Likelihood Free Parameter Estimation for Kilonovae Light Curves

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Outline

What are Kilonovae?

- EM radiation from mergers of compact binaries: two neutron stars (BNS), or a neutron star with a black hole (NSBH)
- Short-lived events that are difficult to detect
- Important to our understanding of heavy element synthesis, nuclear equation of state

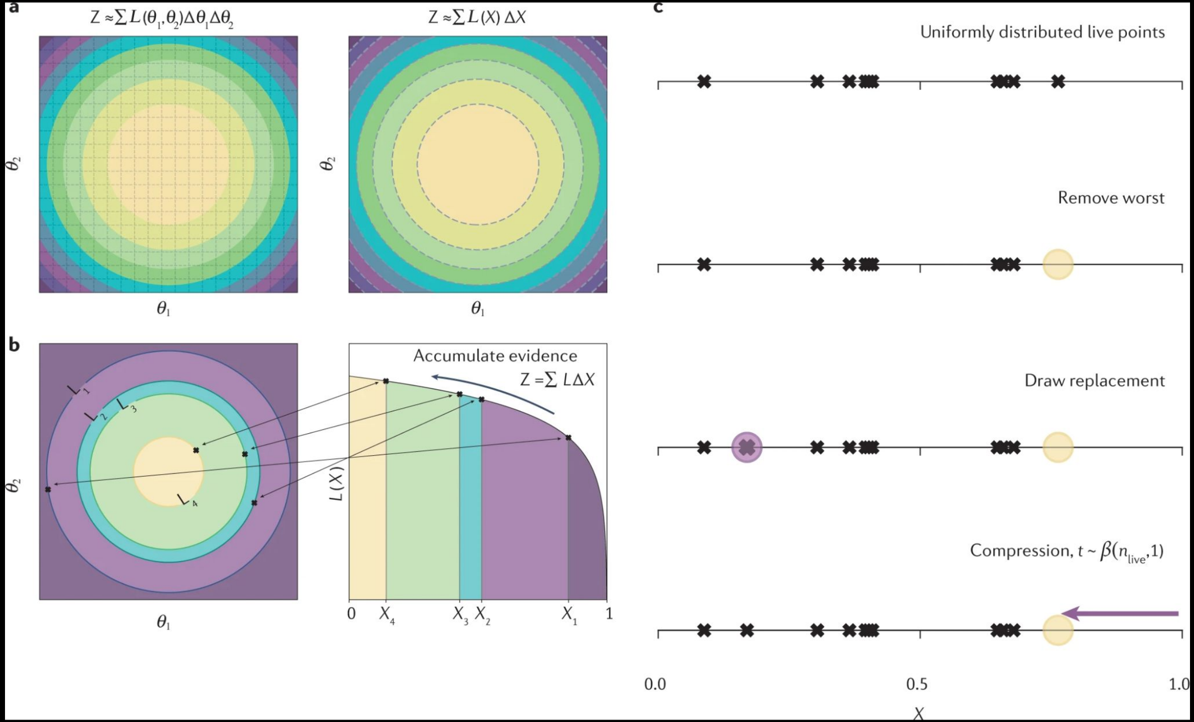
AT2017gfo[1]

NASA / ESA / A.J. Levan, University of Warwick / N.R. Tanvir, University of Leicester / A. Fruchter & O. Fox, STScI.

[1]Abbott, B. P. et al., PRL, 119, 161101

How is current parameter estimation done?

- Through Bayesian inference
- We use PyMultiNest to perform nested sampling, resulting in a posterior distribution[2]
- Right: nested sampling schematic[3]



[2]Buchner, J. et al., 2014 A&A.
[3]Ashton, G., Bernstein, N., Buchner, J. *et al. Nat Rev Methods Primers* 2, 39 (2022).

Why improve parameter estimation?

01 Avoid computationally expensive liklihood calculation at each inference step

02 Increase in signal complexity results in increased computing cost

03 Real-time inference is transferable to other parameter estimation problems

Intrinsic Parameters of the Signal

01 Mass

02 Velocity

03 Lanthanide Fraction

Extrinsic Parameters of the Signal

01 Arrival Time

02 Luminosity Distance

Data Generation

- Using the Kasen 2017 hydrodynamical grid model[4]
- Simulate light curves as seen by ZTF in the g,r,i bands using the NMMA package[5]
- encode non-detections as ZTF limiting magnitude 22.0 in all bands

Data Processing

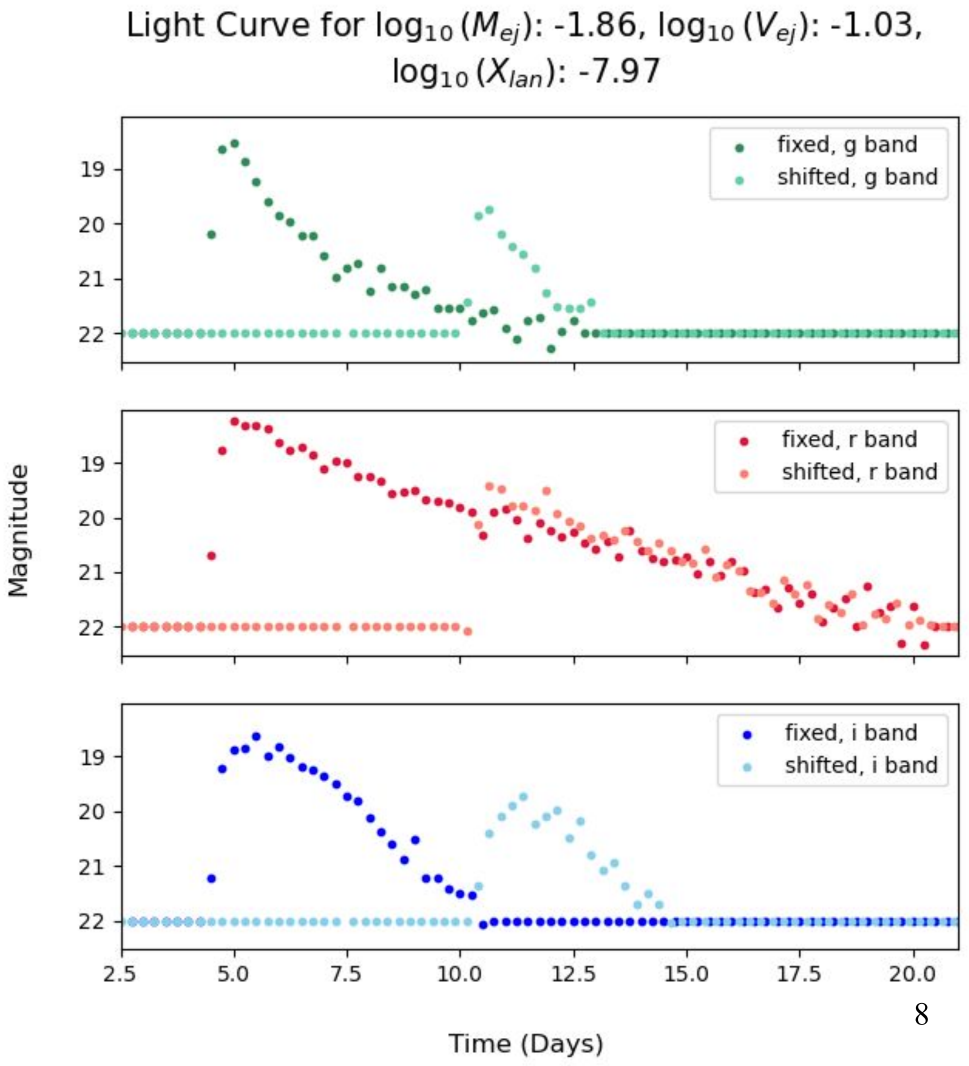
- ensure all light curves have the same number of points
- limit data to a minimum of 8 detections across all bands

Challenge: Data generation is time-consuming and heavy

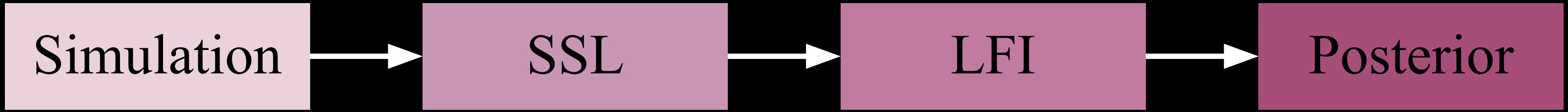
[4]Kasen et al. Nature, 551(7678):80–84, Nov. 2017.
[5]Pang et al. Nature, 14(1):8352, Dec. 2023.

Fixed vs. Shifted

- Unique noise instance for each light curve
- All fixed data generated at t=0 days, d_L = 50 Mpc
- Right: fixed and shifted (t=+5.65 days, d_L = 86.3 Mpc) light curves shown for all 3 ZTF bands for the same injection parameters



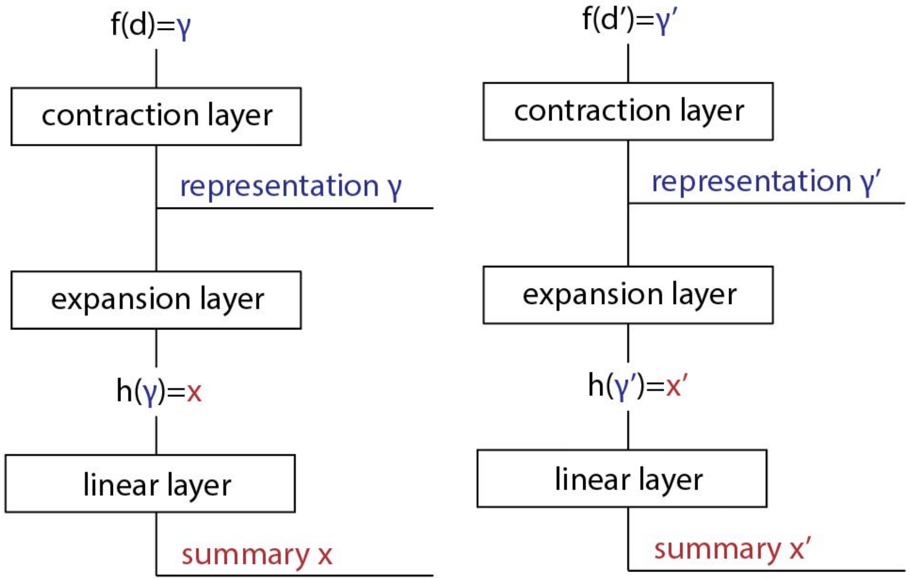
Implementing Likelihood Free Inference (LFI)



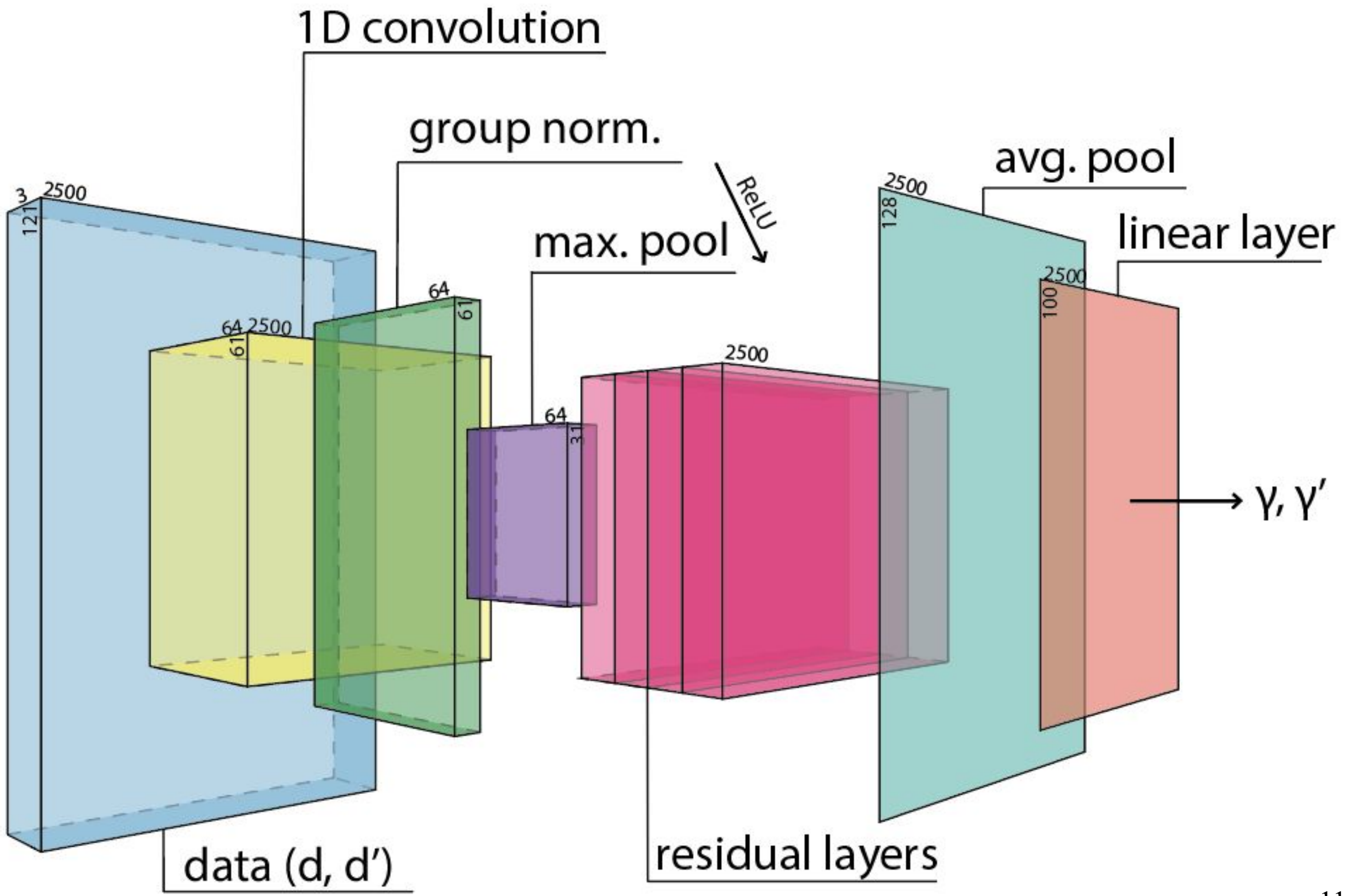
- Avoid likelihood calculation
- We use self-supervised learning (SSL), where the model generates labels for the data, to create a representation
- We use normalizing flows as our LFI to produce a posterior distribution

Data Summary Γ

$$\Gamma \equiv h \circ f$$



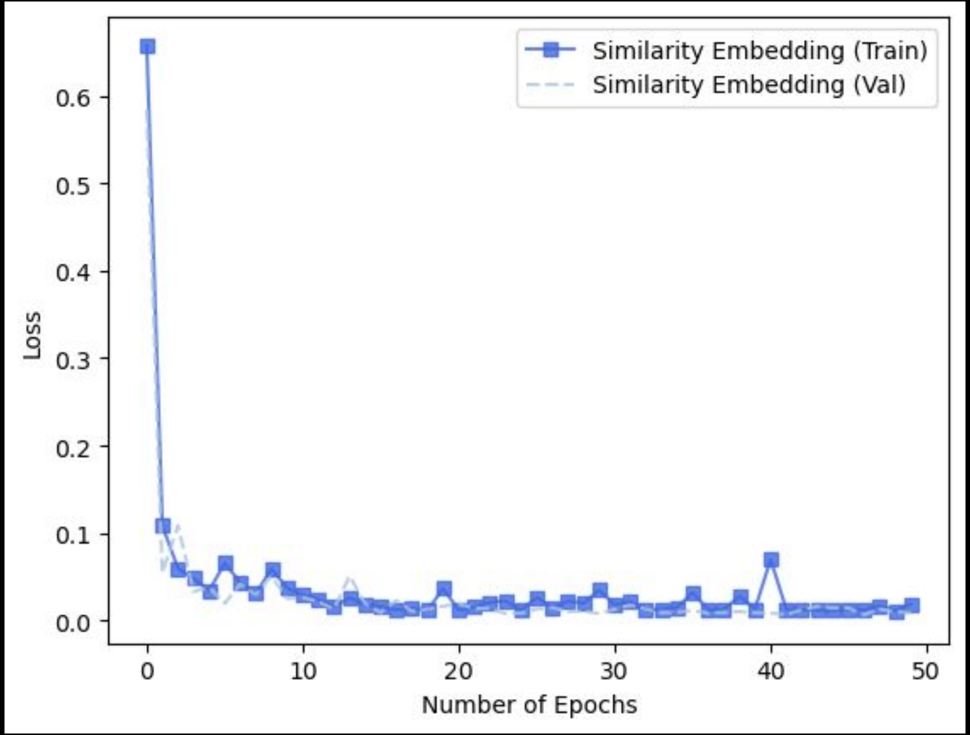
$f(d, d') =$


1D convolution
group norm.
ReLU
max. pool
avg. pool
linear layer
3
2500
121
64
2500
61
64
61
64
31
2500
2500
128
2500
100
γ, γ′
data (d, d′)
residual layers

Variance-Invariance-Covariance Regularization Loss

$$\mathcal{L} = \text{Var} + \text{Invar} + \text{Covar}$$

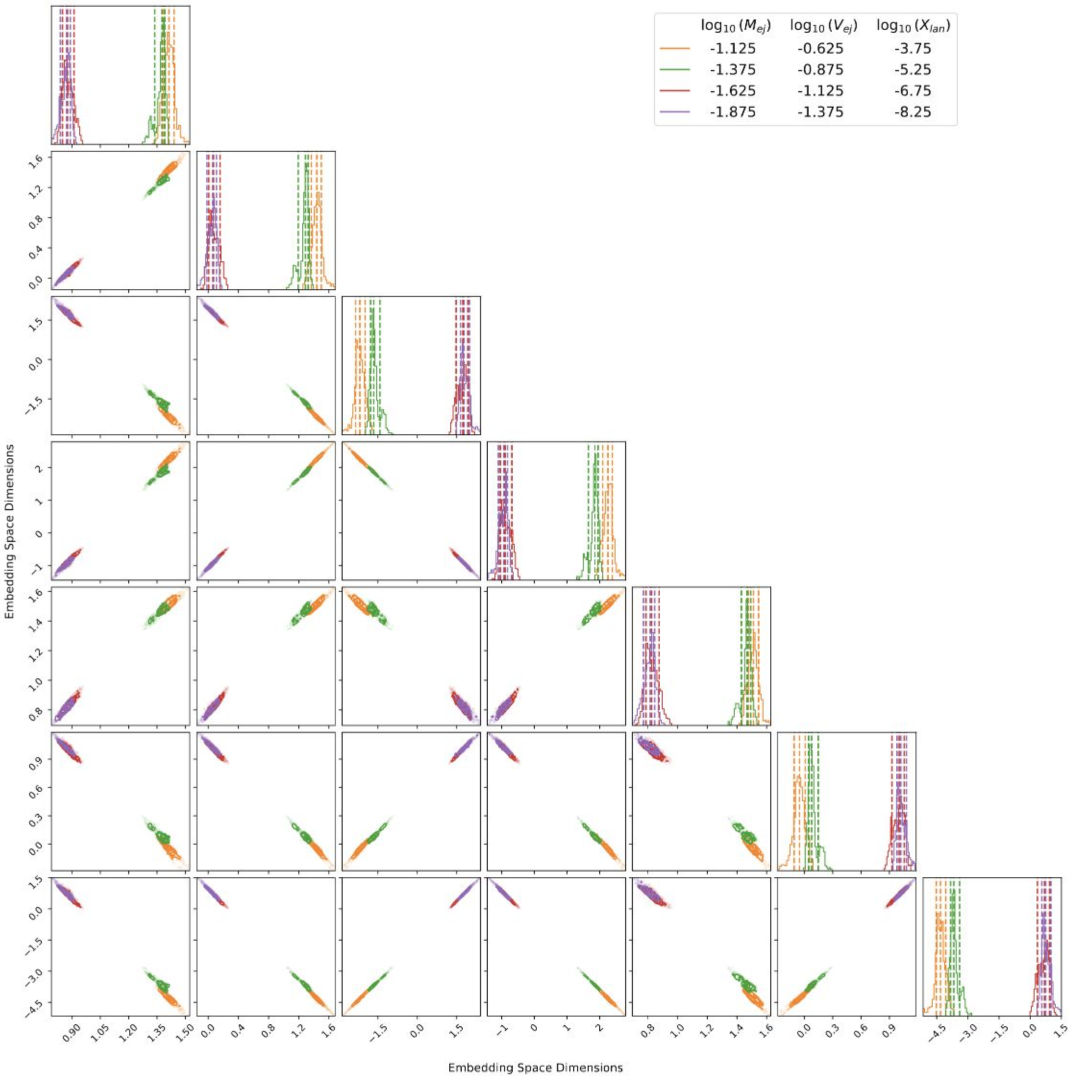
- Use a weighted loss function composed of 3 parts[6]
- Invariance is captured through MSE
- Right: training loss for the embedding
- 20 mins to train on GPU



[6]A. Bardes, J. Ponce, and Y. LeCun., ICLR 2022.

Similarity Embedding

- Parameters are embedded in a 7-dimensional space to summarize data
- Dimensionality and size of network determined by hyperparameter tuning
- Right: displays clustering of similar injection parameters regardless of t and d_L



Normalizing Flows

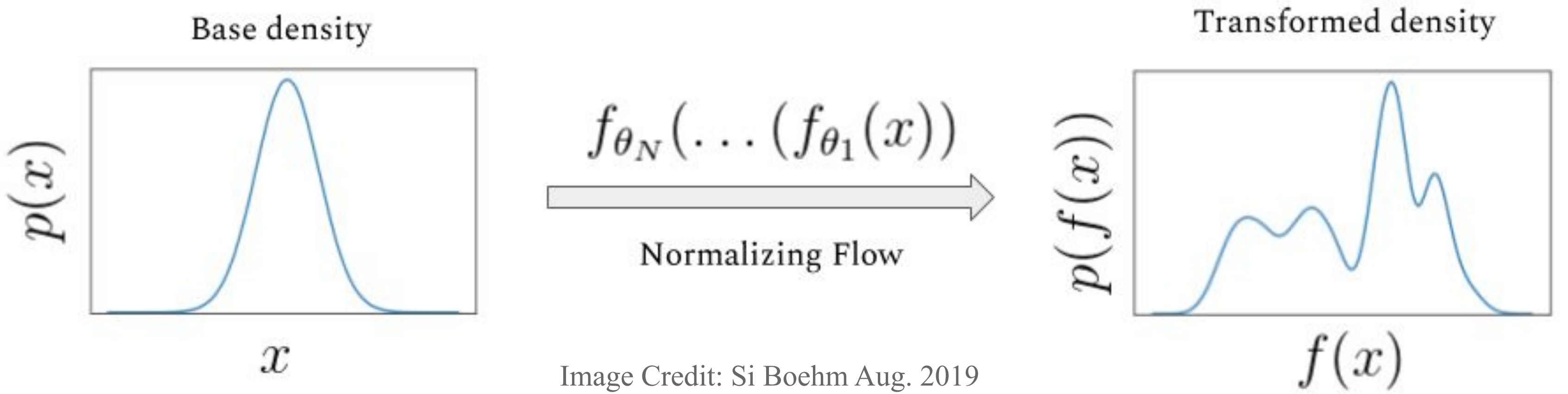
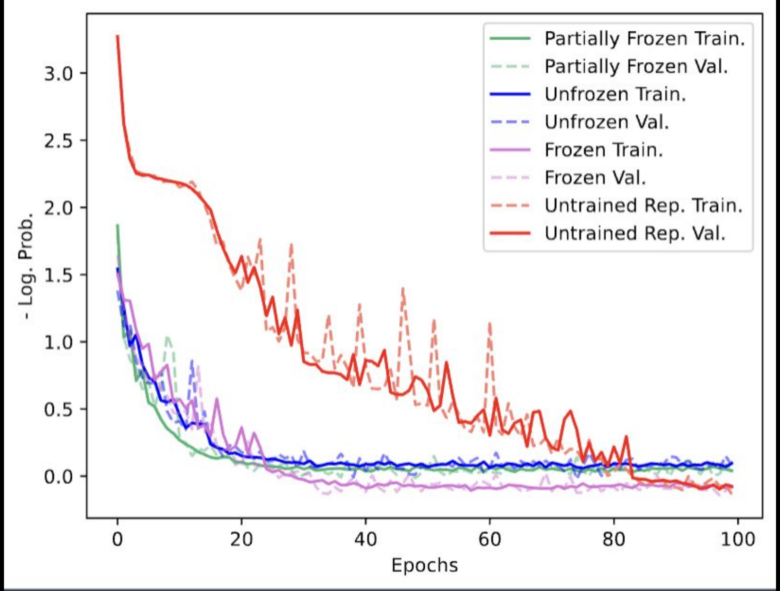


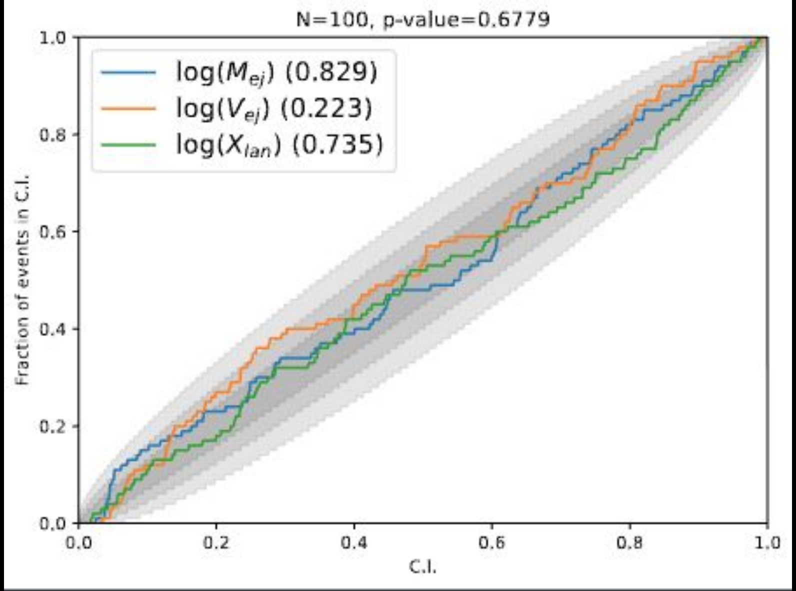
Image Credit: Si Boehm Aug. 2019

- Transforms standard normal distribution to a complex sampling distribution[7]
- We use Masked Affine Autoregressive Transforms
- Not informed of the time and distance shifts

[7] Papamakarios et al. Journal of Machine Learning Research 22, Mar. 2021.

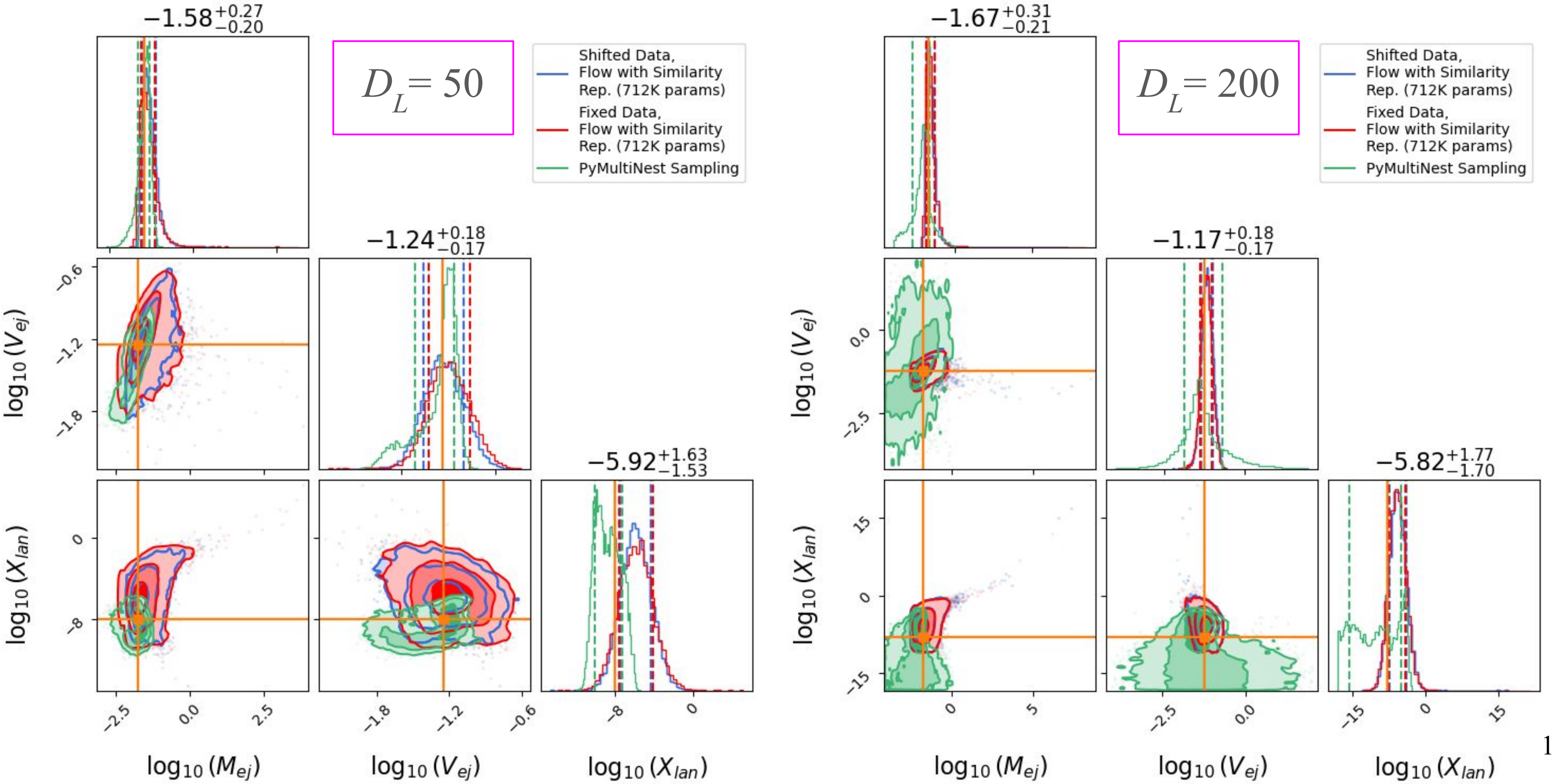
Loss Curve and PP Plot





- Left: Training with the embedding converges faster
- Training takes ~50 mins
- Right: Test sampling remains within 3 standard deviations

Results for M_{ej} = -1.75, V_{ej} = -0.75, X_{lan} = -8



Broader Applications

- Similar infrastructure can be used for sky localization of gravitational waves, other physics problems
- Works very well for simple waveforms such as simple harmonic oscillator and sine-gaussian pulse[8]

[8] Chatterjee et al. arXiv:2312.07615. Dec 2023.

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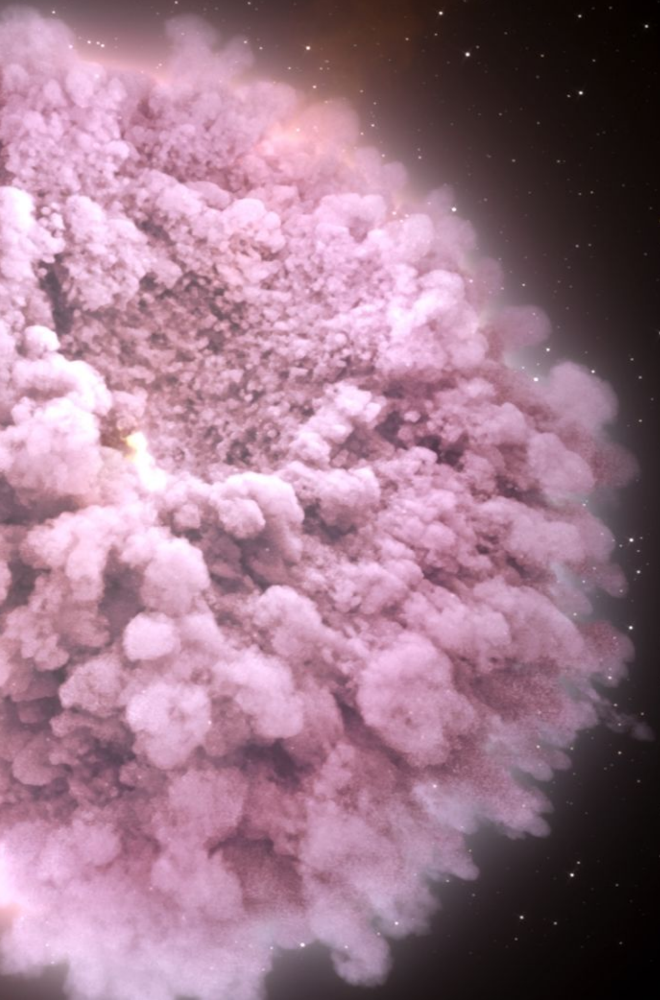

Questions?

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