Sequestered Dark Matter

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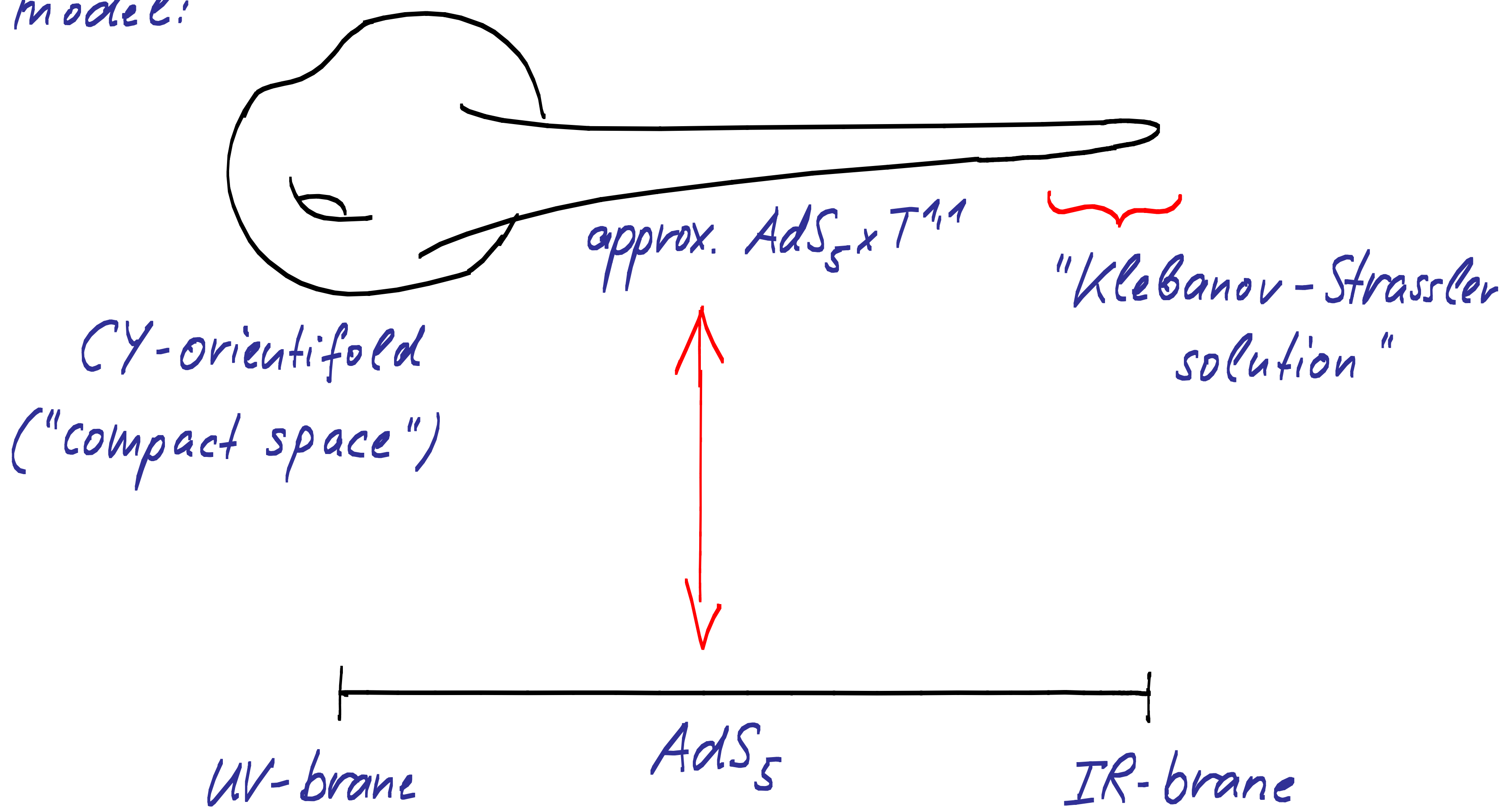
Outline

- Motivation of throats in the type IIB landscape
- Energy transfer to throats ($\equiv$ sequestered sectors)
- Energy density evolution in the throat
- Relics in the throat and their decay to the SM
- Dark matter abundance and detection via decays

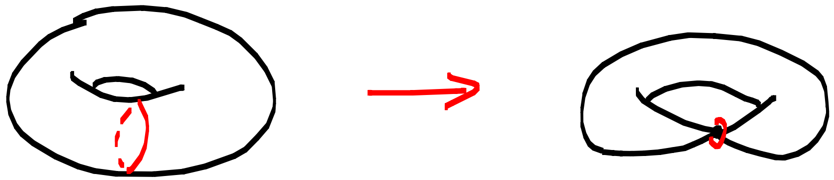
Introduction

Klebanov-Strassler Throat as a "stringy" version of the RS model:



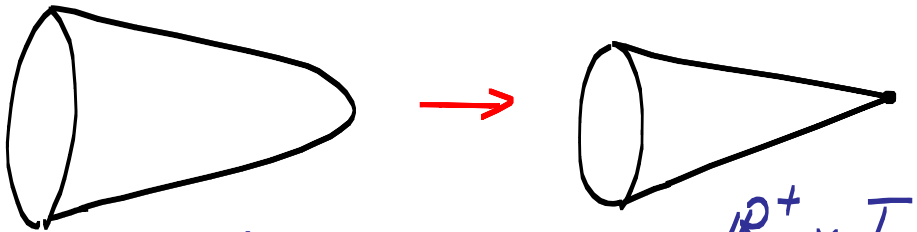
Why should we care about such special solutions?

- Moduli space of CY has many points where singularities develop:



(shrinking cycle)

- A generic shrinking 3-cycle produces a conifold singularity:

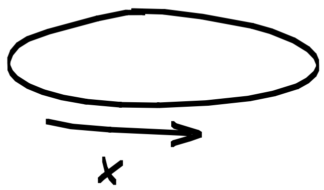


approximate $\mathbb{R}^+ \times T^{1,1}$

$\mathbb{R}^+ \times \underbrace{T^{1,1}}_{\sim S^3 \times S^2}$

Recall the general idea of flux on a cycle:

- consider S^1-cycle with some field theory on it:



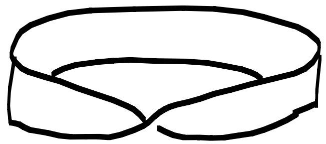
field: $\varphi(x)$

- introduce boundary conditions excluding $\varphi(x) \equiv 0$:

$$\varphi(x+2\pi) = \varphi(x) + c$$

$\Rightarrow$ gradient energy is enforced by geometry

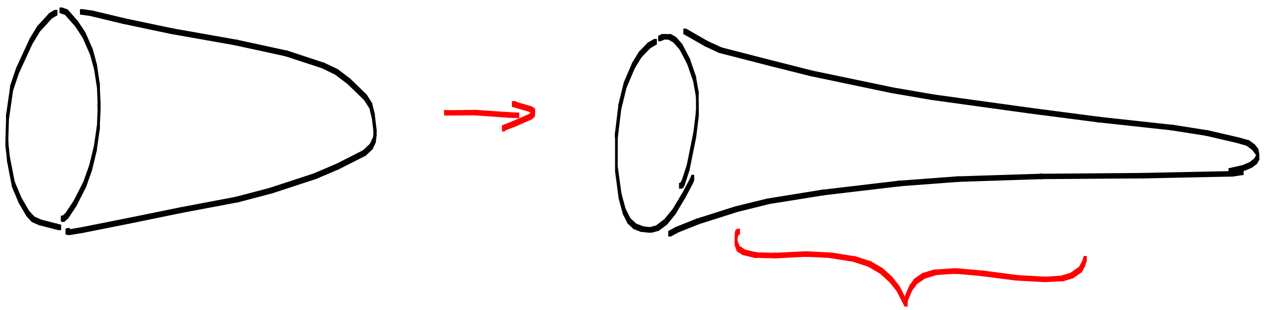
intuitive picture: Möbius strip



($\varphi(x)$ is encoded in angular position of the band)

- Let all 3-cycles carry flux
- Let the "conifold 3-cycle" carry a small flux number

$\Rightarrow$ This cycle shrinks to almost zero size ;
We arrive at the throat geometry :



This geometry is a result of the backreaction of fluxes.

(The accumulation of flux vacua near conifold points, implying throat geometries, has been discussed, e.g., by Denef/Douglas, '04.)

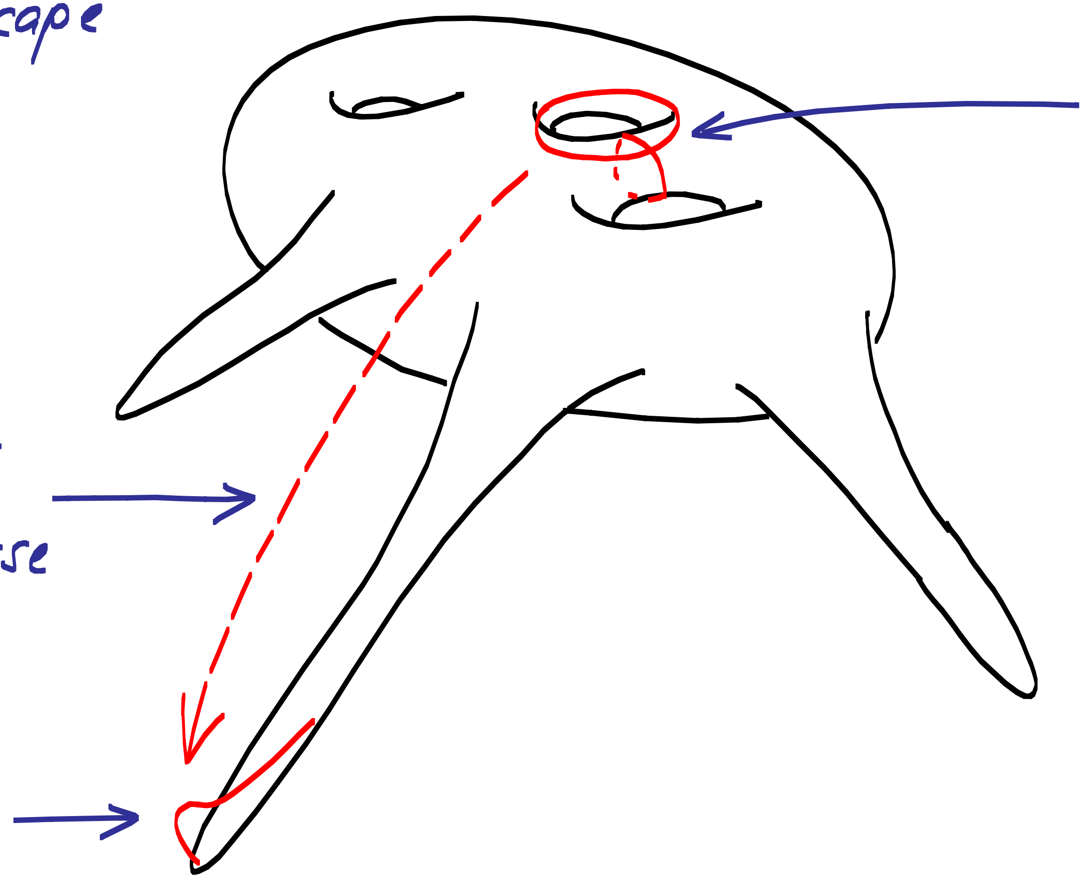
The ubiquity of throats in the type IIB landscape can be further quantified: (A.H., J. March-Russell, '06)

- fine-tuning of Λ in flux discretuum needs many 3-cycles
- probability for some of these cycles to carry small flux ("by chance") is large $\Rightarrow$ expect many throats

More detailed analysis shows:

- 60 cycles ; $c = 3$ $\Rightarrow$ warp factors down to 10^{-3}
- 200 cycles ; $\underbrace{c = 1/3}_{\text{O(1)-number parameterizing our ignorance of generic CY moduli spaces}}$ $\Rightarrow$ warp factors down to 10^{-80} (+ many shorter throats)

⇒ the following situation may be a "prediction" of the landscape



SM sector realized by brane models

Energy transfer in early universe

Wave fcts. of light KK modes in throat

Energy transfer to the throat

very roughly: Throat $\hat{=}$ N D3-branes $\hat{=}$ $SU(N)$ gauge theory

$$\Rightarrow \quad \dot{\varsigma} \sim \frac{N_1^2 N_2^2}{M_{10}^{16}} \cdot \left(\frac{T^{13}}{A^8} + \frac{T^9}{L^{12}} \right)$$

(cf. Harling, Hebecker, Noguchi, '07)

↑ dominates for generic A

Our application: $N_1 \to g$ ($g \sim 100$ for SM)

$N_2 \to N$ (of $SU(N)$ of KS-Throat)

$$\Rightarrow \quad \dot{\varsigma} \sim g^2 N^2 \frac{T^9}{M_4^4}$$

(This energy is quickly transferred to $\underbrace{\text{lowest KK modes in throat}}_{\hat{=}\ \text{glueballs of mass } m_{IR}}$.)

- Energy transfer is dominated by period immediately after reheating:

total ρ: $\quad \rho \sim g^{1/2} N^2 \dfrac{T_{RH}^7}{M_4^3}$

Time evolution of energy density

1) $m_{IR} > T_{RH}$ – no energy deposition

2) $T_{RH} > m_{IR} > m_{IR,c}$ (The IR-scale for which the throat is heated precisely to its phase transition temperature.)

   - glueballs always non-relativistic; scaling: $\rho \sim a^3$

3) $m_{IR,c} > m_{IR}$

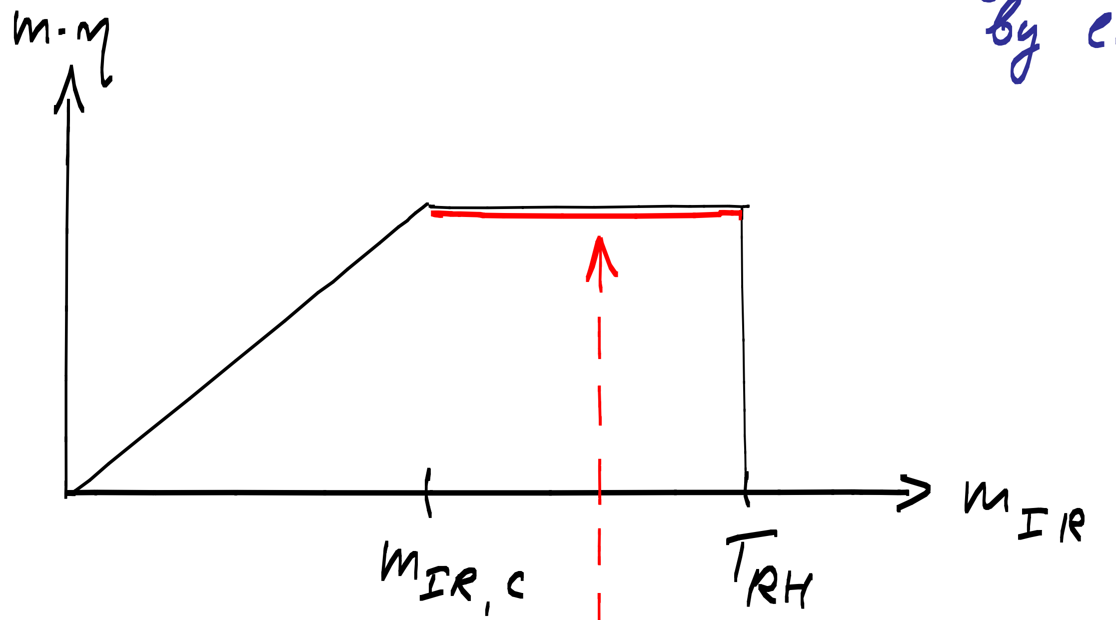
   - throat heated to deconfined phase
   - initial scaling: $\rho \sim a^4$; later on: $\rho \sim a^3$

Resulting "dark matter" density

- convenient quantity : $\frac{\rho}{s} = m \cdot \frac{n}{s} = m \cdot \underbrace{\eta}_{}$

glueball # density normalized by entropy density

$\Rightarrow$



This "maximal" glueball density can account for all dark matter if $T_{RH} \sim 10^{11}\,\mathrm{GeV}$ (for $N \sim 10$)

$$T_{RH} \sim 10^{11}\,\text{GeV} \quad \Rightarrow \quad m_{IR,c} \sim 10^{6}\,\text{GeV}$$

$\Rightarrow$ optimal DM-abundance for $\boxed{10^{6}\,\text{GeV} < m_{IR} < 10^{11}\,\text{GeV}}$

Decay processes in the throat

- The energy in the throat very quickly ends up in the lightest glueball states (which can not decay into each other)
- In most cases, this will be the lightest scalar glueball & its fermionic superpartner

(As we will see, this supersymmetric spectrum is crucial. This has not been considered in the previous analysis of Chen & Tye.)

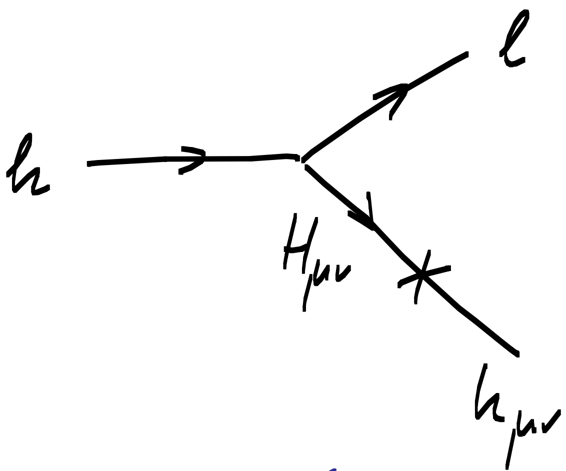
- The heavier glueball abundance is depleted by processes

$$\text{heavy} + \text{heavy} \longrightarrow \text{light} + \text{light}$$

(before these processes decouple)

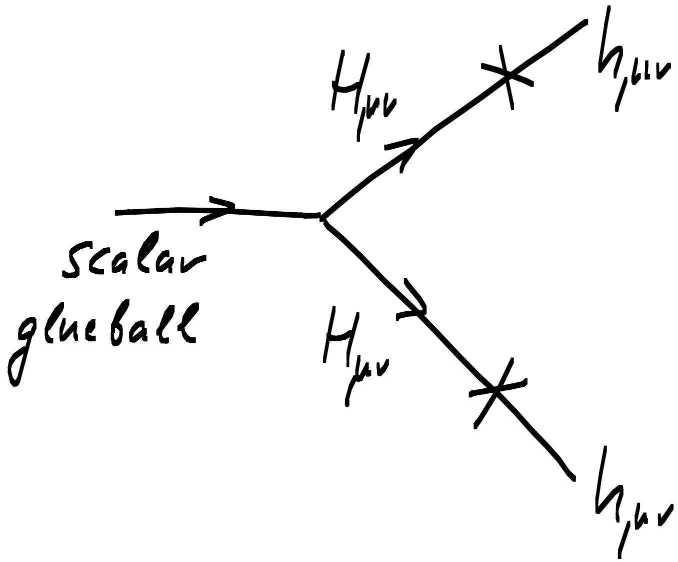
- The depletion factor is $\dfrac{n_h}{n_\ell} \sim \dfrac{H(T_{PT})}{m_{IR}} \sim \dfrac{g^{1/2} m_{IR} M_4^{1/2}}{N \cdot T_{RH}^{3/2}}$

- At later times, decays require emission of a graviton:



(4d graviton)

and



- The SUSY-analogues of these processes involve the gravitino as a decay product
(which is impossible for high-scale SUSY-breaking, which is our main focus)

$\Rightarrow$ The lightest fermionic glueball can be completely stable!

- The lightest bosonic glueball is not a suitable dark matter candidate since it decays to two gravitons with a lifetime

$$\tau \sim 10^{15}\,s \qquad (\text{for } m_{IR} \sim 10^6\,\text{GeV})$$

$$(\tau_{\text{universe}} \sim 10^{17}\,s)$$

However: If m_{IR} is slightly smaller, we may find

$$\tau \sim \tau_{universe},$$

with several interesting consequences:

- disappearing dark matter
- dark matter decaying to two photons (with fixed energy! clean signal!)

Nevertheless: The canonical outcome is a fermionic glueball as dark matter candidate

The generic decay rate to a different sector (such as the SM) can be calculated:

$$\Gamma \sim g\, N^2 \frac{m_{IR}^{\;9}}{M_{10}^{\;8}}$$

<u>However:</u> specifically for the SM, one faces the problem that there are no uncharged light fermions (assuming high-scale SUSY breaking)

- There is one operator which can induce decays of fermionic glueballs to the SM: $\boxed{\lambda \, \bar{\ell}_{\text{lepton doublet}} \, \underbrace{\psi}_{\text{modulino (e.g. dilatino)}} \, \underbrace{H}_{\text{Higgs doublet}}}$

- The coupling λ can be $O(1)$ or $\sim m/M_4$ with some low mass scale m.

- From a SUSY-point-of-view, this violates R-parity (assuming the modulus to be uncharged under R-symmetry)

- The resulting decay rate is

$$\Gamma \sim \lambda^2 N^2 \frac{m_{IR}^7}{M_{10}^8 / M_4^2}$$

Dark matter detection

- For $m_{IR} \sim 10^6\,\mathrm{GeV}$ (the long optimal throat) we find

$$\tau \sim \left(\frac{M_{10}\,\lambda^{-1/4}}{2\cdot 10^{16}\,\mathrm{GeV}}\right)^8 \cdot \underbrace{10^{26}\,s}$$

for appropriate combinations of λ & M_{10}, detection is possible!

This is the lifetime limit from diffuse γ-rays based on EGRET

- If scalar glueballs survive, they may be discovered via $\gamma\gamma$-decay

$$\tau \sim \left(\frac{M_{10}}{3\cdot 10^{13}\,\mathrm{GeV}}\right)^8 \cdot 10^{26}\,s$$

- This EGRET / GLAST signal is not very impressive since it does not see the $\gamma\gamma$-line (the photons are strongly red-shifted)
- Seeing the line in decays happening today is, in principle, possible with HESS. However, the energy resolution is limited. The flux is

$$F \sim \underbrace{\left(\frac{10^5\,\text{GeV}}{\Delta E}\right)}_{\substack{\text{energy resolution}\\ \text{(main problem)}}}\left(\frac{10^6\,\text{GeV}}{m_{IR}}\right)\left(\frac{10^{26}\,\text{s}}{\tau}\right)\underbrace{10^{-12}\,(\text{m}^2\cdot\text{sr}\cdot\text{s}\cdot\text{GeV})^{-1}}_{\text{HESS background}}$$

For short optimal throats ($m_{IR} \sim 10^{11}$ GeV), only the fermionic glueballs are interesting.

The life time is
$$\tau \sim \left(\frac{M_{10}\, \lambda^{-1/4}}{5 \cdot 10^{20}\, \text{GeV}} \right)^8 \cdot 10^{27}\, s$$

(We need $\lambda \ll 1$ for a lifetime that avoids exclusion by EGRET.)

Many throats (statistics in the landscape)

Example 1: $c = 1$, 200 3-cycles, $M_{10} \sim 10^{14}$ GeV

(here we focus on long throats, since such throats are sufficiently frequent) specifically: $\bar{n}\left(5\cdot 10^5\,\mathrm{GeV} < m_{IR} < 5\cdot 10^6\,\mathrm{GeV}\right) \simeq 0.5$

expected # of throats

$\Rightarrow$ significant fraction of vacua has appropr. throat

<u>Example 2:</u> $c = 1$, 60 3-cycles, $M_{10} \sim 10^{18}\,\mathrm{GeV}$

$$\Rightarrow \quad \bar{n}\left(10^{10}\,\mathrm{GeV} < m_{IR} < 10^{11}\,\mathrm{GeV}\right) \simeq 0.3$$

(Note: In this case, the longer throats are improbable)

Comment on SUSY-Breaking in throat

$$\mathcal{L} = \int d^4\theta\, \varphi\bar{\varphi}\,\Omega + \left(\int d^2\theta\, \varphi^3 W + h.c.\right)$$

Sequestering: $\Omega = \Omega(X,\bar{X}) + \Omega(T,\bar{T})$

$$W = W(X) + W(T)$$

X: glueball superfield $\quad$ T: univ. Kähler modulus

Masses are governed by $\langle F_\varphi \rangle$ in

$$\mathcal{L} \supset \int d^4\theta\, \varphi\bar{\varphi}\, X\bar{X} + \left(\int d^2\theta\, m X^2 \varphi^3 + h.c.\right)$$

$\Rightarrow$ $m_{1,2}^2 = 4m^2 \pm 2m\,|\langle F_\varphi\rangle|$ (for scalar masses & $\langle F_\varphi\rangle \ll m$)

⇒ one scalar is lighter than its fermionic superpartner

Alternatively: $\langle F_\varphi \rangle \gg m$;

We can view this from the perspective of the limit $m \to 0$ (massless chiral superfield)

⇒ The fermion stays light after SUSY-breaking ; expect lightest fermionic glueball

(This is our "canonical" scenario.)

Summary

- Throat- or Sequestered Dark Matter is a likely possibility in the type IIB string theory landscape
- Discovery either via decay to "ℓH"

  (for fermionic glueball)

  or to $\gamma\gamma$

  (for bosonic glueball, if decay to $h_{\mu\nu} h_{\mu\nu}$ can be avoided)
- Many technical issues await better treatment:

  SUSY in throat; role of SUSY in mediating decays

  detection of narrow γ-line at high energies; ....