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Refining the Search for Sub-threshold Lensed Gravitational Waves

LIGO SURF 2021

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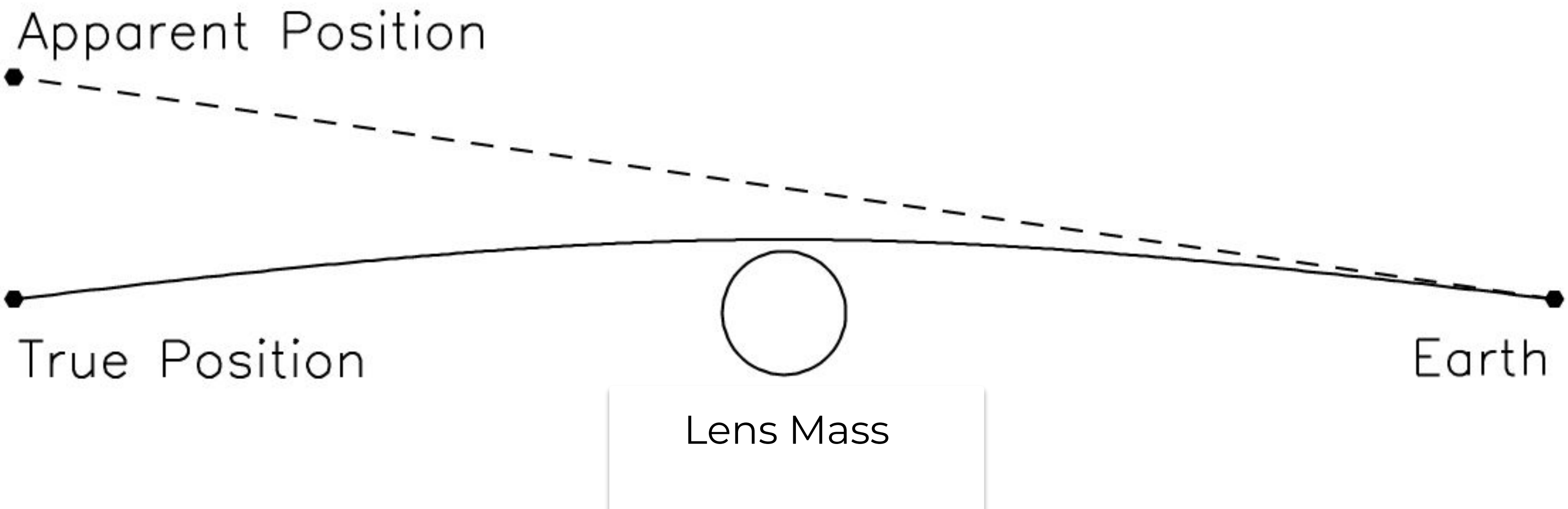
What is Lensing?

Change in:
- apparent position



What is Lensing?

Change in:
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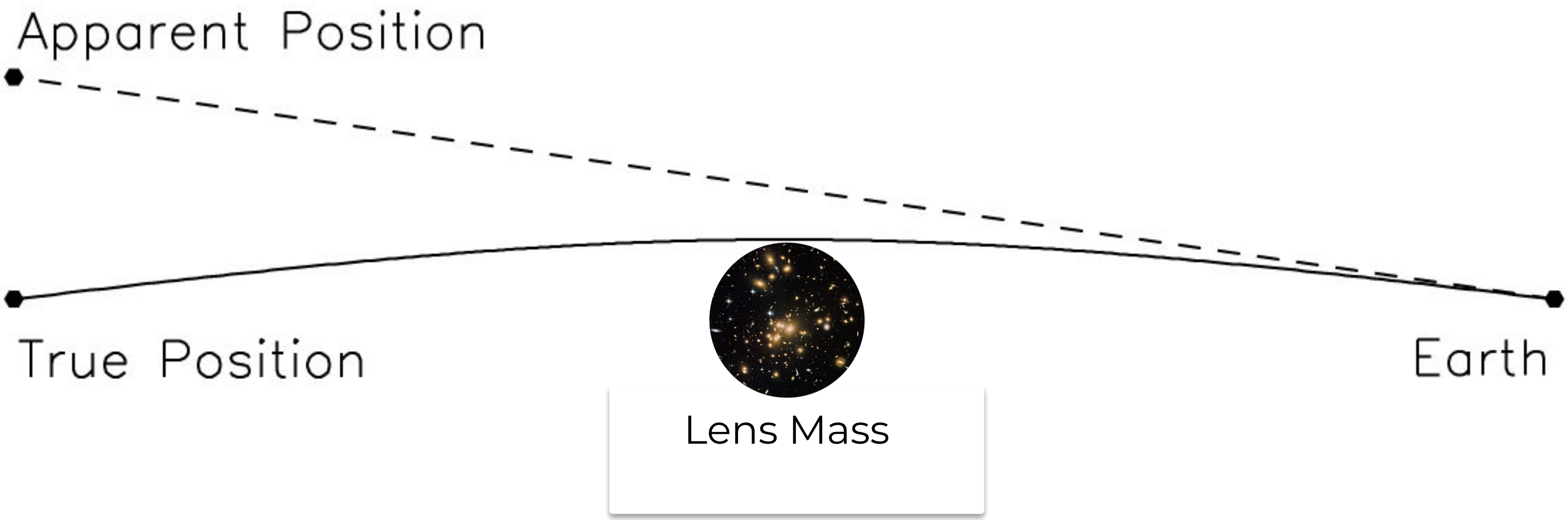

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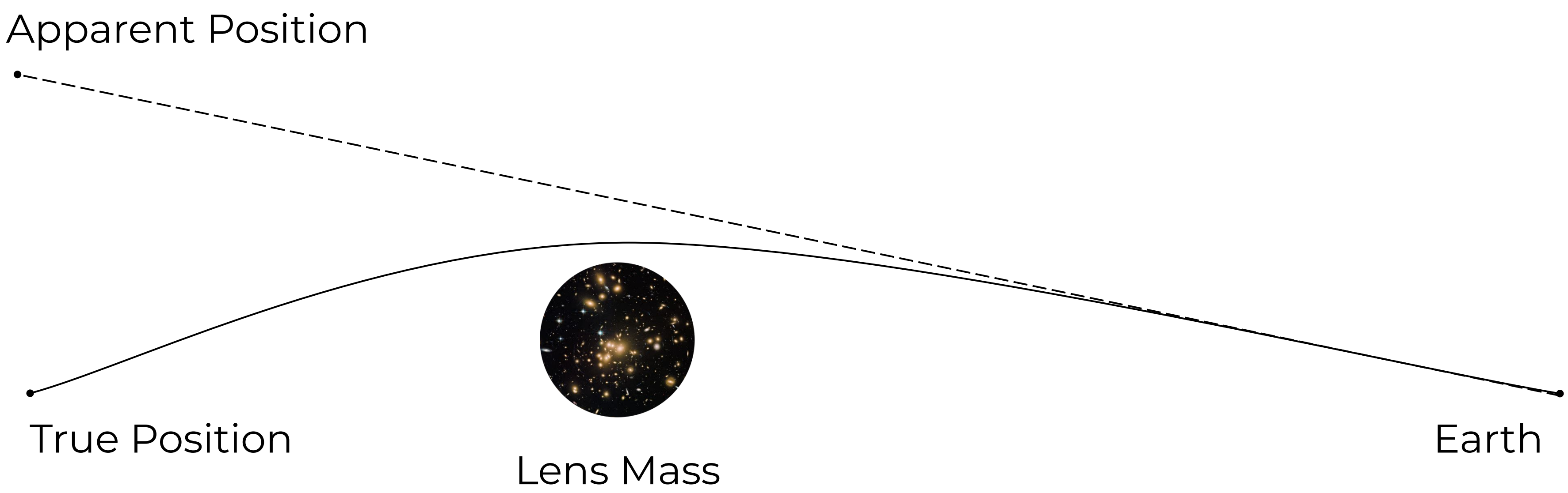

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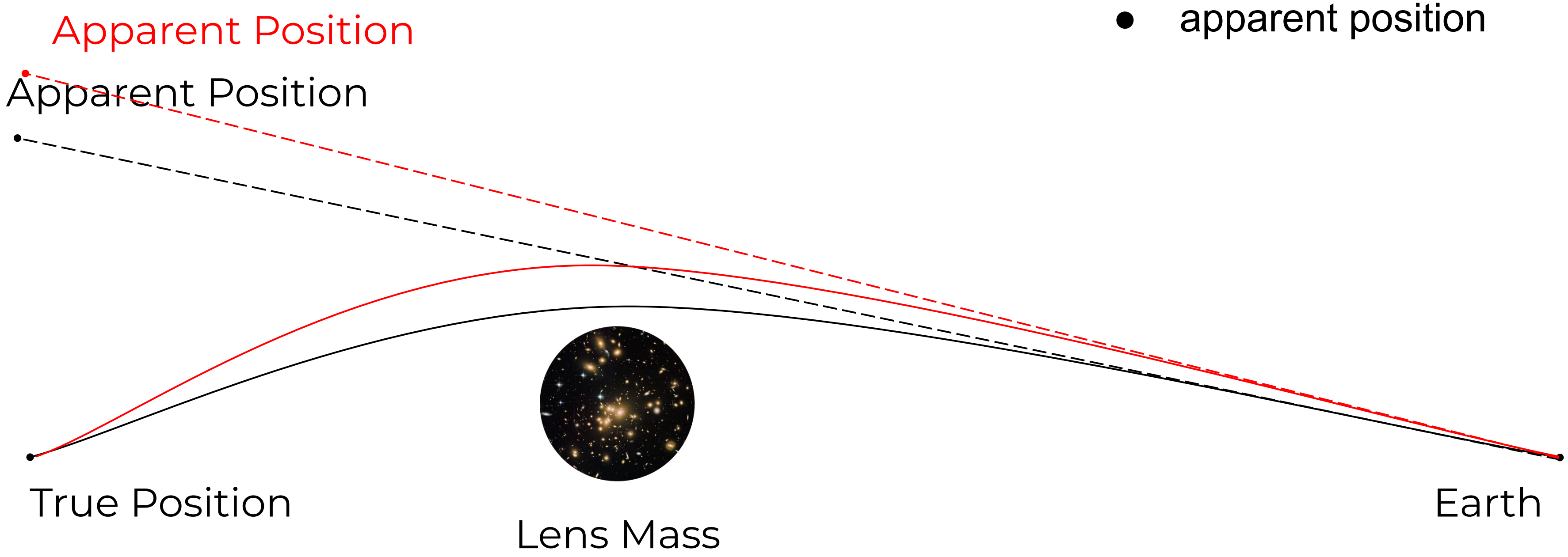
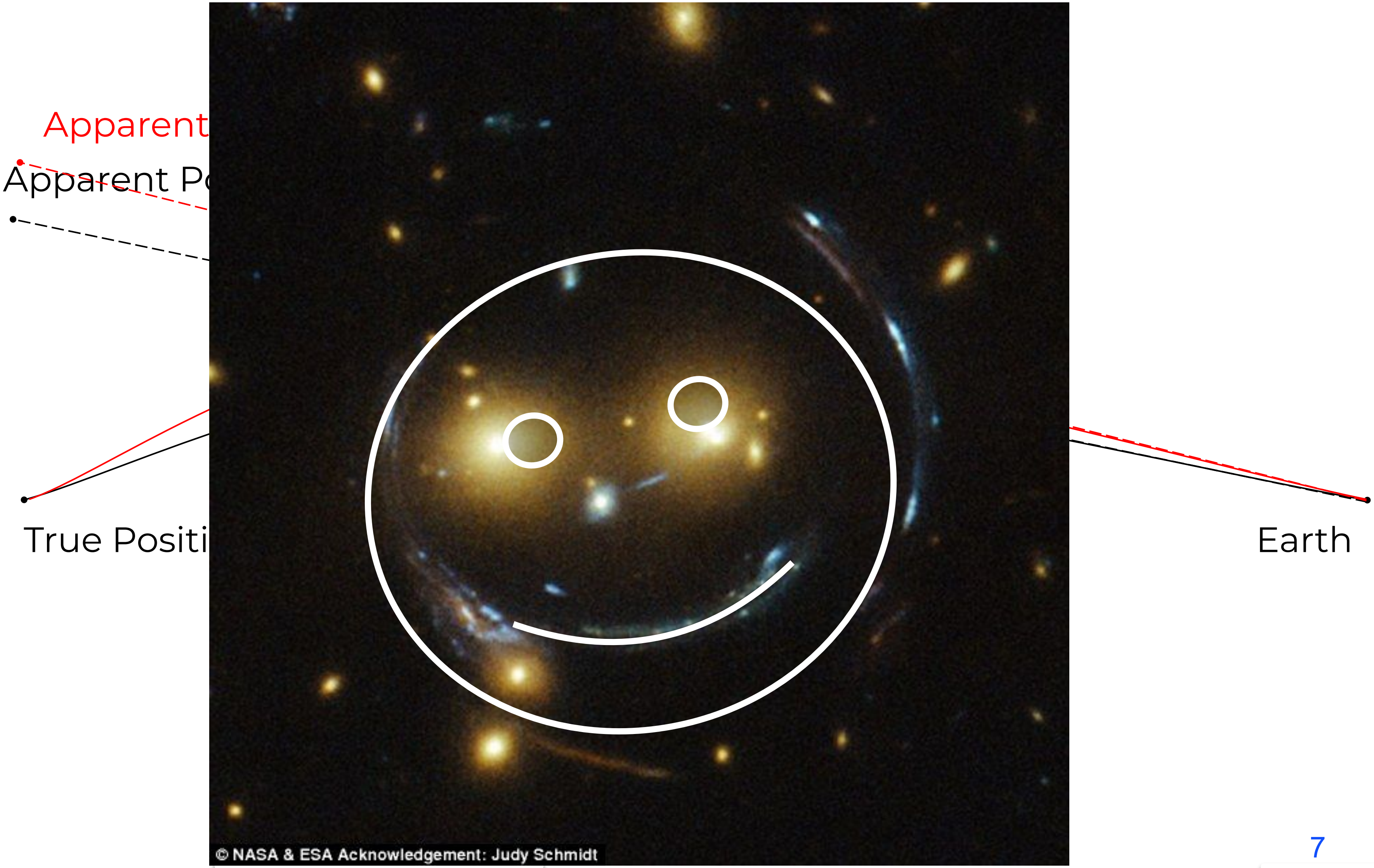
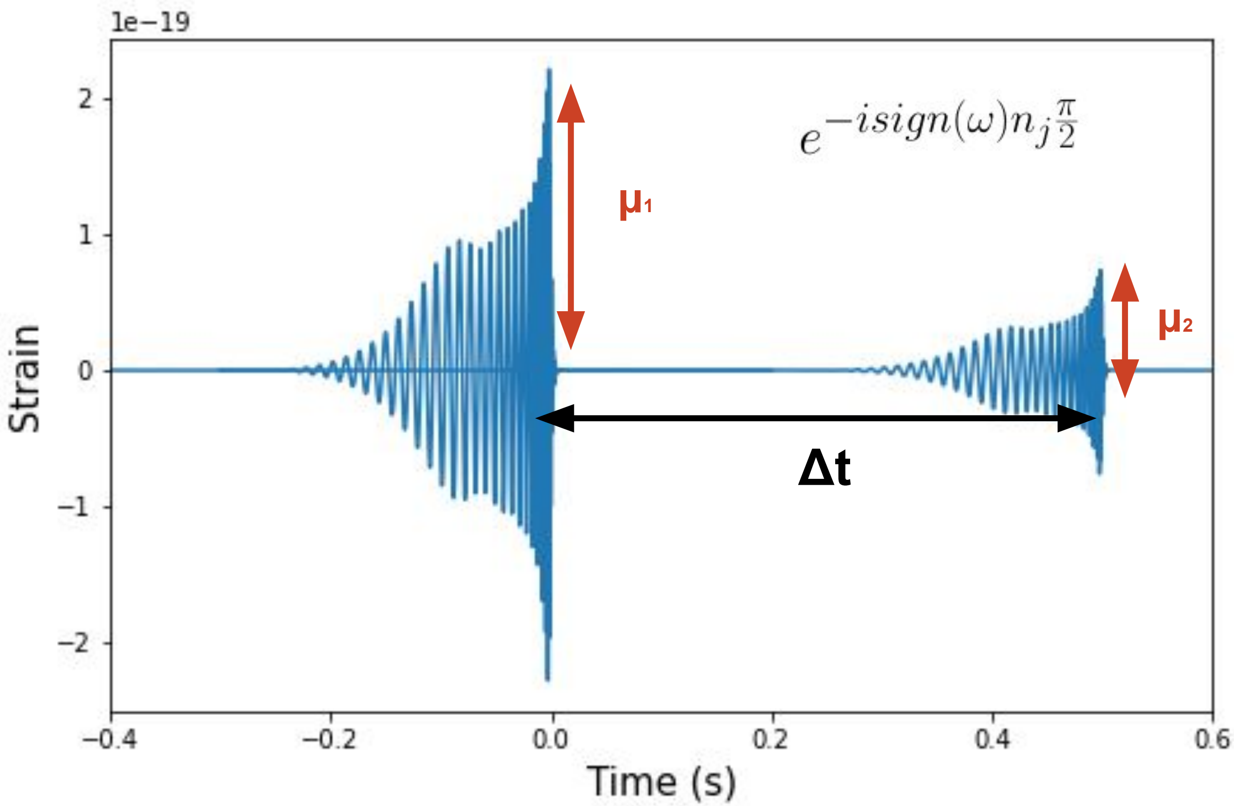


What is Lensing?



What is Lensing (Of GWs)?

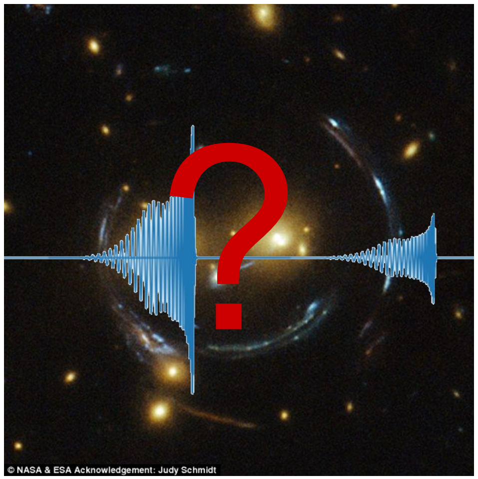


Change in:

- apparent position
- arrival time
- amplitude
- morse phase

Why look for Lensing of Gravitational Waves?

1. Not yet seen in Gravitational waves...



2. Although everyone is looking...

1. arXiv:2106.12466 [pdf, other] gr-qc astro-ph.HE astro-ph.IM
   Rapid Identification of Strongly Lensed Gravitational-Wave Events with Machine Learning
   Authors: Srashti Goyal, Harikrishnan D., Shasvath J. Kapadia, Parameswaran Ajith
   Abstract: A small fraction of the **gravitational**-... ▽ More
   Submitted 23 June, 2021; **originally announced** June 2021.
   Comments: 11 pages, 6 figures

2. arXiv:2106.09630 [pdf, other] gr-qc astro-ph.HE
   Lensing of Gravitational Waves as a Novel Probe of Graviton Mass
   Authors: Ka-Wai Chung, Tjonnie Guang Feng Li
   Abstract: The diffraction patterns of **lensed**... ▽ More
   Submitted 17 June, 2021; **originally announced** June 2021.
   Comments: 6 pages, 4 figures
   Report number: KCL-PH-TH 2021/41, LIGO Document number of P2100192-v2

5. arXiv:2106.06545 [pdf, other] gr-qc astro-ph.CO
   Evidence for lensing of gravitational waves from LIGO-Virgo
   Authors: Jose M. Diego, Tom Broadhurst, George Smoot
   Abstract: Recently, the LIGO-Virgo Collaboration (LVC) concluded that there is no evidence for **lensed gravitational waves** (GW) in the first half of the run, claiming "We find the observation of **lensed** events to be unlikely, with the fractional... ▽ More
   Submitted 11 June, 2021; **originally announced** June 2021.
   Comments: 7 pages with 2 figures

6. arXiv:2106.06303 [pdf, other] astro-ph.HE gr-qc
   Beyond the detector horizon: Forecasting gravitational-wave strong lensing
   Authors: A. Renske A. C. Wierda, Ewoud Wempe, Otto A. Hannuksela, Léon V. E. Koopmans, Chris Van Den Broeck
   Abstract: When **gravitational**... ▽ More
   Submitted 22 June, 2021; **v1** submitted 11 June, 2021; **originally announced** June 2021.

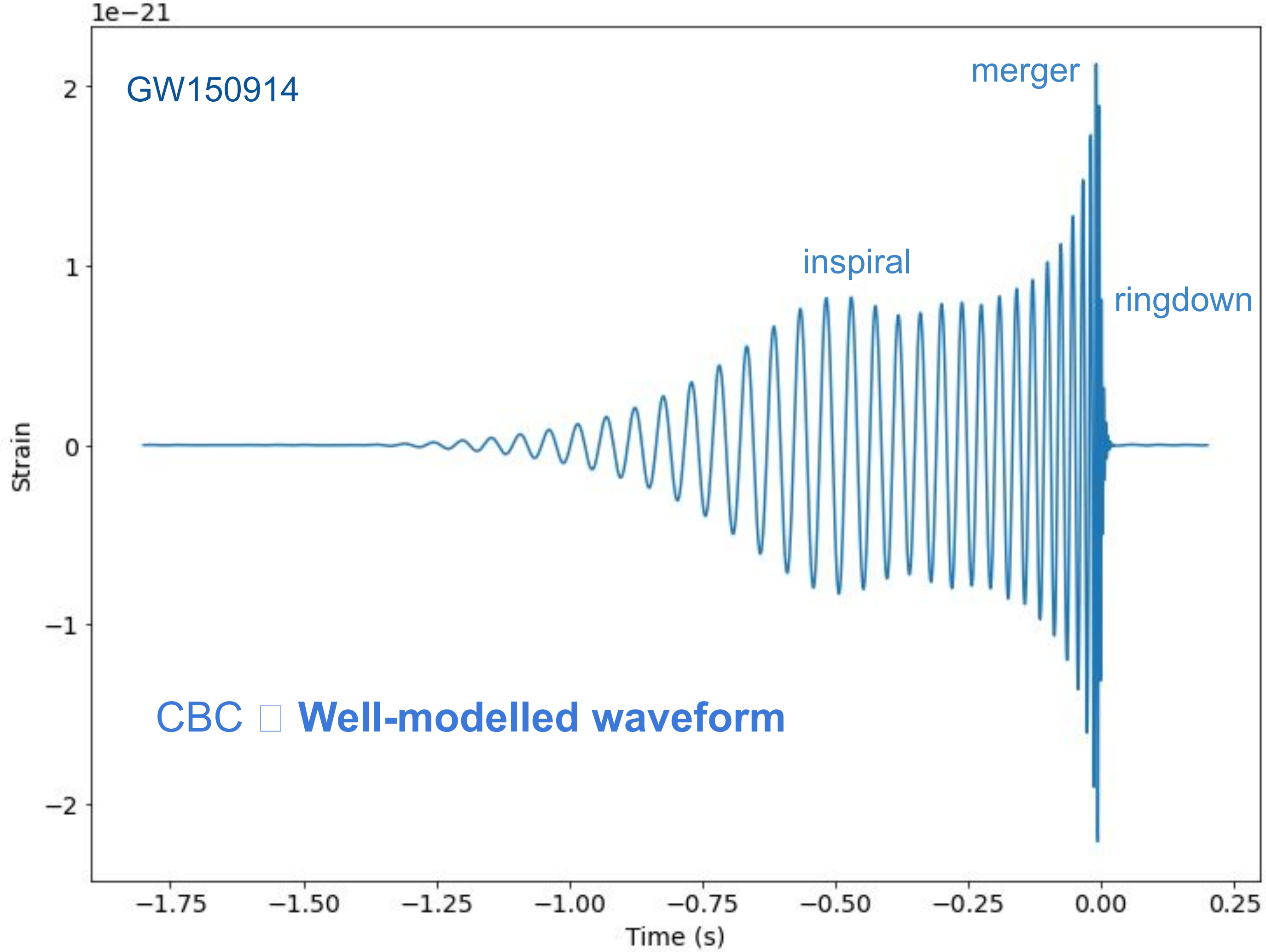
9. arXiv:2106.00392 [pdf, other] gr-qc astro-ph.CO astro-ph.GA astro-ph.HE
   Impact of astrophysical binary coalescence timescales on the rate of lensed gravitational wave events
   Authors: Suvodip Mukherjee, Tom Broadhurst, Jose M. Diego, Joseph Silk, George F. Smoot
   Abstract: The expected event rate of **lensed gravitational wave** sources scales with the merger rate at redshift $z \geq 1$, where the optical depth for **lensing** is high. It is commonly assumed that the merger rate of the astrophysical compact objects is... ▽ More
   Submitted 1 June, 2021; **originally announced** June 2021.
   Comments: 10 pages, 6 figures

10. arXiv:2105.14390 [pdf, other] astro-ph.CO astro-ph.GA astro-ph.HE
    Please repeat: Strong lensing of gravitational waves as a probe of compact binary and galaxy populations
    Authors: Fei Xu, Jose Maria Ezquiaga, Daniel E. Holz
    Abstract: Strong **gravitational**... ▽ More
    Submitted 29 May, 2021; **originally announced** May 2021.
    Comments: 26 pages, 13 figures

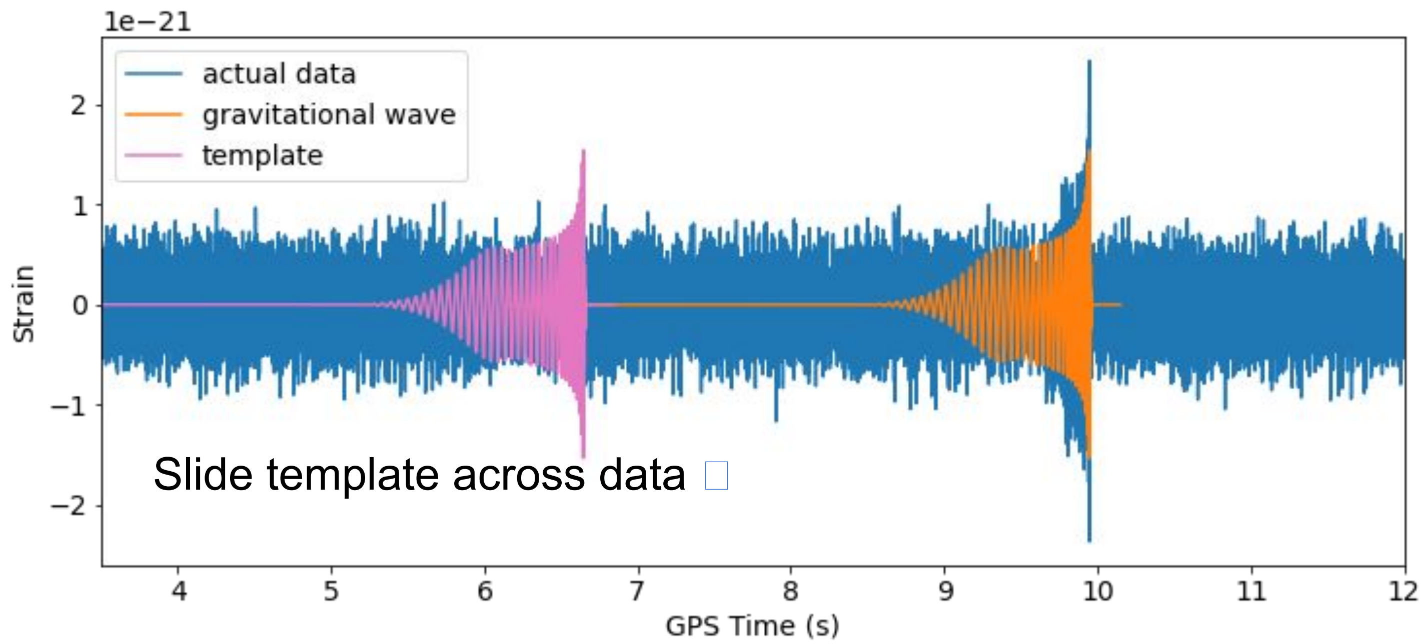
11. arXiv:2105.07011 [pdf, other] astro-ph.GA
    Event rate predictions of strongly lensed gravitational waves with detector networks and more realistic templates
    Authors: Lilan Yang, Shichao Wu, Kai Liao, Xuheng Ding, Zhiqiang You, Zhoujian Cao, Marek Biesiada, Zong-Hong Zhu

3. Can constrain important values for cosmology and the structure of the local Universe...

What is a Waveform?

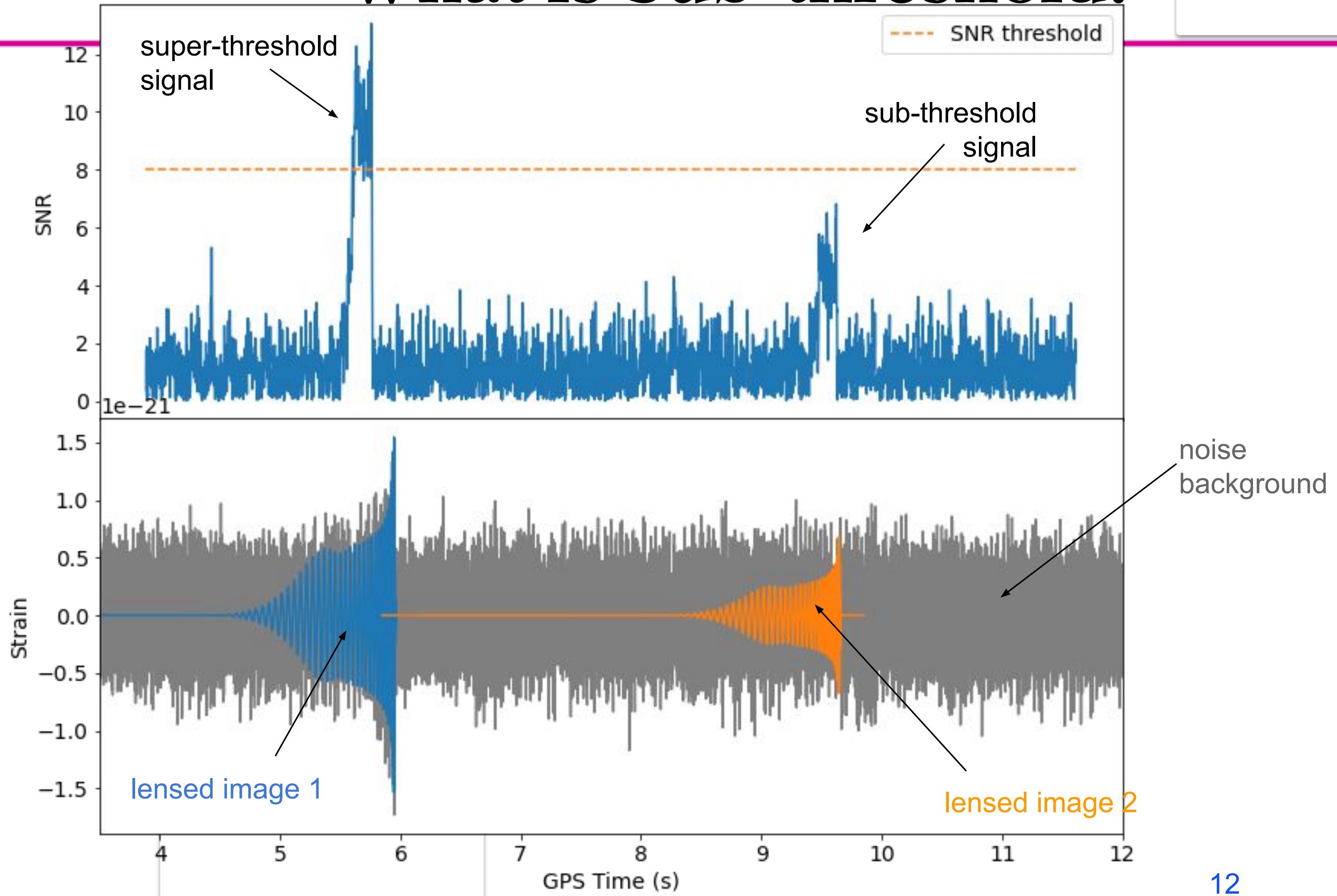


What is a Matched Filtering?

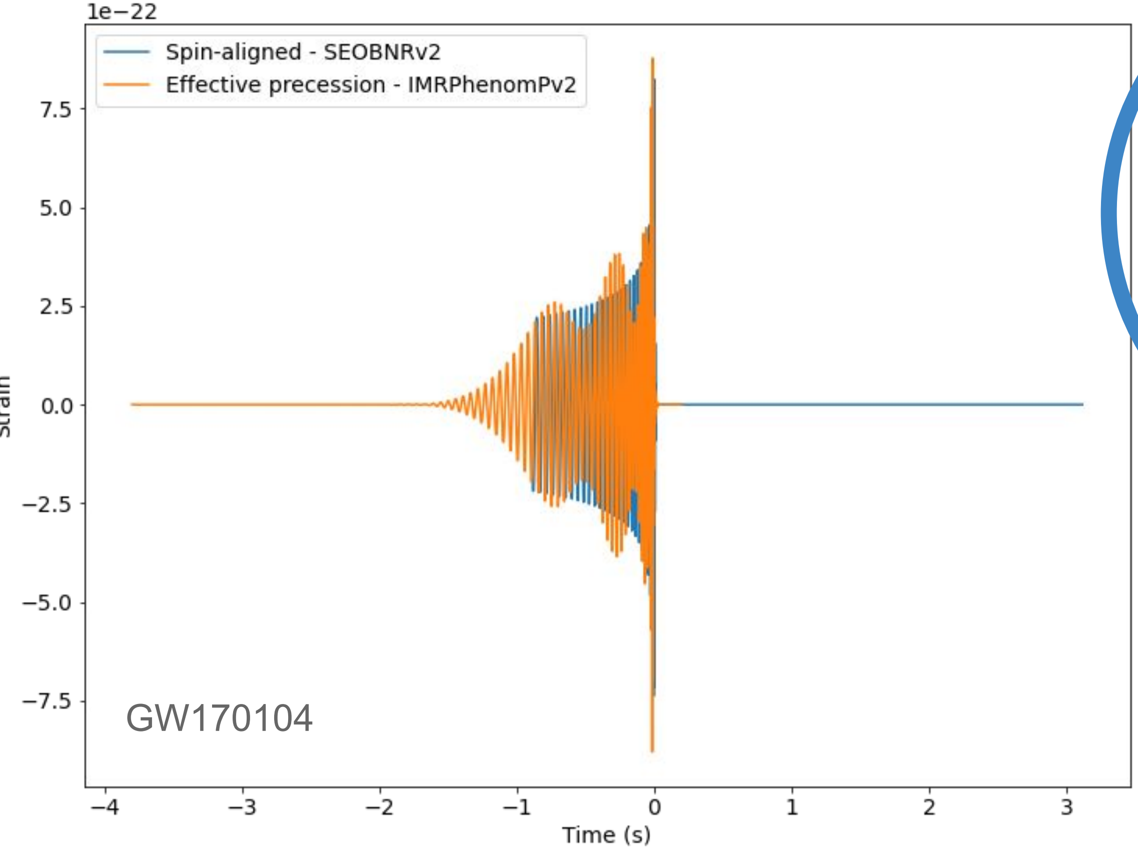


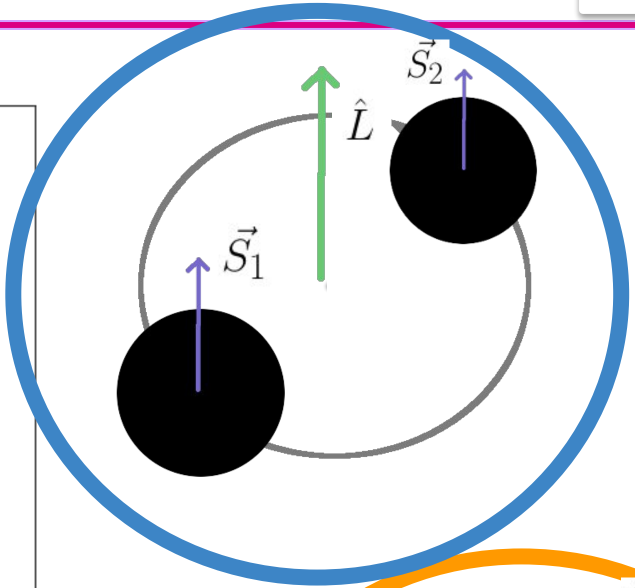
Measure the **correlation** between data and template to get **SNR**

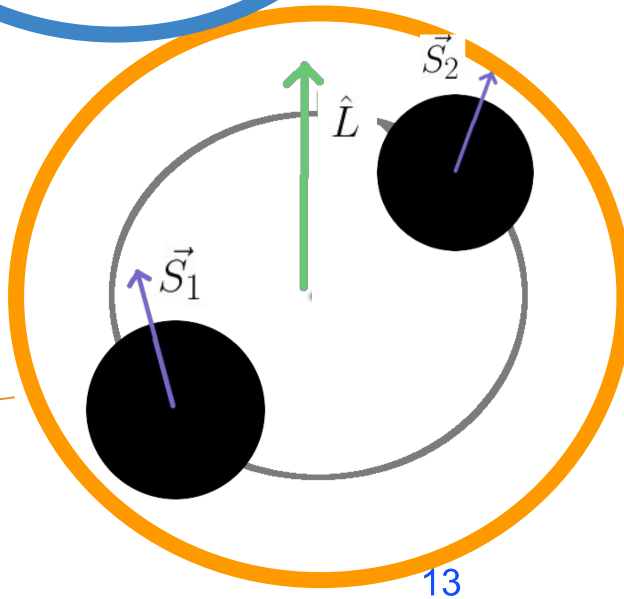
What is Sub-threshold?



What is a waveform family?





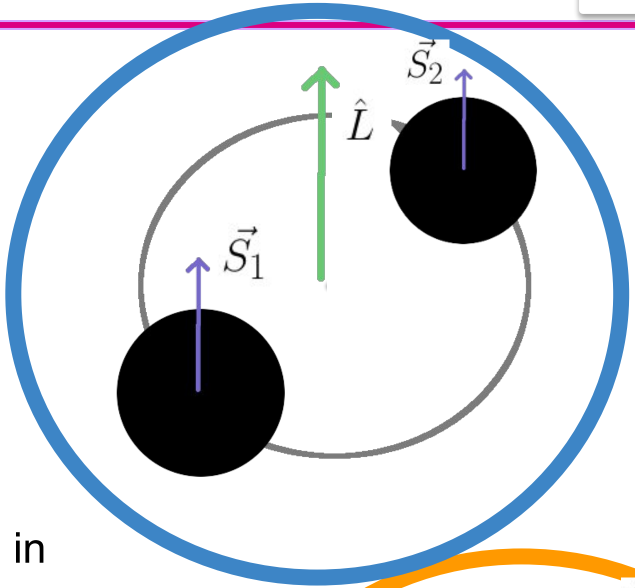


amplitude and frequency modulation

What is a waveform family?

Spin Aligned, e.g. SEOBNRv2, IMRPhenomD

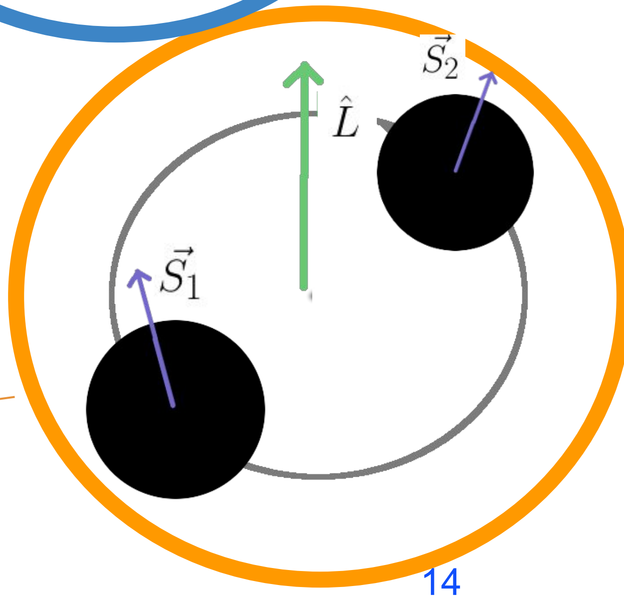
Precession included, e.g. IMRPhenomPv2



□ Different waveform families used in different lensing pipelines

GstLAL pipeline: spin-aligned waveforms

PyCBC pipeline: considers precession



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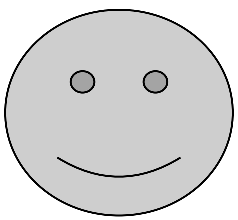
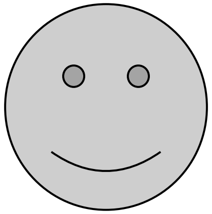
What is the motivation?

"You might lose potential candidates due to the waveform families you are using in the pipeline!"



"You should consider the differences between waveform families!"



What is reality?

- All **O1, O2, and O3a super-threshold events** have been **recovered** from sub-threshold lensing searches with both spin-aligned and precessing waveforms

□Evidence that the waveform family does not alter the chances of detecting a **super-threshold** gravitational wave

What am I doing?

- How to find out if waveform family does not alter the search pipeline for finding **sub-threshold signals**?

What I'm working on:

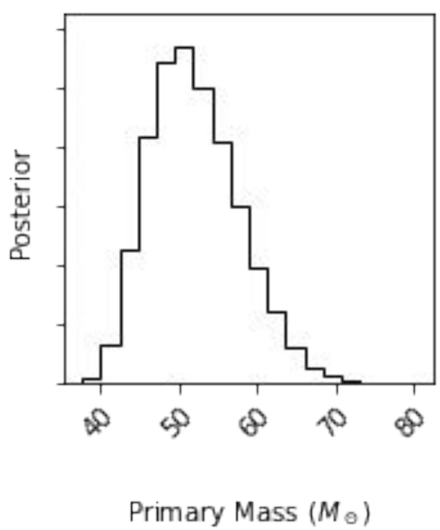
Finding the **match** between O1 and O2 events plotted with **spin-aligned** and **non-spin aligned** waveform families

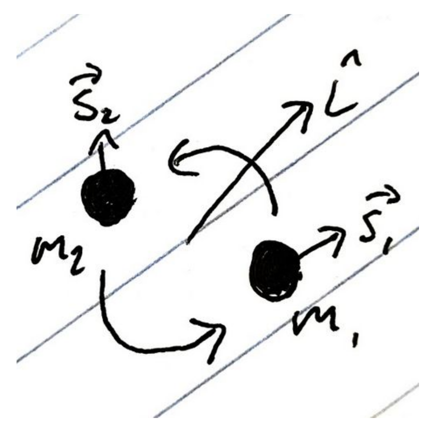
Waveform Matching - Method

Intrinsic parameters:
masses (m_1, m_2) ,
spins $(\vec{S}_1, \vec{S}_2)$,

Extrinsic parameters:
time (t_c), reference phase (φ_c),
sky position (α, δ), distance (d_L),
orbital orientation (θ_{Jn}, ψ),

1. Load in essential parameter **posterior samples** found with both spin aligned and non-spin aligned waveform families from previous analyses, find sample with the **maximum log likelihood**





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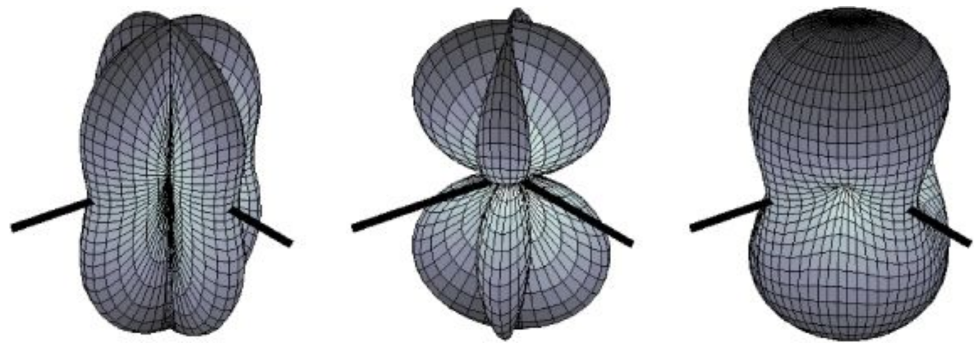
Waveform Matching - Method

2. Include Antenna Pattern function: how the strain appears in the detector



$$F_+(\zeta,\Phi,\Psi) = \frac{1}{2}(1+\cos^2\zeta)\cos 2\Phi \cos 2\Psi - \cos\zeta \sin 2\Phi \sin 2\Psi$$

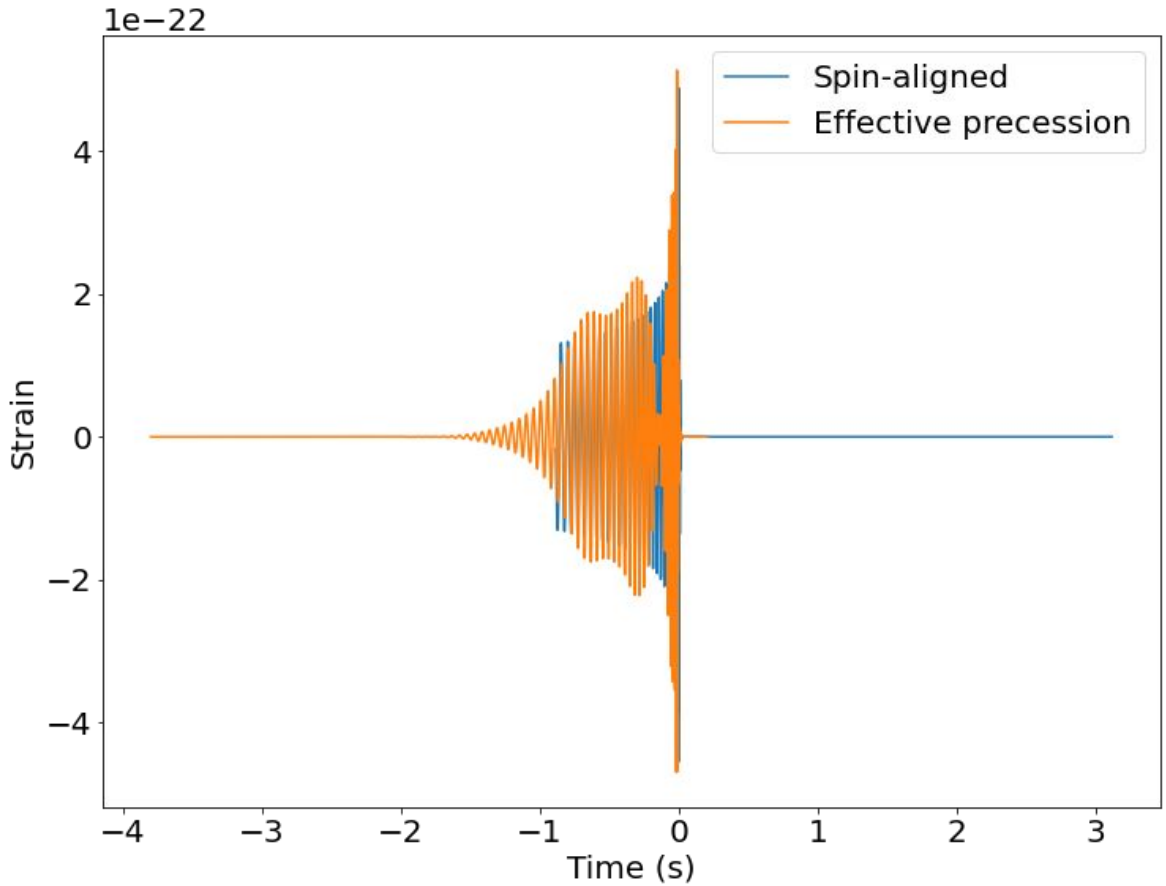
$$F_\times(\zeta,\Phi,\Psi) = \frac{1}{2}(1+\cos^2\zeta)\cos 2\Phi \sin 2\Psi + \cos\zeta \sin 2\Phi \cos 2\Psi$$

antenna pattern function depends on sky location, polarisation angle

total strain = $F_+(\zeta,\Phi,\Psi)h_+(t) + F_\times(\zeta,\Phi,\Psi)h_\times(t)$

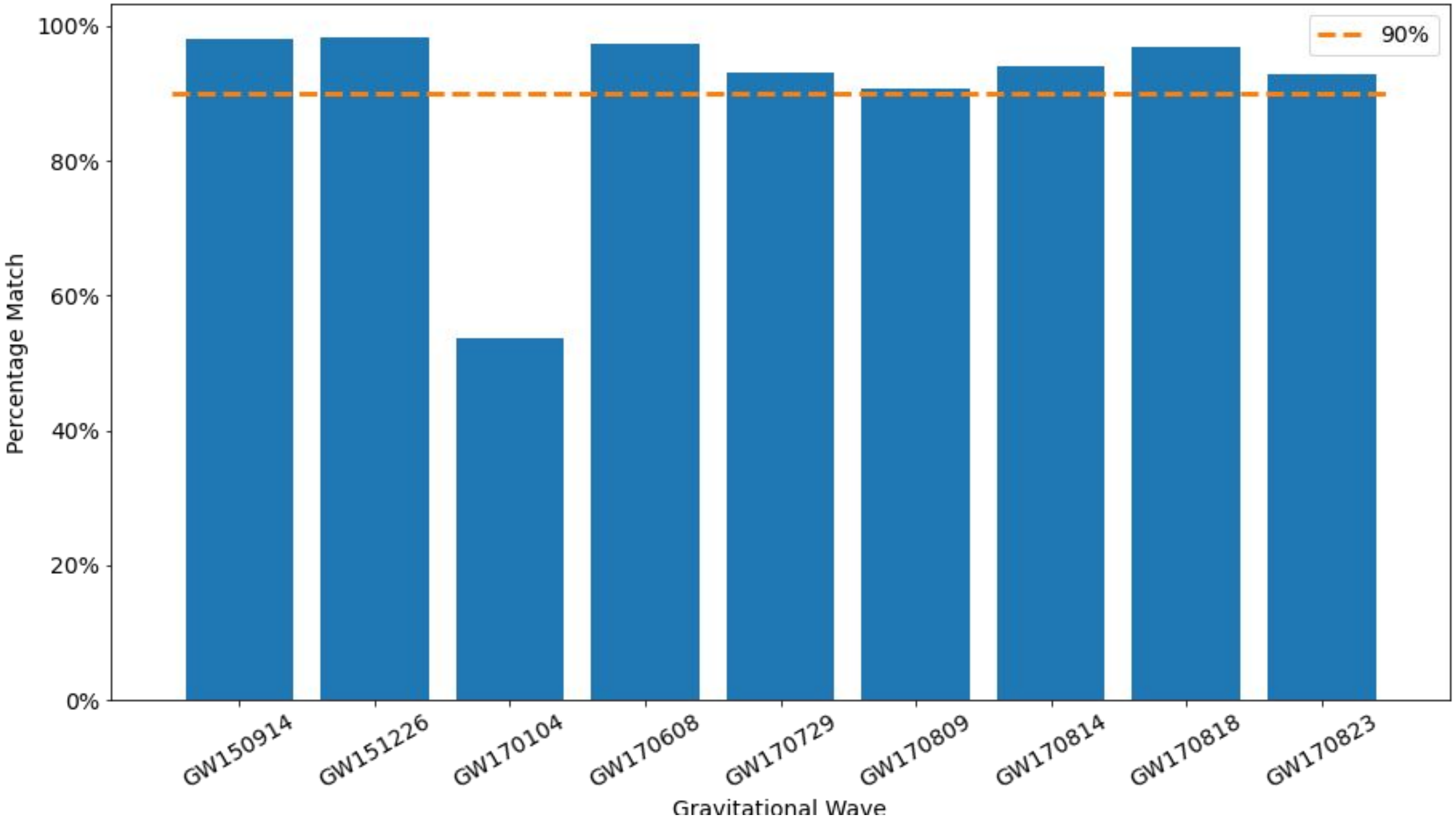
Waveform Matching - Method

3. Find the **match** between the strain for spin-aligned and precessing waveforms in each of the Hanford and Livingston detectors



GW170104 in Hanford Detector

Waveform Matching - Results



All above 90% match! Well, apart from GW170104….. evidence for precession?

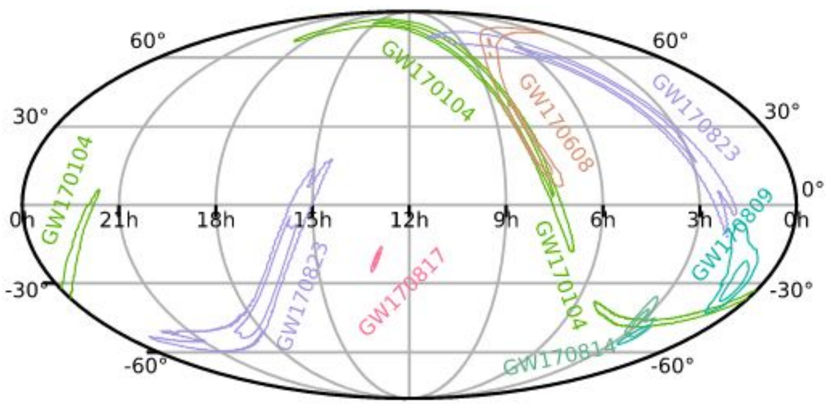
Waveform Matching - Conclusion

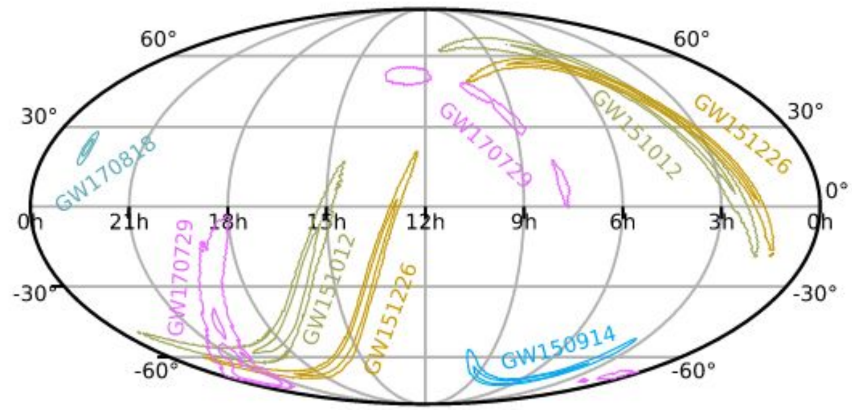
- If GW170104 is really precessing > SNR loss for aligned spin waveform

Might lose sub-threshold signals

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

Next Steps - Fundamentals



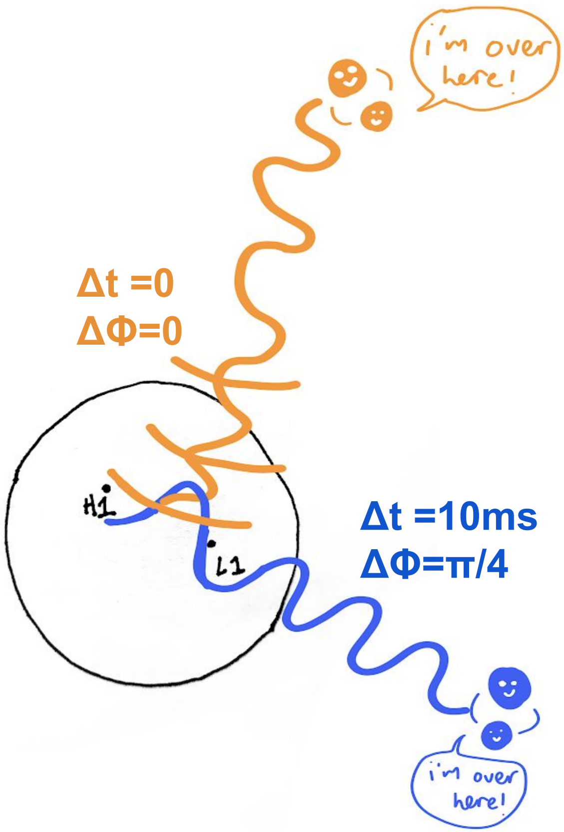


- Lensed images will come from approximately the same sky area
- Can rank lensed candidates higher based on their sky localisations

Next Steps - Ranking

$$\mathcal{L} = \frac{\textit{Probability the that data is is a true signal}}{\textit{Probability that the data is noise}}$$

Log Likelihood Ratio - Ranking Statistic



Both depend on **Δt** and **ΔΦ**:
the difference in arrival time and arrival phase between 2 detectors [1]

□Δt and ΔΦ both depend on the sky location of the source!

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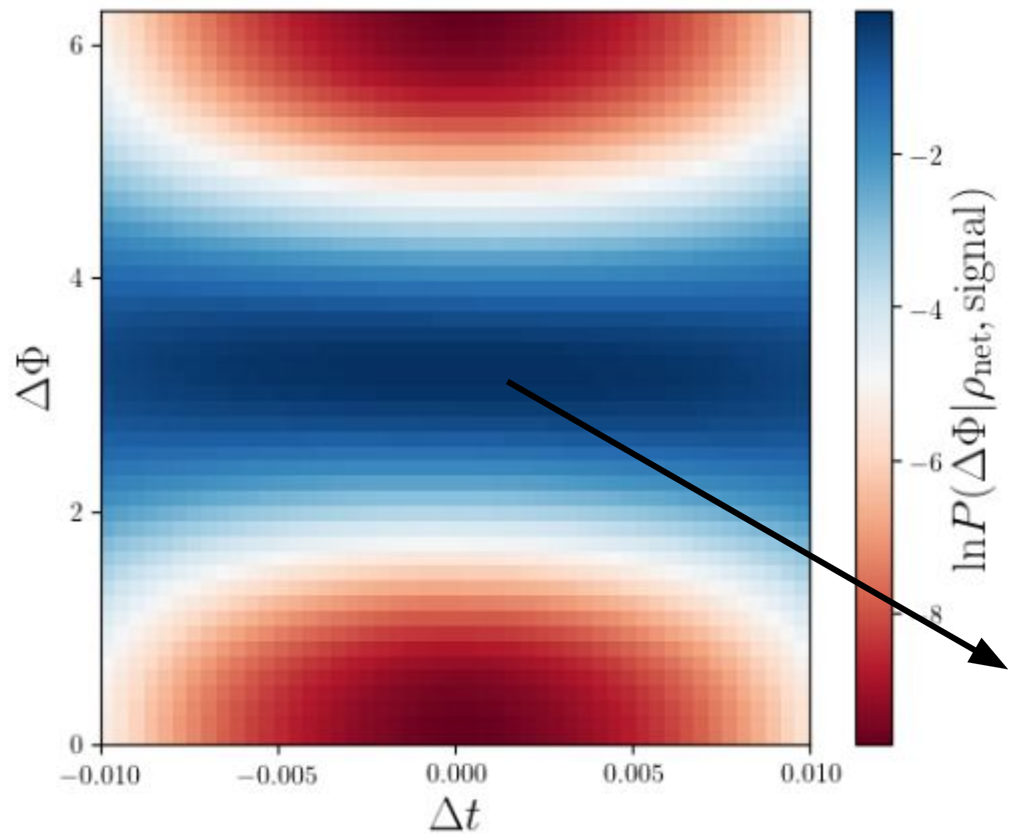
Next Steps - Ranking

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



Ranking of higher probability blue areas is boosted in pipeline

But what if we constrain the sky location…..?

img: [1]

Next Steps - Objectives

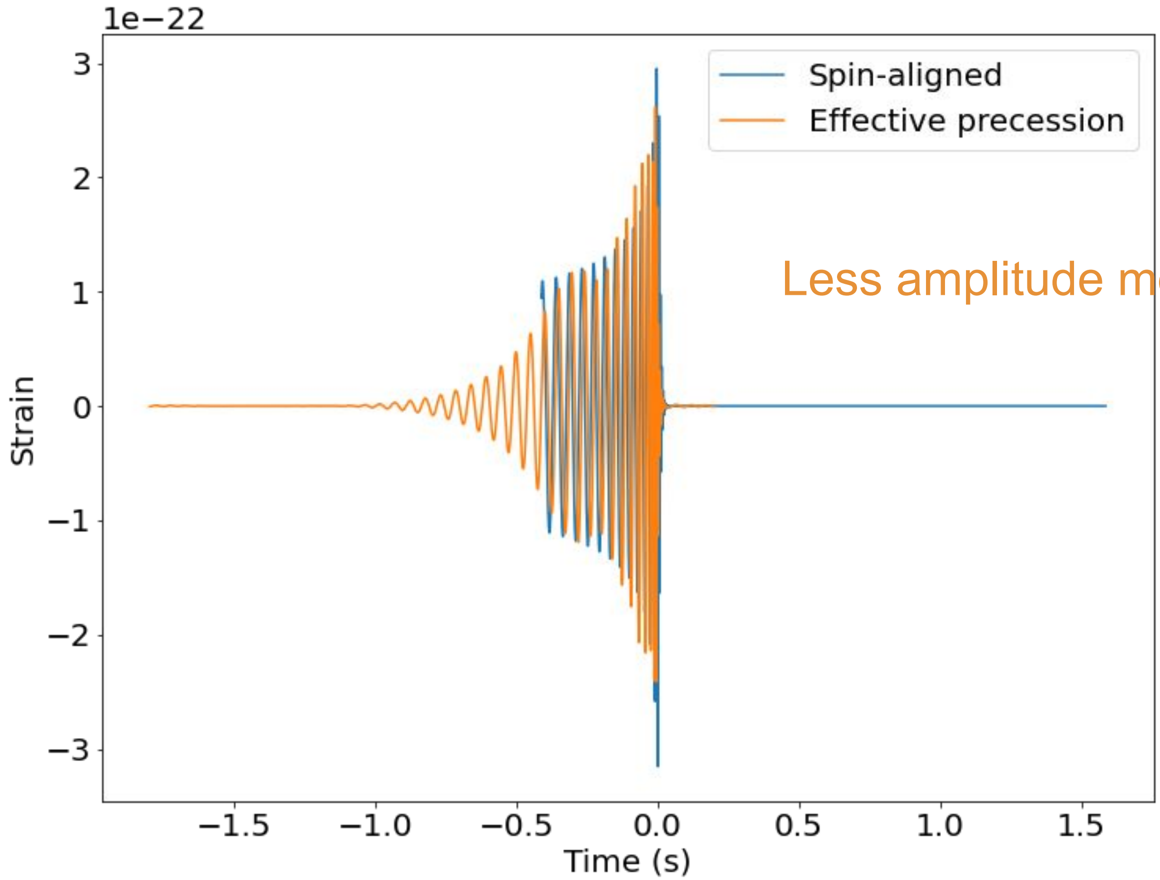
- Figure out how the **PDF of ΔΦ and Δt changes** when considering a **smaller sky location**
- Implement this new constraint on ΔΦ and Δt into the search pipeline to **target the search based on the sky location** of the super-threshold event
- Thus **boost ranking of lensed counterparts with similar sky location** to the target

References

[1] S. Sachdev, S. Caudill, H. Fong et. al. "The gstlal search analysis methods for compact binary mergers in advanced ligo's second and advanced virgo's first observing runs," (2019), arXiv:1901.08580

Questions?

Extra Slide - GW170608 in Hanford



Less amplitude modulation