Weak Gravity Conjecture as a Razor Criterium for Exotic D-brane instantons

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We discuss implications of Weak gravity conjecture (WGC) for exotic D-brane instantons. In particular, WGC leads to indirect stringent bounds on non-perturbative superpotentials generated by exotic instantons, with many implications for phenomenology: R-parity violating processes, neutrino mass, μ-problem, Neutron-Antineutron transitions and collider physics.

I. INTRODUCTION

The Weak Gravity Conjecture (WGC) states that the weakest force is gravity \[1\]. This implies that for each abelian gauge boson \(U_X(1)\), there must be a light charged particle with mass \(m\) and charge \(q_X\) satisfying the bound

\[ \frac{m}{q_X} \leq M_{Pl} \]

(1)

In other words, for every \(U_X(1)\) gauge in 4-d there is a new UV scale satisfying the bound

\[ \Lambda_X = g_X M_{Pl} = \frac{g_X}{\sqrt{G_N}} \]

(2)

The WGC is motivated by two main arguments: i) global abelian symmetries cannot exist in string theory; ii) the absence of black hole remnants, motivated by holography \[22\]. We mention that a possible test of the WGC applied to a long-range \(U(1)\) can be in Neutron-Antineutron oscillation experiments (See \[19, 21\] for recent analysis of stringent limits on B-L couplings to neutrons (antineutrons)).

A more surprising result is that, according to Weak gravity conjecture, Eq. \(1\) should be also true for magnetic monopoles. For example, for a t’Hooft-Polyakov monopole obtained by the Higgsing \(SU(2) \to U(1)\), the Weak gravity conjecture sets a bound which reads

\[ M_{mon} \leq g_m M_{Pl} \sim \frac{1}{g_X} M_{Pl} \]

(3)

where \(g_m\) is the monopole magnetic charge. This bound is also understood by the fact that a fundamental monopole cannot have an energy density higher than black hole one. As is well known, monopoles and gauge instantons are always in a correspondence. In particular, gauge instantons in a d-dimensional YM theory correspond to monopole solutions in higher dimensional YM theories closed by domain walls \[34\]. In particular, the action of instantons is \(S = M_{mon}/v_X\), i.e. it is bounded by Eq. \(3\). These arguments can be generalized in string theories. In particular Euclidean D-brane instantons in IIA and IIB superstring theories can be understood as a generalization of the soliton/instanton correspondence: a stringy instanton in the effective low energy 4-d theory corresponds to a Euclidean D-brane in the 10-d superstring theory. As is known, Euclidean D-(p-4) branes wrapping the same n-cycles of ordinary D-p branes on the Calabi-Yau internal space reproduce YM gauge instantons in the low energy 4-d gauge theory (\(c' = l_p^2 \to 0\)). However, it exists a new class of instantons, dub exotic instantons, associated to Euclidean D-(p-4) branes wrapping different n-cycles than background D-p branes. This implies that exotic instantons are not related to any gauge couplings of the \(d = 4\) effective gauge theory. Intriguingly, they can generate new effective superpotential terms among fields even if not allowed at perturbative level \[34\]. Recently, we discussed possible implications of exotic instantons in \(B - L\) physics. In fact, contrary to gauge instantons, exotic instantons could violate \(U(1)\) vector-like symmetries like \(B - L\) with a strong coupling. For example, \(\Delta B = 2\) violating processes like Neutron-Antineutron transitions can be generated from several different models, without destabilizing the proton \[22-34\]. So that, it is important to identify a possible razor principle for exotic instantons which, rephrasing Arkani-Hamed et al (in Ref. \[1\]), could select D-brane instantons of the Landscape against ones of Swamplands. In this paper, we suggest an extension of the Weak gravity conjecture to exotic stringy instantons. In particular, we will see how the weak gravity conjecture on exotic instantons can provide stringent constrains for internal spaces and n-cycle geometries. We will show how the WGC on exotic instantons leads to interesting predictions in phenomenology.

II. WGC BOUNDS TO E2-BRANES IN IIA STRING THEORY

In this section, we will discuss the WGC on Exotic Instantons in the specific context of IIA open string

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[2] We mention that recently many papers on weak gravity conjecture in context of N-field and axion monodromy inflation appeared \[2, 4–7, 9–12\]. Other recent applications can be found in Refs. \[13–18\]. (See also Ref. \[39\] for a review on D-brane instantons).
theories with intersecting D6-brane stacks wrapping 3-cycles in the CY3 and Euclidean D2-brane (E2-brane, exotic) instantons wrapping (different) 3-cycles in the CY3. Of course, the following considerations can be easily generalized to other open string theories: i) type IIB open string theories, with space-filling D3-branes and D7-branes wrapping holomorphic divisors in a CY3 and (exotic) E3-branes wrapping (different) holomorphic divisors, ii) type I open string theories with magnetized D9-branes wrapping a CY3 and (exotic) magnetized E5-branes.

\[ \Pi_A = \sum_r p_{Ar} C_r \]  

On the other hand, the coupling of a second D6B-brane to the RR axions \( a_r \) demands the shift symmetry

\[ a_r \to N_B(p_{Br} - p_{B+r})A_B \]  

This implies the shift symmetry

\[ e^{-S_{E2}} \to e^{-i \sum A N_A((I_{MA} - I_{MA'}) \Lambda_A e^{-S_{E2}}} \]  

Constrains in the intersection numbers of E2-branes and D6-branes 3-cycles:

\[ I_{Ma} - I_{Ma'} = I_{Mb} - I_{Mb'} = 0 \]  

\[ I_{Mc} - I_{Mc'} = I_{Md} - I_{Md'} = 2 \]  

where \( I_{Ma} = \Pi_M \cdot \Pi_a \) are the numbers of intersections among the E2-brane and D6-branes. Under this condition, the shift term of \( \Phi^N \) under \( U(1) \) is exactly compensated by the shift symmetry of the instanton coupling.

### B. Weak gravity conjecture and E2-branes

The E2-brane is charged with respect to \( n \) RR fields in turns related to the Stückelberg breaking of \( n \) (anomalous and non-anomalous) \( U(1) \)'s. On the other hand, ordinary E2-branes corresponding to gauge instantons are constrained by the low energy limit bound \( 3 \), \( M \leq g_Y^{-1} M_P l \) where \( g_Y^2 M = (2\pi)^4 g_s V_{\Pi_3}^{-1} \). The generalized WGC bound on a Dp-brane with tension \( T_p \) and sum of Dp-brane charges \( Q \) is

\[ \frac{T_p}{Q} \leq M_P^{p+1} \]  

For an E2-brane, Eq.\[11] corresponds to

\[ \frac{V_{\Pi_3}}{g_s} \leq \left( \sum_r c_r \right) \left( \frac{M_P}{M} \right)^3 = \left( \sum_r c_r \right) \left( \frac{\sqrt{g_s}}{(2\pi)^{3/2} g_s} \right)^3 \]  

which in turn corresponds to

\[ |e^{S_{E2}}| \leq \left( \frac{\sqrt{\sum_c c_c}}{2\pi} \frac{\sqrt{g_s}}{(2\pi)^{3/2} g_s} \right)^3 \]  

The violation of Eq.\[12\] implies that an extremal black hole remnant with RR E-brane charges equal to the black hole mass (normalized in Planck units) could be formed, which is in contrast with holographic arguments.

The WGC bounds should be combined with the semiclassical approximation bound

\[ |e^{S_{E2}}| \geq e^{\sqrt{(\frac{\sqrt{g_s}}{2\pi})^2 + (\sum_r c_r)^2}} \]  

\[ \frac{T_p}{Q} \leq M_P^{p+1} \]  

\[ \frac{V_{\Pi_3}}{g_s} \leq \left( \sum_r c_r \right) \left( \frac{M_P}{M} \right)^3 = \left( \sum_r c_r \right) \left( \frac{\sqrt{g_s}}{(2\pi)^{3/2} g_s} \right)^3 \]  

\[ |e^{S_{E2}}| \leq \left( \frac{\sqrt{\sum_c c_c}}{2\pi} \frac{\sqrt{g_s}}{(2\pi)^{3/2} g_s} \right)^3 \]  

\[ |e^{S_{E2}}| \geq e^{\sqrt{(\frac{\sqrt{g_s}}{2\pi})^2 + (\sum_r c_r)^2}} \]
where $\mathcal{V}_s$ is the string volume of the 3-cycles. For example, for a 3-cycle cilindrical geometry, $\mathcal{V}_s = \pi^2$. Essentially, Eq. 2 is an universal stringy bound on the instanton-antinstanton bubbles or instanton partition functions.

So that, weak gravity conjecture constrains 3-cycle size wrapped by the E2-branes, the string coupling the internal volume (the string scale over the planck scale).

Finally, if $M \geq M_{Pl}$ in the superpotential Ref. [4] for $N > 3$, quantum gravity (mainly corrections to the superpotential from reggeized gravitons exchanges) corrections should affect our instantonic calculations. So that, we impose a calculability bound

$$|e^{S_{E2}}| \leq \left( \frac{M_{Pl}}{M_s} \right)^{N-3} = \left( \frac{\sqrt{6}}{(2\pi)^{7/2}g_s} \right)^{N-3}$$

for $N > 3$. On the other hand, for $N = 2$ (bilinear superpotentials), $M \leq M_{Pl}$ in order to neglect quantum gravity corrections and

$$|e^{-S_{E2}}| \leq \left( \frac{M_s}{M_{Pl}} \right) = \left( \frac{\sqrt{6}}{(2\pi)^{7/2}g_s} \right)^{-1}$$

### III. IMPLICATIONS IN PHENOMENOLOGY

![FIG. 2. (Un)oriented quiver theory embedding the (MS)SM and generating through an Exotic E-brane Instanton a six quark superpotential (See Eq. (22). This model was discussed in companion papers [51]–[52]. For instance, this quiver is (locally) compatible with the tadpole cancellations and SM hypercharge conditions discussed and applied in Refs. [51]–[55].)](image)

In this section, we will discuss the application of WGC and the semiclassical bound for a set of superpotentials generated by exotic E-brane instantons studied in literature [29]–[31], [39]–[41], [50].

![FIG. 3. In the same model of Fig.2, an Exotic E-brane instanton generating a Weinberg operator as Eq. (21) is displayed.](image)

For Trilinear Yukawa couplings, the window allowed by WGC and semiclassical bounds is

$$e^{-\sqrt{2}(\sum e, c)} \left( \frac{\sqrt{6}}{(2\pi)^{7/2}g_s} \right)^3 \leq |e^{S_{E2}}| \leq e^{-\sqrt{2}(\sum e, c)^2}$$

These constraints allow a various set of possible coupling $|e^{S_{E2}}|$. For example, for high scale string theory $M_s \approx 10^{15}$ GeV, $\mathcal{V}_s g_s \approx 1$, $g_s \approx 10^{-3}$, WGC lower bound is easily satisfied ($|e^{S_{E2}}| \geq e^{-10^{15}}$ or so), while the semiclassical upper bound is expected to be of order one because of RR charge contribution. So that, R-parity violating operators destabilizing the proton like

$$Y_1 e^{-S_{E2}} U^c D^c D^c, \quad Y_2 e^{-S_{E2}} LQD^c, \quad Y_3 e^{-S_{E2}} U^c LLE^c$$

(18)

can be naturally suppressed without violating the WGC. As well as the generation of a small Dirac mass term for the neutrino like

$$\mathcal{L} = y_e e^{-S_{E2}} \langle H \rangle \tilde{\nu}_{LR}$$

(19)

without any see-saw mechanisms. However, we should note that this imposes a bound on the number of RR charges. As a consequence, a quiver theory with a large number of D-brane stacks (order $N_{stacks} > 10^3$) would enhance the WGC bound for non-perturbative trilinear couplings. This seems to imply that SM has to be embedded in a quiver with few D-brane stacks nodes (this is also desired for minimalism).

For bilinear terms like the $\mu$-term and $\mu' HL$, with $\mu = M_S e^{-S_{E2}}$ and similarly $\mu'$, a combination of Eqs. (13), (14), (16).

This means that a scenario in which $M_S \approx M_{GUT} \approx 10^{15}$ GeV with $\mu \approx TeV$ ($|e^{-S_{E2}}| \approx 10^{-12}$) is constrained...
by WGC, because $\mathcal{V}_6, \mathcal{V}_{11} \geq 1$ while $g_s \leq 1$. In particular,
\[ e^{-\sqrt{2} \left( \sum_r c_r \right) \left( \frac{\sqrt{V_6}}{(2\pi)^{7/2} g_s} \right)^3} \leq |e^{-S_{E2}}| \leq 10^{-12} \]
implying
\[ \sqrt{2} \left( \sum_r c_r \right) \left( \frac{\sqrt{V_6}}{(2\pi)^{7/2} g_s} \right)^3 \geq 12 \]
which can be easily satisfied in perturbative string theory.

Let us now discuss a proton decay superpotential generated by E2-brane instantons:
\[ \mathcal{W} = \frac{e^{-S_{E2}}}{M_s} QQQL \rightarrow O_{p-decay} = \frac{e^{-S_{E2}}}{M_s M_{SUSY}} qqql \] (20)
which is constrained up to
\[ M_s M_{SUSY} e^{+S_{E2}} > (10^{15} \text{GeV})^2 \]
Let us suppose a scenario with $M_s, M_{SUSY} \simeq 1 \div 100 \text{TeV}$. In this case, the $e^{+S_{E2}} > 10^{18} \div 10^{24}$, which constrains $(g_s^{-1}, \mathcal{V}_{11}, \mathcal{V}_6) >> 1$. In the opposite regime $M_s \simeq M_{SUSY} \simeq 10^{15} \text{GeV}$, the coupling $e^{+S_{E2}}$ could be much smaller in order to satisfy the experimental constraints, i.e. $\mathcal{V}_6, \mathcal{V}_{11} \simeq 1$. However, semicalssical and quantum gravity bounds imply that the effective proton-decay scale is $M_s \leq M_{p-decay} \leq M_{Pl}$. The same proton-decay bounds can be applied to E2-branes (directly) generating a Weinberg superpotential as
\[ \mathcal{W} = \frac{e^{-S_{E2}}}{M_s} H_u H_d L \rightarrow \frac{e^{-S_{E2}}}{M_s M_{SUSY}} hhlh \] (21)
Assuming $M_s, M_{SUSY} \simeq 1 \div 100 \text{TeV}$, the effective scale $e^{+S_{E2}} M_s M_{SUSY} \simeq 10^{12} \div 10^{13} \text{GeV}$. So that, in analogy with proton-decay operator, $e^{+S_{E2}} >> 1$ ($e^{+S_{E2}} \simeq 10^{15} \div 10^{21}$). As for proton decay, WGC demands $(g_s^{-1}, \mathcal{V}_{11}, \mathcal{V}_6) >> 1$. A scenario with $M_{SUSY} \simeq M_s \simeq 10^{15} \text{GeV}$ is not compatible for any value of $e^{+S_{E2}}$ with a scale $10^{12} \div 10^{13} \text{GeV}$ for the neutrino Majorana mass. A possible scenario which is compatible with WGC is $e^{+S_{E2}} \simeq 1$ while $M_s M_{SUSY} \simeq (10^{12} \div 10^{13} \text{GeV})^2$. However, $e^{+S_{E2}} \simeq 1$ violates the semiclassical bound.

In Refs. [30, 31], we suggested that a six quark $\Delta B = 2$ transition can be generated by only one exotic instanton solution as
\[ \mathcal{W} = \frac{1}{M_S^4} e^{-S_{E2}}(f_{1f_2} f_{3f_4} f_{5f_6} U_{f_1} U_{f_2} D_{f_3} D_{f_4} D_{f_5} D_{f_6}) \] (22)
After the supersymmetric quark-quark reduction (mediated by gauginos), this operator can generate an effective neutron-antineutron operator
\[ O_{n\bar{n}} = \frac{Y_1}{\Lambda_{n\bar{n}}^{25}} u^c d^c d^c u^c d^c d^c \] (23)
where $300 \text{TeV}$ is the current best experimental bound.

Next generation of experiments can enhance the current bound up to $1000 \text{TeV}$ scale. Let us assume that $M_{SUSY} \simeq M_s$. In principle, in order to generate a $1000 \text{TeV} n-\bar{n}$ transition with a $M_s = 10 \text{TeV}$, one could consider a $\mathcal{Y}_1|e^{S_{E2}}| \simeq 10^{10}$ which corresponds to large 3-cycles wrapped by the $E2$. However, the weak gravity conjecture sets a bound on the largeness of the (inverse) instanton coupling. For example, in a scenario in which $g_s^{-1}\sqrt{V_6} \simeq 1$, a large instantonic mass scale is excluded: the string scale must be $M_s << M_{Pl}$, i.e. $\mathcal{V}_6 > g_s^2$. So that, in this scenario Regge stringy states can be searched in the next run of LHC while KK-modes cannot be TeV-ish particles.

A situation which is interesting for future $100 \text{TeV}$ proton-proton colliders beyond LHC is $M_s \simeq M_{SUSY} \simeq 50 \div 100 \text{TeV}$. In this case, a $1000 \text{TeV}$ neutron-antineutron transition can be generated for $\mathcal{Y}_1|e^{S_{E2}}| \simeq 10^{10} \div 10^6$, which is not viable for $g_s^{-2}\sqrt{V_6} \simeq 1 (M_s \simeq M_{Pl})$ because of WGC. So that, in this scenario $M_s << M_{Pl}$, i.e. Regge states and no KK-modes for a 100 TeV proton-antineutron collider. In this case, there is also the interesting possibility to observe the $\Delta B = 2$ exotic instanton in direct binary quark collisions, as $qq \rightarrow q\bar{q}q\bar{q}$. In fact, while neutron-antineutron transitions are constrained up to 300 TeV, other six quarks operators involving heavier flavors can be tested in 100 TeV colliders, i.e. the Yukawa matrix components of other flavors are not directly constrained by $n-\bar{n}$ experiments. For instance, the cross section is expected to be polynomially growing with the CM energy for $E_{CM} < M$, while unitarized and exponentially softened for $E_{CM} > M$ at fixed scattering angle [31].

IV. CONCLUSIONS AND REMARKS

In this letter, we have discussed many implications of the Weak Gravity Conjecture for exotic stringy instantons. In particular, we have considered the case of type IIA open string theory. We have shown how WGC on exotic instantons can provide a strong bound on effective superpotentials generated by E-branes. For instance, WGC constrains 3-cycles geometries of the E2-brane instantons, the string coupling and the internal six-dimensional volume. For example, we have argued that, if a 1000 TeV neutron-antineutron transition was observed, WGC, applied on the direct generation mechanism from a $E2$-brane instanton in low scale string the-
ory, would imply a precise set of observables for the next generation of colliders. Assuming the string scale $M_s = 10\div 100 \text{ TeV}$, we have shown how the internal space volume must be very large, i.e. $100 \text{ TeV}$ proton-proton colliders beyond LHC should observe Regge string states and not KK states.

We have also discussed WGC implications on bilinear and trilinear R-parity violating operators, Dirac neutrino mass, proton decay operators and $\mu$-term from exotic instantons.

We conclude that the Weak Gravity Conjecture, which is a statement on quantum gravity and black holes, seems to be unexpectedly predictive in string-inspired particle physics. Exotic instantons may have an important role in the UV completion of the standard model of particles and cosmology from basic principles of the string theory. WGC could be a razor criterium which may be crucially important for our understanding of string phenomenology.

**Acknowledgments**

I would like to thank organizers and participants of String Phenomenology 2016 (Ioannina, Greece) for inspiring talks and conversations, as well as A.P. Wine for interesting suggestions and remarks. My work was supported in part by the MIUR research grant Theoretical Astroparticle Physics PRIN 2012CP-PYP7 and by SdC Progetto speciale Multiassse La Societ`a della Conoscenza in Abruzzo PO FSE Abruzzo 2007-2013.

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