The impact of astrophysical population model choices on post-Newtonian deviation tests of general relativity

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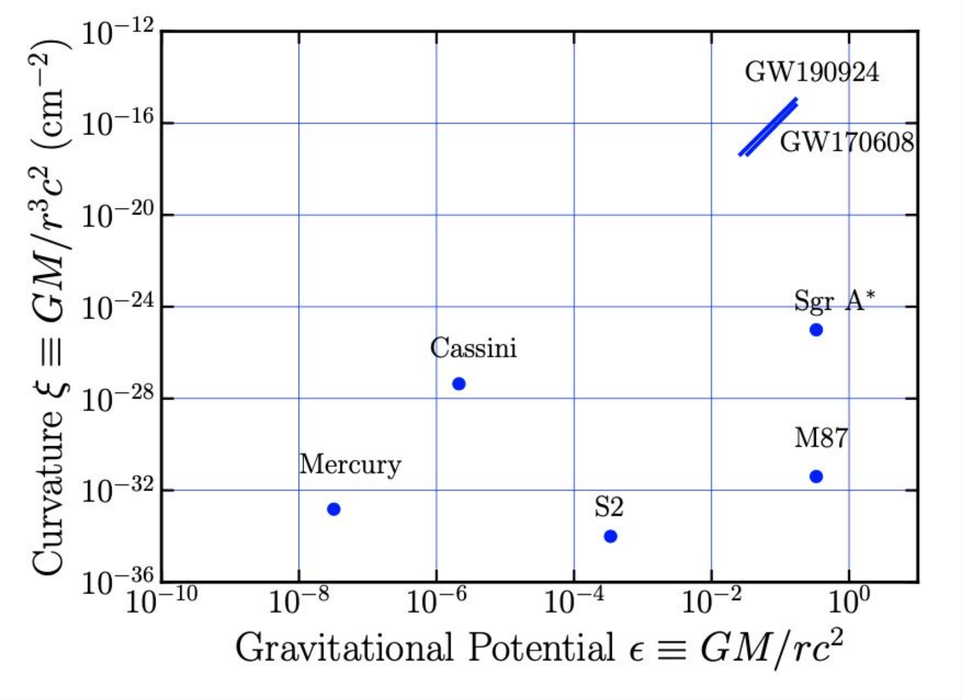
Why we test GR with GWs

Einstein’s theory of general relativity (GR)

Gravitational waves (GWs) as a consequence

Can use GWs to test GR → **the best test**



From Psaltis et al. (2021)

Testing GR (TGR) with individual events

Post-Newtonian tests

Lowest order: quadrupole formula

1. convert GW inspiral data into frequency domain
2. create PN description of inspiral
3. make modifications to PN phase evolution parameters

Bayes' Theorem

Learn about Universe from data by inferring the distribution probable for parameters of events analyzed

$$\overset{\text{posterior}}{p(\theta|d)} = \frac{\overset{\text{likelihood}}{p(d|\theta)}\,\overset{\text{prior}}{\pi(\theta)}}{\mathcal{Z} \xleftarrow{} \text{evidence}}$$

Hierarchically testing GR

Hierarchical (inferring the population parameters from individual events) **TGR relies on inference of the astrophysical population**

likelihood for each individual event

prior for each event

hyper-parameters

population likelihood

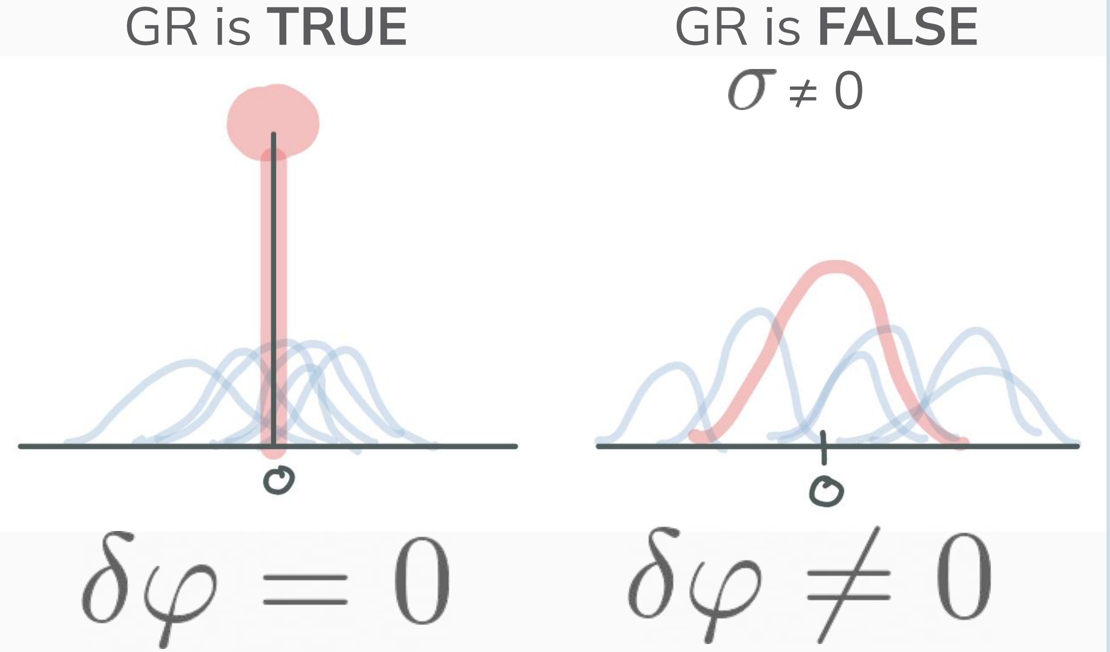
$$p(\{d\}|\Lambda) = \frac{1}{\xi(\Lambda)^N} \prod_{i=1}^{N} \int d\theta_i p(d_i|\theta_i)\pi(\theta_i|\Lambda)$$

collection of N observations

detection fraction

GR deviation model

Gaussian model for GR deviations ⇒ (mean, SD) = **(0,0)** implies **consistency with GR**



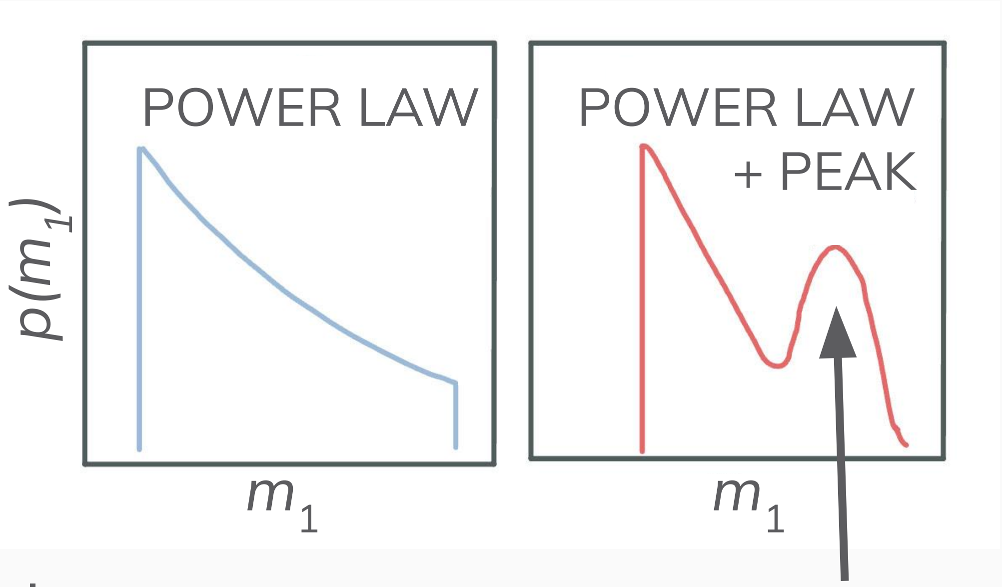
Primary mass population models

POWER LAW and POWER LAW + PEAK

Inject a certain model

Recover with a certain model

Some models can be described by other models



Gaussian peak

Why is this important?

Incorrect astrophysical population model ⇒ <u>biases in supposed deviations from GR</u>

Assuming no astrophysical population model is an incorrect population model

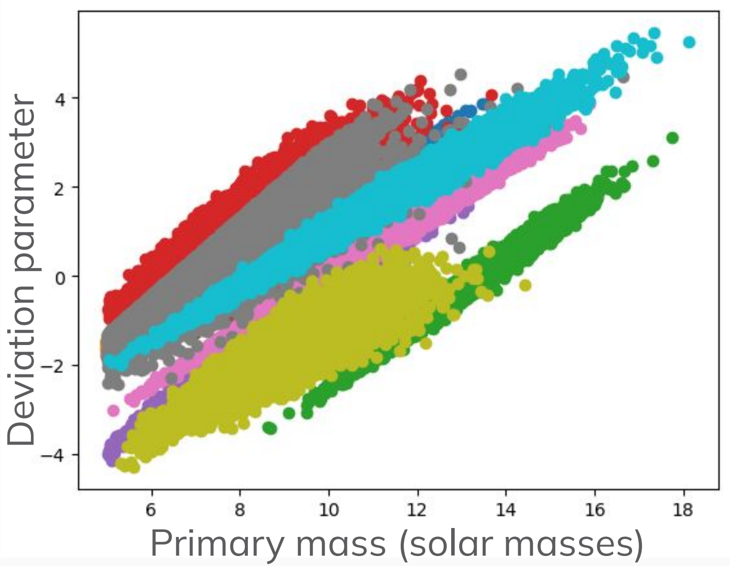
Can implicitly assume an astrophysically impossible population model

I injected...

POWER LAW, POWER LAW + PEAK

Alpha = 2
Beta = 0
Mu = 0
Sigma = 0, 0.25, 0.5

for only POWER LAW + PEAK:
Peak_frac = 0.1
Peak_mu = 35
Peak_sigma = 7

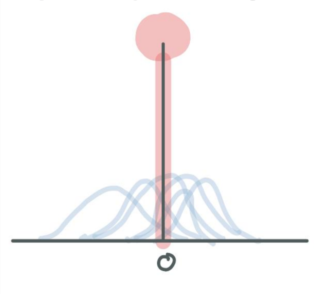


N = 100 events
GWFish to simulate posteriors from 3rd generation GW detectors
Deviation parameter correlated to mass

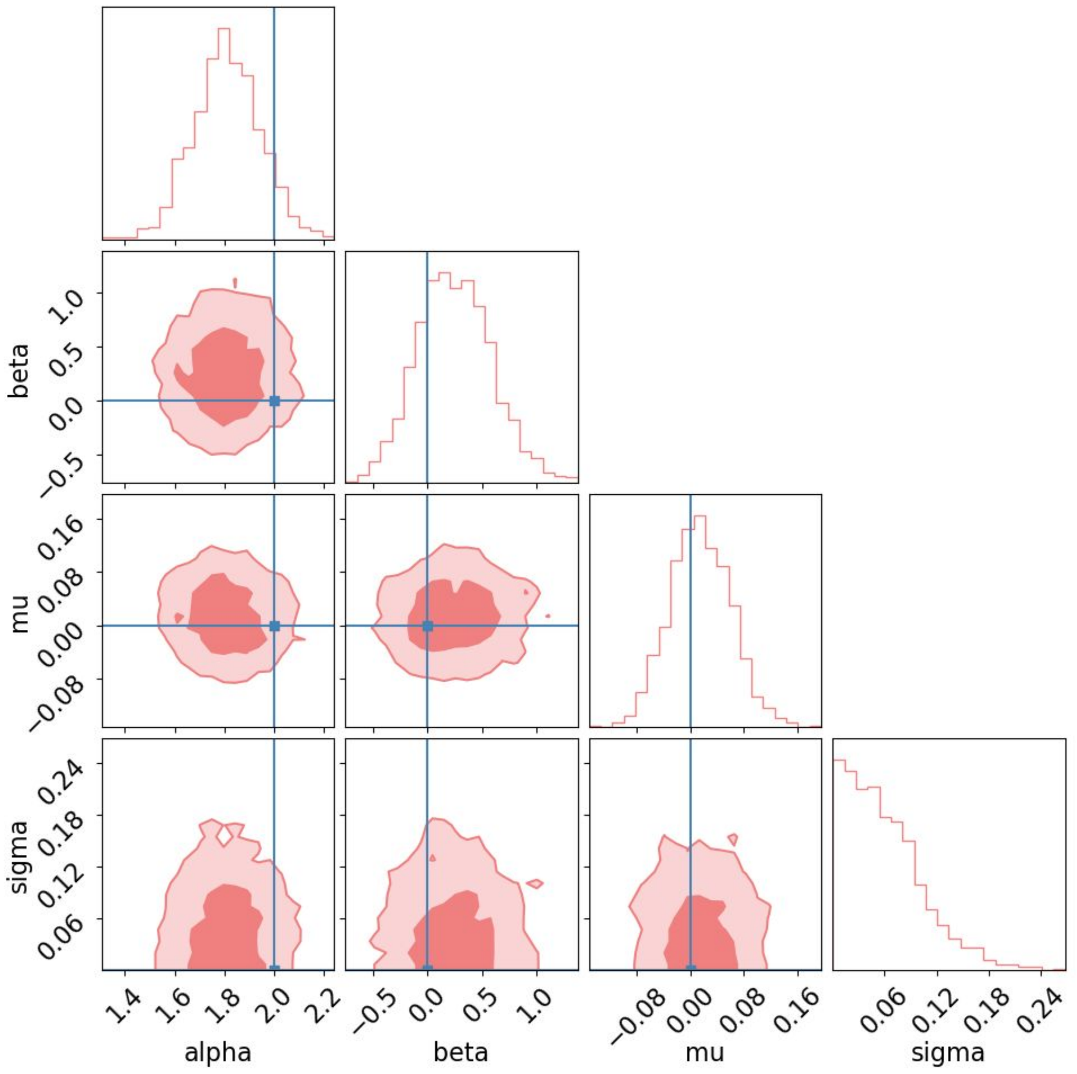
Injected:
POWER LAW
Recovered:
POWER LAW

GR is injected to be **True**

GR is **TRUE**



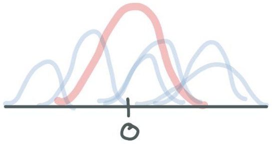
$$\delta\varphi = 0$$



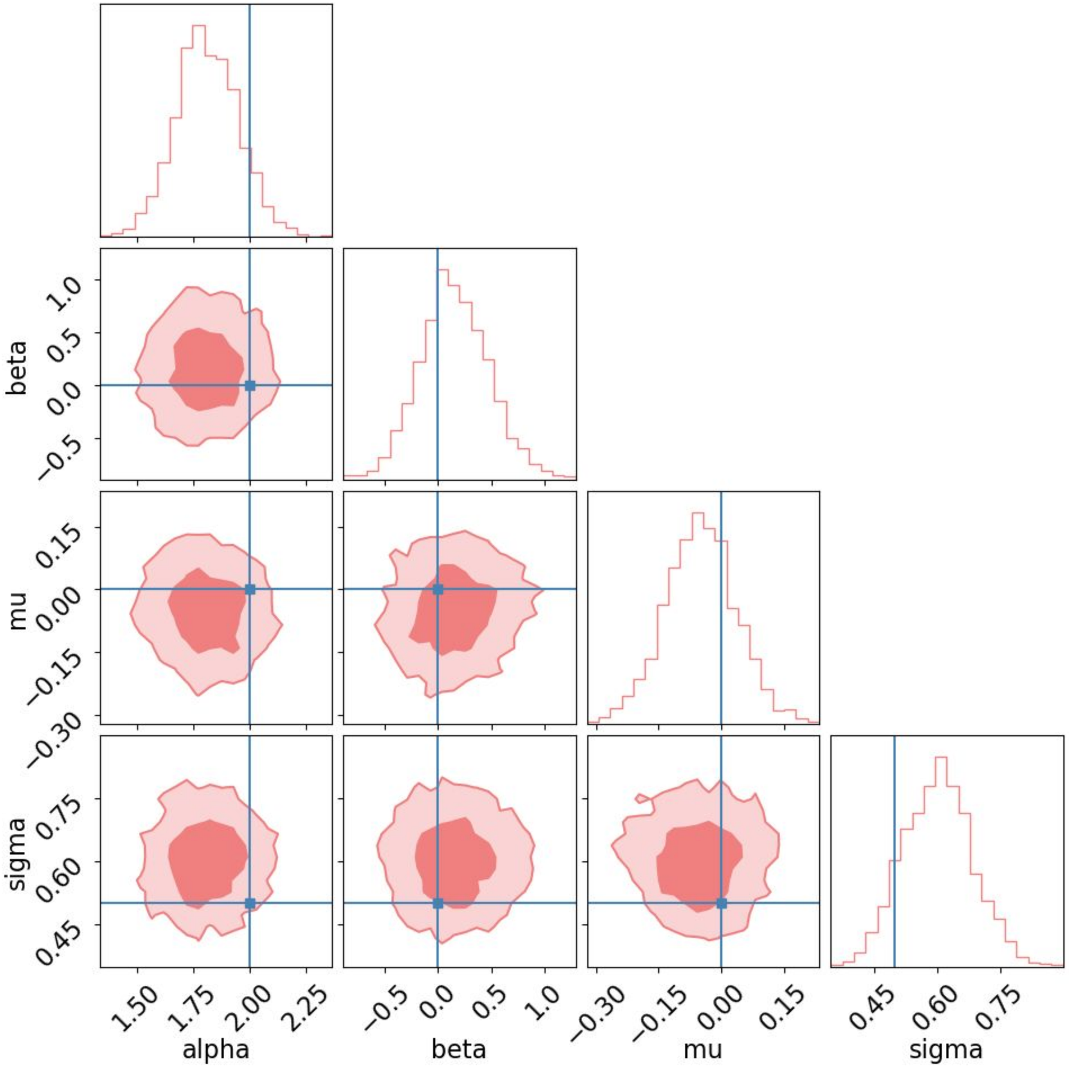
Injected:
POWER LAW
Recovered:
POWER LAW

GR is injected to be **False** with a sigma of **0.5**

GR is
FALSE
$\sigma \neq 0$



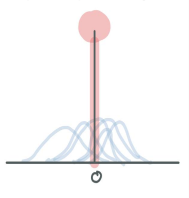
$$\delta\varphi \neq 0$$



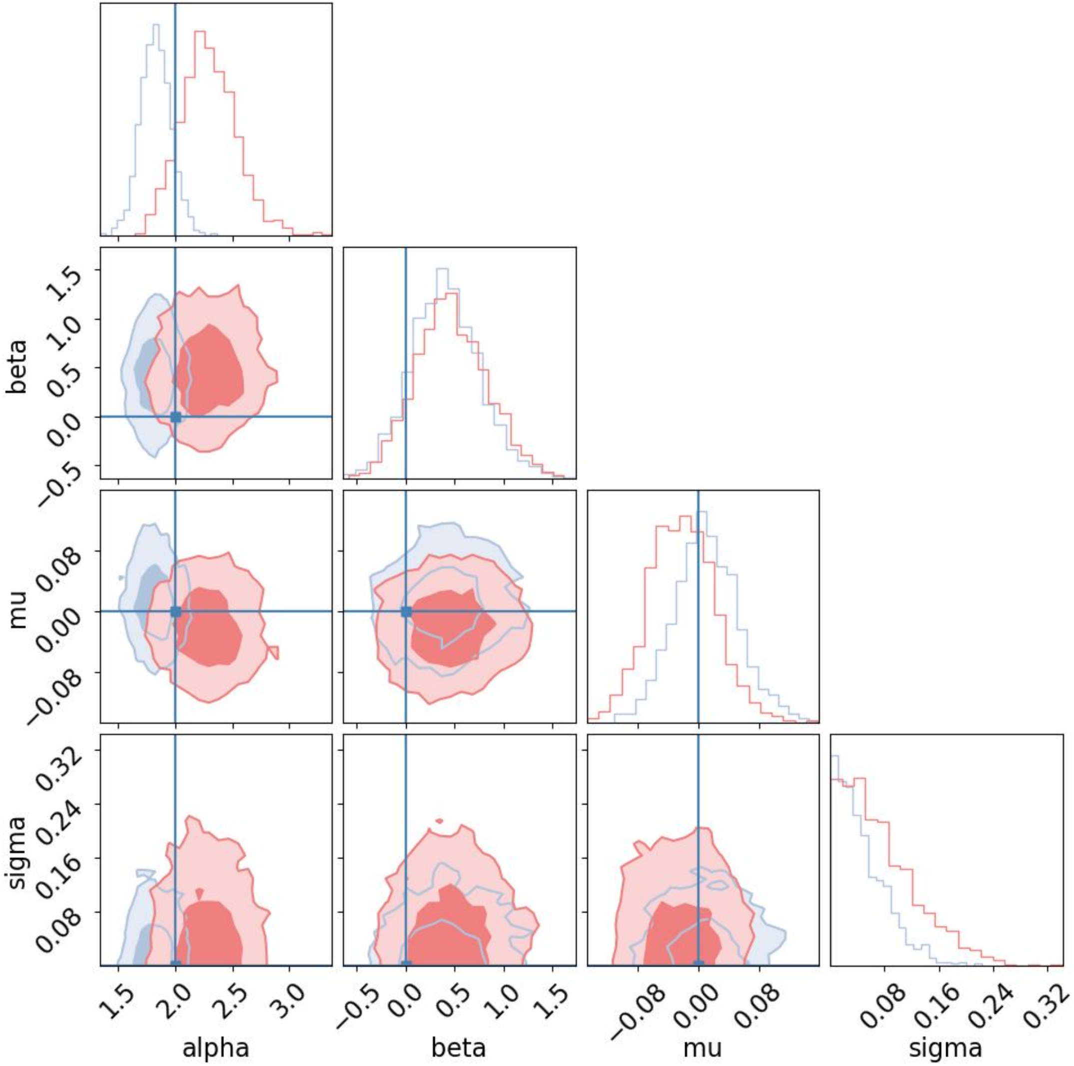
Injected:
POWER LAW + PEAK
Recovered:
POWER LAW
POWER LAW + PEAK

GR is injected to be **True**

GR is **TRUE**



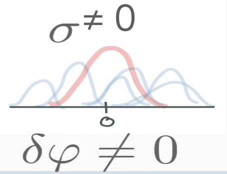
$\delta\varphi = 0$

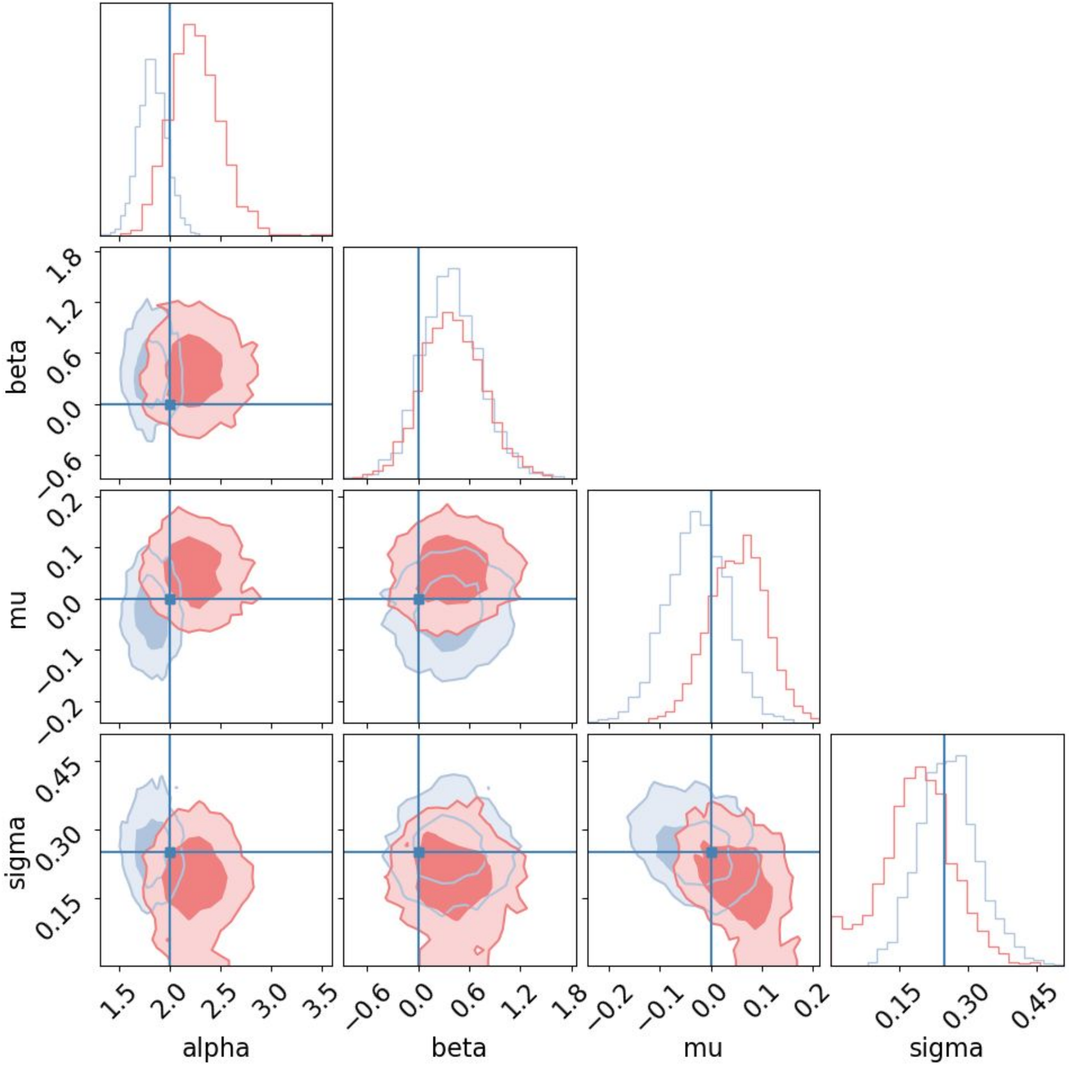


Injected:
POWER LAW + PEAK
Recovered:
POWER LAW
POWER LAW + PEAK

GR is injected to be **False** with a sigma of **0.25**

GR is **FALSE**



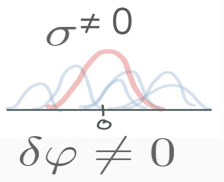


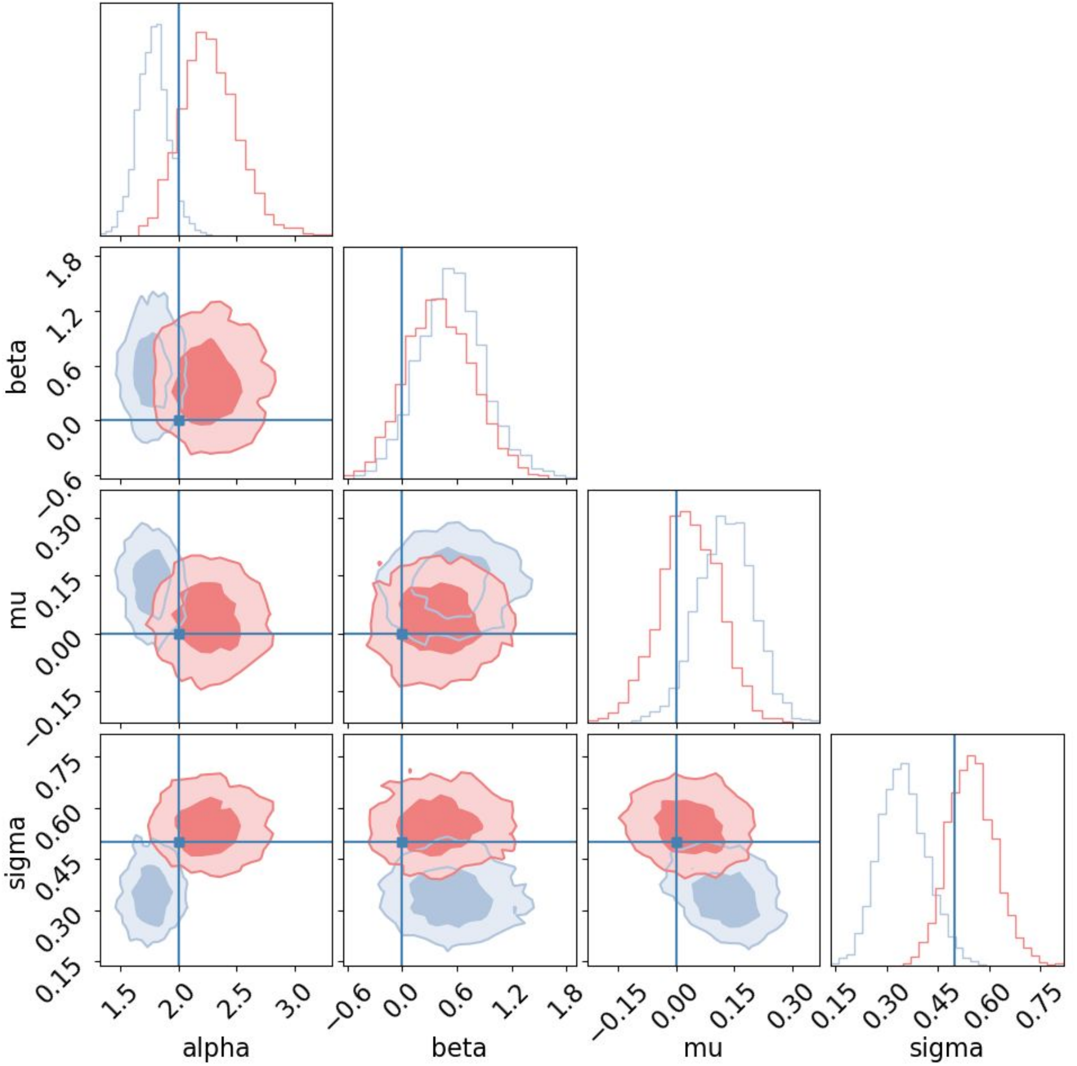
Injected:
POWER LAW + PEAK

Recovered:
POWER LAW
POWER LAW + PEAK

GR is injected to be **False** with a sigma of **0.5**

GR is **FALSE**

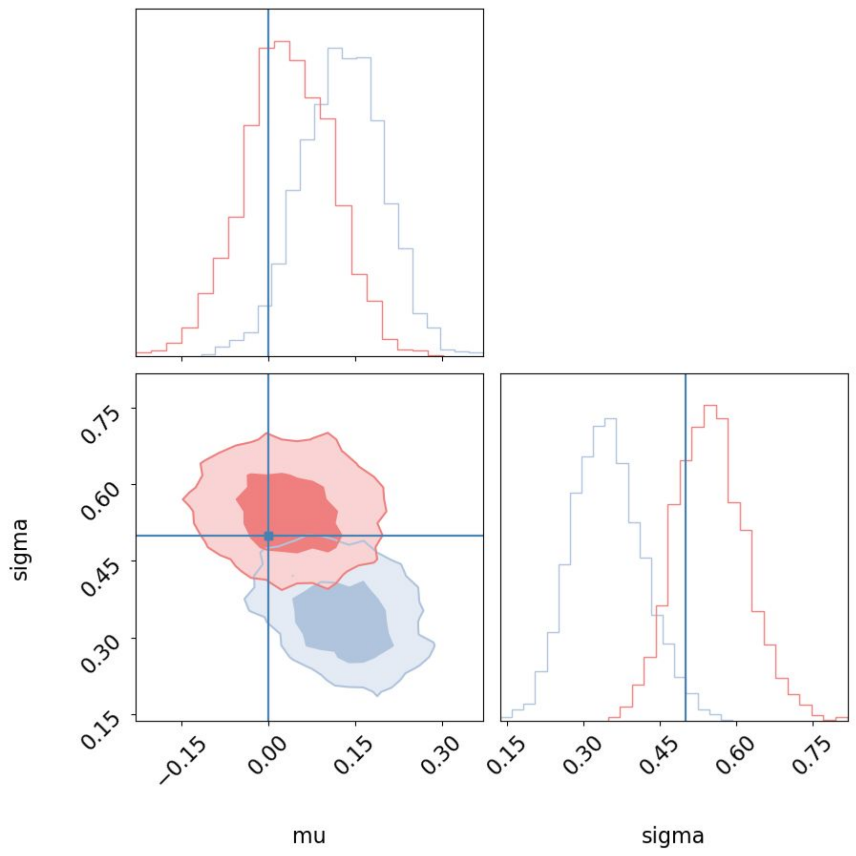




Implications

Using a misspecified astrophysical population model leads to **inaccurate recoveries of GR deviations**

⇒ it could be plausible that **inconsistencies with GR are masked** by using a misspecified astrophysical population model



Conclusion

Hierarchical TGR (Gaussian model of GR deviations) relies on an astrophysical population model

Generated simulated catalog of 100 events using POWER LAW and POWER LAW + PEAK models, sampled with GWFish

Correlated primary mass and GR deviation parameter to simulate PN deviation test

Markov chain Monte Carlo to recover GR deviation parameters using each model

Acknowledgements

This work was supported by the National Science Foundation Research Experience for Undergraduates (NSF REU) program, the LIGO Laboratory Summer Undergraduate Research Fellowship program (NSF LIGO), and the California Institute of Technology Student-Faculty Programs. I would like to thank my mentor, Ethan Payne, my fellow LIGO SURF-ers, my family and friends, and all of the faculty and mentors at the LIGO SURF program, especially Alan Weinstein and Jonah Kanner.

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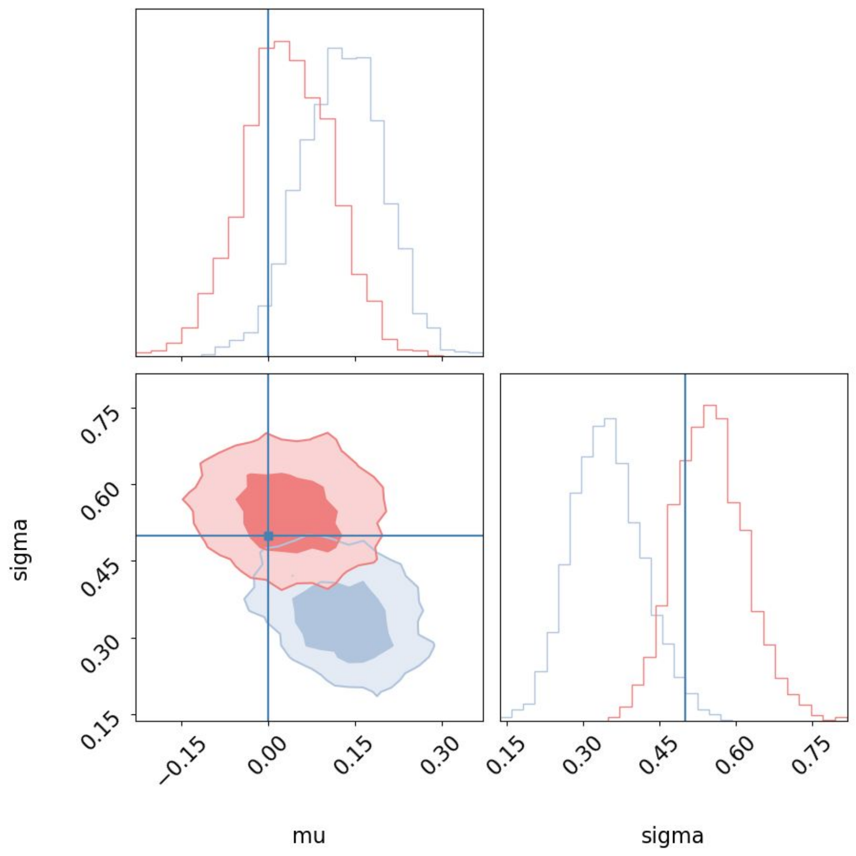
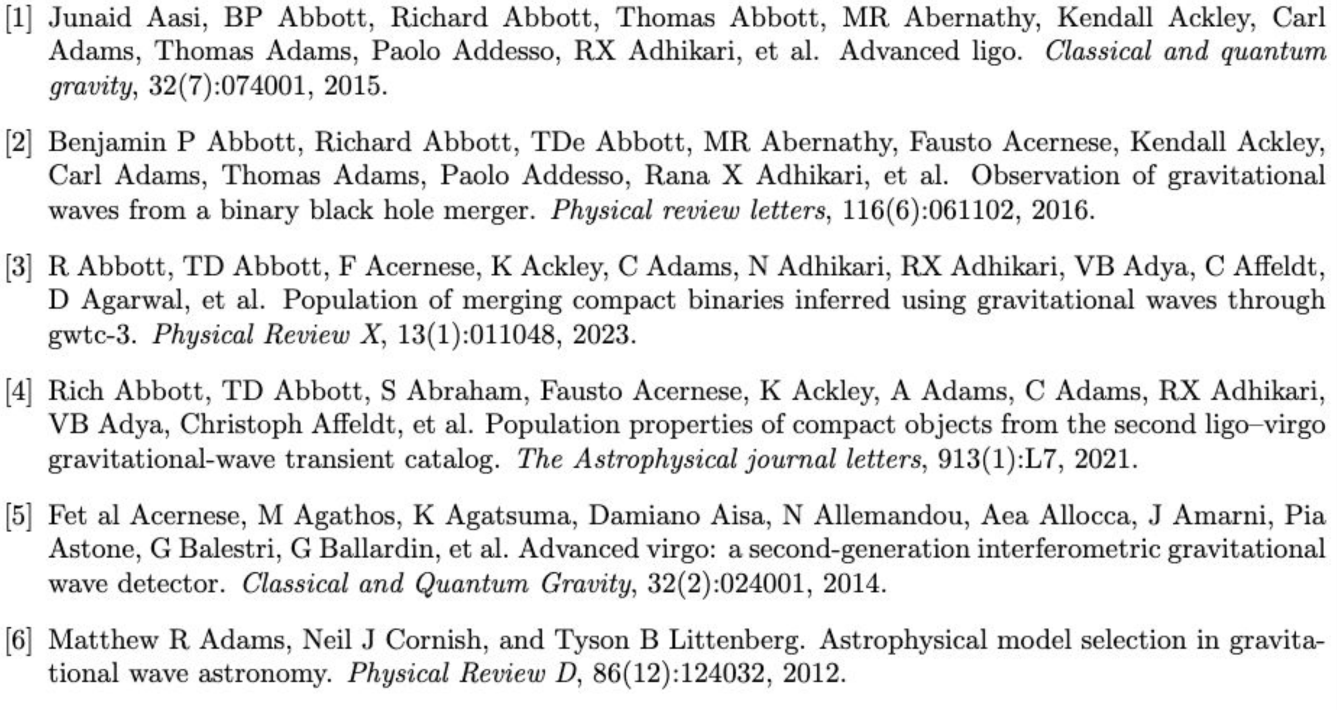


Important conclusions

Using a misspecified astrophysical population model leads to **inaccurate recoveries of GR deviations**

It is possible that **inconsistencies with GR are masked** by using a misspecified astrophysical population model

References



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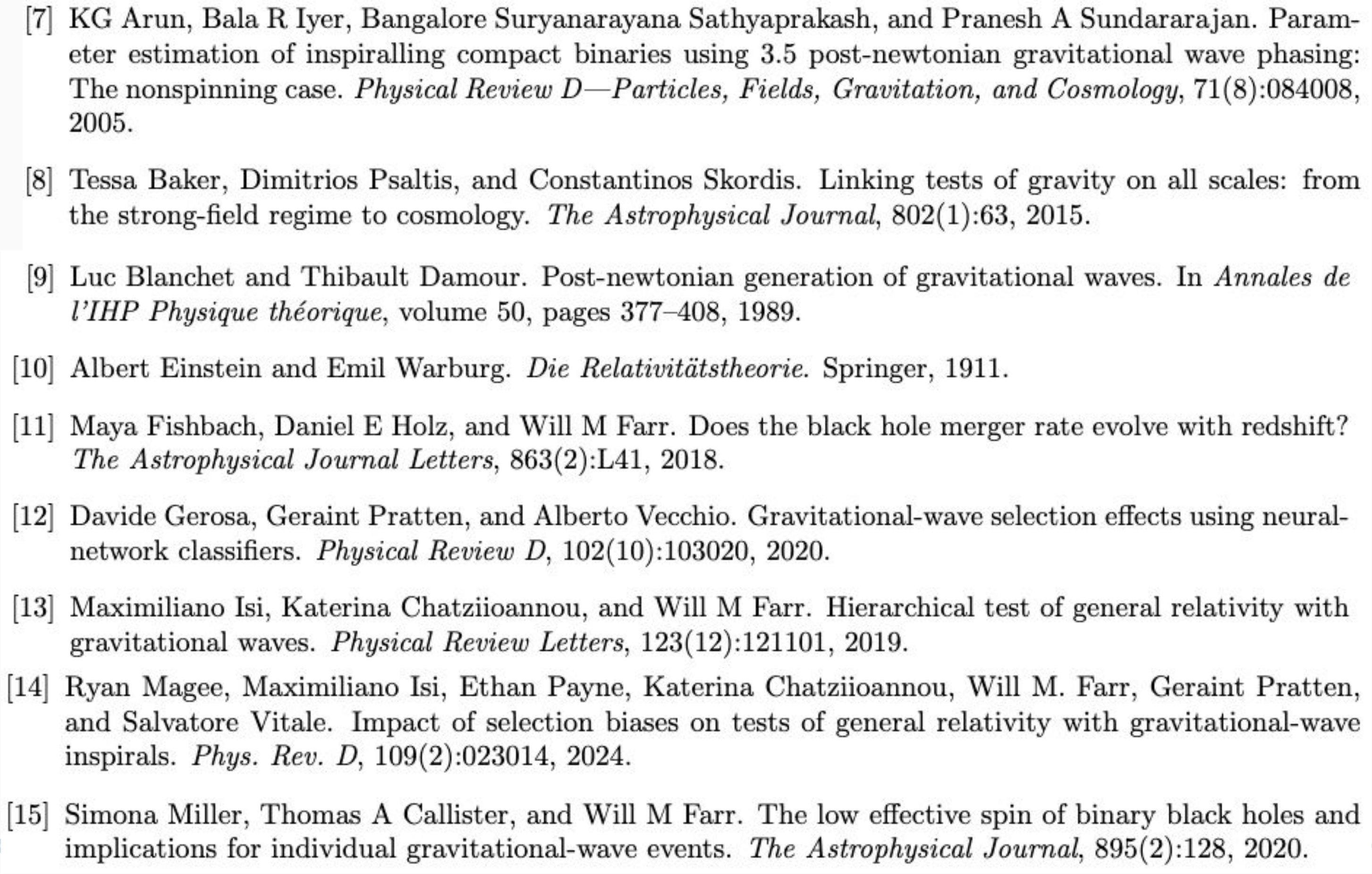

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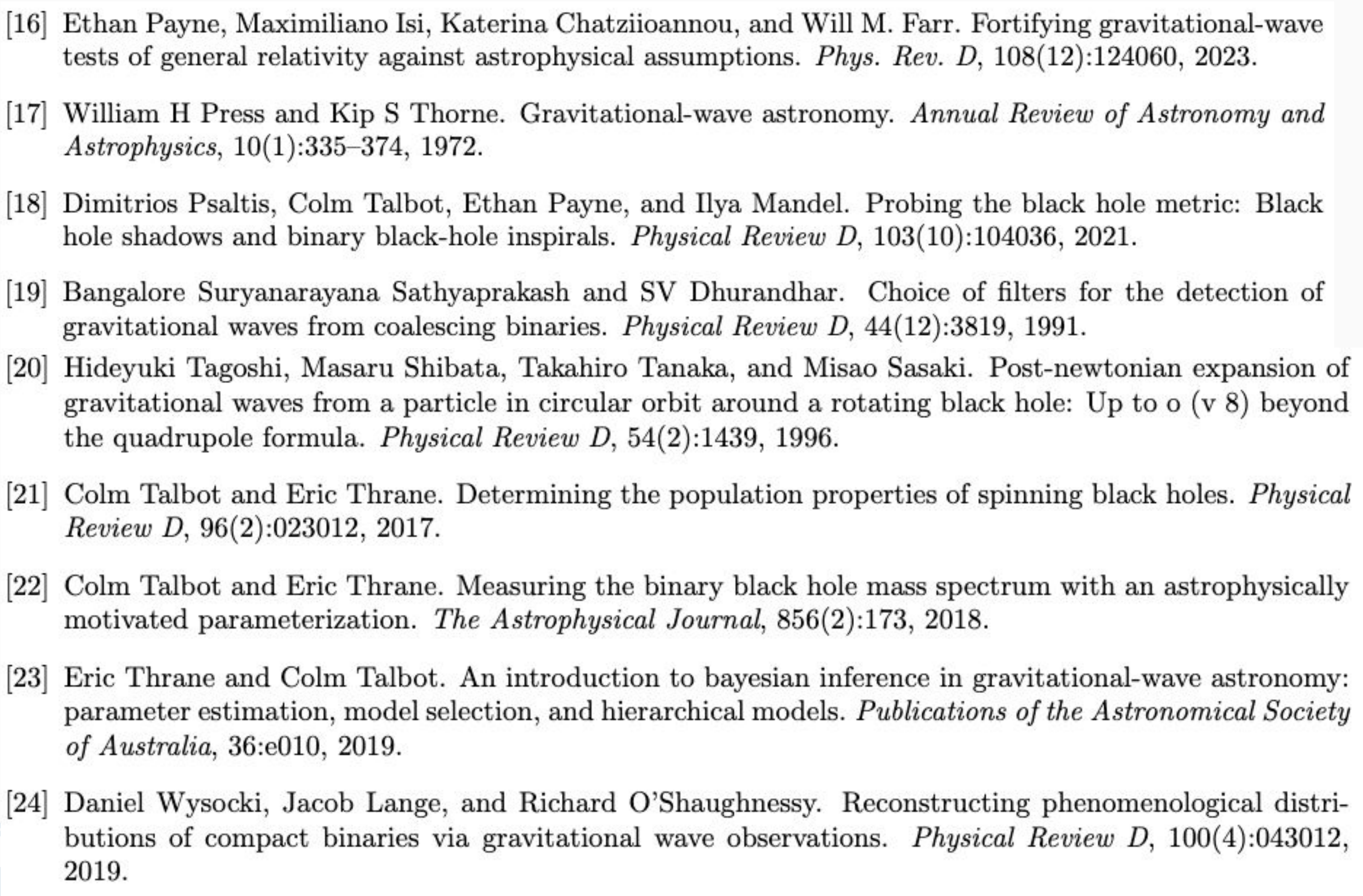

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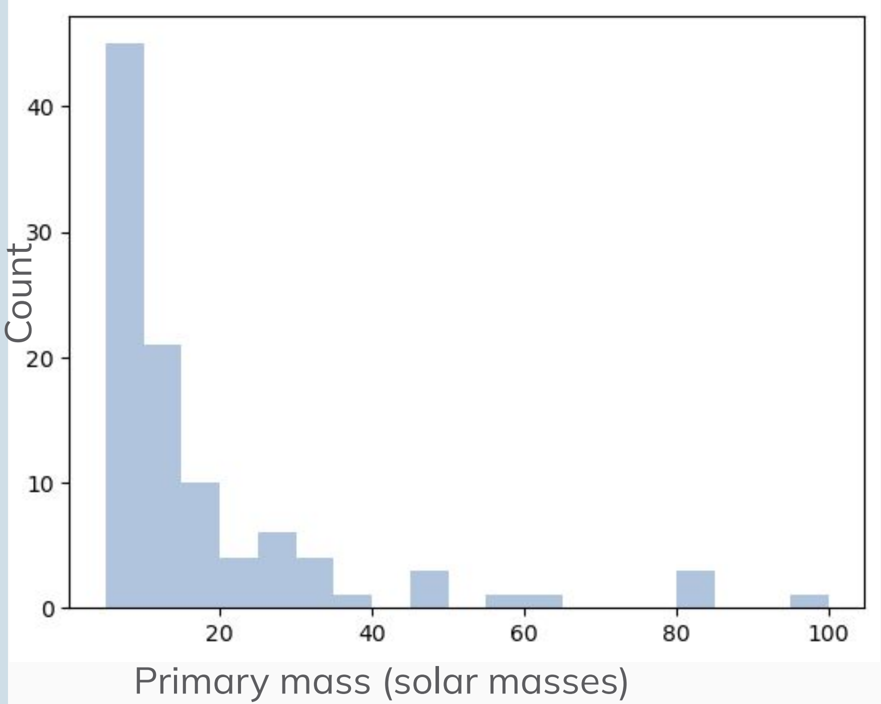
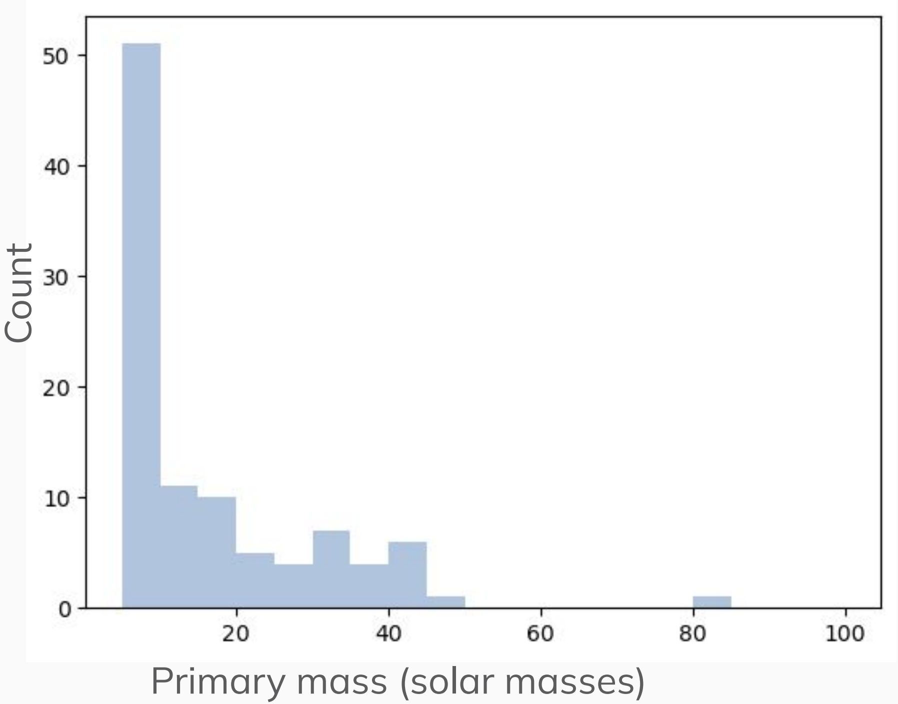
POWER LAW population

POWER LAW + PEAK population

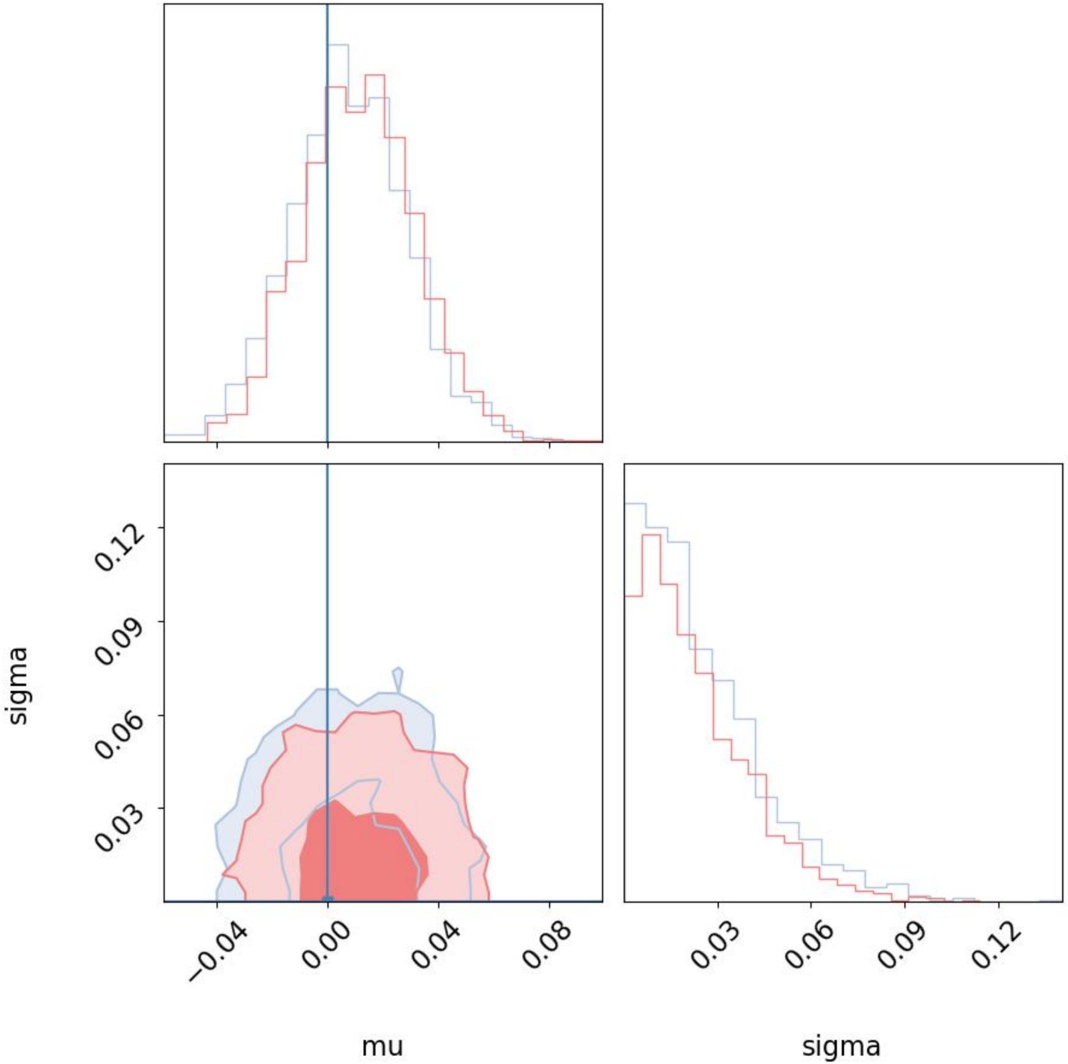




Injected: POWER LAW **Recovered:** POWER LAW POWER LAW + PEAK

GR is injected to be **True**

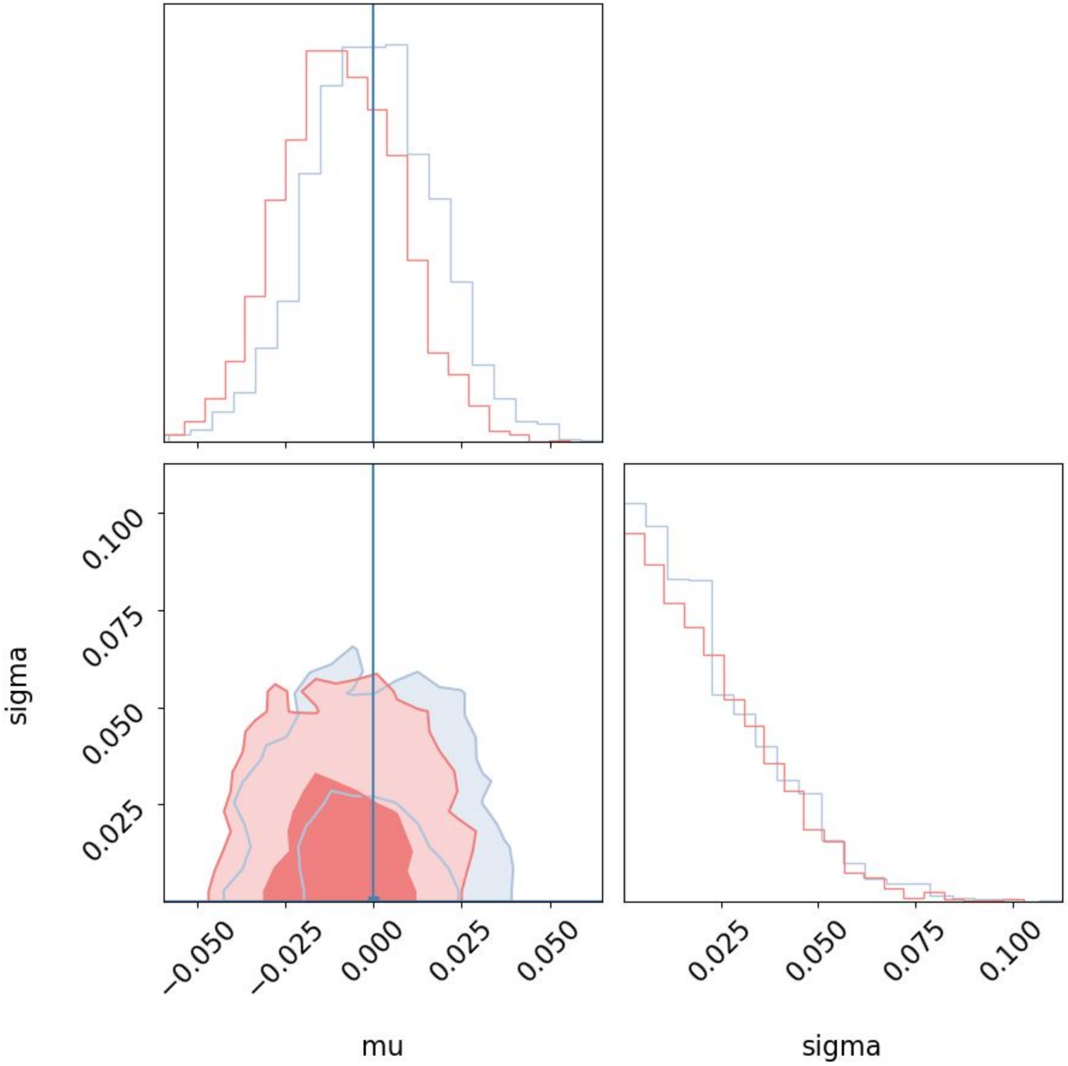
N = 250



Injected:
POWER
LAW
Recovered:
POWER
LAW
POWER
LAW +
PEAK

GR is
injected to
be **True**

N = 500



Injected:
GAUSSIAN
Recovered:
POWER
LAW

GR is injected to be **True**

N = 500