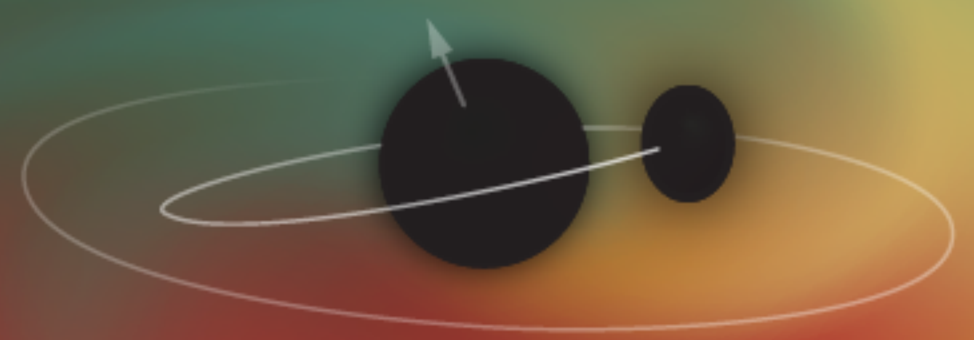
APS physics APRIL MEETING 2021

Q2C quarks cosmos

APRIL 17–20 ONLINE



Testing GR with LIGO & Virgo

Maximiliano Isi

NASA Einstein Fellow

Massachusetts Institute of Technology

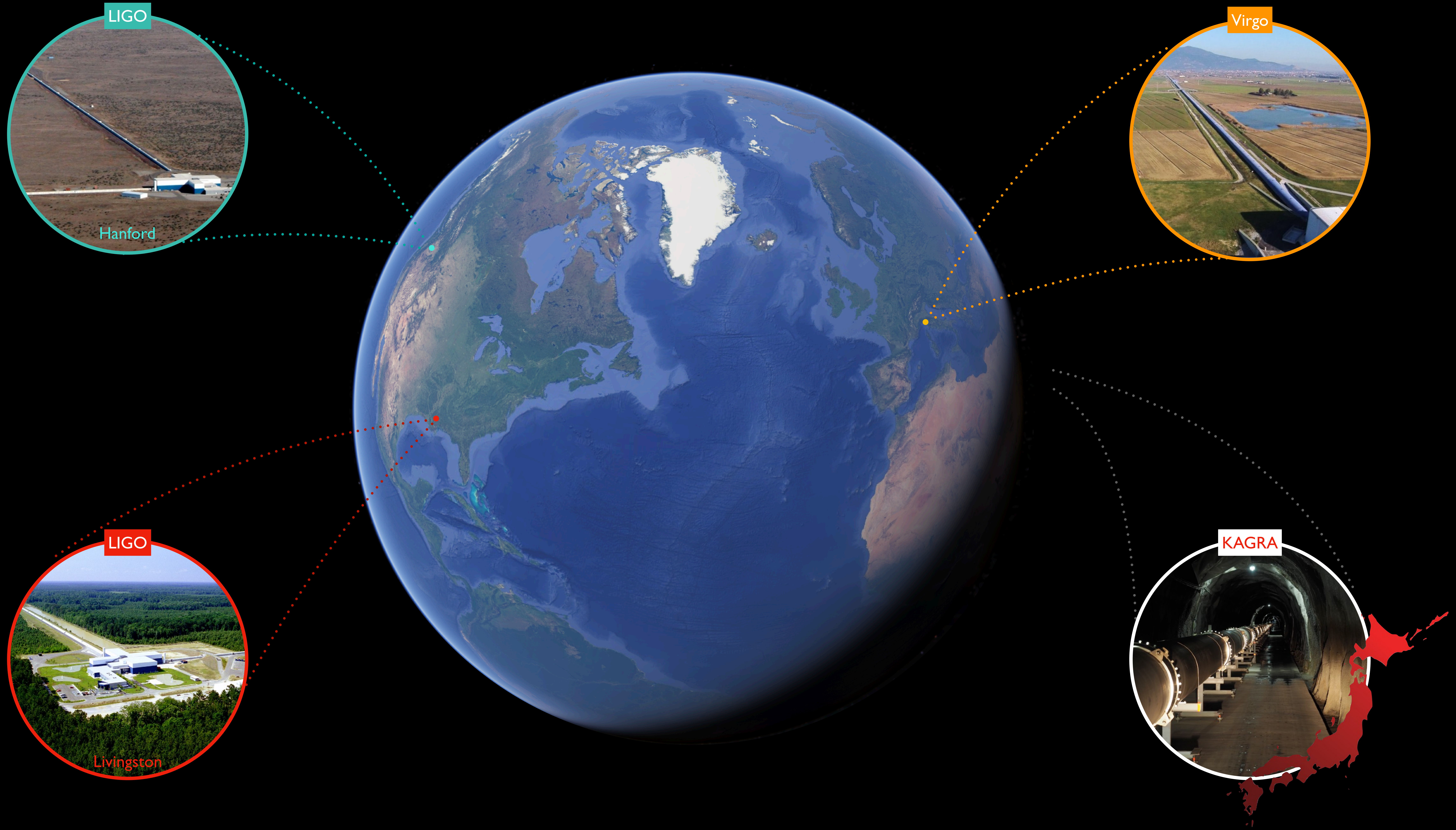


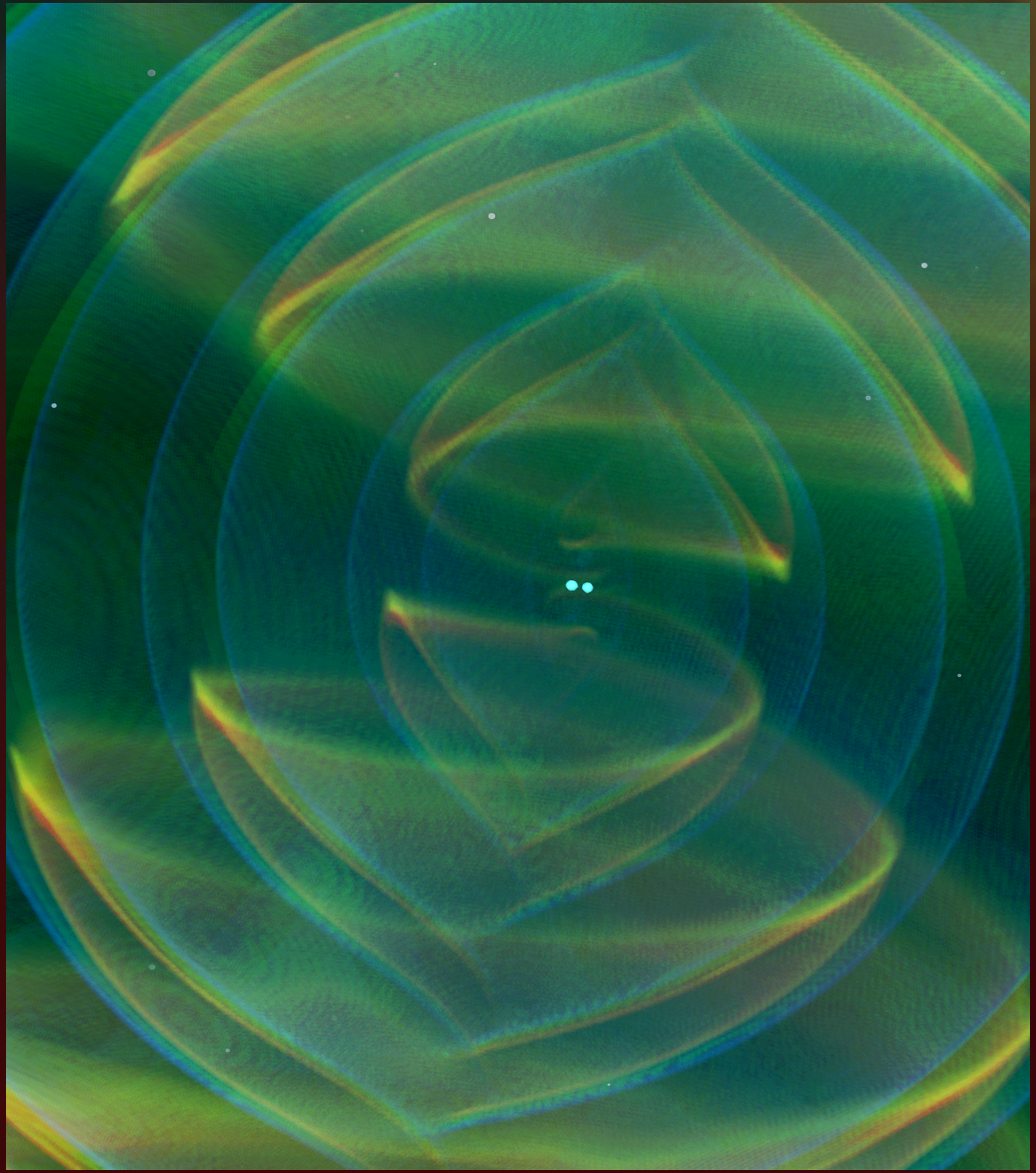
Image credits: Caltech, MIT, LIGO Lab | Virgo Collaboration, N. Baldocchi | KAGRA | Google, SIO, NOAA, US Navy, NGA, GEBCO Landsat / Copernicus IBCAO USGS INEGI

*GW150914 band-passed Hanford data

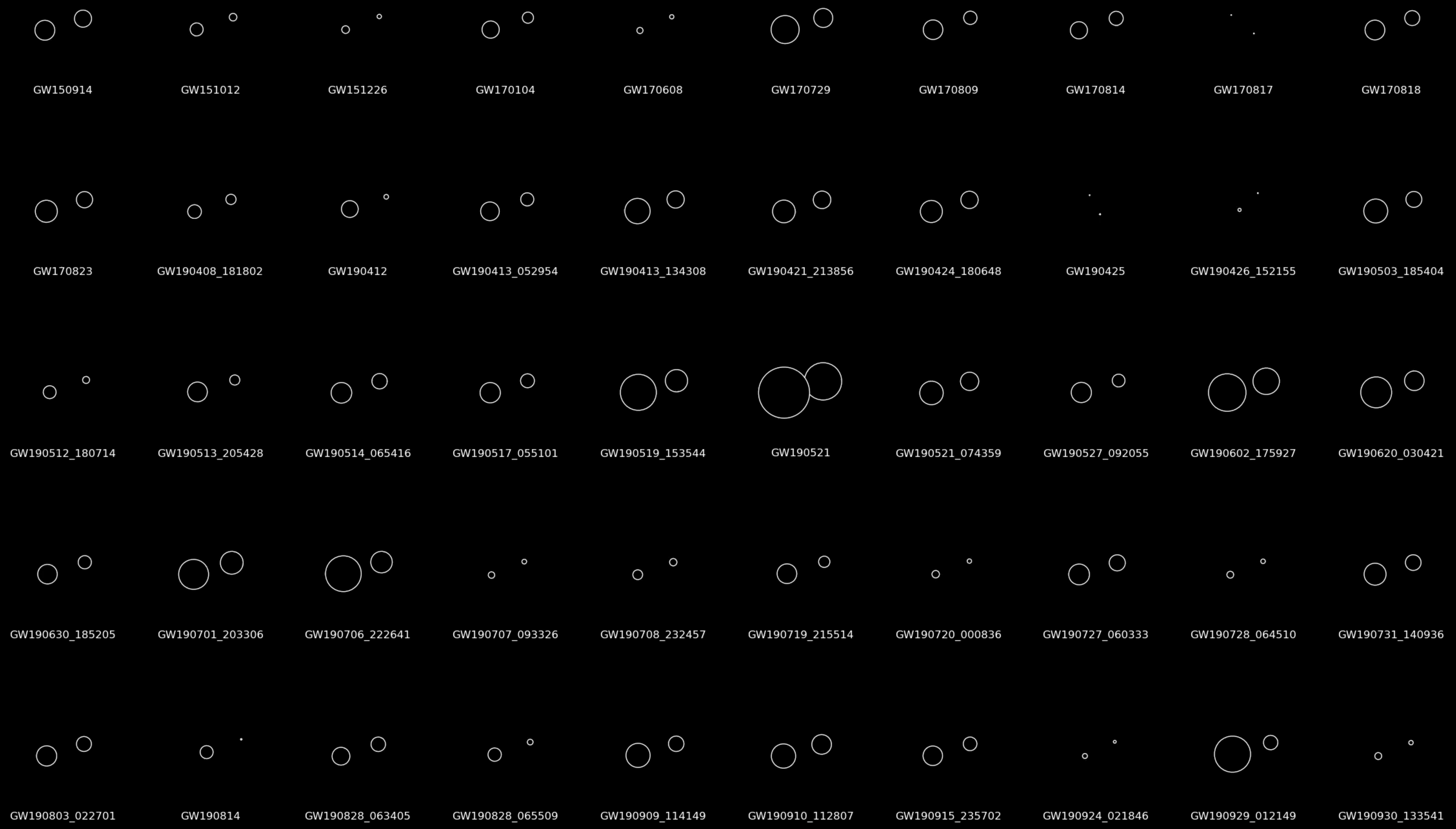
GW150914

Credit: SXS collaboration, LIGO

GW170817



Credit: T. Dietrich, S. Ossokine, H. Pfeiffer, A. Buonanno (MPI), BAM collaboration



Credit: Z. Doctor (LIGO-G2001856)

GWTC-2

second LIGO-Virgo transient catalog

Abbott et al (2020) [arXiv:2010.14527]

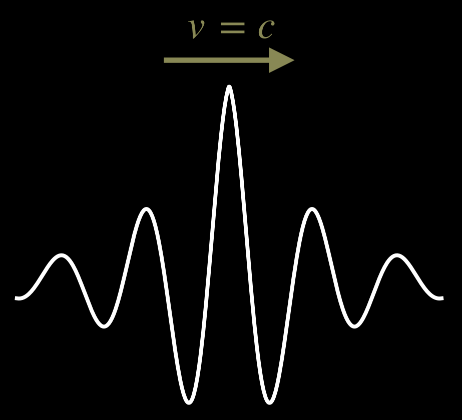
*many related talks, including overviews by
Surabhi Sachdev (T01.00003) & Tom Dent (K01.00002)

Credit: Z. Doctor (LIGO-G2001856)

testing GR with GWs

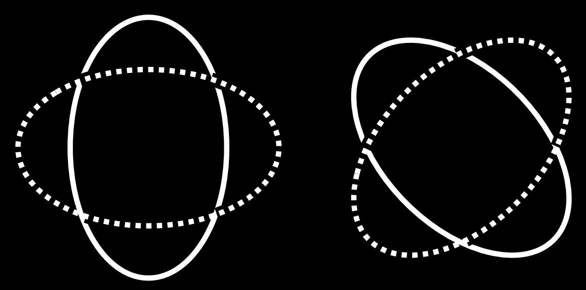
general relativity makes *very* specific predictions

radiation properties



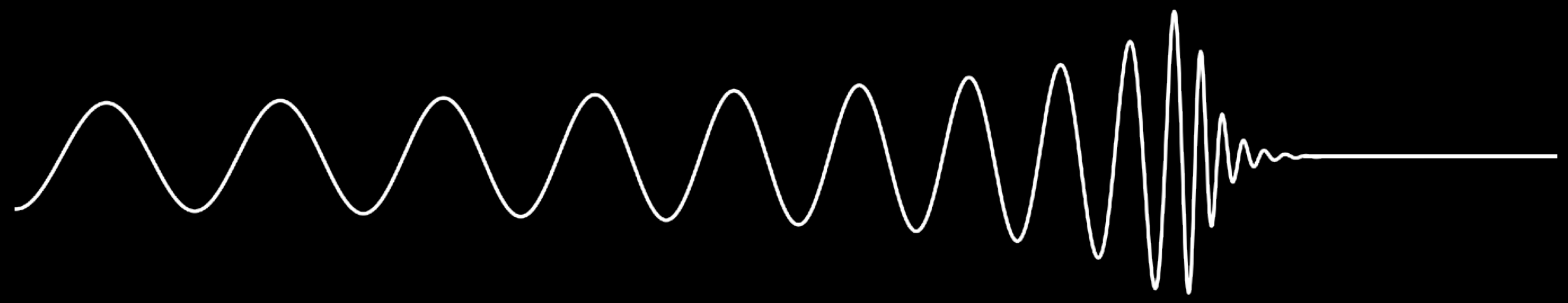
speed

non-dispersion

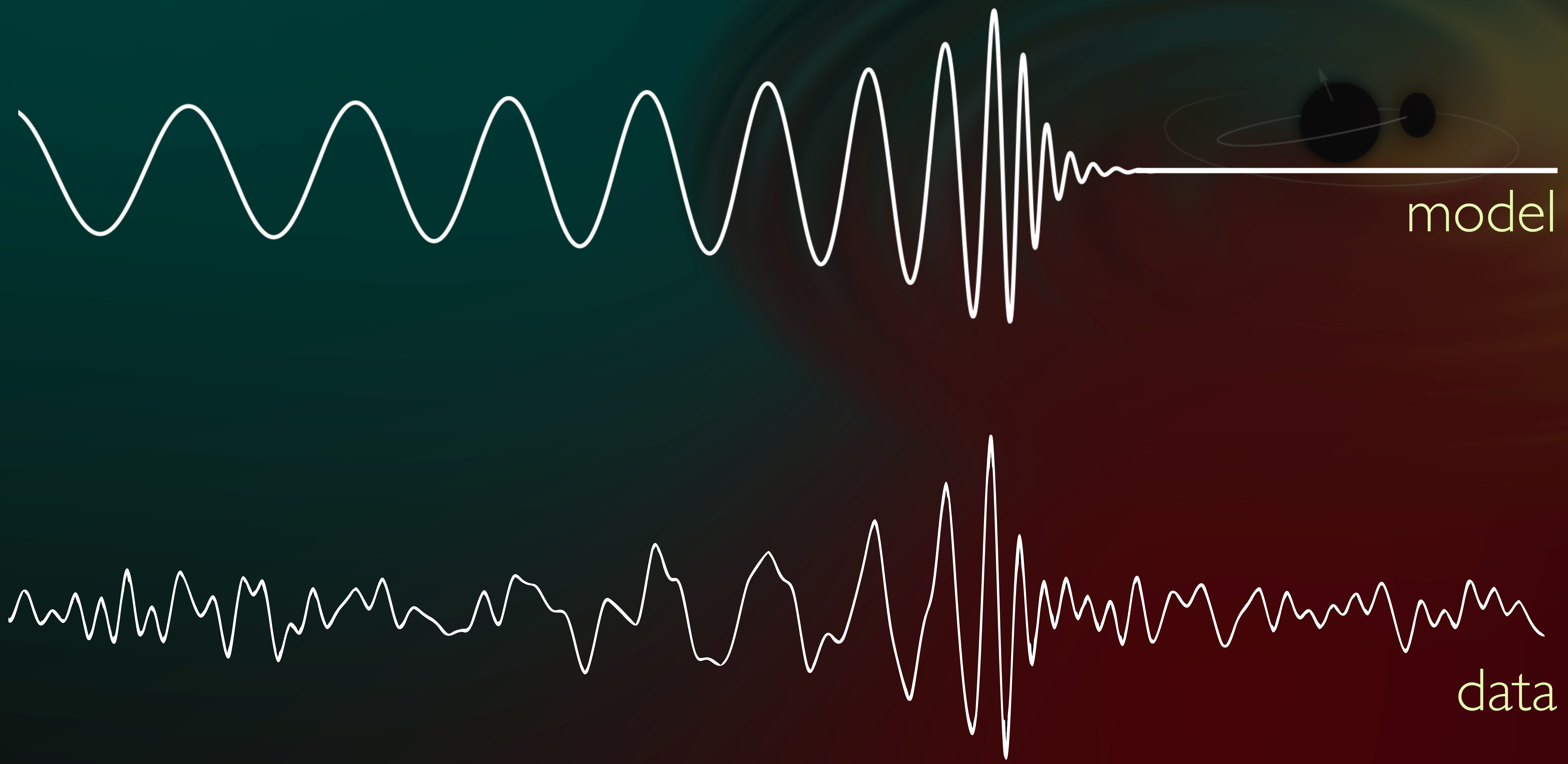


polarization

source dynamics



precise phase evolution



*GW150914 band-passed Hanford data

testing the model

model

GR + **approx** + **source** + **instrument**

approx: derive prediction efficiently

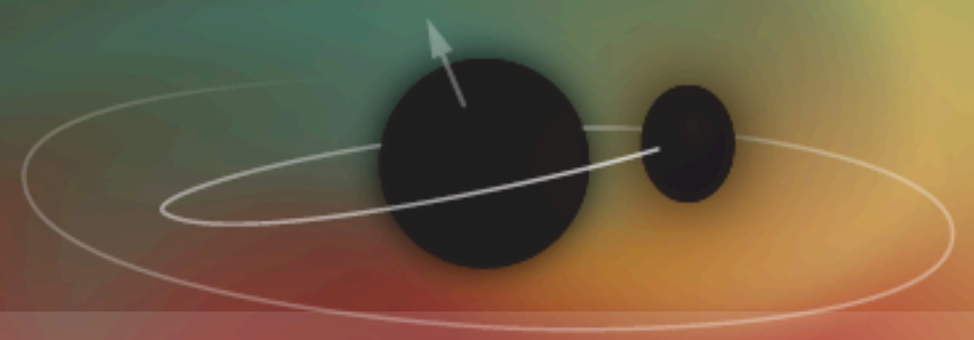
source: type of system, priors

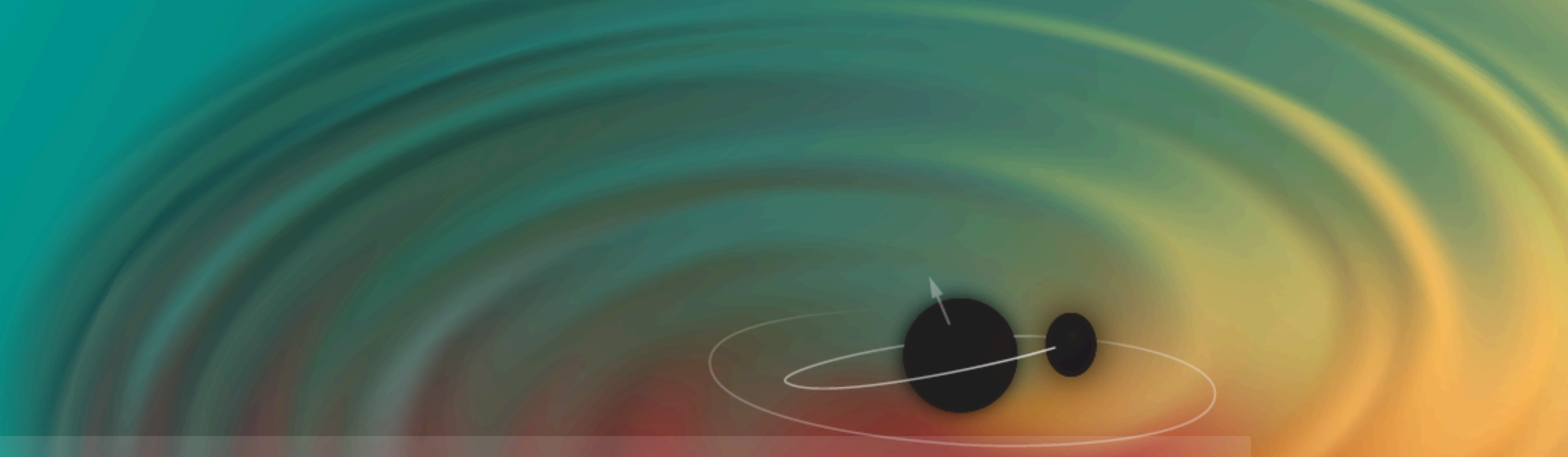
instrument: statistical behavior, calibration

example **null hypothesis**

signal from a non-eccentric binary BH within GR,
in stationary Gaussian noise of well-calibrated detectors

observational results

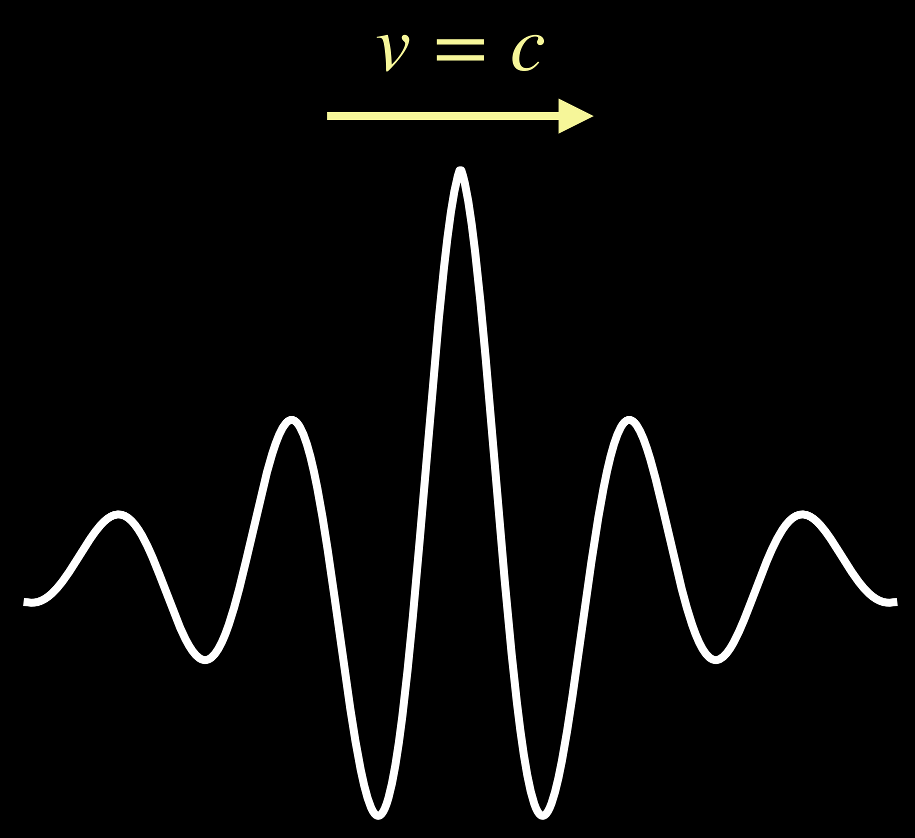




basic properties of gravitational waves

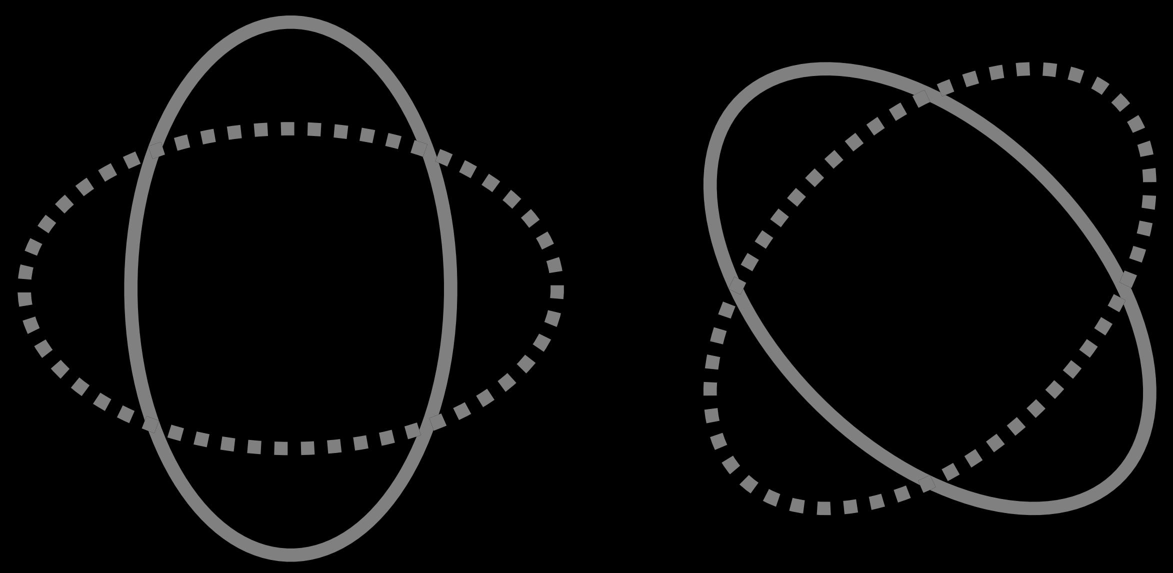
predictions

general relativity predicts basic gravitational-wave properties



speed

non-dispersion



polarization

speed

measure inter-detector arrivals ($\sim \pm 0.5c$)

Cornish+2017 [arxiv:1707.06101]

compare arrival to EM counterpart

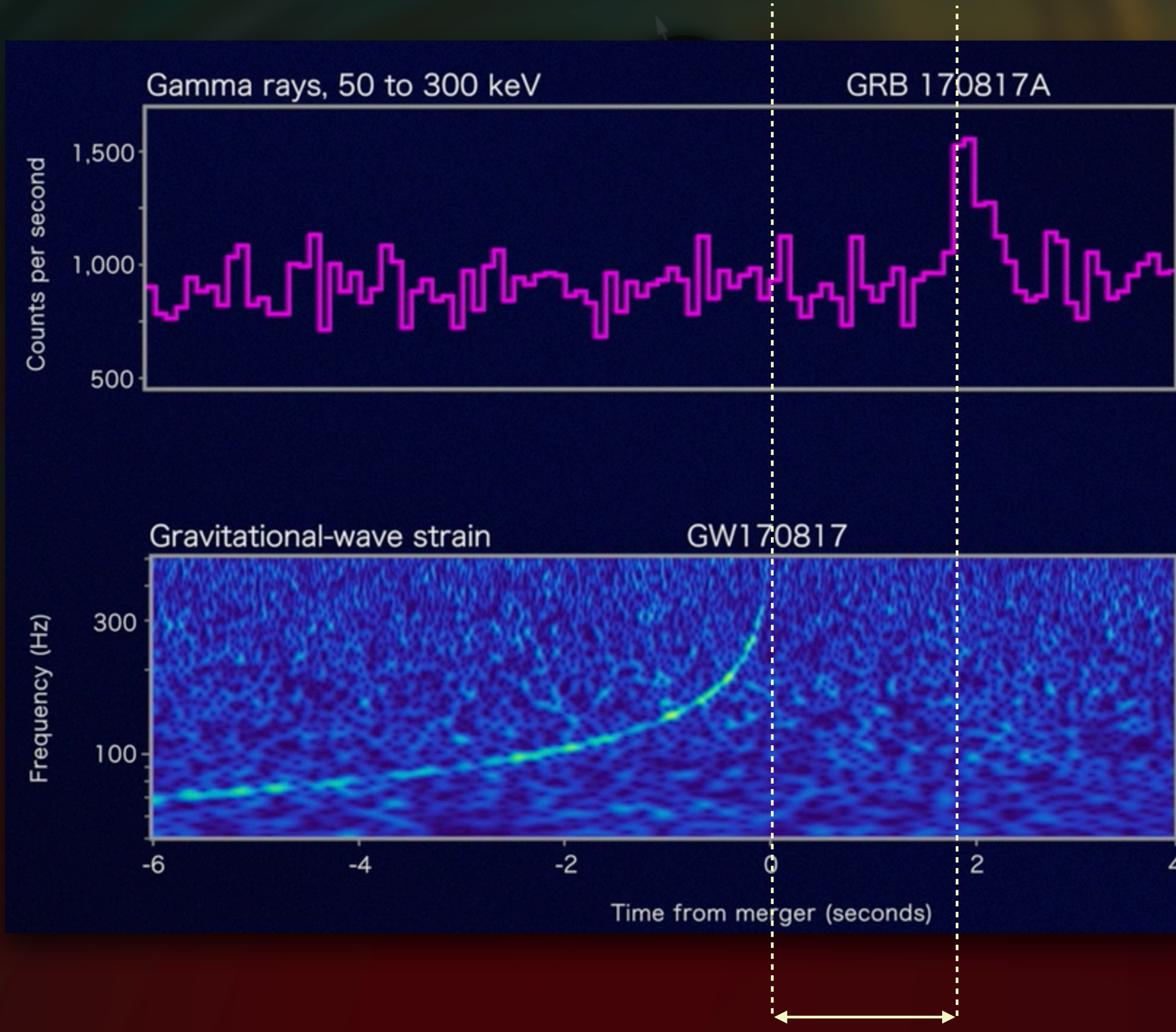
GW170817

$$-3 \times 10^{-15} \leq c_{\rm gw}/c - 1 \leq 7 \times 10^{-16}$$

Abbott+2017 [arxiv:1710.05834]

severely constrains cosmological-scale corrections to GR

Baker+2017 [arxiv:1710.06394], Creminelli+2017 [arxiv:710.05877], Ezquiaga+2017 [arxiv:1710.05901], Sakstein+2017 [arxiv:1710.05893]

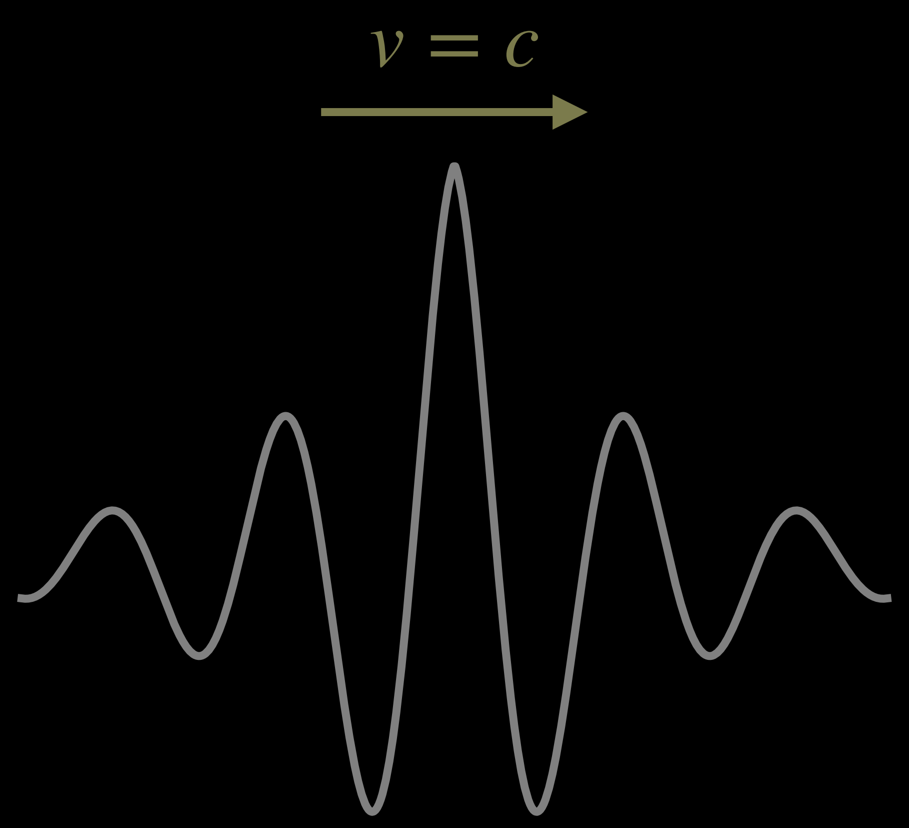


~1.7 s delay over ~40 Mpc

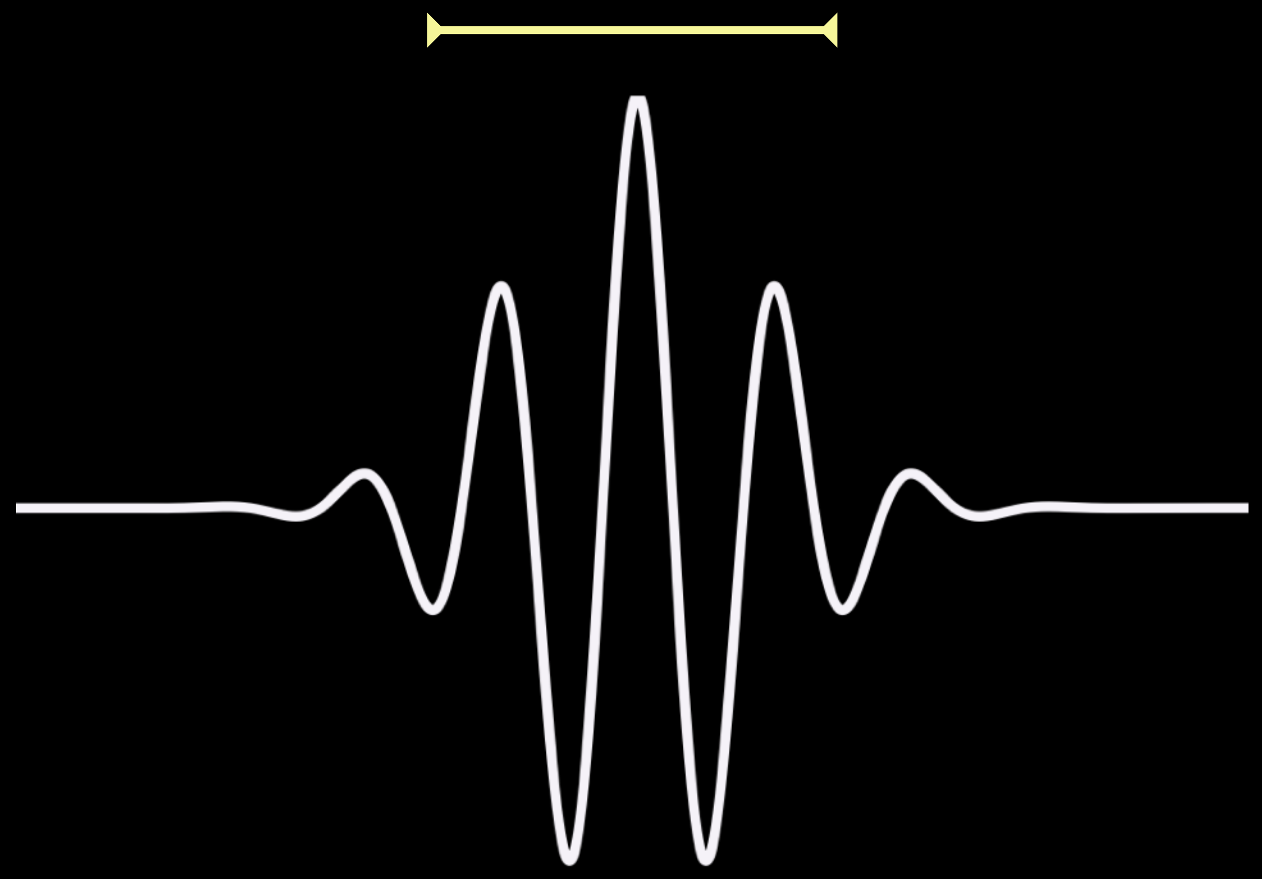
Graphic credit: NASA GSFC & LIGO-Virgo

predictions

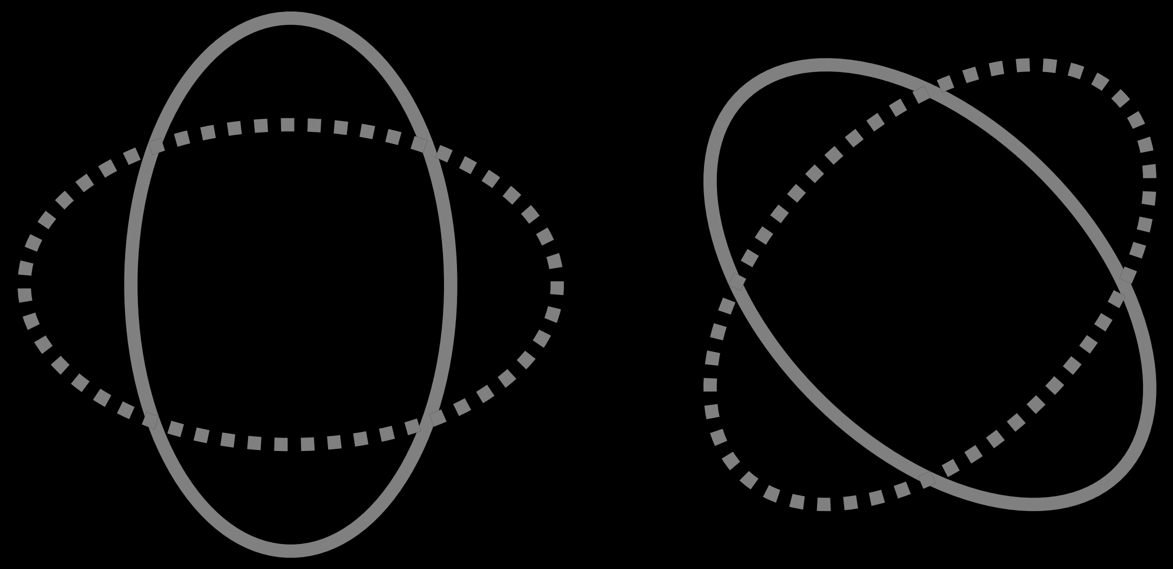
general relativity predicts basic gravitational-wave properties



speed



non-dispersion



polarization

dispersion

modify wave equation so GWs no longer exactly null

$$\omega^2 = k^2c^2 + \epsilon \longrightarrow v_\omega \approx c(1 + \epsilon/2\omega^2) \xrightarrow{\phi \approx \omega D/v} \Delta\phi \approx -\frac{D}{c}\frac{\epsilon}{2\omega}$$

adding a constant **ε** corresponds to a *massive graviton*

$$E^2 = p^2c^2 + m^2c^4 \longrightarrow \Delta\phi \propto -Dm^2/\omega$$

Will 1998 [arxiv:gr-qc/9709011]

more generally, make correction a function of frequency

$$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha \longrightarrow \Delta\phi \propto -DA_\alpha \omega^{\alpha-1}$$

Mirshekari+2012 [arxiv:1110.2720]

Lorentz violations

e.g., $\alpha = 3, 4$ in some quantum-gravity models

except for $\alpha = 1$, if so $\Delta\phi \propto DA_\alpha \ln\omega$

dispersion

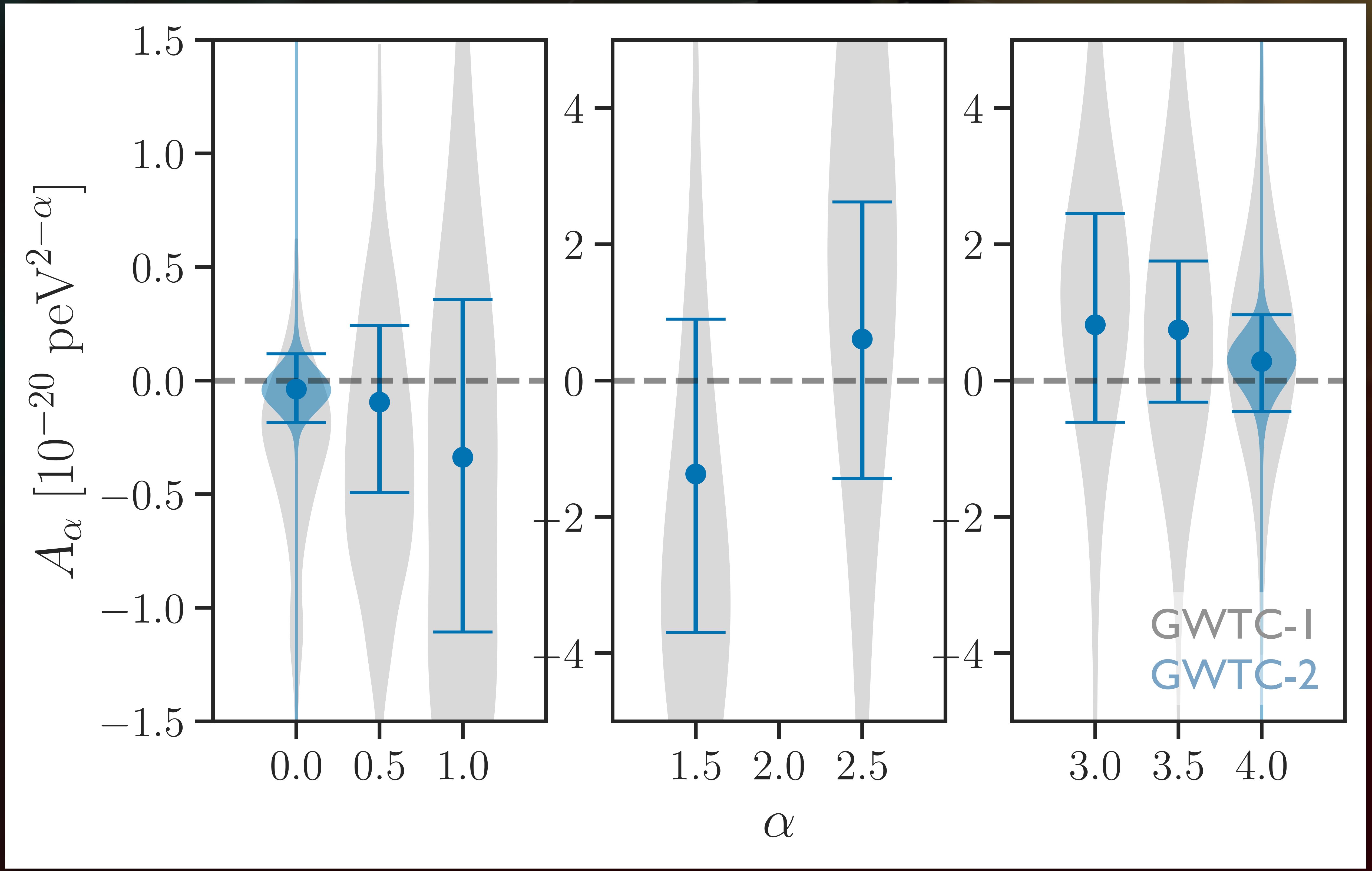
can straightforwardly combine results from many detections

GWTC-1 Abbott+2019 [arxiv:1903.04467]
GWTC-2 Abbott+2020 [arxiv:2010.14529]

binary BHs provide powerful limits thanks to large distances

$$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$$

dimensions of $E^{2-\alpha}$
$1\,\mathrm{peV} \approx h \times 250\,\mathrm{Hz}$



dispersion

$m_g = \sqrt{A_0}/c^2$

can straightforwardly combine results from many detections

GWTC-1 Abbott+2019 [arxiv:1903.04467]
GWTC-2 Abbott+2020 [arxiv:2010.14529]

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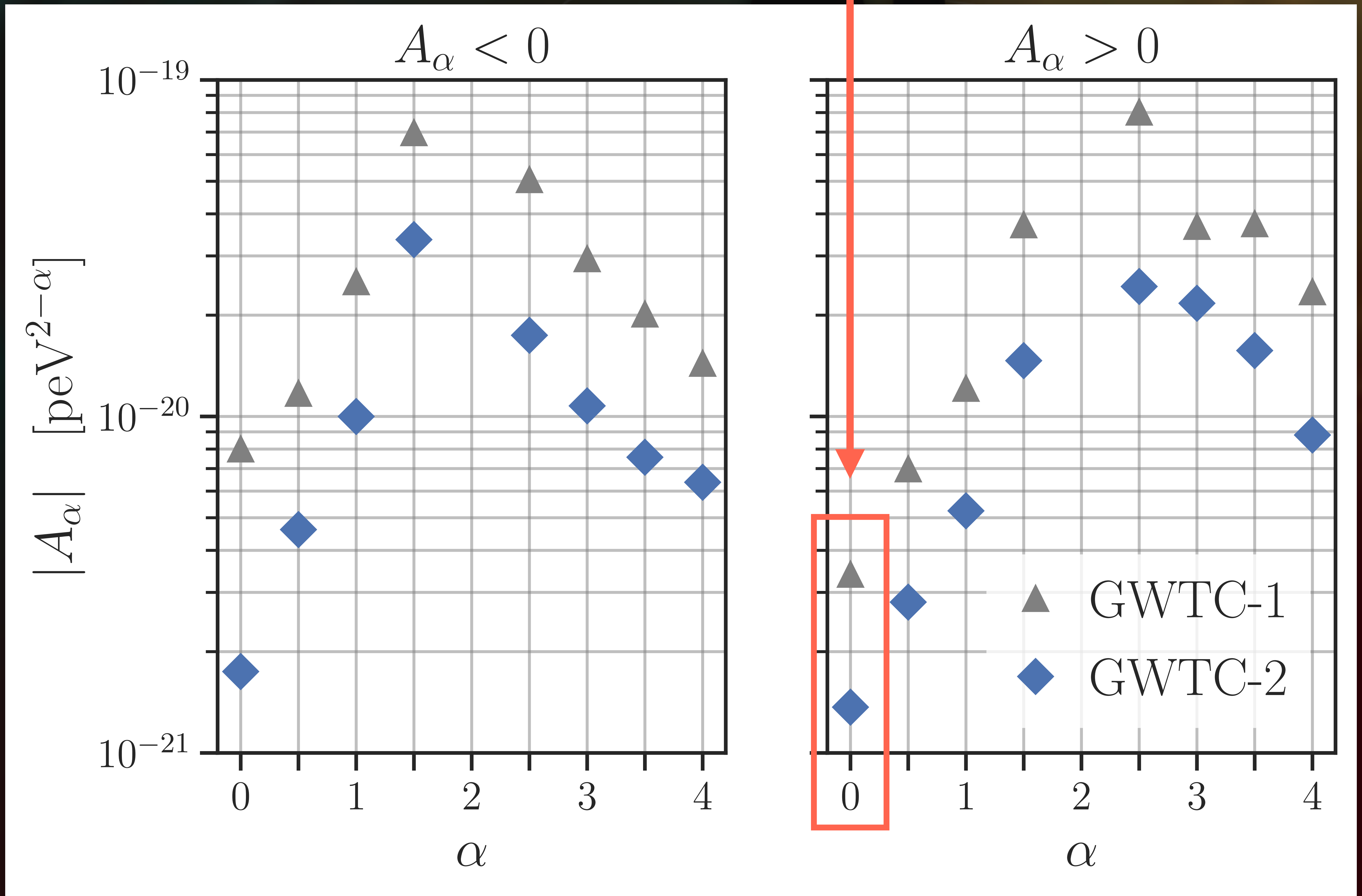


$$m_g \leq 1.76 \times 10^{-23}\ \mathrm{eV}/c^2$$

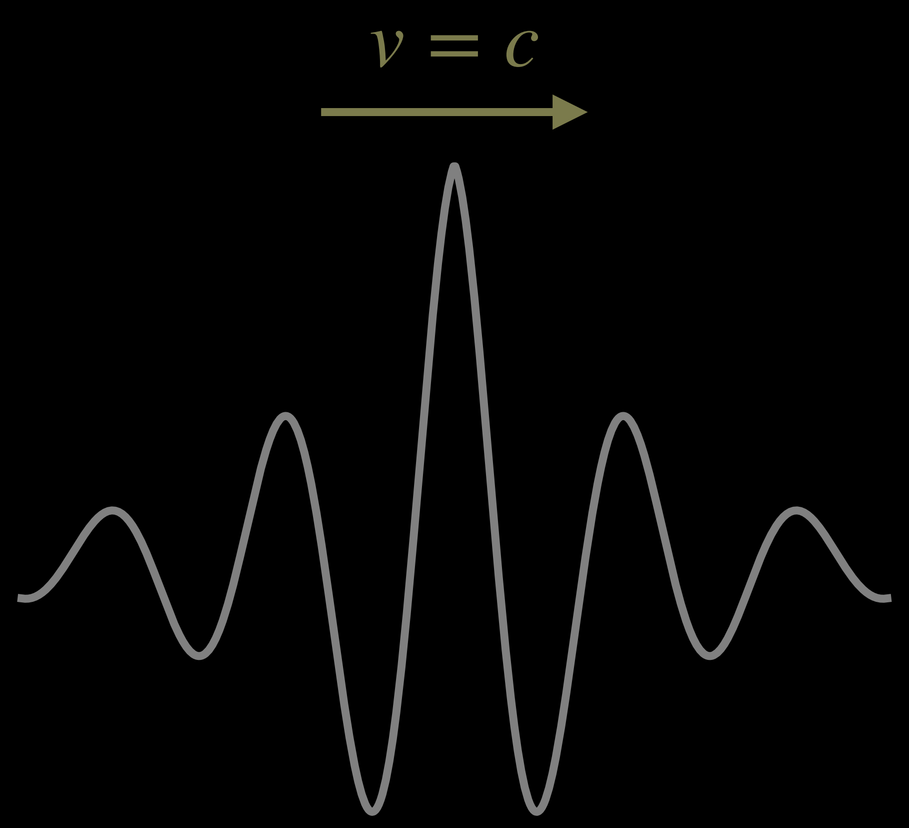
~1.8x more stringent than Solar System bounds

Bernus+2020 [arxiv:2006.12304]

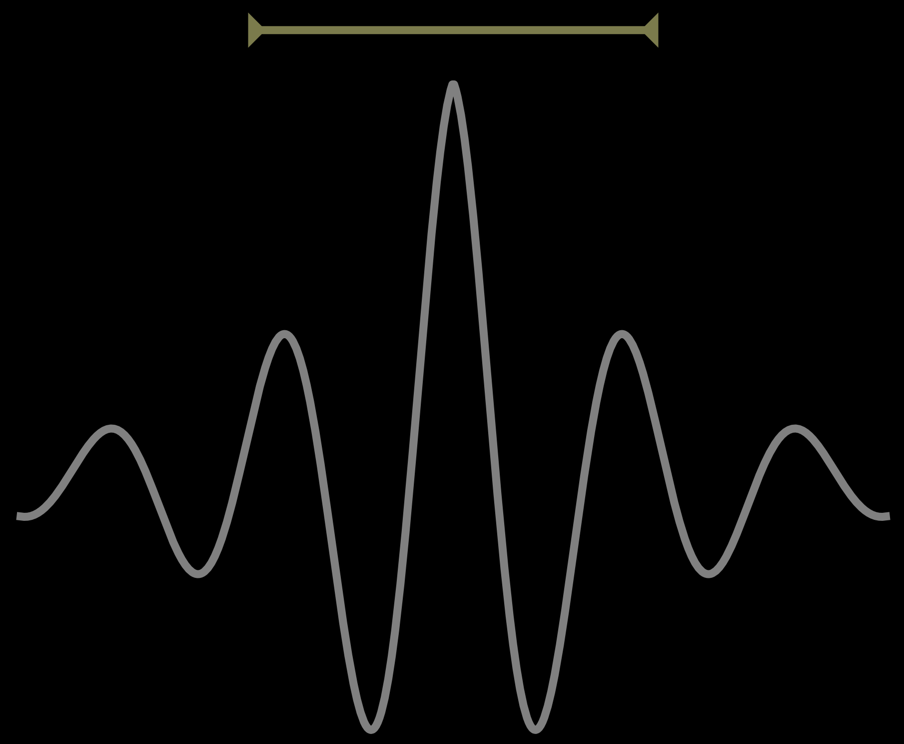
*all intervals quoted at 90% credibility

predictions

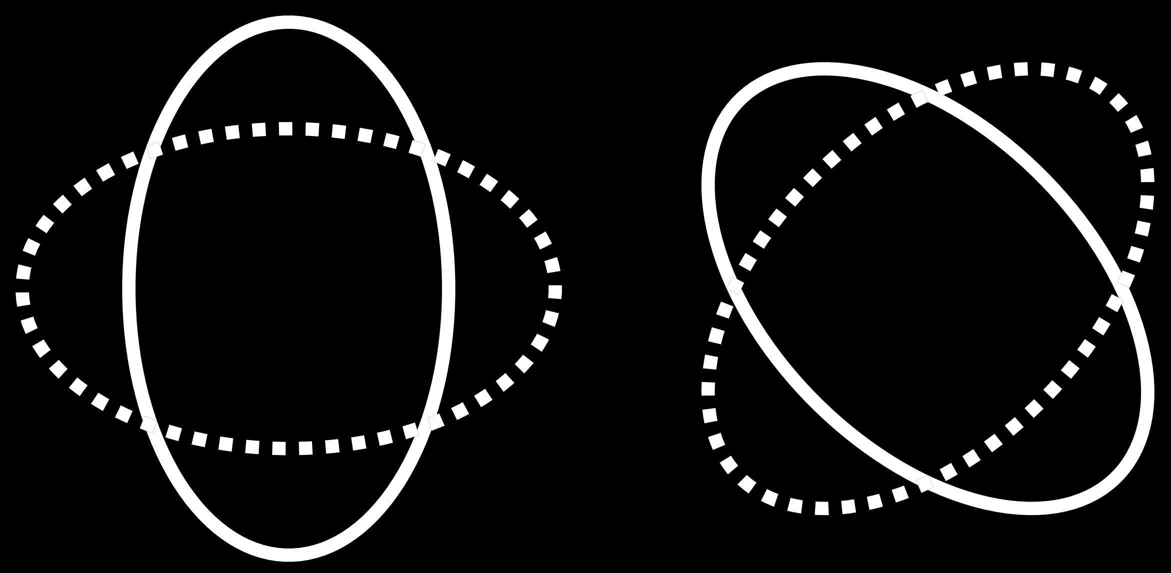
general relativity predicts basic gravitational-wave properties



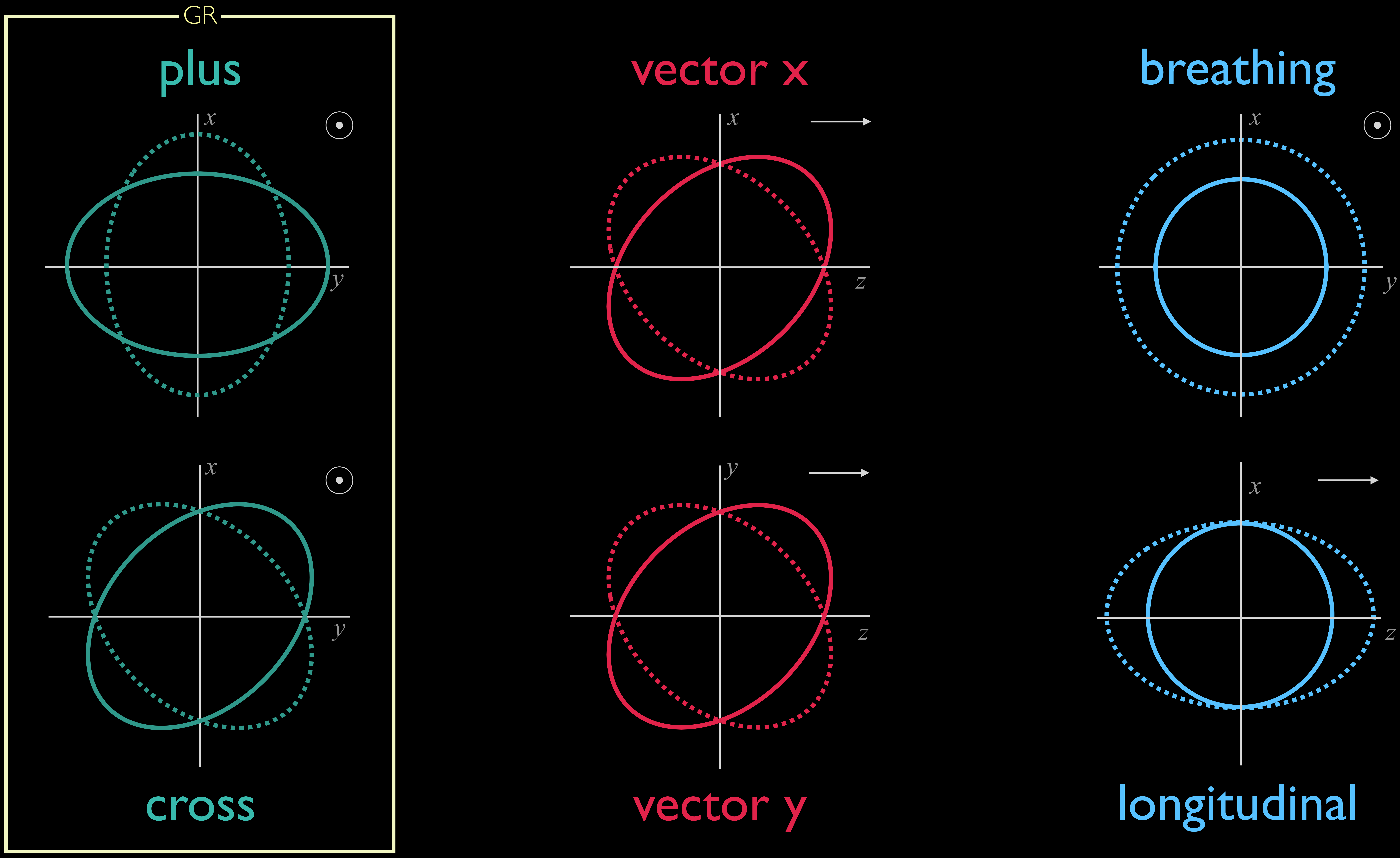
speed



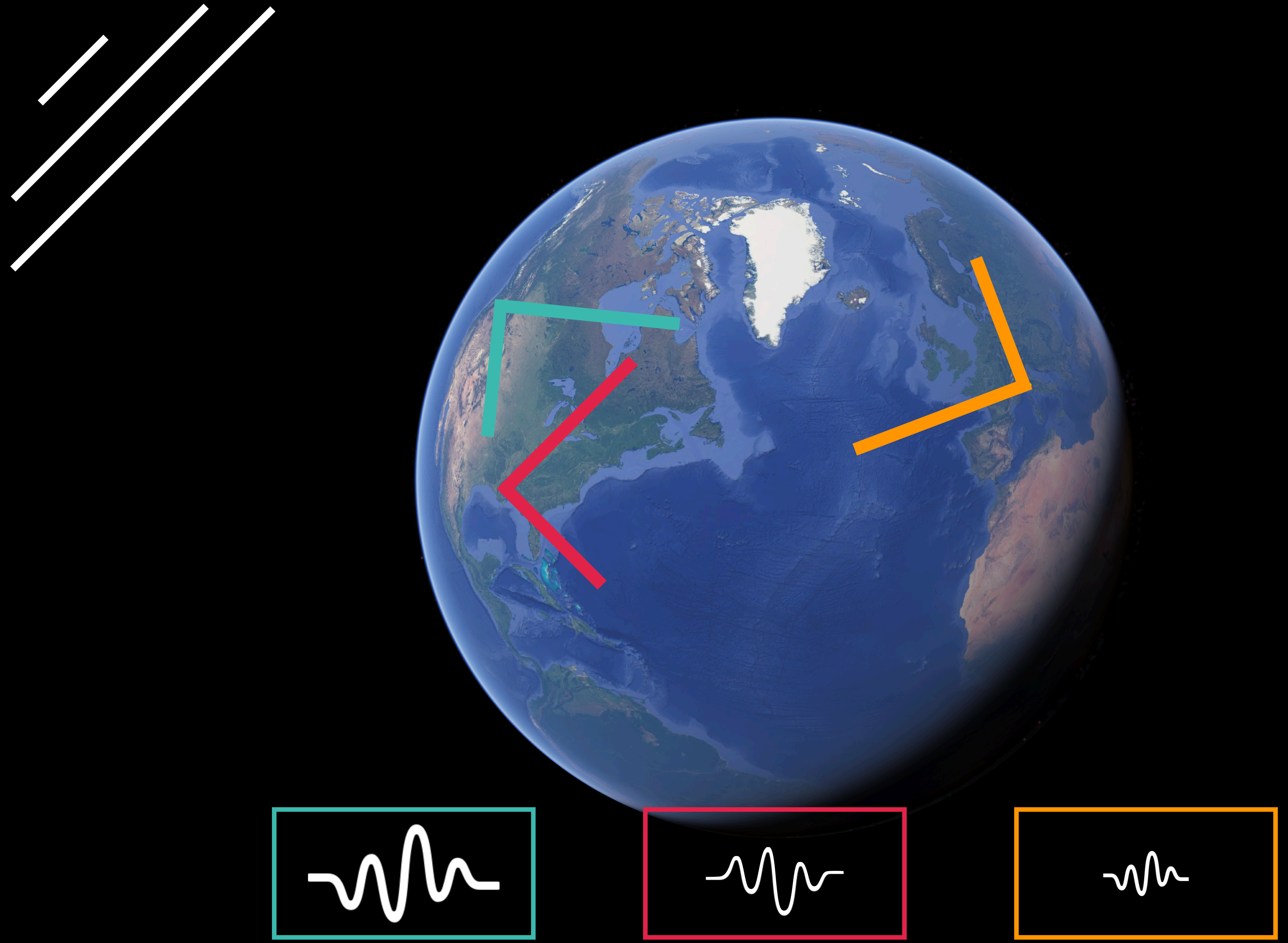
non-dispersion



polarization



wave propagates always in *z*-direction



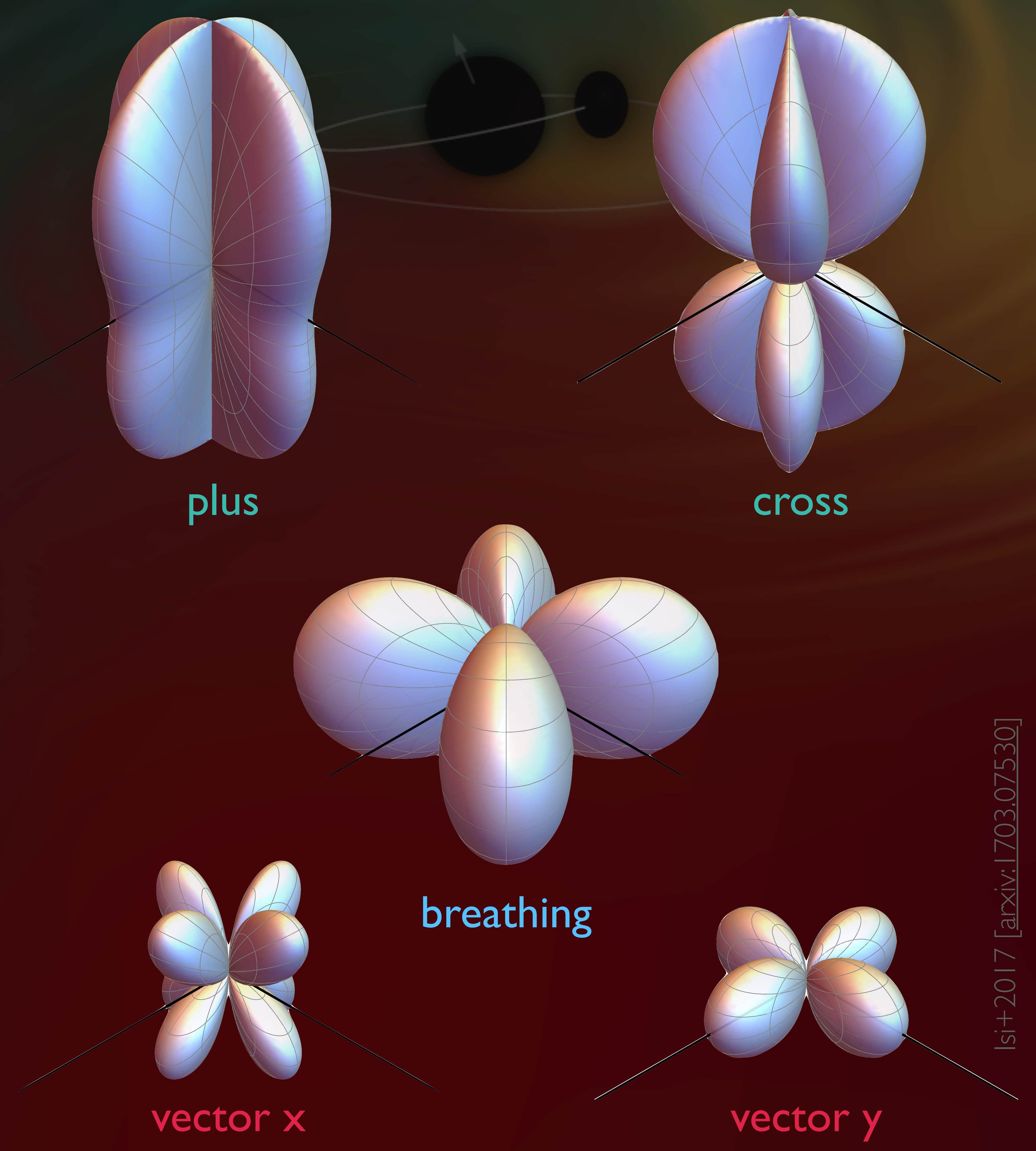
polarizations

get polarization from relative amplitudes and phases at different instruments

with transient signals need 5 detectors to break all (breakable) degeneracies

so far, limited studies disfavoring full-vector or full-scalar, driven by GW170817

Abbott+2017 [arxiv:1709.09660], Abbott+2019 [arxiv:1811.00364], Abbott+2019 [arxiv:1903.04467], Abbott+2020 [arxiv:2010.14529], Isi+2017 [arxiv:1710.03794], Pang+2020 [arxiv:2003.07375]



sensitivity to each polarization for sky locations relative to interferometer arms (black lines)

polarizations

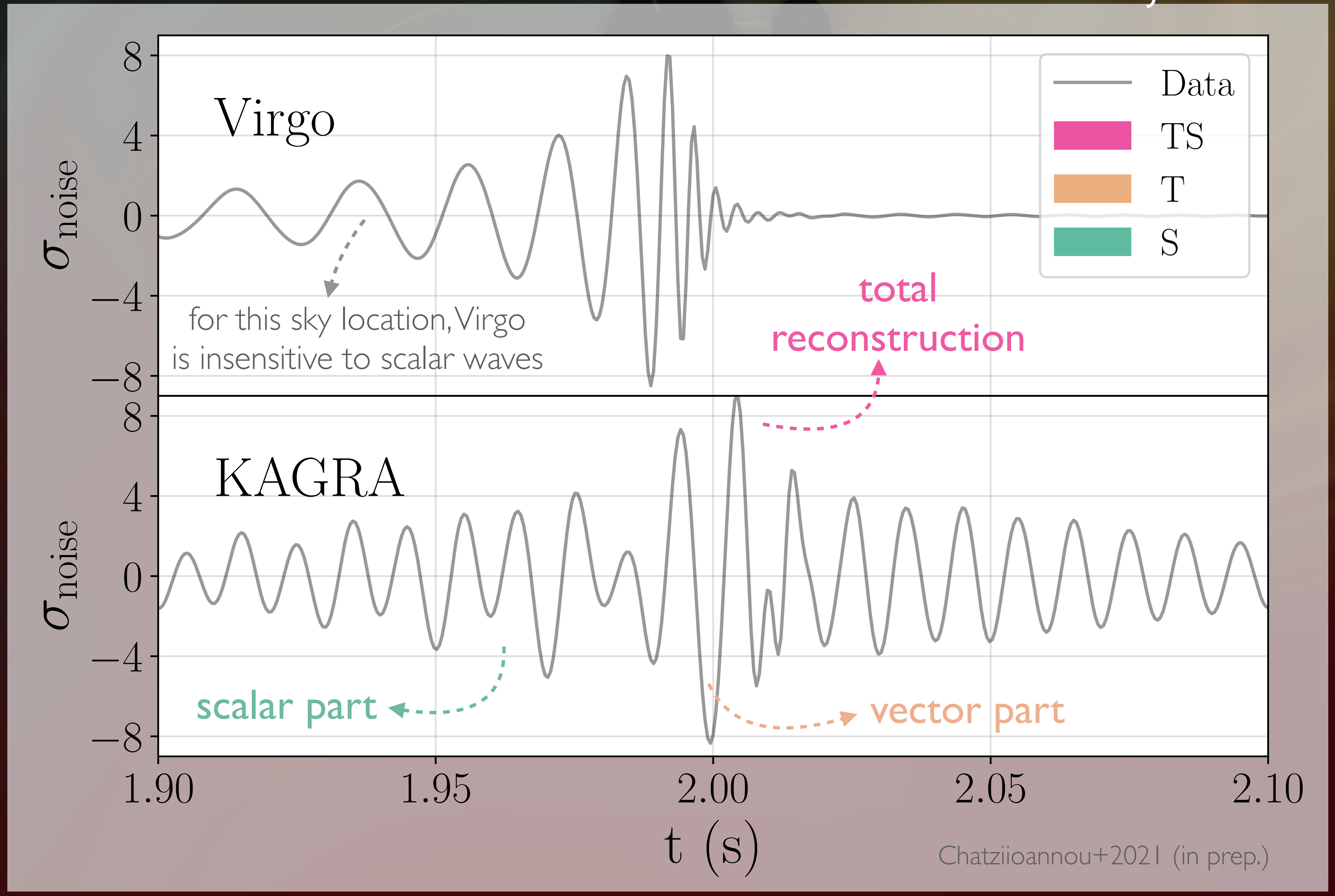
get polarization from relative amplitudes and phases at different instruments

with transient signals need 5 detectors to break all (breakable) degeneracies

so far, limited studies disfavoring full-vector or full-scalar, driven by GW170817

Abbott+2017 [arxiv:1709.09660], Abbott+2019 [arxiv:1811.00364], Abbott+2019 [arxiv:1903.04467], Abbott+2020 [arxiv:2010.14529], Isi+2017 [arxiv:1710.03794], Pang+2020 [arxiv:2003.07375]

scalar-tensor injection



unmodeled reconstruction of scalar-tensor signal using HLVK network (only V and K shown); we can easily separate individual tensor (T) and scalar (S) contributions from full signal (TS)

will soon do much better thanks to KAGRA!

Chatziioannou, Isi, Haster, Lyttenberg (in prep.)

could have done this already if we had long-lived signals!

Isi+2017 [arxiv:1703.07530], Callister+2017 [arxiv:1704.08373]

predictions

general relativity predicts basic gravitational-wave properties

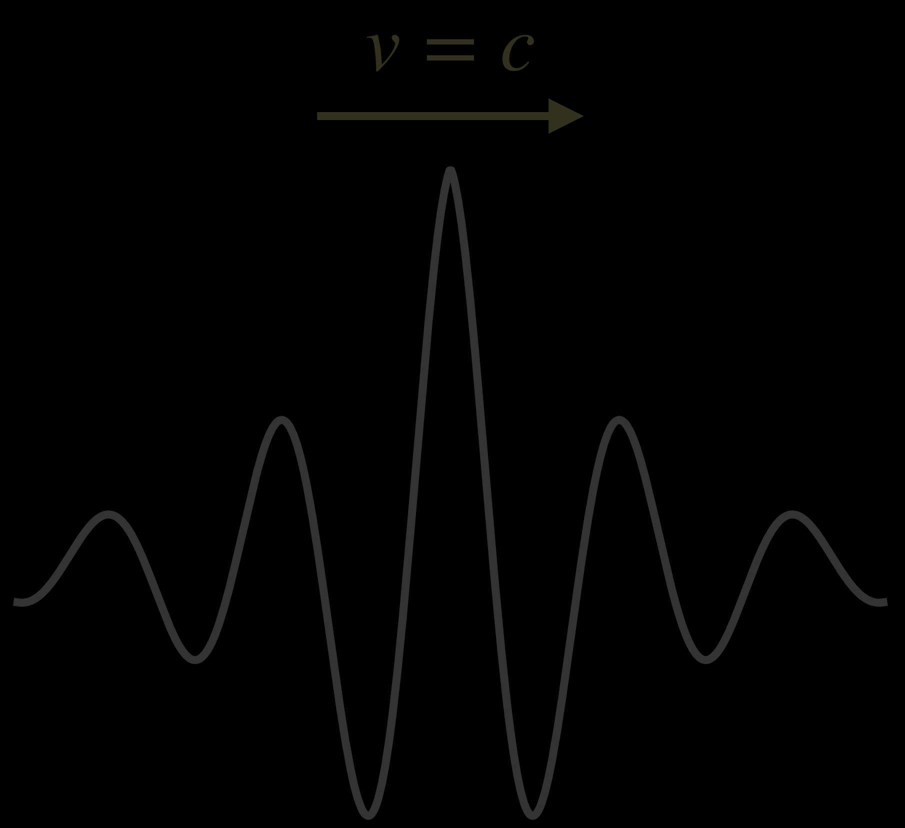
there are other possible effects

birefringence

Shao+2020 [arxiv:2002.01185], Wang+2020 [arxiv:2002.05668], Mewes 2020 [arxiv:1905.00409], Okounkova+2021 [arxiv:2101.11153], …

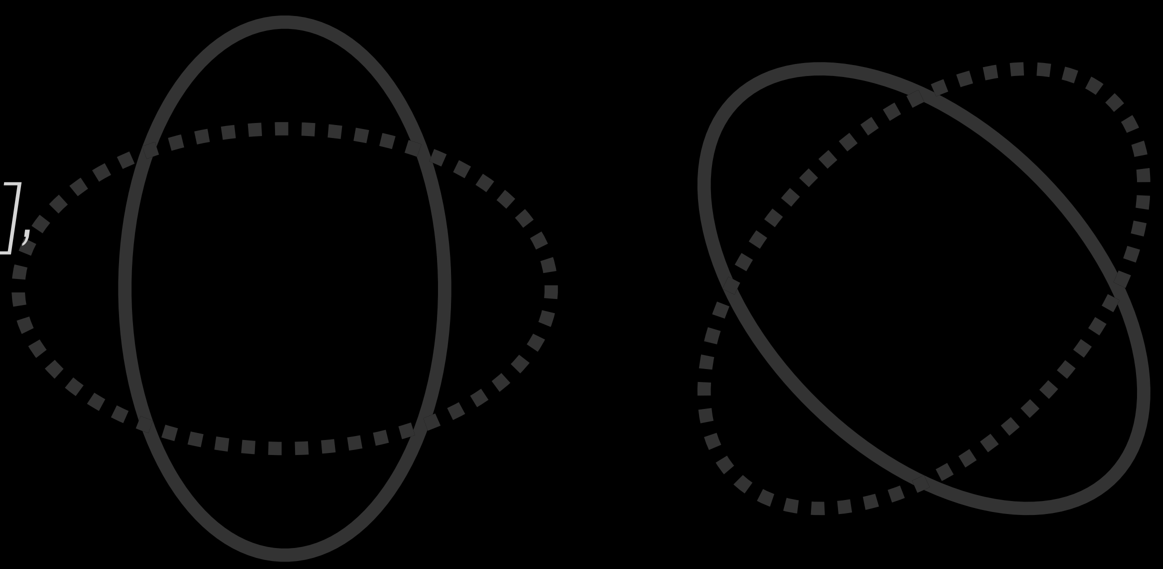
damping / leakage

Pardo+2018 [arxiv:1801.08160], Abbott+2019 [arxiv:1811.00364], Ezquiaga+2021 [arxiv:2104.05139]



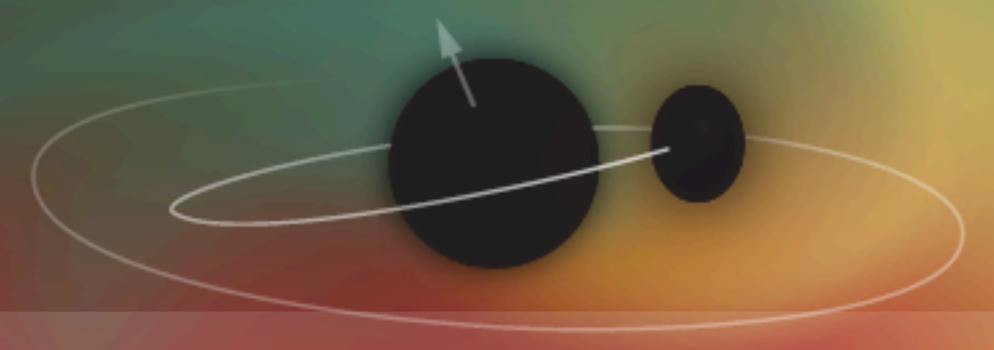
speed

non-dispersion

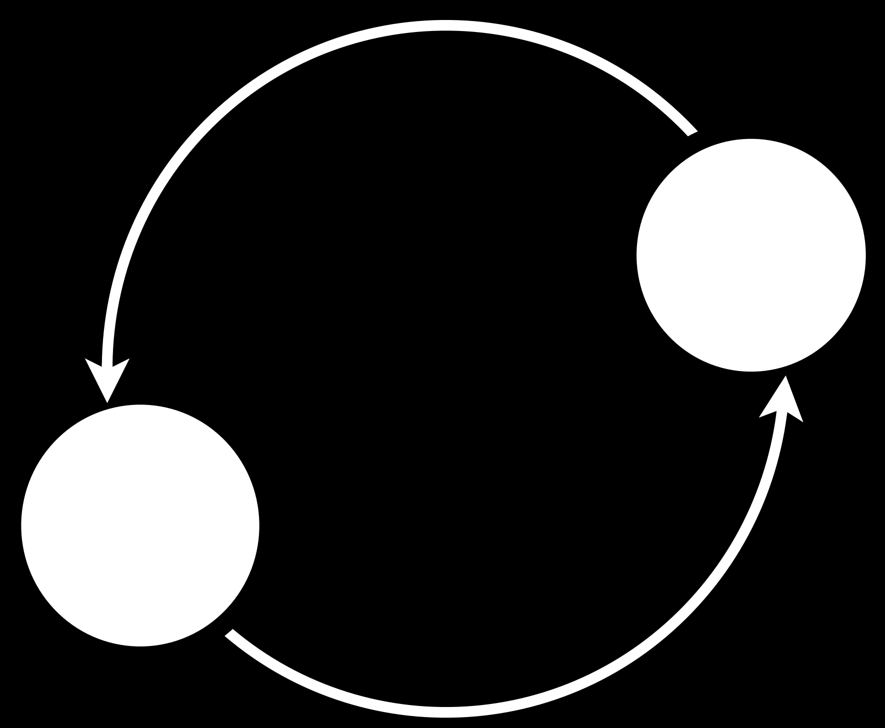


polarization

…



radiation mechanisms and source dynamics



non-eccentric binary
black hole coalescence

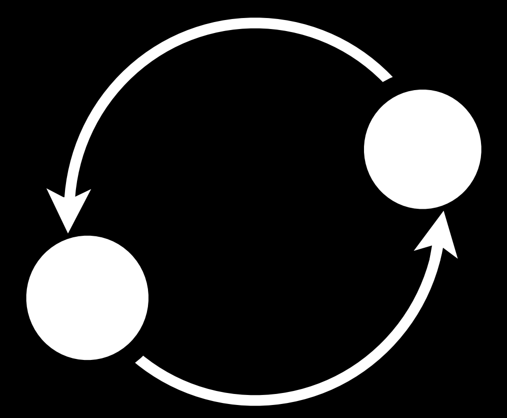

GW150914 simulated by SXS


GW150914 simulated by SXS


GW150914 simulated by SXS


inspiral
interm.
merger-rd

orbital dynamics



express **inspiral** phase as a series expansion in the orbital velocity v

(or, equivalently, GW frequency $f \propto v^3/M$ by Kepler)

GW tails

$$\Phi(v) = \left(\frac{v}{c}\right)^{-5}\left[\varphi_0 + \varphi_1\left(\frac{v}{c}\right) + \varphi_2\left(\frac{v}{c}\right)^2 + \ldots + \varphi_{5l}\ln\left(\frac{v}{c}\right)\left(\frac{v}{c}\right)^5 + \ldots + \varphi_7\left(\frac{v}{c}\right)^7\right]$$

0PN + **0.5PN** + **1PN** + … + **2.5PN(l)** + … + **3.5PN**

GR

$\mathscr{M} \equiv \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$

(quadrupole formula)

$q = m_2/m_1$

(spins χ_1 & χ_2 starting at 1.5PN)

parameterized deviations

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

or absolute deviations if $\varphi_i = 0$ in GR

$\left[\,\phi_i \sim f^{(i-5)/3}\,\right]$

 e.g., Blanchet+1995 [arxiv:gr-qc/9501027], Arun+2006 [arxiv:gr-qc/0604067], Yunes+2009 [arxiv:0909.3328], Li+2012 [arxiv:1110.0530], Agathos+2014 [arxiv:1311.0420]

inspiral **interm.** **merger-rd**

$\delta\hat{\varphi}_i$ $\delta\hat{\beta}_i$ $\delta\hat{\alpha}_i$

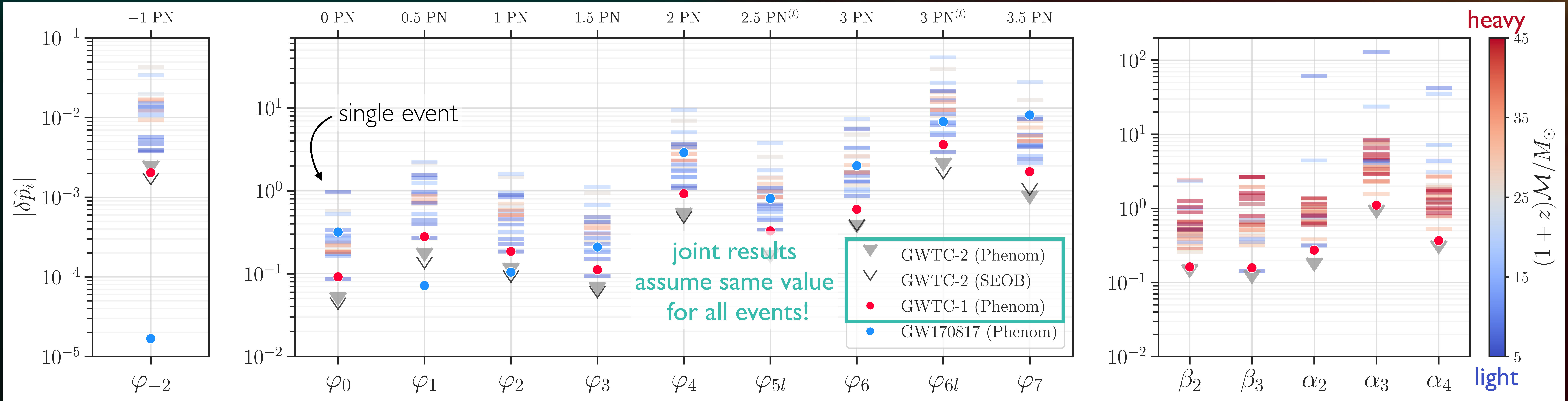
$$p_i \to \left(1 + \delta\hat{p}_i\right) p_i$$

diagram for illustration only, we define regions in freq. domain

parameterized tests

GWTC-2 results: 90%-credible upper limit on each deviation parameter

$\sim f^{-7/3}$ (dipole)



Abbott+2020 [arxiv:2010.14529]

← lower frequency —— $\phi_i \sim f^{(i-5)/3}$ inspiral, β_i intermediate, α_i merg.-rd —— higher frequency →

combining results

deviations from GR are likely to affect each system *differently*
(e.g., as a function of parameters)

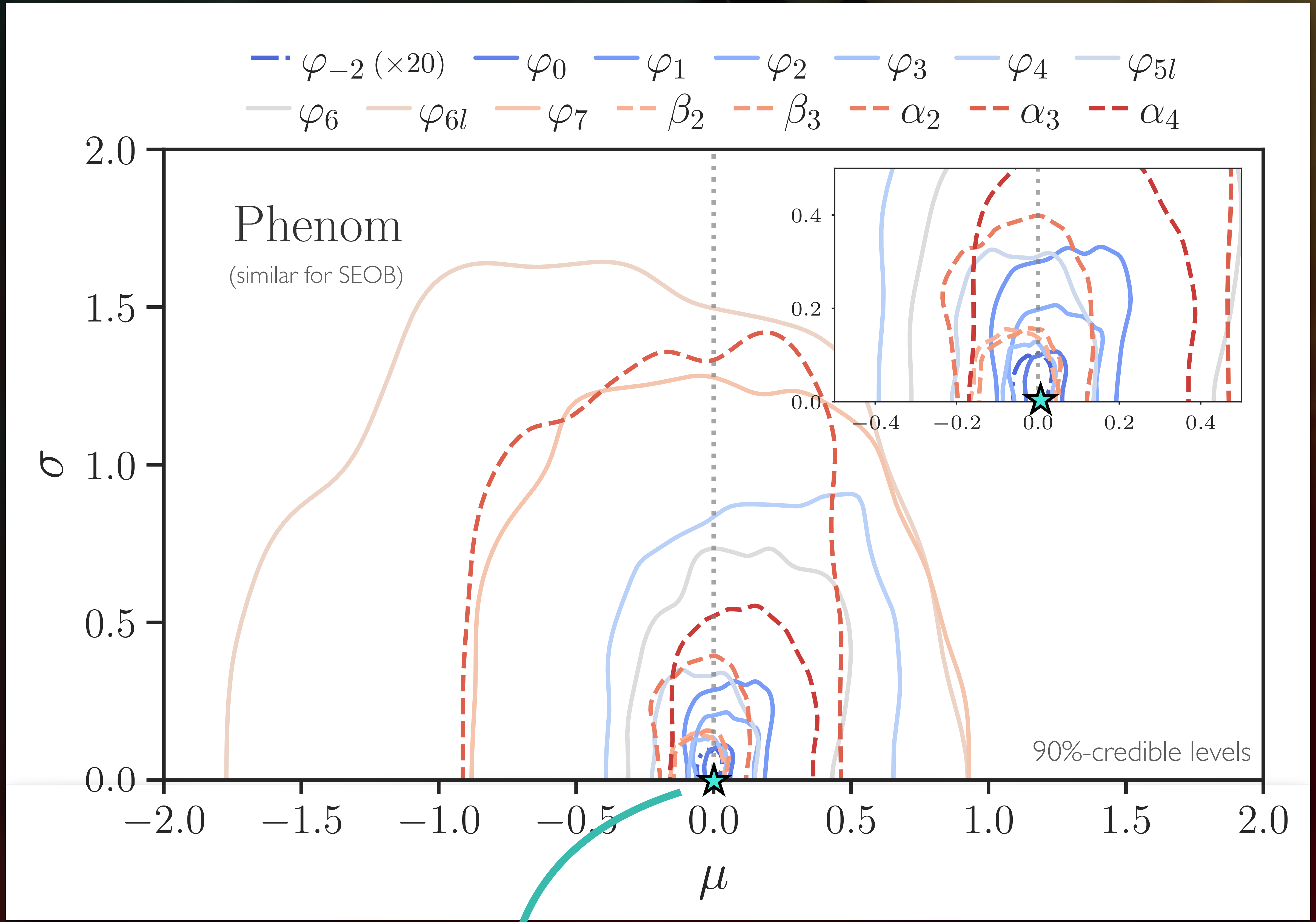
cannot simply multiply likelihoods or Bayes factors Zimmermann+2019 [arxiv:1903.11008]

model the **distribution** of observations
(hierarchical Bayesian inference)

$$\delta\hat{p}_i^n \equiv \delta\hat{p}_i[n^{\text{th}} \text{ event }] \sim \mathcal{N}(\mu_i, \sigma_i)$$

infer μ_i & σ_i from all events at once!

Isi+2019 [arxiv:1904.08011]

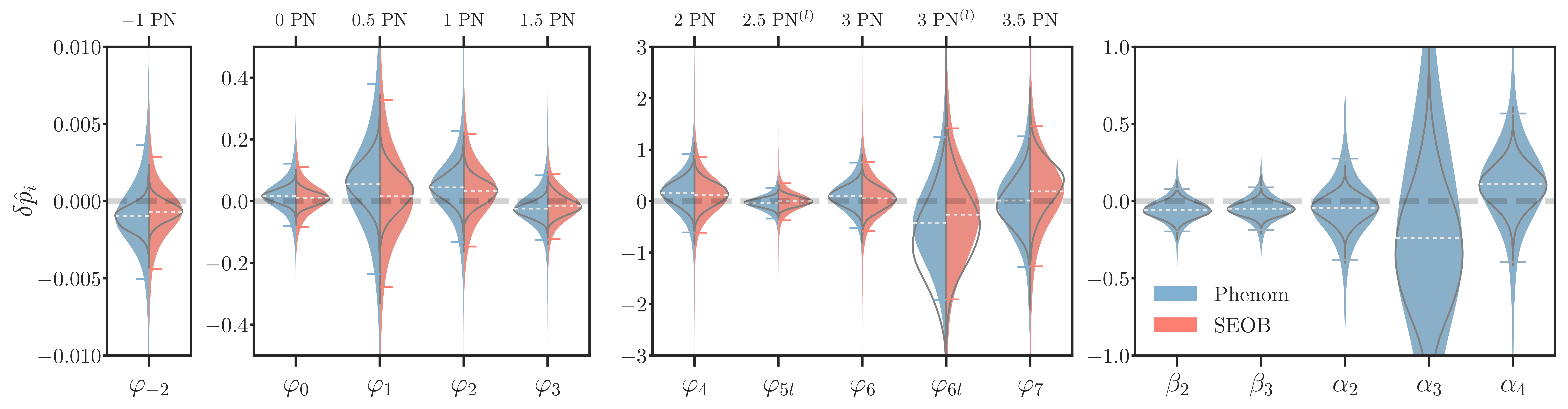


Abbott+2020 [arxiv:2010.14529]

GR prediction ($\mu = \sigma = 0$)

parameterized tests

GWTC-2 results: combined posteriors

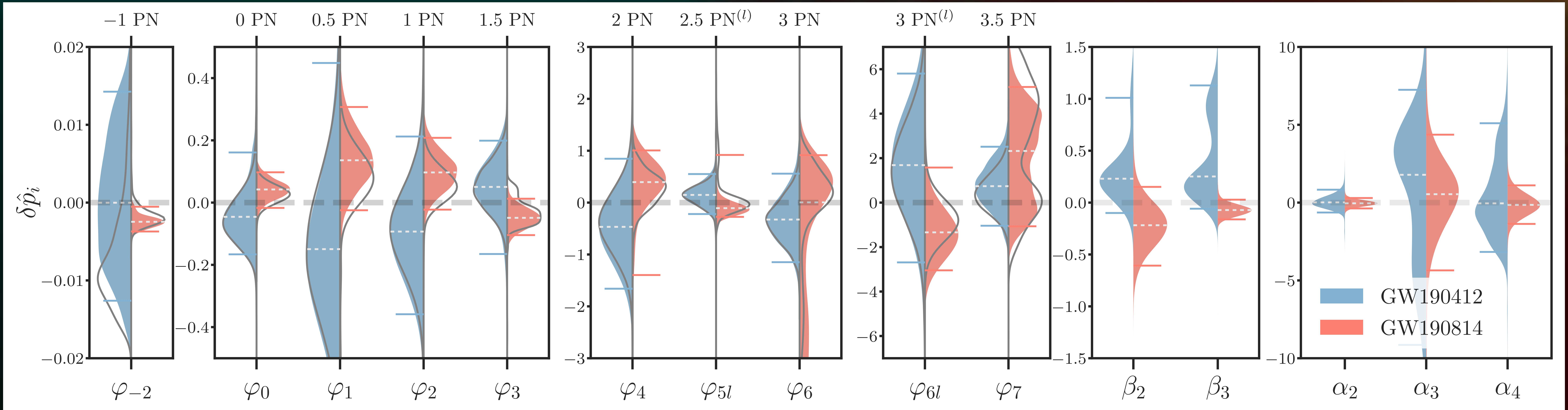


empty = shared deviation; filled = non-shared deviation (hierarchical)

Abbott+2020 [arxiv:2010.14529]

parameterized tests

first constraints with higher modes!



empty = SEOB; filled = Phenom

Abbott+2020 [arxiv:2010.14529]

all individual-event posteriors available online
[LIGO-P2000438]


inspiral
interm.
merger-rd

Kerr black holes

in general relativity, a black hole has only three properties

mass
spin
~~**charge**~~ no charge for *astrophysical* BHs

no-hair theorem

spacetime described by the *Kerr* metric

if not true, not a vanilla BH in GR

should hold for a merger remnant!

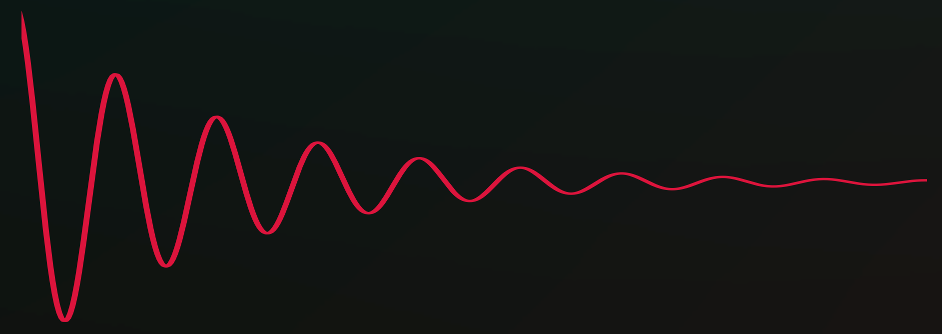
Image credit: F. Jimenez Meca, Shutterstock

ringdown

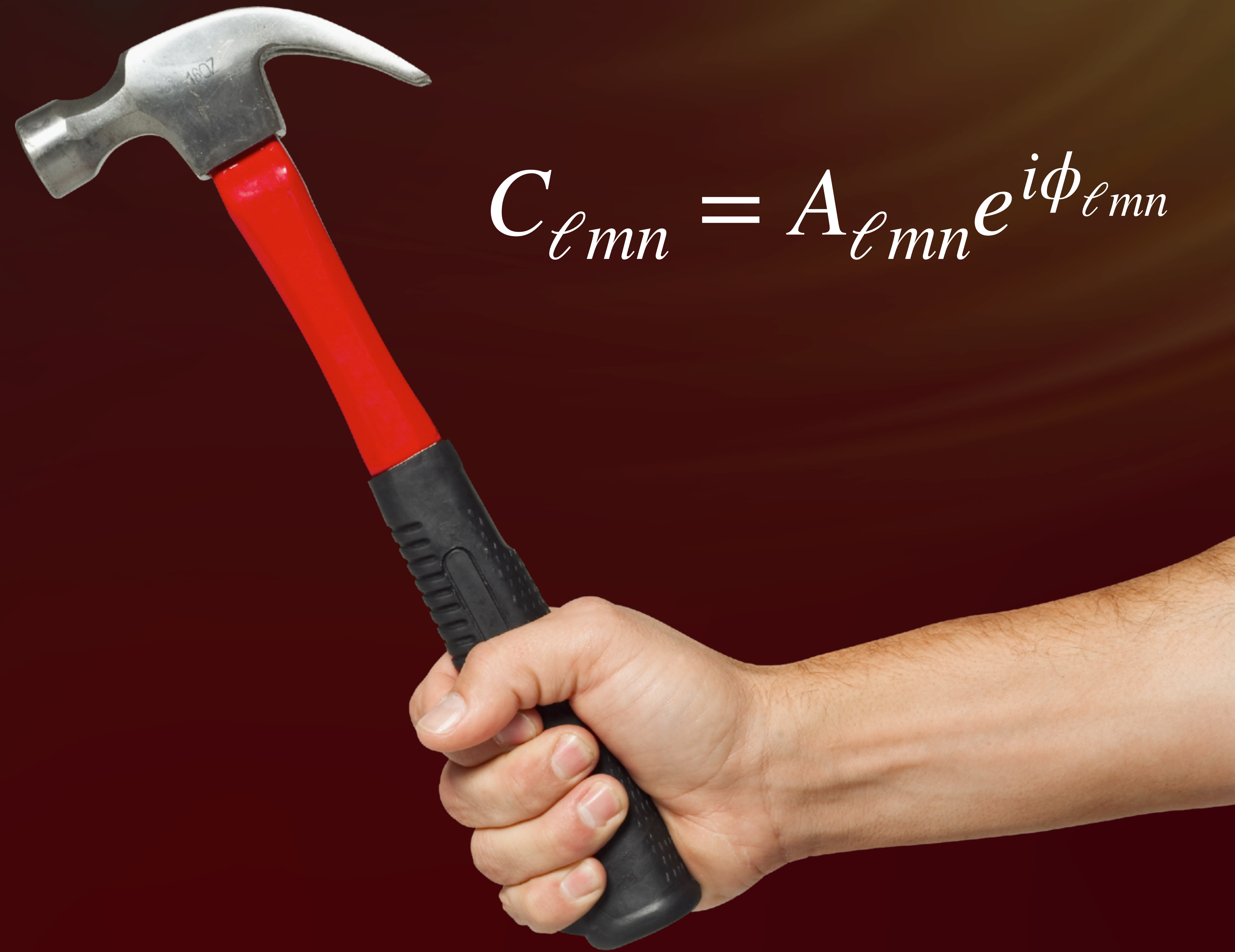
learn about BH properties from its GW ringing

$$h = \sum_{\ell mn} C_{\ell mn} e^{-i\omega_{\ell mn} t}$$

measure different modes, as in *atomic spectroscopy*



$\omega_{\ell mn}(M, \chi)$



$C_{\ell mn} = A_{\ell mn} e^{i\phi_{\ell mn}}$

$\omega_{\ell mn}$: intrinsic geometry

$C_{\ell mn}$: initial conditions

ringdown

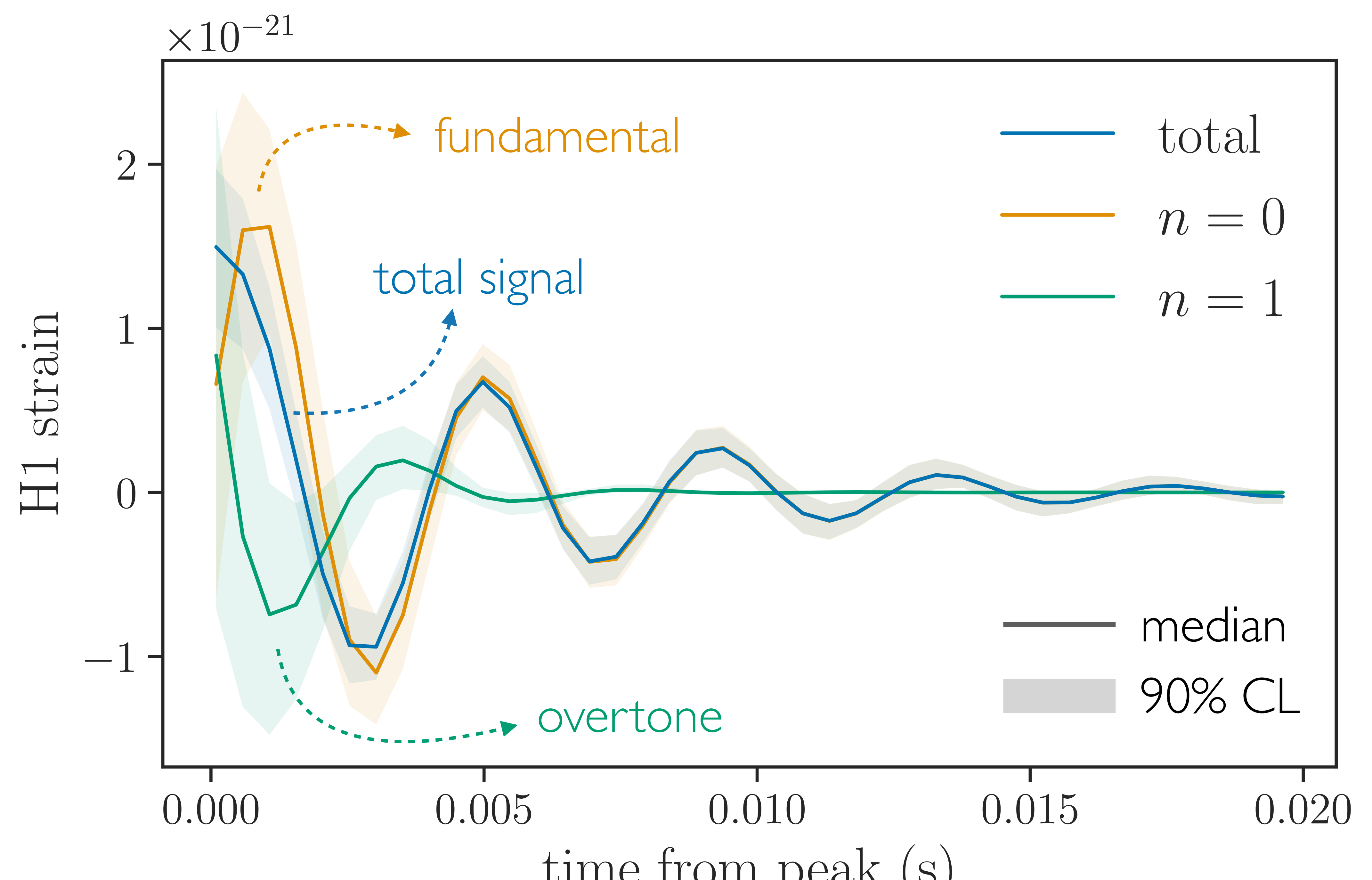
tricky data analysis

nuances introduced by start of ringdown model demand careful, bespoke treatment

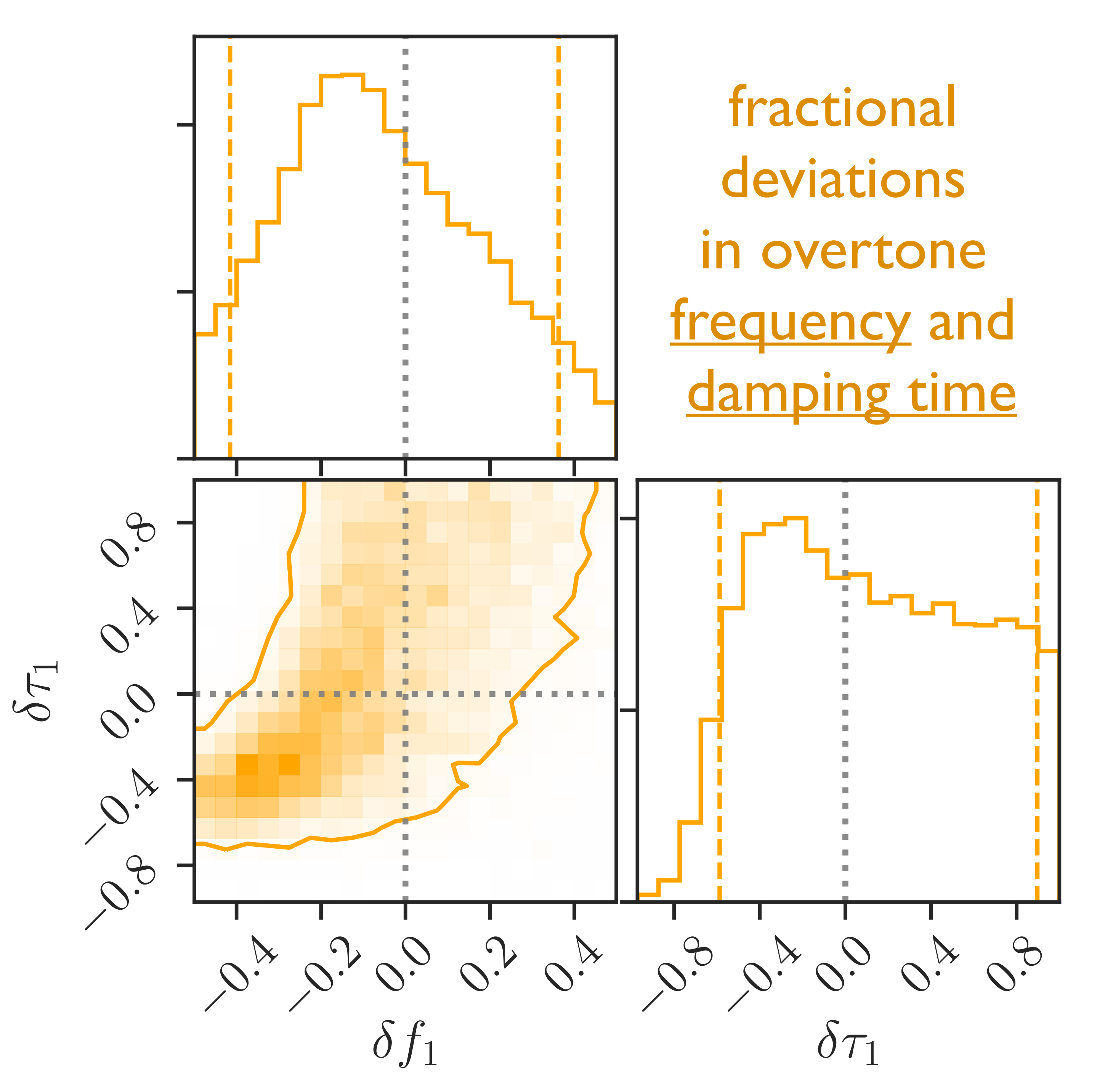
Carullo+2018 [arxiv:1805.04760], Isi+2019 [arxiv:1905.00869] Cabero+2018 [arxiv:1711.09073], Brito+2018 [arxiv:1805.00293], Isi & Farr 2021 (in prep.)

GW150914

black hole spectroscopy



*this fit assumes Kerr



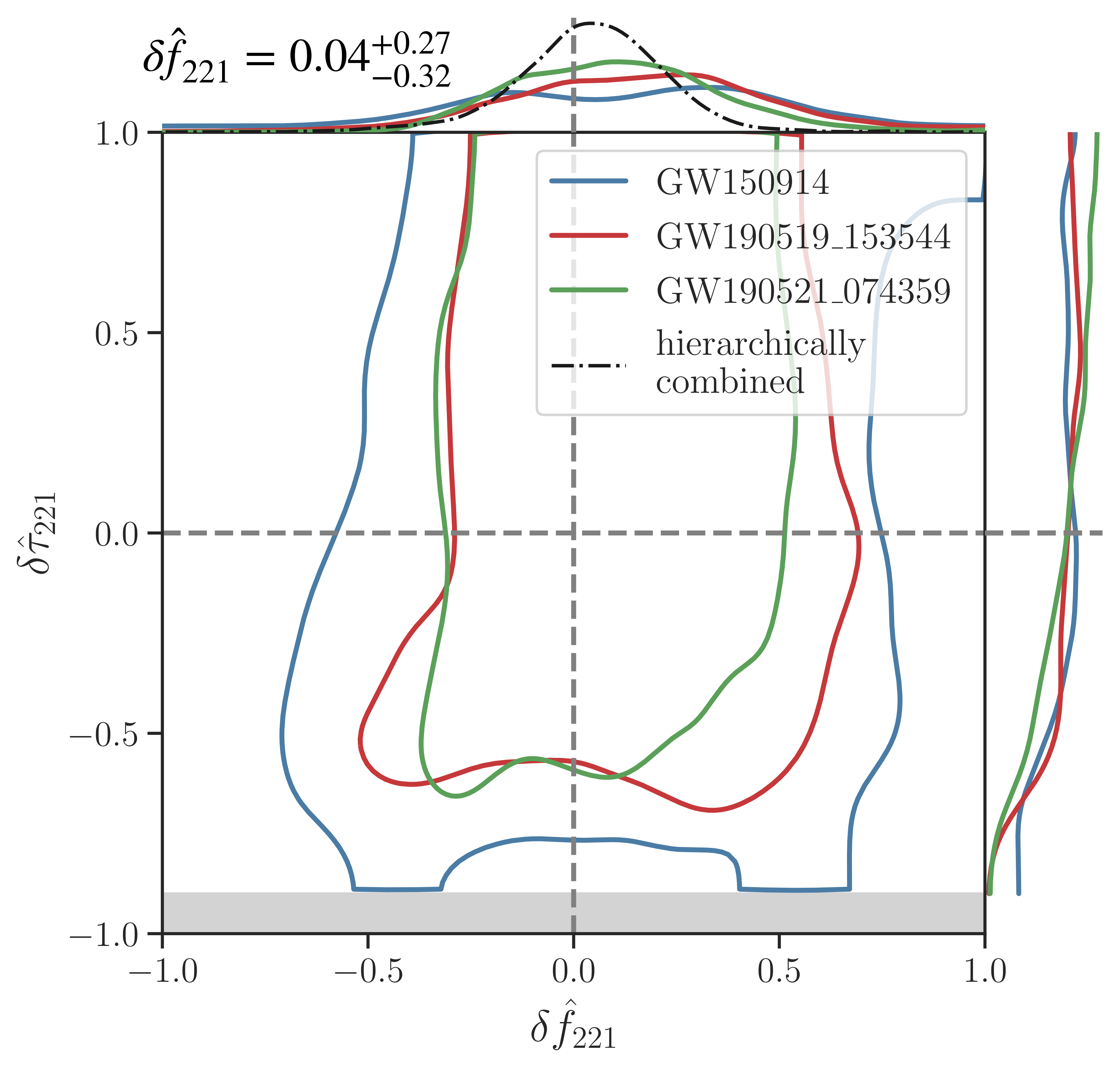
reconstruct fundamental and overtone of 22 mode

agreement with Kerr ~ 20% at 1σ

Isi+2019 [arxiv:1905.00869]

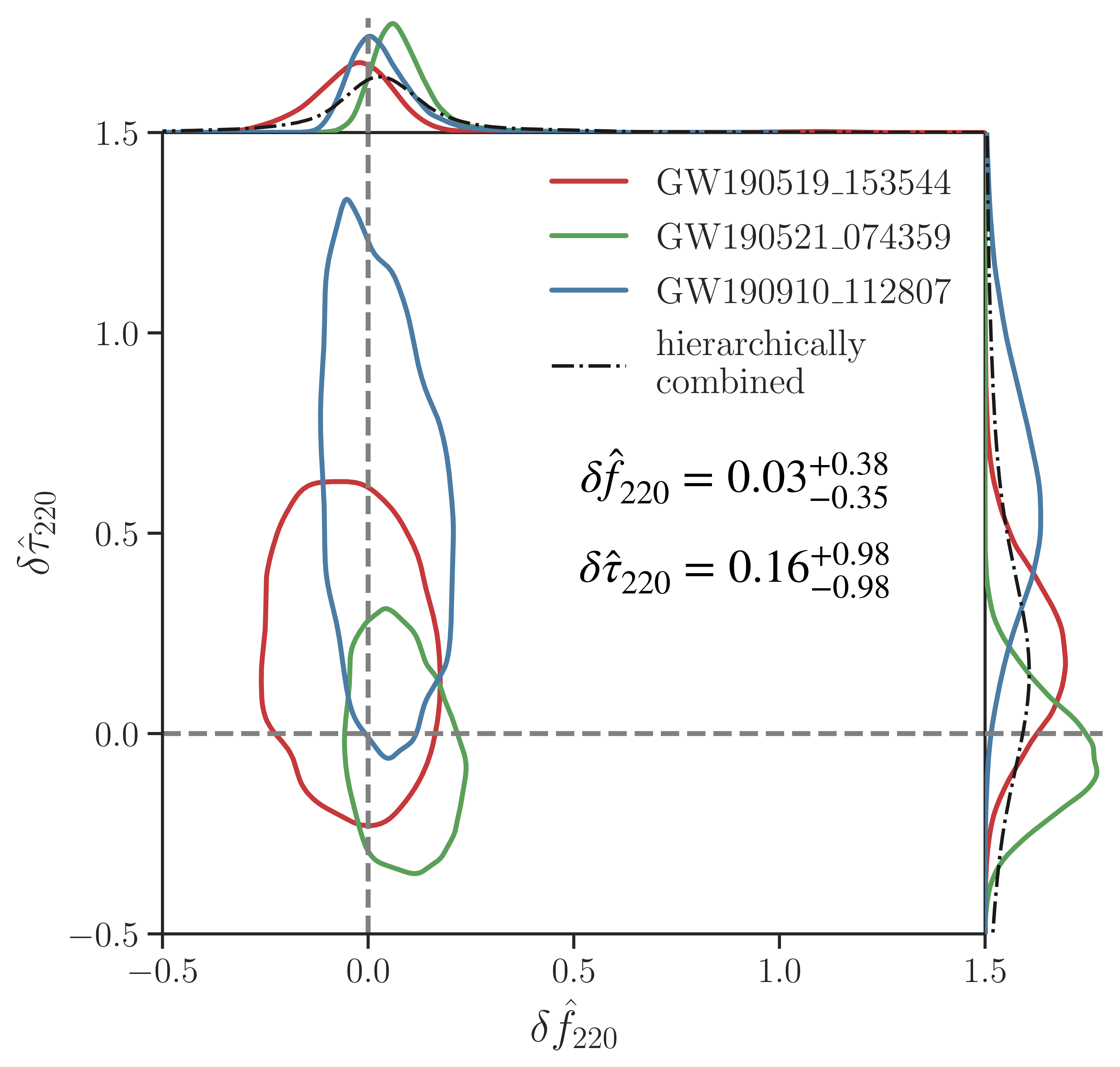
GWTC-2 ringdowns

damped sinusoids



Carullo+2018 [arxiv:1805.04760], Isi+2019 [arxiv:1905.00869]

enhanced IMR model



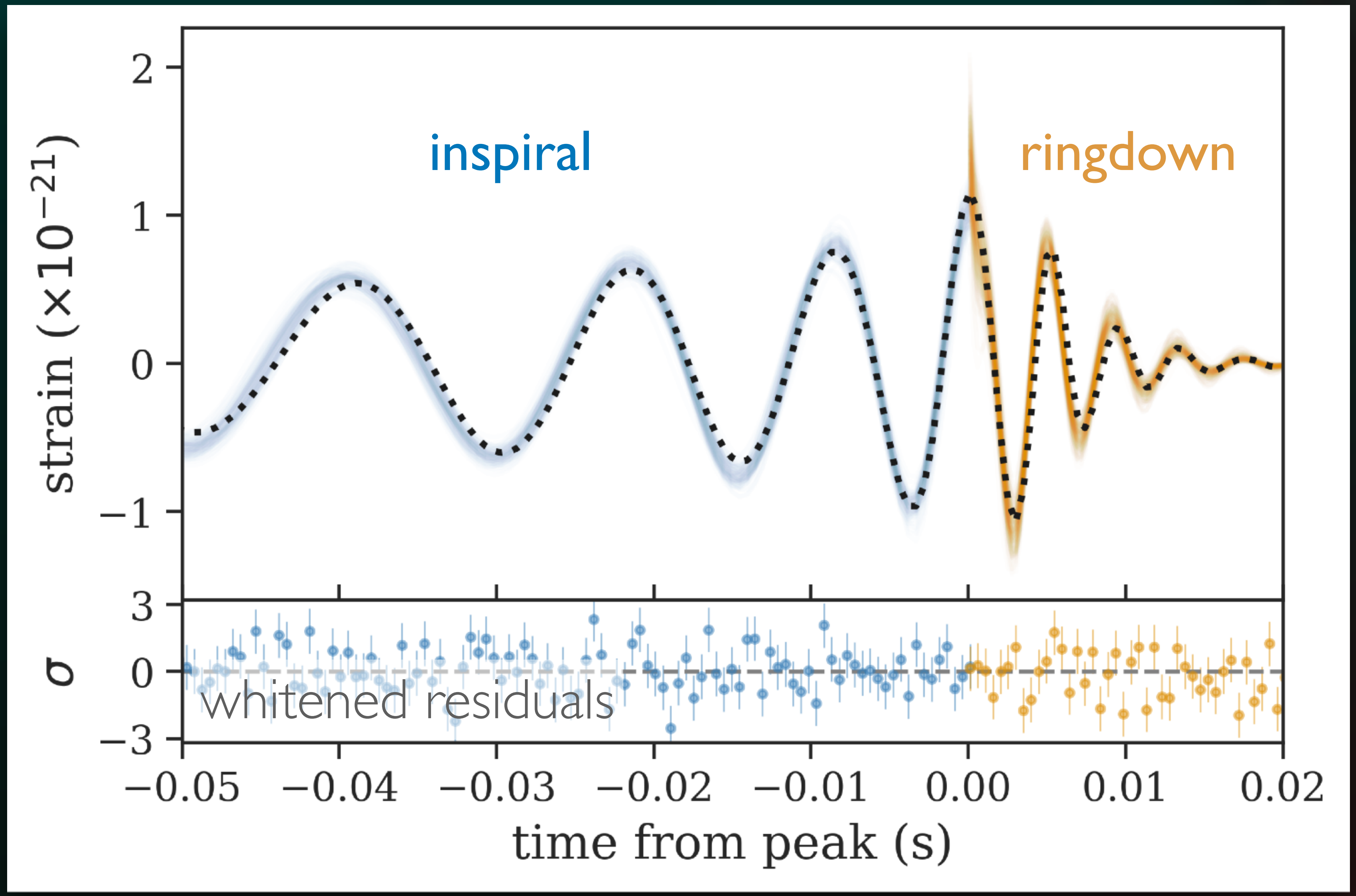
Brito+2018 [arxiv:1805.00293], **UPDATED RESULTS** Ghosh+2021 [arxiv:2104.01906]

Abbott+2020 [arxiv:2010.14529]

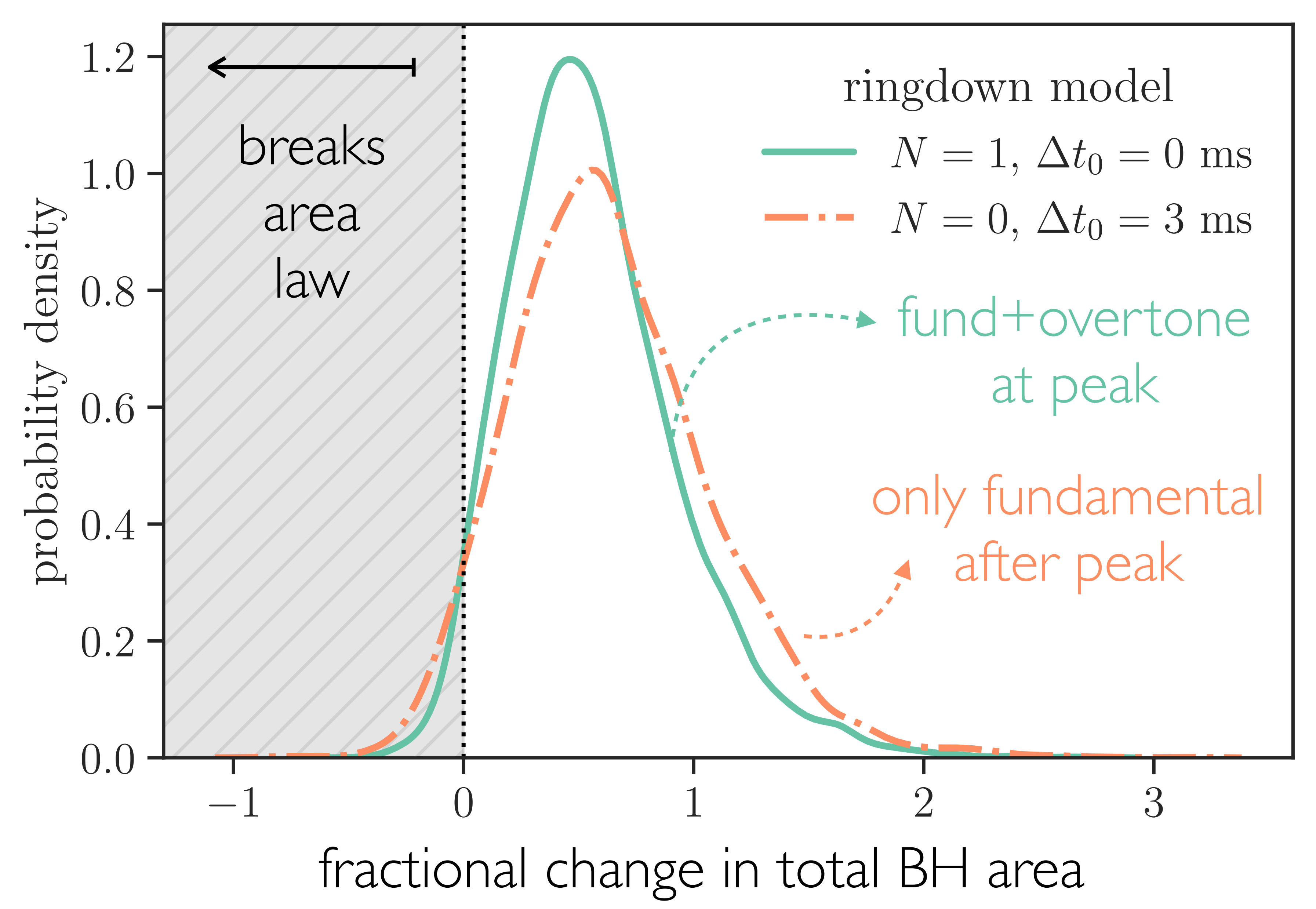
GW150914

see Saul Teukolsky's talk on Tuesday (X01.00002)

total BH area must not decrease

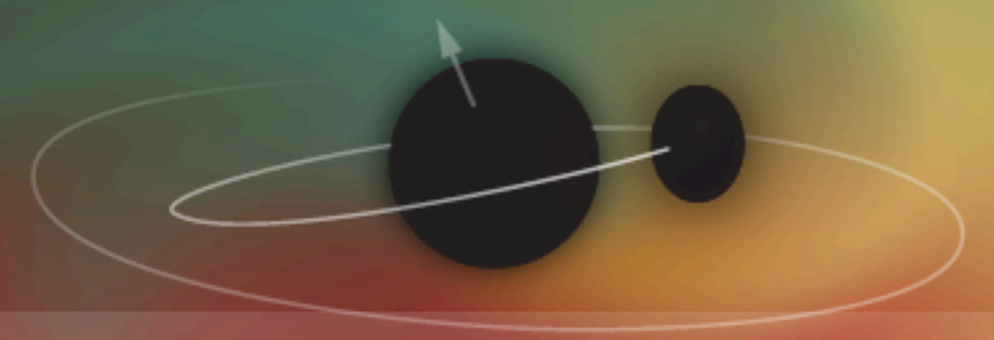


independent ringdown and inspiral measurements



agreement with area law with ~97% credibility

Isi+2020 [arxiv:2012.04486]

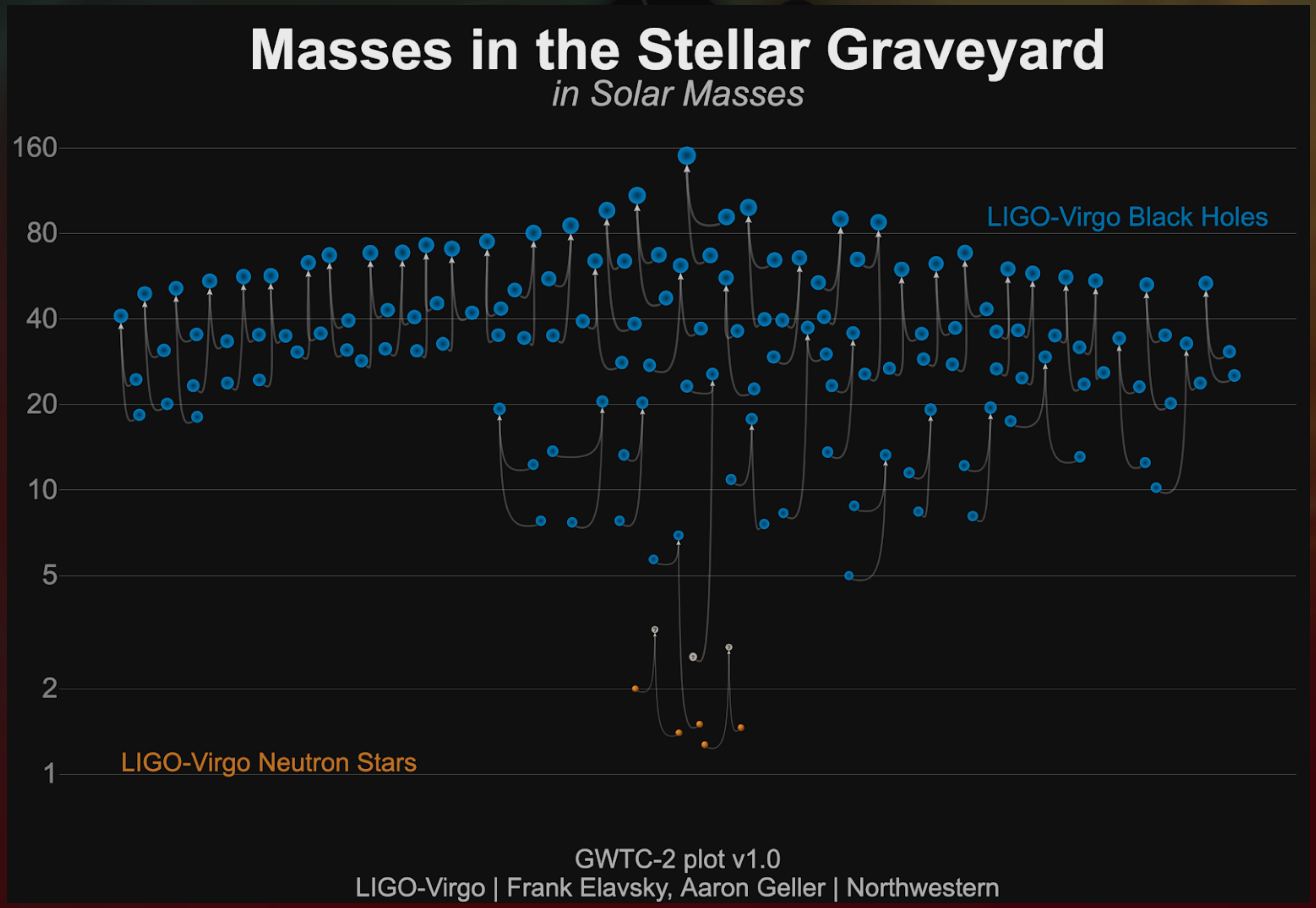


conclusion

conclusion

GWTC-2 Abbott+2020 [arxiv:2010.14529]

- no statistically significant deviations from GR, or unaccounted systematics
- improved GWTC–1 constraints by factors of ~2–3
- introduced new analyses, and statistical techniques



still lots to do!

- understand systematics
- bridge to theory

more to come!

M. Isi thankfully acknowledges support from

This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.