Testing GR with LISA II

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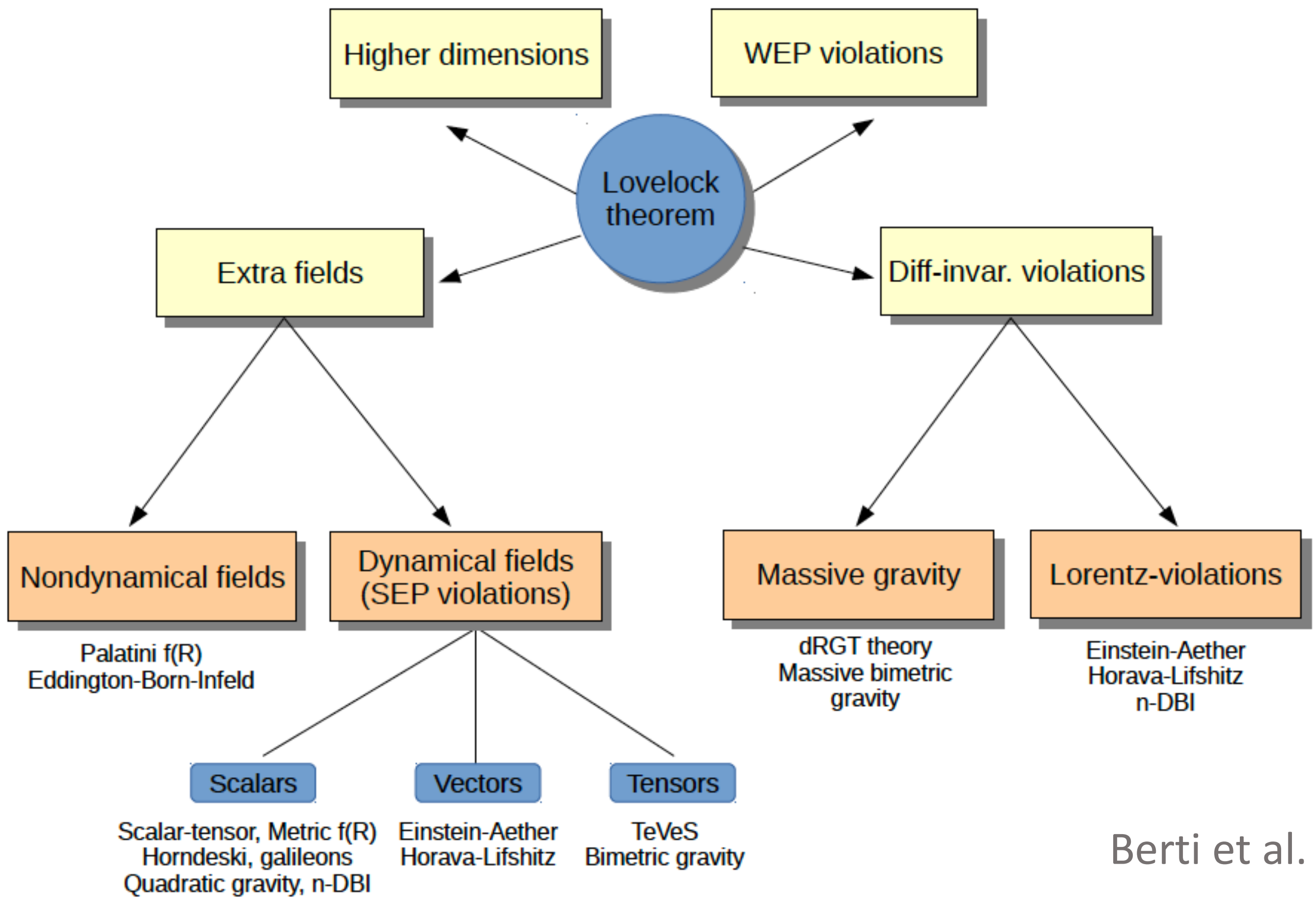
Black holes beyond GR and Lovelock's theorem

- **Lovelock's theorem**: **Einstein's field equations are unique**, assuming that:
  - ✓ We are working in **four dimensions**
  - ✓ **Diffeomorphism invariance** is respected
  - ✓ The **metric** is the **only field** mediating gravity
  - ✓ The **field equations are second-order** differential equations



Berti et al. CQG (2015)

GR modifications $\longleftrightarrow$ Additional fields

- Looking for **deviations from GR** largely amounts to looking for **new fields**
- Most of these modification will contain **one or more additional (effective) fields**
- How to **demonstrate this mathematically**:
  - ✓ **Compactifying** spacetime down to 4-dimensions
  - ✓ **Introducing additional fields** to restore diffeomorphism invariance
  - ✓ Performing **field redefinitions**
- Additional field normally carry associated "**charges**"
- Field theory intuition tells us that **accelerating charges radiate** $\Rightarrow$ for binaries beyond GR **energy loss and binary dynamics** will be affected (later in the talk)

BHs with scalar hair beyond GR

- **No-hair theorems exist** Bekenstein (1972); Hawking (1972); Heuser (1992,1996)
- Models that manage **to circumvent no-hair theorems** are expected to lead to more prominent deviations from GR in GW signals.
- Scalar fields **sourced by:**
  - ✓ **Gauss–Bonnet invariant or the Pontryagin density** (dynamical Chern-Simons gravity) Campbell et al. (1992); Kanti et al. (1996); Yagi et al. (2012); Yunes and Pretorius (2009); Yunes and Stein, (2011); Sotiriou and Zhou (2014); Delsate et al., 2018; Delgado et al. (2020)
  - ✓ **Horndeski theories** Maselli at al. (2015), Saravani & Sotiriou (2019)
  - ✓ **Matter** around the BHs Cardoso et al. (2013), Herdeiro et al. (2018)
  - ✓ **Spontaneous scalarization** within these theories DD and Yazadjiev (2018); Silva et al. (2018), Antoniou et al. (2018)
- Normally possible to have black hole with scalar hair for **smaller mass BHs**

BHs beyond GR

- **Superradiance**:
  - ✓ It can support **long-lived scalar clouds** for very light scalars (Arvanitaki and Dubovsky (2011); Brito et al. (2015))
  - ✓ Lead to hairy BHs for **complex scalars** with a time dependent phase (Herdeiro and Radu (2014))
- **Long-lived scalar "wigs"** can be formed around a Schwarzschild BH (Barranco et al., (2012, 2014))
- Configurations with **time-dependent scalar fields** can be supported by some **non-trivial cosmological boundary conditions** (Berti et al., 2013, Babichev and Charmousis, 2014)
- Going to **vector fields** – black holes in generalized Proca theories (Babichev et al., 2017; Heisenberg et al., 2017; Herdeiro et al., 2016)
- Black holes in **Lorentz-violating theories**, such as **Einstein-Aether theory and Horava gravity** will generically carry hair (see next talk)

Example: EMRIs with a non-Kerr massive black hole

Example: Testing the existence of fundamental scalar field

- **EMRIs: Scalarization of the small body – the talk before**
- Scalar hair can exist for **massive black holes –** Kerr black holes with synchronized scalar hair

Superradiant instability and scalar clouds

- Consider the **Klein-Gordon equation** on the Kerr background (massive scalar field with $V(\Phi) = \frac{1}{2}\mu^2\Phi$)

$$\Box\Phi = \mu^2\Phi$$

- **Separate** the variables

$$\Phi = e^{im\varphi - i\omega t} S_{lm}(\theta) R_{lm}(r)$$

where $S_{lm}(\theta)$ are the spheroidal harmonics and $R_{lm}(r)$ satisfies the **radial Teukolsky equation**

- The solution for Φ are actually the **quasinormal modes** of the Kerr black hole
- There is a **critical oscillation frequency** below which $\omega^I < 0$ – **superradiance instability**
  $\omega < \omega_c = m\Omega_H$, where Ω_H is the horizon angular velocity.
- At $\omega = \omega_c$ the imaginary part vanishes and **bound states** can exist – **Kerr BH with scalar clouds** Hod (2012)

- Consider the **GR** action **plus a minimally coupled complex massive scalar field** Φ

$$S = \int \left[\frac{R}{2} - g^{\mu\nu}\partial_\mu \Phi^* \partial_\nu \Phi - 2U(\Phi) \right] \sqrt{-g}\, d^4x \,, \quad \text{with} \quad U = \frac{1}{2}\mu^2 |\Phi|^2$$

- The system is **invariant under U(1) transformations**, $\Phi \rightarrow \Phi e^{i\alpha}$, that leads to the presence of a **conserved current**

$$j^\mu = -i(\Phi^* \partial^\mu \Phi - \Phi \partial^\mu \Phi^*)$$

and thus a **Noether charge**

$$Q = \int_{\Sigma \backslash \mathcal{H}} j^\mu n_\mu dV$$

- The **Noether charge** can be interpreted as the **number of particles**.

- Such scalar field leads to **boson star solutions**.

Stationary and axisymmetric hairy black holes

- **Stationarity and axisymmetry** of the black hole require that

$$\Phi = \phi(r,\theta)e^{i(\omega t + m\varphi)}$$

  where ω is its natural frequency and m is the (integer) winding number

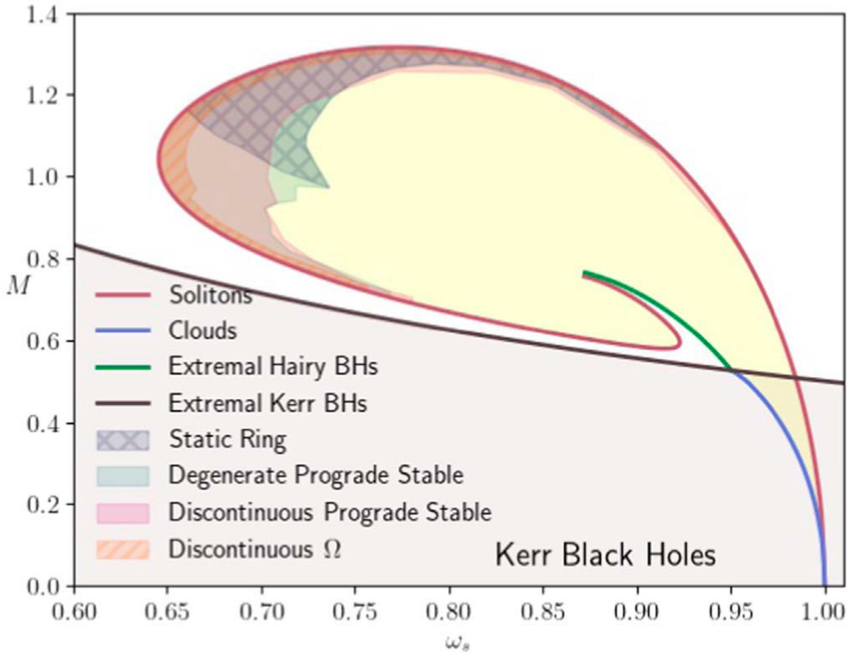
- The **regularity** at the BH horizon requires $\boldsymbol{\omega = m\Omega_H}$.

- The effective **scalar field energy momentum tensor** is **independent on $\boldsymbol{t}$ and $\boldsymbol{\varphi}$**.

- There is **no scalar field flux** onto the black hole hole.

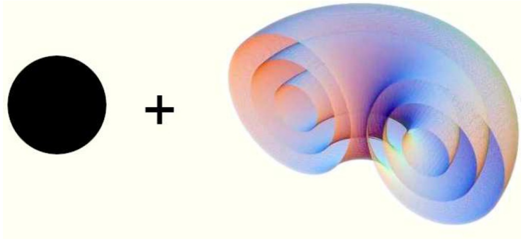
EMRIs of Numerical BH Spacetimes

- The scalar field distributes itself in a torus. **Thus the metric functions might feature different local maxima and minima.**



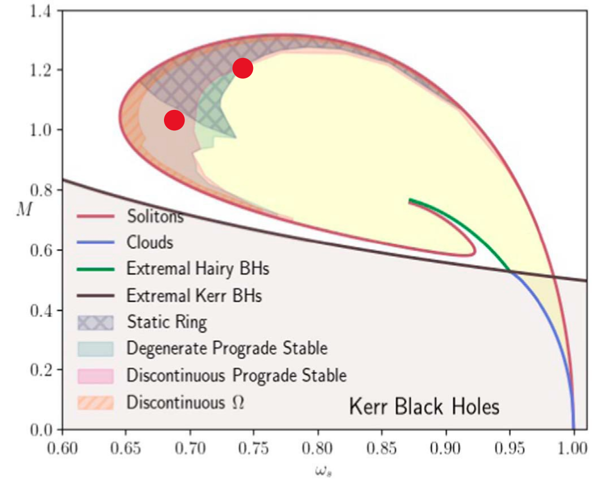
Collodel, DD, Yazadjiev, (2020)

Kerr BH + Rotating Boson Star

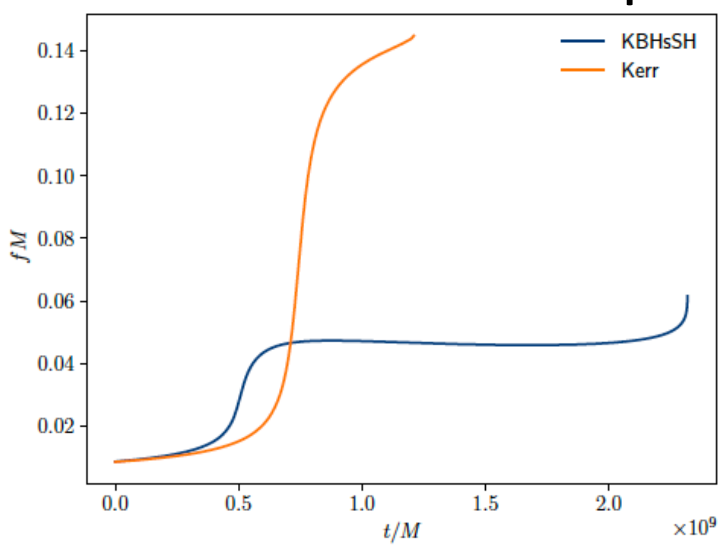


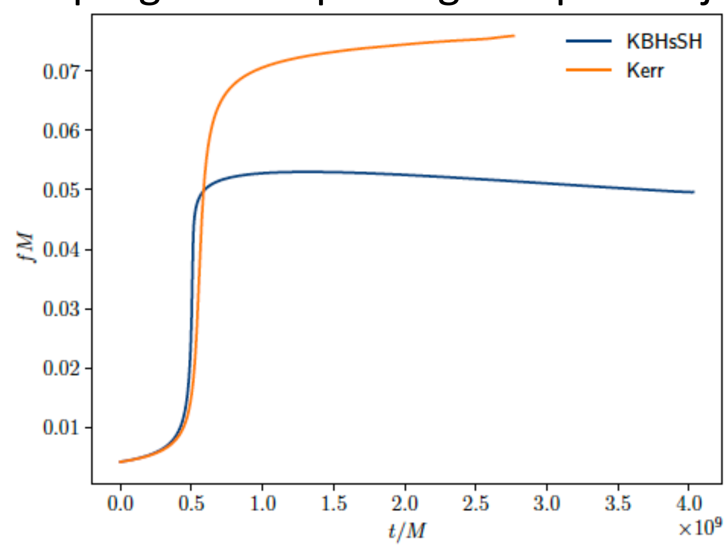
Herdeiro&Radu, RPL (2014)

- Detecting **completely new features** of the signal for Kerr black holes with synchronized scalar hair Collodel, DD, Yazadjiev, (2021)



Time evolution of the **GW frequency** of the prograde inspiraling compact object





Tests of GR with black hole coalescence

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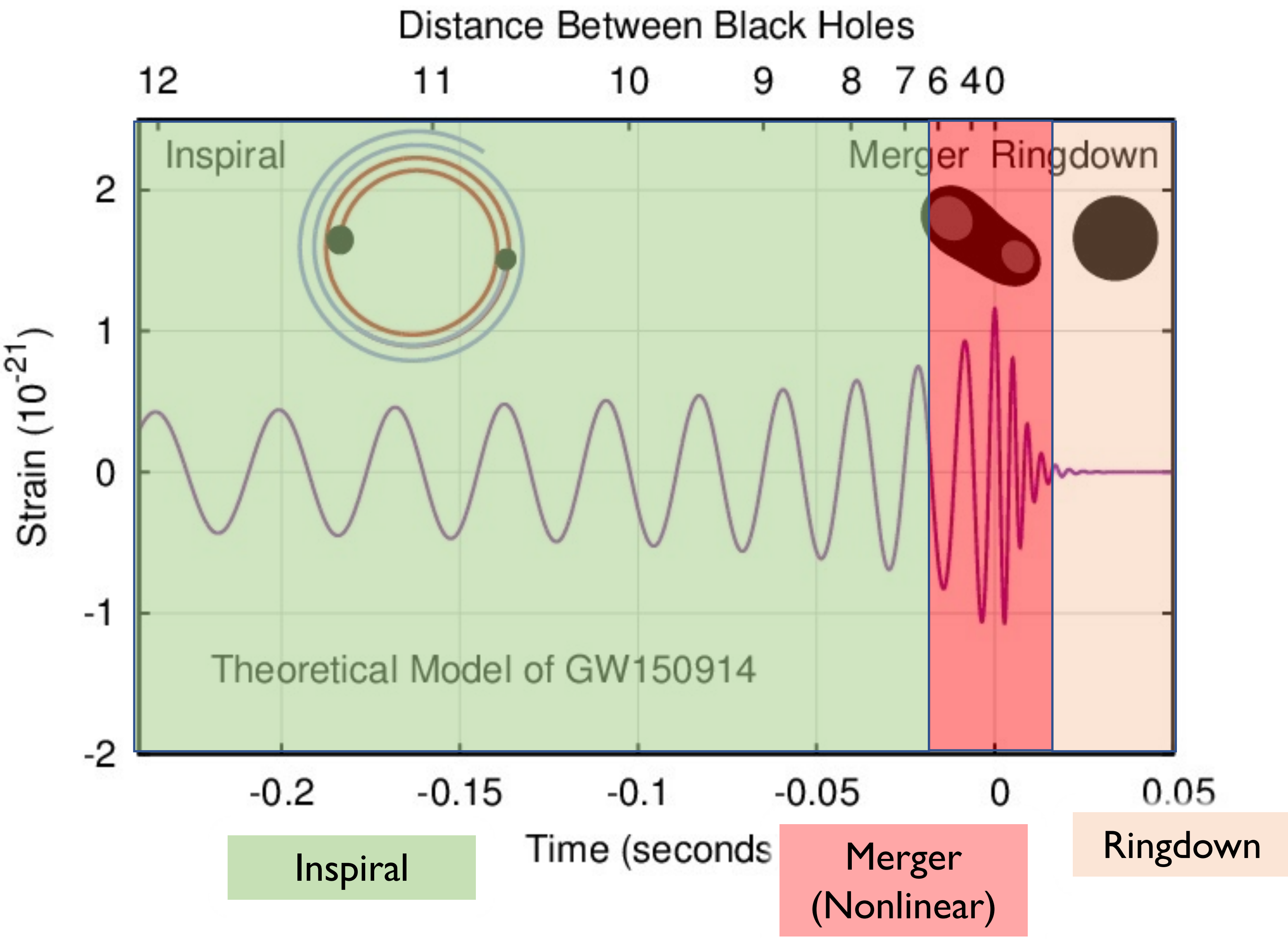
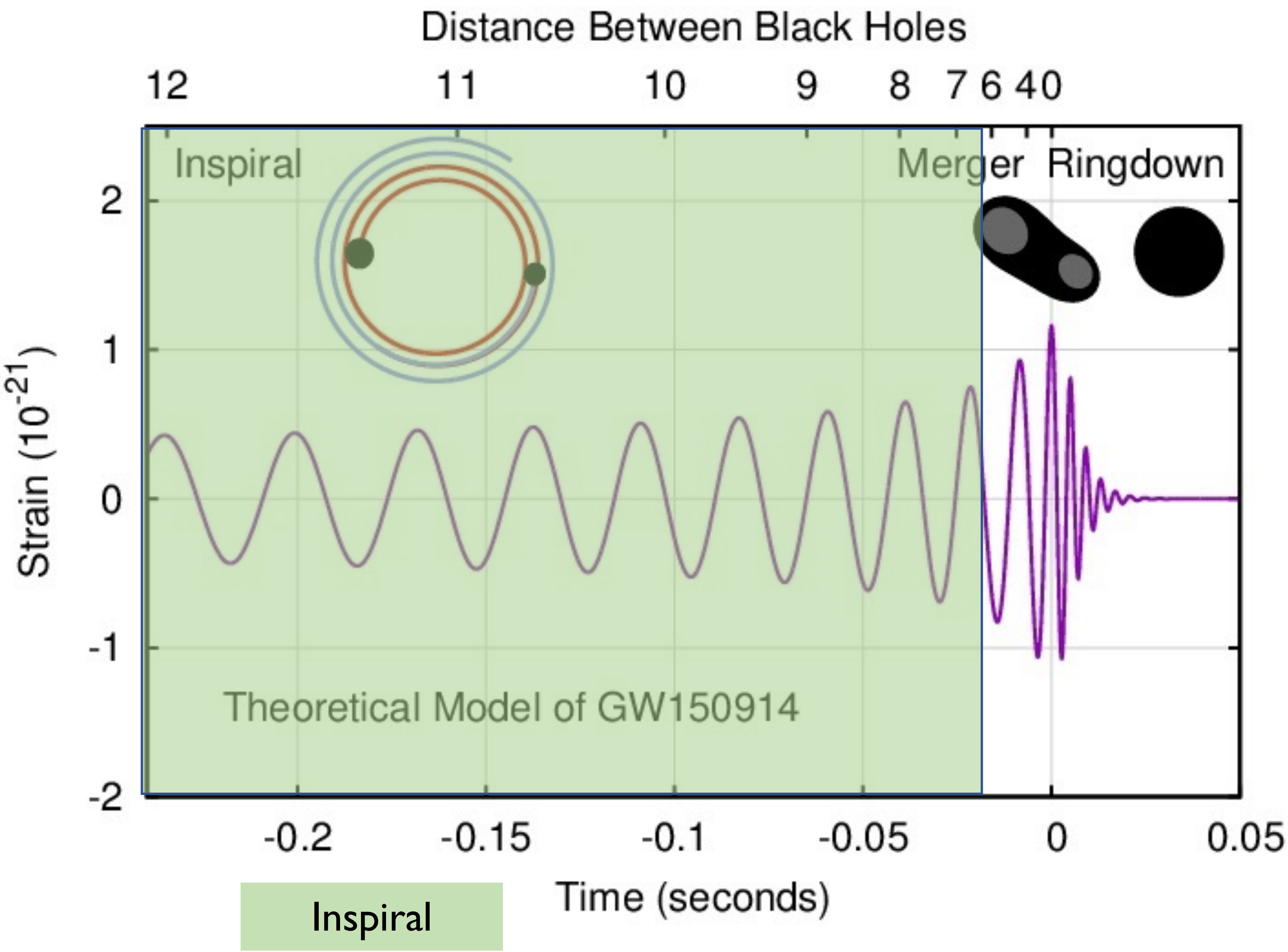


Source: http://ccrg.rit.edu/GW150914

Tests of GR with black hole coalescence



Source: http://ccrg.rit.edu/GW150914

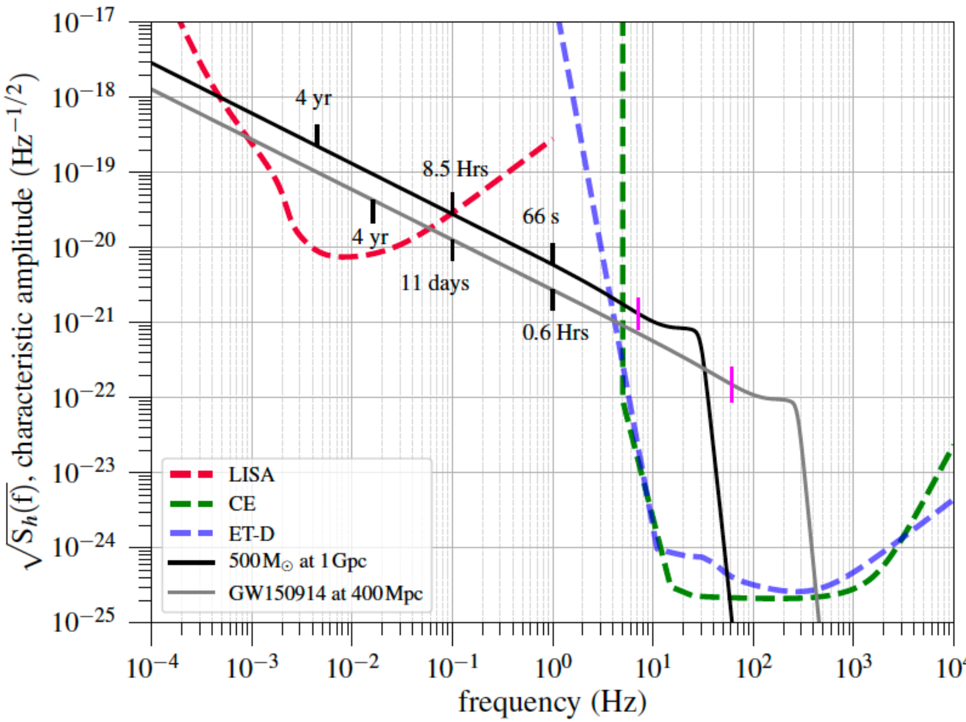
Inspiral

- LISA will observe very **long inspiral phases** ⇒ **high precision tests** of gravity
- Can be **modelled using approximate techniques,** e.g. PN expansion (Poisson&Will, 2014), or the parameterized post-Einsteinian approach (Yunes & Pretorius, 2009) – see talks on Wednesday
- GR tests with inspirals can be done **model-independent** up to a large extend but linking with particular modified theories of gravity is important (Berti et al., 2018).
- Inspiral observations with LISA will **improve the constraints** on different non-GR predictions by **several orders of magnitude compared to LIGO**, e.g. scalar dipole radiation, Lorenz symmetry, mass of the graviton, etc. (Chamberlain and Yunes, 2017).
- Testing **new features** of the modified theories of gravity – non-zero **tidal deformation of BHs** (Cardoso et al., 2017)

Inspiral – multiband detection

(see Cutler et al. (2019))

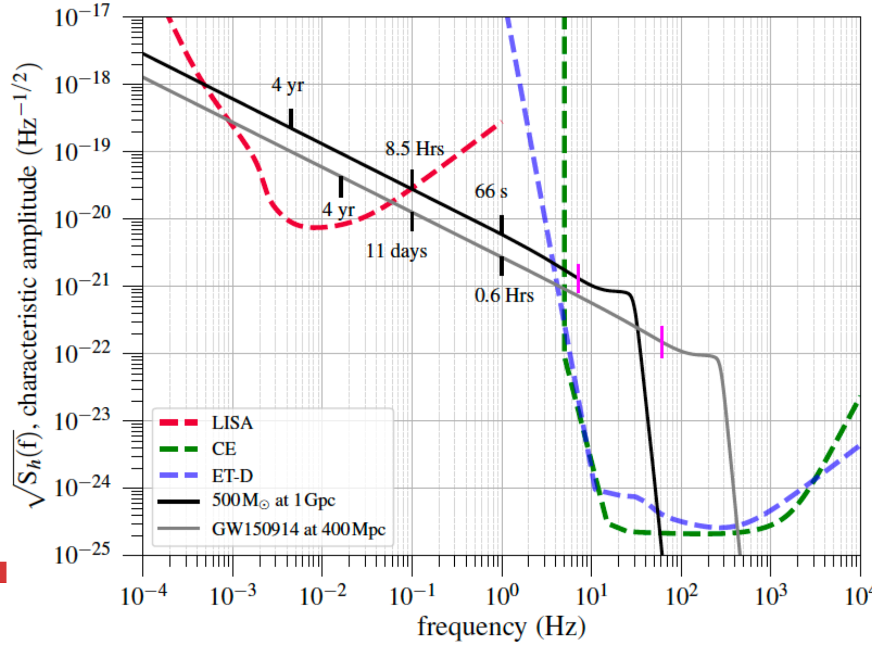
- LISA will provide hours to months of **advance warning** for some mergers
- Give us **access to features** of the gravitational waveforms **absent in ground-based data** Nishizawa et al. (2016)
- **Remove degeneracies** between parameters or improve parameter estimation Vitale (2016)
- Multiband observations are expected to yield **stringent tests of general relativity** Barausse PRL (2016), Chamberlain&Yunes PRD (2017), Berti et al. GRG (2018)



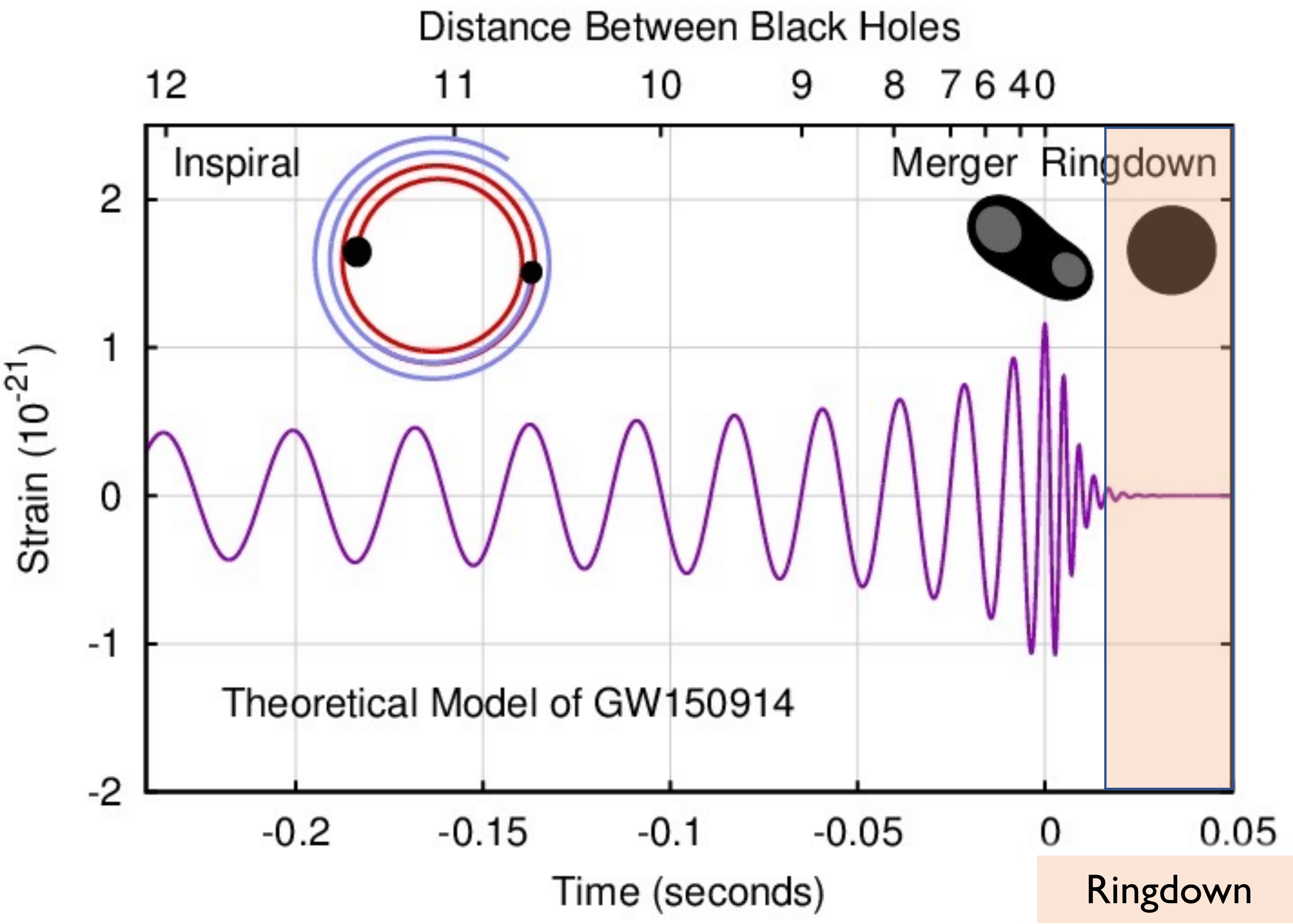
Datta et al. PRD (2021)

Inspiral – multiband detection
Testing GR modifications – Example

- Modified gravity usually means **additional channels of energy loss** during merger
- Assuming GR, one can then obtain **high-accuracy predictions** of **the time of the merger** observable by ground-based detectors and its **sky position** (Sesana, 2016)
- Any **deviation of the GR predictions** in the signal observed by a ground based detector, would imply a **breakdown of Einstein's gravity**.
- Example: **joint observations** of a LIGO/Virgo and LISA of GW150914 would **improve constraints on BBH dipole emission** by 6 orders of magnitude (Barausse et al., 2016; Toubiana et al., 2020), or constrain **dynamical BH scalarization** (Khalil et al., 2019).



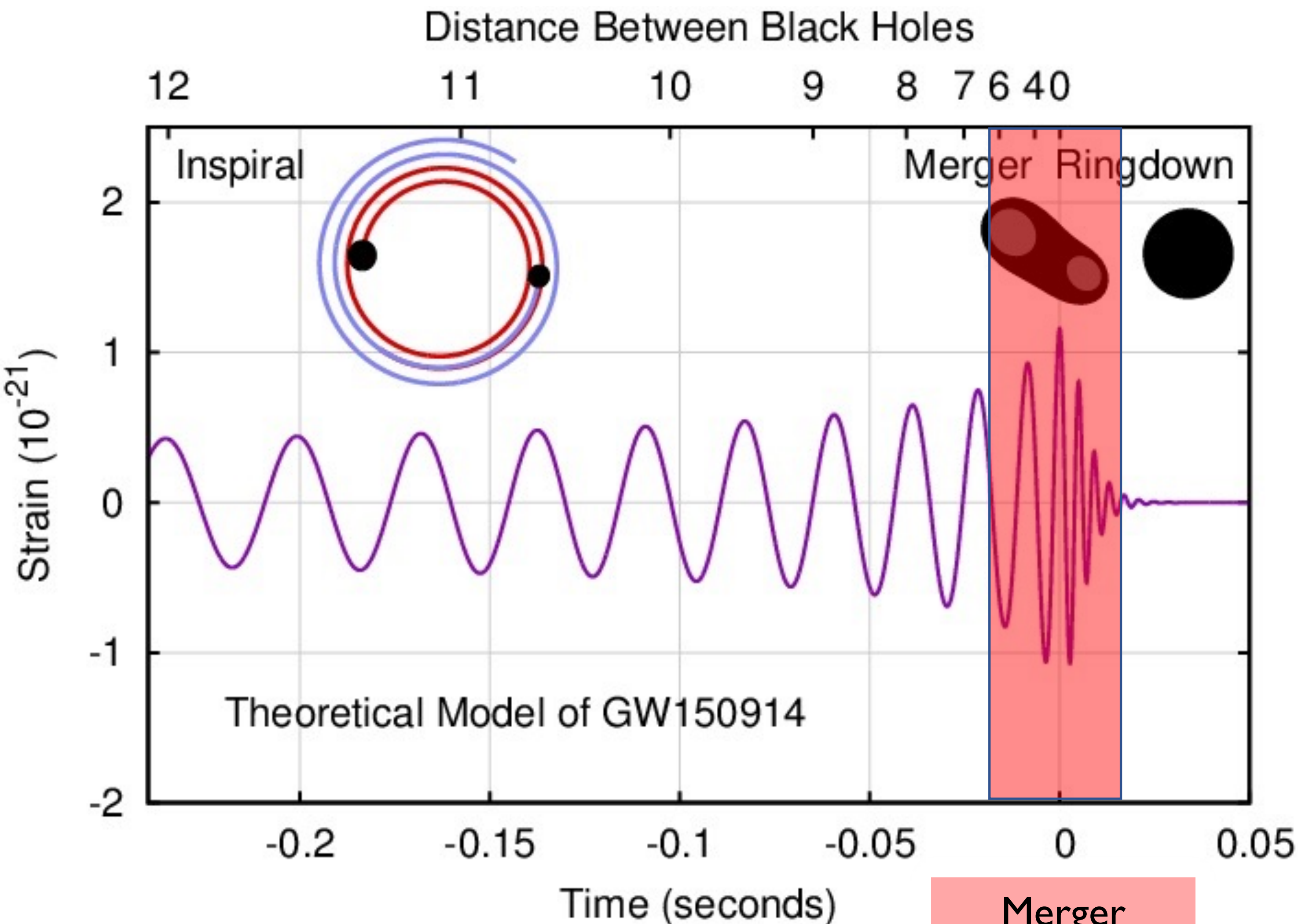
Datta et al. PRD (2021)



Source: http://ccrg.rit.edu/GW150914

Ringdown

- Measuring several QNMs would allow for **BH spectroscopy** Detweiler, (1980), Dreyer et al. (2004), Berti et al. (2006)
- The **number and amplitude of QNMs** excited during the ringdown is determined by the individual BHs and their orbital parameters prior to merger Kamaretsos et al.(2012)
- If **at least two of the QNMs** can be measured from the ringdown of a BH then **GR can be tested** (Berti et al., 2006; Dreyer et al., 2004).
- For a **high SNR massive BBH** event measured by LISA, it can be verified that the observations are consistent with a Kerr BH to high precision (e.g. Gossan et al. 2012).
- One can **combine the deviation parameters from multiple BBH** events measured by LISA Maselli et al. (2020)
- **Challenges**: computing the QNMs in modified theories is very difficult especially for rotating BHs (see e.g. Jose Luis Blázquez-Salcedo (2016,2019))
- **Parametrized tests** can be used instead, still mapping to particular theories of gravity is important – see the talks on Wednesday



Merger (Nonlinear)

Source: http://ccrg.rit.edu/GW150914

Merger

- In the merger phase the nonlinear effects of gravity truly manifest themselves ⇒ **very challenging**
- A model-independent self-consistency test, such as the **IMR consistency test** (Ghosh et al., 2016a, 2017) could be used in order to avoid having to model the merger in alternative theories of gravity.
- Important since it can explore deviations from GR that do not affect other parts of the waveform — e.g. **new fields highly excited by nonlinear effects** and decay rapidly
- **Numerical simulations beyond GR** have only been performed in a handful of cases:
  - ✓ **Gauss-Bonnet and Chern-Simons gravity** Benkel et al. (2016, 2017); Cayuso and Lehner (2020); East and Ripley (2021); Okounkova et al. (2017, 2019), 2020; Silva et al. (2021); Witek et al. (2019), Doneva&Yazadjiev (2022)
  - ✓ **Einstein–Maxwell-dilaton** theory Hirschmann et al., 2018
  - ✓ BHs immersed in **an inhomogeneous scalar field** Healy et al. (2012)
- **Approximations are usually adopted**, e.g. working perturbatively in the new coupling constants
- **Nonlinear evolution beyond GR is one of the major challenges in GW modelling**

Black hole models beyond GR

- **Pin down theories and scenarios** that could lead to deviations that are **observable by LISA.**
- Produce **rotating BH solutions beyond GR**
- **Not always easy** to use numerically calculated black hole solutions for **further calculations**

Tests of GR with black hole coalescence

- Accurate and complete development of **GW waveforms beyond GR** for the inspiral phase. **PN expansion** in theories beyond GR.
- Simulating the **BH merger in its full nonlinearity and modelling the ringdown phase** in modified theories of gravity to get more adequate templates