Title: Astrophysically Motivated Metrics for Designing the Next Generation of Gravitational-Wave Interferometers

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Abstract:

Gravitational Wave Telescopes: Some Cosmological Considerations

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Astrophysically motivated metrics for designing the next generation of gravitational-wave interferometers

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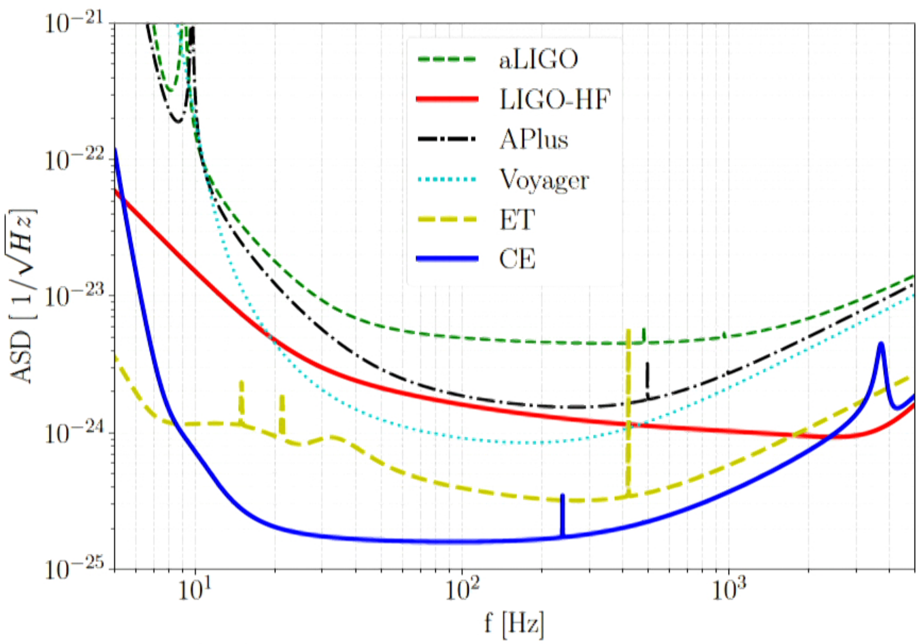
Outline

Motivation

- The design of 3G detectors is still to be determined.
- How much do we gain/loose from different designs?
- We propose astrophysically-motivated metrics to design interferometers

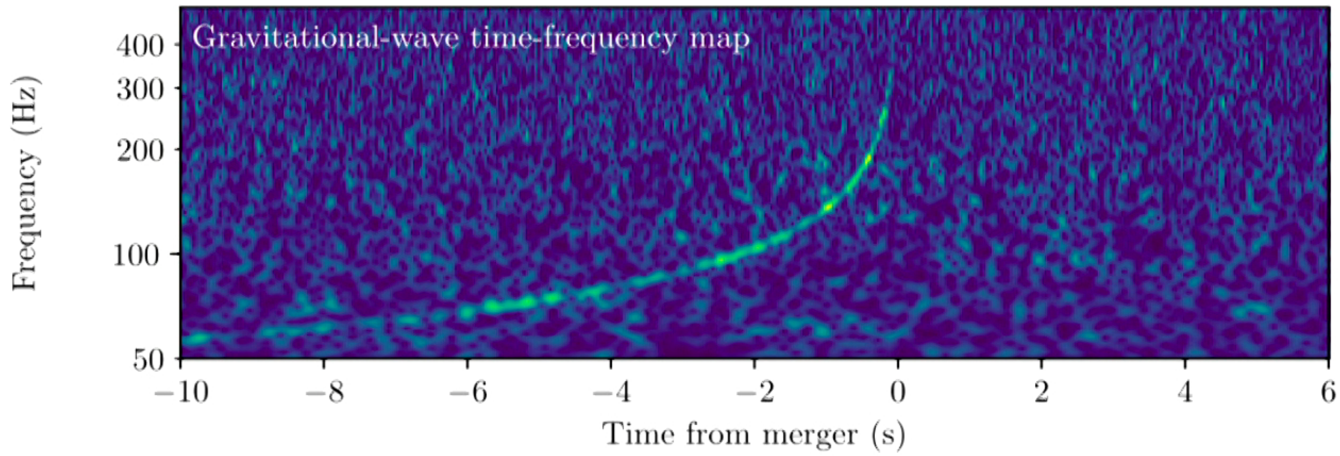


Outline

1. Motivation
2. Metrics
   - Neutron Star Science
     - Tidal Deformabilities
     - Post merger remnants metrics
     - Tidal Disruption
   - Cosmology
   - BBH and BNS detection
   - Gravitational wave background
3. Conclusions and future work

Neutron Stars

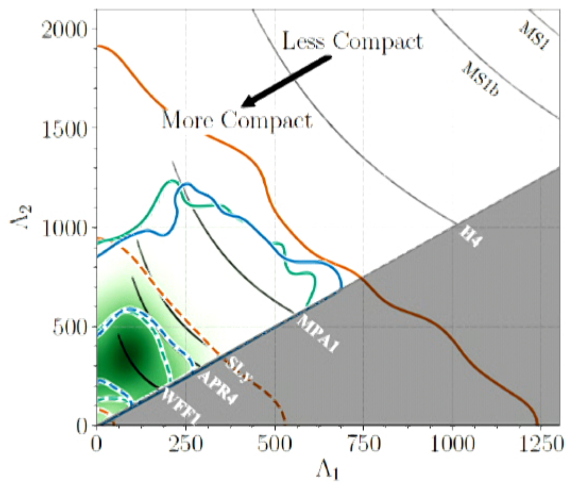
- NS are ideal objects to study matter under extreme conditions
- The way matter behaves is given by the equation of state (EoS)



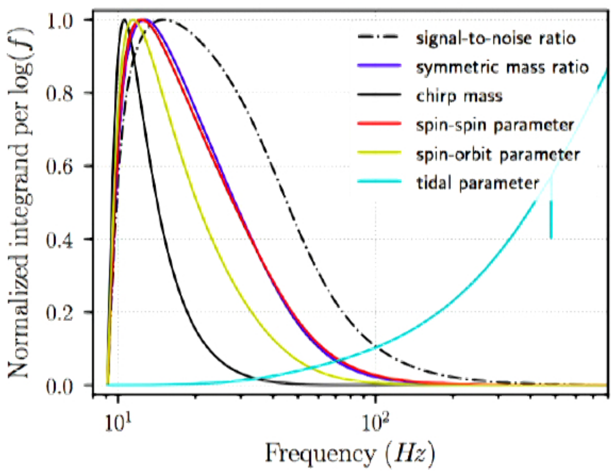
GW170817, Abbot *et al.* (2017)

Tidal Deformabilities

- The EoS can be measured during a BNS inspiral.
- The tidal deformability $\Lambda \propto R^5/M^5$



Abbot *et al.* (2018)



Harry and Hinderer (2018)

Metric

Calculate the error in $\tilde{\Lambda}$ using a Fisher Matrix analysis.

Fisher matrix

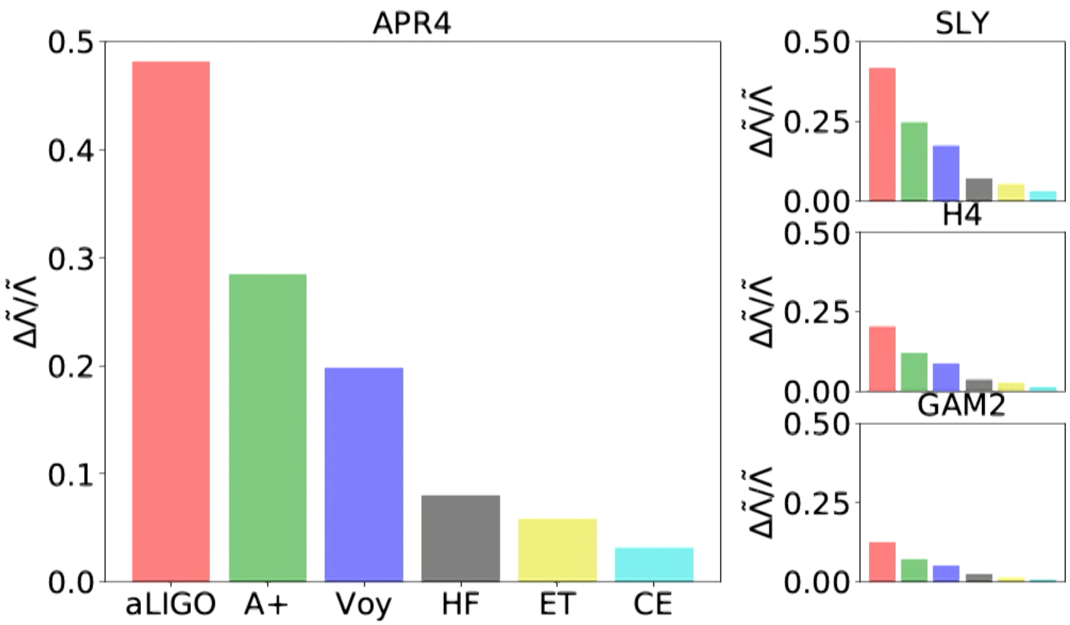
- For high SNR, the best-fit parameters will have a Gaussian distribution centered around true values $\vec{\theta}$

$$p(\Delta\theta) = p^{(0)} e^{-\Gamma_{ab}\Delta\theta^a \Delta\theta^b} \qquad (1)$$

- Γ_{ab} is the Fisher information matrix.
- The variance-covariance matrix is given by $\Sigma_{ab} = \Gamma_{ab}^{-1}$
- The errors in a parameter θ_a are caclulated by $\sigma_a = \sqrt{\Sigma_{aa}}$

Results

- Errors in the tidal deformability $\Delta\tilde{\Lambda}/\tilde{\Lambda}$ for a BNS
- Mass: $1.35M_{\odot} - 1.35M_{\odot}$, Distance: 50 Mpc
- Parameters: $\vec{\theta} = (\mathcal{M}, \eta, \tilde{\Lambda}, t_c, \phi_c, \mathcal{A})$



Post-merger remnants

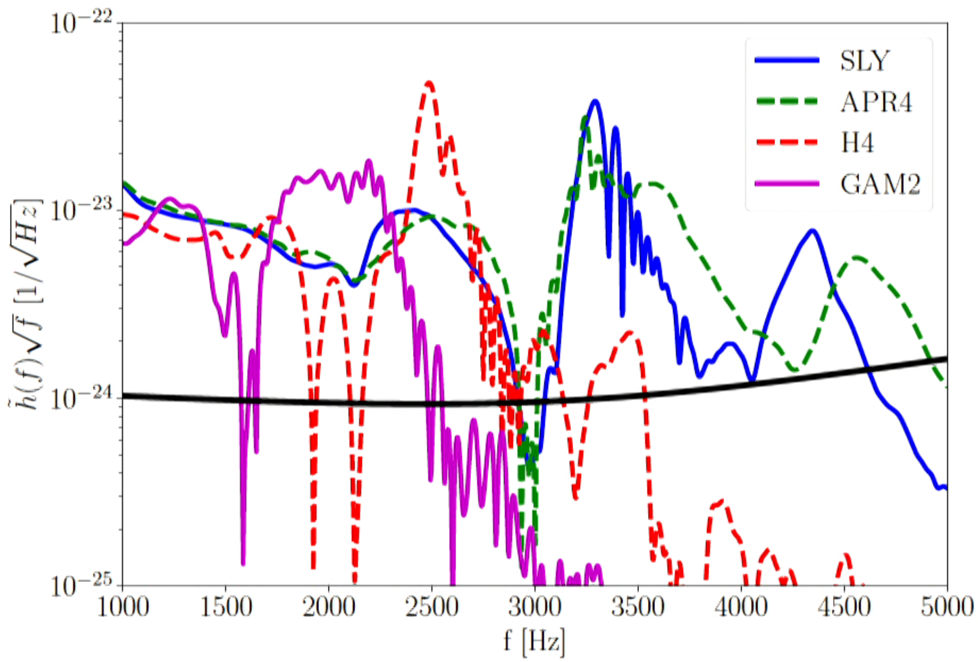
- Quantify our ability to detect NS post-merger remnants
- To detect post-merger remnants, good sensitivity at high frequency is required.

Metric

- How well different designs can detect post-merger remnants
- How well we can distinguish between different EoS?

EoS used

- We take 4 EoS from Takami *et al.* (2014)
- Mass: $1.35M_{\odot} - 1.35M_{\odot}$, Distance: 50 Mpc
- GW170817 favors compact EoS (softer EoS).



Method

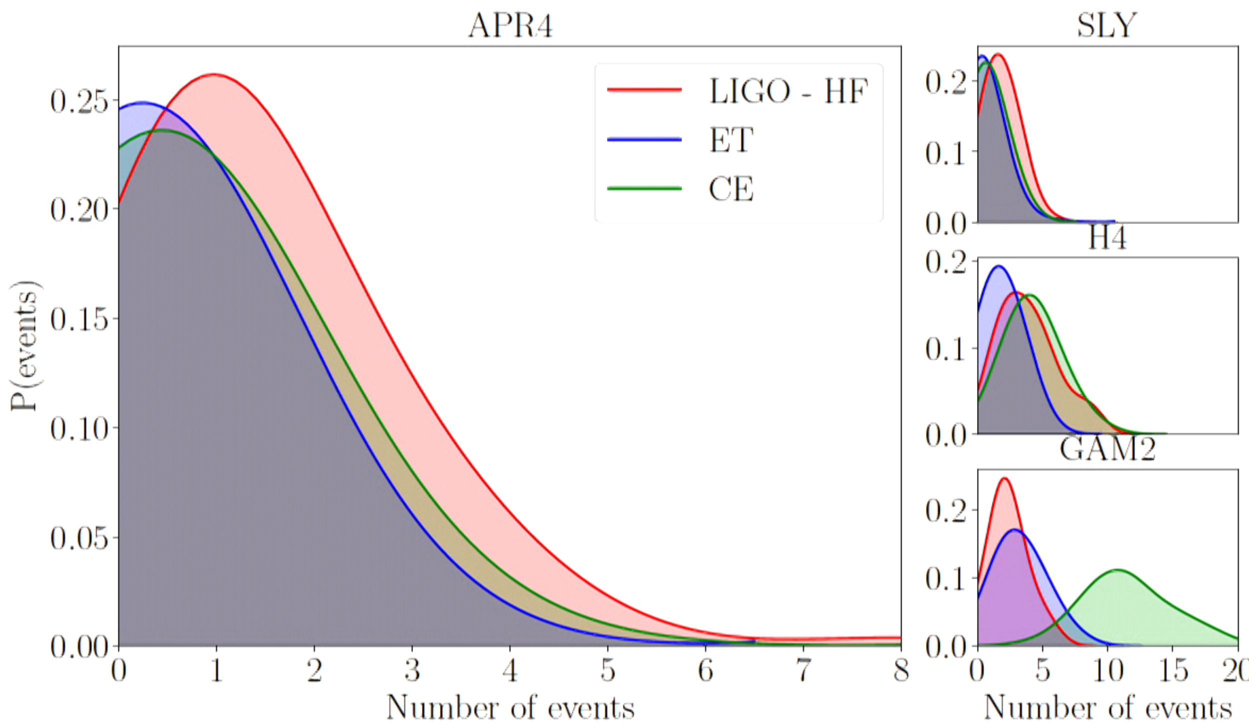
- Perform 100 Monte-Carlo post-merger simulations
- Mass: $1.35M_{\odot} - 1.35M_{\odot}$, Merger rate: of 1540 $\text{Gpc}^{-3}\text{yr}^{-1}$
- A signal is considered to be detected if SNR$\geq$5

Merger rate

The number of detected events depend directly in the merger rate used, therefore our results are bound to change as newer estimates come out.

Results

- Number of detected events after one year of observation



Model Comparison

- How well 3G detectors will distinguish between different EoS?
- We use a Bayesian model selection analysis

Bayes Factor

$$B = \frac{Z_1}{Z_2} \quad (2)$$

- Z is the Bayesian evidence

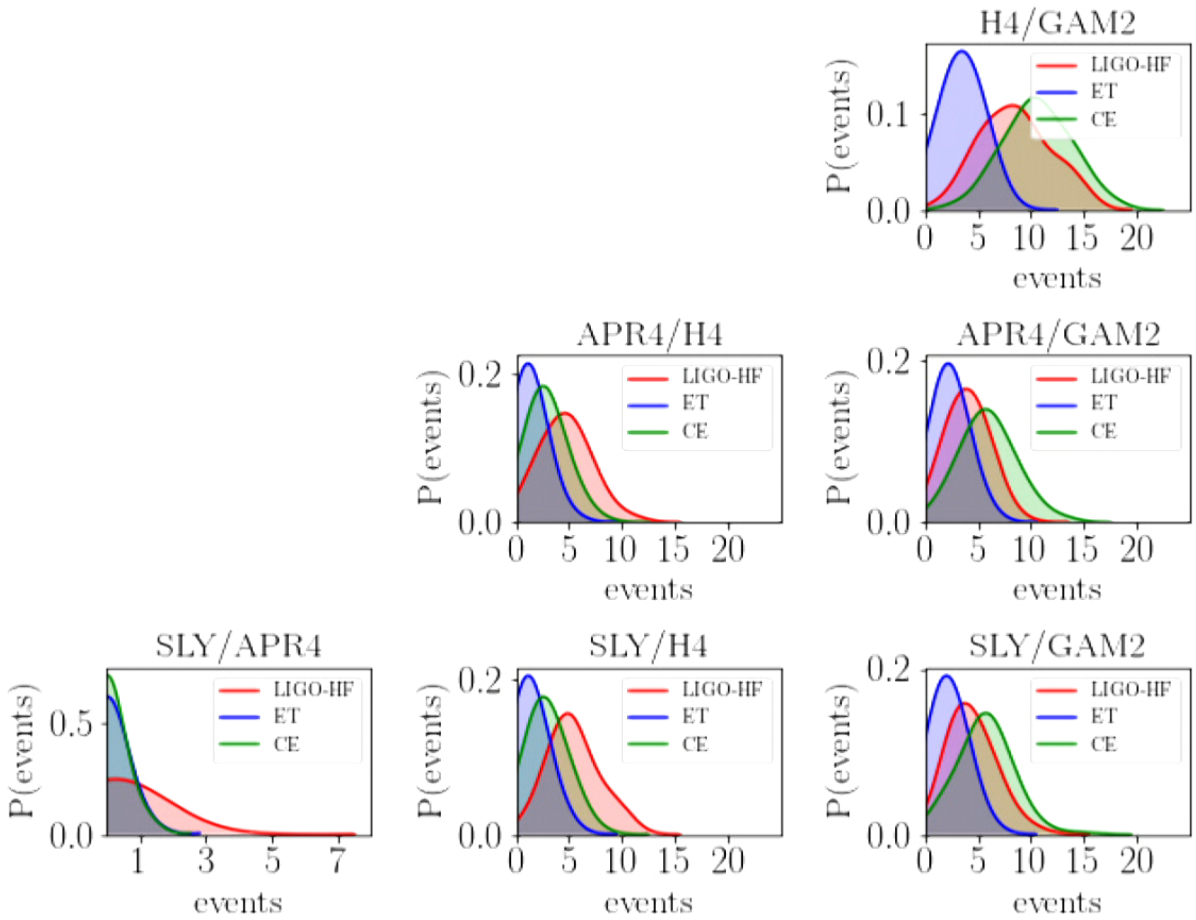
$$Z = \int d\vec{\theta}\, L(\vec{d}|\vec{\theta}, \mathcal{H}_s)\, \pi(\vec{\theta}_{EoS}) \quad (3)$$

- $L(\vec{d}|\vec{\theta})$ is the likelihood probability function and $\pi(\vec{\theta}_{EoS})$ is the prior probability function

Model Comparison

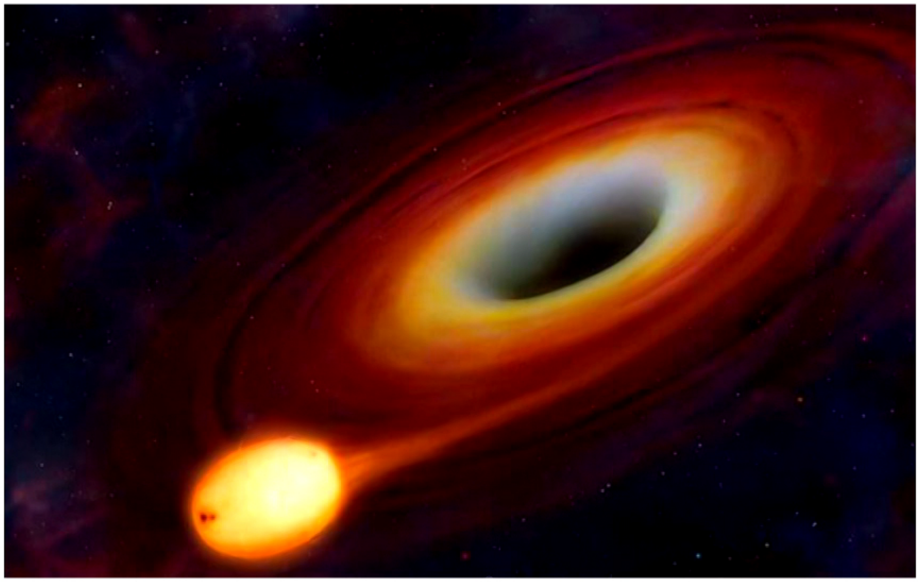
- Determine how many post-mergers will be distinguishable
- Two EoS can be distinguished if $\log B > 8$.

Model comparison distributions



Tidal Disruption

- Shibata *et al.* (2009) showed that 3 different types of waveforms could be distinguished when analyzing NSBH systems.



NSBH systems

- Type 1: Low mass BH , tidal disruption occurs during the inspiral
- Type 2: Tidal disruption occurs inside ISCO
- Type 3: Higher mass BH, similar behavior to a BBH

Metric

Calculate the SNR of NSBH merger/post-merger

Results

- We use analytical NSBH fitted waveforms
- NSBH post-merger, EoS: $\Gamma = 2$ (GAM2)
- Distance: 100 Mpc

Type	M_{BH}/M_{NS}	$\mathrm{SNR_{HF}}$	$\mathrm{SNR_{ET}}$	$\mathrm{SNR_{CE}}$
I	1.5	1.59	1.37	2.00
II	3	3.65	2.44	3.272
III	5	4.05	2.984	4.18

Cosmology

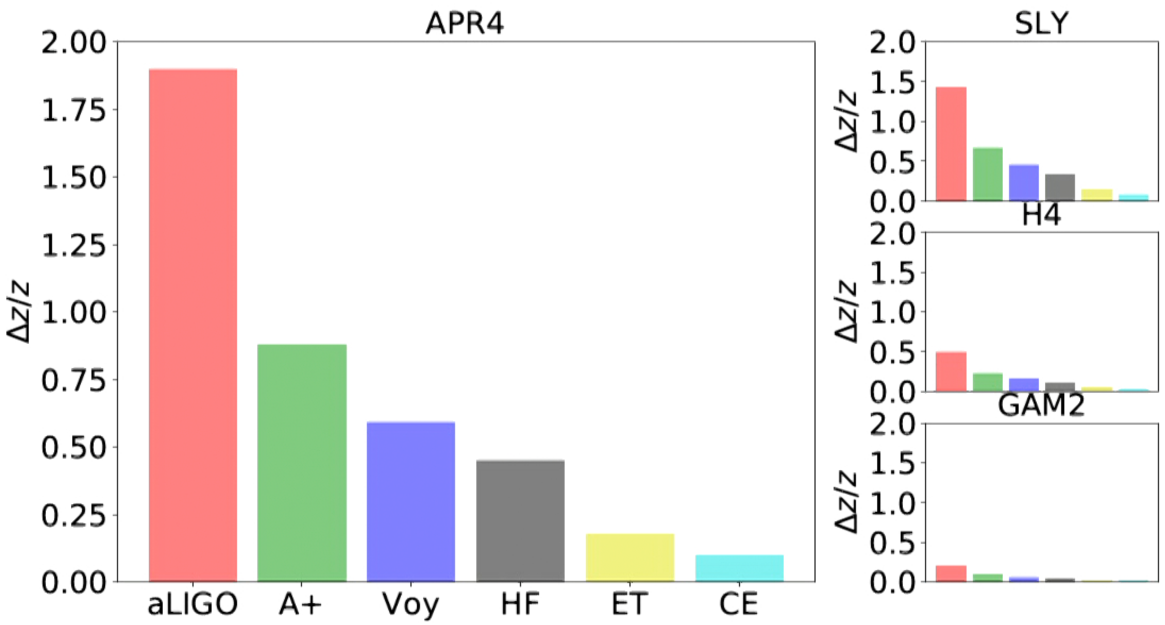
- If the EoS is known, it is possible to measure redshift z, Messenger and Read (2012)
- The tidal deformability Λ dependents on M_r
- M_z is known
- $M_z = (1+z)M_r$

Metric

Calculate the error in redshift $\Delta z/z$ using a Fisher matrix analysis

Results

- Mass: $1.35 M_\odot - 1.35 M_\odot$
- Optimally oriented source at $z = 0.01$
- Parameters: $\vec{\theta} = (\mathcal{M}, \eta, \mathcal{A}, z, t_c, \phi_c)$



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BBH and BNS detection rate

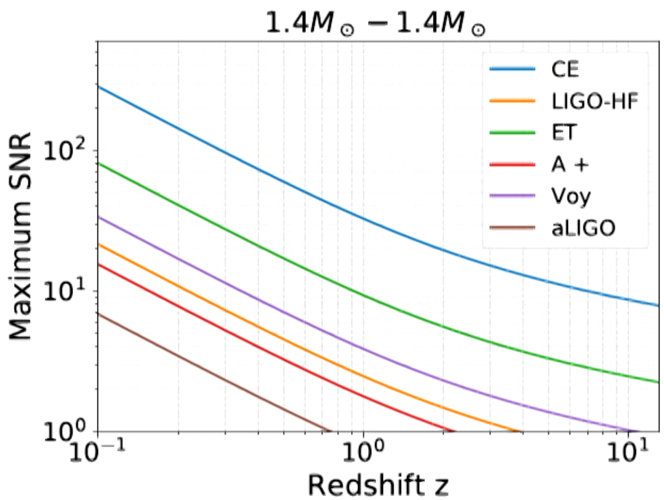
Metrics

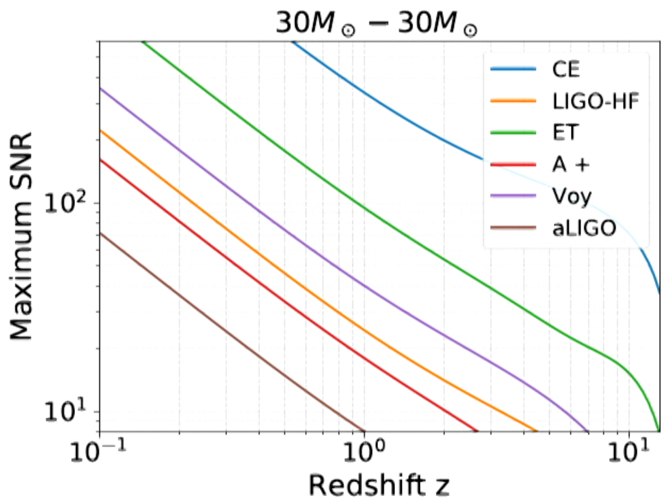
How many BBH and BNS events can different designs detect assuming non spinning binaries?

- Perform a Monte-Carlo simulation, events with SNR>8 are detectable
- Merger Rate: Use the star formation rate (SFR) as a proxy for the merger rate

SNR as a function of redshift

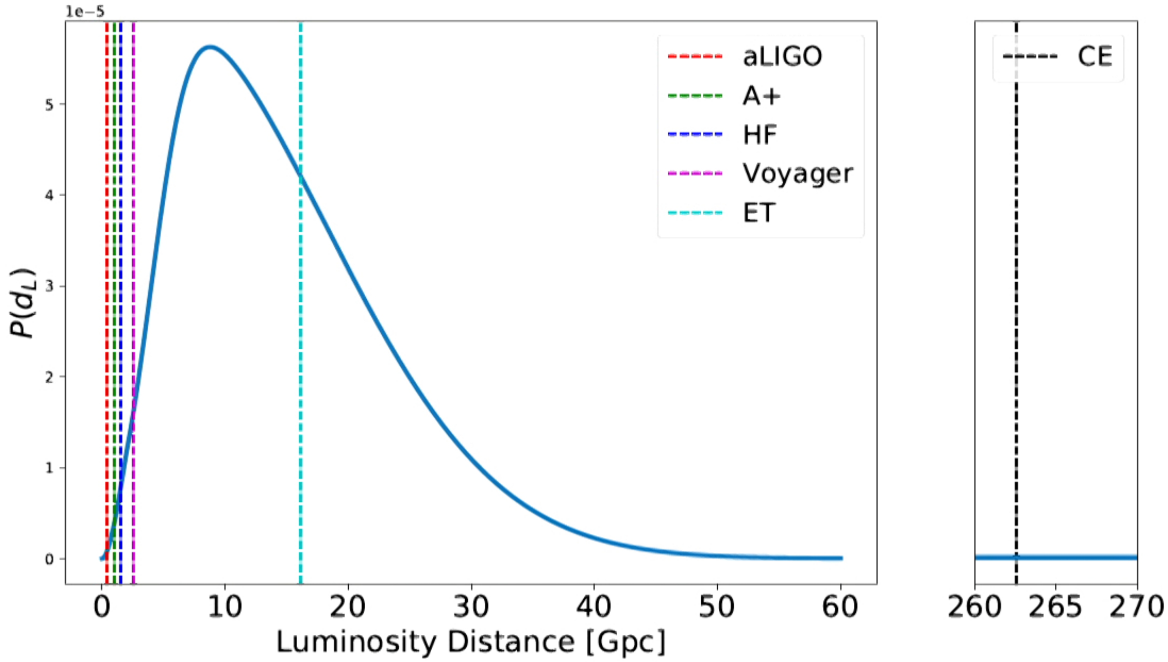
- Plots of the maximum SNR as a function of redshift for BBH and BNS systems





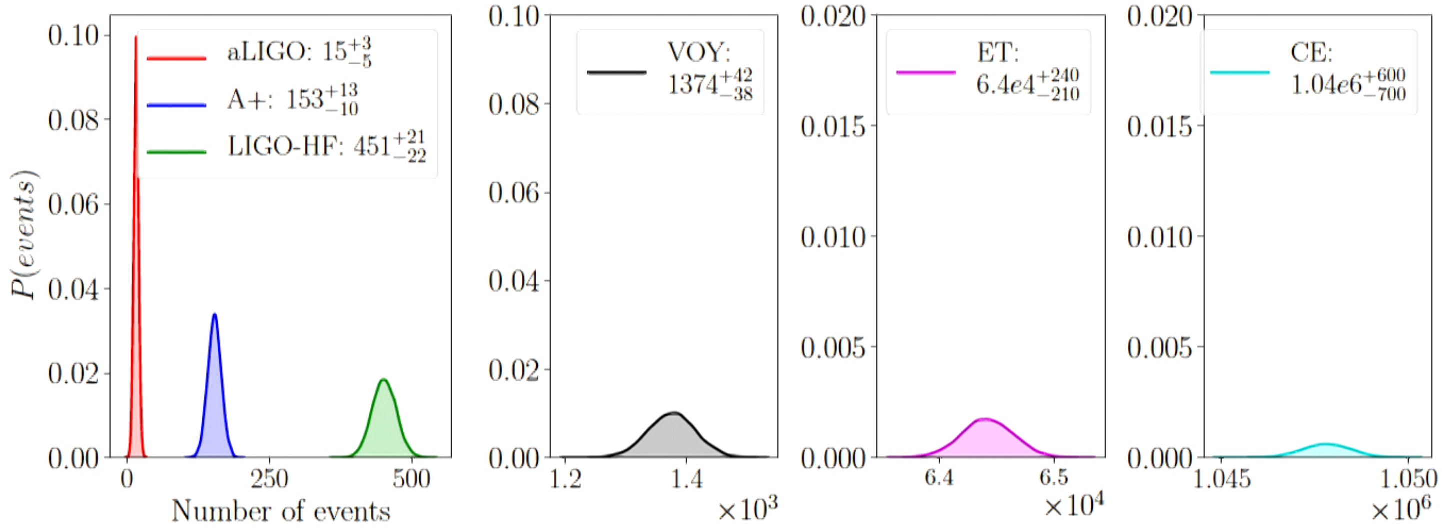
SFR probability distribution

- Plot of the SFR probability distribution
- Vertical dashed lines: Horizon distances for a $1.4M_\odot - 1.4M_\odot$ BNS.



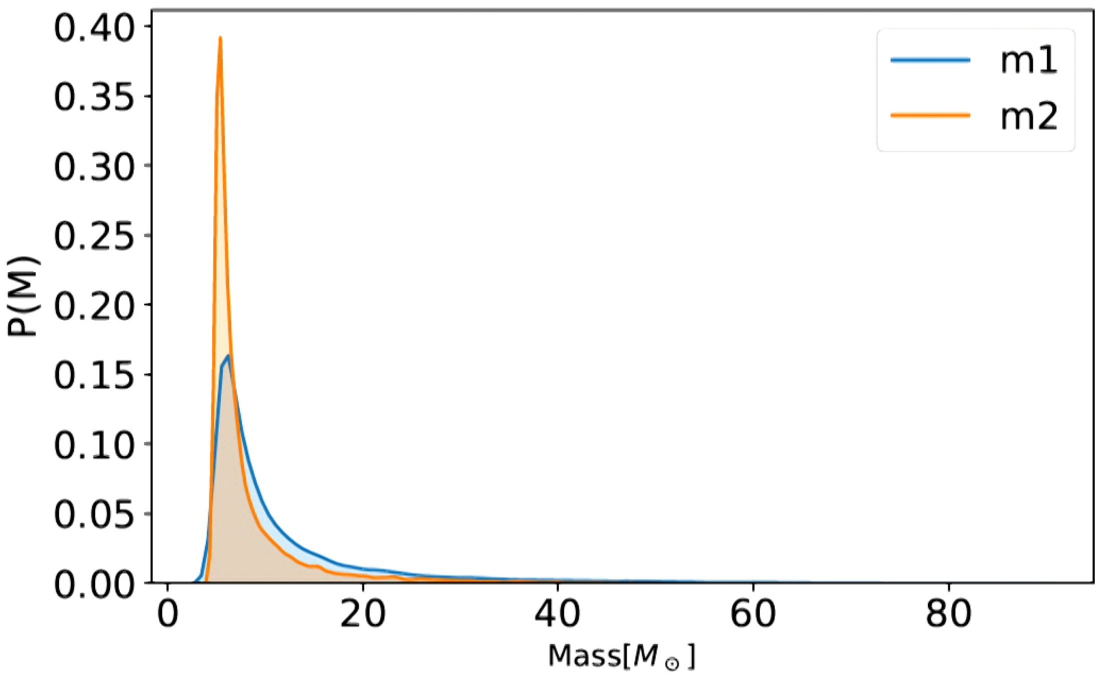
BNS Results

- Mass: $1.4M_\odot - 1.4M_\odot$
- Number of mergers: $\sim 2 \times 10^6$ BNS mergers in one year



BBH mass distribution

- We assume that BBH follow a power law distribution



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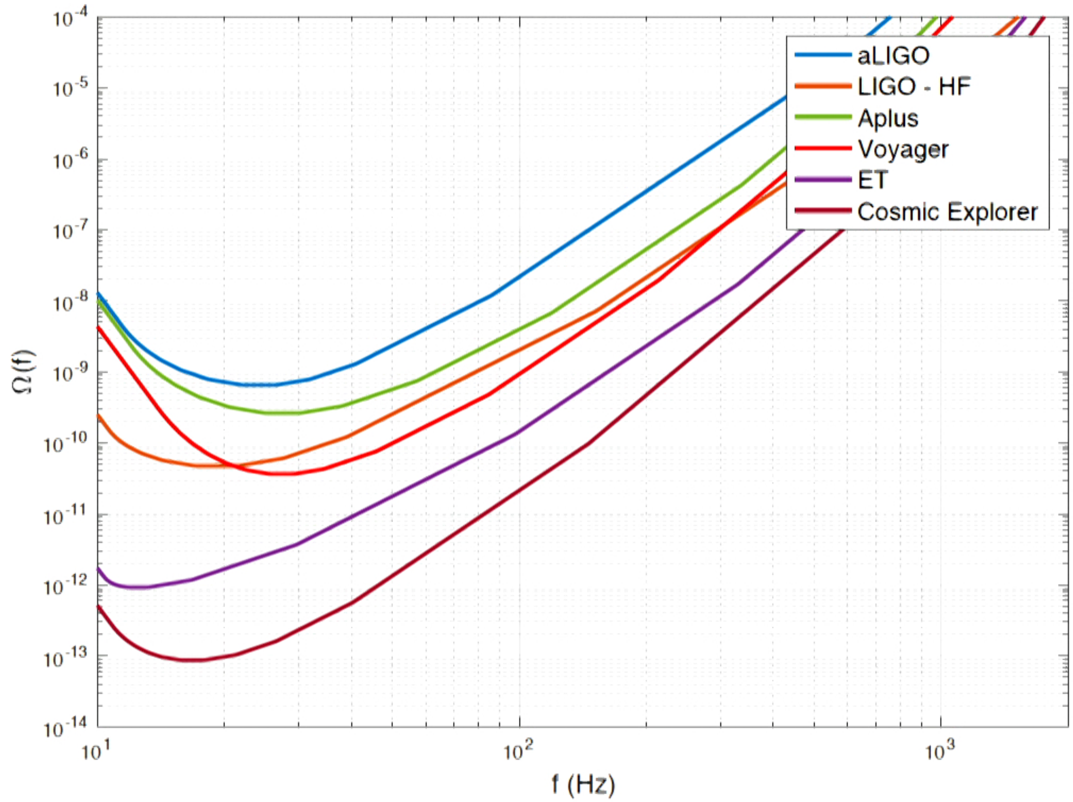
Gravitational wave background

- The stochastic gravitational wave background is searched by cross-correlating data from 2 interferometers, Thrane and Romano (2013)
- We locate 2 interferometers with the same characteristics at the current LIGO Hanford and Livingston facilities

Metric

Plot the fractional energy density of gravitational waves $\Omega_{gw}(f)$

Gravitational wave background



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Conclusions

Conclusions:

- We have presented astrophysically motivated metrics to compare gravitational wave detectors
- The metrics presented here could be used as starting point to design 3G detectors

Future work:

- Cosmology using post-merger remnants
- Arm length optimization