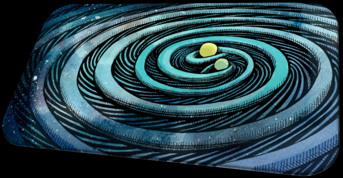
The 7th KAGRA International Workshop

18-20 Dec 2020, Hybrid-style Workshop



北京大學
PEKING UNIVERSITY

Propagation of GWs with CPT violation

Kavli Institute for Astronomy and Astrophysics

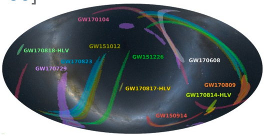
Speaker: Lijing Shao (邵立晶)

KAGRA International Workshop

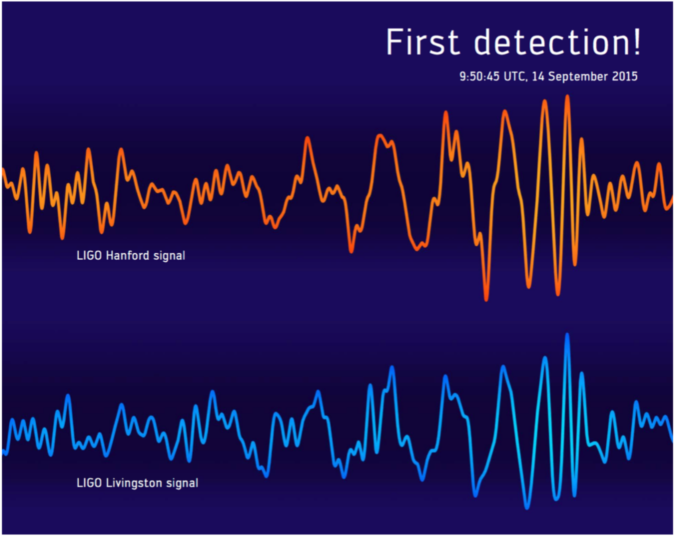
Content

- The **most generic propagation** of GWs depends on
  - GW **frequency**
  - GW **polarization**
  - GW source **direction**
- For the first time, we combined 11 GW events in the catalog **GWTC-1**, and bounded *multiple* coefficients for generic Lorentz/CPT violation

L. Shao, Phys. Rev. D **101** (2020) 104019 [arXiv:2002.01185]
"Combined search for anisotropic birefringence in the gravitational-wave transient catalog GWTC-1"

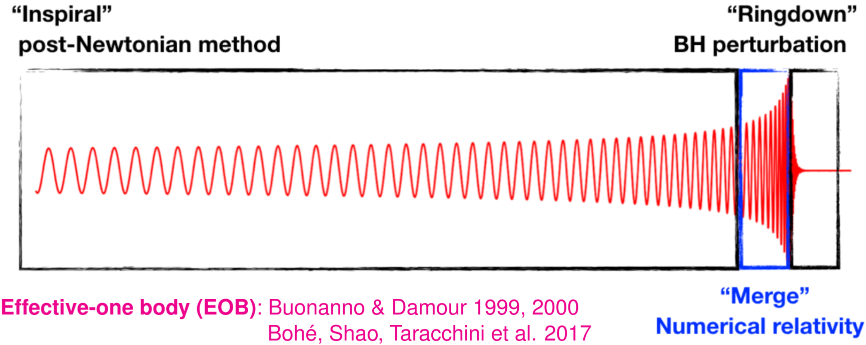


Gravitational-wave Data



Gravitational Waveform (Time Domain)

- **Inspiral**: post-Newtonian expansion
- **Merger**: numerical relativity
- **Ringdown**: black hole perturbation

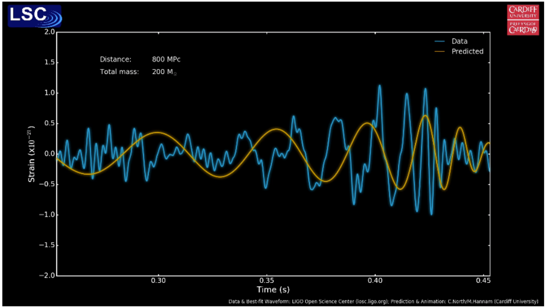


Effective-one body (EOB): Buonanno & Damour 1999, 2000
Bohé, Shao, Taracchini et al. 2017

Matched Filter

- **Matched fitlering** is a standard analysis method for **wideband** time series data [Finn 1992]

$$(\mathbf{g}|\,\mathbf{k}) \equiv 2\int_0^{\infty} \frac{\tilde{g}^*(f)\tilde{k}(f) + \tilde{g}(f)\tilde{k}^*(f)}{S_n(f)}\mathrm{d}f$$



Parameter Estimation: GW150914

- GW data encode plenty of information of GW sources
  - Apply Matched filter to data & theory

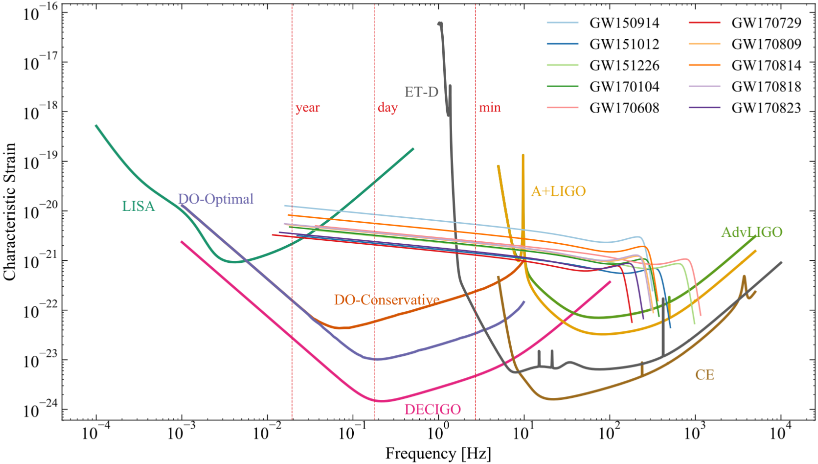
Primary black hole mass	$36^{+5}_{-4} M_{\odot}$
Secondary black hole mass	$29^{+4}_{-4} M_{\odot}$
Final black hole mass	$62^{+4}_{-4} M_{\odot}$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

LIGO/Virgo 2016, PRL

GW Transient Catalog GWTC-1 (LIGO/Virgo 2019)

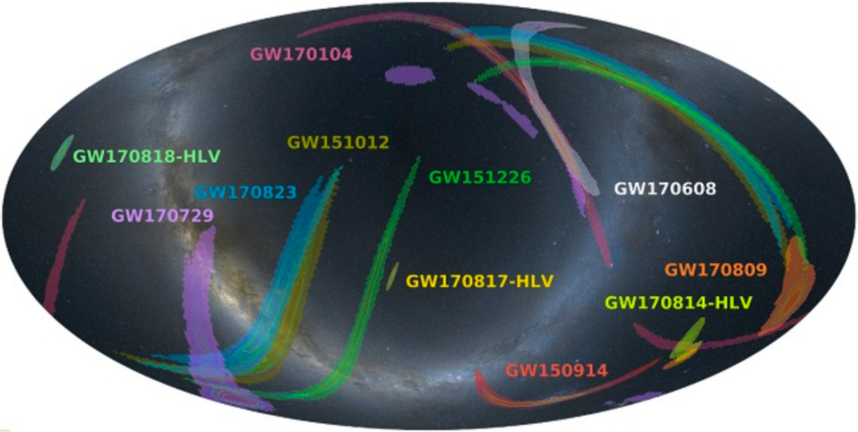
	Type	m_1 $[M_\odot]$	m_2 $[M_\odot]$	d_L [Mpc]	Redshift z
GW150914	BBH	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$
GW151012	BBH	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$
GW151226	BBH	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$
GW170104	BBH	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$
GW170608	BBH	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$
GW170729	BBH	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$
GW170809	BBH	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$
GW170814	BBH	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$
GW170817	**BNS**	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$
GW170818	BBH	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$
GW170823	BBH	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$

Signals of GW Events



Liu, Shao, Zhao, Gao 2020, MNRAS [arXiv:2004.12096]

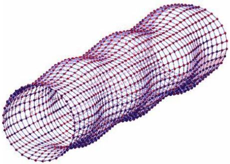
GWTC-1: Sky Position (LIGO/Virgo 2019)



Graviton Dispersion Relation

- **GR**: massless spin-2 metric field $\Rightarrow$ $E = p$
- Lorentz-invariant massive graviton $\Rightarrow$ $E^2 = p^2 + m^2$
  - Both the phase velocity E/p and the group velocity $\partial E/\partial p$ depend on the energy/frequency of graviton
  - GWs gain *frequency-dependent* time delays when they arrive at the Earth
  - In a FRW spacetime, one has [Will 1998, PRD57:2061]

$$\Delta t_a = (1+z)\left[\Delta t_e + \frac{D}{2\lambda_g^2}\left(\frac{1}{f_e^2} - \frac{1}{f_e'^2}\right)\right]$$

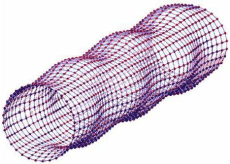


Propagation of GWs

- The extra time delay results in a phase shift in $h(f) \propto \mathrm{e}^{i\Psi(f)}$

$$\Psi(f) = \Psi_{\mathrm{GR}}(f) - \frac{\pi^2 D\mathcal{M}}{\lambda_g^2(1+z)}(\pi\mathcal{M}f)^{-1}$$

- On the other hand, the waveform is *totally* calculable and deterministic in GR
- Therefore, GWs provide an observational window to the dispersion relation of graviton



Standard-model Extension

- The most generic linearized gravity has the Lagrangian

  [Kostelecký & Mewes 2018]

$$\mathcal{L}_{\mathcal{K}^{(d)}} = \frac{1}{4} h_{\mu\nu} \hat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} h_{\rho\sigma}$$

where $\hat{\mathcal{K}}^{(d)\mu\nu\rho\sigma} = \mathcal{K}^{(d)\mu\nu\rho\sigma i_1 i_2 \cdots i_{d-2}} \partial_{i_1} \partial_{i_2} \cdots \partial_{i_{d-2}}$

- It predicts a modified dispersion relation for GWs

$$\omega = \left(1 - \zeta^0 \pm \sqrt{(\zeta^1)^2 + (\zeta^2)^2 + (\zeta^3)^2}\right) p$$

Standard-model Extension

$$\omega = \left(1 - \zeta^0 \pm \sqrt{\left(\zeta^1\right)^2 + \left(\zeta^2\right)^2 + \left(\zeta^3\right)^2}\right) p$$

$$\zeta^0 = \sum_{djm} \omega^{d-4} Y_{jm}(\hat{\boldsymbol{n}}) k^{(d)}_{(I)jm}$$

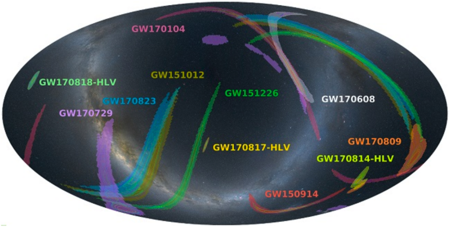
$$\zeta^1 \mp i\zeta^2 = \sum_{djm} \omega^{d-4}_{\pm 4} Y_{jm}(\hat{\boldsymbol{n}}) \left[k^{(d)}_{(E)jm} \pm i k^{(d)}_{(B)jm}\right]$$

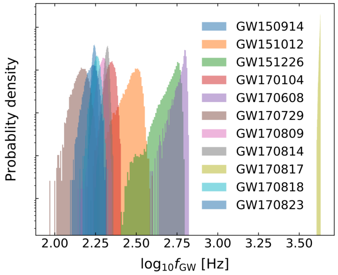
$$\zeta^3 = \sum_{djm} \omega^{d-4} Y_{jm}(\hat{\boldsymbol{n}}) k^{(d)}_{(V)jm}$$

- Therefore, gravitons of different **polarization** or **frequency**, coming from different **directions** have different velocity

GWTC-1 Events

A simplified/naive approach: $|\omega_{\rm GW}\Delta t| \leq 2\pi/\rho$

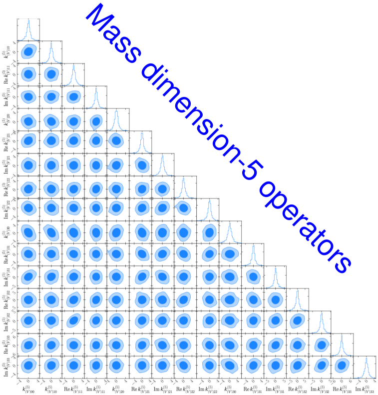


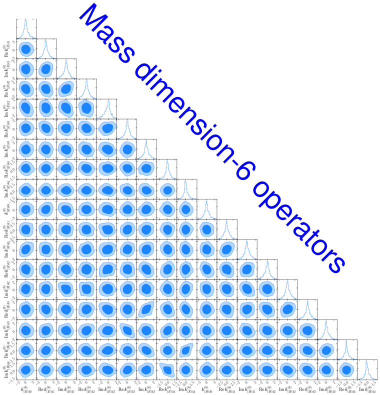


We have all the information available to perform the test

Shao 2020, PRD101:104019

Anisotropic Birefringence Combined Search





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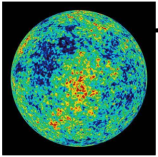
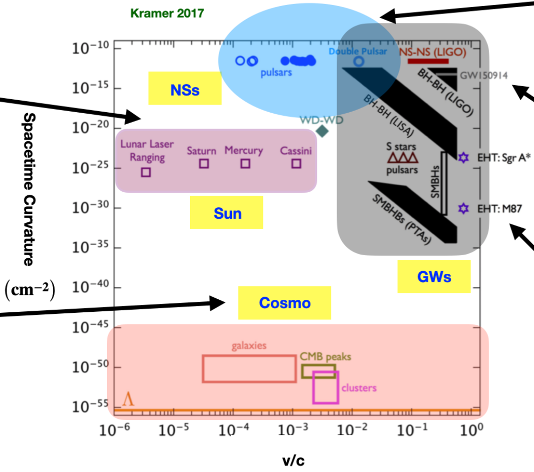
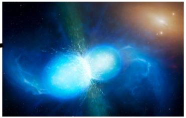
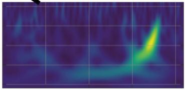
Shao 2020, PRD101:104019

Parameter Space in Gravity Tests

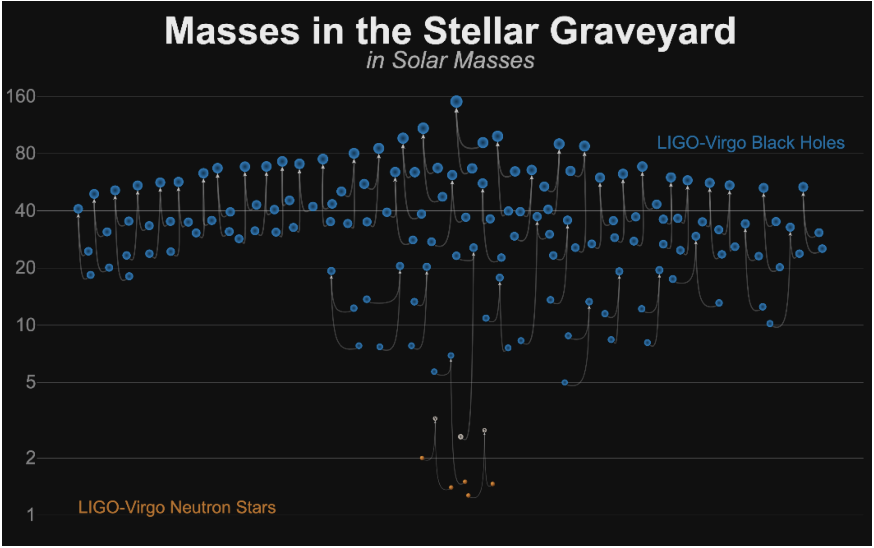




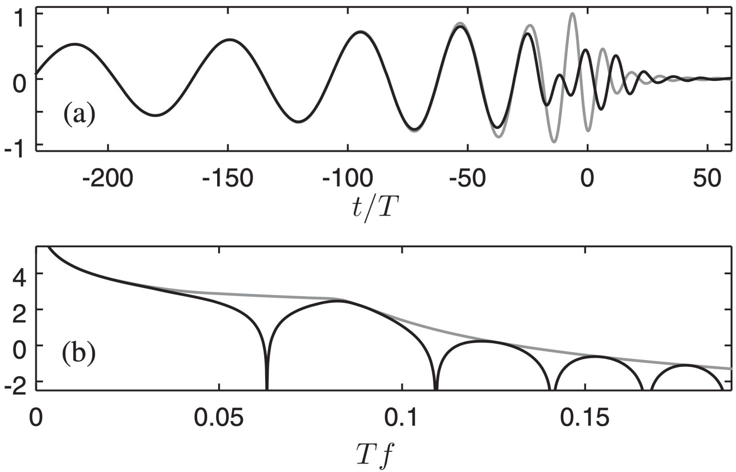




GWTC-2: Released Recently! (LIGO/Virgo 2020)



Matched Filter Analysis



Mewes, PRD99:104062

Thank you!