Lightning-Fast Gravitational Wave Parameter Inference through Neural Amortization

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Motivation

Gravitational waves from compact binaries are routinely analyzed using MCMC sampling algorithms which typically requires days of computation. We show how neural simulation-based inference can speed up the inference time from days to minutes.

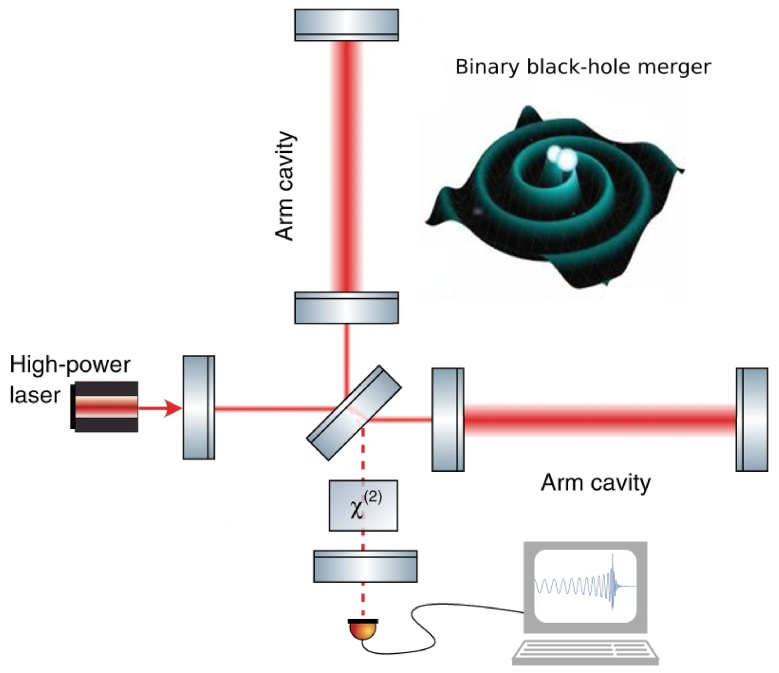


Figure: Adapted from Korobko et al., 2019

$\boldsymbol{\vartheta}$: Binary black-hole merger parameters of interest
$\boldsymbol{\theta}$: Nuisance parameters
$\boldsymbol{x}$: Gravitational wave signal

Objective: Given a detected gravitational wave $\boldsymbol{x}_0$, compute $p(\boldsymbol{\vartheta}|\boldsymbol{x}=\boldsymbol{x}_0)$ based on a model for $p(\boldsymbol{x}|\boldsymbol{\vartheta},\boldsymbol{\theta})$ and a prior $p(\boldsymbol{\vartheta},\boldsymbol{\theta})$

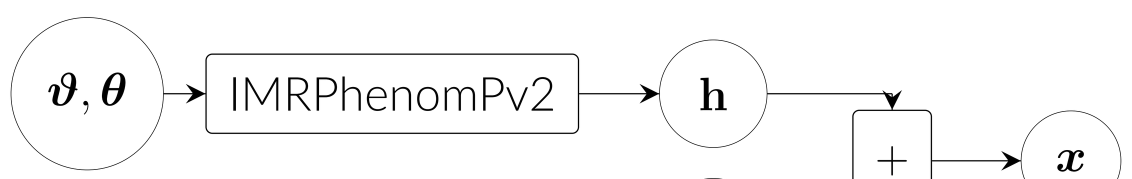
$$p(\boldsymbol{\vartheta}|\boldsymbol{x}=\boldsymbol{x}_0) = \frac{p(\boldsymbol{x}_0|\boldsymbol{\vartheta})}{p(\boldsymbol{x}_0)}p(\boldsymbol{\vartheta}) = \frac{\int p(\boldsymbol{x}_0|\boldsymbol{\vartheta},\boldsymbol{\theta})d\boldsymbol{\theta}}{\underbrace{\int p(\boldsymbol{x}_0|\boldsymbol{\vartheta},\boldsymbol{\theta})d\boldsymbol{\vartheta}d\boldsymbol{\theta}}_{\text{Intractable}}}p(\boldsymbol{\vartheta}).$$

Current analyses

- Sample from $p(\boldsymbol{\vartheta},\boldsymbol{\theta}|\boldsymbol{x}=\boldsymbol{x}_0)$ using MCMC techniques.
- Estimate $p(\boldsymbol{\vartheta}|\boldsymbol{x}=\boldsymbol{x}_0)$ based on those samples.

→ Works but **slow**!

Signal model



$\boldsymbol{x}$:
- Signals such as detected by the Hanford (H1) and Livingston (L1) detectors
- 4 seconds of signal (~ from 3.5 s before merge time to 0.5 s after merge time)
- sampled at 2048 Hz

Preprocessing:
- Whitenning
- 20 Hz high-pass filtering

Amortization

Amortization principle

- Build a model for $p(\boldsymbol{\vartheta}|\boldsymbol{x})$ beforehand (**slow**)
- Use this model to evaluate $p(\boldsymbol{\vartheta}|\boldsymbol{x}=\boldsymbol{x}_0)$ (**fast**)

We aim to approximate the likelihood-to-evidence ratio

$$r(\boldsymbol{x}|\boldsymbol{\vartheta}) \equiv \frac{p(\boldsymbol{x}|\boldsymbol{\vartheta})}{p(\boldsymbol{x})}.$$

We train a convolutional neural network s to discriminate between

$$(\boldsymbol{x},\boldsymbol{\vartheta}) \sim p(\boldsymbol{x},\boldsymbol{\vartheta}) \to y=1 \quad \text{and} \quad (\boldsymbol{x},\boldsymbol{\vartheta}) \sim p(\boldsymbol{x})p(\boldsymbol{\vartheta}) \to y=0.$$

We use it to compute an approximation of the likelihood-to-evidence ratio [Hermans et al., 2019]

$$\hat{r}(\boldsymbol{x}|\boldsymbol{\vartheta}) = \frac{s(\boldsymbol{x},\boldsymbol{\vartheta})}{1-s(\boldsymbol{x},\boldsymbol{\vartheta})}, \qquad \hat{p}(\boldsymbol{\vartheta}|\boldsymbol{x}) = \hat{r}(\boldsymbol{x}|\boldsymbol{\vartheta})p(\boldsymbol{\vartheta}).$$

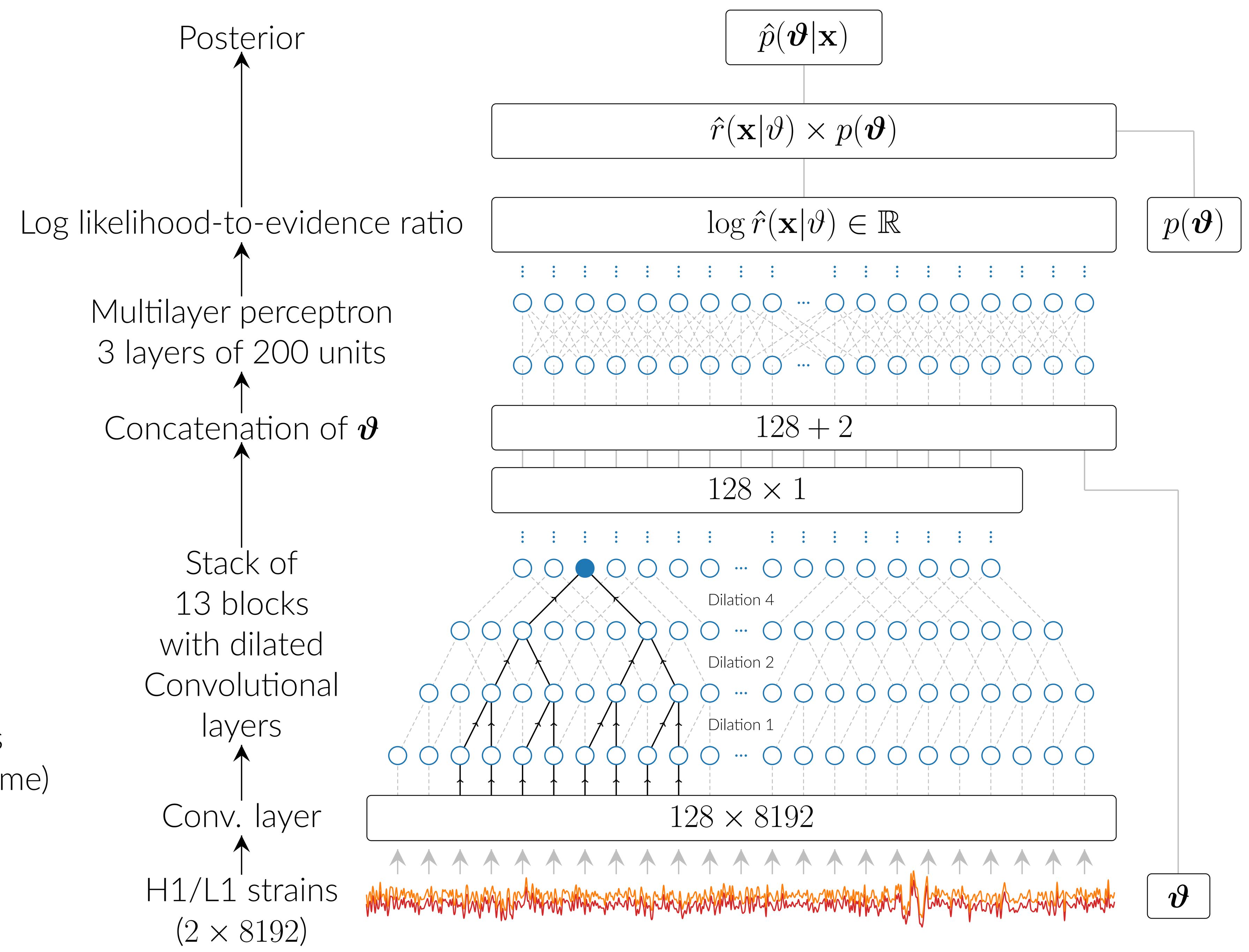
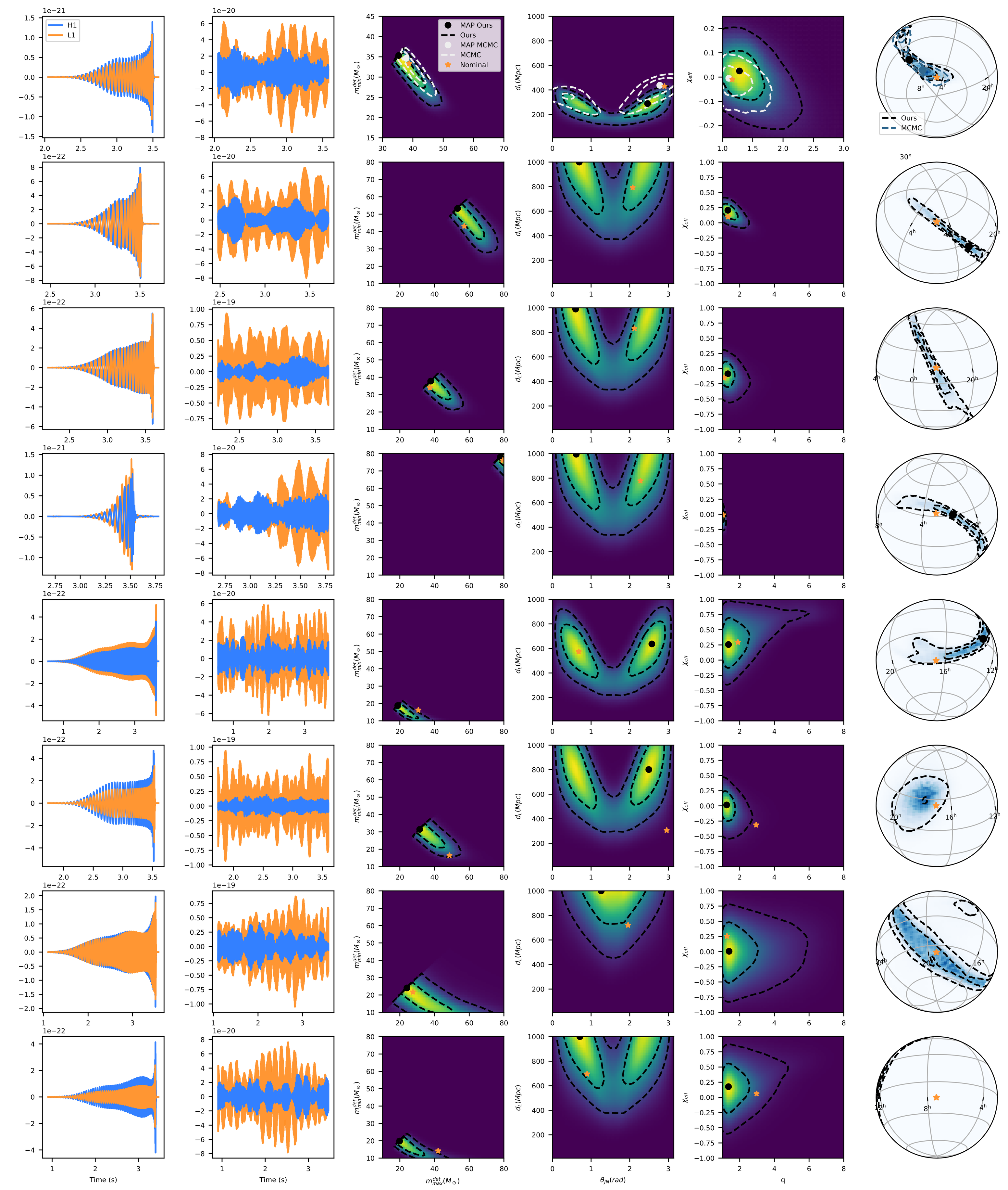


Figure: Adapted from Gebhard et al., 2019.

Results

Credible intervals derived using our method on simulated gravitational waves.
First line: comparison between our method and MCMC.

MCMC : ~ 1 day
Our method : ~ 1 minute



Take-home message

- Neural amortization reduces inference time from days to minutes.
- Our method produces credible intervals that are less constrained than those produced with MCMC techniques but results are promising.
- Further assessments of the statistical validity of the estimated posteriors would be needed before making any reliable scientific claims.