Stochastic Cosmological Background Study with 3G Gravitational Wave Detectors : Probing the Very Early Universe

Second Year PhD Progress Report

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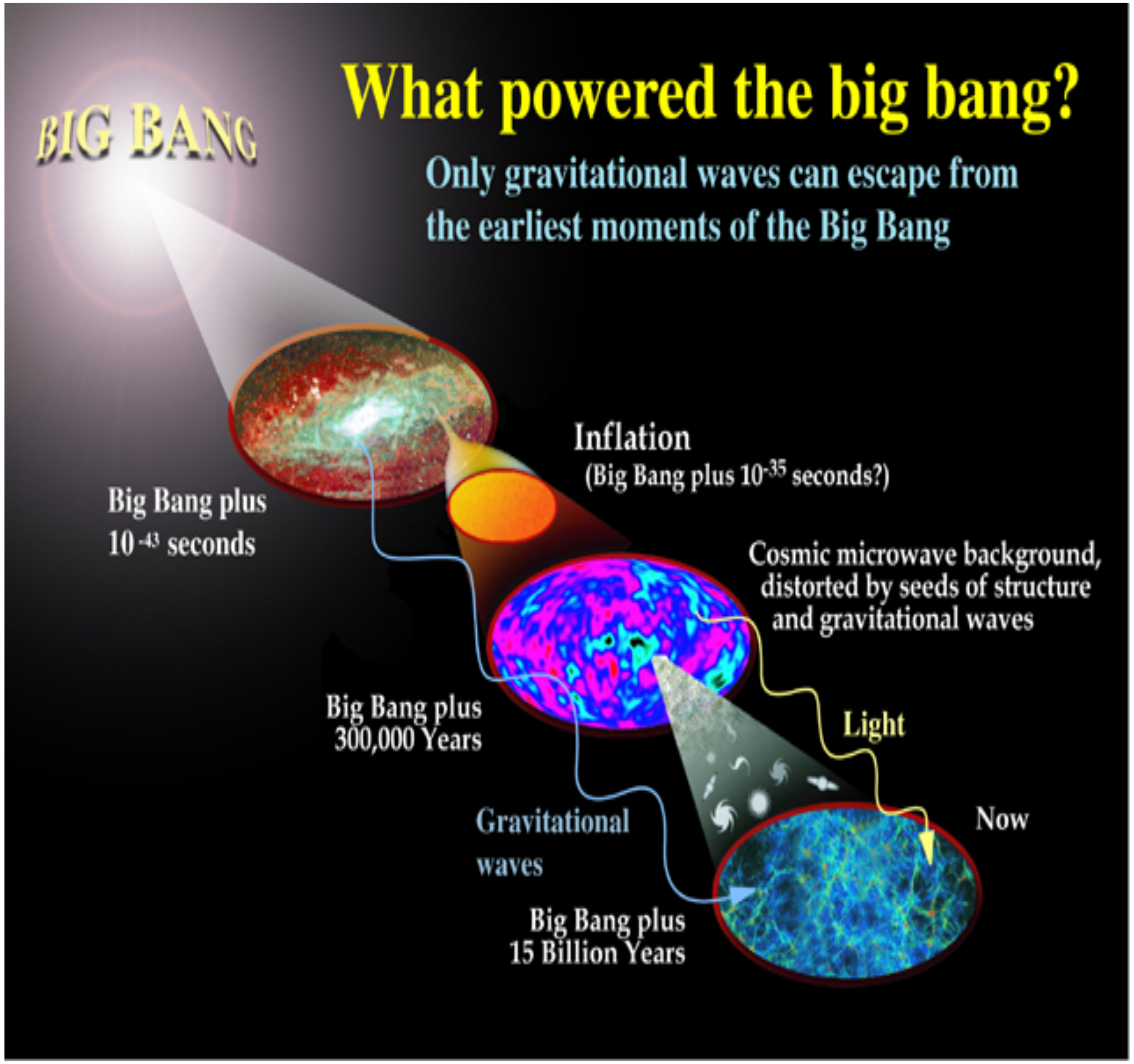
Outline

- Motivation
- Stochastic background
- Cosmological source of GWs
- Best-fit subtraction
- Projection method
- Results
- Conclusion

Motivation

- A GW stochastic background may be next class signal detected.
- It would be a statistical detection, confidence level will grow with the observation time.
- Produced very shortly after big bang.
- Carry Information to study early universe phenomenon not accessible by EM ways.
- signals will help us to understand the characteristics of the primordial signals, the fundamental physics and the evolution of the Universe.

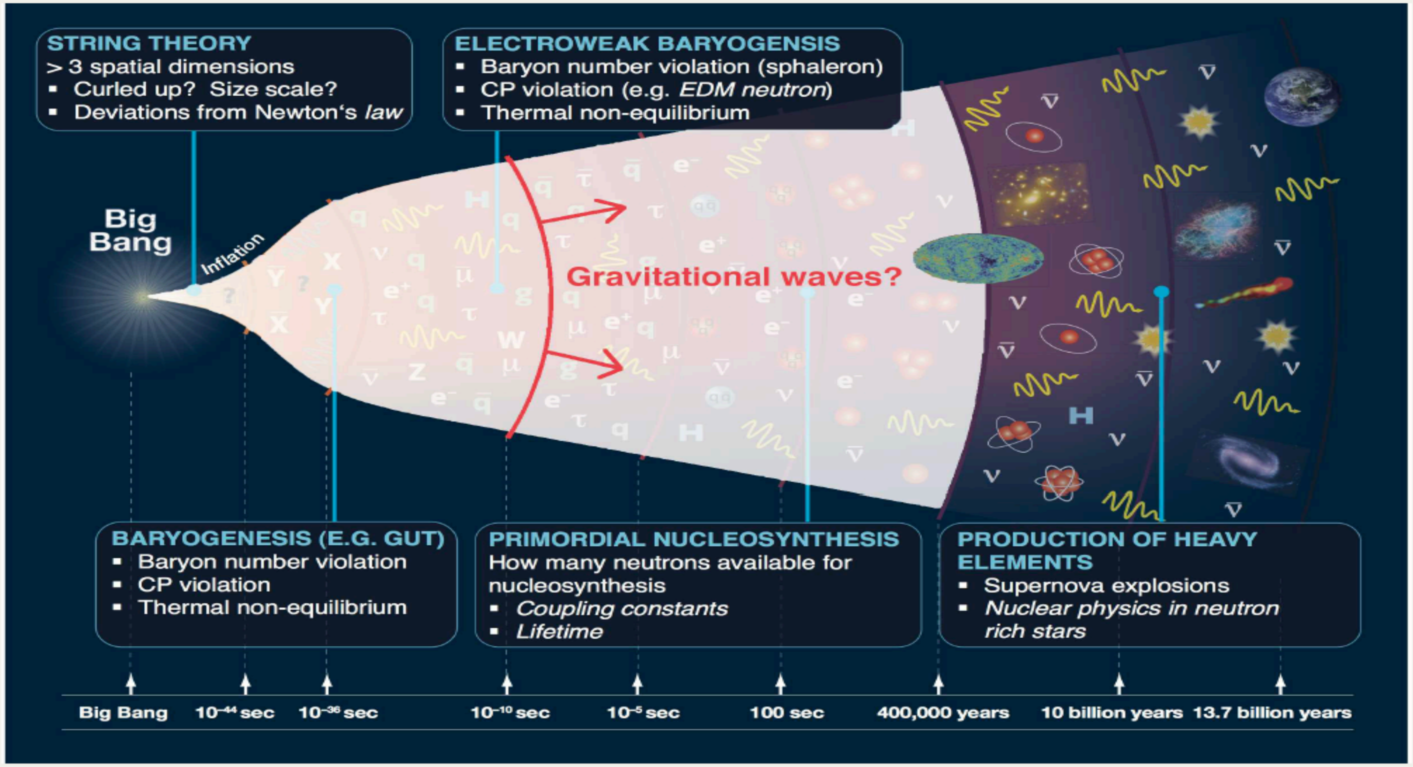


Stochastic Background

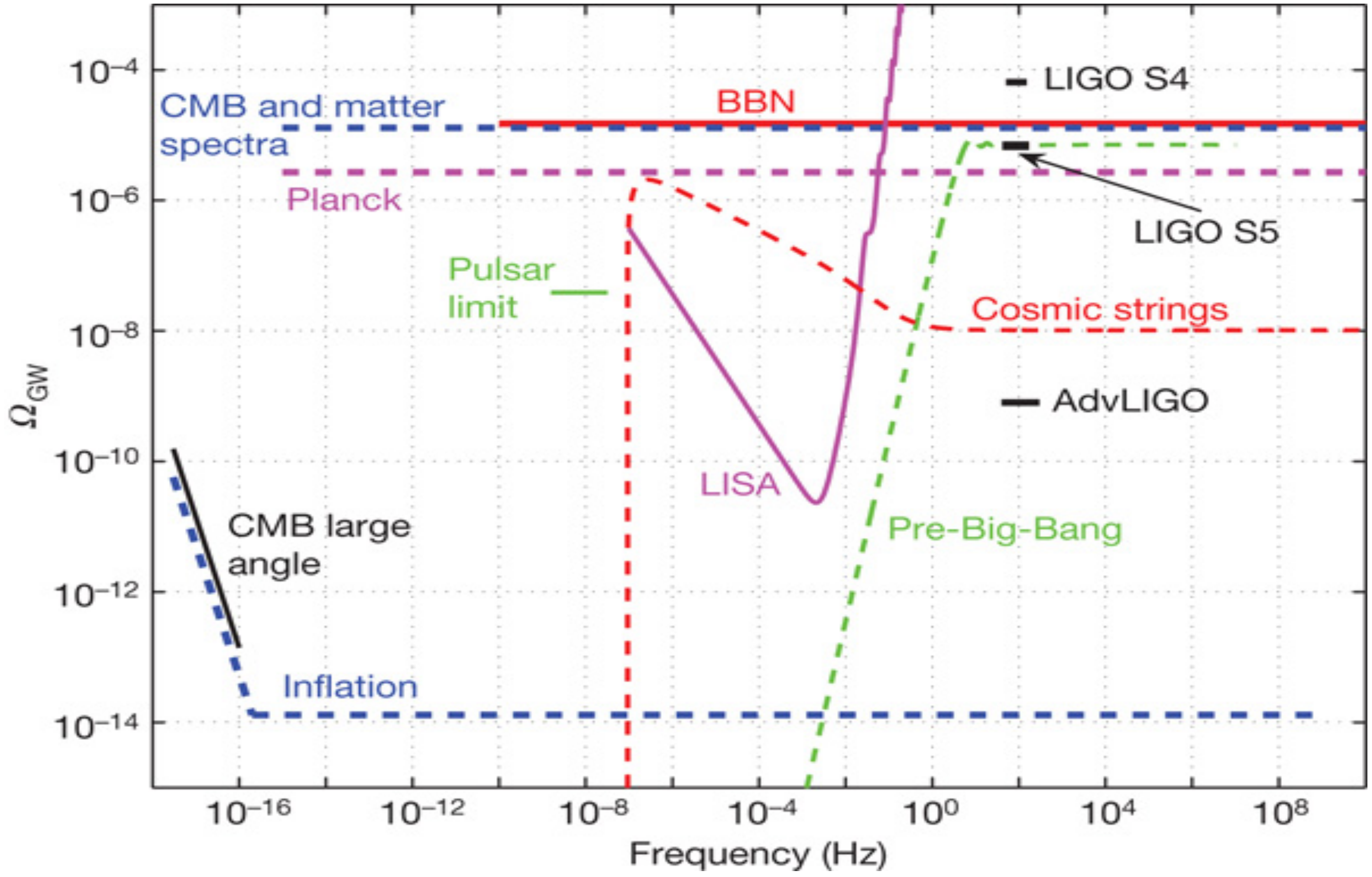
- An incoherent superposition of large number of resolved and unresolved sources defined by statistical properties, isotropic, unpolarized, stationary and Gaussian.

$$\Omega_{GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{GW}}{d\ln f} \quad , \rho_c = \frac{3\,c^2 H_0^2}{8\pi G}$$

- Uncorrelated gravitational wave sources can be of astrophysical or cosmological sources.
- Cosmological: Signal of Early Universe
  - Inflationary epoch
  - Phase transitions
  - Cosmic Strings
- Astrophysical
  - Supernovae
  - Magnetars
  - Binary Objects (BH, NS)

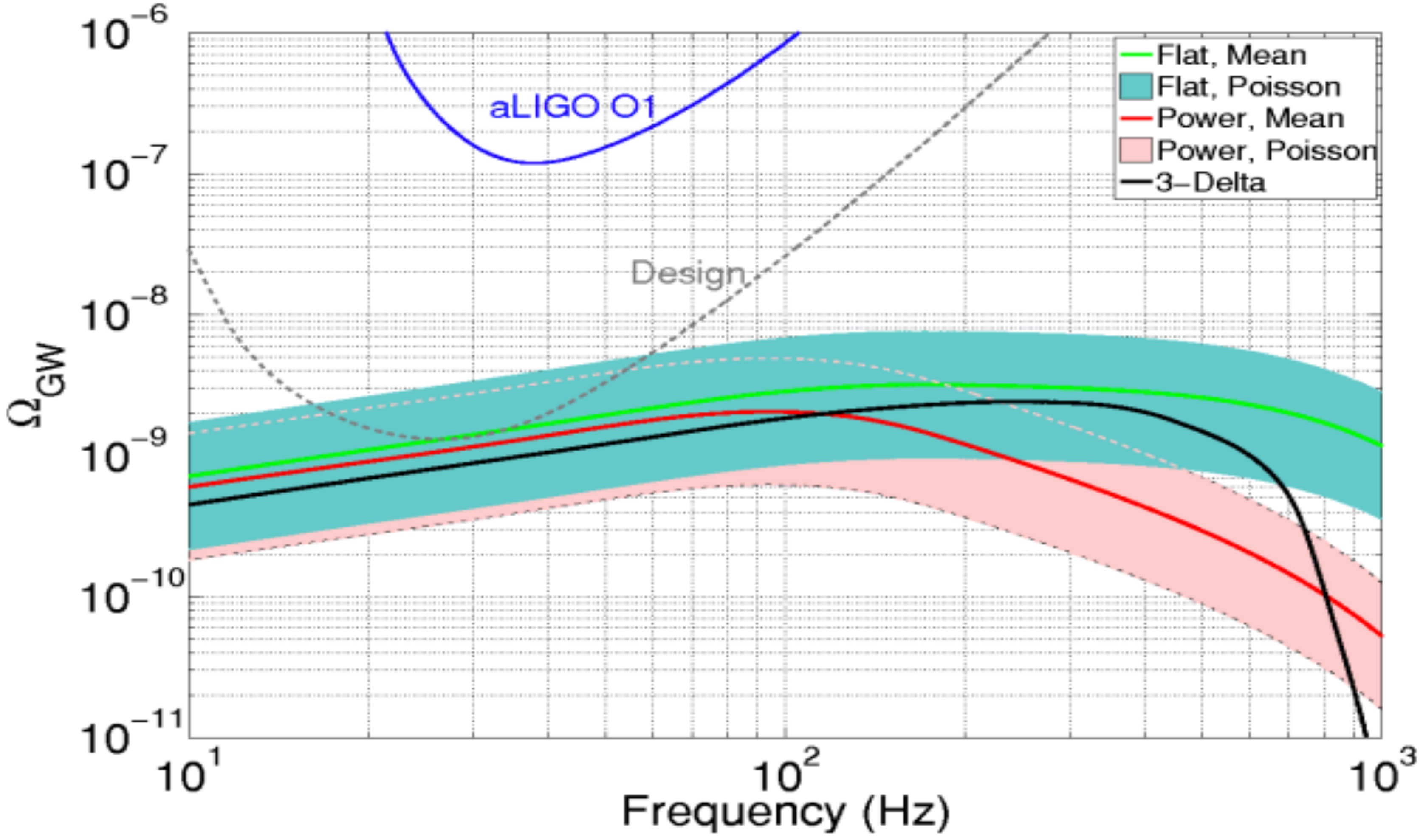


Energy Spectra of SCGW Backgrounds



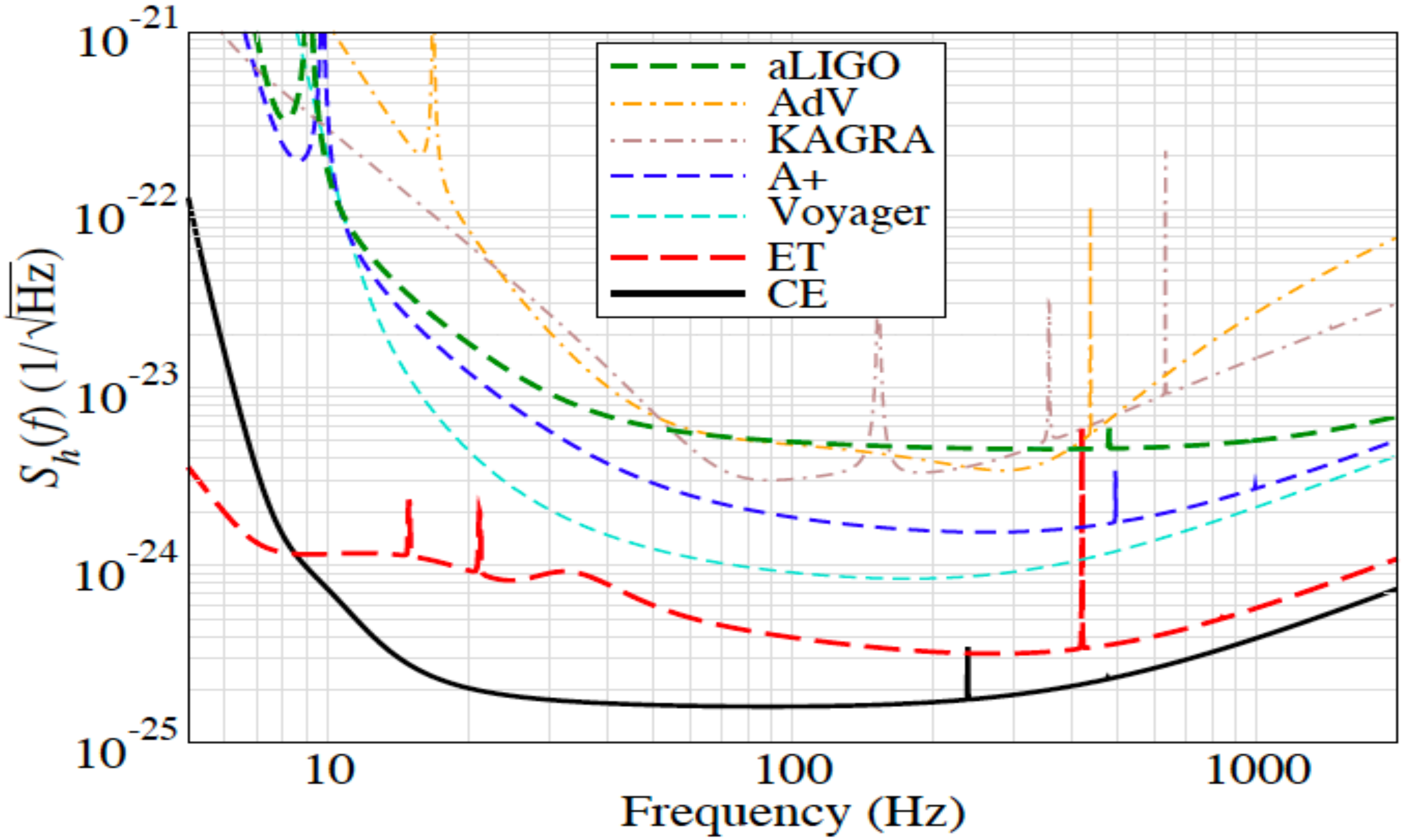
LVC, *Nature* **460**, 990-994 (2009)

BBH Background Spectrum



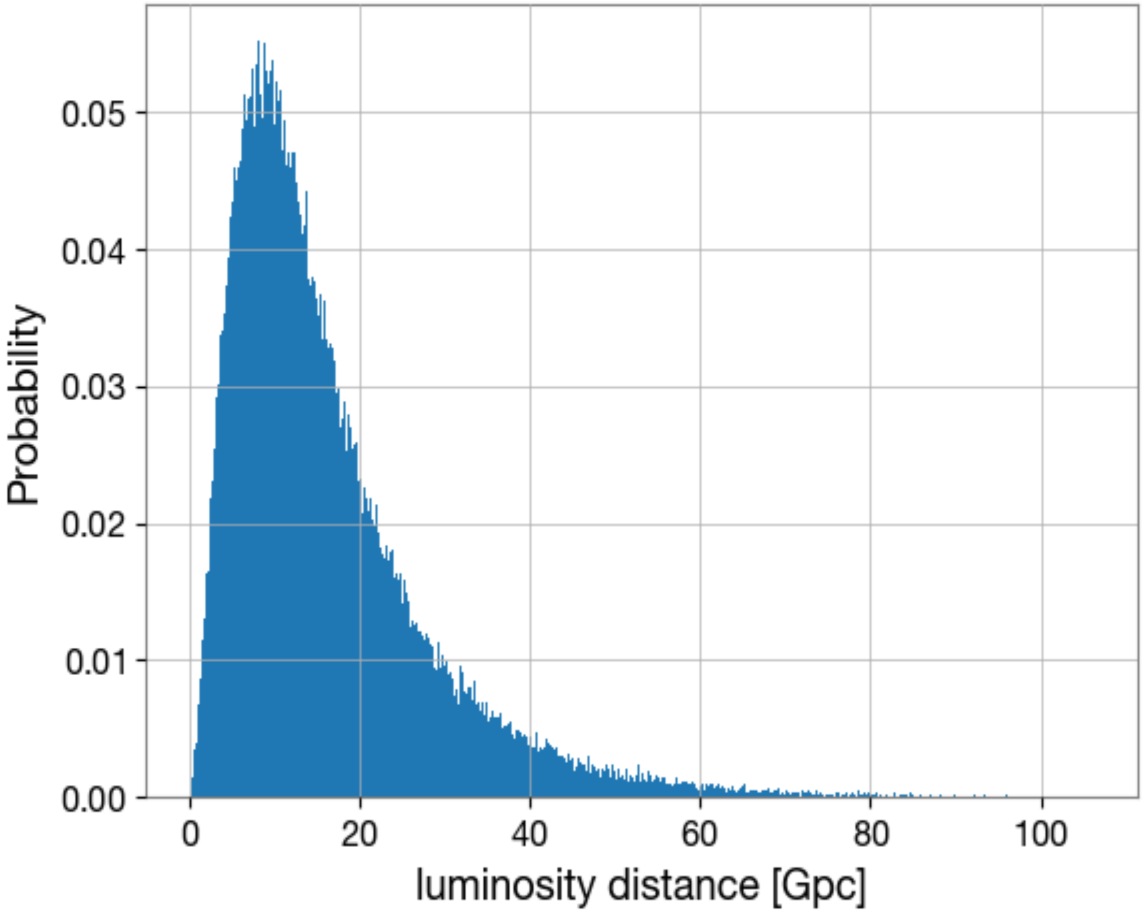
LVC, PRL 119, 029901 (2017)

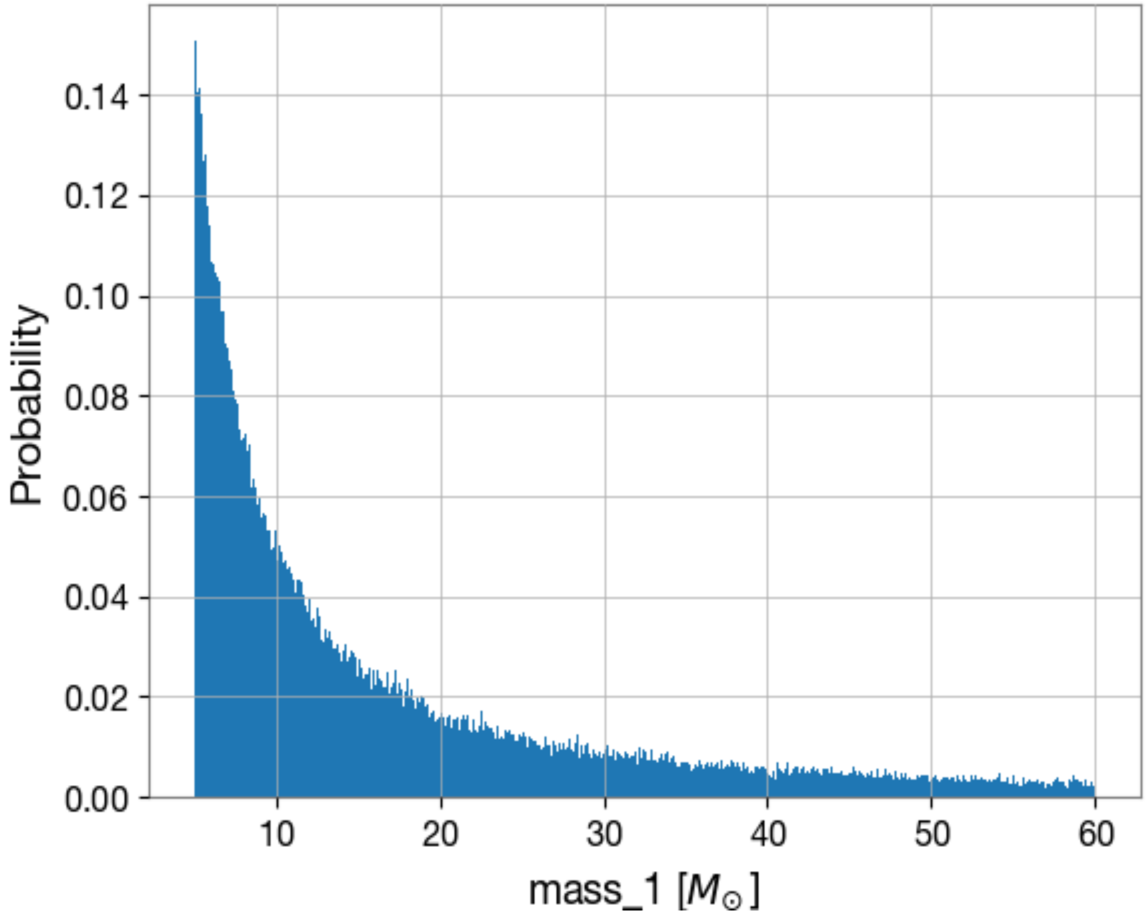
Sensitivity Level for GW Detectors



T. Regimbau et al, PRL 118 (2017) 15, 151105

Luminosity Distance and Binary mass Distribution





Subtraction- Noise Projection Method

- This method is based on a geometrical interpretation of matched filtering and allows to access the weak signals like a stochastic GW background, irrespective of the residual noise in the data.
- How we used this method
  - Injections: Generated a frequency domain strain containing the instrumental noise and signal for 1000 binary black-holes (BH).
  - Subtraction: Performing the parameter estimation to best-fit waveform, which will give us residual noise data after subtraction
  - Projections: Using residual noise data and Fisher matrix to perform the projection method to project out the residual noise data and search for stochastic background.

Fisher Matrix : Signal Model and It's derivatives

$$\Gamma_{\alpha\beta} = \left\langle \partial_\alpha T^m \middle| \partial_\beta T^m \right\rangle$$

$$\Gamma_{\alpha\beta} = 2\int_0^\infty df \, \frac{Re(\partial_\alpha T^m(f)\partial_\beta T^{m*}(f))}{S^n(f)}$$

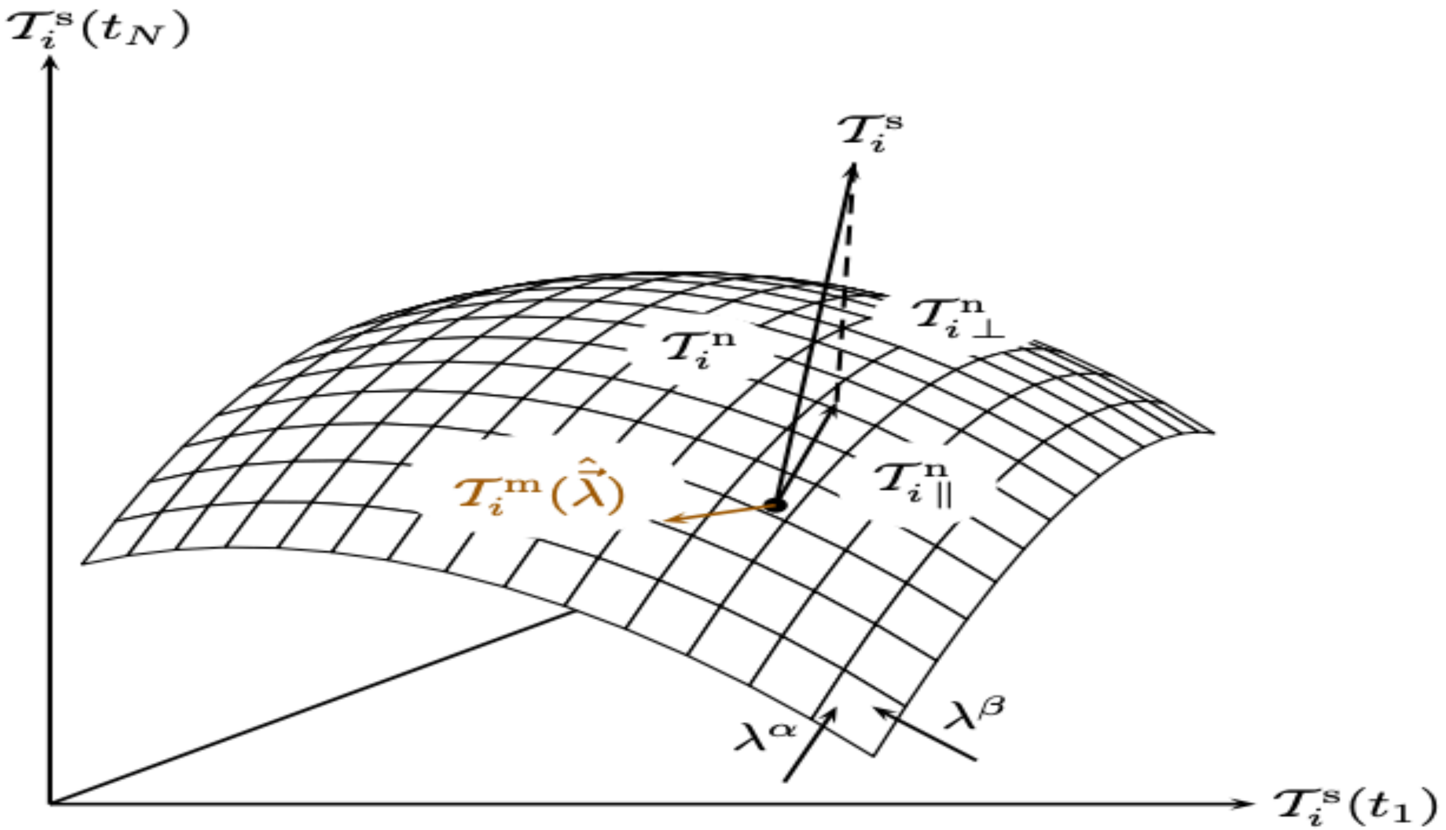
- T^m represent the signal model depending on λ^α parameters used to analyse the data.
- Fisher matrix defined the manifold of all physical waveform of binary objects.
- Normalized Fisher matrix and Inverse Fisher matrix are computed to define the subtraction noise projection operator.

Projection of Subtraction Errors

Projection operator $P = 1 - \Gamma^{\alpha\beta}\, |\partial_\alpha H\rangle\langle\partial_\beta H\,|$

Projected data stream

$$PT^{residual}(f) = T^{residual}(f) - \Gamma^{\alpha\beta}\,\langle\partial_\beta T^m\,|T^{residual}\rangle\partial_\alpha T^m(f)$$

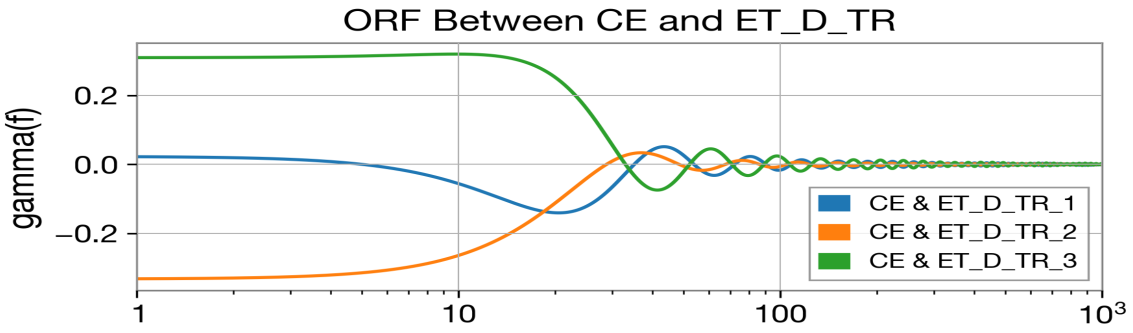


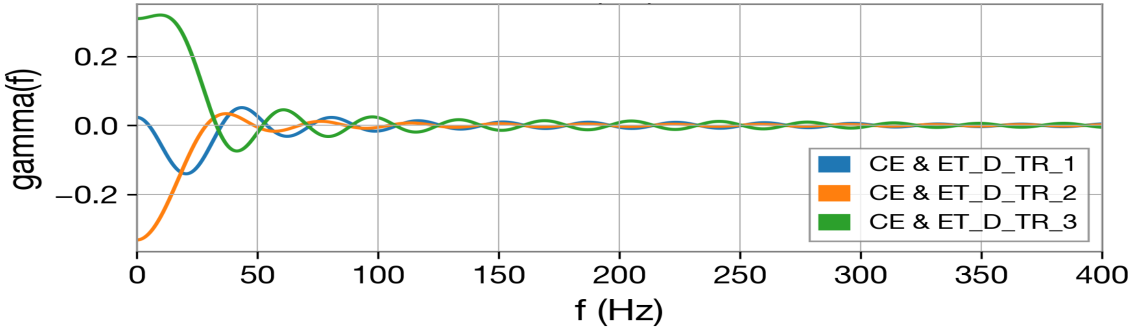
Overlap Reduction Function And Optimal Filter

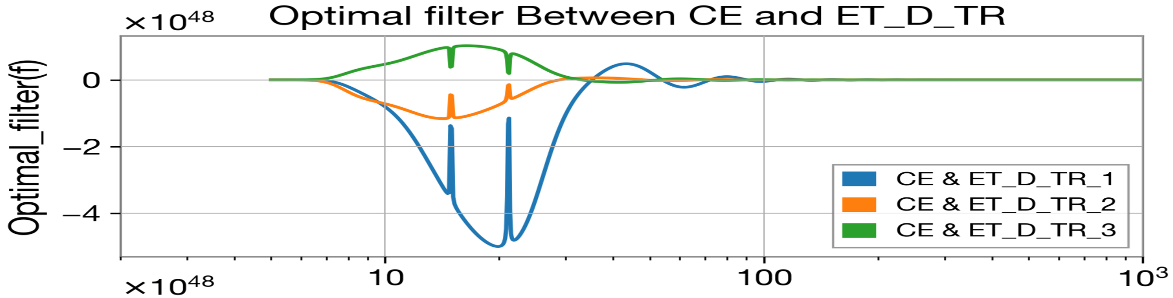
- Quantify the instrumental influence on the correlation strength of detector outputs.

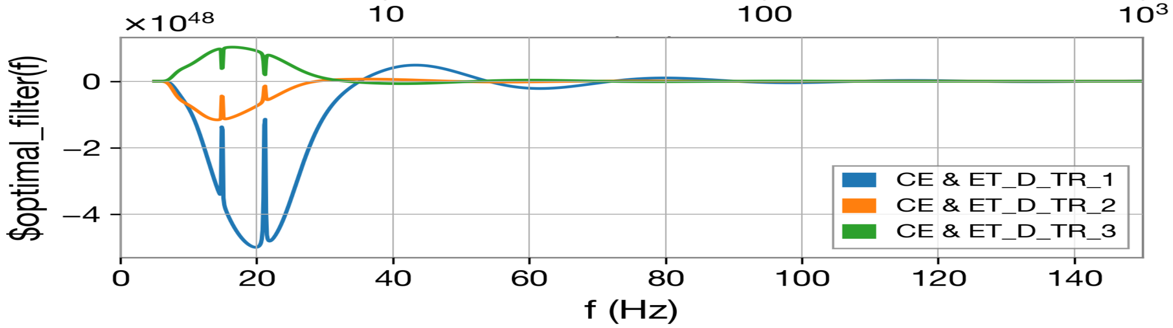
$$\gamma_{ij}(f) = \frac{5}{8\pi}\sum_{A}\int d\hat{\Omega}\, e^{i2\pi f\hat{\Omega}\cdot\frac{\overrightarrow{\Delta x}}{c}} F_1^A(\hat{\Omega})F_2^A(\hat{\Omega})$$

$$F_i^A(\hat{\Omega}) = e_{ab}^A(\hat{\Omega})d_i^{ab} = e_{ab}^A(\hat{\Omega})\frac{1}{2}\left(X_i^a X_i^b - Y_i^a Y_i^b\right)$$





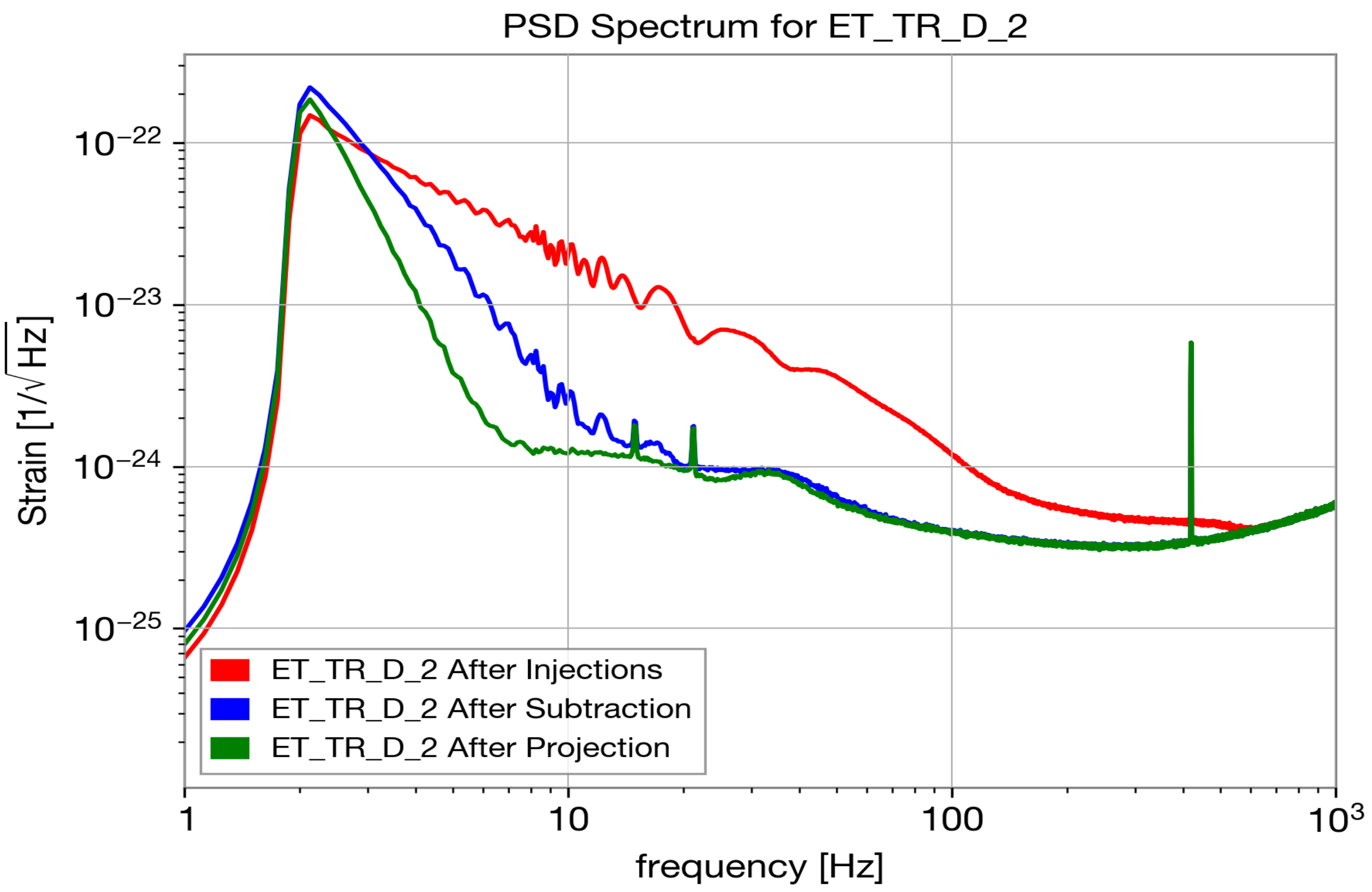




- The choice of filter depends upon the statistical properties of stochastic background and location and orientation of detectors.

$$Q_{ij}(f) = \frac{\gamma(f)\Omega_{GW}(f)H_0^2}{f^3\, P_i(f)P_j(f)}$$

Detector Sensitivity After Subtraction-Noise Projection



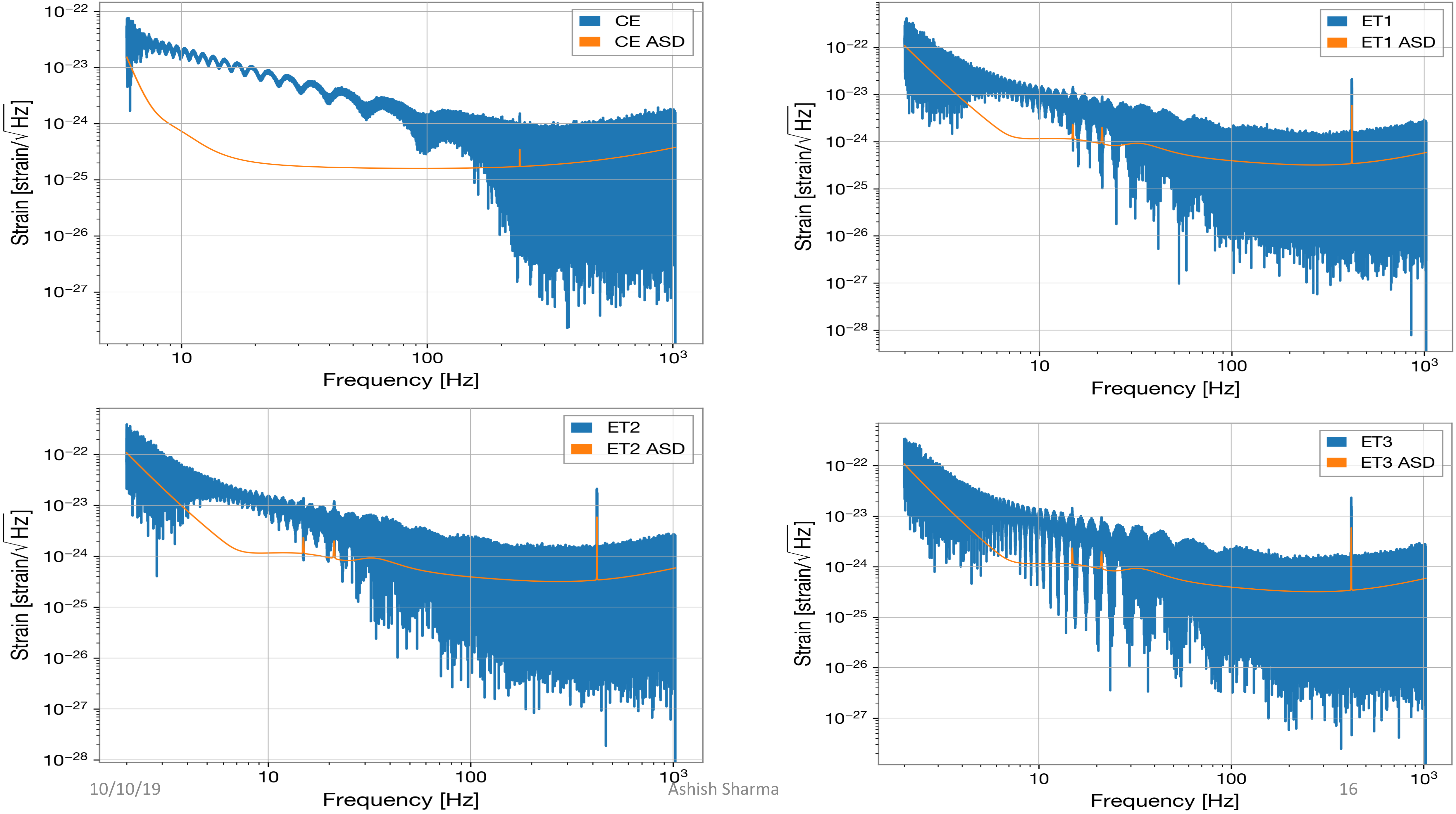
Conclusion

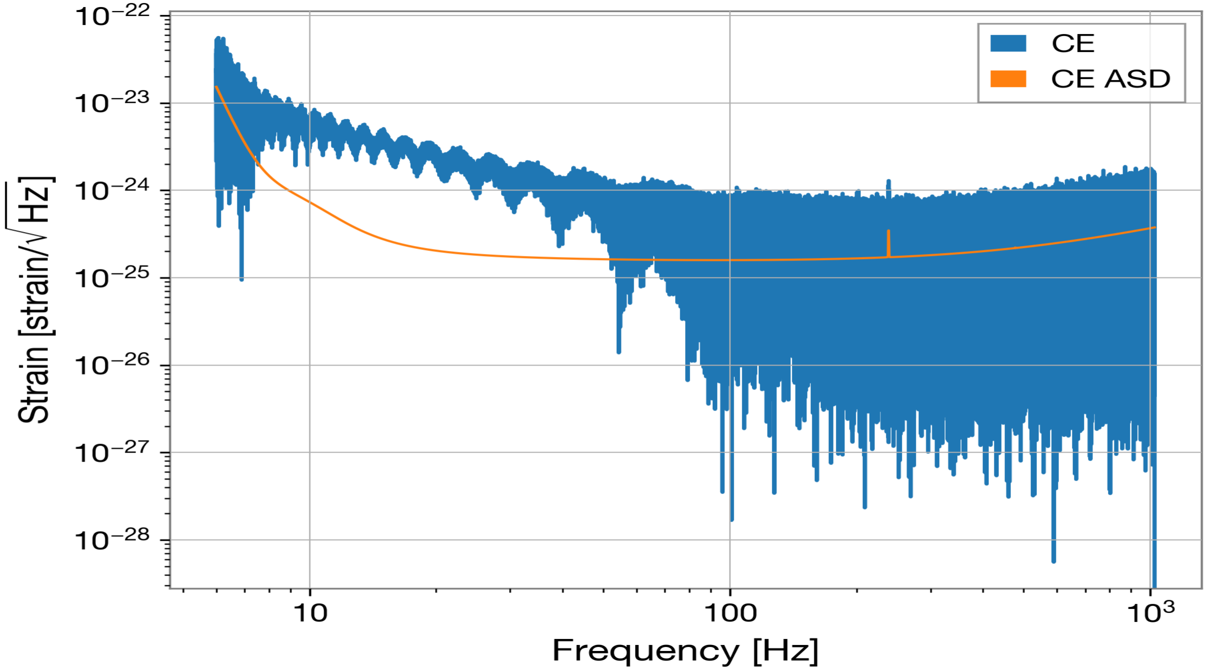
- Subtraction noise projection method is effective in reducing the residual noise data.
- Geometrical Interpretation of matched filtering and parameter estimation easy and realistic approach for such a method.
- Increasing the possibility of detecting a cosmological background signal with third generation gravitational wave detectors.

Thank you

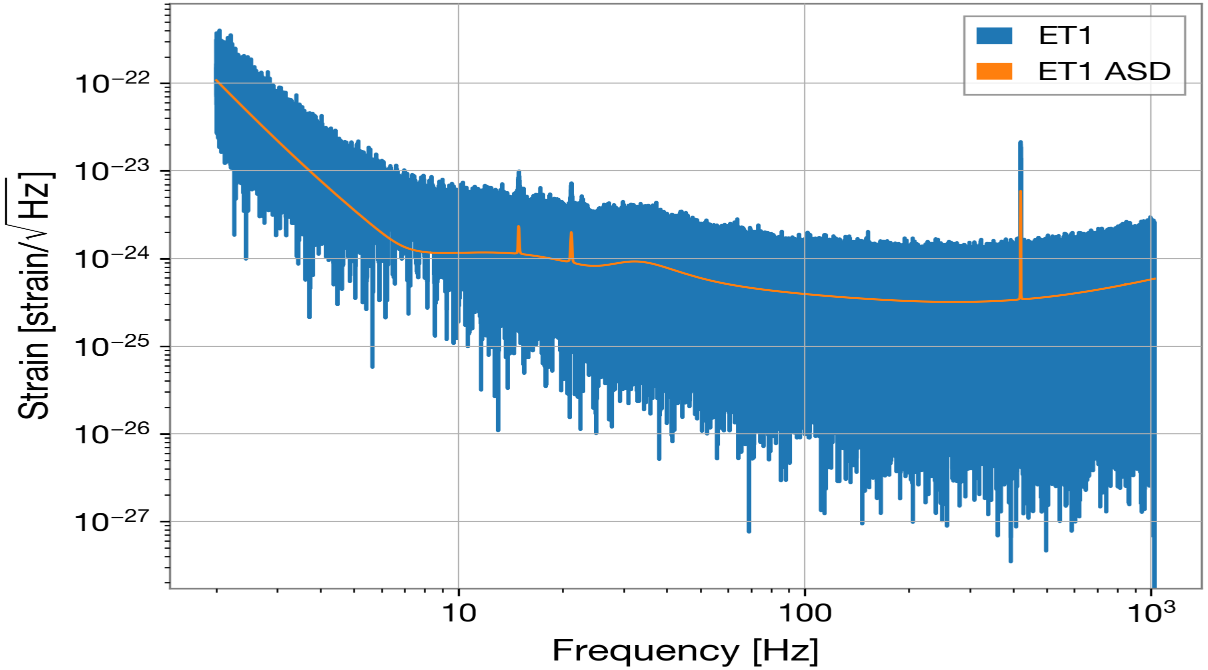
Plan for Following Year

- Testing efficiency of projection method on low-SNR CBC signals.
- Check compatibility of subtraction-noise projection methods with arbitrary waveforms and compare the dependence of the subtraction and projection on the model for search.
- Injection of different types of primordial backgrounds into data and assess their detectability with 3G networks, sensitivity of 3G detectors network towards stochastic backgrounds with and without the projection.
- Comparing the projection method with alternative approaches (computationally expensive full Bayesian analysis of a CBC foreground + primordial background).
- Implementing the projection pipeline in existing LIGO/Virgo codes.

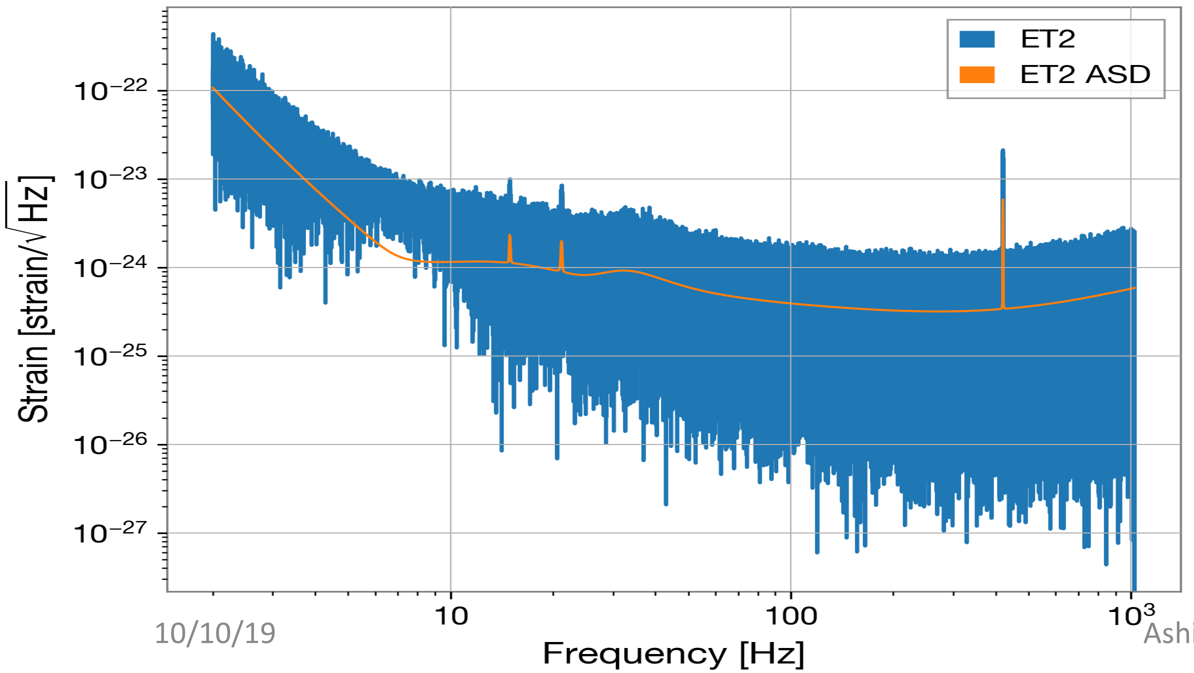

CE
CE ASD
ET1
ET1 ASD
ET2
ET2 ASD
ET3
ET3 ASD
Strain [strain/√Hz]
Frequency [Hz]



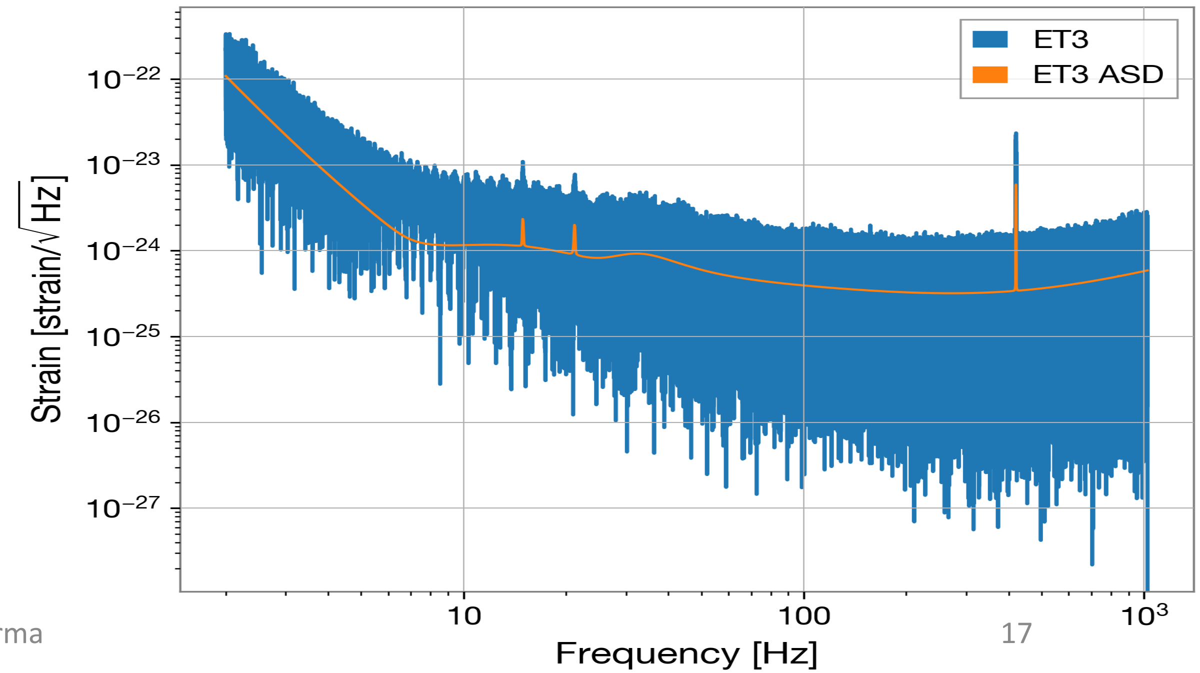
CE
CE ASD
Strain [strain/√Hz]
Frequency [Hz]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10
100
10^{3}



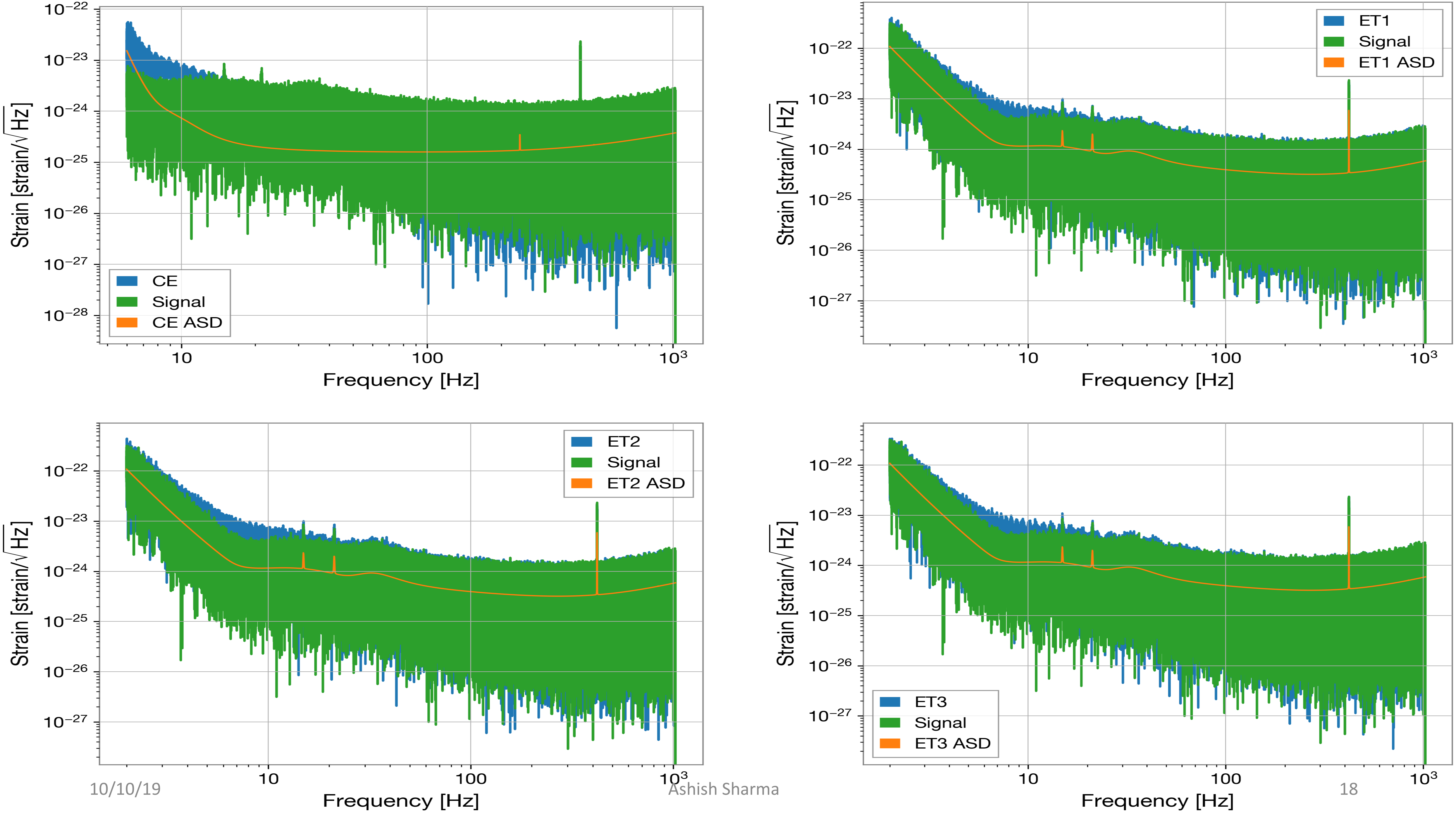
ET1
ET1 ASD
Strain [strain/√Hz]
Frequency [Hz]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10
100
10^{3}

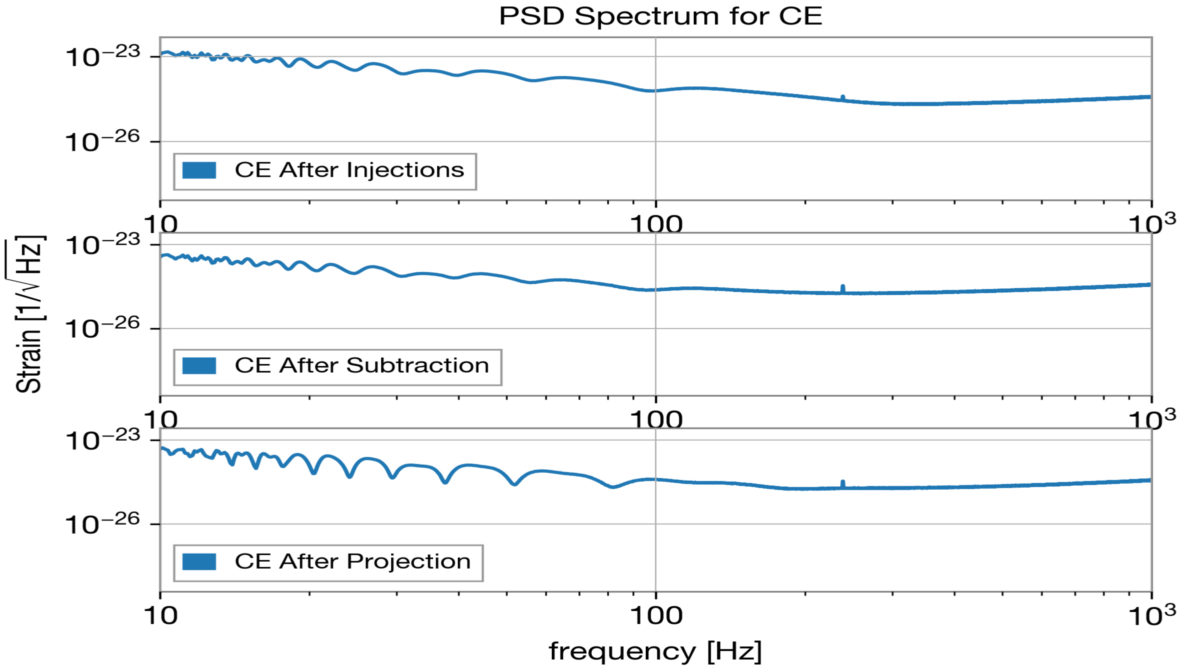


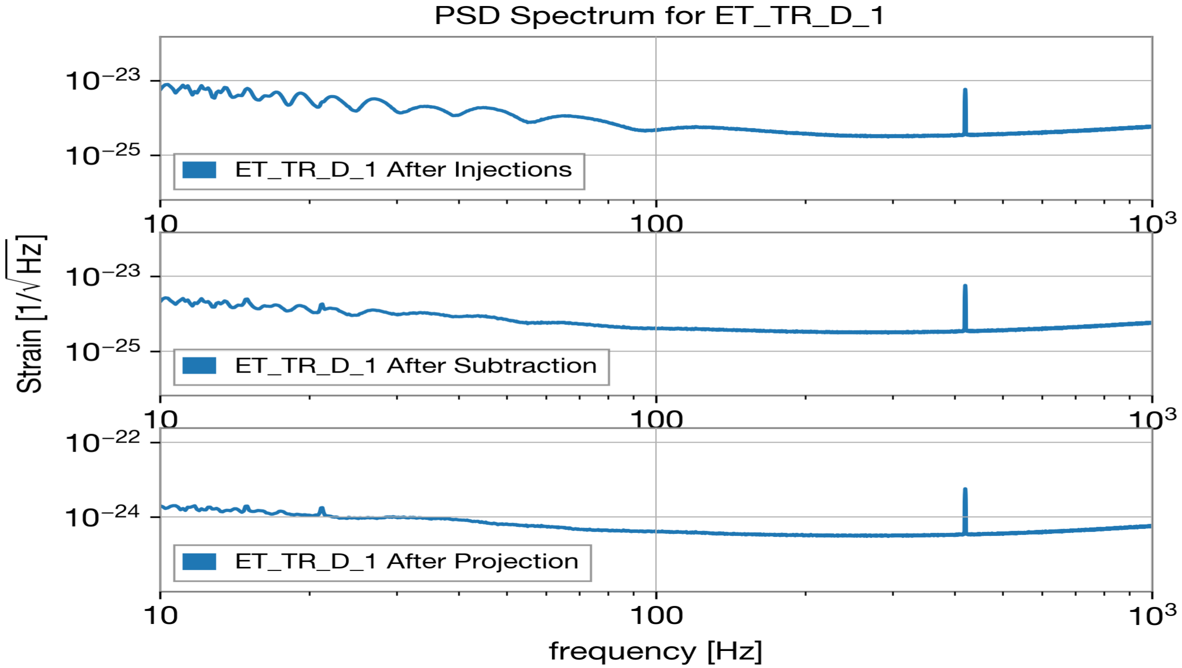
ET2
ET2 ASD
Strain [strain/√Hz]
Frequency [Hz]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10
100
10^{3}

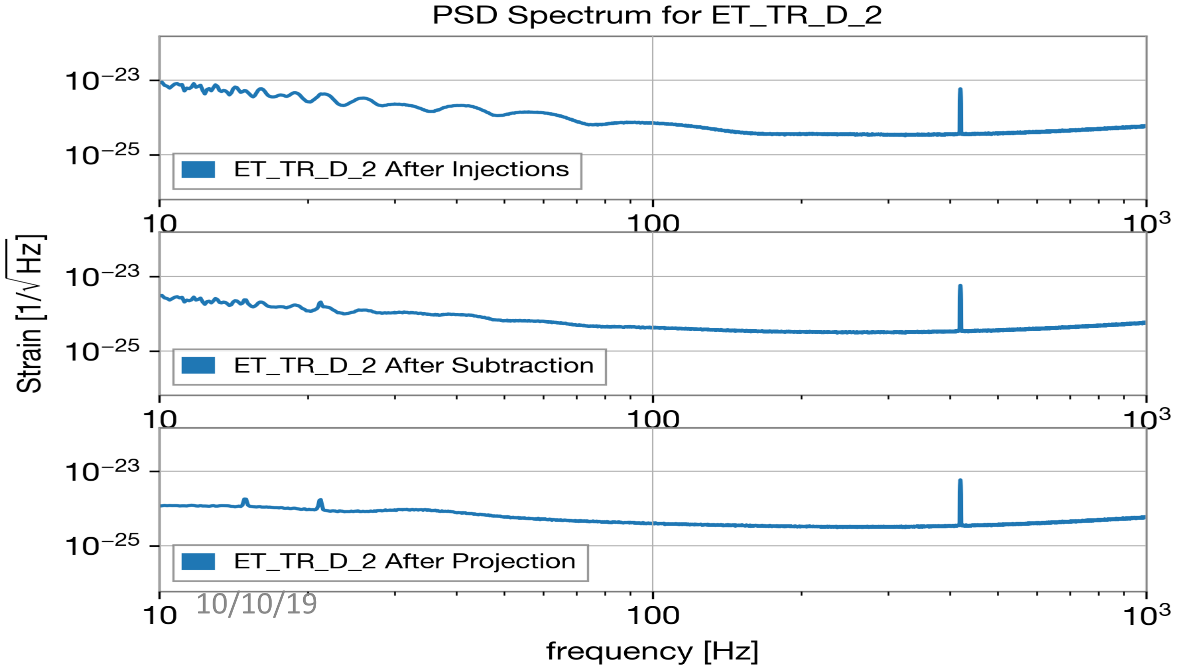


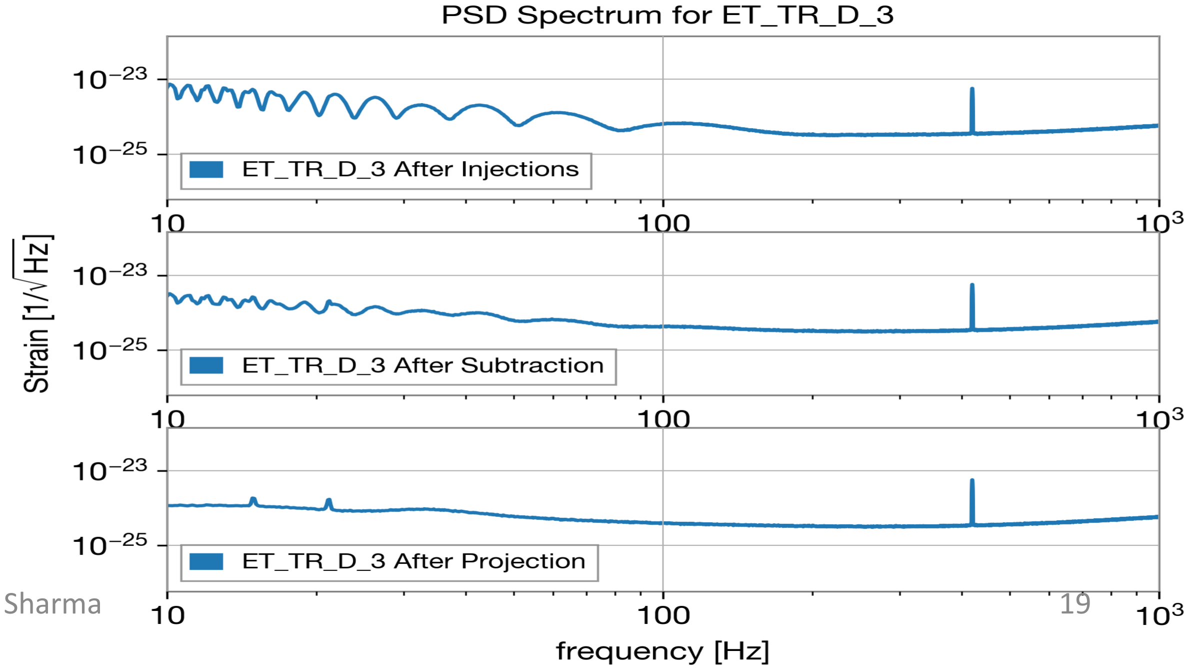
ET3
ET3 ASD
Strain [strain/√Hz]
Frequency [Hz]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10
100
10^{3}

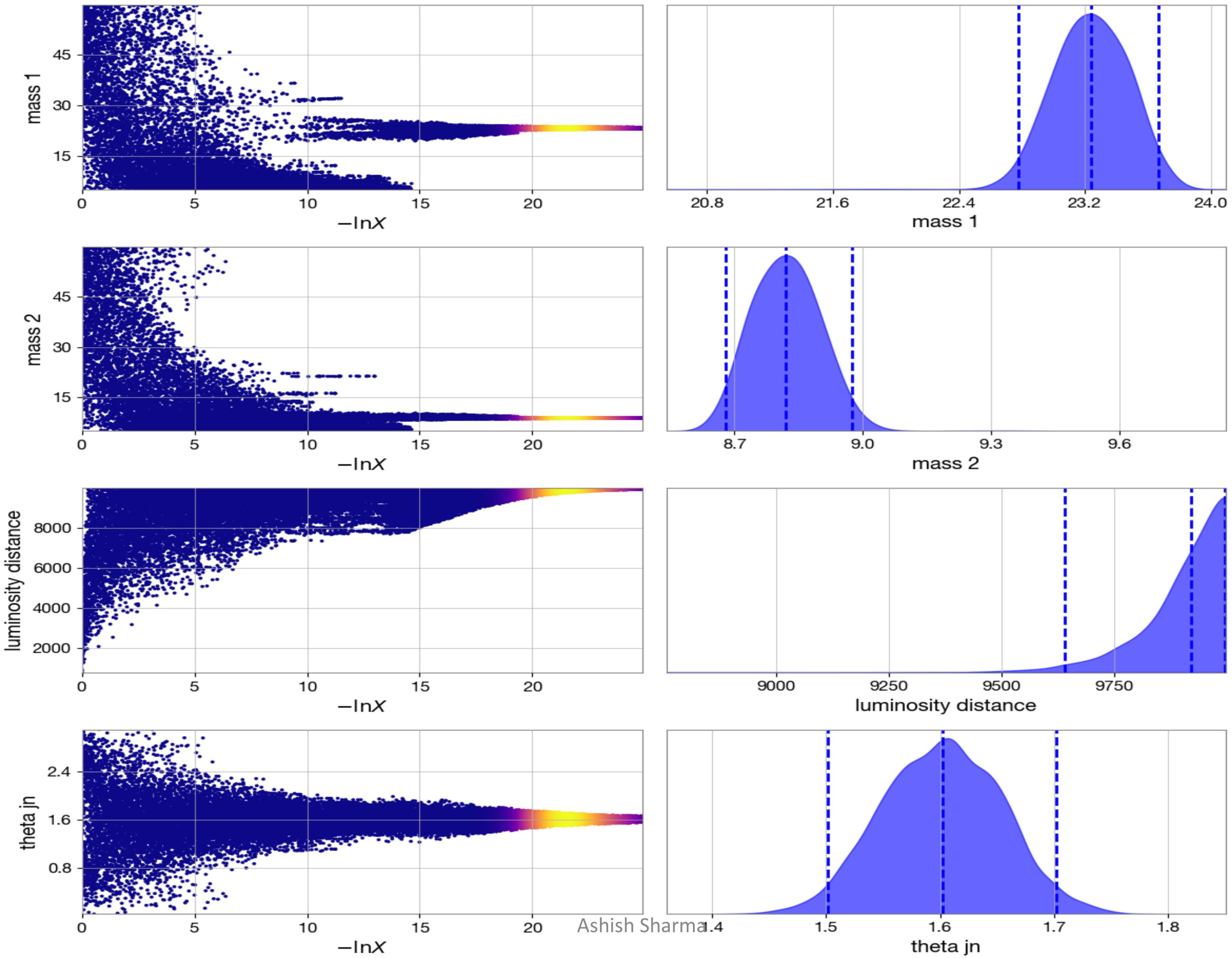

CE
Signal
CE ASD
ET1
Signal
ET1 ASD
ET2
Signal
ET2 ASD
ET3
Signal
ET3 ASD
Strain [strain/√Hz]
Frequency [Hz]
10
100
10^3
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}


PSD Spectrum for CE
CE After Injections
CE After Subtraction
CE After Projection
Strain [1/√Hz]
frequency [Hz]


PSD Spectrum for ET_TR_D_1
ET_TR_D_1 After Injections
ET_TR_D_1 After Subtraction
ET_TR_D_1 After Projection
Strain [1/√Hz]
frequency [Hz]


PSD Spectrum for ET_TR_D_2
ET_TR_D_2 After Injections
ET_TR_D_2 After Subtraction
ET_TR_D_2 After Projection
Strain [1/√Hz]
frequency [Hz]


PSD Spectrum for ET_TR_D_3
ET_TR_D_3 After Injections
ET_TR_D_3 After Subtraction
ET_TR_D_3 After Projection
Strain [1/√Hz]
frequency [Hz]



mass 1
45
30
15
0
5
10
15
20
−lnX
20.8
21.6
22.4
23.2
24.0
mass 1
mass 2
45
30
15
−lnX
8.7
9.0
9.3
9.6
mass 2
luminosity distance
8000
6000
4000
2000
−lnX
9000
9250
9500
9750
luminosity distance
theta jn
2.4
1.6
0.8
−lnX
1.4
1.5
1.6
1.7
1.8
theta jn