Gravitational waves in alternative theories of gravity

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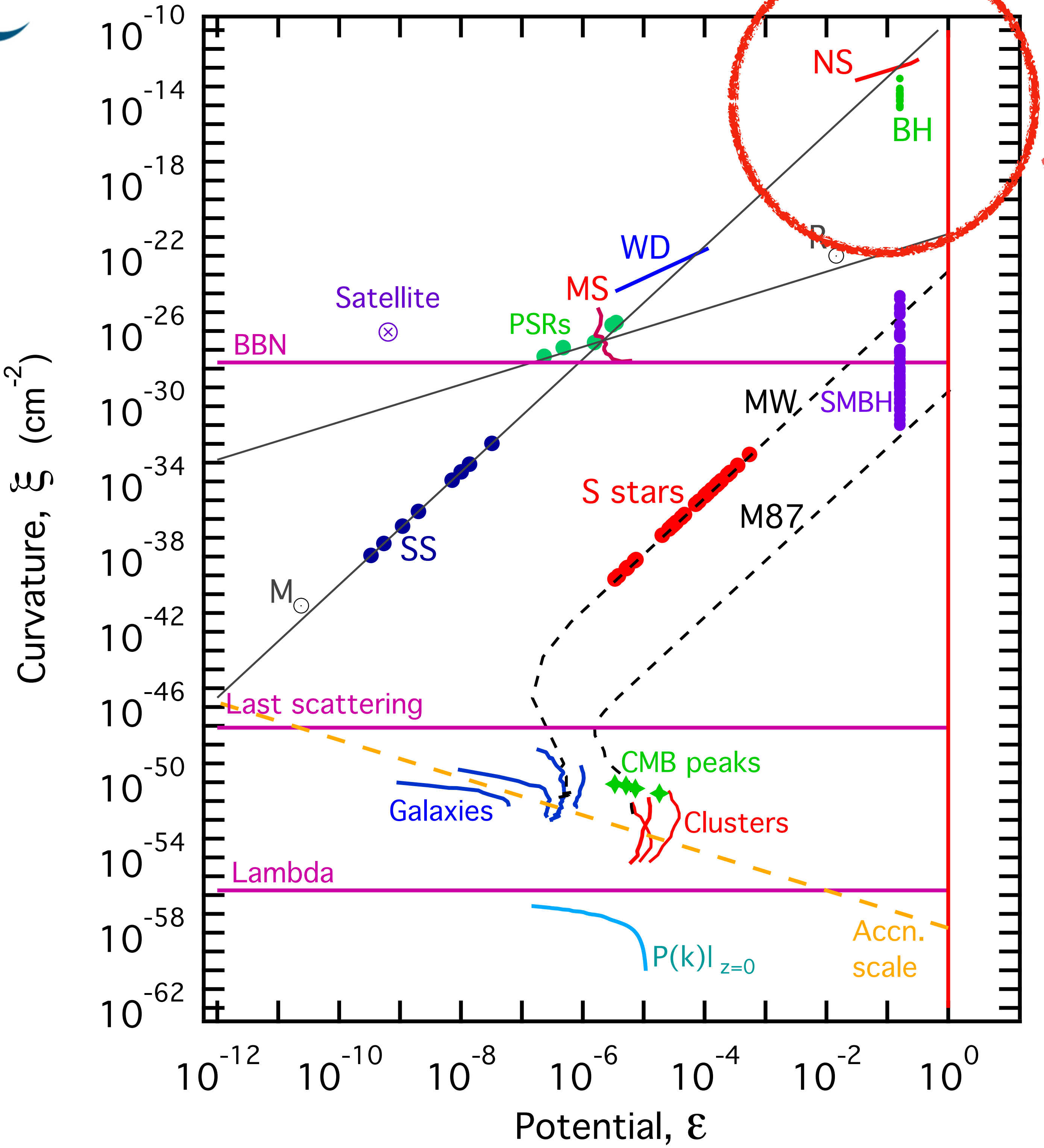
Testing a new regime



Untested combination of curvature and potential

taken from T. Baker, D. Psaltis, C. Skordis, ApJ 802, 63 (2015)

Modelling new physics

To be tested with GW it

- has to leave an imprint on BHs/NSs
- has to persist in the classical regime
- to be modelled! (i.e. we need equations!)

We can test

- deviations from GR
- extensions of the standard model that couple non-minimally to gravity

In both cases, we are looking for new fields!

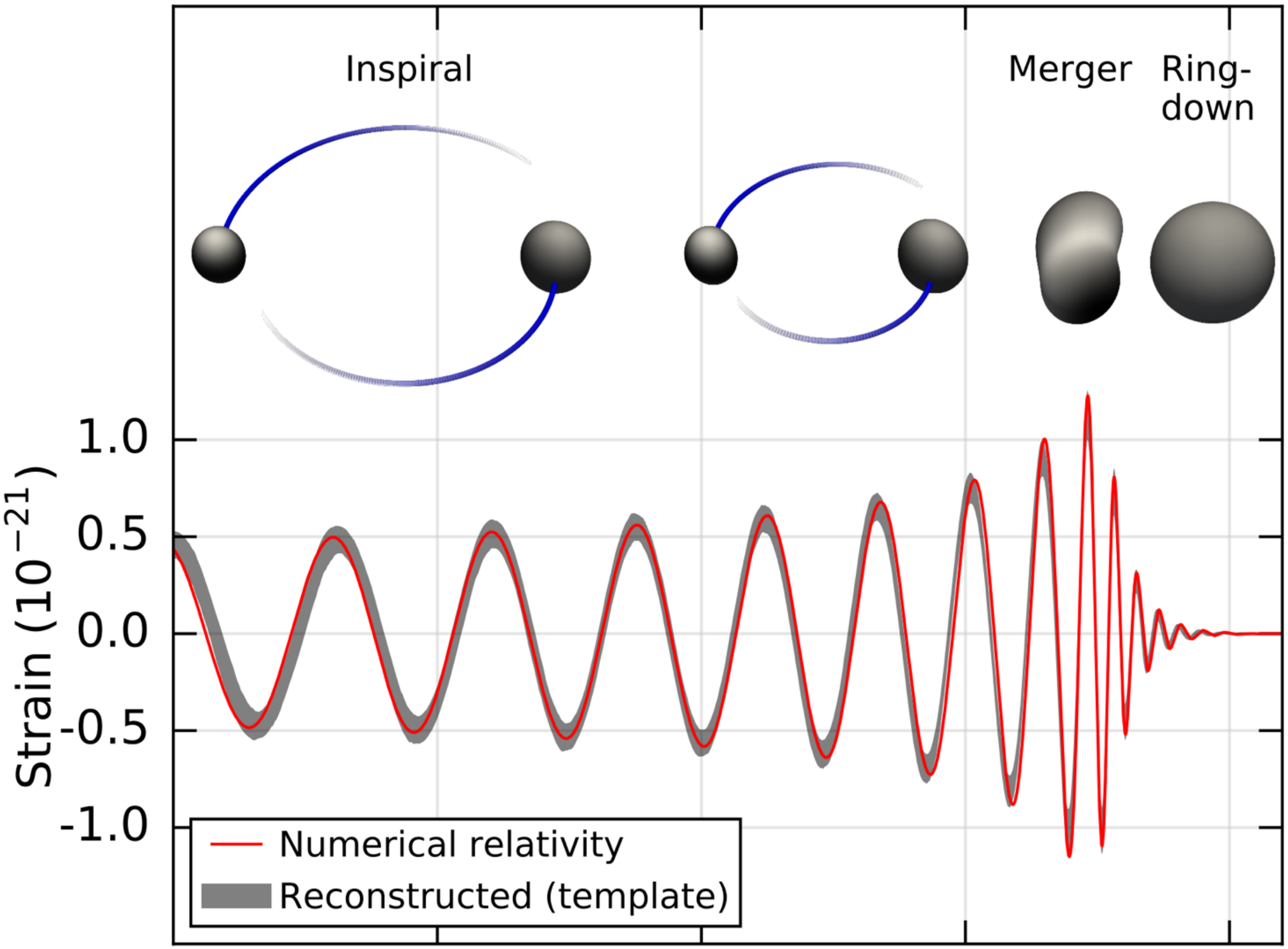
Lovelock and GR

Lovelock's theorem leads to GR under assumptions:

- 4 dimensions
- Covariance
- Second order equations
- No extra fields
- Locality

Not all of them are equally important for phenomenology!

Waveform



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

Extracting new physics

Step-by-step guide for your favourite candidate:

- Study compact objects and determine their properties
  Signatures: hair, tidal properties, etc.
  Hurdle: degeneracies
- Model the inspiral (post-Newtonian)
  Signatures: new polarizations, dephasing, tidal effects…
  Hurdle: "sensitivities"
- 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

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).

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.
  Hurdle: degeneracies
- Model the inspiral (post-Newtonian)
  Signatures: new polarizations, dephasing, tidal effects…
  Hurdle: "sensitivities"
- Model the ringdown (perturbation theory)
  Signatures: different QNM spectrum
  Hurdle: (no) separability beyond Kerr
- Do full-blown numerics to get the merger
  Signatures: various/unknown
  Hurdle: initial value formulation and well-posedness

Model-dependent tests

Testing Principles, e.g.

- **Lorentz symmetry**
  Einstein-aether theory, Horava gravity
  (superluminal propagation, multiple/universal horizons)
- **Mass of the graviton**
  massive and bimetric gravity, ? (multiple metrics)
- **Parity**
  dynamical Chern-Simons gravity, ? (3rd order equations)

Looking under the lamppost

- Example: Most general scalar-tensor theory

Pinning down the theory

For a given observed system, what kind of theory could exhibit new effects, while consistent with other observations?

Pinning down the theory

Assume that

- system of interest: black holes
- field: massless scalar

No mass requires shift symmetry. No-hair theorem!

S.W. Hawking, Comm. Math. Phys. 25, 152 (1972)
L. Hui, A. Nicolis, Phys. Rev. Lett. 110, 241104 (2013).

…but there is also a unique exception.

T.P.S. and S.-Y. Zhou, Phys. Rev. Lett. 112, 251102 (2014)

$$S = \frac{m_P^2}{8\pi}\int d^4x\sqrt{-g}\left(\frac{R}{2} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \alpha\phi\mathcal{G}\right)$$

The exception

The corresponding scalar equation is

$$\Box\phi + \alpha\mathcal{G} = 0$$

- All black holes are hairy
- At small coupling/weak field identical to exponential coupling of dilaton in string theory

P. Kanti et al., Phys. Rev. D 54, 5049 (1996)
N. Yunes and L. Stein, Phys. Rev. D 83, 104002 (2011)

- First dynamical simulations done

R. Benkel, T.P.S. and H. Witek, Phys. Rev. D 94 (R), 121503 (2016); Class. Quant. Grav. 34, 064001 (2017)
H. Witek, L. Gualtieri, P. Pani and T.P.S., arXiv:1810.05177

- Neutron stars have no scalar monopole!

K.Yagi, L. Stein and N. Yunes, Phys. Rev. D 93, 024010 (2016)

NR beyond GR: challenges

- Establishing well-posedness: Existence, uniqueness and continuous dependence on initial data
- Interpreting well/ill-posedness in the context of effective field theory (EFT)
- Numerical challenges associated with the above and with having extra fields

NR and EFT

- The most interesting theories are likely to look ill-posed, cf. no-hair theorems, e.g.

S.W. Hawking, Comm. Math. Phys. 25, 152 (1972)
T. P. S. and V. Faraoni, Phys. Rev. Lett. 108, 081103 (2012)

Possible ways to "cure" ill-posedness

- working perturbatively in the coupling

R. Benkel, T.P.S. and H. Witek, Phys. Rev. D 94 (R), 121503 (2016); Class. Quant. Grav. 34, 064001 (2017)
M. Okunkova et al., Phys. Rev. D 96, 044020 (2017)
H. Witek, L. Gualtieri, P. Pani and T.P.S., arXiv:1810.05177

- Israel-Stewart-like approach

J. Cayuso, N. Ortiz, and L. Lehner, Phys. Rev. D 96, 084043 (2017)

- Other?

Prospects

- Alternative theories can 'parametrize' new physics in the strong field regime
- Exciting phenomenology waits to be tested!
- Major obstacle: lack of predictions
- We will soon need new theories!

Interesting prospect: strong field phase transitions (e.g. scalarization)

T. Damour and G. Esposito-Farese, Phys. Rev. Lett. 70, 2220 (1993)
A. Coates, M. Horbatsch and T.P.S., PRD 95, 084003 (2017)
F. Ramazanoglu, Phys. Rev. D 96, 064009 (2017)
D. D. Doneva and S. S. Yazadjiev, PRL 120, 131103 (2018)
H. O. Silva, J. Sakstein, L. Gualtieri, T.P.S, and E. Berti, PRL 120, 131104 (2018)