Ultra-Light Axions, Weak Gravity, and Euclidean Wormholes

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including work with

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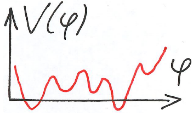
Outline

- The Landscape/Swampland program.
- dS-Swampland / KKLT: A mini summary.
- Most of this talk:

  Gravitational Instantons / Wormholes
  and the flatness of small-f axion potentials.

Landscape vs. Swampland

- 10d Superstring $\rightarrow$ geometry/fluxes $\rightarrow$ 

  Landscape: Any EFT obtained from string theory as above.

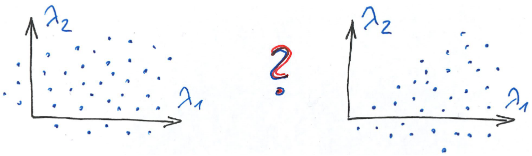
  Swampland: Any other naively consistent EFT
  (always including gravity).

- One the one hand, the existence of such a swampland is a key possibility of how string theory could be predictive in the IR.

- One the other hand, this existence is almost trivial:
  The landscape is discrete, the space of EFTs is continuous.
  $\Rightarrow$ Almost any EFT is in the Swampland.

Landscape vs. Swampland

- What is less obvious is the presence of well-defined 'empty' regions in the field-parameter space:



- Thus, this presence of unaccessible regions in parameter space might be the more useful 'swampland' definition.

- Another twist: Demand 'consistency in quantum gravity' (not necessarily string theory).

  This is of course much harder. See however talk by Javi Serra

  In particular, hard to get to claims about the deep IR.

Concrete 'Swampland Criteria'

- Specific quantum-gravity consistency citeria have been discussed since a long time ....

No exact global symmetries

Completeness

see e.g. Banks/Seiberg '10 and refs. therein

[the charge lattice is fully occupied]

The swampland distance conjecture

[infinite distances in moduli space come with exponentially light states]

Vafa '05, Ooguri/Vafa '06

The weak gravity conjecture

[$g \cdot q \gtrsim m_q / M_P$]

Arkani-Hamed/Motl/Nicolis/Vafa '06

dS conjectures

Obied/Ooguri/Spodyneiko/Vafa '18, $\cdots$

De Sitter swampland conjectures – a mini summary

- $|V'|/V$ conjecture:
  may fall by exp. constraints...

  Obied/Ooguri/Spodyneiko/Vafa, ...
  Denef/AH/Wrase, ...
  Choi/Chway/Shin '18

- 'Asymptotic' dS conjecture:
  probably true, but still hard to prove...

  Ooguri/Palti/Shiu/Vafa
  (see however AH/Wrase)

- 'Mild' or 'refined' dS conjecture:
  ...basically leads to question about KKLT & Co.

  Danielsson/Van Riet; Grag/Krishnan; Ooguri et al.

- Questioning KKLT:

  specifically 10d perspective:
  Moritz/Retolaza/Westphal '17

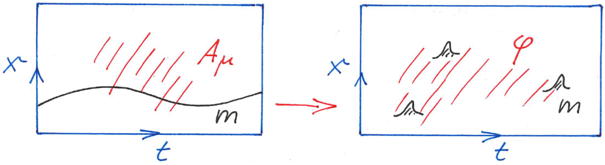
  Tangible progress has been achieved; Better understanding of 10d Einstein eqs. and 10d gaugino condensate; One may now more optimistic ...

  Hamada/AH/Shiu/Soler '18+'19
  (see also/however: Carta/Moritz/Westphal;
  Gautason/Van Hemelryck/Van Riet/Venken)

Rest of this talk:

Can the swampland constrain / forbid ultra-light axions?

- Recall basic WGC bound: $g \gtrsim m/M_P$
- Axion analogue: $(1/f) \gtrsim S$ or $f\,S \lesssim 1$



- Usually, this is used to argue against large f (not here).
- Instead, let us try to argue against flat axionic potentials:

$$A \cos(\varphi) \;\gtrsim\; e^{-1/f} \cos(\varphi) \qquad [M_P \equiv 1]$$

- The axionic-WGC bound $S \lesssim 1/f$ has important caveats.
- First, the ususal BH-based arguments for the WGC do not apply.
- Second, even if they do, they may be satisfied by very heavy objects (here: higher instantons)

Rudelius; Brown/Cottrell/Shiu/Soler '15
talk by Javi Serra

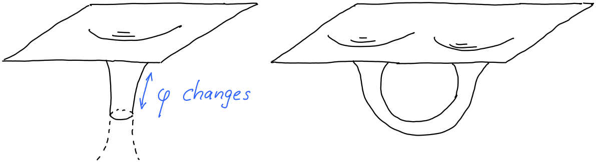
- Intriguingly, a much more direct, non-conjecture-based argument for the gravitational breaking of axionic shift symmetries exists: **Euclidean Wormholes**
We turn to this next.

Apologies to the authors of all the interesting work in the large-f context:
Choi, Kaloper, Westphal, Rompieneve, von Harling, ...

Euclidean Wormholes or (Gravitational) instantons

- In Euclidean Einstein gravity, supplemented with an axionic scalar φ , instantonic solutions exist:

Giddings/Strominger '88
...



- The 'throat' is supported by the kinetic energy of $\varphi = \varphi(r)$, with r the radial coordinate of the throat/instanton.

- Analogously to gauge-instantons, resummation leads to a cosine-type potential for the originally shift-symmetric field φ.

Hawking/Coleman/Preskill '89.......... Montero/Uranga/Valenzuela '15

Gravitational instantons (continued)

- The underlying lagrangian is simply

$$\mathcal{L} \sim \mathcal{R} + f^2 |d\varphi|^2 \,, \quad \text{now with} \quad \varphi \equiv \varphi + 2\pi \,.$$

- This can be dualized $(dB_2 \equiv f^2 * d\varphi)$ to give

$$\mathcal{L} \sim \mathcal{R} + \frac{1}{f^2} |dB_2|^2 \,.$$

- The 'throat' exists due the compensation of these two terms. Reinstating M_P, allowing n units of flux (of $H_3 = dB_2$) on the transverse S^3, and calling the typical radius R, we have

$$M_P^2 \, R^{-2} \sim \frac{n^2}{f^2} R^{-6} \quad \Rightarrow \quad M_P \, R^2 \sim \frac{n}{f} \,.$$

Gravitational instantons (continued)

- Returning to units with $M_P = 1$, their instanton action is

$$S \sim n/f \qquad \text{(with } n \text{ the instanton number).}$$

- Their maximal curvature scale is $\sqrt{f/n}$, which should not exceed the UV cutoff:

$$f/n < \Lambda^2$$

- This fixes the lowest n that we can trust and hence the minimal size of the instanton correction to the potential $V(\varphi)$:

$$\boxed{\delta V \sim e^{-S} \sim e^{-n/f} \sim e^{-1/\Lambda^2}}$$

Gravitational instantons (continued)

- It turns out, that wormholes do not endanger natural inflation even if the cutoff Λ is relatively high.

  AH/Mangat/Rompineve/Witkowski '15
  AH/Mangat/Theisen/Witkowski '16

- But here, we are asking a different question:

  Let $\Lambda \sim 1$.

  Let $f \ll 1$ (not by too much), such that even the $n = 1$ instanton is semiclassically controlled.

  Do wormholes make an interesting prediction for the cosine-potential?

  Urbano/Alonso '17
  AH/Mikhail/Soler '18

Wormholes and the QCD axion

Rey '89 ..... Alonso/Urbano '17

- For example, for a QCD axion with (relatively) high f, the wormhole effect might be relevant:

$$V(\varphi) = \Lambda_{QCD}^4 \cos(\varphi) + r_0^{-4} e^{-S_w/2} \cos(\varphi + \delta)\,.$$

- Here $r_0 \sim 1/\sqrt{f}$ and $S_w = \pi\sqrt{3/8}/f$.
- It turns out that for $f \gtrsim 10^{16}$ GeV the solution to the strong CP problem is lost.
- But are we certain about the relative phase?

Wormholes and BH superradiance

Alonso/Urbano '17

- Spinning BHs deposit large part of their angular momentum in scalar-field cloud (if scalar with $m \sim 1/R$ available).

- Observation of spinning stellar-mass BHs already rules out

$$6 \times 10^{-13}\text{eV} \;\lesssim\; m \;\lesssim\; 2 \times 10^{-11}\text{eV}\,.$$

- For the QCD axion, this corresponds to

$$3 \times 10^{17}\text{GeV} \;\lesssim\; f \;\lesssim\; 10^{19}\text{GeV}\,.$$

- A discovery at the boundary of this window could (cf. previous slide) overthrough quantum gravity expectations!

Wormholes and BH superradiance

AH/Mikhail/Soler

- But: How do we know that we are observing the superradiance effect of the QCD axion?

- Let's say we see superradiance with some axion with mass m. Taking the wormhole effect seriously, f is sharply predicted:

$$\text{previous } m\text{-window} \quad \rightarrow \quad 1.23 \times 10^{16}\text{GeV} \lesssim f \lesssim 1.28 \times 10^{16}\text{GeV}\,.$$

- Measure f simultaneously with m (for some axion)!
  $\Rightarrow$ Smoking gun for the wormole effect.

- This could indeed be possible using the 'bosenova effect'.
  $\Rightarrow$ Potentially very exciting prospects!

Wormholes and Fuzzy Dark Matter

- Ultralight scalar DM (Fuzzy DM) is another way where tiny potentials could manifest themselves

- A key formula in this context is

$$\Omega_{DM} h^2 \simeq 0.1 \left(\frac{f}{10^{17} \text{GeV}} \right)^2 \left(\frac{m}{10^{-22} \text{eV}} \right)^{1/2} .$$

.... Hui et al. '16 .... Alonso/Urbano '17

- Intriguingly, this the discovery may be interpreted as a conflict with QG or WGC expectations:

  Indeed, the FDM-requirement $m \lesssim 10^{-21}\text{eV}$ together with the relation above implies

$$f \, S_{inst/wh} \gtrsim 5 M_P .$$

AH/Mikhail/Soler

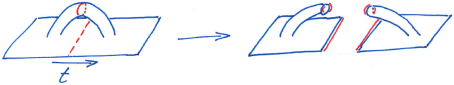
Gravitational instantons / wormholes - conceptual issues

- Motivated by the above, it is worthwhile revisiting some very fundamental conceptual issues of (euclidean) wormholes.

  Hawking '78..'88, Coleman '88, Preskill '89
  Giddings/Strominger/Lee/Klebanov/Susskind/Rubakov/Kaplunovsky/..
  Fischler/Susskind/...

  ... cf. our recent review (AH/Soler/Mikhail)

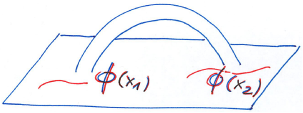
- First, once one allows for wormholes, one has to allow for baby universes.



- Second, with baby universes comes a 'baby universe state' (α vacuum) encoding information on top of our 4d geometry.

Conceptual issues (continued)

- Crucially, α-parameters remove the disastrous-looking bilocal interaction.



$$\exp\left(\int_{x_1}\int_{x_2}\Phi(x_1)\Phi(x_2)\right) \quad \rightarrow \quad \int_\alpha \exp\left(-\frac{1}{2}\alpha^2 + \alpha\int_x \Phi(x)\right)$$

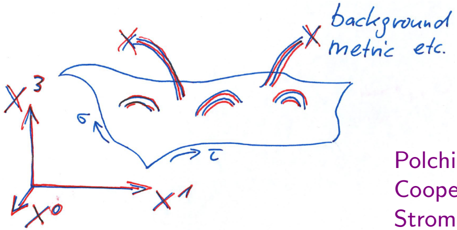
- In our concrete (single-axion) case, an α parameter now governs the naively calculable $e^{-S}\cos(\varphi/f)$-term.
- But, what is worse, all coupling constants are 'renormalized' by α parameters are hence not predictable in principle.

Conceptual issues (continued)

- Most naively, 4d measurements collapse some of the many α parameters to known constants.
- But in a global perspective, both different 4d geomtries and α parameters have to be integrated over.
- But this leads to the
  'Fischler-Susskind-Kaplunovsky catastrophy'.
- The problem is that, through certain higher operators, high densities of even very large wormholes are rewarded;
  $\rightarrow$ exponential suppression overcome.
- Finally, just integrating over the α parameters is clearly not sufficient - one needs to consider their full quantum dynamics.

Conceptual issues (continued)

- Indeed, consider the case of 1+1 dimensions with a number of scalar fields (in addition to gravity).
- This is, of course, well known as string theory and the α parameters characterize the geometry the target space.



Polchinski, Banks/Lykken/O'Loughlin, Cooper/Susskind/Thorlacius, Strominger '89...'92

- The latter has a quantum dynamics of its own, the analogue of which in case of 3+1 dimensions is completely unknown.
- All this raises so many complicated issues, that one might want to dismiss wormholes altogether.

Conceptual issues (continued)

- But this is not easy, for example because we know that in string theory wormholes correspond to string loops and are a necessary part of the theory.

- Thus, forbidding for example topology change in general does not appear warranted.

- Is there a good reason to forbid topology change just in $d > 2$?

- Arguments have been given that the euclidean Giddings-Strominger solution has negative modes and should hence be dismissed.

  Rubakov/Shvedov '96, Maldacena/Maoz '04, see however Alonso/Urbano '17, ...

- But, while this is even technically still an open issues, it does not appear to be a strong enough objection ....

Conceptual issues (continued)

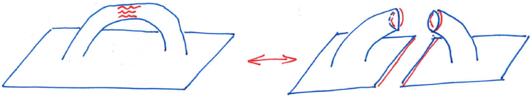
- Indeed, once a non-zero amplitude

$$\text{universe} \;\rightarrow\; \text{universe} \;+\; \text{baby-universe}$$

is accepted, the reverse process is hard to forbid.

- As a result, one gets all the wormhole effects.

- The negative mode issue may be saying:
'Giddings-Strominger' does not approximate the amplitude well.



- ..hard to see, how it would dispose of the problem altogether..

For further problems (and possible resolutions) see e.g.
Bergshoeff/Collinucci/Gran/Roest/Vandoren/Van Riet '04,
Arkani-Hamed/Orgera/Polchinski '07, Hertog/Trigiante/Van Riet '17

Summary/Conclusions

- Euclidean wormholes are the universal, semiclassical counterpart of instantons
- They (may) predict a minimal value of the cosine-potential for small-f axions.

  see however AH/Leonhardt/Moritz/Westphal '19 for potential counterexamples ('Thraxion')
- Interesting applications include: θ_{QCD}, superradiance, FDM.
- But: These effects come at the price of α vacua (and other disasters).
- Worthwhile reviving this fundamental unresolved issue?