota}{(M_2 + M_3)^{2/3}} \cos\left(\frac{2\pi t}{P_3} + \phi_3\right)$$

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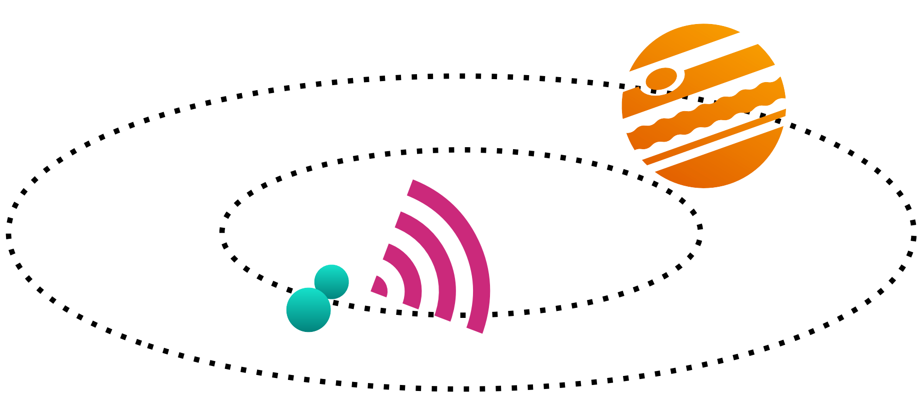

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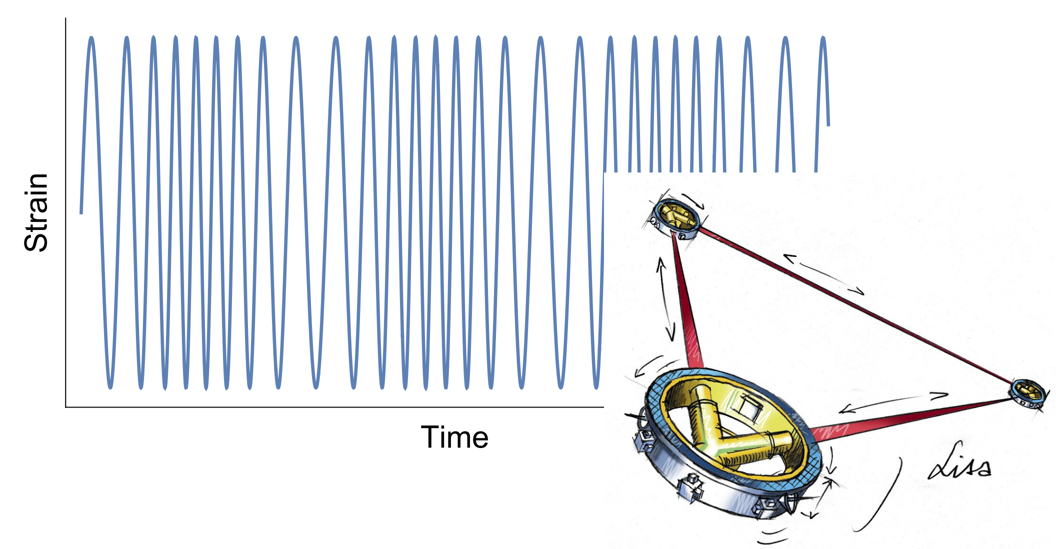

Center-of-Mass Effect on GWs

observed frequency

emitted frequency

binary's center-of-mass velocity
along the line-of-sight

LISA Radio FM

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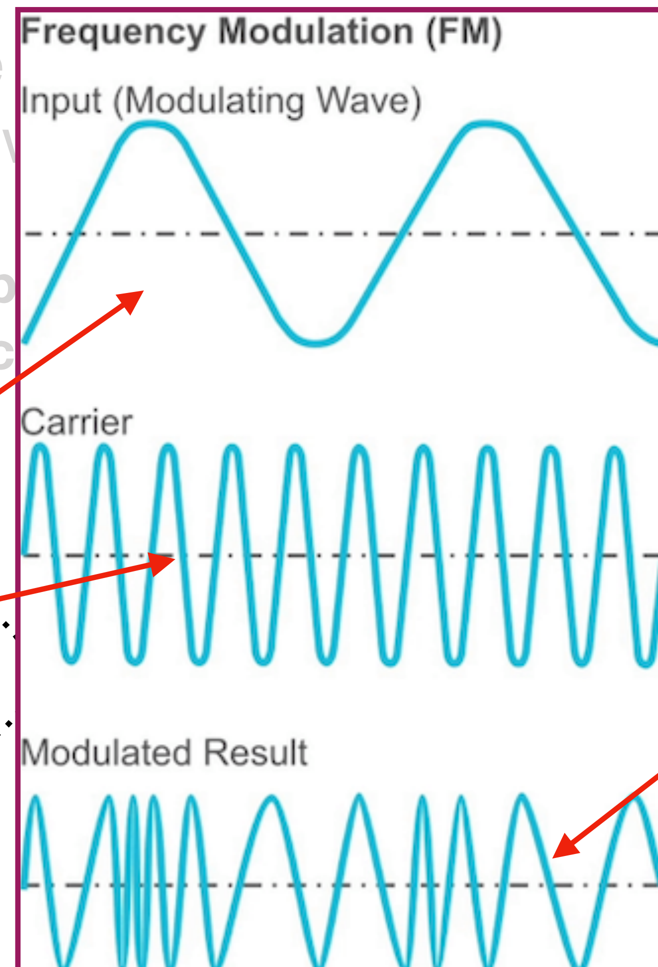
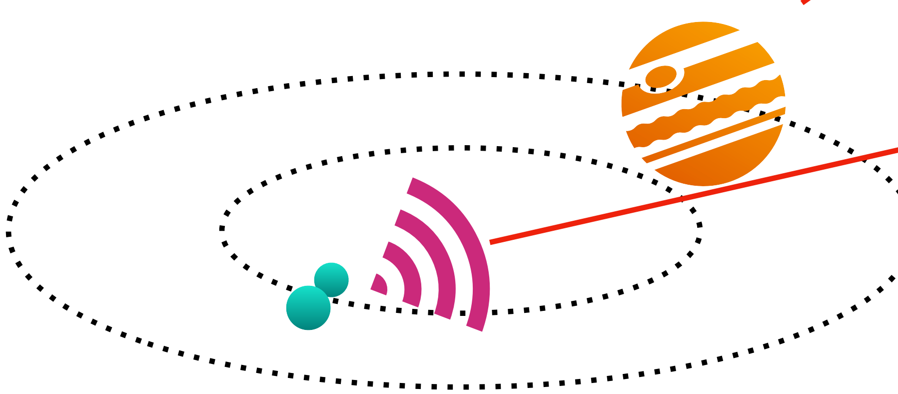
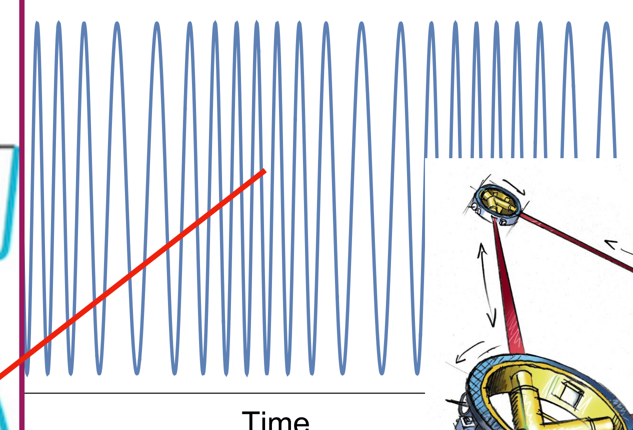
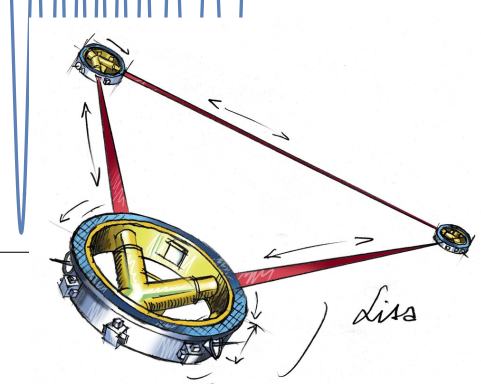


Continuous GW signal emitted b… binary in orbit with a third objec…

…bserved GW waveform Doppler modulated in frequency





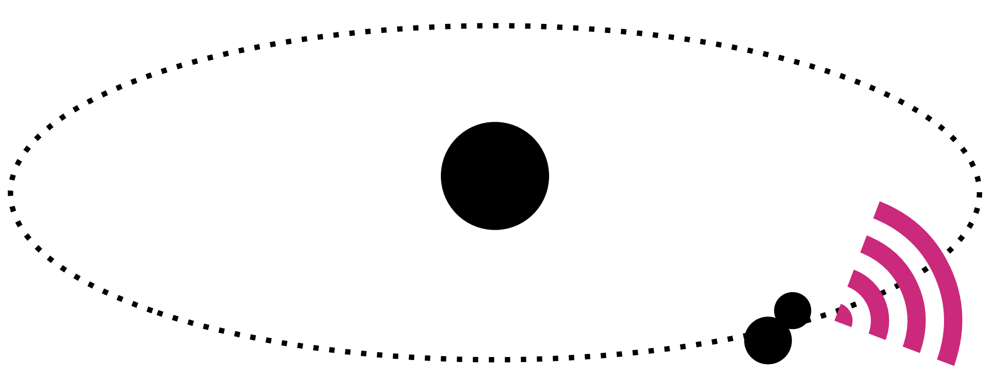


Applications

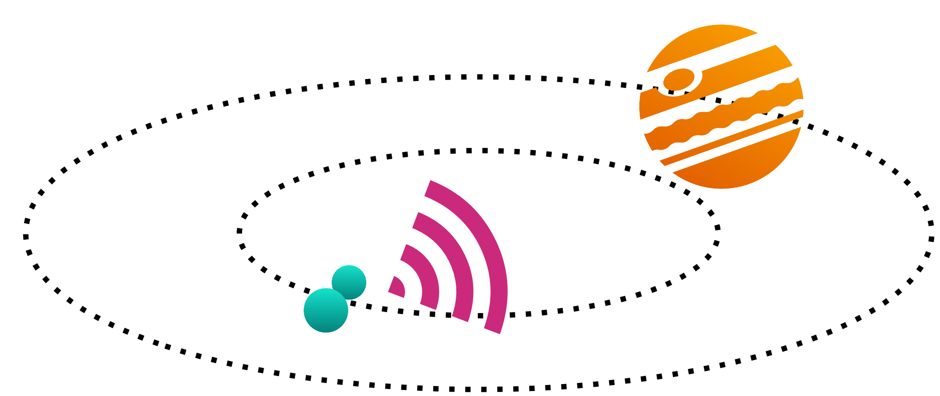
The center-of-mass of a GW binary can be accelerated by gravitational attraction only, i.e if there is a sufficiently close and sufficiently massive third body nearby

There are mainly two cases relevant for LISA:

BBHs in close orbit around a MBH/SMBH (e.g. globular clusters or AGN disks)



Galactic DWD binaries in orbit with a third object (planet, star, ...)



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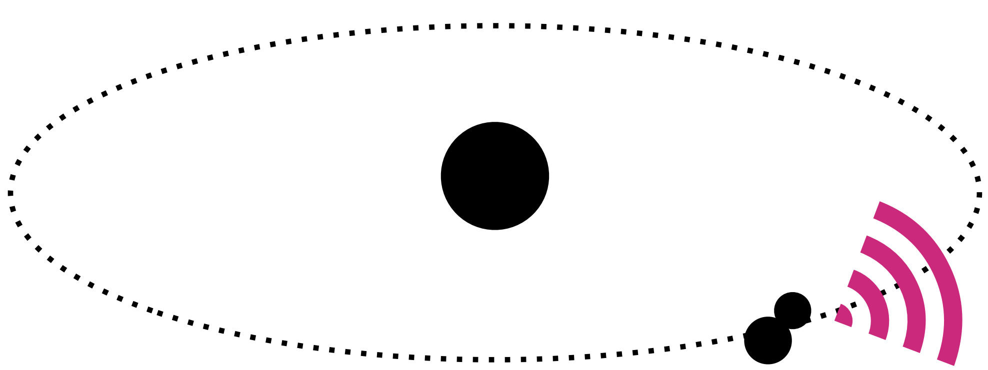

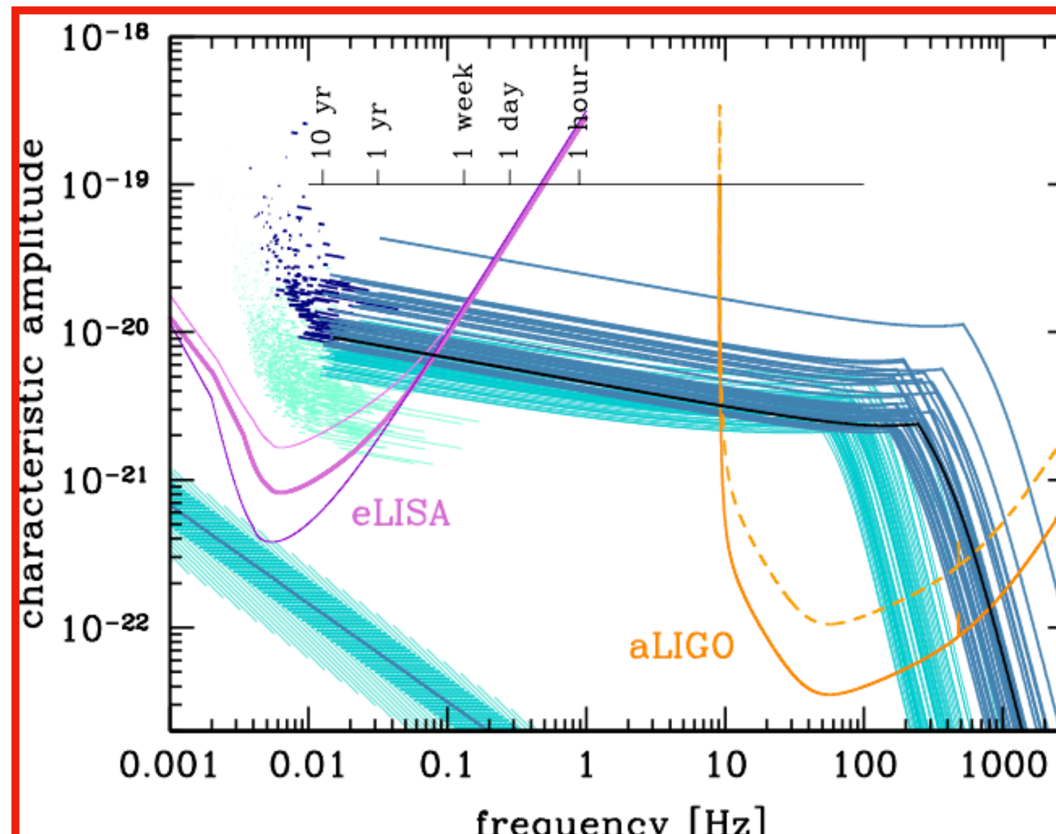

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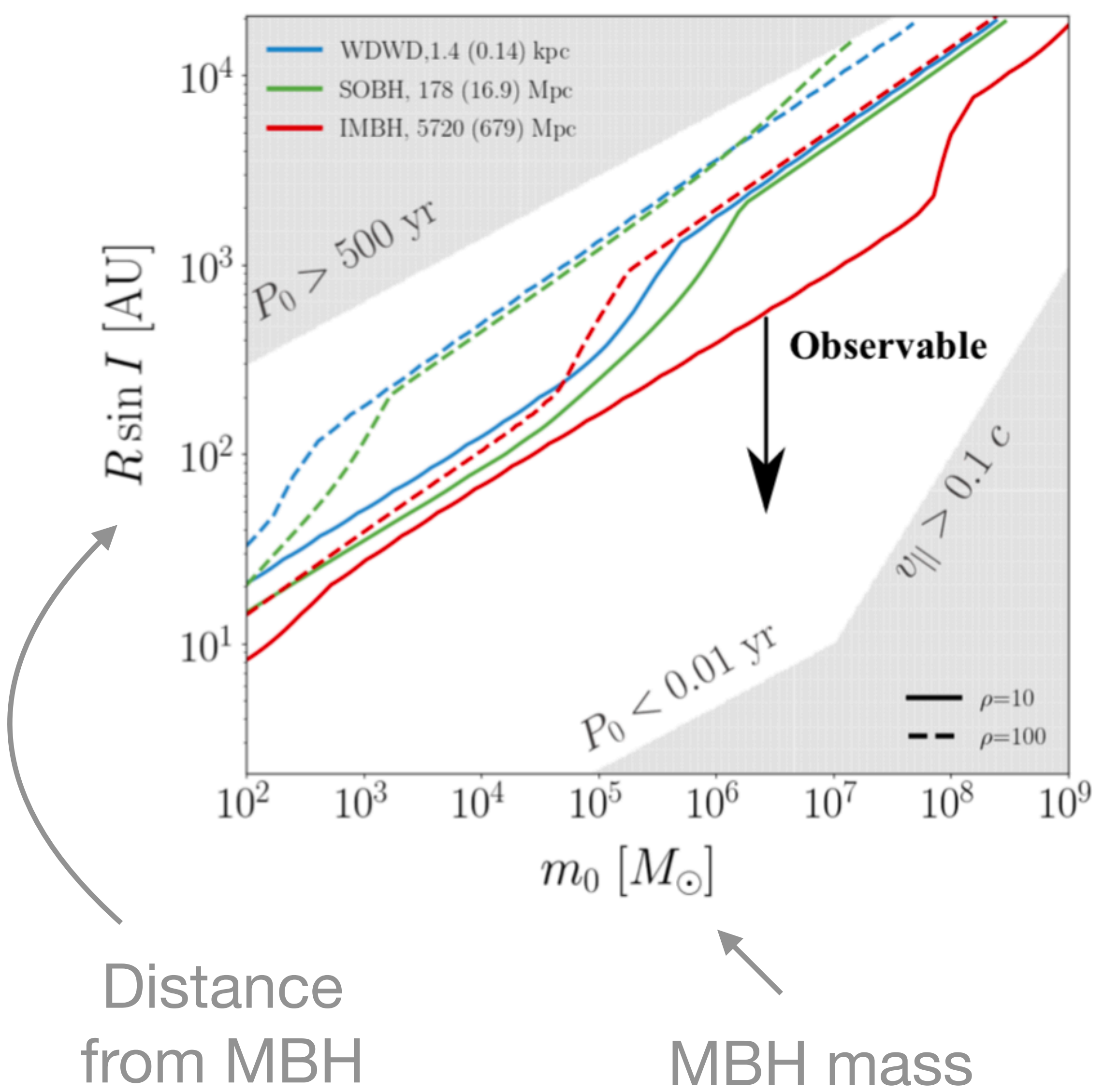


[Wong+, *MNRAS*, 488, 5665 (2019), arXiv:1902.01402]

If outer orbital period ≫ observational time, then the center-of-mass acceleration can be considered constant:
One-parameter (acceleration) modification of the GW waveform (effective -4PN term)

[Bonvin+, *PRD*, 25, 044029 (2017), arXiv:1609.08093]

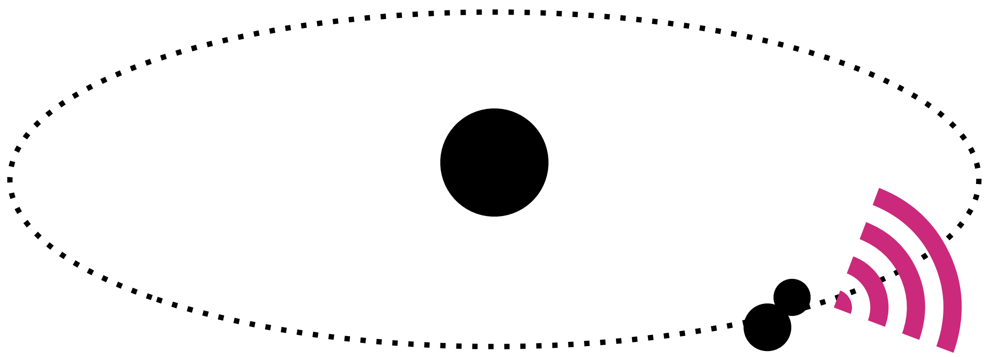
For such cases only sources that significantly chirp over the LISA band will yield a detectable peculiar acceleration:
Interesting targets for multi-band GW observations with stellar-mass BBHs

[Tamanini+, *PRD*, 101, 063002 (2019), arXiv:1907.02018]

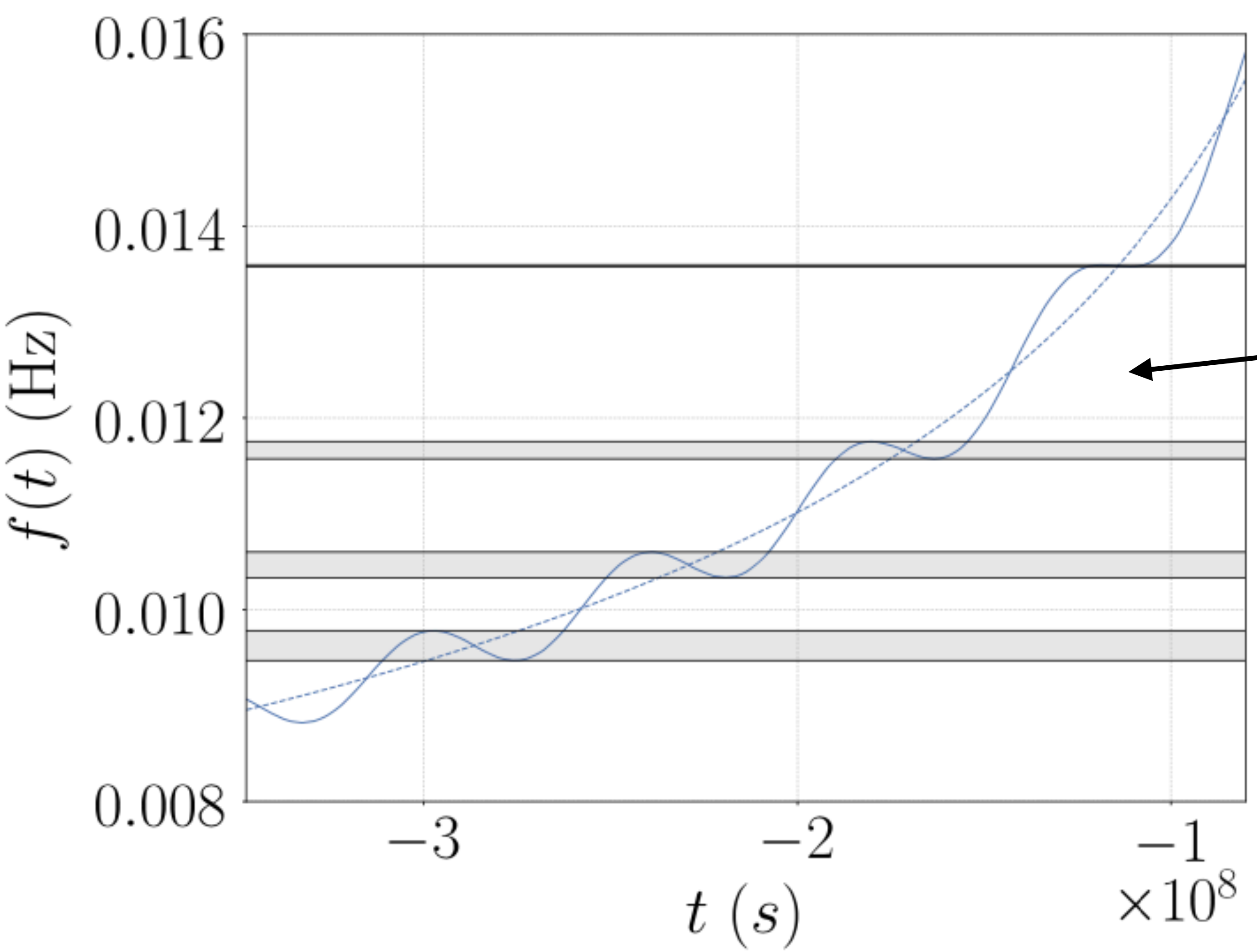
The effect can be used to probe the environment of BBHs, providing information on their formation and evolution in AGN disks or clusters

[Inayoshi+, *PRD*, 96, 063014 (2017), arXiv:1702.06529]
[Randall & Xianyu, *ApJ*, 878 (2017), arXiv:1805.05335]

Applications: BBHs



If the period of the BBH around the MBH is comparable or shorter than the observational time, then the full orbit of the BBH must be taken into account

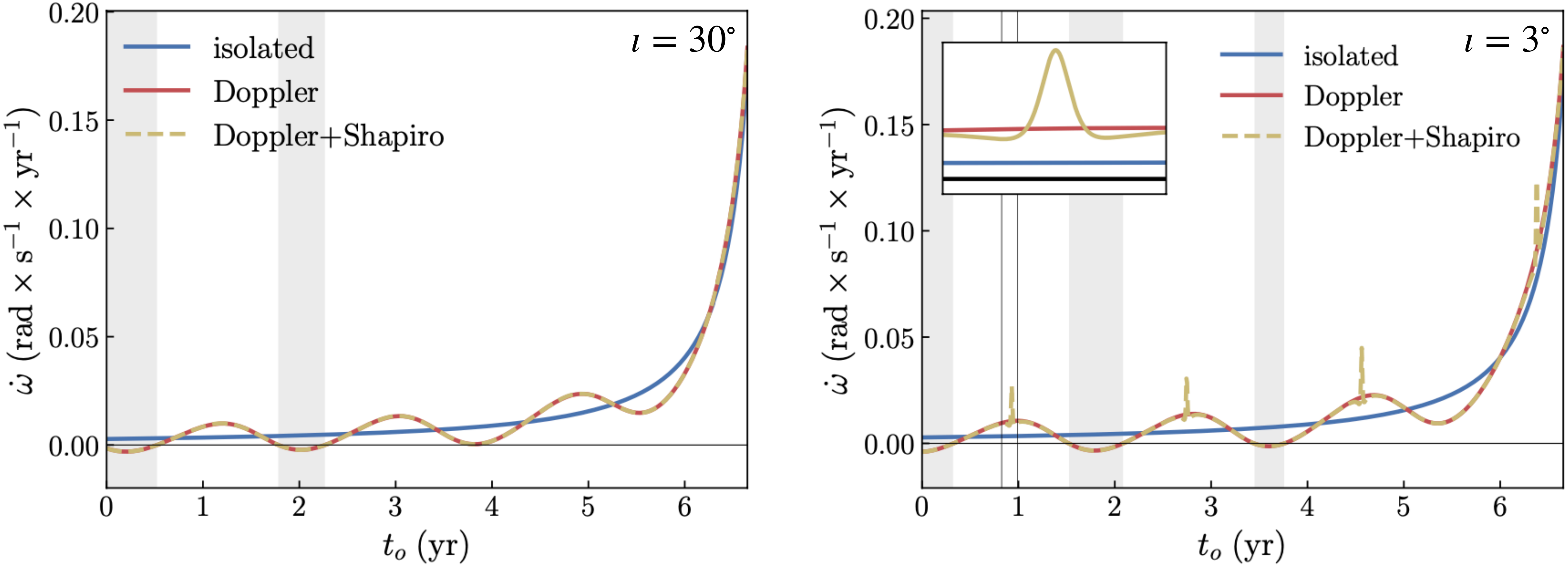


The Doppler effect will give a periodic modulation the frequency of the BBH along its usual chirping evolution

[Toubiana+, *PRL* 126, 101105 (2021), arXiv:2010.06056]
[Sberna+ (2022), arXiv:2205.08550]

Applications: BBHs

The Doppler modulation however is not the only effect expected for such binaries. If their orbital inclination around the MBH is sufficiently edge-on then the Shapiro time-delay will become relevant



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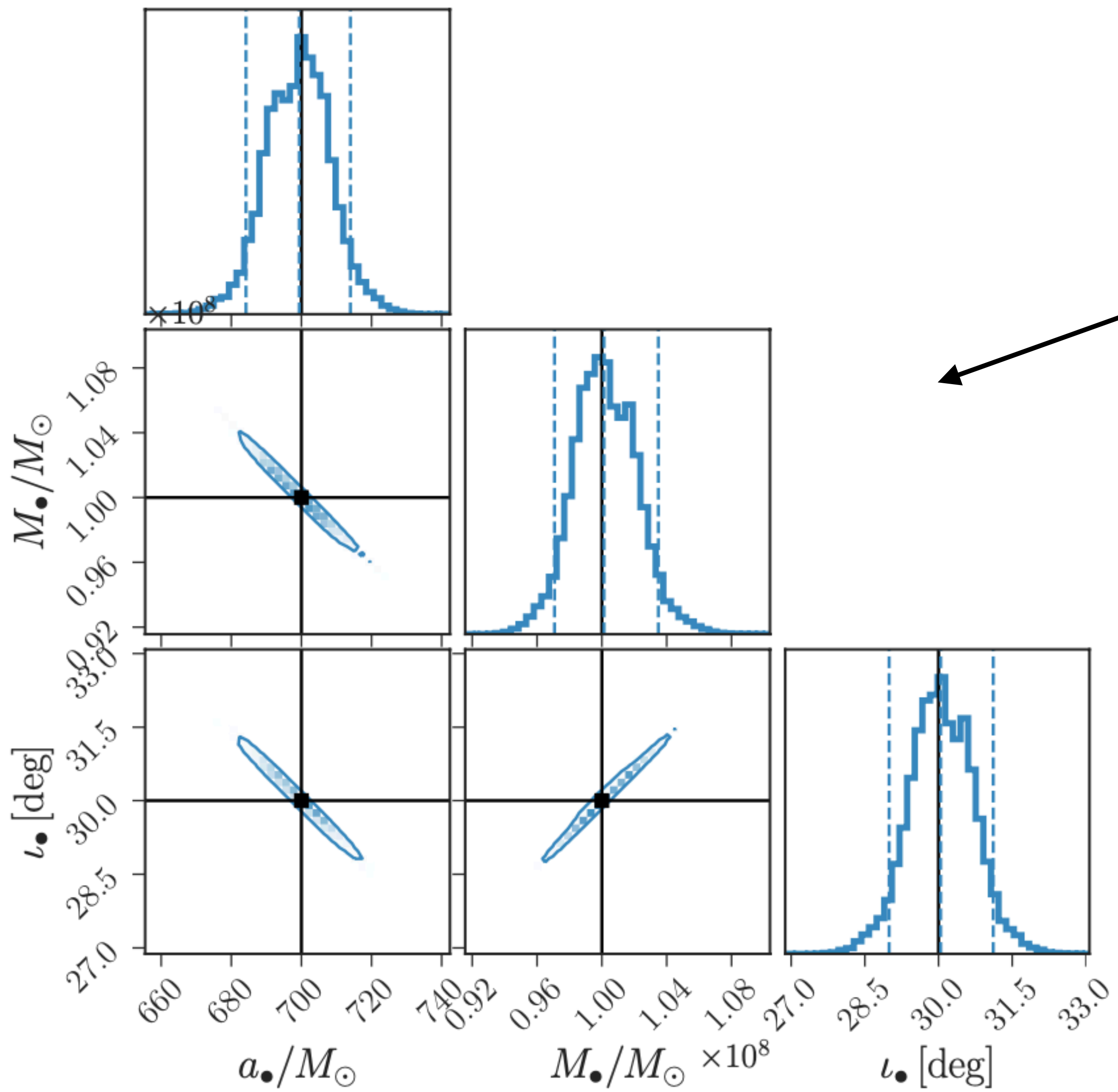

The combined Doppler and Shapiro effects on the waveform can allow us to measure the MBH orbital parameters:

- MBH mass
- BBH separation from the MBH
- BBH orbital inclination around the MBH

[Toubiana+, *PRL* 126, 101105 (2021), arXiv:2010.06056]
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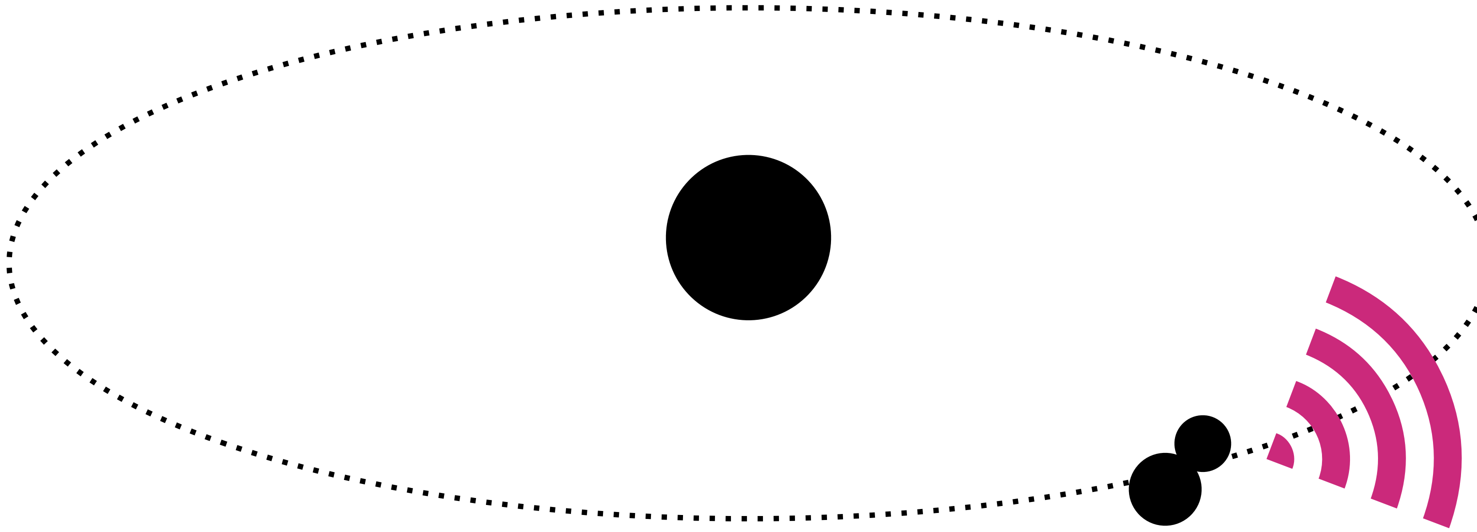

If the BBH is sufficiently close to the MBH other effects will become important:

- Lensing of the MBH (for edge-on orbits)
- Interactions with the AGN disk (accretion, dynamical friction, …)
- Kozai-Lidov resonances
- Spin-orbit and spin-spin interactions
- Relativistic effects (gravitational redshift, de Sitter and Lense-Thirring precessions, …)
- Tidal perturbations
- Aberration
- …

A lot of work remains to be done!

[Toubiana+, *PRL* 126, 101105 (2021), arXiv:2010.06056]
[Sberna+ (2022), arXiv:2205.08550]

Applications: DWDs

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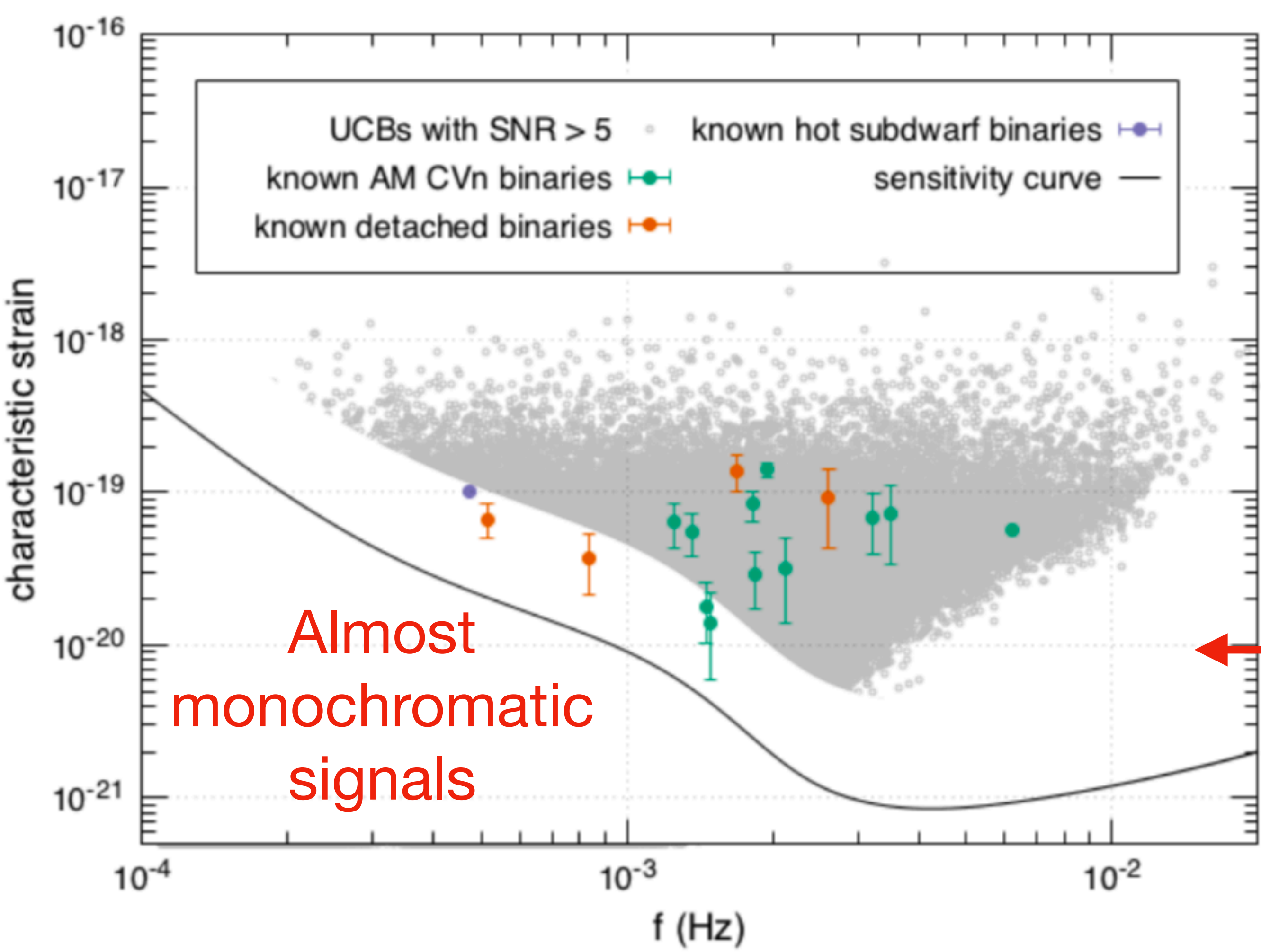

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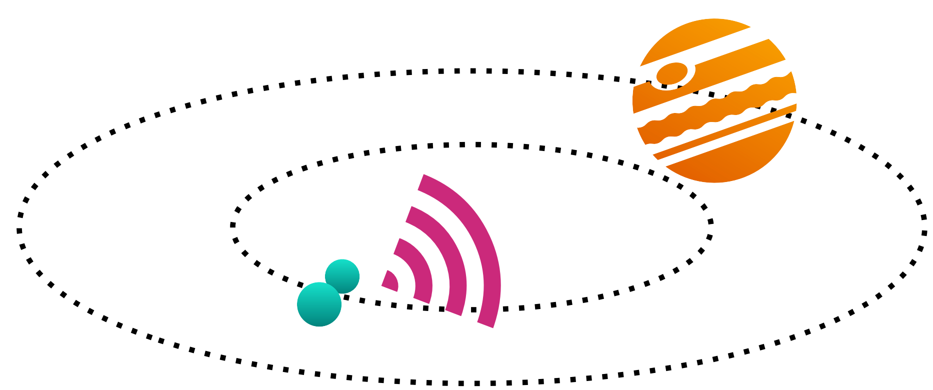


Applications: DWDs

What are white dwarfs? Here are some facts:

~ MASS OF THE SUN
max 1.4 $\mathrm{M}_\odot$

~ SIZE OF THE EARTH

~ 98% OF THE STARS WILL BECOME A WD


White dwarf star Sirius B compared to Earth. Source: ESA

PHOTOM. STABLE
to better than 1% on 1-hr to 10-d

PROGENITOR
$M_* \leq 8 - 10\ \mathrm{M}_\odot$

INTRINSICALLY FAINT
10^4 fainter than progenitors

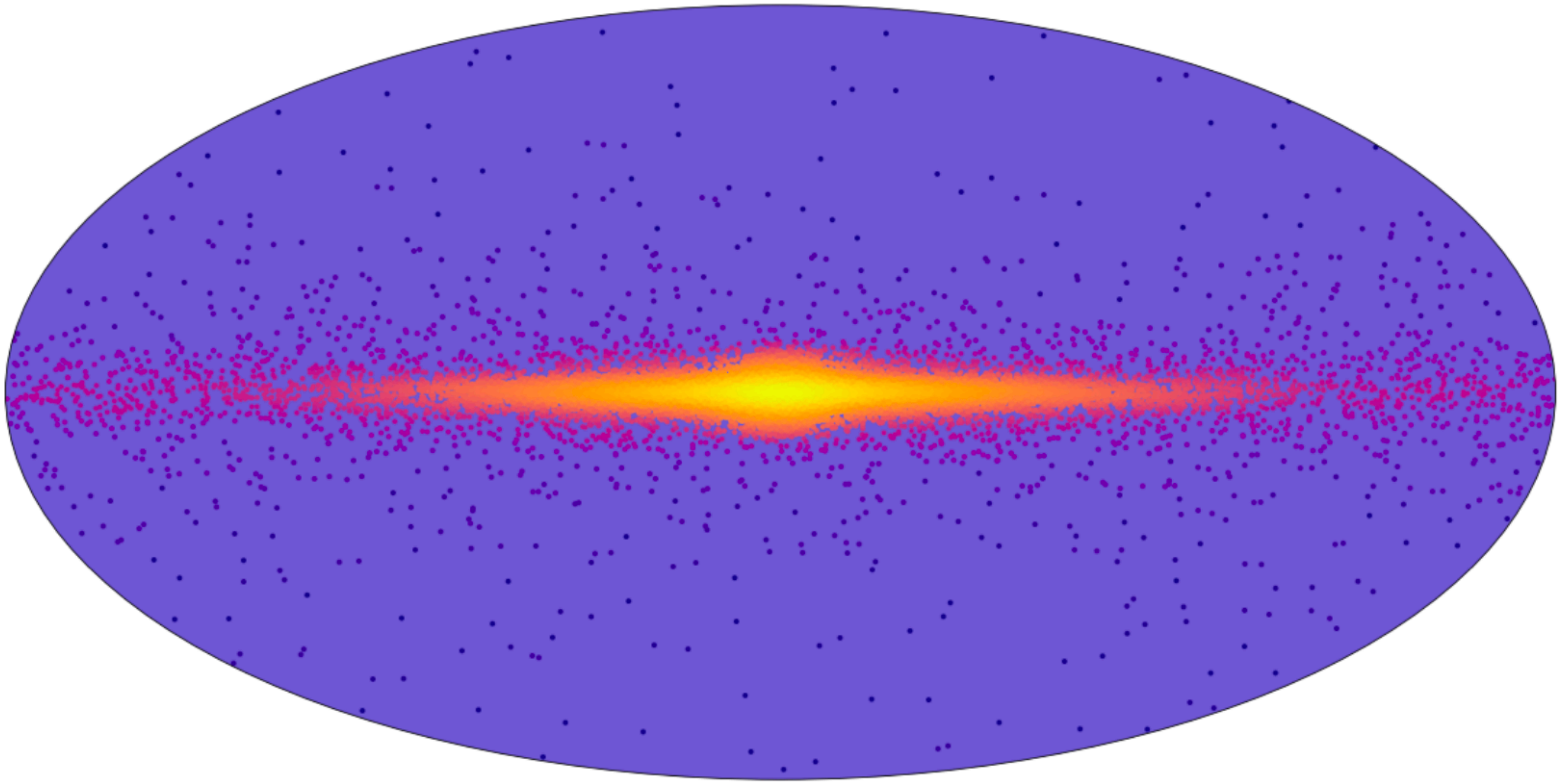
COOLING STAR
Radiation reddens

CLOSE-IN (< 0.02 AU)
LONG-LIVED and STABLE H.Z.

NATURAL CLOCKS:
PRECISE AGE FROM L

Applications: DWDs

LISA will detect tens of thousands of double white dwarf (DWD) binaries all over the Milky Way and beyond



[Korol+, *MNRAS*, 470, 1894 (2017); arXiv:1703.02555]
[Korol+, *MNRAS*, 483, 5518 (2019); arXiv:1806.03306]
[Lamberts+, *MNRAS*, 490, 5888 (2019); arXiv:1907.00014]

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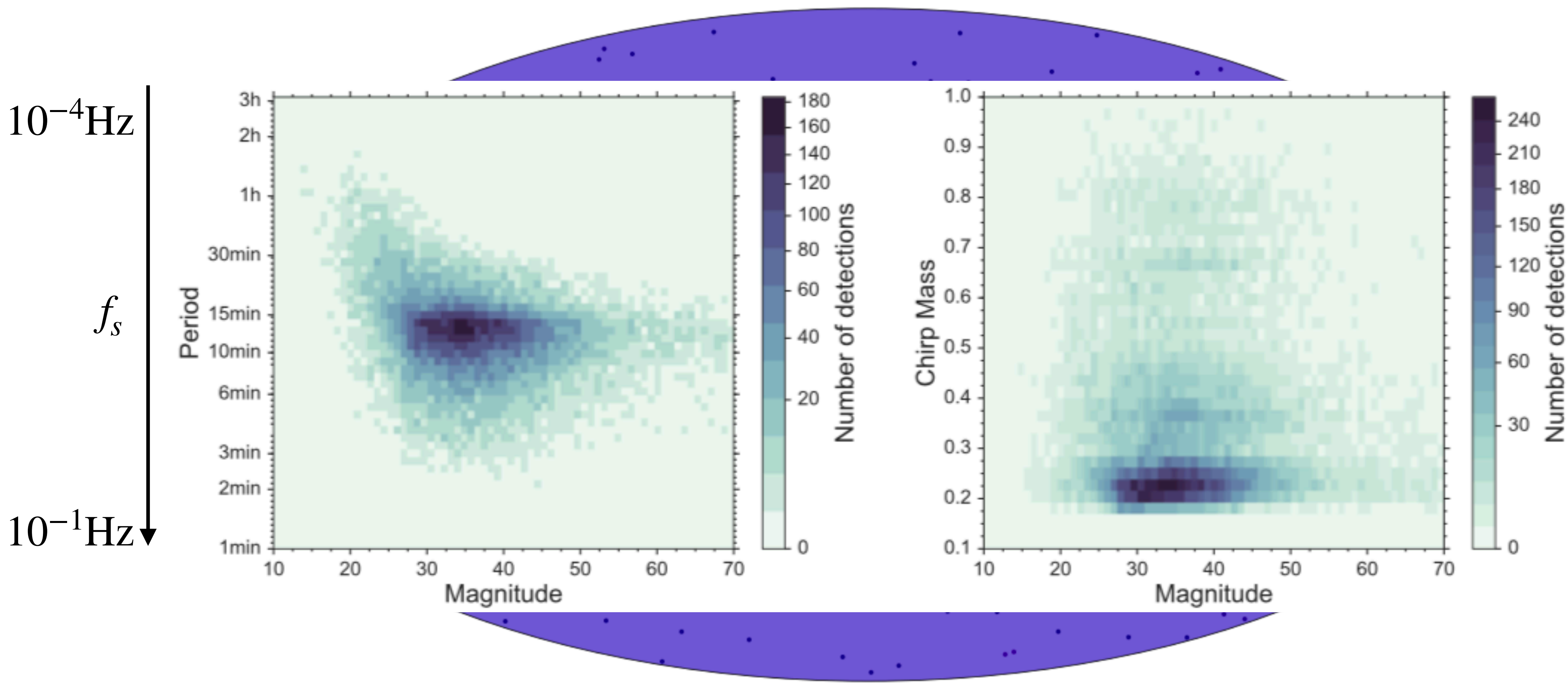

$$\dot{f}_s(t) = \frac{96\pi^{8/3}}{5}\left(\frac{GM_c}{c^3}\right)^{5/3} f_s(t)^{11/3} \sim 0$$

Almost constant frequency!

[Korol+, *MNRAS*, 470, 1894 (2017); arXiv:1703.02555]
[Korol+, *MNRAS*, 483, 5518 (2019); arXiv:1806.03306]
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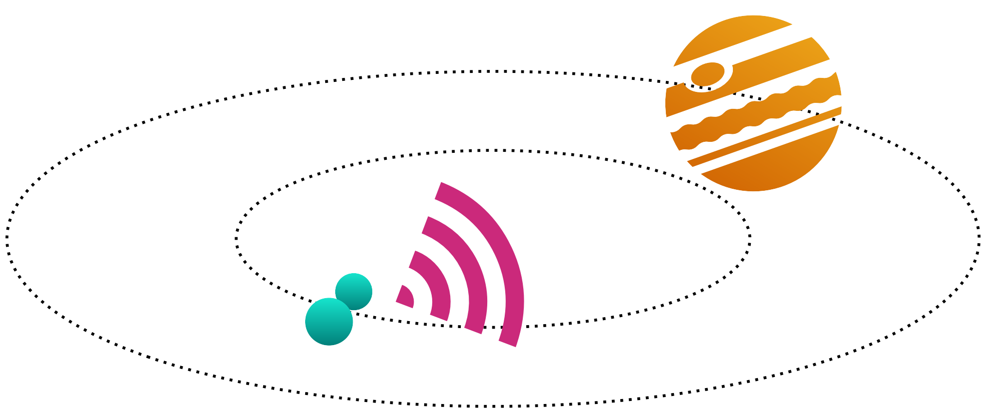
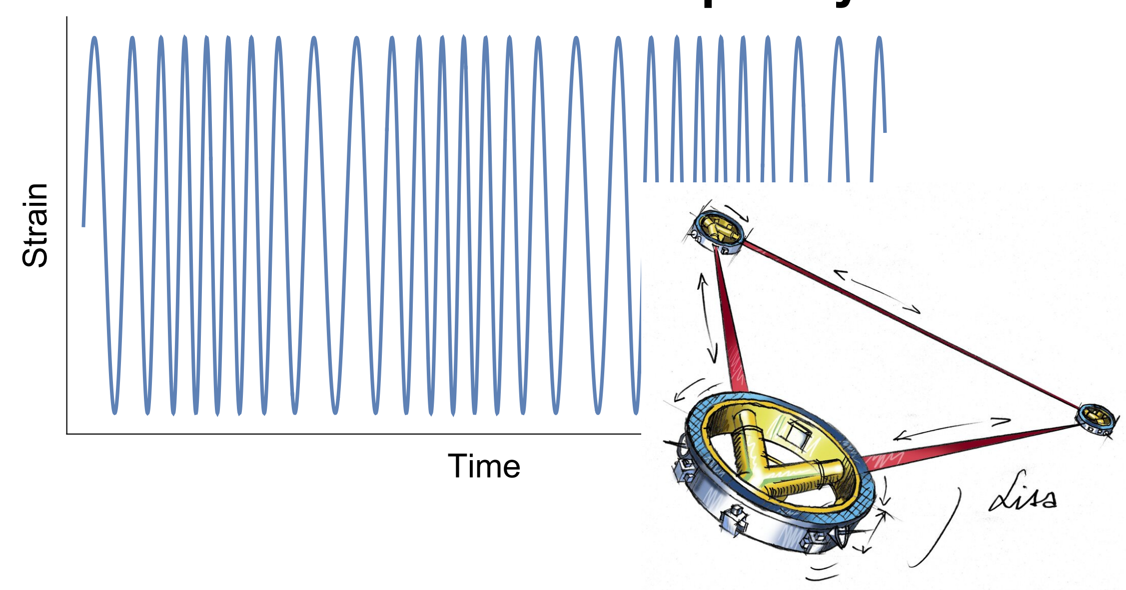
Applications: DWDs

The gravitational attraction of a third circumbinary object orbiting a DWD, will imprint a <u>Doppler frequency modulation</u> on the GW signal observed by LISA

Continuous GW signal emitted by DWD in orbit with a third object



Observed GW waveform Doppler modulated in frequency



[Seto, *ApJ*, 677 (2008); arXiv:0802.3411]
[Tamanini & Danielski, *Nature Astron.*, 3, 858 (2019); arXiv:1812.04330]
[Robson, Cornish, Tamanini, Toonen, *PRD*, 98, 064012 (2018); arXiv:1806.00500]

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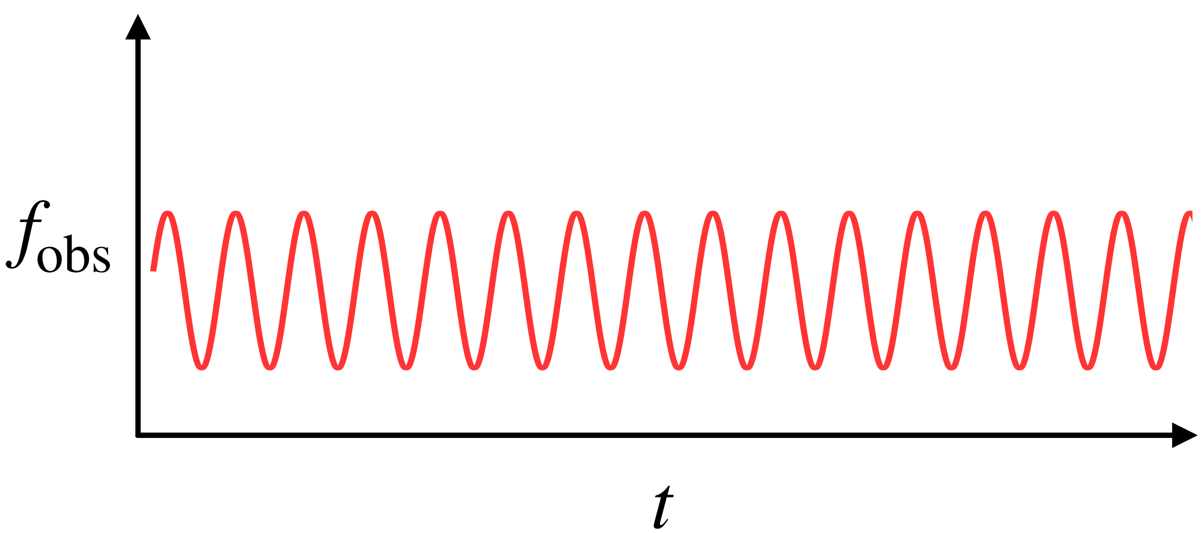
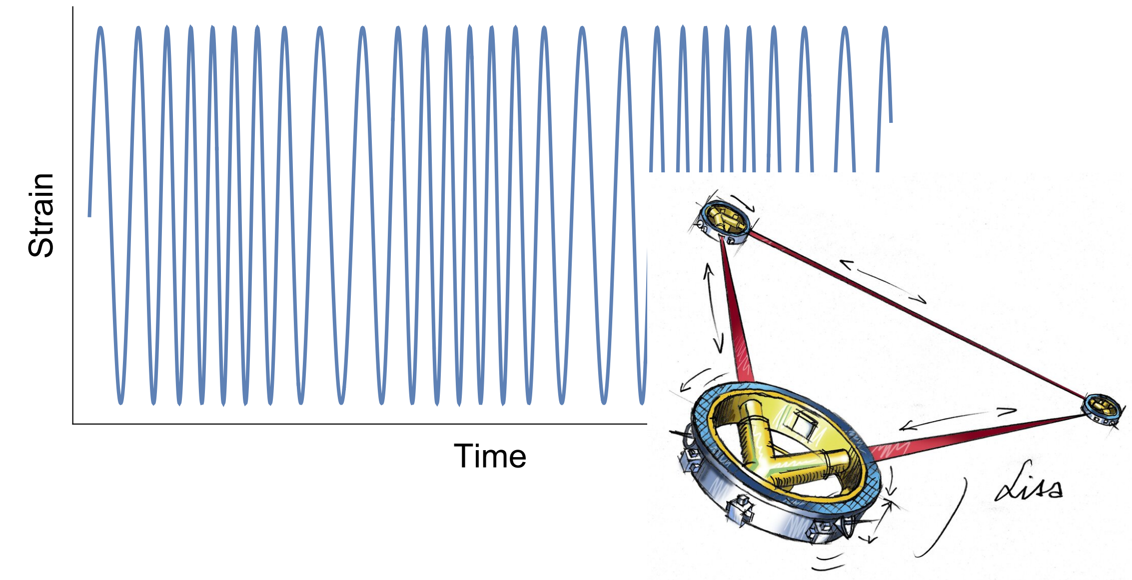


Modulation over a constant frequency evolution

Observed GW waveform Doppler modulated in frequency



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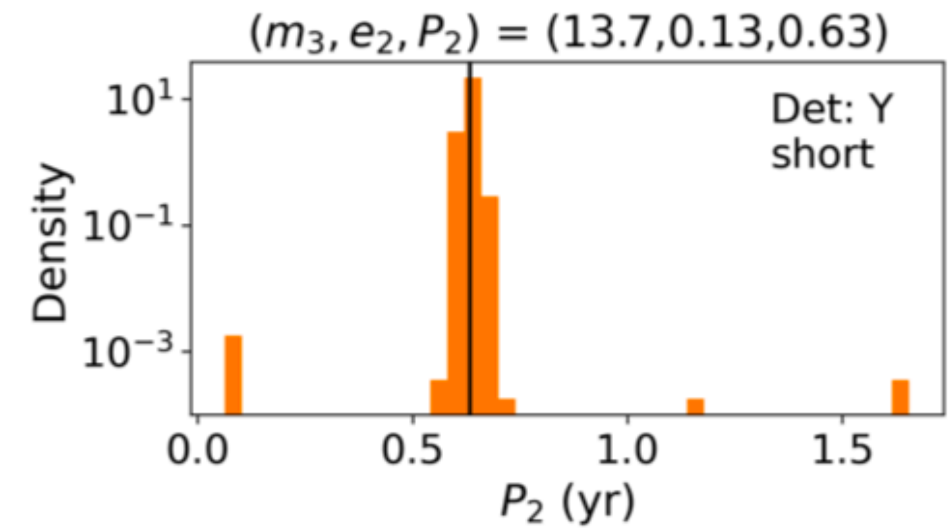
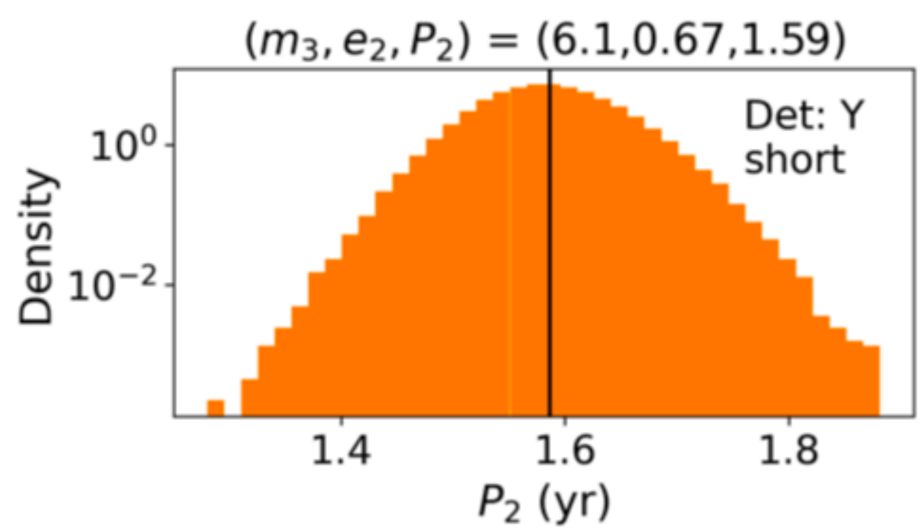
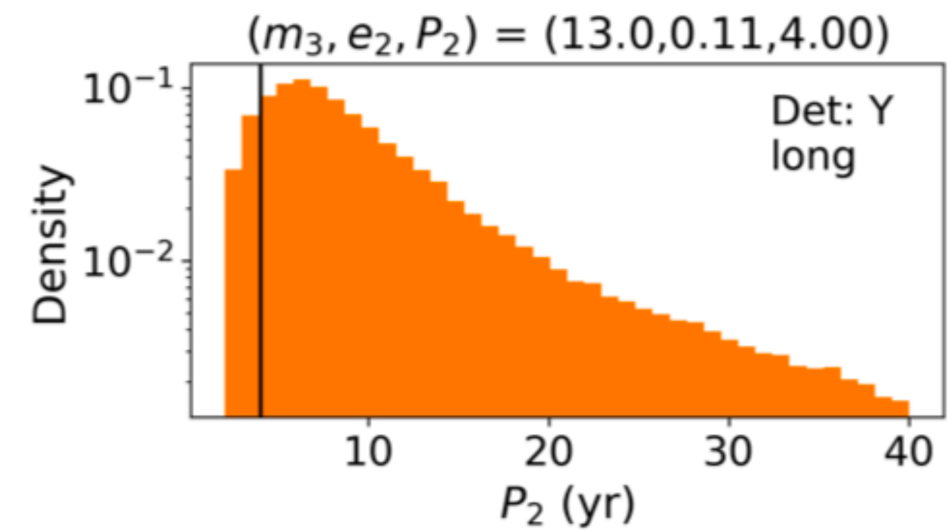
Applications: DWDs

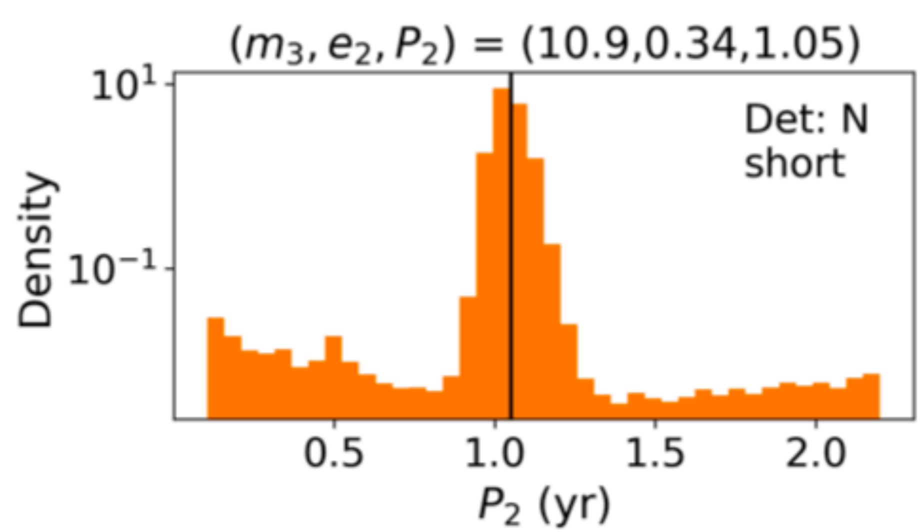
The full Bayesian MCMC analysis of third-body around DWDs is very complex

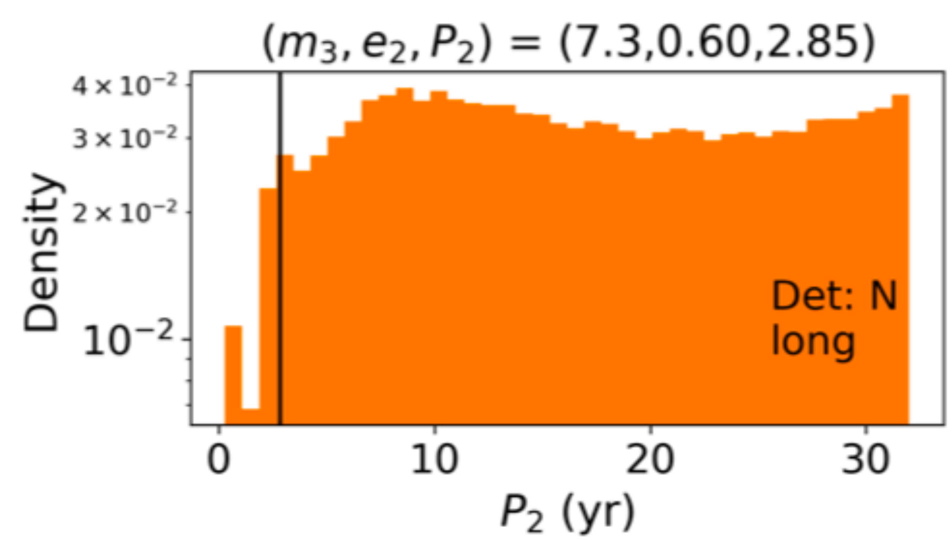
Different behaviour for short ($P_2 < T_{\rm obs}/2$) and long ($P_2 > T_{\rm obs}/2$) 3rd-body periods







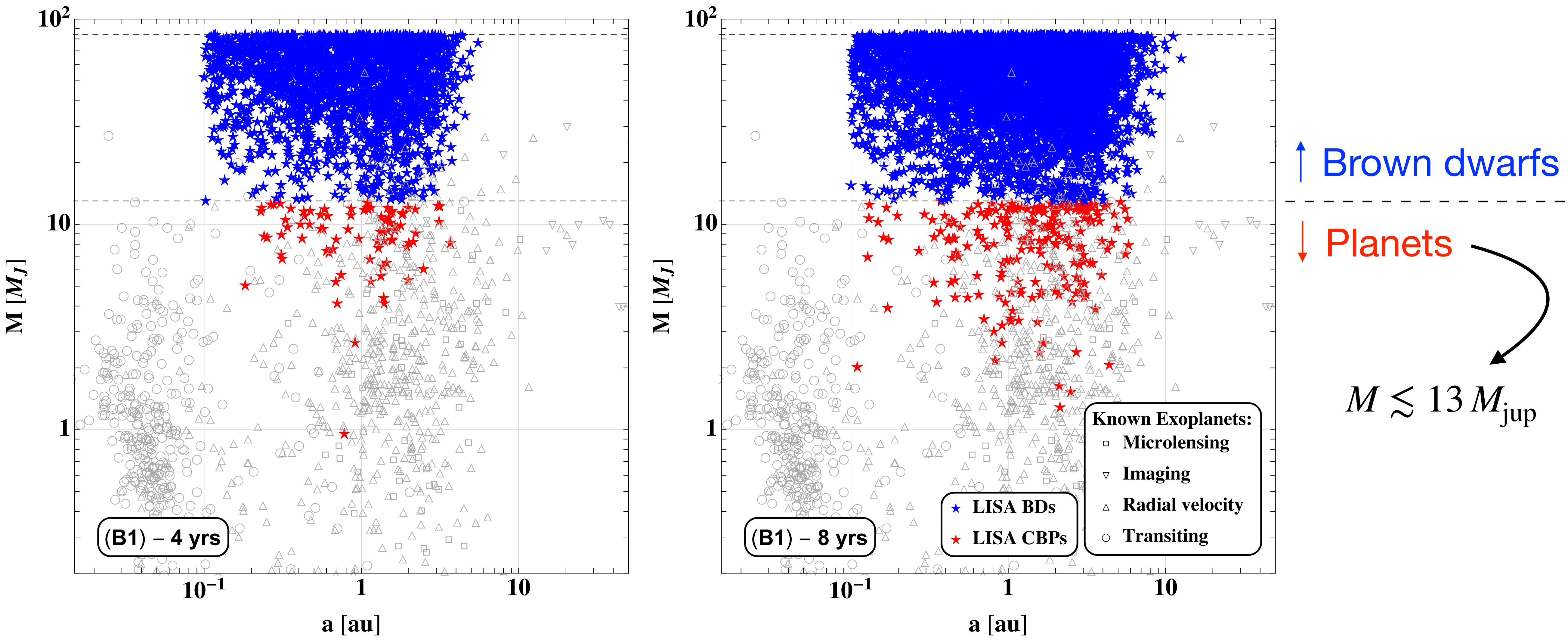




[Katz+, arXiv:2205.03461]

Applications: DWDs

Observable circumbinary bodies will have masses above Jupiter's and maximum periods comparable to LISA observational time



[Tamanini & Danielski, *Nat. Astron.*, 3, 858 (2019); arXiv:1812.04330]
[Danielski, Korol, Tamanini, Rossi, *A&A*, 632, 113 (2019); arXiv:1910.05414]

Applications: DWDs

Number of detected circumbinary bodies:

DETECTIONS (4 years)

	A) $\mathcal{U}_a$ (0.1-200 au)		B) log $\mathcal{U}_a$ (0.1-200 au)		C) logNormal$_a$ (0.1-200 au)		D) $a^{-0.61}$ (0.1-200 au)	
	CBPs	BDs	CBPs	BDs	CBPs	BDs	CBPs	BDs
1) $\mathcal{U}_M$ (1M$_\oplus$ - 0.08 M$_\odot$)	**3 (0.011%)**	79 (0.302%)	**83 (0.317%)**	**2218 (8.482%)**	18 (0.069%)	503 (1.924%)	28 (0.107%)	820 (3.136%)
2) $M^{-1.31}$	6 (0.023%)	**14 (0.054%)**	30 (0.115%)	316 (1.209%)	5 (0.019%)	85 (0.325%)	13 (0.050%)	131 (0.501%)

In 4 years of LISA observations:

- From 3 to 83 exoplanets
- From 14 to 2218 brown dwarfs (M > 13 M_j)

In 8 years of LISA observations:

- From 8 to 215 exoplanets
- From 43 to 4684 brown dwarfs

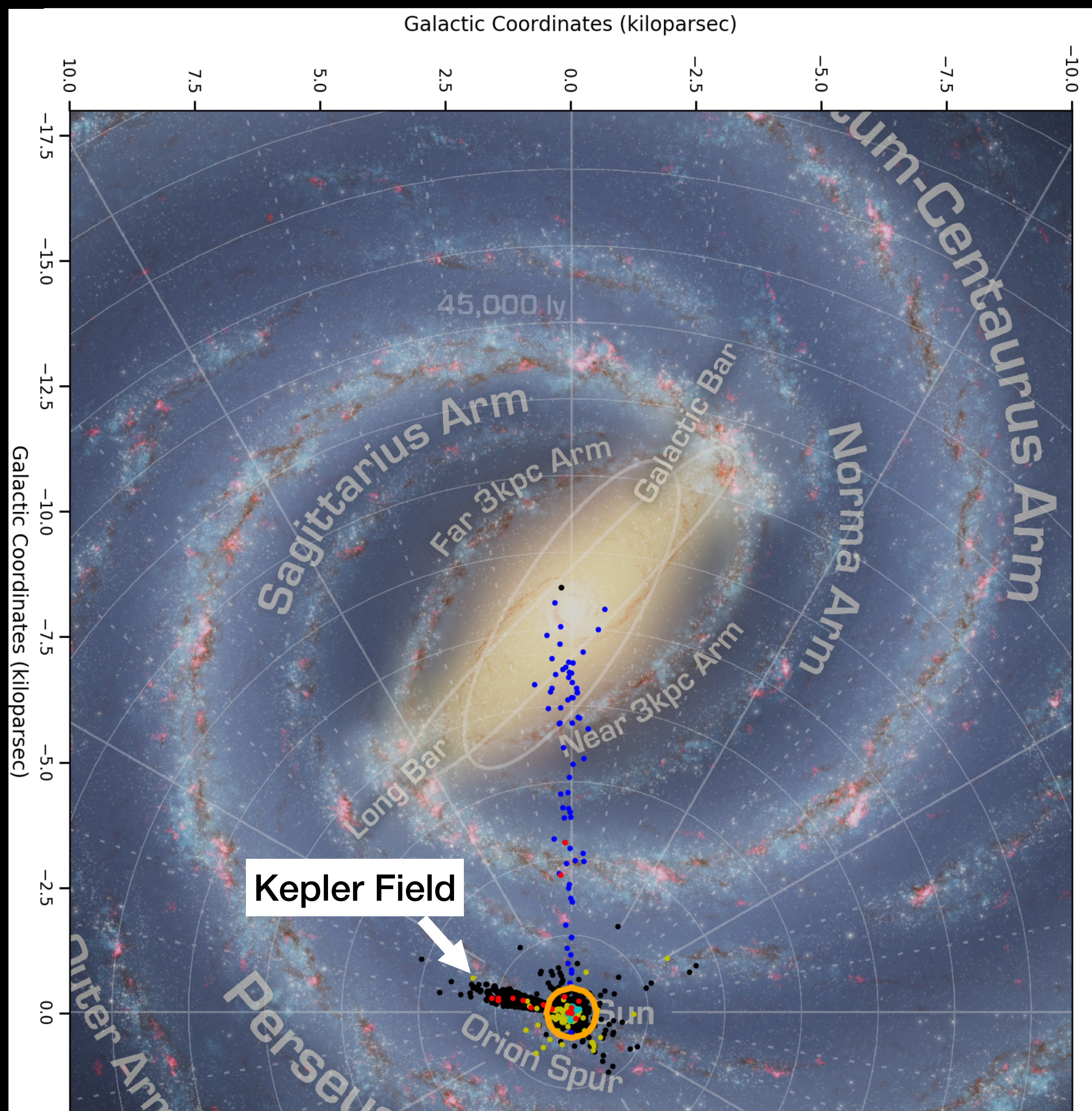
DETECTIONS (8 years)

	CBPs	BDs
B1	215 (0.822%)	4684 (17.913%)
A1	8 (0.02%)	295 (0.733%)
A2	11 (0.027%)	43 (0.107%)

[Tamanini & Danielski, *Nat. Astron.*, 3, 858 (2019); arXiv:1812.04330]
[Danielski, Korol, Tamanini, Rossi, *A&A*, 632, 113 (2019); arXiv:1910.05414]

Applications: DWDs

EM horizon



~ 3 kpc average
~ 8 kpc microlensing

Microlensing
Transit
Imaging
RV

Gaia plan. limit 500 pc
CBPs

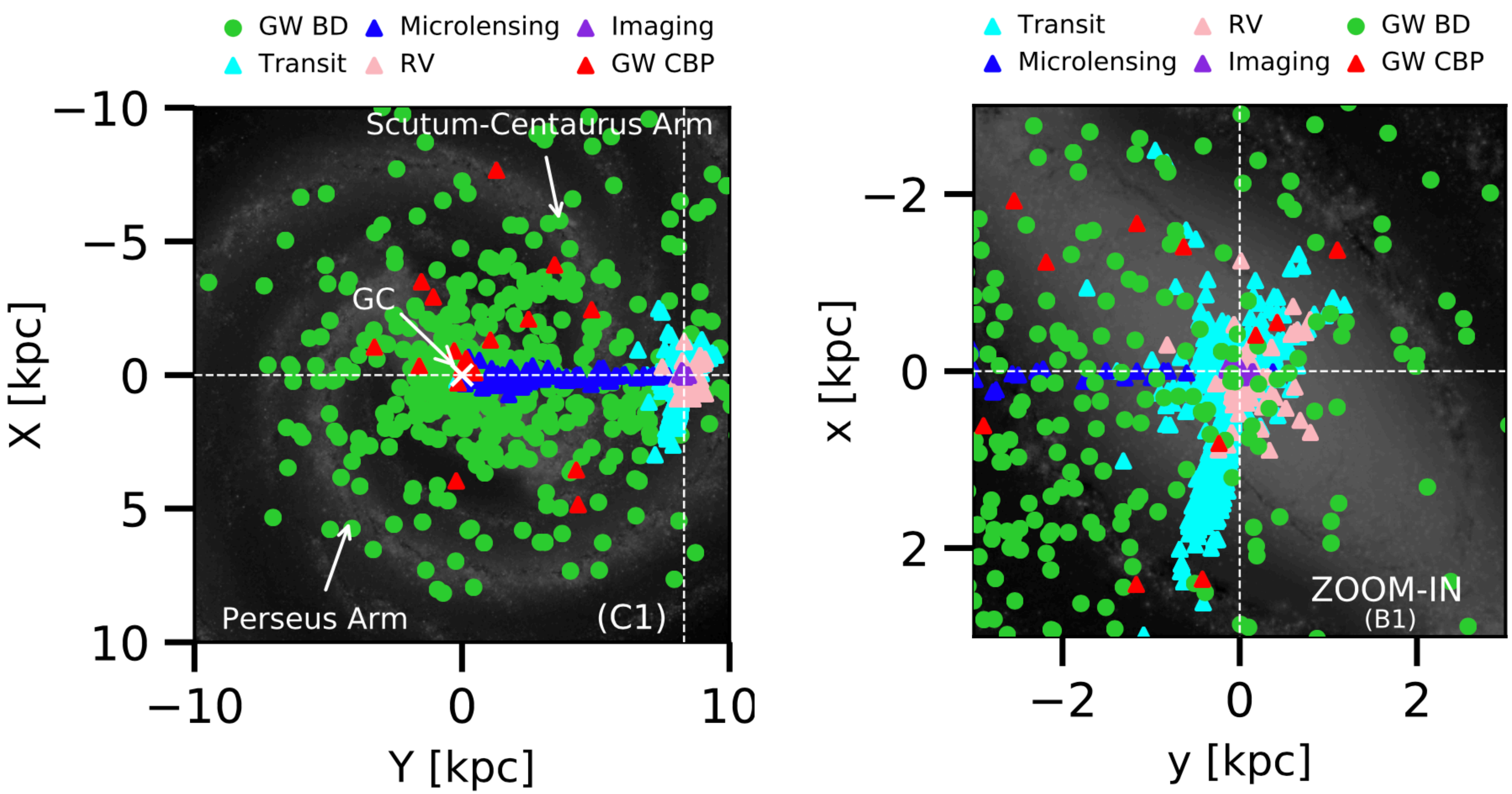
Tamanini & Danielski 2019
arXiv: 1812.04330

Credits @ Camilla Danielski

[Tamanini & Danielski, *Nat. Astron.*, 3, 858 (2019); arXiv:1812.04330]
[Danielski, Korol, Tamanini, Rossi, *A&A*, 632, 113 (2019); arXiv:1910.05414]

Applications: DWDs

LISA will detect circumbinary planets <u>everywhere in the Milky Way</u>, overcoming the limitation in distance of EM observations



[Tamanini & Danielski, *Nat. Astron.*, 3, 858 (2019); arXiv:1812.04330]
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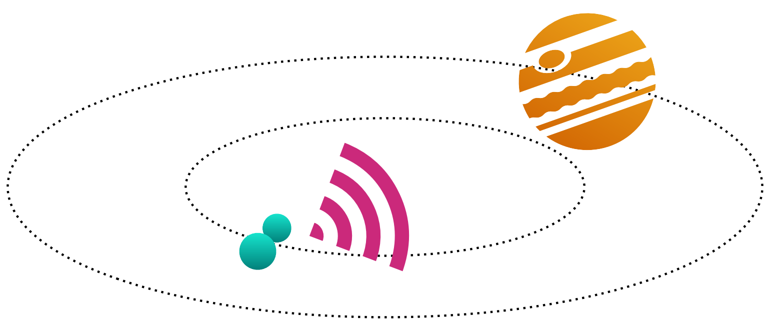
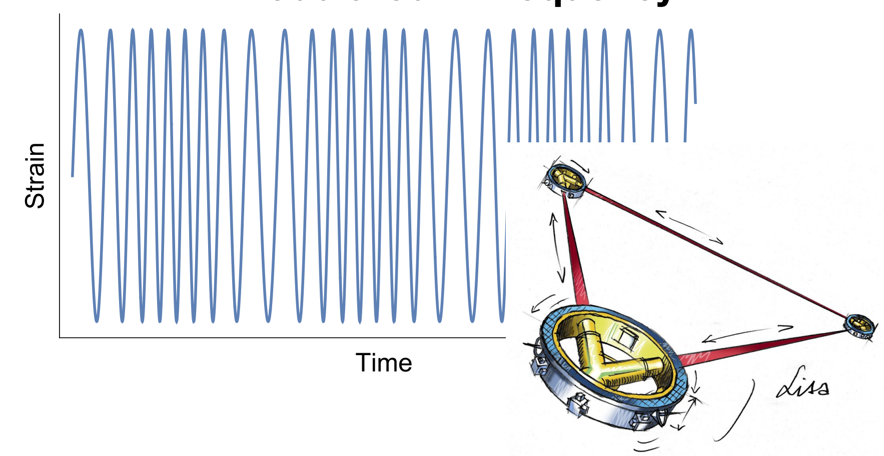
Applications: DWDs

Circumbinary planets might be detected even from Milky Way satellite galaxies, a target beyond standard EM observations

Continuous GW signal emitted by DWD in orbit with a third object

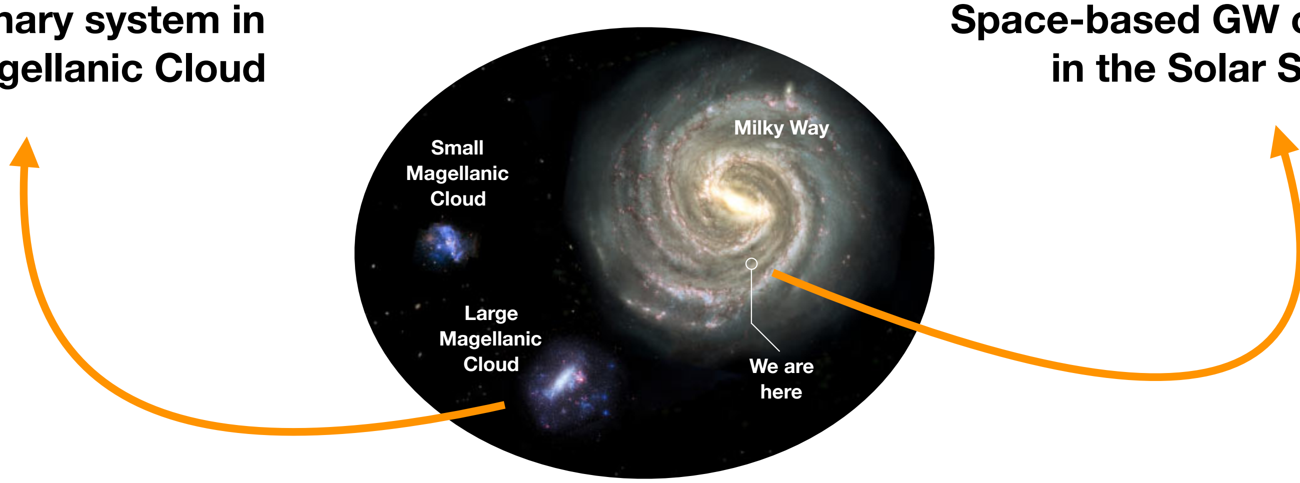


Observed GW waveform Doppler modulated in frequency



Circumbinary system in Large Magellanic Cloud

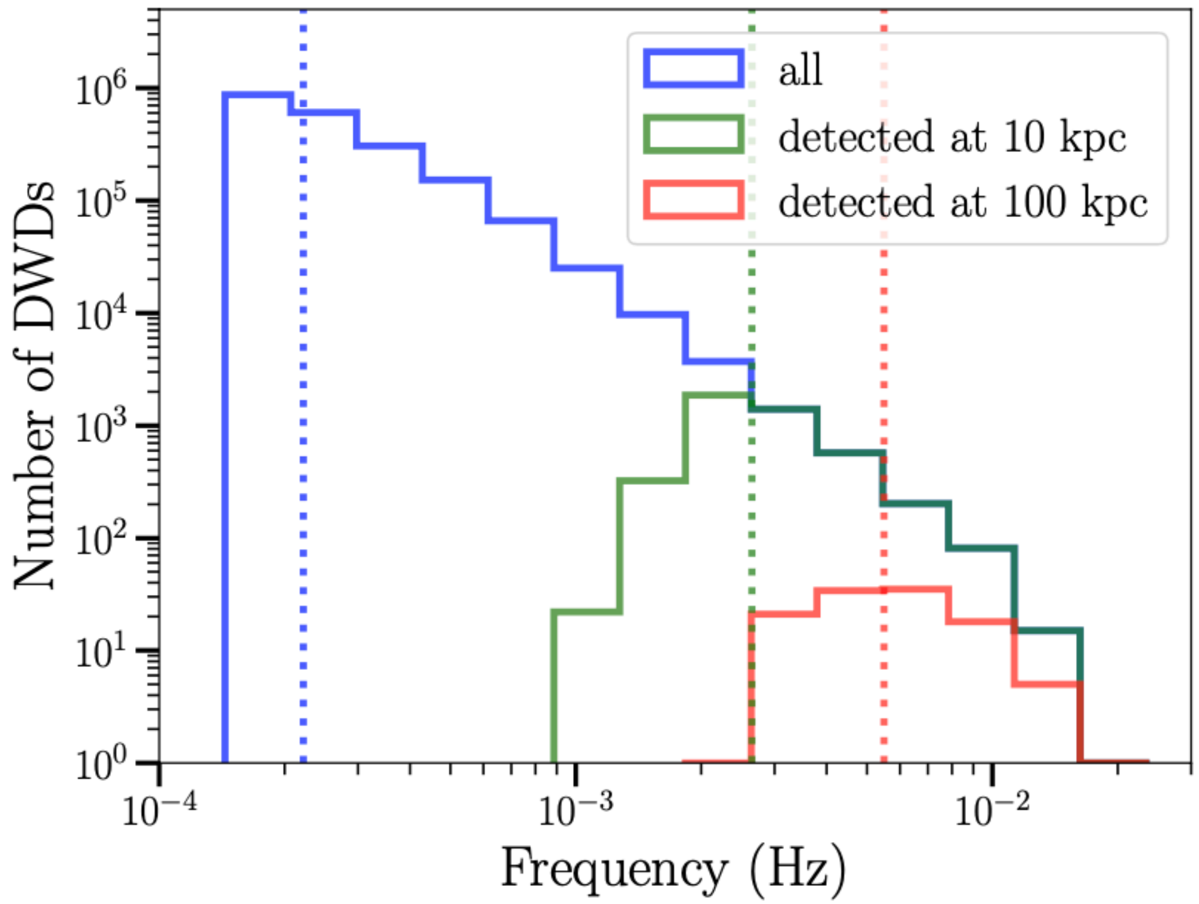
Space-based GW observatory in the Solar System



[Korol+, *ApJL*, 866, 20 (2018); arXiv:1808.05959]
[Korol+, *A&A*, 638, 5518 (2020); arXiv:2002.10462]
[Roebber+, *ApJL*, 894, 15 (2020); arXiv: 2002.10465]
[Danielski & Tamanini, *IJMPD* (2020); arXiv:2007.07010]

Applications: DWDs

Circumbinary planets might be detected even from Milky Way satellite galaxies, a target beyond standard EM observations



Name	d (kpc)	$M_\star (\times 10^6\, M_\odot)$	4 yr	10 yr
LMC	51	1500	70	150
SMC	64	460	15	30
Sagittarius	26	21	3	9
Fornax	147	20	0.1	0.3
Sculptor	86	2.3	0.04	0.1

LISA can detect a planet in LMC only if $M \gtrsim 10\ M_j$ with optimal orbit (limit of planet detectability)

GWs could one day detect extra-galactic bound exoplanet
(unbound extra-galactic planetary masses already detected with microlensing)

[Korol+, *ApJL*, 866, 20 (2018); arXiv:1808.05959]
[Korol+, *A&A*, 638, 5518 (2020); arXiv:2002.10462]
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Implications for Exoplanets

Are these circumbinary planets actually out there?
Current evidences are inconclusive

LISA will have the potential to probe a yet unobserved population of exoplanets (orbiting compact DWDs), and to gather useful information on the final phases of an exoplanet's life:

If they are out there:
Up to tens/hundreds of new circumbinary exoplanets (and hundreds/thousands brown dwarfs) everywhere in the Milky Way

- How do they formed and evolved?
- First or second (or third?) generation?
- How do they interact/evolve with the DWD?

If they are not out there:
LISA will yield no detections and constrain their rates

- Important information on final phases of planetary evolution

[Danielski, Korol, Tamanini, Rossi, *A&A*, 632, 113 (2019); arXiv:1910.05414]

Future Work

The work done so far is only the beginning. To understand if LISA will really observe exoplanets, several investigations are need:

- Improve and expand data analysis tools:
  - Integrate and test it within global fit analyses (LDC)
- Assess the role of orbital components
  - Planet-binary interactions (Kozai-Lidov, tides, …)
  - Multiple circumbinary objects and disks
- Explore synergy with EM observations
  - Identify pre-LISA candidates (verification triple systems?)
  - Set follow-up strategies (transits? direct imaging? RV?)
  - What can we learn from combined EM-GW observations?
- Further develop planetary evolution theories
  - More observations of possible ancestors planets
  - Better theoretical insight to draw final evolutionary phase

Conclusions

- LISA will open the mHz GW window, bringing GW astronomy into space
- Among all LISA GW sources, long-living compact binaries will provide observational signatures of their center-of-mass motion
- From this effect we can probe the environment of stellar-mass BBHs and observe the effects of their orbit around MBH
- We can also look for circumbinary bodies orbiting Galactic ultra-compact binaries, in particular DWD binaries:
  - $\sim 10^4$ DWDs detected by LISA
  - Circumbinary masses detectable above Jupiter's mass and periods comparable to LISA observational time
  - Implications:
    - New GW test of a yet unprobed population of exoplanets
    - Provide useful information on planetary evolution theories
    - Detect exoplanets in the whole Milky Way and possibly beyond, overcoming EM selection effects

Back-up slides

Applications: DWDs

Can planets be found around (double) WDs?
Can planets survive the red giant/common envelope phase of stellar evolution?

Observational evidences:

- WDs pollution: ~50% of WDs show signs of atmosphere pollution, best explanation is given by orbiting planets supplying metal-rich material [Veras (2016), arXiv:1601.05419]
- At least 2 planetesimals found orbiting single WDs [WD 1145+017, SDSS J122859.93+104032.9] [Vanderbourg+, *Nature* (2015) arXiv:1510.06387; Manser+, *Nature* (2019), arXiv:1904.02163]
- Indirect evidence for a giant planet orbiting a WD from the nature of circumbinary disk [WD 1145+017] [Gänsicke+, *Nature* (2019), arXiv:1912.01611]
- Discovery of a giant planet candidate transiting a WD (period 1.4 days, mass < 14 $M_{\rm Jup}$, size of Jupiter) [WD 1856+534] [Vanderburg+, *Nature* (2020), arXiv:2009.07282]
- 6 known P-type circumbinary systems with one WD (other star is usually a low mass star) [NNSer (b,c), DP Leo (b), RRCae (b), UZ For (b,c), HU aqr (b), PSR B1620-26 (b)]

⇒ Post main-sequence and WD-orbiting exoplanets exist!

LISA Exoplanets Forecasts

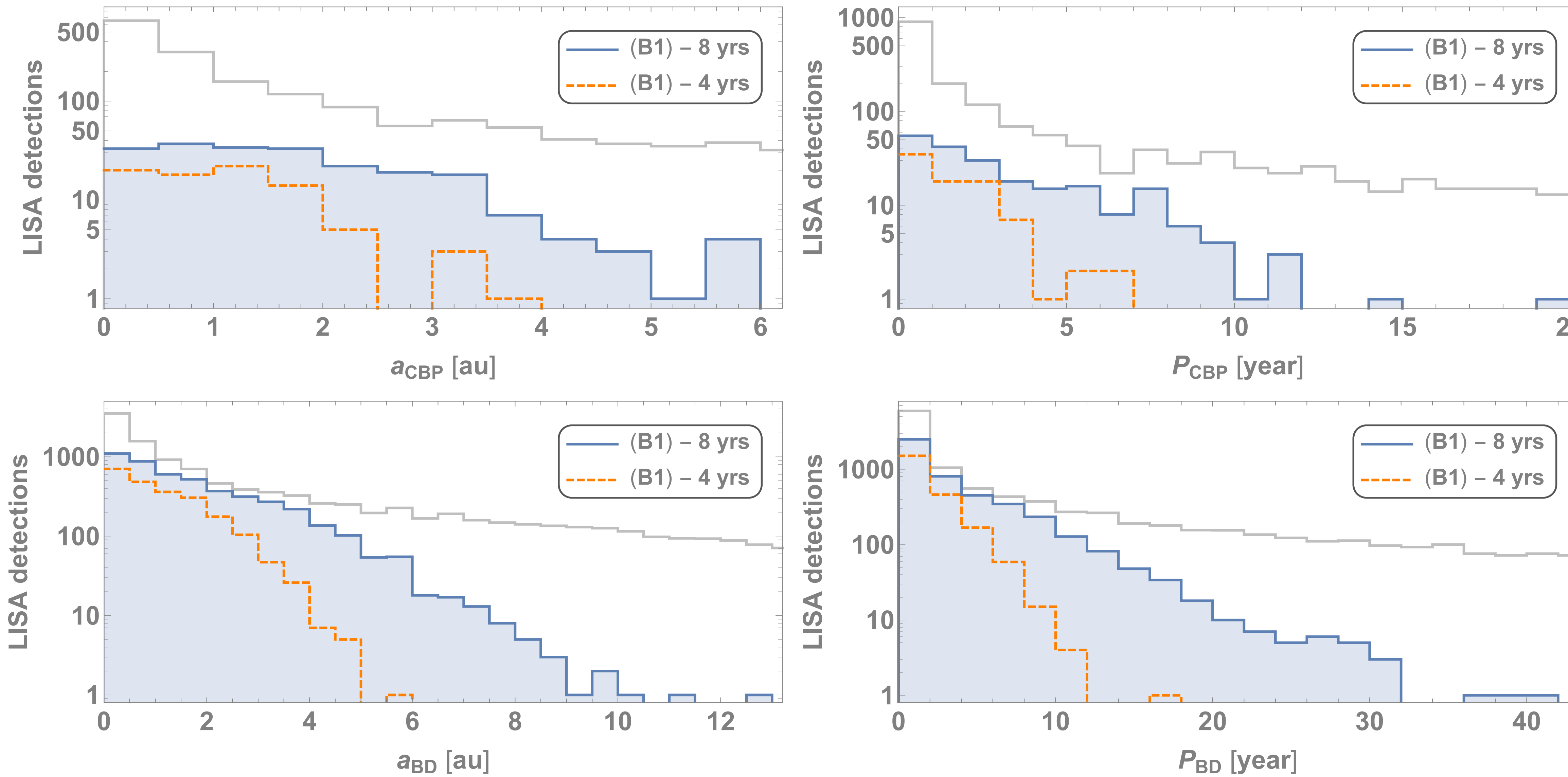
To forecast how many exoplanets will be detected by LISA through their GW Doppler modulation, we adopted the following strategy:

- We started from a realistic DWD Galactic population (population synthesis code of [Korol+, *MNRAS*, 470, 1894 (2017); arXiv:1703.02555])
- We injected a population of sub-stellar circumbinary companions assuming they trigger WD pollution:
  - Occurrence rates set by WD pollution observations: ~50%
  - Only one circumbinary companion per polluted DWD
  - Circumbinary companion has sub-stellar mass (dark): $M < 0.08 M_\odot$ (if $M < 13 M_{\rm Jup}$ companion is exoplanet; otherwise is a **brown dwarf**)
  - Circumbinary companion separation up to 200 au
  - 8 different injection scenarios: 2 mass and 4 separation distributions
- Fisher matrix analysis to perform fast LISA parameter estimation
- Third-body detected if both P_3 and $K \approx |v_{\rm los}|$ measured better than 30%

[Tamanini & Danielski, *Nat. Astron.*, 3, 858 (2019); arXiv:1812.04330]
[Danielski, Korol, Tamanini, Rossi, *A&A*, 632, 113 (2019); arXiv:1910.05414]

LISA Exoplanets Forecasts

Observable circumbinary bodies will have masses above Jupiter's
and maximum periods comparable to LISA observational time



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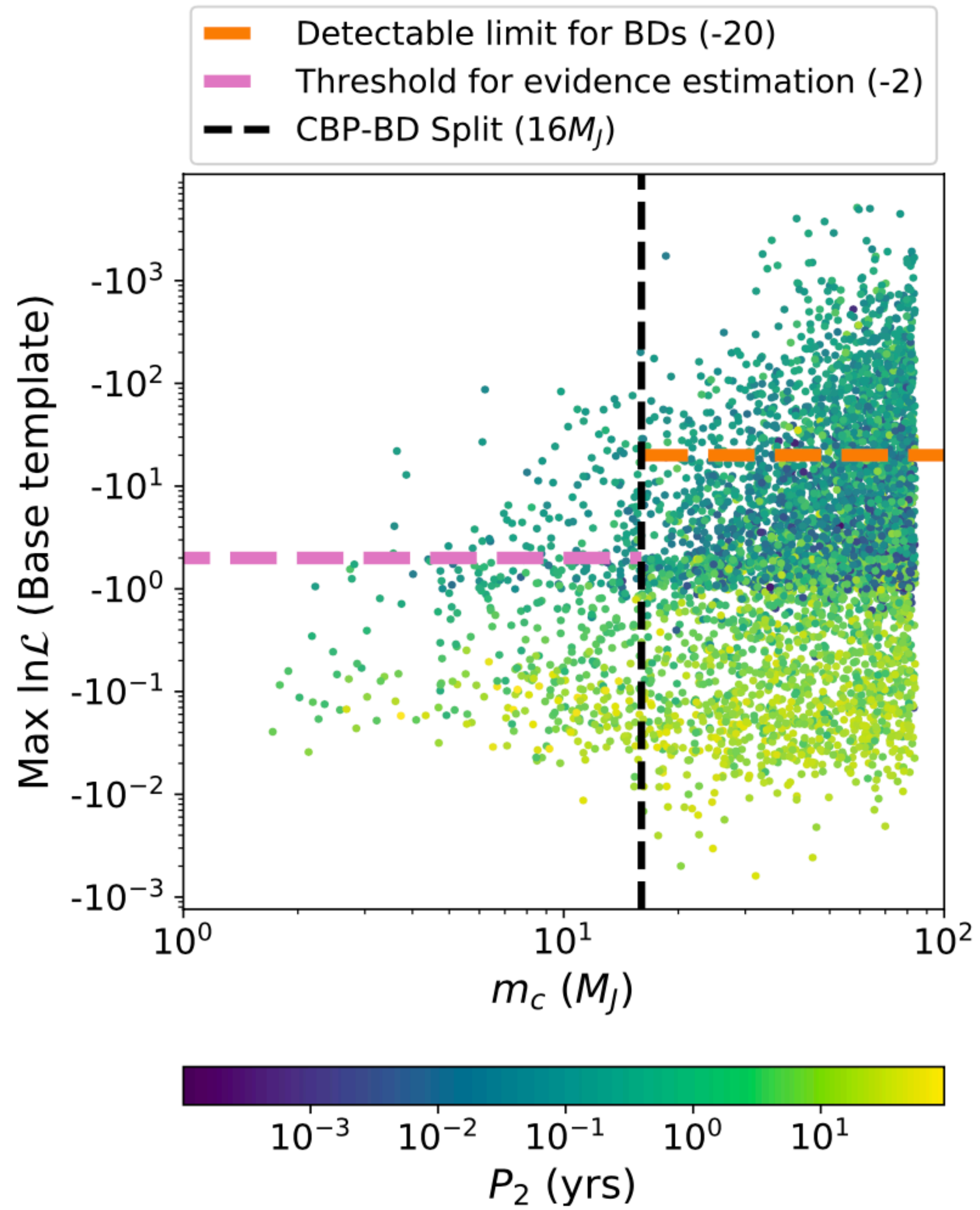
Recent Work

- 3rd body eccentricity added according to observed eccentricity of wider inner binaries
- Bayesian model selection: 2-body waveform vs 3-body waveform

B_{12}	$2\log B_{12}$	Evidence for model 1
<1	<0	Negative (supports model 2)
1 to 3	0 to 2	Not worth more than a bare mention
3 to 12	2 to 5	Positive
12 to 150	5 to 10	Strong
>150	>10	Very Strong

First cut on the catalog done using phase-maximised Likelihood at the injection parameters with different threshold for CBPs and BDs



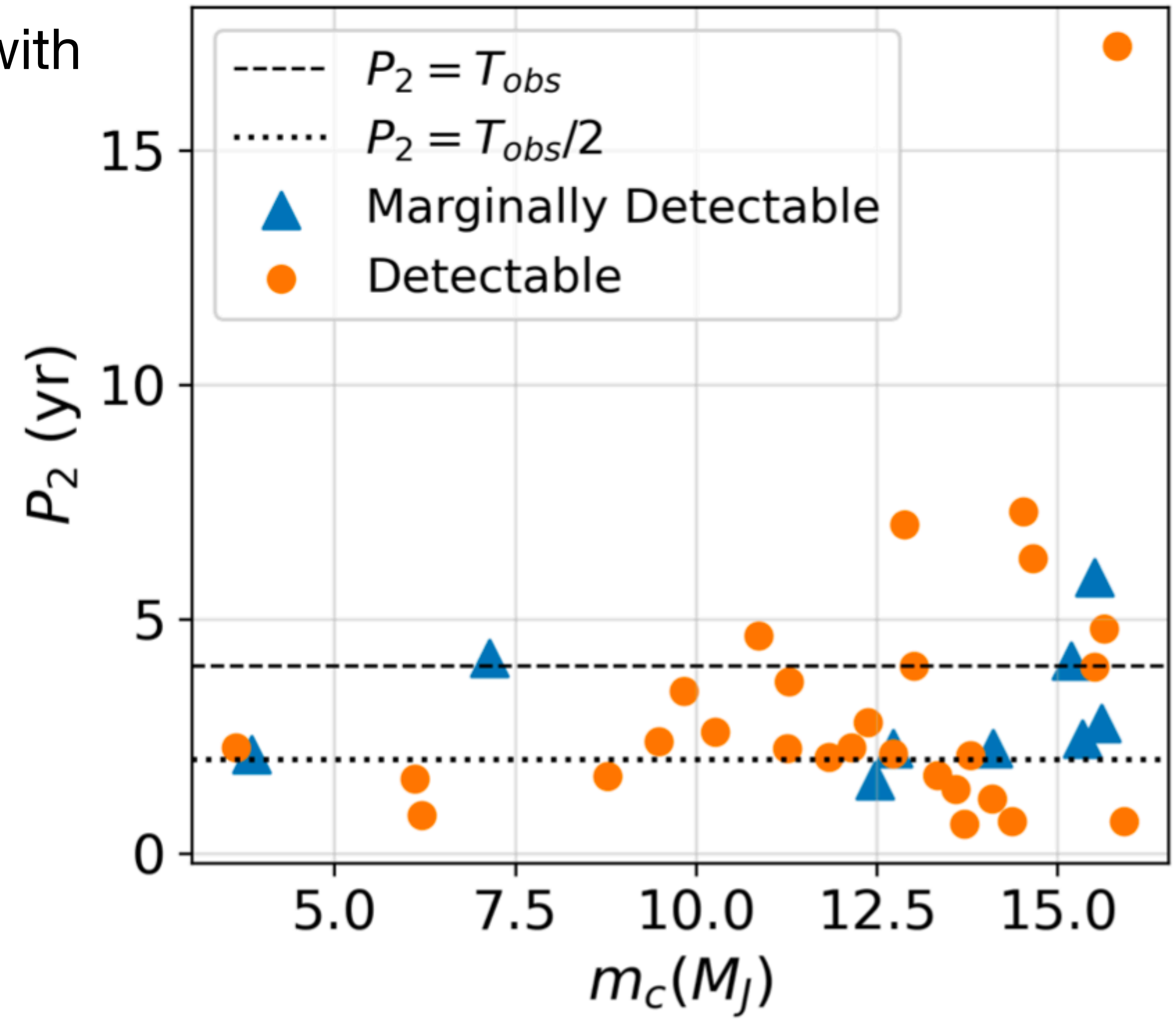
[Katz+, arXiv:2205.03461]

Recent Work

The remaining CBPs are then investigated using a full MCMC computation of the evidence and likelihood

Different behaviour for short ($P_2 < T_{\rm obs}/2$) and long ($P_2 > T_{\rm obs}/2$) 3rd-body periods

Detectability is then set to $2\log B_{12} > 5$, with marginal detections for $0 < 2\log B_{12} < 5$



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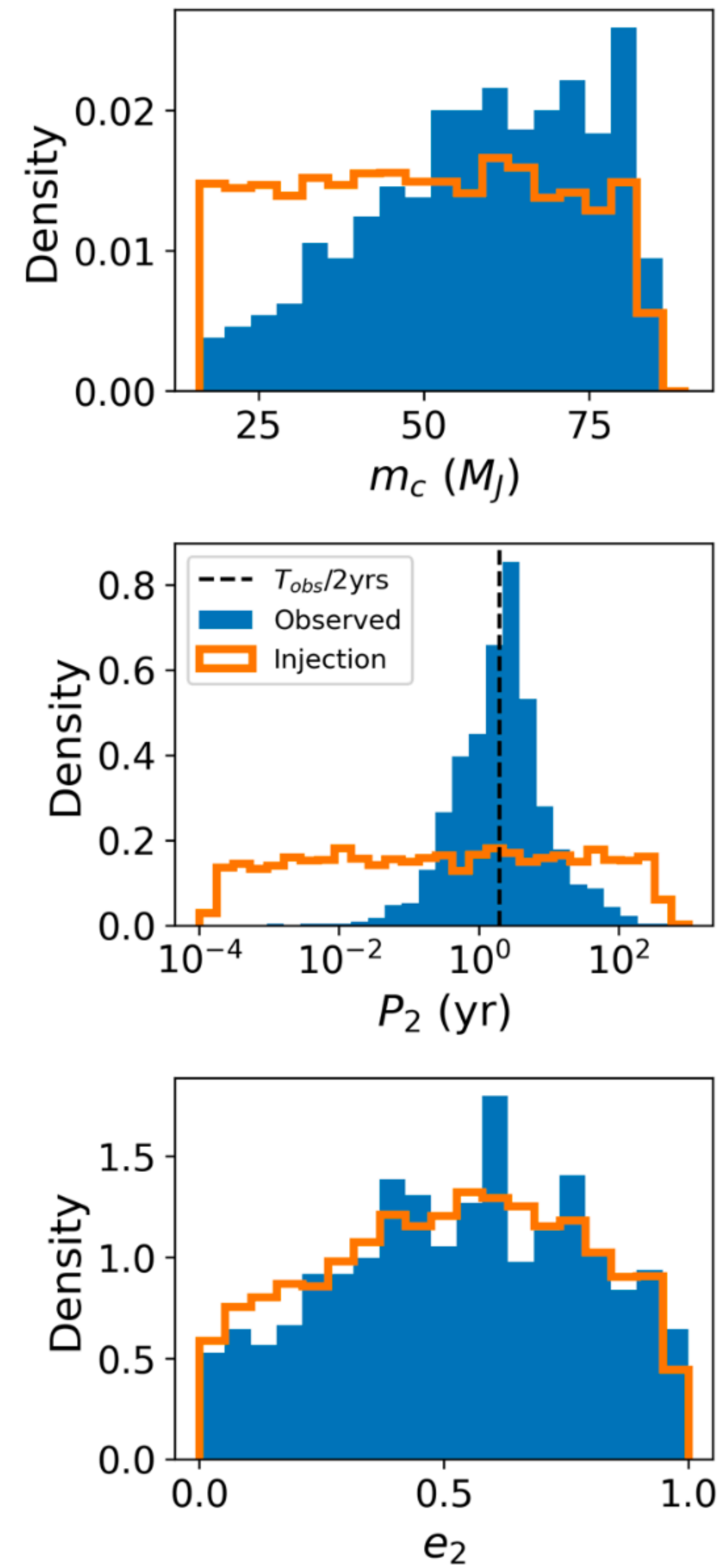
3rd-bodies are preferentially detected at higher masses and periods around $T_{\rm obs}/2$



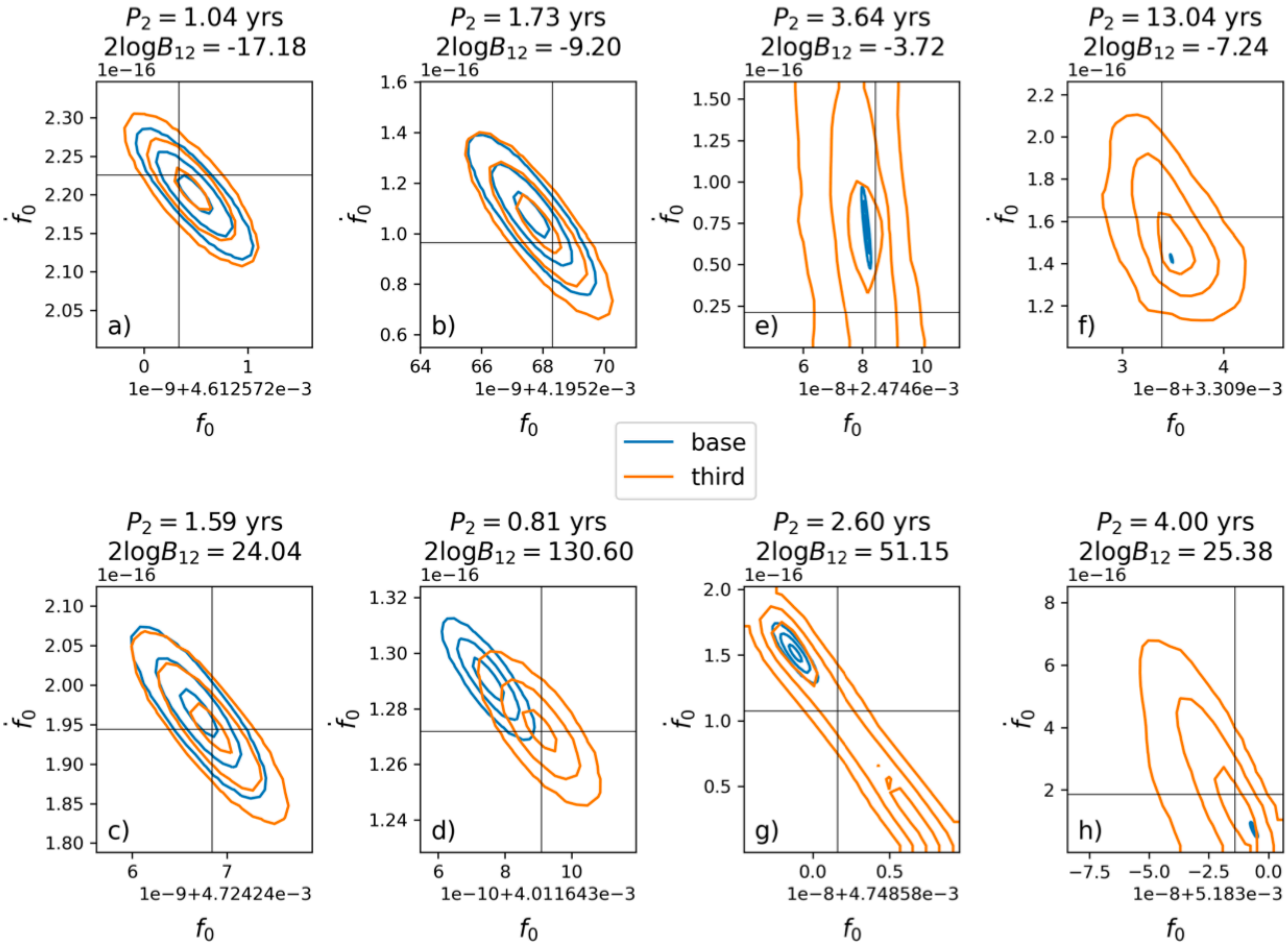
[Katz+, arXiv:2205.03461]

Recent Work

How biased are Galactic binaries in the presence of a 3rd-body?

Undetectable 3rd-body

Detectable 3rd-body



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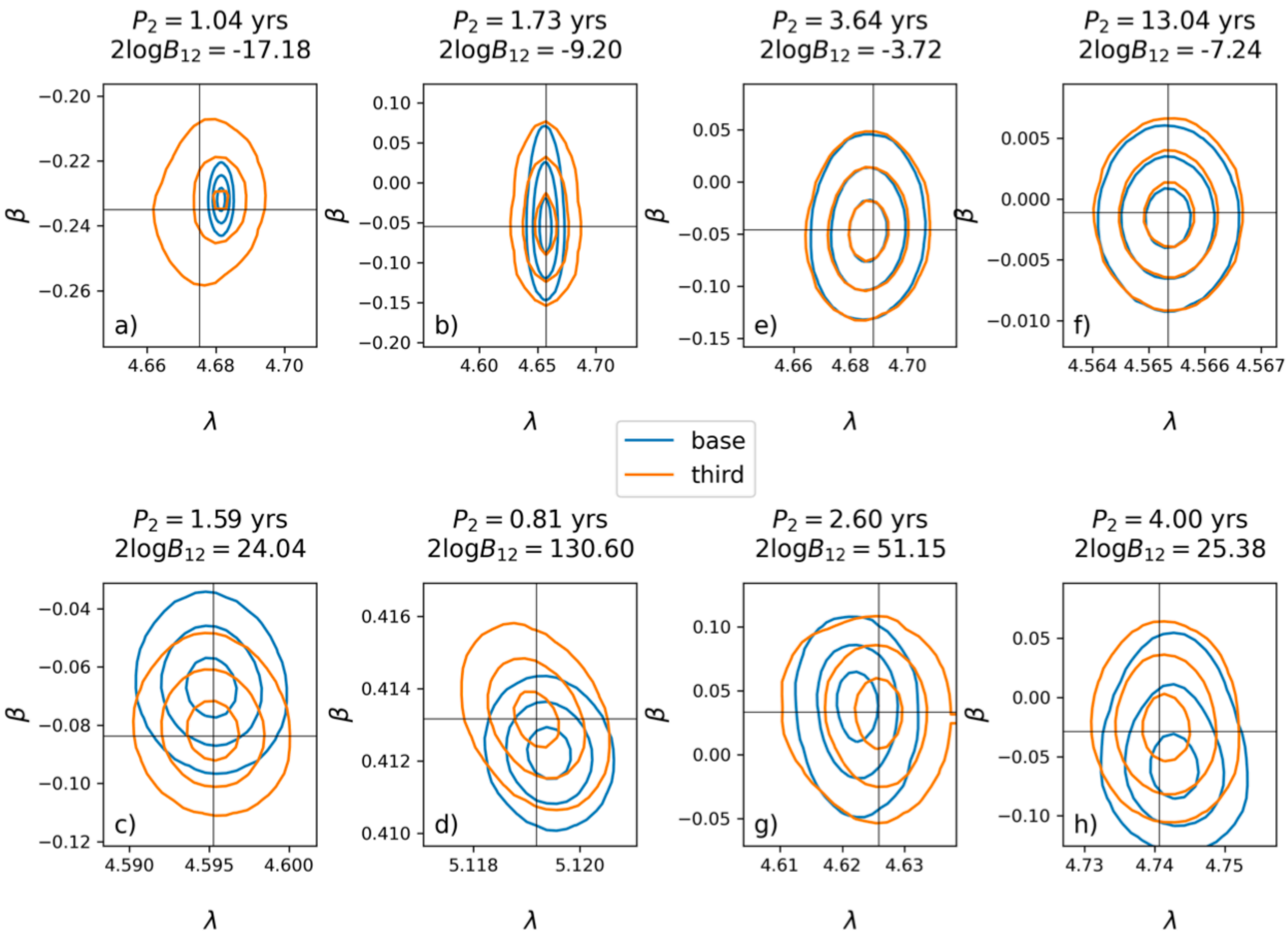
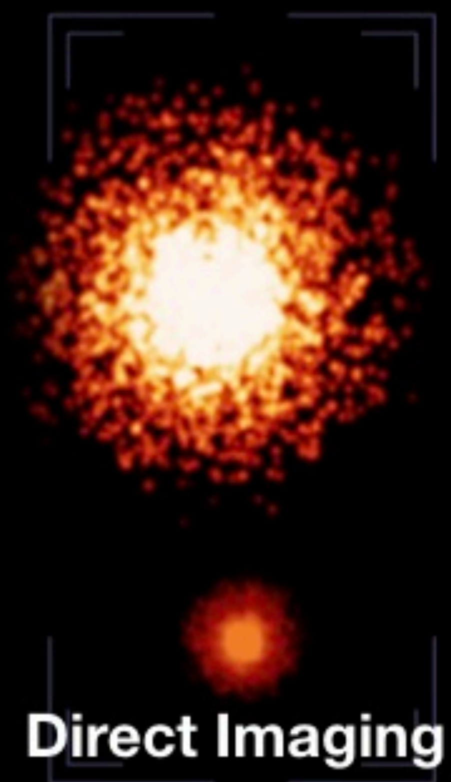
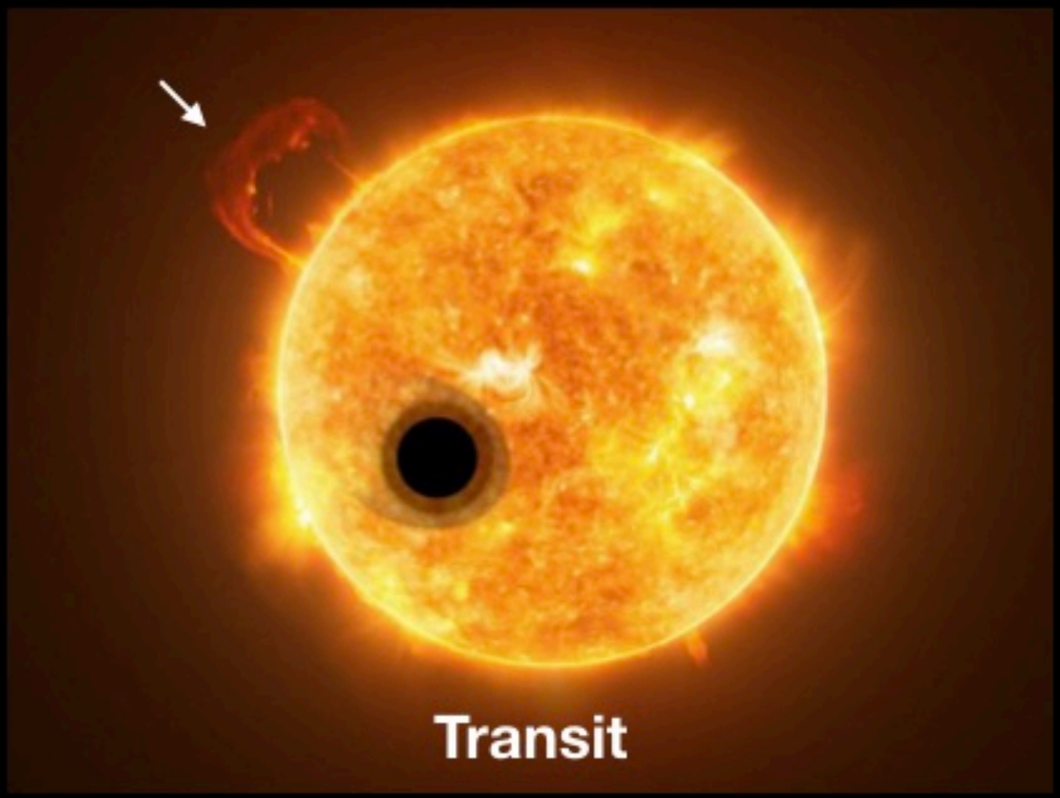
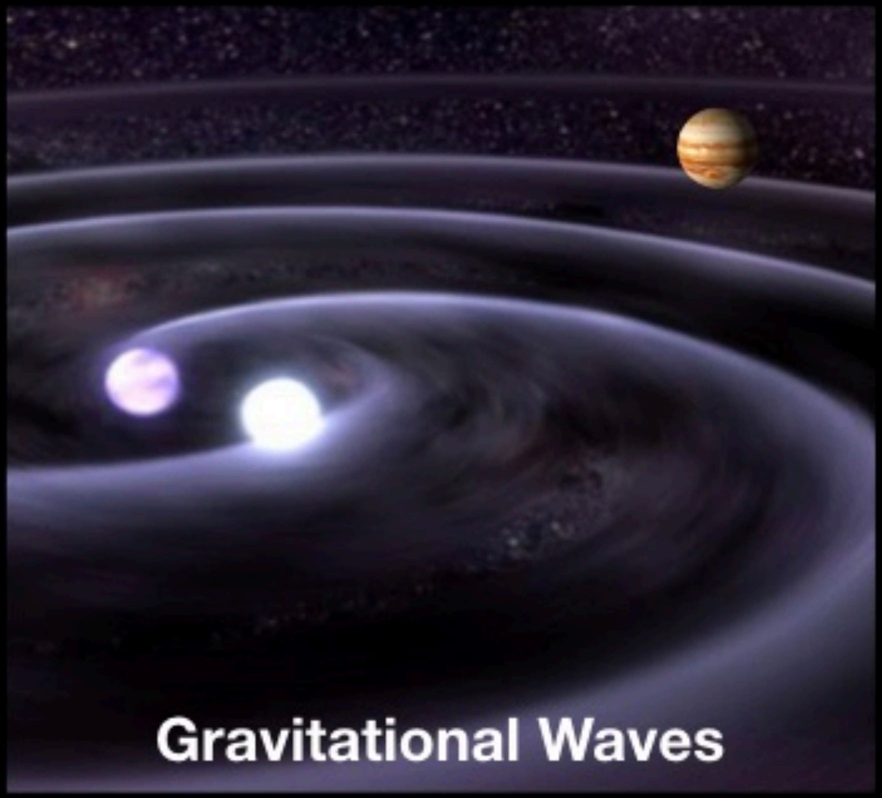


[Katz+, arXiv:2205.03461]

THE LIFE OF A GAS GIANT







~ 10^{8} yrs

~ 10^{9} yrs

JWST ARIEL GAIA LISA