Probing Gravity with 3G detectors

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Outline

- What kind of fundamental physics do we want to test and why?
- How do we model it?
- What's the gravitational wave imprint?

Astro 2020 Science White Paper: Extreme Gravity and Fundamental Physics, arXiv: 1903.09221 [astro-ph.HE]

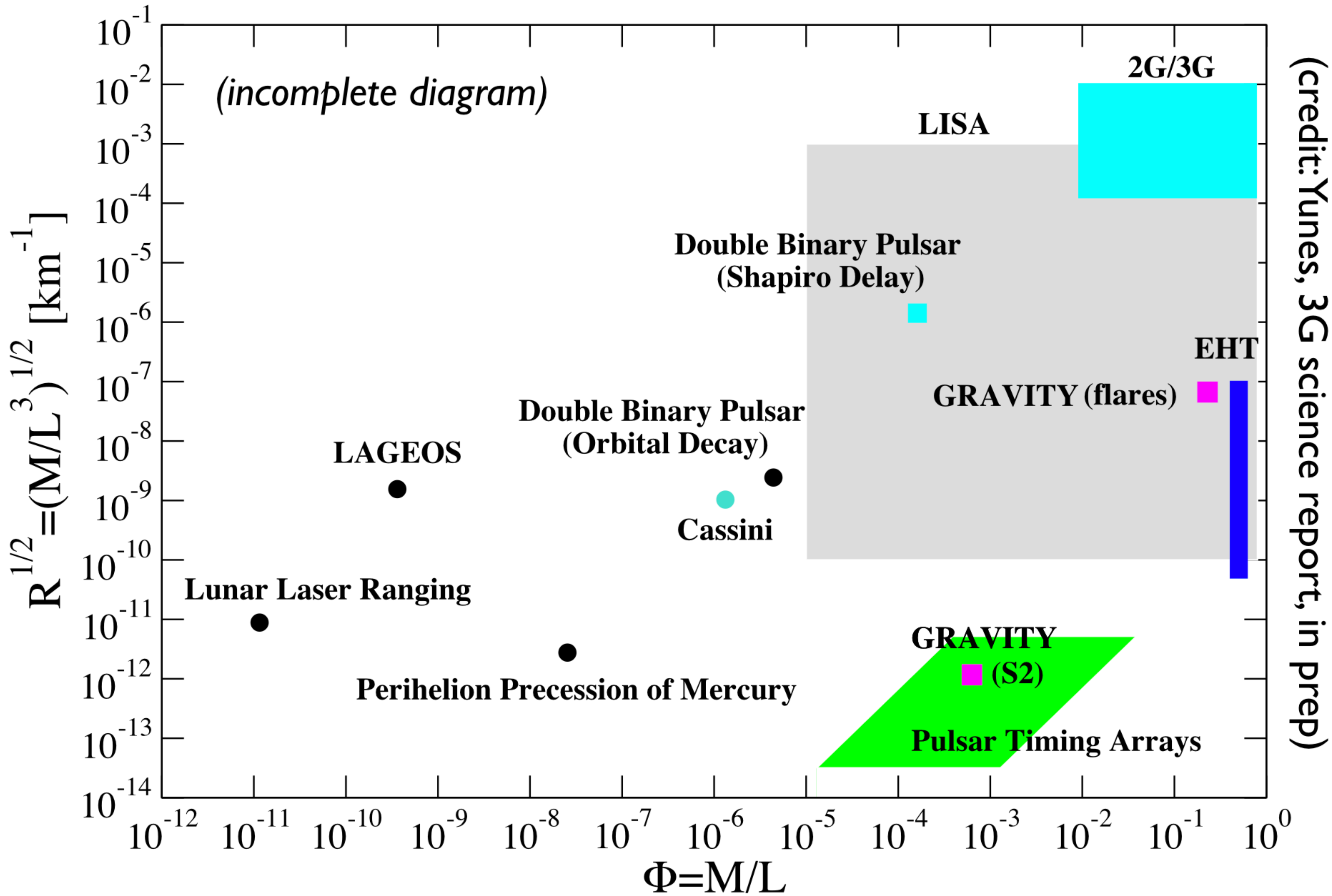
'Gravitational Waves, Black holes, and Fundamental Physics' COST Action roadmap: arXiv:1806.05195 [gr-qc]

Nature of gravity

- **Lorentz symmetry**
  Einstein-aether theory, Horava gravity
- **Mass of the graviton**
  massive and bimetric gravity
- **Parity**
  dynamical Chern-Simons gravity
- **New fields, particles, interactions**
  Quantum gravity, Extensions of the Standard Model

Caveat: Do we really expect new physics at these curvatures and field strengths?

Nature of gravity



taken from arXiv:1903.09221

Nature of compact objects

- **Structure of black holes**
  'Hairy' black holes, multiple horizons, etc.
- **Are 'black holes' actually black holes?**
  Firewalls, fuzzballs, gravastars, boson stars, etc.
- **Structure of neutron stars**
  (overlap with testing EOS)

Caveats: No-hair theorems; elusive nature of horizons; EOS-related degeneracies

Nature of DM and DE

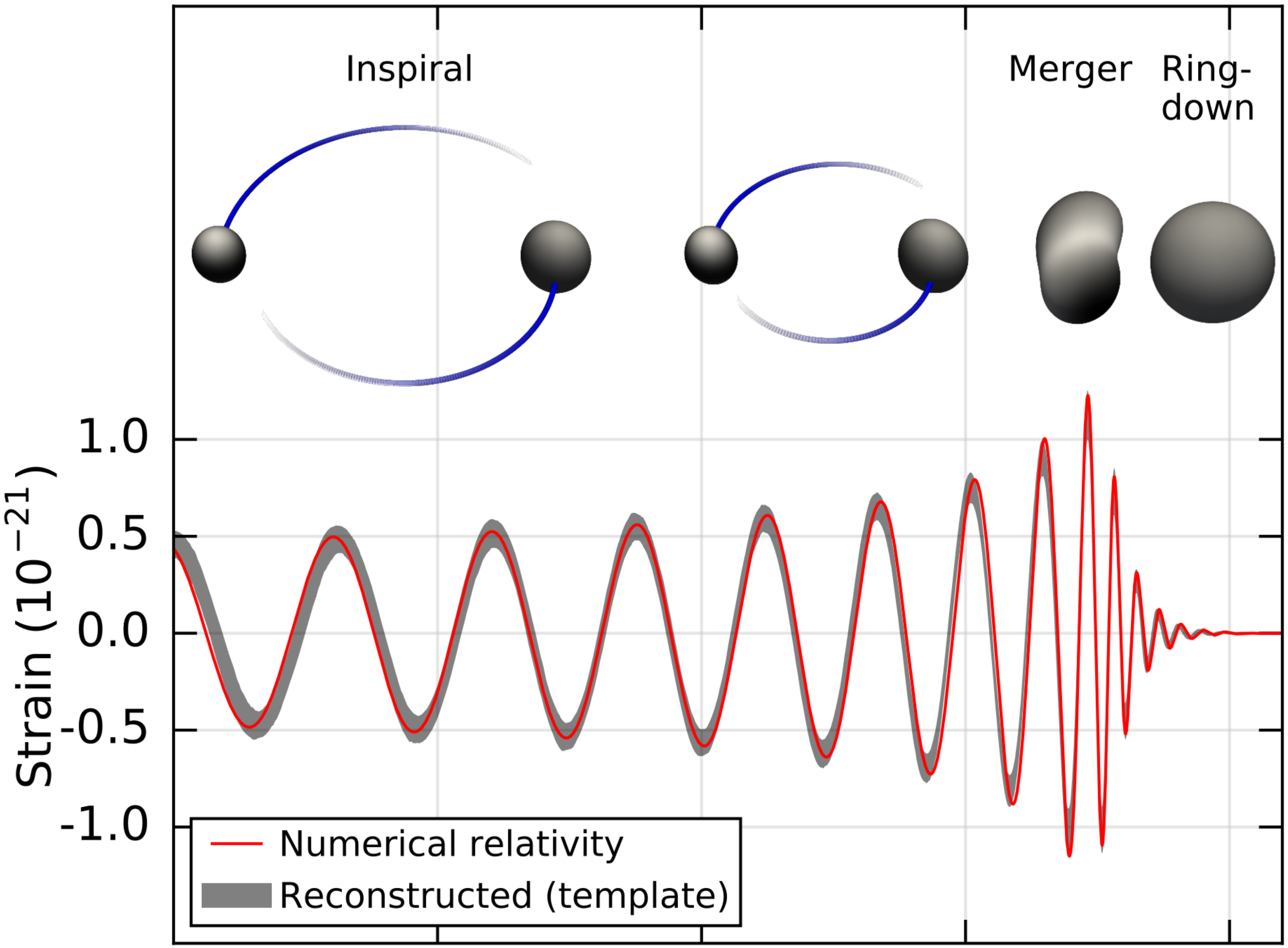
- **Black holes as dark matter**
  Primordial black holes (overlap)
- **Dark matter detection with compact objects**
  Orbital effect due to DM, light scalars as DM
- **GW as probes of cosmology**
  e.g. standard sirens (part of cosmology with GW), or interaction with DE

Caveat: Reliance on specific models of DM and DE

Modelling new physics

Always GR plus (nonminimally coupled) extra fields

Waveform



taken from B. P. Abbott et al. (LIGO -Virgo) Phys. Rev. Lett. 116, 061102 (2016)

Propagation effects

$$E^2 = m_g^2 \pm M_1 p + c_g^2 p^2 \pm \frac{p^3}{M_3} \pm \frac{p^4}{M_4^2} + \ldots$$

- Strong bound on the mass of the graviton, M_1, M_3
- But marginally interesting from a theory perspective
- Weak bounds on M_4 in eV range
- Strong constraint from BNS and EM

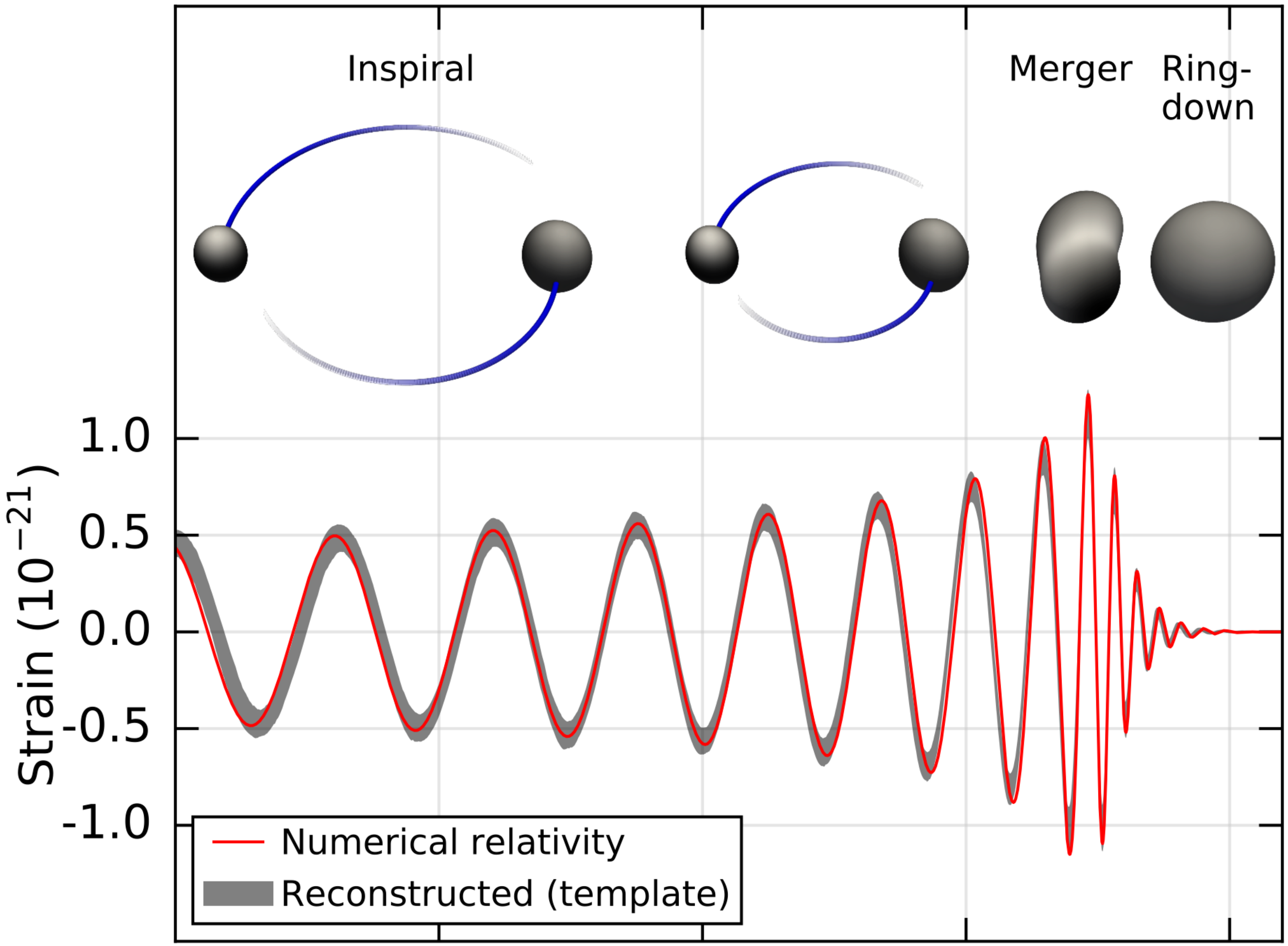
$$|\Delta c_g/c| \lessapprox 10^{-15}$$

This rules out several dark energy models that predict $c_g \neq c$

But we can do better in constraining Lorentz violations by looking for other polarisations!

T.P.S., Phys. Rev. Lett. 120, 041104 (2018);
A. E. Gumrukcuoglu, M. Saravani and T.P.S., Phys. Rev. D 97, 024032 (2018).

Waveform



taken from B. P. Abbott et al. (LIGO -Virgo) Phys. Rev. Lett. 116, 061102 (2016)

Parametrizations vs. theories

Advantages of parametrizations:

- We do not need to know the theory!

Disadvantages of parametrizations:

- They only get us half way there - they need interpretation in terms of a theory
- They give us a false sense of achievement - constraints can be meaningless or not independent
- They have limited range of validity

We need theory-specific tests as well!

Extracting new physics

Step-by-step guide for your favourite candidate:

- Study compact objects and determine their properties
  Signatures: hair, tidal properties, etc.
- Model the inspiral (post-Newtonian)
  Signatures: new polarizations, dephasing, tidal effects…
- Model the ringdown (perturbation theory)
  Signatures: different QNM spectrum
  Hurdle: non-separability, non-trivial background
- Do full-blown numerics to get the merger
  Signatures: various/unknown
  Hurdle: initial value formulation and well-posedness

Well-posedness

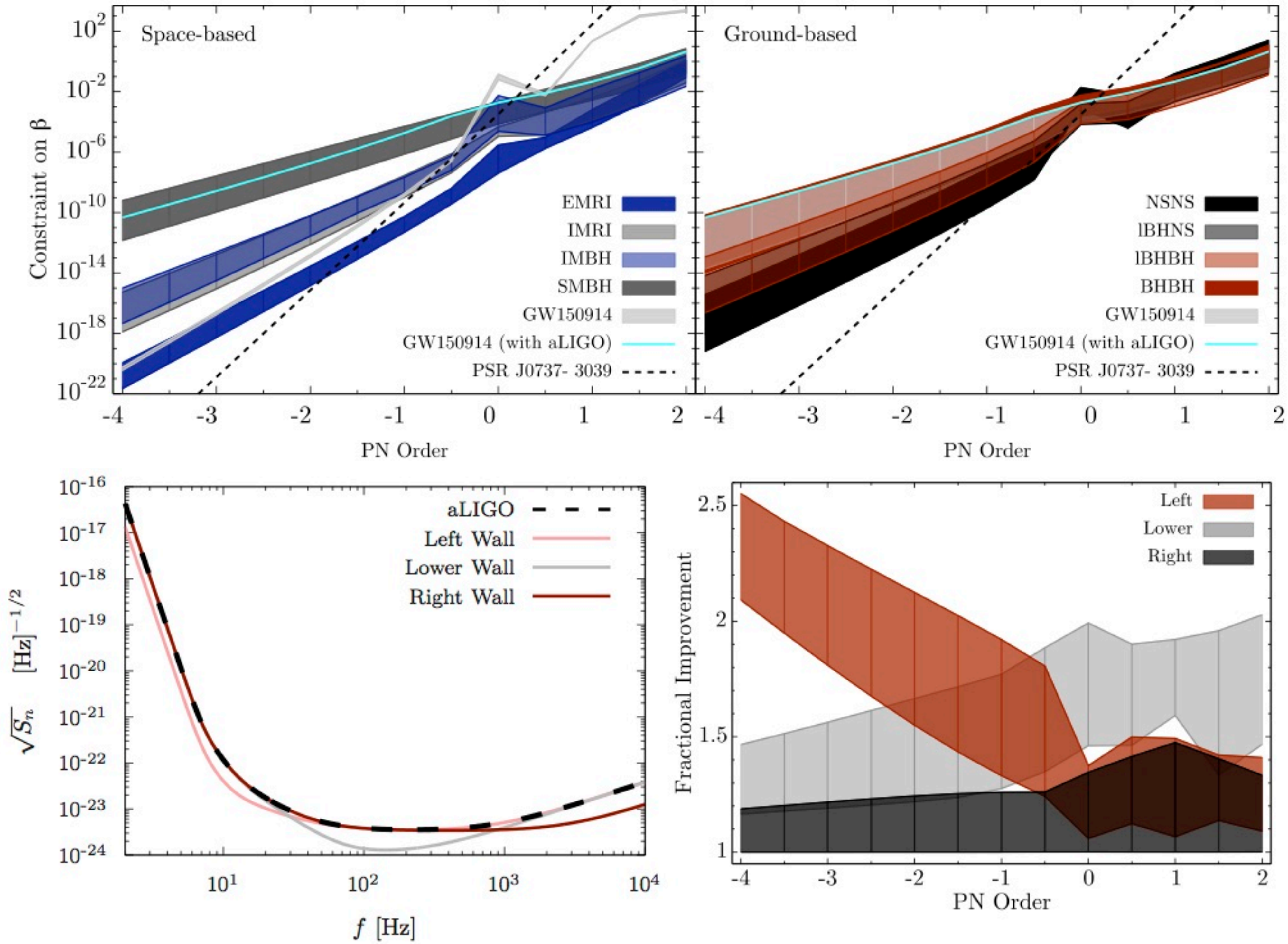
Interesting theories tend to look ill-posed, e.g.

- **Lorentz symmetry**: Einstein-aether theory, Horava gravity
  Faster than light propagation
- **Mass of the graviton:** massive and bimetric gravity
  Multiple metrics
- **Parity:** dynamical Chern-Simons gravity
  3^{rd} order equations

"Screening" requires nonlinearity and derivative interactions which also leads to seemingly ill-posed theories

No-hair theorems also suggest that obviously well-posed theories are unlikely to be very interesting in strong field

Low vs high frequencies



taken from Chamberlain & Yunes, Phys. Rev. D 96, 084039 (2017)

Theoretical input

- Mass can suppressed deviations during early or even late inspiral

  F. Ramazanoglu and F. Pretorius, Phys. Rev. D 93, 064005 (2016)

- Emission might be strongly system dependent
  - Scalarization

    T. Damour and G. Esposite-Farese, Phys. Rev. Lett. 70, 2220, (1993)
    D. D. Doneva and S. S. Yazadjiev, Phys. Rev. Lett. 120 131103 (2018)
    H. O. Silva et al., Phys. Rev. Lett. 120, 131104 (2018)
  - Curvature couplings

    M. Okounkova et al., Phys. Rev. D 96, 044020, (2017)
    H. Witek et al., Phys. Rev. D 99, 064035 (2019)

- Lack of simulations and prediction means limited insight beyond inspiral

Prospects

- Plenty of new physics to be tested
- Alternative theories can ‘parametrize’ it in the strong field regime
- But new physics is always speculative and subject to change!
- Detecting and constraining it should certainly be a goal, and it is high risk – high gain

Well-posedness

Sometimes things are better than they seem…

- Einstein-aether theory appears to be well-posed

O. Sarbach, E. Barausse, and J. A. Preciado-Lopez, Class. Quant. Grav. 36, 165007 (2019)

Sometimes things are complicated…

- Horava gravity is an elliptic-hyperbolic problem

D. Blas and S. Sibiryakov, Phys. Rev. D 84, 124043 (2011)
M. Colombo, J. Bhattacharyya, and T.P.S, Class. Quant. Grav. 33, 235003 (2016)
J. Bhattacharyya, A. Coates, M. Colombo, and T.P.S., Phys. Rev. D 93, 064056 (2016)

Sometimes things are probably just bad

- General scalar-tensor theories are not strongly hyperbolic in generalized harmonic gauge in weak field

G. Papallo, and H. S. Reall, Phys. Rev. D 96, 044019 (2017)

- Numerics suggest that they are ill-posed for certain data

J. L. Ripley, and F. Pretorius, Phys. Rev. D 99, 084014 (2019)