Music of the Spheres: the gravitational wave signal from exoplanets

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Motivating Question

With more than 3700 exoplanets discovered to date, could any individual planetary system or **population of planetary systems** be detected by LISA?

from the Abstract

•We consider exoplanets as a source of Gravitational Waves (GW) for the **LISA space-based detector**;
•LISA is the Laser Interferometer Space Antenna, a joint ESA/NASA project expected to launch in 2034;
•The rich variety of exoplanets include many with **high eccentricity** which moves their GW spectrum to the LISA band.

Theory - GWs from Binaries

Masses in orbit exhibit a **time-changing mass quadrupole moment** and therefore emit GWs (Peters and Mathews, Maggiore). **Averaged over a full orbit**, they define the function

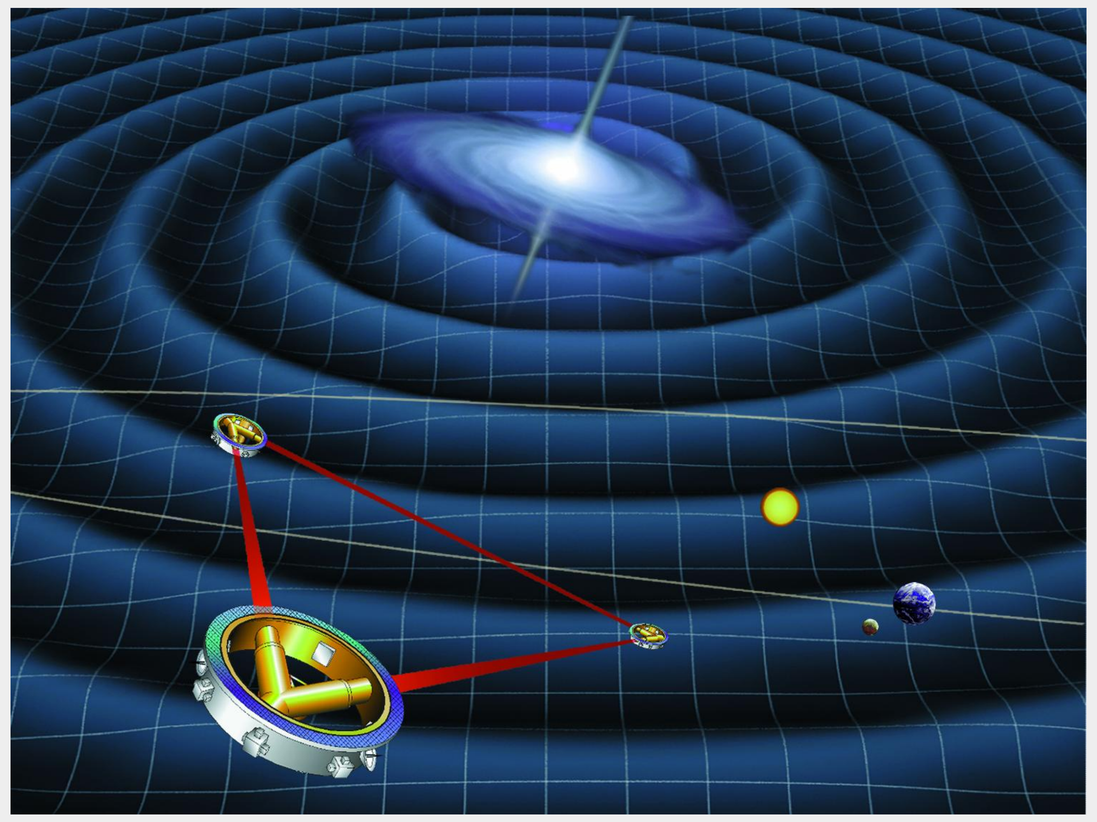
g(n,e) = (GW Power at $f=n*f_0$) / (GW Power Equiv. Circ. orbit at $f=2f_0$)

And following Amaro-Seoane et al., the dimensionless strain can be written

$$\boxed{h_n = \left(\frac{G^{5/3}}{c^4}\right) 2\sqrt{\frac{32}{5}}\,\frac{\mathcal{M}^{5/3}\,(2\pi f_0)^{2/3}}{r}\,\frac{\sqrt{g(n,e)}}{n}}$$

where the mass is the "chirp mass" and is $m_1^{3/5}m_2^{3/5}/(m_1+m_2)^{1/5}$, and h_n is at a multiple of the orbital frequency f_0, nf_0 *with* $n=[1,2,3...]$.

LISA Constellation



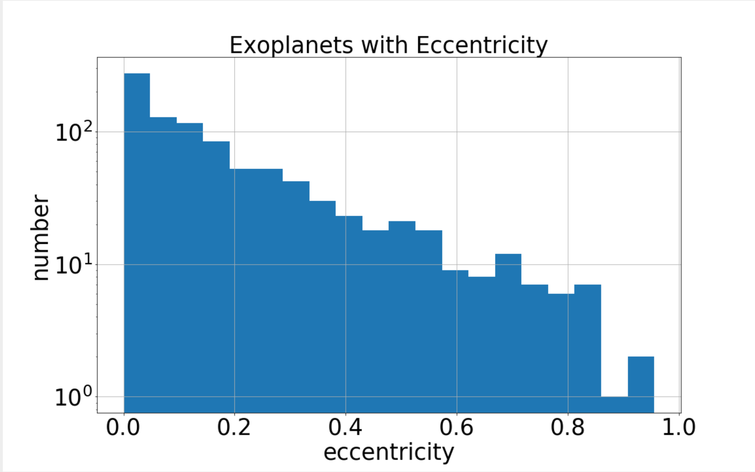
(credit NASA)

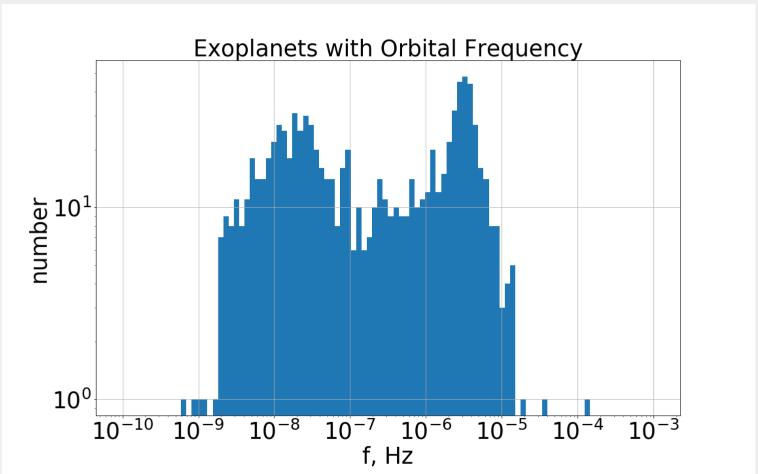
Observed Exoplanets

https://exoplanetarchive.ipac.caltech.edu/

3711 Confirmed Planets as of 12 April 2018

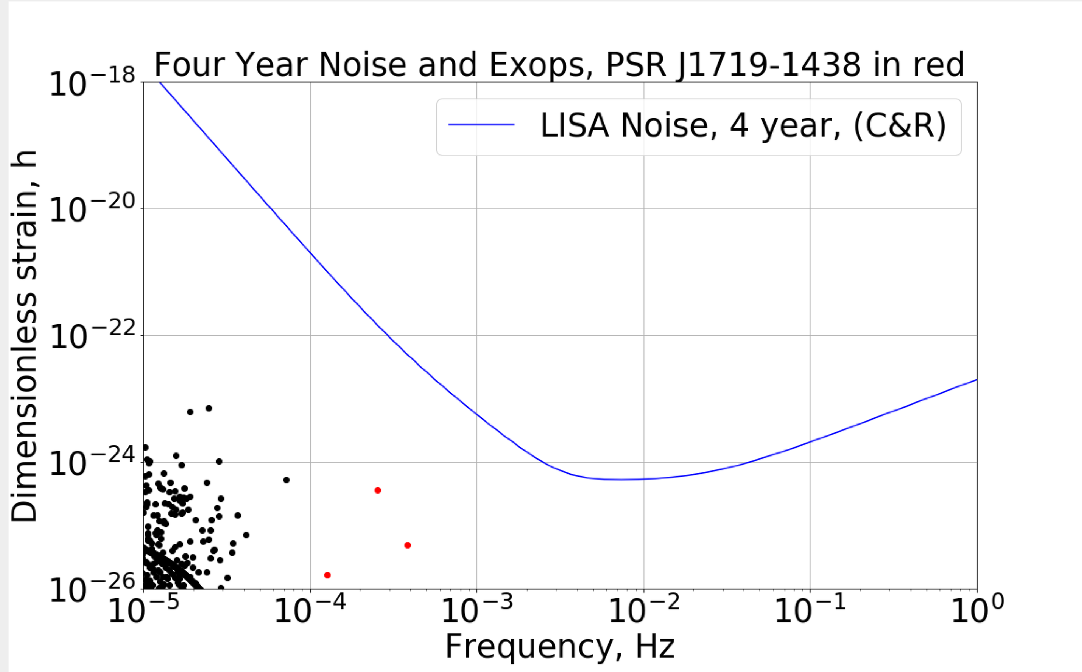
For GW strain calculation we need the following physical attributes of the planetary system: m_1 stellar mass, m_2 planetary mass, *r* distance to system, *e* orbital eccentricity, *P* orbital period. Which leaves **910** exoplanets that we can use for GW calculations.





LISA Sensitivity / Noise

Following **Cornish and Robson (2018) on the LISA sensitivity curve** with the following caveats:
•exoplanet GW frequencies are much less than laser round trip time (16.7s, equiv 60mHz) or f_star (19mHz), so in the "LIGO Limit";
•no frequency evolution assumed over the four year integration time;
•using the *R* function, so nominally sky position and polarization averaged.



Exoplanet GW Modes and LISA Senstivity Curve

Signal-to-Noise for top few planets

$$\boxed{\left(\frac{S}{N}\right)^2 = 2T\sum_{n=1}^{n_*}\frac{|h_n(n\,f_0)|^2}{S_n(n\,f_0)}}$$

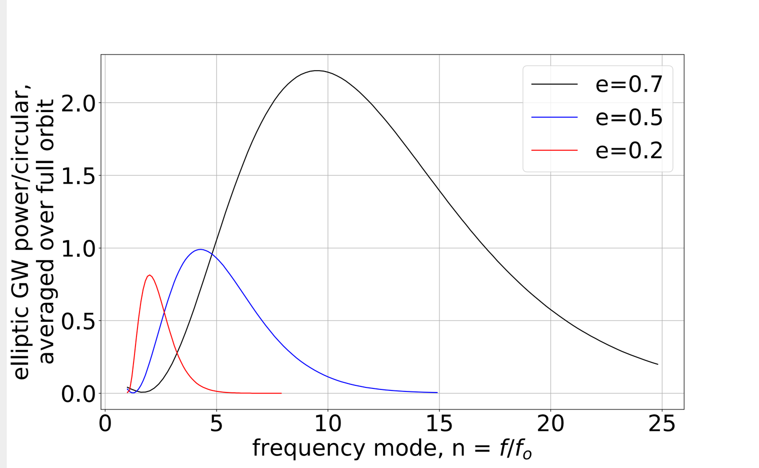
host star	eccentricity	orbital period(d)	SNR
PSR J1719-1438	0.06	0.09071	0.001331
PSR J2322-2650	0.0017	0.323	4.899E-05
WASP-18	0.0092	0.9415	2.654E-05
KELT-1	0.0099	1.218	1.106E-05
WASP-43	0	0.8135	6.012E-06
WASP-19	0.002	0.7888	1.734E-06
HATS-18	0.166	0.8378	1.649E-06

Future Work

•Consider **collections of planetary systems** on GW signal;
•Refine the noise/sensitivity curve analysis;
•Consider **errors in exoplanet parameters** for the SNR and noise/sensitivity analysis;
•Consider what parameters would make a planetary system detectable for LISA;
•Work our way up the mass scale: brown dwarf binaries, etc.

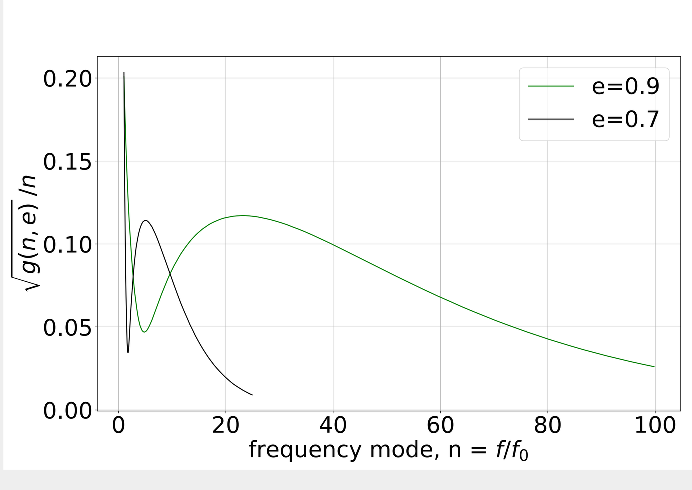
Eccentricity Increases GW Frequency

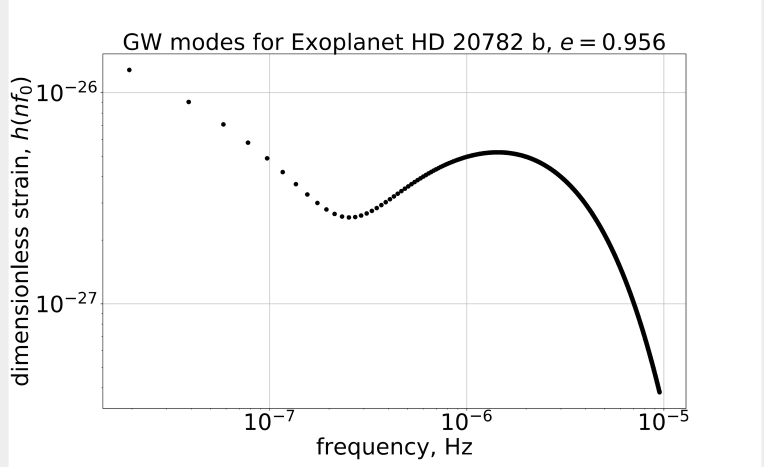
g(n,e) Ratio GW Power elliptical to circular



GW Strain

$$h_n \propto \sqrt{g(n,e)}/n$$





Strain modes for one planet and its star

References

P. C. Peters and J. Mathews, "Gravitational Radiation from Point Masses in Keplerian Orbit," Phys. Rev. **131** (1963) 435;
M. Maggiore, "Gravitational Waves: Volume 1: Theory and Experiment," Oxford Univ. Press, 2008;
Amaro-Seoane et al., "Triplets of supermassive black holes: astrophysics, gravitational waves and detection," Mon. Not. Royal Astro. Soc. **402** (2010) 2308;
NASA Exoplanet Archive, This research has made use of the archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program;
N. Cornish and T. Robson, "The construction and use of LISA sensitivity curves," 2018, arXiv:1802.01944;
A. Ain, S. Kastha, and S. Mitra, "Stochastic Gravitational Wave Background from Exoplanets," Phys. Rev. D, **91** (2015) 124023, arXiv:1504.01715v2.