Fundamental fields, asymmetric binaries, and LISA observations within a Self-Force approach

@ Gravitational Waves Meet Effective Field Theories
Benasque, 23rd Aug 2023

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Motivation

Flood of data coming from a web of current GW/EM detectors (*LVK, EHT, PTAs, NICER*) and of future GW/EM facilities (*LISA, Athena, ET, CE, PTAs*)

- Observations put at test the nature of black holes and neutron stars

  → *Can we use them to search for new physics?*

key points

- new physics → new fundamental fields
- New theories predict structure and evolution of COs

science case

- scalar fields and black holes
- Light scalars ubiquitous in extensions of GR or the SM

observables and methodology

- Gravitational waves from asymmetric binaries

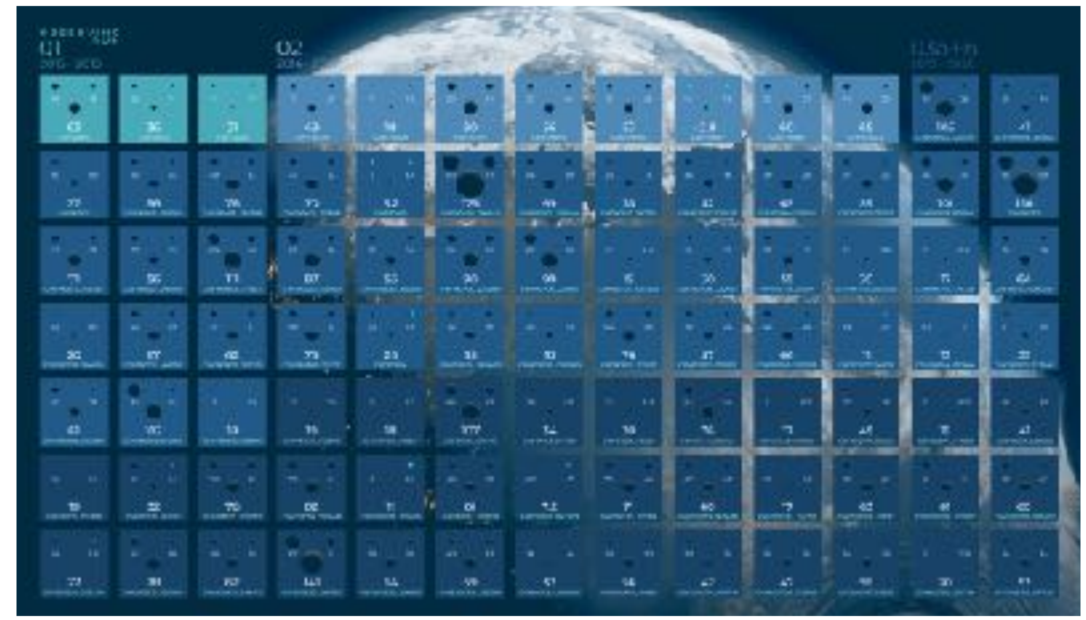
Why Asymmetric Binaries?

90+ events observed so far from LVK, spanning a relatively small interval of mass ratios $q \sim 1:30$

- 3G detectors are expected to beat down such value by several orders of magnitudes

$$q \sim 10^{-6} - 10^{-7}$$

- dynamics dictated by q, with the duration of the inspiral & number of cycles growing as q decreases



LVK, GWTC 3 2111.03605

Discovery potential

1. Slow inspiral phase which could allow to continuously observe AB for very long periods, from months to years
2. dynamical evolutions with an uncommon richness, with resonances, large eccentricities and off-equatorial orbits, etc.
3. astro-fundamental physics setups

EMRIs in nuce

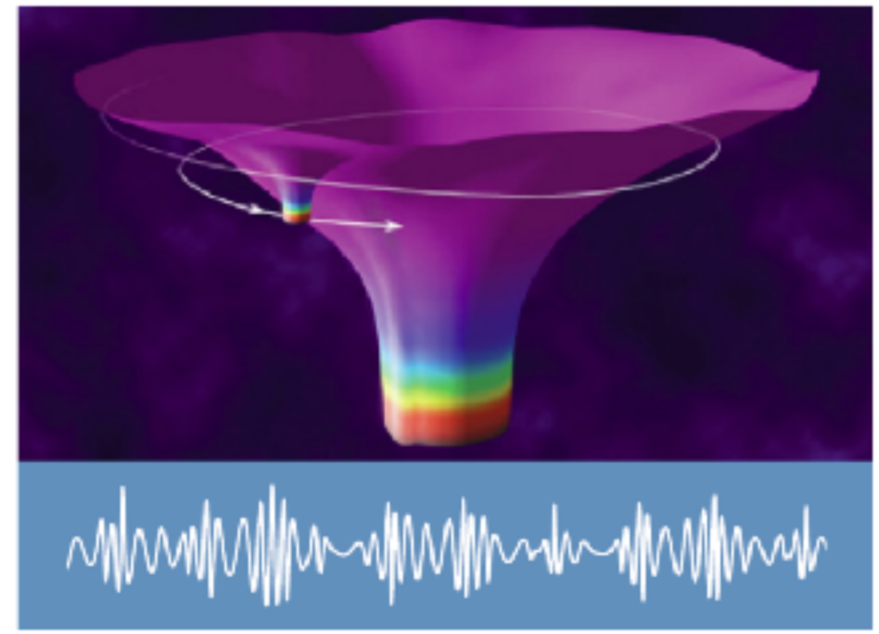
Binary systems with a stellar-mass body inspiralling into a massive BH

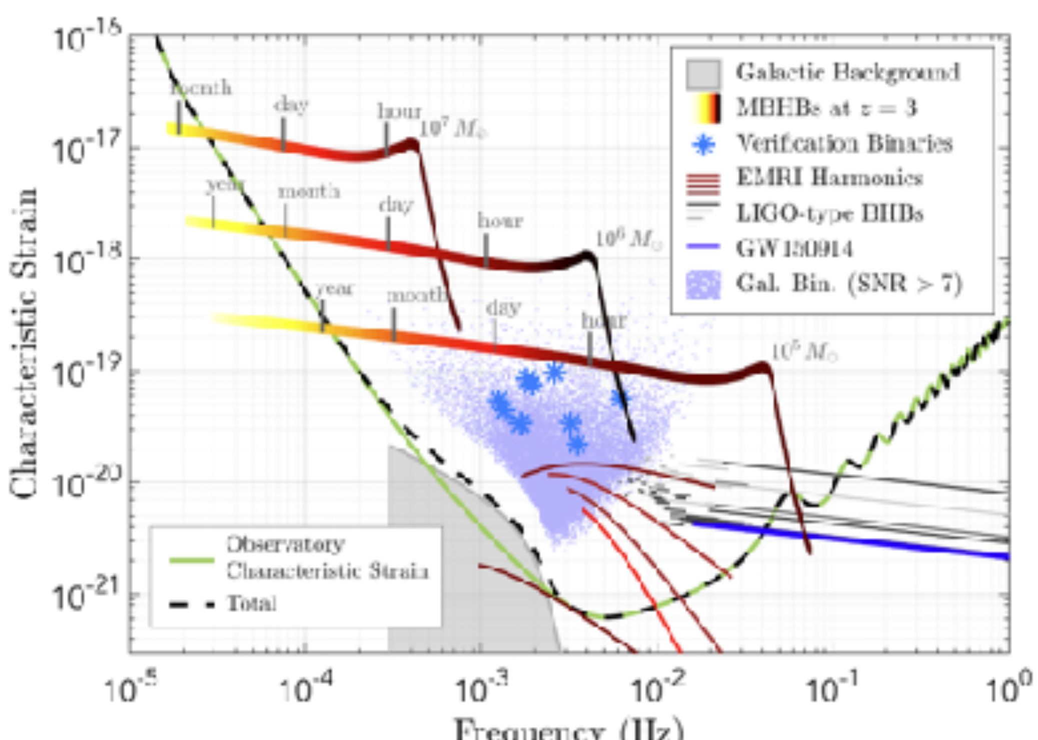
- Primary with $M \sim (10^4 - 10^8)M_\odot$

- Secondary such that the mass ratio

$$q = m_p/M \sim (10^{-6} - 10^{-3})$$

Key point of theoretical description





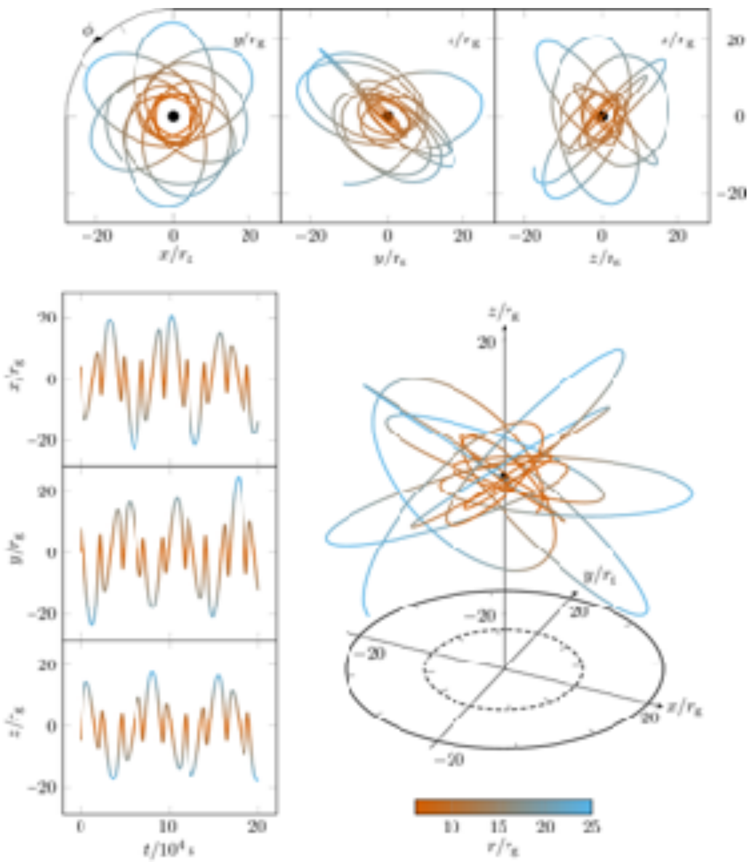
T. Baker +, Astro2020 1907.06482 (2019)

- Emit GWs in the mHz band, golden targets for LISA

EMRIs in nuce

EMRIs provide a rich phenomenology, due to their orbital features

1 *2*



Berry +, Astro2020 1903.03686 (2019)

- Non equatorial orbits
- Eccentric motion
- Resonances
- Complete $\sim (10^4 - 10^5)$ cycles before the plunge

blessing & **disguise**

Tracking EMRIs for O(year) requires accurate templates

Very appealing to test fundamental & astro-physics

Precise space-time map and accurate binary parameters

EMRIs in GR

How do we study EMRI in GR?

- The asymmetric character introduces a natural parameter to study the problem in perturbation theory $q = m_p/M \ll 1$

$$g_{\alpha\beta} = g^{(0)}_{\alpha\beta} + h_{\alpha\beta} + \dots$$

$$G_{\mu\nu} = T^{\rm p}_{\mu\nu} = 8\pi m_{\rm p} \int \frac{\delta^{(4)}(x - y_p(\lambda))}{\sqrt{-g}} \frac{dy_p^\alpha}{d\lambda} \frac{dy_p^\beta}{d\lambda} d\lambda$$

leading → *adiabatic*

Regge-Wheleer-Zerilli (Schwarzschild)

Teukolsky (Kerr)

- The solution determines the phase evolution

adiabatic — *first post-adiabatic*

$$\phi(t) = \phi_{\rm diss-1} + \dots$$

$\mathcal{O}(1/q)$ — $\mathcal{O}(1)$

EMRIs in GR

$$\mathbf{g}_{\alpha\beta} = g_{\alpha\beta} + q h_{\alpha\beta} + q^2 h^{(2)}_{\alpha\beta} + \mathcal{O}\left(q^3\right)$$

Contributions to the orbital trajectory

$$\frac{D^2 z^\alpha}{d\tau^2} = q f_1^\alpha + q^2 f_2^\alpha + \mathcal{O}(q^3)$$

Inspiral evolution on radiation-reaction time t_{rr}

$$t_{rr} = \mathcal{E}/\dot{\mathcal{E}} \sim M/q$$

cumulative shift → *of second order SF*

$$\delta z^\alpha \sim q^2 f_2^\alpha t_{rr}^2 \sim q^0$$

- Match filtering require error in phase << 1 radian: f_2^α ✓ f_3^α ✗

$$\Phi(t) = \frac{1}{q}\left[\Phi_0(t) + q\Phi_1(t) + \mathcal{O}(q^3)\right]$$

$\Phi_0(t)$ → $f^\alpha_{1,\mathrm{diss}}$

$\Phi_1(t)$ → $f^\alpha_{1,\mathrm{cons}}$, $f^\alpha_{2,\mathrm{diss}}$

T. Hinderer & E. Flanagan, PRD 78, 064028 (2008)

The perturbation scheme

For the gravitational sector

$$h_{\alpha\beta} = h^{\rm pol}_{\alpha\beta} + h^{\rm ax}_{\alpha\beta}$$

$h^{\rm pol}_{\alpha\beta} \rightarrow (-1)^\ell$ $\qquad$ $h^{\rm ax}_{\alpha\beta} \rightarrow (-1)^{\ell+1}$

$$\mathbf{h} = \sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{\ell} \mathcal{A}^{(0)}_{\ell m}\mathbf{a}^{(0)}_{\ell m} + \mathcal{A}^{(1)}_{\ell m}\ \mathbf{a}^{(1)}_{\ell m} + \mathcal{A}_{\ell m}\mathbf{a}_{\ell m} + \mathcal{B}^{(0)}_{\ell m}\ \mathbf{b}^{(0)}_{\ell m} + \mathcal{B}_{\ell m}\ \mathbf{b}_{\ell m} + \mathcal{Q}^{(0)}_{\ell m}\ \mathbf{c}^{(0)}_{\ell m} + \mathcal{Q}_{\ell m}\ \mathbf{c}_{\ell m}$$
$$+ \mathcal{D}_{\ell m}\ \mathbf{d}_{\ell m} + \mathcal{G}_{\ell m}\ \mathbf{g}_{\ell m} + \mathcal{F}_{\ell m}\ \mathbf{f}_{\ell m}$$

$$\mathbf{b}_{\ell m} = \frac{n_\ell r}{\sqrt{2}}\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & Y^{\ell m}_{,\theta} & Y^{\ell m}_{,\phi} \\ 0 & Y^{\ell m}_{,\theta} & 0 & 0 \\ 0 & Y^{\ell m}_{,\phi} & 0 & 0 \end{pmatrix}$$

- 7 **polar** components + 3 **axial** harmonics
  - For a spherically symmetric background the 2 families decouple
- In the Regge - Wheeler - Zerilli gauge the components reduce to **1** axial and **1** polar functions

Regge & Wheeler, PRD 108, 1063 (1957)
Zerilli, PRD 2, 2141 (1970)

The wave equations

2 master equations for 2 perturbations for Schwarzschild

$$\frac{d^2 R_{\ell m}}{dr_\star^2} + \left[\omega^2 - e^{-\lambda}\left(\frac{\ell(\ell+1)}{r^2} - \frac{6M}{r^3}\right)\right] R_{\ell m} = J^{\rm ax}_{\ell m}$$

***R**egge-**W**heeler*

$$\frac{d^2 Z_{\ell m}}{dr_\star^2} + \left[\omega^2 - \frac{18M^3 + 18M^2 r\Lambda + 6Mr^2\Lambda^2 + 2r^3\Lambda^2(1+\Lambda)}{r^3(3M + r\Lambda)}\right] Z_{\ell m} = J^{\rm pol}_{\ell m}$$

***Z**erilli*

Miraculous decoupling for Kerr

$$\Delta^2 \frac{d}{dr}\left(\frac{1}{\Delta}\frac{dR_{\ell m}}{dr}\right) - \left[-\frac{1}{\Delta}(K^2 + 4i(r-M)K) + 8i\omega r + \lambda\right] R_{\ell m} = J_{\ell m}$$

Teukolsky

- Perturbations are needed to compute GW fluxes at infinity and at the horizon

$$\dot{E}^{(\pm)}_{\rm grav} = \sum_{\ell m} \alpha_{\ell m} \frac{|Z^{\pm}_{\ell m}|^2}{4\pi\omega_m^2} \qquad \dot{L}^{(\pm)}_{\rm grav} = \sum_{\ell m} \alpha_{\ell m} \frac{m|Z^{\pm}_{\ell m}|^2}{4\pi\omega_m^3}$$

- Which drive the orbital evolutions

$$\frac{dr(t)}{dt} = -\dot{E}\frac{dr}{dE_{\rm orb}} \qquad \frac{d\phi(t)}{dt} = \frac{M^{1/2}}{r^{3/2} + M^{3/2}\chi}$$

waveform →

$$h_+\left[r(t), \Phi(t)\right]$$

$$h_\times\left[r(t), \Phi(t)\right]$$

Are EMRI sensitive to new fields?

Extra polarizations as generic features of modified theories of gravity

- Typically, proposed theories feature extra fields or can be reformulated in terms of them

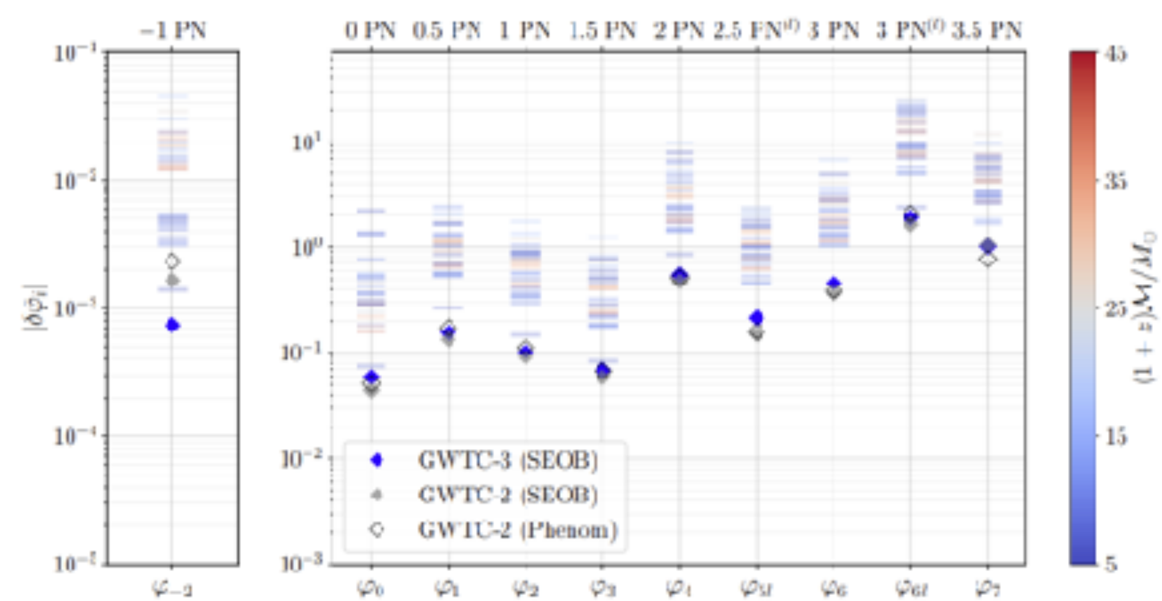
Compact binaries can probe the existence of such new fields

- Comparable mass in the inspiral: dipole emission at -1PN

E. Barausse +, PRL 116, 241104 (2016)

- Comparable mass in the merger/post-merger

M. Okounkova + PRD 100, 104026 (2019)
H. Witek +, PRD 99, 064035 (2019)
E. Maggio +, 2212.09655
H. Silva + PRD 107, 044030 (2023)



Abbott +, PRL 2112.06861 (2021)

What about very asymmetric binaries like EMRIs?

No hairs and exceptions

Scalar fields in BH spacetime. No hair for asymptotically flat BHs

- Minimally coupled; stationary

  S.W. Hawking, Comm. Math. Phys. 25, 152 (1972)

- Self interacting, scalar tensor theories; stationary

  T. Sotiriou & V. Faraoni, PRL 108, 081103 (2012)

- Shift-symmetric; static, slowly rotating solutions (assumption on the current)

  L. Hui & A. Nicolis, PRL 110, 241104 (2013)

However

- Perturbations are different

  E. Barausse & T. Sotiriou, PRL 101, 099001 (2008)

- Notable exceptions as superradiance

  R. Brito +, Lect.Notes Phys. 971 (2020)

- Relaxing symmetries of the scalar

  C. Herdeiro & E. Radu, PRL 112, 221102 (2014)

- Loopholes

  T. Sotiriou & Y. Zhou PRL 112, 251102 (2104)
  E. Babichev & C. Charmousis, JHEP 1408, 106 (2014)

- ….

No hairs and exceptions

Linear Gauss-Bonnet coupling

P. Kanti +, PRD 54, 5049 (1996)
T. Sotiriou & Y. Zhou PRL 112, 251102 (2104)
K. Yagi +, PRD 93, 024010 (2016)

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(\frac{R}{2} - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi + \alpha_{\rm GB}\varphi\mathcal{G}\right) \longrightarrow \Box\varphi + \alpha_{\rm GB}\mathcal{G} = 0$$

- Introduces hair to BHs (difficult to constrain with weak field tests)
- Small coupling expansion of a more general theory

The BH charge is fixed by regularity conditions at the horizon

$$\varphi' = \alpha\frac{16M^2 - Cr^3}{r^4(r-2M)} \xrightarrow{\text{regularity}} d \sim \frac{\alpha_{\rm GB}}{M^2}$$

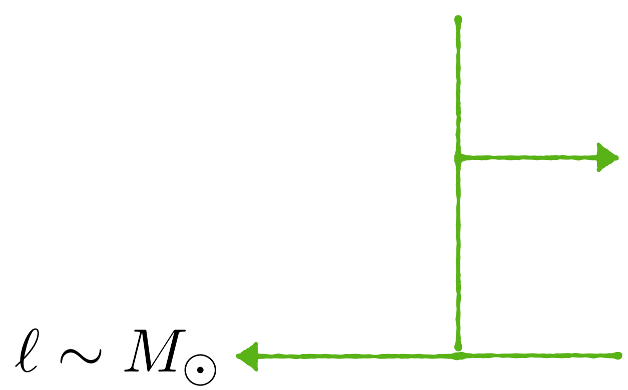
- If M is the only relevant scale for the BH

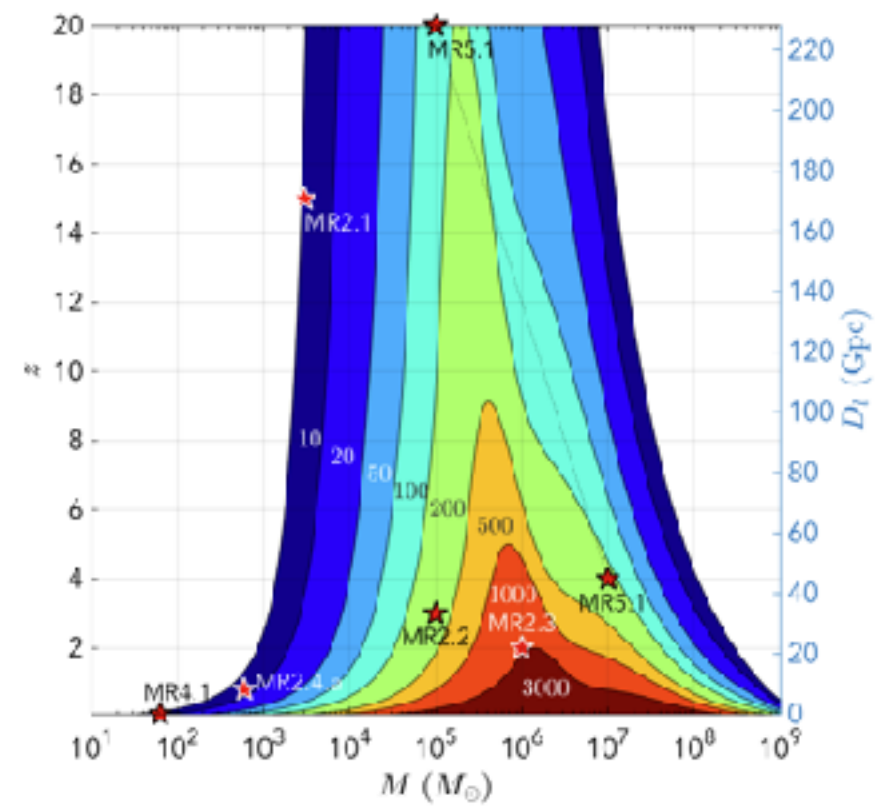
$$\alpha_{\rm GB} \ll M^2 \longleftrightarrow d \ll 1$$

New fields for LISA?

It may be tempting to answer maybe not

- In most scalar-tensor theories BHs feature no-hair theorems, same as in GR
- For hairy BHs, scalar fields that couple with high-order curvature terms, tend to feature dimensionful couplings
    - GR deviations scale as $\sim (\ell/M)^n$





Massive, large-snr, binaries look less suited than expected for testing GR
(but superradiance/spin-induced scalarization)

R. Brito +, Lect.Notes Phys. 971 (2020)
A. Dima +, PRL 125, 231101 (2020)

The Setup

Scalar field φ non-minimally coupled to the gravity sectors

A.M. +, PRL 125, 14101 (2020)

$$S[\mathbf{g}_{ab},\varphi,\Psi] = S_0[\mathbf{g}_{ab},\varphi] + \alpha S_{\rm c}[\mathbf{g}_{ab},\varphi] + S_{\rm m}[\mathbf{g}_{ab},\varphi,\Psi]$$

$$S_0[\mathbf{g}_{ab},\varphi] = \int \frac{\sqrt{-\mathbf{g}}}{16\pi}\left(R - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi\right)d^4x$$

Non-minimal coupling

Matter fields

- α has dimensions $[\text{length}]^n$ $n \geq 2$
  - in pp units ~ negative mass dimensions

We assume the <u>primary</u> is a black hole

- Hairs have to be introduced by S_c
  - for shift-symmetric theories $\alpha_{\rm GB}\varphi\mathcal{G}$ introduces a scalar hair
  - The scalar charge is not an independent parameter $\sim \alpha_{\rm GB}/M^2$

The Setup

- Additional shift - symmetric interactions can be added to S_c
  - other term other than linear coupling with $\mathcal{G}$ with and controlled by α_i

    contribute to *d* as ⟶ $\alpha_{\rm GB}\alpha_i$

M. Saravani and T. Sotiriou, PRD 99, 124004 (2019)

For the <u>secondary</u>, consider the *skeletonized* approach

Eardley, ApJ 196 L59-62 (1975)
Damour & EF, CGQ 9, 9 (1992)

$$S_{\rm p} = -\int_\gamma m[\varphi] ds = -\int_\gamma m[\varphi]\sqrt{\mathbf{g}_{ab}\mathbf{u}^a\mathbf{u}^b} d\tau$$

- Extended body treated as point particle
- $m(\varphi)$ scalar function

$$\Box_{\mathbf{g}}\varphi = 16\pi\int_\gamma m'[\varphi]\frac{\delta^4[x^\mu - z_{\rm p}^\mu[\tau]]}{\sqrt{-\mathbf{g}}} d\tau - \alpha\frac{16\pi}{\sqrt{-\mathbf{g}}}\frac{\delta S_c}{\delta\varphi}$$

Perturbations

Solutions to field's equations are continuously connected to GR as $\alpha \to 0$

- Introduce the dimensionless parameter $\zeta = \frac{\alpha}{M^n} = q^n \frac{\alpha}{m_p^n}$ with $\frac{\alpha}{m_p^n} \sim \mathcal{O}(1)$

  → any GR deviation is controlled by $\zeta \ll 1$

  → contributions to S_c are suppressed at least by q^n

  - The mass ratio can be used as the sole perturbative parameter $\mathbf{A} = \mathbf{A}^{(0)} + q\mathbf{A}^{(1)} + q^2\mathbf{A}^{(2)} + \mathcal{O}(q^3)$

  - Background metric is Kerr

- First order field's equations

$$G^{(1)}_{ab} = 8\pi m_{\rm p} \int_\gamma \frac{\delta^4[x^m_p - z^\mu_{\rm p}[\tau]]}{\sqrt{-g}} u_a u_b d\tau$$

$$\Box\varphi^{(1)} = -4\pi d \int_\gamma \frac{\delta^{(4)}[x^\mu - z^\mu_{\rm p}[\tau]]}{\sqrt{-g}} d\tau$$

(→ $d \sim m'(\varphi_0)/m(\varphi_0)$)

$$a^a_{(1)\rm scal} = -\frac{m_{\rm p} d}{4}(g^{ab}_{(0)} + u^a u^b)\nabla_b \varphi^{(1)}$$

Change in the EMRI dynamics universally captured by the scalar charge of the secondary

The GW energy flux

The solution can be used to compute the full scalar first order SF piece $f^{\alpha}_{1,\mathrm{scal}}$

A. Spiers +, in preparation (2023)

$$f_1^{\alpha} = f^{\alpha}_{1,\mathrm{grav}} + f^{\alpha}_{1,\mathrm{scal}}$$

- At the adiabatic order

$$\dot{E}^{(\pm)}_{\mathrm{grav}} = \sum_{\ell m} \alpha_{\ell m} \frac{|Z^{\pm}_{\ell m}|^2}{4\pi\omega_m^2} \qquad \dot{E}^{(\pm)}_{\mathrm{scal}} = \frac{1}{16\pi} \sum_{\ell m} \omega k^{\pm} |\varphi^{(1)\pm}_{\ell m}|^2$$

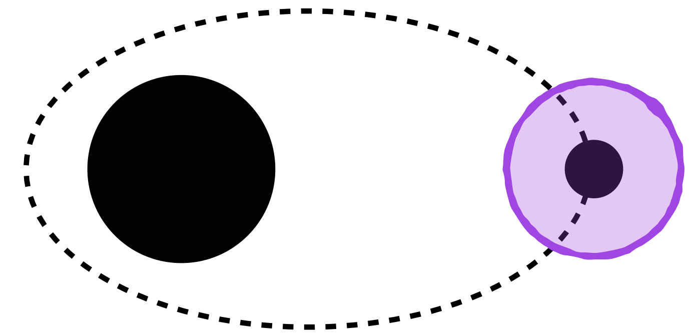
Overall luminosity contribution

$$\dot{E} = \sum_{i=+,-} \left[\dot{E}^{(i)}_{\mathrm{grav}} + \dot{E}^{(i)}_{\mathrm{scal}} \right] = \dot{E}_{\mathrm{GR}} + d^2 \delta \dot{E}$$

- The binary accelerates due to the extra leakage of energy given by the scalar field

Waveforms

The recipe to generate EMRI waveforms



1. Compute the total energy flux emitted $\dot{E} = \dot{E}_{\rm GR} + d^2 \delta \dot{E}$

2. Determine the dynamics $\frac{dr(t)}{dt} = -\dot{E}\frac{dr}{dE_{\rm orb}}$ $\quad \frac{d\phi(t)}{dt} = \frac{M^{1/2}}{r^{3/2} + M^{3/2}\chi}$

3. Build the GW polarizations $h_+[r(t), \Phi(t)]$, $h_\times[r(t), \Phi(t)]$

4. Given the source localization, construct the strain

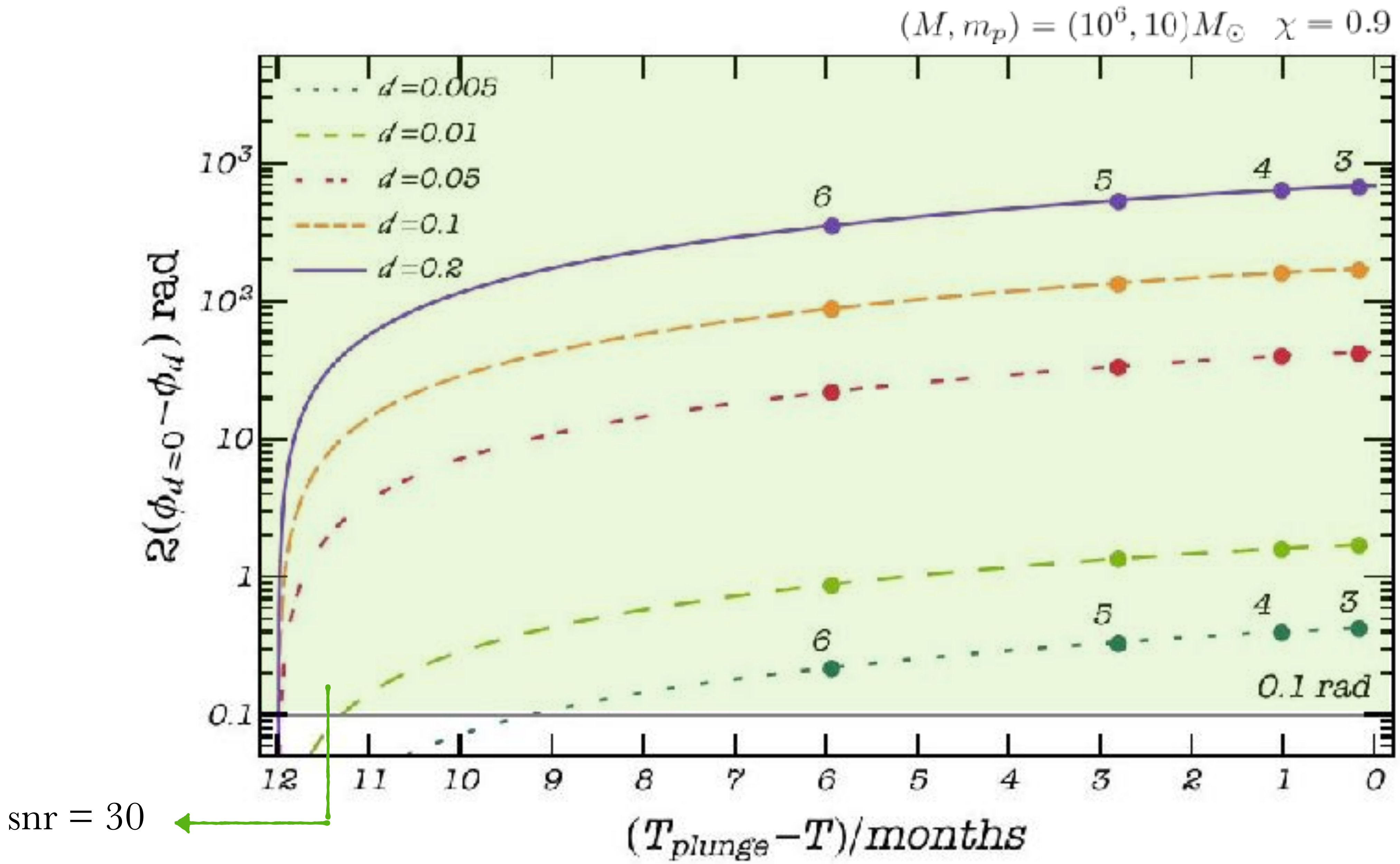
$$h(t) = \frac{\sqrt{3}}{2}[h_+ F_+(\theta, \phi, \psi) + h_\times F_\times(\theta, \phi, \psi)]$$

Everything as in GR but $\delta \dot{E}_d$, that only depends on the scalar charge

- Universal family of waveforms to be tested against GR

How much dephasing?

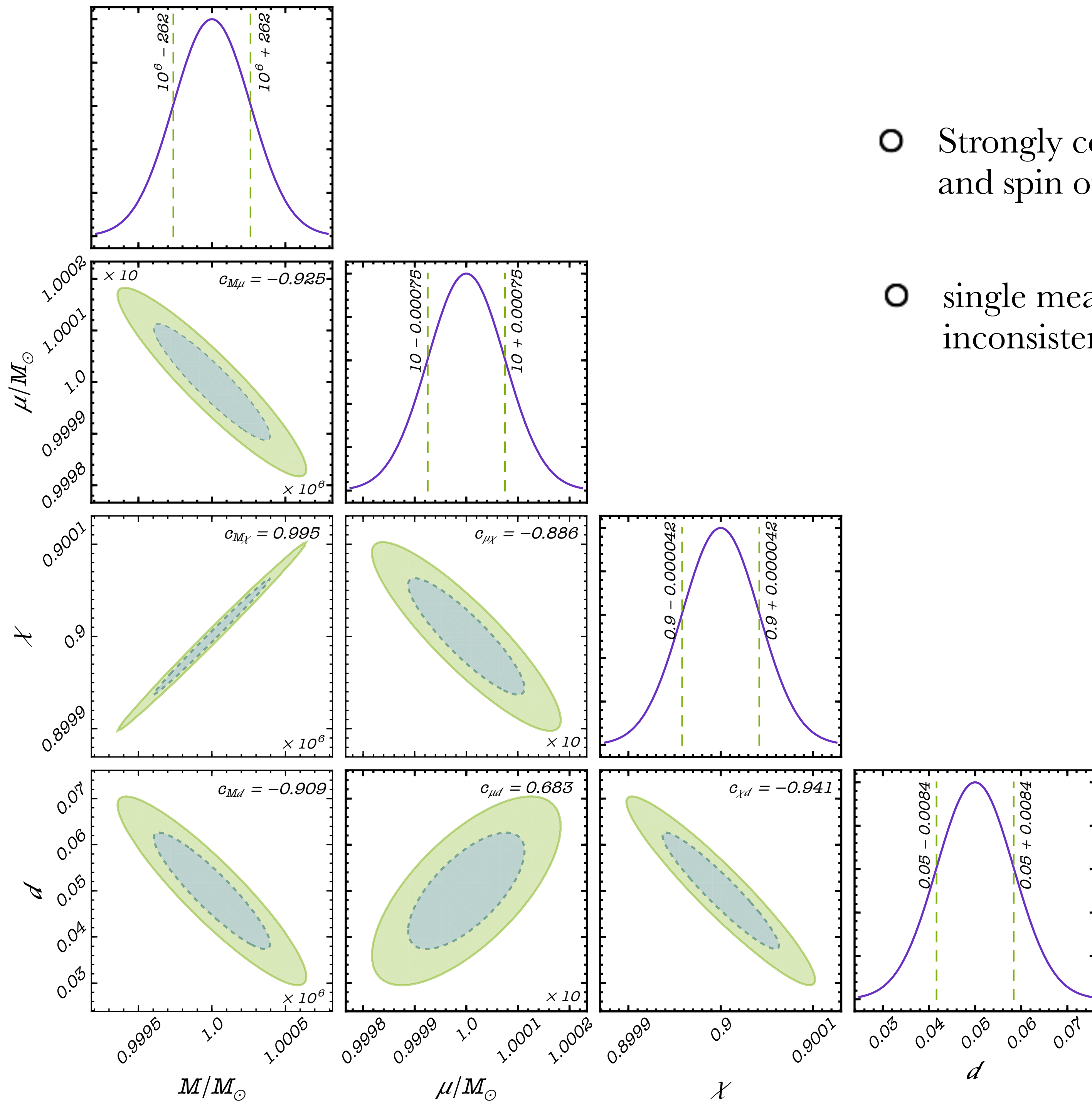
Difference in phase evolution of EMRI in GR v.s. GR+d



Potentially able to observe changes induced by scalar charges $d \sim 0.005$

Forecast on LISA bounds

Constraints on the scalar charge for prototype EMRIs $(M, m_p) = (10^6, 10)M_\odot$ $\chi = 0.9$



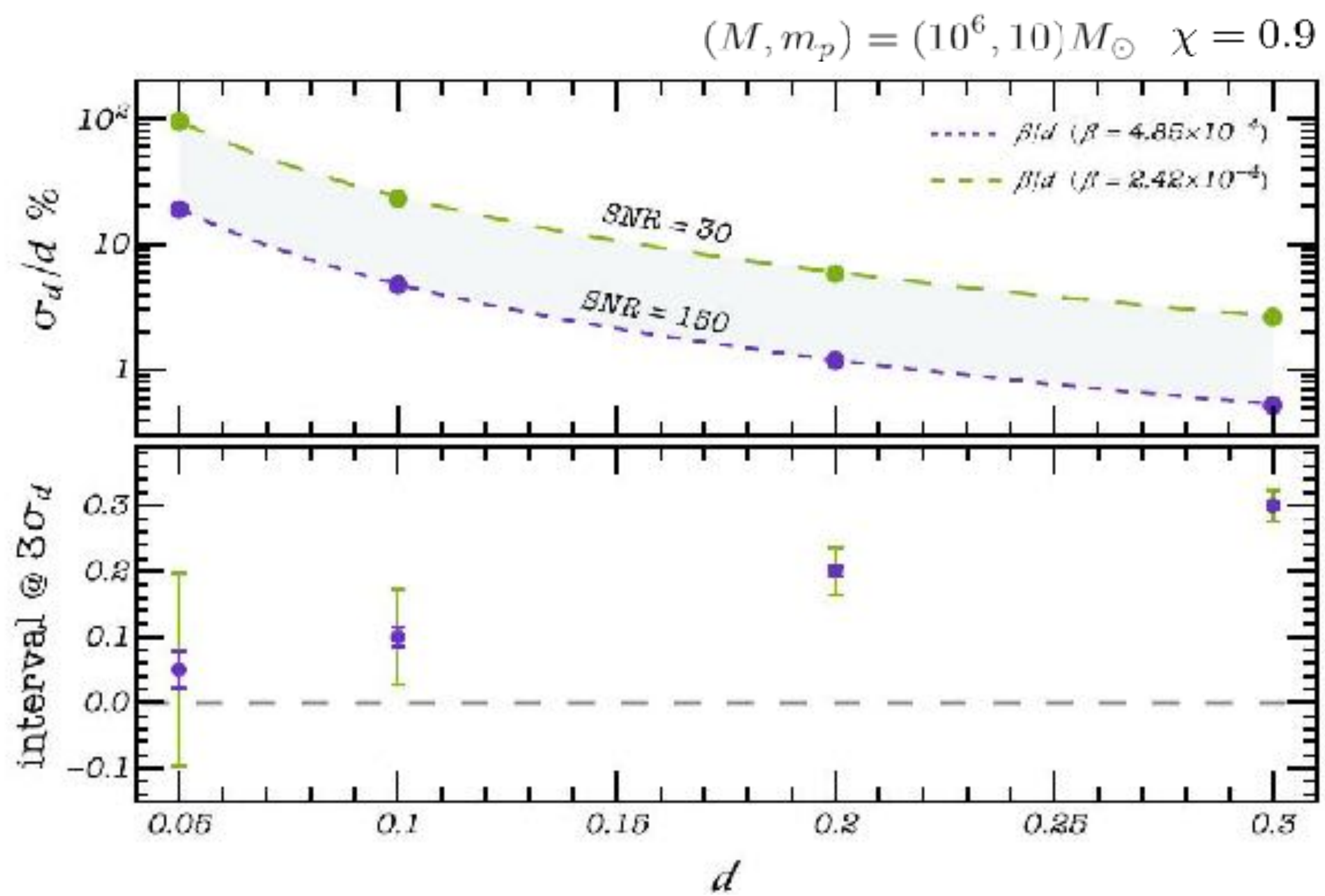
- Strongly correlated with mass and spin of the primary
- single measurement inconsistent with GR @ 3-σ

Forecast on LISA bounds

Constraints on the scalar charge for prototype EMRIs with SNR = (30,150)

A.M. +, Nature Astronomy 6, 4 464-470 (2022)

- Bounds via Fisher Matrix approach



- LISA potentially able to measure d with % accuracy and better
- LISA potentially able to constrain d ~ 10^{-1} to be inconsistent with zero @ 3-σ

Tracing back the couplings

A notable example: scalar Gauss-Bonnet (sGB) gravity

F. Julié & E. Berti, PRD 100, 104610 (2019)

$$\alpha S_c = \frac{\alpha}{4}\int d^4x \frac{\sqrt{-g}}{16\pi} f(\varphi)\mathcal{G}$$

- n =2, $[\alpha] = [length^2]$ → $\zeta = q^2 \frac{\alpha}{m_{\rm p}^2}$
- $f(\varphi)$ generic function of the scalar field
- $\mathcal{G} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}$ Gauss Bonnet invariant
- Scalar charge proportional to the dimensionless coupling constant $\beta = \frac{\alpha}{m_p^2}$

$$f(\varphi) = e^{\varphi}$$

(exponential)

$$d = 2\beta + \frac{73}{30}\beta^2 + \frac{15577}{2520}\beta^3$$

$$f(\varphi) = \varphi$$

(shift-symmetric)

$$d = 2\beta + \frac{73}{60}\beta^3$$

For hairy BHs bounds on d can be mapped to bounds on couplings

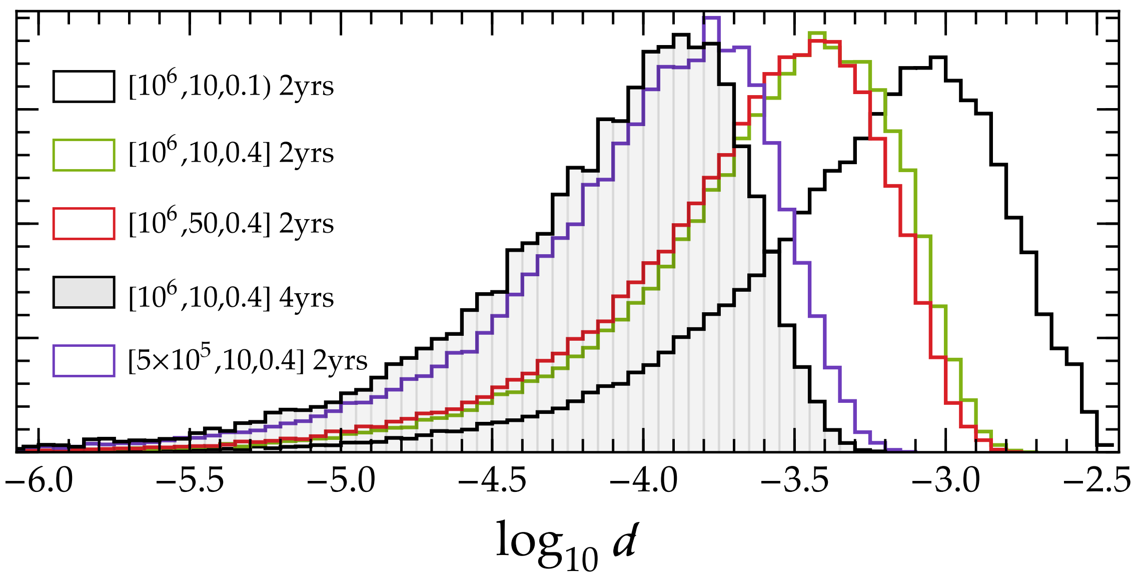
Fast EMRI Waveforms

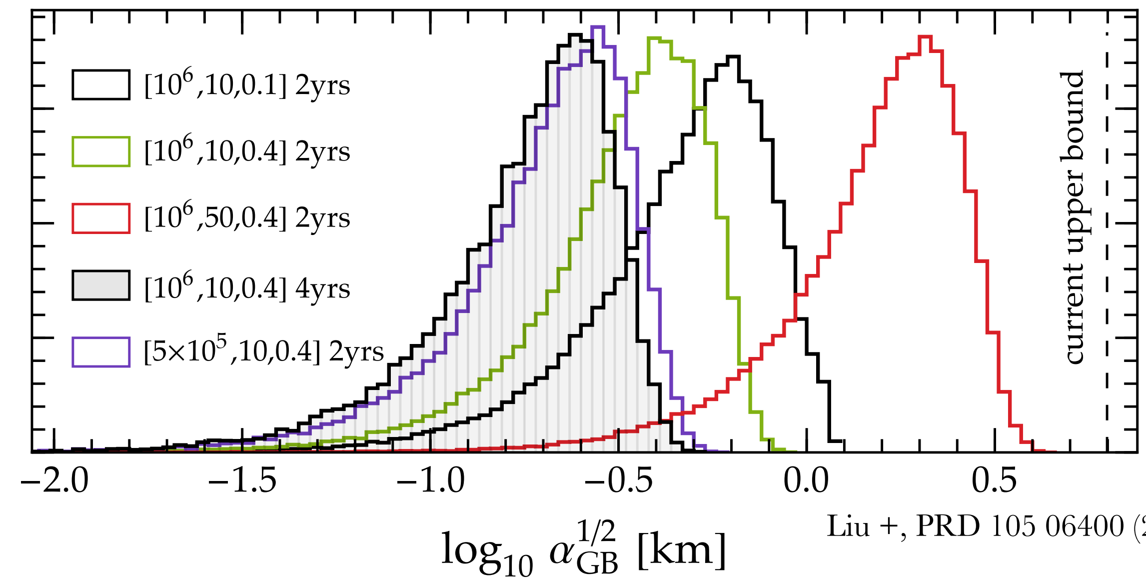
Installation of non-GR waveforms into the LISA pipeline **FEW**

Katz +, PRD 104 064047 (2021)

- Fast generation of EMRI signals with generic orbits
- Tools for Bayesian analysis

Speri +, in preparation (2023)





Liu +, PRD 105 06400 (2022)

	GR	Beyond-GR Scalar Field	Waveform
Kerr eccentric	✓	✓	AAK
Schwarzschild eccentric	✓	✓	Fully Relativistic
Kerr circular off-equatorial	✗	✗	AAK

Status of EMRI waveform models (massless fields)

Post-adiabatic corrections

At second order in the Self-Force expansion

- Need to split metric and scalar perturbations into singular/regular pieces

$$h_{ab} = h^{\mathcal{S}}_{ab} + h^{\mathcal{R}}_{ab} \qquad \varphi = \varphi^{\mathcal{S}} + \varphi^{\mathcal{R}}$$

- Field's equations and secondary acceleration to compute dissipative (& conservative) corrections → $f^{\alpha}_{2} = f^{\alpha}_{2,\mathrm{grav}} + f^{\alpha}_{2,\mathrm{scal}}$

  - $a^{a}_{(2)} = a^{a}_{(2)\mathrm{grav}} + a^{a}_{(2)\mathrm{scal}}$

  - $$G^{(2)}_{ab} = \frac{1}{2}\partial_a\varphi^{(1)}\partial_b\varphi^{(1)} - \frac{1}{4}g_{ab}\partial_c\varphi^{(1)}\partial^c\varphi^{(1)} + 4\pi m_{\mathrm{p}}\int_{\gamma}\frac{\delta^4[x^\mu - z^\mu_{\mathrm{p}}[\tau]]}{\sqrt{-g}} \left[(2u_a u_b - u_a u_b(g^{cd}_{(0)} - u^c u^d)h^{\mathcal{R}(1)}_{cd} + 4h^{\mathcal{R}(1)}_{ac}u^c u_b) - \frac{d}{2}\varphi^{(1)}_{\mathcal{R}}u_a u_b\right]d\tau$$

  - $$\Box\varphi^{(2)} = -\frac{8\pi\mathcal{G}}{\sqrt{-g}} - h^{ab}_{(1)}\nabla_a\nabla_b\varphi^{(1)} - (\nabla^a h^{(1)}_{ab})\nabla^b\varphi^{(1)} + \frac{1}{2}(\nabla^b h_{(1)})\nabla_b\varphi^{(1)} + 16\pi m_{\mathrm{p}}\int_{\gamma}\left[d^{(1)}\varphi^{(1)}_{\mathcal{R}} + \frac{d}{8}(g^{ab} + u^a u^b)h^{\mathcal{R}(1)}_{ab}\right]\frac{\delta^{(4)}[x^\mu - z^\mu_{\mathrm{p}}[\tau]]}{\sqrt{-g}}d\tau$$

Massive fields

Extension to massive scalar fields

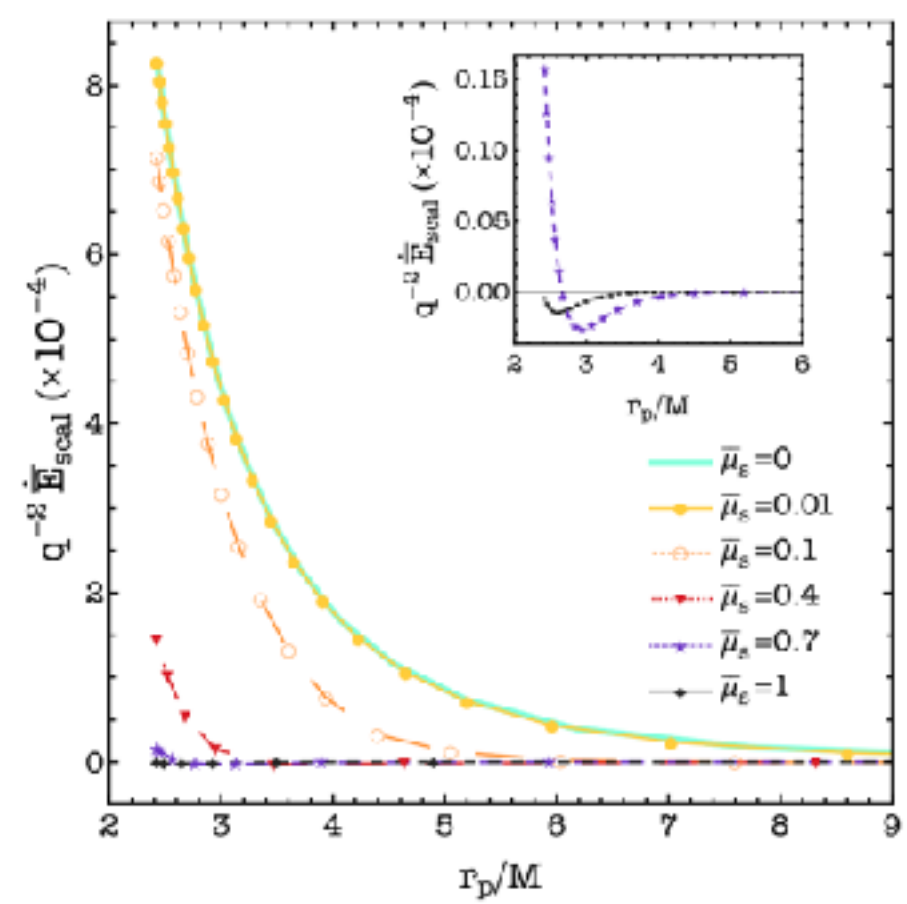
$$S_0 = \int d^4x \frac{\sqrt{-g}}{16\pi} \left(R - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - \frac{1}{2}\mu_s^2\varphi^2 \right)$$

New effects arising in the inspiral

- Scalar flux at infinity vanishes for $\omega < \mu_s$
  - For each (ℓ, m) a radius $r > r_s$ → $\dot{E}^{\infty}_{\rm scal} = 0$
  - Flux at the horizon always active (enough?)
- Scalar field resonances
  - Floating orbits: the binary stalls

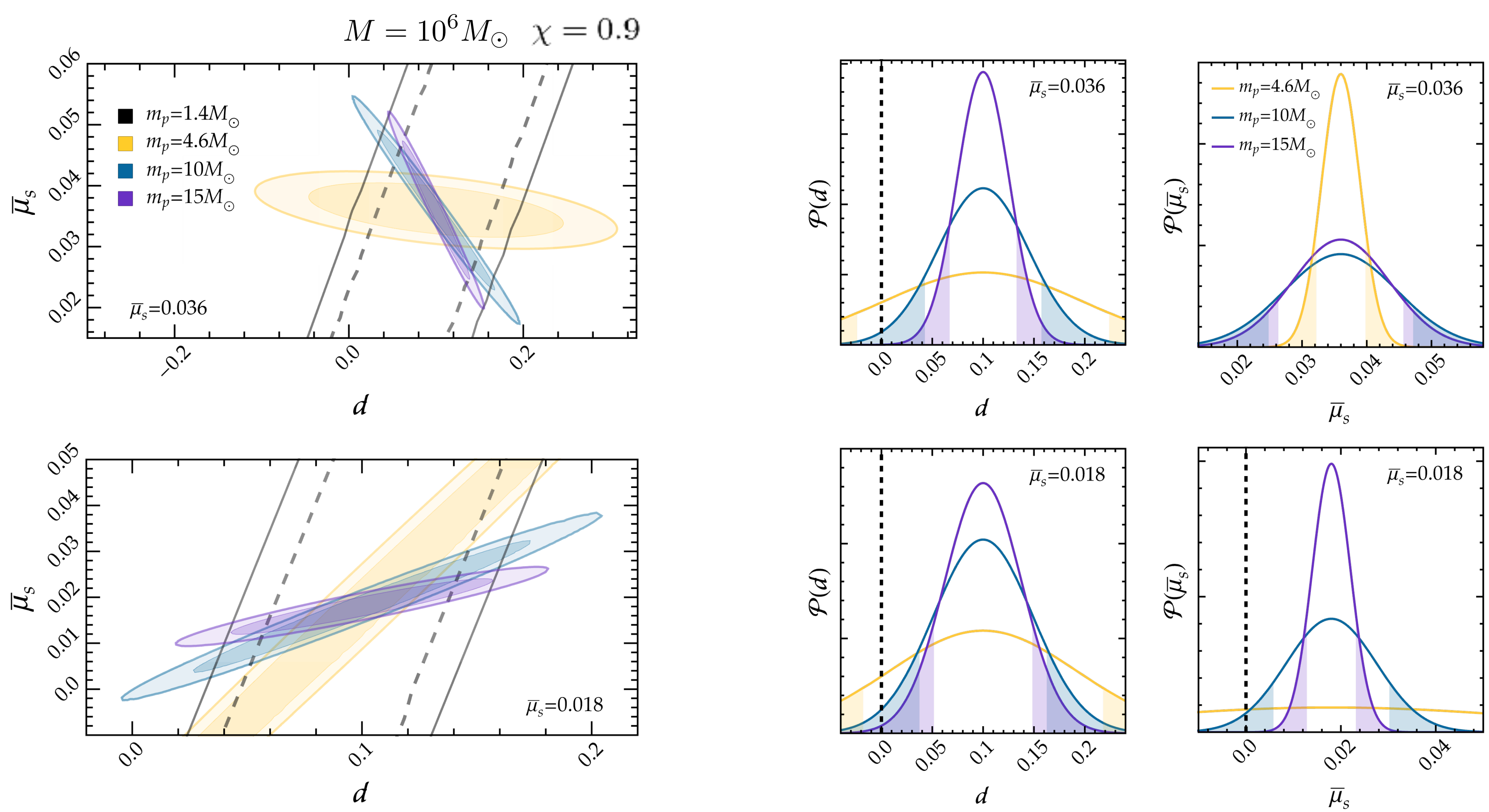
N. Yunes +, PRD 85, 102003 (2012)
V. Cardoso +, PRL 107, 241101 (2011)

S. Barsanti +, PRL 131, 051401 (2023)



Forecast on LISA bounds

Constraints from 1yr of EMRI observation

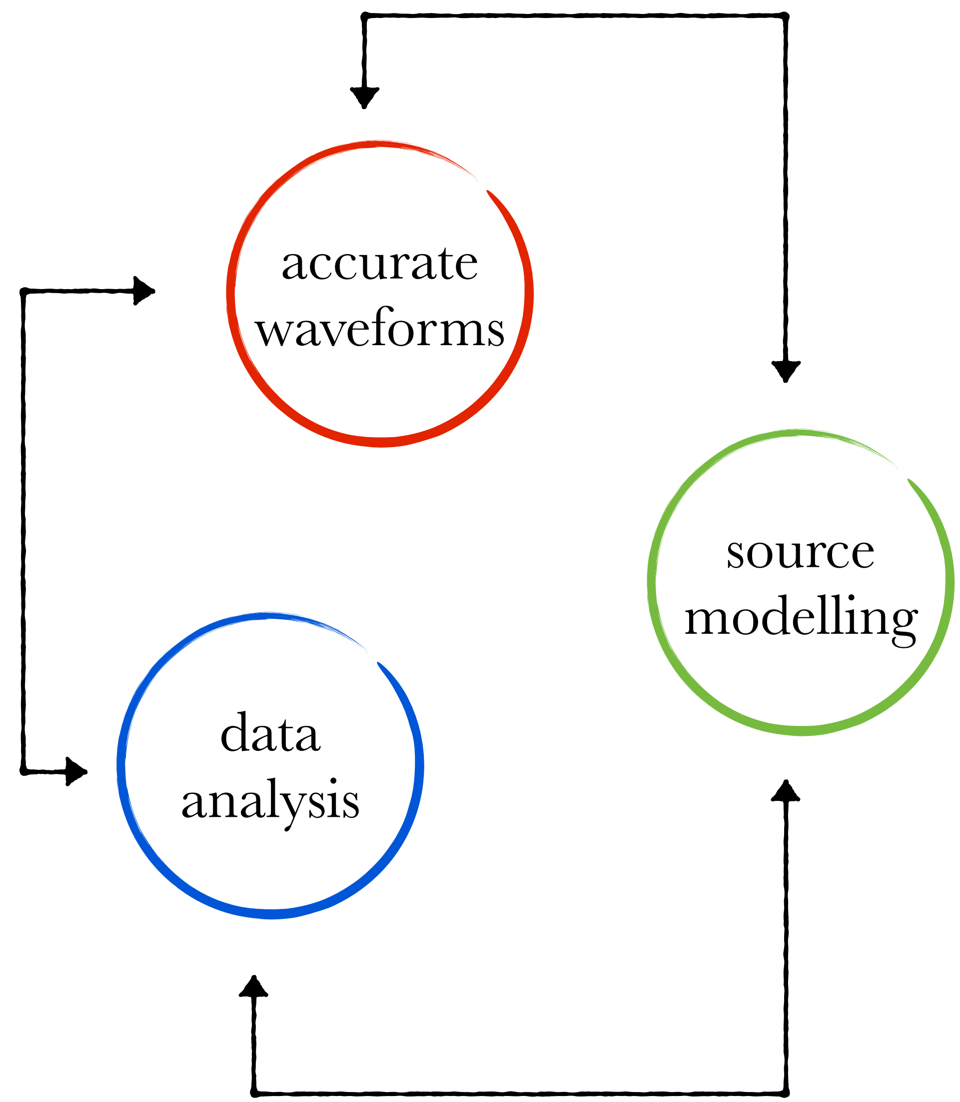


Joint constrains on the scalar field mass and on the charge of the secondary

Are EMRI sensitive to new fields?

Yes…

- Key simplifications occur for a vast class of theories
- (leading) GR deviations are universal and only controlled by the scalar charge of the little guy
- Universal family of waveform to test GR. Ready-to-use waveforms
- Scalar fields can leave a significant (detectable) imprint in the GW signal emitted by EMRIs.
- charge constraints can be mapped to theory's couplings



But

- Actual computation of SF contributions
- What about other fields?
- Correlation with astrophysical effects
- Generic orbits, resonances?

AB and scalar fields