Environmental Effects on Black Hole physics

@ GR24 and Amaldi 16

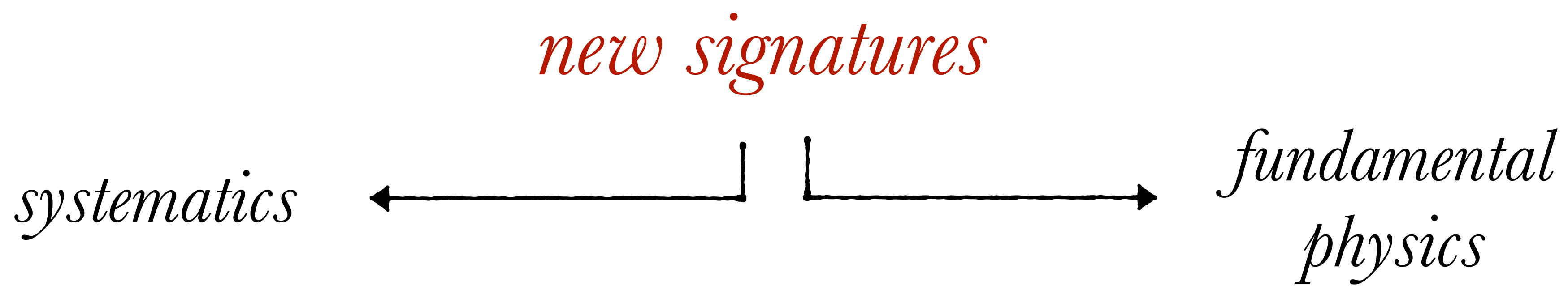
Glasgow, July 17, 2025

Andrea Maselli

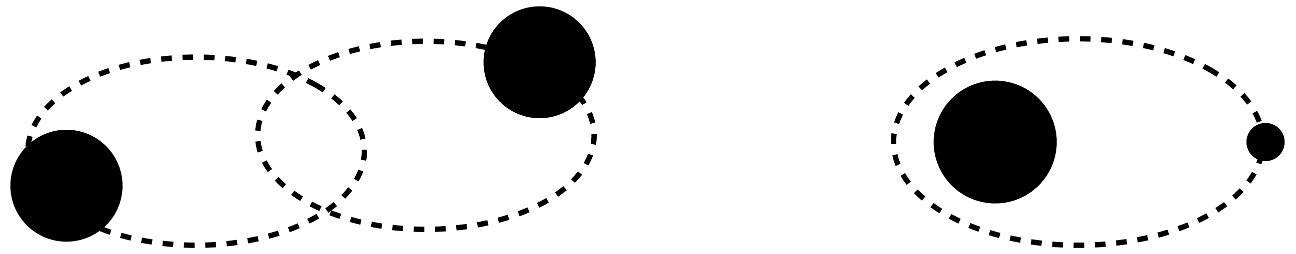
Environments Effects: opportunity and choices

Environmental effects as clear science case for high precision detectors E. Barausse +, 2014

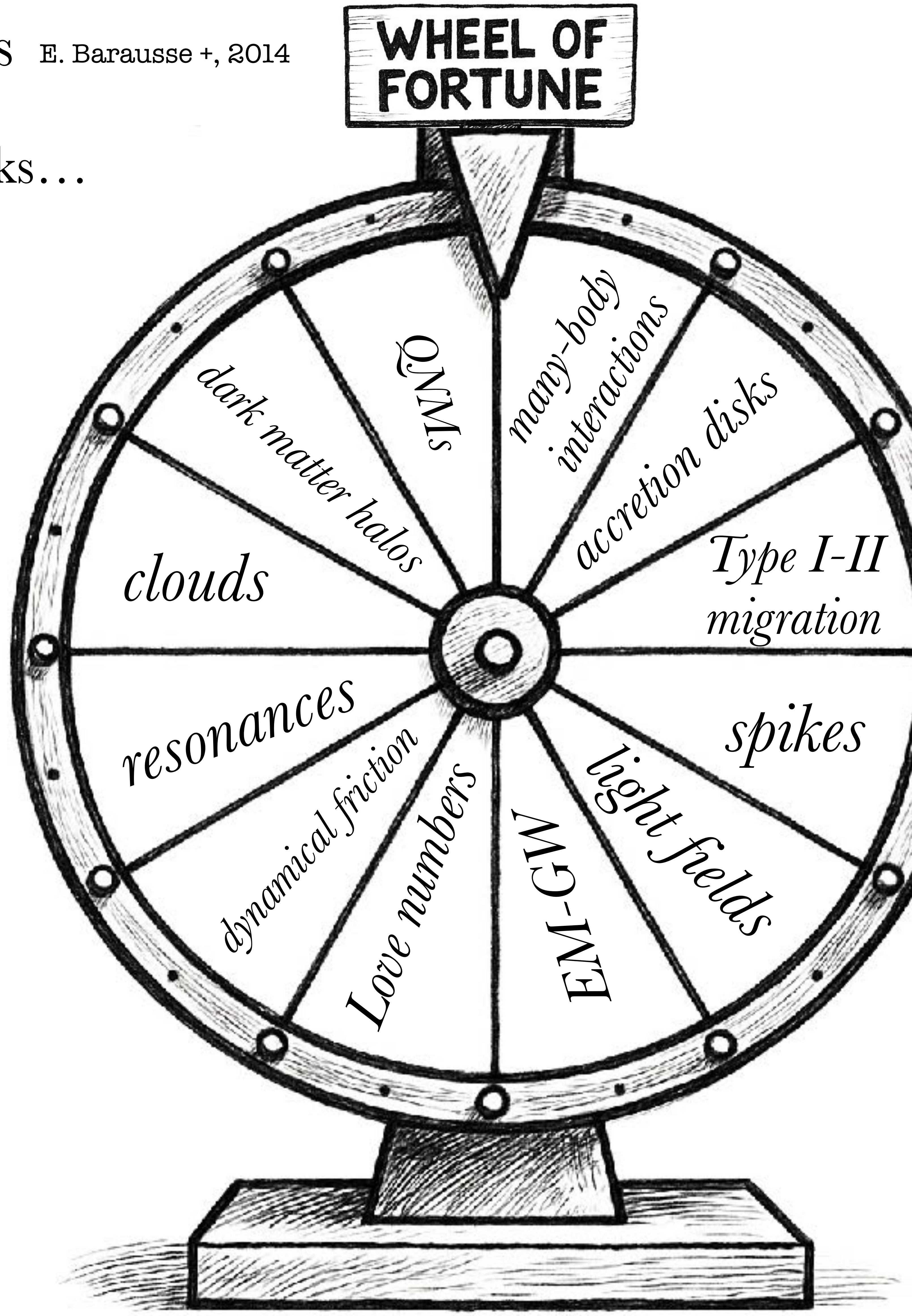
- Massive BHs evolving in DM-rich fields, binary formation in accretion disks…
- Binaries as Table-Top experiments: target and moving probes of their surroundings



- Next-gen detectors will target binaries with different scales and dynamical regimes



- (some) Common observables but: different approaches, simplifications, waveform models



Dynamical Friction

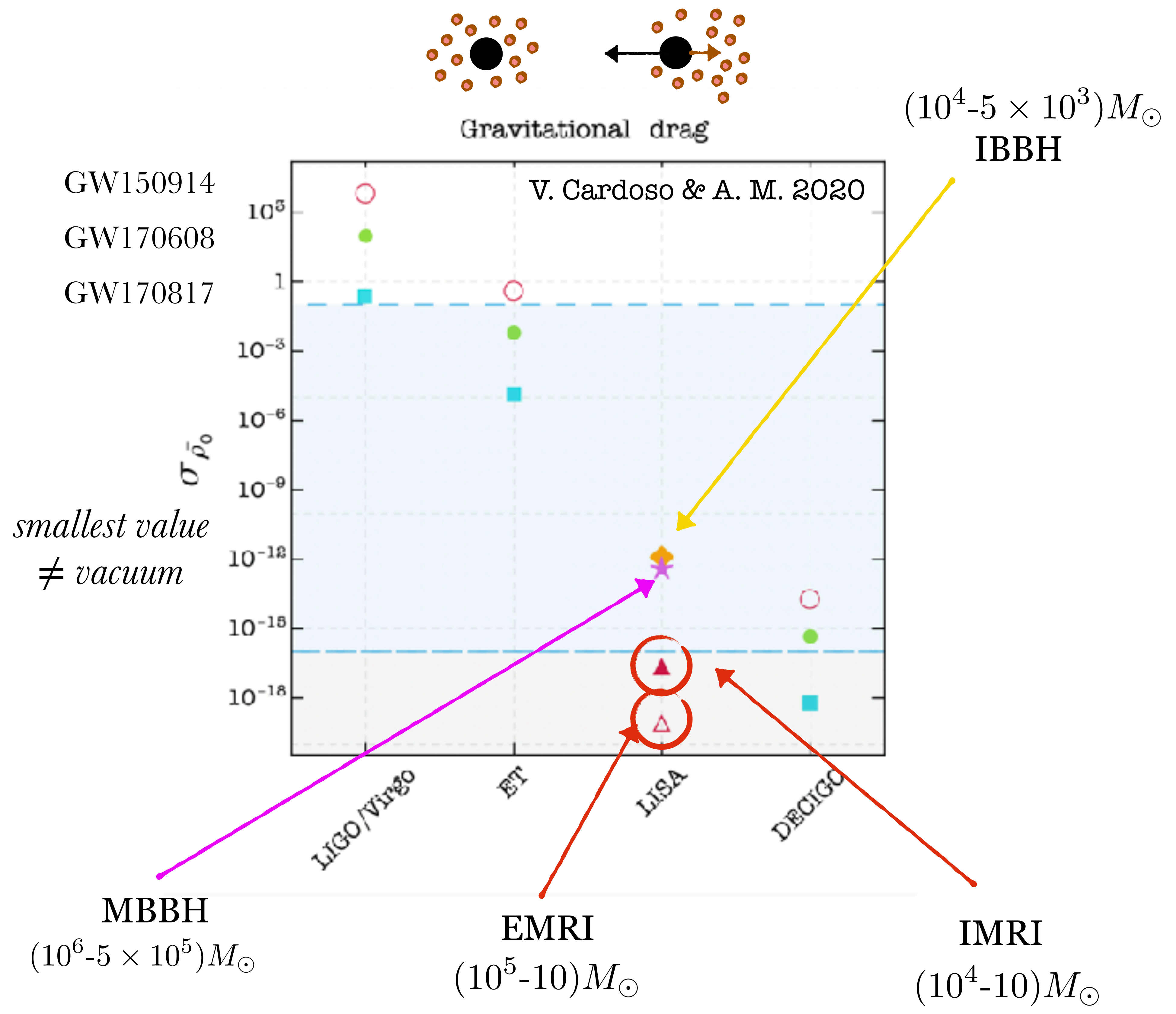
Interactions with particle in a medium transfers of momentum/energy from the orbital motion to the environment, inducing a drag force on the moving body S. Chandrasekhar, 1973

- DF changes in the dynamics translate into a phase shift

$$\psi_{\rm GW} \propto (m\pi f)^{-5/3}\left[vacuum + \delta\psi_{\rm env}\right] \qquad \delta\psi_{\rm env} \propto \rho_0(\pi m f)^{-11/3}$$

- Environmental effects *typically* contribute at low frequencies
  - Asymmetric binaries and next-gen detectors made for each other

- Analysis on GWTC-1/2 LVK binaries show no evidence of environmental effects G. C. Santoro +, 2025



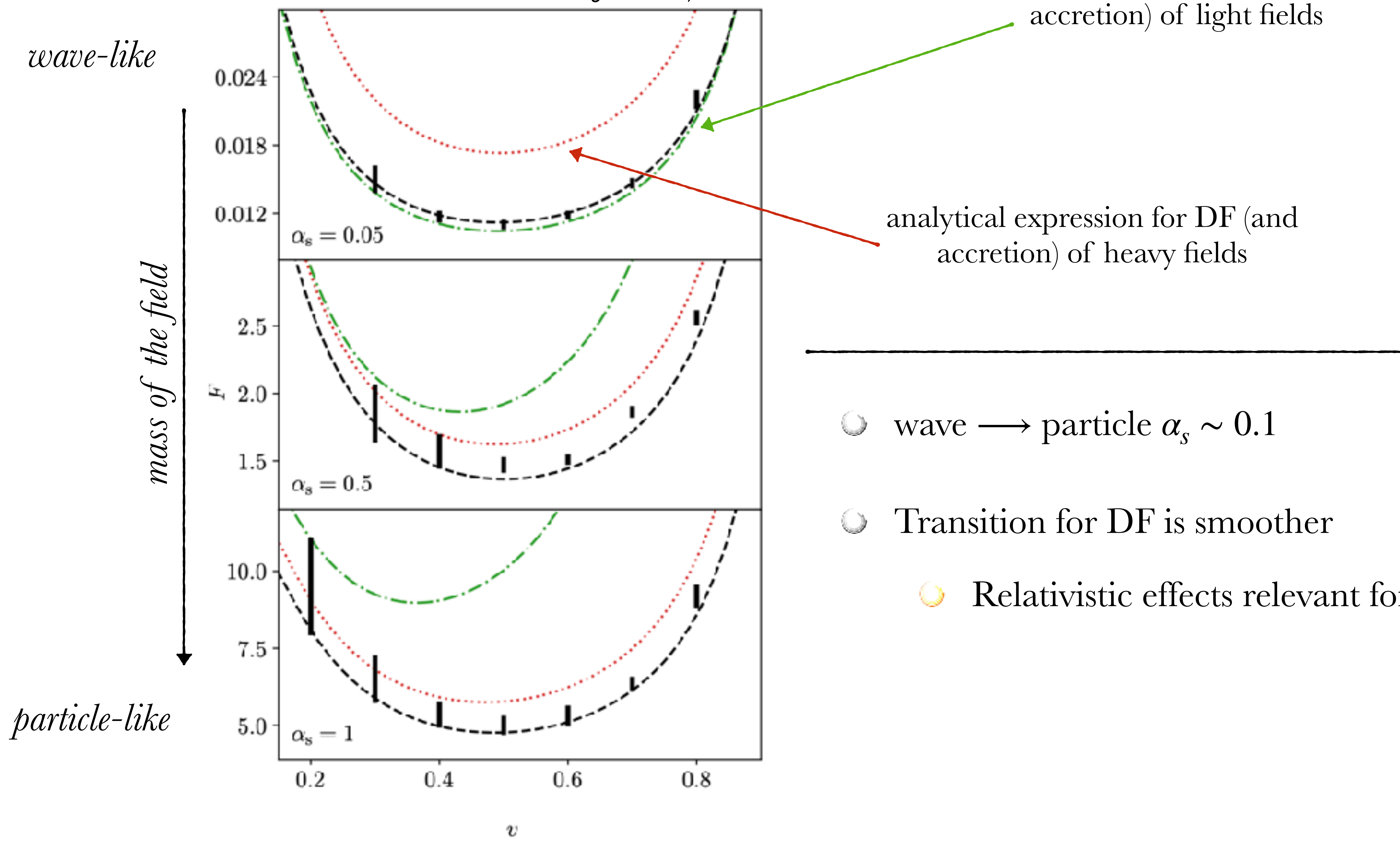
Dynamical Friction

DF extended to perturber moving through a gaseous (collisional) medium, scalar field cloud, and including relativistic corrections

L. I. Petrich +, 1989; D. Syer, 1994; E. Ostriker, 1999, L. Hui +, 2017; Y. Rephaeli +, 1980; E. Barausse, 2007; L. Annulli +, 2020; S. Hartman +, 2021; R. Vicente & V. Cardoso, 2022; D. Traykova +, 2022; Z. Wang + 2024; J. Bamber +, 2022; J. Aurrekoetxea +, 2023; J. Aurrekoetxea +,, 2023

- Comparisons/calibrations between numerical and semi-analytical results

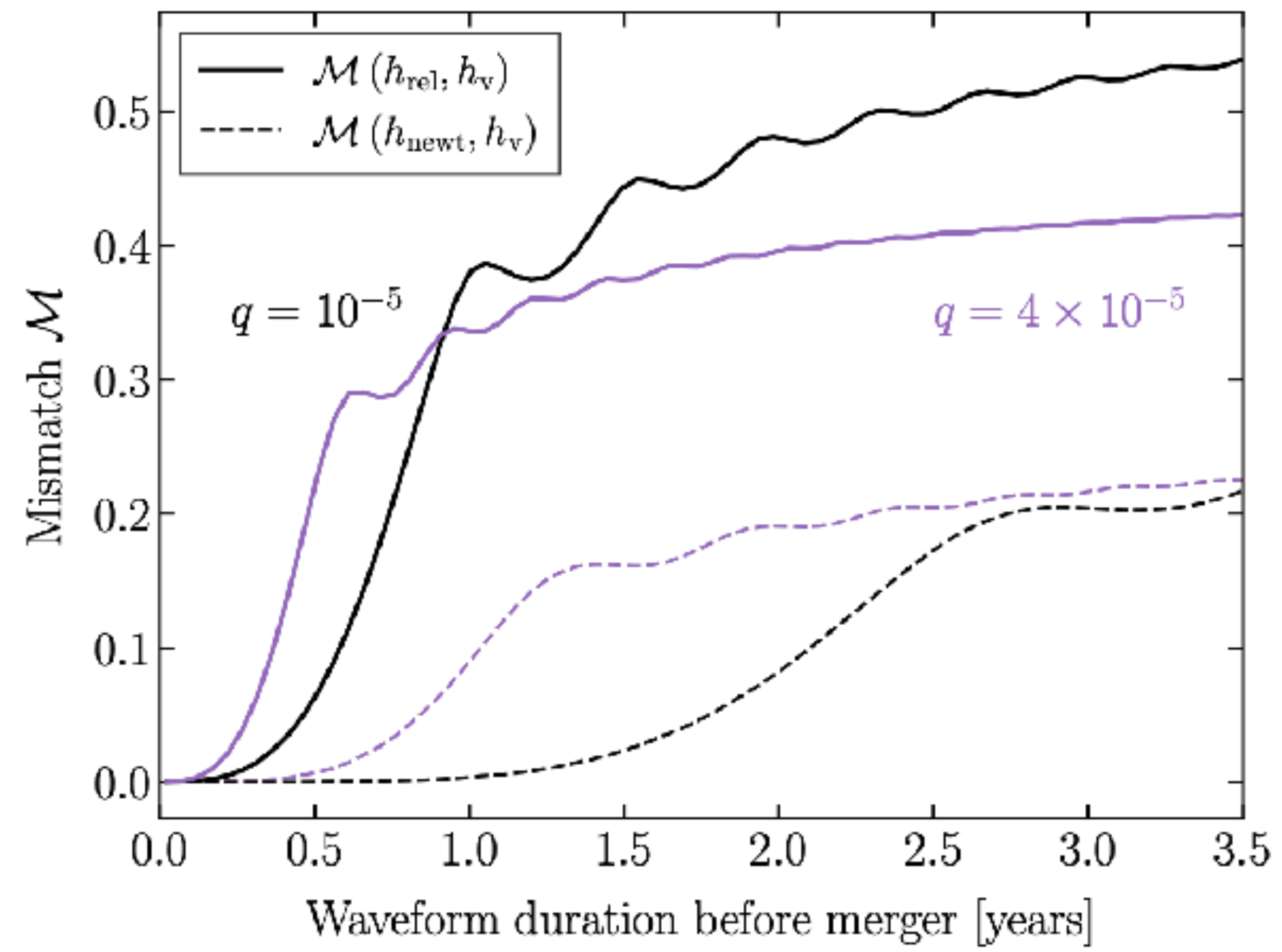
D. Traykova +, 2023



- wave ⟶ particle $\alpha_s \sim 0.1$
- Transition for DF is smoother
  - Relativistic effects relevant for $\alpha_s > 0.1$

EMRI relativistic evolution in overdense region with DF corrections

R. Vicente +, 2025



Mismatch with respect to vacuum waveforms

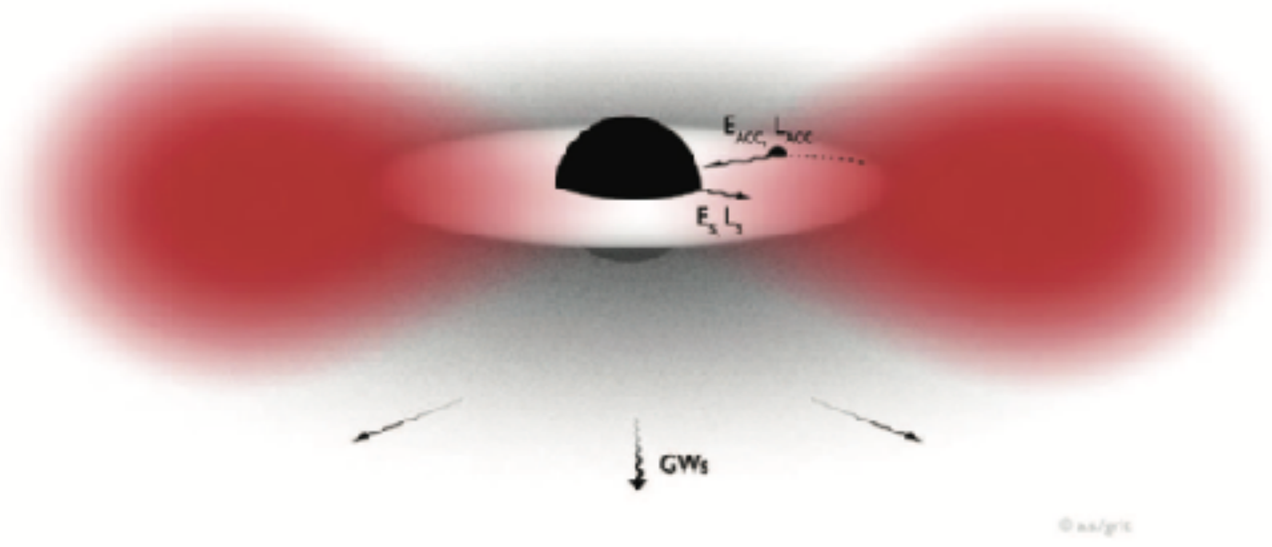
Cloudy environments

Ultra-light boson clouds can grow and create *overdesnities* around spinning BHs, due to accretion or superradiance

D. Baumann +, 2019, 2022; R. Brito +, 2015

- Perturbations enhanced at specific orbital frequencies

    - Backreaction on the secondary evolution



- When the orbital distance ~ cloud size, the cloud gets ionised
  G. Tomaselli +, 2023; G. Tomaselli, 2025

    - Transition from bound to unbound states: energy supplied by the binary

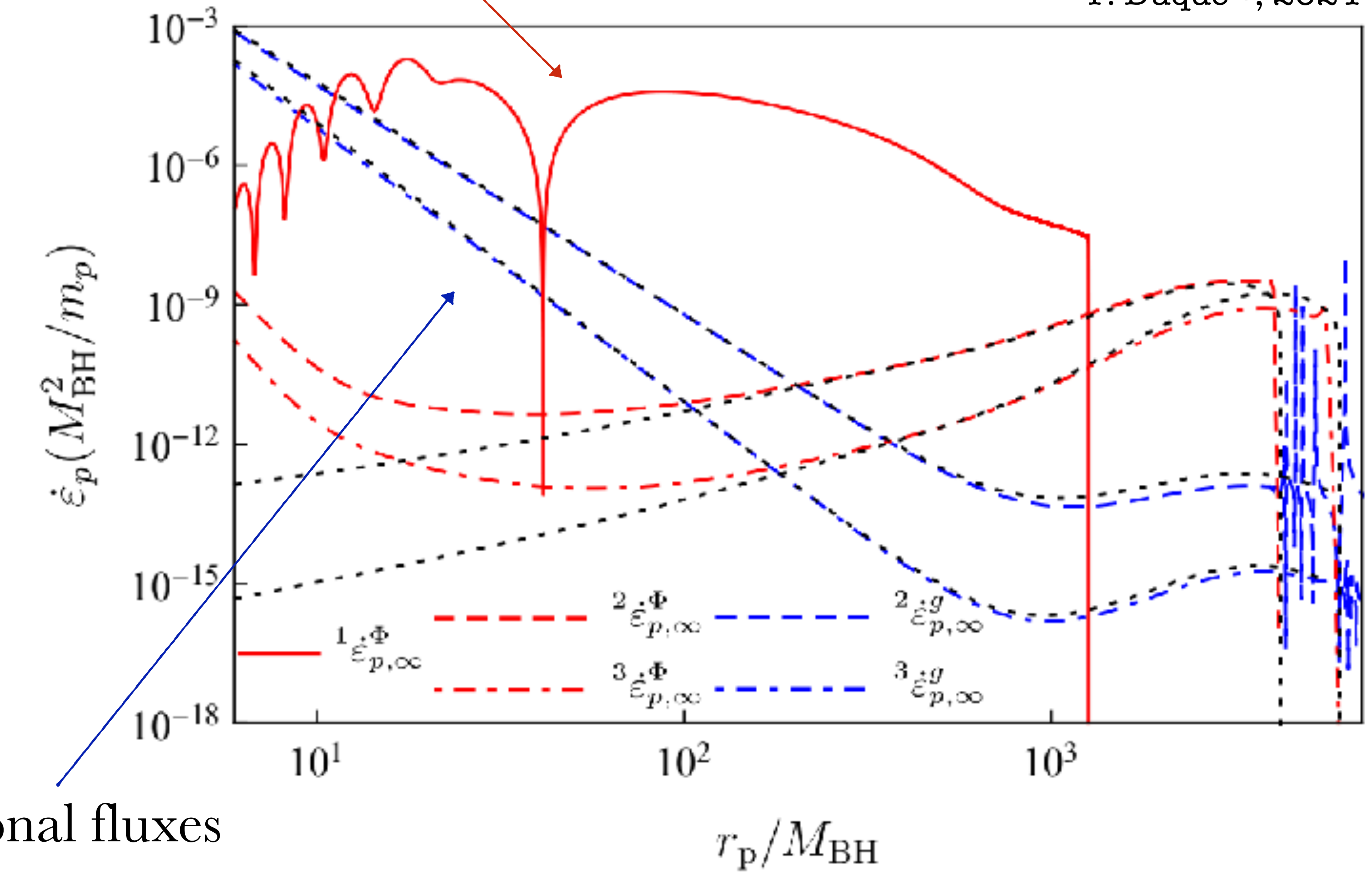
    - The inspiral is (also) driven by the interaction with the cloud (aka dynamical friction)

        - Sharp features in the emission R. Brito & S. Shah, 2024

        - Scalar radiation can dominate over GW emission at large distances

scalar fluxes

F. Duque +, 2024



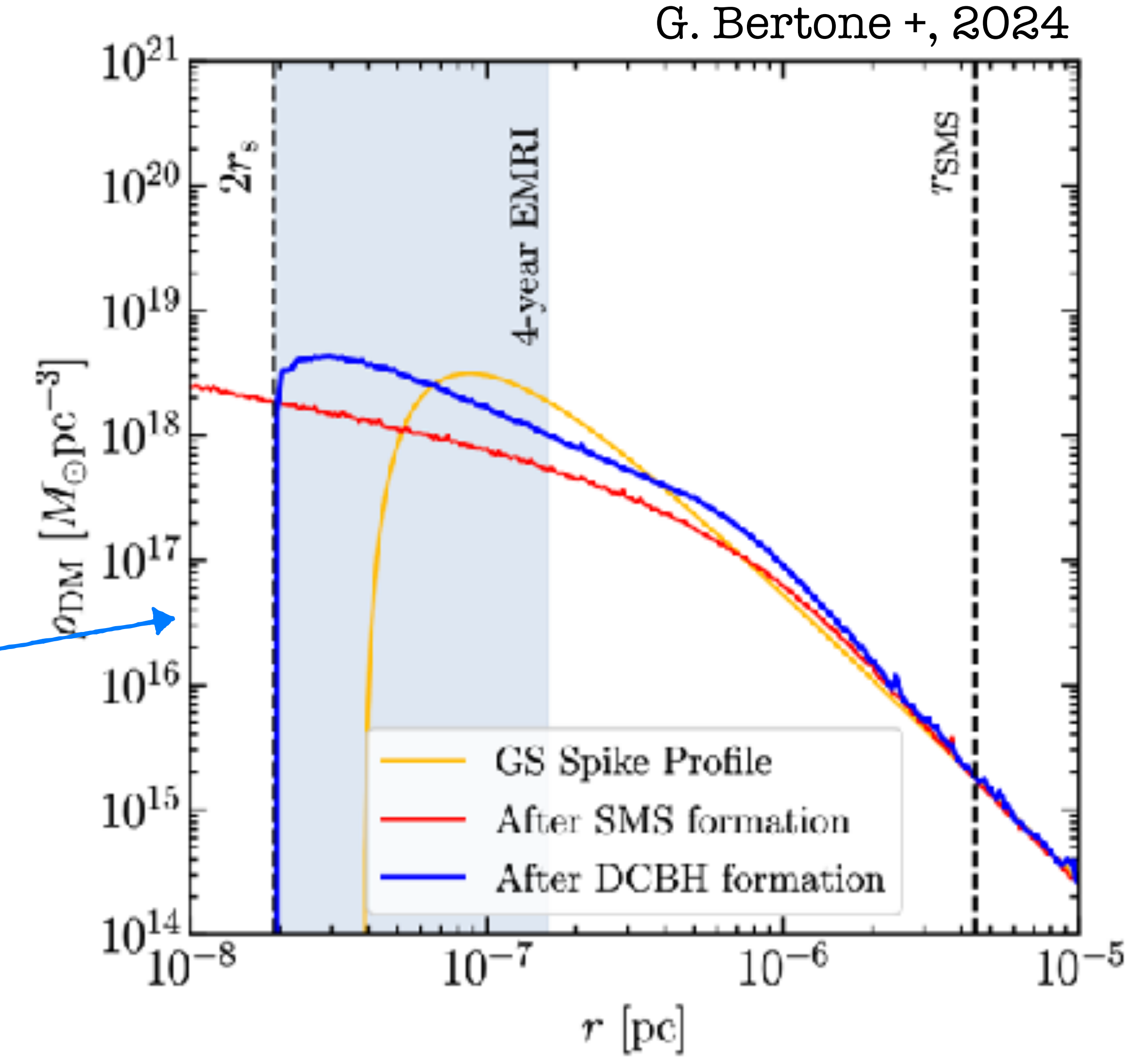
gravitational fluxes

Spikes

Simulations of BH accretion predict spikes with overdensities P. Gondolo & J. Silk, 1999; L. Sadeghian +, 2013; F. Ferrer +, 2017

$$\rho = \rho_0 \left(r/r_0\right)^{-\gamma} \xrightarrow{\bar{\gamma} > \gamma} \rho \sim \left(1 - \frac{4M}{r}\right)^{\alpha} r^{-\bar{\gamma}}$$

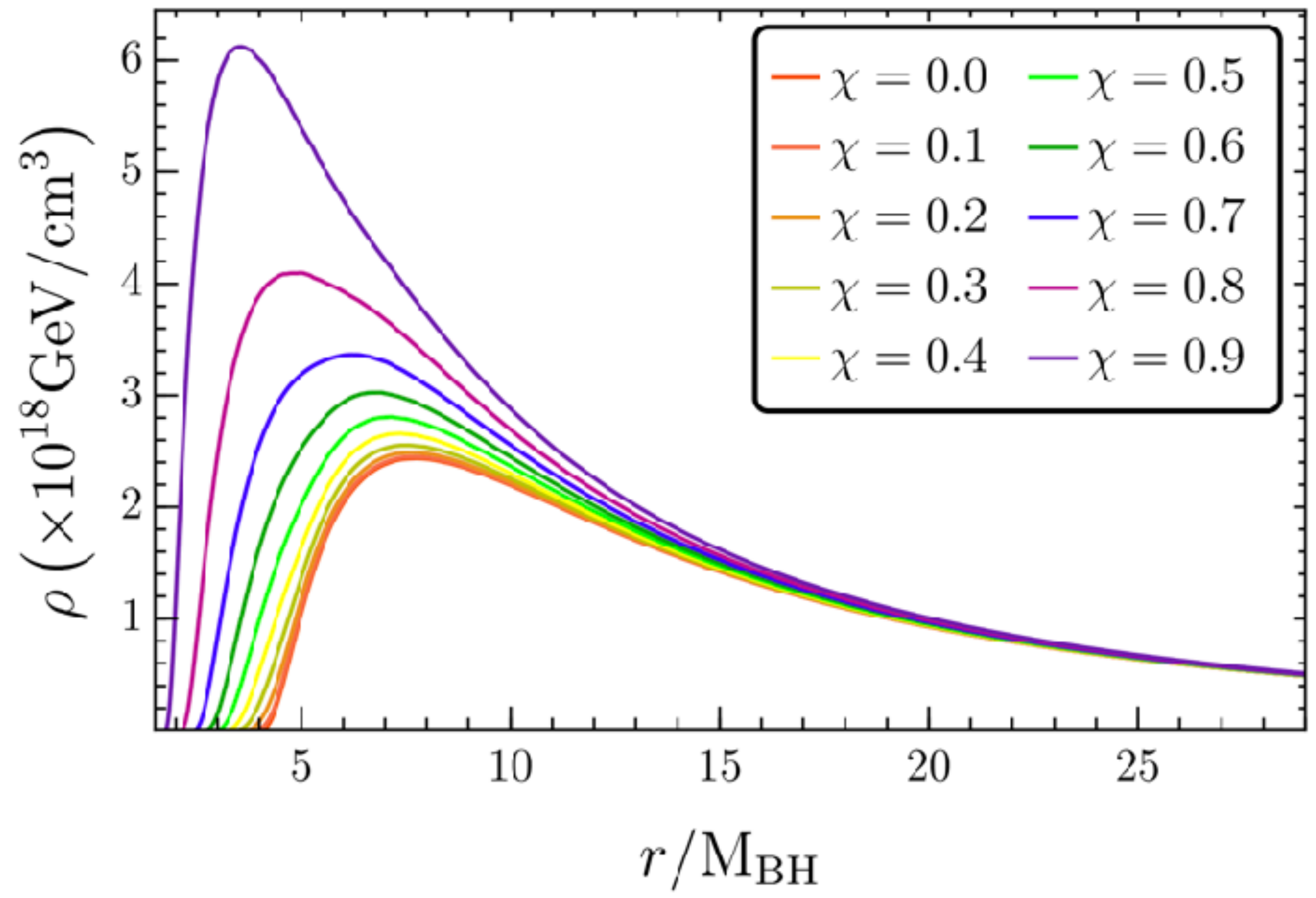
G. Bertone +, 2024



- Dynamics and GW emission of BBHs affected (and enhanced) by the spike

EMRI window

N. Speeney +, 2023 ; S. Mitra +, 2025



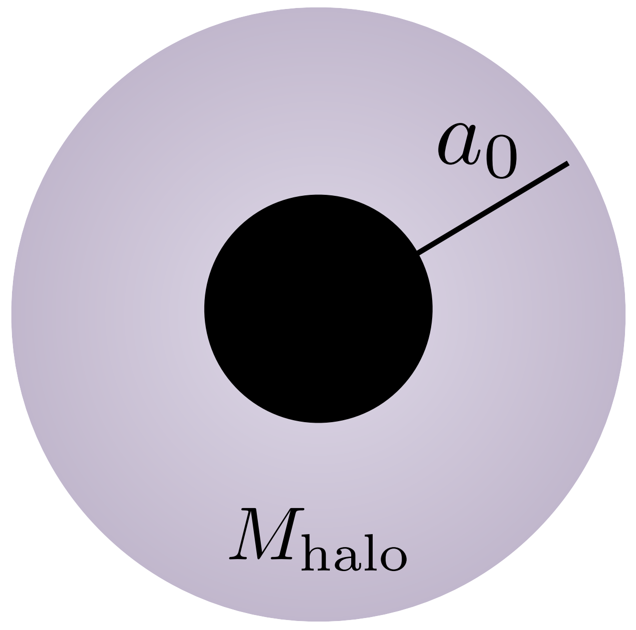
$\xrightarrow[\text{for BHB}]{\text{systematic study}}$ Primary spin significantly improves detection prospects of DM spikes with LISA

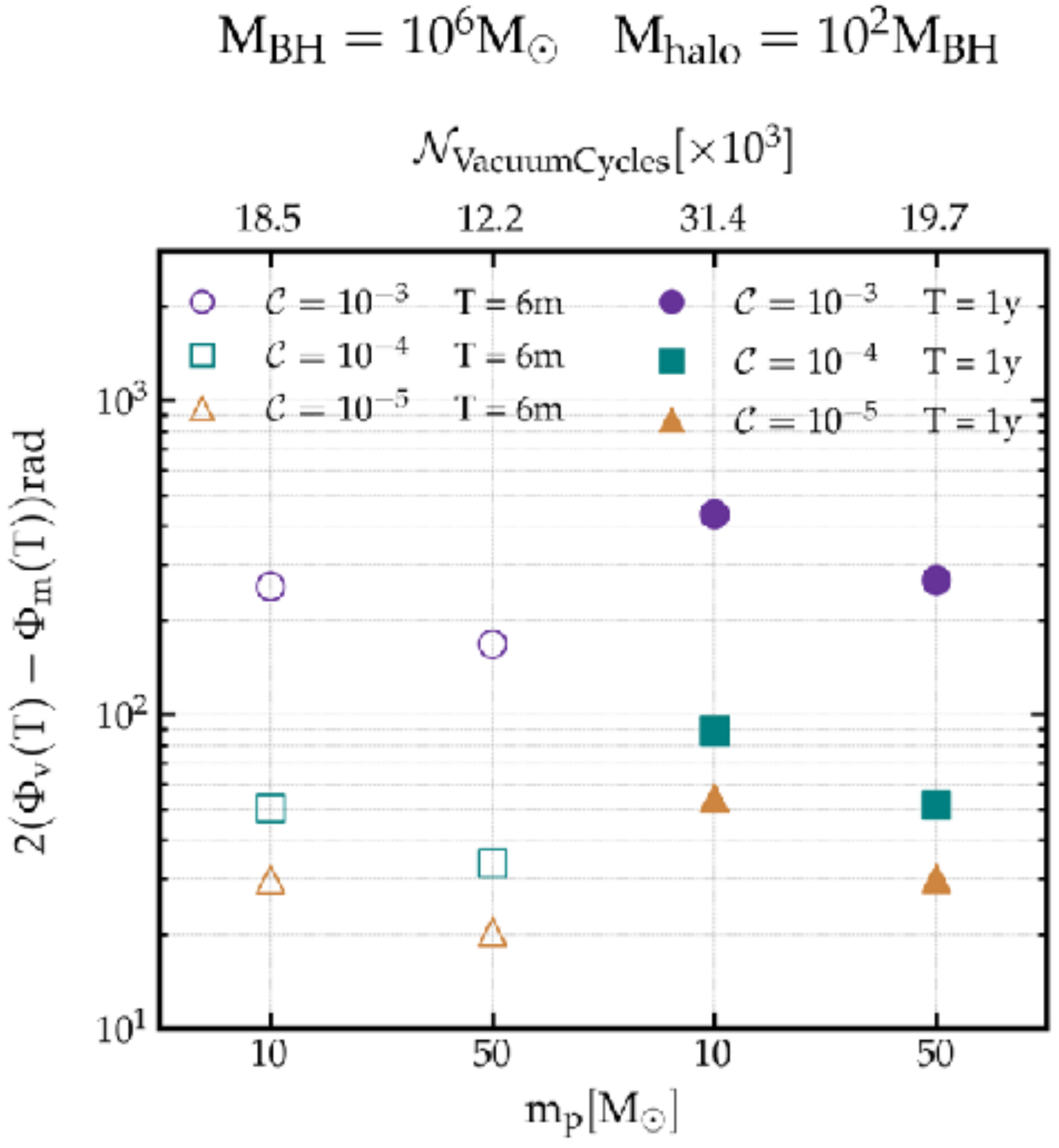
Spikes

Relativistic EMRI evolution within a DM spike

V. Cardoso +, inc. A. M., 2022, 2023, Y. Zhao +, 2024; N. Speeney + inc. A. M., 2024; S. Gliorio + inc. A. M, 2025; P. Fernandes & V. Cardoso, 2025; M. Rahman & T. Takahashi+, 2025

- Changes mostly dependent on the halo "compactness" $\mathscr{C} = M_{\rm halo}/a_0$ ($\lesssim 10^{-4}$)





phase difference compared to vacuum
for EMRIs in an NFW profile

changes due to

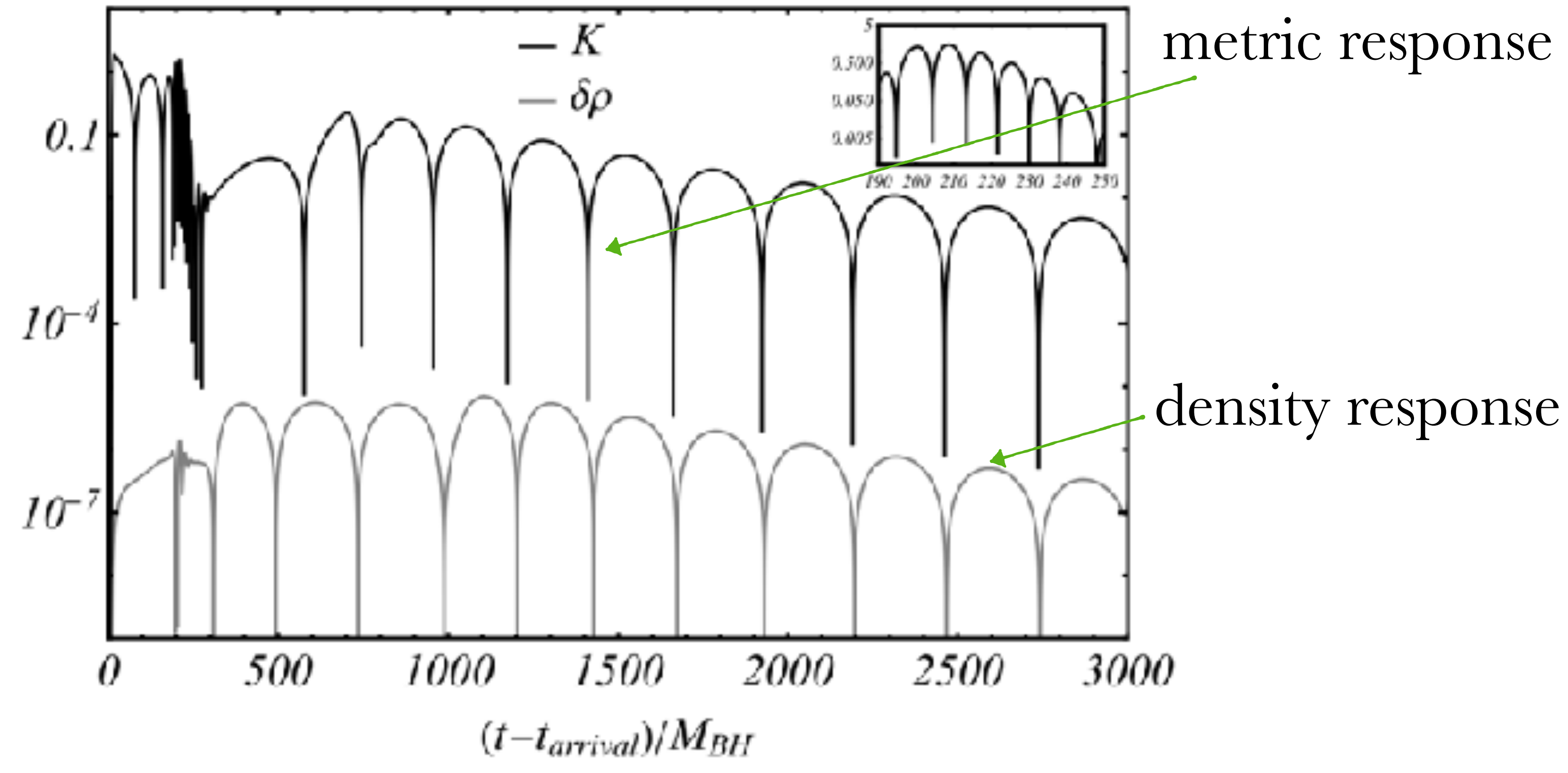
- *redshift* effect
- couplings with fluid modes

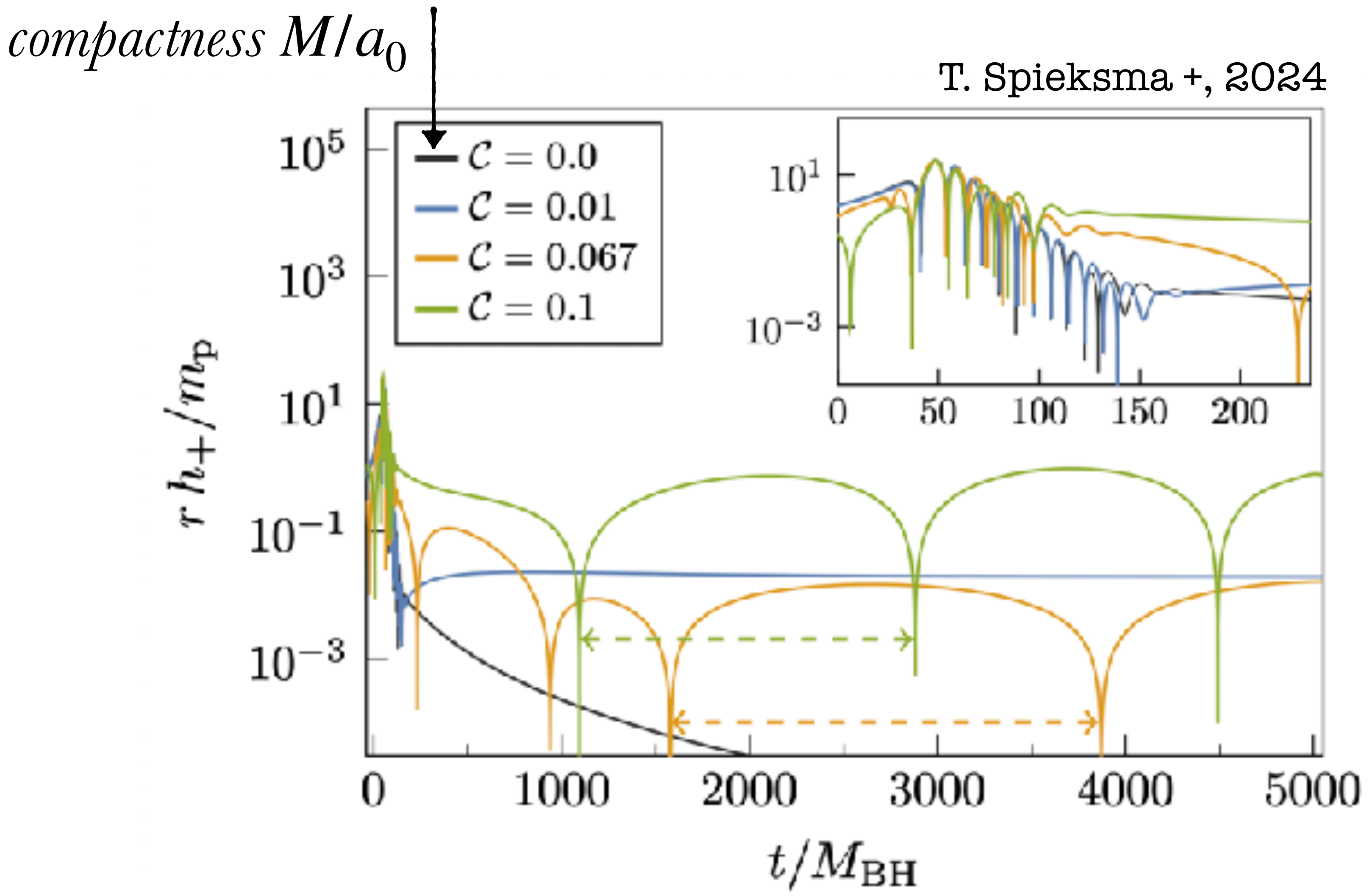
QNMs intermezzo

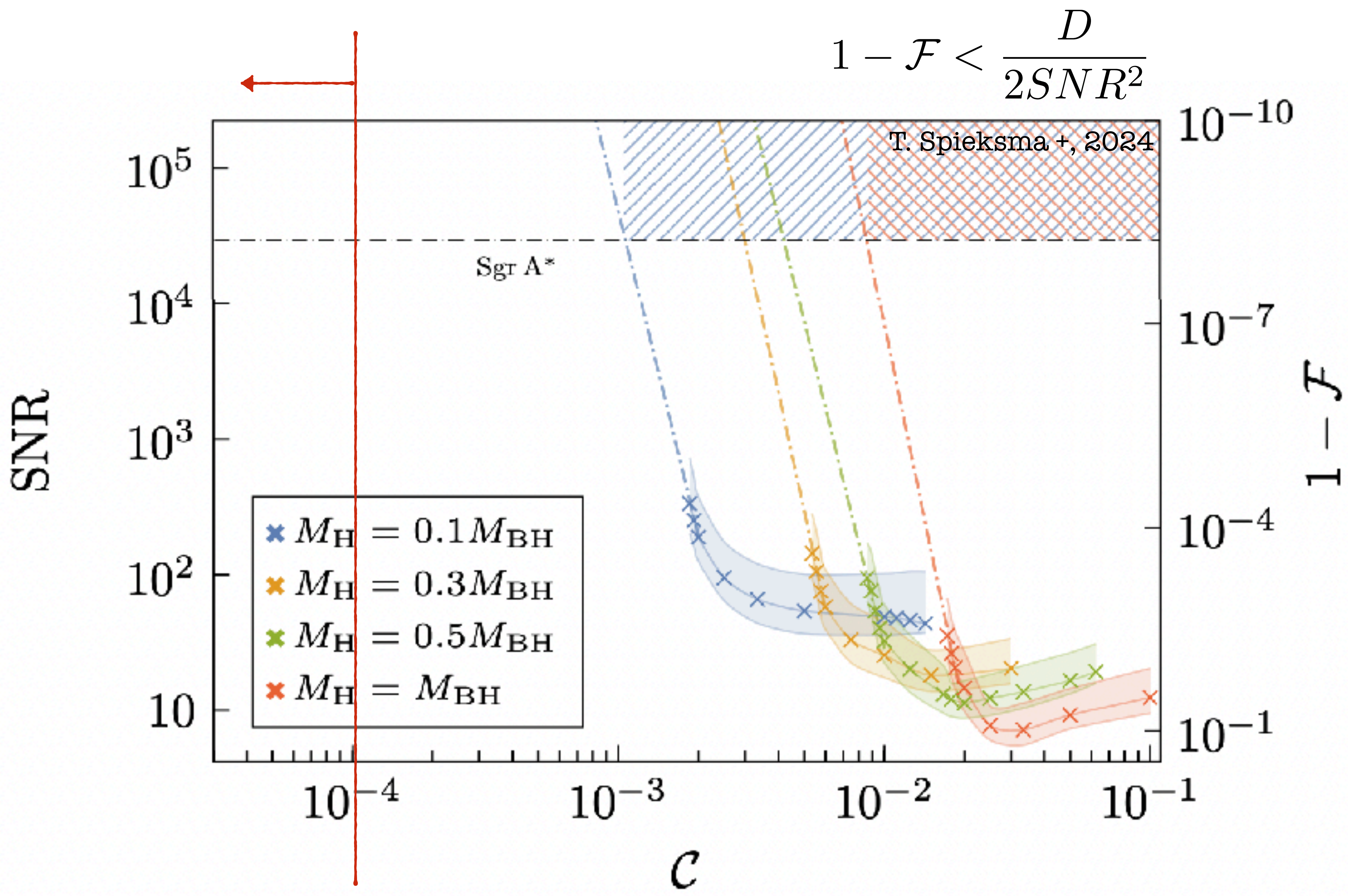
The Quasi Normal Mode spectrum of a BH surrounded by spherical DM distribution

L. Pezzella +, inc. A. M., 2024; T. Spieksma +, 2024

conversion between metric and fluid modes





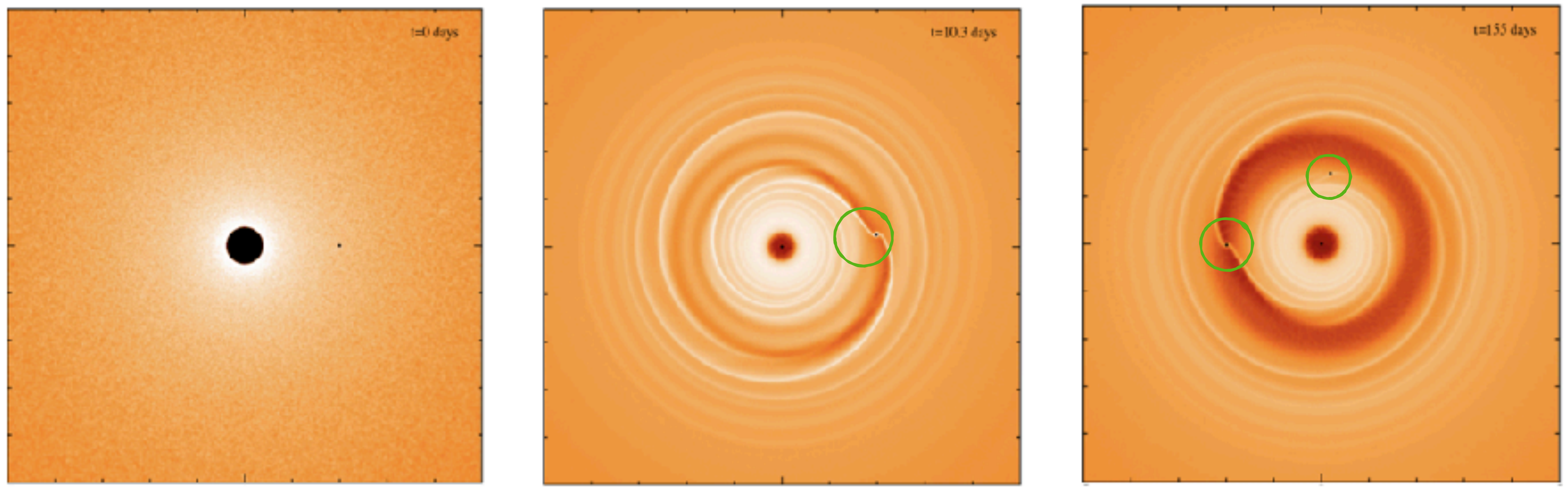


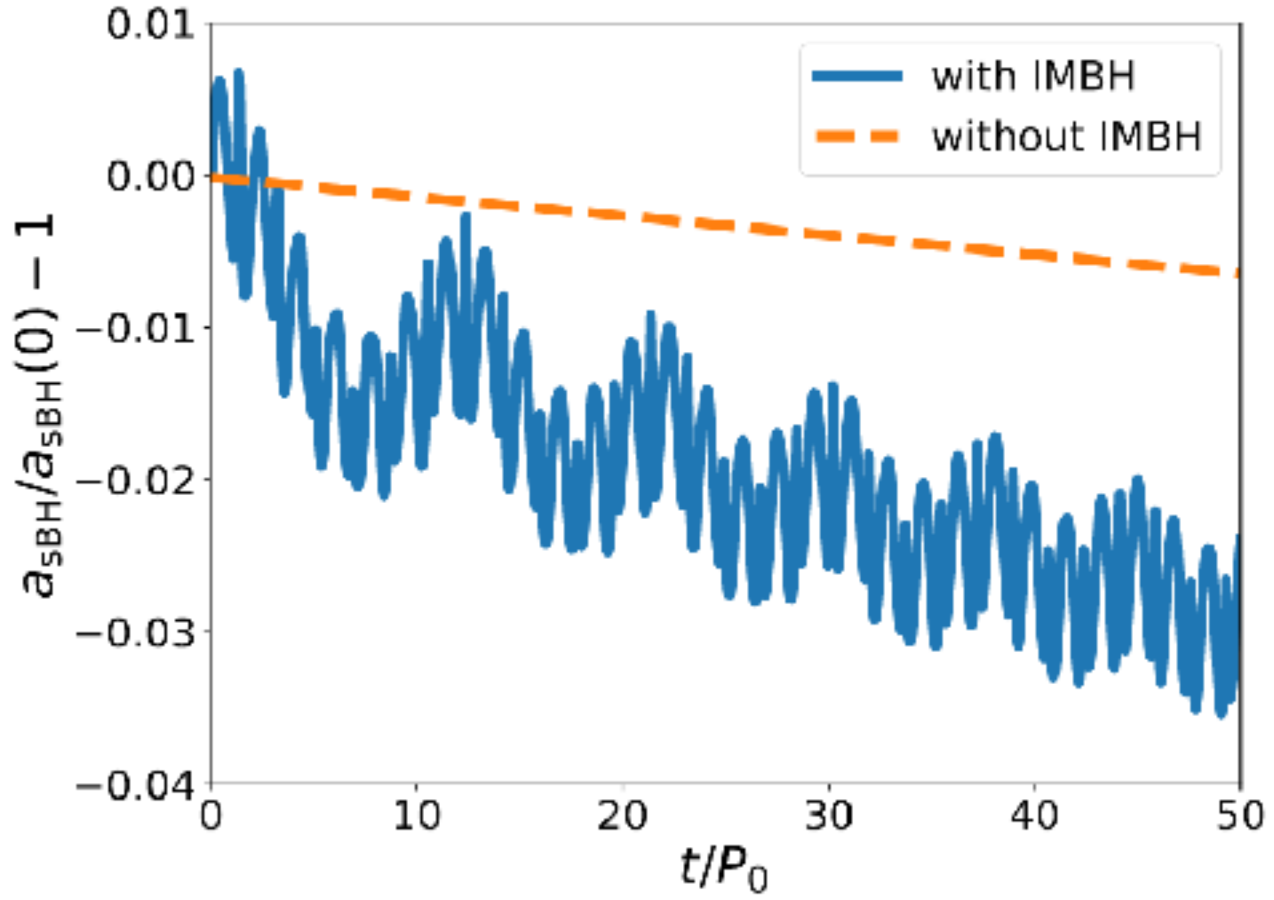
SNR required to distinguish the ringdown signal from vacuum

Life in an accretion disk

IMBH and a sBH evolving in the AGN disk of a supermassive BH

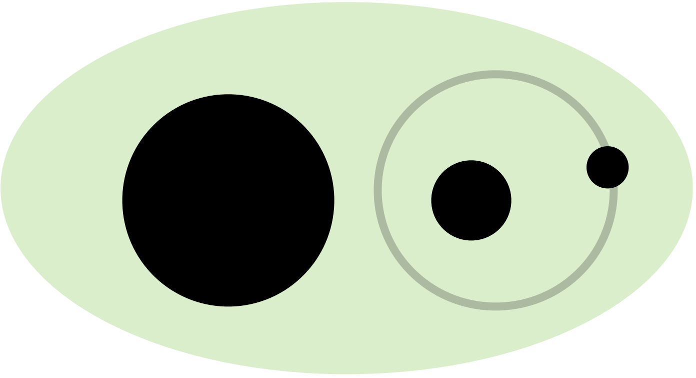
P. Peng +, 2024



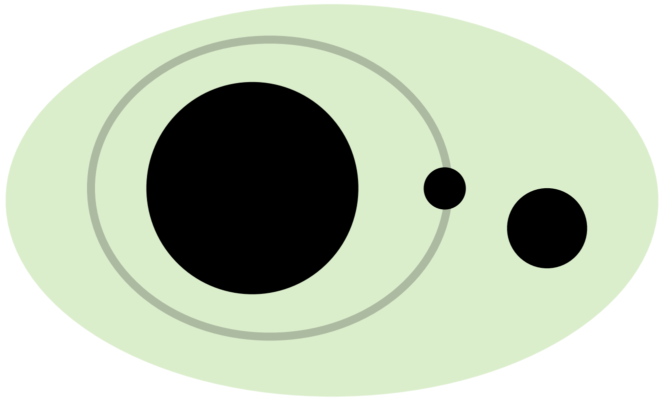


- sBH migrates faster when IMBH is present
  - sBH affected by tidal torques, type-I migration, interfering waves
- The sBH migrates synchronously with the IMBH, $a(t)/a(t=0) - 1 \sim$ the same
- Different outcomes depending on the sBH initial configuration

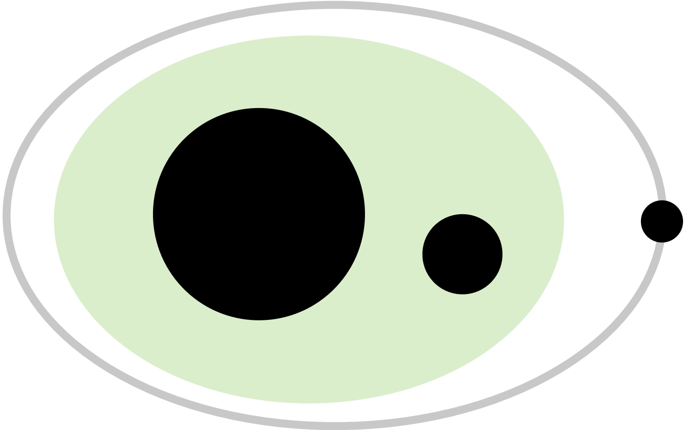
IMRI-IMRI



EMRI-IMRI



IMRI-EMRI

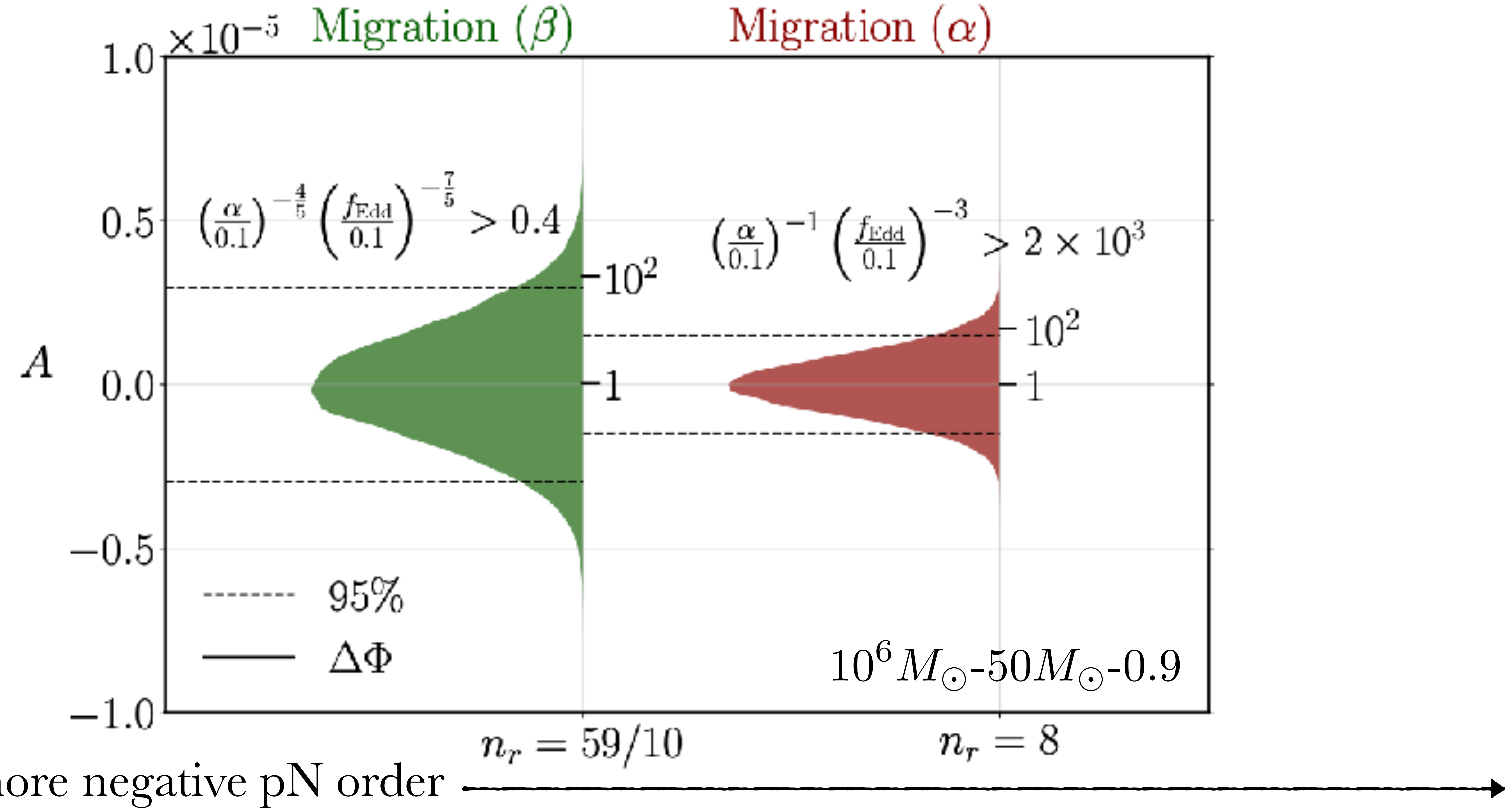


Accretion disk torques

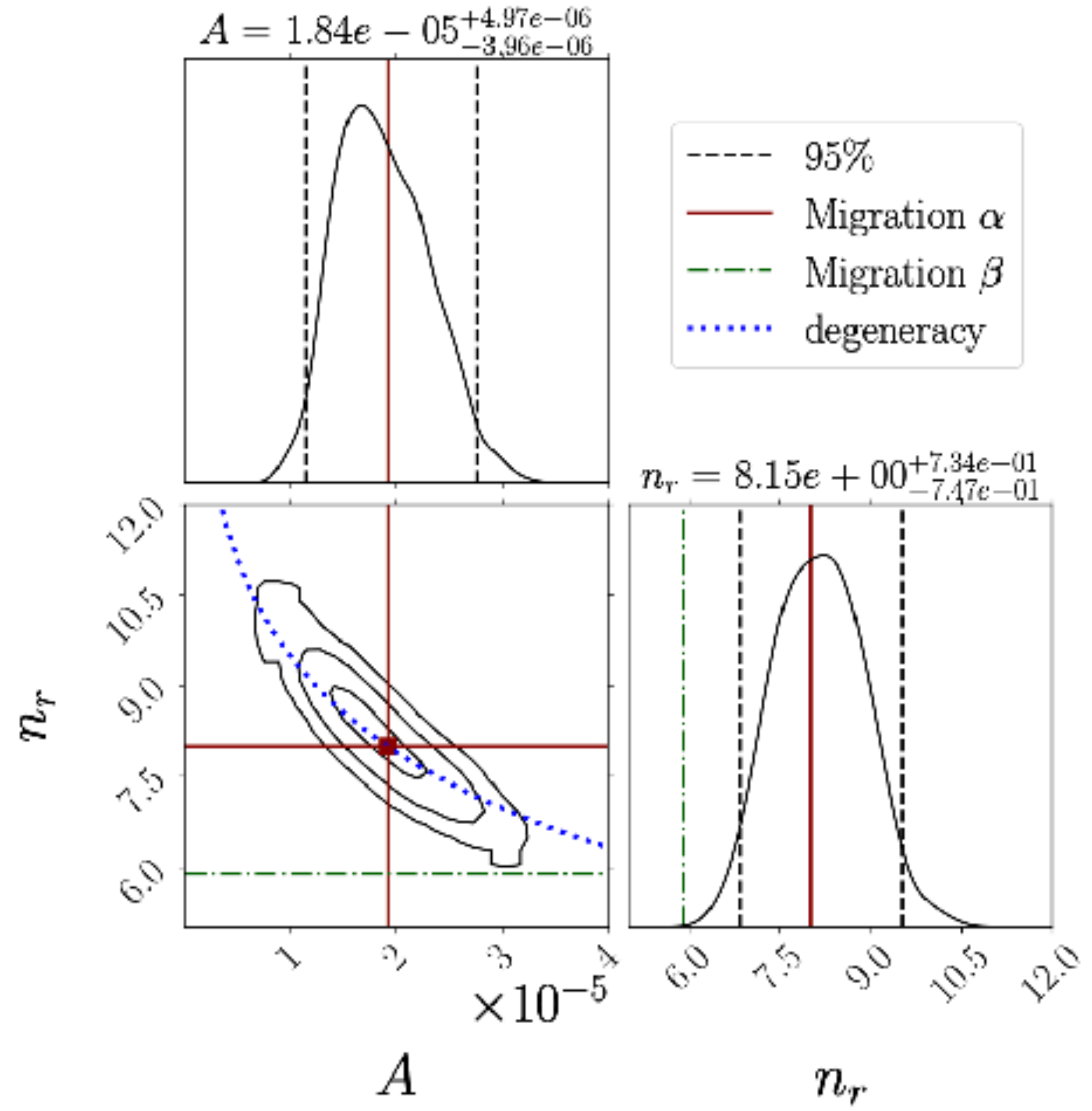
B. Kocsis +, 2011; E. Barausse +, 2014; M. Garg + 2024; L. Speri + 2023

Accretion disks induce torques that can affect EMRI trajectories

$$\dot{L} = \dot{L}_{\rm GW} + \dot{L}_{\rm disk} \qquad \dot{L}_{\rm disk} \sim A \dot{L}^{(0)}_{\rm GW} r^{n_r} \longrightarrow -n_r\, pN$$



posterior on the amplitude for agnostic search (vacuum injection)

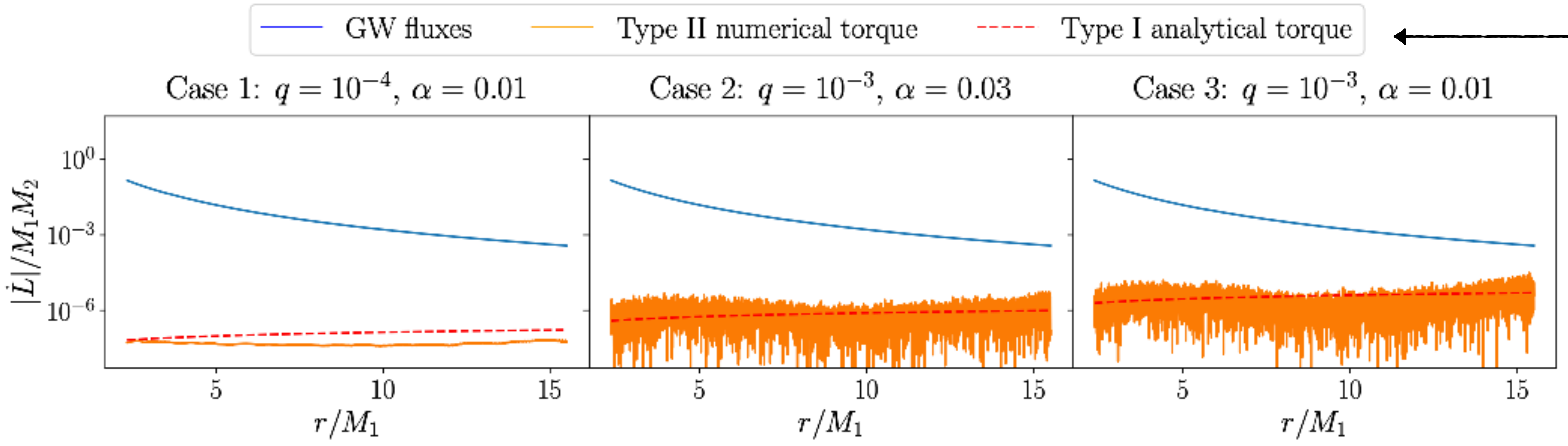


torque parameters posteriors (non-vacuum injection)

- Torques can be detected by agnostic templates with a power-law of the radius
- A physical model (A, n_r) can be mapped to viscosity & efficiency of the disk

Accretion disk torques

Catching torque variability with semi-analytical approximations L. Copparoni +, 2025; A. Derdzinski +, 2021, P. Duffel +, 2020

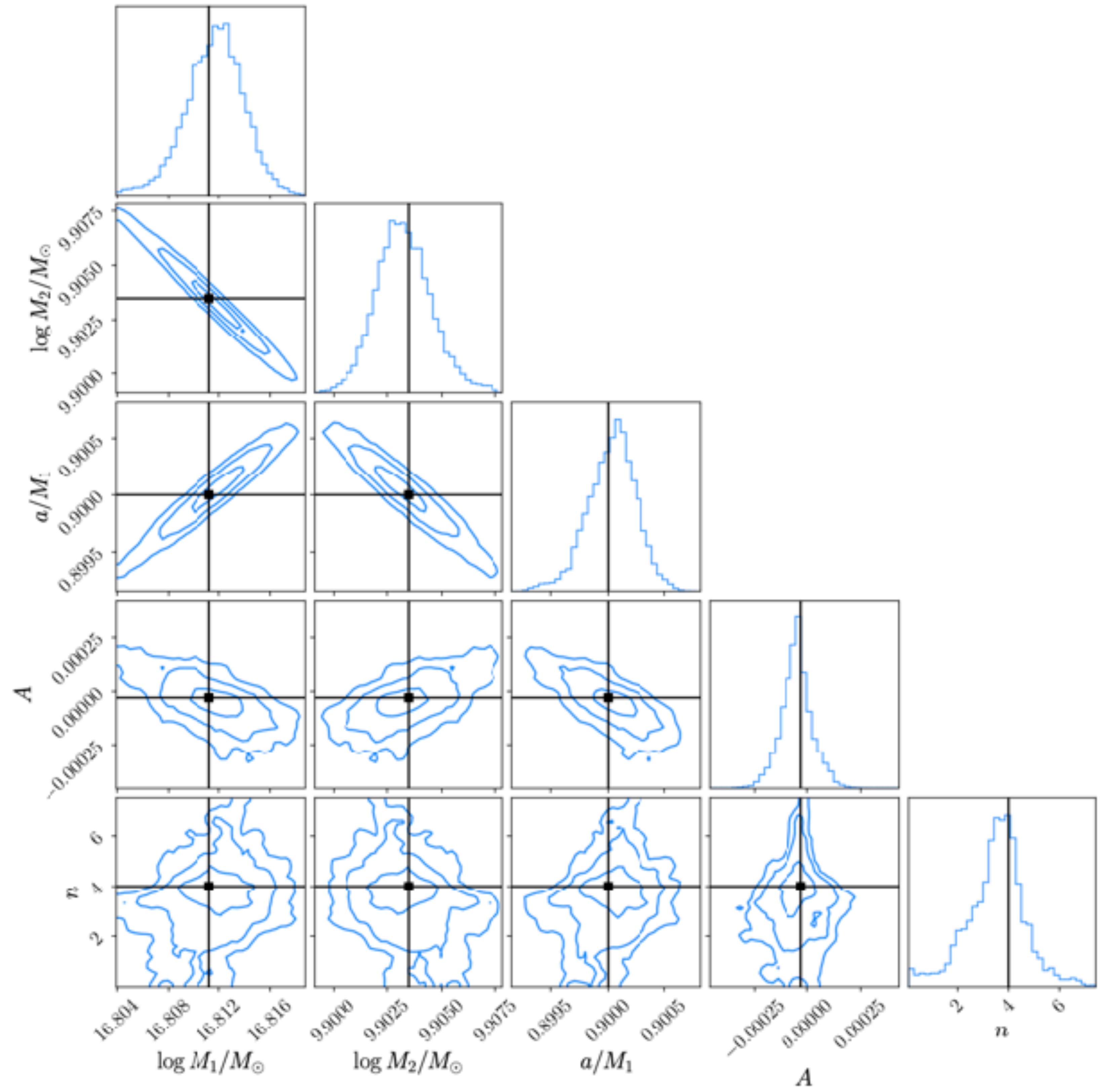


$$\dot{L}_{\rm I} = \Sigma(r) r^4 \Omega^2 q^2 \mathcal{M}^2$$

- Analytic expressions fail to capture the stochastic behavior

Parameter reconstruction with analytic models $\dot{L}_{\rm disk} \sim A \dot{L}^{(0)}_{\rm GW} r^{n_r}$

- Bias on vacuum parameters is always small. Recovered values close to expected values
- Amplitude of the torque may be compatible with vacuum for large variability
- Mapping of (A, n_r) to physical parameters may be problematic



Multi-Parameter expansions

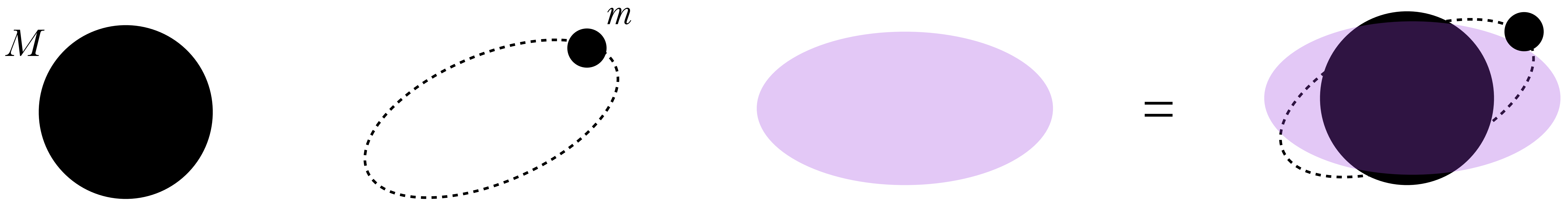
Going towards Self-Force calculations

- Modelling environmental effects on top of vacuum solutions

secondary ← → *environment*

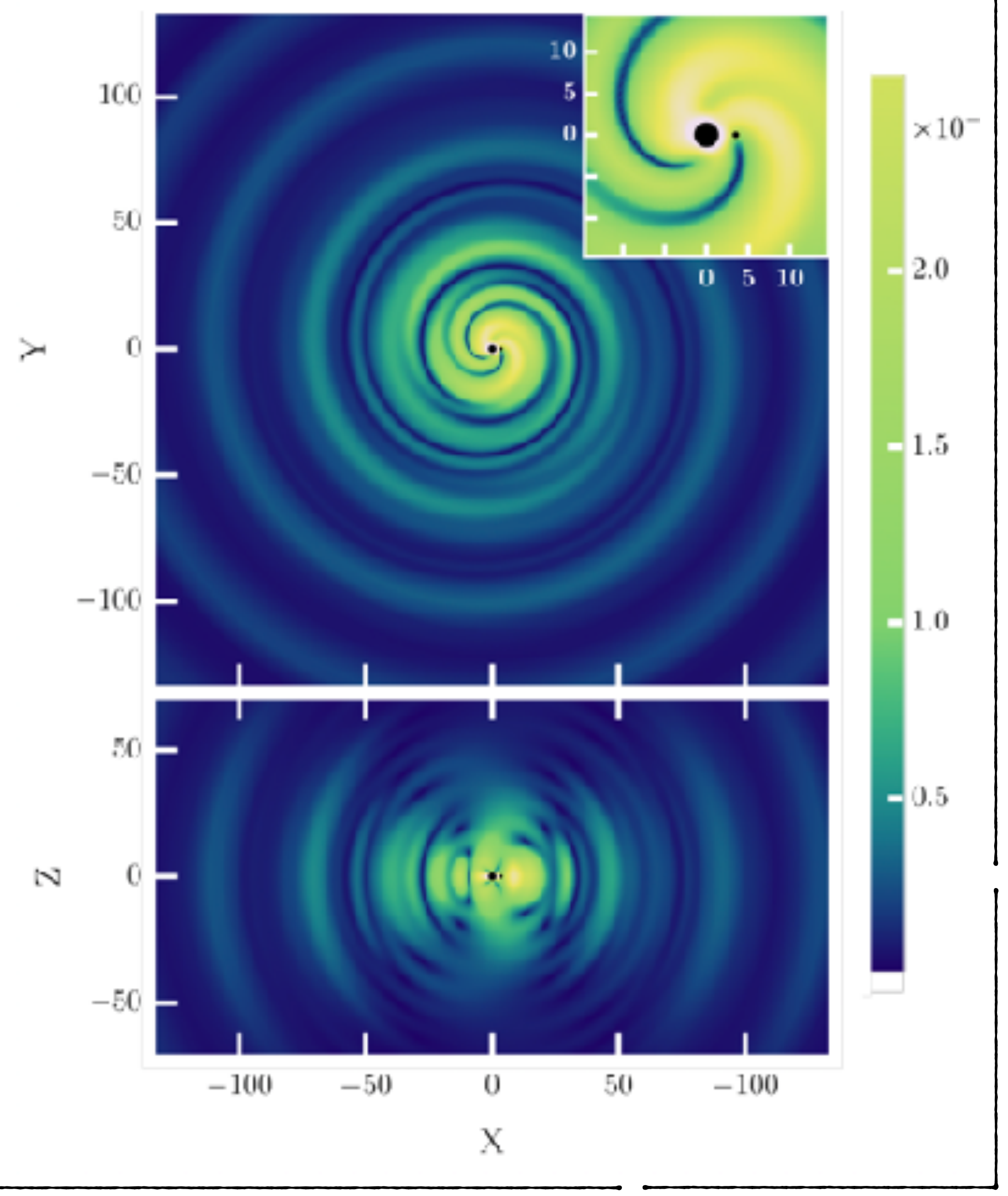
$$g_{\mu\nu} = g^{(0,0)}_{\mu\nu} + g^{(1,0)}_{\mu\nu} + g^{(0,1)}_{\mu\nu} + g^{(1,1)}_{\mu\nu}$$

multi-parameter → *expansion*



Kerr $\qquad q = m_p/M \qquad \epsilon$

wake profile of matter due to the secondary



Solve perturbatively Einstein equations +

- scalar field environments

R. Brito & S. Shaha, 2024
C. Dyson +, 2025
DongJun Li +, 2025

- fluid environments

M. Rahman & T. Takahashi+, 2025
S. Datta & A. M., 2025

modularity with → vacuum

RW-Zerilli-like equations

$$[\partial^2_{r_\star} - \partial^2_t + V^P]\psi^{(1,0)}_{\ell m}(t,r) = S^{P(1,0)}_{\ell m}(t,r)$$

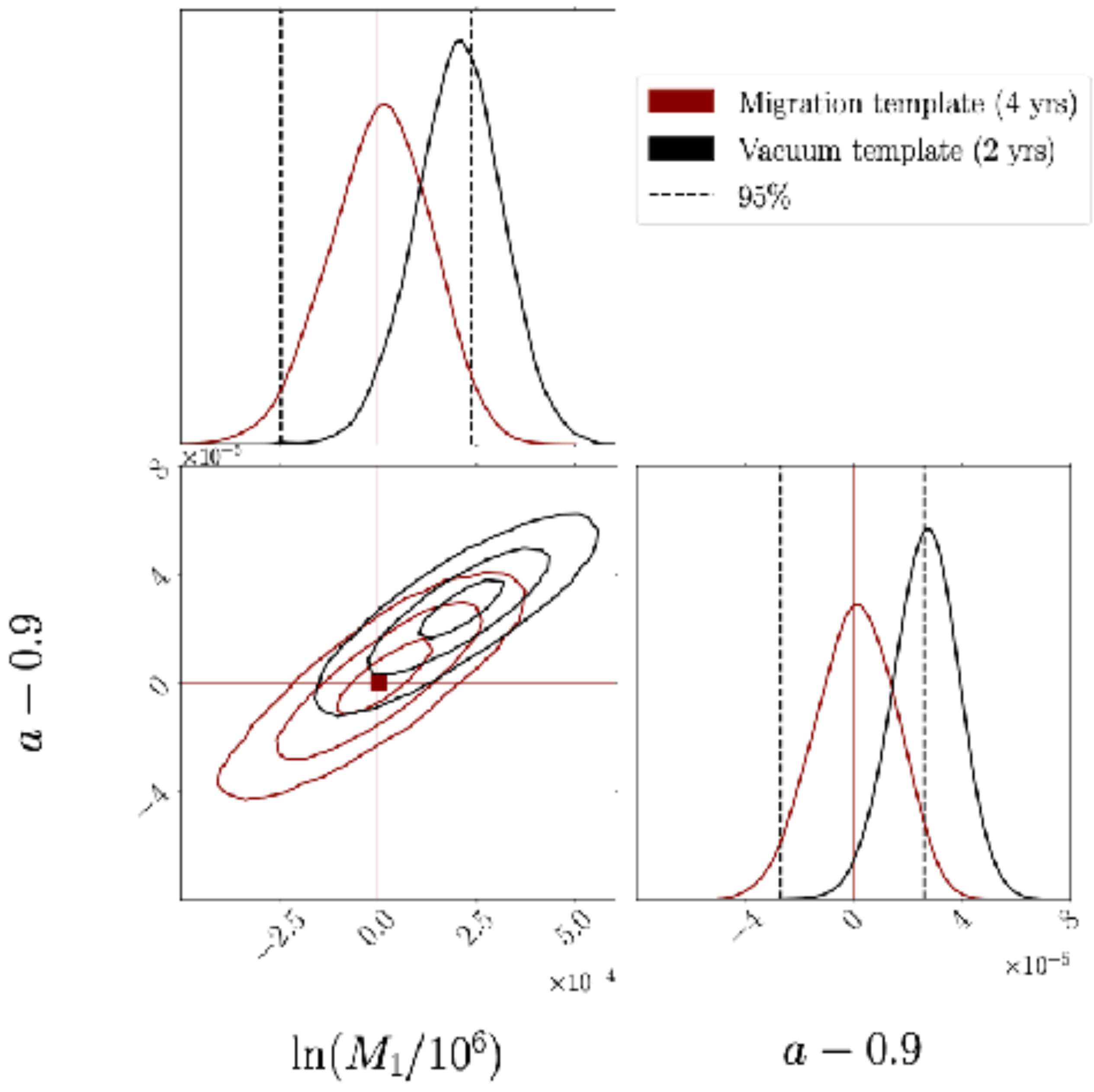
$$[\partial^2_{r_\star} - \partial^2_t + V^P]\psi^{(1,1)}_{\ell m}(t,r) = S^{P(1,1)}_{\ell m}(t,r)$$

Contaminations & biases: one at a time

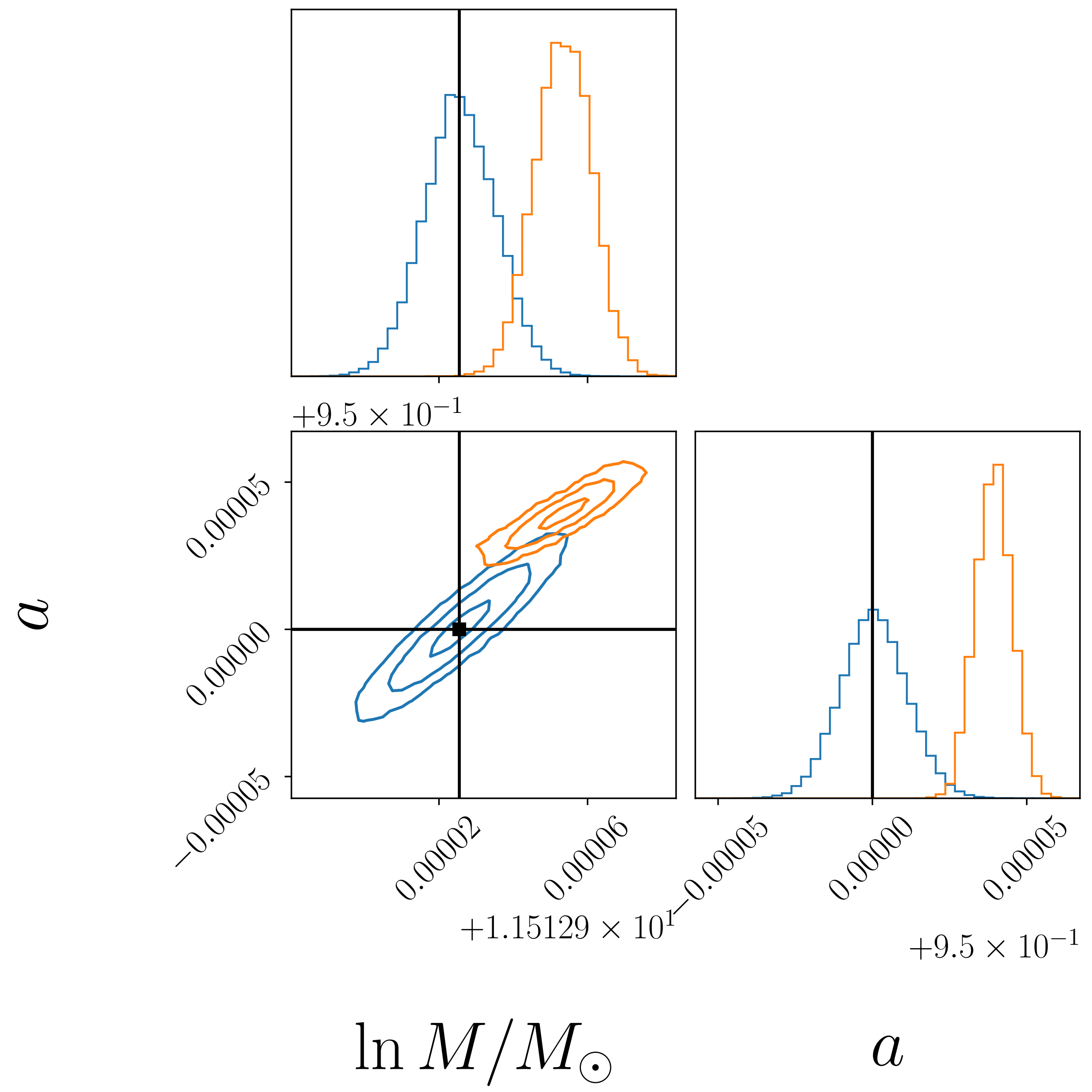
Does mismodeling affect parameters reconstruction, and other tests of fundamental physics (tests of GR)?

L. Speri +, 2023; L. Speri + inc. A. M., 2024; S. Barsanti + inc. A. M., 2025

accretion disks



scalar field



- Bias in the source intrinsic parameters is small
- Problematic for 'small' deviations, like beyond GR/environmental corrections

Contaminations & biases: multiple effects

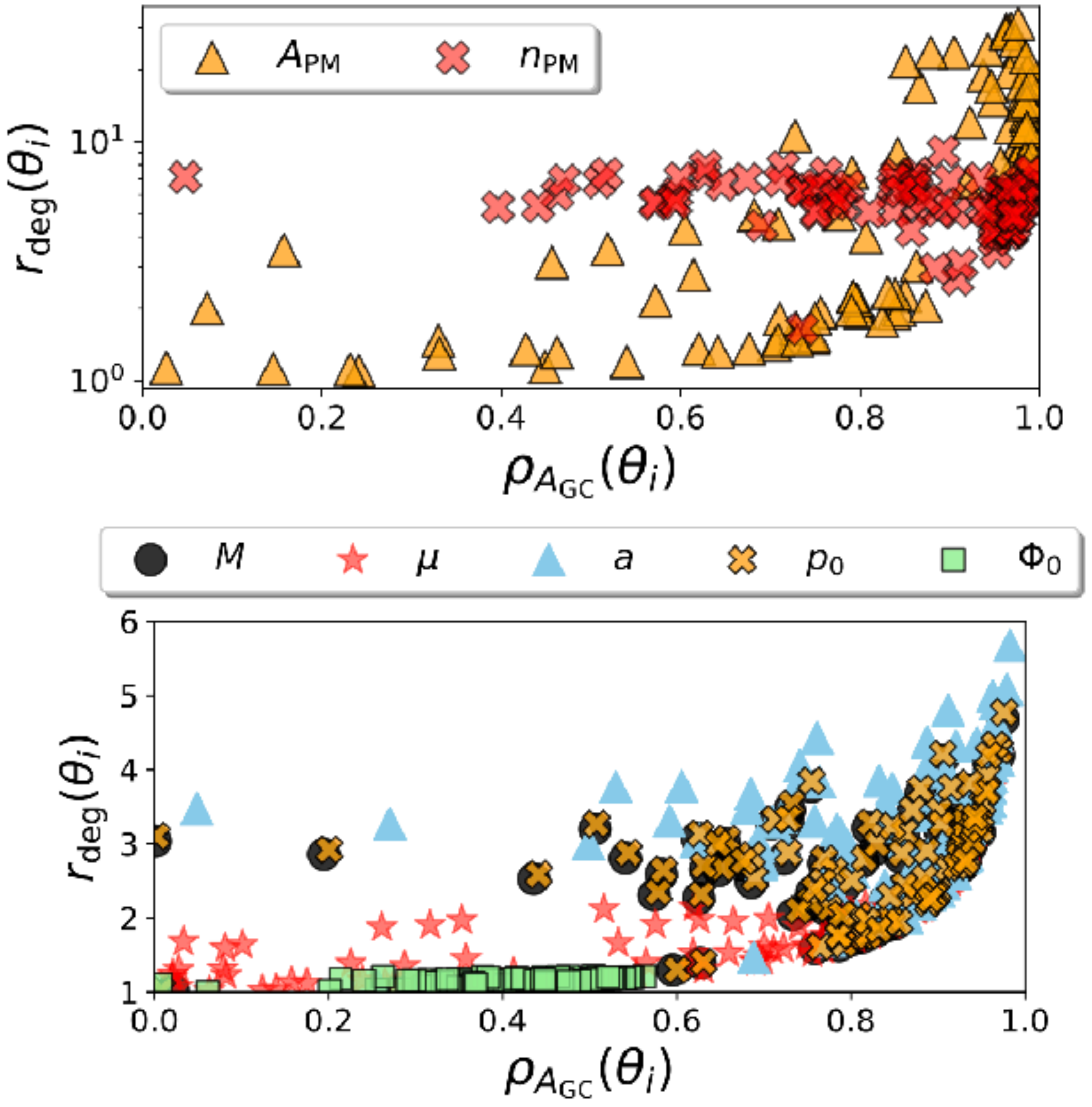
Does mismodeling affect parameters reconstruction, and other tests of fundamental physics (tests of GR)?

$r_{\rm deg} = \sigma_{\theta_i}$ *(joint parameters)*$/\sigma_{\theta_i}$ *(single parameter)*
for vanishing beyond GR amplitude

$\delta\psi$ = *bias/statistical error*

EMRIs

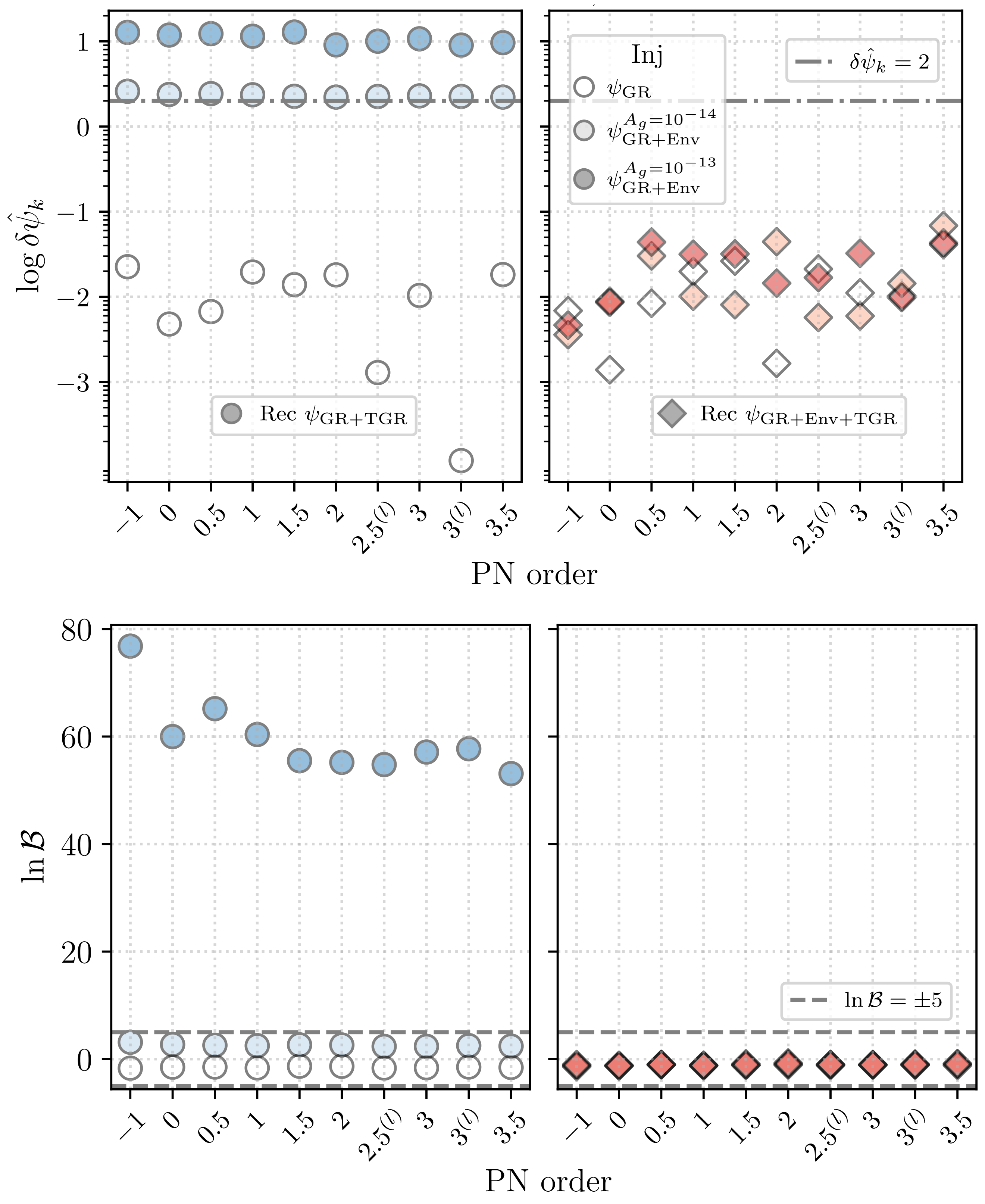
S. Kejriwal +, 2023



correlation with beyond GR

MBHBs

M. Garg +2024



injection
circular + gas accretion

○ recovery
circular + beyond GR

◇ recovery
circular + gas accretion + beyond GR

pN order of beyond GR phase shift

Take home messages

Astrophysical environments are there (we know) and can be measured (maybe)

- Waveform modelling, in particular for asymmetric binaries
- Interface with numerical simulations
- Complementarity of agnostic and physical models
- Correlations with vacuum parameters
- Correlations with other fundamental physics parameters

Much more environments around

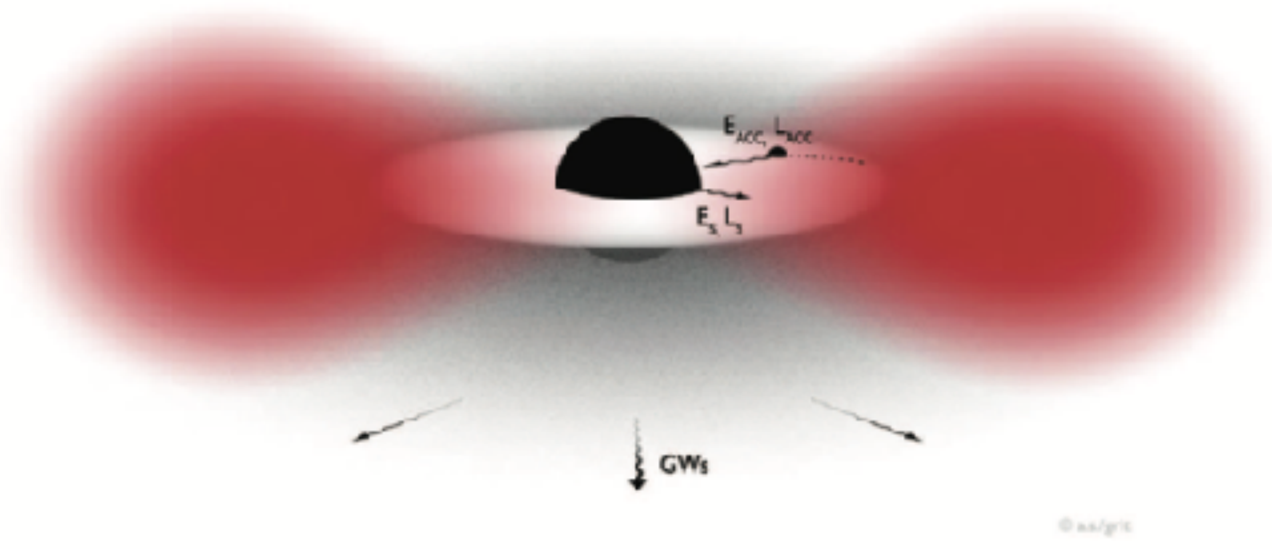
- Interplay between eccentricity and environmental effects F. Duque + 2025; M. Garg + 2024
- Tidal resonances B. Bonga + 2019; P. Gupta +, 2021
- Repeated interactions with black hole disks S. Kejriwal + 2024; T. Spieksma & E. Cannizzaro+ 2025
    - Multi-messenger observations and studies of BH environments A. Caputo +, 2020; A. Toubiana + 2021; L. Sberna +, 2022

Back up

Cloudy environments

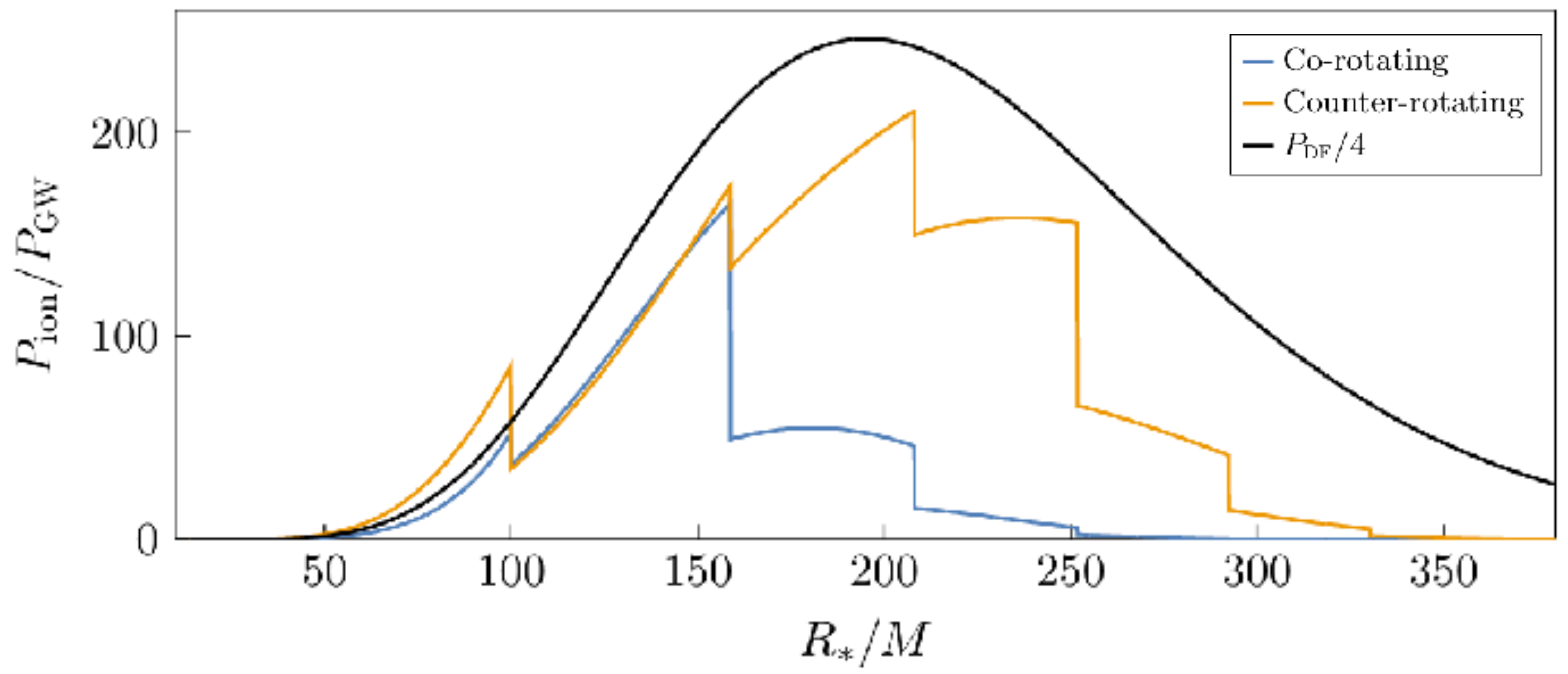
Ultra-light boson clouds can grow around spinning BHs, due to accretion or superradiance

D. Baumann +, 2019, 2022; R. Brito +, 2015



- Perturbations enhanced at specific orbital frequencies
    - Backreaction on the secondary evolution

G. Tomaselli +, 2023; G. Tomaselli, 2025



Ionization/GW power v.s. secondary radius

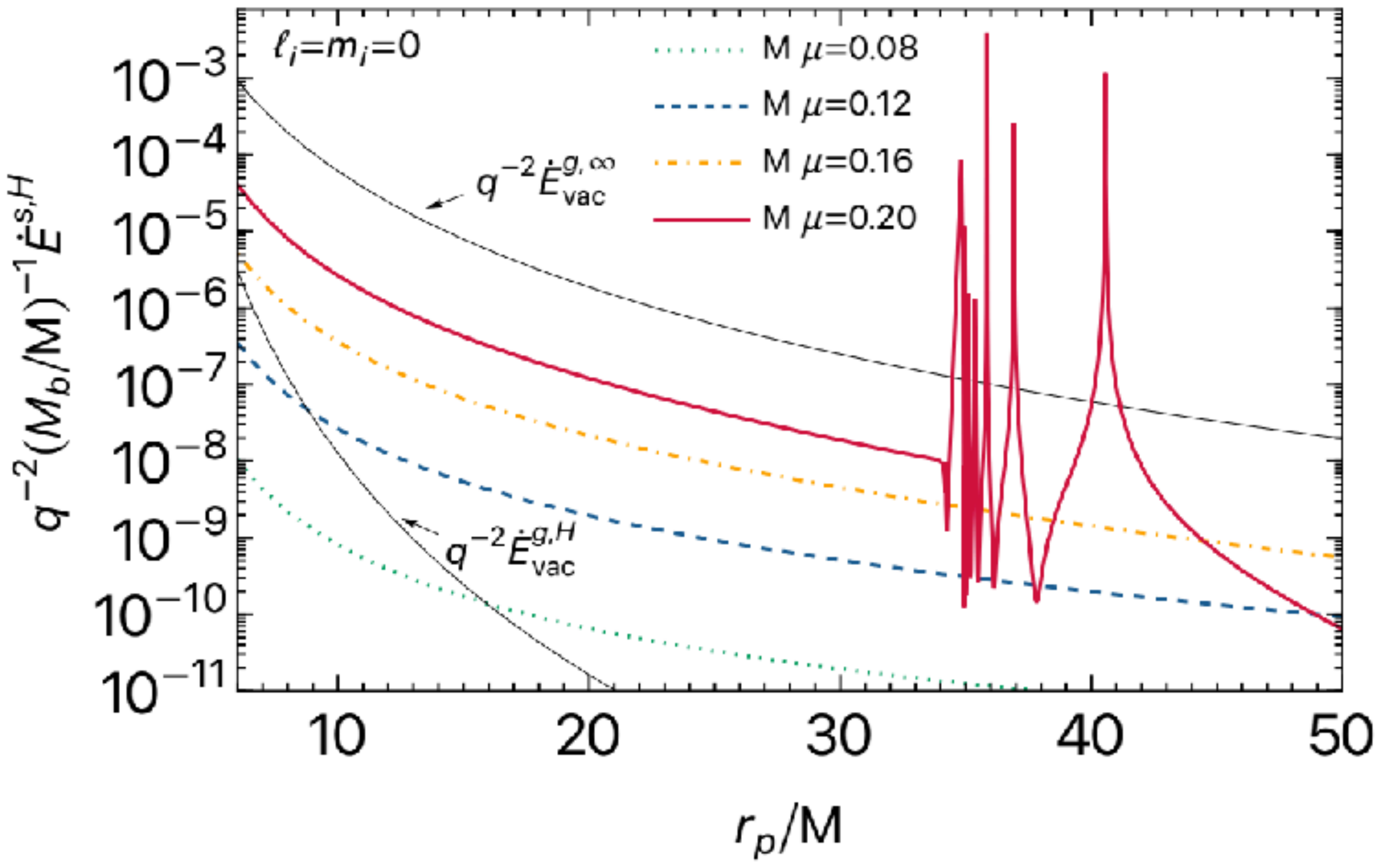
- When the orbital distance ~ cloud size, the cloud gets ionised
    - Transition from bound to unbound states: energy supplied by the binary
    - The inspiral is (also) driven by the interaction with the cloud (aka dynamical friction)
        - Sharp features in the emission

Cloudy environments

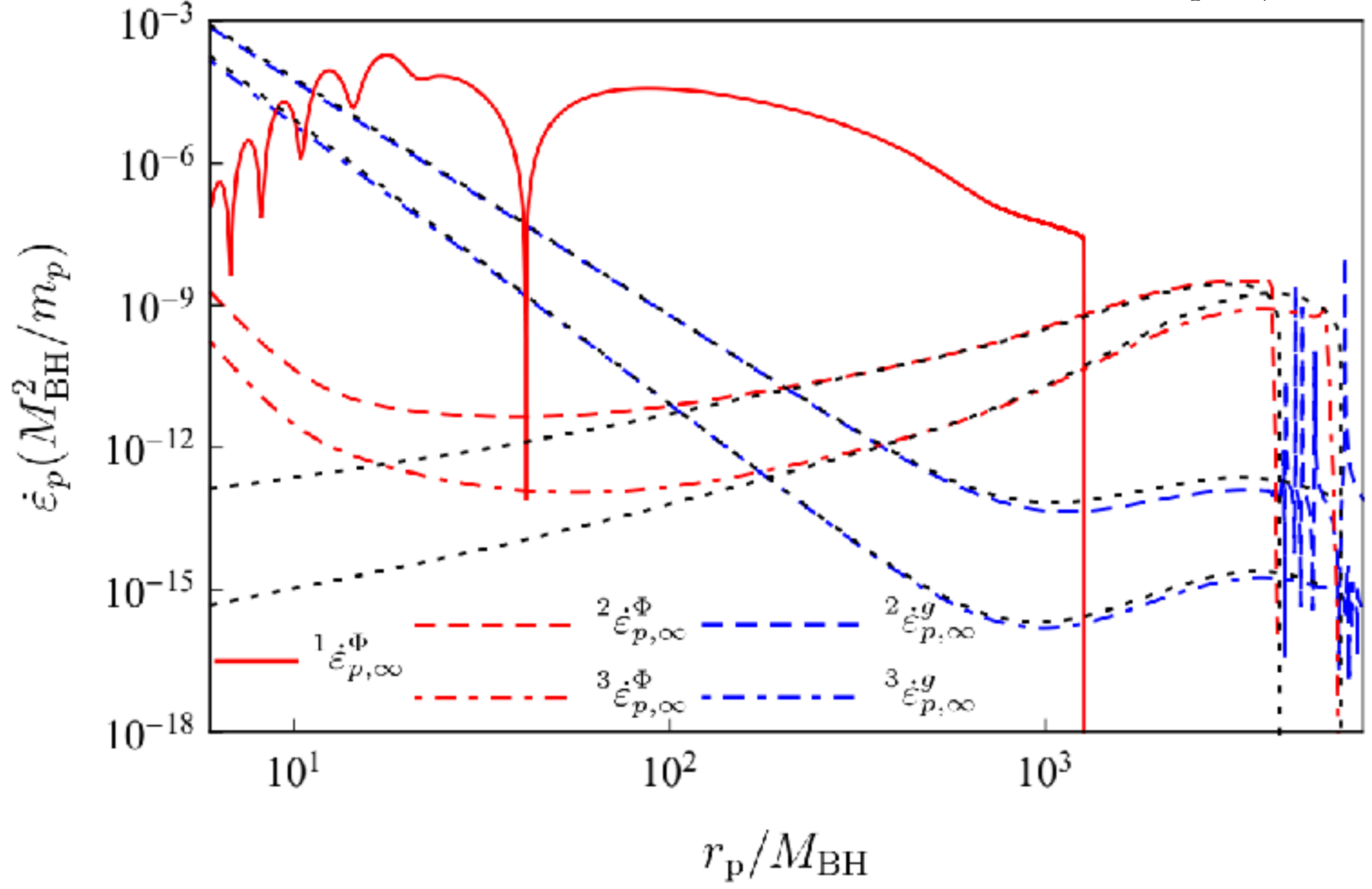
Towards a relativistic description of EMRIs within scalar clouds ⟶ $g_{\mu\nu} = g^{\text{cloud}}_{\mu\nu} + q h_{\mu\nu}$

- Adiabatic fluxes of a BH surrounded by an ultra-light field

R. Brito & S. Shah, 2024



F. Duque +, 2024

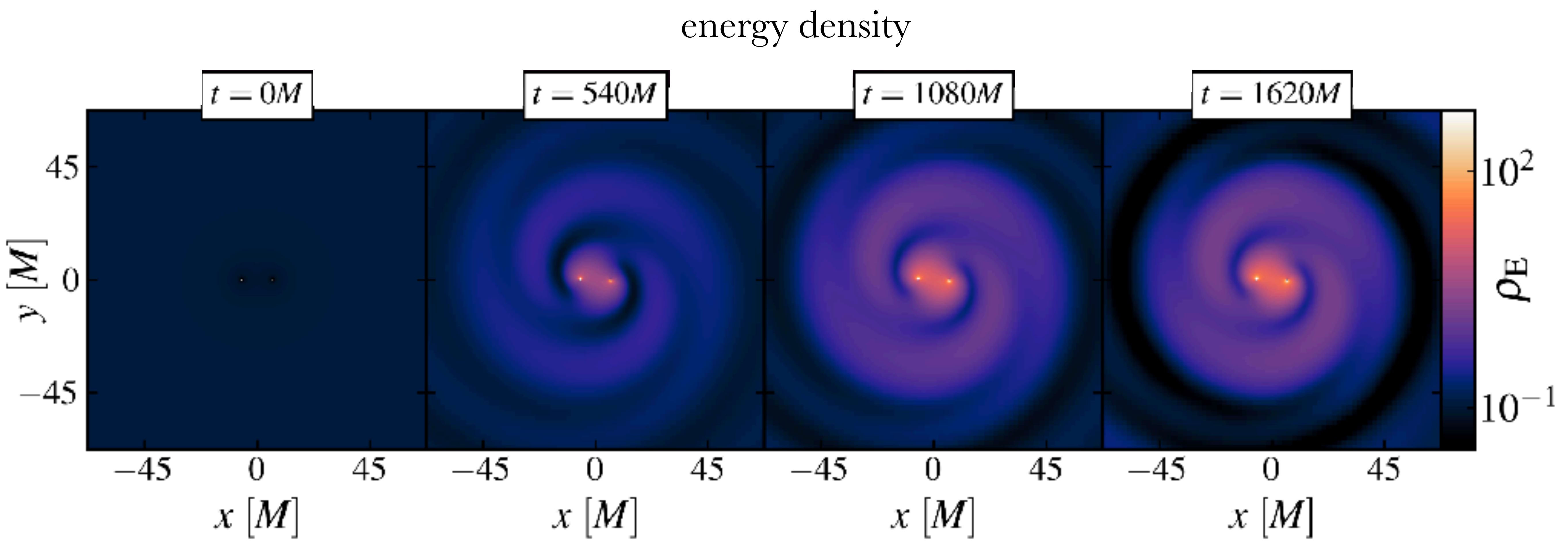


- Sharp features as resonances in the horizon flux & cut-off at large radii
- Scalar radiation can dominate over GW emission at large distances

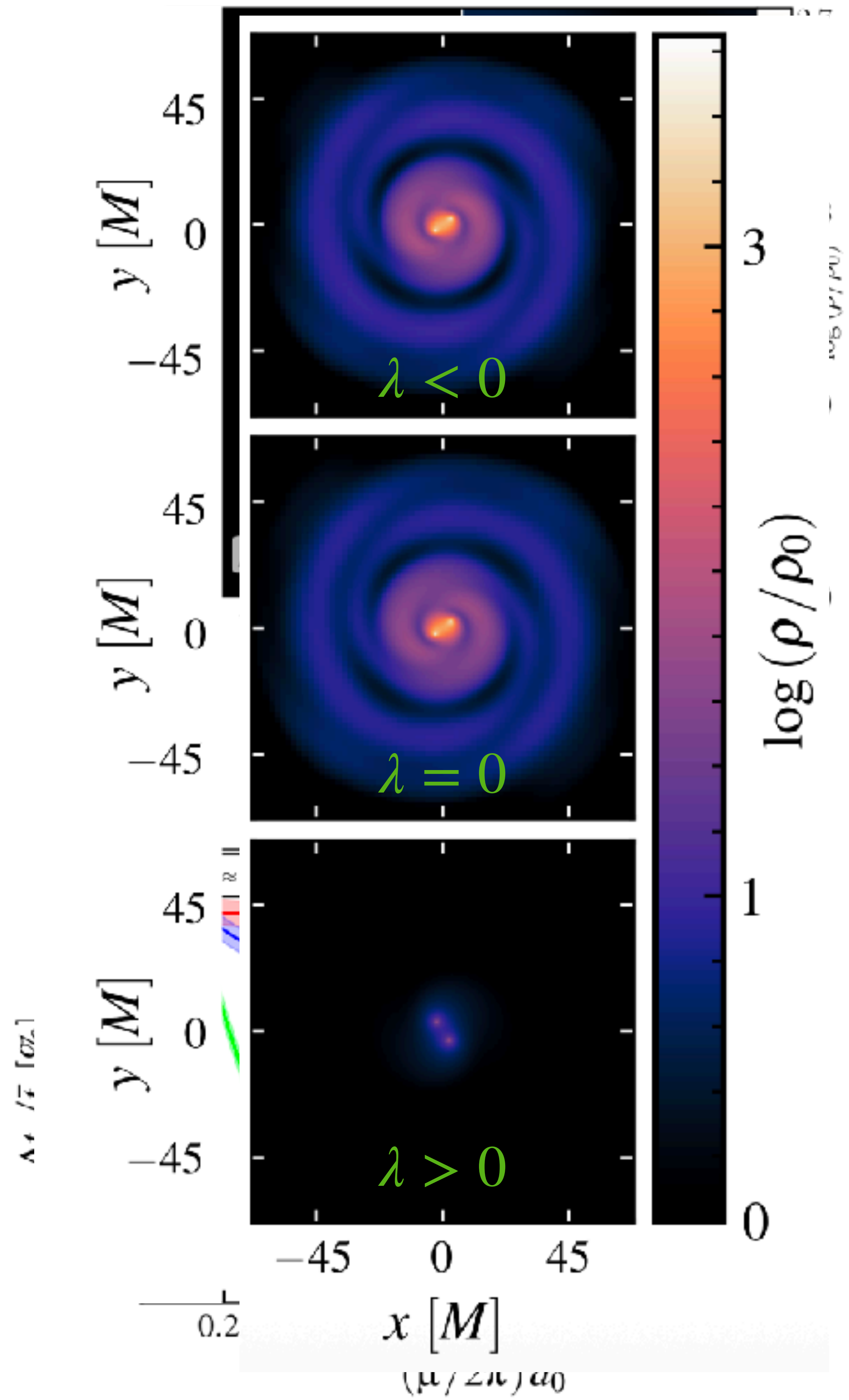
Wave-like DM and overdensities

Numerical simulations of wave-like DM on equal mass BH mergers J. Bamber +, 2022; J. Aurrekoetxea +, 2023; J. Aurrekoetxea +,, 2023

- Orbital evolution of BBHs in an initially homogeneous dark matter environment, with different initial configurations



- Choices of initial data converged to the same distribution over the course of several orbits.
- Potential probe for self interactions $V(|\Phi|) = \frac{\mu^2}{2}|\Phi|^2 + \frac{\lambda}{4}|\Phi|^4$
- Wave-like case seems to resist dispersal, and to form a central overdensity
- Repulsive (attractive) self interactions tend to reduce the central density



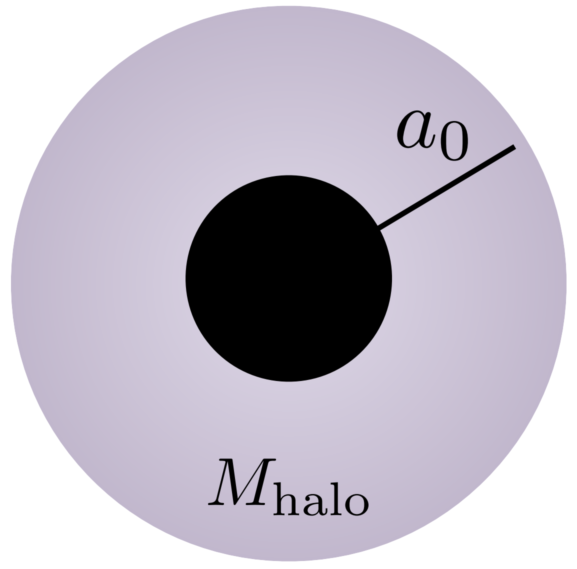
Spikes

BH solutions within a DM profile and perturbations

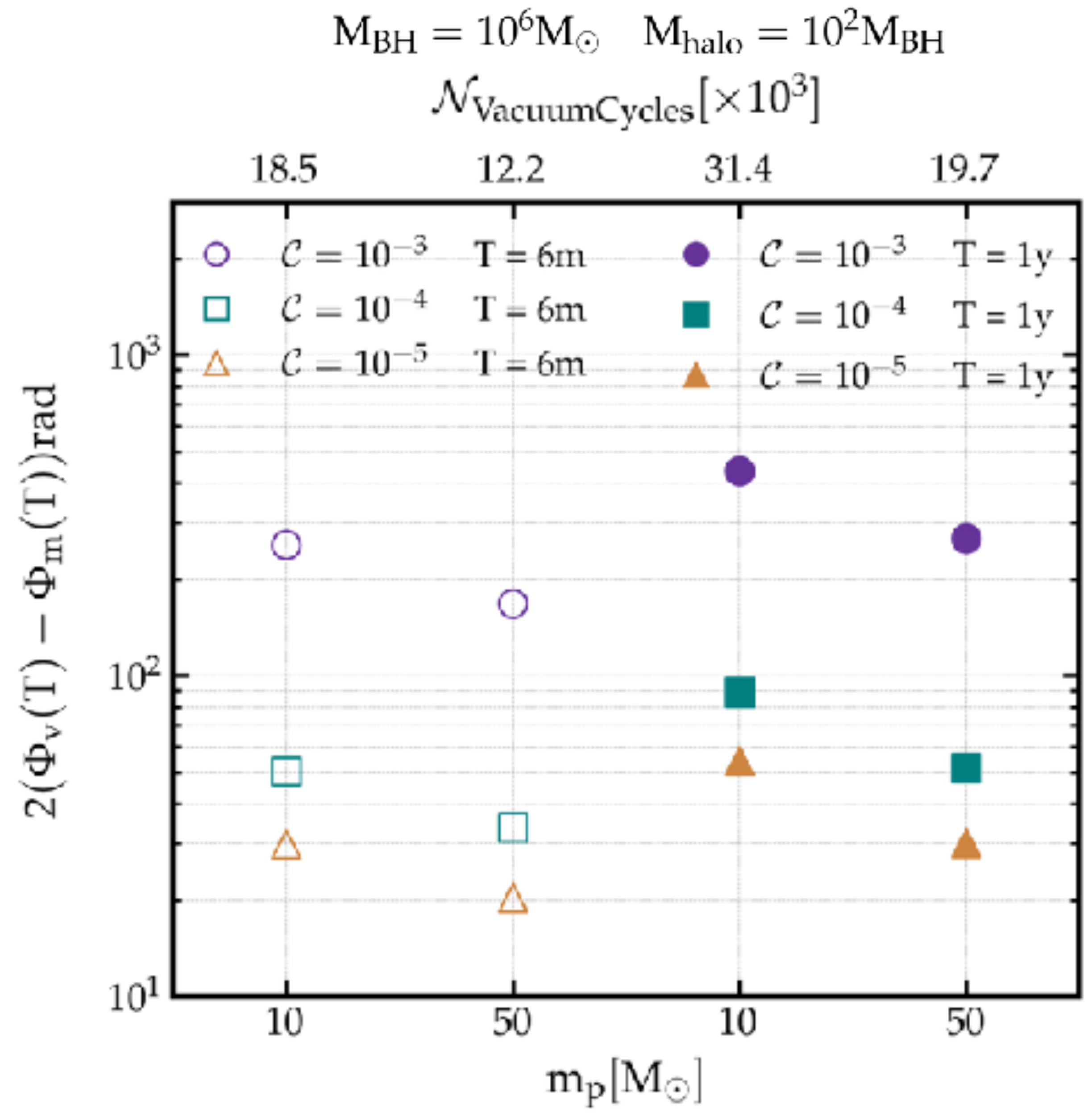
V. Cardoso +, inc. A. M., 2022, 2023, Y. Zhao +, 2024; N. Speeney +, 2024; S. Glorio + inc. A. M, 2025; P. Fernandes & V. Cardoso, 2025; M. Rahman & T. Takahashi+, 2025

$g_{\mu\nu} = g^{(\mathrm{back})}_{\mu\nu} + h_{\mu\nu}$ coupled with fluid perturbations

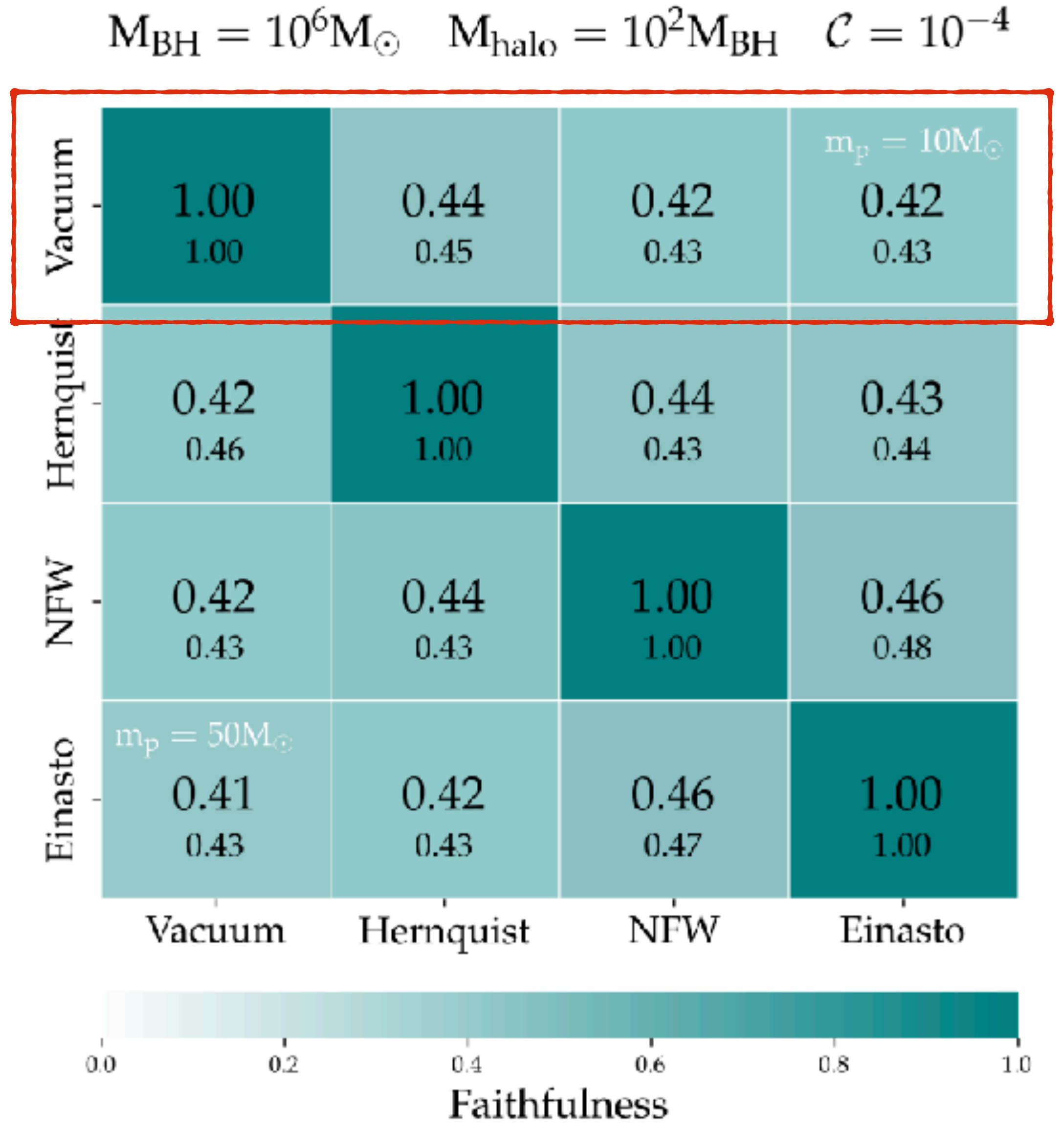
background properties — particle trajectories — adiabatic evolution



- Changes mostly dependent on the halo "compactness" $\mathscr{C} = M_{\mathrm{halo}}/a_0$ ($\lesssim 10^{-4}$)



phase difference compared to vacuum
for EMRIs in an NFW profile

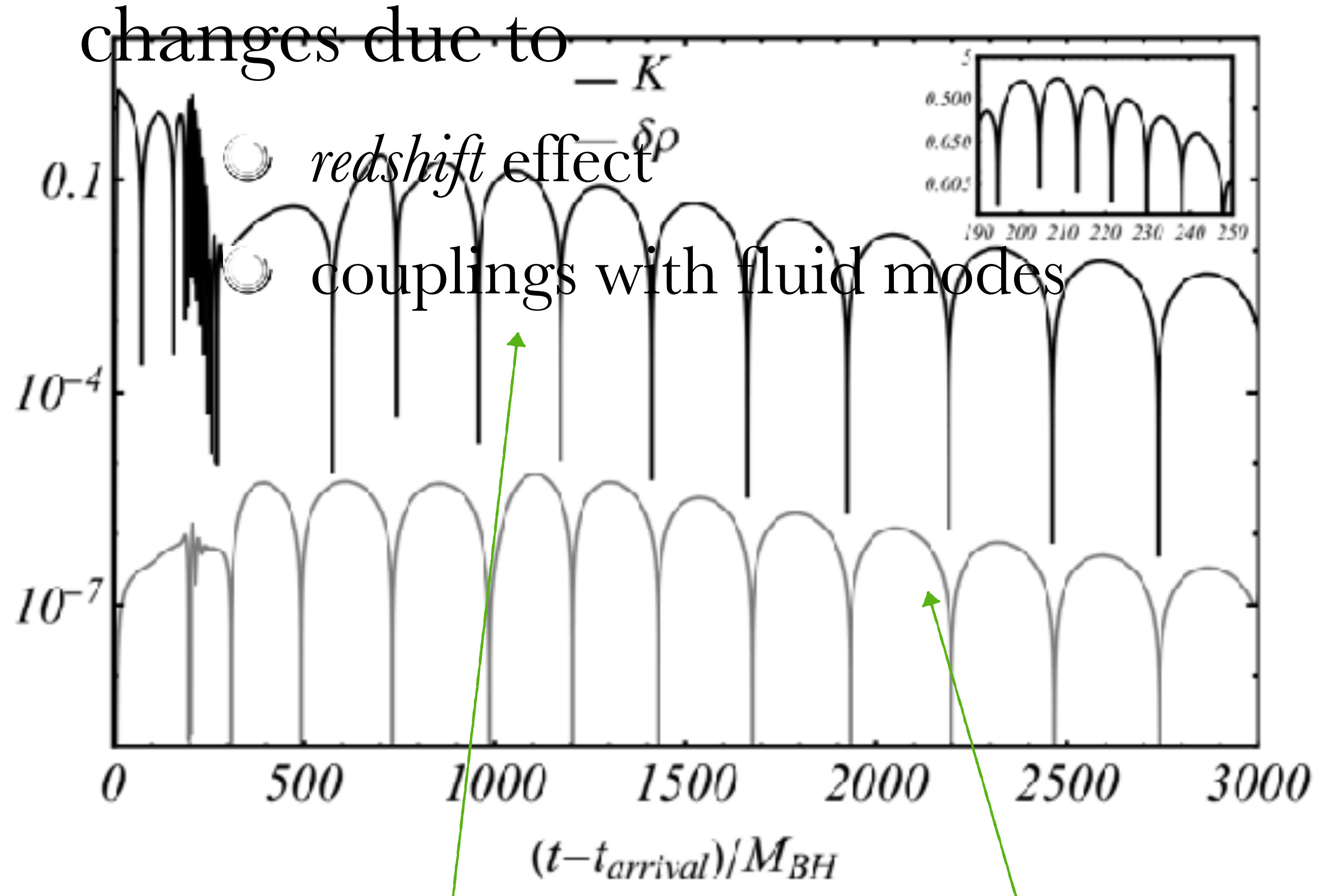


	Vacuum	Hernquist	NFW	Einasto
Vacuum	1.00 / 1.00	0.44 / 0.45	0.42 / 0.43	0.42 / 0.43
Hernquist	0.42 / 0.46	1.00 / 1.00	0.44 / 0.43	0.43 / 0.44
NFW	0.42 / 0.43	0.44 / 0.43	1.00 / 1.00	0.46 / 0.48
Einasto	0.41 / 0.43	0.42 / 0.43	0.46 / 0.47	1.00 / 1.00

faithfulness $\sim \langle h_{\mathrm{vac}} | h_{\mathrm{halo}} \rangle$

conversion between metric and fluid modes

changes due to
- *redshift* effect
- couplings with fluid modes

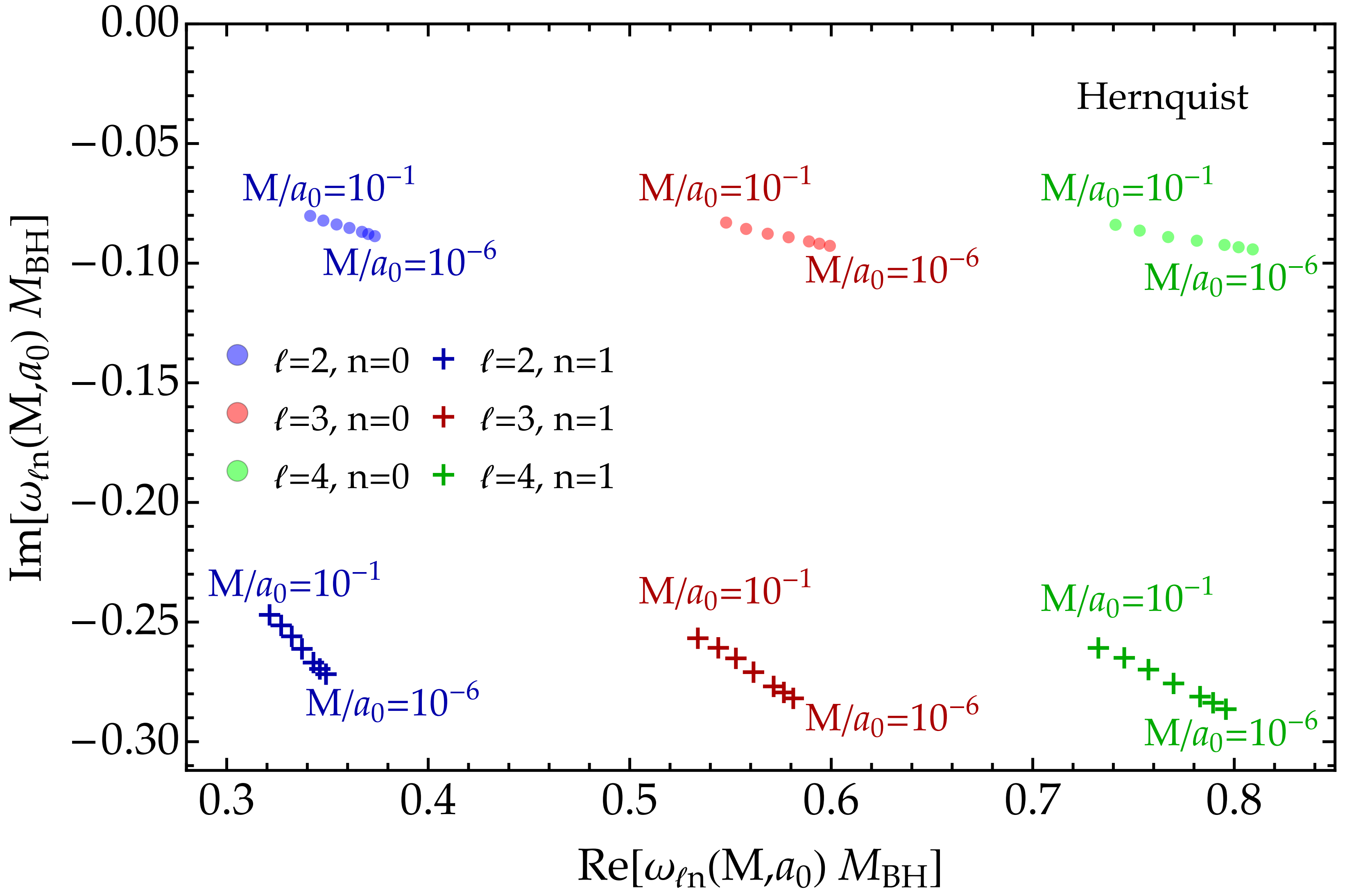


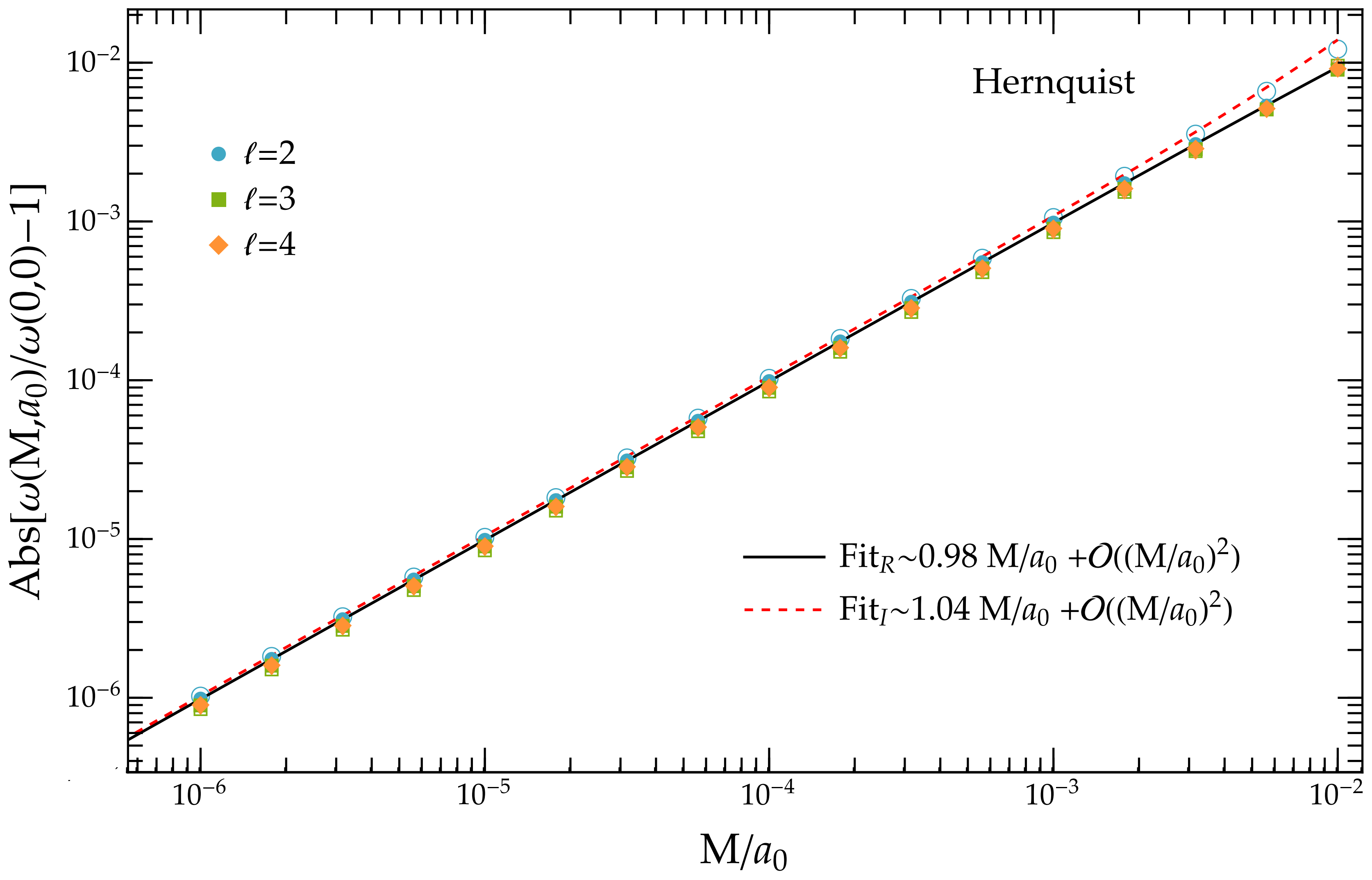
metric response — density response

QNMs intermezzo

Axial Quasi Normal Modes for a BH surrounded by spherical DM distribution

L. Pezzella +, inc. A. M., 2024



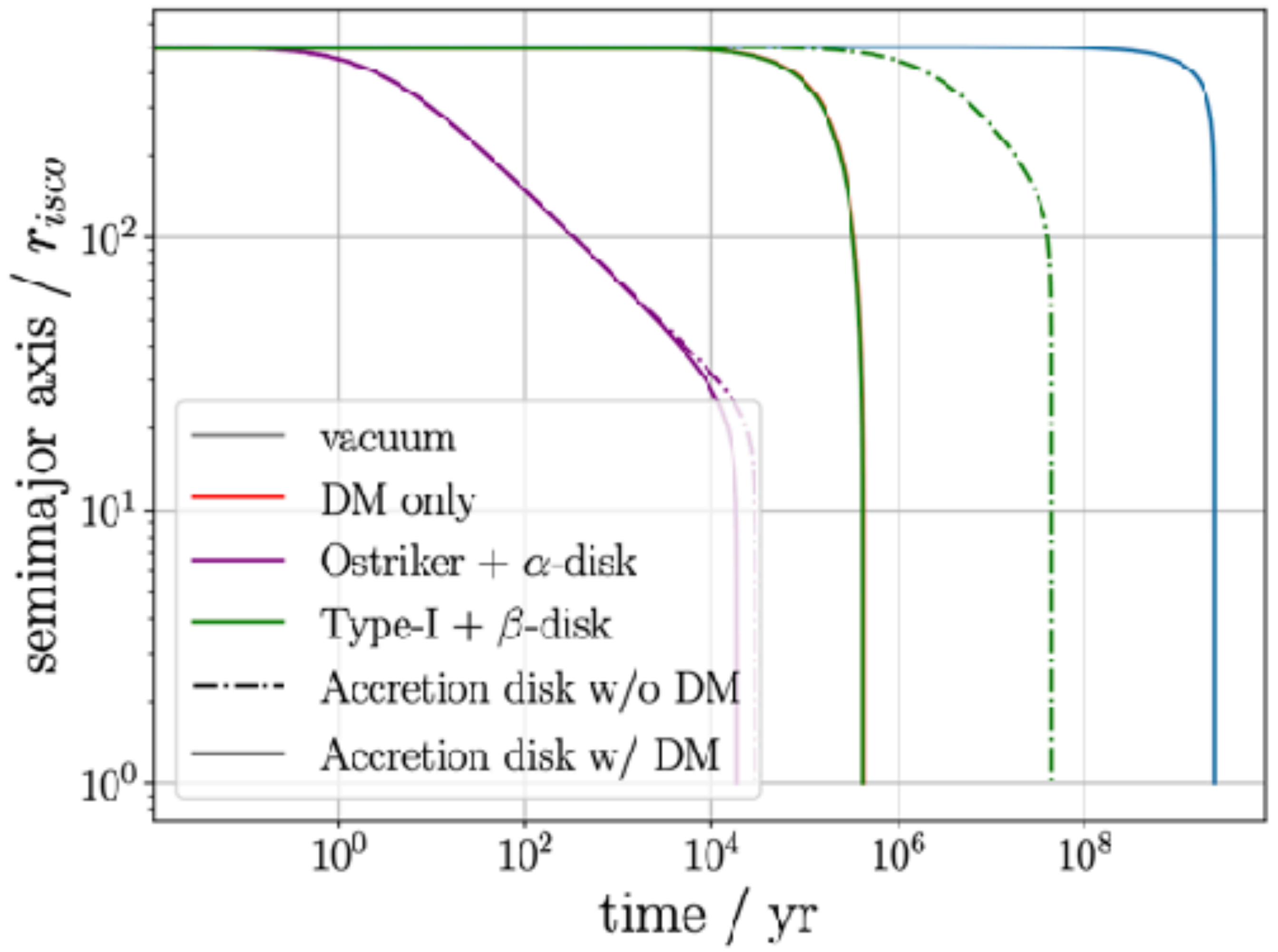


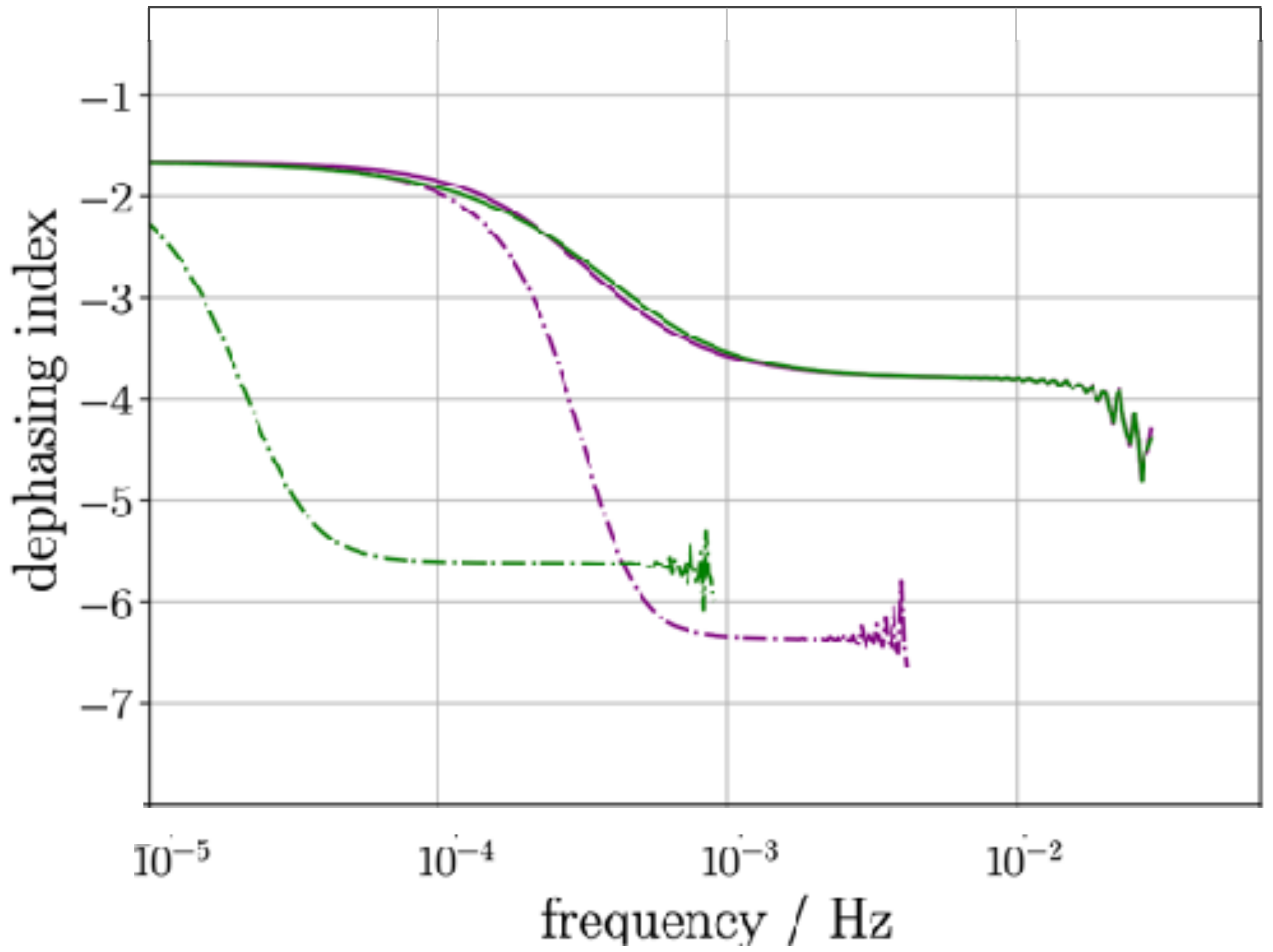
- Frequencies (damping times) decrease (increase) as the compactness M/a_0 increases
- Very little dependence on the mass of the distribution
- For small compactness $\frac{\omega_R}{\omega_R^{\rm vac}} \sim 1 - \frac{M}{a_0}$ $\quad \frac{\omega_I}{\omega_I^{\rm vac}} \sim 1 - \frac{M}{a_0}$

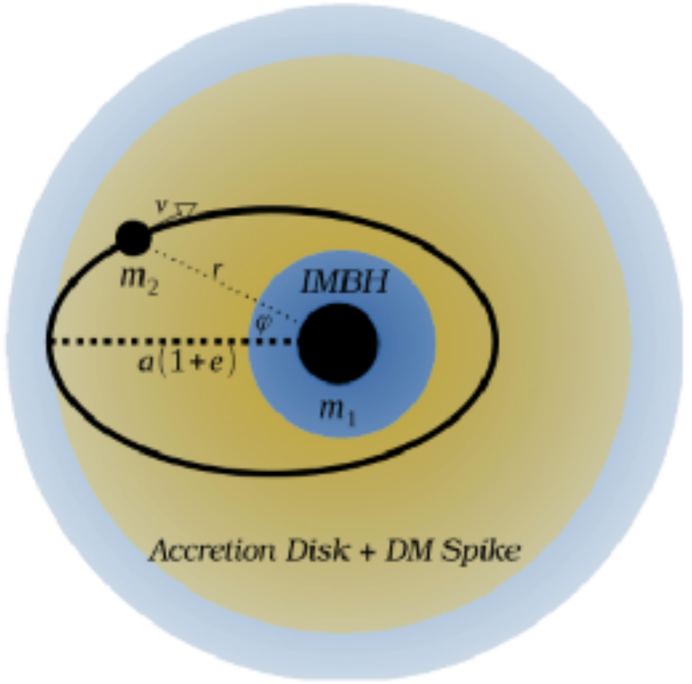
Contaminations: multiple effects

Can we disentangle different environmental effects with LISA? P. Cole +, 2023

N. Becker & L. Sagunski, 2023







DM spikes & accretion disks

- Spikes and accretion dominating at different times/separations
  - E/IMRIs in different frequency ranges carry complementary informations
  - Multiple diagnostics: dephasing index, eccentricity evolution…

Love numbers for BHs in matter

Tidal deformabilities Λ for Kerr BHs in vacuum vanish

T. Hinderer, 2008; T. Binnington & E. Poisson, 2009; T. Damour & A. Nagar, 2008; P. Landry & E. Poisson, 2015; P. Pani + inc. A. M., 2015; N. Gürlebeck, 2015; A. Le Tiec +, 2021; V. Cardoso + inc. A. M., 2017

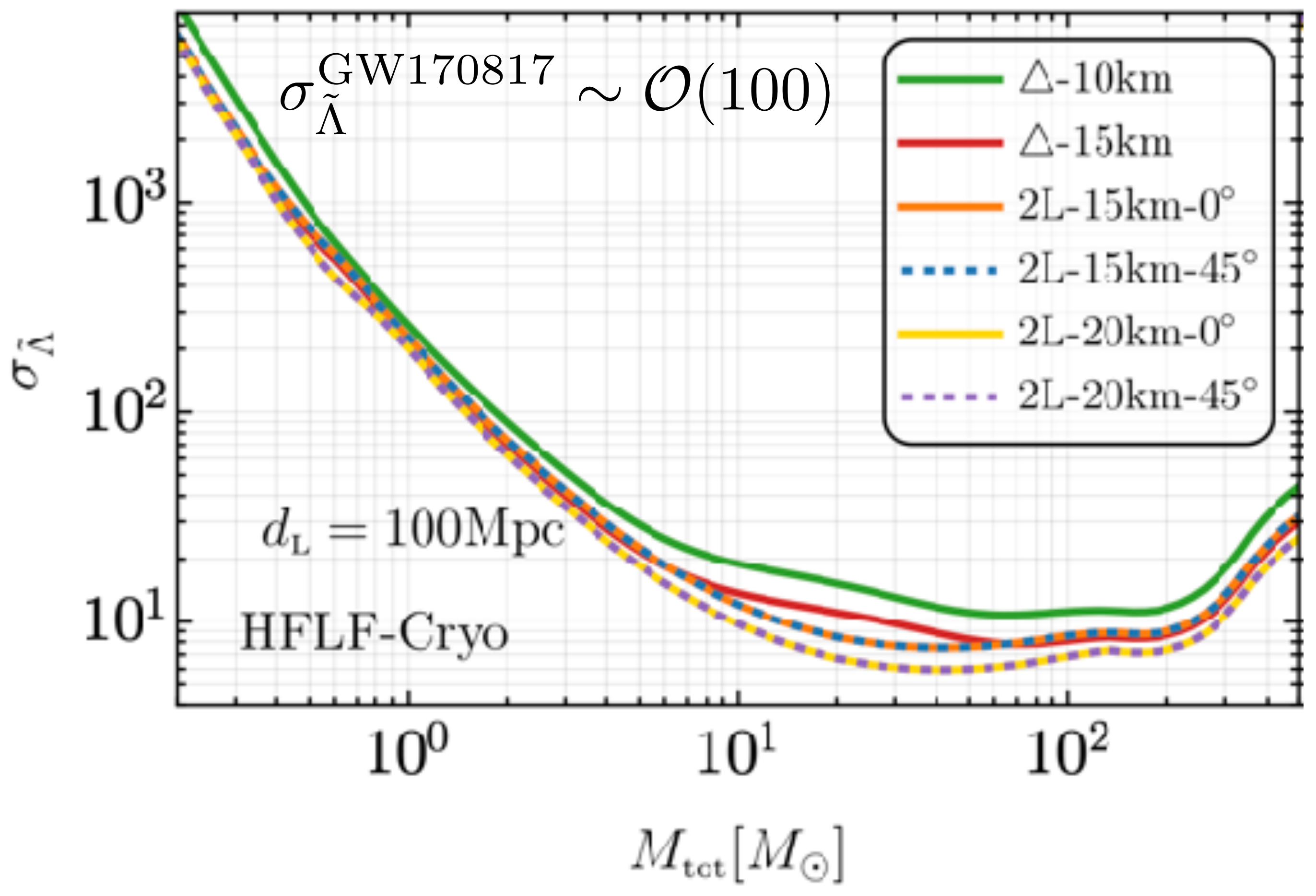
- For BHs dressed by matter: $\Lambda \neq 0$

$$\varphi = 2\pi f t_c - \varphi_c - \pi/4 + \frac{3}{128\eta x^{5/2}} \times \left(\sum_{i=0}^{7} \varphi_{\,\mathrm{pp},i/2} x^{i/2} + \varphi_{\mathrm{T},5} x^5 + \varphi_{\mathrm{T},6} x^6 \right)$$

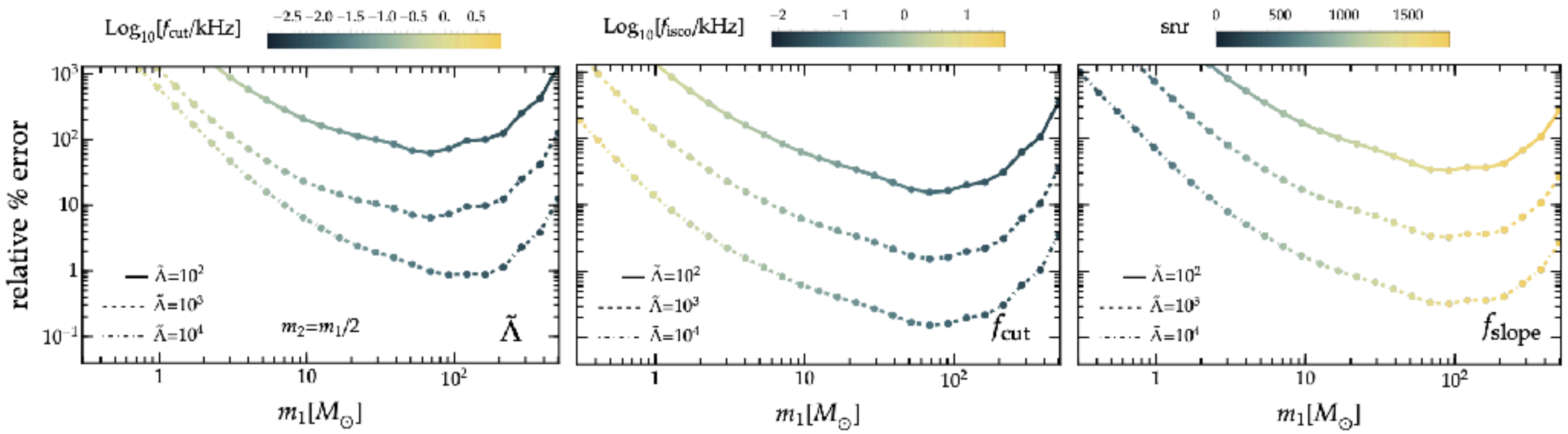
point-particle

tidal

M. Branchesi +, 2023



$$\vec{\theta} = \{\mathcal{M}, \eta, \chi_s, \chi_a, t_c, \phi_c, d_L, \theta, \phi, \psi, \iota, \tilde{\Lambda}, f_{\mathrm{cut}}, f_{\mathrm{slope}}\}$$



$$\tilde{\Lambda} \to \mathcal{S}(f) \cdot \tilde{\Lambda} = \left[\frac{1 + e^{-f_{\mathrm{cut}}/f_{\mathrm{slope}}}}{1 + e^{(f - f_{\mathrm{cut}})/f_{\mathrm{slope}}}} \right] \cdot \tilde{\Lambda}$$

V. De Luca, A. M., P. Pani, 2023

smoothing function going to zero as $f > f_{\mathrm{cut}}$

- Interesting science case for multiband analyses (LISA+ET)

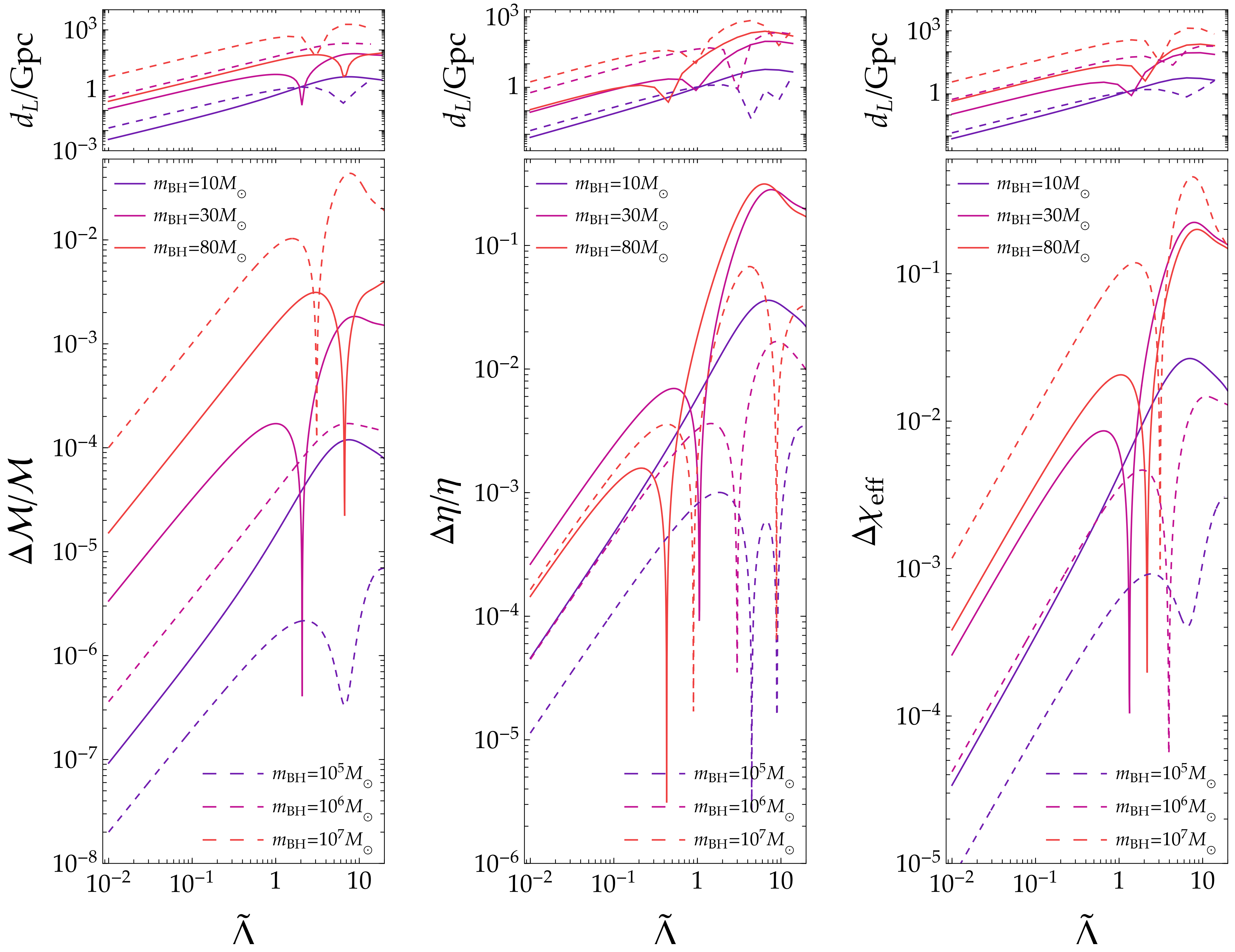
Love numbers in matter: systematics effects

Is there any systematic error in the source parameters when using a wrong waveforms model? V. De Luca + inc. A. M, 2025

- Equal mass binaries observed by ET & LISA

Injection: GW signal with $\tilde{\Lambda} \neq 0$ ⟷ Recovery: GW signal with $\tilde{\Lambda} = 0$ ⟶ $\Delta\theta \propto \Lambda$

bias over injected value ⟵



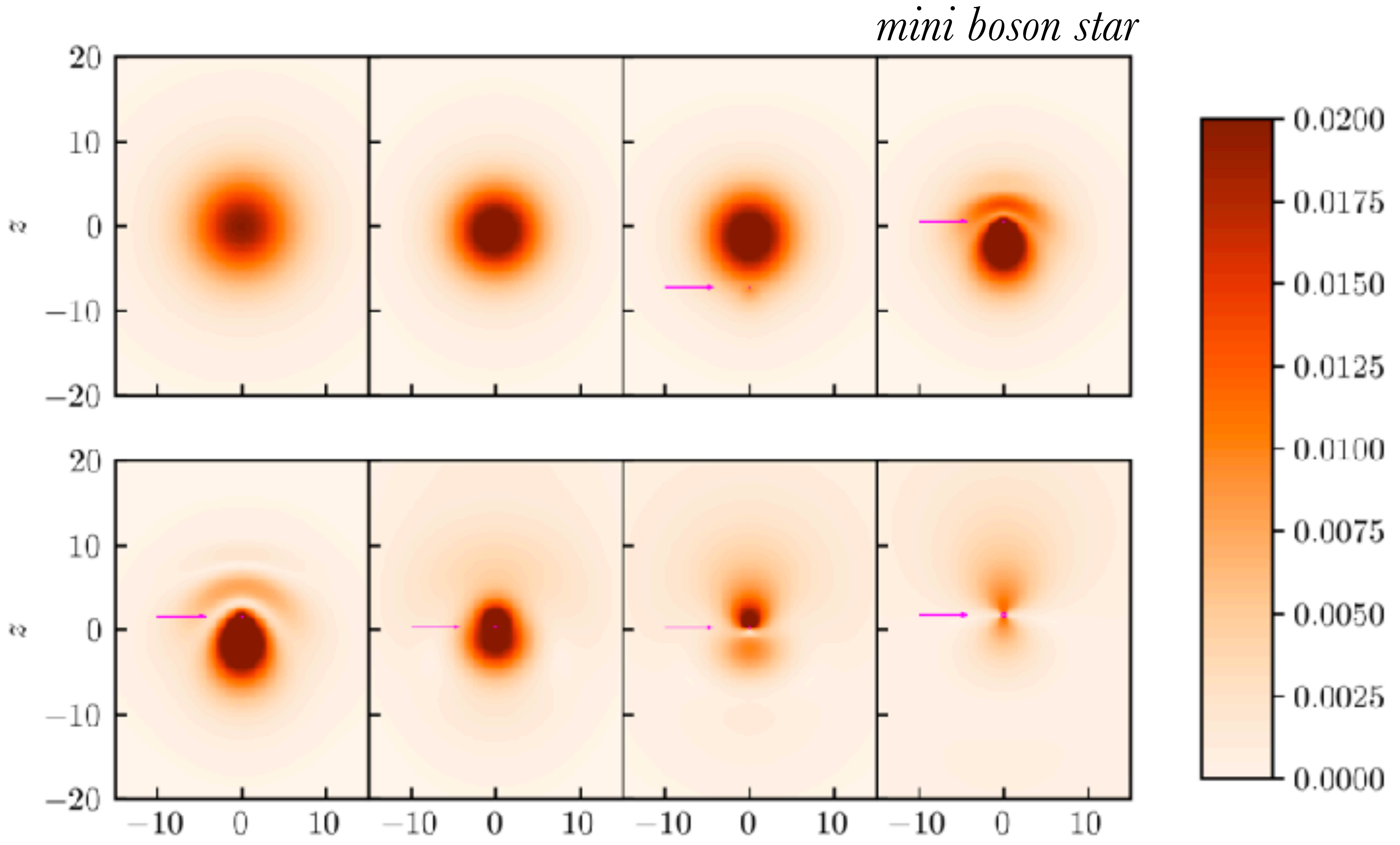
⟶ *distance @ bias $\gtrsim$ statistical error*

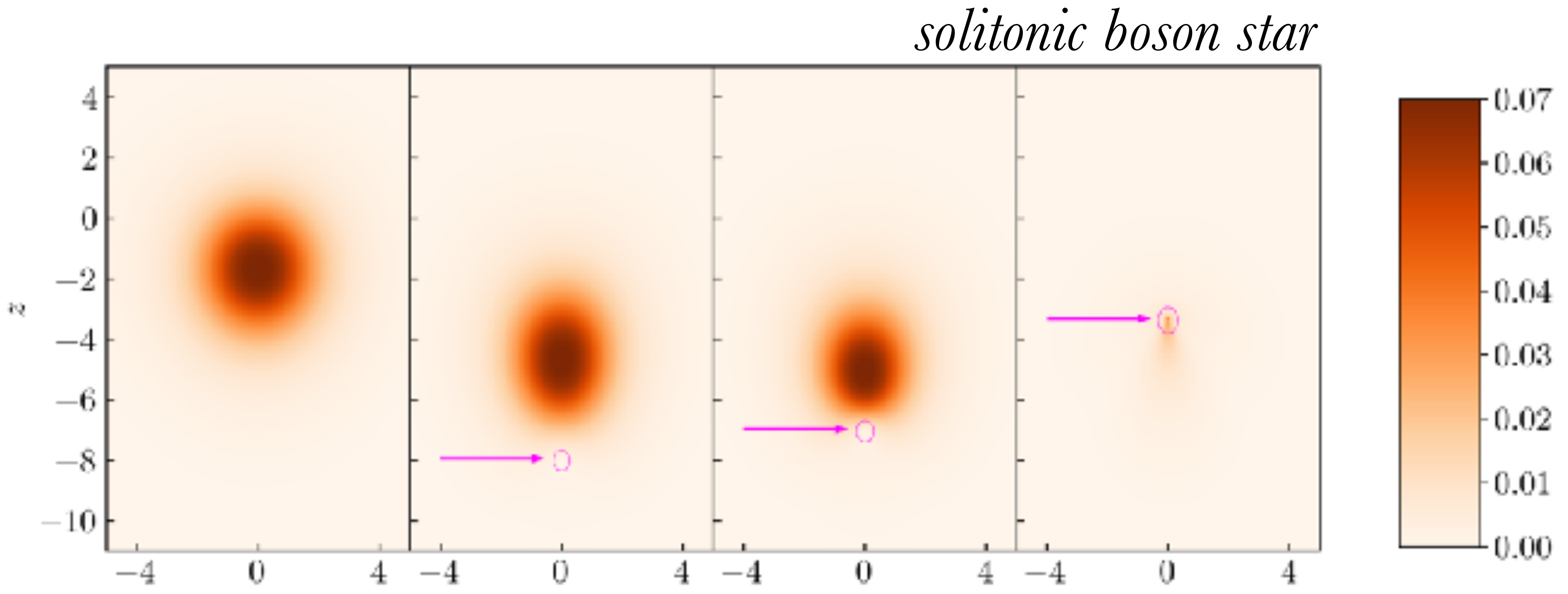
Parasitic BHs

V. Cardoso + 2022, Z. Zhong +, 2023

Small black hole moving through a much massive scalar field distribution

- Tidal effects, accretion, DF, GW emission…





- DF effective at $r \lesssim (M_{\rm BH}/M)R_{98}$
    - Hard to disentangle DF from tidal effects and accretion