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SMR.1508 - 40

SUMMER SCHOOL ON PARTICLE PHYSICS

16 June - 4 July 2003

DARK ENERGY

Special Lecture - Part 2

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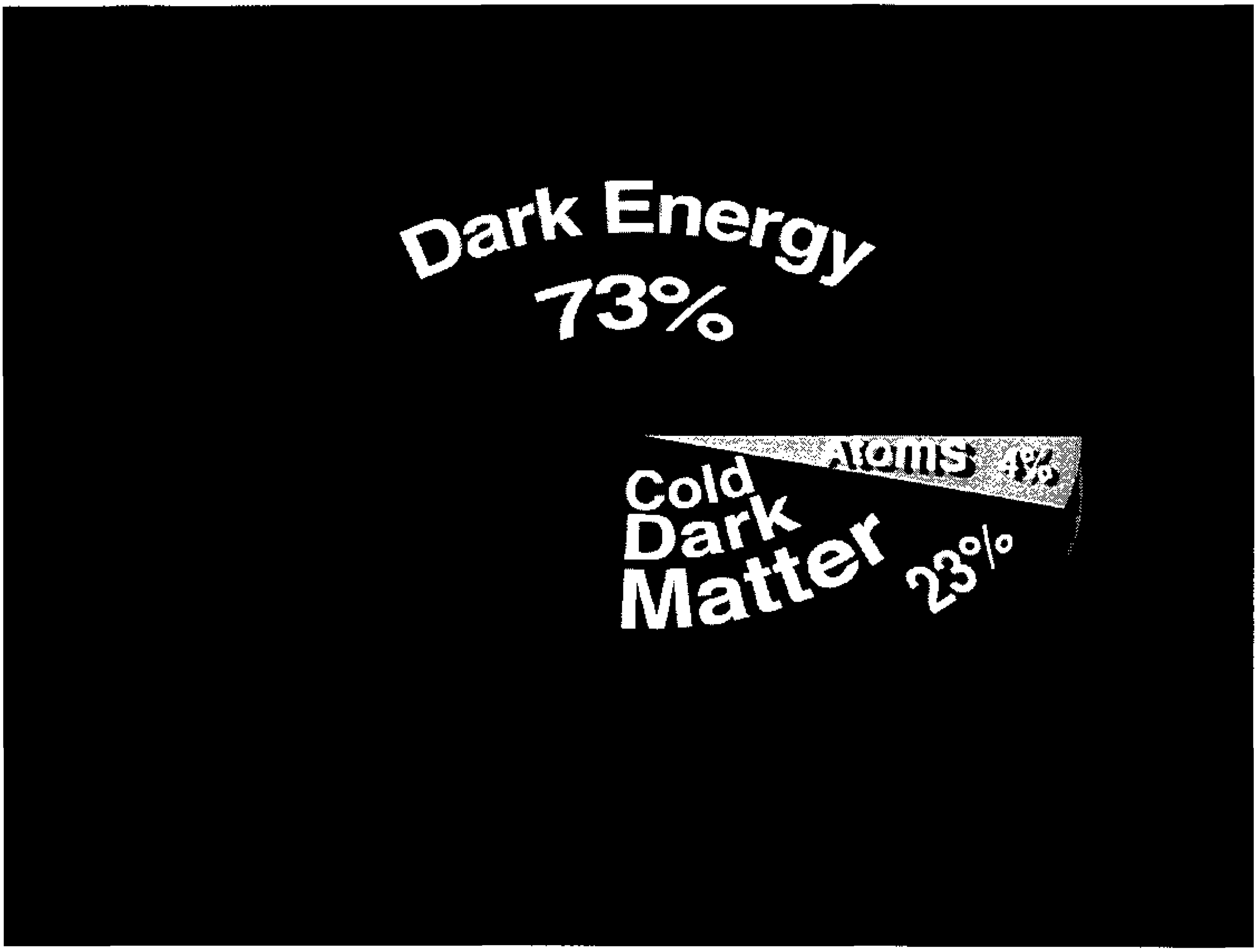
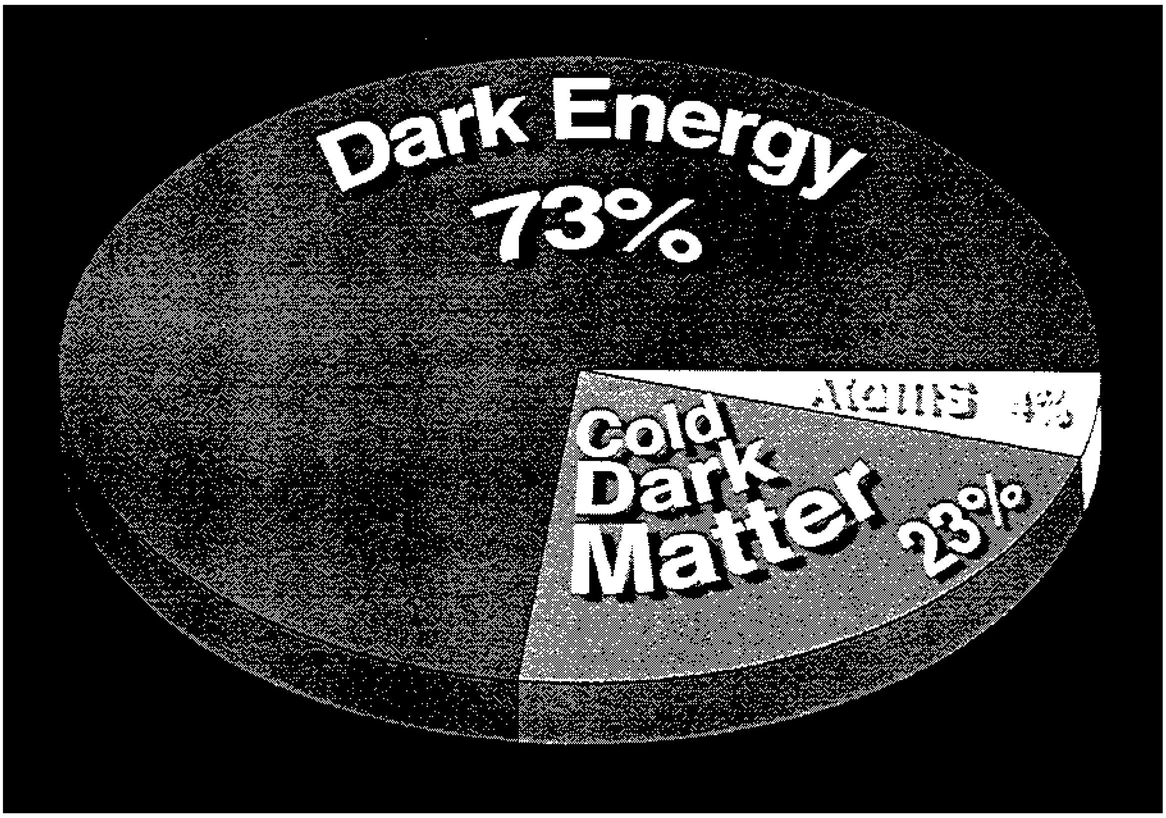

Dark Energy
73%
Atoms 4%
Cold
Dark
Matter
23%


Dark Energy
73%
Atoms 4%
Cold
Dark
Matter
23%

Cosmological Constant Problem

The simplest possibility:

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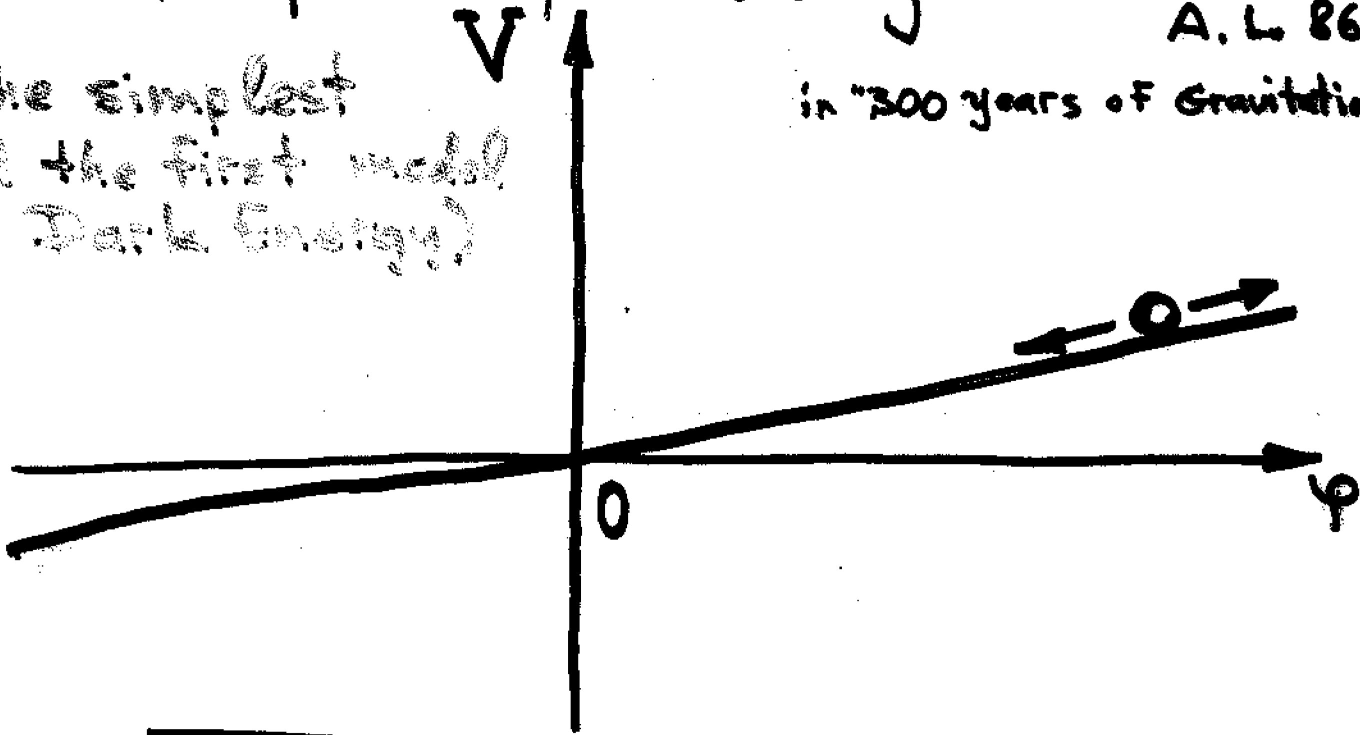
in "300 years of Gravitation"

(the simplest and the first model of Dark Energy)



$$\boxed{V = \alpha\varphi}$$

$$\cancel{\ddot\varphi}^{\,0} + 3H\dot\varphi = -V' = -\alpha \qquad H^2 = \frac{V}{3}$$

$$\Delta t = H^{-1} \qquad \Delta V \ll V$$

$$\Delta V = V'\Delta\varphi = V'\dot\varphi\,\Delta t = \frac{\alpha^2}{3H^2} = \frac{\alpha^2}{V}$$

Condition: $|\alpha| < V \approx 10^{-120}$

Anthropic Bound:

$$|V| \lesssim 10^{-118}$$

Anthropic solution to the cosmological constant problem:

During the early stage of eternal inflation in this model, the universe becomes divided into exponentially many exponentially large domains containing <u>all</u> possible values of the field φ with <u>all</u> possible values of $V(\varphi)$

We can live only in those parts where

$$|V(\varphi)| \lesssim 10^2 \rho_0 \sim 10^{-27} \text{g/cm}^3$$

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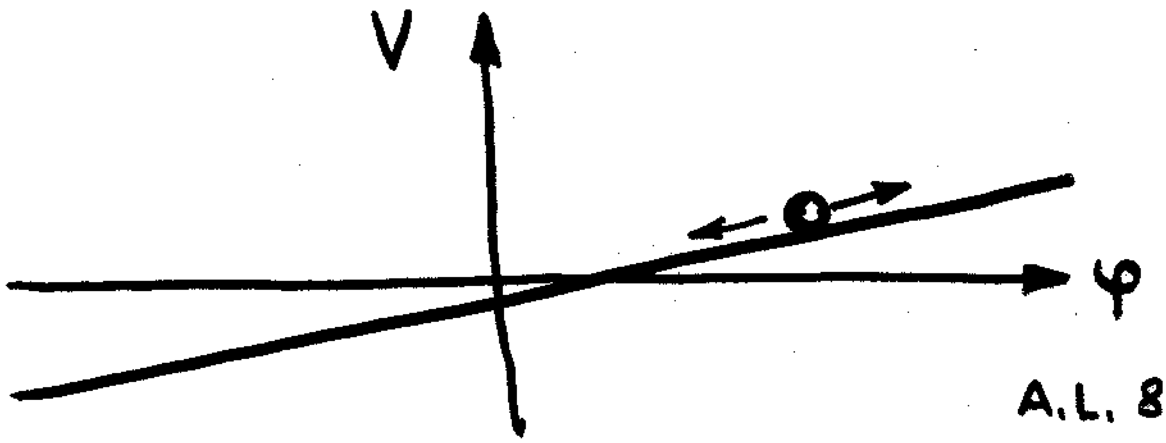
A more detailed study:

Weinberg 87
Efstathiou 95
Martel, Shapiro, Weinberg 98
Garriga, Vilenkin 2000-2002

Simplest dark energy model



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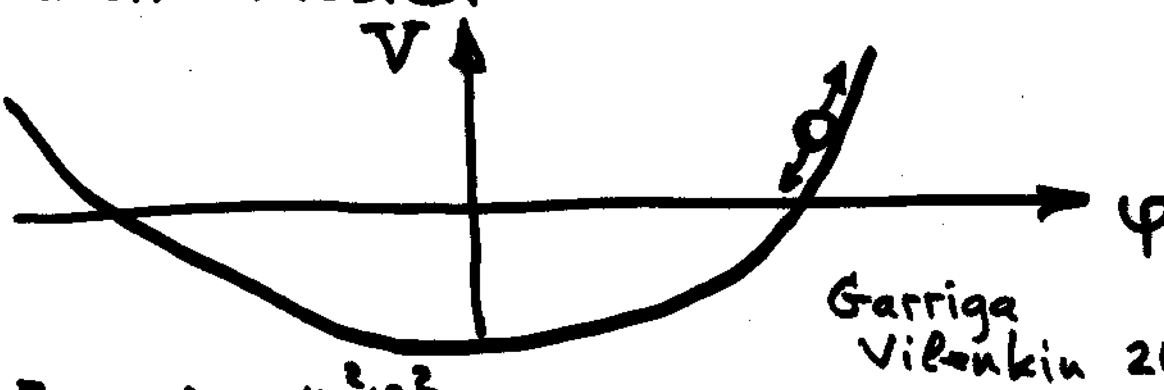
$$V = \alpha \varphi \qquad \alpha < 10^{-120}$$

Eternal infation puts φ to different places in different parts of the universe, and then the field stays there $> 10^{10}$ years

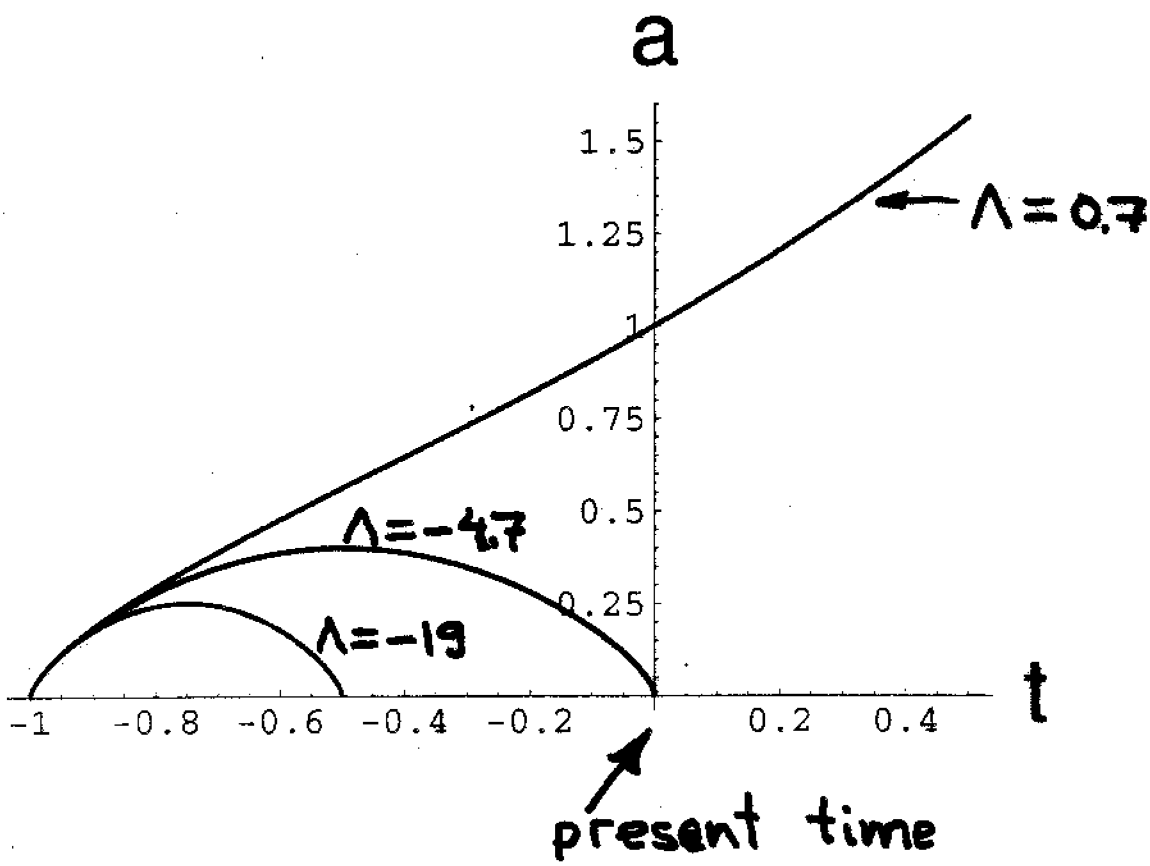
We can live there only if
$$|V| \lesssim 10^{-27} - 10^{-28}\ g/cm^3$$

A similar model



Garriga
Vilenkin 2000

$$V = -\Lambda + \frac{m^2\varphi^2}{2} \qquad m < 10^{-240}$$



<u>Flat</u> universe, ΛCDM

Λ is in units of $\rho_0 = 10^{-29}\ \mathrm{g/cm^3}$

Predictions?

In each of these models separately

$w \approx -1$

Global collapse in $t \ggg 10^{10}$ years

Garriga, Vilenkin 2002

In a combination of these two models $V = \alpha\varphi + \frac{m^2\chi^2}{2} + C$

$w > -1$

Global collapse in $10^{10} - 10^{11}$ years

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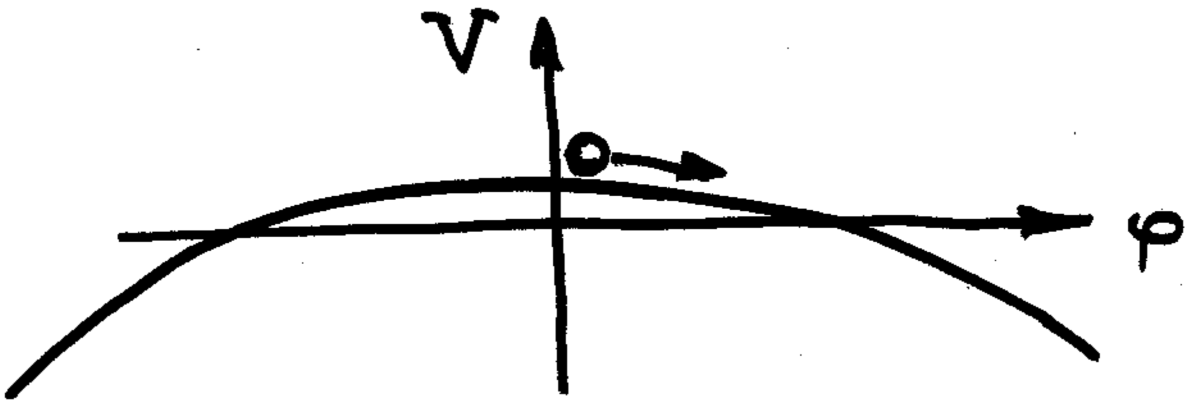
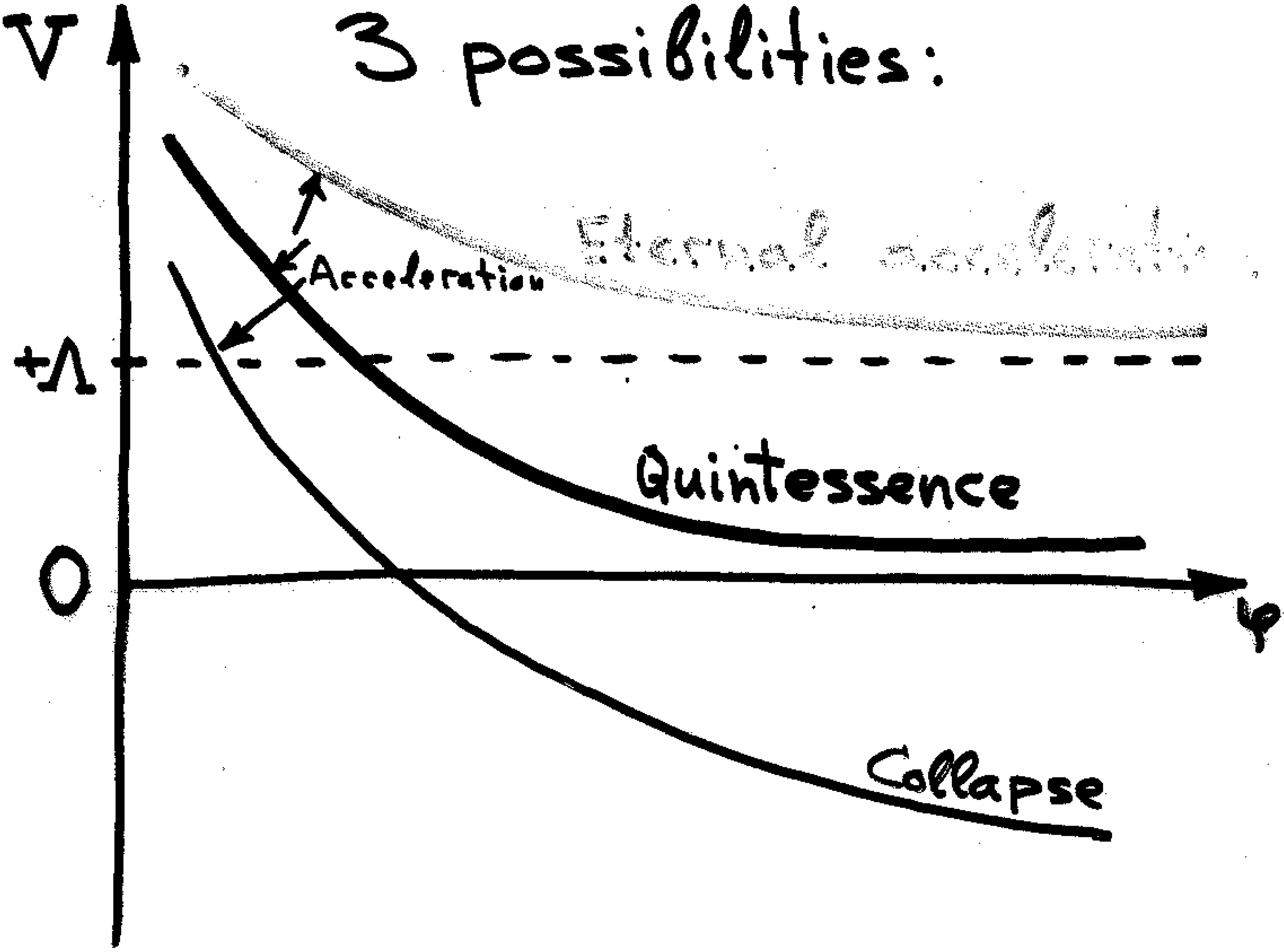
Similar result is valid for models based on N=8 SUGRA



Kallosh, A.L., Prokushkin, Shmakova 2002

A more general case



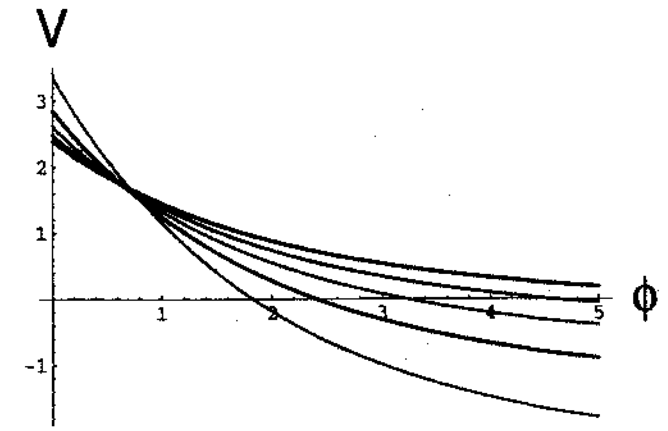


FIG. 2. Effective potential $V = \Lambda_C\left(e^{\phi/2} - C\right)$ with $C = 0$, 0.1 , 0.2, 0.3 and 0.4. The coefficients Λ_C are fixed by the condition that for each value of c one should have the same value of the Hubble constant and $\Omega_D = 0.7$ at the present moment $t = t_0$.

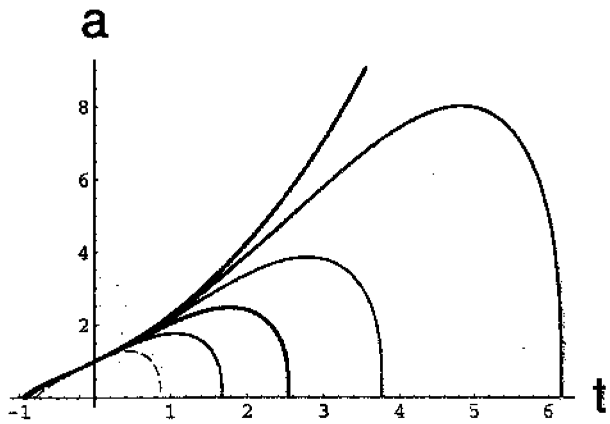


FIG. 4. Scale factor $a(t)$ in the model with the potential $V = \Lambda_C\left(e^{\phi/2} - C\right)$. The upper (red) curve corresponds to the model with $c = 0$. The curves below it correspond to $C = 0.1$, 0.2, 0.3 and 0.4. The dashed curve corresponds to $C = 0.5$. The present moment is $t = 0$. Time is given in units of $H^{-1}(t = 0) \approx 14$ billion years.

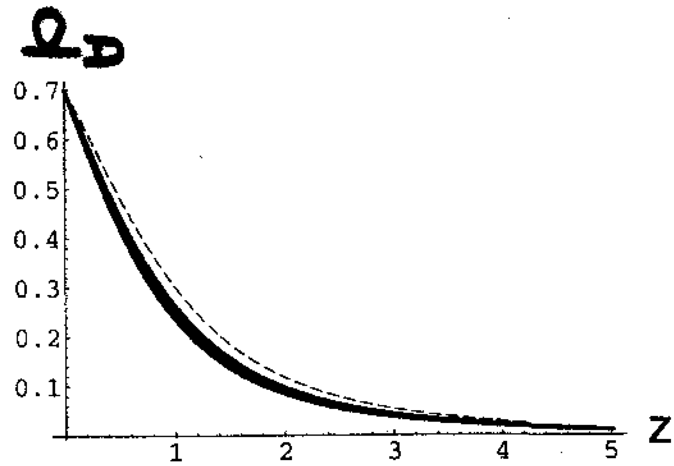


FIG. 3. Dark energy Ω_D as a function of redshift z for $V = \Lambda_C\left(e^{\phi/2} - C\right)$ with $C = 0, 0.1$, 0.2, 0.3, 0.4 and 0.5. The present time corresponds to $z = 0$. As we see, all curves are practically indistinguishable, except for the dashed curve corresponding to $C = 0.5$.

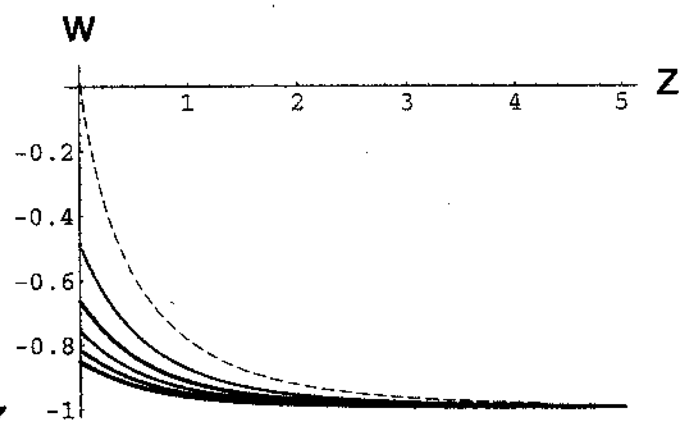


FIG. 5. Equation of state w as a function of redshift z for $C = 0$, 0.1 , 0.2, 0.3, 0.4 and 0.5. For $C = 0.5$ this function sharply rises to $w > 0$ near $z = 0$, which is ruled out by observational data. The red (thick) line $w = -1$ corresponds to the model with $C = 0$.

$|m^2| \sim H^2$ in all models of quintessence. That is why $t_{collapse} \sim m^{-1} \sim H^{-1} \sim t_{today} \sim 10^{10}$ yrs

SNAP, Planck and our future

Kallosh, Kratochvil, A.L., Linder, Shmakova

Even if SNAP + Planck establish that $w = -1$, $w' = 0$ (cosmological constant), this will only mean, for our linear model $V = V_0 + \alpha\varphi$, that the global collapse will not occur during the next $30 \cdot 10^9$ yrs, at 95% confidence level.

No statements can be made concerning acceleration for the next 50 – 100 billion years

Conclusion

1. In the simplest model of dark energy providing an anthropic solution to the cosmological constant problem the stage of <u>acceleration</u> ends by a <u>global collapse</u> of the universe.

2. <u>The same is true for N=8 SUGRA</u>, which is the second model where the cosmological constant problem is solved

3. The only known realization of dS space in string theory is <u>unstable</u>.

In <u>none</u> of these models do we have eternal acceleration of the universe.

In <u>some</u> of these models the universe collapses within 10 - 100 billion years

In <u>most</u> of these models the universe <u>decelerates</u> before collapsing.

If this is the case, we can find it using cosmological observations (SNAP, weak lensing, LSS, etc.)

The main conclusion:

Astronomical observations are not about finding w, Ω_D or H

They are about our future and the fate of the Universe

An important feature of this model:

Sooner or later, $V(\varphi)$ becomes negative

But total energy density $\rho = \frac{\dot{\varphi}^2}{2} + V$ cannot become negative:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \rho/3 \geq 0$$

At the moment when $\rho \Rightarrow 0$ expansion stops, $H = \frac{\dot{a}}{a} = 0$, and then the universe collapses despite the fact that it is flat