Improved Targeted Sub-Threshold Search for Strongly Lensed Gravitational Waves with Sky Location Constraint

Progress Update 25/4

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Mentors during LIGO SURF 2022

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Likelihood Ratio

- The likelihood ratio of a trigger that is produced by a real gravitational wave is given by:

$$\mathcal{L} = \frac{P(\vec{D}_H, \vec{O}, \vec{\rho}, \vec{\xi}^2, [\Delta\vec{t}, \Delta\vec{\phi}] | \vec{\theta}, \text{signal})}{P(\vec{D}_H, \vec{O}, \vec{\rho}, \vec{\xi}^2, [\Delta\vec{t}, \Delta\vec{\phi}] | \vec{\theta}, \text{noise})} \cdot \frac{P(\vec{\theta}|\text{signal})}{P(\vec{\theta}|\text{noise})}$$

- $\overrightarrow{\Delta t}$: arrival time difference between detectors
- $\overrightarrow{\Delta\phi}$: arrival phase difference between detectors
- By constraining the sky location, we are constraining these 2 terms
- Originally calculated in inspiral_extrinsics.py

Replacing Original code with a Sampler

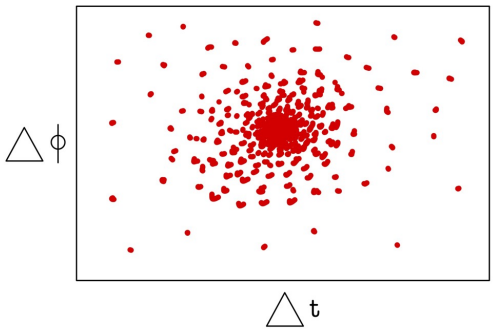
- Inspiral_extrinsics.py is the original code in GstLAL to calculate P($\Delta t, \Delta\phi$)

- Limitations
  - **Low** and **fixed** pixel density: 3072 pixels for the skymap, 33 angles for the inclination and polarisations…
  - One mass fits all searches
  - Complicated and lengthy calculations
    - Computationally costly
    - Generate a map takes O(hours).
  - **Hard to modify** it for other applications that also requires P($\Delta t, \Delta\phi$), e. g. targeted searches

Advantage of a GW Sampler

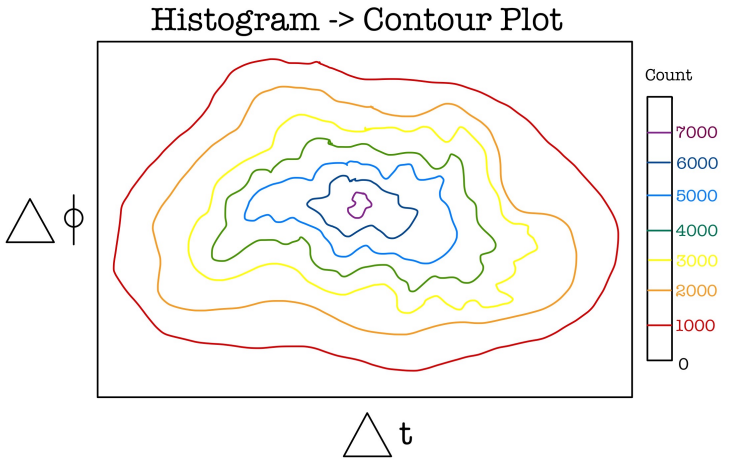
- Easy to modify the domain of parameters
- Easy to change pixel density (just sample more in a smaller area)
- Easily modified to suit different needs
  - Adding sky location constraints (EM counterpart)
  - Changing physical models (cosmology/lensing)
- **Simple!**
  - Fast computation (?) (we still do not know how many samples we need)
  - Generating a sample takes ~1s

Getting a PDF Map

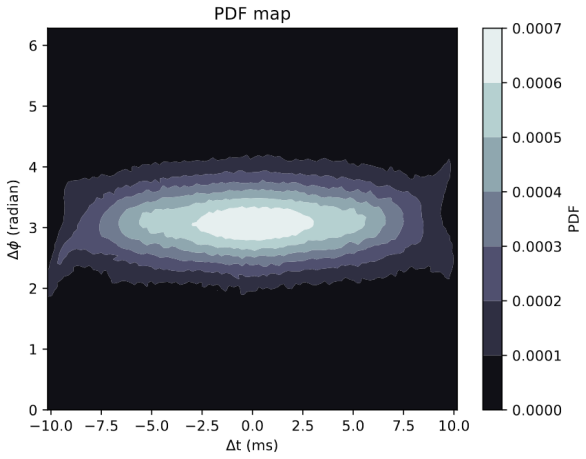


Sample a lot of data

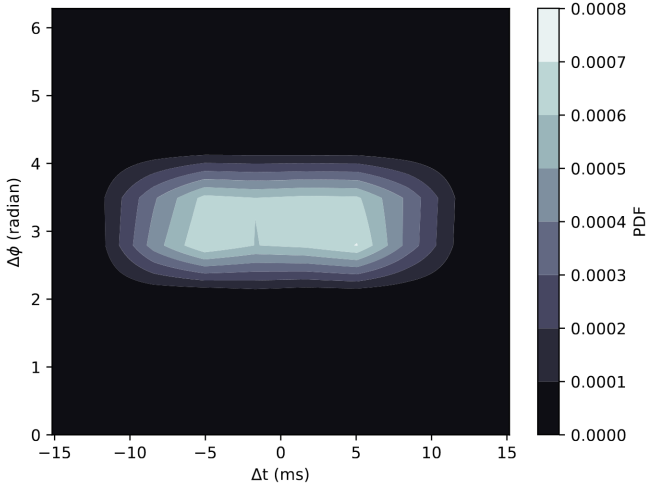
Get a histogram



Normalise by total count and perform interpolation to get a PDF map



(inspiral_extrinsics)



(my generator)

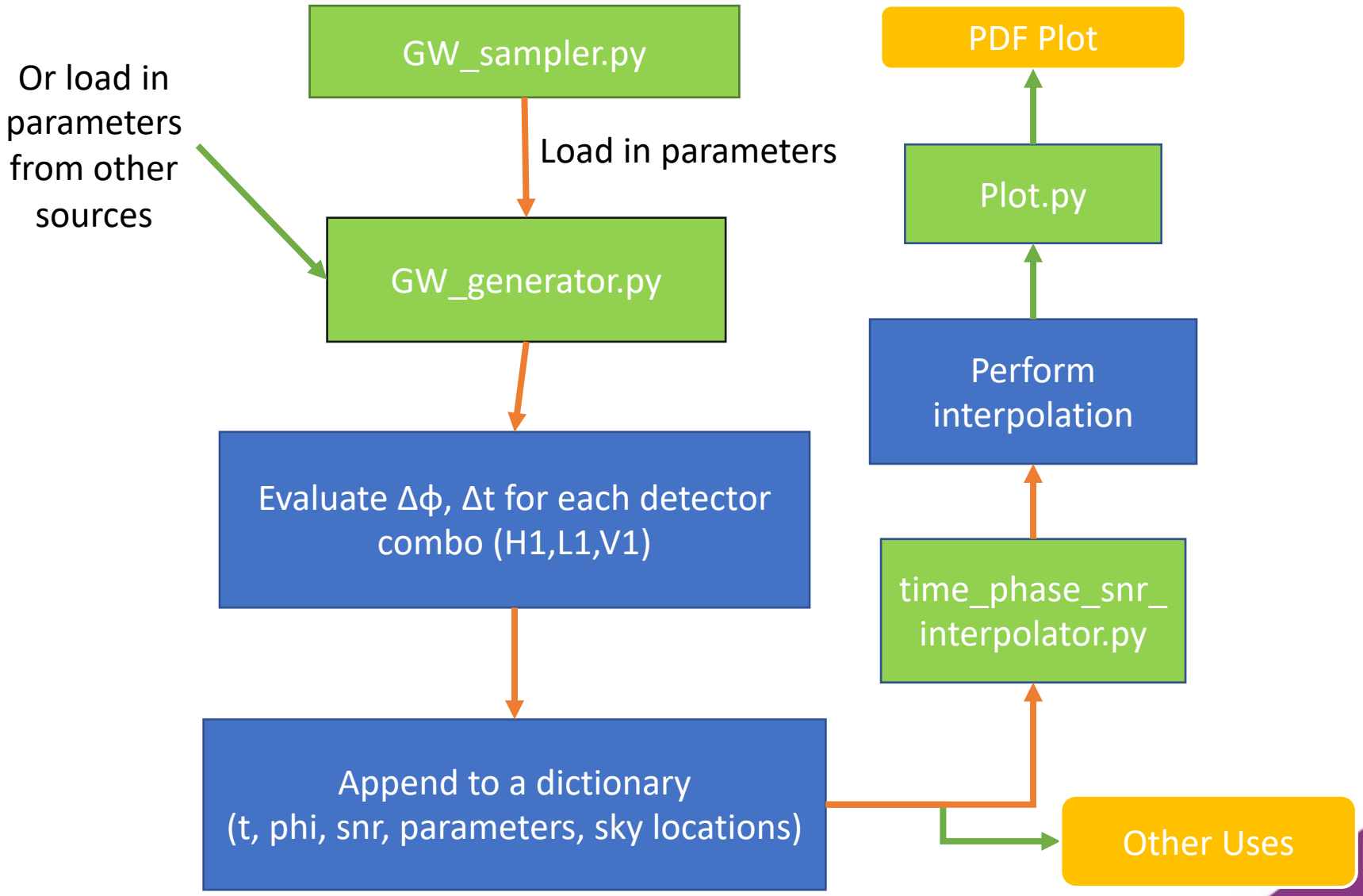
Scripts Overview

- **GW_generator.py**
  - Storing lots of functions for sampling different parameters and simulating GWs using LALSim -> calculate t, phi, snr
  - Mass
  - Spin
  - Distance
  - Inclination
  - Polarization
  - Waveform approximants
  - Sky location (either by loading in a healpy skymap or choose a specific coordinate)
  - Target trigger time (in progress)
  - Lensing image types (in progress)

Scripts Overview (cont.)

- **GW_sampler.py**
  - Call GW_generator.py and store the samples in a dictionary
- **time_phase_snr_interpolator.py**
  - Find detector pairs
  - Calculate dt, dphi, dsnr for detector pairs
  - rate.py for binning
  - Interpolate using scipy
- **Plot.py**
  - Output a plot of the PDF
  - Store the data for plotting in a nd.array

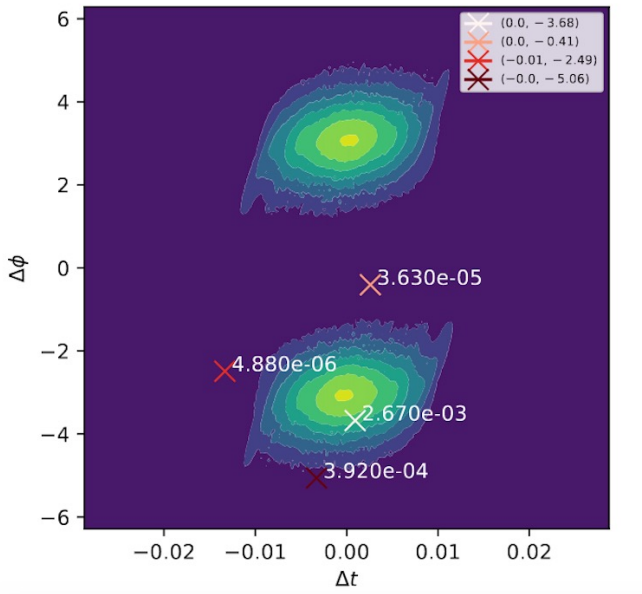
Programme Flow



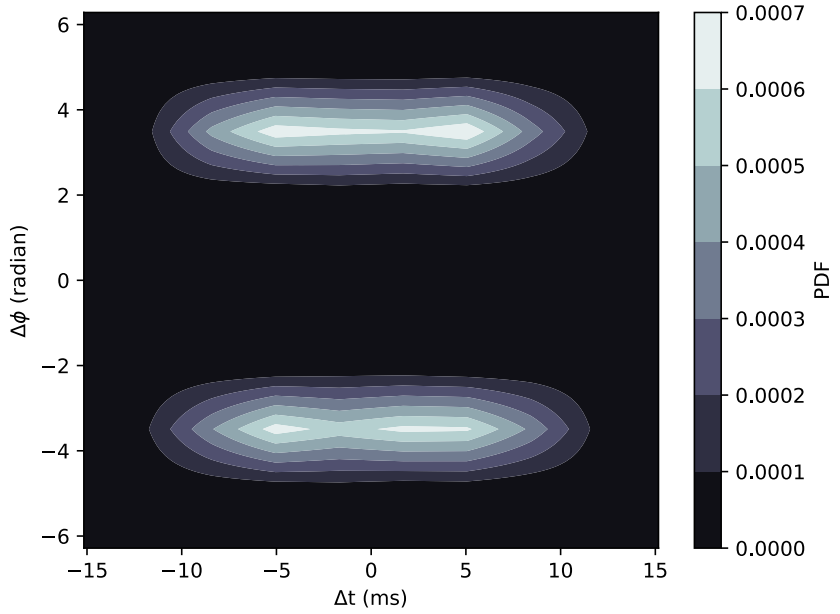
Current Progress

H1 and L1

(From original code)



(From my generator)

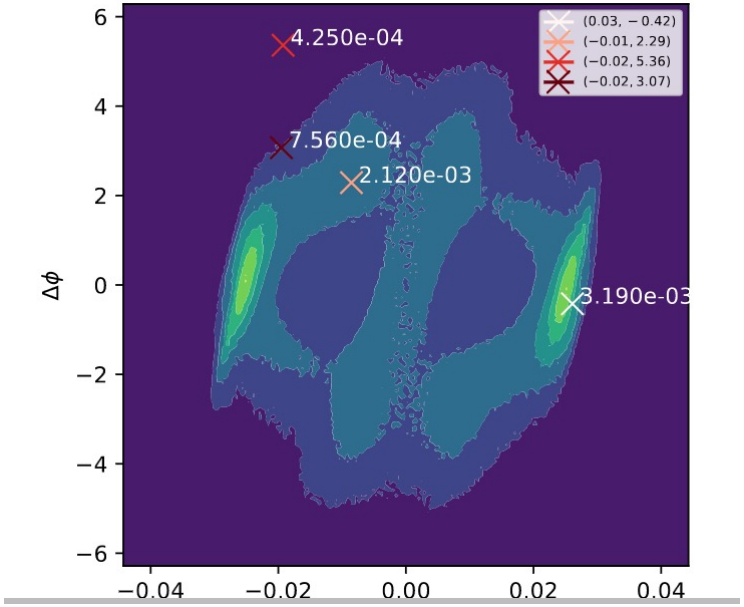


Samples: 10k
Interpolation: 10 steps
Snr ratio between detectors: 1

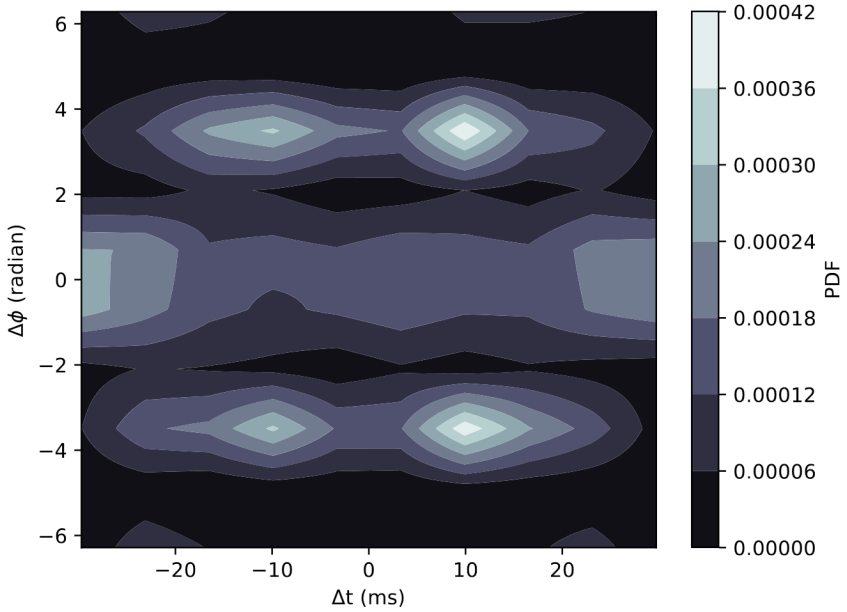
Current Progress

H1 and V1

(From original code)



(From my generator)

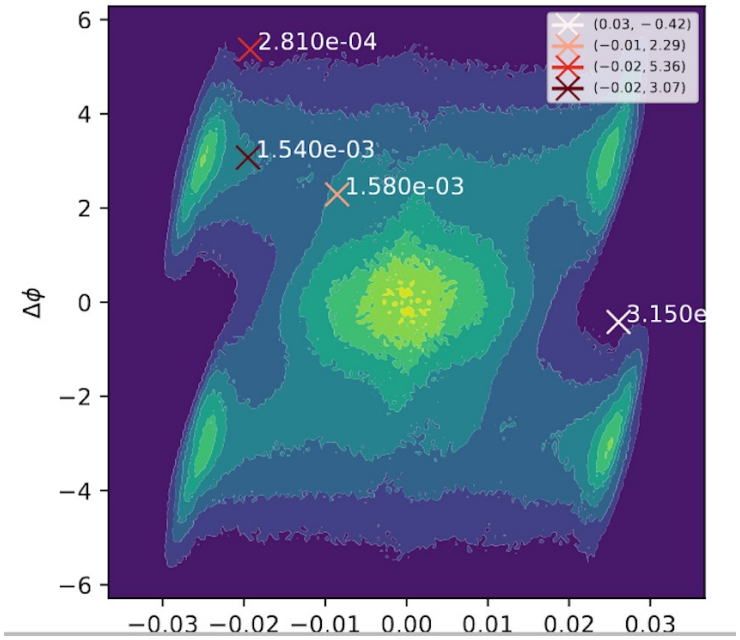


- We need more samples

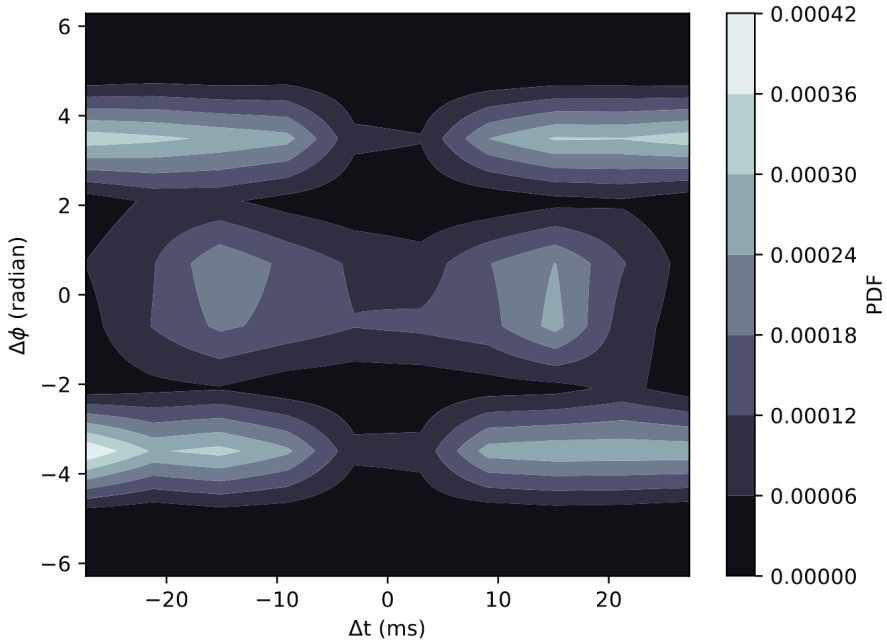
Current Progress

L1 and V1

(From original code)



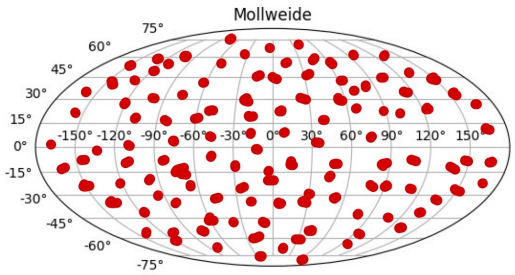
(From my generator)

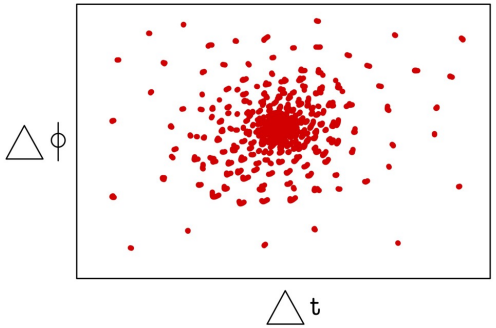


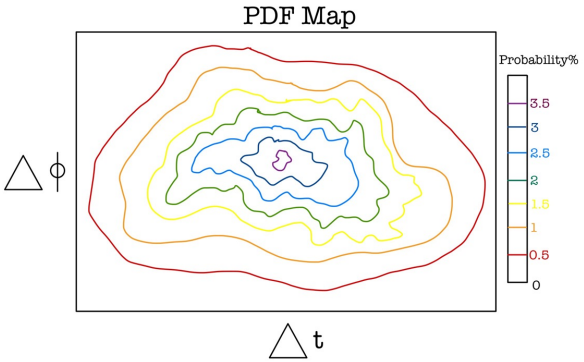
- We need more samples

General Search vs Targeted Search

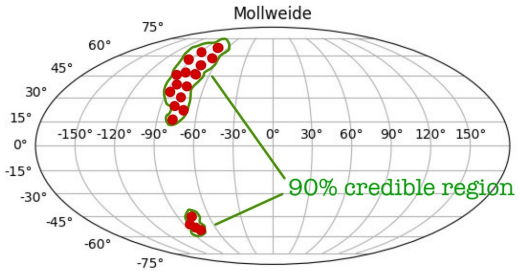
General Search

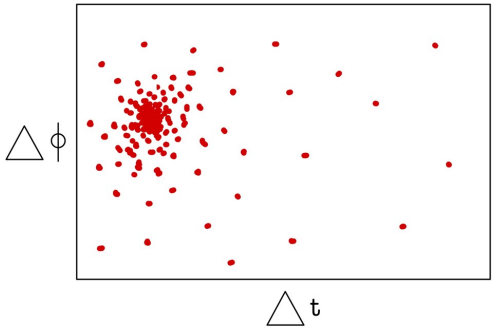


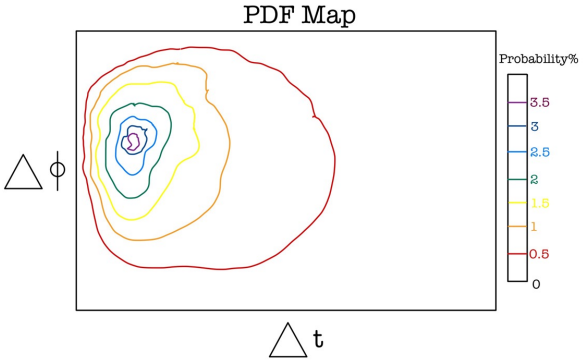




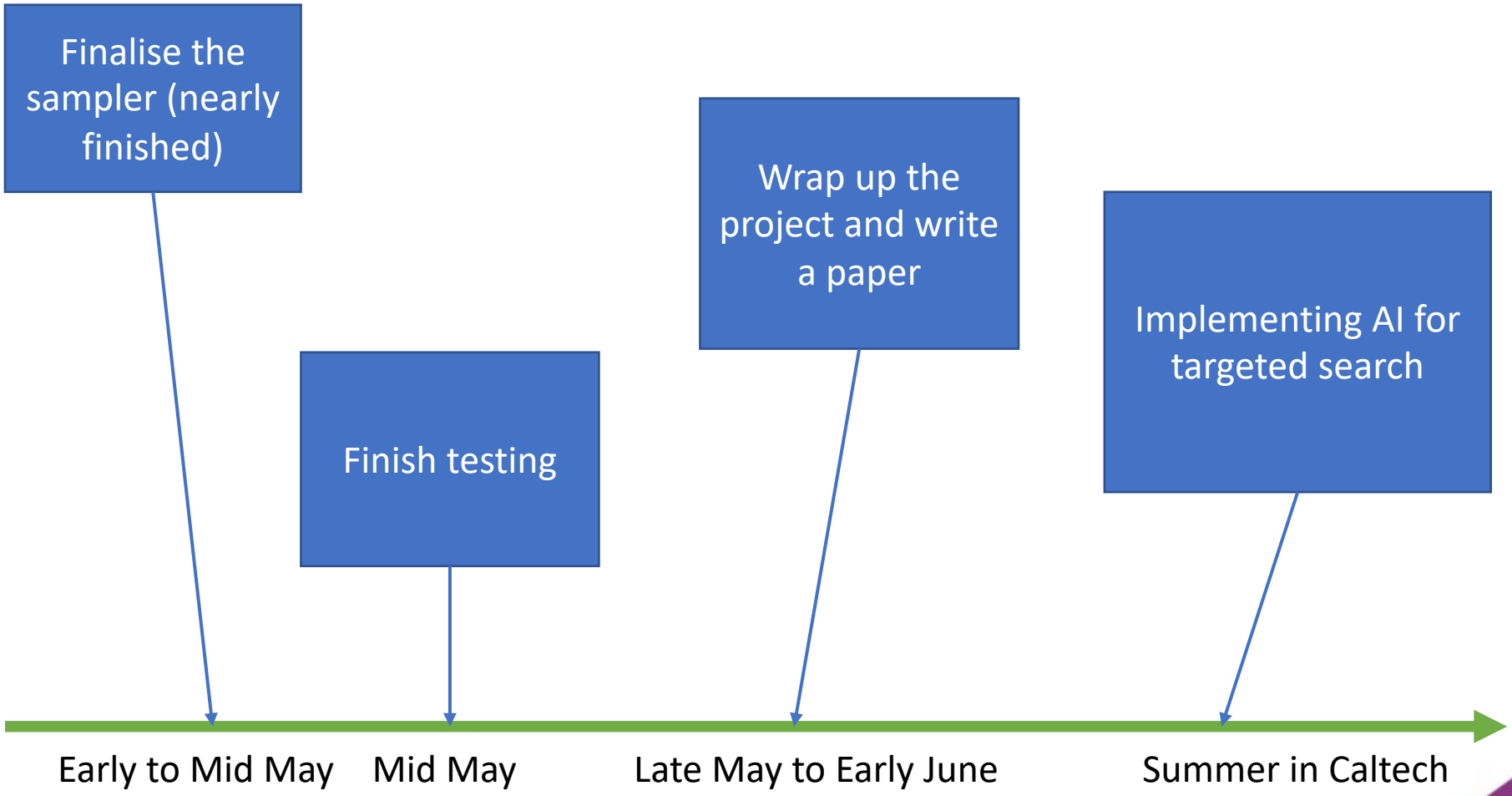
Targeted Search







Timeline


Finalise the sampler (nearly finished)
Finish testing
Wrap up the project and write a paper
Implementing AI for targeted search
Early to Mid May
Mid May
Late May to Early June
Summer in Caltech

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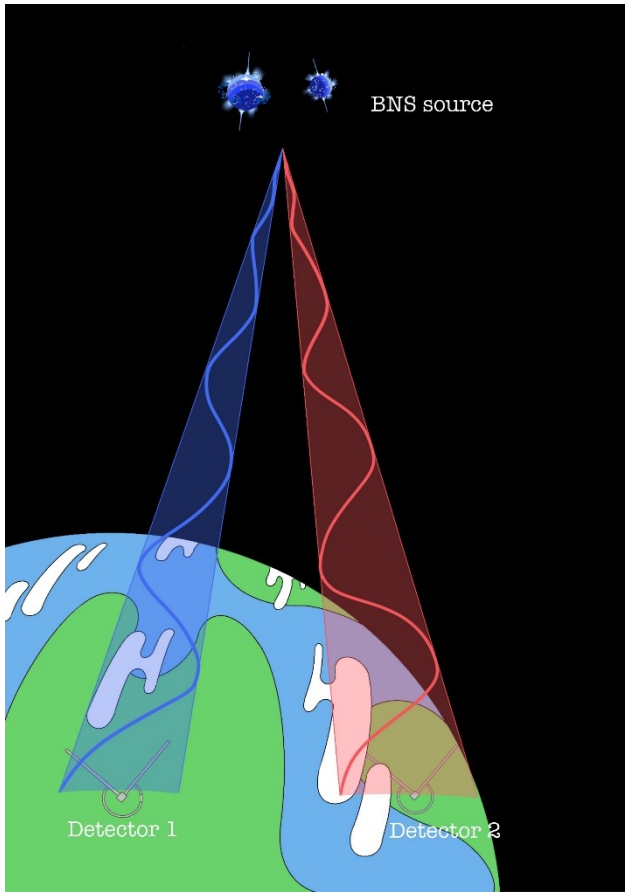
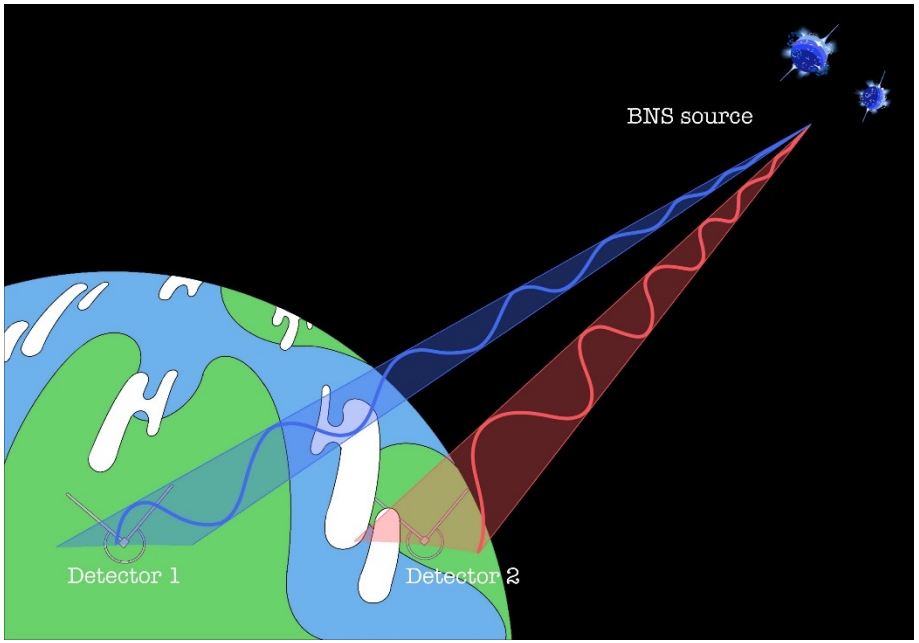
The End

Different Sky Location

$\overrightarrow{\Delta t} = 0, \overrightarrow{\Delta \phi} = 0$

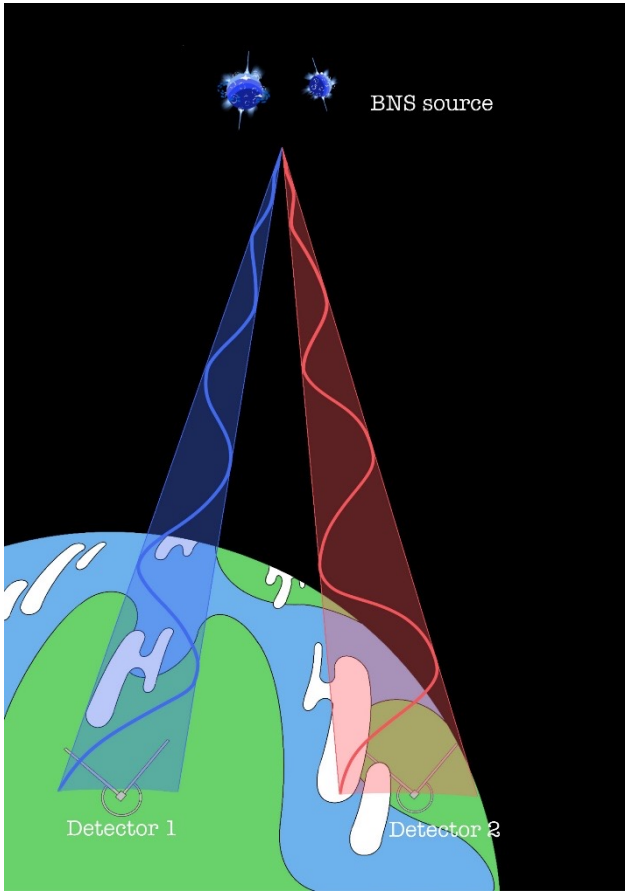




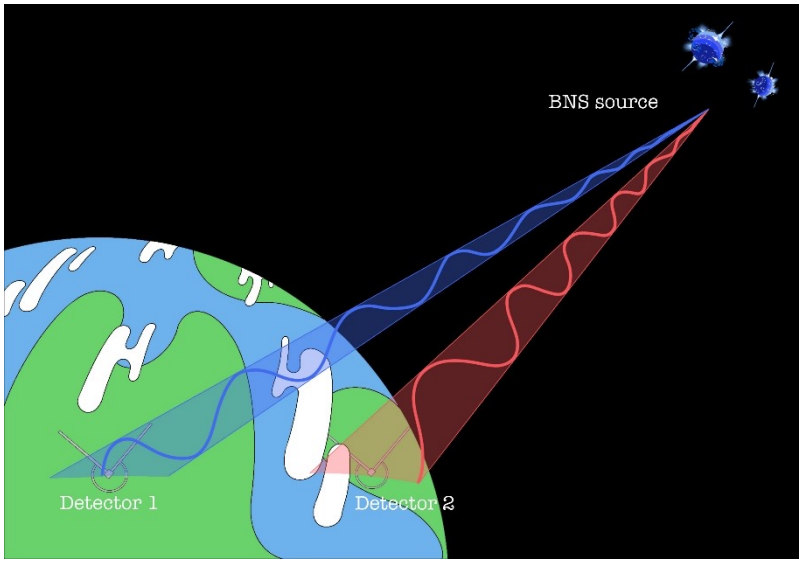
$\overrightarrow{\Delta t} > 0, \overrightarrow{\Delta \phi} > 0$

Earth Rotation

- $\Delta t, \Delta\phi$ would be different at different times
- need PDFs at different times
- Lensing might cause delays in O(months)
- E.g. the time delay between 2 of the lensed images of SN Refsdal (a supernova) is 42 days.

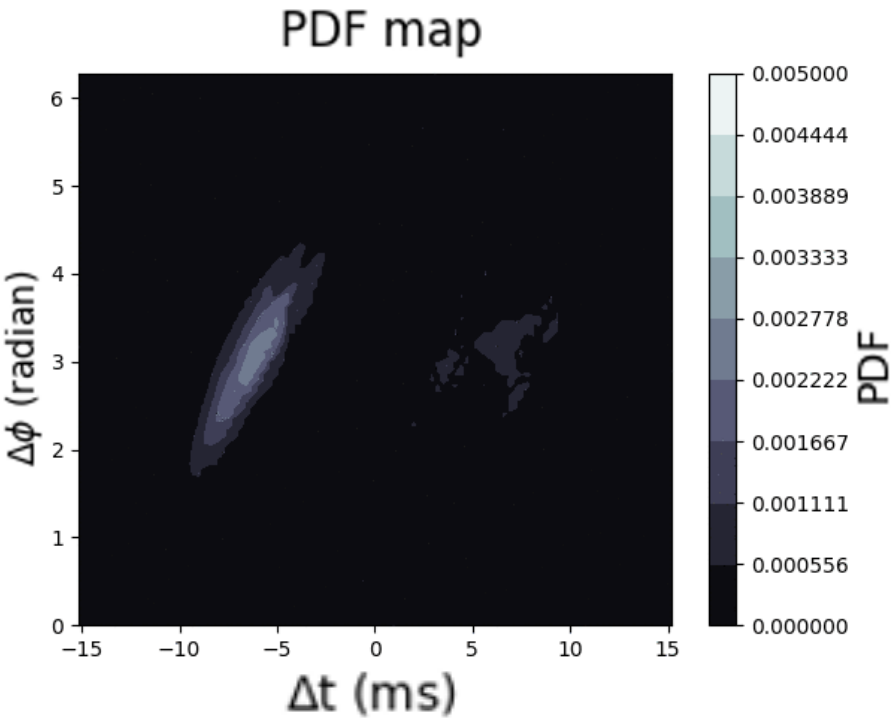


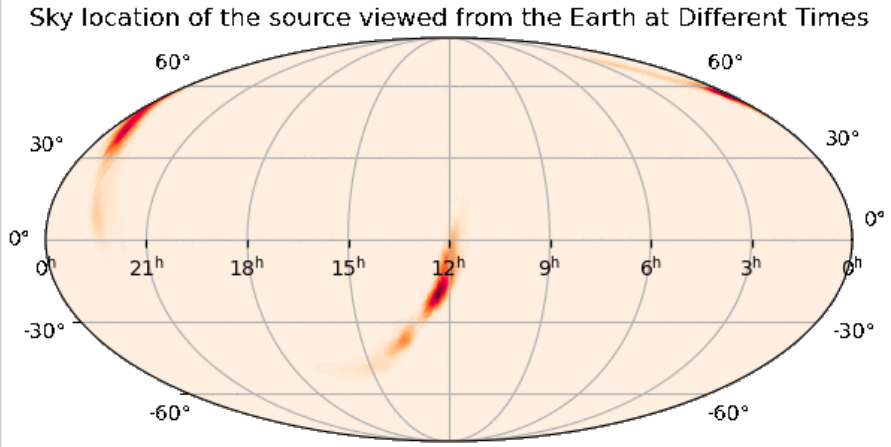
12:00pm



9:00am

Rotating for a whole cycle





Event: GW190519
Frequency: 240 steps per sidereal day rotation
Detectors: H1 and L1
SNR = 10

Programme Flow