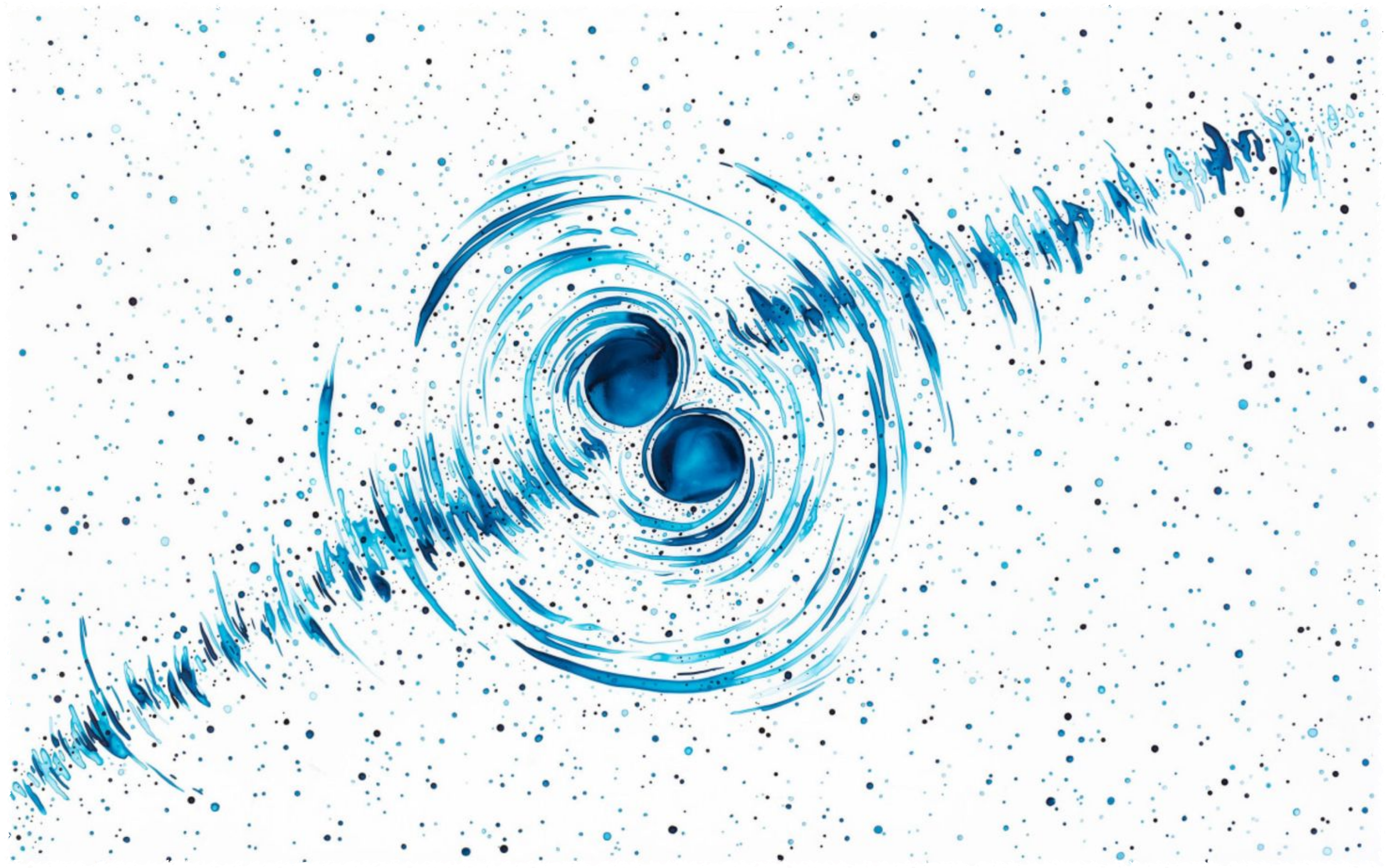
Black Hole Environments and Dark Matter with Gravitational Waves

Rodrigo Vicente
(GRAPPA, University of Amsterdam)



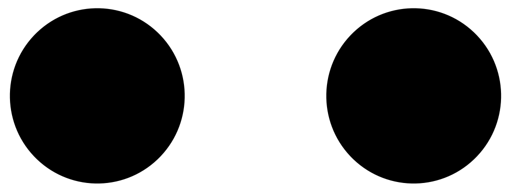
Lia Halloran, WS600 Warped Spacetime, 2023

New Frontiers in Strong Gravity @ Benasque (July 24, 2026)

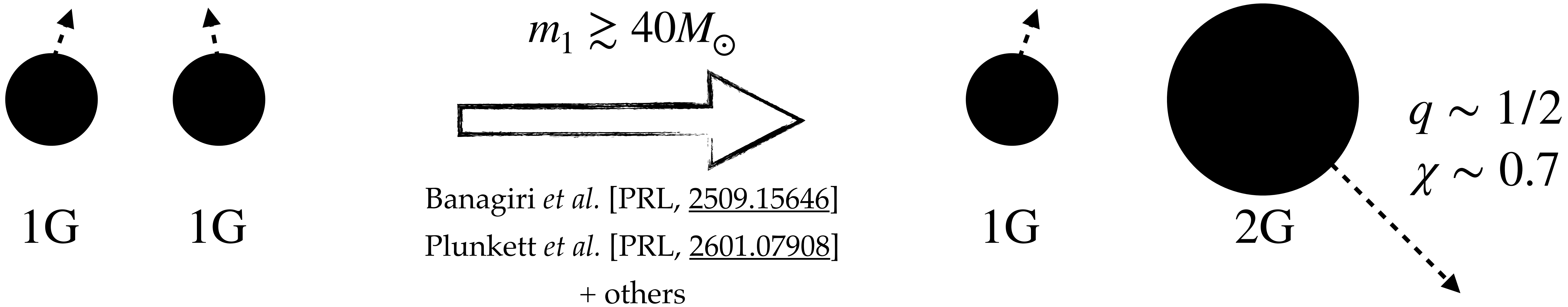
Some binaries carry signs of a dense formation history

nearly 400 compact binary events → population inference

$\{M,\ q,\ \chi_{\rm eff},\ \chi_{\rm p}\}$



High-mass, high-spin population → $\mathcal{O}(10\%)$ hierarchical contribution?



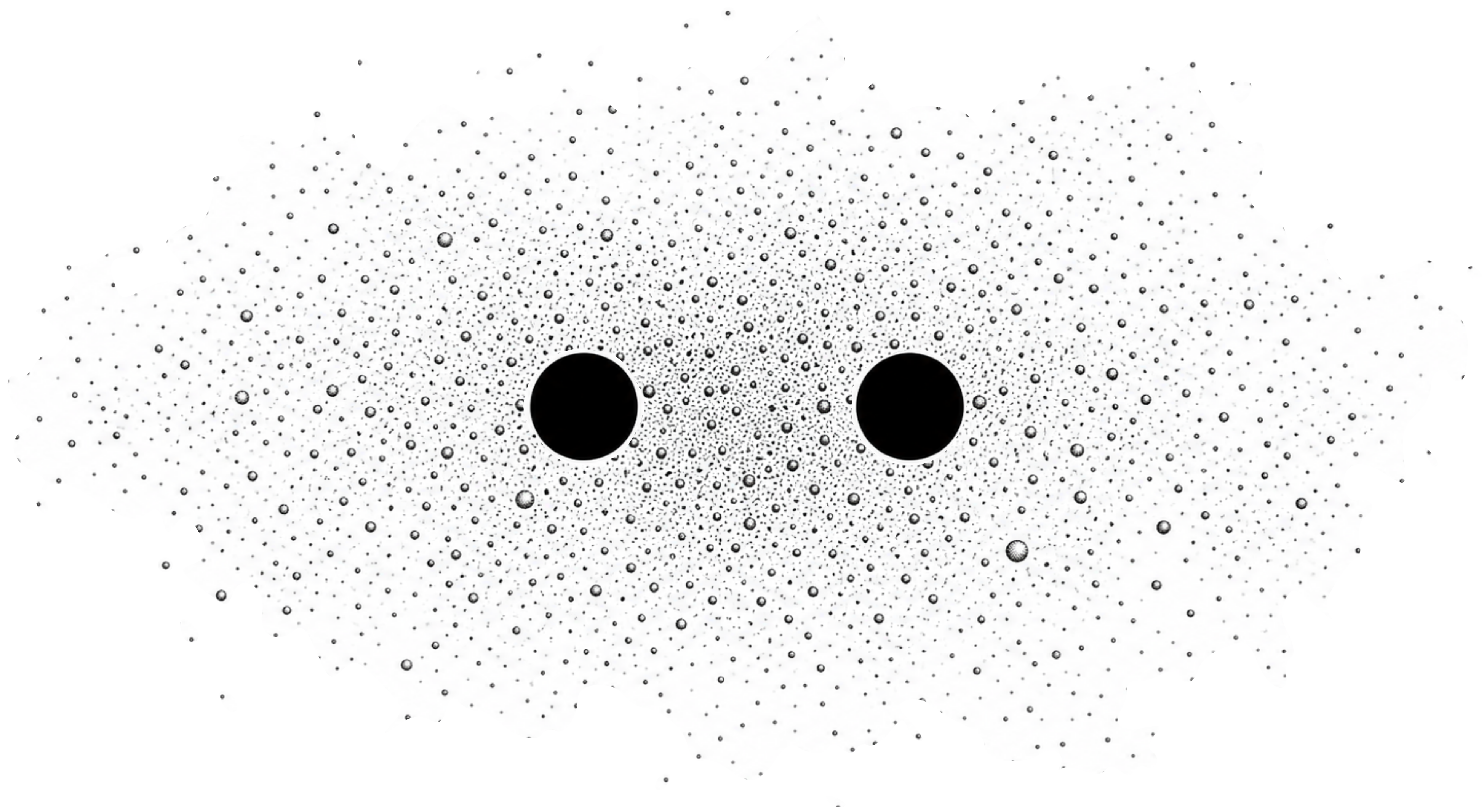
Banagiri *et al.* [PRL, 2509.15646]
Plunkett *et al.* [PRL, 2601.07908]
+ others

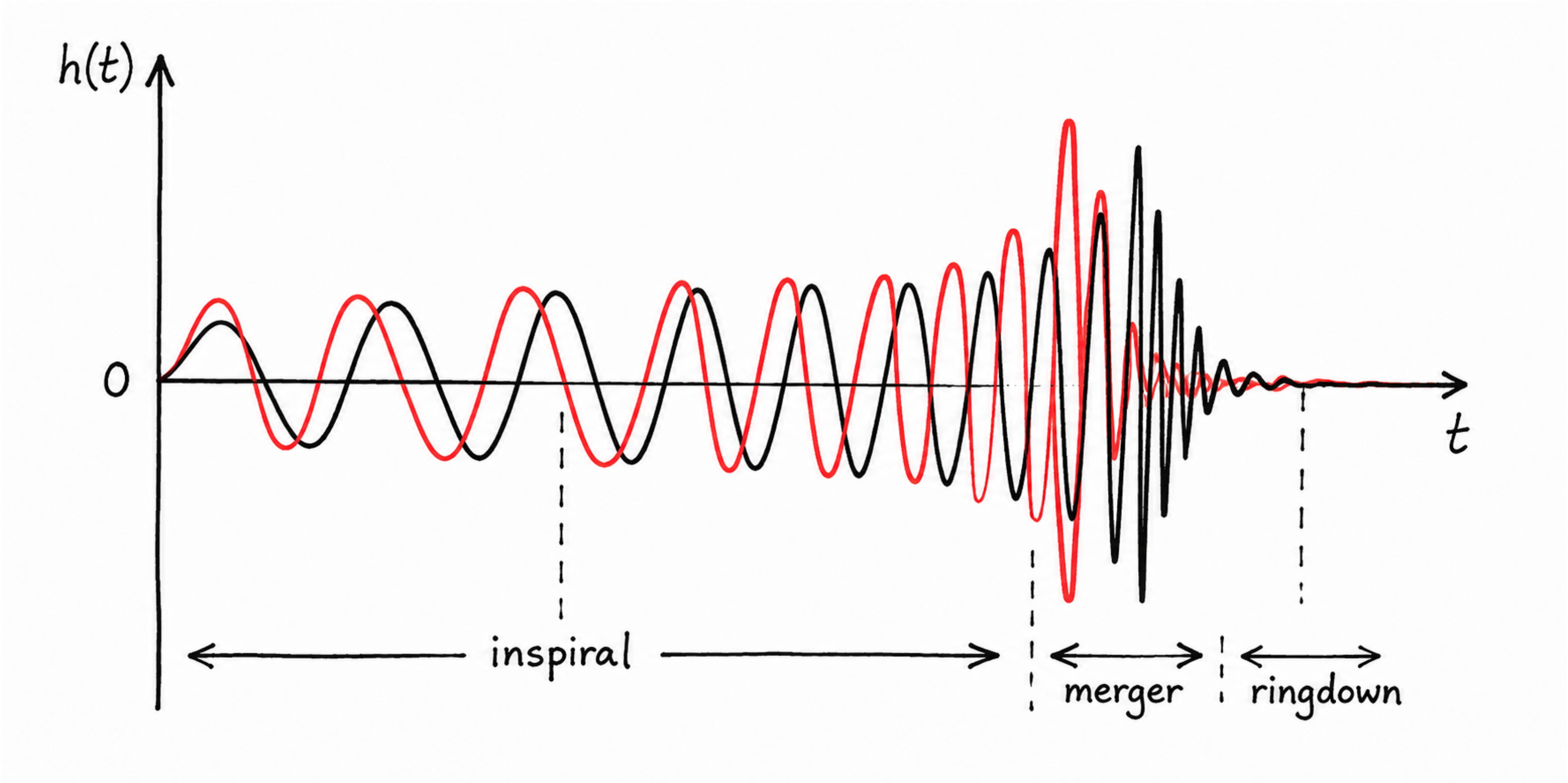
A non-negligible fraction may merge in dense hosts (nuclear star clusters and AGN disks).

Can such environments leave an observable imprint on waveforms?

Environmental effects are both a systematic and a signal

Small forces can accumulate over many orbital cycles

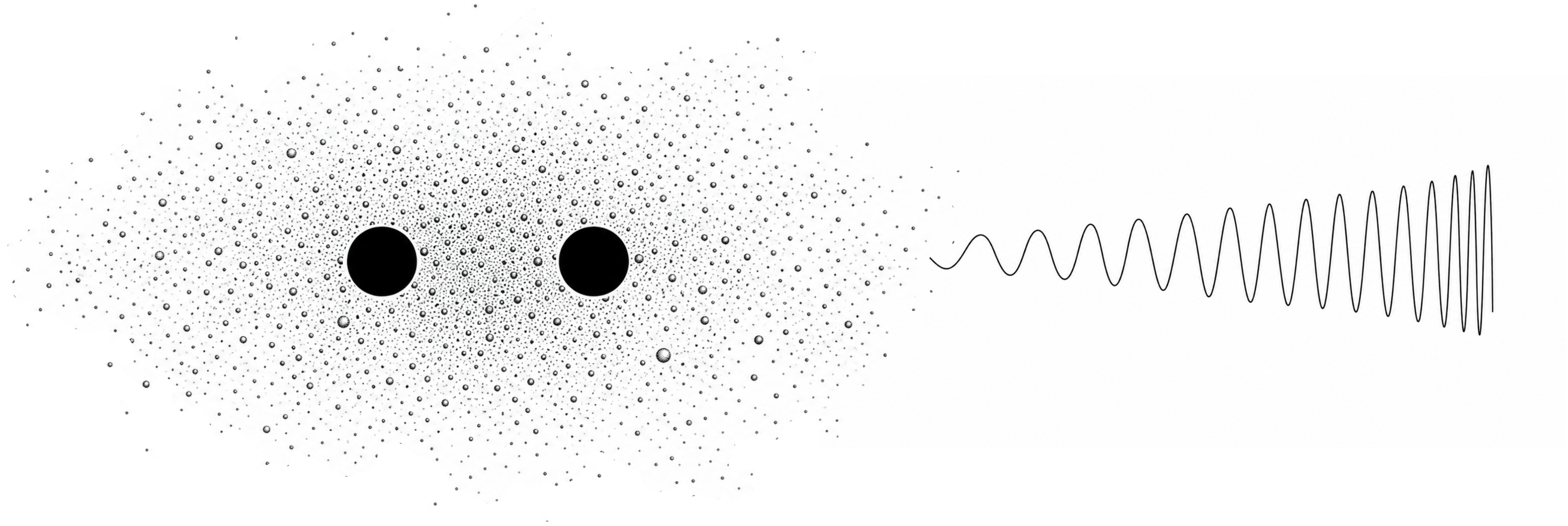




Ignore it → biased source parameters or apparent deviations from GR

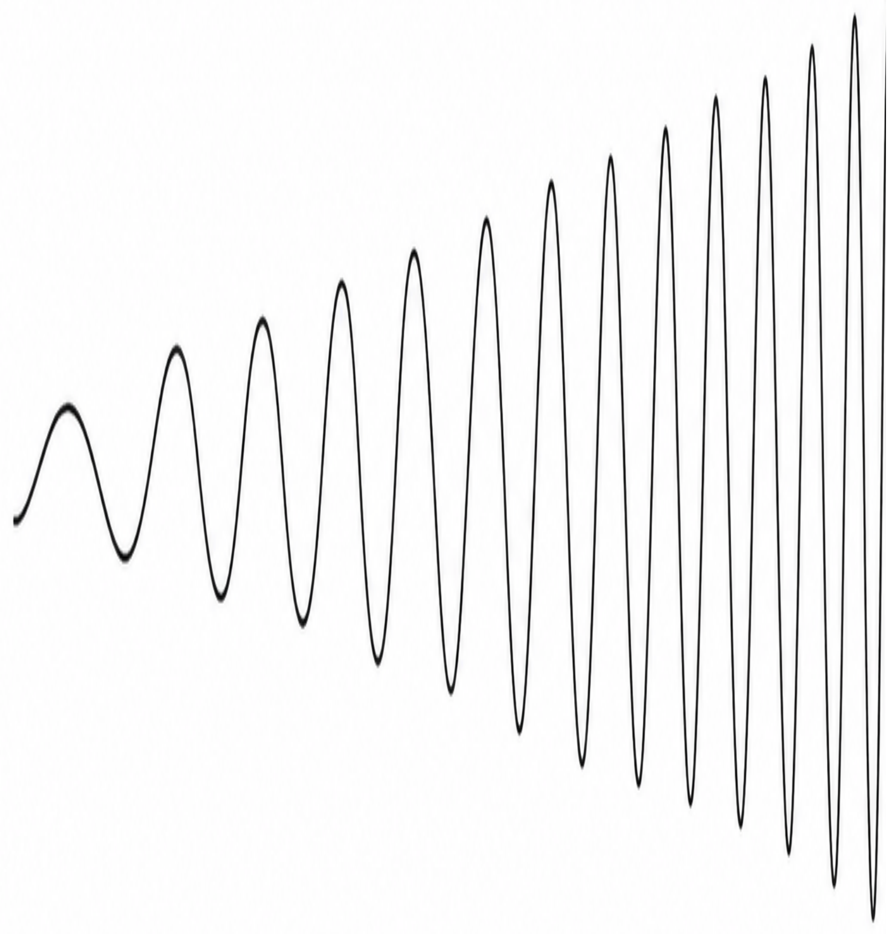
Model it → probe gas, stars, and dark matter

Environments enter via dynamics, kinematics, and propagation



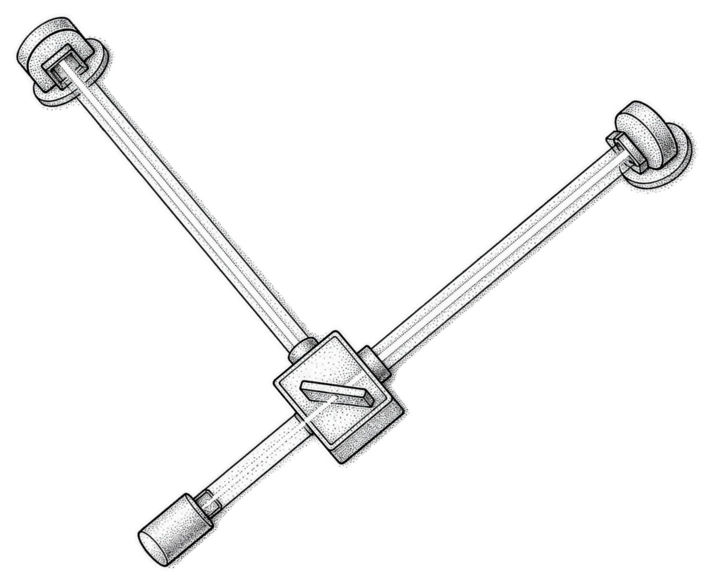
Source Dynamics (e.g. drag/torques, accretion)

$$\dot{\Omega} = \underbrace{\left(\frac{dE_{\rm orb}}{d\Omega}\right)^{-1}}_{\text{conservative}} \underbrace{\left[-\mathscr{F}_{\rm GW} + \dot{E}_{\rm env}\right]}_{\text{non-conservative}}$$



CoM kinematics (e.g. LoSA)

$$z_{\parallel}(t) = z_0 + \Gamma t, \qquad \Gamma \equiv \frac{a_{\parallel}}{c}$$



Propagation

(e.g. gravitational lensing)

From orbital dynamics to an inspiral waveform

Frequency-domain waveform (SPA)

$$\tilde{h}_{22}(f) \simeq A_{22}(t_f)\sqrt{\frac{\pi}{\dot{\Omega}(t_f)}}e^{i\Psi_{22}(f)}, \qquad \Omega(t_f) = \pi f$$

with $\Psi_{22}(f) = 2\pi f\, t_f - 2\,\phi(t_f) - \frac{\pi}{4}$

Modified source dynamics

Environment waveform

$$\tilde{h}_{\rm env}(f) \simeq \tilde{h}_{\rm vac}(f)\left[1 + \delta A_{\rm env}(f)\right] e^{i\Delta\Psi_{\rm env}(f)}$$

Negative PN corrections:

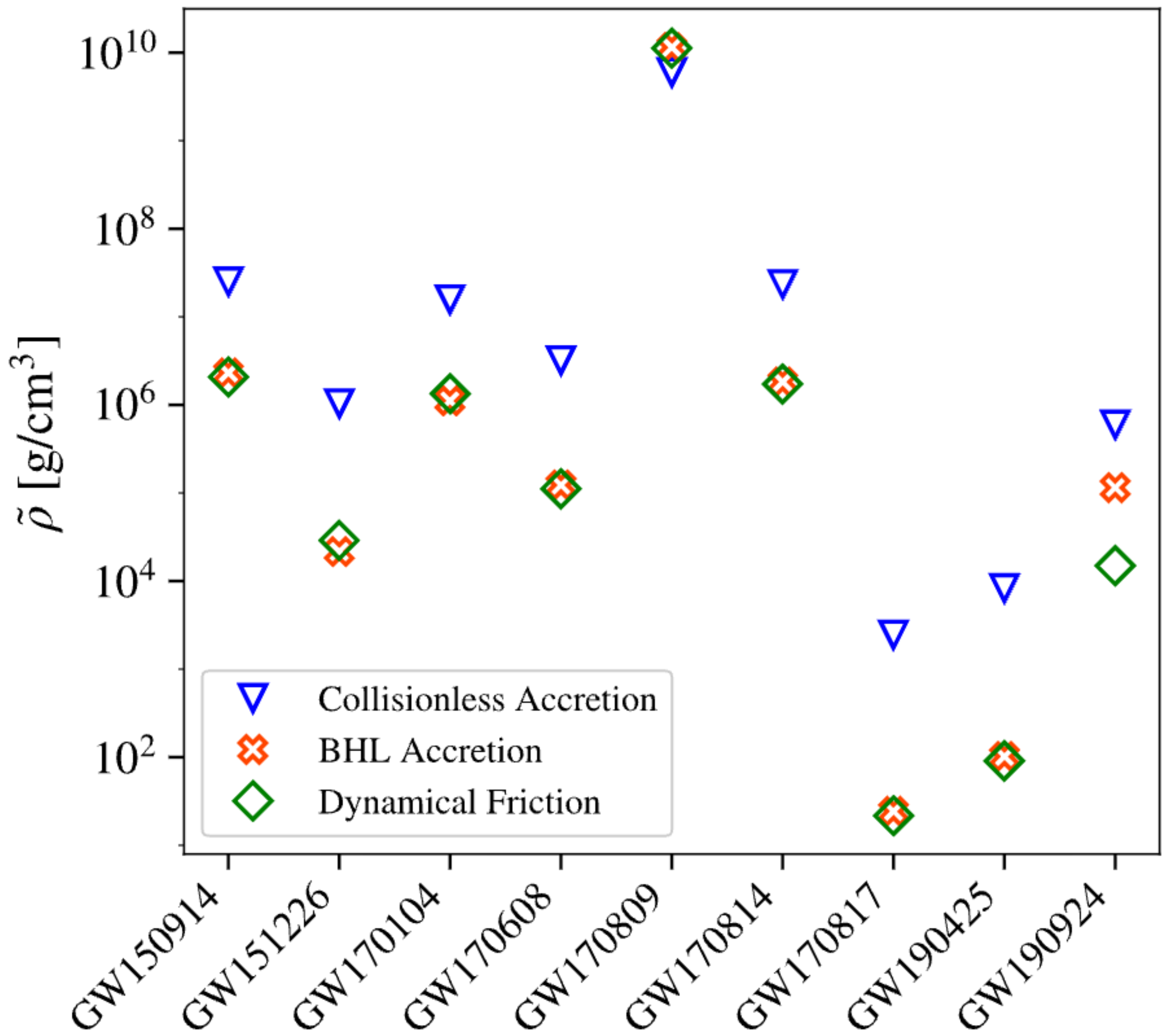
$$\Psi(f) = \Psi_{\rm N}(f)\,[1 + {\rm PN}(f) + \delta_{\rm env}(f)], \qquad \delta_{\rm env} \propto v^{-11}\ ({\rm DF/BHLA}), \quad v^{-9}\ ({\rm CA}), \quad v^{-8}\ ({\rm LoSA/CBD})\,.$$

How large does gaseous density needs to be to lead to an observable effect in present observations?

G. Caneva Santoro, S. Roy, **RV**, *et al.* [PRL, 2309.05061]

When does matter matter?

"the observed signals look like compact binaries in vacuum general relativity"



Analysing GWTC-1 and selected GWTC-2 events, we found that the density of potential gaseous environments would have to be extremely large…

GW170817 gives stringent 90% upper bound on gas density:
It corresponds roughly to the density of gold on Earth!

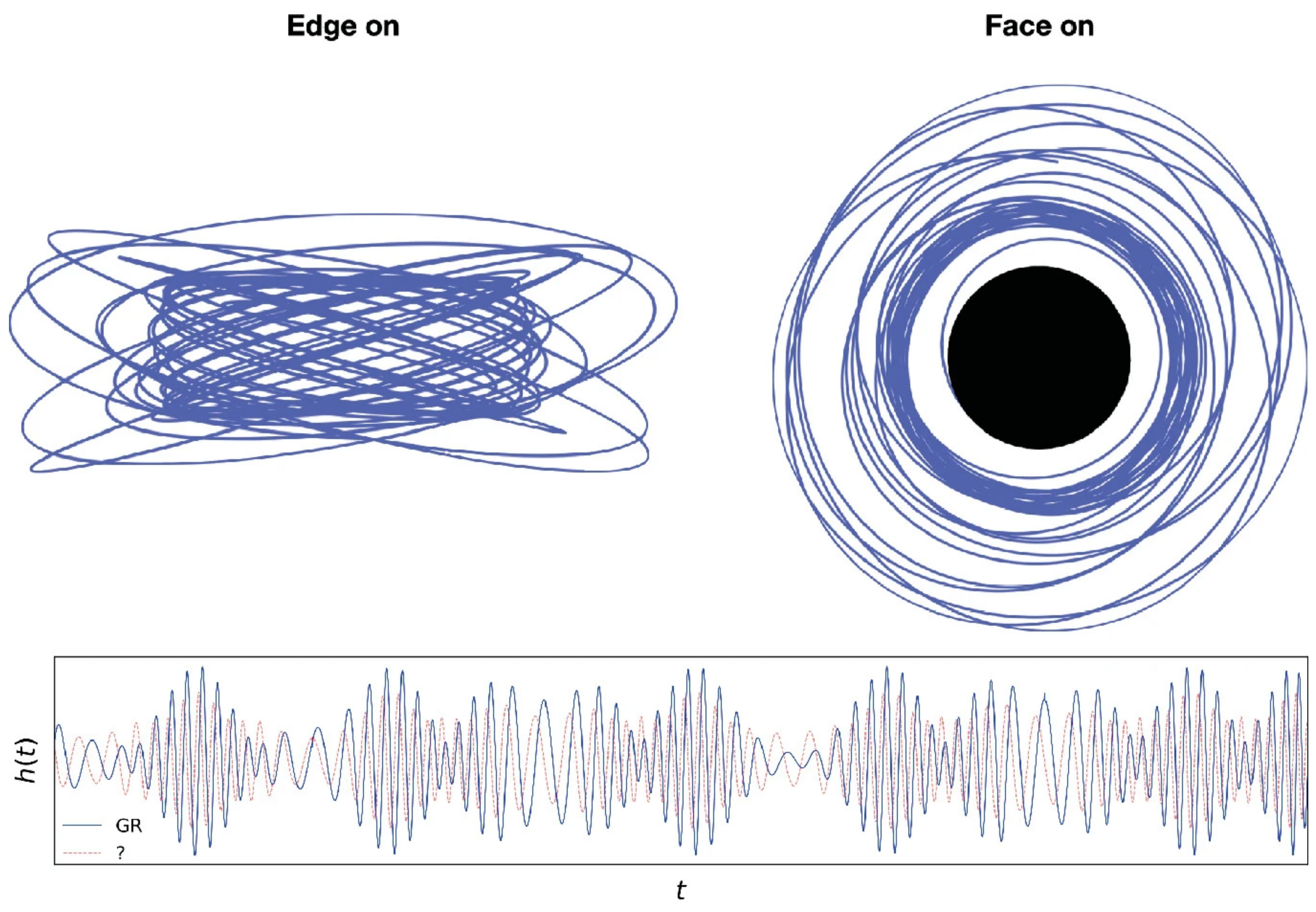
Different situation for XG detectors:

Gas effects in AGN disks observable by LISA or B-DECIGO
(and maybe ET, if very eccentric [Zwick *et al.*, 2511.04540]).

ET will be able to detect LoSA in dense hosts (e.g. AGN disks)

Long EMRIs turn tiny effects into measurable phase shifts

LISA will follow the phase of EMRIs over months to years (accumulating 10^{4-5} cycles)

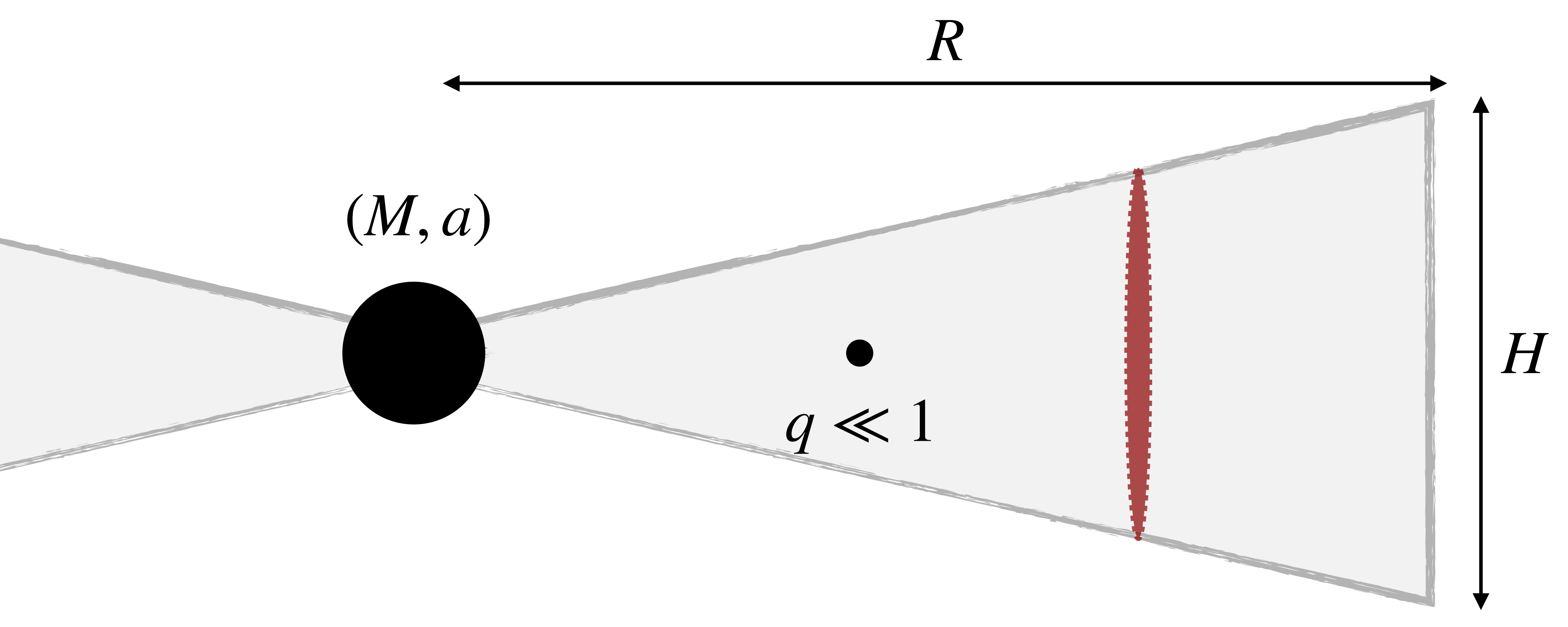


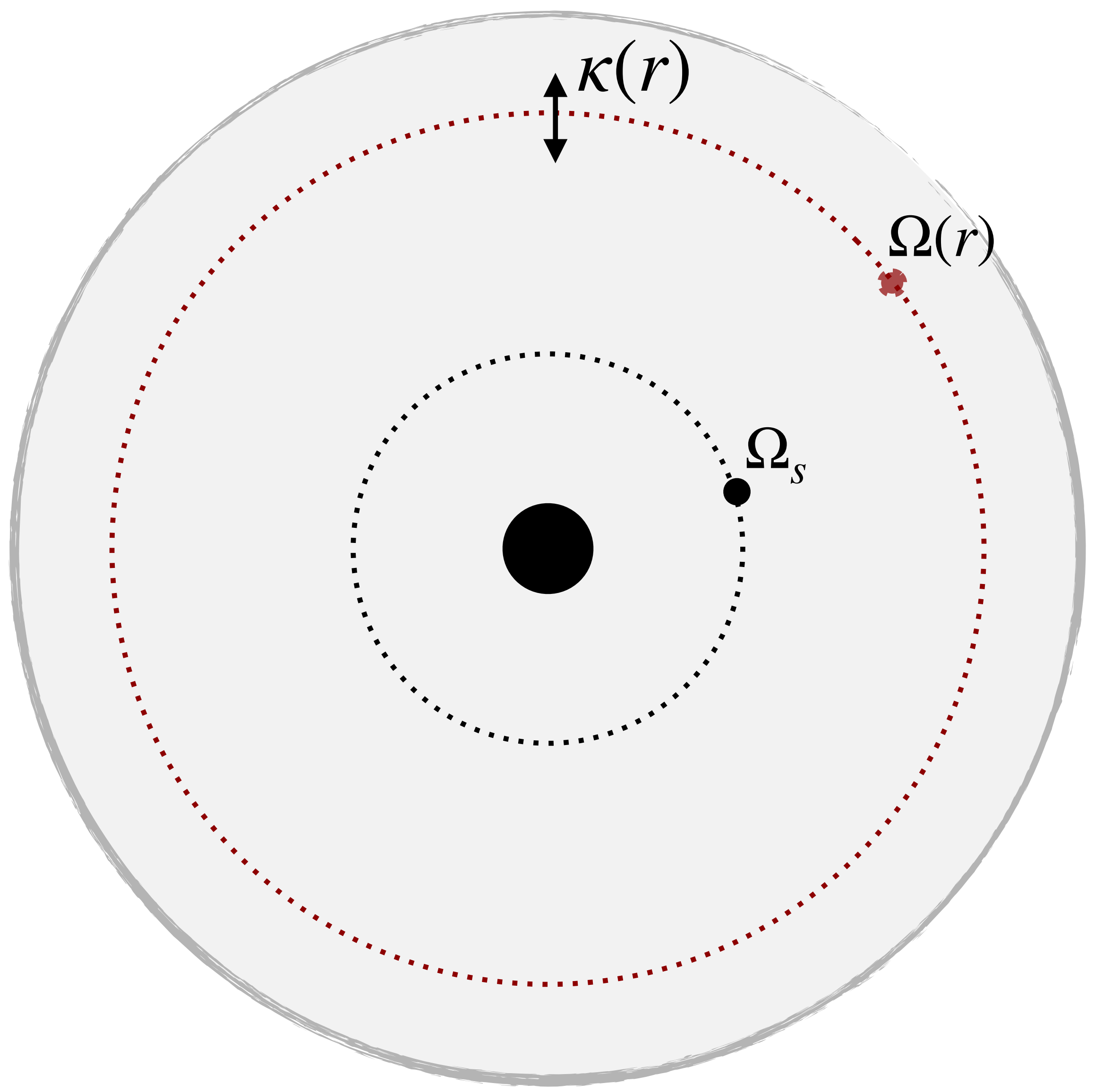
A. Cárdenas-Avendaño and C.F. Sopuerta [2401.08085]

Allows for a two-parameter expansion (on mass-ratio and an environmental parameter, such as density)

Disk torques from orbital resonances

An extreme-mass-ratio inspiral in a (pressureless) relativistic thin disk





C. Hirata [1010.0759] related the torque at each resonance to the asymptotic behaviour of solutions of the Teukolsky equation

Resonances in pressureless disks accumulate near the companion. Pressure effects lead to a physical cutoff!

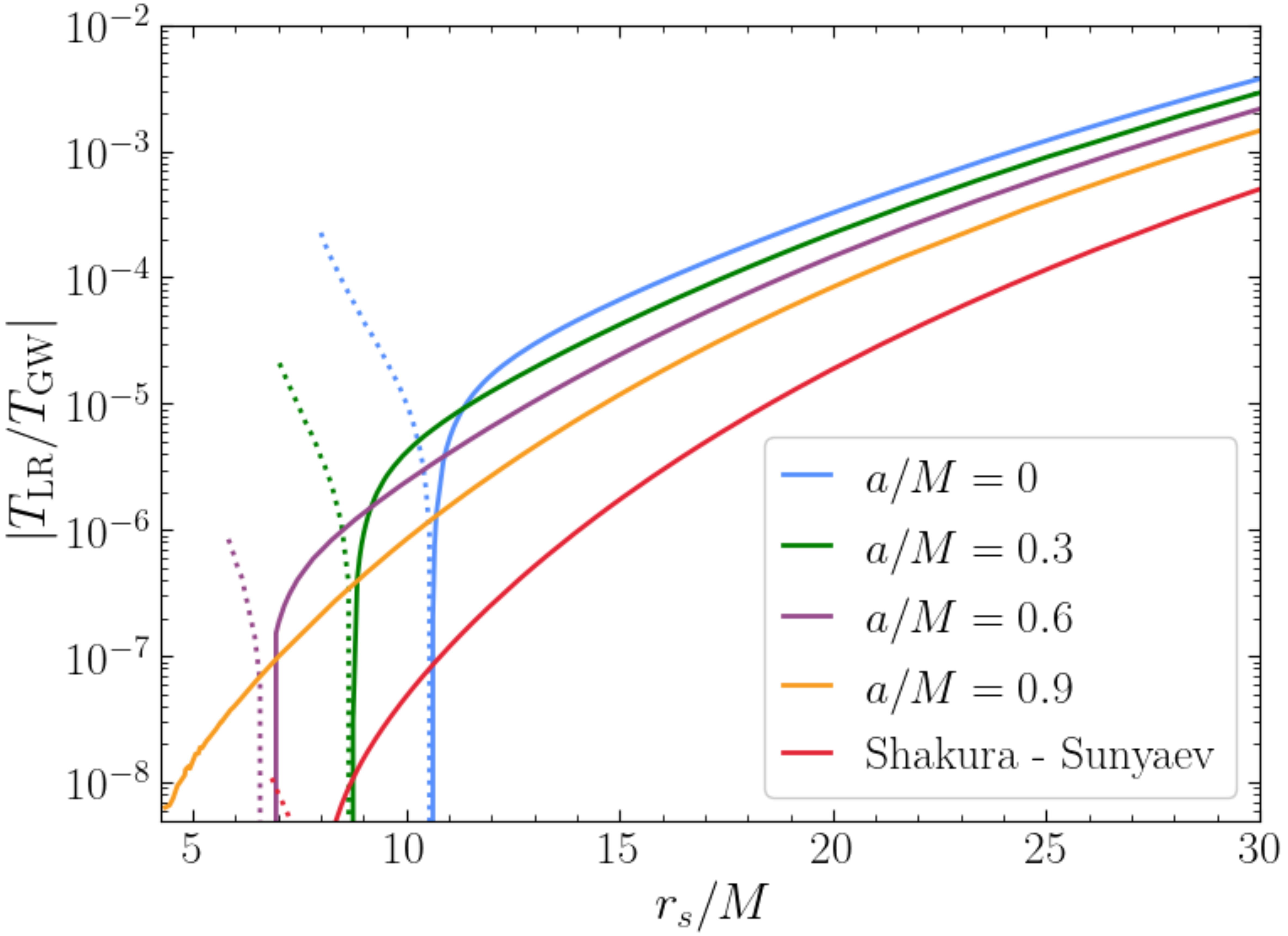
Resonances happen at discrete radii in the disk

$$D[r] := m(\Omega[r] - \Omega_s) \mp \kappa[r]\,, \quad m \in \mathbb{N}$$

Does general-relativistic corrections change the torque?

F. Duque, L. Sberna, A. Spiers, & **RV** [2510.02433]

Strong gravity can amplify (and even reverse) disk torques



Independent calculation agrees at percent level

Hegade, Gammie, Yunes [2510.03564]

First-principles pressure treatment is consistent, with detailed comparison ongoing

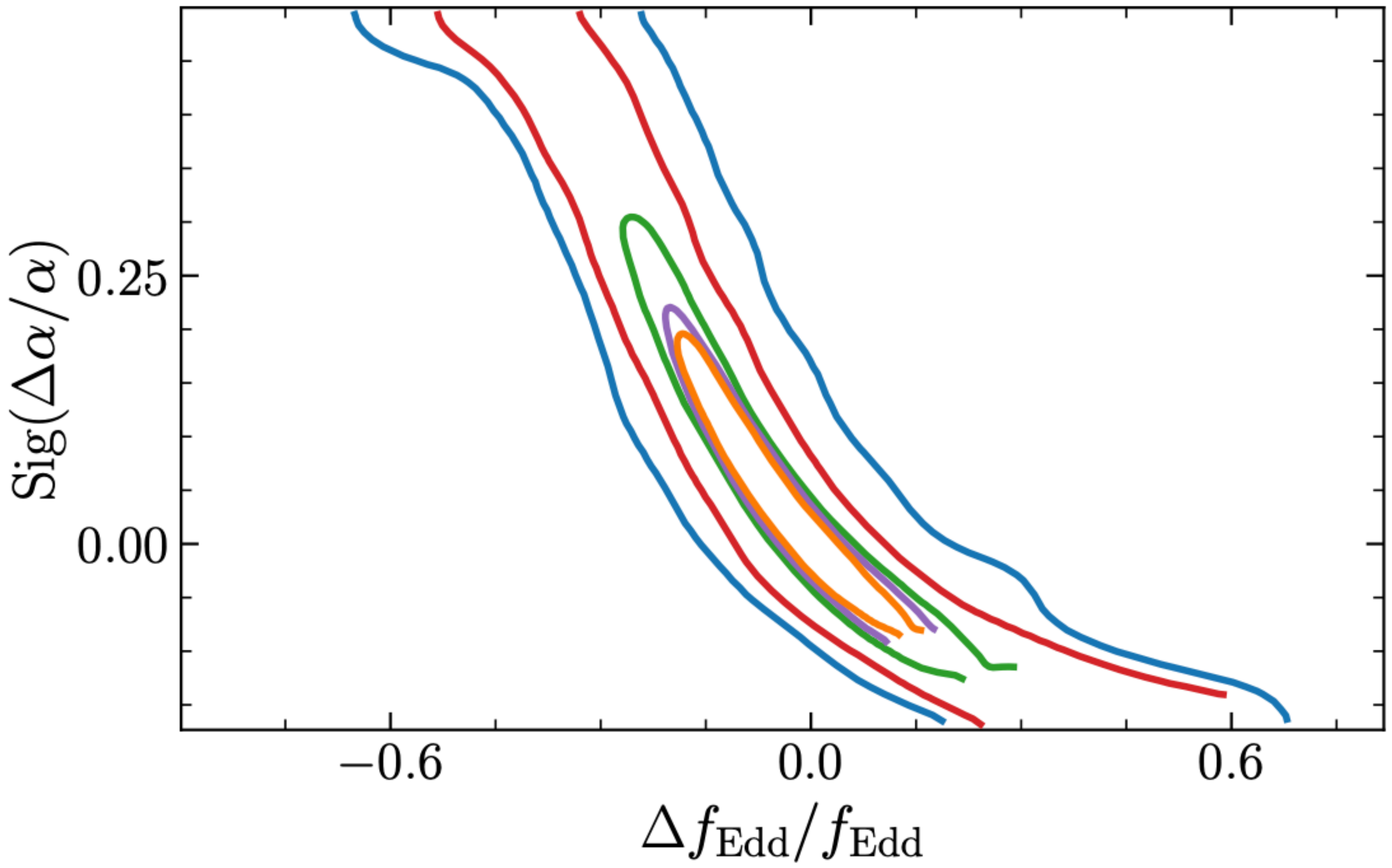
C. Dyson, D. D'Orazio [2601.19123]

Does this extra structure gives us more science?

F. Fantoccoli, F. Duque, & J. Gair [2606.12531]

Relativistic torques can turn an EMRI into an accretion-physics experiment

LISA EMRIs could probe accretion physics at (sub)micro-pc scales

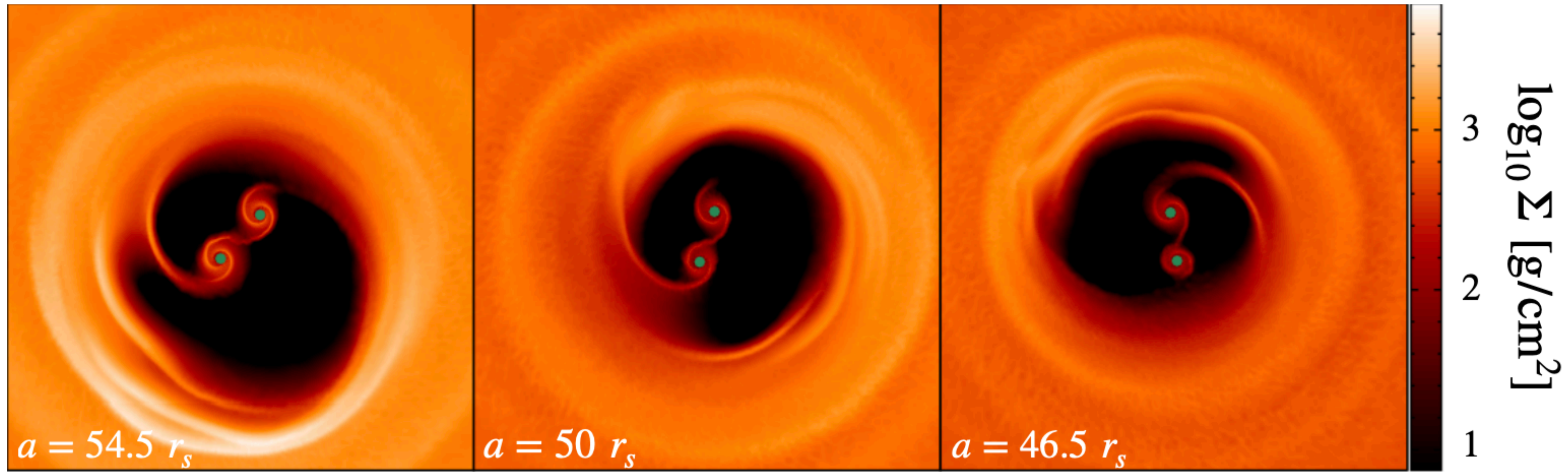


Applications to the understanding of how MBH grow and for EMRI dark siren cosmology (by helping identify host galaxy)

Unmodelled disk torques can look like new gravitational physics

M. Garg, A. Franchini, A. Lupi, M. Bonetti, & L. Mayer [2410.17305]

M. Garg, A. Franchini, & A. Lupi [2606.20787]



3D hydro live simulations of massive BH binaries in circumbinary disks show dephasing possibly observable by LISA

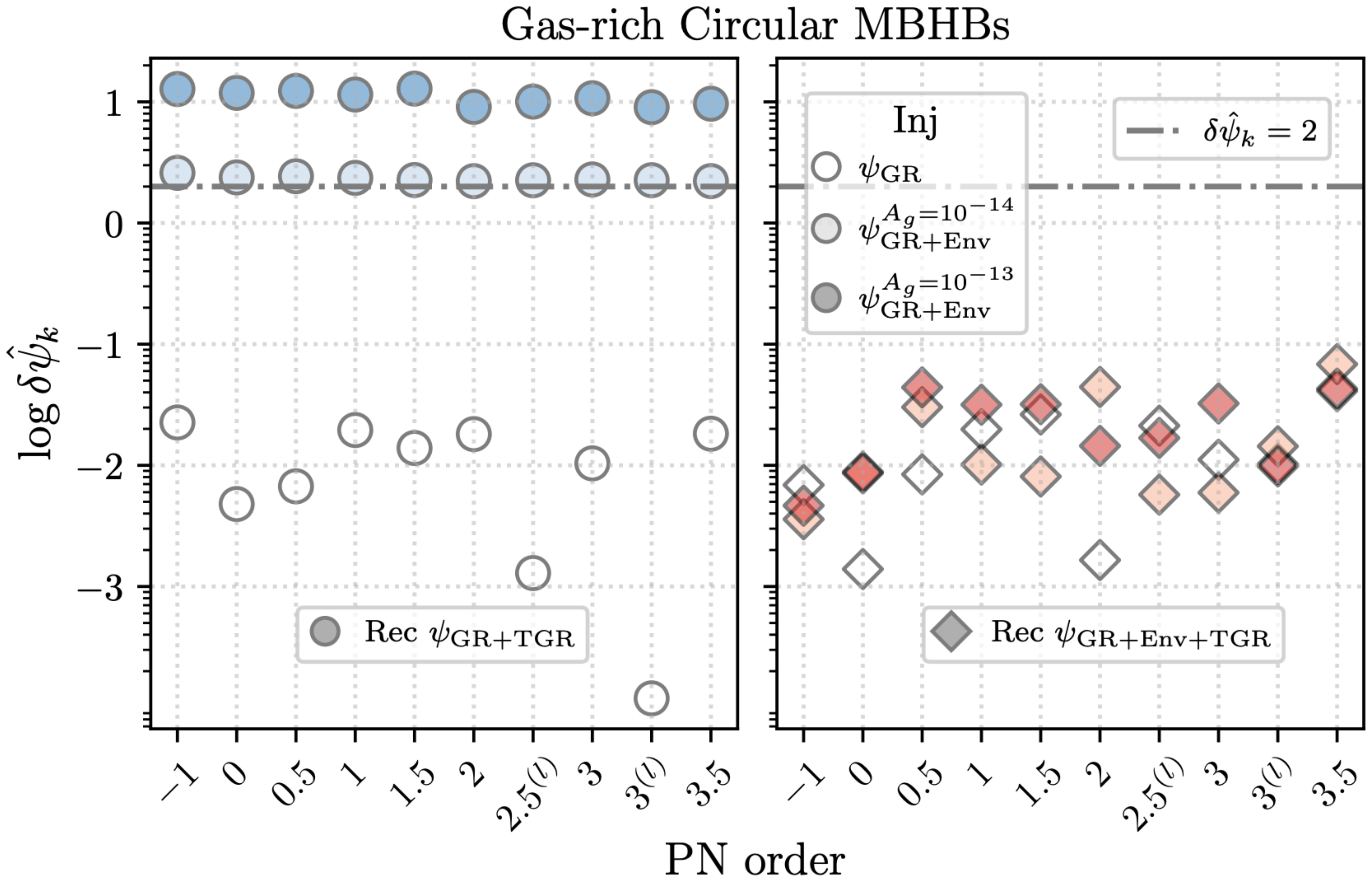
At leading order the disk torques appear at -4 PN

Adiabatic approximation might not be valid for these systems…

Then how can we model these systems?

[with P. Moesta, L. Krauth, B. Slootmaekers, E. Vira, & J. Navis]

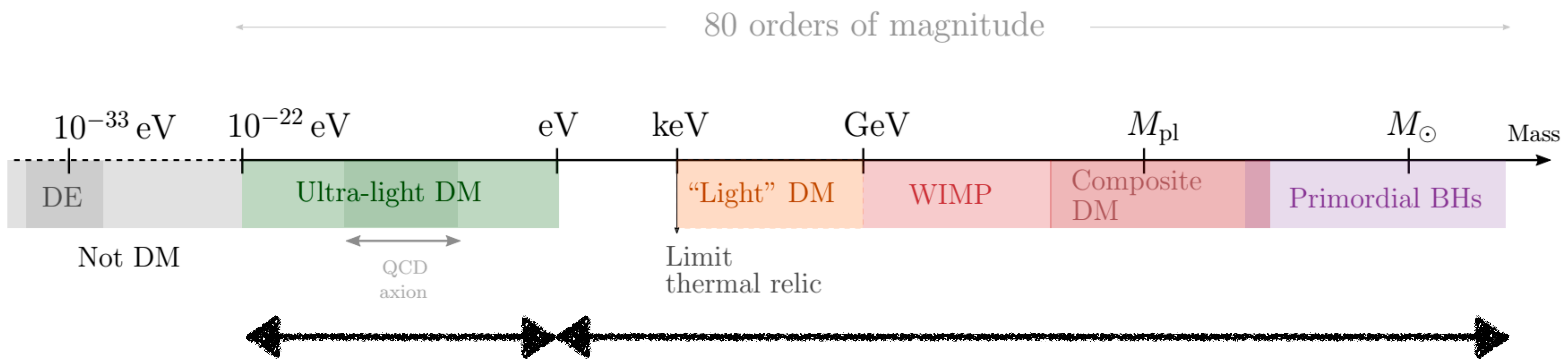
M. Garg, L. Sberna, L. Speri, F. Duque, & J. Gair [2410.02910]



Similar to our results injecting NR waveforms in dense gaseous environments [S. Roy & **RV** [2410.16388]]

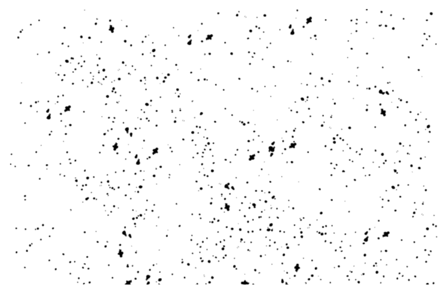
What is dark matter?

The astonishing 80 orders of magnitude of ignorance



Wave

Particle

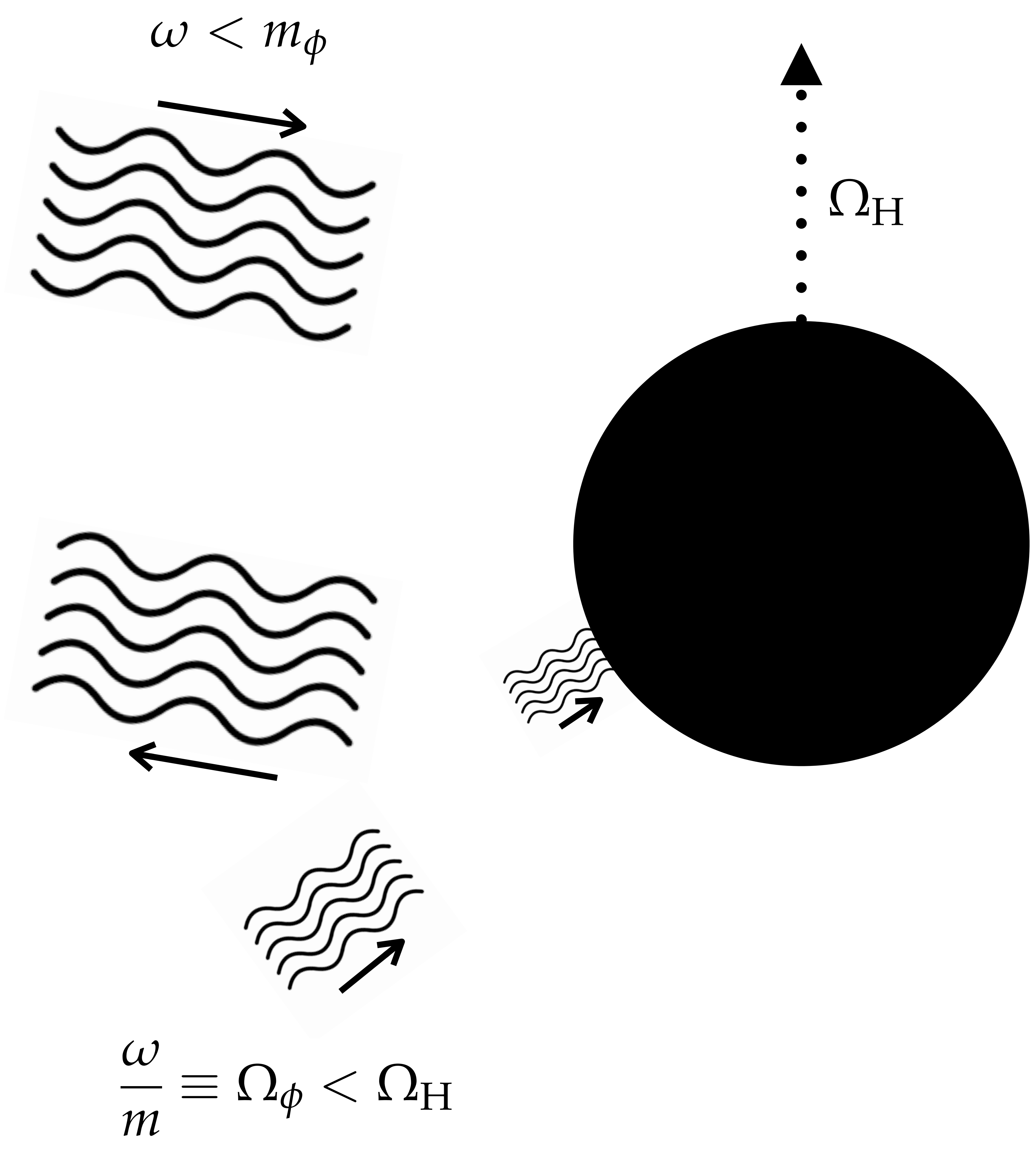


Ultralight bosons are ***Wavy*** at macroscopic scales
(axion-like particles, dark photon, ...)

$$\lambda_{\rm dB} = \frac{2\pi}{m_\phi v}$$

$$L \lesssim \lambda_{\rm dB} \implies m_\phi \lesssim 30\,\text{eV}$$

Superradiance can build **dense and predictive** boson clouds



Instability efficient at wavelength matching:

$$\alpha \equiv \frac{GM\mu}{\hbar c} = \frac{r_g}{\lambda_C} \lesssim 1$$

Superradiant growth and saturation:

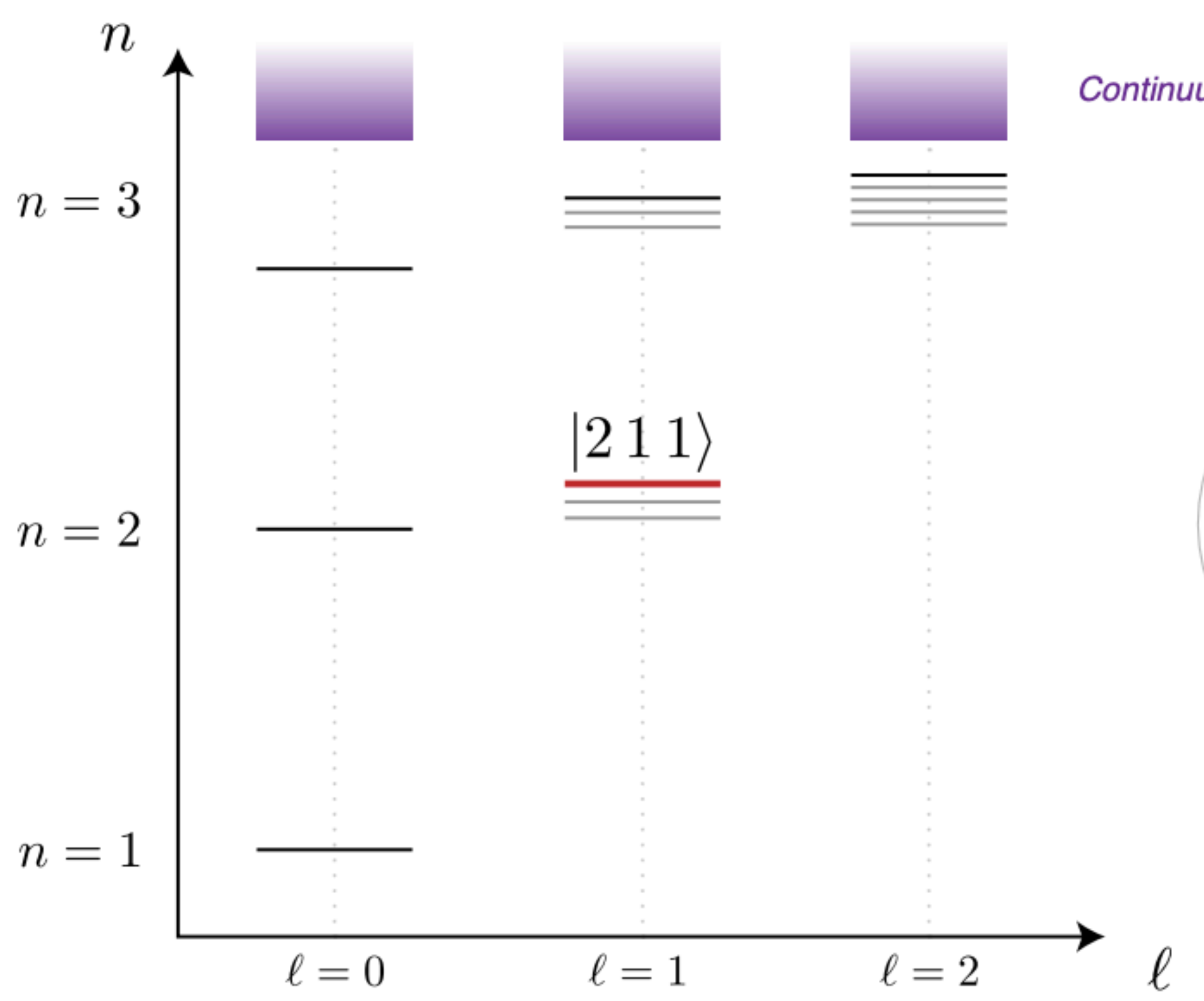
$$\Omega_c \equiv \frac{\omega}{m} < \Omega_H \quad \longrightarrow \quad \Omega_c \simeq \Omega_H \text{ at saturation}$$

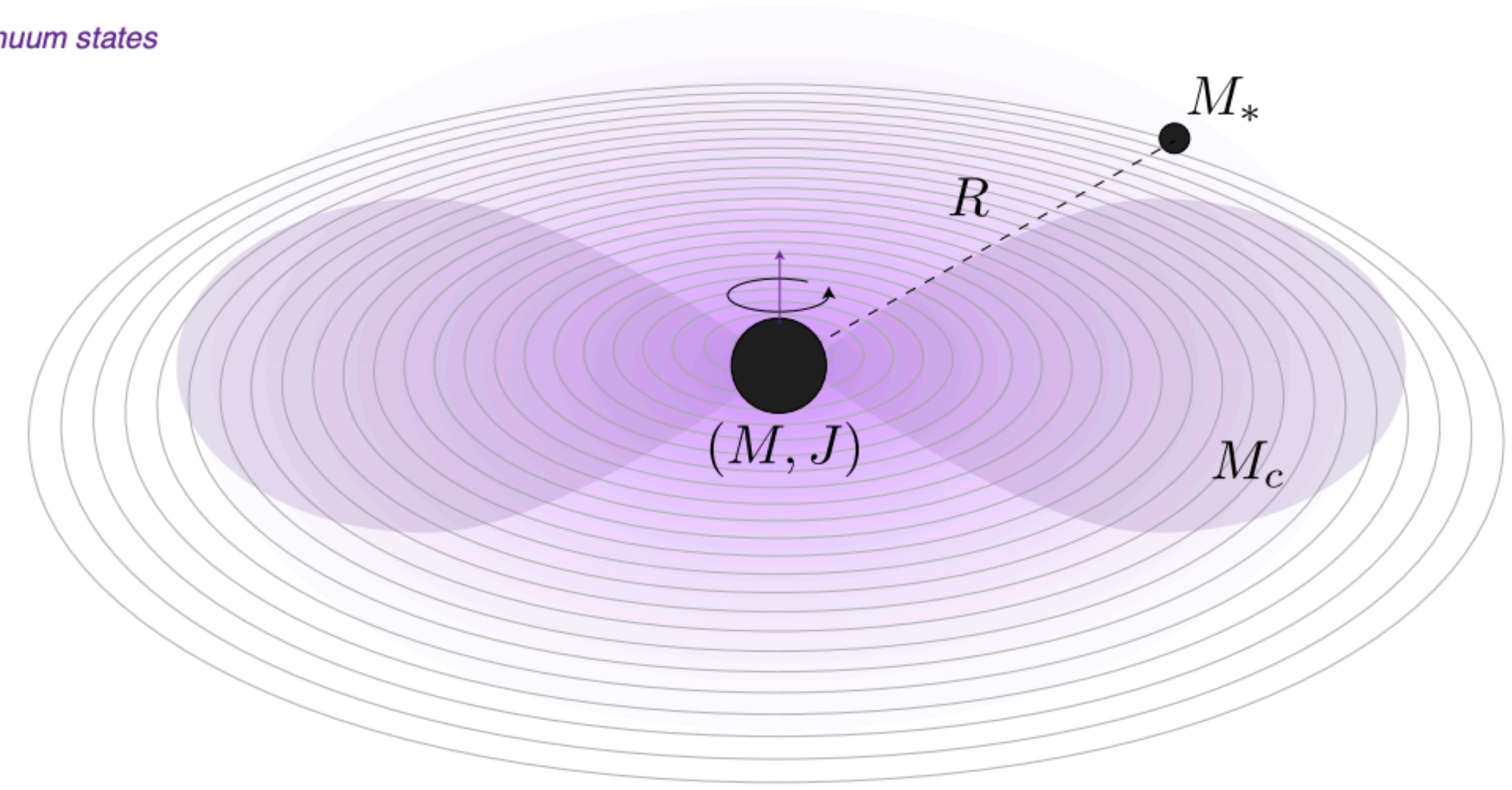
Cloud size and characteristic density:

$$r_c \sim \frac{r_g}{\alpha^2}, \qquad \frac{M_c}{M} \lesssim \mathcal{O}(\alpha) \quad \Longrightarrow \quad \bar{\rho}_c \propto \frac{\alpha^7}{M^2}$$

$$\bar{\rho}_c \lesssim 10^8\,\mathrm{g\,cm^{-3}} \left(\frac{\alpha}{0.1}\right)^7 \left(\frac{10 M_\odot}{M}\right)^2$$

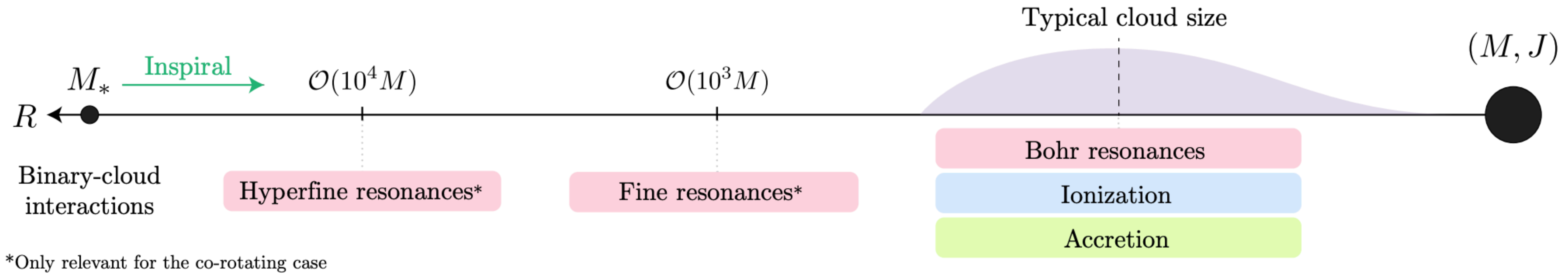
A companion drives transitions (and may eventually disrupt the cloud)





(ratio of companion's tidal field to cloud's binding energy)

$$\epsilon \equiv q \frac{r_\phi}{\max(r_\phi, r_*)} \ll 1$$



Expansion breaks in late inspiral of close-to-equal mass binaries!

R. Della Monica & R. Brito (2025)

A simple angular-momentum model captures the dominant backreaction

Multipole expansion of binary's gravitational field:

$$U \approx \sum_{\ell_\star, m_\star} \frac{4\pi\bar{\lambda}M}{2\ell_\star + 1} Y^*_{\ell_\star m_\star}\left(\theta_{2\star}, \varphi_{2\star}\right) Y_{\ell_\star m_\star}\left(\theta, \varphi\right) \mathscr{F}_{\ell_\star}\left(r, r_{2\star}\right)$$

$$\mathscr{F}_{\ell_\star} \propto \beta^{\ell_\star + 1}$$

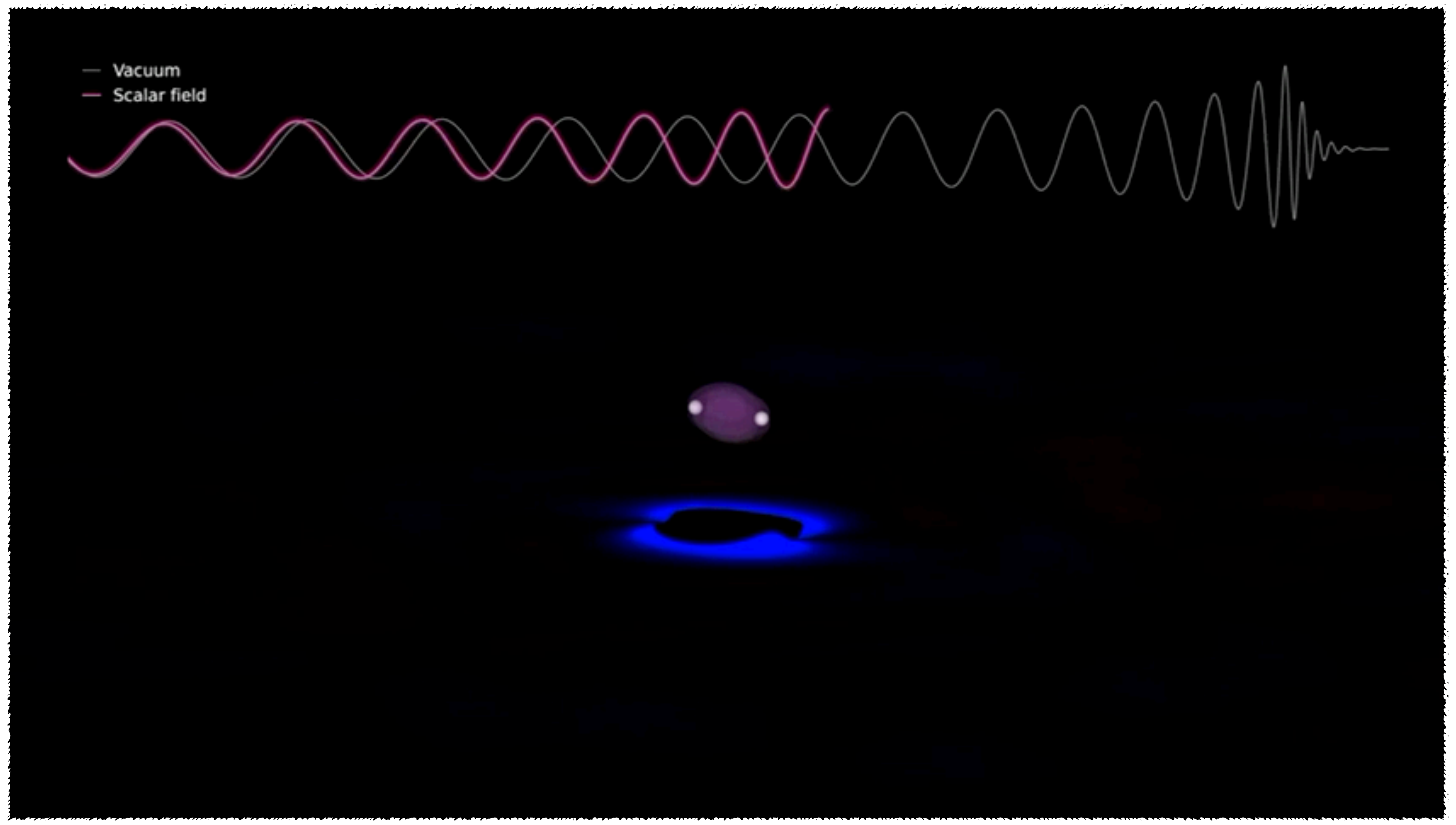
We do a perturbative treatment in $\beta \equiv \frac{R}{r_\phi} \ll 1$

For LVK sources, we have:

$$\beta \sim 0.1 \left(\frac{\alpha}{0.1}\right)^2 \left[\frac{100\,\mathrm{Hz}}{f} \frac{20 M_\odot}{M}\right]^{2/3}$$

Orbital effects found from angular momentum conservation:

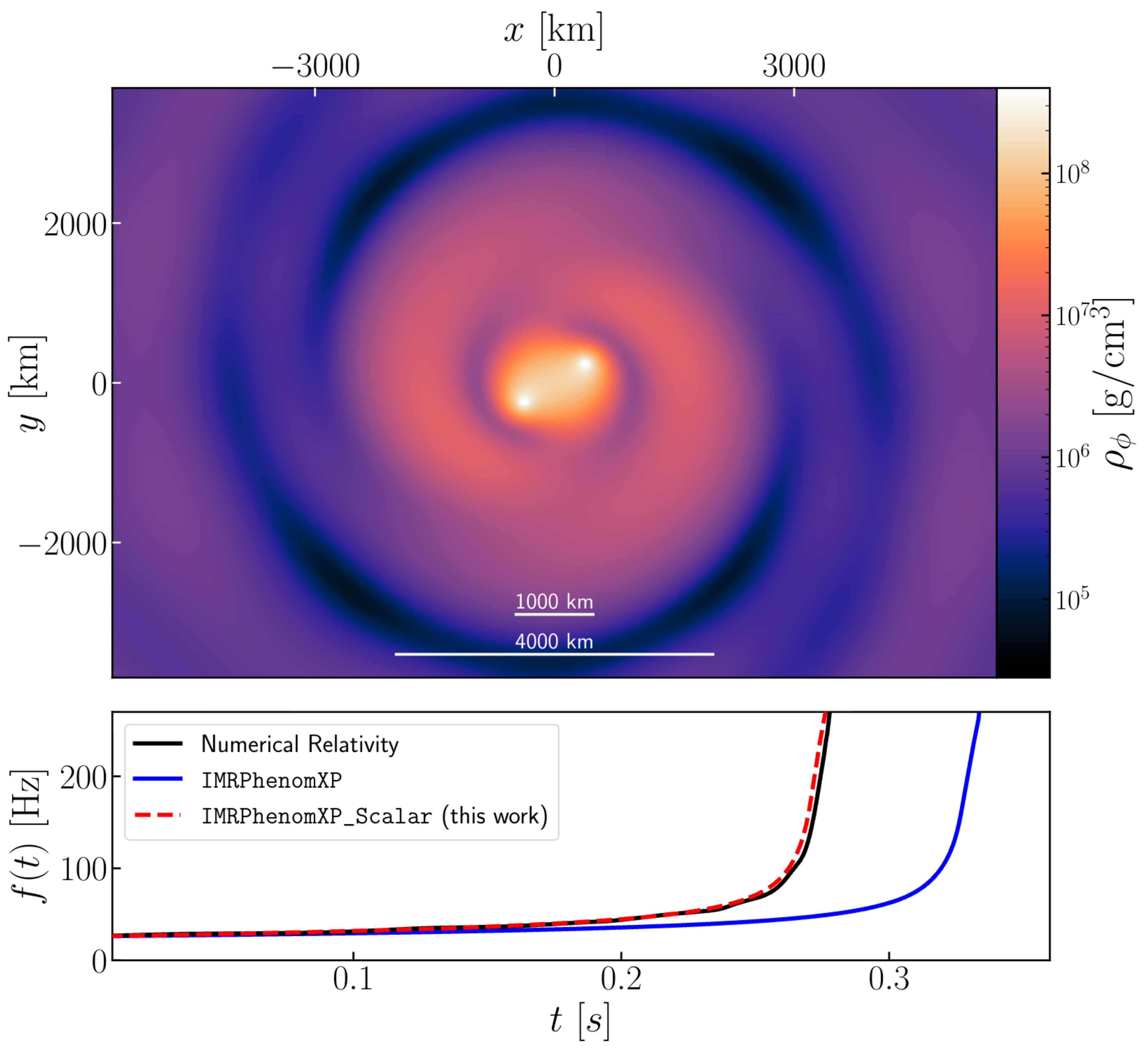
$$\frac{\dot{L}_\phi}{M} \approx -4\pi\bar{\rho}_\phi M^2 \frac{\mathcal{I}(v, \alpha, q)}{v^4}$$

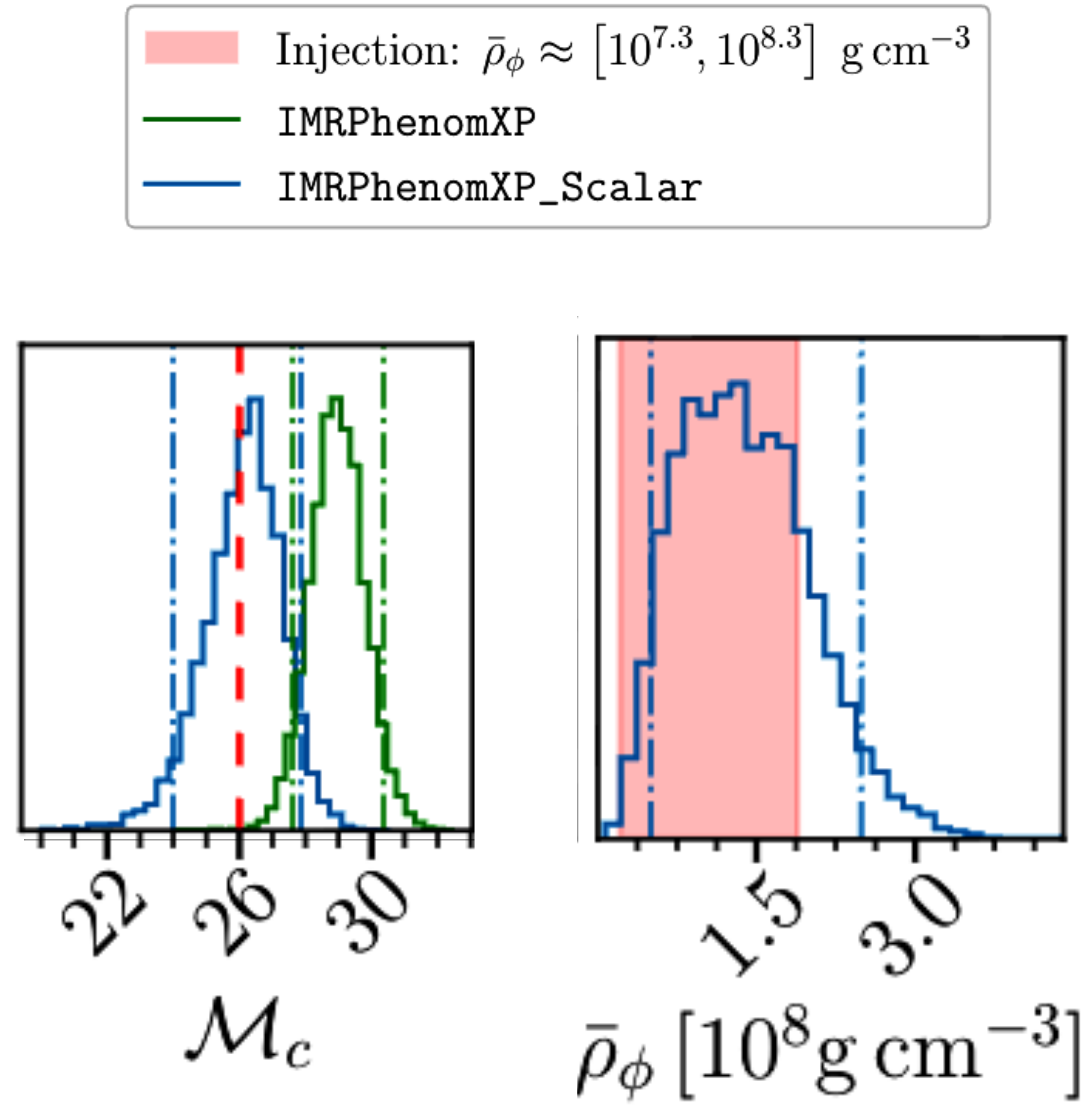


Roy, **RV,** Aurrekoetxea, Clough, Ferreira [PRL, 2510.17967]

S. Roy, **RV,** J. Aurrekoetxea, K. Clough, P. Ferreira [PRL, 2510.17967]

A simple cloud model survives a numerical-relativity test

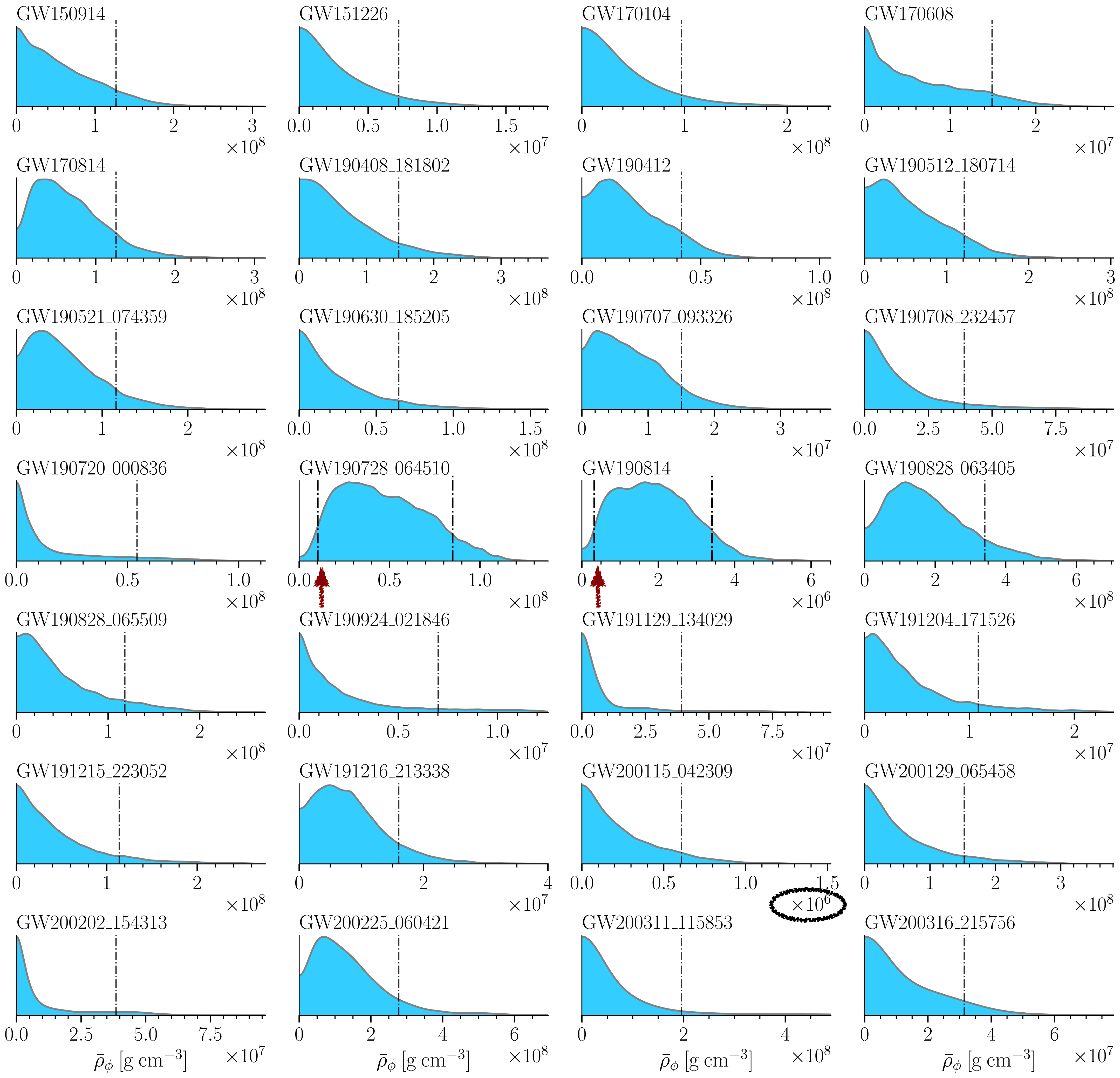




IMRPhenomXP_Scalar can recover the true binary parameters and estimate the scalar field local density

S. Roy, **RV,** J. Aurrekoetxea, K. Clough, P. Ferreira [PRL, 2510.17967]

A first search across 28 GW events found two outliers



Selection criteria:

FAR $< 10^{-3}\,\mathrm{yr}^{-1}$

inspiral SNR > 6

28 events analysed

Most bounds are smaller than the densities of saturated superradiant boson clouds

GW190728 & GW190814:
vacuum is outside 90% credible interval!

S. Roy, **RV,** J. Aurrekoetxea, K. Clough, P. Ferreira [PRL, 2510.17967]

Superradiant priors remove GW190814… but not GW190728!

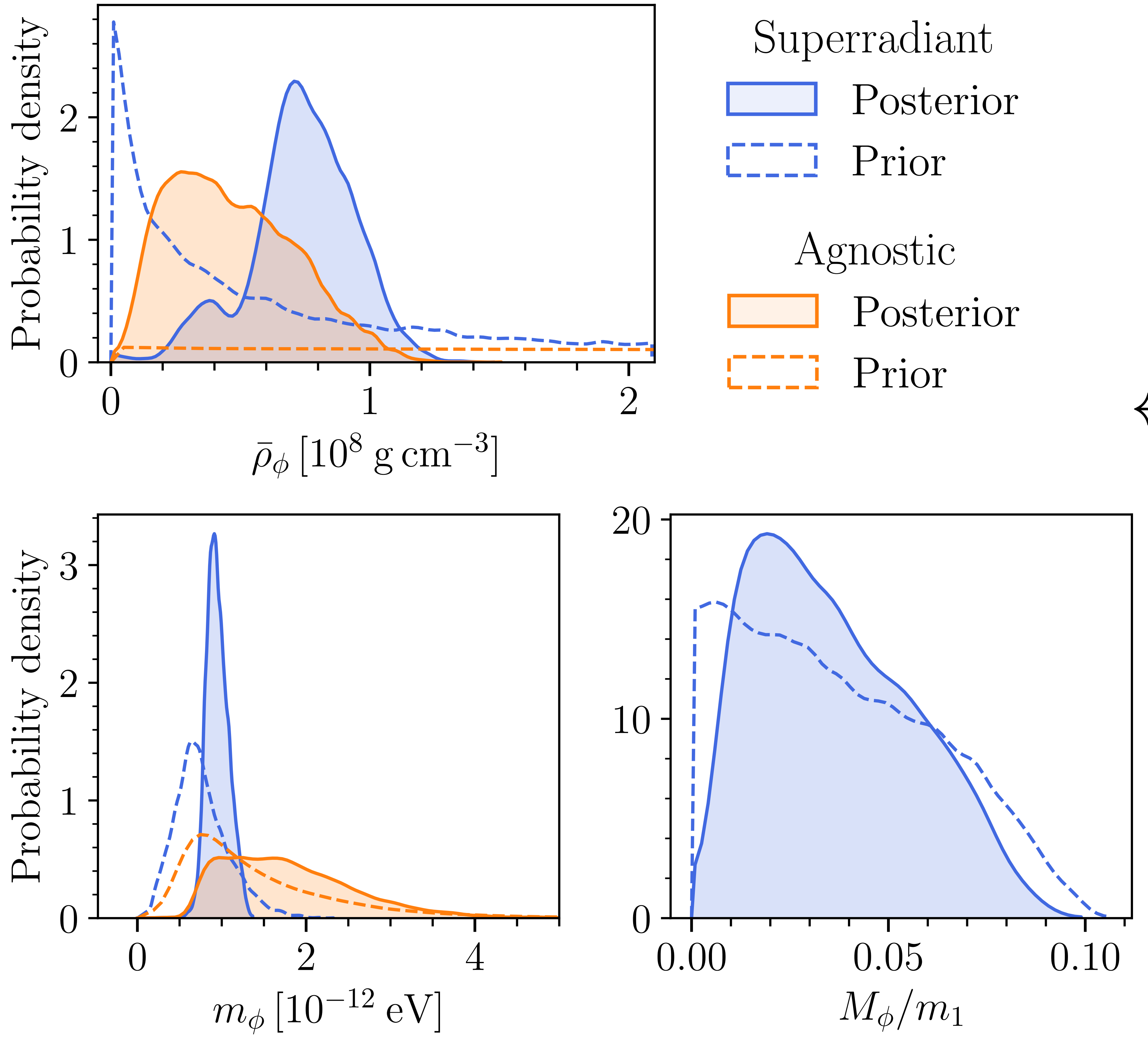
***Superradiant Scalar* priors:**

1. Must have time to grow around the **primary**

2. Must not have decay away before merger

3. Mass is bounded by **rotational energy extracted**

GW190814 shows no evidence for superradiant scalars.
But… GW190728 shows **tentative** evidence!



$\leftarrow \tau_\mathrm{d} = 10^6$ yrs

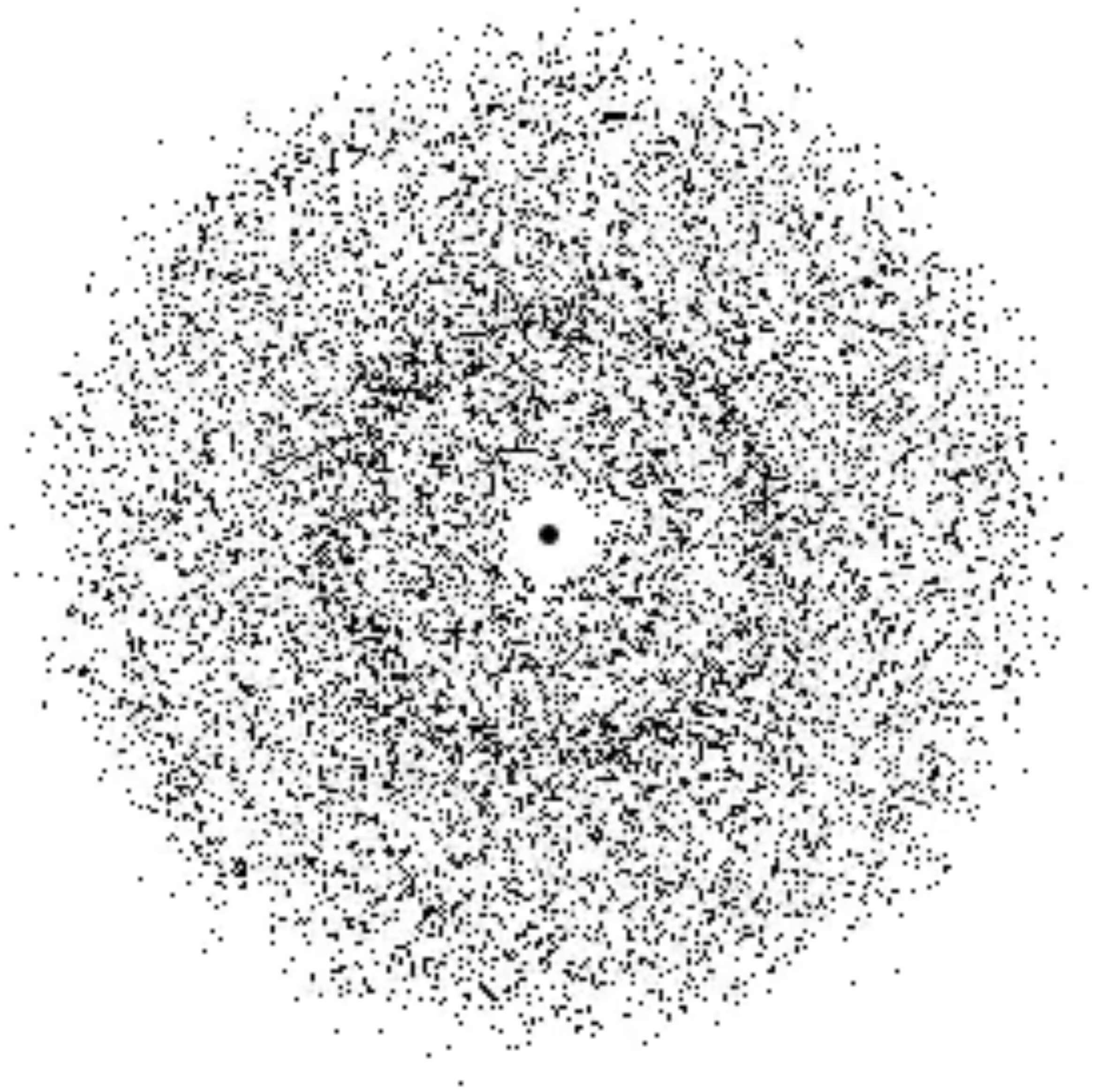
$$\ln \mathcal{B}^{\rm env}_{\rm vac} \approx (3.4, 3.5, 3.5, 2.8) \;\; \text{for} \;\; \tau_\mathrm{d}[\text{yrs}] = (10^5, 10^6, 10^7, 10^8)$$

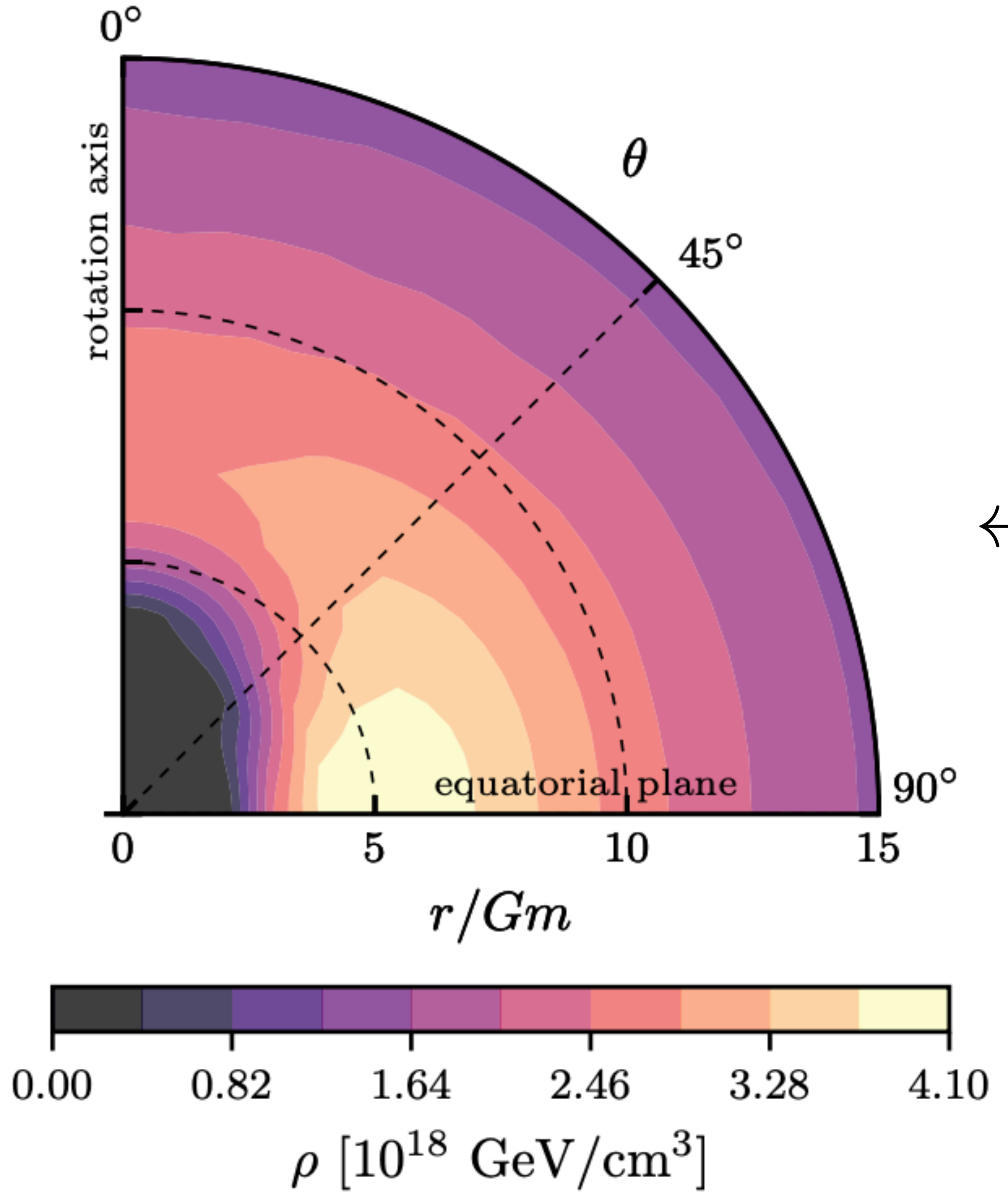
P. Gondolo & J. Silk [PRL, 9906391]
L. Sadeghian, F. Ferrer, & C.M. Will [1305.2619]
F. Ferrer, A.M. da Rosa, & C.M. Will [1707.06302]

MBH growth can create steep dark matter spikes

Adiabatic contraction of a cold and collisionless dark matter halo

$$\oint \mathrm{d}\varphi \, p_\varphi = 2\pi \, p_\varphi = \text{const} \qquad \oint \mathrm{d}\theta \, p_\theta = \text{const} \qquad \oint \mathrm{d}r \, p_r = \text{const}$$



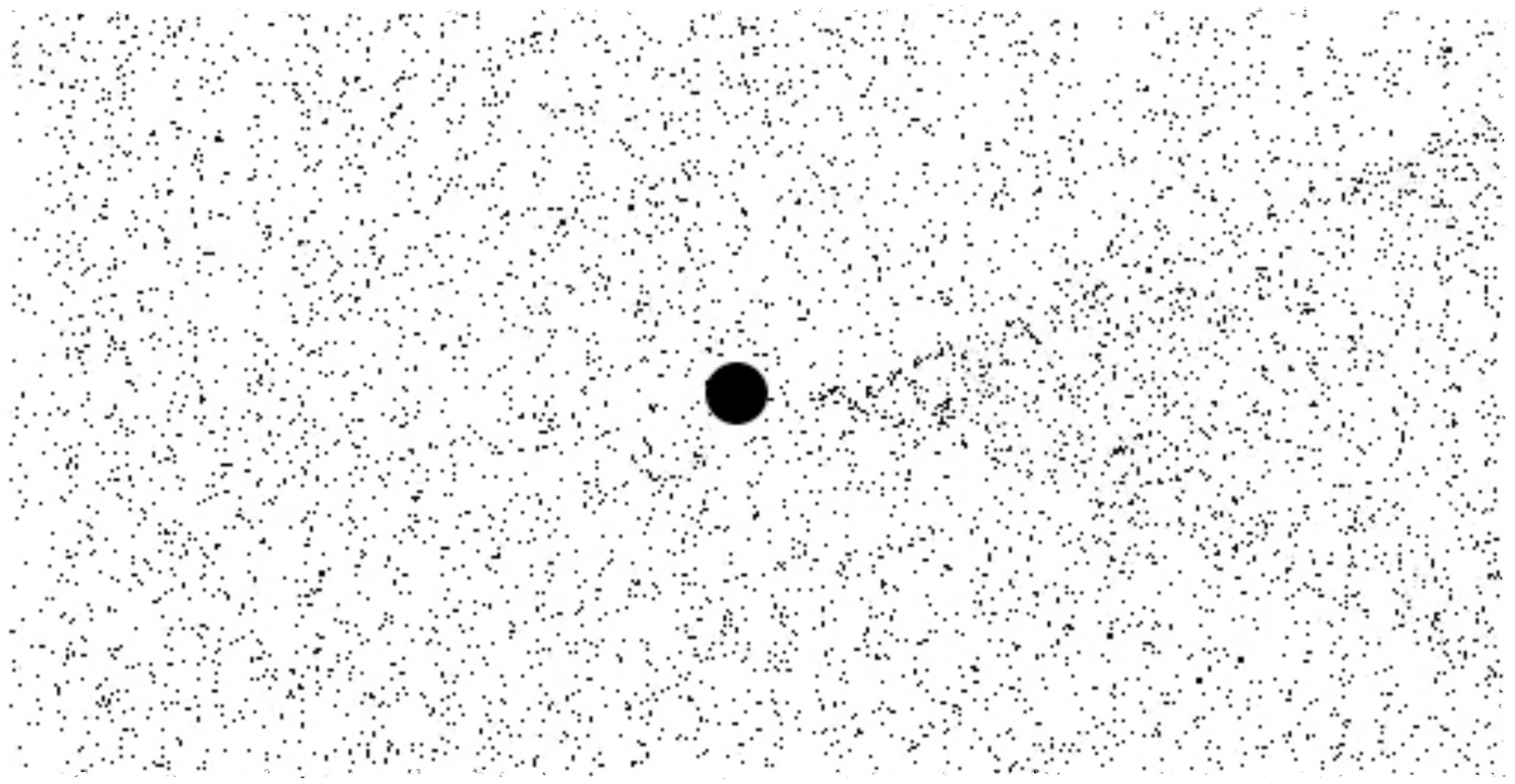


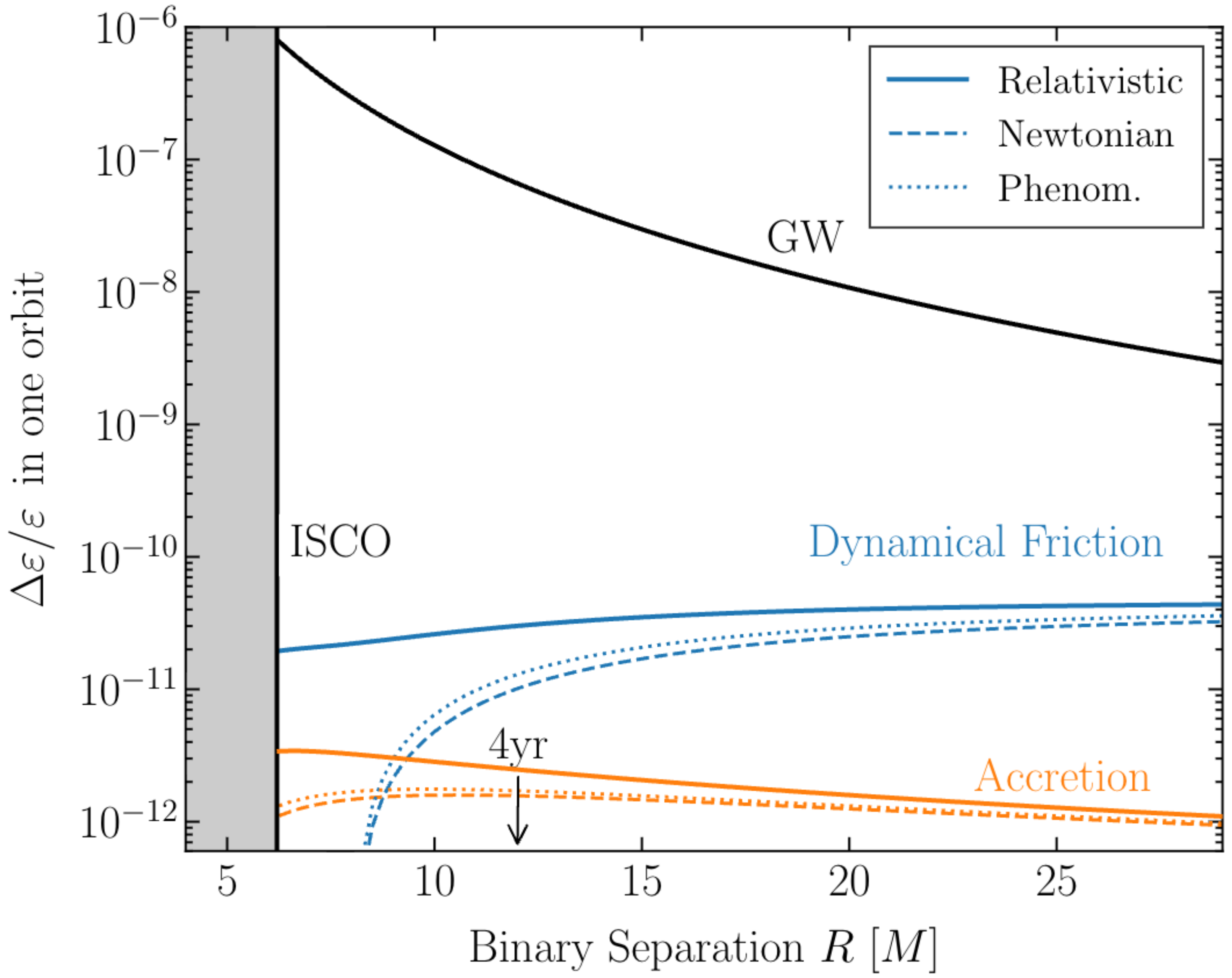
$\leftarrow \tilde{a} = 0.8$

How dark matter spikes imprint on EMRIs

Relativistic effects are crucial to accurately model EMRIs

$$\boldsymbol{a} = \frac{1}{m}\int \frac{\mathrm{d}N}{\mathrm{d}V\,\mathrm{d}^3v^i}\, v\left[\sigma_{\rm acc}(v) + \sigma_{\rm scat}(v)\right]\boldsymbol{p}_\perp\,\mathrm{d}^3v^i$$





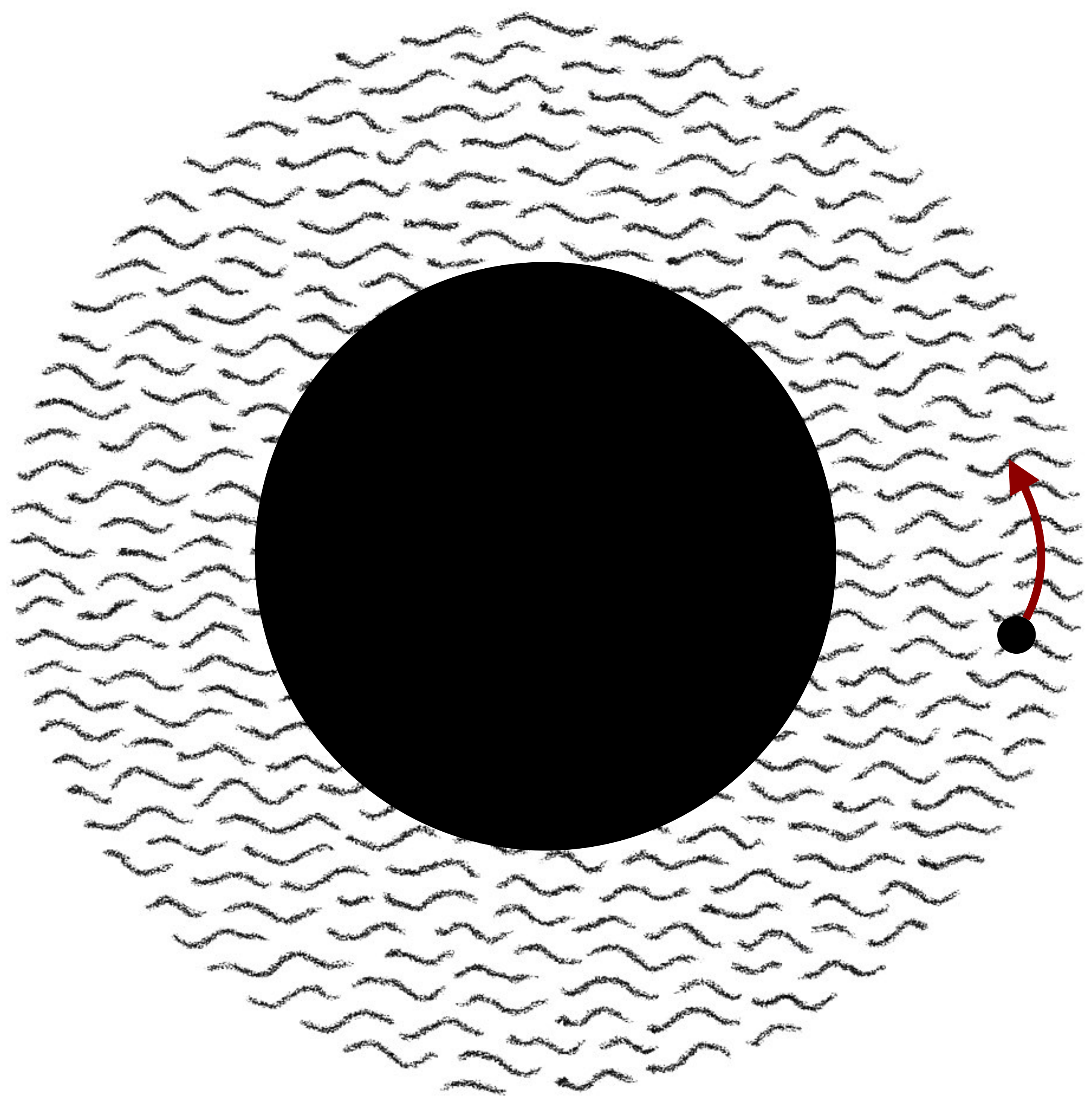
Waveforms are distinguishable in a couple of weeks! But could we learn something about the **nature of dark matter**?

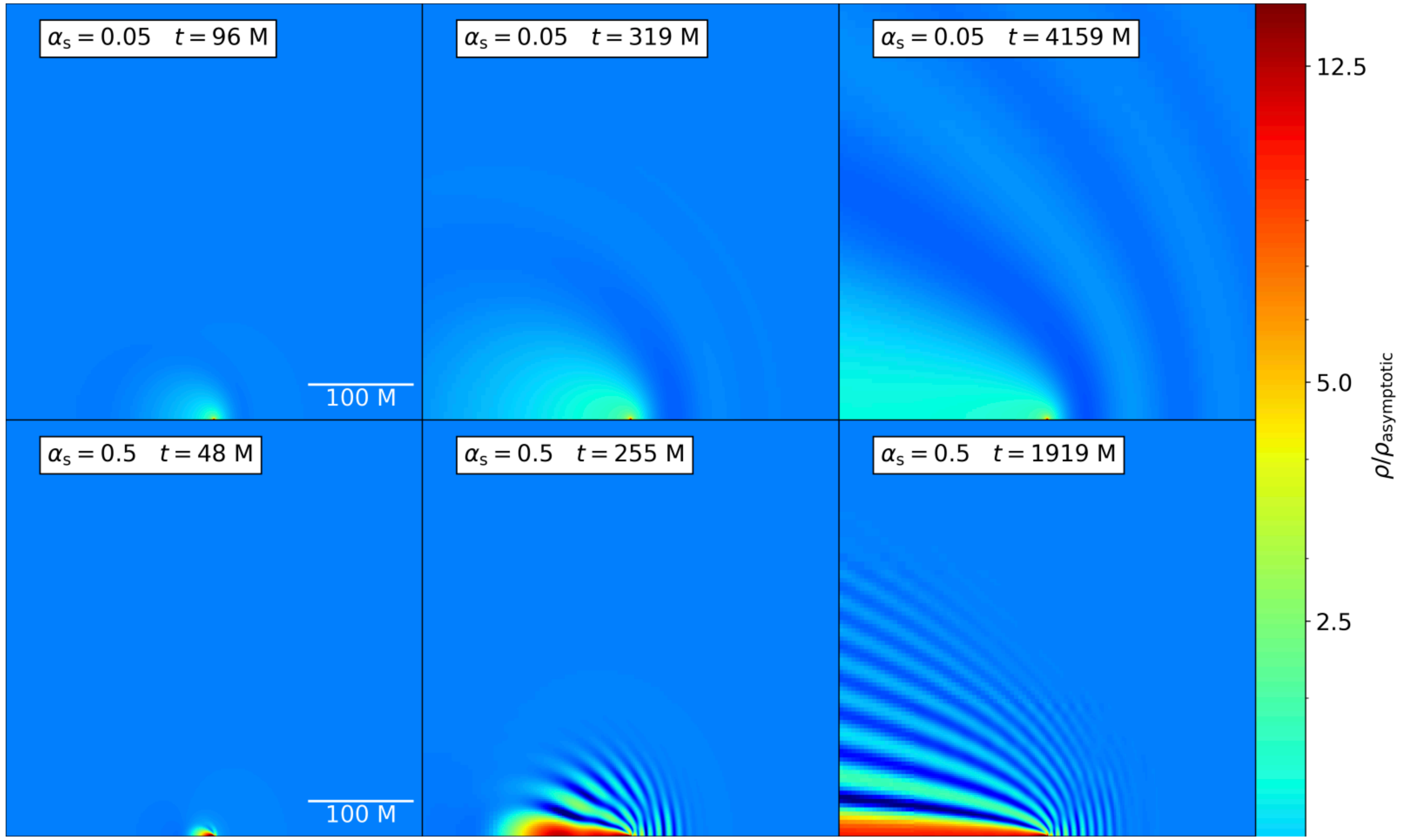
EMRIs and the Particle-Wave duality

RV, V. Cardoso [2201.08854]

D. Traykova, K. Clough, T. Helfer, E. Berti, P.G. Ferreira, L. Hui [2106.08280]

D. Traykova, **RV**, K. Clough, T. Helfer, E. Berti, P.G. Ferreira, L. Hui [2305.10492]

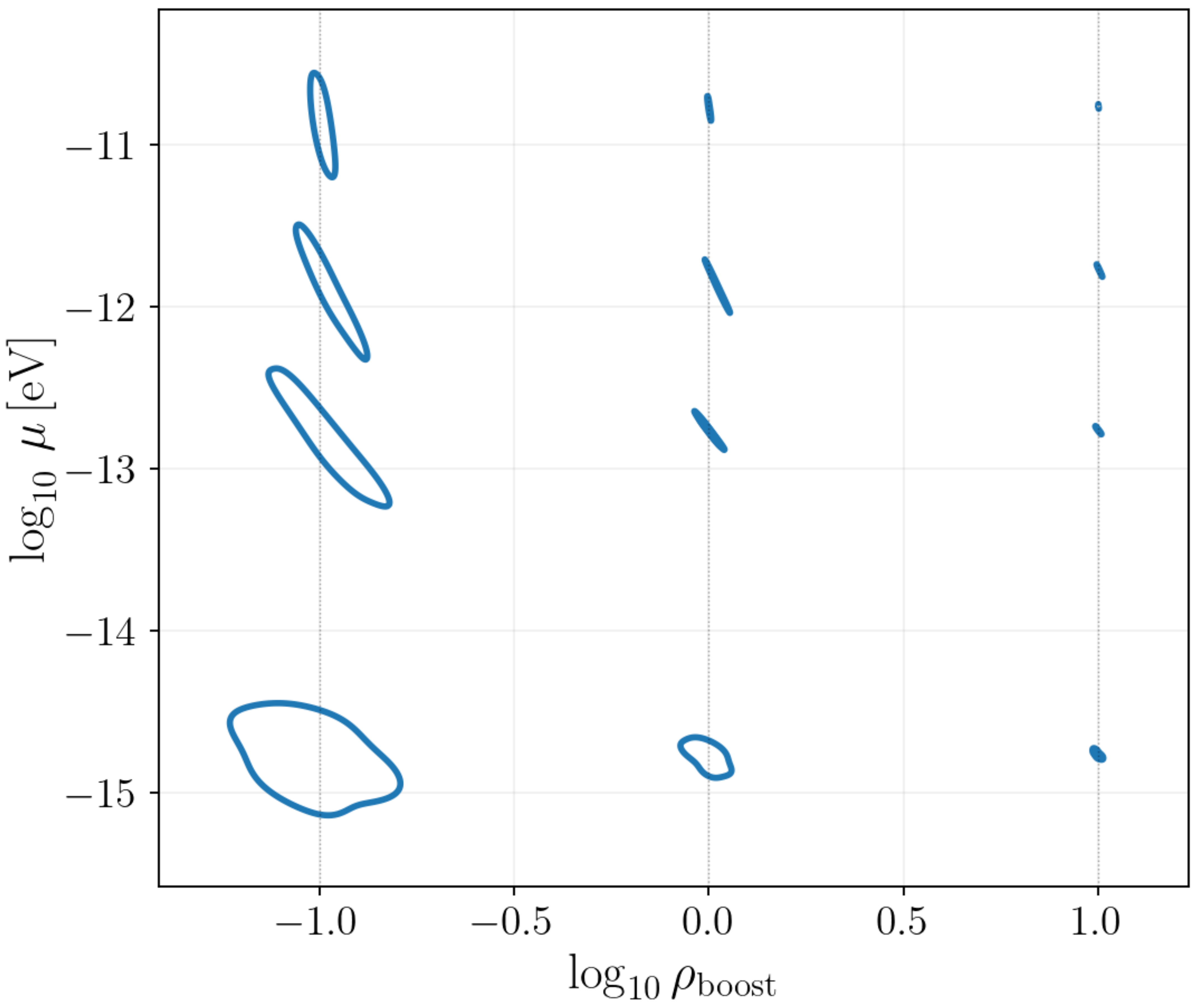




$\sigma_{\rm acc}(v, \alpha)$ $\sigma_{\rm scat}(v, \alpha)$

RV, F. Duque, T. Karydas, G. Bertone [in progress]

LISA EMRIs could weigh wave-like dark matter



Summary

Many studies are showing a strong case for including environmental effects in waveform modelling (with application from accretion physics to dark matter)

These are all (probably) optimistic:

They assume we know how to accurately model these effects

<u>But the risks are there:</u>

If environmental effects are detectable but unmodelled, they will lead to systematics!