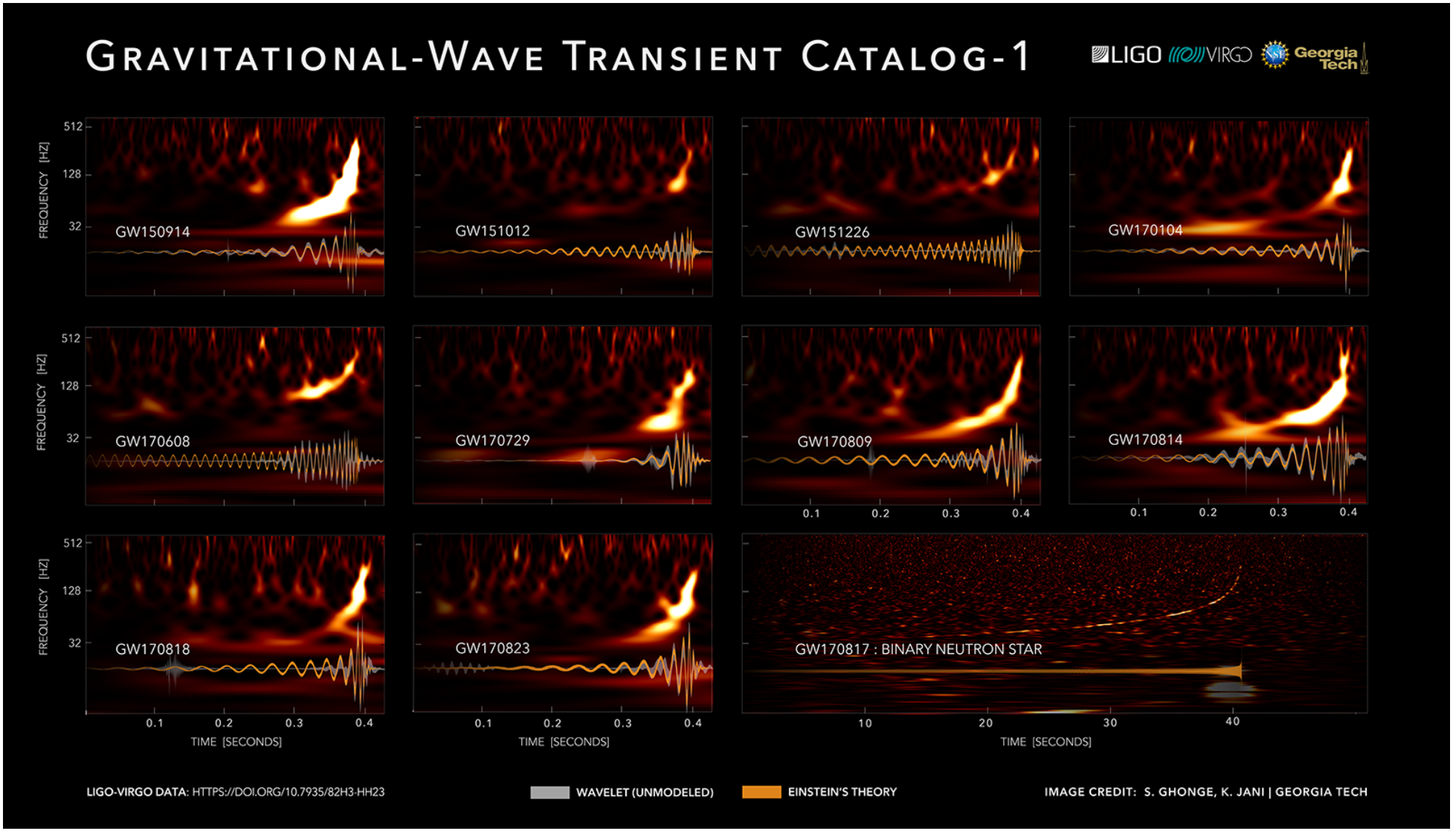
Gravitational-wave observations

Archisman Ghosh
Nikhef, Amsterdam

24$^{\text{th}}$Symposium on Astroparticle Physics in the Netherlands
Wijk aan Zee; 2019 June 21

Nikhef

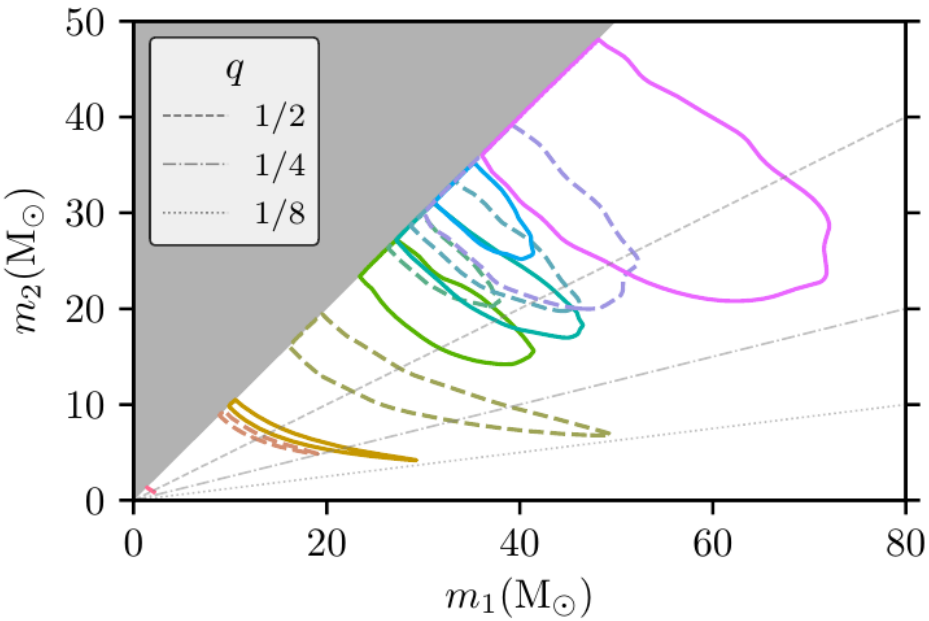
LSC VIRGO

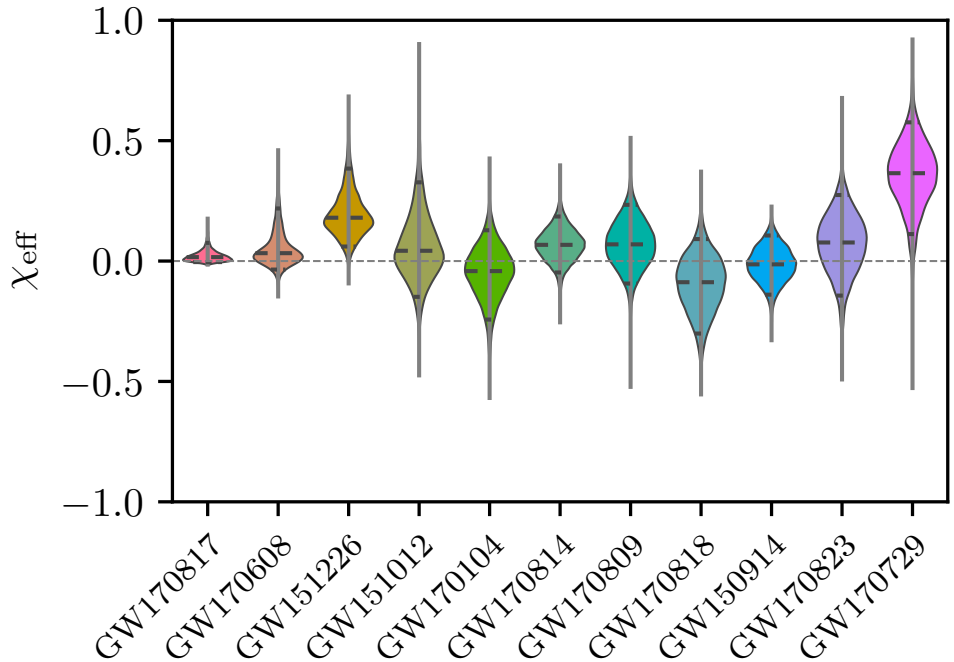

GRAVITATIONAL-WAVE TRANSIENT CATALOG-1
LIGO VIRGO Georgia Tech
FREQUENCY [HZ]
512
128
32
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
GW170817 : BINARY NEUTRON STAR
0.1
0.2
0.3
0.4
10
20
30
40
TIME [SECONDS]
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23
WAVELET (UNMODELED)
EINSTEIN'S THEORY
IMAGE CREDIT: S. GHONGE, K. JANI | GEORGIA TECH

GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs

The LIGO Scientific Collaboration and The Virgo Collaboration
(Compiled: 3 December 2018)

Abbott *et al.* arXiv:1811.12907 [astro-ph.HE]





GW170817 GW151226 GW170104 GW170809 GW150914 GW170729
GW170608 GW151012 GW170814 GW170818 GW170823

This talk: some highlights of the science results

- **Tests of general relativity**

Tests of General Relativity with the Binary Black Hole Signals from the LIGO-Virgo Catalog GWTC-1

The LIGO Scientific Collaboration and the Virgo Collaboration

Abbott *et al.* arXiv:1903.04467 [gr-qc]

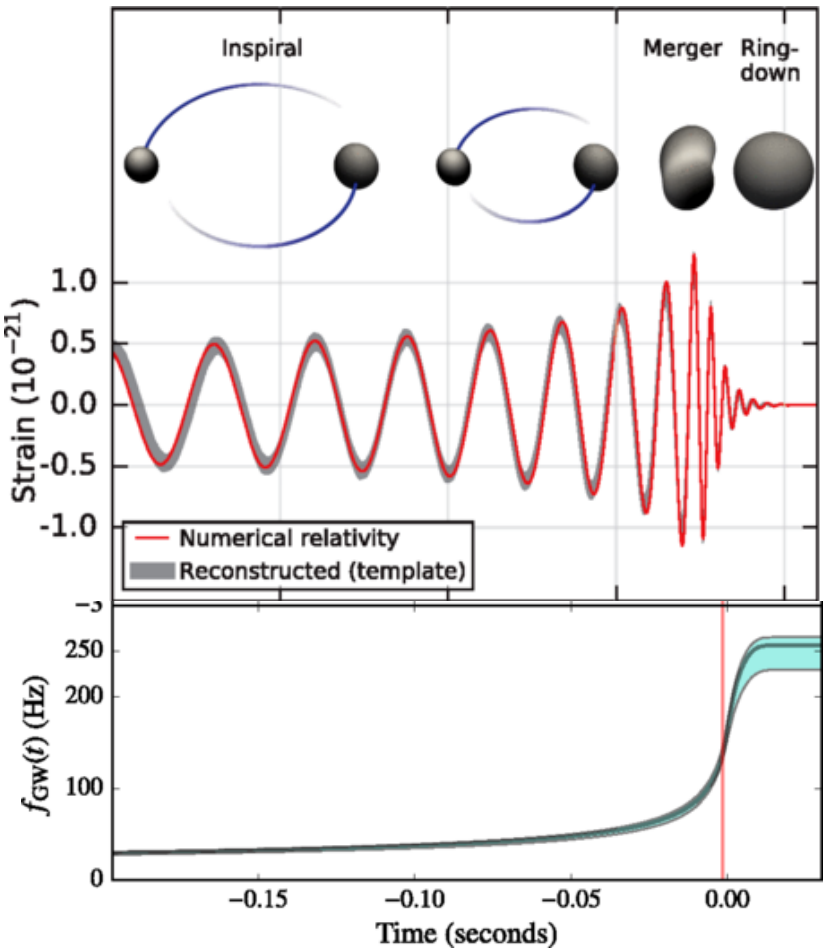
- Measurement of **internal properties of the neutron star**

- **Cosmology** with gravitational waves

Probing strong-field gravity

First probes into the dynamical regime of strong field general relativity (GR).

Abbott *et al.*, PRL **116**, 061102 (2016)



Abbott *et al.*, PRL **116**, 221101 (2016)

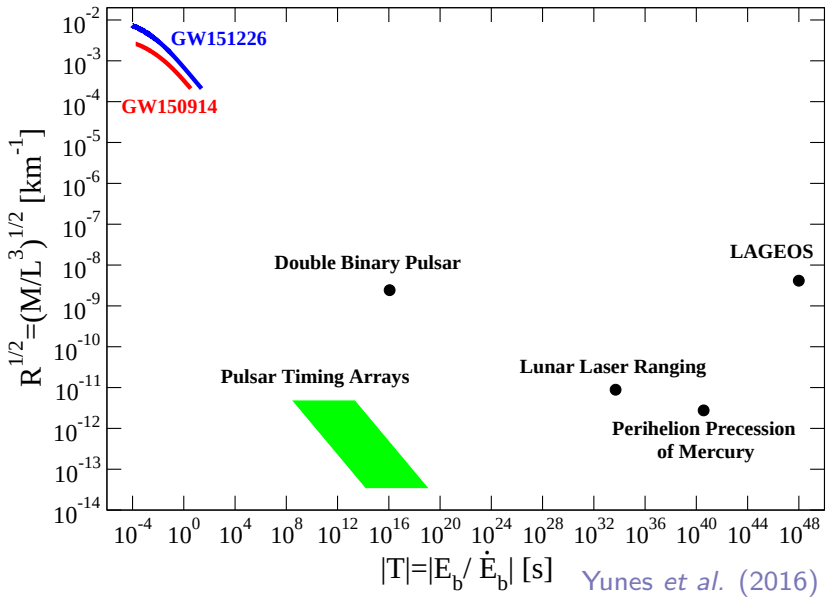
IMR sweeps through a range of frequencies.

PRL **116,** 221101 (2016) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 3 JUNE 2016

Tests of General Relativity with GW150914

B. P. Abbott *et al.**
(LIGO Scientific and Virgo Collaborations)

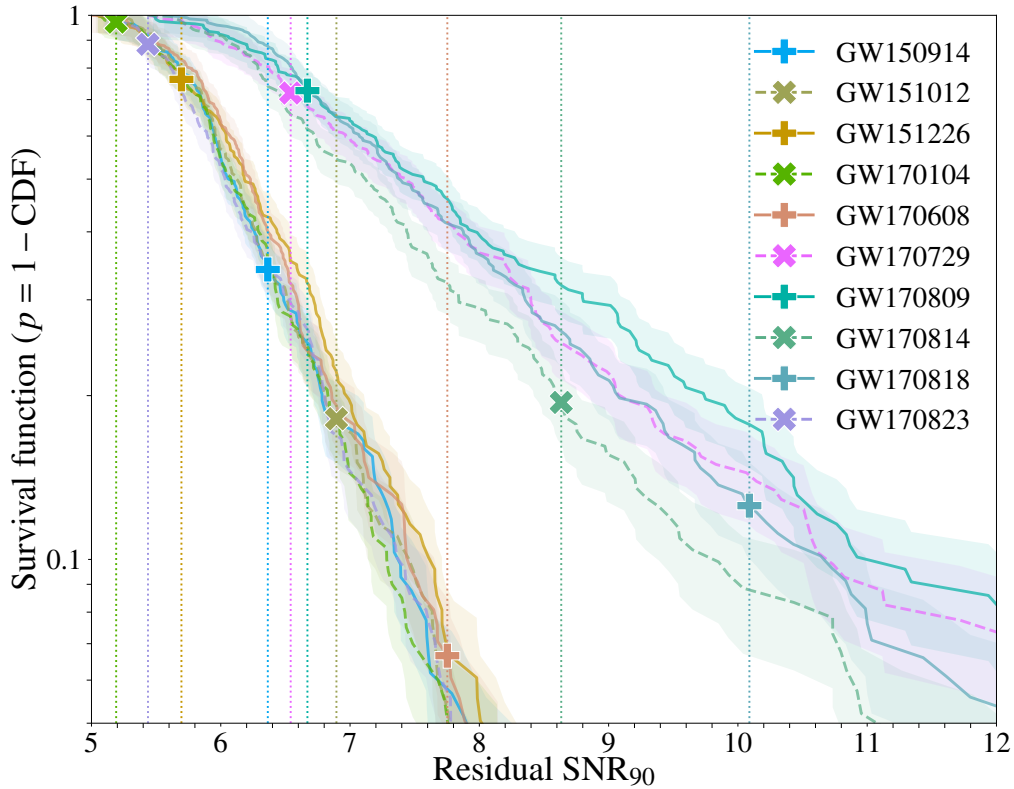
(Received 26 March 2016; revised manuscript received 9 May 2016; published 31 May 2016)



Yunes *et al.* (2016)

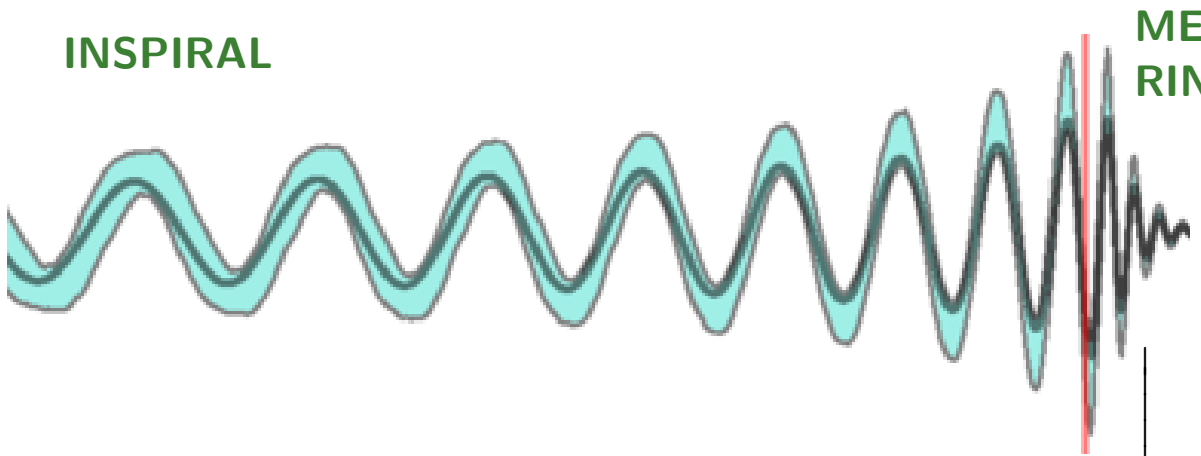
Residuals test

- Residuals of the data after subtracting the best-fit GR waveforms are statistically consistent with detector noise at other times when no signal is present.



Abbott *et al.* arXiv:1903.04467 [gr-qc]

Inspiral-merger-ringdown consistency test



Final mass and spin

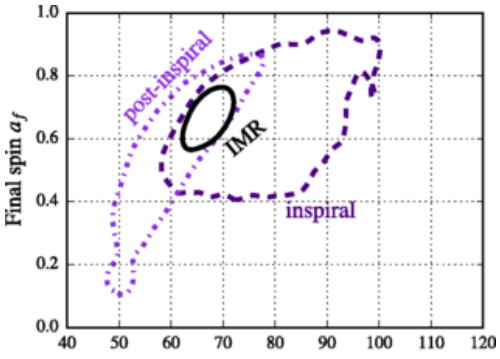
COMPARE!

Numerical relativity fit

Initial masses and spins

Independent prediction of final mass and spin

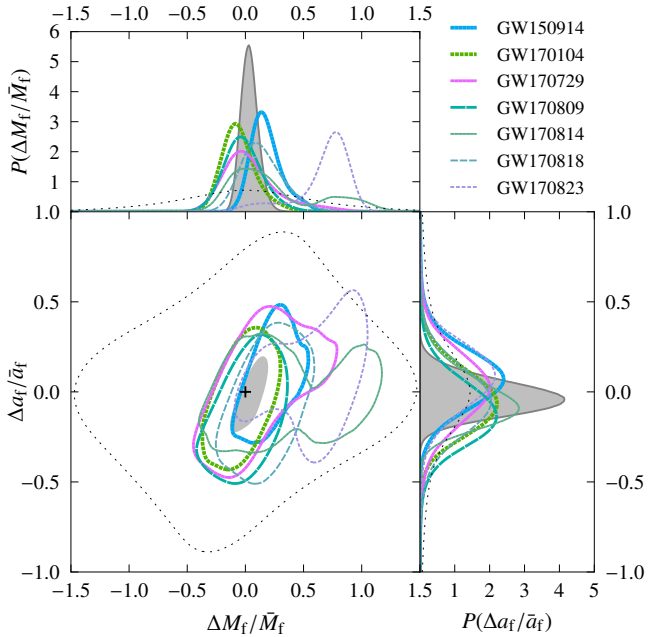
Inspiral-merger-ringdown consistency test



GW150914

Abbott *et al.*, PRL **116**, 221101 (2016)

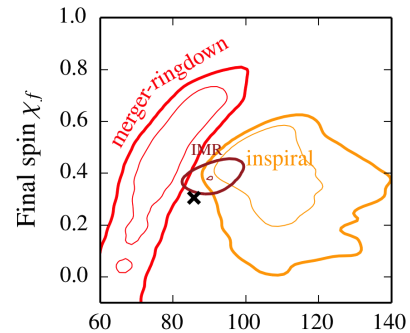
Abbott *et al.* arXiv:1903.04467 [gr-qc]



Mass and spin of the remnant object estimated from the inspiral and merger-ringdown parts agree with each other given GR predictions.

Ghosh *et al.* (2016); Ghosh *et al.* (2017)

Might not have been true in modified GR.



PHYSICAL REVIEW D **94,** 021101(R) (2016)

Testing general relativity using golden black-hole binaries

Abhirup Ghosh,[1] Archisman Ghosh,[1] Nathan K. Johnson-McDaniel,[1] Chandra Kant Mishra,[1] Parameswaran Ajith,[1] Walter Del Pozzo,[2] David A. Nichols,[3] Yanbei Chen,[4] Alex B. Nielsen,[5] Christopher P. L. Berry,[2] and Lionel London[6]

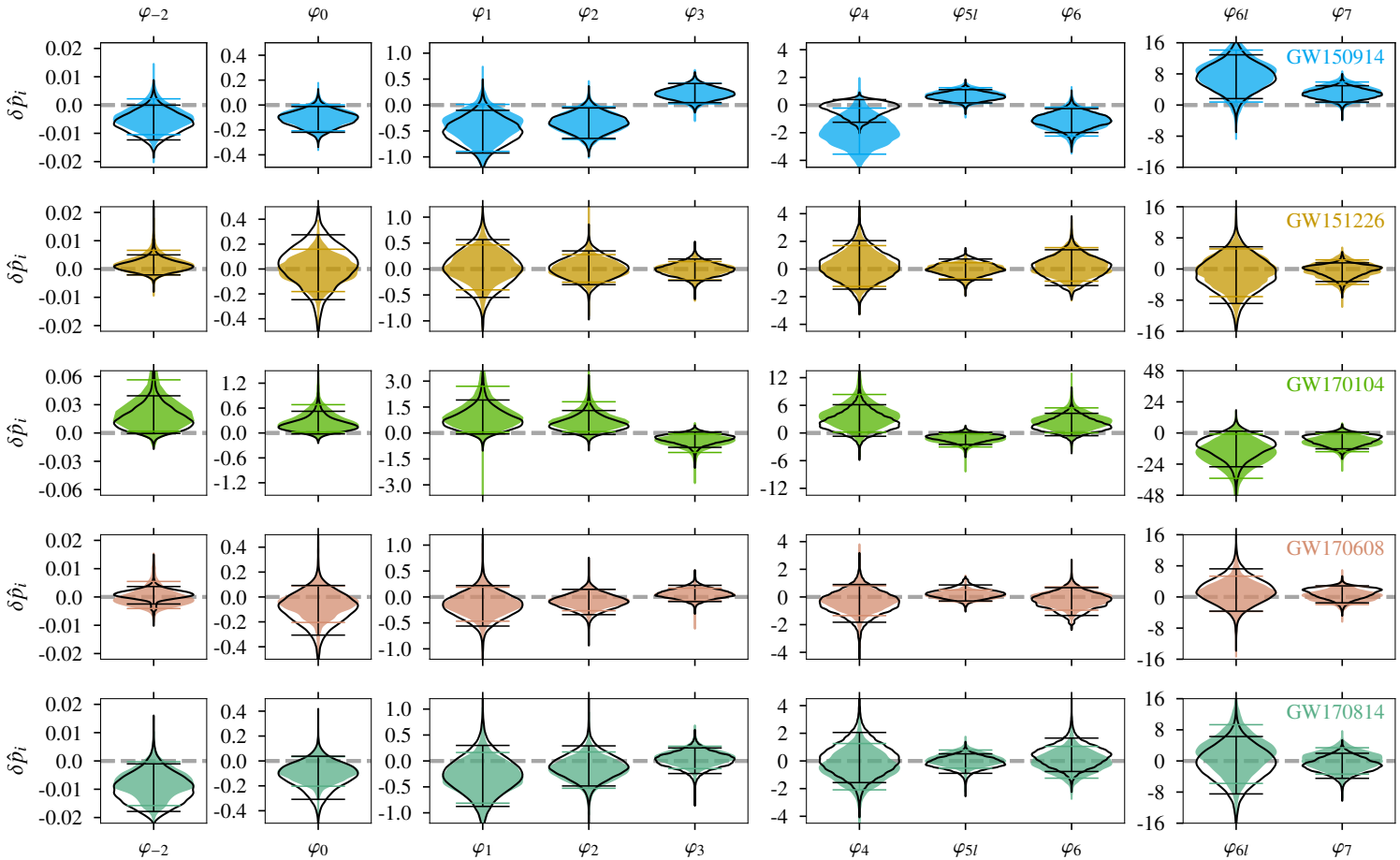
Stronger constraints on systematic departures from GR combining information from multiple detections.

Constraints on parameterized deformations from GR

Allowing coefficients in waveform models to deviate from their GR values, the deviation parameters do not show any departure from their GR values.

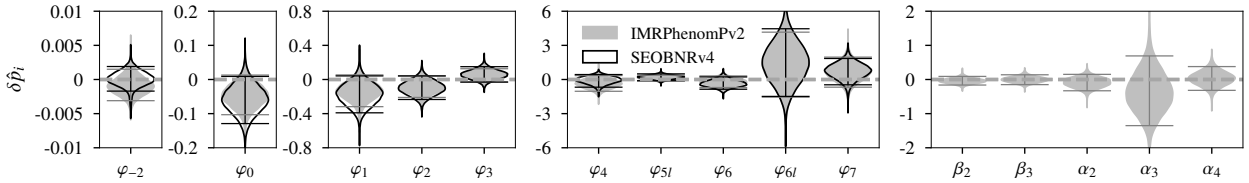
Li *et al.* (2011); Agathos *et al.* (2013); Meidam (PhD thesis, 2017); Meidam *et al.* (2017)

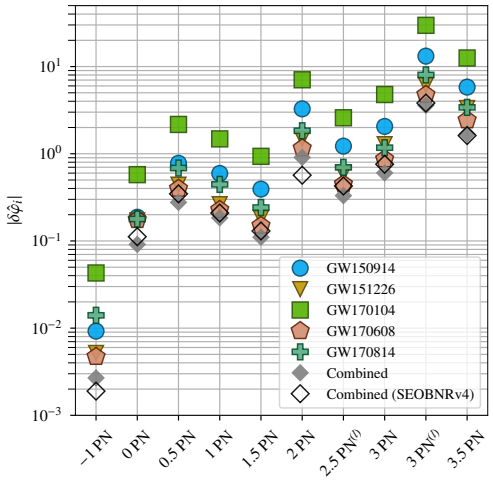
Abbott *et al.* arXiv:1903.04467 [gr-qc]



Constraints on parameterized deformations from GR

Stronger constraints on parameterized deformations from multiple detections!





Abbott *et al.* arXiv:1903.04467 [gr-qc]

Dipole radiation

Measurement of orbital dynamics beyond leading order in v/c.

Deviation in $\left(\frac{v}{c}\right)^3$ coefficient constrained to $\mathcal{O}(10\%)$

Dynamical self-interaction of spacetime

Spin-orbit interaction

Constraints from modified dispersion

Will (1998); Mirshekari *et al.* (2012)

Modified dispersion relation:

(different frequencies travel with different speeds)

$$E^2 = p^2c^2 + \mathbb{A}\, p^\alpha c^\alpha$$

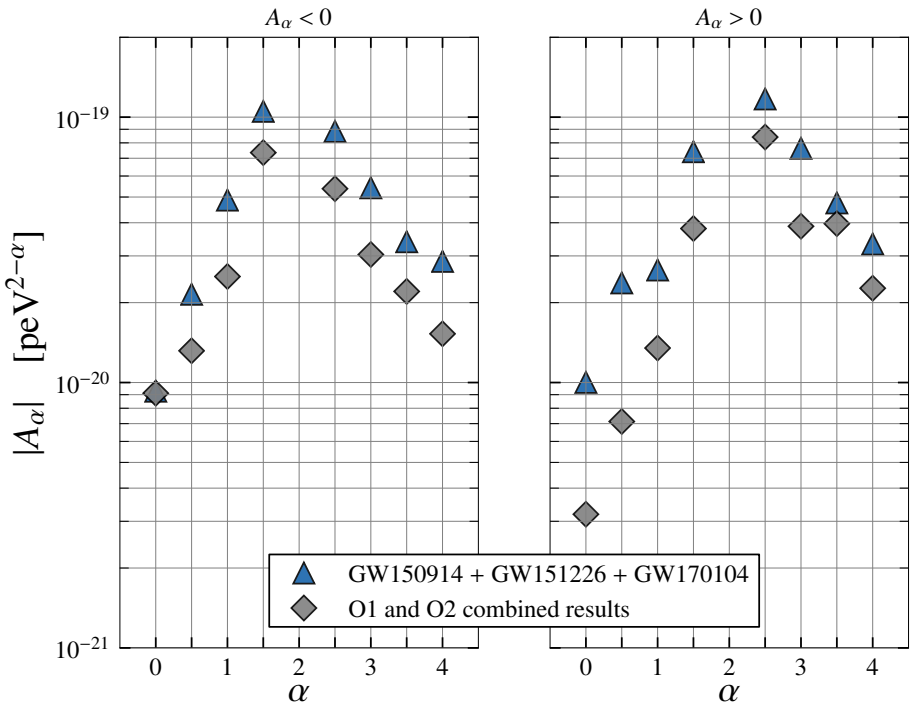
$$\lambda_{\mathbb{A}} \equiv hc\mathbb{A}^{1/(\alpha-2)}$$

$\alpha \neq 0 \quad \rightarrow \quad$ local Lorentz invariance violation

$\alpha = 0 \quad \rightarrow \quad$ massive graviton (for $\mathbb{A} > 0$)

$$\lambda_g \equiv \frac{h}{m_g c} > 2.5 \times 10^{13}\mathrm{km}$$

$$m_g < 5 \times 10^{-23}\mathrm{eV}/c^2$$

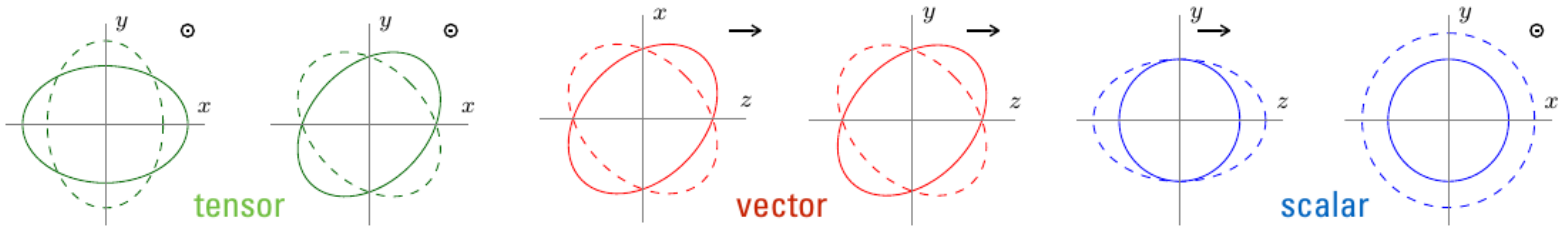


Abbott *et al.* arXiv:1903.04467 [gr-qc]

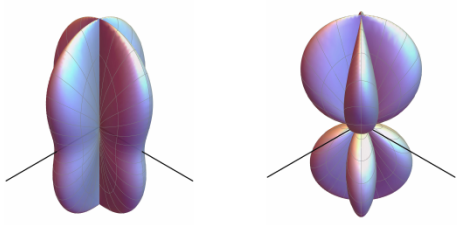
Agathos (PhD thesis, 2016); Samajdar (PhD thesis, 2017); Samajdar & Arun (2017)

Hubble scale $\approx 1.3 \times 10^{23}\mathrm{km}$

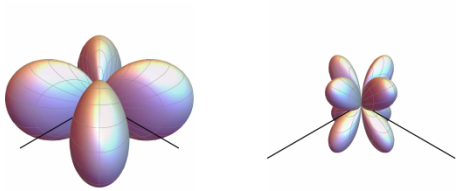
Polarization from 3-detector observation of GW170814



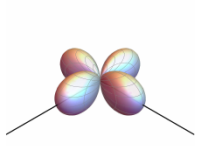
six polarizations $\longrightarrow$ distinct antenna patterns



(a) Plus (+) (b) Cross (×)



(c) Vector-x (x) (d) Vector-y (y)



(e) Scalar (s)

$$|F^I_{\rm t}(\alpha,\delta)| \equiv \sqrt{F^I_+(\alpha,\delta)^2 + F^I_\times(\alpha,\delta)^2}\,,$$

$$|F^I_{\rm v}(\alpha,\delta)| \equiv \sqrt{F^I_{\rm x}(\alpha,\delta)^2 + F^I_{\rm y}(\alpha,\delta)^2}\,,$$

$$|F^I_{\rm s}(\alpha,\delta)| \equiv \sqrt{F^I_{\rm b}(\alpha,\delta)^2 + F^I_{\rm l}(\alpha,\delta)^2}$$

In GR: GW are transverse, traceless
only tensor polarizations

pure tensor / pure scalar = 1000 / 1
pure tensor / pure vector = 200 / 1

Isi & Weinstein (2017)

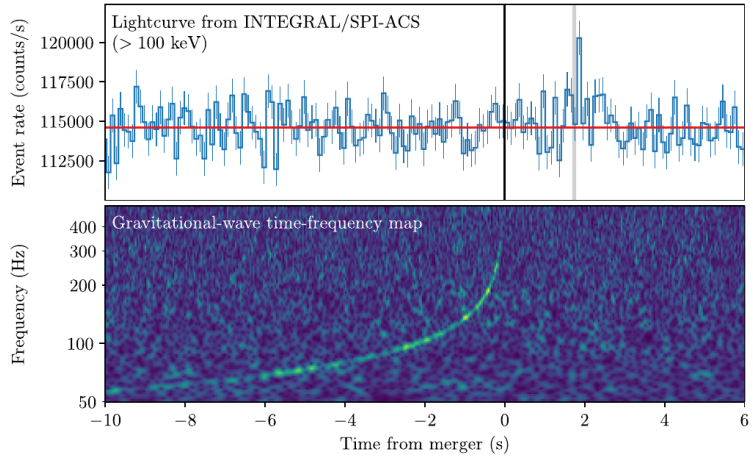
Need multiple detectors: **thanks to Virgo!**

Abbott *et al.*, PRL **119**, 141101 (2017)

Constraints from GW170817+GRB

Delay of only a few seconds after a propagation over one hundred million light years.

$$t_{\mathrm{EM}} - t_{\mathrm{GW}} = 1.74 \pm 0.05\,\mathrm{s}$$



Constraints on speed of gravity assuming GRB emitted within 10s of GW

$$-3 \times 10^{-15} \leqslant \frac{v_{\mathrm{GW}} - v_{\mathrm{EM}}}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}$$

"Shapiro time delay" of GW and EM in the gravitational potential of our galaxy:

$$-2.6 \times 10^{-7} \leqslant \gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}} \leqslant 1.2 \times 10^{-6}$$

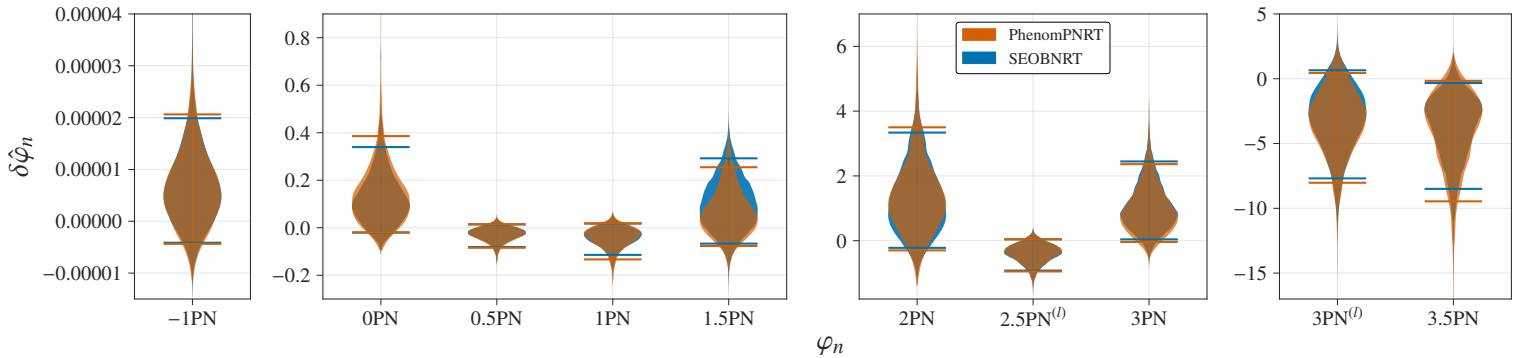
Test of the equivalence principle.

Abbott *et al.* Astrophys. J. **848** #2, L13 (2017)

Tests of general relativity with GW170817

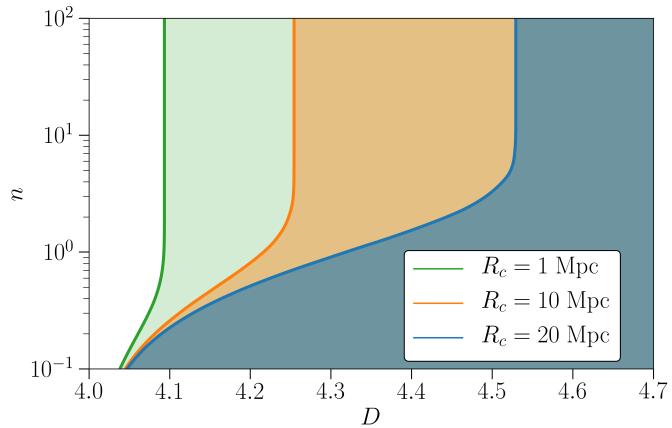
Dipole radiation

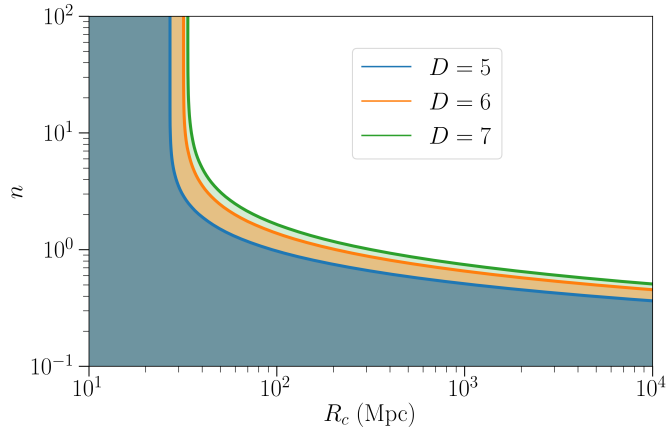
Abbott *et al.* arXiv:1811.00364 [gr-qc]



- Parameterized deviations do not show any departures from GR values.

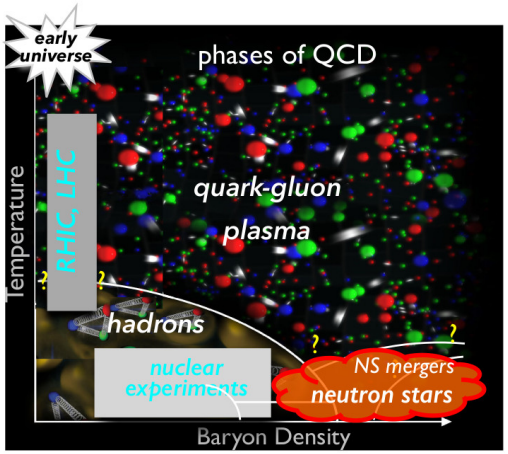
- Expected $1/r$ fall-off $\rightarrow$ constraints on extra dimensions.

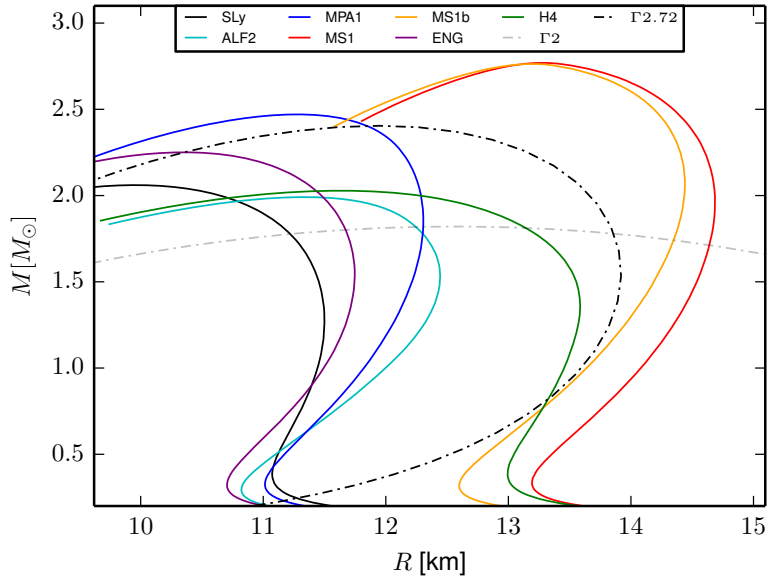


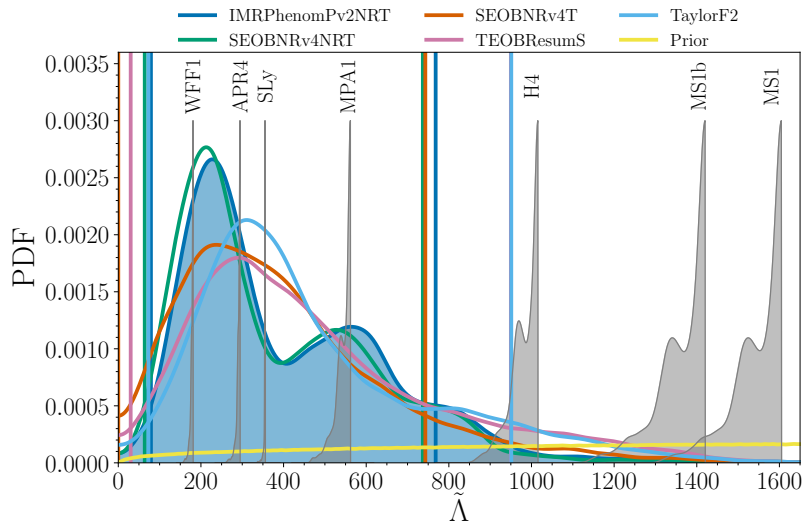


GW170817: measurement of properties of the neutron star

Figure from: Dietrich *et al.* (2015)







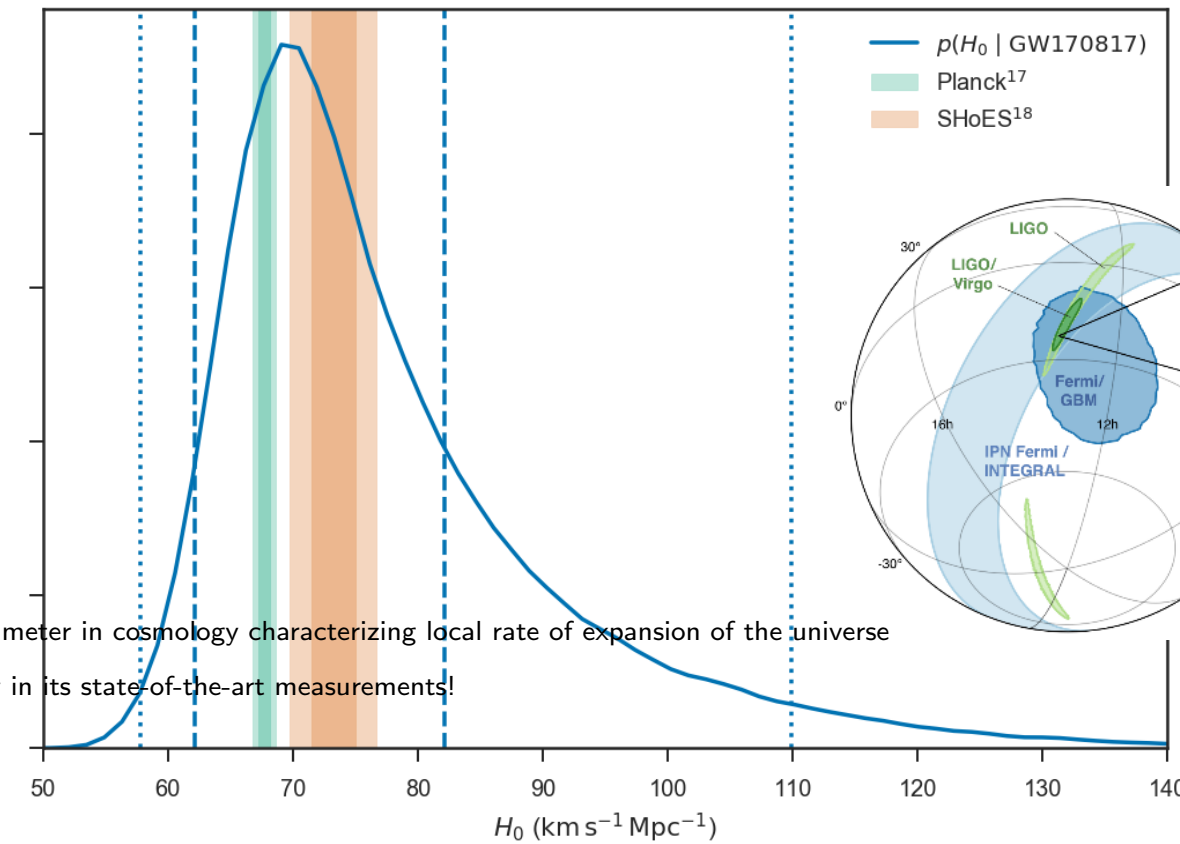
Abbott *et al.* arXiv:1811.12907 [gr-qc]

LETTER

doi:10.1038/nature24471

A gravitational-wave standard siren measurement of the Hubble constant

The LIGO Scientific Collaboration and The Virgo Collaboration*, The 1M2H Collaboration*, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration*, The DLT40 Collaboration*, The Las Cumbres Observatory Collaboration*, The VINROUGE Collaboration* & The MASTER Collaboration*



BNS: **GW170817**

Crucial parameter in cosmology characterizing local rate of expansion of the universe

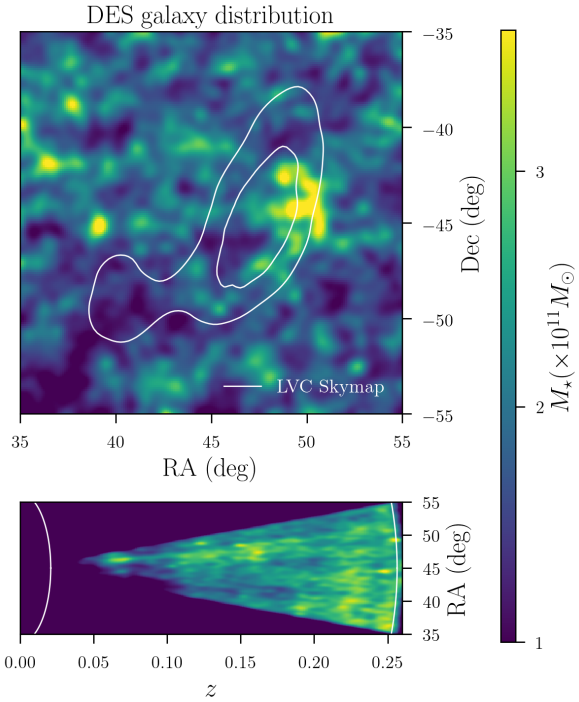
Discrepancy in its state-of-the-art measurements!

Optical counterpart: SSS17a

Multimessenger astronomy with GW and EM

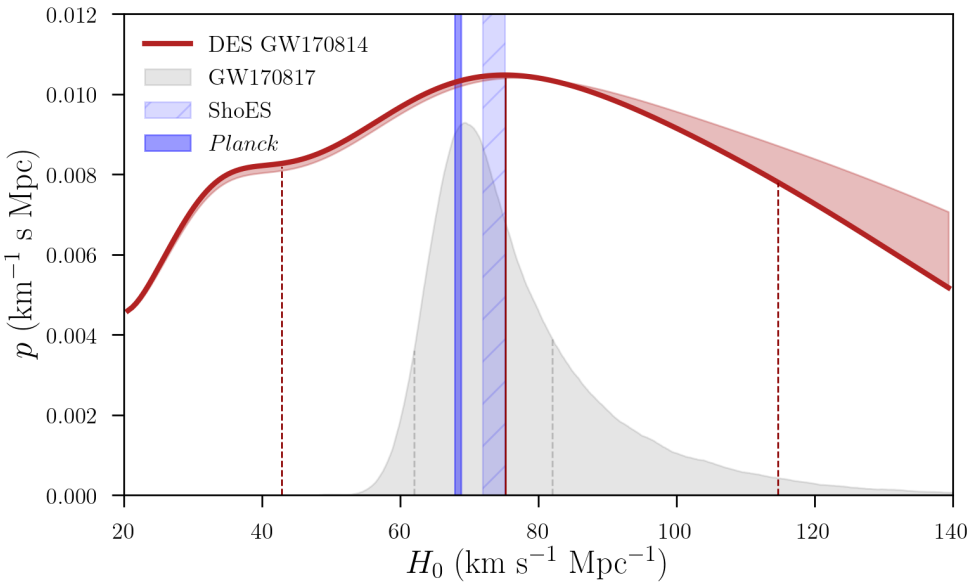
H_0 with DES galaxy catalogue and GW170814

- **DES Y3 "gold" catalogue:** thoroughly surveyed GW170814 sky region.



Possible galaxies from catalogues in absence of an EM counterpart.

Soares-Santos *et al.* (2019)



Future prospects

- Probing the nature of compact objects

Are they really black holes, or exotic compact objects mimicking black holes?

Boson stars, dark matter stars, gravastars, shells, wormholes, . . .

- Precise (multimessenger) measurement of the neutron star equation-of-state

- Precise GW measurement of H_0 and beyond

APRIL 2019

Sun	Mon	Tue	Wed	Thu	Fri	Sat
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14	15	16	17	18	19	20
X 21	22	23	24	X 25	X 26	27
28	29	30				

Credit: LVC/MPI-GP/Abhirup Ghosh

MAY 2019

SUN	MON	TUE	WED	THU	FRI	SAT
			1	2	3 X	4
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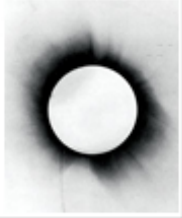
26	27	28	29 	30	31	