# A1: Quintessence, Branes and Higher Dimensions

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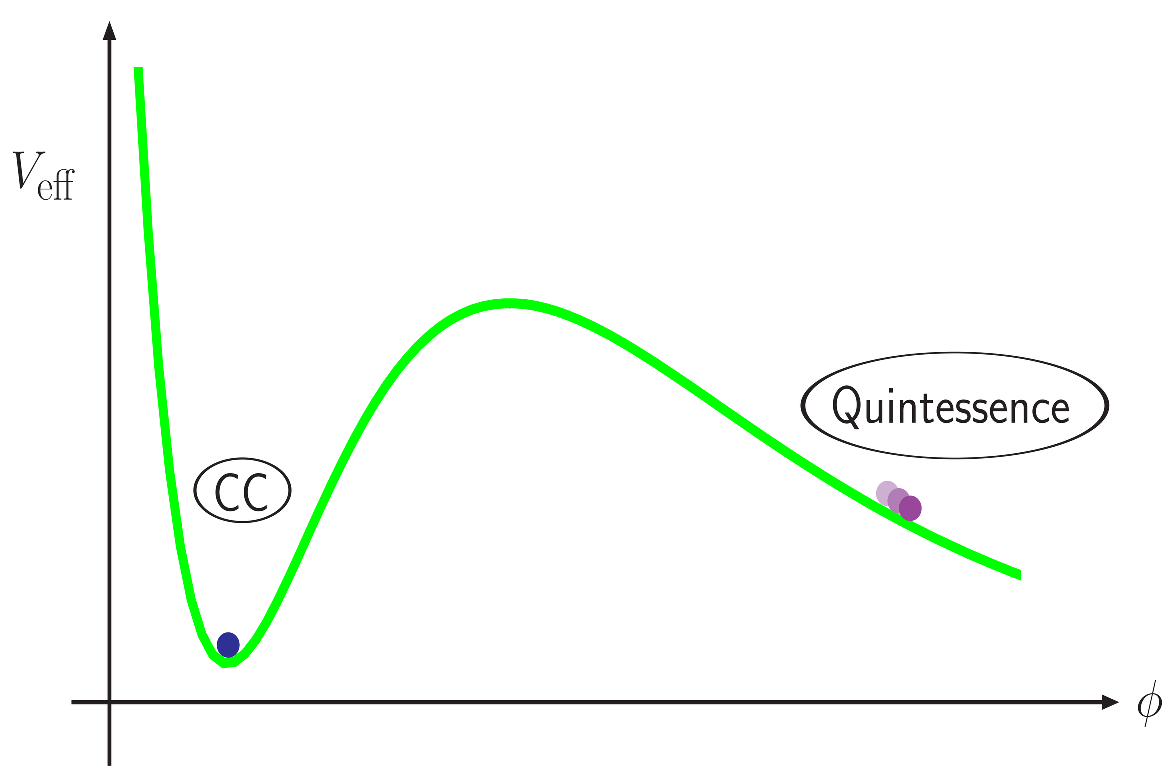
## Project Overview

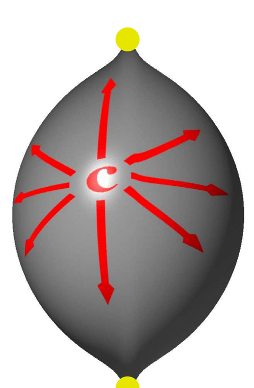
Project A1 is concerned with the realisation of dark energy in higher-dimensional theories and the possible observational consequences. This encompasses

- moduli stabilisation in heterotic string theory and F-theory,
- mechanisms to up- or downlift the vacuum energy to the right value,
- the connection of uplifting to supersymmetry breaking and mirage mediation,
- realisation of quintessence from an (anomalous) dilatation symmetry,
- and possible time variations of fundamental constants.

## Dark Energy in Higher-Dimensional Theories

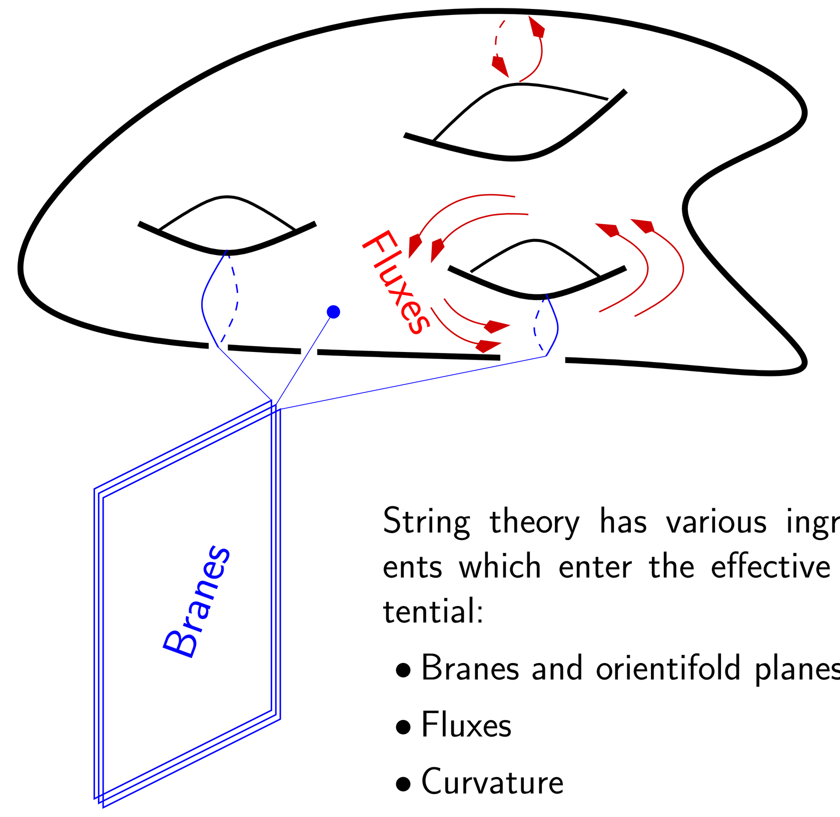



- Effective potential is generally a sum of different contributions (curvature, branes, singularities, fluxes, higher-dimensional cosmological constants, ...)
- Two possible places for dark energy:
  - tunable minimum: acts as cosmological constant (CC)
  - runaway directions: quintessence
- Quintessence implies that the dark energy equation of state, and possibly fundamental constants, vary in time
- In the (metastable, long-lived) minimum, only one number measurable, need indirect clues
- Realisation in string theory: Moduli stabilisation and up-/downlifting of minimum provide correct value for vacuum energy, generating particular mass spectra
- Bottom-up approach: dilatation symmetry, conical singularities in extra dimensions provide quintessence potentials or tuning mechanisms



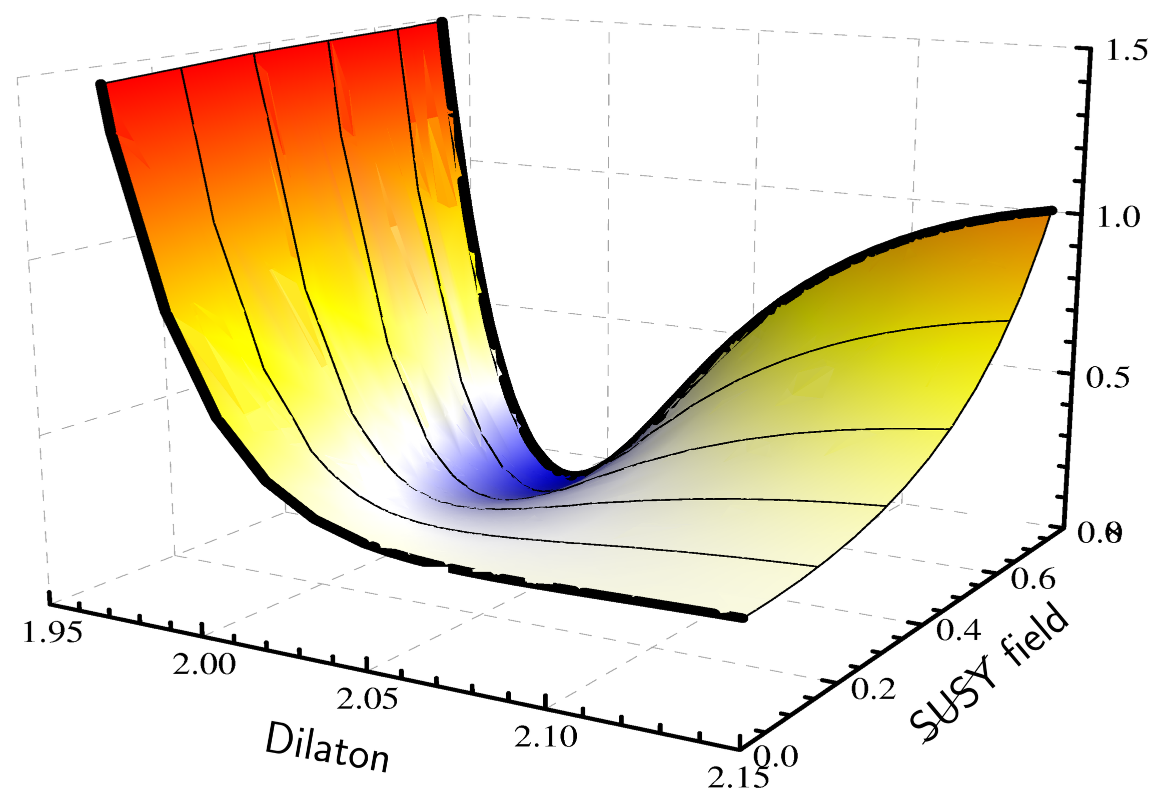
Conical singularities, characterised by a deficit angle, in rugby-shaped extra dimensions. The internal space is stabilised by a bulk cosmological constant and a gauge field flux. The deficit angle can (partially) cancel a cosmological constant on the branes.

## String Theory Realisation: Type II, Heterotic




String theory has various ingredients which enter the effective potential:

- Branes and orientifold planes
- Fluxes
- Curvature
- Gaugino condensates
- Localised Matter fields




[Löwen, Nilles, Phys. Rev. D77; Braun, Hebecker, Lüdeling, Valandro, Nucl. Phys. B815]

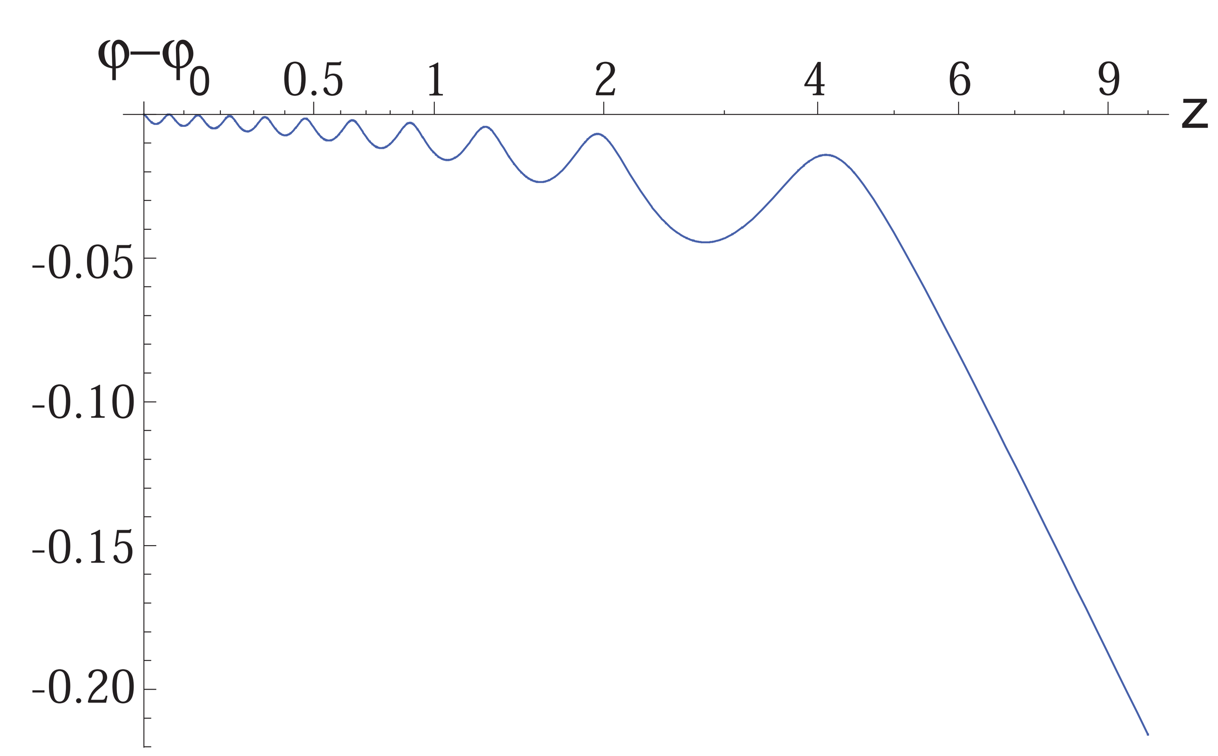
String compactifications generally have a number of scalar "moduli" fields that parameterise e.g. the size and shape of the extra dimensions, brane configurations or gauge couplings. These fields are initially massless and need to be stabilised to obtain a reasonable low-energy theory. This can be accomplished e.g. by introducing fluxes, background values of $p$-form field strengths, or by including non-perturbative effects such as gaugino condensation.

Furthermore, supersymmetry needs to be broken and the vacuum energy must be adjusted to the observed value. These effects are related e.g. in the KKLT scenario where $\overline{\text{D3}}$ branes are used and in heterotic models with hidden sector matter fields.

## Rolling Quintessence

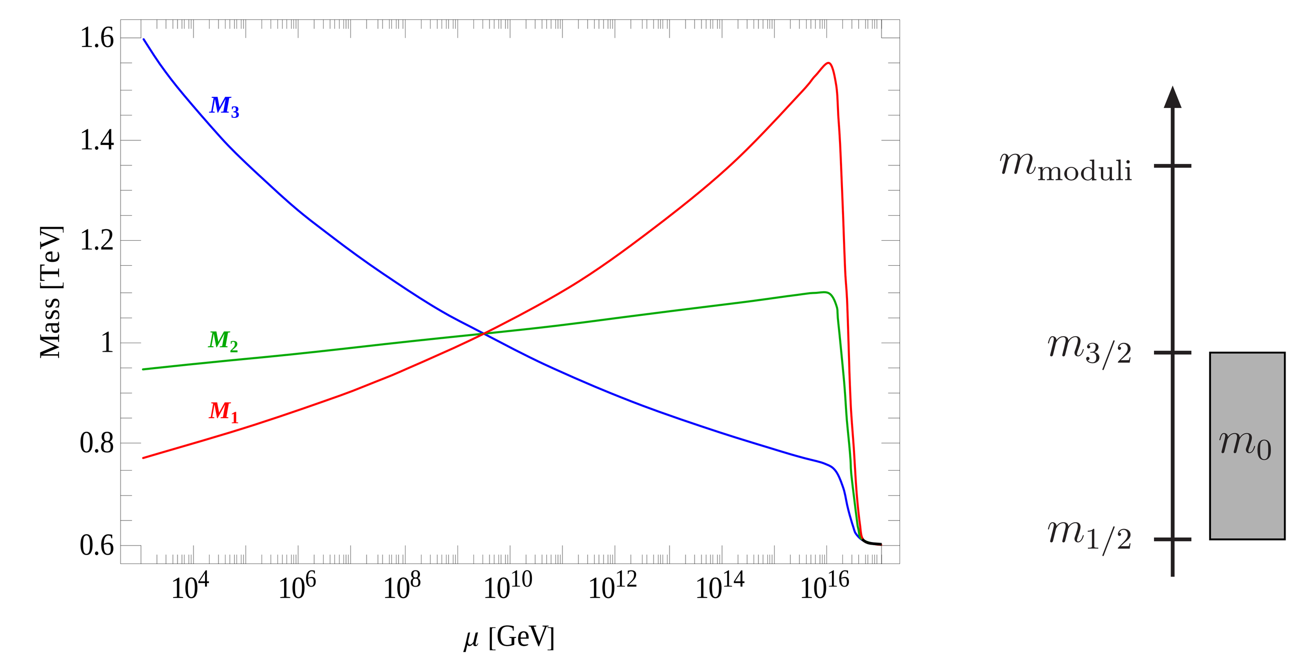
In many higher-dimensional models, couplings are related to the expectation values of fields (for example, in the heterotic string, the gauge coupling is a function of the dilaton). A rolling scalar field can hence lead to the variation of couplings and masses. Indeed a variation of the fine structure constant has been claimed to be detected ($\alpha$ being smaller in the past). These observations, made by looking at the light coming from distant quasars, seem to be inconsistent with low redshift constraints, such as the Oklo natural reactor and meteorites, but also laboratory experiments with atomic clocks. Current data, therefore, suggests that any variation of the fine structure constant has to be negligible at low redshift and it can only be consistent with nonzero variation claimed by of Murphy et al. provided the scalar field has a non-linear evolution. This could in principle be accomplished in the mass-varying neutrino scenario.

Evolution of quintessence field $\varphi$ as function of redshift in a "stopping growing neutrinos" scenario:




[Wetterich, Phys. Lett. B655; Dent, Stern, Wetterich, JCAP 0901]

## Mirage Spectrum

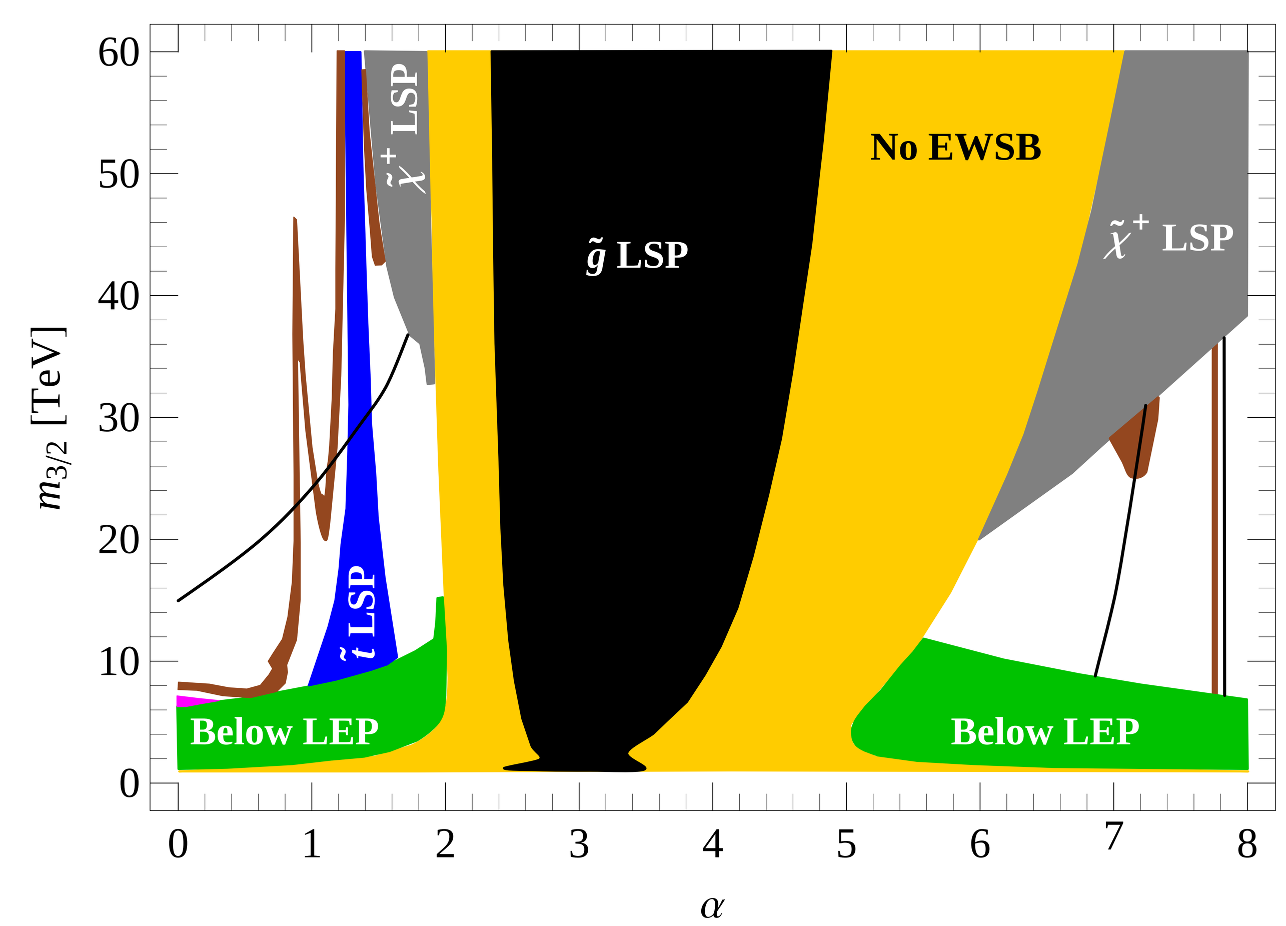



After adjusting the vacuum energy, a mirage pattern appears both in KKLT-like type IIB flux compactification and in heterotic models:

[Choi,Falkowski, Nilles, Olechowski, Nucl. Phys B718; Löwen, Nilles, Phys. Rev. D77]

- Mixture of modulus- and anomaly-mediated supersymmetry breaking
- Apparent unification of gaugino masses at intermediate "mirage" scale without actual thresholds
- Masses of moduli, gravitino and gauginos separated by "little hierarchy" $\Omega = \log \frac{M_P}{m_{3/2}} \sim 4\pi$, while soft scalar masses show larger model dependence
- Gaugino masses exhibit distinct pattern [Choi, Nilles, JHEP 0704]

## Mirage Spectrum: Cosmological Bounds




[Löwen, Nilles, Nucl. Phys. B827]

The mirage spectrum is controlled by a parameter $\alpha$ which determines the ratio of modulus and anomaly mediation ($\alpha = 0$ corresponds to pure modulus mediation, $\alpha = \infty$ to pure anomaly mediation). The plot shows constraints on the $\{\alpha, m_{3/2}\}$ parameter space from various mostly cosmological bounds. In the brown strip, the neutralino thermal abundance satisfies the WMAP bound.