

End of Year 2 Seminar

Candidate

Chiara Anselmo

Supervisor

Davide Gerosa

Tutor

Matteo Fossati

@ University of Milano-Bicocca

Sep 7 2026

Research

Analysis of gravitational-wave data from ground-based detectors

Completed Work

Black-hole ringdown parameter estimation with spin precession

Published in June

Ongoing Work

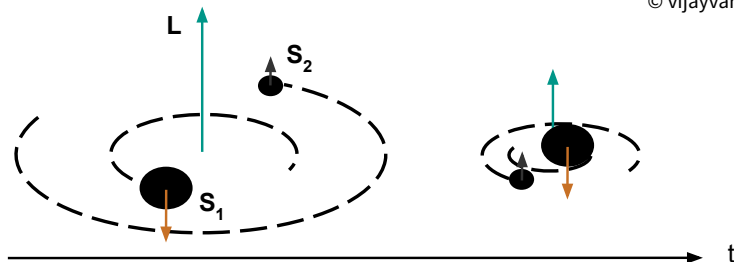
Population inference of eccentric black-hole binaries

Probing spin precession from the ringdown

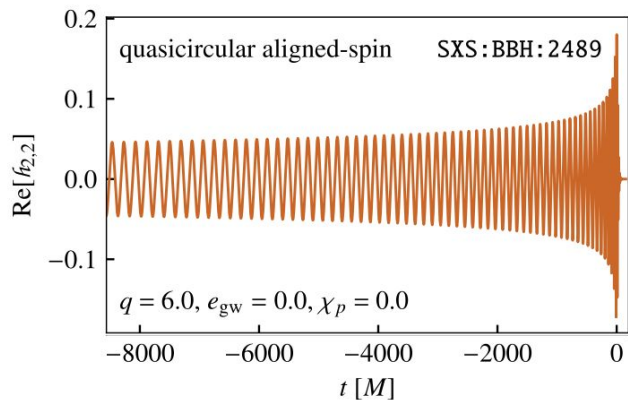
With C. Pacilio & D. Gerosa

Spin-induced precession

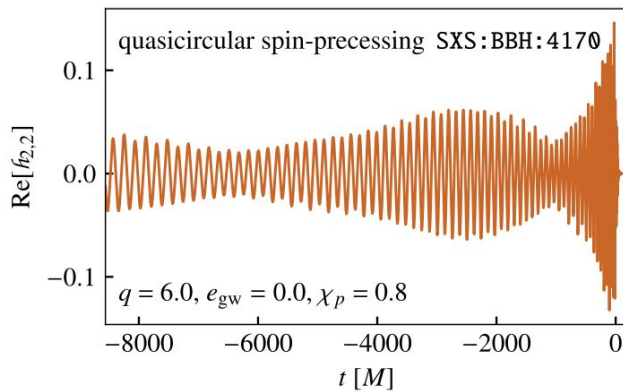
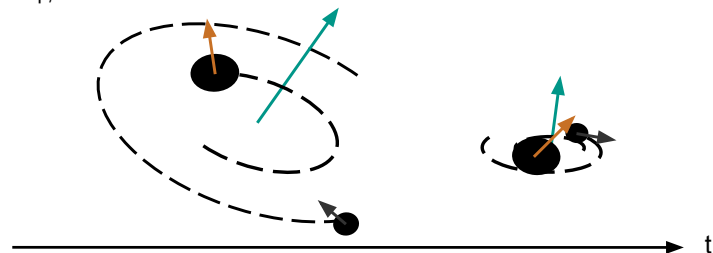
Spin (anti-)alignment



© vijayvarma392.github.io/binaryBHexp/

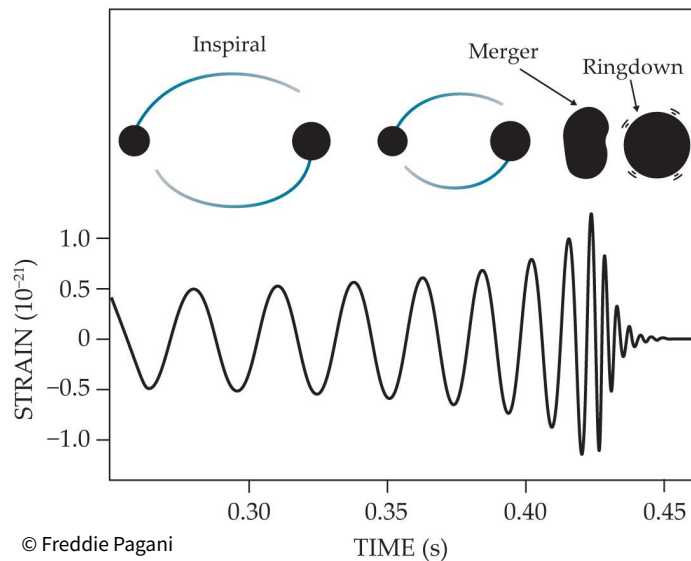


Spin misalignment



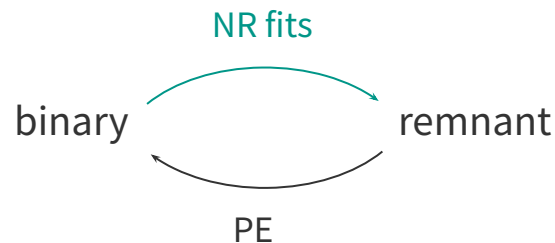
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Black hole ringdown



- Quasi-normal mode decomposition

$$h \sim \sum_{\ell mn} \mathcal{A}_{\ell mn} e^{-t/\tau_{\ell mn}} \cos(2\pi f_{\ell mn} t + \phi_{\ell mn}) Y_{\ell mn}$$



NR surrogates

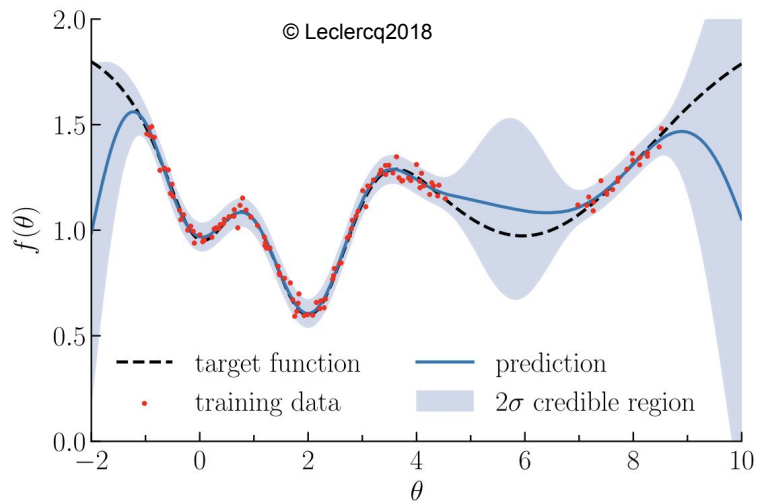
Physics-driven (PN/EMRI limits) & Data-driven (GPR)

- Spin-aligned regime

Pacilio+2024, Magaña Zertuche+2025

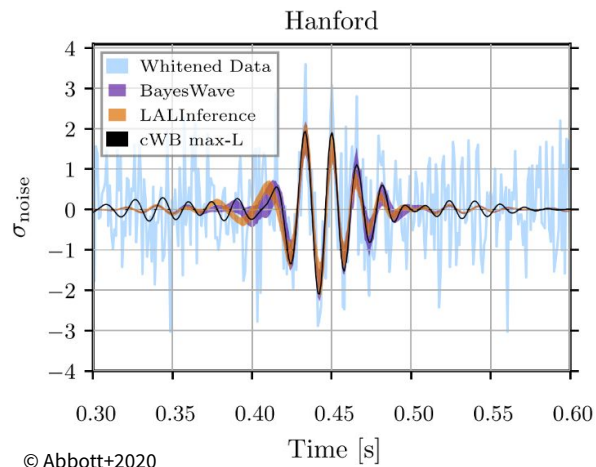
- Precessing regime

Nobili+2025

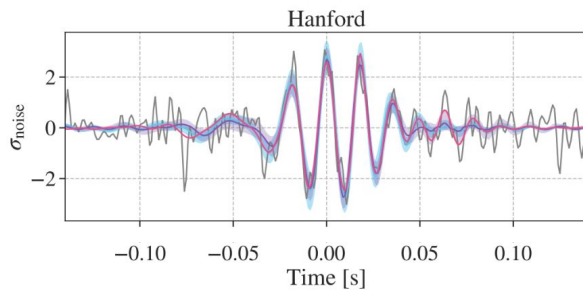


Why only the ringdown?

Merger-ringdown-dominated events

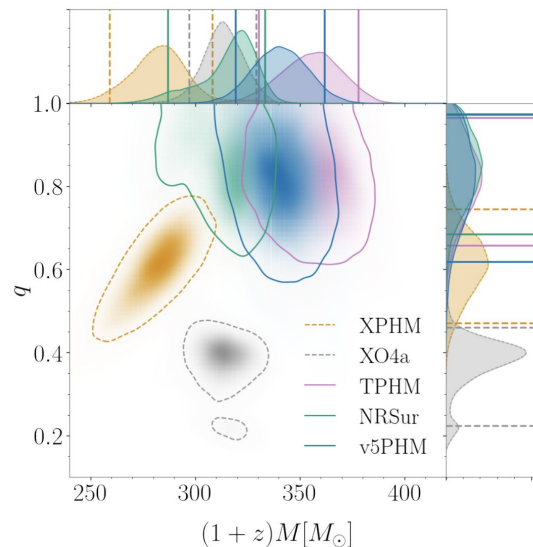


GW190521



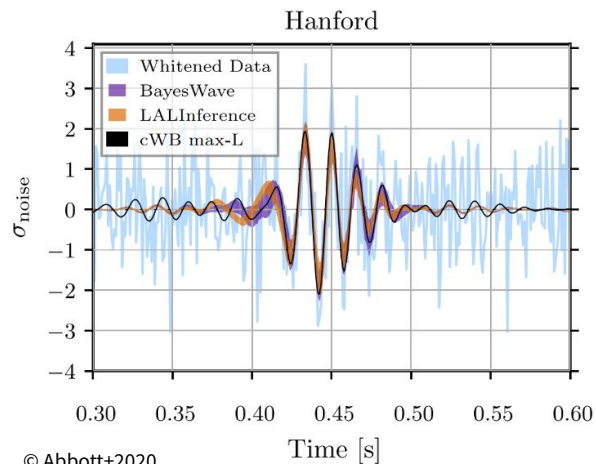
GW231123

Waveform systematics



Case study: GW190521

Massive source ($M \sim 150 M_{\odot}$) $\rightarrow$ Short signal ($\Delta t \sim 0.1$ s)



Conflicting interpretations

	Inspiral-Merger-Ringdown	Ringdown-only
eccentricity / precession	Estellés+2021 Romero-Shaw+2020 Gamba+2021 Gayathri+2020	Siegel+2023 <u>Anselmo+2025</u>
overtones / higher harmonics	Abbott+2020 Estellés+2021	Abbott+2020 Siegel+2023 Capano+2023 <u>Anselmo+2025</u>

Ringdown template(s)

$$h_{\ell mn} = \frac{M}{d_L} A_{\ell mn} e^{-i(2\pi f_{\ell mn} t + \phi_{\ell mn})} e^{-t/\tau_{\ell mn}} {}_{-2}Y_{\ell mn}(\iota, \varphi)$$

$$\{(2, \pm 2, 0), (3, \pm 3, 0), (2, \pm 1, 0)\}$$

Spin-aligned

$$\{\chi_{1z}, \chi_{2z}\}, \quad \chi_{1x} = \chi_{1y} = \chi_{2x} = \chi_{2y} = 0$$

$$A_{\ell-|m|n} = (-1)^\ell A_{\ell+|m|n}$$

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Precessing

$$\{\chi_1, \chi_2\}$$

$$A_{\ell-|m|n} \neq (-1)^\ell A_{\ell+|m|n}$$

#16

GPR models

Trained on SXS simulations

Boyle+2019

- QNM amplitudes

7D model from postmerger

Pacilio+2024, Nobili+2025

- Remnant mass and spin

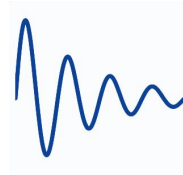
Anselmo+2025



q, χ_1, χ_2

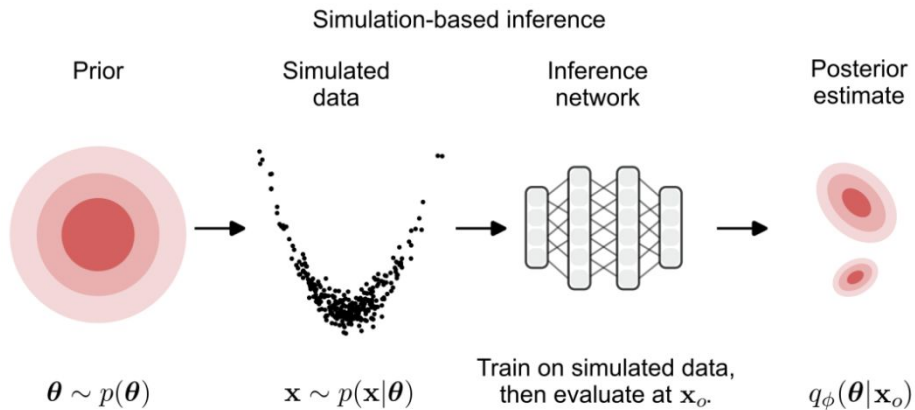
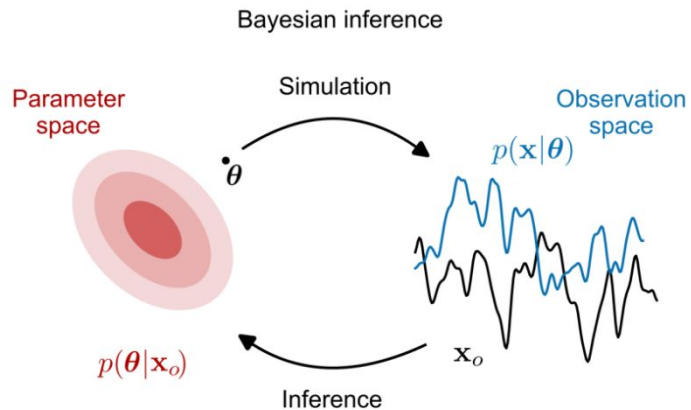


$M_f, \chi_f, A_{\ell mn}$



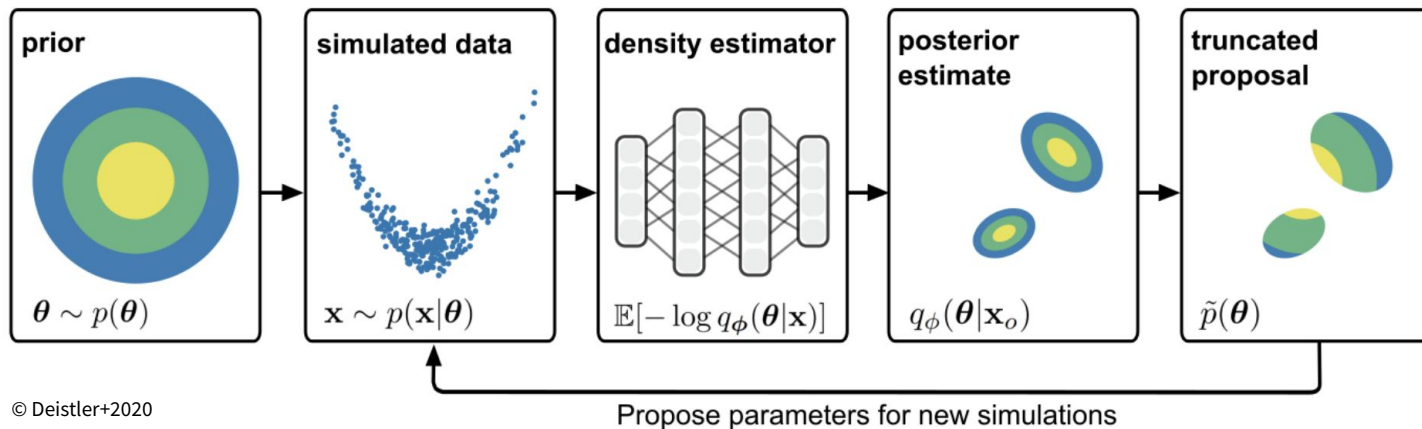
Methods

Simulation-based/Likelihood-free inference



Methods

Truncated Sequential Neural Posterior Estimation (TSNPE)

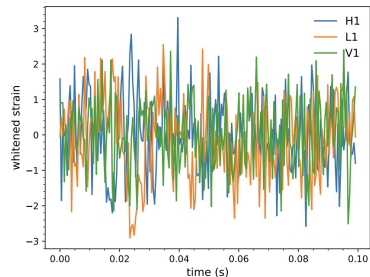


Setup

Fixed

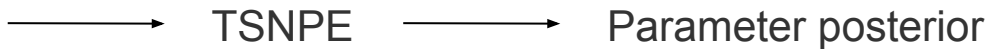
- location $(\alpha, \delta), t_{\text{peak}}$
- start times: 6, 12 ms

Time-domain strain

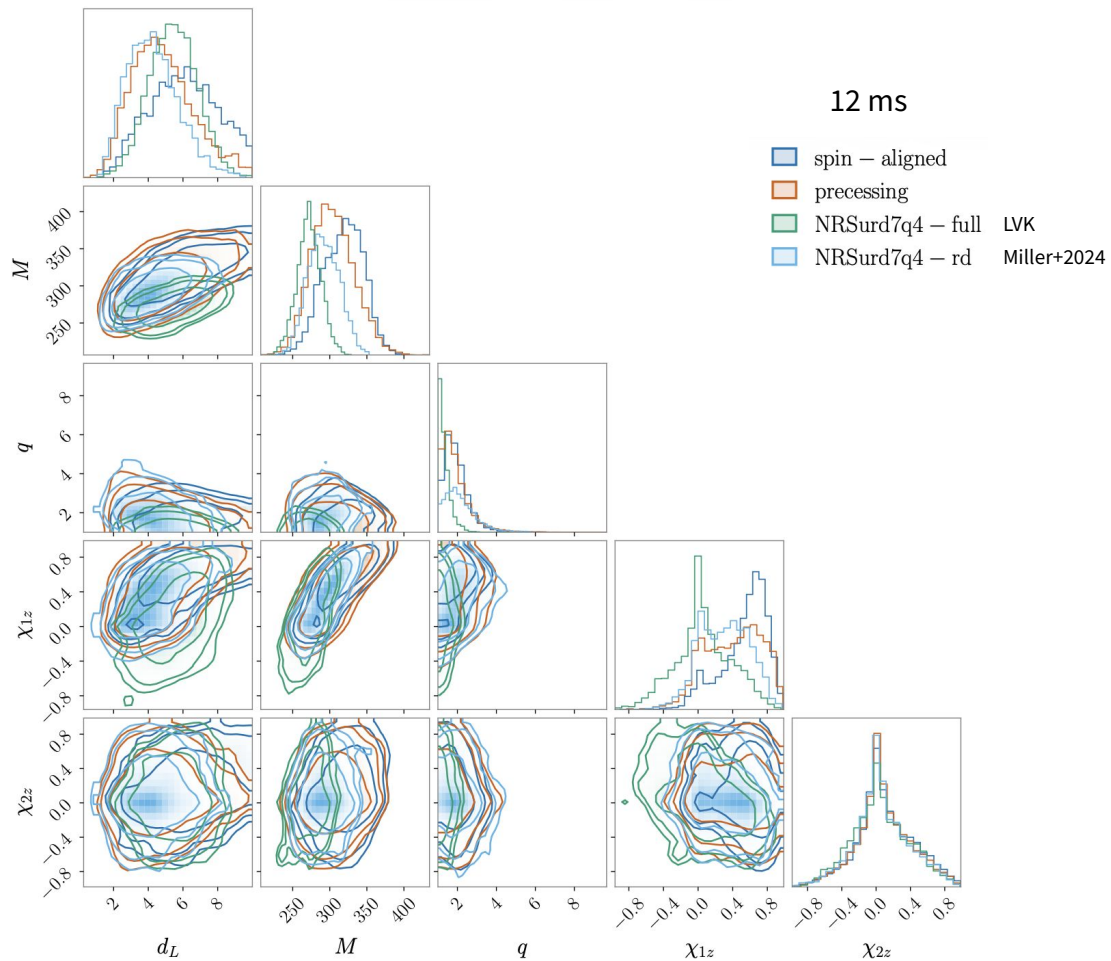


Inferred

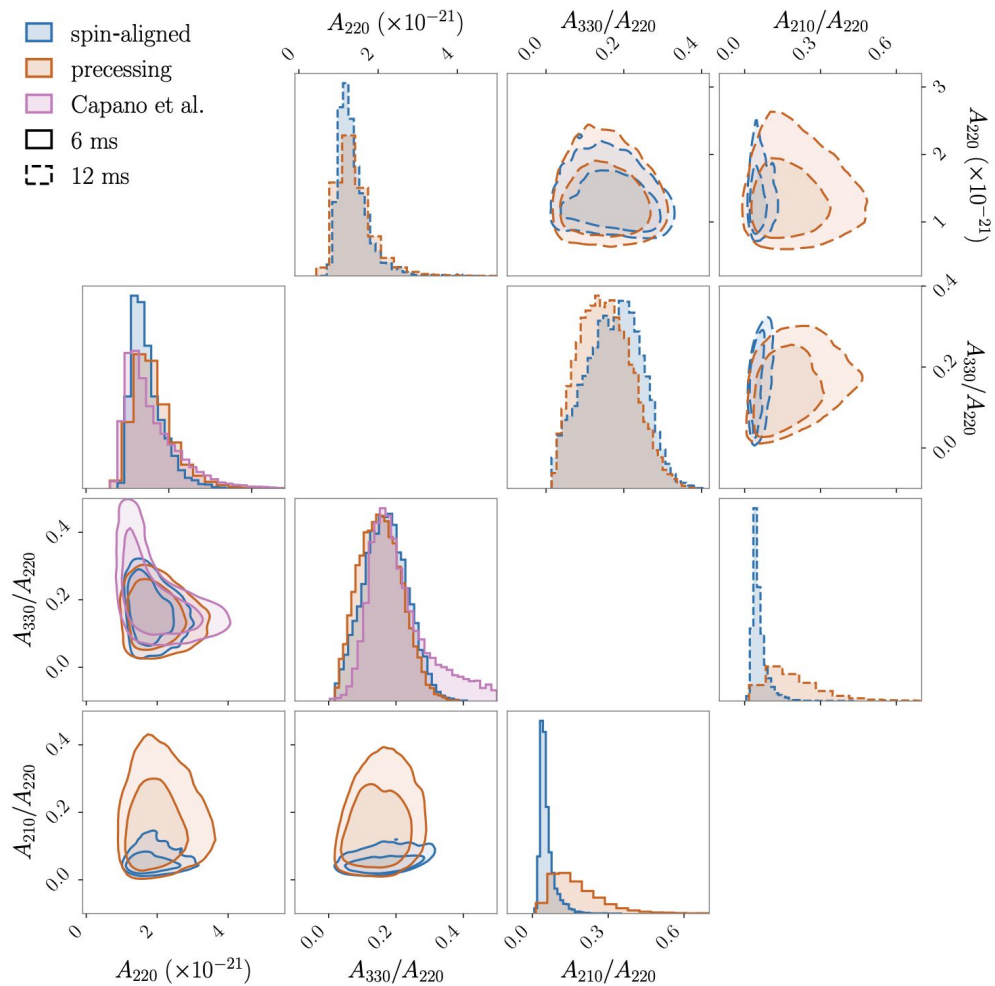
- shared $\{\cos(\iota), d_L, M, q, \phi_{lmn}\}$
- spin-aligned $\{\chi_{1z}, \chi_{2z}\}$
- precessing $\{\chi_1, \cos(\gamma_1), \varphi_1, \chi_2, \cos(\gamma_2), \varphi_2\}$



Results



Results



Conclusions

First implementation of ringdown templates including precession

- Modest shifts in inferred parameters
- No evidence of precession in GW190521 ringdown

Future prospects

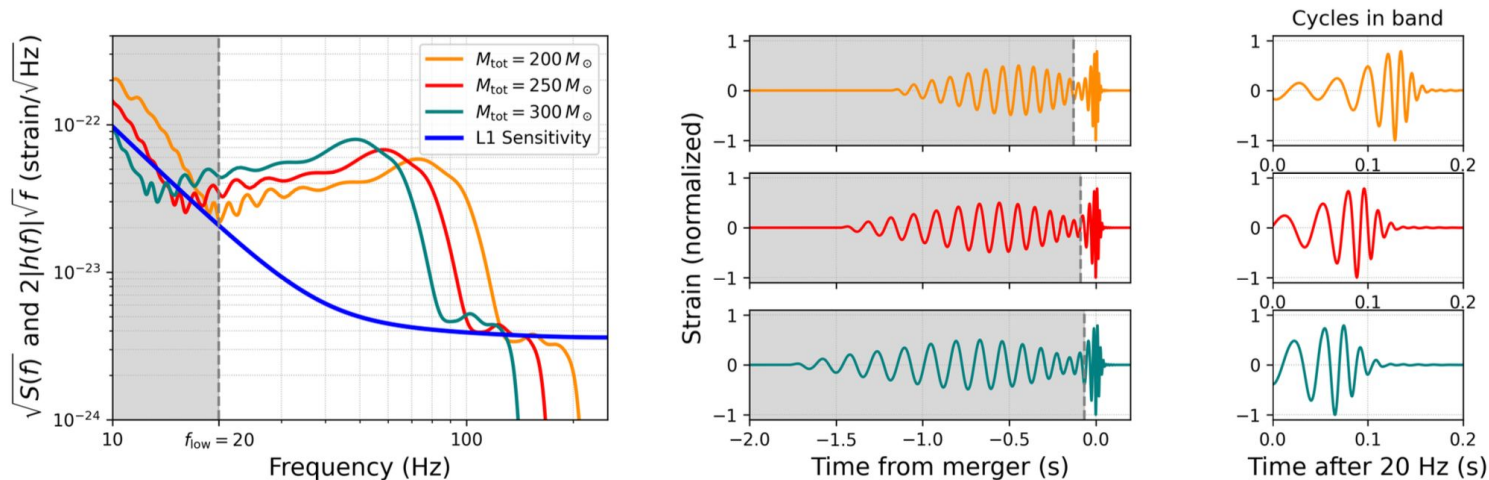
- GPR model improvements: + modes, + simulations
- Parameter estimation of GW231123

Population inference with eccentricity

With G. Fumagalli (Caltech) & D. Gerosa

Population inference with time-varying quantities

Parameters θ defined at $f_{\text{ref}} \rightarrow$ different point in evolution for different sources

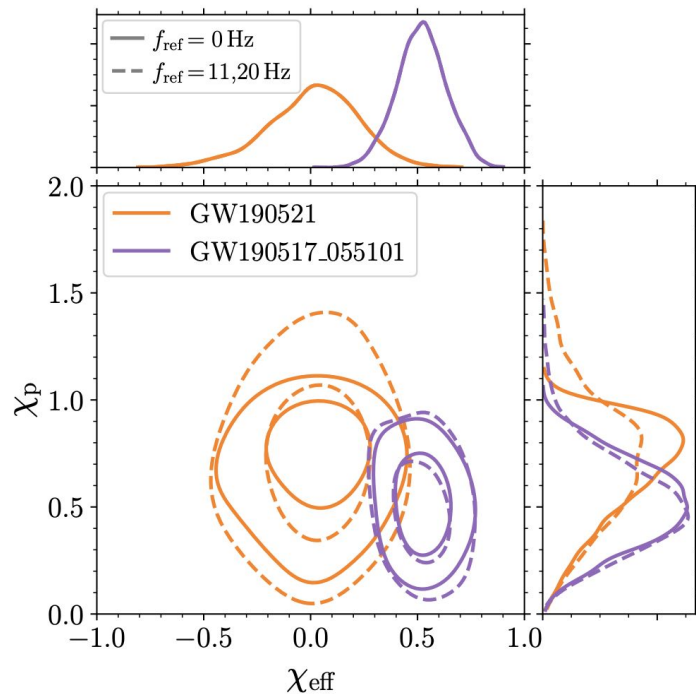
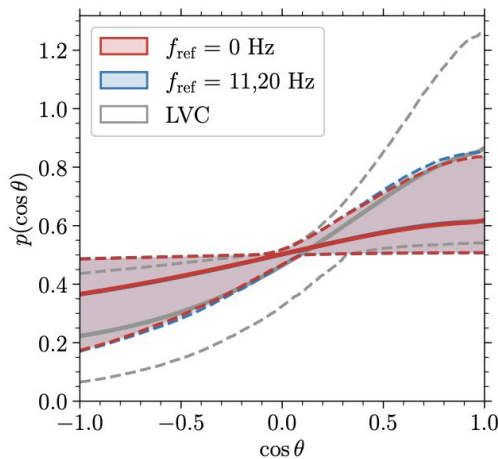
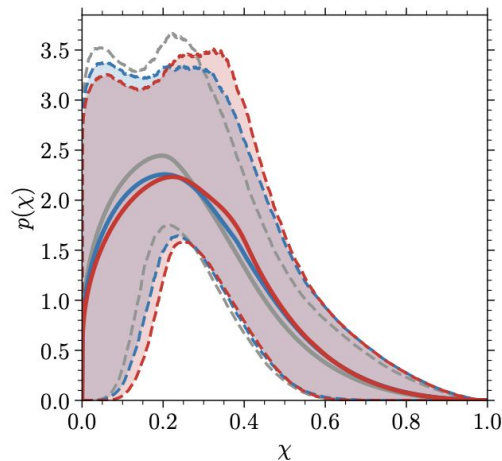


Population inference with time-varying quantities

Going to $t = -\infty / f_{\text{ref}} = 0$ Hz

- Spin directions

Mould & Gerosa, 2022



Population inference with time-varying quantities

Going to $t = -\infty / f_{\text{ref}} = 0 \text{ Hz}$

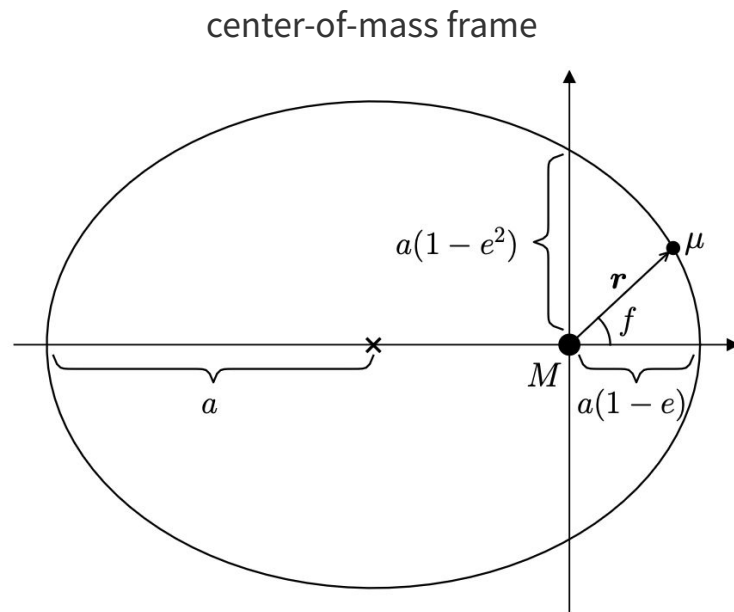
- Spin directions Mould & Gerosa, 2022
- Eccentricity?

Eccentricity

Newtonian Gravity

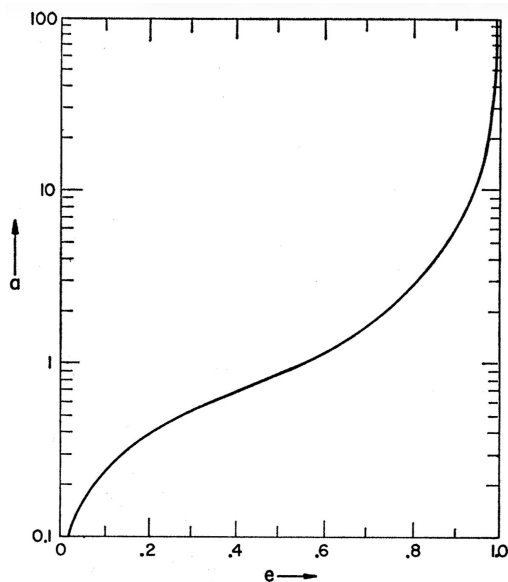
- $\mu = m_1 m_2 / M$ $d^2 \mathbf{r} / dt^2 = - M \mathbf{r} / r^3$
- Constants of motion

$$\left\{ \begin{array}{l} |E| = \frac{Mq}{2(1+q)a} \\ L = \frac{q}{(1+q)^2} \sqrt{M^3 a (1-e^2)} \end{array} \right.$$



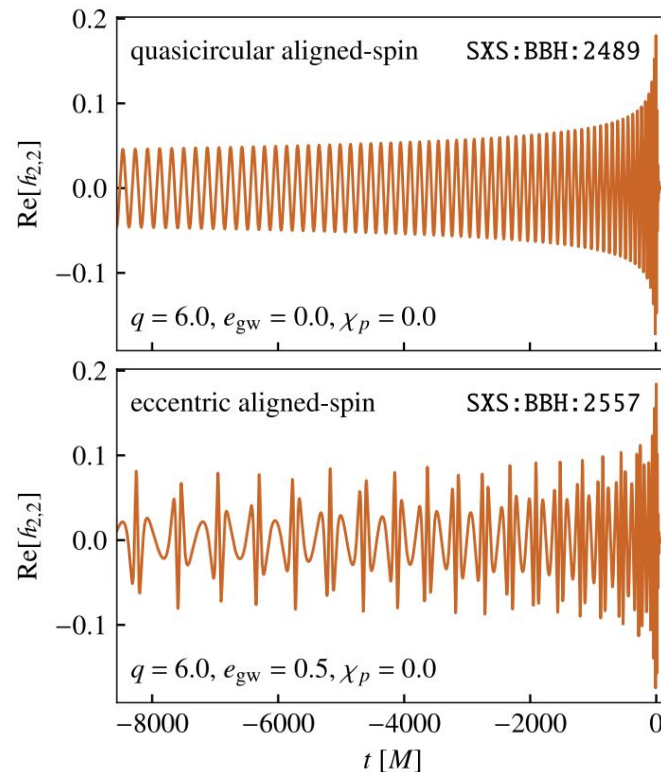
Eccentricity

General Relativity: energy/momentum loss



© Peters, 1964

$$\left\{ \begin{array}{l} da/dt \neq 0 \\ de/dt \neq 0 \end{array} \right. \downarrow a(e)$$



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Orbital angular momentum

At $t = -\infty$ / $f = 0$ Hz,

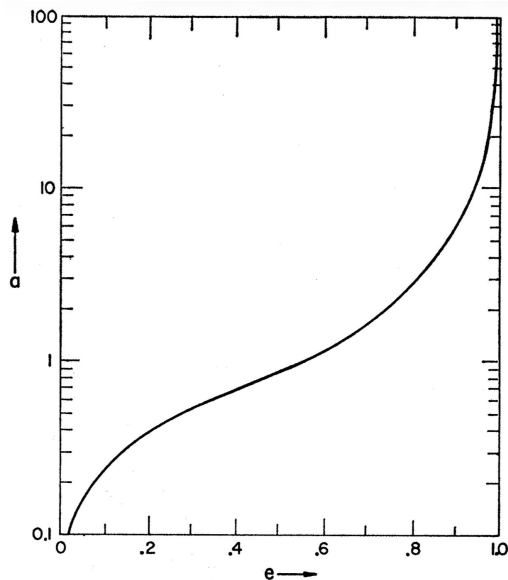
$$e \rightarrow 1 \quad a \rightarrow \infty$$

However,

$$\lim_{t \rightarrow -\infty} a \propto \frac{1}{1 - e^2}$$



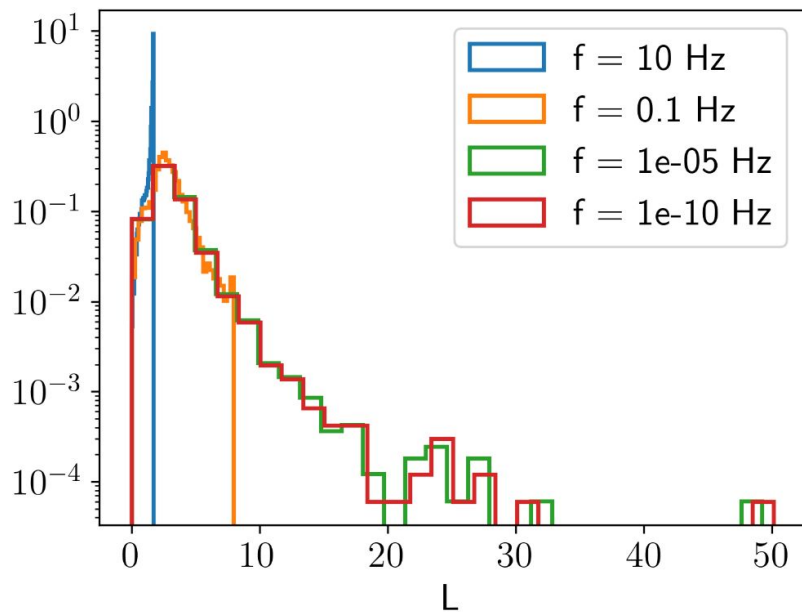
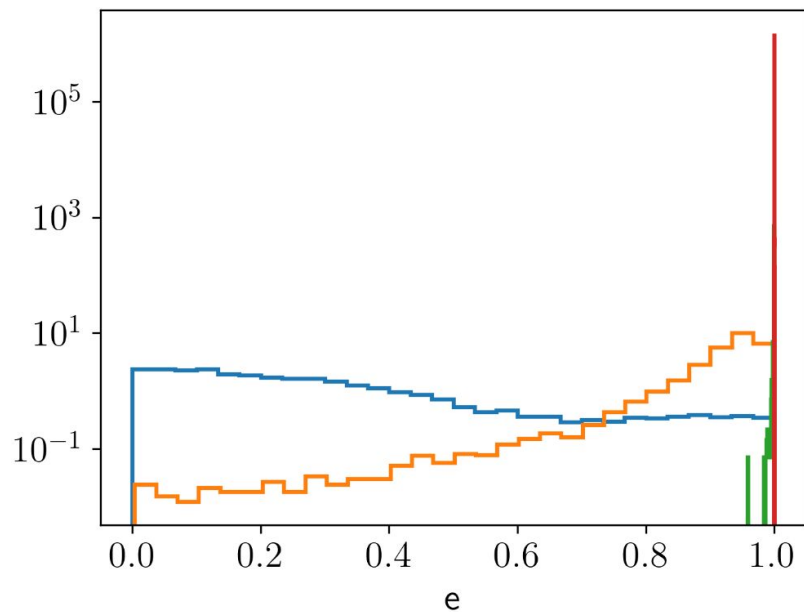
$$L \propto \sqrt{a(1 - e^2)} \rightarrow \text{const.}$$



© Peters, 1964

Orbital angular momentum

Population propagated backward in time ($f \searrow$)



Hierarchical inference

Hyperposterior

$$p(\lambda \mid D) = \frac{\pi(\lambda)\mathcal{L}(D \mid \lambda)}{p(D)}$$

Hyperlikelihood

$$\mathcal{L}(D \mid \lambda) = \prod_{\text{obs}} \frac{\int \mathcal{L}(d \mid \theta)\pi(\theta \mid \lambda)d\theta}{\alpha(\lambda)}$$

Fraction of detectable events

$$\alpha(\lambda) = \int \pi(\theta \mid \lambda)p(\text{det} \mid \theta)d\theta$$

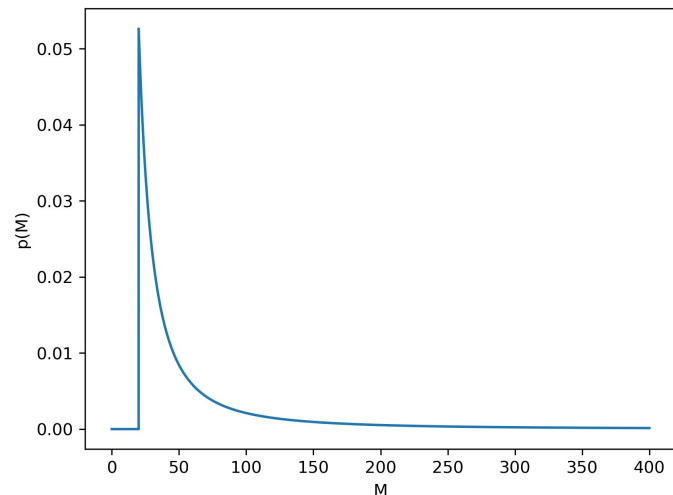
Population model (M, q, z, e)

Assuming independent source parameters:

$$\pi(M, q, z, e \mid \lambda) = \pi(M \mid \lambda_M) \pi(q \mid \lambda_q) \pi(z \mid \lambda_z) \pi(e \mid \lambda_e)$$

Truncated power law

$$\lambda_M = \{k, M_{\min}, M_{\max}\} \quad \# 3$$



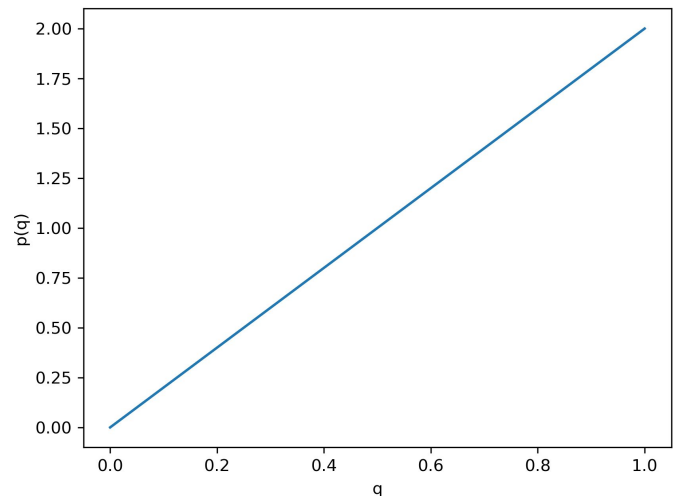
Population model (M, q, z, e)

Assuming independent source parameters:

$$\pi(M, q, z, e \mid \lambda) = \pi(M \mid \lambda_M) \pi(q \mid \lambda_q) \pi(z \mid \lambda_z) \pi(e \mid \lambda_e)$$

Power law in [0,1]

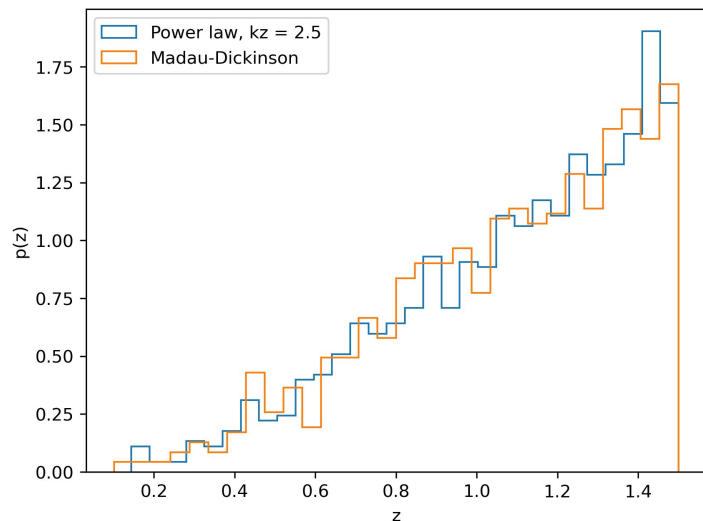
$$\lambda_q = \{a\} \quad \# 1$$



Population model (M, q, z, e)

Assuming independent source parameters:

$$\pi(M, q, z, e \mid \lambda) = \pi(M \mid \lambda_M) \pi(q \mid \lambda_q) \pi(z \mid \lambda_z) \pi(e \mid \lambda_e)$$



Computed with `gwfast` Iacovelli+2022

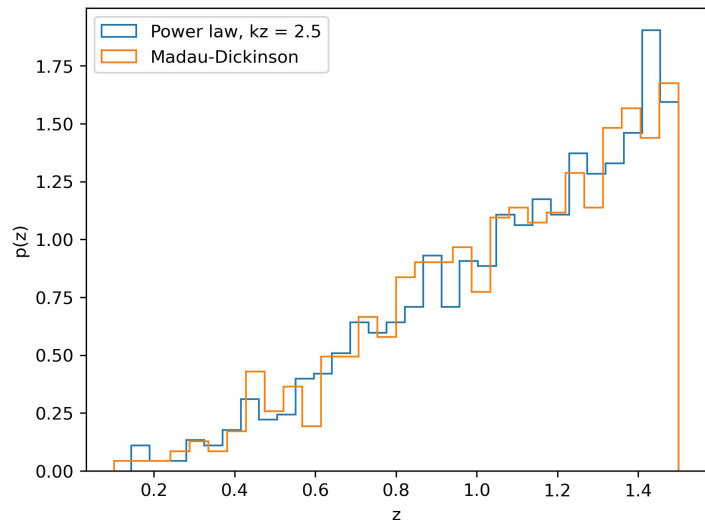
Merger rate depends on redshift

$$\pi(z \mid \lambda_z) \propto \frac{1}{1+z} \frac{dV_c}{dz} \mathcal{R}(z \mid \lambda_z)$$

Population model (M, q, z, e)

Assuming independent source parameters:

$$\pi(M, q, z, e \mid \lambda) = \pi(M \mid \lambda_M) \pi(q \mid \lambda_q) \pi(z \mid \lambda_z) \pi(e \mid \lambda_e)$$



Power law in $[0, 1.5]$

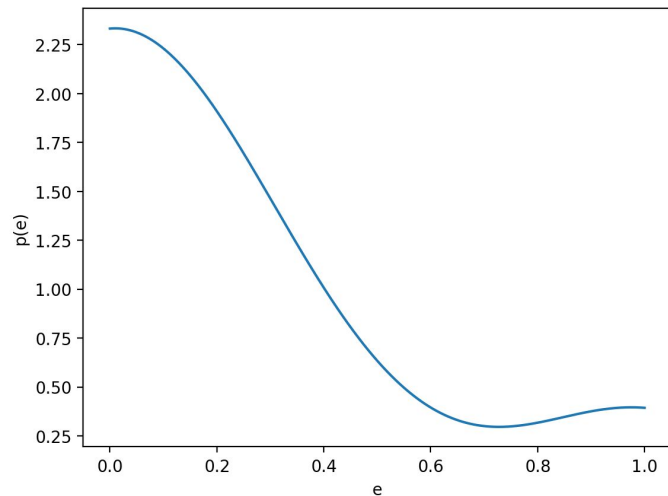
$$\mathcal{R}(z \mid k_z) \propto (1 + z)^{k_z}$$

$$\lambda_z = \{k_z\} \quad \# 1$$

Population model (M, q, z, e)

Assuming independent source parameters:

$$\pi(M, q, z, e \mid \lambda) = \pi(M \mid \lambda_M) \pi(q \mid \lambda_q) \pi(z \mid \lambda_z) \pi(e \mid \lambda_e)$$



Two-Gaussian mixture in [0,1]

$$\lambda_e = \{\sigma_1, \sigma_2, w\} \quad \# 3$$

Selection effects

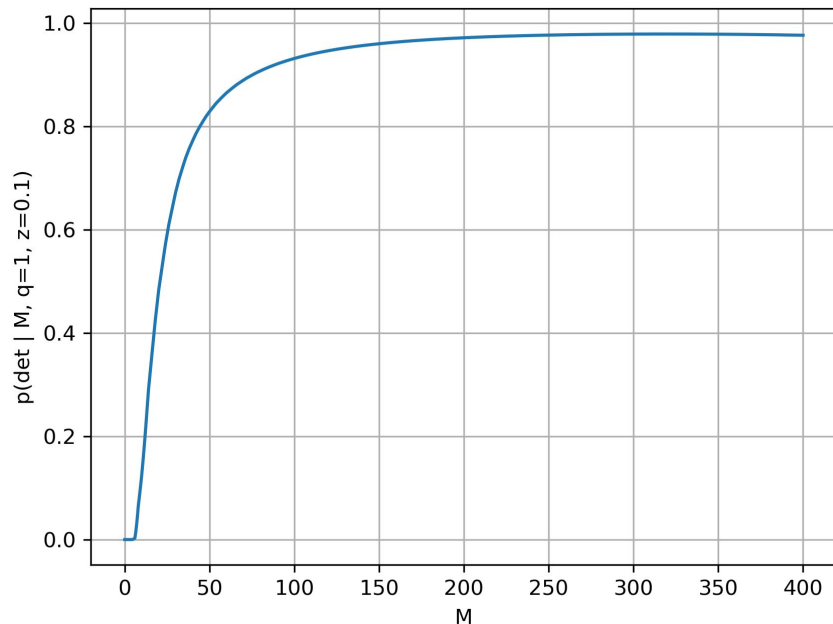
$$p(\text{det} \mid \theta) = p(\text{det} \mid M, q, z)|_{\text{circ}} \cdot p(\text{det} \mid e)$$

Selection effects

$$p(\text{det} \mid \theta) = \boxed{p(\text{det} \mid M, q, z)|_{\text{circ}}} \cdot p(\text{det} \mid e)$$

Computed with `gwdet` github.com/dgerosa/gwdet

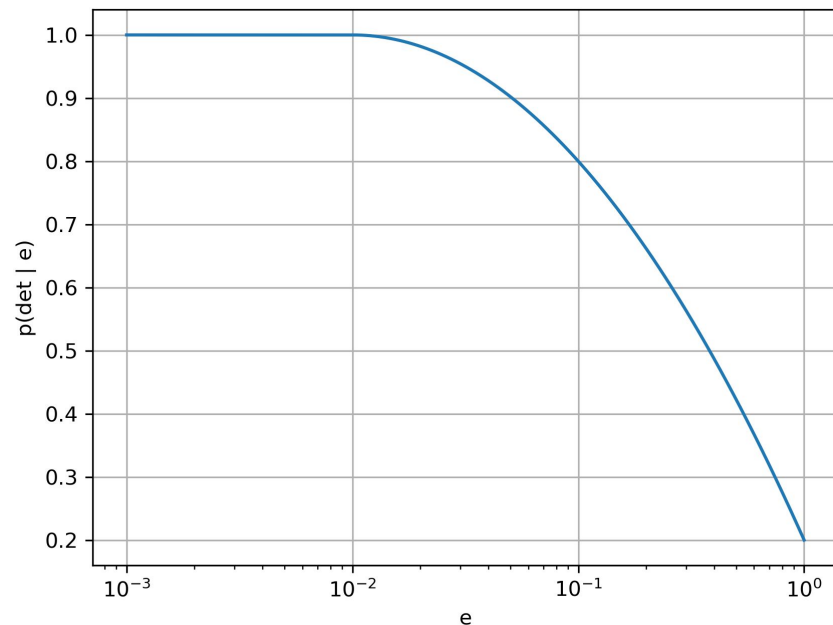
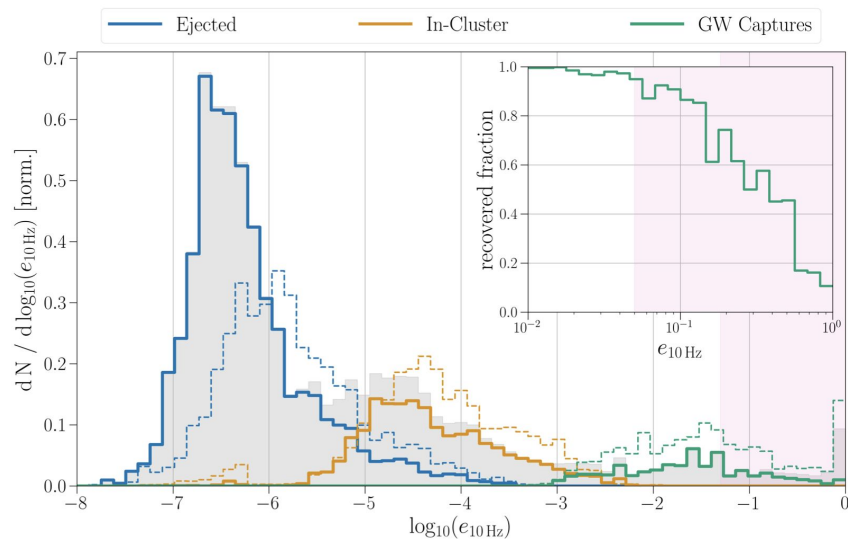
$$\begin{aligned} p(\text{det} \mid m_1, m_2, z) &= P\left(> \frac{\rho_{\text{th}}}{\rho_{\text{opt}}}\right) \\ &= P\left(> \frac{8}{\rho_{\text{opt}}}\right) \end{aligned}$$



Selection effects

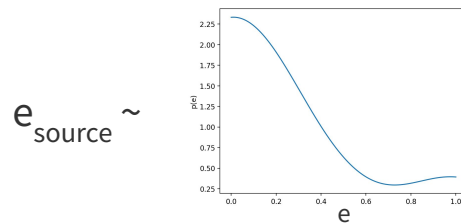
$$p(\text{det} \mid \theta) = p(\text{det} \mid M, q, z)|_{\text{circ}} \cdot p(\text{det} \mid e)$$

Inspired by Zevin+2021



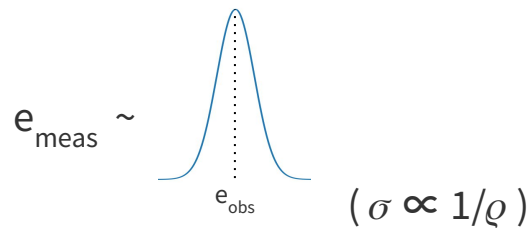
Data preparation

1. Draw N_{source} sources from population

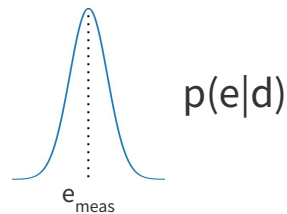


2. Filter by detection probability $\rightarrow N_{\text{obs}} \leq N_{\text{source}}$

3. Simulate noisy measurement with offset



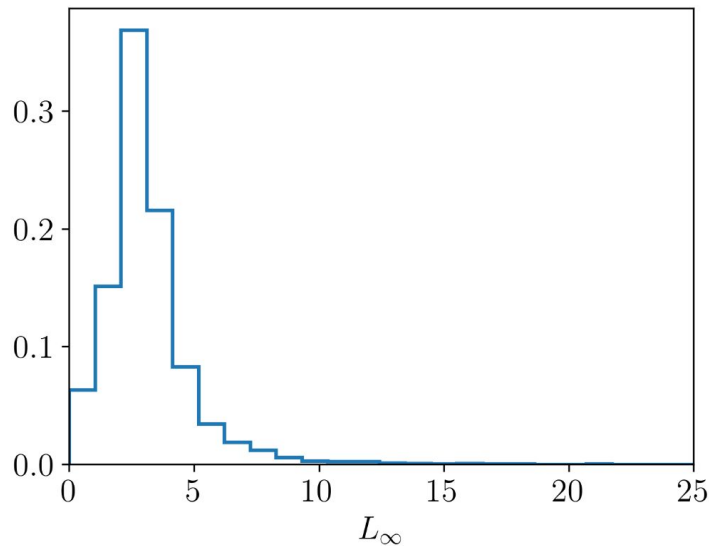
4. Generate mock Gaussian posterior



L at past-time infinity

Integrate Peters' eq., evaluate at $e = 1$

$$L_{\infty} = M^2 \frac{q}{(1+q)^2} \sqrt{\frac{a_0(1-e_0^2)}{M} \frac{(425)^{870/2299}}{e_0^{12/19} (304 + 121e_0^2)^{870/2299}}}$$



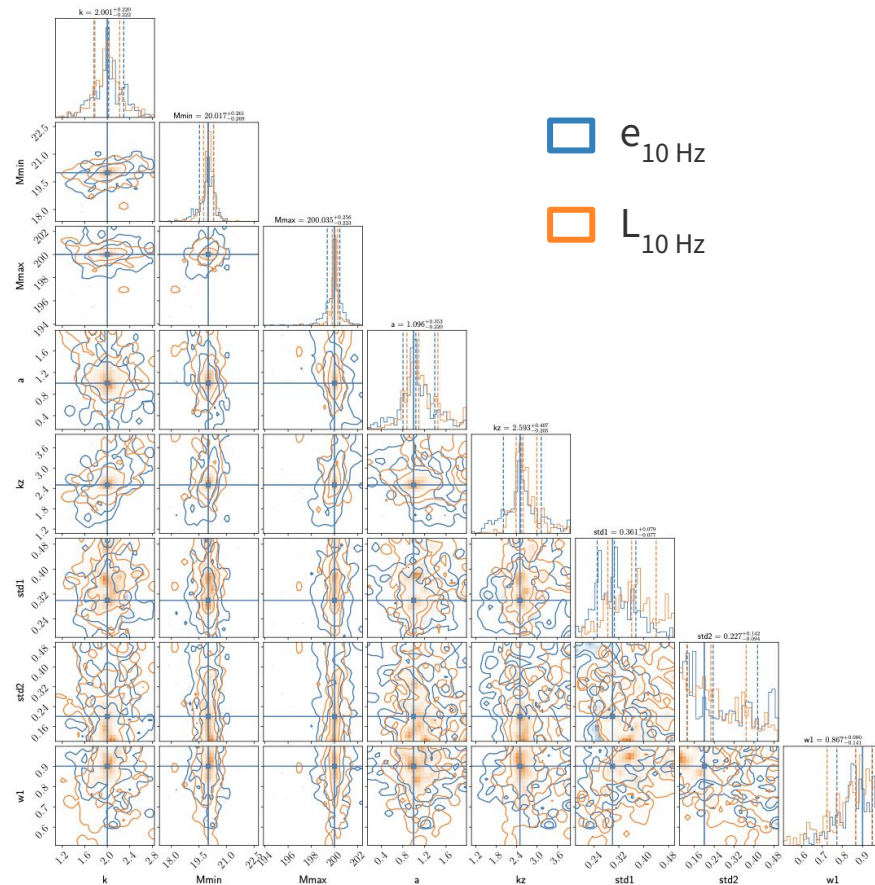
Preliminary test

$$N_{\text{obs}} = 50$$

Next steps:

- $e_{<10 \text{ Hz}}$
- L_{∞}

... and compare



Other activities



Conferences and Workshops

- SIGRAV, Sep 8-12 2025, Milan
- TEONGRAV, Jan 14-16 2026, Pisa

Research Visit Abroad

- Apr 13 – Jul 13, Caltech, USA
- TAPIR Seminar, May 8 2026

Tutoring: exercise sessions for the Physics I course

Credits: 7/11 completed, no courses attended