From regular black holes to horizonless objects: quasinormal modes, instabilities and spectroscopy

SISSA

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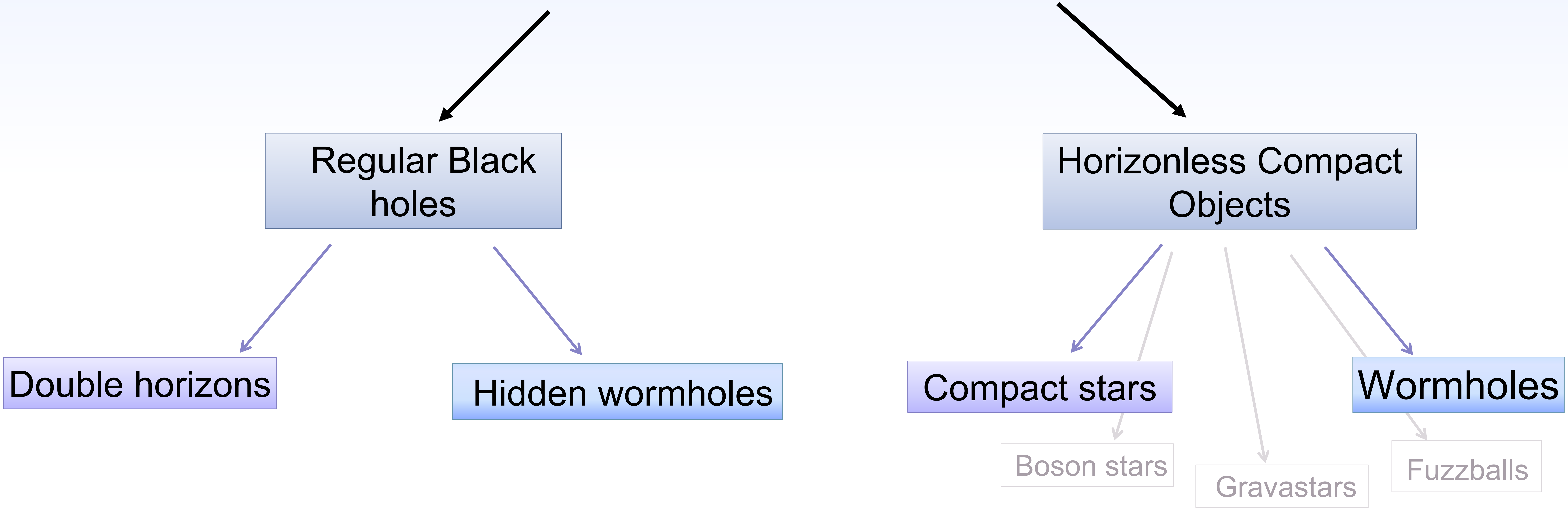
Black holes Mimickers

In a complete theory of **quantum gravity** we expect **spacetime singularities to be regularized**

There are basically two possible **alternatives to singular black holes** to describe the ultra-compact objects that we see in the sky



*we are considering spherical symmetric objects

Two families of (spherically symmetric) Black holes Mimickers

both can interpolate between the two alternatives*

$$ds^2 = -e^{-2\phi(r)} f(r)\,dt^2 + \frac{dr^2}{f(r)} + r^2\left(d\theta^2 + \sin^2\theta\, d\varphi^2\right), \quad f(r) = 1 - \frac{2m(r)}{r}.$$

From Double horizons to Compact stars (varyng ℓ)

$$\phi(r) = 0$$

and

$$m(r) = M\frac{r^3}{r^3 + 2M\,\ell^2} \quad \text{(Hayward metric)}$$

or

$$m(r) = M\frac{r^3}{(r^2 + \ell^2)^{3/2}} \quad \text{(Bardeen metric)}$$

or...

From Hidden wormholes to traversable Wormholes (varying ℓ)

$$\phi(r) = \frac{1}{2}\log\left(1 - \frac{\ell^2}{r^2}\right)$$

and

$$m(r) = M\left(1 - \frac{\ell^2}{r^2}\right) + \frac{\ell^2}{2\,r} \quad \text{(Simpson-Visser)}$$

*Carballo-Rubio et al. 2023

Study of gravitational Perturbations

We considered the metric
as a solution of Einstein equations
sourced by a non-linear coupled
magnetic field

$$\mathcal{S} = \int \mathrm{d}^4x \sqrt{-g}\left(\frac{1}{16\pi}R - \frac{1}{4\pi}\mathcal{L}(F)\right),$$

With

$$F = \frac{1}{4}F^{\mu\nu}F_{\mu\nu} = \frac{\ell^2}{2\,r^4}$$

and

$$\mathcal{L}(F) = \frac{m\prime(r)}{r^2} \neq F$$

$$\nabla_\mu\left(\mathcal{L}_F F^{\alpha\mu}\right) = 0\,,$$

$$G_{\mu\nu} = 2\left(\mathcal{L}_F F_\mu{}^\lambda F_{\nu\lambda} - g_{\mu\nu}\mathcal{L}\right),$$

We perturbed both the metric and the matter fields and we solved the field equations linearly in the perturbation

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

$$A_\mu = A^{(0)}_\mu + \delta A_\mu$$

(We report the computation for “Double horizons” metrics)

Harmonic perturbations

$g_{\mu\nu}$(t,r)= $e^{-i\omega t} g_{\mu\nu}$(r) A_{μ}(t,r)= $e^{-i\omega t} A_{\mu}$(r)

Important issue: the magnetic field has opposite polarity to respect to the metric.

↓

axial gravitational perturbations are actually coupled with polar perturbations of the magnetic field

(as well as polar gravitational perturbations are coupled with axial perturbations of the magnetic field)

$$\frac{d^2\psi_{ij}(r)}{dr_*^2} + \left(\omega^2 - V_{ij}(r)\right)\psi_{ij}(r) = 0$$

\+

Boundary conditions

↓

Discrete set of frequencies (QNMs)

Where $\psi_{ij}(\mathrm{r})$ are related to the metric and matter perturbation $h_{\mu\nu}$(t,r) and δA_{μ} and the tortoise coordinate is defined as

$$dr_* = \frac{e^{\phi(r)}}{f(r)} dr$$

Study of test field perturbations

Test field:
we obtain the equations of motion from the Einstein equations
demanding that the perturbations do not change the stress-energy tensor (at least) to first order

- No need to interpret the stress-energy tensor as some form of matter (no need to interpret the spacetime as a solution in GR)

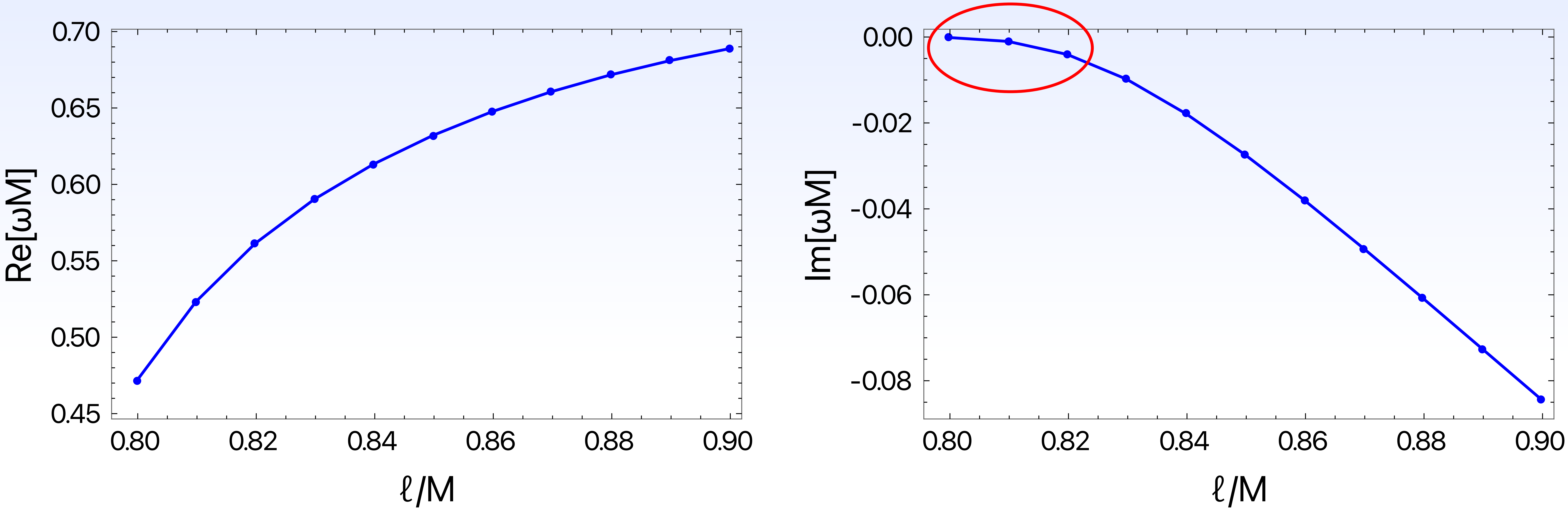
$$\frac{d^2\psi(r)}{dr_*^2} + \left(\omega^2 - V(r)\right)\psi(r) = 0$$

$$V = f(r)\left(e^{-2\,\phi(r)}\,\frac{l(l+1)}{r^2} + \frac{2(1-s^2)\,m(r)}{r^3} - (1-s)\left(\frac{2\,m'(r)}{r^2} + \frac{f(r)\phi'(r)}{r}\right)\right)$$

where s is the spin of the perturbation
(s=0 for scalr perturbations, s=1 for vector perturbations and so on..).

Horizonless compact object branch

Boundary conditions: regular at the center, purely outgoing at infinity

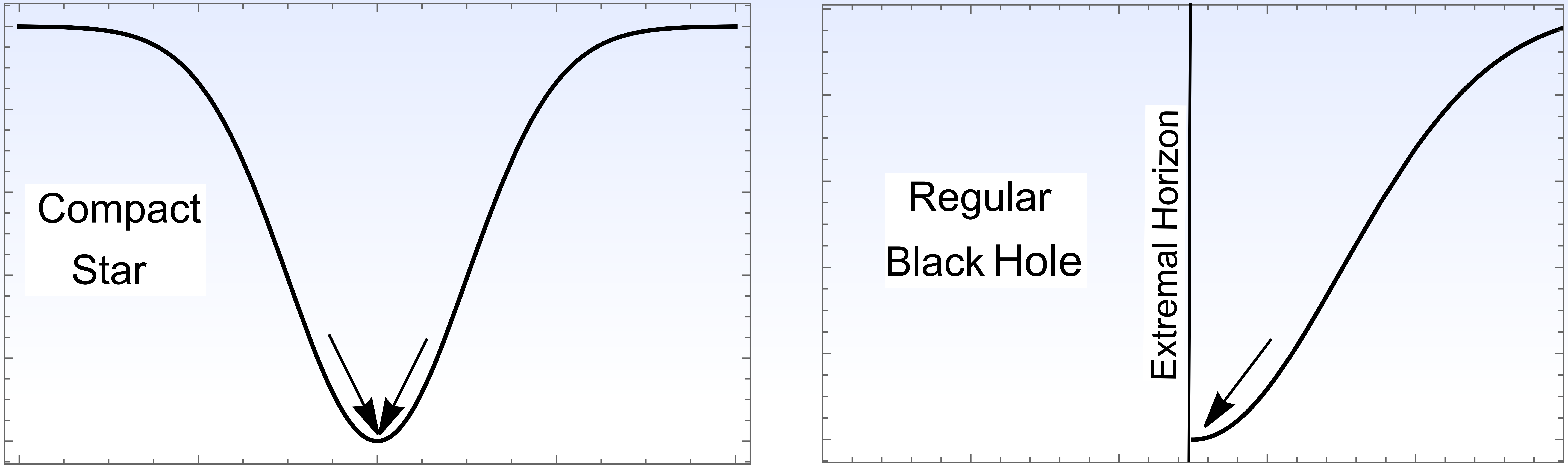


$e^{i\omega t} = e^{iRe[\omega]t}\, e^{-Im[\omega]t}$

$\boldsymbol{\tau = \frac{1}{Im[\omega]}}$ is the damping time

Small $Im[\omega]$ → **long living modes** connected with the presence of a **stable lightring!**

Lightring and Aretakis instabilities



The perturbation accumulates near the minimum of the potential causing possible non-linear instabilities

The "stable lightring" is already present in the extremal RBH case!
Connection to the Aretakis Instability?

Detectability

Parspec framework* at order 0 in the spin

A data analysis framework for the GW ringdown of BHs in modified theories of gravity

$$\omega_i := Re\,[\omega_i] = \frac{1}{M_i}\omega_{Kerr}^{(0)}\,(1+\gamma_i\delta\omega^{(0)})$$

$$\tau_i := \frac{1}{Im[\omega_i]} = M_i\,\tau_{Kerr}^{(0)}\,(1+\gamma_i\delta\tau^{(0)})$$

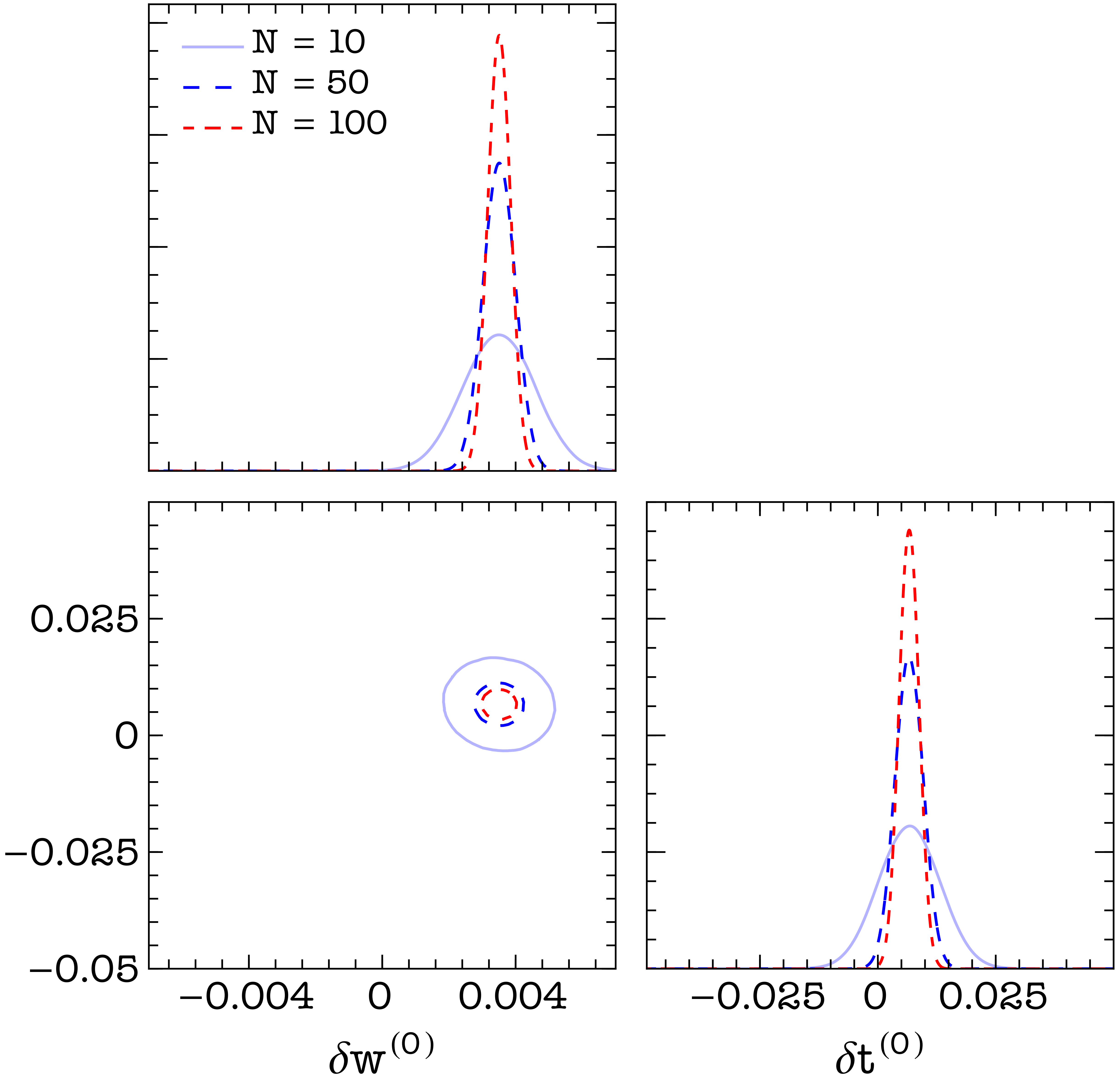
($\gamma_i = 1$ in our case)

- You simulate N observations of ringdown signals from regular BHs binary merger

- Isolating the dependence of the corrections on the masses of the sources you can combine different observations to obtain more precise results on $\delta\omega$ and $\delta\tau$

- Through a Monte Carlo Markov chain you obtain the posterior probability distribution for $\delta\omega$ and $\delta\tau$

*Maselli et al. 2019



From the observations of the ringdown
of 0(100) RBHs with **SNR∼100**
we can exclude the GR hypothesis at
90% confidence level
for macroscopic values of ℓ

but remember this is at **order 0 in the spin…**

Conclusions

- There are two alternatives to singular BHs: **regular BHs** and **horizonless compact objects**. They can both be described by the same metric

- The quasi-normal modes of these objects **deviates** from the Schwarschild one and in the horizonless branch **long living modes** suggest non-linear instability

- These deviations from the spectrum of singular BHs seems to be **detectable with the next Generation of GW detectors stacking multiple events**!