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

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

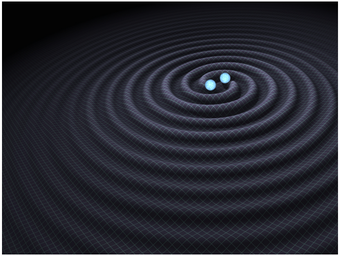
$G_{\mu\nu}$: Einstein tensor G: Gravitational constant

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

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

$g_{\mu\nu}$: Metric $\eta_{\mu\nu}$: Minkowski metric

$h_{\mu\nu}$: Small perturbation



Credit: R. Hurt (Caltech-IPAC)

Gravitational waves

Degrees of freedom : $16 \xrightarrow{symmetry} 10 \xrightarrow[gauge]{Lorenz} 6 \xrightarrow[gauge]{TT} 2$

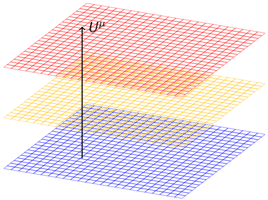
Lorenz gauge: $\partial_\mu \bar{h}^{\nu\mu} = 0$

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

Wave equation

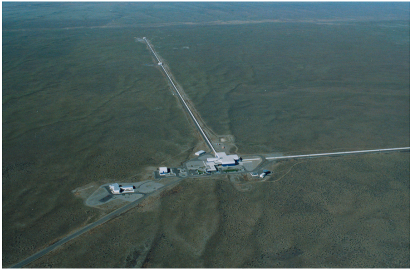
$$\Box \bar{h}_{\mu\nu} = 0$$

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

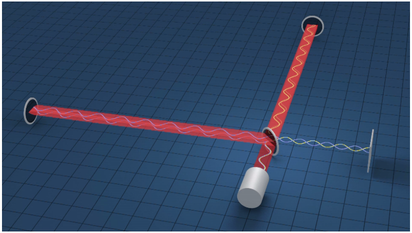


Ground-based observatories

Giant Michelson interferometer in Hanford



Credit: Caltech/MIT/LIGO Lab



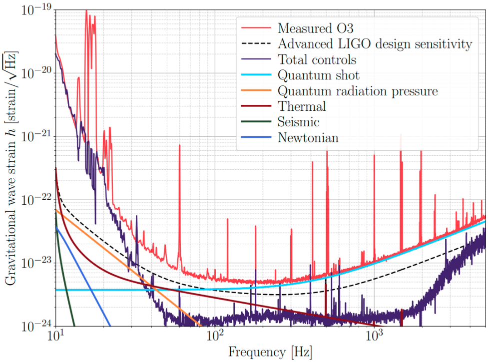
Credit: T. Pyle/LIGO

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

$S(t)$: Total signal $\quad$ $h(t)$: Gravitational waves signal $\quad$ $n(t)$: Noise signal

LIGO noise budget

Hanford detector

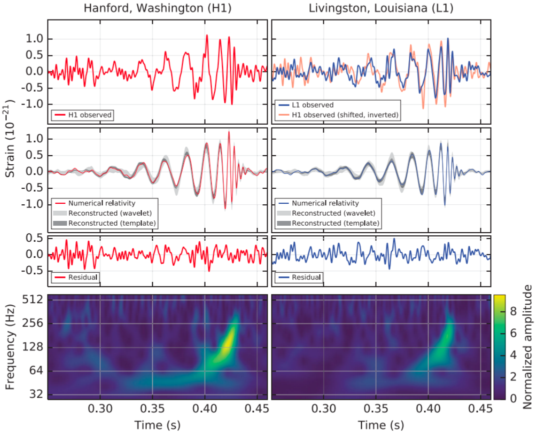


Credit: Craig Cahillane et al., 2022

Dominant noise:

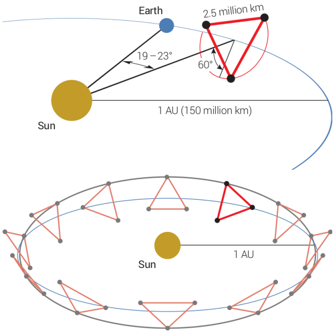
- Quantum shot in high frequency
- Seismic noise in low frequency

First detection of gravitaional wave (GW150914)

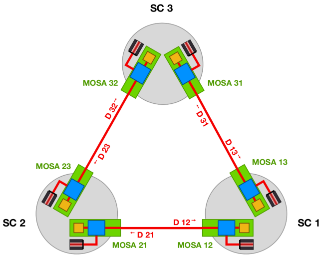


Credit: B. P. Abbott et al., 2016

Laser Interferometer Space Antenna (LISA)



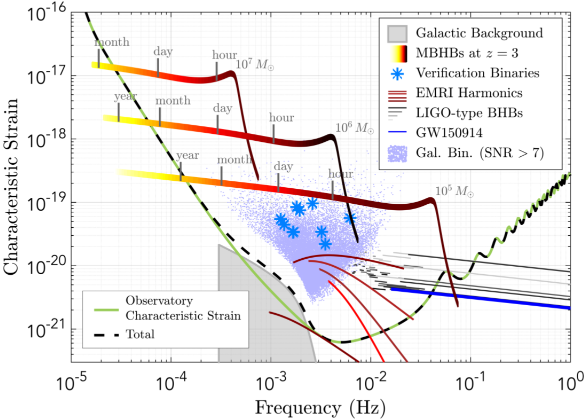
Credit: Karsten Danzmann et al., 2017



Credit: Jean-Baptiste Bayle et al., 2021

Using time delay interferometry to reduce laser frequency noise.

LISA Band

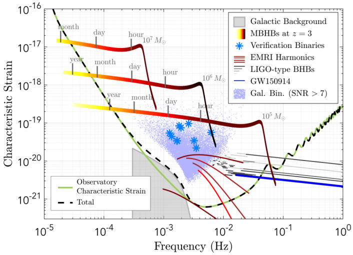


Credit: Karsten Danzmann et al., 2017

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

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

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- LISA sources are expected to be long-lived.
- GW signals will be overlapping in time (frequency).
- Some signals can be resolvable due to a high signal-to-noise ratio.
- Remaining signals will affect the sensitivity as an extra noise (confusion noise).

Method

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

SNR

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

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

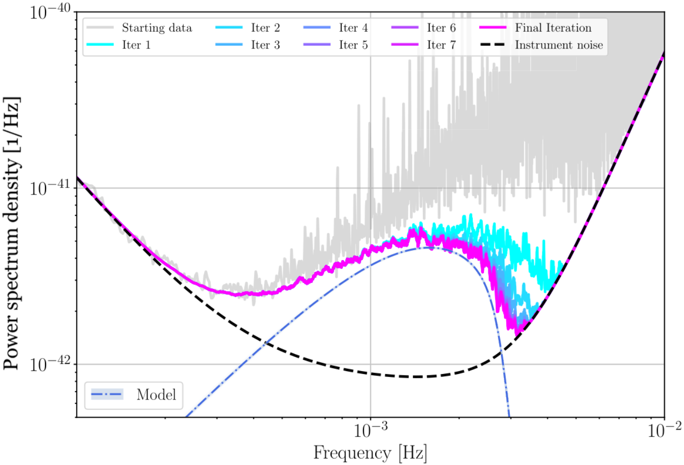
$$\tilde{S}_n(f) = \tilde{S}_{instr}(f) + \tilde{S}_{conf}(f)$$

Method

1. Simulation of the objects*.
2. Calculating the power spectrum density of the signal and the instrumental noise.
3. Estimating the signal-to-noise ratio of each source w.r.t the power spectrum density of the data (ρ_i).
4. If $\rho_i > \rho_0$ the source will be subtracted from the data.
5. Iterate the process until no sources exceed the threshold (ρ_0).

*Objects: 1-CGBs 2-SBBHs

1-Compact Galactic Binaries



Credit: Nikolaos Karnesis et al., 2021

1-Compact Galactic Binaries

Analytical model for the estimated confusion foreground:

Confusion foreground model

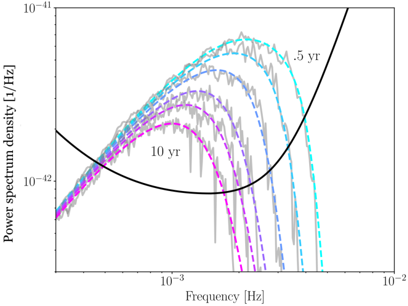
$$S_{gal} = \frac{A}{2} f^{-7/3} e^{-(f/f_1)^{\alpha}} (1 + \tanh((f_{knee} - f)/f_2))$$

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

f: Frequency $\quad$ α: Smoothness parameter

f_1 and f_{knee} depend on observation time T_{obs}

1-Compact Galactic Binaries



Credit: Nikolaos Karnesis et al., 2021

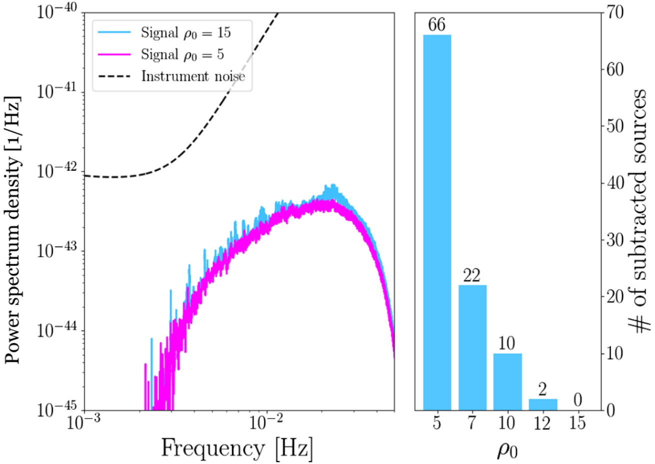
	No. of sources recovered			
	Running mean		Running median	
T_{obs} [yr]	$\rho_0 = 5$	$\rho_0 = 7$	$\rho_0 = 5$	$\rho_0 = 7$
0.5	8031	4491	8850	5111
1	14170	8487	14918	9305
2	22681	14206	23849	15441
4	35891	22951	37684	25025
6	45925	30097	48179	32702

Credit: Nikolaos Karnesis et al., 2021

2-Stellar-mass binary black holes

- For CGBs they used a cataloge for estimating their population and simulating their GWs signal.
- The population of SBBHs observed by LISA depends on the merger rate of SBBHs ($\mathcal{R}$).
- ▶ $\mathcal{R}$ can be estimated from data of ground-based observatories.
- LISA is sensitive to the early inspiral stage of orbit evolution of SBBHs.
- ▶ They appear in the high-frequency reigon of LISA band.
- There is a very low chance for the transition of SBBHs from LISA band to LIGO band during the LISA observation time.

2-Stellar-mass binary black holes



Credit: Nikolaos Karnesis et al, 2021

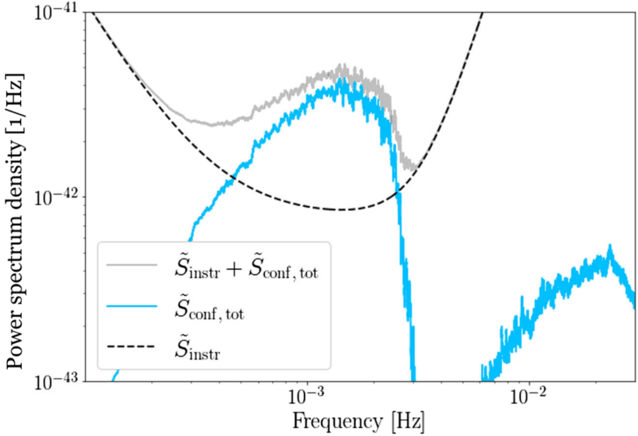
Combining the populations

- Doing the same process again!
- Instead of iterating over one type, iterate over all types
- Comparing SNR of each type with itself
- The final result is just a 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



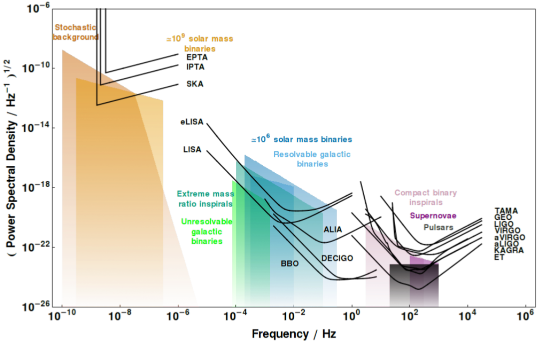
Credit: Nikolaos Karnesis et al., 2021

Conclusion

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

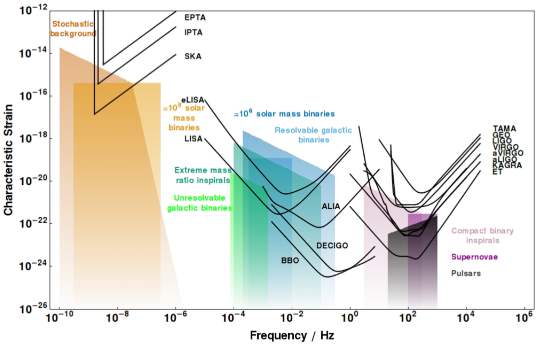
Thank you!

Power Spectrum Density (PSD)



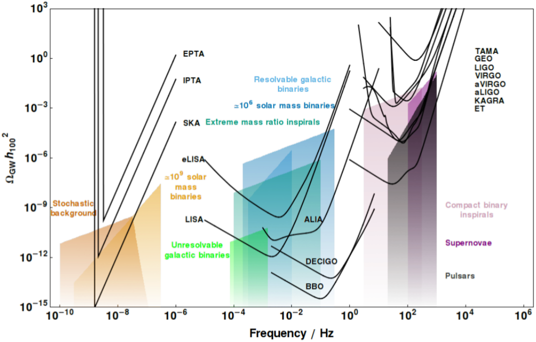
Credit: C J Moore et al., 2014

Characteristic strain



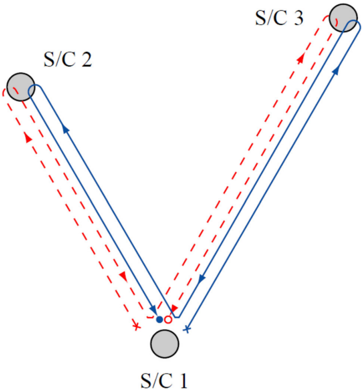
Credit: C J Moore et al., 2014

Dimensionless energy density

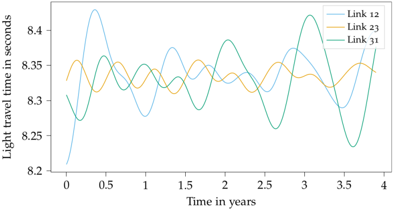


Credit: C J Moore et al., 2014

Time Delay Interferometery (TDI)



Credit: Massimo Tinto et al., 2020



Credit: Olaf Hartwig, 2021

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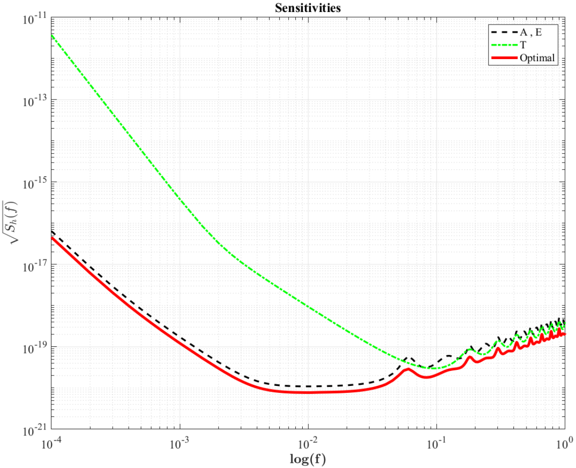

Credit: Massimo Tinto et al., 2020

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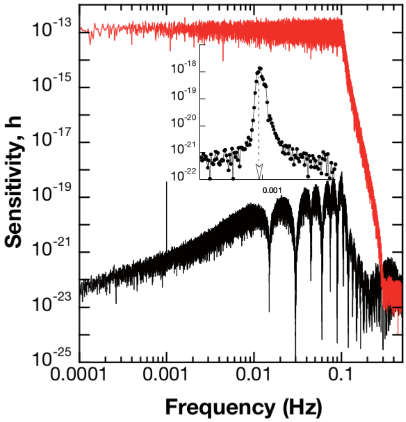
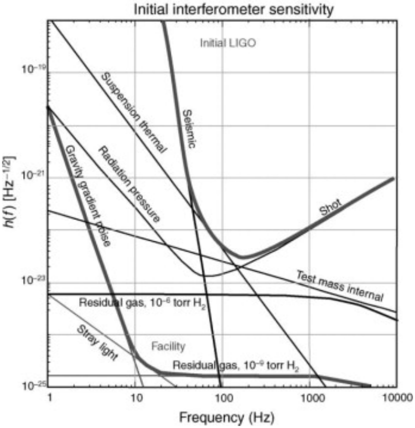


Credit: Antoine Petiteau et al., 2008

LIGO noise budget



Credit: Rainer Weiss, 2018