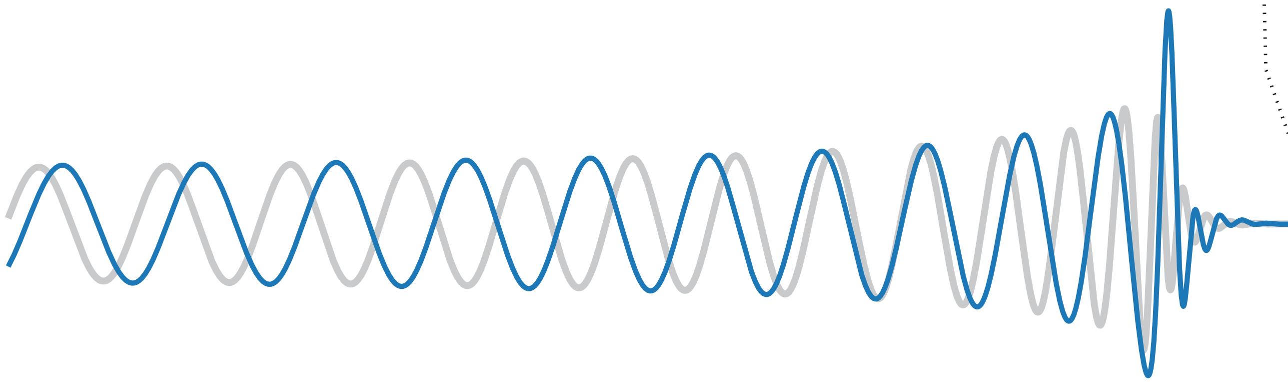
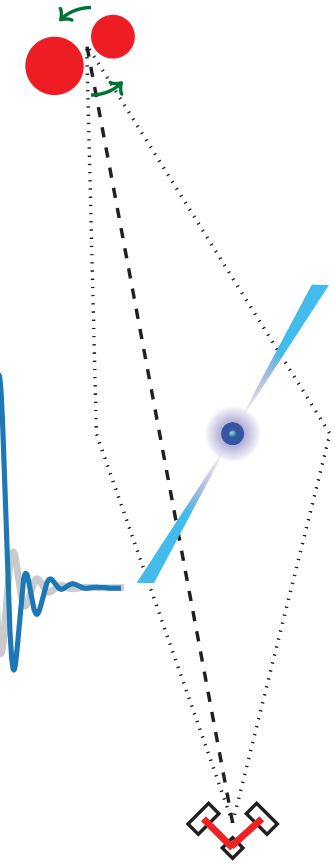
Mor$_{s}$e than Just a Phase:
Propagating the Phase Information from Gravitational Waves





Wayne Hu

Pollica, September 2024

[with Giulia Campailla, Jose María Ezquiaga, Macarena Lagos,
Qiuyue Liang, Meng-Xiang Lin, Rico Lo, Marco Raveri, Mark Trodden, Fei Xu]

GW Sounding out the Universe

- As sirens for distance measures [– not this talk]
- As sonar, propagating through the universe:
  - GW speed, mass, modified dispersion relation (MDR)
  - Gravitational lensing, additional Morse phase information
  - GW propagation echoed in PTA timing residuals

- 2203.13252: J.M. Ezquiaga, W. Hu, M. Lagos, M.X. Lin, F. Xu

  2308.06616: J.M. Ezquiaga, W. Hu, R.K.L. Lo; PHAZAP

  2408.11774: W. Hu, Q. Liang, M-X Lin, M. Trodden

  PHAZAP + TENSIOMETER: w. G. Campailla, J.M. Ezquiaga, M. Raveri

- PHAZAP: A tool for extracting phase information from standard parameter estimation pipelines

https://github.com/ezquiaga/phazap

Propagation Effects

- Dispersion relation, small correction from GR (see Will; LVK analysis)

$$\omega^2 = k^2(1 + Ak^{\alpha-2})$$

– Special Cases:

- $\alpha = 0$: graviton mass term m_g
- $\alpha = 1$:

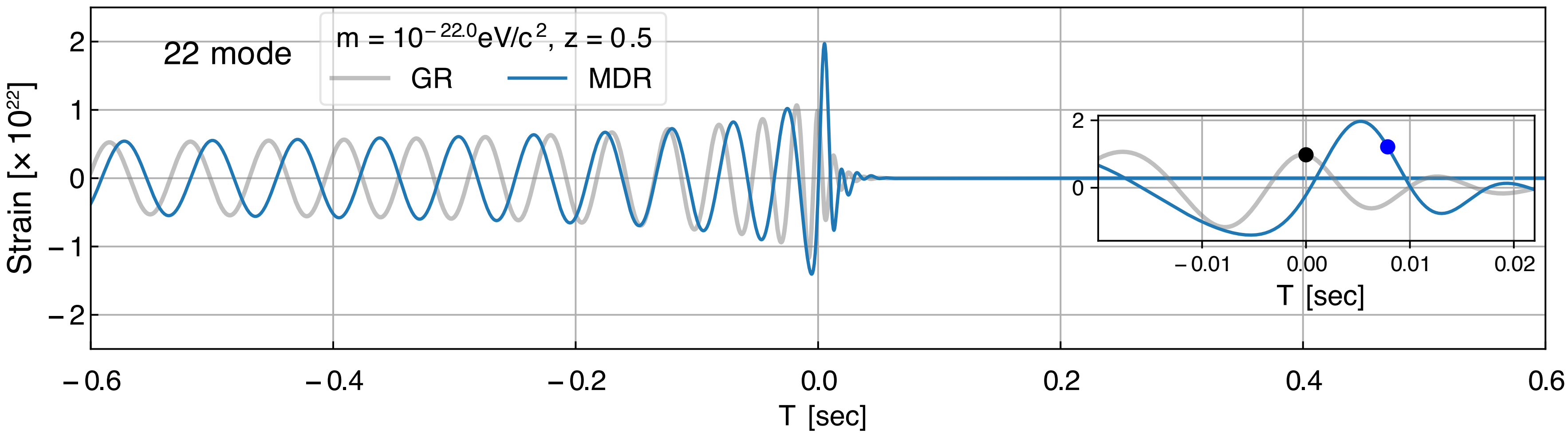
  phase velocity $v_p = \omega/k \neq 1$

  group velocity $v_g = \partial\omega/\partial k \approx 1$
- $\alpha = 2$: change in GW speed $v_p = v_g \neq 1$

  well constrained by binary NS with EM counterpart

Phase Shift

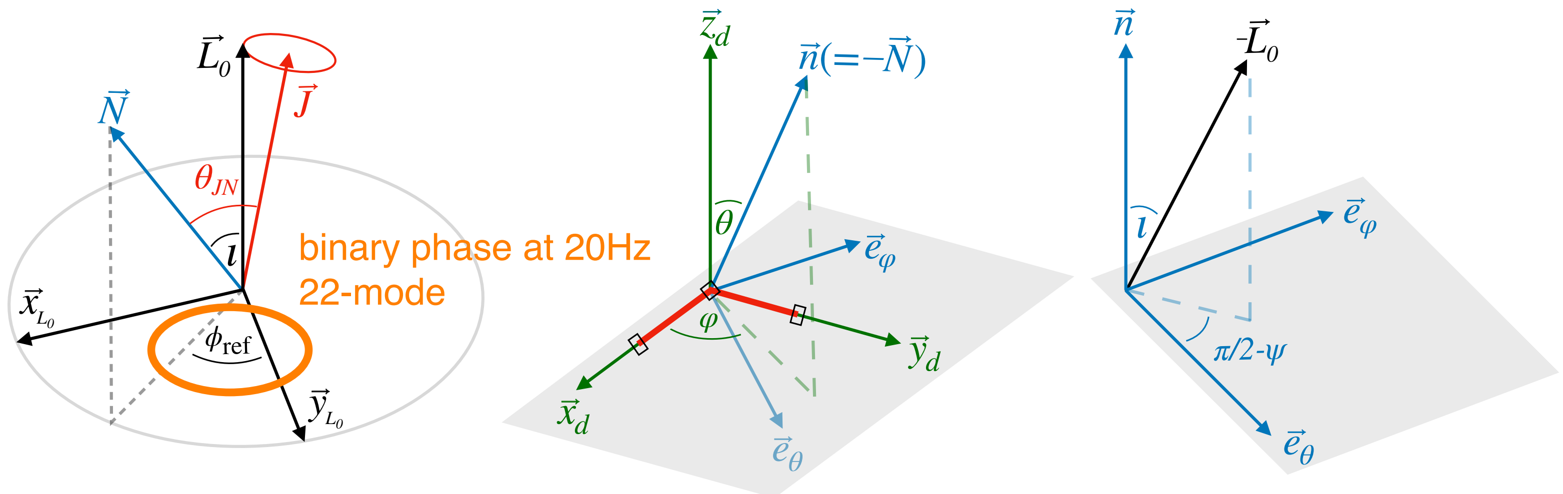
- Observable phase shift occurs when the group and phase velocity differ ($\alpha = 0$, mass term)



- Phase shift is degenerate (exactly for $\alpha = 1$, partially for $\alpha \neq 1$) with binary orbital reference phase ϕ_{ref} for the dominant quadrupole mode $\ell = 2, m = 2$ or ("22")

What's Your Angle?

- Reference phase ϕ_{ref} is one of many angles....



(a) Source (b) Earth detector (c) Sky

defining the orientation of the binary system and the detector arms

What's Your Angle?

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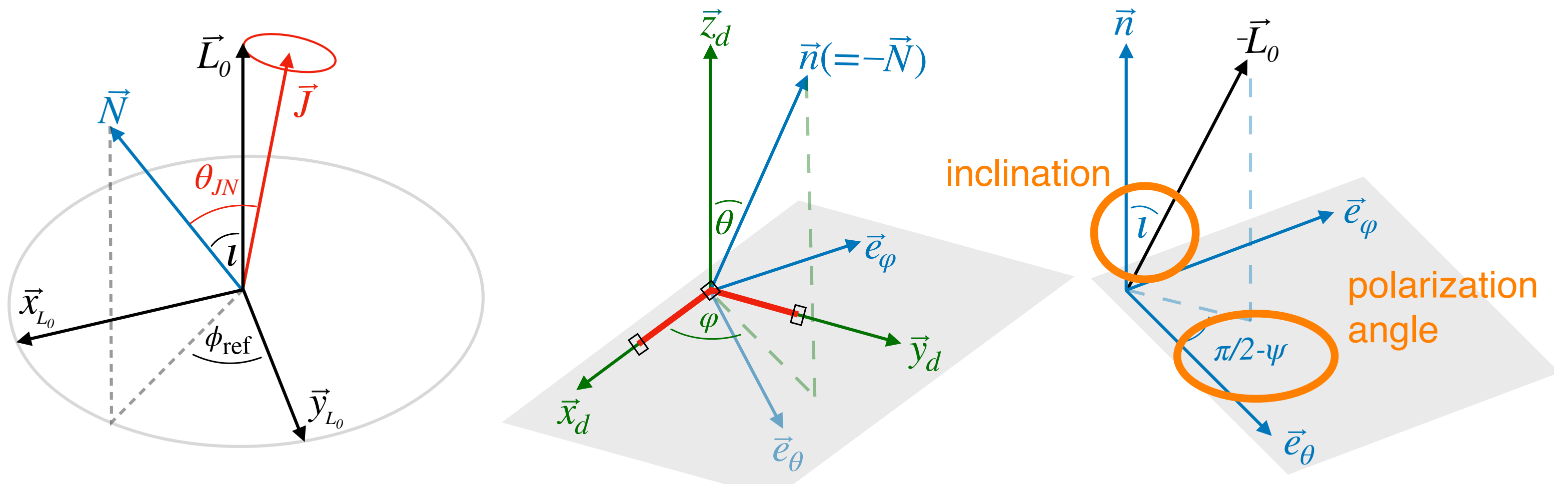


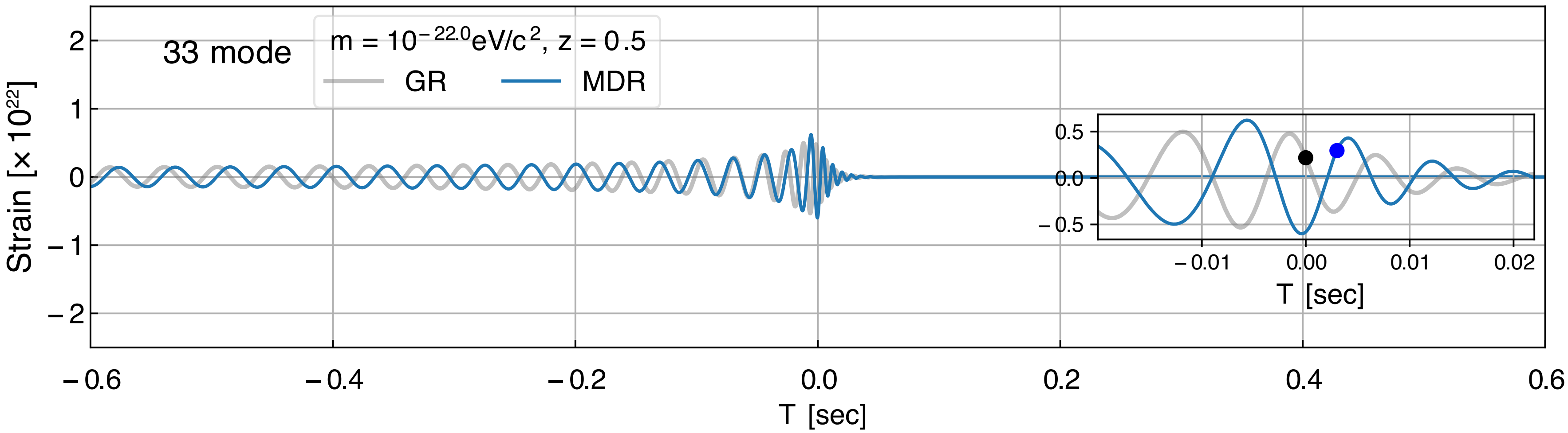
(a) Source (b) Earth detector (c) Sky

defining the orientation of the binary system and the detector arms

- Fun (?!) with Euler angles and tracking down definitions
- Phase shift is also partially degenerate with polarization angle ψ
- PHAZAP uses this mapping to undo parameter estimation and to (re)derive phases as seen by the detectors

Higher Modes

- With a high mass ratio ($q = 0.1$) and inclination away from face-on/off, higher azimuthal modes ($m = 3...$)

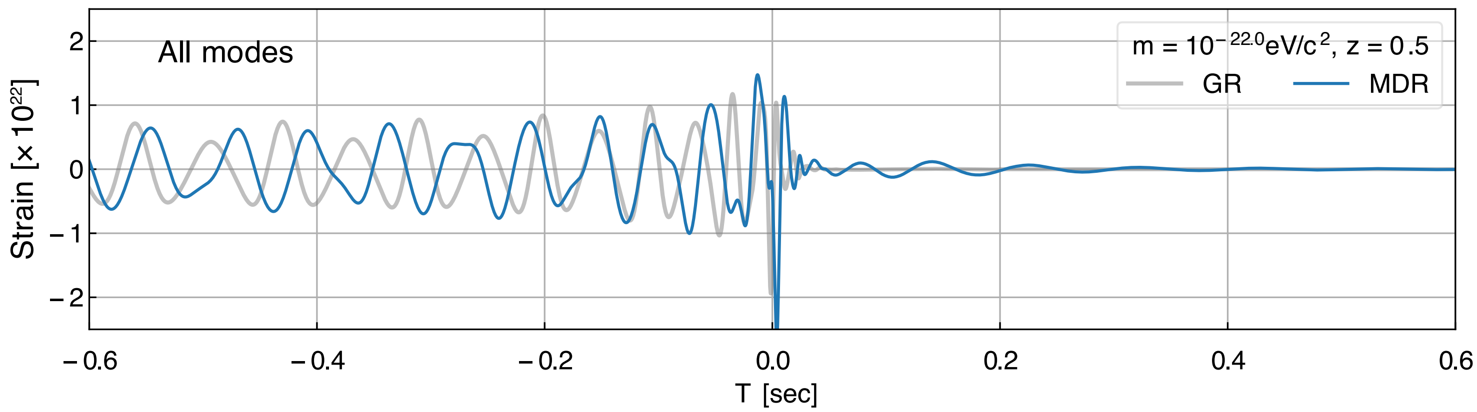


break the degeneracy with orbital reference phase $\phi_{\rm ref}$

- Arrival times also shift if $v_g \neq 1$

Phase Shift

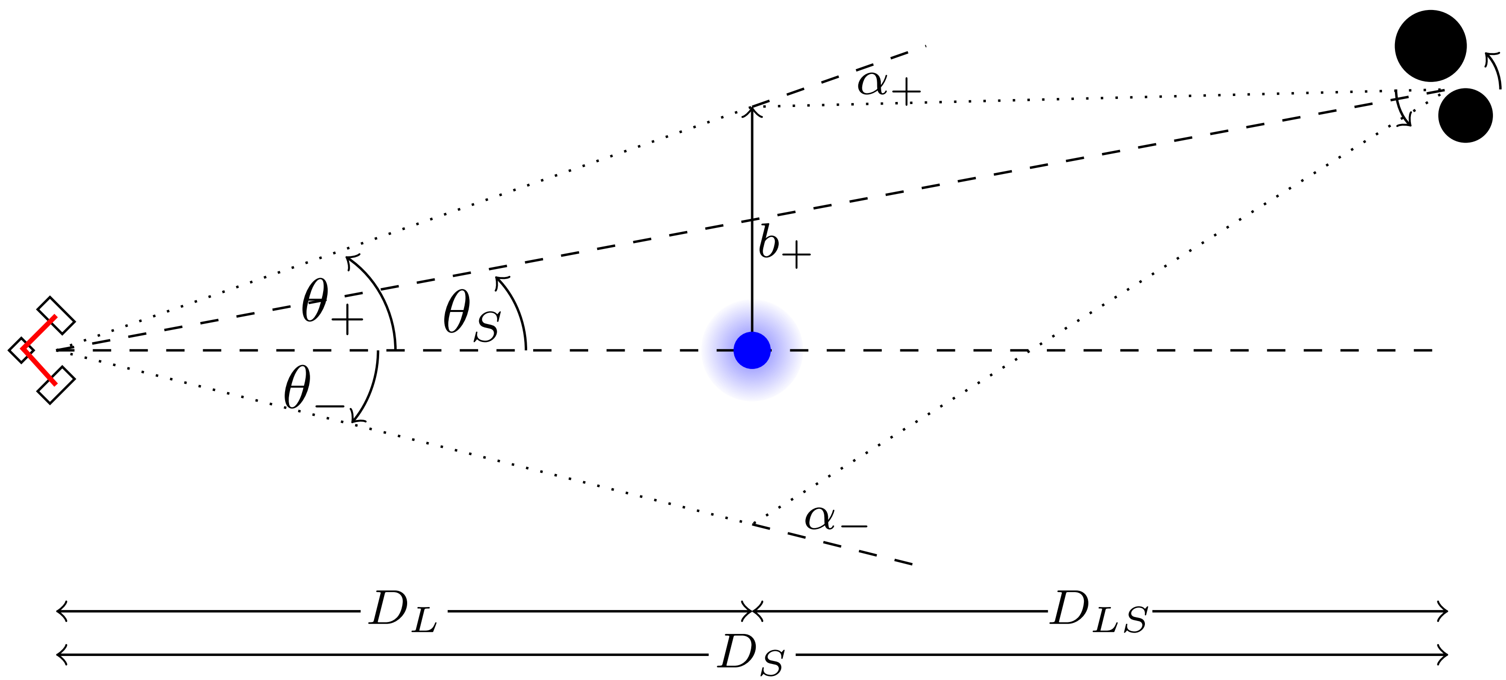
- Total waveform summed over all modes



- Propagation time delay can make low frequency modes invert and inspiral signal arrives after coalescence
- However, distinguishability requires high mass ratio, high SNR
- Also for single events can be confused with the Morse shift from gravitational lensing...

Strong Gravitational Lensing

- As with optical lensing, multiple images/events from a single source



- But with phase information (both in geometric optics, where images don't interfere, and wave optics)
- In geometric optics, the independent images/events are phase shifted depending on which extrema of time delay

Morse Phase

- Morse phase:

  I: minima = $0 \times \pi$

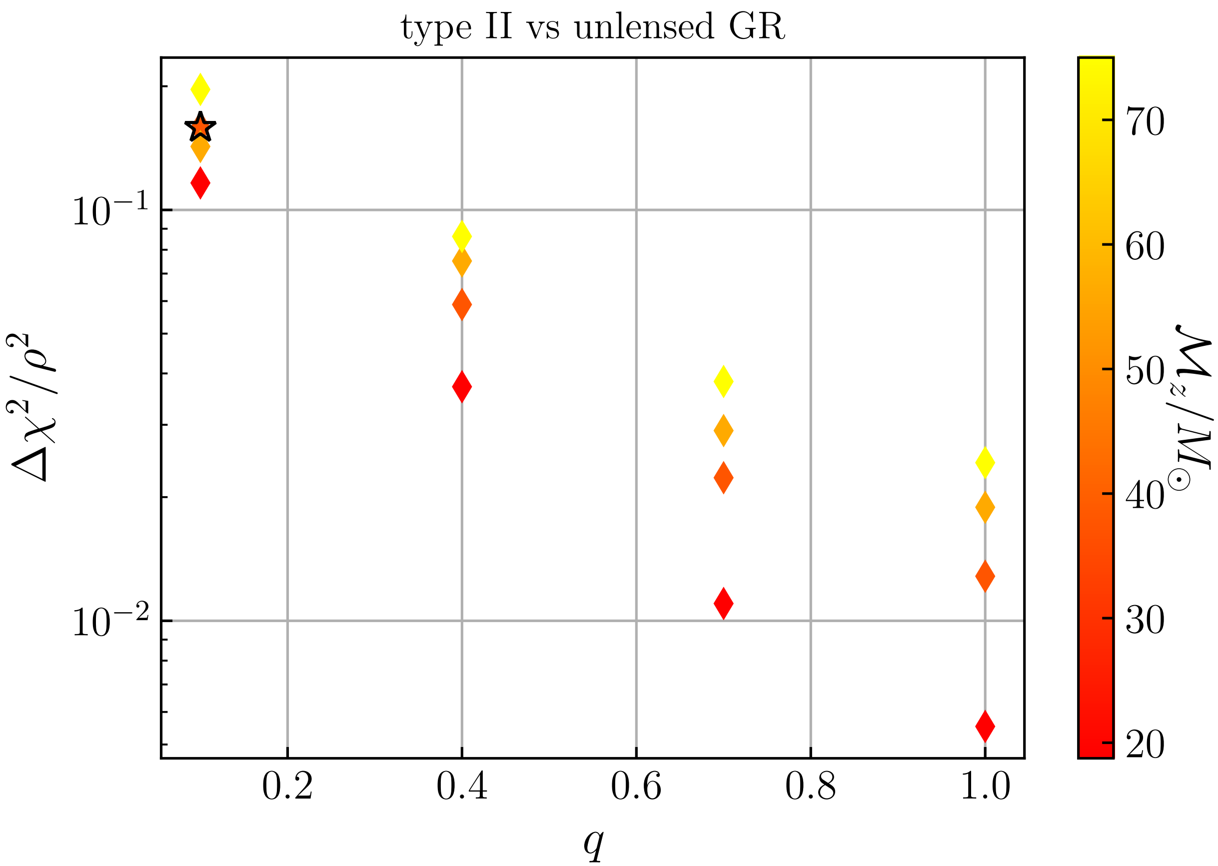
  II: saddle = $\frac{1}{2} \times \pi$

  III: maxima = $1 \times \pi$

- Achromatic just like an $\alpha = 1$ propagation phase shift but at specific values
- Searching for such propagation effects and waveform distortions also searches for gravitational lensing
- Gravitational lensing could be confused with propagation effects

Single Event Detectability

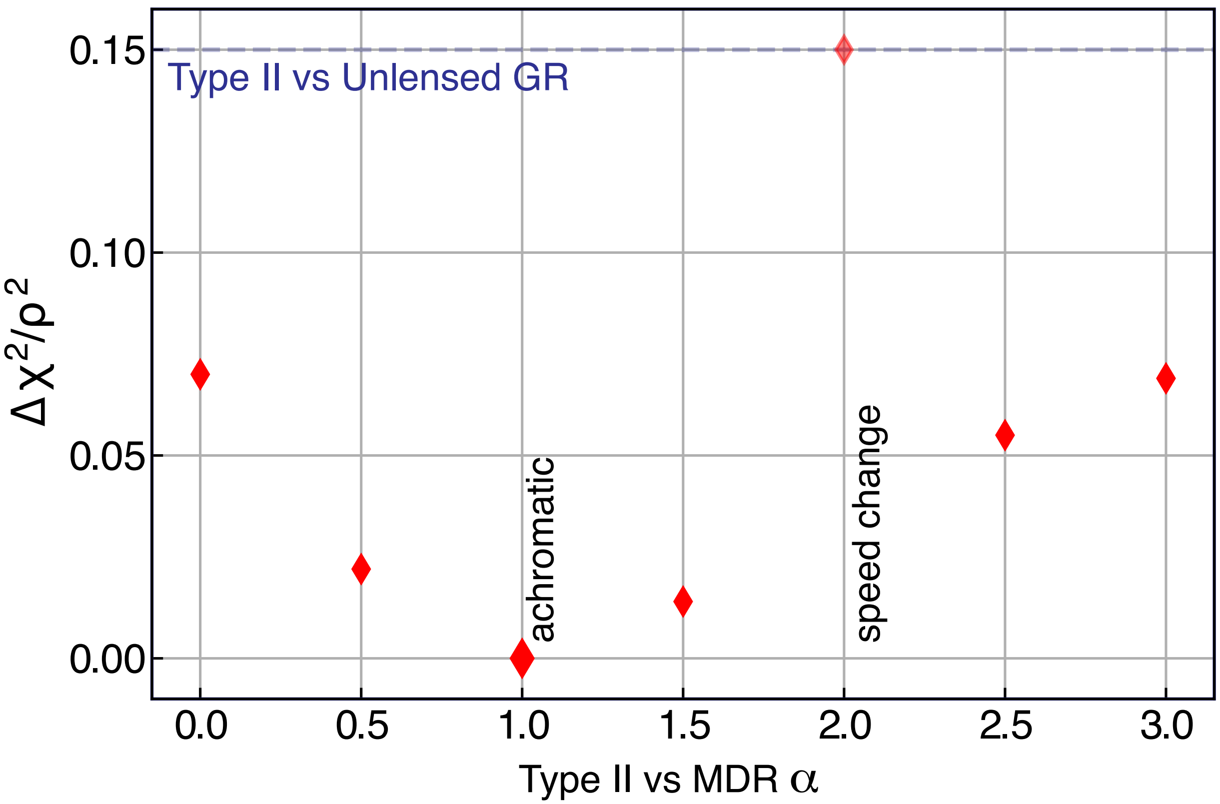
- Distinguishability of phase shift vs binary parameters requires high SNR ρ and high mass ratio



- e.g. for $\star$ case: $\Delta\chi^2 = 25 = 0.15\rho^2 \rightarrow \rho^2 \approx 167$

Modified Gravity vs Lensing Confusion

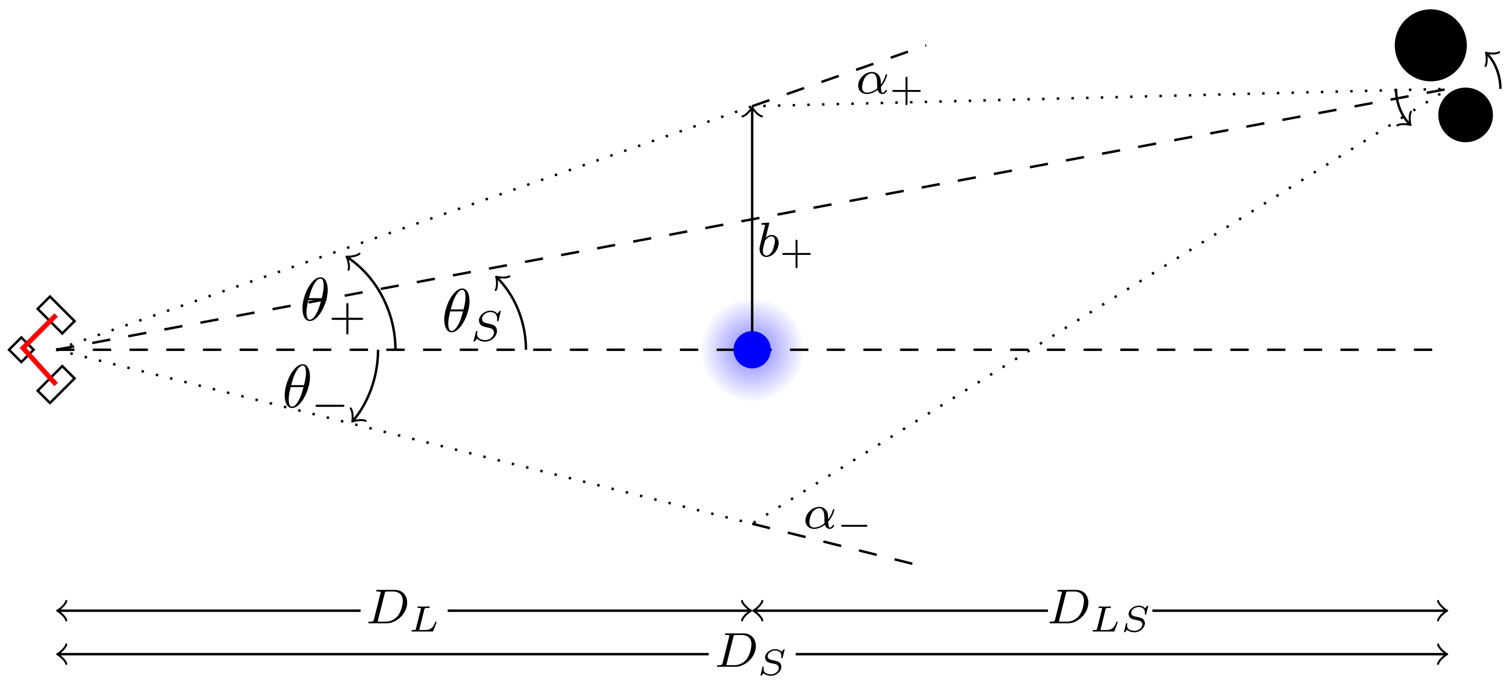
- Exactly degenerate with $\alpha = 1$, partially with $\alpha = 0$ mass term
- Further confusion between modfied propagation and lensing



- Requires even higher SNR to distinguish modified gravity from lensing in single event

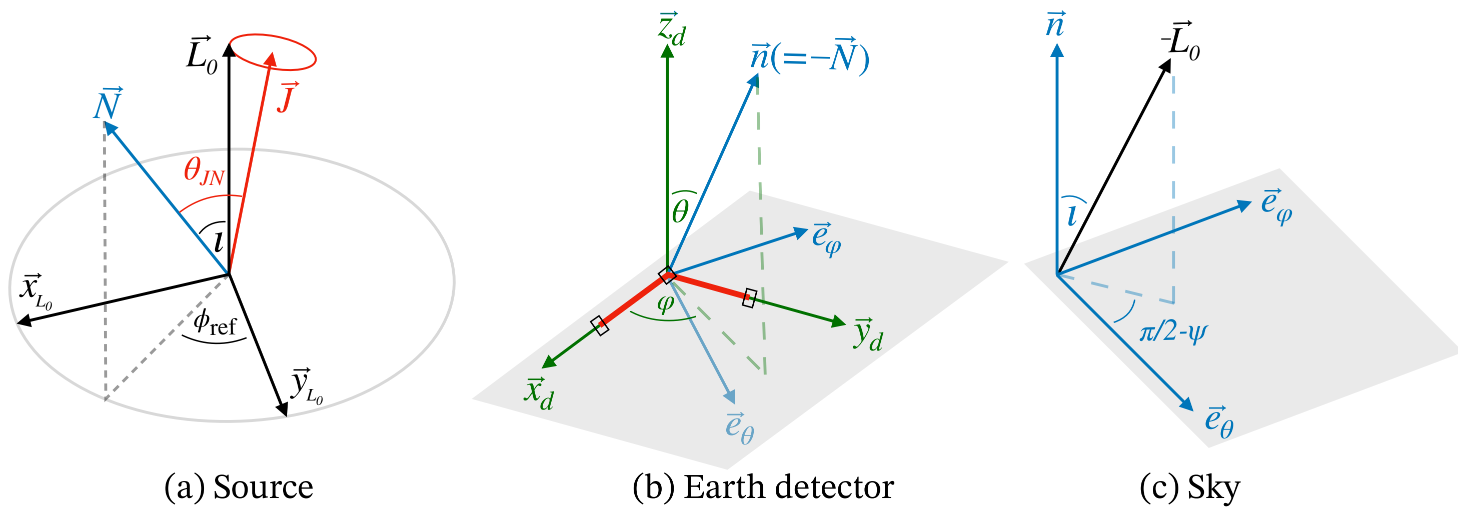
Multiple Images/Events

- Multiple events that are lensed should share the same binary parameters
- Except for Morse phase shifted 22 reference phase $\phi_{\text{ref}} \pm n\pi/2$ and luminosity distance due to magnification
- Search for pairs of events that are Morse phase shift consistent



Finding Events

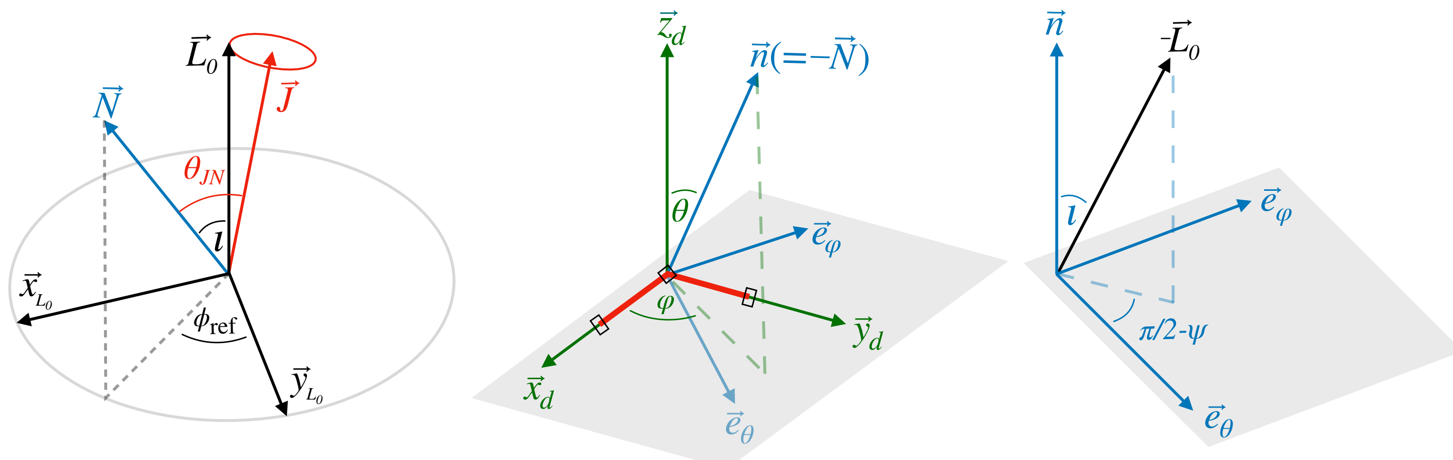
- With 2 to 3 detectors LIGO (L,H), Virgo (V) base parameters are highly degenerate and often multimodal, due again to detector vs source reference frames



- Fast approaches are inefficient at comparing events
- Evidence based approaches are compute-intensive and Jeffreys scale can be very conservative in rejecting lensing hypothesis

PHAZAP Reconstruction

- PHAZAP: reconstruct what the detectors see: phases at the detectors as a function of frequency (see also Roulet et al)

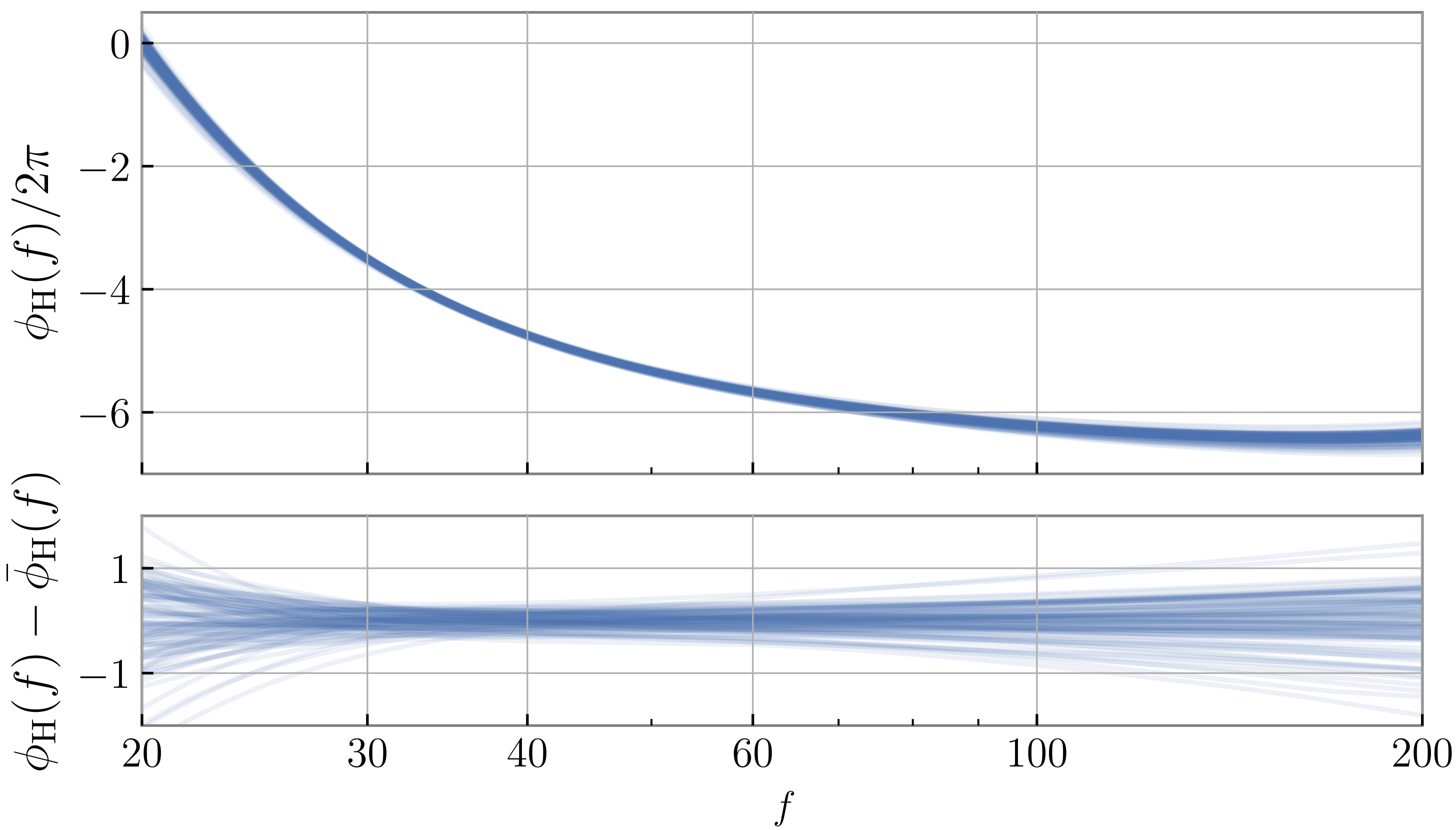


(a) Source (b) HLV detectors (c) Sky

- Requires only postprocessing of standard parameter estimation
- Uses all of information to infer reconstructed parameters, regardless of what was or wasn't measured in detectors, e.g. V parameters when Virgo offline

PHAZAP Phases

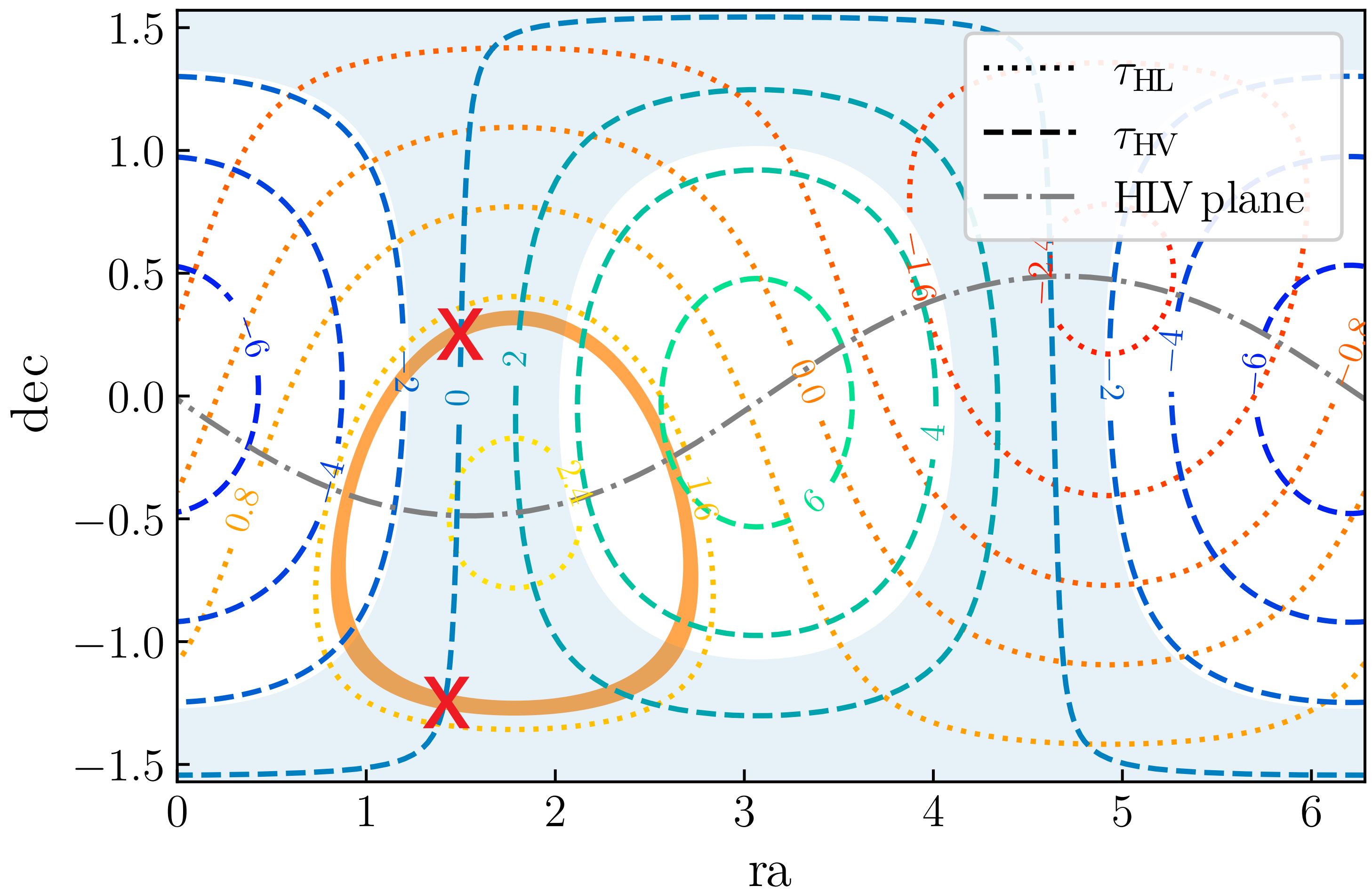
- GW phase evolution at LIGO Hanford for the OG: GW150914



- Best measured at $\sim$ 40Hz not $f_{\rm ref} = 20$Hz and phase difference $\Delta\phi_f = \phi_{100\rm Hz} - \phi_{20\rm Hz}$ better measured than chirp mass

PHAZAP Localization

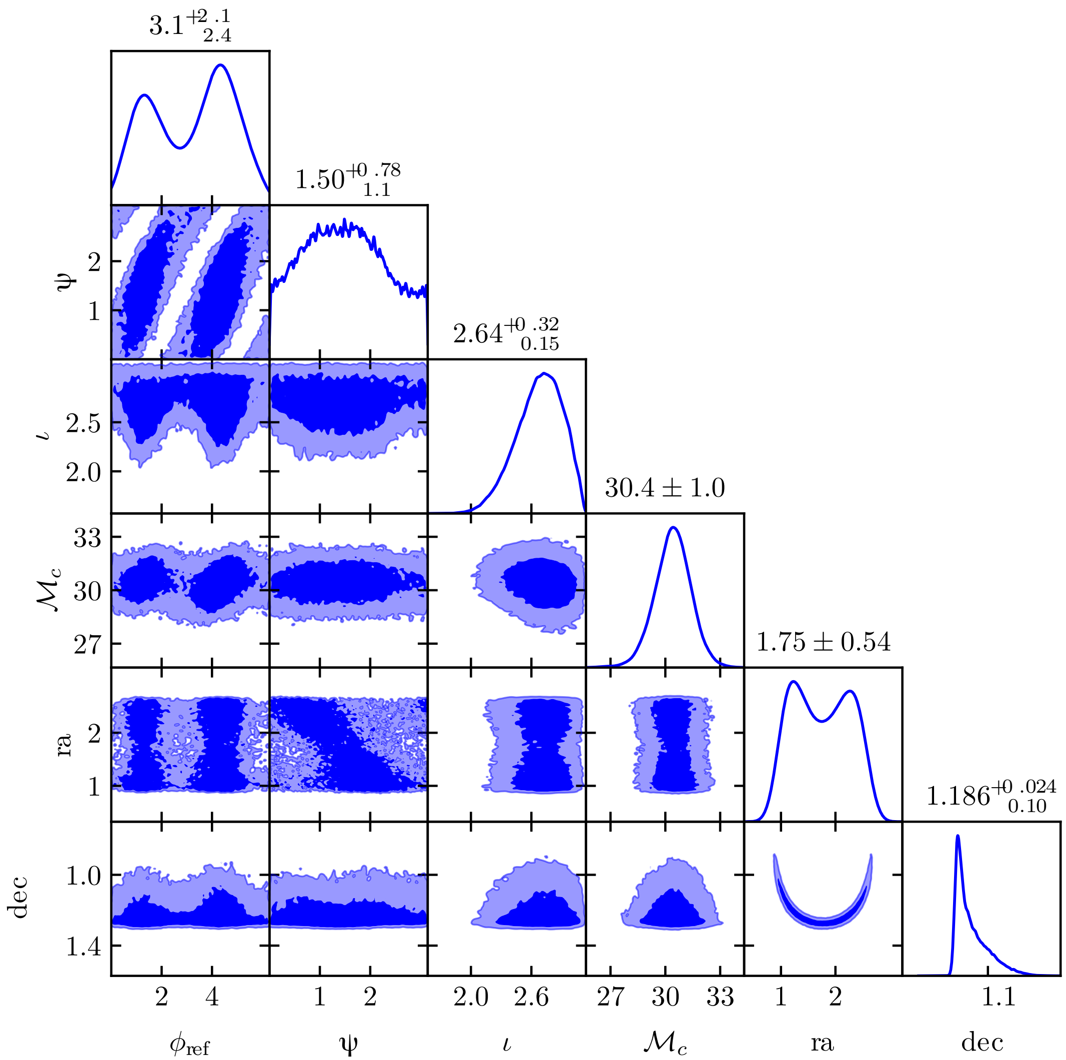
- Time delays (in units of cycles) between detectors, HL and HV



- 3 detectors → 2 rings intersecting: 1 above, 1 below detector plane

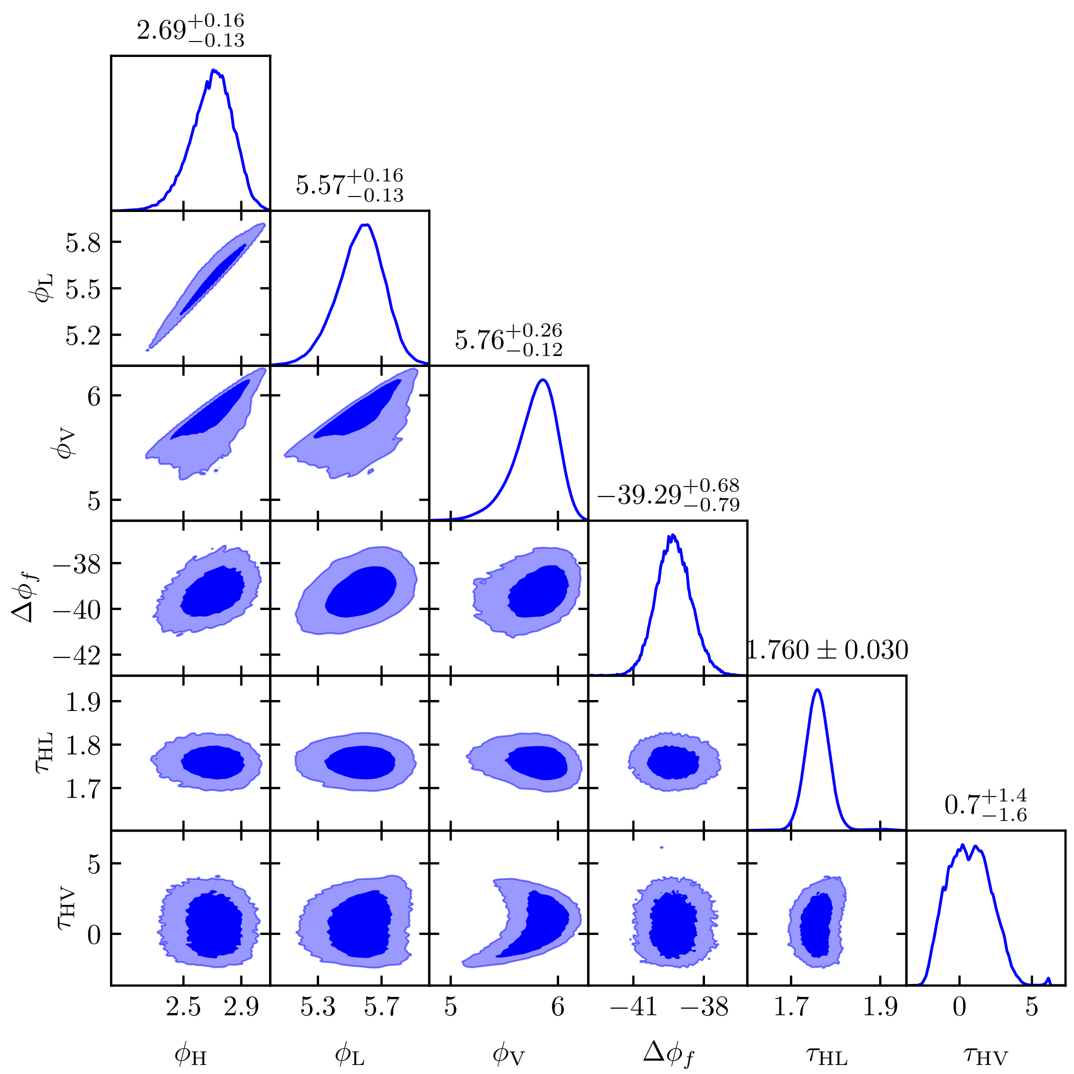
PHAZAP Change of Basis

- Original binary basis (lensing consistency related parameters)



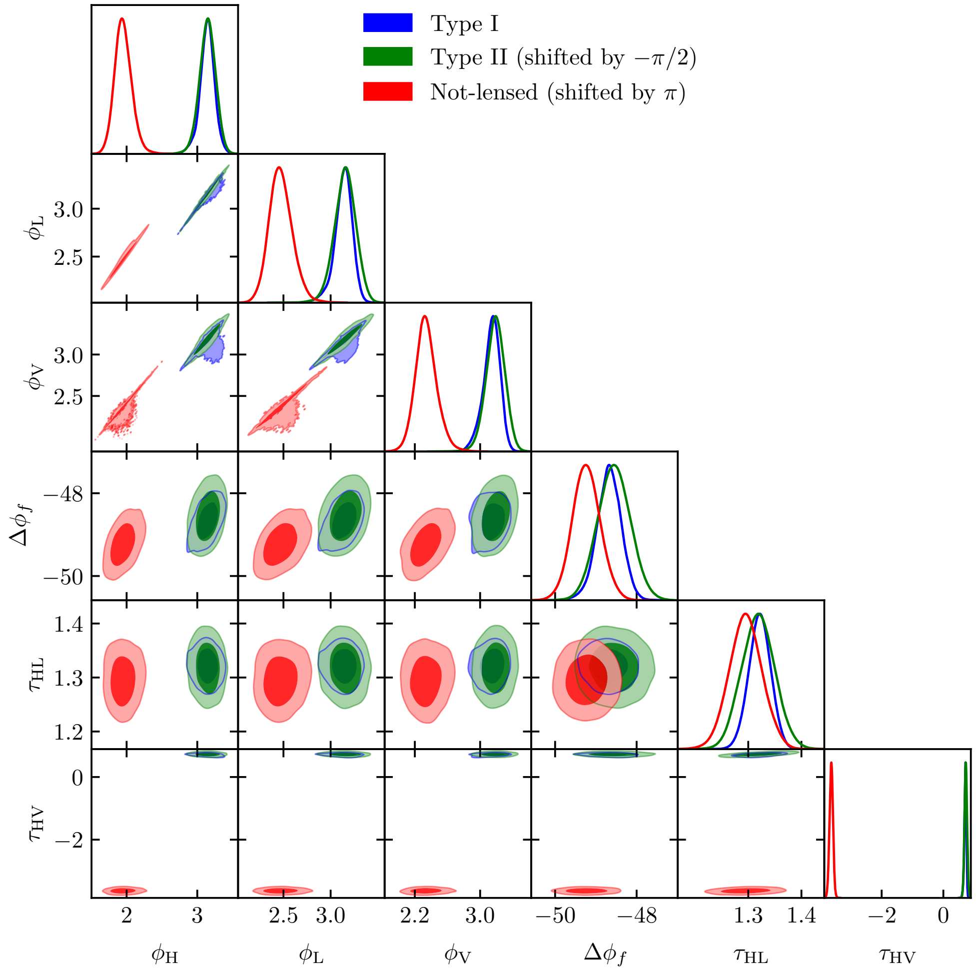
PHAZAP Change of Basis

- PHAZAP basis (more Gaussian except those not detected in V)



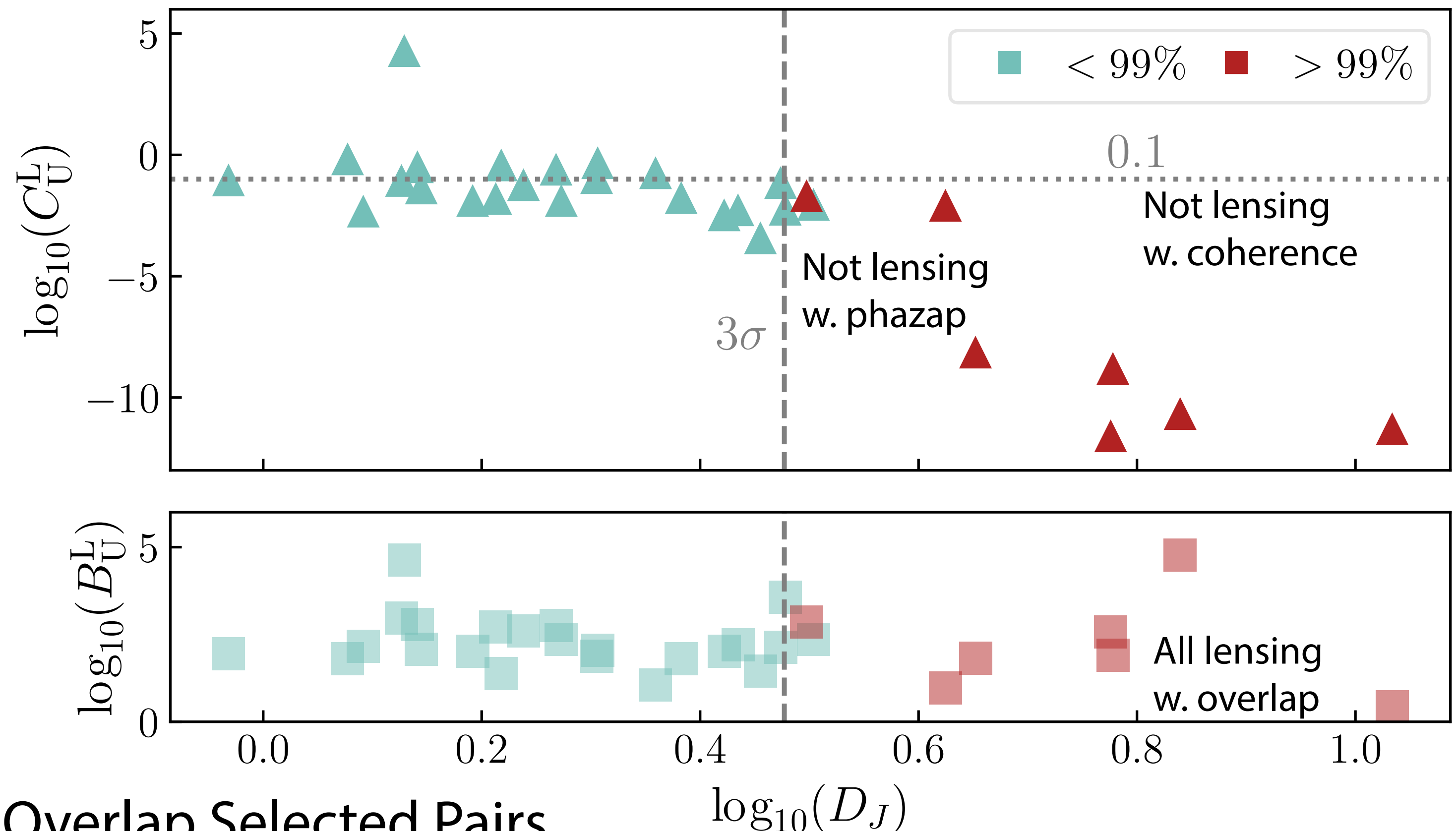
PHAZAP Parameter Difference

- For event pairs, where detectors have rotated with Earth between events, choose a common basis for comparison
- Injected (not)lensed events



PHAZAP on GWTC-3

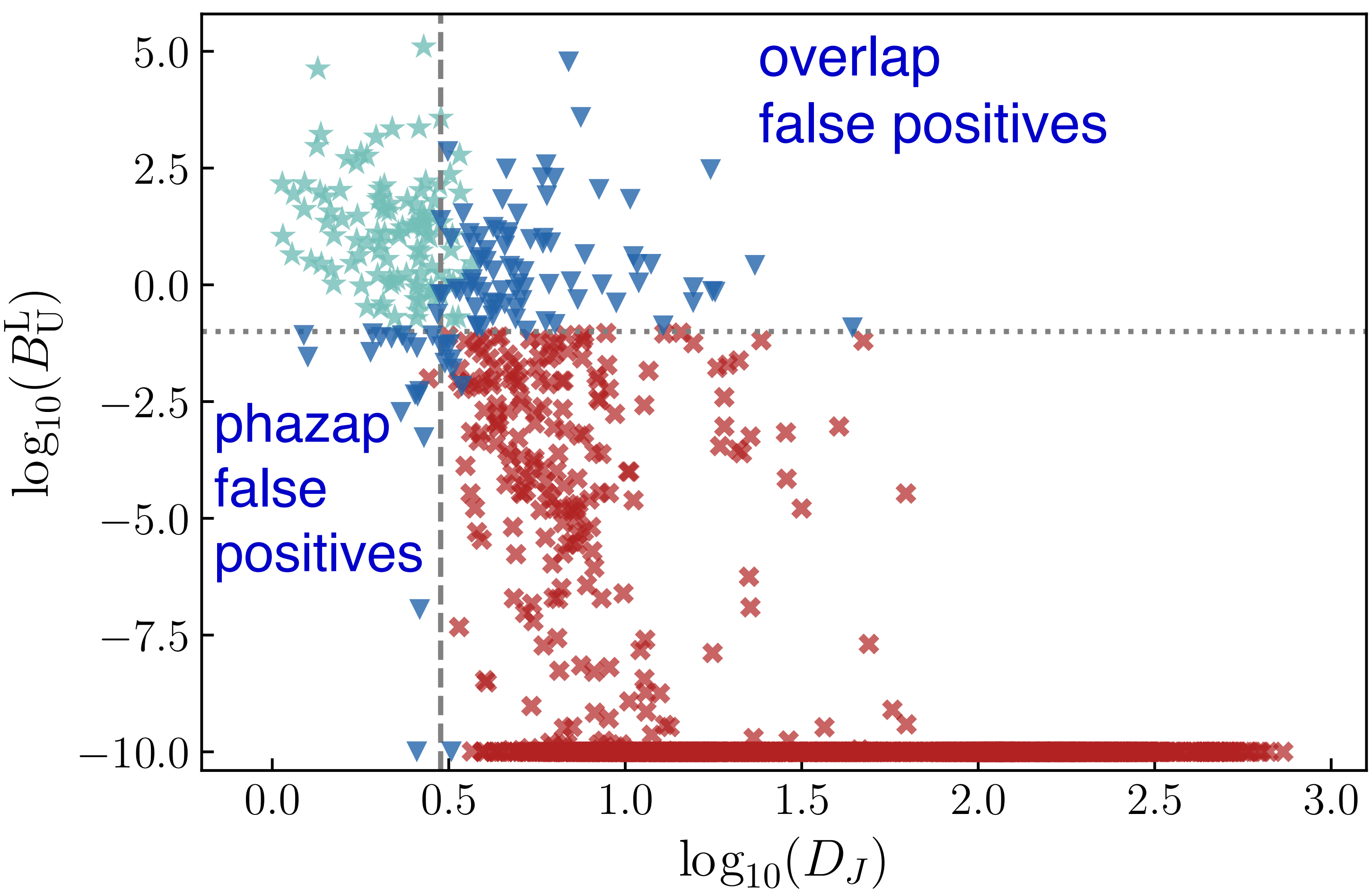
- Candidates based on Gaussianized distance D_J of parameters
- PHAZAP highly correlated with intensive joint PE coherence ratio C_L^U compared with overlap method B_L^U where all selected pairs overlap by definition



Overlap Selected Pairs

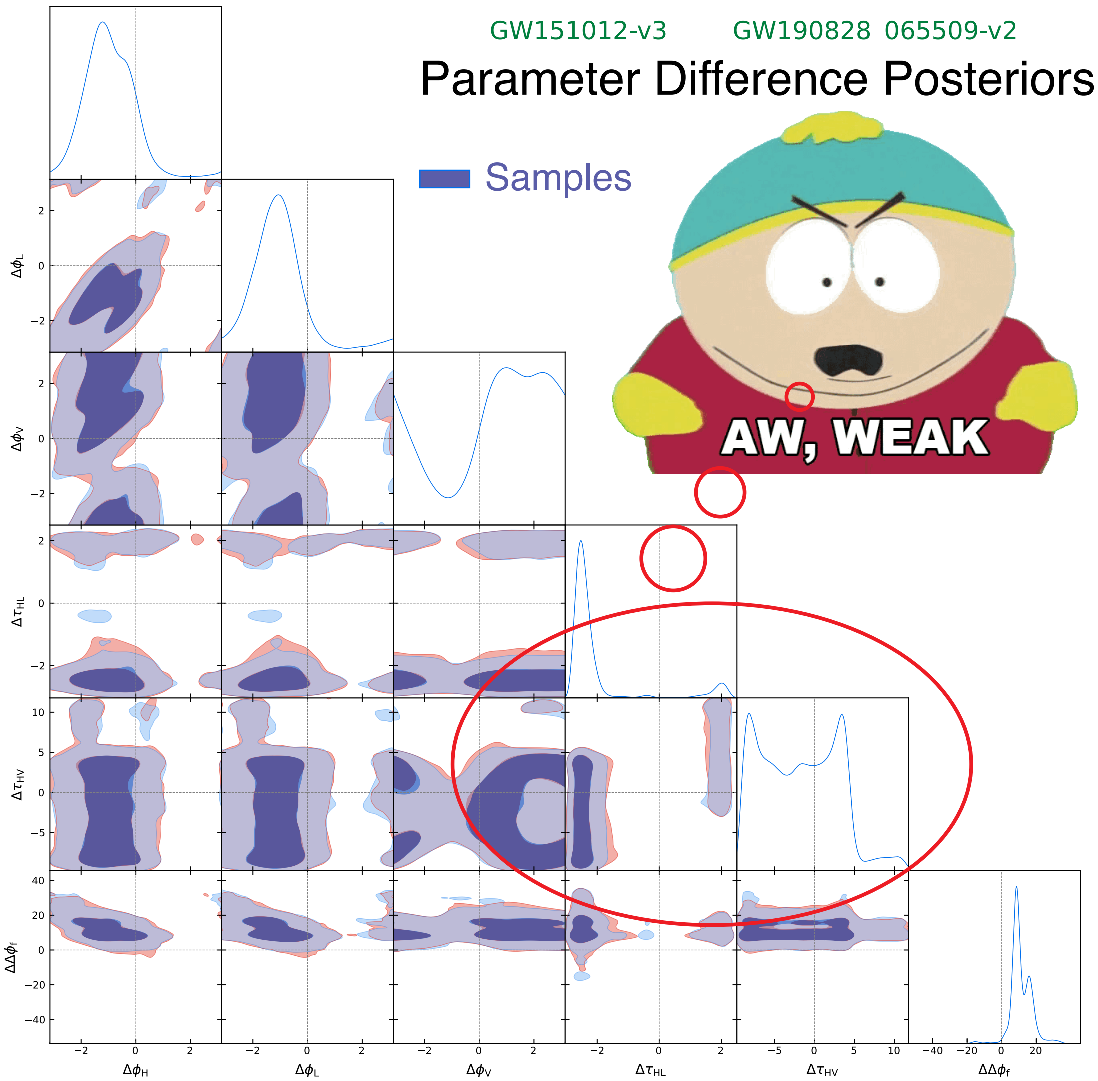
PHAZAP on GWTC-3

- PHAZAP selection efficiently rejects candidates which aren't lensing, compared with overlap



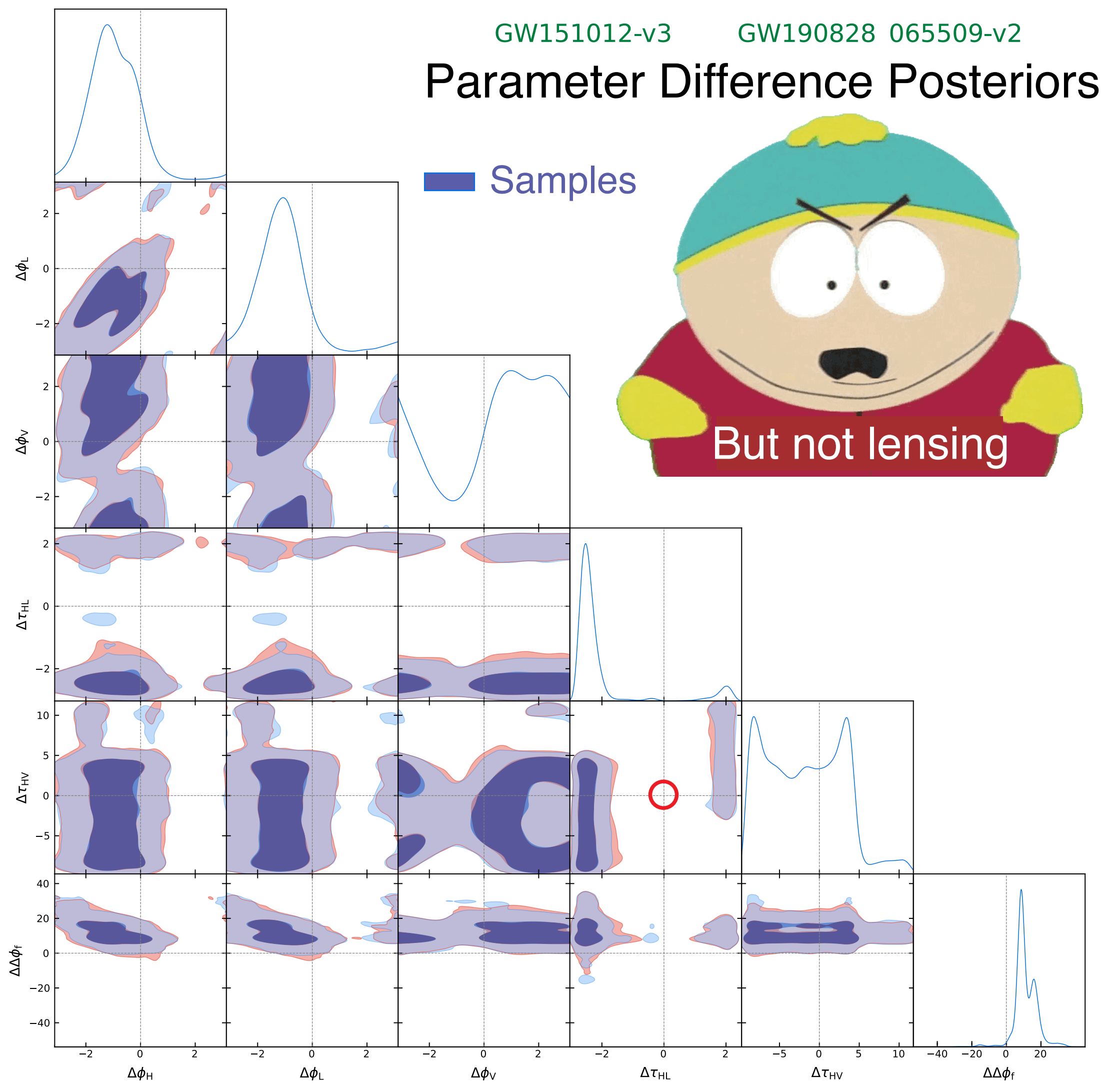
TENSIOMETER

- Most of PHAZAP false positives are due to Gaussianizing poor localization due to weak V(irgo) constraints



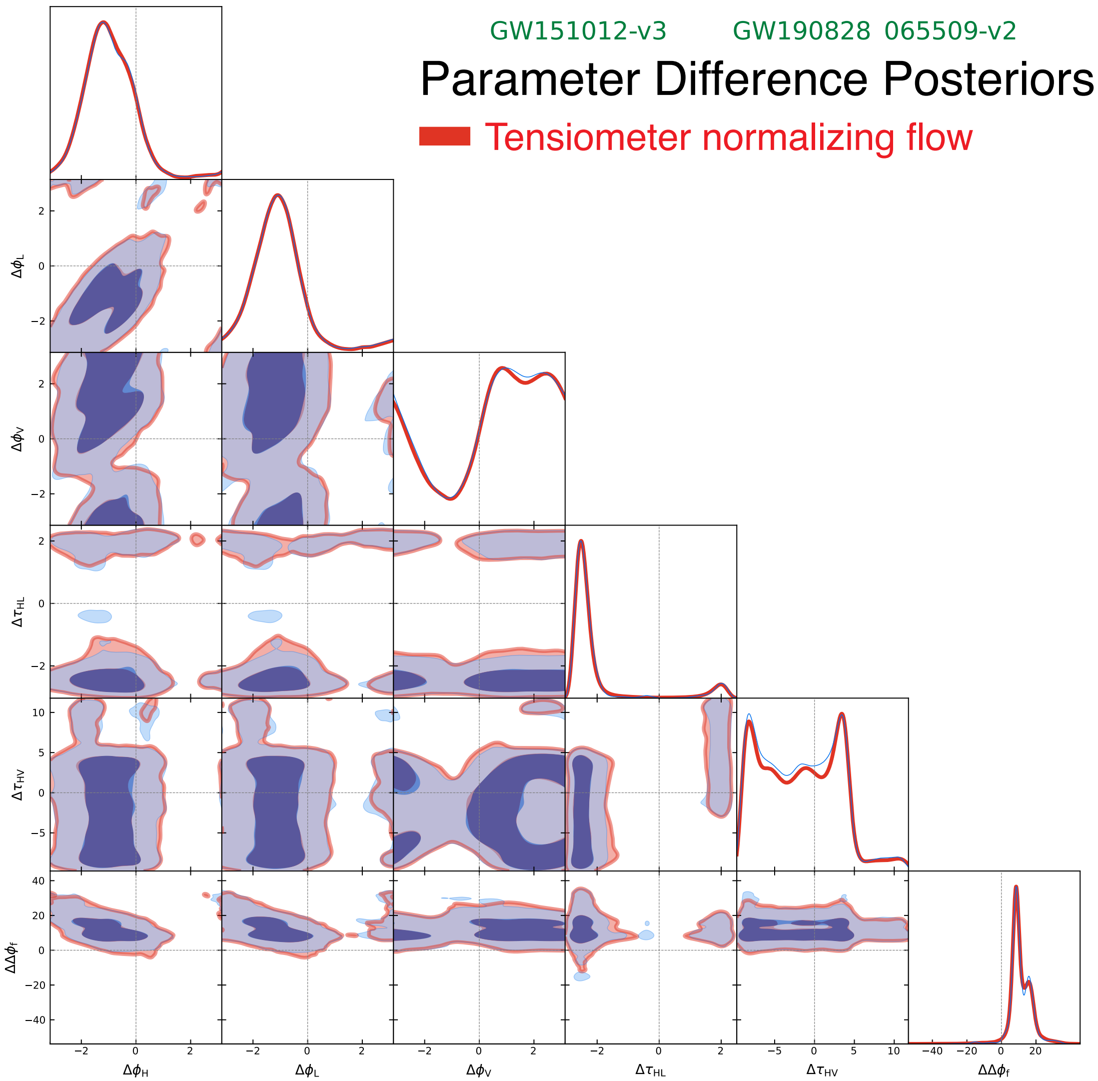
TENSIOMETER

- Lacking V, degeneracy in LIGO HL time delays is broken by other waveform information and rejects lensing



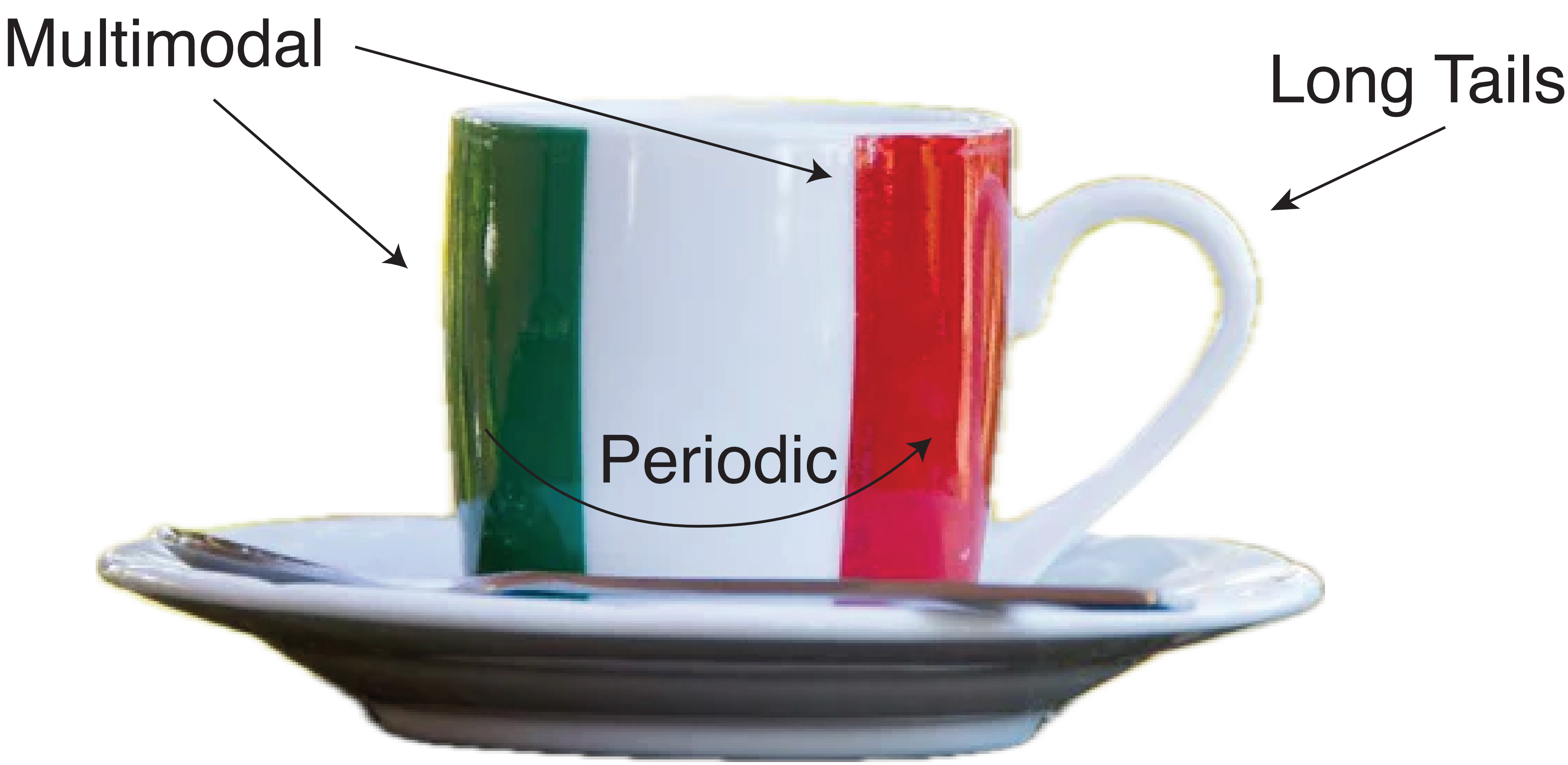
TENSIOMETER

- TENSIOMETER learns difference posterior with normalizing flows, integrates the model to find probability of parameter differences



TENSIOMETER

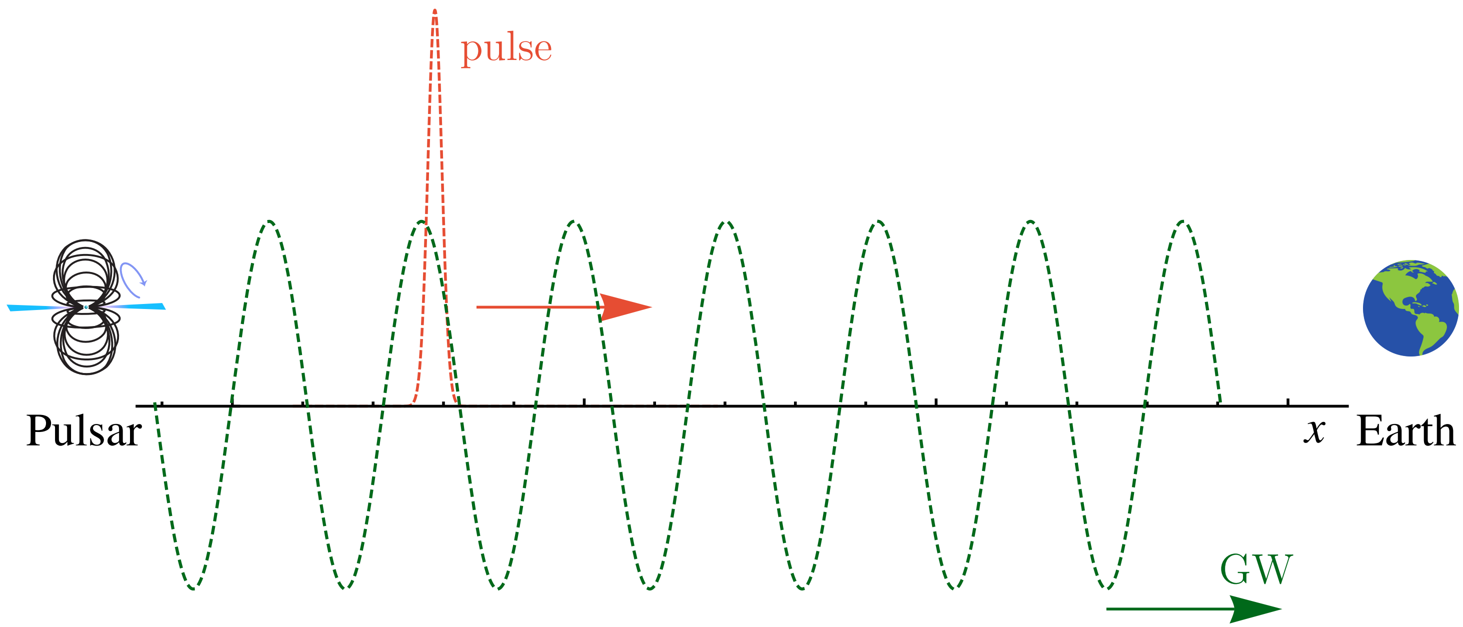
- Ask Giulia and Marco for TENSIOMETER details over an espresso!



https://github.com/mraveri/tensiometer

PTA Redshift

- Monochromatic GW

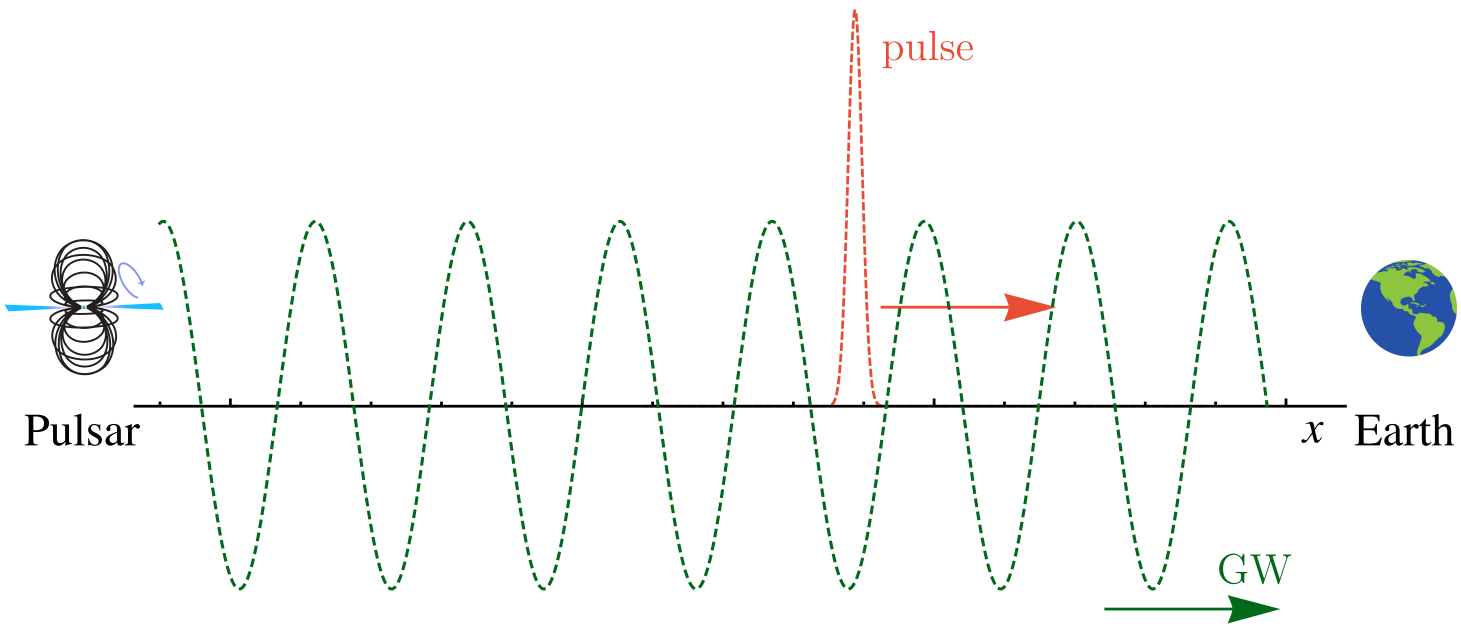


- Pulses experience redshifts through integral of $\dot{h}$ along the path
- But the GW traveling at v_p along $\hat{\mathbf{k}}$ can lead or lag the pulse propagating from the pulsar with $\hat{\mathbf{n}}$ direction

$$v_p t = (\hat{\mathbf{k}} \cdot \hat{\mathbf{n}}) x$$

PTA Redshift

- Monochromatic GW



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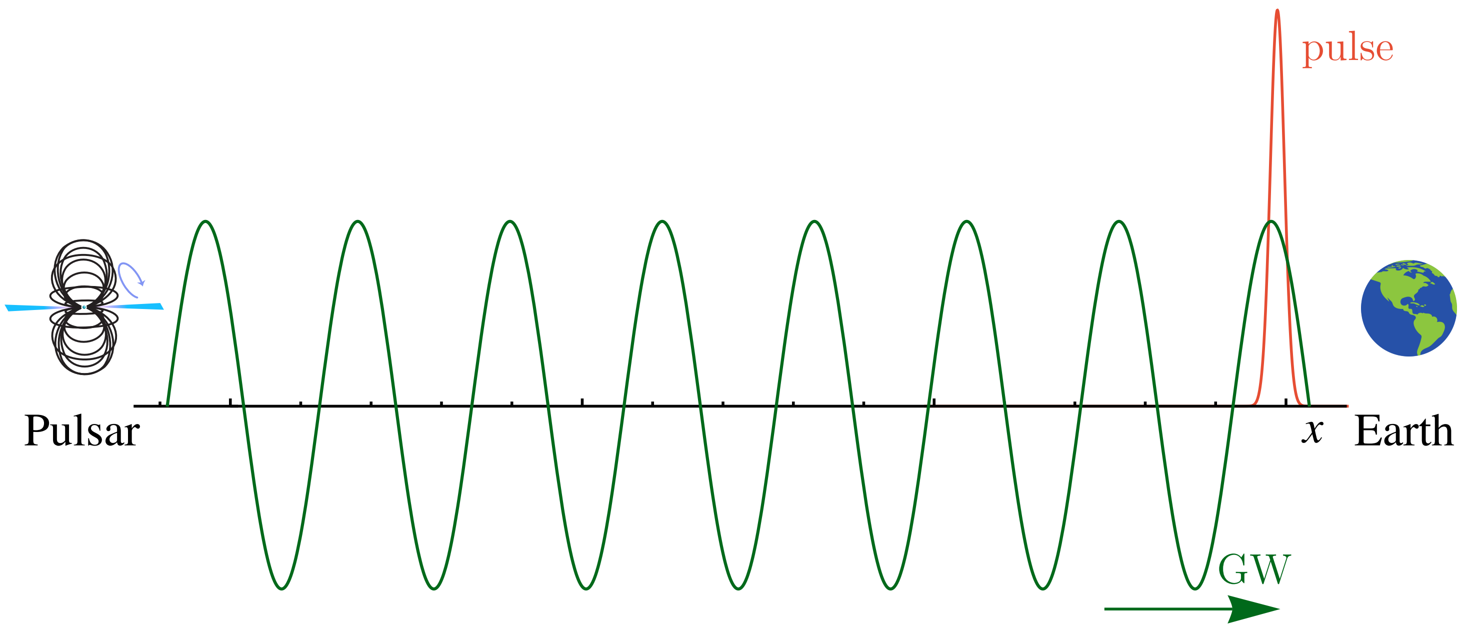

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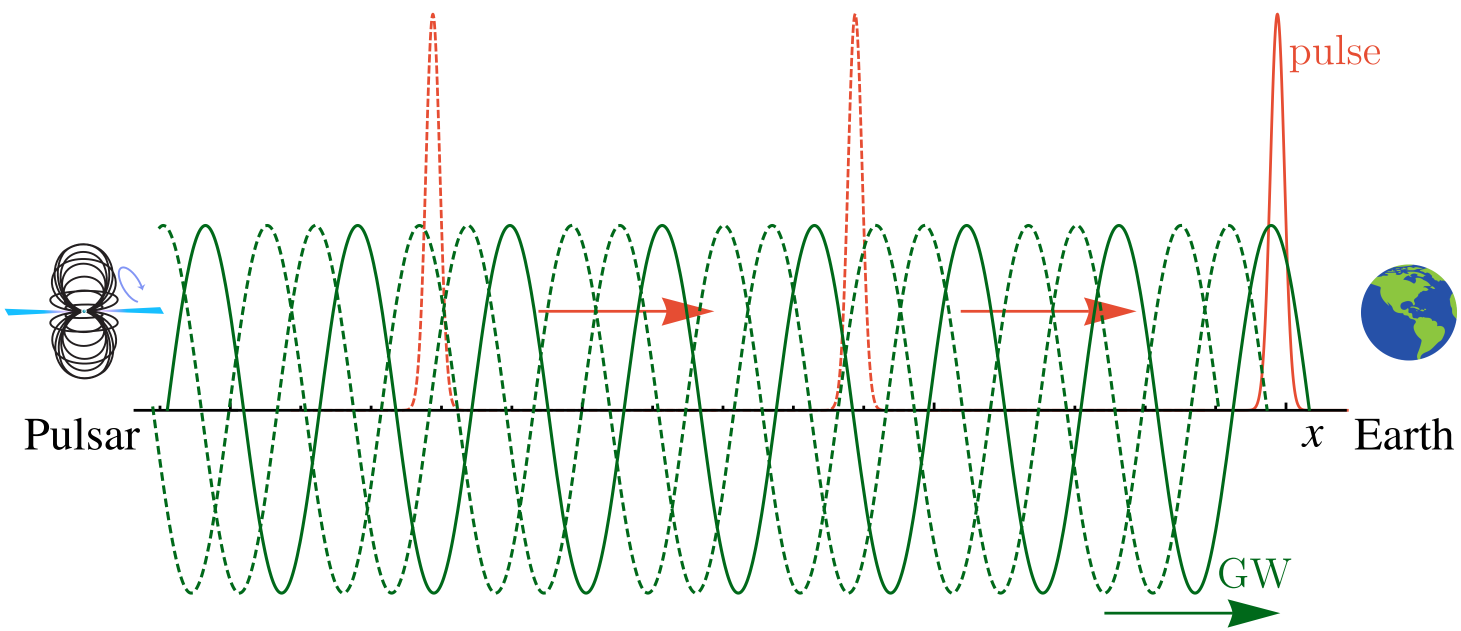


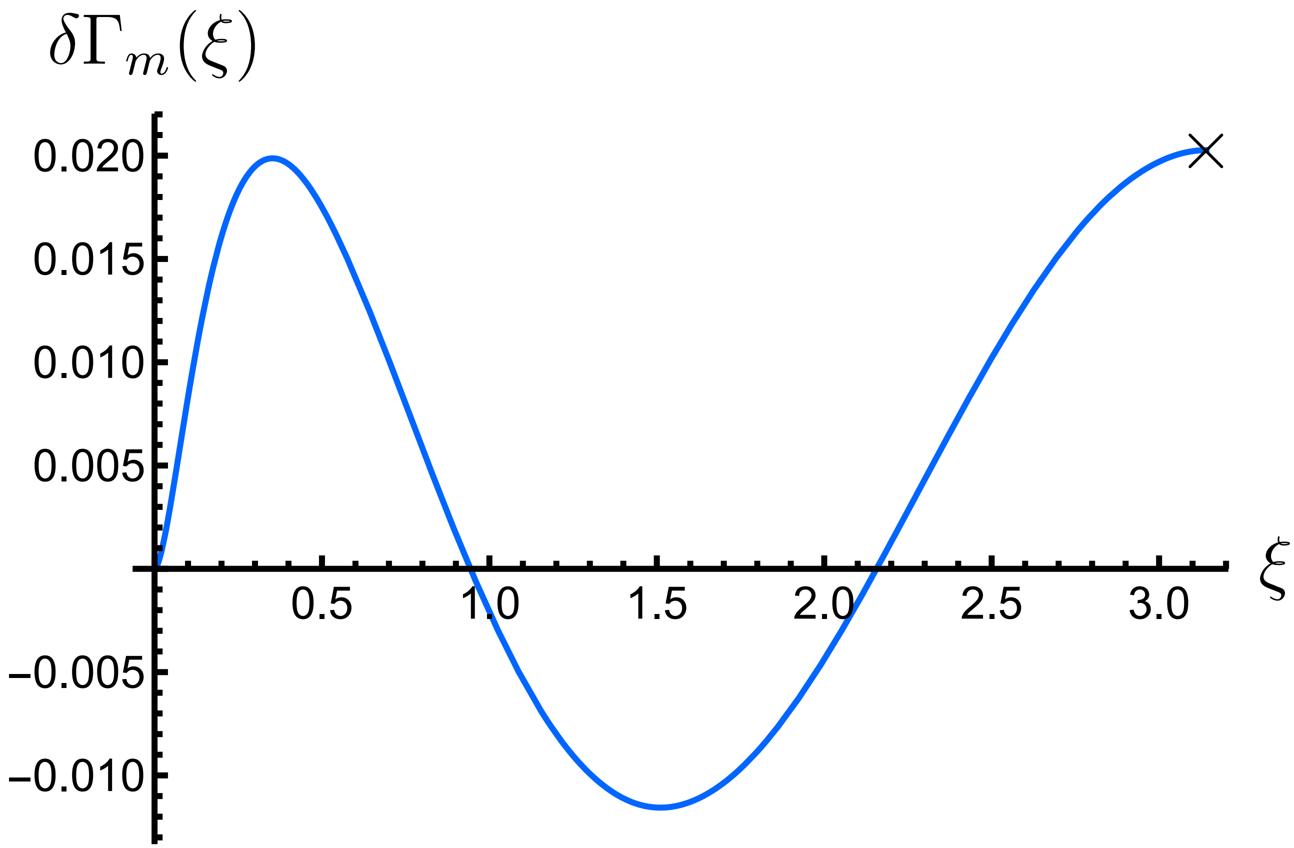
- Integrating a total derivative leaves only a dependence on amplitude and phase of GW at pulsar and earth and

  pulsar direction $\hat{\mathbf{n}}$

  GW phase veloctiy v_p

PTA Angular Correlations

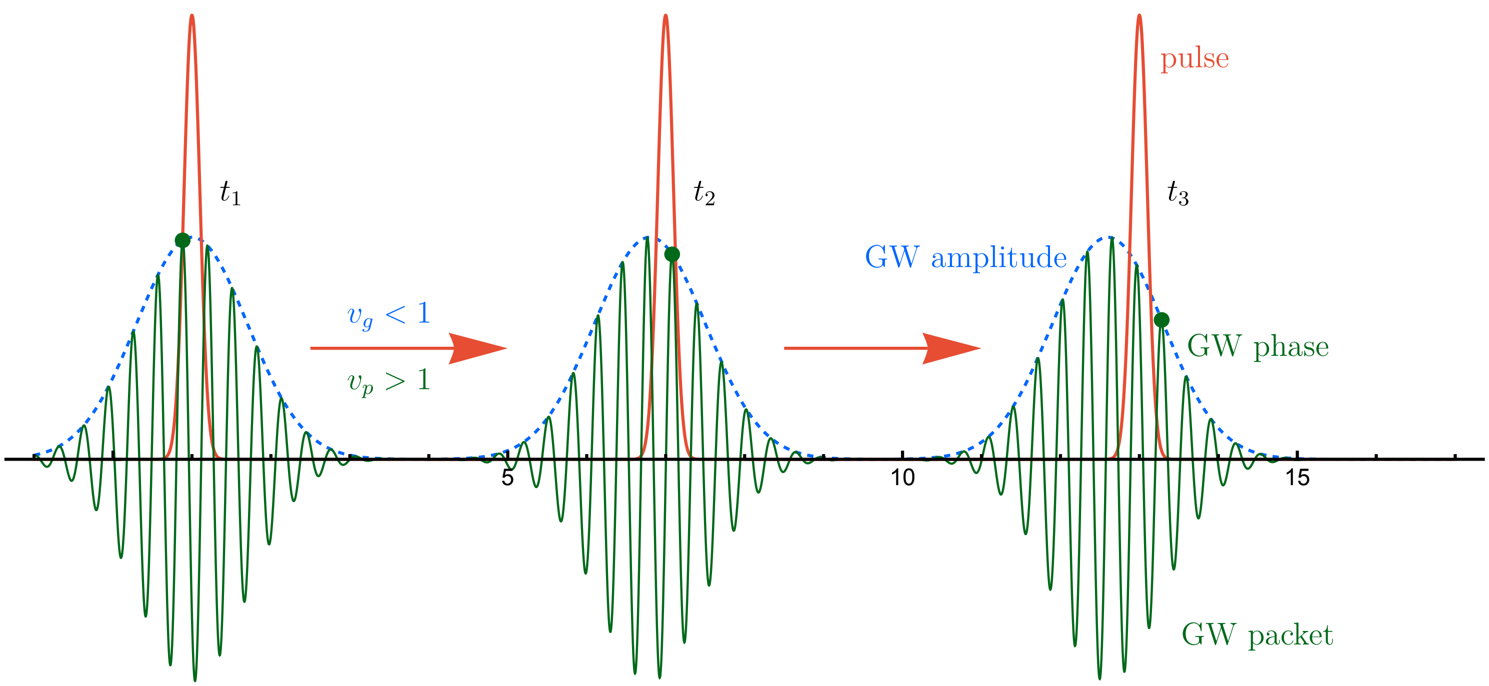
- Generalized Hellings-Down curve Γ_m gives the correlated timing residual between pulsars of different direction $\cos\xi = \hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}}_2$
- Deviation from GR: $v_p - 1 \equiv \epsilon = 0.01$



- More generally $\delta\Gamma_m(\pi) = -(0.6 + 0.57\ln\epsilon)\epsilon$

Unresolved GW Background

- What if background is unresolved sources?
- A real source cannot produce a monochromatic plane wave (that travels at v_p), instead is a wave packet propagating at v_g



where the phase at the peak changes due to v_p

Unresolved GW Background

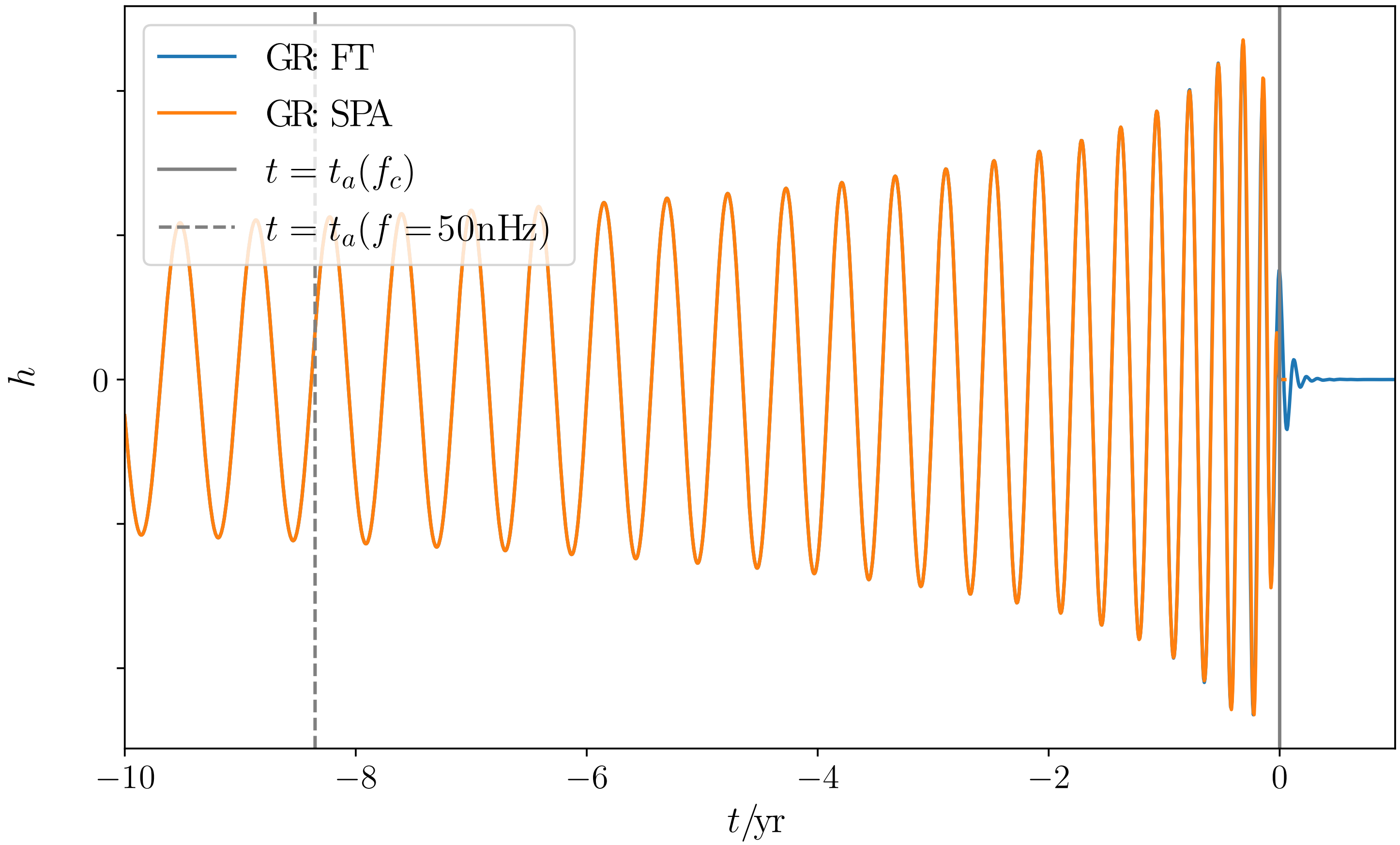
- E.g. if wavepacket remains between pulsar and earth throughout the pulse propagation: no pulsar/Earth term
- Nonetheless, each Fourier component of the wavepacket obeys the monochromatic Γ_m
- Explicitly check that integrating over the wavepacket propagation with the pulse gives same answer as superimposing the Fourier components at pulsar and Earth
- Key: unlike a truly stochastic background, the Fourier modes must be correlated

$$\langle h(f)h(f')\rangle \text{ is not } \propto \delta(f-f')$$

  with arrival frequency determined by group, not phase, velocity v_g
- In principle also changes the correlation of pulsar timing residuals

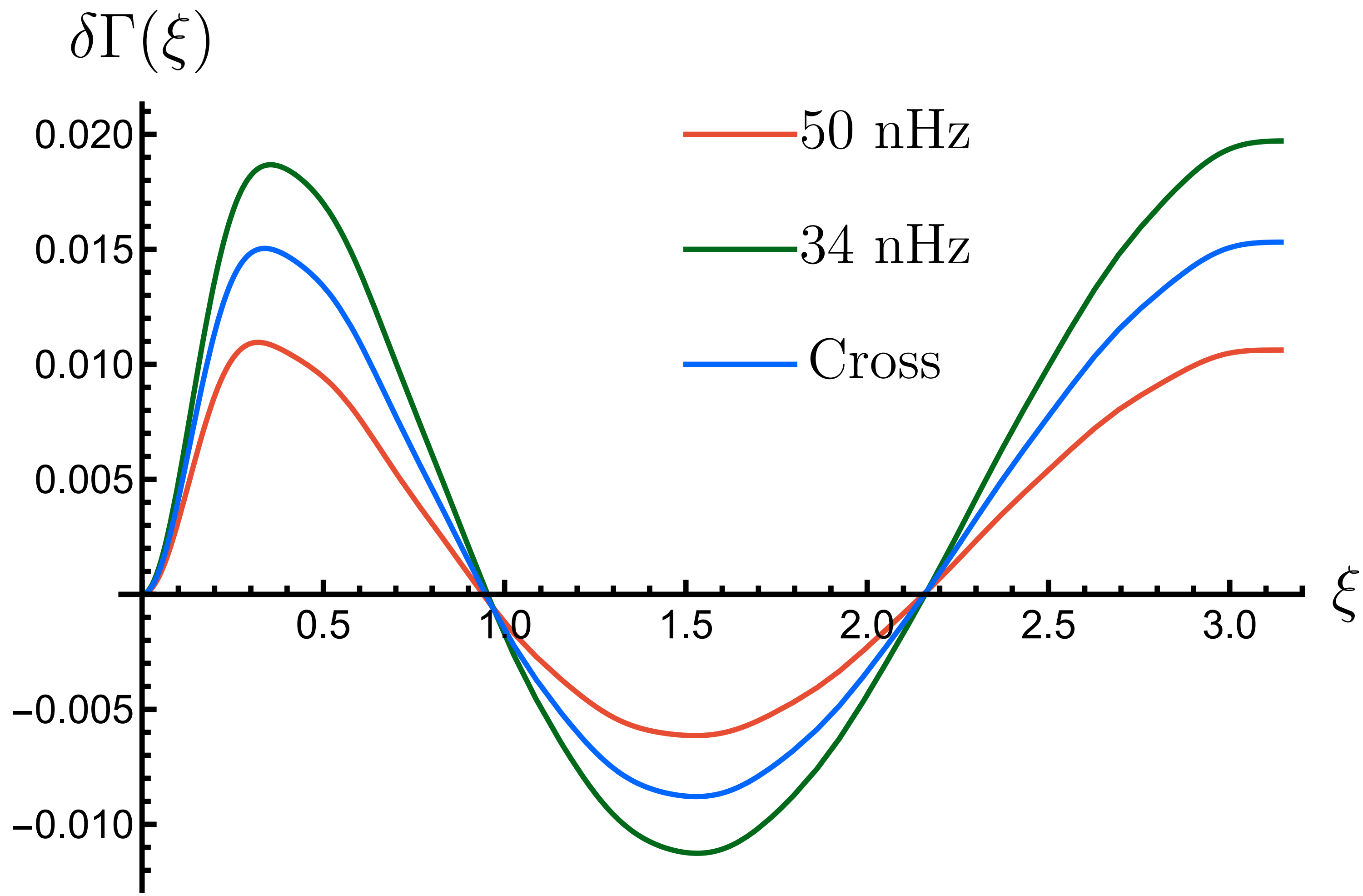
Binary Merger Signal

- Chirp, and more generally frequency content of GW waveform, gives frequency correlation between arrival times



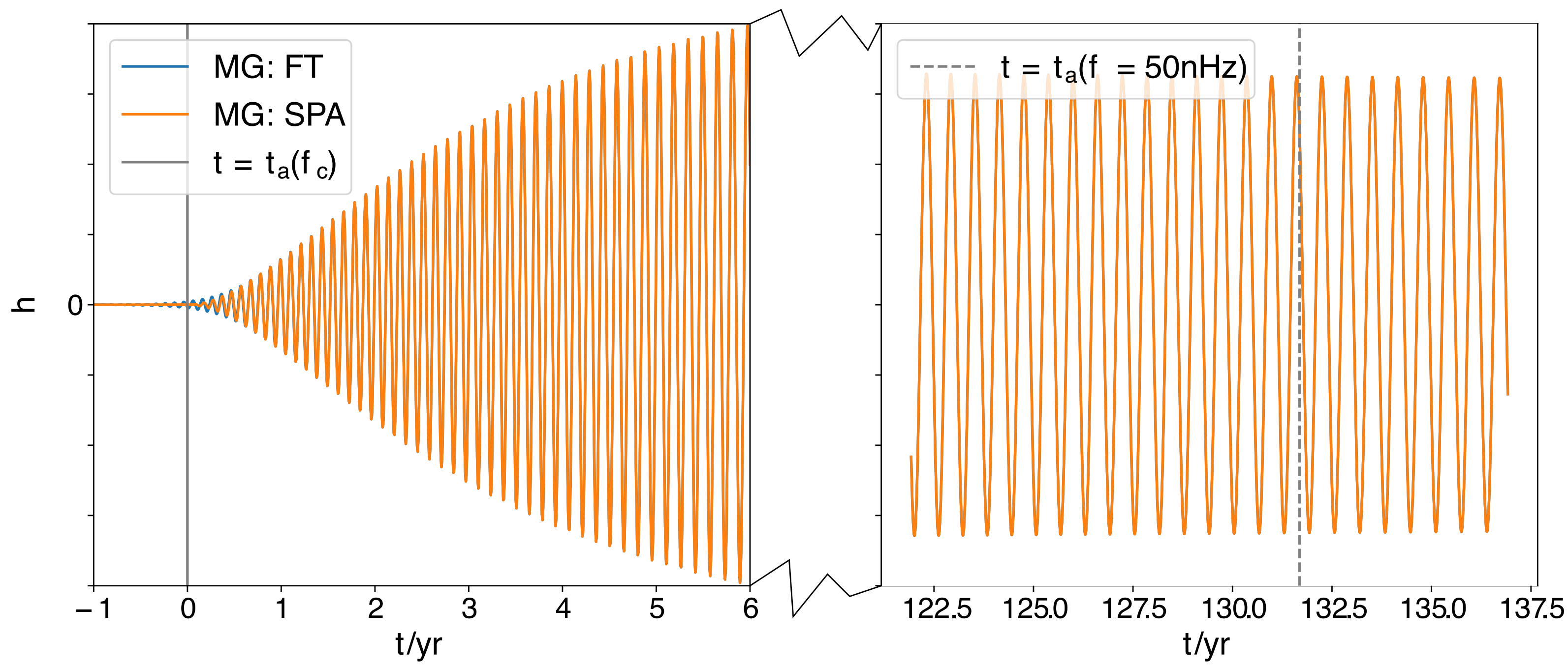
Binary Merger Signal

- Correlated frequencies of unresolved sources (unlike a fully stochastic background) induces PTA correlations with different ORFs



Propagation Time Delay

- But propagation delay from group velocity dispersion between frequencies make event more monochromatic for $\alpha = 0$ mass term



- Waveform distorted: reversed and stretched if group velocity dispersion dominates at GW source large distances
- For $\alpha = 0$ mass term is a catch-22 (mode): when deviation is large, propagation effects make frequency evolution slow

Conclusions

- Propagation and phase effects test
  - Fundamental physics of GW: dispersion relation
  - Gravitational lensing
  - Phase velocity of stochastic GWB in PTA
  - In principle, group velocity for unresolved GW sources
- PHAZAP: useful tool for reconstructing phase information from PE
  - Fast postprocessing of preexisting PE
  - Choose detector phases optimally for single event
  - Common nearly optimal basis for event pairs, echoes
  - Fast Gaussianized rejection of inconsistent pairs
- TENSIOMETER normalizing flows for quantifying pair probabilities for highly non-Gaussian and multimodal distributions