Refining the Search for Sub-threshold Lensed Gravitational Waves

LIGO SURF 2021

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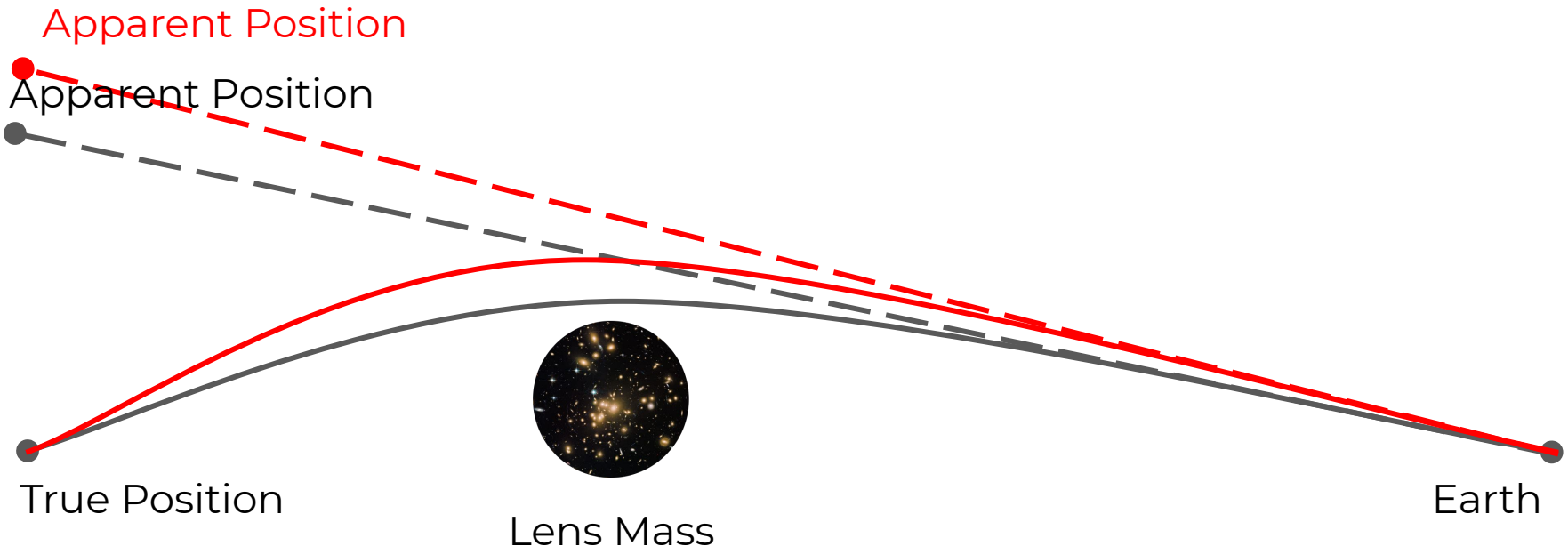
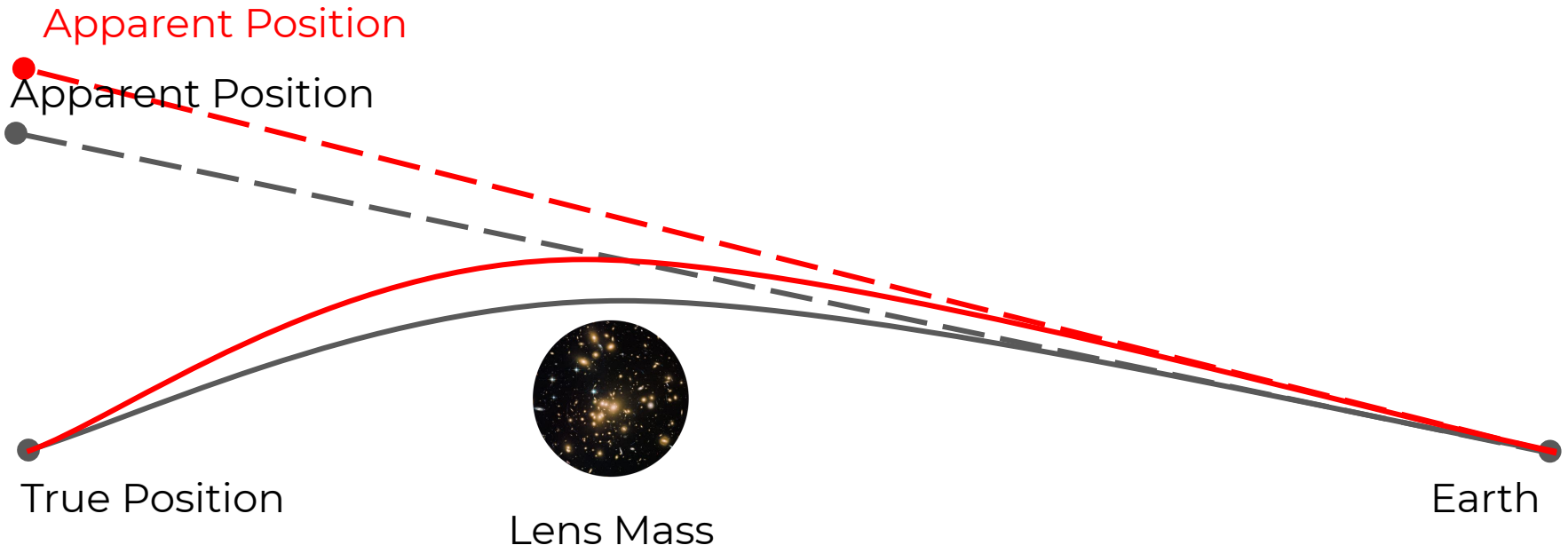
Key Points

- Background: What's a sub-threshold lensed GW? How do we look for them?
- Refining 2 ways:
  - **by waveform** - Aims, Methods, Results
  - **by sky location** - Aims, Methods, Results
- Next steps and Summary

Gravitational Lensing - Optical



Gravitational Lensing - Optical



But GWs are **transient** signals…..

Refining the Search for Sub-threshold Lensed Gravitational Waves

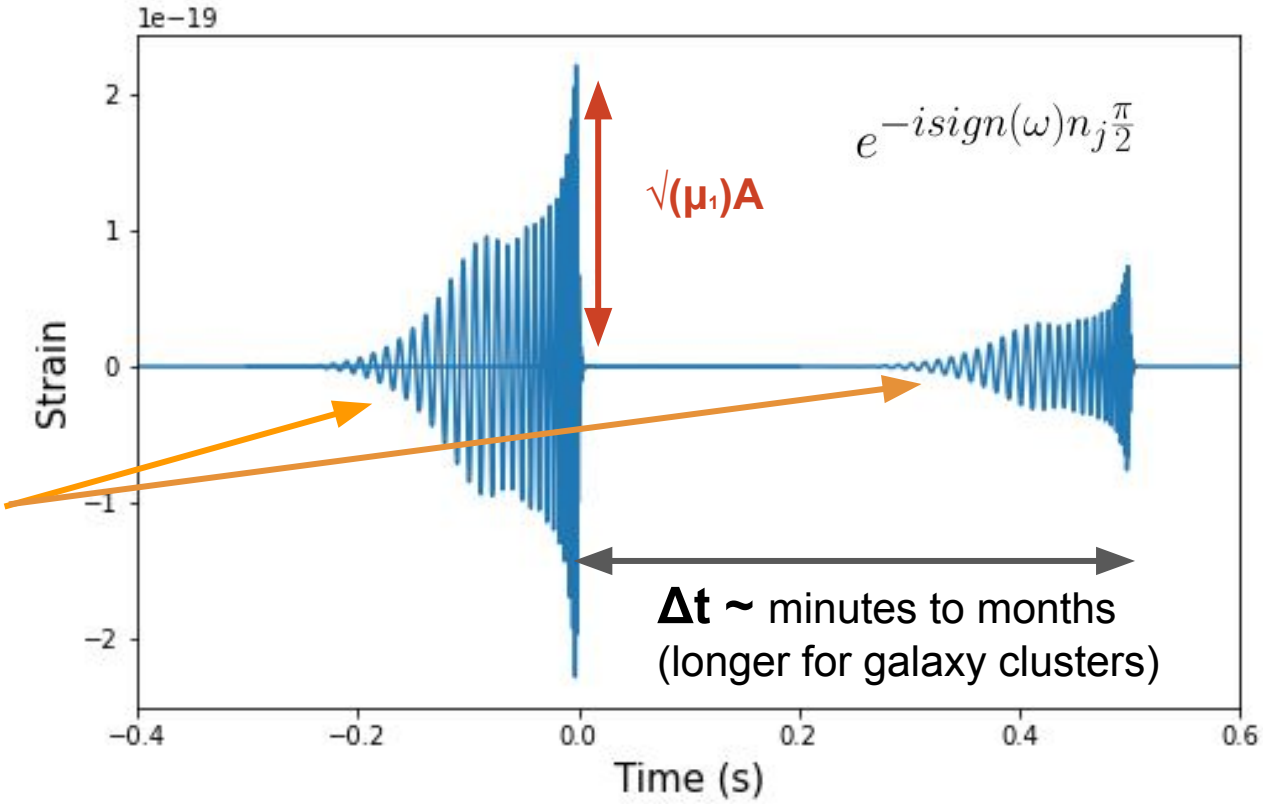
MASTER EQUATION FOR STRONG LENSING

- Lensed waveform identical* to original except from:

$$h_j^{lensed}(f, \bar{\Theta}, \mu_j, \Delta t_j, \Delta\phi_j) = \sqrt{|\mu_j|} \times h^{original}(f, \bar{\Theta}, \Delta t_j) \times exp(isign(f)\Delta\phi_j)$$

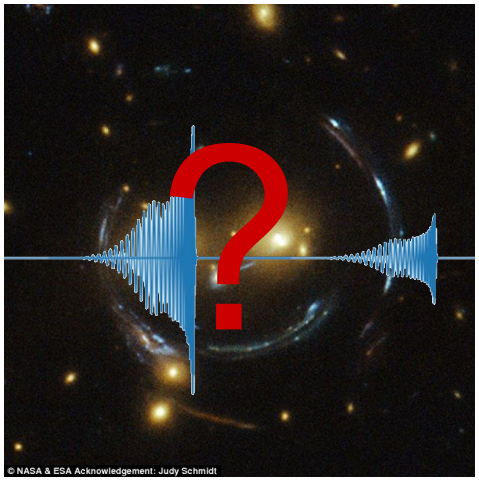
  - **Magnification factor**
  - **Time delay between a pair of lensed images**
  - **Morse phase shift**
- *under the geometric optics limit
- where f is frequency and Θ are the CBC parameters (mass, spin...)

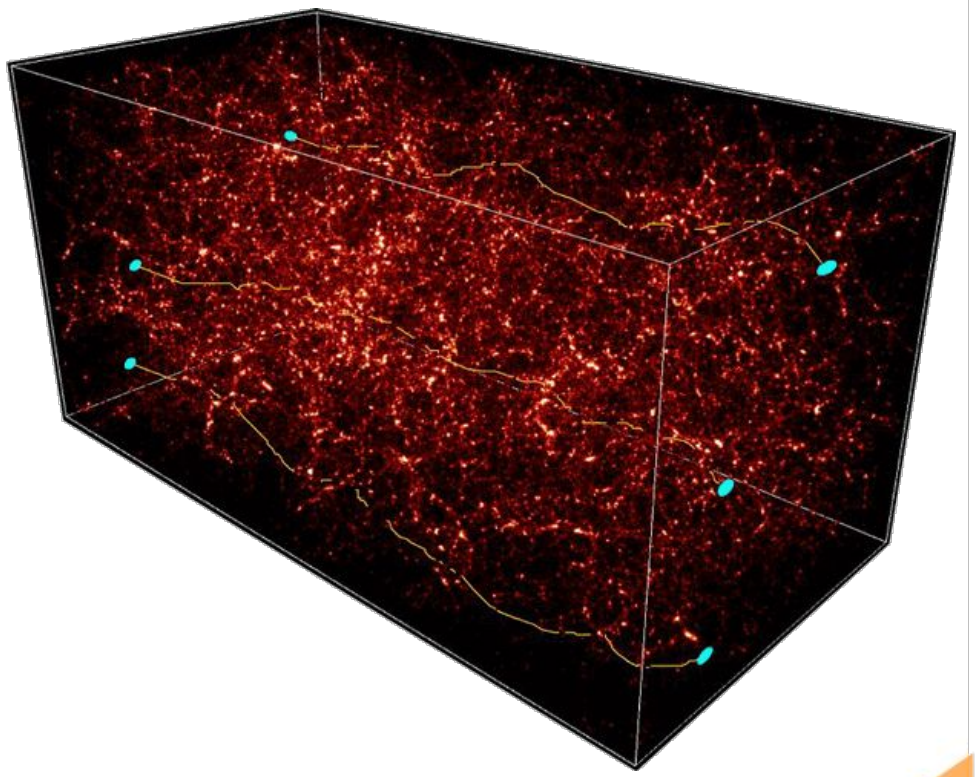
Lensed GWs in the time domain



Why do we want to observe Lensed GWs?

Lensed GWs have not yet been observed!





Would allow us to probe the structure of the universe and constrain CBC merger rates and cosmological values

Are Lensed GWs even detectable?

Lensing rate :

$0.06 - 5\mathrm{yr}^{-1}$!

Ref: Ng et al.(2018); Oguri (2018); Li et al.(2018)].

+ Increasing detector sensitivity **=>**

Lensed GWs would actually be detectable soon!!!!

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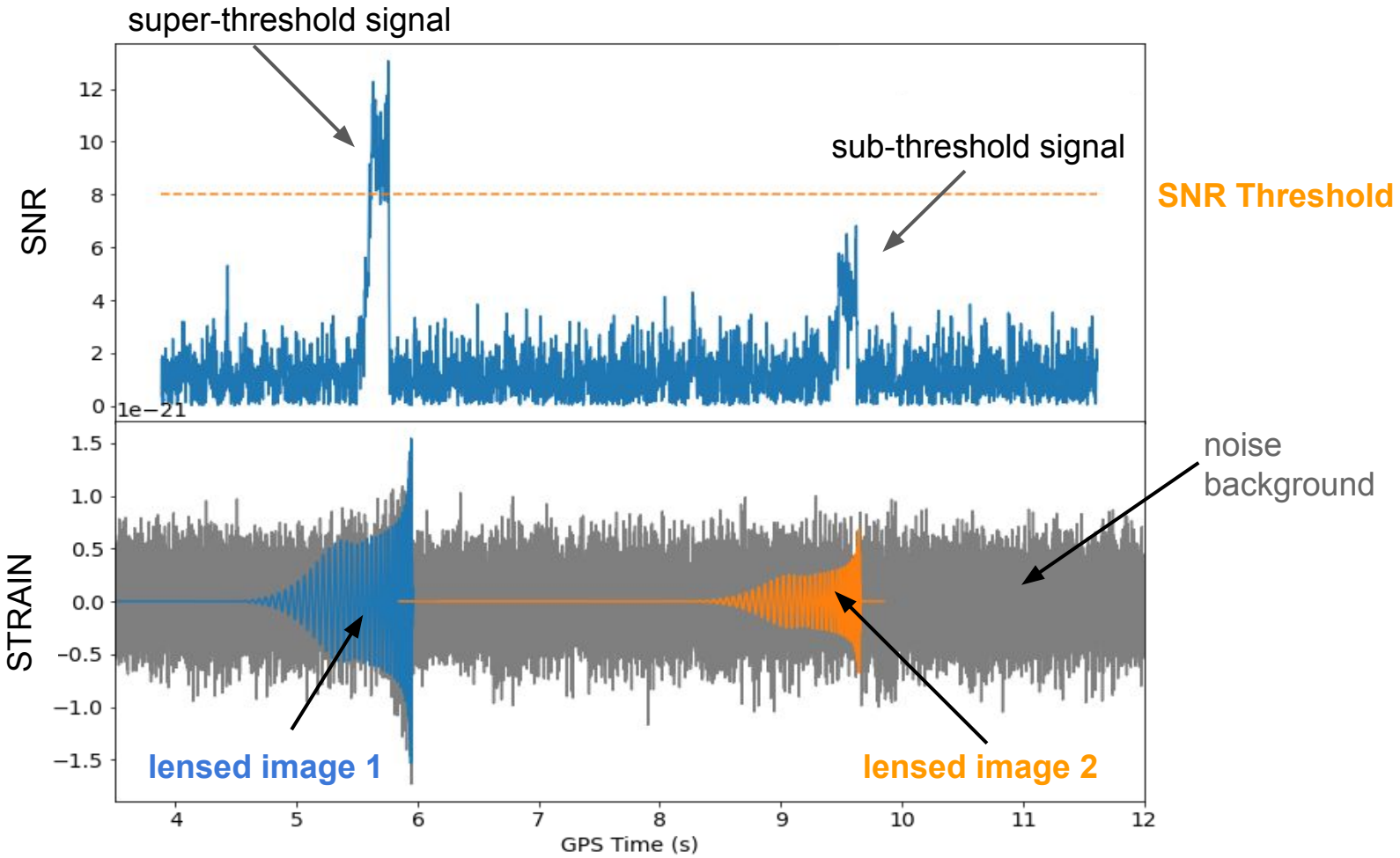
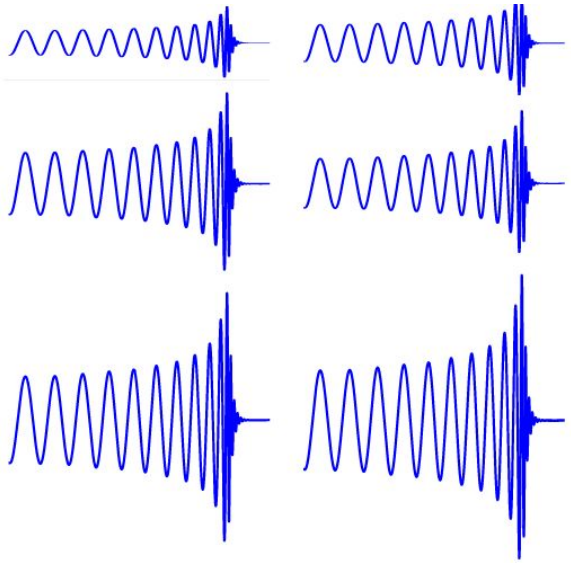


TargetEd Sub-threshold Lensing seArch Pipeline (TESLA)

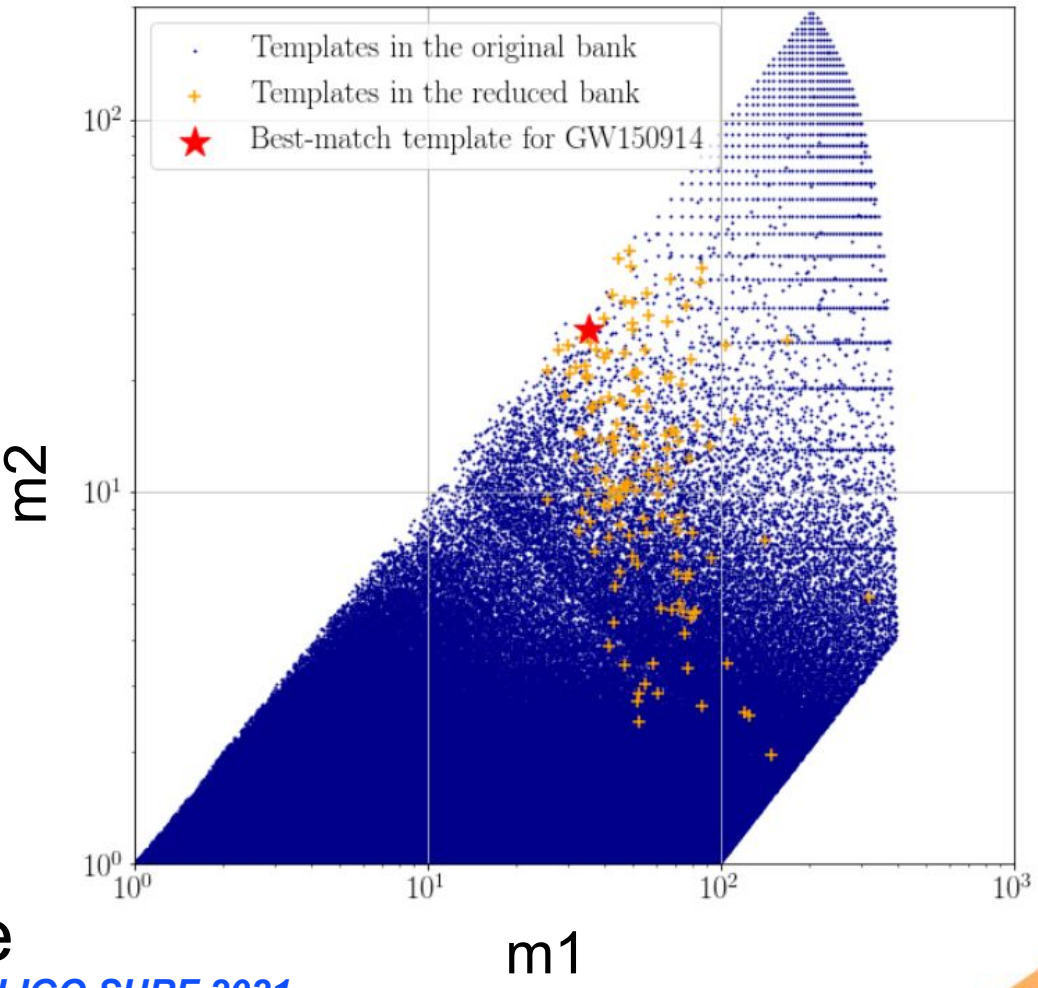
Original Template bank finds target event

+

New injection run with original bank and scaled injections



= Targeted Template Bank



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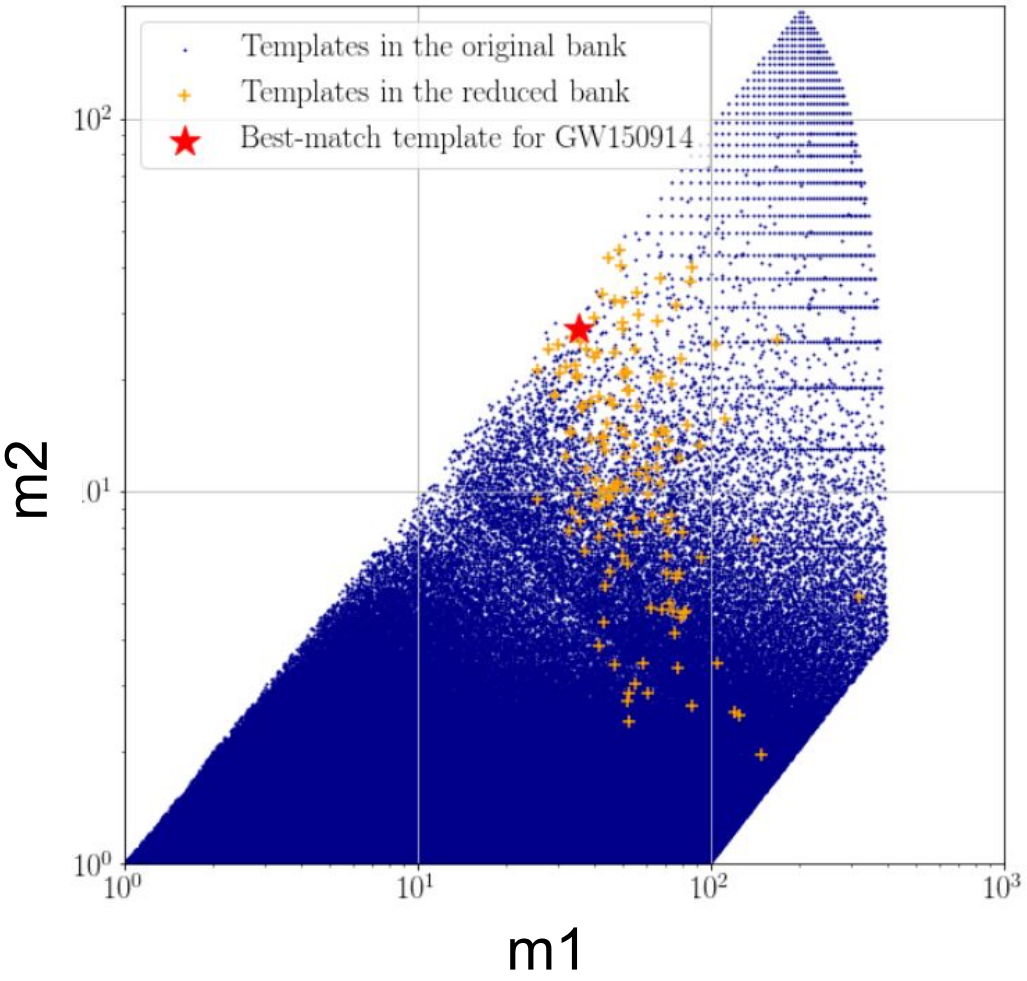


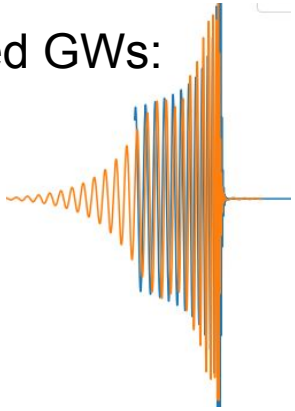
targeted search with reduced noise background using reduced template bank

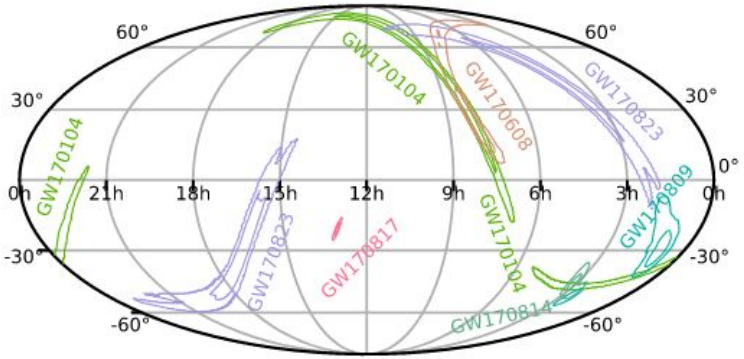
Refining the Search for Sub-threshold Lensed Gravitational Waves

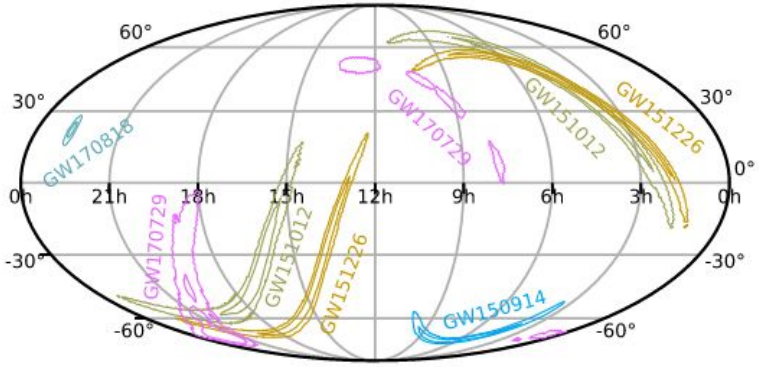
How are we trying to refine the search for lensed GWs:

(1) by waveform family

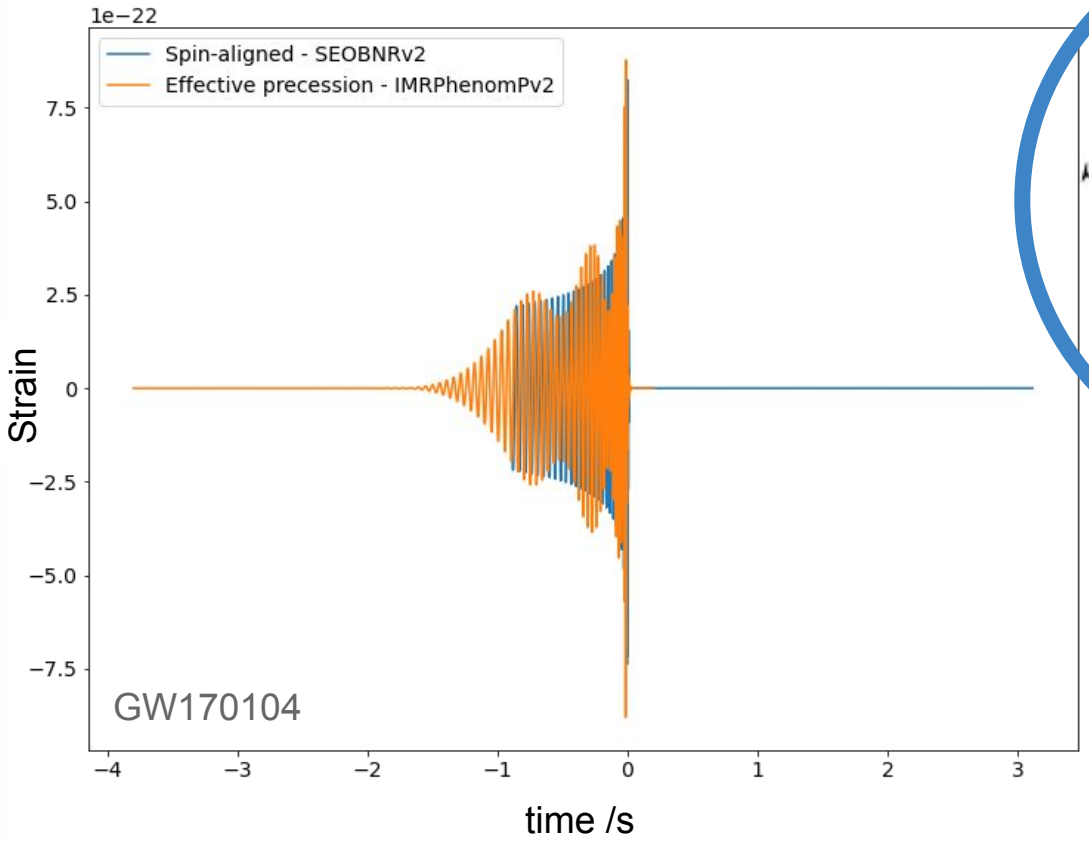
(2) by sky location

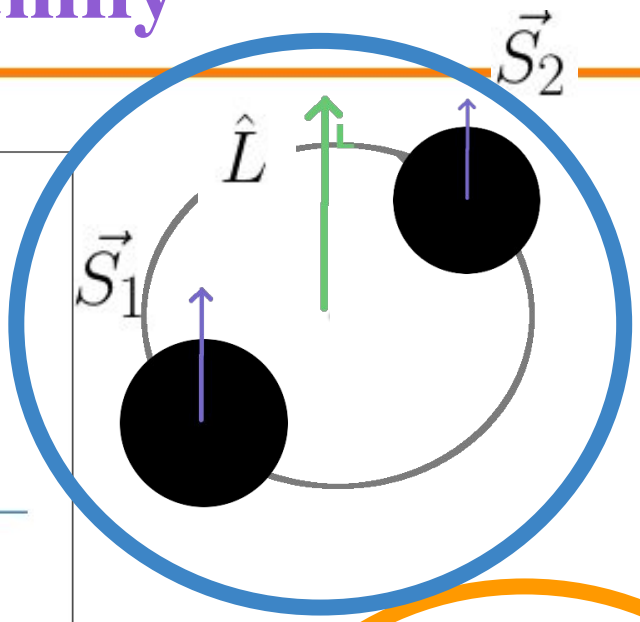


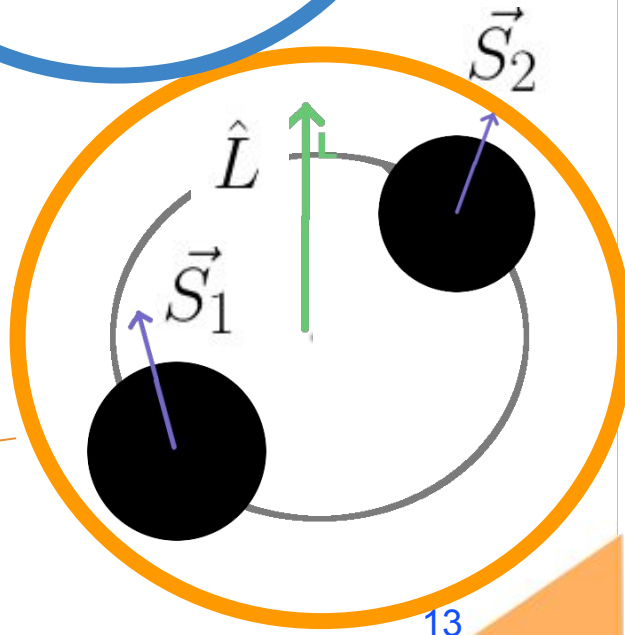




Refining the Search by waveform family







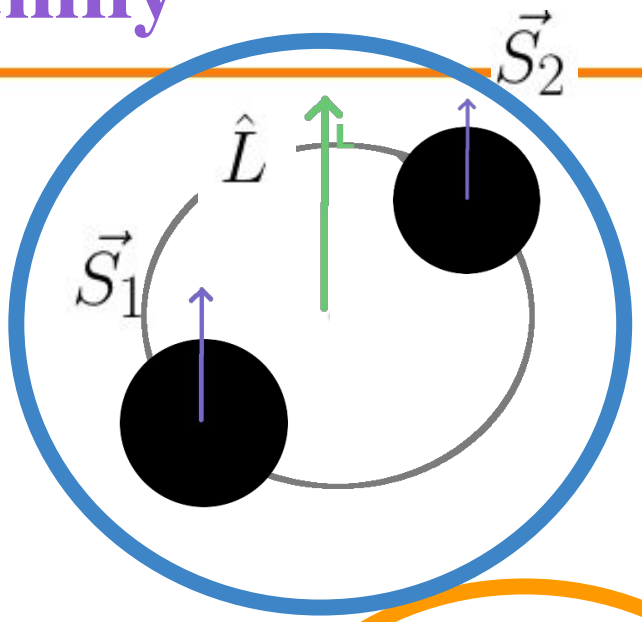
amplitude and frequency modulation

Refining the Search by waveform family

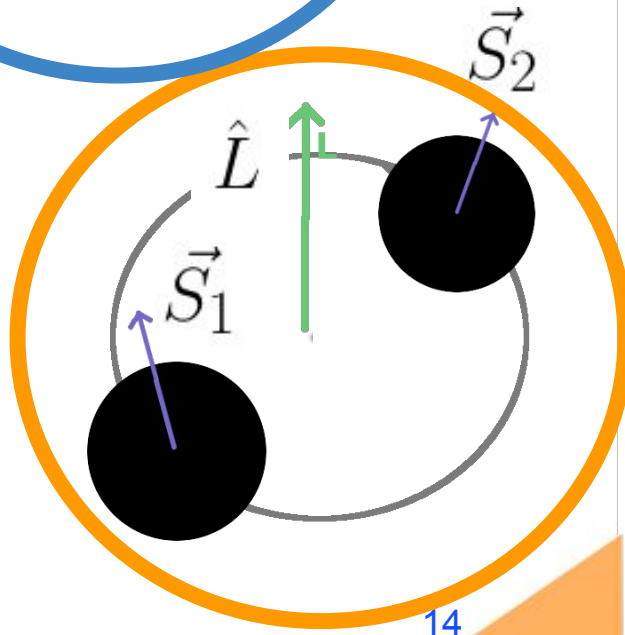
- Different waveform families used in different sub-threshold lensing pipelines

GstLAL pipeline: **spin-aligned waveforms**

PyCBC pipeline: **considers precession**



Will precession change the detectability of sub-threshold lensed signals?



Refining the Search by waveform family - Methods

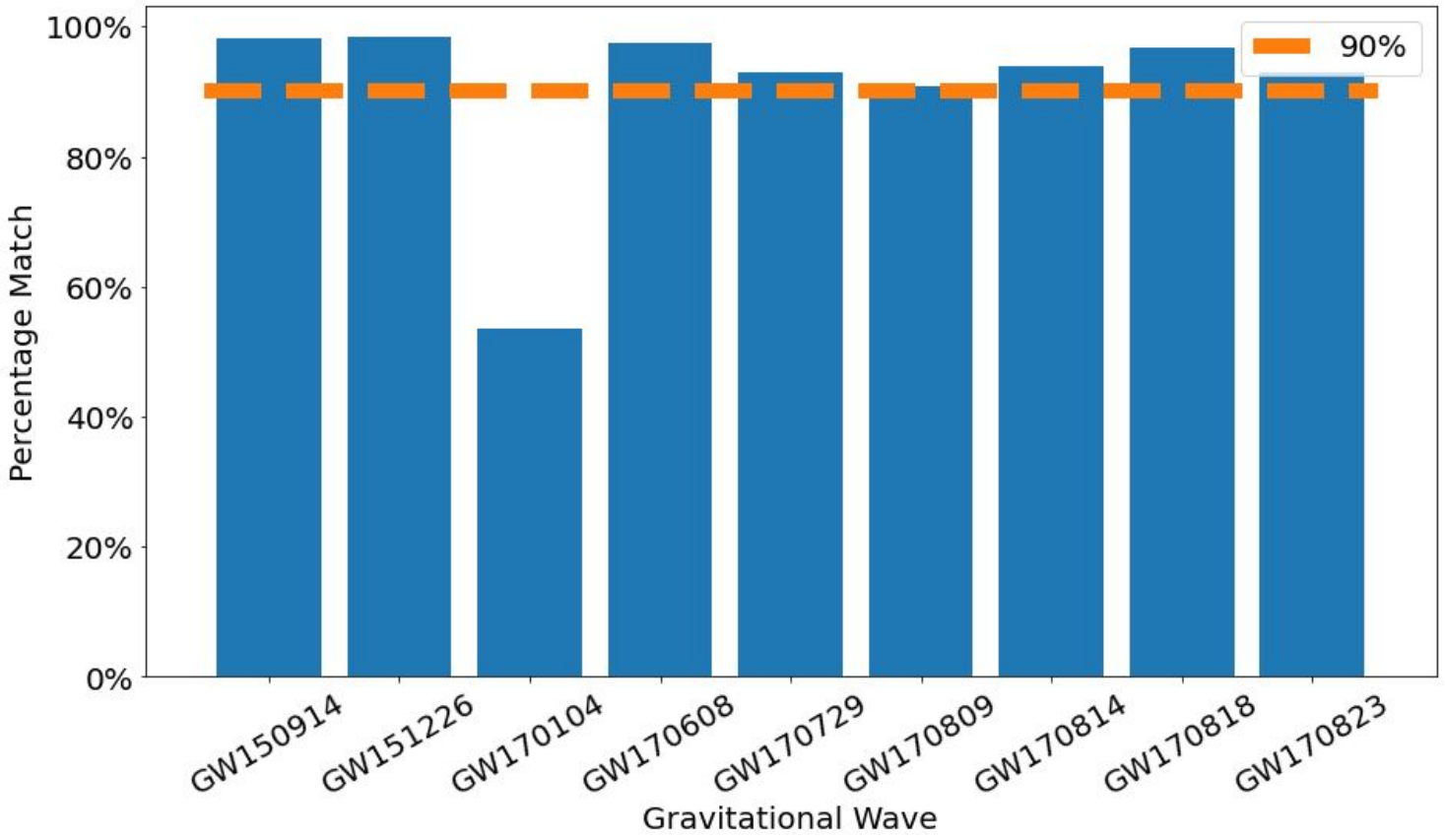
Found the **match between** O1 and O2 events plotted with **spin-aligned** **and** **precession-included** **waveform** families:

1. used posterior samples to generate waveforms

2. considered detector response function

3. calculated match

Refining the Search by waveform family - Results



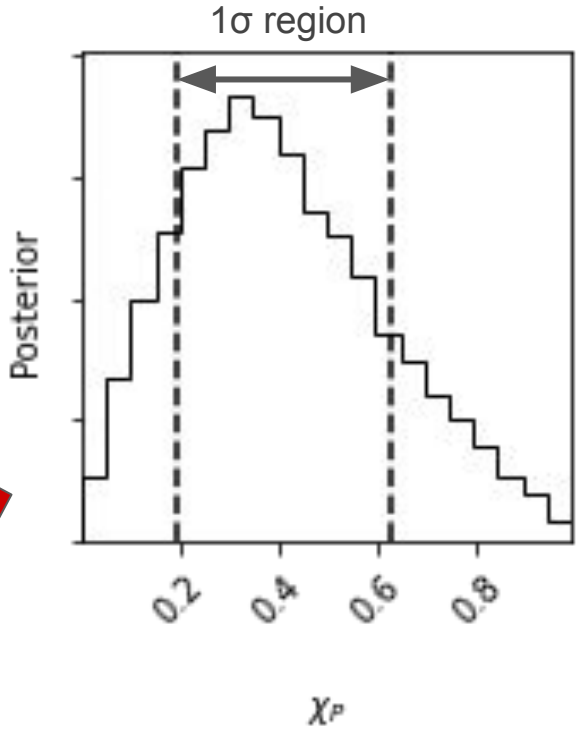
All above **90% match**! Well, apart from GW170104….. is it precessing?

Refining the Search by waveform family - Conclusions 2

- If GW170104 is really precessing > SNR loss for aligned spin waveform

Might lose sub-threshold signals

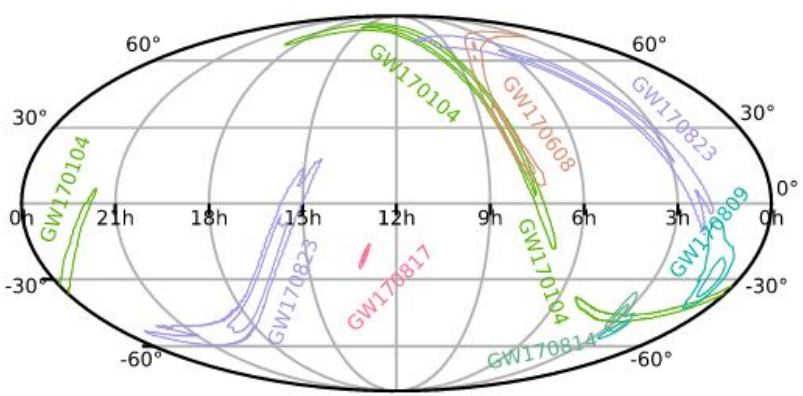
- If there is large uncertainty in precession (very likely) then either waveform should be suitable, not necessarily SNR loss

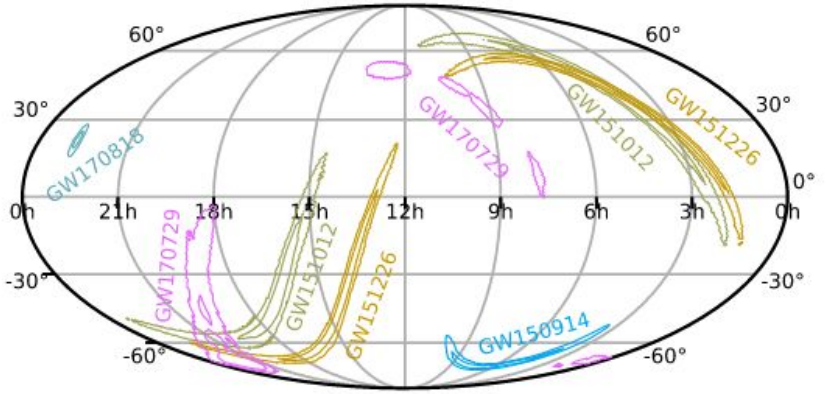


Effective precession spin parameter Posterior Distribution of GW170104

Refining the Search by Sky Location

Key Point: Lensed images will come from approximately the same sky location!





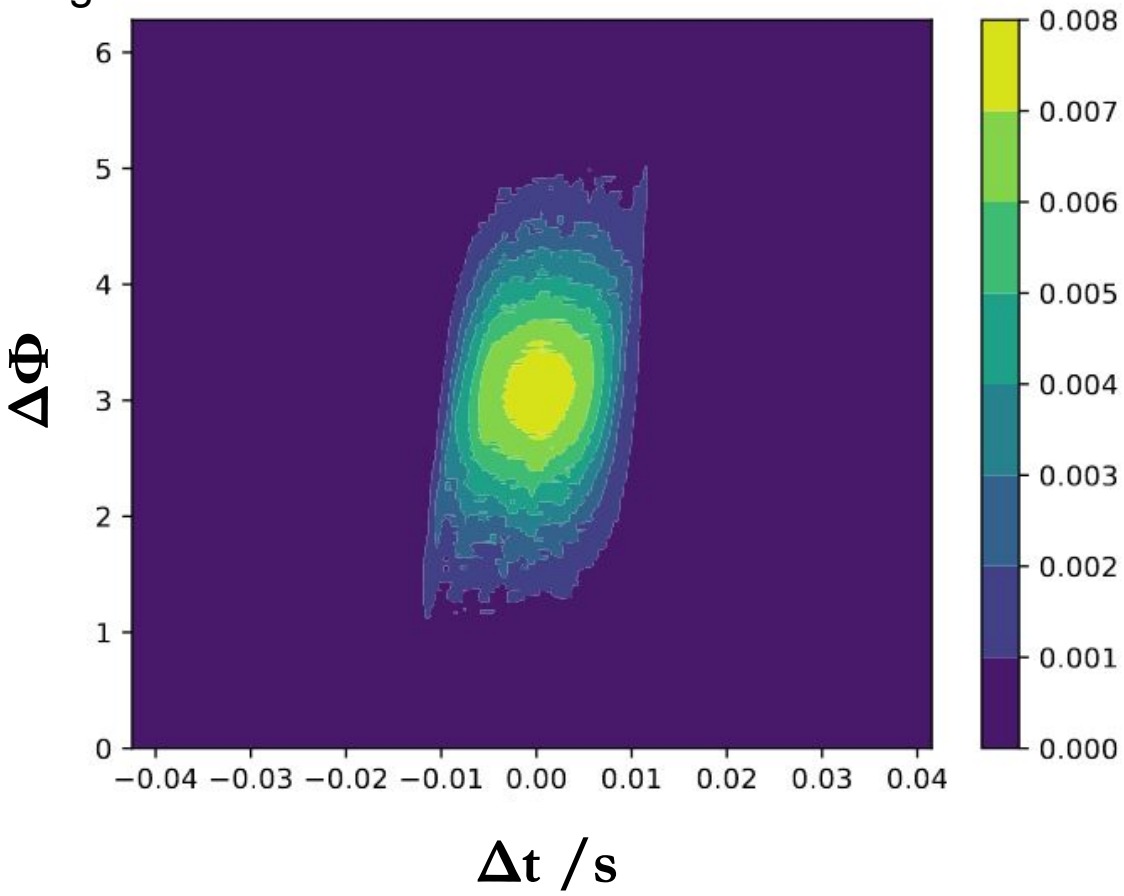
Lensed image separation ~1 arcsec verses Sky Localisation of 100s of degrees squared

Refining the Search by Sky Location
Ranking by Likelihood

$$\mathcal{L} = \frac{P(\{D_1, D_2\}\{d_1, d_2\}, \rho_1, \rho_2, \xi_1^2, \xi_2^2, \Delta\phi, \Delta t | signal)}{P(\{D_1, D_2\}\{d_1, d_2\}, \rho_1, \rho_2, \xi_1^2, \xi_2^2, \Delta\phi, \Delta t | noise)}$$

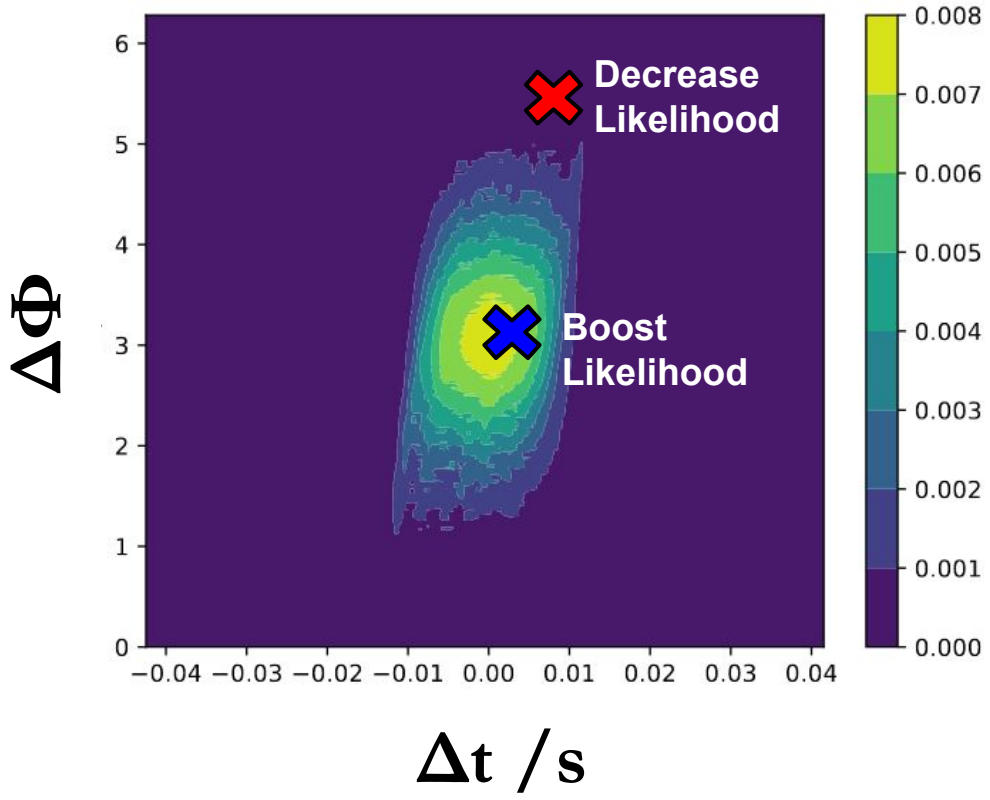
Refining the Search by Sky Location
ΔΦ and Δt PDF

2D Probability distribution for ΔΦ and Δt considering signals **across the whole sky** for Hanford and Livingston:



Refining the Search by Sky Location Aims

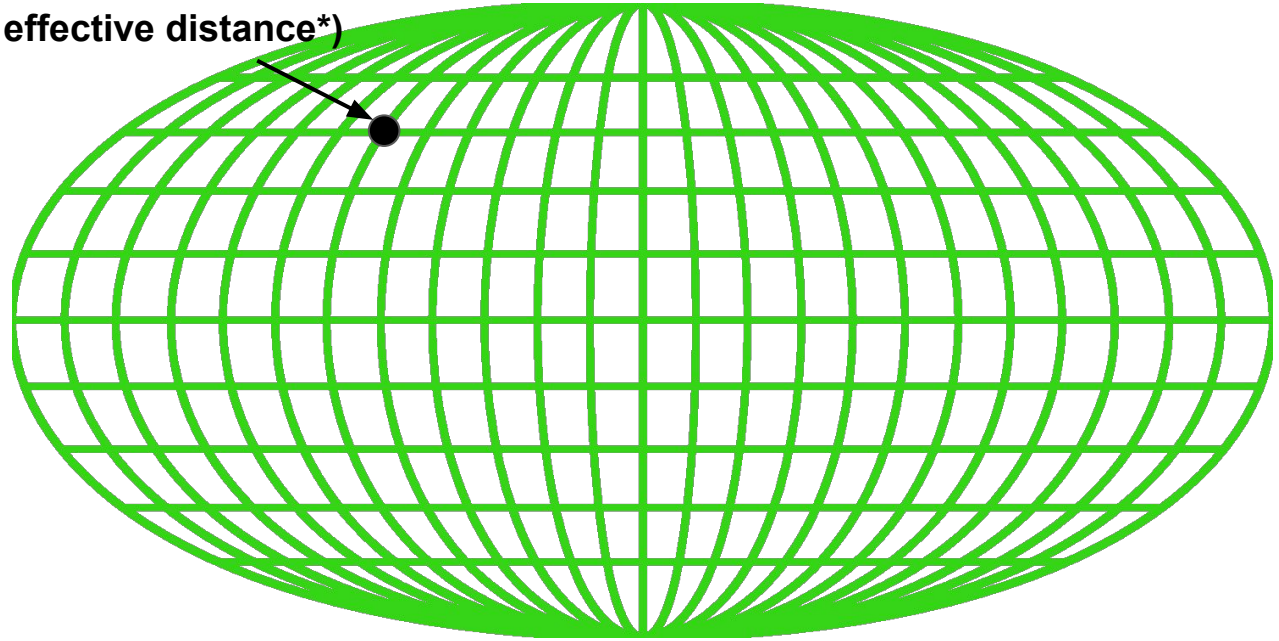
Aiming to **boost rankings of lensed images with similar sky localisations** by finding this PDF with a **targeted sky localisation**



Inside the ΔΦΔt PDF Calculation:

- GstLAL finds the PDF of ΔΦ and Δt with a tiling function: tiles **the whole sky** with even probability of event from each direction

Calculates for each detector:
(time, phase, effective distance*)



***equivalent to SNR**

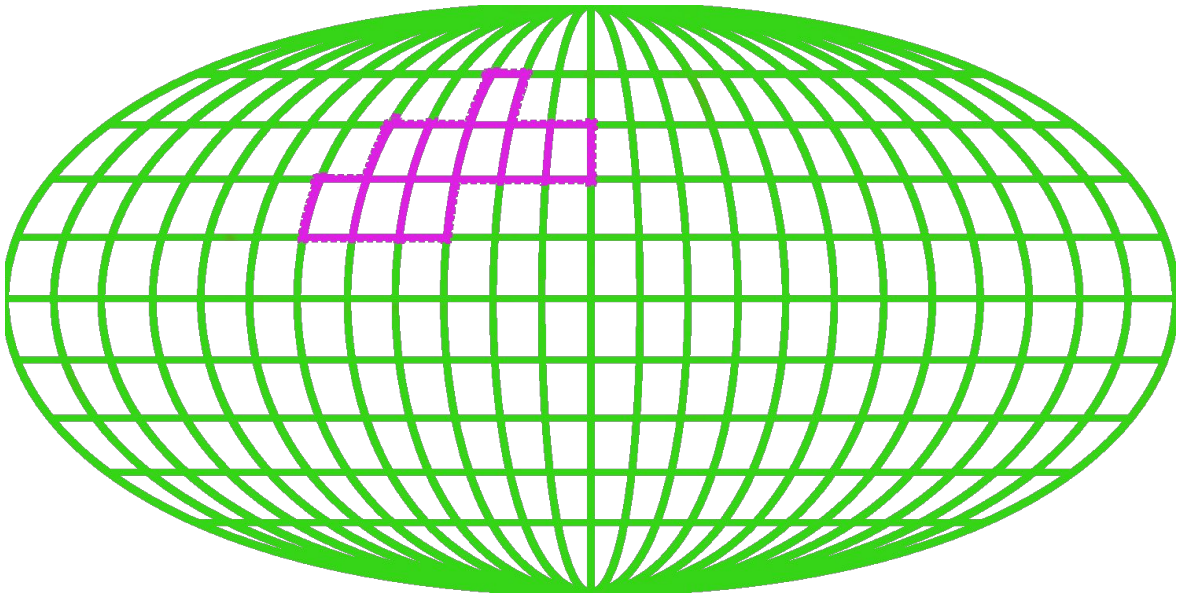
Inside the ΔΦΔt PDF Calculation:

- Obtain **Δt, ΔΦ, ΔD_{eff}** between **each of the detectors** for **each point**

- **Use this to calculate the PDF** using the covariance matrix, with lots more maths [Hanna et al., 2019]

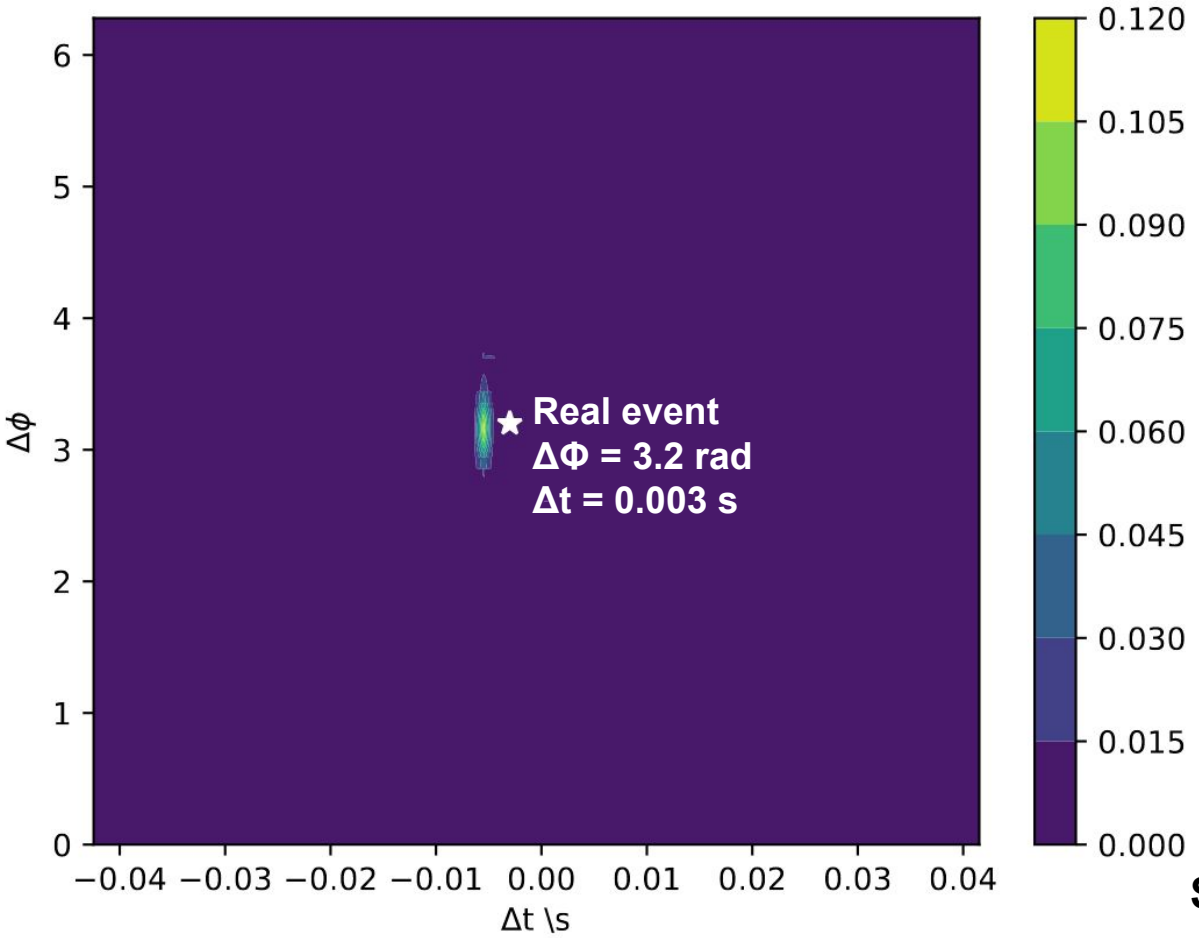
Inside the New Improved ΔΦΔt PDF Calculation:

- We modify GstLAL to find the PDF of ΔΦ and Δt with a tiling function: tiles the **90% credible region** of a real target event with even probability
- PDF then found as before…..



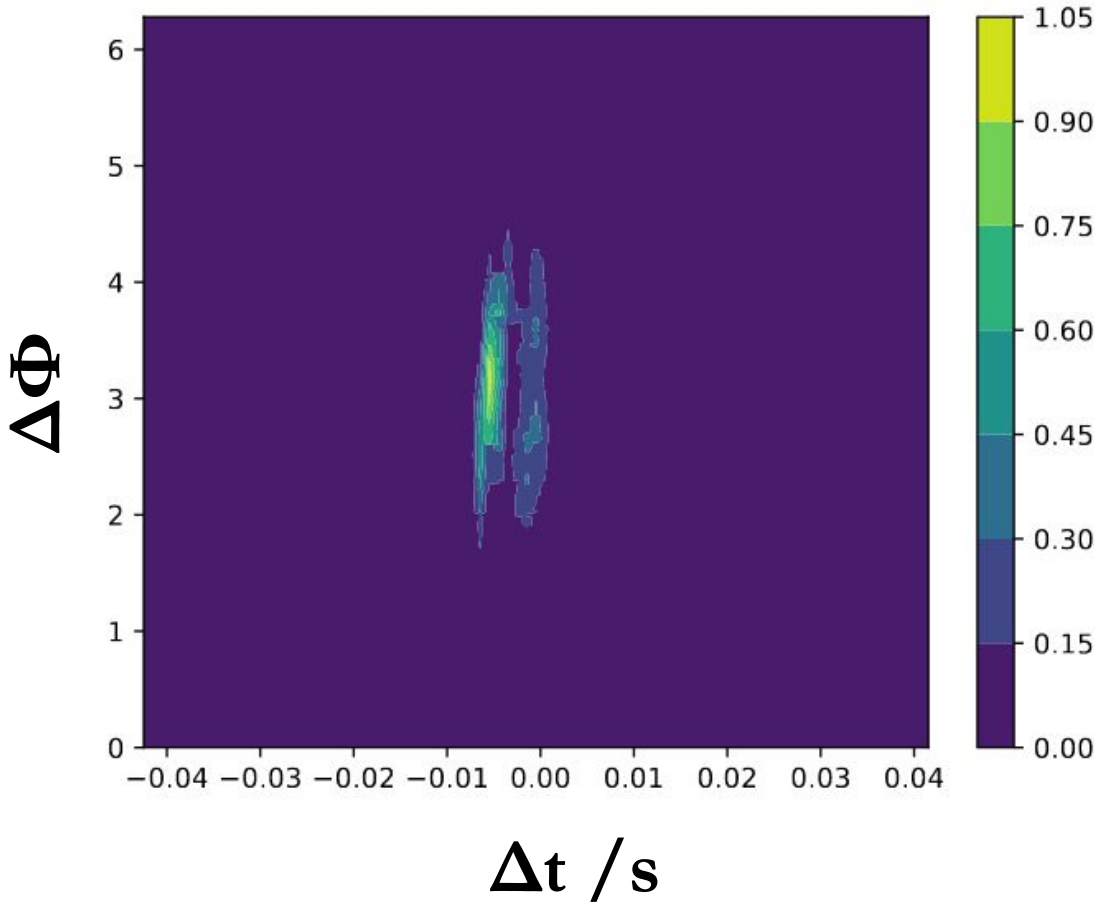
Results…. With Real SNRs!

ΔΦ Δt PDF for **S190408an** for **H1L1** with detector SNRs equal to event values



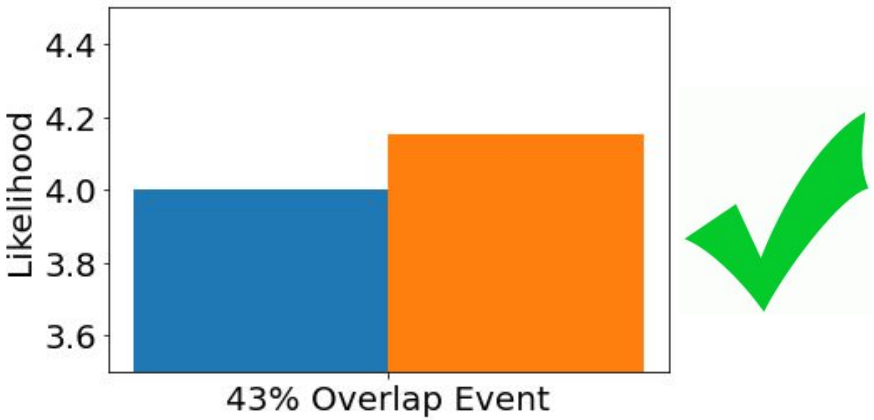
Success…?

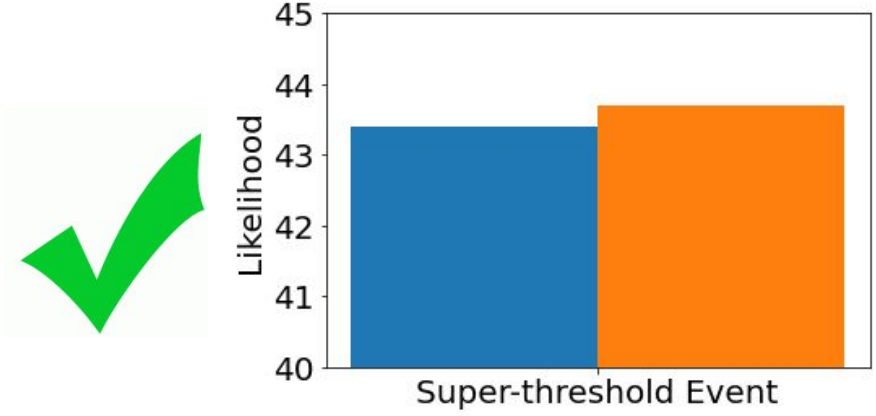
Implementing this into the Search Pipeline



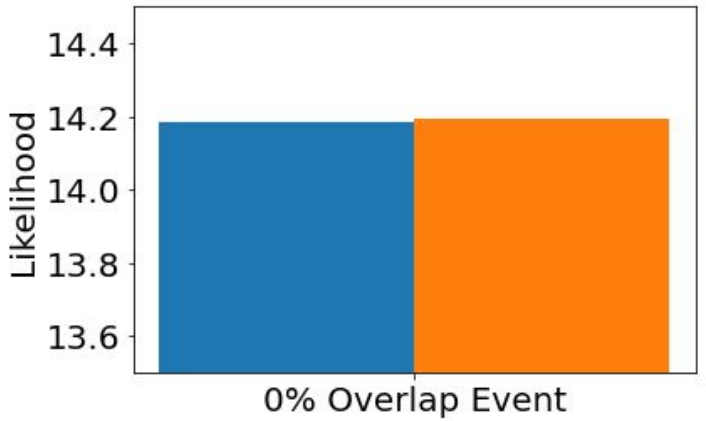
- Generate ΔΦΔt PDF with SNRs = 4, as looking for low SNR triggers
- Use this PDF in GstLAL pipeline to search and rank candidates for section of O3a data

Implementing this into the Search Pipeline - Likelihood results

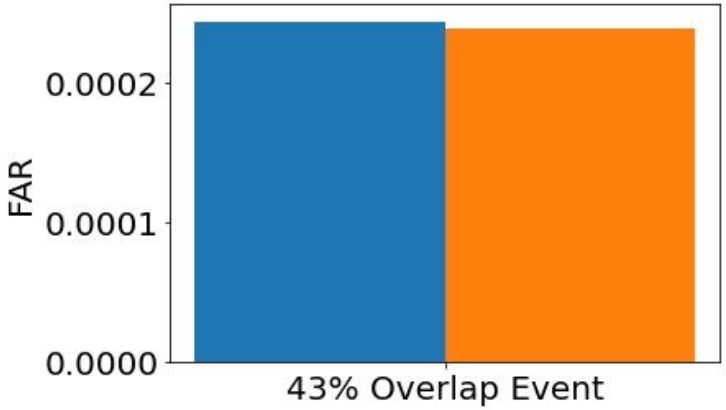




Before Targeted Skymap
Using Targeted Skymap



Implementing this into the Search Pipeline



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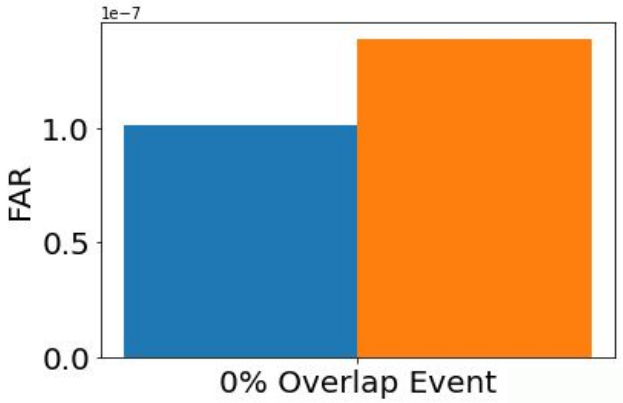

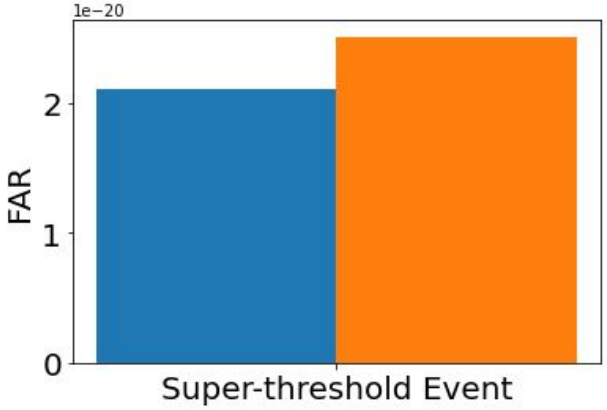

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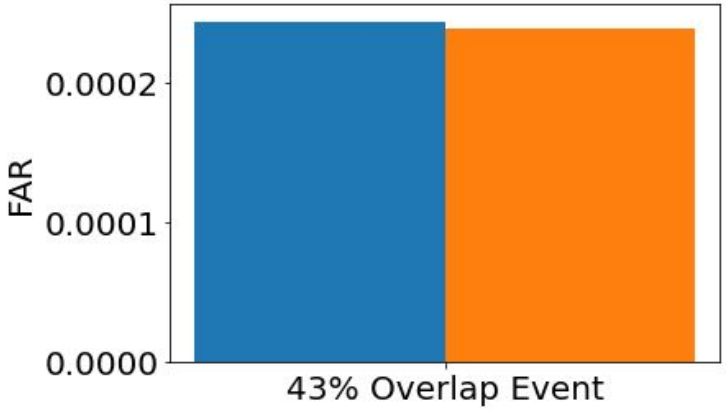

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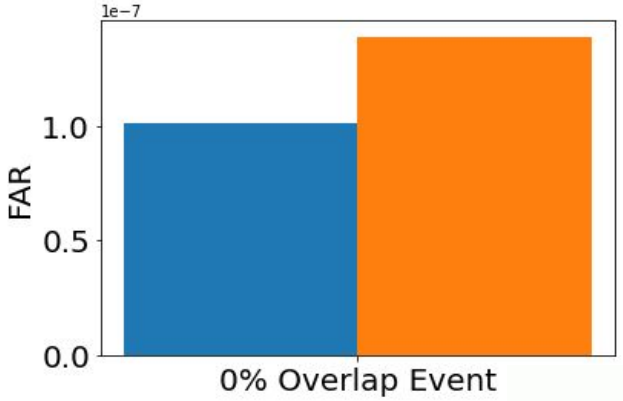

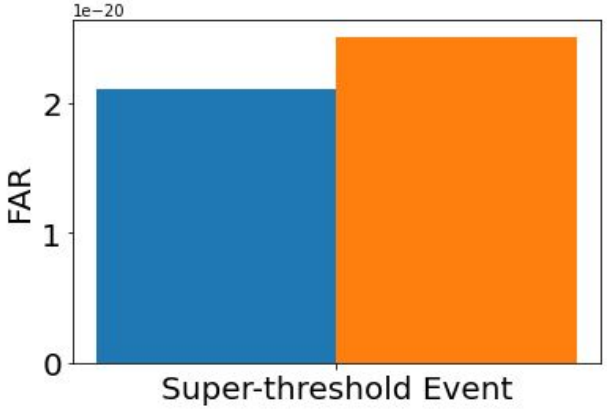

noise model estimation assumes isotropic sky location

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gstLAL

One Small step for Likelihoods, one big step for LIGOkind

Next Steps

- Target the noise model in the pipeline
- Compare boosted rankings to whole data for O3a
- Investigate ΔΦ Δt PDF discrepancies
- Possibly implement it quasi-real time to search for sub-threshold signals as data is being observed

Summary

- Trying to find **sub-threshold gravitationally lensed GWs** through a **targeted search pipeline**

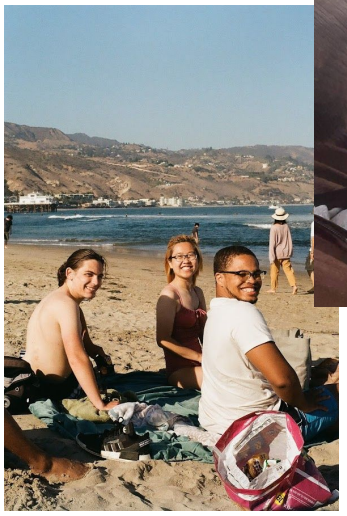
- **Refining this pipeline** considering:
    1. Spin-aligned versus precession-included waveforms
        - determined if waveform would result in lost SNR of sub-threshold events
        - if spin was better known maybe this would be a problem
    2. Targeted Skymap rankings
        - Introduced targeted ΔΦΔt PDF using super-threshold skymap
        - partially successful boosting implemented to search pipeline!!! now we need to perfect it

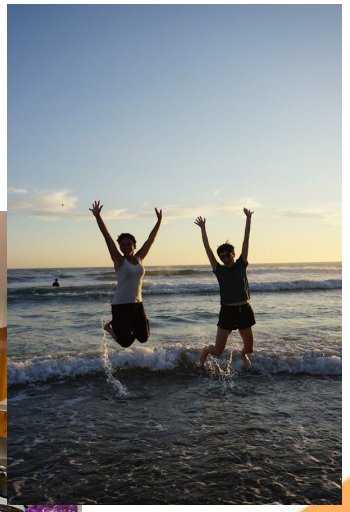
Acknowledgements

Thank you to my mentors Alvin Li and Alan Weinstein for helping me learn so much this summer! Shoutout to Ryan Magee for being a GstLAL expert to turn to in scary times...

Thank you to the LIGO Lab, Caltech and the NSF.

And super thanks to all of the LIGO SURFs, grad students and postdocs who made this summer such a fun experience!! :-)





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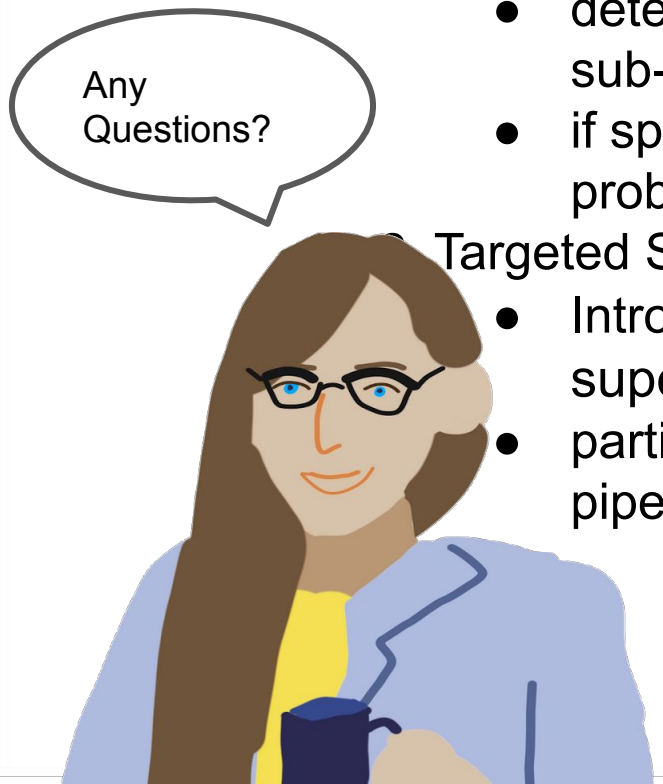

Extra Slide - Morse Phase Shift