# GPE: GPU-accelerated Parameter Estimation for gravitational waves with x360 acceleration

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# Outline

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# Gravitational wave parameter estimation

- Use Bayes' theorem to estimate the posterior distribution of the source parameters.
- Stochastically sample the posterior
- Time-consuming process
  - One parameter estimation run requires collecting tens of thousands of samples from the posterior.
  - Each sample is found by conducting thousands of random walks.
  - Each random walk involves one waveform generation.
    - One parameter estimation run requires more than millions of waveform calculations
- May take several days to several weeks to run parameter estimation on a single event.

Bayes' theorem

$$\underbrace{p(\theta|d,H)}_{\text{posterior}} = \frac{\overbrace{p(\theta|H)}^{\text{prior}}\overbrace{p(d|\theta,H)}^{\text{likelihood}}}{\underbrace{p(d|H)}_{\text{evidence}}}$$

# Speedup Motivation

- Increase in detection rate
- Statistical studies
  - e.g. detector observing scenarios
  - Parameter estimation of large number of events.
- EM follow-up
  - Fast and accurate production of sky localization regions.

# GPE Overview

- Adapted from the **nested sampling** flavor of LALInference (lalinference_nest)
- Newly written in C++ and CUDA
- Produces same output for *cbcBayesPostProc*
- Precision choices
  - Double precision
  - Single precision

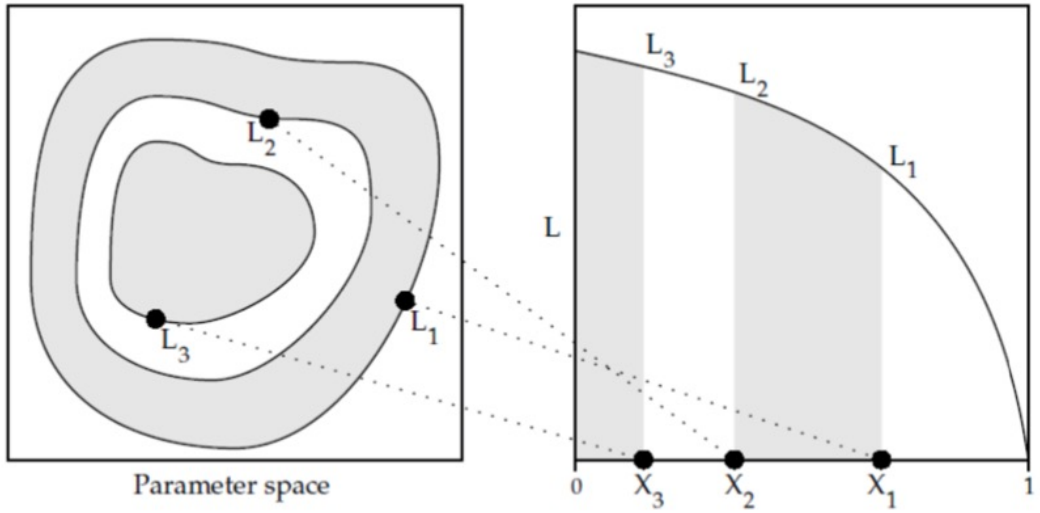
# Parallelization method #1: Waveform

- Dominant source of time consumption
- Two frequency-domain waveforms:
  - TaylorF2
  - IMRPhenomPv2
- Calculations in each frequency bin are independent from each other, therefore they are highly parallelizable.
- Calculations for each detector are also independent.
- Each GPU thread -> each frequency bin of each detector

- ~33,000 parallel calculations per waveform call (two detectors)
- ~1,000 calls per iteration
- ~16,000 iterations per run
- ~$10^{11}$ calculations per run

# Parallelization method #2: Nested Sampling

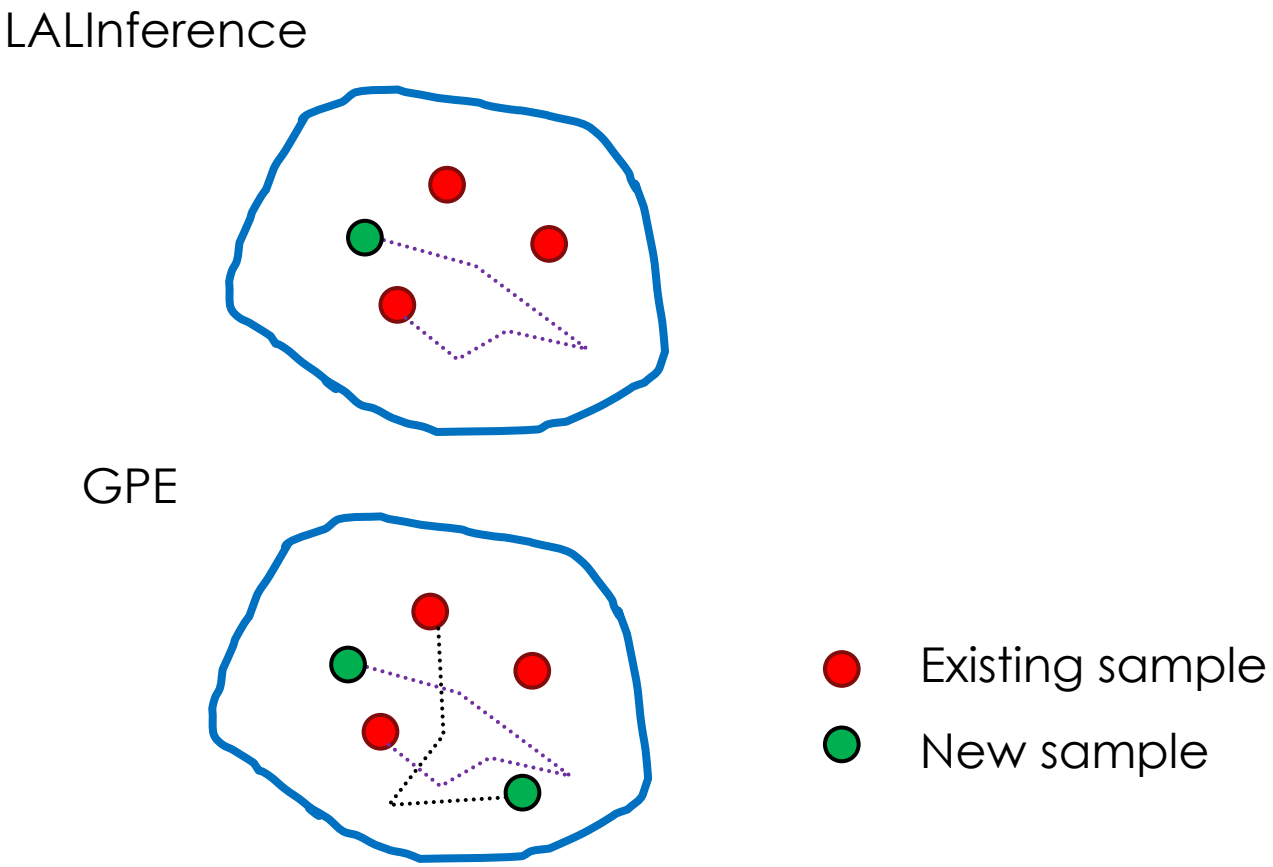
- Calculates the **evidence** (Z) and produces the **posterior** as a by product
- Maps multi-dimensional parameter space into one-dimensional priormass space.
  - By defining "nested" likelihood contours and their enclosed priormass
- Algorithm:
  - Sprinkle several samples uniformly in prior.
  - At each iteration, replace lowest likelihood sample with new sample within a likelhood contour.
  - Finding a new sample => **Parallelization!**




Skilling, J. (2006).

# Parallelization method #2: Nested Sampling

- LALInference:
  - Copy one existing sample
  - Perform several random walks
  - Find one new point
- GPE:
  - Copy **many** existing samples
  - Perform several random walks for many points **at the same time**
  - Find **many** new points
  - Save additional points for later use

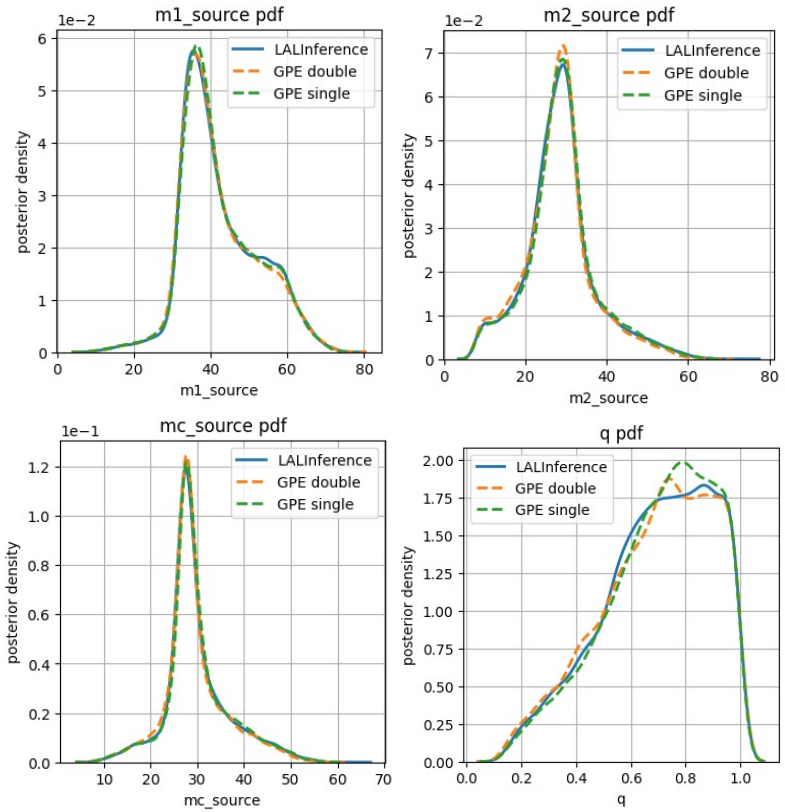


# Comparison with LALInference: GW150914

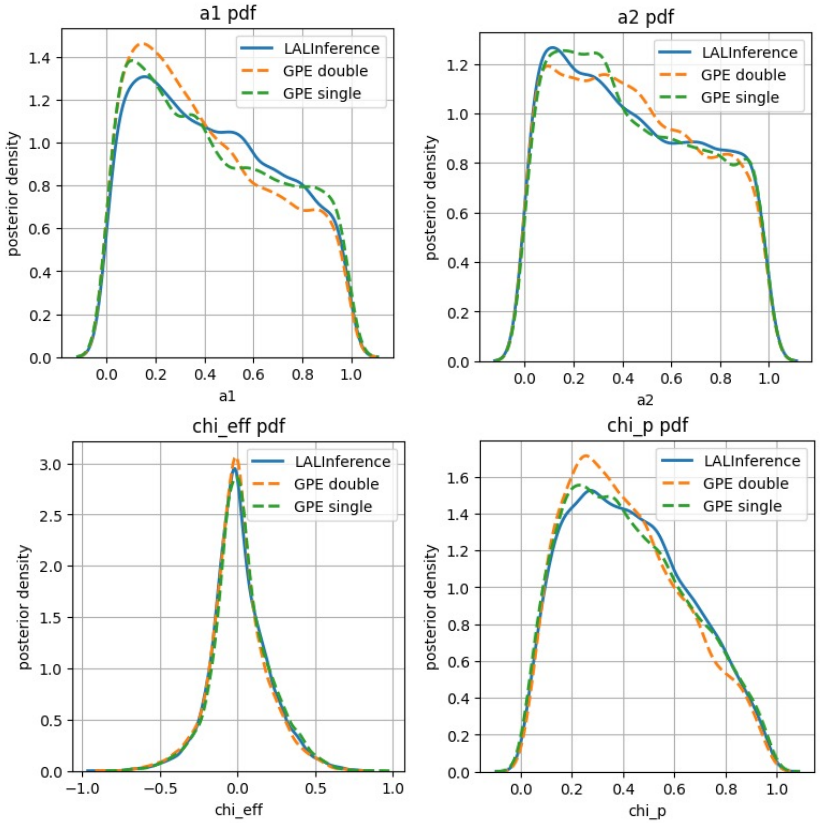
- Use GW150914 data from LIGO Open Science Center
- Number of live points: 500
- LAL: use lalinference_nest with IMRPhenomPv2 waveform
- GPE: parallelized IMRPhenomPv2 waveform
  - Double precision
  - Single precision

# Parameter estimation result

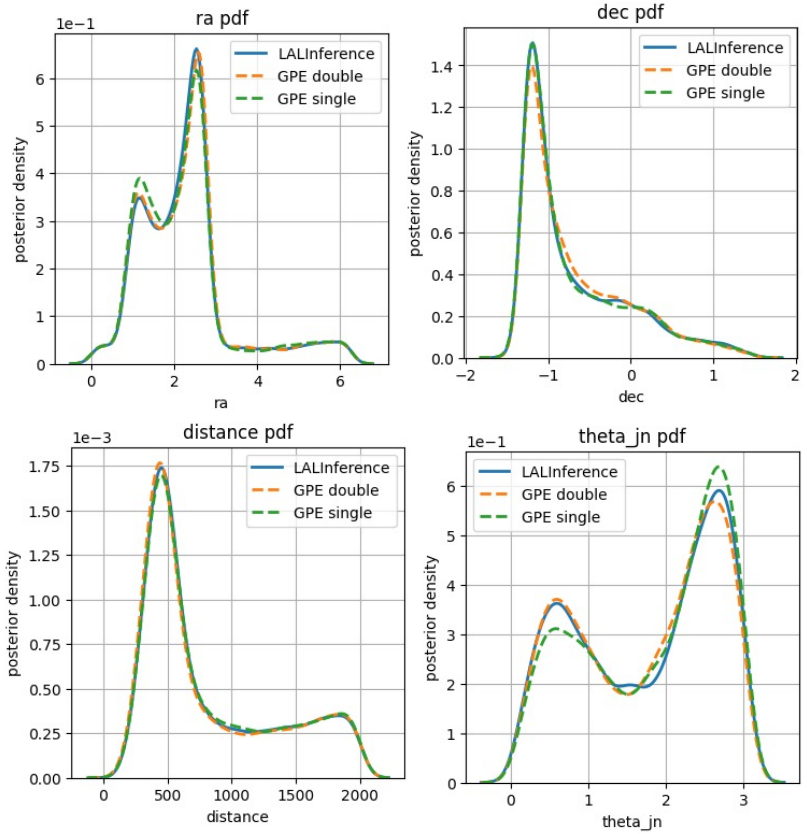
## Mass




## Spin




## External



# Performance test: 1 CPU v.s. 1 GPU

| Code | Parallelization Method | Precision | Hardware | Cores | Max Clock rate | Wall time | Speedup w.r.t. LAL |
|---|---|---|---|---|---|---|---|
| LAL | | Double | Core™ i7-8700 CPU | 1 | 3.20 GHz | 20h53m37.7s | |
| GPE | Waveform | Double | GeForce GTX 1080 Ti | 3584 | 1.58 GHz | 26m2.0s | ×48.2 |
| | | Single | | | | 13m45.9s | ×91.1 |
| | Waveform + Nested Sampling | Double | | | | 10m56.0s | ×114.7 |
| | | Single | | | | 3m27.4s | ×362.7 |

# Summary

- GPE can achieve a 360 times acceleration
- GPE can produce consistent results with LALInference
- Speedup is essential for
  - Parameter estimation of real events in multi-detection era
  - Large simulations
  - EM follow-up