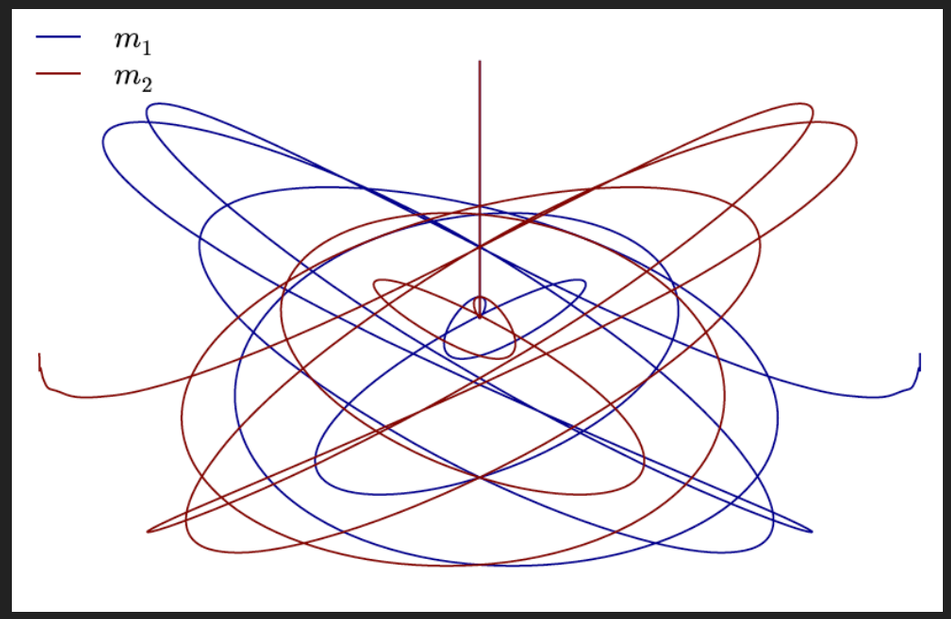
The ASFAE's research projects acknowledge the financial support from the MCIU with funding from the European Union NextGenerationEU and Generalitat Valenciana.



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ASFAE 2024 WORKSHOP – ESCUELA POLITÉCNICA SUPERIOR (EPS) UNIVERSITY OF ALICANTE

TESTING MIRROR SYMMETRY IN THE UNIVERSE WITH LIGO-VIRGO BLACK-HOLE MERGERS

del Río, Sanchis-Gual, Mewes, Agullo, Font, Navarro-Salas (PRL2020); Sanchis-Gual, del Río (PRD2023) Bustillo, del Rio, Sanchis-Gual, et al. (2024) *arXiv preprint arXiv:2402.09861*.

MOTIVATION

Agullo, I., Del Rio, A., & Navarro-Salas, J. (2017). Electromagnetic duality anomaly in curved spacetimes. *Physical review letters*, *118*(11), 111301. del Rio, A. (2021). Chiral anomalies induced by gravitational waves. *Physical Review D*, *104*(6), 065012.

- **Source-free Maxwell action is invariant** under electric-magnetic duality rotations in arbitrary spacetimes.
- **Conserved classical Noether charge**: in the **classical theory** this **symmetry guarantees that the circularly polarized state of electromagnetic waves** remains **constant**.
- Then, one could expect that, in **any dynamical gravitational field, photons** should be **created in pairs of opposite helicity**.

MOTIVATION

Agullo, I., Del Rio, A., & Navarro-Salas, J. (2017). Electromagnetic duality anomaly in curved spacetimes. *Physical review letters*, *118*(11), 111301. del Rio, A. (2021). Chiral anomalies induced by gravitational waves. *Physical Review D*, *104*(6), 065012.

- However, it was found that this **conservation law is broken at the quantum level in the presence of a background classical gravitational field** with a nontrivial **Chern-Pontryagin invariant**.

Chern-Pontryagin invariant.

$$\langle Q_{\mathcal{J}^+} \rangle - \langle Q_{\mathcal{J}^-} \rangle \sim \hbar \int_M \mathrm{Tr}\, R \wedge R \sim \hbar \int_M d^4V\, R_{abcd}{}^{\star} R^{abcd}$$

- The **net polarization of the quantum electromagnetic field** is **not necessarily conserved**.
- A **flux of circularly polarized photons** can be emitted.

THEORETICAL BACKGROUND

Agullo, I., Del Rio, A., & Navarro-Salas, J. (2017). Electromagnetic duality anomaly in curved spacetimes. *Physical review letters*, *118*(11), 111301.
del Rio, A. (2021). Chiral anomalies induced by gravitational waves. *Physical Review D*, *104*(6), 065012.

- Asymptotically flat, stationary spacetimes (Kerr-Newman): 0

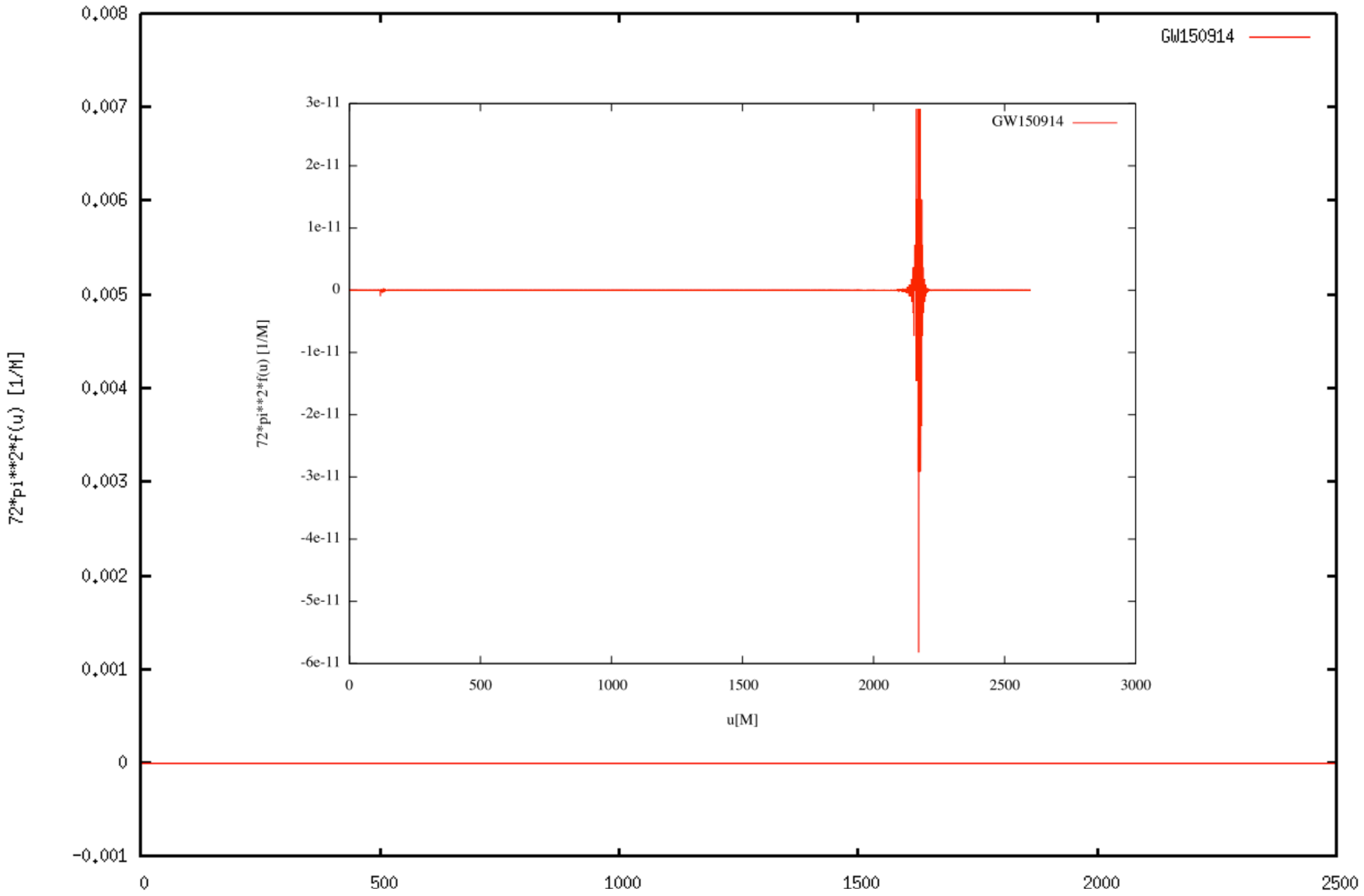
Dynamical spacetimes

- We can use GWs to identify the relevant systems:

$$\langle Q_5(\text{ scri }+)\rangle - \langle Q_5(scri-)\rangle = \hbar \int_0^\infty \frac{d\omega\omega^3}{24\pi^3} \sum_{\ell m} \left[\left| h_+^{\ell m}(\omega) + i h_\times^{\ell m}(\omega) \right|^2 - \left| h_+^{\ell m}(\omega) - i h_\times^{\ell m}(\omega) \right|^2 \right]$$

$$\frac{-1}{96\pi^2} \int_M d^4x \sqrt{-g} R_{abcd} {}^\star R^{abcd} = \int_{-\infty}^{\infty} du f(u) \equiv \Delta Q_{\mathcal{J}^+},$$

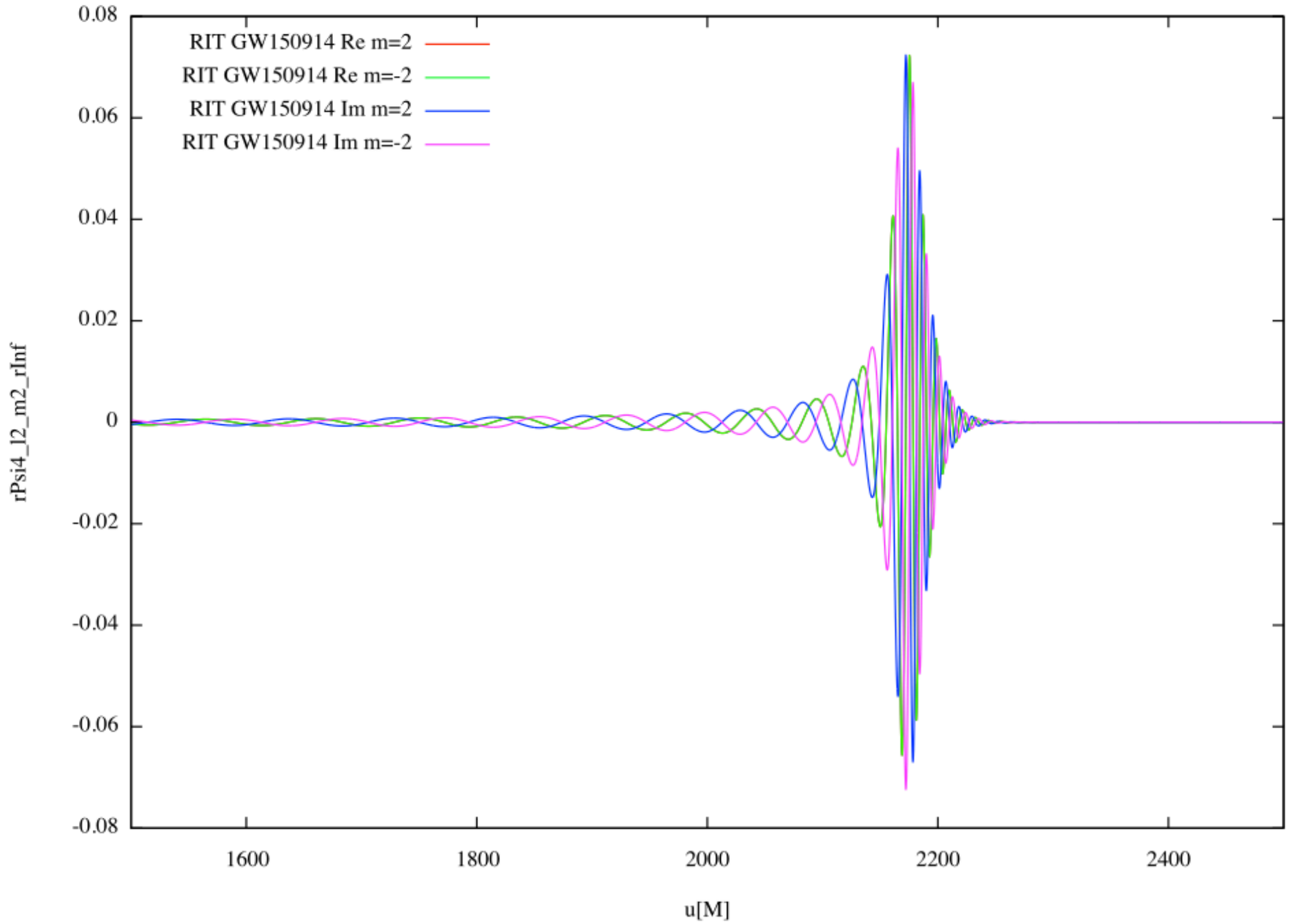
$$f(u) = \frac{1}{72\pi^2} \int_{-\infty}^{u} du' \sum_{\ell m} \text{Im} \left[\Psi^0_{4,\ell m}(u) \bar{\Psi}^0_{4,\ell m}(u') \right].$$



GW150914

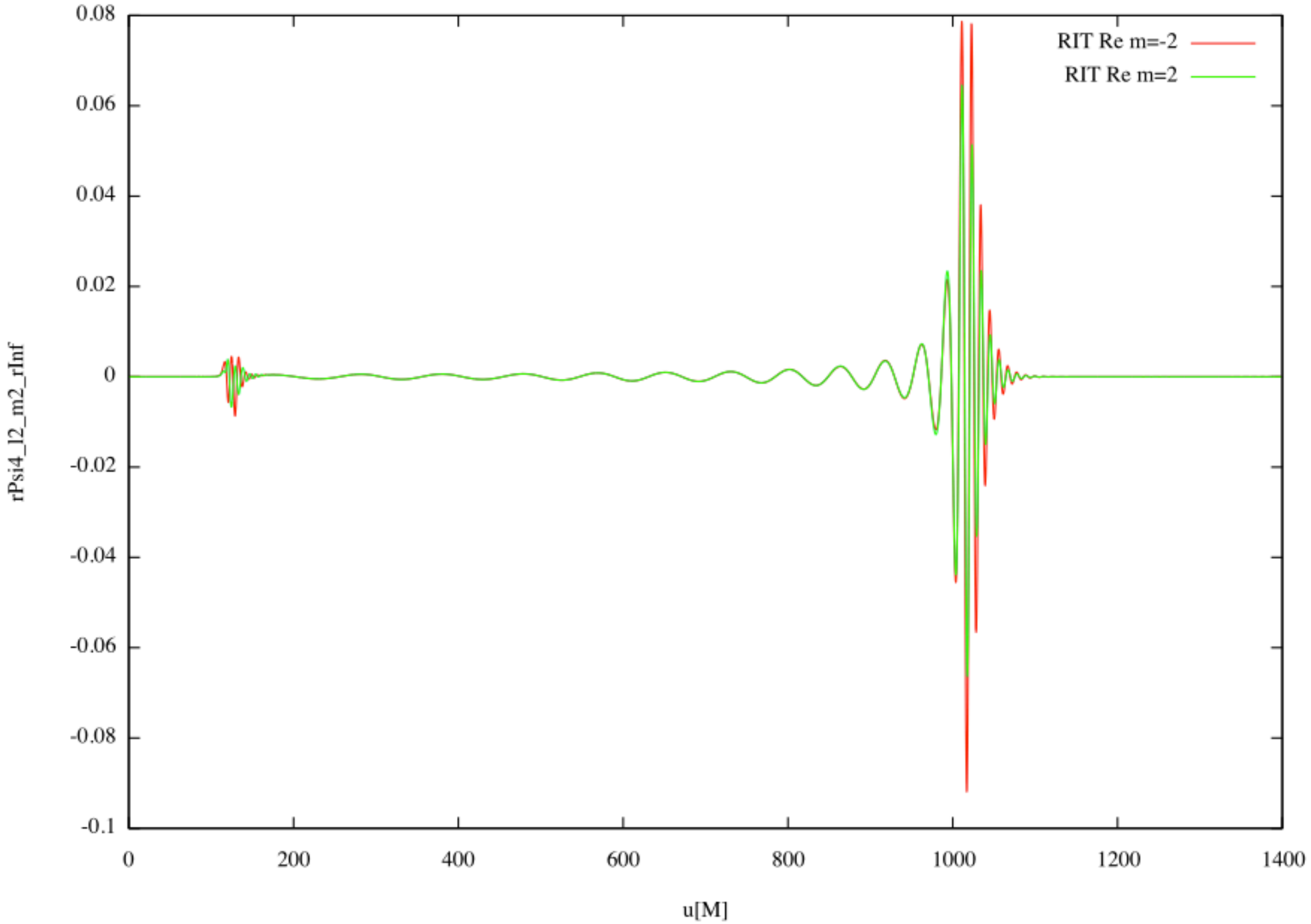
$$f(u) = \frac{1}{72\pi^2} \int_{-\infty}^{u} du' \sum_{\ell m} \mathrm{Im}\left[\Psi^0_{4,\ell m}(u)\bar{\Psi}^0_{4,\ell m}(u')\right]$$

GW150914



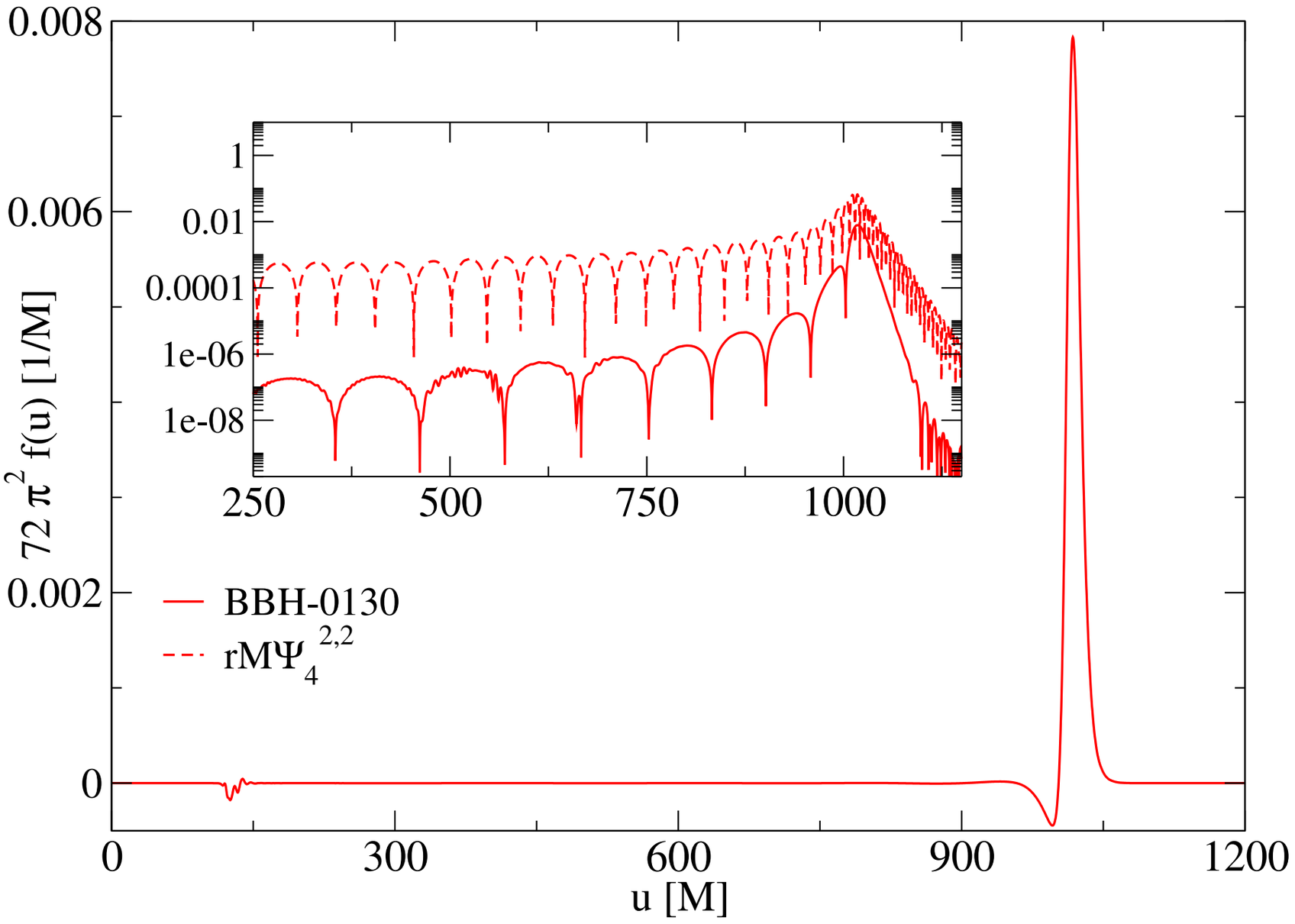
$$f(u) = \frac{1}{72\pi^2} \int_{-\infty}^{u} du' \sum_{\ell m} \mathrm{Im}\left[\Psi^0_{4,\ell m}(u)\bar{\Psi}^0_{4,\ell m}(u')\right]$$

RIT CATALOGUE



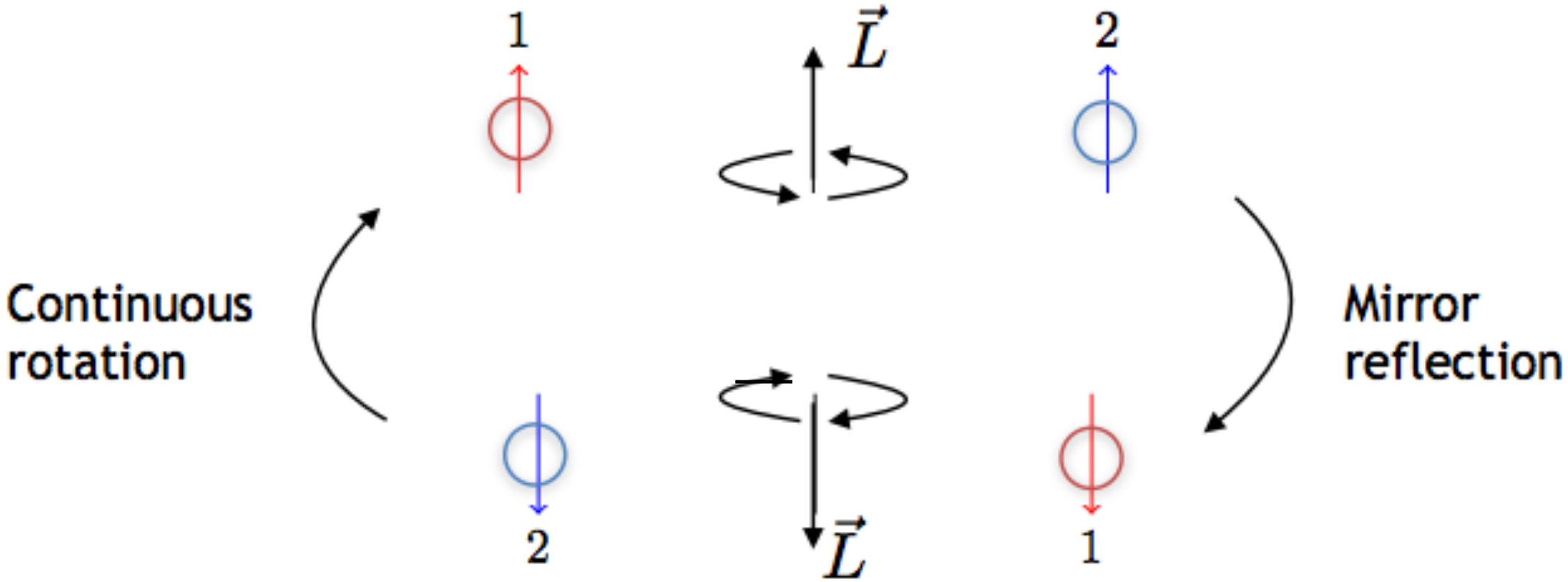
RIT CATALOGUE

- Which ones? Precessing BBHs! **circularly polarized GWs**



$$f(u) = \frac{1}{72\pi^2} \int_{-\infty}^{u} du' \sum_{\ell m} \mathrm{Im}\left[\Psi^0_{4,\ell m}(u)\bar{\Psi}^0_{4,\ell m}(u')\right]$$

MIRROR SYMMETRY

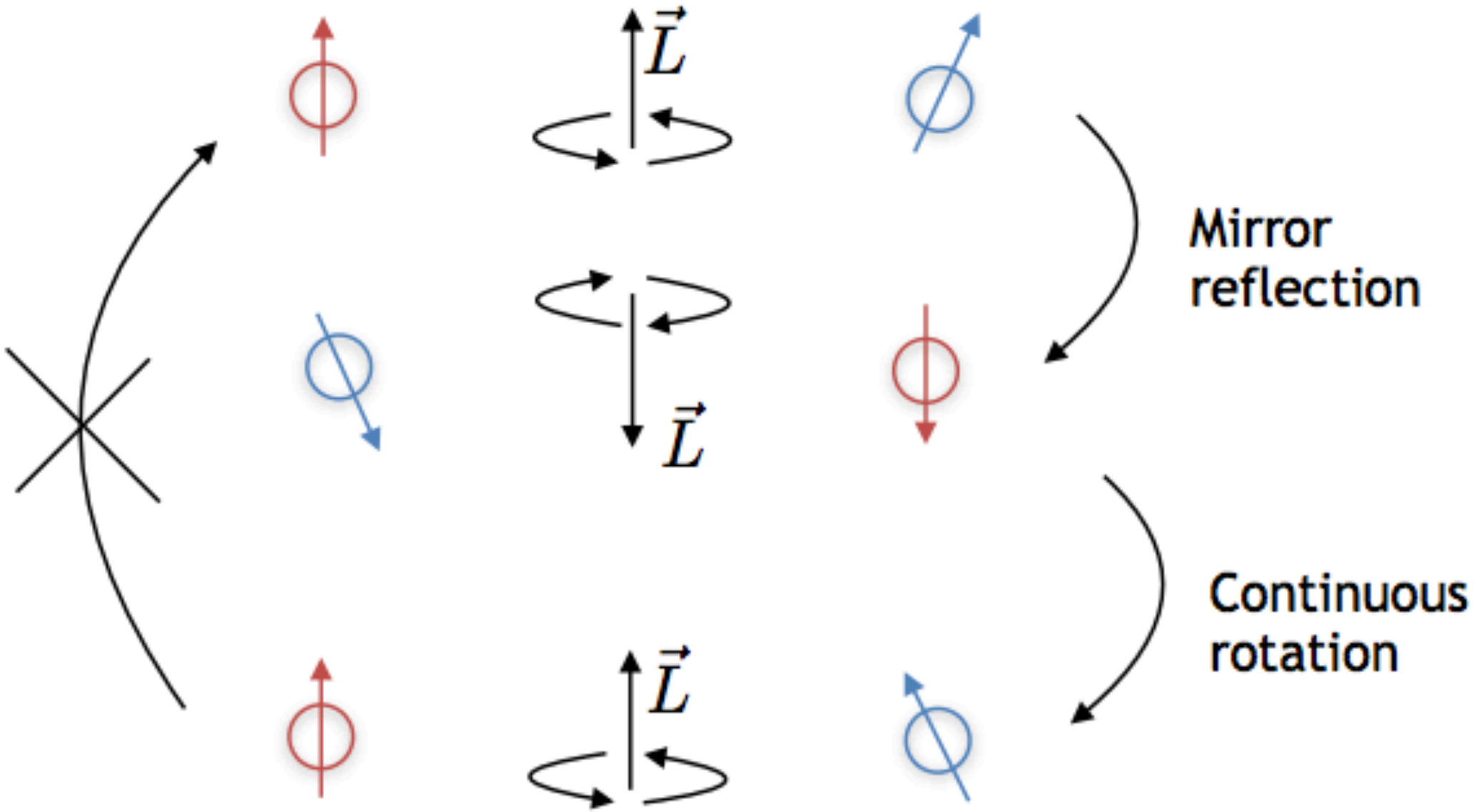


The direction of the pseudovector is changed if we change the handedness of the coordinate system. Typical vectors are momentum, coordinate, electric field etc. Angular momentum, spin, magnetic field etc. are pseudovectors.

MIRROR SYMMETRY

- The **Chern-Pontryagin invariant** is a pseudo-scalar.
- It flips sign under a reflection **I** of the metric (improper rotation) and remains invariant under a proper rotation **R** of the metric, namely **F[(R∘I)gab] = −F[gab]**.
- If the metric of a binary system is invariant under a mirror transformation with respect to some coordinate plane, then one also has **F[(R ∘ I)gab] = F[gab].**
- **T**herefore **F[gab] = 0** in these cases.

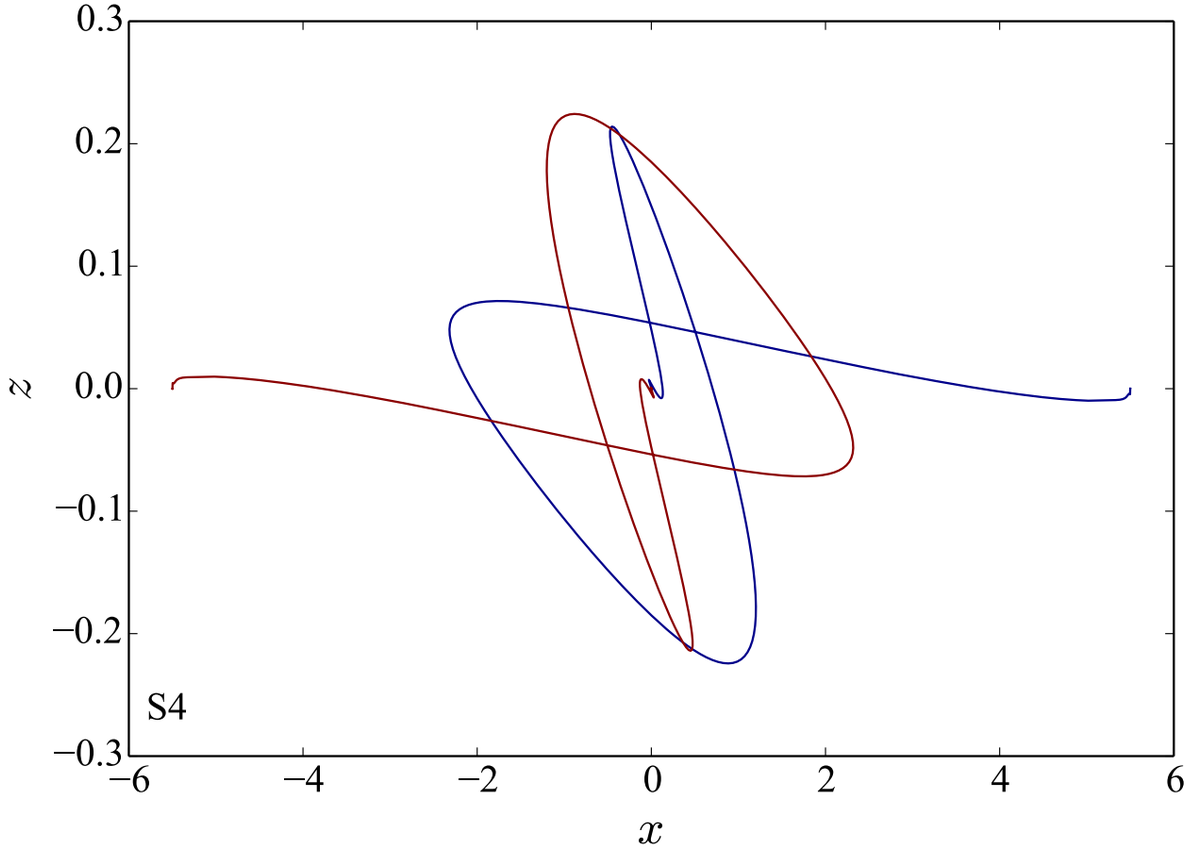
MIRROR SYMMETRY

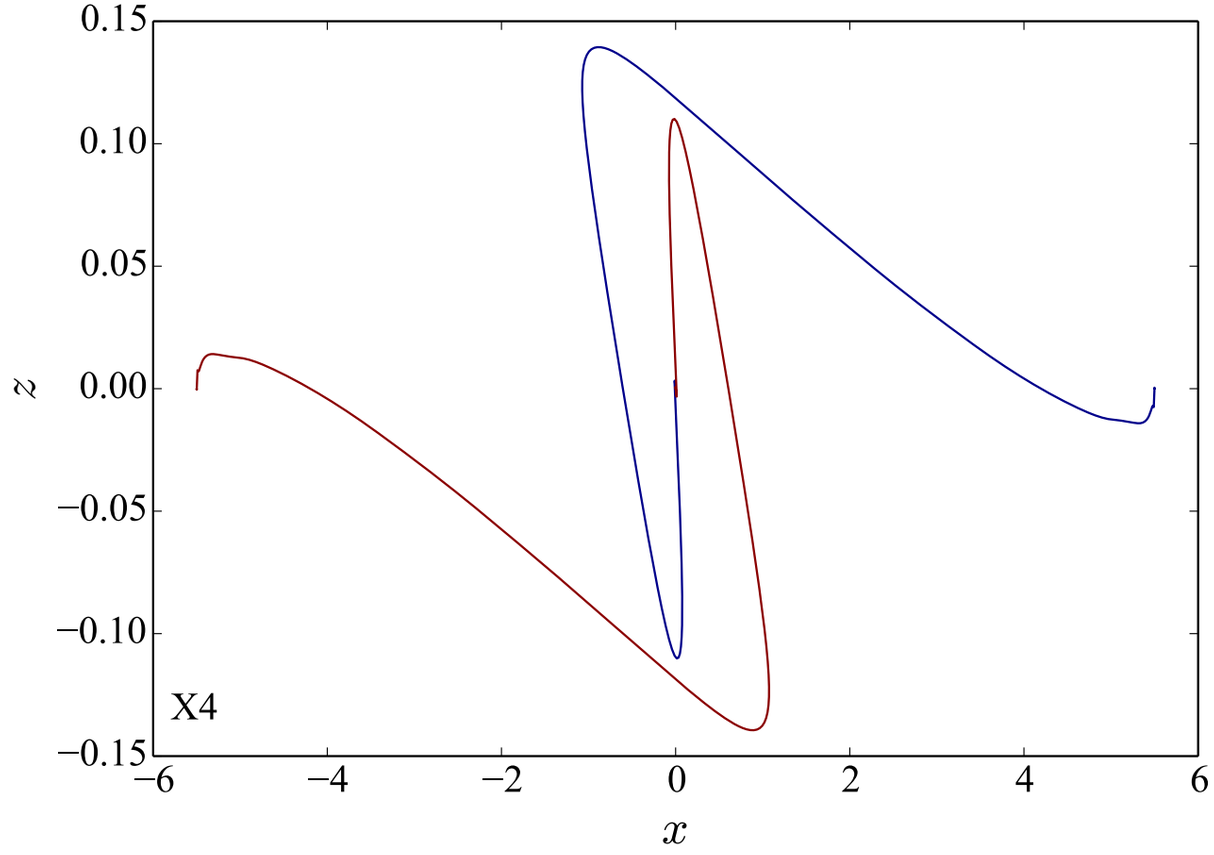


BBH SIMULATIONS

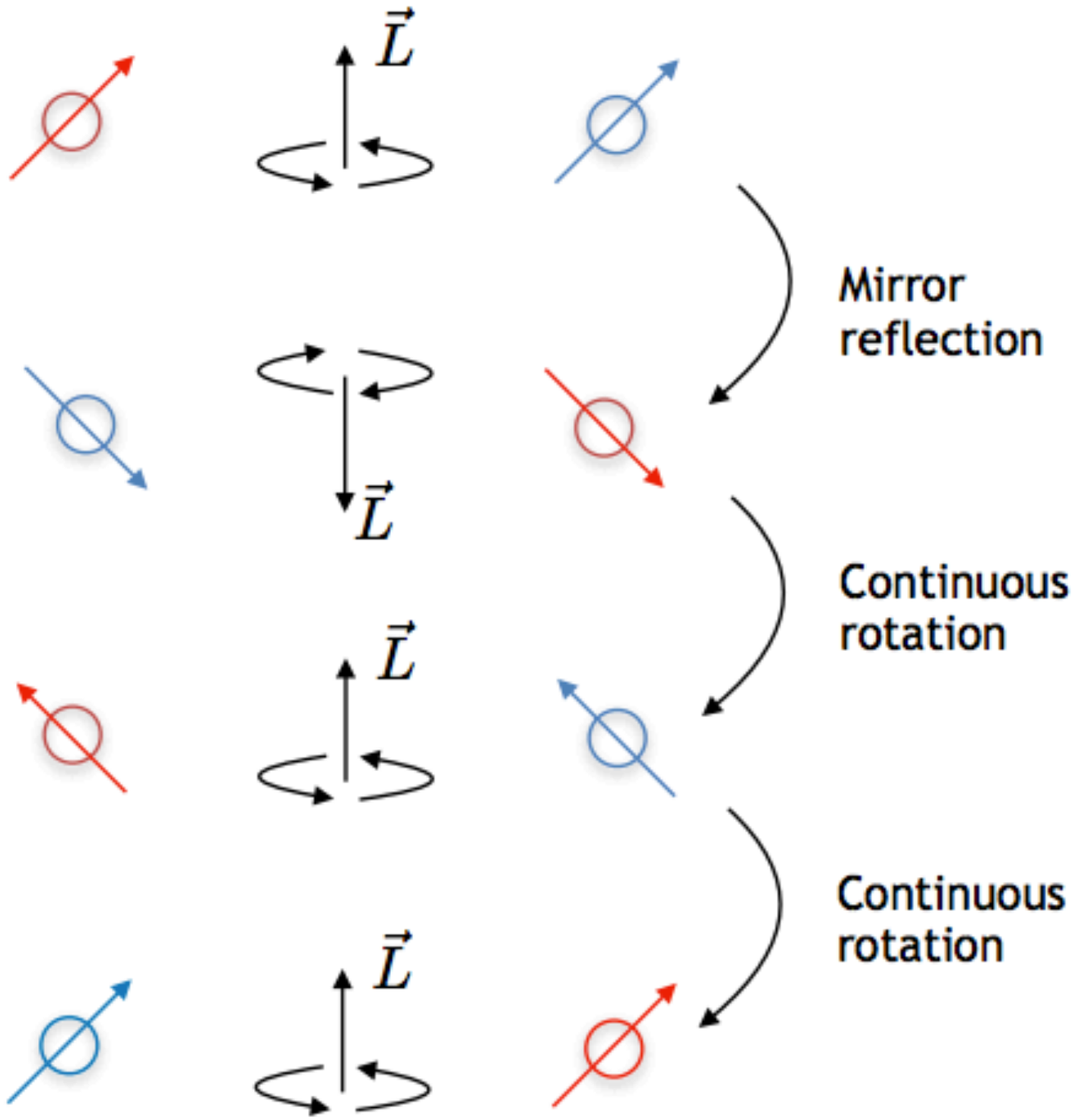
- Precessing BBH system lead to a non-zero contribution:

But **not all precessing binaries**!



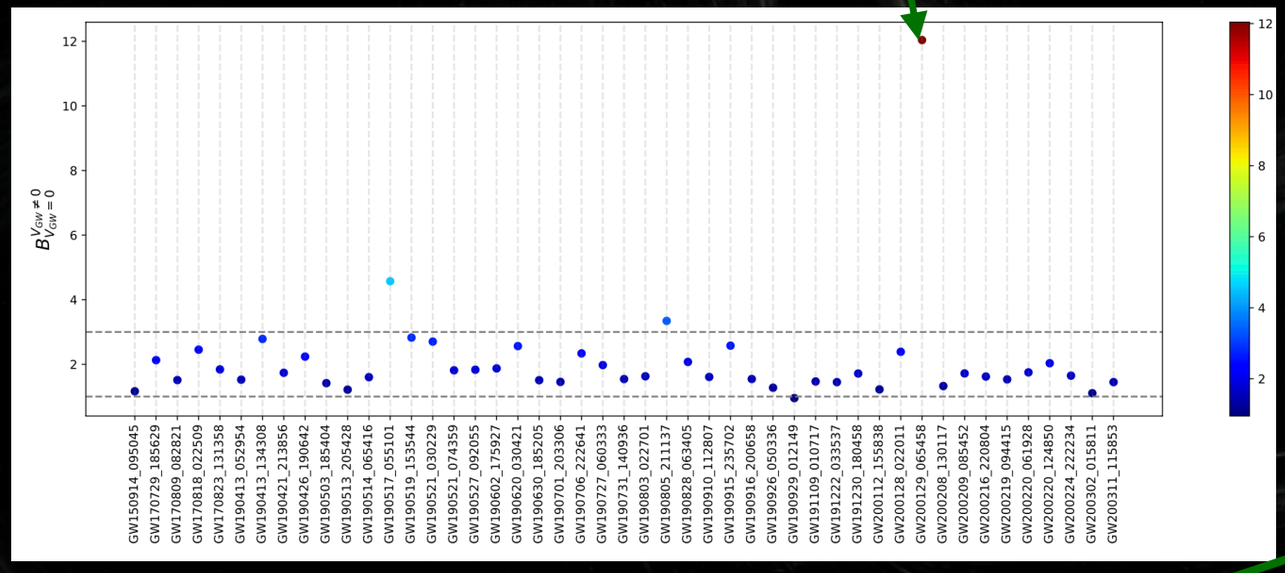


MIRROR SYMMETRY



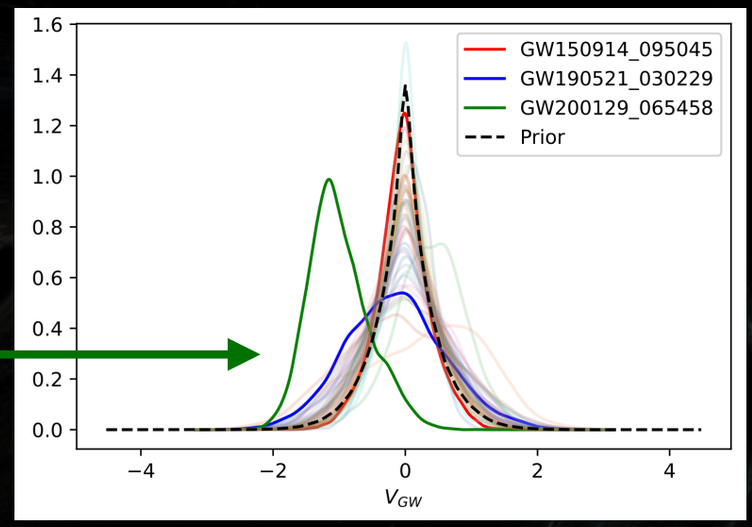
V_GW in LVK Events

- **47 events analysed by Islam et. al.** NRSur7dq4: precession + higher modes
  - Measure V_GW for each event, using Islam et. al., posteriors
  - Evidence for V_GW: Savage-Dickie ratio: $\mathcal{B}^{V_{GW}\neq 0}_{V_{GW}=0} = \frac{\pi(0)}{p(0)}$
- $\mathcal{B}^{V_{GW}\neq 0}_{V_{GW}=0} > 1$ **for all events**
- **Only GW200129 shows "strong" evidence** $\mathcal{B}^{V_{GW}\neq 0}_{V_{GW}=0} \simeq 12$

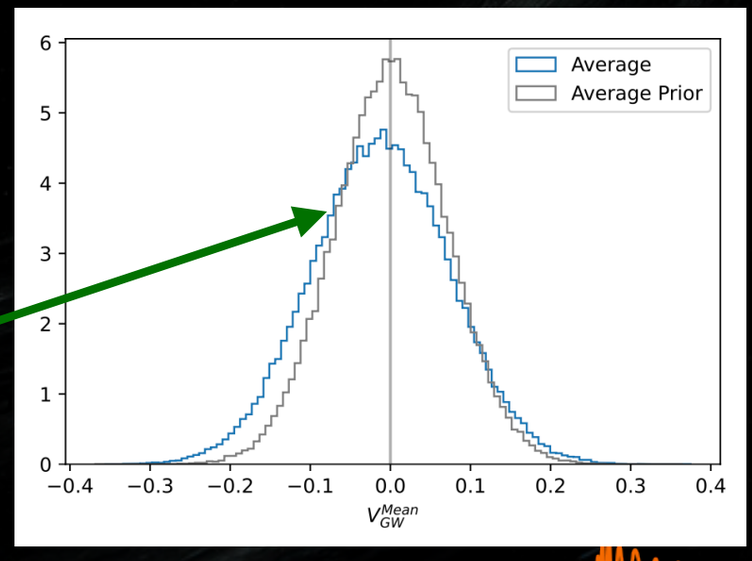


- **Posterior for average V_GW consistent with <V_GW> = 0**
  - Removing GW200129 returns the prior

Individual event posteriors



Posterior for the average



CONCLUSIONS

- The **conservation of the net polarization of the quantum electromagnetic field is broken at the quantum level in the presence of a background classical gravitational field** with a nontrivial **Chern-Pontryagin invariant**.
- In **BBH**: some **precessing systems** without any symmetry, in which the two spins and the orbital angular momentum are all three misaligned.
- Contribution of other systems.
- **Measured over 47 LIGO-Virgo events: all but one, positive evidence for non-zero circular polarization.**
- **Only GW200219 shows strong evidence for non-zero V_GW.**

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THANK YOU!

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