Large Volume Flux Compactifications and Open Strings

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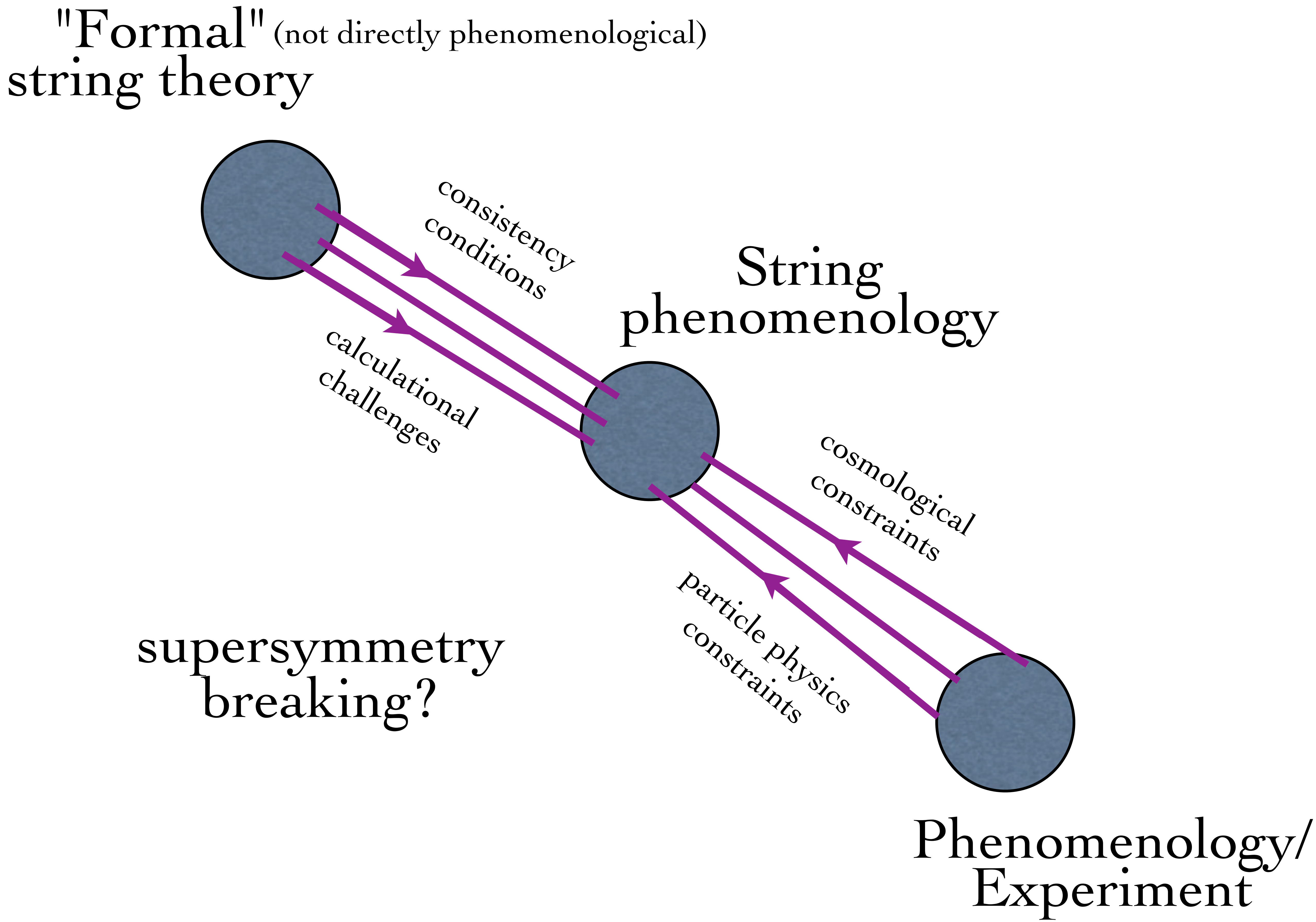
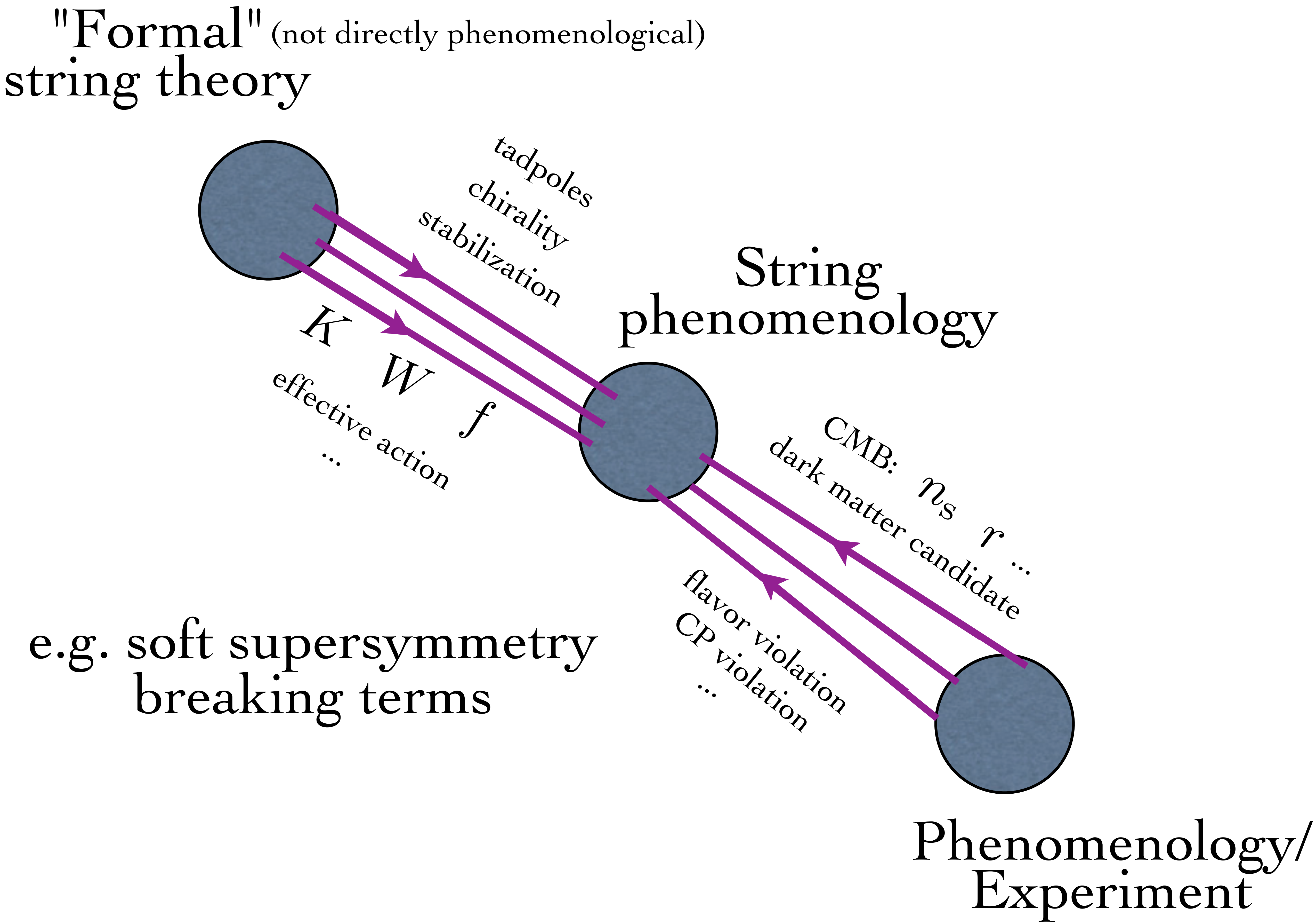
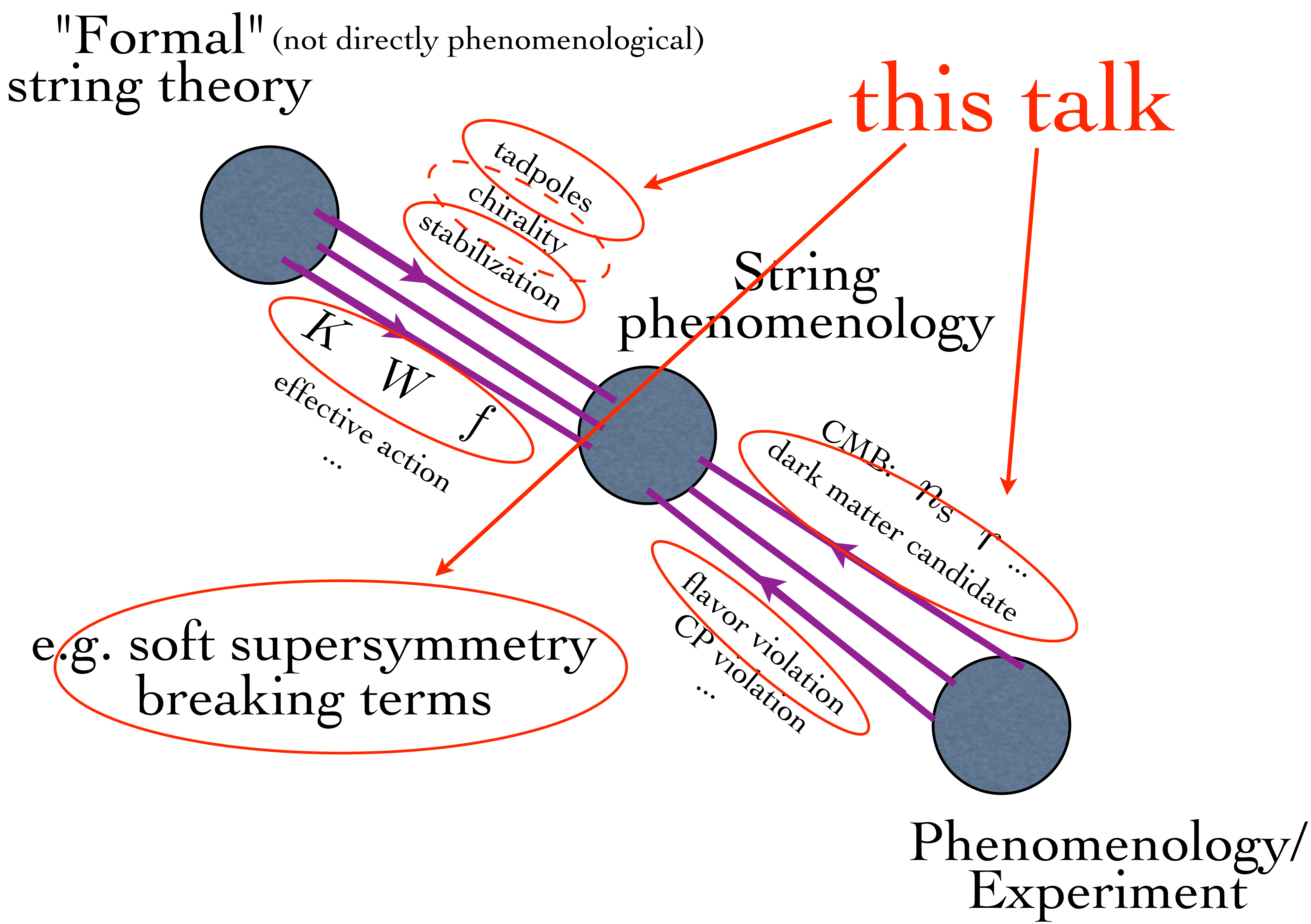
talk available at www.physto.se/~mberg


"Formal" (not directly phenomenological)
string theory
consistency conditions
calculational challenges
String phenomenology
cosmological constraints
particle physics constraints
supersymmetry breaking?
Phenomenology/
Experiment


"Formal" (not directly phenomenological)
string theory
tadpoles
chirality
stabilization
String
phenomenology
K
W
f
effective action
...
CMB: n_s r ...
dark matter candidate
flavor violation
CP violation
...
e.g. soft supersymmetry
breaking terms
Phenomenology/
Experiment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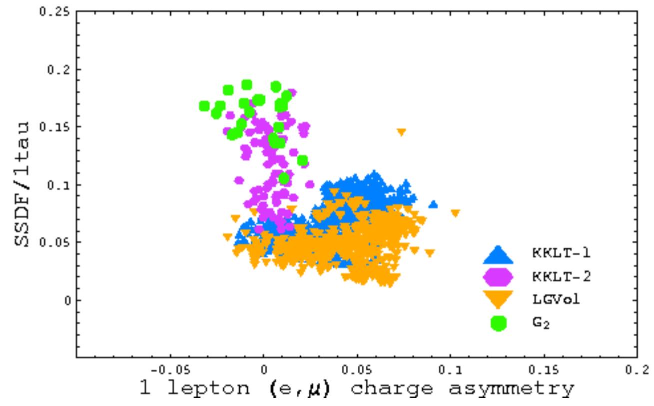
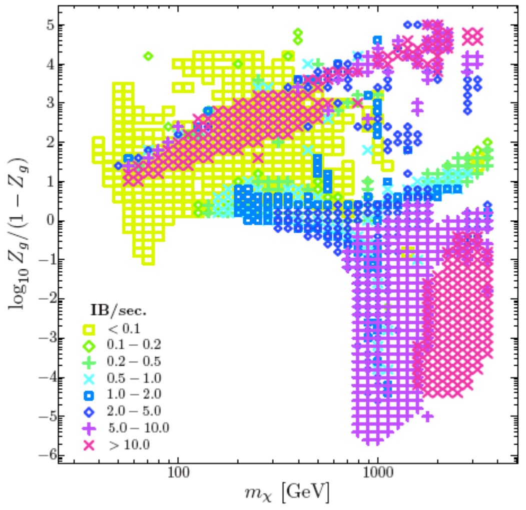
“Real phenomenology”?

MSSM-like effective field theory models

LHC observables



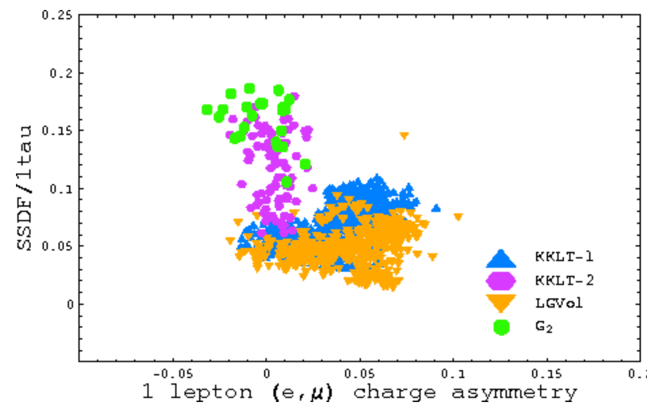
SUSY dark matter



“Real phenomenology”?

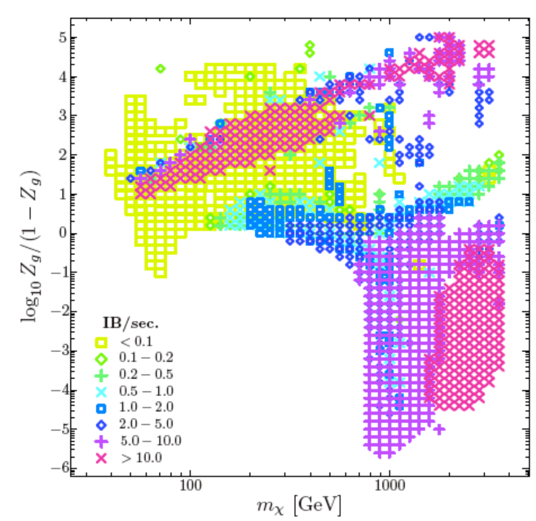
MSSM-like effective field theory models

LHC observables



e.g.

SUSY dark matter

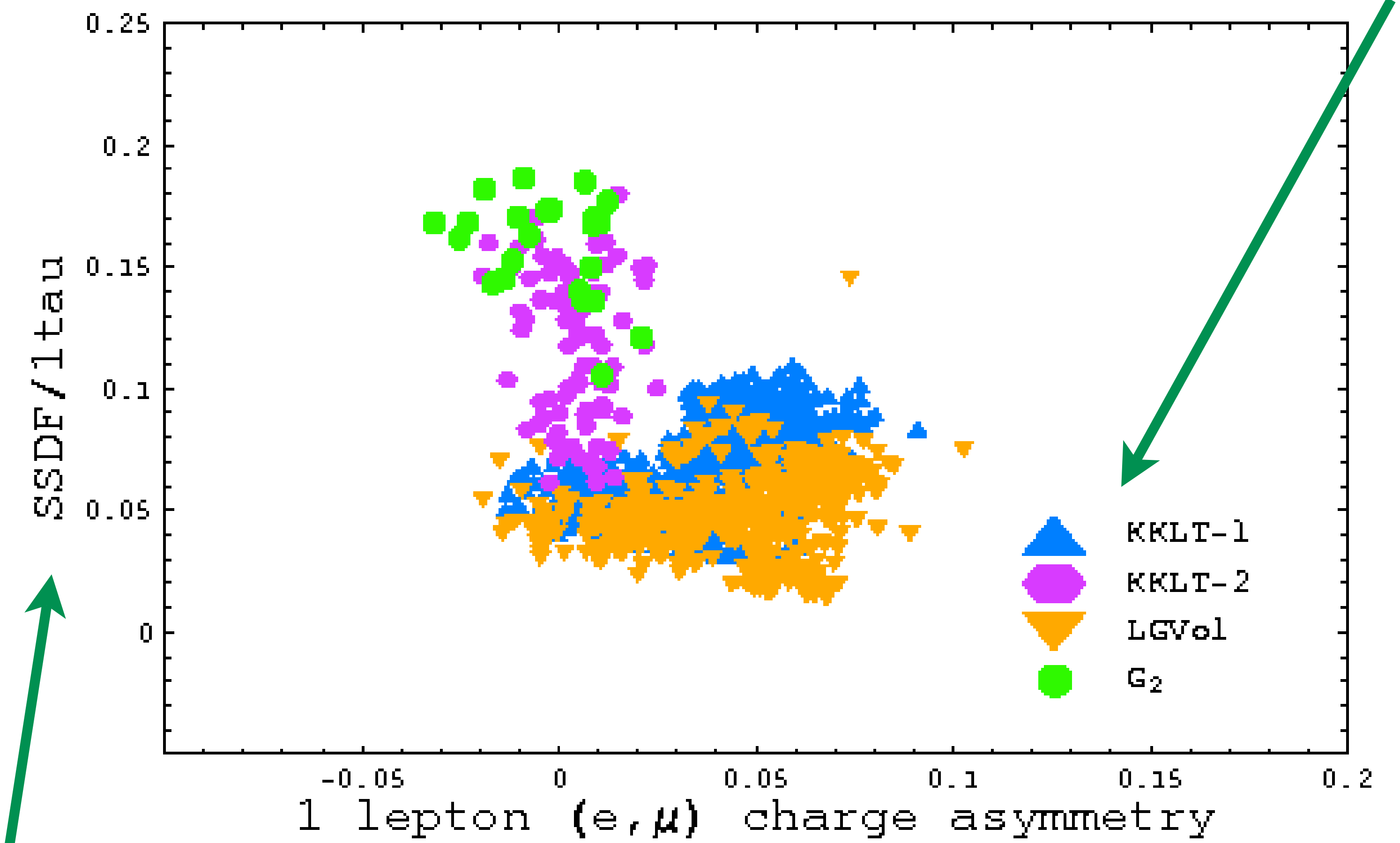


e.g.

LHC counting signatures

Kane, Kumar, Shao '07 (hep-ph)

different "string" models



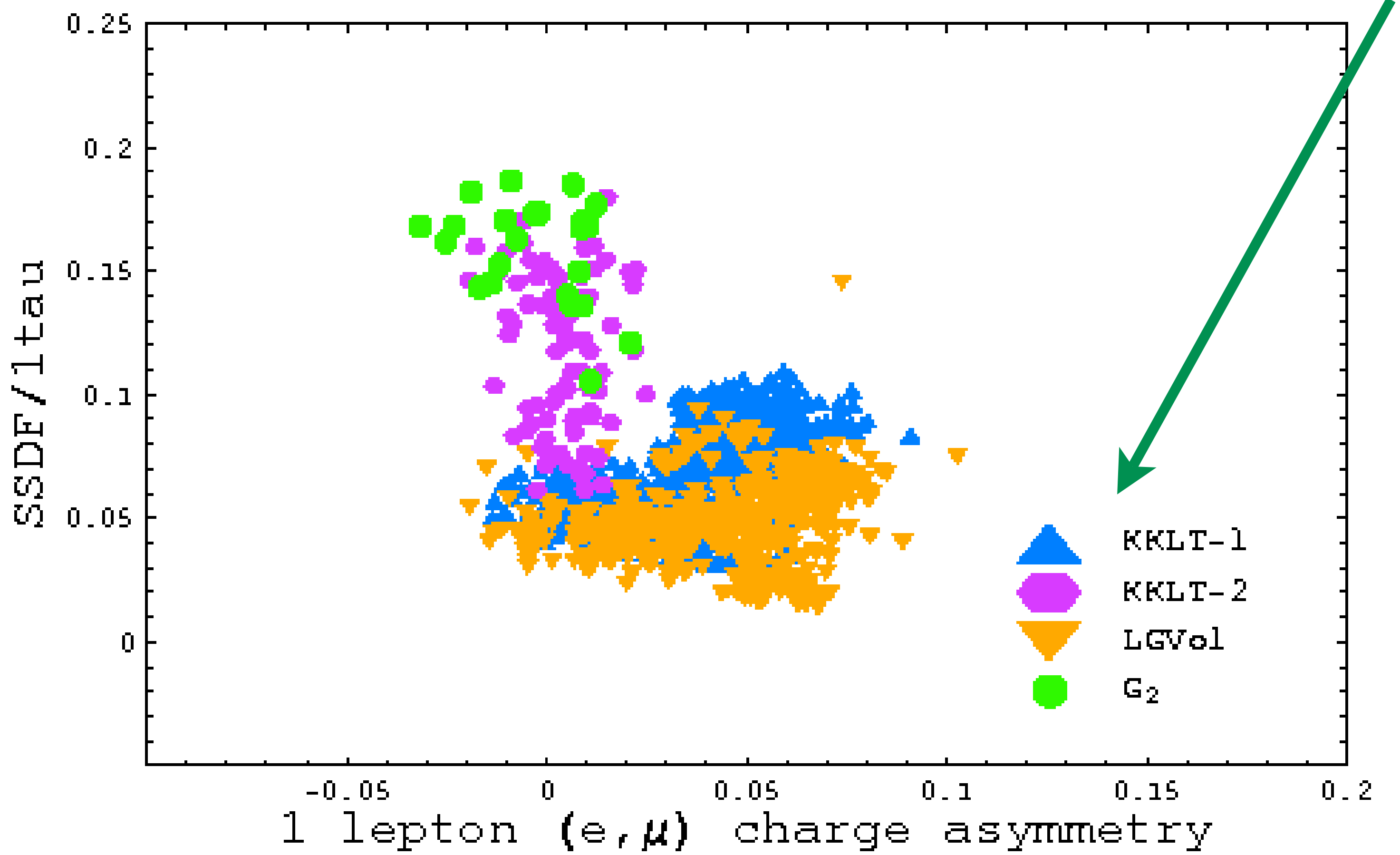
$$\frac{\text{same sign, different flavor dilepton events}}{1\ \tau\ \text{events}}$$

$$\frac{N_\ell^+ - N_\ell^-}{N_\ell^+ + N_\ell^-}$$

LHC counting signatures

Kane, Kumar, Shao '07 (hep-ph)

different "string" models



KKLT1, LGVol: light squarks ⇒ squark production

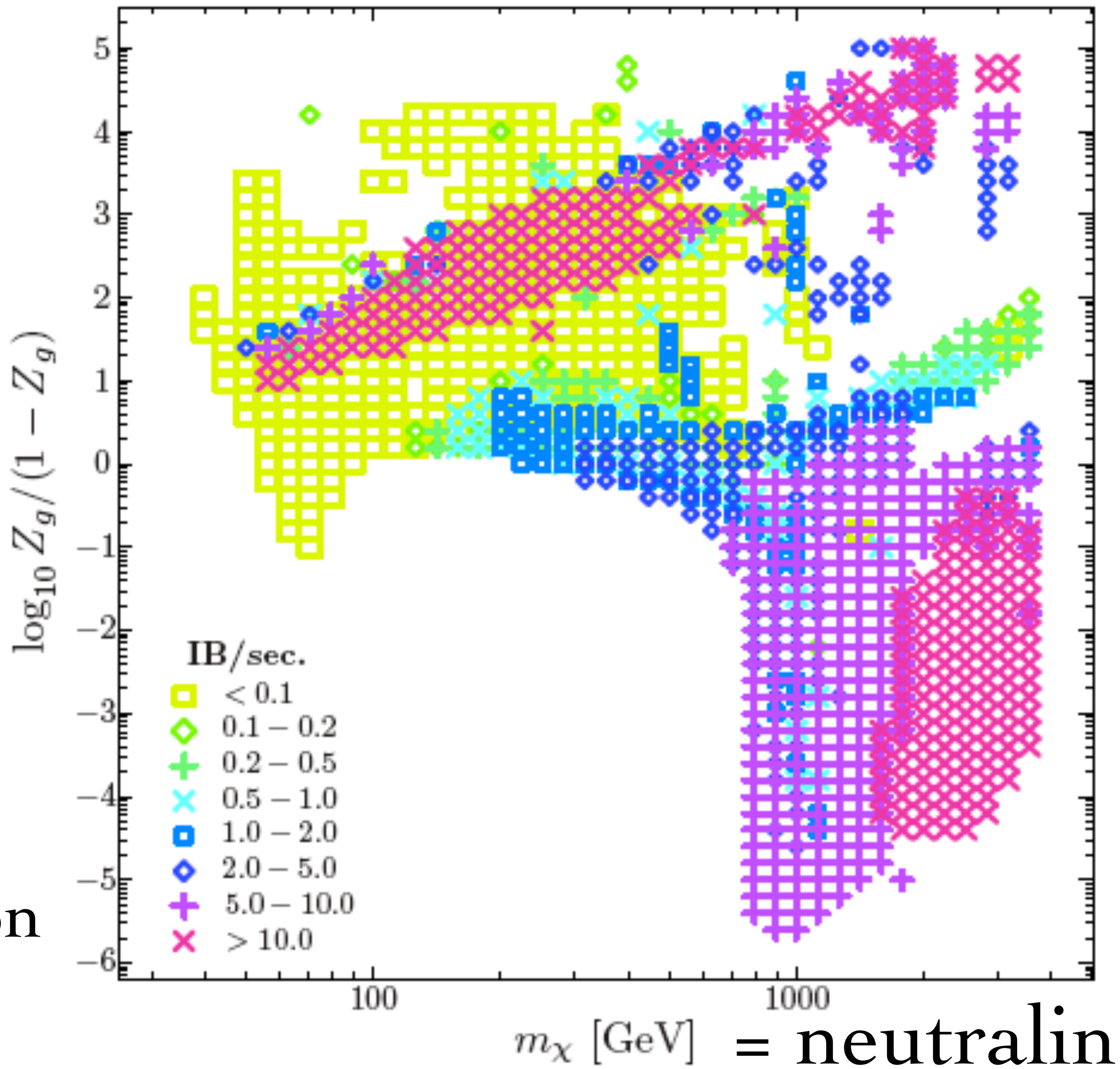
⇒ (electric) charge asymmetry

G_2 : heavy squarks ⇒ gluino production

⇒ less charge asymmetry

SUSY dark matter

Bringmann, Bergström, Edsjö '07 (hep-ph)



Z_g
= gaugino fraction (in LSP)

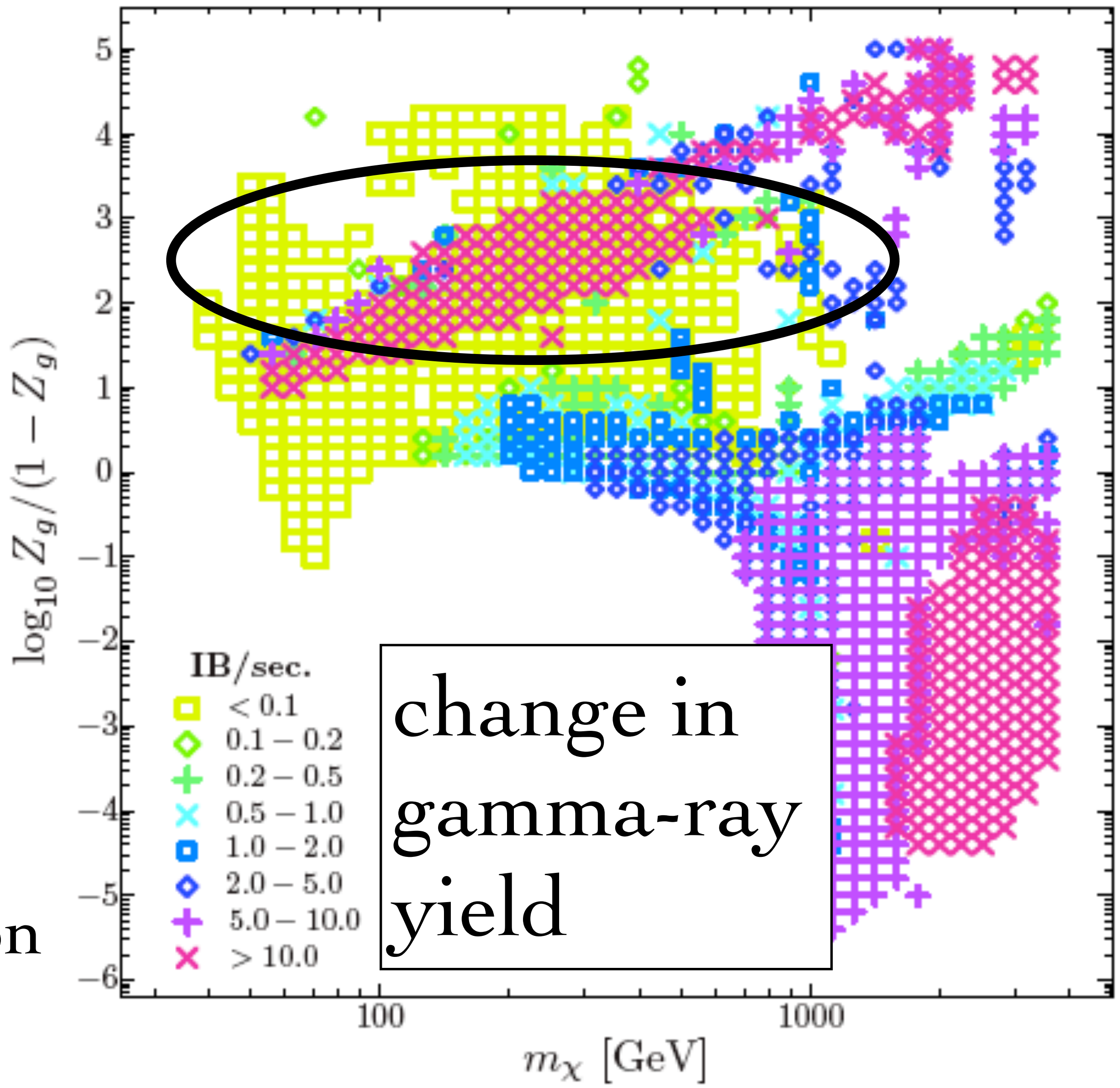
= neutralino mass
= dark matter particle

different MSSM models:

- satisfy (at least some) accelerator constraints
- give WMAP cosmological dark matter relic density

SUSY dark matter

Bringmann, Bergström, Edsjö '07 (hep-ph)



Z_g
= gaugino fraction
(in LSP)

GLAST (launch May 16, 2008):
up to 300 GeV

What is the "added value" of string phenomenology?

(compared to standard MSSM phenomenology)

First of all: if TeV string scale: radically different!

- long shot, but might keep in mind
- experience so far: difficult to satisfy experimental constraints

Here: string scale >> TeV

string theory gives some effective field theory... but if that's it, so what?

<u>What is the "added value" of string phenomenology?</u>

most of MSSM phenomenology:
severely restricted parameter space
(e.g. start with 105, keep 3)

	Why?
• restrict flavor violation (beyond SM)	Experiment
• restrict CP violation (beyond SM)	Experiment
• renormalizable	"Energy desert" (gauge unification)

What is the "added value" of string phenomenology?

most of MSSM phenomenology:
severely restricted parameter space
(e.g. start with 105, keep 3)

	Why? (really...)
• restrict flavor violation (beyond SM)	Naturalness
• restrict CP violation (beyond SM)	Naturalness
• renormalizable	Naturalness

What is the "added value" of string phenomenology?

bulk of MSSM phenomenology:
severely restricted parameter space (e.g. 105 to 3)

	String phenomenology
• restrict flavor violation (beyond SM)	Naturalness?
• restrict CP violation (beyond SM)	Naturalness?
• renormalizable	Naturalness?

?

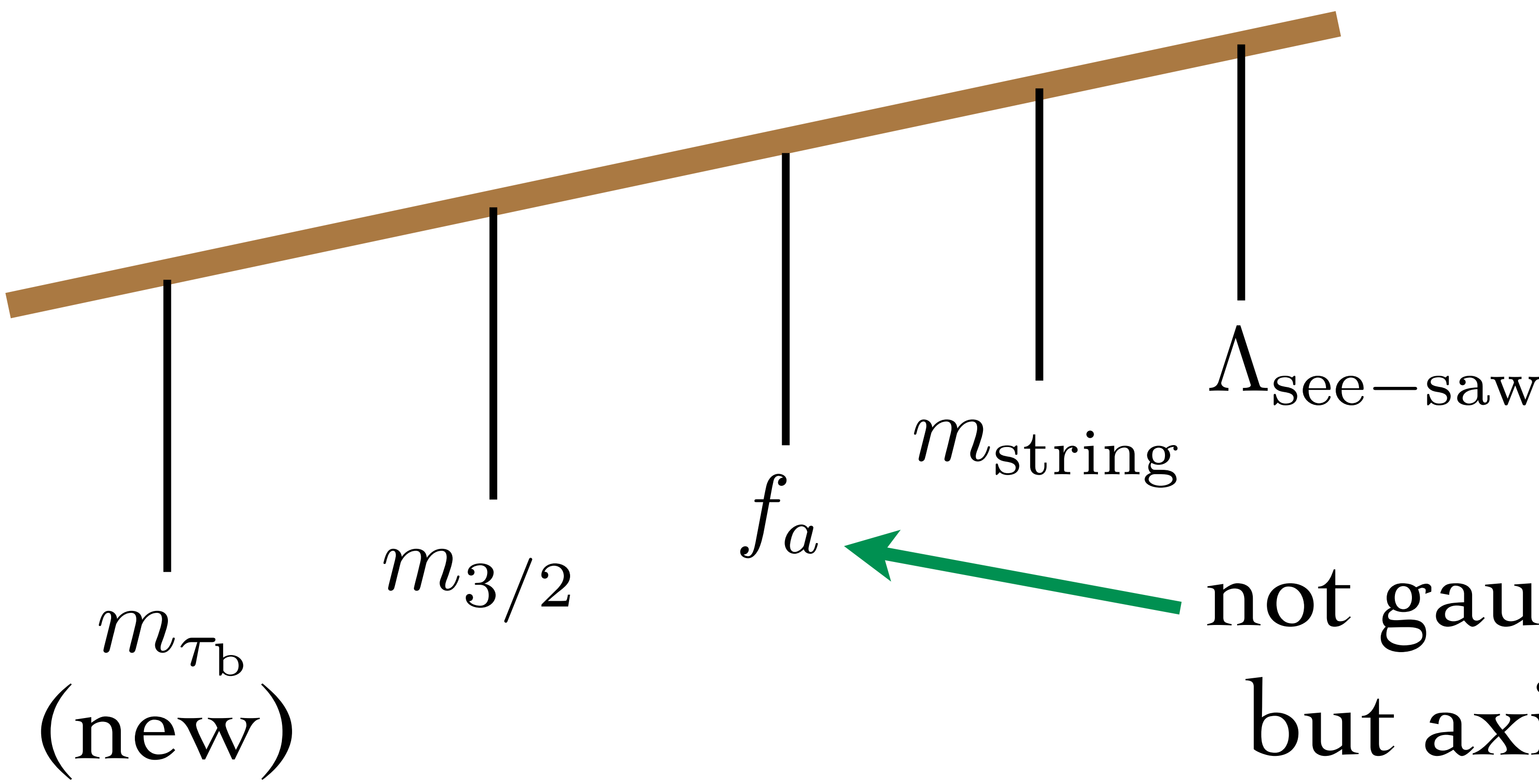
remainder of talk:
classes of string phenomenologies that predict something?

Example: Large Volume Scenario

(variant of KKLT – more later)

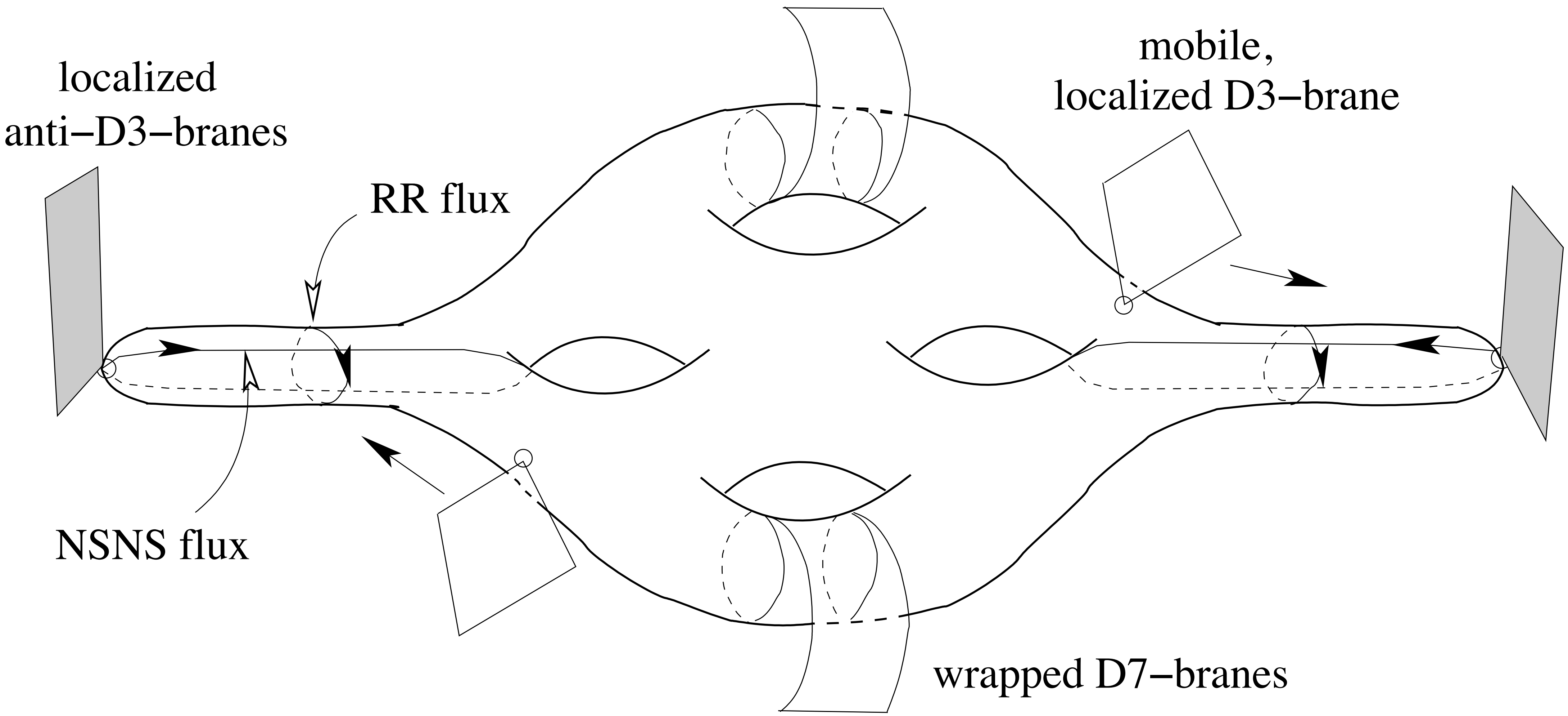
yoke

the scales are "yoked"

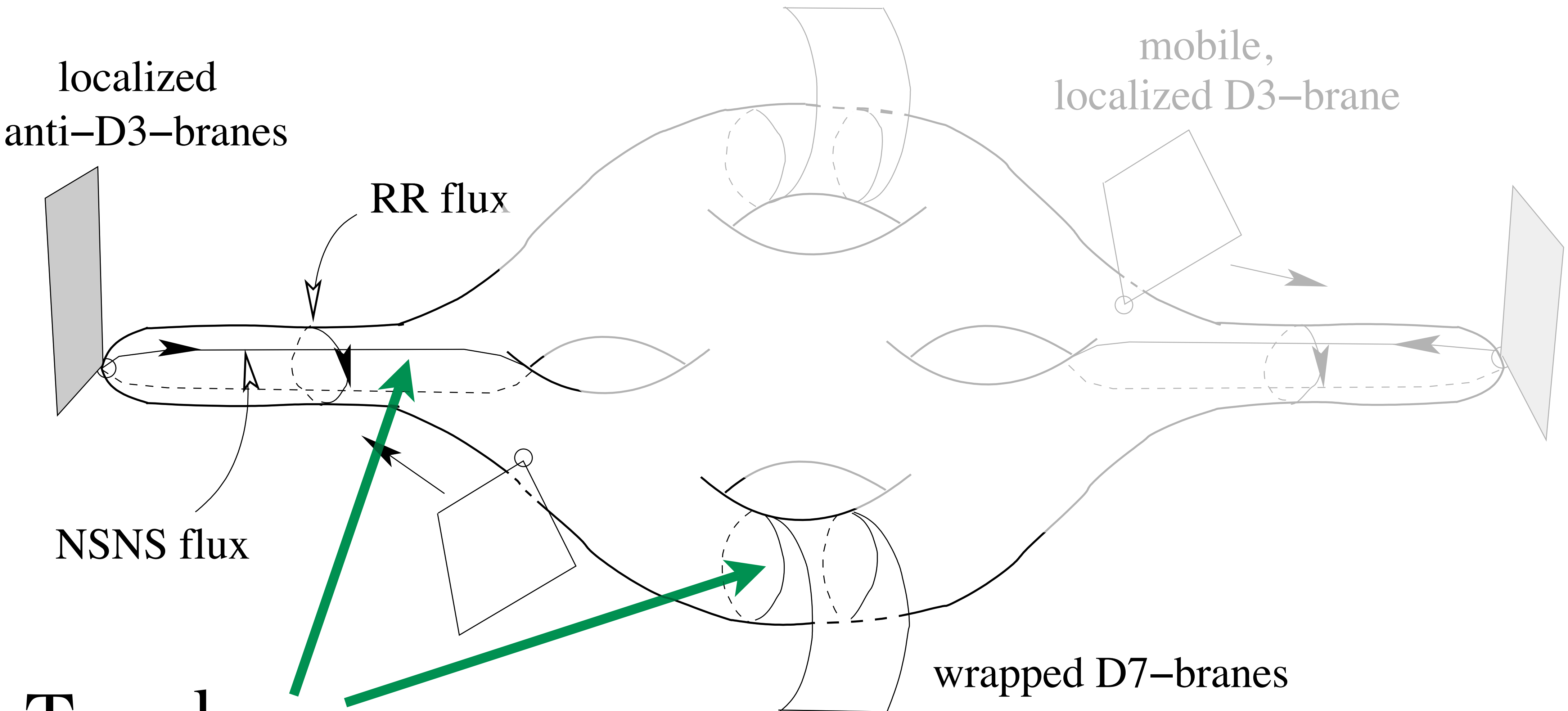


not gauge kinetic function,
but axion decay constant

The KKLT internal space: a Calabi-Yau IIB orientifold with fluxes and warping



The KKLT internal space: a Calabi-Yau IIB orientifold with **fluxes** and warping

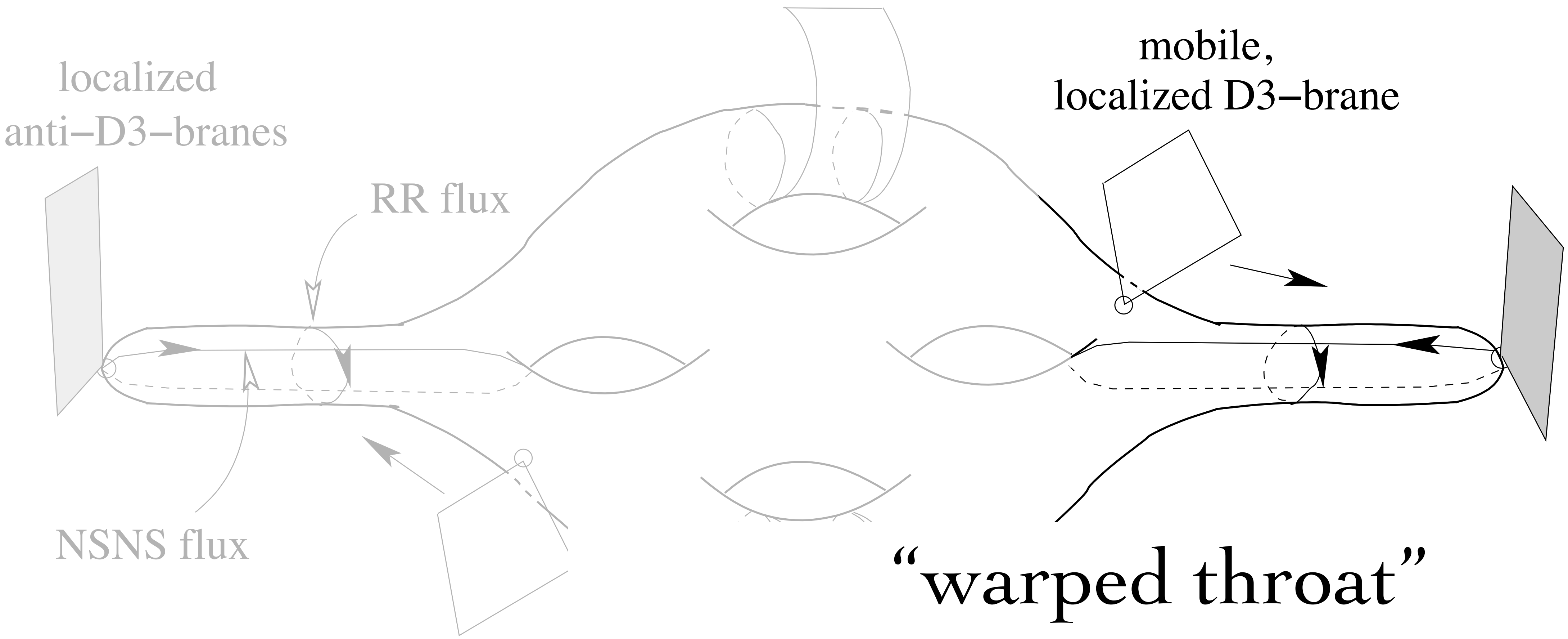


Topology

↓

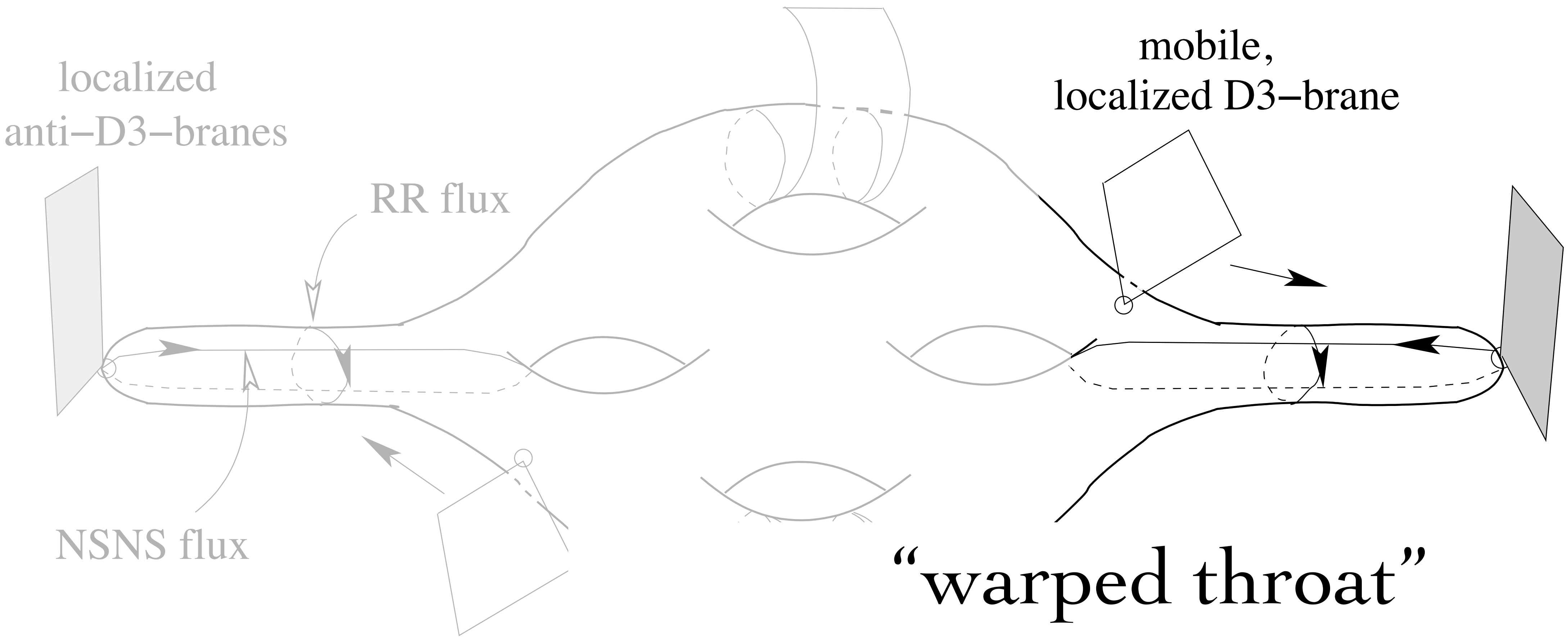
flux stabilization (vacuum selection)

The KKLT internal space: a Calabi-Yau IIB orientifold with fluxes and **warping**



"warped throat"
i.e. Klebanov-Strassler 6d metric;
i.e. "Randall-Sundrum in 10d"

The KKLT internal space: a Calabi-Yau IIB orientifold with fluxes and **warping**



"warped throat"
often approximated
with AdS + UV cutoff

KKLT D=4, N=1 effective theory

closed string (would-be) moduli: S, T_i, U_α

$$K = -\ln(S+\bar{S}) - 2\ln\mathcal{V}(T_i+\bar{T}_i) + K^U$$

$$W = W_{\rm flux} + W_{\rm np}$$

stabilize S and U
(i.e. minimize potential V with respect to S and U)

$$W = W_0 + \sum_i A_i e^{-a_i T_i}$$

KKLT D=4, N=1 effective theory

6d overall volume, function of Kähler moduli

closed string moduli: S, T_i, U_α

$$K = -\ln(S+\bar{S}) - 2\ln \mathcal{V}(T_i + \bar{T}_i) + K^U$$

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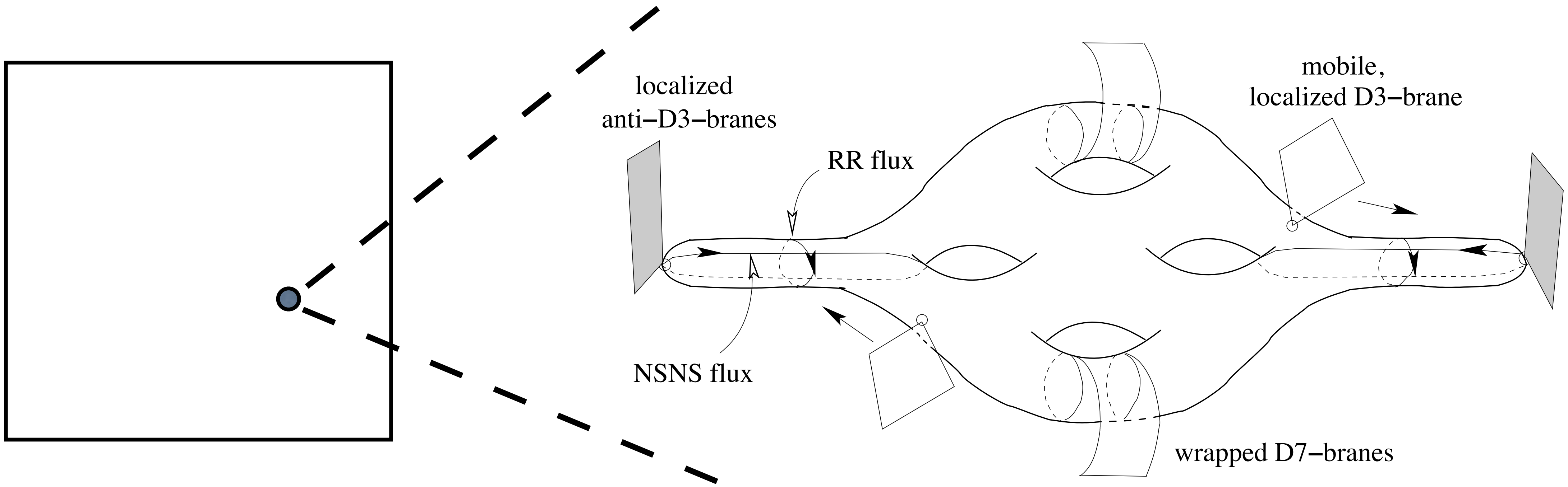
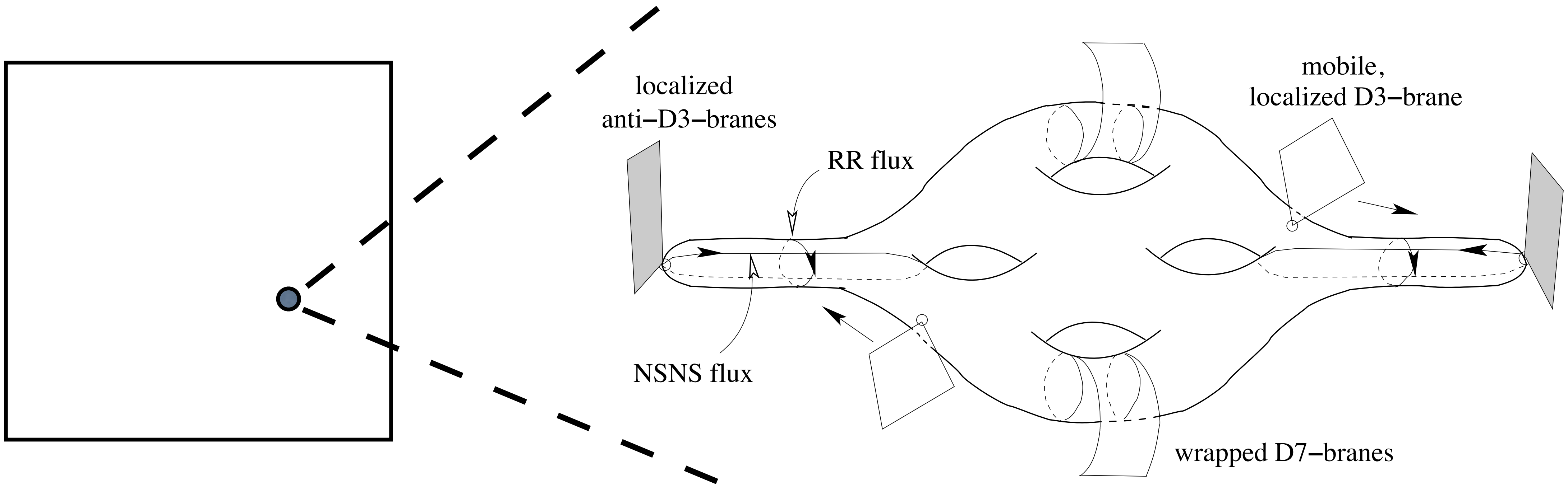


KKLT: external space deSitter

The KKLT internal space: a Calabi-Yau IIB orientifold with fluxes and warping



here: Minkowski external space

KKLT D=4, N=1 effective theory

closed string moduli potential:

$$
\begin{aligned}
V &= (\text{terms that vanish as } W_{\rm np} \to 0) \\
&\quad + e^{K}(G^{\bar{\jmath}i} K_{\bar{\jmath}} K_i - 3)|W|^2
\end{aligned}
$$

for tree-level K from previous slide,

$$
G^{\bar{\jmath}i} K_{\bar{\jmath}} K_i = 3 \qquad \Rightarrow \qquad V(T) = 0
$$

"no-scale structure"
at supergravity tree-level

KKLT D=4, N=1 effective theory

closed string moduli potential:

$$V = (\text{terms tha}$$
$$+e^{K}($$

broken by perturbative and nonperturbative string corrections

for tree-level K fro

$$G^{\bar{j}i}K_{\bar{j}}K_i = 3 \qquad \Rightarrow \qquad V(T) = 0$$

“no-scale structure” at supergravity tree-level

KKLT D=4, N=1 effective theory

closed string moduli potential : $\quad (\tau_i = \mathrm{Re}\, T_i)$

$$\frac{V}{e^K} = e^{-a\tau}\left(4|A|^2 a\tau e^{-a\tau}\left(\tfrac{1}{3}a\tau + 1\right) - 4a\tau|A||W_0|\right)$$

for tree-level K from previous slide, $G^{\bar{\jmath}i}K_{\bar{\jmath}}K_i = 3$

in KKLT, no-scale structure
broken by nonperturbative superpotential

KKLT D=4, N=1 effective theory

closed string moduli potential : $(\tau_i = \mathrm{Re}\, T_i)$

$$\frac{V}{e^K} = e^{-a\tau} \left(4|A|^2 a\right.$$

In KKLT, all closed string moduli are stabilized

for tree-level K fro

in KKLT, no-scale structure broken by nonperturbative superpotential

Some drawbacks with original KKLT

closed string moduli potential : $(\tau_i = \mathrm{Re}\, T_i)$

$$\frac{V}{e^K} = e^{-a\tau}\left(4|A|^2 a\tau e^{-a\tau}(\tfrac{1}{3}a\tau + 1) - 4a\tau|A||W_0|\right)$$

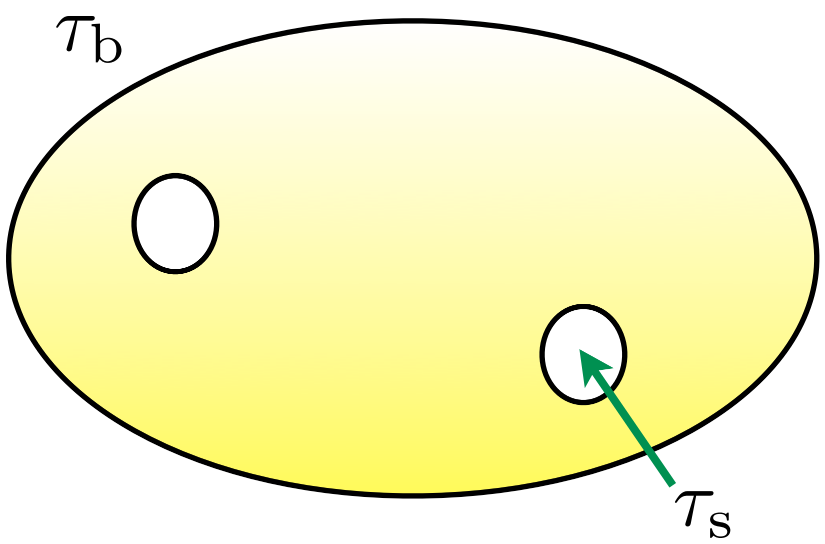
- only works for limited range of a, W_0, A
- volume not stabilized big (no "problem", but see later)
- supersymmetry breaking "at the end" (least understood part)
- "two-step stabilization" (S, U, then T) sometimes fails (not algorithmic)

The Large Volume Scenario (LVS)

Balasubramanian, Berglund, Conlon, Quevedo '05

"Swiss cheese" Calabi-Yau:

$\tau_{\mathrm{b}} \gg \tau_{\mathrm{s}}$



$$\{T_i\} \to \{T_{\mathrm{b}}\}, \{T_{\mathrm{s}}\}$$

$$\mathcal{V} = \tau_{\mathrm{b}}^{3/2} - f(\tau_{\mathrm{s}}) \qquad (\tau_i = \mathrm{Re}\, T_i)$$

special Calabi-Yau

$$K = K_{\mathrm{KKLT}} + \xi \frac{S_1^{3/2}}{\mathcal{V}}$$

$$W = W_{\mathrm{KKLT}}$$

α' (higher derivative) correction

Becker, Becker, Haack , Louis '02

The Large Volume Scenario (LVS)

Balasubramanian, Berglund, Conlon, Quevedo '05

Truncation problem: it typically makes no sense to attempt to "improve" any leading-order string model by string/ quantum corrections

LVS is one case where this intuition may fail (under investigation!)

$$\{T_i\} \to \{T_{\rm b}\}, \{T_{\rm s}\}$$

$$\mathcal{V} = \tau_{\rm b}^{3/2} - f(\tau_{\rm s}) \qquad (\tau_i = {\rm Re}\, T_i)$$

special Calabi-Yau

$$K = K_{\rm KKLT} + \xi \frac{S_1^{3/2}}{\mathcal{V}}$$

$$W = W_{\rm KKLT}$$

α' (higher derivative) correction

Becker, Becker, Haack , Louis '02

LVS moduli stabilization

change variables $(\tau_{\rm b}, \tau_{\rm s}) \to (\mathcal{V}, \tau_{\rm s})$

$$X = Ae^{-a\tau_{\rm s}}$$

$$V = (\ldots)\frac{X^2}{\mathcal{V}} + (\ldots)\frac{X}{\mathcal{V}^2} + (\ldots)\frac{\xi}{\mathcal{V}^3}$$

$$\frac{\partial V}{\partial \mathcal{V}} = 0 \quad \Rightarrow \quad \mathcal{V} = \frac{f(\tau_{\rm s})}{X}$$

$$(\tau_i = \mathrm{Re}\, T_i)$$

$$\frac{\partial V}{\partial \tau_{\rm s}} = 0 \quad \Rightarrow \quad X = \frac{g(\tau_{\rm s})}{\mathcal{V}}$$

$$\Rightarrow \quad f(\tau_{\rm s}) = g(\tau_{\rm s})$$

$$\overset{a\tau_{\rm s} \gg 1}{\Longrightarrow} \quad \tau_{\rm s} \sim \xi^{2/3}$$

$$\Rightarrow \quad \mathcal{V} \sim e^{a\tau_{\rm s}}$$

dial: $\mathcal{V} \sim 10^{15} \ell_{\rm s}^6$

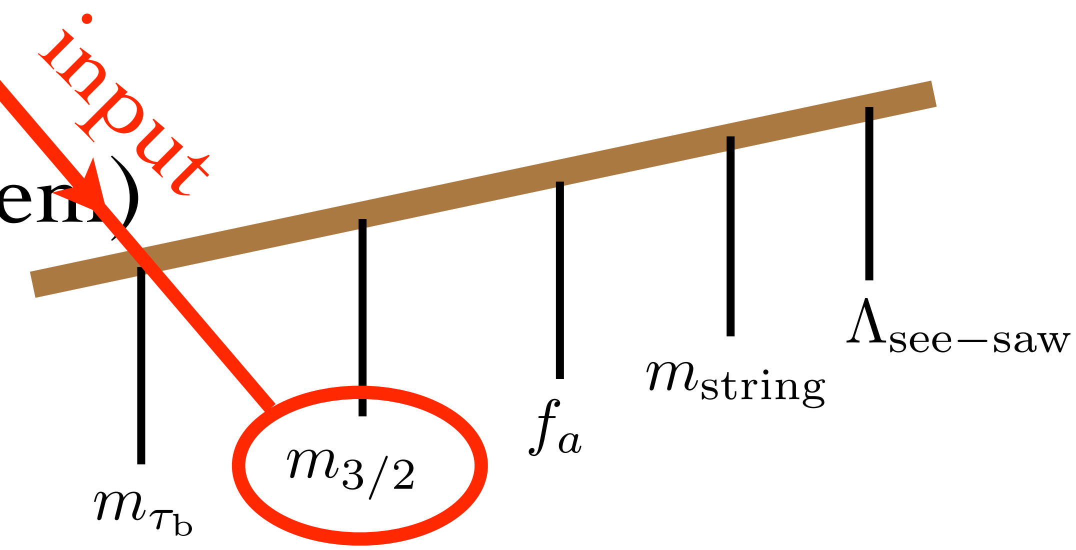
Why $\mathcal{V} \sim 10^{15} \ell_s^6$?

Conlon, Quevedo, Suruliz '05

1. Why is big good?
   - α' (inverse volume) expansion under control
   - "two-step" integrating out becomes algorithmic
   - matter fields: $K(\phi, \bar{\phi}) \sim \mathcal{V}^p k(\phi, \bar{\phi})$
   - soft supersymmetry breaking terms: simplifications

2. Why $\mathcal{V} \sim 10^{15} \ell_s^6$?
   - TeV scale supersymmetry
   - QCD axion (strong CP problem)
   - neutrino masses

the scales are "yoked"



Sample soft terms: gaugino masses

Conlon, Abdussalam, Quevedo, Suruliz '06

Assume MSSM

$$M_a = \frac{1}{2\,\mathrm{Re} f_a} \sum_I F^I \partial_I f_a$$

$$\begin{aligned} F^{\tau_s} &= e^{K/2}(G^{\bar{s}s}\partial_{\bar{s}}\bar{W} + (G^{\bar{s}s}K_{\bar{s}} + G^{\bar{b}s}K_{\bar{b}})\bar{W}) \\ &= 2\tau_s e^{K/2}\bar{W}_0 \left(\left(1 - \frac{3}{4a\tau_s}\right) - 1 + \ldots \right) \end{aligned}$$

$$|M_s| \sim \frac{m_{3/2}}{\ln(M_P/m_{3/2})}\left(1 + \frac{(\ldots)}{\ln(M_P/m_{3/2})} + \ldots\right)$$

Gaugino masses suppressed by factor of 30 compared to gravitino mass

"Mirror mediation"

Conlon '07

(cf. heterotic model-building) ... Kaplunovsky, Louis '93 ...

Flavor structure from only one kind of modulus (here U)

soft scalar masses

$$m^2_{\alpha\beta} = m^2\delta_{\alpha\beta} + \frac{f_{\alpha\beta}(U)}{M} + \mathcal{O}\left(\frac{1}{M^2}\right)$$

- New nonrenormalizable couplings at each mass threshold M
- Hard to calculate $f_{\alpha\beta}(U)$ in concrete models

Gaugino masses suppressed by factor of 30 compared to gravitino mass

Consistency conditions

M.B., Haack, Pajer '07,
+ work in progress

$$\Delta K_{\alpha'} : \Delta K_{g_s} \quad \sim \quad \alpha'^3 \ : \ g_s^2 \alpha'^2$$

dimensional analysis:

$$\Delta K_{\alpha'} \quad \sim \quad g_s^{-3/2} \mathcal{V}^{-1}$$
$$\Delta K_{g_s} \quad \sim \quad g_s \mathcal{V}^{-2/3}$$

cancellation (to be shown):

$$\Delta V_{\alpha'} \quad \sim \quad g_s^{-1/2} \mathcal{V}^{-3}$$
$$\Delta V_{g_s} \quad \sim \quad g_s \mathcal{V}^{-3}$$

should consider D-brane corrections in LVS!

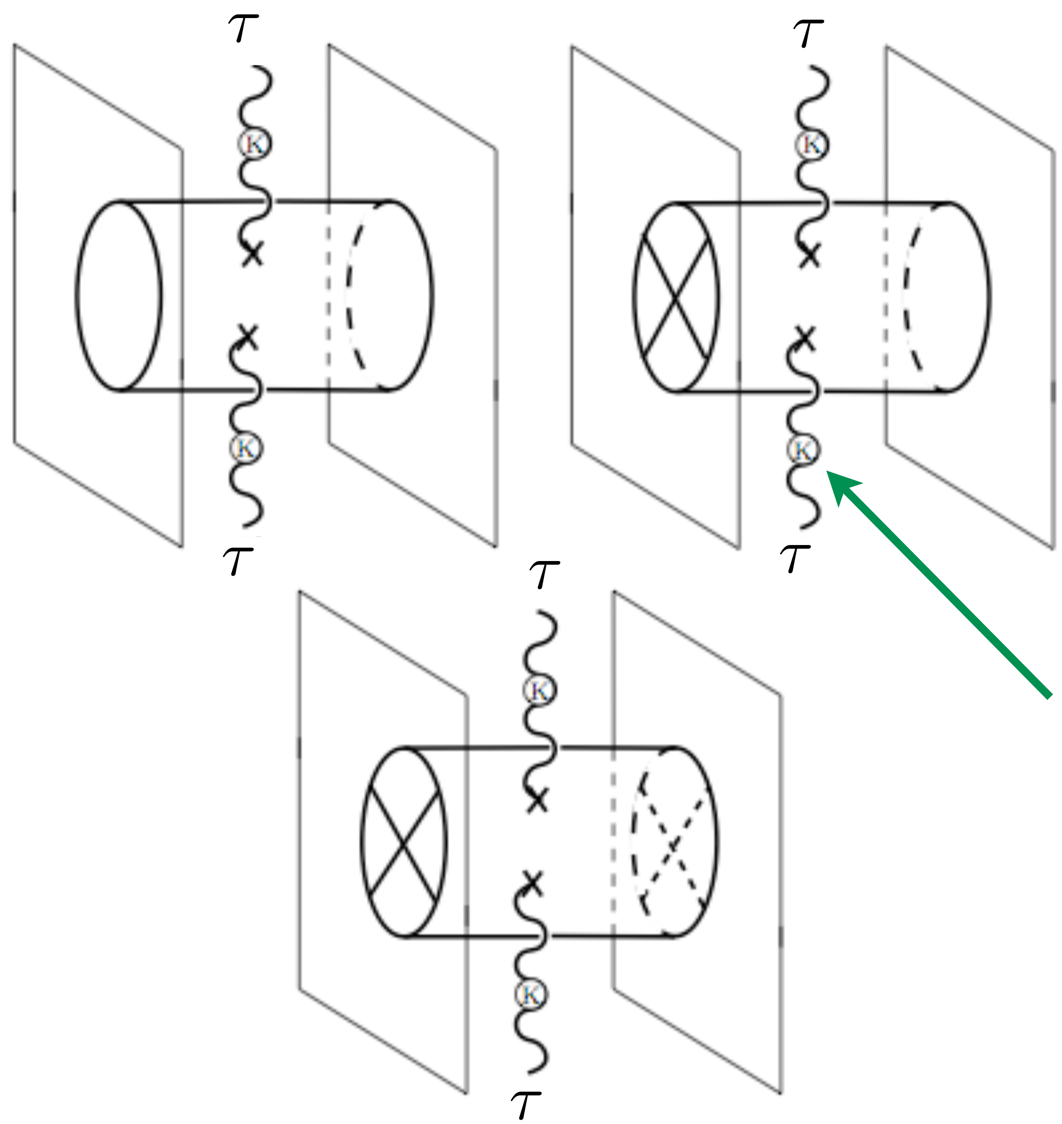
D-Brane Corrections to Kähler potential

M.B., Haack, Körs, '05

brane at arbitrary position ϕ

$\tau = \mathrm{Re}\, T$

$$\langle \tau \, \tau \rangle =$$

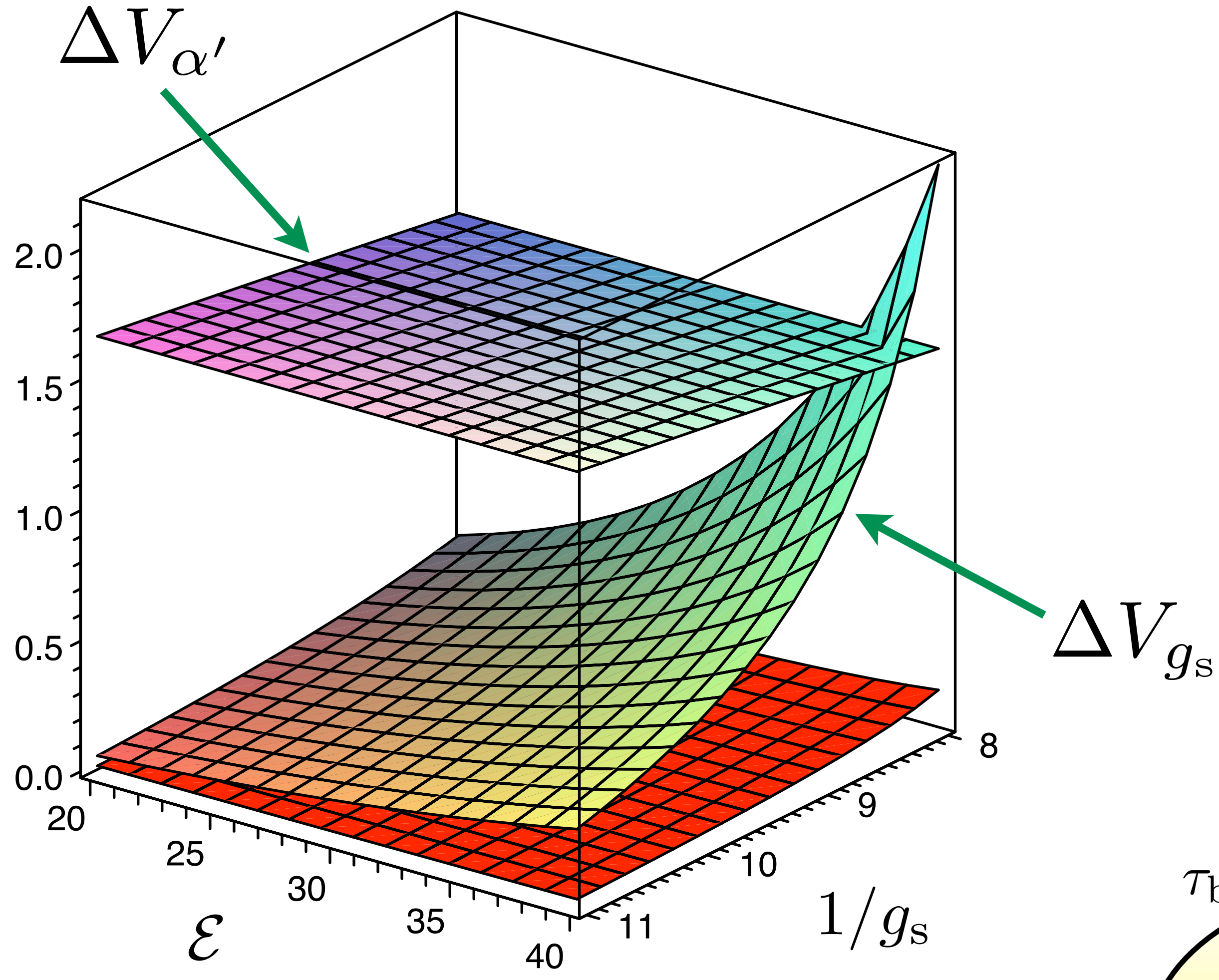


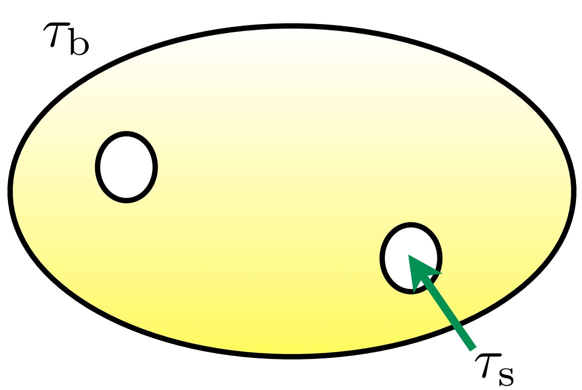
"Kähler adapted vertex operators"

D-Brane Corrections to Kähler potential

M.B., Haack, Körs, '05

use toroidal result for scaling estimates:





for "Swiss cheese" Calabi-Yaus, loop corrections negligible

...can we trust these estimates?

D-brane corrections in flux compactifications?

M.B., Haack, Körs '04
Giddings, Maharana '05
Baumann, Dymarsky, Klebanov, Maldacena, McAllister, Murugan '06

gauge coupling corrections ~ eigenfunction of Laplacian
– claim that this is **open/closed duality**

- generalize to warped deformed conifold (!) with general holomorphic D7-brane embedding specified by integers p_i

$$A = A_0 \left(\frac{\mu^P - \prod_{i=1}^4 w_i^{p_i}}{\mu^P} \right)^{1/N_{\mathrm{D7}}} \qquad P = \sum_{i=1}^{4} p_i$$

D-brane corrections in flux compactifications?

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gauge coupling corrections ~ eigenfunction of Laplacian
– claim that this is **open/closed duality**

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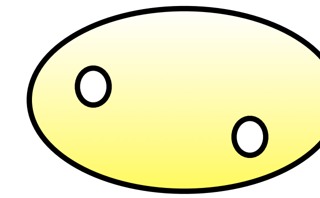
much work left to do!

Summary



- Variants of KKLT can be surprisingly controllable
- Checks must be performed – whole classes can disappear
- Existing results, if correct, are potentially interesting for LHC counting signatures and SUSY dark matter
- With more details, would be more interesting...
- Development about loop corrections in very general backgrounds interesting in its own right

Outlook

..., Dine, Seiberg, Thomas '07
Randall '07

- What about nonrenormalizable operators? "BMSSM"?
- What about LVS for other Calabi-Yaus?
- Check "Green's function method" in simpler (!) cases
- Cosmology very interesting but even trickier
    - brane inflation (time-dependence?)
    - dark energy? (need uplift details...)