Title: Astrophysics and Cosmology with Gravitational-Wave Population Inference

Date: Jun 12, 2018 10:00 AM

URL: http://pirsa.org/18060051

Abstract:

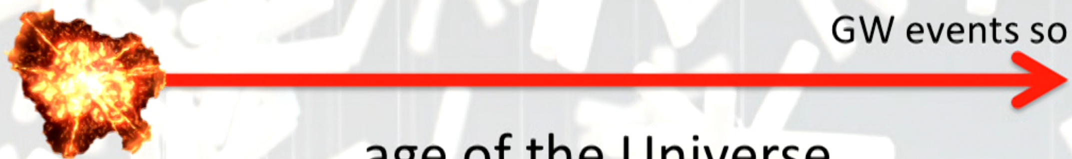
Outline

3. primordial backgrounds

2. unresolved binaries

1. ensembles of events

GW events so far



age of the Universe

4. sky localisation (requested by Denis)

3

Hundreds of mergers per day

- Every ~200s, a pair of black holes merge somewhere in the Universe.
- Every ~13s, a pair of neutron stars merge.
- This implies about
  - 140K BBH/year
  - 2.4M BNS/year
- Six published detections, design sensitivity rate: ~1/day.

Rates estimates uncertain to about ±50%.
B. P. Abbott et al., Phys. Rev. Lett. **120** 091101 (2018)

One versus many

- We will continue to highlight extreme events: the most massive, the most distant, the fastest spinning, etc.
- However, the focus is already shifting from individual events to populations.
- What can we learn from populations?

5

Part I: Population inference

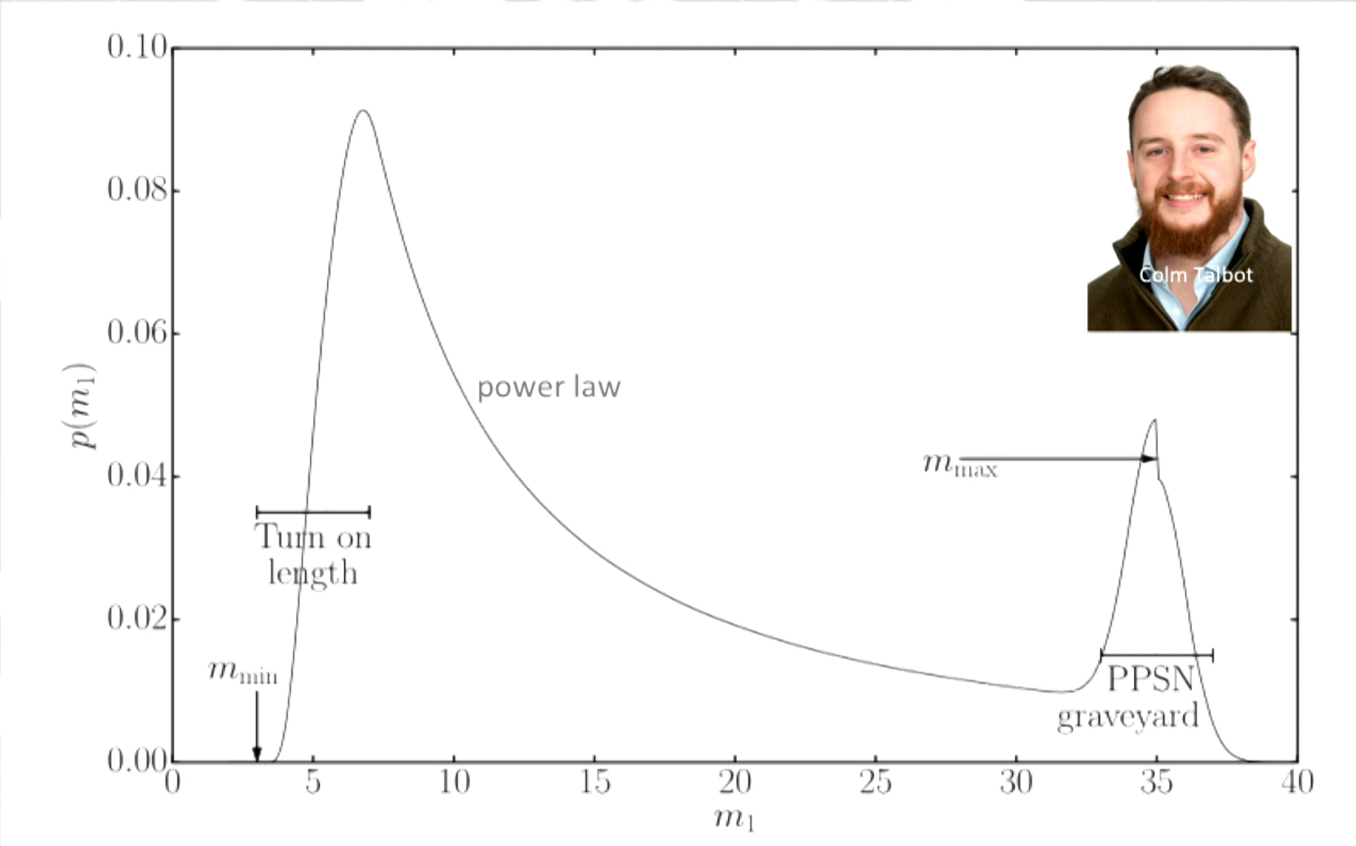
- **The formation mechanism of BBH** is imprinted on the distribution of spin and eccentricity.
- **Stacking BNS probes neutron star physics** including the equation of state, post-merger physics, and magnetic field decay.
- **Stacking BBH facilitates tests of GR** including measurement of memory, no-hair, area theorem.
- **Cosmology** including Hubble, lensing, and more.
- **Stellar physics** leaves an imprint on the mass and spin distribution of BBH.

Pair instability supernovae (PISN/PPSN)

- Massive stars (>80 $M_\odot$) become hot enough to produce e^+e^- pairs.
- The pressure drops, the star heats up, leading to a runaway effect.
- Above 130 $M_\odot$, the star is totally disrupted.
- For 80-130 $M_\odot$, tens of solar masses ejected.
- Prediction: cut-off in the black hole mass spectrum with a bump around 40 $M_\odot$.

Heger, A., & Woosley, S. E. 2002, ApJ **567** 532

BBH mass spectrum



C. Talbot & E. Thrane, ApJ **856** 173 (2018)

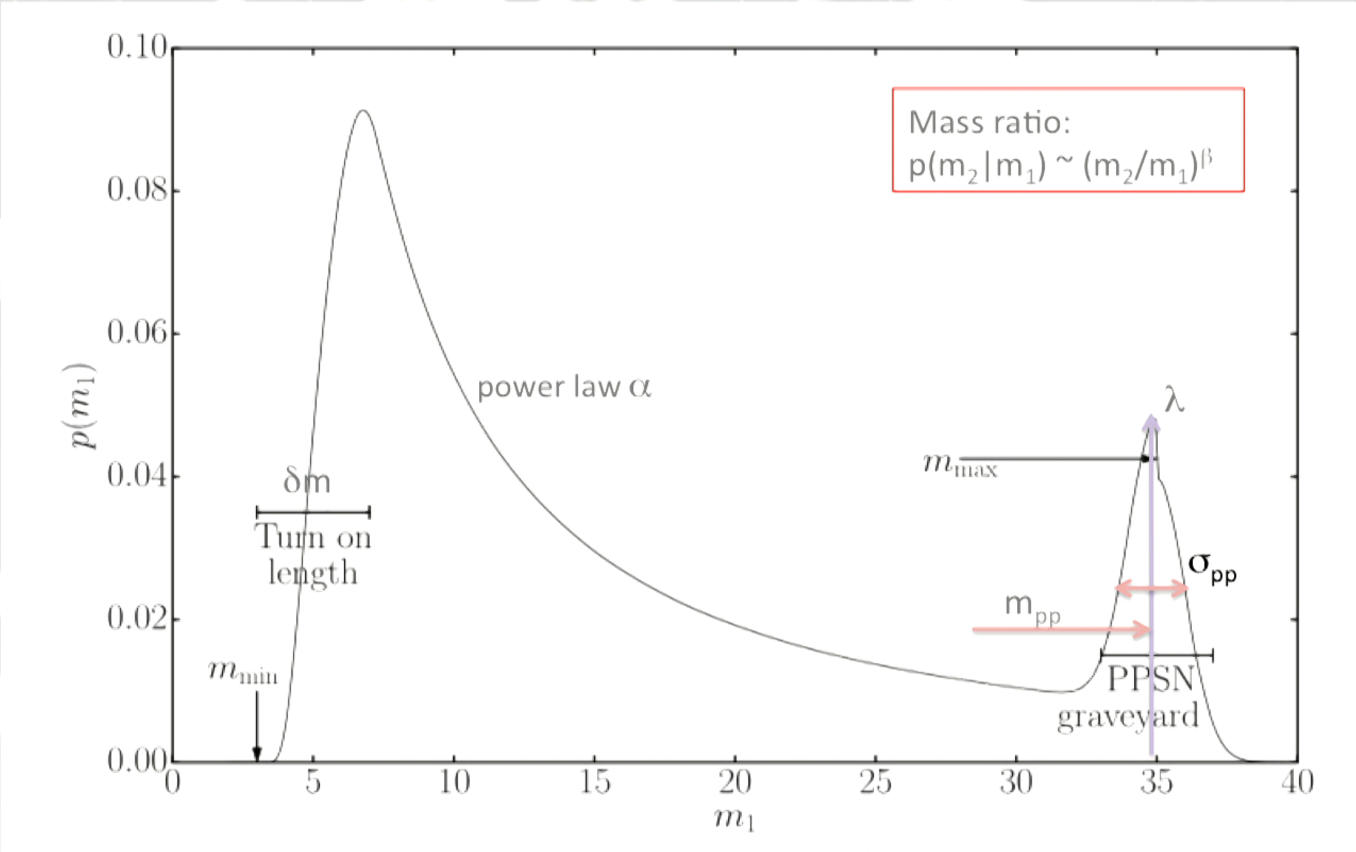
See also: Fishbach, M., & Holz, D. E. 2017, ApJL **851** L25

8

Measuring the PPSN peak

- In order to measure the PPSN peak, we parameterise the BBH mass spectrum.
- Parameters describing the population properties of BBH are called *hyper-parameters* versus parameters for individual BBH.
- Combining data from ensembles yields posterior distributions for the hyper-parameters describing the population.

BBH hyper-parameters



10

C. Talbot & E. Thrane, ApJ **856** 173 (2018)

Monte Carlo study: Observed versus astrophysical

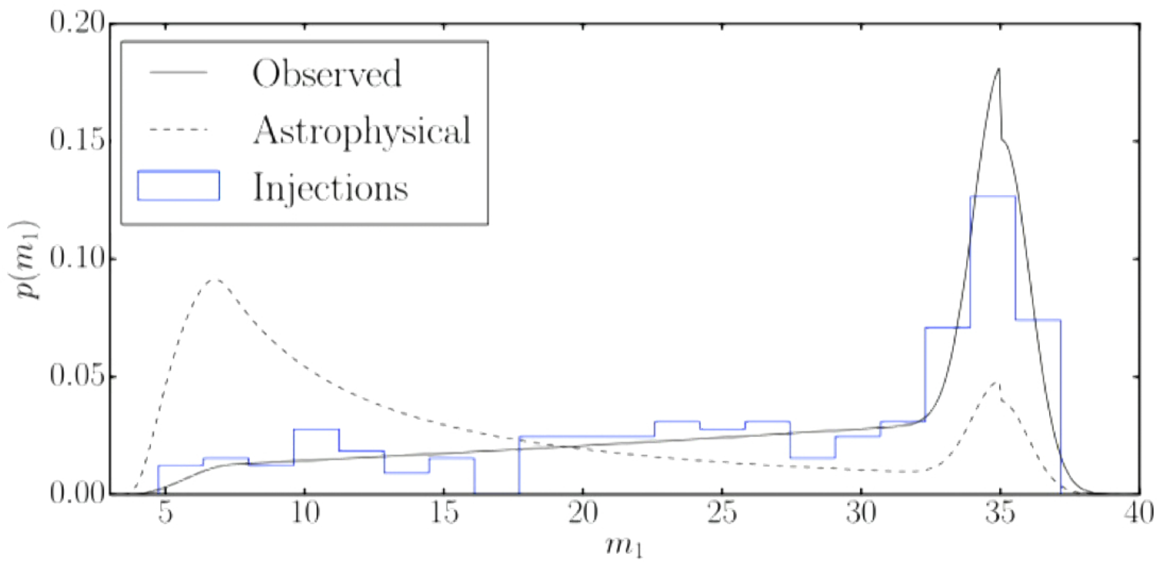


Figure 2. The distribution of source-frame primary mass and mass ratic ($q \equiv m_2/m_1$) for our simulated universe, see Table 2. The dashed and solic lines show the distribution before and after accounting for selection biases respectively. The blue histogram indicates the injected values.

C. Talbot & E. Thrane, ApJ **856** 173 (2018)

Measuring the PPSN remnant mass

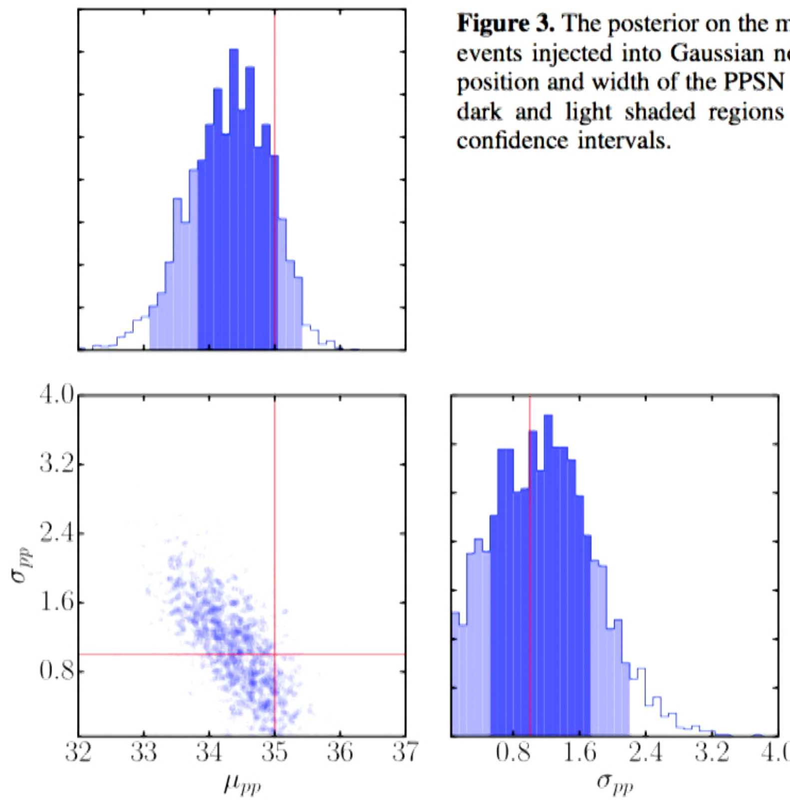


Figure 3. The posterior on the mean and width of the PPSN peak using our 200 events injected into Gaussian noise. After 200 detections we can measure the position and width of the PPSN peak to within $\sim$1 $M_\odot$ at 95% confidence. The dark and light shaded regions indicate the one-dimensional 68% and 95% confidence intervals.

I am skipping Bayesian details; ask if you're interested.

C. Talbot & E. Thrane, ApJ **856** 173 (2018)

What fraction of LIGO/Virgo detections come from PPSN BH?

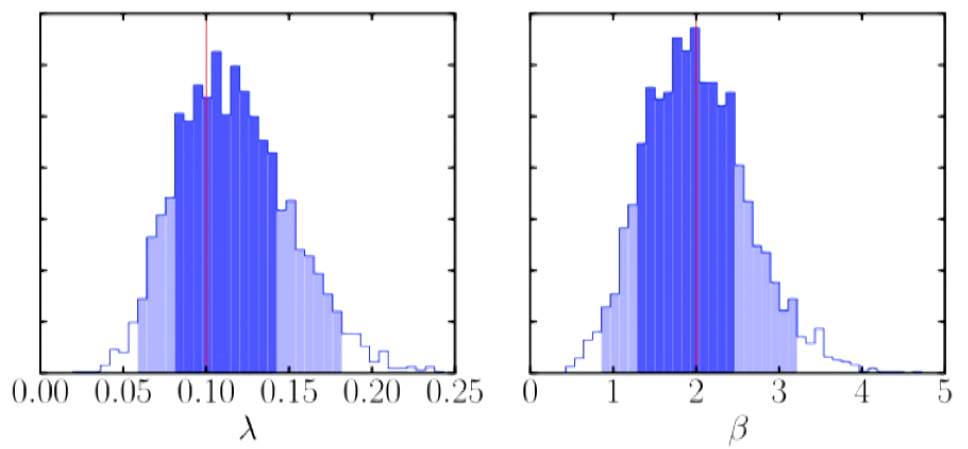


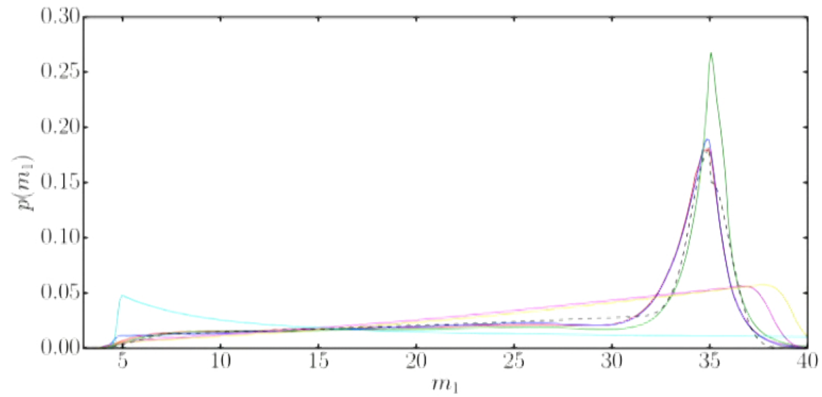
Figure 4. The posterior on the fraction of black holes formed through PPSNe and the power-law index on the mass ratio using our 200 events injected into Gaussian noise. We can measure the fraction of black holes formed through PPSNe to be $\lambda \sim 0.11^{+0.07}_{-0.04}$ at 95% confidence. We can determine the spectral index of the distribution of mass ratios to within ± 1 at 95% confidence with 200 detections.

13

C. Talbot & E. Thrane, ApJ **856** 173 (2018)

Reconstructed distribution

- The shape of the mass spectrum can be reconstructed with a posterior predictive distribution (PPD).



- Stay tuned for O2 LIGO-Virgo population paper.

C. Talbot & E. Thrane, ApJ **856** 173 (2018)

Part II: Astrophysical backgrounds

- All but the most ambitious detectors produce a population of unresolved binaries: the astrophysical background.
- Goal: probe high-redshift BBH that we cannot resolve individually
- Measure population properties of unresolved BBH
- Unified treatment of compact binary search + stochastic background search

R. Smith & E. Thrane, Phys. Rev. X **8** 021019 (2018)

Cross-correlation vs. optimal search

- Standard search: cross-correlate data from two detectors: $$\hat{\Omega}(f) \propto \sum_i \tilde{s}_1^*(f;t_i)\tilde{s}_2(f;t_i)$$
- Optimal for Gaussian backgrounds, but sub-optimal for non-Gaussian backgrounds.
  - How could it be?!
- What is the optimal search strategy for a background of BBH?

PhysRevD.59.102001

The optimal search

- Divide data from run into segments.
- Run parameter estimation (e.g., LAL INFERENCE) on each segment whether or not there is a CBC trigger associated with it.
- Calculate Bayesian evidence.
- Combine Bayesian evidences with generalised likelihood.
- Uses a lot of information: waveforms!

R. Smith & E. Thrane, Phys. Rev. X **8** 021019 (2018)

The algorithm

- Likelihood

number of segments

duty cycle

$$\mathfrak{L}^{\mathrm{tot}}(\{\vec{s}\}|\xi) = \prod_{i}^{n} \left(\xi\, \mathcal{Z}_S^i + (1-\xi)\mathcal{Z}_N^i\right).$$

noise evidence

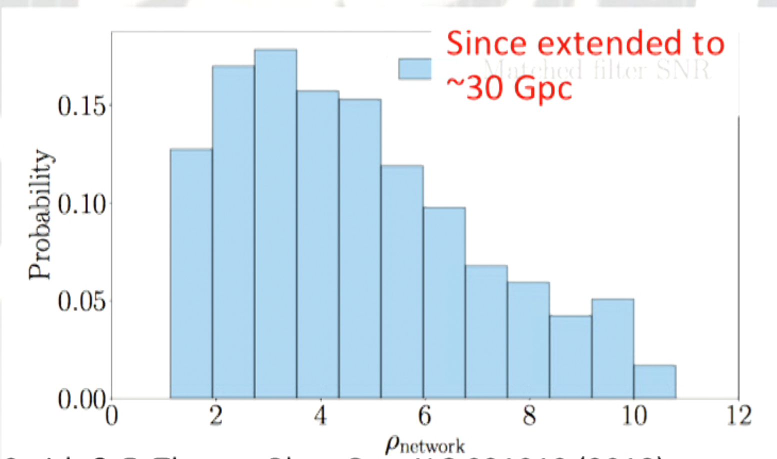
signal evidence

- Detection when ξ=0 is excluded at high confidence.
- From ξ, we obtain energy density Ω_{gw} and rate R.

R. Smith & E. Thrane, Phys. Rev. X **8** 021019 (2018)

Monte Carlo Demonstation

- Two datasets, each with ~300 4s segments.
- Gaussian noise dataset
- Gaussian noise + signal: add random BBH signal with ρ<12 from (0.5, 5) Gpc.

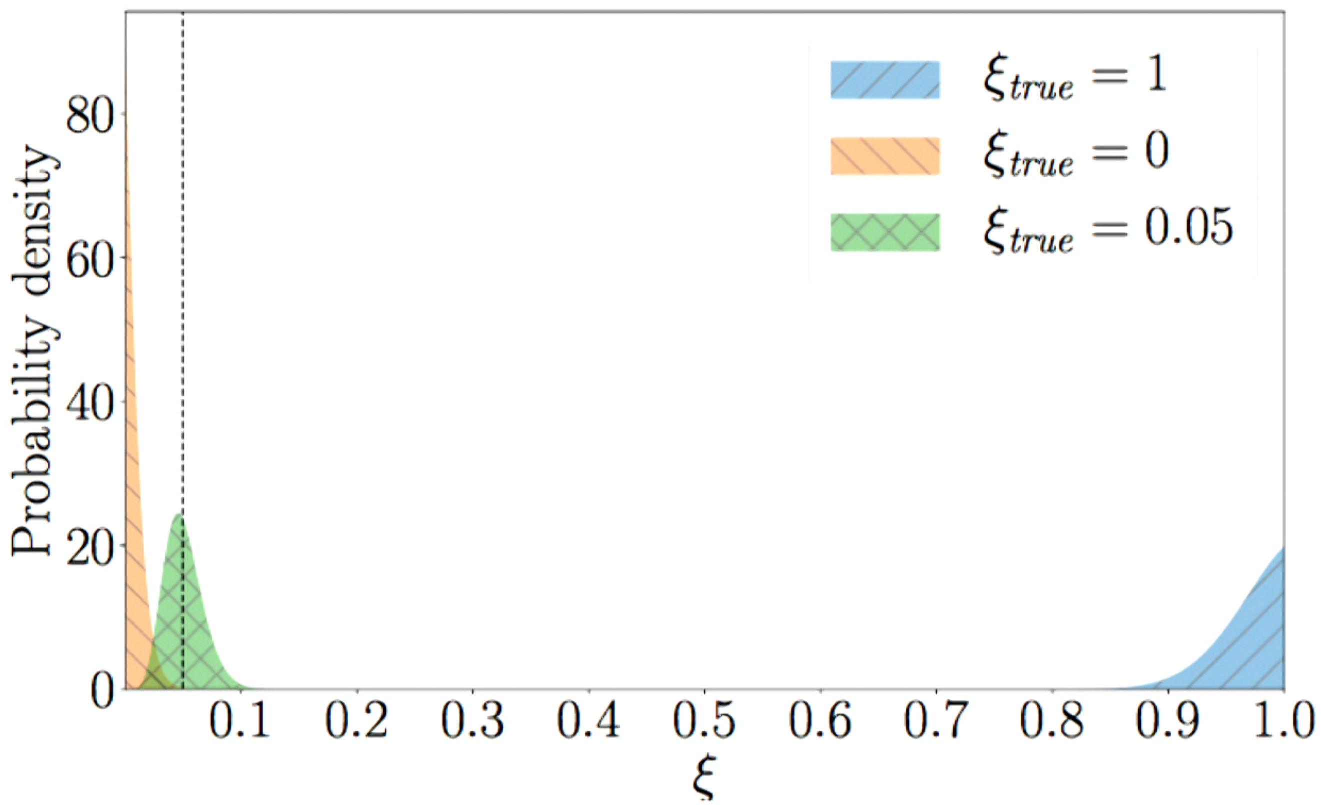


R. Smith & E. Thrane, Phys. Rev. X **8** 021019 (2018)

Other Details:

- Uniform in volume
- Total Mass: (48, 80) $M_\odot$
- Random angles
- IMRPhenomPv2
- Mass ratio: (1, 8)
- Spin: (0, 0.89)

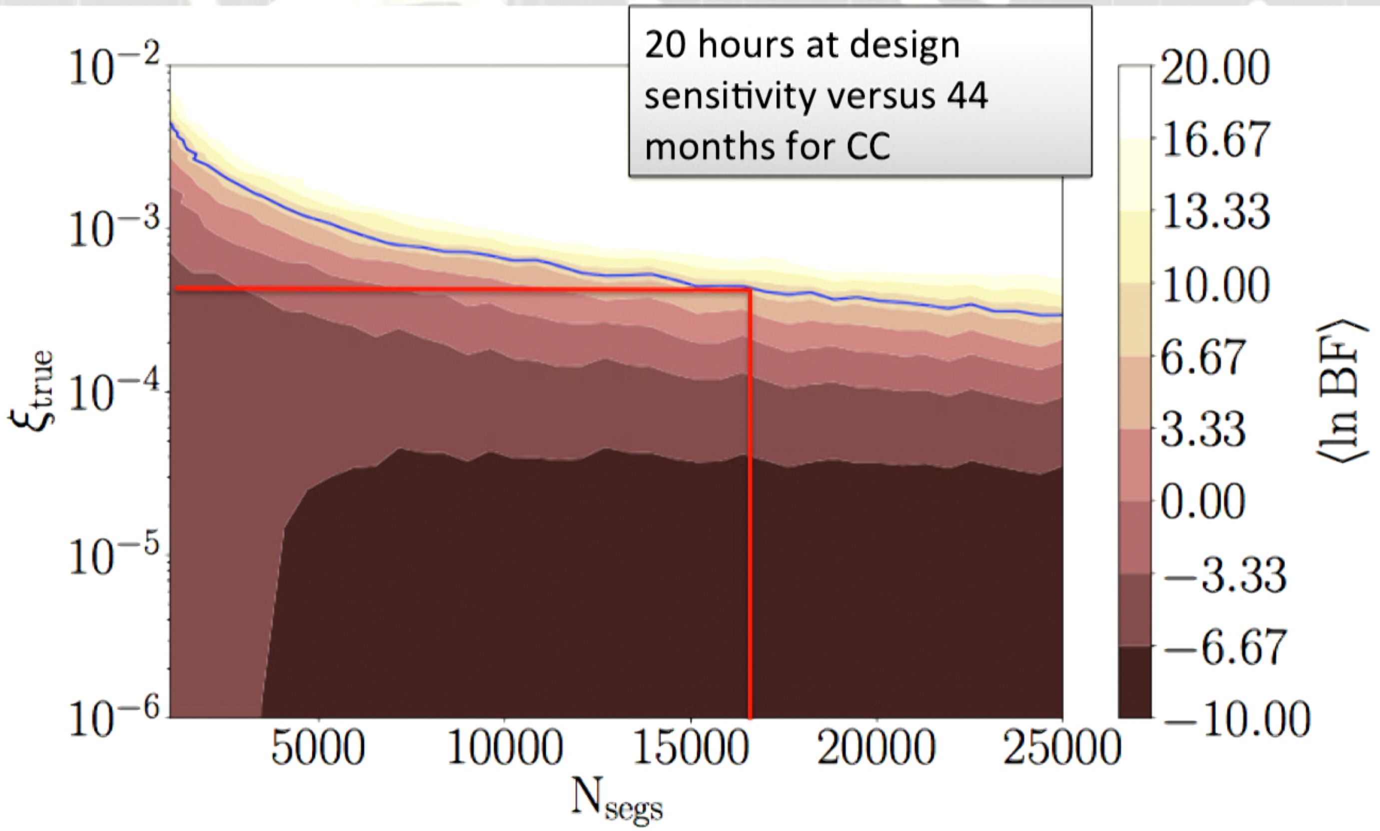
Safe, effective, unbiased



20

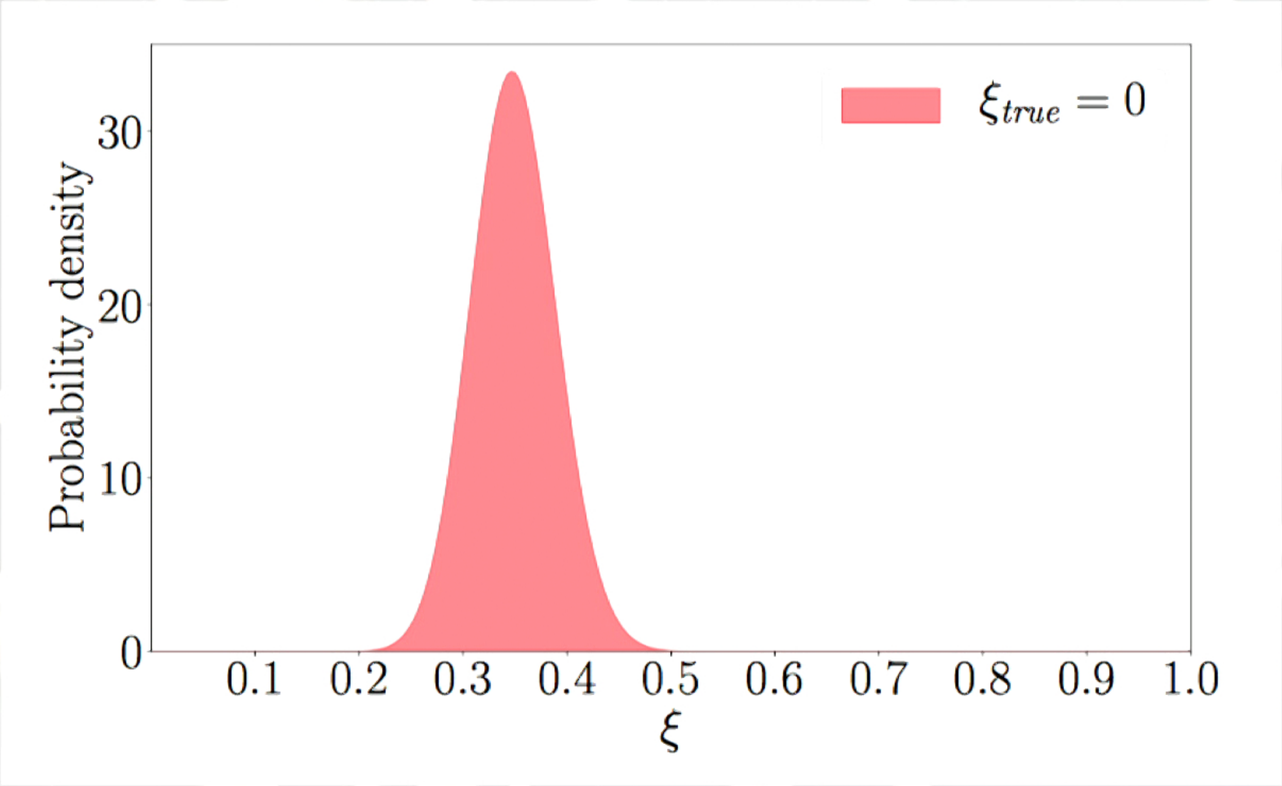
R. Smith & E. Thrane, Phys. Rev. X **8** 021019 (2018)

Time to detection



R. Smith & E. Thrane, Phys. Rev. X **8** 021019 (2018)

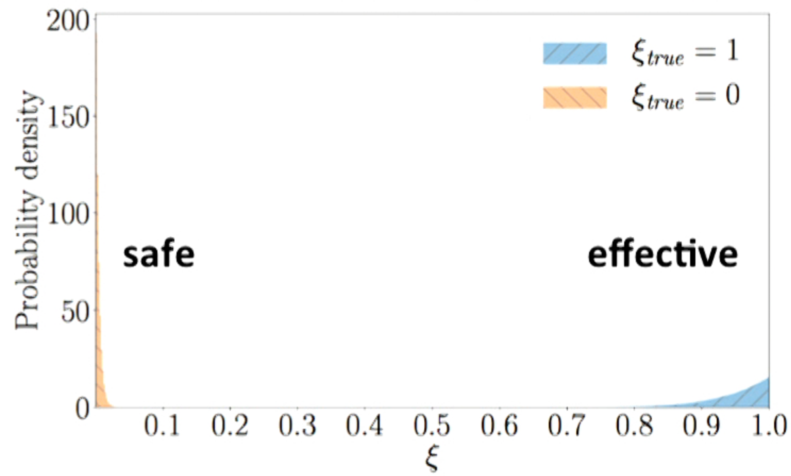
Glitches



R. Smith & E. Thrane, Phys. Rev. X **8** 021019 (2018)

Accounting for glitches

$$\begin{aligned}\mathfrak{L}(\vec{s}_i|\xi,\xi_g^{(1)},\xi_g^{(2)}) =& \xi\left(1-\xi_g^{(1)}\right)\left(1-\xi_g^{(2)}\right)\mathcal{Z}_S^i + \\ & (1-\xi)\left(1-\xi_g^{(1)}\right)\left(1-\xi_g^{(2)}\right)\mathcal{Z}_N^i + \\ & (1-\xi)\,\xi_g^{(1)}\left(1-\xi_g^{(2)}\right)\mathcal{Z}_g^{i,(1)}\,\mathcal{Z}_N^{i,(2)} + \\ & (1-\xi)\left(1-\xi_g^{(1)}\right)\xi_g^{(2)}\,\mathcal{Z}_N^{i,(1)}\,\mathcal{Z}_g^{i,(2)} + \\ & (1-\xi)\,\xi_g^{(1)}\,\xi_g^{(2)}\,\mathcal{Z}_g^{i,(1)}\,\mathcal{Z}_g^{i,(2)} + \\ & \xi\,\xi_g^{(1)}\left(1-\xi_g^{(2)}\right)\mathcal{Z}_{S+g}^{i,(1)} + \\ & \xi\left(1-\xi_g^{(1)}\right)\xi_g^{(2)}\,\mathcal{Z}_{S+g}^{i,(2)} + \\ & \xi\,\xi_g^{(1)}\,\xi_g^{(2)}\,\mathcal{Z}_{S+g}^{i,(1,2)} \end{aligned} \quad (33)$$



23

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More key results

- Computational cost: ~500K CPU hours for ~20 hours of data (3K CPU running for one week).
- Estimation of hyper-parameters describing BBH populations.
- Possible extensions, e.g., to BNS background.
- Simultaneous measurement of a non-Gaussian foreground and a Gaussian background.

R. Smith & E. Thrane, Phys. Rev. X **8** 021019 (2018)

Summary of Part II

- Unified framework for stochastic and compact binary searches.
- Detection may be possible much sooner than expected.
- In progress:
  - mock data challenge using one day of data
  - population inference on unresolved binaries
  - apply to binary neutron stars

25

Part III: Primordial backgrounds

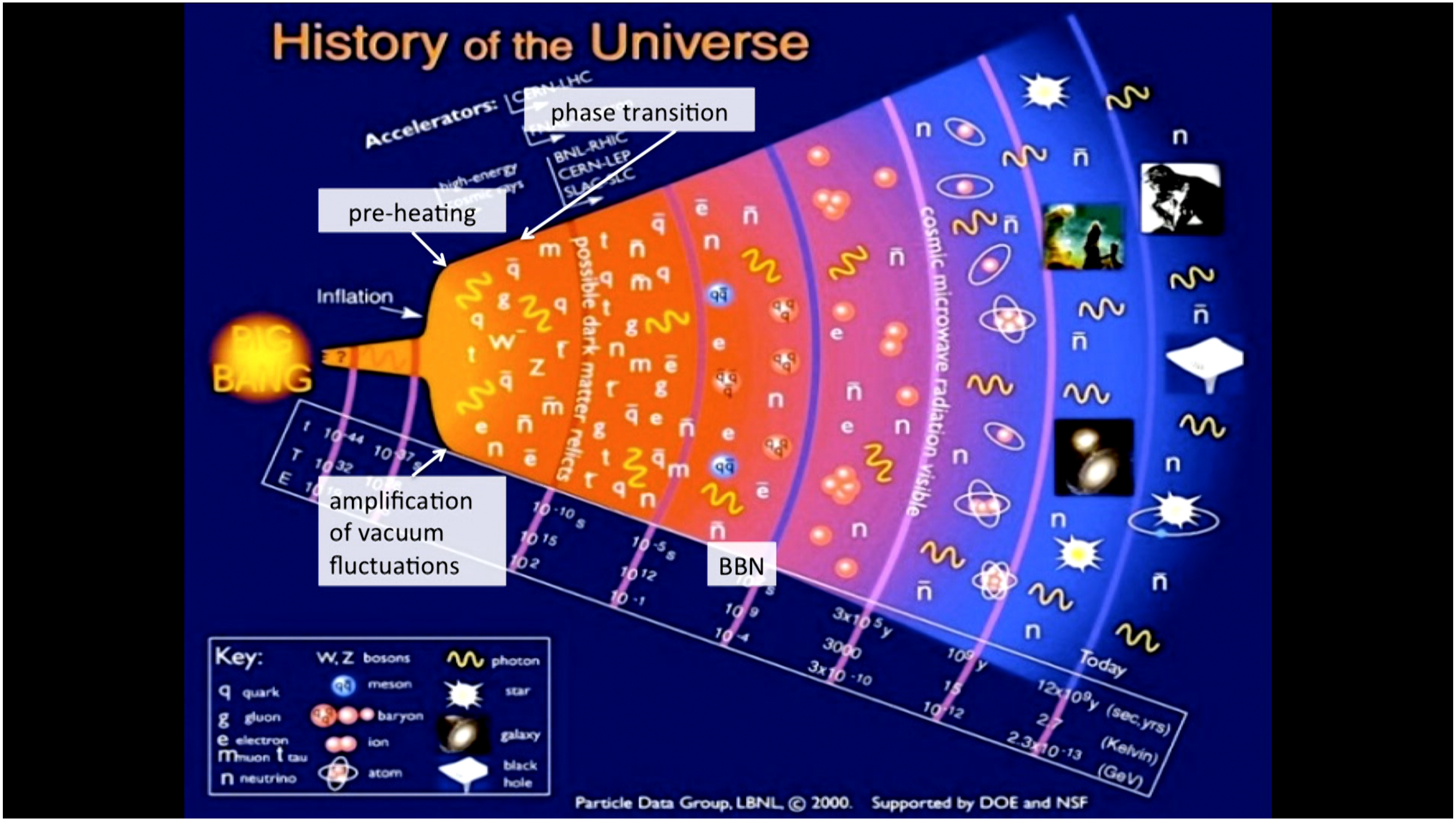
- Two kinds: inflationary scenarios and phase transitions
- Vanilla inflation: Ω_{gw}=10^{-15}
- Pre-heating: Ω_{gw} = ~10^{-11}
- Phase transitions: Ω_{gw} = ~$10^{-12\pm2}$
- Probe energies not accessible with colliders:

$$\Omega_{\rm gw}(f) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm gw}}{d\ln f},$$

$$f_0 \approx 170\,{\rm Hz}\left(\frac{T_*}{10^9\,{\rm GeV}}\right).$$

For comparison, proton/neutron ratio determined at t=1 s, T=1 MeV.

[1] https://doi.org/10.1016/S0370-1573(99)00102-7
[2] PhysRevD.90.107502


History of the Universe
Accelerators:
phase transition
pre-heating
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
amplification of vacuum fluctuations
BBN
Today
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
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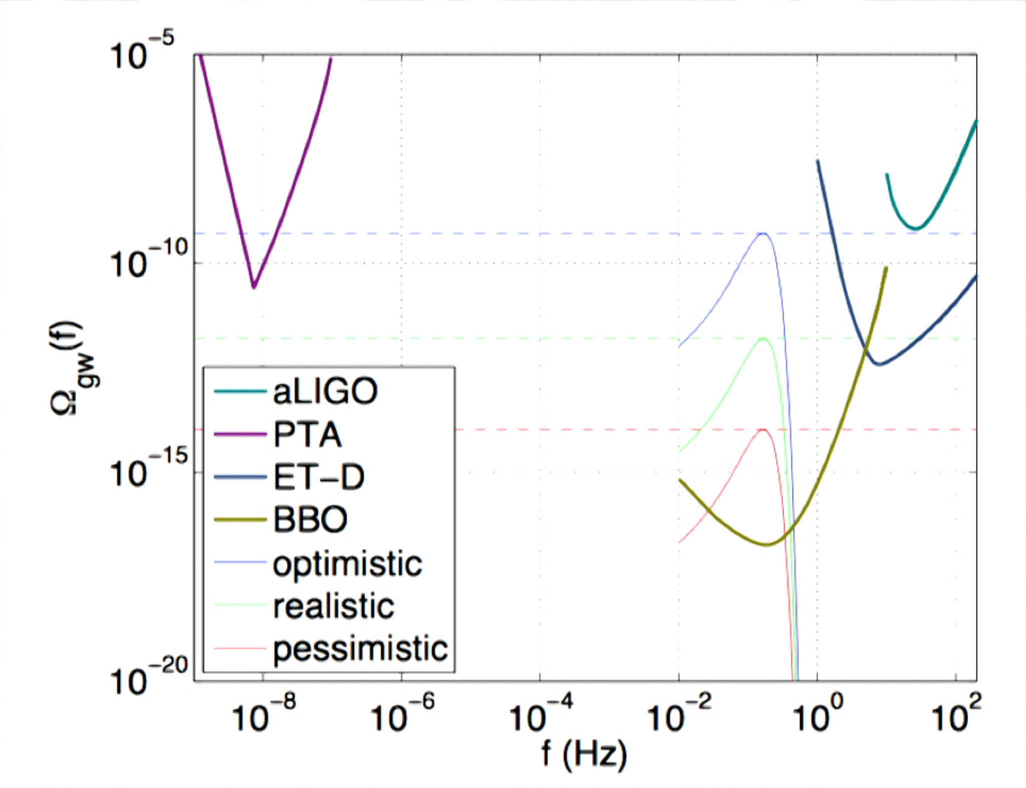
Sensitivity



PhysRevD.90.107502

Subtraction

- Energy density from compact binaries: Ω_{gw}(f=25 Hz) > 10^{-9}.
- In the audio band, the primordial background will probable be ≥2 orders of magnitude weaker.
- Subtraction of resolvable and unresolved signals:
  - Cutler & Harms: PhysRevD.73.042001
  - Regimbau et al: PhysRevLett.118.151105
  - Smith & Thrane: PhysRevX.8.021019