Echoes from backreacting exotic compact objects

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Exotic compact objects (ECO)

We know that very compact objects exist in our Universe

GR and SM

QG and BSM

Black holes

breakdown of General Relativity: presence of singularities where the theory is not predictive and the spacetime is not defined

Fuzzballs

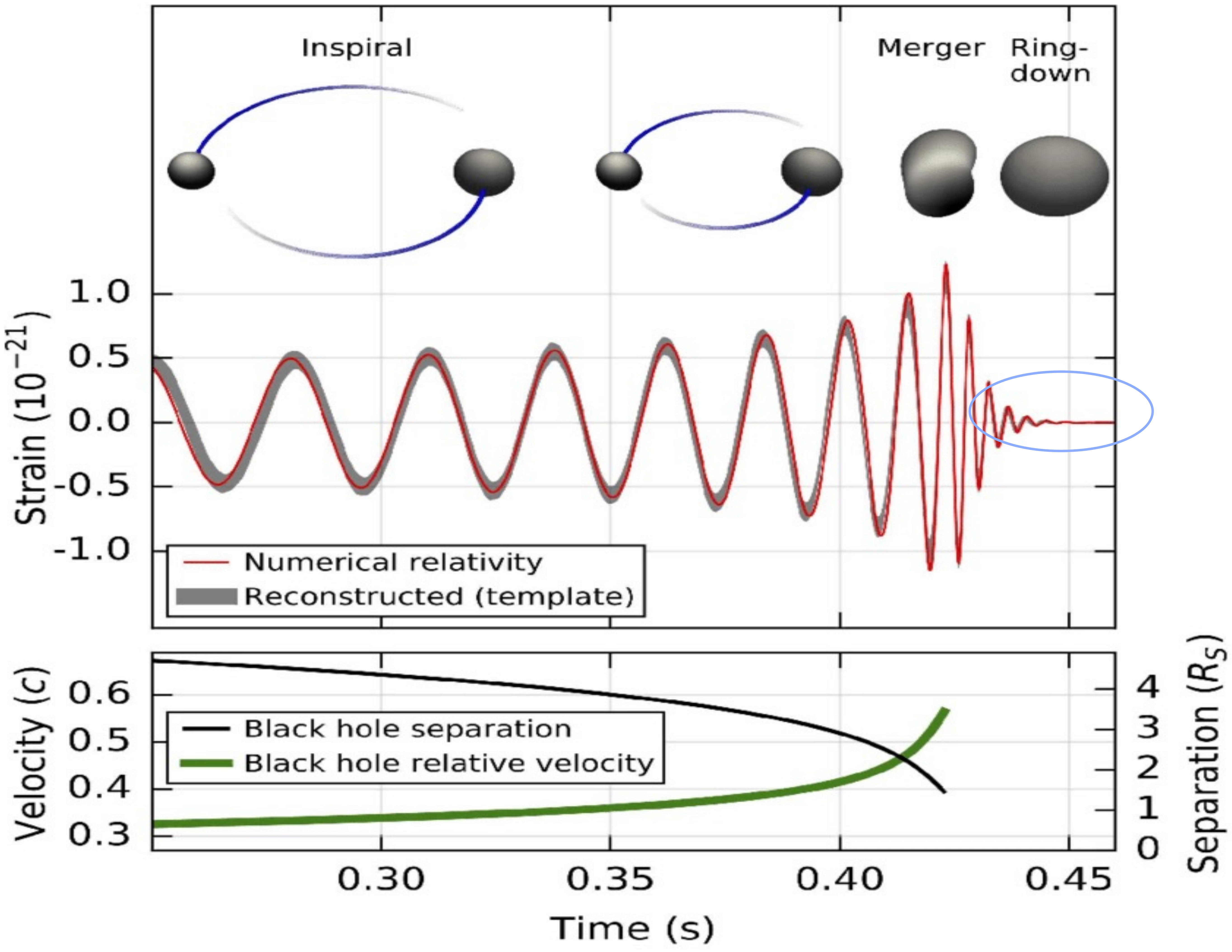
Boson stars

Gravastars

The source of echoes

The last phase of the GW signal coming from the coalescence of two compact objects is the **ringdown**.

It is caused by the characteristic oscillations of the final object: it can be considered a **gravitational perturbation in the final object space-time**



Echoes

Consider a (scalar) perturbation around a (spherically symmetric) BH or **horizonless ECO**

$$\Phi = \sum_{lm} Y_{lm}(\theta,\phi)\Psi_{lm}(r)/r$$

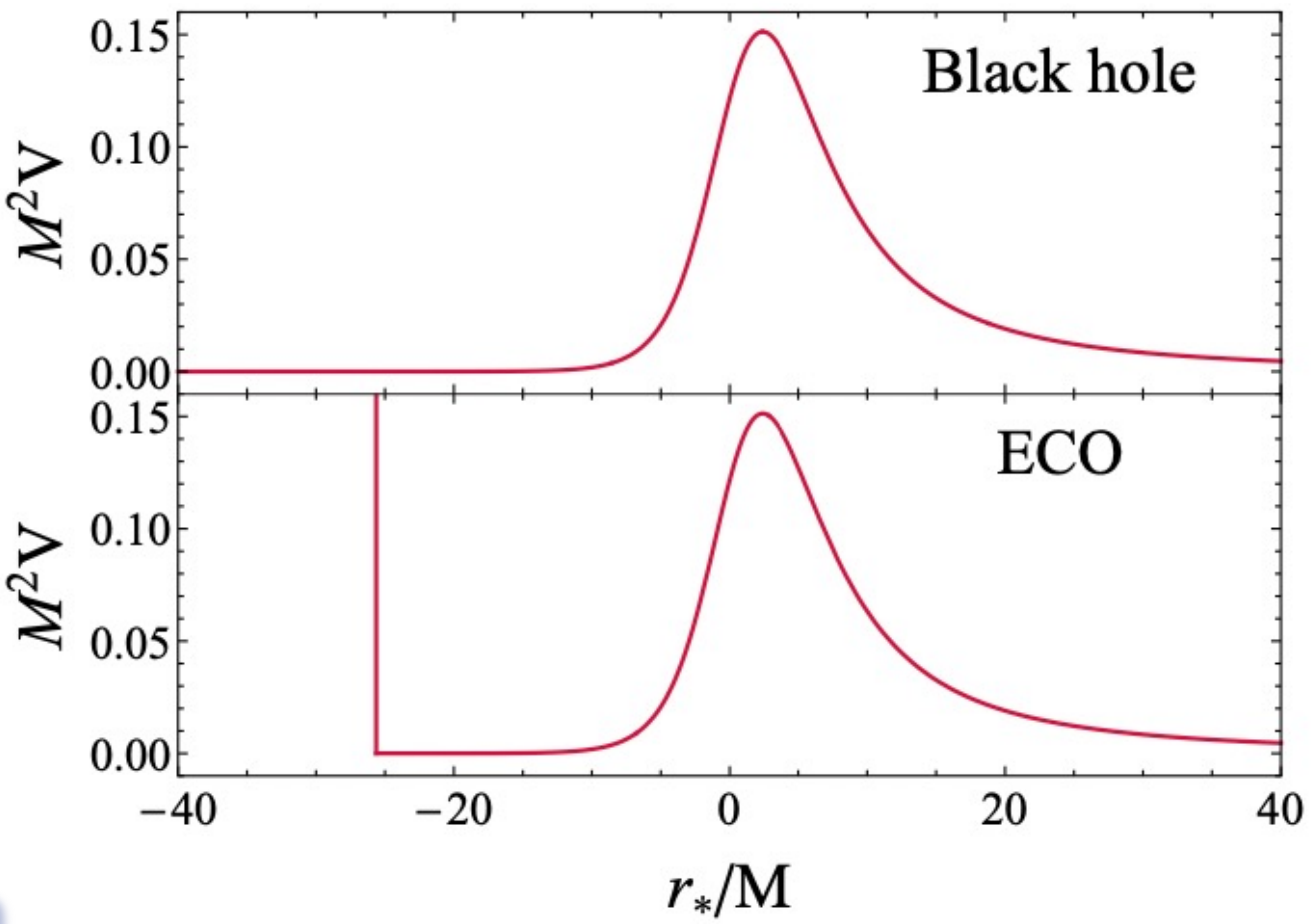
At linear level the field equation is:

$$\left[-\frac{\partial^2}{\partial t^2}+\frac{\partial^2}{\partial r_*^2}-V_l(r)\right]\Psi_{lm}(t,r)=0$$

But the potential is very different in the two cases

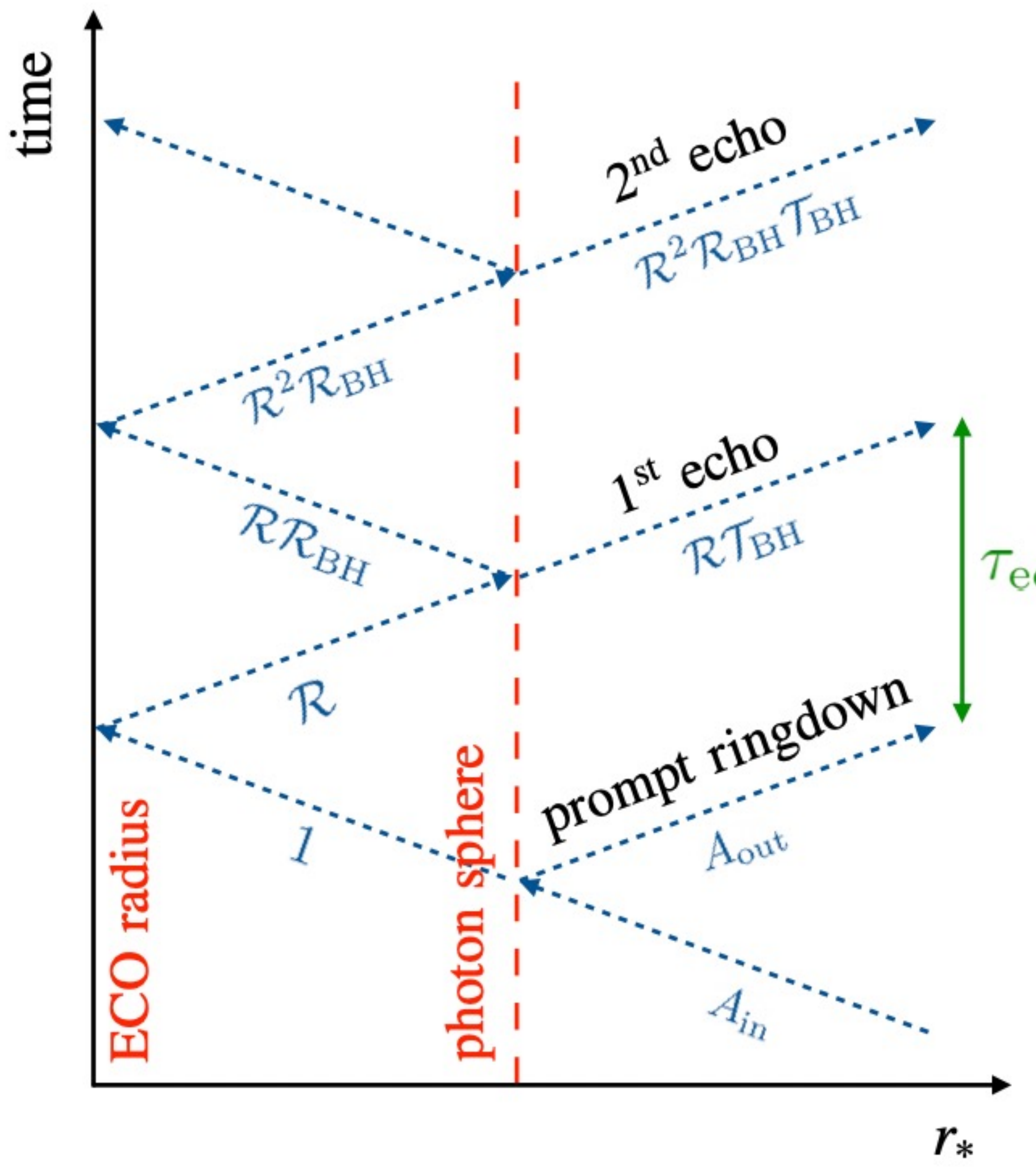
We see echoes of the original signal

Photon sphere r~3M

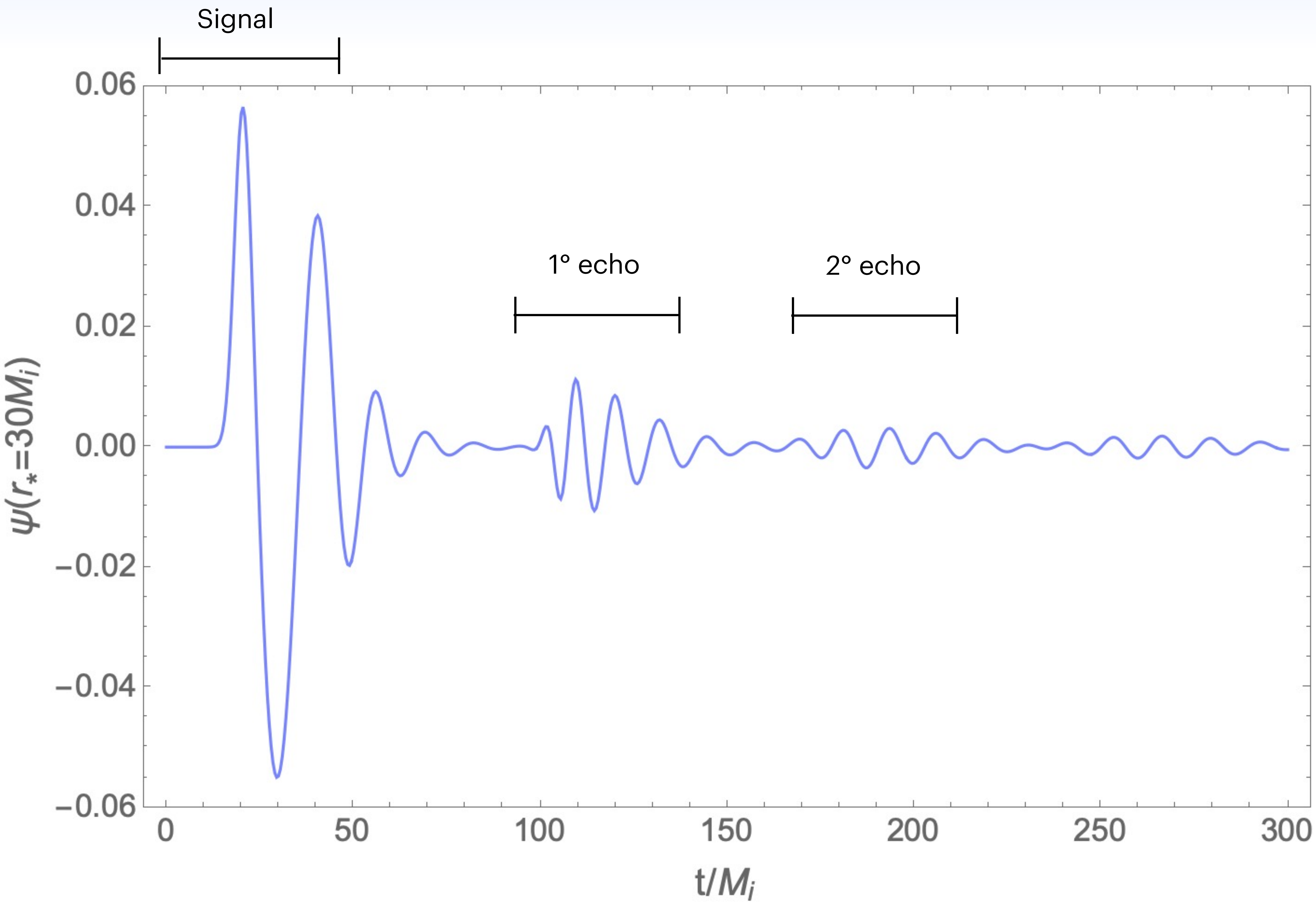


From arXiv:2105.06410
E. Maggio, P. Pani, G. Raposo

Echoes



time
2^{nd} echo
$\mathcal{R}^2\mathcal{R}_{BH}\mathcal{T}_{BH}$
$\mathcal{R}^2\mathcal{R}_{BH}$
1^{st} echo
$\mathcal{R}\mathcal{R}_{BH}$
$\mathcal{R}\mathcal{T}_{BH}$
τ_{echo}
$\mathcal{R}$
prompt ringdown
1
A_{out}
A_{in}
ECO radius
photon sphere
r_*



Signal
1° echo
2° echo
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
$\psi(r_*=30M_i)$
0
50
100
150
200
250
300
t/M_i

Time delay

Defining the compactness parameter as:

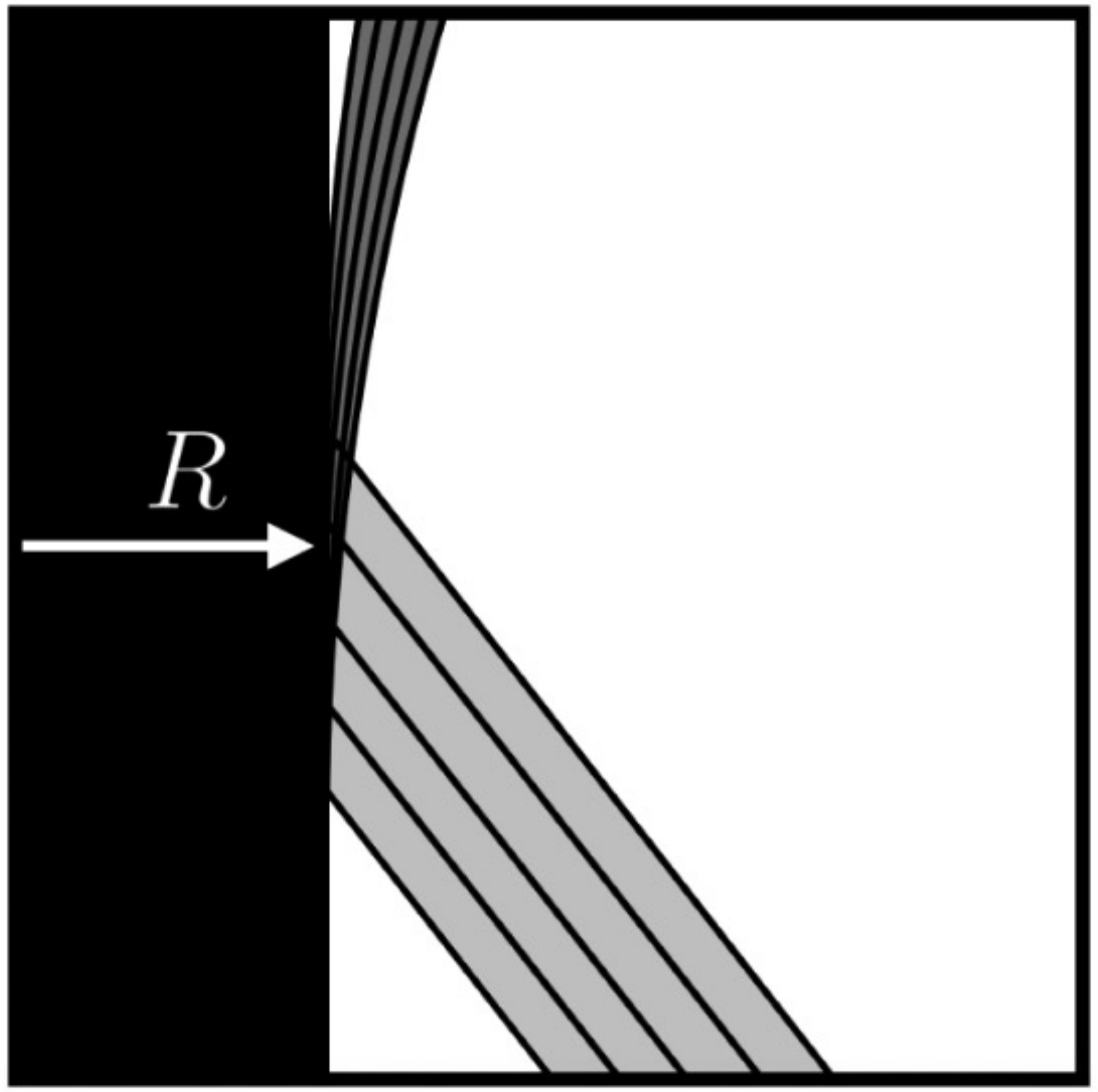
$$\sigma = \frac{r_0}{2M} - 1$$

↓

$$\Delta t_{echo} = 2 \int_{r_0=2M(\sigma+1)}^{r_{peak}\sim 3M} g_{rr} dr = 2 \int_{r_0=2M(\sigma+1)}^{r_{peak}\sim 3M} \frac{dr}{1-\frac{2M}{r}} \simeq 2M(1 - 2\sigma - 2\ln(2\sigma))$$

The logarithmic dependence on σ would allow to detect even Planckian corrections ($\sigma \sim l_{Planck}$/M) at the horizon scale

Limits of linear approximation



From arXiv:1809.08238
Raúl Carballo-Rubio, Francesco Di Filippo, Stefano Liberati, Matt Visser

Peeling of outgoing geodesic

The accumulation of geodesics around the gravitational radius produces high densities

Instability

If partial absorption is taken into account, the mass of the object can even increase over the hoop limit $r_0 = 2M$

Non linear interactions should be taken into account

Absorption beyond the test field limit

Partial absorption of the first echo → $M_0 \to M = M_0 + \Delta E_{1st\ ehco}$

→ $\sigma_{2nd\ echo} \ll \sigma_{1st\ echo}$ → $\Delta t_{2nd\ echo} > \Delta t_{1st\ echo}$

For high compact object
very small ΔM causes big changes
in the compactness!

For example, if $\Delta M = (5 \cdot 10^{-8}) M_0$:

$$\sigma_0 = \frac{r_0}{2M_0} - 1 = \frac{2\,M_0(1+10^{-7})}{2\,M_0} - 1 = 10^{-7}$$

$$\sigma_f = \frac{r_0}{2M_f} - 1 = \frac{2\,M_0(1+10^{-7})}{2\,M_0(1+5\cdot 10^{-8})} - 1 = 5 \cdot 10^{-8}$$

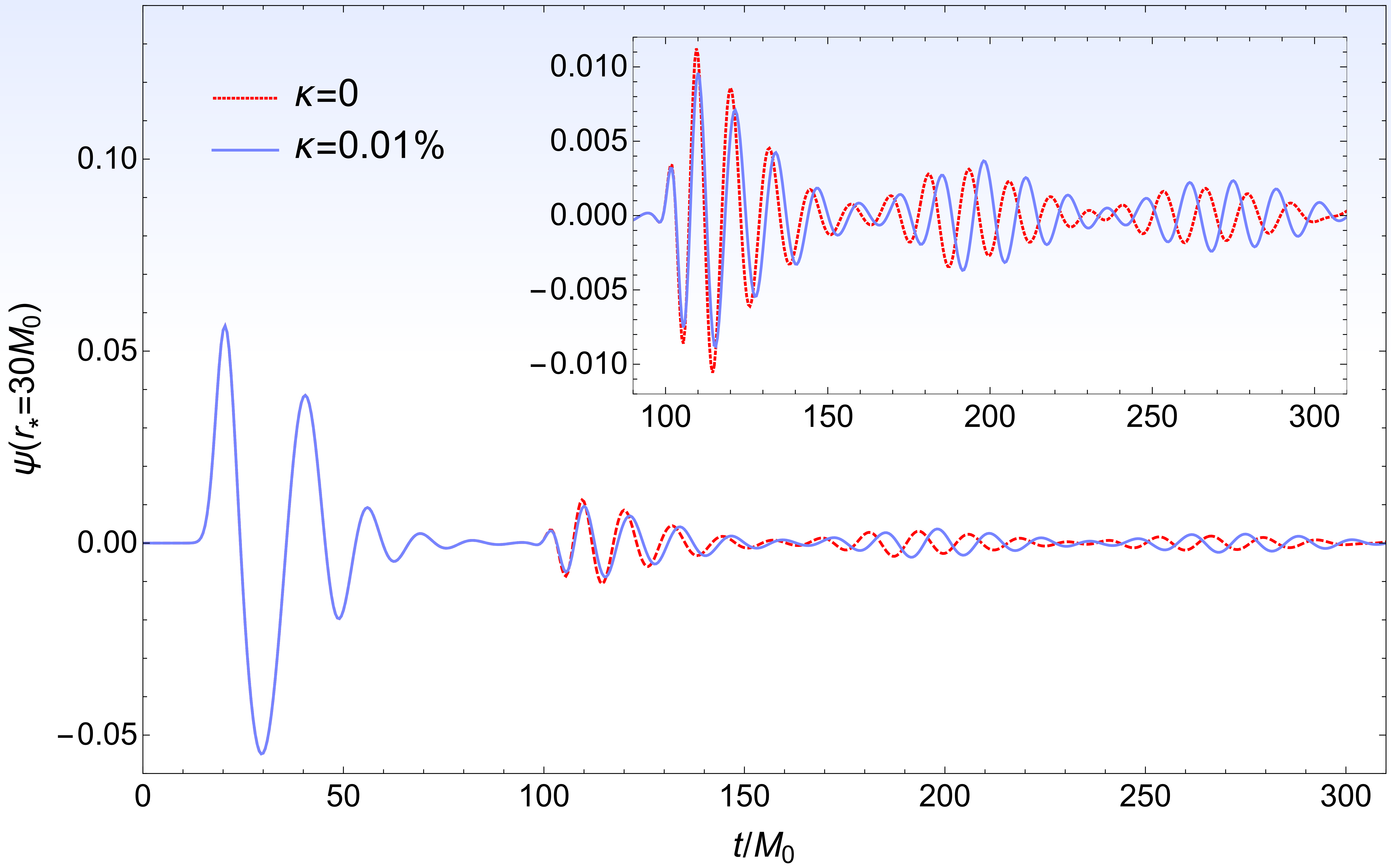
$$\Delta t_0 \sim -4\ln(2\,\sigma_0) = 61.7\,M_0$$

$$\Delta t_f \sim -4\ln\left(2\,\sigma_f\right) = 64.5\,M_0$$

arXiv:2205.14170
V.V. , E. Franzin, S. Liberati

Absorption beyond the test field limit

Scalar field in the Schwarschild space time with $M \to M(t)$ and a (partially) reflective boundary at $r = r_0$



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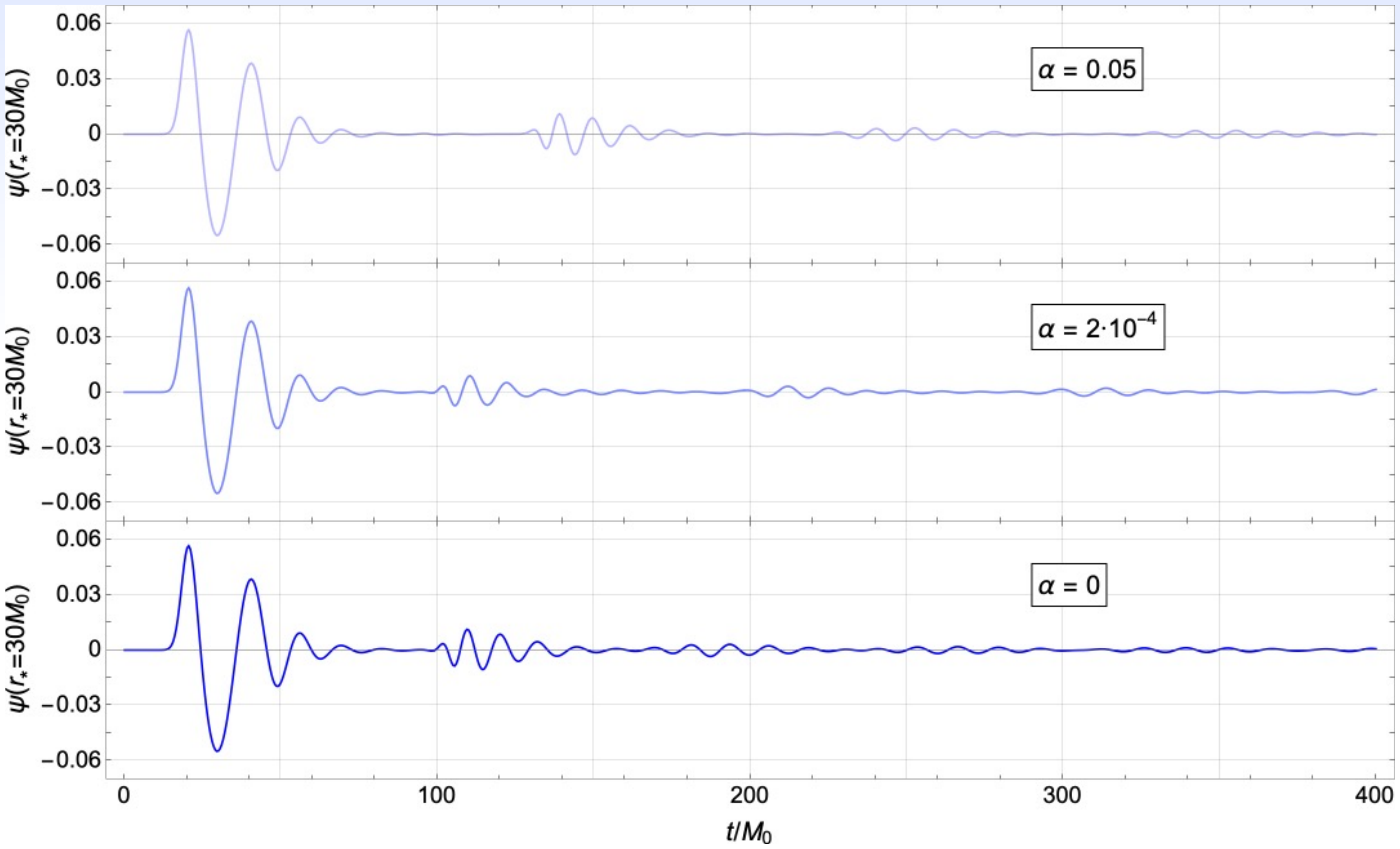
Preventing instability I: Asymptotic compactness



Absorption coefficient:

$$\kappa(\sigma) = \alpha \left(1 - \tanh\frac{\beta}{\sigma - \sigma_{Planck}}\right)$$

$$\beta = 10^{-10}$$

Preventing instability II: Expansion

Expansion at constant compactness

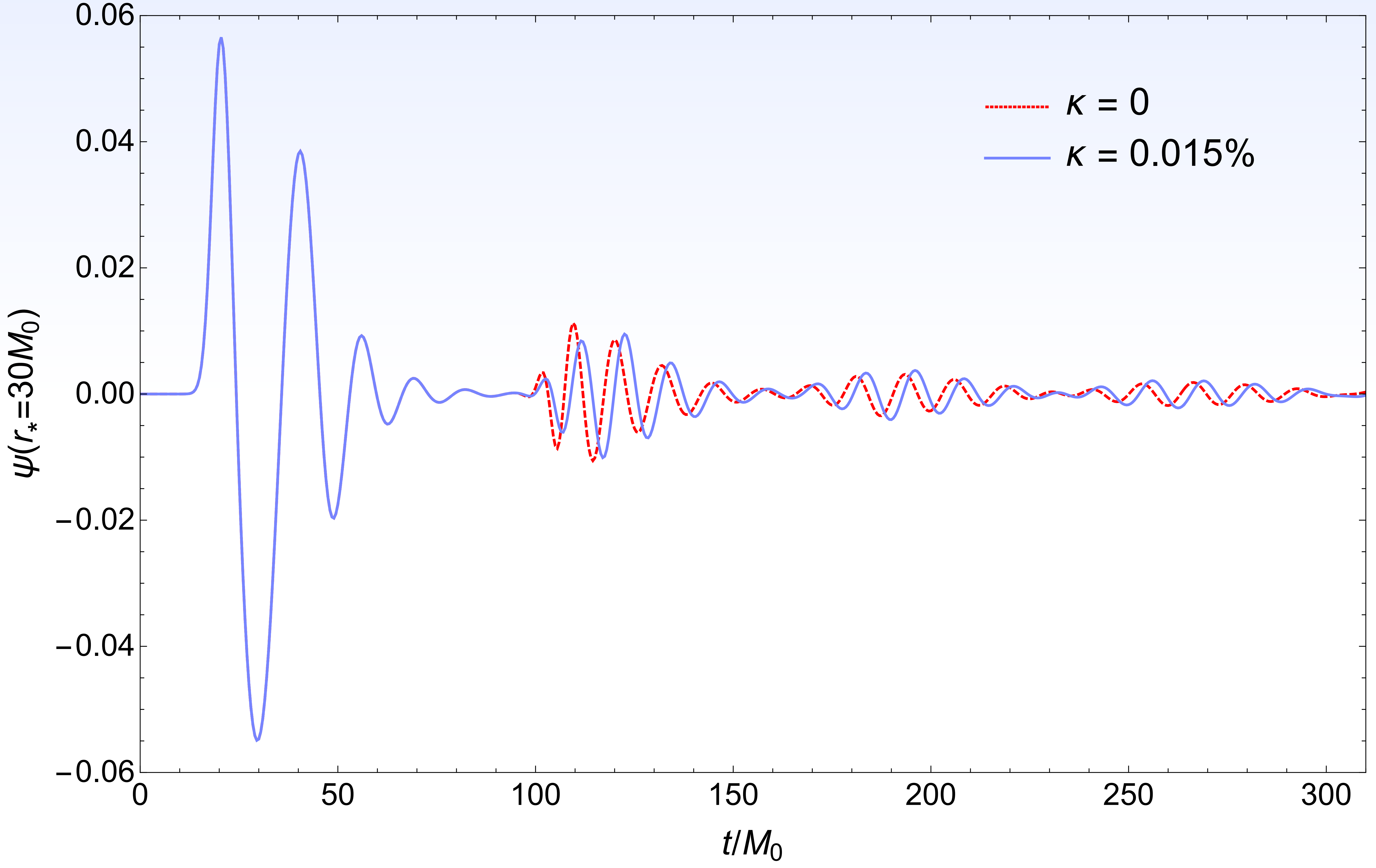
$$\frac{r_0(t)}{2\,M(t)} = \sigma_0 + 1$$

$$\Delta t_{echo} \sim constant$$

BUT

- There might be a transient phase
- Other, more general model of expansion can be possible

Transient phase $\tau \sim 65 M_0 > \Delta t_{echo}$



Conclusions

We saw that, taking into account **possible non linear interaction** between the ECO and the perturbation field, may lead to the partial lost of the main feature of **echoes signal**: the quasi-periodicity

This is important because the searches for echoes in GW ringdown are usually based on this **quasi-periodicity**

It seems that further investigations in the theory and phenomenology of ECOs and more refined searching strategy for such objects are needed.