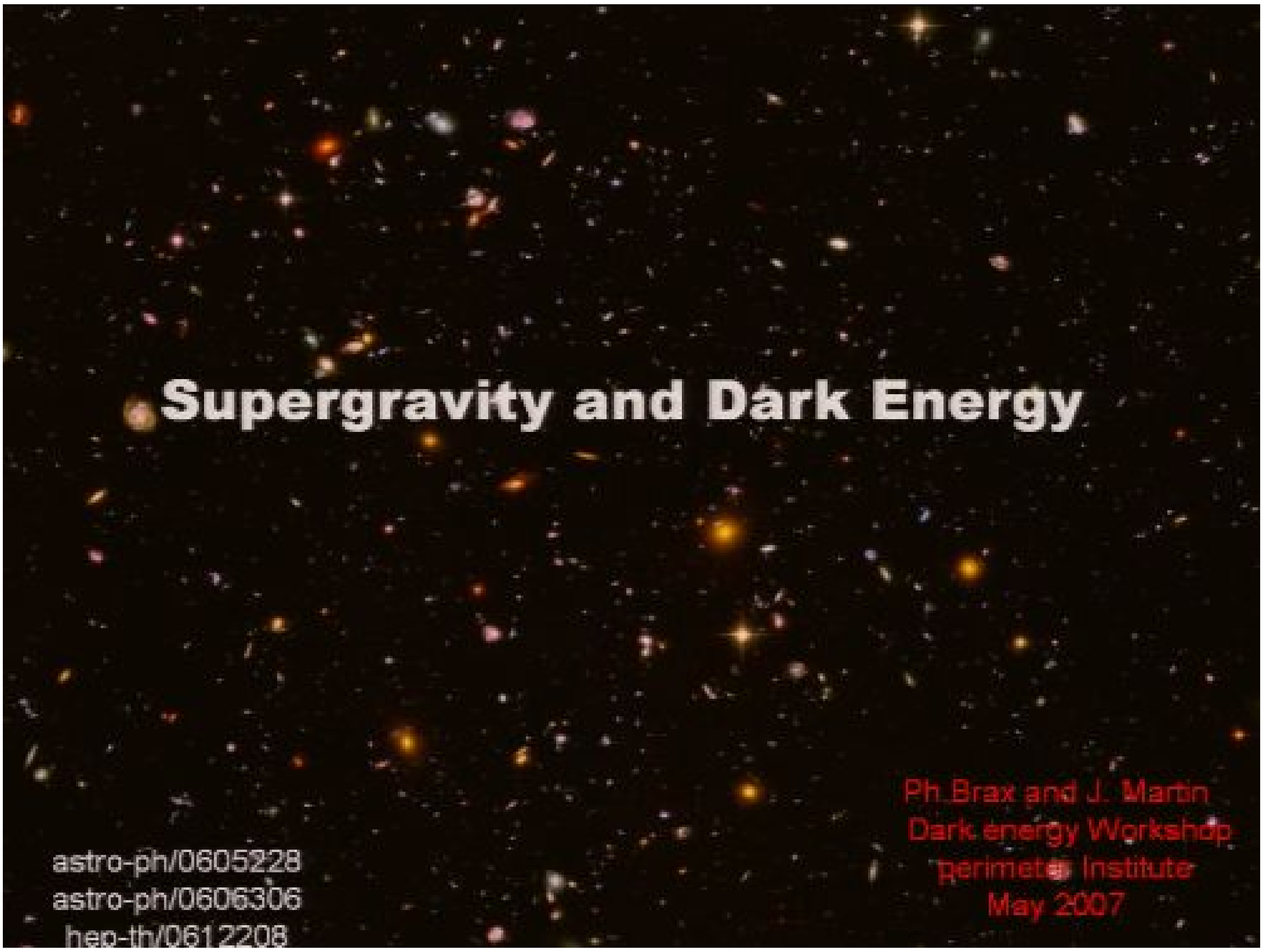
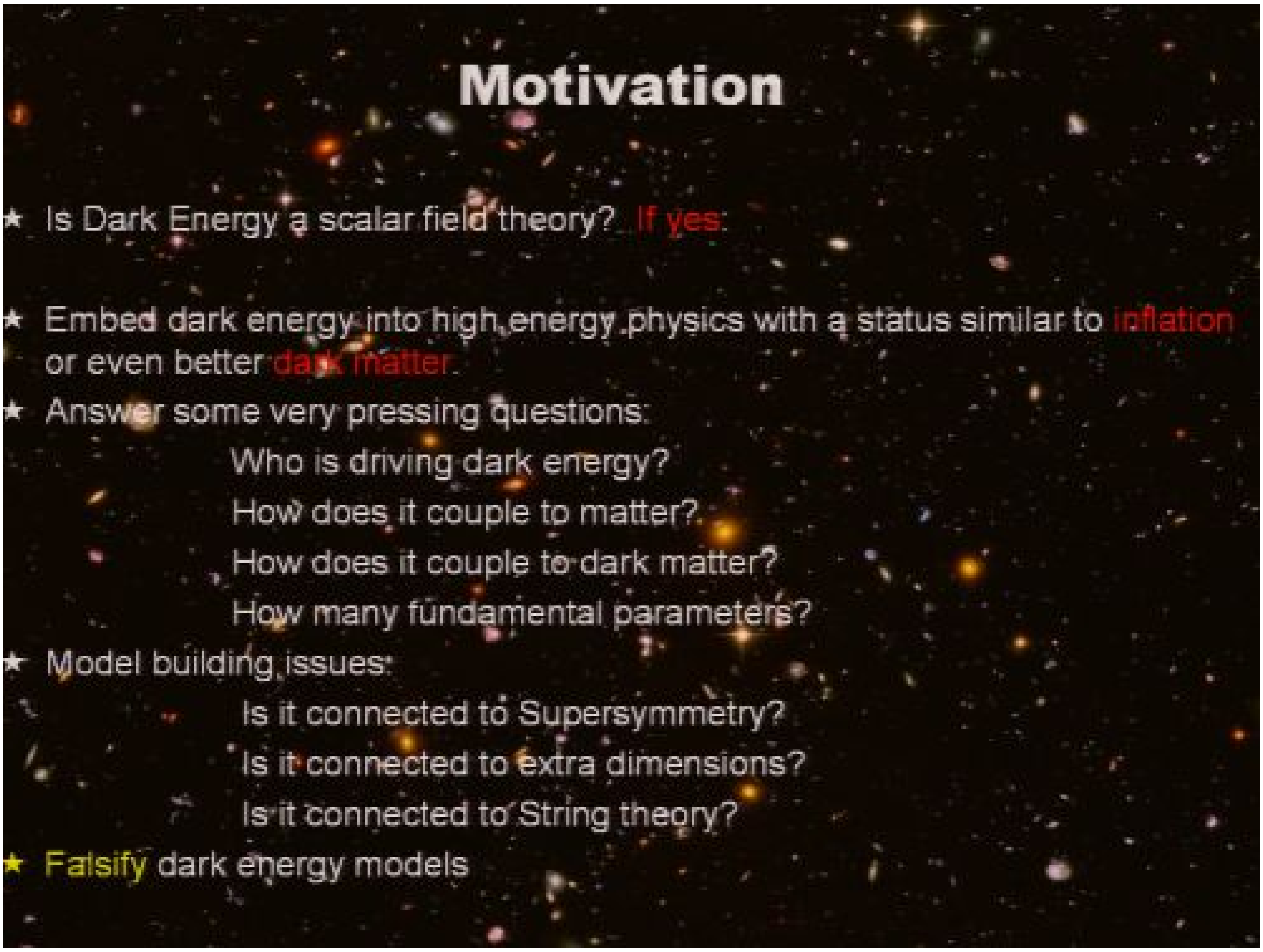
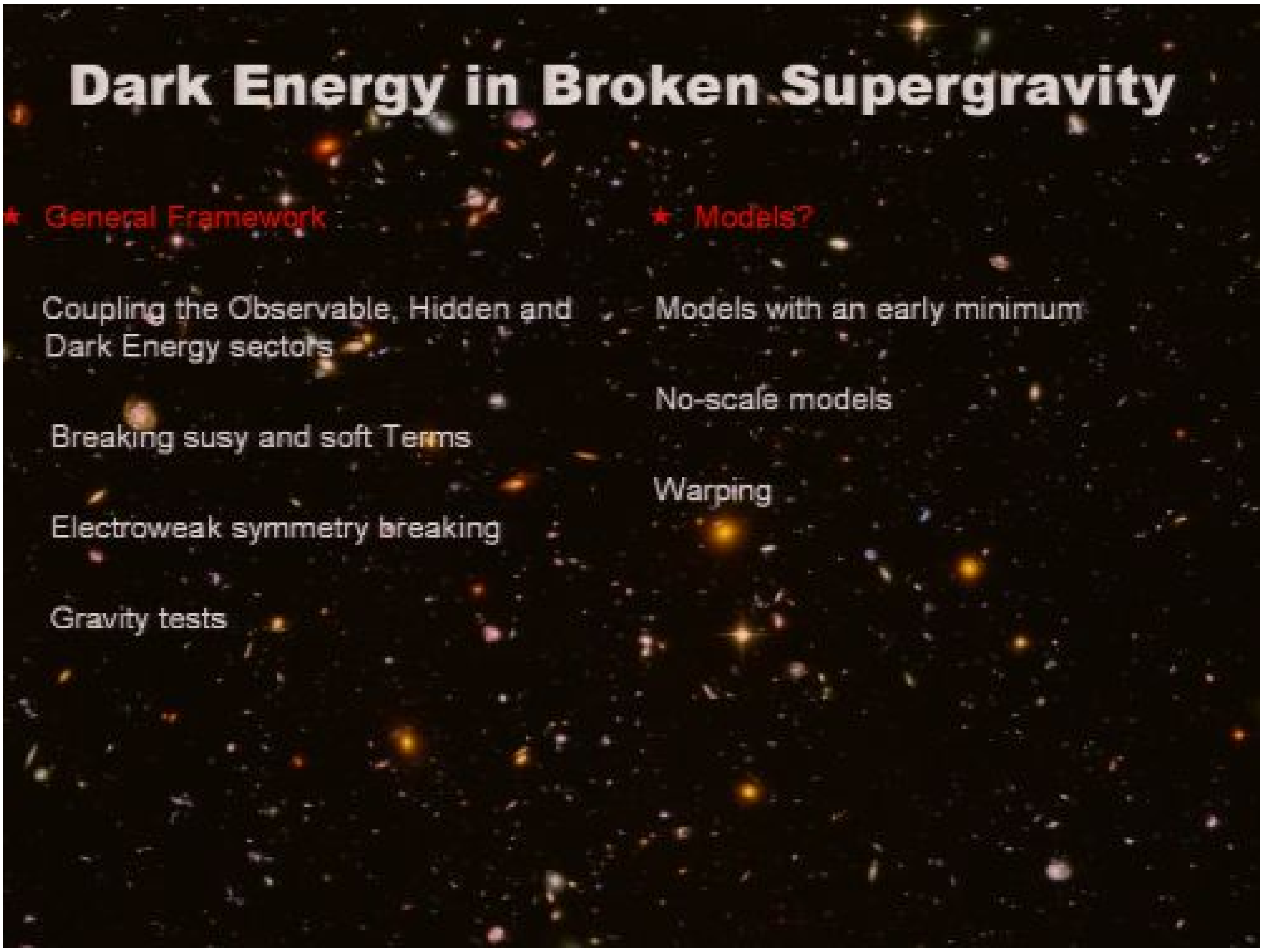
Title: Embedding Quintessence in Spontaneously Broken N=1 Supergravity

Date: 2007-05-18 11:00:00

Abstract:


Supergravity and Dark Energy
astro-ph/0605228
astro-ph/0606306
hep-th/0612208
Ph.Brax and J. Martin
Dark energy Workshop
perimeter Institute
May 2007


Motivation
Is Dark Energy a scalar field theory? If yes:
Embed dark energy into high energy physics with a status similar to inflation or even better dark matter.
Answer some very pressing questions:
Who is driving dark energy?
How does it couple to matter?
How does it couple to dark matter?
How many fundamental parameters?
Model building issues:
Is it connected to Supersymmetry?
Is it connected to extra dimensions?
Is it connected to String theory?
Falsify dark energy models

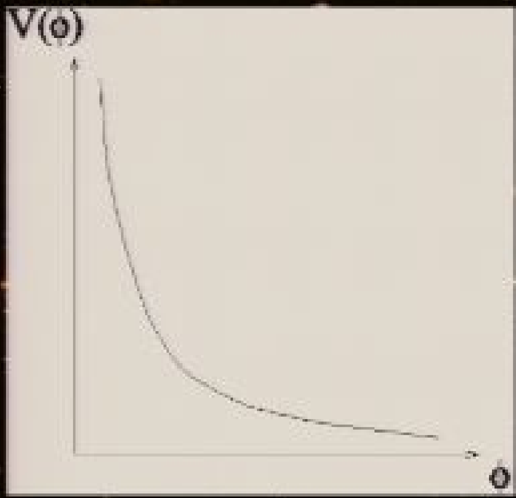

Dark Energy in Broken Supergravity
★ General Framework
Coupling the Observable, Hidden and Dark Energy sectors
Breaking susy and soft Terms
Electroweak symmetry breaking
Gravity tests
★ Models?
Models with an early minimum
No-scale models
Warping

Large Field Attractor

- Quintessence and Attractors:

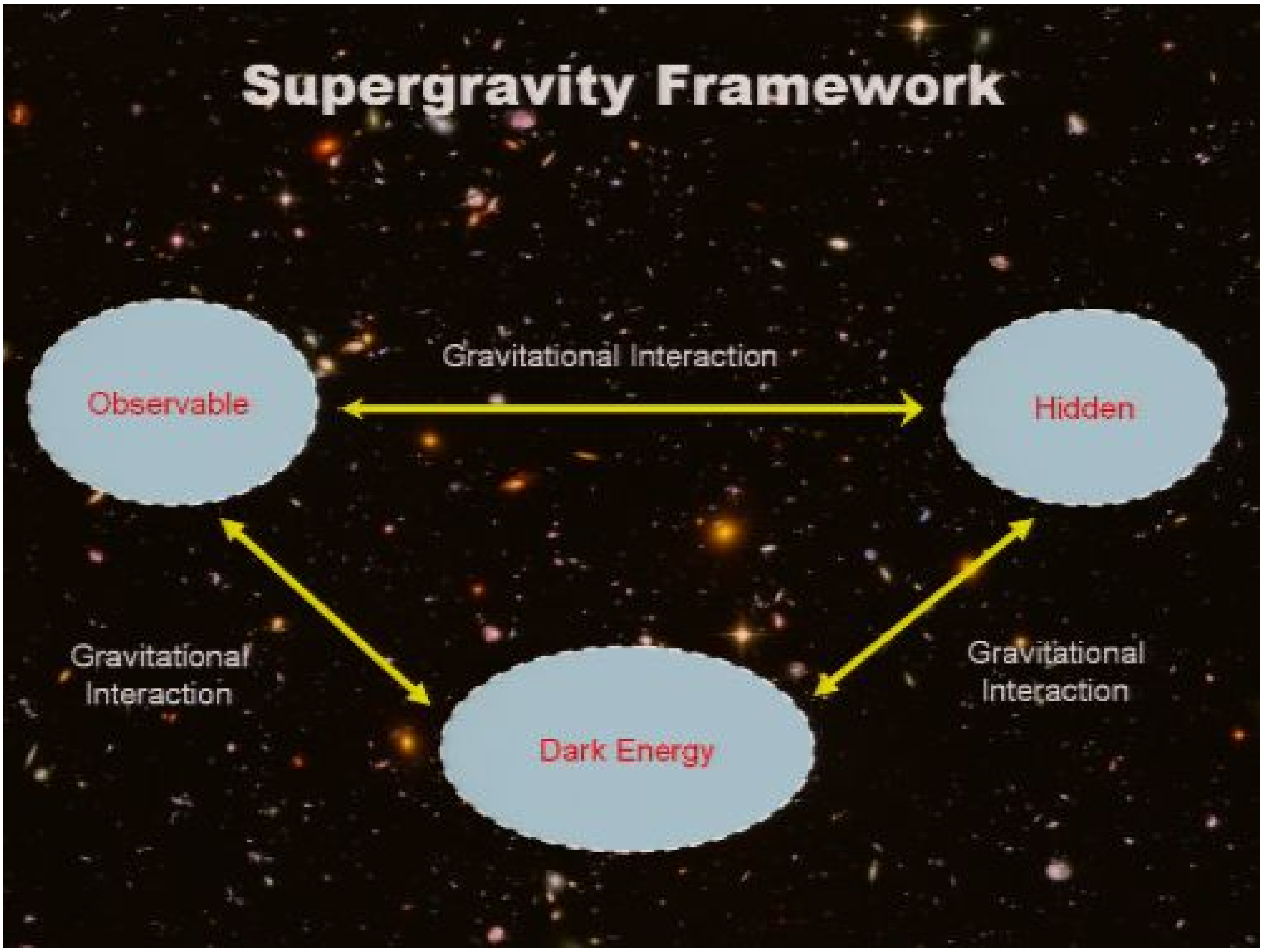
most quintessence models with insensitivity to initial conditions require an attractor mechanism

e.g. inverse power law potentials, exponential potentials ......



- Large values of $Q_{\text{now}} \approx m_{\text{P}}$

Supergravity can handle large field values and connects gravity with high energy physics


Supergravity Framework
Gravitational Interaction
Observable
Hidden
Gravitational
Interaction
Dark Energy
Gravitational
Interaction

Three Sectors

★ Hidden sector

Kahler potential $K_{\text{hid}} = \sum_i z_i \bar{z}_i + \ldots$

Superpotential $W_{\text{hid}}(z_i)$

★ Observable Sector

Kahler potential $K_{\text{obs}} = \sum_a \phi_a \bar{\phi}_a + \ldots$

Superpotential

$$W_{\text{obs}} = \frac{1}{3} \sum_{abc} \lambda_{abc} \phi_a \phi_b \phi_c + \frac{1}{2} \sum_{ab} \mu_{ab} \phi_a \phi_b + \ldots$$

★ Dark Energy sector

Kahler potential K_{quint}

Superpotential W_{quint}

Fields $\{\mathrm{d}_\alpha\} \equiv \{\mathrm{Q}, \mathrm{X}_\alpha, \mathrm{Y}_\alpha\}$

Quintessence field Q

Spontaneous Susy Breaking

- ★ Susy broken in the Hidden sector $$\frac{\partial V}{\partial z_i} = 0$$

- ★ Parameterised by the vev's

$$\kappa^{1/2} < z_i > \sim a_i(Q), \quad \kappa < W_{\text{hid}} > \sim M_s(Q), \quad \kappa^{1/2} < \partial_i W_{\text{hid}} > \sim c_i(Q) M_s(Q)$$

- ★ Susy broken by the F-term vev's

$$F_{z_i} = e^{\kappa K_{\text{quint}} + \sum_i |a_i|^2} \frac{1}{\kappa^{1/2}} \left[(M_s + \kappa < W_{\text{quint}} >) a_i + M_s c_i \right]$$

- ★ The gravitino mass

$$m_{3/2} = e^{\kappa K_{\text{quint}} + \sum_i |a_i|^2} (M_s + \kappa < W_{\text{quint}} >) \equiv e^{\kappa K_{\text{quint}}} m_{3/2}^0$$

The Effective Theory

★ After susy breaking, effective theory for Observable sector coupled to Dark Energy

$$m_{\rm Pl} \to \infty, \quad m_{3/2} \quad \text{fixed}$$

★ The Dark Energy potential

$$\begin{aligned} V_{\rm DE} &= e^{\sum_i |a_i|^2} V_{\rm quint} + M_S^2 e^{\kappa K_{\rm quint} + \sum_i |a_i|^2} [(K^{-1})^{d_\alpha^\dagger d_\beta} \frac{\partial K_{\rm quint}}{\partial d_\beta} \frac{\partial K_{\rm quint}}{\partial d_\alpha^\dagger} - \frac{3}{\kappa}] \\ &+ M_S e^{\kappa K_{\rm quint} + \sum_i |a_i|^2} \{ [(K^{-1})^{d_\alpha^\dagger d_\beta} \frac{\partial K_{\rm quint}}{\partial d_\beta} \frac{\partial K_{\rm quint}}{\partial d_\alpha^\dagger} - \frac{3}{\kappa}] (\kappa W_{\rm quint} + \kappa W_{\rm quint}^\dagger) \\ &+ (K^{-1})^{d_\alpha^\dagger d_\beta} (\frac{\partial K_{\rm quint}}{\partial d_\beta} \frac{\partial W_{\rm quint}^\dagger}{\partial d_\alpha^\dagger} + \frac{\partial K_{\rm quint}}{\partial d_\alpha^\dagger} \frac{\partial W_{\rm quint}}{\partial d_\beta}) \} + \sum_i |F_{z_i}|^2 , \end{aligned}$$

with

$$\begin{aligned} V_{\rm quint}(Q) &= e^{\kappa K_{\rm quint}} [(K_{\rm quint}^{-1})^{d_\alpha^\dagger d_\beta} \left(\kappa W_{\rm quint} \frac{\partial K_{\rm quint}}{\partial d_\beta} + \frac{\partial W_{\rm quint}}{\partial d_\beta} \right) (\kappa W_{\rm quint}^\dagger \frac{\partial K_{\rm quint}}{\partial d_\alpha^\dagger} \\ &+ \frac{\partial W_{\rm quint}^\dagger}{\partial d_\alpha^\dagger}) - 3\kappa W_{\rm quint} W_{\rm quint}^\dagger] . \end{aligned}$$

- highly dependent on the susy breaking sector

The Soft Breaking Terms

- ★ Susy , spontaneously broken, leads to soft terms

$$
\begin{aligned}
V_{\mathrm{mSUGRA}} &= \cdots + \mathrm{e}^{\kappa K} V_{\mathrm{susy}} + A_{abc}\left(\phi_a\phi_b\phi_c + \phi_a^\dagger\phi_a^\dagger\phi_c^\dagger\right) + B_{ab}\left(\phi_a\phi_b + \phi_a^\dagger\phi_b^\dagger\right) \\
&\quad + m_{a\bar{b}}^2\phi_a\phi_b^\dagger .
\end{aligned}
$$

- ★ Soft terms depend on the dark energy sector

$$
\begin{aligned}
A_{abc} &= \lambda_{abc}\mathrm{e}^{\kappa K_{\mathrm{quint}}+\sum_i |a_i|^2}\Big\{(M_{\mathrm{S}} + \kappa W^\dagger_{\mathrm{quint}}) + \frac{1}{3}(M_{\mathrm{S}} + \kappa W^\dagger_{\mathrm{quint}})[\kappa\left(K^{-1}\right)^{d_\alpha^\dagger d_\beta} \\
&\quad \times \frac{\partial K_{\mathrm{quint}}}{\partial d_\beta}\frac{\partial K_{\mathrm{quint}}}{\partial d_\alpha^\dagger} + \sum_i |a_i|^2 - 3] + \frac{1}{3}\kappa\left(K^{-1}\right)^{d_\alpha^\dagger d_\beta}\frac{\partial K_{\mathrm{quint}}}{\partial d_\alpha^\dagger}\frac{\partial W_{\mathrm{quint}}}{\partial d_\beta} \\
&\quad + \frac{1}{3}M_{\mathrm{S}}\sum_i a_i c_i\Big\} , \\
B_{ab} &= \mu_{ab}\mathrm{e}^{\kappa K_{\mathrm{quint}}+\sum_i |a_i|^2}\Big\{(M_{\mathrm{S}} + \kappa W^\dagger_{\mathrm{quint}}) + \frac{1}{2}(M_{\mathrm{S}} + \kappa W^\dagger_{\mathrm{quint}})[\kappa\left(K^{-1}\right)^{d_\alpha^\dagger d_\beta} \\
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m_{a\bar{b}}^2 &= \mathrm{e}^{\kappa K_{\mathrm{quint}}+\sum_i |a_i|^2}\left[M_{\mathrm{S}}^2 + M_{\mathrm{S}}\left(\kappa W_{\mathrm{quint}} + \kappa W^\dagger_{\mathrm{quint}}\right) + \kappa^2 W_{\mathrm{quint}} W^\dagger_{\mathrm{quint}}\right]\delta_{a\bar{b}}
\end{aligned}
$$

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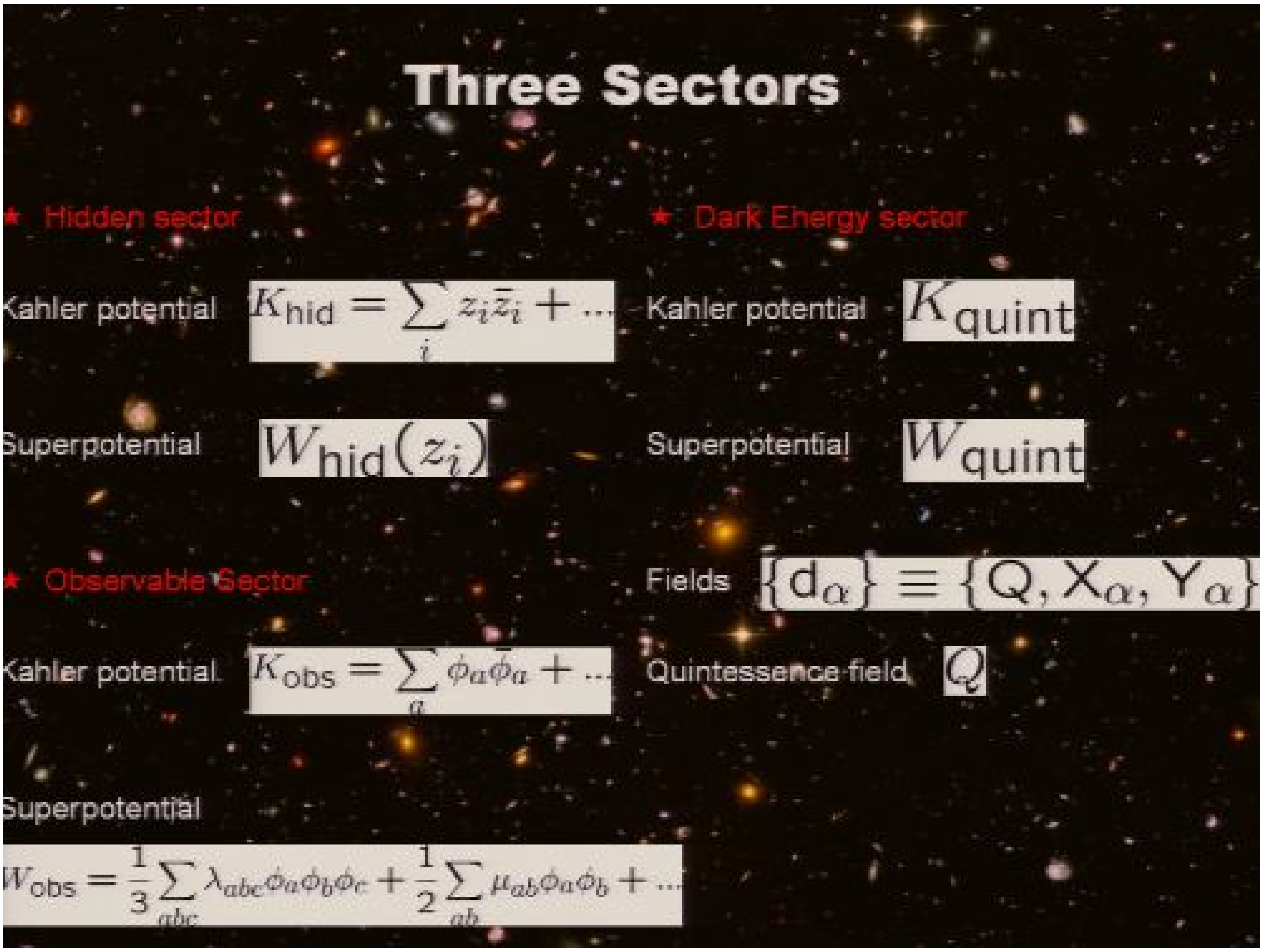
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Superpotential $W_{\text{hid}}(z_i)$
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&+ \frac{1}{3}M_{\mathrm{S}}\sum_i a_i c_i\Big\} , \\
B_{ab} &= \mu_{ab} e^{\kappa K_{\mathrm{quint}} + \sum_i |a_i|^2}\Big\{(M_{\mathrm{S}} + \kappa W^\dagger_{\mathrm{quint}}) + \frac{1}{2}(M_{\mathrm{S}} + \kappa W^\dagger_{\mathrm{quint}})[\kappa\left(K^{-1}\right)^{d_\alpha^\dagger d_\beta} \\
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&+ \frac{1}{2}M_{\mathrm{S}}\sum_i a_i c_i\Big\} , \\
m^2_{a\bar{b}} &= e^{\kappa K_{\mathrm{quint}} + \sum_i |a_i|^2}\left[M_{\mathrm{S}}^2 + M_{\mathrm{S}}\left(\kappa W_{\mathrm{quint}} + \kappa W^\dagger_{\mathrm{quint}}\right) + \kappa^2 W_{\mathrm{quint}} W^\dagger_{\mathrm{quint}}\right]\delta_{a\bar{b}}
\end{aligned}$$

Gaugino Masses

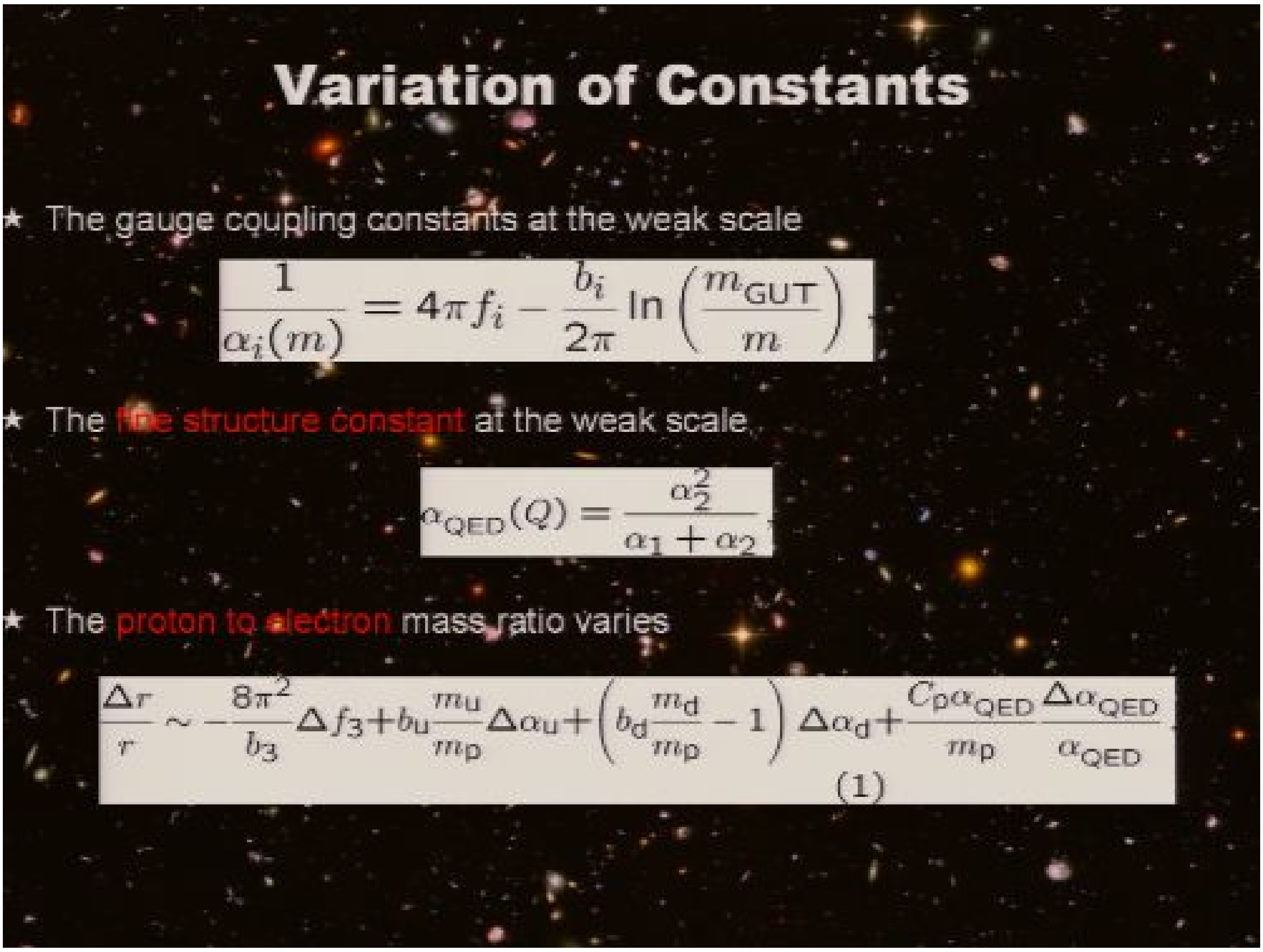
★ Gauginos acquire a mass depending on the gauge coupling function

$$\Re\left[f_G(d_\alpha, z_i)\right] = \frac{1}{g_G^2}$$

★ The mass depends on the F-terms breaking supersymmetry

$$\left(m_{1/2}\right)_G = \frac{1}{f_G + f_G^\dagger}\left(\sum_\alpha F^{d_\alpha}\frac{\partial f_G}{\partial d_\alpha} + \sum_i F^{z_i}\frac{\partial f_G}{\partial z_i}\right) \equiv e^{\kappa K_{\mathrm{qunt}}/2}\left(m^0_{1/2}\right)_G \quad (1)$$

★ The gauge coupling dependence on the dark energy sector leads to variations of constants


Variation of Constants
★ The gauge coupling constants at the weak scale
$$\frac{1}{\alpha_i(m)} = 4\pi f_i - \frac{b_i}{2\pi} \ln\left(\frac{m_{\mathrm{GUT}}}{m}\right)$$
★ The fine structure constant at the weak scale
$$\alpha_{\mathrm{QED}}(Q) = \frac{\alpha_2^2}{\alpha_1 + \alpha_2}$$
★ The proton to electron mass ratio varies
$$\frac{\Delta r}{r} \sim -\frac{8\pi^2}{b_3}\Delta f_3 + b_{\mathrm{u}}\frac{m_{\mathrm{u}}}{m_{\mathrm{p}}}\Delta\alpha_{\mathrm{u}} + \left(b_{\mathrm{d}}\frac{m_{\mathrm{d}}}{m_{\mathrm{p}}} - 1\right)\Delta\alpha_{\mathrm{d}} + \frac{C_{\mathrm{p}}\alpha_{\mathrm{QED}}}{m_{\mathrm{p}}}\frac{\Delta\alpha_{\mathrm{QED}}}{\alpha_{\mathrm{QED}}} \quad (1)$$

Electro-weak Symmetry Breaking

★ The Higgs potential depends on the dark energy sector via the soft terms evaluated at the electro-weak scale

$$V^{\rm Higgs} = e^{\kappa K_{\rm quint}}[\left(|\mu|^2 e^{\sum_i |a_i|^2} + m^2_{H_{\rm u}}\right)\left|H^0_{\rm u}\right|^2 + \left(|\mu|^2 e^{\sum_i |a_i|^2} + m^2_{H_{\rm d}}\right)\left|H^0_{\rm d}\right|^2 - 2\mu B(Q)\left|H^0_{\rm u}\right|\left|H^0_{\rm d}\right|] + \frac{1}{8}\left(g^2 + g'^2\right)\left(\left|H^0_{\rm u}\right|^2 - \left|H^0_{\rm d}\right|^2\right)^2 .$$

★ The two Higgs vev's depend on quintessence too

$$< H^0_u > \equiv v_{\rm u} = v \sin\beta, \quad < H^0_d > \equiv v_{\rm d} = v \cos\beta$$

★ The angle β depends on quintessence

$$\tan\beta(Q) = \frac{2|\mu|^2 e^{\sum_i |a_i|^2} + m^2_{H_{\rm u}}(Q) + m^2_{H_{\rm d}}(Q)}{2\mu B(Q)} \times \left(1 \pm \sqrt{1 - 4\mu^2 B^2(Q)\left[2|\mu|^2 e^{\sum_i |a_i|^2} + m^2_{H_{\rm u}}(Q) + m^2_{H_{\rm d}}(Q)\right]^{-2}}\right) .$$

Boson and Fermion Masses

★ The Higgs scale becomes (large $\tan\beta \gg 1$ regime)

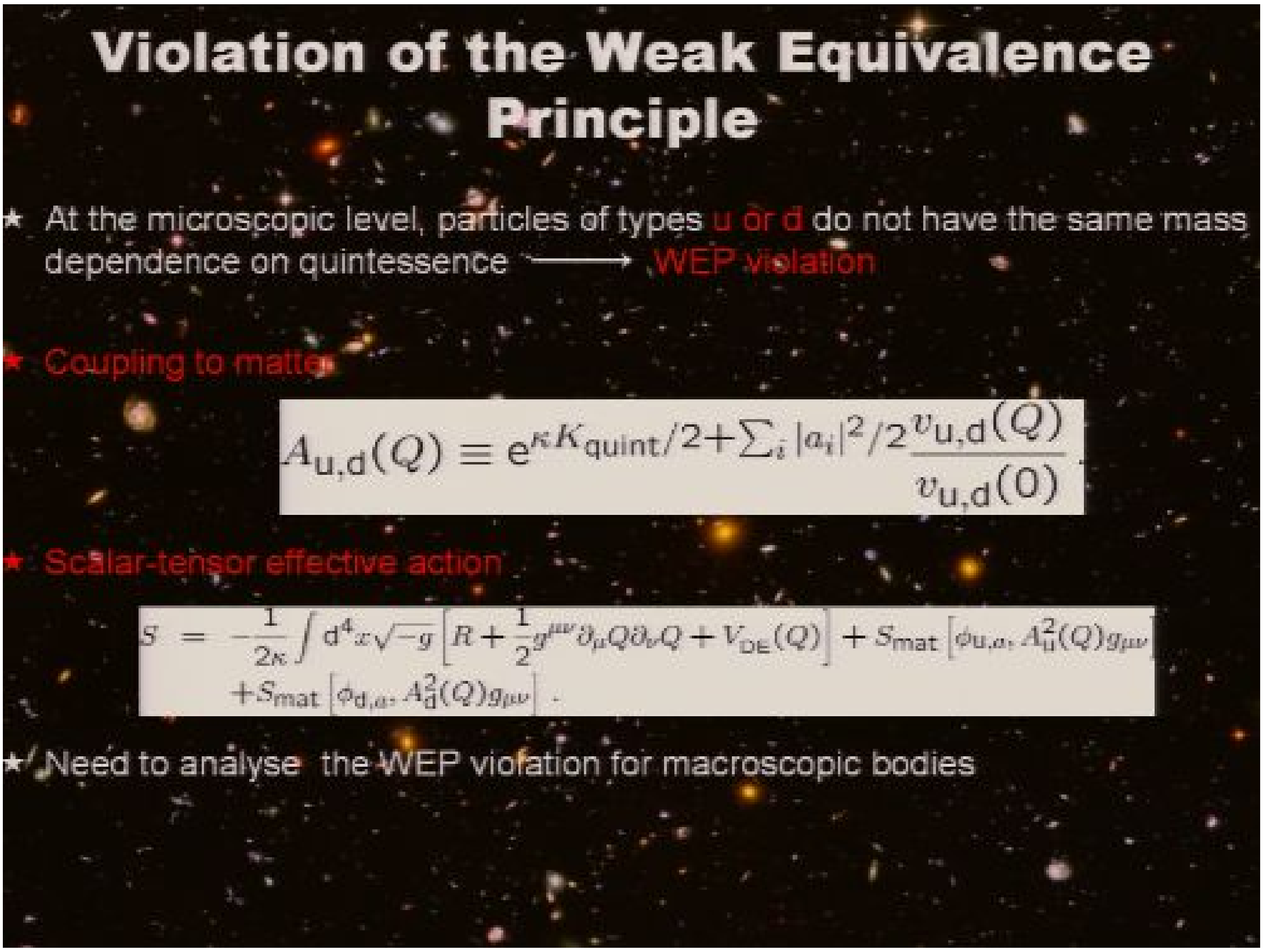
$$v(Q) = \frac{2\mathrm{e}^{\kappa K_{\mathrm{quint}}/2}}{\sqrt{g^2+g'^2}} \sqrt{\left| |\mu|^2\, \mathrm{e}^{\sum_i |a_i|^2} + m^2_{H_{\mathrm{u}}} \right|} + \mathcal{O}\left(\frac{1}{\tan\beta}\right)$$

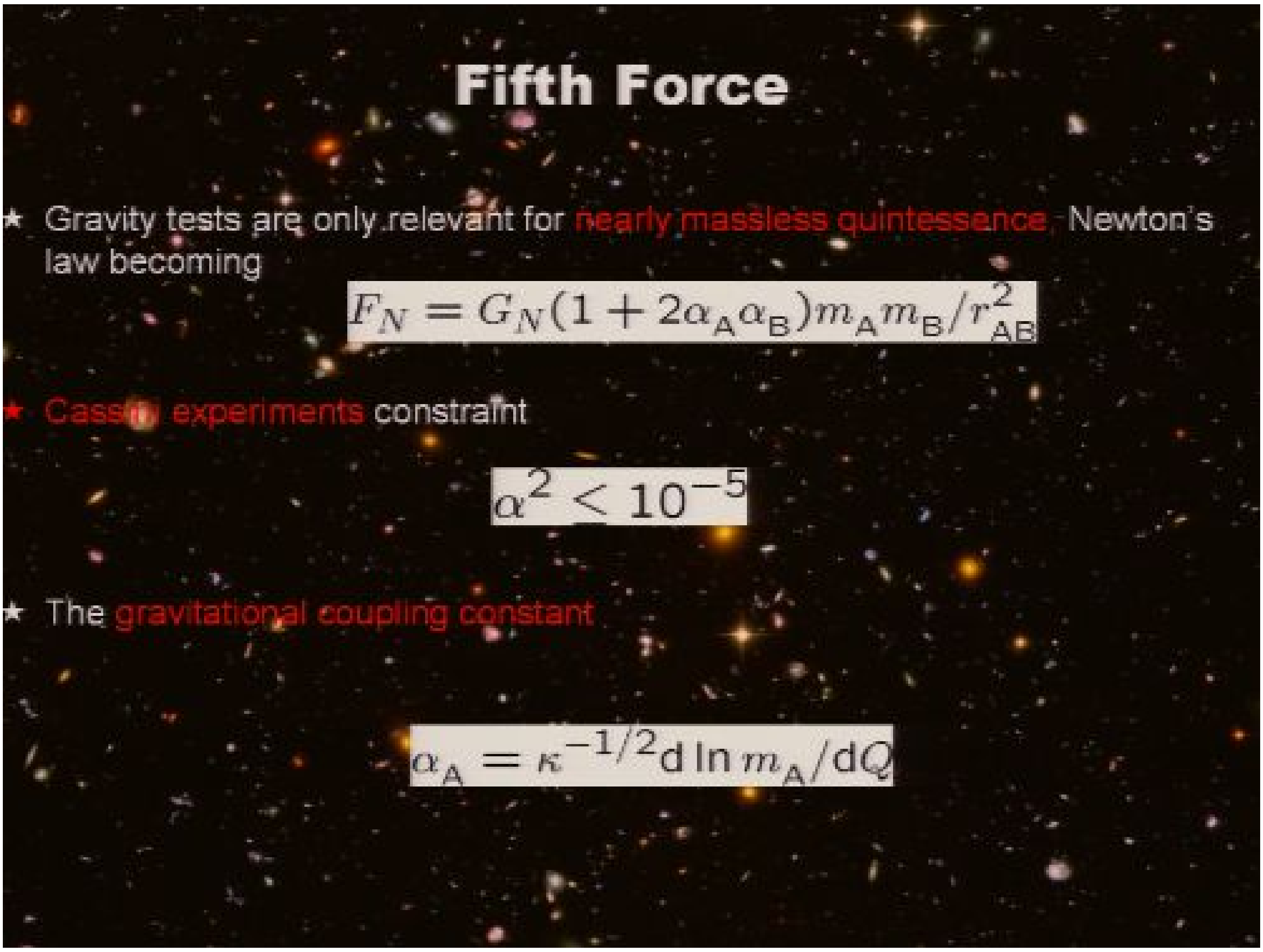
★ The gauge boson masses depend on quintessence

$$m^2_{W^\pm} = \frac{g^2}{2}\left(v_{\mathrm{u}}^2 + v_{\mathrm{d}}^2\right) \equiv \frac{g^2}{2} v^2\,, \quad m^2_{Z^0} = \frac{1}{2}\left(g^2 + g'^2\right)\left(v_{\mathrm{u}}^2 + v_{\mathrm{d}}^2\right)$$

★ The matter Fermion masses depend on quintessence

$$m^{\mathrm{F}}_{\mathrm{u},a}(Q) = \lambda^{\mathrm{F}}_{\mathrm{u},a} \mathrm{e}^{\kappa K_{\mathrm{quint}}/2 + \sum_i |a_i|^2/2} v_{\mathrm{u}}(Q)\,, \quad m^{\mathrm{F}}_{\mathrm{d},a}(Q) = \lambda^{\mathrm{F}}_{\mathrm{d},a} \mathrm{e}^{\kappa K_{\mathrm{quint}}/2 + \sum_i |a_i|^2/2} v_{\mathrm{d}}(Q)$$


Violation of the Weak Equivalence Principle
★ At the microscopic level, particles of types u or d do not have the same mass dependence on quintessence ⟶ WEP violation
★ Coupling to matter
$A_{\mathrm{u,d}}(Q) \equiv \mathrm{e}^{\kappa K_{\mathrm{quint}}/2+\sum_i |a_i|^2/2}\frac{v_{\mathrm{u,d}}(Q)}{v_{\mathrm{u,d}}(0)}$
★ Scalar-tensor effective action
$S = -\frac{1}{2\kappa}\int \mathrm{d}^4x\sqrt{-g}\left[R+\frac{1}{2}g^{\mu\nu}\partial_\mu Q\partial_\nu Q+V_{\mathrm{DE}}(Q)\right]+S_{\mathrm{mat}}\left[\phi_{\mathrm{u},a}, A_{\mathrm{u}}^2(Q)g_{\mu\nu}\right] + S_{\mathrm{mat}}\left[\phi_{\mathrm{d},a}, A_{\mathrm{d}}^2(Q)g_{\mu\nu}\right]$.
★ Need to analyse the WEP violation for macroscopic bodies


Fifth Force
★ Gravity tests are only relevant for nearly massless quintessence. Newton's law becoming
$F_N = G_N(1 + 2\alpha_A\alpha_B)m_A m_B/r_{AB}^2$
★ Cassini experiments constraint
$\alpha^2 \lesssim 10^{-5}$
★ The gravitational coupling constant
$\alpha_A = \kappa^{-1/2} \mathrm{d} \ln m_A / \mathrm{d}Q$

Coupling to matter

$$
\begin{aligned}
\alpha_{\mathrm{u}} &= \frac{\kappa^{1/2}}{2}\partial_Q K_{\mathrm{quint}} + \frac{\kappa^{-1/2}}{2}\sum_i \partial_Q |a_i|^2 + \frac{\kappa^{-1/2}}{v}\frac{\mathrm{d}v}{\mathrm{d}Q} + \mathcal{O}\left(\frac{1}{\tan^2\beta}\right), \\
\alpha_{\mathrm{d}} &= \frac{\kappa^{1/2}}{2}\partial_Q K_{\mathrm{quint}} + \frac{\kappa^{-1/2}}{2}\sum_i \partial_Q |a_i|^2 - \kappa^{-1/2}\left(\frac{\mathrm{d}m^2_{\mathrm{H_u}}}{\mathrm{d}Q} + \frac{\mathrm{d}m^2_{\mathrm{H_d}}}{\mathrm{d}Q}\right) \\
&\times \left(2|\mu|^2 \mathrm{e}^{\sum_i |a_i|^2} + m^2_{\mathrm{H_u}} + m^2_{\mathrm{H_d}}\right)^{-1} + \kappa^{-1/2}\frac{\mathrm{d}\ln B(Q)}{\mathrm{d}Q} + \frac{\kappa^{-1/2}}{v}\frac{\mathrm{d}v}{\mathrm{d}Q} \\
&+ \mathcal{O}\left(\frac{1}{\tan^2\beta}\right).
\end{aligned}
$$

Scalar Potential and Gravitino Mass

★ The scalar potential has the structure:

$$V(Q) = \kappa_4^2 M^6 v_1(\kappa_4 Q) + M_s M^3 v_2(\kappa_4 Q) + \frac{M_s^2}{\kappa_4^2} e^{\kappa_4^2 K}(\kappa_4^2 K^{Q\bar{Q}} K_Q K_{\bar{Q}} - 3) + \sum_i |F_{z_i}|^2$$

for the superpotentials

$$W_{\text{quint}} = M^3 \mathcal{W}(\kappa_4 Q), \quad W_{\text{hid}} = M_s^3 \mathcal{W}_{\text{hid}}(z_i)$$

★ For regular Kahler potentials:

$$K_{\text{quint}} = Q\bar{Q} + \dots$$

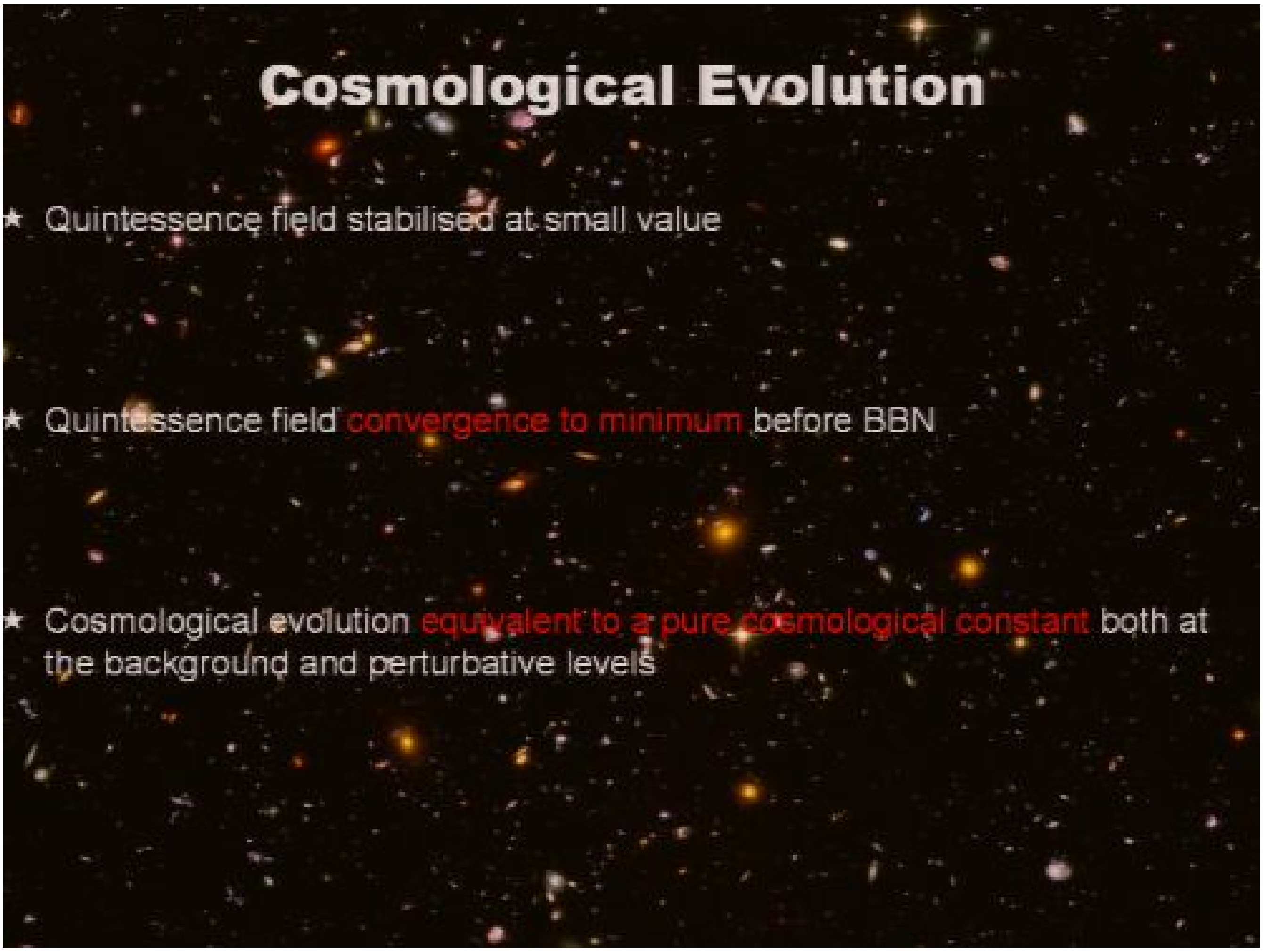
★ The scalar potential becomes

$$V(Q) = M_s M^3 v_2(\kappa_4 Q) + m_{3/2}^2 |Q|^2$$

★ There is a minimum, typically very small compared to the Planck scale

★ The mass of the quintessence field is very large

$$m_Q \approx m_{3/2}$$


Cosmological Evolution
★ Quintessence field stabilised at small value
★ Quintessence field convergence to minimum before BBN
★ Cosmological evolution equivalent to a pure cosmological constant both at the background and perturbative levels

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No-scale

- ★ No gravitino mass for the quintessence field:

$$K = -\frac{n}{\kappa_4^2} \ln[\kappa_4(Q + \bar{Q})]$$

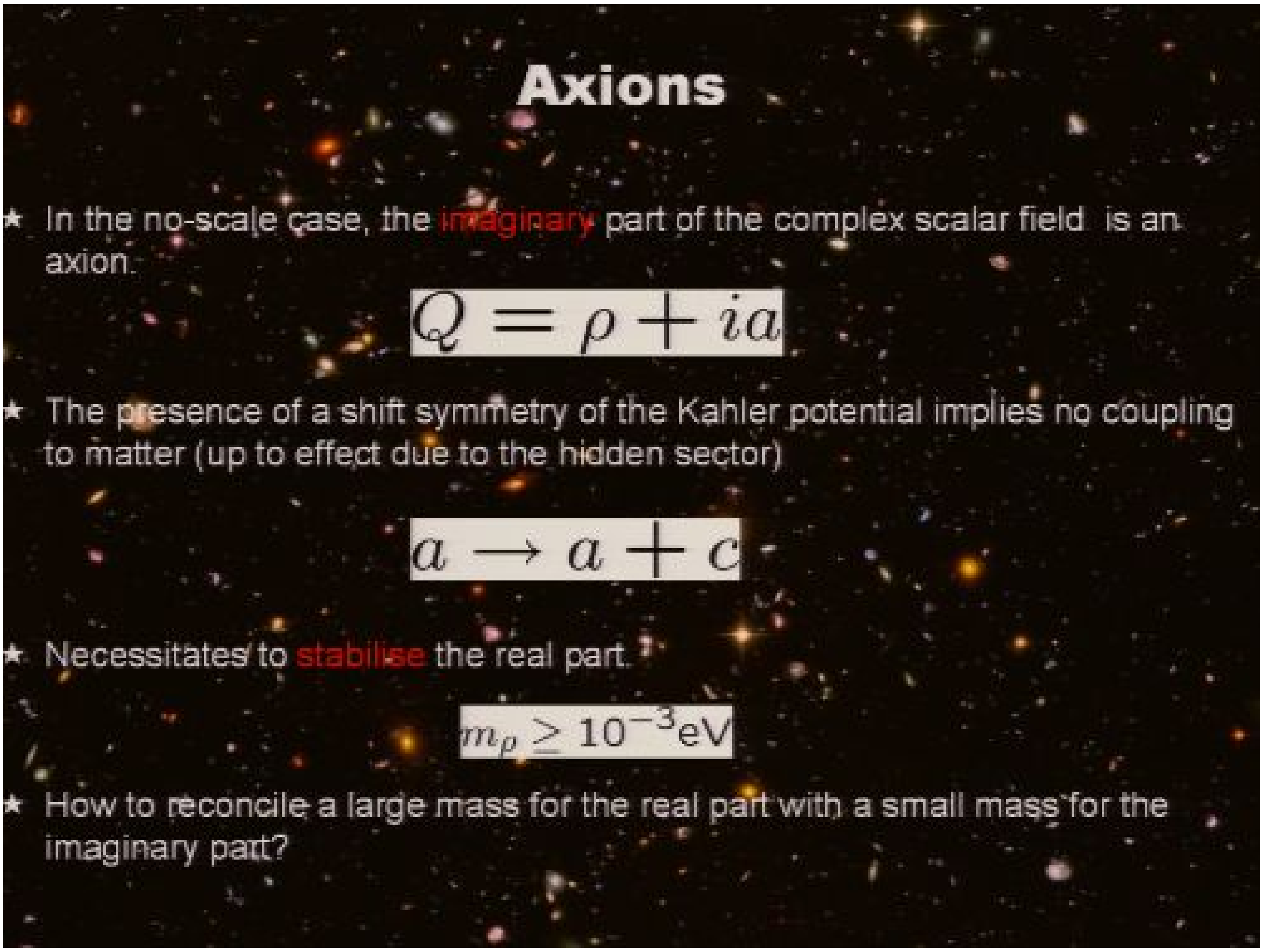
- ★ The scalar potential becomes runaway

$$V(Q) = M_s M^3 v_2(\kappa_4 Q)$$

- ★ Large coupling to gravity

$$\alpha_Q = \sqrt{2n} + \ldots$$

- ★ No chameleon effect despite coupling to matter


Axions
In the no-scale case, the imaginary part of the complex scalar field is an axion.
$Q = \rho + ia$
The presence of a shift symmetry of the Kahler potential implies no coupling to matter (up to effect due to the hidden sector)
$a \to a + c$
Necessitates to stabilise the real part.
$m_\rho \geq 10^{-3}\text{eV}$
How to reconcile a large mass for the real part with a small mass for the imaginary part?

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★ Explicit example:

$$K = -\frac{3}{\kappa_4^2}\ln(\kappa_4(Q+\bar{Q}) - \frac{\kappa_4^2}{3}(k_{\rm obs}+k_{\rm hid}))$$

★ Matter and hidden sectors on D3 branes, quintessence=moduli

★ No gravitino mass but large gravitational coupling....

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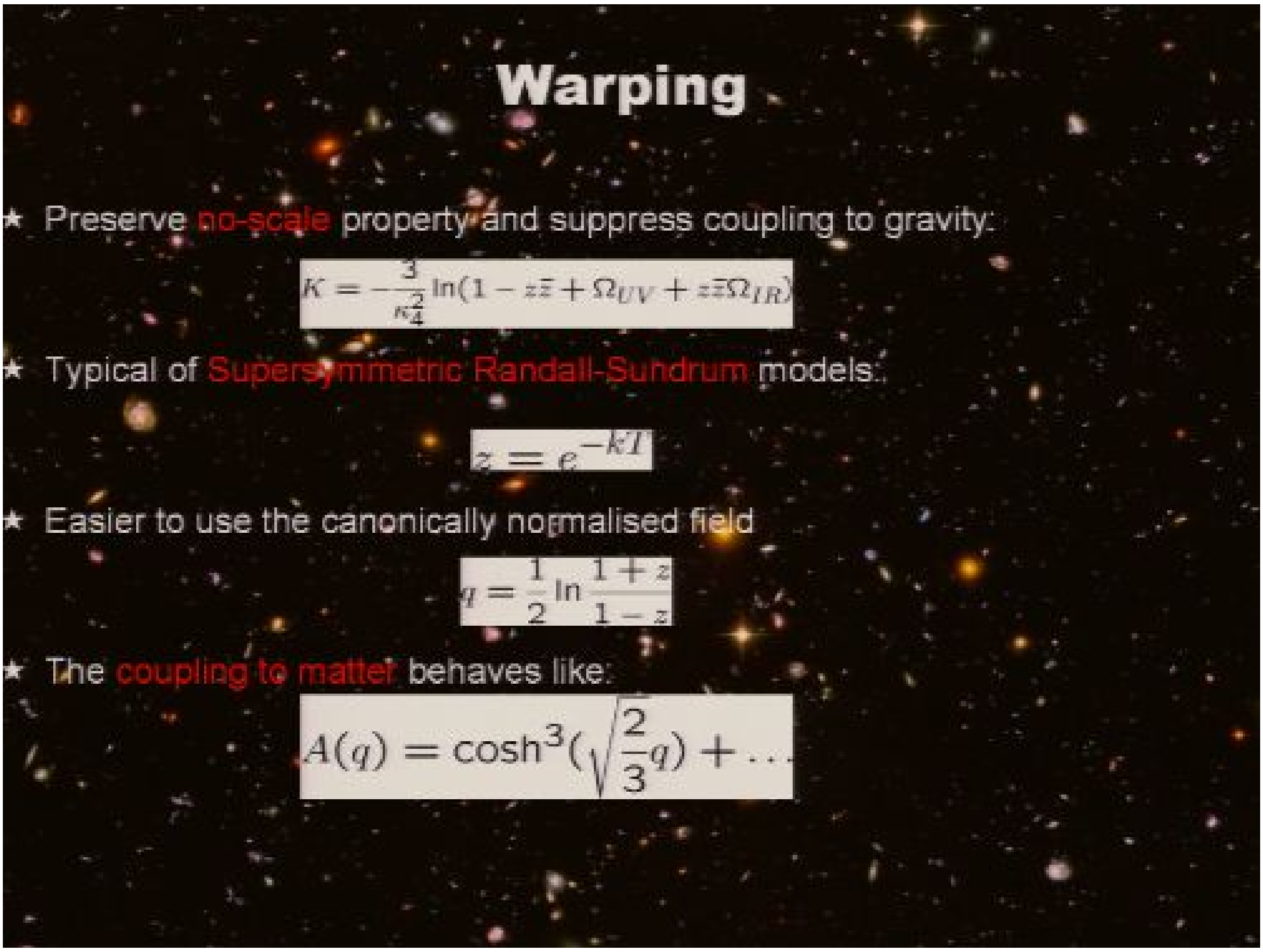
Warping
★ Preserve no-scale property and suppress coupling to gravity:
$K = -\frac{3}{\kappa_4^2} \ln(1 - z\bar{z} + \Omega_{UV} + z\bar{z}\Omega_{IR})$
★ Typical of Supersymmetric Randall-Sundrum models:
$z = e^{-kT}$
★ Easier to use the canonically normalised field
$q = \frac{1}{2} \ln \frac{1+z}{1-z}$
★ The coupling to matter behaves like:
$A(q) = \cosh^3(\sqrt{\frac{2}{3}}q) + \dots$

Small Field Dark Energy

- ★ The gravitational coupling is large at short distance:

$$\alpha_q = \sqrt{6}, \ z = O(1)$$

- ★ The gravitational coupling is small at large distance:

$$\alpha_q = 2q = 2z, \ z \ll 1$$

- ★ This leads to the possibility of studying small field dark energy models akin to small field inflation models (hybrid etc…)

Conclusion

- Coupling quintessence to particle physics in supergravity would lead to very interesting phenomenology
- Obstruction to quintessence models
- Warped models?