Robust parameter estimation within minutes on gravitational wave signals from binary neutron star inspirals

Wouters et al., arxiv:2404.11397

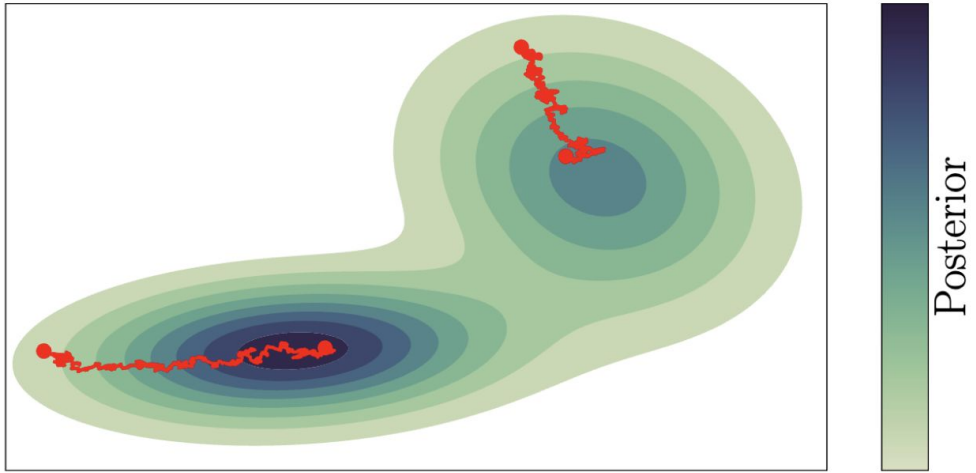
Peter T. H. Pang

Nikhef

Utrecht University

Parameter estimation

$$p(\vec{\theta}|d) = \frac{p(d|\vec{\theta})p(\vec{\theta})}{p(d)}$$
$$= \frac{\text{likelihood} \times \text{prior}}{\text{evidence}}$$



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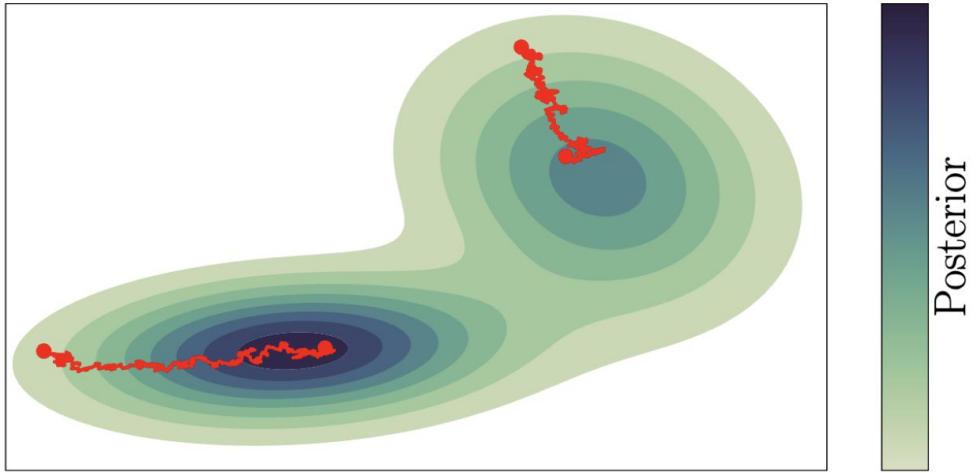
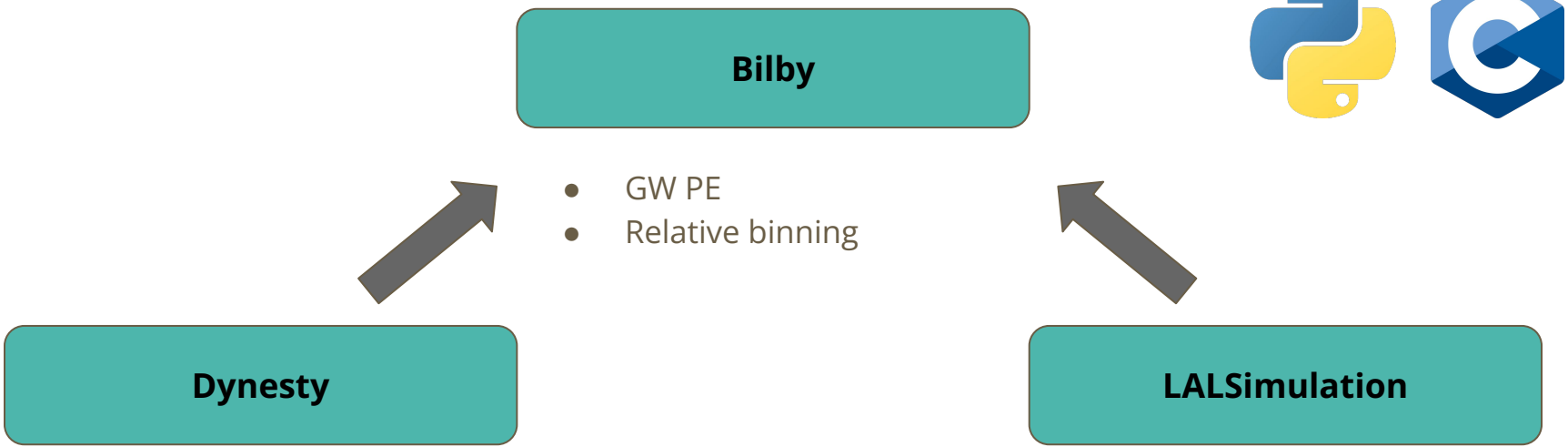


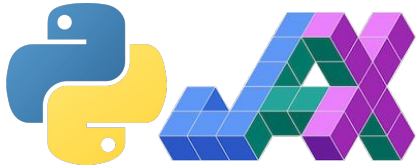
Parameter estimation is expensive!!

Overview


Bilby
GW PE
Relative binning
Dynesty
Nested sampling
LALSimulation
Waveforms

Overview

- JIM: Fast and robust parameter estimation pipeline of GW signal powered by JAX
- PE on BBH within minutes (Wong et al. *Astrophys.J.* 958 (2023) 2, 129)



JIM

- GW PE
- Relative binning

- Auto-differentiable
- Hardware acceleration
- Just-in-time compilation

FlowMC

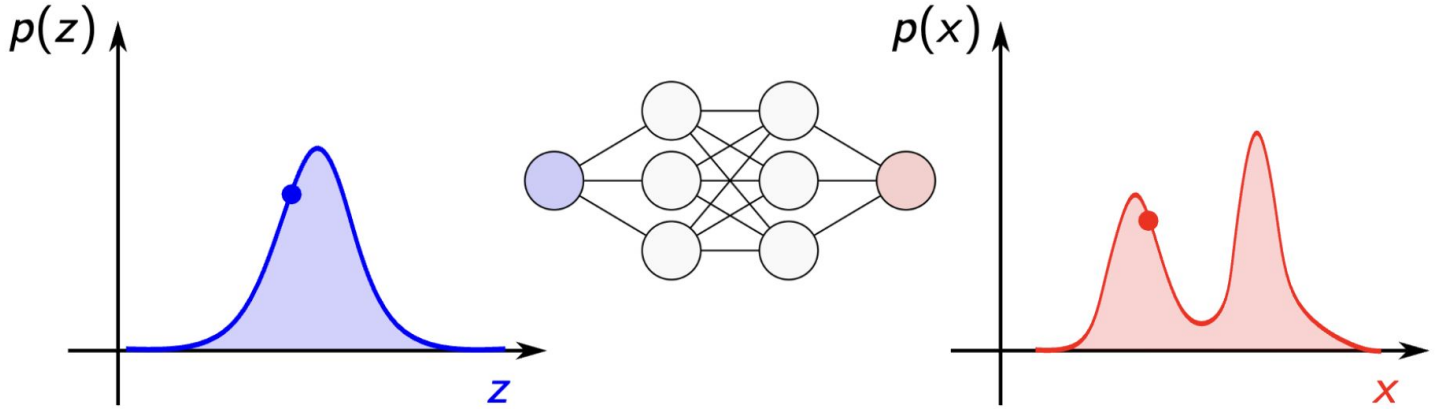
- Gradient-based MCMC
- Normalizing flow

Ripple

- JAX waveforms
- Auto-differentiable

Normalizing flow

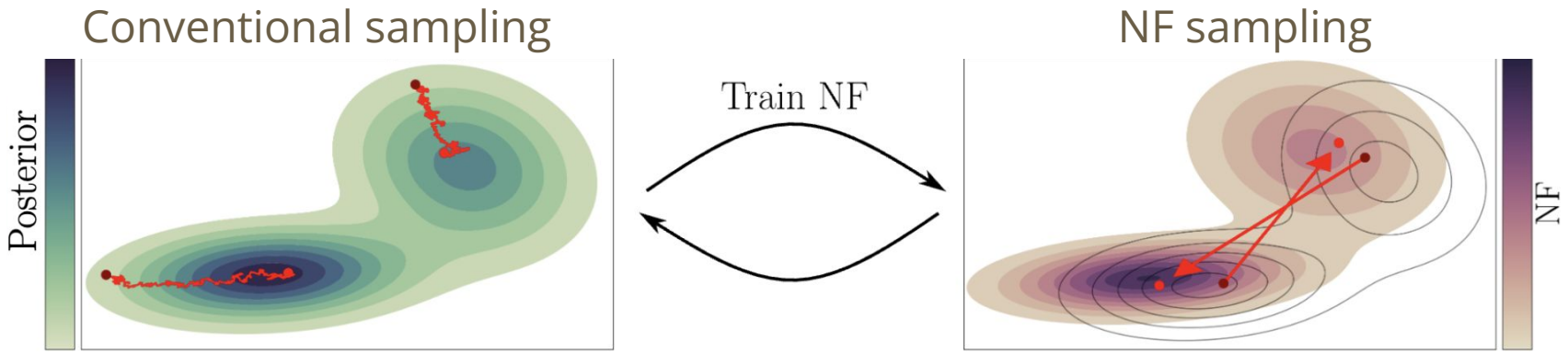
- Generative machine learning model
- Learn the mapping between **latent** space and **parameter** space
- Approximate sampling from complicated distributions
- Preliminary MCMC samples → Efficient proposal distribution



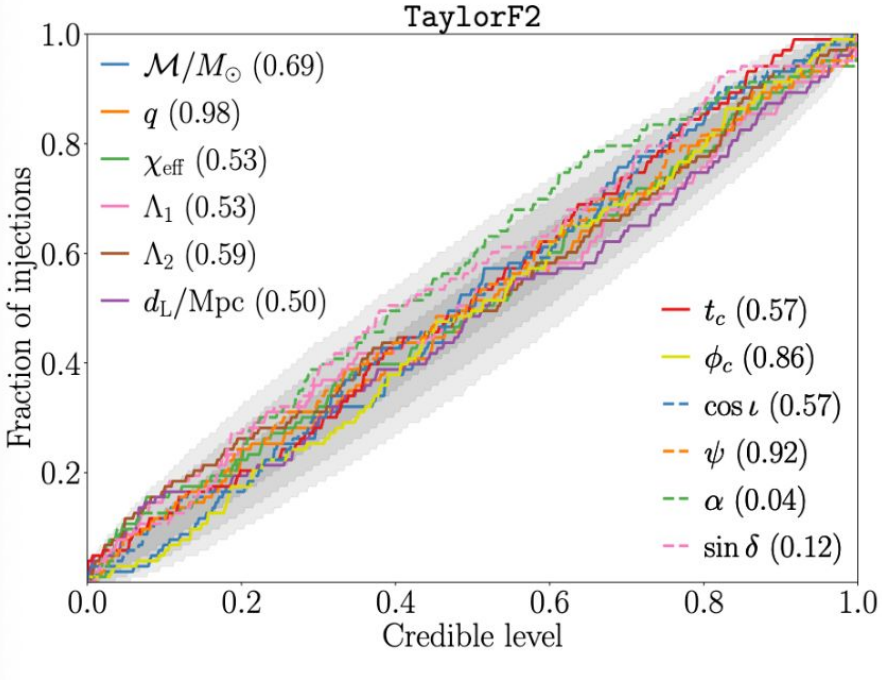
FlowMC

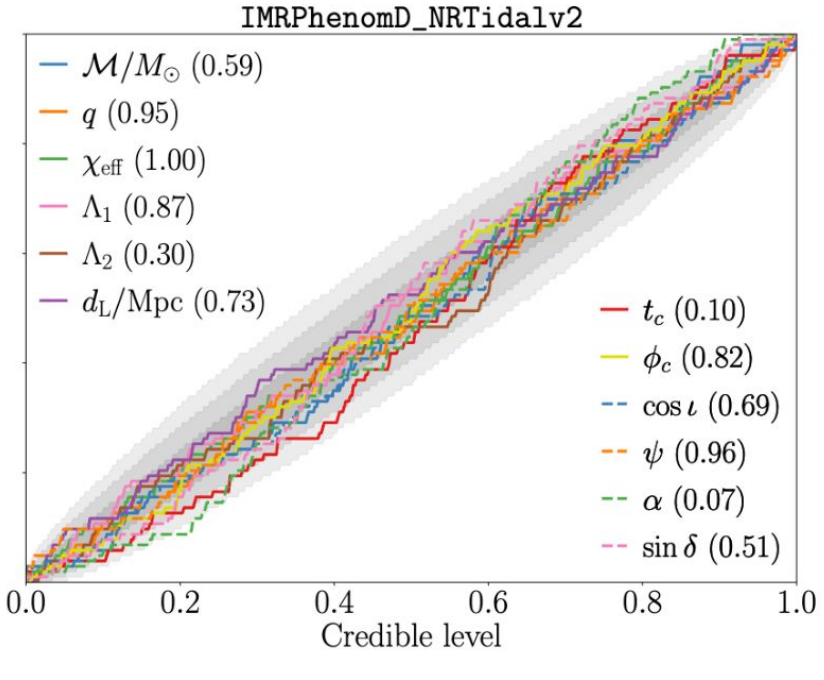
Normalizing-flow (NF) enhanced MCMC sampling

1. Gradient-based sampler (Conventional sampling)
2. Train the NF with the samples output
3. Sampling with the NF

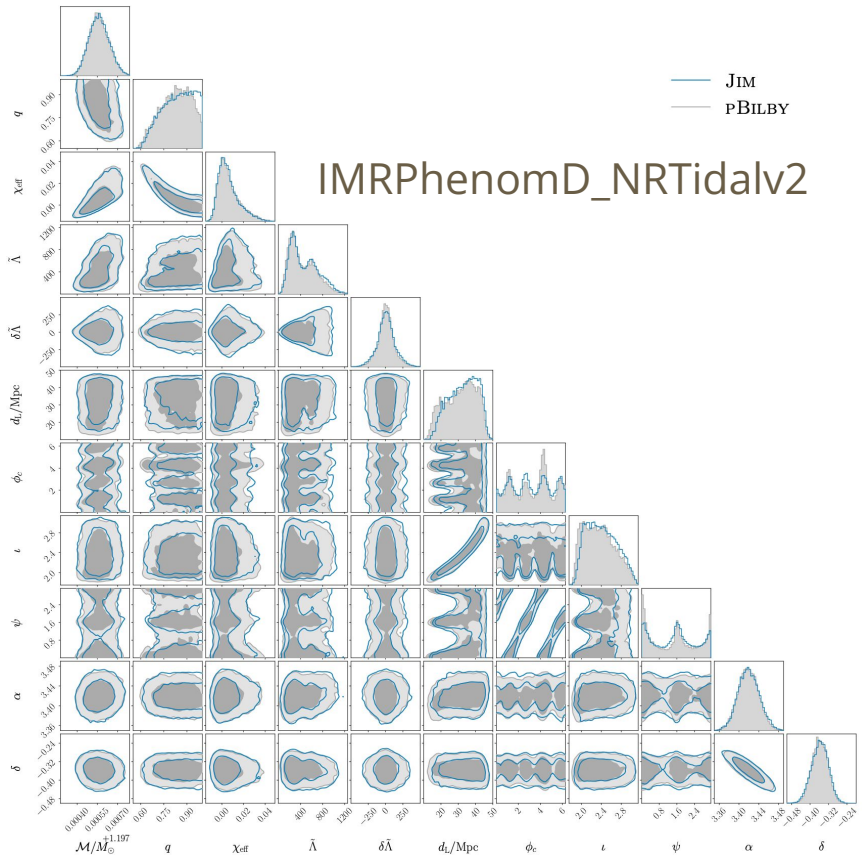


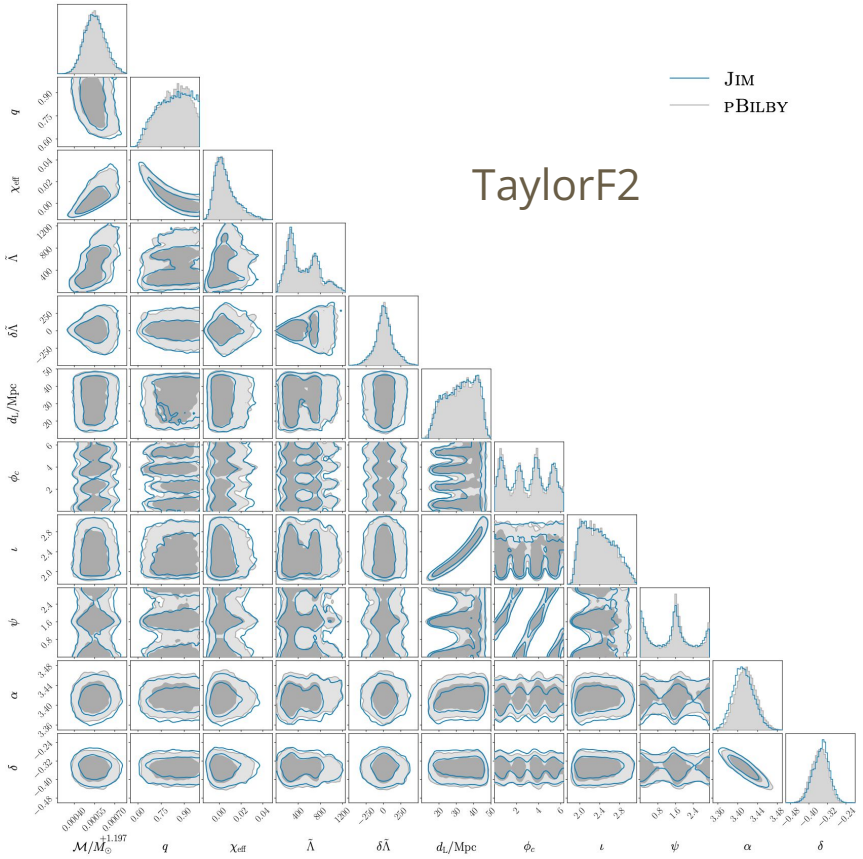
Validation with pp-plot





GW170817





Runtime

- JIM wall time
  - Finding the maximum likelihood parameters for relative binning
  - Training the NF
  - Sampling

Event	Waveform	JIM (1 GPU)	pBILBY (480 cores)	RB-BILBY (24 cores)	ROQ-BILBY (24 cores)
GW170817	TF2	(9.70 + 17.00) min	9.64 h	3.18 h	–
	NRTv2	(5.69 + 28.02) min	10.99 h	4.68 h	1.65 h
GW190425	TF2	(5.13 + 16.49) min	4.08 h	2.30 h	–
	NRTv2	(6.15 + 15.37) min	4.69 h	4.68 h	0.97 h
Injection	TF2	24.76 min	–	–	–
	NRTv2	18.02 min	–	–	–

Environmental impact

- JIM is more **environmental friendly** than existing pipelines
- Energy consumption for 204 BNS runs

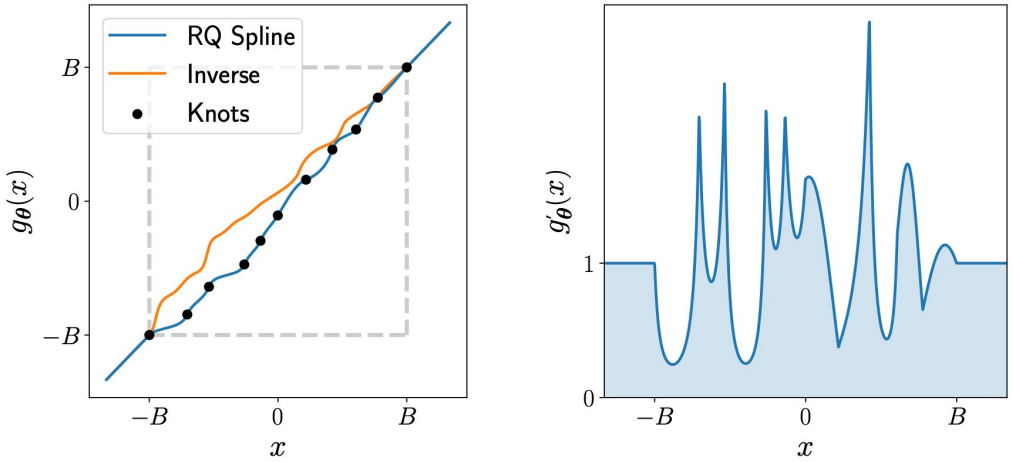
		kWh	CO_2 [kg]	Trees[†]
JIM		34	11	0.55
pBILBY		3599	1180	59.02
RB-BILBY		91	30	1.49
ROQ-BILBY	sampling	32	10	0.52
	precompute[‡]	27	9	0.44

Conclusion

- JIM: Fast, robust and environmental friendly parameter estimation pipeline of GW signal
- Conduct PE for BNS in < 30 min without any pre-training needed
- Future applications:
  - For next generation detectors e.g. Einstein Telescope
  - Multi-messenger astrophysics
  - Population study
  - And more....

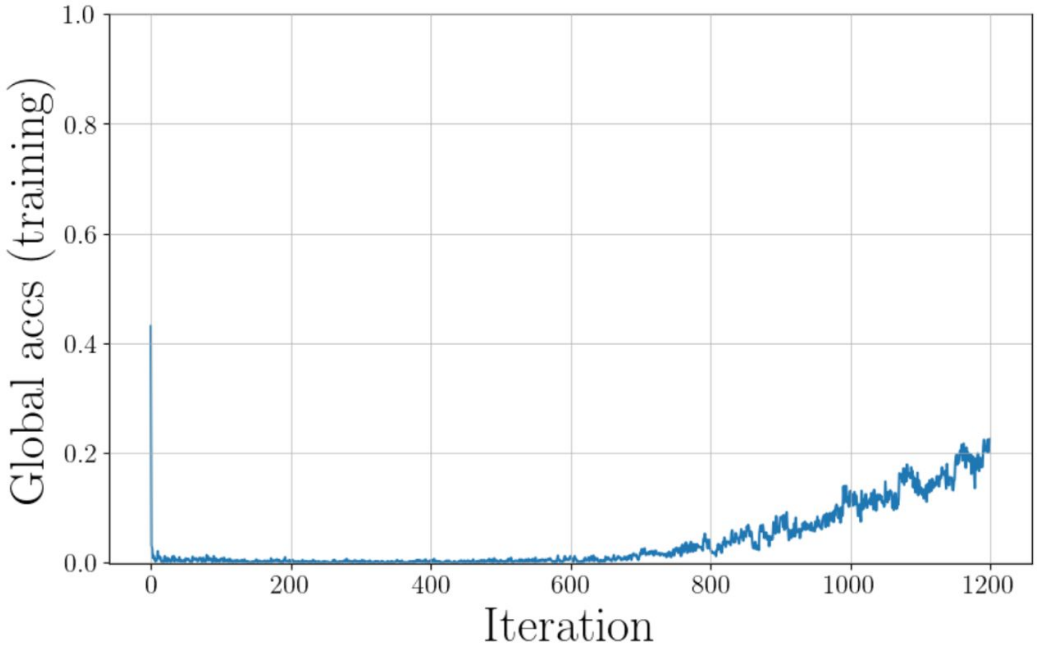
NF details

- Rational-quadratic neural spline flows
- 10 layers 8 bins
- 128 neuron in hidden layers
- Adam optimizer, learning rate decay with polynomial schedule



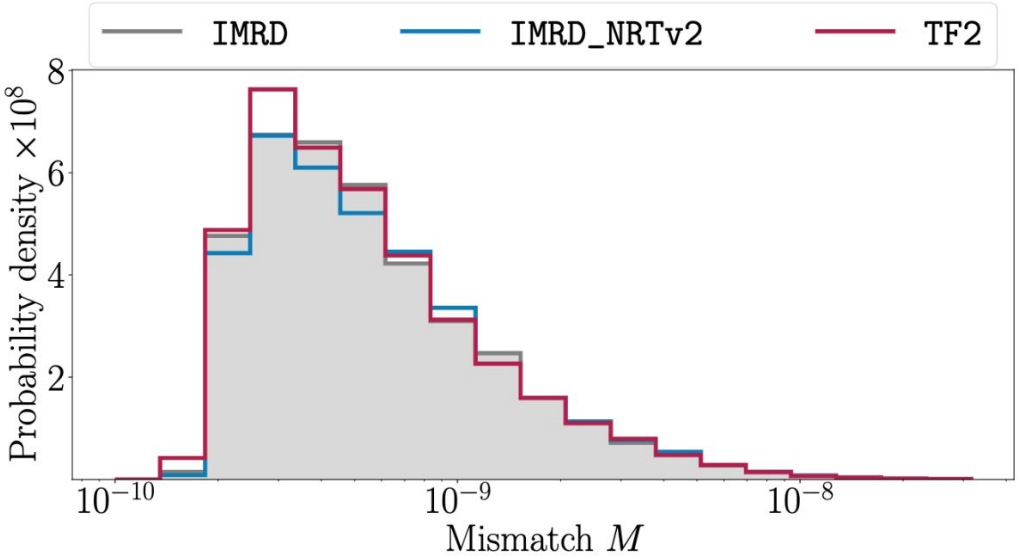
Stopping criterion

- The NF is frozen when it reached an acceptance rate threshold

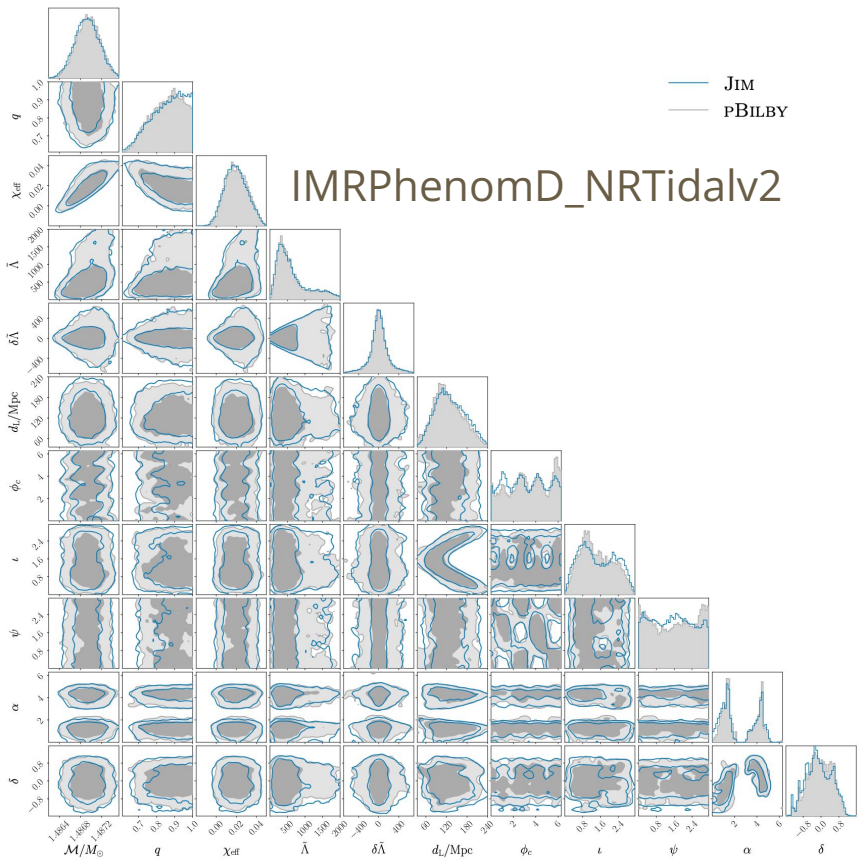


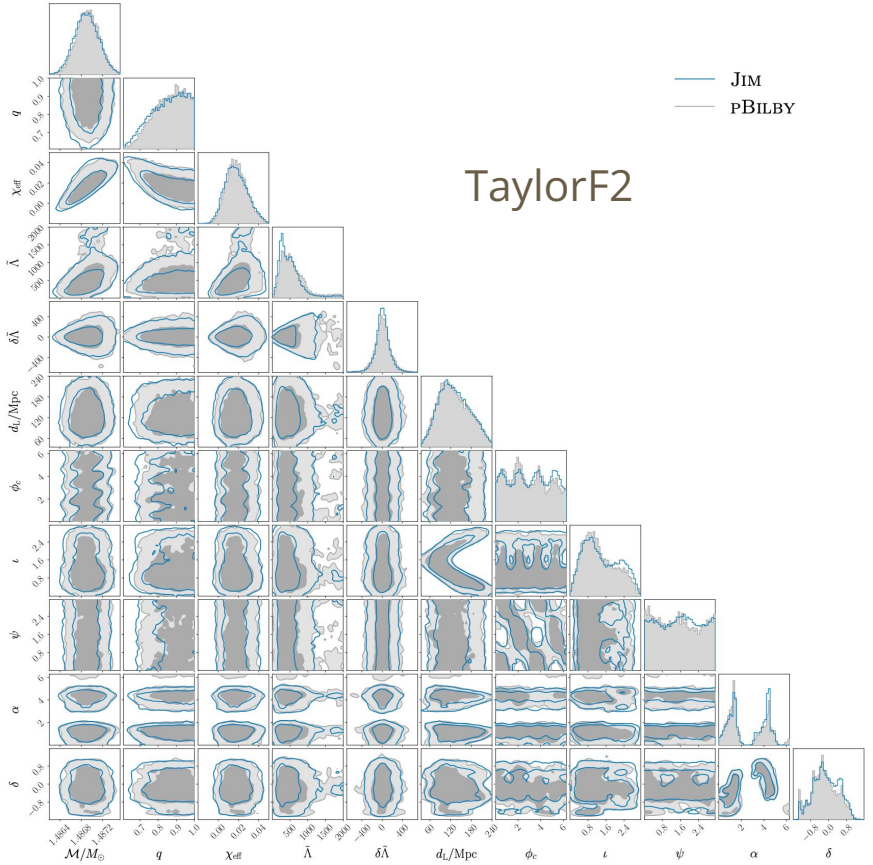
Waveform cross-checking

Parameter	Range
Component masses	$[0.5M_\odot, 3M_\odot]$
Component aligned spins	$[-0.05, 0.05]$
Dimensionless tidal deformabilities	$[0, 5000]$
Inclination angle	$[0, \pi]$



GW190425


Jim
pBilby
IMRPhenomD_NRTidalv2
$\mathcal{M}/M_\odot$
q
$\chi_{\rm eff}$
$\bar{\Lambda}$
$\delta\bar{\Lambda}$
$d_{\rm L}$/Mpc
ϕ_c
ι
ψ
α
δ


Jim
pBilby
TaylorF2
$\mathcal{M}/M_\odot$
q
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$\delta\bar{\Lambda}$
$d_{\rm L}$/Mpc
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Priors

Parameter	Injection	GW170817	GW190425
$\mathcal{M}$ $[M_\odot]$	$[0.88, 2.61]$	$[1.18, 1.21]$	$[1.485, 1.490]$
q	$[0.5, 1]$	$[0.125, 1]$	$[0.125, 1]$
χ_i	$[-0.05, 0.05]$	$[-0.05, 0.05]$	$[-0.05, 0.05]$
Λ_i	$[0, 5000]$	$[0, 5000]$	$[0, 5000]$
d_L [Mpc]	$[30, 300]$	$[1, 75]$	$[1, 500]$
t_c [s]	$[-0.1, 0.1]$	$[-0.1, 0.1]$	$[-0.1, 0.1]$
ϕ_c	$[0, 2\pi]$	$[0, 2\pi]$	$[0, 2\pi]$
$\cos\iota$	$[-1, 1]$	$[-1, 1]$	$[-1, 1]$
ψ	$[0, \pi]$	$[0, \pi]$	$[0, \pi]$
α	$[0, 2\pi]$	$[0, 2\pi]$	$[0, 2\pi]$
$\sin\delta$	$[-1, 1]$	$[-1, 1]$	$[-1, 1]$