Non-GR challenges

Panel: Laura Bernard, Katy Clough, Paolo Pani

What is “Non GR”?

(everything NOT included in standard GR waveform templates)

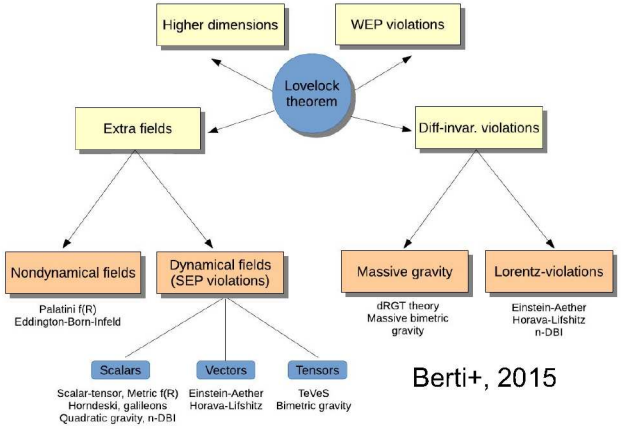
- **Modified Gravity - GR as an effective theory**

But also widely interpreted as...

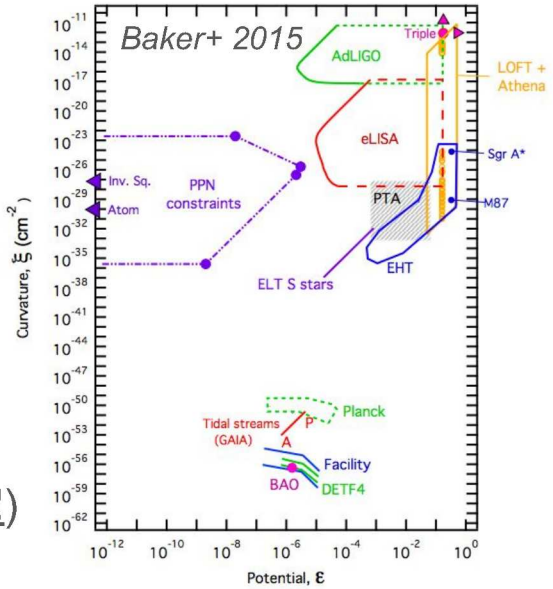
- **Beyond Standard Model particles, e.g Dark Matter**
  - Ultralight bosons (e.g. axions, fuzzy DM, dark photons…)
  - Primordial BHs
  - Dark Matter environments
- **Exotic Compact objects** **(in GR and beyond)**
  - Boson stars
  - Horizonless ultracompact objects
- **Environmental effects?**
  - Accretion, disks, gravitational pull, dynamical friction, planetary migration

Motivation

- **Why testing GR?**
  - Because now we can better than ever
  - Outstanding problems in foundational physics:
    - *The nature of gravity*
    - *The nature of dark matter*
    - *The nature of dark energy*
    - *The nature of supermassive compact objects*



Berti+, 2015



- **Why testing GR *with LISA* *(after LIGO)*?**
  - New scale(s) and regime(s) to probe
  - Unique sources (e.g. EMRIs)
  - Unparalleled precision tests (require accurate modelling!)

FP WG on-going work: The Matrix

The goal of this document is to come up with a classification of the sub-items that will be studied within the LISA Fundamental Physics Working group. There is clearly a very large number of ways to classify this work, so we have here made a choice based on current research interests. This choice classifies interests based on 2 dimensions (type of fundamental physics and source used). Ideally, different members of the working group will populate the cells of this table, with one or two people identified per cell as "captains" of the respective topic. Members of the working group are encouraged to opulate multiple cells of the table.

Fundamental Physics / Source Type	Modified Dispersion Relations and the Speed of Gravity	Violations of the Equivalence Principle and Fundamental Symmetries	Tests of the Nature of Black Holes	Dark Energy Candidates and Screening	Dark Matter Candidates and Primordial Black Holes	Other Model Independent Tests	Stacking and Astrophysical Systematics	Waveform Systematics
SMBH Binaries								
EMRIs and IMRIs								
Multi-Band Sources								
Galactic Binaries								
Stochastic Backgrounds								

Notes:

The classification above implicitly assumes that one work on theoretical development, waveform generation or data analysis within any of these topics.
"Tests of the Nature of Black Holes" includes ringdown "no-hair" tests, quadrupolar deformation tests and chaos tests
"Tests with tidal deformabilities" can be included in the "Tests of the Nature of BHs" column
"Violations of Equivalence Principle, etc" can include theories like EdGB or quadratic gravity, as well as theories that have Kerr as a solution but with other degrees of freedom that modify the dissipative sector.
"Astrophysical Systematics" and "Waveform Systematics" are about how astrophysical effects or incorrect modeling of GR waveforms can impact test GR
"Astrophysical Systematics" also includes stacking ideas
"Other model-independent tests" includes things like residual tests, tests of waveform consistency, and ppE tests
"Violations of Fundamental Symmetries" includes violations of gravitational parity and violations of Lorentz symmetry and other violations of SEP
"Tests of the BH Nature" incldues tests of the Kerr hypothesis, sesarch for ECOs and echoes
"Dark Energy Candidates and Screening" includes massive gravity, and other Horndeski theories
"Cosmic strings" is already included in another cosmology work-package.
"Primordial BHs" is probably also already in another cosmology work-package, also they would already be under SMBHs or as EMRIs or as other Multi-band sources (a small mass BH wouldn't be visible in LISA, unless it's an EMRI)

https://goo.gl/gK3j2p

- ***Source-driven members* VS *phenomenon-driven* members**

FP WG on-going work: “Manifesto”*

FP WG Chairs: Hertog, Jetzer, Yunes

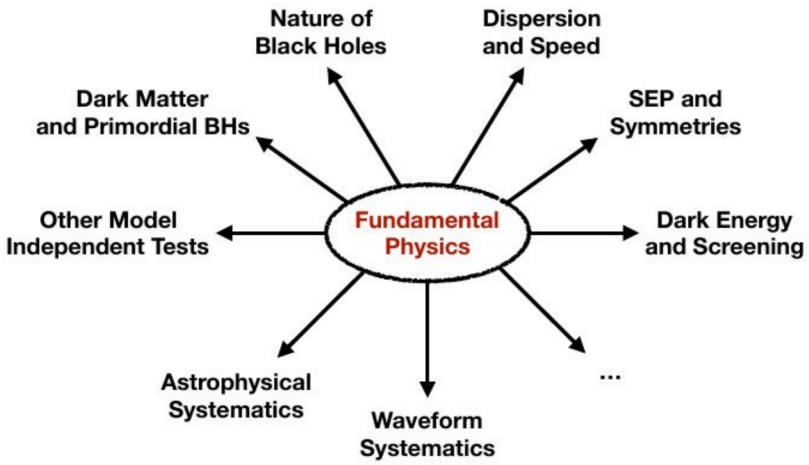


FIG. 1. Science-first organization of the current activities in the Fundamental Physics working group. Each of these topics will constitute a section in the rest of this document. The ellipses stand for topics that may be added in the future.

- Some overlap and complementary with *CosmoWG*, *AstroWG, WavWG*
- Some topics require interactions with **WP1**, **WP5**, **WP8**

** Wait...isn’t this yet another White Paper? Probably YES...*

Sources & Challenges in non-GR modelling #1

1. **MBHBs** [WP 1.3.3]
   - Basic ingredients can be ported from LIGO waveforms, **but** more stringent accuracy requirements, eccentricity, mass ratio, spins, etc..
   - **Inspiral:** PN corrections worked out only for few theories
   - **Merger:** urgent need of simulations in well-motivated extensions of GR and exotic binaries
   - **Ringdown**: Lack of a generic framework, Poor constraints for the (most interesting?) theories [Gauss-Bonnet, Chern-Simons, EFT], role of the overtones? Extra modes
   - **Echoes**: Several developments, but better modeling of echoes waveforms needed [WP1]
   - **IMR approximants**: EOB / phenom models beyond GR
2. **EMRIs & IMRIs** [WP 1.2.3]
   - Open issues in modelling already in GR
   - Corrections both to the **multipolar structure** and the **dynamics (fluxes)**
   - More effects: e.g. **resonances, floating orbits, non-integrable orbits, chaos**
   - Bounds using phenomenological kludge models→ enough for exploratory studies?

Sources & Challenges in non-GR modelling #2

1. **SOBHBs**
   - Promising for *negative-PN corrections* (e.g. dipole, env effects, etc)
2. **Stochastic background**
   - PBHs
   - Boson-BH condensates
   - ECOs
3. **Nearly-continuous sources**
   - Galactic binaries white dwarfs / neutron stars (dipole radiation)
   - Boson-BH condensates from superradiance (direct detection, mass-spin distribution, follow-up searches, stochastich bkg, effects in EMRIs

Parametrized vs specific

- Parametrized deviations from GR

$$h(f) = \mathcal{A}(f)\, e^{i\, p(f)(1+\delta\hat{p}(f))}$$

  - Constrain PN terms order by order
- Pros
  - Generic: most theories encoded
  - Fast
- Cons
  - Hard to translate into constraints on a theory
  - Degeneracies between PN orders, parameters
  - Do not track new, non perturbative effects

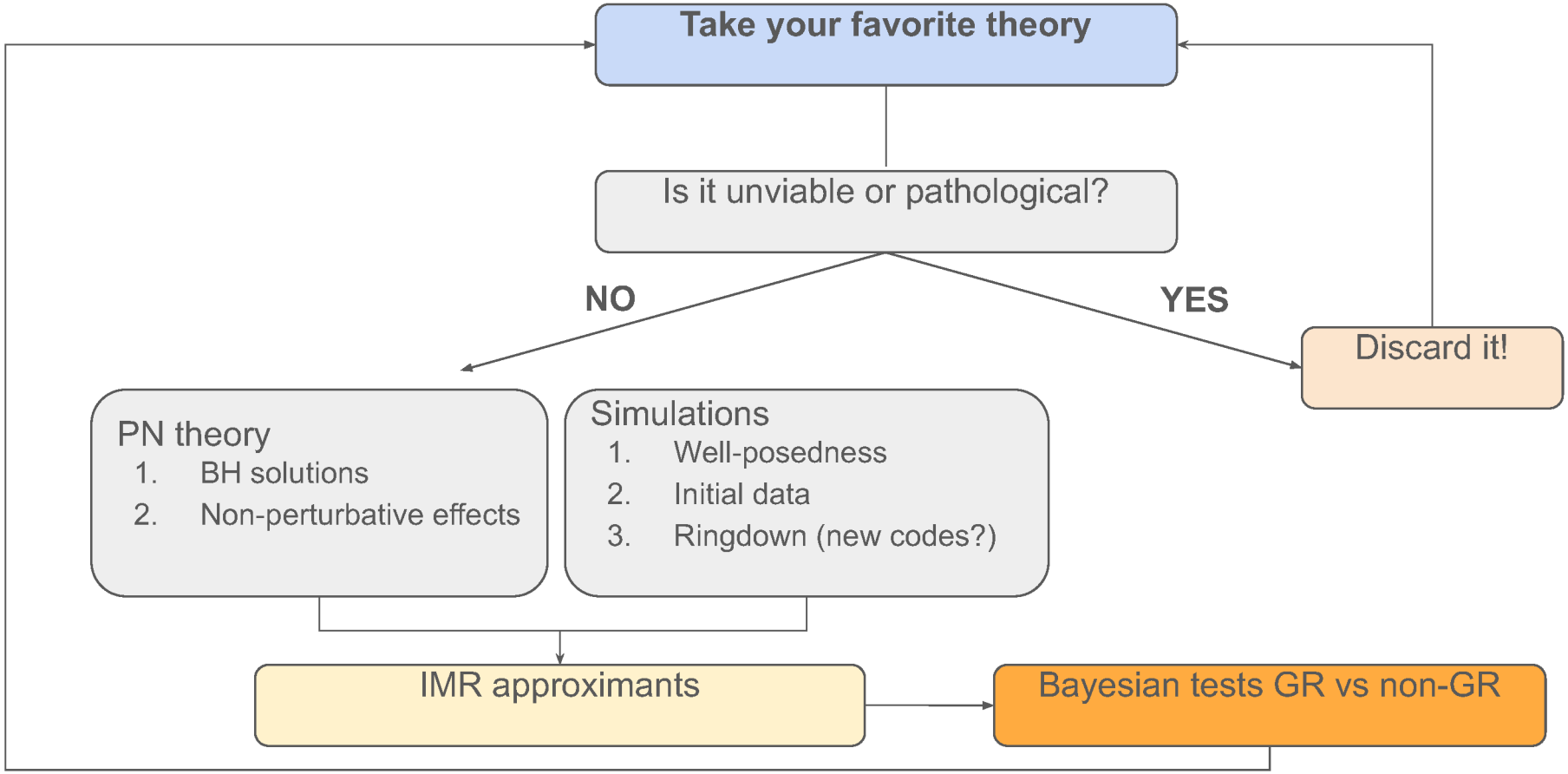
- Build complete IMR waveform templates for a specific theory
  - To be match-filtered against the data
- Pros
  - Directly relates to the parameters of the theory
  - Describes all and new effects
- Cons
  - Time-consuming: PN + NR simulations
  - There are too many theories

➔ Following a mixed approach is the solution

Non-GR Challenges in NR

- Need NR for merger phase
- Need a specific MG model for NR simulations
- Well-posedness of the model
- Many possible models and parameters
- Time consuming to modify and test new code, and run it
- Lack of expertise (and interest!) in turning results into usable waveforms
- Boson-star binaries more advanced but still not systematically studied
- For (most of) other ECOs → lack of a first-principle framework

Roadmap for testing a “golden” modified gravity theory



Discussion topics

- **Beyond GR coalescences:** progress in some EFT, waveforms? Beyond EFT?
- **ECO coalescences:** IMR waveforms for boson stars? Other ECOs? [short-blanket problem]
- **Echoes:** improve current templates; other approaches? [bursts, resonances]
- **EMRIs:** Current projected bounds too optimistic? [simplistic waveforms, enchilada problem]
- **EMRIs: 1 radiant requirement**: enough for PE? And for tests of GR? Prescription?
- **EMRIs:** Quadrupolar and tidal corrections beyond PN modelling? Or is enough?
- **Tides in MBHBs:** LISA can constrain Λ for ECOs (~LIGO with NSs) [probing Planck?]
- **Ringdown**: general framework, role of overtones, extra modes (~new polarization)
- **Axion-like particles & superradiance:** vectors? Tensors? Porting pipeline from LIGO?
- **DM environment:** waveforms?
- **PBHs:** interaction with CosmoWG

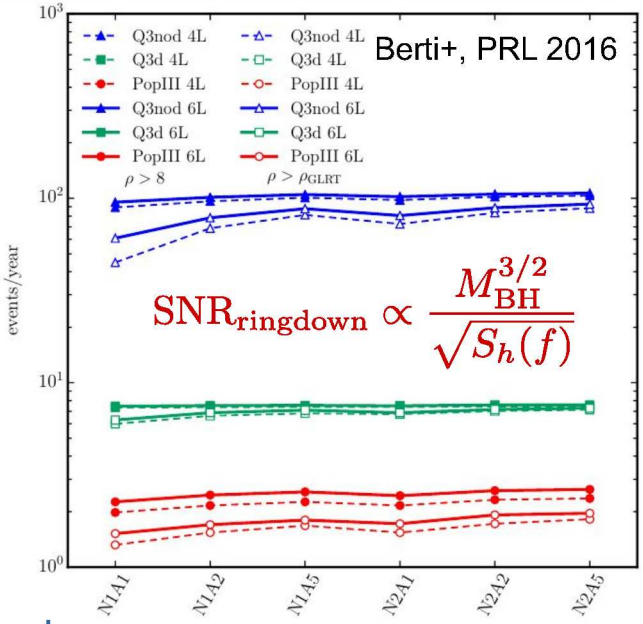
Backup slides

No-hair tests: ringdown

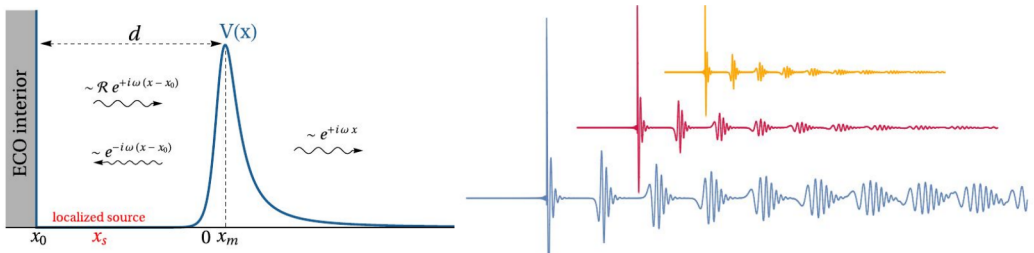
- **Kerr QNMs depend only on mass and spin:**

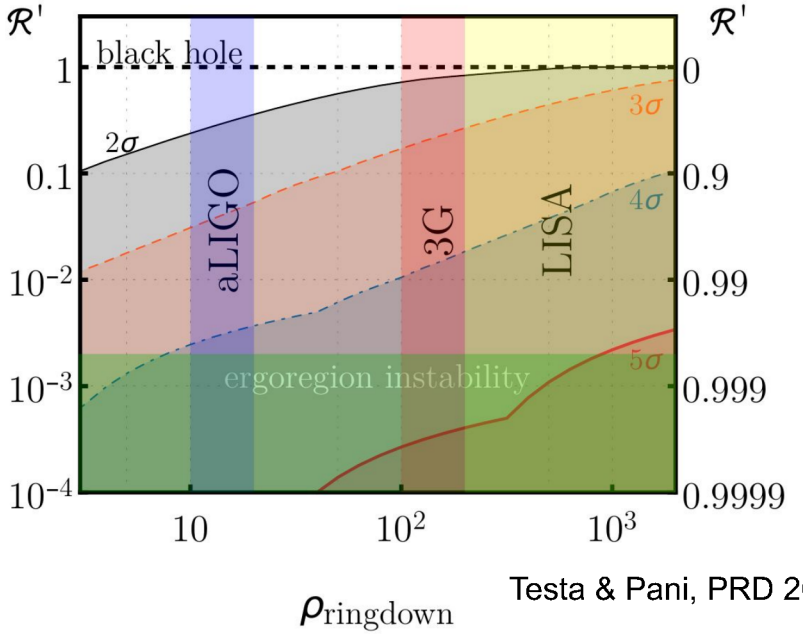
$$\omega = \omega^{\rm Kerr}(\chi) + \delta\omega$$
$$\tau = \tau^{\rm Kerr}(\chi) + \delta\tau$$

- **Smoking guns of beyond-GR effects:**
  - Mode shift
  - New QNMs
  - Isospectrality breaking
- **Pros**
  - SNR favors SMBHs → LISA is unparalleled
  - large event rates, independent tests with multiple modes
- **Cons:**
  - Poor constraints for the (most interesting?) theories [Gauss-Bonnet, Chern-Simons, EFT]
  - Lack of a generic framework [**WP1**] [Barausse+ PRD 2014, Tattersall+; PRD 2018, Cardoso+, 1901.01265, ...]



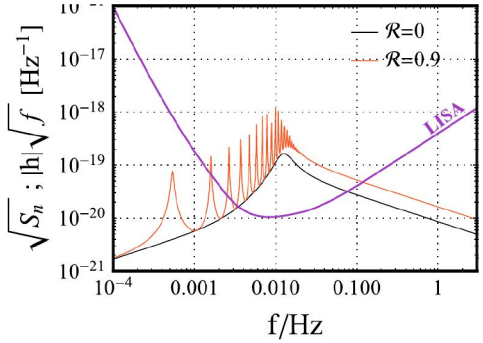
GW echoes: detectability with LISA





Testa & Pani, PRD 2018

•d=100 M, M=10^6 Msun, D=100 Gpc

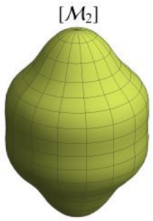


- Echoes might be louder than ringdown, signal strongly depends on reflectivity
- Several developments, but better modeling of echoes waveforms needed [WP1]

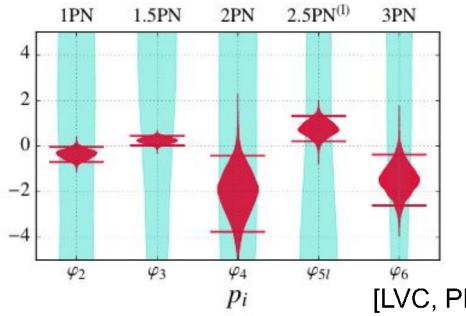
No-hair tests: multipole moments

- **Mass quadrupole moment (M_2) easier to constrain**

$$\bar{M}_2 = -\chi^2 + \delta\bar{M}_2(\chi, \text{coupling})$$



- Comparable-mass inspirals:
  - quadrupole enters at 2PN $\rightarrow \delta\bar{M}_2 \lesssim 0.2$
  - Factor ~20 better with LISA or 3G [Krishnendu+ PRL 2017]
  - Requires highly-spinning BHs (favors LISA?)
  - Complementary to tests of dipolar emission

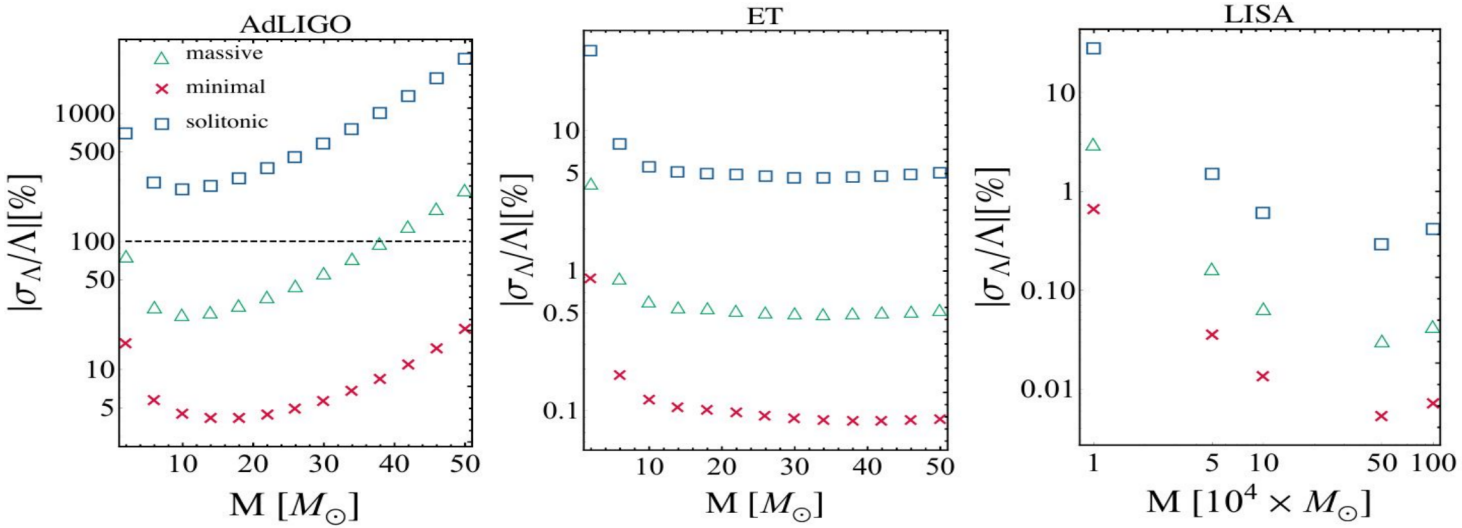


[LVC, PRL 2017]

- EMRIs:
  - Probe both the multipolar structure and the dynamics (fluxes)
  - More effects: e.g. resonances, floating orbits [Cardoso+, PRL 2011], non-integrable orbits, chaos [Cárdenas-Avendaño+ CQG 2018]
  - Bounds using a phenomenological model [Babak+ PRD 2017] $\rightarrow \delta\bar{M}_2 \lesssim 10^{-4}$
  - Something to discuss: current projected bounds with EMRIs too optmistic? [simplistic waveforms, isolated source in band, enchilada problem] [**WP1, WP5**]

BH/NS vs Boson Stars: Love numbers

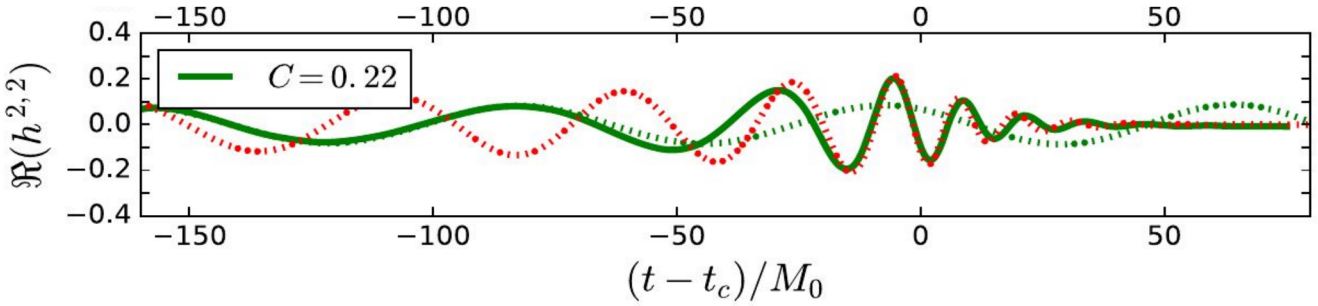
$$\mathcal{L} = \frac{R}{16\pi G} - \partial_\mu \phi \, \partial^\mu \phi^\star - m^2 |\phi|^2 + \lambda |\phi|^4 + \gamma |\phi|^6 + \ldots$$



- aLIGO can exclude only BS vs BH models with relatively small compactness [Cardoso+ (2017), Sennet+ PRD 96 024002 (2017), Johnson-McDaniel+, 1804.08026]
- 3G & LISA will be able to distinguish BHs vs *any* BS model

BBSs or BBHs?

•Can BBSs mimick the full signal from BBH coalescence?

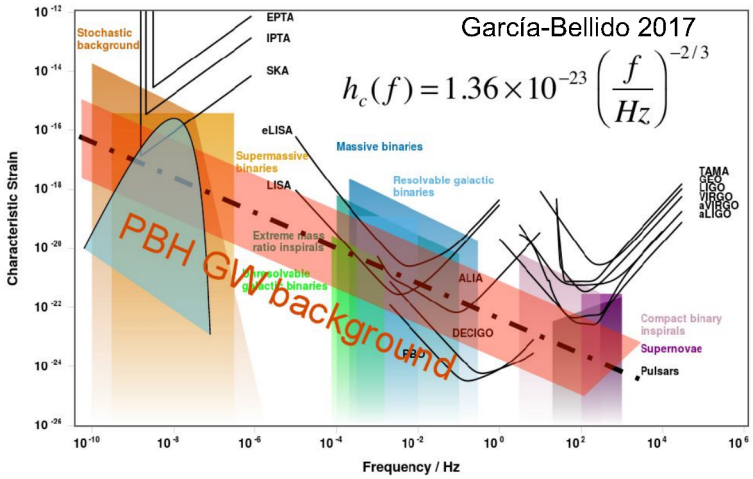


[Palenzula, PP+, PRD96, 104058 (2017)]

•"Short-blancket" problem: mimicking IMR signal of BBHs is hard

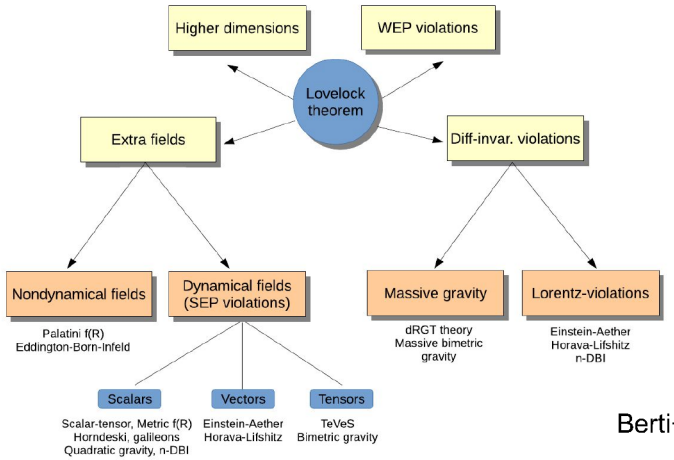
Dark matter & primordial BHs

- Ultralight bosons (e.g., axions) trigger superradiant instabilities in spinning BHs [Arvanitaki+, 2012-2014, Brito, Cardoso, Pani, "Superradiance" 2015]
  - Highly-spinning BHs are disfavored ("gaps in the BH Regge plane")
  - GWs from boson condensate
  - Modified inspiral dynamics due to self-gravity, accretion, dyn. friction [Macedo+ 2013, Hannuksela+ 2019]
- Primordial BHs
  - Stochastic bkg from recomb.
  - Stochastic bkg from coalesc.
  - EMRIs?
- Other DM candidates for LISA?



Violation of SEP & of fundamental symmetries

- **Lovelock theorem:** route to modify GR
- Generic effect: **Extra degrees of freedom**
  - Extra polarizations (es. dipole)
  - Corrections to inspiral, EMRIs
  - Extra QNMs
- Typically: **modified BH solutions**
- Model-dependent effects:
  - Parity violations → birefringence
  - Lorentz violations → aether
  - Diffeormophism violations → reference metric
  - Massive gravity → 5 polarizations
- Careful with suppression of corrections for SMBHs & EMRIs



Berti+, 2015

Violation of SEP & of fundamental symmetries

Chamberlain & Yunes, PRD 2017

GR Deviation	PN	Parameter	Best Space Const.	Best Ground Const.	Current Const.	Best Space Sys.	Best Ground Sys.
Dipole Radiation	-1	β	4.9×10^{-12}	1.9×10^{-10}	4.4×10^{-5}	EMRI	NSNS
		$\delta\dot{E}_{\rm Dip}$	7.8×10^{-8}	3.2×10^{-8}	1.8×10^{-3}	EMRI/GW150914	NSNS
Large Extra-Dimension	-4	β	2.2×10^{-22}	6.4×10^{-20}	9.1×10^{-11}	EMRI	NSNS
		ℓ $[\mu m]$	3.0×10^{2}	7.5×10^{4}	$10 - 10^{3}$ [28–32]	EMRI/GW150914	BHBH
Time-Varying G	-4	β	2.2×10^{-22}	6.4×10^{-20}	9.1×10^{-11}	EMRI	NSNS
		$\dot{G}$ $[1/yr]$	6.8×10^{-8}	1.1×10^{-3}	$10^{-12} - 10^{-13}$ [33–37]	EMRI	NSNS
Einstein-Æther Theory	0	β	4.0×10^{-8}	6.7×10^{-5}	3.4×10^{-3}	EMRI	ℓBHNS
		(c_+, c_-)	$(10^{-3}, 3 \times 10^{-4})$	$(10^{-2}, 4 \times 10^{-3})$	$(0.03, 0.003)$ [38, 39]	EMRI	NSNS
Khronometric Gravity	0	β	4.0×10^{-8}	6.7×10^{-5}	3.4×10^{-3}	EMRI	ℓBHNS
		$(\beta_{\rm KG}, \lambda_{\rm KG})$	$(10^{-4}, 10^{-2})/2$	$(10^{-2}, 10^{-1})/5$	$(10^{-2}, 10^{-1})/2$ [38, 39]	EMRI	GW150914
Graviton Mass	+1	β	4.3×10^{-5}	1.0×10^{-3}	8.9×10^{-2}	EMRI/IMBH	ℓBHBH
		m_g $[eV]$	9.0×10^{-28}	9.9×10^{-25}	$10^{-29} - 10^{-18}$ [40–44]	SMBH/IMRI	GW150914

TABLE I. Table summary of the best constraints on a variety of modified gravity modifications, listed in the first column. The second column indicates the PN order at which the modification first enters the gravitational wave phase. The third column labels the parameters that can be constrained. The fourth (fifth) column shows the best projected constraint achievable with a space-based (ground-based) detectors, which is to be compared with current constraints on β (listed as the best constraint obtained with either of the GW150914 or GW151226 detections), and with current constraints on theory parameters as given by the most stringent of either aLIGO *or* other observations. The last two columns show the class of the system that lead to the best constraint. Constraints on Einstein-Æther/khronometric Gravity are given as rough constraints on $(c_+, c_-)/(\beta_{\rm KG}, \lambda_{\rm KG})$ (for the contours, see Figs. 8 and 9).

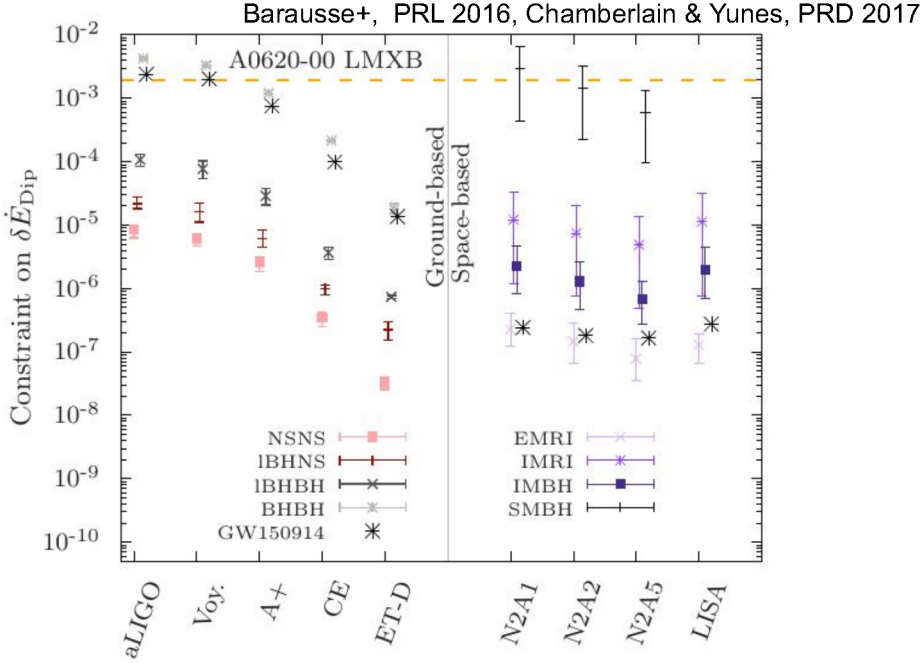
- Note: some projected constraints are less stringent than current bounds

Violation of SEP & of fundamental symmetries

Constraints on dipole radiation

$$\dot{E}_{\rm GW} = \dot{E}_{\rm GR}\left[1 + B\left(\frac{Gm}{r_{12}c^2}\right)^{-1}\right]$$

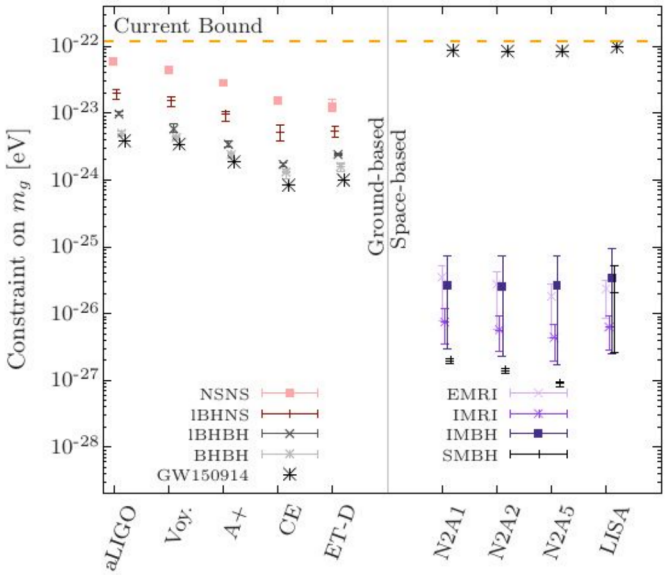
Barausse+, PRL 2016, Chamberlain & Yunes, PRD 2017

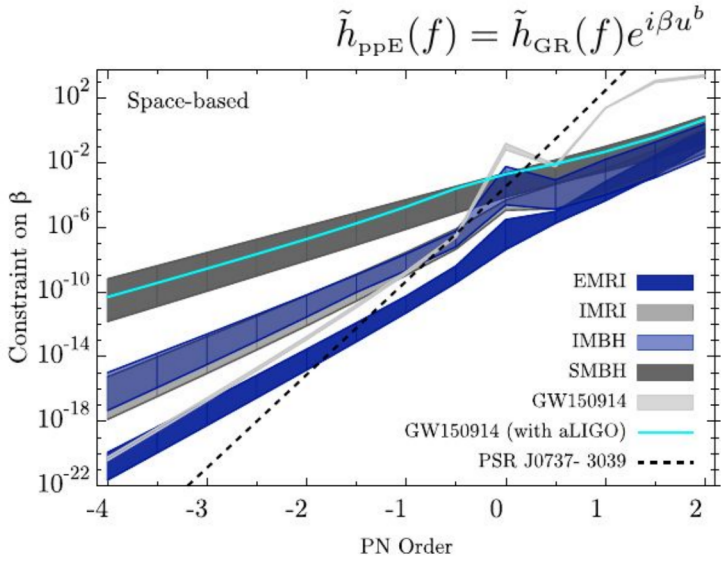


Modified dispersion relations

Chamberlain & Yunes, PRD 2017

$$\omega^2 = k_i k^i + \frac{m_g^2}{\hbar^2} + A(k_i k^i)^\alpha$$

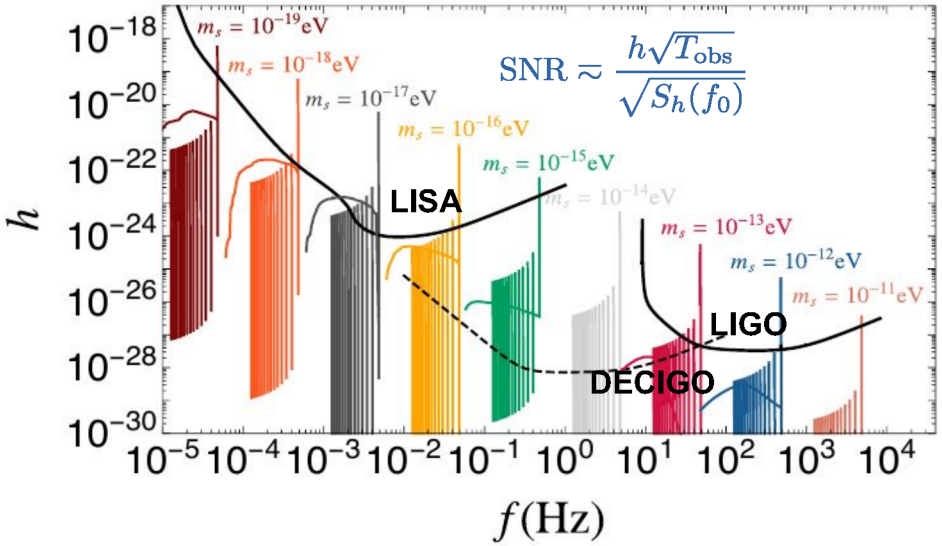




- Bounds on ppE parameters can be mapped to bounds on dispersion relation and to specific models (SME, massive gravity, Horava-Lifshitz, DSR, extra dim...)

GW periodic signal from axions

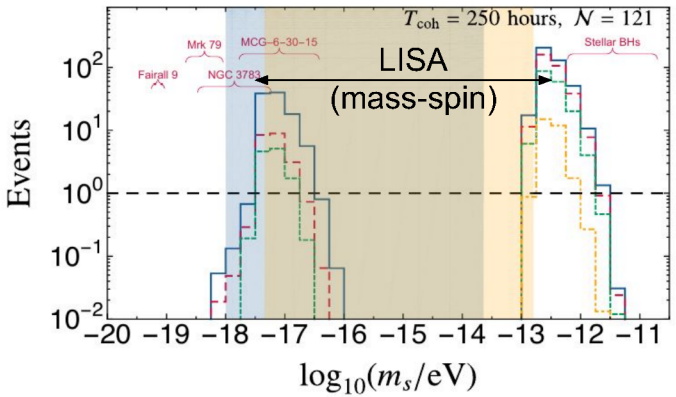
Brito+, PRL 2017, PRD 2017



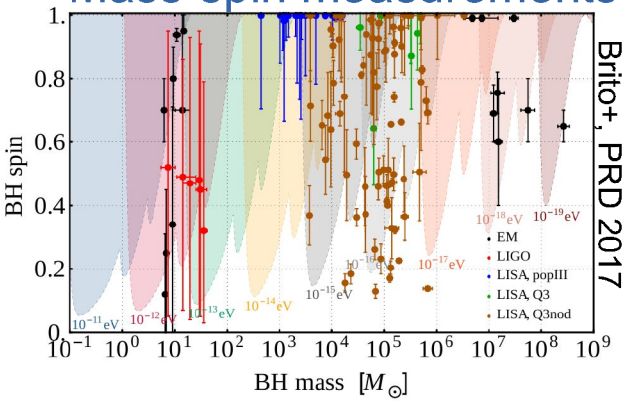
Multiband GW constraints on ultralight fields

GW signatures of axions

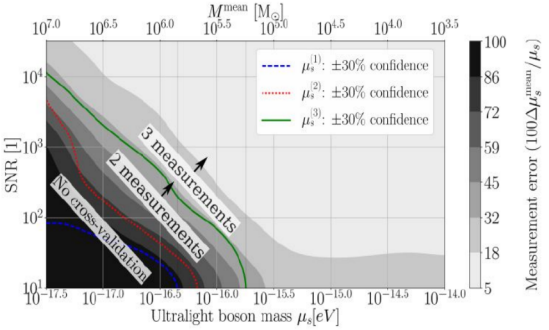
- Direct detection



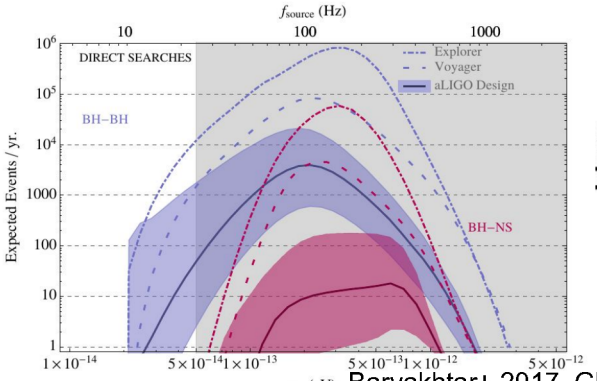
- Mass-spin measurements



EMRIs & resonances



- Follow-up searches



Baryakhtar+ 2017, Ghosh+, 2018

- Stochastic background from ALPs