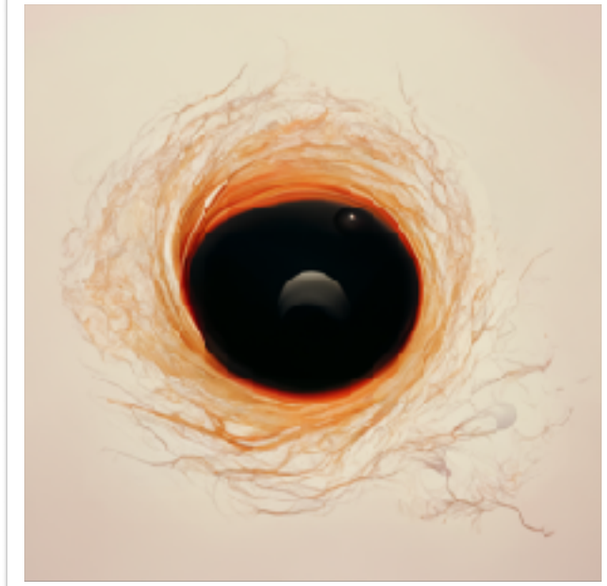
Astrophysical and Waveform Systematics from the Working Package Perspective

@ Fundamental Physics Working Group Meeting
Niels Bohr Institute, 11th Aug 2023



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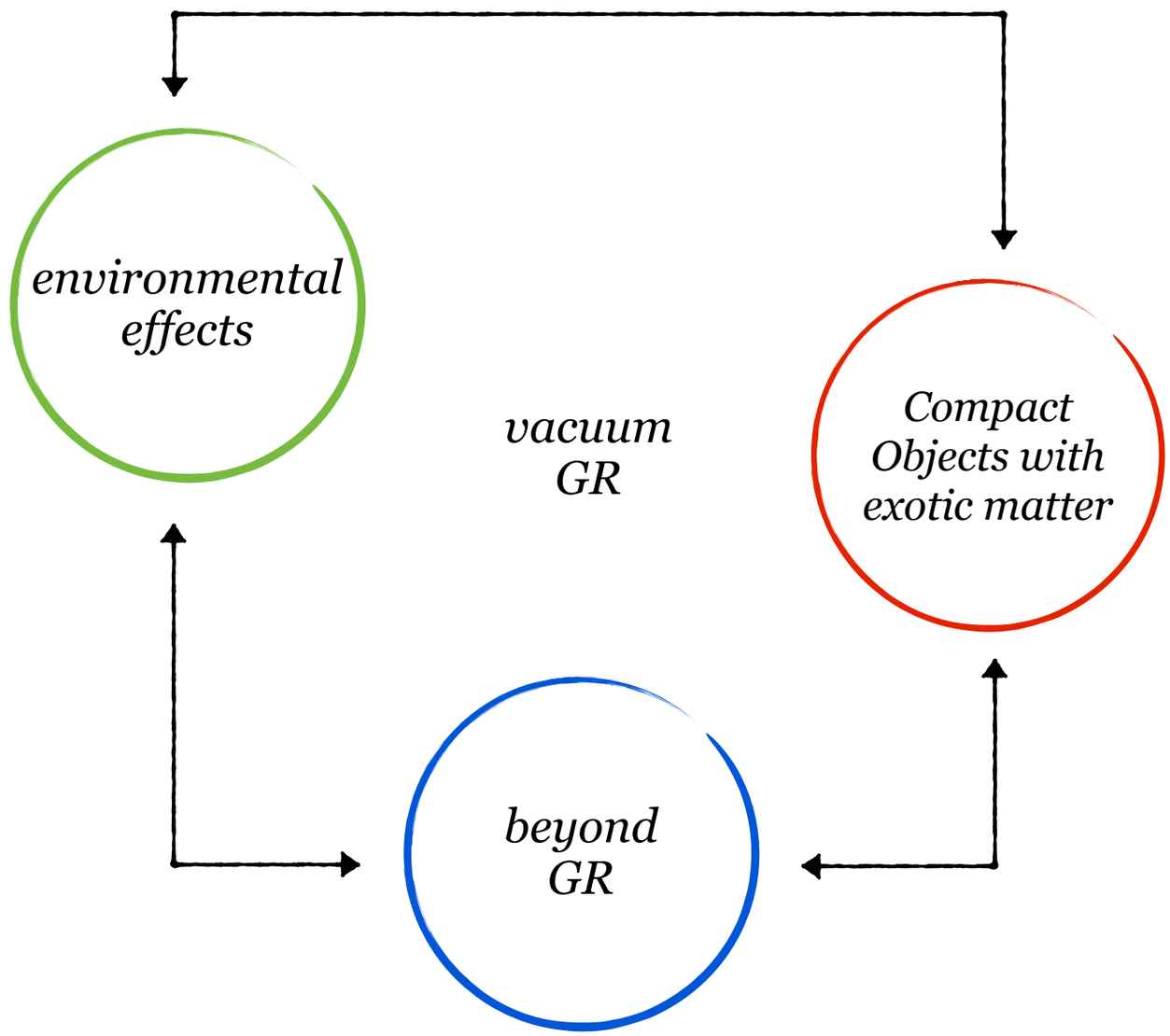
Where do we look for problems

<u>Reverse engineering</u>: where do we look, and how big are the "things" we're looking for

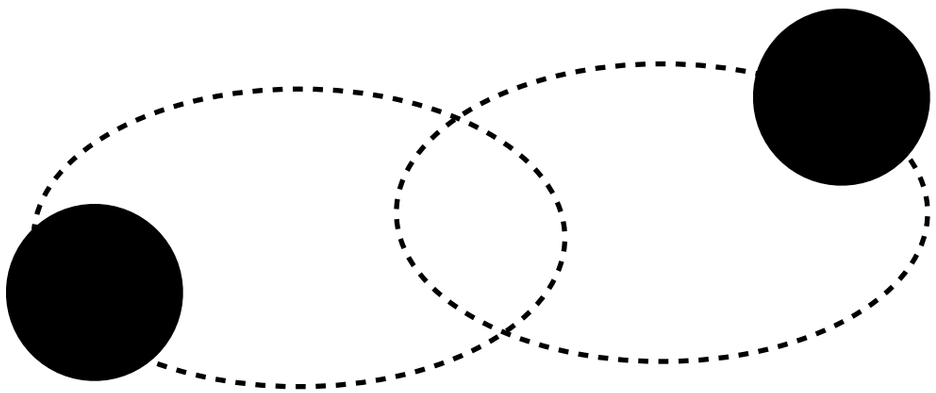
- *Where do effects are expected to pop-up in the waveform?*
- *Status and prospect of waveform modelling to assess systematics*



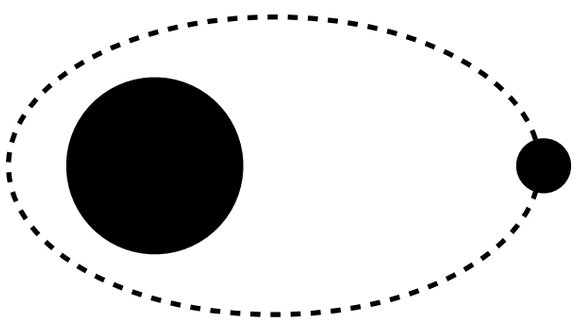
Scales & new families

LISA will observe old-and-new families of binaries

- *Huge potential for new science cases and new challenges (problems)*



comparable mass binaries



(very) asymmetric binaries

- *Challenges for waveform modelling of systems on different scales are different*
  - *mathematical approaches*
  - *astro-physical set up*
  - *dynamical features*

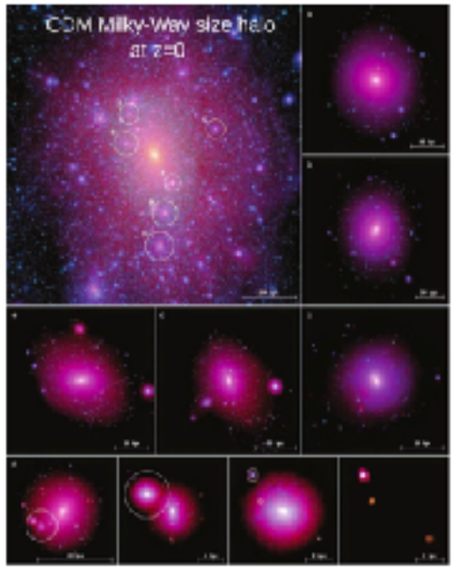
Environment

Dirty BHs

GW sources evolve embedded in a variety of gas/matter contents/fields, which may leave detectable imprints on GW

- *Can we infer properties on the environment in which binaries evolve?*
- *Are vacuum waveform models safe?*

L. Sberna +, PRD 106, 064056 (2022)
L. Speri + PRX 143,021035 (2023)
A. Toubiana +, PRL 126, 101105 (2021)
A. Coogan + PRD 105, 043009 (2022)
N. Speeney+ PRD 106, 044027 (2022)
...



V. Springel et al., Mon. Not. Roy. Astron. 391 (2008)

G. Bertone et al., Nature 562, 7725 (2008)

MBH and inspirals evolve in DM-rich environment, within galaxies

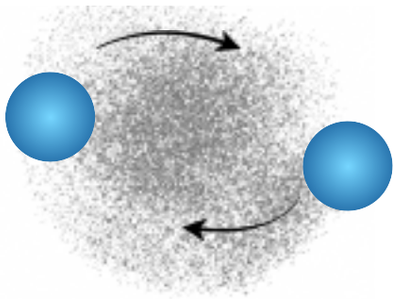
IMRI/EMRI can assemble in accretion disks

→ *particle physics laboratories*

- *The landscape of calculations for asymmetric binaries is relatively virgin*

Dirty BHs

The environment affects the binary orbital motion



→ *changes generation and propagation of GWs*

- *different effects can be included adding specific corrections the post-Newtonian waveforms*

E. Barausse +, PRD 89, 104059 (2014)
B. Kocsis +, PRD 84, 024032 (2011)
V. Cardoso & A. M., A&A 644, A147 (2020)

$$\psi_{\rm GW} \propto (m\pi f)^{-5/3}\left[1 + (\text{PN corrections}) + \delta\psi_{\rm env}\right]$$

- *Generic correction due to the binary environment*

$$\delta\psi_{\rm env} \propto \rho_{\rm env}(\pi m f)^{-\gamma}$$

density of the medium

$\gamma = 11/3$ *gravitational drag*

$\gamma = 3$ *accretion*

$\gamma = 2$ *gravitational pull*

- *GW can be used to bound the density of the matter distribution in which binary evolve*

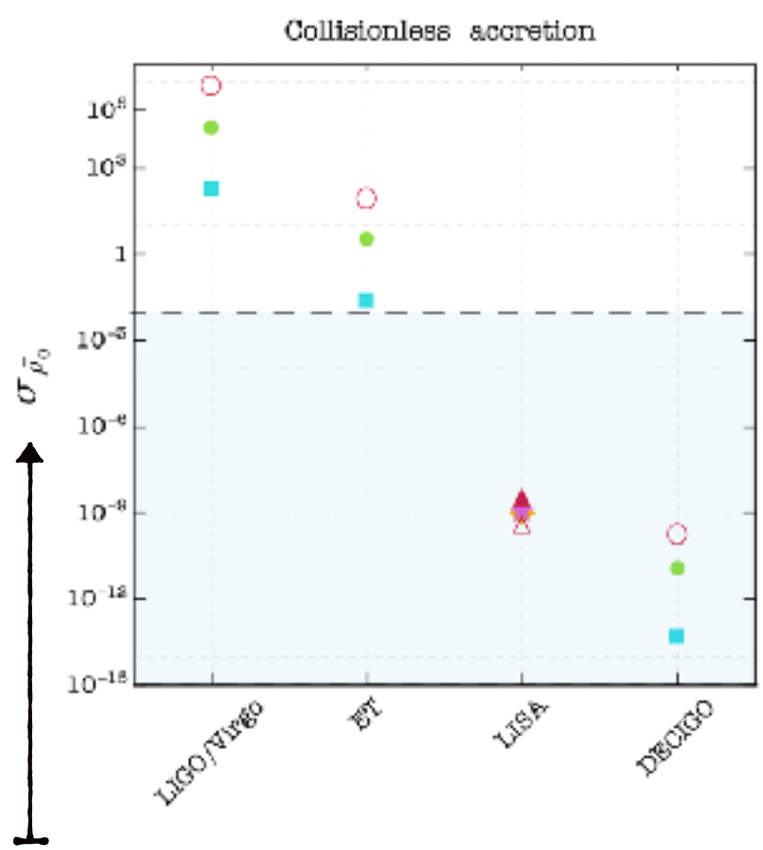
Which family?

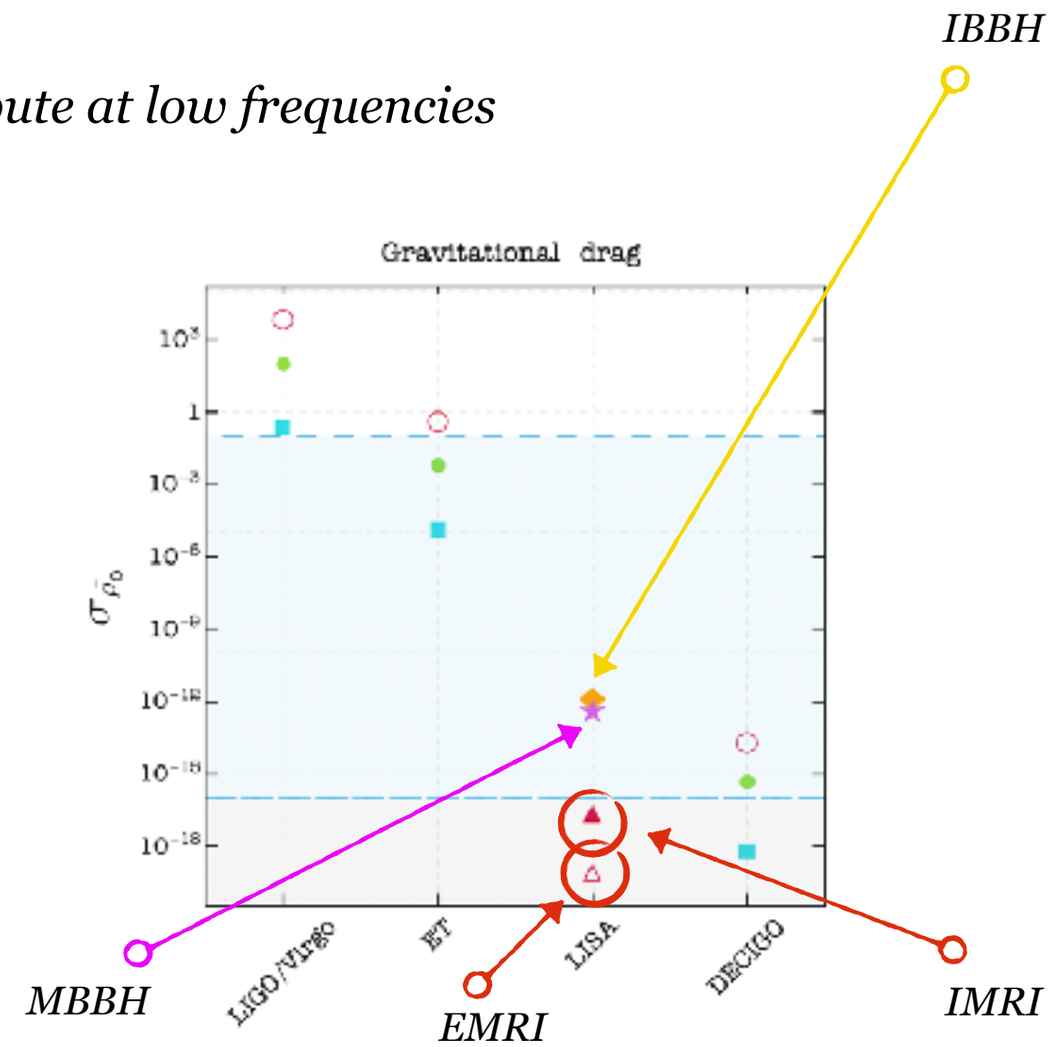
Constraints on the environment's density from different effects/sources/ detectors

V. Cardoso & A. M., A&A 644, A147 (2020)

Useful lessons from PN

- *environmental effects typically contribute at low frequencies*





density of medium

Asymmetric binaries work (really) well

Is it worth?

High(er)-order vacuum corrections or environmental effects?

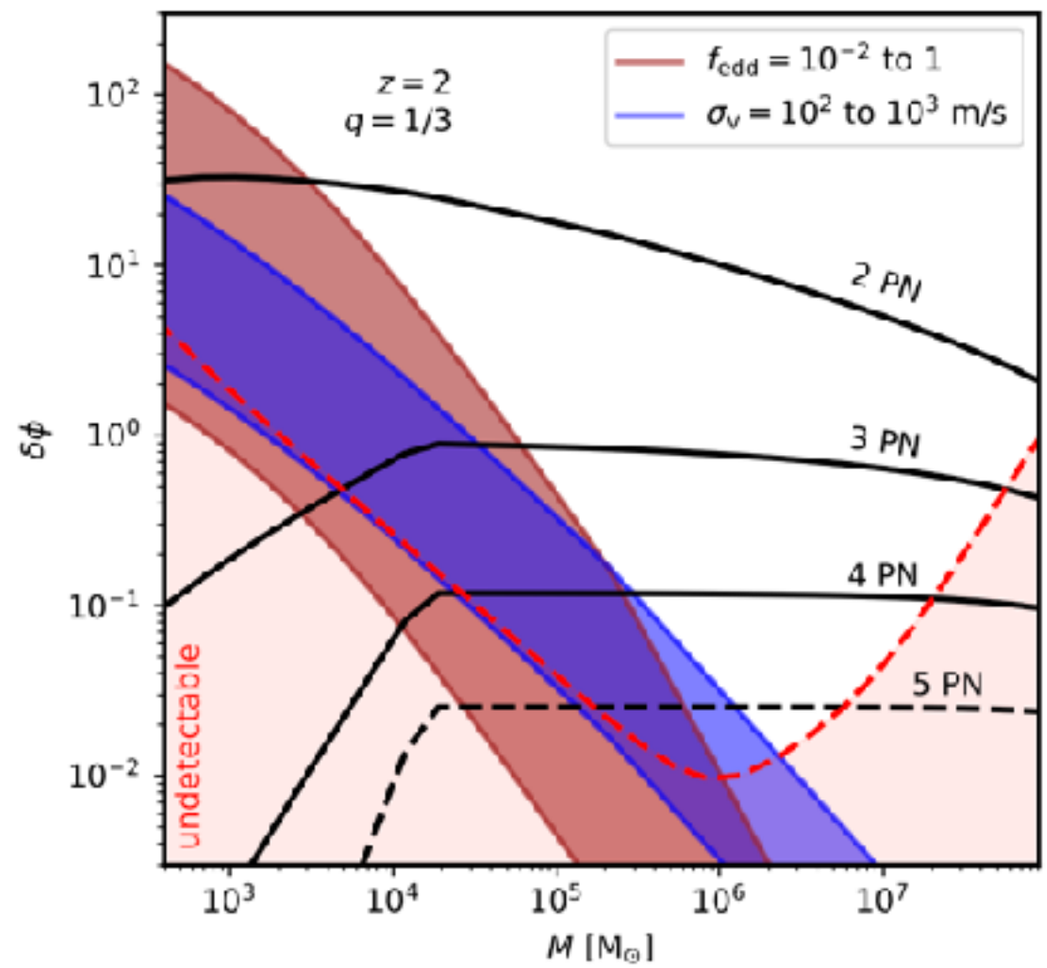
L. Zwick+ 2209.04060 (2022)

- *where do we need to focus our efforts in the mHz modelling?*

Systematic comparison of phase contribution due to

- *known environmental effects*
- *high pN order (5 pN benchmark)*

gas torques from viscous forces
third body effect



- *phase shift distinguishable from noise*

$$\delta\phi > \arccos\left(1 - \left(\frac{\delta\mathrm{SNR}}{\mathrm{SNR}}\right)^2\right)$$

detectability criterion with $\delta\mathrm{SNR} = 8$

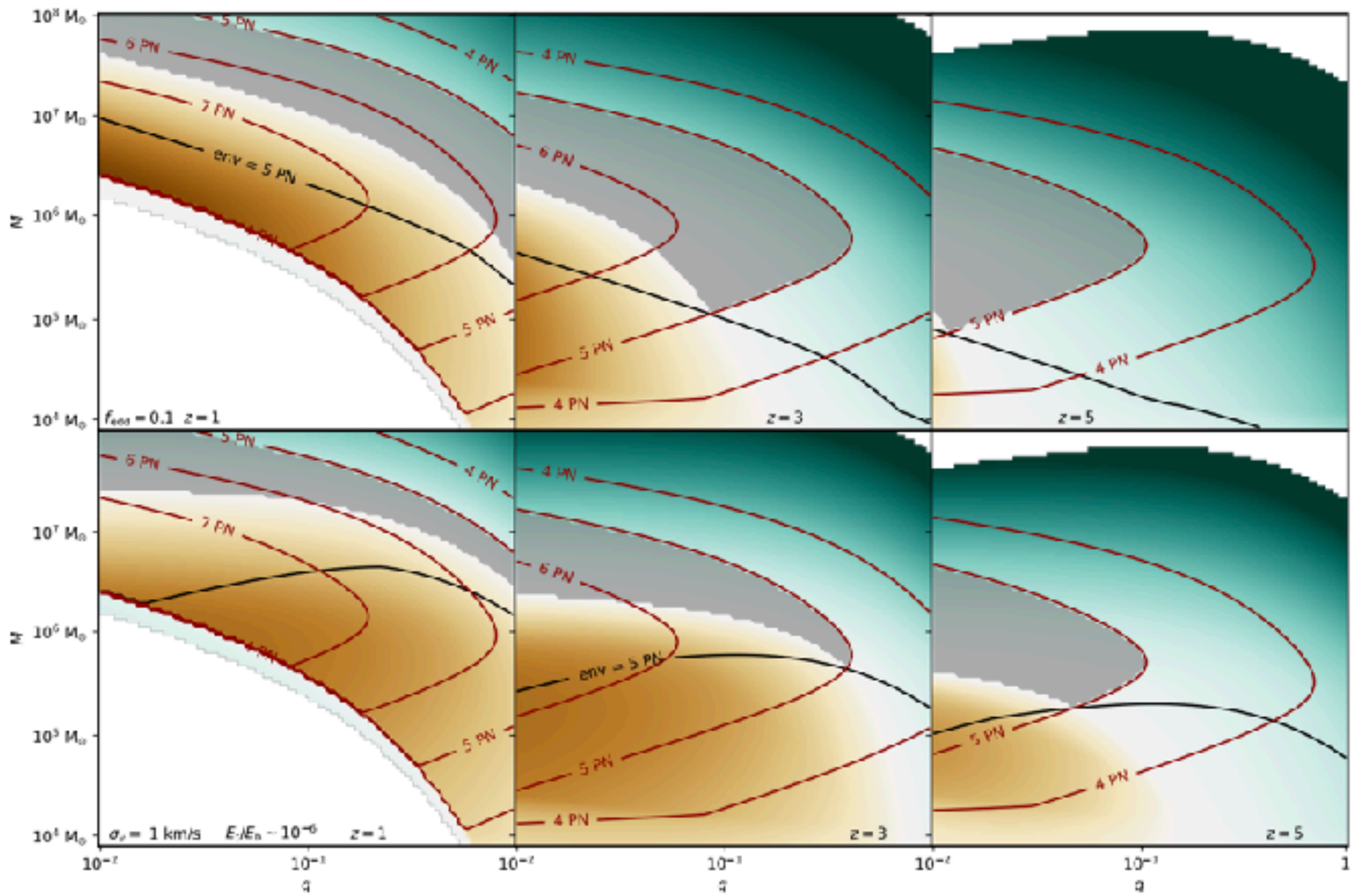
Is it worth?

Parameter space of LISA comparable-mass SMBH at different redshifts

$$\delta\phi \gtrless \mathrm{arcos}\left(1-\left(\frac{\delta\mathrm{SNR}}{\mathrm{SNR}}\right)^2\right)$$

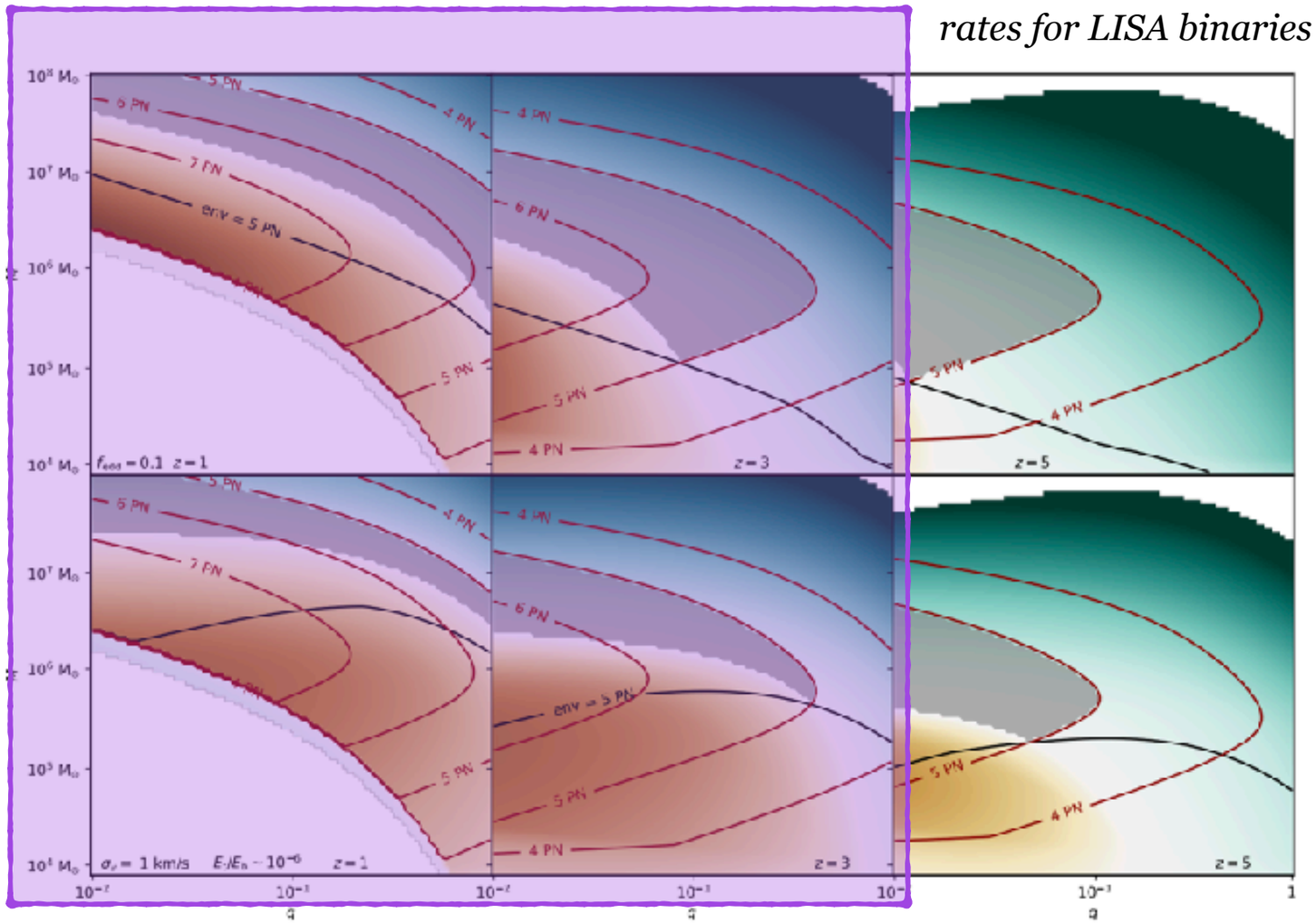
gas torques

third body



Is it worth?

rates for LISA binaries



env detectable

env non-detectable

env non-detectable & pN > 5 detectable

max detectable pN order

env ~ 5 pN order

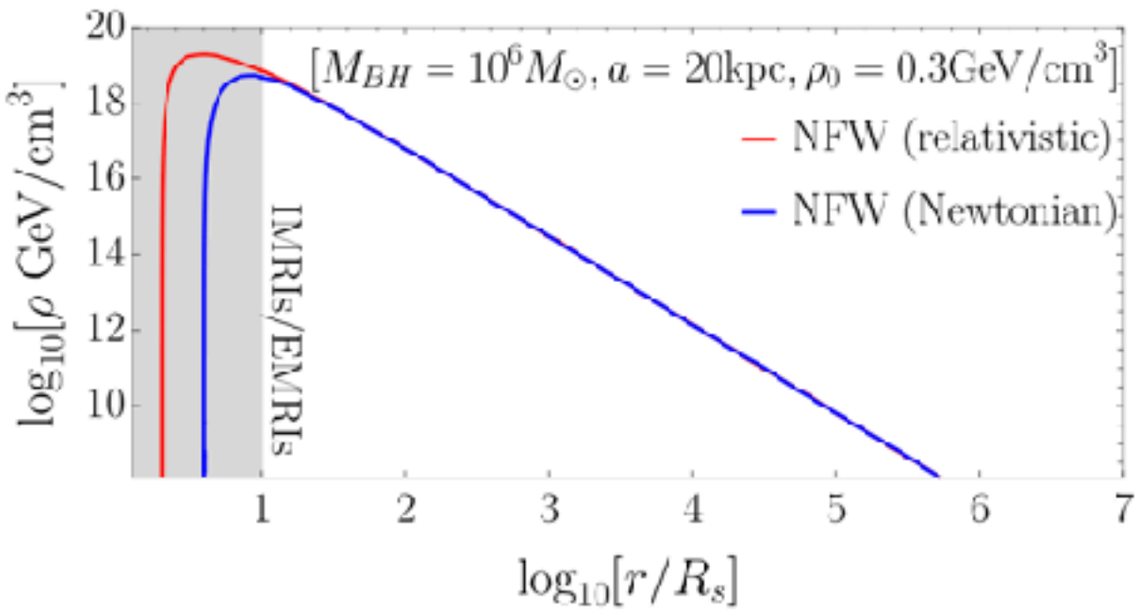
- *heavy BBH,* $M \gtrsim 10^8 M_\odot$ *, can be safely modelled by vacuum waveforms due to low SNRs*
- *for* $M \lesssim 10^7 M_\odot$ *the largest unmodelled perturbations are environmental effects*
- *largest SNRs are for and* $M \sim 10^6 M_\odot$ *and* $q \lesssim 0.2$
  - $z \lesssim 2$ — *env detectable*
  - $z > 2$ — *high-order vacuum dominate*

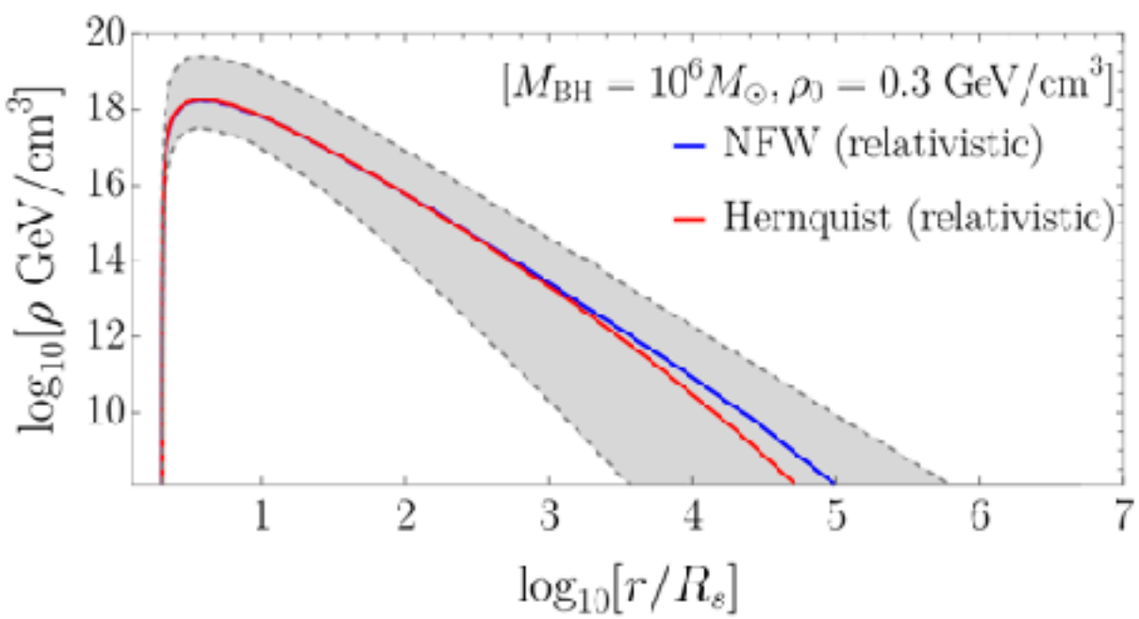
Rising spikes

Dark Matter forms spikes in the presence of a BH

N. Speeney+ PRD 106, 044027 (2022)

$$\rho(r) = \rho_0 (r/a_0)^{-\gamma} [1 + (r/a_0)^{\alpha}]^{(\gamma-\beta)/\alpha}$$





density peak

Newtonian $4R_s$

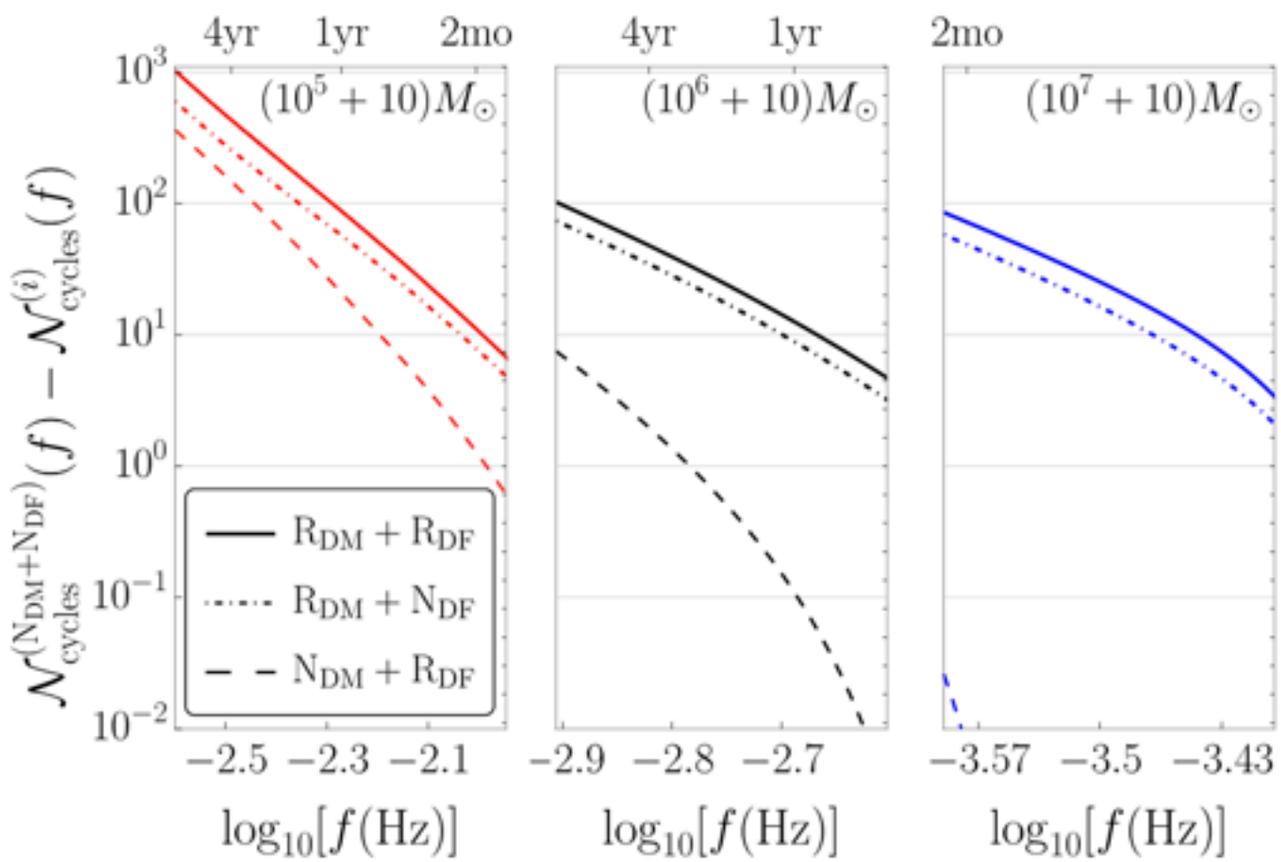
Relativistic $2R_s$

- *relativistic cut-off deeper in the BH field, and less steep*
- *potential to lead larger effects on the dynamics of binaries in DM environments*

Rising spikes

How much do relativistic corrections weigh?

_____ *v.s. Newtonian term*

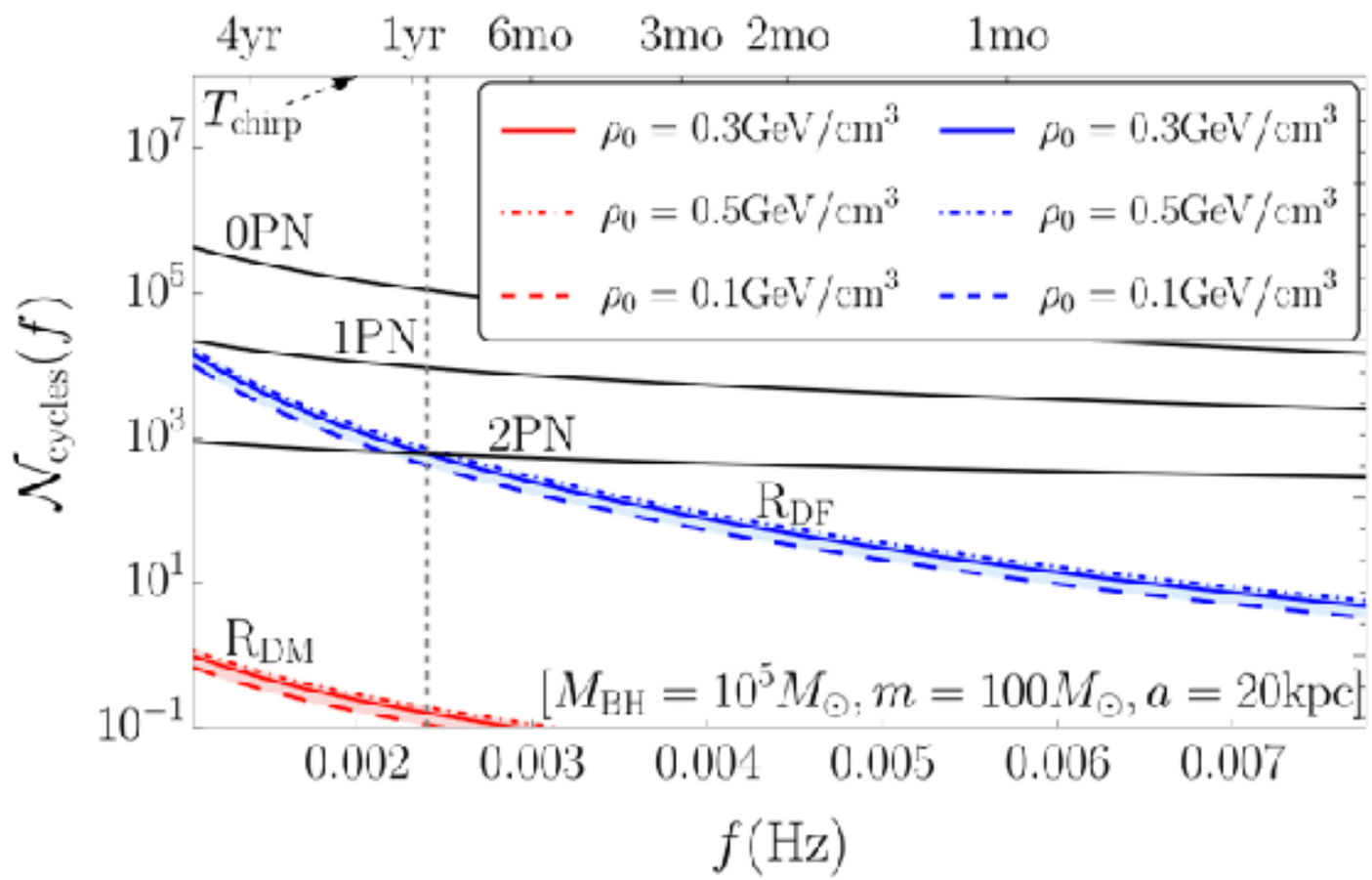


	relativistic correction	
	spike	*dynamical friction*
$R_{DM}+R_{DF}$	✓	✓
$R_{DM}+N_{DF}$	✓	✓
$N_{DM}+R_{DF}$	✓	✓

- *Both contributions relevant and should be included*
- *Correction to spike always leads larger dephasing*
- *For very large primaries DF becomes irrelevant*

Rising spikes

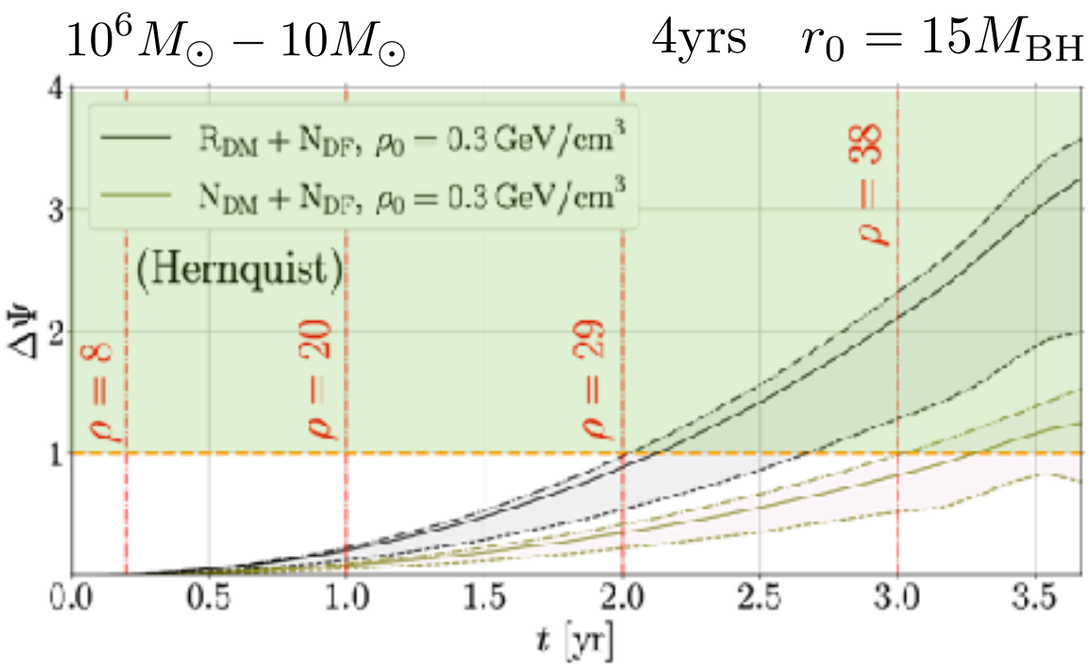
What pN order DM and DF are comparable to?

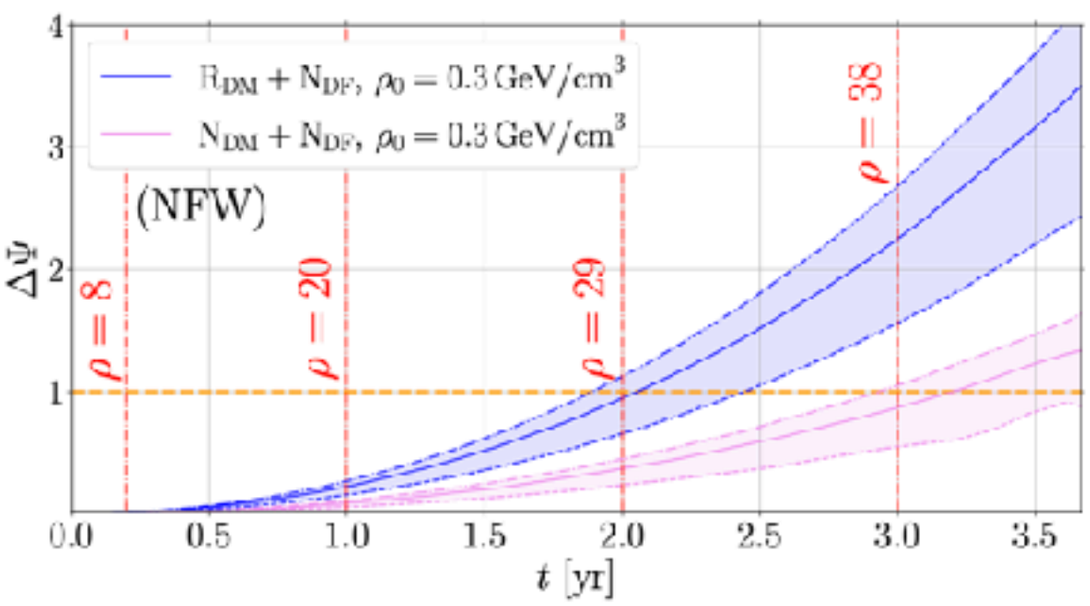


- *Clear hierarchy: (0, 1)PN << R_{DM} << R_{DF}*
- *DF can dominate over the 2 pN term after 1yr of observation*
- *For lower masses DF becomes more comparable with lower pN orders as the spikes grows*

Rising spikes

How are EMRI affected by relativistic corrections?



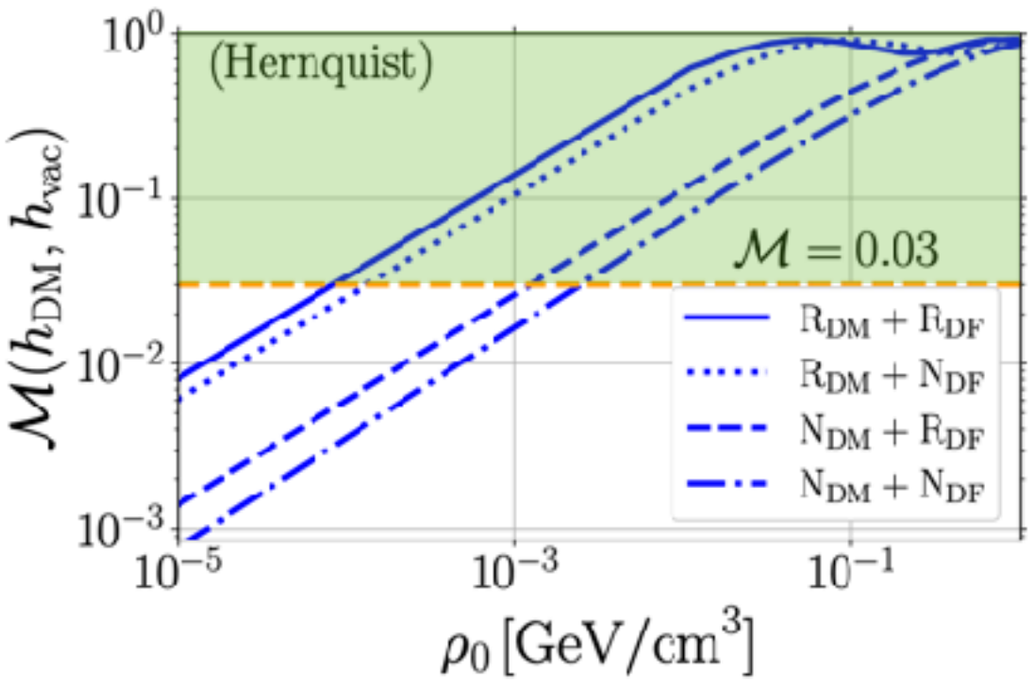


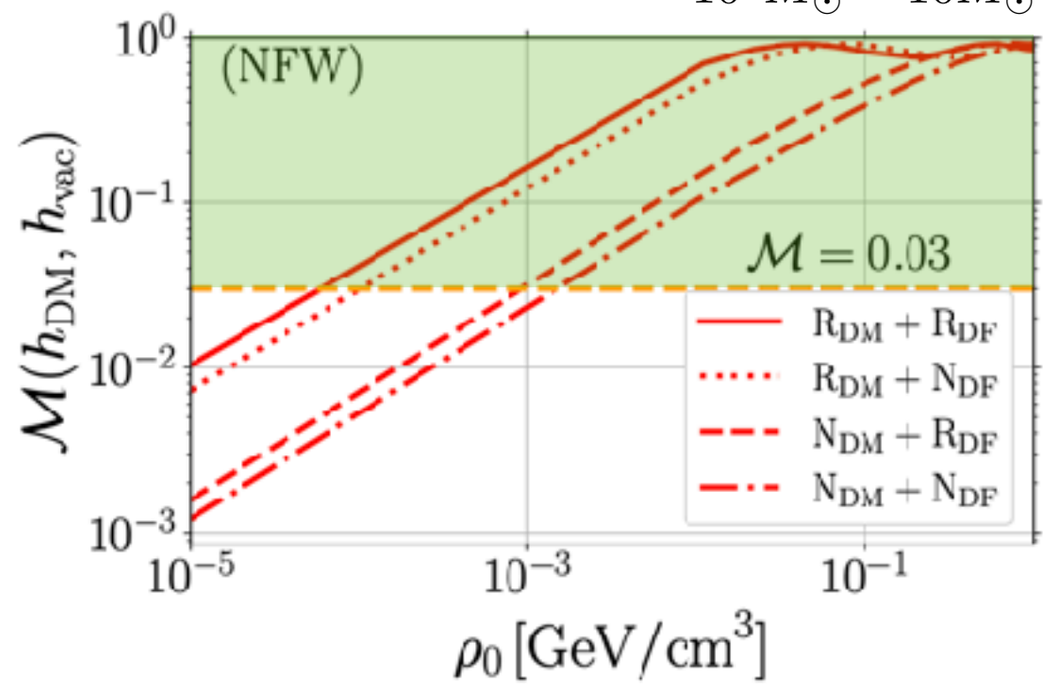
relativistic corrections allow to spot DM effects earlier

Rising spikes

Mismatch $\mathcal{M} = 1 - \frac{(h_{\rm DM}|h_{\rm vac})}{\sqrt{(h_{\rm DM}|h_{\rm DM})(h_{\rm vac}|h_{\rm vac})}}$

$10^6 M_\odot - 10 M_\odot$





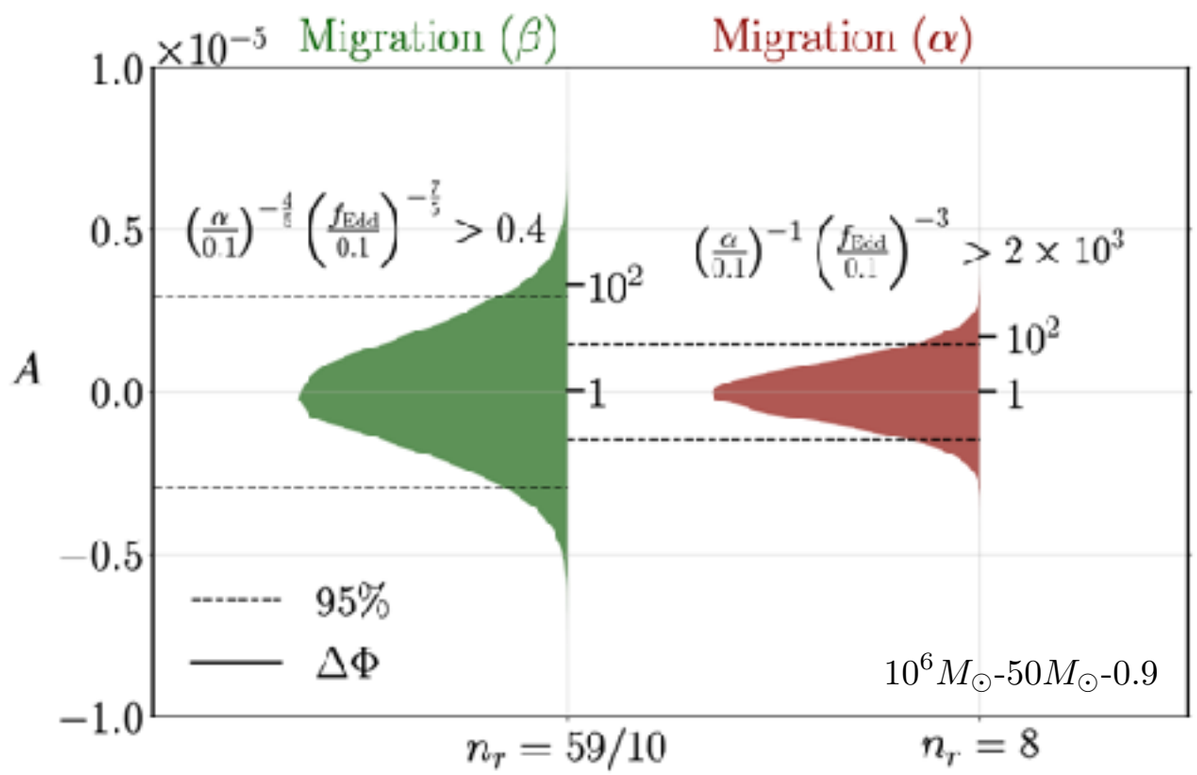
- *Spikes large enough to provide detectable effects in EMRI observations by LISA*

Accretion disks

Accretion disks induce torques that can affect EMRI trajectories

L. Speri + PRX 143, 021035 (2023)

- *Subdominant compared to GW emission but potentially observable*



posterior on the amplitude for agnostic search (vacuum injection)

$$\dot{L} = \dot{L}_{\rm GW} + \dot{L}_{\rm disk}$$

amplitude

slope

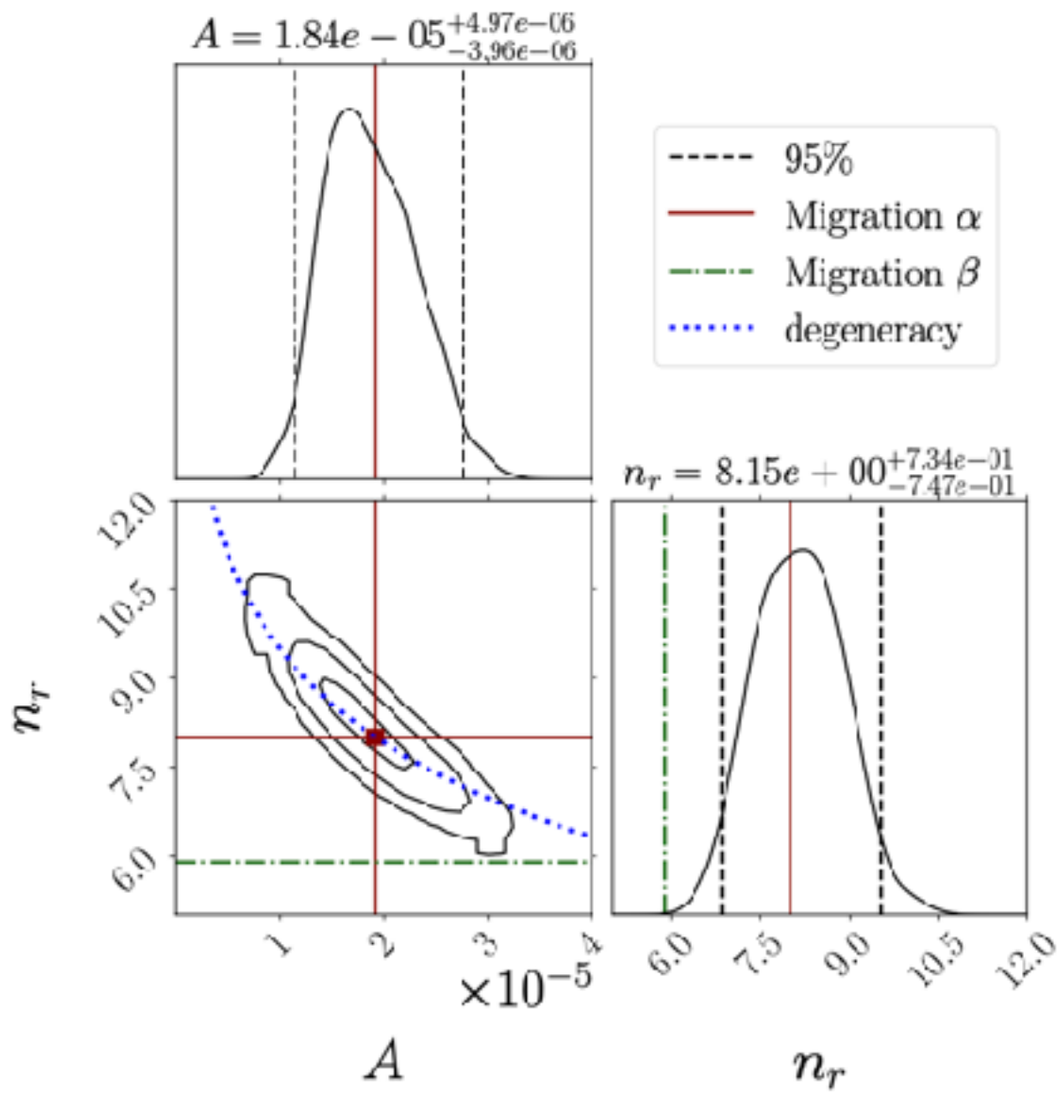
$$\dot{L}_{\rm disk} = A\left(\frac{r}{10M_1}\right)^{n_r}\dot{L}^{(0)}_{\rm disk}$$

-n_r pN

- *Torques may not be detectable even if dephasing larger than* $\Delta\Phi \gtrsim 1$
- *Torques may not be detectable for typical value of the disk viscosity* α

Accretion disks

Detectability of torques, for a non-vacuum injection

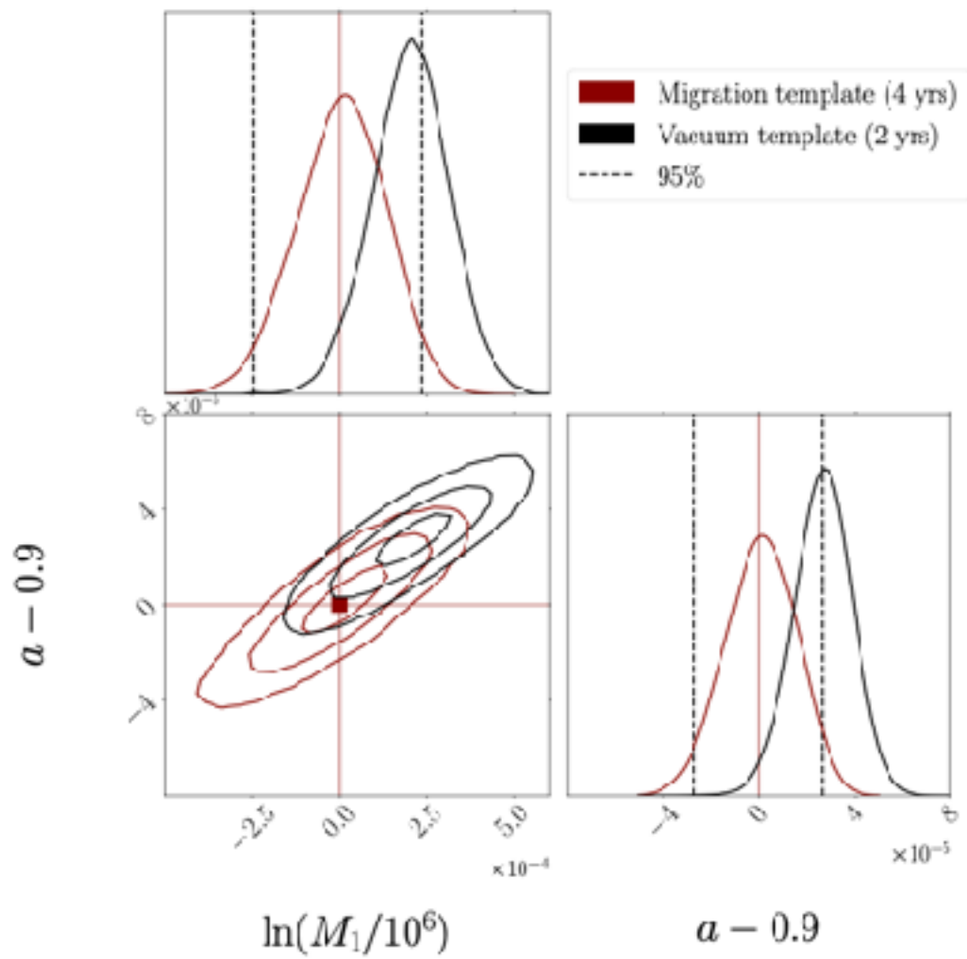


- *Strong correlation between amplitude and slope*
- *Posterior inconsistent with A=0 @ more than* 3σ
- *Torque can be detected by agnostic template provided it can be described by a power-law of the radius*

- *If we have a physical model, (A,n_r) can be mapped to viscosity & efficiency of the disk*

Accretion disks

Parameter's bias due to mismodelling of the 'true' signal



- *Good match only on a shorter portion of the signal*
- *Bias in the source intrinsic parameter is small* → *won't affect astro-conclusions*
- *problematic for 'small' deviations, like beyond GR corrections*

The curious case of a rigorous spacetime

Relativistic BH spacetime surrounded by a matter distribution

V.Cardoso +, PRD Lett. 105, L061501, (2022)
V.Cardoso +, PRL 129, 241103, (2022)
E. Figueiredo +, PRD 107, 104033, (2022)

- *Spherical symmetry + anisotropic stress energy tensor*

$$\langle T^{\mu\nu} \rangle = \frac{n}{m_p} \langle P^\mu P^\nu \rangle \longleftrightarrow T^\mu{}_\nu = \mathrm{diag}(-\rho, 0, p_t, p_t)$$

A. Einstein, Annals Math. 40 (1939)

- *Focused on DM rich environments*

average density *typical scale*

$$\rho(r) = \rho_0 (r/a_0)^{-\gamma} [1 + (r/a_0)^\alpha]^{(\gamma-\beta)/\alpha}$$

Hernquist *NFW*

$$\rho(r) = \rho_e \exp\left\{-d_n[(r/r_e)^{1/n} - 1]\right\}$$

Einasto

- *Study geodesic structure and perturbations*
  - *Compute axial/polar fluxes* → *study EMRI dynamics*

BH & halo: background

Background spacetime experiencing a "redshift" effect $(M_{\rm BH}, a_0, M)$

$$g_{tt} = a(r) = \left(1 - \frac{2M_{\rm BH}}{r}\right) e^{\Gamma}$$

$$e^{\Gamma} \xrightarrow[r \to 2M_{\rm BH}]{} 1 - 2M/a_0$$

Redshift factor

- *To mimic galaxy observations* $a_0 \gtrsim 10^4 M$ $\longrightarrow$ $M_{\rm BH} \ll M \ll a_0$

- *Orbital frequencies*

$$M_{\rm BH}\Omega_{\rm LR} \simeq \frac{1}{3\sqrt{3}}\left(1 - \frac{M}{a_0} + \frac{M(M + 18M_{\rm BH})}{6a_0^2}\right)$$

$$M_{\rm BH}\Omega_{\rm ISCO} \simeq \frac{1}{6\sqrt{6}}\left(1 - \frac{M}{a_0} + \frac{M(M + 396M_{\rm BH})}{6a_0^2}\right)$$

redshift factor

non-linear corrections

- *At the leading order the halo only redshifts the dynamics*

BH & halo: axial modes

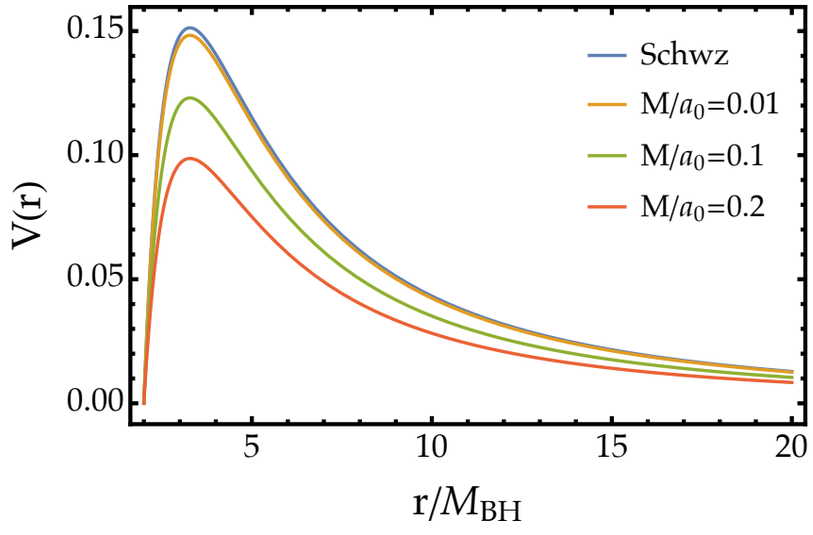
How does the halo change the axial perturbations of the BH?

- *Same functional form but...*

$$\frac{d^2 R_{\ell m}}{dr_\star^2} + [\omega^2 - V^{\rm ax}]R_{\ell m} = J_{\rm ax}$$

$$V^{\rm ax} = \frac{a(r)}{r^2}\left[\ell(\ell+1) - \frac{6m(r)}{r} + m'(r)\right]$$

- *Homogenous and in-homogenous problems provide the set up to study QNM and EMRI dynamics*



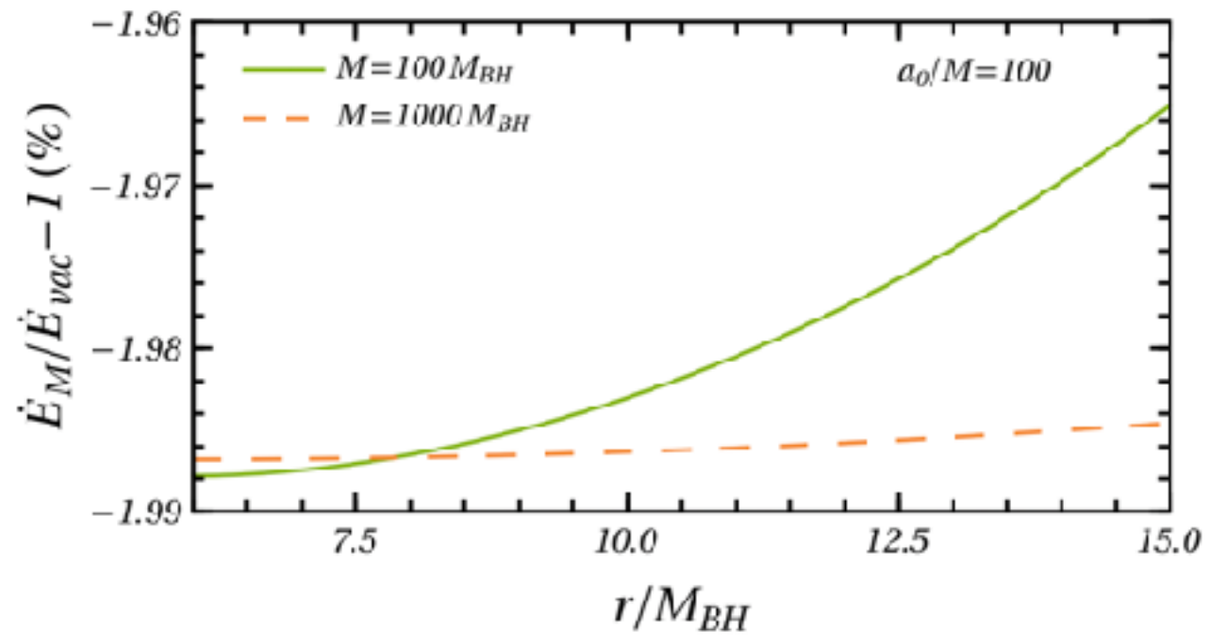
Change in the scattering potential due to the halo compactness

- *The halo affects the structure of the potential, as well the boundary conditions of the wave propagation at the horizon and at infinity*
- *axial modes **are not** coupled to fluid perturbations*

BH & halo: axial modes

The halo properties affect the GW emission and hence the EMRI inspiral evolution (already) at adiabatic level

Relative change in the axial flux v.s. vacuum



- *The difference with vacuum grows with M*
- *Suppression as M/a_0 decreases*
- *Difference << 1% as* $M/a_0 \sim 10^{-3}$

1 year observation — *before the plunge*

~ 500 radians

look promising but...

The redshift strikes back

Series expansion for low compactness $M/a_0 \ll 1$

$$V^{\rm ax} \approx \left(1 - \frac{2M}{a_0}\right) V^{\rm ax}_{\rm Schw} \qquad J^{\rm ax}_{\ell m} \approx \mu \left(1 - \frac{3M}{a_0}\right) J^{\rm ax,Schw}_{\ell m} \qquad \frac{dr}{dr_\star} \approx \left(1 - \frac{M}{a_0}\right) \frac{dr}{dr_{\star,\rm Schw}}$$

$$\frac{d^2 R_{\ell m}}{dr^2_{\star,\rm Schw}} + \left[\left[\omega\left(1 + \frac{M}{a_0}\right)\right]^2 - V^{\rm ax}_{\rm Schw}\right] R_{\ell m} = \mu \left(1 - \frac{M}{a_0}\right) J_{\rm ax,Schw}$$

$$\Omega_p \to \tilde{\Omega}_p = \Omega_p \left(1 - \frac{M}{a_0}\right)$$

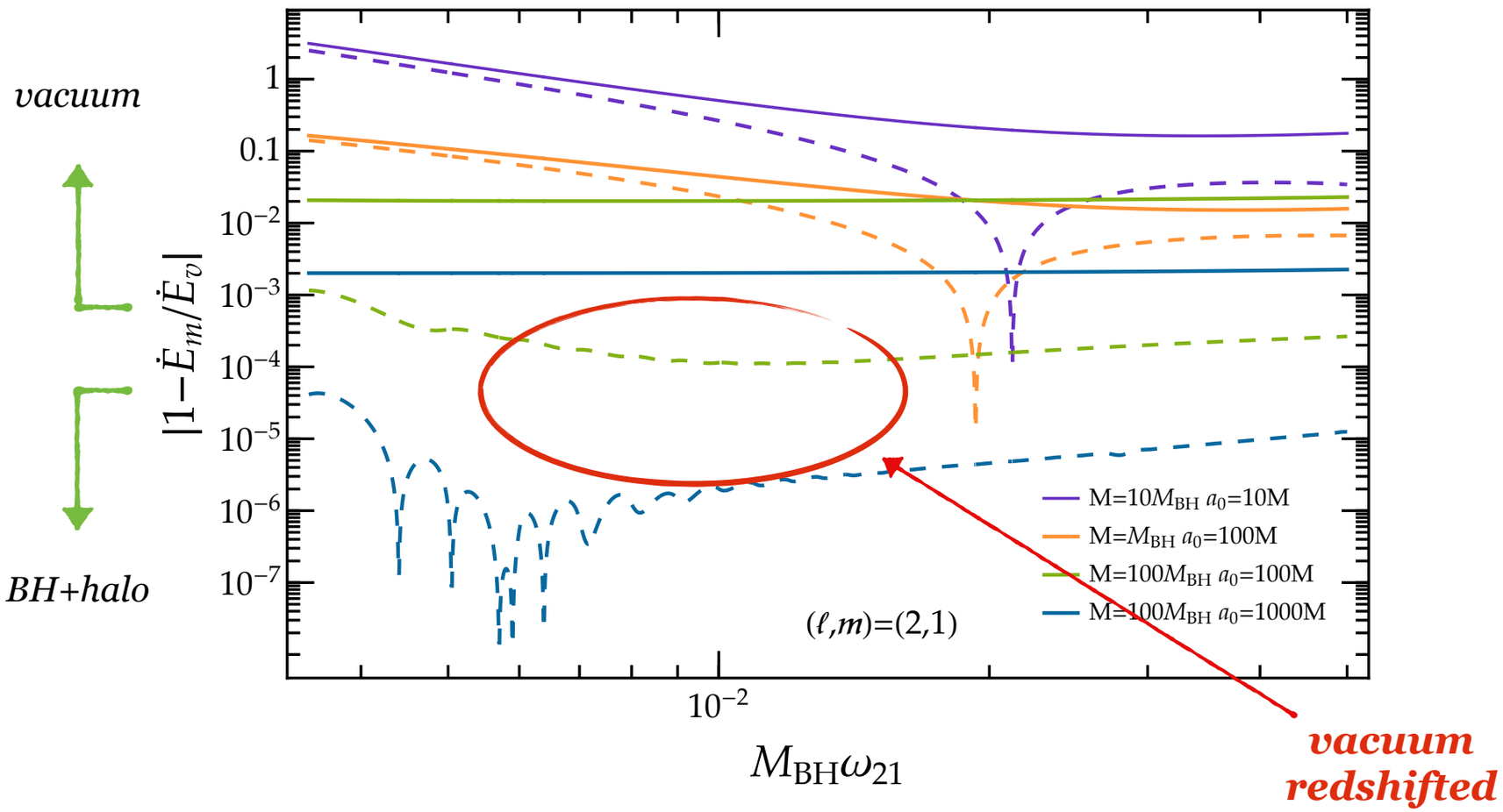
$$\mu \to \tilde{\mu} = \mu \left(1 + \frac{M}{a_0}\right)$$

Equivalent to a vacuum solution with rescaled parameters (redshift of the BH mass scale)

The redshift strikes back

(2,1) axial flux emitted by an EMRI on circular motion

- *fluxes tend to be smaller in the presence of the halo*



- *Redshifted quantities drastically reduce the discrepancy for realistic halos*
- *Unless new effects pop up in the polar sector, the halo seems undetectable*

BH & halo EMRI: polar modes

Polar sector is more challenging due (more variables &) couplings between matter and metric components

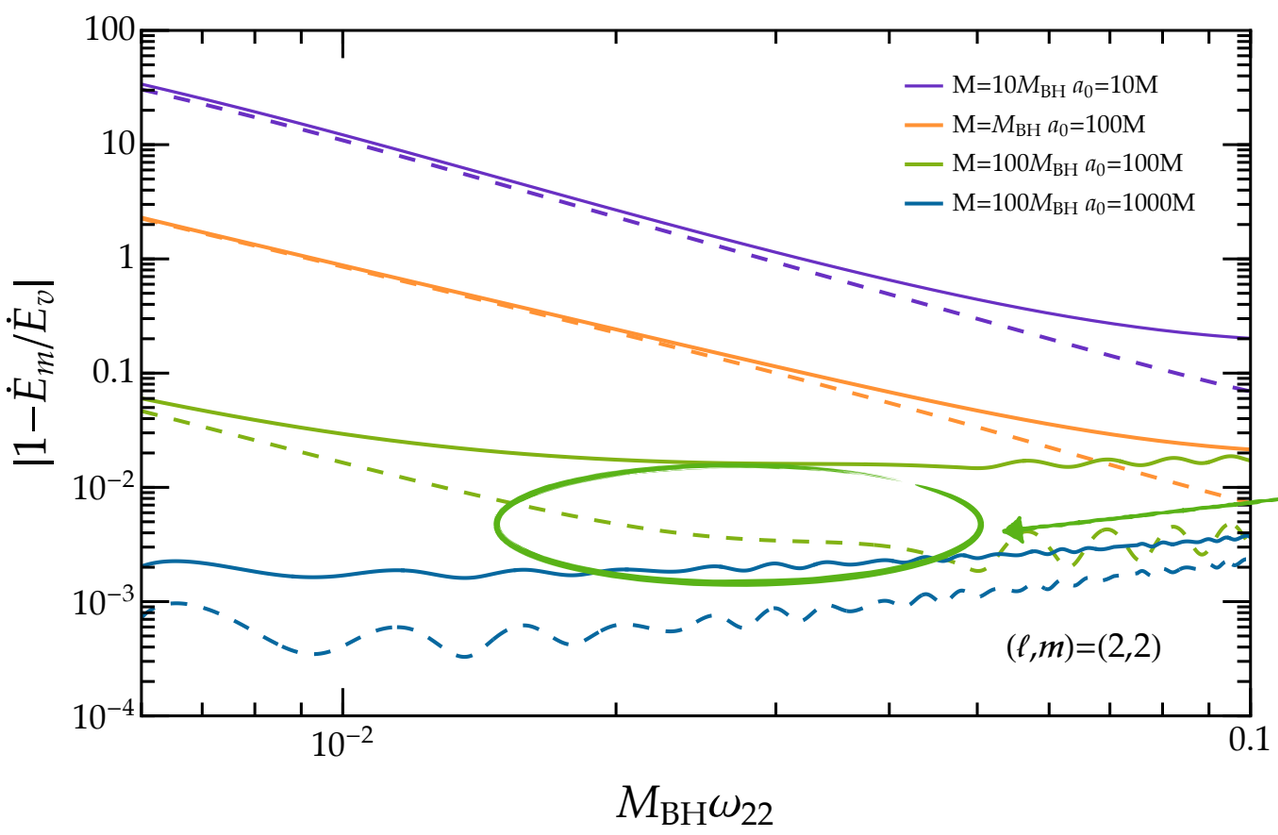
- *System of 5 coupled differential equations for* $\vec{V} = (H_1, H_0, K, W, \delta\rho)$

$$\frac{d\vec{V}}{dr} = \mathbf{A}\vec{V} = \vec{S}$$

speeds of sound

$$\delta p_{r,\ell m} = c_{s_r}^2 \delta\rho_{\ell m}$$
$$\delta p_{t,\ell m} = c_{s_t}^2 \delta\rho_{\ell m}$$

(2,2) polar flux emitted by an EMRI on circular motion



- *Redshift rescaling not enough to take into account shift in the fluxes*
- *Matter couplings matter*
- *deviations seem "promising" in terms of detectability*

vacuum
redshifted

new waveform models to build

Beyond GR

New fields for LISA?

Typically, beyond GR theories feature extra fields or can be reformulated in terms of them

- *Affects both generation and propagation mechanisms*

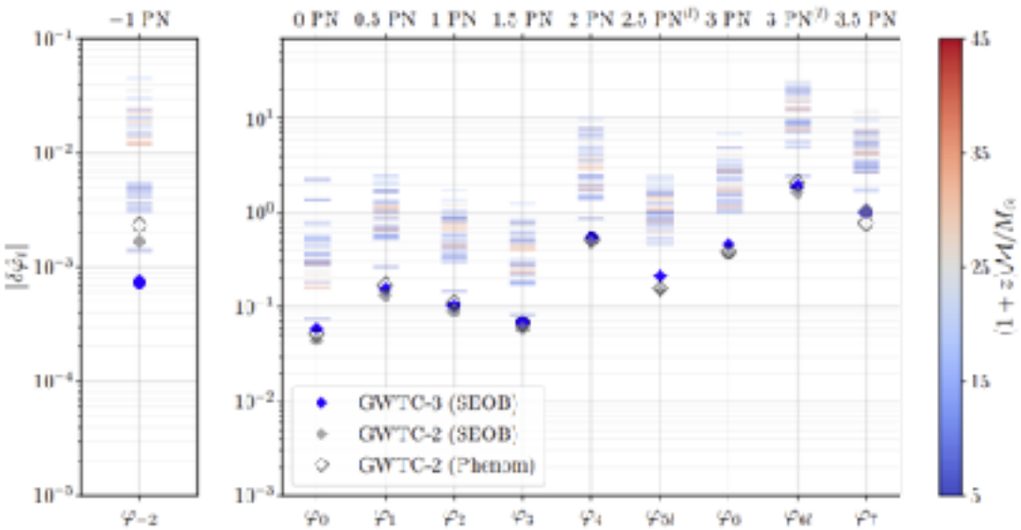
Compact binaries can probe the existence of such new fields

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

  Barausse+, PRL 116, 241104 (2016)

- *Comparable mass in the merger & post-merger*

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



Abbott +, PRL 2112.06861 (2021)

What about binaries we expect to observe with LISA?

Beyond GR inspiral

pN map to specific theories of gravity

amplitude *type*

$$\phi(f) \longrightarrow \phi(f) + \beta(\mathcal{M}\pi f)^{(2\gamma-5)/3}$$

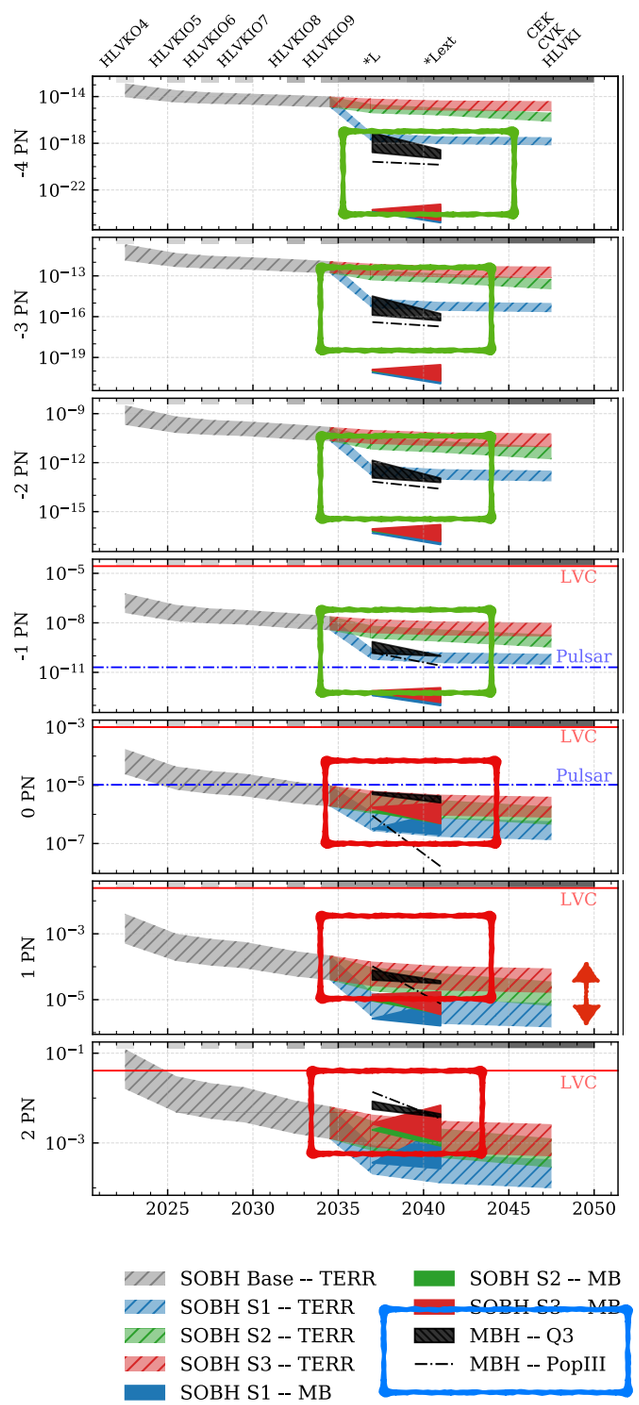
Theory or physical process	Physical modification	G/P	PN order	β	Theory parameter	$2\gamma - 5$
Generic dipole radiation	Dipole radiation	G	-1	(B2)	$\delta\dot{E}$	-7
Einstein-dilaton Gauss-Bonnet	Dipole radiation	G	-1	(B3)	$\sqrt{\alpha_{\rm EdGB}}$	-7
Black Hole Evaporation	Extra dimensions	G	-4	(B6)	$\dot{M}$	-13
Time varying G	LPI	G	-4	(B7)	$\dot{G}$	-13
Massive Graviton	Nonzero graviton mass	P	1	(B11)	m_g	-3
dynamical Chern-Simons	Parity violation	G	2	(B8)	$\sqrt{\alpha_{\rm dCS}}$	-1
Noncommutative gravity	Lorentz violation	G	2	(B10)	$\sqrt{\Lambda}$	-1

- *same type may correspond to different physical effect when mapped to a given theory beyond GR*
  - *coupling's theory can depend on the <u>source's properties</u>*
    - *actual constraints can change due to scalings and/or correlations*

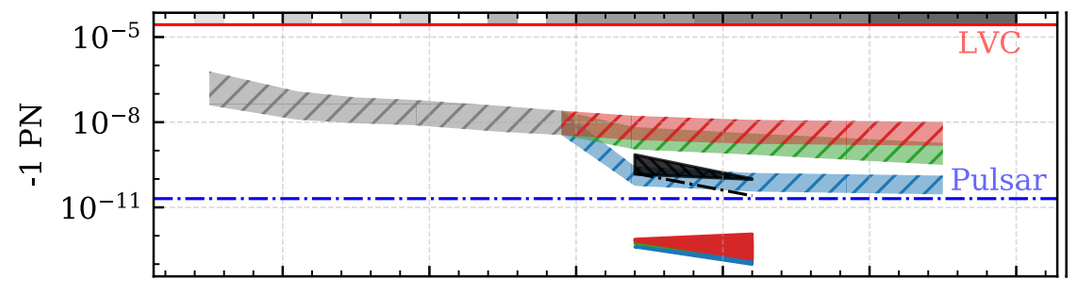
Beyond GR inspiral

Constraints from next generation detectors

S. Perkins+, PRD 103, 044024 (2021)



massive LISA sources



dipole phase correction

what do we learn?

New fields for LISA?

It may be tempting to answer NOPE

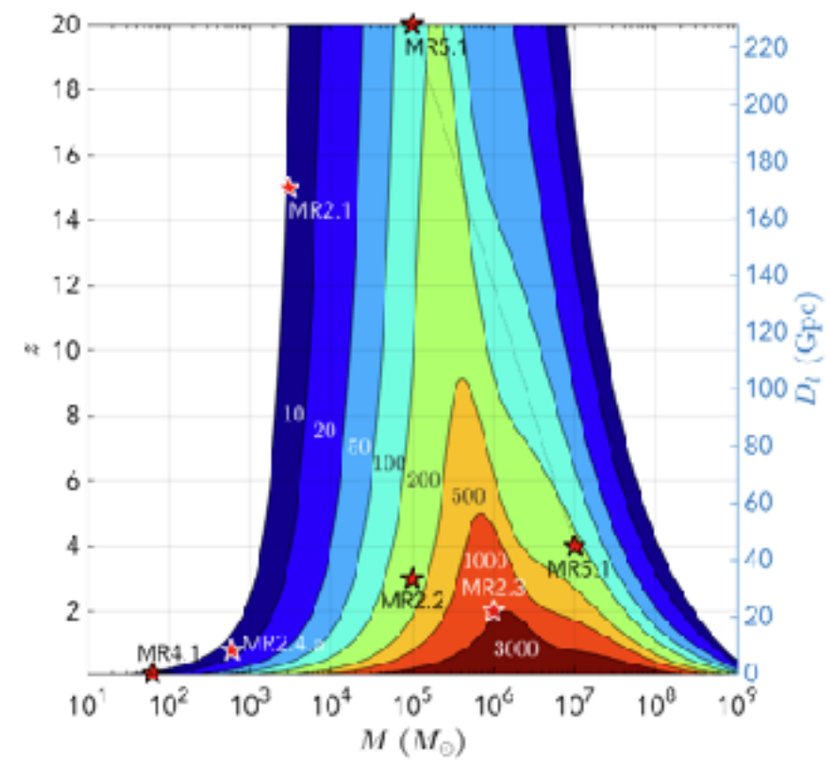
- *In most scalar-tensor theories BHs feature no-hair theorems:* ***same*** *as in GR*

- *For hairy BHs, the scalar field generally couples with high-order curvature terms,* $\sim R^n_{\alpha\beta\mu\nu}$*, i.e. features* ***dimensionful*** *couplings*

  - *GR deviations scale as* $\sim (\ell/M)^n$

length scale of the coupling

$\ell \sim M_\odot$ ← *astrophysical observations*



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

Beyond GR inspiral

Gauss Bonnet

$$\beta_{\rm EdGB} = -\frac{5}{7168}\frac{\zeta_{\rm EdGB}}{\eta^{18/5}}\frac{\left(m_1^2 s_2^{\rm EdGB} - m_2^2 s_1^{\rm EdGB}\right)^2}{m^4}$$

$$s_i^{\rm EdGB} = \frac{2\left[\left(1-\chi_i^2\right)^{1/2} - 1 + \chi_i^2\right]}{\chi_i^2},$$

$$\zeta_{\rm EdGB} \sim \alpha_{\rm EdGB}^2/m^4$$

Chern Simons

$$\beta_{\rm dCS} = -\frac{5}{8192}\frac{\zeta_{\rm dCS}}{\eta^{14/5}}\frac{\left(m_1 s_2^{\rm dCS} - m_2 s_1^{\rm dCS}\right)^2}{m^2} + \frac{15075}{114688}\frac{\zeta_{\rm dCS}}{\eta^{14/5}}\frac{\left(m_2^2\chi_1^2 - \frac{350}{201}m_1 m_2 \chi_1\chi_2 + m_1^2\chi_2^2\right)}{m^2}$$

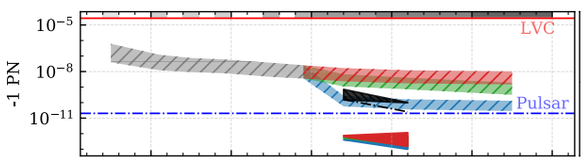
$$s_i^{\rm dCS} \equiv \frac{2 + 2\chi_i^4 - 2\left(1-\chi_i^2\right)^{1/2} - \chi_i^2\left[3 - 2\left(1-\chi_i^2\right)^{1/2}\right]}{2\chi_i^3},$$

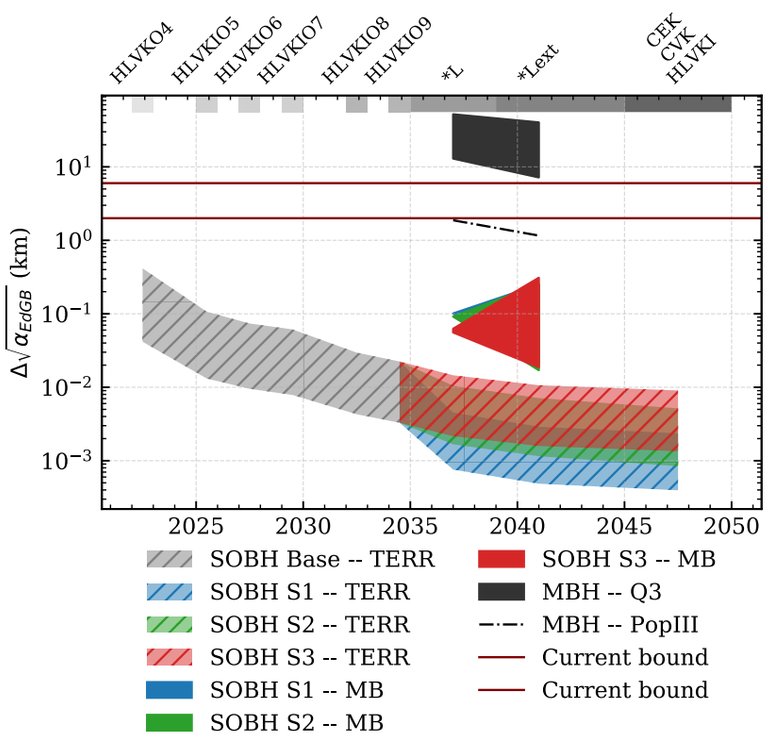
$$\zeta_{\rm dCS} \sim \alpha_{\rm dCS}^2/m^4$$

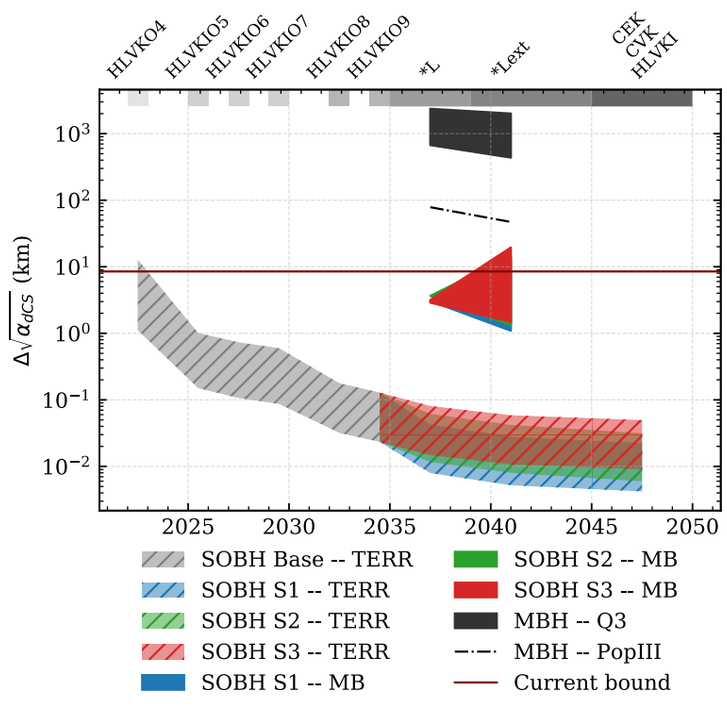
Massive graviton

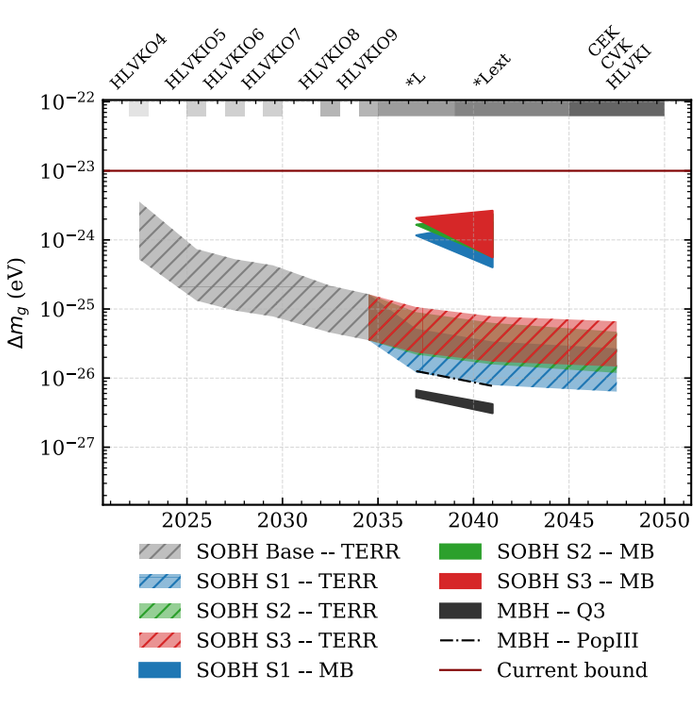
$$\beta_{\rm MG} = \pi^2 \frac{D_0}{1+z}\frac{\mathcal{M}_z}{\lambda_{\rm MG}^2}$$

$$D_0 \equiv (1+z)\int_0^z \frac{1}{H(z')}\frac{dz'}{(1+z')^2}$$





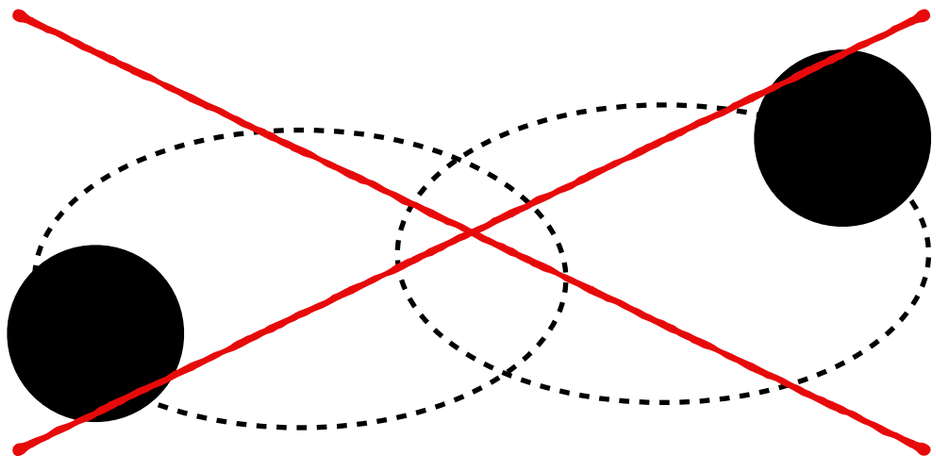




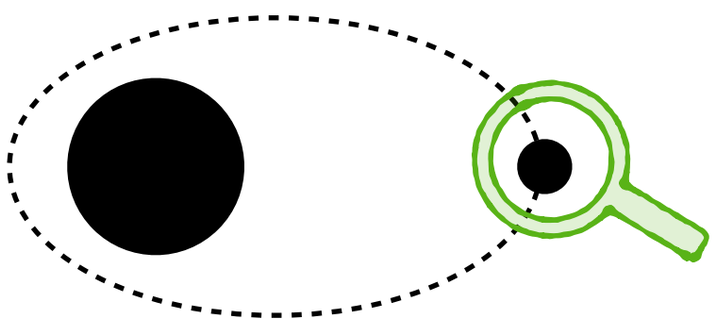
Scales & new families

LISA will observe old-and-new families of binaries

- *Huge potential for new science cases and new challenges (problems)*



comparable mass binaries



(very) asymmetric binaries

most promising sources for fundamental physics for LISA

sources to deeply focus for source modelling, systematics ...

The Setup

Scalar field φ non-minimally coupled to the gravity sectors

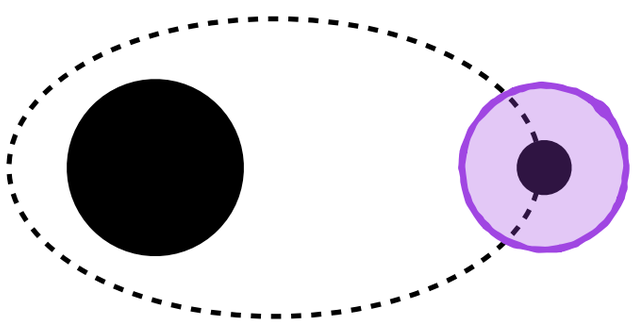
A.M. +, PRL 125, 14101 (2020)

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

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

Non-minimal coupling

Matter fields



primary described by the Kerr metric

*secondary endowed with a scalar charge **d***

At the leading order Teukolsky waveforms are exact

1. *Everything as in GR but for fluxes* $\dot{E} = \dot{E}_{\rm GR} + d^2\delta\dot{E}_{\rm d}$
2. *$\dot{E}$ drives 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. *and the waveforms* $h_+[r(t),\Phi(t)]$, $h_\times[r(t),\Phi(t)]$

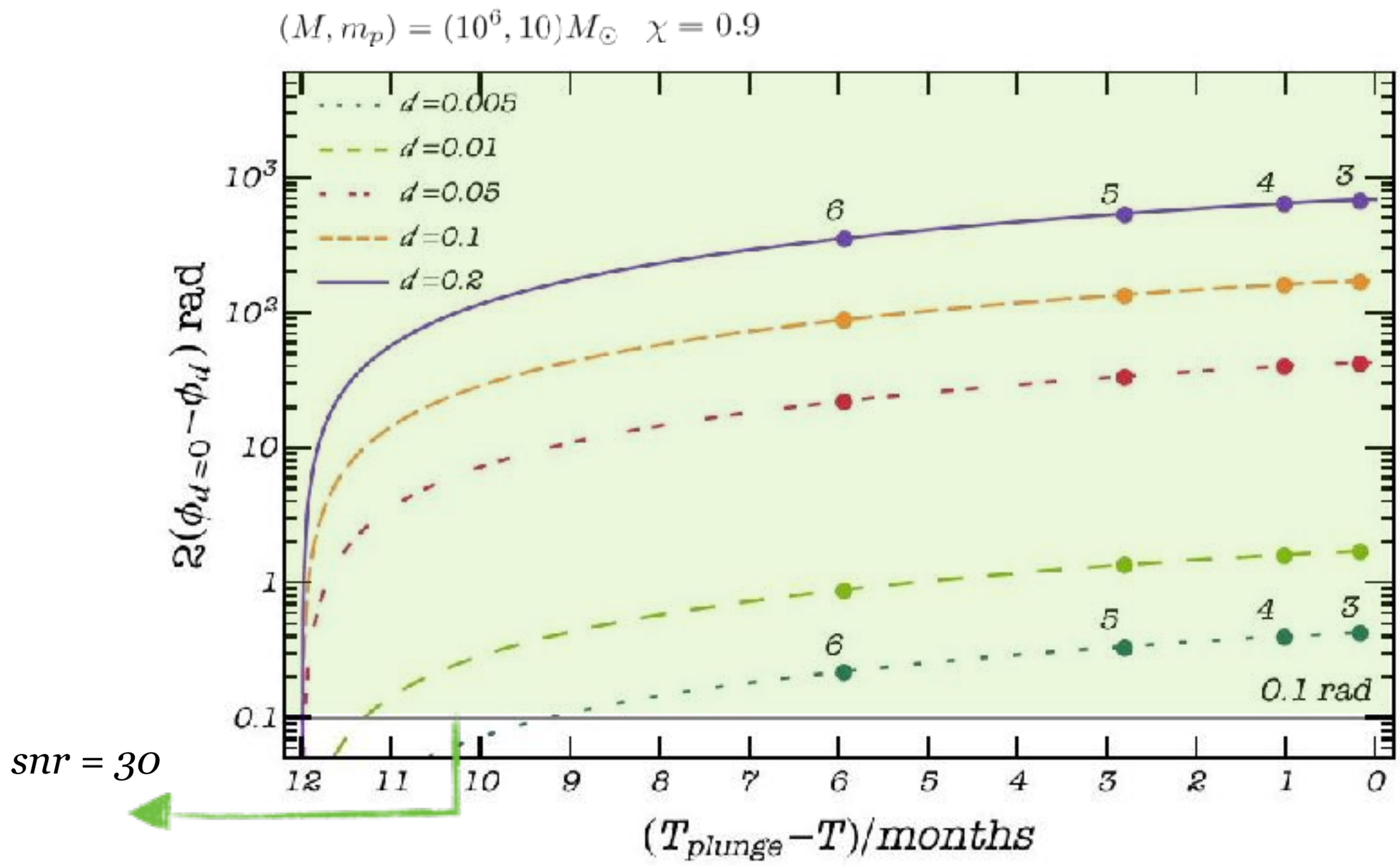
already implemented in LISA pipelines

*all changes captured by **d***

How much dephasing?

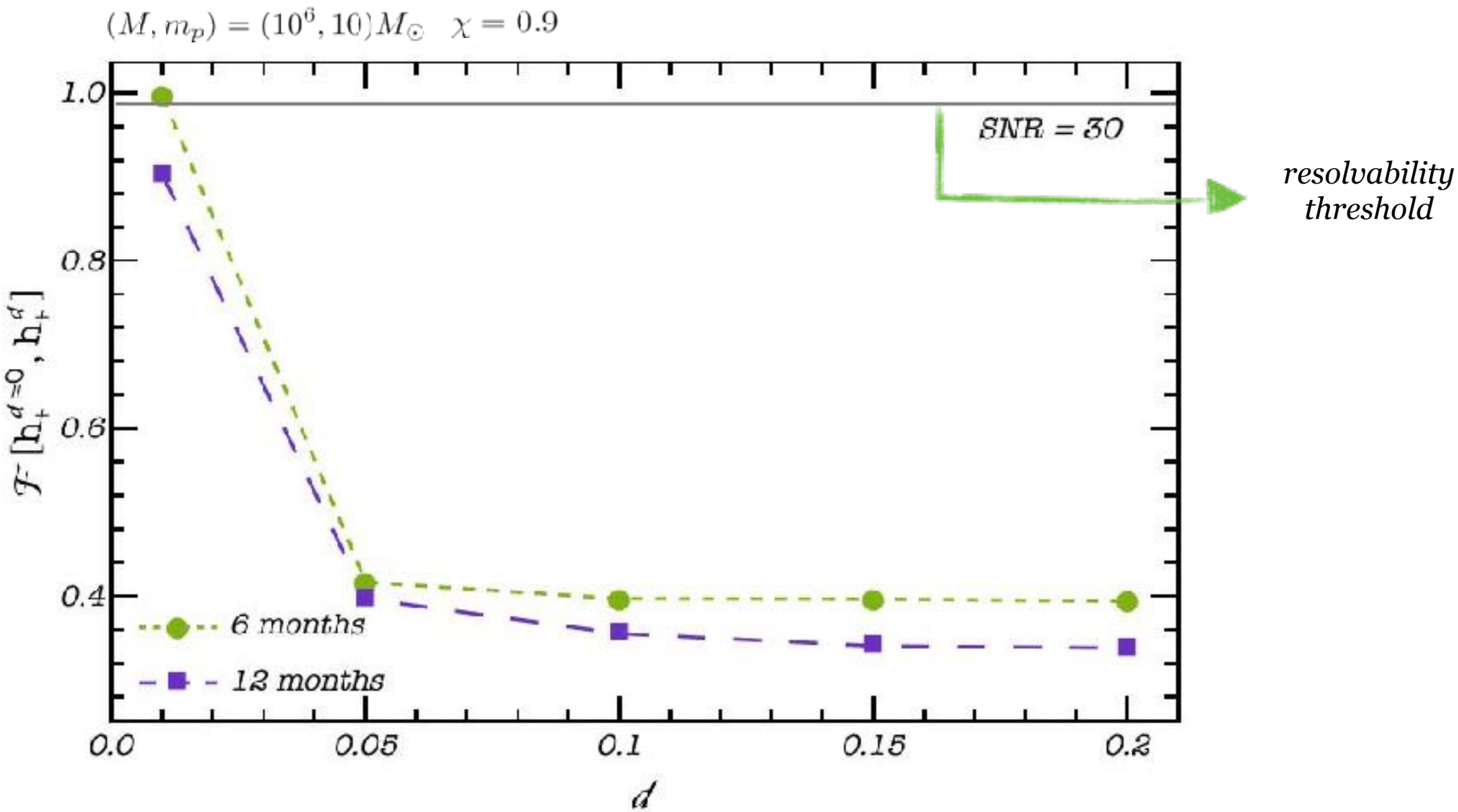
*Difference between GR - GR**d** phase evolution during the inspiral*

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



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

Overlap & Faithfulness



- *Potentially able to observe changes induced by scalar charges* $d \sim 0.005 - 0.01$

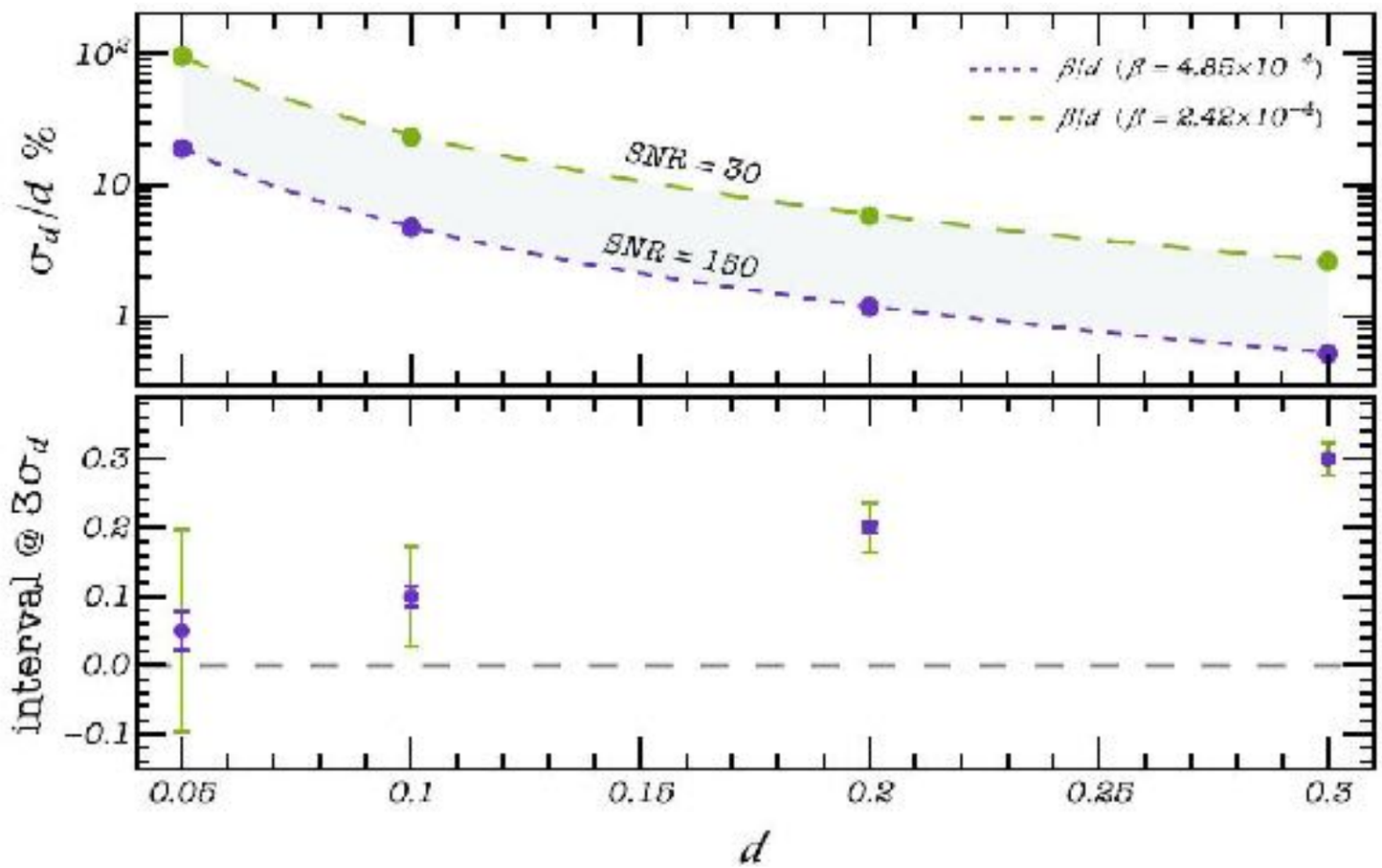
Forecast on LISA bounds

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

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

- *Bounds via a Fisher Matrix approach*

$(M, m_p) = (10^6, 10) M_\odot \quad \chi = 0.9$



- *LISA potentially able to measure **d** with % accuracy and better*
- *LISA potentially able to constrain **d** ~ 0.05 to be inconsistent with zero @ 3- σ*

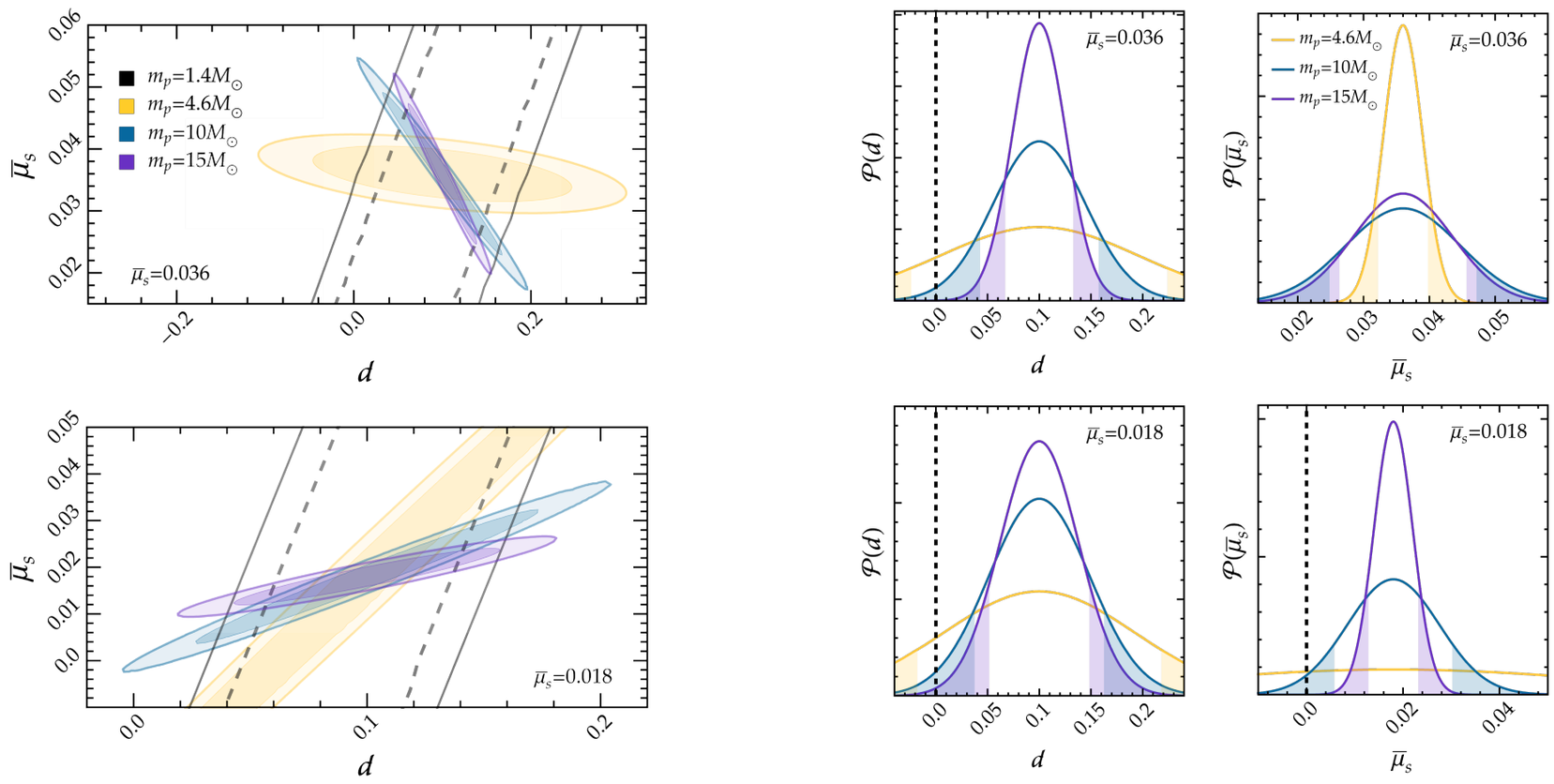
Forecast on LISA bounds

Extension to massive scalar fields

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

- *The approach suits perfectly for massive scalars*

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



- *First analysis on capability of EMRI & LISA simultaneously constrain mass and scalar charge of the secondary*

Tracing back the couplings

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

Julie & Berti, PRD 100, 104610 (2019)

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

- $n = 2$, $[\alpha] = mass^2$ → $\zeta \equiv \frac{\alpha}{M^2} = q^2 \frac{\alpha}{m_2^n}$
- $f(\varphi)$ *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*
- *The scalar charge is 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***

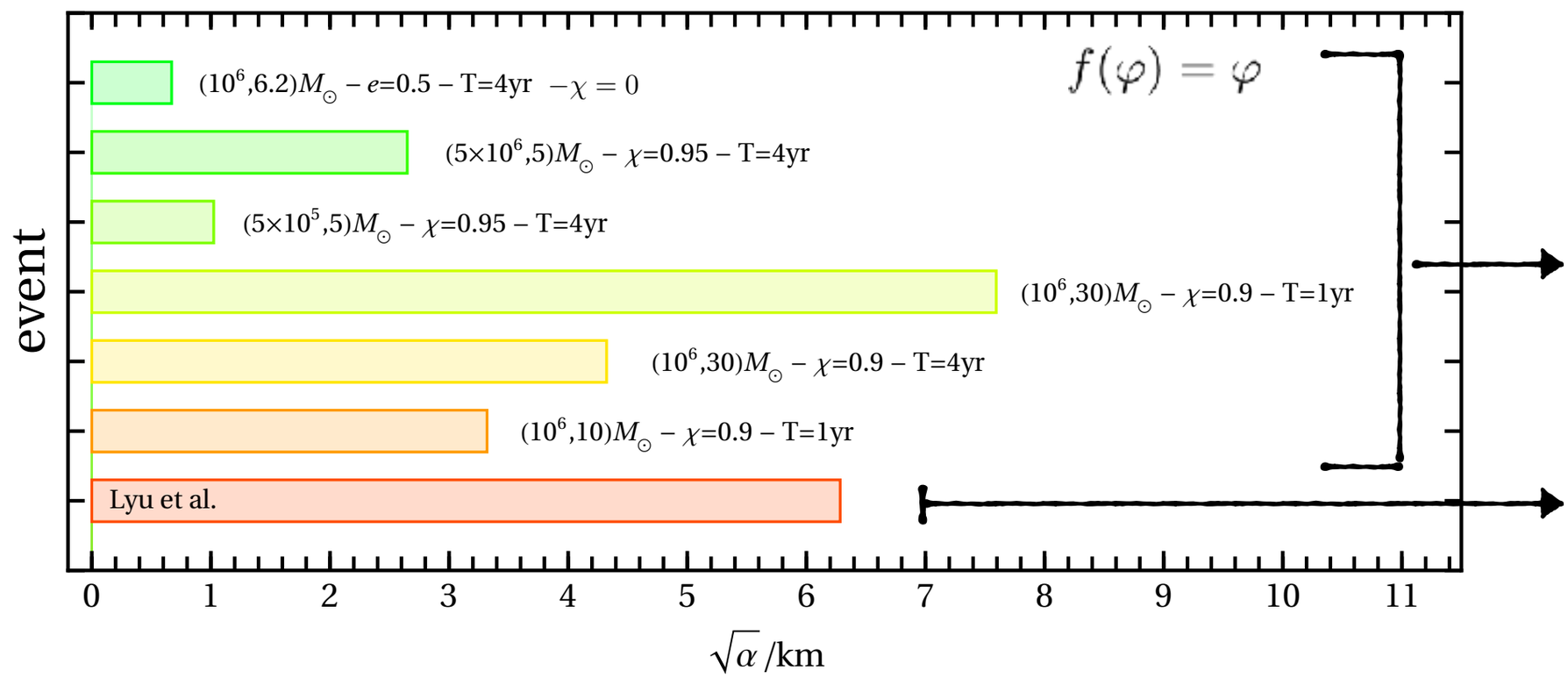
Fast EMRI Waveforms

*We (Lorenzo Speri) are implementing non-GR waveforms into **FEW***

Katz +, PRD 104 064047 (2021)

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

Speri +, in preparation (2023)



EMRI

Best LVC constraint

Perkins +, PRD 104 024060 (2021)

Liu +, PRD 105 06400 (2022)

Prospects

Variety of studies supporting the idea that astro-fundamental-physics modifications to vacuum GR can be constrained by GW observations

- *Final outcome depends on the physical effect considered (also affects the best family of binaries to exploit)*

Efforts in various directions, but waveform modelling is a long road ahead

- *relativistic calculations to pN templates suggest the relevance of such contributions*
- *Modelling for asymmetric binaries is at infancy*
  - *Ab initio calculations provide a broader view (the redshift affair)*

Mismodelling can have little impact on astro-conclusions

- *Affect fundamental physics problems (beyond GR, BH nature...)*
- *What about correlations between them ?*

Back up

More general than it looks

Approach extended to generic density profiles

E. Figueiredo +, PRD 107, 104033, (2022)

- *Developed a fully numerical approach to treat any* $\rho(r)$
- *applied to new DM models*

$$\rho(r) = \rho_0 (r/a_0)^{-\gamma}[1 + (r/a_0)^{\alpha}]^{(\gamma-\beta)/\alpha}$$

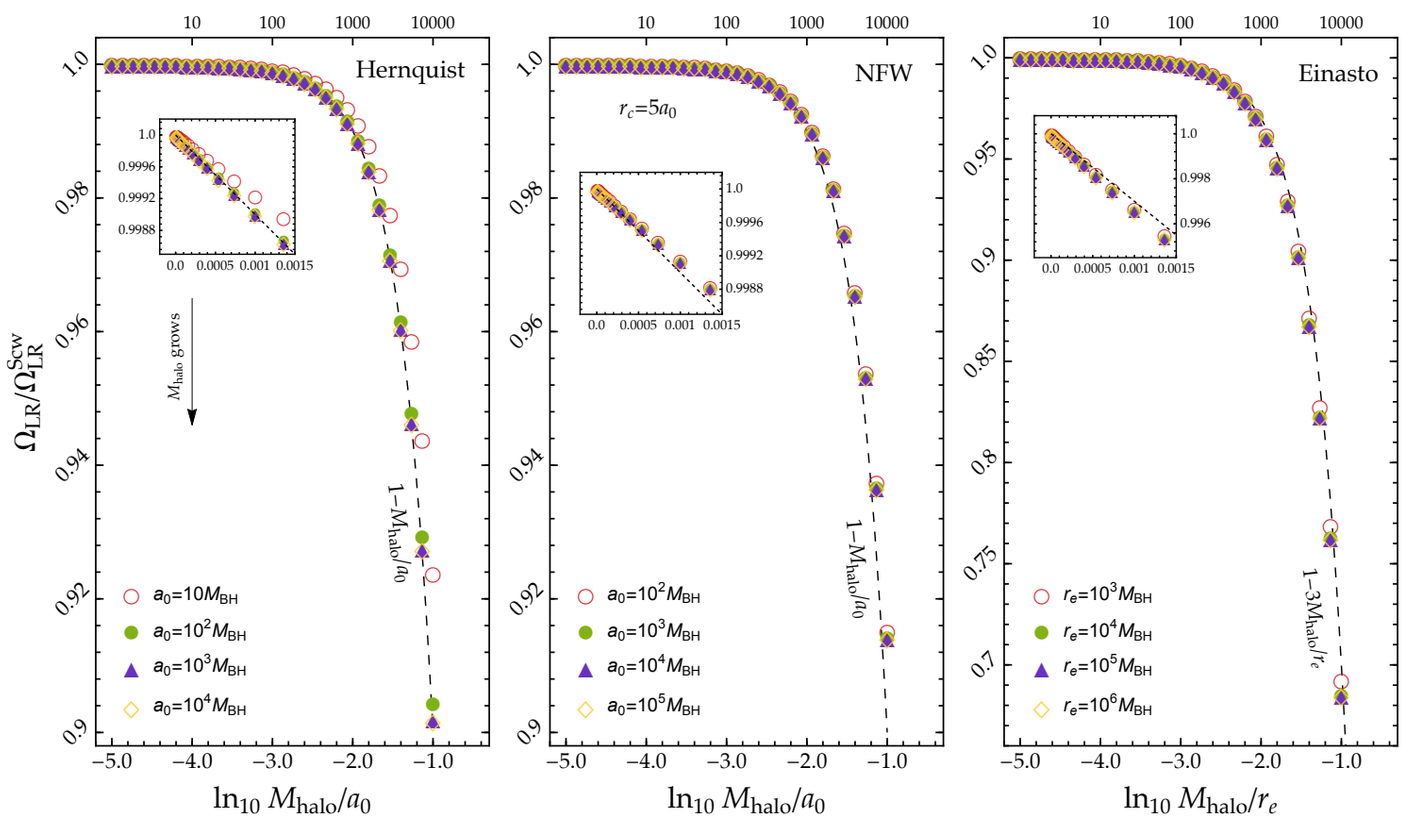
Hernquist & Navarro-Frenk-White

$$\rho(r) = \rho_e \exp\left\{-d_n[(r/r_e)^{1/n} - 1]\right\}$$

Einasto

geodesic frequency @ Light Ring

universal behaviour for $M/a_0 \lesssim 10^{-3}$

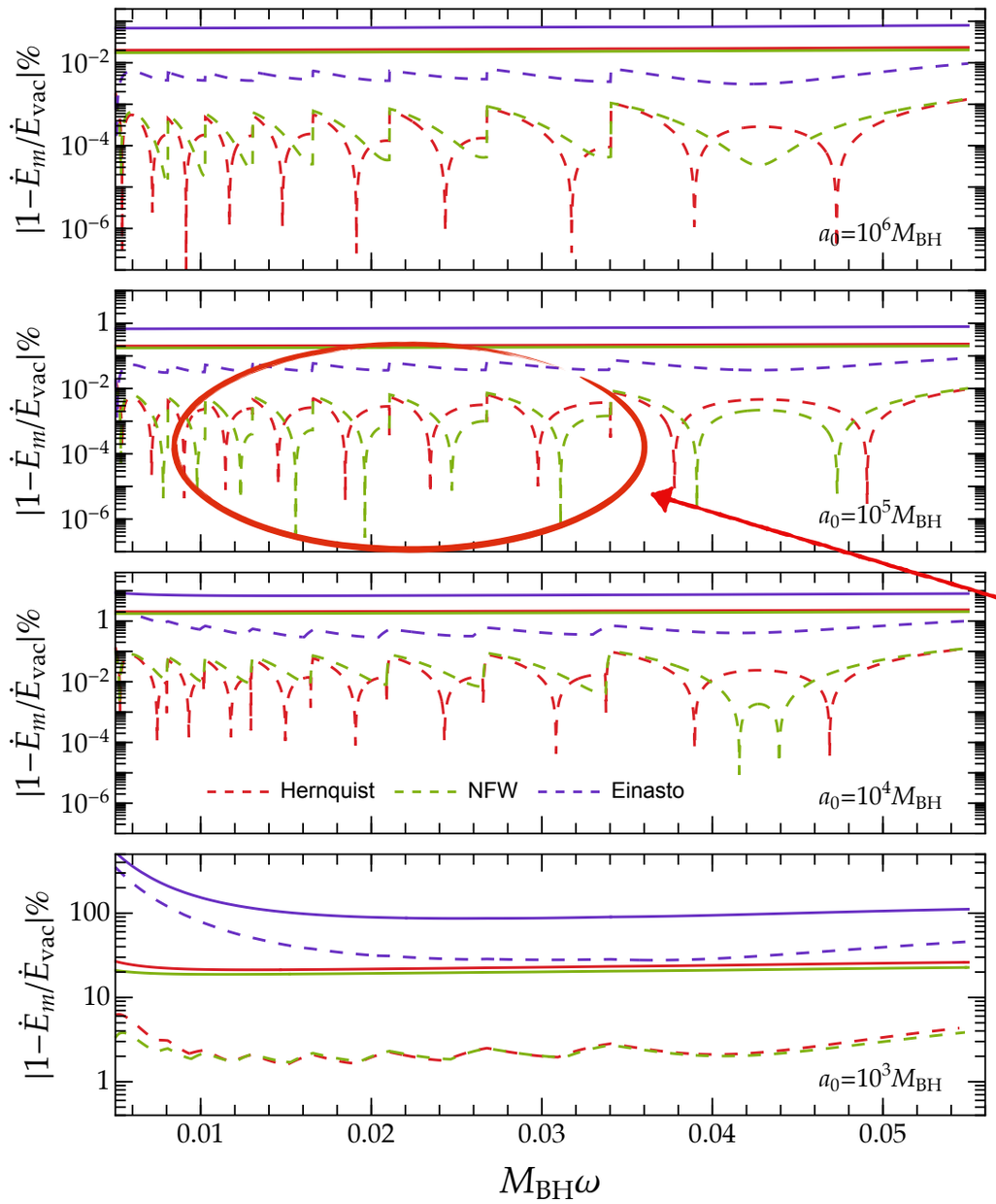


- *Changes with respect to vacuum can be interpreted in terms of a "redshift" scaling*

More general than it looks

Axial fluxes from EMRIs on circular orbits

E. Figueiredo +, PRD 107, 104033, (2022)



vacuum redshifted

- *redshift (again) tends to suppress differences*

The Setup

Scalar field φ non-minimally coupled to the gravity sectors

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

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

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

Non-minimal coupling

Matter fields

1) Theories with no-hair theorems

2) Theories which evade no-hair but have dimensionful coupling α with $n \geq 1$

- *Assume BH solutions are connected to GR solutions* $\alpha \to 0$
- *any GR deviations must depend on* $\zeta = \frac{\alpha}{M^n} = q^n \frac{\alpha}{m_p^n} = q^n \zeta_p \ll 1$
- *For the background spacetime, contributions to S_c are suppressed by q^n*

→ *primary space-time described by the Kerr metric*

The Setup

Therefore, at the leading order in the mass ratio q

- *The large black hole is described by the Kerr metric*
- *The small compact objects acts as a point particle moving on geodesics*
- *The scalar is constant in the background spacetime*

In a buffer zone in the small body world tube

scalar charge

$$\varphi = \varphi_0 + \frac{m_{\rm p}\, d}{\tilde{r}} + O\left(\frac{m_{\rm p}^2}{\tilde{r}^2}\right)$$

The field's equations

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

Change in the EMRI dynamics universally captured by the scalar charge

The GW energy flux

The full solutions at infinity/horizon are needed to compute the emitted gravitational wave fluxes

$$\dot{E}^{\pm}_{\rm grav} = \frac{1}{64\pi}\sum_{\ell=2}^{\infty}\sum_{m=-\ell}^{\ell}\frac{(\ell+2)!}{(\ell-2)!}(\omega^2|Z^{\pm}_{\ell m}|^2 + 4|R^{\pm}_{\ell m}|^2) \qquad \dot{E}^{\pm}_{\rm scal} = \frac{1}{32\pi}\sum_{\ell=1}^{\infty}\sum_{m=-\ell}^{\ell}\omega^2|\delta\varphi^{\pm}_{\ell m}|^2$$

- *The total contribution*

$$\boxed{\dot{E} = \dot{E}^{+}_{\rm grav} + \dot{E}^{-}_{\rm grav} + \dot{E}^{+}_{\rm scal} + \dot{E}^{-}_{\rm scal} = \dot{E}_{\rm GR} + \delta\dot{E}_d}$$

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

- $\delta\dot{E}_d$ *enters at the* ***same*** *order in* ***q*** *as the GR leading dissipative contribution*

The Waveform

The recipe to generate EMRI waveforms

- *Compute the total energy flux emitted by the binary* $\dot{E} = \dot{E}_{\rm GR} + \delta \dot{E}_d$
- *The flux drives the binary orbital evolution*

$$\frac{dr(t)}{dt} = -\dot{E}\frac{dr}{dE_{\rm orb}} \quad , \quad \frac{d\Phi(t)}{dt} = \frac{M^{\frac{1}{2}}}{r_p^{3/2}}$$

- *Build the GW polarizations* $h_+[r(t), \Phi(t)] \quad , \quad h_\times[r(t), \Phi(t)]$
- *Given the source localization, construct the strain*

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

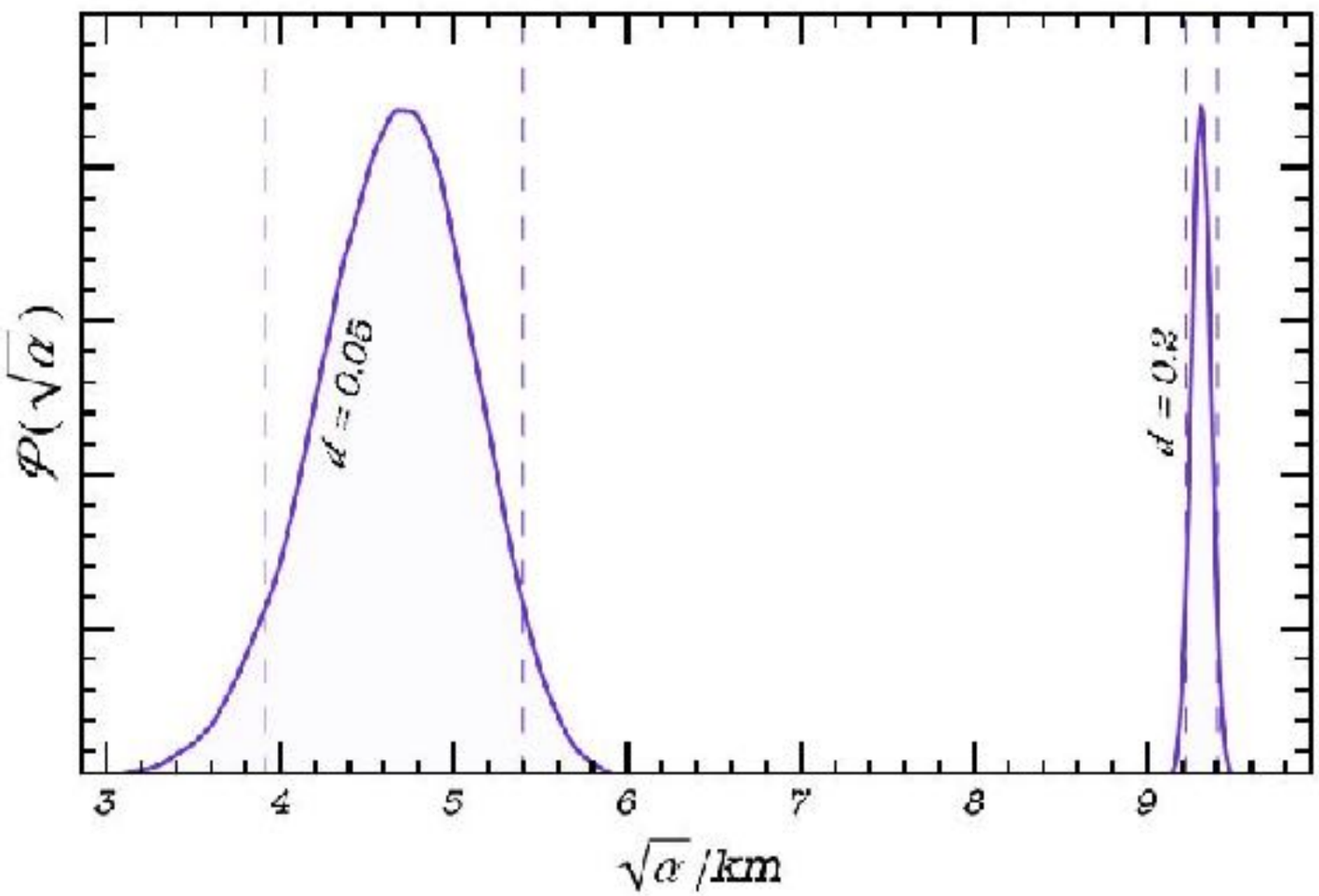
Everything as in GR but $\delta \dot{E}_d$*, that only depends on the scalar charge*

- *Universal family of waveforms to be tested against GR*

Forecast on LISA bounds: couplings

Map constraints on the charge to constraints on the coupling $d(\beta) \leftrightarrow \beta(d)$

Shift symmetric sGB $f(\varphi) = \varphi$



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

ECO

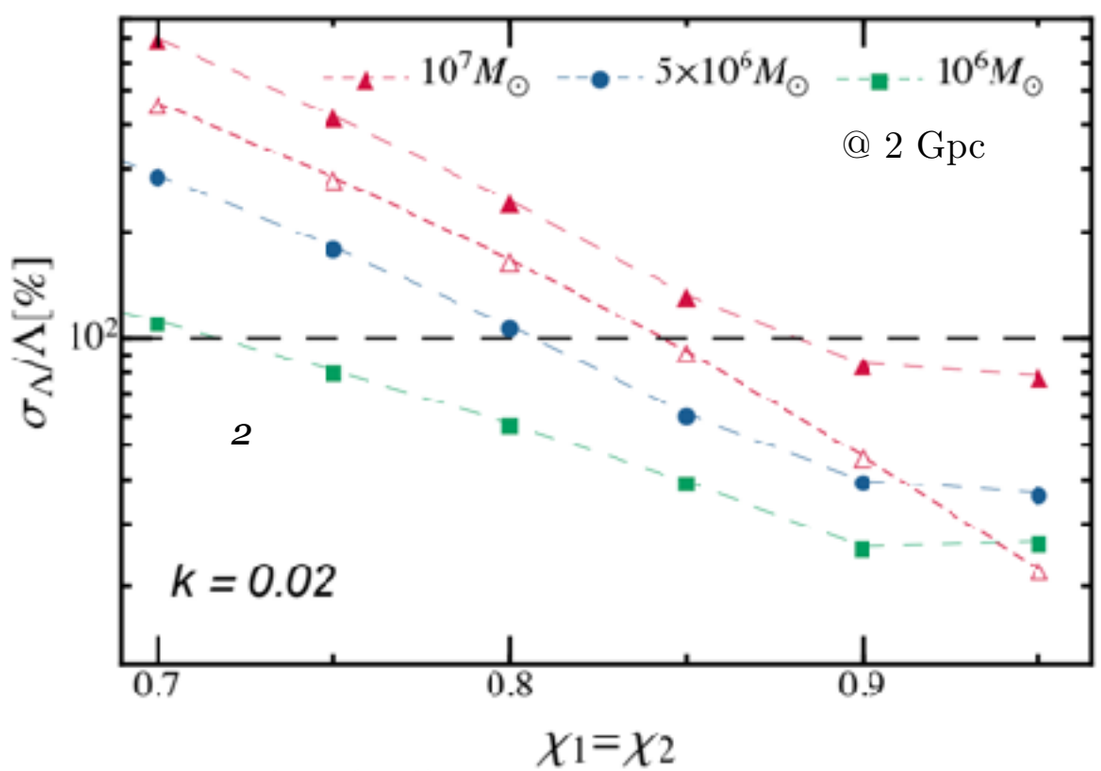
Love from the Inspiral

Tidal Love numbers are smoking gun signatures of horizonless objects (and BHs beyond GR)

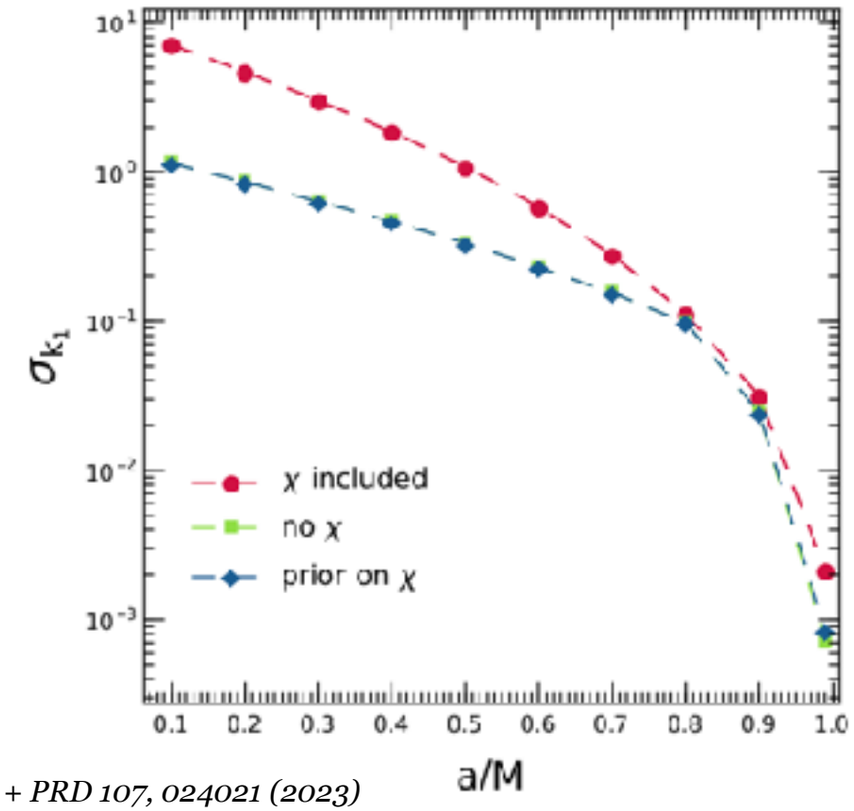
- *Moving from zero: tidal parameters for Kerr BHs vanish*
- *different families of tidal quantities, as scalar tidal love numbers*

  L. Bernard + PRD 101, 021501 (2020)
- *LISA expected to provide the best constraints on tidal deformability* $\Lambda \sim k_2 M^5$

agnostic constraints on comparable mass BBHs → *boost for EMRIs*



A. M. + PRL 120, 081101 (2018)



G. Piovano. + PRD 107, 024021 (2023)