Detecting scalar charge with EMRIs

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Motivation

A host of current (LVK, EHT, PTAs, NICER, …) and future (LISA, Athena, ET, Cosmic Explorer, PTAs, …) observations will reveal the nature of black holes and neutron stars

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

Key points:

- New physics → New fields
- Theories predict structure and dynamics of compact objects

Case study: scalar fields and black holes

→ Light scalars ubiquitous in extensions of GR or the SM
→ Can we measure scalar charge with EMRIs?

No-hair theorems

Asymptotically flat black holes have no scalar hair

- Minimally coupled, Brans-Dicke; stationary

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

- Self-interacting, Scalar-tensor theories; stationary

T. P. S. and V. Faraoni, Phys. Rev. Lett. 108, 081103 (2012)

- Shift-symmetric; static, spherically symmetric/slowly rotating, assumptions on the current

L. Hui, A. Nicolis, PRL 110, 241104 (2013)
T.P.S. and S.-Y. Zhou, PRL112, 251102 (2014)

No difference from GR?

Actually there is...

- Perturbations are different

E. Barausse and T.P.S., Phys. Rev. Lett. 101, 099001 (2008)

- …but hard to excite in astrophysical setting!

- Interesting exceptions exist, e.g. superradiance for axions

A. Arvanitaki and S. Dubovksy, Phys. Rev. D 83, 044026 (2011)
R. Brito, V. Cardoso and P. Pani, Lect.Notes Phys. 906, 1 (2015)

Hairy black holes

Consider the action

T.P.S. and S.-Y. Zhou, PRL 112, 251102 (2014);
Phys. Rev. D 90, 124063 (2014).

$$S = \frac{m_P^2}{8\pi} \int d^4x \sqrt{-g} \left(\frac{R}{2} - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi + \alpha \phi \mathcal{G} \right)$$

The corresponding scalar equation is

$$\Box \phi + \alpha \mathcal{G} = 0$$

At small coupling/weak field identical to exponential coupling of dilaton in string theory

P. Kanti et al., Phys. Rev. D 54, 5049 (1996)
N. Yunes and L. Stein, Phys. Rev. D 83, 104002 (2011)

Solve to first order in the coupling

- metric is Schwarzschild, $$\phi' = \alpha \frac{16M^2 - Cr^3}{r^4(r - 2M)}$$

Scalar charge

Regularity on the horizon implies $C = 2/M$

$$\phi' = -\frac{2\alpha(r^2 + 2Mr + 4M^2)}{Mr^4}$$

The scalar charge is fixed to be $$P = \frac{2\alpha}{M}$$

Confirmed with numerical scalar collapse

R. Benkel, T.P.S. and H. Witek, Phys. Rev. D 94 (R), 121503 (2016); Class. Quant. Grav. 34, 064001 (2017)

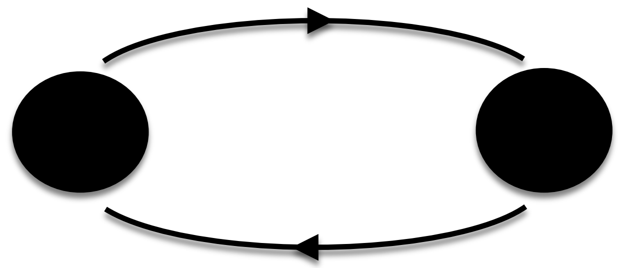
More generally, for shift-symmetric scalars

$$P \propto \alpha \int_{\mathcal{H}} n_a \mathcal{G}^a \qquad \mathcal{G} = \nabla_a \mathcal{G}^a$$

M. Saravani & T.P.S., Phys. Rev. D 99, 12, 124004 (2019)

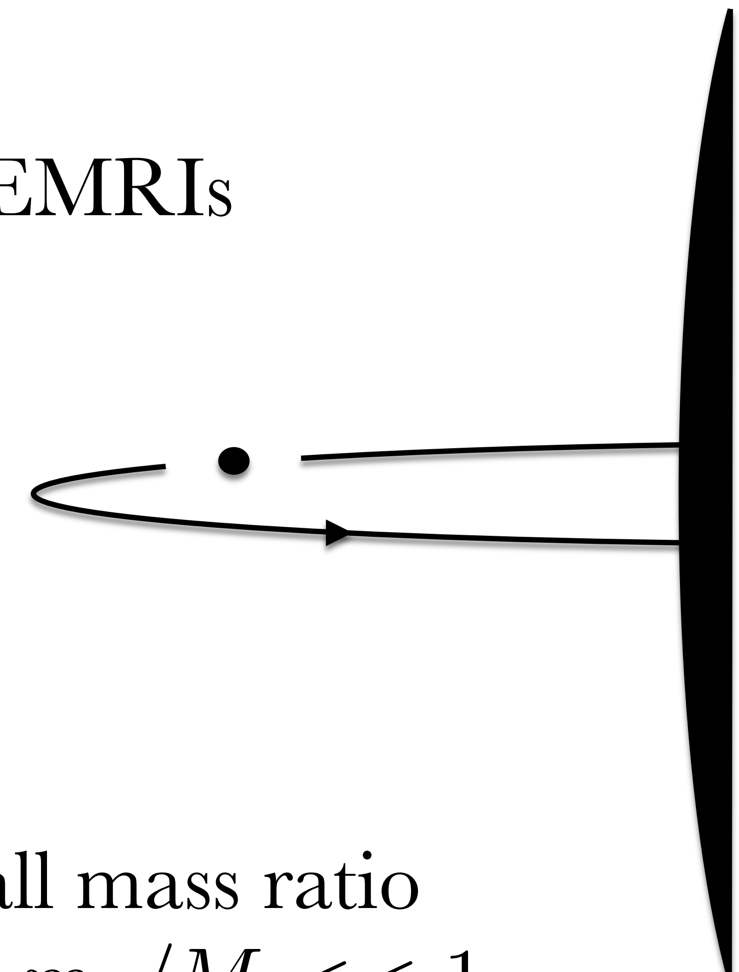
Light scalars and GW

BH Binaries



- dipole emission
- additional energy flux, i.e. change in orbital dynamics
- Modified waveform

EMRIs



- Small mass ratio $q = m_p/M << 1$
- very long inspiral
- Precise mapping of spacetime of the primary

BH mass and charge

So far we've seen two cases

- Theories that are covered by no-hair theorems
- An exception in which the scalar charge is fixed to be

$$P = \frac{2\alpha}{M}$$

More generally, for shift-symmetric scalars

$$P \propto \alpha \int_{\mathcal{H}} n_a \mathcal{G}^a \qquad \qquad \mathcal{G} = \nabla_a \mathcal{G}^a$$

M. Saravani & T.P.S., Phys. Rev. D 99, 12, 124004 (2019)

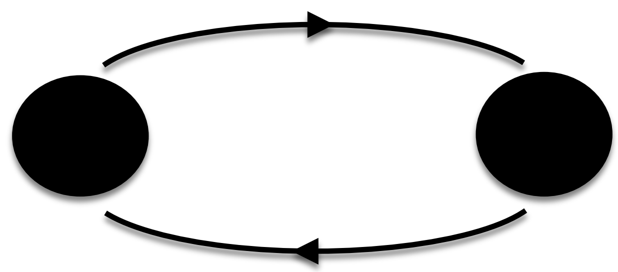
If M is the only relevant scale for the BH

$$\alpha << M^2 \rightarrow P/M << 1$$

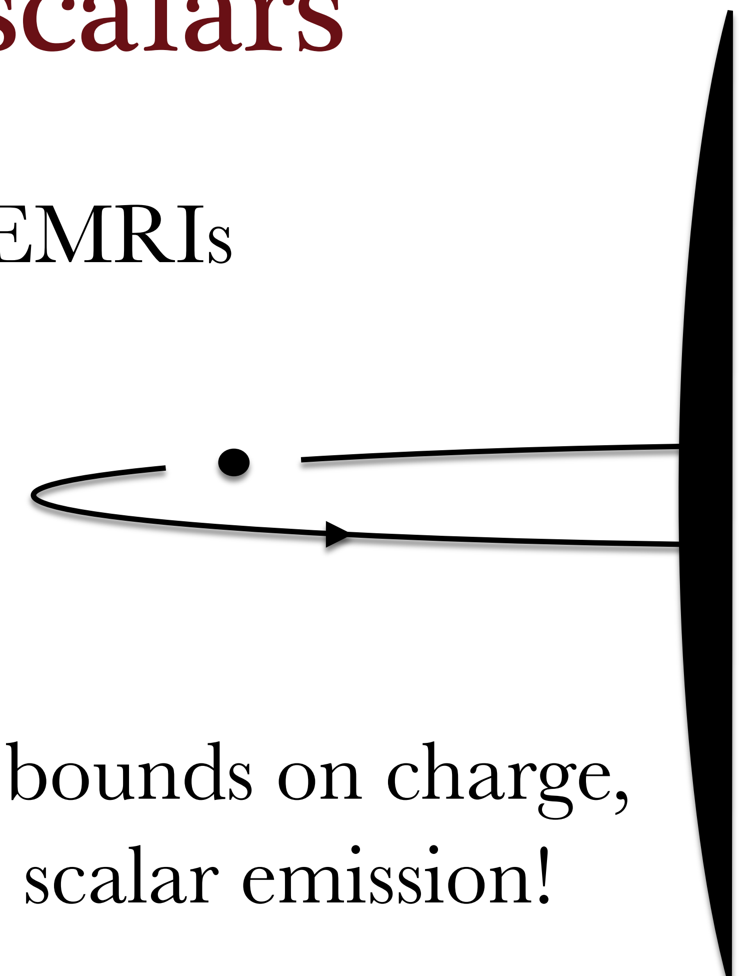
and large (enough) BHs are effectively Kerr BHs!

Probes for massless scalars

BH Binaries



EMRIs



weaker bounds on charge for larger masses

stronger bounds on charge, but from scalar emission!

A. Maselli, N. Franchini, L. Gualtieri, and T.P.S, PRL 125, 14, 141101 (2020)
A. Maselli, N. Franchini, L. Gualtieri, T.P.S, S. Barsanti, P. Pani, Nature Astronomy (2022)

Ultra-light scalars: same except

S. Barsanti, A. Maselli , T.P.S, L. Gualtieri, PRL (accepted), arXiv:2212.03888 [gr-qc]

- superradiance-powered clouds
- spin-induced scalarization

A. Dima, E. Barausse, N. Franchini, and T.P.S, PRL 125, 231101 (2020)

EMRIs beyond GR

A. Maselli, N. Franchini, L. Gualtieri, and T.P.S, PRL 125, 14, 141101 (2020)

$$S\left[\mathbf{g},\varphi,\Psi\right]=S_0\left[\mathbf{g},\varphi\right]+\alpha S_{\mathrm{c}}\left[\mathbf{g},\varphi\right]+S_{\mathrm{m}}\left[\mathbf{g},\varphi,\Psi\right]$$

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

Define dimensionless $\zeta\equiv\frac{\alpha}{M^n}=q^n\frac{\alpha}{m_p^n}$

Assume $\frac{\alpha}{m_p^n}\leq 1$

and solutions continuously connected to GR as $\alpha\to 0$

Then contributions from S_c are suppressed by at least q^n

EMRIs beyond GR

A. Maselli, N. Franchini, L. Gualtieri, and T.P.S, PRL 125, 14, 141101 (2020)

The field equations then become

$$G^{\alpha\beta} = 8\pi m_p \int \frac{\delta^{(4)}\left(x - y_p(\lambda)\right)}{\sqrt{-g}} \frac{dy_p^\alpha}{d\lambda} \frac{dy_p^\beta}{d\lambda} d\lambda$$

$$\Box\varphi = -4\pi d m_{\mathrm{p}} \int \frac{\delta^{(4)}\left(x - y_p(\lambda)\right)}{\sqrt{-g}} d\lambda$$

We use these to study an EMRI with

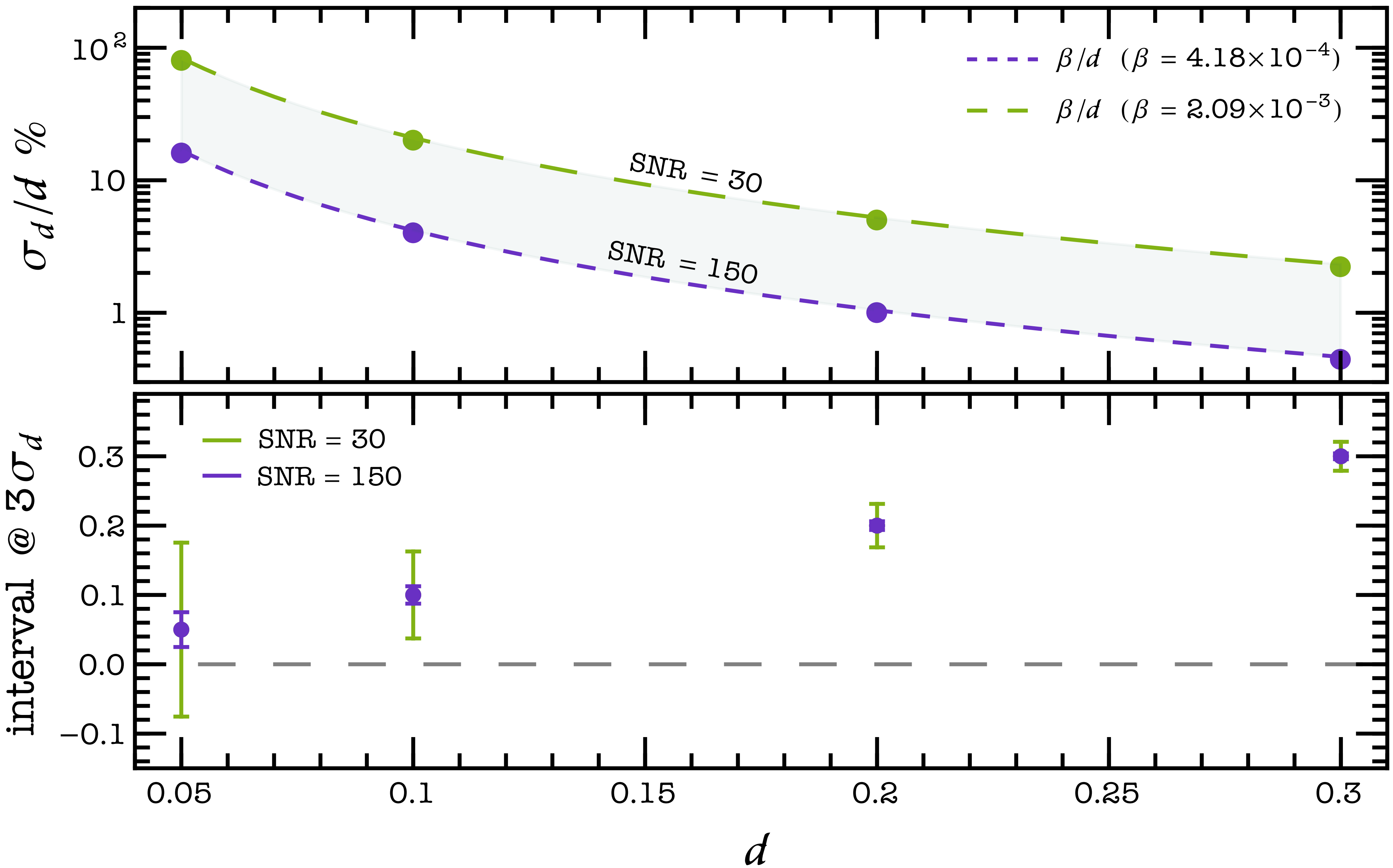
$$M = 10^6 M_\odot \qquad J/M^2 = 0.9 \qquad m_p = 10 M_\odot$$

Modelling: perturbative, quadrupole approximation, equatorial orbit

Parameter estimation: Fischer matrix analysis

Scalar Charge

A. Maselli, N. Franchini, L. Gualtieri, T.P.S, S. Barsanti, P. Pani, Nature Astronomy (2022)



Perspectives

More accurate modelling and data analysis is needed

- eccentric orbits

S. Barsanti, N. Franchini, L. Gualtieri, A. Maselli , T.P.S, Phys. Rev. D 106, 044029 (2022)]

- light scalars

S. Barsanti, A. Maselli , T.P.S, L. Gualtieri, PRL (accepted), arXiv:2212.03888 [gr-qc]

- improved waveforms and MCMCs

L. Speri et al, in preparation

- resonances
- environmental effects
- finite-size effects and self-force

A. Spiers, A. Maselli, T.P.S., in preparation

sGB coupling

A. Maselli, N. Franchini, L. Gualtieri, T.P.S, S. Barsanti, P. Pani, Nature Astronomy (2022)