COMPACT OBJECTS AND THE SWAMPLAND

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[arXiv: 1811.10844 [hep-th]]

[1] Introduction

★ Swampland

It originated in string Landscape.
(S. Kachru, R. Kallosh, A. D. Linde, S. P. Trivedi, hep-th/0301240)
(L. Susskind, hep-th/0302219)

The number of possible consistent flux compactifications of F-theory to 4D is at least
10^{272000} !!
(W. Taylor and Y.-N. Wang, arXiv:1511.03209 [hep-th])

There is huge number of choices to make when using string theory for model building.

String Landscape - large space of inequivalent string backgrounds

It is difficult for us to construct string vacua from a very large number of possible choices
⇒ Is there no predictability in string theory?

The attitude towards identifying the correct string vacuum has shifted from using a top-down approach to a bottom-up one over the past decade.
(T. D. Brennan, F. Carta and C. Vafa, arXiv:1711.00864 [hep-th])

Top-down： 10d string ⇒ 4d EFT
Bottom-up： 4d QFT ⇒ 4d QFT + gravity

- Not all consistent looking effective field theories is able to be coupled consistently to gravity with a UV completion.

- We call the set of all effective field theory which is ultimately inconsistent with a string theory as the swampland.
  (C. Vafa, hep-th/0509212)
  (H. Ooguri, C. Vafa, hep-th/0605264)

- There are some conjectures, minimal criteria that allows us to exclude a theory from the string landscape.

☆ Swampland conjecture

Theory of quantum gravity coupled to two scalar fields (in reduced Planck units) :

$$\frac{R}{2} - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi^1\partial_\nu\phi^1 - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi^2\partial_\nu\phi^2 - V(\phi^1\,,\;\phi^2) + \cdots$$

Criterion 1 : (C. Vafa, hep-th/0509212)
(H. Ooguri and C. Vafa, hep-th/0605264)

The range of the scalar field has an upper bound.

$$\triangle\phi^i \sim \mathcal{O}(1)$$

There is a finite radius in field space where the effective Lagrangian above is valid.

Criterion 2 :

(G. Obied, *et. al.*, arXiv:1806.08362 [hep-th])

For V > 0, there is a lower bound on the relative variation of the potential in field space.

$$\frac{|\nabla V|}{V} > c \sim \mathcal{O}(1)$$

The parameter *c* can depend on the macroscopic dimension of spacetime *d*.

This is motivated by the observation that it appears to be difficult to construct any reliable de Sitter vacua in string theory.

Our motivation :

Swampland conjectures which exclude de Sitter vacua in string theory have been much discussed.

However, little attention has been given to examine the swampland criteria in the context of solitonic compact objects or other physics made up of scalar fields.
cf)
(H. Murayama, *et. al.*, arXiv:1809.00478 [hep-th])
(M. Artymowski, I. Ben-Dayan, arXiv:1902.02849 [hep-th])
(L. Heisenberg, *et. al.*, arXiv:1902.03939 [hep-th])

Our motivation for the present work is to improve this situation.

♠Boson Star

(D. J. Kaup, Phys. Rev. 172 (1968) 1331)
(R. Ruffini and S. Bonazzola, Phys. Rev. 187 (1969) 1767)

- Boson stars have been proposed as black hole mimickers and dark matter candidates.
  (P. V. P. Cunha, *et.al.*, arXiv:1709.06118 [gr-qc])
  (A. Sumgez, *et. al.*, arXiv:1302.0903 [astro-ph.CO])

- Appearance of the boson star in the context of string compactifications
  (S. Krippendorf, F. Muia and F. Quevedo, arXiv:1806.04690 [hep-th])

- Rotating boson stars belong to a larger family of solutions of such as hairy black holes
  (F. E. Schunck and E. W. Mielke, Phys. Lett. A 249 (1998) 389)

[2]Application to boson stars and hairy black holes

Our model：

(Colpi, S. L. Shapiro and I. Wasserman, Phys. Rev. Lett. 57 (1986) 2485)

$$\mathcal{L} = \frac{R}{2} - \frac{1}{2} g^{\alpha\beta} \partial_\alpha \psi \partial_\beta \psi^* - V(|\psi|) \,,$$

$$V(|\psi|) = \frac{\mu^2}{2} |\psi|^2 + \frac{\lambda}{4} |\psi|^4 \,, \quad \psi \equiv \phi^1 + i\phi^2$$

For $\lambda \neq 0$, making boson stars with astrophysical (solar) masses compatible with standard model order masses for the elementary bosonic particles.

The potential is renormalizable in QFT.

In our model, the two criteria become

$$\textbf{Criterion 1}: \Delta|\psi| \lesssim 1\,,$$

$$\textbf{Criterion 2}: \left|\frac{\partial V}{\partial|\psi|}\right| \frac{1}{V(|\psi|)} \gtrsim 1\,.$$

The second criterion, becomes, explicitly, in terms of the chosen potential,

$$\left|\frac{\partial V}{\partial|\psi|}\right| \frac{1}{V(|\psi|)} = \frac{2}{|\psi|} \frac{1+\frac{\lambda|\psi|^2}{\mu^2}}{1+\frac{\lambda|\psi|^2}{2\mu^2}} \gtrsim 1$$

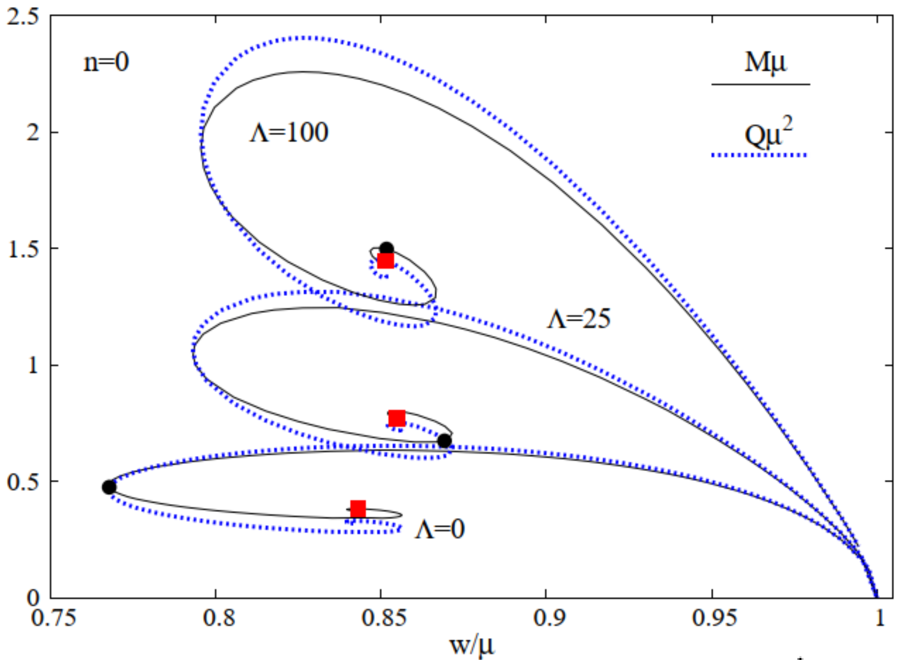
For $\lambda = 0$, criterion 2 translates into $|\psi| \lesssim 2$. It follows that all solutions which satisfy criterion 1.

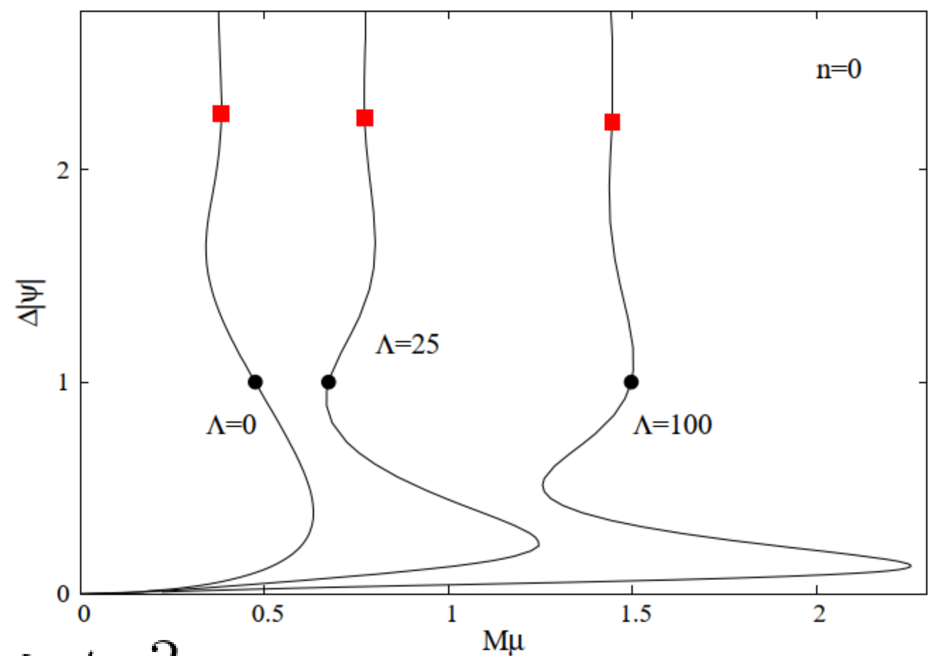
In the general case with self-interactions, $\lambda \neq 0$, criterion 1 implies criterion 2.

It is a novel feature of the vacua we are analyzing that the two criteria are not independent.

Static spherically symmetric boson stars with a quartic self-interaction

$$\psi = f(r)e^{-iwt}$$



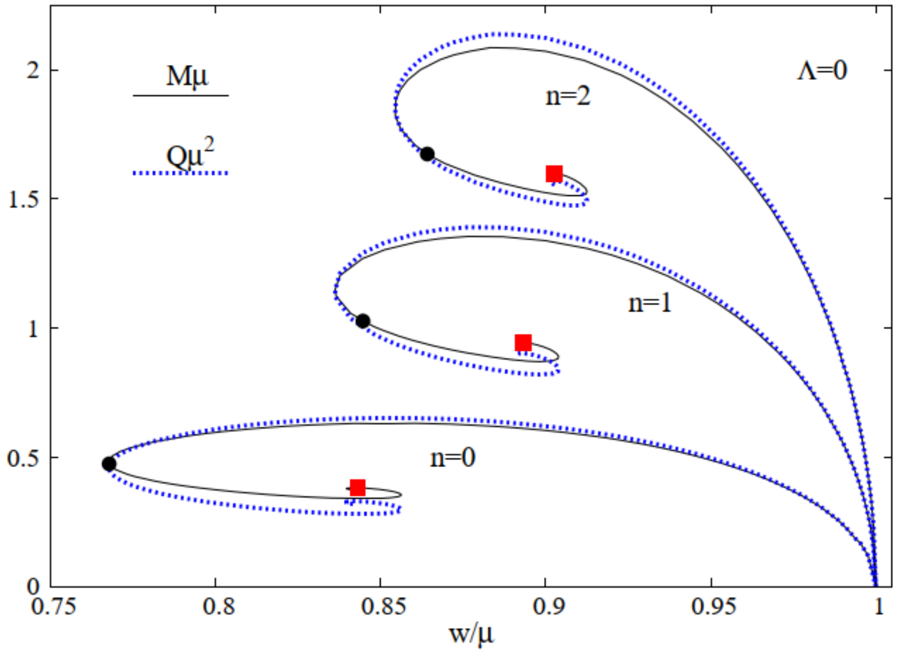


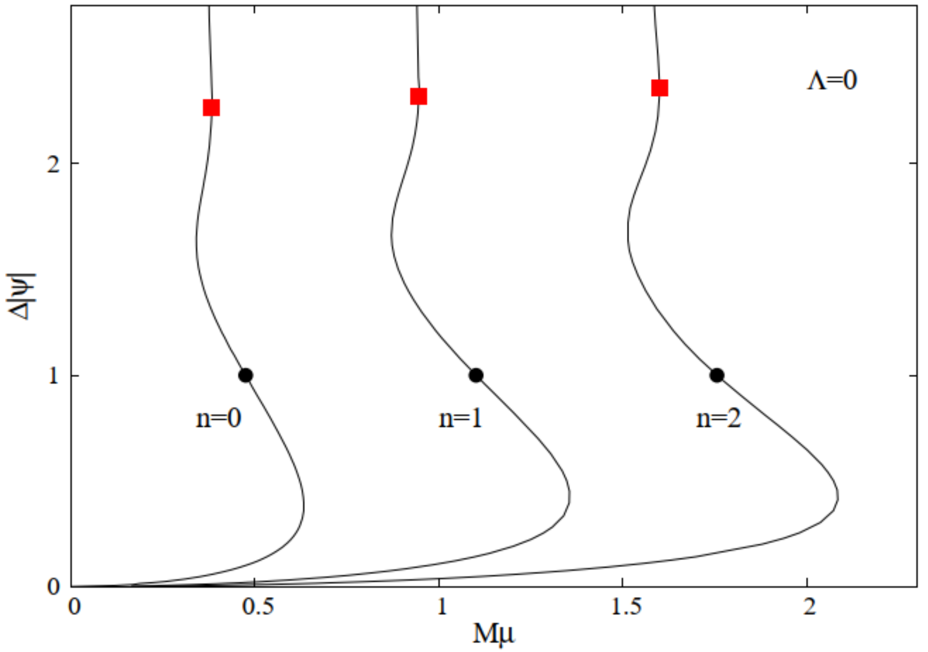
$$\Lambda = \lambda/\mu^2$$

ADM mass M or Noether charge Q vs. scalar field frequency w

Maximal variation of the scalar field as a function of the ADM mass

Excited states ($n \neq 0$) without self-interactions ($\lambda = 0$)





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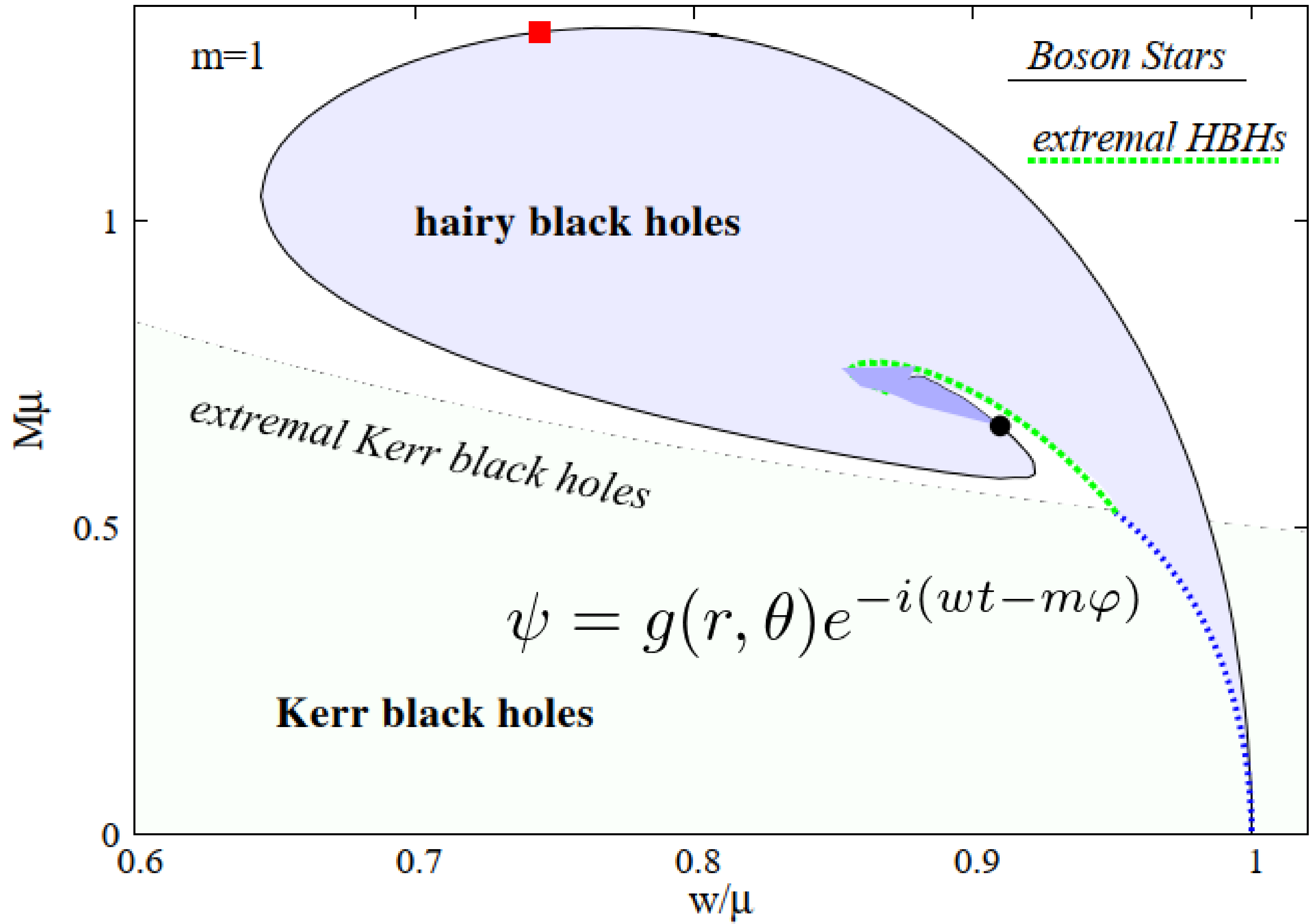

Fundamental rotating boson star solutions with m = 1 (black solid line) in a mass vs. scalar field frequency.

[3] Discussion and remarks

(1) Swampland criteria：

- Whether vacua describing solitonic compact objects or hairy black holes may be part of the swampland or the string landscape.
- The criteria are not independent.

(2) In all boson star models studied so far,

when the swampland criteria fail the solutions are unstable.

all stable solutions we have analyzed are compatible with the landscape.

(3) boson stars with light rings (ultra-compact)

- For non rotating case, these are in Swampland.

- Rotating boson stars are part of the landscape.

(4) Hairy black hole

- The region where the swampland conditions fail is the strong gravity region.

- This does not intersect with the region in the domain of existence where such black holes may be astrophysically viable.