What is “Non GR” in Extreme Gravity?

“Within-GR” Extreme Gravity: interesting GR effects, esp. beyond-leading order.

“Non-GR” Extreme Gravity: *(everything NOT included in standard GR waveform templates, esp. strong-field tests)*

- **Modified Gravity - The nature of gravity (EXG 2, Tuesday)**
  But also widely interpreted as…

- **Beyond Standard Model particles, e.g Dark Matter (EXG 1, Wednesday)**
  - Ultralight bosons (e.g. axions, fuzzy DM, dark photons…)
  - Primordial BHs
- **Exotic Compact objects (in GR and beyond) (EXG 1, Wednesday)**
  - Boson stars
  - Horizonless ultracompact objects
- **Environmental effects? (EXG X?)**
  - Accretion, disks, gravitational pull, dynamical friction, planetary migration

EXG 2:
The nature of gravity

EXG 2 Discussion: the nature of gravity

- What developments in modified gravity theory are needed? (PN, NR, …)
  - **Beyond GR coalescences:** progress in some EFT, waveforms? Beyond EFT?
  - **EOB beyond GR**
  - What mass ratios needed for 3G?
- What developments in GR waveforms are needed to probe "extreme gravity"? (See also WFM session.)
- **GR signatures:** higher modes, tails, memory, eccentricity, ... (others?)...
- What are **key science targets** with respect to extreme gravity for O4/A+ and 3G?
- What are the **most promising GR alternatives**? Can physically-motivated lower-bounds on beyond-GR parameters be determined?

EXG 2 Discussion: the nature of gravity

- **Multipole mapping problem/no-hair tests.** What can be done w/ LISA vs. 3G?
  - **Ringdown**: general framework, role of overtones, extra modes (~new polarization)
  - **EMRIs/IMRIs:** GR waveform improvements needed (self-force, resonance, chaos). Then beyond GR case?
- **Propagation constraints:** dispersion, speed of gravity, birefringence, extra dimensions. Improvements to modeling and analysis?
- **Testing GR data analysis:** event by event vs. combining multiple events?
- Parameterized tests: what is required for deviation to be believed? How to map back deviation to theory constraints?
- Events with EM/neutrino counterparts: how critical for improving mod-grav constraints?
- Multiband events (e.g., LISA + 3G): how critical for improving mod-grav constraints?

EXG 2 Discussion: the nature of gravity

- BH/NS? Heavy BBH? What new features do these contribute to EXG/TGR?
- Extreme gravity contributions from non-CBC sources? [continuous waves (isolated NS, wide binaries), CCSN, cosmic strings, cosmological stochastic background …?)
- Where will tests of GR from other areas (binary pulsar tests, solar system tests, CMB tests, …) compete with 2G/3G constraints? (I.e., where will other experiments provide better constraints?)
- Contamination from astrophysical environment? How important for 3G?
- Dark matter signatures? Where do 3G/GW measurements fit in context of projected future constraints from astrophysics or particle direct detection experiments?

EXG 2: the nature of gravity

- **BBHs**
  - **Inspiral:** PN corrections worked out only for few theories [Yagi+ 2014]
  - **Merger:** urgent need of simulations in well-motivated extensions of GR [Okounkova+ 2017, Witek+ 2019] and exotic binaries [Palenzuela+ 2018]
  - **Ringdown**: Lack of a generic framework to map back, Poor constraints for the (most interesting?) theories [GB, DCS, EFT], role of the overtones? Extra modes
  - **Echoes**: Several developments, but better modeling of echoes waveforms needed (EXG1)
  - **IMR approximants**: EOB / phenom models beyond GR [Julié 2017]
- **Stochastic background**
  - PBHs
  - Boson-BH condensates [Brito+ 2017]
  - ECOs [Barausse+ 2018]
- **Nearly-continuous sources**
    - Galactic binaries white dwarfs / neutron stars (dipole radiation)
    - Boson-BH condensates from superradiance (direct detection, mass-spin distribution, follow-up searches, stochastic bkg, effects in EMRIs

Non-GR Challenges in NR (slide by Katy Clough)

- 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

Backup slides

Parametrized vs specific

- Parametrized deviations from GR

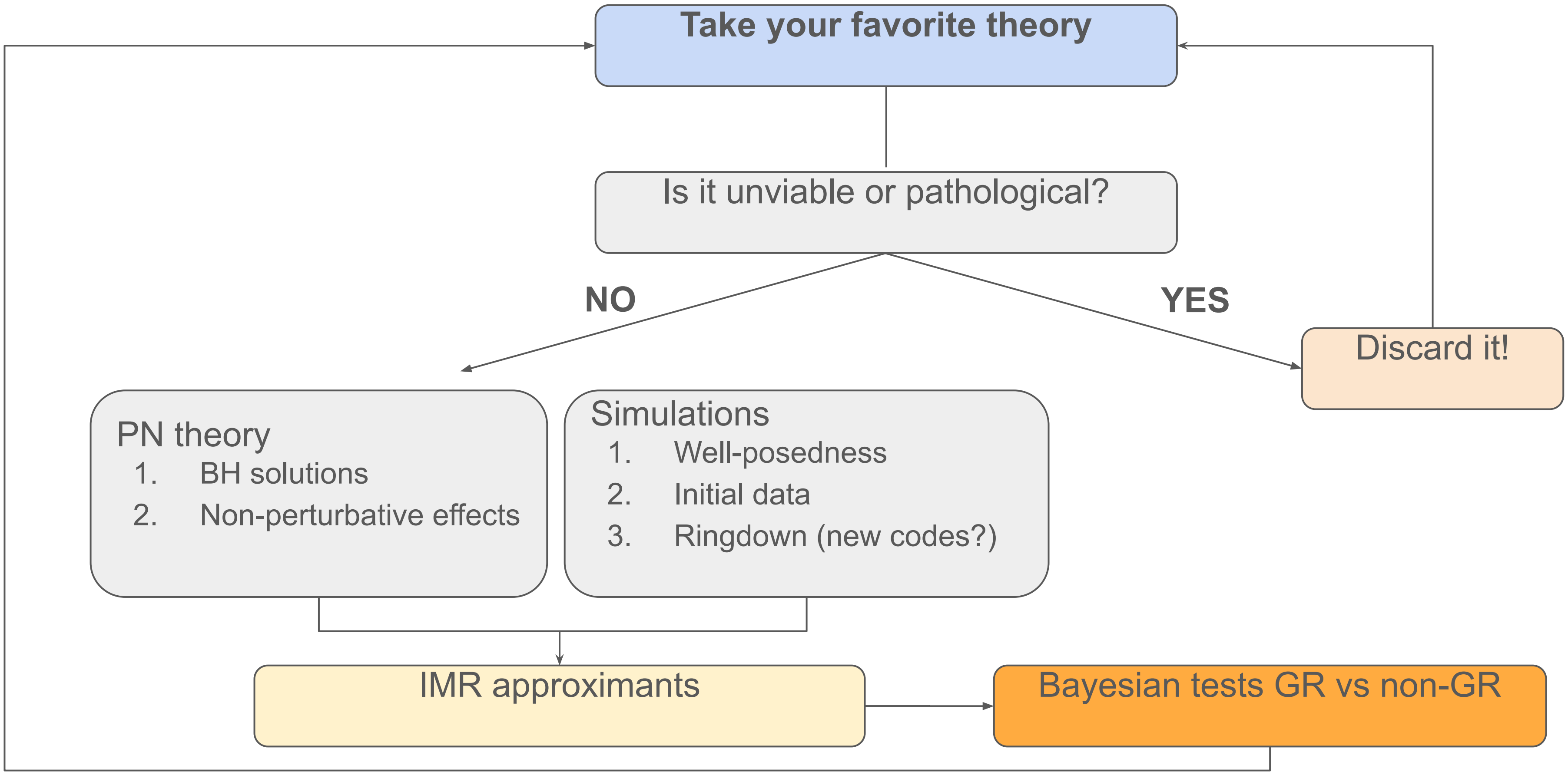
$$h(f) = \mathcal{A}(f)\, \mathrm{e}^{i\, p(f)(1+\delta\hat{p}(f))}$$

  - 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

Roadmap for testing a “golden” modified gravity theory



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 [μm]	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

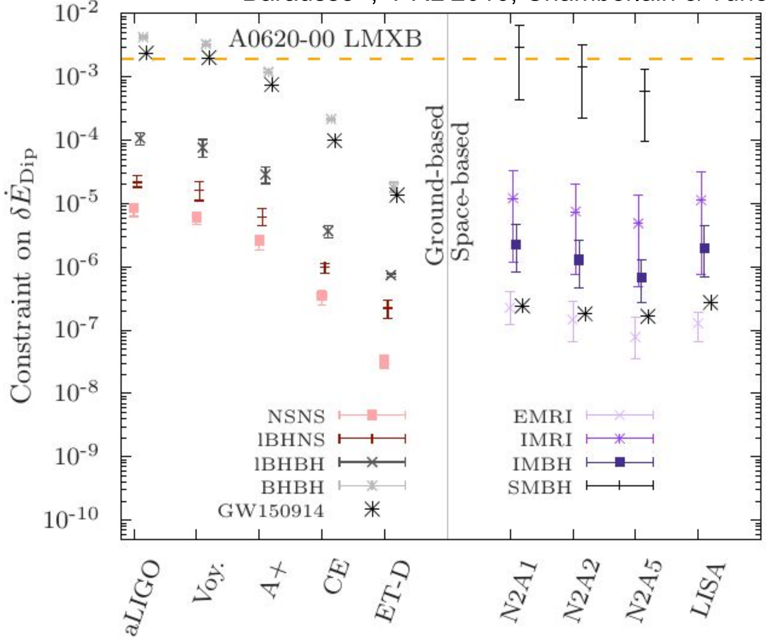
TABLE I. Table summary of the best constraints on a variety of modified gravity modifications, listed in the first column. The second column indicates the PN order at which the modification first enters the gravitational wave phase. The third column labels the parameters that can be constrained. The 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

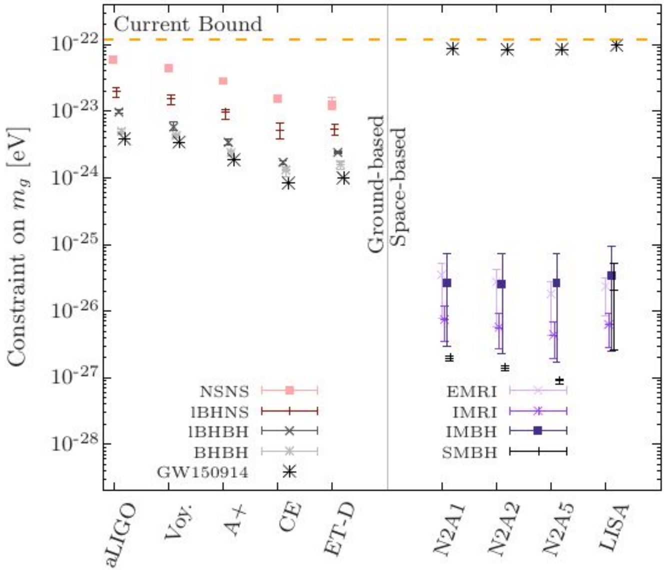
Constraints on dipole radiation

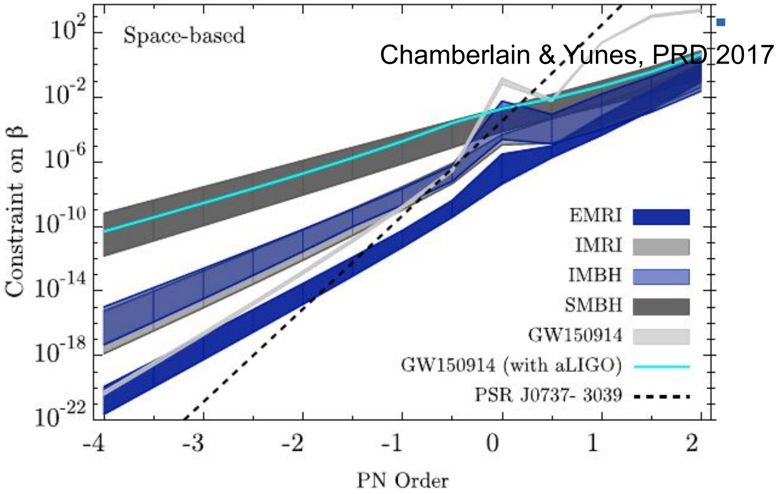
Barausse+, PRL 2016, Chamberlain & Yunes, PRD 2017



Modified dispersion relations

$$\omega^2 = k_i k^i + \frac{m_g^2}{\hbar^2} + \ldots$$





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

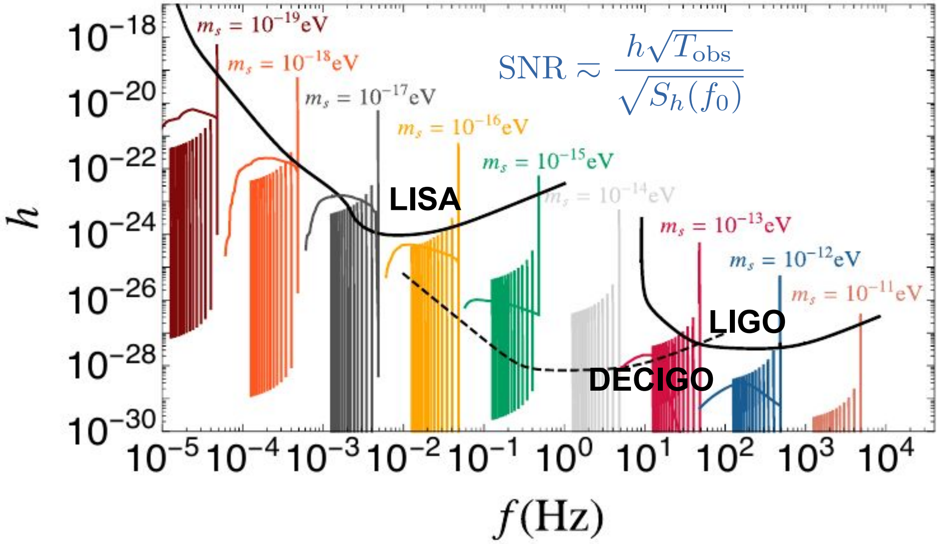
EXG 1:
The nature of compact objects

EXG 1: the nature of compact objects

- **ECO coalescences: [short blanket problem]**
  - **IMR waveforms:** for boson stars? Anisotropic stars? Other ECOs?
  - **Echoes:** improve current templates; other approaches? [bursts, resonances]
- **Axion-like particles & superradiance:** vectors? Tensors?
- **Tidal effects:** should we model them better? (see WFM session)
- **EMRIs?** (different multipoles, no horizon, Love numbers, resonances)
  - Current projected bounds too optimistic? [simplistic waveforms, enchilada problem]
  - 1 radian requirement: enough for PE? And for tests of GR? Prescription?
  - Quadrupolar and tidal corrections beyond PN modelling? Or is enough?
  - Compare bounds on ECOs with those coming from 3G
- **Ringdown**: general framework, role of overtones, extra modes (~new polarization)
- **DM environment:** waveforms?
- **PBHs: ?**

GW periodic signal from axions

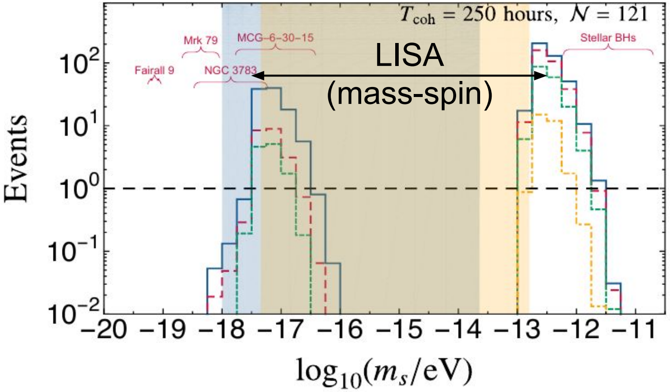
Brito+, PRL 2017, PRD 2017



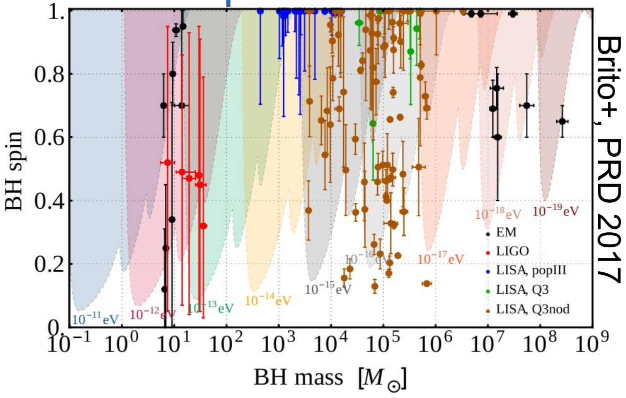
Multiband GW constraints on ultralight fields

GW signatures of axions

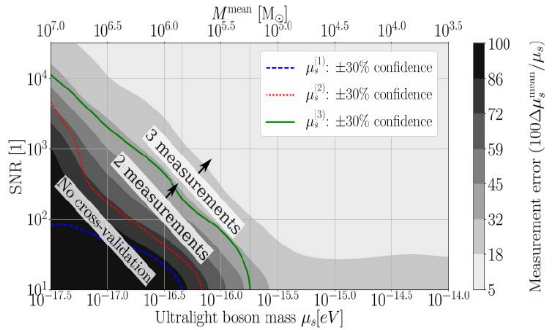
- Direct detection



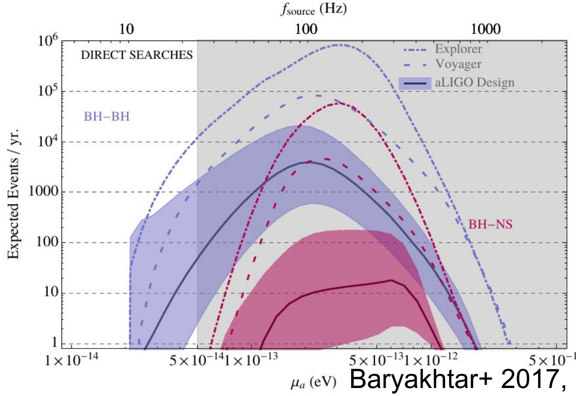
- Mass-spin measurements



EMRIs & resonances

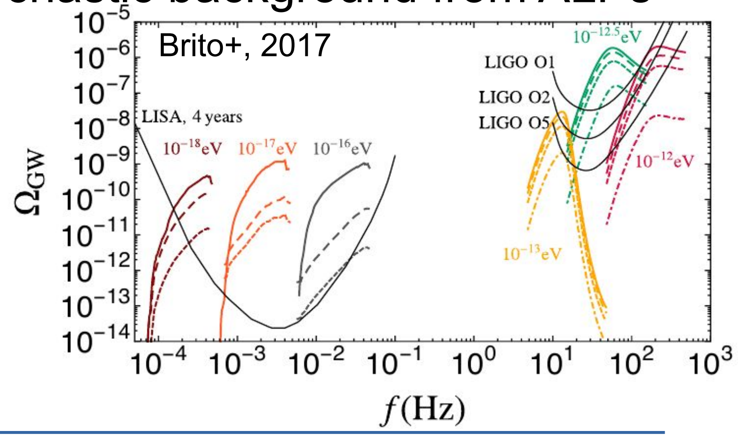


- Follow-up searches



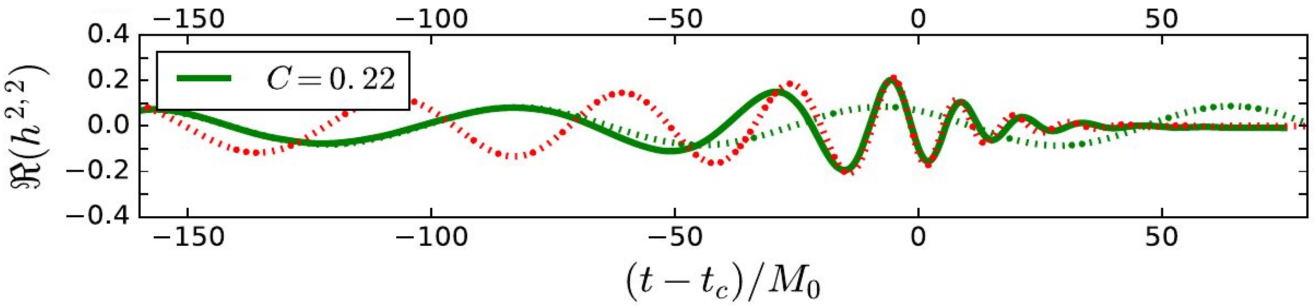
Baryakhtar+ 2017, Ghosh+, 2018

- Stochastic background from ALPs



BBSs or BBHs?

•Can binary boson stars mimic the **full** signal from BBH coalescence?

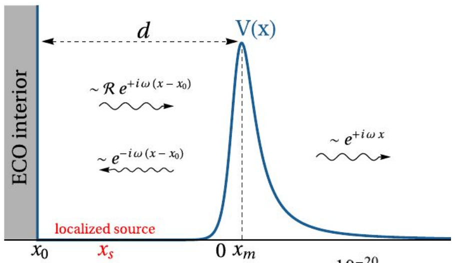


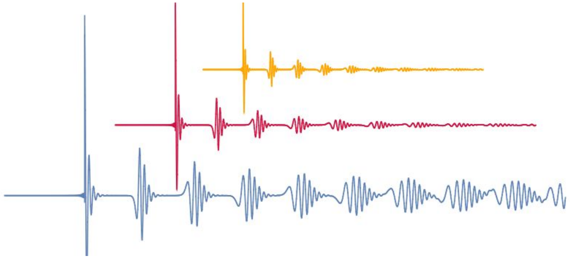
[Palenzula, PP+, PRD96, 104058 (2017)]

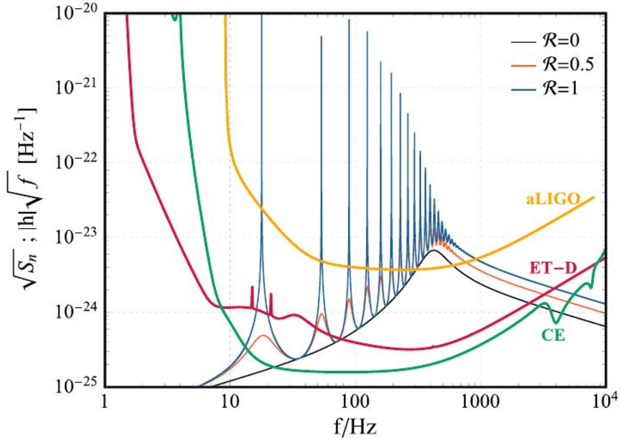
•“Short-blancket” problem: mimicking IMR signal of BBHs is hard

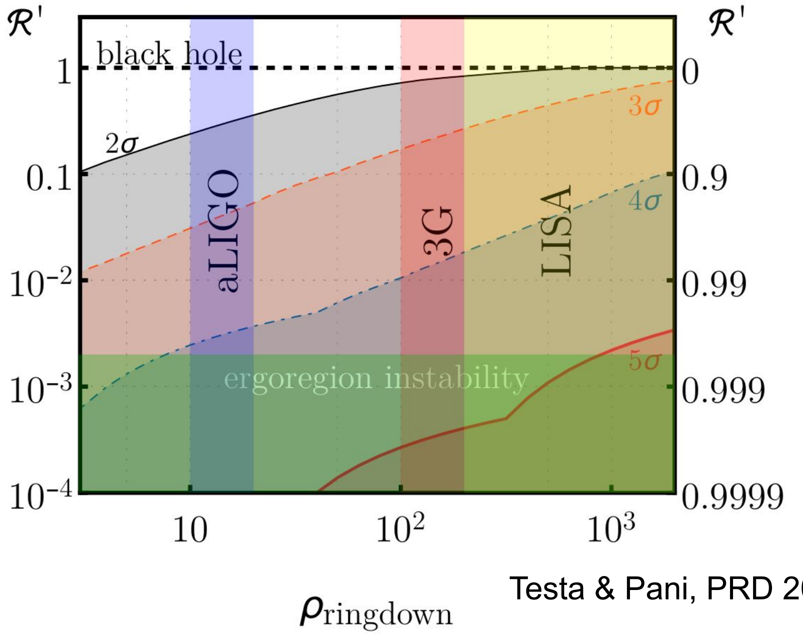
Backup slides

GW echoes: detectability







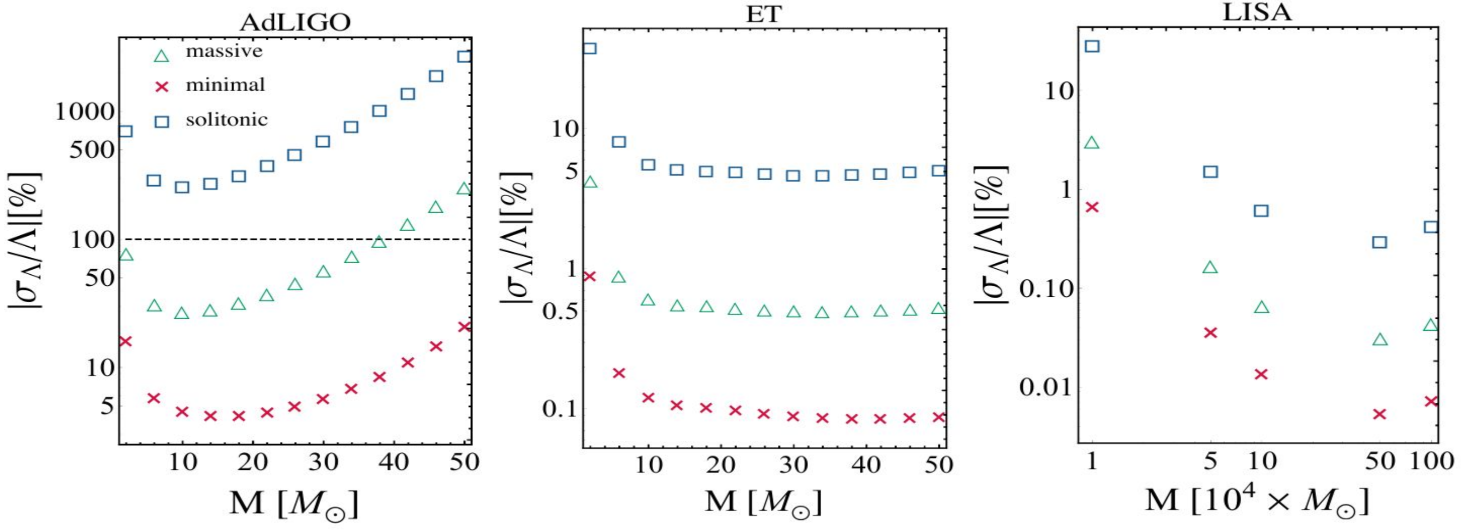


Testa & Pani, PRD 2018

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

BH/NS vs Boson Stars: Love numbers

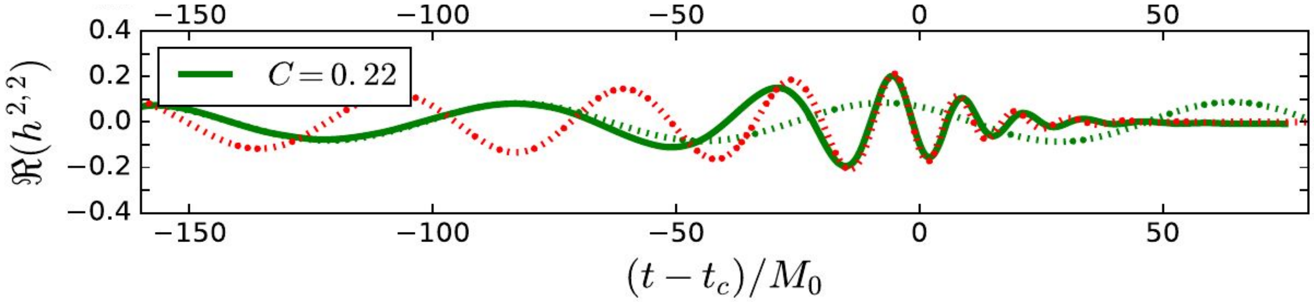
$$\mathcal{L} = \frac{R}{16\pi G} - \partial_\mu \phi \, \partial^\mu \phi^\star - m^2|\phi|^2 + \lambda|\phi|^4 + \gamma|\phi|^6 + \ldots$$



- 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 mimic the full signal from BBH coalescence?



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

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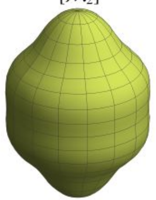
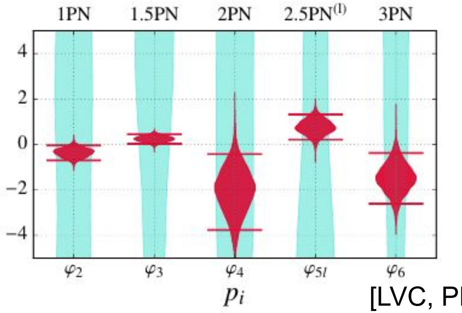
No-hair tests: multipole moments

- **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 → $\delta\bar{M}_2 \lesssim 0.2$
  - 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] →$\delta\bar{M}_2 \lesssim 10^{-4}$
  - Something to discuss: current projected bounds with EMRIs too optmistic? [simplistic waveforms, isolated source in band, enchilada problem]

BH/NS vs Boson Stars: Love numbers

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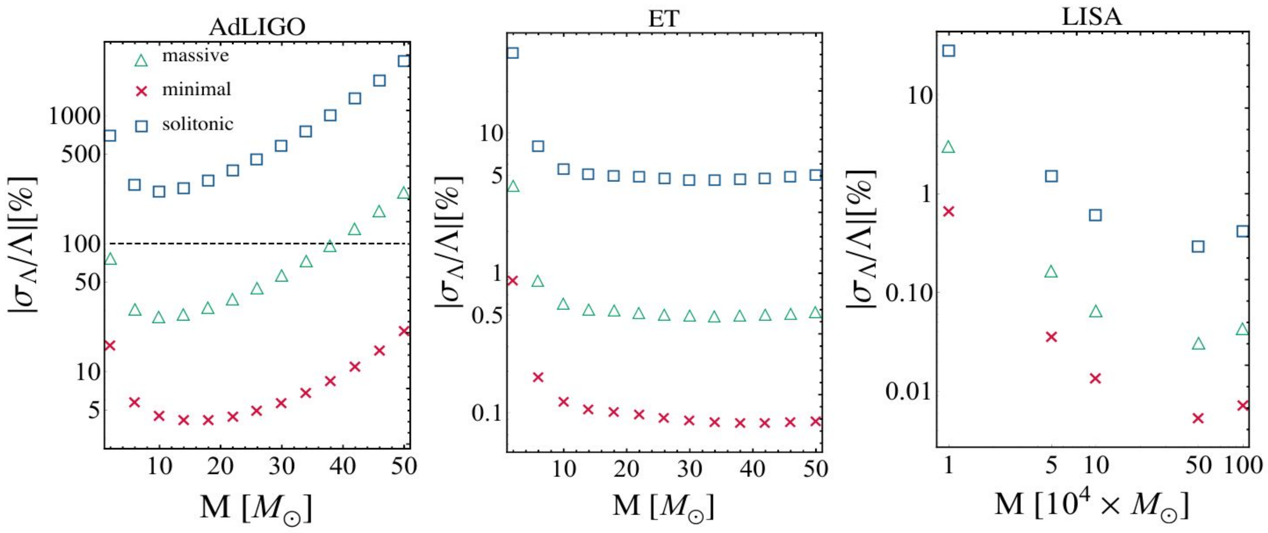

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