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Neural Posterior Estimation for BBH Foreground Subtraction in 3G SGWB Searches (a manuscript is in preparation)

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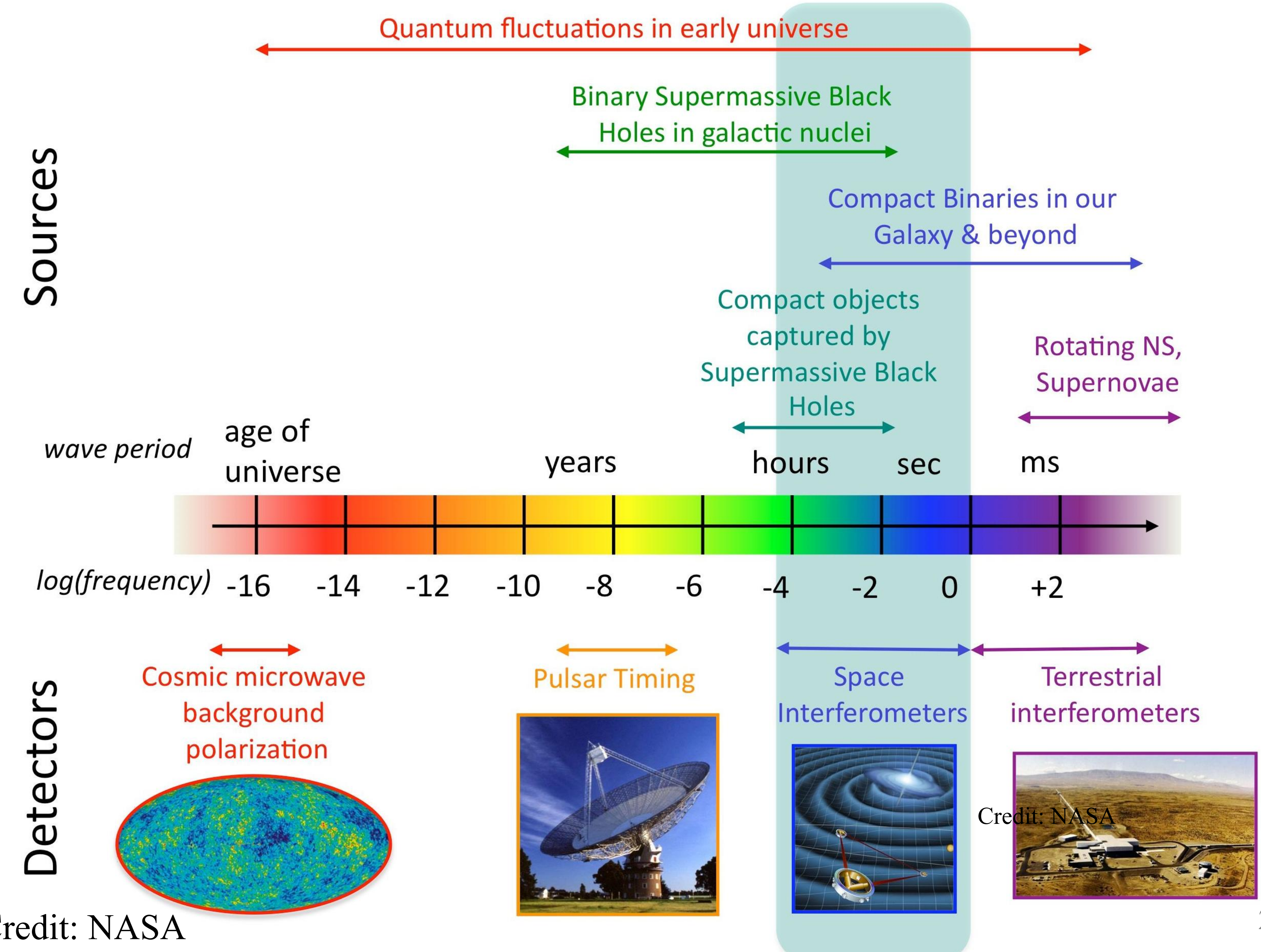
The Gravitational Wave Spectrum



Credit: NASA

LIGO-Virgo-KAGRA Detections

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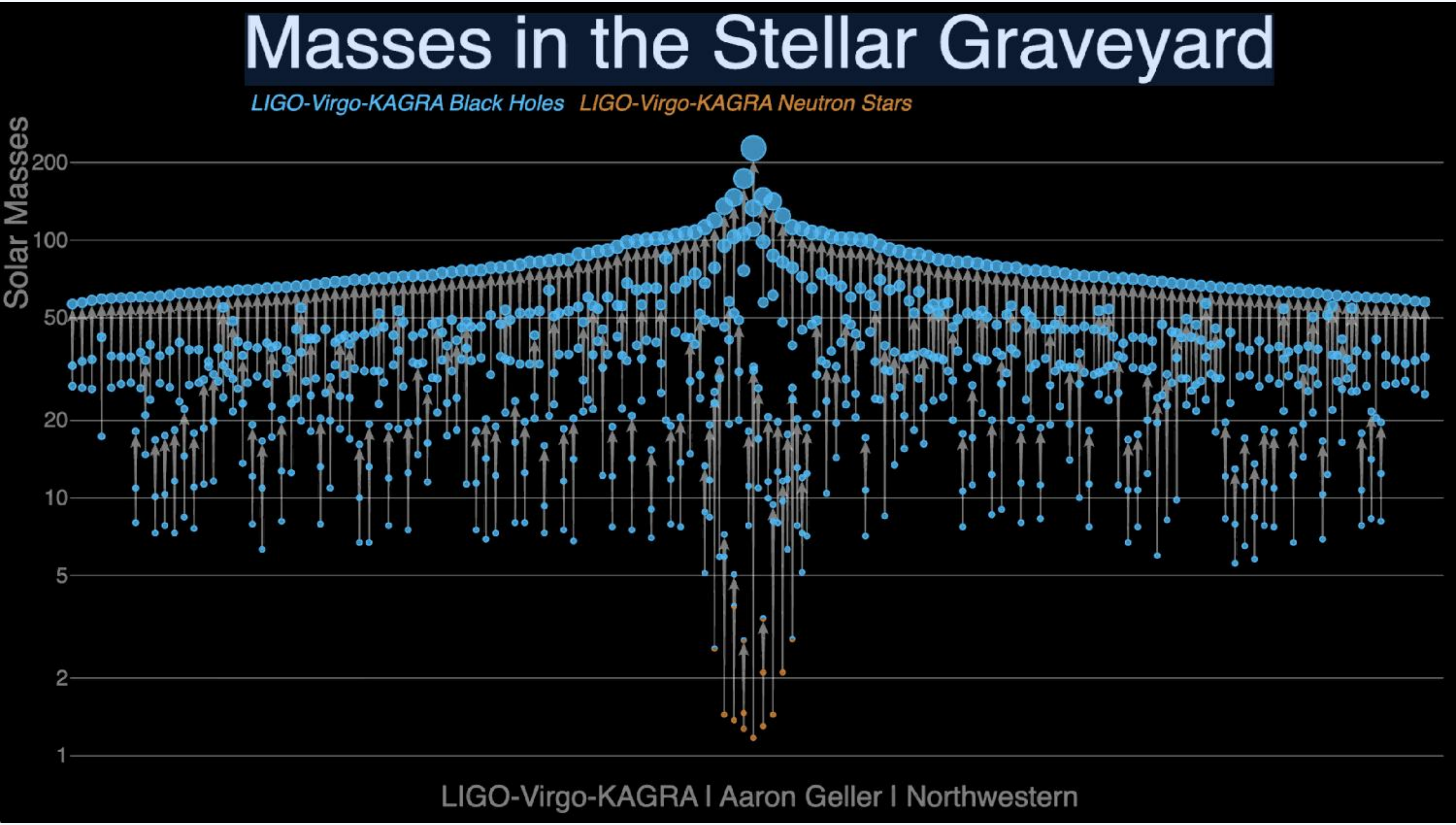

390 detections uptill now

SGWB & Foreground Subtraction

- CBC foreground

$$\Omega_{\rm GW}(f) := \frac{1}{\rho_{\rm crit}}\frac{d\rho_{\rm GW}}{d\ln f} = \frac{4\pi^2}{3H_0^2} f^3 H(f)$$

$$H(f) = \frac{2}{\langle F_+^2\rangle + \langle F_\times^2\rangle}\frac{1}{T}\sum_i |h(f)|_i^2 = \frac{5}{T}\sum_i |h(f)|_i^2$$

$$h(f) = F_+(\theta,\phi,\psi)h_+(f) + F_\times(\theta,\phi,\psi)h_\times(f)$$

- Foreground subtraction

Step 1: $\delta h(f) = h(f) - h^{\rm ML}(f)$

Step 2: $\delta_1^{\rm rfn} H(f) = \frac{5}{T}\sum\{|\delta h(f;\Theta)|^2 - \langle|\delta h(f;\Theta^{\rm ML}(d))|^2\rangle\}_i$

$$\langle|\delta h(f;\Theta)|^2\rangle = \langle\, h(f;\Theta) - h(f;\Theta^{\rm bst}|\Theta)\ ^2\rangle$$

Calculaed via Fisher matrix

1, effectiveness of Fisher's method at SNR ~10 ?

2, real noise ?

Pan & Yang (2024), PRD

SGWB & Foreground Subtraction

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- CBC foreground with ‘real data’

Fisher

$$\Omega_{\mathrm{GW}}(f) = \frac{4\pi^2}{3H_0^2} f^3 H(f)$$

$$H(f) = \frac{5}{T}\sum_i |h(f)|_i^2$$

$$\boxed{d_i = h_i + n_i}$$

Flow

$$\Omega_{\mathrm{total}}(f) = \frac{4\pi^2}{3H_0^2} f^3 H(f)\,,$$

$$H(f) = \frac{5}{T}\sum_i |d(f)|_i^2$$

- Foreground subtraction

Step 1: $\delta h(f) = h(f) - h^{\mathrm{ML}}(f)$ $\quad$ $\delta d(f) = d(f) - h^{\mathrm{ML}}(f)$

Step 2:

$$\delta_1^{\mathrm{rfn}} H(f) = \frac{5}{T}\sum \left\{|\delta h(f;\boldsymbol{\Theta})|^2 - \langle|\delta h(f;\boldsymbol{\Theta}^{\mathrm{ML}}(d))|^2\rangle\right\}_i$$

$$\delta_1^{\mathrm{rfn}} H(f) = \frac{5}{T}\sum_i \left\{|\delta d(f;\boldsymbol{\Theta})|^2 - \langle|\delta d(f;\boldsymbol{\Theta}^{\mathrm{ML}}(d))|^2\rangle\right\}_i$$

$$\langle|\delta h(f;\boldsymbol{\Theta})|^2\rangle = \langle\; h(f;\boldsymbol{\Theta}) - h(f;\boldsymbol{\Theta}^{\mathrm{bst}}|\boldsymbol{\Theta})\;^2\rangle$$

$$\langle|\delta d(f;\boldsymbol{\Theta})|^2\rangle = \langle\; d(f;\boldsymbol{\Theta}) - h(f;\boldsymbol{\Theta}^{\mathrm{bst}}|\boldsymbol{\Theta})\;^2\rangle$$

SGWB & Foreground Subtraction

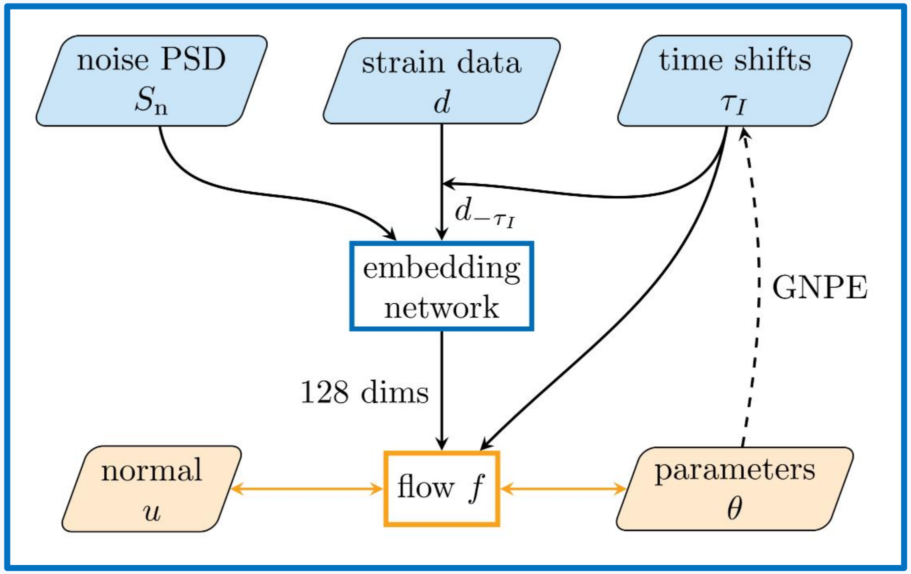
- Fisher is not sufficiently accurate, especially at low SNRs (8–20) and in real noise.

- Bayesian methods are time-consuming for analyses with more than $O(10^4)$ events, often requiring days of inference even on a computing cluster.

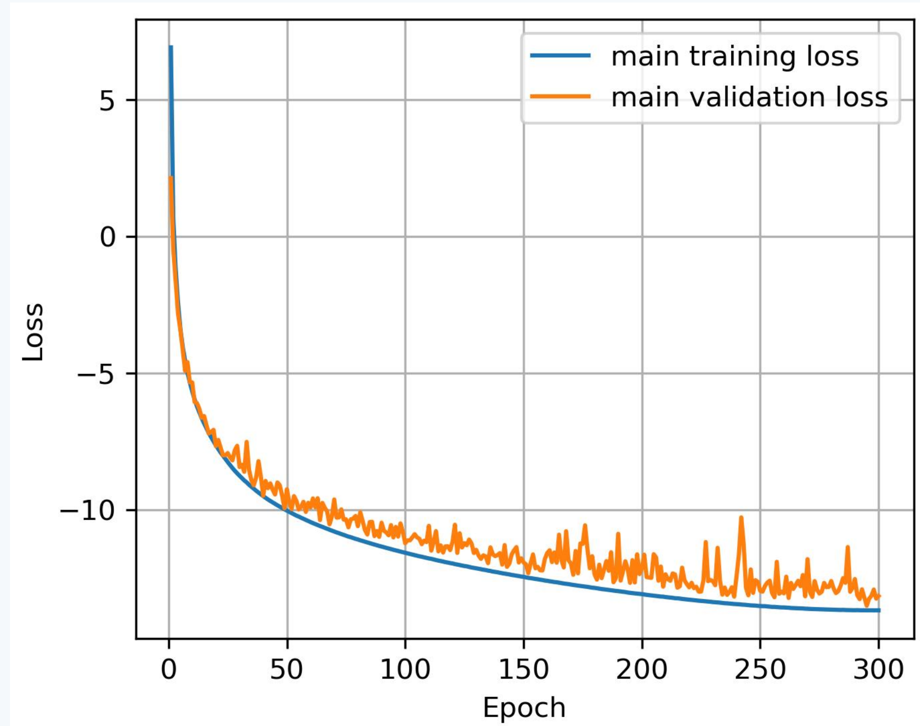
- Neural Posterior Estimation (M. Dax, S. Green, et al.), with 5 seconds per inference.

- Poipulation model: GWTC-4.0 (arXiv:2508.18083), GWTC-5.0 (arXiv:2605.27226)

Neural Posterior Estimation (NPE)

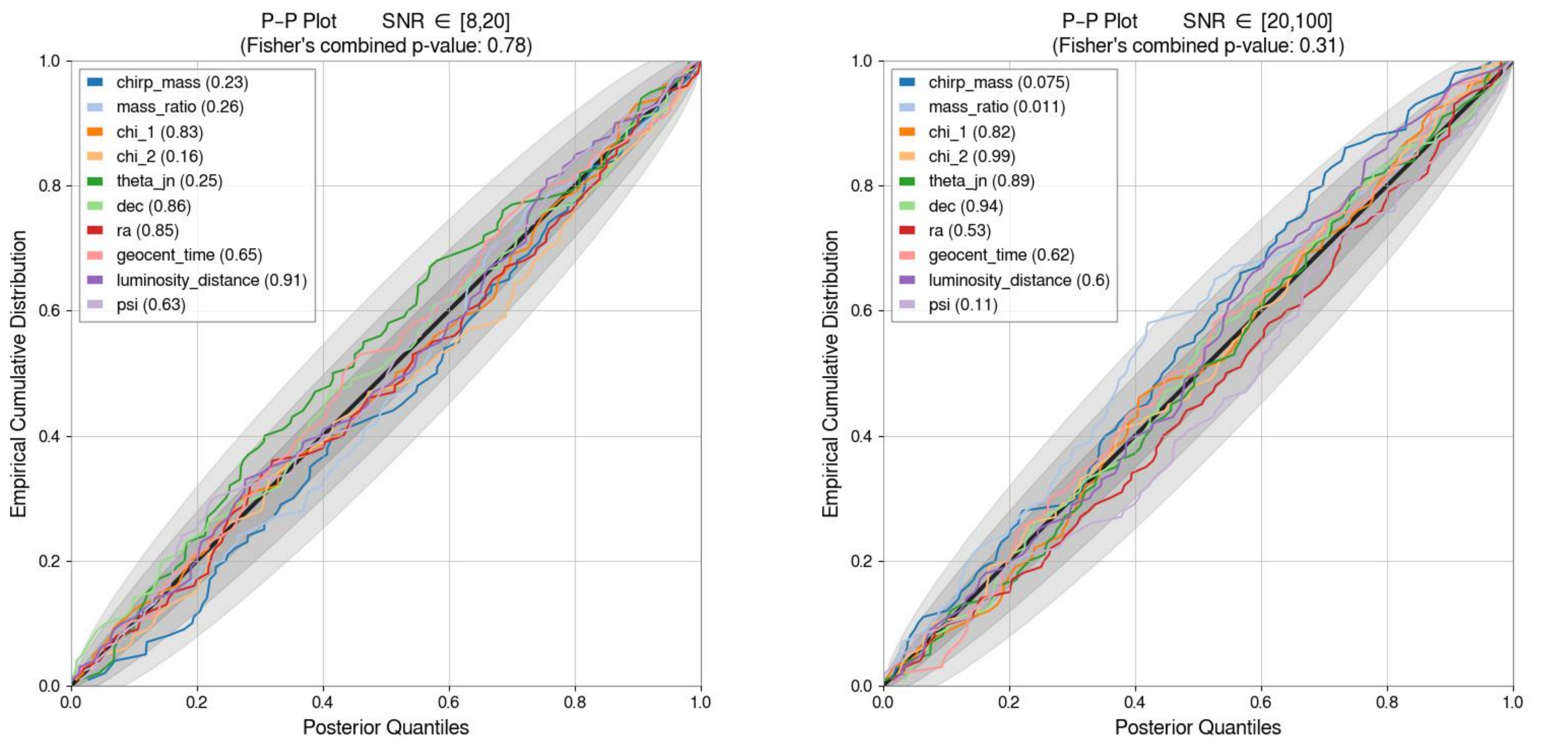


(Dax et al. PRL, 2021)



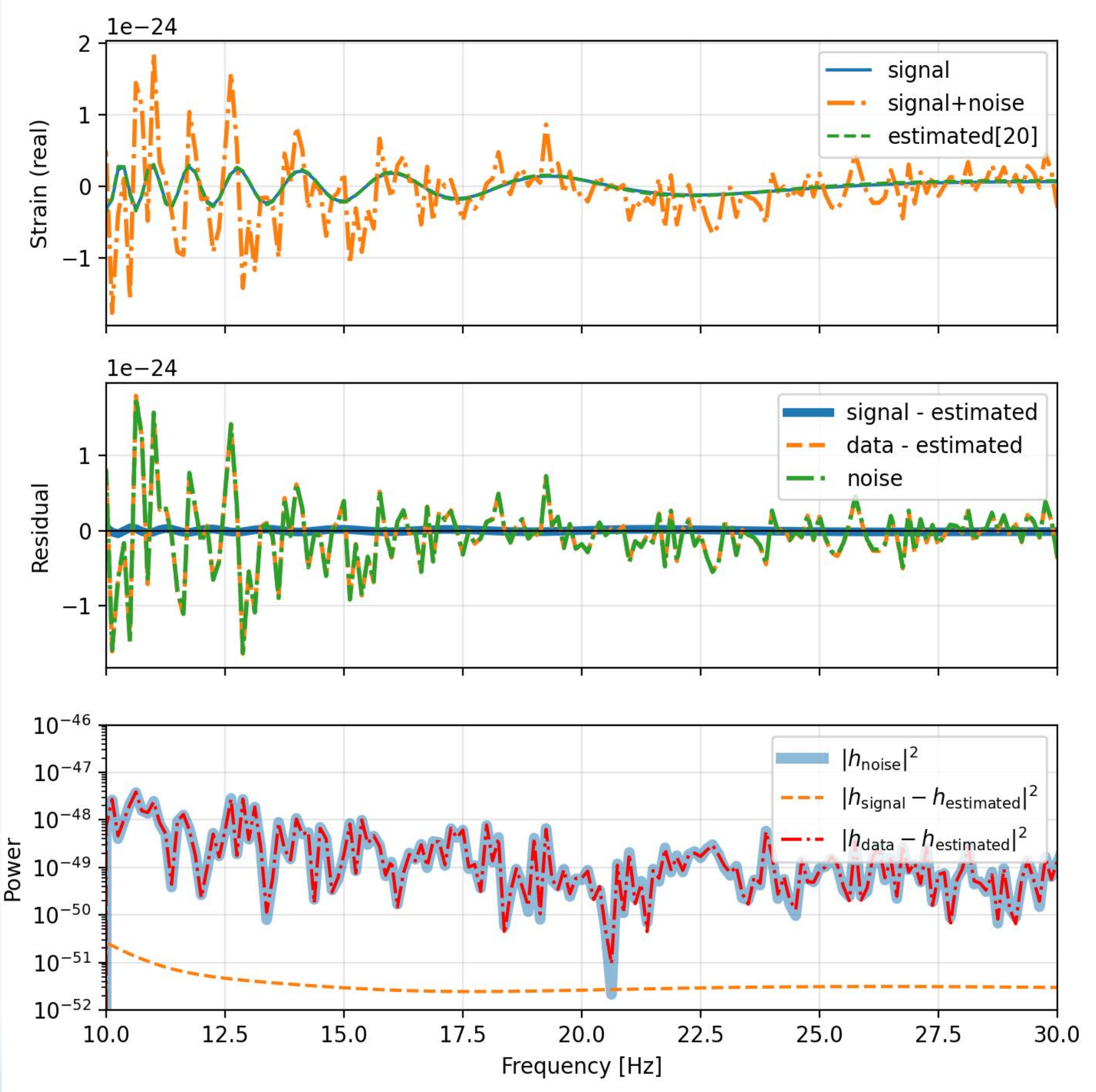
- Twenty million (10^6) mock samples drawn from the LVK-constrained population, assuming CE sensitivity;
- Aligned-spin IMRPhenomD (11D), Trained for 1 epoch in 1 hour, with 5 seconds per inference on RTX 4090 24G.

Probability-Probability (P-P) plot



P–P plot for 100 injections

Single Event Recovery

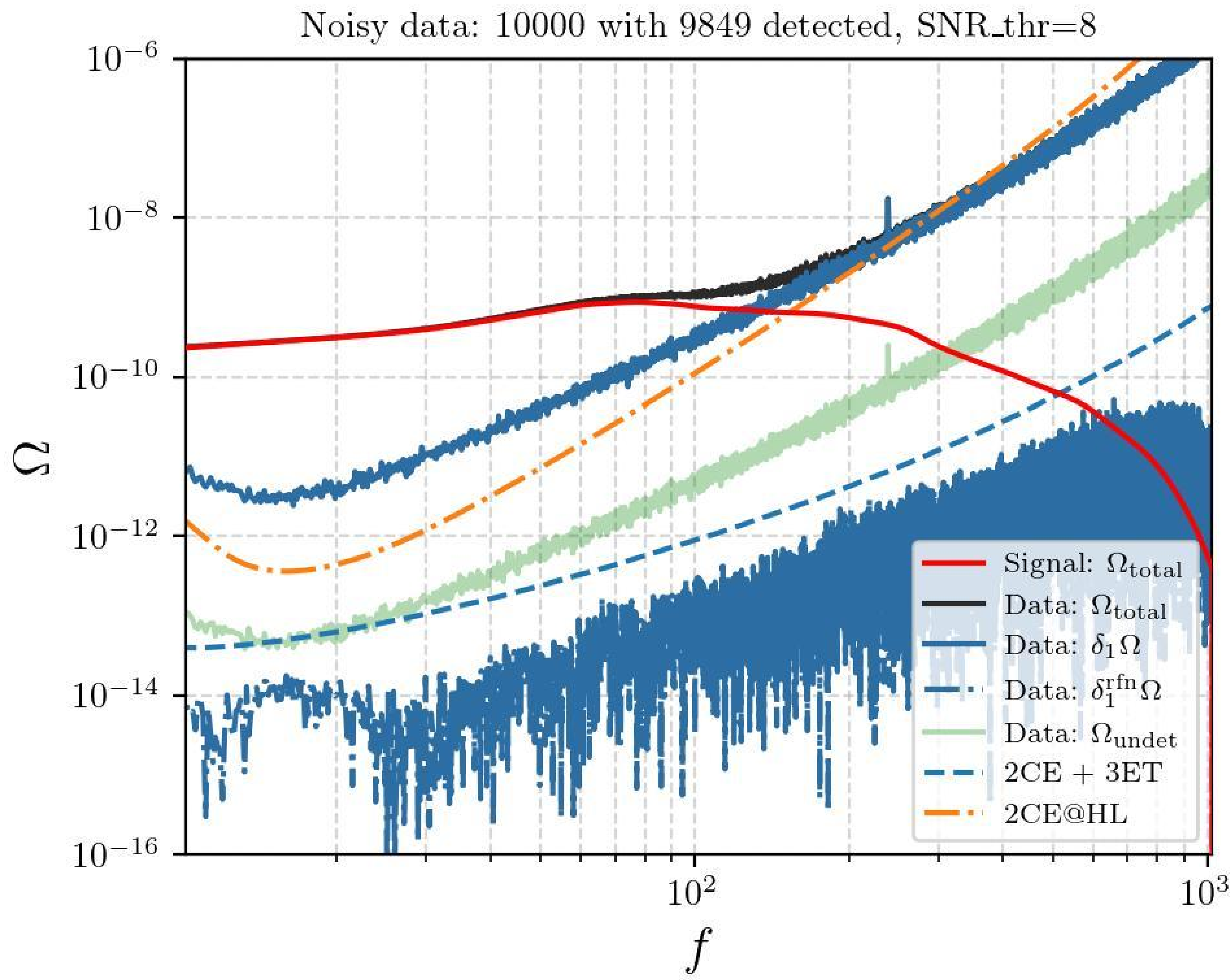


Mc = 48

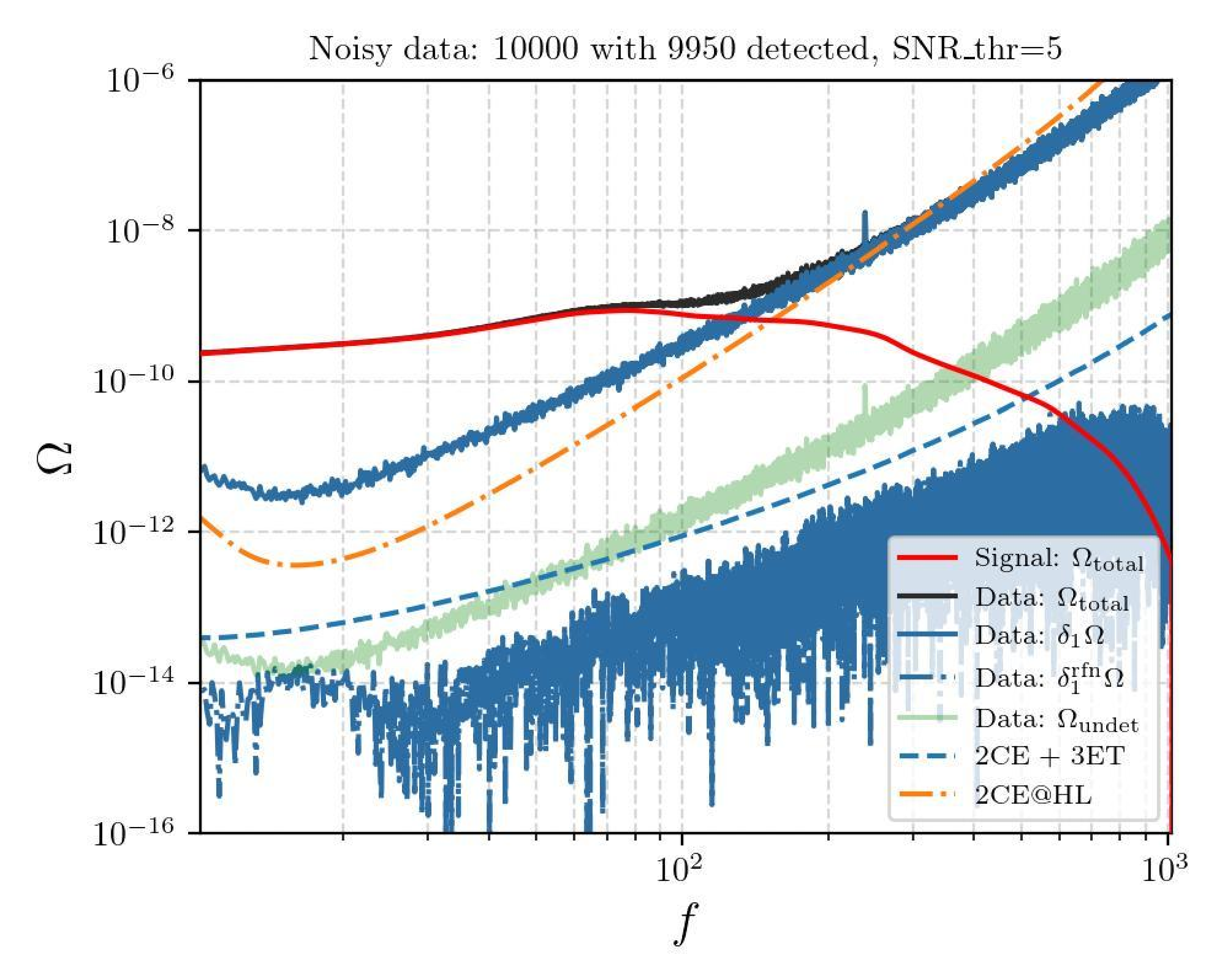
SNR = 10

One tricky point is shifting the phase

Subtraction Results: Noisy Data



Subtraction Results: Noisy Data



Results and Takeaways

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- Neural Posterior Estimation

  vs. Fisher: more accurate at low SNRs (8–20)

  vs. Bayesian: in real noise, for aligned-spin IMRPhenomD (11D), training takes 1 hour for 1 epoch, with 5 seconds per inference.

- Science: GW foreground subtraction is sufficiently clean for SGWB detection; the remaining challenge may be resolving low-SNR candidates.

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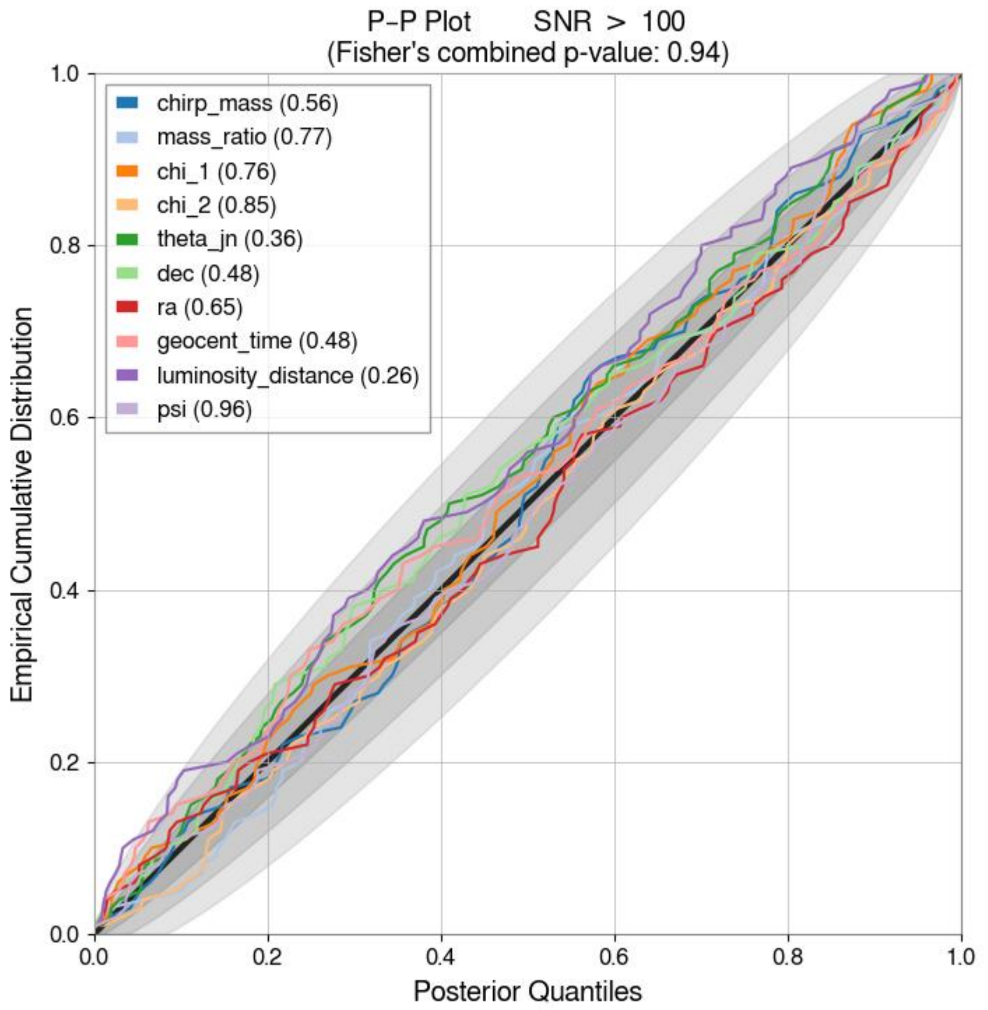
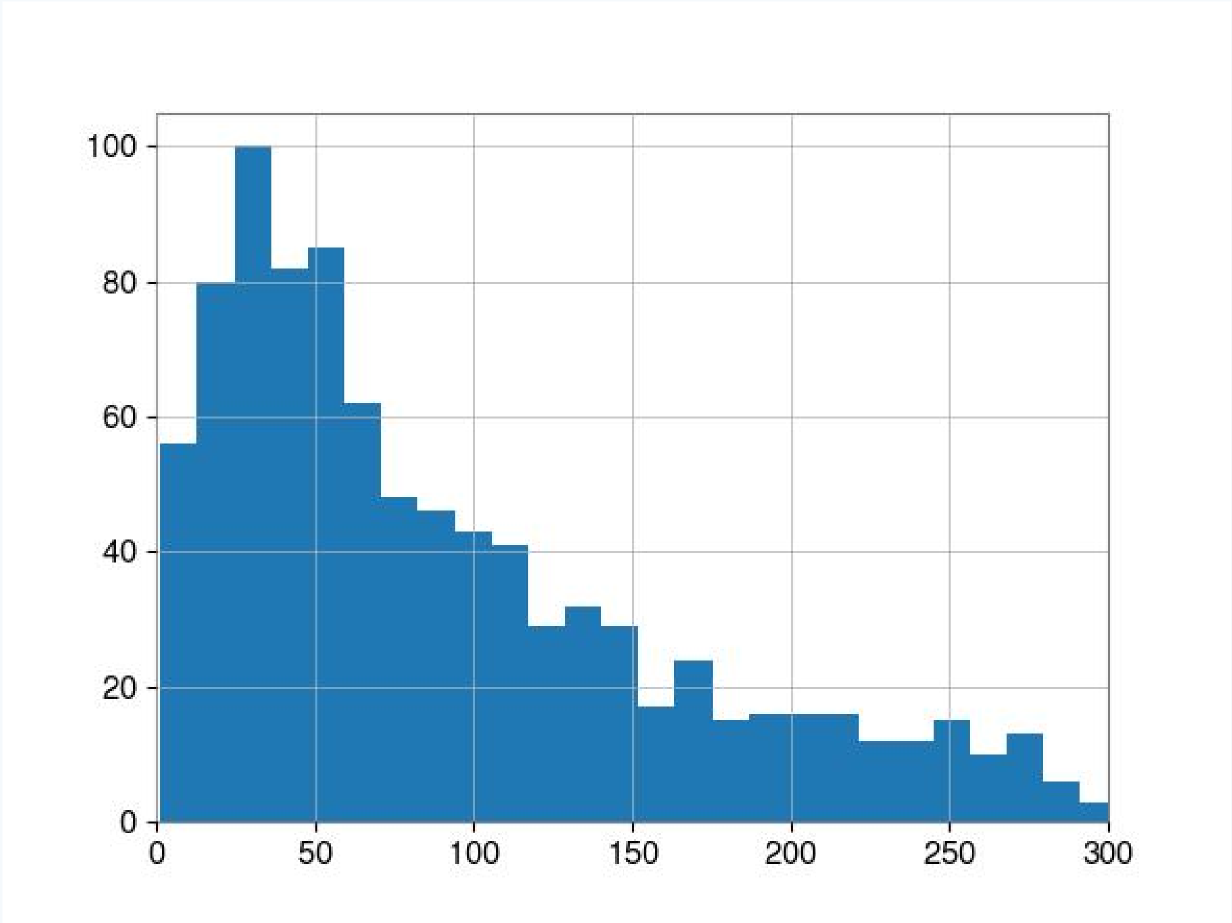
Thanks for your attention.

Backup slides

SWGB - NPE



P–P Plot SNR > 100
(Fisher's combined p-value: 0.94)
chirp_mass (0.56)
mass_ratio (0.77)
chi_1 (0.76)
chi_2 (0.85)
theta_jn (0.36)
dec (0.48)
ra (0.65)
geocent_time (0.48)
luminosity_distance (0.26)
psi (0.96)
Empirical Cumulative Distribution
Posterior Quantiles
0.0
0.2
0.4
0.6
0.8
1.0


100
80
60
40
20
0
0
50
100
150
200
250
300