Discovering new physics with LISA and EMRIs

Richard Brito
Sapienza University of Rome
22nd Capra Meeting, Rio de Janeiro, 20 June 2019

New Physics?

- By new physics I will either mean non-GR corrections but also possibly the existence of new fundamental fields (that may modify gravity or not).

Commonly motivated by:

- **UV completeness:** GR must be modified at large curvature/energy scales

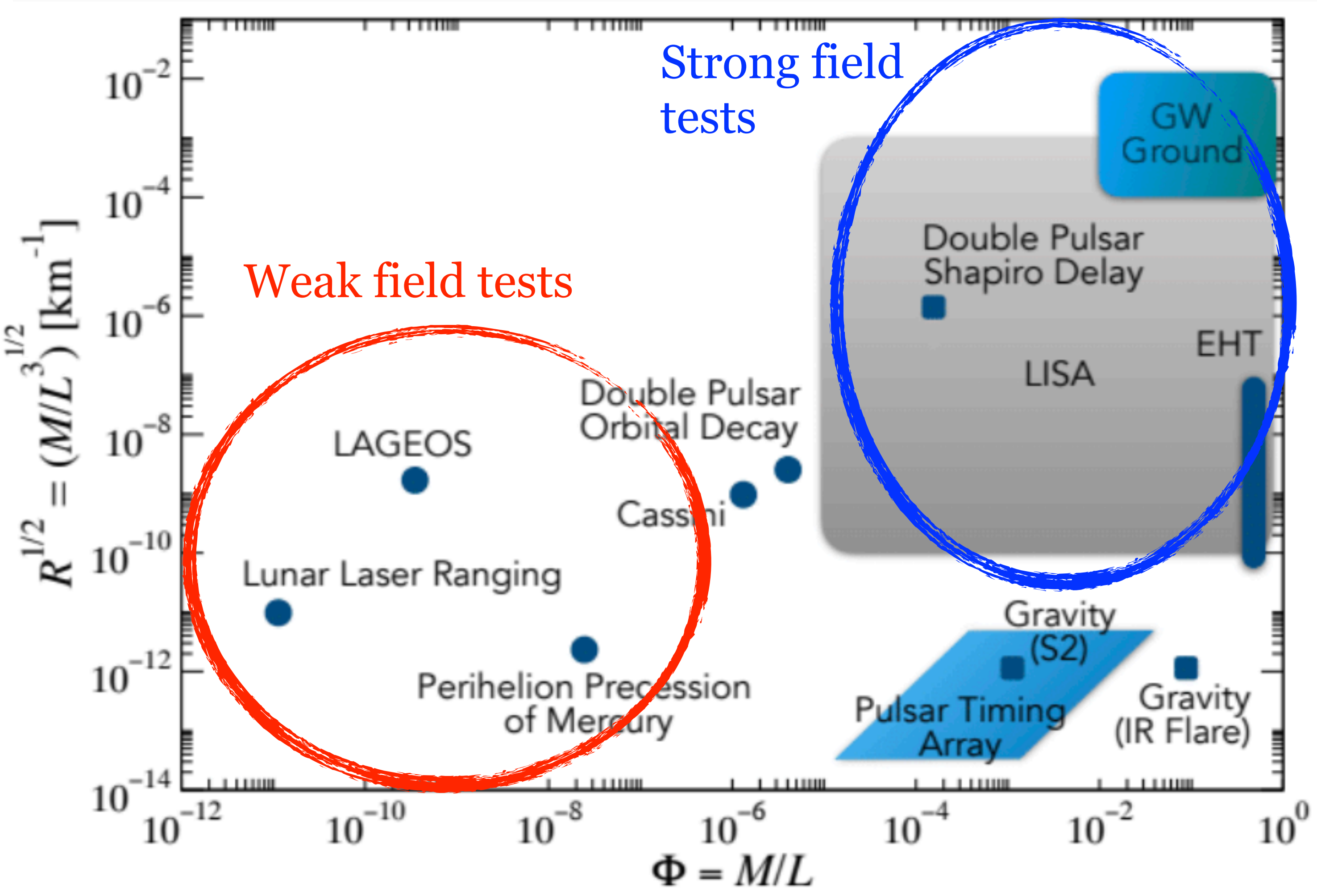
- **Dark matter:** nature unknown, but we know it interacts gravitationally.

- **Dark energy:** Cosmological acceleration as modified gravity?

But also

- Even in the case we do not find evidence for new (fundamental) physics with GWs, as scientists it is our job to test our best theoretical models against the observational data and to quantify how certain we are that they are the correct description of nature.

The "parameter space" of tests of gravity



Credit: 3G science case document. Adapted from N. Yunes, K. Yagi and F.Pretorius, PRD94, 084002 (2016).

- We are only now starting to probe the strong field regime of GR.
- In the strong field regime, precision tests only at their infancy.

The "uniqueness" of GR

The Four-Dimensionality of Space and the Einstein Tensor

David Lovelock
Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario, Canada
(Received 10 January 1972)

All tensors of contravariant valency two, which are divergence free on one index and which are concomitants of the metric tensor, together with its first two derivatives, are constructed in the four-dimensional case. The Einstein and metric tensors are the only possibilities.

D. Lovelock, Journal of Mathematical Physics 13, 874 (1972)

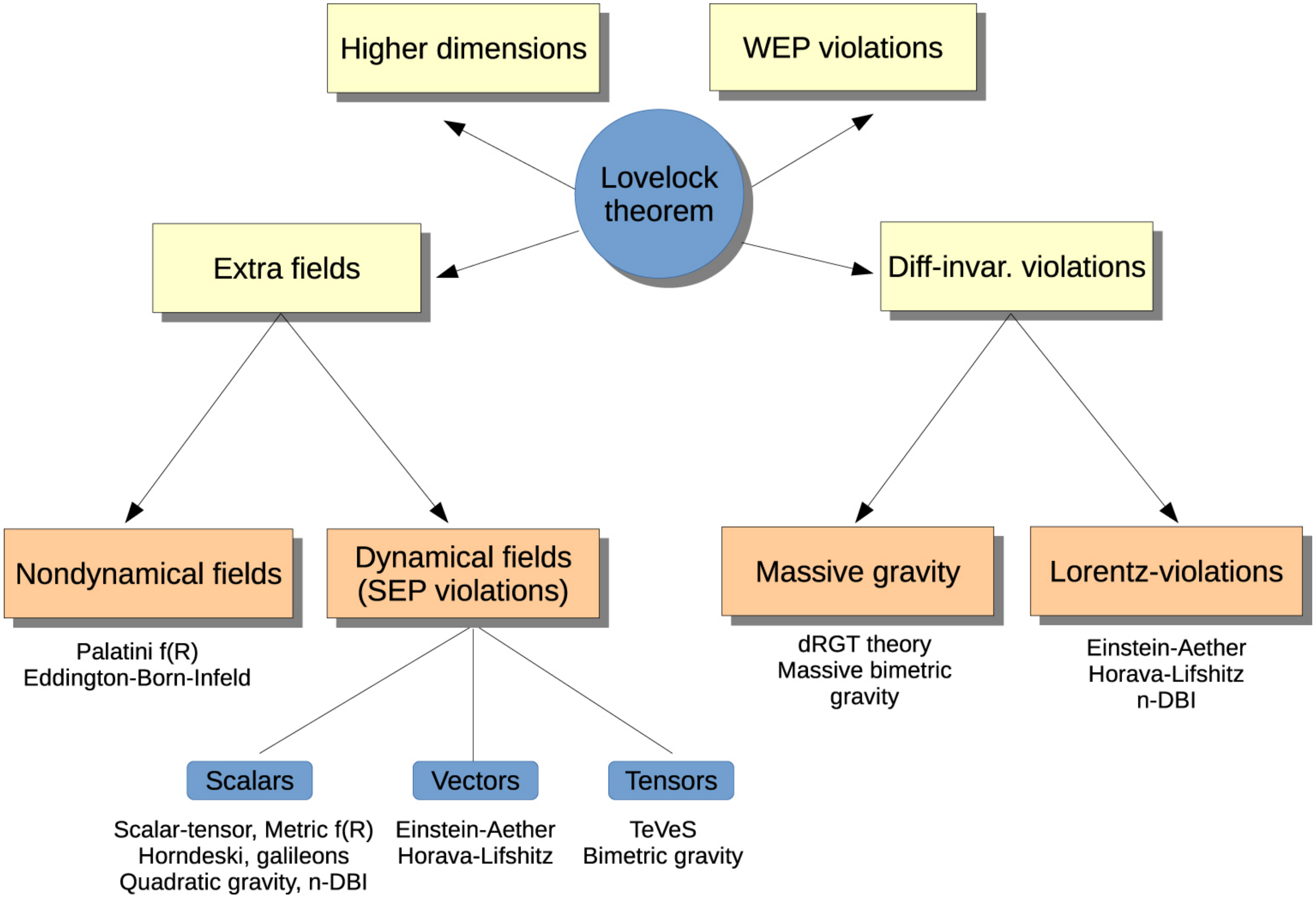
PHYSICAL REVIEW VOLUME 138, NUMBER 4B 24 MAY 1965

Photons and Gravitons in Perturbation Theory: Derivation of Maxwell's and Einstein's Equations*

STEVEN WEINBERG†
Department of Physics, University of California, Berkeley, California
(Received 7 January 1965)

We shall find within this perturbative dynamical framework that *Maxwell's theory and Einstein's theory are essentially the unique Lorentz-invariant theories of massless particles with spin $j=1$ and $j=2$.* By "essentially" we mean only that the conserved current $\mathcal{J}^\mu$ and $\mathcal{J}^{\mu\nu}$ to which the photon and graviton are coupled need

How to modify GR?



From: E. Berti et al, Class. Quantum Grav. 32 243001 (2015)

Properties of (some) beyond GR theories

From: E. Berti et al, Class. Quantum Grav. 32 243001 (2015)

Theory	Field content	Strong EP	Massless graviton	Lorentz symmetry	Linear $T_{\mu\nu}$	Weak EP	Well-posed?	Weak-field constraints
Extra scalar field								
Scalar-tensor	S	✗	✓	✓	✓	✓	✓ [34]	[35–37]
Multiscalar	S	✗	✓	✓	✓	✓	✓ [38]	[39]
Metric $f(R)$	S	✗	✓	✓	✓	✓	✓ [40, 41]	[42]
Quadratic gravity								
Gauss-Bonnet	S	✗	✓	✓	✓	✓	✓?	[43]
Chern-Simons	P	✗	✓	✓	✓	✓	✗✓? [44]	[45]
Generic	S/P	✗	✓	✓	✓	✓	?	
Horndeski	S	✗	✓	✓	✓	✓	✓?	
Lorentz-violating								
Æ-gravity	SV	✗	✓	✗	✓	✓	✓?	[46–49]
Khronometric/ Hořava-Lifshitz	S	✗	✓	✗	✓	✓	✓?	[48–51]
n-DBI	S	✗	✓	✗	✓	✓	?	none ([52])
Massive gravity								
dRGT/Bimetric	SVT	✗	✗	✓	✓	✓	?	[17]
Galileon	S	✗	✓	✓	✓	✓	✓?	[17, 53]
Nondynamical fields								
Palatini $f(R)$	–	✓	✓	✓	✗	✓	✓	none
Eddington-Born-Infeld	–	✓	✓	✓	✗	✓	?	none
Others, not covered here								
TeVeS	SVT	✗	✓	✓	✓	✓	?	[37]
$f(R)\mathcal{L}_m$	?	✗	✓	✓	✓	✗	?	
$f(T)$	?	✗	✓	✗	✓	✓	?	[54]

Table 1. Catalog of several theories of gravity and their relation with the assumptions of Lovelock's theorem. Each theory violates at least one assumption (see also Figure 2.1), and can be seen as a proxy for testing a specific principle underlying GR. See text for details of the entries. Key to abbreviations: S: scalar; P: pseudoscalar; V: vector; T: tensor; ?: unknown; ✓?: not explored in detail or not rigorously proven, but there exist arguments to expect ✓. The occurrence of ✗✓? means that there exist arguments in favor of well-posedness within the EFT formulation, and against well-posedness for the full theory. Weak-field constraints (as opposed to strong-field constraints, which are the main topic of this review) refer to Solar System and binary pulsar tests. Entries below the last horizontal line are not covered in this review.

BH solutions in beyond GR theories

From: E. Berti et al, Class. Quantum Grav. 32 243001 (2015)

Theory	Solutions	Stability	Geodesics	Quadrupole
Extra scalar field				
Scalar-tensor	≡GR [55–60]	[61–67]	–	–
Multiscalar/Complex scalar	⊃GR [56, 68, 69]	?	?	[68, 69]
Metric $f(R)$	⊃GR [58, 59]	[70, 71]	?	?
Quadratic gravity				
Gauss-Bonnet	NR [72–74]; SR [75, 76]; FR [77]	[78, 79]	SR [75, 80, 81]; FR [77]	[76, 82]
Chern-Simons	SR [83–85]; FR [86]	NR [87–90]; SR [79]	[74, 91]	[85]
Generic	SR [80]	?	[80]	Eq. (3.12)
Horndeski	[92–94]	? [95, 96]	?	?
Lorentz-violating				
Æ-gravity	NR [97–99]	?	[98, 99]	?
Khronometric/ Hořava-Lifshitz	NR, SR [98–101]	? [102]	[98, 99]	?
n-DBI	NR [103, 104]	?	?	?
Massive gravity				
dRGT/Bimetric	⊃GR, NR [105–108]	[109–112]	?	?
Galileon	[113]	?	?	?
Nondynamical fields				
Palatini $f(R)$	≡GR	–	–	–
Eddington-Born-Infeld	≡GR	–	–	–

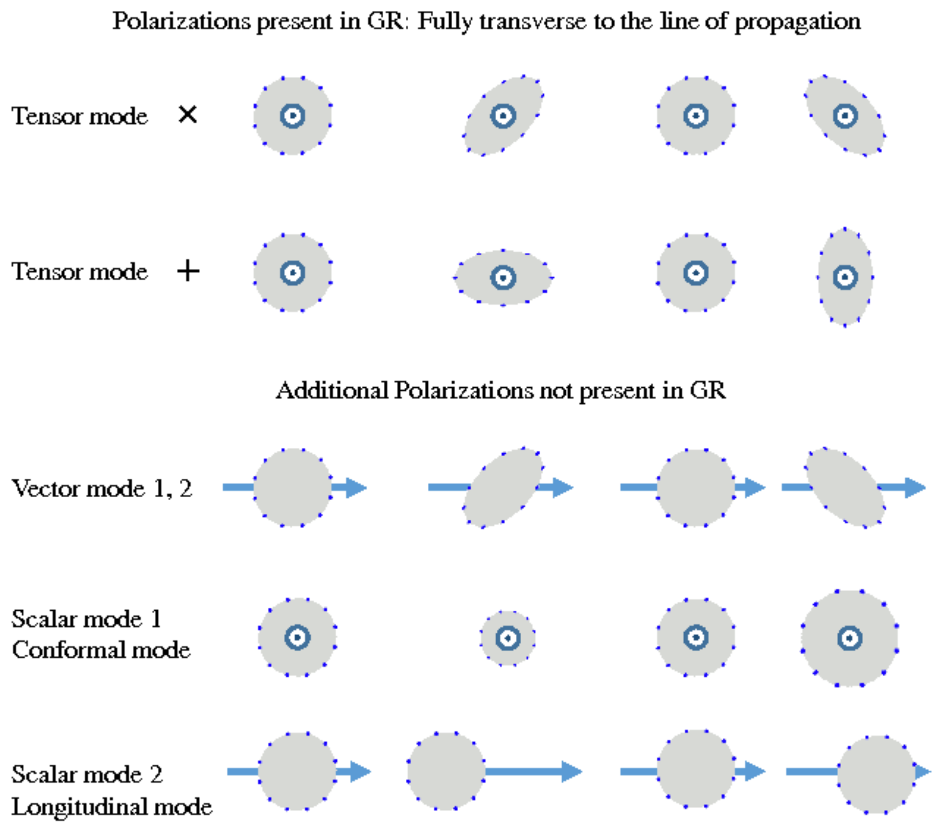
Table 2. Catalogue of BH properties in several theories of gravity. The column "Solutions" refers to asymptotically-flat, regular solutions. Legend: ST="Scalar-Tensor," ≡GR="Same solutions as in GR," ⊃GR="GR solutions are also solutions of the theory," NR="Non rotating," SR="Slowly rotating," FR="Fast rotating/Generic rotation," ?=unknown or uncertain.

- Theories that admit GR black hole solutions do not necessarily have the same dynamics as in GR (e.g. BH ringdown might be different).

Consequences for GW physics

C. Will, Living Rev. Relativity (2014); N. Yunes & X. Siemens Living Rev. Relativity (2013); Gair *et al*, Living Rev. Relativity (2013)

- Additional polarizations (up to 6 independent polarizations for a metric theory)
- Additional channels for energy loss, e.g. dipolar radiation
- Modified graviton dispersion relation (graviton mass; Lorentz violations)
- Parity violations (amplitude birefringence)
- Different BH ringdown and new families of QNMs
- Hairy BHs
- Non-zero tidal Love numbers
- …



From: C. Rham, Living Rev. Relativity 17, (2014)

How to test gravity?

Theory-specific

- Pick a theory and test it.
- Pros:
  - Stronger constraints on the parameters of interest (in general).
  - Easy to combine information from different events.
  - Possibility of finding smoking-gun effects with potentially large corrections from GR.
- Cons:
  - Large number of theories.
  - For most of the theories almost everything is still to be done.
  - Technically VERY challenging.
  - No real motivation to study some theories over others (for most cases).

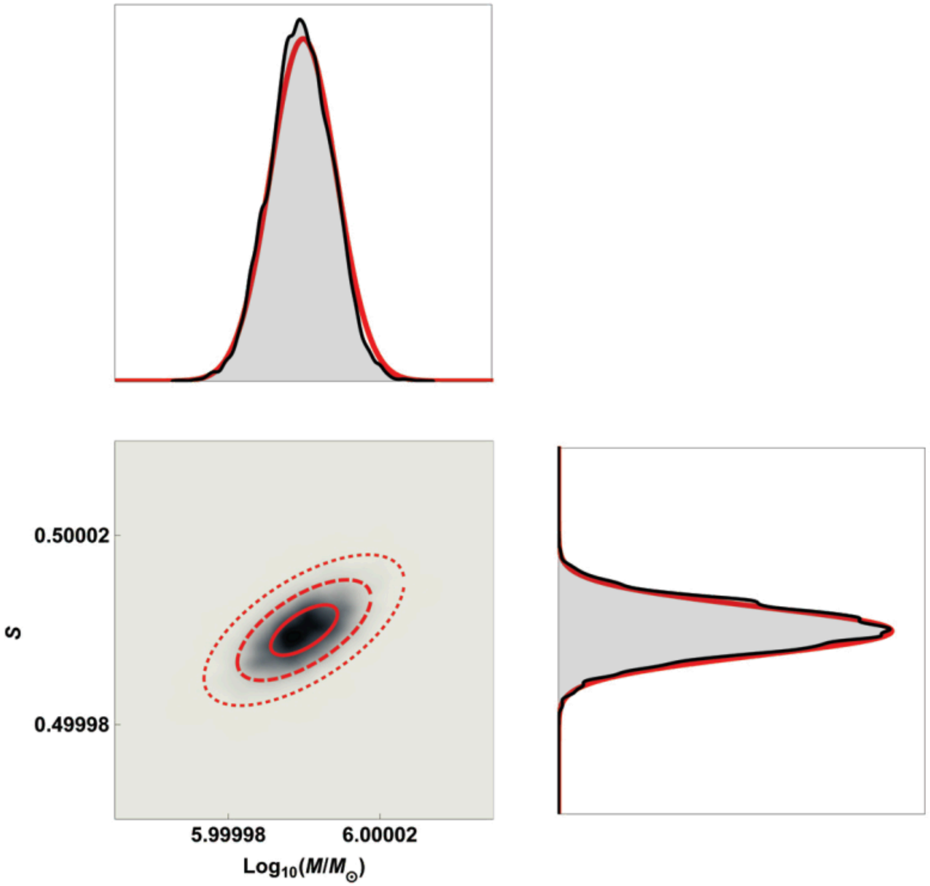
Theory-agnostic

- Search/constrain model-independent deviations from GR (ppN, ppE, bumpy BHs,...).
- Pros:
  - Easy to implement.
  - Only need to know the GR waveform good enough.
  - Ideally: generic enough to encompass several theories
- Cons:
  - Sufficiently general?
  - Too many parameters.
  - Map between parameterisation and specific theories not always trivial.
  - For most cases only focuses on part of the waveform.

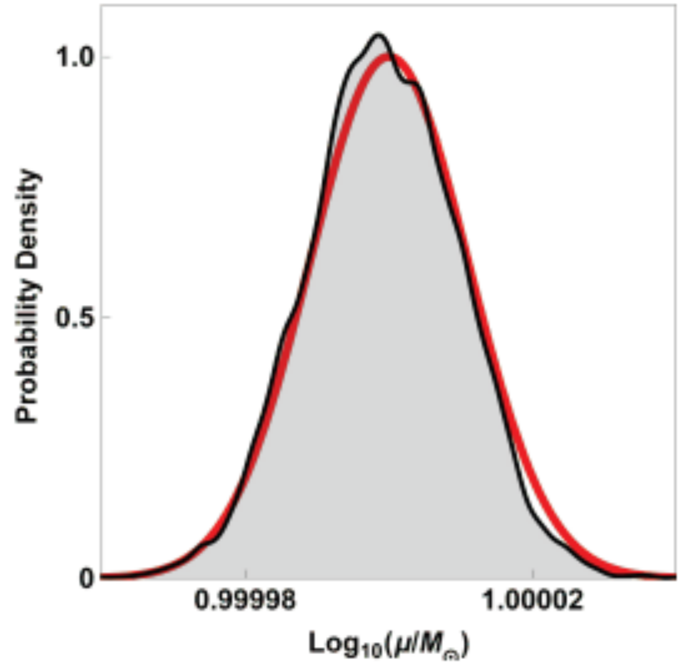
Extreme mass-ratio inspirals

- Large number of GW cycles in band $\sim \mathcal{O}(10^5)$ —> measure waveform parameters with very high precision. Masses and spin (of the central BH) could be measured with precisions as small as $\sim 10^{-4} - 10^{-6}$.
  (Barack and Cutler, '06; Babak et al '17)

- Naturally expect it to be a unique probe to perform high precision test of gravity.



From: Moore, Chua & Gair, 2017, arXiv:1703.09722



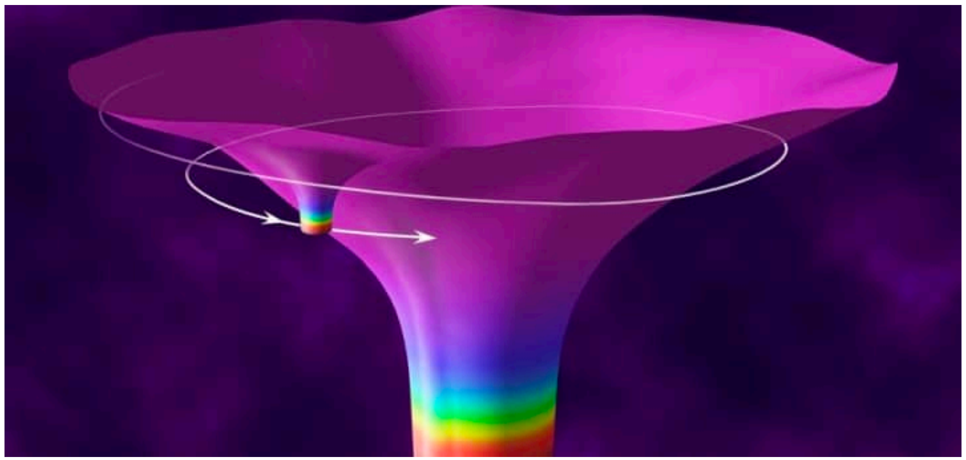
- Injected signal with a SNR of "only" 30. Roughly same SNR as GW170817 (the BNS).

Tests of GR with EMRIs

EMRIs especially good to test:

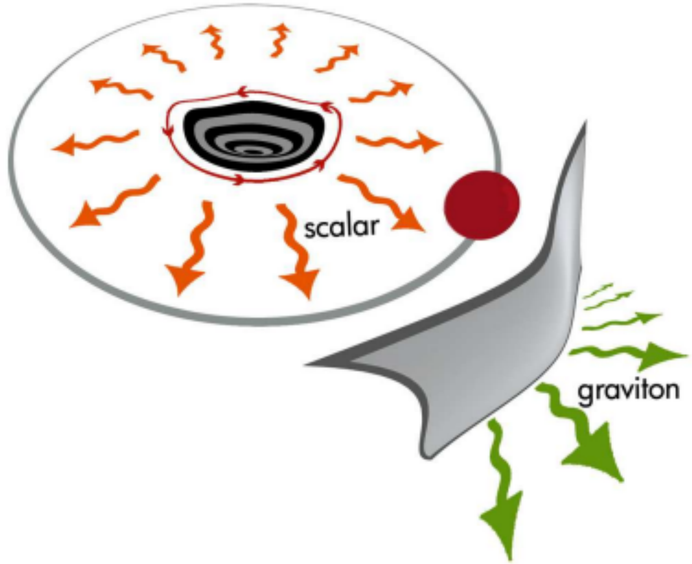
The spacetime geometry (e.g. multipolar structure)

$$g_{\mu\nu} = g_{\mu\nu}^{\mathrm{Kerr}} + \delta g_{\mu\nu}$$



GW emission during inspiral (e.g. extra d.o.f.)

$$\dot{E} = \dot{E}_{\mathrm{GR}}(1 + \delta \dot{E})$$



Testing the spacetime structure

- Multipole moments of a Kerr spacetime can be expressed in terms of its spin and mass alone: (R. Hansen, ’74)

$$\mathscr{M}_\ell^{\rm Kerr} + i\mathscr{S}_\ell^{\rm Kerr} = M^{\ell+1}(i\chi)^\ell$$

- Measurement of three multipole moment, e.g. mass, spin and mass quadrupole moment, provides a null-hypothesis **test of the Kerr metric**.

- Multipole moment structure imprinted in GW waveform. (F. Ryan, ’95,’97)

LISA could measure mass quadrupole moment with an accuracies of the order

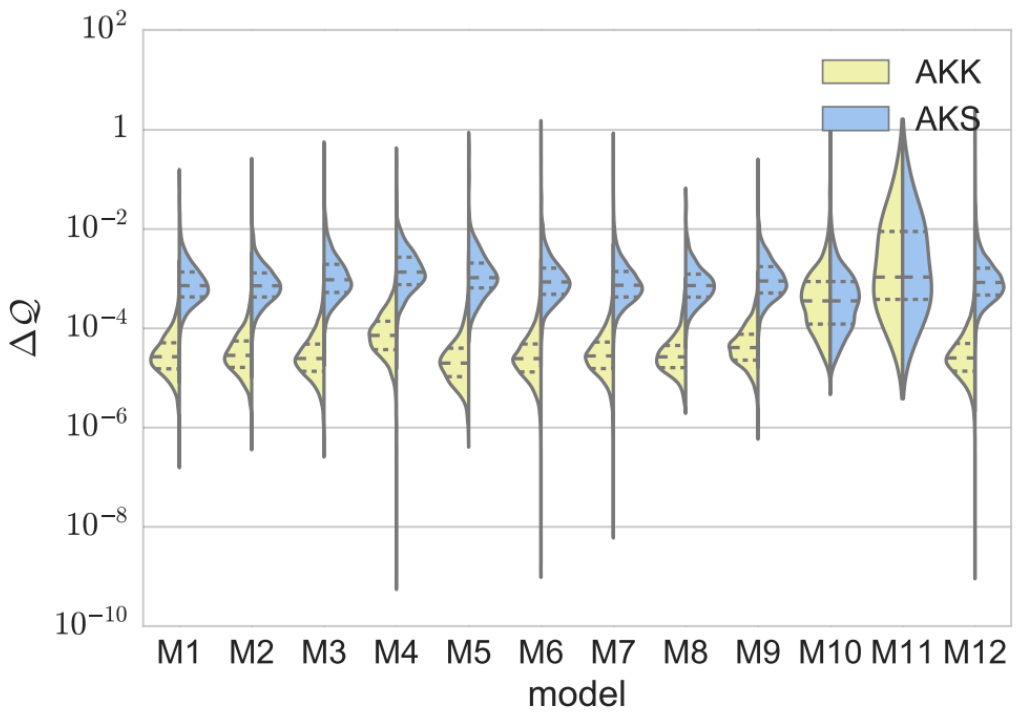
(Barack and Cutler, ‘06)

$$\Delta\mathscr{Q} \sim 10^{-4} - 10^{-2}$$

where

$$\Delta\mathscr{Q} = (\mathscr{M}_2 - \mathscr{M}_2^{\rm Kerr})/M^3$$

$$\mathscr{M}_2^{\rm Kerr} = -M^3\chi^2$$

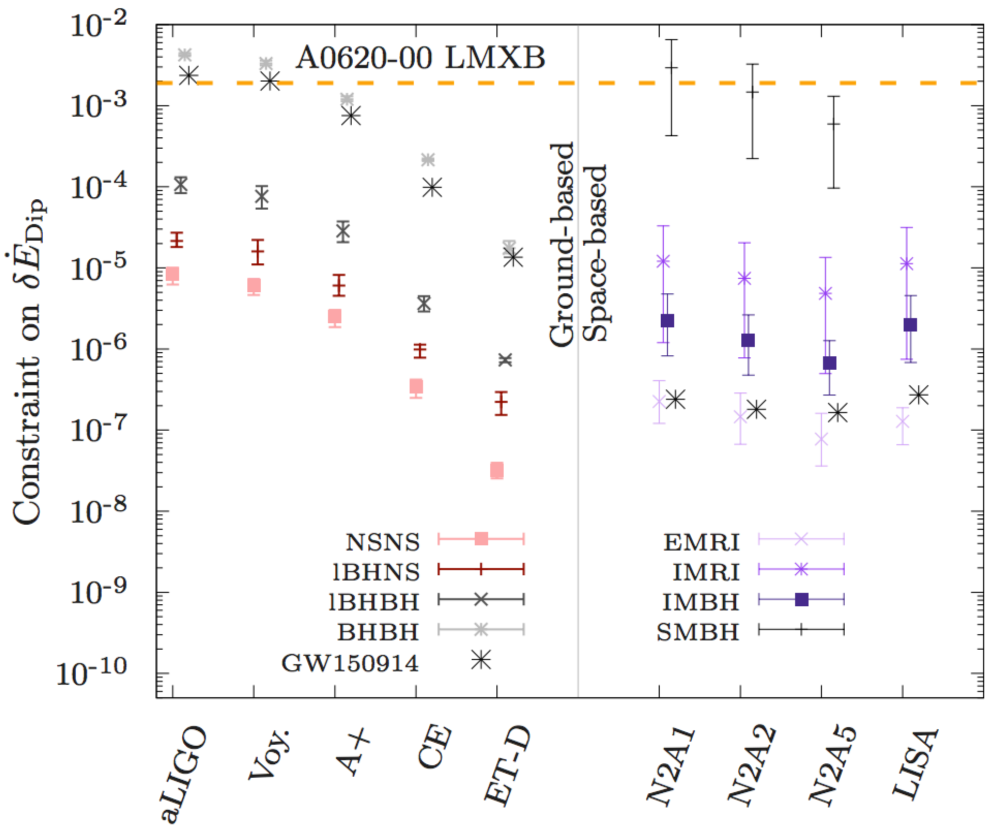


From: Babak *et al*, 2017, arXiv:1703.09722

Testing GW emission

- A typical example of modification in the GW flux: the existence of dipolar emission.

$$\dot{E} = \dot{E}_{GR}\left(1 + \delta\dot{E}_{Dip}v^{-2}\right)$$



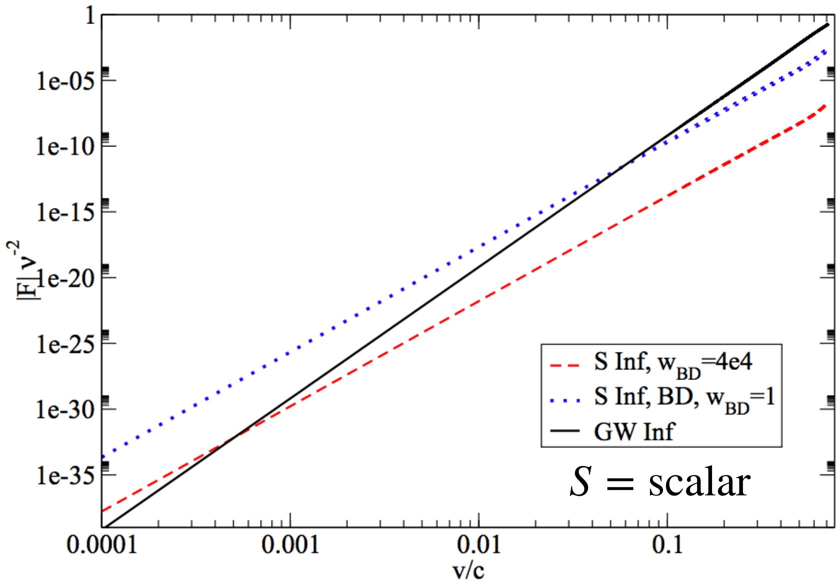
Credit: Chamberlain and Yunes, '17, arXiv:1704.08268

- Enviromental effects expected to be especially important at low frequencies and could potentially blur this kind of tests. However majority of EMRIs should be "matter-free". [Barausse, Cardoso and Pani '14]

EMRIs beyond GR: specific examples

Brans-Dicke-like scalar-tensor theories:

$$S = \int d^4\sqrt{-g}\left(\frac{R^{(E)}}{16\pi} - \frac{1}{2}g^{(E)}_{\mu\nu}\partial^\mu\Phi\partial^\nu\Phi + V(\Phi)\right) + S_m\left(\Phi_m; A(\Phi)^2 g_{\mu\nu}\right)$$



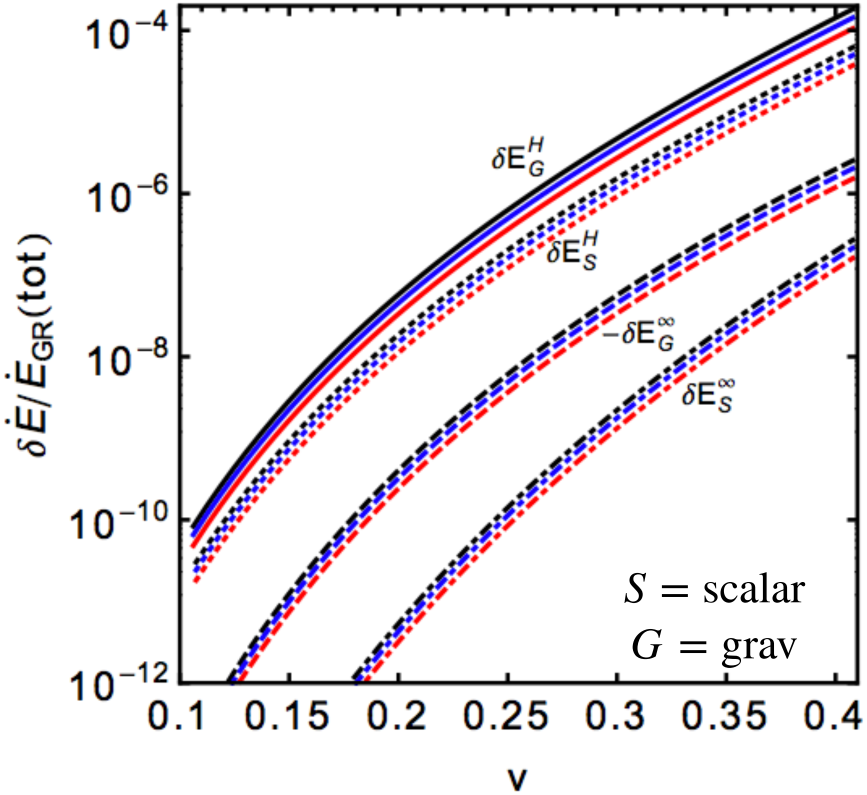
From: Yunes, Pani & Cardoso arXiv:1112.3351

- The "simplest" of all the modifications to GR. Kerr is an exact solution of these theories.
- Only neutron stars can "scalarize" for this flavour of ST theories. For BHs everything as in GR.
- Only non-GR theory where self-force equations of motion were fully derived (as far as I know). [P.Zimmerman, '15]

EMRIs beyond GR: specific examples

Dynamical Chern-Simons:

$$S = \frac{1}{16\pi}\int d^4\sqrt{-g}R + \frac{\alpha}{4}\int d^4x\sqrt{-g}\theta {}^*RR - \frac{\beta}{2}\int d^4x\sqrt{-g}g^{ab}\nabla_a\theta\nabla_b\theta + S_m$$



Credit: Pani, Cardoso & Gualtieri arXiv:1104.1183

[also Canizares, Gair & Sopuerta, '12 Sopuerta, Yunes '09 for studies with kludge waveforms]

- Extension to a spinning background highly difficult either because analytical spinning BH solution (for any spin) unknown and/or pert. equations do not separate in a spinning background.

- Motion integrable around spinning BHs? [Cárdenas-Avendaño *et al* '18]

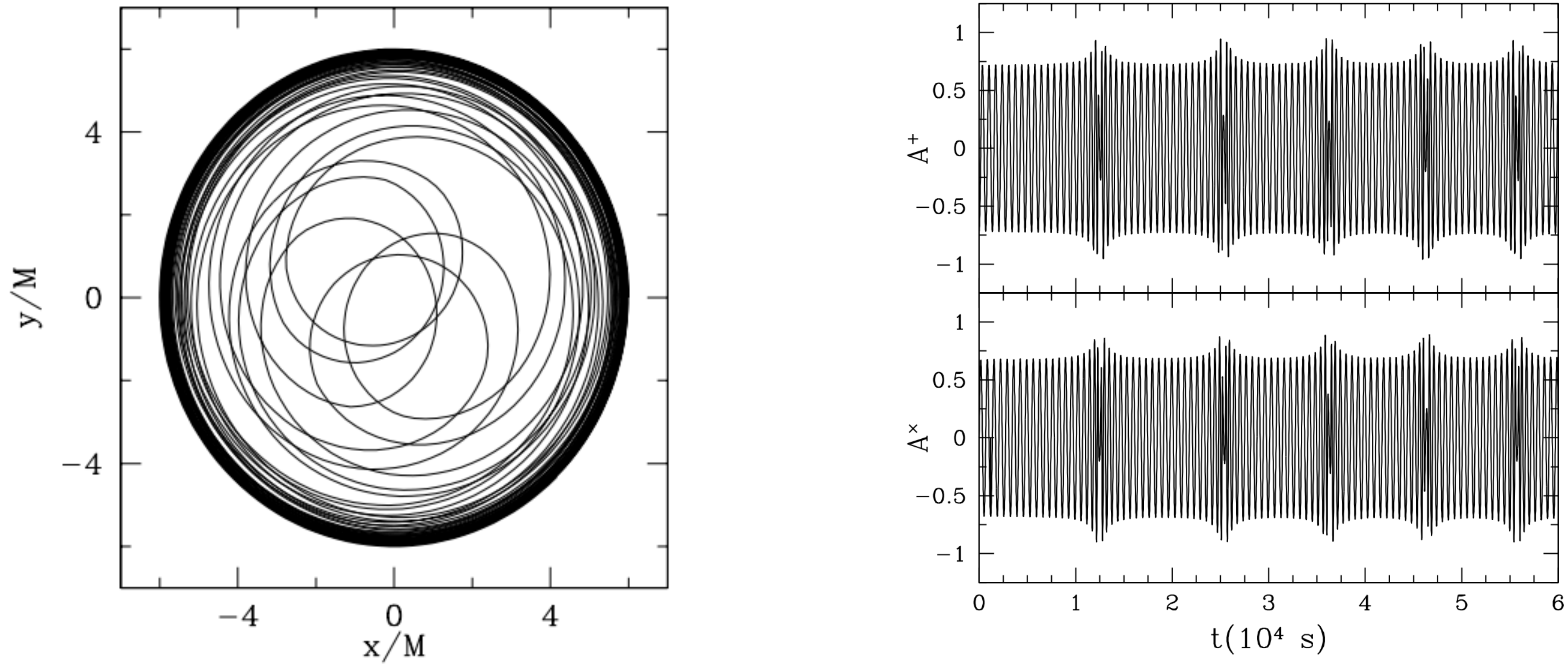
Testing the BH paradigm

What if the central object is not a BH?

- In general, exterior expected to be different than Kerr (no uniqueness theorem), so multipolar structure different.
- Non-vanishing tidal love numbers (which are identically zero for vacuum BHs in GR).
- GW emission after the plunge.
- Modifications to the GW dissipation at the event horizon.

EMRIs around boson stars

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{2\kappa} - g^{ab}\partial_a\Phi^*\partial_b\Phi - V(|\Phi|^2)\right]$$

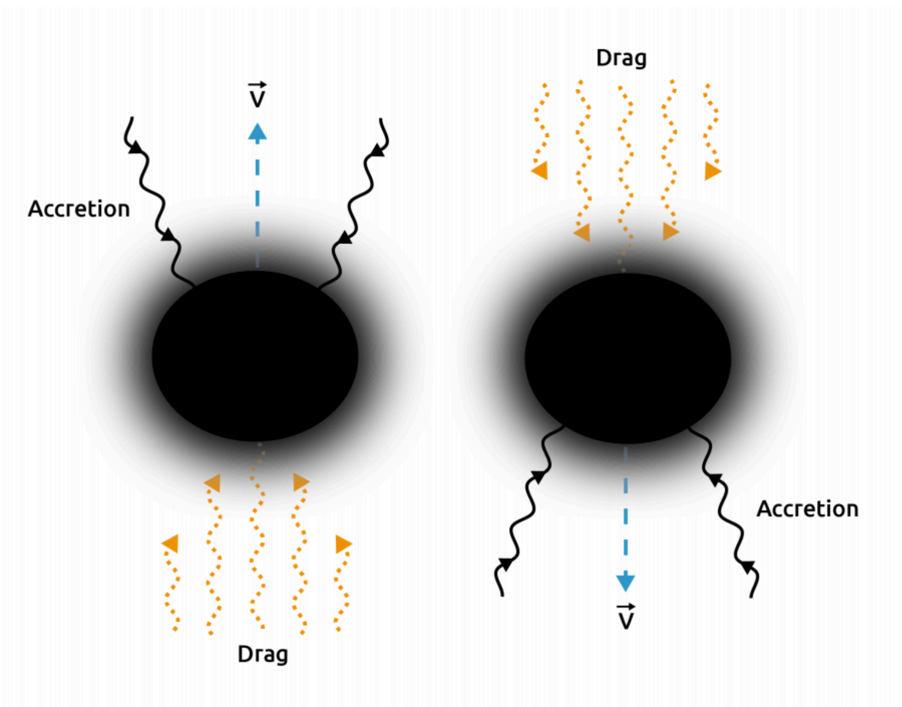


From: Kesden, Gair & Kamionski,PRD71 (2005) 044015

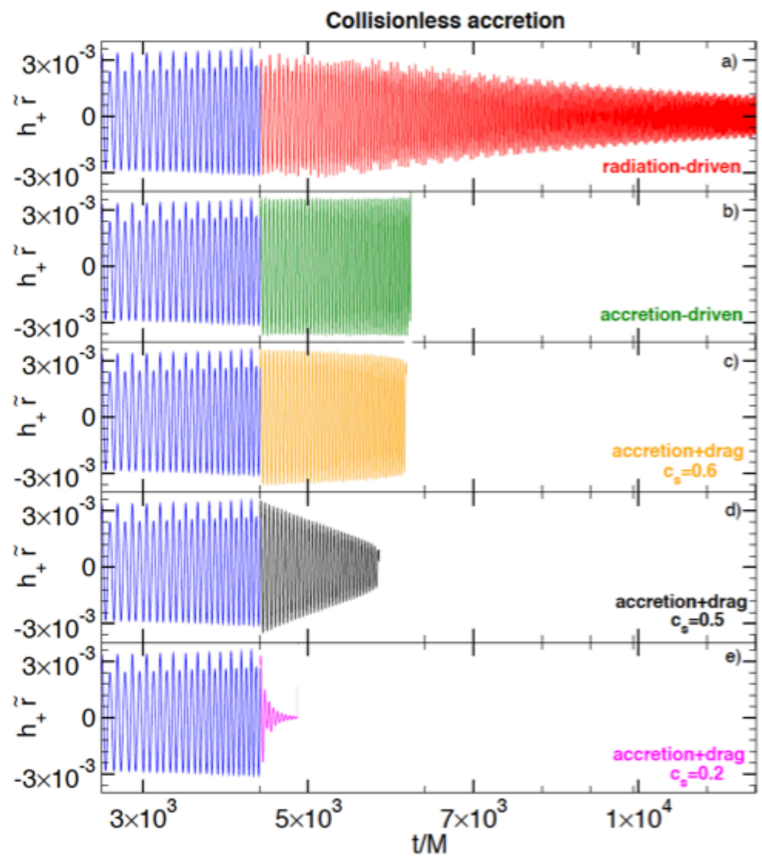
- If sufficiently compact, boson stars can have stable orbits in their interior. Signal persist after plunge.

Accretion and gravitational drag

- Two additional effects may play a role when the small object moves inside the star:
- **Gravitational drag** (dynamical friction): gravitational interaction of the compacts objects with their own wake in the medium.
- **Accretion**: small object accretes matter while traveling through the medium.
- Both effects contribute to decelerate the small object.



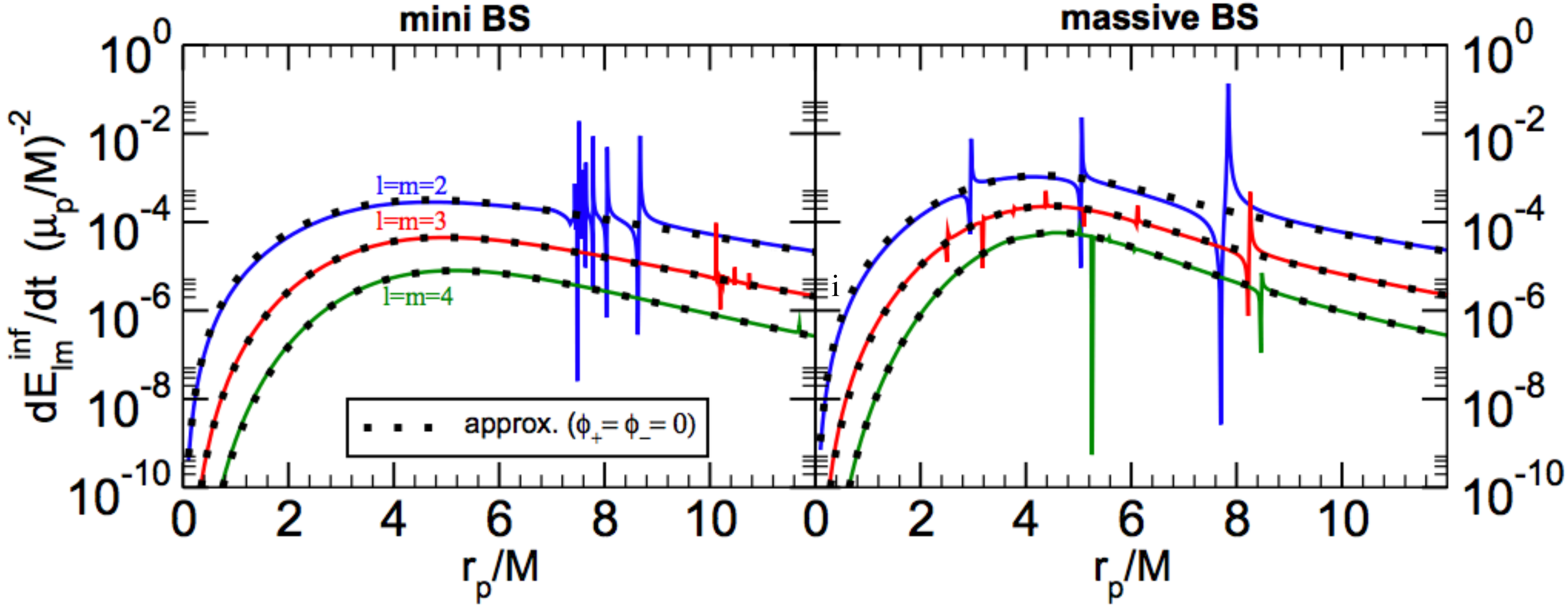
From: Barack *et al* arXiv: 1806.05195



From: Macedo, Pani, Cardoso & Crispino arXiv: 1302.2646

Excitation of the object's QNMs

Macedo, Pani, Cardoso, Crispino '13



From: Macedo, Pani, Cardoso & Crispino, arXiv: 1302.2646

- Small object can excite boson star's QNMs during the inspiral. Occurs also for other compact horizonless objects (e.g. gravastars).(Pani *et al* '10)

- Could lead to huge dephasing:

$$\delta\phi_{\rm GW} \approx 8.6 \times 10^3 \text{rads} \left[\frac{10^5 M_\odot}{M}\right] \left[\frac{T_{\rm obs}}{1\text{yr}}\right]$$

Testing the existence of an horizon

- The nature of the compact object is also encoded in the amount of radiation that it can possibly absorb ("tidal heating"): [Hartle '73]

$$\dot{E}_T = \dot{E}_\infty + \dot{E}_H$$

- For an equatorial circular orbit around a spinning BH:

$$\dot{E}_H \propto \Omega_{\rm orb}(\Omega_{\rm orb} - \Omega_H)$$

- For exotic compact objects tidal heating expected to be different. Assuming $\dot{E}_H = 0$ can lead to large GW dephasing (especially for large BH spin and late stages of the inspiral). [Hughes '01]

- Systematic study of possible constraints on $\dot{E}_H$ with EMRIs still needed but possibly an easy way to parameterize deviations close to the BH horizon. [e.g. Maselli+ '17]

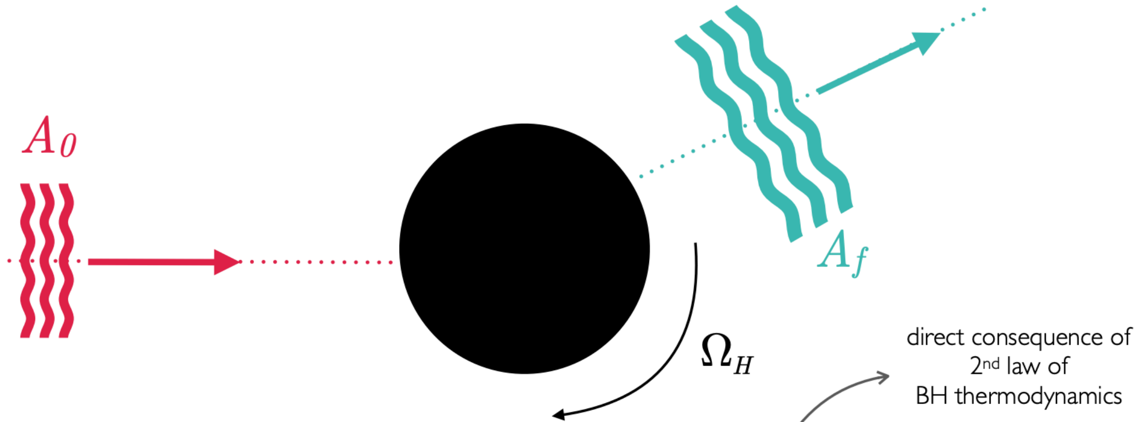
Superradiance

Zel'dovich, '71; Misner '72; Press and Teukolsky ,'72-74; Review: RB, Cardoso & Pani '15

$$\dot{E}_H \propto \Omega_{\rm orb}(\Omega_{\rm orb} - \Omega_H)$$

- Depending on the BH spin and orbital frequency effect of $\dot{E}_H$ is either to decelerate ($\Omega_{\rm orb} < \Omega_H$) of accelerate ($\Omega_{\rm orb} > \Omega_H$) the orbit (analogous to tidal deceleration and acceleration). (e.g. Sullivan & Hughes '14-'16)

- For a BH can be understood in terms of superradiant scattering.



$$\omega_0/m < \Omega_H \Longrightarrow A_0 < A_f$$

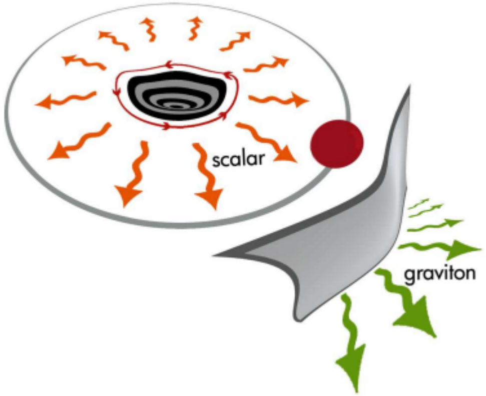
wave frequency, ω ; azimuthal quantum number, m

- Can $\dot{E}_T = \dot{E}_\infty + \dot{E}_H = 0$ occur ("floating orbit")? Not around Kerr BHs in GR.

Misner '72; Press and Teukolsky ,'72, Hughes '01, Kapadia, Kennefick and Glampedakis '13

Floating orbits in scalar-tensor theories

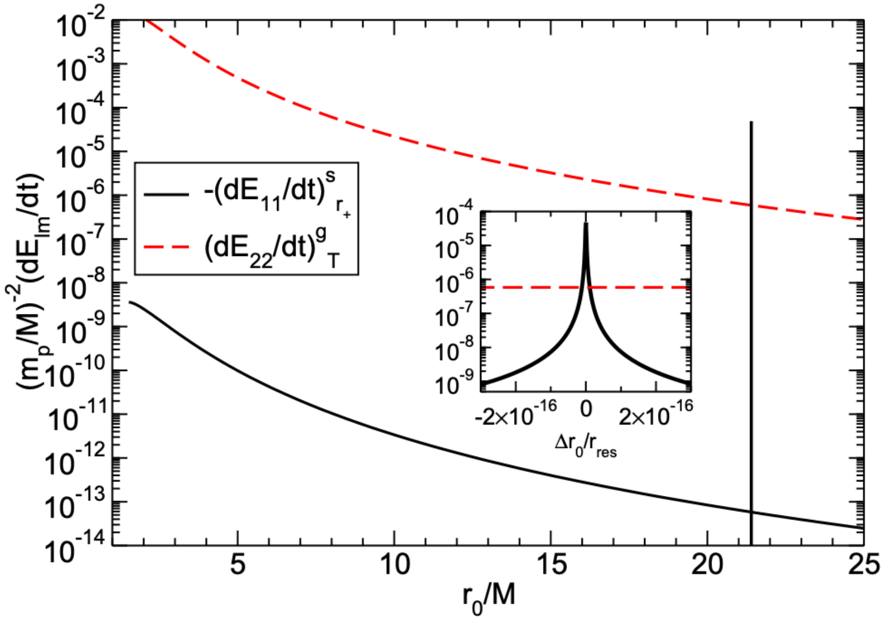
Cardoso, Chakrabarti, Pani, Berti, Gualtieri '11

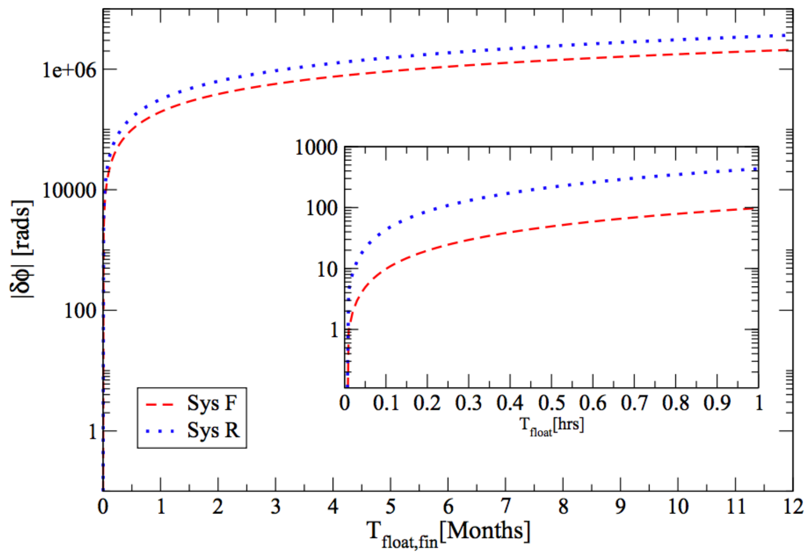


$$\left[\Box - \mu_s^2\right] \varphi = \alpha \mathcal{T}$$

$$\omega_{\rm res}^2 = \mu_s^2 - \mu_s^2 \left(\frac{\mu_s M}{l+1+n}\right)^2$$

$$dE_{\rm orb}/dt = -\left(\dot{E}_{\rm S} + \dot{E}_{\rm GW}\right)$$





- ❖ Excitation of massive scalar QNMs can lead to resonances during inspiral.
- ❖ Superradiant energy extraction can compensate GW emission.
- ❖ Survives for eccentric orbits.

(Fujita and Cardoso '17)

From: Yunes, Pani & Cardoso arXiv:1112.3351

Massive bosonic fields around BHs (within GR)

Damour '76; Detweiler '80; Dolan '07; Pani *et al* '12; RB, Cardoso & Pani '13; Frolov, Krtous, Kubizňák & Santos '18, Dolan '18...

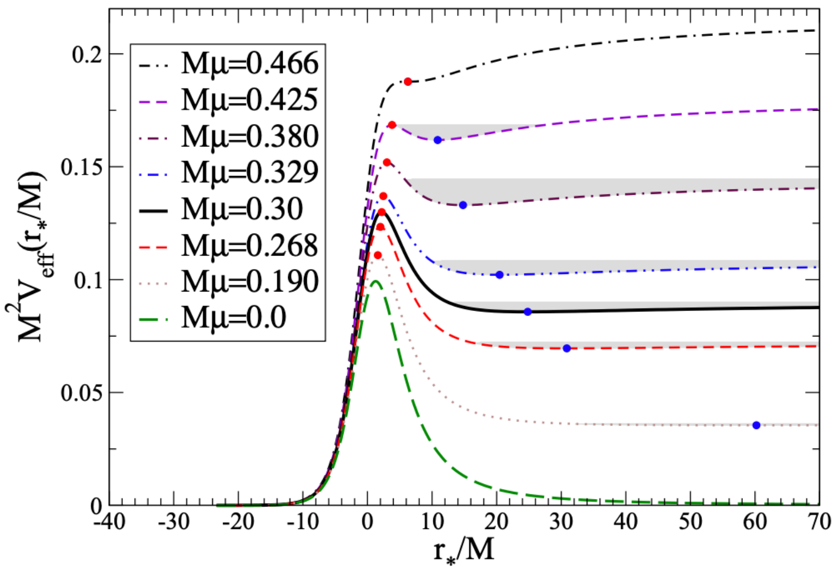
The Yukawa potential of a **massive bosonic field** confines low-frequency waves with $\omega < \mu$ that can satisfy the condition $\omega < m\Omega_H$.

$$\Box\Phi - \mu^2\Phi = 0 \quad \text{with} \quad \mu = \lambda^{-1}$$

$$\Phi(t, r, \theta, \phi) = \sum_{jm} e^{-i\omega t}\frac{\phi(r)}{r}Y_{jm}(\theta, \phi)$$

$$\frac{d^2\phi}{dr_*^2} + V_{\rm eff}\phi = 0$$

$$\omega = \omega_{njm} + i\Gamma_{njm}$$



From: Barranco et al' *11*

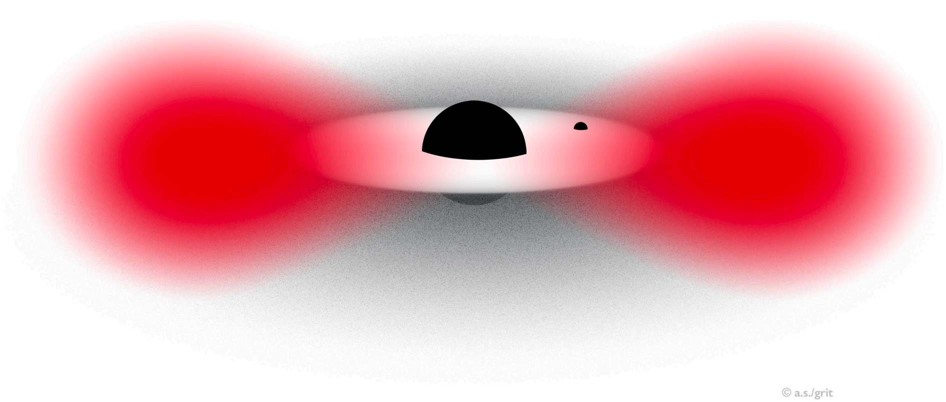
$$\omega_{n\ell m} \simeq \mu\left(1 - \frac{(M\mu)^2}{2(j+n+1)^2}\right)$$

$$\Gamma_{njm} \propto (M\mu)^{4j+5}\left(m\Omega_H - \omega_{njm}\right)$$

- Black hole slowly loses spin and mass until it reaches saturation $\omega_{njm} = m\Omega_H$ (analogous to "tidal locking"). [e.g. RB, Cardoso & Pani '15; East'18; East & Pretorius, '17]
- Can lead to formation of long-lived boson "clouds" around rotating BHs.

An idea to detect boson clouds with EMRIs

Hannuksela, Wong, RB, Berti, Li ’18

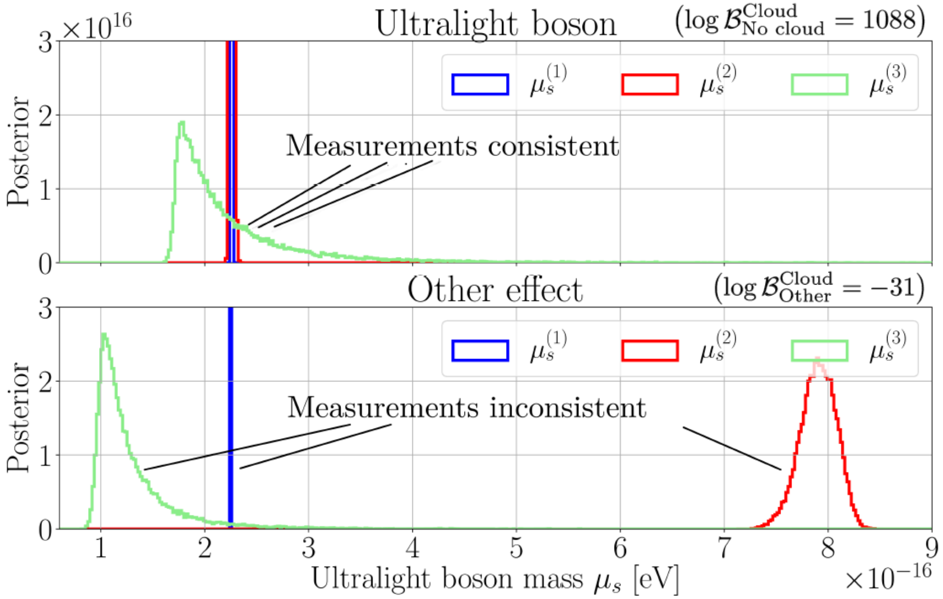


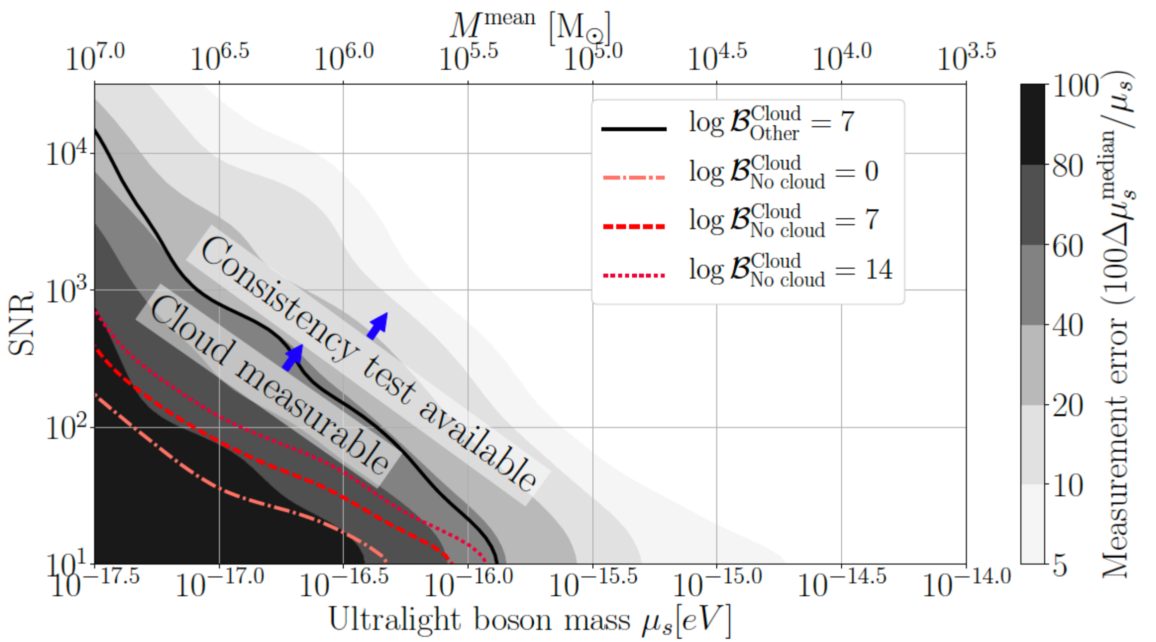
$$\Phi_b(r) \simeq A^2 e^{-Br} F(M, r, B)$$

(i) $$\mu_s^{(1)} \simeq \frac{a}{2Mr_+}$$

(ii) $$\mu_s^{(2)} = (M/B)^{-1/2}$$

(iii) $$\mu_s^{(3)} \simeq 2\left[\frac{\pi A^2}{MM_s}\left(\sqrt{1+\frac{2M_s}{A^2 M\pi}}-1\right)\right]^{1/2}$$





LISA Science Group: Working Package 1.2

WP1.2 Provide EMRI waveforms (priority 2 -- 5 years)

- Overall lead - Leor Barack
- 1.2.1 Theory of self-force in GR - Adam Pound
  - Proposed projects: https://tinyurl.com/ybsul6vs
- 1.2.2 Implementation/numerics/waveforms - Niels Warburton
  - Proposed projects: https://tinyurl.com/y9qt4jjh
  - How the 1.2.1 and 1.2.2 projects interact: https://tinyurl.com/y84qxw6f
- 1.2.3 non-GR signatures in EMRIs - Richard Brito
  - Proposed projects: https://tinyurl.com/y283dnma

- sub-WP 1.2.3 also includes projects on "environmental signatures in EMRIs"
- If interested in contributing contact me at: richard.brito@roma1.infn.it

Final Remarks

- EMRIs will likely be able to test the Kerr black hole hypothesis with a very high precision and are likely the best source to do so (together with measurements of QNMs).

- Constraints dependent on having accurate waveforms models within GR and assume that environmental effects are not a problem.

- Building non-GR waveforms highly non-trivial, but studying some test-case theories useful to gain insight for the best parameterisations to use for theory-agnostic tests.

- Are current proposed parameterised tests (e.g. bumpy BHs) enough to detect deviations? Perhaps yes, but might be hard to map constraints/ detections to specific theories.

- Resonances, floating orbits, presence of boson clouds could lead to large deviations from vacuum GR BHs. Might we entirely miss them if such sources exist?