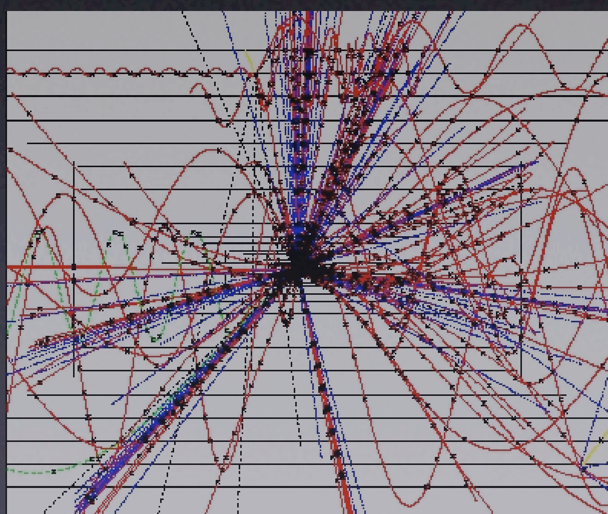
Warped compactification phenomenology



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String phenomenology 2006 -- KITP

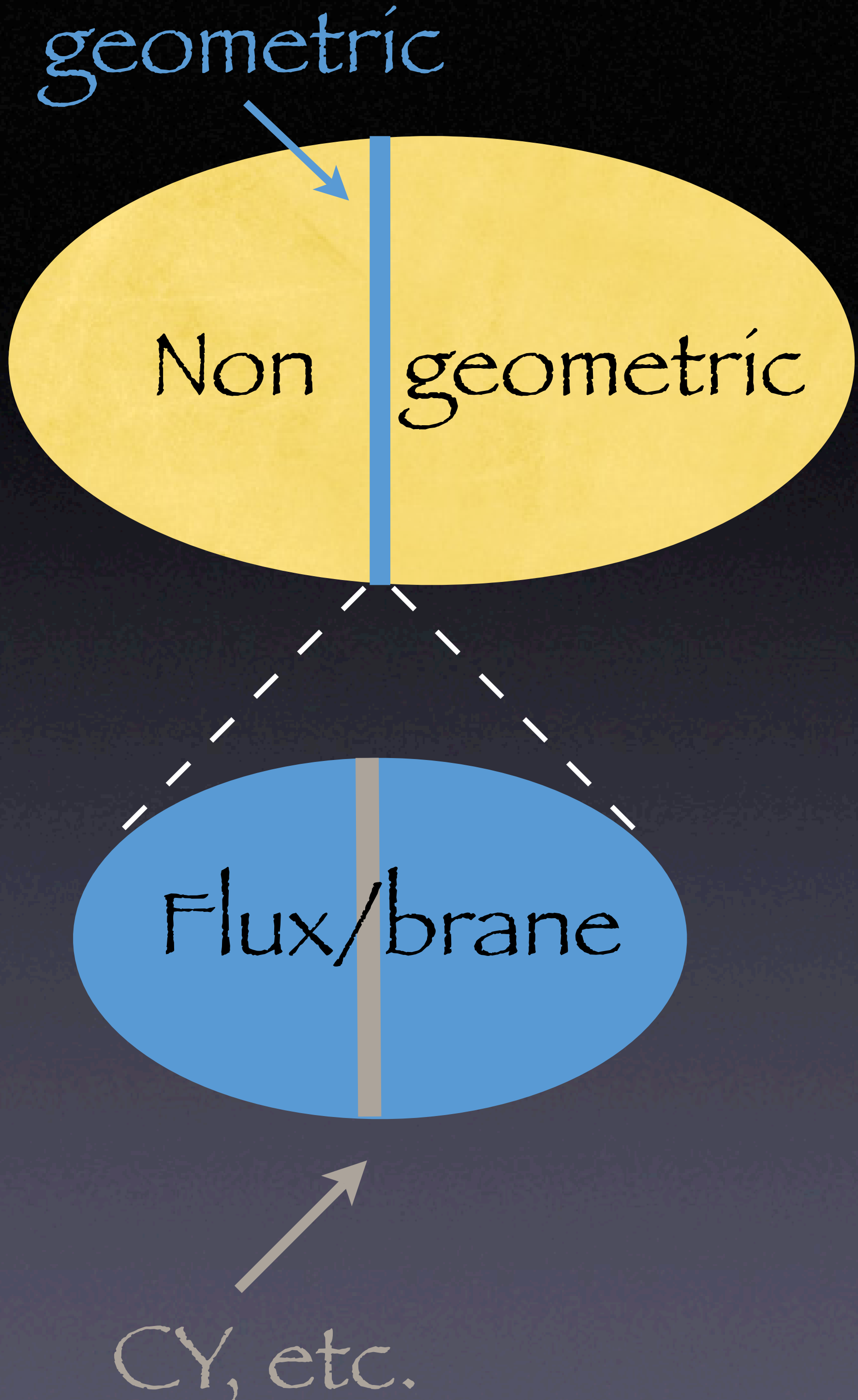
10d, 11d
String/M theory → 4d phenomenology

~Unique

Non-unique??

↑

String
"compactifications"



Some guesses:

1. Non-geom >> geom

(e.g. Shelton, Taylor, Wecht)

2. Flux + branes >> unadorned geometries

But:

What is a string vacuum?

(kill string landscape??)

Geometric regime, w/fluxes + branes:

1) fairly general ~controlled approximations

2) interesting physics:

a) moduli fixing; SUSY breaking; dS

(DRS, GKP, KKLT, ...)

b) warping generic

Warping generic:

$$ds^2 = e^{2A(y)} d\tilde{s}_4^2(x) + e^{-2A(y)} \tilde{g}_{mn} dy^m dy^n$$

$$G^\mu_\nu = \kappa_{10}^2 T^\mu_\nu \ , \ G^m_n = \kappa_{10}^2 T^m_n \Rightarrow$$

$$\boxed{\tilde{\nabla}^2 A = \frac{1}{4} e^{-4A} \tilde{R}_4 + \frac{\kappa_{10}^2}{8} e^{-2A} (T^m_m - T^\mu_\mu)}$$

$= 0$ flat

> 0 dS

> 0 :

p − brane , $p < 7$

q − flux , $q > 1$

Geometric regime, w/fluxes + branes:

1) fairly general ~controlled approximations

2) interesting physics:

a) moduli fixing; SUSY breaking; dS

(DRS, GKP, KKLT, ...)

b) warping generic:

hierarchies (~RS mechanism)

new inflation scenarios

low scale strings/BHs (potential jackpot)

(KKLMMT, Silverstein-Tong cf Tye, Shiu talks)

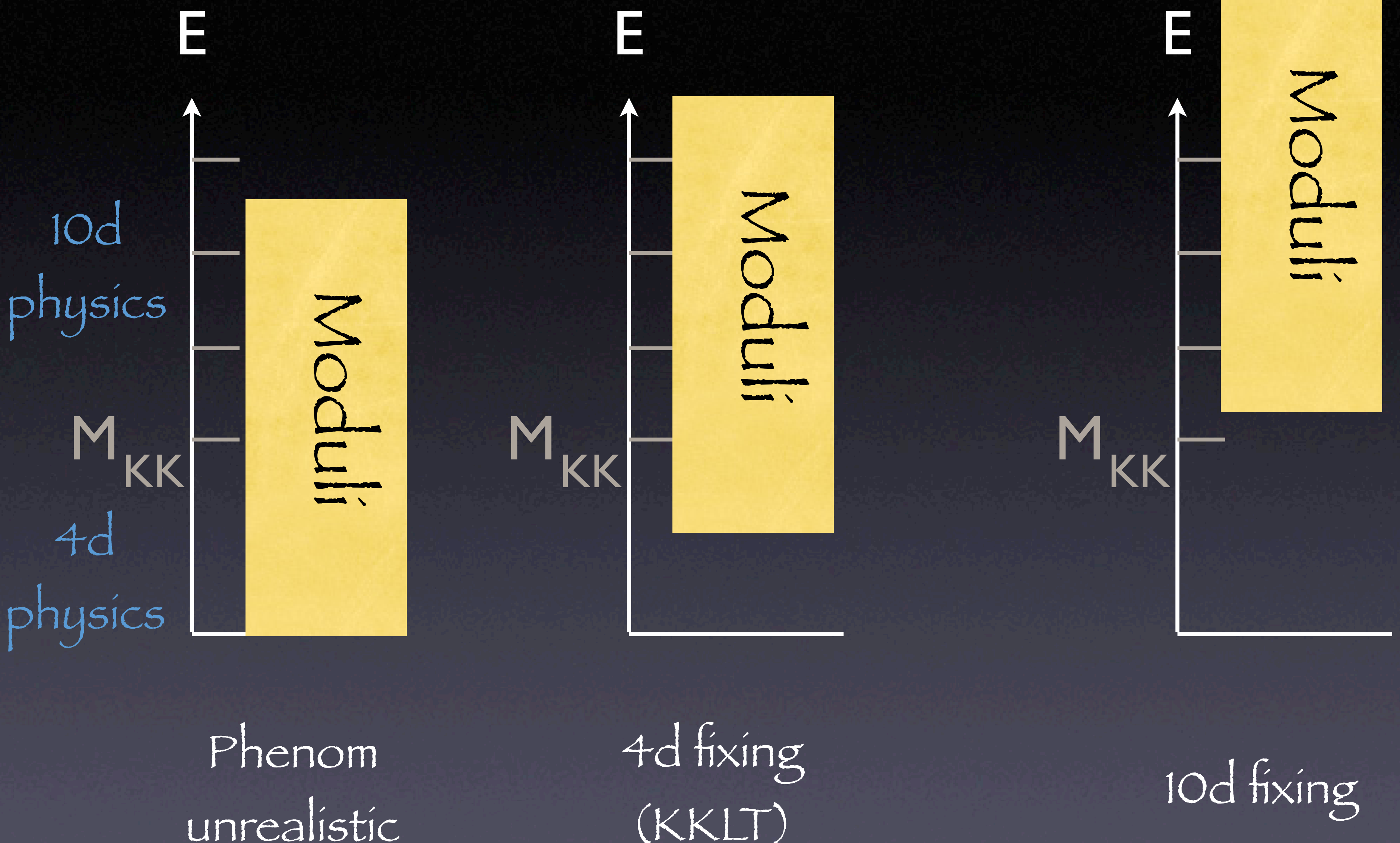
Warped compactification phenomenology:
4d effective theory

- Intricate interplay 10d/4d
- more complicated than usual KK
- rather incomplete understanding

Refs:

DeWolfe & SBG hep-th/0208123
SBG & Maharana hep-th/0507158
Frey & Maharana hep-th/0603233
Burgess, deAlwis, SBG, Maharana, Quevedo, Suruliz (WIP)
SBG & Maharana (WIP)

E.g. different moduli fixing scenarios



(M_{KK} can be suppressed)

Depends on values of moduli;

in particular: "scale" modulus

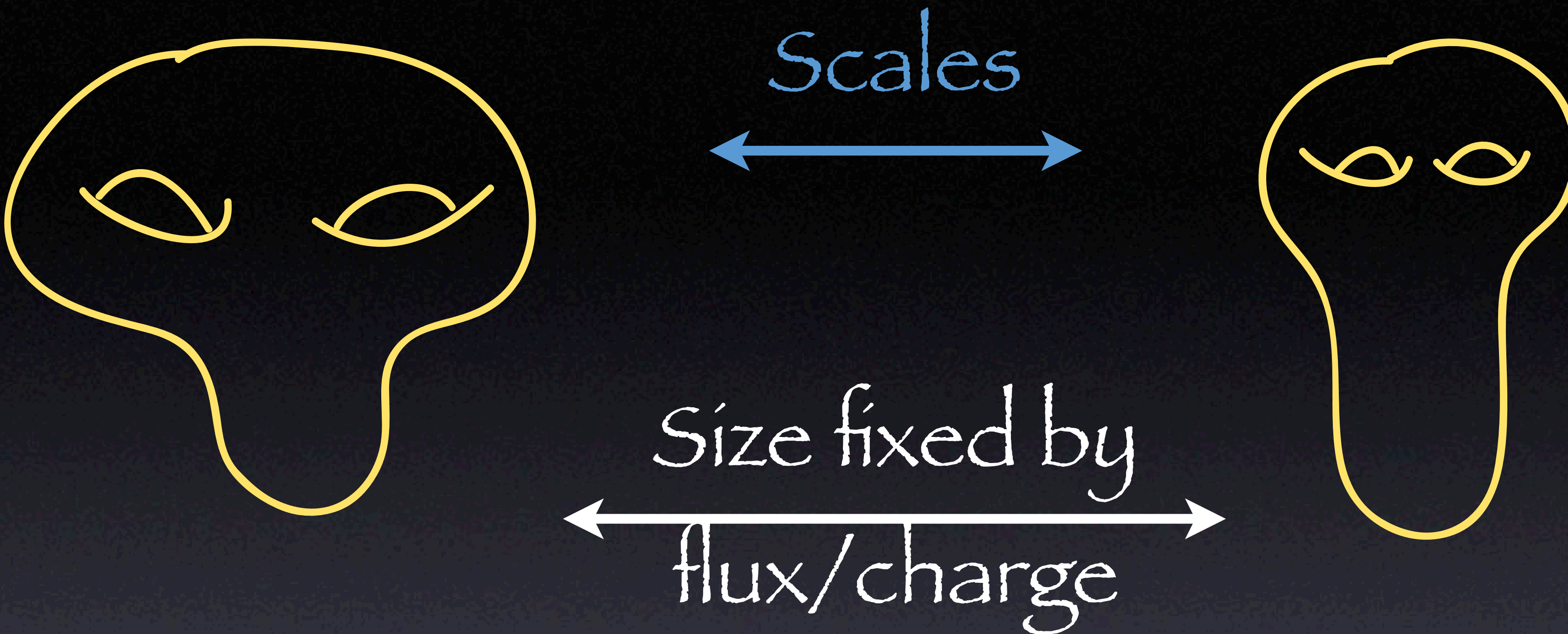
... more complicated for WCs:

$$\tilde{g}_{mn} \to \lambda^{-1} \tilde{g}_{mn}$$

$$\tilde{\nabla}^2 A = \frac{1}{4} e^{-4A} \tilde{R}_4 + \frac{\kappa_{10}^2}{8} e^{-2A} (T^m_m - T^\mu_\mu)$$

λ $\qquad$ λ^0 $\qquad$ $\lambda^{(9-p)/2}$ $\quad$ $\mathrm{p-brane}$

λ^q $\quad$ $\mathrm{q-flux}$


Scales
Size fixed by
flux/charge

E.g. IIB flux compactifications (GKP):

$$\tilde{\nabla}^2(e^{-4A}) \sim G_{mnp}\widetilde{\bar{G}^{mnp}} + T_3\tilde{\rho}_3$$

$$e^{-4A_0} \to e^{-4A_0} + c$$

Large c: $c \sim (\text{Radius})^4$

$c \gg e^{-4A_0}$ (large radius):

warping disappears

Effect on spectrum:

E.g. scalar ϕ, ~modulus

(SBG & Maharana; Frey & Maharana)

$$\nabla^2_{10}\phi \sim g_s G_{mnp}\bar{G}^{mnp}\phi$$

$$A_m$$

$c > e^{-A_m}$:

$$m^2 \sim \frac{1}{c^2} \ll m_{KK} \sim \frac{1}{c}$$

$c < e^{-A_m}$:

$$m^2 \sim e^{2A_m} \sim m_{KK}^2$$

Likewise for gravitino (WIP)

c

No throat

e^{-4A_m}

moderate warping

$$m_{3/2} \sim \frac{1}{c} \ll m_{KK} \sim \frac{1}{\sqrt{c}}$$

throat

e^{-A_m}

strong warping

$$m_{3/2} \sim e^{A_m} \sim m_{KK}$$

Implications for 4d effective theory:

moderate warping $c > e^{-A_m}$:

4d SUSY; spont. or explicitly broken at $m_{3/2}$

→ Find W, K, L_{soft} ... (SUSY lagrangian + soft breaking)

(SBG & Maharana WIP)

strong warping $c < e^{-A_m}$:

No 4d SUSY (BDGMQS, WIP)

→ Find G_{ij}, U ... (non-SUSY lagrangian)

Supersymmetry breaking: 4d

Dine-Gorbatov-Thomas - a refinement

I) SUSY broken

IA) SUSY spontaneously broken

IB) SUSY explicitly broken

} $M_{SUSY} < M_{KK}$

IC) SUSY broken, $M_{SUSY} > M_{KK}$

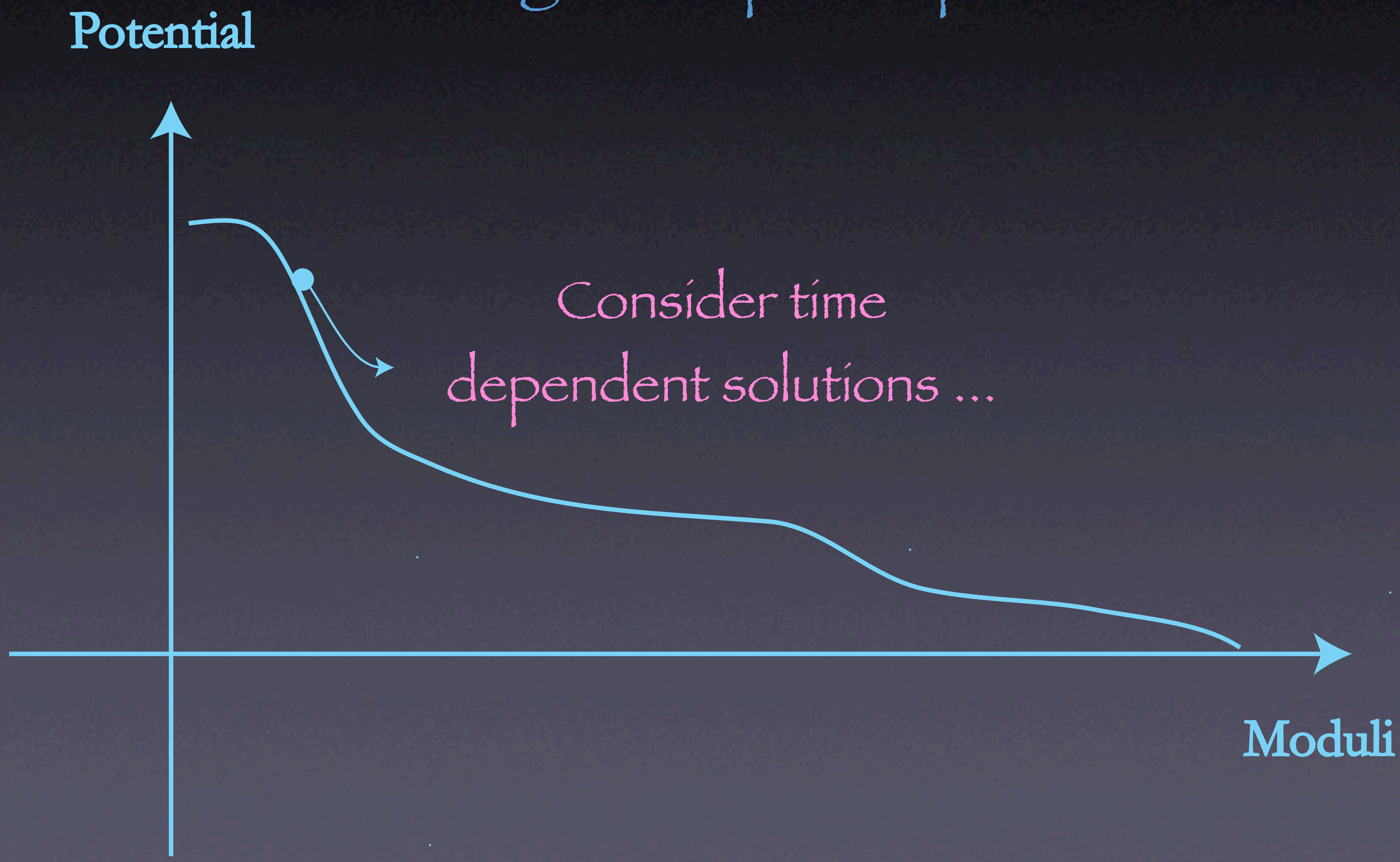
II) SUSY unbroken, $W \neq 0$

III) SUSY unbroken, $W = 0$

U: How to derive 4d effective potential from 10d physics?

(deAlwis, ...: subtleties)

A general prescription:



General 10d metric, homo/iso in 3d:

$$ds^2 = e^{2A(y,t)}\left[-dt^2 + a^2(t)ds_3^2\right] + 2e^{2A(y,t)}\beta_m(y,t)dy^m dt + e^{-2A(y,t)}\tilde{g}_{mn}(y,t)dy^m dy^n$$

For such a solution, also have:
(from homogeneity, isotropy)

$$T^\mu_\nu = -\delta^\mu_\nu U_{10}(y,t) + (\text{velocities})^2$$

(10 dim)

Input from 10d physics

$$ds^2 = e^{2A}\left[-dt^2 + a^2(t)ds_3^2\right] + 2e^{2A}\beta_m dy^m dt + e^{-2A}\tilde{g}_{mn}dy^m dy^n$$

Examine constraint equations:

10d:

$$e^{2A}\left[-2\tilde{\nabla}^2 A + 4(\widetilde{\nabla A})^2 - \frac{1}{2}\tilde{R}_6\right] + e^{-2A}\,{}^4G^t_t + \mathcal{O}(v^2, \beta^2, \beta v) = -\kappa_{10}^2 U_{10}$$

y indep

Solve for ${}^4G^t_t$, identify potential from

4d:

$${}^4G^t_t = \kappa_4^2 U + \mathcal{O}(v^2)$$

This gives:

$$\kappa_4^2 U = \frac{1}{V_W^2} \int d^6y \sqrt{\tilde{g}} \left[\kappa_{10}^2 e^{-2A} U_{10} + 4(\widetilde{\nabla A})^2 - \frac{1}{2}\tilde{R}_6 + e^{-2A}\mathcal{O}(\beta^2) \right]$$

with $V_W = \int d^6y \sqrt{\tilde{g}} e^{-4A}$

Suppressed in KK expansion

$$\kappa_4^2 U = \frac{1}{V_W^2} \int d^6y \sqrt{\tilde{g}} \left[\kappa_{10}^2 e^{-2A} U_{10} + 4(\widetilde{\nabla A})^2 - \frac{1}{2}\tilde{R}_6 + e^{-2A}\mathcal{O}(\beta^2) \right]$$

- Bridge: formula giving 4d potential due to general 10d physics ... fluxes, branes, NP effects, alpha' corrections, etc. (enter through U_{10})
- Also need A ... determined by 10d constraint eqn.

E.g. 1: spacefilling p-brane or O-plane

$$T^{\mu}_{\nu} = -T_p \delta^{\mu}_{\nu} \delta(\Sigma)$$

gives

$$\delta U_p = \frac{\kappa_{10}^2}{V_W^2} T_p \int_\Sigma d^{p-3}z \sqrt{\tilde{g}_{\rm ind}} e^{(7-p)A} + (\text{warping corrections})$$

$$\sim 1/R^{15-p}$$

w/manifold radius R ... correct answer

E.g. 2: q-form flux

$$T^{\mu}_{\nu} = -\frac{1}{4\kappa_{10}^2}\delta^{\mu}_{\nu}\frac{F_q^2}{q!}$$

$$\delta U_q = \frac{1}{4V_W^2}\int d^6y\sqrt{\tilde{g}_6}e^{-2A}\frac{F_q^2}{q!} + (\text{warping corrections})$$

$$\sim 1/R^{2q+6}$$

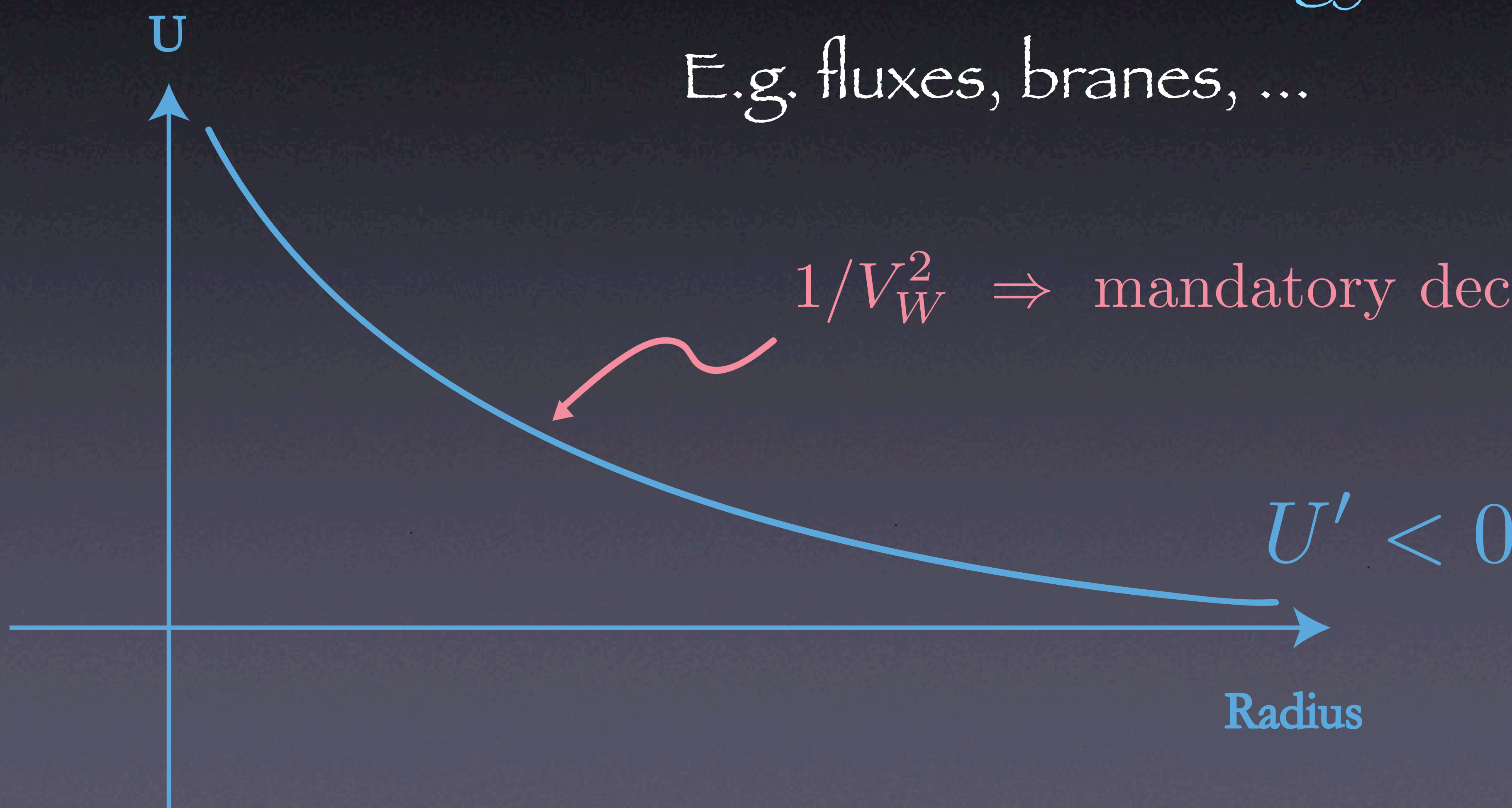
w/manifold radius R ... correct answer

Application #1: Criterion for dS Vacua

$$\kappa_4^2 U = \frac{1}{V_W^2}\int d^6y\sqrt{\tilde{g}}\left[\kappa_{10}^2 e^{-2A}U_{10} + 4(\widetilde{\nabla A})^2 - \frac{1}{2}\tilde{R}_6 + e^{-2A}\mathcal{O}(\beta^2)\right]$$

Typically, $U_{10} \geq 0$ (~weak energy condition)

E.g. fluxes, branes, ...

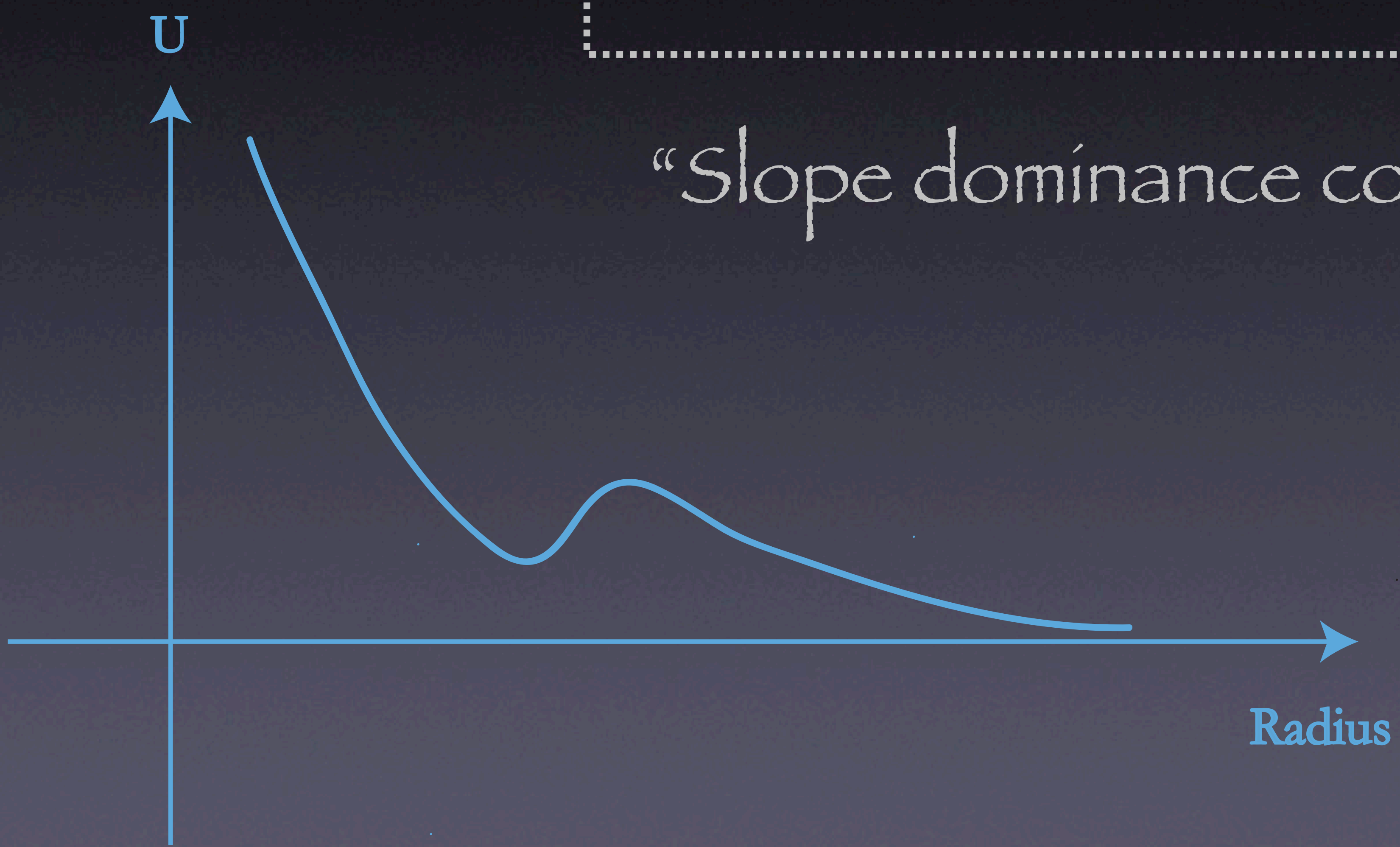


$$\kappa_4^2 U = \frac{1}{V_W^2} \int d^6y \sqrt{\tilde{g}} \left[\kappa_{10}^2 e^{-2A} U_{10} + 4(\widetilde{\nabla A})^2 - \frac{1}{2}\tilde{R}_6 + e^{-2A}\mathcal{O}(\beta^2) \right]$$

Want $U' > 0$:

1) $U_{10}^I < 0$, 2) $|U_{10}'^I| > |U_{10}'^{rest}|$

"Slope dominance condition"



E.g. KKLT

1) $\overline{D3}$: $\delta U \sim T_3 \frac{e^{4A(\bar{y})}}{V_W^2}$ >0

(General expression interpolating between results in KKLT and KKLMMT)

2) Non-perturbative effects:

E.g. ED3's

4 cycle;

instanton sum:

$$W_{NP} \sim e^{-S_{brane}} \sim e^{-T_3 \int_i d^4 z \sqrt{\tilde{g}} e^{-4A} + i\mu_3 \int C_4 + \cdots}$$

(Similar story for D7's)

Origin of slope dominance:

$$S_{NP} \sim \bar{W}_0 \partial_\rho W_{NP} + hc + \cdots$$

$$\int G \wedge \Omega$$

$\propto e^{i\int C_4}$: axion phase adjusts to $U_{10,NP} < 0$

Then fine tune to achieve slope dominance

Application #2: D3-$\overline{\text{D3}}$ potentials and brane inflation

- Identification of holo modulus (rho problem):

$$W_{NP} \sim e^{-S_{brane}} \sim e^{\underbrace{-T_3 \int_i d^4 z \sqrt{\tilde{g}} e^{-4A} + i\mu_3 \int C_4}_{\rho} + \cdots}$$

(Now checked: Baumann, Dymarsky, Klebanov, Maldacena, McAllister, Murugan)

- Computation of V$(y,\bar{y})$ via potential formula:

$$V \sim e^{2A_m} V_{D\bar{D}} + \delta V$$

$\leftarrow \propto H^2$ (eta problem; D-celeration)

Input for comparison to cosmo data

Other progress

(cf hep-th/0507158, ...)

Systematics of linearized perturbations

Systematics of corrections

Towards K , W , $\mathcal{L}_{soft}$, ...

(or G_{ij} , U , $\cdots$)

future ...

Warped compactifications

- Possibly ubiquitous among geometric solutions
- Potentially quite rich phenomenology: moduli stabilization, SUSY breaking, dS, hierarchies, inflation ...
- These features rely on 4d effective theories (and aspects of 10d physics) whose subtleties we've only begun to unravel