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New limits on the Lorentz/CPT symmetry through fifty gravitational-wave events

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The Astrophysical Journal, 921:158

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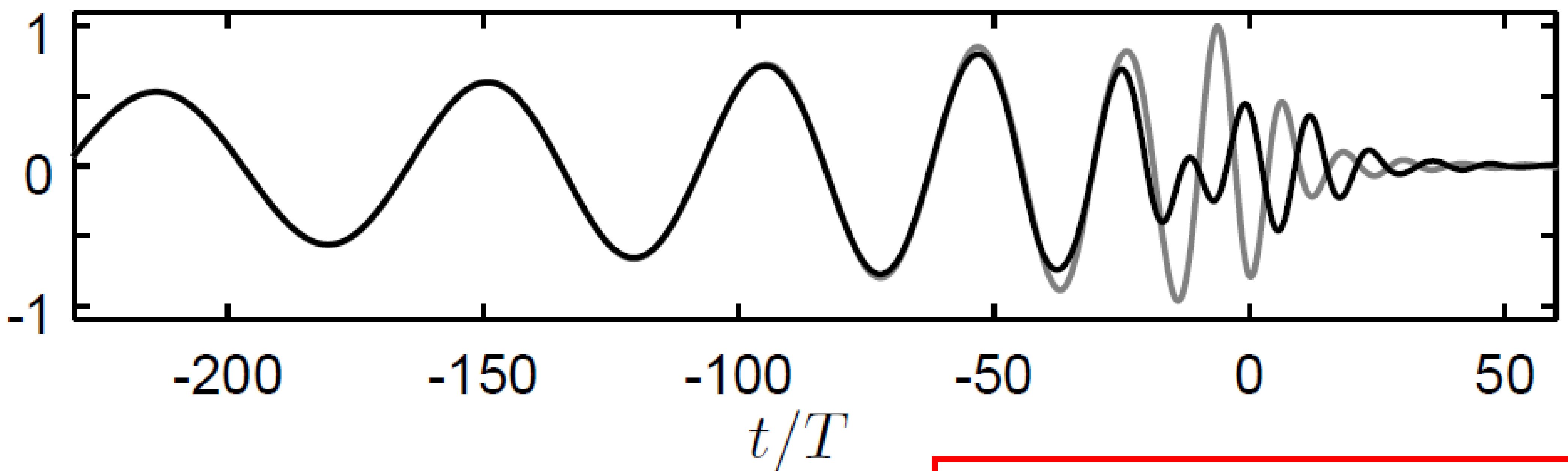

M. Mewes, Phys. Rev. D **99,** 104062 (2019)

Ⅰ. Introduction

- **Lorentz invariance** plays a fundamental role in modern physics
- However, the Lorentz symmetry may break at some yet unknown energy scale
- Originated from extreme astrophysical environments, Gravitational Waves (GWs) provide fantastic approaches for testing the Lorentz symmetry
- The Standard-Model Extension (SME) is a powerful and popular framework to explore Lorentz Invariance Violation (LIV)

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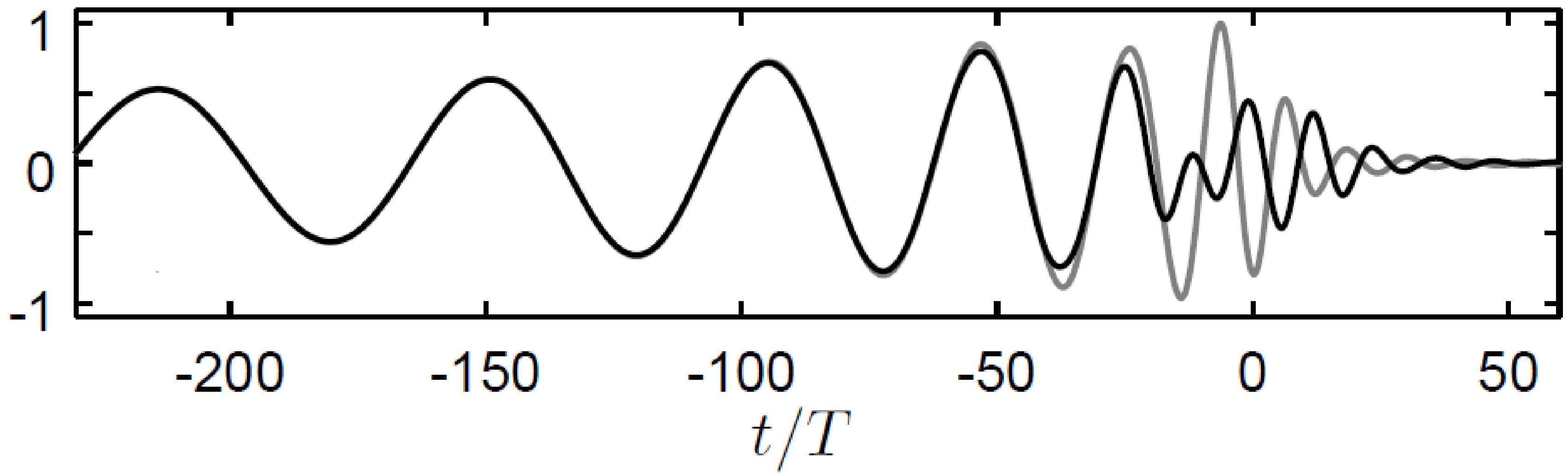
Ⅰ. Introduction

- Physical objects : Gravitational waves
- Framework : SME
- Phenomena : Birefringence of GWs
  - Differences of the arrival times between two modes of GWs
  - Splitting of detected GW waveforms
- Units : Natural units ($\hbar = c = 1$)

M. Mewes, Phys. Rev. D 99, 104062 (2019)



Ⅱ. Birefringence of GWs

- Phase speed of GWs in SME

$$v_{\pm} = 1 - \varsigma^0 \boxed{\pm |\vec{\varsigma}|}$$

birefringence term

where $|\vec{\varsigma}| \equiv \sqrt{|\varsigma_{(+4)}|^2 + |\varsigma_{(0)}|^2}$

M. Mewes, Phys. Rev. D 99, 104062 (2019)

$$\varsigma^0 = \sum_{djm} (-1)^j \, \omega^{d-4} \, {}_0Y_{jm}(\hat{\boldsymbol{p}}) \, k^{(d)}_{(I)jm} \, ,$$

$$\varsigma_{(+4)} = \sum_{djm} (-1)^j \, \omega^{d-4} \, {}_{-4}Y_{jm}(\hat{\boldsymbol{p}}) \, \left(k^{(d)}_{(E)jm} + i k^{(d)}_{(B)jm}\right)$$

$$\varsigma_{(0)} = \sum_{djm} (-1)^j \, \omega^{d-4} \, {}_0Y_{jm}(\hat{\boldsymbol{p}}) \, k^{(d)}_{(V)jm} \, .$$

mass dimension ***d***

spin-weighted spherical harmonics

SME coefficients (or LIV coefficients)

Time Difference between Two Modes

- Assuming that gLIV mainly occurs at a specific dimension, in an expanding universe, the **theoretical** time difference between two modes

V. A. Kostelecký and M. Mewes, Phys. Lett. B **757**, 510 (2016)

The frequency when GWs were emitted

$$\Delta t = 2\,|\vec{\varsigma}|^{(d)} \left(\frac{\omega}{1+z}\right)^{d-4} \int_0^z \frac{(1+z')^{d-4}}{H(z')} \mathrm{d}z' \qquad (1)$$

Cosmological redshift

Hubble parameter

- Now there is "no" splitting in the detected signal, we assume that the **observed** time difference between two modes satisfies

L. Shao, Phys. Rev. D **101**, 104019 (2020)

$$|\Delta t| \leq \frac{1}{\rho f} \qquad (2)$$

network signal-to-noise ratio

GW frequency at the amplitude peak

Ⅲ. Constraints on the LIV Coefficients

- Take ***d*** = 5 for example. At mass dimension 5, there are **16** independent components in total

- Based on Eqs. (1-2), for the *i*-th GW event we construct an inequality of the SME coefficients

only depend on the GW event parameters

$$\left|\sum_{jm} a_i^{jm} k^{(5)}_{(V)jm}\right| \leq \frac{1}{\rho_i f_i}$$

- Every GW event gives one limit on the SME coefficients. These combinations are linearly independent because GW events scatter in different sky areas

Multiple Events

- At the time of previous work, one only have a few events to constrain the SME coefficients

V. A. Kostelecký and M. Mewes, Phys. Lett. B **757**, 510 (2016)

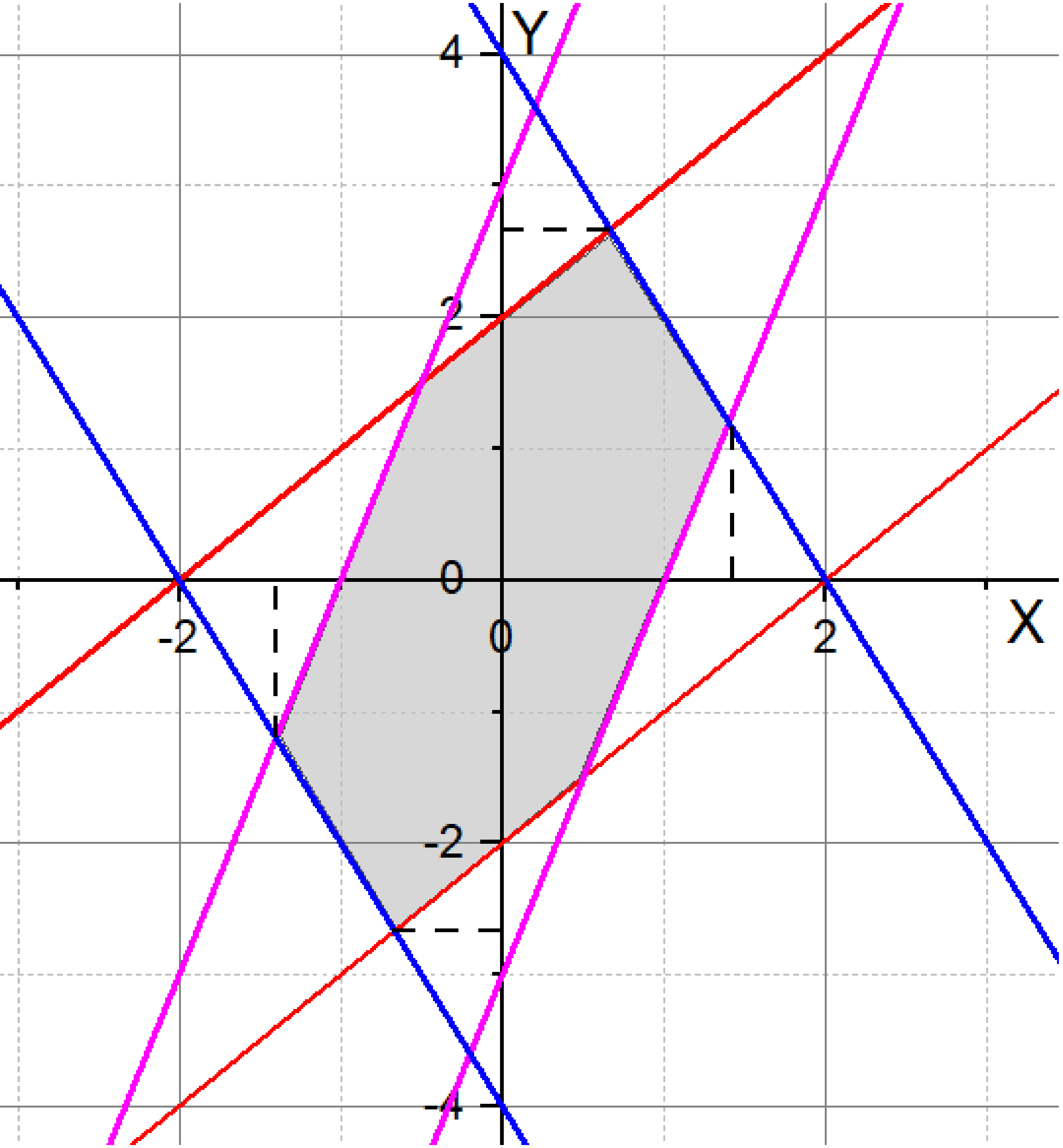
L. Shao, Phys. Rev. D **101**, 104019 (2020)

- However, there are **50** events in the whole GWTC-1 and GWTC-2 catalog

B. P. Abbott *et al.* , Phys. Rev. X, 9, 031040 (2019); 11, 021053 (2021)

- **Now we can completely break the coupling among the SME coefficients (at some specific dimension) for the first time !**

Break the Degeneracy among Coefficients



- For every GW event, the inequality gives an area between two hypersurfaces symmetrical about the origin
- The 50 pairs of hypersurfaces can enclose a closed region where every coefficient is bounded

IV. Results and Summary

- To obtain the distribution of these SME coefficients, one requires the distribution of the "measured" time delay
- Assuming that the "measured" time delay obeys a Gaussian normal distribution with $\mu = 0$ and $\sigma = 1/(\rho f)$

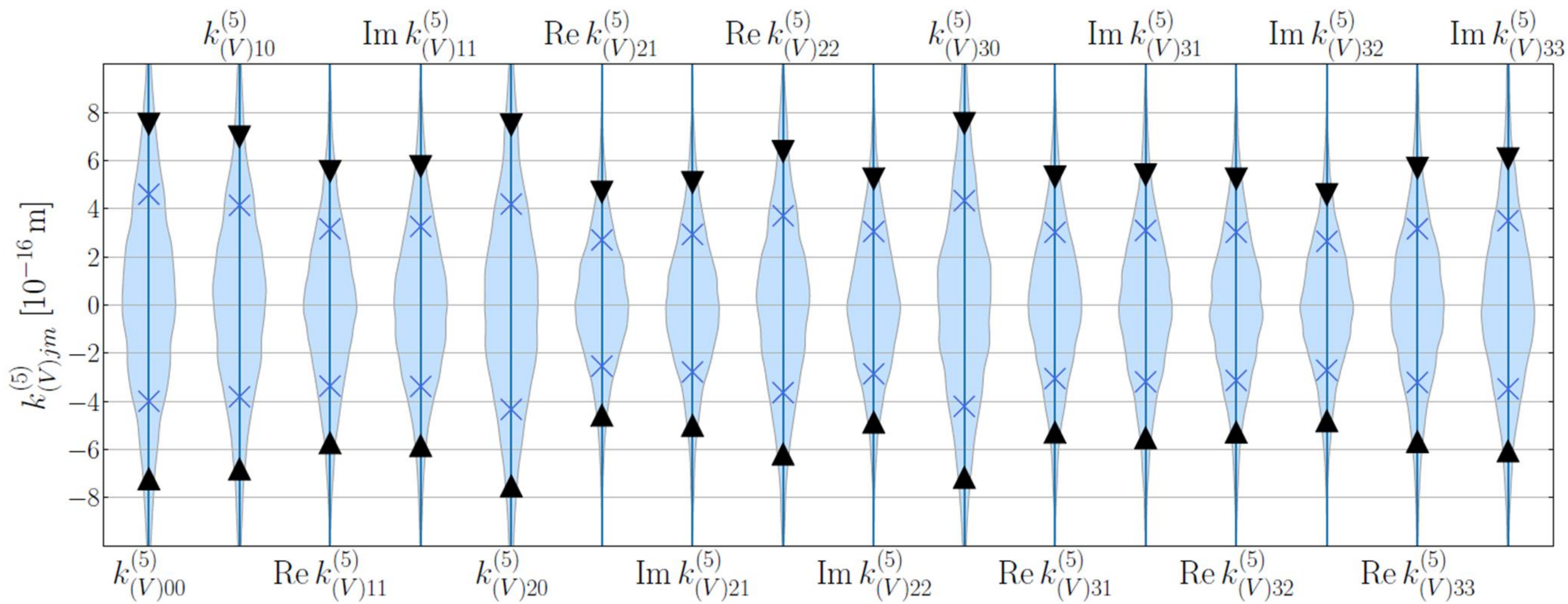


Figure 1. Violin plots of the 16 independent components at mass dimension $d = 5$. The 68% and 90% confidence intervals are tagged with "×" and "△" respectively.

Summary

- LIV will lead to the birefringence of GWs
- LIV can be described by SME coefficients
- Multiple GW events can break the degeneracy among coefficients

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Thanks for listening!

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2022/3/19