Planck 2014, Paris, 29 May 2014

DARK RADIATION

IN GENERAL LARGE VOLUME SCENARIOS

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based on `arXiv:1403.6810` with
Arthur Hebecker, Patrick Mangat and Fabrizio Rompineve

MOTIVATION

- Dark Radiation (DR): Extra relativistic hidden species. Natural extension of LCDM.
- Typically parameterised by $\Delta N_{eff} = N_{eff} - 3.046$
- Experiment:

$$N_{eff} = 3.30^{+0.54}_{-0.51}$$ (95% CL, Pl+WP+high L+BAO)

$$N_{eff} = 3.52^{+0.48}_{-0.45}$$ (95% CL, Pl+WP+high L+BAO+H0)

$$\vdots$$

[Planck Collaboration 1303.5076]

- String Theory:
  In certain class of string models DR unavoidable
  $\Rightarrow$ DR can constrain / rule out string models

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I. String compactifications contain many scalars fields with gravitational-strength couplings (= moduli).

II. During inflation: scalars displaced from minimum.
After inflation: oscillate in potential as DM.

III. Matter scales as a^{-3}, radiation scales as a^{-4}.
Lightest scalar ϕ will dominate energy density.

IV. Decay of ϕ :
- reheat SM through decays $\phi \to visible$.
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Large Volume Scenario: ϕ typically volume saxion.

(see however S. Angus' talk)

IV. Decay of ϕ :

- reheat SM through decays $\phi \to visible$.
- If DR candidate present ϕ can also decay to DR.
  Large Volume Scenario: axion (ALP) as DR candidate.
  Get Cosmic Axion Background → axion-photon conversion in galaxy clusters.
  (see A. Powell's talk)

MOTIVATION: GENERATION OF DR

Lightest scalar ϕ

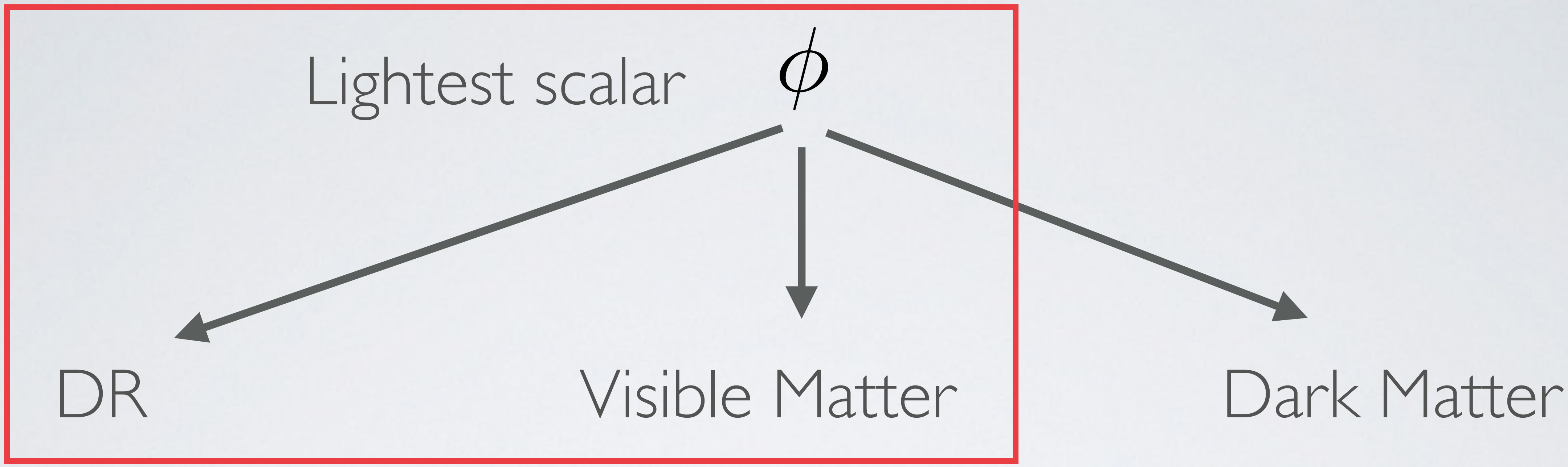
DR　　　Visible Matter　　　Dark Matter

DR prediction:

$$\Delta N_{eff} = \left.\frac{\rho_{DR}}{\rho_{\nu 1}}\right|_{\nu \text{ decoupling}} = \frac{43}{7}\left(\frac{10.75}{g_*(T_{RH})}\right)^{1/3} \left.\frac{\rho_{DR}}{\rho_{SM}}\right|_{T=T_{RH}}$$

$$= \frac{43}{7}\left(\frac{10.75}{g_*(T_{RH})}\right)^{1/3} \frac{\Gamma_{\phi\to DR}}{\Gamma_{\phi\to SM}}$$

MOTIVATION: GENERATION OF DR



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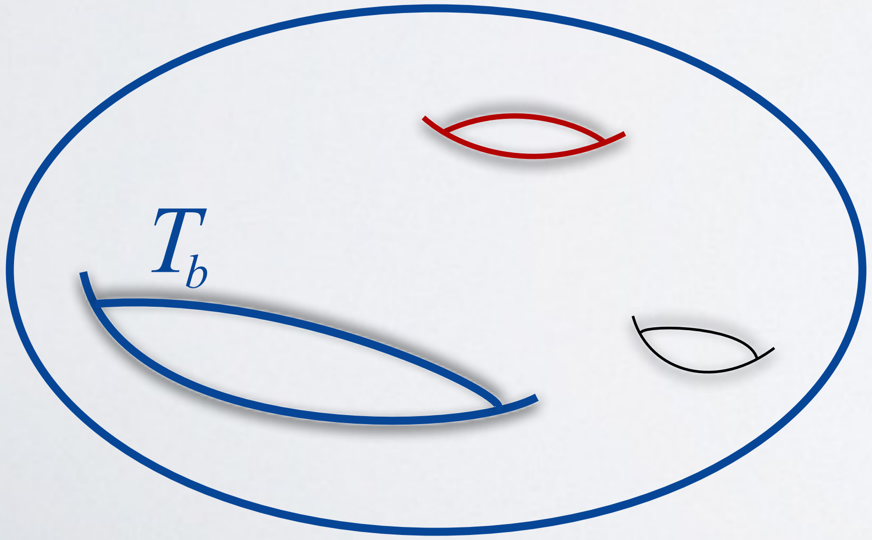
DR IN THE LVS

- Large Volume Scenario (LVS): scheme to stabilise Kähler moduli, and in particular volume of extra dimensions by perturbative and non-perturbative corrections.

Kähler moduli: complex scalars $T = \tau + ia$.

- τ parameterises volumes of internal 4-cycle.
- a is an axion-like particle (ALP).
- Have a shift-symmetry: $T \to T + i\epsilon$.



LVS:

- lightest modulus: τ_b
- DR candidate: a_b

$$m_{\tau_b} \sim \frac{M_{pl}}{\mathcal{V}^{3/2}} \qquad m_{a_b} \sim M_{pl}\, e^{-\mathcal{V}^{2/3}} \simeq 0$$

DR IN THE LVS

- Decays into DR: $K = -2\ln\mathcal{V} = -\ln(T_b + \bar{T}_b)^{3/2} + \ldots$

$$\boxed{\Rightarrow \Gamma_{\tau_b \to a_b a_b} = \frac{1}{48\pi}\,\frac{m_{\tau_b}^3}{M_{pl}^2}}$$

always present in LVS.

$$\Delta N_{eff} = \frac{43}{7}\left(\frac{10.75}{g_*(T_d)}\right)^{1/3} \frac{\boxed{\Gamma_{\tau_b \to DR}}}{\Gamma_{\tau_b \to vis}}$$

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So far:

Cicoli, Conlon, Quevedo	1208.3562;
Higaki, F. Takahashi	1208.3563;
Angus, Conlon, Haisch, Powell	1305.4128;
Higaki, Nakayama, F. Takahashi	1304.7987;
Allahverdi, Cicoli, Dutta, Sinha	1401.4364
Angus	1403.6473

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Here: how small can ΔN_{eff} be in LVS?

- Low ΔN_{eff} = high $\Gamma_{\tau_b \to vis}$
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DECAYS INTO ...

- Gauge bosons: $$\Gamma_{\tau\to AA} = \frac{N_g}{128\pi}\frac{|\partial_T f|^2}{(\mathrm{Re}\ f)^2 K_{T\bar{T}}}\frac{m_\tau^3}{M_{pl}^2}$$

- Higgs: from $$K \supset K_{H\bar{H}}(T_i,\bar{T}_i)\left[H_u\bar{H}_u + H_d\bar{H}_d + (zH_uH_d + \mathrm{c.c.})\right]$$

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- SM fermions: from $K \supset K_{i\bar{j}}C^i\bar{C}^{\bar{j}}$ get $\Gamma_{\tau\to f\bar{f}} \sim \dfrac{m_f^2\ m_\tau}{M_{pl}^2}$

- SUSY partners:

  SUSY scalars: $\Gamma_{\tau\to\tilde{q}\bar{\tilde{q}},\tilde{l}\bar{\tilde{l}}} \sim \dfrac{m_{soft}^2\ m_\tau}{M_{pl}^2}$

  gauginos, higgsinos: $\Gamma_{\tau\to\lambda\lambda,\tilde{h}\tilde{h}} \sim \dfrac{m_{\lambda,\tilde{h}}^2\ m_\tau}{M_{pl}^2}$

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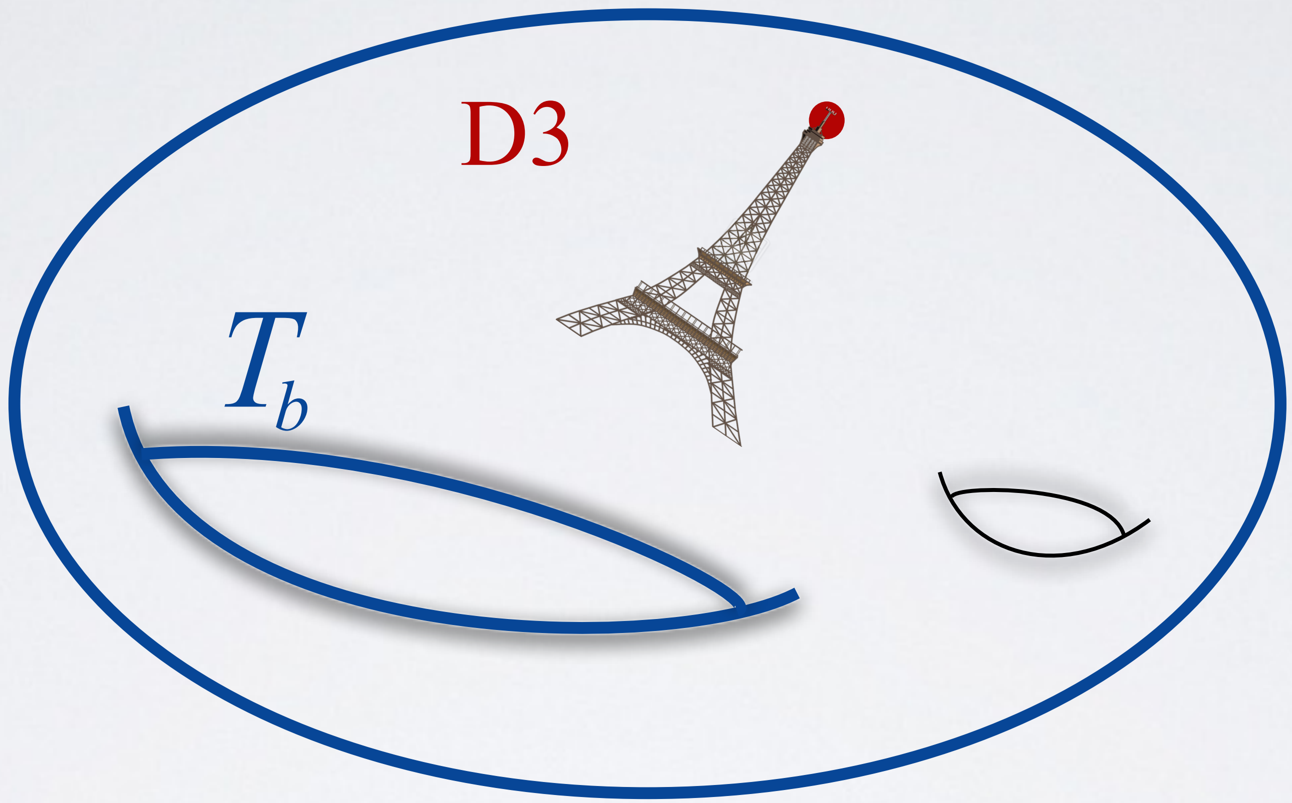
VISIBLE SECTOR ON D3-BRANES

D3-branes at singularity give chiral matter.



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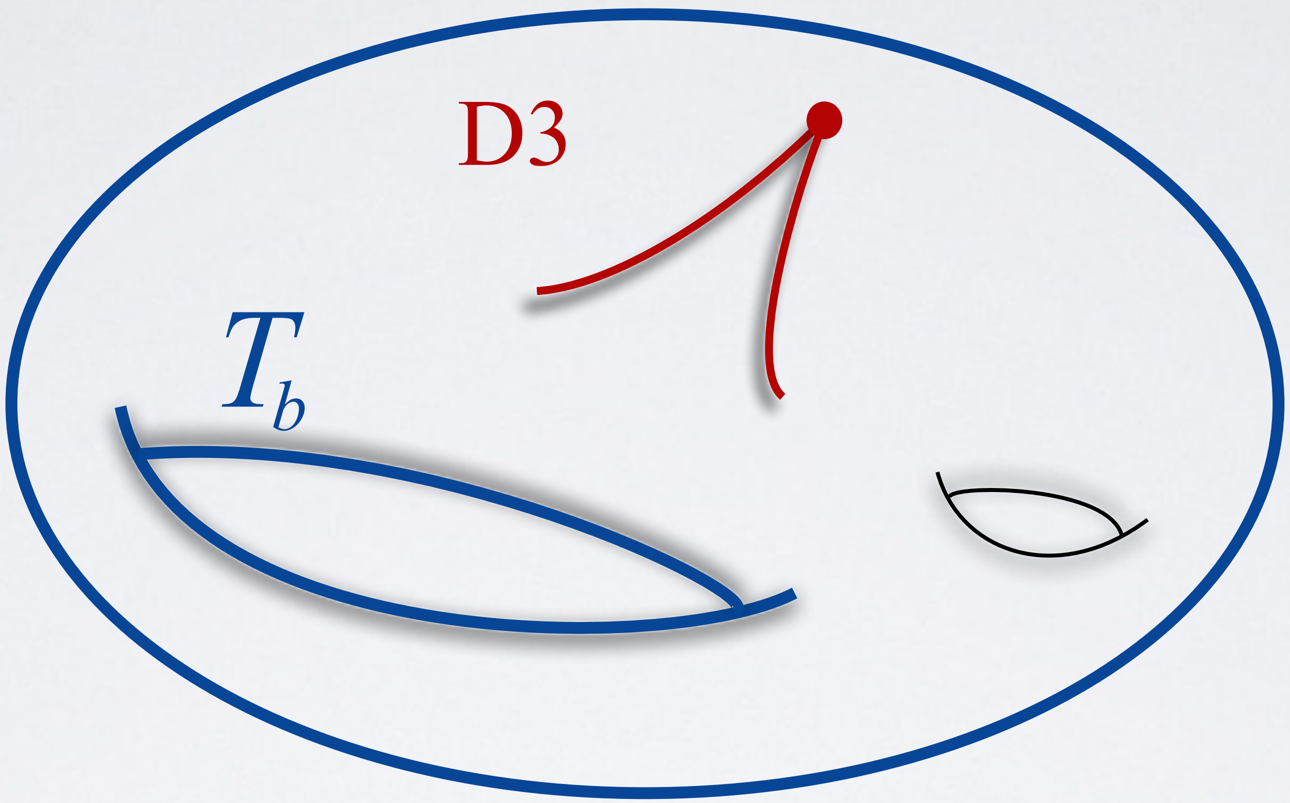

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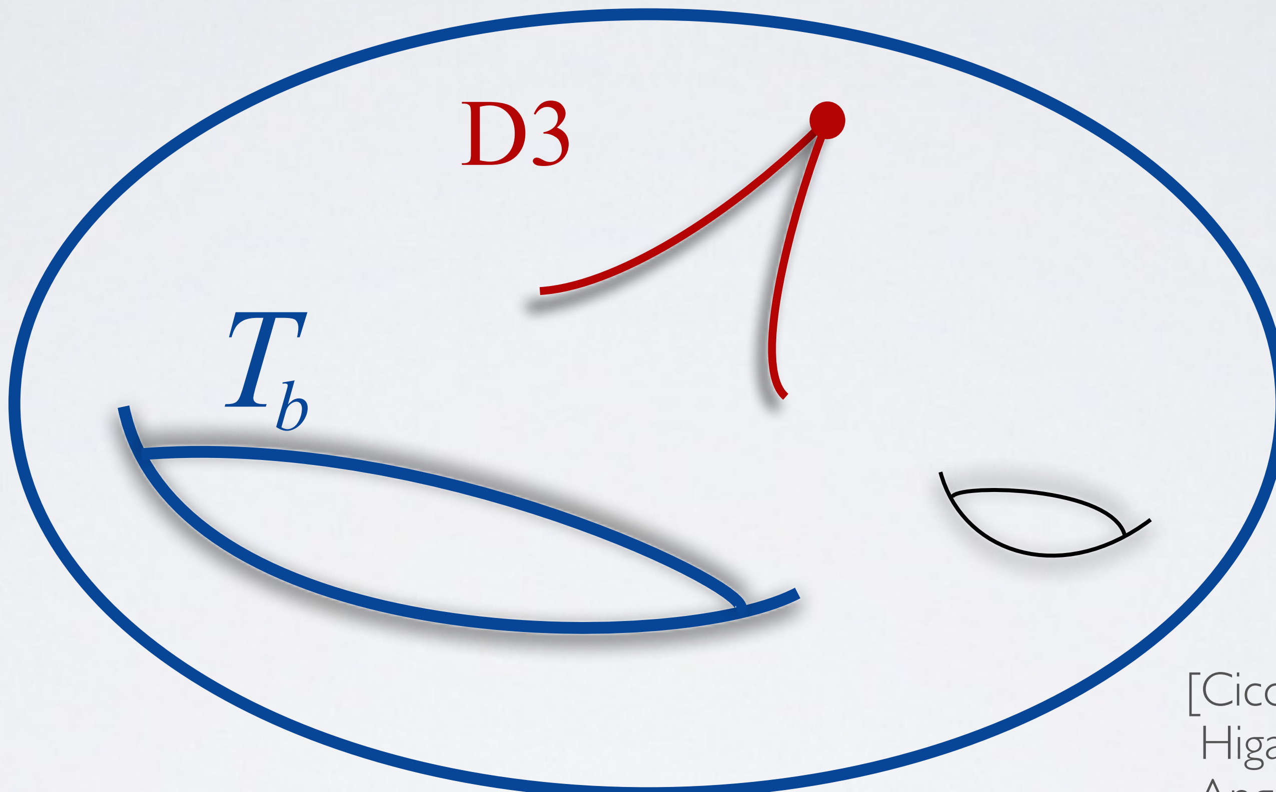

[Cicoli, Conlon, Quevedo 1208.3562;
Higaki, F. Takahashi 1208.3563;
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Lightest modulus: $\tau_b = \mathrm{Re}\, T_b$. DR candidate $a_b = \mathrm{Im}\, T_b$

- Gauge kinetic function $f_{D3} = S$ independent of T_b .

  No decays of τ_b into gauge bosons. Can we do better?

VISIBLE SECTOR ON D7-BRANES

D7-branes wrap 4-cycle associated with modulus T_{vis}.
Stabilise $\tau_{vis} = \mathrm{Re}\, T_{vis}$ in geometric regime by

- String loop-corrections:
  ALP $a_{vis} = \mathrm{Im}\, T_{vis}$ remains light $\longrightarrow$ more DR.
- Non-perturbative effects:
  Tension between n.p. effect and visible sector.
  DR overproduction slightly ameliorated w.r.t. above.
- D-terms:
  Lightest saxion can decay into both Higgs and gauge bosons.
  Study this case in more detail.

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$\longrightarrow$ Incompatible with TeV SUSY to avoid Cosmological Moduli Problem as $m_{soft} \sim M_{1/2} \sim A_{ijk} \sim m_{3/2}$.

VISIBLE SECTOR — D-TERM STABILISATION

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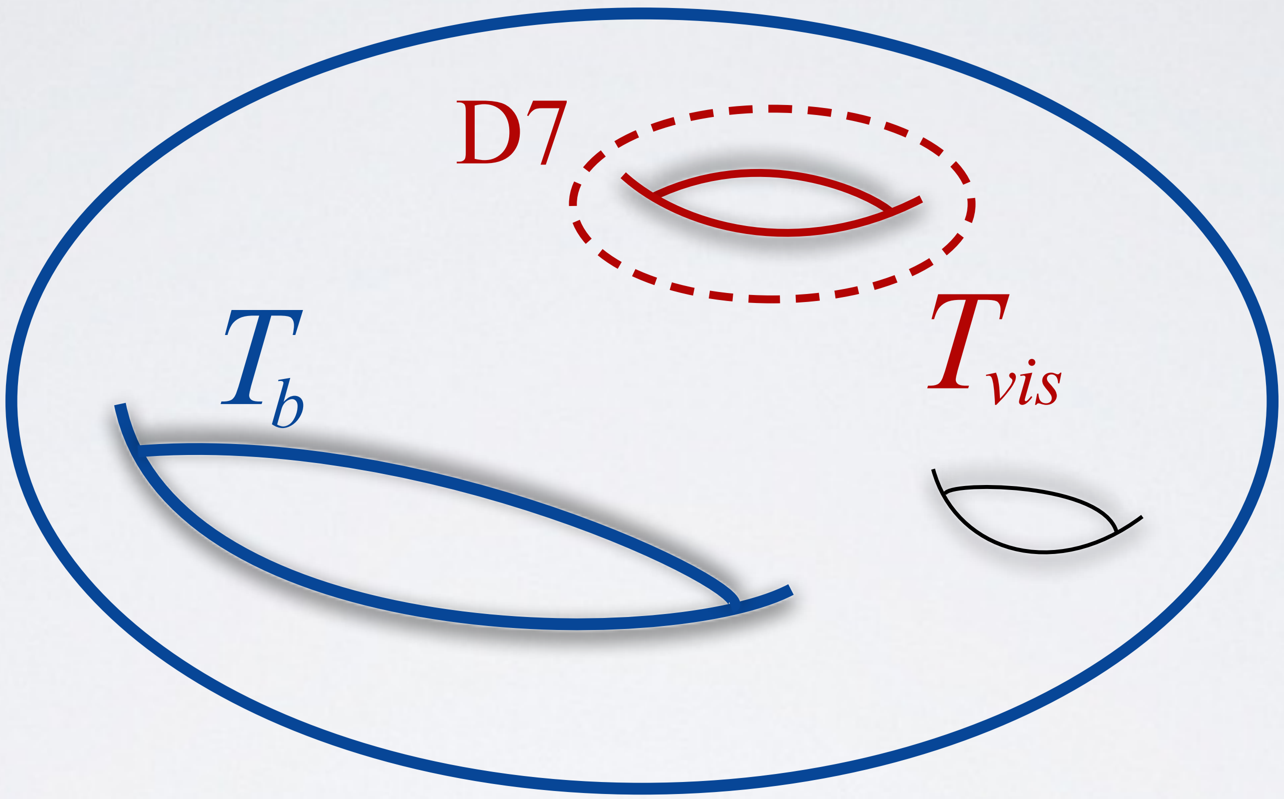

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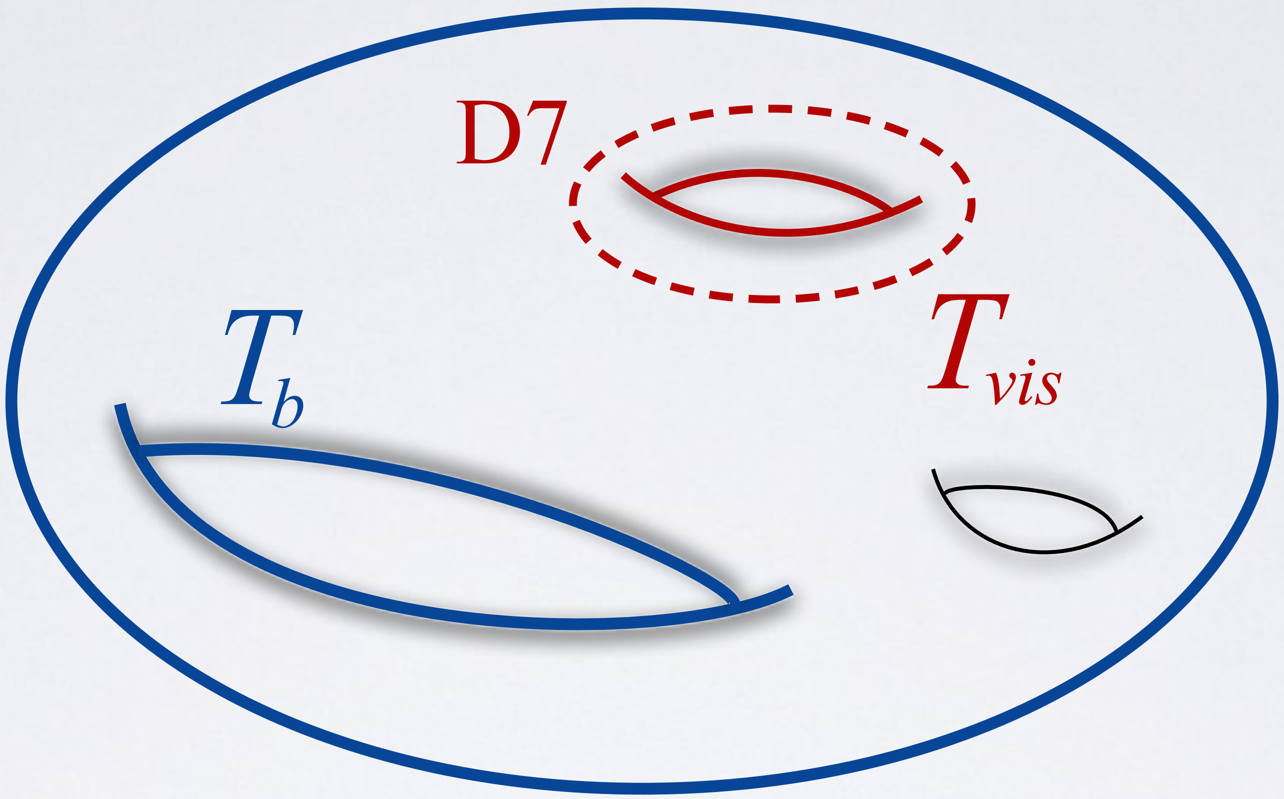

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- D-terms fix ratios of 2-cycles ⋯⋯▸ fix ratios of 4-cycles:

$$\Rightarrow T_{vis} = c\, T_b$$

VISIBLE SECTOR ON D7-BRANES

- gauge kinetic function: $$f_{vis} = T_{vis} + hS = cT_b + hS$$
- Higgs Kähler metric: $$K_{H\bar{H}} = \frac{\left(T_{vis} + \bar{T}_{vis}\right)^{1/2}}{T_b + \bar{T}_b} = \frac{1}{\left(T_b + \bar{T}_b\right)^{1/2}}$$
- After integrating out T_{vis}: $$\mathcal{V} = \alpha(T_b + \bar{T}_b)^{3/2} - \gamma_i(T_{s_i} + \bar{T}_{s_i})^{3/2}$$

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Dominant decay rates:

Decays into DR: $$\Gamma_{\tau_b \to a_b a_b} = \frac{1}{48\pi} \frac{m_{\tau_b}^3}{M_P^2} \,,$$

Decays into SM: $$\Gamma_{\tau_b \to hh} = \frac{z^2}{96\pi} \frac{\sin^2(2\beta)}{2} \frac{m_{\tau_b}^3}{M_P^2} \,,$$

$$\gamma \equiv \frac{\tau_{vis}}{\tau_{vis} + h \, \mathrm{Re}(S)}$$

$$\Gamma_{\tau_b \to AA} = \frac{N_g}{96\pi} \gamma^2 \frac{m_{\tau_b}^3}{M_P^2}$$

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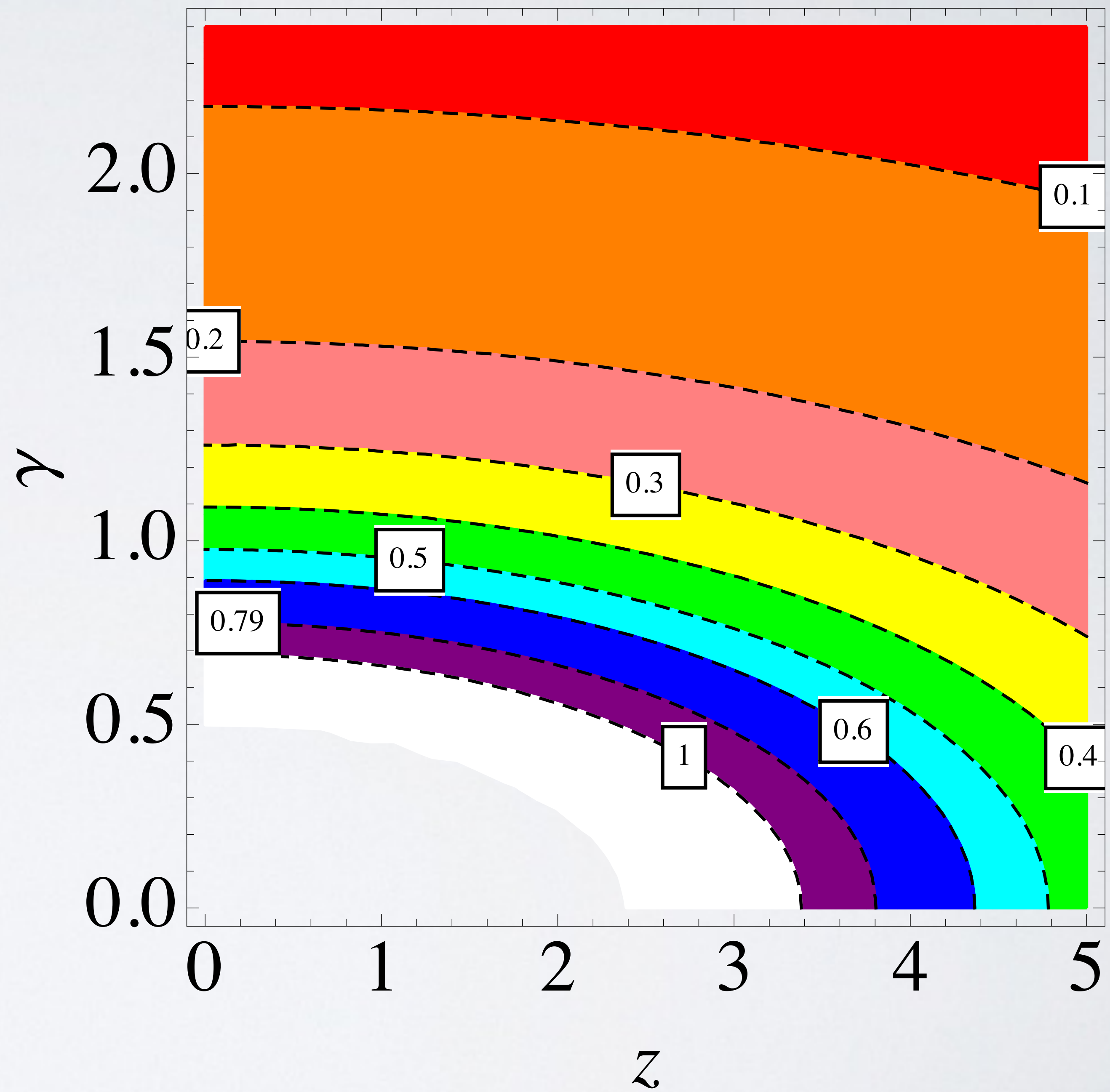
Contour plot of ΔN_{eff}



CONCLUSION

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2. Limits on ΔN_{eff} can be used to rule out many realisations of visible sectors in LVS setups.

3. Current limits on ΔN_{eff} can be satisfied with minimal matter content (MSSM) and for "natural" values of parameters. Incompatible with TeV SUSY.

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Merci beaucoup!