CUHK SURE 2022
LIGO SURF 2022

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

Physics Conference 2022

Aidan Chong[1]

Mentors

Alvin Li[2], Ryan Magee[2], Juno C.L. Chan[1], Cody Messick[3], Alan J. Weinstein[2]

1. Department of Physics, The Chinese University of Hong Kong
2. LIGO Laboratory, California Institute of Technology
3. LIGO Laboratory, Massachusetts Institute of Technology

LIGO
SURF
LENSING SEARCHES

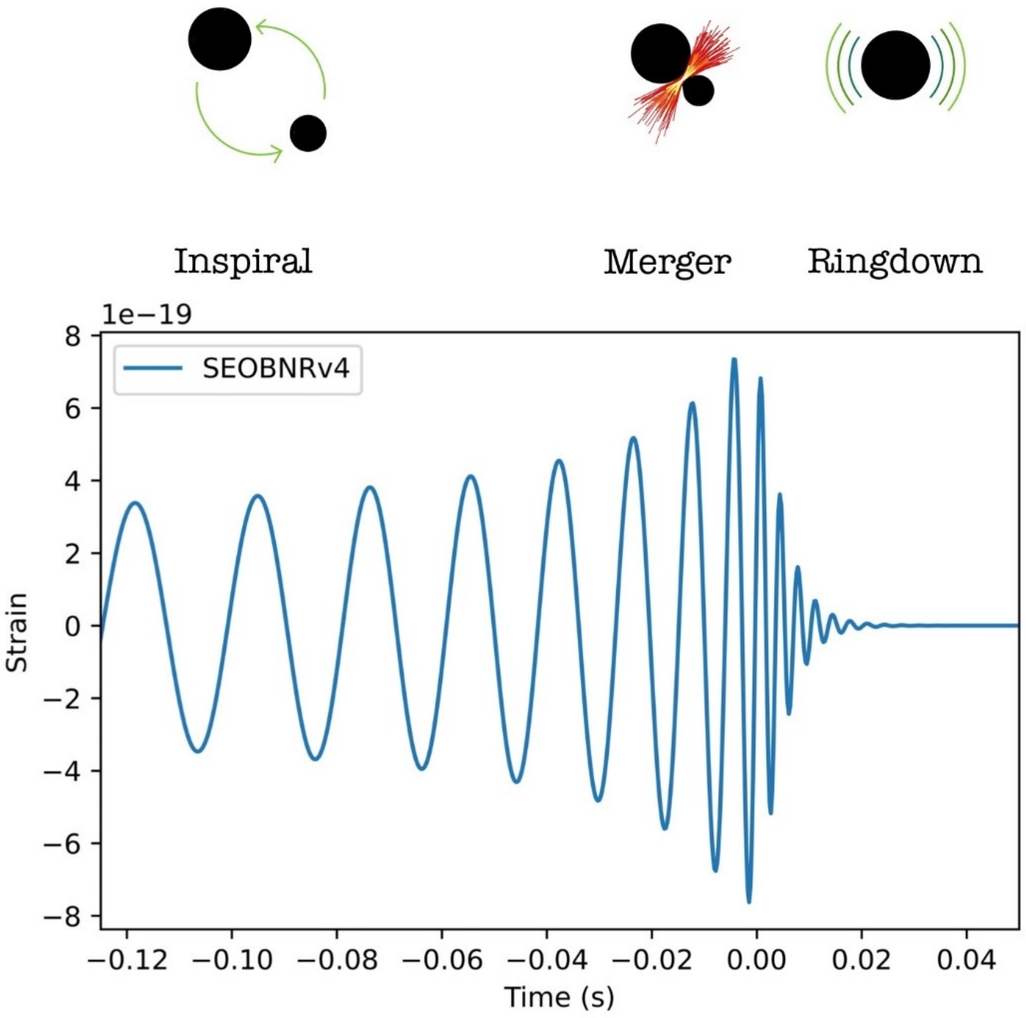
PART 1.0

Gravitational Waves

General Relativity

- Einstein's Field equations: $G_{\mu\nu} = 8\pi T_{\mu\nu}$
- Massive object would curve space-time
- Accelerating objects create ripples in space-time → gravitational waves

Waveform

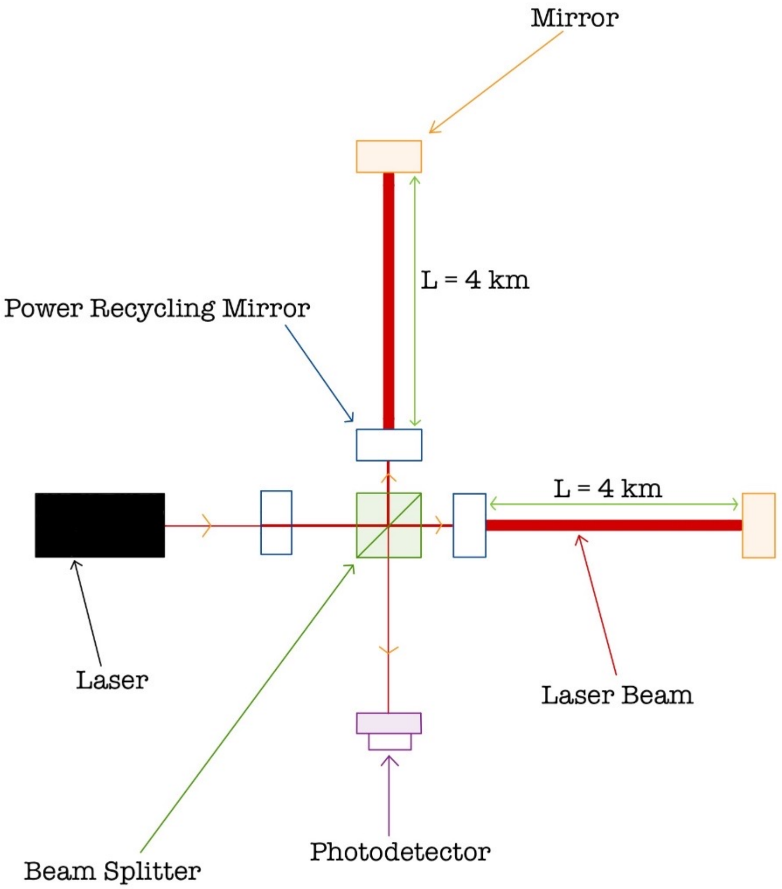


GW from compact binary coalescence

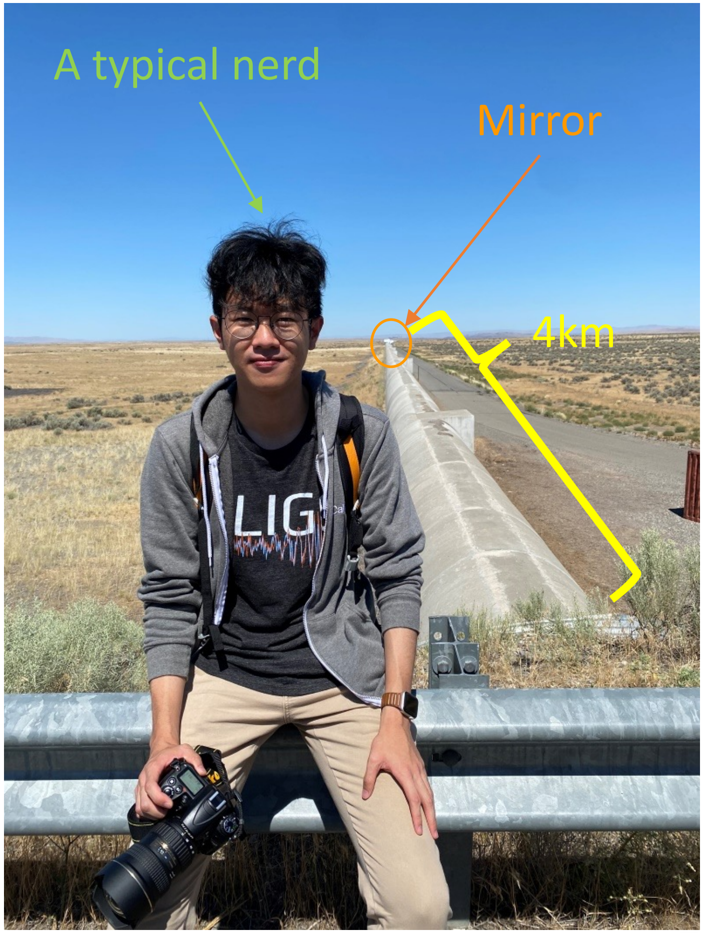
- Neutron stars
- Blackholes

Detection

Schematic diagram of a LIGO detector



Size comparison



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

LIGO SURF LENSING SEARCHES

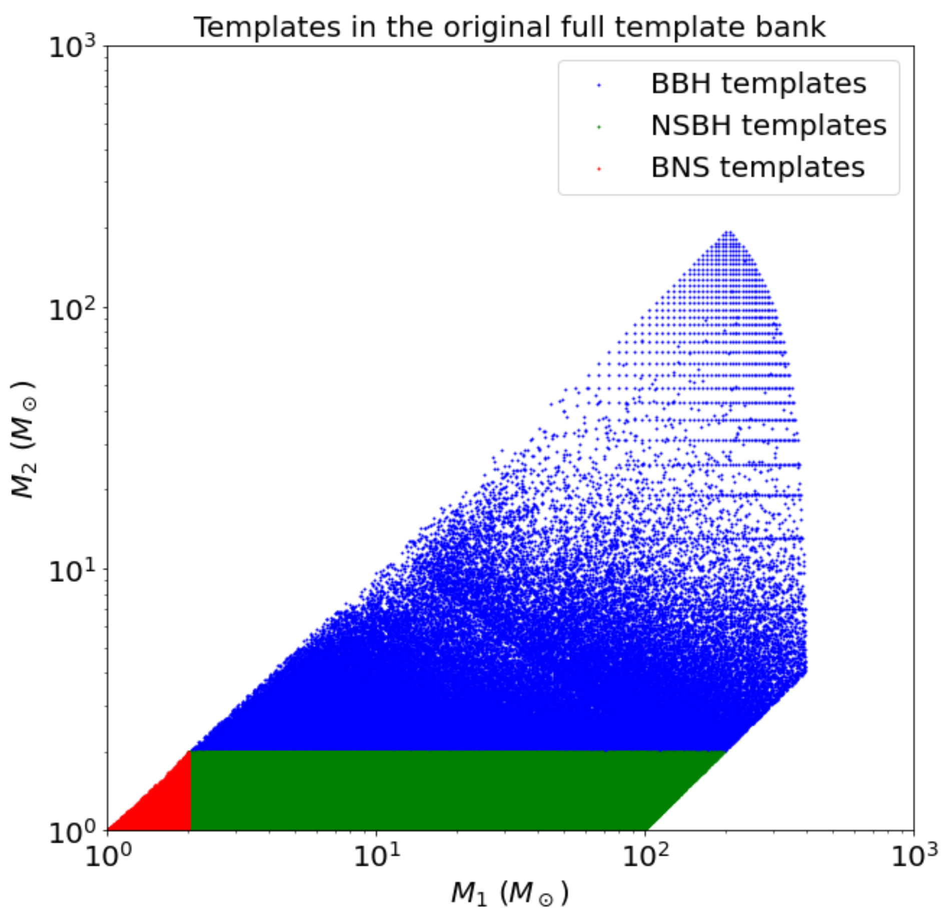
PART 2.0

Searching Lensed Gravitational Waves

General Search Pipeline

Matched filtering using templates

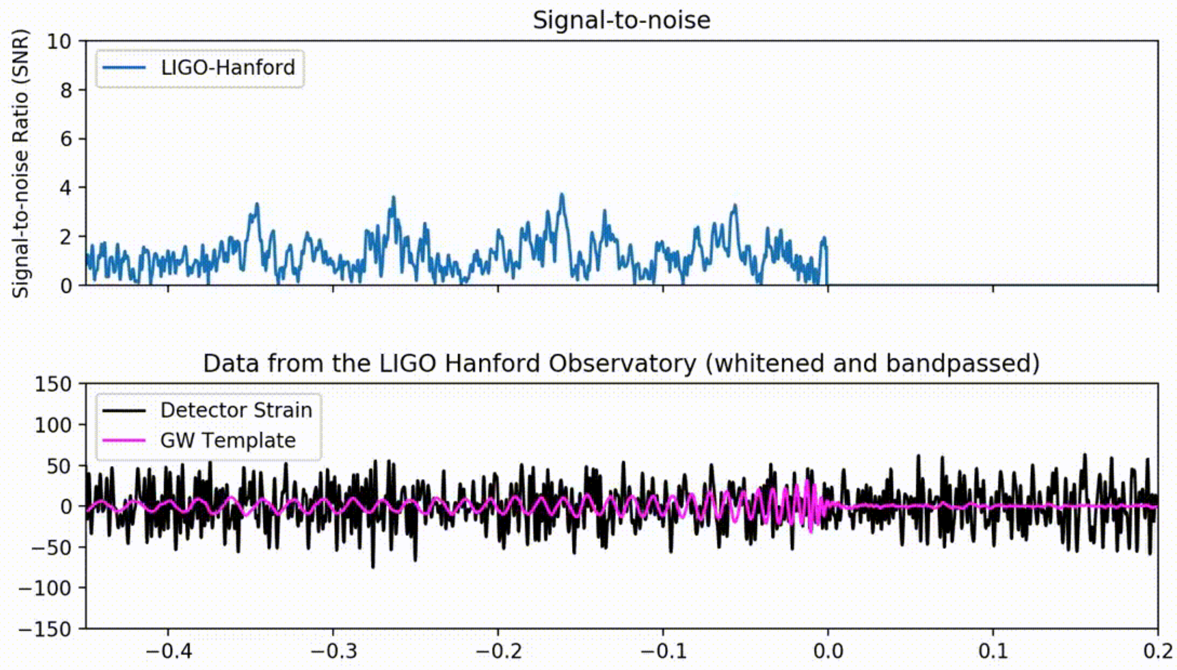
e.g. GstLAL and PyCBC

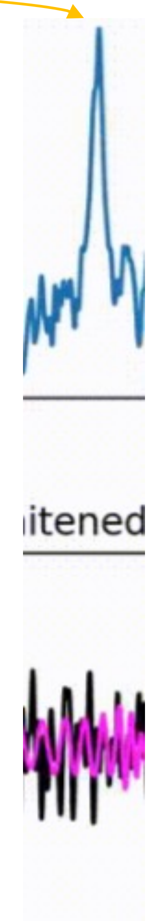


→ Output a <u>ranked list</u> of **possible** GW candidates
For future follow up

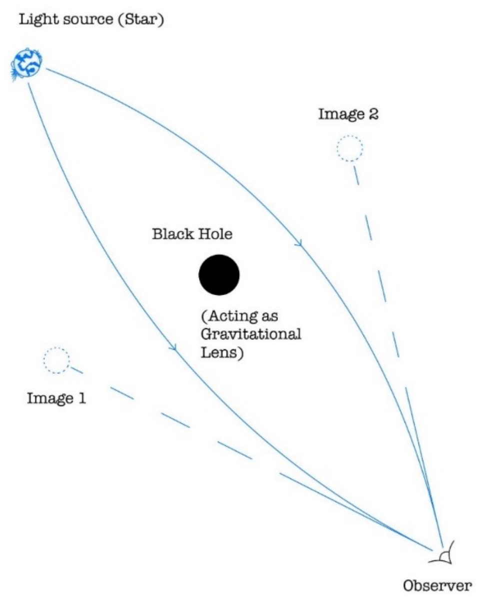
Matched Filtering

Trigger

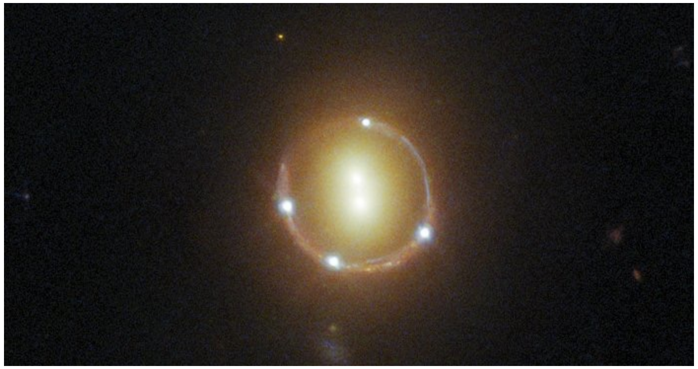




Gravitational Lensing



- Change in Image position
- Change in amplitude
- Change in arrival time
- Similar to a lens placed between the observer and the light source.



➢ Einstein Ring

ESA/Hubble & NASA, T. Treu; Acknowledgment: J. Schmidt

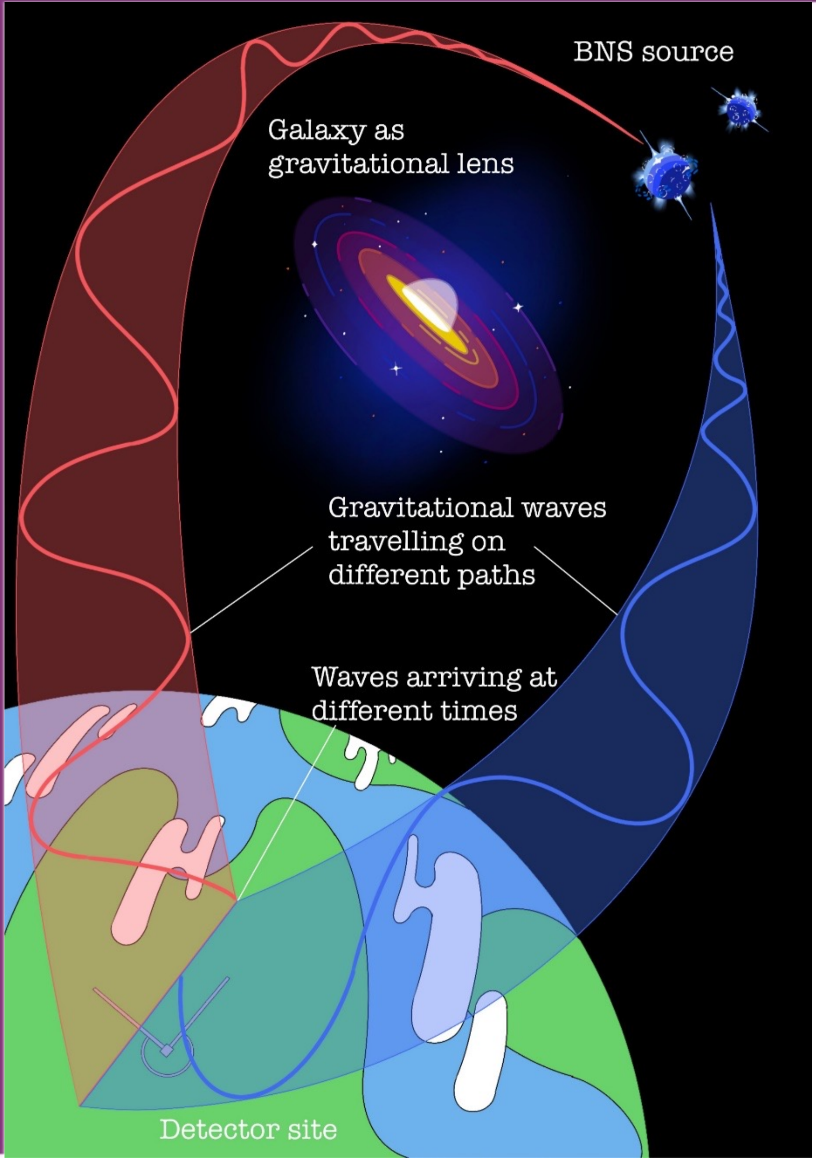
Lensed Gravitational Waves

Strongly lensed Gravitational Waves:

$$h_j^{lensed} = \sqrt{|\mu_j|} \times h^{original}(f, \theta, \Delta t_j) \times e^{i\,sign(f)\Delta\phi_j}$$

- Magnification factor
- Arrival time difference between a pair of lensed images
- Morse phase shift
- f is the frequency of the GW and θ represents other CBC parameters => same morphology

Visualisation



- Difference in amplitude
- Difference in arrival times

I drew it :)

Importance of GW Lensing

- Astrophysics
  - Give information on the source and the lens
- Cosmology
  - Distribution of dark matter
  - Find out the large-scale geometry of the universe
  - Calculate the Hubble's parameter
    - Expansion rate of our universe
- Test of General Relativity
  - No lensed GW have been detected yet
  - Detecting a lensed GW would prove Einstein right (Again)

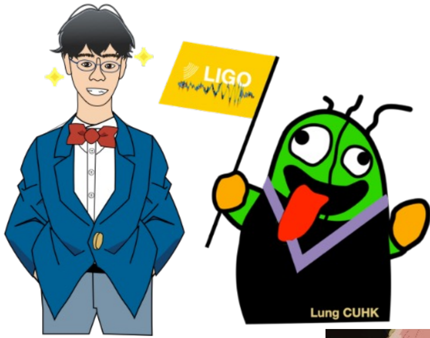
Improved Targeted Sub-Threshold Search for Strongly Lensed Gravitational Waves with Sky Location Constraint

2 Categories of Signals

- Super-threshold signals
  - Events that have high enough ranking statistics
  - Relatively high amplitude
  - All confirmed GWs in the LIGO catalogue are super-threshold signals
- Sub-threshold signals
  - SNR **high enough** to produce a trigger
  - Insignificant ranking statistics

Lensing Search Pipelines

傻Alvin

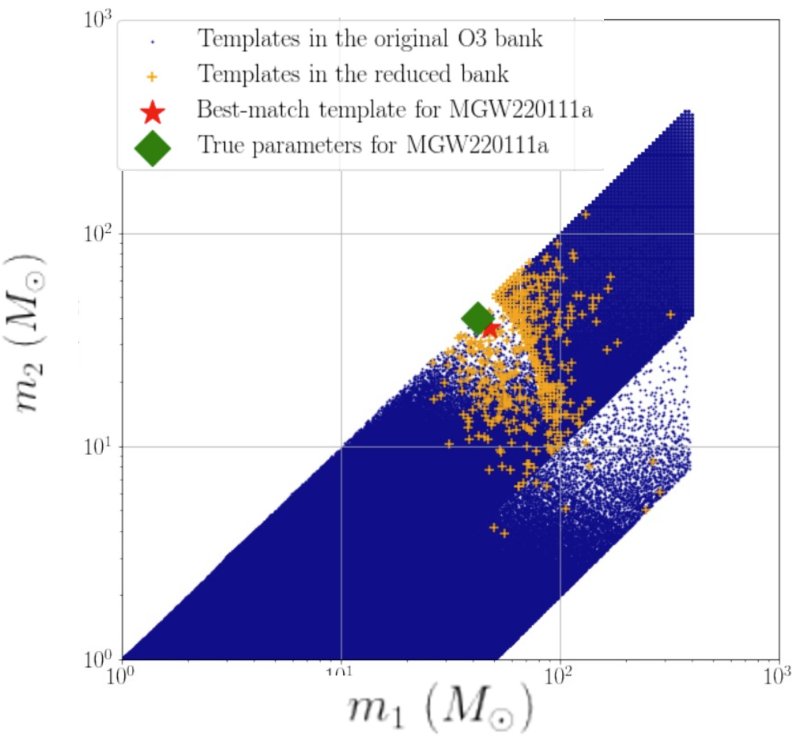


傻Juno

- Examples
  - TESLA (GstLAL based)

  - PyCBC

- Strongly lensed images would have similar intrinsic parameters
- Targeted Search
  - Only use template banks similar to the targeted GW event



Li et al.

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

LIGO SURF LENSING SEARCHES

PART 3.0

Methodology

Why am I still here?

- Each targeted search can return O(10) candidates
- O4 would probably produce O(100) events -> return ~1000 candidates

very costly to do analysis

My Aim

- Retrieve lensed GW signals
- Improve Sensitivity of the pipeline
- Add sky localisation constraints to improve the ranking statistics of candidates according to their location on the sky relative to the target

Me in Los Angeles

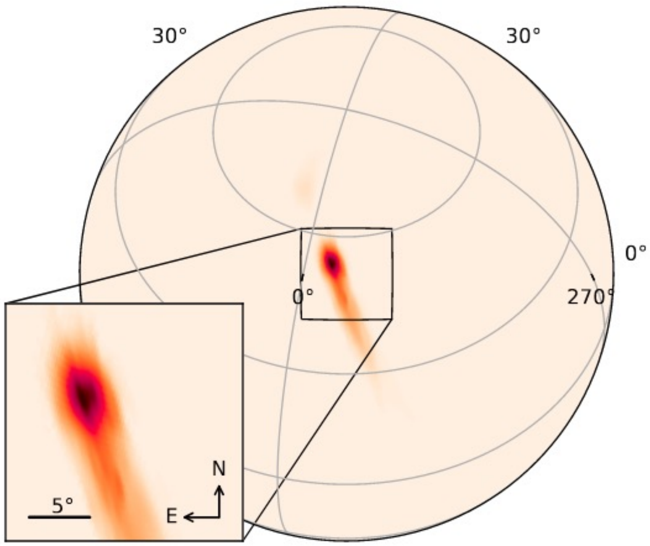
Why is it possible

- LIGO can only constrain the sky location to the order of degrees

BUT

- Shift in image position due to lensing is in the order of arc seconds

➢ **can safely assume that both images would come from the same sky location**



Skymap of GW190408

Likelihood Ratio

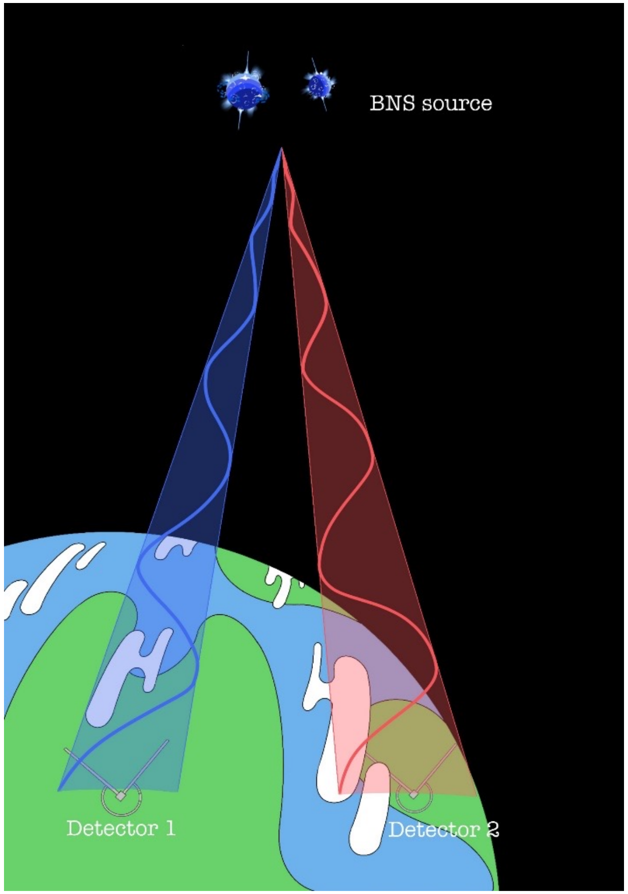
- The likelihood ratio of a trigger that is produced by a real gravitational wave is given by:

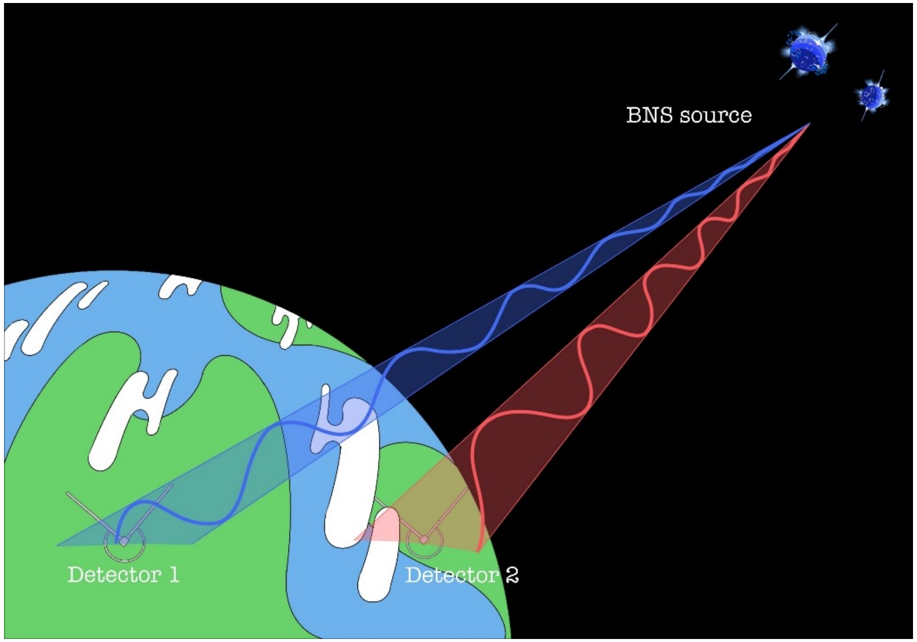
$$\mathcal{L} = \frac{P(\vec{D}_H, \vec{O}, \vec{\rho}, \vec{\xi}^2, [\vec{\Delta t}, \vec{\Delta\phi}] | \vec{\theta}, \text{signal})}{P(\vec{D}_H, \vec{O}, \vec{\rho}, \vec{\xi}^2, [\vec{\Delta t}, \vec{\Delta\phi}] | \vec{\theta}, \text{noise})} \cdot \frac{P(\vec{\theta}|\text{signal})}{P(\vec{\theta}|\text{noise})}$$

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

Visualisation

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





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

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

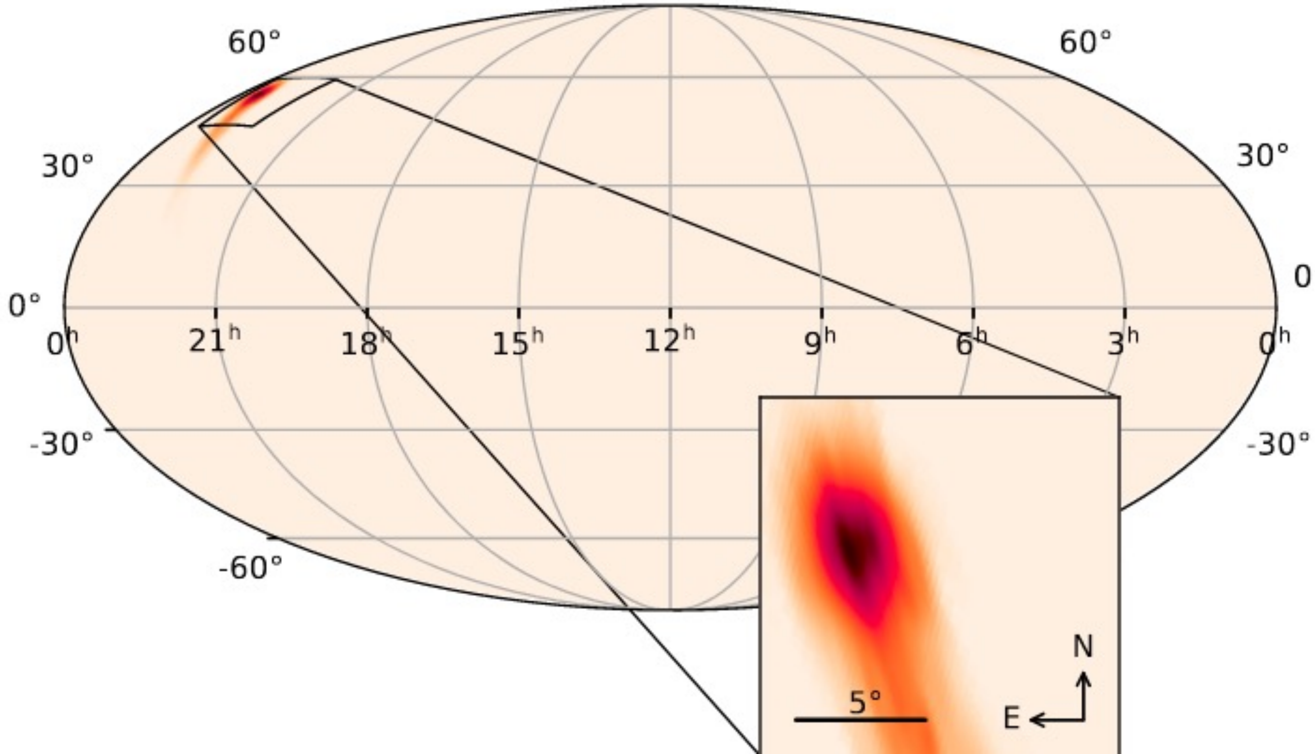
LIGO
SURF
LENSING SEARCHES

PART 3.0 + 1.0

Re-calculate the PDF

Reading Skymaps

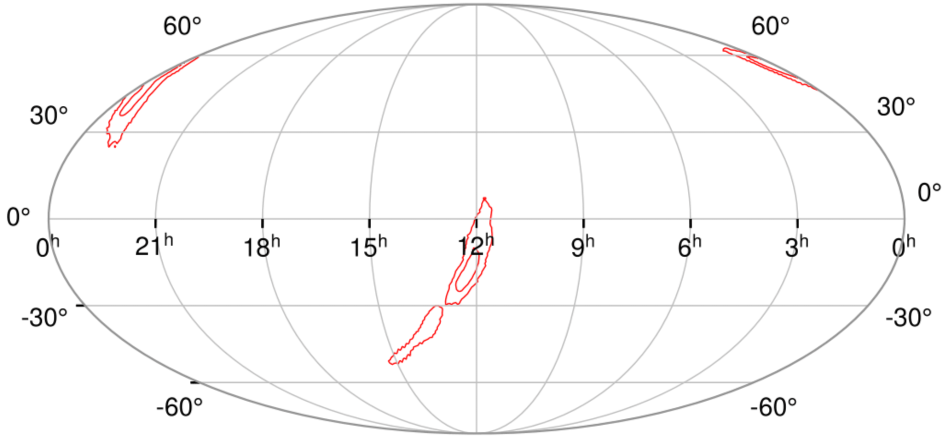
- Modify the GstLAL pipeline to allow the user to input LIGO skymap



Sky Tiling

- The probability density is calculated grid by grid
- The image would come from the same patch of sky if it is the lensed counterpart of the target

➢ Re-calculate the probability density



Removing unnecessary jobs

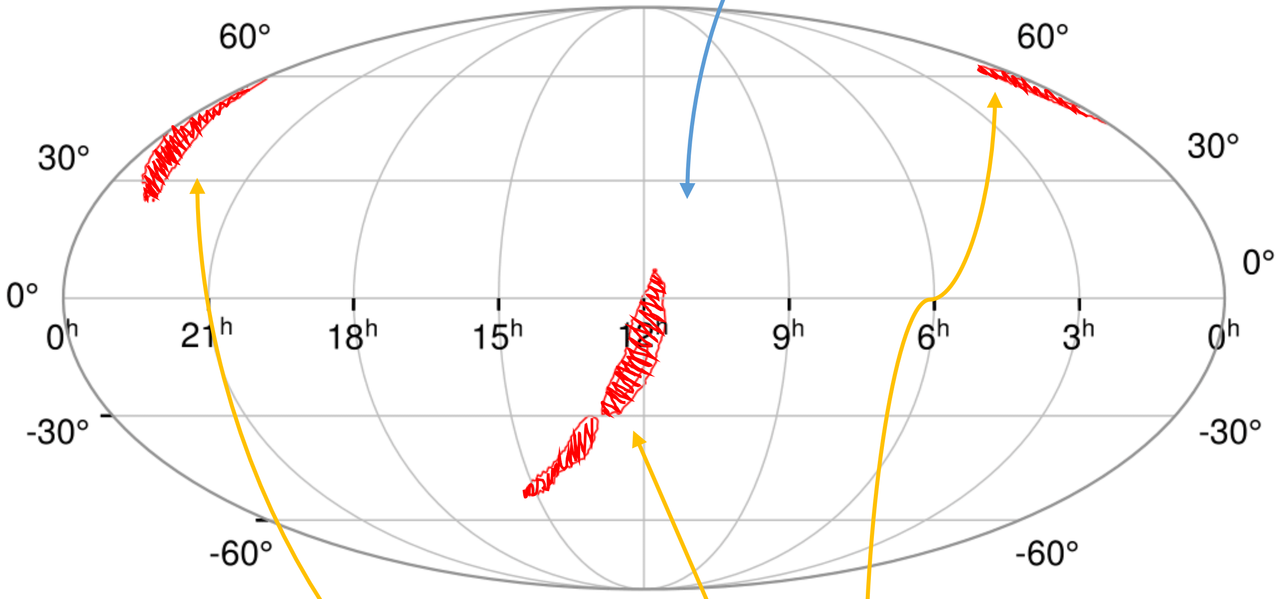
- Reducing 3000+ jobs to O(10) of jobs (67 jobs for GW190519)

- Completing a PDF map in about 2 hours

Probability Distribution

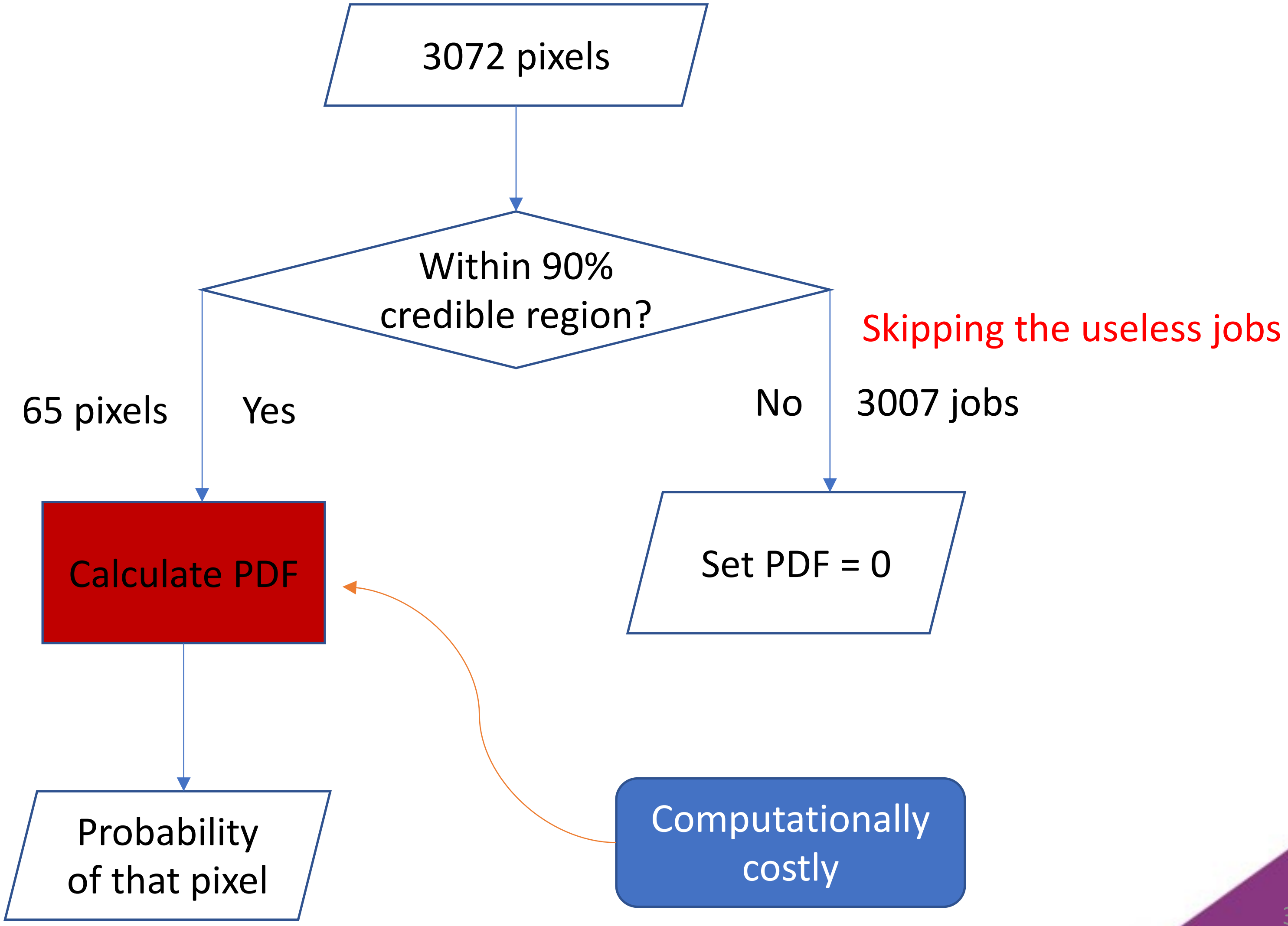
Skymap of GW190519

PDF = 0 under the assumption that the lensed counterpart must not come from these sky locations

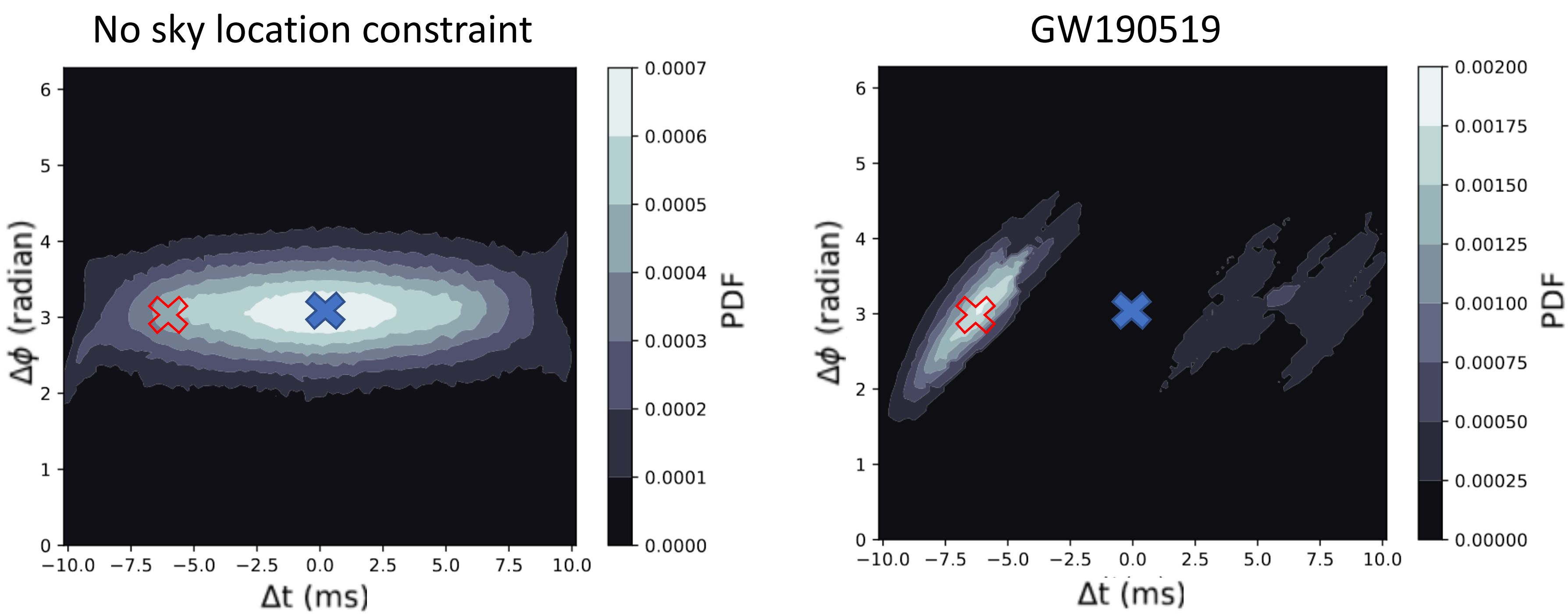


90% credible region: PDF > 0. We are assuming they have equal probability to be coming from any of these pixels

Calculating the PDF



Example



Red trigger: 0.0004 -> 0.002 [up-ranked]

Blue trigger: 0.0007 -> 0 [down-ranked]

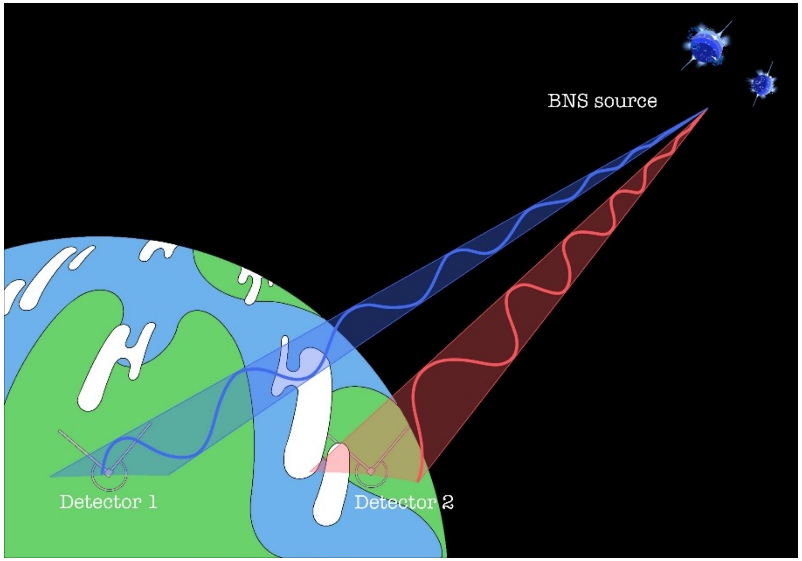
LIGO SURF LENSING SEARCHES

PART 3.0 + 2.0

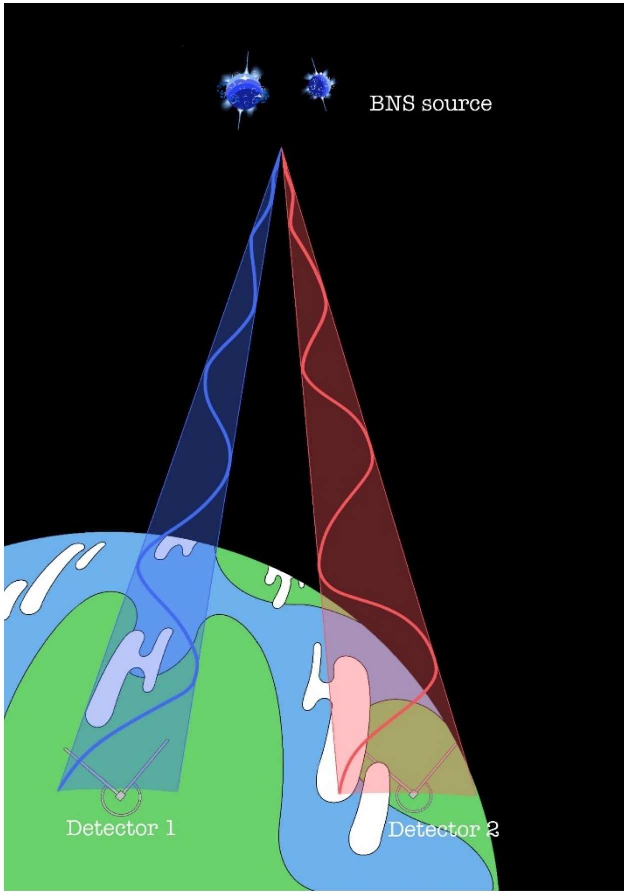
Account for the Rotation of the Earth

The Earth is rotating…

- $\Delta t, \Delta\phi$ would be different at different times
- Calculate many 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.

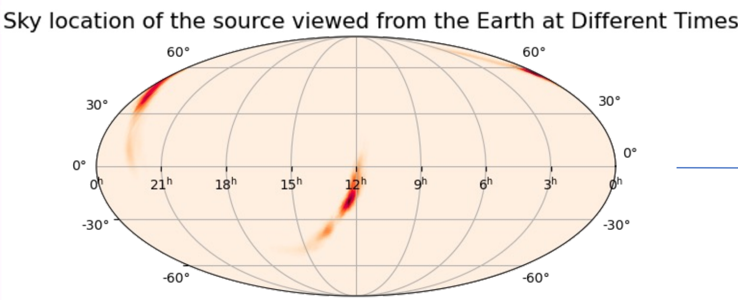


9:00am

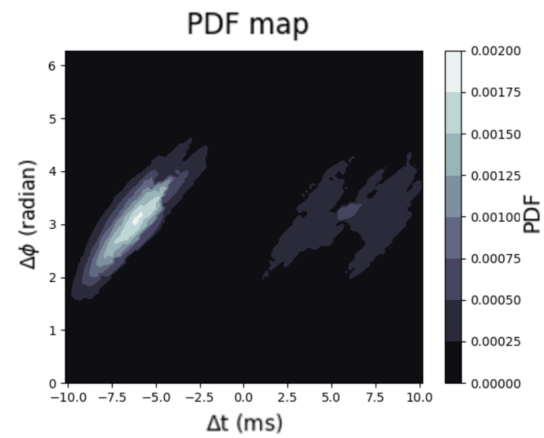


12:00pm

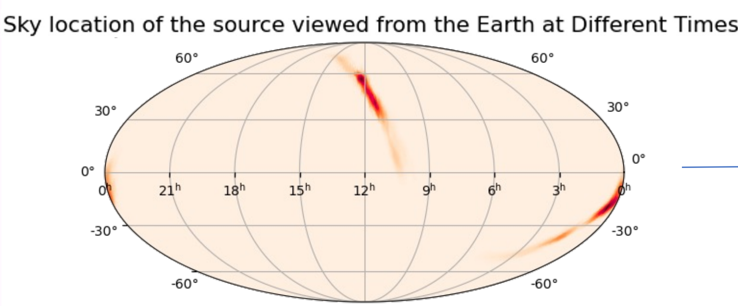
Rotating the skymaps



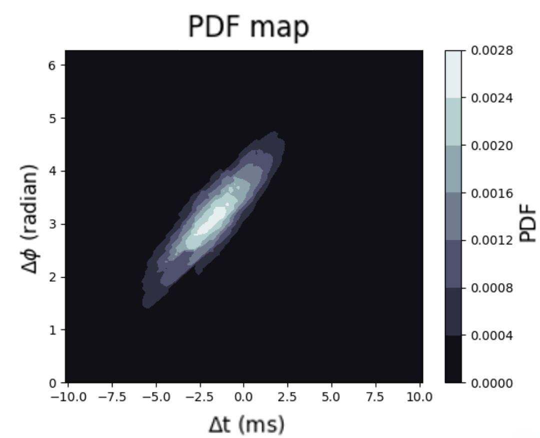
Calculate and plot dtdphi PDF



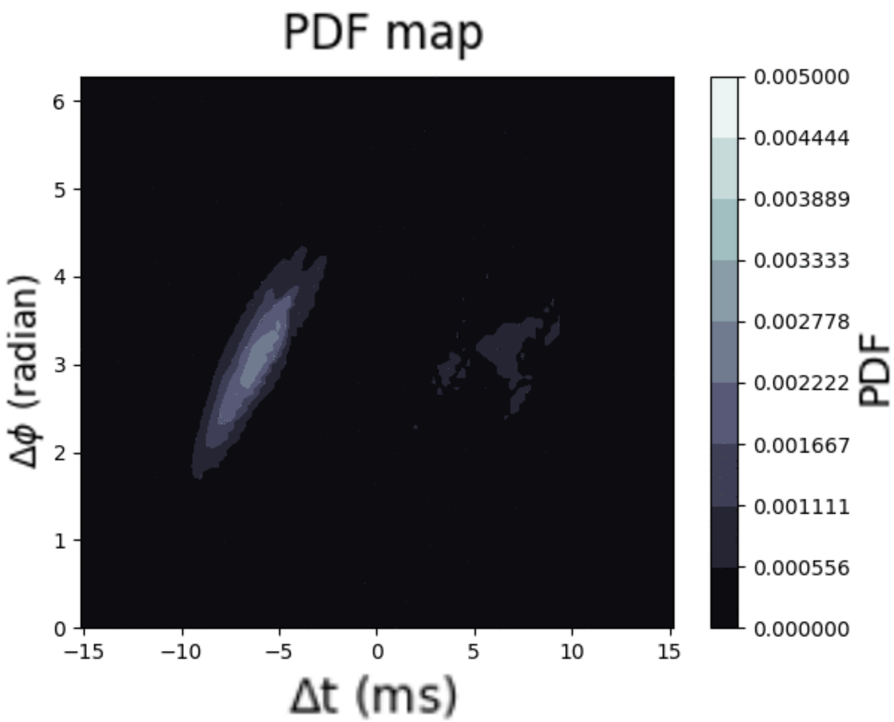
Rotates 180 degree to the right

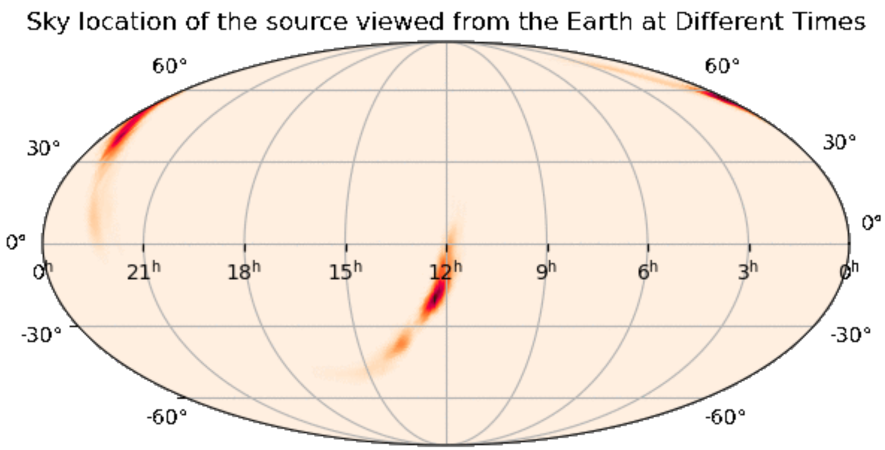


Calculate and plot dtdphi PDF



Rotating for a whole cycle





Event: GW190519

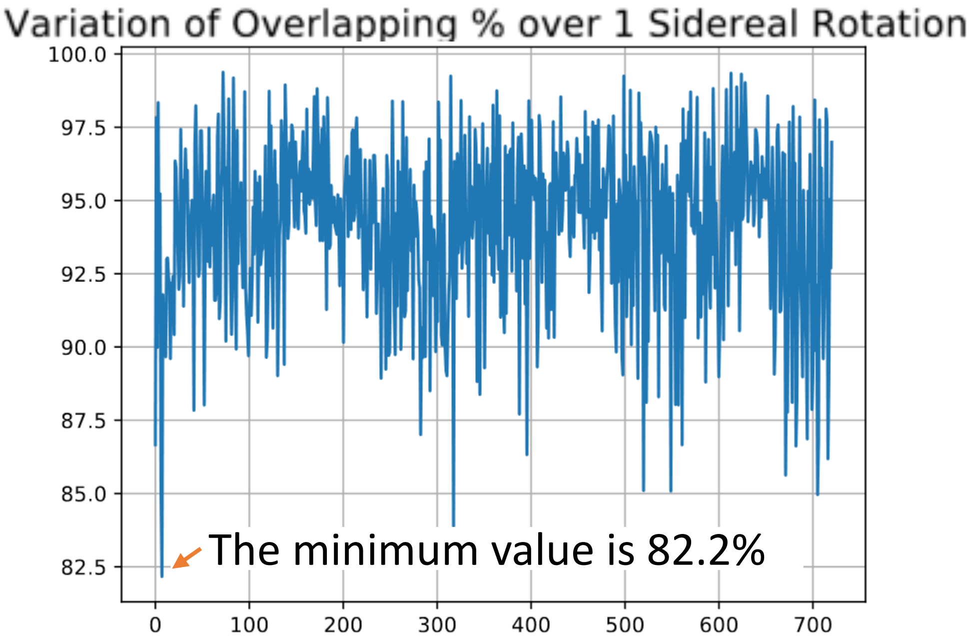
Frequency: 240 steps per sidereal day rotation

Detectors: H1 and L1

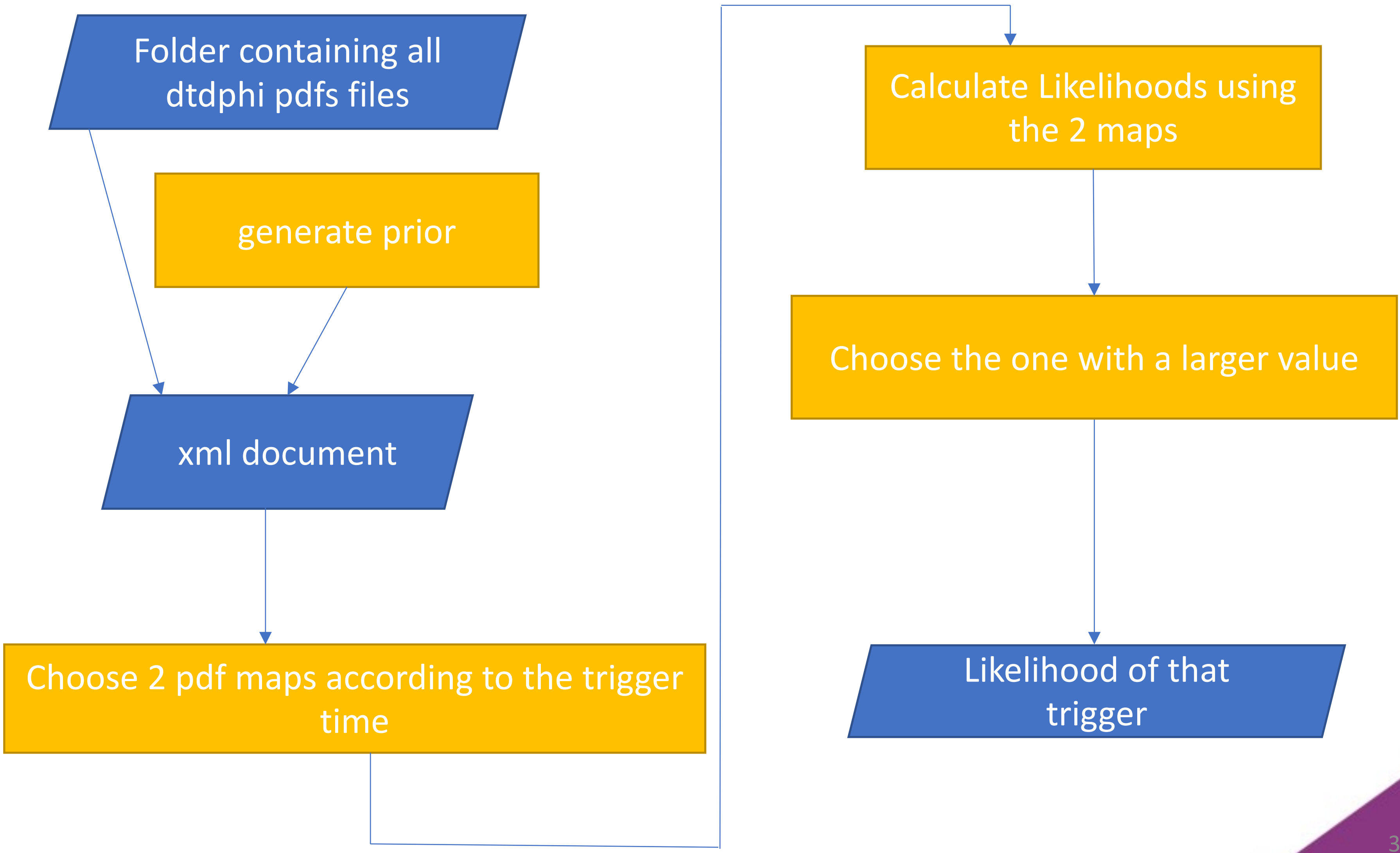
SNR = 10

How many maps do I need?

- Criteria: At least overlap 80%
- Generate a new map for every 0.5 degrees of rotation/720 steps per sidereal day gives a **minimum** overlapping value of 82%



Implementation



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

LIGO
SURF
LENSING SEARCHES

ONE MORE FINAL:

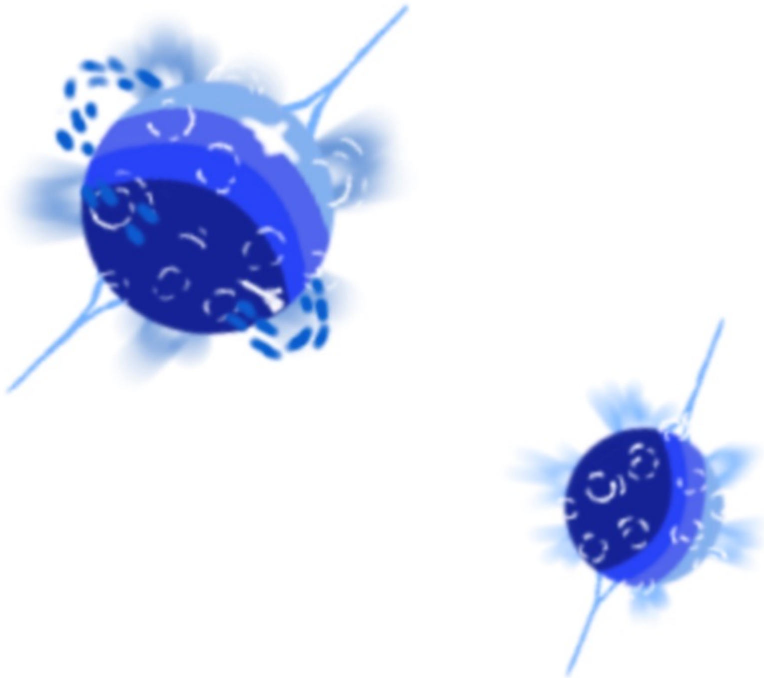
Future Plan(s)

Mock Data Challenge

- Inject simulated signals into real noise data and try to retrieve the injections using the new searching pipeline.
- Compare the efficiency and accuracy between the modified and original pipeline.

Possible Applications

- GW from <u>G</u>amma <u>R</u>ay <u>B</u>urst (GRB) events
  - BNS merger
- GW from supernovae



Acknowledgement

Thanks for

- NSF, LSC and Caltech for making the programme possible
- The Chinese University of Hong Kong for funding my trip and giving valuable my supports
- All of my mentors
- All other people who had helped me along the way

LIGO SURF

LENSING SEARCHES

THE END OF PRESENTATION

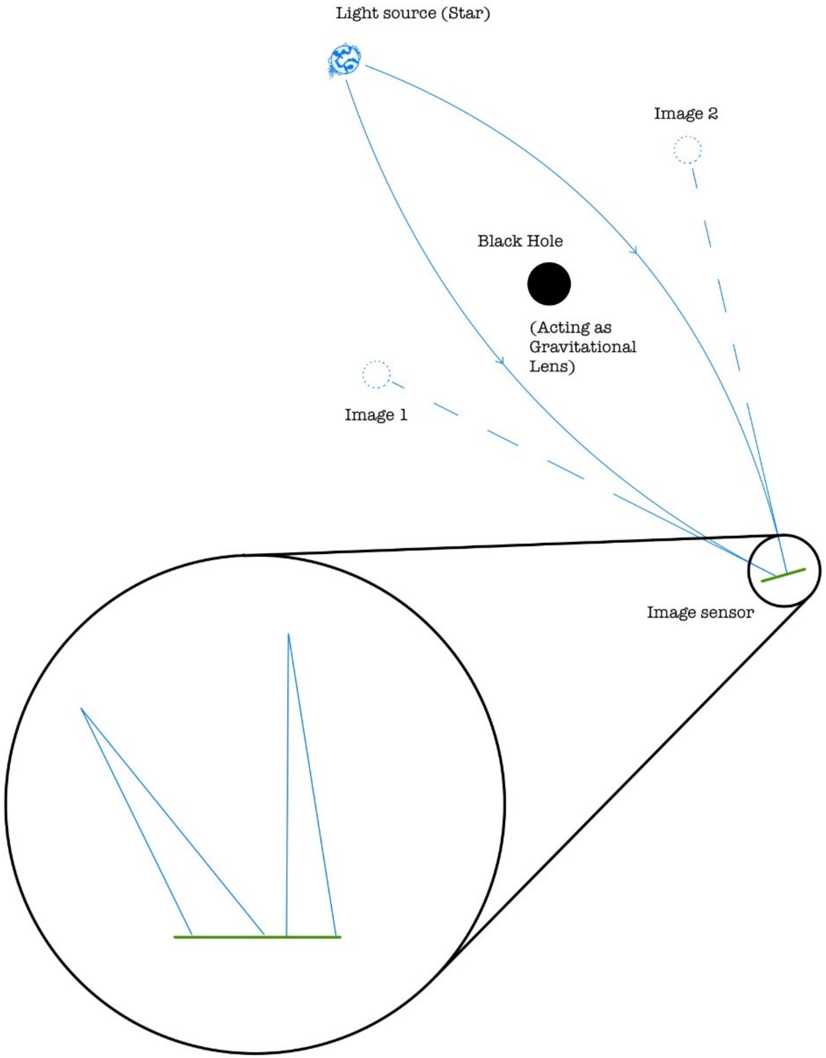
Q&A

Appendix

Contemporary Research

- LVK O3a lensing paper
  - Lensing statistics
  - Re-analysing events under lensing hypothesis
  - Multi-image search
  - Microlensing search

Multi-image Search



- Images might be amplified or deamplified
  - Incident angle
  - Path of travel

Relativistic Deflection angle

Finding the deflection angle around a spherical object (e.g. BH/NS) (Assumed strong lensing)

- Starting from Schwarzschild metric

$$ds^2 = -\left(1 - \frac{2GM}{r}\right)dt^2 + \left(1 - \frac{2GM}{r}\right)^{-1} dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta \, d\phi^2$$

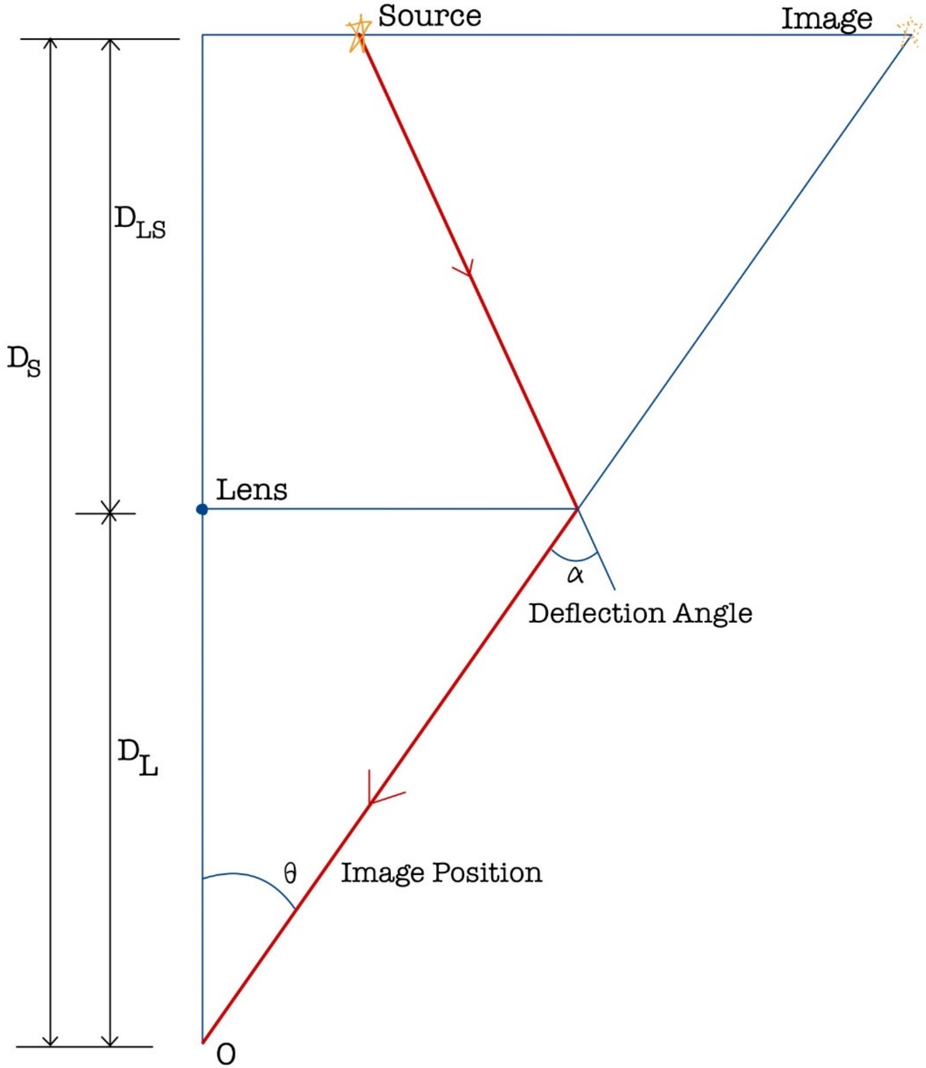
- Geodesic equation gives:

$$\frac{d}{d\tau}\left(g_{\mu\nu}\frac{dx^\nu}{d\tau}\right) - \frac{1}{2}\partial_\mu g_{\alpha\beta}\frac{dx^\alpha}{d\tau}\frac{dx^\beta}{d\tau} = 0$$

- Solving it gives:

$$\alpha = \frac{4GM}{r_c}$$

Image Position & Deflection Angle



- Deflection angle:

$$\alpha = \frac{4GM}{r_c}$$

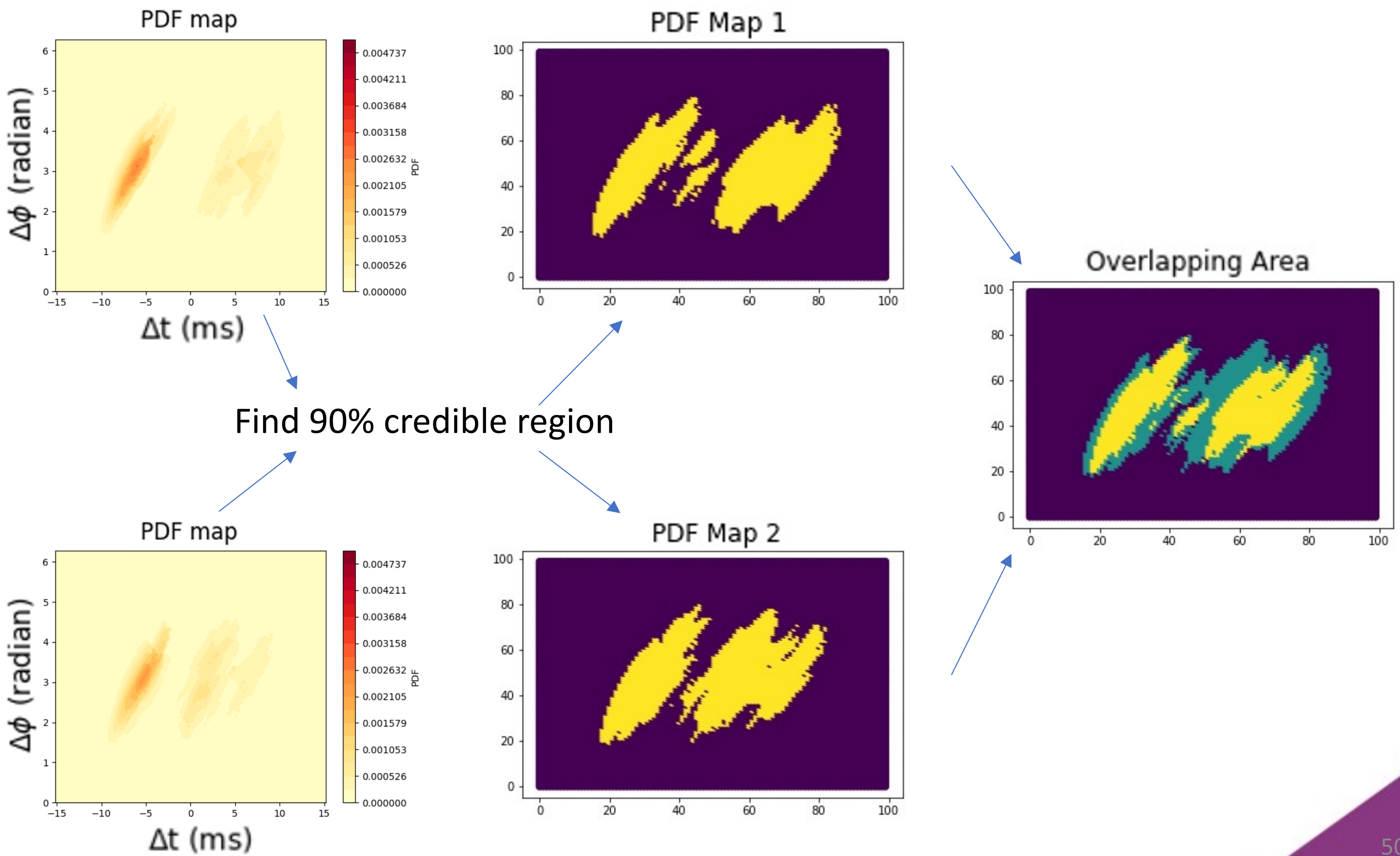
- When the source, lens and the observer are perfectly aligned on a plane, the image position is:

$$\theta = \sqrt{4GM \frac{D_{LS}}{D_L D_S}}$$

Generate PDF maps on the run?

- Around O(10000) triggers for 1 targeted search
- Many maps would be needed
- Generating a map takes O(hours) (even after massive efficiency improvement)
- Very inefficient

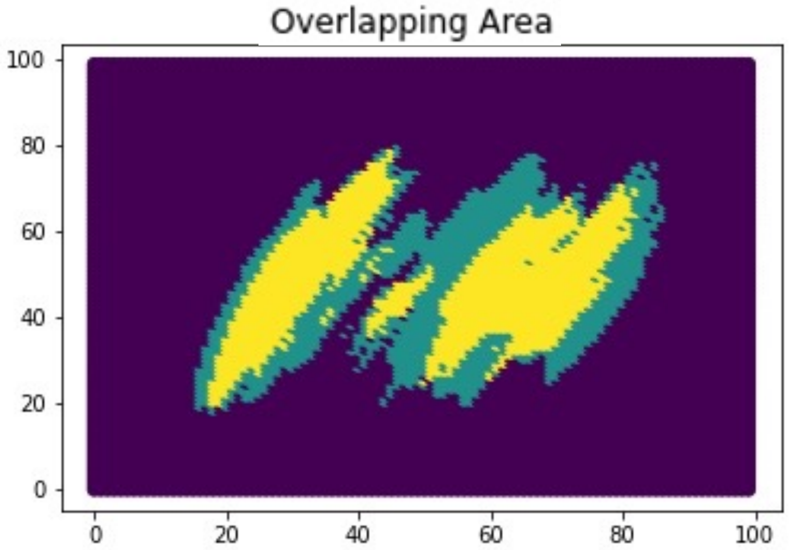
How many is enough?



Overlapping Area

- Yellow Region: pixels within the 90% credible regions of **both** maps
- Green Region: pixels within the 90% credible region of **only 1** map

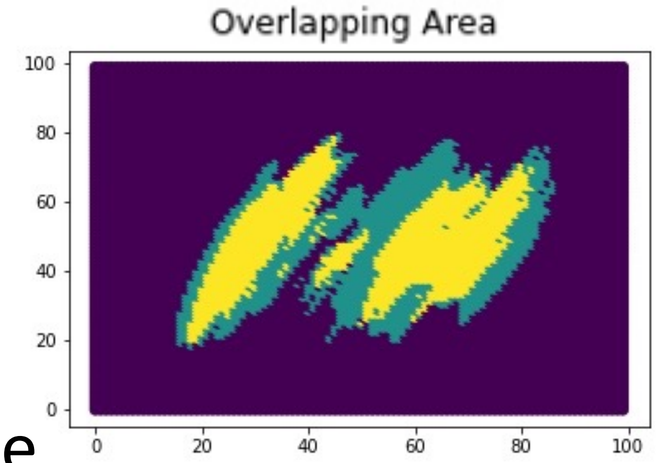
Purple Region: pixels that are outside the 90% credible regions of both maps



Overlapping Percentage

- Overlapping percentage:

$$\frac{\text{yellow region}}{\text{yellow region+green region}} \times 100\%$$



- Requirement: the percentage of the least overlapping adjacent maps over one sidereal day rotation would be larger than 80%

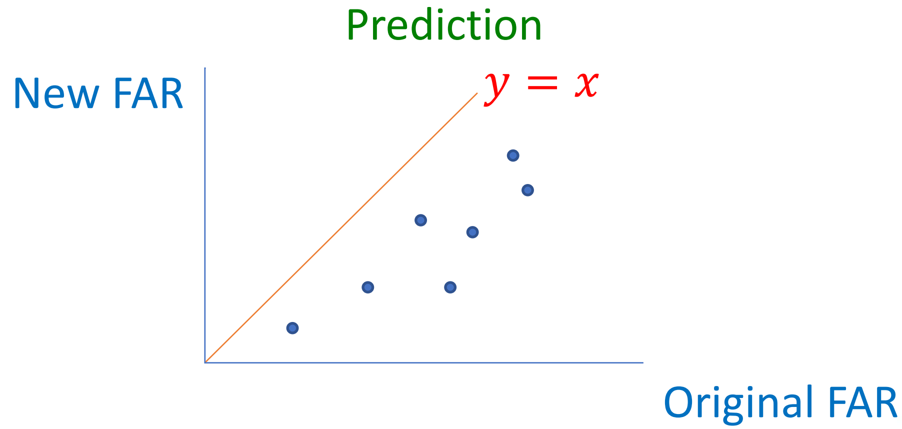
Mock Data Challenge

- Choose a real super-threshold signal / generate a simulated signal
- Produce copies of the signal with lower amplitudes (simulate sub-threshold signals)
- Inject both types of signals into real noise data
- Use searching pipelines to search the data and try to retrieve all injected signals

Mock Data Challenge

Test for:

- How many injections we could retrieve
- Efficiency of the search
  - Number of real injections retrieved vs number of noise triggers with the same ranking statistic threshold
  - **F**alse **A**larm **R**ates of the real injections before (vanilla TESLA pipeline) and after the implementation of the sky location-constrain method



backup

- All maps will be stored and selected for likelihood calculation according to the trigger time