Machine Learning Identification of Strongly Lensed Gravitational Waves Events

Giulia Campailla

University of Genova

GraSP 2024:

Exploring New Sources of Gravitational Waves

October 23-25, 2024, University of Pisa

Looking for Strongly Lensed Gravitational Waves

In collaboration with:

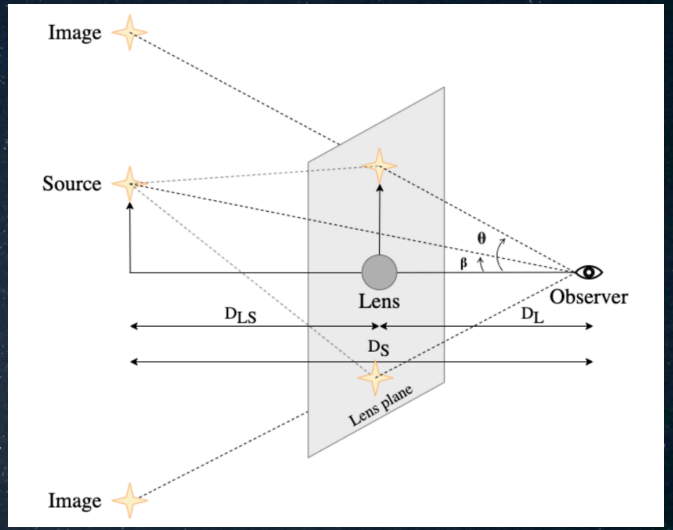
Jose Maria Ezquiaga (Niels Bohr Institute, LIGO)

Wayne Hu (University of Chicago)

Marco Raveri (University of Genova)

Strong Lensing: one source, multiple images

The "Twin Quasar" Q0957+561 (Walsh et al, 1979, HST).



Gravitational wave lensing review from Martina's talk!

On the right: 'Strong Gravitational Lensing of Gravitational Waves: A Review', Universe 2023, 9, 200. https://doi.org/10.3390/universe9050200

We do not *see* GW lensing…

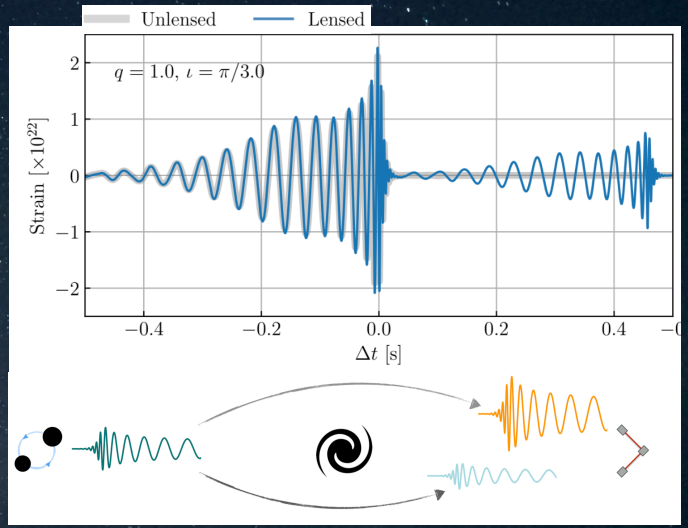
The "Twin Quasar" Q0957+561 (Walsh et al, 1979, HST).

multiple *images*

We do not *see* GW lensing…we *hear* it!

The "Twin Quasar" Q0957+561 (Walsh et al, 1979, HST).

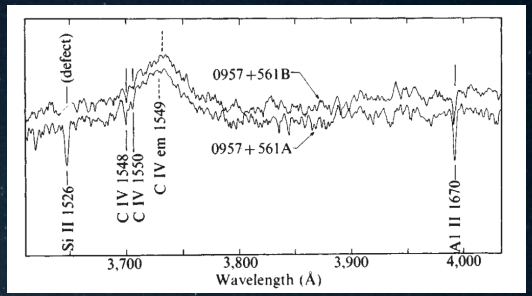
multiple *images*



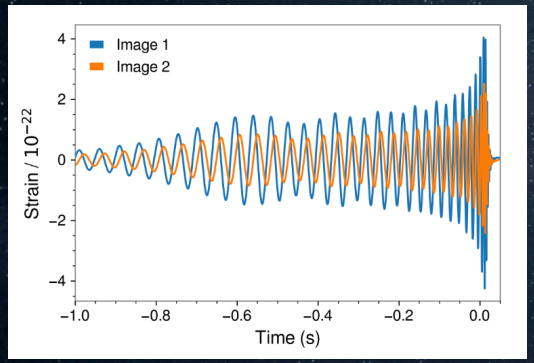
multiple *chirps*

On the right: Phase effects from strong gravitational lensing of gravitational waves, J. M. Ezquiaga, D. E. Holz, W. Hu, M. Lagos and R. M. Wald, arXiv: 2008.12814

How can we distinguish?



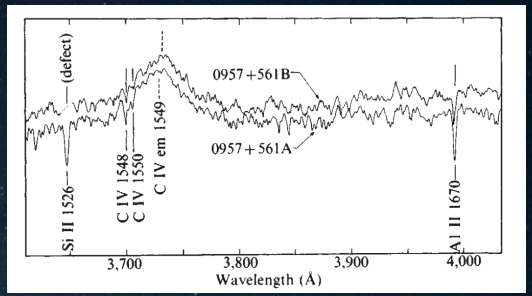
Spectroscopy



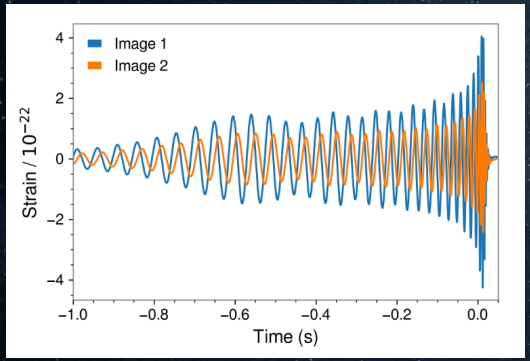
Two events
or
Just one strongly lensed?

Top right: 0957+561 A, B: twin quasistellar objects or gravitational lens?, Walsh, D.; Carswell, R. F.; Weymann, R. J., Nature, Vol. 279, p. 381-384 (1979)

How can we distinguish?



Spectroscopy



GW parameters!

Top right: 0957+561 A, B: twin quasistellar objects or gravitational lens?, Walsh, D.; Carswell, R. F.; Weymann, R. J., Nature, Vol. 279, p. 381-384 (1979)

Multiple images in formulas

- Solve the GW propagation equation in a curved spacetime

(more details from Nicola's talk earlier this morning!)

Weak-gravity + Thin lens approximation

$$h_L(\omega) = F(\omega, \theta_S)\, h(\omega)$$

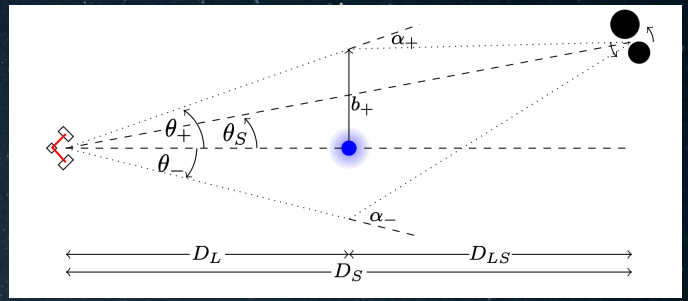
$$F \sim \Sigma_j \; \mu(\theta_j)^{1/2} \exp[i(\omega t_d(\theta_j) - \pi n_j)]$$

Magnification

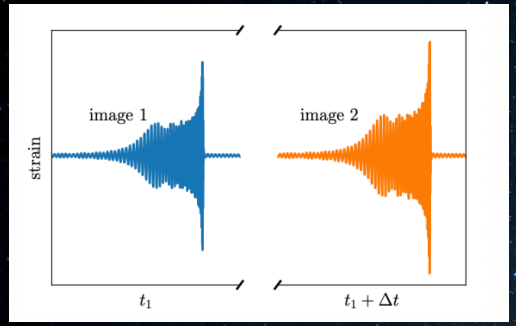
Time delay

Morse phase shift

$n_j = 0,\ 1/2,\ 1$ (Type I, II, III images)



Strongly lensed GW: *almost* twins



Follow-up Analyses to the O3 LIGO-Virgo-KAGRA Lensing Searches [arXiv:2306.03827].

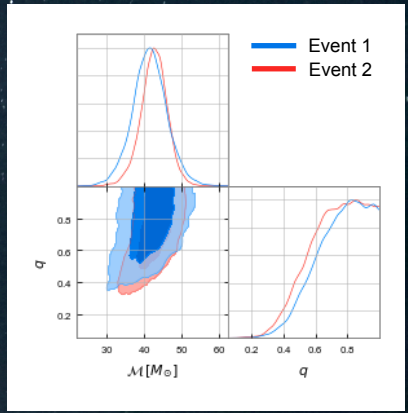
Data compression

$\neq$

Arrival time (t_d),
Luminosity distance (μ),
Phase information (Morse shift)

$=$

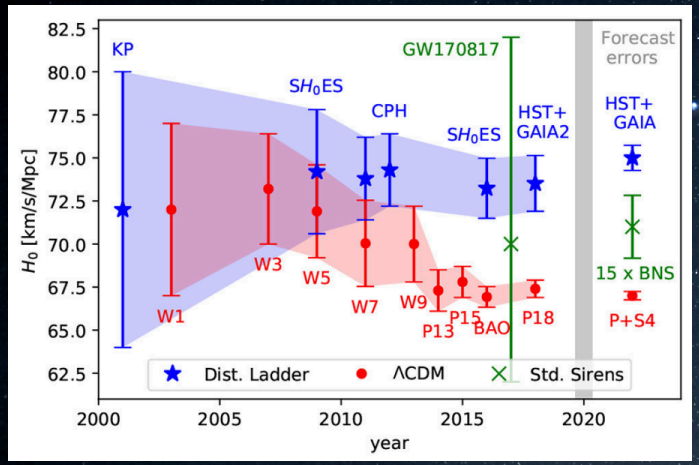
Compatibility of instrinsic parameters



Paper in prep.

Giulia Campailla

The idea: "t*ension*" between GW couples



The Hubble tension: measurements of H_0 in the local universe (in blue), derived values of H_0 from the CMB assuming ΛCDM (in red), direct measurements of H_0 with standard sirens following GW170817 (in green).

We compute 'distances' between parameters from two GW events → Small tension = high SL probability!

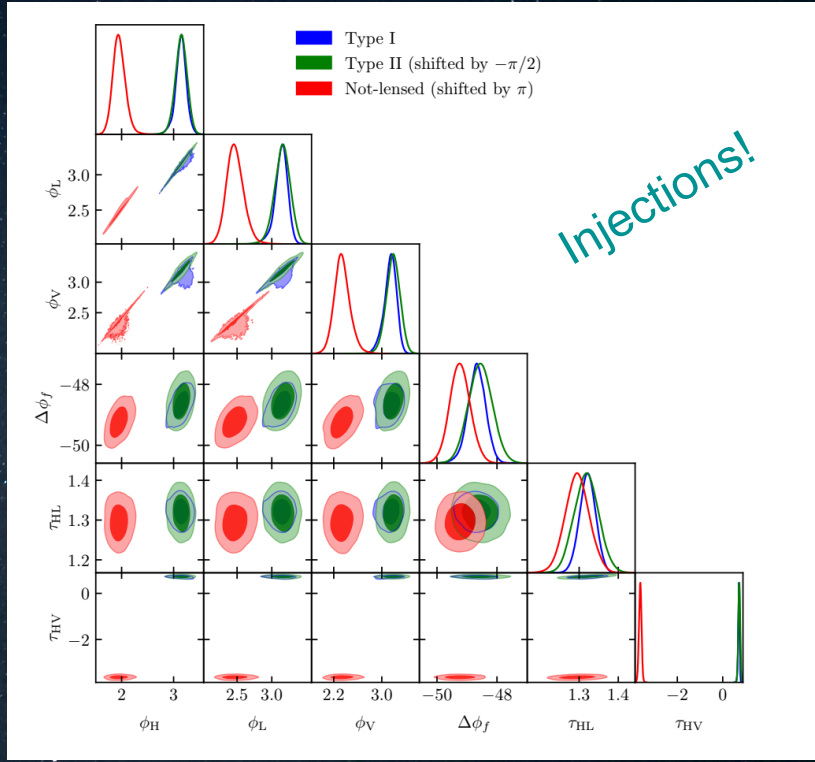
Top left: Dark Energy in Light of Multi-Messenger Gravitational-Wave Astronomy; J.M. Ezquiaga and M. Zumalacárregui; Front. Astron. Space Sci. 5:44. (2018)

Testing SL hypothesis in parameter space

Search for pairs of events that are Morse phase shift consistent

Gaussian Linear Model

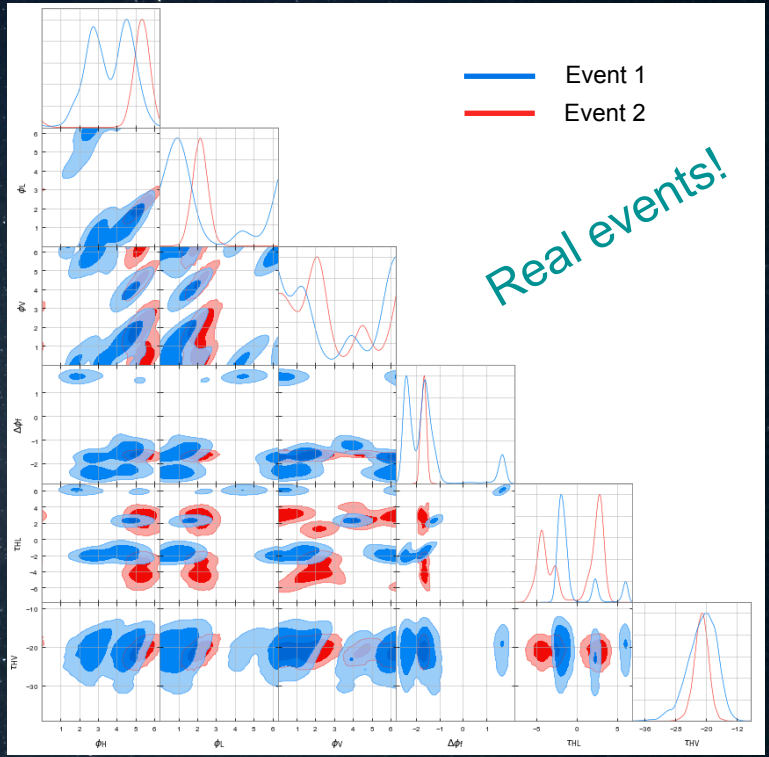
"Concordance and Discordance in Cosmology", [M. Raveri and W. Hu, arXiv: 1806.04649v1]



Identifying strongly lensed gravitational waves through their phase consistency, J. M. Ezquiaga, W. Hu and Rico K. L. Lo, arXiv: 2308.06616

Reality is more challenging

- High dimensional space
- Non-Gaussianities
- Multimodality

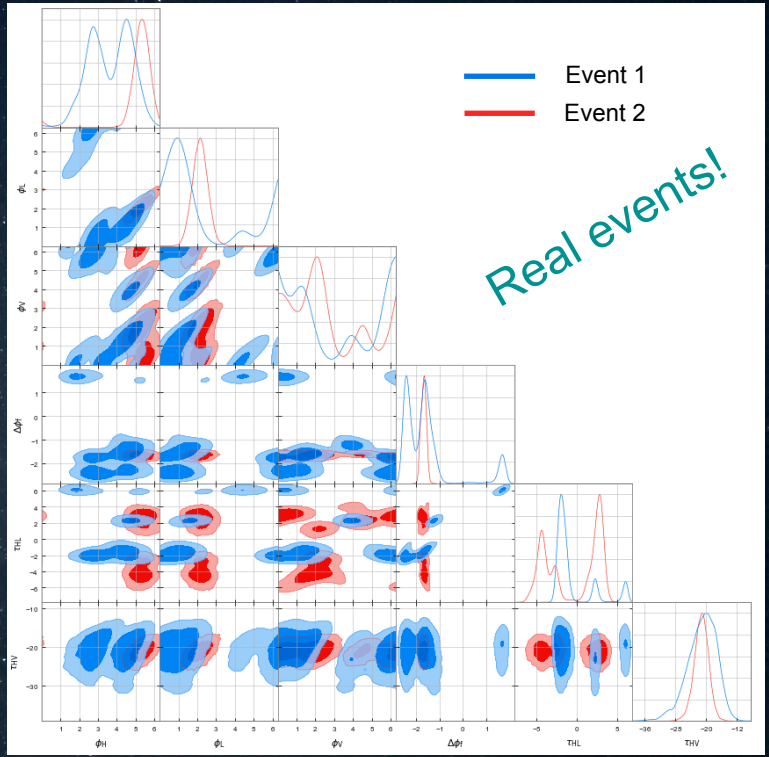


Paper in prep.

Reality is more challenging

- High dimensional space
- Non-Gaussianities
- Multimodality

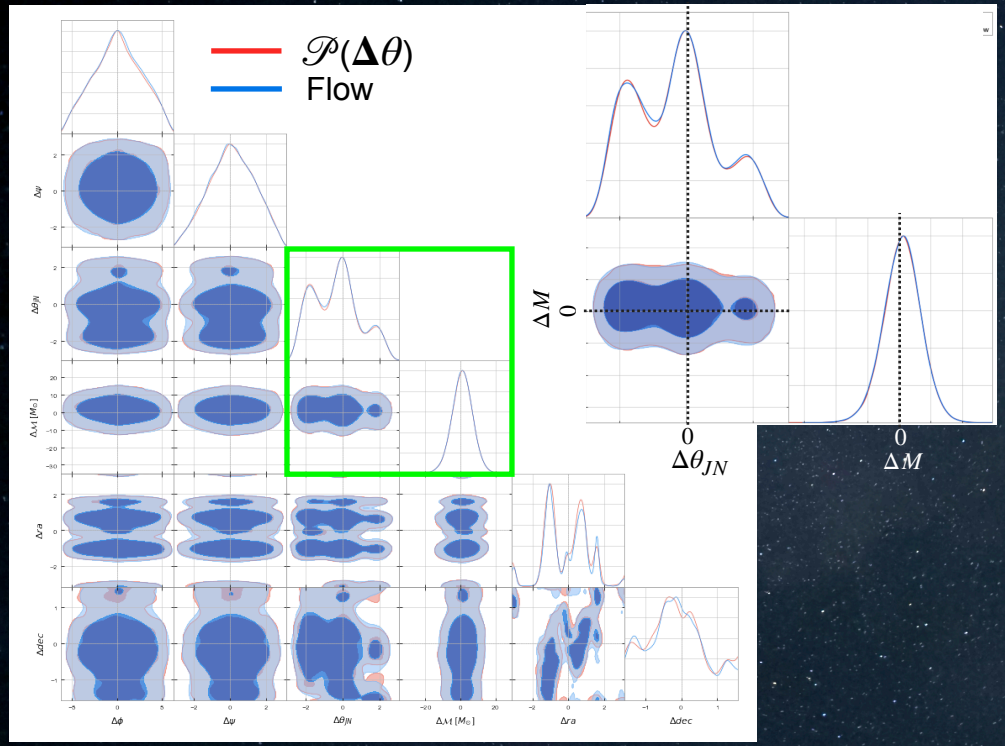
We need machine learning!



Paper in prep.

Giulia Campailla

Normalising Flows (NF) at work



Parameter difference distribution
$\mathscr{P}(\Delta\theta)$

NF

Statistical significance of the shift

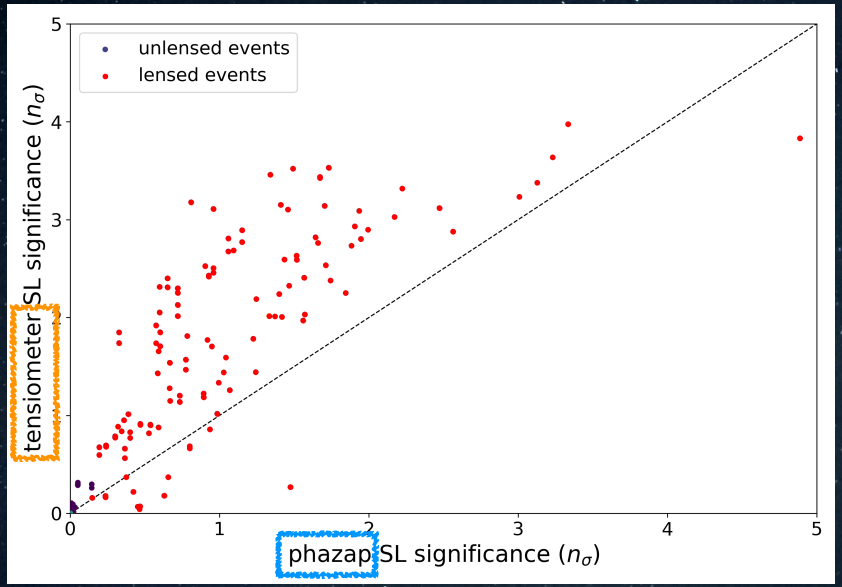
$$\Delta = \int_{\mathcal{P}(\boldsymbol{\Delta\theta})>\mathcal{P}(\mathbf{0})} \mathcal{P}(\boldsymbol{\Delta\theta})\,\mathrm{d}\boldsymbol{\Delta\theta}$$

Exact! Not approximated!

Paper in prep.

Unblind the algorithm performance

Non-Gaussian method (Normalising Flow)



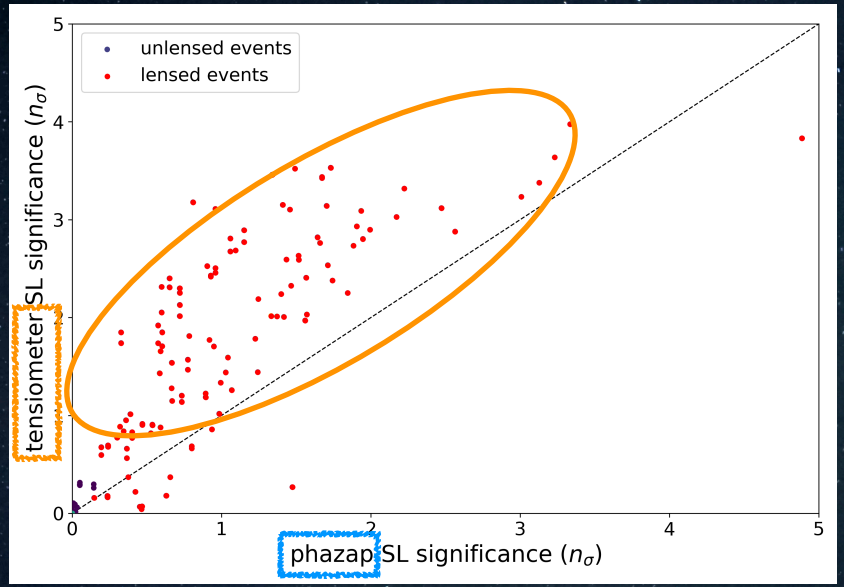
Gaussian approximation method

Paper in prep.

Giulia Campailla

Unblind the algorithm performance

Non-Gaussian method (Normalising Flow)



Gaussian approximation method

✓ Simulations

↓

✓ O3 real data

↓

Road to O4 data release!

Paper in prep.

Giulia Campailla

Takeaways messages and future prospects

- Why is it important to search for SL GW pairs?
  - Never seen…
  - Physical properties of the lens system (Astrophysics!)
  - Big dream: matter distribution and large scale structure (Cosmology!)

- What was the focus of my work?
  - Testing the SL hypothesis looking at the consistency of GW parameters
  - Non-Gaussian + high dimensions = ML methods (NF!)

- What about real events? Are there any lensed GWs?
  - Let's see what O4 holds! Check the arXiv!

Thank you!