STATISTICS OF LOW-ENERGY PHYSICS IN THE LANDSCAPE

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BASED ON:

i) BRÖCKEL, MC, MAHARANA, SINGH, SINHA, 2007.04327 ← SUSY

ii) BRÖCKEL, MC, MAHARANA, SINGH, SINHA, 2105.02889 ← AXION PHYSICS

TESTING STRING THEORY?

- STRING THEORY (LIKE QFT) IS A FRAMEWORK, NOT A MODEL (AS SM)
- GENERIC FEATURES: STRINGS AND EDs → CANNOT BE TESTED WITH TODAY'S ACCELERATORS

→ FOCUS ON LOW-ENERGY 4D IMPLICATIONS

- STRING THEORY YIELDS A LANDSCAPE OF 4D VACUA

i) ARE THEY ACTUAL SOLUTIONS?
ii) HOW ARE THEY CONNECTED?
iii) IS THERE A SELECTION PRINCIPLE?

NEED TO UNDERSTAND FULL QUANTUM DYNAMICS OF STRINGS

- 2 APPROACHES IN THE ABSENCE OF COMPLETE ANSWERS:

1) FOCUS ON A VACUUM
   - PRO: EXPLICIT COMPUTATION
   - CON: LAMPPOST EFFECT

2) EXTRACT STATISTICS
   - PRO: FIND GENERIC FEATURES
   - CON: TRUSTABILITY OF RESULTS → MODULI STABILISATION

SU$\cancel{S}$Y STATISTICS NEGLECTING KÄHLER MODULI

- FOCUS ON TYPE IIB FLUX LANDSCAPE
  - i) MOST WELL-UNDERSTOOD COMPACTIFICATIONS WITH MODULI STAB. AND SU$\cancel{S}$Y
  - ii) SM-LIKE CONSTRUCTIONS WITH D-BRANES
  - iii) HUGE (10^{500}) NUMBER OF VACUA
- PREVIOUS RESULTS:
  1) UNIFORM DISTRIBUTION OF SU$\cancel{S}$Y SCALE FROM UNIFORM DISTRIBUTION OF F-TERMS [Douglas; Denef, Douglas]
  2) LOGARITHMIC DISTRIBUTION OF SU$\cancel{S}$Y SCALE FROM DYNAMICAL SU$\cancel{S}$Y [Dine, Gorbatov, Thomas]

BUT:

- KÄHLER MODULI STABILISATION IGNORED
- ASSUMPTION: SU$\cancel{S}$Y STATISTICS DECOUPLED FROM COSM. CONSTANT

TYPE IIB FRAMEWORK

- TREE-LEVEL EFT:

AXIO-DILATON

$$W_{\rm tree} = \int_X G_3 \wedge \Omega(U) \qquad\qquad K_{\rm tree} = -2\ln\mathcal{V} - \ln(S+\bar{S}) - \ln\left(-{\rm i}\int_X \Omega(U)\wedge\bar{\Omega}(\bar{U})\right)$$

BACKGROUND FLUXES

CX STR. MODULI

CY VOLUME DEPENDING ON REAL PART OF KÄHLER MODULI:

$T_i = \tau_i + i\vartheta_i \qquad i = 1, \dots, h^{1,1}$

VOLUME OF 4-CYCLE Σ_4^i

AXION $\int_{\Sigma_4^i} C_4 = \vartheta_i$

- SCALAR POTENTIAL

$$V_F = e^K\left(K^{i\bar{j}}D_iW D_{\bar{j}}\overline{W} - 3|W|^2\right) = K_{i\bar{j}}F^i\overline{F}^{\bar{j}} - 3m_{3/2}^2$$

$$F^i = e^{K/2}K^{i\bar{j}}D_{\bar{j}}\overline{W} \qquad\qquad m_{3/2} = e^{K/2}|W|$$

$$\longrightarrow \qquad V_{\rm tree} = |F^S|^2 + |F^U|^2 + |F^T|^2 - 3m_{3/2}^2$$

NEGLECTED BY DENEF-DOUGLAS SINCE T-MODULI ARE NOT FIXED BY FLUXES AT TREE-LEVEL

DISTRIBUTION OF $\cancel{\text{SUSY}}$ SCALE

- NUMBER OF FLUX VACUA AT $\Lambda = 0$:

$$dN_{\Lambda=0}(F) = \prod d^2F^S\, d^2F^U\, d\hat{\Lambda}\, \rho(F,\hat{\Lambda})\, \delta\left(|F^S|^2 + |F^U|^2 - \hat{\Lambda}\right) \qquad \hat{\Lambda} = 3\, m_{3/2}^2$$

- ASSUMPTION: $\cancel{\text{SUSY}}$ DECOUPLED FROM Λ

$$\longrightarrow \quad dN_{\Lambda=0}(F) = d^2F\, \rho(F)$$

$$|F|^2 = 3\, m_{3/2}^2 \qquad d^2F^2 \sim |F|\, d|F| \sim m_{3/2}\, dm_{3/2}$$

$$\longrightarrow \quad dN_{\Lambda=0}(m_{3/2}) \simeq \rho(m_{3/2})\, m_{3/2}\, dm_{3/2}$$

- F-TERMS ARE UNIFORMLY DISTRIBUTED $\longrightarrow$ $\rho(m_{3/2}) \sim$ const.
- MORE IN GENERAL: $\rho(m_{3/2}) \sim m_{3/2}^{\beta}$ $\qquad \beta \geq 0$

$$\longrightarrow \quad dN_{\Lambda=0}(m_{3/2}) \simeq m_{3/2}^{\beta+1}\, dm_{3/2}$$

WITH $\beta = 0$ WHEN KÄHLER MODULI ARE NEGLECTED

IMPORTANCE OF KÄHLER MODULI

- T-MODULI DO NOT APPEAR IN W_{tree} $\rightarrow$ $F^T = e^{K/2}\overline{W}K^{T\bar{T}}K_{\bar{T}}$

$$\rightarrow \quad V_{\rm tree} = |F^S|^2 + |F^U|^2 + m_{3/2}^2\left(\underbrace{K_{\bar{T}}K^{\bar{T}T}K_T - 3}_{\overset{\shortparallel}{0}}\right)$$

NO-SCALE CANCELLATION

- 3 CONSEQUENCES: [Burgess,MC,Ciupke,Krippendorf,Quevedo]

i) $\mathcal{V}$ RUN-AWAY WHEN EITHER $F^U \neq 0$ OR $F^S \neq 0$

$$V_{\rm tree} = |F^S|^2 + |F^U|^2 = \frac{e^{K_{cs}}}{\mathcal{V}^2\left(S+\bar{S}\right)}\left[|D_S W|^2 + |D_U W|^2\right]$$

$\rightarrow$ STABILITY REQUIRES $F^U = F^S = 0$
(MORE PRECISELY $F^S \sim F^U \ll F^T$)

ii) $|F^T|^2 = 3\, m_{3/2}^2$ $\rightarrow$ NO REASON TO EXPECT $\beta = 0$
$\rightarrow$ NEED TO INCLUDE QUANTUM CORRECTIONS TO FIX T AND $m_{3/2}$

iii) $m_{3/2}$ DOES NOT NECESSARILY FIX M_{soft} ON D3s ($f_3 = S$) OR D7s ($f_7 = T$)

$$K_{\rm tree} = -3\ln\left(T+\bar{T}-\bar{\phi}_3\phi_3\right) - \ln\left(S+\bar{S}-\bar{\phi}_7\phi_7\right) \simeq K_0 + \tilde{K}_3\,\bar{\phi}_3\phi_3 + \tilde{K}_7\,\bar{\phi}_7\phi_7$$

$$m_0^2 = m_{3/2}^2 - \overline{F}^{\bar{i}}F^j\partial_{\bar{i}}\partial_j \ln\tilde{K} \qquad M_{1/2} = \frac{1}{2\,{\rm Re}(f)}F^i\partial_i f$$

$$\rightarrow \left\{\begin{array}{ll} {\rm D3:} & m_0 = M_{1/2} = 0 \\ {\rm D7:} & m_0 = |M_{1/2}| = m_{3/2}\end{array}\right.$$

TYPE IIB KÄHLER MODULI STABILISATION

• 2 MAIN STABILISATION SCHEMES

1) KKLT

$$W = W_0 + A\, e^{-aT} \longrightarrow V_{KKLT} = \frac{2e^{-2a\tau}a^2A^2}{3s\mathcal{V}^{2/3}}\left(1+\frac{3}{a\tau}\right) - \frac{2e^{-a\tau}aAW_0}{s\mathcal{V}^{4/3}}$$

MINIMISATION:

$$e^{a\langle\tau\rangle} = \frac{2Aa\langle\tau\rangle}{3W_0}\left(1+\frac{3}{2a\langle\tau\rangle}\right) \simeq \frac{2Aa\langle\tau\rangle}{3W_0} \longrightarrow \langle\tau\rangle \simeq \frac{1}{a}\,|\ln W_0|$$

i) $\langle \tau \rangle \gg 1$ REQUIRES W_0 EXPONENTIALLY SMALL → TUNING

ii) SUSY AdS MINIMUM WITH $F^T = 0$

→ ADD $\overline{D3}$ WITH NILPOTENT SUPERFIELD IN EFT → dS

NEW VACUUM:

$$e^{a\langle\tau\rangle} = \frac{2Aa\langle\tau\rangle}{3W_0}\left(1+\frac{5}{2a\langle\tau\rangle}\right) \rightarrow \langle\tau\rangle \simeq \frac{1}{a}\,|\ln W_0|$$

~~SUSY~~ AND Λ

DECOUPLING OK

GRAVITINO MASS:

$$m_{3/2} \simeq \sqrt{\frac{g_s}{8\pi}}\frac{|W_0|}{\langle\mathcal{V}\rangle} \simeq \frac{\pi\, g_s^{1/2}}{\mathfrak{n}^{3/2}}\frac{|W_0|}{|\ln W_0|^{3/2}}$$

← CONTROLLED BY EXPONENTIALLY SMALL W_0

$M_{SOFT} \sim m_{3/2}$ (UP TO 1-LOOP FACTORS)

TYPE IIB KÄHLER MODULI STABILISATION

2) LVS

CY VOLUME: $\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2}$

$$\begin{cases} K = -2\ln\left(\mathcal{V} + \frac{\xi}{2}\left(\frac{S+\bar{S}}{2}\right)^{3/2}\right) \\ W = W_0 + A_s\, e^{-a_s T_s}, \end{cases} \rightarrow \quad V_{LVS} = \frac{4}{3}\frac{a_s^2 A_s^2 \sqrt{\tau_s} e^{-2a_s\tau_s}}{s\mathcal{V}} - \frac{2a_s A_s |W_0| \tau_s e^{-a_s\tau_s}}{s\mathcal{V}^2} + \frac{3\sqrt{s}\xi |W_0|^2}{8\mathcal{V}^3}$$

MINIMISATION:

$$\langle\mathcal{V}\rangle \simeq \frac{3\sqrt{\langle\tau_s\rangle}\,|W_0|}{4a_s A_s}\, e^{a_s\langle\tau_s\rangle} \qquad \langle\tau_s\rangle \simeq \frac{1}{g_s}\left(\frac{\xi}{2}\right)^{2/3}$$

i) $\langle \tau_b \rangle \gg \langle \tau_s \rangle \gg 1$ CAN BE OBTAINED FOR $g_s \lesssim 0.1$

$\rightarrow$ NO NEED TO TUNE W_0 EXPONENTIALLY SMALL $\rightarrow$ $W_0 \sim O(1-10)$

ii) ~~SUSY~~ AdS VACUUM WITH $V_{LVS} \sim -m_{3/2}^3 M_P$

$\rightarrow$ ~~SUSY~~ AND Λ ARE DECOUPLED SINCE $V_{up} \sim |F_{up}|^2 \sim +m_{3/2}^3 M_P$

FROM: $\overline{D3}$, T-BRANES, $F^U \neq 0$, ...

$\rightarrow$ $\delta M_{SOFT} \sim \frac{|F_{up}|}{M_P} \sim m_{3/2}\sqrt{\frac{m_{3/2}}{M_P}} \ll m_{3/2}$

GRAVITINO MASS:

$$m_{3/2} \simeq \sqrt{\frac{g_s}{8\pi}}\frac{|W_0|}{\langle\mathcal{V}\rangle} \simeq c_1 \frac{g_s}{\mathfrak{n}} e^{-\frac{c_2}{g_s \mathfrak{n}}}$$

CONTROLLED BY e^{-1/g_s}

LVS $\cancel{\text{SUSY}}$ STATISTICS

- GRAVITINO MASS

$$m_{3/2} \simeq M_P \, e^{-1/g_s} \rightarrow dm_{3/2} \simeq \frac{\partial m_{3/2}}{\partial g_s} dg_s \simeq m_{3/2} \, dg_s$$

- g_s IS A REAL VARIABLE ($g_s = \mathrm{Re}(S)$) WHICH WE CHECKED TO BE UNIFORMLY DISTRIBUTED FOR RIGID CYs AND $0.01 \lesssim g_s \lesssim 0.1$ [ALSO TRUE MORE IN GENERAL [Bletzer,Plauschinn;Cole,Schachner,Shiu]]

$$\rightarrow \rho(g_s) \simeq \frac{dN}{dg_s} \sim \text{const.} \rightarrow \frac{dN}{dm_{3/2}} \sim \frac{1}{m_{3/2}}$$

$$\rightarrow \boxed{N_{LVS}(m_{3/2}) \sim \ln\left(\frac{m_{3/2}}{M_P}\right)}$$

LOG-DISTR. AS IN [Dine,Gorbatov,Thomas] ($\beta = -2$)

- SOFT TERMS:

$$M_{SOFT} \sim m_{3/2}^{p} \, M_P^{1-p}$$

D7s $p = 1$

D3s:
- $p = 2$ FOR $M_{1/2}$
- $p = 2$ OR $p = 3/2$ FOR m_0

$$\rightarrow N_{LVS}(M_{SOFT}) \sim \frac{1}{p} \ln\left(\frac{M_{SOFT}}{M_P}\right)$$

KKLT $\cancel{\text{SUSY}}$ STATISTICS

- GRAVITINO MASS:

$$m_{3/2} \simeq |W_0| M_P \rightarrow d\, m_{3/2} \simeq \frac{\partial m_{3/2}}{\partial |W_0|} d|W_0| \simeq m_{3/2} \frac{d|W_0|}{|W_0|}$$

- W_0 IS EXPECTED TO BE UNIFORMLY DISTRIBUTED AS A COMPLEX VARIABLE [Denef,Douglas]

$$\rightarrow \rho(W_0) \simeq \frac{dN}{|W_0|\, d|W_0|} \sim \text{const.}$$

$$\rightarrow \frac{d|W_0|}{|W_0|} \sim \frac{dN}{|W_0|^2} \sim \left(\frac{M_P}{m_{3/2}}\right)^2 dN \qquad \rightarrow \frac{dN}{d\, m_{3/2}} \sim \left(\frac{m_{3/2}}{M_P}\right)$$

$$\rightarrow \boxed{N_{KKLT}(m_{3/2}) \sim \left(\frac{m_{3/2}}{M_P}\right)^2}$$

POWER-LAW DISTR. AS IN [Denef,Douglas]
($\beta = 0$)

BUT

i) HOW GENERIC ARE KKLT VACUA DUE TO THE TUNING IN W_0?

ii) IS W_0 UNIFORMLY DISTRIBUTED ALSO WHEN IT IS EXPONENTIALLY SMALL?
EXPLICIT CONSTRUCTIONS FOUND $|W_0| \sim e^{-1/g_s}$ $\rightarrow$ LOG-DISTR. AS IN LVS
[Demirtas,Kim,McAllister,Moritz]

iii) ENOUGH STATISTICS?

IMPORTANCE OF MODULI STABILISATION FOR AXION PHYSICS

- FOCUS ON MODEL-INDEPENDENT CASE OF C_4 AXIONS ϑ_i ($T_i = \tau_i + i\vartheta_i$)
- CONTINUOS SHIFT SYMMETRY BROKEN TO DISCRETE SHIFT SYMM. BY NON-PERT. EFFECTS
- AXION MASS:

i) τ FIXED BY NON-PERT. EFFECTS (KKLT)

$\rightarrow$ $m_\vartheta \sim m_\tau \sim m_{3/2} \gtrsim \mathcal{O}(50)$ TeV TO AVOID COSMOLOGICAL PROBLEMS

$\rightarrow$ ϑ CANNOT BE QCD AXION

ii) τ FIXED BY PERT. EFFECTS (LVS)

$\rightarrow$ $m_\vartheta \ll m_\tau \sim m_{3/2}$

$\rightarrow$ ϑ CAN BE QCD AXION OR ULTRA-LIGHT ALP (FUZZY DM)

ONLY IF STRINGY INSTANTONS DEVELOP A MASS BELOW THE ONE GENERATED BY QCD INSTANTONS

$$m_{\vartheta,\,STR} \ll m_{QCD} \sim \frac{\Lambda^2_{QCD}}{f_a}$$

DECAY CONSTANT ALSO SET BY MOD. STABIL.

AXION DECAY CONSTANTS

- f_a DETERMINED BY MOD. STAB. AND TOPOLOGY

$$\mathcal{L}_{kin} = \frac{\partial^2 K}{\partial T \partial \bar{T}} \left(\partial_\mu \tau \partial^\mu \tau + \partial_\mu \vartheta \partial^\mu \vartheta \right)$$

SETS f_a^2

- 2 CASES FOR $\mathcal{V} = \tau_B^{3/2} - \tau_S^{3/2}$ WITH $K = -2 \ln \mathcal{V}$

i) BLOW-UP AXION ϑ_s

$$\rightarrow \quad f_{\vartheta_s}^2 \sim \frac{\partial^2 K}{\partial T_s \partial \bar{T}_s} \sim \frac{M_P^2}{\mathcal{V}} \sim M_s^2$$

ii) BULK AXION ϑ_B

$$\rightarrow \quad f_{\vartheta_B}^2 \sim \frac{\partial^2 K}{\partial T_B \partial \bar{T}_B} \sim \frac{M_P^2}{\tau_B^2} \sim M_{KK}^2$$

QCD AXION FROM STRING THEORY

- FOCUS ON LVS BECAUSE OF:

i) PERT. STAB. → CAN KEEP AXIONS LIGHT

ii) α' EXPANSION UNDER CONTROL → $\mathcal{V} \gtrsim (h^{1,1})^7$ [Demirtas,Long,McAllister,Stillman]

→ FOR $h^{1,1} \sim \mathcal{O}(100)$ NEED $\mathcal{V} \gtrsim 10^{14}$ → LVS

- 2 POSSIBILITIES FOR QCD AXION FOR $\mathcal{V} = \sqrt{\tau_1}\,\tau_2 - \tau_3^{3/2} - \tau_4^{3/2}$

NON-PERT. EFFECTS

i) BLOW-UP AXION ϑ_3 WITH SM ON D7s WRAPPING τ_3

→ $f_{\vartheta_3} \sim \frac{M_P}{\sqrt{\mathcal{V}}} \sim M_s$ AND $g_{SM}^{-2} \sim \tau_3$

→ CAN VARY f_{ϑ_3} KEEPING g_{SM} FIXED → LOG-DISTR. OF f_{ϑ_3}

ISOTROPIC EDs: $\tau_1 \sim \tau_2 \gg \tau_3 \sim \tau_4$ WITH PERT. STAB. OF τ_1 AND τ_3

→ 2 ULTRA-LIGHT ALPs ϑ_1 AND ϑ_2

WITH $\begin{cases} m_{\vartheta_1}^2 \sim M_P^2\, e^{-\tau_1} \sim 0 & \text{AND} \quad f_{\vartheta_1} \sim \frac{M_P}{\tau_1} \\ m_{\vartheta_2}^2 \sim M_P^2\, e^{-\tau_2} \sim 0 & \text{AND} \quad f_{\vartheta_2} \sim \frac{M_P}{\tau_2} \end{cases}$ → LOG-DISTR. OF f_{ϑ_1} AND f_{ϑ_2}

QCD AXION FROM STRING THEORY

ii) BULK AXION WITH SM ON D7s WRAPPING τ_1 $\left(\mathcal{V} = \sqrt{\tau_1}\,\tau_2 - \tau_3^{3/2} - \tau_4^{3/2}\right)$

NON-PERT. EFFECTS

→ $f_{\vartheta_1} \sim \frac{M_P}{\tau_1}$ AND $g_{SM}^{-2} \sim \tau_1$

→ CANNOT VARY f_{ϑ_1} KEEPING g_{SM} FIXED → $f_{\vartheta_1} \sim M_{GUT} \sim 10^{16}$ GeV

NO DISTRIBUTION

ANISOTROPIC EDs: $\tau_2 \gg \tau_1 \sim \tau_3 \sim \tau_4$ WITH PERT. STAB. OF τ_1

LESS GENERIC THAN ISOTROPIC CASE SINCE IT REQUIRES TUNING

→ 1 ULTRA-LIGHT ALP ϑ_2

WITH $m_{\vartheta_2}^2 \sim M_P^2\, e^{-\tau_2} \sim 0$ AND $f_{\vartheta_2} \sim \frac{M_P}{\tau_2}$ → LOG-DISTR.

→ ULTRA-LIGHT ALPs ARE GENERIC FEATURES OF 4D STRING VACUA WHERE EFT IS UNDER CONTROL

STATISTICS OF AXION PHYSICS

- DECAY CONSTANTS:

$$f_a \sim M_P\, e^{-\lambda/g_s} \qquad f_{\vartheta_1} \sim f_{\vartheta_2} \sim M_P\, e^{-\mu/g_s}$$

$$\rightarrow \quad df \simeq \frac{\partial f}{\partial g_s}\, dg_s \simeq f\, dg_s \simeq f\, dN$$

$$\rightarrow \quad \boxed{N(f_a) \sim \ln\left(\frac{f_a}{M_P}\right)} \qquad N(f_{\vartheta_i}) \sim \ln\left(\frac{f_{\vartheta_i}}{M_P}\right) \qquad i = 1,2$$

- MASSES:

$$\begin{cases} m_a \simeq \dfrac{\Lambda_{QCD}^2}{f_a} & \rightarrow \quad \boxed{N(m_a) \sim -\ln\left(\dfrac{m_a}{M_P}\right)} \\ m_{\vartheta_i} \sim M_P\, e^{-c\, M_P/f_{\vartheta_i}} & \rightarrow \quad N(m_{\vartheta_i}) \sim \ln\left(\dfrac{m_{\vartheta_i}}{M_P}\right) \end{cases}$$

- COUPLINGS:

$$g_{a\gamma\gamma} \sim \frac{1}{f_a} \quad \rightarrow \quad \boxed{N(g_{a\gamma\gamma}) \sim -\ln(g_{a\gamma\gamma})}$$

$$g_{a\gamma_h\gamma_h} \sim \frac{1}{\sqrt{f_a}} \left(\frac{f_a}{M_P}\right) \frac{1}{M_P} \quad \rightarrow \quad N(g_{a\gamma_h\gamma_h}) \sim \ln(g_{a\gamma_h\gamma_h})$$

AXION DM ABUNDANCE

- AXION DM VIA MISALIGNMENT MECHANISM

i) QCD AXION: $\frac{\Omega_{QCD}h^2}{0.112} \simeq 6.3 \cdot \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \left(\frac{\theta_{\rm in}}{\pi}\right)^2$ NEED $f_a \simeq 10^{11}$ GeV FOR $\vartheta_{in} \simeq \pi$

ii) ALP: $\frac{\Omega_{ALP}h^2}{0.112} \simeq 1.4 \cdot \left(\frac{m_{\theta_i}}{1\,\mathrm{eV}}\right)^{1/2} \left(\frac{f_{\theta_i}}{10^{11}\,\mathrm{GeV}}\right)^2 \left(\frac{\theta_{i,\rm in}}{\pi}\right)^2$

NEED $f_{\vartheta_i} \simeq 10^{16}$ GeV AND $m_{\vartheta_i} \simeq 5 \cdot 10^{-21}$ eV

FOR $\vartheta_{i,in} \simeq \pi$ (FUZZY DM)

- QCD AXION DM

$$d(\Omega_{QCD} h^2) = \frac{7}{6} (\Omega_{QCD} h^2) \frac{d f_a}{f_a} \simeq (\Omega_{QCD} h^2)\, dN$$

$$\rightarrow \boxed{N(\Omega_{QCD} h^2) \sim \ln(\Omega_{QCD} h^2)}$$

- ALP DM DOMINATED BY m_{ϑ_i} SINCE $m_{\vartheta_i} \sim M_P\, e^{-\beta M_P / f_{\vartheta_i}}$

$$d(\Omega_{ALP} h^2) \simeq \frac{d m_{\vartheta_i}}{m_{\vartheta_i}} (\Omega_{ALP} h^2) \simeq (\Omega_{ALP} h^2)\, dN$$

$$\rightarrow N(\Omega_{ALP} h^2) \sim \ln(\Omega_{ALP} h^2)$$

GENERIC CASE WITH MANY MODULI

- CASE WITH ARBITRARY $h^{1,1}$ QUALITATIVELY SIMILAR TO ISOTROPIC CASE

$$\mathcal{V} = \frac{1}{6}\sum_{i,j,k=1}^{N} \underbrace{k_{ijk}t_it_jt_k}_{N \gg 1 \text{ ULTRA-LIGHT ALPs } \vartheta_i \text{ WITH } f_{\vartheta_i} \sim \frac{M_P}{\tau_i}} - \gamma_{SM}\tau_{SM}^{3/2} - \gamma_{\rm np}\tau_{\rm np}^{3/2} \qquad N = h^{1,1} - 2 \gg 1$$

ϑ_{SM} IS QCD AXION WITH $f_a \sim \frac{M_P}{\sqrt{\mathcal{V}}}$

- LVS MOD. STAB. WITH:

$\mathcal{V} \sim W_0\, e^{1/g_s} \gg 1$ AND $\tau_i \sim \mathcal{V}^{2/3}$ $\forall i = 1, \dots, N$ VIA α' EFFECTS AT HIGHER F-TERM ORDER

[MC,Ciupke,deAlwis,Muia]

- LOG-DISTRIBUTIONS FOR DECAY CONSTANTS, MASSES, COUPLINGS AND DM ABUNDANCE

VALID AT FIXED $h^{1,1}$ WHEN MOVING IN KÄHLER MODULI SPACE BY VARYING g_s

- COMPLEMENTARY TO RESULTS OF [Mehta,Demirtas,Long,Marsh,McAllister,Stott]:

i) APPROXIMATE LOG-NORMAL DISTR. OF f_{ϑ_i} FOR A GIVEN CY AT THE TIP OF "STRETCHED KÄHLER CONE"

POINT FOR WHICH α' EXPANSION IS UNDER CONTROL

$\tau_i \gtrsim (h^{1,1})^3 \quad \forall i$

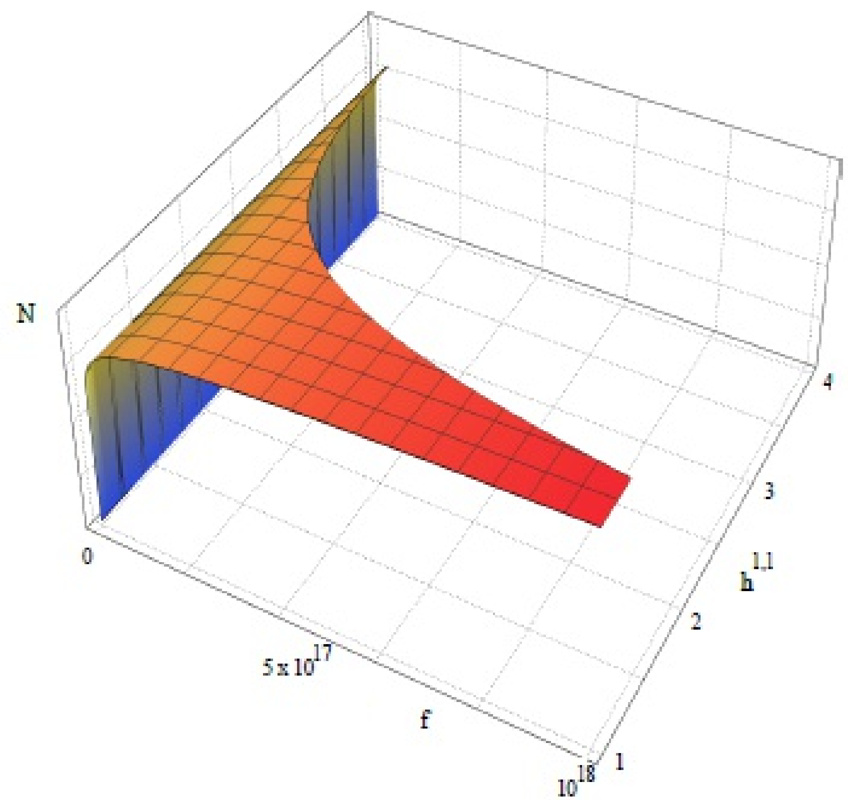
ii) MEAN VALUE OF f_{ϑ_i} DECREASES WHEN $h^{1,1}$ INCREASES

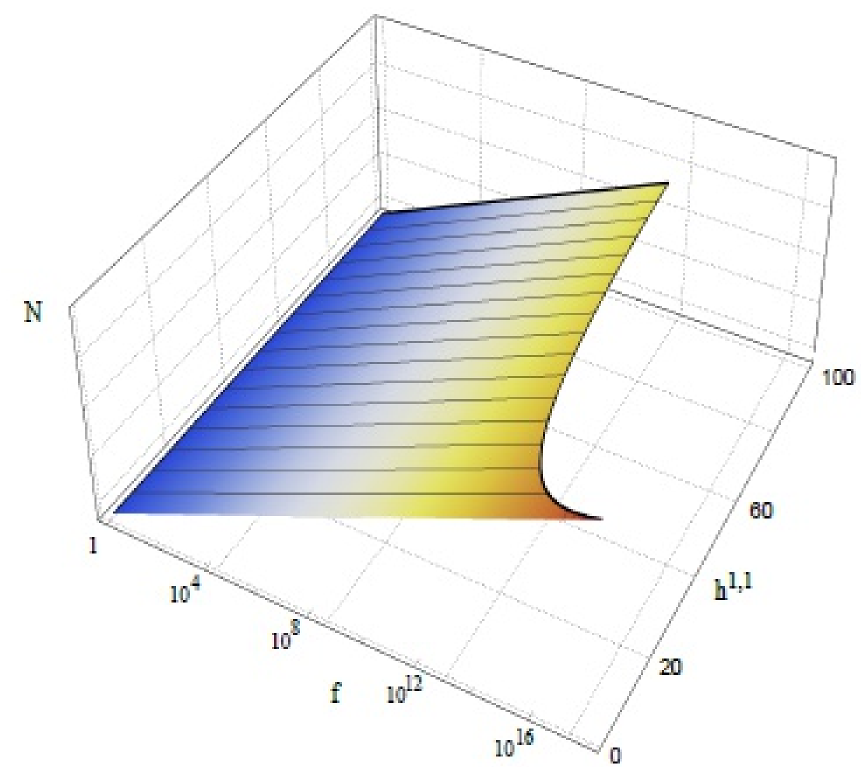
SINCE $f_{\vartheta_i} \sim \frac{M_P}{\tau_i}$

GENERIC CASE WITH MANY MODULI

- RESULTS OF [Mehta,Demirtas,Long,Masrch,McAllister,Stott] SET THE UPPER BOUND FOR THE VALIDITY OF OUR LOG-DISTRIBUTIONS

$$\rightarrow \boxed{N(f, h^{1,1}) \sim \ln\left(\frac{f}{M_P}\right)} \qquad \text{WITH} \qquad f \lesssim f_{max}(h^{1,1}) \simeq \frac{M_P}{(h^{1,1})^3}$$





CONCLUSIONS

- SUSY SCALE AND AXION PHYSICS SEEMS TO BE LOGARITHMICALLY DISTRIBUTED IN TYPE IIB FLUX LANDSCAPE
- MILD STATISTICAL PREFERENCE FOR HIGH-SCALE SUSY AND $f_a \sim M_{GUT}$

→ LOW-ENERGY SUSY AND QCD AXION NOT SO TUNED FROM LANDSCAPE PERSPECTIVE?

- GENERICITY OF LOG-DISTRIBUTIONS AND ULTRA-LIGHT ALPs?

SO FAR WE STUDIED ONLY CLASSES OF VACUA WHERE EFT IS UNDER CONTROL DUE TO LEADING ORDER SUSY AND WEAK COUPLINGS (α' AND g_s)

- HOW CAN MAKE SHARP PREDICTIONS FOR RELATIVELY FLAT DISTRIBUTIONS?

→ STUDY CORRELATIONS AMONG DIFFERENT OBSERVABLES DUE TO UNDERLYING UV PHYSICS

e.g. $m_{3/2} \sim 10^{11}$ GeV $\leftrightarrow$ $f_a \sim 10^{16}$ GeV

$m_{3/2} \sim 1$ TeV $\leftrightarrow$ $f_a \sim 10^{11}$ GeV

- WHAT ABOUT COSMOLOGY? CORRELATED CONSTRAINTS FROM INFLATION, COSMOLOGICAL MODULI PROBLEM, DARK RADIATION FROM ALPs, ...

AXIONS AND MODULI STABILISATION

- LEADING ORDER EFFECTS FOR $\mathcal{V} \gg 1$ AND ISOTROPIC CASE

$$\begin{cases} K = -2 \ln\left(\mathcal{V} + \dfrac{\xi}{2 g_s^{3/2}}\right) \\ W = W_0 + A_4 \, e^{-a_4 T_4} \end{cases}$$

$$\mathcal{V} = \sqrt{\tau_1}\, \tau_2 - \tau_3^{3/2} - \tau_4^{3/2}$$

SM CYCLE

- FIXING:

$$\mathcal{V} \sim W_0 \, e^{a_4 \tau_4} \qquad \tau_4 \sim \frac{1}{g_s} \, \xi^{2/3} \qquad \vartheta_4 = (2k+1) \frac{\pi}{a_4} \qquad k \in \mathbb{Z}$$

- MASSES:

$$\begin{cases} m_{\tau_4} \sim m_{\vartheta_4} \sim m_{3/2} \sim \dfrac{|W_0|}{\mathcal{V}} M_p \\ m_{\mathcal{V}} \sim m_{3/2} \sqrt{\dfrac{m_{3/2}}{M_p}} \end{cases}$$

AXIONS AND MODULI STABILISATION

- SUBLEADING EFFECTS
- NON-PERT. EFFECTS ON τ_3 SUPPRESSED BY CHIRALITY
- GAUGE FLUXES

$$\mathcal{F}_{SM} = f_{SM}\,\hat{D}_3 + \frac{1}{2}\hat{D}_3 - B \qquad \mathcal{F}_{E3} = \frac{1}{2}\hat{D}_3 - B = 0 \quad \rightarrow \quad B = \frac{1}{2}\hat{D}_3$$

$\rightarrow$ SM - E3 CHIRAL INTERSECTIONS

$$I_{SM-E3} = \int_{CY} (\mathcal{F}_{SM} - \mathcal{F}_{E3}) \wedge \hat{D}_3 \wedge \hat{D}_3 = f_{SM}\, k_{333} \neq 0$$

- $U(1)$ - CHARGE OF T_3

$$q_{T_3} = \int_{CY} \mathcal{F}_{SM} \wedge \hat{D}_3 \wedge \hat{D}_3 = f_{SM}\, k_{333} \neq 0 \qquad \delta T_3 = i\, q_{T_3}$$

$$\rightarrow \quad W_{E3} = A\, \varphi^m\, e^{-a_3 T_3}$$

MATTER FIELD WITH $\delta\varphi = i\, q_\varphi\, \varphi$ TO MAKE W_{E3} INVARIANT FOR $m = \frac{q_{T_3}}{a_3 q_\varphi}$

$$\rightarrow \quad W_{E3} = 0 \quad \text{FOR} \quad \langle \varphi \rangle = 0$$

[OR W_{E3} NEGLIGIBLE FOR $\langle \varphi \rangle \ll 1$]

AXIONS AND MODULI STABILISATION

- D-TERMS

$$\xi_{SM} = \frac{1}{4\pi \mathcal{V}} \int_{CY} J \wedge \mathcal{F}_{SM} \wedge \hat{D}_3 \simeq - q_{SM} \frac{\sqrt{\tau_3}}{\mathcal{V}}$$

$\rightarrow$ $$V_D = \frac{g_{SM}^2}{2} \left(q_\varphi |\varphi|^2 + \xi_{SM} \right)^2$$

$$\varphi = |\varphi| e^{i \vartheta_\varphi}$$

$\rightarrow$ $V_D = 0 \quad \longleftrightarrow \quad \langle |\varphi|^2 \rangle \simeq \frac{\sqrt{\tau_3}}{\mathcal{V}}$

[OPEN STRING AXION ϑ_φ EATEN BY ANOMALOUS $U(1)$]

- τ_3 FIXED BY F-TERMS OF φ AND STRING LOOPS

$$\begin{cases} V_{matter} = m_{3/2}^2 |\varphi|^2 = c \dfrac{W_0^2 \sqrt{\tau_3}}{\mathcal{V}^3} \\ V_{loop} = d \dfrac{W_0^2}{\mathcal{V}^3 \sqrt{\tau_3}} \end{cases} \rightarrow \langle \tau_3 \rangle = \frac{d}{c} \sim \mathcal{O}(10) \sim g_{SM}^{-2}$$

- ϑ_3 IS STILL FLAT

$\rightarrow$ ϑ_3 CAN BE QCD AXION WITH $m_{\vartheta_3} \sim \frac{\Lambda_{QCD}^2}{f_{\vartheta_3}}$

AND $f_{\vartheta_3} \sim \frac{M_P}{\sqrt{\mathcal{V}}}$ WITH $10^{10}\ \mathrm{GeV} \lesssim f_a \lesssim 10^{16}\ \mathrm{GeV}$

CORRELATES WITH $m_{3/2} \sim \mathcal{O}(1-10)\ \mathrm{TeV}$

AXIONS AND MODULI STABILISATION

- τ_1 FIXED BY STRING LOOPS [MC,Burgess,Quevedo]

$$V_{loop} = \left(g_s^2 \frac{A}{\tau_1^2} - \frac{B}{\mathcal{V}\sqrt{\tau_1}}\right)\frac{W_0^2}{\mathcal{V}^2} \quad \rightarrow \quad \langle\tau_1\rangle = \left(\frac{4A}{B}\right)^{2/3} g_s^{4/3} \langle\mathcal{V}\rangle^{2/3}$$

$$\rightarrow \quad \tau_1 \sim \tau_2 \sim \mathcal{V}^{2/3} \quad \text{ISOTROPIC CY}$$

WITH $\mathcal{V} \sim W_0\, e^{1/g_s} \gg 1$

$$\rightarrow \quad m_{\tau_1} \sim m_{3/2}\left(\frac{m_{3/2}}{M_P}\right)^{2/3}$$

- ϑ_1 AND ϑ_2 ARE 2 ULTRA-LIGHT ALPs FIXED BY

$$W \supset A_1\, e^{-a_1 T_1} + A_2\, e^{-a_2 T_2}$$

$$\rightarrow \quad m_{\vartheta_1}^2 \sim M_P^2\, e^{-a_1\tau_1} \sim 0 \quad \text{AND} \quad m_{\vartheta_2}^2 \sim M_P^2\, e^{-a_2\tau_2} \sim 0$$

$$f_{\vartheta_1} \sim \frac{M_P}{\tau_1} \quad \text{AND} \quad f_{\vartheta_2} \sim \frac{M_P}{\tau_2}$$

- AXION – GAUGE BOSONS COUPLINGS:

$$\mathcal{L}_{ax-gauge} = \frac{a}{f_a}\left[\frac{\lambda_1}{\langle\tau_3\rangle}\tilde{F}_{vis}F_{vis} + \frac{\sqrt{\langle\tau_3\rangle}}{\langle\mathcal{V}\rangle}\left(\underbrace{\lambda_2\tilde{F}_1F_1 + \lambda_3\tilde{F}_2F_2}_{\text{HIDDEN SECTOR GAUGE BOSONS}}\right)\right] + \lambda_4\frac{a_1}{M_p}\tilde{F}_1F_1 + \lambda_5\frac{a_2}{M_p}\tilde{F}_2F_2$$

QCD AXION

$$f_a \sim \frac{M_P}{\sqrt{\mathcal{V}}}$$

ALPs