The Ubiquitous Scalar Fields

ESF workshop

Porto March 2008

Outline

1-Moduli Fields

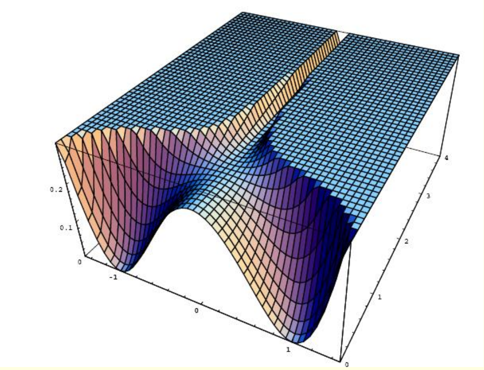
2-Modular Inflation

3-Chameleon Fields

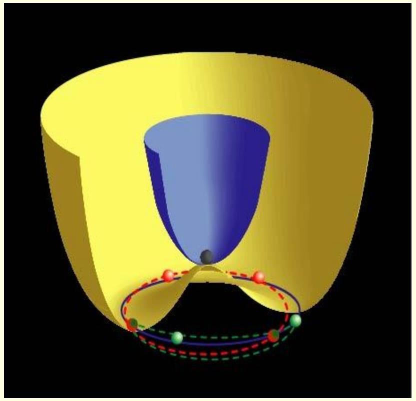
4-Quantum Difficulties

Ubiquitous Scalars

Theorists always resort to scalar fields when at loss:



The Inflaton

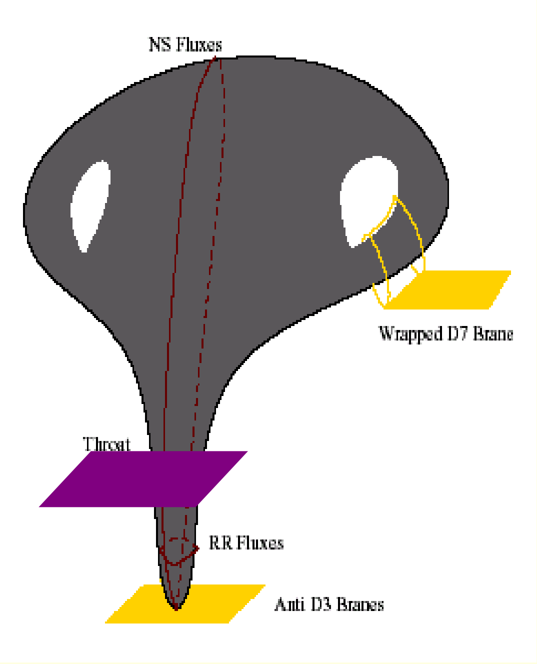


The Higgs field

Moduli Fields

Nasty Beasts: the Moduli

KKLT scenario



Beyond the standard model physics leads to the existence of myriads of scalar fields: the moduli

A few examples

The dilaton is a moduli as string perturbation theory does not fix its value:

Dilaton $\longleftrightarrow$ gauge coupling constant

A few examples

Moduli fields parameterise flat directions of the scalar potential in supersymmetric models:

Flat direction $\longleftrightarrow$ gauge invariants

A few examples

Flat directions can have a direct geometric origin, e.g. shape moduli (Kahler or complex structure)

Shape $\longleftrightarrow$ Newton's constant

A few examples

Moduli can have a dynamical origin, e.g. brane distances of BPS configurations (no force).

Brane distance $\longleftrightarrow$ inflaton

Moduli Problems?

No massless scalar particles have ever been observed. Need to give a mass to the moduli:

How massive??

Which potential??

How Massive?

Long lived moduli couple gravitationally with ordinary matter, leading to the presence of a new Yukawa interaction:

$$\boxed{F_{12} = \frac{G_N m_1 m_2}{r^2}(1 + \alpha_1 \alpha_2 e^{-mr})}$$

Unless the coupling is dynamically reduced (chameleons), fifth force experiments imply that the mass of moduli must be

$$\boxed{m \geq 10^{-3}\ \text{eV}}$$

corresponding to a range lower than a millimetre.

Moduli can decay. Depending on their mass, they can either decay early in the universe or be still present now.

Long Lived Moduli

Gravitational problems are only present for long-lived moduli.
If decay rate:

$$\Gamma = \frac{m^3}{m_{\rm Pl}^2}$$

smaller than the Hubble rate now, moduli have not decayed, i.e.

$$m \leq 20\text{MeV}$$

moduli behave like matter in the radiation era. Its energy density may dominate now unless

$$m \leq 10^{-26}\text{eV}$$

Low mass moduli with gravitational couplings are not compatible with cosmology.

Short Lived Moduli

Moduli can be very massive and may have decayed well before the present day.

The decay must happen before Big Bang Nucleosynthesis as it releases an enormous amount of entropy

$$\frac{S_{\text{decay}}}{S_{\text{radiation}}} \sim \frac{m_{\text{Pl}}}{m}$$

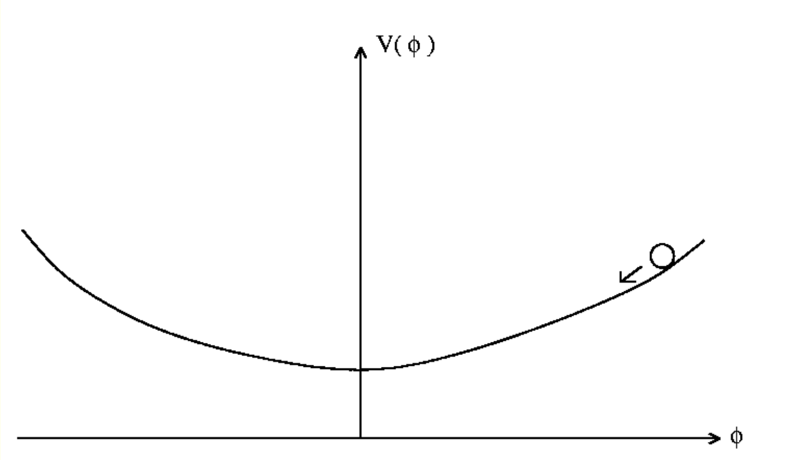
The reheat temperature due to the decay is greater than 1 MeV (BBN) provided:

$$m \geq 10\,\text{TeV}$$

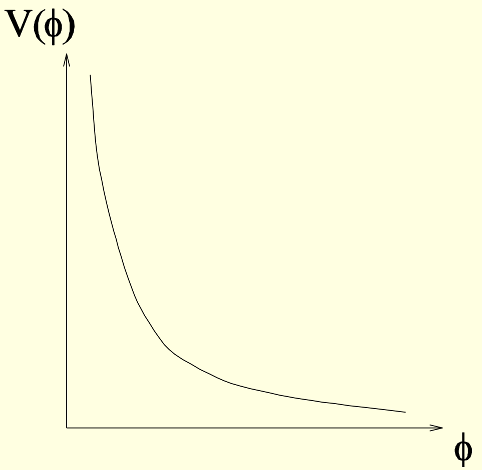
very heavy moduli are favoured.

Stable Moduli?

If stable then moduli must be very massive- TeV range.



Another attractive possibility: runaway behaviour. Possibility of generating inflation and/or dark energy



The w sieve

Energy density and pressure:

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi), \; p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

Runaway fields can be classified according to

$$\boxed{w = \frac{p}{\rho}}$$

$m \gg H_0$	very fast roll	$w \approx 1$
$m \ll H_0$	slow roll	$w \approx -1$ (inflation)
$m \approx H_0$	gentle roll	$w \neq -1$ (quintessence)

$H_0 \approx 10^{-43}\mathrm{GeV}$ $\longrightarrow$ strong gravitational constraints

Which Potential?

Moduli parameterise flat directions to all order of perturbation theory in supersymmetric theory. Necessitates non-perturbative arguments like in ordinary QCD.

Prototype non-perturbative results occur in SUSY QCD

The low energy physics is well described by the physics of mesons (condensates of quarks and antiquarks)

The flat direction is lifted by the superpotential:

$$\boxed{W \sim \left(\frac{\Lambda^{3N_c - N_f}}{\det M} \right)^{1/(N_c - N_f)}}$$

Ratra- Peeble Attractor

During matter era, moduli with potential

$$V = \frac{\Lambda^{4+\alpha}}{\phi^{\alpha}}$$

converge to an attractor

$$\phi \sim a^{4/(\alpha+2)}, \ \rho \sim a^{-3\alpha/(\alpha+2)}$$

whose equation of state is

$$\boxed{w = -\frac{2}{\alpha + 2}}$$

Modular Inflation

Modular Inflation

Models where moduli play the role of the inflaton

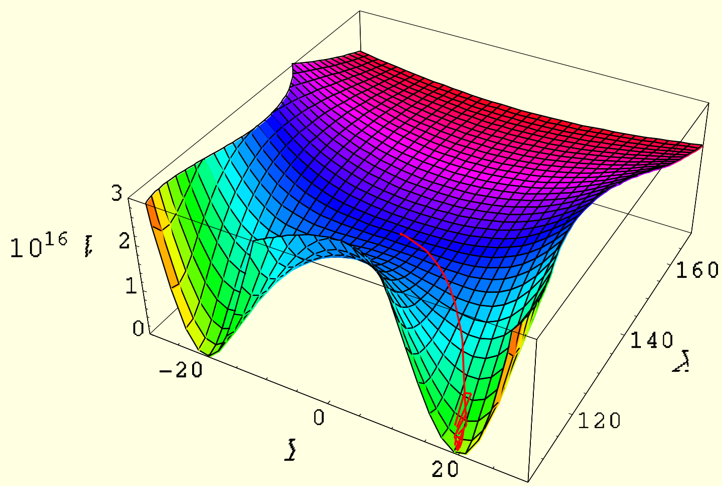
Uses the the potential in the imaginary part of T (whose real part is the radius of compactification) to generate inflation.

The original racetrack uses

$$\boxed{W = W_0 + Ae^{-aT} + Be^{-bT}}$$

The inflaton starts from a saddle point and rolls down towards the Minkowski minimum.

Racetrack Inflation



D-uplifted racetrack

The superpotential is

Non-perturbative potential

$$W = W_0 + A\Phi^{-ra}e^{-aT} + B\Phi^{-bT}e^{-bT}$$

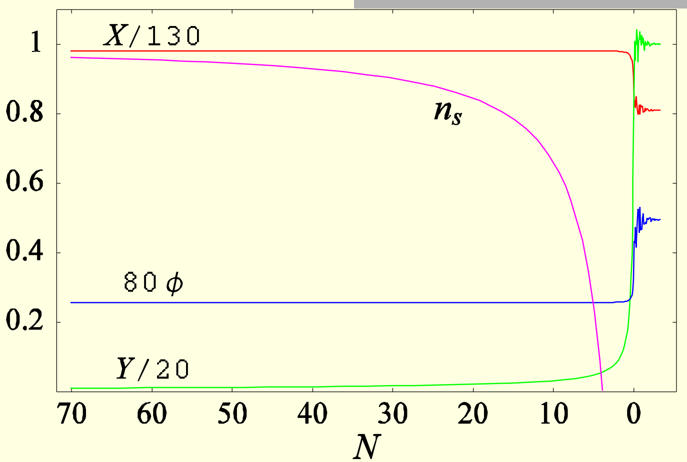
The field Φ is a meson formed from quarks.

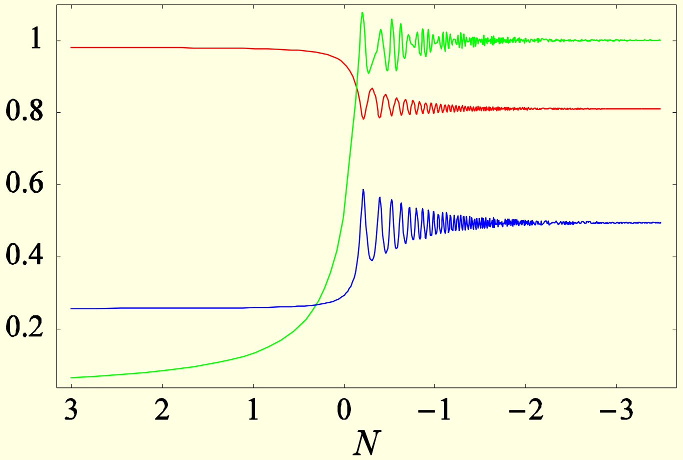
$$\Lambda \sim e^{-aT}$$

- The moduli X and Φ evolve between the saddle point and the Minkowski vacuum.
- Inflation leads to no gravitational waves and

$$\boxed{n_s \approx 0.948}$$

WHY ?





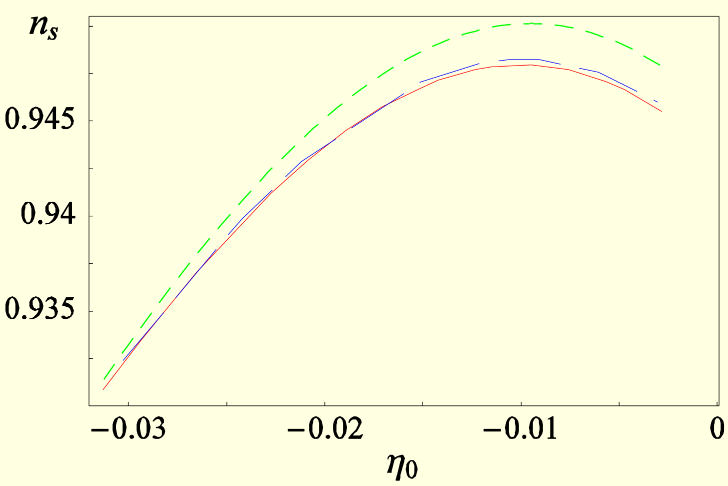
Effective Potential

- All the racetrack potentials are described by an effective potential around the saddle point

$$V = V_{\mathrm{sad}}(1 + \frac{\eta_0}{2} y^2 + C\frac{y^4}{4} + \ldots)$$

- The spectral index is a function of the η parameter at the saddle point only.

$$n_s = 1 + 2\eta_0 - \frac{6\eta_0}{1 - e^{-2N\eta_0}}$$



- The error is of the order of 1 per mil explaining the robustness of the spectral index in racetrack inflationary models.

Chameleons and dark energy

Dark Energy Effective Theory

Effective field theories with gravity and scalars

$$S=\int d^4x\sqrt{-g}(\frac{1}{16\pi G_N}R-\frac{1}{2}(\partial\phi)^2-V(\phi)+\mathcal{L}_m(\psi_m,A^2(\phi)g_{\mu\nu}))$$

deviation from Newton's law

$$\alpha=\frac{\partial\ln A}{\partial\phi}$$

The radion

The distance between branes in the Randall-Sundrum model:

$$\boxed{A(\phi) = \cosh \frac{\phi}{\sqrt{6}}}$$

where

$$R = \frac{1}{k} \ln \tanh \frac{\phi}{\sqrt{6}}$$

Deviations from Newton's law

$$\alpha = \frac{1}{\sqrt{6}} \tanh(\frac{\phi}{\sqrt{6}})$$

Far away branes $\longrightarrow$ small deviations

close branes $\qquad A(\phi) = \exp \frac{\phi}{\sqrt{6}}$

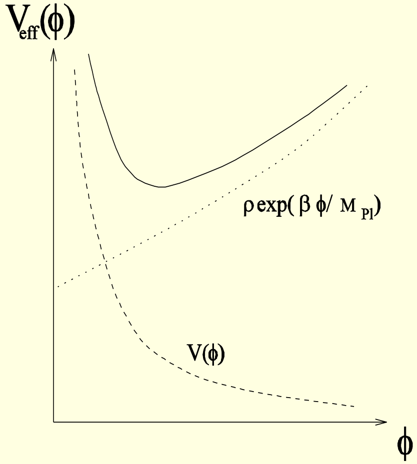
constant coupling constant

$$\boxed{\alpha = \frac{1}{\sqrt{6}}}$$

The Chameleon Mechanism

When coupled to matter, scalar fields have a matter dependent effective potential

$$\boxed{V_{eff}(\phi) = V(\phi) + \rho_m A(\phi)}$$



Chameleon field: field with a matter dependent mass

$$\boxed{m_Q^2 \approx 8\pi G_N \rho_{\mathrm{matter}}}$$

A way to reconcile gravity tests and cosmology:

Nearly massless field on cosmological scales

Massive field in the laboratory

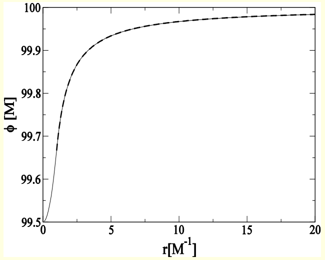
The Thin Shell Effect

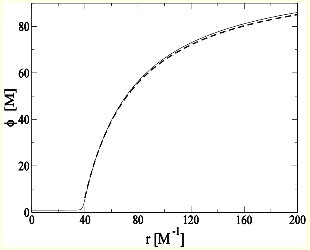
The field outside a compact body of radius R interpolates between the minimum inside and outside the body

Inside the solution is nearly constant up to the boundary of the object and jumps over a thin shell

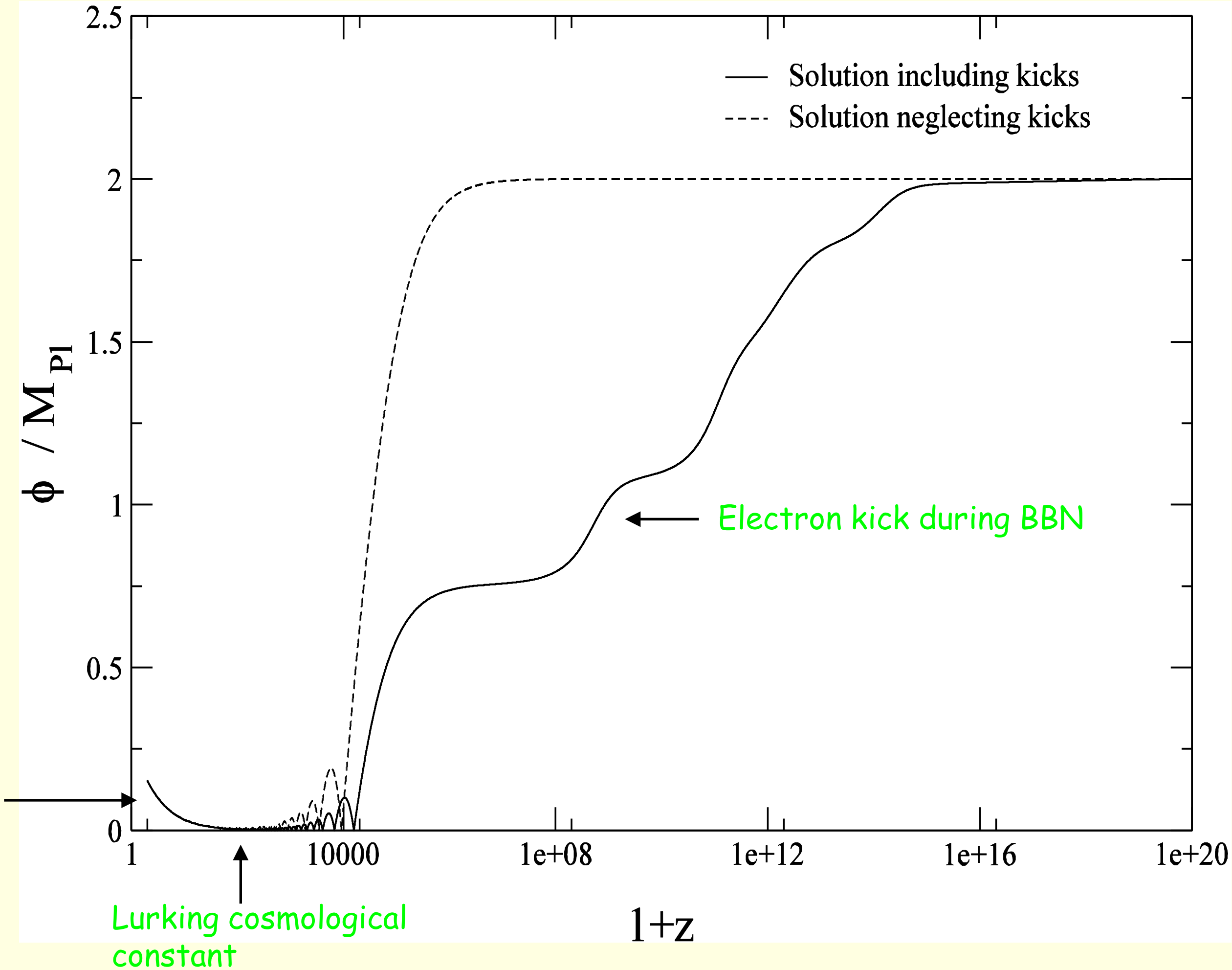
$$\alpha^2 = \beta \frac{\phi_\infty - \phi_c}{m_p \Phi_N}$$

bodies with large Newtonian potential on their surface interact very weakly





Chameleon Cosmology



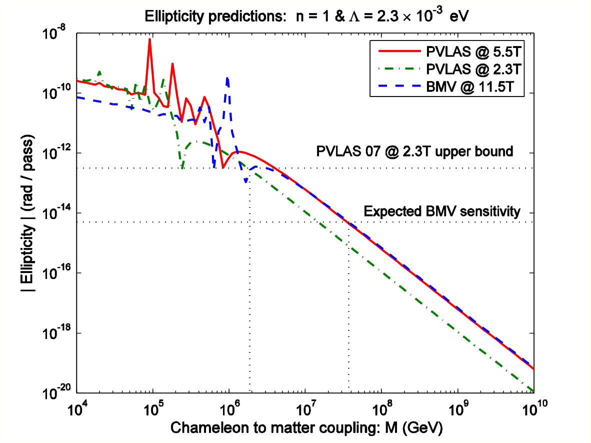
Late time acceleration

Possibility of variation of constants

Testing Chameleons in the Laboratory

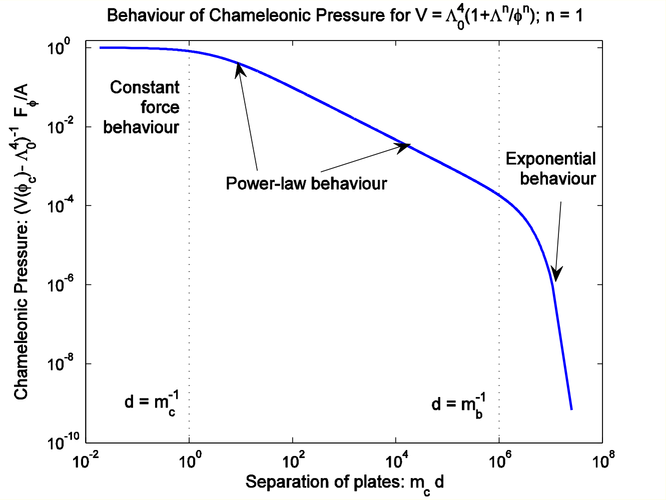
Optical Experiments:

Measuring the induced ellipticity of polarised laser beam through a magnetic field



Casimir Force:

Necessitates to see deviations from the Casimir force of order 1% at 10 microns.



Loop Corrections

Quantum fluctuations destabilise all the previous results

$$\boxed{\delta V = \frac{\Lambda^4}{16\pi^2}\mathrm{Str}M^0 + \frac{1}{32\pi^2}\mathrm{Str}M^2\Lambda^2 + \ldots}$$

Cosmological constant problem

Hierarchy problem (Higgs mass)

Large contributions due to scalars

Symmetries, Naturally!

In particle physics, small couplings are allowed and natural when their vanishing increases the symmetries of the model., e.g. gauge symmetries for massive gauge bosons, chiral symmetries for fermion masses. For scalar masses, Goldstone bosons after breaking of global symmetries have protected masses (little Higgs models)

What about the cosmological constant?

Scale invariance:

Snag…. masses exists (Weinberg's no-go theorem)

Supersymmetry:

But supersymmetry is broken (have you seen a selectron?)

$$\delta\rho \approx M^2_{\text{susybreaking}} m^2_{\text{Pl}}$$

Enormous !

Corrections to Scalar-Tensors

The loop corrected scalar potential in scalar tensor theories

$$\delta V = \Lambda_0^4 A^4(\phi)$$

(this excludes the effects from graviton exchange)

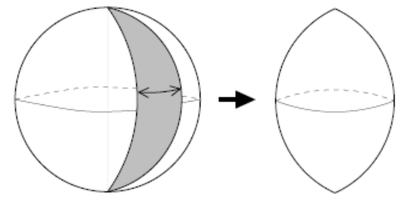
Only one fine-tuning!

Maybe there is some new physics at 10^{-3} eV ???

Supersymmetric Large Extra Dimensions (Burgess et al.)

The standard model at the north pole, up to 10 TeV.

Spherical compactification from supersymmetric 6d to 4d. Sphere of radius 10 microns.



Quantum corrections in 4d lead to a defect angle in the 2-extra dimensions

The 4d quantum corrections are transferred to the extra dimensional curvature.

The quantum corrections due to the particles living in 6d lead to a quintessence-like potential for the spherical radius

Testable at the LHC: missing energy due to gravitons flying off in to the bulk

Conclusions

- Scalar fields are too easy to obtain!
- Associated with quantum problems
- What shall we do?

Weinberg's no-go theorem

Take a field theory with scalar fields of dimension one transforming as

$$\phi \to \phi/l$$

under scaling transformations. Assume that there is a vacuum breaking the scale invariance spontaneously. Associated with it is a Goldstone mode called the dilaton parameterising a flat direction in field space

$$\phi_i = < \phi_i > e^{-\sigma}$$

connecting the non-trivial vacuum to the origin in field space where the vacuum energy vanishes too.

Quantum corrections lift this flat directions as the couplings of the model are renormalised. A non-trivial vacuum after renormalisation group evolution would satisfy

$$\partial_{\phi_i} V = V = 0$$

Giving N+1 equations for N unknown fields. Only satisfied if the couplings are related by one non-trivial relation amongst the couplings which should be invariant under the renormalisation group evolution

$$f(\lambda_j) = 0$$

Would require an extra symmetry to guarantee this relation, highly non-generic. Generically only vacuum is the origin where the cosmological constant vanishes but all masses too! Unphysical result