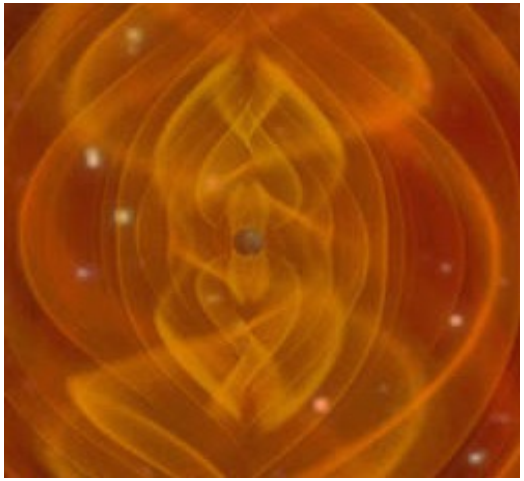


Probing strong gravity with gravitational waves

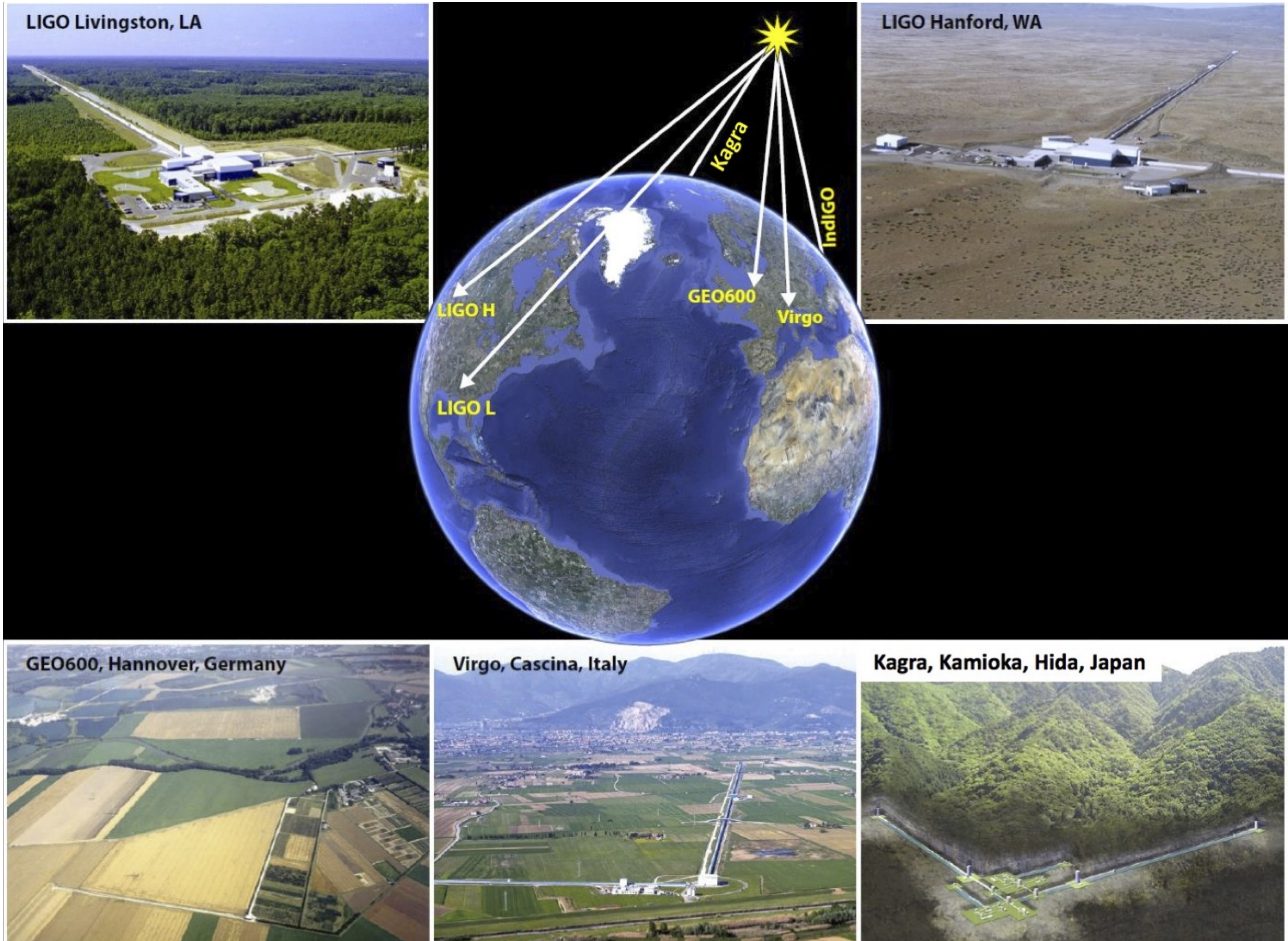
Chris Van Den Broeck

Utrecht University

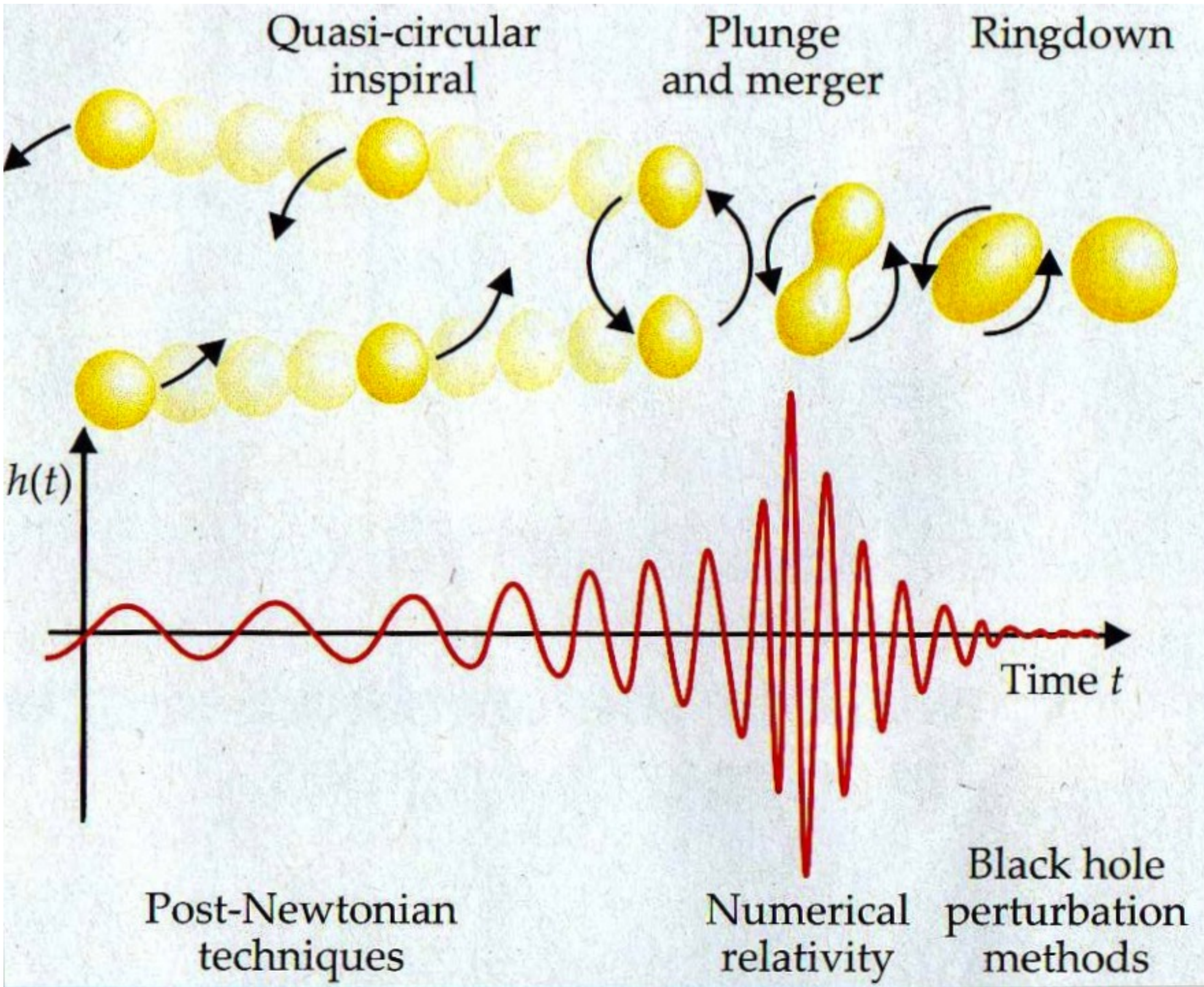
LIGO VIRGO

Nikhef

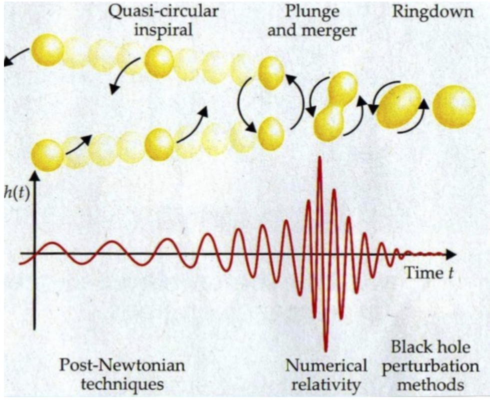
Theory of Relativity Seminar, June 4th, 2021

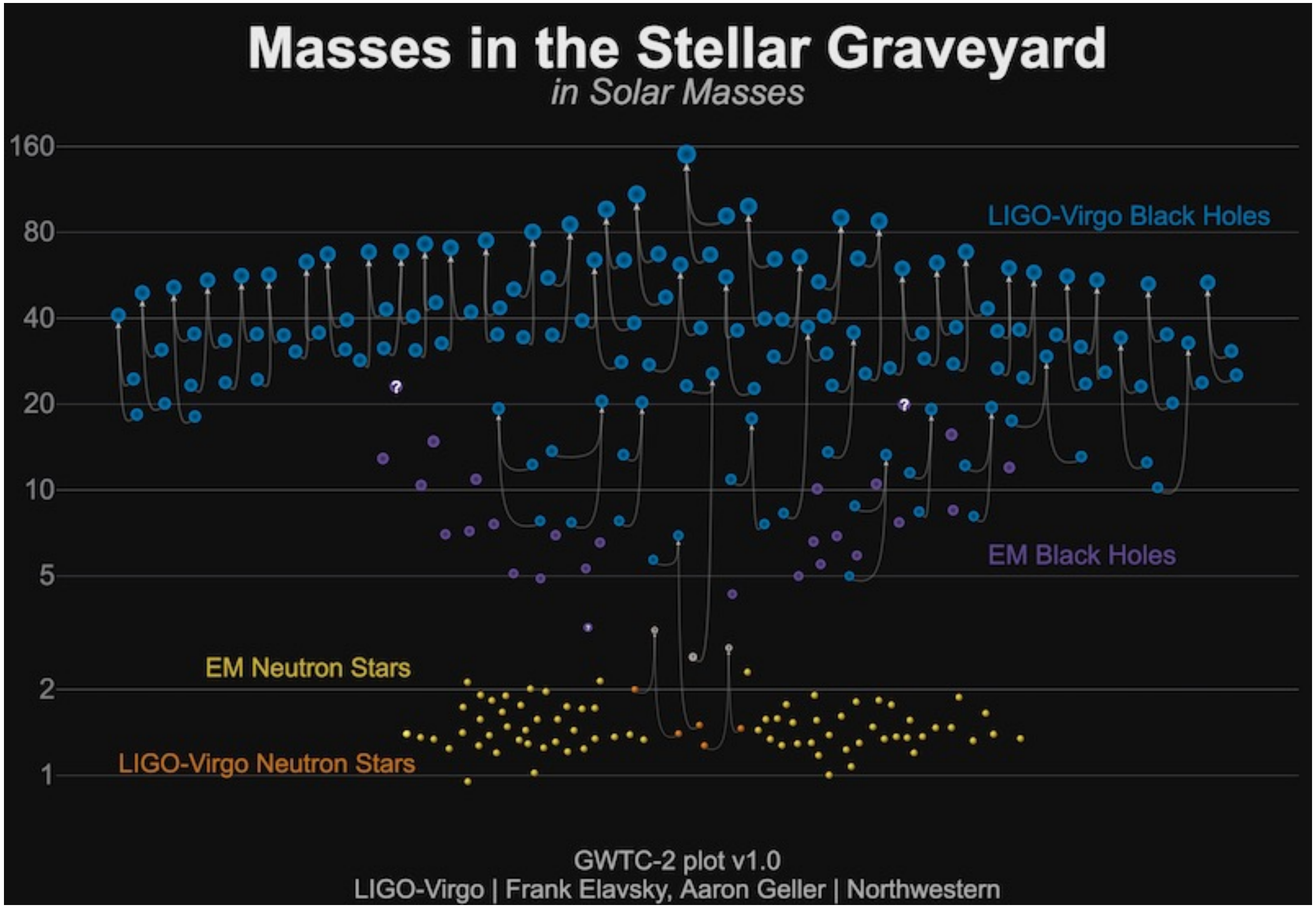

LIGO Livingston, LA
Kagra
IndIGO
LIGO Hanford, WA
LIGO H
GEO600
Virgo
LIGO L
GEO600, Hannover, Germany
Virgo, Cascina, Italy
Kagra, Kamioka, Hida, Japan

The coalescence of compact binaries



The first 50 detections

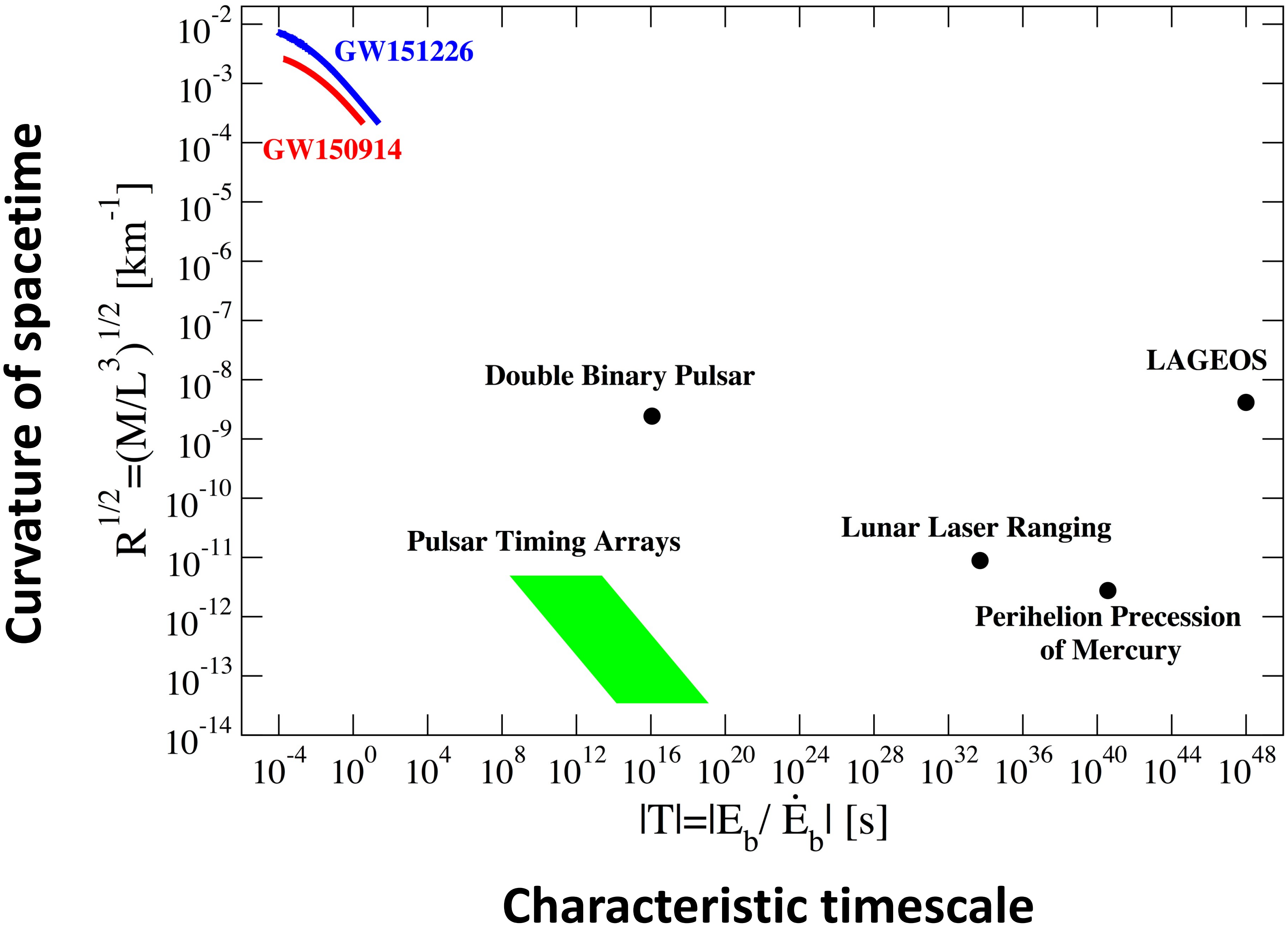




- Mostly binary black holes
- Binary neutron stars: GW170817, GW190425

LIGO + Virgo, arXiv:2010.14527

Access to strongly curved, dynamical spacetime



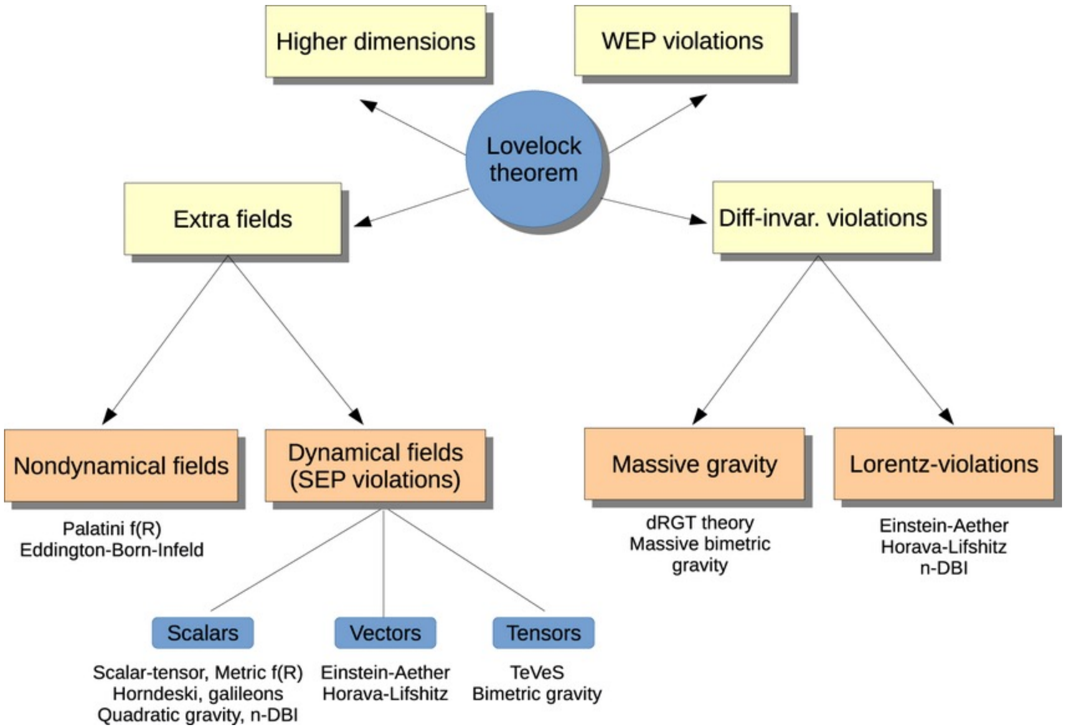
Yunes et al., PRD **94**, 084002 (2016)

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**

Fundamental physics with gravitational waves

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

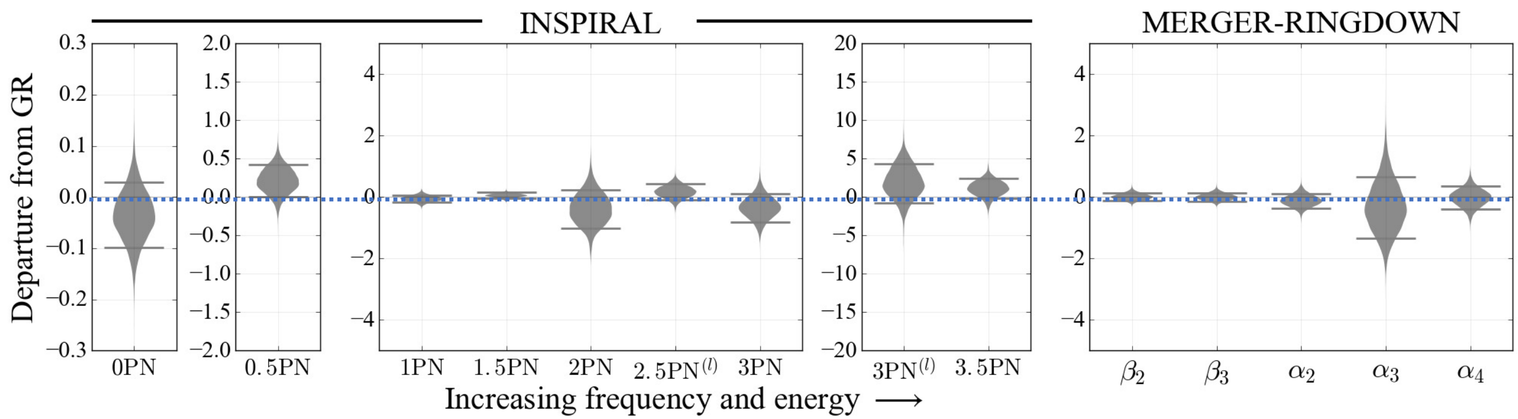
1. The strong-field dynamics of spacetime

- 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 $1/\sqrt{N_{\mathrm{det}}}$

2. The propagation of gravitational waves

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

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

  - Group velocity:

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

  - 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:

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

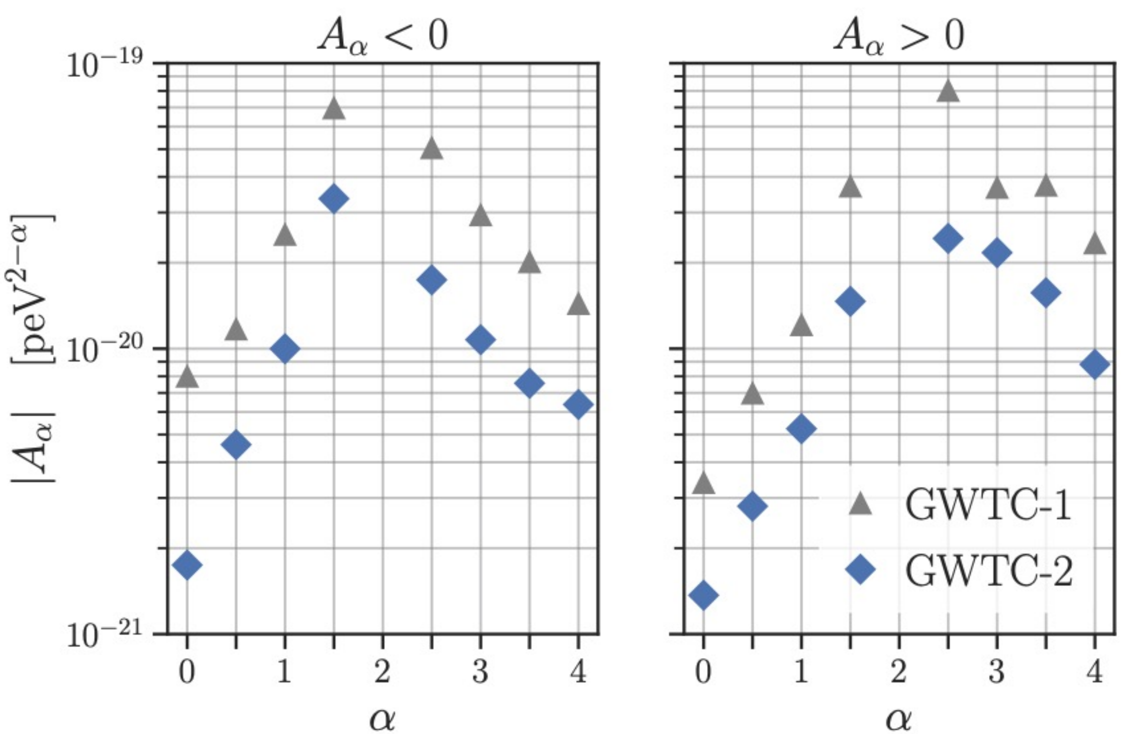
LIGO + Virgo, arXiv:2010.14529

2. The propagation of gravitational waves

- More general forms of dispersion:

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

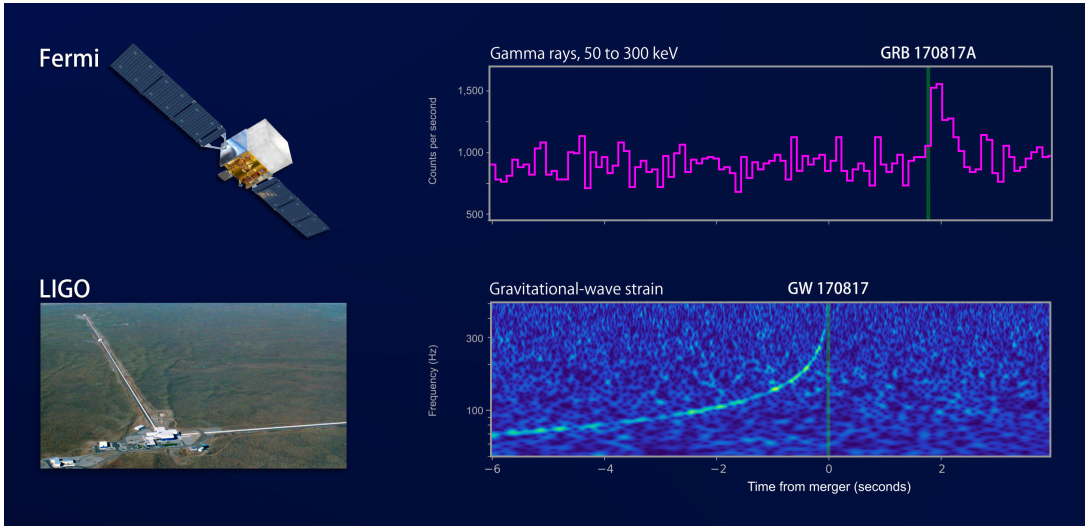
  - $\alpha \neq 0$ corresponds to violation of local Lorentz invariance
  - $\alpha = 2.5$ multi-fractal spacetime
  - $\alpha = 3$ doubly special relativity
  - $\alpha = 4$ higher-dimensional theories



LIGO + Virgo, arXiv:2010.14529

2. 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:

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

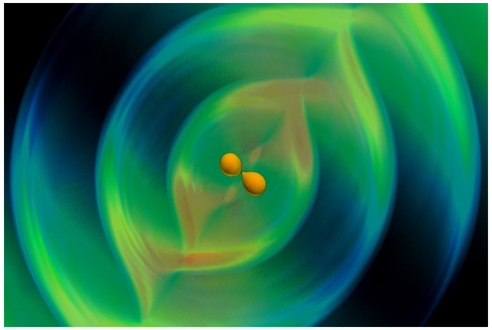
- Excluded certain alternative theories of gravity designed to explain dark matter or dark energy in a dynamical way

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

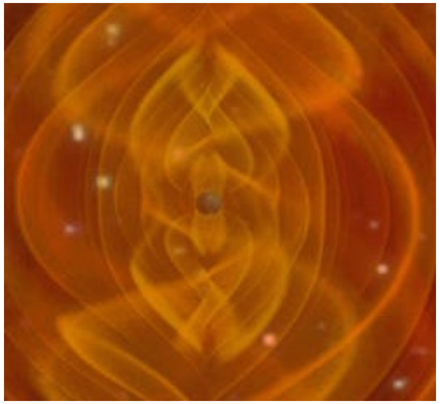
3. What is the nature of compact objects?

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

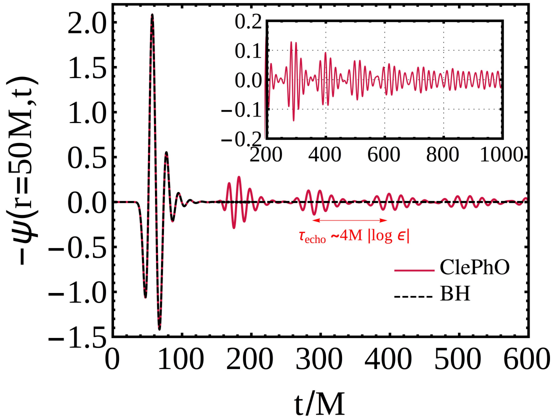
3. What is the nature of compact objects?



Anomalous effects during inspiral

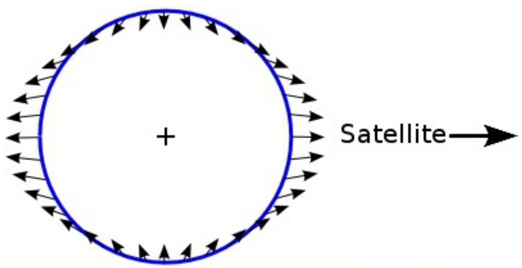


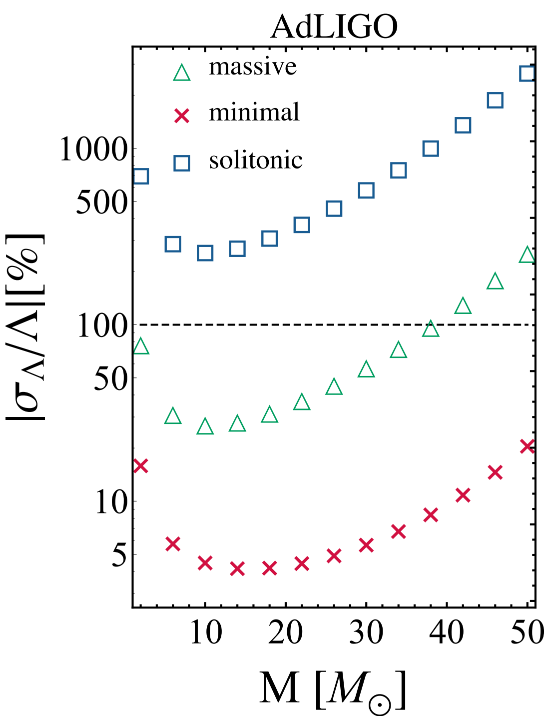
Ringdown of newly formed object



Gravitational wave echoes

Anomalous effects during inspiral





- 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: $\lambda < 0$

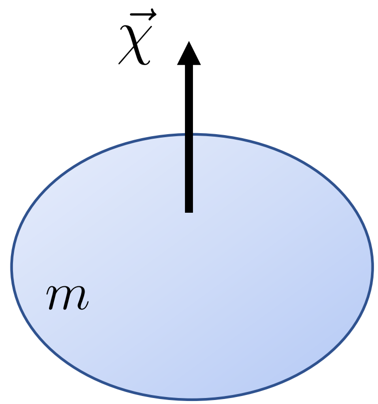
- Enters inspiral phase at 5PN order, through

  $$\lambda(m)/m^5 \propto (R/m)^5$$

  - *O*(10^2 - 10^3) 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



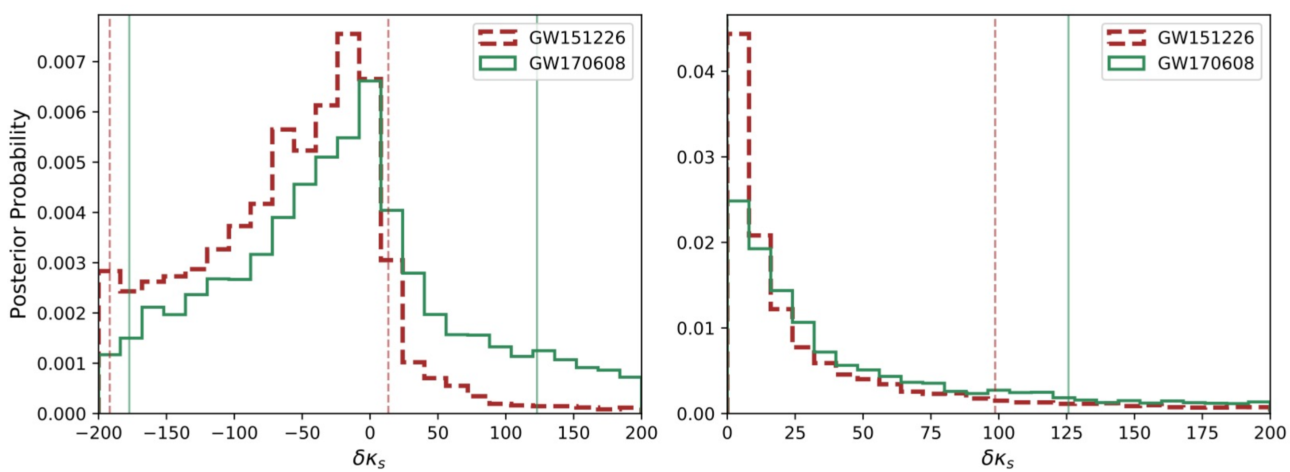
- Spin of an individual compact object also induces a quadrupole moment:

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

  - Black holes: $\kappa = 1$
  - Boson stars, dark matter stars: $\kappa > 0$
  - Gravastars: $\kappa < 0$

- 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)

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:

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

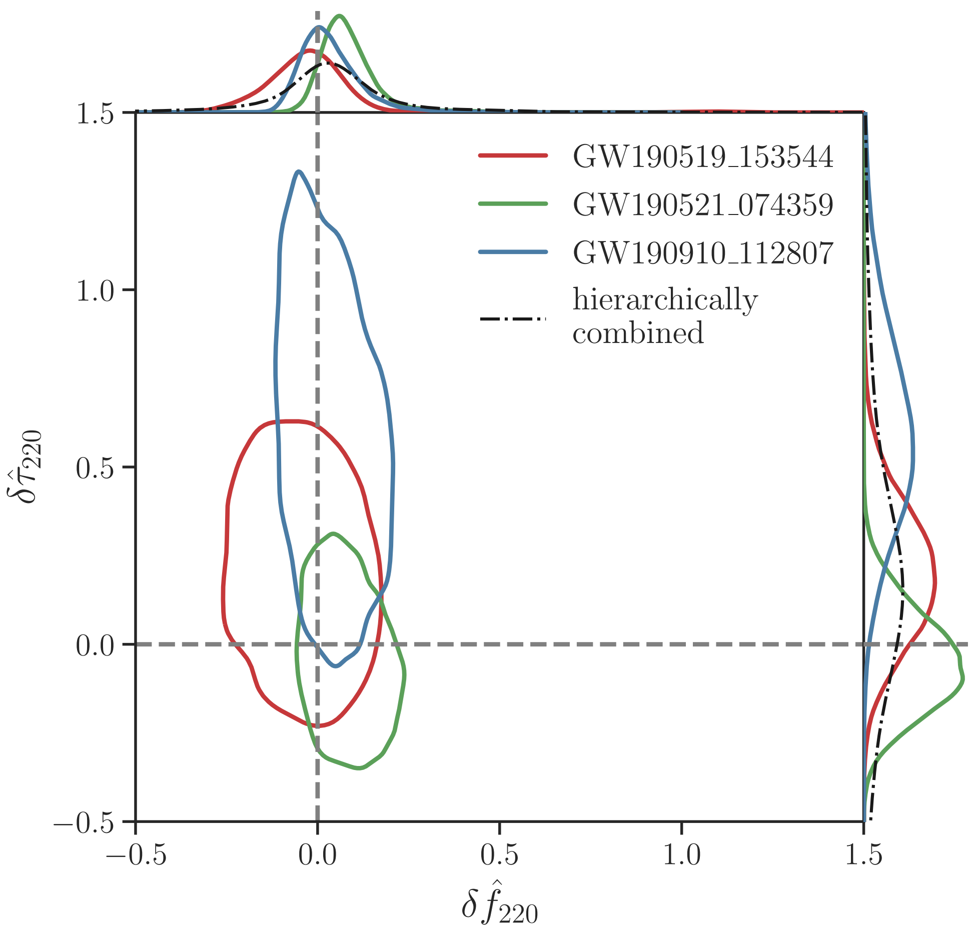
Carulllo et al., PRD **98**, 104020 (2018)
Brito et al., PRD **98**, 084038 (2018)

Ringdown of newly formed black hole

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

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

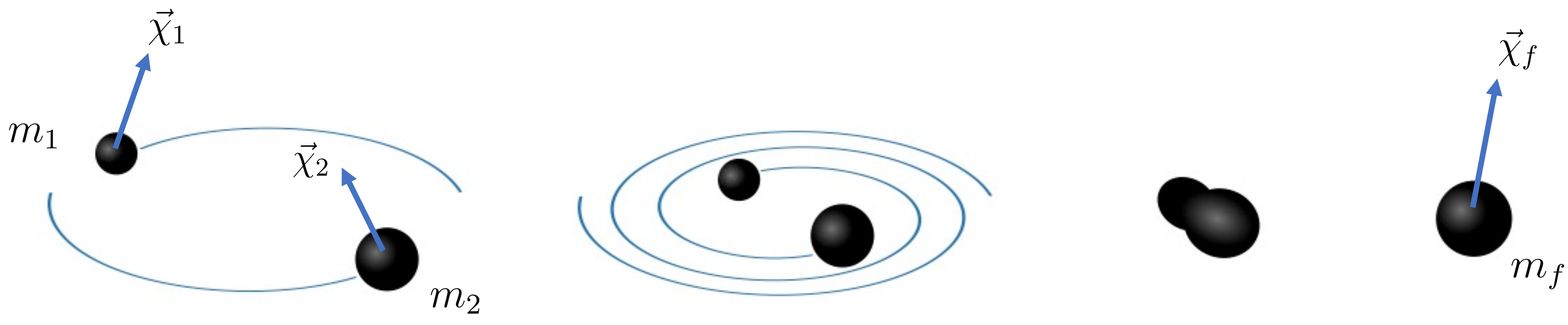
- First measurements:



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:

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

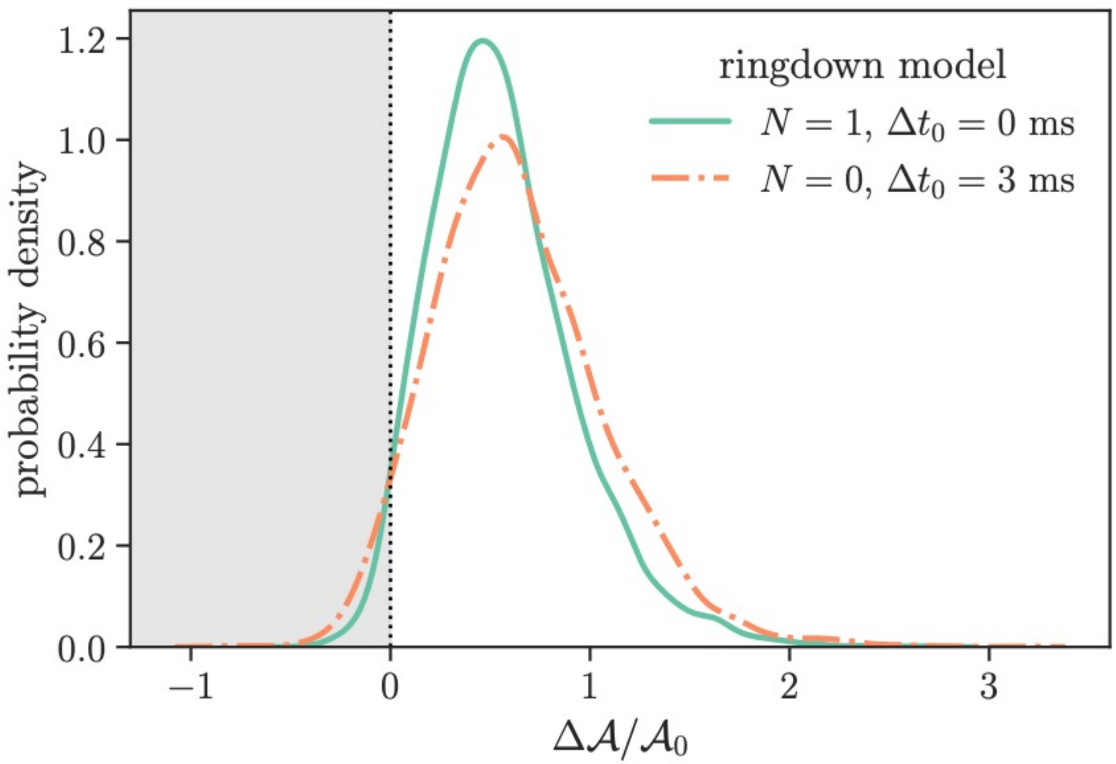
- According to the theorem: $\Delta\mathcal{A}/\mathcal{A}_0 = (\mathcal{A}_f - \mathcal{A}_0)/\mathcal{A}_0 \geq 0$

First tests of Hawking's area increase theorem

➢ According to the theorem:

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

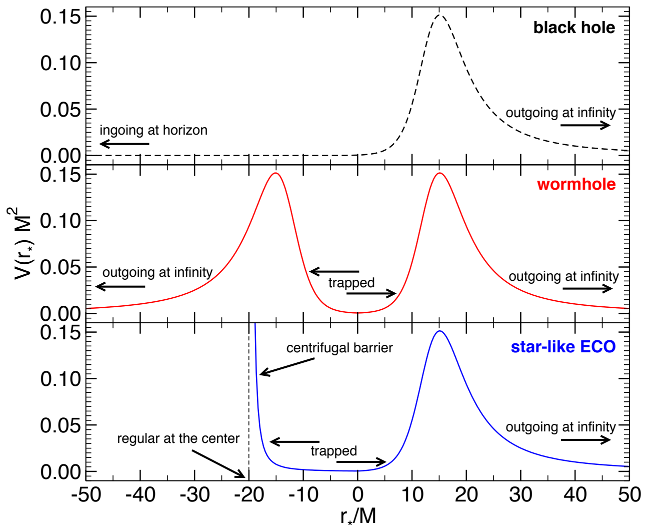
➢ Measurement on GW150914:

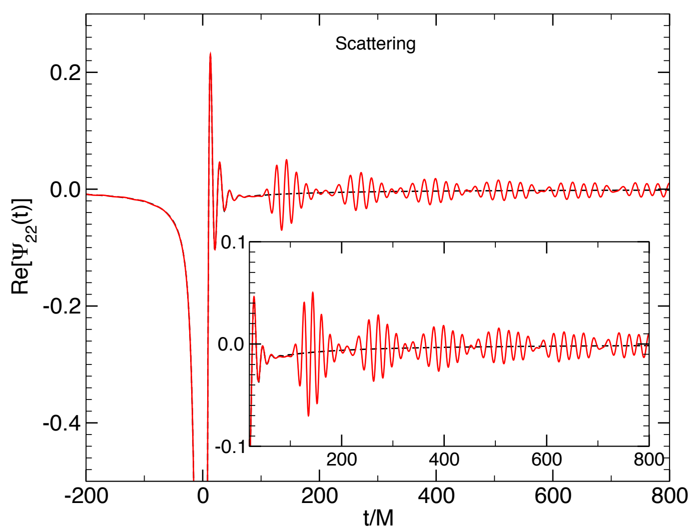


Isi et al., arXiv:2012.04486

- Agreement at > 95% probability

Gravitational wave echoes





- Exotic objects with corrections near horizon: inner potential barrier for radial motion
- After formation/ringdown: continuing bursts of radiation called *echoes*
- If microscopic horizon modification $\ell \ll M$ then time between successive echoes

$$\Delta t \sim -nM \log\left(\frac{\ell}{M}\right)$$

where *n* set by nature of object:

  - *n* = 8 for wormholes
  - *n* = 6 for thin-shell gravastars
  - *n* = 4 for empty shell

- For GW150914 (M = 65 M_{sun}), taking $\ell = \ell_{Planck}$, and *n* = 4: **Δ**t = 117 ms

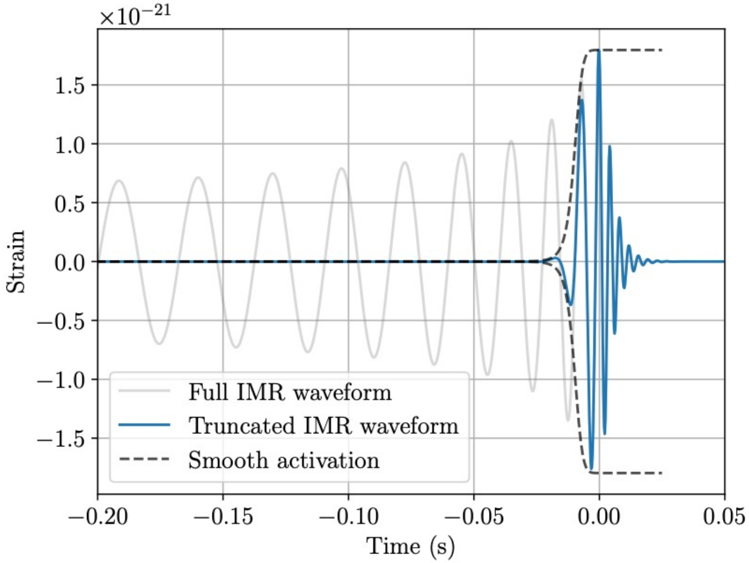
Cardoso et al., PRL **116**, 171101 (2016)
Cardoso et al., PRD **94**, 084031 (2016)

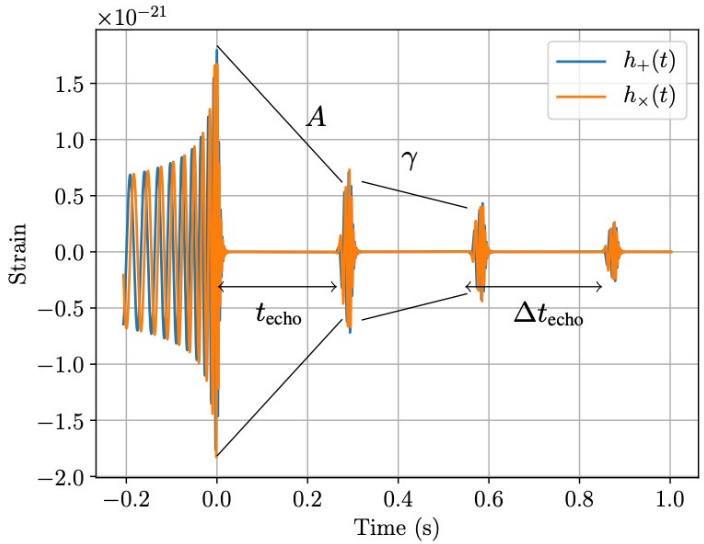
Gravitational wave echoes

- 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



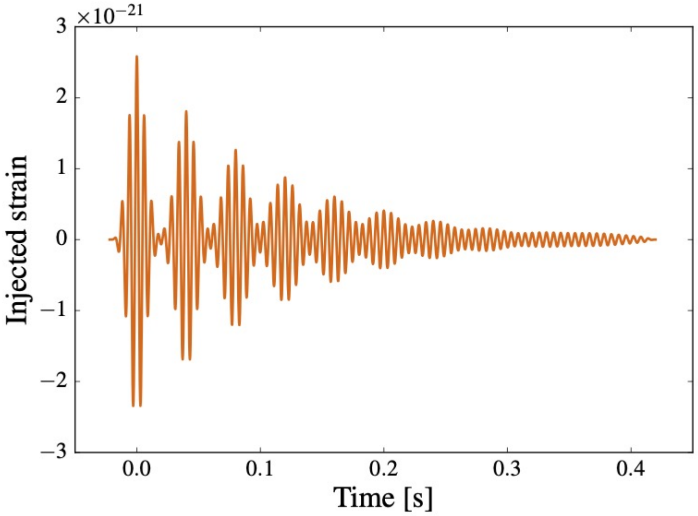


Abedi et al., PRD **96**, 082004 (2017)
Westerweck et al., PRD **97**, 124037 (2018)
Lo et al., PRD **99**, 084052 (2019)

- 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

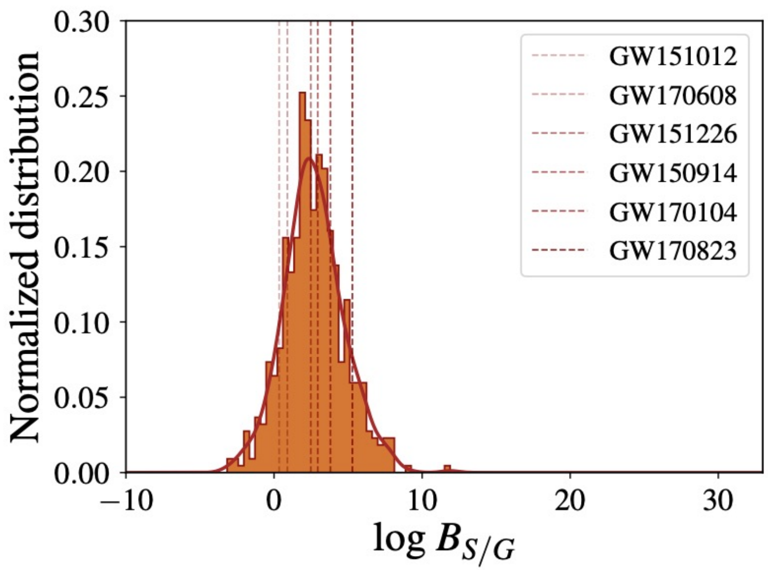
  - Compare 3 hypotheses for data from a **network** of detectors:

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

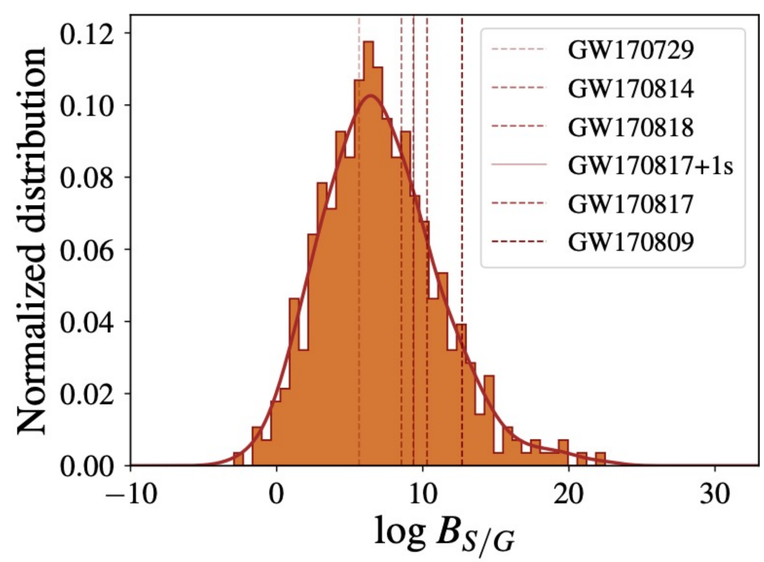
  - A signal is by definition coherent between detectors, and consistent with a particular sky position and source orientation
    - If a signal is present, $\mathcal{H}_{\rm signal}$ has less degrees of freedom than $\mathcal{H}_{\rm glitch}$
    - Bayesian analysis will then favor $\mathcal{H}_{\rm signal}$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

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



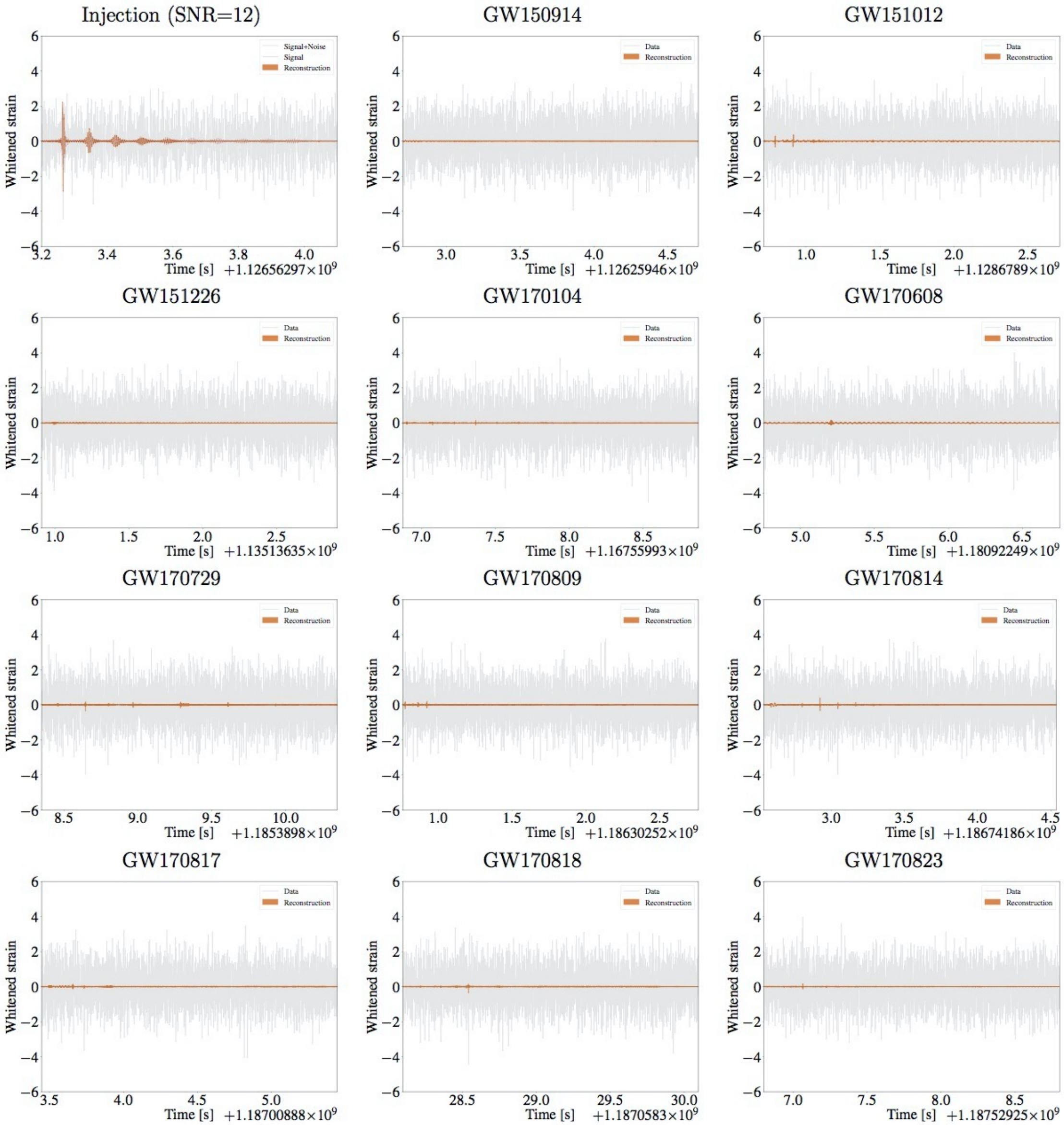
3-detector events

- 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)

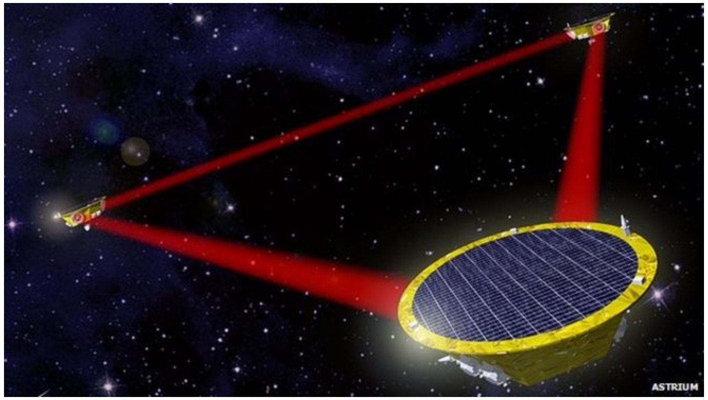
Gravitational wave echoes

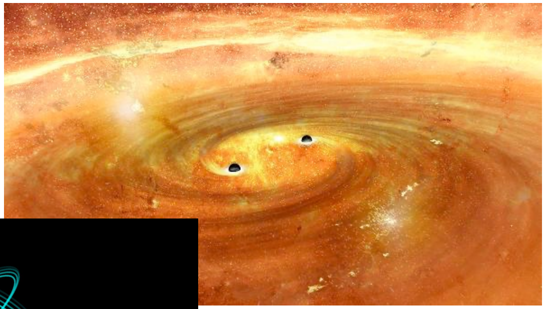
- Signal reconstructions:

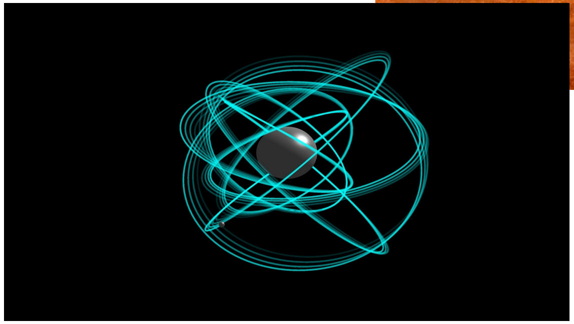


Tsang et al., PRD **101**, 064012 (2020)

LISA: A gravitational wave detector in space (2034)

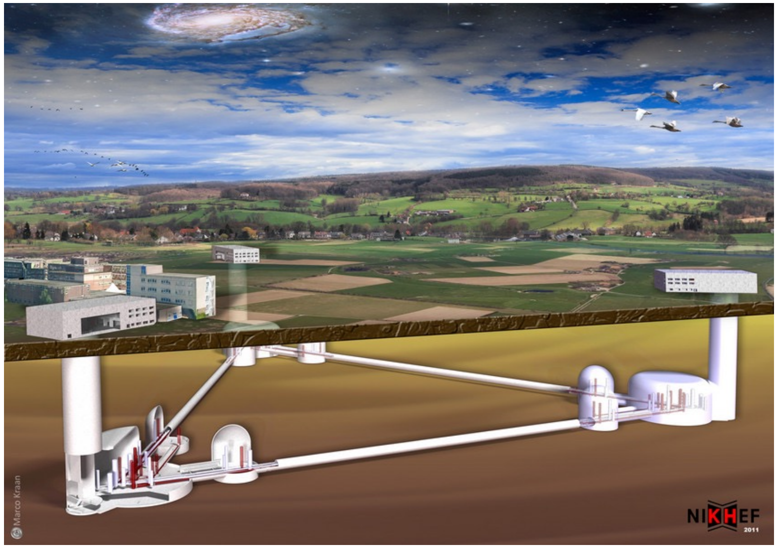


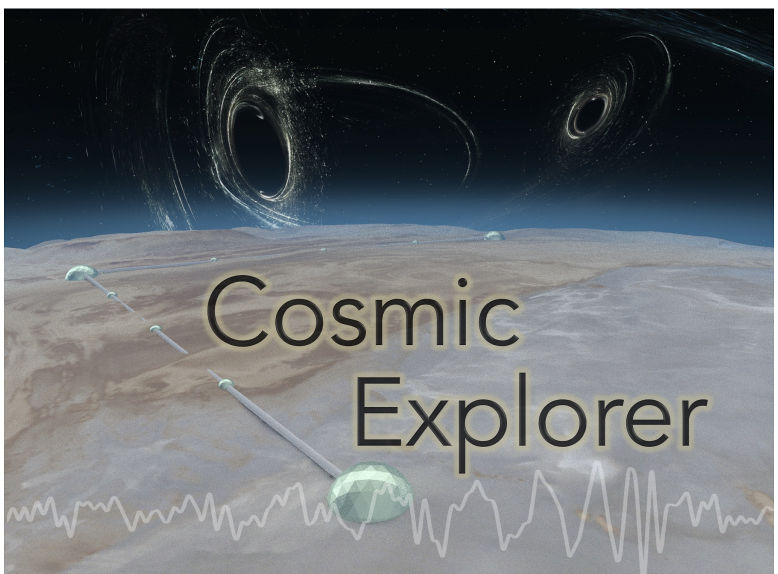




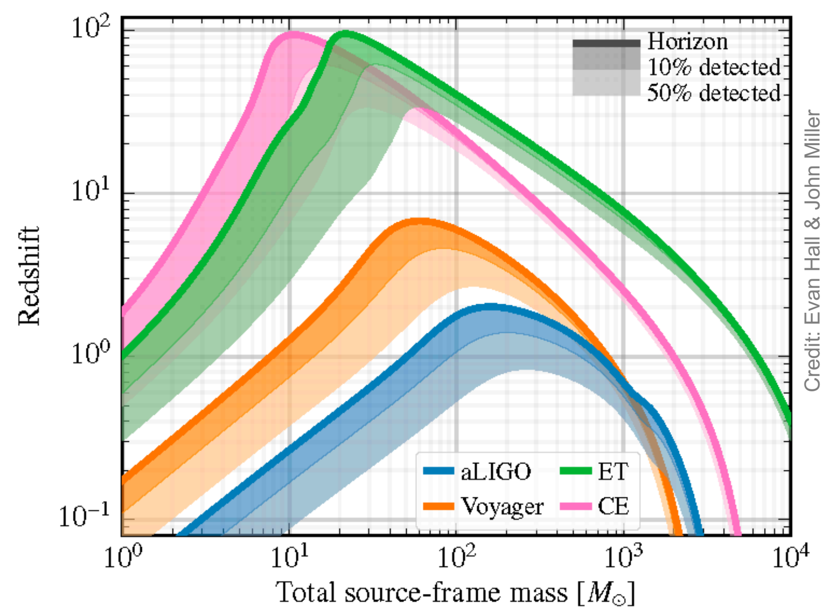
- Laser Interferometer Space Antenna
- Three probes in orbit around the Sun, exchanging laser beams
  - Triangle with sides of a few million kilometers
  - Sensitive to low frequencies (10^{-4} Hz - 0.1 Hz)
  - Approved by ESA for launch in 2034
- Different kinds of sources:
  - Merging *supermassive* binary black holes ($10^5 – 10^{10}\ M_{sun}$)
  - Smaller objects in complicated orbits around supermassive black hole

Einstein Telescope and Cosmic Explorer (2035?)





- Next-generation ground-based facilities
  - Factor 10 improvement in sensitivity over LIGO/Virgo design sensitivity
  - Merging binary black holes ($3 - 10^4$ M_{sun}) and neutron stars throughout the visible Universe
  - 10^5 detections per year!



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% probability

- 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