Characterization of the stochastic signal originating from compact binary populations as measured by LISA

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Gravitational waves

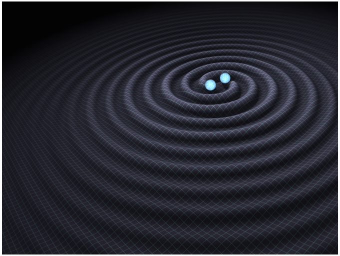
Ripples in space-time caused by accelerated masses.

Einstein field equations

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$G_{\mu\nu}$: Einstein tensor $\quad G$: Gravitational constat

$T_{\mu\nu}$: Energy-momentum tensor $\quad c$: Speed of light



Credit: R. Hurt (Caltech-IPAC)

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad |h| << 1$$

Gravitational waves

$$16 \xrightarrow{symetry} 10 \xrightarrow[gauge]{Lorenz} 6 \xrightarrow[gauge]{TT} 2$$

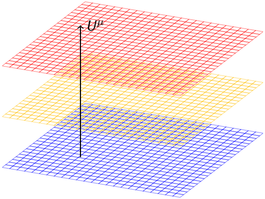
Lorenz gauge: $\partial_\mu \bar{h}^{\nu\mu} = 0$

$$h_{\mu\nu} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Wave equation

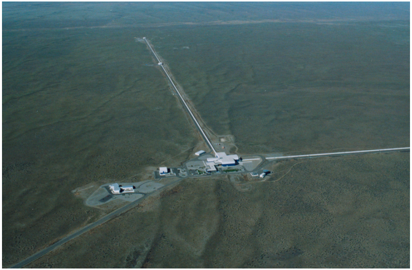
$$\Box \bar{h}_{\mu\nu} = 0$$

Transverse traceless gauge:
$\bar{h}_{\mu\nu} U^\mu = 0$ and $\bar{h}_\mu{}^\mu = 0$

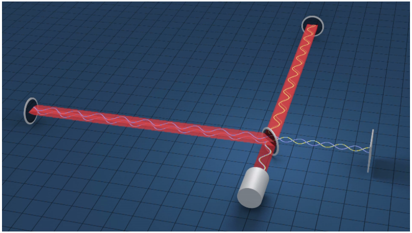


Ground-base observatiories

Giant Michelson interferometer in Hanford



Credit: Caltech/MIT/LIGO Lab



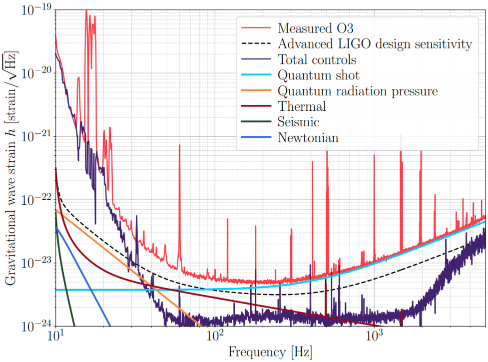
Credit: T. Pyle/LIGO

$$S(t) = h(t) + n(t)$$

$h(t)$: Probable gravitational waves signal $\quad$ $n(t)$: Noise signal

LIGO Noise budget

Hanford detector

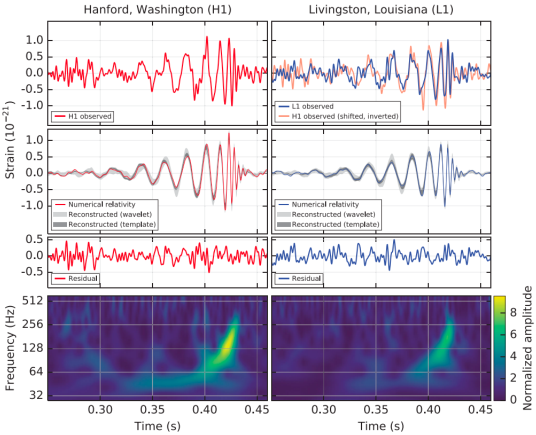


Credit: Craig Cahillane et all, 2022

Dominant noise:

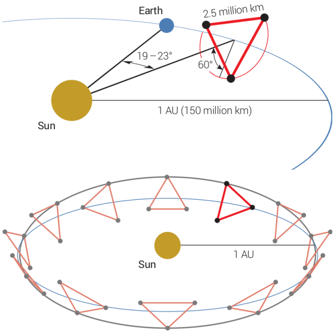
- Quantum shot in high frequency
- Seismic noise in low frequency

First detection (GW150914)

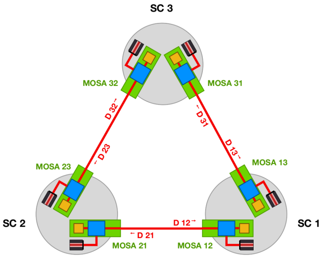


Credit: B. P. Abbott et al., 2016

Laser Interferometer Space Antenna (LISA)



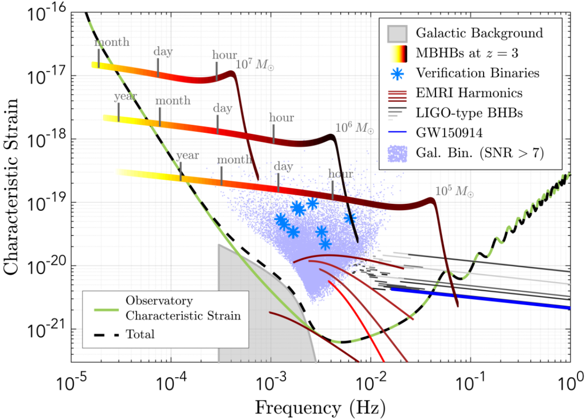
Credit: Karsten Danzmann et al., 2017



Credit: Jean-Baptiste Bayle et al., 2021

Using time delay interferometery to reduce laser frequency noise.

LISA Band

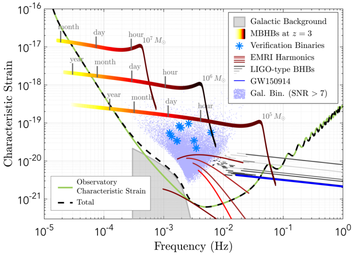


Credit: Karsten Danzmann et al., 2017

LISA Band

GW sources in LISA band

- Supermassive binary black holes (SMBHBs)
- Stellar-mass binary black holes (SBBHs)
- Ultracompact galactic binaries (CGBs)
- Verification galactic binaries
- Extreme mass ratio inspiral (EMRIs)
- Stochastic GWs background



Credit: Karsten Danzmann et al., 2017

LISA Isuues

- LISA data are expeted to be signal dominated
- LISA sources are expected to be long-lived
- GW signals will be overlapping in time(frequency)

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- GW signals will be overlapping in time(frequency)
- Some signals can be resolvable due to high signal to noise ratio
- remaining signals will affect the sensitivity as extra noise (confusion noise)

Overview

- Simulating around 30 milion CGBs from Radler LISA data challenge dataset
- Simulating the instumental noise using the LISA code simulatior
- For each T_{obs} gererate the idealized dataset in the frequency domain
- Apply the method to find the final sensitivity
- Fit the data with theoretical curve

Method

- Assumpion: Bright sources with a signal-to-noise ratio larger than a given threshold are detected and characterized without systematic bias or source cofusion.

SNR

$$\rho^2_{tot} = \sum_k (h_k|h_k), \quad \text{k:noise-orthogonal TDI variables}$$

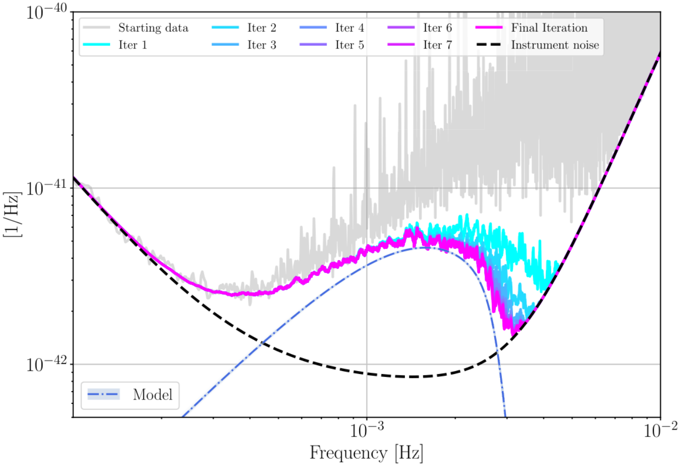
$$h_k|h_k = 4\int_0^\infty df \frac{|\tilde{h}_k(f)|^2}{\tilde{S}_n(f)}, \quad \tilde{S}_n(f) : \text{one-sided PSD}$$

$$\tilde{S}_n(f) = \tilde{S}_{instr}(f) + \tilde{S}_{conf}(f)$$

Method

1. Simulating 30 milions CGBs
2. Calculating the PSD of the signal and the instrumental noise
3. Calculating the SNR of each source with respect to the instrumental noise (ρ_i^{iso})
4. Stimating the SNR of each source using either a running mean or median on the power spectrum of the data (ρ_i)
5. If $\rho_i > \rho_0$ the source will be subtracted from the data
6. Iterate the process until no sources exceed the threshold (ρ_0)

Compact Galactic Binaries



Credit: Nikolaos Karnesis et al, 2021

Compact Galactic Binaries

Analytical model for the estimated confusion foreground:

Confusion foreground model

$$S_{gal} = \frac{A}{2} f^{-7/3} e^{-(f/f_1)^{\alpha}} (1 + \tanh((f_{knee} - f)/f_2))$$

A: Amplitude $\quad$ f_1, f_2 and f_{knee}: Scaling frequencies

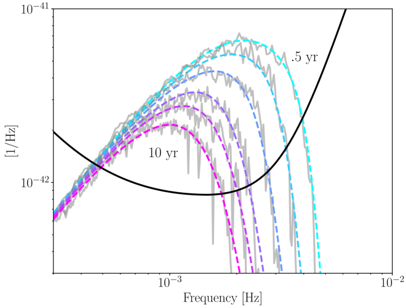
f: Frequency $\quad$ α: Smoothness parameter

Approximation for f_1 and f_{knee}:

$$\log_{10}(f_1) = a_1 \log_{10}(T_{obs}) + b_1$$
$$\log_{10}(f_{knee}) = a_k \log_{10}(T_{obs}) + b_k$$

a_1, b_1, a_k and b_k are amplitude calibration parameters

Compact Galactic Binaries



Credit: Nikolaos Karnesis et al, 2021

	Estimated			
	Running mean		Running median	
Parameter	$\rho_0 = 5$	$\rho_0 = 7$	$\rho_0 = 5$	$\rho_0 = 7$
a_1	−0.16	−0.25	−0.15	−0.15
a_k	−0.34	−0.27	−0.34	−0.37
b_1	−2.78	−2.70	−2.78	−2.72
b_k	−2.53	−2.47	−2.55	−2.49
$A \times 10^{-44}$	1.15	1.14	1.14	1.15
f_2	0.00059	0.00031	0.00059	0.00067
α	1.66	1.80	1.66	1.56

	No. of sources recovered			
	Running mean		Running median	
T_{obs} [yr]	$\rho_0 = 5$	$\rho_0 = 7$	$\rho_0 = 5$	$\rho_0 = 7$
0.5	8031	4491	8850	5111
1	14170	8487	14918	9305
2	22681	14206	23849	15441
4	35891	22951	37684	25025
6	45925	30097	48179	32702

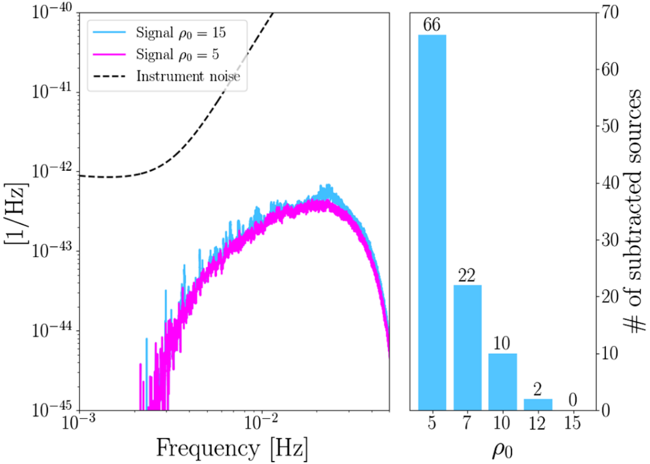
Stellar-mass binary black holes

- LISA is sensitive to the early inspiral stage of orbit evolution of SBBHs
- They appear in the high-frequency tail of LISA band (until $3\mathrm{mHz}$)
- There is a very low chance for the transition of SBBHs from LISA band to LIGO band during the LISA observation time
- The population of SBBHs observed by LISA depends on the merger rate of SBBHs ($\mathcal{R}$)
- $\mathcal{R}$ can be stimated from data of ground-base observatories

Stellar-mass binary black holes

- Simulating the dataset using PhenomD waveform model (S. Khan et al, 2016)
- Observation time of $T_{obs} \sim 2.7$ yr
- Doing the same process as CGBs

Stellar-mass binary black holes



Credit: Nikolaos Karnesis et al, 2021

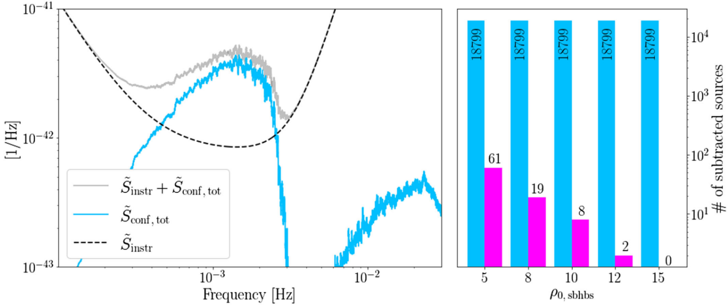
Combining the populations

- Doing the same process again!
- Instead of iterating over one type, iterate over all types
- Comparing SNR of each type with itself
- Final result is just superposition of the foreground signals from all given types of sources

Superposition

$$\tilde{S}_n(f) = \tilde{S}_{instr}(f) + \sum_t \tilde{S}_{conf,t}(f)$$

Combining the populations



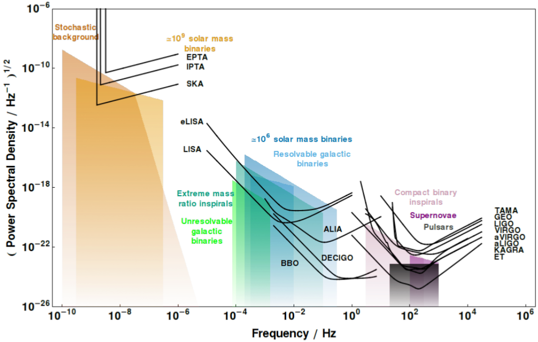
Credit: Nikolaos Karnesis et al, 2021

Conclusion

- Simulation of CGBs and SBBHs population
- using an iterative process to estimate forground noise
- Fit a theoretical model to confusion noise of CGBs
- SBBHs signal is not strong enough to affect the final result
- Due to the presence of CGBs the most sensitive firequency of LISA is going to increase

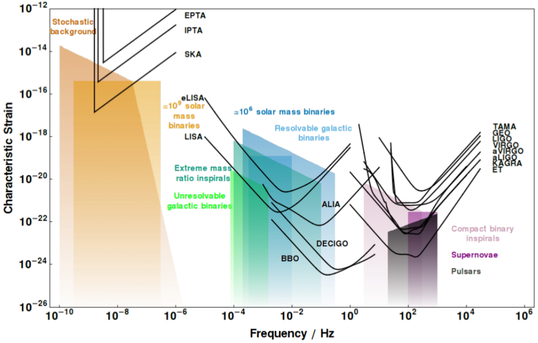
Thank you!

PSD



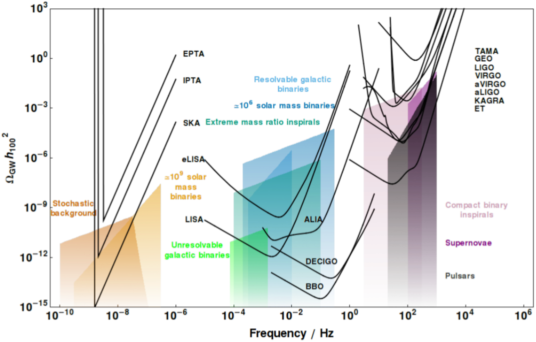
Credit: C J Moore et al, 2014

Characteristic strain



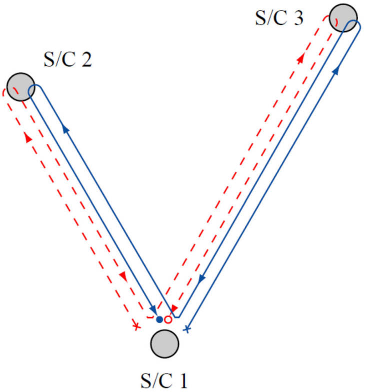
Credit: C J Moore et al, 2014

Dimensionless energy density

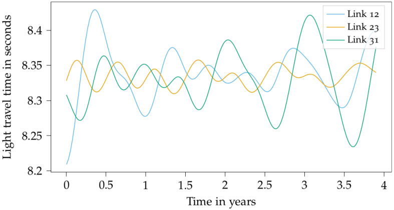


Credit: C J Moore et al, 2014

Time Delay Interferometery (TDI)



Credit: Massimo Tinto et al, 2020



Credit: Olaf Hartwig, 2021