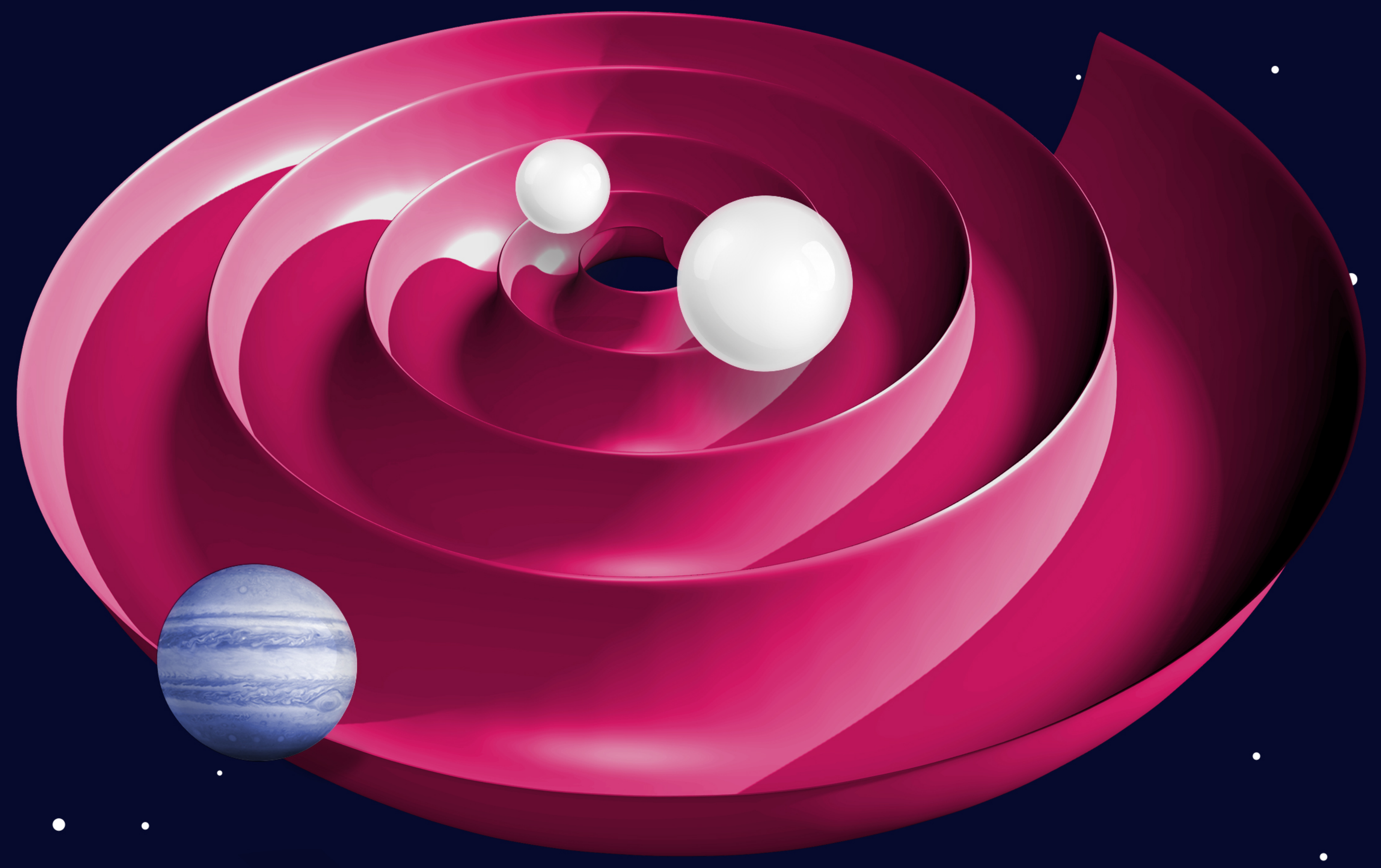
Image credit: S. Definis



CBPs with the LISA mission

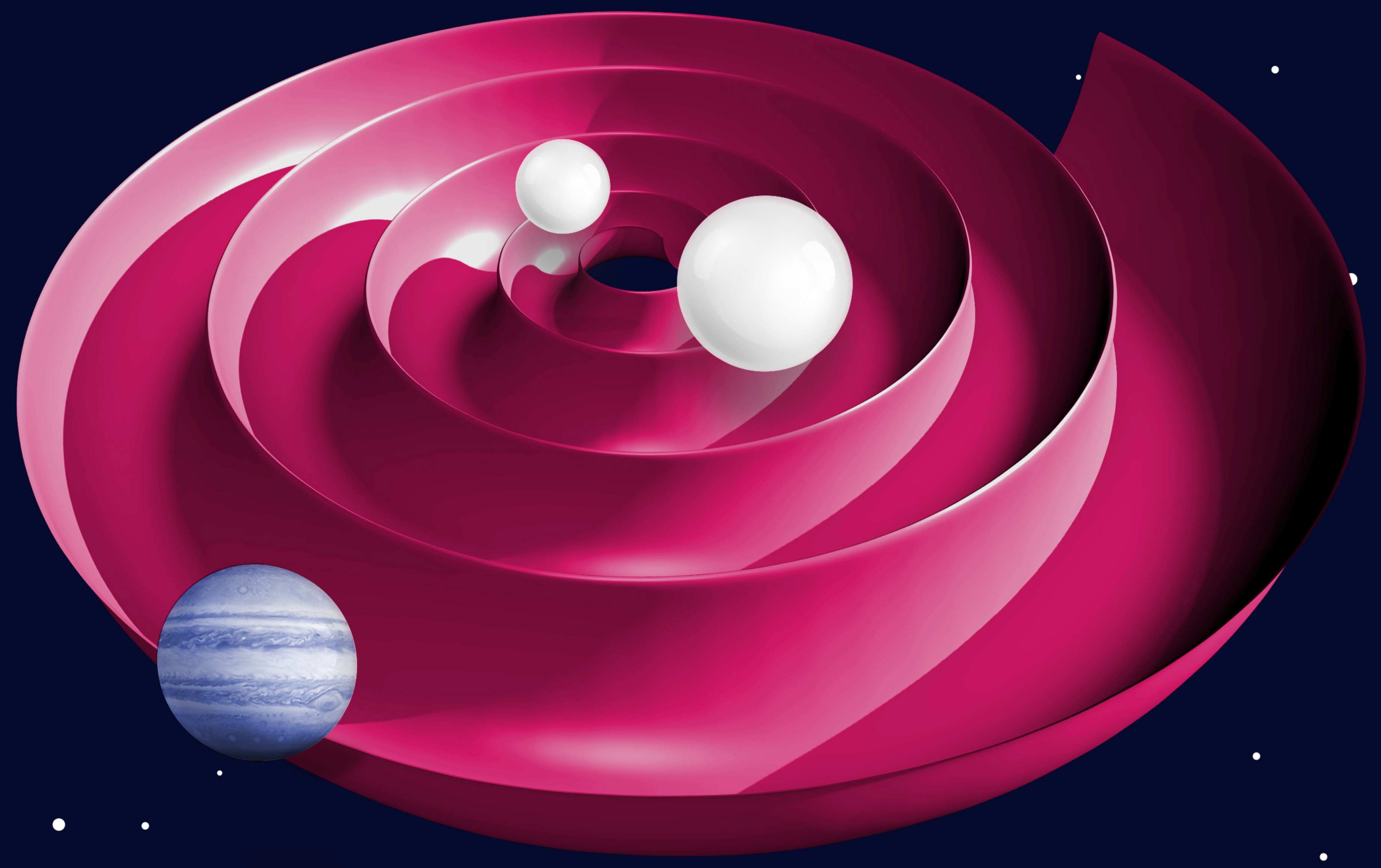
CAMILLA DANIELSKI

G. COLUMBA, N. J. CORNISH, A. DOROZSMAI, V. GUPTA, N. KARNESIS, M. KATZ, V. KOROL, T. B. LITTENBERG, S. LEDDA., A. NIGIONI, N. TAMANINI, S. TOONEN, D. TURRINI

INAF Astrophysics Fellowship in Italy

OSSERVATORIO ASTROFISICO DI ARCETRI – INAF ISTITUTO NAZIONALE DI ASTROFISICA

Image credit: S. Definis



CBPs with the LISA mission

The quest for **Magrathea** !

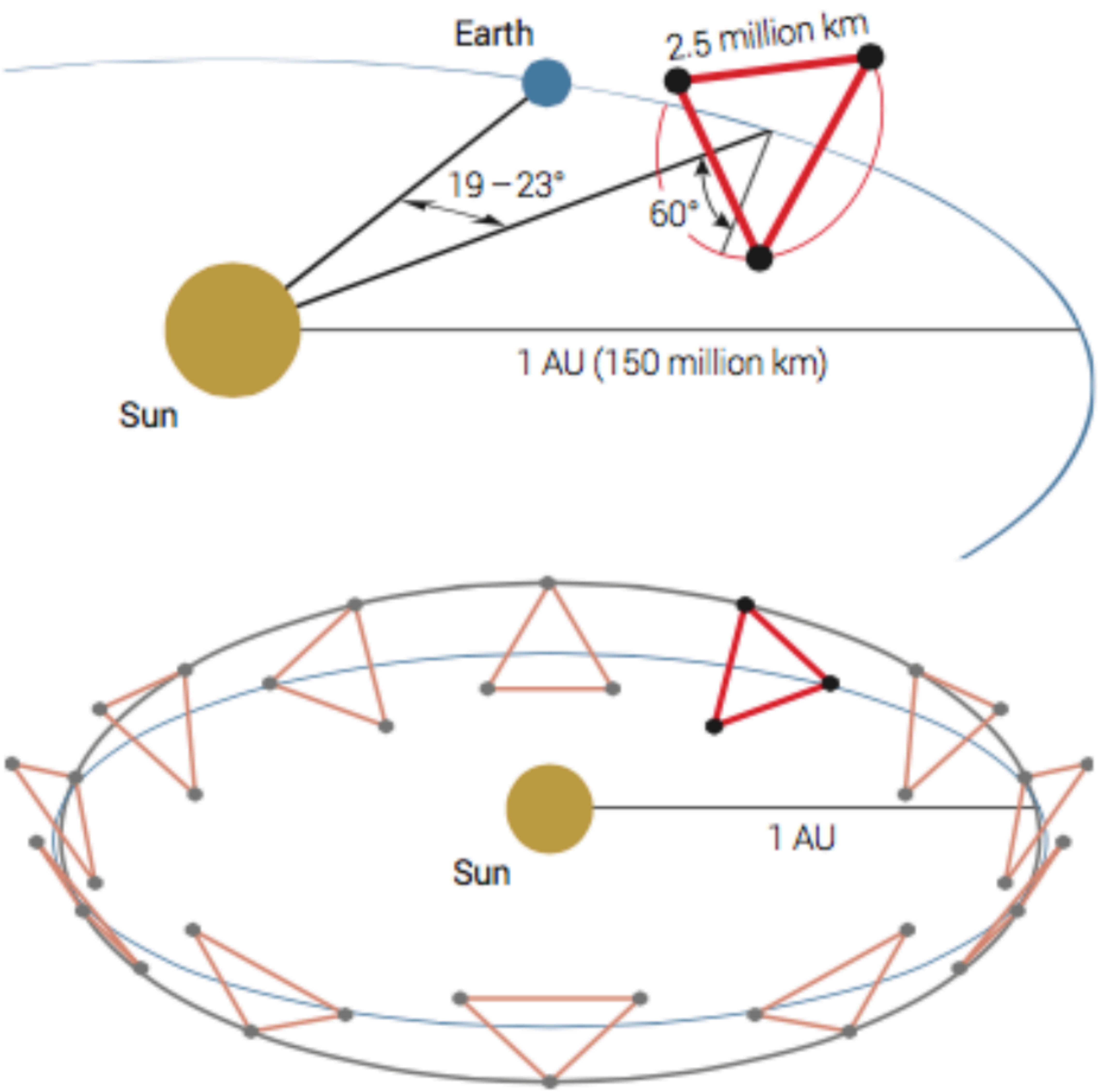
Astrophysics Fellowship in Italy

The Laser Interferometer Space Antenna

DESIGN:

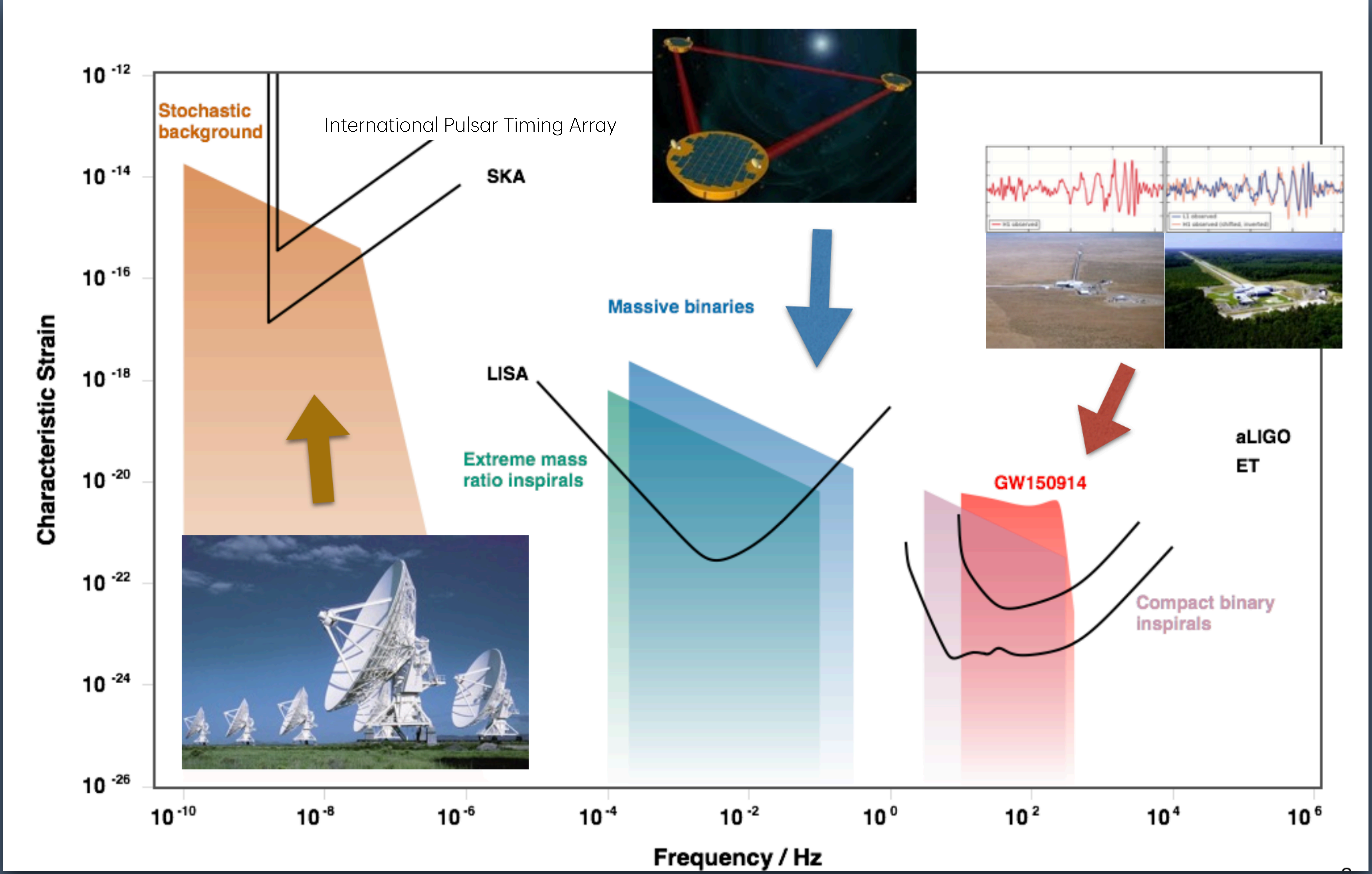
- ESA - L3 mission
- 3 spacecrafts orbiting the Sun
- Near equilateral triangular formation in heliocentric orbit (trailing Earth by ~50 million km)
- 6 laser links (3 active arms)
- Arm-length: 2.5 million km
- Mission duration: 4 to 10 yrs
- Adoption Jan 2024, Launch: 2034/2037s

[LISA (2017), arXiv:1702.00786]



https://sci.esa.int/lisa

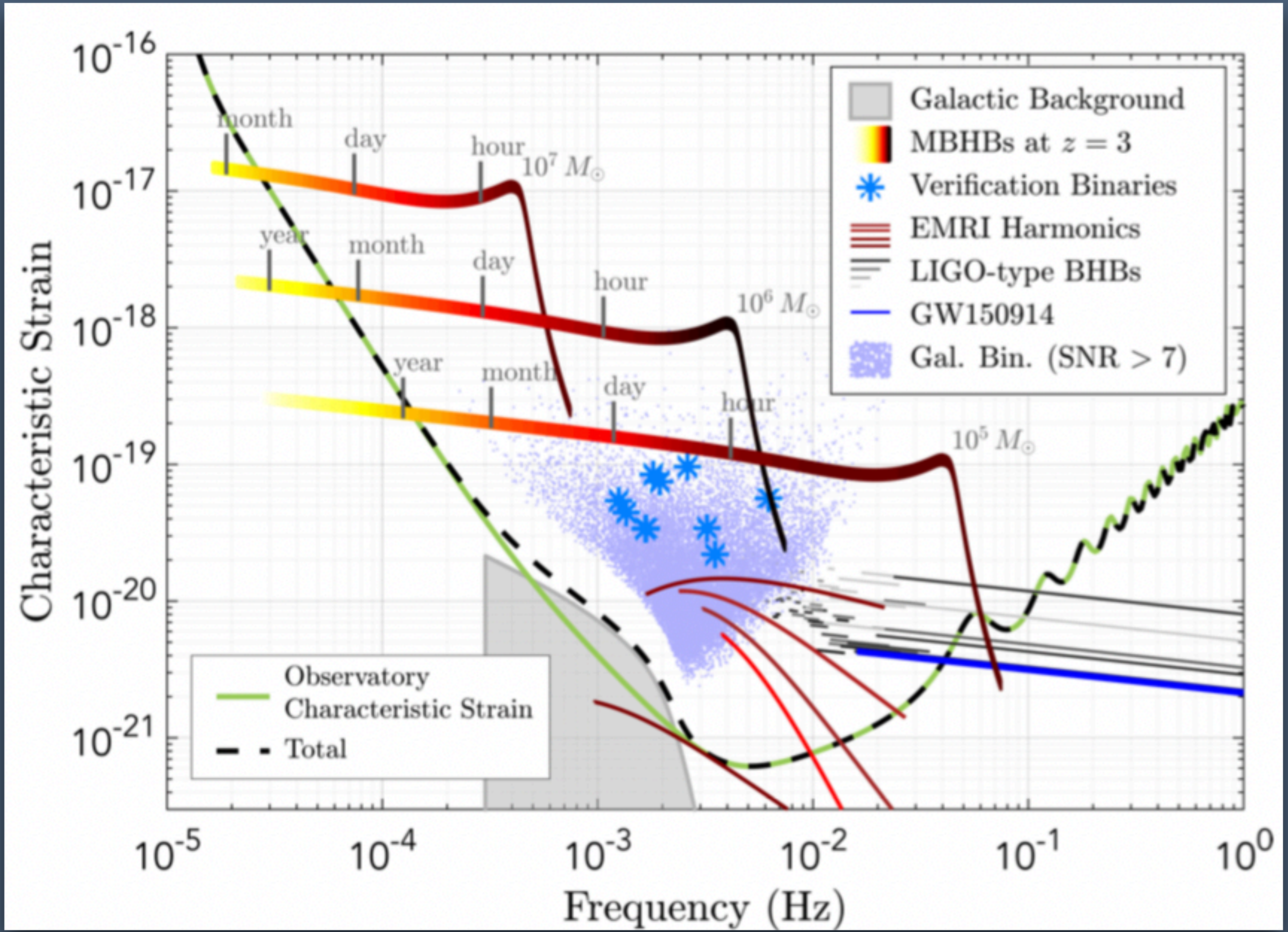
Introduction



LISA

LISA GW target sources:

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



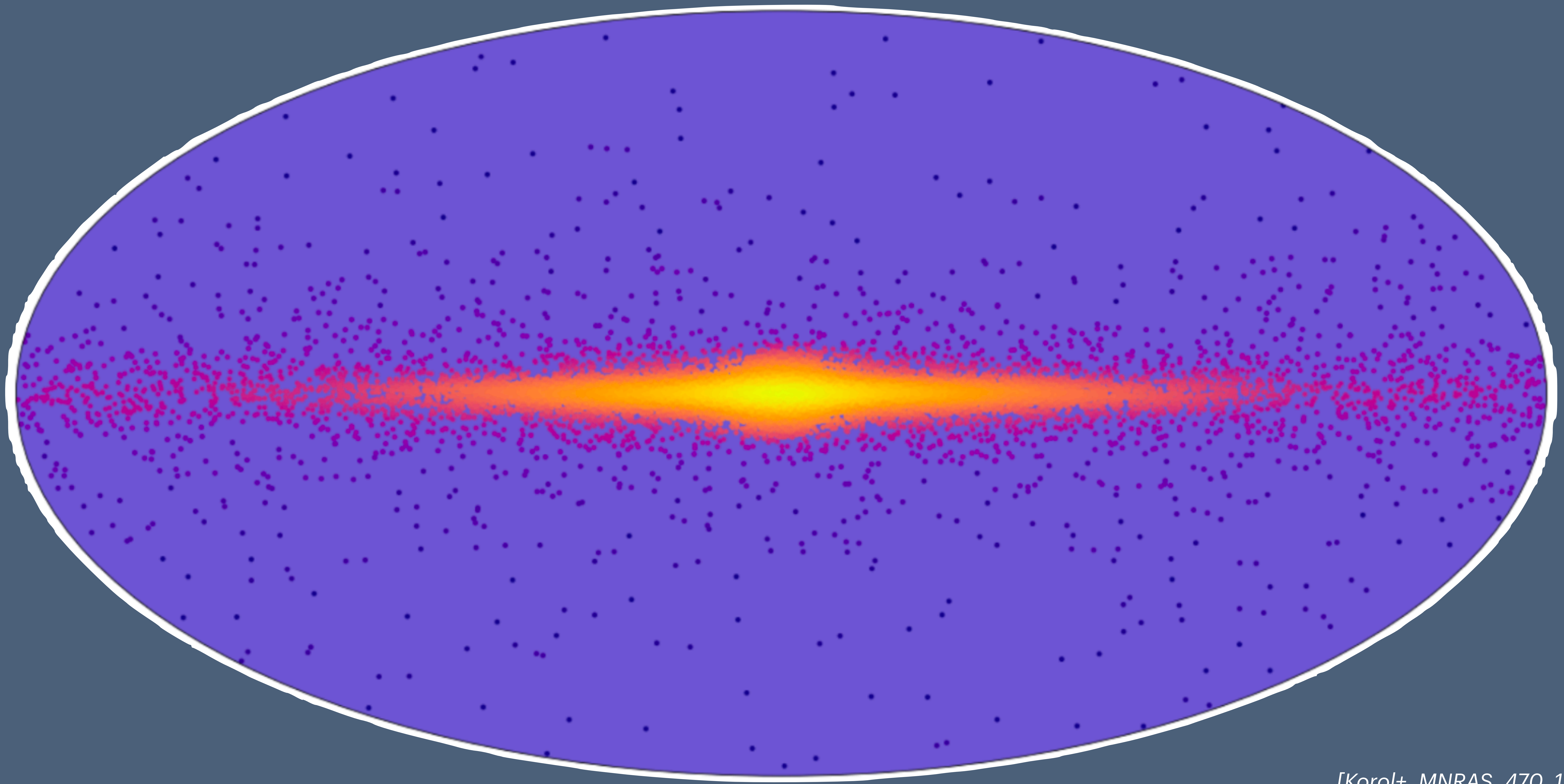
10 mHz - 0.1 Hz

[LISA (2017), arXiv:1702.00786]

The Double white dwarf population

Tens of thousands of double white dwarf binaries all over the Milky Way (and beyond)

26k nominal - 40k extended



[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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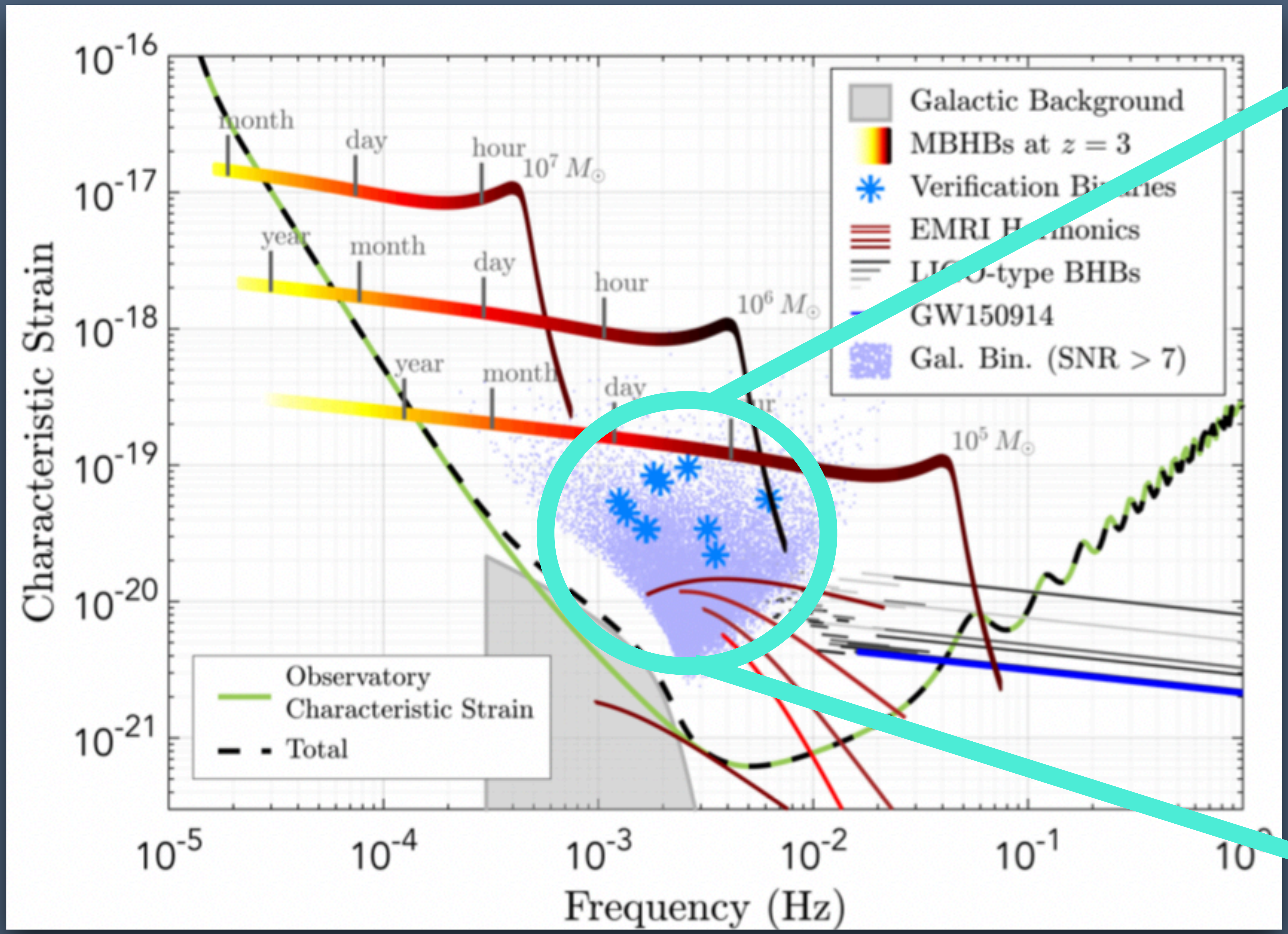
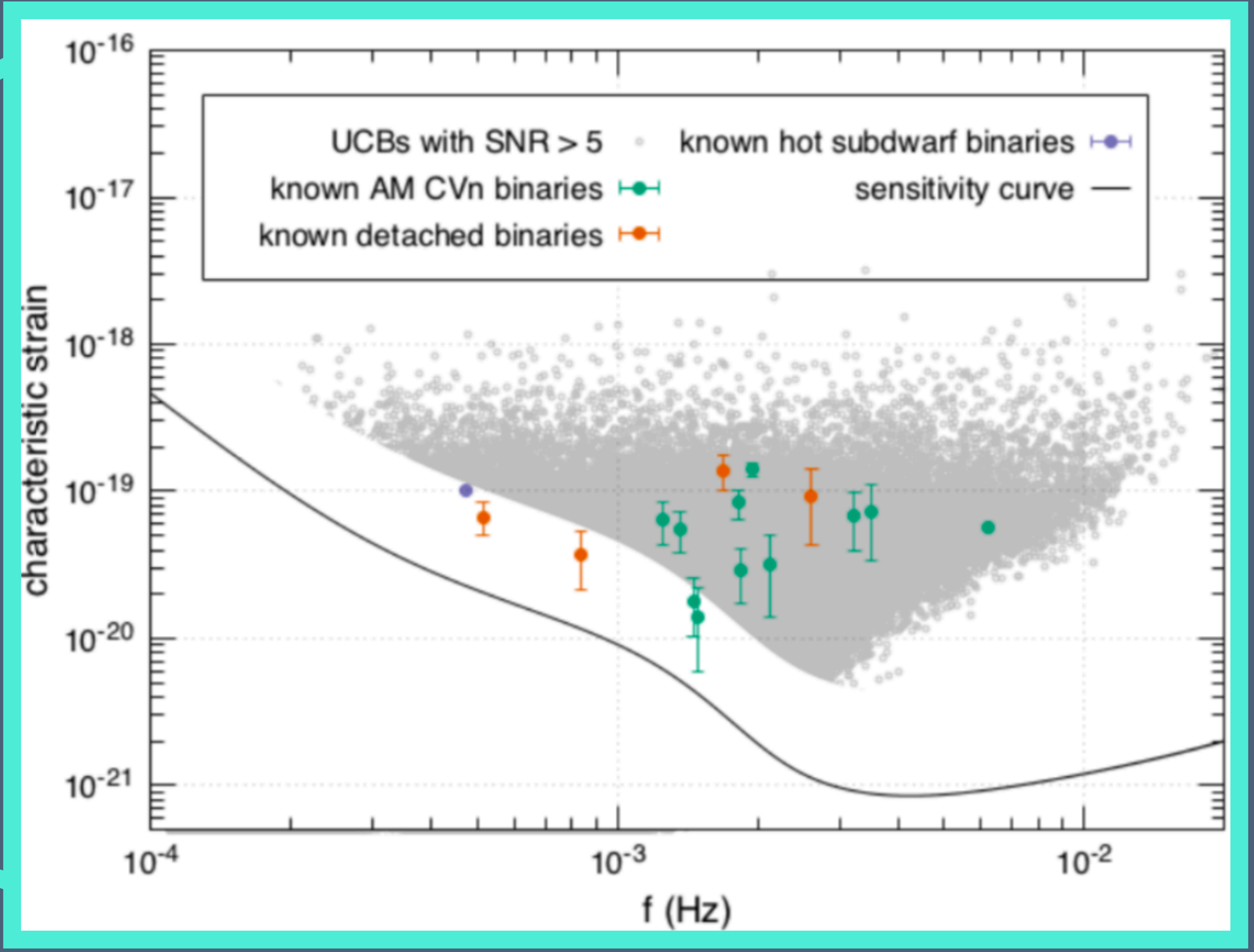


[LISA (2017), arXiv:1702.00786]

Double White Dwarfs

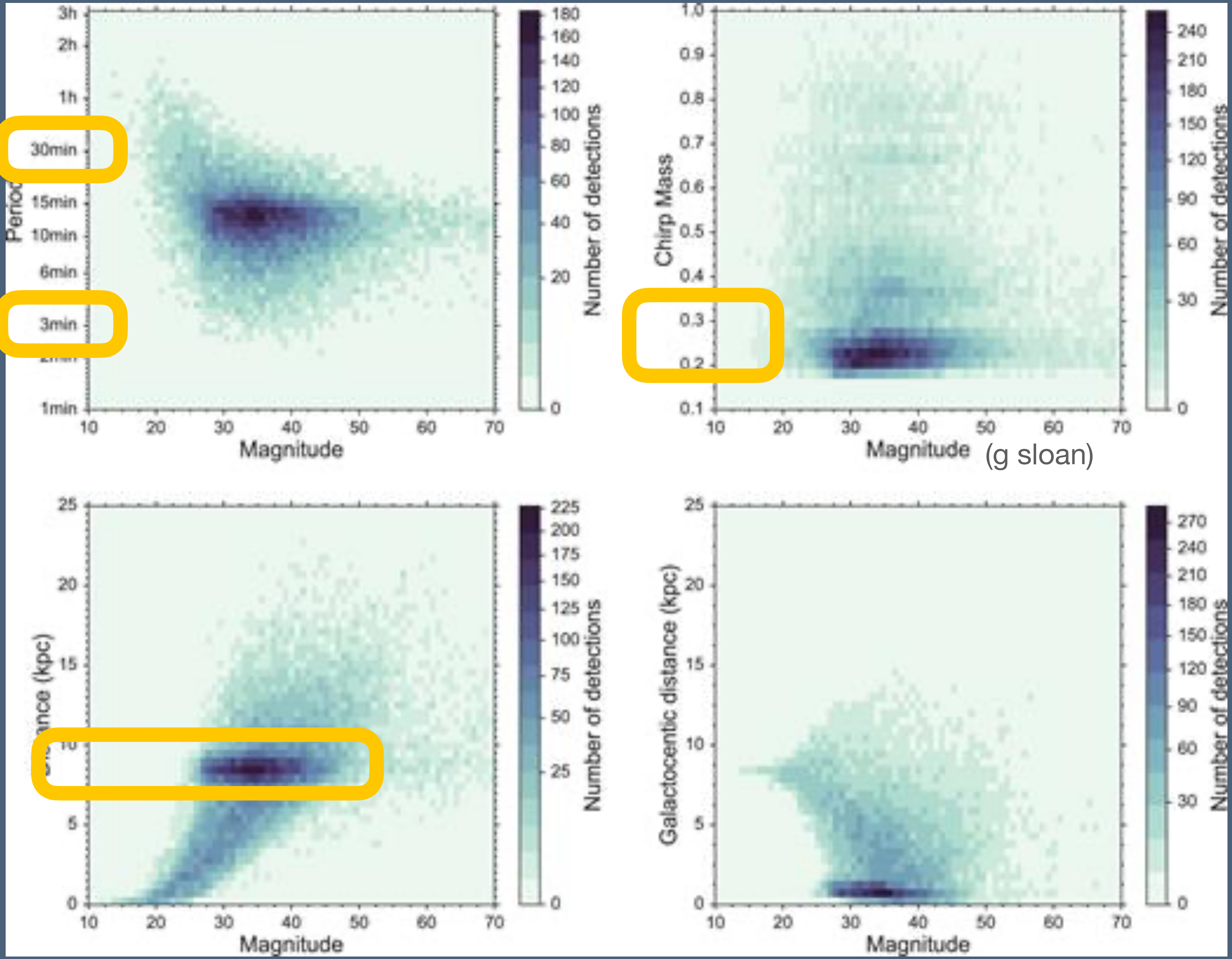


[Littenberg+ (2019), arXiv:1903.05583]
[Kupfer+, MNRAS, 480, 302, (2018); arXiv:1805.00482]

Courtesy of N. Tamanini

The Double white dwarf population

Faint stars in a very short period



Chirp mass: $M_c = \frac{(M_1 * M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$

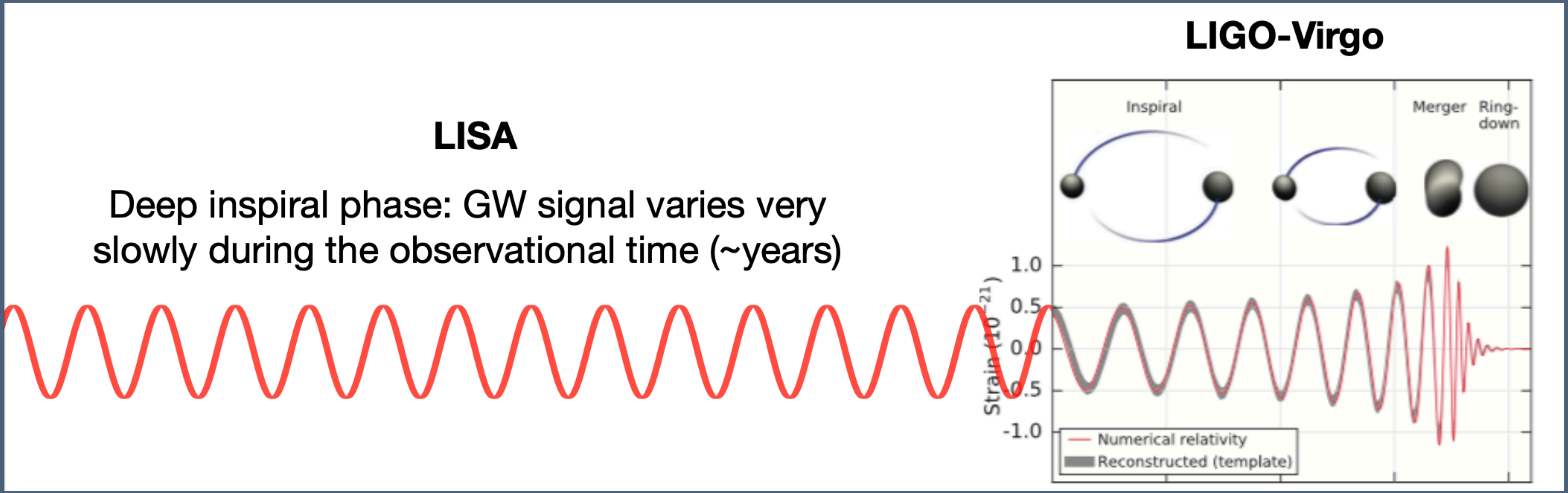
Most of the stars are located in the Galaxy centre

Binary Periods mostly between 30 min and 3 min.

[Korol et al. 2017 arXiv:1703.02555]

Center of Mass effect on GWs

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



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

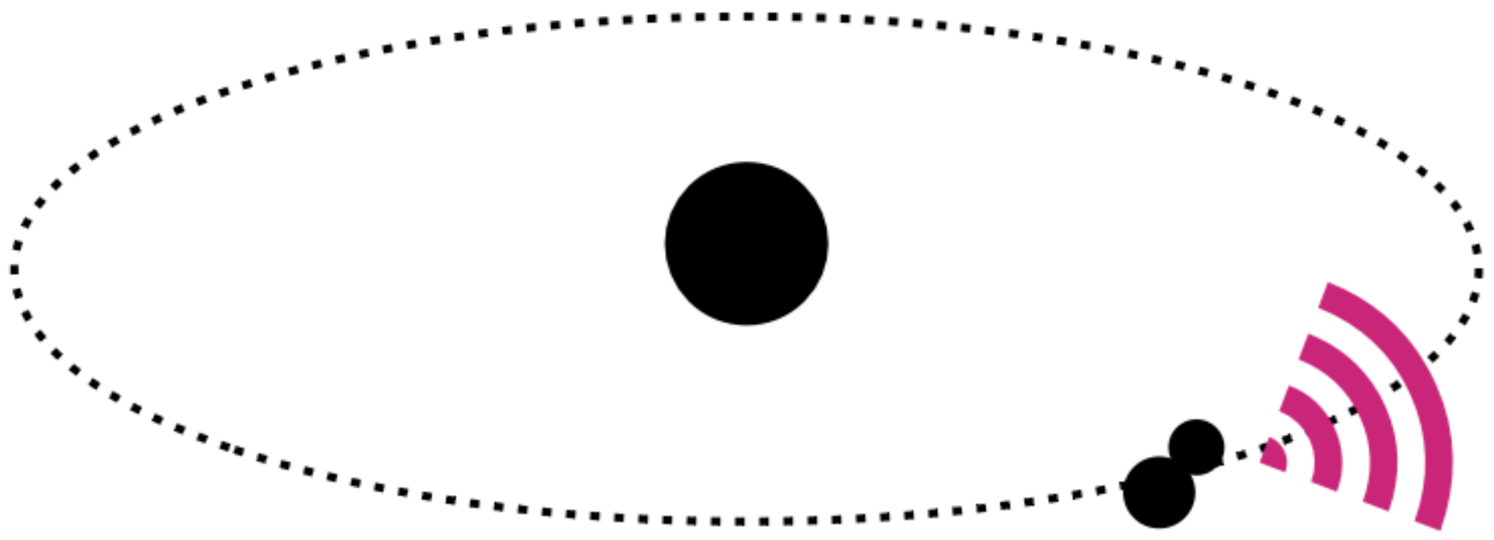
Courtesy of N. Tamanini

Applications

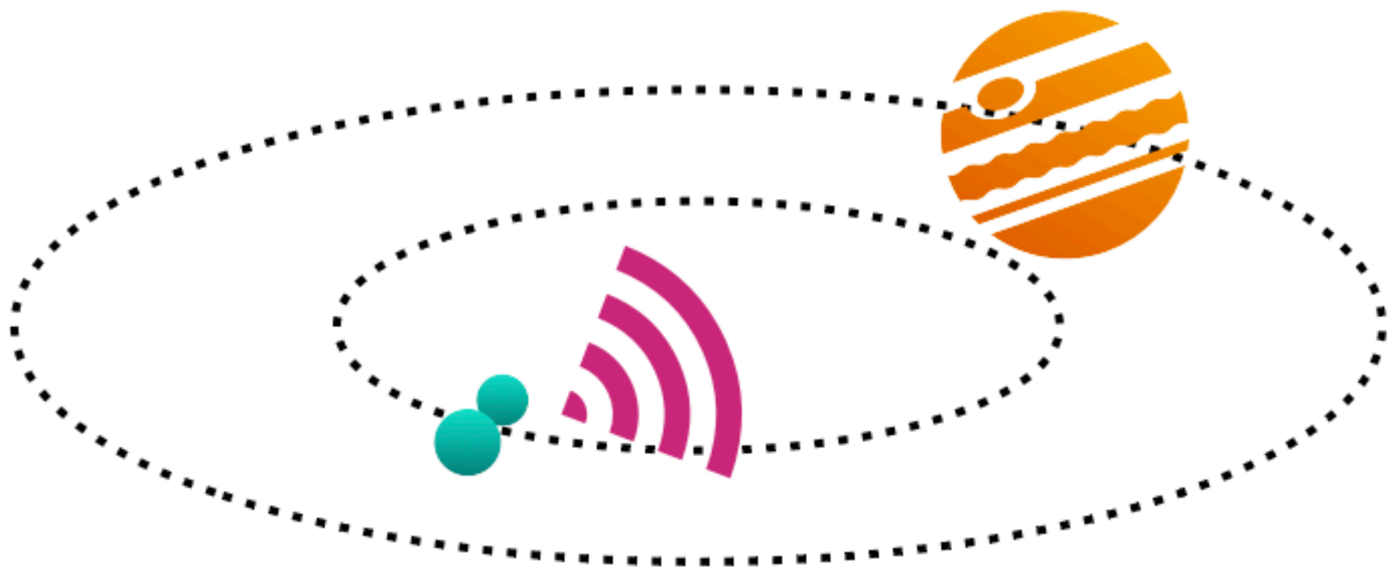
The center-of-mass of a GW binary can be accelerated by gravitational attraction only, i.e if there is a sufficiently close and sufficiently massive third body nearby

There are mainly two cases relevant for LISA:

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



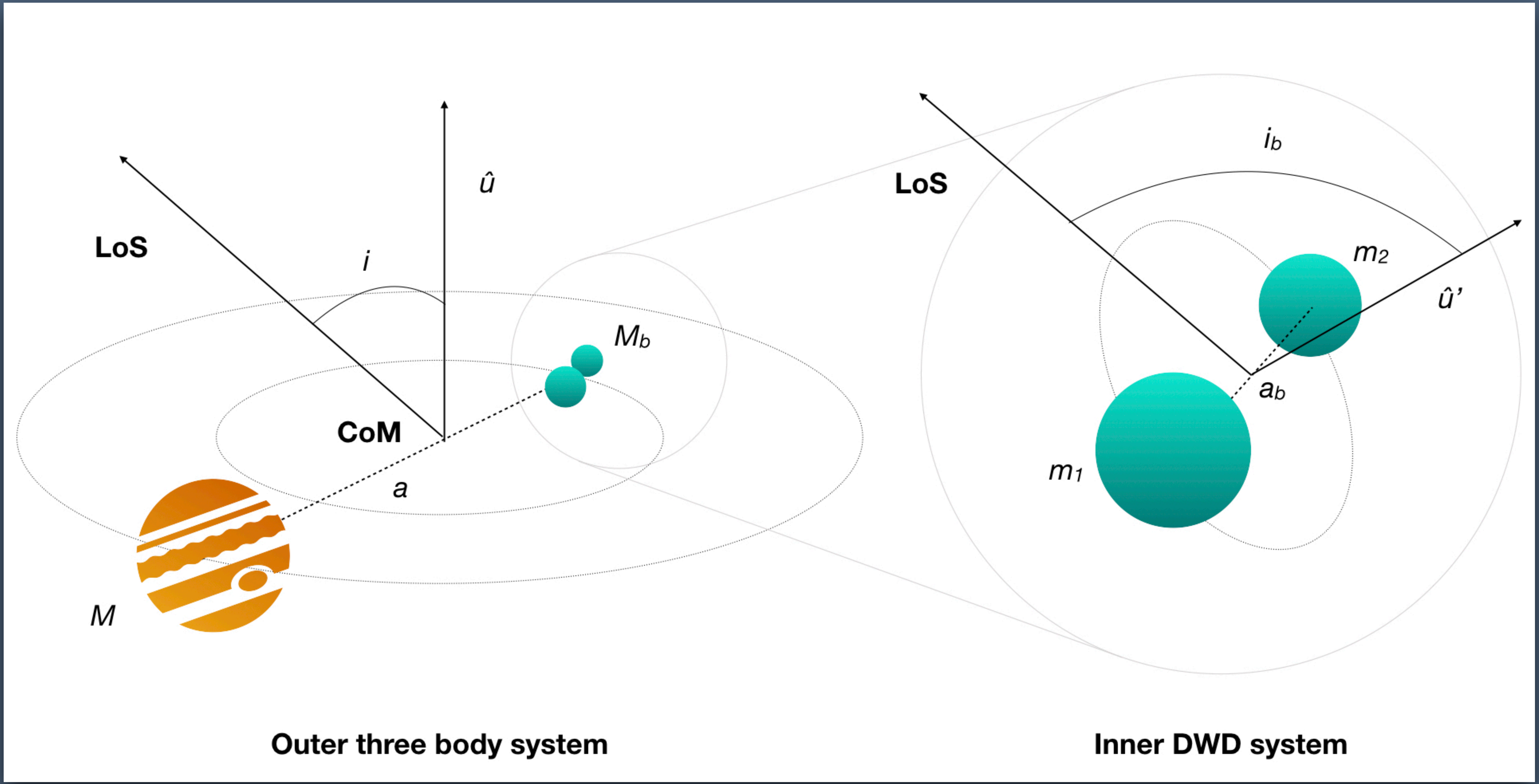
Galactic DWD binaries in orbit with a third object (planet, star, …)



Courtesy of N. Tamanini

WD binaries perturbed by a circumbinary companion

The center of mass (CoM) of the DWD will move on a Keplerian orbit.



two separate two-body problems.

Pp >> Pb

[Tamanini & Danielski, Nat. Astron., 3, 858 (2019); arXiv:1812.04330]
[Robson+, PRD, 98, 064012 (2018); arXiv:1806.00500]

WD binaries perturbed by a circumbinary companion

The gravitational attraction of third circumbinary object will imprint a **Doppler frequency modulation** on the GW signal (as long as the dynamics is non-relativistic):

$$f_{obs}(t) = \left(1 + \frac{v_{com}(t)}{c}\right) f_{GW}(t)$$

Where (assuming circular orbits):

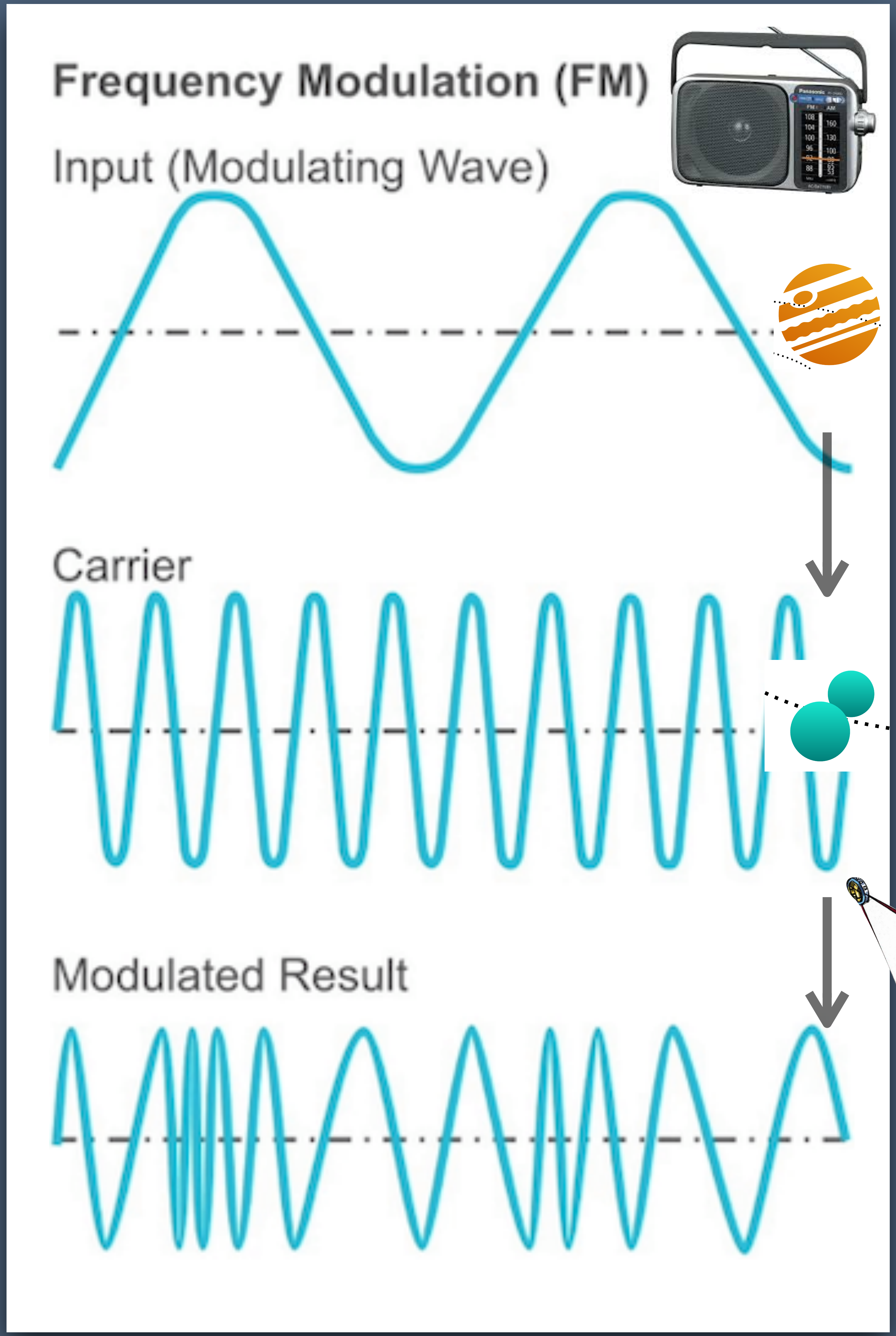
$$f_{GW}(t) = f_0 + f_1 t + \mathcal{O}(t^2)$$

$$v_{com} = -K \cos\left(\frac{2\pi t}{P_P} + \phi_0\right)$$

$$K = \left(\frac{2\pi G}{P_P}\right)^{1/3} \frac{M_P}{(M_B + M_P)^{2/3}} \sin i$$

WDs orbit slowly shrinks:
—> low GW energy
—> Monochromatic GW
—> constant (frequency changing on timescales >> observational times) —> series expansion around the initial observed frequency suffice in describing their time evolution

WD binaries perturbed by a circumbinary companion



The CoM motion

$$v_{com} = -K \cos\left(\frac{2\pi t}{P_P} + \phi_0\right)$$

modulates the GW signal

$$f_{GW}(t) = f_0 + f_1 t$$

similarly to FM broadcasting.

Three new parameters can be determined from the signal:

P_P period

ϕ_0 orbital phase

K RV semi-amplitude

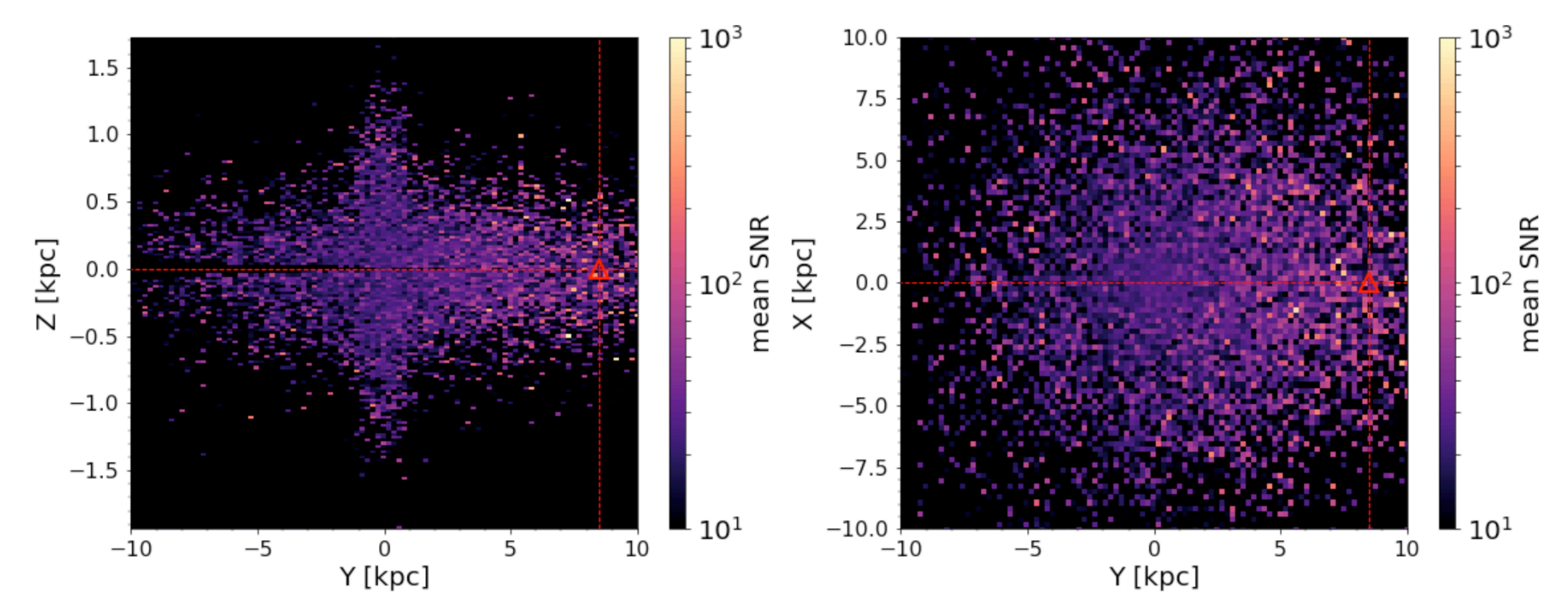
\+ e ? Eccentricity

[Tamanini & Danielski, Nat. Astron., 3, 858 (2019); arXiv:1812.04330]
[Robson+, PRD, 98, 064012 (2018); arXiv:1806.00500]

DWDs detected by LISA

4 yr observations

Galactocentric Cartesian coordinate system.



[Danielski et al, A&A, 632, 113 (2019); arXiv:1910.05414]

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

Scenarios of detection everywhere in the MW

Depending by the separation and mass distributions of sub-stellar objects

1) Simulation of the Galactic DWD population
2) Injection of circumbinary sub-stellar bodies
3) LISA detections

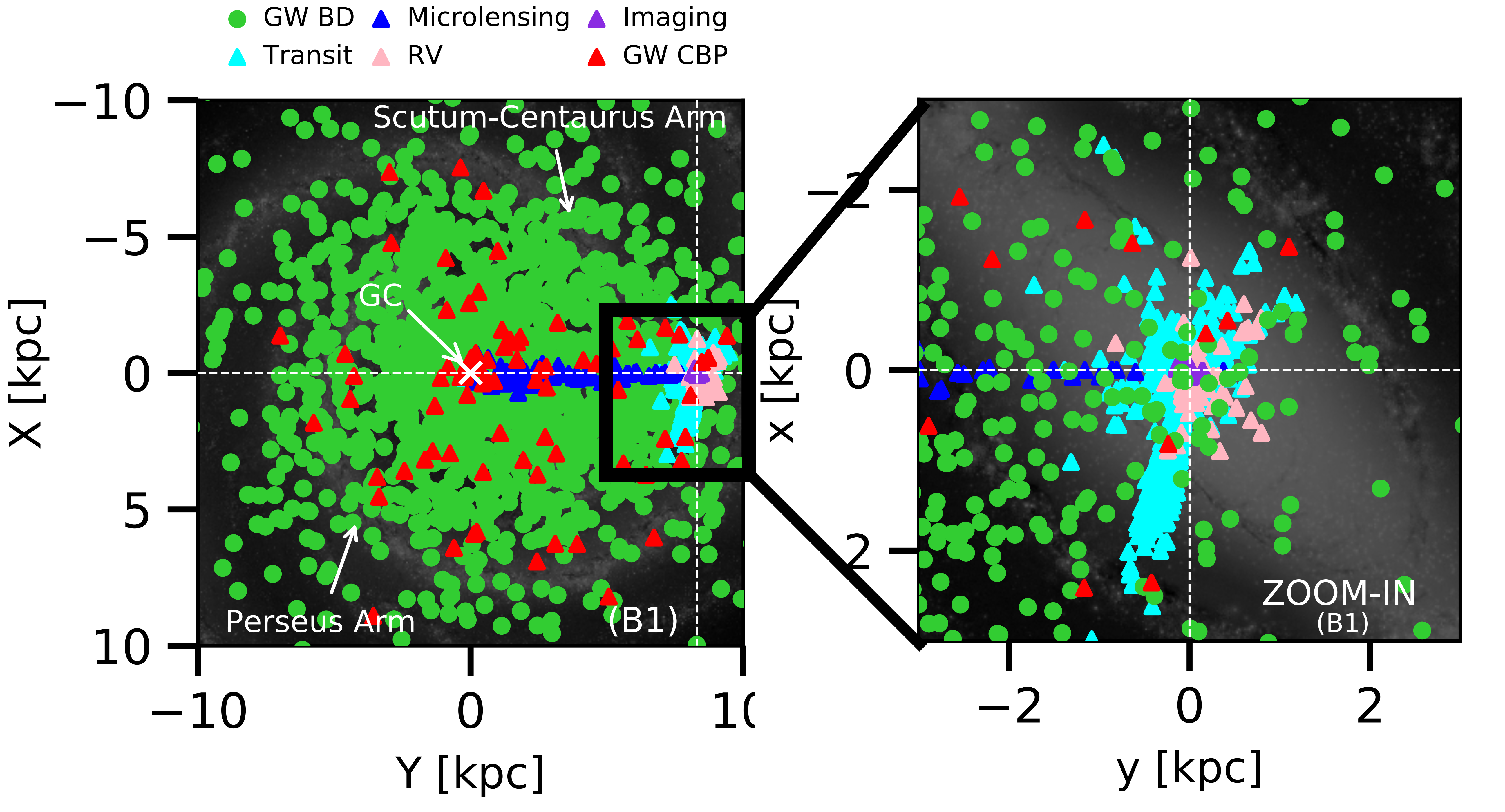
Methods: Information matrix analysis
Assumptions: one planet in a circular orbit

Information matrix is used to calculate the covariance matrices associated with maximum-likelihood estimates.

$$SNR \propto M_P\ ,\ f_0\ ,\frac{1}{d}$$

Detection:

$$\sigma_P, \sigma_K < 30\ \%$$



Optimistic

Solar neighbourhood

E.M. HORIZON:
~ 3 kpc average and ~ 8 kpc with microlensing

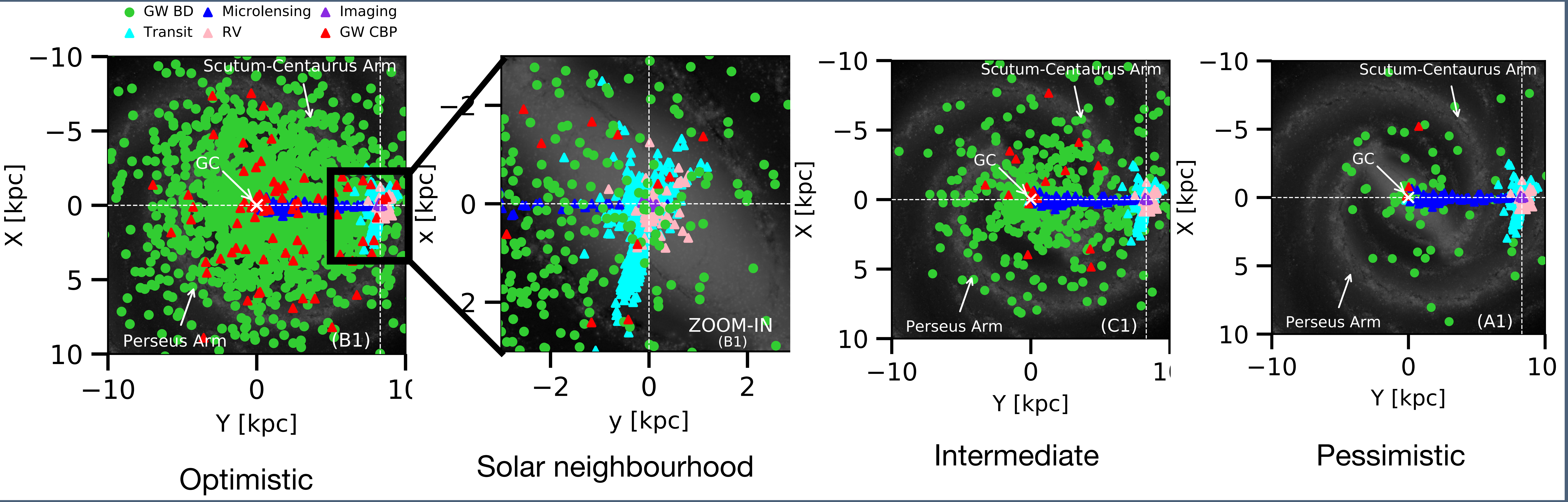
[**Danielski**+, *A&A*, 632, 113 (2019); arXiv:1910.05414]

Scenarios of detection everywhere in the MW

Depending by the separation and mass distributions of sub-stellar objects

1) Simulation of the Galactic DWD population
2) Injection of circumbinary sub-stellar bodies
3) LISA detections

Lower number of detections but still away from solar neighbourhood



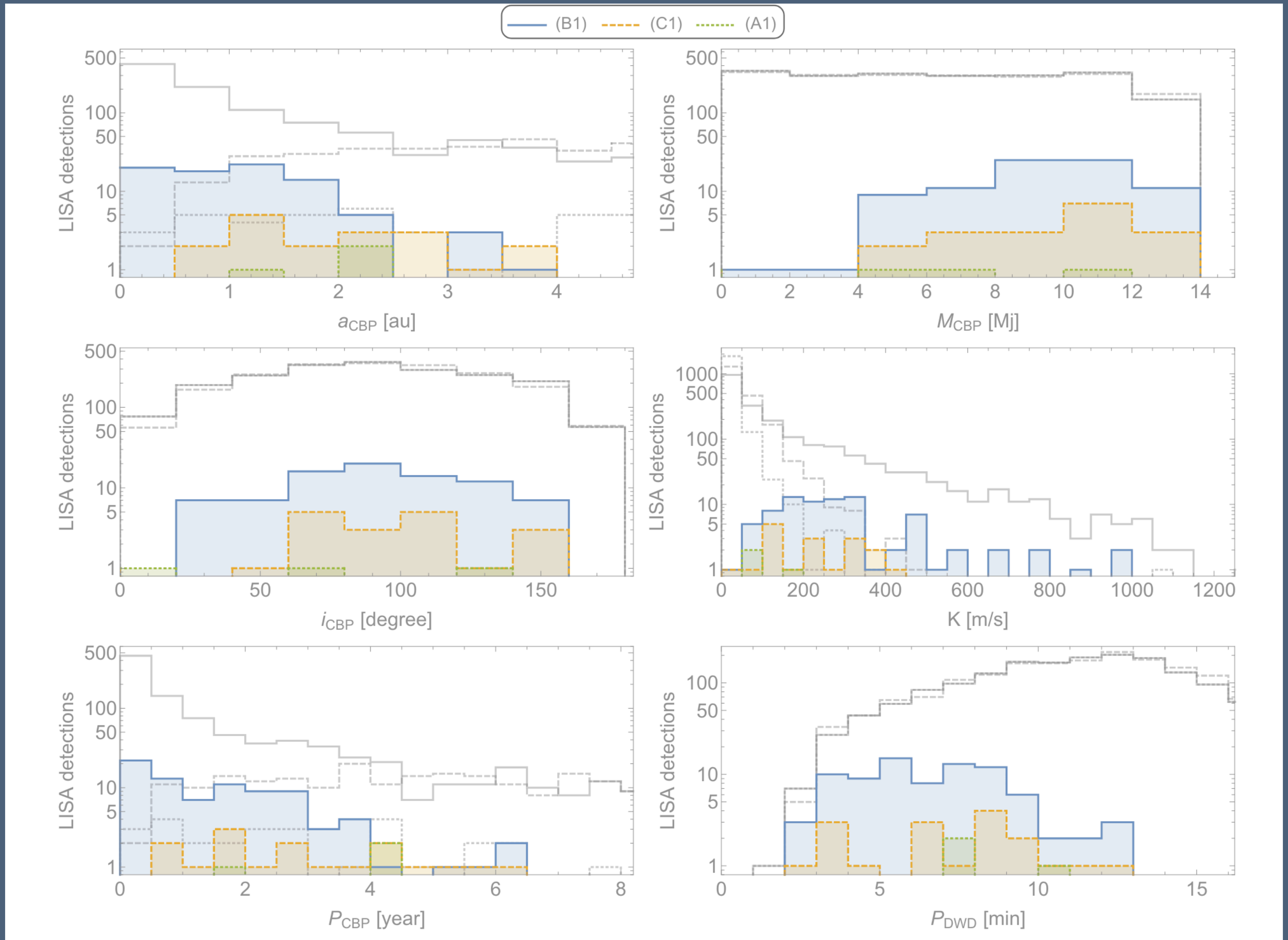
[**Danielski**+, *A&A*, 632, 113 (2019); arXiv:1910.05414]

Scenarios of detection everywhere in the MW

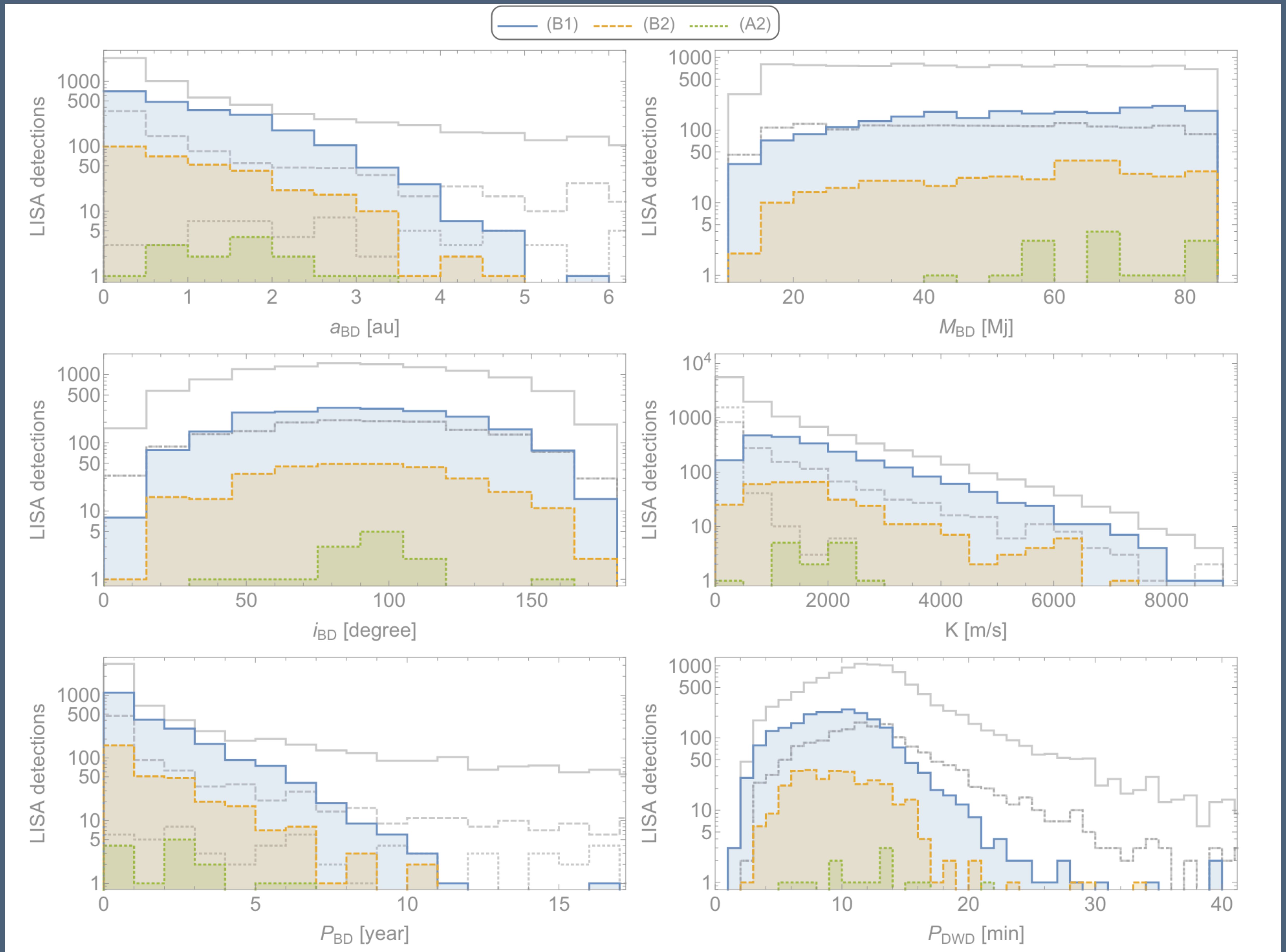
	$S/N_{\rm DWD}$	d [kpc]	m_1 [$M_\odot$]	m_2 [$M_\odot$]	P_b[min]	i_b [deg]	M [$M_{\rm J}$]	a [au]	i [deg]	P [yr]	$\Delta\Omega$ [arcmin^2]	K [m s^{-1}]
(x)	290	8.12	0.53585	0.53146	4.29	26.8	0.27	2.22	119.33	3.19	1.77	4.3
(y)	963	1.55	0.74955	0.47068	5.25	119.8	10.99	0.61	130.79	0.43	0.14	272.30
(z)	182	6.35	0.32285	0.30066	2.66	42.22	11.11	3.67	138.36	8.82	12.6	137.11

Exoplanets VS Brown Dwarfs

Exoplanets

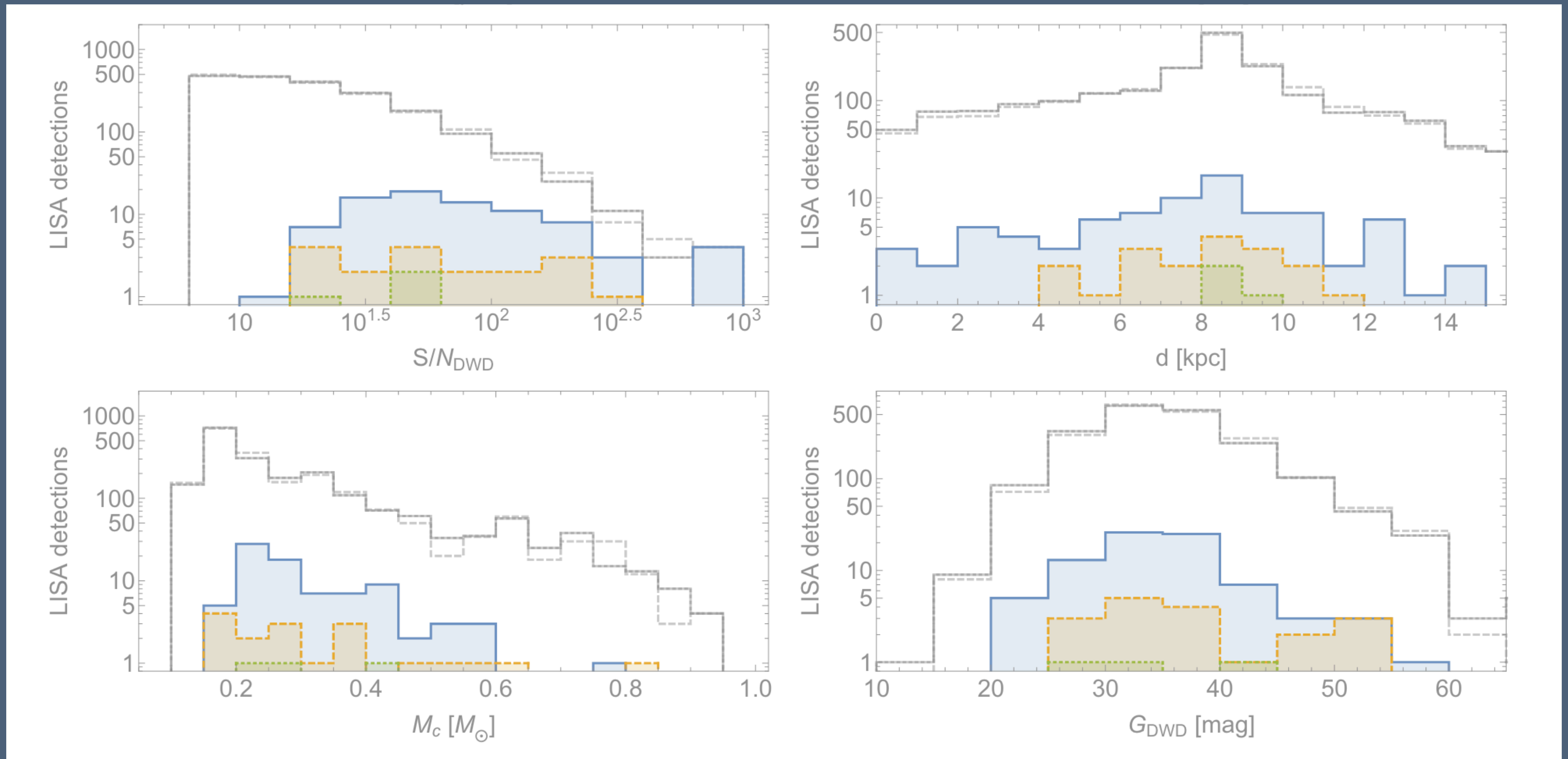


Brown Dwarfs

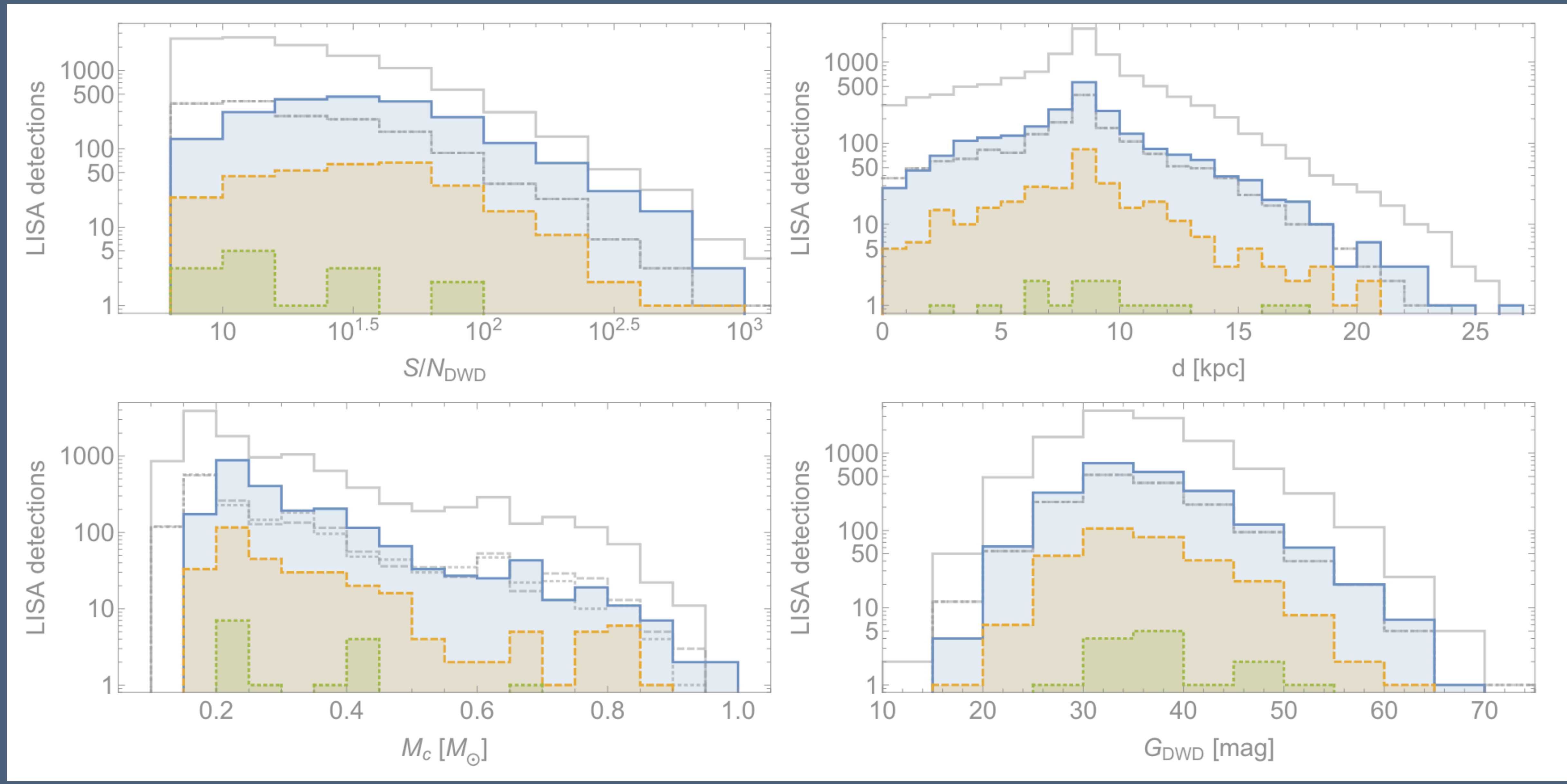


Exoplanets VS Brown Dwarfs

Exoplanets

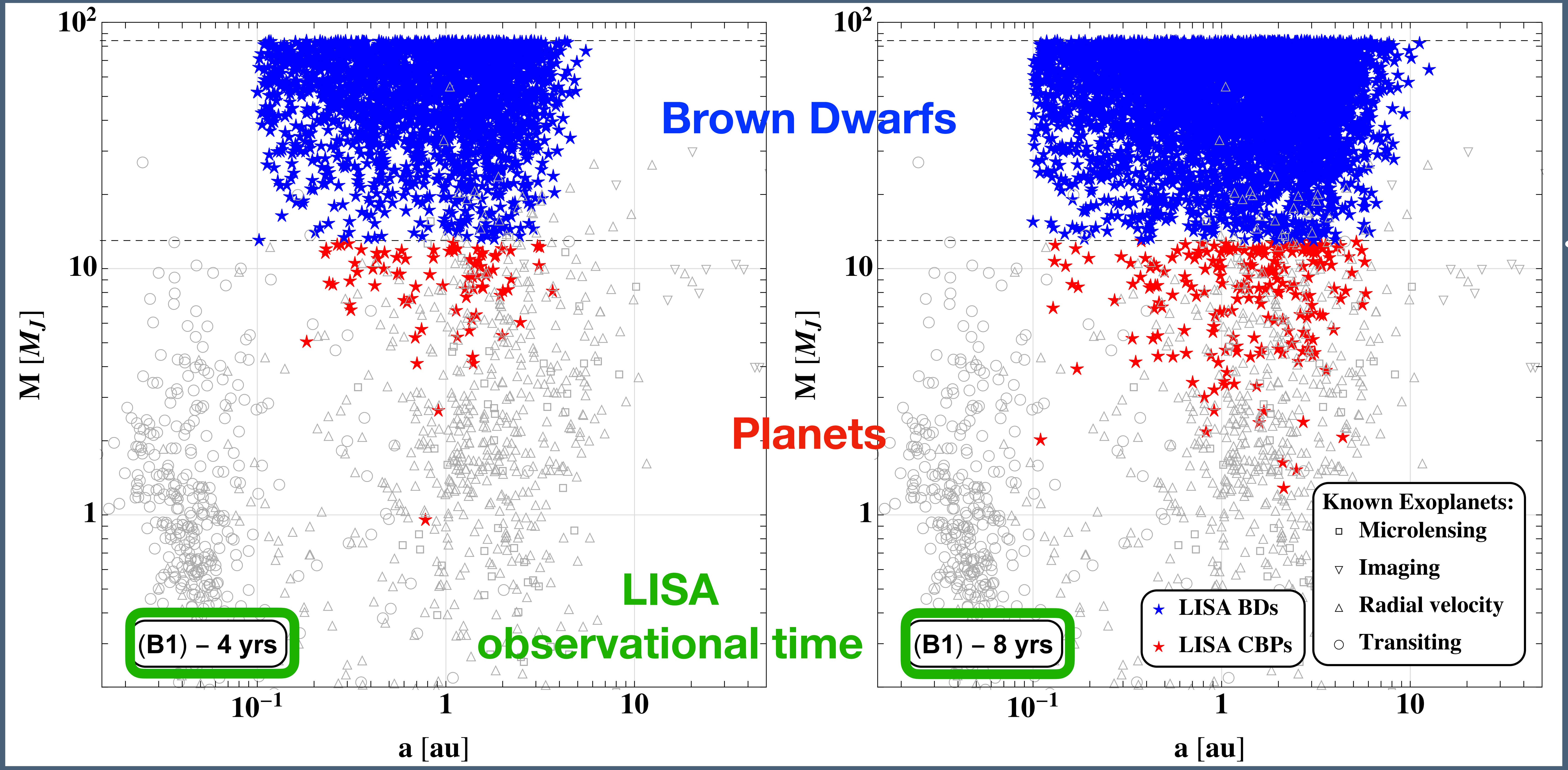


Brown Dwarfs



Optimistic scenario VS LISA observation time

$M_P > 1\ M_{Jup}$, $P_P <$ LISA observing time



13 Mj : 2H burning limit

	4 YEARS	8 YEARS
PLANETS	3 - 83	8 - 215
BDs	14 - 2218	43 - 4684

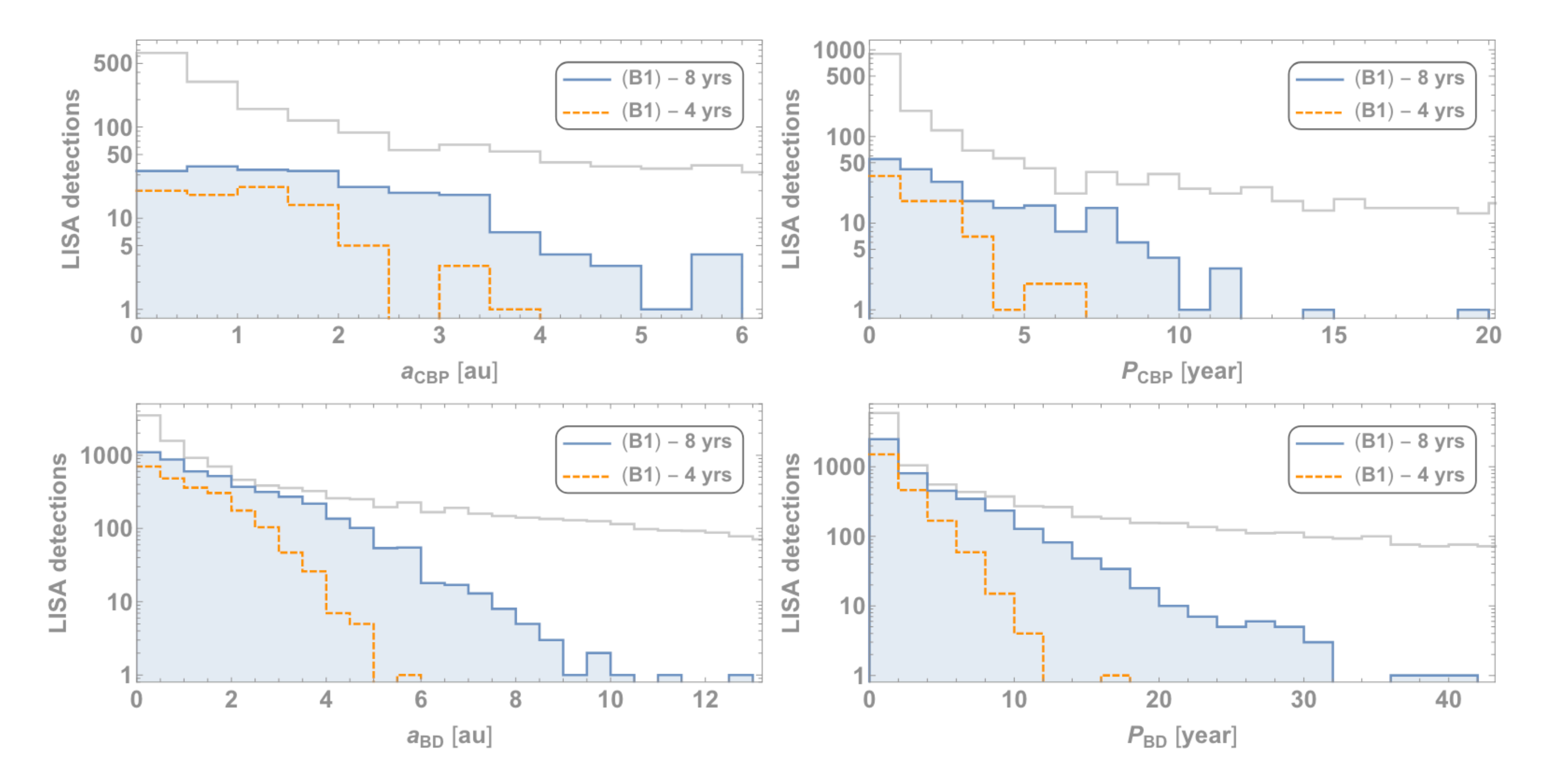
Optimistic

Pessimistic

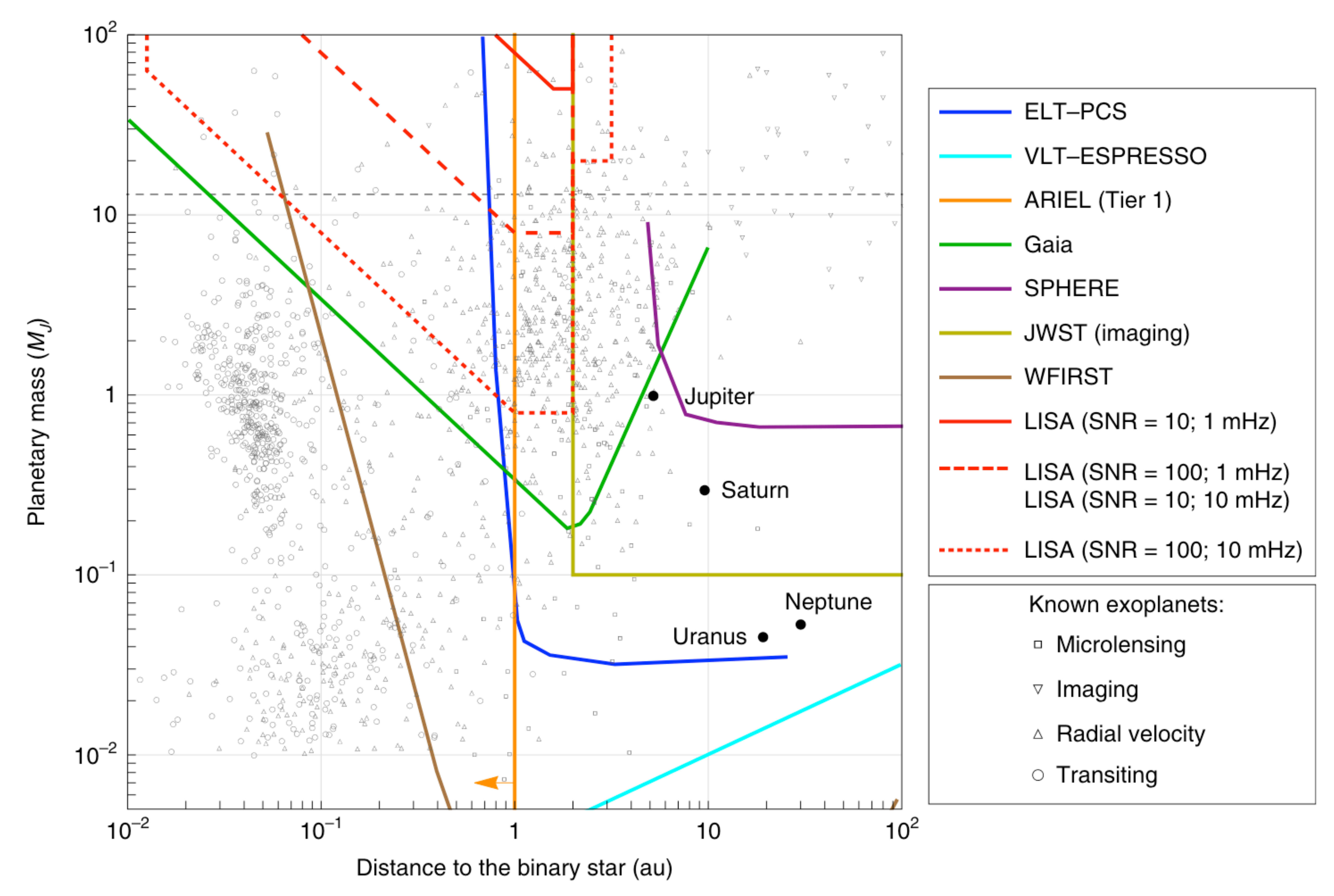
[Tamanini & Danielski, Nat. Astron., 3, 858 (2019); arXiv:1812.04330]
[Danielski+, A&A, 632, 113 (2019); arXiv:1910.05414]

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

8 versus 4 years of observations



Selection functions of both LISA and of main EM

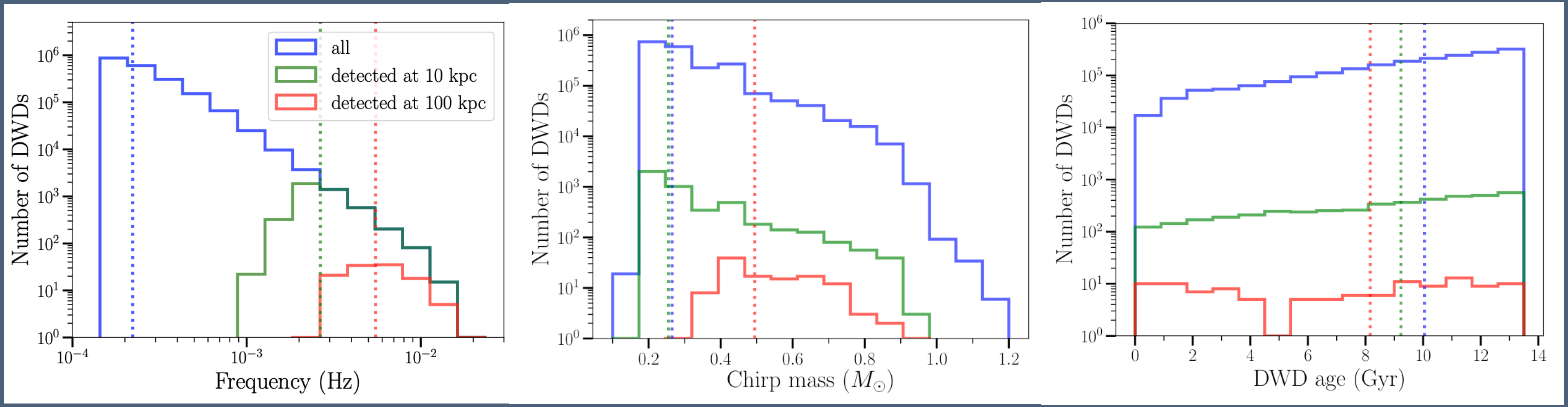


[Tamanini & Danielski, Nat. Astron., 3, 858 (2019); arXiv:1812.04330]

Done with information matrix, to be updated with new upcoming results

LISA could detect extragalactic planets

A target beyond standard EM observations



[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]

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

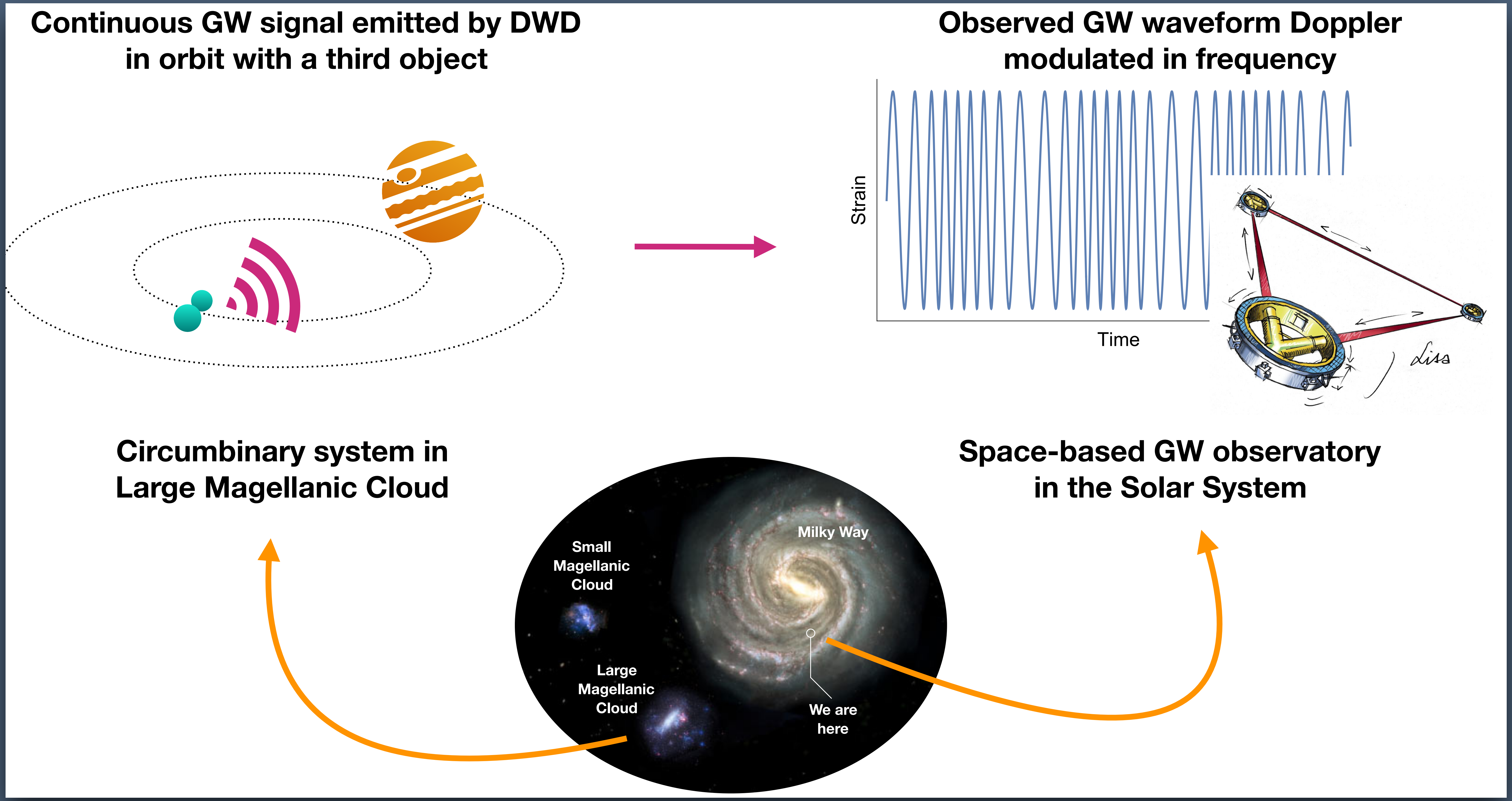
Strength of the signal mainly depends on three intrinsic binary parameters: f (or P), M_c and d.

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

LISA could detect extragalactic planets

A target beyond standard EM observations

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

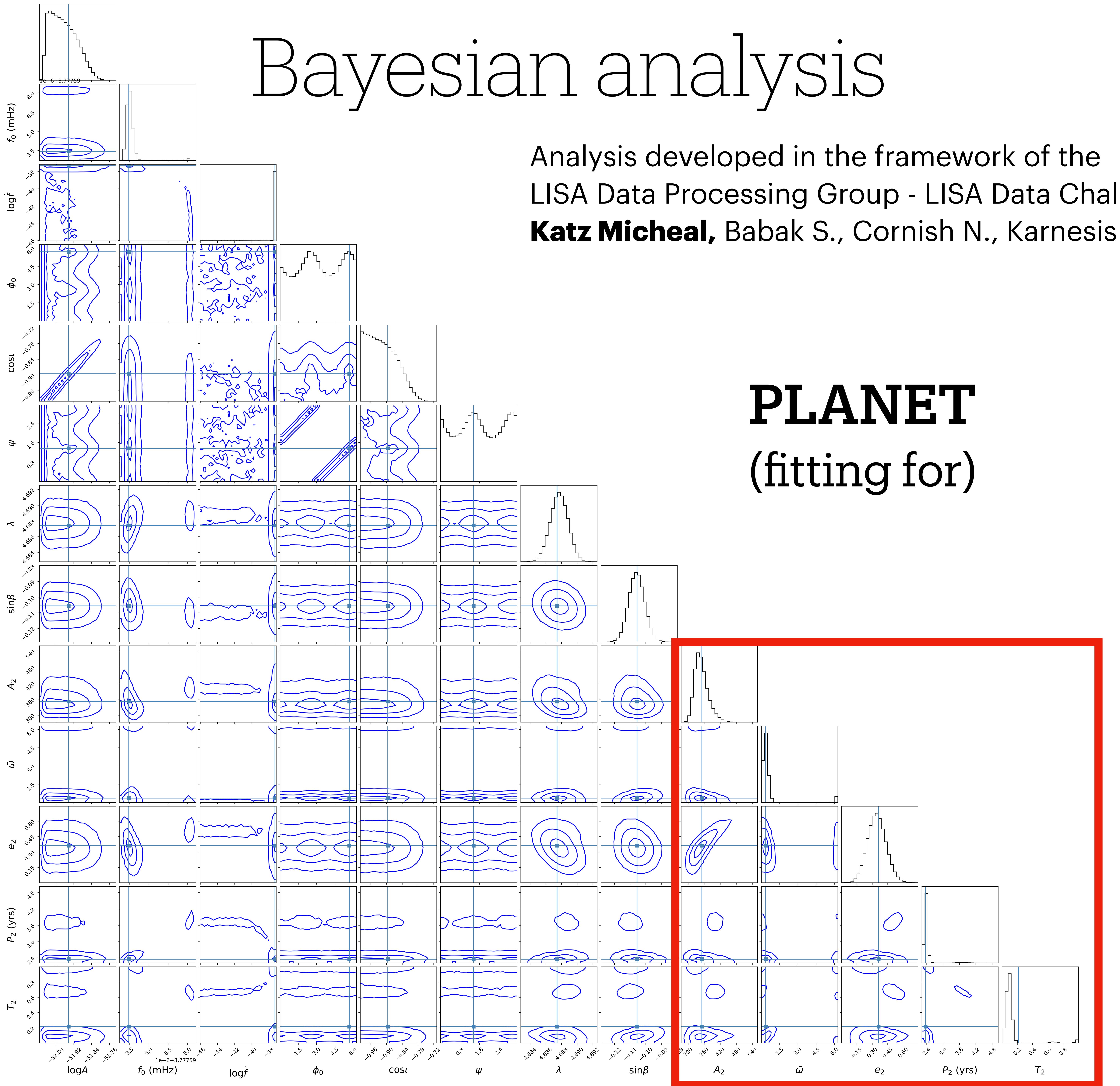


[Danielski & Tamanini, IJMPD (2020); arXiv:2007.07010]

Bayesian analysis

[Katz, Danielski et al., 2022, MNRAS]

Analysis developed in the framework of the
LISA Data Processing Group - LISA Data Challenge
Katz Micheal, Babak S., Cornish N., Karnesis N., Littenberg T., Petiteau A., Pieroni M., Tamanini N.



PLANET
(fitting for)

Inclusion of eccentricity

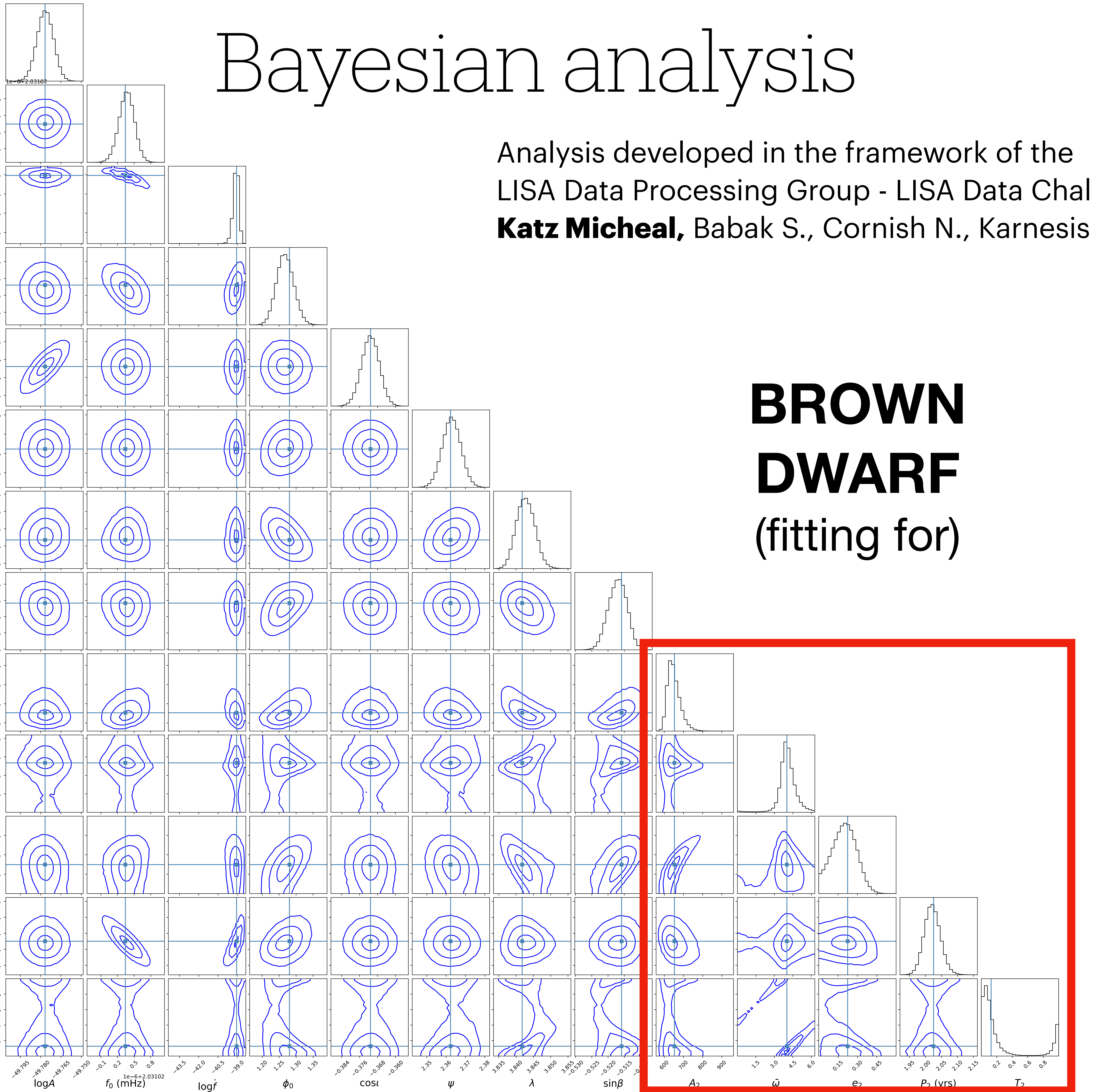
Mp = 12 Mjup
a = 4.20 au
e = 0.362
P = 2.35 years

SNR = 89
P_bin = 0.00612775 days
d = 4.305 kpc
wd1_mass = 0.23 Msun
wd2_mass = 0.28 Msun

Bayesian analysis

[Katz, Danielski et al., 2022, MNRAS]

Analysis developed in the framework of the
LISA Data Processing Group - LISA Data Challenge
Katz Micheal, Babak S., Cornish N., Karnesis N., Littenberg T., Petiteau A., Pieroni M., Tamanini N.



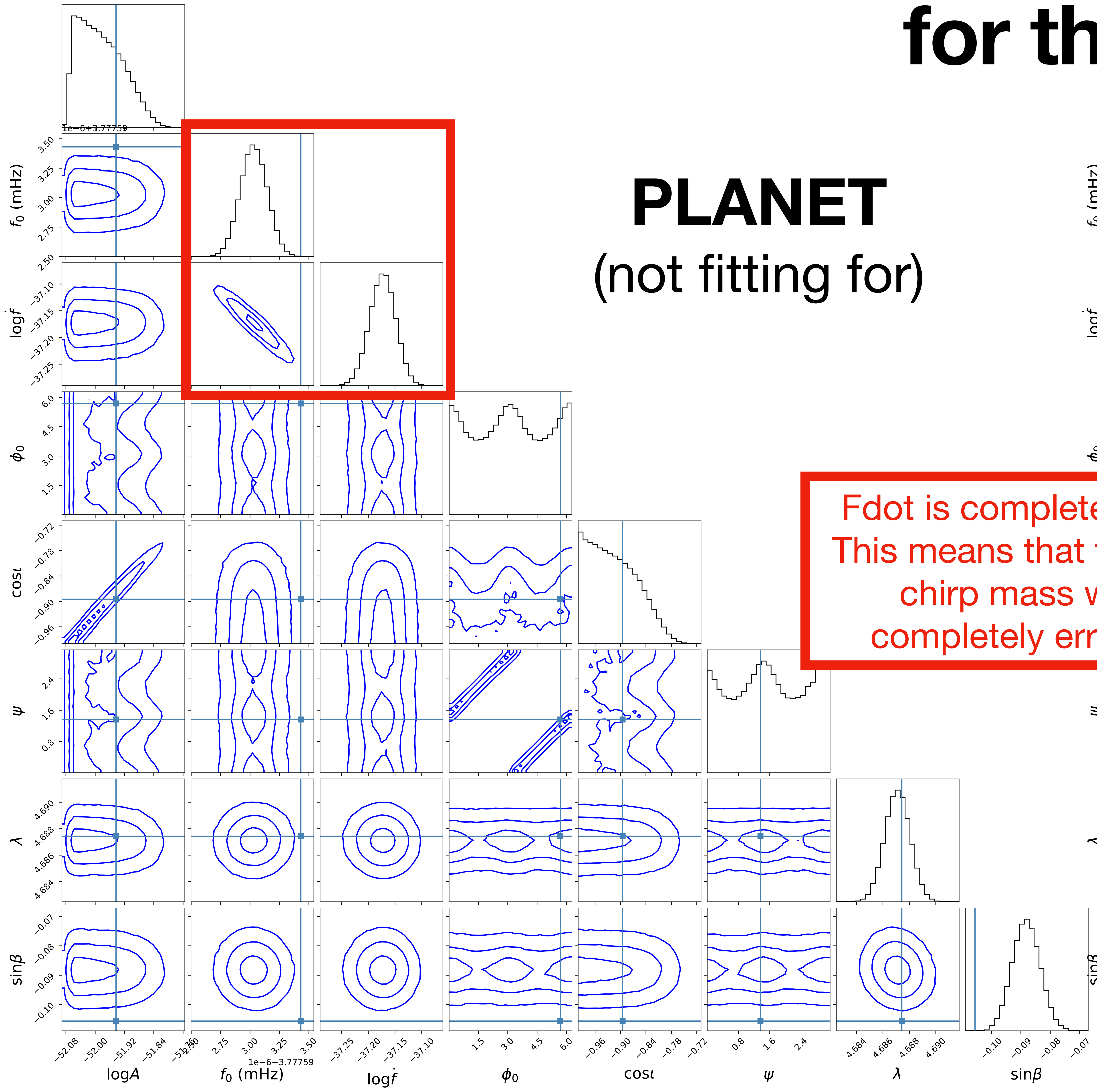
BROWN DWARF
(fitting for)

Inclusion of eccentricity

M = 30 Mjup
a = 5 au
e = 0.224
P = 2.05 years

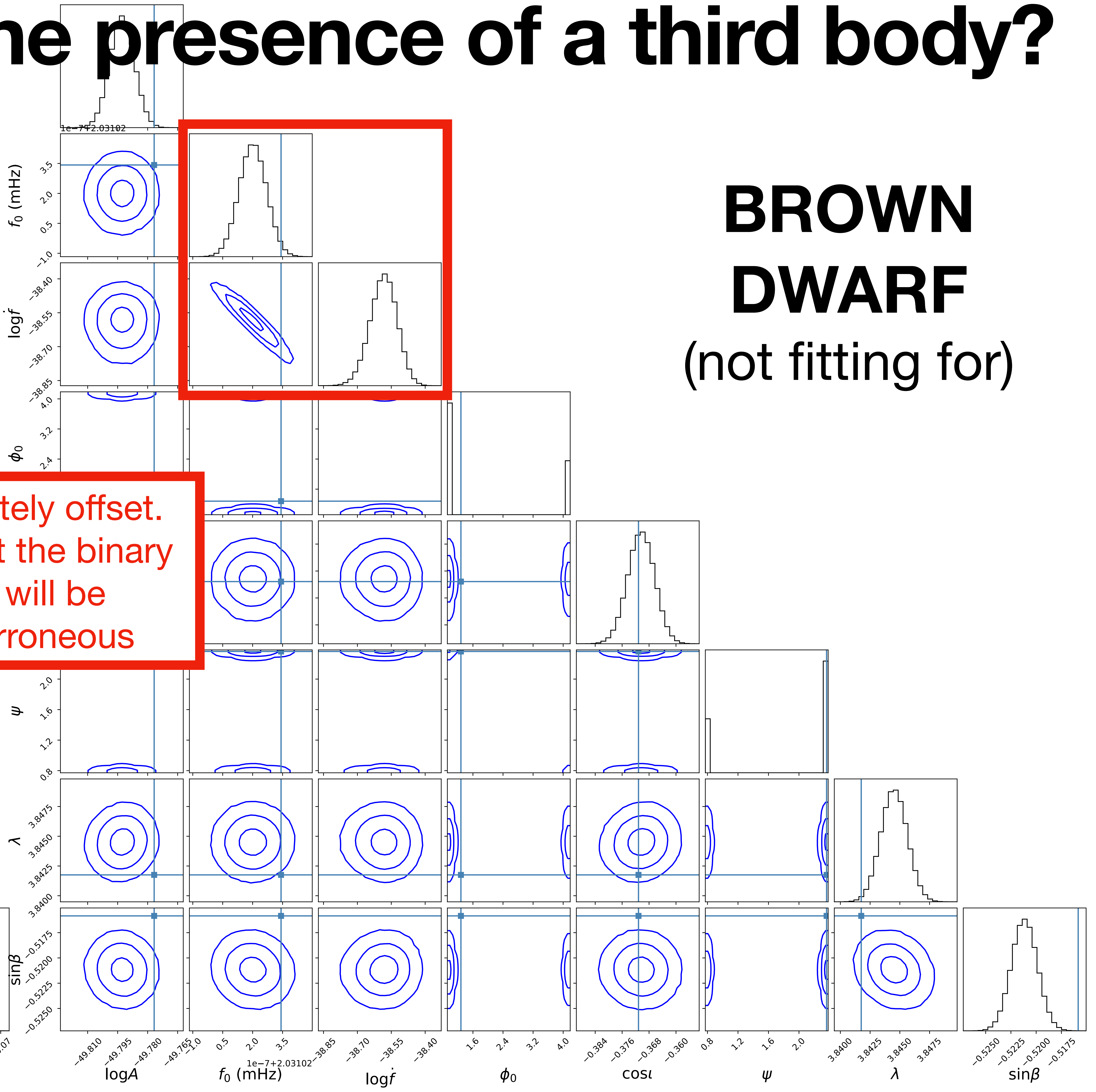
SNR = 883
P_bin = 0.0113972 days
d = 0.556 kpc
wd1_mass = 0.416 Msun
wd2_mass = 0.302 Msun

What happens when we don’t account for the presence of a third body?



PLANET

(not fitting for)



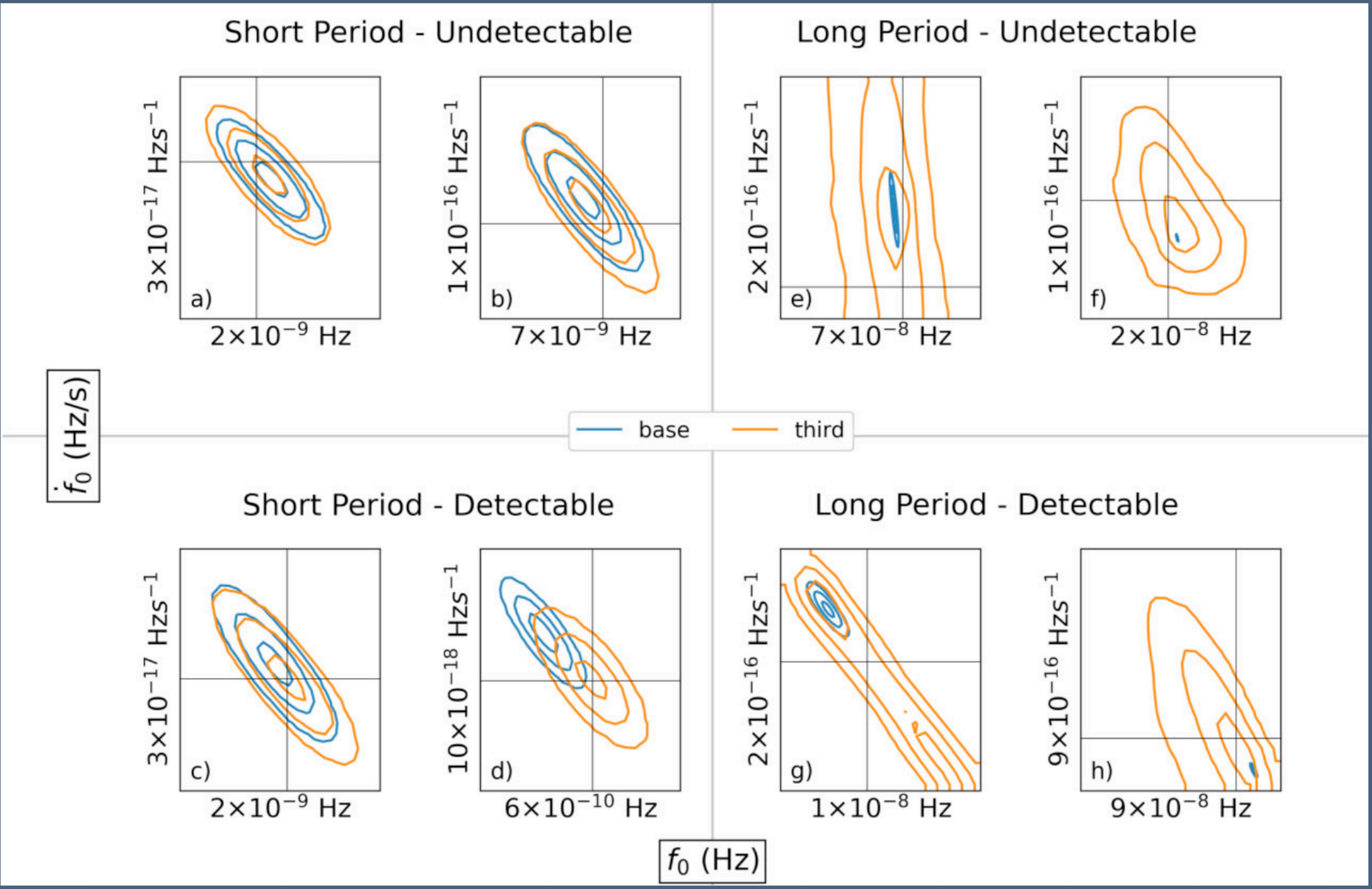
BROWN DWARF

(not fitting for)

Fdot is completely offset. This means that the binary chirp mass will be completely erroneous

What happens when we don't account for the presence of a third body?

[Katz, Danielski et al., 2022, MNRAS]



GR only template

Third body template

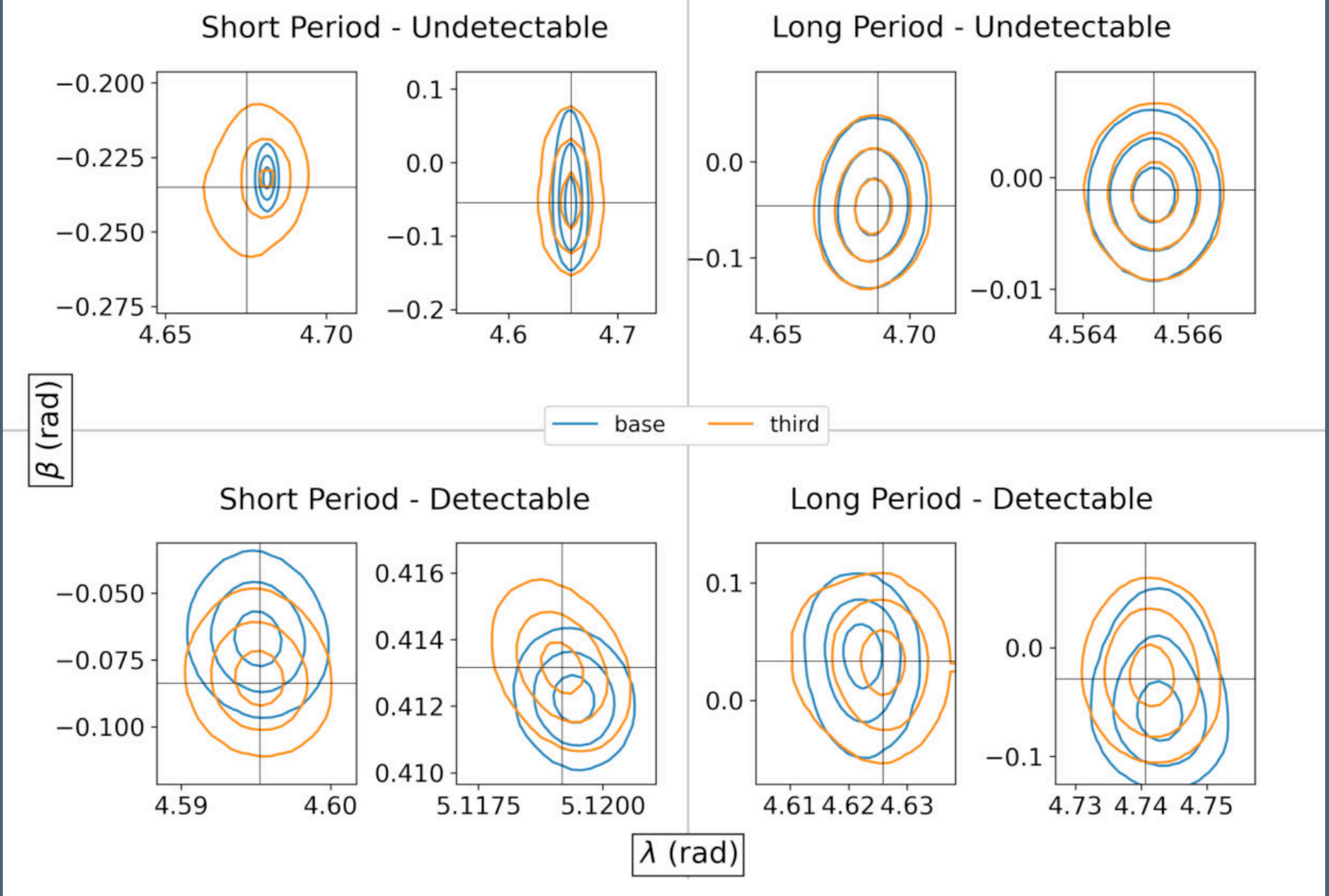
2D marginalized posterior distributions

Undetectable (log B12 < 5)
detectable (log B12 ≥ 5)
systems

(B12 is the Bayes factor)

What happens when we don't account for the presence of a third body?

[Katz, Danielski et al., 2022, MNRAS]



GR only template

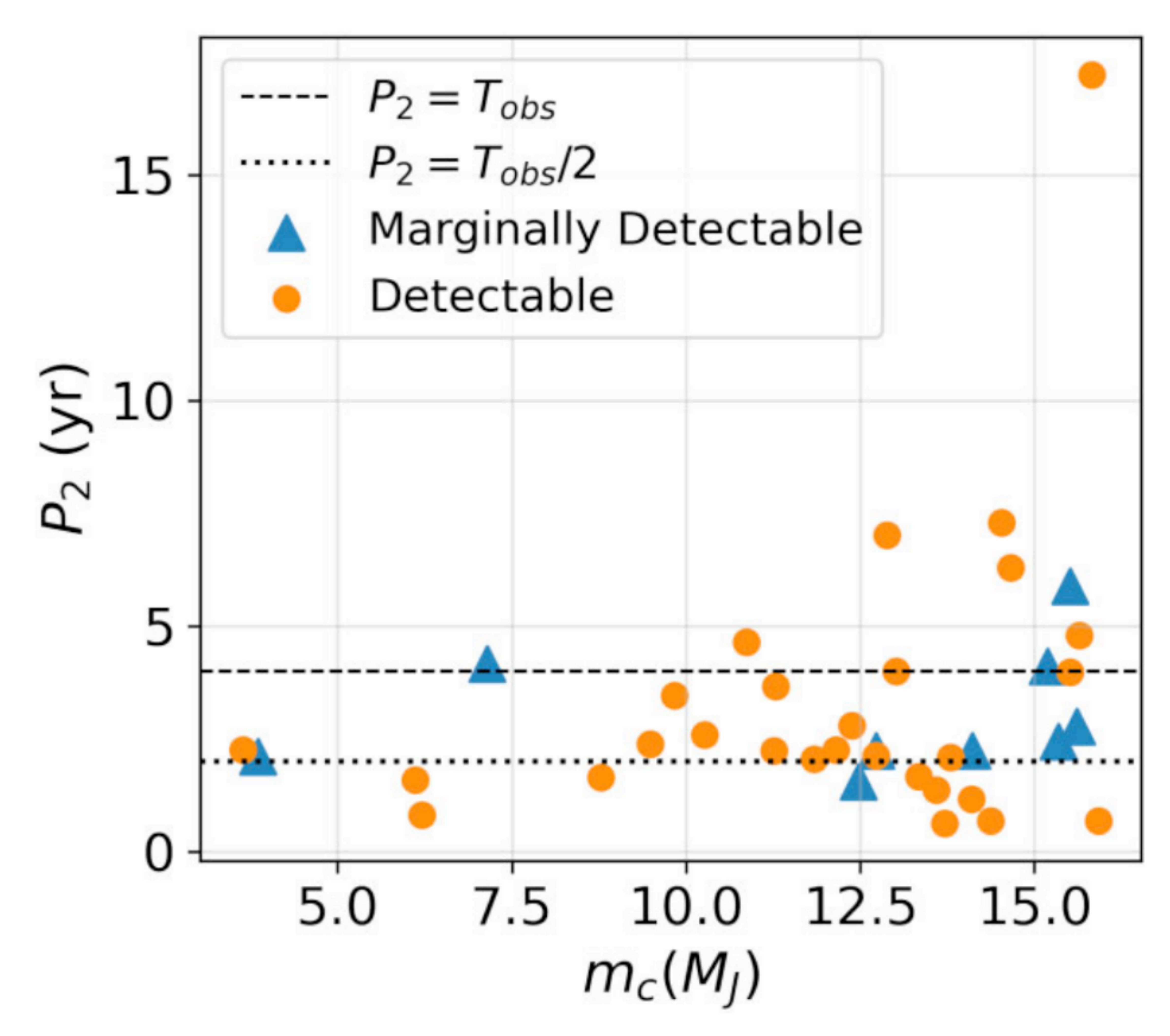
Third body template

SKY LOCALIZATION PLANE

Undetectable (log B12 < 5)
detectable (log B12 ≥ 5)
systems

(B12 is the Bayes factor)

Detections in optimistic scenario



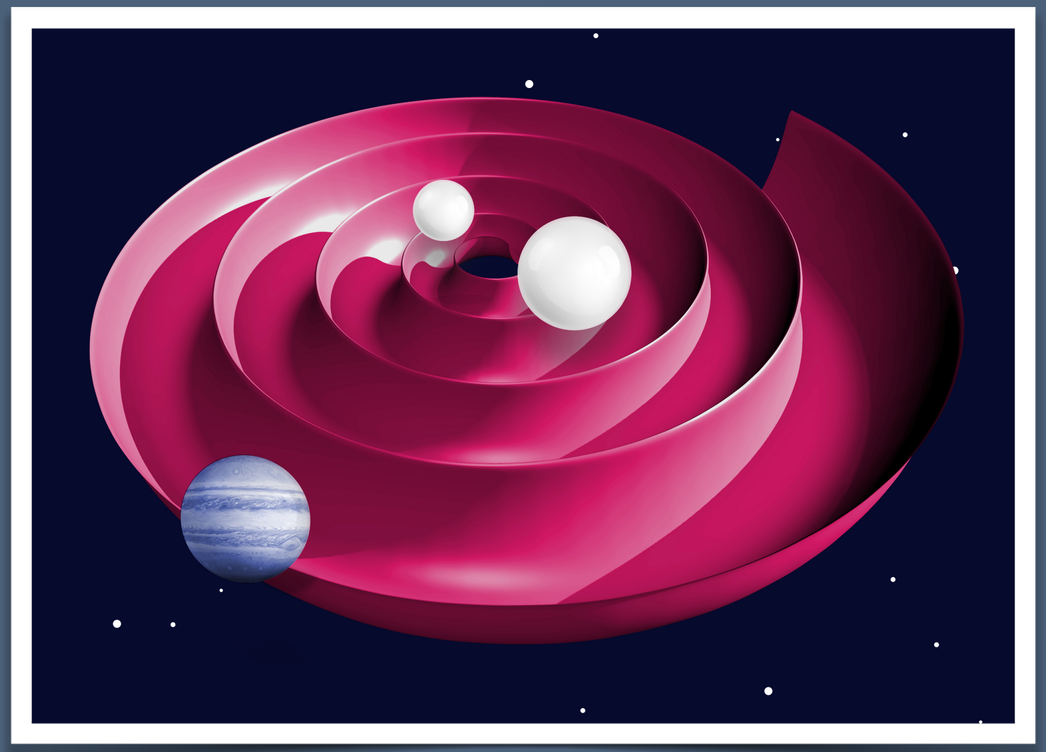
[Katz, Danielski et al., 2022, MNRAS]

Sources with
P2 < Tobs/2 (Tobs = 4 yr),
which represents the
Nyquist sampling criterion
to completely sample the
third-body orbital evolution

Injection values

The quest for Magrathea

Current status of the science case

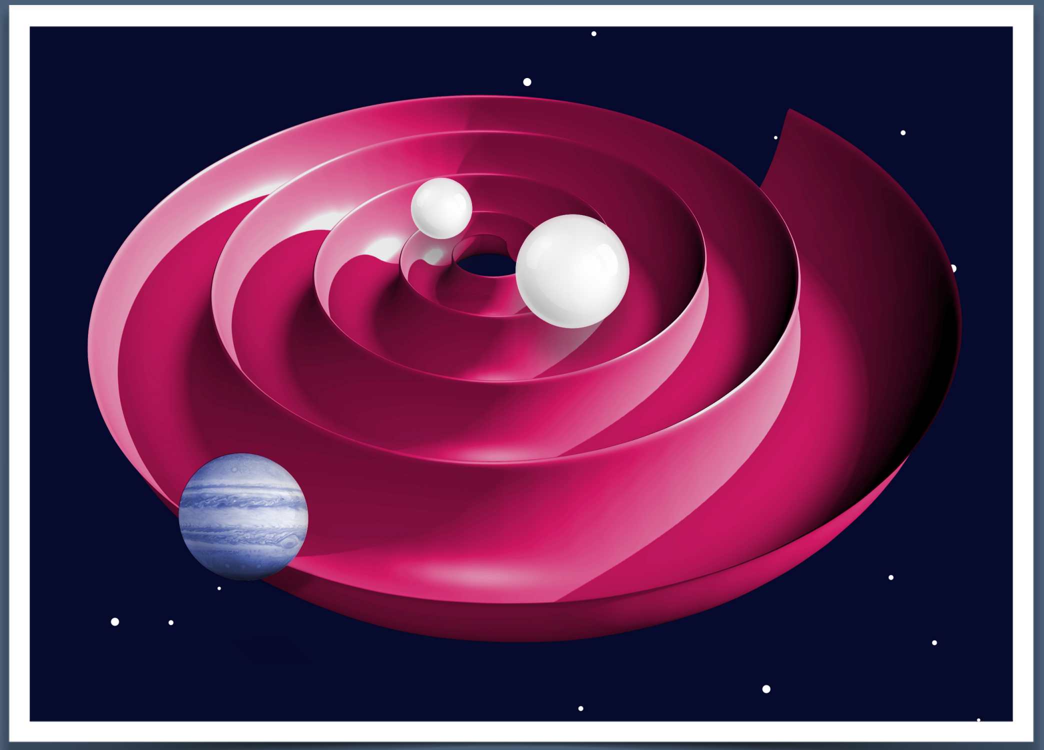


- **Data analysis:**
  - Method development + EM synergies overview (Tamanini & Danielski, 2019)
  - Information matrix analysis with LISA DWD MW population (Danielski et al, 2019)
    - P, phi, K
  - Frequency-domain (Bayesian) PE code (Katz et al, 2022) - inclusion of pl. eccentricity

- **Assess the role of orbital components**
  - Planetary eccentricity (Danielski et al, in prep : bayesian population analysis)

- **Planetary evolution theories**
  - DWD + planet co-evolution analysis (Columba et al, 2023)
  - Second generation planetary formation around DWD (Ledda et al, 2023)
  - Orbital stability of second generation Magrathea planets (Nigioni et al, in review)

What's needed ?



- **Assess the role of orbital components**
  - Eccentricity of inner binary
  - Planet-binary interactions (Kozai-Lidov, tides, ...)
  - Multiple circumbinary objects
  - GR effects in closer orbits
  - Definition of minimum acceleration of CoM for being detected by LISA

- **Further develop planetary evolution theories**
  - DWD + post-AGB disc interaction:
  - Orbital stability and new generation formation studies accounting for interaction of first generation with newly formed planets

- **Explore synergy with EM observations**
  - Identify pre-LISA candidates (verification triple systems?) - 47 Tuc ?
  - Develop follow-up strategies (microlensing, transits, direct imaging, ...
  - More detection of CBP around MS compact binaries

Key for a **global characterisation** of these planets (radius, mass, density, system orbital architecture) + priors on CBP around MS, or post AGB systems for pop synthesis purposes.

- **Data analysis**
  - Integration of pipeline and test it within global fit analyses (LDC - far future)