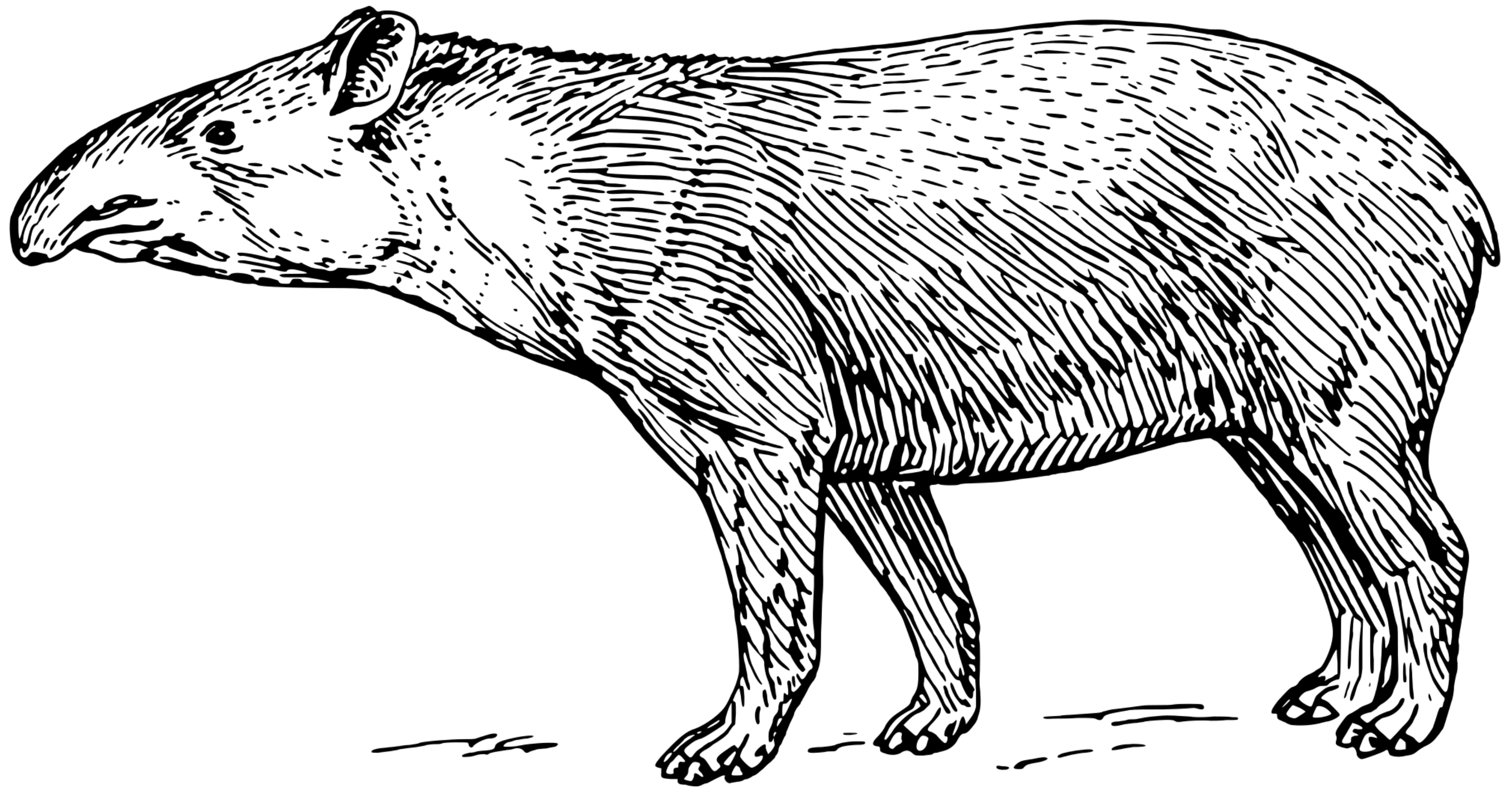
Instability of exotic compact objects and its implications for GW echoes

Baoyi Chen (*TAPIR, Caltech*)



arXiv:1902.08180 with **Yanbei Chen**, **Yiqiu Ma**, **Ka-Lok R. Lo** and **Ling Sun**

Perimeter Institute April 25, 2019

The punch line

"Incoming gravitational waves can
easily cause exotic compact objects
to collapse into black holes, leaving
NO gravitational-wave echoes
towards null infinity! "

Why questioning black holes?

- Quantum gravity
- Quantum information considerations
- BH interior has pathology due to the Cauchy horizon
- ...

Also because we can!

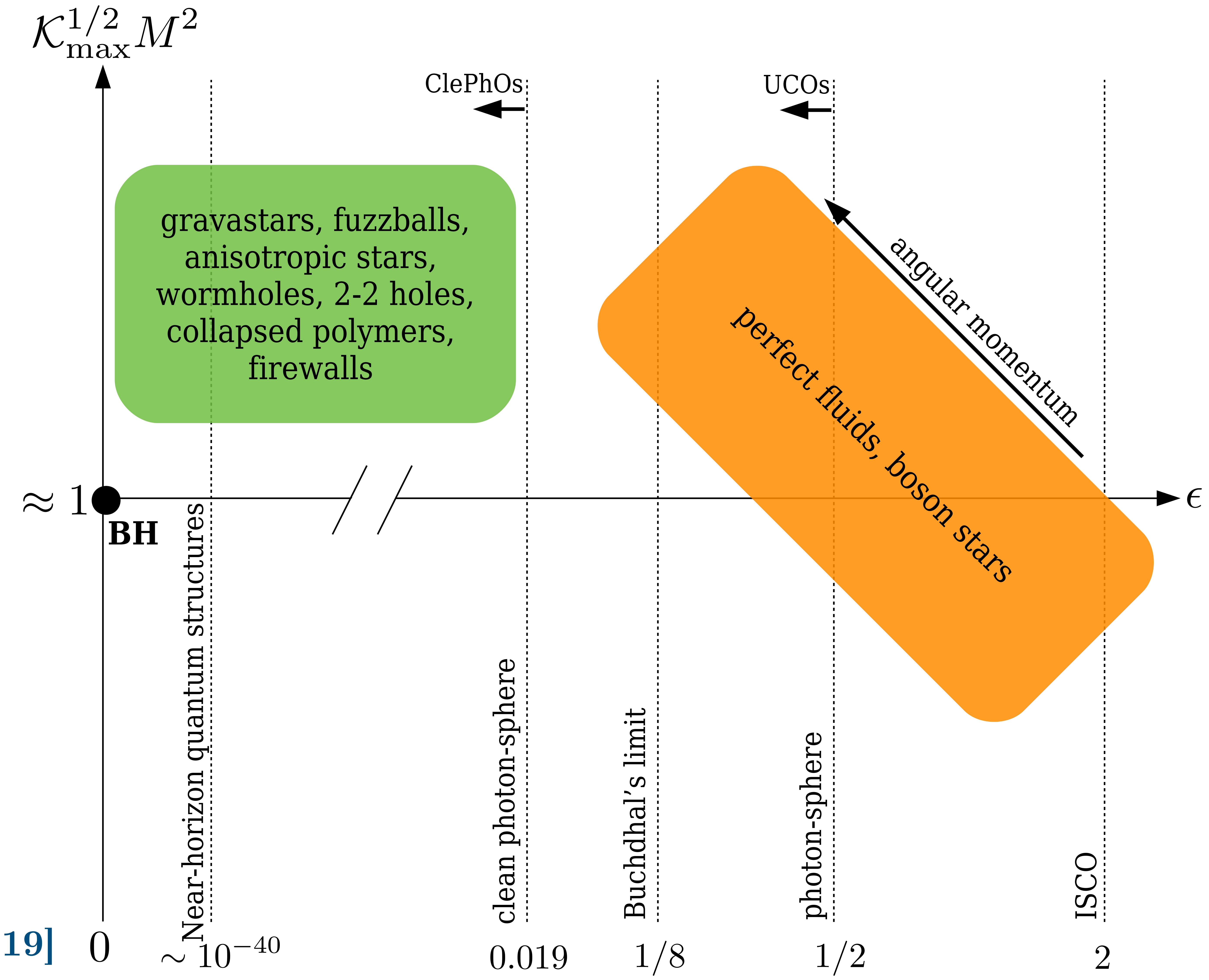
- Advanced LIGO, LISA, future GW detectors...
- Event horizon telescope...

precision GW astrophysics!

Black hole (BH) vs Exotic compact object(ECO)

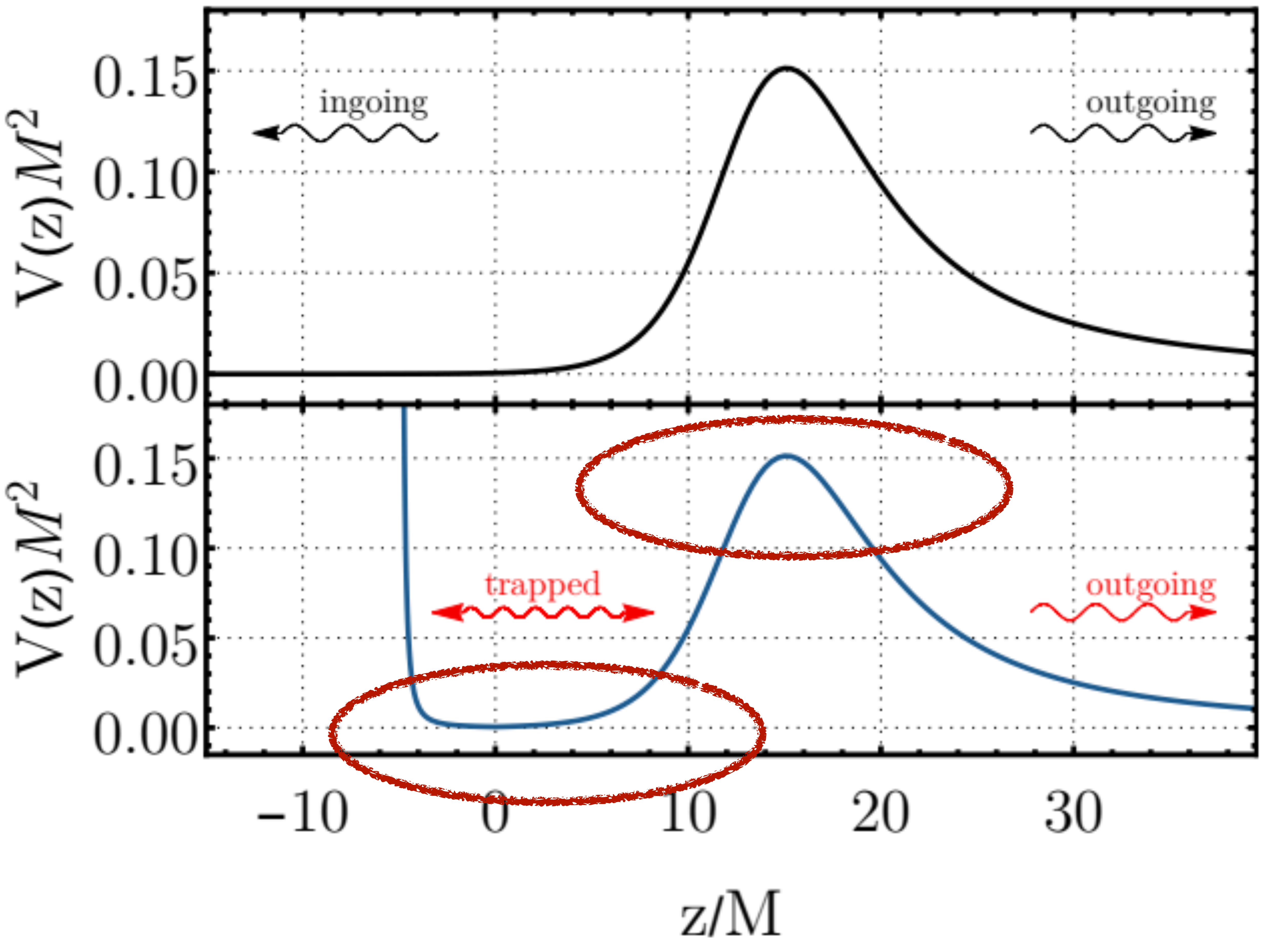
Black holes	Exotic compact objects
solutions to GR	inspired by quantum gravity
event horizon	horizonless
information paradox	no information paradox
perfect ingoing boundary	<u>reflecting</u> boundary
Ringdown	Ringdown + <u>Echoes</u>

The ECO models



[Cardoso & Pani 2019]

Instability of ECOs



[Cardoso & Pani 2019]

photons can accumulate near the stable light ring

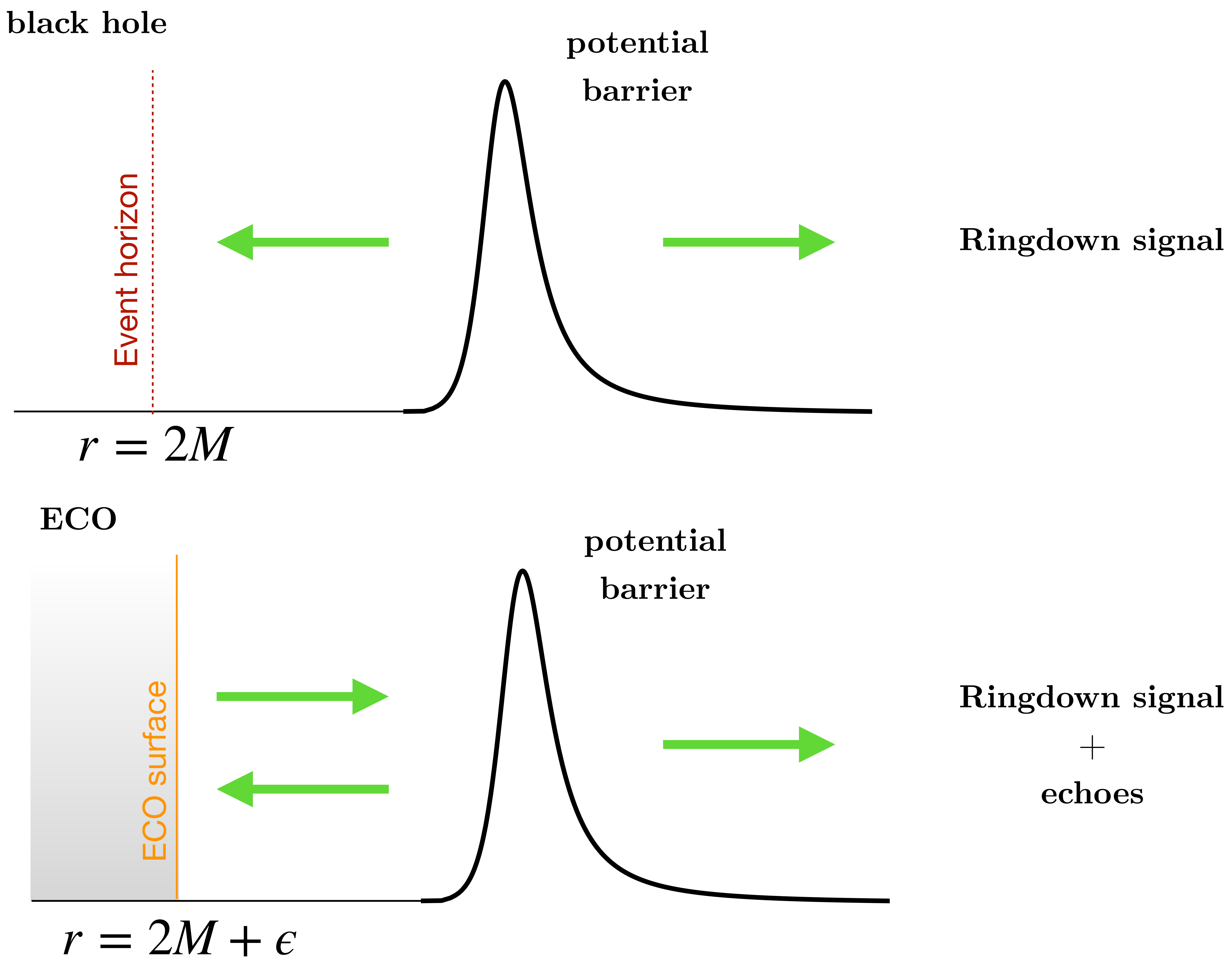
double light rings

nonlinear instabilities (?)

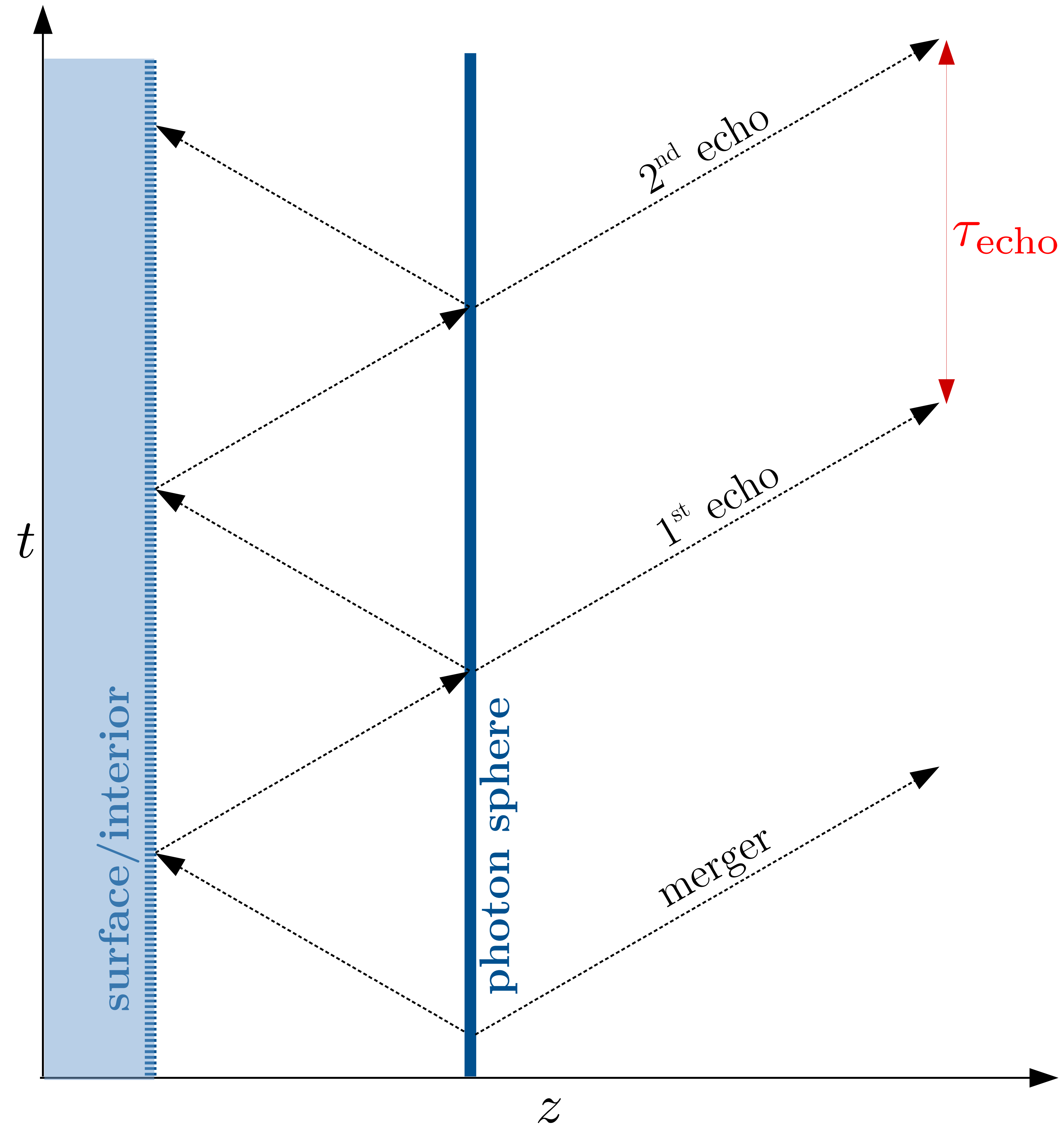
[Cunha, Berti, et al 2017]

The GW echoes

- Ringdown signal generated near the potential barrier
- Ingoing waves get reflected at the ECO surface, giving rise to echoes
- Echo amplitude depends on the surface reflectivity
- Further filtered by the potential barrier



The GW echoes



[Cardoso & Pani 2019]

More than one echo!

$$\tau_{\rm echo} = 2|r_*^{\rm LR} - r_*^{\rm ECO}| \approx 2M + 4M\log(M/\epsilon)$$

Search these signatures in the LIGO data!

Motivations

- There are claims that echoes exist in the LIGO signals (still being debated)
- ECO can be unstable due to accreting matter **[Rubio et al 2018]**
- Let us consider a star or a particle plunging into an ECO...

How does the ECO respond to the incoming GW signals?

Back-reactions on the ECO spacetime?

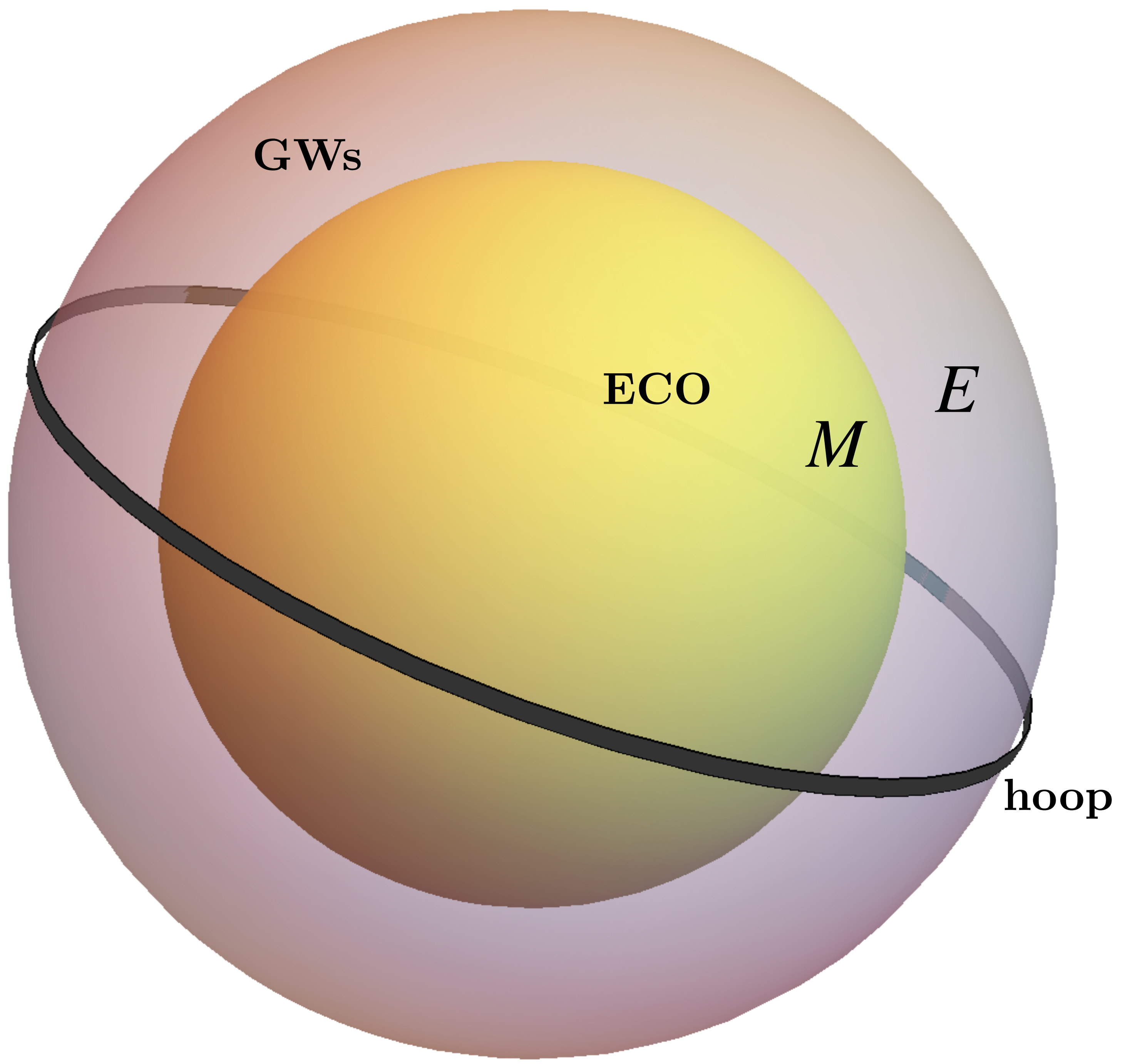
Will the ECO simply collapses into a black hole?

The “Hoop Conjecture”

- Black hole forms when all matter are within the “hoop”
- The “hoop” is placed at the Schwarzschild radius

$$r_{\text{hoop}} = 2(M + E)$$

- More compact ECOs are easier to be put into the hoop
- Upper bound on the ECO compactness



[Thorne 1972]

Estimates on the bound

- GW pulse with duration T and Energy E

$$r_* = r + 2M\log(r/2M - 1)$$

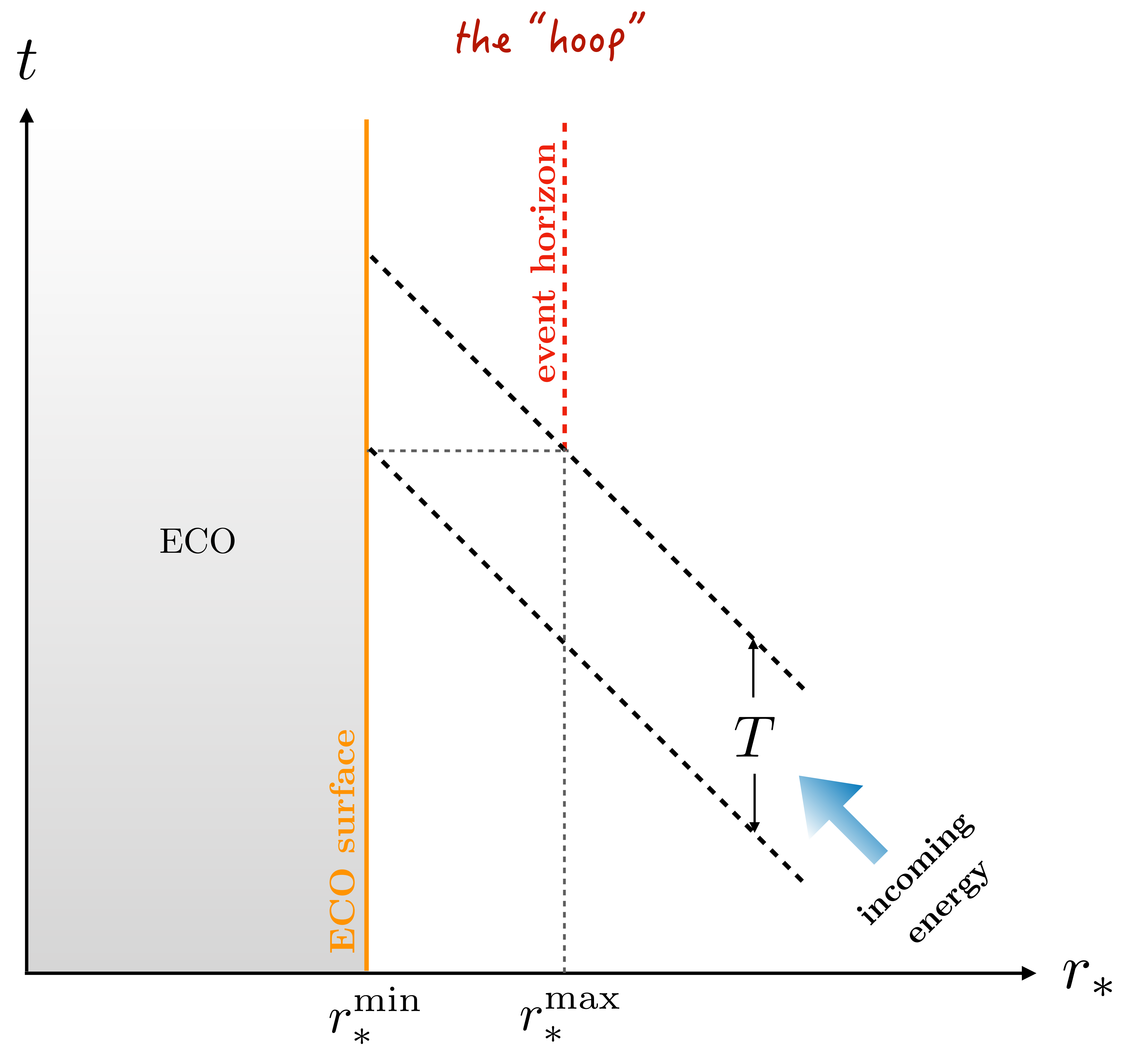
"tortoise coordinate"

- At any given moment (in Schwarzschild time)

$$r_*^{\max} - r_*^{\min} = T$$

- Black hole can form for a critical T_c

$$r_*^{\max} = 2(M+E)$$
$$r_*^{\min} = r_*^{\mathrm{ECO}}$$



Estimates on the bound

- To avoid black hole formation

$$T < 2E + 2M \log\left(\frac{2E}{r_{\mathrm{ECO}} - 2M}\right)$$

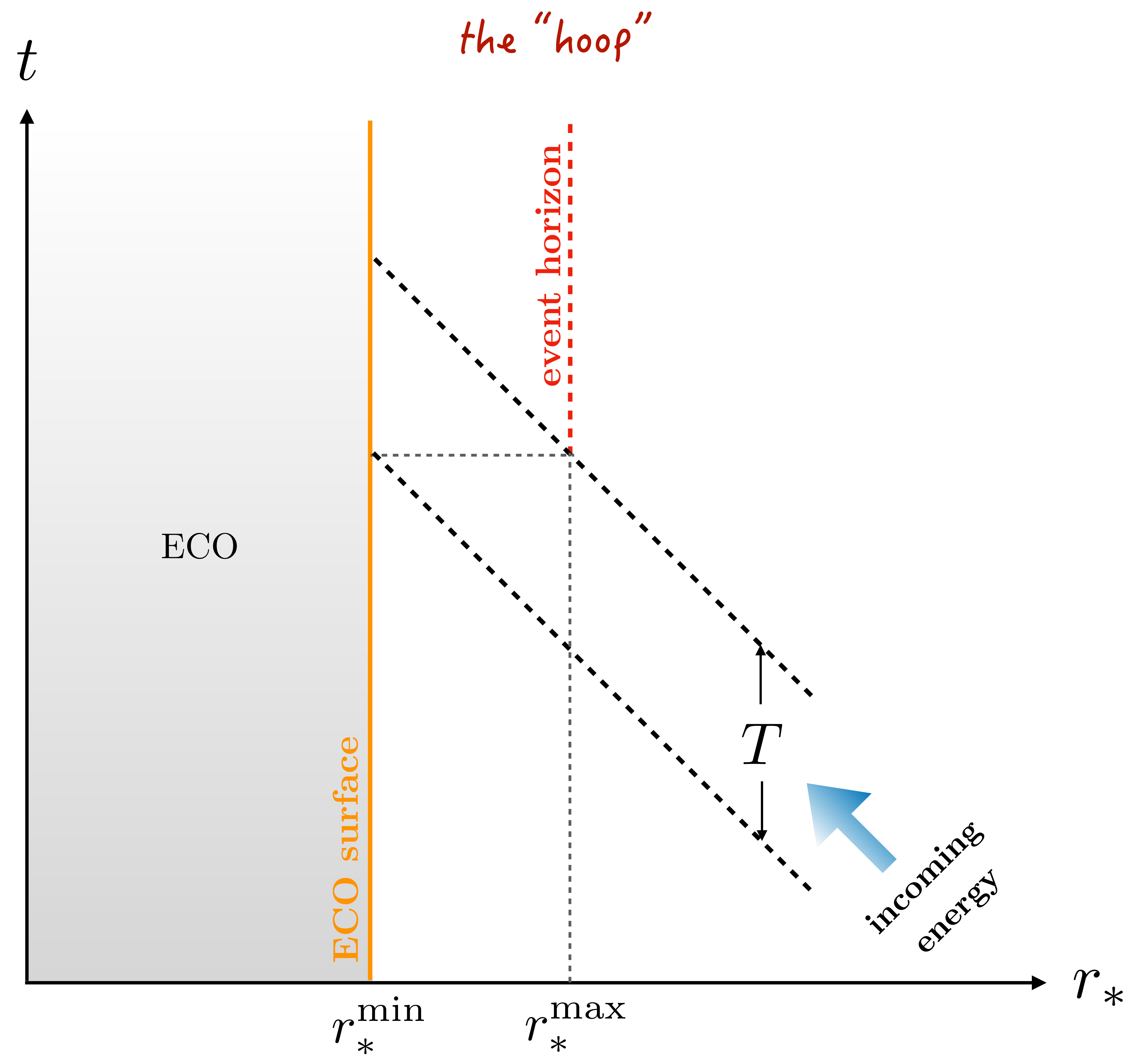
- Ringdown energy

$$E(t) = \alpha_{\mathrm{H}} \eta M (1 - e^{-2\gamma t})$$

3%-10%

Symmetric mass ratio

Imaginary part of the QNM frequency



Estimates on the bound

- To avoid BH formation, the location of the ECO surface must satisfy

$$r_{\rm ECO} - 2M > 0.015\eta M \left(\frac{M\gamma}{0.1}\right)\left(\frac{\alpha_{\rm H}}{0.05}\right)$$

- Typical values $M\gamma \sim 0.1, \quad \alpha_{\rm H} \sim 0.05$

- Far from Planck scale!

$$r_{\rm ECO} - 2M \gg l_{\rm p}$$

- Rough estimates, no back reactions

Estimates that includes back reactions

- In-going Vaidya spacetime

advanced time

$$ds^2 = -\left[1 - \frac{2M(v)}{r}\right] dv^2 + 2drdv + r^2 d\Omega^2$$

- A spherically-symmetric spacetime absorbing null dust $T_{ab} = \frac{dM/dv}{4\pi r^2} l_a l_b$
- Back reaction included
- Still an approximation
    - GW energy is not spherically symmetrically distributed
    - Does not capture GW oscillations

Ingoing Vaidya spacetime

- Location of the trapped surface

$$r = 2M(v)$$

- Location of the event horizon

$$r_{\rm EH}(v) = 2M(v) + \delta(v)$$

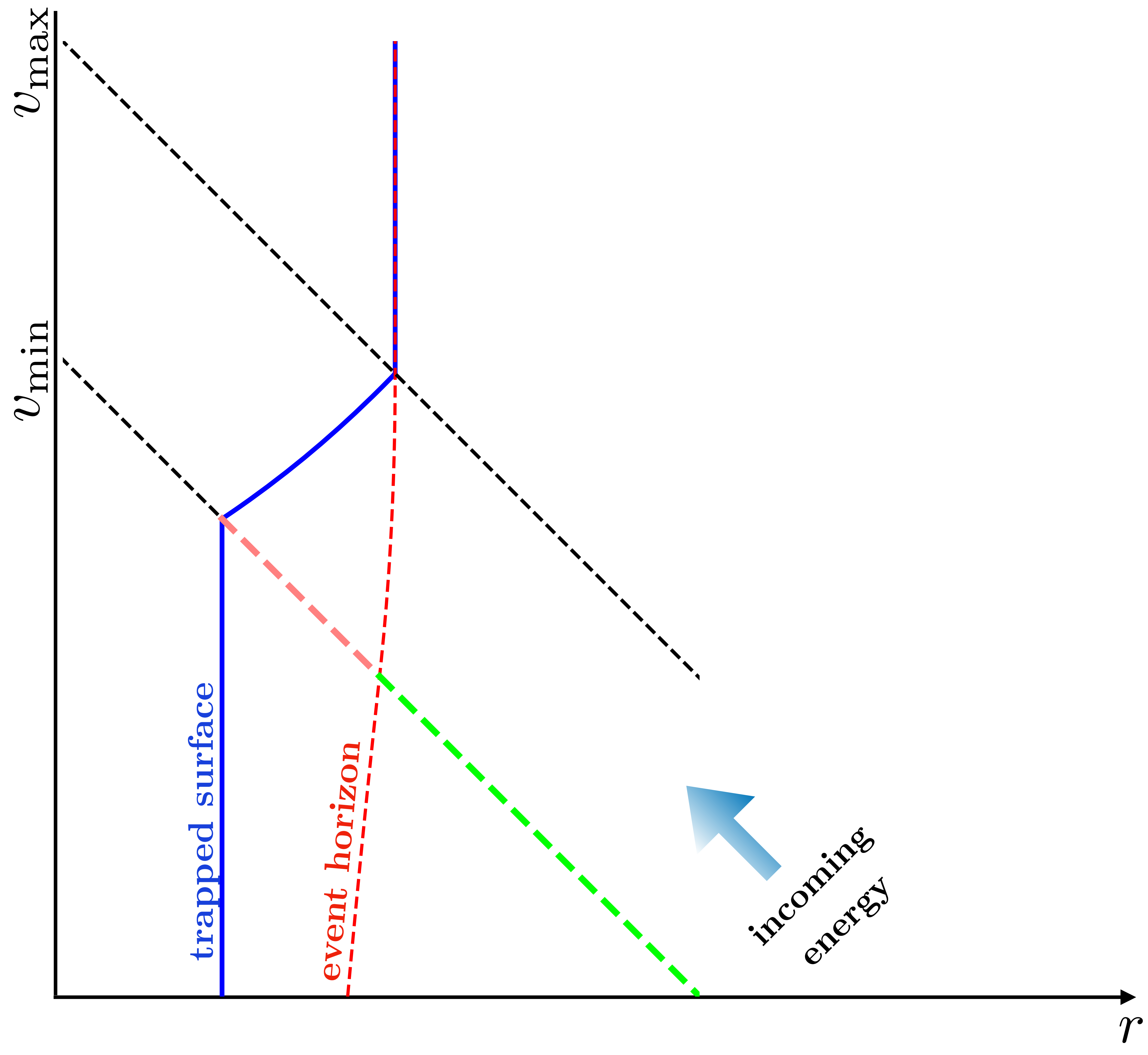
- Event horizon's teleological nature

outgoing null geodesic

$$2dr/dv = 1 - 2M(v)/r(v)$$

final condition

$$r_{\rm EH}(v_{\rm max}) = 2(M_0 + E_{\rm tot})$$



Three scenarios for static ECOs

- Type (a): ECO promptly collapses

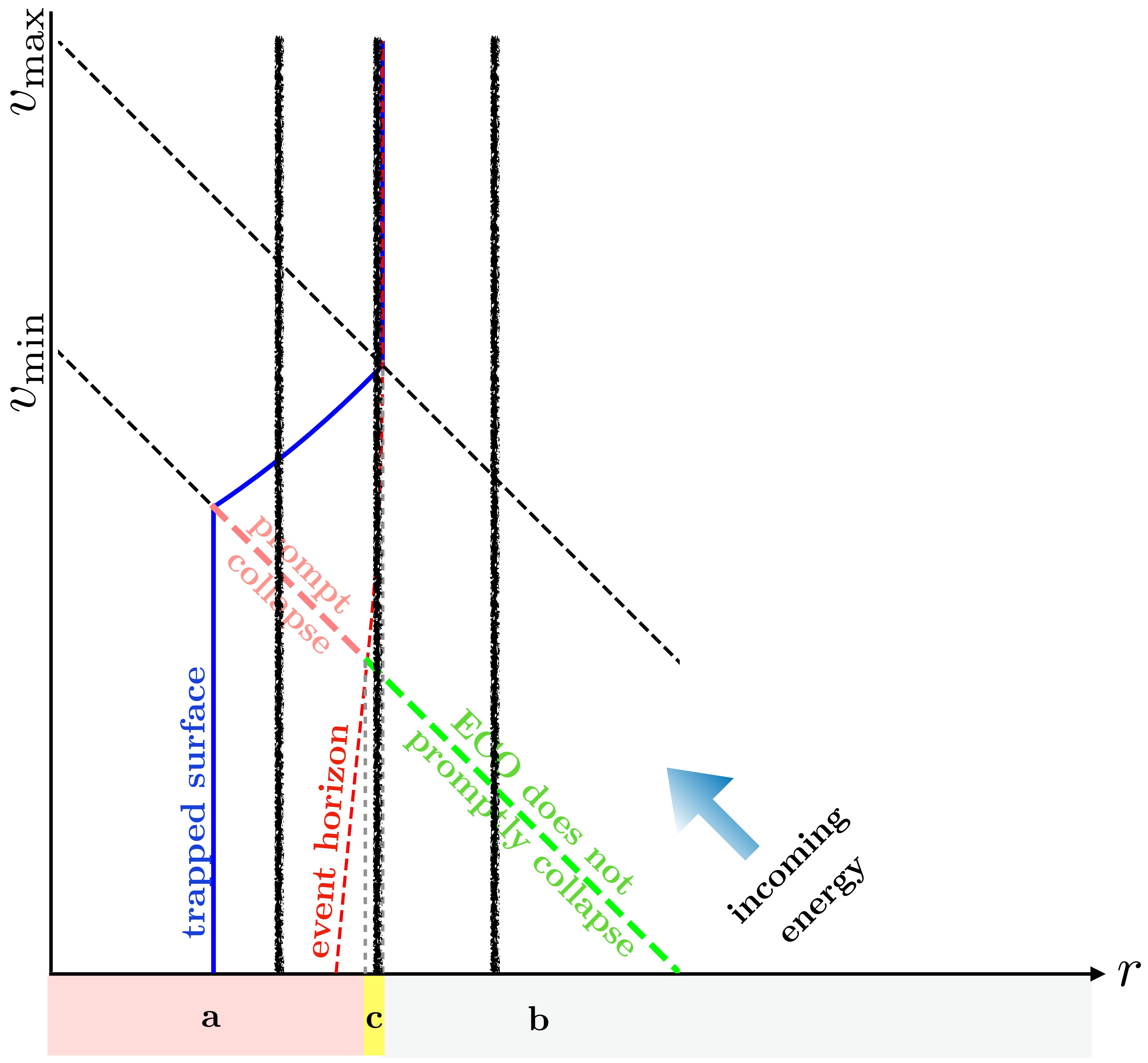
$$r_{\mathrm{ECO}} < 2M_{\mathrm{min}} + \epsilon_{\mathrm{th}}$$

- Type (b): ECO does not collapse

$$r_{\mathrm{ECO}} > 2M_{\mathrm{max}}$$

- Type (c): ECO collapses after a while

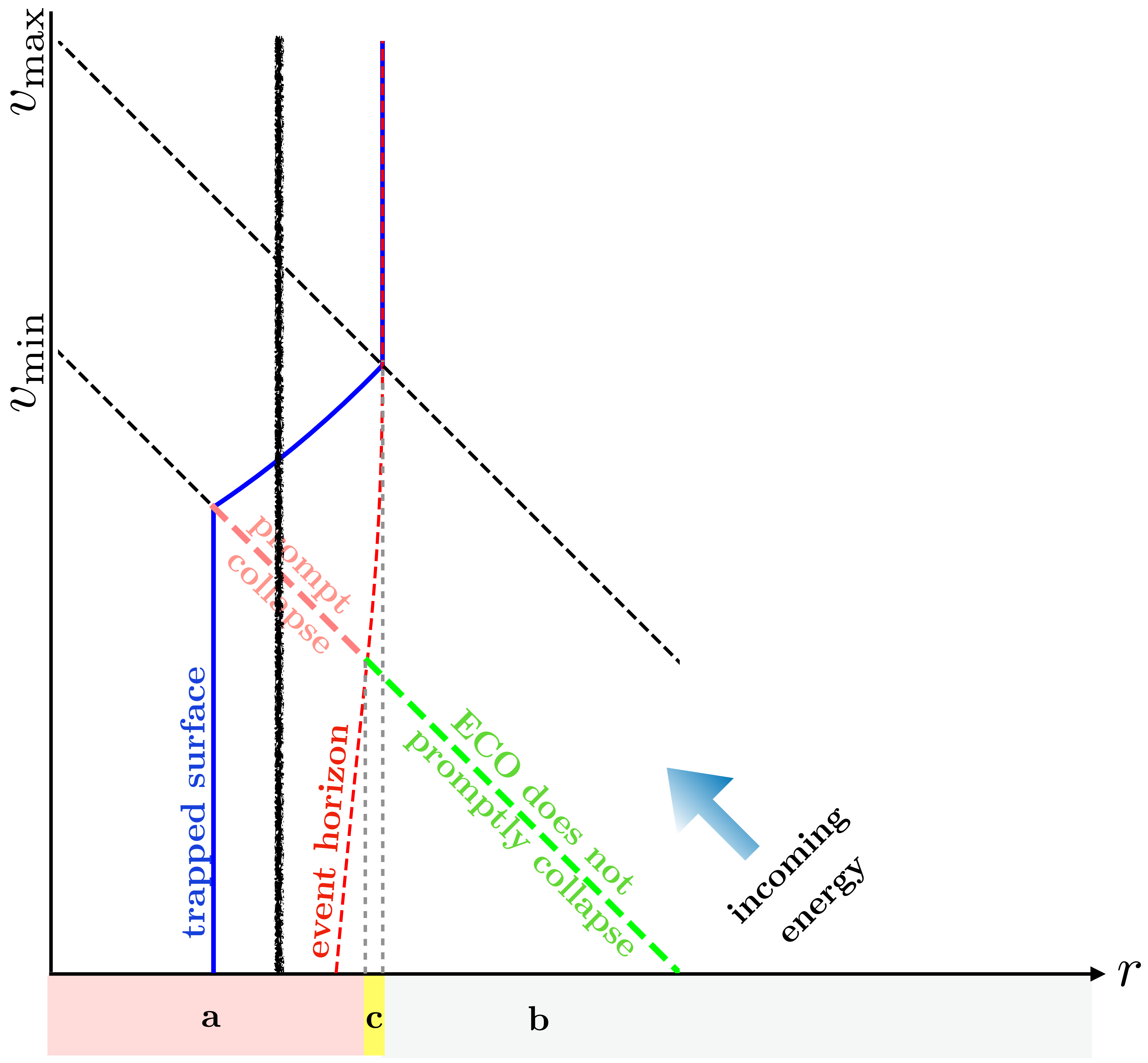
$$2M_{\mathrm{min}} + \epsilon_{\mathrm{th}} < r_{\mathrm{ECO}} < 2M_{\mathrm{max}}$$



Type (a)

- ECO promptly collapses
- All GWs cross the event horizon first
- No reflected waves—no GW echoes
- Consistent with our previous argument

Very compact ECOs are unstable against incoming GWs!



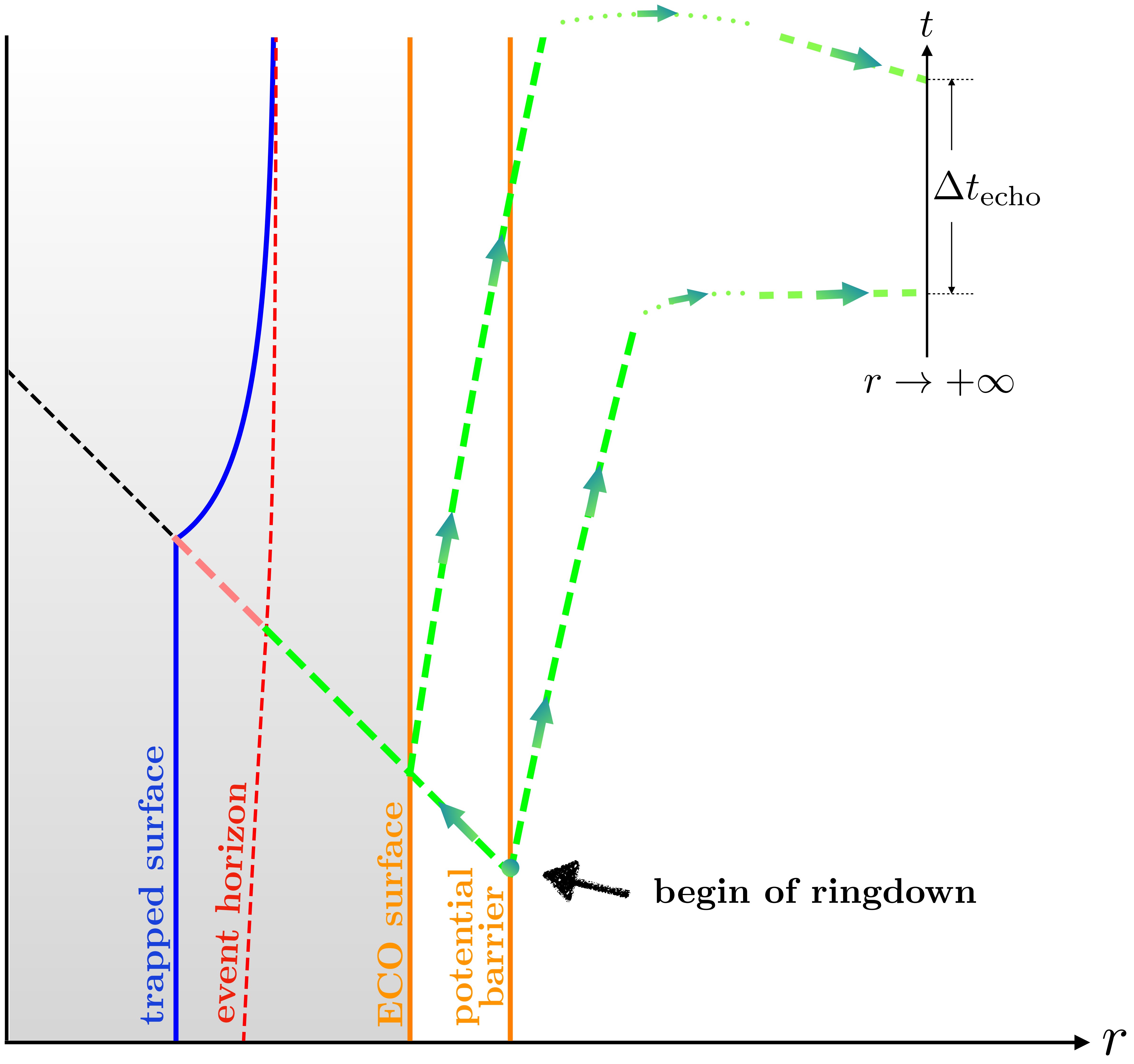
Type (b)

- ECO does not collapse

- Conventional echoes form

- Subsequent echoes also exist

More than one echo!

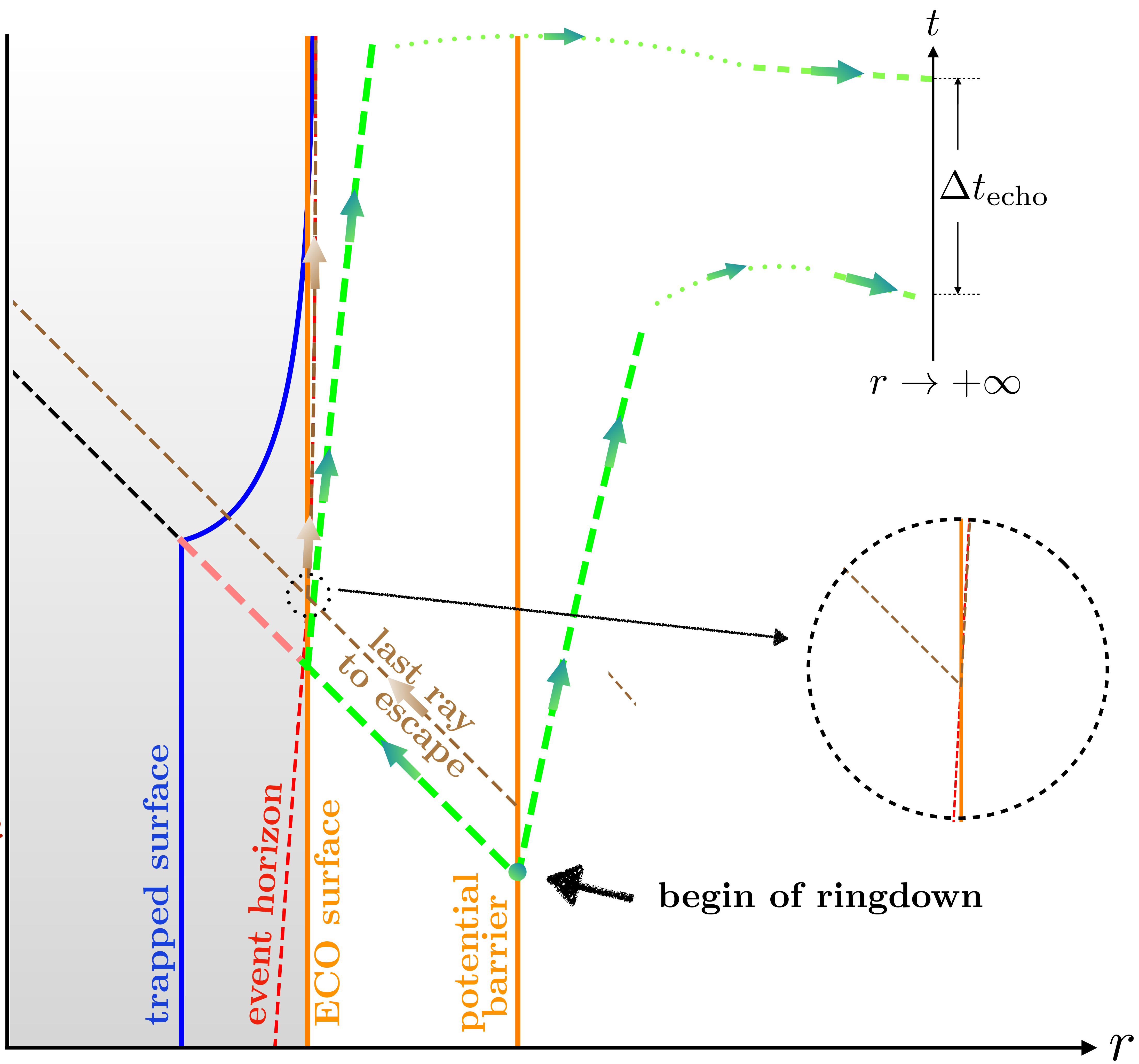


Type (c)

- First part of GWs gets reflected
- Echo arises until the last ray to escape
- No subsequent echoes due to collapse
- Reflected waves seen “frozen”

  redshifted due to gravitational collapse
- Observer sees a weakened QNM

  filtered by the potential barrier



Upper bounds on ECO compactness

- Using the Vaidya spacetime, we obtain the threshold compactness as

$$\frac{\epsilon_{\rm th}}{2M} = 5.6 \times 10^{-3} \left(\frac{\alpha_{\rm H}}{0.05}\right) \left(\frac{\eta}{0.25}\right)$$

- In terms of proper length

$$\Delta_{\rm th} = 0.6\sqrt{M_1 M_2}\sqrt{\frac{\alpha_{\rm H}}{0.05}}$$

- For both CBCs and EMRIs, both distances are much larger than the Planck length

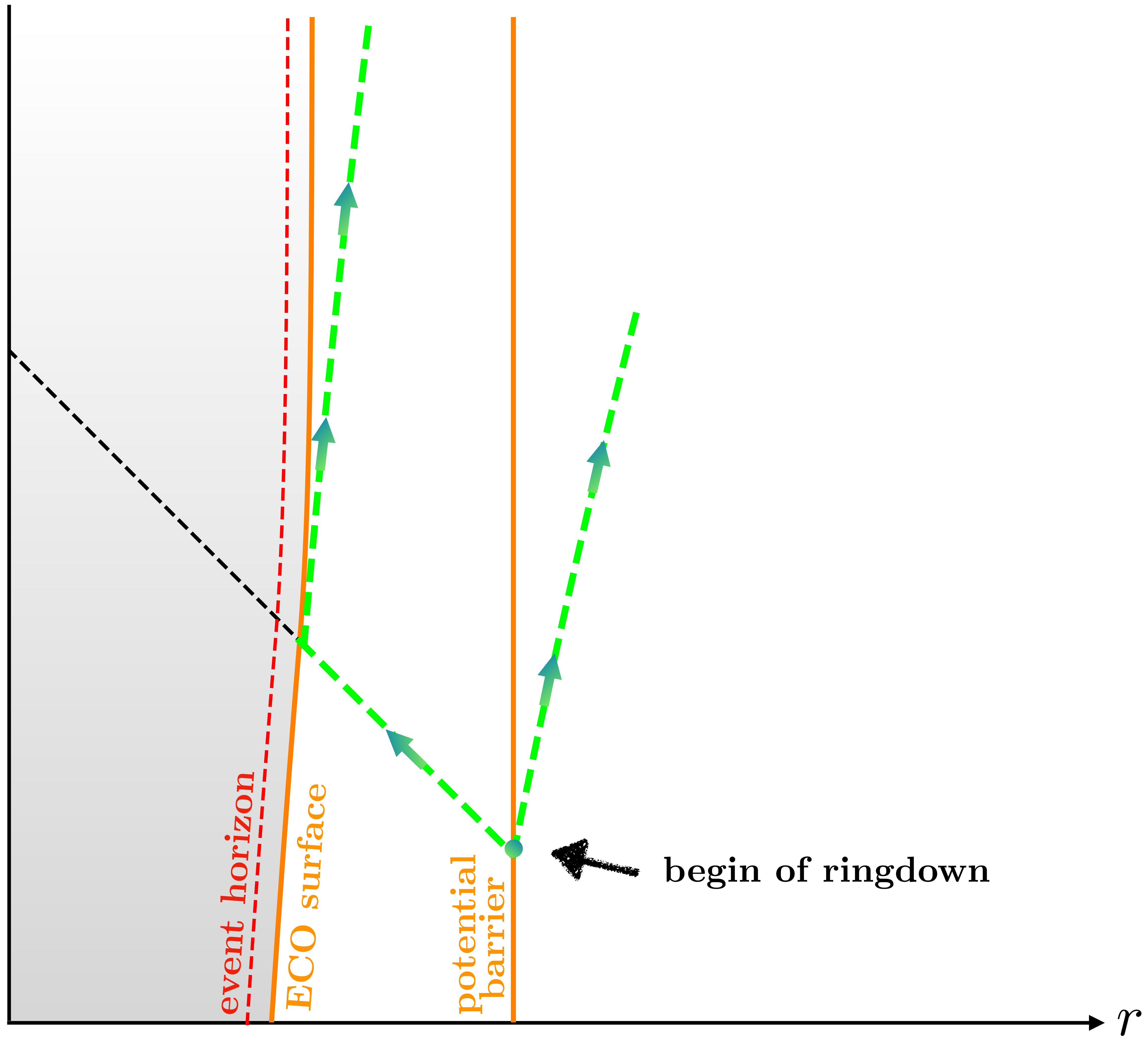
- For stellar mass CBCs, the proper length of the bound is at least Kilometer-scale

Expanding ECOs

- So far we only assume a static ECO
- ECOs may expand in response to future incoming energy (exotic physics, etc)
- ECOs with Planck-scale compactness need to expand accordingly with the event horizon

"teleological"

non-local interactions

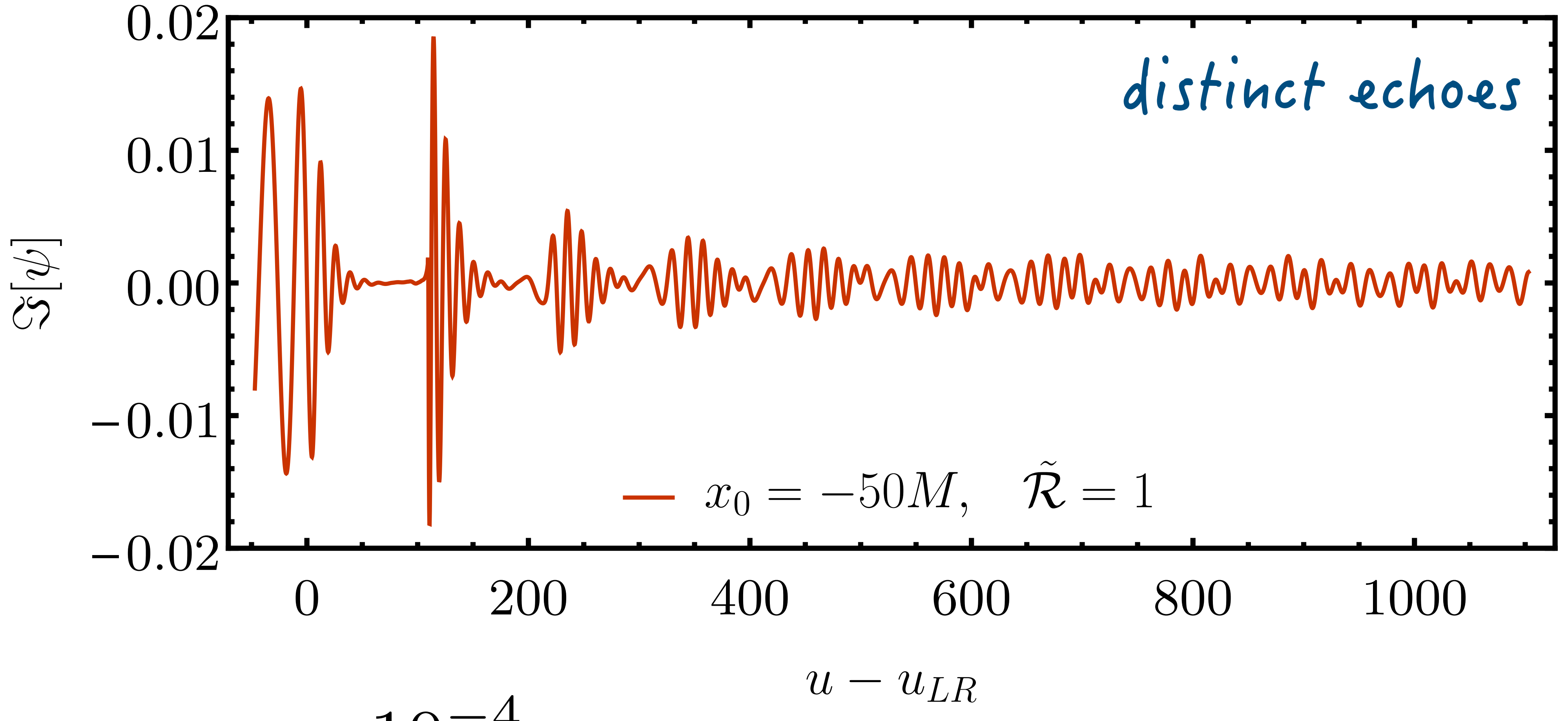


Issues with small compactness

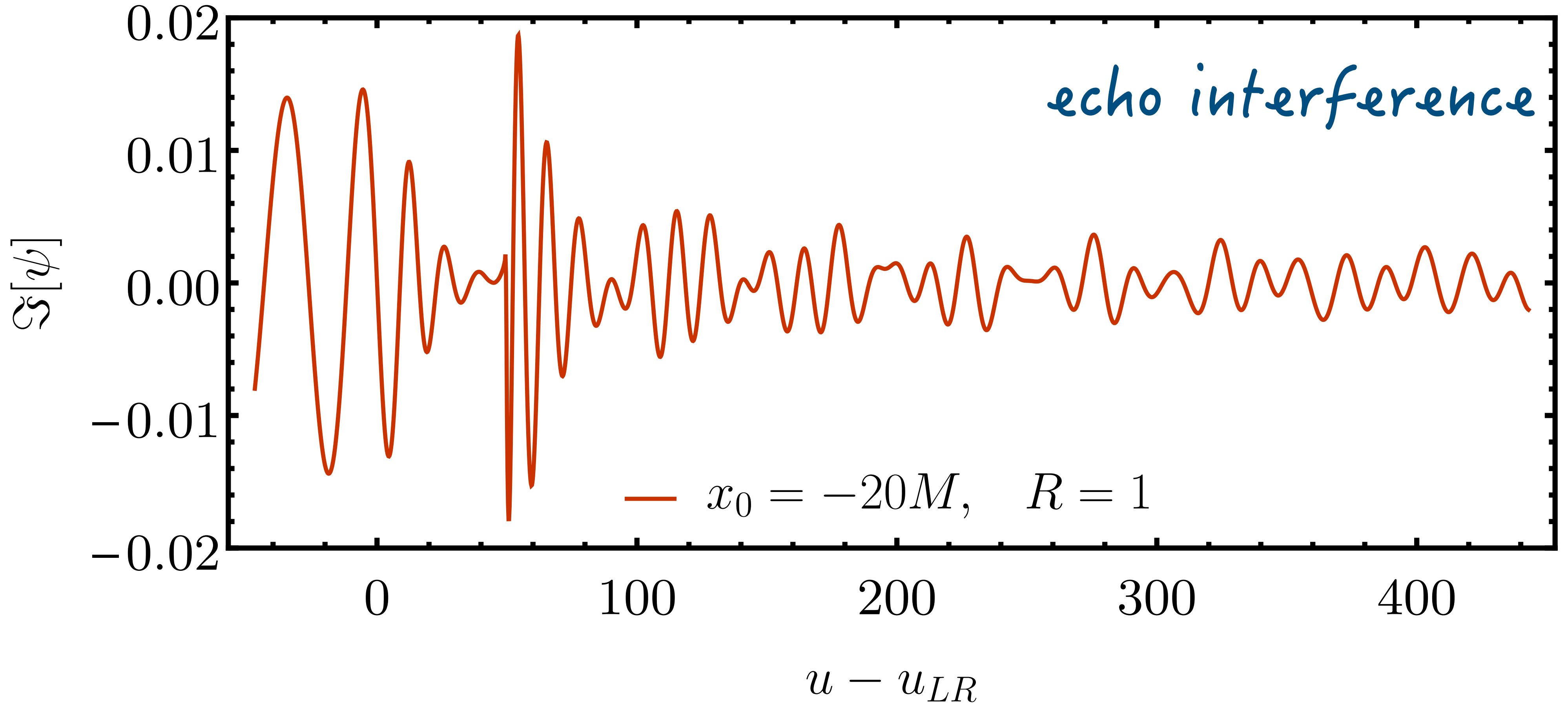
- Distinct echo pulses when spacing of echoes is larger than the echo duration

- Echoes can interfere with each other when their spacing is comparable to the echo duration

$\epsilon \sim 10^{-11}$



$\epsilon \sim 10^{-4}$



[Mark et al 2017]

Issues with small compactness

- Waveform resembles a single decaying sinusoid

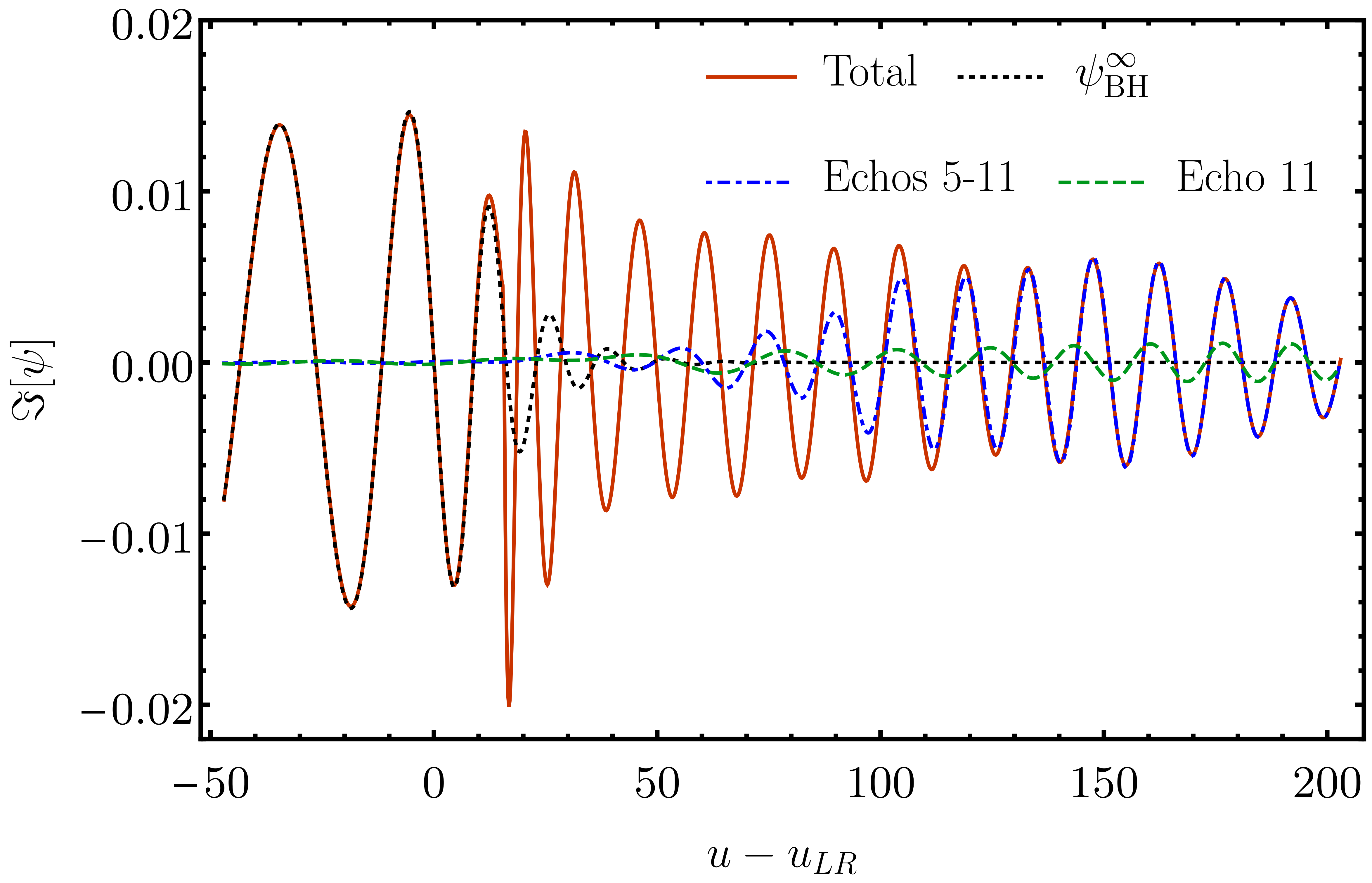
- Coherent superpositions of the late echoes

  almost the same frequencies

- No distinct echoes can be found

  difficult for extractions from GW waveforms!

$\epsilon \sim 0.15$



Quantifying the distinguishability

- Define a ratio between the two time scales

spacing of echoes

$$R \equiv \frac{\Delta t_{\rm echo}}{\tau_{\rm echo}} \sim 4M\gamma \log \frac{M}{\epsilon}$$

ringdown time scale $\sim 1/\gamma$

- The echo is separated from the main wave when

$$R \gg 1$$

- Otherwise echoes can be indistinguishable

Quantifying the distinguishability

- Connecting two bounds for type (b) ECOs

threshold compactness

$$\frac{r_{\rm ECO}}{M} - 2 = \frac{\epsilon_{\rm th}}{M} + \exp\left(\frac{-R}{4M\gamma} + \frac{1}{2}\right)$$

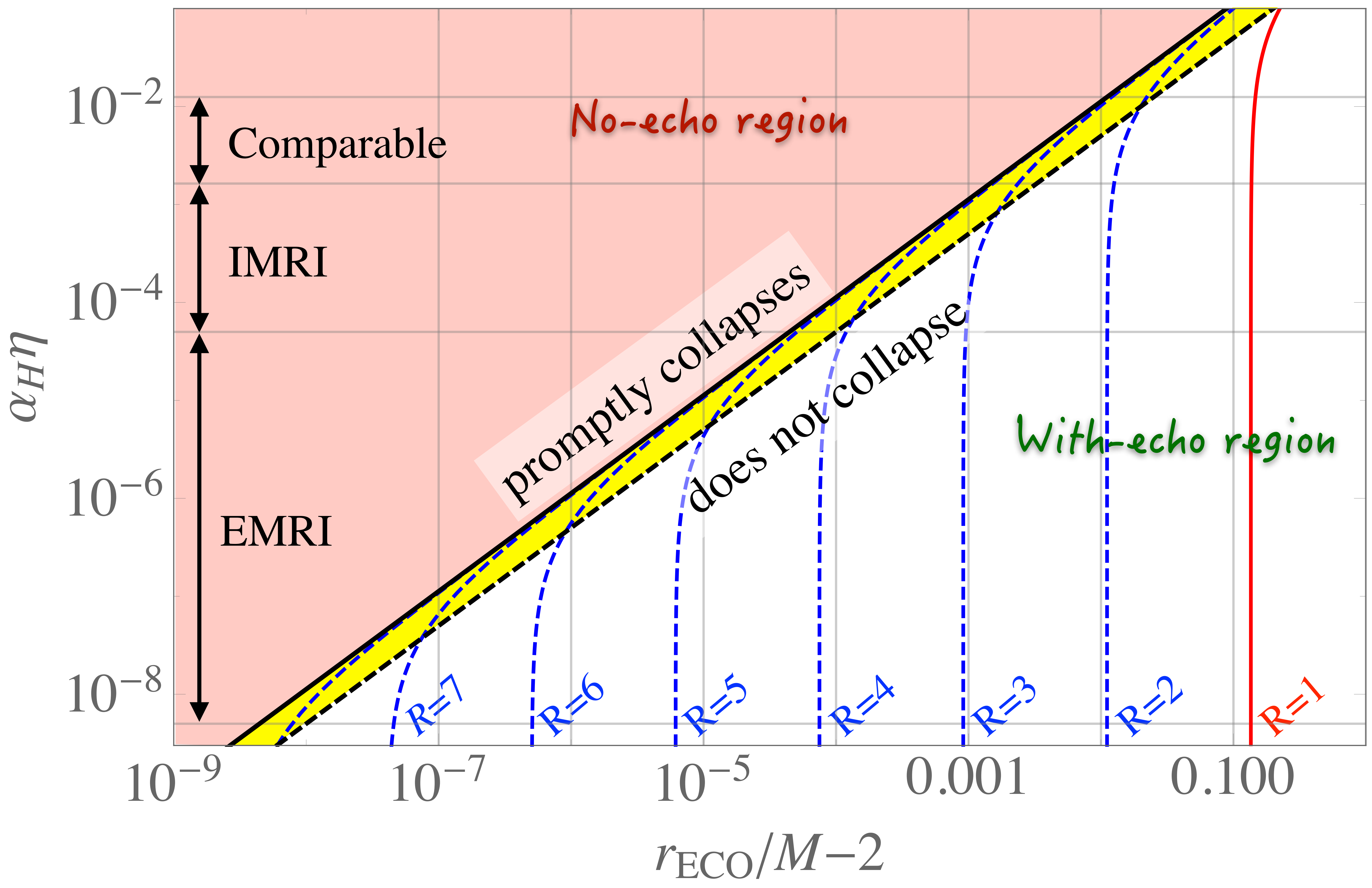
- LIGO CBCs:

$M_1 \sim M_2$ $\quad$ $R_{\rm th} \sim 1.9$ $\quad$ less distinct echoes

- LISA EMRIs:

$M_2/M_1 = 10^{-6}$ $\quad$ $R_{\rm th} \sim 7.8$ $\quad$ distinct echoes

Summary of GW-echo phenomenology



LIGO only sees a "fine-tuned" region

LISA can see a much larger region

Limits of our arguments

- Only focused on the echoes of reflective type, without considering those of transmissive type

  model dependent!

- The ingoing Vaidya spacetime does not capture the backreaction of the reflected GW waves

  can be important for large reflectivity!

- Did not describe what happens as the star impacts the ECO

  takes place roughly as the ringdown signals impinge on the final object!

Details

arXiv:1902.08180

Reflected waves for type (c) ECOs ?

Back-reactions of reflected waves?

Spinning cases?

Echo waveform from Teukolsky equations?

Numerical relativity simulations?