High-Scale Supersymmetry from Flux Compactification

Wilfried Buchmüller
DESY, Hamburg

Planck Conference, Warsaw, May 2017

UV Completion of the Standard Model

- Structure of Standard Model points towards "grand unification" of strong and electroweak interactions (quark and lepton content, gauge group, "unification" of gauge couplings, small neutrino masses ...)

- Strong theoretical arguments for supersymmetry at "high" energy scales (gravity, extra dimensions, string theory)

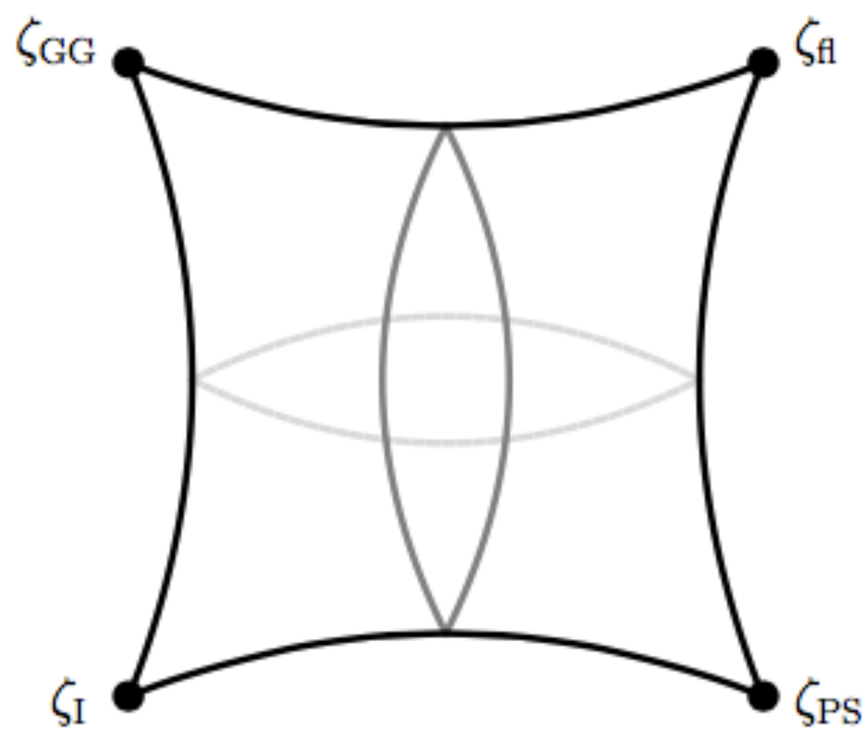
- Energy scale of grand unification: $\Lambda_{\mathrm{GUT}} \simeq 10^{15} \ldots 10^{16}\ \mathrm{GeV}$
  energy scale of supersymmetry breaking: $\Lambda_{\mathrm{SB}} \simeq$??

- This talk: 6d supergravity GUTs, $\Lambda_{\mathrm{SB}} \sim R_c^{-1} \sim \Lambda_{\mathrm{GUT}}$

Split symmetries

WB, Dierigl, Ruehle, Schweizer '15, '16

Consider SO(10) GUT group in 6d, broken at orbifold fixed points to standard SU(5)xU(1), Pati-Salam SU(4)xSU(2)xSU(2) and flipped SU(5)xU(1), with SM group as intersection; bulk fields 45, 16, 16*, 10's [Asaka, WB, Covi '02; Hall, Nomura et al '02; ...]; full 6d gauge symmetry:



$$SO(10) \times U(1)_A$$

N 16's from charged bulk 16-plet and N flux quanta:

$$\mathbf{16}\ [SO(10)] \sim \mathbf{5}^* + \mathbf{10} + \mathbf{1}\ [SU(5)] \sim \mathbf{q}, \mathbf{l}, \mathbf{u^c}, \mathbf{e^c}, \mathbf{d^c}, \nu^\mathbf{c}\ [G_{\rm SM}]$$

Higgs fields from uncharged bulk 10-plets, form split multiplets:

$$H_1 \supset H_u\,, \quad H_2 \supset H_d\,, \quad \Psi \supset D^c, N^c\,, \quad \Psi^c \supset D, N$$

Flux **breaks supersymmetry** [Bachas '95], soft SUSY breaking only for quark-lepton families:

$$M^2 = m_{\tilde{q}}^2 = m_{\tilde{l}}^2 = \frac{4\pi N}{V_2} \sim (10^{15}\ \mathrm{GeV})^2$$

$$m_{3/2} \sim 10^{14}\ \mathrm{GeV}\,, \quad m_{\tilde{q}}^2 = m_{\tilde{l}}^2 > m_{3/2} \sim m_{1/2} \gg m_{\tilde{h}}$$

Emerging picture of **Split Symmetries** (reminiscent of "split/spread SUSY" [Arkani-Hamed, Dimopoulos; Giudice, Romanino '04; Hall, Nomura '11]):

- supersymmetry breaking is large for scalar quarks and leptons *because* they form *complete* GUT multiplets

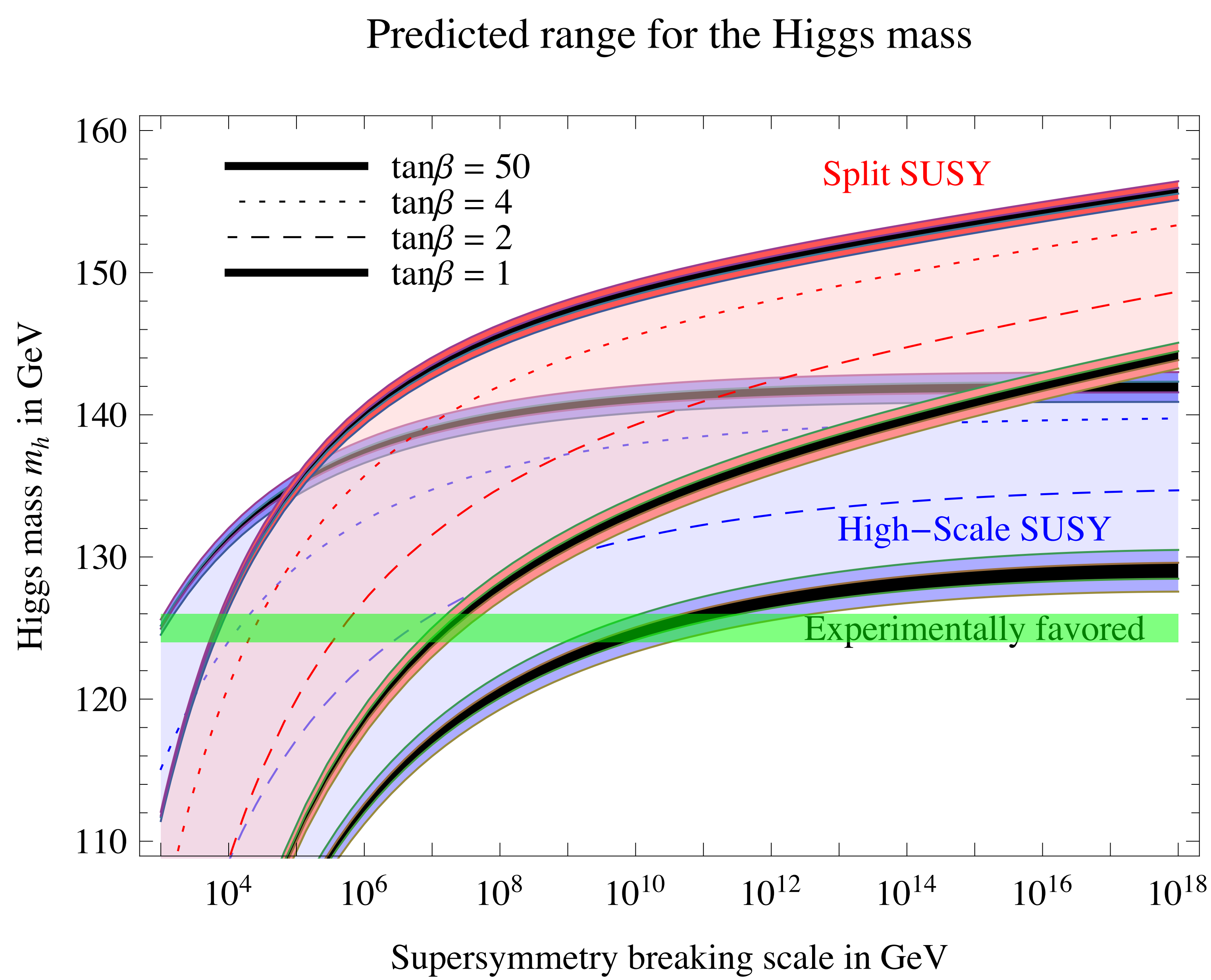
- supersymmetry breaking can be small for gauge and Higgs fields *because* they form *incomplete* GUT multiplets (THDM)

[Supersymmetry preserving flux compactifications -> talk by Hiroyuki Abe]

Can GUT-scale SUSY breaking be viable?

- Is a matching of THDMs to SUSY at GUT scale consistent with RG running and vacuum stability? What can we hope for at LHC?
- Can all moduli be stabilized (D-term breaking, F-term breaking ...) with de Sitter (Minkowski) vacua?
- How do **quantum corrections** change the tree-level picture? (hope: magnetic flux -> talk by Emilian Dudas)
- Can the 6d SO(10)xU(1) SUGRA models be embedded into string theory?

Extrapolation of Standard Model



[Degrassi et al '12]

Matching of SM Higgs coupling to MSSM at SUSY breaking scale for \`Split SUSY' (one Higgs doublet, higgsinos and gauginos light) and \`High-scale SUSY' (one Higgs doublet light). Strong upper bounds on SUSY breaking scale!

Extrapolating the THDM to the GUT scale

Bagnaschi, Brummer, WB, Voigt, Weiglein '15

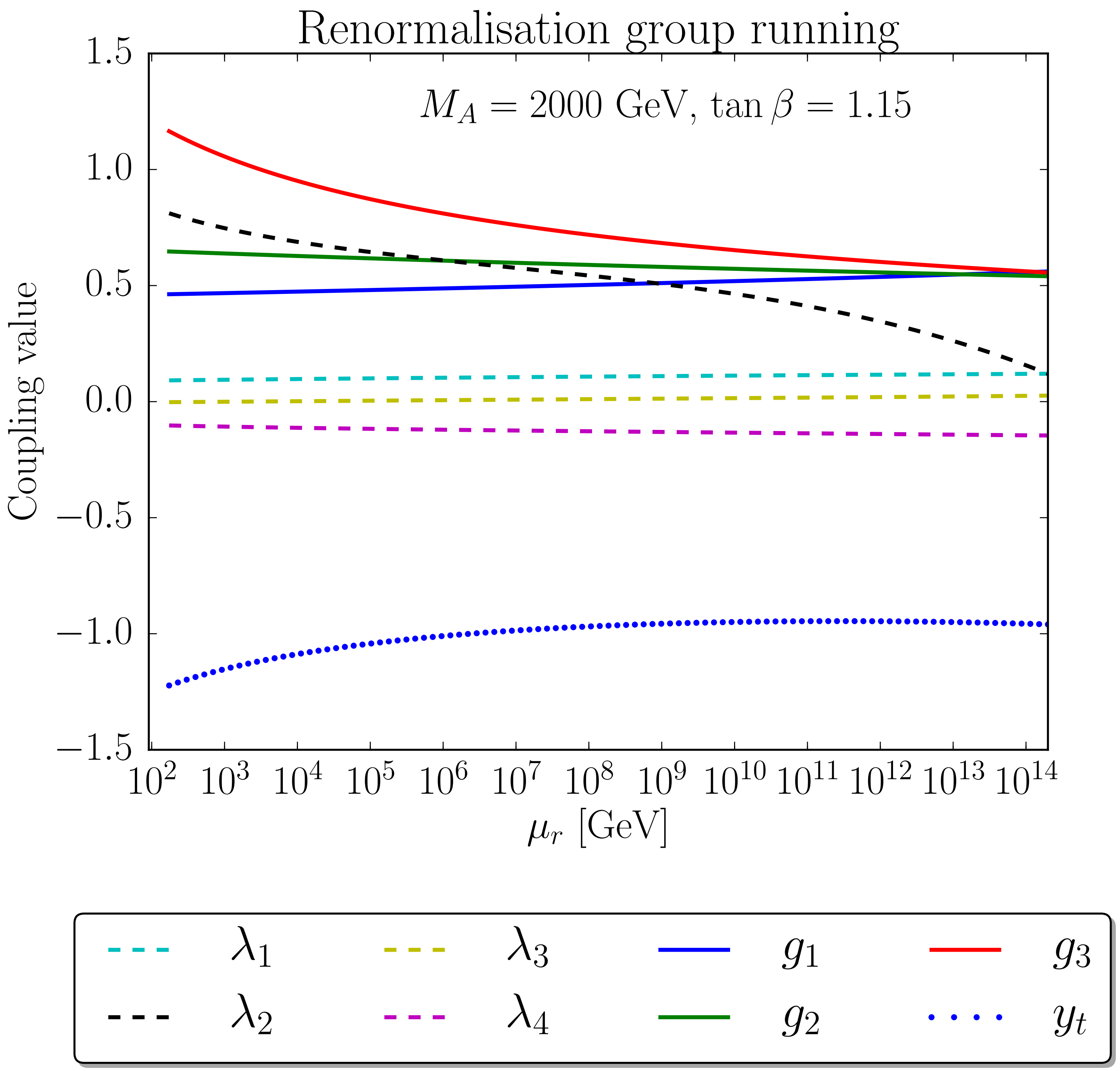
Is SUSY breaking at the GUT scale consistent with RG running of couplings and vacuum stability? 6d GUT model yields THDM (tree level), study RG running [Gunion, Haber '03... Lee, Wagner '15]):

$$V = m_1^2\, H_1^\dagger H_1 + m_2^2\, H_2^\dagger H_2 - \left(m_{12}^2\, H_1^\dagger H_2 + \text{h.c.}\right) + V_4\,,$$

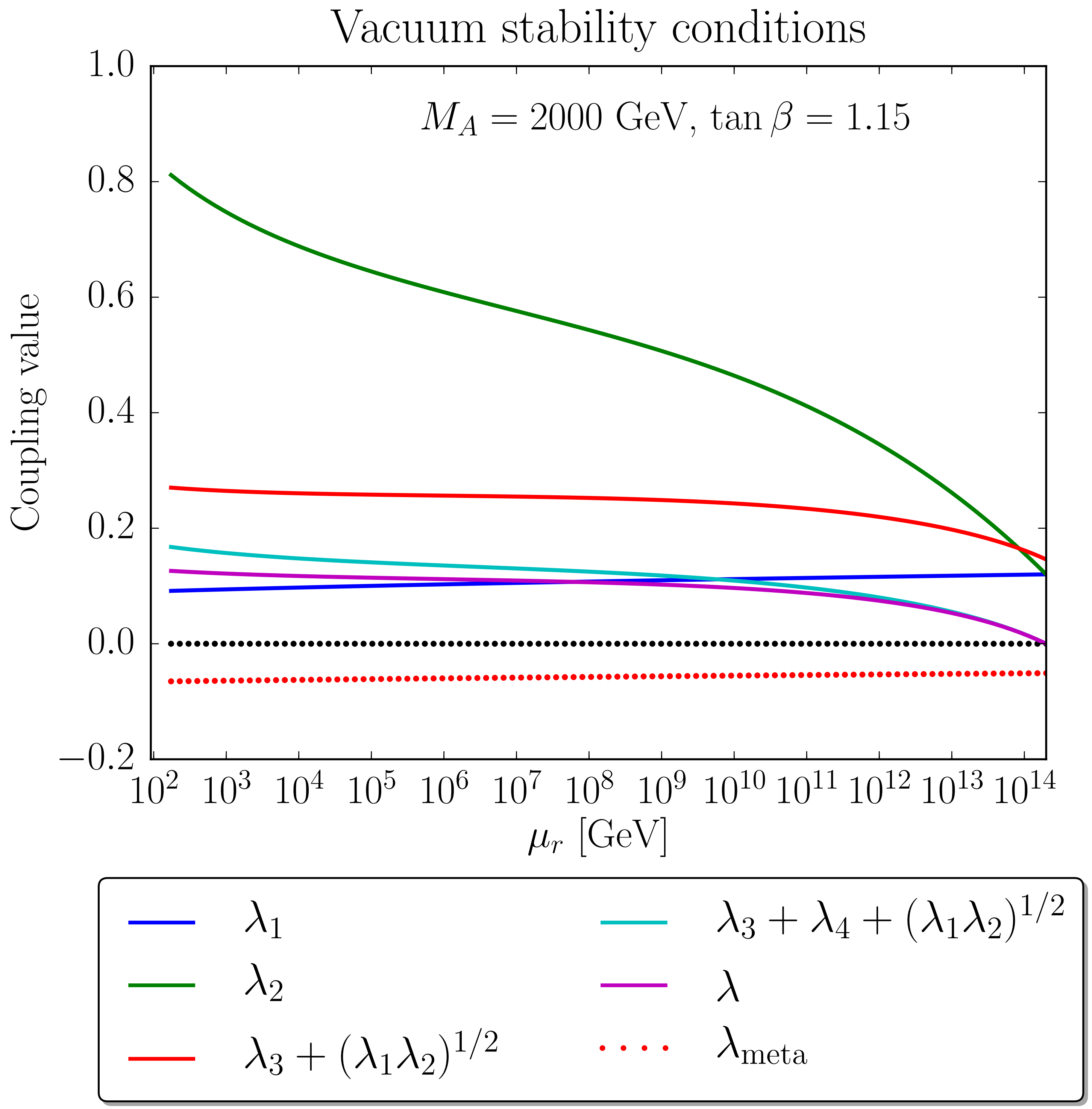
$$V_4 = \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4|H_1^\dagger H_2|^2$$
$$+ \left(\frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \lambda_6(H_1^\dagger H_2)(H_1^\dagger H_1) + \lambda_7(H_1^\dagger H_2)(H_2^\dagger H_2) + \text{h.c.}\right)$$

Matching conditions at SUSY breaking scale determine quartic couplings:

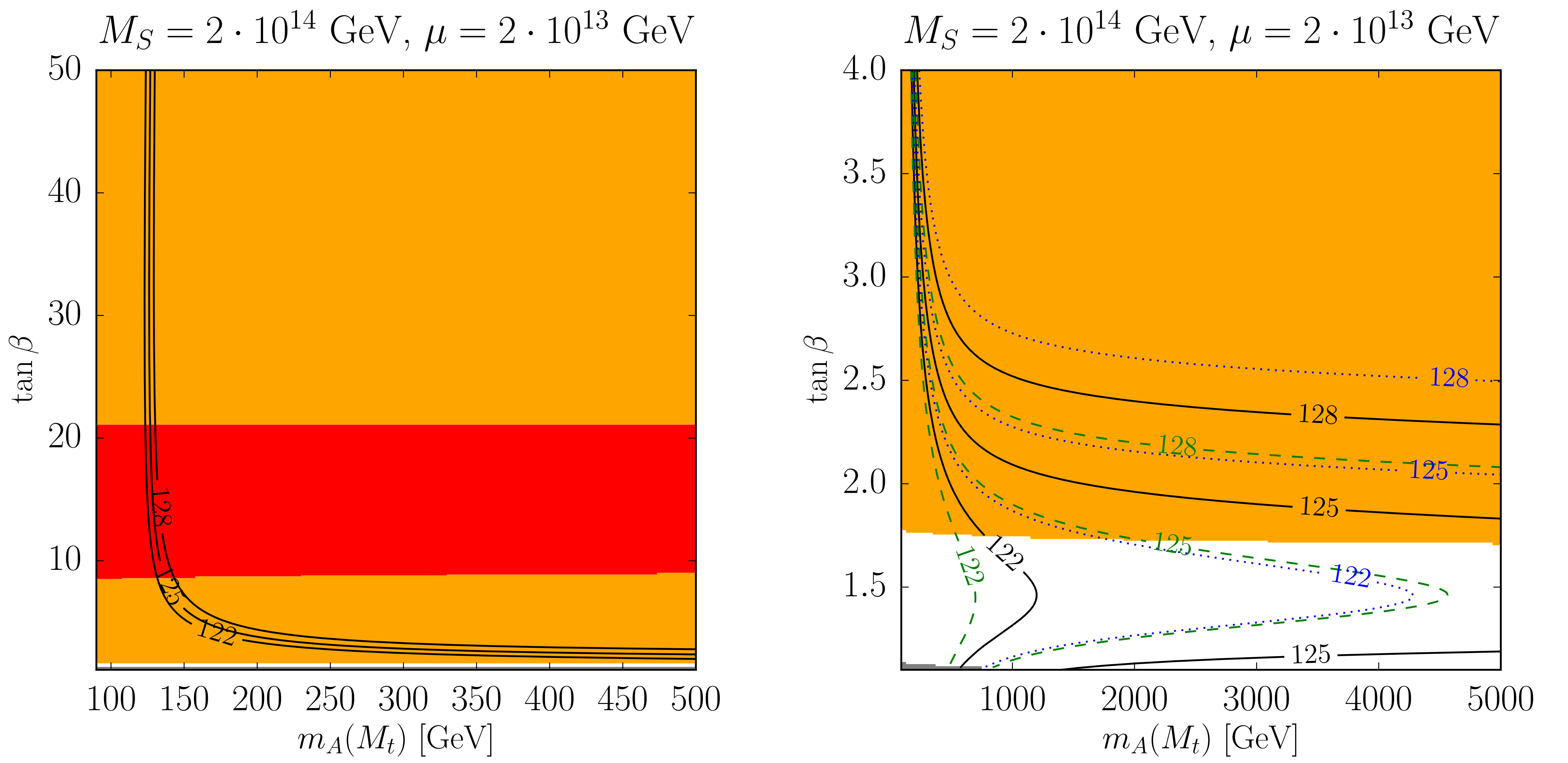
$$\lambda_1 = \frac{1}{4}\left(g^2 + {g'}^2\right)\,, \quad \lambda_2 = \frac{1}{4}\left(g^2 + {g'}^2\right)$$
$$\lambda_3 = \frac{1}{4}\left(g^2 - {g'}^2\right)\,, \quad \lambda_4 = -\frac{1}{2}g^2\,, \quad \lambda_5 = \lambda_6 = \lambda_7 = 0$$



example of RG running of gauge, Yukawa and quartic couplings; reasonable gauge coupling unification



for this example vacuum stability conditions are fulfilled; additional Higgs bosons are heavy!



result of parameter scan; red: excluded by vacuum stability; orange: meta-stable vacuum; large tanβ excluded, small tanβ allowed with $M_A > 1$ TeV; **light higgsino** possible, split SUSY inconsistent!

Moduli stabilization & SUSY breaking

Supersymmetric low-energy effective Lagrangian, given in terms of Kahler potential, gauge kinetic function (magnetic flux f induces FI D-term [Quevedo et al '03, Hebecker et al '07,...]):

$$K = -\ln(S + \bar{S} + iX^S V) - \ln(T + \bar{T} + iX^T V) - \ln(U + \bar{U}) \,,$$

$$S = \frac{1}{2}(s + ic) \,, \quad T = \frac{1}{2}(t + ib) \,,$$

$$X^T = -i\frac{f}{\ell^2} \,, \quad X^S = -i\frac{N+1}{(2\pi)^2}$$

U is shape modulus; Killing vectors due to quantized flux and Green-Schwarz term, note opposite signs! Gauge kinetic function [cf. Ibanez, Nilles '87]:

$$H = h_S S + h_T T \,, \quad h_S = 2 \,, \quad h_T = -\frac{2\ell^2}{(2\pi)^3}$$

Note **opposite sign** of the two contributions! Result: no scale model with gauged shift symmetry, involving S and T!

Gauge invariant KKLT-type superpotential at fixed points (F-term):

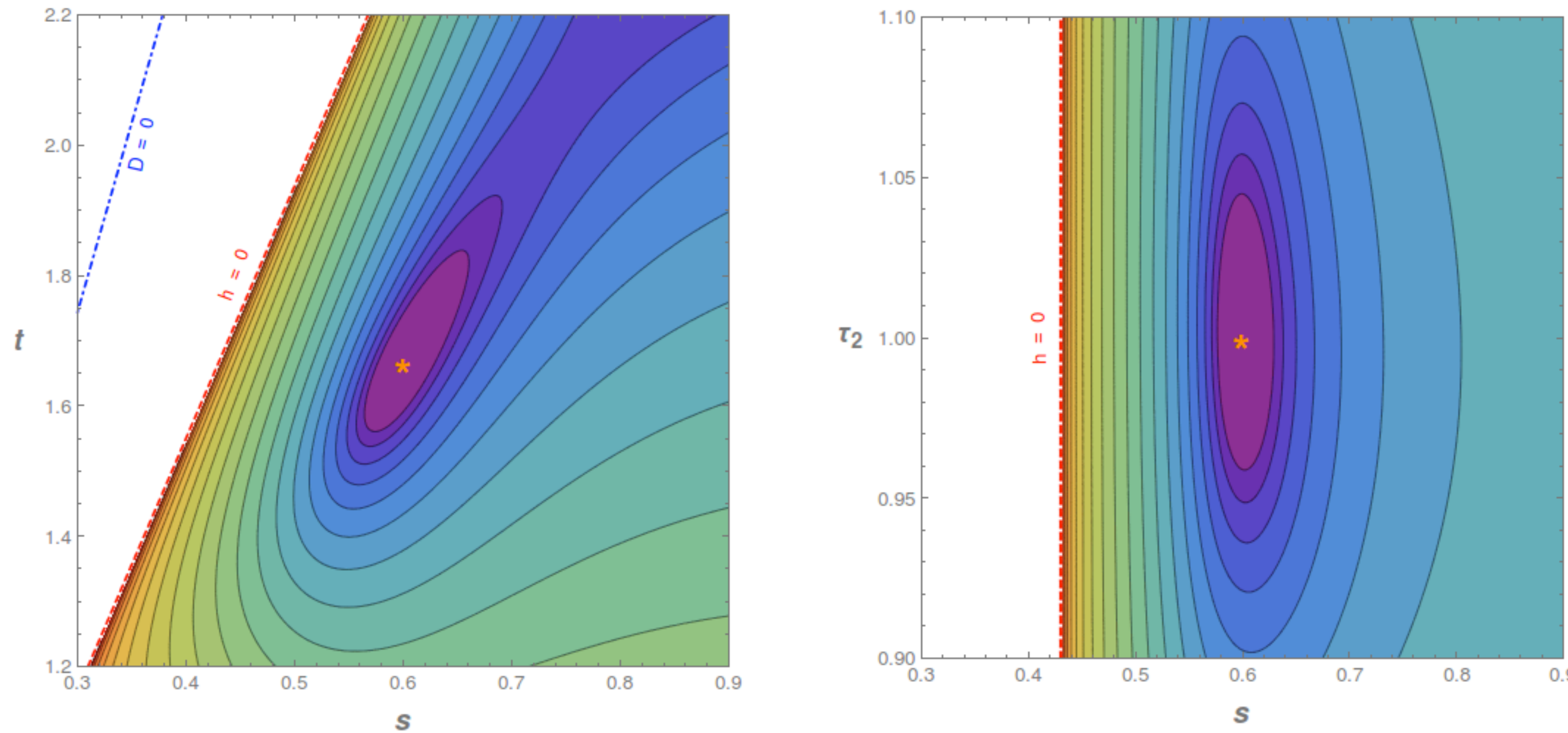
$$W = W(Z,U) = W_0 + W_1\, e^{-aZ} + W_2\, e^{-\tilde{a}U}\,, \quad Z = -iX^T S + iX^S T$$

Scalar potential involving F- and D-terms:

$$V = V_F + V_D = e^K (K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2) + \frac{1}{2h} D^2\,,$$

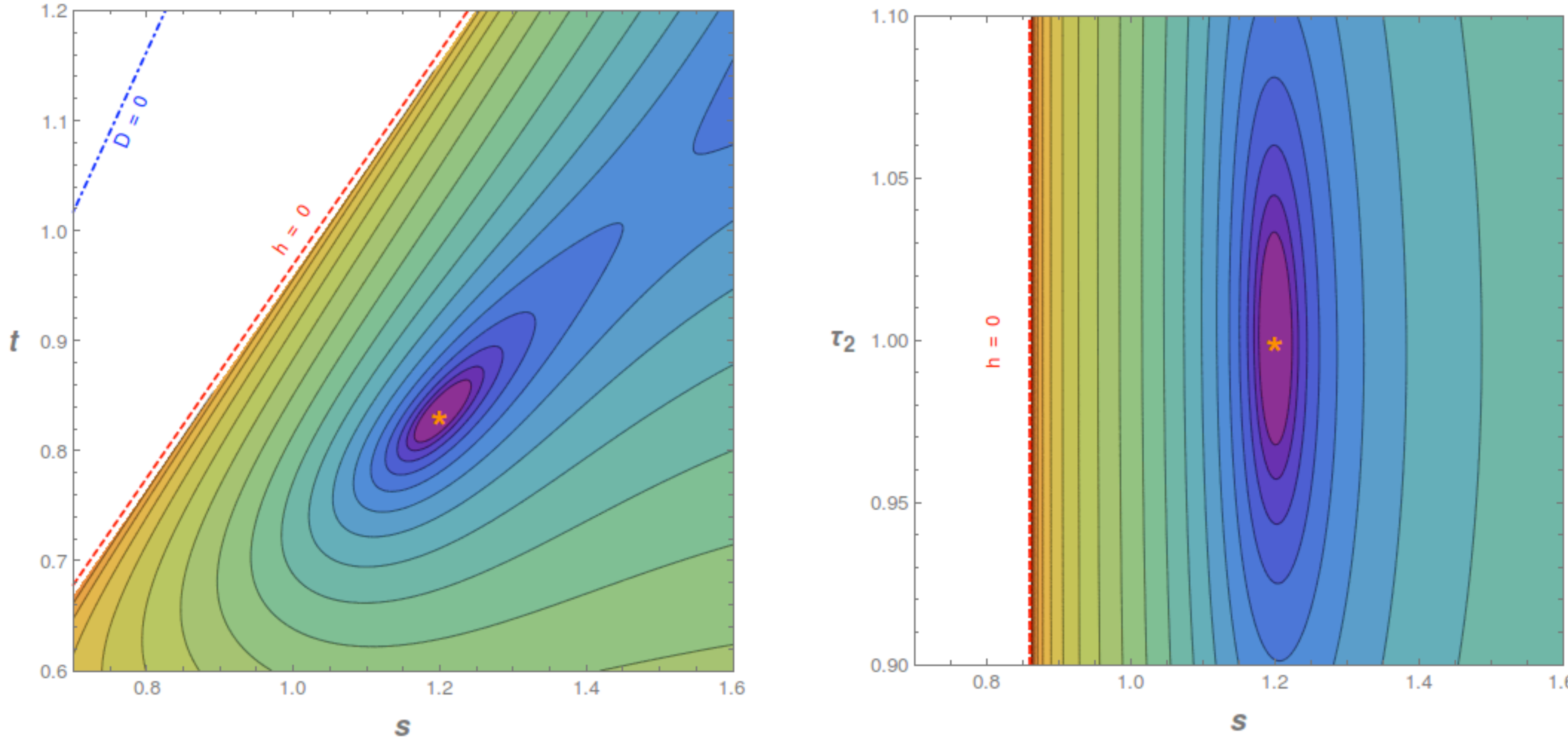
$$D = iK_i X^i = -\frac{i}{s} X^S - \frac{i}{t} X^T\,.$$

Due to flux AND quantum corrections to gauge kinetic function and Killing vectors, **de Sitter vacua exist** without further F-term uplift (e.g. Polonyi)! Size of extra dimensions determined by parameters of superpotential; example: $W_0 \sim W_1 \sim 10^{-3}\,, a \sim 1 \rightarrow r\ell \sim 10^2$, i.e. GUT scale extra dimensions. Hence most basic ingredients of 6d compactifications sufficient to obtain de Sitter vacua and moduli stabilization!



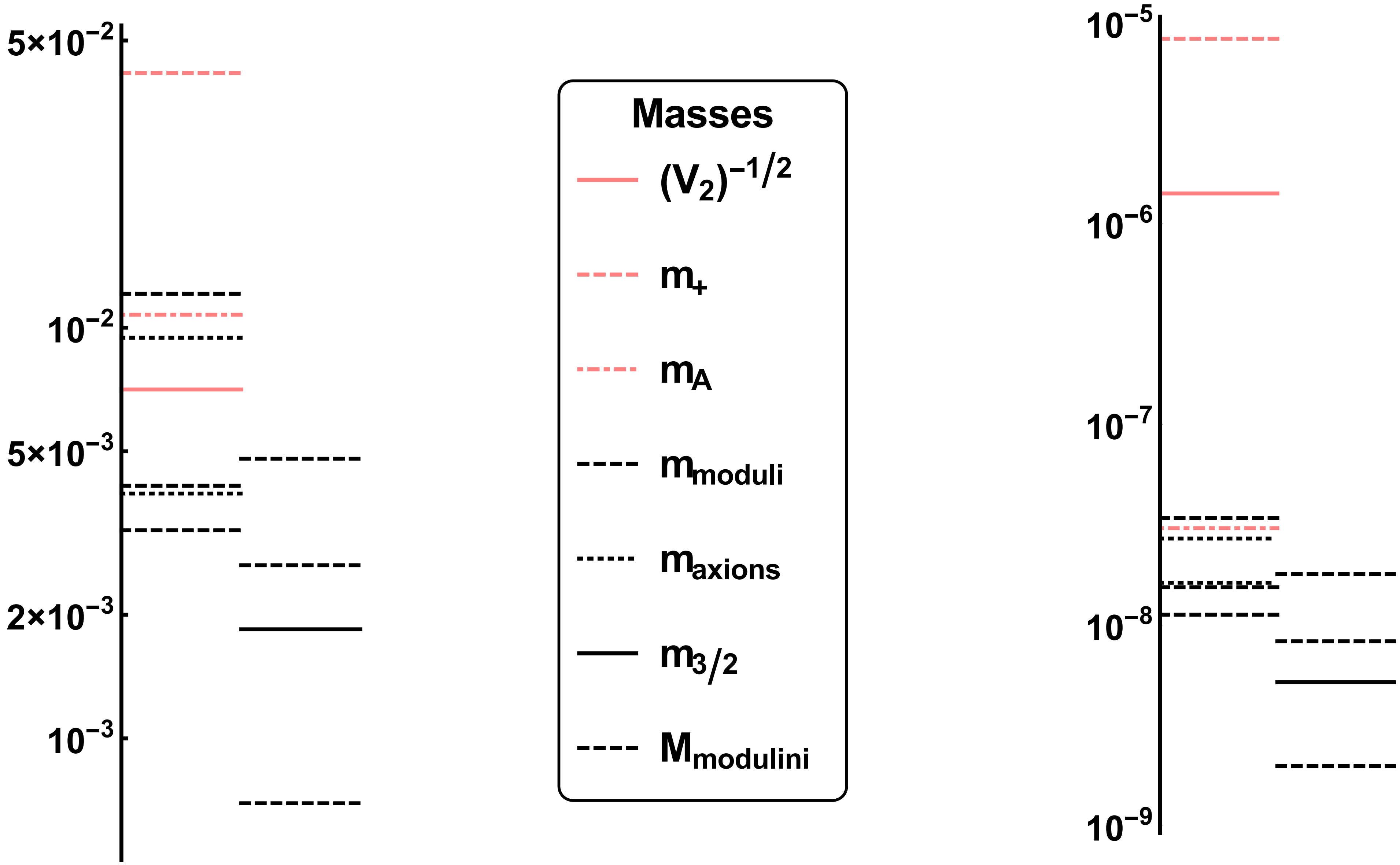
de Sitter (Minkowski) metastable minimum with GUT scale extra dimensions:

$$g = 0.2\,, \quad L = 200\,, \quad W \sim 10^{-2}$$



de Sitter (Minkowski) metastable minimum with intermediate scale extra dimensions:

$$g = 4 \cdot 10^{-3}\,, \quad L = 10^{6}\,, \quad W \sim 10^{-8}$$



boson and fermion masses for GUT scale and "large" extra dimensions:

$$m_A^2 \propto L^{-3}\,, \quad m^2_{\rm moduli} \propto L^{-3}\,, \quad m^2_{\rm axions} \propto L^{-3}$$

$$m_{3/2} \propto L^{-3/2}\,, \quad M_{\rm modulini} \propto L^{-3/2}$$

6d F-theory vacua

work in progress: WB, Dierigl, Oehlmann, Ruehle

Start from K_3 manifold, torus (in Weierstrass form) fibered over base $\mathbb{P}^1$,

$$F = -y^2 + x^3 + fx + g = 0$$

with dependence on base coordinates $z_0,\ d_i(z_0, z_1)$,

$$\begin{aligned} f =& z_0^2 \left(-\frac{1}{3} d_5^2 d_7^2 + z_0 R_1 + \mathcal{O}(z_0^2) \right) , \\ g =& z_0^3 \left(-\frac{2}{27} d_5^3 d_7^3 + z_0 R_2 + \mathcal{O}(z_0^2) \right) \end{aligned}$$

torus is singular at point (x, y) if discriminant vanishes,

$$F = \frac{\partial F}{\partial x} = \frac{\partial F}{\partial y} = 0 \,,$$

$$\Delta = 4f^3 + 27g^2 = 0$$

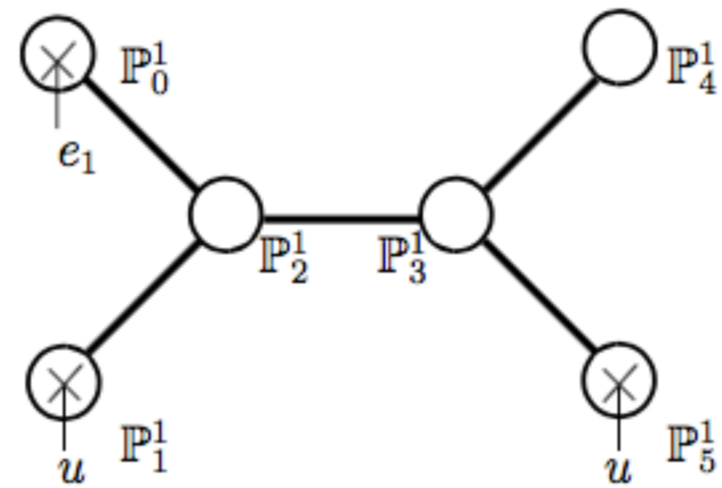
Kodaira classification: order of singularity determines non-Abelian gauge group, $\mathrm{Ord}(f,g,\Delta)=(2,3,7)$ yields $SO(10)$:

$$\Delta = z_0^7(P + z_0 R + \mathcal{O}(z_0^2))\,,$$
$$P = -d_5^3 d_7^3 (d_3 d_5 - d_1 d_7)^2 d_9^2$$

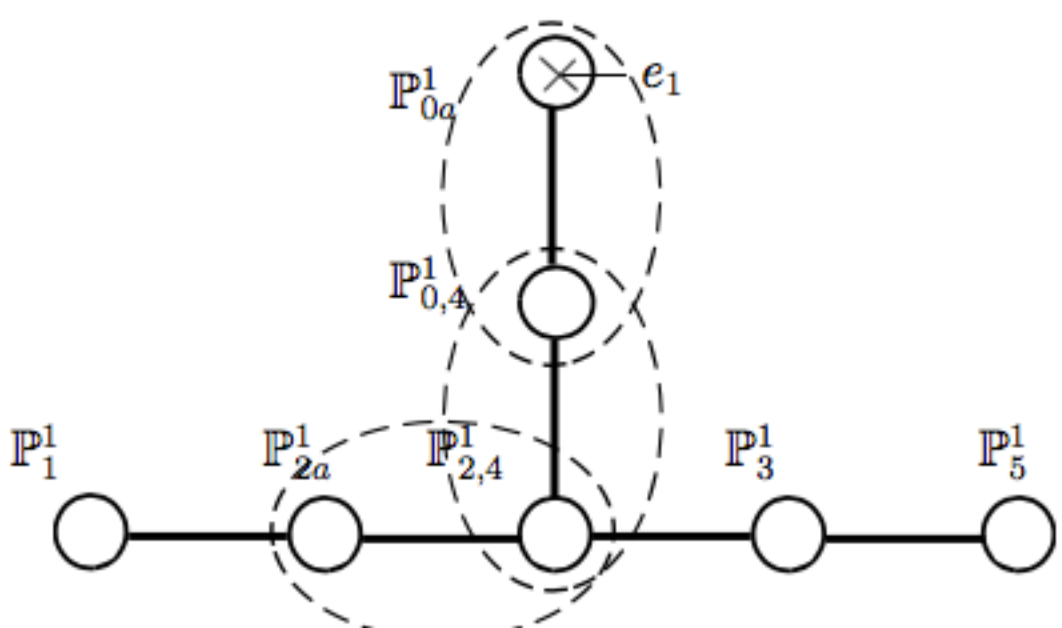
Vanishing of P at some points of basis leads to stronger singularities, and therefore larger symmetries, at these points:

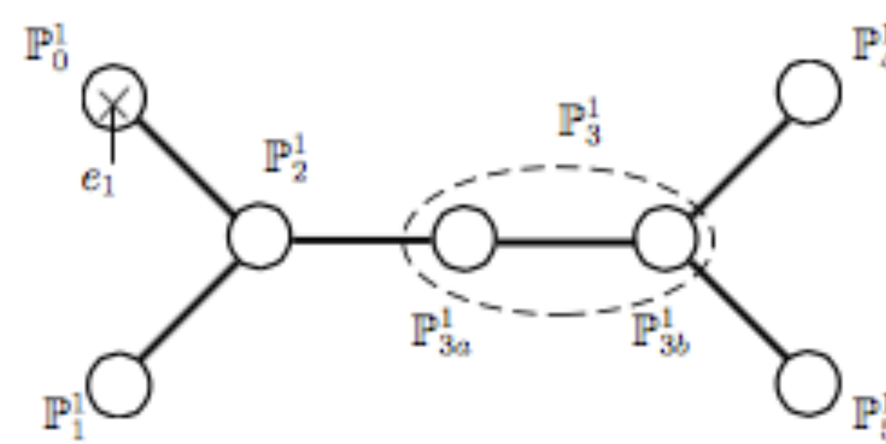
locus	$\mathrm{Ord}(f,g,\Delta)$	fiber singularity
$z_0 = 0$	$(2,3,7)$	$SO(10)$
$z_0 = d_9 = 0$	$(2,3,8)$	$SO(12)$
$z_0 = d_5 = 0$	$(3,4,8)$	E_6
$z_0 = d_7 = 0$	$(3,4,8)$	E_6
$z_0 = d_3 d_5 - d_1 d_7 = 0$	$(2,3,8)$	$SO(12)$

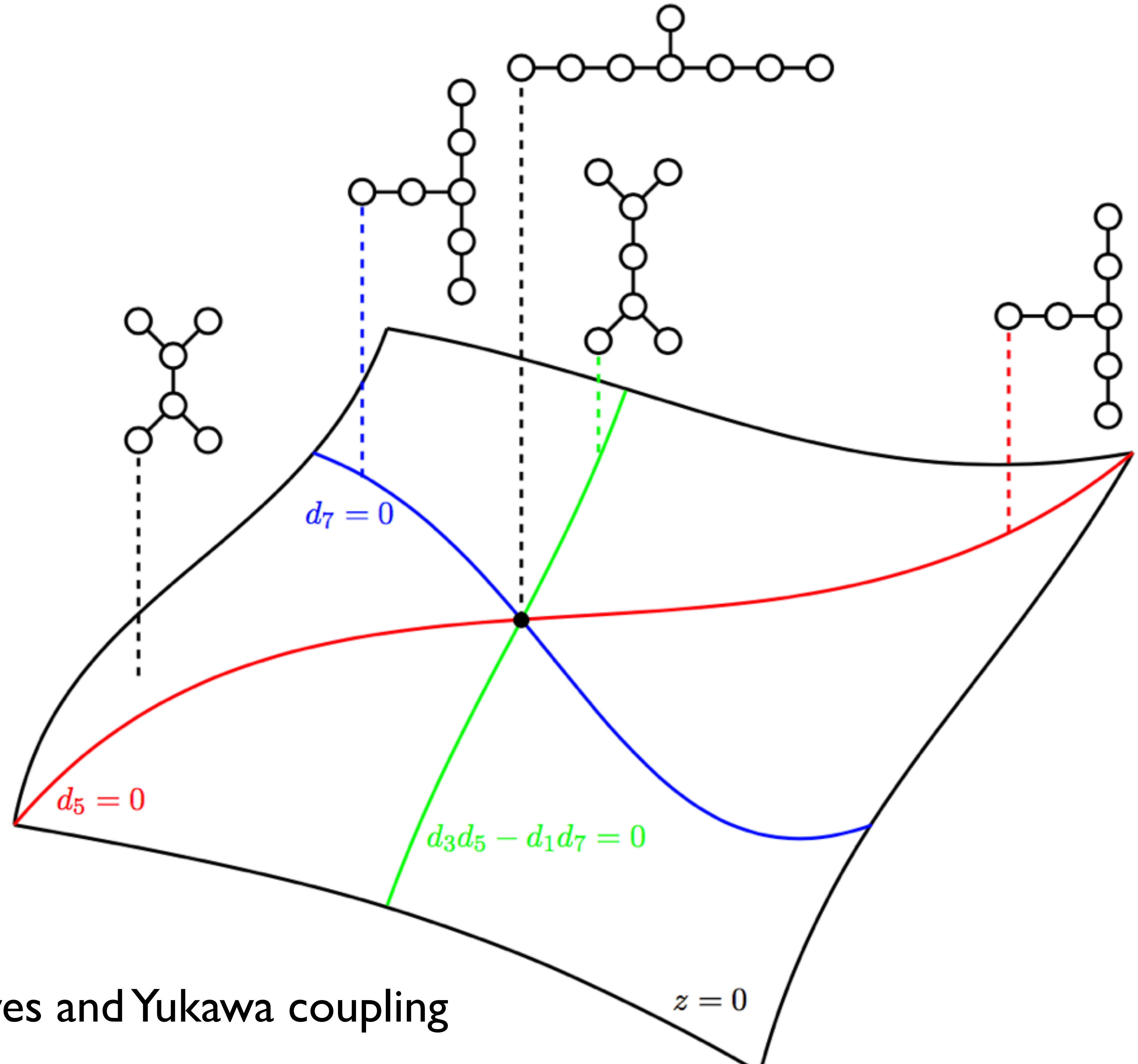
Intersection pattern at resolved $SO(10)$ singularity:



Global GUT model building, starting from toric geometry [Morrison, Taylor, Schafer-Nameki, Weigand, Grimm, Palti, Cvetic, Klevers, Ruehle, Oehlmann, ... '12 ...]; at enhanced symmetry points `coset matter' is generated, i.e. 16's and 10's:







matter curves and Yukawa coupling

Conclusions

- Supersymmetric extensions of Standard Model strongly motivated, but what is the scale of SUSY breaking?

- Higher-dimensional GUT models with flux lead to GUT scale for SUSY breaking; emerging low energy spectrum reminiscent of `spread' SUSY (THDM + higgsino + ...)

- Flux and F-term breaking allows for moduli stabilization

- Embedding of 6d SUGRA with SO(10)xU(1) symmetry into F-theory possible

- Effect of flux on quantum corrections? Fine-tuning of electroweak scale?

Backup Slides

representation	locus	multiplicity
$\mathbf{10}_{3/2}$	$z = d_9 = 0$	2
$\mathbf{16}_{3/4}$	$z = d_5 = 0$	0
$\mathbf{16}_{-1/4}$	$z = d_7 = 0$	4
$\mathbf{10}_{-1/2}$	$z = d_3 d_5 - d_1 d_7 = 0$	4
$\mathbf{45}$	$z = 0$	0
$\mathbf{1}_3$	$d_8 = d_9 = 0$	2
$\mathbf{1}_2$	$V(2)$	36
$\mathbf{1}_1$	$V(3)$	76
$\mathbf{1}_0$	moduli	$51 + 1$
T	tensor	1