Testing Cosmological Isotropy with Gravitational Waves and Gamma-ray Bursts

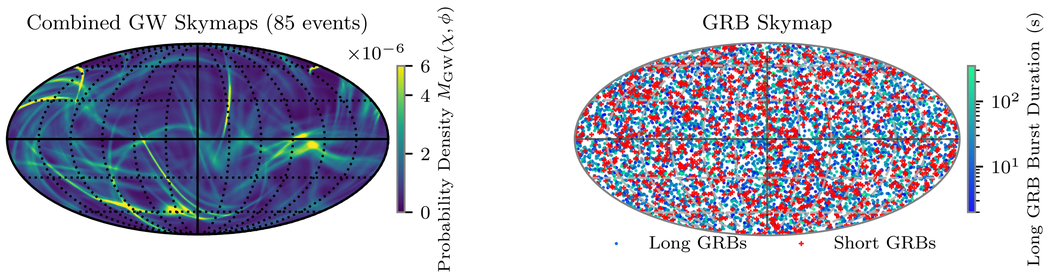
Brian H. Y. Cheng, Donniel C. Cruz, Otto A. Hannuksela, Davendra S. Hassan, Christian Heiderijk, Leo Q. Hu, Souvik Jana, Jinwon Kim, Albert K. H. Kong, Peony K. K. Lai, Samuel C. Lange, Samson H. W. Leong, Matteo Lulli, Li-Ting Ma, Paul Martens, Boris H.-L. Ng, Thomas C. K. Ng, Surojit Saha, Gwangeon Seong, Helen Xian, and Yanyan Zheng

Long Debate of Cosmic Anisotropy

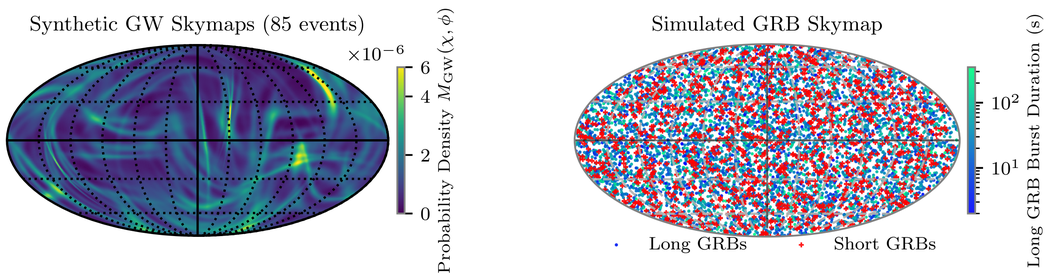
- Cosmological principle expected to hold: Isotropic and Homogeneous
- Isotropy challenged by some Gamma-ray bursts (GRBs)/Cosmic microwave background observations[1]
- Gravitational Waves (GWs) as independent probe
- We test isotropy with both GWs and GRBs

Data and simulation

- Observations used: GW events from LVK O4a data, GRBs from GRBweb[2]



Data of new GWs from GWTC-4.0 and GRBs from GRBWeb in form of skymaps to focus on spatial analysis. The skymaps and parameter estimation data are used in tests for cosmological anisotropies.



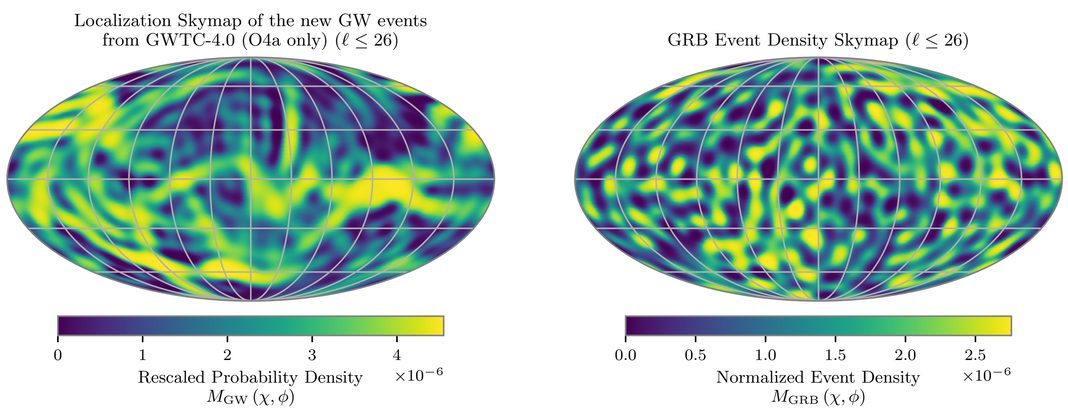
Synthetic skymaps for GWs and GRBs assuming spatial isotropy. Anisotropy testes are based on deviations of observed data from this simulation of isotropic events.

- Simulated data matches with GW sensitivites, SNR, and event parameters of GRBs for benchmarking derivation from isotropy of observations

Angular power spectrum and cross-correlation

- Stack data to probability distribution function map $M_{\mathsf{X}}(\chi,\phi)$, then decompose into spherical harmonics:

$$M_{\mathsf{X}}(\chi,\phi) = \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{+\ell} \beta^{\mathsf{X}}_{\ell m} Y_{\ell m}(\chi,\phi)\,.$$



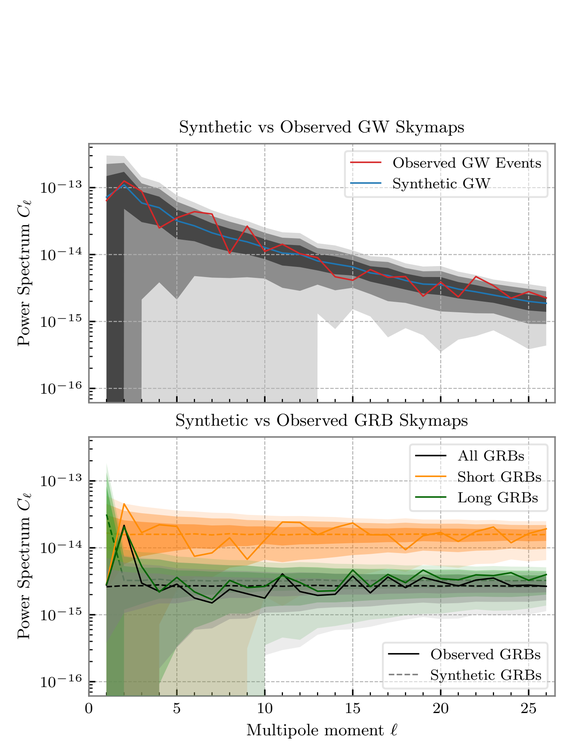
Reconstruction of the GWTC-4.0 (left) and GRB (right) event density skymaps from their harmonics decomposition, cut at the 26$^{\text{th}}$ order in multipoles to match the 'GW' skymap resolution. The spatial isotropy of GW and GRB events can then be compared. Their cross-correlation can also be estimated properly.

- Compare angular power spectrum and angular cross-correlation function with simulated data:

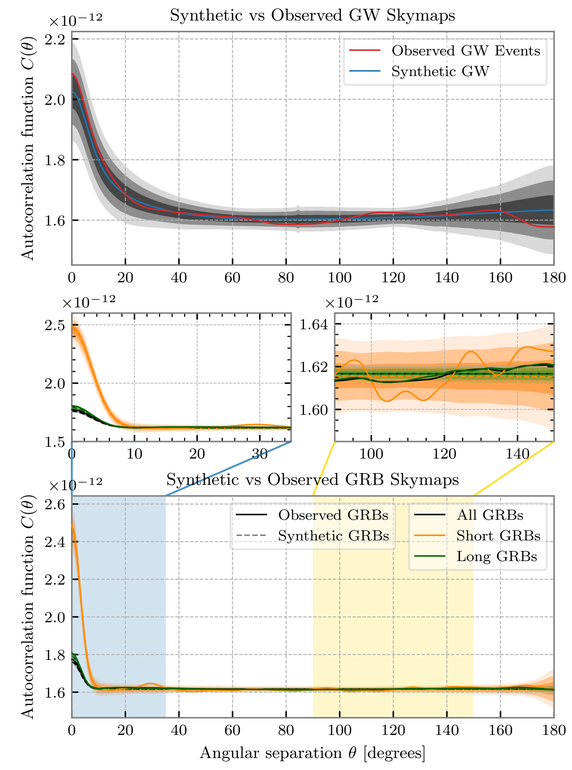
$$C^{\mathsf{X}}_{\ell} = \frac{1}{2\ell+1}\sum_{m} \beta^{\mathsf{X}}_{\ell m}\bar{\beta}^{\mathsf{X}}_{\ell m},\quad C_{\mathsf{X}\times\mathsf{Y}}(\theta) = \frac{1}{4\pi}\sum_{\ell,m} W_{\ell}(\theta)\beta^{\mathsf{X}}_{\ell m}\bar{\beta}^{\mathsf{Y}}_{\ell m} P_{\ell}(\cos\theta)\,.$$

- $C_{\mathsf{X}\times\mathsf{X}}$ expected to remain constant for all angular separations for isotropic universe.

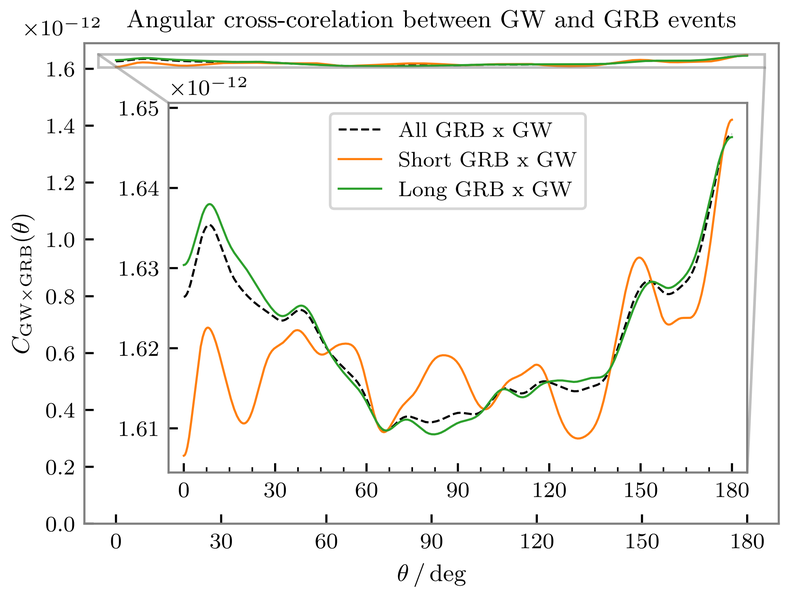
Results



Angular power spectrum of observed GWs and GRBs. There is a peak at lower order multipoles for GWs, but both GWs and GRBs are consistent with isotropic simulations. This further supports the cosmic isotropy.



Angular auto-correlation function between observed GWs and GRBs. The value of function diverge from constant at smaller scales, likely due to finite observation and blurred sky localization. At larger angular scales, the correlation is consistent with isotropic expectations, supporting large-scale isotropy.



The angular cross-correlation function between GRB and GW events. There are larger fluctuations for short GRBs comparing to overall distribution, but scale of fluctuation is similar to the case of auto-correlation function at larger angular scales, showing no major signature of anisotropy.

Conclusion

- Further support of cosmological principle combining GRB observations and GW events which is an independent test of anisotropy
- The correlation analysis show no significant correlations between observed GWs and GRBs
- This approach of anisotropy analysis can be further applied to future multi-messenger observations

References

arxiv id of this paper: 2604.17746, submitted to Astronomy and Astrophysics
[1] Planck 2018 results, doi:10.1051/0004-6361/201935201
[2] https://icecube.wisc.edu/~grbweb_public

Contact Information
Brian H. Y. Cheng
hycheng@link.cuhk.edu.hk