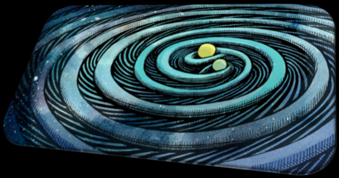
That would be one of the most fascinating things man cloud do, because it would tell you very much how the universe started.

— Rainer Weiss



北京大學
PEKING UNIVERSITY

Testing Gravity with GWs

Kavli Institute for Astronomy and Astrophysics

Speaker: Lijing Shao (邵立晶)

CCNU: June 10, 2020

Outline

1. Gravity Tests

Absence of Quantum Gravity

- On one hand, we have Quantum Field Theory to describe the electromagnetic, strong, and weak interactions
- On the other hand, we have General Relativity to describe the gravity, as the dynamics of curved spacetime
- However, QFT and GR are not compatible at their face values!

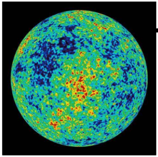
No one wanted to talk with Albert?

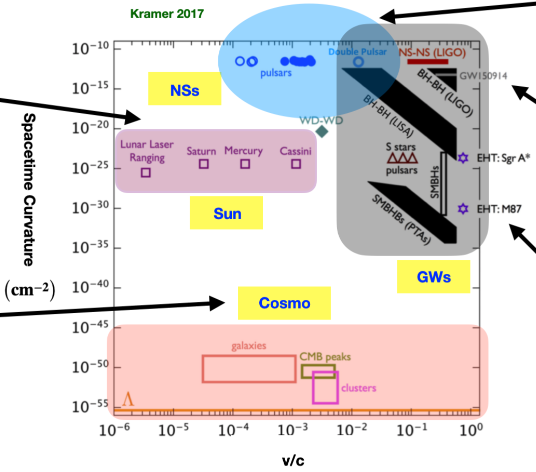
Theoretical physics is beautiful,

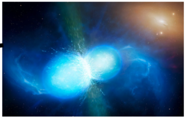
but not yet complete

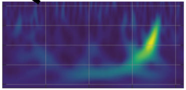
Gravity may be holding the key

Parameter Space in Gravity Tests



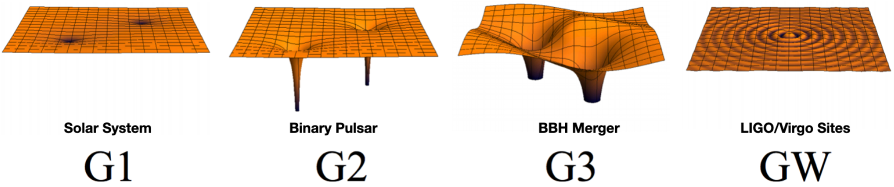






Parameter Space in Gravity Tests

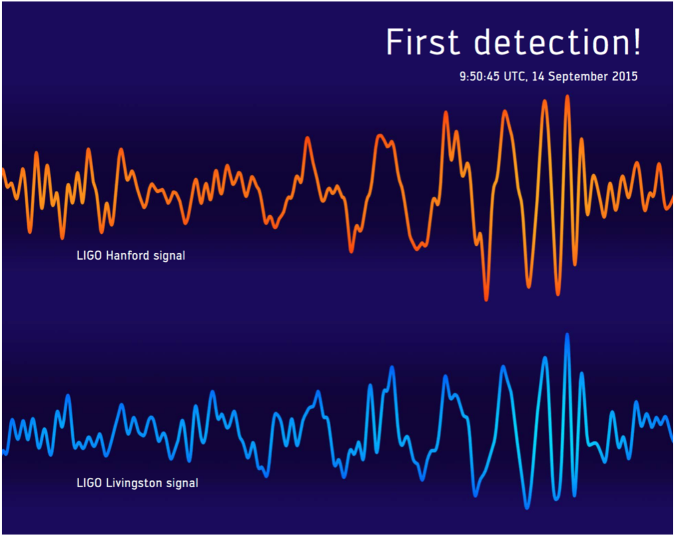
- **G1**: Quasi-stationary weak-field regime
- **G2**: Quasi-stationary strong-field regime
- **G3**: Highly dynamical strong-field regime
- **GW**: Radiation regime



Wex 2014 (arXiv:1402.5594)

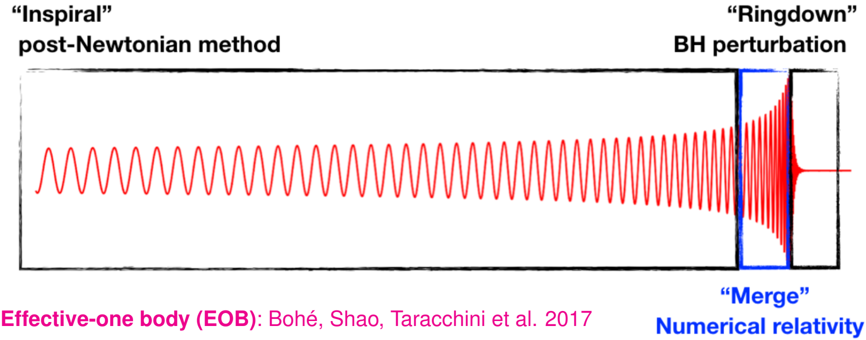
2. Introduction to GWs

Gravitational-wave Data



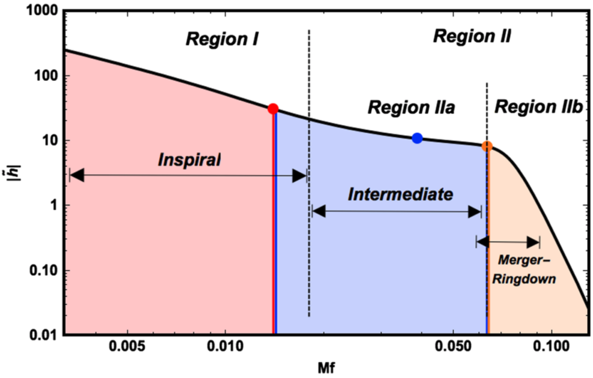
Gravitational Waveform (Time Domain)

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



Effective-one body (EOB): Bohé, Shao, Taracchini et al. 2017

Gravitational Waveform (Frequency Domain)

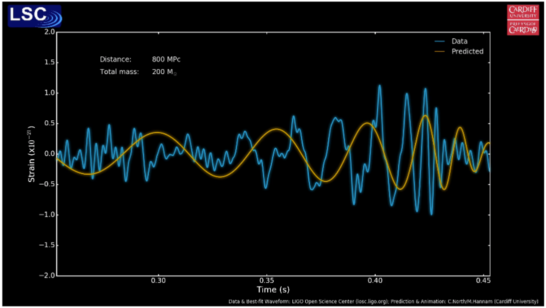


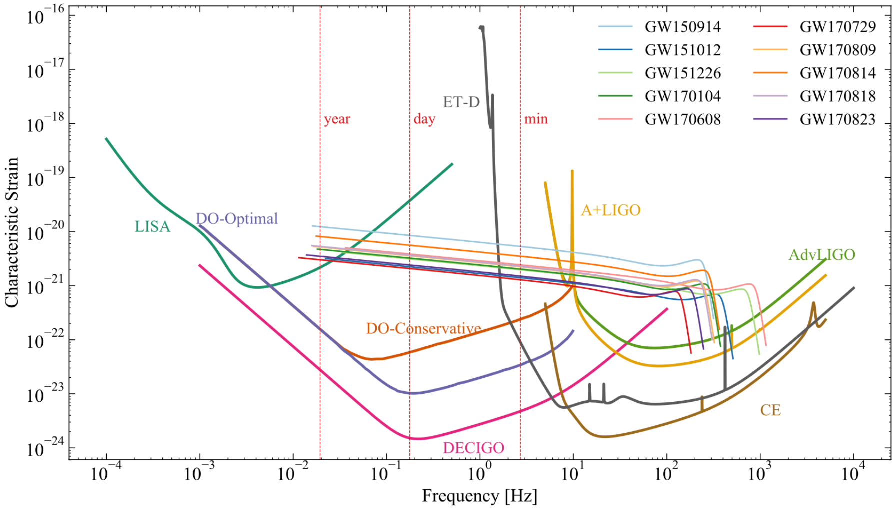
Phenomenological waveform: Husa et al. 2016, PRD; Khan et al. 2016, PRD

Matched Filter

- **Matched fitlering** is a standard analysis method for **wideband** time series data

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

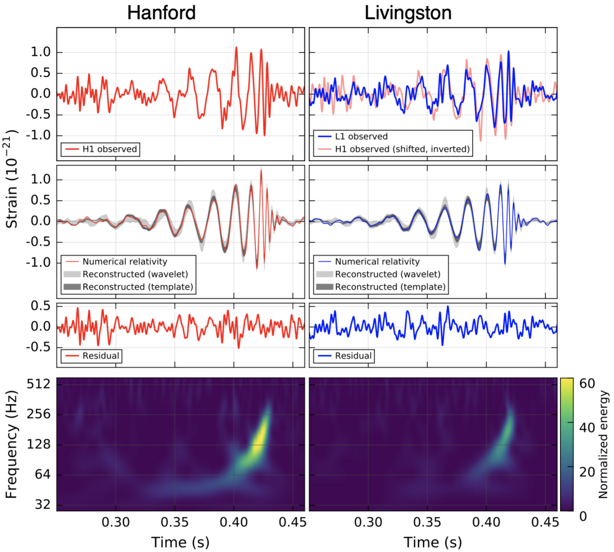




Liu, Shao, et al. 2020, MNRAS (arXiv:2004.12096)

GW150914 (LIGO/Virgo 2016)

$36 + 29\,M_\odot$: 0.2 sec, SNR=23



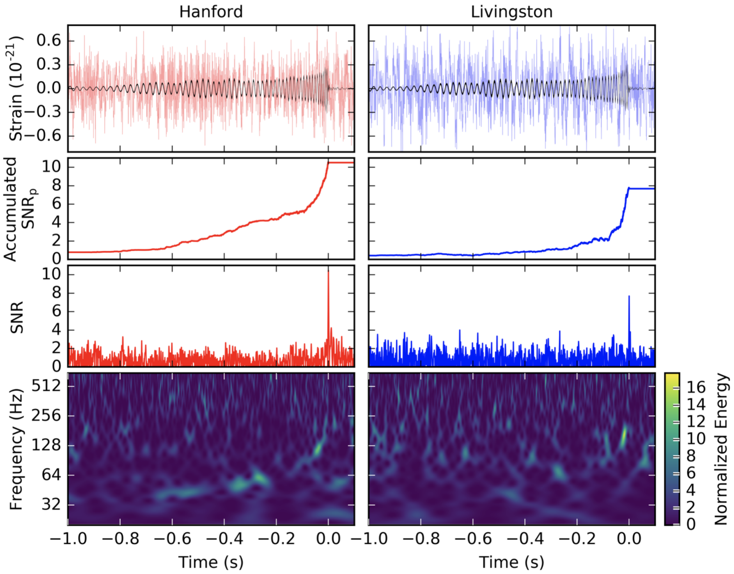
Parameter Estimation: GW150914

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

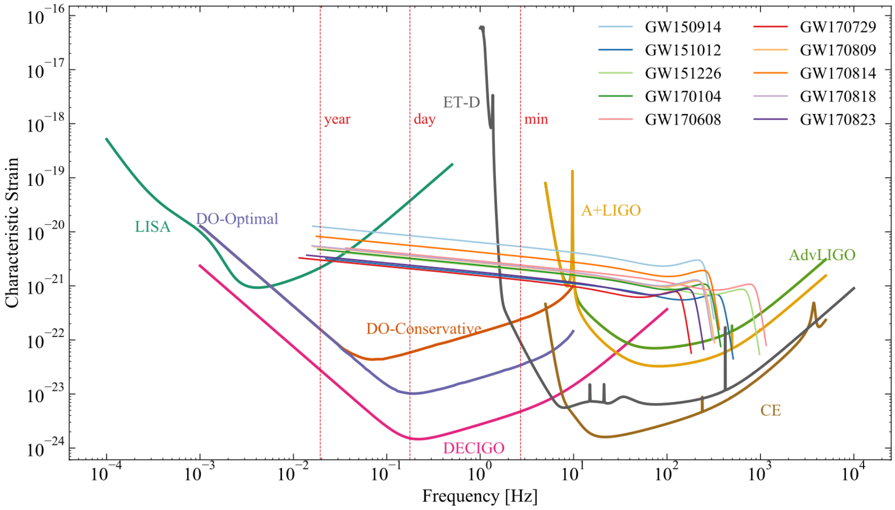
GW151226 (LIGO/Virgo 2016)

$14 + 8\,M_\odot$: 1 sec, SNR=13



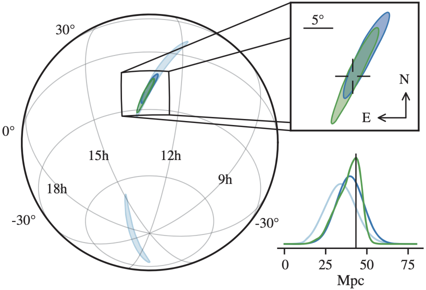
GW Transient Catalog GWTC-1 (LIGO/Virgo 2019)

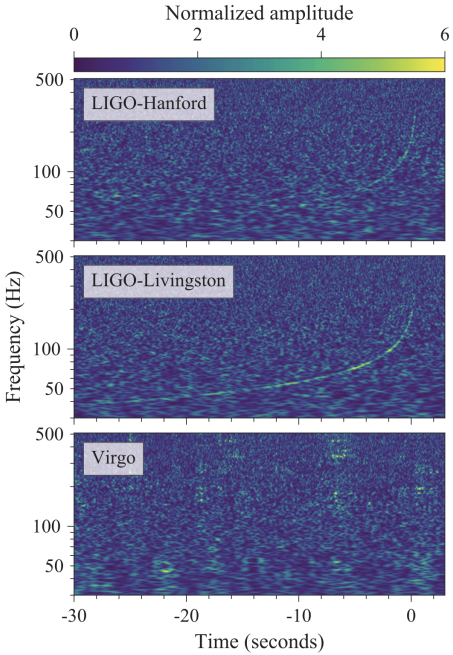
	Type	m_1 $[M_\odot]$	m_2 $[M_\odot]$	d_L [Mpc]	Redshift z
GW150914	BBH	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$
GW151012	BBH	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$
GW151226	BBH	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	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}	$0.34^{+0.13}_{-0.14}$



Liu, Shao, et al. 2020, MNRAS (arXiv:2004.12096)

GW170817 (LIGO/Virgo 2017)

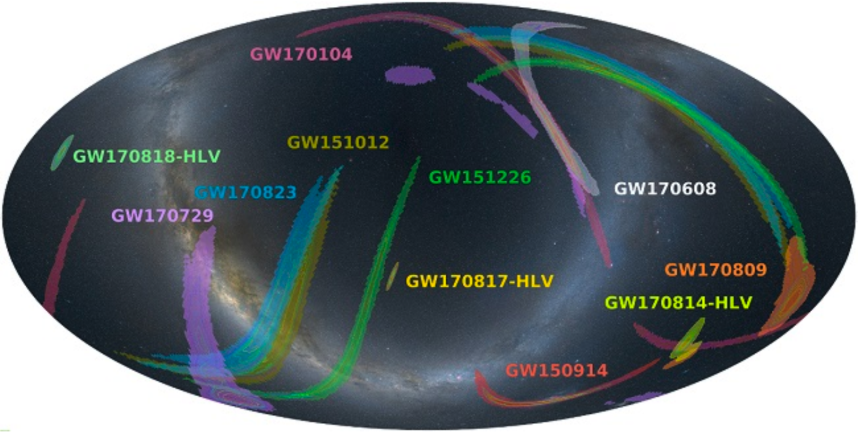




1 min, SNR=32

3000 cycles from 30 Hz

GWTC-1: sky position (LIGO/Virgo 2019)



3. Binary Black Holes

Testing Gravity with BBHs

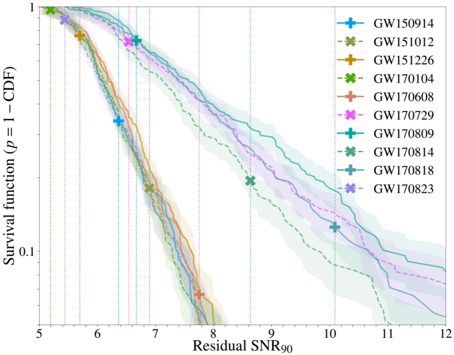
- Residual tests (RT)
- Inspiral-merger-ringdown consistency tests (IMR)
- Parameterized tests: inspiral & post-inspiral (PI & PPI)
- Modified dispersion relation (MDR)

Event	Properties				SNR	GR tests performed				
	D_L [Mpc]	M_{tot} [$M_\odot$]	M_f [$M_\odot$]	a_f		RT	IMR	PI	PPI	MDR
GW150914[b]	430^{+150}_{-170}	$66.2^{+3.7}_{-3.3}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$25.3^{+0.1}_{-0.2}$	✓	✓	✓	✓	✓
GW151012[b]	1060^{+550}_{-480}	$37.3^{+10.6}_{-3.9}$	$35.7^{+10.7}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$9.2^{+0.3}_{-0.4}$	✓	–	–	✓	✓
GW151226[b,c]	440^{+180}_{-190}	$21.5^{+6.2}_{-1.5}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$12.4^{+0.2}_{-0.3}$	✓	–	✓	–	✓
GW170104	960^{+440}_{-420}	$51.3^{+5.3}_{-4.2}$	$49.1^{+5.2}_{-4.0}$	$0.66^{+0.08}_{-0.11}$	$14.0^{+0.2}_{-0.3}$	✓	✓	✓	✓	✓
GW170608	320^{+120}_{-110}	$18.6^{+3.1}_{-0.7}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$15.6^{+0.2}_{-0.3}$	✓	–	✓	✓	✓
GW170729[d]	2760^{+1380}_{-1340}	$85.2^{+15.6}_{-11.1}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$10.8^{+0.4}_{-0.5}$	✓	✓	–	✓	✓
GW170809	990^{+320}_{-380}	$59.2^{+5.4}_{-3.9}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$12.7^{+0.2}_{-0.3}$	✓	✓	–	✓	✓
GW170814	580^{+160}_{-210}	$56.1^{+3.4}_{-2.7}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$17.8^{+0.3}_{-0.3}$	✓	✓	✓	✓	✓
GW170818	1020^{+430}_{-360}	$62.5^{+5.1}_{-4.0}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$11.9^{+0.3}_{-0.4}$	✓	✓	–	✓	✓
GW170823	1850^{+840}_{-840}	$68.9^{+9.9}_{-7.1}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$12.1^{+0.2}_{-0.3}$	✓	✓	–	✓	✓

Residual Tests (LIGO/Virgo 2019)

- **Model**: best fitted model
- Residual = Data − Model
- Residual tests: consistent with noise distribution!

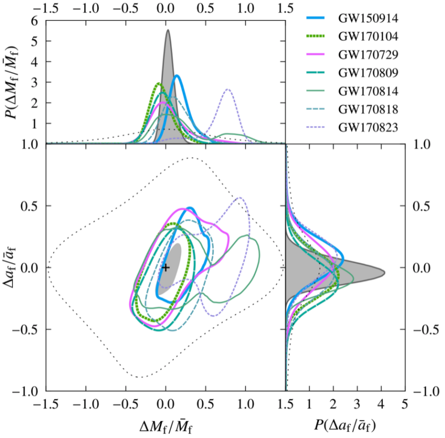
Event	IFOs	Residual SNR_{90}	Fitting factor	*p*-value
GW150914	HL	6.4	≥ 0.97	0.34
GW151012	HL	6.9	≥ 0.81	0.18
GW151226	HL	5.7	≥ 0.91	0.76
GW170104	HL	5.2	≥ 0.94	0.97
GW170608	HL	7.8	≥ 0.90	0.07
GW170729	HLV	6.5	≥ 0.87	0.72
GW170809	HLV	6.7	≥ 0.91	0.73
GW170814	HLV	8.6	≥ 0.90	0.19
GW170818	HLV	10.1	≥ 0.78	0.13
GW170823	HL	5.4	≥ 0.92	0.89



IMR Consistency Tests (LIGO/Virgo 2019)

- Parameter estimation *separately* with inpsiral and merger + ringdown
- Check consistency!

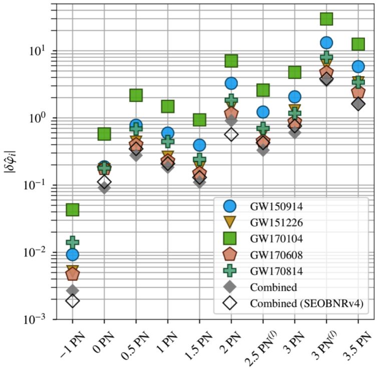
Event	f_c [Hz]	ρ_{IMR}	ρ_{insp}	$\rho_{post-insp}$	GR quantile [%]
GW150914	132	25.3	19.4	16.1	55.5
GW170104	143	13.7	10.9	8.5	24.4
GW170729	91	10.7	8.6	6.9	10.4
GW170809	136	12.7	10.6	7.1	14.7
GW170814	161	16.8	15.3	7.2	7.8
GW170818	128	12.0	9.3	7.2	25.5
GW170823	102	11.9	7.9	8.5	80.4

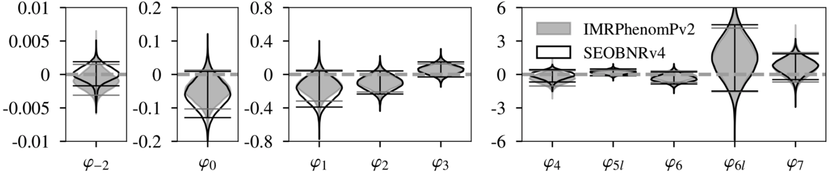


Parameterized Tests (LIGO/Virgo 2019)

$$\psi \sim \frac{3}{128\eta}(\pi f M)^{-5/3} \sum_{i=0}^{n} \varphi_i^{\rm GR} (\pi f M)^{i/3}$$

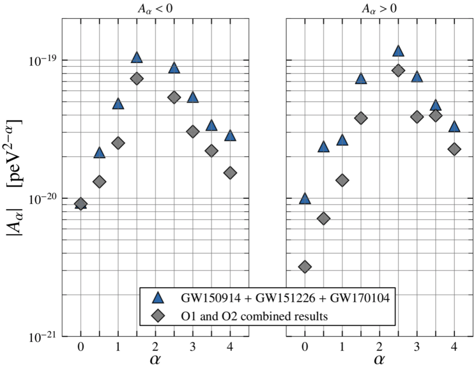
$$\varphi_i \to (1 + \delta\hat{\varphi}_i)\, \varphi_i^{\rm GR}$$





Modified Dispersion Relation (LIGO/Virgo 2019)

- **Lorentz violation**: $E^2 = p^2 c^2 + A_\alpha p^\alpha c^\alpha$
  - except $\alpha = 0$: massive gravity
  - LIGO/Virgo GWTC-1 $\Rightarrow m_g \leq 5.0 \times 10^{-23} \mathrm{eV}/c^2$



Modified Dispersion Relation (massive graviton)

- **Binary pulsars** are also used to constrain the graviton mass via bounding the gravitational backreaction
  - **Linearized gravity** with a massive graviton [Miao, Shao, et al. 2019]

$$S = \frac{1}{64\pi}\int \mathrm{d}^4 x \left[\partial_\lambda h_{\mu\nu}\partial^\lambda h^{\mu\nu} - 2\partial^\nu h_{\mu\nu}\partial_\lambda h^{\mu\lambda} + 2\partial^\nu h_{\mu\nu}\partial^\mu h \right.$$
$$\left. -\partial^\mu h \partial_\mu h - 32\pi h_{\mu\nu} T^{\mu\nu} + m_g^2 \left(h_{\mu\nu} h^{\mu\nu} - \frac{1}{2} h^2 \right) \right]$$

  - **Cubic Galileon** with screening mechanics [Shao, Wex, Zhou 2020]

$$S = \int \mathrm{d}^4 x \left[-\frac{1}{4} h^{\mu\nu} (\mathcal{E} h)_{\mu\nu} + \frac{h^{\mu\nu} T_{\mu\nu}}{2M_{\mathrm{Pl}}} - \frac{3}{4} (\partial \pi_s)^2 \left(1 + \frac{1}{3\Lambda^3} \Box \pi_s \right) + \frac{\pi_s T}{2M_{\mathrm{Pl}}} \right]$$

Modified Dispersion Relation

- 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

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

Modified Dispersion Relation

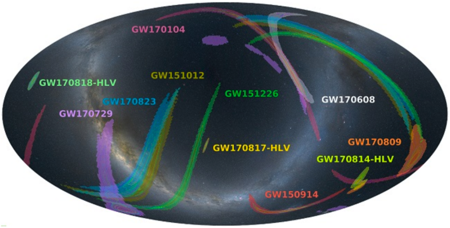
$$\omega = \left(1 - \zeta^0 \pm \sqrt{\left(\zeta^1\right)^2 + \left(\zeta^2\right)^2 + \left(\zeta^3\right)^2}\right) p$$

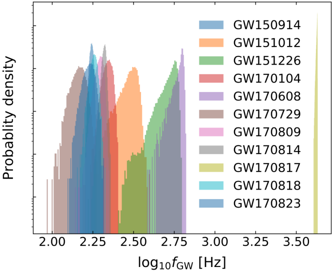
$$\zeta^0 = \sum_{djm} \omega^{d-4} Y_{jm}(\hat{\boldsymbol{n}}) k^{(d)}_{(I)jm}$$

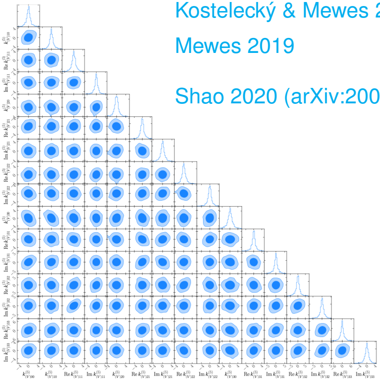
$$\zeta^1 \mp i\zeta^2 = \sum_{djm} \omega^{d-4}_{\pm 4} Y_{jm}(\hat{\boldsymbol{n}}) \left[k^{(d)}_{(E)jm} \pm i k^{(d)}_{(B)jm}\right]$$

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

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



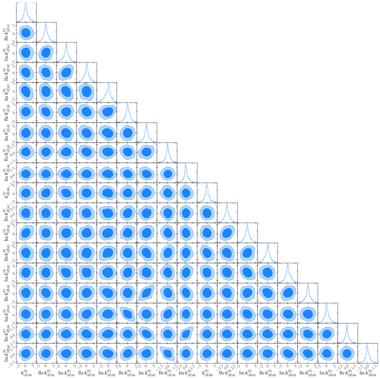




Kostelecký & Mewes 2016

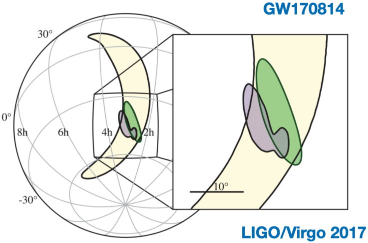
Mewes 2019

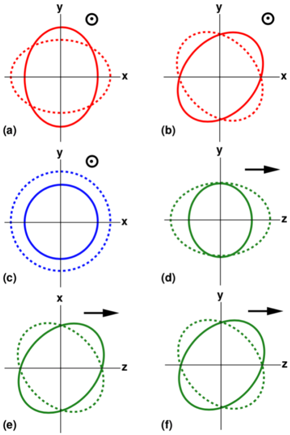
Shao 2020 (arXiv:2002.01185)



Polarization Tests (LIGO/Virgo 2019)

- **Triple** detections
  - GW170729, GW170809, GW170814, GW170818
- Bayes factors: 10^1–10^2
  - tensor vs vector
  - tensor vs scalar

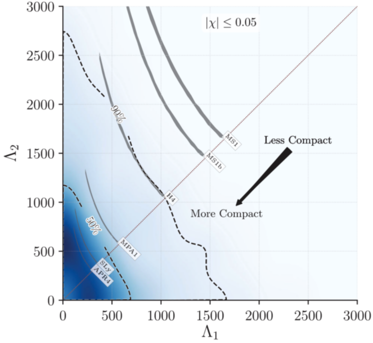


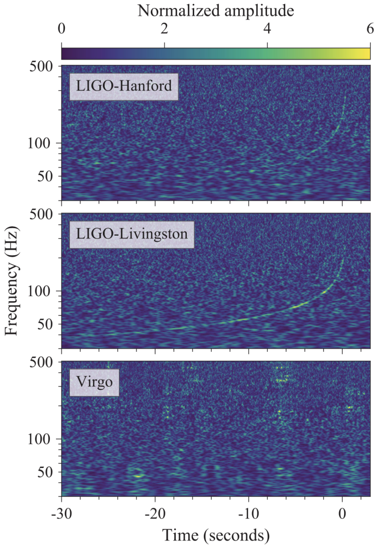


4. Binary Neutron Stars

Waveform: tidal deformability (LIGO/Virgo 2017)

- **SEOBNRv4T**
  - tidal deformability
  - equation of state



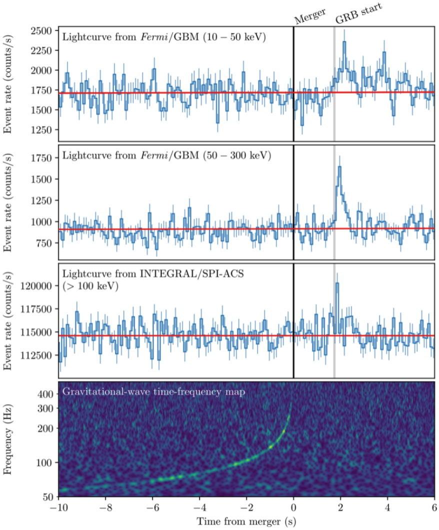


Speed of Gravity (LIGO/Virgo 2017)

- The famous 1.7 sec

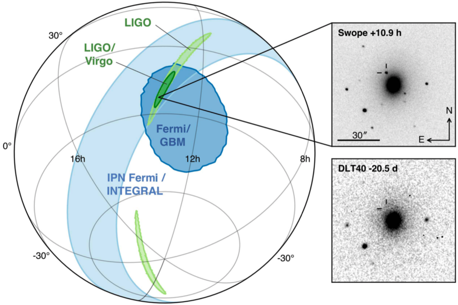
$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\rm EM}} \leqslant +7 \times 10^{-16}$$

- strong implications on cosmological models
  - ... tons of PRL papers



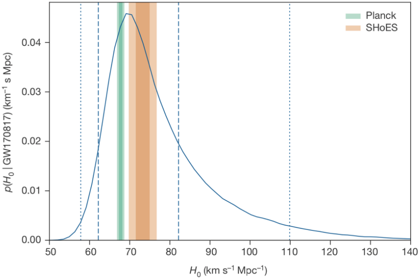
Polarization Tests (LIGO/Virgo 2019)

- Precise localization: NGC 4993
- Bayes factors
  - tensor vs vector: 10^{21}
  - tensor vs scalar: 10^{23}
- **much** tighter than BBHs

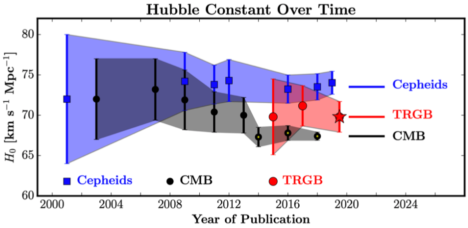


Hubble Constant (LIGO/Virgo 2017)

- By simultaneously measuring redshift and luminosity distance, GWs provide an independent way to probe cosmological parameters [Schutz 1986]



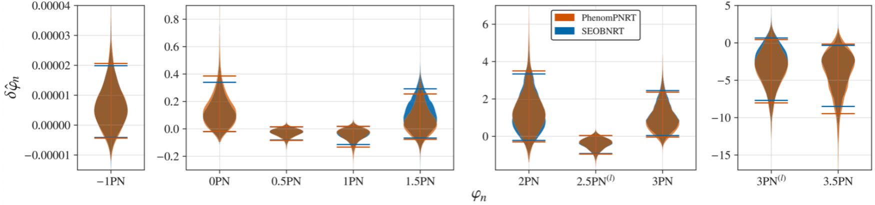
LIGO/Virgo 2017



arXiv:1907.05922 (ApJ, in press)

The Carnegie-Chicago Hubble Program

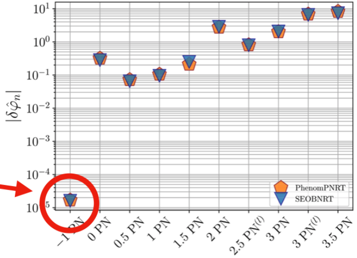
Parameterized Tests (LIGO/Virgo 2019)



$$\phi \sim \frac{3}{128\eta}(\pi f M)^{-5/3} \sum_{i=0}^{n} \varphi_i^{\rm GR} (\pi f M)^{i/3}$$

$$\varphi_i \to \left(1 + \delta\hat{\varphi}_i\right) \varphi_i^{\rm GR}$$

A tight constraint on dipole radiation

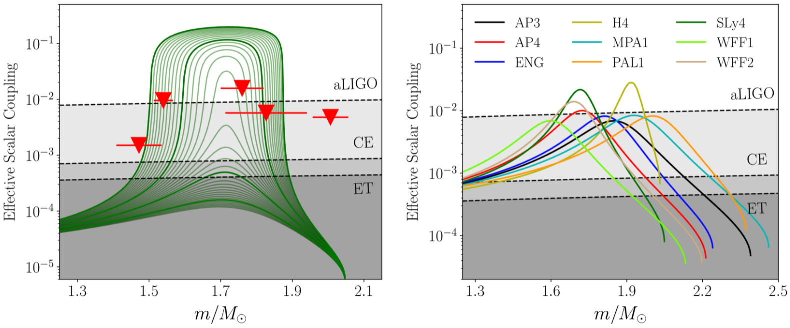


LIGO/Virgo 2019

Dipole Radiation strong-field scalarization

- Strong-field calarization happens for NSs

$$S = \frac{c^4}{16\pi G_*} \int \frac{d^4x}{c} \sqrt{-g_*} \left[R_* - 2g_*^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi - V(\varphi) \right] + S_m \left[\psi_m ; A^2(\varphi) g^*_{\mu\nu} \right]$$

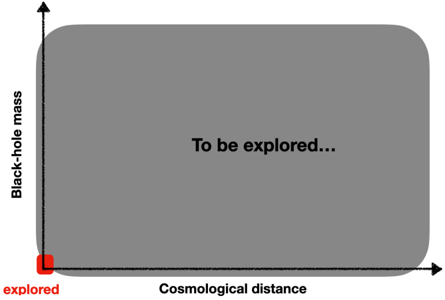


Damour & Esposito-Farèse 1993, PRL; Shao et al. 2017, PRX; Zhao, Shao, et al. 2019, PRD

5. Summary

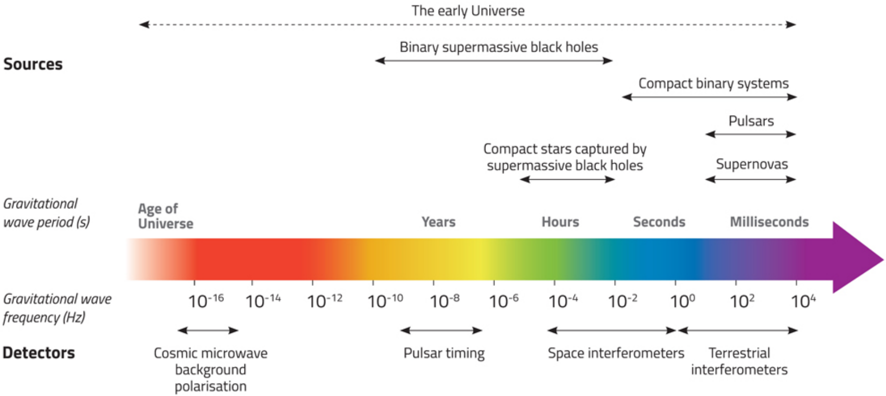
Summary

- **Einstein is still right**
- GWs launch a new era to test gravity
- Hope something new emerges *soon*



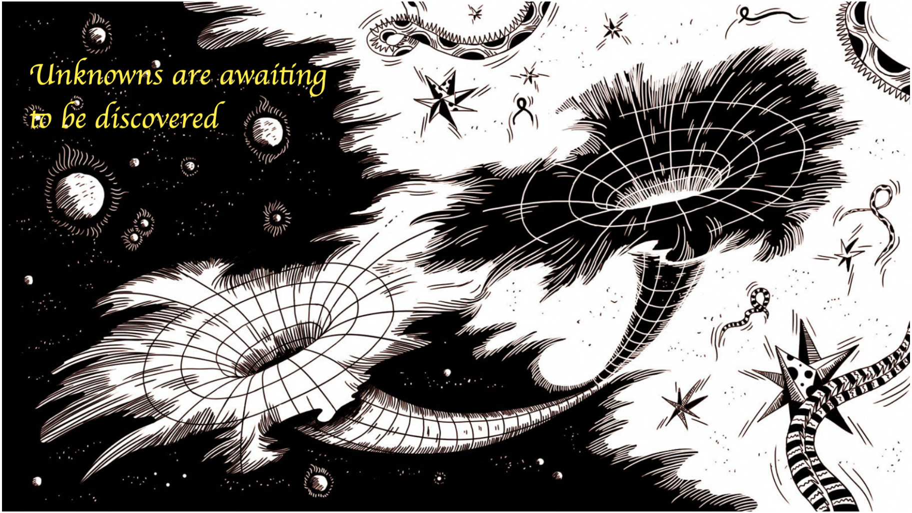
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Albert Einstein (1915)



Only a tiny part of GW spectrum was revealed by now

Stay tuned!



An exciting era for astronomers & physicists


THANK YOU