Detecting fundamental fields with LISA observations of extreme mass ratio inspirals

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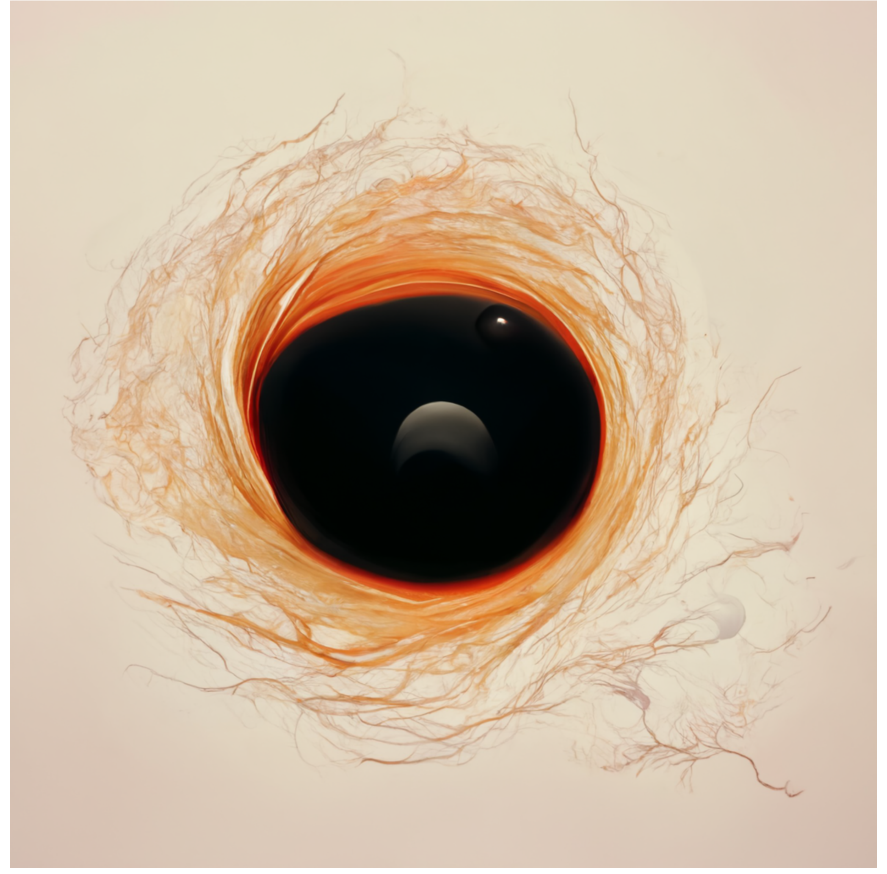


Andrea Maselli

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

MUR PRIN

LISA CONSORTIUM

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?*

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

Science case

- Scalar fields and black holes
- Light scalars ubiquitous in extension of GR and Standard Model

Observables and methodology

- Gravitational waves from very asymmetric binaries

Why EMRIs?

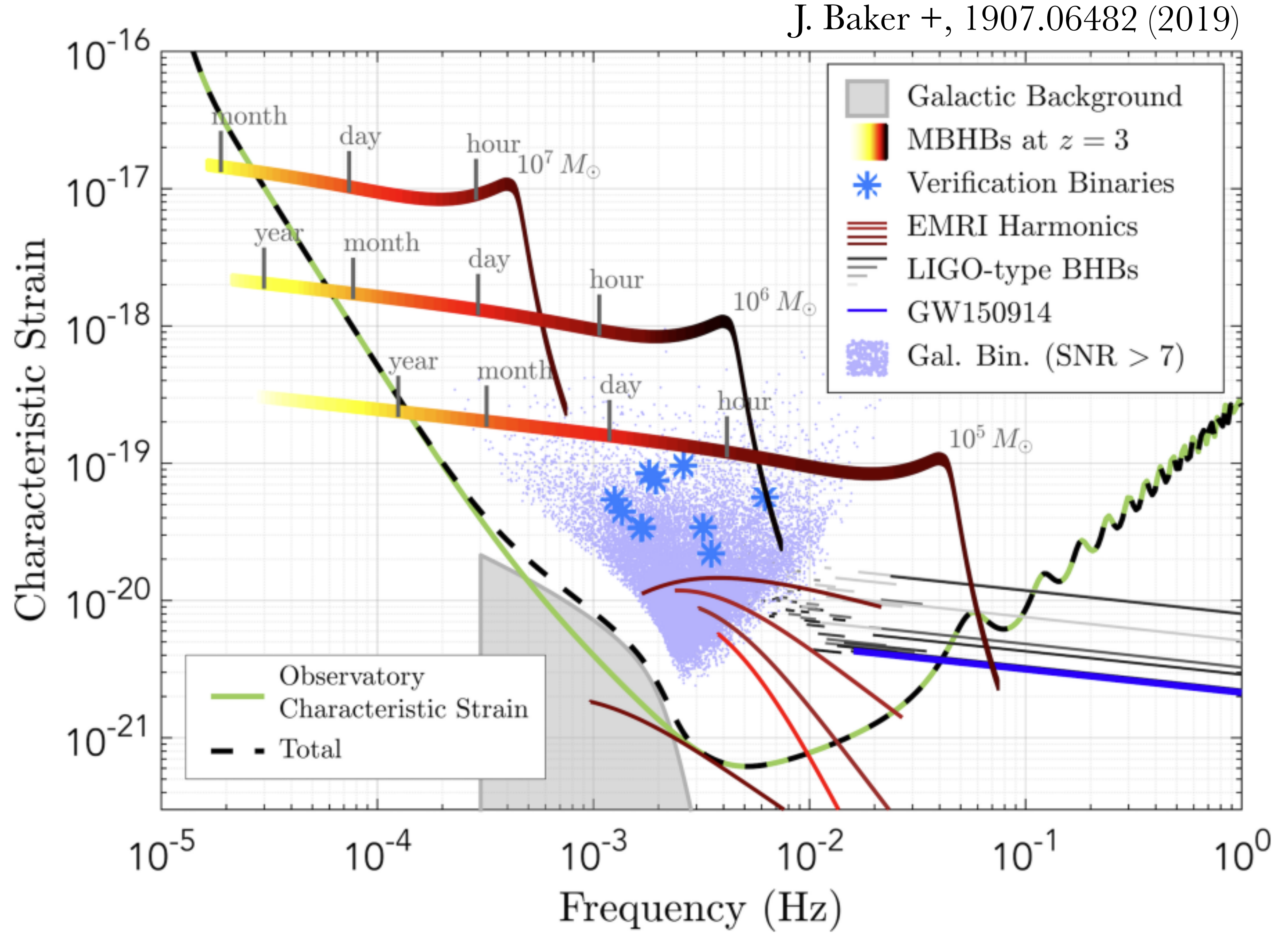
90+ events observed so far from LVK, spanning a relatively small interval of mass ratios $q \sim 1:30$

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

$$m/M = q \sim 10^{-6} - 10^{-7}$$

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

J. Baker +, 1907.06482 (2019)

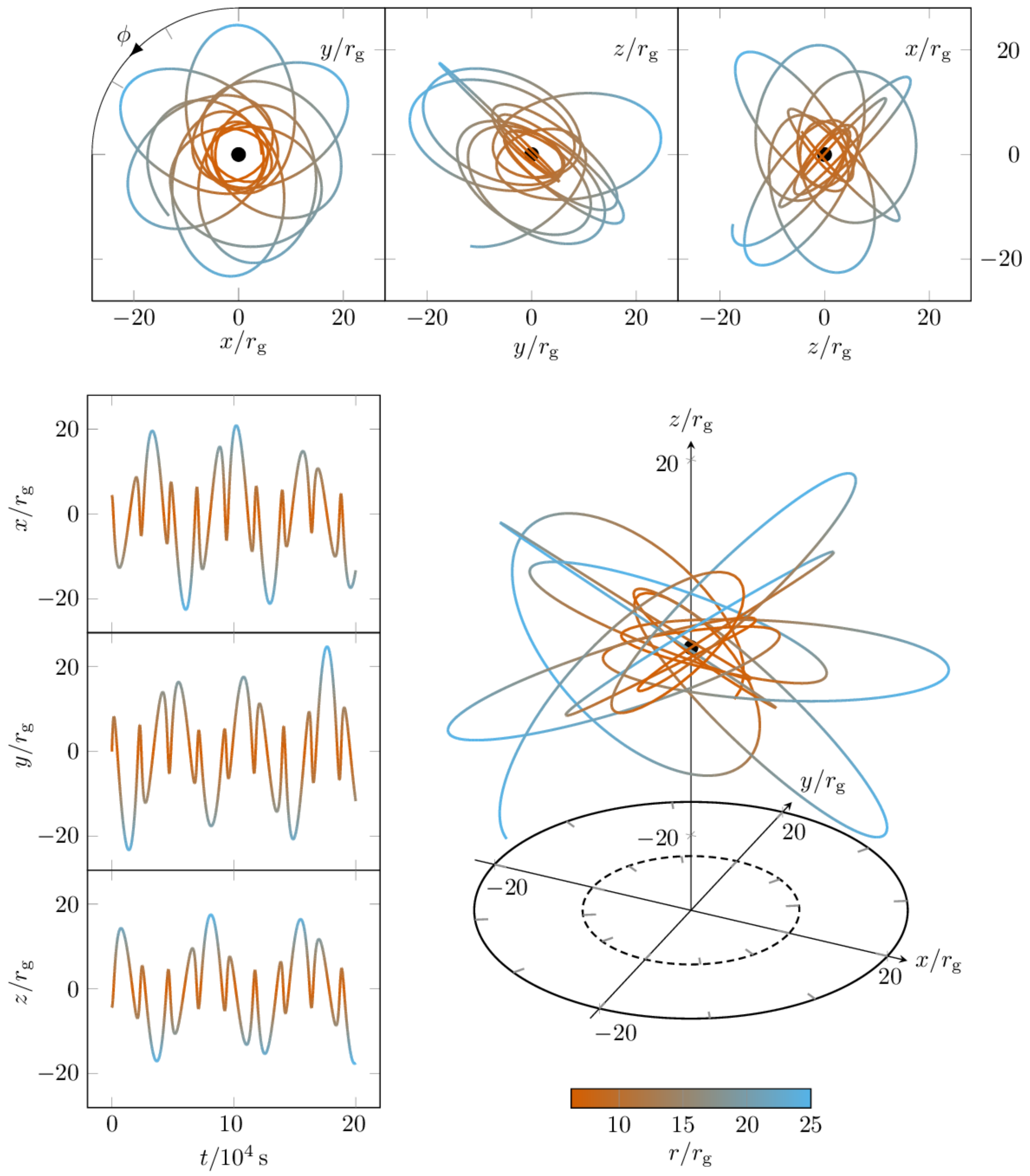


Discovery potential

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

Why EMRIs?

EMRIs provide a rich phenomenology, due to their orbital features



Berry +, Astro2020 1903.03686 (2019)

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

blessing in **disguise**

Tracking EMRIs for O(year) requires accurate templates

Precise space-time map and accurate binary parameters

Very appealing to test fundamental & astro-physics

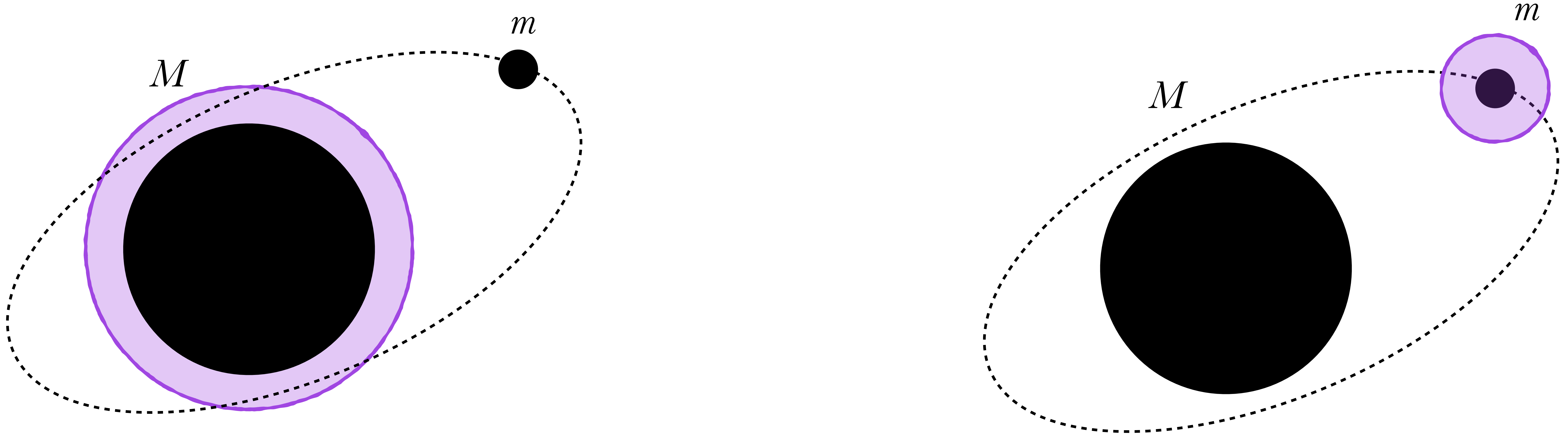
- How do we include and test *new physics* with such sources?
- Do we need a *case-by-case* study?

Why EMRIs? A tale of two sides

A. Avendāno & C. Sopuerta, 2401.08085 (2024)

EMRI conventionally though as probes of the massive BH spacetime

- Fundamental physics will come from testing deviations induced by the primary (new fields, matter components, Kerr hypothesis…)
    - Highly non-trivial task (perturbations on non-Kerr background) A. Chung & N. Yunes, 2006.11986 (2024)



- In some cases decoupling of scales makes deviations from the massive primary negligible
    - Natural simplifications for SF calculations
    - EMRIs as probes of fundamental physics because of the secondary

Why EMRIs? Are we sensitive to new fields?

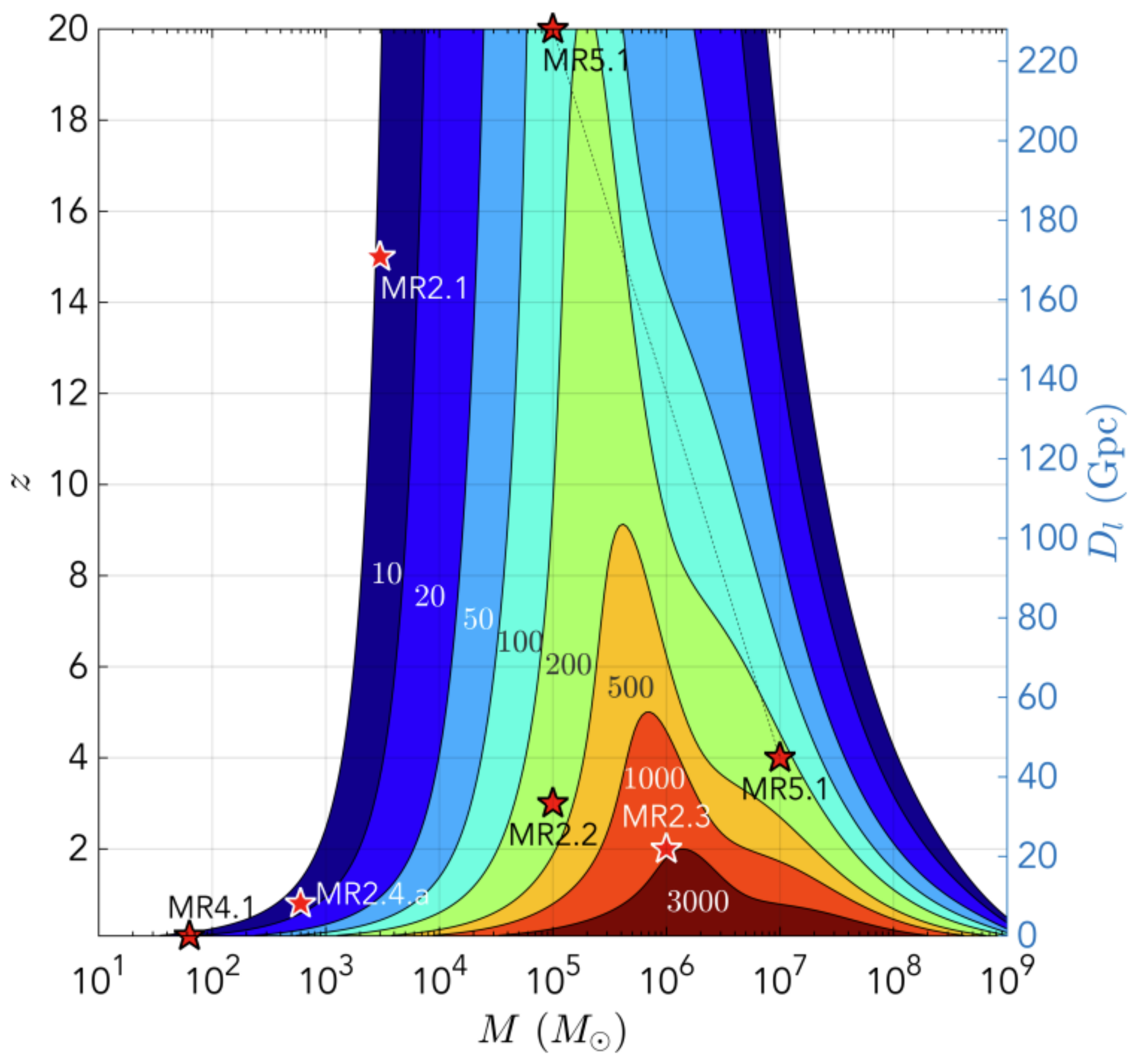
Do large signal-to-noise ratios provide a better opportunity to test General Relativity?

- LISA is expected to detect the loudest events in the Universe
- Can we use them to test GR deviations?

It may be tempting to answer NO

- Many theories have no-hair theorems: same BH as in GR
- When no-hair is violated, GR deviations tend to have dimensionful couplings and scale as $1/mass^n$

Massive, large-snr, BBH are less suited than expected for testing GR



- Never forget of the little ones! (NS or stellar BH) → *EMRIs are the most promising sources for fundamental physics for LISA*

EMRIs: now and then

How do we study EMRIs in GR?

- The asymmetric character introduces a natural parameter to work in perturbation theory, $q = m/M \ll 1$
- The Self-Force program in GR is at work for more than two decades to produce waveforms for LISA (no full waveforms yet!!)

L. Barack & A. Pound, Rept. Prog. Phys. 82, 016904 (2019)

How do we go beyond GR?

- Complexity of calculations beyond GR grows (extremely) fast due to extra degrees of freedoms and couplings
- hard to find Kerr solution beyond GR
    - Fully numerical, low spin expansion
- Which theory should we go after?

→ desirable to have general, minimal framework, possibly built to exploit the Self-Force formalism developed in GR

A new approach

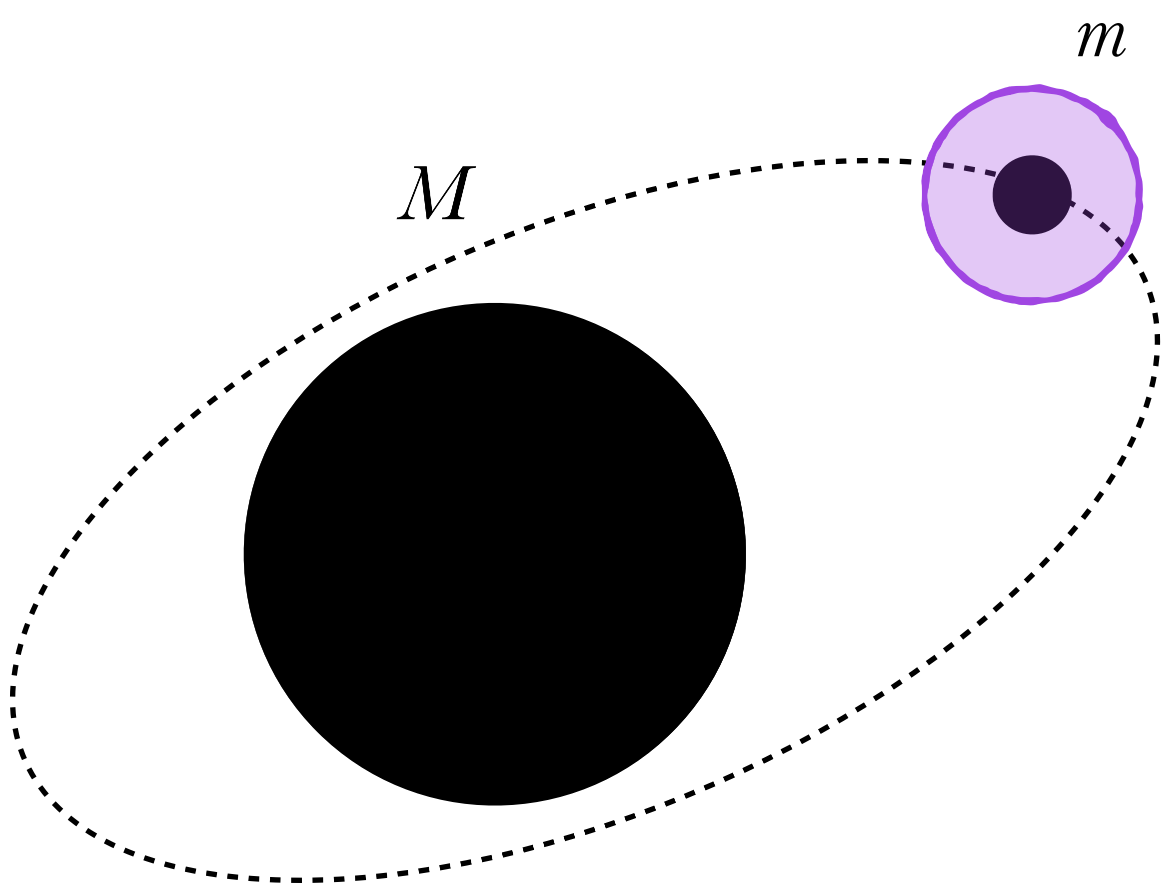
Use suppressions of GR deviations in our "favour" for theories with new (massless) scalar fields

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

GR — scalar field coupling — matter fields

- deviations from GR scale as $\alpha/(mass)^n$
- black hole "charges": primary charge ~ α/M^n and secondary charge ~ α/m^n

EMRI decoupling → *MBH described by Kerr* + *secondary endowed with a charge* ***d***



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

- Only change given by extra emission of energy due to the scalar field

A.M. +, PRL 125, 141101 (2020)
A. Spiers, A. M., T. Sotiriou, PRD 109, 064022 (2024)

Universal family of waveforms

The recipe to generate EMRI waveforms

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

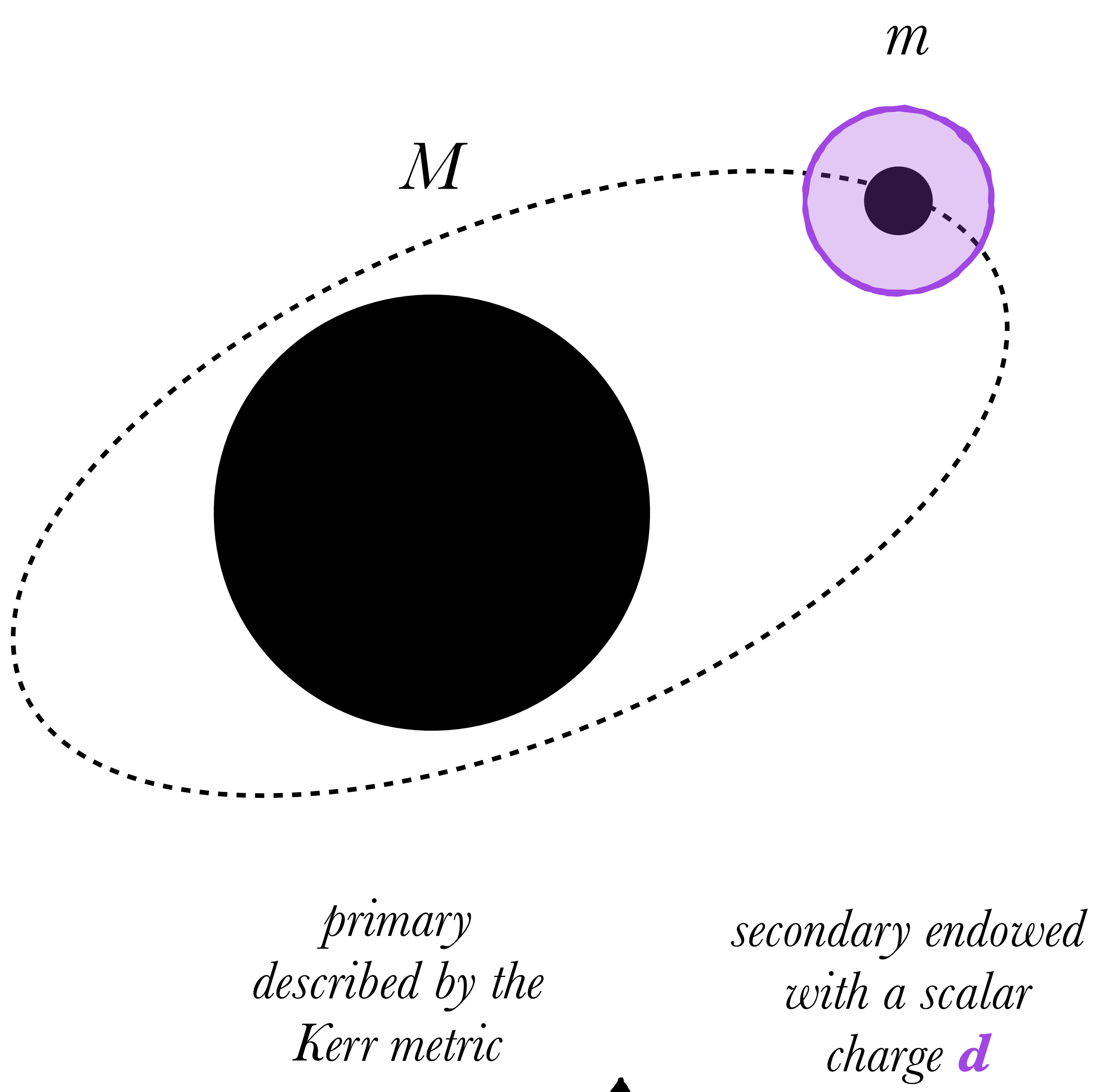
2. Determine the dynamics $\frac{dr(t)}{dt} = -\dot{E}\frac{dr}{dE_{\rm orb}}$ $\quad \frac{d\phi(t)}{dt} = \frac{M^{1/2}}{r^{3/2} + M^{3/2}\chi}$

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 $d^2\delta\dot{E}$, which depends on the scalar charge



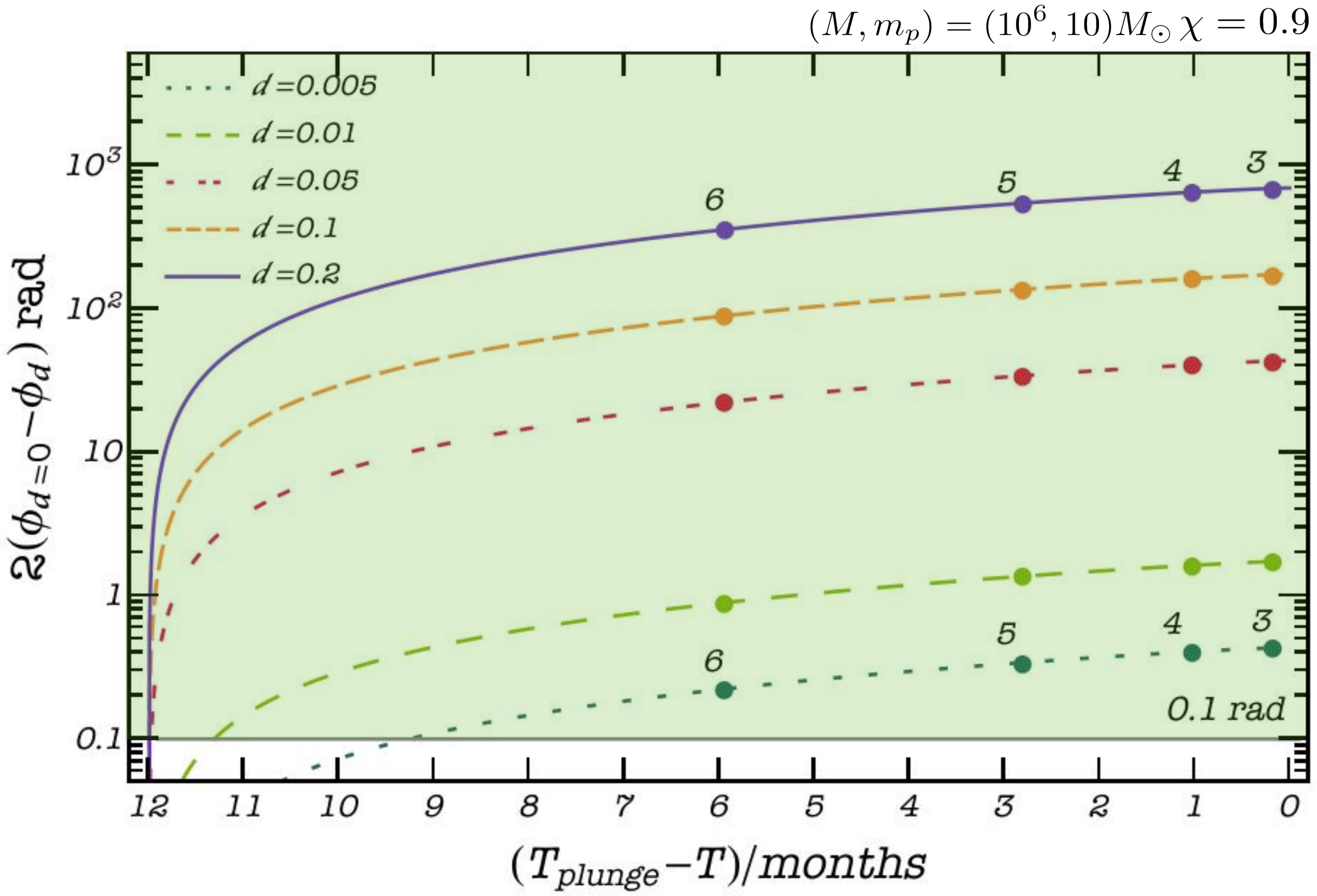
The binary accelerates due to the extra leakage

- Universal family of waveforms to be tested against GR

GW dephasing

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

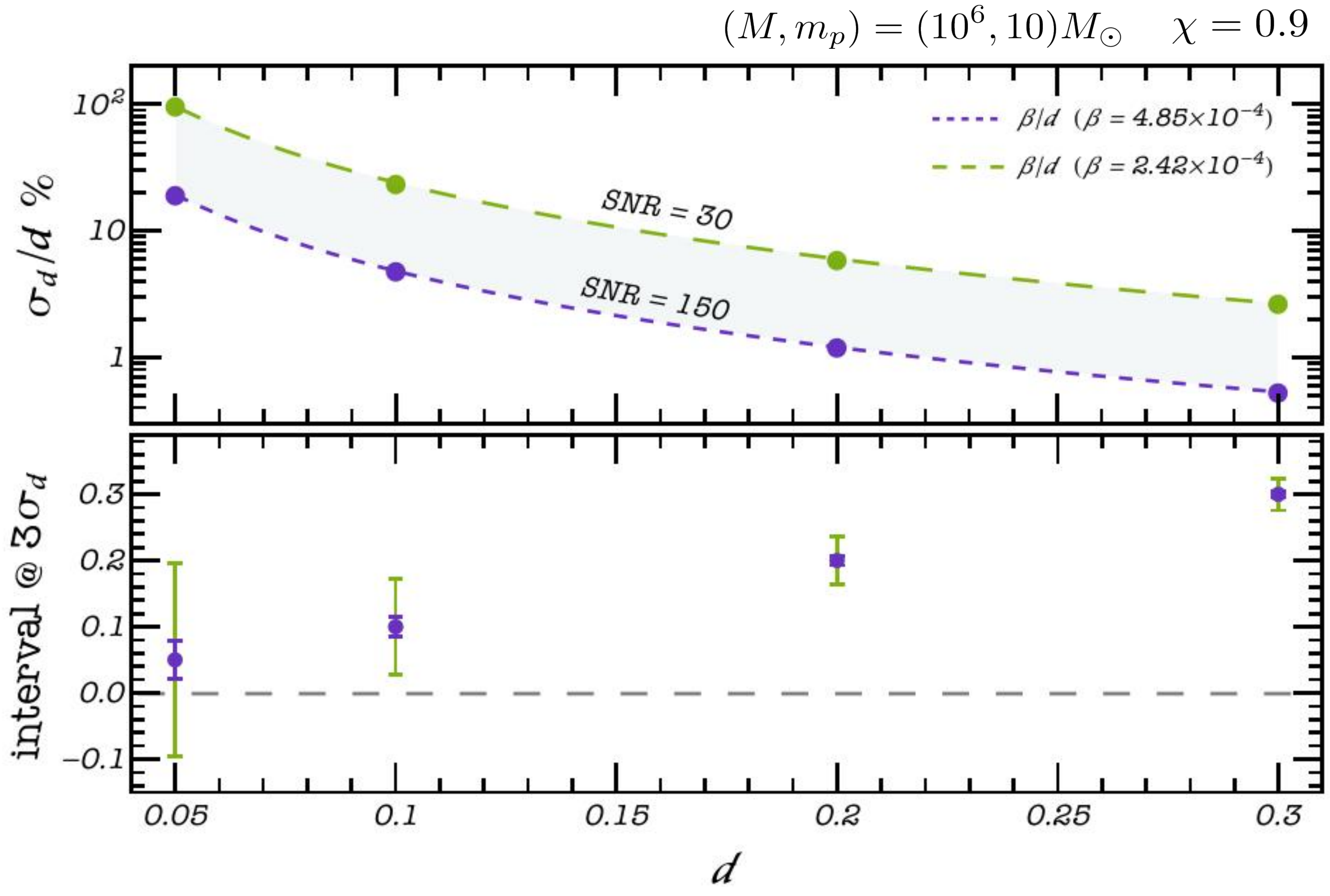
Difference in phase evolution of EMRI in GR v.s. GR scalar charge d



First constraints

Constraints on the scalar charge for prototype EMRIs with SNR = (30,150) and 1 year of evolution in LISA

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



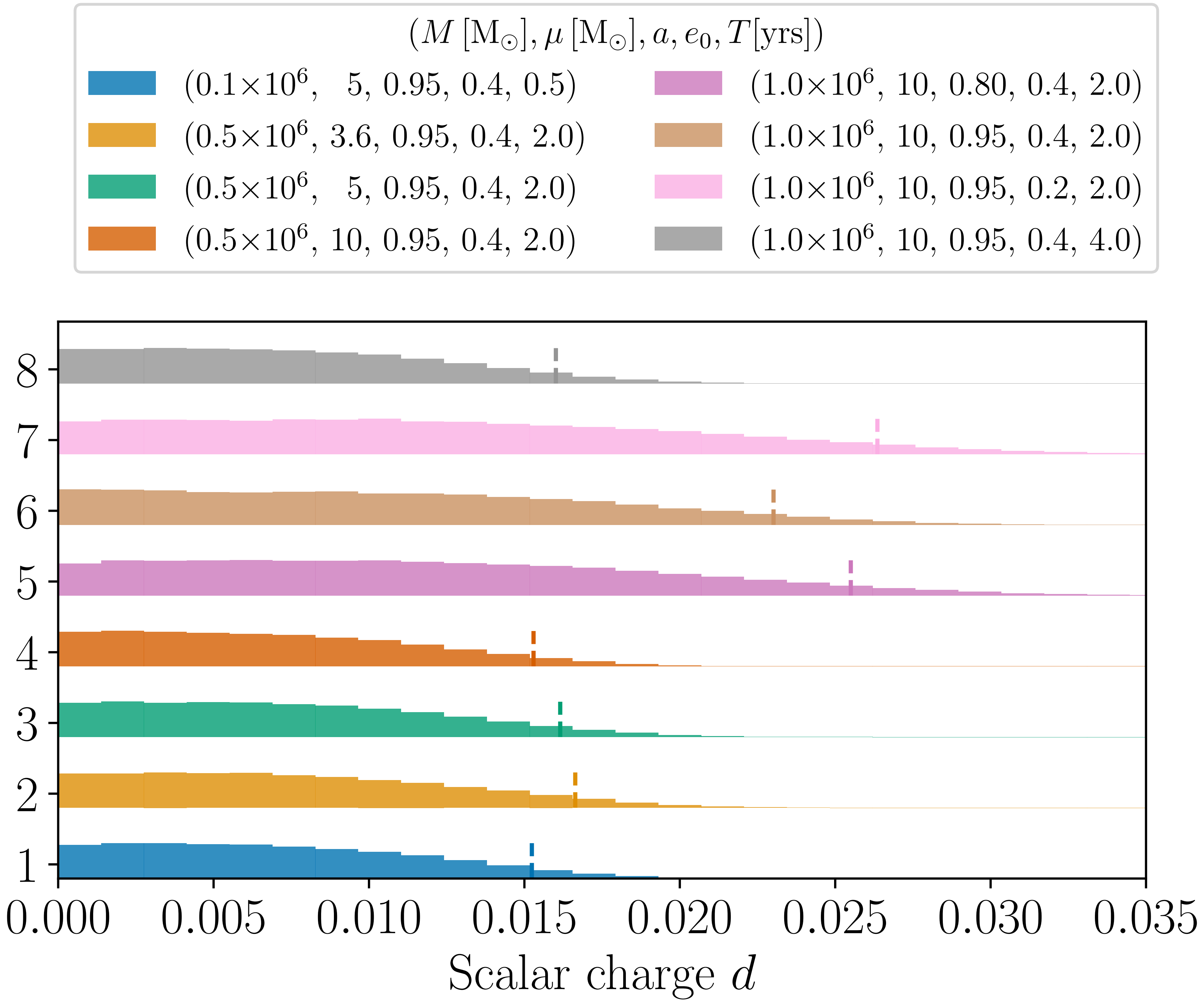
- LISA potentially able to measure the charge d with % accuracy and better

Fast EMRI Waveforms

Non-GR waveforms installed into the LISA pipeline FastEmriWaveforms [L. Speri +, 2406.07607 (20214)]

- First fully Bayesian *agnostic* constraints on d from LISA
  - Waveforms with equatorial, eccentric orbits around Kerr

Smallest detectable charge for different EMRI configurations

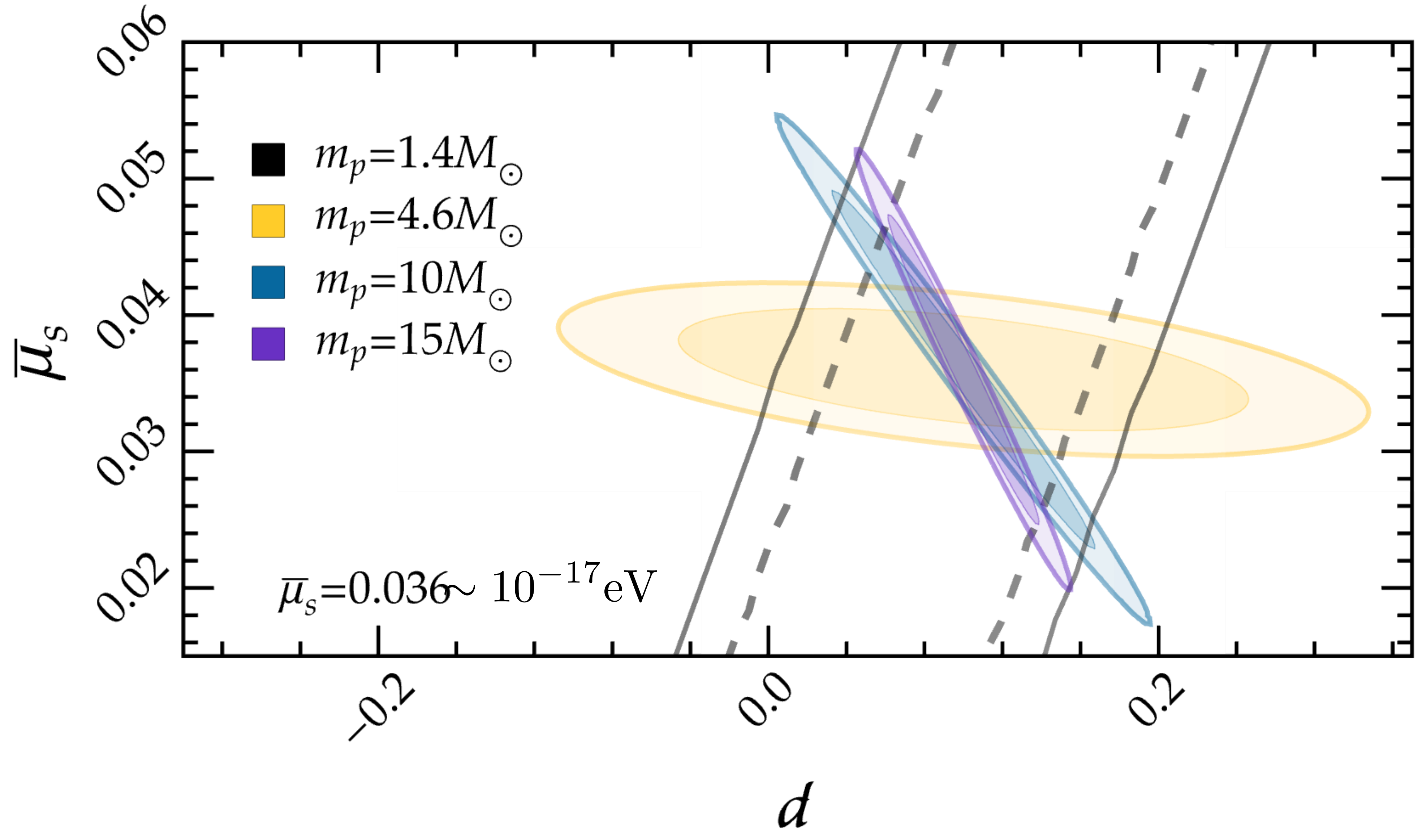


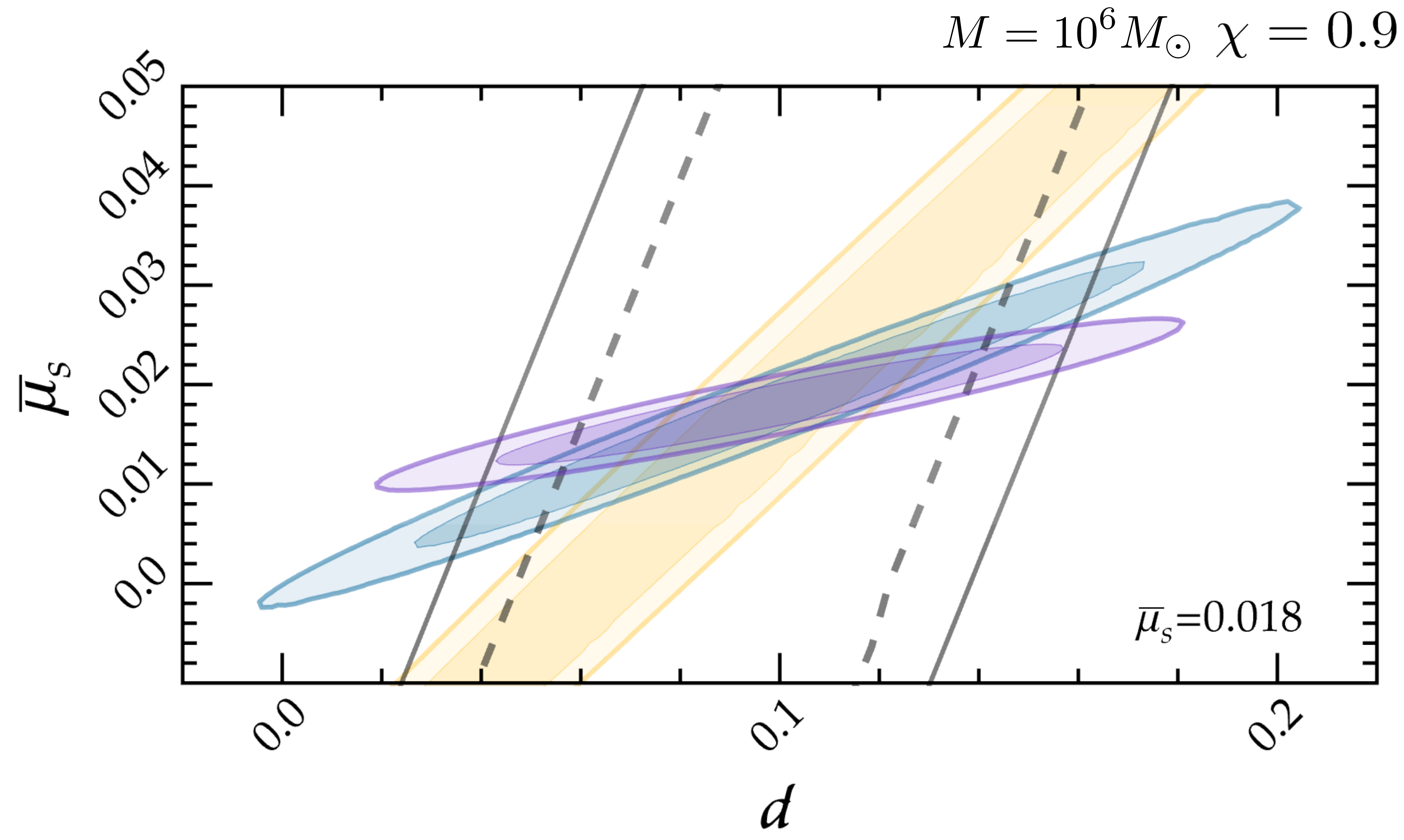
Ultra-light fields

Extension to massive fields: joint constrains on the scalar field mass and on the charge [S. Barsanti +, PRL 131, 051401 (2023)]

- Appealing as they are common to BSM models and dark matter candidates

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



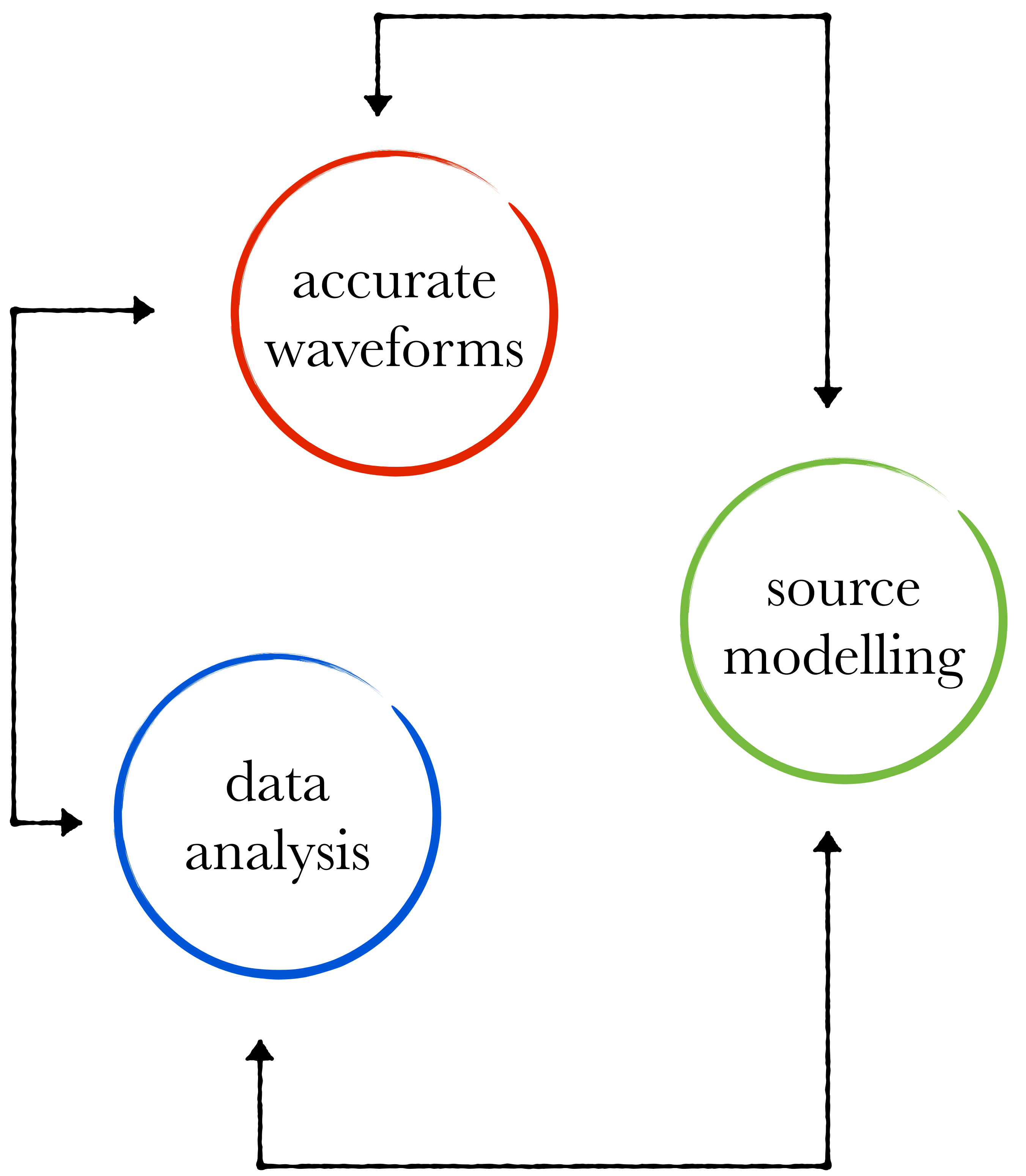


Summary

Can we test the existence of fundamental fields with LISA?

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
- Scalar fields can leave a significant (detectable) imprint in the GW signal emitted by EMRIs.
- Universal family of waveform to test GR. Ready-to-use waveforms



But

- What about other fields?
- Correlation with astrophysical effects?
- Generic orbits, resonances? (work in progress S. Gliorio, M. Della Rocca, S. Barsanti)

Back up

Decoupling of scales

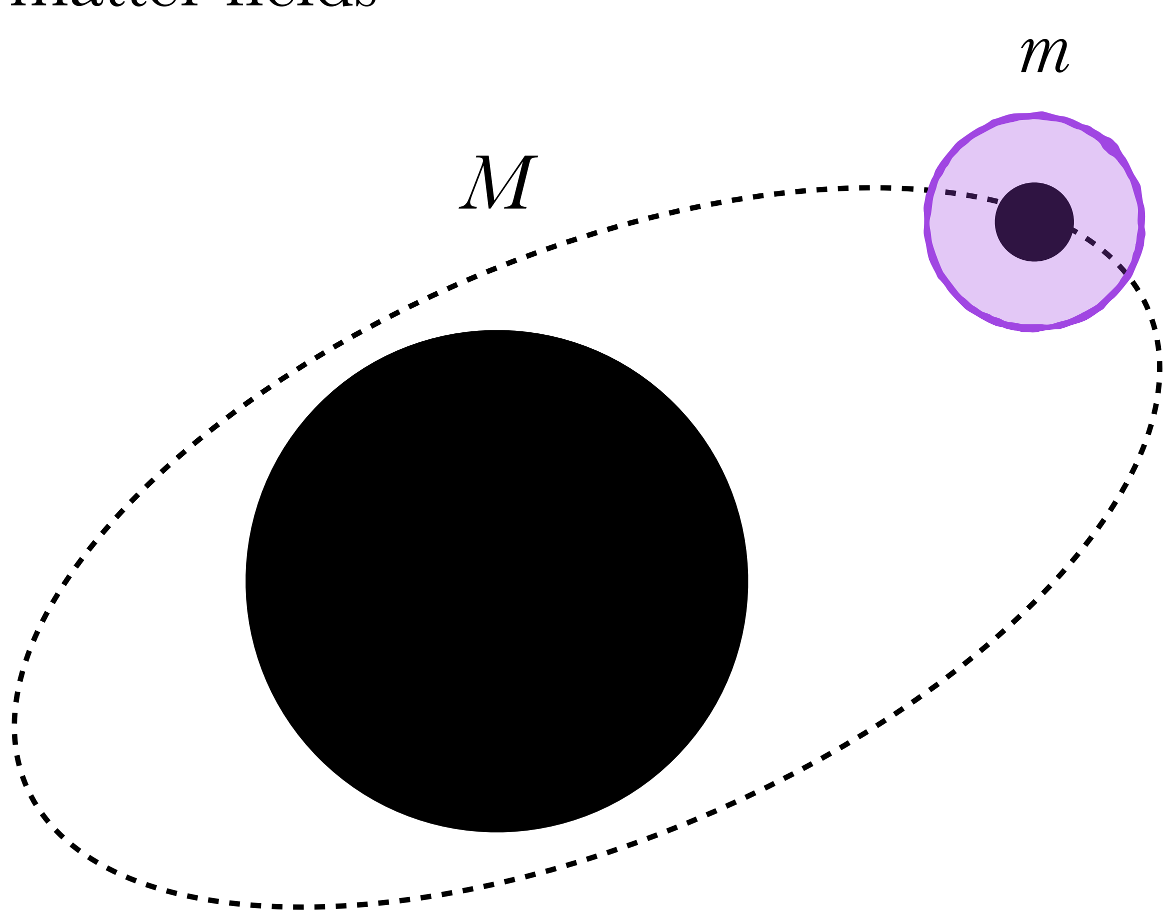
Shift-symmetric theories with massless scalar field(s) φ non-minimally coupled to gravity

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

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

non-minimal coupling

matter fields



- α has dimensions [length]^n $n \geq 2$ (negative energy dimensions)
- deviations from GR scale as $\alpha/(mass)^n$
  - black hole "charges" $\sim \alpha/M^n$ and α/m^n

EMRI decoupling → *MBH described by Kerr* + *secondary endowed with a charge* ***d***

A.M. +, PRL 125, 141101 (2020)
A. Spiers, A. M., T. Sotiriou, PRD 109, 064022 (2024)

Decoupling of scales

A. Spiers, A.M., T. Sotiriou, PRD 109, 064022 (2024)

Consistent expansion within the SF approach, given $\alpha/M^n = q^n(\alpha/m^n)$

- mass ratio q as single expansion parameter
- modularity with Self-Foce calculations in GR
- field's equations at the linear order $g_{\mu\nu} = g^{(0)}_{\mu\nu} + qh^{(1)}_{\mu\nu} + \ldots$ $\quad \varphi = \varphi^{(0)} + q\varphi^{(1)} + \ldots$

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

↓ *Teukolsky equation as in GR*

↓ *Scalar wave equation on a Kerr background*

$\text{GSF}^{(1)} + \text{SSF}^{(1)}$ → *agnostic waveforms for free*

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

$$\mathbf{a} = \mathbf{a}_{(1)\rm grav} + \mathbf{a}_{(1)\rm scal} + \mathbf{a}_{(2)\rm grav} + \mathbf{a}_{(2)\rm scal} \longleftrightarrow \text{GSF}^{(1)} + \text{SSF}^{(1)} + \text{GSF}^{(2)} + \text{SSF}^{(2)}$$

Ultra-light fields

S. Barsanti A. M., T. Sotiriou, L. Guatlieri, PRL 131, 051401 (2023)

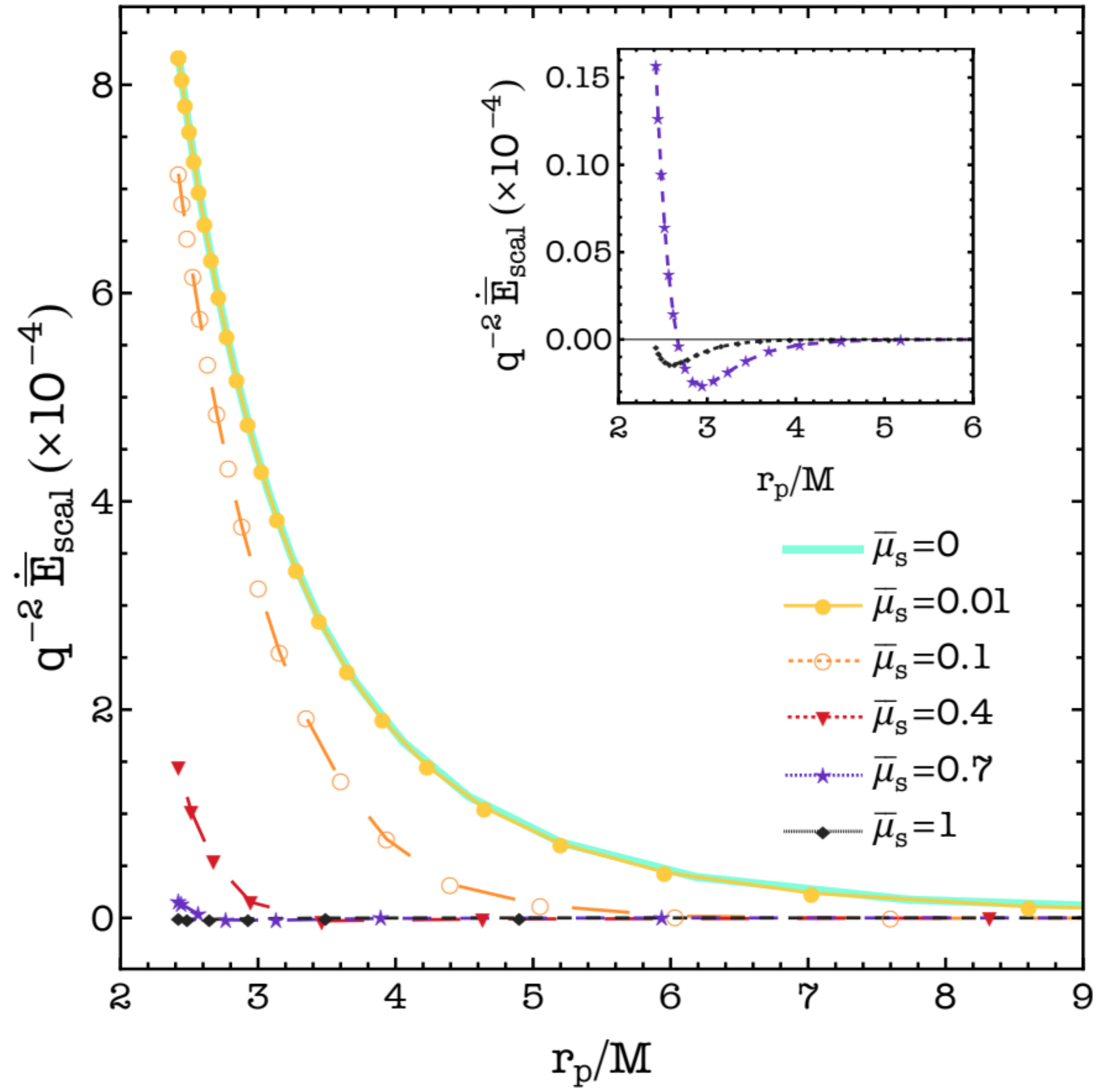
Extension to massive scalar fields

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

New effects arising in the inspiral

- Scalar flux at infinity vanishes for $\omega < \mu_s$
  - For each (ℓ, m) a radius $r > r_s$ $\longrightarrow$ $\dot{E}^{\infty}_{\rm scal} = 0$
  - 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)



Tracing back the couplings

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

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

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

- $[\alpha] = [length^2]$
- $f(\varphi)$ generic function of the scalar field
- $\mathcal{G} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\alpha\beta\mu\nu}R^{\alpha\beta\mu\nu}$ Gauss Bonnet invariant
  - Scalar charge proportional to the dimensionless coupling constant $\beta = \dfrac{\alpha}{m_p^2}$

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

(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

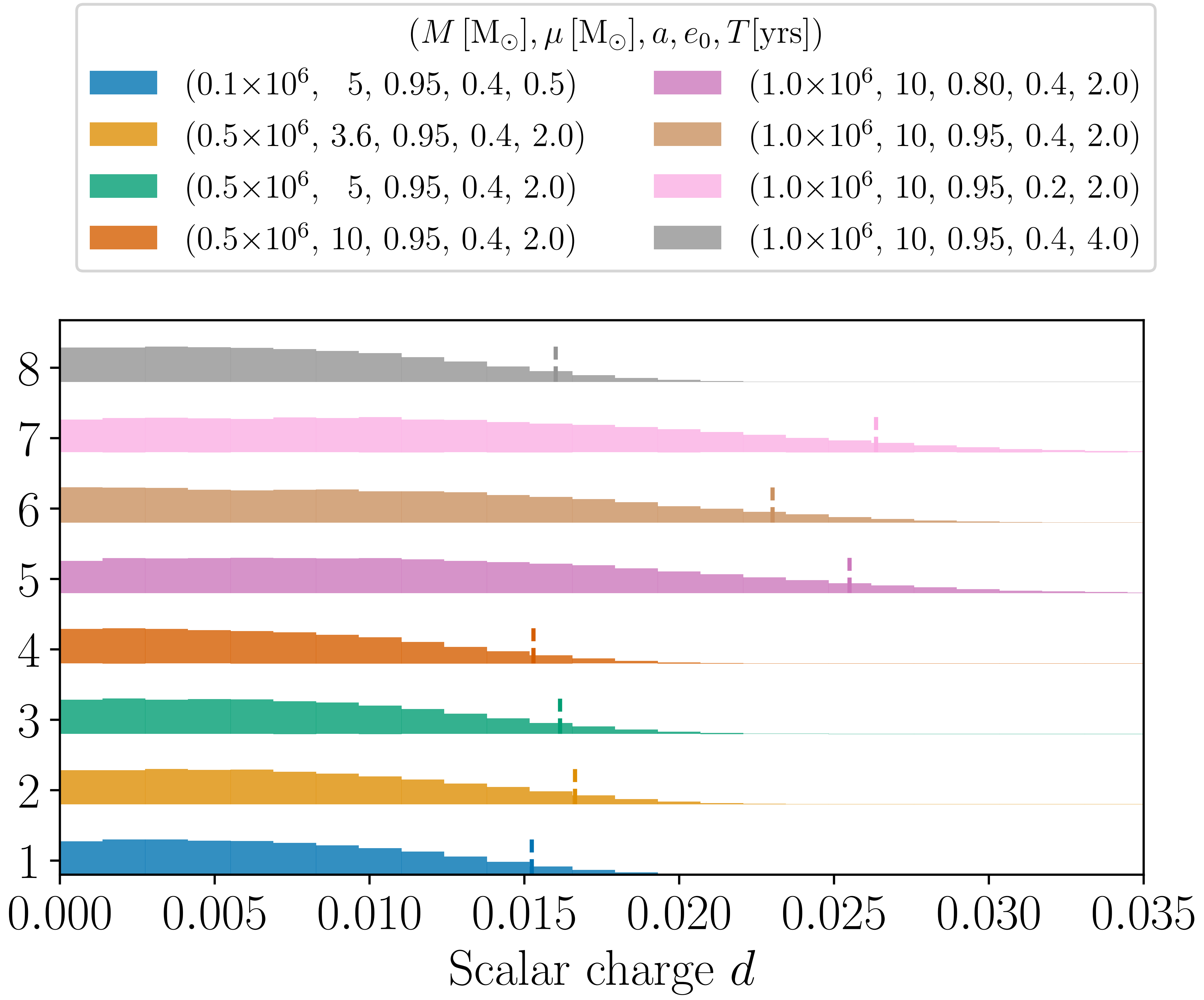
Tracing back the couplings

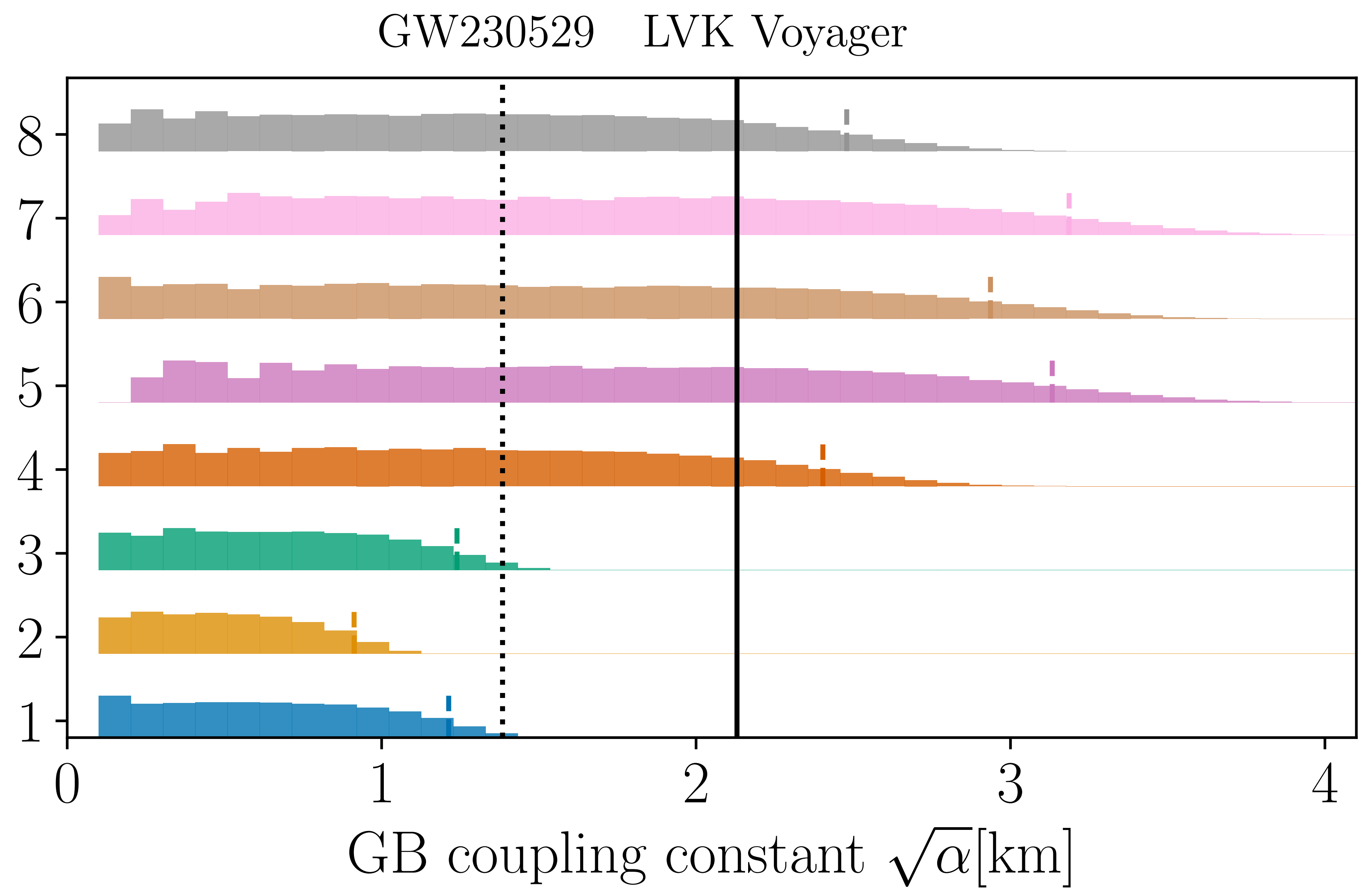
A.M. +, Nature Astronomy 6, 4 464-470 (2022)
F. Julié & E. Berti, PRD 100, 104610 (2019)

Map constraints on the charge to the coupling of shift-symmetric GB gravity

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

$$d \sim \frac{2\alpha}{m^2}$$





B. Gao +, 2405.13279 (2024)
E. Sanger +, 2406.03568 (2024)
S. E. Perkins +, PRD 103, 044024 (2021)