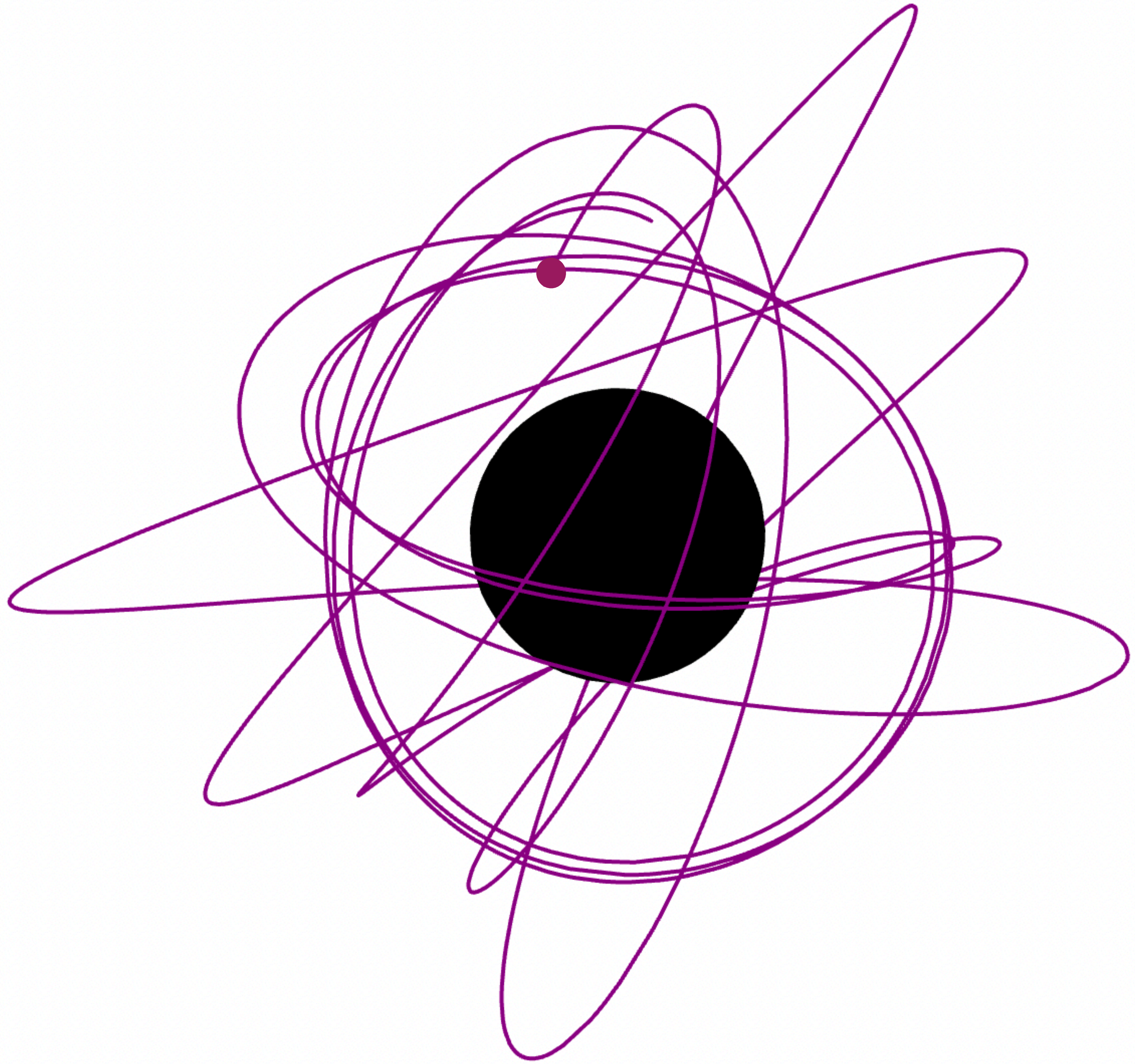

EMRIs & new fundamental fields

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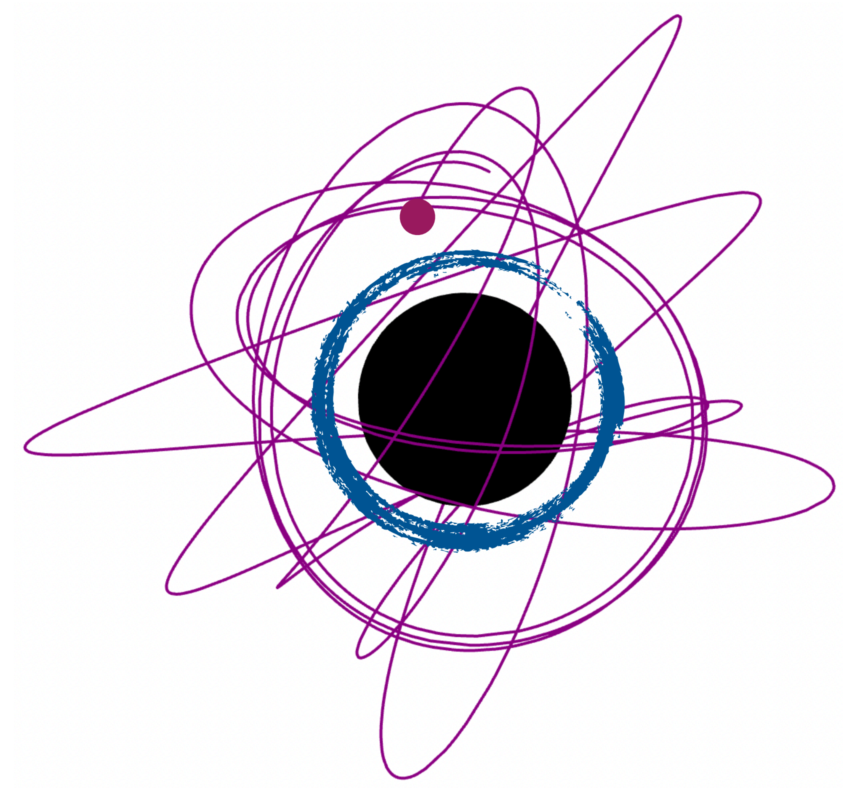
Asymmetric Binaries: Extreme Mass Ratio Inspirals

Stellar mass compact object (BH or NS) inspiralling into a massive black hole (MBH)

- Primary of $M \in (10^5, 10^9)\ M_\odot$
- Secondary of $m_p \ll M$, so that the mass ratio $q = m_p/M \sim (10^{-7} - 10^{-4})$
- Emit GWs in the mHz, main targets of LISA
- Complete $\sim 10^4 - 10^5$ orbits before the plunge



Focus on the *PRIMARY*:

- Detailed map of the spacetime around the *primary*
- Pinpoint deviation induced by the primary (new fields, Kerr hypothesis ..)
- EMRIs as probes of the MBH spacetime
- Perturbations on a non-Kerr background

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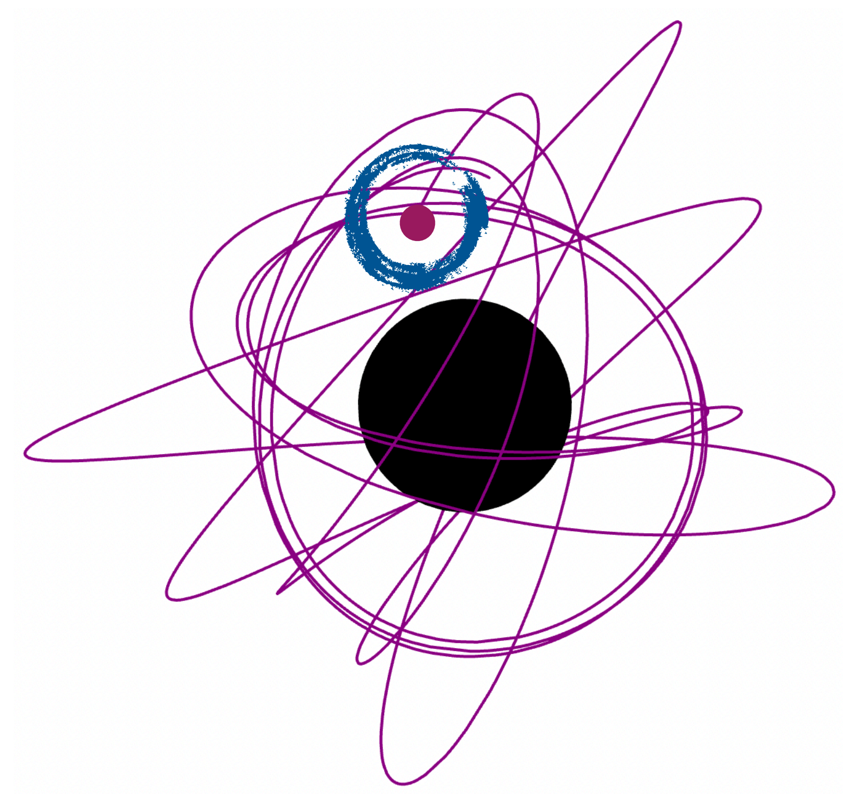


Change of the paradigm: Focus on the *SECONDARY!*

- In some cases, due to the asymmetry in the masses the deviations from the primary are negligible
- Deviations come from the secondary
- Perturbations on a Kerr background

The Action

Theory agnostic approach: shift-symmetric theories with a new massless scalar field

- *generalised scalar-tensor theories*
- *scalar Gauss-Bonnet*
- *dynamical Chern Simons*
- *f(R) theories ...*

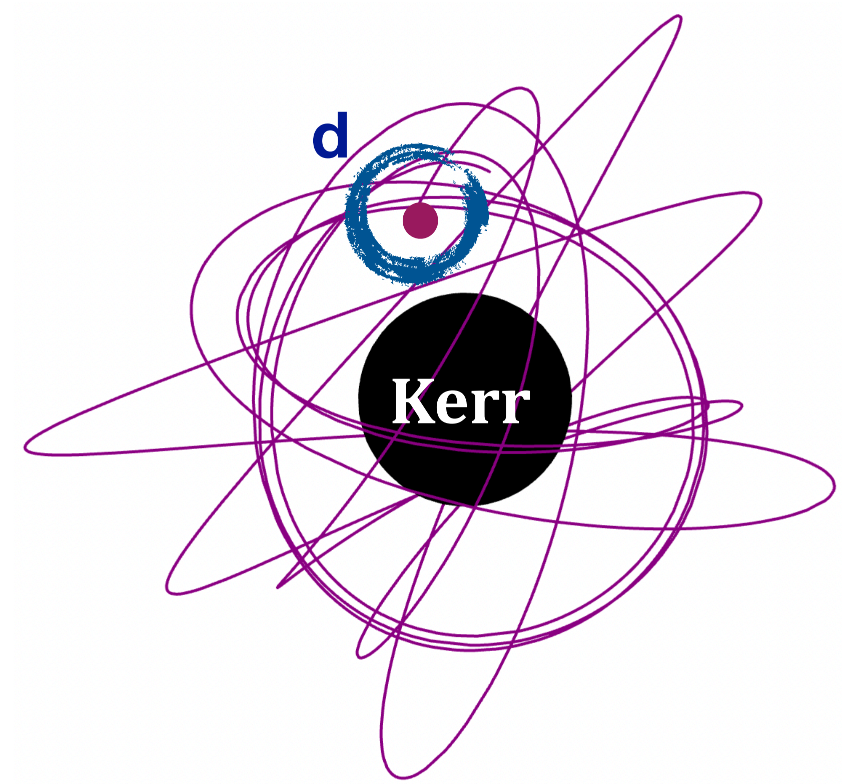
$$S\left[\mathbf{g},\varphi,\Psi\right]=S_0\left[\mathbf{g},\varphi\right]+\alpha S_c\left[\mathbf{g},\varphi\right]+S_m\left[\mathbf{g},\varphi,\Psi\right]$$

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

Non minimal coupling

matter fields Ψ

- $[\alpha]=(\mathrm{mass})^{\mathrm{n}}$
- $n\geq 2$
- BH scalar "charge" $\sim\dfrac{\alpha}{(\mathrm{mass})^n}$
- For EMRIs: black hole charges $\sim\alpha/M^n$ and α/m_p^n



Decoupling of scales: **Kerr** **MBH** + **secondary** with scalar charge **d**

Fields Equations

- Dimensionless coupling $\zeta \equiv \frac{\alpha}{M^n} = q^n \frac{\alpha}{m_p^n} \ll 1$
- Single expansion parameter: mass ratio q
- Self-Force (SF) scheme $\longrightarrow g_{\mu\nu} = g^{(0)}_{\mu\nu} + q h^{(1)}_{\mu\nu} + \mathcal{O}(q^2)$

  [A. Spiers+, Phys.Rev.D 109 (2024) 6, 064022] $\longrightarrow \varphi = \varphi^{(0)} + q\varphi^{(1)} + \mathcal{O}(q^2)$

<u>First order:</u>

$$G^{(1)}_{\mu\nu} = 8\pi m_p \int \frac{\delta^{(4)}(x - y_p(\lambda))}{\sqrt{-g}} \frac{dy^p_\mu}{d\lambda} \frac{dy^p_\nu}{d\lambda} d\lambda \qquad \Box\, \varphi^{(1)} = -4\pi\, d\, m_p \int \frac{\delta^{(4)}(x - y_p(\lambda))}{\sqrt{-g}} d\lambda$$

- same as in GR

- universal: all the information of the theory are enclosed in d

Solved with the Teukolsky approach: $\psi^{(s)}(t, r, \theta, \phi) = \int d\omega \sum_{\ell m} R^{(s)}_{\ell m}(r, \omega) S^{(s)}_{\ell m}(\theta, \omega) e^{im\phi} e^{-i\omega t}$

<u>Second order:</u> $a = a_{(1)grav} + a_{(1)scal} + a_{(2)grav} + a_{(2)scal}$

The research project: mindset & literature

- EMRIs + scalar fields: *A. Maselli+, Phys.Rev.Lett.* 125 (2020) 14, 141101

➡ **<u>Post-adiabatic terms</u>**

- Formalism: *A. Spiers+, Phys.Rev.D 109 (2024) 6, 064022*
- Implementation: In progress…

➡ **<u>Orbits</u>**

- Equatorial eccentric around Kerr: *S.B+, Phys.Rev.D 106 (2022) 4, 044029*
- Circular inclined around Kerr : *M. Della Rocca+, Phys.Rev.D 109 (2024) 10, 104079*
- Generic (eccentric&inclined): In progress… *S. Glorio+*

➡ **<u>Parameter estimation</u>**

- Fisher Information Matrix: *A. Maselli+, Nature Astron. 6 (2022) 4, 464-470*
- Markov Chain Monte Carlo: *L. Speri+, ArXiv2406.07607*

➡ **<u>Non shift-symmetric fields</u>**

- Massive scalar fields: *S.B+, Phys.Rev.Lett. 131 (2023) 5, 051401*

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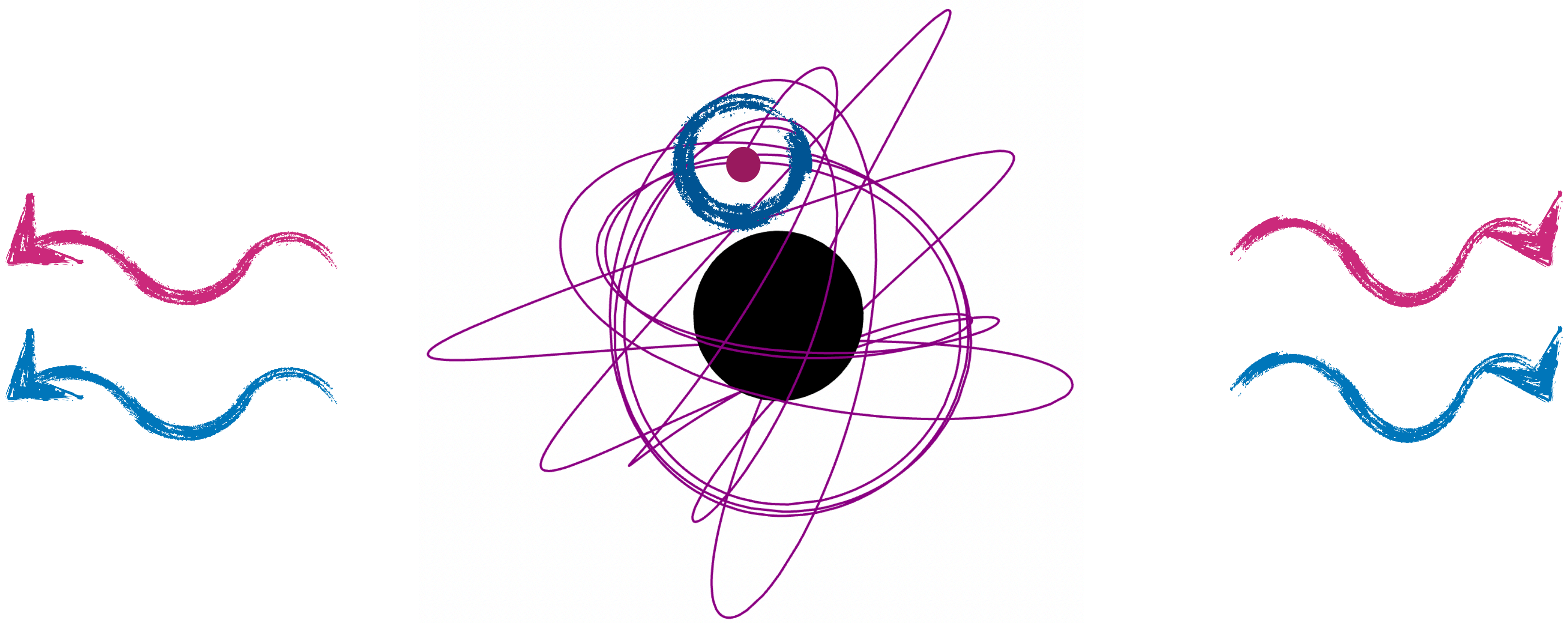
Modeling Steps



- *Energy emission trough gravitational and scalar waves*

$$\dot{E}_W = \sum_{i=+,-} [\dot{E}^{(i)}_{\rm grav} + \dot{E}^{(i)}_{\rm scal}] = \dot{E}_{grav} + \dot{E}_{scal} \longrightarrow \dot{E}_{scal} \propto d^2$$

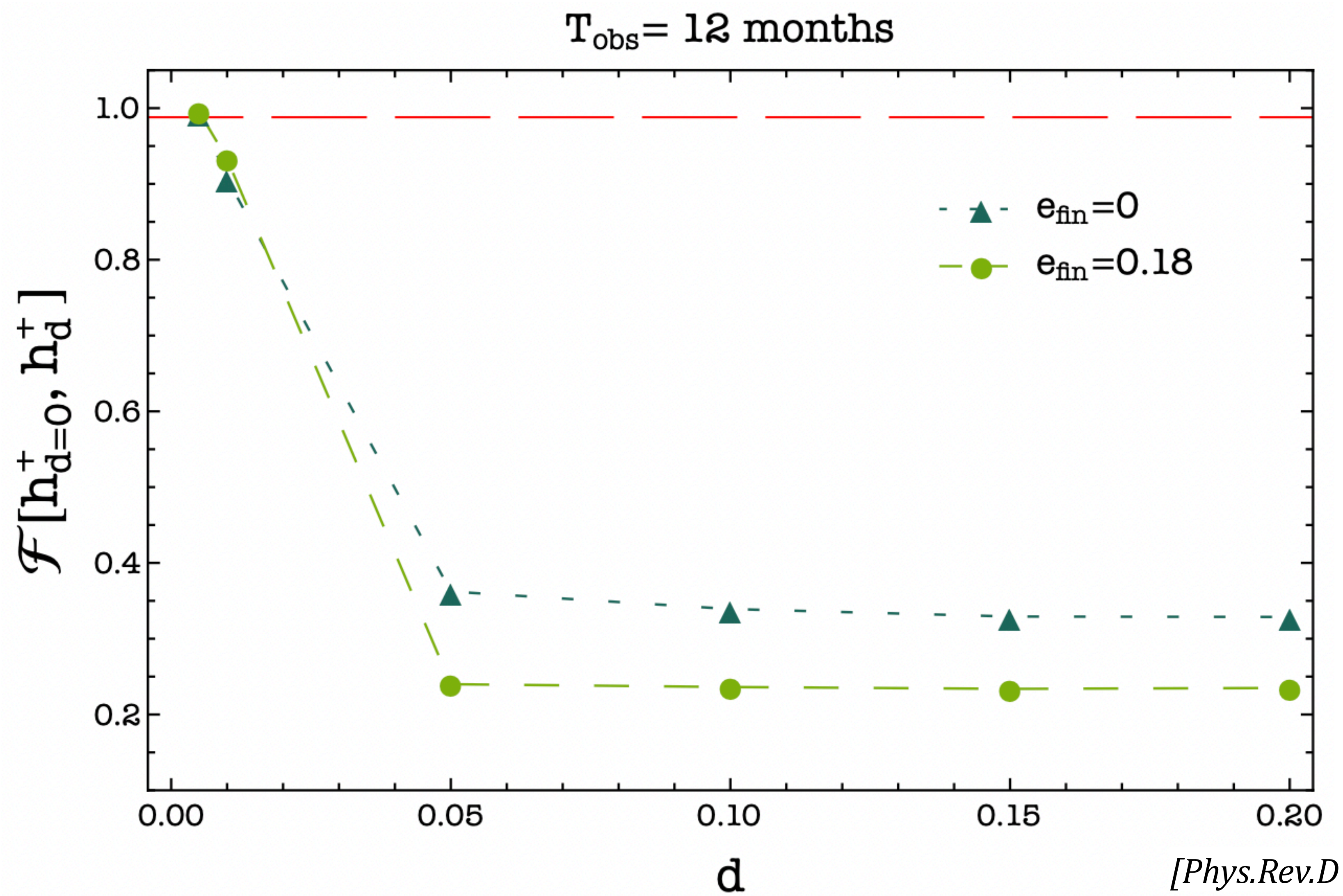
EXTRA emission *simply added* to the gravitational one!

- *Adiabatic orbital evolution through a sequence of geodesics*
- *Imprint on the gravitational waves: dephasing, faithfulness*
- *Parameter estimation: FIM, MCMC*

Faithfulness: Equatorial ECCENTRIC EMRIs

Estimate of how much two signals differ: $\mathcal{F}[h_1, h_2] = \max_{\{t_c,\phi_c\}} \frac{\langle h_1|h_2\rangle}{\sqrt{\langle h_1|h_1\rangle\langle h_2|h_2\rangle}}$

Inner product $\langle h_1|h_2\rangle = 4\Re \int_{f_{min}}^{f_{\max}} \frac{\tilde{h}_1(f)\tilde{h}_2^\star(f)}{S_n(f)} df$ LISA power spectral density

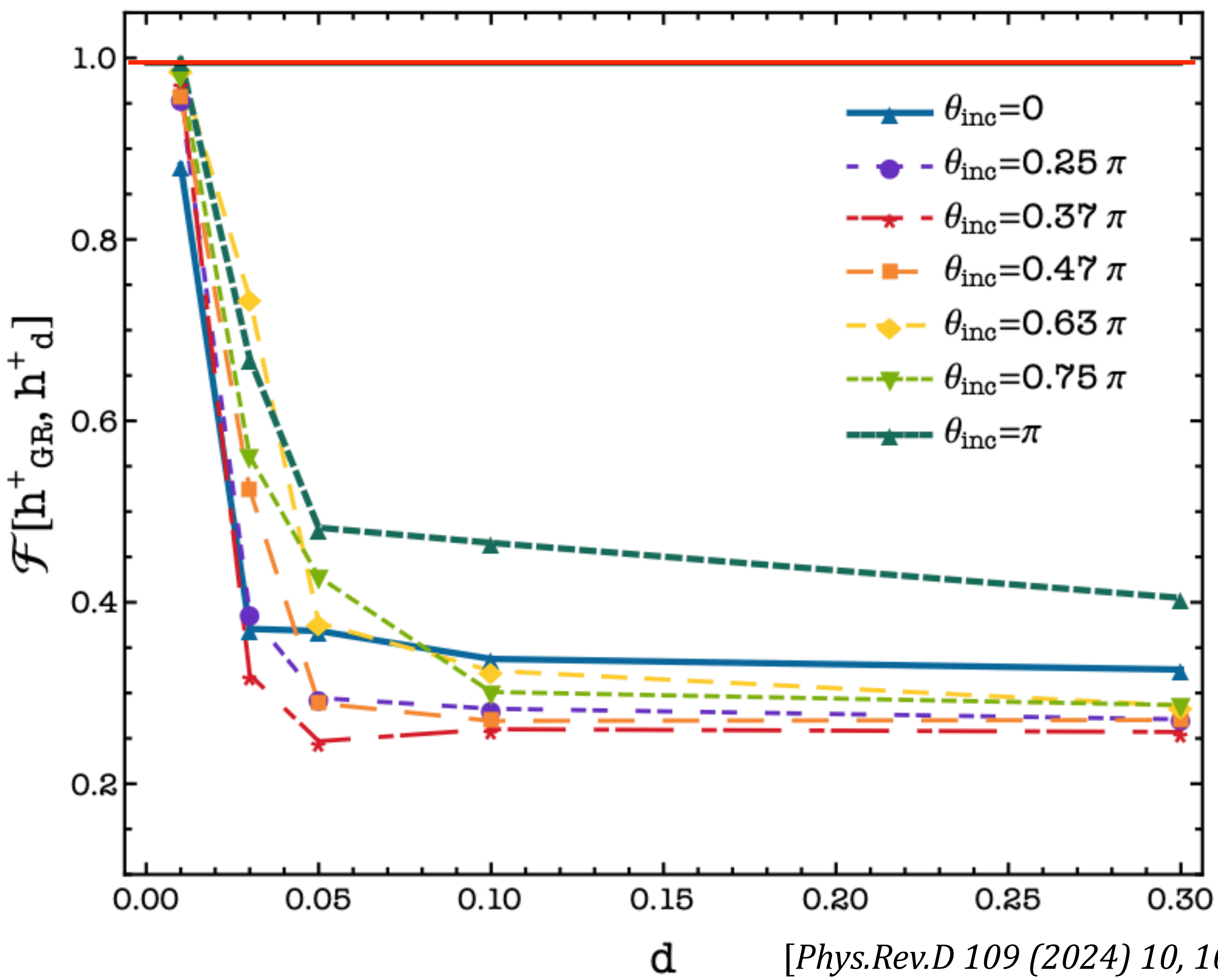


[Phys.Rev.D 106 (2022) 4, 044029]

detectable effect !

- Red line: threshold under which the signals are significantly different - $\mathcal{F} \lesssim 0.994$ for $SNR = 30$
- After 1year $\mathcal{F}$ is always smaller than the threshold for scalar charges as small as $d = 0.01$
- For the eccentric inspirals the distinguishability increases

Faithfulness: INCLINED Circular EMRIs



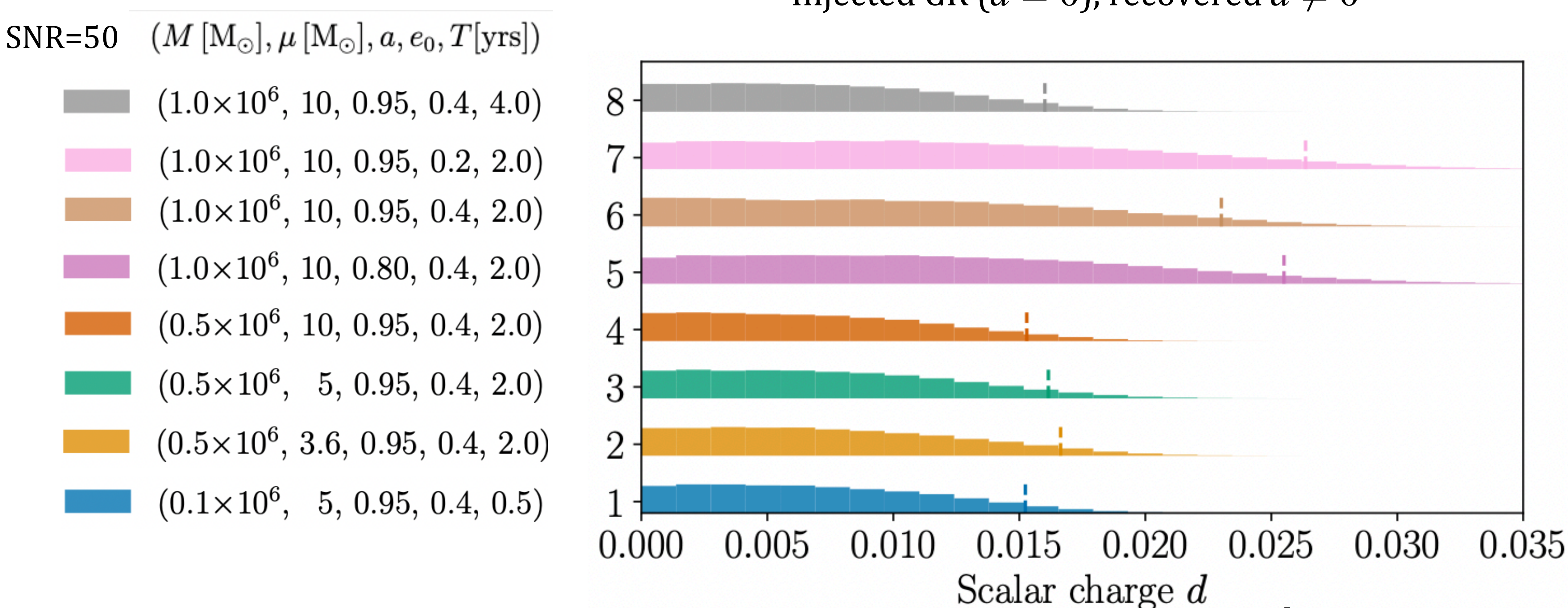
[*Phys.Rev.D 109 (2024) 10, 104079*]

- Red line: threshold under which the signals are significantly different - $\mathcal{F} \lesssim 0.994$ for $SNR = 30$
- After 1year $\mathcal{F}$ is always smaller than the threshold for scalar charges as small as $d \simeq 0.05$
- The mismatch increases with the increasing of the orbital inclination, for prograde orbits

Bayesian Analysis

FastEMRIWaveforms: fully relativistic equatorial **eccentric** inspiral, **AAK** waveforms

Injected GR ($d = 0$), recovered $d \neq 0$

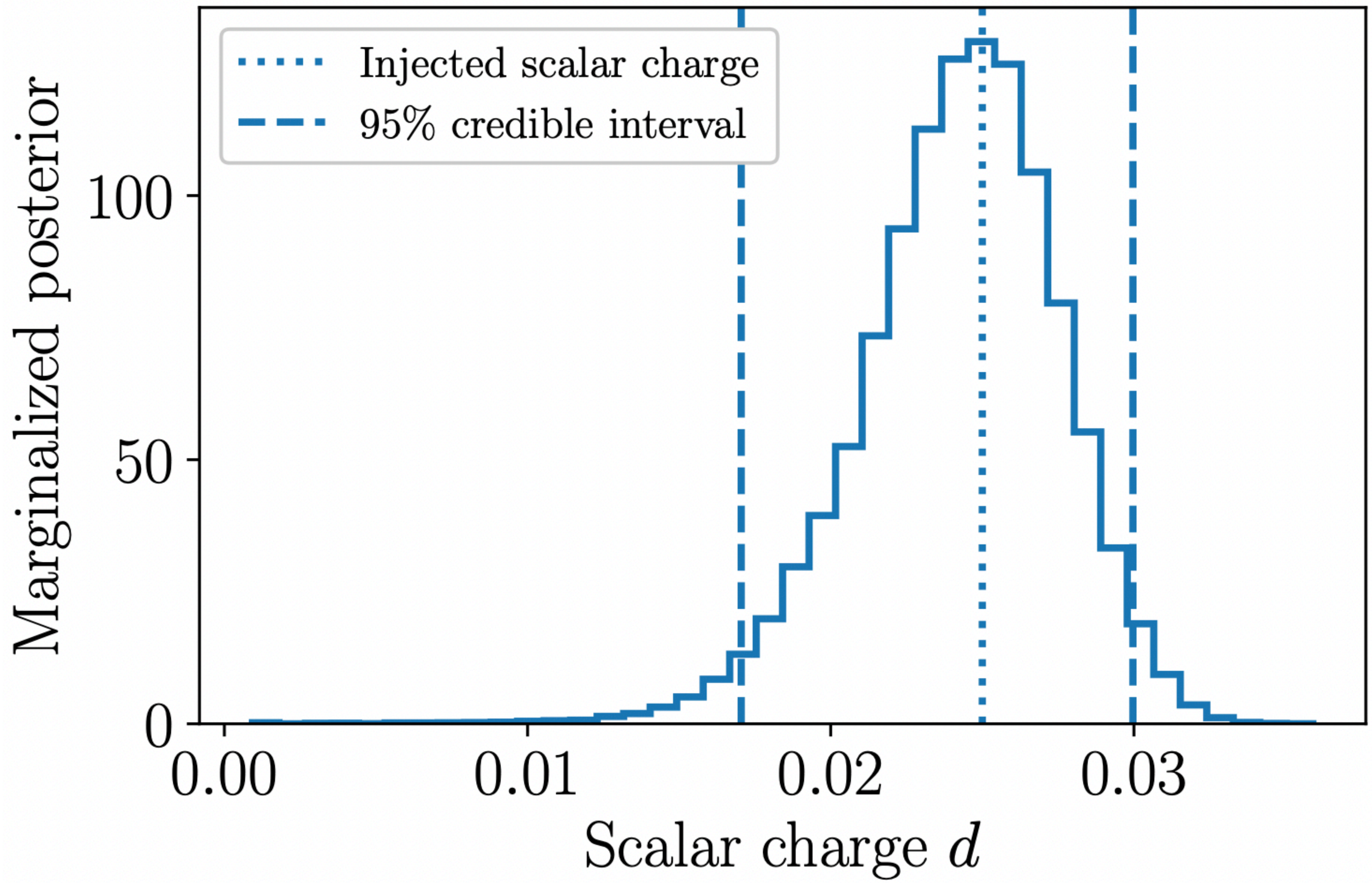


[L. Speri+, ArXiv2406.07607]

Reference System 6 vs

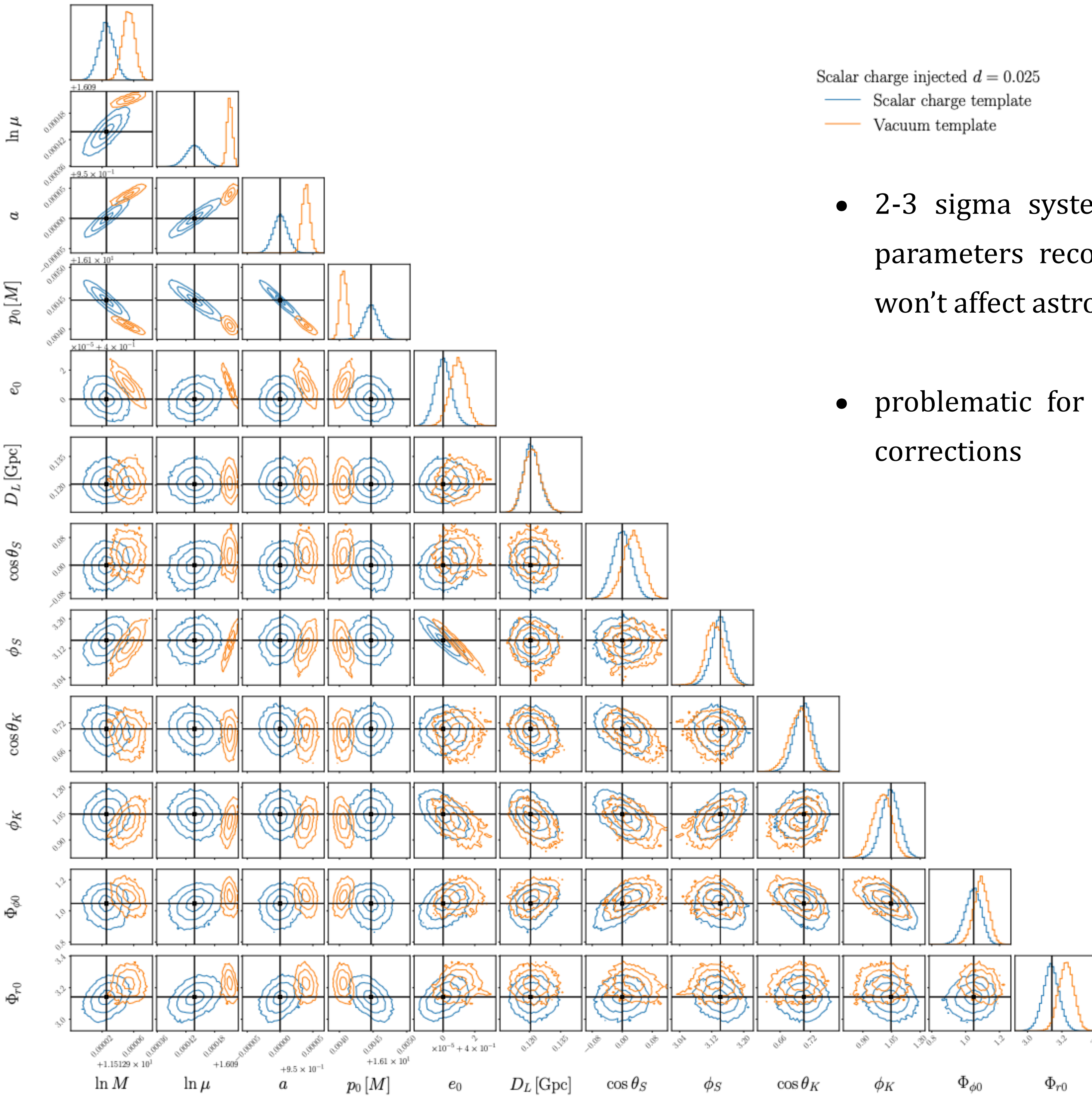
- System 7 (larger e_0) and System 5 (larger spin): slightly tighter bounds;
- System 4: comparable mass systems provide better bounds than more extreme mass ratios;
- System 3: fixed mass ratio but smaller secondary;
- System 8: comparing T;
- System 1: larger p_0, better bound on d;

Bayesian Analysis: Single measurement



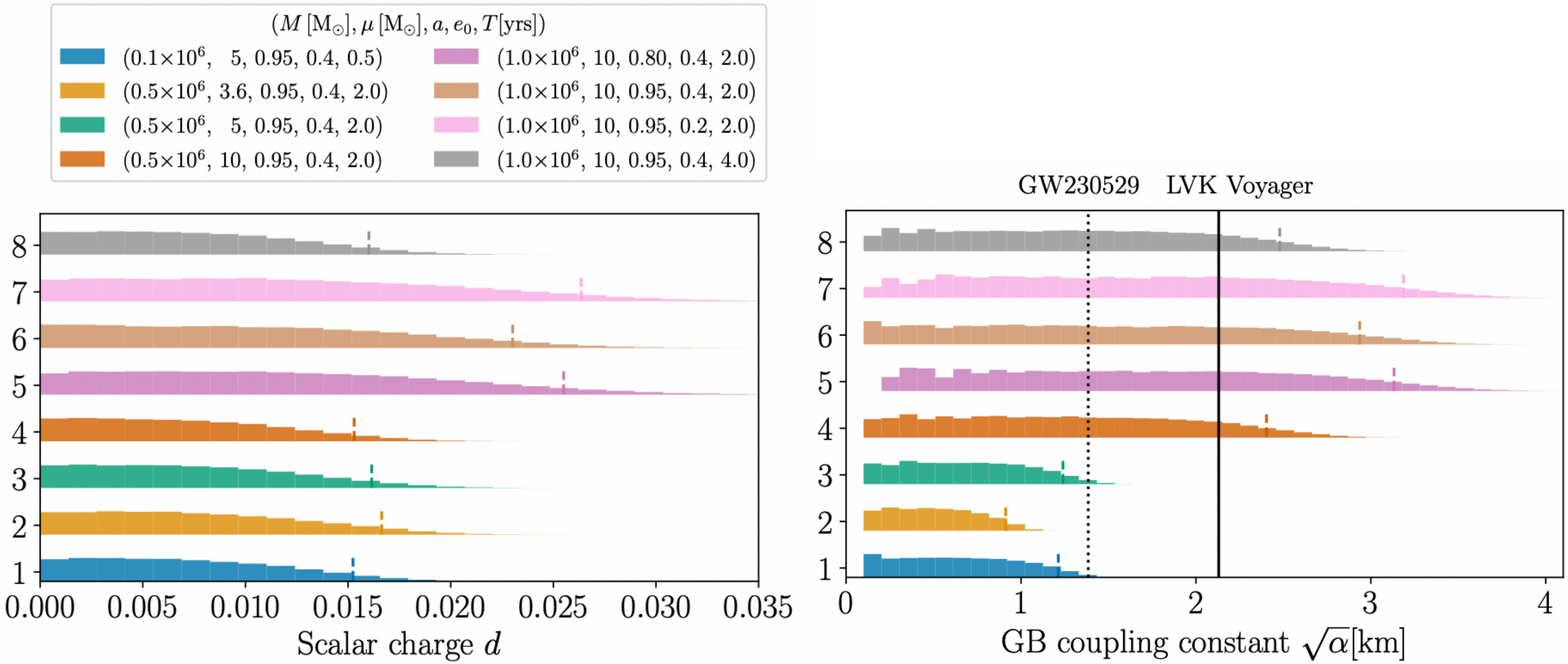
- Injected scalar charge: $d = 0.025$
- $M = 10^5 M_\odot$, $\mu = 5M_\odot$
- $T = 2$ yrs
- $SNR = 50$
- 95 % credible interval : $0.0244^{+0.006}_{-0.007}$

Bayesian Analysis: Bias



- 2-3 sigma systematic biases in the intrinsic parameters recovered with the GR template: won’t affect astrophysical conclusion
- problematic for small deviations: beyond GR corrections

Bayesian Analysis: From d to α



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

$$\longrightarrow \quad \alpha \simeq 2dm_p^2$$

- System 2: secondary of the same mass of the BH in GW230529

$$\mathscr{G} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\alpha\beta}R^{\mu\nu\alpha\beta}$$

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

$$\alpha \simeq 2dm_p^2 - \frac{73}{240}d^3m_p^2$$

EMRIs with massive scalars

Non shift-symmetric theories : the massive case

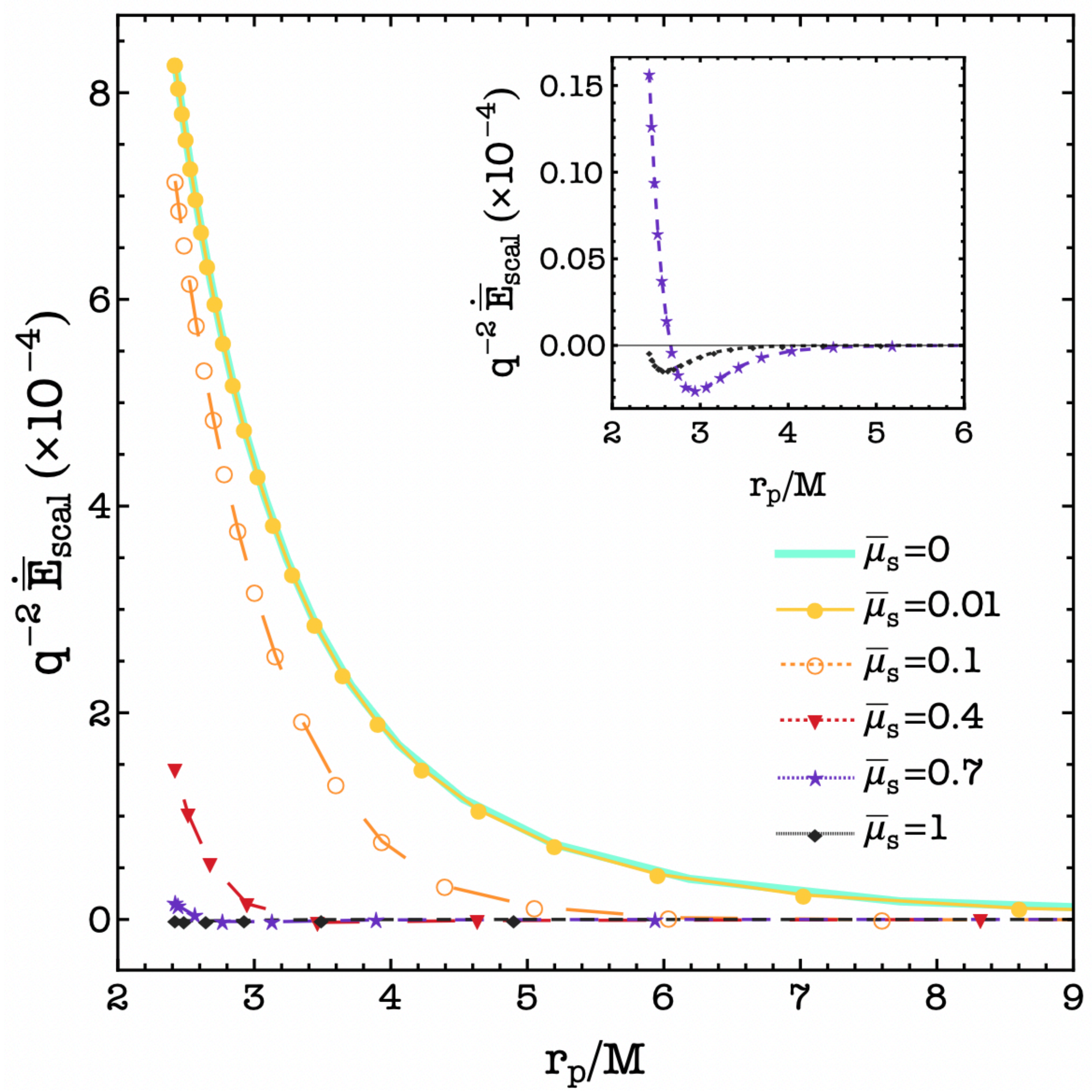
$$S = \int d^4x \frac{\sqrt{-g}}{16\pi}\left(R - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - \frac{1}{2}\mu_s^2\varphi^2\right) + \alpha S_c\left[\mathbf{g},\varphi\right] + S_m\left[\mathbf{g},\varphi,\Psi\right]$$

$$\left(\Box - \mu_s^2\right)\varphi = -4\pi d m_p \int \frac{\delta^{(4)}(x - y_p(\lambda))}{\sqrt{-g}} d\lambda$$

- $\left(\frac{\mu_s M}{0.75}\right)\cdot\left(\frac{10^6 M_\odot}{M}\right) 10^{-16}\ eV$
- $\bar{\mu}_s = \mu_s M$

Scalar energy emission:

- The scalar flux at infinity *vanishes* for $\omega < \mu_s$
  - — For each (ℓ, m) exist r_s such that $\dot{E}^{\infty}_{scal}(r > r_s) = 0$
- The flux at the horizon is active during all the inspiral
  - — Resonances for certain ω
  - — Floating orbits $\dot{E}_{grav} = \dot{E}_{scal}$

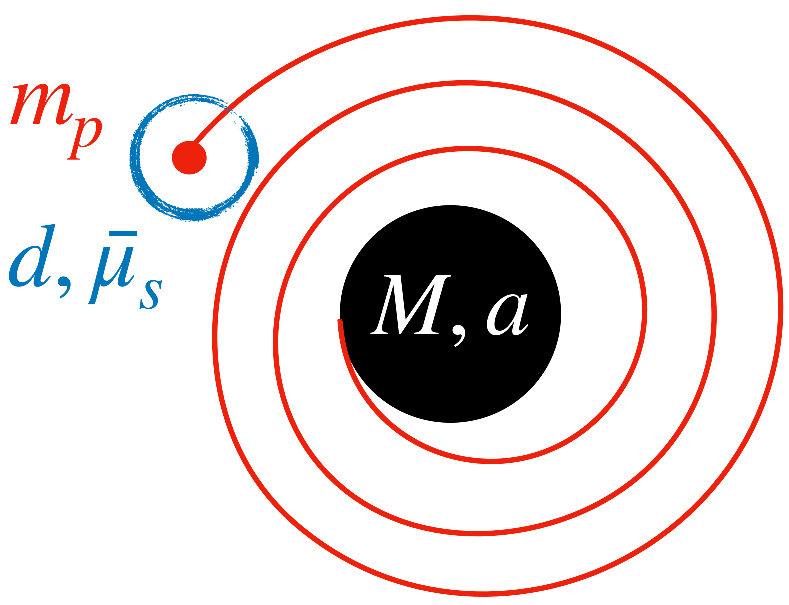


EMRIs with massive scalars: Fisher analysis

- Inject parameters to generate the waveform: $\vec{\theta} = \left(\ln M, \ln m_p, \frac{a}{M}, \ln D, \theta_S, \phi_S, \theta_L, \phi_L, r_0, \Phi_0, d, \bar{\mu}_s \right)$
- Posterior probability in the limit of large SNR: $\log p(\vec{\theta}|o) \propto \log p_0(\theta) - \frac{1}{2}\Delta_i \Gamma_{ij} \Delta_j$
- Fisher Information Matrix (FIM) analysis

$$\Gamma_{ij} = \left\langle \frac{\partial h}{\partial \theta_i} \middle| \frac{\partial h}{\partial \theta_j} \right\rangle_{\theta=\hat{\theta}} \longrightarrow \mathbf{\Sigma} = \mathbf{\Gamma}^{-1} \longrightarrow \sigma_i = \Sigma_{ii}^{1/2} \quad , \quad c_{\theta_i \theta_j} = \Sigma_{ij}^{1/2}/(\sigma_{\theta_i}\sigma_{\theta_j})$$

- We considered just the dipole for the scalar emission $(\ell = 1)$
- 1 year of observation before the plunge



— Primary :
- $M/M_\odot = 10^6$
- $a/M = 0.9$

— Secondary :
- $m_p/M_\odot = 1.4,\ 4.6,\ 10,\ 15$
- $d = 0.1$
- $\bar{\mu}_s = 0.018,\ 0.036 \simeq 2.4,\ 4.8 \times 10^{-18} eV$

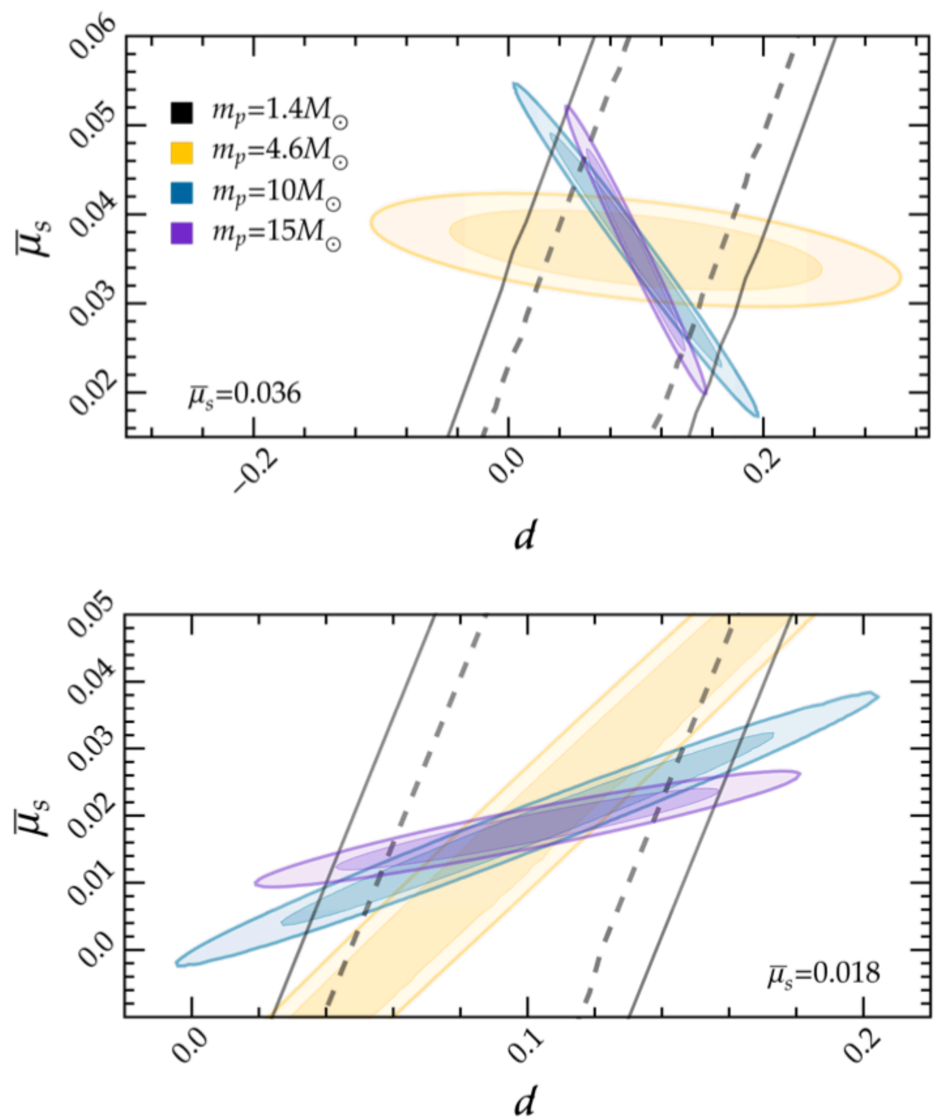
— $(\theta_S, \phi_S, \theta_L, \phi_L) = (\pi/2,\ \pi/2,\ \pi/4,\ \pi/4)$

- The scalar flux at infinity is significant throughout the entire inspiral

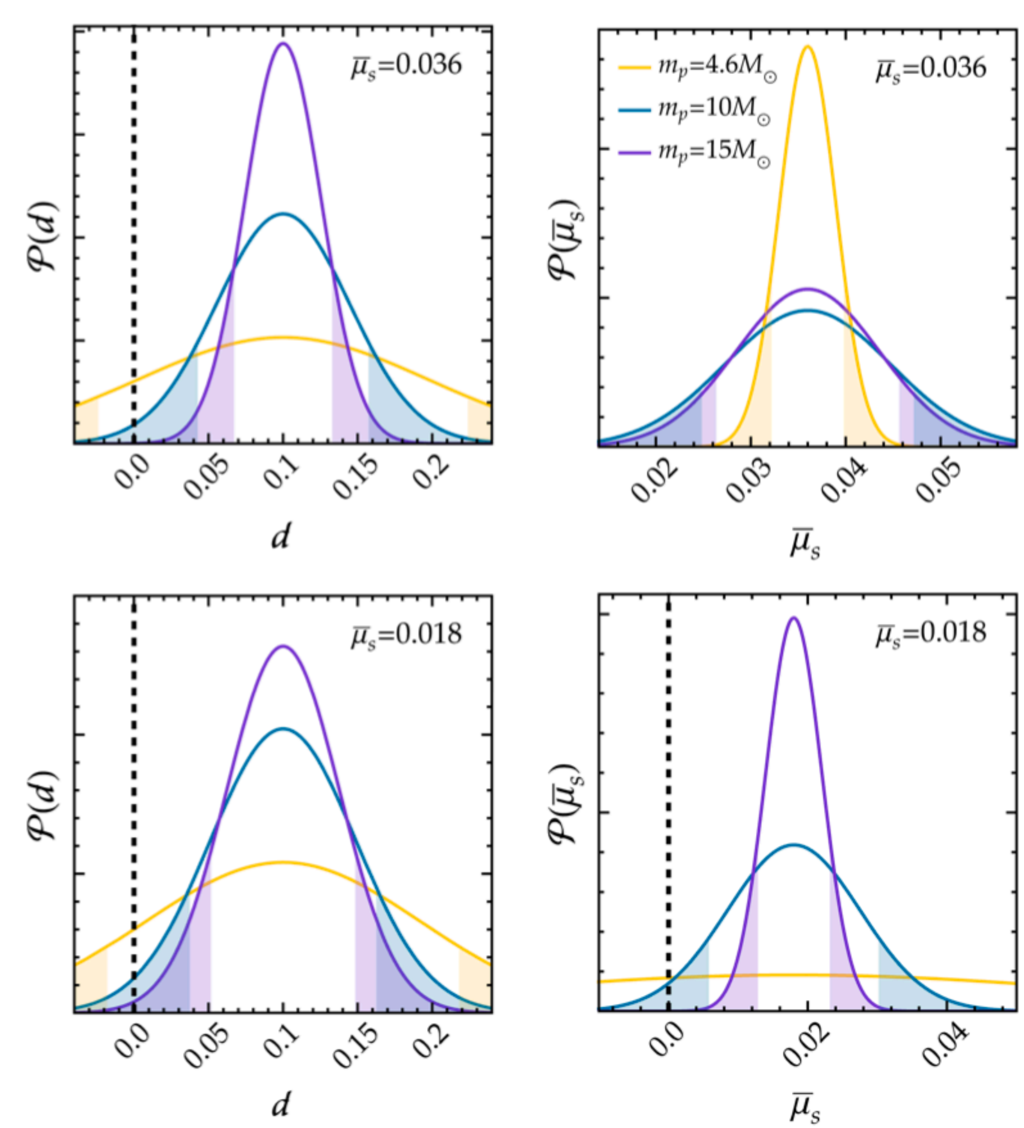
EMRIs with massive scalars: Fisher analysis

$m_p[M_\odot]$	$\bar{\mu}_s$	σ_d/d	$\sigma_{\bar{\mu}_s}/\bar{\mu}_s$	$c_{d\bar{\mu}_s}$
1.4	0.018	345%	2364%	0.997
	0.036	363%	391%	0.992
4.6	0.018	92%	243%	0.995
	0.036	97%	8%	−0.485
10	0.018	49%	53%	0.984
	0.036	45%	24%	−0.990
15	0.018	38%	22%	0.938
	0.036	26%	21%	−0.986

SIMULTANEOUS **detection of** ***BOTH*** **the scalar charge and mass with single event observations!**



Credible intervals at 68 % and 90 % for the joint $\mathscr{P}$ of $d, \bar{\mu}_s$



White area between shaded regions: 90 % of $\mathscr{P}$

Conclusions

- EMRIs are ideal sources to test GR and search for new fundamental fields
- Theory-agnostic approach to model EMRIs in beyond-GR and beyond-SM theories with extra scalar fields
- The extra scalar energy loss affects the binary coalescence and leaves an imprint in the emitted GW
- Bayesian analysis to forecast upper bounds on the scalar charge
- For non shift-symmetric fields: fisher analysis shows how LISA could simultaneously measure both the scalar charge and mass with enough accuracy to detect new ultra-light scalar fields

TO DO:

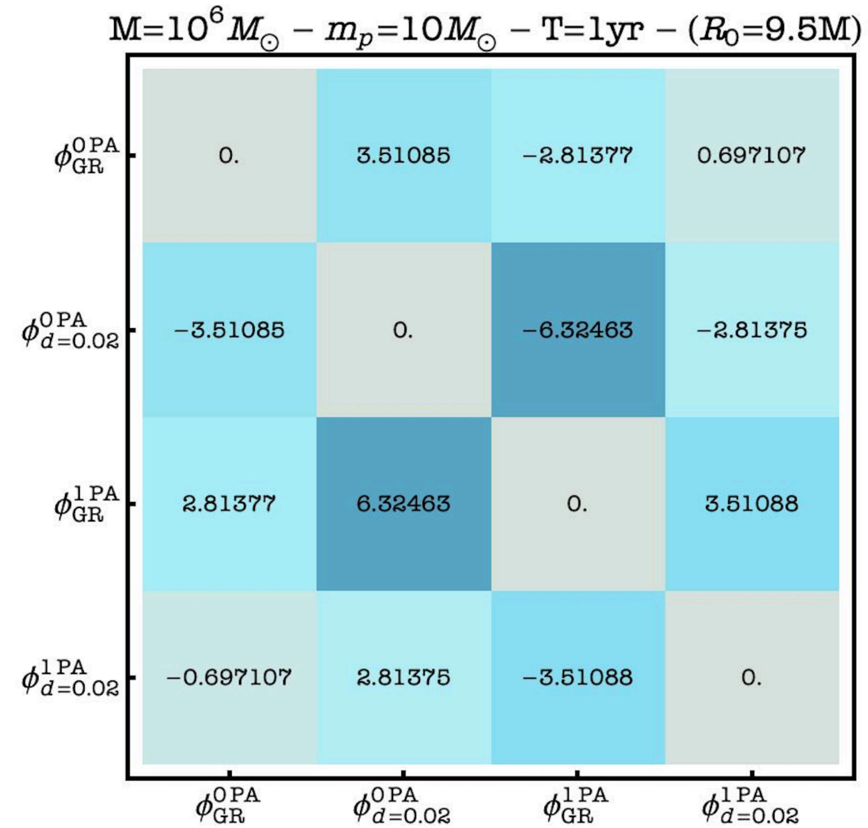
➡ **Explore the parameter space**

➡ **Post-adiabatic corrections**

➡ **Generic orbits**

➡ **Environmental effects ..**

Work in progress !



→ **Post-Adiabatic terms**

with A. Spiers, O. Burke, A.Maselli, T.Sotiriou, N. Warburton

→ **MEW**: **M**odified **E**MRI **W**aveform

with S. Gliorio, M. Della Rocca+

Thank you for the attention!