Throats, Compactifications and Dark Matter

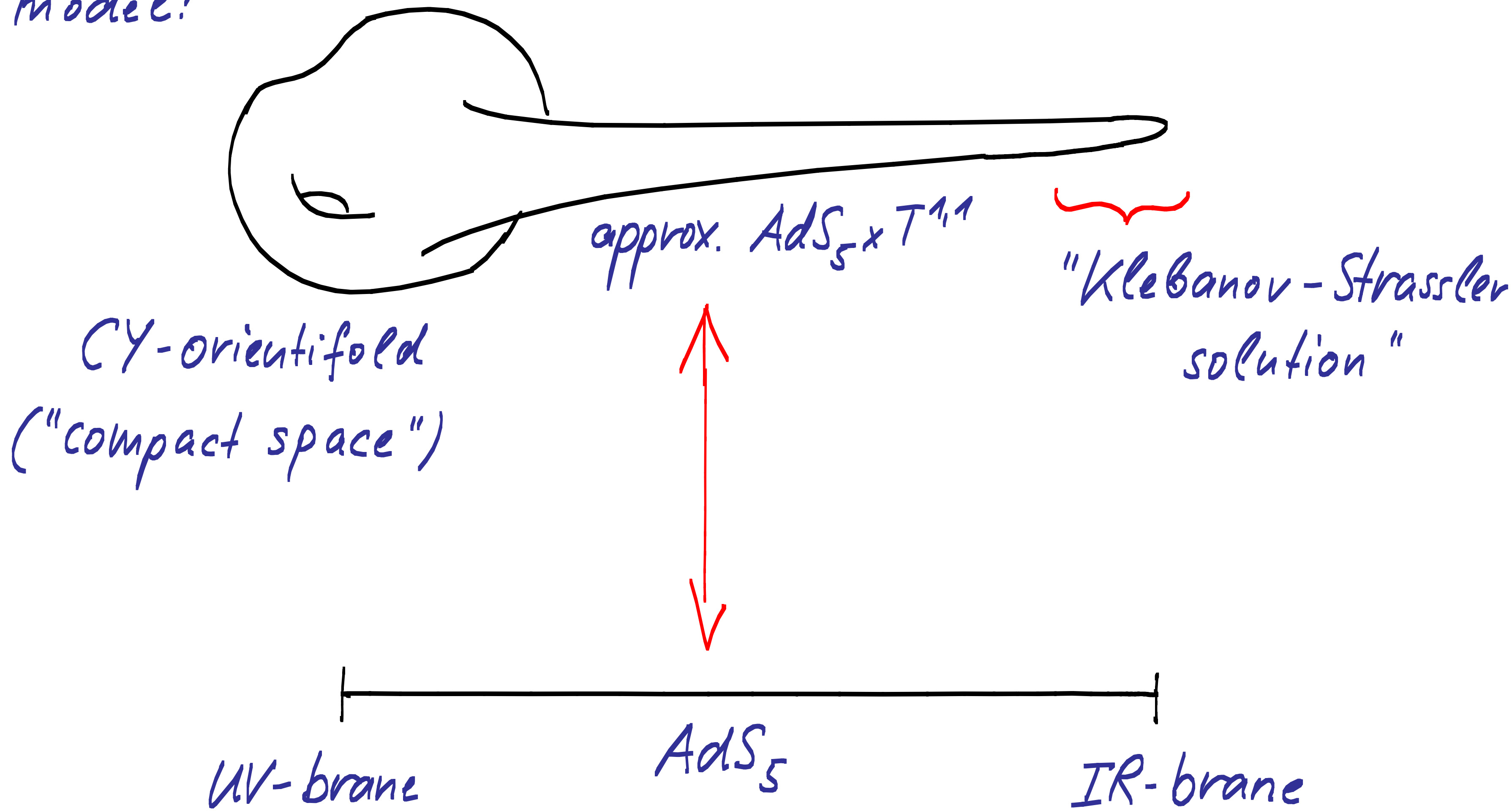
(in collaboration with Benedict von Harling)

Outline

- Motivation of throats in the type IIB landscape
- Energy transfer from heated Standard Model to throats ≡ 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

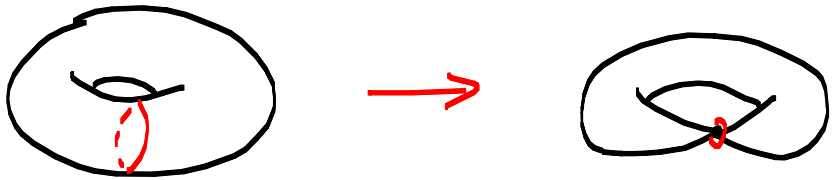
Introduction

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



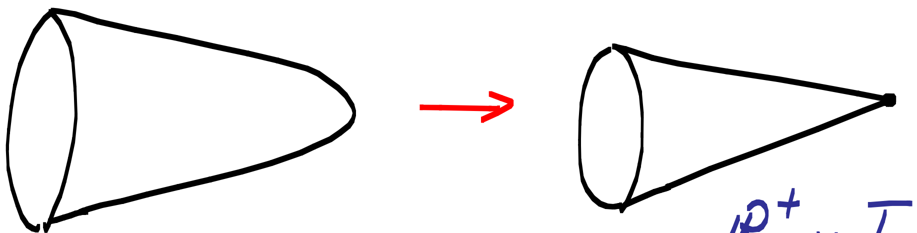
Why should we care about such special solutions?

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



(shrinking cycle)

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

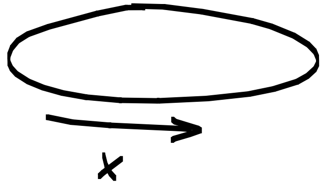


approximate $\mathbb{R}^+ \times T^{1,1}$

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

Recall the general idea of flux on a cycle:

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



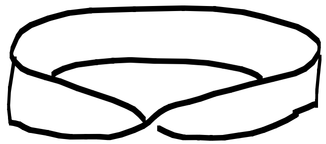
field: $\varphi(x)$

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

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

$\Rightarrow$ gradient energy is enforced by geometry

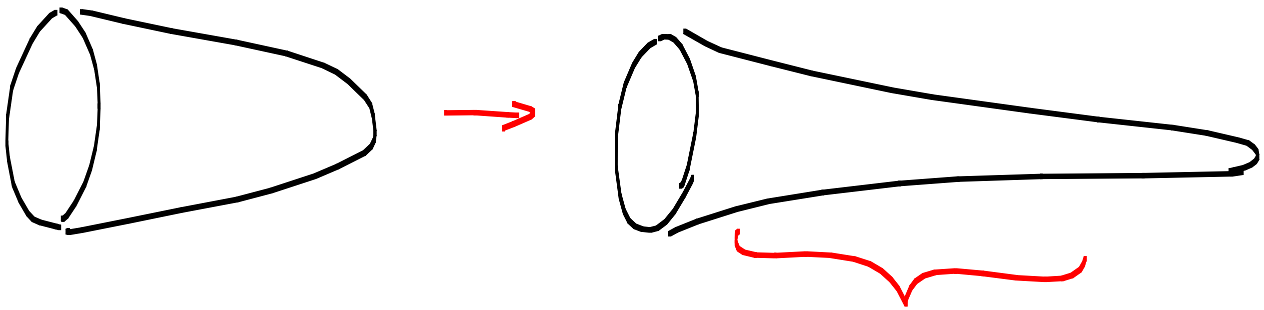
intuitive picture: Möbius strip



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

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

⇒ 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)

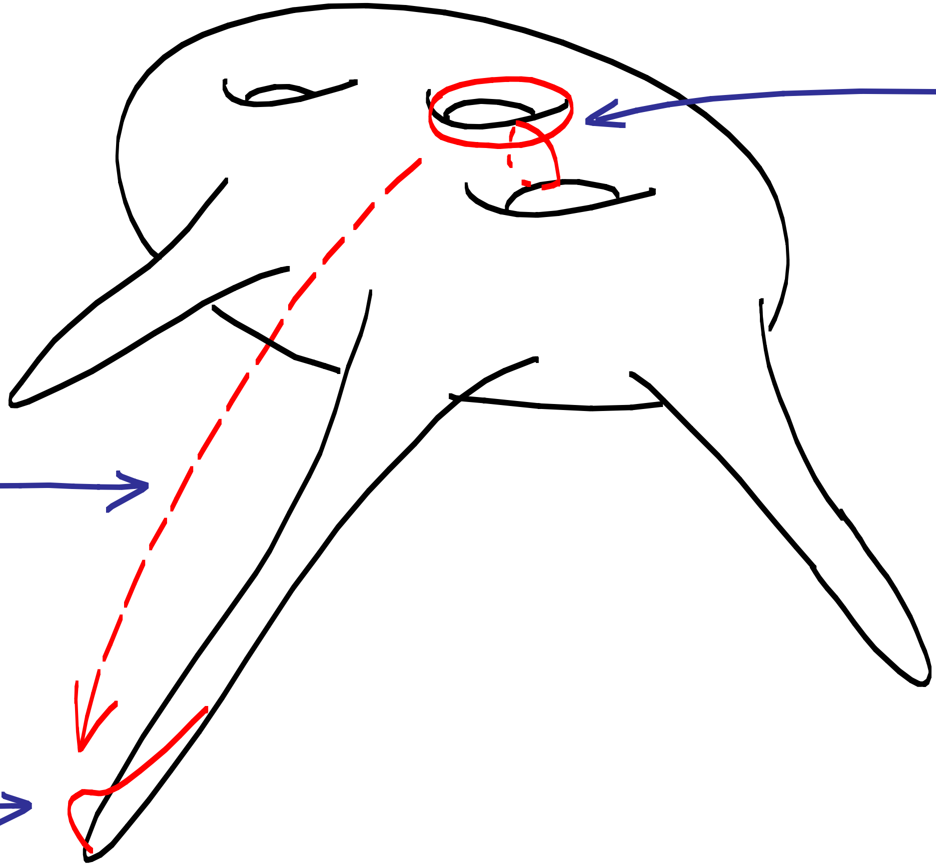
- fine-tuning of Λ in flux discretuum needs many 3-cycles
- probability for some of these cycles to carry small flux ("by chance") is large $\Rightarrow$ expect many throats

More detailed analysis shows:

- 60 cycles ; $c = 3$ $\Rightarrow$ warp factors down to 10^{-3}
- 200 cycles ; $c = 1/3$ $\Rightarrow$ warp factors down to 10^{-80} (+ many shorter throats)

$\mathcal{O}(1)$-number parameterizing our ignorance of generic CY moduli spaces

⇒ 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

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

(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)

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

(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:

<u>total ρ:</u> $\rho \sim g^{1/2} N^2 \frac{T_{RH}^7}{M_4^3}$

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

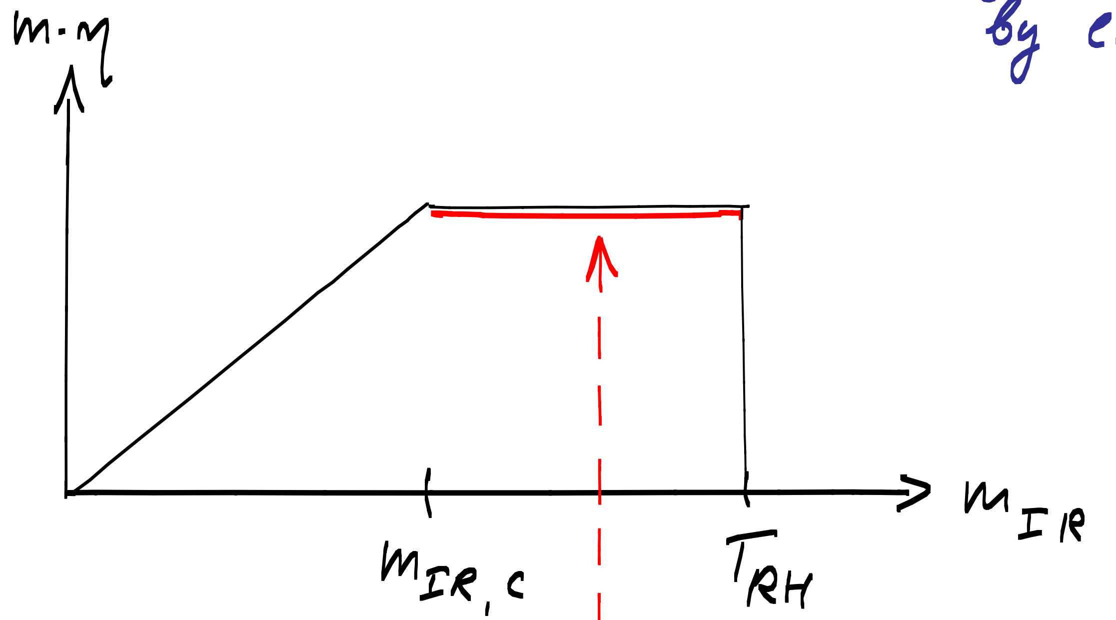
   - throat heated to deconfined phase
   - initial scaling: $\rho \sim a^4$; later on: $\rho \sim a^3$

Resulting "dark matter" density

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

glueball # density normalized by entropy density

$\Rightarrow$

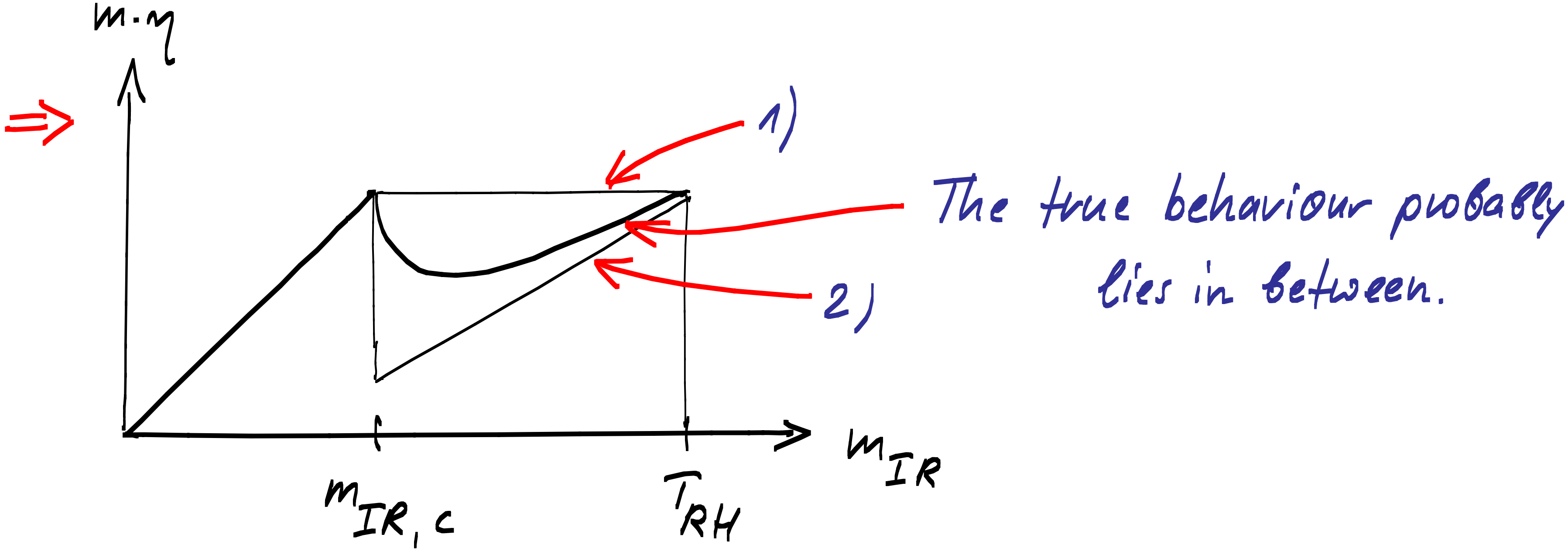


In deriving this line, we assumed non-relativistic glueballs in the confined phase. However, the original energy deposition is in portions $E > m_{IR}$. This may lead to relativistic glueballs.

Extreme case 1) Each energy injection $E \sim T_{RH}$ settles in large number of slow glueballs

Extreme case 2) Each energy injection $E \sim T_{RH}$ leads to an $O(1)$ number of fast glueballs (with energy $\sim T_{RH} \gg m_{IR}$)

$\Rightarrow$



These are the two "optimal" throat lengths.

To realize the observed DM-density in an optimal throat, we need

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

(The DM-particle mass is 10^{11} GeV or 10^{6} 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.)

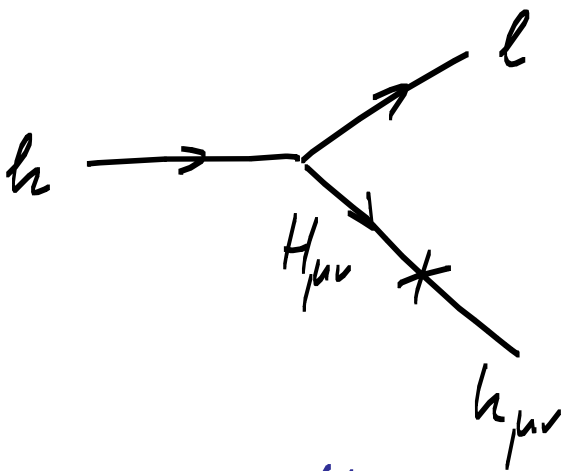
- The heavier glueball abundance is depleted by processes

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

(before these processes decouple)

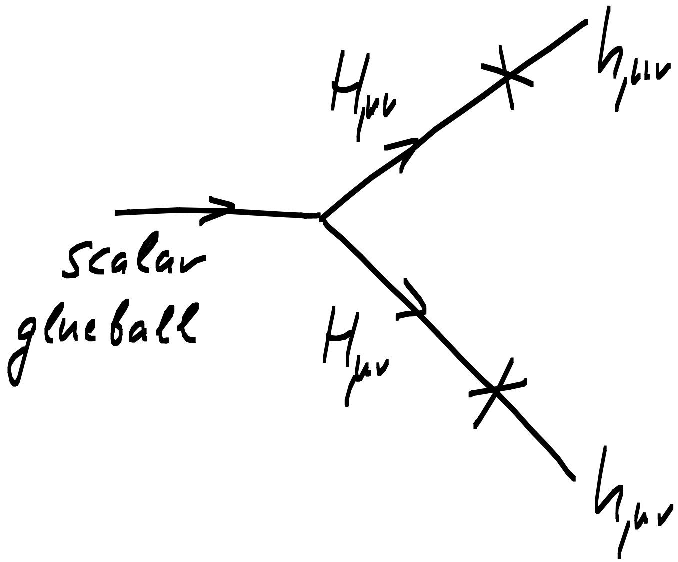
- The depletion factor is $\dfrac{n_h}{n_\ell} \sim \dfrac{H(T_{PT})}{m_{IR}} \sim g^{1/2} \dfrac{m_{IR} M_4^{1/2}}{N \cdot T_{RH}^{3/2}}$

- 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

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

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

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:

$$\boxed{\lambda\, \bar{\ell}\, \psi\, H}$$

lepton doublet

moduling (e.g. dilatino)

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

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

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

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

- 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 bad. The flux is

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

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

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

(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: $\bar{n}\,(5\cdot 10^5\,\mathrm{GeV} < m_{IR} < 5\cdot 10^6\,\mathrm{GeV}) \simeq 0.5$

expected # of throats

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

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

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

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

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

glueball superfield   univ. Kähler modulus

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

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

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

$\Rightarrow$ 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)

$\Rightarrow$ 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; energy evolution in KS-theory; detection of narrow γ-line at high energies; ....