Sequestered SUSY breaking

UNIVERSITY OF OXFORD

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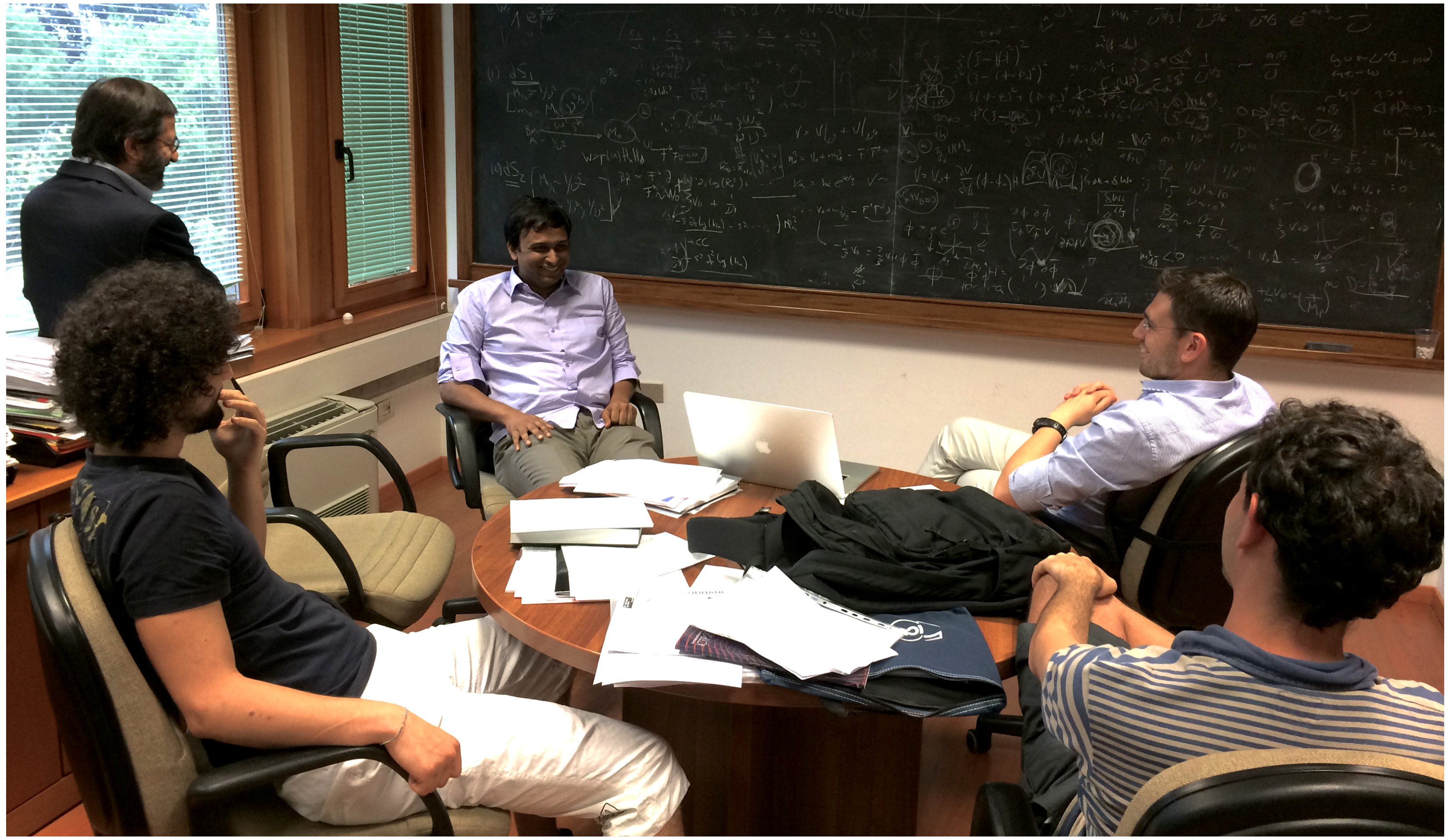
Rudolf Peierls Centre for Theoretical Physics
String Group Seminar, Liverpool, 28/10/2014

based on:



- L. Aparicio, M. Cicoli, SK, A. Maharana, F. Muia, F. Quevedo: Sequestered dS string scenarios: soft terms 1409.1931
- R. Blumenhagen, J. Conlon, SK, S. Moster, F. Quevedo: Sequestered soft-masses in LVS 0906.3297
- M. Cicoli, SK, C. Mayrhofer, F. Quevedo, R. Valandro: Global realisations 1206.5237

Motivation

Status of SUSY

- 126 GeV Higgs, no sign of SUSY yet but not excluded.
- How is the hierarchy problem addressed?
  `Best fit' SUSY (compared to: compositeness, just SM, X-dim):
    a) particular corner of MSSM (e.g. natural SUSY, N^RMSSM)
    b) split SUSY
    c) large (intermediate) SUSY breaking scale
- Problems: a) Why this special corner? b) Fine-tuning for hierarchy problem. c) Even more fine-tuning

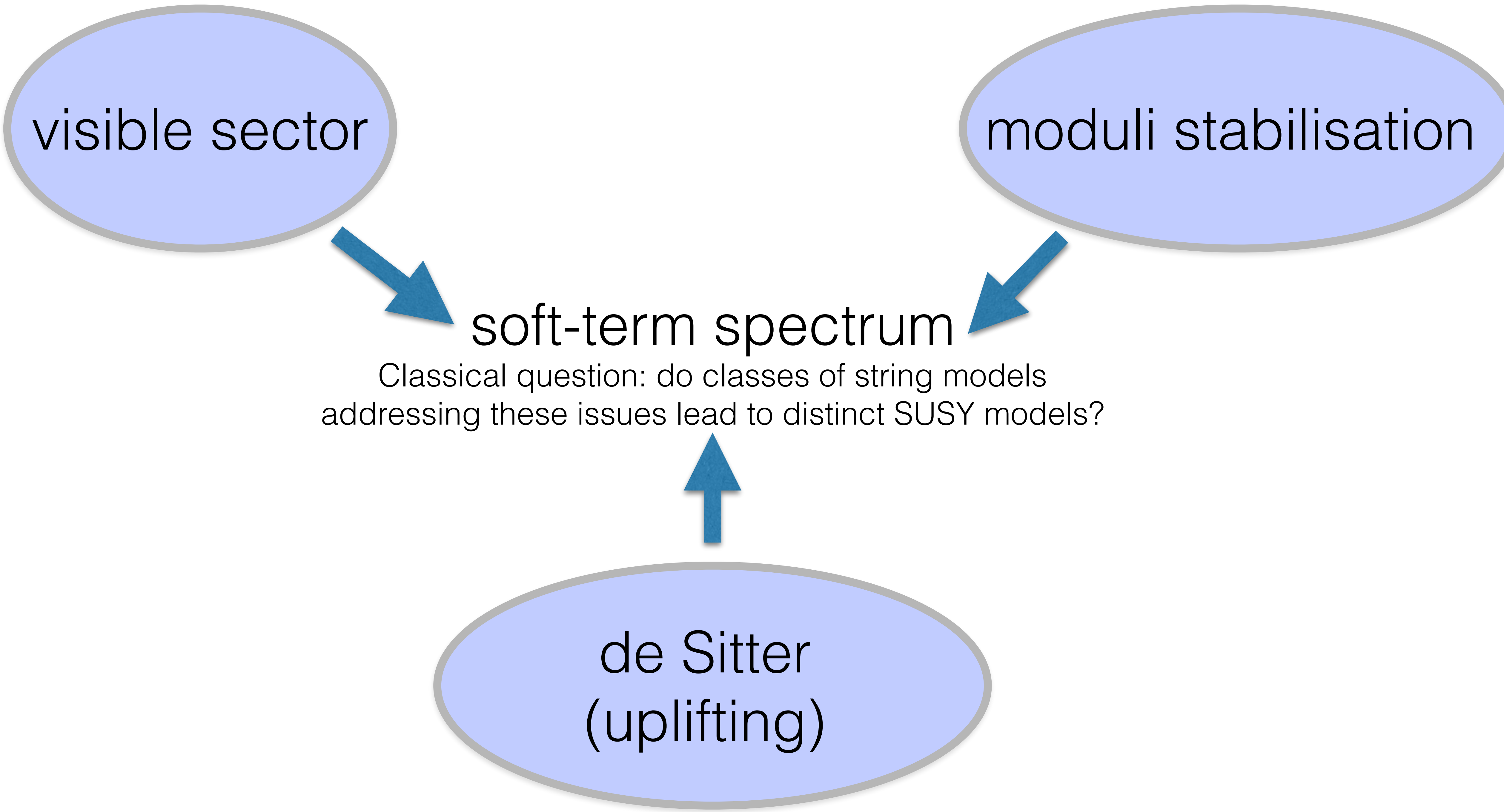
Problems should be addressed in UV completion of SM (guidance, explicit realisations, alternatives)

String Models of ~~SUSY:~~ crucial ingredients

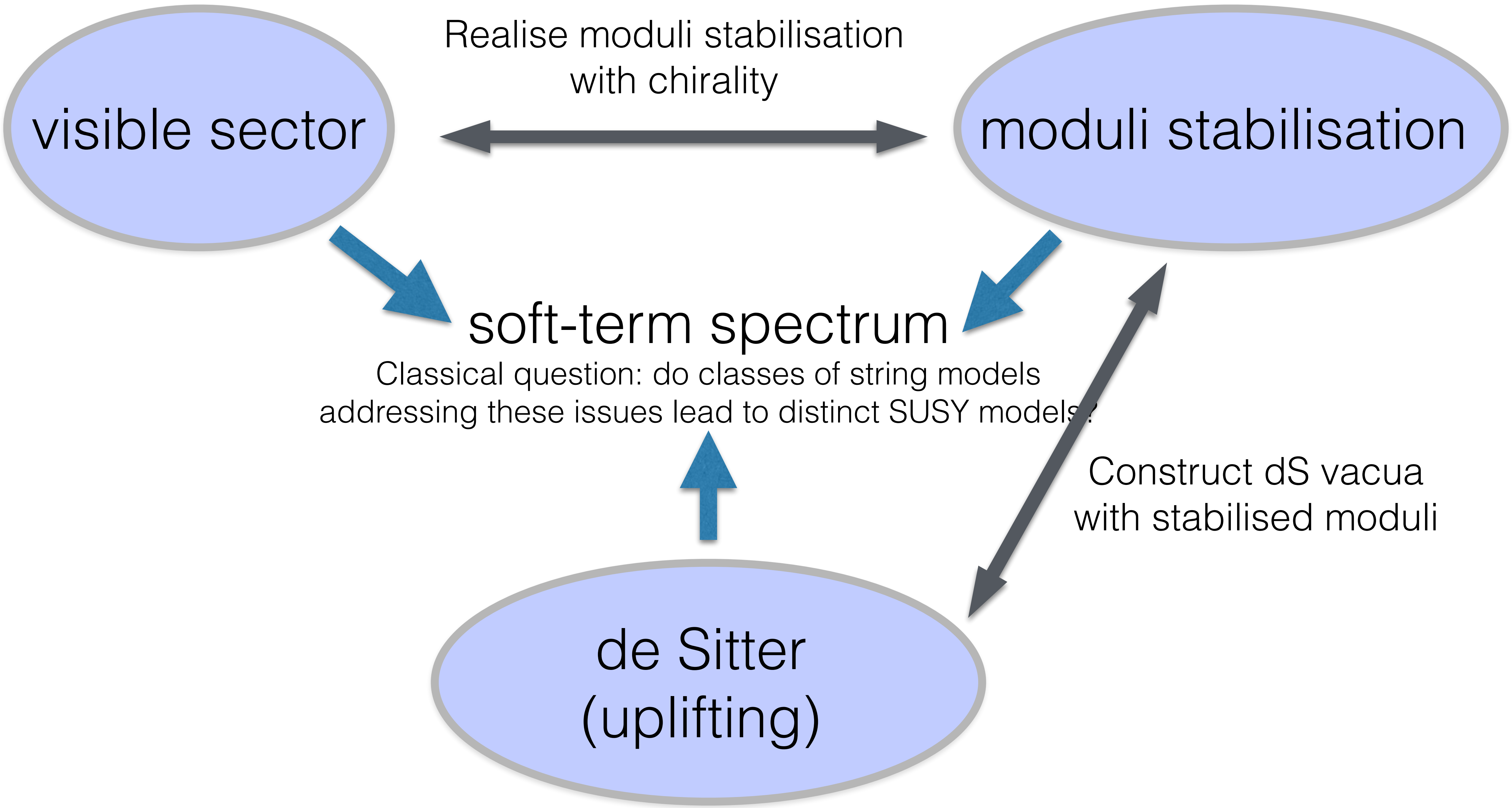
soft-term spectrum

Classical question: do classes of string models addressing these issues lead to distinct SUSY models?

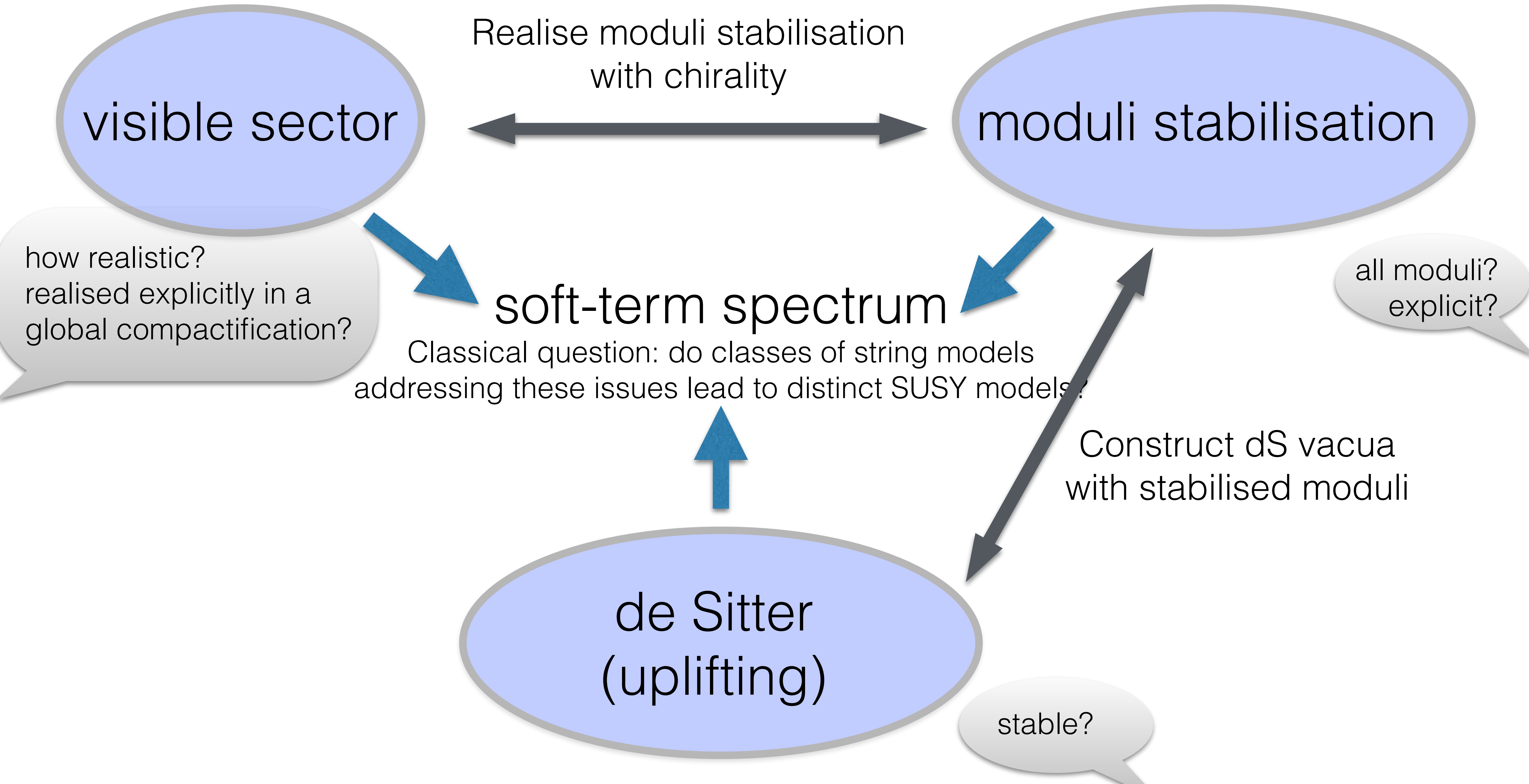
String Models of ~~SUSY:~~ crucial ingredients



String Models of ~~SUSY:~~ crucial ingredients

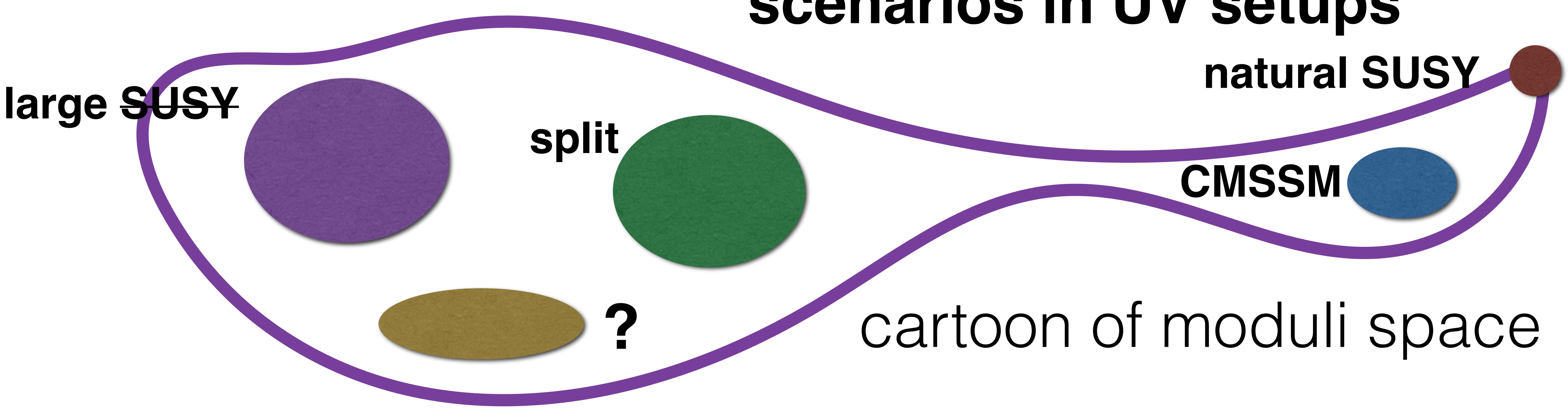


String Models of ~~SUSY:~~ crucial ingredients



Why now?

- Progress in string constructions (chiral, global, de Sitter models with branes at singularities)
  Cicoli, (Klevers), SK, Mayrhofer, Quevedo, Valandro (2012, 2013)
- Spectrum of soft-masses relevant for cosmology (dark matter, CMP, dark radiation, CAB)
  work by Cicoli, Conlon, Marsh, Quevedo, et al.
- LHC14, future SUSY searches. Can string theory be relevant in SUSY phenomenology discussion?
  ➥ **golden opportunity: interpolating between scenarios in UV setups**



What's new?

- towards complete models
  global realisation with visible sector and dS moduli stabilisation
- uplifting dependence of soft-masses determined
- D-terms in LVS soft-masses
- pheno-ready soft-masses/parametrisation
- UV realisations of interesting SUSY phenomenology scenarios (split susy, non-universal soft-masses)

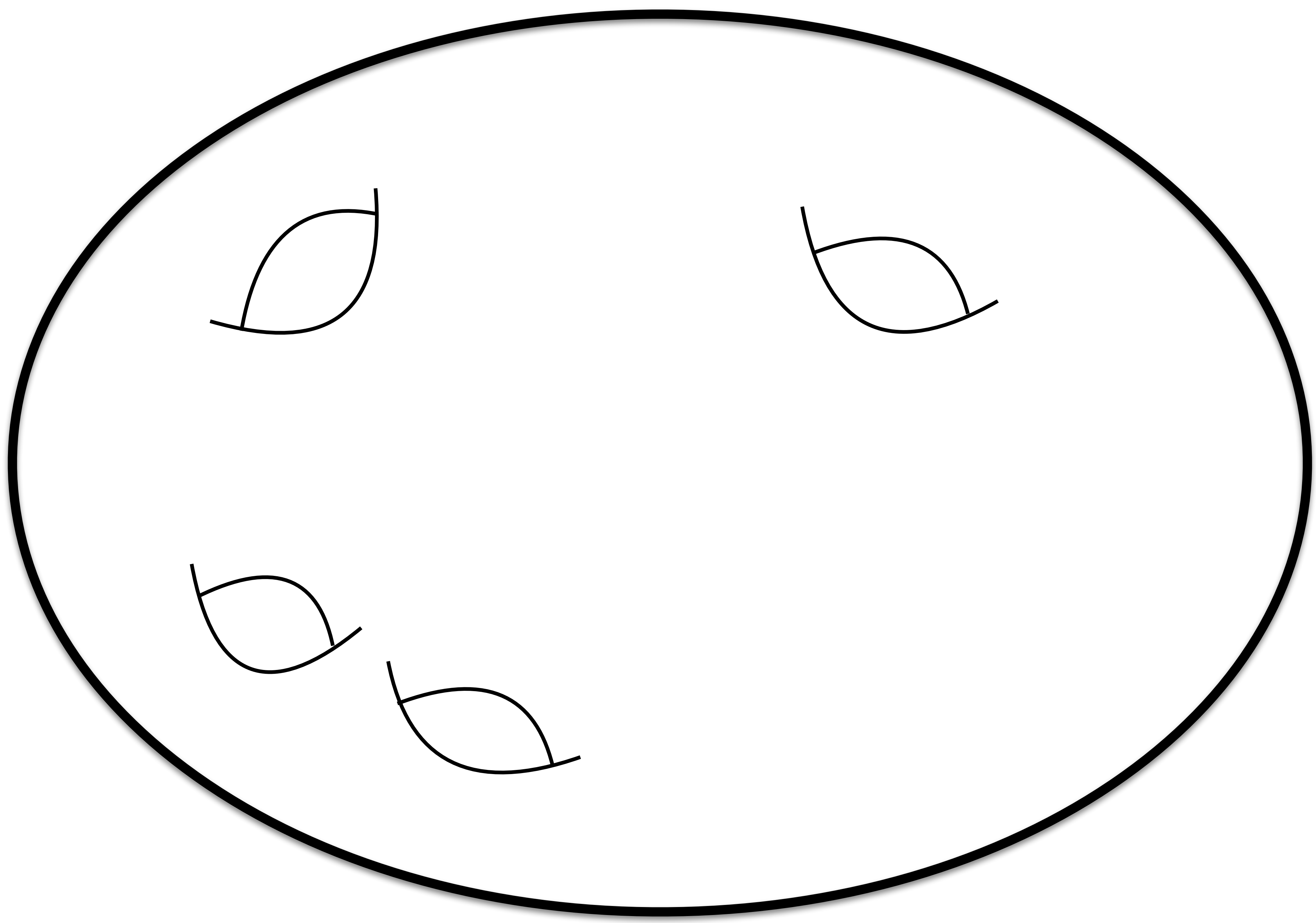
Content

- Explicit type IIB models with moduli stabilisation, dS, chirality and broken SUSY
- Soft-terms for sequestered models

Strategy: general

- Find classes of consistent compactification + ingredients (branes + fluxes)
- Determine EFT, stabilise moduli
- Determine phenomenological UV soft-terms
- Analyse soft-terms @ low-energies

A roadmap towards realistic string vacua in IIB



global realisation: MC, SK, CM, FQ, RV 1206.3297

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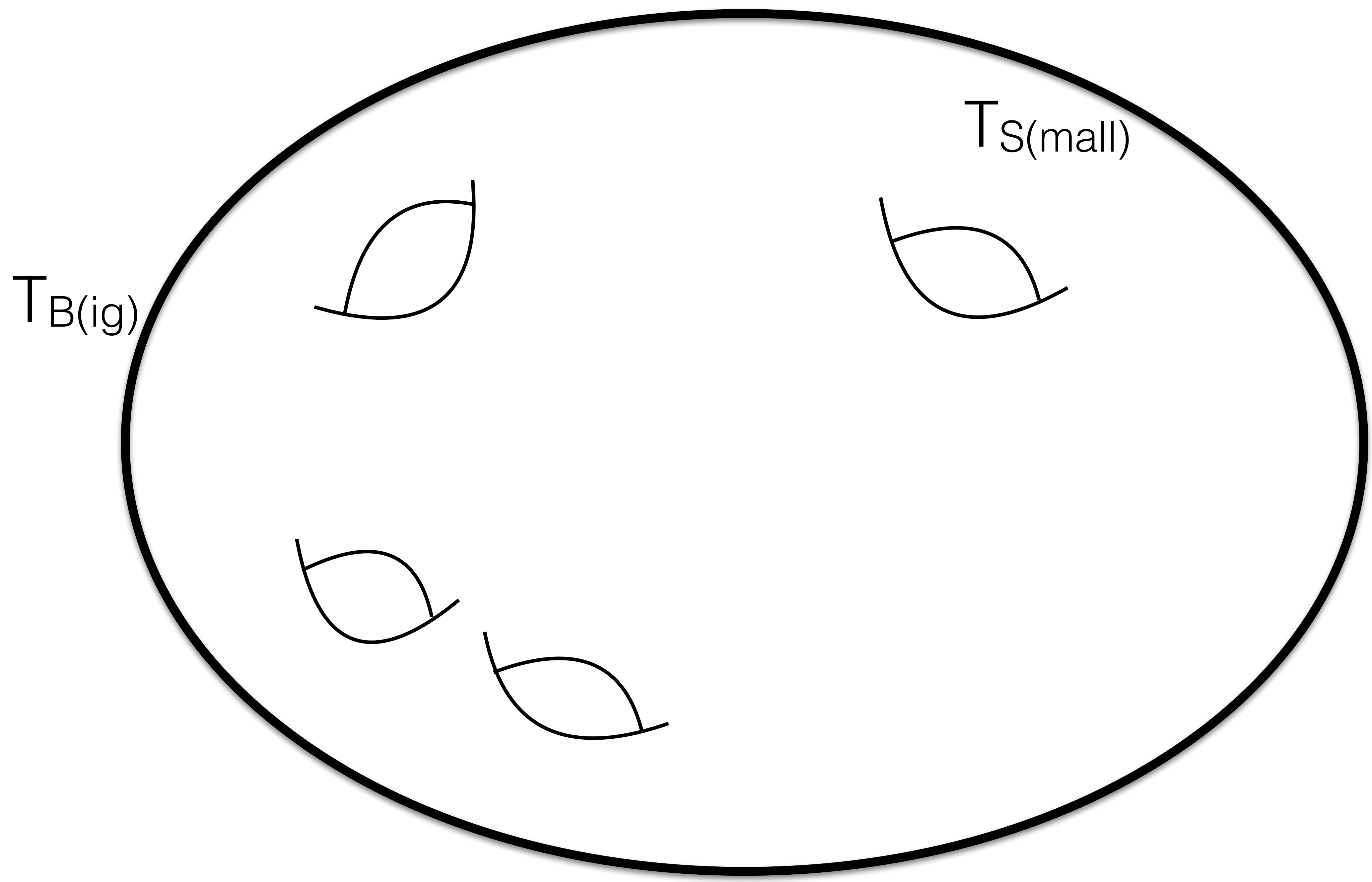

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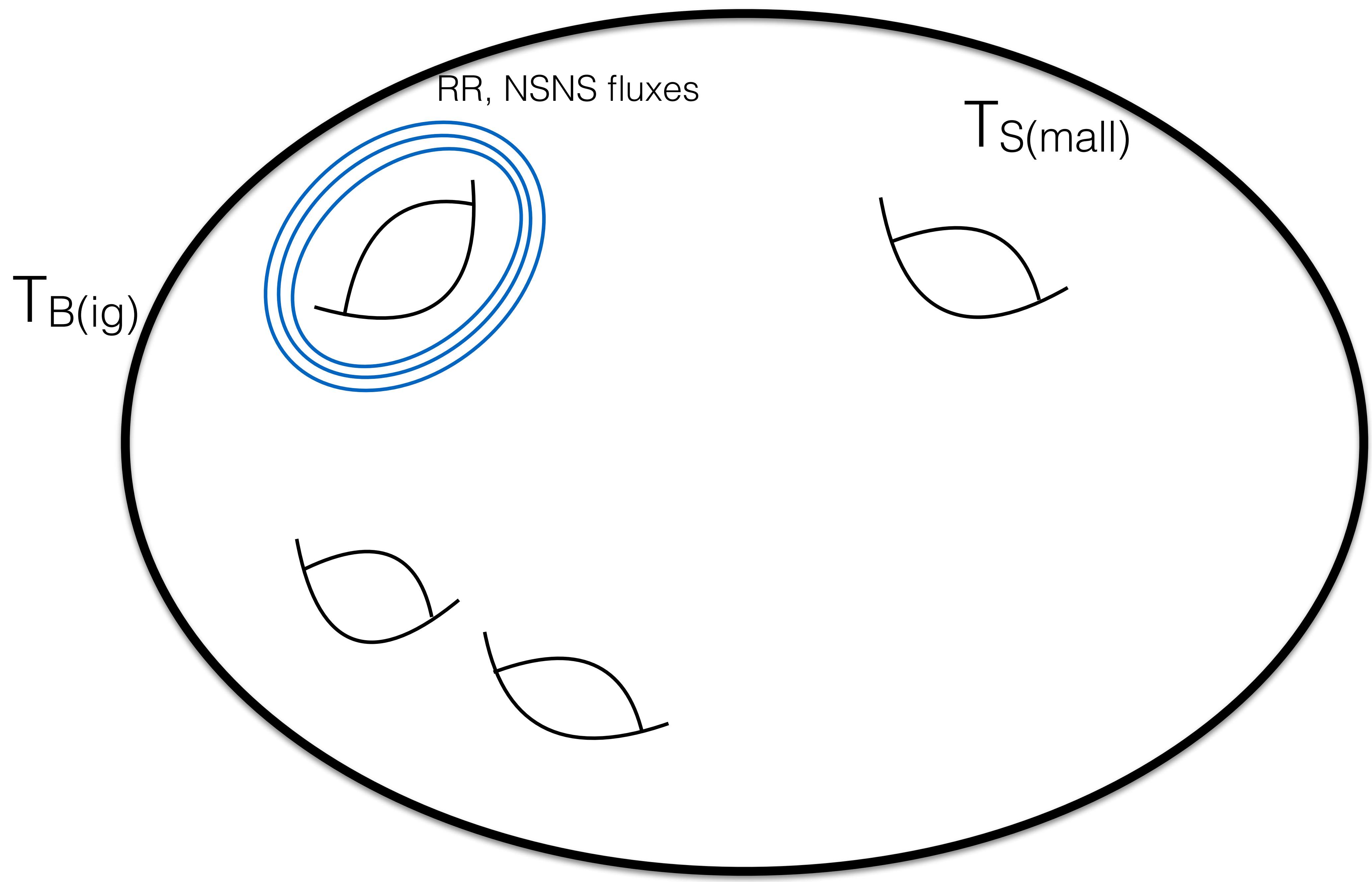

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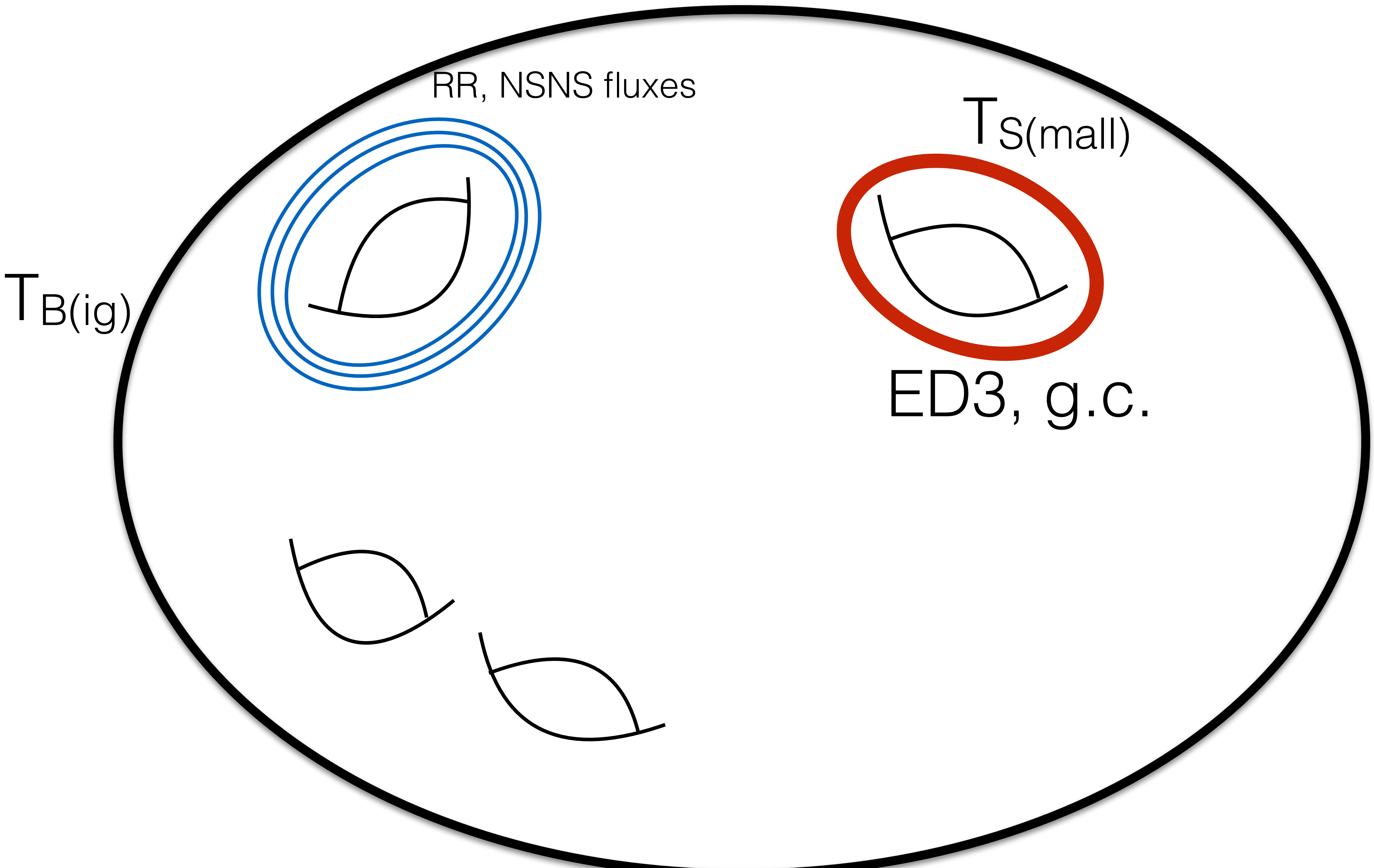

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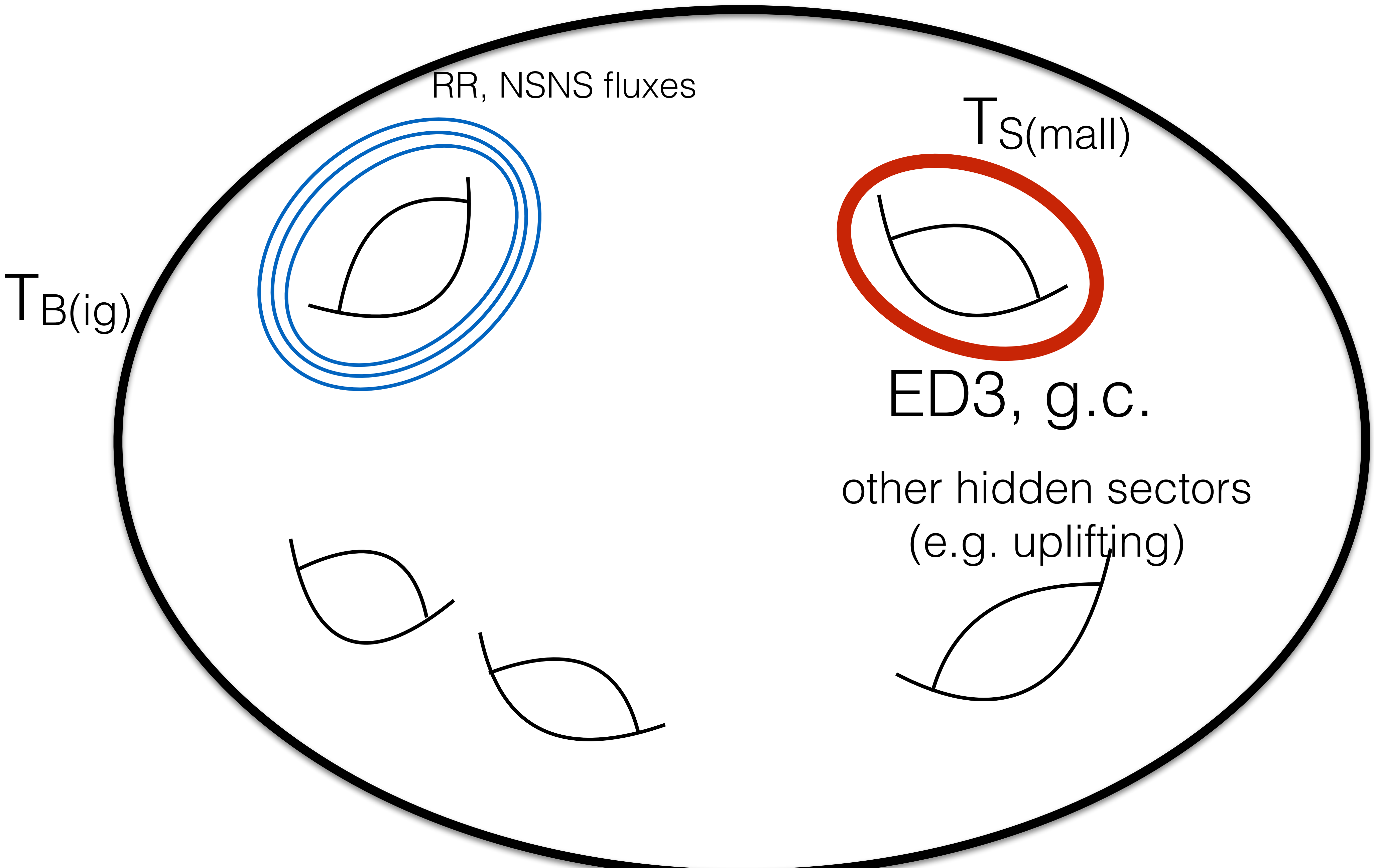

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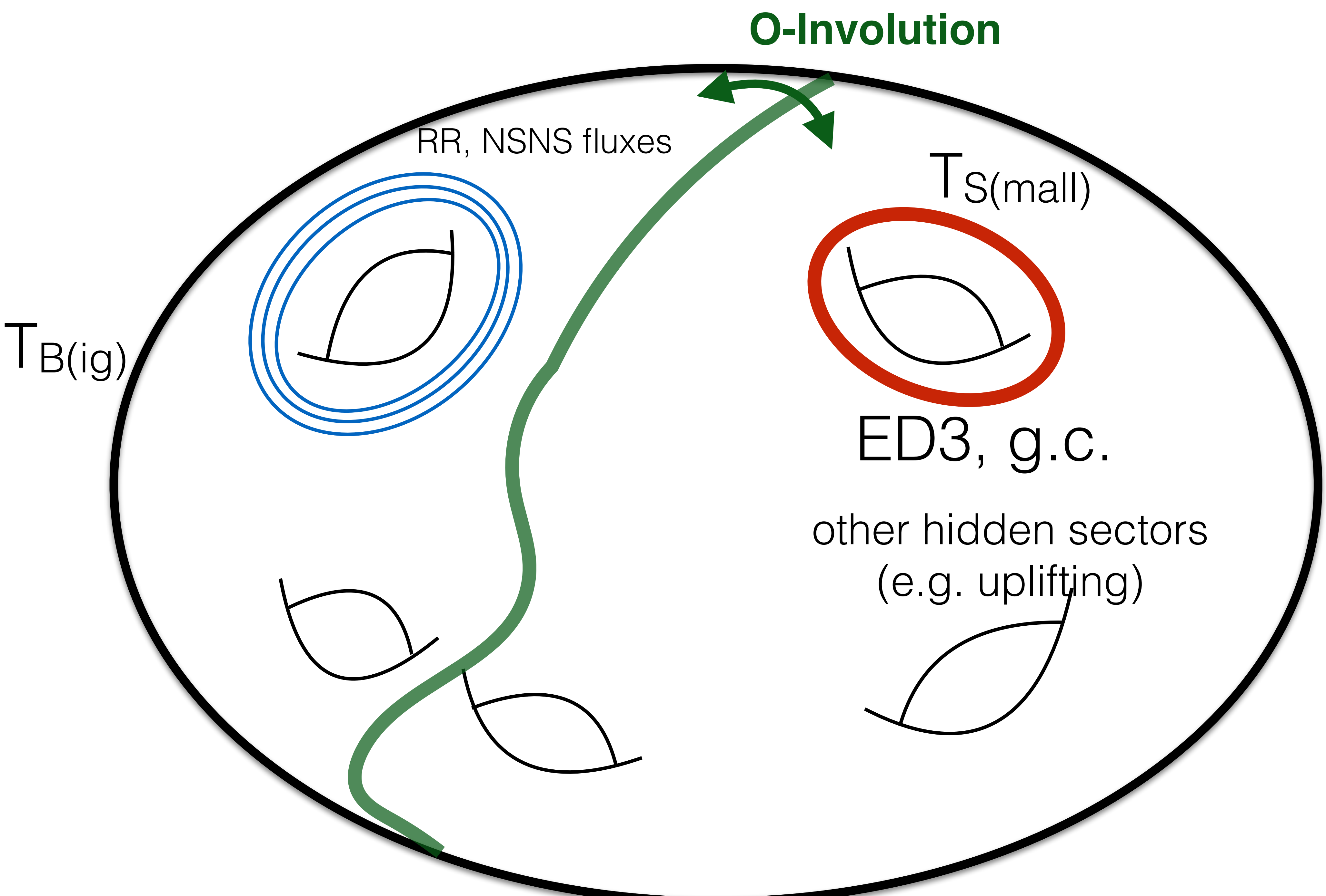

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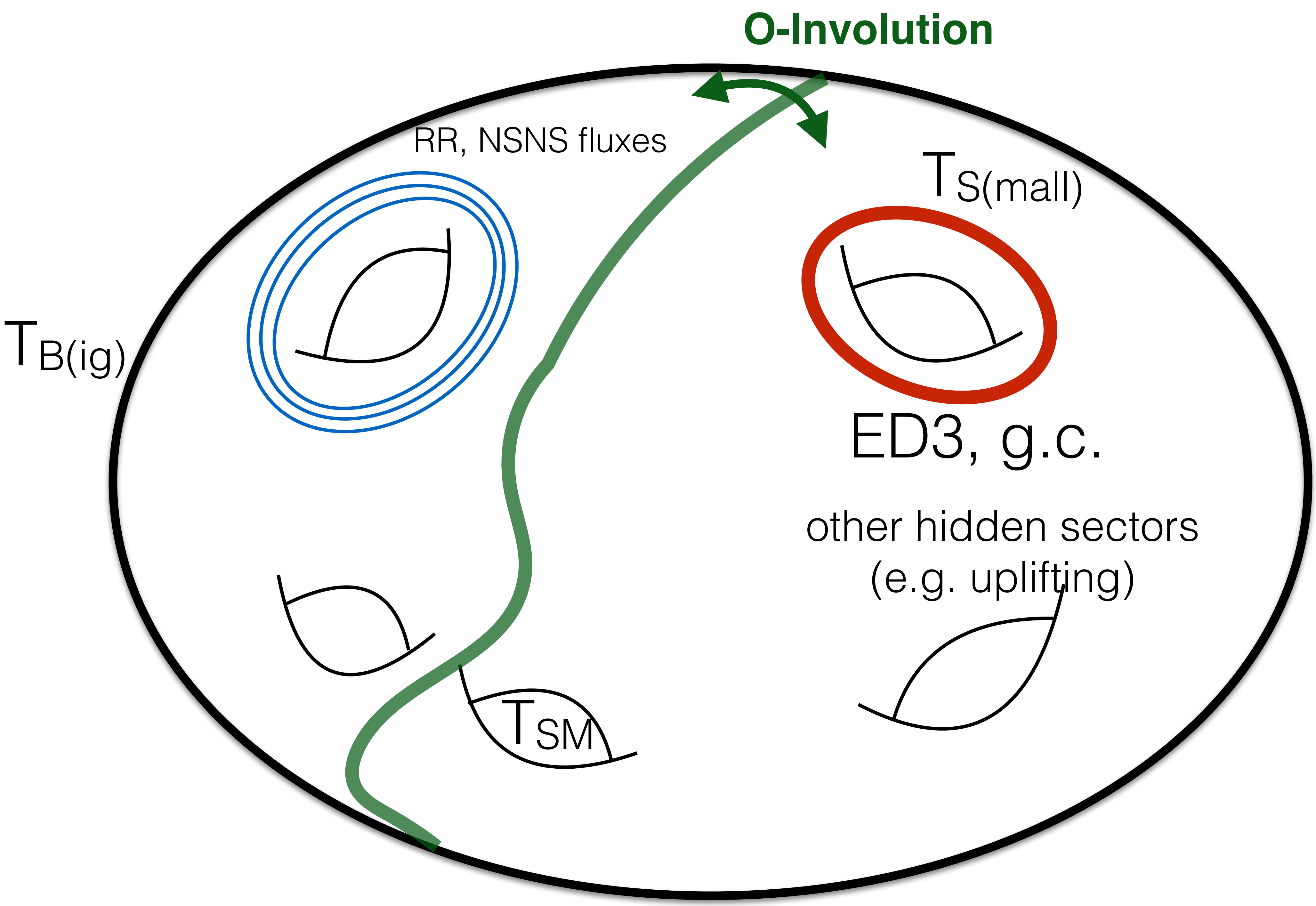

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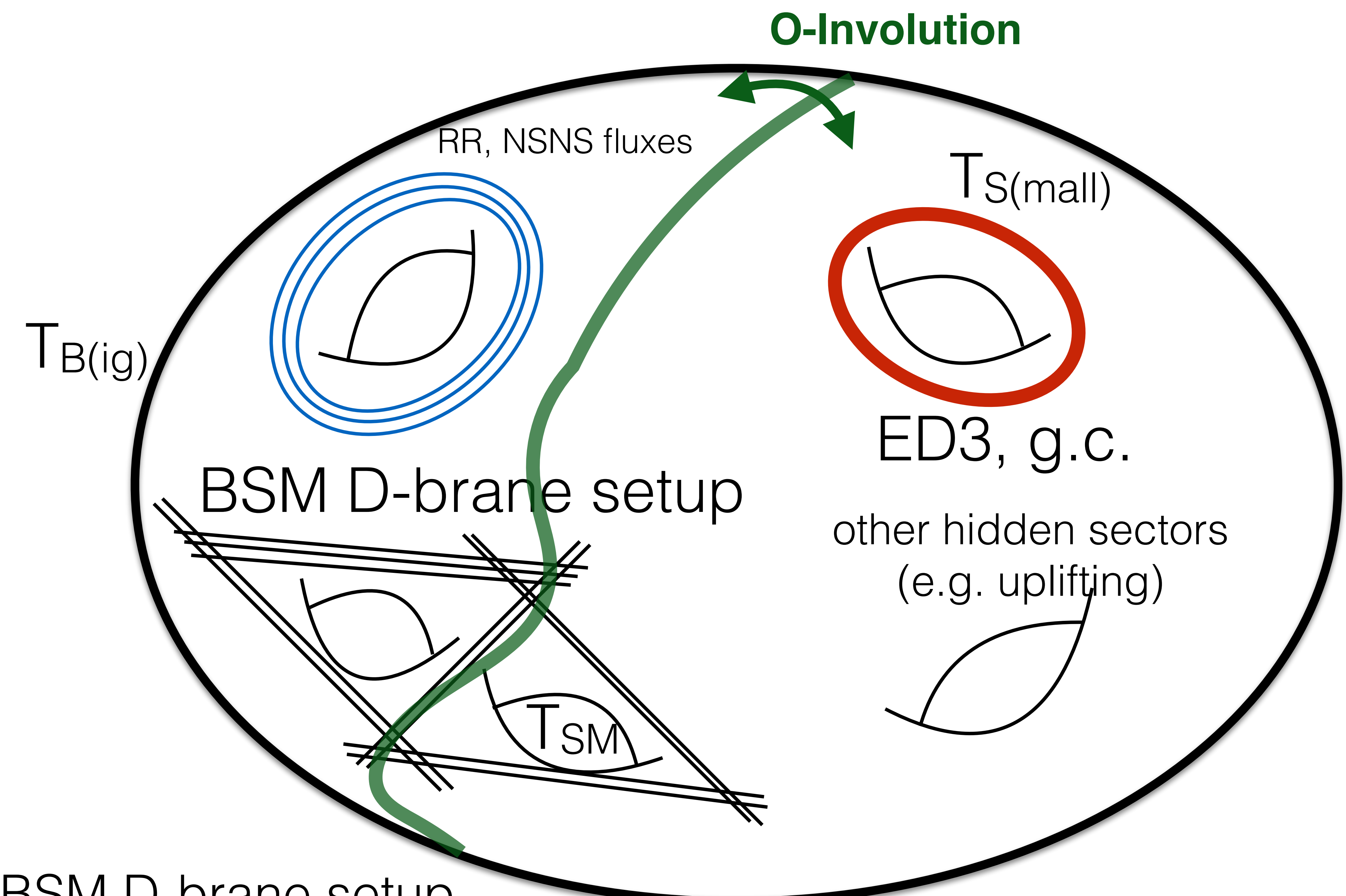


here: BSM D-brane setup
from D-branes at singularities

global realisation: MC, SK, CM, FQ, RV 1206.3297

Realisation of Roadmap

- CY in Kreuzer-Skarke database with desired properties: LVS (blow-up), O-involution exchanging 2 dP_n singularities for BSM D-brane models, no intersection non-perturbative and blow-up SM divisor

- add D-branes, world-volume fluxes, check consistency conditions

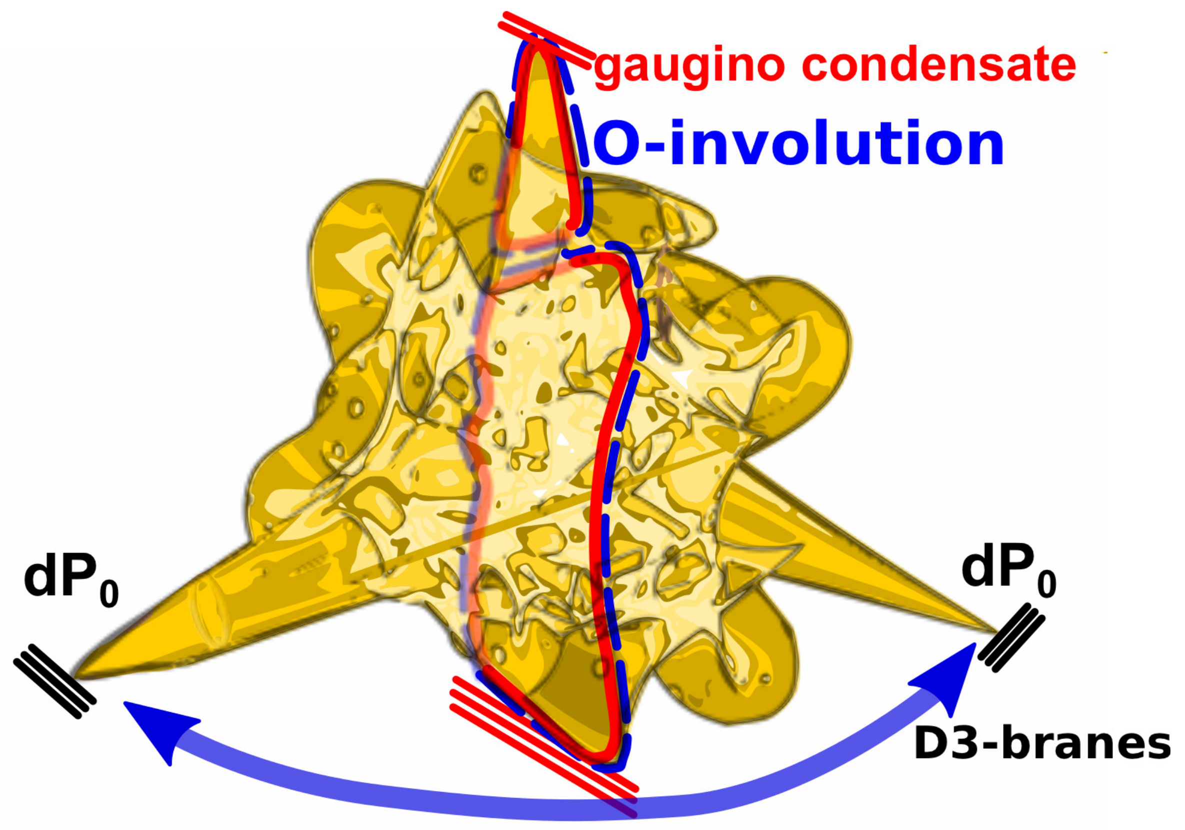
- stabilise Kähler moduli (and complex structure moduli) explicitly

global realisation: MC, (DK), SK, CM, FQ, RV 1206.3297, (1404.7127)

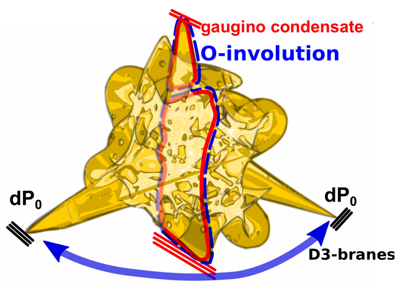
- analyse low-energy theory…

A benchmark model

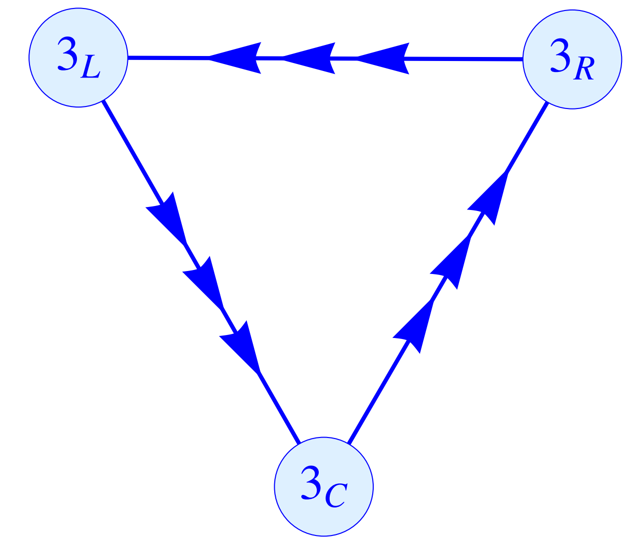
…taken from a whole class



1206.5237



A benchmark model



- From search in Kreuzer-Skarke database, $h^{1,1}=4$, $h^{1,2}=112$: visible sector $2 \mathrm{x} dP_0$, hidden sector $1 \mathrm{x} dP_0$

- O-involution exchanging visible sector, can realise g.c. on hidden sector and simple visible sector with trinification model

- All consistency conditions satisfied (tadpoles, K-theory charges)

Moduli Stabilisation

- complex structure assumed to be stabilised with 3-form fluxes (D3 tadpole allows to turn on fluxes.)
- EFT: $$K = -2\ln\left(\mathcal{V} + \frac{\zeta}{g_s^{3/2}}\right) + \frac{(T_+ + \bar{T}_+ + q_1 V_1)^2}{\mathcal{V}} + \frac{(G + \bar{G} + q_2 V_2)^2}{\mathcal{V}} + \frac{C^i \bar{C}^i}{\mathcal{V}^{2/3}}\,,$$

$$W = W_{\text{local}} + W_{\text{bulk}} = W_0 + y_{ijk}\, C^i C^j C^k + A_s\, e^{-\frac{\pi}{3}\,T_s} + A_b\, e^{-\frac{\pi}{2}\,T_b}$$

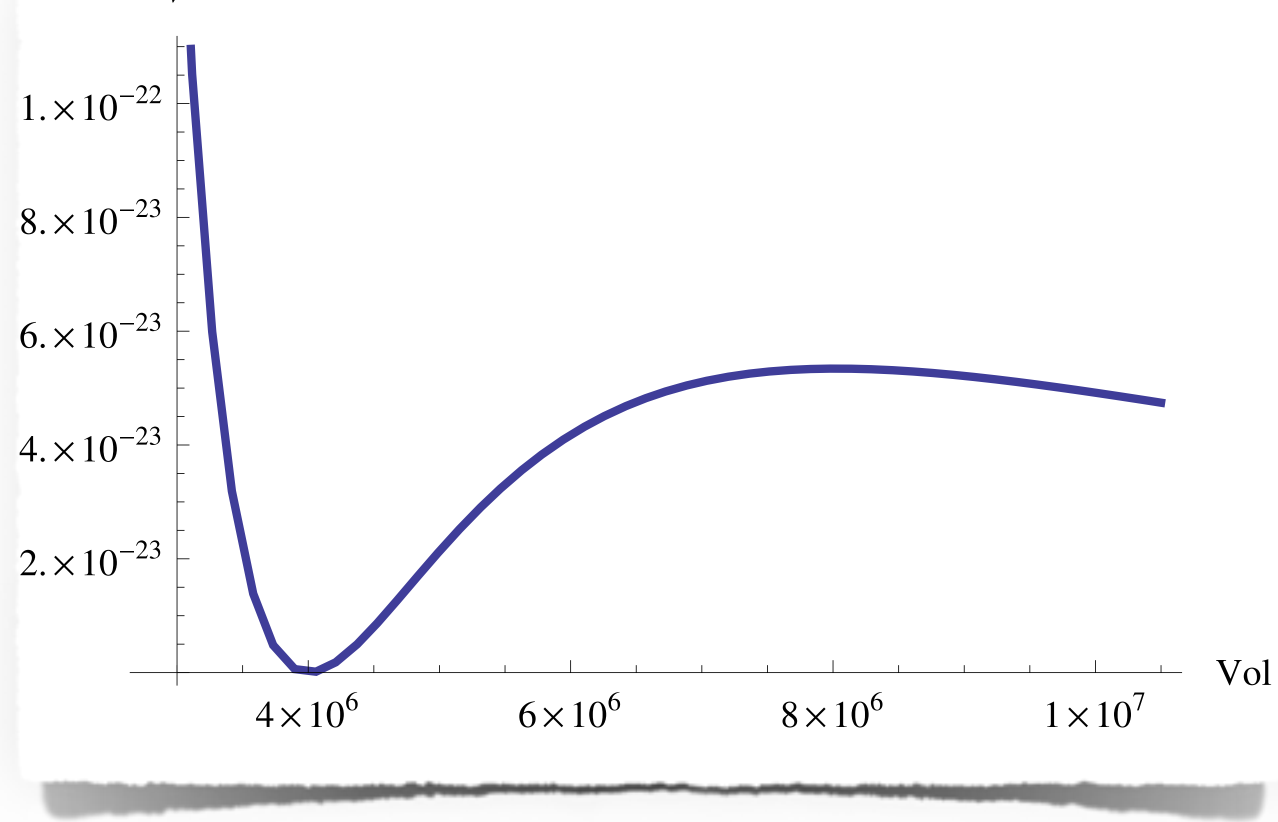
$$\mathcal{V} = \frac{1}{9}\sqrt{\frac{2}{3}}\left(\tau_b^{3/2} - \sqrt{3}\tau_s^{3/2}\right)$$

- singularity stabilisation: D-term minimum at ξ_i=0 and C_i=0 (soft-masses), F-terms sub-leading

$$V_D = \frac{1}{\mathrm{Re}(f_1)}\left(\sum_i q_{1i} K_i C_i - \xi_1\right)^2 + \frac{1}{\mathrm{Re}(f_2)}\left(\sum_i q_{2i} K_i C_i - \xi_2\right)^2\,,$$

$$\xi_1 = -4 q_1 \frac{\tau_+}{\mathcal{V}} \qquad \xi_2 = -4 q_2 \frac{b}{\mathcal{V}}$$

Moduli Stabilisation



- F-term potential

$$V_F \simeq \frac{8}{3}(a_s A_s)^2 \sqrt{\tau_s}\, \frac{e^{-2\,a_s\tau_s}}{\mathcal{V}} - 4\,a_s A_s W_0 \tau_s \frac{e^{-a_s\tau_s}}{\mathcal{V}^2} + \frac{3}{4}\frac{\zeta W_0^2}{g_s^{3/2}\mathcal{V}^3}$$

$$\langle\mathcal{V}\rangle \simeq \frac{3W_0\sqrt{\tau_s}}{4a_s A_s}\, e^{a_s\langle\tau_s\rangle} \qquad \langle\tau_s\rangle \simeq \left(\frac{3\zeta}{2}\right)^{2/3}\frac{1}{g_s}$$

$$\zeta \simeq 0.522 \quad W_0 \simeq 0.2 \quad g_s \simeq 0.03 \quad A_s \simeq 1$$

- FW flux on large four-cycle (matter fields), D-term potential

$$V_{\rm tot} = V_D + V_F \simeq \frac{p_1}{\mathcal{V}^{2/3}}\left(\sum_j q_{bj}|\phi_{c,j}|^2 - \frac{p_2}{\mathcal{V}^{2/3}}\right)^2 + \sum_j \frac{W_0^2}{2\mathcal{V}^2}\,|\phi_{c,j}|^2 + V_F(T)$$

- can account for dS/Minkowski minima...

$$V \simeq \frac{p\,W_0^2}{\mathcal{V}^{8/3}} + V_F(T) \qquad \langle V\rangle = \frac{W_0^2}{\langle\mathcal{V}\rangle^3}\left\{-\frac{3}{4\,a_s^{3/2}}\sqrt{\ln\left(\frac{\langle\mathcal{V}\rangle}{W_0}\right)} + \frac{p}{9}\,\langle\mathcal{V}\rangle^{1/3}\right\}$$

Two ways of getting dS

- dS1: Hidden matter fields (1206.5237):
  balancing 10 vs. 100 (log(V) vs $V^{1/3}$), get on with what's there

$$\langle V \rangle = \frac{W_0^2}{\langle \mathcal{V} \rangle^3} \left\{ -\frac{3}{4\, a_s^{3/2}} \sqrt{\ln\left(\frac{\langle \mathcal{V} \rangle}{W_0}\right)} + \frac{p}{9} \langle \mathcal{V} \rangle^{1/3} \right\}$$

- dS2: Dilaton dependent non-perturbative effects
  (MC, AM, FQ, CB 1203.1750)

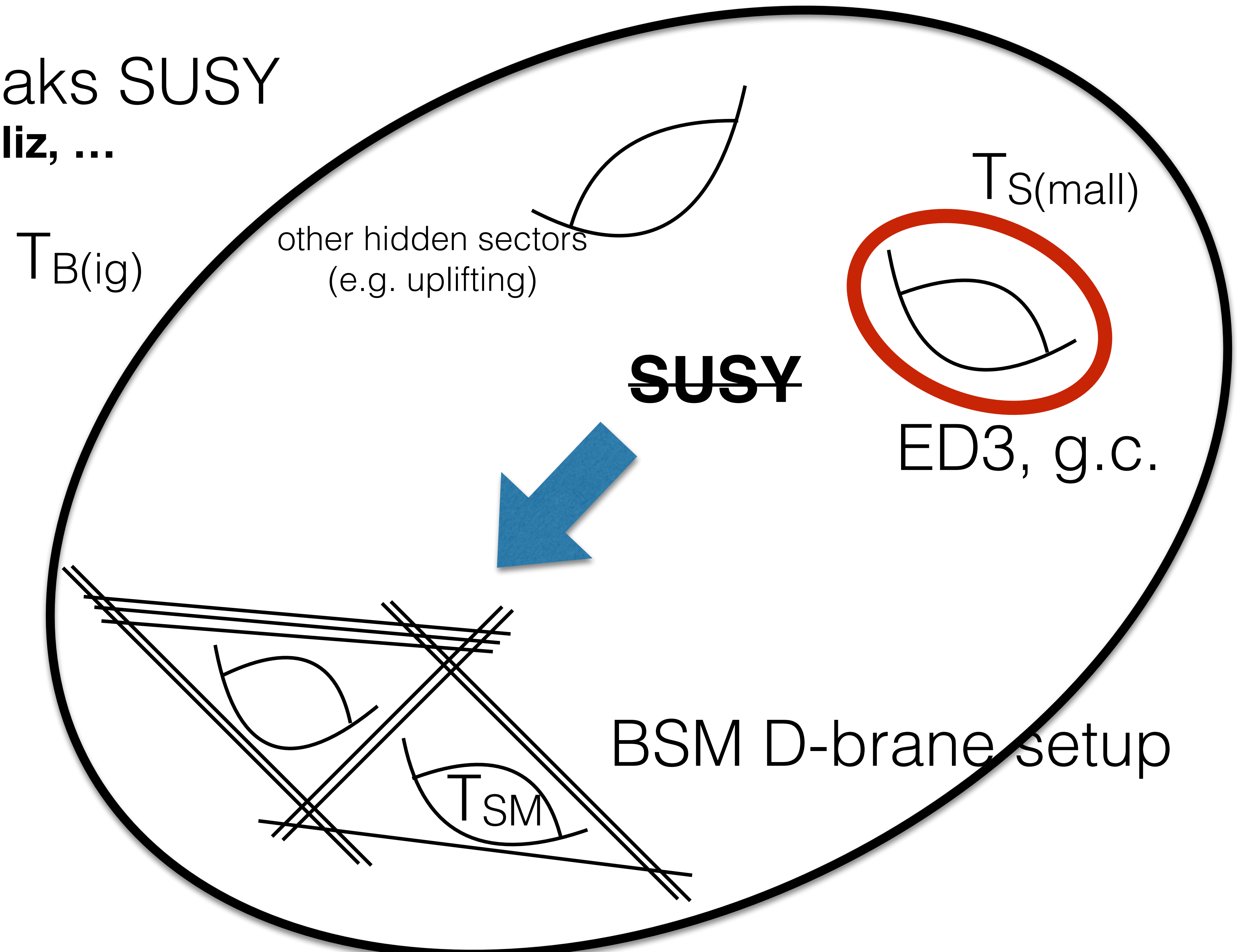
$$W_{\rm dS} = A_{\rm dS}(U,S)\, e^{-a_{\rm dS}(S+\kappa_{\rm dS} T_{\rm dS})} \qquad K_{\rm dS} = \lambda_{\rm dS} \frac{\tau_{\rm dS}^2}{\mathcal{V}}$$

$$V_{\rm tot} = V_{\mathcal{O}(\mathcal{V}^{-3})} + \frac{(\kappa_{\rm dS} a_{\rm dS} A_{\rm dS})^2}{\lambda_{\rm dS} s} \frac{e^{-2a_{\rm dS} s}}{\mathcal{V}} \qquad \left(\frac{\kappa_{\rm dS} a_{\rm dS} A_{\rm dS}}{W_0}\right)^2 e^{-2a_{\rm dS} s} = \frac{9\lambda_{\rm dS}}{32} \frac{\epsilon_s \hat{\xi}}{\mathcal{V}^2}$$

SUSY-breaking

SUSY breaking in LVS

LVS minimum breaks SUSY
Conlon, Quevedo, Suruliz, ...



$$m_{3/2} = \left(\frac{g_s^2}{2\sqrt{2\pi}}\right)\frac{W_0 M_P}{\mathcal{V}} + \dots$$

What are m_{soft}?

3 SUSY scenarios

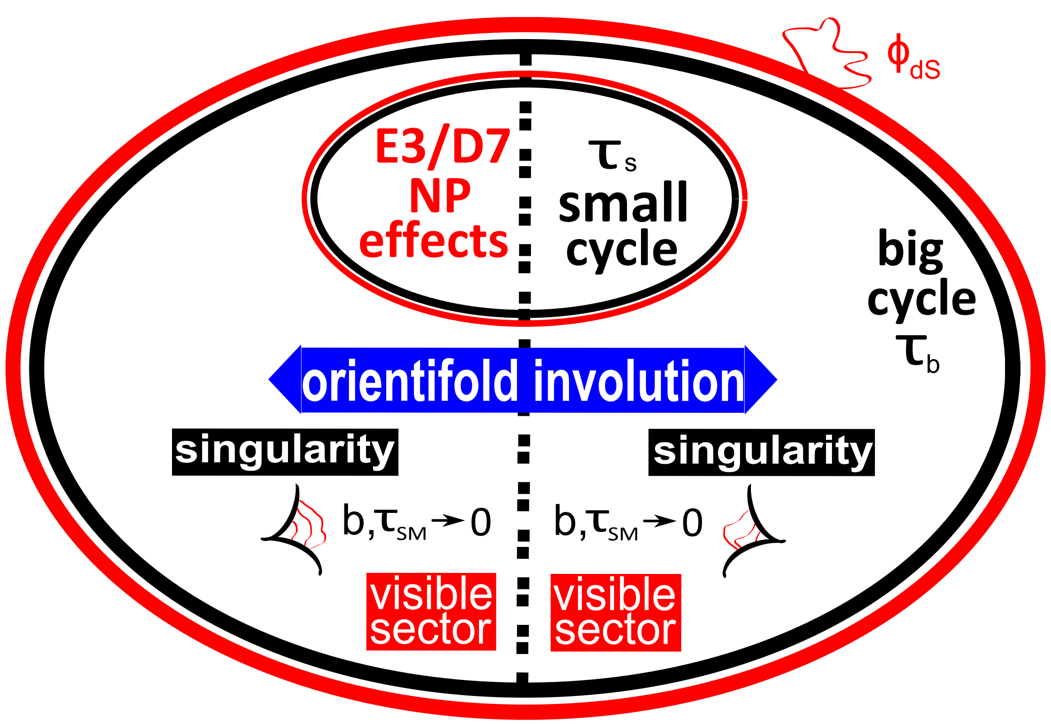
- Unsequestered GUT scale scenarios ($F^{TSM} \neq 0$):
  $M_s \sim M_{GUT}$, $V \sim 10^3 - 10^7$, $M_{SOFT} \sim m_{3/2}$
  (intermediate-scale SUSY, no CMP, W0 tuning)

- Unsequestered intermediate scale strings ($F^{TSM} \neq 0$)
  $M_s \sim 10^{10}$ GeV, $V \sim 10^{10} - 10^{15}$, $M_{SOFT} \sim m_{3/2} \sim 1$ TeV
  (mild hierarchies, low-scale SUSY, CMP)

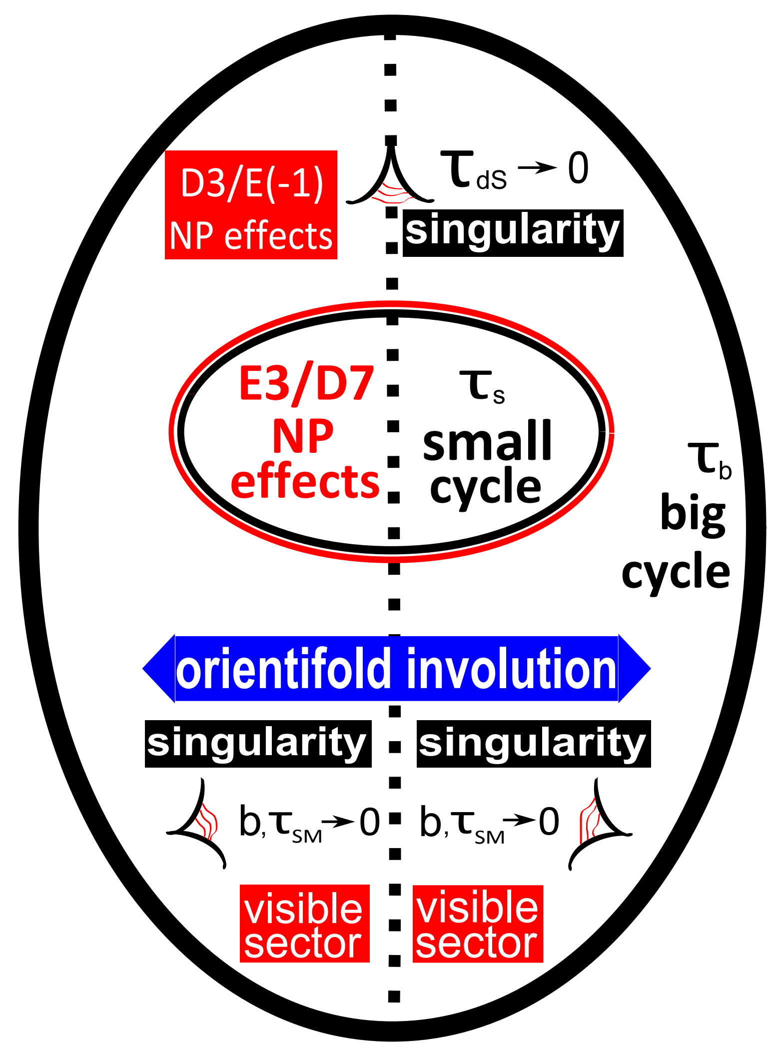
- Sequestered high scale string models ($F^{TSM} = 0$)
  $M_s \sim 10^{15}$ GeV, $V \sim 10^6 - 10^7$, $M_{SOFT} << m_{3/2}$
  (compatible with GUT, split and low-scale SUSY scenarios, no CMP)

Focus: sequestered scenarios

dS1: hidden matter



dS2: dilaton dep. no-effects



EFT

$$K = -2\ln\left(\mathcal{V} + \frac{\hat{\xi}}{2}\right) - \ln(2s) + \lambda_{SM}\frac{\tau_{SM}^2}{\mathcal{V}} + \lambda_b\frac{b^2}{\mathcal{V}} + K_{\rm dS} + K_{\rm cs}(U) + K_{\rm matter}$$

$$W = W_{\rm flux}(U,S) + A_s(U,S)\,e^{-a_sT_s} + W_{\rm dS} + W_{\rm matter}$$

- Kähler matter potential

$$K_{\rm matter} = \tilde{K}_\alpha(M,\overline{M})\overline{C}^{\overline{\alpha}}C^\alpha + [Z(M,\overline{M})H_uH_d + {\rm h.c.}]$$

$$\tilde{K}_\alpha = \frac{f_\alpha(U,S)}{\mathcal{V}^{2/3}}\left(1 - c_s\frac{\hat{\xi}}{\mathcal{V}} + \tilde{K}_{\rm dS} + c_{\rm SM}\tau_{\rm SM}^p + c_b b^p\right)$$

- Gauge kinetic function

$$f_a = \delta_a S + \kappa_{ak}T_k \qquad f_a = S + \kappa_a T_{\rm SM}$$

- Superpotential

$$W_{\rm matter} = \mu(M)H_uH_d + \frac{1}{6}Y_{\alpha\beta\gamma}(M)C^\alpha C^\beta C^\gamma + \cdots$$

dS dep. on minimum and F-terms

- Sub-leading shift in LVS minimum:

$$\tau_s^{3/2} = \frac{\hat{\xi}}{2}\left[1 + f_{\mathrm{dS}}(\epsilon_s)\right] \qquad \mathcal{V} = \frac{3\sqrt{\tau_s}W_0 e^{a_s\tau_s}}{4a_sA_s}\frac{(1-4\epsilon_s)}{(1-\epsilon_s)}$$

$$\epsilon_s \equiv \frac{1}{4a_s\tau_s} \sim \mathcal{O}\left(\frac{1}{\ln\mathcal{V}}\right) \ll 1$$

$$f_{\mathrm{dS1}} = 18\epsilon_s + 297\epsilon_s^2 \qquad f_{\mathrm{dS2}} = 3\epsilon_s + 12\epsilon_s^2$$

- F-terms

$$\frac{F^{T_b}}{\tau_b} \simeq -2m_{3/2}\left(1 + \frac{x_{\mathrm{dS}}}{a_s^{3/2}\mathcal{V}\sqrt{\epsilon_s}}\right) \qquad \frac{F^{T_s}}{\tau_s} \simeq -6m_{3/2}\epsilon_s \qquad \begin{array}{l} x_{\mathrm{dS1}} = -45/16 \\ x_{\mathrm{dS2}} = 0 \end{array}$$

$$\frac{F^S}{s} \simeq \frac{3\omega'_S(U,S)}{8a_s^{3/2}}\frac{m_{3/2}}{\mathcal{V}\epsilon_s^{3/2}} \qquad F^{U_i} \simeq -\frac{K^{U_i\overline{U}_{\bar{j}}}}{2s^2}\frac{\omega_{\overline{U}_{\bar{j}}}(U,S)}{\omega'_S(U,S)}F^S \equiv \beta^{U_i}(U,S)F^S$$

$$\frac{F^{\phi_{\mathrm{dS}}}}{\phi_{\mathrm{dS}}} \simeq m_{3/2} \qquad F^{T_{\mathrm{dS}}} \simeq \frac{3}{4\sqrt{2}a_s^{3/4}}\frac{m_{3/2}}{\epsilon_s^{1/4}}$$

Soft-terms in detail

soft-term formulae: Brignole, Ibanez, Munoz; Dudas Vempati; …

Gaugino Masses

$$F^G = F^{T_{\rm SM}} = 0 \qquad\qquad f_a = S + \kappa_a T_{\rm SM}$$

$$M_a = \frac{1}{2{\rm Re}\,(f_a)} F^I \partial_I f_a$$

$$M_{1/2} = \frac{F^S}{2s} \simeq \frac{3\omega'_S(U,S)}{16 a_s^{3/2}} \frac{m_{3/2}}{\mathcal{V}\epsilon_s^{3/2}} \sim \mathcal{O}\left(m_{3/2}\frac{(\ln\mathcal{V})^{3/2}}{\mathcal{V}}\right) \ll m_{3/2}$$

(Ultra)-Local

$$\hat{Y}_{\alpha\beta\gamma} = e^{K/2}\,\frac{Y_{\alpha\beta\gamma}(U,S)}{\sqrt{\tilde{K}_\alpha \tilde{K}_\beta \tilde{K}_\gamma}} \qquad \tilde{K}_\alpha = h_\alpha(S,U)\, e^{K/3} \simeq \frac{h_\alpha(U,S)\, e^{K_{\rm cs}/3}}{(2s)^{1/3}\mathcal{V}^{2/3}}\left(1 - \frac{\hat{\xi}}{3\mathcal{V}} + \frac{1}{3}K_{\rm dS}\right)$$

- Additional no-scale cancellations:

$$\begin{aligned} m_\alpha^2 &= \left[m_{3/2}^2 + V_0 - \bar{F}^{\bar{m}}\left(\partial_{\bar{m}}\partial_n \log(\tilde{K}_\alpha)\right)F^n\right] \\ &= \tilde{K}_\alpha\left[m_{3/2}^2 - \bar{F}^{\bar{m}}\left(\partial_{\bar{m}}\partial_n \frac{K}{3}\right)F^n\right] = -\tilde{K}_\alpha \frac{V_0}{3} = 0 \end{aligned}$$

- Local: Holds at V^{-1}, Ultra-Local: Holds exactly

Scalar masses

Scalar masses

$$m_{i\bar{j}} = \partial_i \partial_{\bar{j}} V = \nabla_i \nabla_{\bar{j}} V$$

Scalar masses

$$m^2_{i\bar{j}} = \left(e^G \left[G_{i\bar{j}} + \nabla_i G^{\bar{k}} \nabla_{\bar{j}} G_{\bar{k}} - R_{i\bar{j}k\bar{l}} G^k G^{\bar{l}} \right] + \frac{1}{2} g_A^2 D_A^2 \left(G_i G_{\bar{j}} - G_{i\bar{j}} \right) \right.$$
$$\left. - g_A^2 D_A \left(G_{\bar{j}} \partial_i D_A + G_i \partial_{\bar{j}} D_A - \partial_i \partial_{\bar{j}} D_A \right) + g_A^2 \partial_i D_A \partial_{\bar{j}} D_A \right) \left(\tilde{K}_i \tilde{K}_{\bar{j}} \right)^{-1/2}$$

Scalar masses

$$m^2_{i\bar{j}} = \left(e^G \left[G_{i\bar{j}} - R_{i\bar{j}k\bar{l}} G^k G^{\bar{l}}\right] - \frac{1}{2} g_A^2 D_A^2 G_{i\bar{j}} + g_A^2 D_A \partial_i \partial_{\bar{j}} D_A\right) \left(\tilde{K}_i \tilde{K}_{\bar{j}}\right)^{-1/2}$$

Scalar masses

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dS1:

local:

$$m_0^2\big|_F \simeq m_{3/2}^2 - \left(\frac{F^{T_b}}{2}\right)^2 \partial^2_{\tau_b} \ln \tilde{K} \simeq \frac{5\left(c_s - \frac{1}{3}\right)}{\omega'_S} m_{3/2} M_{1/2} \sim \mathcal{O}\left(m_{3/2}^2 \frac{(\ln \mathcal{V})^{3/2}}{\mathcal{V}}\right)$$

ultra-local:

$$m_0^2\big|_D = \frac{6\epsilon_s}{\omega'_S} m_{3/2} M_{1/2} \sim \mathcal{O}\left(m_{3/2}^2 \frac{\sqrt{\ln \mathcal{V}}}{\mathcal{V}}\right)$$

dS2:

ultra-local:

$$m_\alpha^2 = c_\alpha M_a^2 \neq 0$$

mu-term

- Kähler potential contributions

$$\hat{\mu} = \left(m_{3/2} Z - \overline{F}^{\overline{I}} \partial_{\overline{I}} Z \right) \left(\tilde{K}_{H_u} \tilde{K}_{H_d} \right)^{-1/2} \quad \text{and} \quad B\hat{\mu} = B\hat{\mu}|_F + B\hat{\mu}|_D$$

$$B\hat{\mu}|_F = \left\{ 2m_{3/2}^2 Z - m_{3/2} \overline{F}^{\overline{I}} \partial_{\overline{I}} Z + m_{3/2} F^I \left[\partial_I Z - Z \partial_I \ln \left(\tilde{K}_{H_u} \tilde{K}_{H_d} \right) \right] \right.$$

$$\left. - F^I \overline{F}^{\overline{J}} \left[\partial_I \partial_{\overline{J}} Z - \partial_I Z \partial_{\overline{J}} \ln \left(\tilde{K}_{H_u} \tilde{K}_{H_d} \right) \right] \right\} \left(\tilde{K}_{H_u} \tilde{K}_{H_d} \right)^{-1/2},$$

$$B\hat{\mu}|_D = \left(\tilde{K}_{H_u} \tilde{K}_{H_d} \right)^{-1/2} \left(\sum_i g_i^2 D_i \partial_{H_u} \partial_{H_d} D_i - V_{D,0} Z \right)$$

$$Z = \gamma(U,S) \tilde{K}$$

$$B\hat{\mu} = c_B m_0^2 \qquad \hat{\mu} = c_\mu M_{1/2}$$

mu-term

- superpotential contributions

$$\hat{\mu} = \mu\, e^{K/2} \left(\tilde{K}_{H_u} \tilde{K}_{H_d}\right)^{-1/2}$$

$$B\hat{\mu} = \mu\, e^{K/2} \left[F^I \left(K_I + \partial_I \ln \mu - \partial_I \ln\left(\tilde{K}_{H_u} \tilde{K}_{H_d}\right)\right) - m_{3/2}\right] \left(\tilde{K}_{H_u} \tilde{K}_{H_d}\right)^{-1/2}$$

$$W \supset e^{-aT} H_u H_d \quad \Rightarrow \quad \mu_{\rm eff} = e^{-aT}$$

$$W \supset e^{-b(S+\kappa T)} H_u H_d \quad \Rightarrow \quad \mu_{\rm eff} = e^{-b(S+\kappa T)}$$

$$\hat{\mu} \simeq \frac{c_\mu(U,S)}{\mathcal{V}^{n+\frac{1}{3}}} \qquad \text{and} \qquad B\hat{\mu} \simeq \frac{c_B(U,S)}{\mathcal{V}^{n+\frac{4}{3}}}$$

$$T = T_s \text{ and } a = n a_s$$

- via matter fields (model dependent)

Summary of soft-terms

Soft term	Local Models	Ultra Local dS_1	Ultra Local dS_2
$M_{1/2}$	$c_{1/2}\, m_{3/2}\, \frac{m_{3/2}}{M_P} \left[\ln\left(\frac{M_P}{m_{3/2}}\right)\right]^{3/2}$		
m^2_α	$c_0\, m_{3/2} M_{1/2}$	$c_0\, \frac{m_{3/2} M_{1/2}}{\ln(M_P/m_{3/2})}$	$(c_0)_\alpha\, M^2_{1/2}$
$A_{\alpha\beta\gamma}$	$(c_A)_{\alpha\beta\gamma}\, M_{1/2}$		
$\hat{\mu}$	$c_\mu\, M_{1/2}$ (contribution from K) $c_\mu M_P \left[\frac{m_{3/2}}{M_P}\right]^{n+1/3}$ (contribution from W)		
$B\hat{\mu}$	$c_B\, m_0^2$ (contribution from K) $c_B m_{3/2} \left[\frac{m_{3/2}}{M_P}\right]^{n+1/3}$ (contribution from W)		

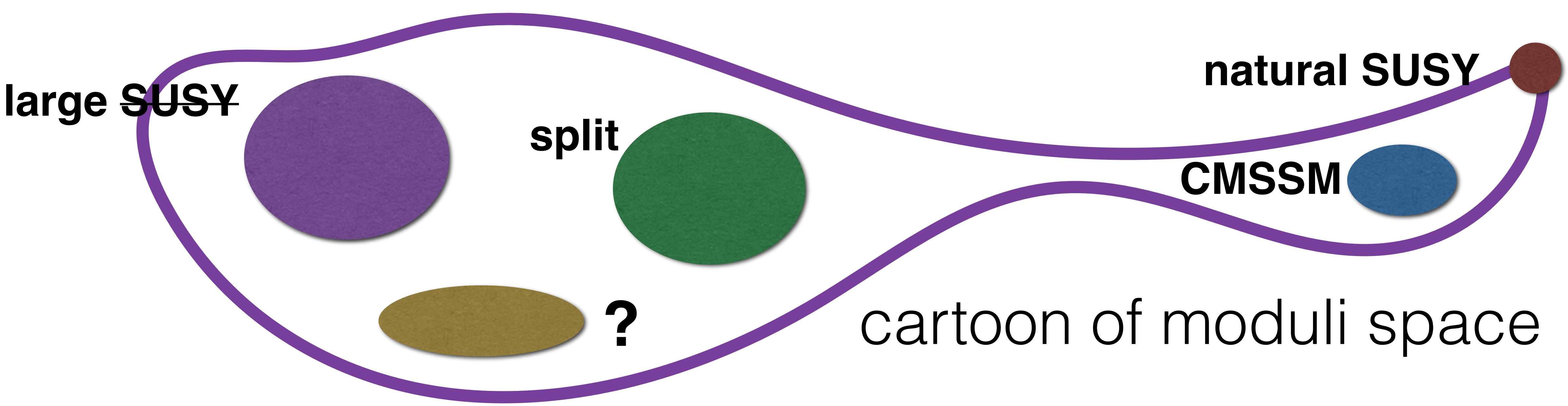
$W \supset A_{\rm H} e^{-n a_s T_s} H_u H_d \qquad Z = \gamma(U,S)\tilde{K}$

Future goals

- Reduce assumptions by increasing string theory input:
  - MSSM vs. real D-brane configurations
  - Improved understanding of EFT: Kähler matter metric (non-universalities)
  - Realising more uplifting scenarios explicitly

- Phenomenology analysis

- Making string SUSY landscape more precise:



Conclusions

- Global models with dS moduli stabilisation and chiral matter, allow more refined view on SUSY breaking in LVS
- New benchmark scenarios for sequestered SUSY breaking. Stay tuned for phenomenological analysis
- D-terms are important and interesting for soft-masses
- Low-energy SUSY can address hierarchy problem, fluxes used for mild hierarchies
- Way of flux landscape interpolating between local and ultra-local scenarios

Thank you!