Peculiar obstructions in string vacua and cosmology

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Based on:

• arXiv:1812.11909 - PRD 100, 066009, 2019;

See also:

 $arXiv:1705.11071 - PRD 96, 083529, 2017;$

• arXiv:1910.06233; $\mathbf{r} = \mathbf{r} \cdot \mathbf{r}$

Introduction

The Standard Model of particles The Standard Model of particles of SM are in irreducible representations of the proper Lorentz group. In SM, we only have fields of spin \mathcal{L} in irreducible representations of the representations of the irreducible representations of a group which is a group wh of individual groups. The generators (of each individual group) shall be the dimension of the symmetry group. We shall thus have 8(= 3² 1) *SU*(3) gauge fields *^G^a µ*, 3(2) and 3(2) substituting the substitution of $\overline{1}$ *u I* he Stand

- (1) Spacetime symmetry: $\left(1\right)$ S_{pino}rstine of spinors: $\left(1\right)$
	- Spacetime symmetry group is Poincare group,
	- ✦ All fields irreducible representation of Lorentz group, opacentic symmetry group is a official group,

	All fields irreducible representation of Lorentz group *µ µ µ I I I I I I I I O r* specifies and *SU(3)*, $\frac{1}{3}$, $\frac{1}{3}$, $\frac{1}{3}$, $\frac{1}{3}$, and *C*(1), and *C*(3), and *SU*(3), and *SU*(3 *q* is a rational number of the representation of *L*orentz group,
	- \star Allow only spins 0, 1/2 and 1; continuous complexious (i.e. all the symmetry $\frac{1}{2}$ and $\frac{1}{2}$), (i.e. \star Allow only spins 0, 1/2 and 1;
- (2) Internal symmetry:
	- ✦ SM is a gauge theory (local, continuous internal symmetries), local). The internal symmetry group of SM is the direct product product product product product and simple compact and simple c \star SM is a gauge theory (local, continuous internal symmetries), \rightarrow SM is a gauge theory (local, continuous internal symmetries), c mory (local) comme
	- \rightarrow Internal (gauge) symmetry group: $SU(3) \times SU(2) \times U(1)$. \rightarrow Internal (gauge) symmetry group: $SU(3) \times SU(2) \times U(1)$ σ (see all $SU(3) \times SU(2) \times U(1)$
c 11 \cdot 1. \cdot
	- \rightarrow Thus, spin 1 gauge fields in adjoint representation; q Thus $\sin 1$ nouse fields in adjoint representation. all fermions in terms in terms of left-handed weights (the second weights (the first)
	- (3) Spinors: generation are called *q, u,* ¯ ¯ In this notation, the *SU*(3) gauge fields *G^a* δ) Spinors δ
	- $\overrightarrow{ }$ Left Handed Weyl fermions in three copies of the representation Let radice w y hermons in three copies of the representation $(3, 2, +\frac{1}{6}) \oplus (3, 1, -\frac{1}{3}) \oplus (3, 1, +\frac{1}{3}) \oplus (1, 2, -\frac{1}{2}) \oplus (1, 1, +1)$ of the symmetry group. We shall thus have 8(= 3² 1) *SU*(3) gauge fields *^G^a d,* `*, e*¯) in three copies (i.e. tensor product) of the representation ⁴ $(3, 2, +$ 1 $\frac{1}{6})\oplus (\bar{3},1,-\frac{2}{3})\oplus (\bar{3},1,+$ 1 $\frac{1}{3})\oplus(1,2,-\frac{1}{2})\oplus(1,1,+1)$

(4) Scalar: (4) Scalar: Internet scalar field the Higgs field the $\frac{1}{2}$ in the representation i

A complex scalar in representation

$$
(1, 2, -\frac{1}{2})
$$

(5) Lagrangian: \mathcal{S} . The representation of spinors:

- The most general, consistent with symmetries, Representations of the Lie algebra of the internal symmetry group can be parametrized as (*r,* `*, q*), where • The most general, consistent with symmetries, σ \mathbb{E} the symmetry group.
- Ensure that EW symmetry is spontaneously broken, \bullet Er
	- \bullet Only one dimension-full parameter: weak scale. generation are called *q, u,* ¯ ¯ • Only one dimension-full parameter: weak scale.

The Standard Model of Cosmology the spacetime into space-like hypersurface-like hypersurfaces which are homogeneous, isotropic and flat α

At early enough times $(T \sim \text{few MeV})$ enough times (*T* ⇠ O (10) MeV), $\overline{}$

- (1) Gravity: General Relativity
- (2) To leading order: spacetime geometry is spatially flat FRW metric (spacelike hypersurfaces: homogeneous, isotropic, spatially flat), (1) diarry: denerative (2)
(9) T_a leading enders executive geometry is exetially flat FDW metric (coeses)
	- (3) Matter
- ✦ Dark Matter: cold, collisionless, (3) Natter
 \rightarrow Dark Matter: cold, collisionless
	- * cosmological constant (with a very tiny value: $\ell_{\text{Pl}}^2 \Lambda \approx 3 \times 10^{-122}$),
	- ⁺ SM particles: photons, neutrinos (and anti-neutrinos), electrons (and
positrons), protons and poutrons positrons), protons and neutrons. itially, $\overline{}$

(4) Initially,

- baryon to photon ratio is $\mathcal{O}(10^{-9})$
	- · asymmetry in neutral leptons negligible
		- asymmetry in charged leptons s.t. the net electric charge is zero.
- (5) At sub-leading order: scalar metric perturbations:
	- \bullet adiabatic, · adiabatic,
		- Gaussian
- · nearly scale-invariant (tilted red) $\frac{1}{\sqrt{2}}$ Observational: *⌦^b h*² , *⌦^c h*2, 100*✓M C* (related to angular size of sound horizon), *⌧* (optical depth of re-ionization),

New fundamental physics?

Neutrino masses **Baryon Asymmetry** Dark Matter Dark Energy Inflation vacuum stability

energy, inflation), strong CP problem, the flavour problem, precision electroweak constraints,

* UV sensitivity (SM Higgs, Vacuum

- Why this gauge group?
- Why 3 generations?
- Why 1+3 spacetime dimensions?
- Broadly: why the SM and cosmological parameters have the values they have?

- graviton-graviton scattering at Planck scale,
- Resolving the gravitational singularities,
- UV finiteness?
- Hints from BH physics? e.g. holography, information loss paradox, calculation of entropy of BHs from microphysics;
- Other lessons: given GR and QM, no operational way to measure length scales smaller than Planck length etc.

The "Standard Model" of Cosmology the space-like hypersurface-like hypersurface-like hypersurfaces which are homogeneous, isotropic and flat

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		- **• Gaussian**
- · nearly scale-invariant (tilted red) tilted red power spectrum. The contract of the Observational: *⌦^b h*² , *⌦^c h*2, 100*✓M C* (related to angular size of sound horizon), *⌧* (optical depth of re-ionization),

Why this geometry?

Why do we find ourselves in a spatially flat FRW (homogeneous and isotropic spacetime)?

From microphysics…

Every realistic microscopic theory is specified by…

Gauge group,

- \star Representation of fermions,
- Representation of scalars, and,
- **the Scalar Potential**

Cosmic inflation

Large field inflation \mathbb{T} is a controlled set-up \mathbb{T} of scales \mathbb{T} of \mathcal{L} dii \mathcal{L} . \overline{a} constant of fundamental axion must be sub-Planckian: \overline{a} Large held inflation

Too many models?

Some conceptual **issues**

(+4290)

- + (-4673218943712894637281978923) + (+47583920542) + (+7458392157829013278190547825) + (-321) +(unknown, but large contributions)
	- $=$ ORDER (1) NUMBER E.G. 3

Possible but extremely peculiar!

UV sensitivity is ubiquitous…

$$
\delta m_H^2 \sim \alpha_{\rm GUT} M_{\rm GUT}^2
$$

◆

*m*⁴

Lyth bound and future CMB observations... **2 a** $\frac{1}{2}$ ◆ ${ \bf sound}$ an *m*⁴ d future *x*th bound *,* Dirac fermion ⇣ *r* ⌘¹*/*²

◆

⇤⁴*ⁱ*

 $\frac{1}{2}$ (@)2(*i*+1) $r < 0.064$. bound: \int_{0}^{∞} ⇤⁴*ⁱ* observational bound: Current

⇡

In future the **bounds** In future, the bounds will get tighter.

+ *···* (22) **Planckian**

Wilsonian effective theory h ⁶⁴⇡² ln ✓*m*² *µ*2 *,* real scalar

^h⇢ivac ⁼ *^m*⁴

Specify:

- ▶ Symmetries and field content,
- ‣ UV cut-off and Wilson coefficients. t,
ionta

$$
\mathcal{L}_{\text{eff}}[\phi] = \mathcal{L}_{\ell}[\phi] + \sum_{i=1}^{\infty} c_i \frac{\phi^{4+2i}}{\Lambda_0^{2i}} + d_i \frac{(\partial \phi)^2 \phi^{2i}}{\Lambda_0^{2i}} + e_i \frac{(\partial \phi)^{2(i+1)}}{\Lambda_0^{4i}} + \cdots,
$$

¹⁶⇡² ln ✓*m*²

◆

- ‣ Low energy experiments, irrelevant operators,
- ‣ Relevant operators sensitive,
- ‣ Inflaton rolls beyond the cut-off!
- ‣ How come the later terms not important?
- ‣ Symmetries of UV theory could be helpful.

Why large field inflation?

- ‣ Simple potentials, *V* ¹*/*⁴
- ▶ No tuning of initial field value and time derivative, eld valu 0*.*1
- ‣ Testable (in near future).

$$
\frac{V^{1/4}}{M_{\rm Pl}} \approx 10^{-2} \left(\frac{r}{0.1}\right)^{1/4}
$$

For inflaton charged under a gauge symmetry…

- ‣ field value and potential gauge dependent: how trustworthy is Wilsonian argument? *V* () (27)
- ‣ Vacuum energy is gauge independent

What could possibly go wrong?

$\boldsymbol{1}$ es be $\boldsymbol{1}$ o *m* the cu ◆ particle $\mathbf s$ below ◆ *M*Pl 0*.*01 $\bm{New\, particles\ below\ the\ cut-off!}$

Quantum Gravity issues? **162** ssues? \tt{tum} Gr *n w*ity iss ◆

0

◆

- Future observations would put tight constraints on large field inflation,
- Inflation appears to be a sensible mechanism,
	- But harder to come up with concrete models,
- Large field inflation is
	- trivial if one does it carelessly,
	- almost impossible if one does it carefully.

Kim-Nilles-Peloso (KNP) Mechanism in QFT

Axion potential m: ^p*g*⁵⁵ *dx*⁵ (27) z. ^p*g*⁵⁵ *dx*⁵ (27) *M*Pl $\overline{}$ $\frac{1}{2}$ 2 ntial

0

⇣ *r*

2⇡*R* =

⌘¹*/*⁴

$$
\langle \theta' | H | \theta \rangle = 4\pi \delta(\theta - \theta') \left[\sum_{n=1}^{\infty} e^{-nS_1} \cos n\theta \right] + \text{const} \qquad \theta \to \frac{\phi}{f} + \pi
$$

$$
V(\phi) \blacklozenge
$$

$$
V(\phi) = \Lambda_1^4 \sum_{n=1}^{\infty} e^{-nS_1} \left[1 - \cos \left(\frac{n\phi}{\phi} \right) \right]
$$

⇣ *n*

⌘2

✓*wR*

e^s

◆²

$$
V(\phi) = \Lambda_1^4 \sum_{n=1}^{\infty} e^{-nS_1} \left[1 - \cos\left(\frac{n\phi}{f}\right) \right]
$$

*eu*¹

$$
S_1 \gg 1
$$
 $V(\phi) = \Lambda^4 \left[1 - \cos \left(\frac{\phi}{f} \right) \right]$

- \blacktriangleright Compact field space,
- ‣ Natural inflation: axion is the inflaton,
- TTOTA TTTTMOT ‣ For large f, large field inflation, typically, f is Planckian

Global symmetries ¹*.*¹³ ⇥ ¹⁰+3 *^M*Pl

- ‣ Natural inflation: axion is a PNGB of a spontaneously broken (and anomalous) global U(1) symmetry, *M^p* = 0*.*518 *M*Pl *R*¹ = 0*.*035 *M*Pl
- **A** Super-Planckian f could be untrustworthy,
	- ‣ No continuous global symmetries in QG,
	- ‣ Gravitational instantons?
	- ‣ When f can be deduced from QG, it is sub-Planckian. n be ded[.] ان
Seç $?$ OM QG, IT IS SI

$$
S_{\rm gravity} = \frac{n M_p}{f} \implies \delta V \sim e^{-S_{\rm gravity}}
$$

#

3 Review of KnP-Type Natural Inflation of KnP-Type Natural Inflation of KnP-Type Natural Inflation

"

1

$$
V(\phi_1, \phi_2) = \sum_{i=1}^2 \Lambda_i \left(1 - \cos \left[\frac{\phi_1}{f_i} + \frac{\phi_2}{g_i} \right] \right), \qquad \psi_1 = \frac{g_1 \phi_1 + f_1 \phi_2}{\sqrt{f_1^2 + g_1^2}}, \quad \psi_2 = \frac{f_1 \phi_1 - g_1 \phi_2}{\sqrt{f_1^2 + g_1^2}},
$$

$$
\psi_2 \bigotimes \psi_2
$$

$$
V(\psi_1, \psi_2) = \Lambda_1 \left(1 - \cos \left[\frac{\psi_1}{f_1} \right] \right) + \Lambda_2 \left(1 - \cos \left[\frac{\psi_1}{f_2} + \frac{\psi_2}{f_{\text{eff}}} \right] \right)
$$

$$
\psi_1
$$

$$
\psi_2
$$

$$
\psi_1
$$

$$
\psi_2
$$

$$
\psi_1
$$

$$
\psi_1
$$

$$
\psi_2
$$

$$
\psi_1
$$

$$
f'_1 = \frac{f_1 g_1}{\sqrt{f_1^2 + g_1^2}}, \qquad f'_2 = \frac{f_2 g_2 \sqrt{f_1^2 + g_1^2}}{f_1 f_2 + g_1 g_2},
$$

$$
m_{\psi_1}^2 \simeq \Lambda_1 \left(\frac{1}{f_1^2} + \frac{1}{g_1^2} \right), \quad m_{\psi_2}^2 \simeq \frac{\Lambda_2 \left(f_2 g_1 - f_1 g_2 \right)^2}{g_2^2 f_2^2 \left(f_1^2 + g_1^2 \right)}
$$

$$
\psi_1 = 0
$$

 $\frac{1}{2}$

axionic rotation) and alignment leading to the enhancement of decay constant of decay constant of decay constant of α

⌘¹*/*⁴

 $\frac{1}{\sqrt{2}}$

 $\frac{1}{\sqrt{2}}$

⇣ *r*

archy between the two axions rotated in a new basis α axions rotated in a new basis. As we will see explicitly se

the lighter combination also occurs. With the following rotation of axiomatic rotation of axiomatic rotation of

 $\frac{1}{2}$

, (3.4)

in a moment, one can elegantly create a mass hierarchy and (with appropriate

Kim-Nilles-Peloso (KNP) Mechanism in string theory

- ‣ Just like GR: no prior geometry (different solutions have different geometry),
- ‣ String propagation on a slightly curved background:
	- ‣ Einstein equations + small corrections,
- ‣ Product manifold:
	- ‣ E.g. Cylinder, torus etc;
- ‣ Vacuum solution of ten dimensional equations: "maximally symmetric spacetime times a six dimensional compact manifold"

‣ **Geometric moduli:**

- ‣ Kahler moduli: size of extra dimensions
- ‣ Complex structure moduli: shape of the extra dimensions,
- ‣ How many?
	- ‣ topology of the manifold (Hodge numbers),
- ‣ **Axions:**
	- ‣ scalars from zero modes of higher form potentials turned on in extra dimensions,
	- ‣ no energy cost
- ‣ No potential (to begin with),
- ‣ The values of these fields need to be fixed: potential;
- ‣ Turn on field strength of higher form potentials in extra dimensions,
	- ‣ some energy cost,
- ‣ Generates a potential for some scalar fields,
- ‣ fluxes are quantized,
- ‣ Topology determines how many different kinds of fluxes possible.

- FIG. 2: For *^q*¹ = 40, *^q*² = 60, *^h*⁰ = 10, *^f*⁰ = 10 and *^V* = 100, one obtains *s* ⇡ 40, *u*¹ ⇡ 6*.*86, *u*² ⇡ 15*.*43, the resulting Quantity f to be deduced (e.g. axion decay constant, vacuum energy etc);

- $+ f_1 + f_2 + \ldots$ \top J1 \top J2 \top \cdots , ‣ A typical calculation: \rightarrow *• f<M^p* in all known controlled regimes of string theory: i.e. whenever *g^s* and *l* $f = f_0 + f_1 + f_2 + \cdots,$
	- quantities); \overline{a} ▸ Successive terms: smaller (additional factors of small *• f<M^p* in all known controlled regimes of string theory: i.e. whenever *g^s* and *l* enough that the contributions of their higher powers do not matter, *f<Mp*; when *f>Mp*, one *^s/R*² are small enough the contributions of the contributions of μ and μ *p* on μ *f* and μ *f ^s/R*² are large so that we can not trust the conclusion drawn from the I suppose the contribution of the contribution and contributions to $\frac{1}{2}$
		- *i* both perturbative and non-perturbative contributions, <u>mando de la completa de la contexta de l</u> ‣ both perturbative and non-perturbative contributions, $\bullet\;$ both perturbative and non-perturbative contributions,
- $\n **unknown, are they small?**\n$ e subsequent ones are \triangleright all terms till f_i are known, the subsequent ones are also finds that *g^s* and *l* ervurbative and non-perturbative contributions,
g till f i are known the subsequent ones are which fear the compact of the perturbation of the perturbative compact of the perturbative as $\frac{1}{2}$ (i.e., $\frac{1}{2}$ $\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$ *•* all terms till f_i are known, the subsequent ones are unknown, are they small? $\frac{1}{2}$ and $\frac{1}{2}$ and contribution of $\frac{1}{2}$
	- vaces is the energy scale association: $g_s \ll 1$ constant $\alpha^{\prime\prime}$ / $V_6 \ll 1$ α /3 / 1 α 1 Necessary condition: $g_s \ll 1$ $\alpha'^3/\mathcal{V}_6 \ll 1$ the uncessary condition: $y_s \ll 1$ and $y_t \ll 1$
	- \rightarrow Is it sufficient? → Is it sufficient? $\overline{5}$ $\overline{15}$ $\overline{10}$

Beyond trustworthy regimes? (d) Special Kahler geometry; (b) 2*h*(2*,*1) + 2. \mathbf{S} . Calcabi-Yau orientifolds: the orientification symmetry. (a) The angle ✓ specifying the orientifold, 2.5 A few condition to the string connection to the string connection to the string connection to the string c $2.5.1$ Connection to extra-natural inflation to extra-natural inflation to extra-natural inflation \sim 1. We require $\frac{1}{2}$ **d** $\frac{1}{2}$ *p* $\$

s

(a) 2*h*(1*,*1) T_{\odot} + *D* 22 *pecifical* initial polinflotion 225 2.5 A few constructions on the string contract on $\rm N$ R_{in} 2. We know that (from e↵ective action of bosonic string theory) *M*² ⇠ *^g*² *^s M*⁸ *^s V*⁶ *,* (14) Natural inflation???

• The e↵*ect of orientifolding on the spectrum*

8. Calabi-Yau orientifolds: the orientifold has an involution symmetry.

• The e↵*ect of orientifolding on the spectrum*

2.5.1 Connection to extra-natural inflation

2.5 A few comments on string cosmology

1. We require *Rg*4*DM^p* ⌧ 1 for ENI to work,

 \blacktriangleright Whenever we can deduce f, making it P \blacksquare volumes etc. U duk v oldfilop ood. takes us out of the trustworthy reg \triangleright whielever, we can deduce i' the kind IG DI UDO *Ge|F*2*[|]* יח ^{אוו} .t (*d*¹⁰*x Ge|F*2*[|]* ² *.* (15) Recall that we could define *D^µ* = @*^µ iA^µ* (note the absence of *g* here), then, *|F*2*|* anckian 니
이 ▸ Whenever we can deduce f, making it Planckian also Recall that we could define *D^µ* = @*^µ iA^µ* (note the absence of *g* here), then, *|F*2*|* takes us out of the trustworthy regime e.g. small volumes etc.

Extra natural inflation??? *S*gauge = 1 ᄓ $\overline{\mathbf{A}}$ Z a natural inflation??? 4, irrespective of the dimension of spacetime. This is what fixes the power of ↵⁰ in previous expression. α l in *gs V*6*M*⁶ Extra natural inflation???

 $Rg_{4D}M_p \ll 1$ α y_s *m_sn* \leq 1 $\frac{1}{2}s$ $\frac{1}{2}$ **,** $M_p^2 \sim g_s^{-2} M_s^8$ $S_{\text{gauge}} = \frac{1}{\alpha'^3} \int d^{10}x \sqrt{-G}e^{-\phi} |F_2|^2$ and θ action of the θ *S*gauge = 1 α ^{3} $Rg_{4D}M_p \ll 1 \hspace{1cm} M_p^2 \sim g_s^{-2} M_s^8 V_6 \hspace{1cm} S_{\rm gauge} = \frac{1}{\alpha'^3} \int d^{10} x \sqrt{-G} e^{-\phi} |F_2|$ ² *.* (15) $\frac{g_s}{g_s M^6}$ $g_s^{-1/2} M_s R \ll 1$ $g_s^{-1/2} \gg 1$ $R \ll \ell_s$ $\frac{1}{3}M_s^6$ and $\frac{1}{3}s$ is $\frac{1}{3}r$ is the power of $\frac{1}{3}$ in previous expression. This is $\frac{1}{3}$ in previous expression. This is $\frac{1}{3}$ in previous expression. This is $\frac{1}{3}$ in previous expression. Thi $\overline{1}$ $\overline{2}$ $g_{4D}^2 \sim$ *gs* $V_6M_s^6$ $\sqrt{0} - 4$ $\frac{1}{\alpha}$ $\frac{1}{\alpha}$ $\frac{1}{\alpha}$ is the regular that $\frac{1}{\alpha}$ is the regular to $\frac{1}{\alpha}$ P_{α} *M* $\lt 1$ *i g*1*/*² *s a* α ¹⁸ *J* $g_{4D}^2 \sim \frac{g_{\circ}^2}{V_c M^6}$ $g_s^{-1/2} M_s R \ll 1$ *g* $\frac{-1/2}{s} \gg 1$ $R \ll \ell_s$ \cdots σ \cdots *s* 6 ² $F_2|^2$ $\mu^2 M_s R \ll 1$ $g_s^{-1/2} \gg 1$ $R \ll \ell_s$

and (from e $4\leq$ theory, which has gauge group \mathcal{A} theory, which has gauge group \mathcal{A}

4. Thus, the requirement *Rg*4*DM^p* ⌧ 1 implies that

supergravity the superpotential α noted as *i*, then, the Kahler potential *K*(*i,* ¯¯*^j*) is a real larly, the superpotential *W*(*i*) is a holomorphic function public the fields and it has a mass dimension \blacksquare grangian for the scalar sector (for the scalar sector (for those scalars which are scalars which are scalars w
The scalars which are given by the expression of the expression

- ‣ 10 D supergravity to 4 D supergravity, ~ 10 D gunongnority to Λ D gunongnority \rightarrow 10 $\scriptstyle\rm D$ supers x to 4 D Φ *j*^{*Dergravity,*}
- ‣ Kahler potential, super potential and scalar potential not gauge is a paper in the absence of a D-term potential in the T-term potential is a paper in the T-term potential is not by the experience \mathcal{L} are turned on, a superpotential is induced on, a superpotential is induced on, a superpotential is induced on, and tontial is turned on the turned only the turned only the turned only the superport of the superport of the tur
Historia i our dimensional equation theory (i *p*where, the F-term scalar potential is given by the F-term scalar point of the F-ter

$$
\mathcal{L} = K^{i\bar{j}} \partial_{\mu} \phi_i \partial^{\mu} \phi^{\dagger}{}_{\bar{j}} - V_F
$$
\n
$$
V_F = e^{\frac{K}{M_p^2}} \left[K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - \frac{3|W|^2}{M_p^2} \right], \quad D_i W = \partial_i W + \frac{W \partial_i K}{M_p^2}
$$

condition *DaW* = 0 (notice that since we are looking

^L ⁼ *^Kⁱ*¯*^j*@*µi*@*^µ†*

for supersymmetric can not be defined by $\mathcal{O}_\mathcal{A}$

Sitter). By following this procedure, one finds that all the

$$
U_{\lambda} = u_{\lambda} + i v_{\lambda} \qquad S = s + i \sigma
$$

Type IIA flux vacua

- ‣ Type IIA string theory, type IIA supergravity,
	- ‣ Massive type IIA supergravity,
- ‣ Just using the ingredients mentioned, all geometric moduli get fixed,
- ‣ A linear combination of RR axions get fixed,
- ‣ Additional ingredient: Euclidean D2 brane instanton (next slide):
	- ‣ all moduli can be fixed,
- ‣ Supersymmetric AdS vacua easy to find,
- ‣ dS vacua much harder (don't exist?),
- ‣ Study large field excursion in this toy set up;

Non-perturbative ingredient

 \blacktriangleright instanton-like contribution to the path integral, .
P contri $\frac{1}{\sqrt{2}}$ and the path *f* $\frac{1}{3}$

1

‣ semiclassical approximation: action of an "Euclidean Dp-brane" rish contents about the content of an "Euclidean"
Al approximation: action of an "Euclidean" ximation: action c
ximation: action c *f* n nnegrar,
f an "Euclidean *n*=1

Ī

- ‣ branes: soliton-like objects in string theory, *A* ⇠ *e* $\mathsf O$ ⇣ *^µ*² gs i R iJ ن *d*3*x* pdet(*G*)+*iµ*² R 1eor \overline{a}
- ▶ Dp-branes charged under certain (p+1)-form fields ◆ (33) h \overline{r} ⇣ *^µ*² *gs* $\overline{\mathsf{C}}$ $\ddot{}$ \overline{p} *certain* (*p* t 1)-
' f_C

$$
\mathcal{A}\sim e^{-S_E}
$$

$$
\mathcal{A} \sim e^{-\left[-\left(\frac{\mu_2}{g_s} \int_{\Sigma_3} d^3x \sqrt{\det(G)} + i\mu_2 \int_{\Sigma_3} C_3\right)\right]}
$$

$$
\mathcal{A} \sim e^{-T_p \text{Vol}(\Sigma_3) + i\mu_2 \int_{\Sigma_3} C_3}
$$

$$
V(\phi) \sim e^{-S_1} \cos(a)
$$

Low energy theory of axions and instantons $\| \mathbf{L} \mathbf{s} \|$ 1930 - Personal Propinsi II
3 Martin - Personal Propinsi II 1 1 At *Lew energy* we can be an a the remaining low energy fields is given by (see e.g. [38]) and α T. OTAT AN APOTT th \mathbb{R}^n and the canonical given in Eq. (3), one can easily find the canonical value of \mathbb{R}^n s potential by using \mathbf{u} perturbative e \mathbf{e} \boldsymbol{v} energy theory of axions and 17 *n*=1 *enS*¹ heory of axions and

4*u*²

and so, using the equations presented in *§*II 1, we can

 \blacktriangleright Choose appropriate instanton, *^L* ⁼ *^f* ² \blacktriangleright Choose appropriate instanton, \overline{a} ⇣ *^µ*² *gs* R)C *d*3*x* pdet(*G*)+*iµ*² R ton_{\ast}

⁴*s*² *, KU*1*U*¯¹

, the potential would be obtained by $\mathcal{O}(n)$

$$
\mathcal{L} = - f_{\sigma}^{2} (\partial \sigma)^{2} - f_{\nu_{1}}^{2} (\partial \nu_{1})^{2} - [V_{0} + A' e^{-s} (1 - \cos \sigma) \n+ B' e^{-u_{1}} (1 - \cos \nu_{1})],
$$
\n
$$
f_{\sigma} = \frac{1}{2s}, \ f_{\nu_{1}} = \frac{\sqrt{3}}{2u_{1}}.
$$
\n
$$
h_{0} \sigma + q^{1} \nu_{1} = 0
$$
\n
$$
V(\phi) \sim e^{-S_{1}} \cos(a)
$$

p3

f and *f* an

A simple realisation of KNP mechanism

- ‣ a two- dimensional axion field space,
- ‣ there is one heavy direction,
- \triangleright in the direction orthogonal to it, which is flat at the perturbative level, the potential is generated by nonperturbative effects (and hence, is a cosine),
- ‣ CAUTION: is field space still compact?

Fluxes as free parameters.

in two-axion limit of three-axion case, there is additional

freedom which can cause these factors to be very large

energy theory we can think of *s* and *u*¹ as fixed quan- \blacktriangleright increase amplitude and period ior only α *^V* fixed) will cause *^f^u*¹ \blacktriangleright Increase amplitude and period for only one cosine? the period of this second cosine is also large, thus, we e cosine? $f(x)$ space can be found from $f(x)$ $\overline{}$ iod for only one co *f* ‣ Increase amplitude and period for only one cosine?

$$
f_{\psi}^{s} = \frac{N}{q^{1}} = \frac{\sqrt{f_{\sigma}^{2}(q^{1})^{2} + f_{\nu_{1}}^{2}(h_{0})^{2}}}{q^{1}}, s = \frac{2f_{0}\mathcal{V}}{5h_{0}},
$$

$$
f_{\psi}^{u_{1}} = \frac{N}{h_{0}} = \frac{\sqrt{f_{\sigma}^{2}(q^{1})^{2} + f_{\nu_{1}}^{2}(h_{0})^{2}}}{h_{0}}, u_{1} = \frac{3h_{0}s}{q^{1}}.
$$

\blacksquare in this context one context one could think about this context one could think about the poten-**Can we do it?**
The superpotential generated by fluxes receives nonof the things we mean we say that the potential the potential that the potential that the position of the potential

by found by substituting for α from Eq. (17) into the substituting for α

perturbative corrections from Euclidean D2-brane in-

 σ found by substituting for σ \rightarrow Single ax that it is a cost in the cost in that it is a cost in the cost of the cost in that α **b** one detection and the model of **f** $\sum_{i=1}^{\infty}$ ‣ Single axion and two instantons stantons, which is one of the form of the form \mathbf{C} *^L* ⁼ *^f* ²

$$
\mathcal{L} = -\frac{1}{2}(\partial \psi)^2 - \left[V_0' + A'e^{-s} \left(1 - \cos \frac{\psi}{f_{\psi}^s} \right) + B'e^{-u_1} \left(1 - \cos \frac{\psi}{f_{\psi}^{u_1}} \right) \right],
$$

sider the line in (*f, f*⌫¹ ⌫1) plane of the canonically nor-

 \blacktriangleright Can we do it? could get a direction in which the potential is α $\sqrt{2}$ \blacktriangleright Can we do it? $\frac{1}{2}$ by using $\frac{1}{2}$. For the correct choices choices

*u*¹ decreases and *f ^s*

 \mathcal{L}_c and the Lagrangian determining the dynamics of the dynamics of

the remaining low energy fields is given by (see e.g. \mathbb{R}^3 8). The remaining \mathbb{R}^3

4

2

In the rest of this subsection, we shall analyse this

. (12)

$$
f_{\psi}^{s} = \frac{N}{q^{1}} = \frac{\sqrt{f_{\sigma}^{2}(q^{1})^{2} + f_{\nu_{1}}^{2}(h_{0})^{2}}}{q^{1}}, s = \frac{2f_{0}\mathcal{V}}{5h_{0}}, \qquad f_{\sigma} = \frac{1}{2s}, \ f_{\nu_{1}} = \frac{\sqrt{3}}{2u_{1}}.
$$

$$
f_{\psi}^{u_{1}} = \frac{N}{h_{0}} = \frac{\sqrt{f_{\sigma}^{2}(q^{1})^{2} + f_{\nu_{1}}^{2}(h_{0})^{2}}}{h_{0}}, u_{1} = \frac{3h_{0}s}{q^{1}}.
$$

$$
f_{\psi}^{s} = \frac{1}{\sqrt{3}s} = \frac{2f_{\sigma}}{\sqrt{3}}, \qquad f_{\nu_{1}}^{u_{1}} = \frac{\sqrt{3}}{\sqrt{3}}.
$$

 \overline{m} malisted fields, the straight line in Eq. (14) is the straight line in Eq. (14) *h* E. Palti "On Natural Inflation and Eq. (6) and Eq. (6) and Eq. (6) and Eq. (6) μ **decision** is the contract of the this supplied that the supplied of the third that the 14 set of 1*/2* set the 14 set of 1*/2* set I JHEP 1510, 188 (2015) [arXiv:1508.00009 [hep-th]]. and *f^u*¹ , we can not make them so large that *u*¹ and *s* **Moduli Stabilisation in String Theo** \Box \Box . Falli \Diamond n ivalurat injiallon and moduli stabilisation in string Theo increases. and *f^u*¹ are simply proportional to the funoduli Stabilisation in String Theory," \vert $\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 &$ *f* JHEP **1510**, 188 (2015) [arXiv:1508.00009 [hep-th]]. shall also re-In this section, we shall attempt to enhance axion de*h* E. Palti "*On Natural Inflation and Moduli Stabilisation in String Theory*," \vert

Since *f ^s*

Weak Gravity Conjecture for axions \overline{a} .
⊸ *<u>POILJECULLE LUL GALUIRE</u>* ⌃3

*Tp*Vol(⌃3)+*iµ*²

- ▶ Weak Gravity Conjecture for axions...
- ‣ An axion with decay constant f must couple to instantons with action S, such that

 $fS \leq M_p$

$$
\mathcal{L}(a) \supset -f^2(\partial a)^2 - \Lambda^4 \sum_{n=1}^{\infty} e^{-nS} (1 - \cos(na))
$$

- (39) ‣ If f is large, S must be small, so, higher order instanton corrections can't be ignored,
- ‣ this limits the "flat" or monotonic regions in potential,
- \blacktriangleright Obviously deep implications for inflation!

Strong form of axionic WGC h ⇣ *^µ*² pdet(*G*)+*iµ*² R *d*3*x* R

Τ

A ⇠ *e*

- ‣ for any axion
	- ‣ there must always be an instanton where the axion appears with a decay constant that is sub-Planckian,

*C*³

⌘i

- **▶ what is the action of this instanton? the action can be very large**
	- ‣ this effect becomes an insignificant modification of the low-energy potential.
- ‣ The strong form of the WGC:
	- **→** this sub-Planckian instanton must have an action less than that of the super-Planckian instanton responsible for the inflaton potential, and so it forms the dominant contribution to the potential. ion less than that of the

$$
V(\phi) \sim e^{-S_1} \cos\left(\frac{\phi}{f_1}\right) + e^{-S_2} \cos\left(\frac{\phi}{f_2}\right)
$$

E. Palti "On Natural Inflation and Moduli Stabilisation in String Theory," | JHEP **1510**, 188 (2015) [arXiv:1508.00009 [hep-th]].

Is it really true? *^L* ⁼ ¹ 2 (@) ² ¹ E h *V*⁰ + *A*⁰ *^e^s*(1 cos) + *^B*⁰

- \blacktriangleright Worth understanding better! i
- ‣ Choose CY s.t. one more axion present,
- ‣ Diagonalise Kahler metric, low energy theory

2

⌫˜¹ (@⌫˜1)

² ¹

2

⌫˜¹ (@⌫˜1)

*^eu*¹ (1 cos ˜⌫1)

$$
\mathcal{L} = -\frac{1}{2} f_{\sigma}^{2} (\partial \sigma)^{2} - \frac{1}{2} f_{\tilde{\nu}_{1}}^{2} (\partial \tilde{\nu}_{1})^{2} - \frac{1}{2} f_{\tilde{\nu}_{1}}^{2} (\partial \tilde{\nu}_{1})^{2}
$$

$$
- \left[V_{0} + A' e^{-s} (1 - \cos \sigma) + B' e^{-u_{1}} (1 - \cos \tilde{\nu}_{1}) + C' e^{-u_{2}} (1 - \cos \tilde{\nu}_{2}) \right]
$$

‣Explore various directions in field space (the spirit of KNP!), ‣ In terms of the displacement field…

$$
\mathcal{L} = -\frac{1}{2}(\partial\psi)^2 - \left[V'_0 + A'e^{-s}\left(1 - \cos\frac{\psi}{f^s_{\psi}}\right) + B'e^{-u_1}\left(1 - \cos\frac{\psi}{f^{u_1}_{\psi}}\right) + C'e^{-u_2}\left(1 - \cos\frac{\psi}{f^{u_2}_{\psi}}\right)\right]
$$

 $\frac{1}{2}$ G. Goswami "*Enhancement of axion decay constants in type IIA theory*," arXiv:1812.11909 [hep-th].

in the (*,* ⌫1*,* ⌫2) space stays unfixed. **Is it really true?**

 $h_0 \sigma + q^1 \nu_1 + q^2 \nu_2 = 0$,

*f^u*¹ ۳

!

÷,

Н

*f^u*² J

*, f^u*¹

and *^f^u*²

÷,

$$
f_{\psi}^{s} = \left(\frac{f_{\sigma}}{\ell_{\sigma}}\right),
$$

\n
$$
f_{\psi}^{u_{1}} = \left[\frac{\det P f_{\tilde{\nu}_{1}} f_{\tilde{\nu}_{2}}}{P_{22} \ell_{\tilde{\nu}_{1}} f_{\tilde{\nu}_{2}} - P_{21} \ell_{\tilde{\nu}_{2}} f_{\tilde{\nu}_{1}}}\right],
$$

\n
$$
f_{\psi}^{u_{2}} = \left[\frac{\det P f_{\tilde{\nu}_{1}} f_{\tilde{\nu}_{2}}}{P_{11} \ell_{\tilde{\nu}_{2}} f_{\tilde{\nu}_{1}} - P_{12} \ell_{\tilde{\nu}_{1}} f_{\tilde{\nu}_{2}}}\right].
$$

- in terms of normalised eigenvectors of the Kahler metric. ‣ Perturbatively flat plane,
- σ find the found is the found of σ picalio,
otation, explore all directions in the plane. is given by the term in structure brackets in the pressure, ‣ Initial direction, rotation, explore all directions in the plane,
- \triangleright One more "parameter": the angle of rotation.

implementing the formalism description description description in *§III* **B 2. As we vary description of a violence** σ , goswallit *Enhancement of axion , f ^u*¹ $\int \frac{1}{2}$ arXiv:1812.11909 [hen_th] *forment of axion decay constants in type IIA theory*["] say, *in the above the case of constants in type in the ory,* ion deem equations in two H_A theory." G. Goswami "*Enhancement of axion decay constants in type IIA theory*," fluxes while, as mentioned above, as mentioned above, the direction costness while, as a mention costness while

Is it really true?

- ‣ There exist search directions which are flat directions,
- ‣ Fluxes don't have to be adjusted, search direction to be chosen,
- ‣ When there are more axions, there are many more parameters available to specify a direction

FIG. 1: For the fixed choice of fluxes mentioned in the text, we C. COSWAIN ENRURCHICALLY OF ARROY larXiv:1812.11909 [hen_{-th]} G. Goswami "*Enhancement of axion decay constants in type IIA theory*,"

G. Goswami "*Enhancement of axion decay constants in type IIA theory*," $\frac{1}{2}$ **I** $\frac{1}{2}$ **2.** As we vary the angle $\frac{1}{2}$ are $\frac{1}{2}$ are e $\frac{1}{2}$ constants *f ^s , f ^u*¹ and *f ^u*² arXiv:1812.11909 [hep-th].

Enhancement…

- found directions in axion field space such that the scalar potential along the direction is sufficiently flat
	- making sure that the effective decay constant due to one of the axions is large,
	- the vev of the saxion corresponding to the rest of axions are so large that their contribution to the scalar potential is negligible.
- this can always be done for any fixed choice of fluxes,
- Strong form of axionic WGC violated?
- will the field actually go along such a straight line trajectory (though its dynamics is determined by, among other things, its potential)?

- Flat directions: higher order corrections need to be taken into account, so avoid,
	- work with the appropriate solution,
- Consider directions in which the field actually rolls:
	- direction of eigenvector of Hessian with smaller eigenvalue,
- Work with "Cartesian coordinates" in field space.
- Closer in spirit to original KNP mechanism.

$\bf KNP$ realised 2 $\sqrt{2}$ *V* ⁰ ⁰ + *A*⁰ *e^s* \mathbf{a} *^L* ⁼ ¹

$$
(\sigma, \nu_1, \nu_2) \longrightarrow (\chi_1, \chi_2, \chi_3) \longrightarrow \chi_i = P_{il} \xi_l,
$$

\n
$$
\psi_1 = \phi_1 V_1 + \phi_2 W_1,
$$

\n
$$
\psi_2 = \phi_1 V_2 + \phi_2 W_2,
$$

\n
$$
\psi_3 = \phi_2 W_3.
$$

\n
$$
\psi_4 = d_i \xi_i \quad \text{(no sum over } i),
$$

÷

2

e
T

e
T

$$
V(\phi_1, \phi_2) = \left[V_0 + A'e^{-s} \left(1 - \cos \left[\frac{\phi_1}{f_1} + \frac{\phi_2}{g_1} \right] \right) + B'e^{-u_1} \left(1 - \cos \left[\frac{\phi_1}{f_2} + \frac{\phi_2}{g_2} \right] \right) + C'e^{-u_2} \left(1 - \cos \left[\frac{\phi_1}{f_3} + \frac{\phi_2}{g_3} \right] \right) \right],
$$

 $s \gg u_1 > u_2$

Large f ?

- ‣ A very explicit realisation of the alignment mechanism,
- ‣ Still freedom left to adjust fluxes,
- ‣ The "decay constants" are completely known in terms of fluxes;
- ‣ Look for a combination of fluxes which gives a large effective decay constant;
- ‣ Tried 20,100 combinations of fluxes (in the regime of validity of calculations),
- ‣ The maximum value found is 0.66,
- \triangleright I.e.
	- ‣freedom to adjust fluxes to change the values of the individual decay constants,
	- ‣cannot make effective decay constant super-Planckian.

broader issues:

Restrictions and obstructions

- ‣ Finding similar restrictions/obstructions is routine,
- ‣ Many kinds of restrictions known,
- ‣ Focus on those about scalar potentials: important for cosmology!

$arXiv.org > hep-th > arXiv:0711.2512$

High Energy Physics - Theory

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Inflationary Constraints on Type IIA String Theory

Mark P. Hertzberg (MIT), Shamit Kachru (Stanford), Washington Taylor (MIT), Max Tegmark (MIT)

(Submitted on 16 Nov 2007 (v1), last revised 18 Jul 2008 (this version, v3))

We prove that inflation is forbidden in the most well understood class of semi-realistic type IIA string compactifications: Calabi-Yau compactifications with only standard NS-NS 3-form flux, R-R fluxes, D6-branes and O6-planes at large volume and small string coupling. With these ingredients, the first slow-roll parameter satisfies epsilon $>= 27/13$ whenever $V > 0$, ruling out both inflation (including brane/anti-brane inflation) and de Sitter vacua in this limit. Our proof is based on the dependence of the 4-dimensional potential on the volume and dilaton moduli in the presence of fluxes and branes. We also describe broader classes of IIA models which may include cosmologies with inflation and/or de Sitter vacua. The inclusion of extra ingredients, such as NS 5-branes and geometric or non-geometric NS-NS fluxes, evades the assumptions used in deriving the no-go theorem. We focus on NS 5-branes and outline how such ingredients may prove fruitful for cosmology, but we do not provide an explicit model. We contrast the results of our IIA analysis with the rather different situation in IIB.

1. String vacua are dirty!

- ‣ We do not know full string theory! *•* large axion decay constant in realisations of natural inflation in QFT; $\frac{1}{2}$
	- ‣ Trustworthy regimes:
- ‣ large volume, small string length, *•* large axion decay constant in realisations of natural inflation in string theory;
- ‣ small string coupling (but too small not useful), *•* the corresponding results for axion monodromy inflation (e.g. F-term axion monodromy inflation): – control over trans-Planckian regime requires us to violate at least one of the hierarchies in the
	- ‣ Hierarchy of scales:
	- \blacktriangleright $M_{pl} > M_s > M_{KK} > M_{\text{mod}} > H_{\text{inf}} > M_{\text{inf}}$
	- \blacktriangleright Make many assumptions/approximations,
	- \rightarrow probe brane approximation,
		- ‣ large charge approximation,
	- ‣ Mode truncation, \overline{M} if \overline{M} rithmical or drive
	- \blacktriangleright Every term in 4D effective action needs to be understood in terms of its stringy origin, m0 exp(_→ is the properties), here, _→ 1, the properties theory breaks down; here, here, here, here, here, here,

Obstructions

‣ Restrict to solutions which are "trustworthy",

‣ Result:

- ‣ No dS local minima,
- ‣ one of the two potential slow roll parameters large,
- ‣ Even in AdS vacua,
	- ‣ no super-Planckian decay constants for axions,
	- ‣ 4D description valid? separation of scales,
- ‣ distance conjecture,
- ‣ restrictions on large field inflation?
- ‣ Caveat: leading order,
- ‣ But there are more general reasons for the validity
	- ‣Weak Gravity Conjecture etc;
- ‣ Trans-Planckian censorship conjecture,

Cosmological consequences…

$arXiv.org > astro-ph > arXiv:1910.06233$

Astrophysics > Cosmology and Nongalactic Astrophysics

Trans-Planckian Censorship Conjecture and Non-thermal post-inflationary history

Mansi Dhuria, Gaurav Goswami

(Submitted on 14 Oct 2019)

The recently proposed Trans-Planckian Censorship Conjecture (TCC) can be used to constrain the energy scale of inflation. The conclusions however depend on the assumptions about post-inflationary history of the Universe. E.g. in the standard case of a thermal post-inflationary history in which the Universe stays radiation dominated at all times from the end of inflation to the epoch of radiation matter equality, TCC has been used to argue that the Hubble parameter during inflation, H_{inf} , is below $\mathcal{O}(0.1)$ GeV. Cosmological scenarios with a non-thermal postinflationary history are well-motivated alternatives to the standard picture and it is interesting to find out the possible constraints which TCC imposes on such scenarios. In this work, we find out the amount of enhancement of the TCC compatible bound on H_{inf} if post-inflationary history before nucleosynthesis was non-thermal. We then argue that if TCC is correct, for a large class of scenarios, it is not possible for the Universe to have undergone a phase of moduli domination.

Comments: 9 pages, 3 figures, 2 tables

Cosmology and Nongalactic Astrophysics (astro-ph.CO); High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Theory (hep-th) Subjects: arXiv:1910.06233 [astro-ph.CO] Cite as:

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Cosmological consequences…

Swampland, Axions and Minimal Warm Inflation

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Warm inflation has been noted previously as a possible way to implement inflationary models compatible with the dS swampland bounds. But often in these discussions the heat bath dynamics is kept largely unspecified. We point out that the recently introduced Minimal Warm Inflation of arXiv:1910.07525, where an axionic coupling of the inflaton leads to an explicit model for the thermal bath, yields models of inflation that can easily fit cosmological observations while satisfying dS swampland bounds, as well as swampland distance bound and trans-Planckian censorship.

9

¹

^f ² *,* (1)

Broader summary…

- Future observations would put tight constraints on large field inflation,
- Large field inflation model building is trivial if one is careless and cavalier but hopelessly difficult if one is careful,
- Even one toy model of large field inflation without any uncertainties is hard!
- Large axion decay constant may be forbidden,
- Restrictions on scalar potential from UV completion?
- Cosmological consequences.

Thank You