

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

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Gravitational waves

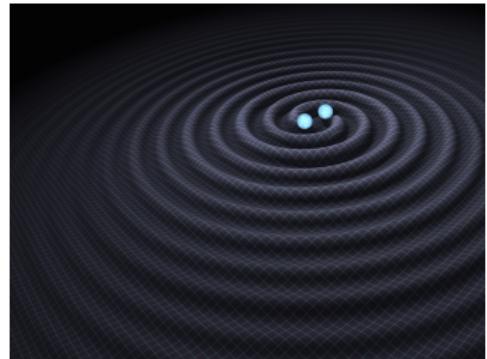
Ripples in space-time caused by accelerated masses.

Einstein field equations

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

$G_{\mu\nu}$: Einstein tensor $T_{\mu\nu}$: Energy-Momentum tensor

G : Gravitational constant c : speed of light



$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad |h| \ll 1$$

Credit: R. Hurt (Caltech-IPAC)

$$\bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h$$

Gravitational waves

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

Wave equation

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

$$\bar{h}_{\mu\nu} = A_{\mu\nu} \exp(ik_\alpha x^\alpha)$$

Transverse traceless gauge:

$$\bar{h}_{\mu\nu} U^\mu = 0 \text{ and } \bar{h}_\mu{}^\mu = 0$$

Gravitational waves

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

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

Wave equation

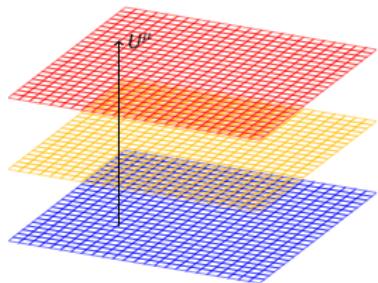
$$\square \bar{h}_{\mu\nu} = 0$$

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

$$\bar{h}_{\mu\nu} = A_{\mu\nu} \exp(ik_\alpha x^\alpha)$$

Transverse traceless gauge:

$$\bar{h}_{\mu\nu} U^\mu = 0 \text{ and } \bar{h}_\mu{}^\mu = 0$$

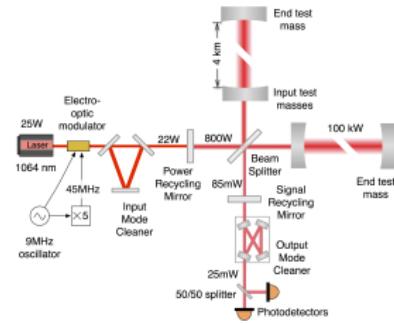


LIGO Structure

Giant Michelson interferometer



Credit: Caltech/MIT/LIGO Lab

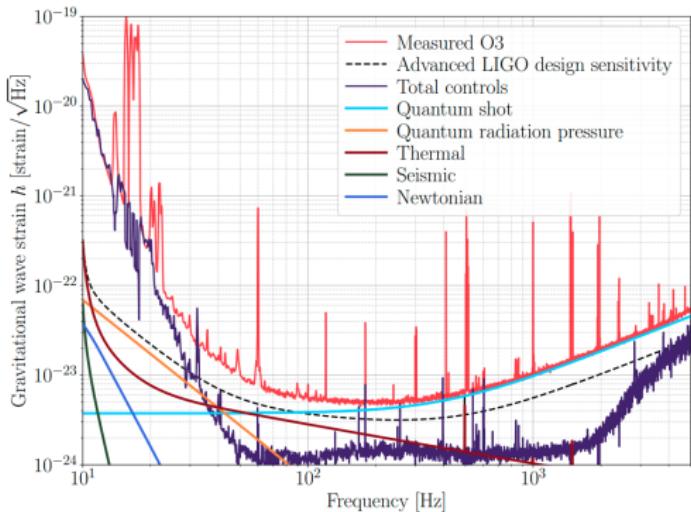


Credit: D. V. Martynov et all, 2018

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

LIGO Noise budget

Hanford detector

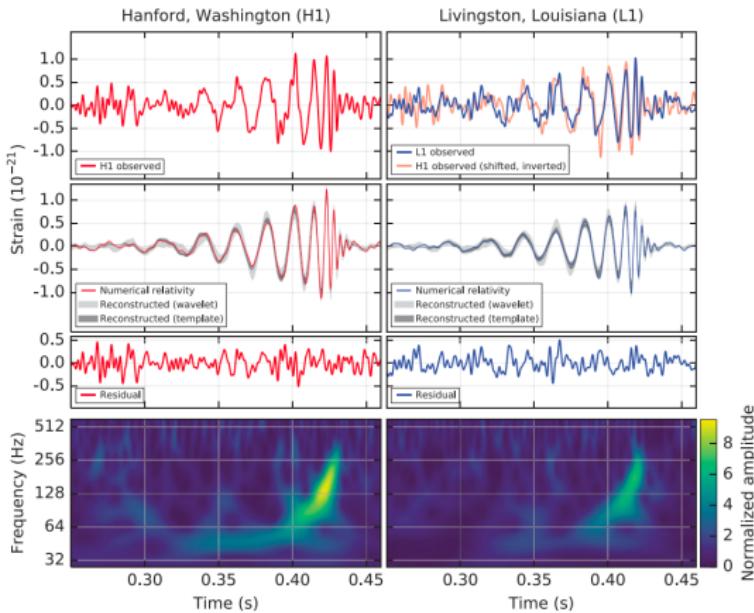


Dominant noise:

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

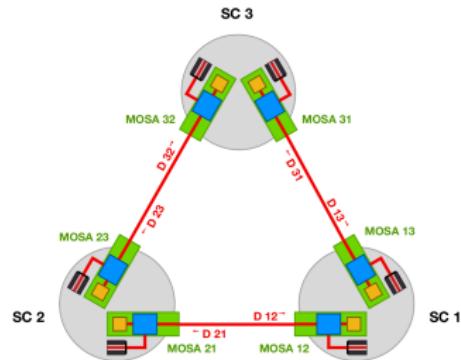
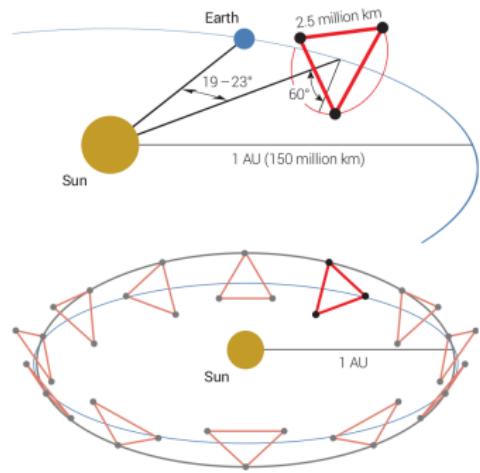
Credit: Craig Cahillane et all, 2022

First detection (GW150914)



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

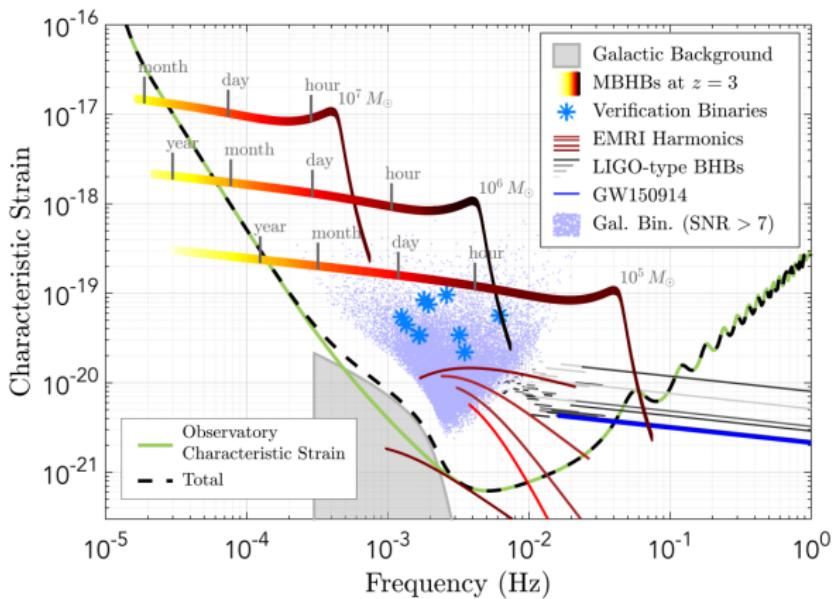
Laser Interferometer Space Antenna (LISA)



Credit: Jean-Baptiste Bayle et al., 2021

Credit: Karsten Danzmann et al., 2017

LISA Band



Credit: Karsten Danzmann et al., 2017

LISA Band

GW sources in LISA band

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

LISA Issues

- 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 data are expected to be signal dominated
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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 instrumental noise using the LISA code simulator
- 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

- 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

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

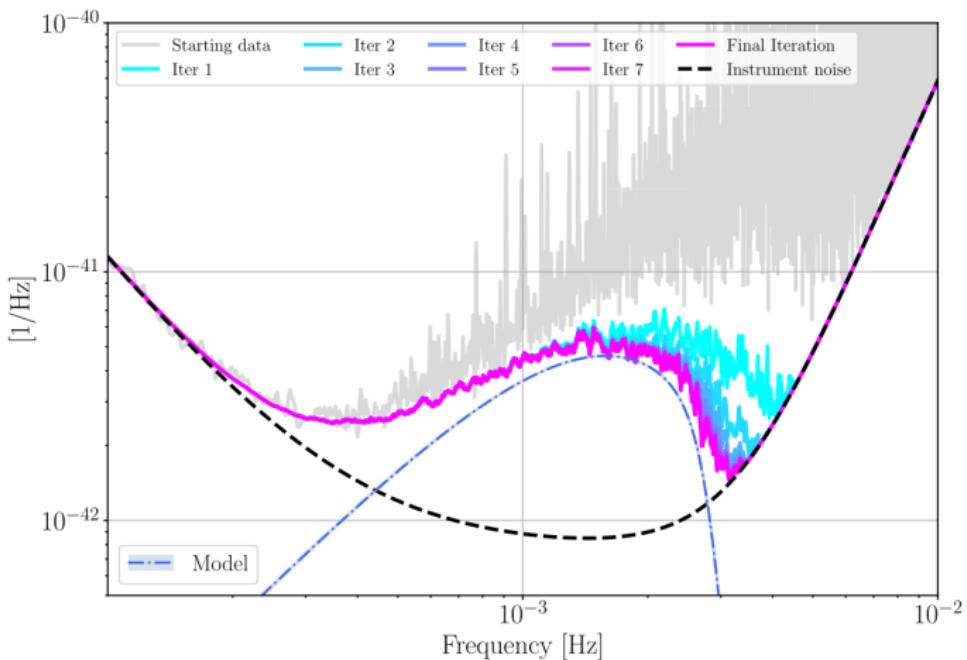
$$h_k | h_k = 4 \int_0^\infty df \frac{|\tilde{h}_k(f)|^2}{\tilde{S}_n(f)}, \quad \tilde{S}_n(f) : \text{one-sided PSD}$$

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

Method

- 1 Simulating 30 millions 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 Estimating 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 f_1, f_2 and f_{knee} : Scaling frequencies

f : Frequency α : Smoothness parameter

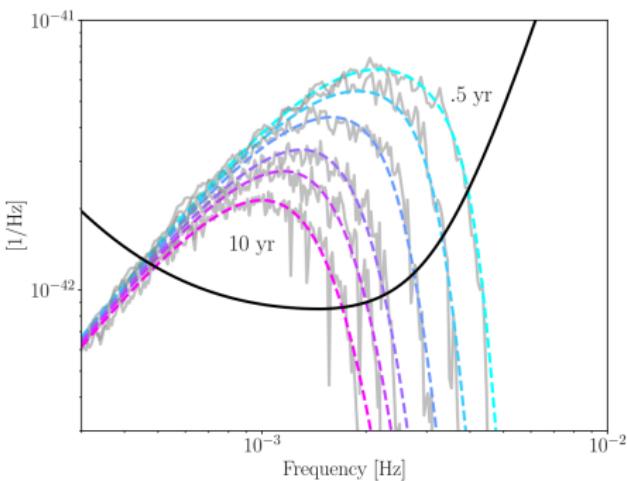
Approximation for f_1 and f_{knee} :

$$\log_{10}(f_1) = a_1 \log_{10}(T_{obs}) + b_1$$

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

a_1, b_1, a_k and b_k are amplitude calibration parameters

Compact Galactic Binaries



Credit: Nikolaos Karnesis et al, 2021

Parameter	Estimated			
	Running mean		Running median	
	$\rho_0 = 5$	$\rho_0 = 7$	$\rho_0 = 5$	$\rho_0 = 7$
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

T_{obs} [yr]	No. of sources recovered			
	Running mean		Running median	
	$\rho_0 = 5$	$\rho_0 = 7$	$\rho_0 = 5$	$\rho_0 = 7$
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

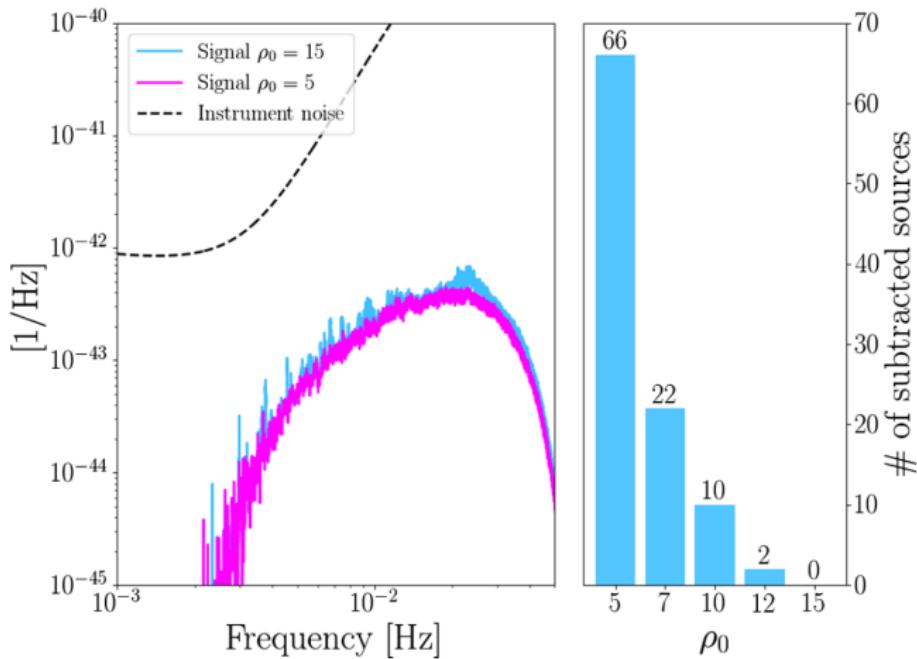
Stellar-mass binary black holes

- LISA is sensitive to the early inspiral stage of orbit evolution of SBBHs
- They appear in the high-frequency tail of LISA band (until 3mHz)
- 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 estimated 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

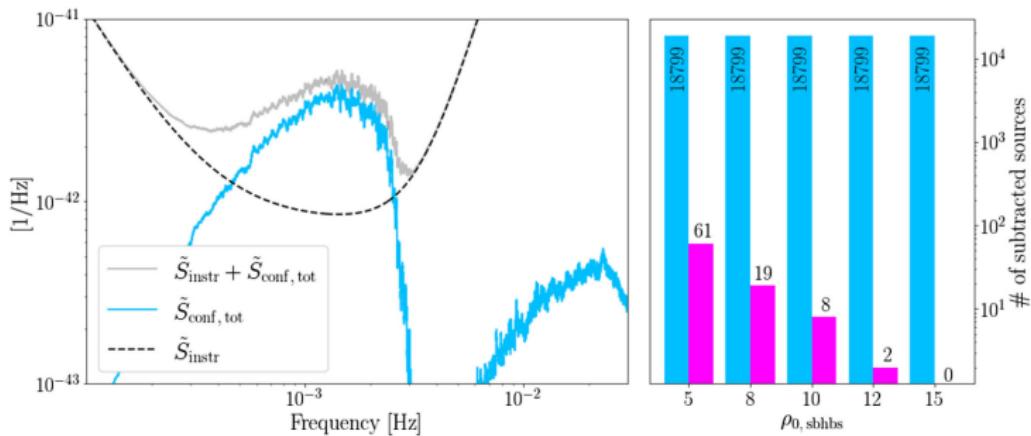
Combining the populations

- 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

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

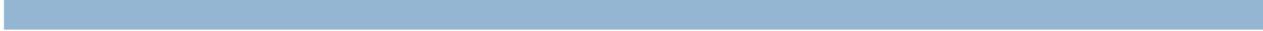
Combining the populations



Credit: Nikolaos Karnesis et al, 2021

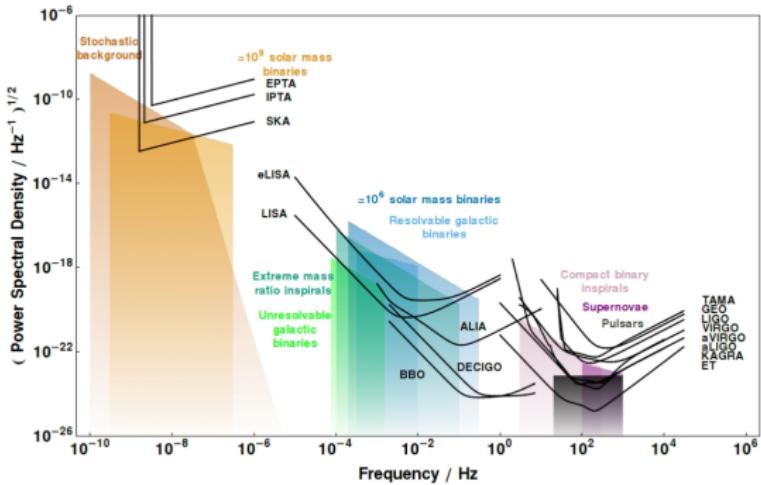
Conclusion

- Simulation of CGBs adn SBBHs population
- using an iterative process to estimate foreground 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



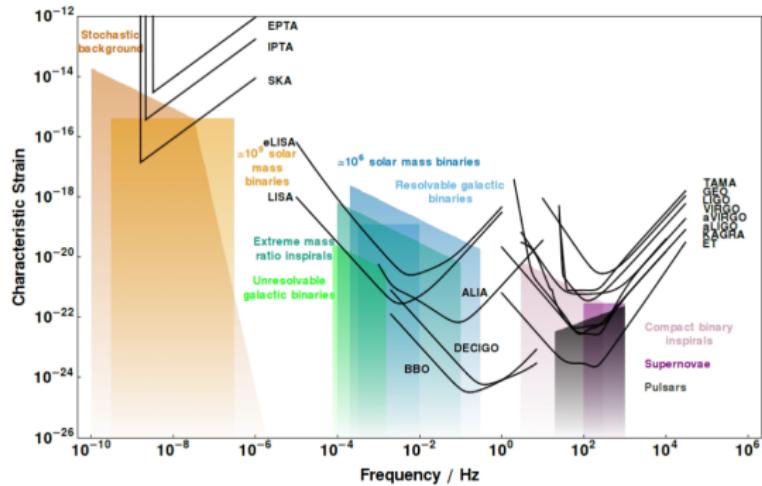
Thank you!

PSD



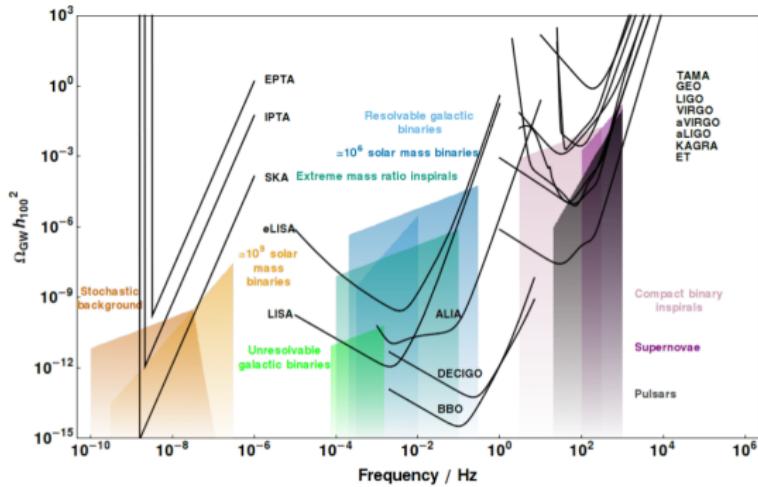
Credit: C J Moore et al, 2014

Characteristic strain



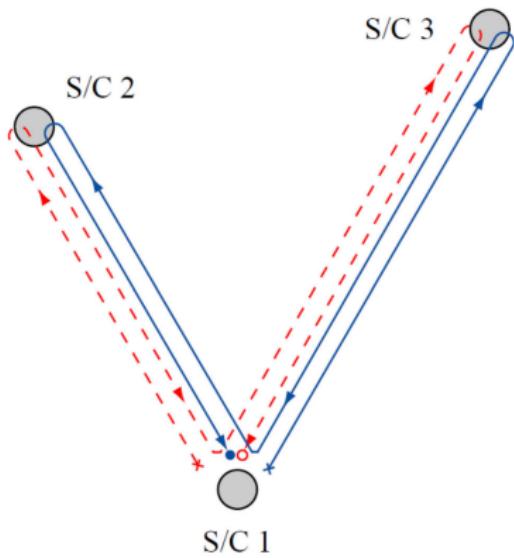
Credit: C J Moore et al, 2014

Dimensionless energy density

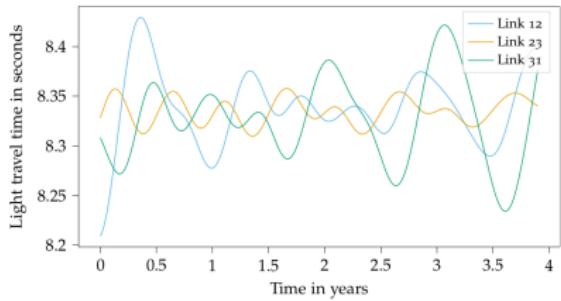


Credit: C J Moore et al, 2014

TDI



Credit: Massimo Tinto et al, 2020



Credit: Olaf Hartwig, 2021