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SUMMER SCHOOL IN COSMOLOGY AND ASTROPARTICLE PHYSICS

10 - 21 July 2006

String Cosmology

Part 1

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String cosmology

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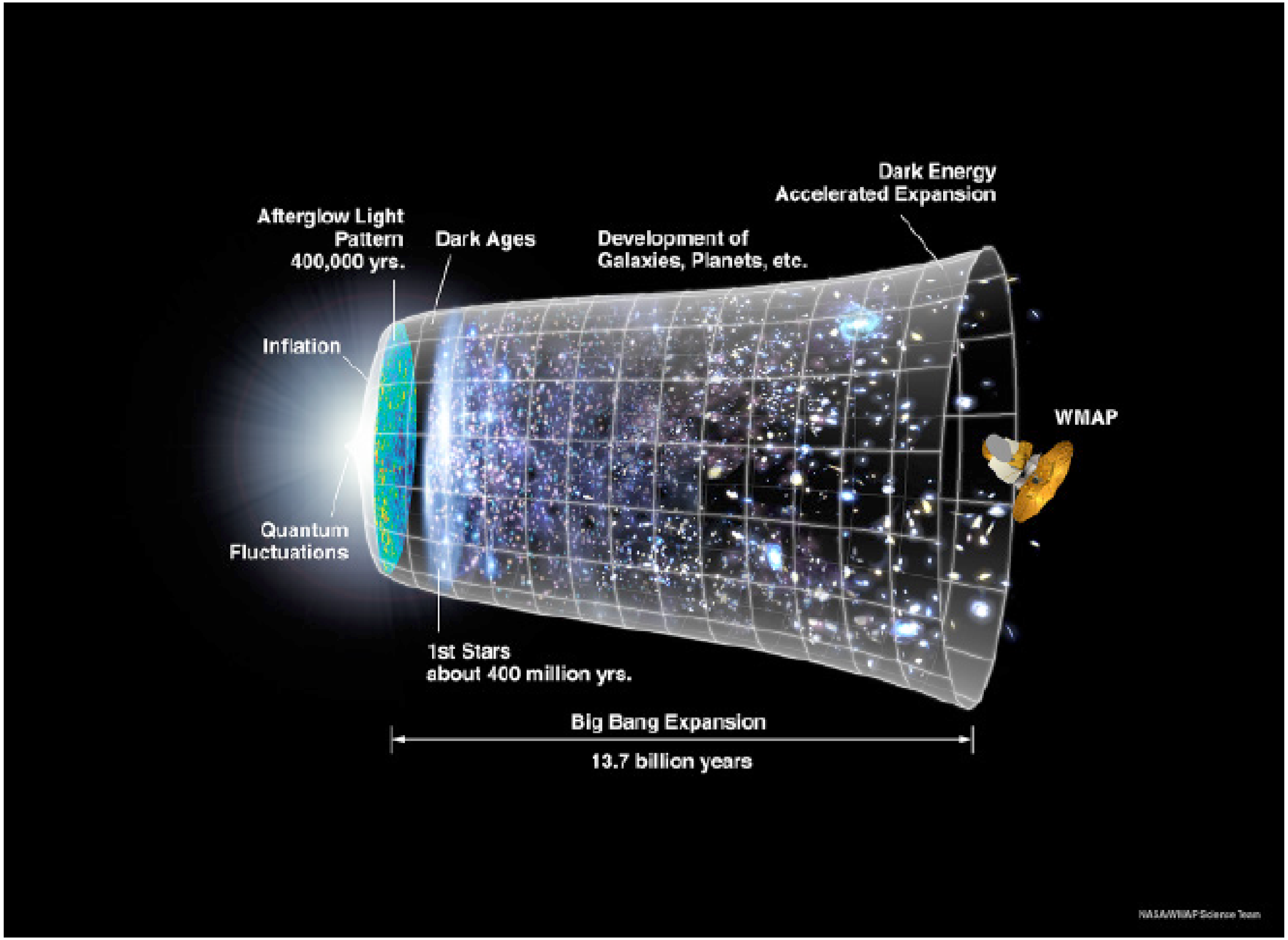
Trieste, ICTP, July 2006

OUTLINE

- General Introduction
- Dark Energy in String Theory and Supergravity
  - Problems with quintessence
  - Meta-Stable de Sitter vacua, landscape
- Stabilization of moduli in string theory
- Inflation in String theory
  - Modular Inflation
  - Brane Inflation
- BPS cosmic strings and domain walls in the landscape

Schematic Time Line



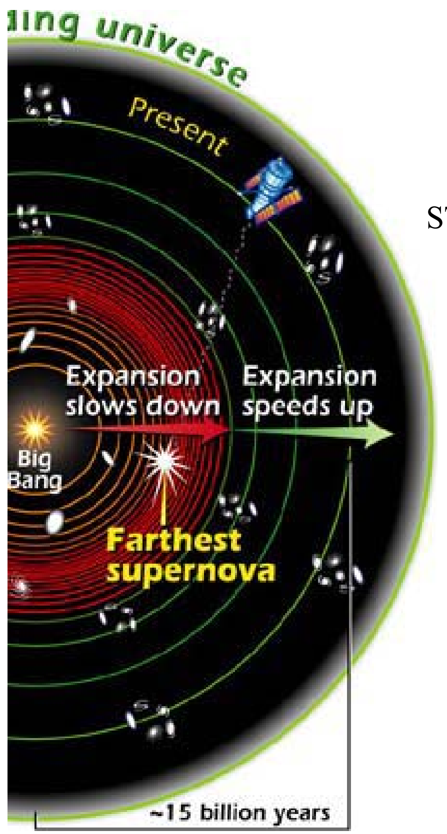
Fundamental Physics

Astrophysics → Cosmology → Effective 4d GR

a(t) → Equation of state w(z) → V(ϕ)

SN
CMB
LSS

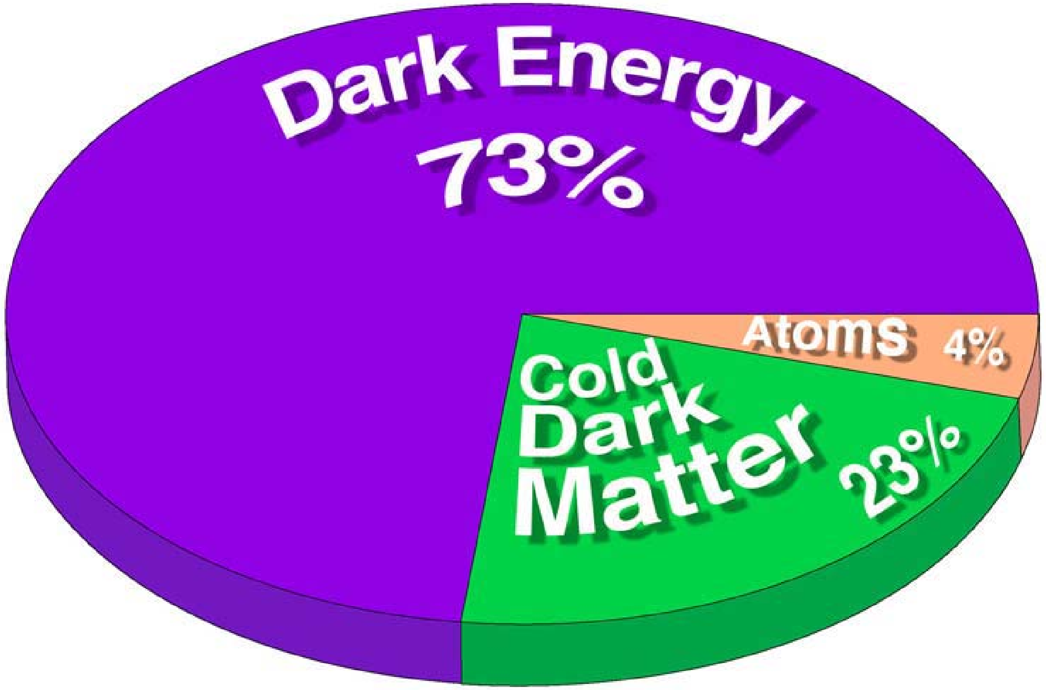
The subtle slowing and growth of scales with time – a(t) – map out the cosmic history like tree rings map out the Earth's climate history.

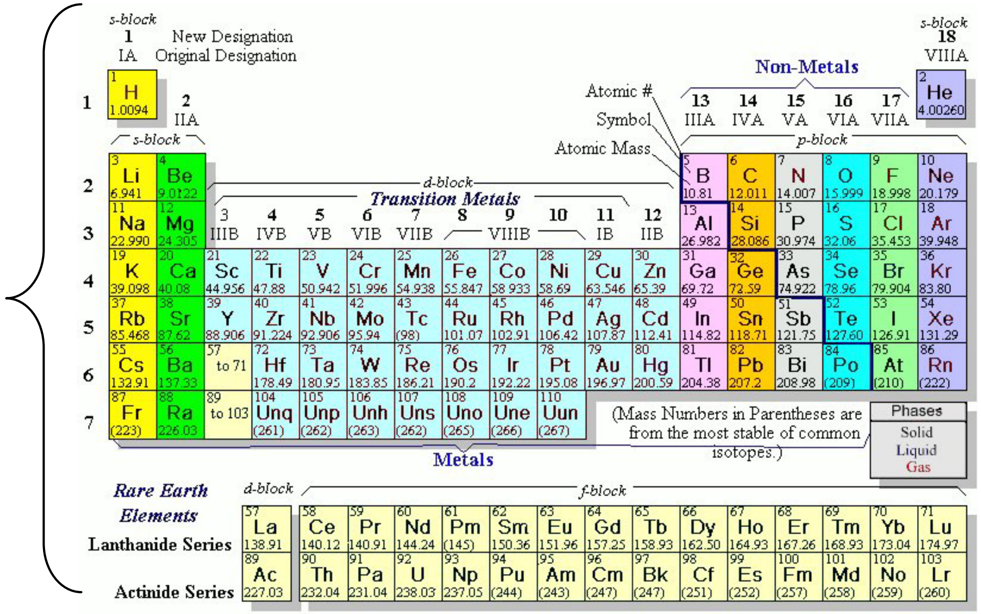


STScI

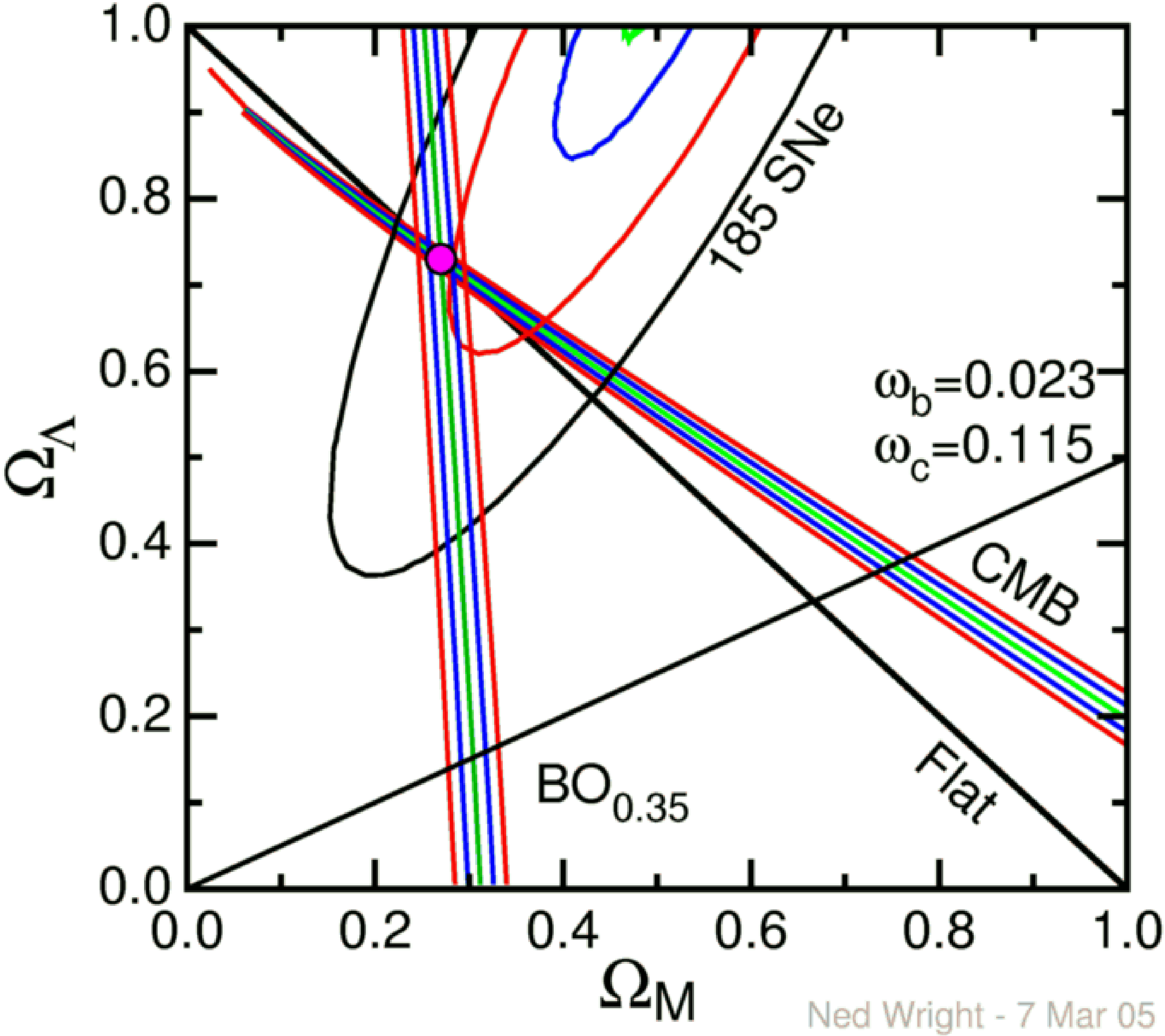
Map the expansion history of the universe

We (and all of chemistry) are a small minority in the Universe





Implications for Ω_M, Ω_Λ



Our Universe is an Ultimate Test of Fundamental Physics

- High-energy accelerators will probe the scale of energies way below GUT scales

- **Cosmology and astrophysics are sources of data in the gravitational sector of the fundamental physics (above GUT, near Planck scale)**

ΛCDM

Cosmological Concordance Model

- Early Universe Inflation
- Near de Sitter space
- 13.7 billion years ago
- During 10^{-30} sec

- Current Acceleration
- Near de Sitter space
- Now
- During few billion years

$$\frac{\dot{a}}{a} = H \approx \text{const}$$

$$V \sim H^2 M_P^2 \qquad V \sim H^2 M_P^2$$

$$H_{infl} \leq 10^{-5} M_p \qquad H_{accel} \sim 10^{-60} M_P$$

$$\frac{\ddot{a}}{a} > 0$$

One can argue that M/String theory is fundamental

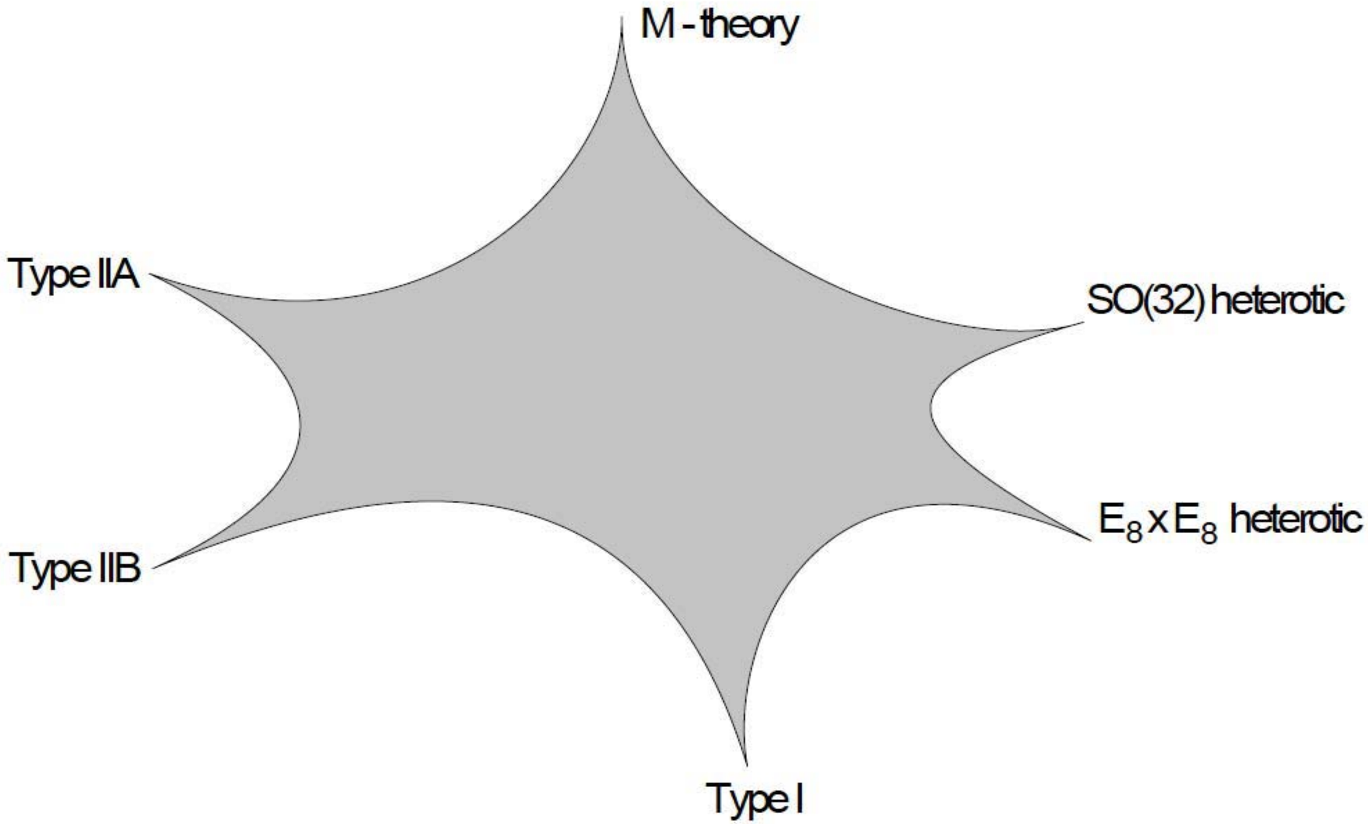
- Perturbative finiteness of quantum gravity
- Beyond standard model particle physics
- Supersymmetry, supergravity: d=10/d=11 maximal dimension, almost unique
- **The best theory we have now**

Impact of the discovery of acceleration of the universe

Until recently, string theory could not describe acceleration of the early universe (inflation)

The discovery of current acceleration made the problem even more severe, but also helped to identify the root of the problem

Space of M/String Theory vacua



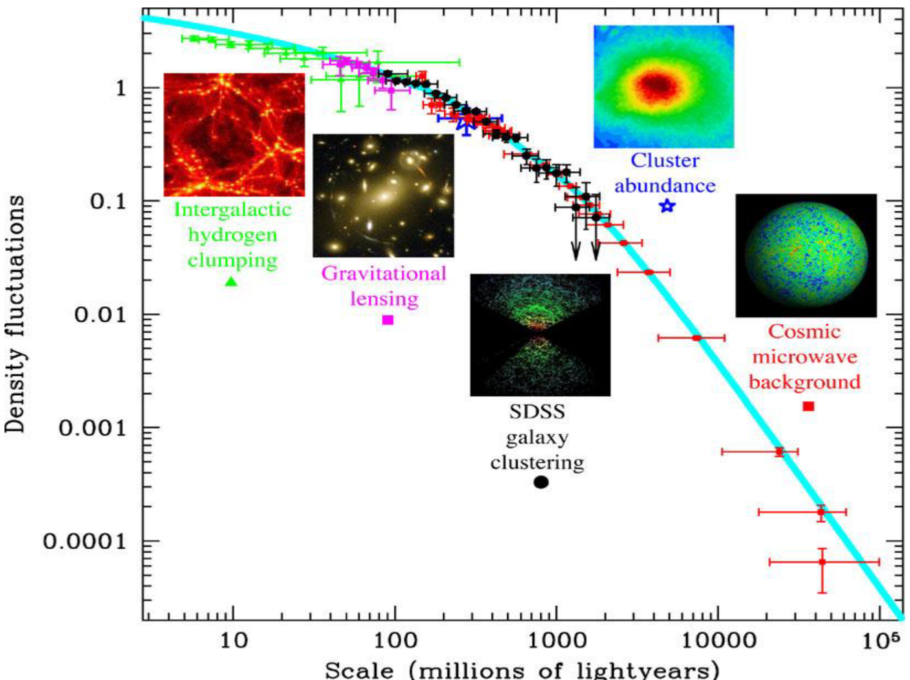
- It was known for 20 years that string theory is not easily compatible with cosmology
- During the last few years this became a very serious issue

String Theory and Cosmology

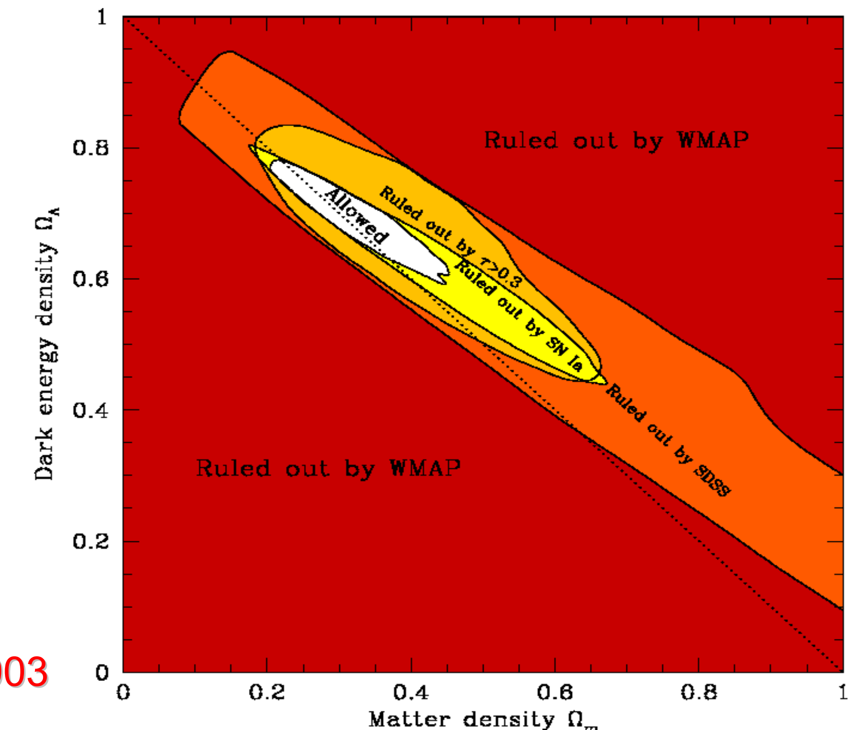
How to get the 4d <u>near de Sitter</u> and/or <u>de Sitter</u> space from the compactified 10d string theory or 11d M-theory?

$$H_{infl} \leq 10^{-5} M_p$$

$$H_{accel} \sim 10^{-60} M_P$$

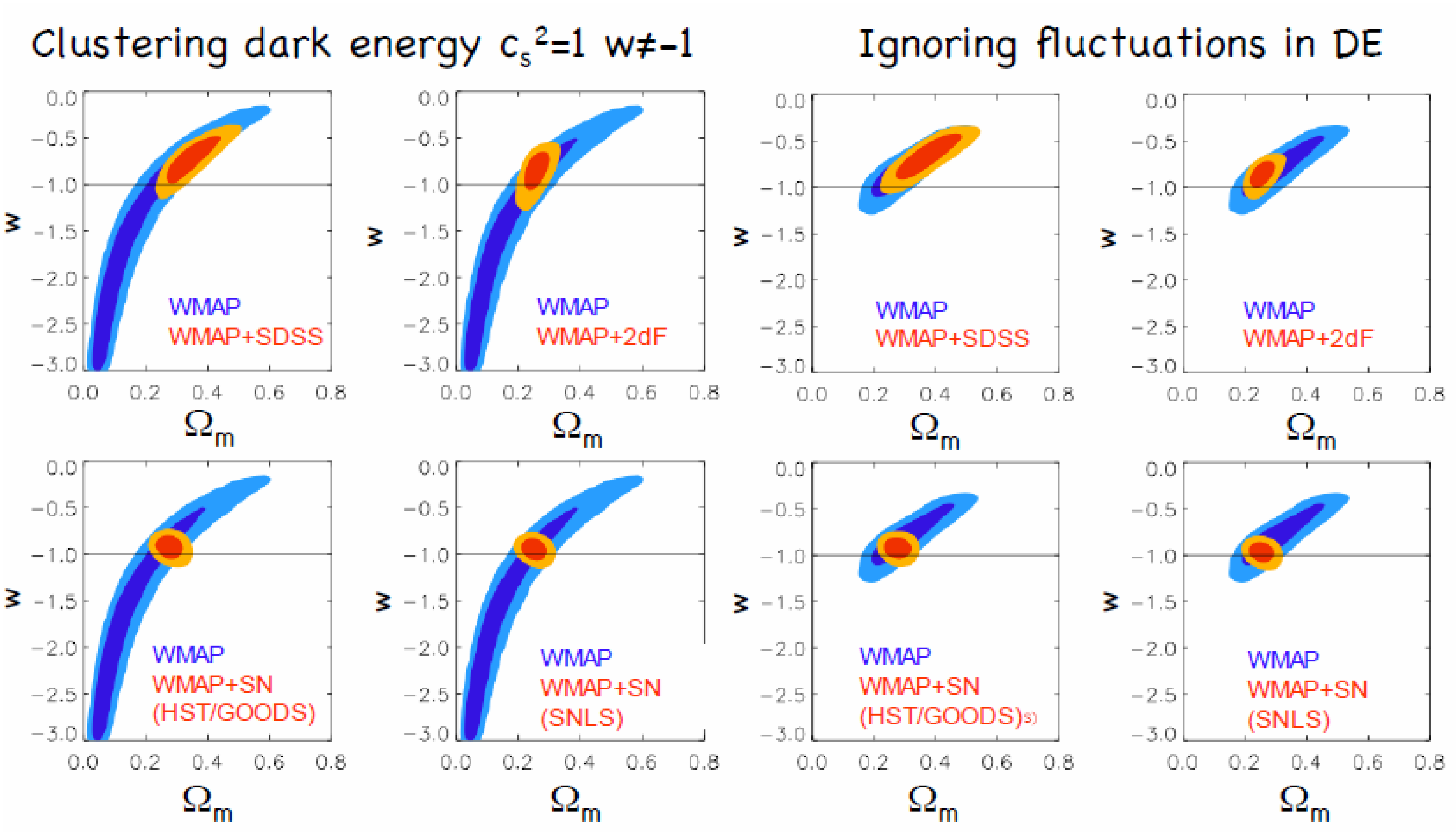


Tegmark, 2003



March 2006 after WMAP3

Dark Energy still consistent with w=-1



Support of the ΛCDM paradigm

May 2006

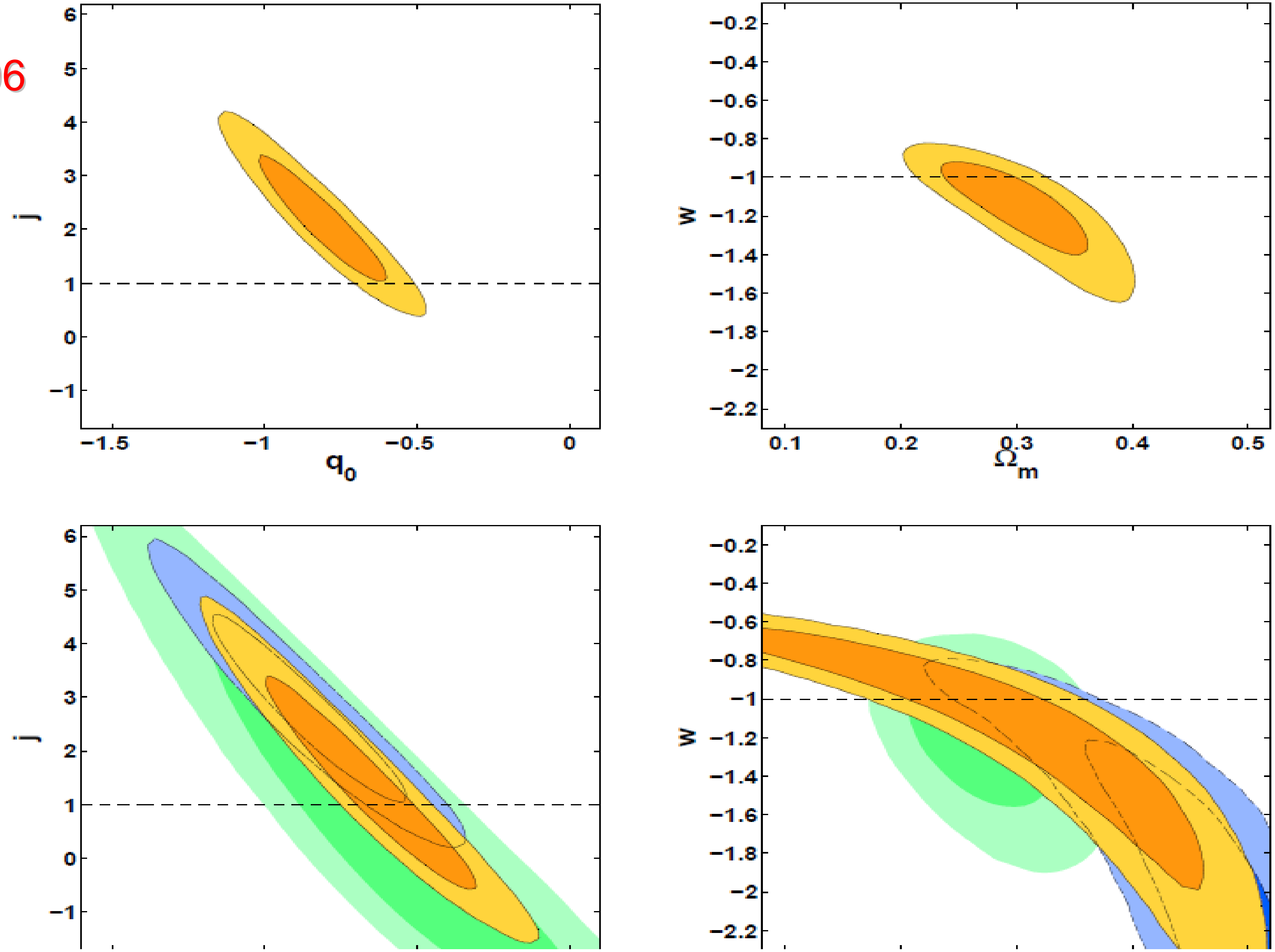


Figure 1. A summary of the results from the kinematical (left panels) and dynamical (right panels) analyses. The top left panel shows the 68.3 and 95.4 per cent confidence limits in the (q_0, j) plane for the kinematical model with a constant jerk, j, obtained using all three data sets: both SNIa data sets (Riess et al. 2004; Astier et al. 2005) and the cluster f_{gas} data of Allen et al. (2006). The top right panel shows the results in the (Ω_m, w) plane obtained using the same three data sets and assuming HST, BBNS and b priors. (Note that the kinematical analysis does not use the HST, BBNS and b priors). The dashed lines show the expectation for a cosmological constant model in both formalisms ($j = 1$, $w = -1$, respectively). The bottom panels show the confidence contours in the same planes for the individual data sets: the SNLS SNIa data (orange contours), the Riess et al. (2004) 'gold' SNIa sample (blue contours) and the cluster f_{gas} data (green contours). Here, the dashed lines again indicate the cosmological constant model.

No-Go Theorems for 4d de Sitter Space

from 10/11d string/M theory

- Gibbons **1985**
- de Wit, Smit, Hari Dass, **1987**
- Maldacena, Nunez, **2001**

How to go around the conditions for de Sitter no-go theorems?

How to perform a compactification from 10/11 dimensions to 4 dimensions and stabilize the moduli?

The major problem:

Few years ago it was not clear how one could possibly incorporate a **positive** cosmological constant **in string theory**

This was **the main reason of embarrassment for string theorists**, because of the cosmological data suggesting that $\Lambda > 0$

$\Lambda \leq 0$ is much more natural for **superstring** theory

Supersymmetric minimum can be Minkowski or anti de Sitter,

never de Sitter

Stable vacua in effective supergravity

- Potential $V = e^K(|DW|^2 - |W|^2) + D^2$

- **Unbroken supersymmetry condition**

$$DW = F = 0, \qquad D = 0$$

- **AdS** $W \neq 0$ $V = -3e^K|W|^2$

- **Minkowski** $W = 0$ $V = 0$

Extremely difficult to find stable non-supersymmetric vacua

Cosmological Observations ⇒ String Theory

From 2003:

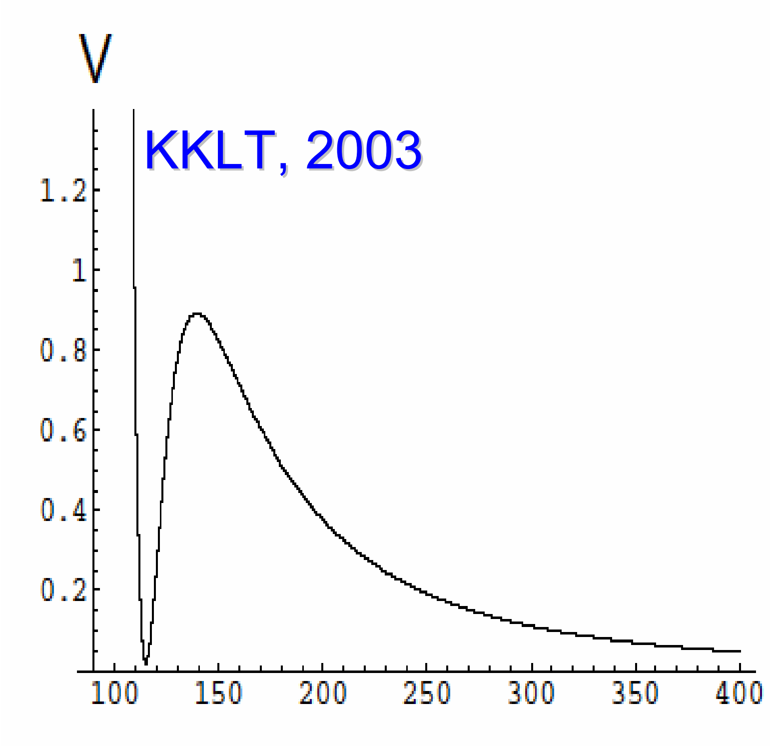
- Stringy Landscape (>10^{500} vacua)
- Moduli stabilization
- Dense set of metastable de Sitter vacua
- Anthropic reasoning

- ⇒ New ideas on "Beyond the Standard model particle physics"

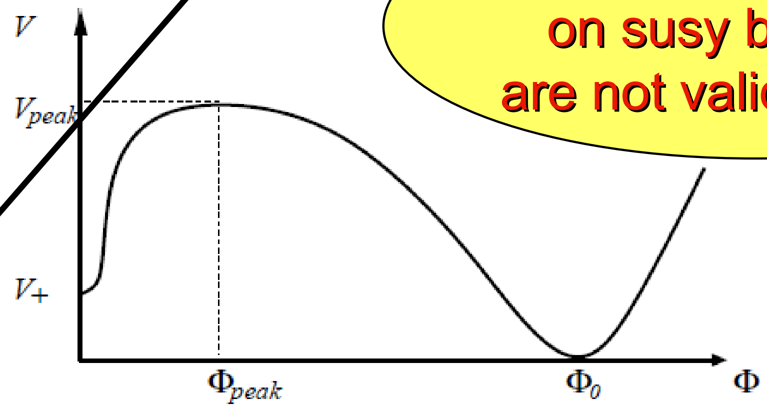
2004
- **Split supersymmetry as an alternative to MSSM**

2006
- **SUSY breaking metastable vacua in gauge theories with lifetime longer than the lifetime of the Universe**

New paradigm in phenomenological model building of supersymmetric extensions of Standard Model



Seiberg et al, Ooguri et al, 2006



Famous no-go theorems on susy breaking are not valid anymore

We point out that new model building avenues are opened up by abandoning the prejudice that models of dynamical supersymmetry breaking must have *no* supersymmetric vacua. This prejudice is unnecessary, because it is a phenomenologically viable possibility

Broken supersymmetry is generic in the landscape of string vacua

The lifetime of meta-stable vacua is longer than the age of the Universe

Dark Energy in String Theory

- **Current solution**: compactification, moduli stabilization, effective 4d general relativity with positive cosmological constant. KKLT-type construction of the meta-stable de Sitter vacua, stringy landscape.

$$\Lambda \sim 10^{-120} > 0 \qquad w = -1$$

- Quinessence ???

$$w(z), \qquad w' \neq 0$$

$M_{Pl}=1$

A general Problem of Dark Energy:

$$V'/V \leq 1 \qquad V''/V \leq 1$$ slow roll conditions

Dark energy can be observationally different from the cosmological constant only if an additional coincidence problem is resolved. In the language of the effective scalar theory, one should require that the slope of the quintessence potential is anomalously small,

$$V < 10^{-120}$$

To distinguish dark energy from the cosmological constant, the slope must be of the same order as the cosmological constant:

$$V' \approx 10^{-120}$$

This would be a coincidence (additional fine-tuning), which does not have any motivation (even anthropic) in most of the dark energy models.

Few exception from this rule

Ghost-Free de Sitter supergravities, consistent reductions from M/String Theory

De Sitter Gauged Supergravities

as a consistent Pauli reduction of M/String theory on hyperbolic spaces $\mathcal{H}^{p,q}$

11/10 d supergravities lead to ghost-free gauged 4d supergravities with extended supersymmetry

dS always correspond to saddle points

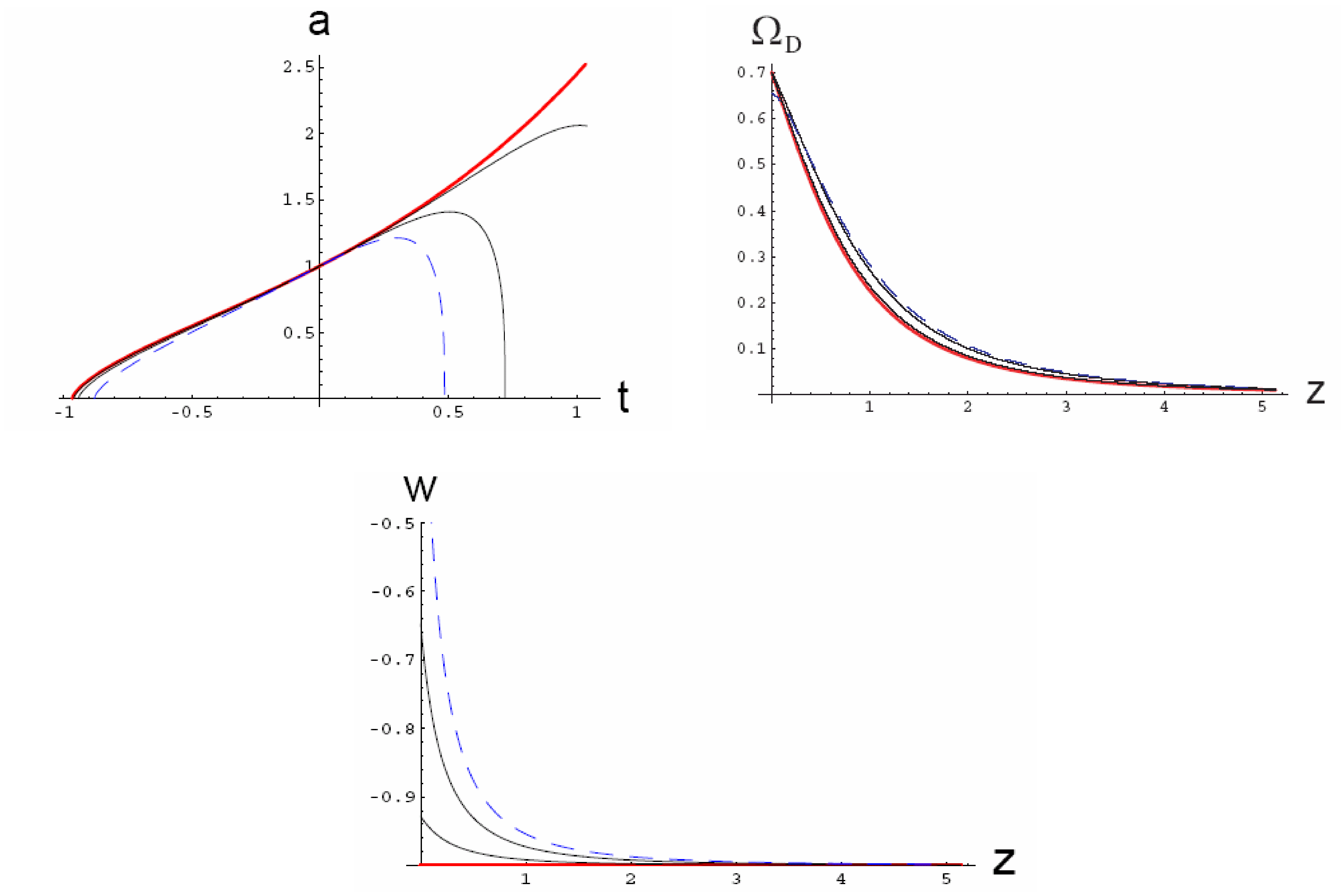
R. K., Linde, Prokushkin, Shmakova, 2002

Cvetic, Gibbons, Pope, 2004

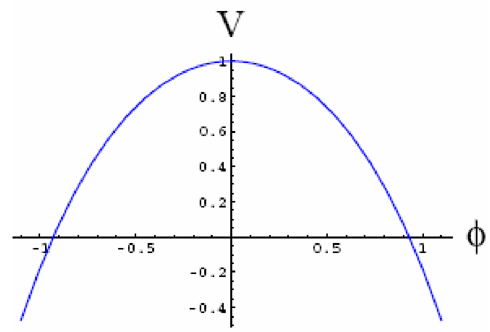
Toy models of dark energy with w(z) > - 1, with future collapse and anthropic explanation of the scale of CC

Dark energy slow-roll conditions are satisfied authomatically

$$m^2 \sim -H^2$$


a
2.5
2
1.5
1
0.5
-1
-0.5
0.5
1
t
Ω_D
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1
2
3
4
5
z
w
-0.5
-0.6
-0.7
-0.8
-0.9
1
2
3
4
5
z

Why future collapse is generic in all M/string theory ghost-free dS supergravities?



M-theory vacuum $AdS_4 \times S^7$

A **ghost-free** analytic continuation to $dS_4 \times \mathcal{H}^{4,4}$

An analytic continuation of the AdS potential to dS one

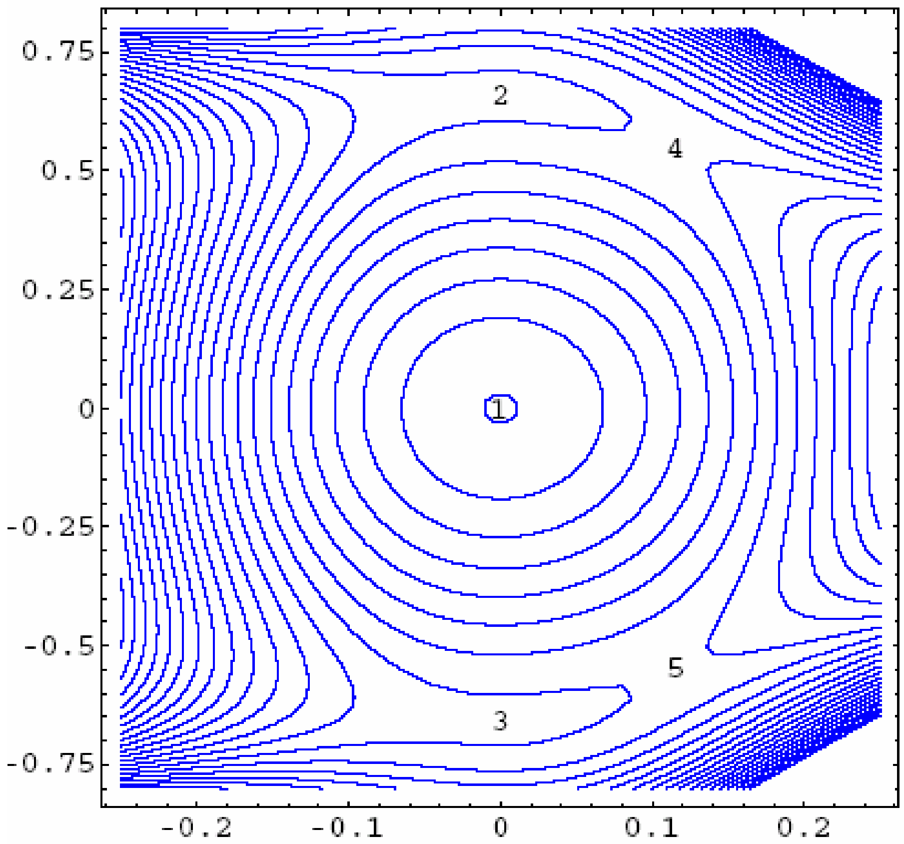
$$V_{AdS} = -8g^2(\cosh\phi_1 + \cosh\phi_2 + \cosh\phi_3)$$

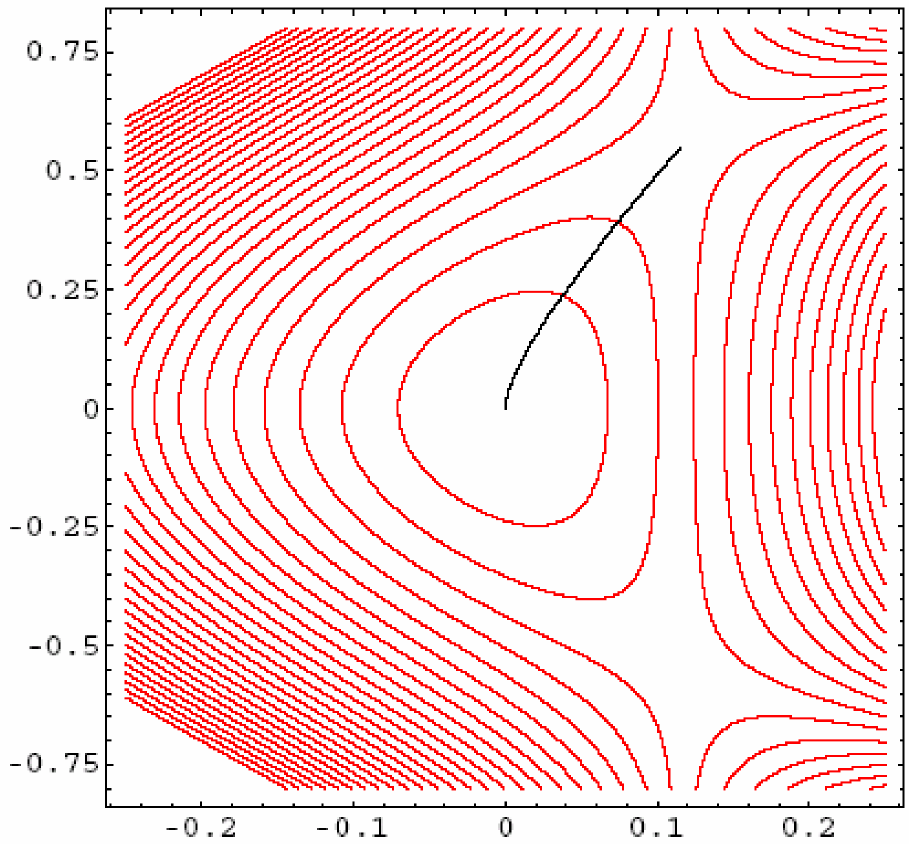
AdS maximum

$$V_{dS} = -8g^2(\cosh\phi_1 - \cosh\phi_2 - \cosh\phi_3)$$

dS saddle point

Typical AdS extrema, maximum and saddle points

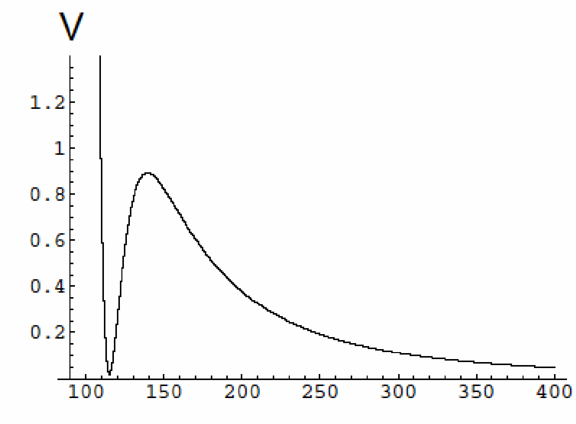




Renormalization Group Flows from Holography–
Supersymmetry and a c-Theorem

D. Z. Freedman[1], S. S. Gubser[2], K. Pilch[3] and N. P. Warner[4]* hep-th/9904017

LIFETIME



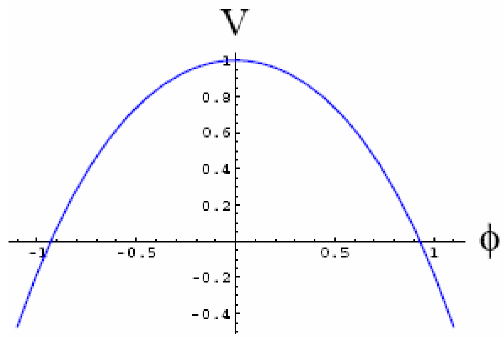
- KKLT model starts with an AdS minimum due to non-perturbative effects. It can be uplifted to dS minimum with the barrier protecting it from the decay. This dS is metastable, practically CC

$$t \sim 10^{10^{120}}$$

- Exact solutions of 11d M/string-supergravity with fluxes: ghost-free dS supergravities. Unstable since dS is a saddle point. Prediction

R. K., Linde

$$T > 10^{10} - 10^{11}$$



Comparable with the age of the universe

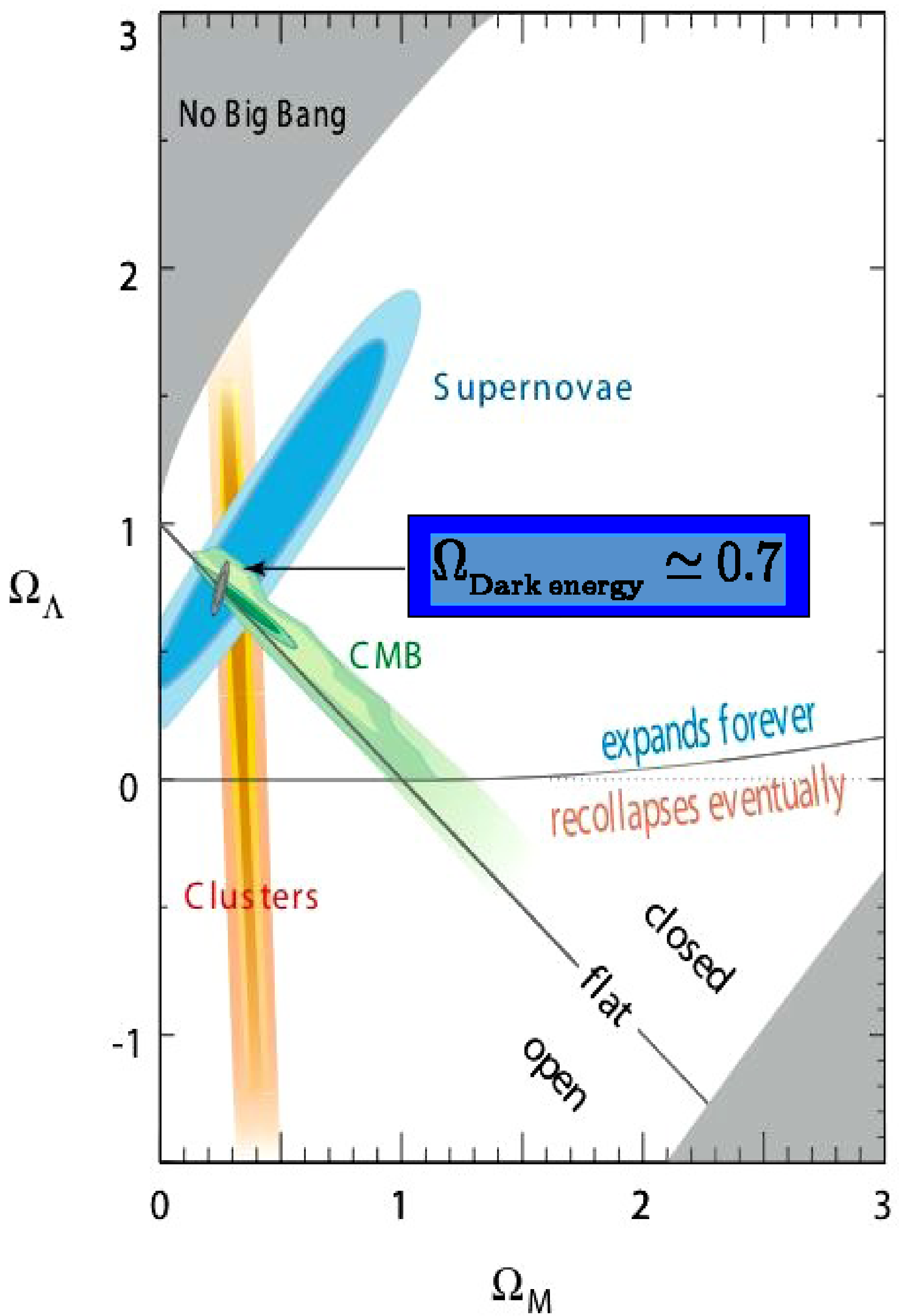
Additional problem with such models

- The models are based on M-theory compactified on hyperbolic spaces. In d=4 they correspond to N=8, N=4 supergravity.

- These models are extremely difficult to relate to particle physics, so they are quite unrealistic

Dark Energy & MSSM

hep-th/0605228 (P. Brax & J. Martin)
astro-ph/0606306 (P. Brax & J. Martin)



Quintessence=alternative to the CC

Insensitivity to the IC

↓

Tracking behavior

↓

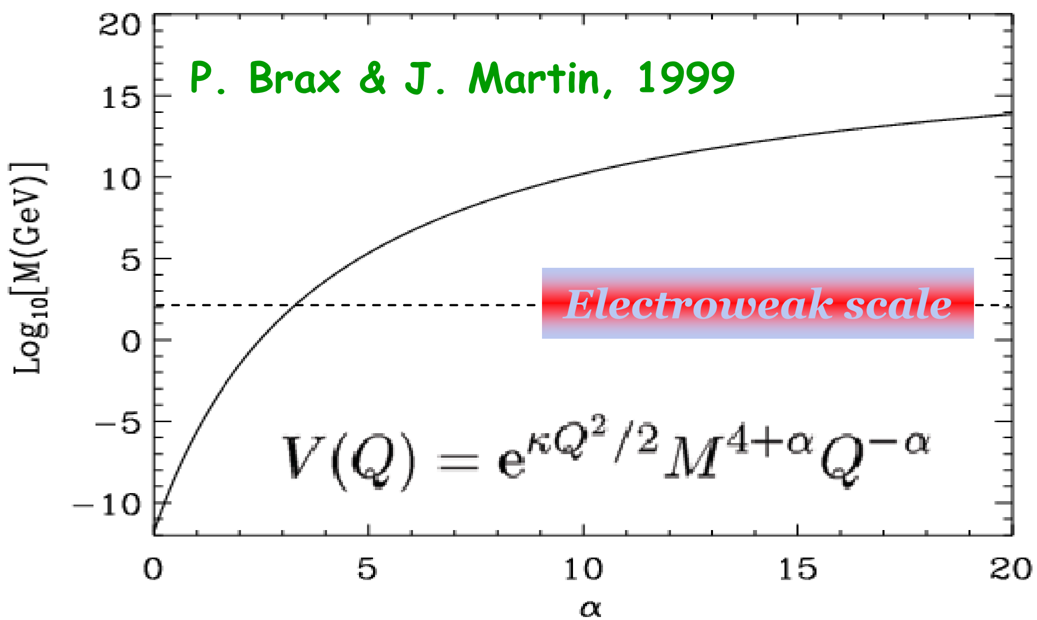
Ratra-Peebles $V(Q) = M^{4+\alpha}Q^{-\alpha}$

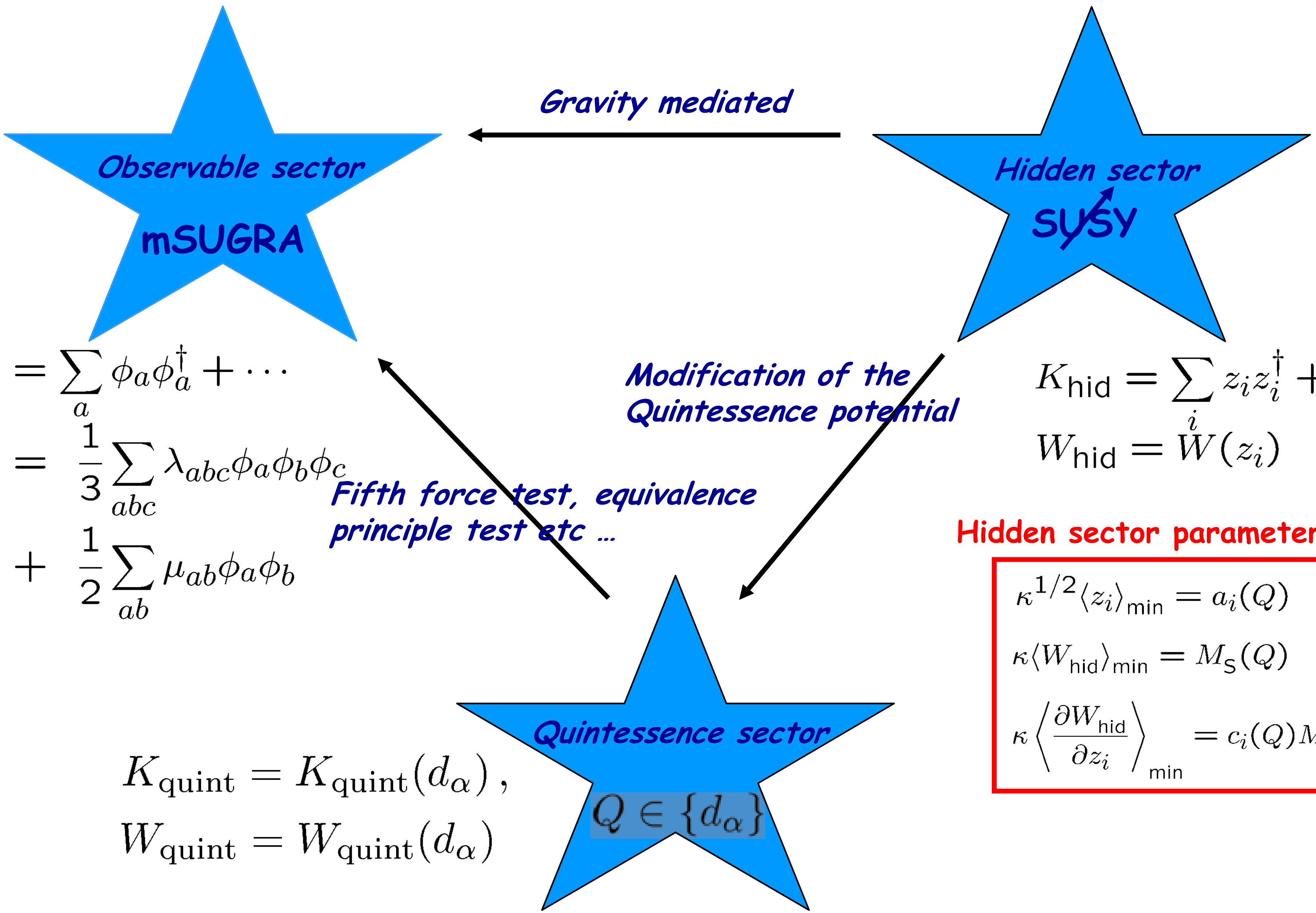
↓

$\langle Q \rangle_{\text{today}} \sim m_{\text{Pl}}$

↓

SUGRA





$$K_{\rm obs} = \sum_a \phi_a \phi_a^\dagger + \cdots$$

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

$$K_{\rm hid} = \sum_i z_i z_i^\dagger + \cdots$$

$$W_{\rm hid} = W(z_i)$$

Hidden sector parameterization

$$\kappa^{1/2} \langle z_i \rangle_{\rm min} = a_i(Q)$$

$$\kappa \langle W_{\rm hid} \rangle_{\rm min} = M_{\rm S}(Q)$$

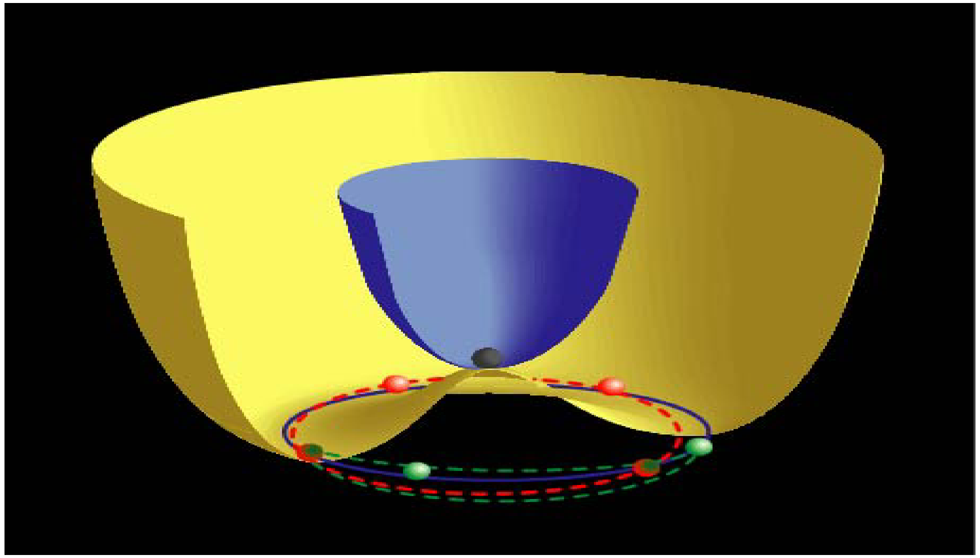
$$\kappa \left\langle \frac{\partial W_{\rm hid}}{\partial z_i} \right\rangle_{\rm min} = c_i(Q) M_{\rm S}(Q)$$

$$K_{\rm quint} = K_{\rm quint}(d_\alpha)\,,$$

$$W_{\rm quint} = W_{\rm quint}(d_\alpha)$$

$$K = K_{\rm quint} + K_{\rm hid} + K_{\rm obs}\,, \qquad W = W_{\rm quint} + W_{\rm hid} + W_{\rm obs}$$

Application to the Higgs Mechanism



$$H_{\mathrm{u}} = \begin{pmatrix} H_{\mathrm{u}}^{+} \\ H_{\mathrm{u}}^{0} \end{pmatrix}, \qquad H_{\mathrm{d}} = \begin{pmatrix} H_{\mathrm{d}}^{0} \\ H_{\mathrm{d}}^{-} \end{pmatrix}$$

$$W_{\mathrm{obs}} = \mu (H_{\mathrm{u}}^{+} H_{\mathrm{d}}^{-} - H_{\mathrm{u}}^{0} H_{\mathrm{d}}^{0}) + \cdots$$

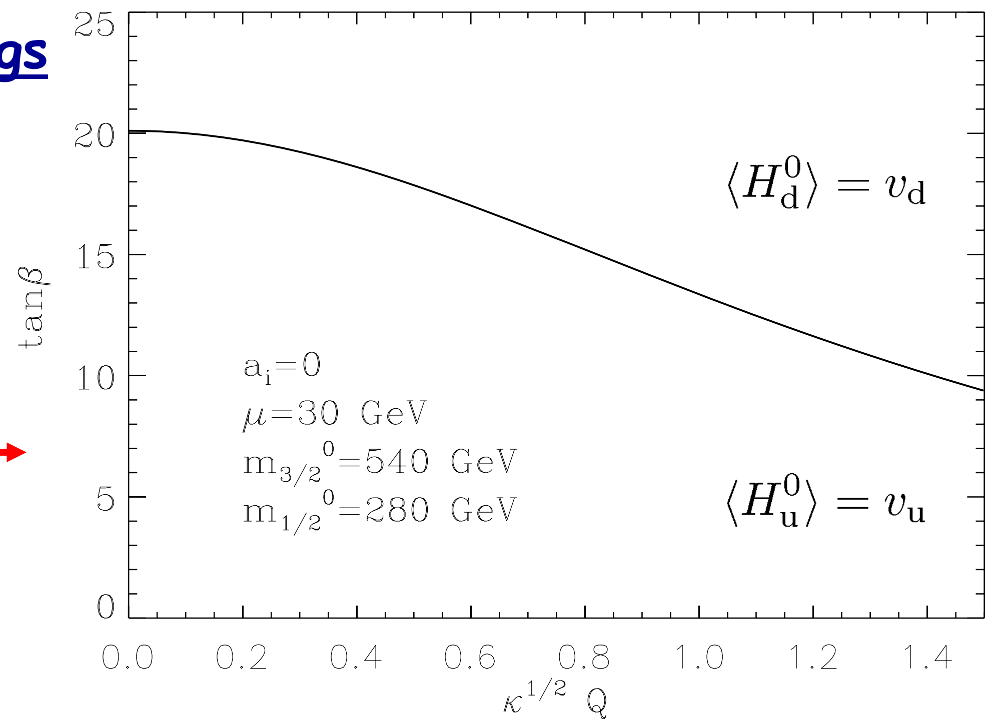
$$V_{\mathrm{mSUGRA}} = \cdots + \mathrm{e}^{\kappa K} V_{\mathrm{susy}} + A_{abc}\left(\phi_a\phi_b\phi_c + \phi_a^\dagger\phi_b^\dagger\phi_c^\dagger\right) + B_{ab}\left(\phi_a\phi_b + \phi_a^\dagger\phi_b^\dagger\right) + m^2_{a\bar{b}}\phi_a\phi_b^\dagger$$

$$\begin{aligned} V_{\mathrm{Higgs}} = \; & \mathrm{e}^{\kappa K_{\mathrm{quint}}}\Bigg\{\left(|\mu|^2 \mathrm{e}^{\sum_i |a_i|^2} + m^2_{H_{\mathrm{u}}}\right)\left(|H_u^+|^2 + |H_u^0|^2\right) + \left(|\mu|^2 \mathrm{e}^{\sum_i |a_i|^2} + m^2_{H_{\mathrm{d}}}\right) \\ & \times\left(|H_{\mathrm{d}}^0|^2 + |H_{\mathrm{d}}^-|^2\right) + \mu B(Q)\left[H_{\mathrm{u}}^+ H_{\mathrm{d}}^- - H_{\mathrm{u}}^0 H_{\mathrm{d}}^0 + \left(H_{\mathrm{u}}^+\right)^\dagger \left(H_{\mathrm{d}}^-\right)^\dagger - \left(H_{\mathrm{u}}^0\right)^\dagger \left(H_{\mathrm{d}}^0\right)^\dagger\right]\Bigg\} \\ & + \frac{1}{8}\left(g^2 + g'^2\right)\left(|H_{\mathrm{u}}^+|^2 + |H_{\mathrm{u}}^0|^2 - |H_{\mathrm{d}}^0|^2 - |H_{\mathrm{d}}^-|^2\right)^2 + \frac{1}{2} g^2 \left|H_{\mathrm{u}}^+ H_{\mathrm{d}}^{0\dagger} + H_{\mathrm{u}}^0 H_{\mathrm{d}}^{-\dagger}\right|^2 \end{aligned}$$

Through the soft terms, the (F-terms) Higgs potential becomes Q-dependent. Additional dependence can show up through the gauge coupling functions (D-terms).

As a consequence, the vev's of the Higgs become Q-dependent

$$v_u = \frac{v \tan\beta}{\sqrt{1+\tan^2\beta}}, \qquad v_d = \frac{v}{\sqrt{1+\tan^2\beta}}$$



Completely calculable in a given model (here the SUGRA model)

$$\tan\beta = \frac{2|\mu|^2 e^{\sum_i |a_i|^2} + m^2_{H_u}(Q) + m^2_d(Q)}{2\mu B(Q)} \left(1 \pm \sqrt{1 - 4\mu^2 B^2(Q)\left[2|\mu|^2 e^{\sum_i |a_i|^2} + m^2_{H_u} + m^2_{H_d}\right]^{-2}}\right)$$

Main Result:

The fermions pick up a Q-dependent mass which is not the same for the "u" or "d" particles. This is calculable entirely from SUGRA.

Yukawa couplings

$$m_u(Q) = \lambda_d e^{\kappa K_{quint}/2 + \sum_i |a_i|^2/2} v_u(Q)$$

$$m_d(Q) = \lambda_d e^{\kappa K_{quint}/2 + \sum_i |a_i|^2/2} v_d(Q)$$

Consequences:

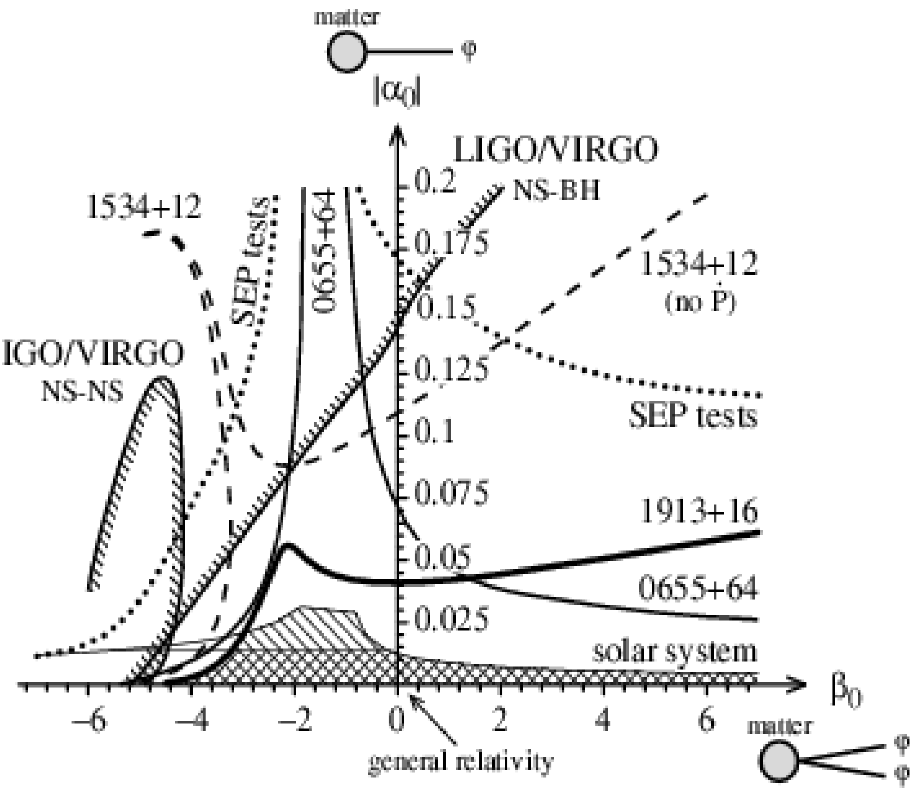
- **Presence of a fifth force**

$$\alpha_{\rm u,d}(Q) = \left| \frac{1}{\kappa^{1/2}} \frac{{\rm d} \ln m_{\rm u,d}(Q)}{{\rm d}Q} \right| < 10^{-2.5}$$

- **Violation of the equivalence principle**

$$\eta_{\rm AB} \equiv \left(\frac{\Delta a}{a} \right)_{\rm AB} = 2 \frac{a_{\rm A} - a_{\rm B}}{a_{\rm A} + a_{\rm B}} \sim \frac{1}{2} \alpha_{\rm E} \left(\alpha_{\rm A} - \alpha_{\rm B} \right)$$

Current limits: $\eta_{\rm AB} = (+0.1 \pm 2.7 \pm 1.7) \times 10^{-13}$



- **Variation of the proton to electron mass ratio** $\frac{\Delta r}{r} = (2.0 \pm 0.6) \times 10^{-5}$

- **Variation of constants (fine structure constant etc ...)** $\frac{\Delta \alpha_{\rm QED}}{\alpha_{\rm QED}} < 10^{-7}$

Conclusions:

- Coupling Dark energy to the observable fields predicts a bunch of different effects. In particular, violation of the EP is directly linked to the fact that there are two Higgs in the MSSM.

- Probing dark energy is not only measuring the equation of state (cosmological test). MICROSCOPE (CNES) will measure the EP in 2008.

- Detailed predictions require detailed models. Can be used to rule out models

$$\langle Q \rangle_{\text{today}} \sim m_{\text{Pl}}$$

We focus on the coupling of the SUGRA quintessence model to the MSSM and investigate two possibilities. First one can preserve the form of the SUGRA potential provided the hidden sector dynamics is tuned. The currently available limits on the violations of the equivalence principle imply a universal bound on the vacuum expectation value of the quintessence field now, $\kappa^{1/2}Q \ll 1$. On the other hand, the hidden sector fields may be stabilised leading to a minimum of the quintessence potential where the quintessence field acquires a mass of the order of the gravitino mass, large enough to circumvent possible gravitational problems. However, the cosmological evolution of the quintessence field is affected by the presence of the minimum of the potential. The quintessence field settles down at the bottom of the potential very early in the history of the universe. Both at the background and the perturbation levels, the subsequent effect of the quintessence field is undistinguishable from a pure cosmological constant.

A very light quitessence field + MSSM seem to contradict EP.
To avoid the problem, put the field into the minimum
of the potential: ⇒ effective positive cosmological constant.

Axion dark energy models

- Very light axions in string theory,
- Shift symmetry a --> a + const
- 10^5 axions, S(inst) ~ 300

$$V \sim M^4 e^{-S_{inst}} (1 - \cos(a)) + V_0$$

$$W = M^3 e^{-S_{inst} + ia} + W_0.$$

$$V \sim m_S^2 M^2 e^{-S_{inst}} (1 - \cos(a)) + V_0$$

- Better undertstanding is required

Problems with old and new axion quintessence

- The instanton effects required for the correct scale of dark energy cannot stabilize the axion partner, f_a field. Unsolved problem.
- Old model, one axion: severe fine-tuning of initial conditions, unstable under quantum fluctuations
- New models, N-flation, N-quinessence,

10^5 axions, S(inst) ~ 300.

Not yet really developed, it is not known if they can be made consistent.

The vacua with positive CC are possible in string theory and supergravity (KKLT construction and generalization) and equation of state with

$$w = -1$$

is consistent with string theory.

To explain any other equation of state of dark energy, like

$$w \neq -1 \qquad\qquad w' \neq 0$$

seems extremely difficult

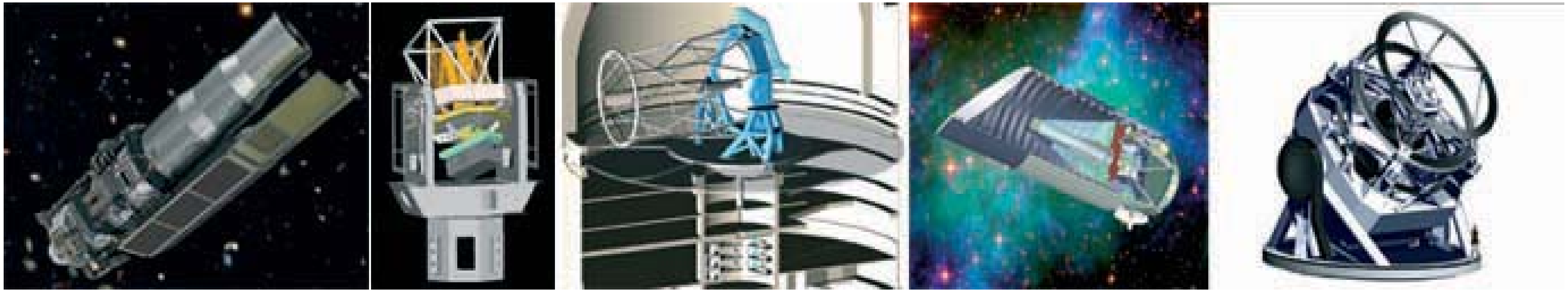
$$w < -1$$

and, particularly,
does not seem possible in consistent string theory.

Modified gravity ???

The Hunt for dark Energy

2017?



- Instruments to study dark energy: (left to right) the Joint Dark Energy Mission - **JDEM** (NASA), the Panoramic Survey Telescope and Rapid Response System - Pan-STARRS (University of Hawaii), the Wide-field Fiber Multi-Object Spectrograph - WFMOS (international colaboration), the Supernova/ Acceleration Probe - **SNAP** (Lawrence Berkeley National Laboratory), the Large Synoptic Survey Telescope - **LSST** (US collaboration)

Dark UNiverse Explorer, **DUNE**, Dark Energy Space Telescope, **Destiny**
Joint Efficient Dark energy Investigation, **JEDI**

Current solution: meta-stable nonsupersymmetric de Sitter vacua are in agreement with the concept of string theory and its landscape

$$\Lambda > 0 \qquad w = -1$$

- Any quitessential form of dark energy is extremely difficult to justify in string theory/supergravity/particle physics and make consistent with equivalence principle etc.

$$w \neq -1 \qquad w' \neq 0$$

- If future observations will prove that $w \neq -1 \quad w' \neq 0$ the fundamental physics will undergo another revolution to explain it consistently (axions? New ideas?)