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STRUCTURES
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Breaking black-hole uniqueness at supermassive scales

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Black-hole uniqueness

- A central prediction of GR is that all vacuum black holes are described exactly by the Kerr metric
- Black holes all have the same spacetime structure, rescaled only by their mass
- The same theoretical model describes astrophysical objects ranging, at least, 10 orders of magnitude in mass, from $M \sim M_\odot$ to $M \sim 10^{10} M_\odot$
- Any deviation from Kerr would signal new physics

Refer to Thomas' talk on motivations to look for new physics in gravity

Where can we potentially observe new physics?

- Cosmological scales
- Strong-gravity regime

New physics should manifest only in these regimes, and agree with GR in all other regimes where it is well-tested (up to experimental accuracy).

Finding an alternative model fulfilling these requirements is highly non-trivial!

Scalarization

Scalarization

Damour et. al, 1993
Doneva et. al, 2017
Antoniou et. al. 2017
Silva et. al, 2017
…

- One way to excite new physics exclusively in certain regimes is through **scalarization**
- Scalarization occurs in gravitational theories obeying the following conditions:

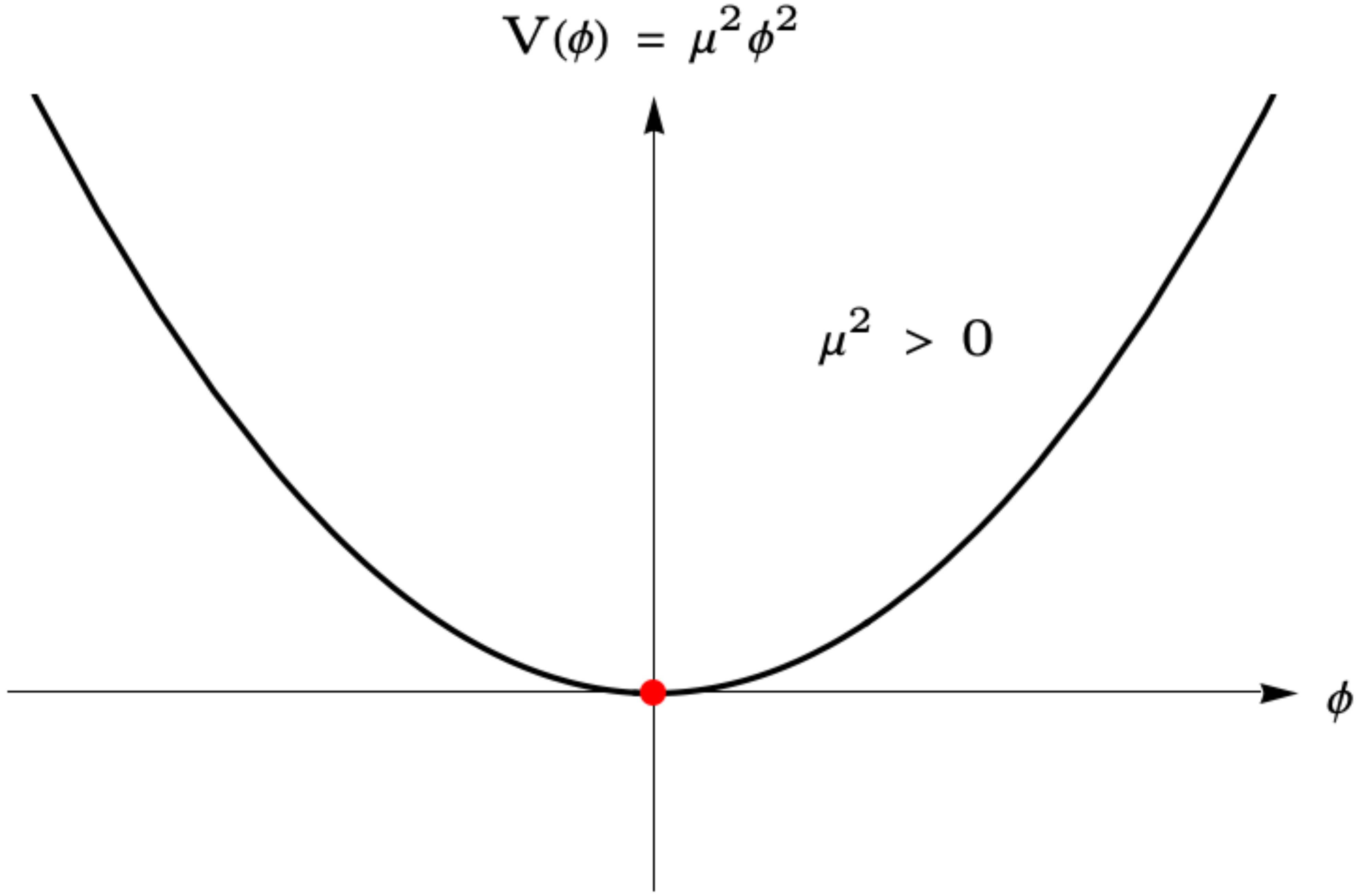
1. There is (at least) one new scalar field
2. The theory allows for (at least) two different branches of solutions:

   (i) a scalar-free solution which coincides exactly with GR

   (ii) a scalarized solution, different from those of GR, which is excited only in certain regimes

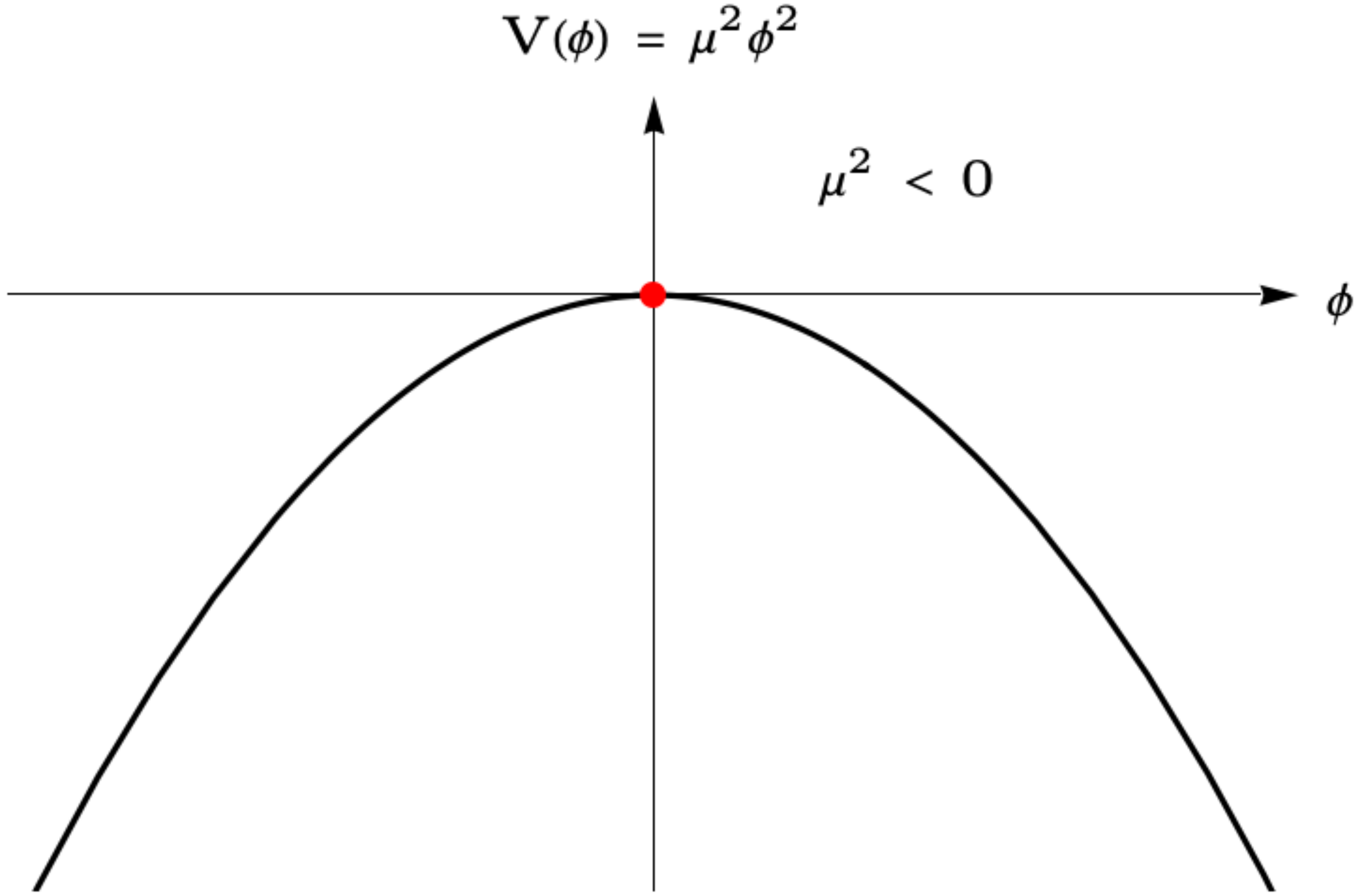
Tachyonic Instabilities

Prelude to scalarization



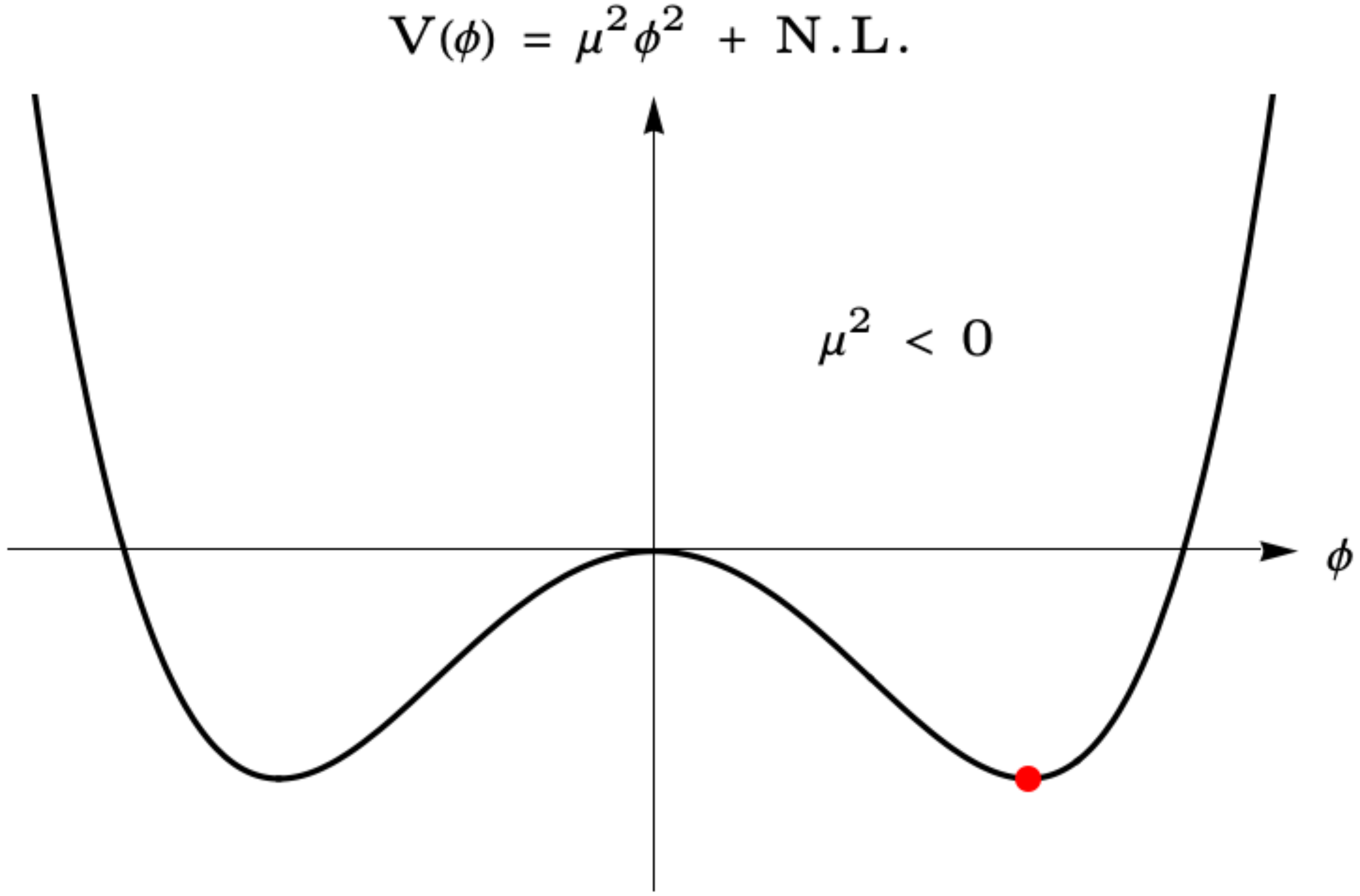
Tachyonic Instabilities

Prelude to scalarization



Tachyonic Instabilities

Prelude to scalarization



Scalarization

- New scalar, ϕ, that obeys the following Klein-Gordon “wave” equation

$$\Box \phi = \mu_{\text{eff}}^2 \phi$$

where $\mu_{\text{eff}} \equiv \mu_{\text{eff}}(x)$ is a (potentially) spacetime dependent effective mass.

- Suppose $\mu_{\text{eff}}^2 \ll 0$ near a compact object. The scalar becomes a tachyon near the compact object, inducing an instability
- Then new physics can be excited near compact objects in certain regimes, even if in all others the scalar is dormant (GR + $\phi = 0$)

Scalarization

An example

- Consider the following theory belonging to the Horndeski class as a proof-of-concept:

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left(R - (\partial\phi)^2 - \mu^2\phi^2 + \alpha\phi^2\mathcal{G}\right)$$

$$\mathcal{G} = R^2 - 4R_{\alpha\beta}R^{\alpha\beta} + R_{\alpha\beta\mu\nu}R^{\alpha\beta\mu\nu}$$

$$[\alpha] = \text{length}^2$$

- The scalar field equation is

$$\Box\phi = \left(\mu^2 - \alpha\mathcal{G}\right)\phi \equiv \mu^2_{\text{eff}}\phi$$

- The field equations allow GR vacuum solutions together with $\phi = 0$

Scalarization of black holes

How does the scalar behave near a Schwarzschild black hole?

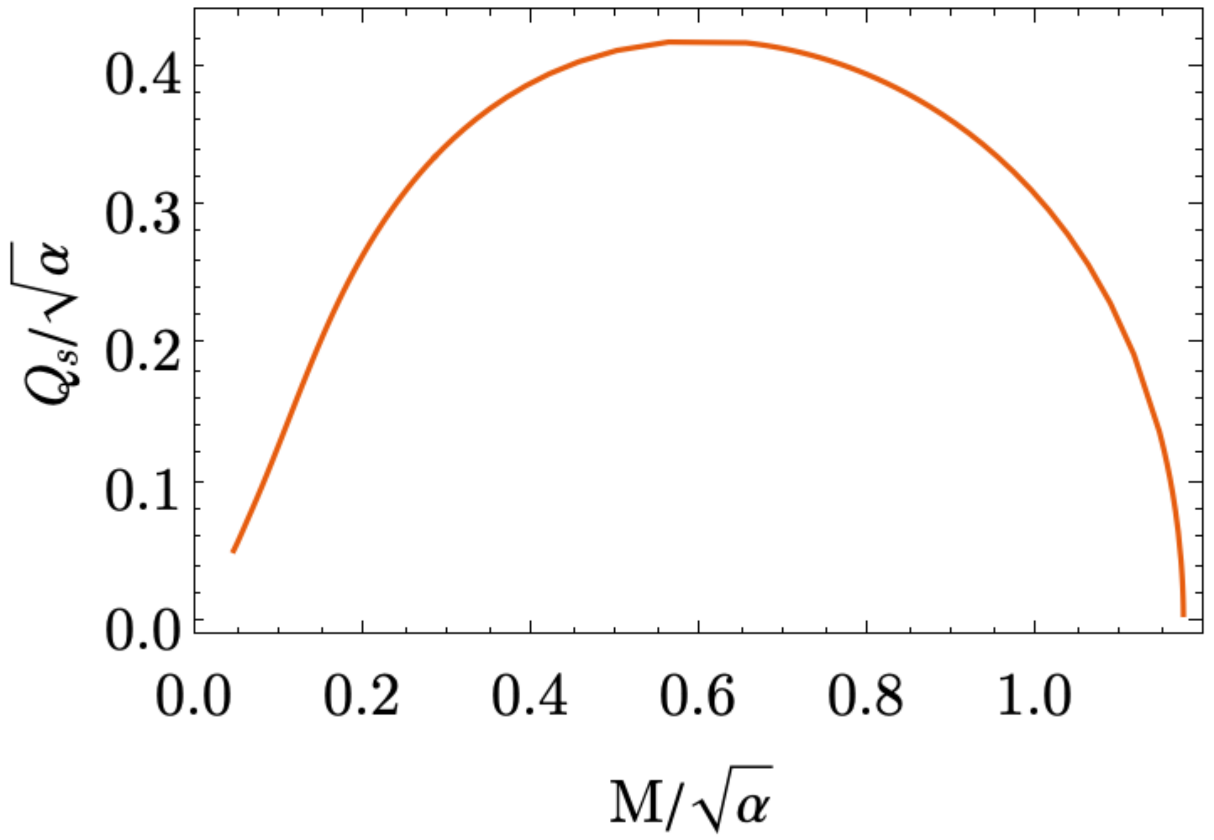
- The closer we are to the horizon ($r_H = 2M$), the larger the GB curvature $\mathscr{G} = \dfrac{48M^2}{r^6} > 0$
- The smaller the black hole, the larger the curvature $\mathscr{G}(r_H) \propto 1/M^4$
- If the black hole is small enough (i.e., the curvature sufficiently large), we can have $\mu_{\text{eff}}^2 = \mu^2 - \alpha\mathscr{G} < 0$ in its vicinity
- In these conditions there is a tachyonic instability around sufficiently small black holes

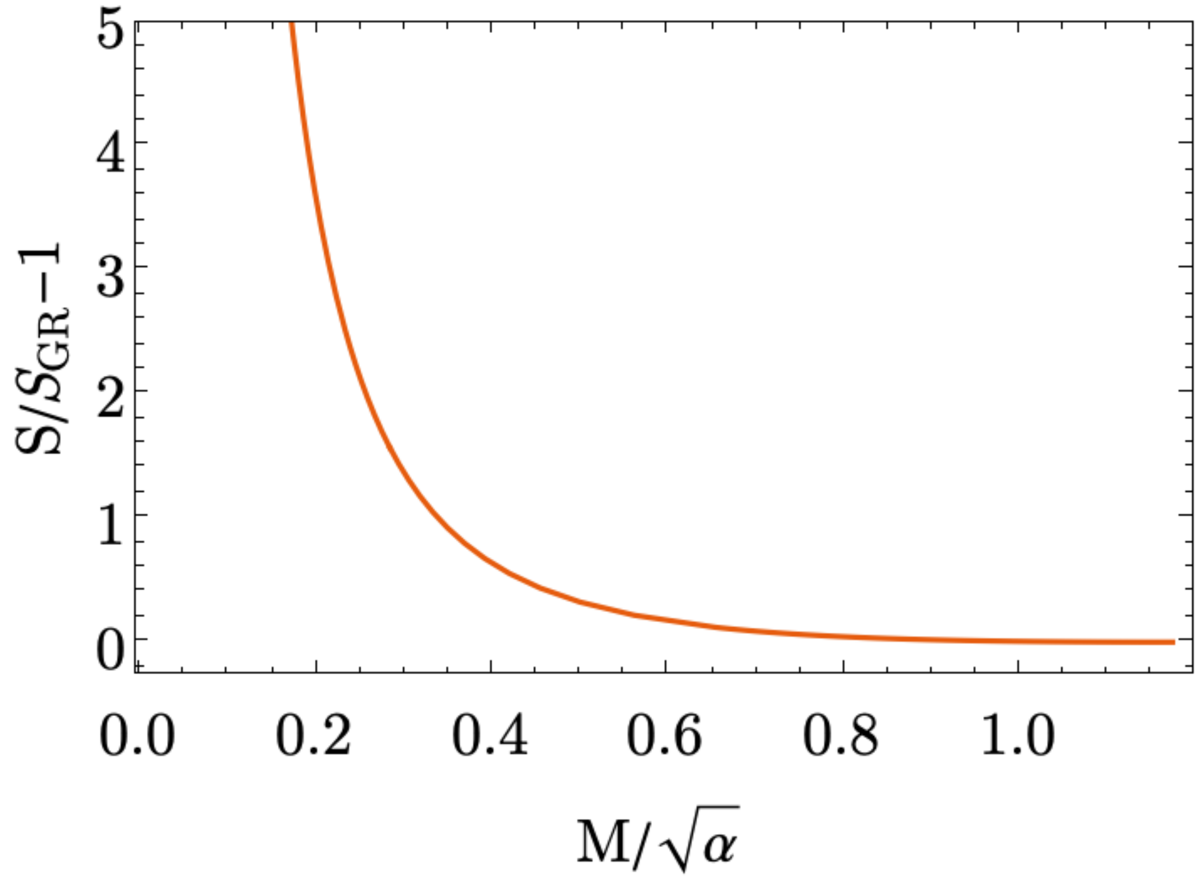
Scalarization of black holes

- Scalarization occurs when

$$M \sim \sqrt{\alpha}$$

- A new branch of *scalarized* black holes branches of Schwarzschild. Black-hole uniqueness is lost in this regime!





Scalarization of black holes

Which black holes scalarize?

- The coupling constant α defines the scale of new physics (only black holes with masses $M \sim \sqrt{\alpha}$ scalarize)

- Can α be arbitrarily large? The answer is “no”

Scalarization of black holes

Which black holes scalarize?

- Neutron stars are also highly compact objects, and therefore susceptible to scalarization
- However, binary pulsar data we have is in great agreement with GR
- The scale of new physics can be at most $\sqrt{\alpha} \sim \mathcal{O}(\mathrm{km})$ [see e.g. Doneva et. al, 2112.03869]
- We can only potentially see new physics in solar-mass black holes

$M_\odot \sim 1\mathrm{km}$

Breaking black-hole uniqueness at supermassive scales

Supermassive scales

- Supermassive scales: black holes with $M \gtrsim 10^5 M_\odot$
- Common expectation: the higher the curvature, the more likely we are to see new physics
- SMBHs have very low horizon curvature
- Intuitively, to significantly impact SMBHs, new length scales/couplings of our theory must be of order of the gravitational radius of the SMBH
- Experiments probing larger black holes such as LISA or the EHT would (likely) be insensitive to new physics

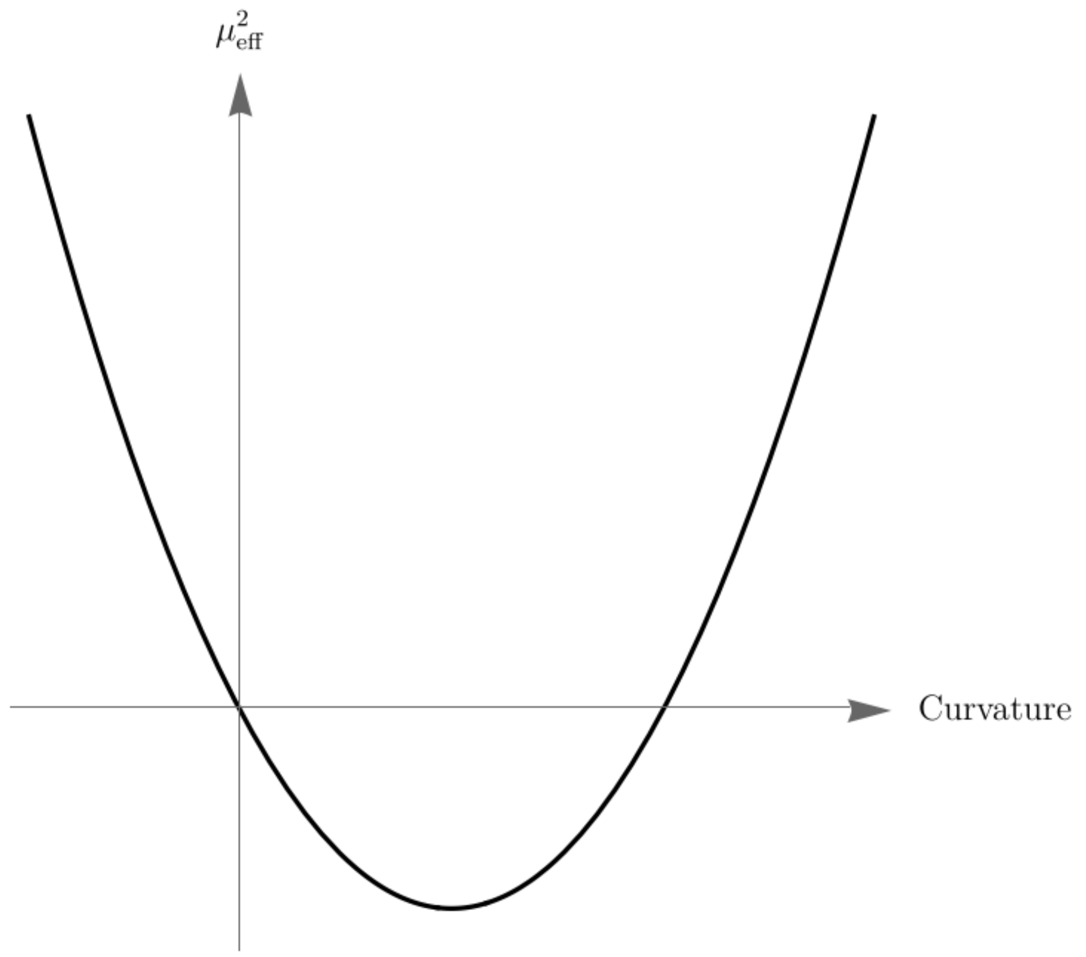
Scalarizing supermassive black holes

- Is it really impossible to have new physics affect SMBHs, while the weak-field limit, neutron stars etc… all remain well-described by GR?
- For SMBHs to scalarize in some model, it must be that

$$\Box\phi = \mu_{\text{eff}}^2\phi$$

$$\mu_{\text{eff}}^2 \sim \begin{cases} \text{significantly negative around supermassive black holes} \\ \text{positive or possibly negative but very small in other regimes} \end{cases}$$

Scalarizing supermassive black holes



- We considered the following expression for the effective mass

$$\mu^2_{\text{eff}} = -\,\alpha_1\,\mathscr{G} + \alpha_2^3\,\mathscr{G}^2$$

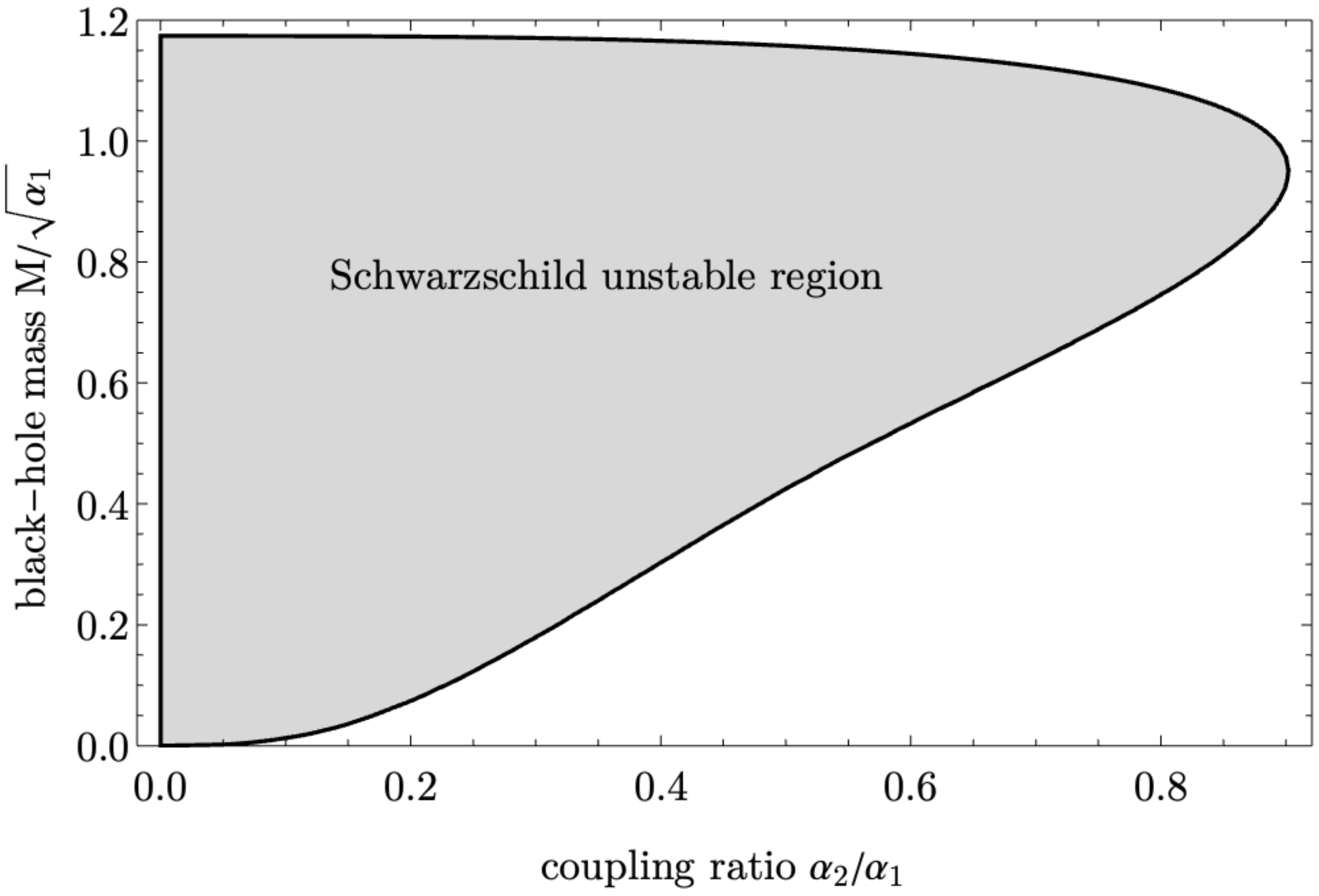
- When $\mathscr{G} \gg 1$, the second term dominates giving a positive contribution to the effective mass

- When curvatures are intermediate, there is an interplay of the two terms, possibly leading to scalarization

- When $\mathscr{G} \ll 1$, so is the effective mass, and we do not expect instabilities

Scalarizing supermassive black holes

Instability of the Schwarzschild black hole

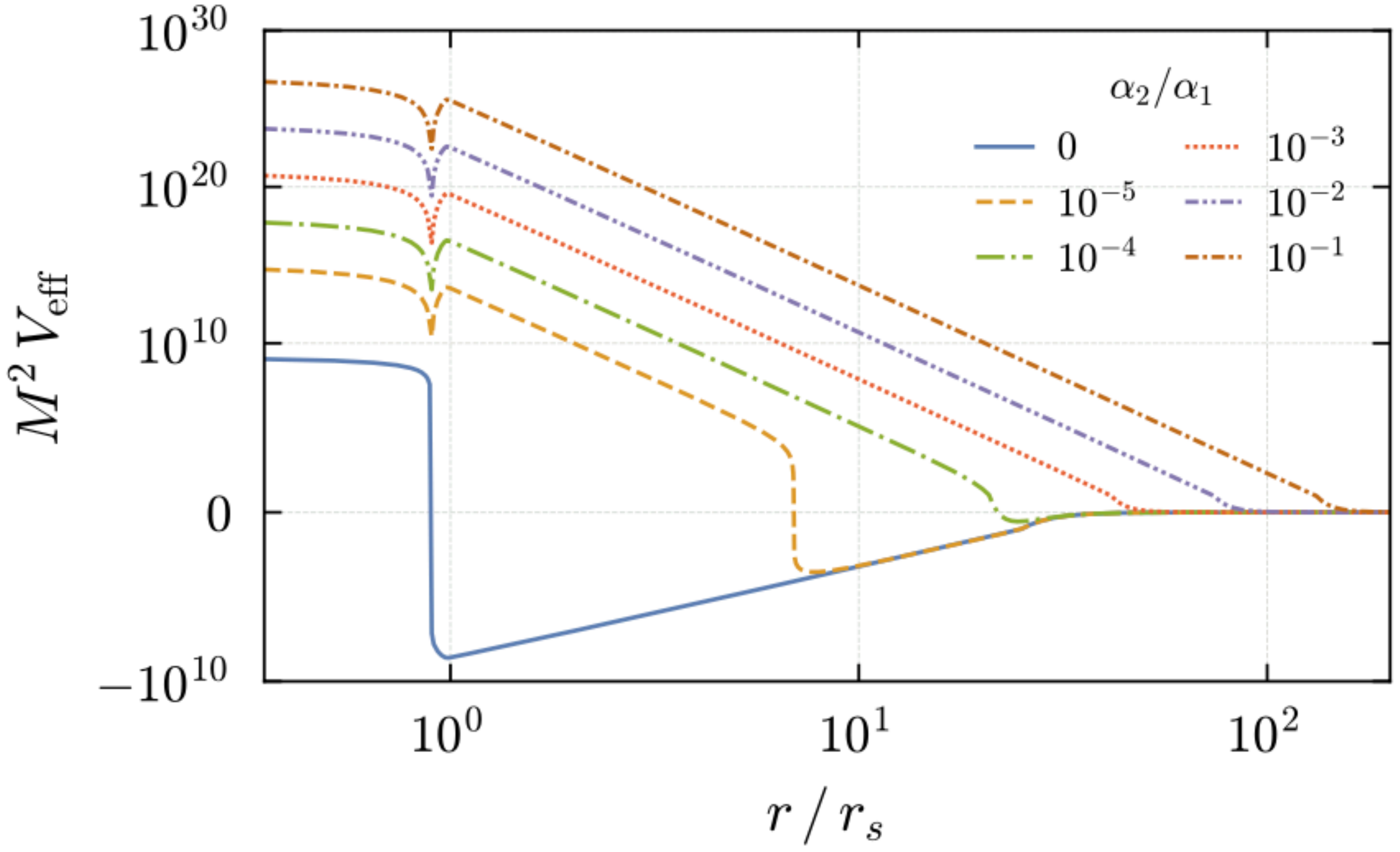


Evading scalarization of other astrophysical objects

Neutron stars

- We do not expect scalarization to occur in neutron stars if both couplings are taken to be in the supermassive scale (curvature is very high)

- Example: Effective potential of scalar perturbations for a neutron star with $M \approx 1.4 M_\odot$, $r_s \approx 11\mathrm{km}$, and taking $\sqrt{\alpha_1} \sim 10^6 M_\odot$



$$\frac{d^2u}{dr_*^2} + \left(\omega^2 - V_{\text{eff}}\right)u = 0$$

Scalarizing supermassive black holes

The model

So far we have only considered the scalar-field equation

$$\Box\,\phi = (-\alpha_1 \mathscr{G} + \alpha_2^3 \mathscr{G}^2)\phi \equiv \mu_{\rm eff}^2 \phi$$

<u>What reasonable model could produce such an equation?</u>

Scalarizing supermassive black holes

The model

- Consider the following theory

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\,\left[R - (\partial\phi)^2 + (\alpha_1\mathcal{G} - \alpha_2^3\mathcal{G}^2)\phi^2\right]$$

- By introducing an auxilliary scalar ψ

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left[R - (\partial\phi)^2 + \alpha_1\phi^2\mathcal{G} - 2\alpha_2^3\left(\psi\mathcal{G} - \frac{\psi^2}{2}\right)\phi^2\right]$$

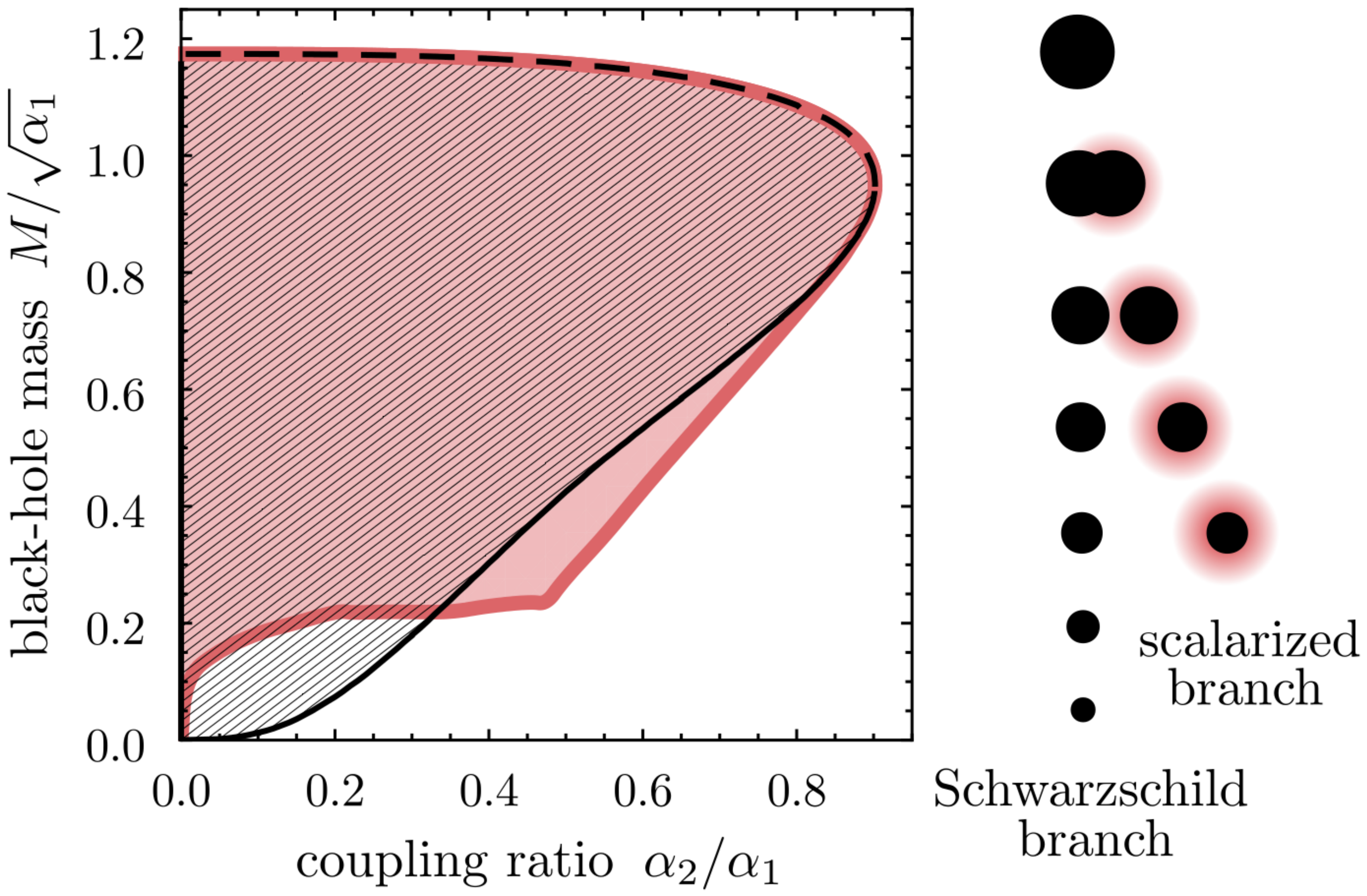
- All equations of motion are second-order in all involved fields, $g_{\mu\nu}$, ϕ and ψ

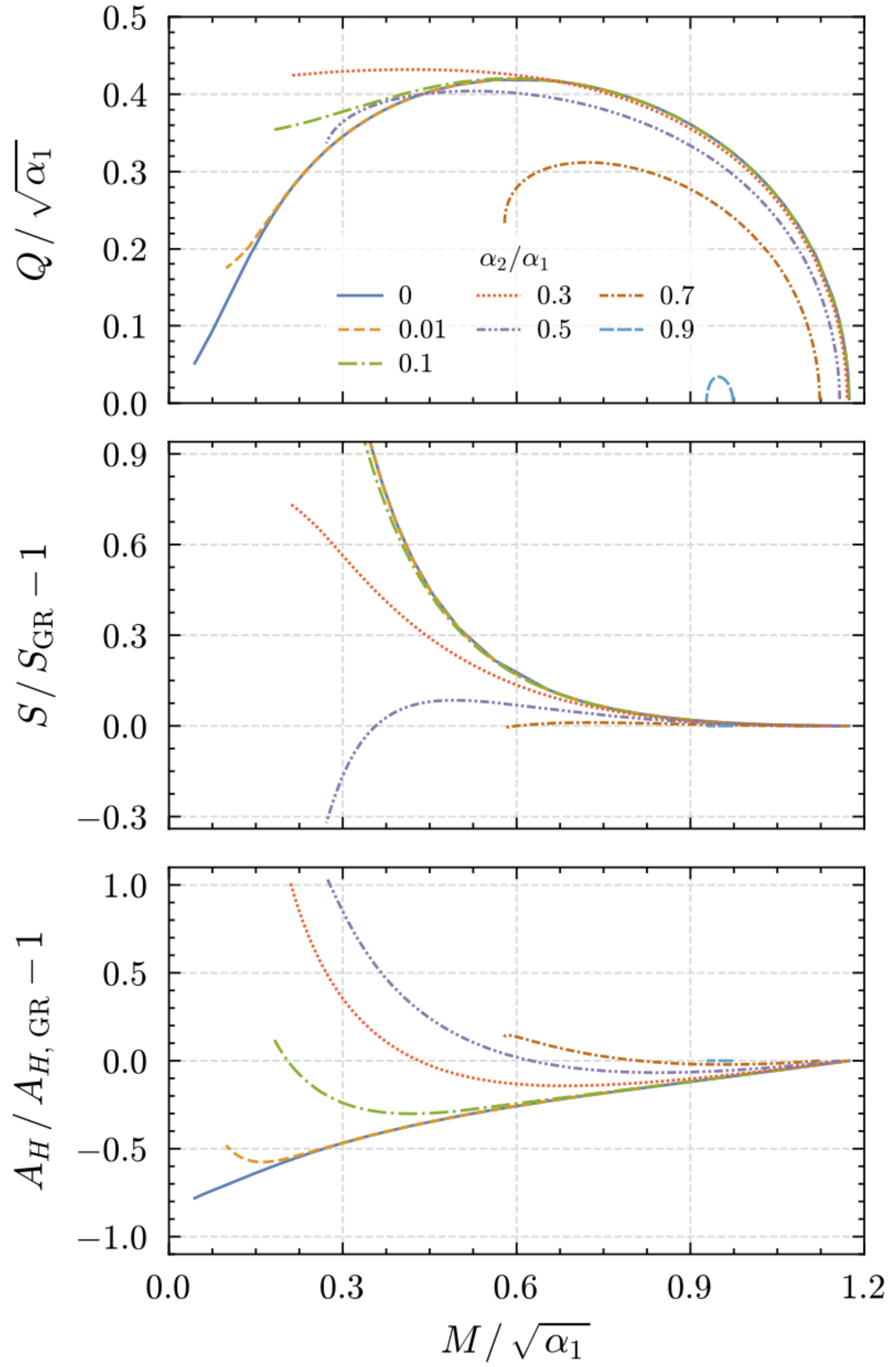
- The model belongs to a bi-scalar extension of Horndeski

Scalarizing supermassive black holes

Scalarized black holes

- We have numerically solved the field equations in spherical symmetry to obtain scalarized black hole solutions





Cosmological stability of the theory

- In the standard scalarization scenario $\mu_{\text{eff}}^2 = -\alpha_1 \mathcal{G}$, which is highly negative during inflation
- Assuming the Universe starts in a GR vacuum, there is catastrophic instability that prevents inflation [Charmousis et. al, 1903.02399]
- In our case $\mu_{\text{eff}}^2 = -\alpha_1 \mathcal{G} + \alpha_2^3 \mathcal{G}^2$. The new term dominates during inflation and prevents any instability
- Compatible with all cosmological evolution described by GR

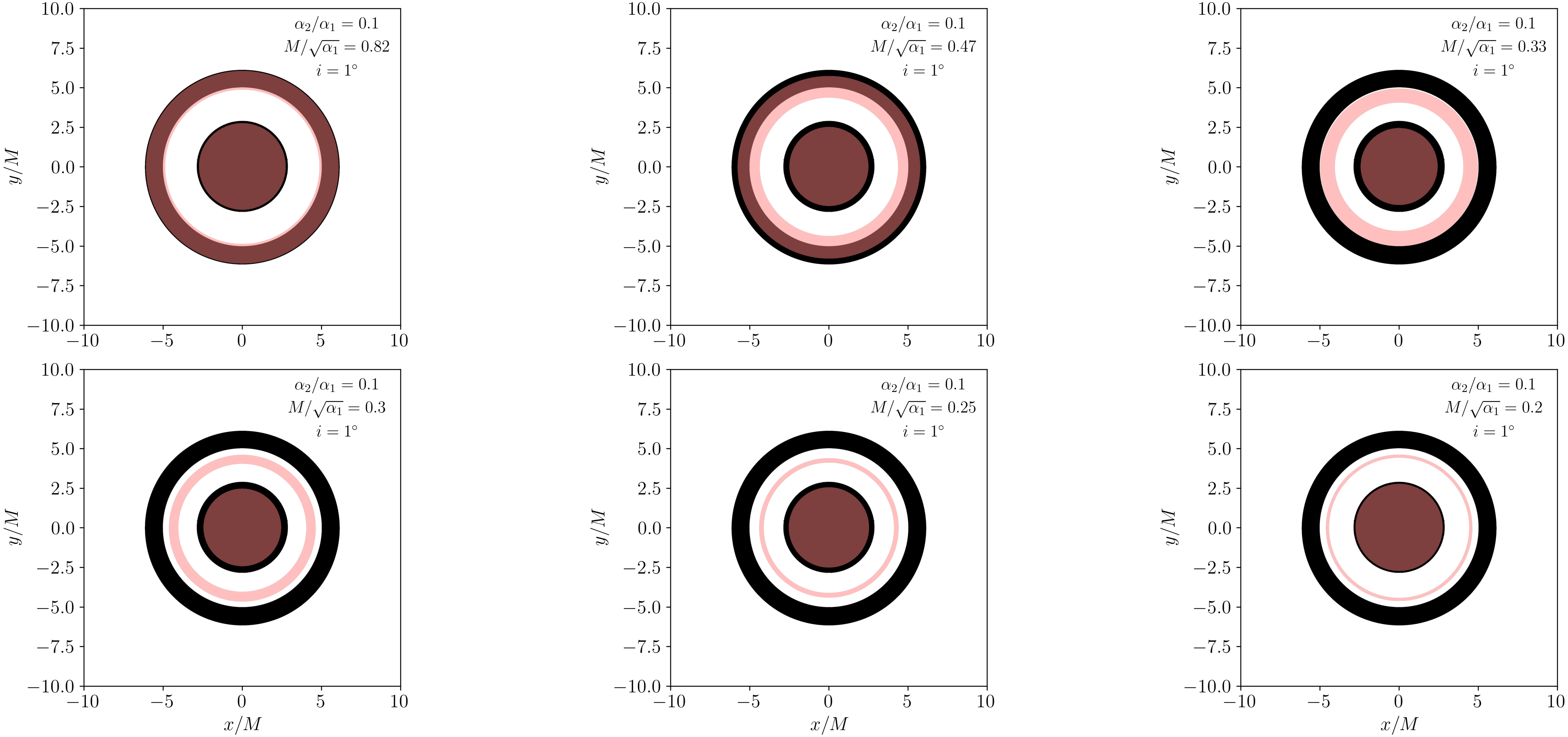
Conclusions

Conclusions

- We introduced a novel scalarization model where new physics manifests only for supermassive black holes
- Consistent cosmological evolution
- To constraint the theory and probe supermassive scales we need experiments targeting those scales
- Potential observational consequences for: EHT, LISA, pulsar-timing arrays…
- This theory serves as a proof-of-concept that supermassive black holes can significantly deviate from Kerr

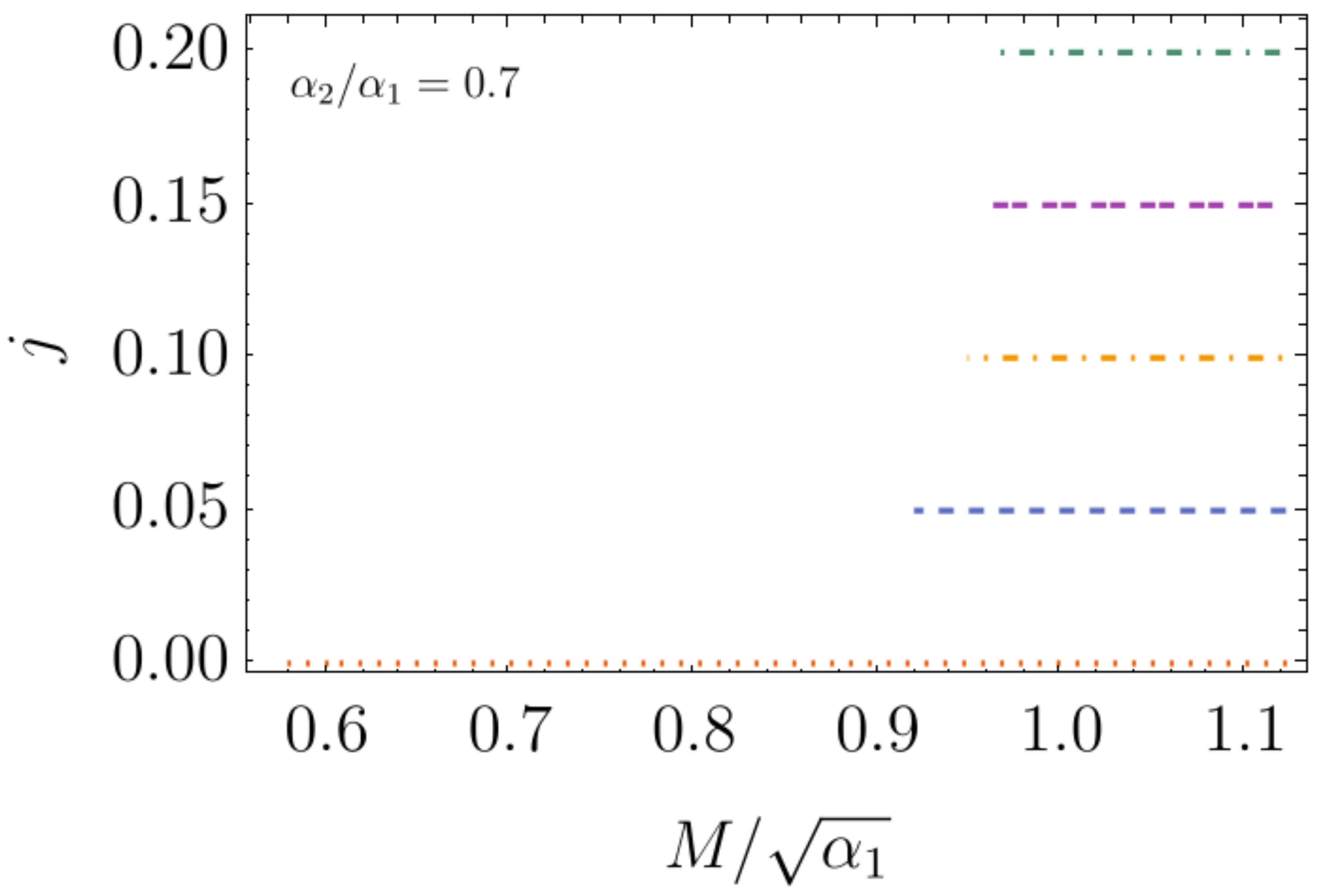
Ongoing and Future Work

Black-Hole Imaging

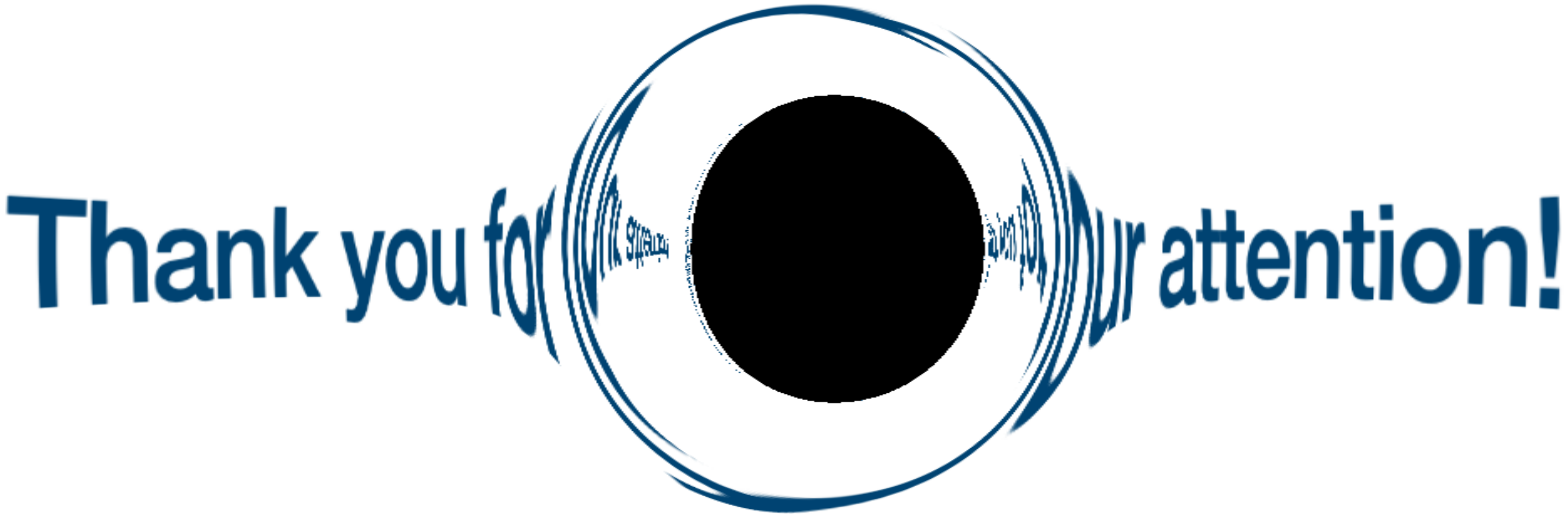


Ongoing and Future Work

- Rotating black holes



- SMBH scalarization from an EFT point of view



Thank you for your attention!