Black Hole Scalarization

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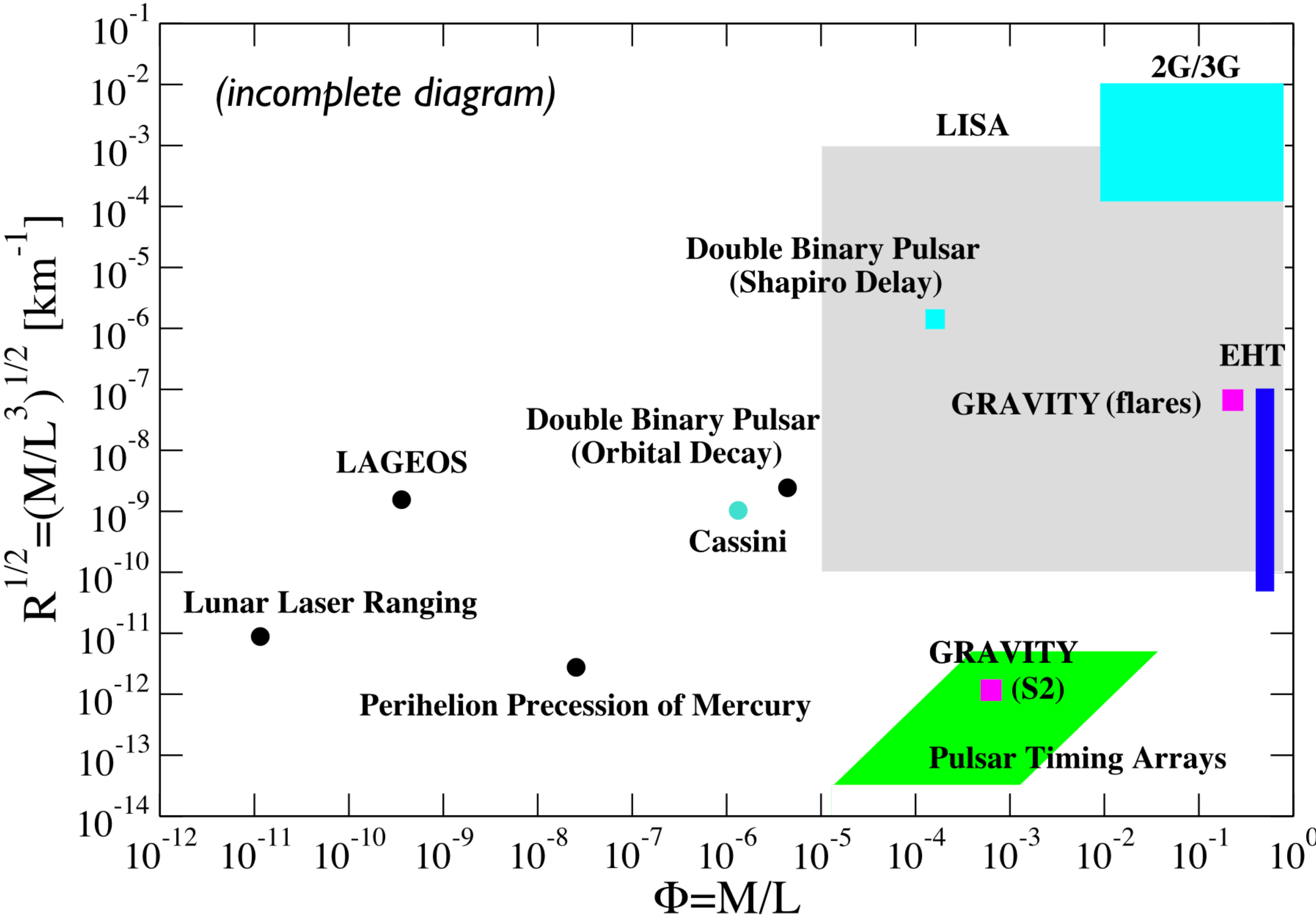
Probing a new regime?



(credit: Yunes, 3G science report, in prep)

taken from arXiv:1903.09221

Spontaneous scalarization

There is need for models where new physics "appears" when gravity gets strong

Example: A theory with an extra scalar field

Jordan frame action:

$$S_{\rm st} = \int d^4x\sqrt{-g}\left(\varphi R - \frac{\omega(\varphi)}{\varphi}\nabla^\mu\varphi\nabla_\mu\varphi - V(\varphi) + L_m(g_{\mu\nu},\psi)\right)$$

Redefinitions:

$$\hat{g}_{\mu\nu} = \varphi g_{\mu\nu} = A^2(\phi)g_{\mu\nu} \qquad 4\sqrt{\pi}\varphi d\phi = \sqrt{2\omega(\varphi)+3}\,d\varphi$$

Spontaneous scalarization

Einstein frame action:

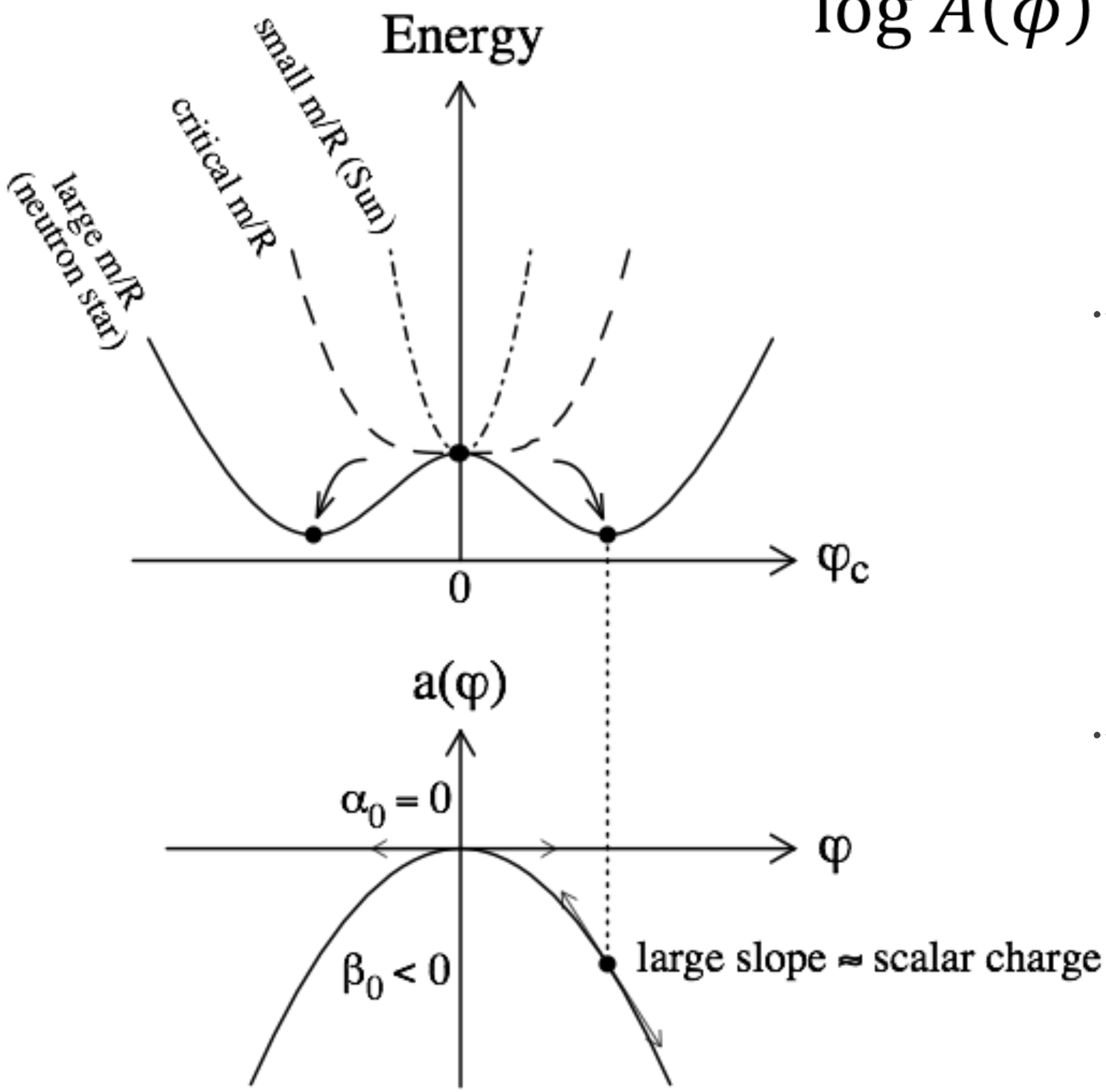
$$S_{\rm st} = \int d^4x\sqrt{-\hat{g}}\left(\frac{\hat{R}}{16\pi} - \frac{1}{2}\hat{g}^{\nu\mu}\partial_\nu\phi\partial_\mu\phi - U(\phi)\right) + S_m(g_{\mu\nu},\psi)$$

Scalar EOM: $\Box\phi = A^3 A' T = U'_{\rm eff}$

- If $A'(\phi_0) = 0$ then the theory will admit GR solutions around matter!
- However they will not necessarily be the only ones...
- The non-GR configuration is preferred for sufficiently large central density

T. Damour and G. Esposito-Farese, Phys. Rev. Lett. 70, 2220 (1993)

Tachyonic instability



$$\log A(\phi) = \alpha_0 + \beta_0(\phi - \phi_0)^2 + \cdots$$

- Severely constrained by binary pulsar tests, unless there is a mass.
- The DEF model only works for stars

Taken from G. Esposito-Farese, arXiv:gr-cq/0402007

Scalar fields in BH spacetimes

The equation
$$\Box\phi = 0$$

admits only the trivial solution in a BH spacetime that is

- stationary, as the endpoint of collapse
- asymptotically flat, i.e. isolated

S.W. Hawking, Comm. Math. Phys. 25, 152 (1972).

The same is true for the equation

$$\Box\phi = U'(\phi)$$

with the additional assumption of local stability

$$U''(\phi_0) > 0$$

T. P. S. and V. Faraoni, Phys. Rev. Lett. 108, 081103 (2012)

No difference from GR?

Actually there is...

- Perturbations are different!

  E. Barausse and T.P.S., Phys. Rev. Lett. 101, 099001 (2008)

- They even lead to new effects, e.g. superradiance

  A. Arvanitaki and S. Dubovksy, Phys. Rev. D 83, 044026 (2011)
  R. Brito, V. Cardoso and P. Pani, Lect.Notes Phys. 906, 1 (2015)

- In general, relaxing the symmetries of the scalar can lead to "hairy" solutions.

  C. A. R. Herdeiro and E. Radu, Phys. Rev. Lett. 112, 221101 (2014)

- Cosmic evolution or matter could also lead to scalar "hair"

  T. Jacobson, Phys. Rev. Lett. 83, 2699 (1999);
  M. W. Horbatsch and C. P. Burgess, JCAP 1205, 010 (2012).
  V. Cardoso, I. P. Carucci, P. Pani and T. P. S., Phys. Rev. Lett. 111, 111101 (2013)

Black hole scalarization

No-hair theorem for the action

$$S = \frac{m_P^2}{8\pi} \int d^4x \sqrt{-g} \left(\frac{R}{2} - \frac{1}{2}\partial_\mu \phi \partial^\mu \phi + f(\phi)\mathcal{G} \right)$$

provided that $\quad f'(\phi_0) = 0\,, \quad f''(\phi_0)\mathcal{G} < 0$

That is, for the equation

$$\Box \phi = -f'(\phi)\mathcal{G}$$

trivial solutions are unique if admissible, if the effective mass is positive

H. O. Silva, J. Sakstein, L. Gualtieri, T.P.S, and E. Berti, PRL 120, 131104 (2018)

- But if it is negative then there can be "scalarization"!

Black hole scalarization

$$\mathcal{G}_{\text{Kerr}} = \frac{48M^2}{(r^2+\chi^2)^6}\left(r^6 - 15r^4\chi^2 + 15r^2\chi^4 - \chi^6\right)$$

- For $\chi = 0$: Schwarzschild and $\mathcal{G} > 0$

  Scalarization for $f''(\phi_0) > 0$

  H. O. Silva, J. Sakstein, L. Gualtieri, T.P.S, and E. Berti, PRL 120, 131104 (2018)
  D. D. Doneva and S. S. Yazadjiev, PRL 120, 131103 (2018)

- For $\chi \neq 0$: $\mathcal{G}$ can change sign near the horizon

  Spin-induced scalarization when $f''(\phi_0) < 0$

  A. Dima, E. Barausse, N. Franchini, and T.P.S, PRL 125, 231101 (2020)
  C. A. R. Herdeiro, E. Radu, H. O. Silva, T.P.S., and N. Yunes, PRL 126, 011103 (2021)
  E. Berti, L. G. Collodel, B. Kleihaus, and J. Kunz, PRL 126, 011104 (2021)

Nonlinear quenching

- Quadratic coupling (minimal model) leads to radially unstable scalarized solutions
- Exponential coupling is not

J. L. Blazquez-Sacedo et al., Phys. Rev. D 98, 084011 (2018)

Explanation:

- quadratic coupling: scalar EOM linear in the scalar
- large metric backreaction necessary to quench the instability

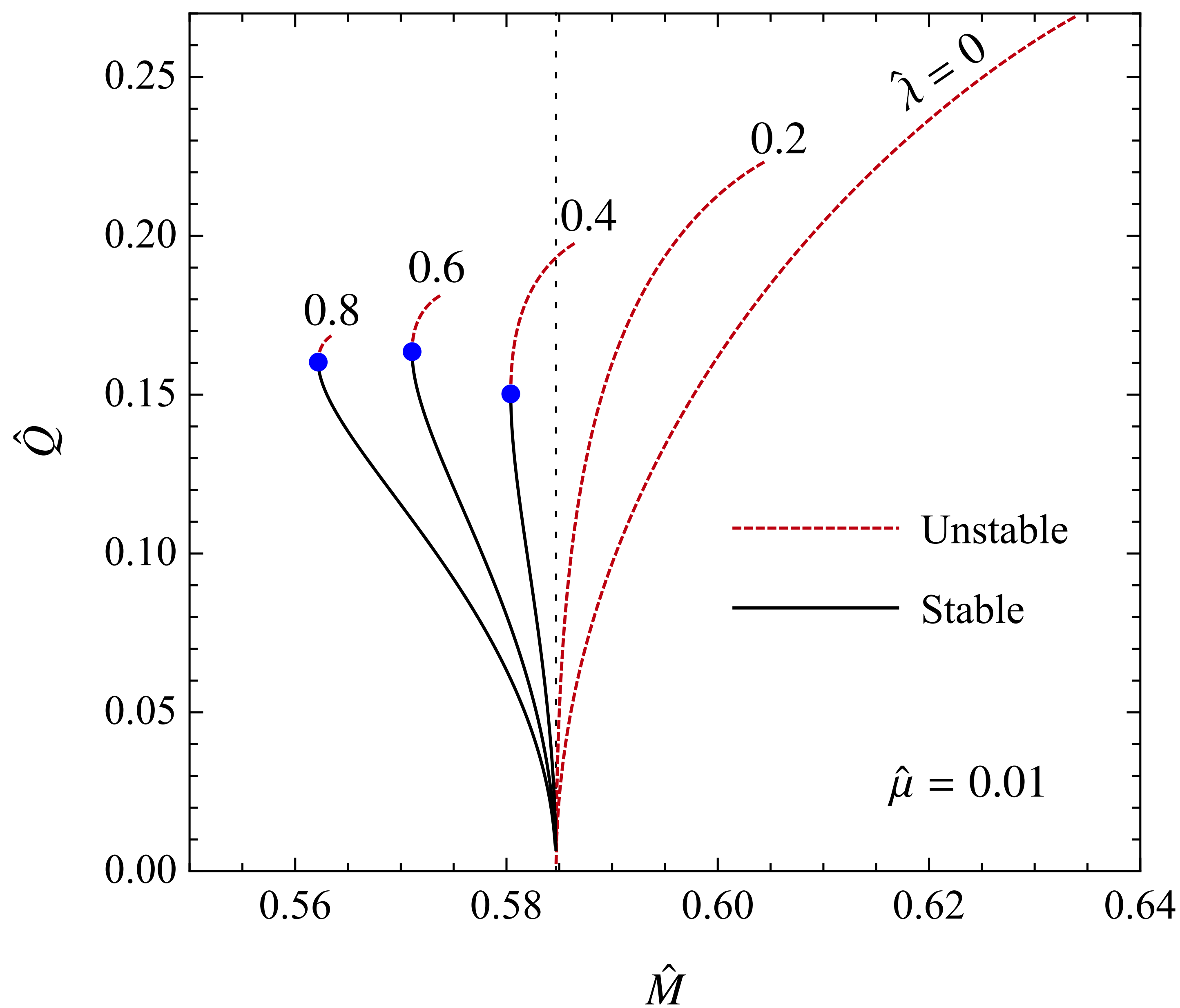
H. O. Silva et al., Phys. Rev. D 99, 064011 (2019)

- …or nonlinearity in the scalar, e.g. standard ϕ^4 potential term will do!

C. F. B. Macedo et al., Phys. Rev D 99, 104041 (2019)

Nonlinear quenching

Potential : $$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{2}\lambda\phi^4$$



Models of scalarization

N. Andreou, N. Franchini, G. Ventagli, and T.P.S, Phys. Rev. D 99, 124022 (2019)

Minimal action for tachyonic instability

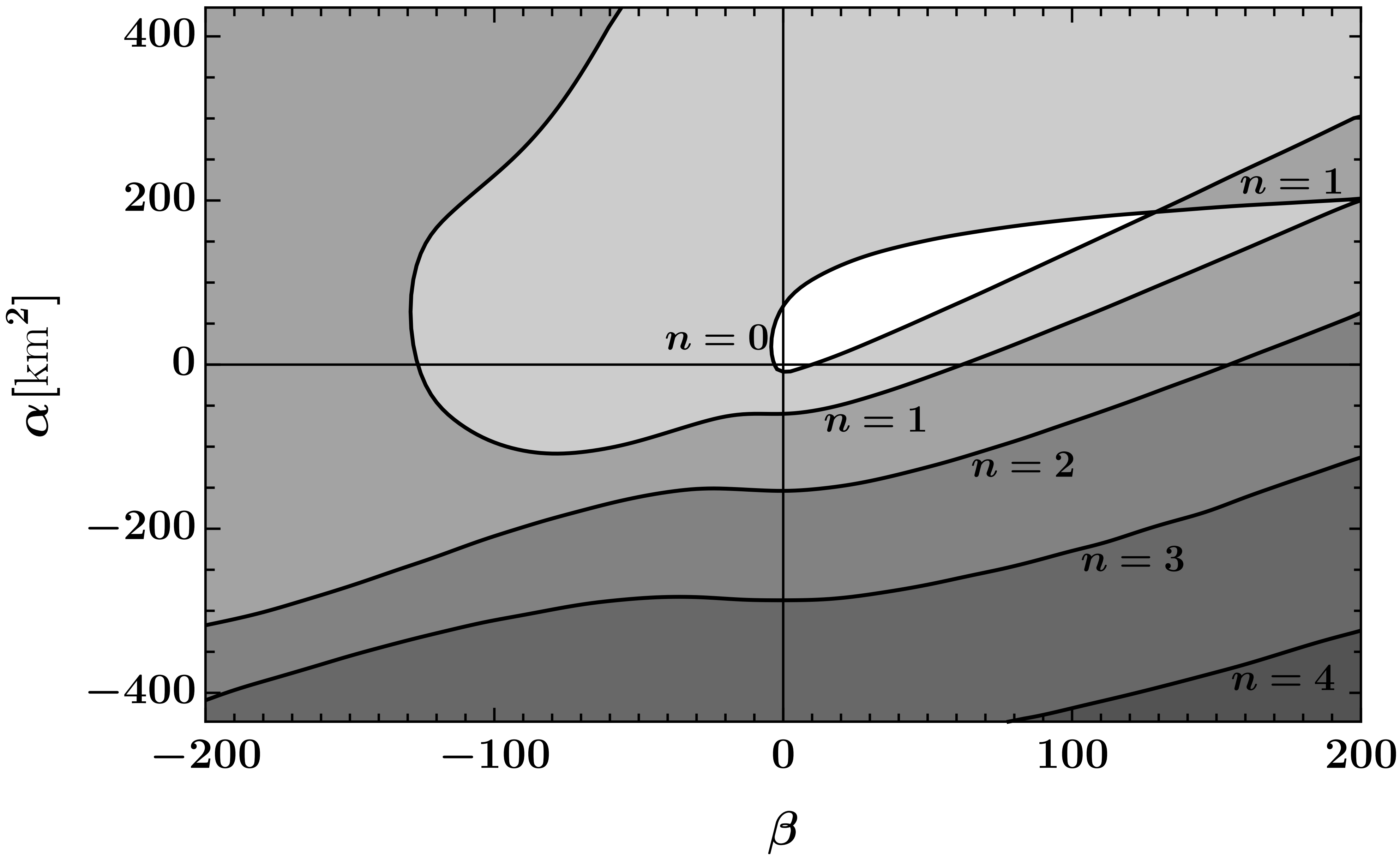
$$L_{\rm min} = R - 2\Lambda - \frac{1+\gamma R}{2}(\partial\phi)^2 + \frac{2m_\phi^2\phi^2 - 2\alpha\phi^2\mathcal{G} + \beta\phi^2 R}{4}$$

Most general up to field redefinition and nonlinear completion:

- $\phi \to f(\phi)$ and $g_{\mu\nu} \to \Omega^2(\phi) g_{\mu\nu}$ lead to DEF model
- $g_{\mu\nu} \to C(\phi) g_{\mu\nu} + D(\phi)\partial_\mu\phi\partial_\nu\phi$ trades the $R(\partial\phi)^2$

  coupling for a disformal coupling with matter

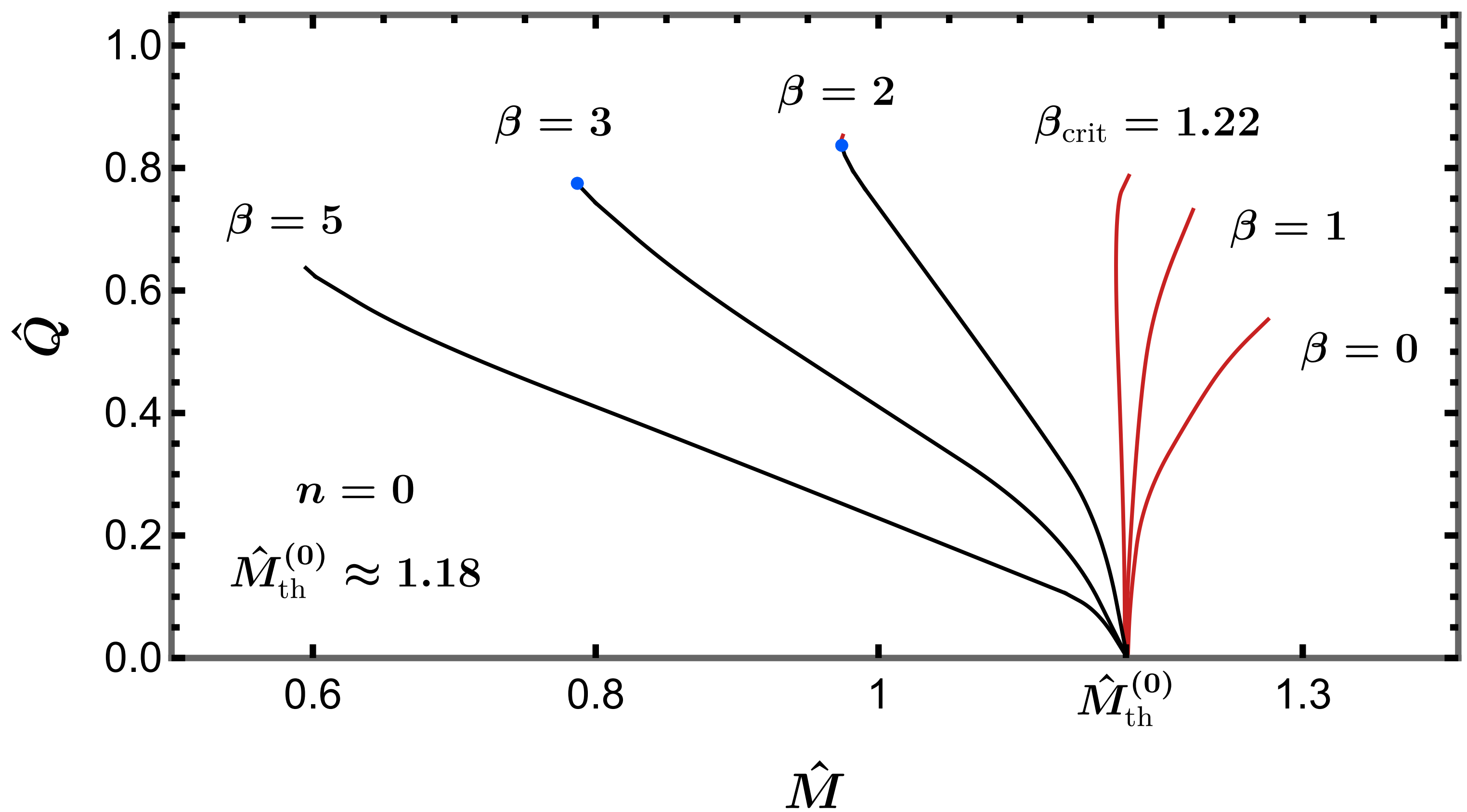
Neutron star scalarization



G. Ventagli, A. Lehebel, and T.P.S, Phys. Rev. D 102, 024050 (2020)

BHs and Ricci coupling

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



G. Antoniou, A. Lehebel, G. Ventagli, and T.P.S, arXiv: 2105.04479 [gr-qc]

$\beta > 0$ also leads to GR as a cosmic attractor!

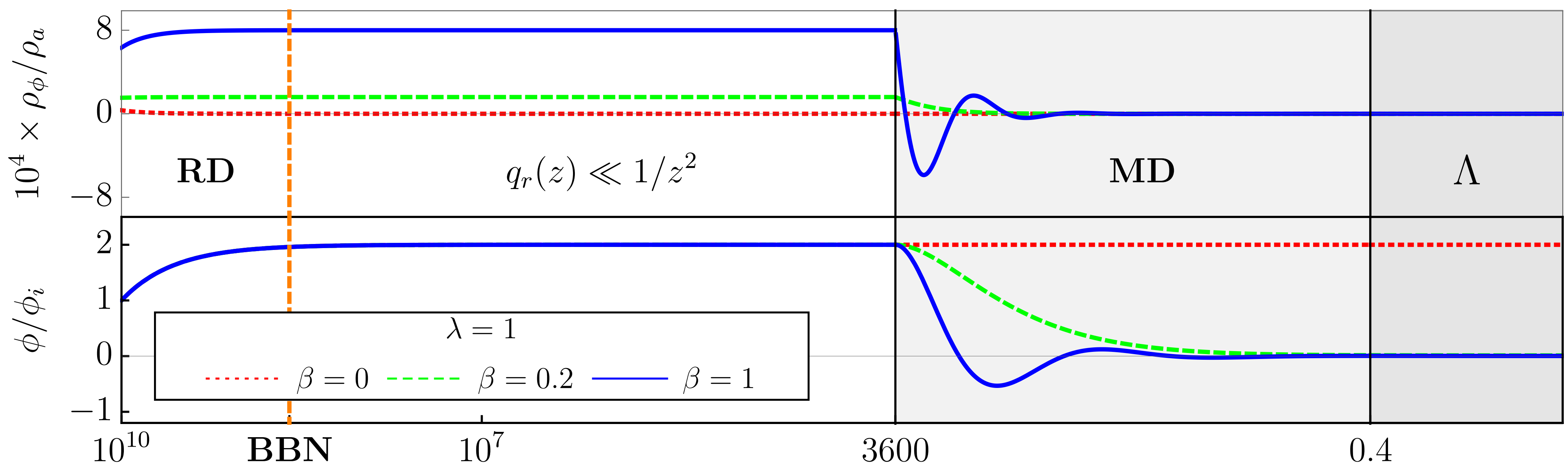
G. Antoniou, L. Bordin, and T.P.S, PRD 103, 024012 (2021)

Scalarization and cosmology

DEF and simple Gauss-Bonnet models require severe tuning of initial conditions!

T. Damour and K. Nordtvedt, PRL 70, 2217 (1993)
D. Anderson, N. Yunes, and E. Barausse, PRD 94, 104064 (2016)
N. Franchini and T.P.S., PRD 101, 064068 (2020)

But $\beta > 0$ leads to GR as a cosmic attractor!



G. Antoniou, L. Bordin, and T.P.S, PRD 103, 024012 (2021)

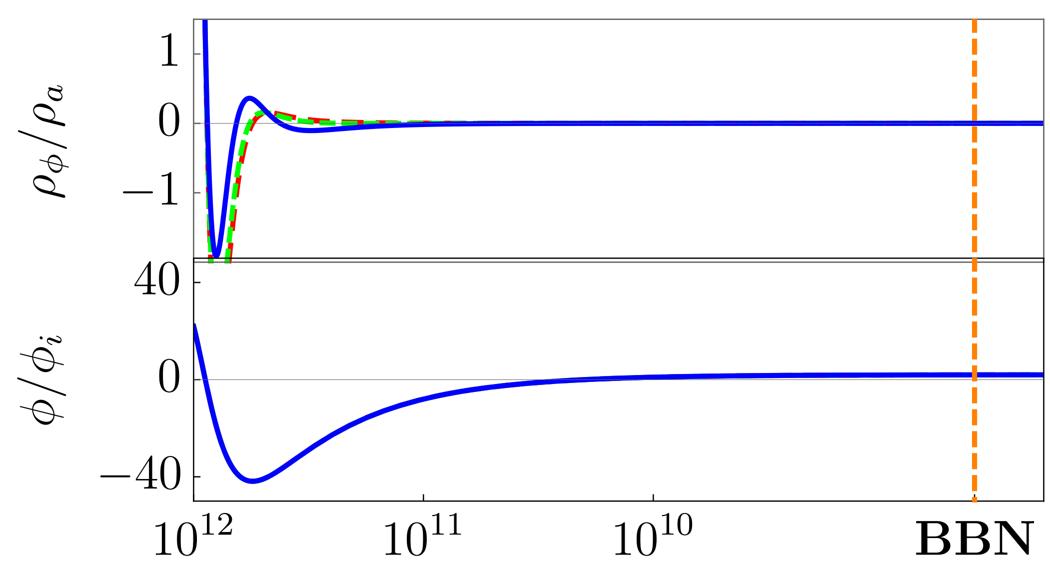
Scalarization and cosmology

Early universe:

- As the universe gets smaller, curvature gets larger, effective mass also gets larger.
- Scalarization can be triggered by quantum fluctuation during inflation

T. Anson, E. Babichev, C. Charmousis, S. Ramazanov, JCAP 06 023 (2019)

- The scalar will dominate and non-linearities will become important.
- Non-linear and UV completion essential.



G. Antoniou, L. Bordin, and T.P.S, PRD 103, 024012 (2021)

Perspectives

- Scalarization "screens" new physics at low curvatures
- Linear instability in strong field, quenched nonlinearly

$$\tilde{g}^{\mu\nu}[g_{\mu\nu},\phi]\nabla_\mu\nabla_\nu\phi = m^2_{\rm eff}[g_{\mu\nu},\phi]\,\phi + \text{nonlinear terms}$$

- Others fields? Vectorisation, tensorisation

F. M. Ramazanoglu, Phys. Rev. D 96, 064009 (2017)
L. Annulli, V. Cardoso, L. Gualtieri, Phys. Rev. D 99, 044038 (2019)
...

- Other instabilities?

F. M. Ramazanoglu, Phys. Rev. D 97, 024008 (2018)
C. A. R. Herdeiro and E. Radu, Phys. Rev. D 99, 084039 (2019)
D. D. Doneva and S. S. Yadzadjiev, arXiv:2107.01738 [gr-qc]
...

- Non-linear evolution and well-posedness

W. E. East and J. L. Ripley, arXiv: 2105.0871 [gr-qc]

...a mechanism that wants to become a theory.