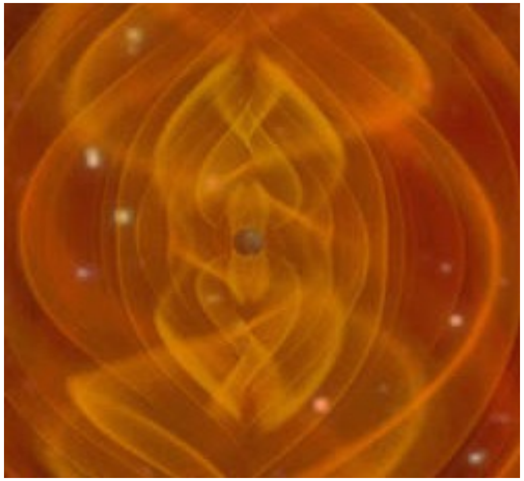

Fundamental physics with gravitational waves

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Utrecht University

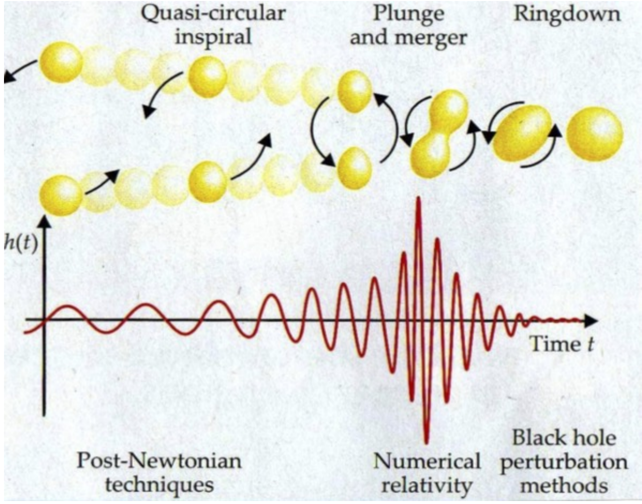
LIGO VIRGO KAGRA

Nikhef

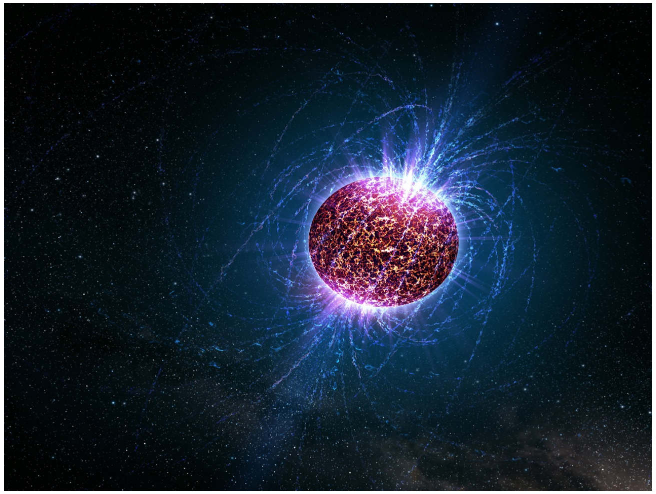
1st MaNiTou Summer School on Gravitational Waves, Marseille/Luminy, 4-8 July 2022

Detectable sources of gravitational waves

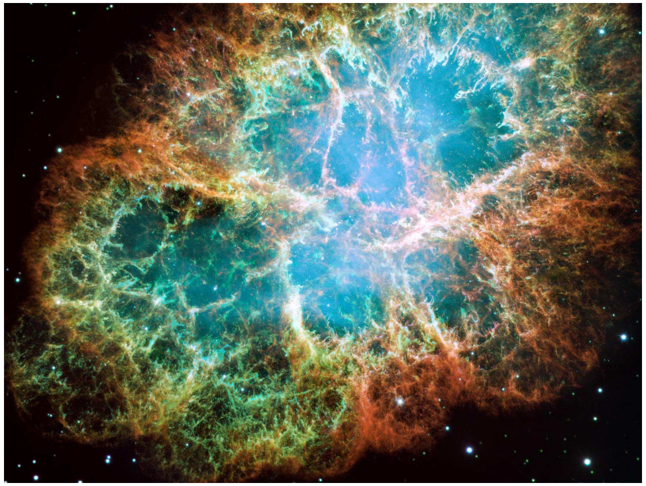
Merging neutron stars, black holes



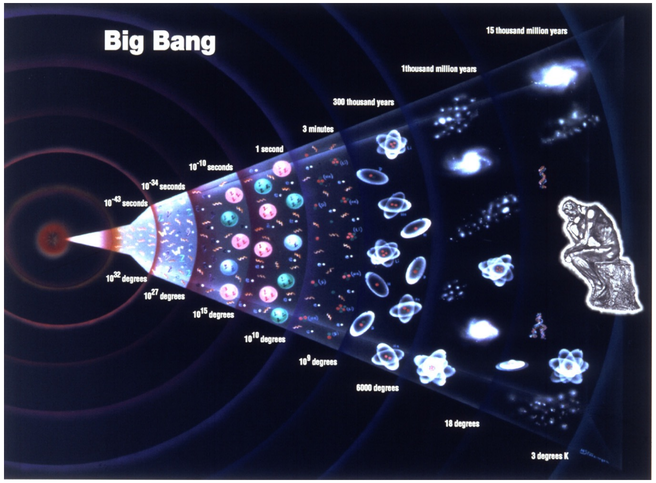
Fast-spinning neutron stars



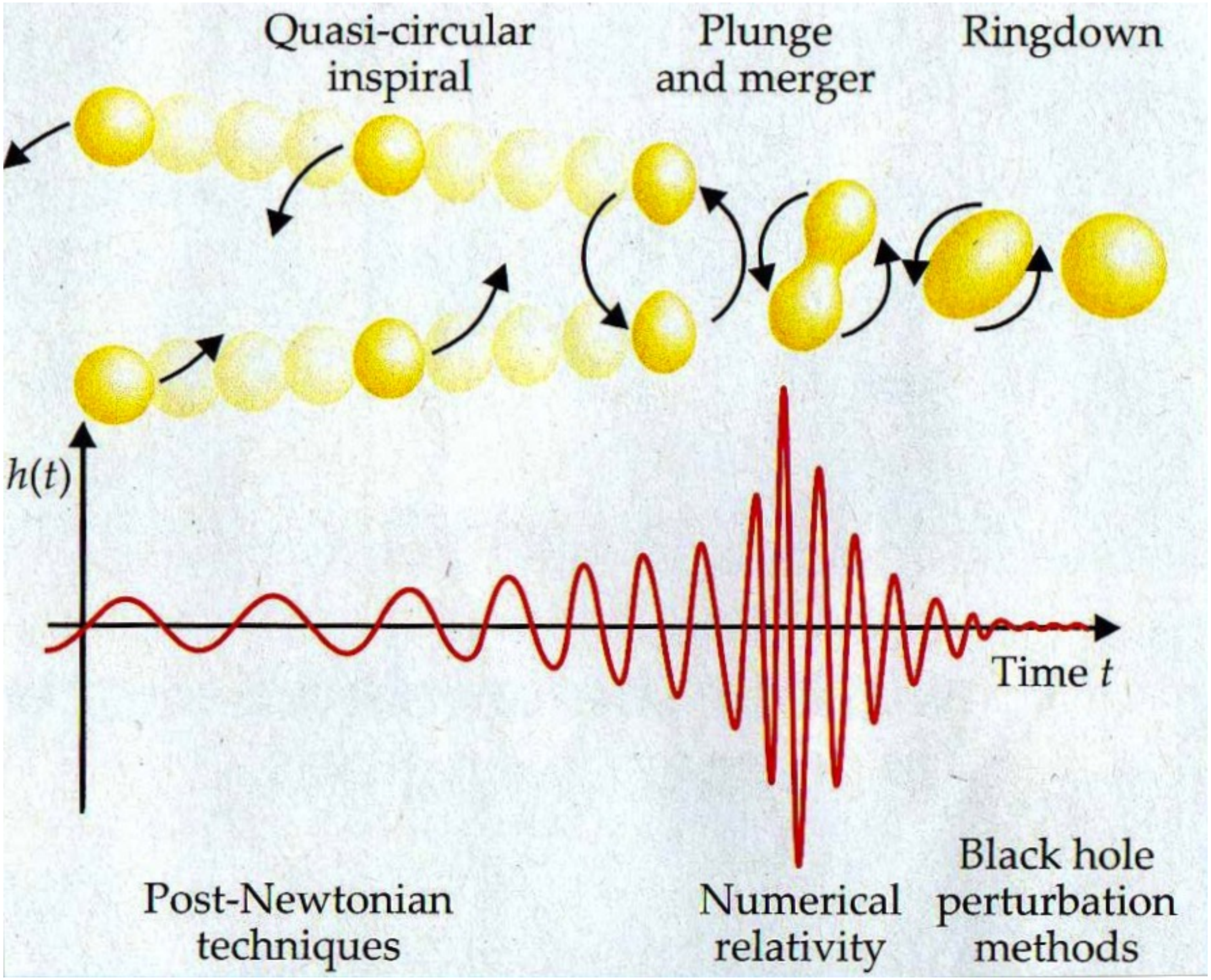
“Burst” sources



Stochastic gravitational waves

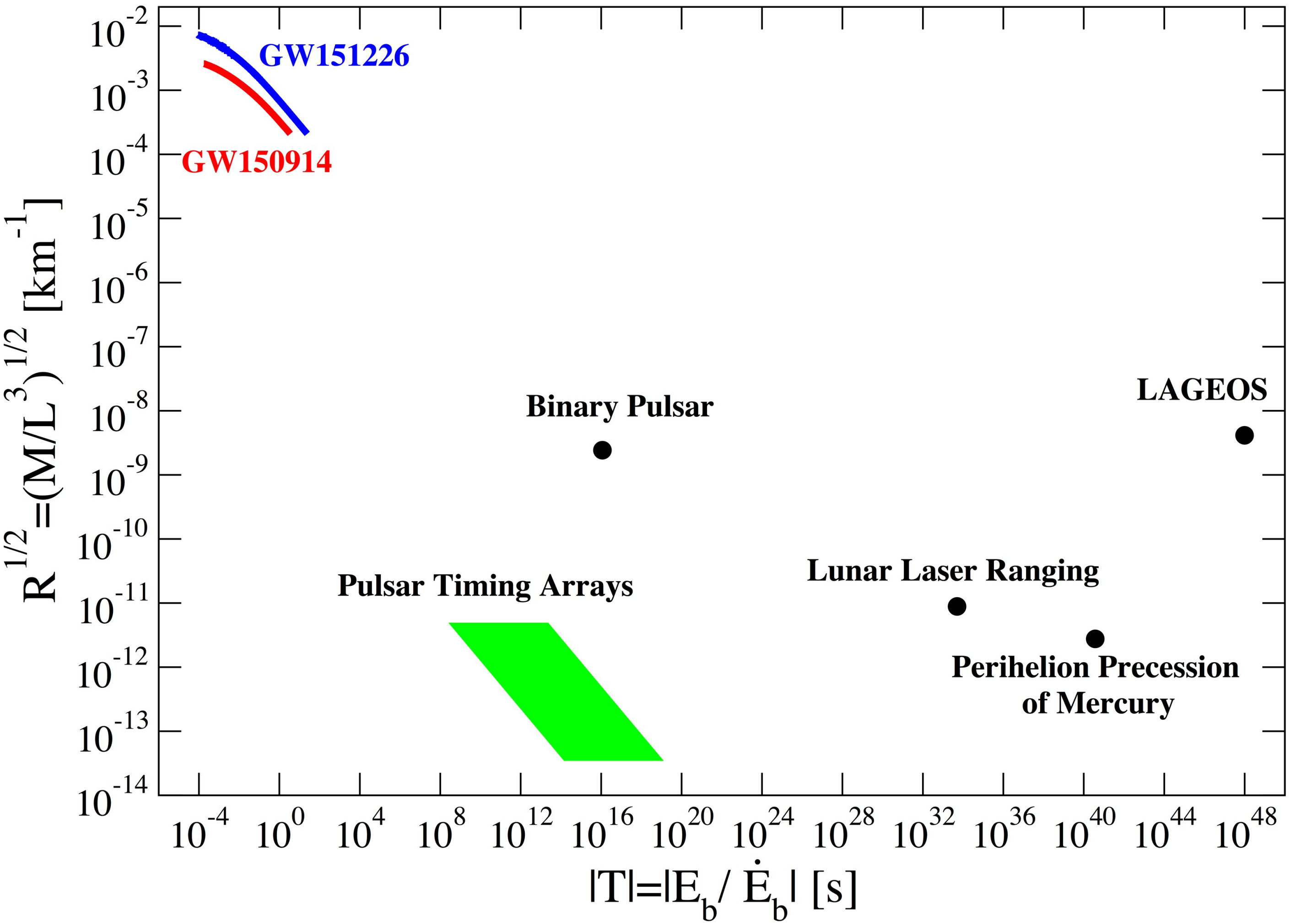


Inspiral-merger-ringdown



Access to strongly curved, dynamical spacetime

Curvature of spacetime



Characteristic timescale

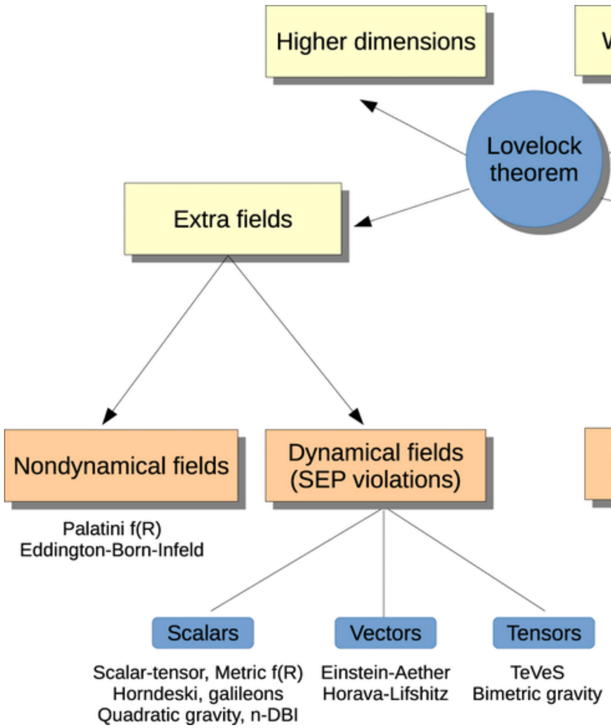
Yunes et al., PRD **94**, 084002 (2016)

The nature of gravity

- Lovelock's theorem:

  "In four spacetime dimensions the only divergence-free symmetric rank-2 tensor constructed solely from the metric $g_{\mu\nu}$ and its derivatives up to second differential order, and preserving diffeomorphism invariance, is the Einstein tensor plus a cosmological term."

- Relaxing one or more of the assumptions allows for a plethora of alternative theories:



Berti et al., CQG **32**, 243001 (2015)

- Most alternative theories: no full inspiral-merger-ringdown waveforms known
  - Most current tests are **model-independent**

Testing general relativity and the nature of black holes

1. The strong-field dynamics of spacetime
   - Is the inspiral-merger-ringdown process consistent with the predictions of GR?

2. The propagation of gravitational waves
   - Evidence for dispersion?

3. What is the nature of compact objects?

   Are the observed massive objects the "standard" black holes of classical general relativity?
   - Are there unexpected effects during inspiral?
   - Is the remnant object consistent with the no-hair conjecture? Is it consistent with Hawking's area increase theorem?
   - Searching for gravitational wave echoes

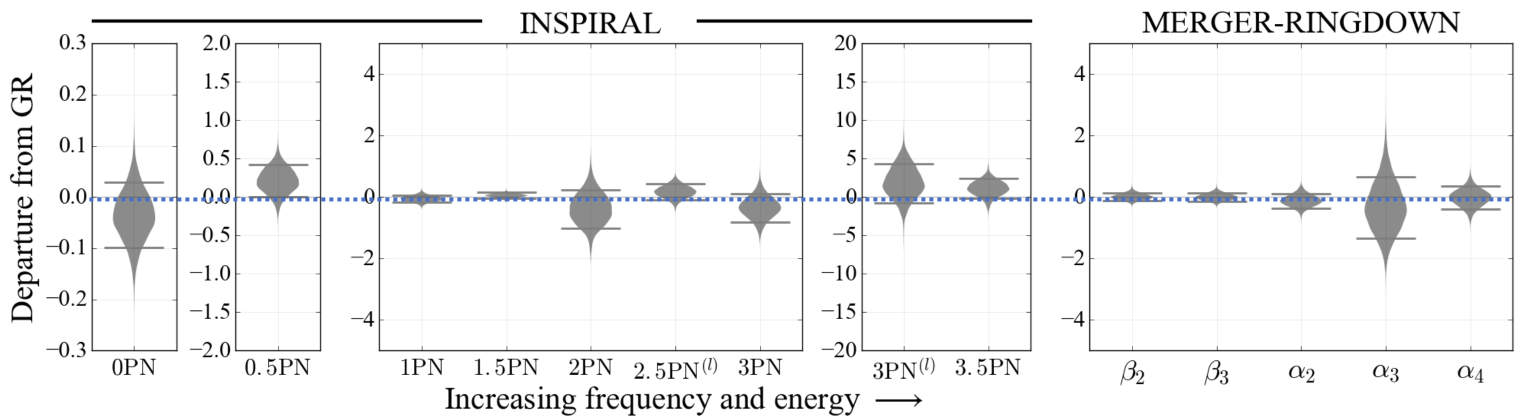
The strong-field dynamics of spacetime

- Inspiral-merger-ringdown process
  - Post-Newtonian description of inspiral phase

$$\Phi(v) = \left(\frac{v}{c}\right)^{-5}\left[\varphi_{0\mathrm{PN}} + \varphi_{0.5\mathrm{PN}}\left(\frac{v}{c}\right) + \varphi_{1\mathrm{PN}}\left(\frac{v}{c}\right)^{2} + \ldots + \varphi_{2.5\mathrm{PN}^{(l)}}\log\left(\frac{v}{c}\right)\left(\frac{v}{c}\right)^{5} + \ldots + \varphi_{3.5\mathrm{PN}}\left(\frac{v}{c}\right)^{7}\right]$$

  - Merger-ringdown governed by additional parameters β_n, α_n

- Place bounds on deviations in these parameters:

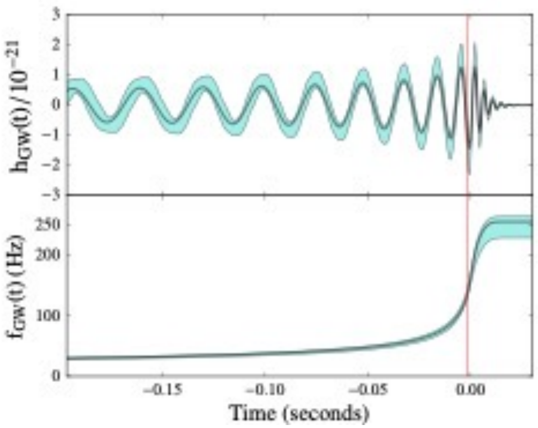


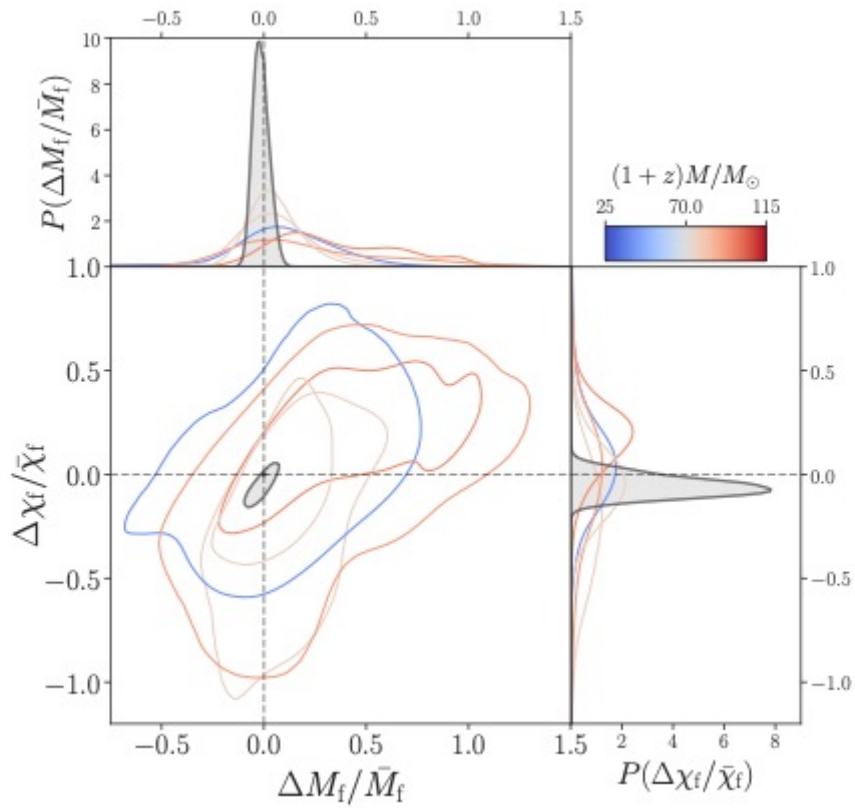
LIGO + Virgo, PRL **118**, 221101 (2017)

- Rich physics:
  Dynamical self-interaction of spacetime, spin-orbit and spin-spin interactions

- Can combine information from multiple detections
  - Bounds will get tighter roughly as $1/\sqrt{N_{\mathrm{det}}}$

Consistency of inspiral and post-inspiral





- Inspiral-merger-ringdown signal
  - At an appropriately chosen frequency, split into **inspiral** and **post-inspiral**
  - From the two parts, estimate component masses and spins
  - Compute from these the mass and spin of remnant black hole
    - **Do they agree**?

LIGO + Virgo, arXiv:2112.06861

The propagation of gravitational waves

- **Dispersion of gravitational waves?**
  E.g. as a result of **non-zero graviton mass**:
  - Dispersion relation:

    $$E^2 = p^2c^2 + m_g^2c^4$$

  - Graviton speed:

    $$v_g/c = 1 - m_g^2c^4/2E^2$$

  - Modification to gravitational wave phase:

    $$\delta\Psi = -\pi Dc/[\lambda_g^2(1+z)\,f] \qquad \lambda_g = h/(m_g c)$$

- Bound on graviton mass:

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

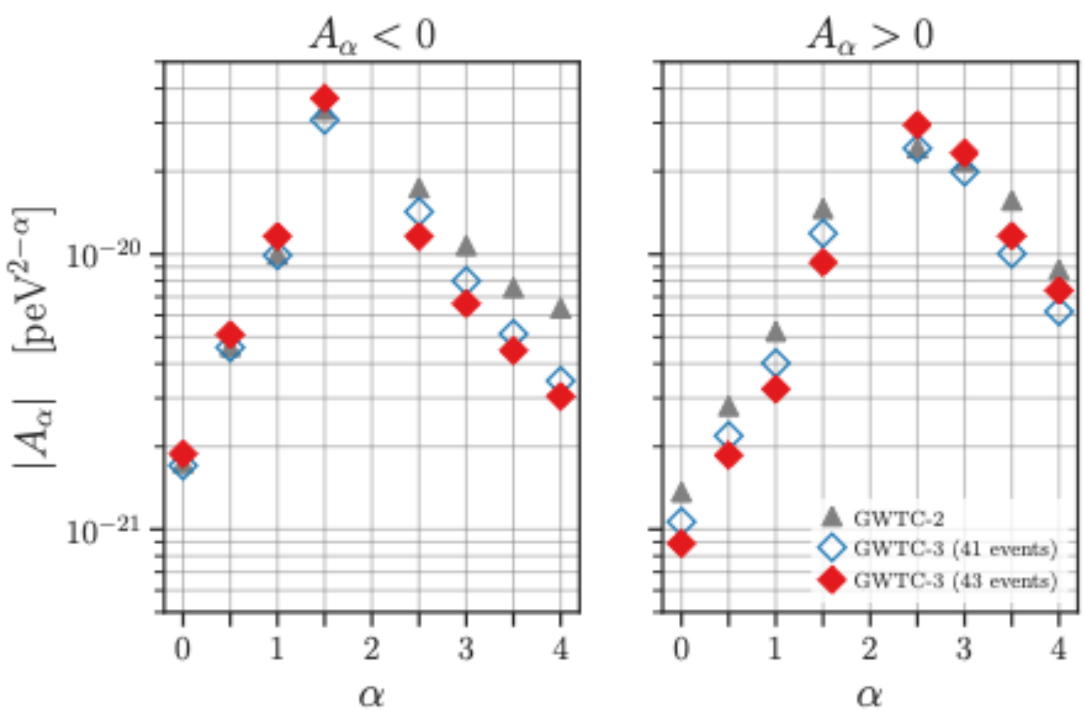
LIGO + Virgo, arXiv:2112.06861

The propagation of gravitational waves

- **More general forms of dispersion**:

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

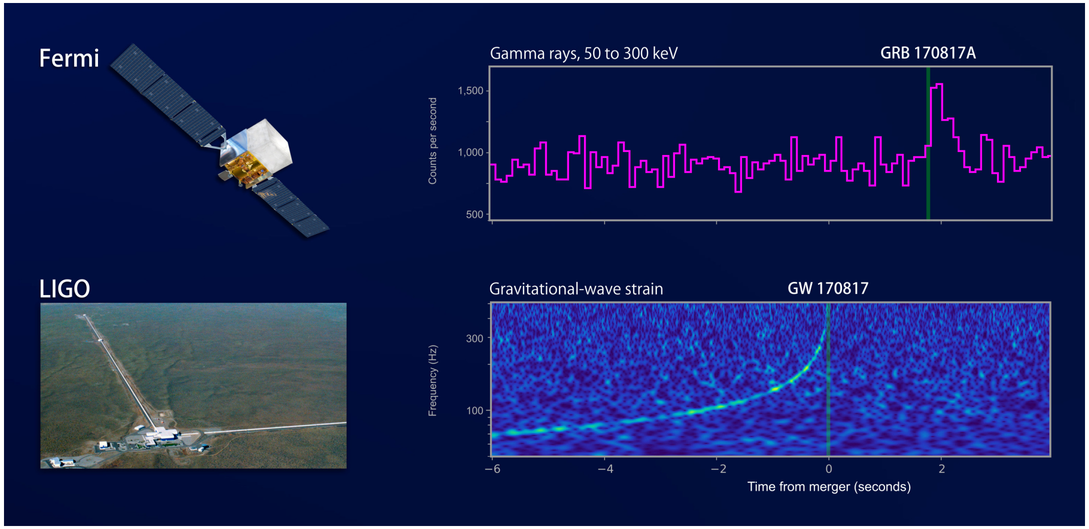
  - $\alpha \neq 0$ corresponds to violation of local Lorentz invariance
  - $\alpha = 2.5$ multi-fractal spacetime
  - $\alpha = 3$ doubly special relativity
  - $\alpha = 4$ higher-dimensional theories



LIGO + Virgo, arXiv:2112.06861

The propagation of gravitational waves

- **Does the speed of gravity equal the speed of light?**
- The binary neutron star coalescence GW170817 came with gamma ray burst, **1.74 seconds afterwards**



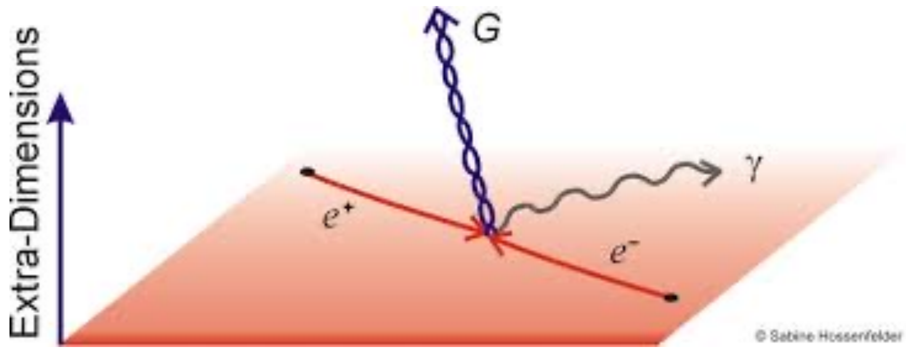
- With a conservative lower bound on the distance to the source:

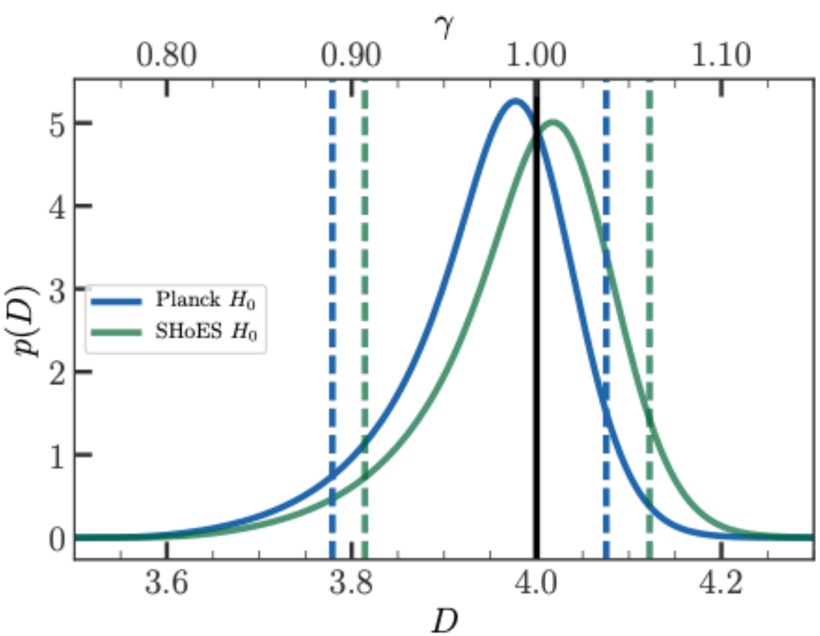
$$-3 \times 10^{-15} < (v_{GW} - v_{EM})/v_{EM} < +7 \times 10^{-16}$$

- Excluded certain alternative theories of gravity designed to explain dark matter or dark energy in a dynamical way

LIGO + Virgo + Fermi-GBM + INTEGRAL, ApJ. **848**, L13 (2017)
LIGO + Virgo, PRL **123**, 011102 (2019)

The propagation of gravitational waves





Pardo et al., JCAP **1807**, 048 (2018)
LIGO + Virgo, PRL **123**, 011102 (2019)

- **How many spacetime dimensions are there?**
- E.g. "braneworld" models:
  - Standard model particles confined to 3D "membrane"
  - Gravity has access to extra dimensions
- If gravitational waves "leak" into large extra dimensions:

$$h \propto \frac{1}{d_{\rm L}^{(D-2)/2}}$$

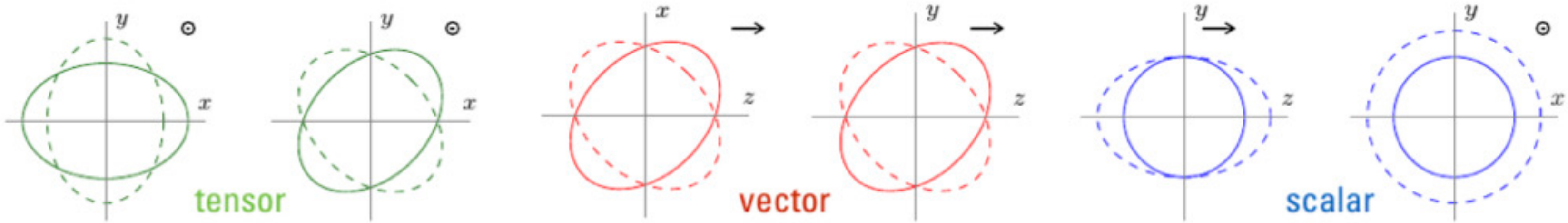
$d_{\rm L}$ luminosity distance,

D number of spacetime dimensions

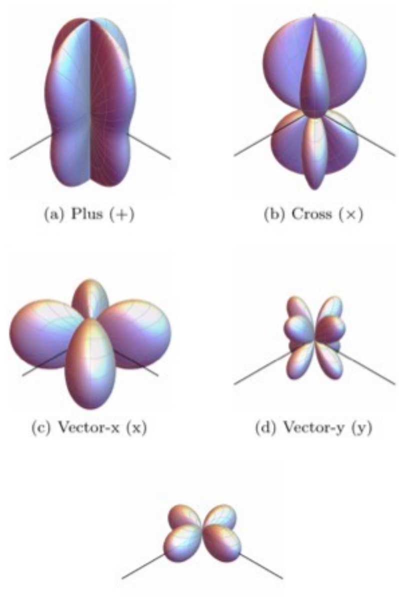
- GW170817: redshift z known because of host galaxy identification
  - Translate into distance using Hubble's law, $cz = H_0 d_{\rm L}$, with H_0 from EM measurements
- More applications of GW propagation:

Mastrogiovanni et al., JCAP **02**, 043 (2021)

Alternative polarizations



- Metric theories of gravity allow up to 6 polarizations
- Distinct antenna patterns:



(a) Plus (+) (b) Cross (×) (c) Vector-x (x) (d) Vector-y (y) (e) Scalar (s)

$$F_+ = \frac{1}{2}(1+\cos^2\theta)\cos 2\phi\cos 2\psi - \cos\theta\sin 2\phi\sin 2\psi$$

$$F_\times = \frac{1}{2}(1+\cos^2\theta)\cos 2\phi\sin 2\psi + \cos\theta\sin 2\phi\cos 2\psi$$

$$F_{\mathrm{X}} = -\sin\theta(\cos\theta\cos 2\phi\cos\psi - \sin 2\phi\sin\psi)$$

$$F_{\mathrm{Y}} = -\sin\theta(\cos\theta\cos 2\phi\sin\psi + \sin 2\phi\cos\psi)$$

$$F_{\mathrm{B}} = -\frac{1}{2}\sin^2\theta\cos 2\phi$$

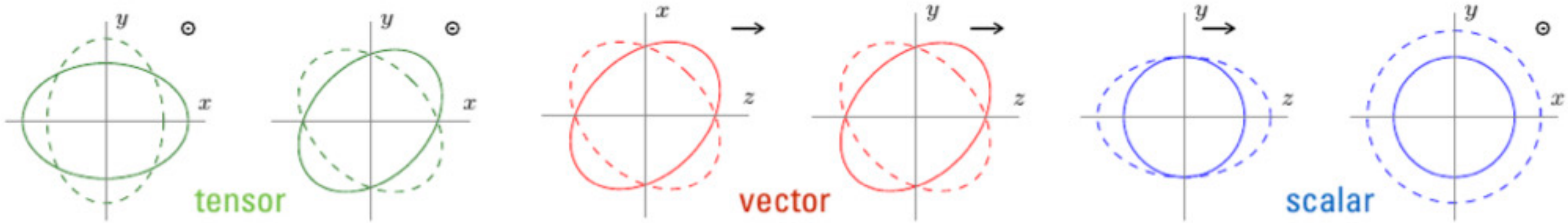
$$F_{\mathrm{L}} = \frac{1}{2}\sin^2\theta\cos 2\phi$$

Isi & Weinstein, PRD **96**, 042001 (2017)

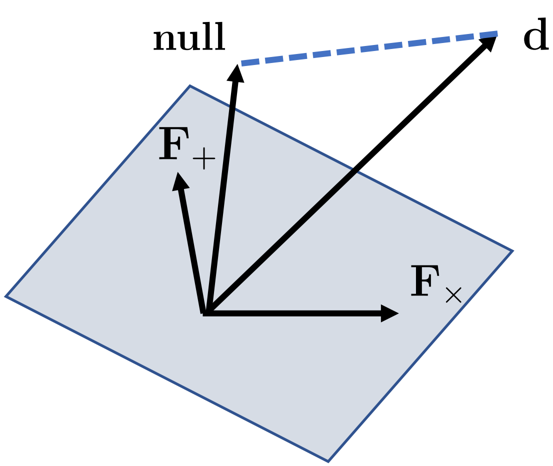
- In the case of GW170817, sky position was known from EM counterpart
  - Pure tensor / pure vector = 10^{21} / 1
  - Pure tensor / pure scalar = 10^{23} / 1

LIGO + Virgo, PRL **123**, 011102 (2019)

Alternative polarizations: null stream



- Using a **null stream**: can look for non-tensorial polarizations (without necessarily being able to tell which ones are present)



- Data from D detectors:

$$\mathbf{d} = \begin{pmatrix} d_0 \\ \vdots \\ d_{D-1} \end{pmatrix}$$

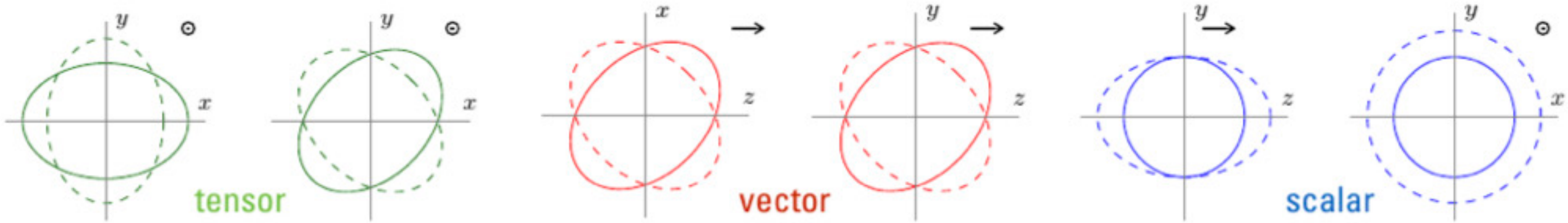
- Antenna pattern functions, known sky location:

$$\mathbf{F} = (\mathbf{F}_+ \;\; \mathbf{F}_\times) = \begin{pmatrix} F_{+,0} & F_{\times,0} \\ \vdots & \vdots \\ F_{+,D-1} & F_{\times,D-1} \end{pmatrix}.$$

- Null stream projects out tensorial content
  - What remains can only contain (mixture of) vector and scalar modes
- No evidence for alternative polarizations in GW170817

Pang et al., PRD **101**, 104055 (2020)

Alternative polarizations in pulsar signals



- **Continuous waves from known pulsars**: sky position (α, δ) also known
- Consider hypotheses $\mathcal{H}_m$ that detector output is

$$h_m(t) = \sum_{p \in m} F_p(\alpha, \delta; t)\, h_p(t)$$

where m is any subset of $\{+, \times, v_X, v_Y, s\}$

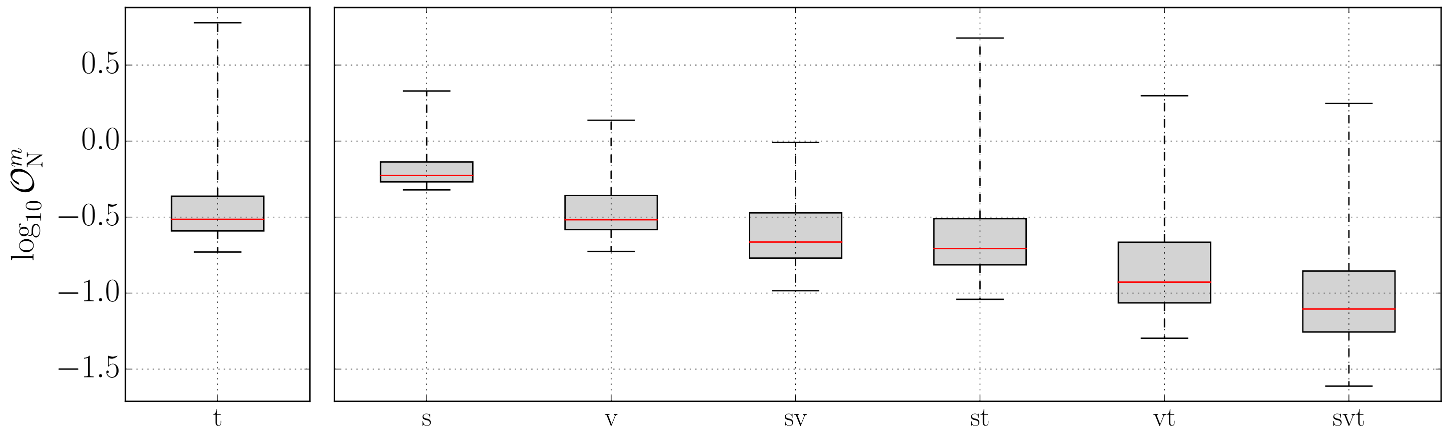
- Calculate odds ratios

$$\mathcal{O}_N^m = \frac{\text{Prob}(\mathcal{H}_m|d)}{\text{Prob}(\mathcal{H}_N|d)}$$

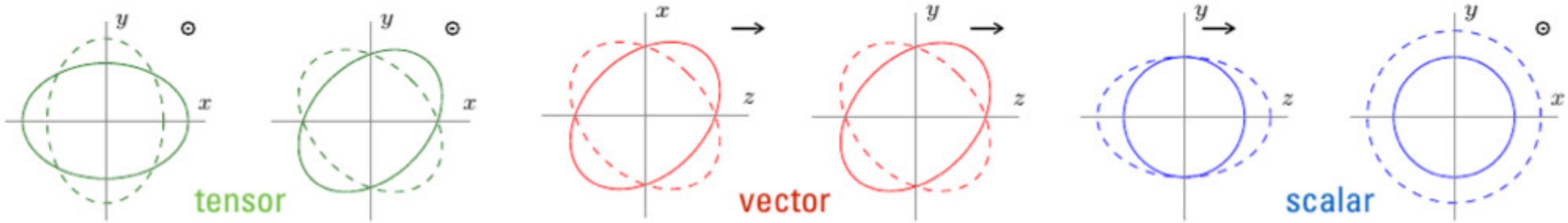
where $\mathcal{H}_N$ is the noise-only hypothesis

- Results for 200 pulsars analyzed:

LIGO + Virgo, PRL **120**, 031104 (2018)



Alternative polarizations in stochastic backgrounds



- **Search for stochastic backgrounds** through cross-correlations of detector outputs:

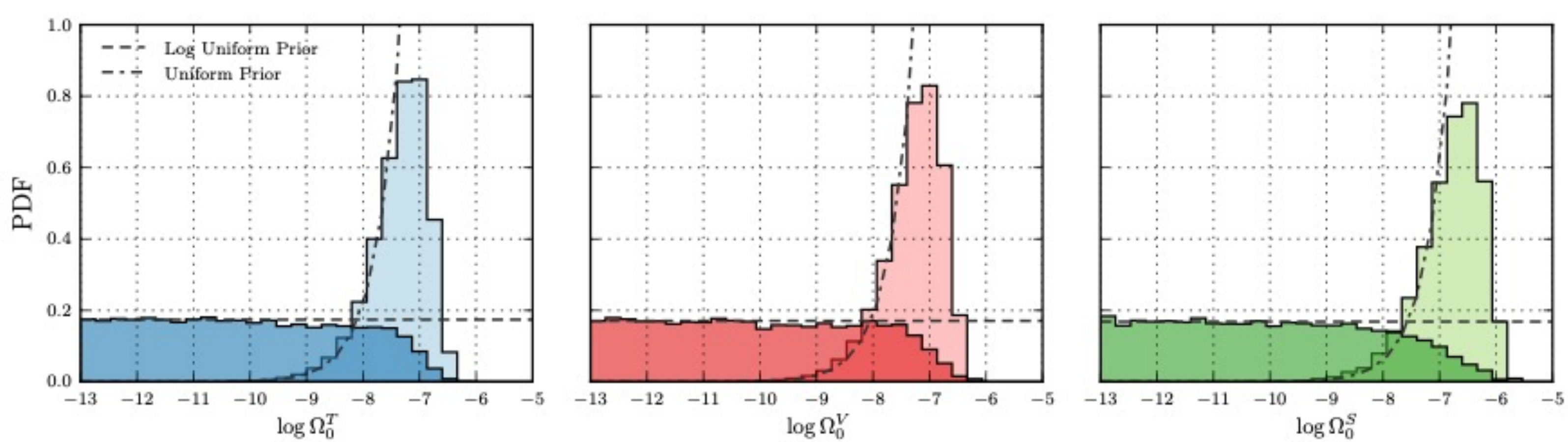
$$Y = \sum_p \int \tilde{s}^*(f)\, \tilde{Q}_p(f)\, \tilde{s}_2(f)\, df \quad \text{with optimal filter} \quad \tilde{Q}_p(f) \propto \frac{\gamma_p(f)\, \Omega_p(f)}{f^3 S_1(f)\, S_2(f)}$$

where $\gamma_p(f)$ the overlap reduction function for polarization p and the energy densities $\Omega_p(f)$ are contributions to

$$\Omega(f) = \Omega_0^T \left(\frac{f}{f_0}\right)^{\alpha_T} + \Omega_0^V \left(\frac{f}{f_0}\right)^{\alpha_V} + \Omega_0^S \left(\frac{f}{f_0}\right)^{\alpha_S}$$

- Parameter estimation on $\Omega_0^T, \Omega_0^V, \Omega_0^S$:

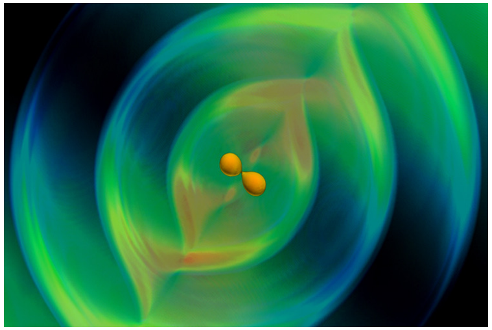
LIGO + Virgo, PRL **120**, 201102 (2018)



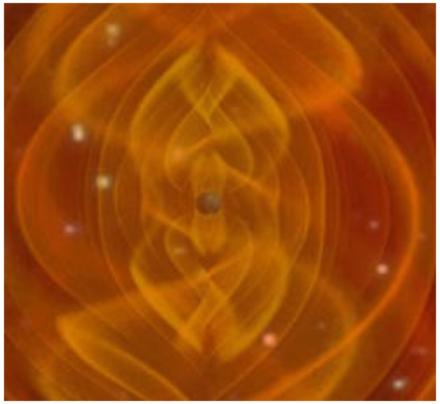
What is the nature of compact objects?

- Black holes, or still more exotic objects?
  - Boson stars
  - Dark matter stars
  - Firewalls, fuzzballs
  - Gravastars
  - Wormholes
  - …
  - *The unknown*

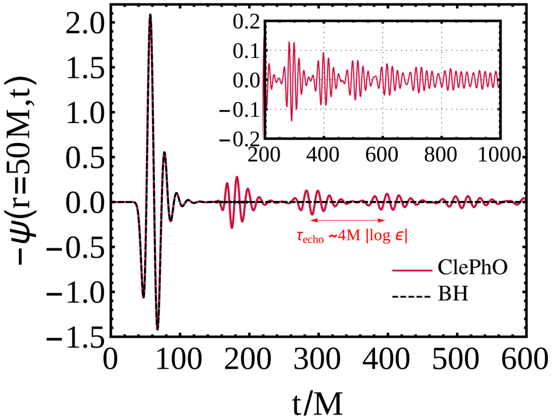
What is the nature of compact objects?



Anomalous effects during inspiral

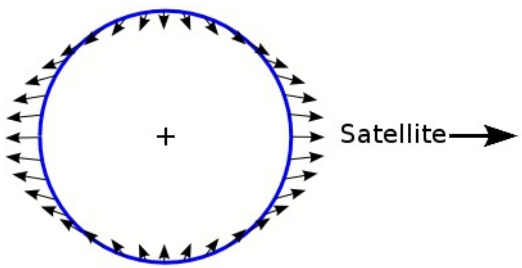


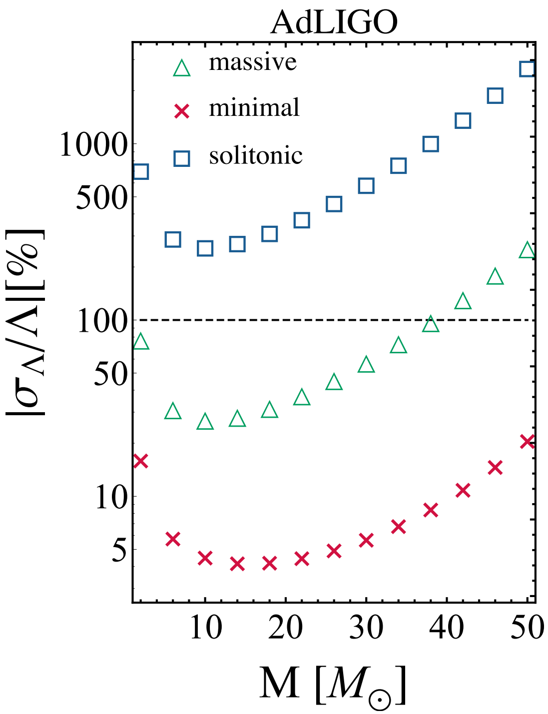
Ringdown of newly formed object



Gravitational wave echoes

Anomalous effects during inspiral: tidal deformation



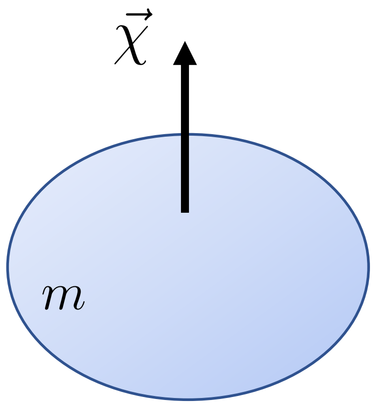


- Tidal field of one body causes quadrupole deformation in the other:
  $$Q_{ij} = -\lambda(\mathrm{EOS}; m)\,\mathcal{E}_{ij}$$
  where $\lambda(\mathrm{EOS}; m)$ depends on internal structure (equation of state)
  - Black holes: $\lambda \equiv 0$
  - Boson stars, dark matter stars: $\lambda > 0$
  - Gravastars: $\lambda < 0$

- Enters inspiral phase at 5PN order, through
  $$\lambda(m)/m^5 \propto (R/m)^5$$
  - $O(10^2$ - $10^4)$ for neutron stars
  - Can also be measurable for black hole mimickers, e.g. boson stars

Cardoso et al., PRD **95**, 084014 (2017)
Johnson-McDaniel et al., arXiv:1804.0826

Anomalous effects during inspiral: spin effects



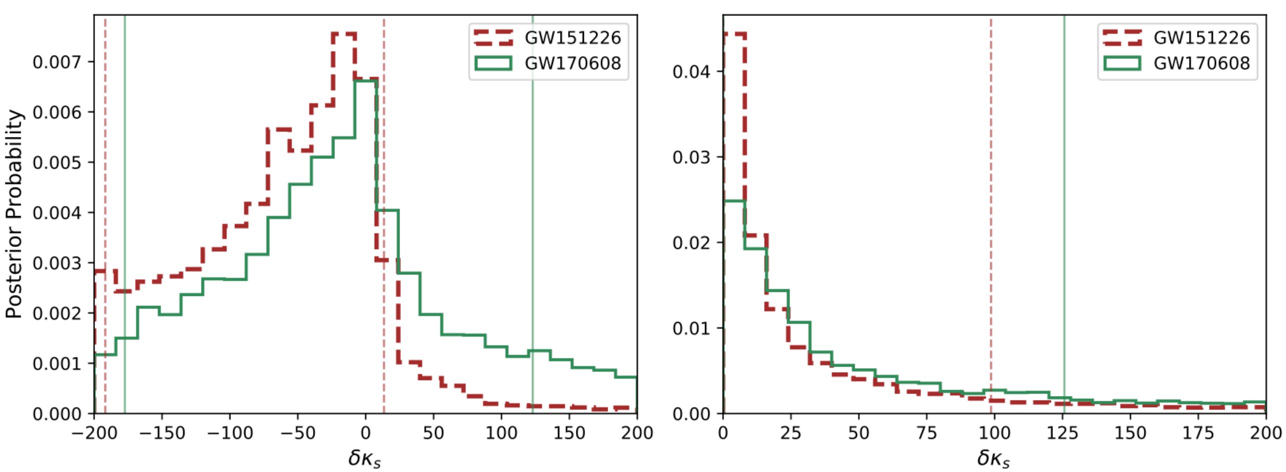
- Spin of an individual compact object also induces a quadrupole moment:

$$Q = -\kappa\, \chi^2 m^3$$

  - Black holes: $\kappa = 1$
  - Boson stars, dark matter stars: $\kappa > 1$
  - Gravastars: $\kappa < 1$

- Allow for deviations from Kerr value:

$$Q = -(1 + \delta\kappa)\, \chi^2 m^3$$



Possible theoretical values for boson stars: $\kappa \sim 10 - 150$

… hence constraints are already of interest!

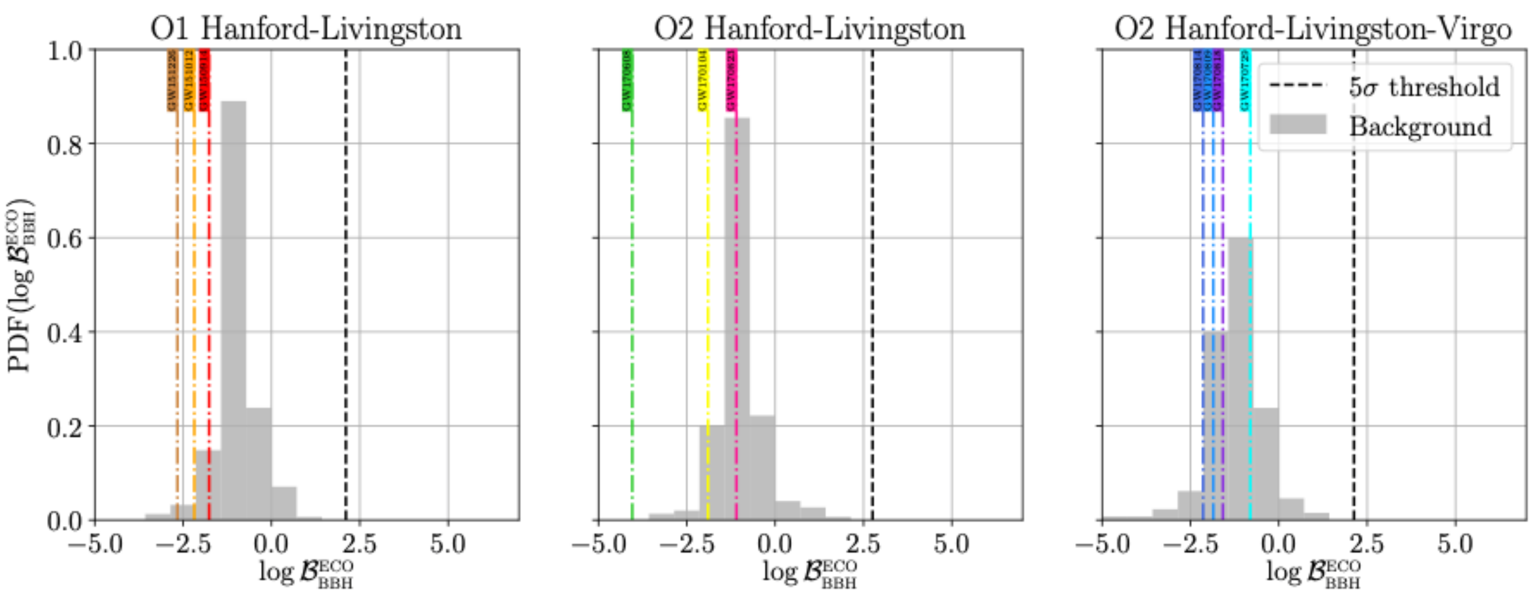
Krishnendu et al., PRD **100**, 104019 (2019)

Anomalous effects during inspiral: resonant excitations

- Exotic compact objects (e.g. boson stars) can undergo **resonant excitations**:
  - When the (monotonically increasing) GW frequency becomes equal to an internal resonance frequency, the object gets excited
  - Leads to dissipation of orbital energy
  - Sudden speed-up of the orbital phase:

$$\Phi(t) = \begin{cases} \Phi_{\rm pp}(t) & \text{if } t < t_0 \\ \Phi_{\rm pp}(t+\Delta t) - \Delta\Phi & \text{if } t \geq t_0 \end{cases}$$

- Hypothesis $\mathcal{H}_{\rm ECO}$: exotic compact object(s), underwent excitation
  Hypothesis $\mathcal{H}_{\rm BBH}$: ordinary binary black hole
  Bayes factor: $\mathcal{B}^{\rm ECO}_{\rm BBH} = \mathrm{Prob}(d|\mathcal{H}_{\rm ECO})/\mathrm{Prob}(d|\mathcal{H}_{\rm BBH})$



Asali et al., PRD **102**, 024016 (2020)

Ringdown of newly formed black hole

- Ringdown regime: Kerr metric + linear perturbations
  - Ringdown signal is a superposition of quasi-normal modes

$$h(t) = \sum_{lmn} \mathcal{A}_{lmn} e^{-t/\tau_{lmn}} \cos(\omega_{lmn} t + \phi_{lmn})$$

  - Characteristic frequencies ω_{lmn} and damping times τ_{lmn}

- No-hair conjecture: stationary, electrically neutral black hole completely characterized by mass M_f, spin a_f
  - Linearized Einstein equations around Kerr background enforce specific dependences:

$$\omega_{lmn} = \omega_{lmn}(M_f, a_f)$$

$$\tau_{lmn} = \tau_{lmn}(M_f, a_f)$$

Berti et al., PRD **73**, 064030 (2006)

  - Look for deviations from the expressions for frequencies, damping times:

$$\omega_{lmn}(M_f, a_f) \;\rightarrow\; (1 + \delta\hat{\omega}_{lmn})\, \omega_{lmn}(M_f, a_f)$$
$$\tau_{lmn}(M_f, a_f) \;\rightarrow\; (1 + \delta\hat{\tau}_{lmn})\, \tau_{lmn}(M_f, a_f)$$

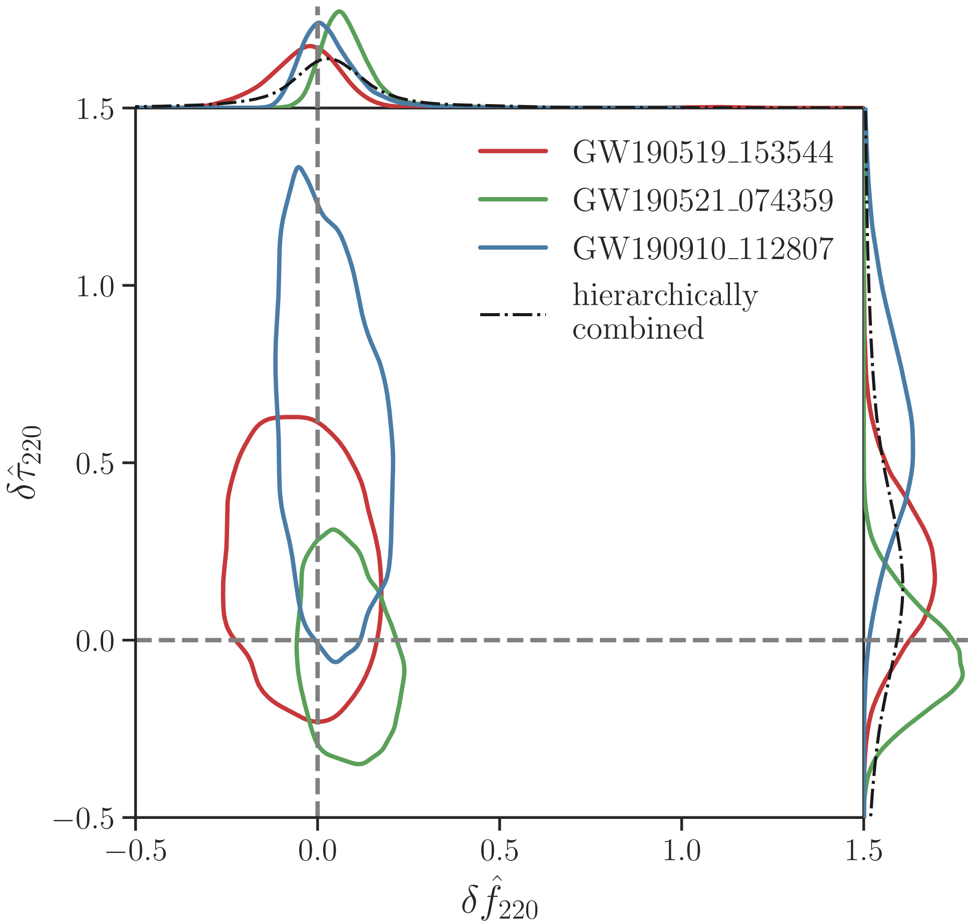
Carulllo et al., PRD **98**, 104020 (2018)
Brito et al., PRD **98**, 084038 (2018)

Ringdown of newly formed black hole

- Look for deviations from the expressions for frequencies, damping times:

$$\omega_{lmn}(M_f, a_f) \;\rightarrow\; (1 + \delta\hat{\omega}_{lmn})\,\omega_{lmn}(M_f, a_f)$$
$$\tau_{lmn}(M_f, a_f) \;\rightarrow\; (1 + \delta\hat{\tau}_{lmn})\,\tau_{lmn}(M_f, a_f)$$

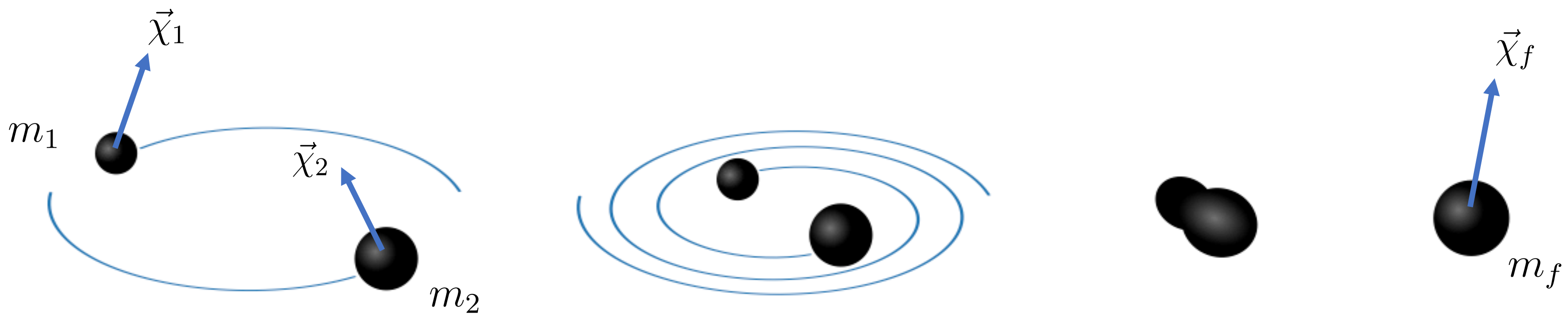
- First measurements:



LIGO + Virgo, arXiv:2010.14529

First tests of Hawking's area increase theorem

- During binary black hole merger, horizon area should not decrease



- "Ingoing" black holes considered Kerr
  - Measure masses m_1 , m_2 and initial spins χ_1 , χ_2 from inspiral signal
  - Total initial horizon area:

$$\mathcal{A}_0 = \mathcal{A}(m_1, \chi_1) + \mathcal{A}(m_2, \chi_2) \quad \text{where} \quad \mathcal{A}(m, \chi) = 8\pi m^2 (1 + \sqrt{1 - \chi^2})$$

- Final black hole also Kerr
  - Obtain mass m_f and spin χ_f from ringdown frequencies and damping times
  - Final horizon area:

$$\mathcal{A}_f = \mathcal{A}(m_f, \chi_f)$$

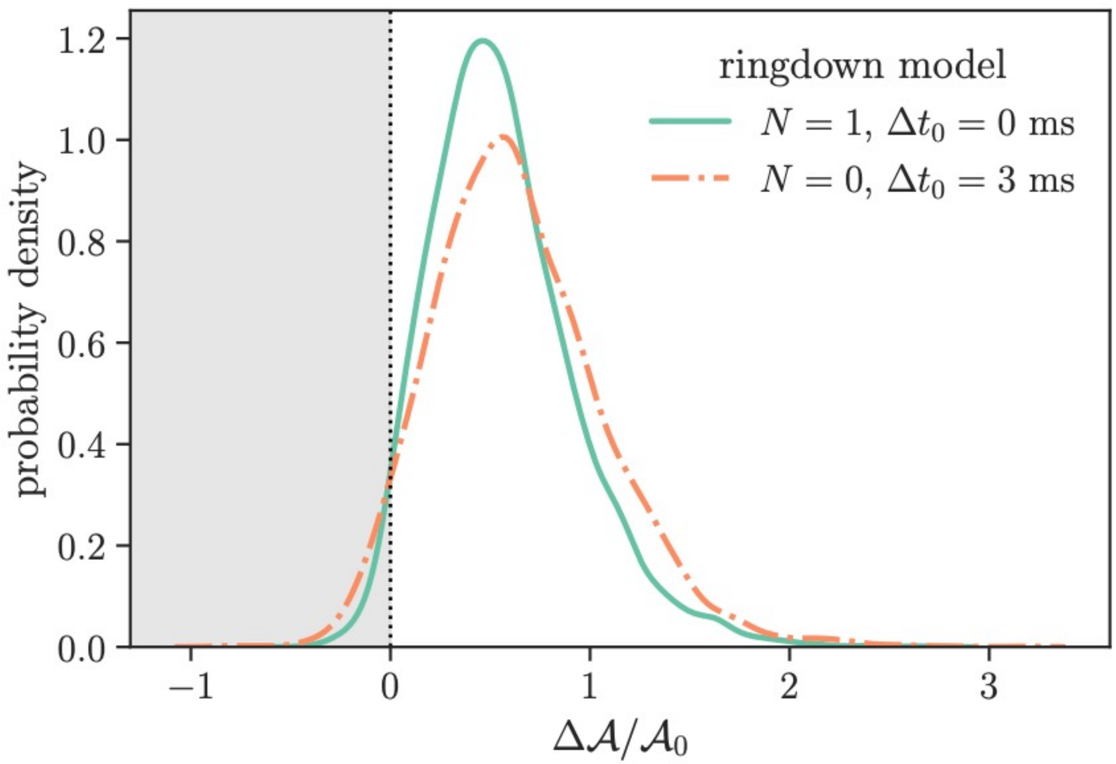
- According to the theorem: $\Delta\mathcal{A}/\mathcal{A}_0 = (\mathcal{A}_f - \mathcal{A}_0)/\mathcal{A}_0 \geq 0$

First tests of Hawking's area increase theorem

- According to the theorem:

$$\Delta\mathcal{A}/\mathcal{A}_0 = (\mathcal{A}_f - \mathcal{A}_0)/\mathcal{A}_0 \geq 0$$

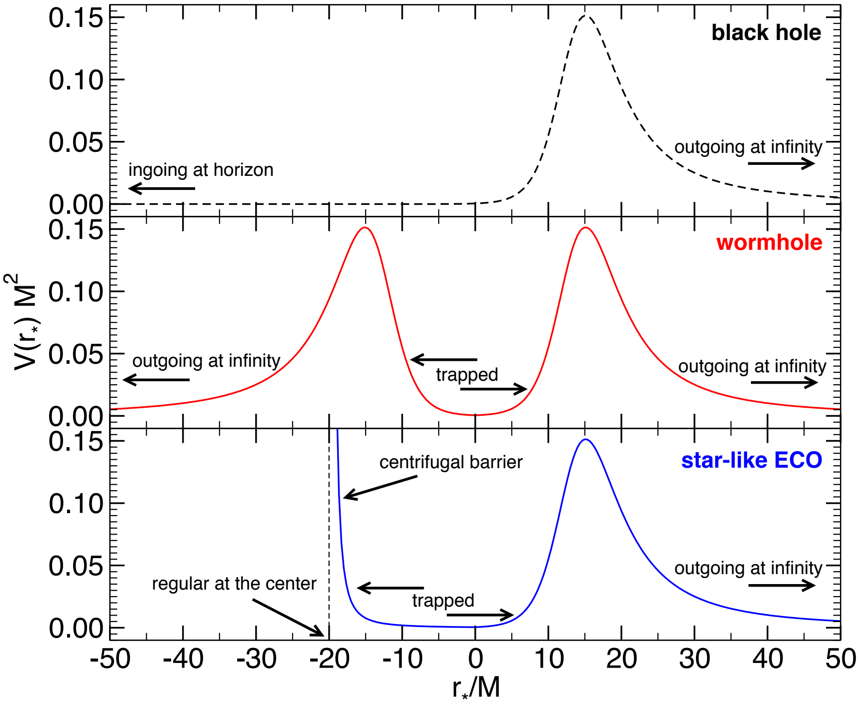
- Measurement on GW150914:



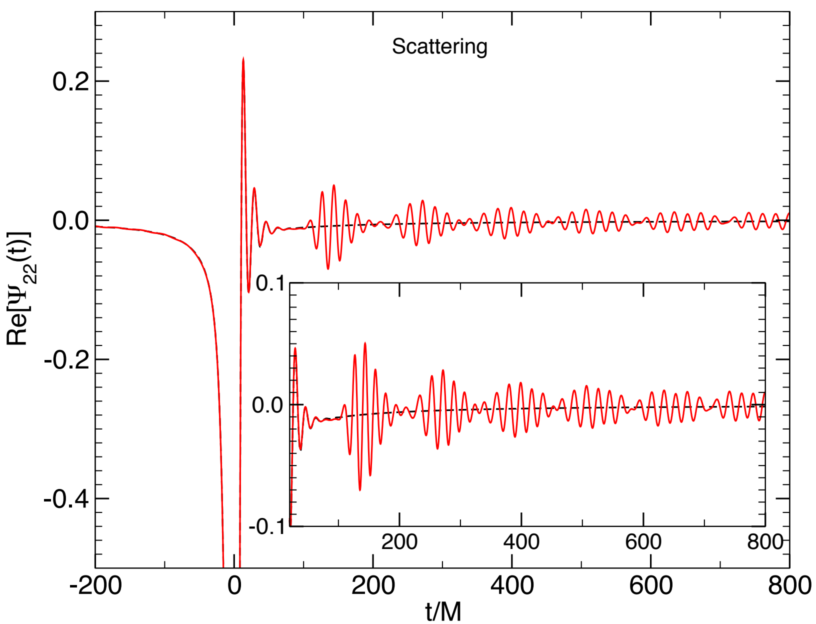
Isi et al., arXiv:2012.04486

- Agreement at > 95% probability

Gravitational wave echoes



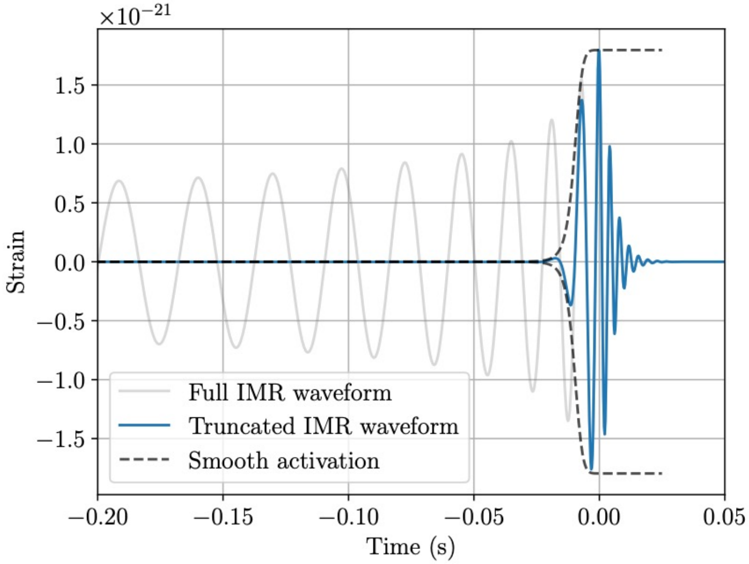
- Exotic objects without horizon: Ingoing gravitational waves bounce between inner/outer potential barriers
- After formation/ringdown: continuing bursts of radiation called *echoes*
- Typical time between echoes O(100) ms for stellar mass objects

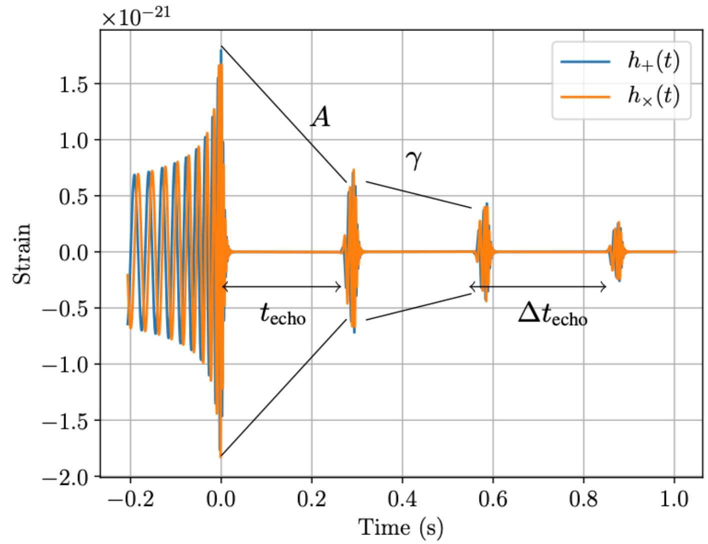


Cardoso et al., PRL **116**, 171101 (2016)
Cardoso et al., PRD **94**, 084031 (2016)

Gravitational wave echoes

- Theoretical predictions still in early stages
- Numerical waveforms for *specific* black hole mimickers + smaller object:
  - "Straw man" exotic object
  - Much higher mass ratio than the systems we currently see with LIGO/Virgo
- When searching for echoes, in practice one often assumes that echoes will be damped and widened copies of (part of) the merger/ringdown signal



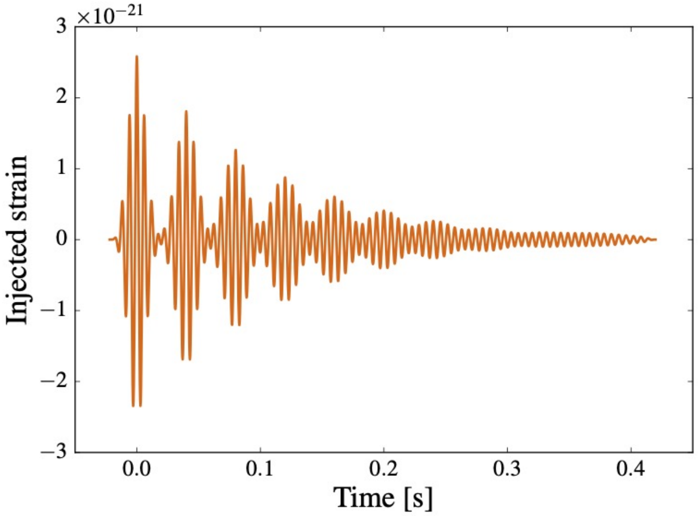


Abedi et al., PRD **96**, 082004 (2017)
Westerweck et al., PRD **97**, 124037 (2018)
Lo et al., PRD **99**, 084052 (2019)

- Alternatively: *morphology-independent* search for echoes

Gravitational wave echoes

- *Morphology-independent* search for echoes:
  - Decompose data into *generalized wavelets*: succession of sine-Gaussians



Characterized by 9 intrinsic parameters:

A overall amplitude

Δt time between sine-Gaussians

γ damping factor

$\Delta\phi$ phase difference

w widening factor

t_0 time of first echo

f_0 central frequency

ϕ_0 reference phase

  - Compare 3 hypotheses for data from a **network** of detectors:

$\mathcal{H}_{\text{signal}}$: data consists of signal + noise

$\mathcal{H}_{\text{glitch}}$: data consists of instrumental glitches + noise

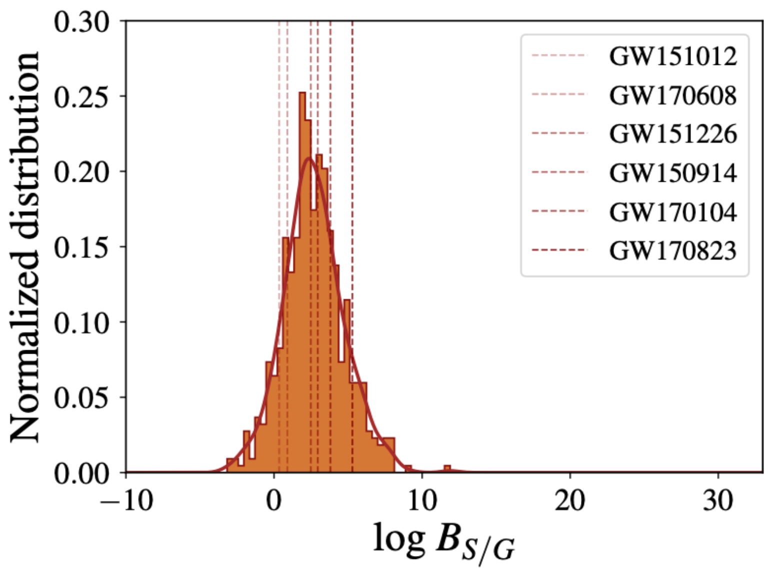
$\mathcal{H}_{\text{noise}}$: data consists only of noise

  - A signal is by definition coherent between detectors, and consistent with a particular sky position and source orientation
    - If a signal is present, $\mathcal{H}_{\text{signal}}$ has less degrees of freedom than $\mathcal{H}_{\text{glitch}}$
    - Bayesian analysis will then favor $\mathcal{H}_{\text{signal}}$ over $\mathcal{H}_{\text{glitch}}$

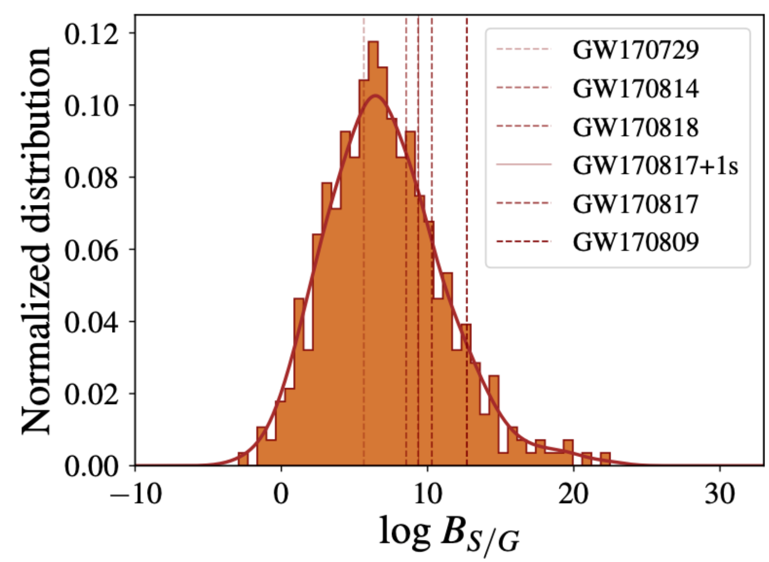
Gravitational wave echoes

- Ratio of evidences for signal versus glitch: Bayes factor $B_{S/G} = \frac{\mathrm{Prob}(\mathbf{d}|\mathcal{H}_{\mathrm{signal}})}{\mathrm{Prob}(\mathbf{d}|\mathcal{H}_{\mathrm{glitch}})}$

- Analysis of data following the detections of binary coalescences in the 1st and 2nd observing runs of Advanced LIGO/Virgo:



2-detector events



3-detector events

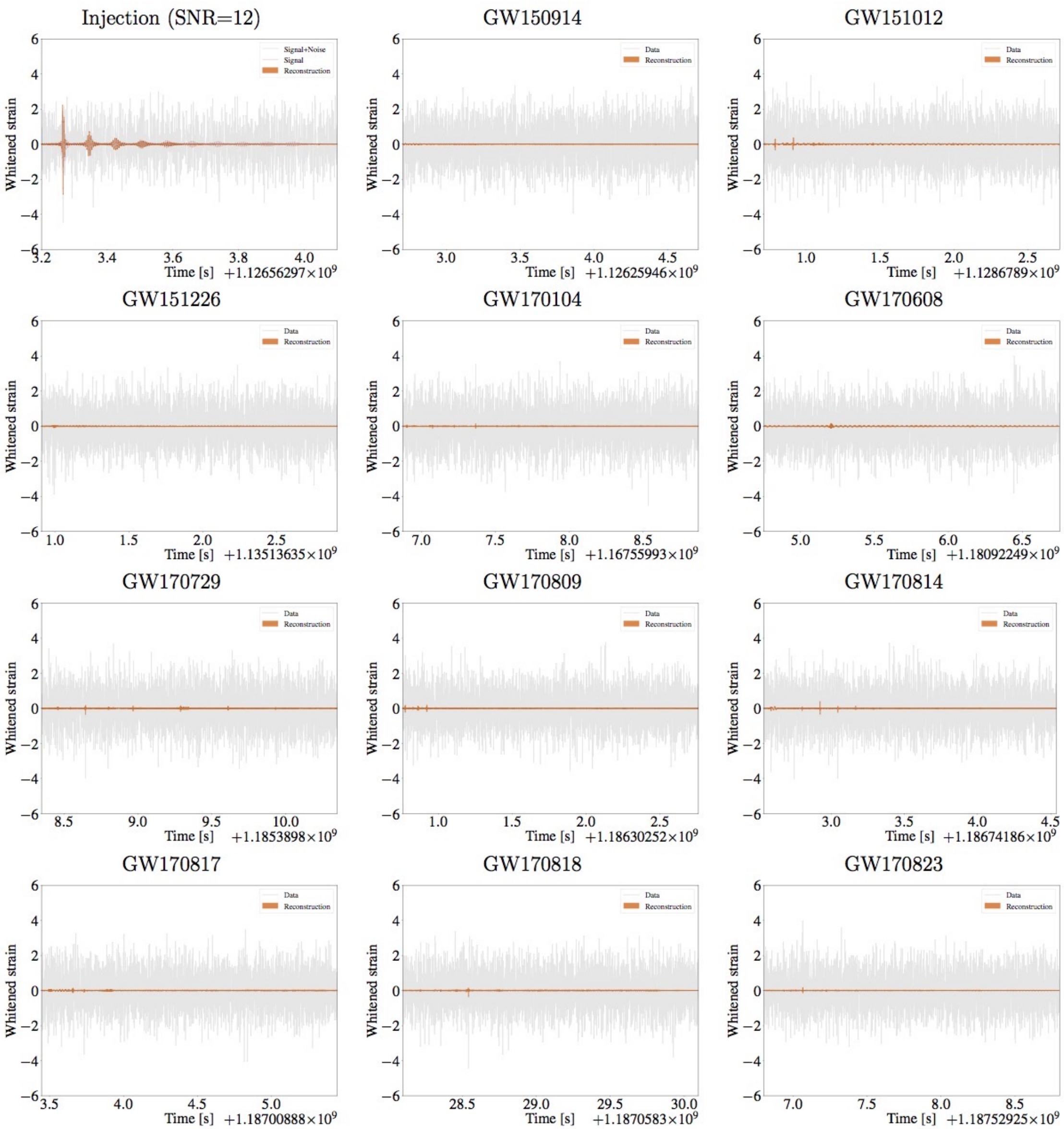
- Similarly for Bayes factor signal versus noise, $B_{S/N} = \frac{\mathrm{Prob}(\mathbf{d}|\mathcal{H}_{\mathrm{signal}})}{\mathrm{Prob}(\mathbf{d}|\mathcal{H}_{\mathrm{noise}})}$

- No statistically significant evidence for echoes following these events

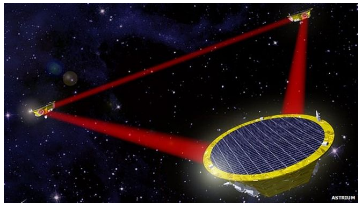
Tsang et al., PRD **98**, 024023 (2018)
Tsang et al., PRD **101**, 064012 (2020)

Gravitational wave echoes

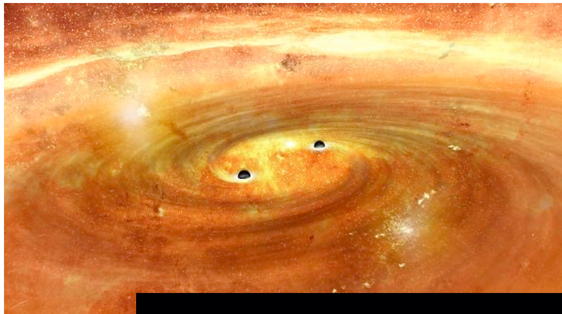
- Signal reconstructions:

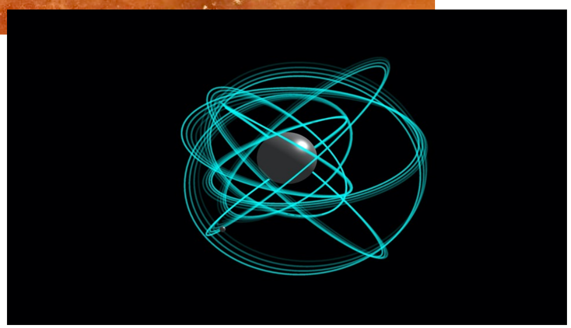


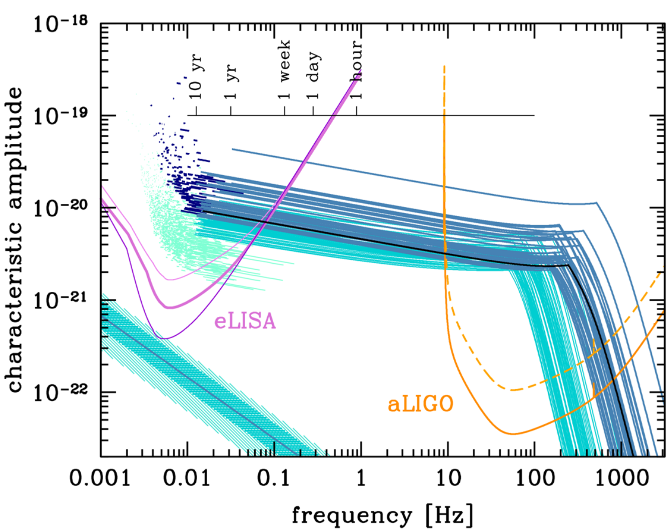
Tsang et al., PRD **101**, 064012 (2020)
LIGO + Virgo + KAGRA, arXiv:2112.06861



Fundamental physics with LISA

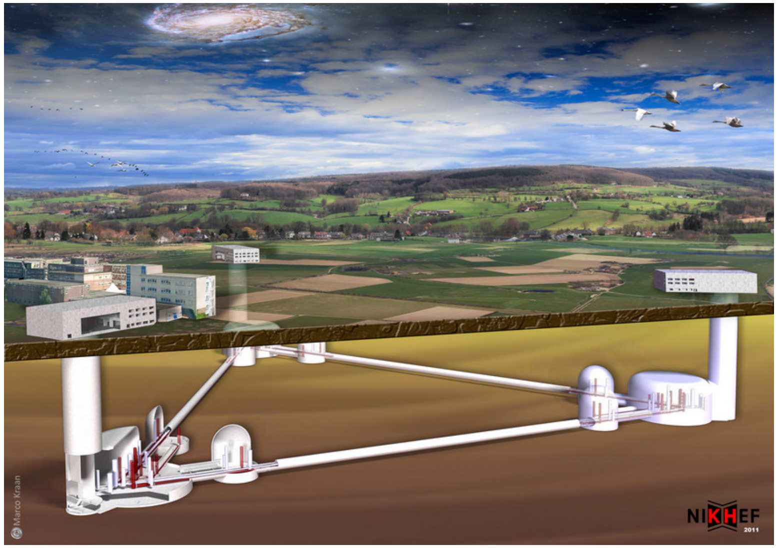




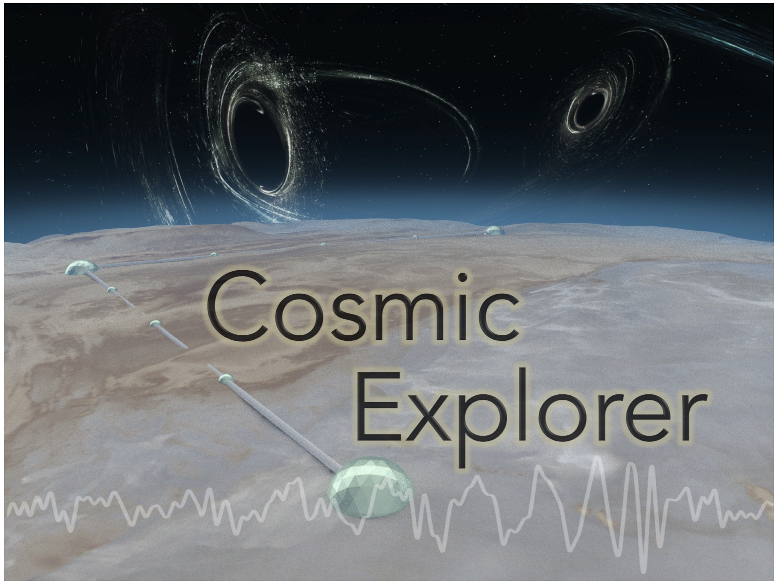


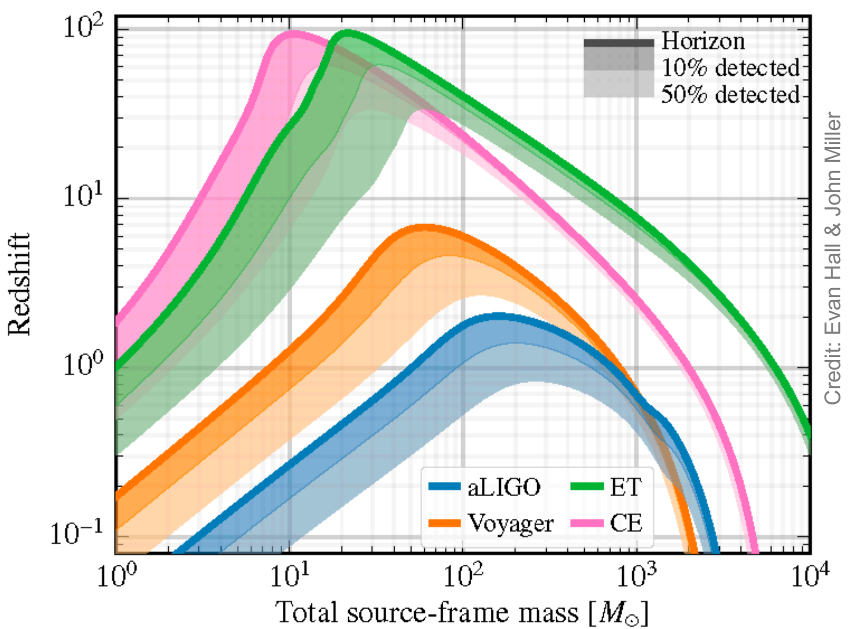
- Merging *supermassive* binary black holes
  - In general relativity, signals scale trivially with total mass
    - Does this hold in reality?
- Extreme mass ratio inspirals
  - Physically rich inspiral process
- Intermediate mass binaries
  - Visible in the LISA and ground-based frequency bands
  - Comparing the two links low-frequency to high-frequency regimes

Einstein Telescope and Cosmic Explorer (2035?)



- Next-generation ground-based facilities
  - O(10^5) detections per year!
    - Combine information across sources
  - Covers the entire visible Universe
    - Exquisitely accurate propagation tests
  - Nearby sources can be studied with extreme accuracy





Summary

- The first direct detection of gravitational waves has enabled unprecedented tests of general relativity:
  - First access to genuinely strong-field dynamics of vacuum spacetime
  - Propagation of gravitational waves over large distances
  - Probing the nature of compact objects

- Some highlights:
  - Higher post-Newtonian coefficients constrained at ~10% level
  - Graviton mass $m_g < 1.76 \times 10^{-23}$ eV/c^2
  - Speed of gravity = speed of light to 1 part in 10^{15}
  - Spin-induced quadrupole moment during inspiral:
    Access to expected values for boson stars
  - No-hair test consistent with no deviations at ~25% level
  - Area increase theorem passes at > 95% confidence

- Ultra-high precision tests with next-generation observatories: LISA, Einstein Telescope, Cosmic Explorer
  - Higher accuracy
  - Larger number of sources
  - Propagation of gravitational waves over cosmological distances
  - *Primordial backgrounds?*