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SMR.1508 - 38

# *SUMMER SCHOOL ON PARTICLE PHYSICS*

**16 June - 4 July 2003**

## PRESENT STATUS OF INFLATIONARY THEORY

## (DIRAC LECTURE)

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# Present Status of Inflationary Theory.

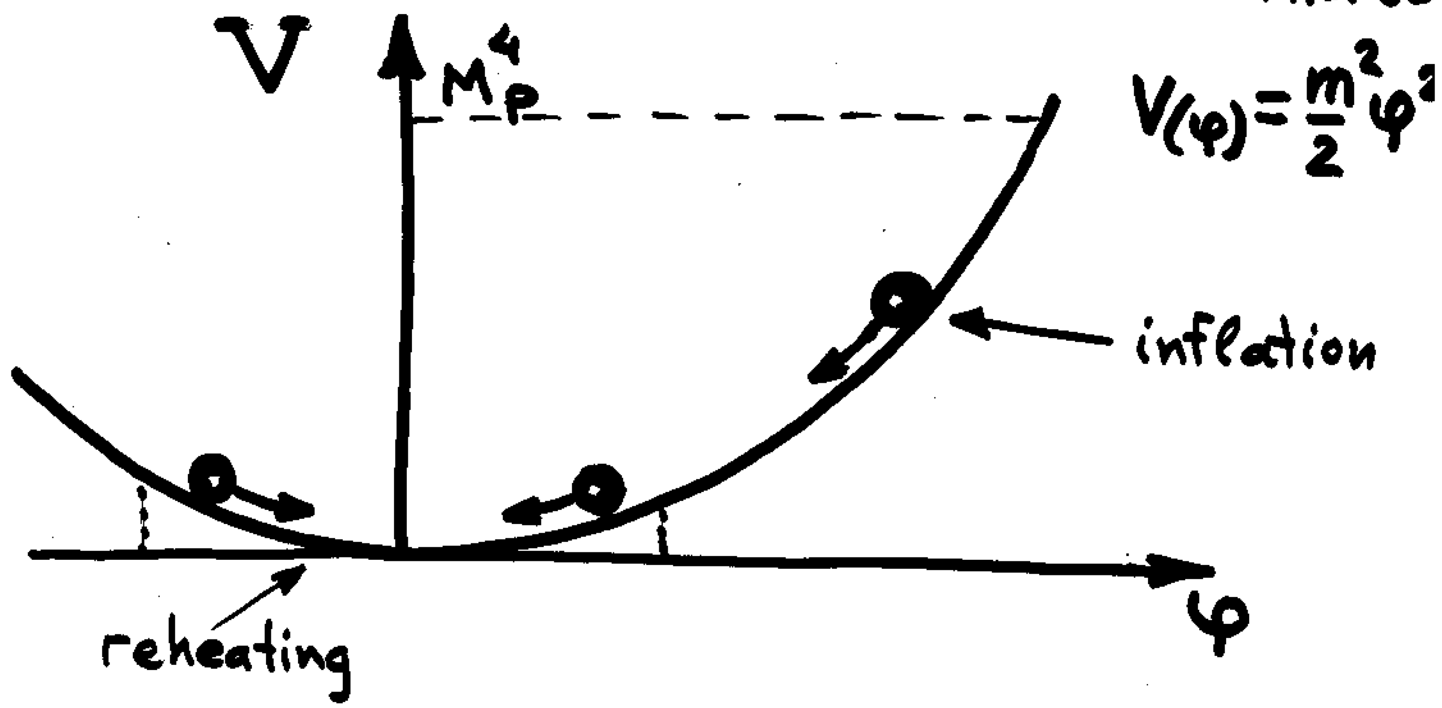
## Plan:

1. Basic scenario
2. Inflation and observations
3. Alternatives ?
4. Inflation now: dark energy and the fate of the universe
5. Towards the theory of inflation and dark energy in the context of M/string theory

# Simplest model

Chaotic inflation

A.L. 83




1) $\ddot{\varphi} + \underset{\sim\sim\sim}{3H\dot{\varphi}} = -m^2\varphi$ Klein-Gordon equation

2) $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3M_p^2} \cdot \frac{m^2\varphi^2}{2}$ Einstein eq. (simplified)

Solution for $\varphi \gtrsim M_p$ (for any $V(\varphi) \sim \varphi^n$)

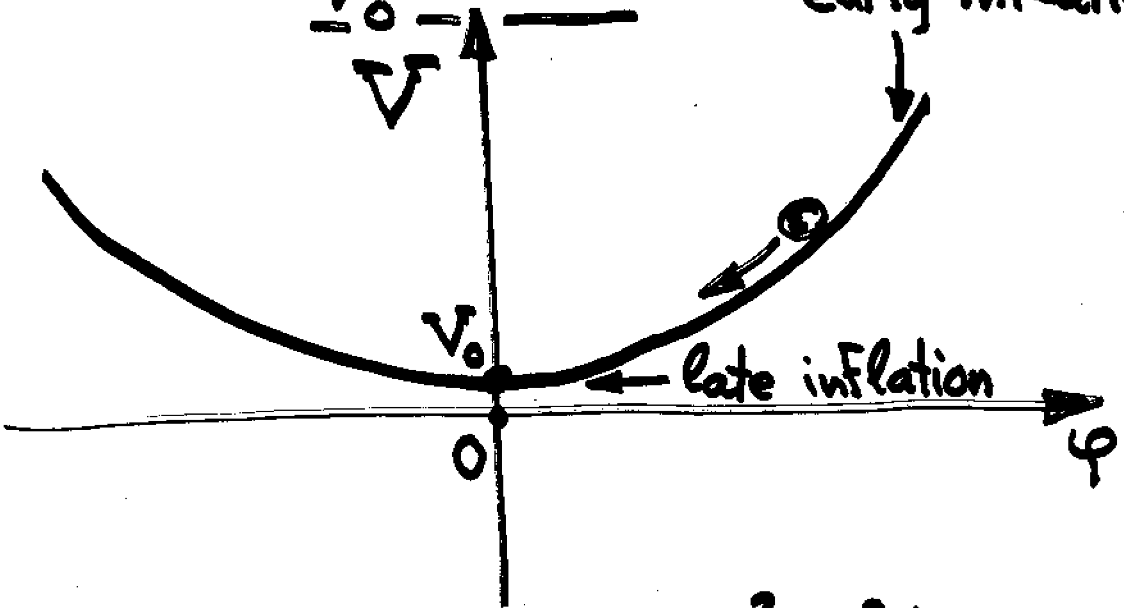
$$\boxed{a \sim e^{Ht}}$$ ← inflation

Typical duration $10^{-35}$ seconds

Typical expansion of the universe during inflation $10^{10^{12}}$ times

$$\boxed{V(\varphi) = \frac{m^2\varphi^2}{2} + V_0}$$

<u>$V_0 > 0$</u>



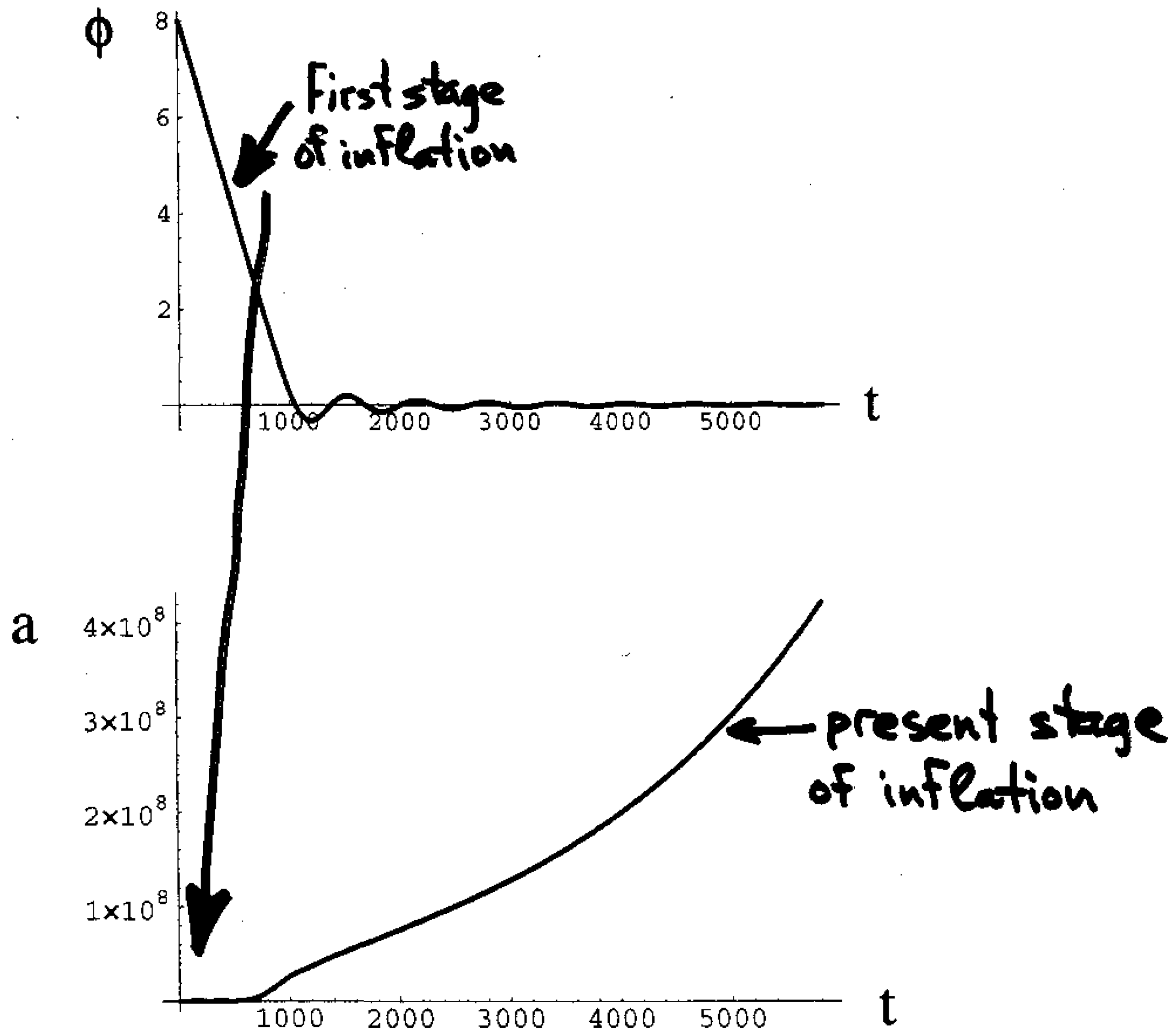

$M_p = 1$

$$H^2 = \frac{1}{3}\left(\frac{\dot{\varphi}^2}{2} + \frac{m^2\varphi^2}{2}\right) + \frac{V_0}{3}$$

$m = 1$

$$\dot{\varphi}^2 + \varphi^2 - 6H^2 = -2V_0$$

<u>Hyperboloid</u> in terms of coordinates $(\varphi, \dot{\varphi}, H)$




Evolution of the scalar field and the scale factor in the model with $V(\phi) = \frac{m^2}{2}\phi^2 + V_0$ with $V_0 > 0$.

# Problems solved

1. Homogeneity
2. Isotropy
3. Flatness/entropy/mass
4. Horizon
5. Creation of large-scale structure
6. Monopoles, gravitinos, ...

# PREDICTIONS

1. Our universe is flat

$$\underline{\Omega} = \rho/\rho_c = \underline{1 \pm 10^{-4}}$$

2. Density perturbations are adiabatic

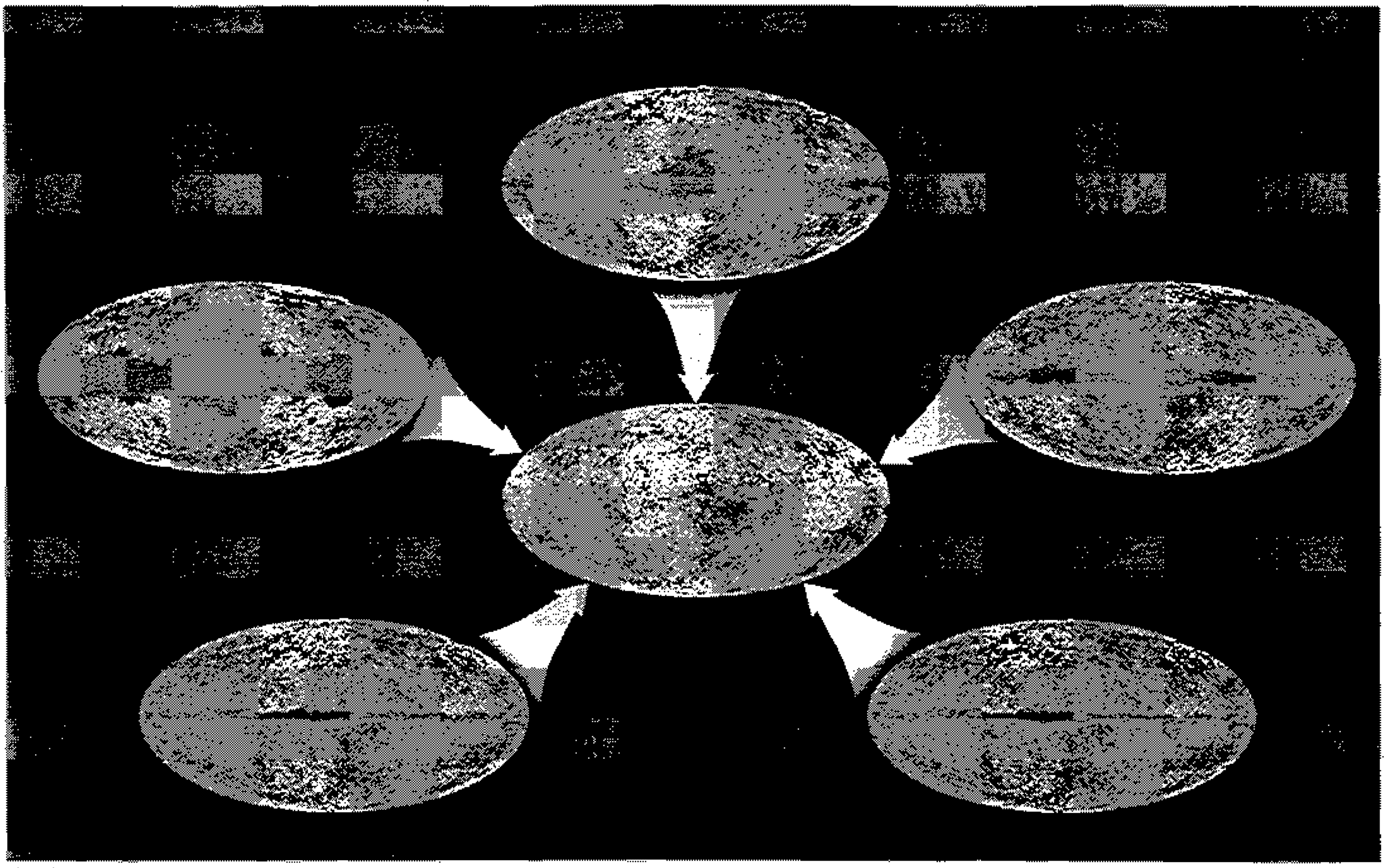
3. They are gaussian

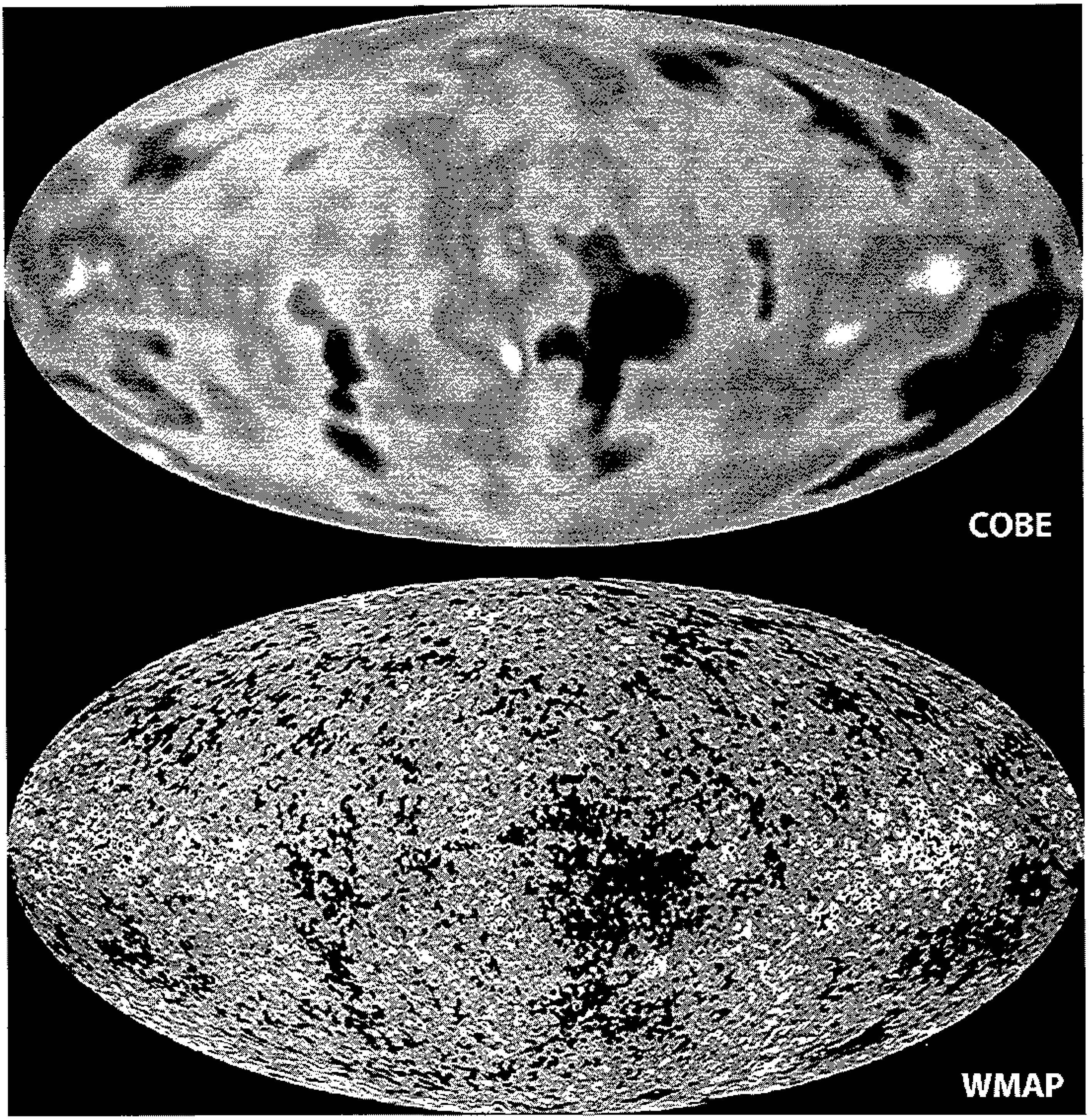
4. They have flat spectrum

$$\underline{n_s \approx 1}$$

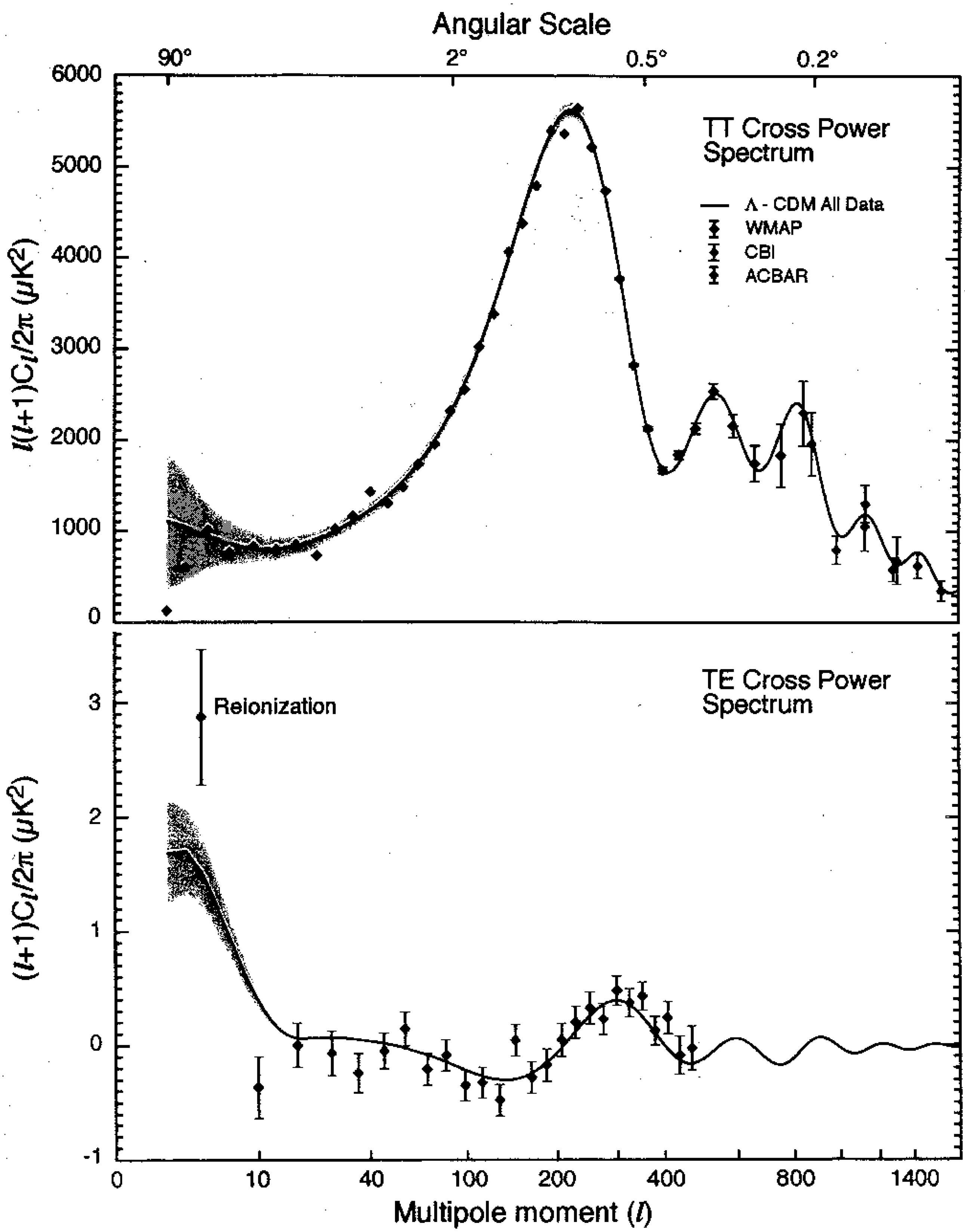
5. They are correlated at large scale, produce acoustic peaks

6. Corellation between TT and TE




COBE
WMAP

Kandinsky Universe


Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
l(l+1)C_l/2π (μK²)
3
2
1
0
-1
Reionization
TE Cross Power Spectrum
(l+1)C_l/2π (μK²)
0
10
40
100
200
400
800
1400
Multipole moment (l)

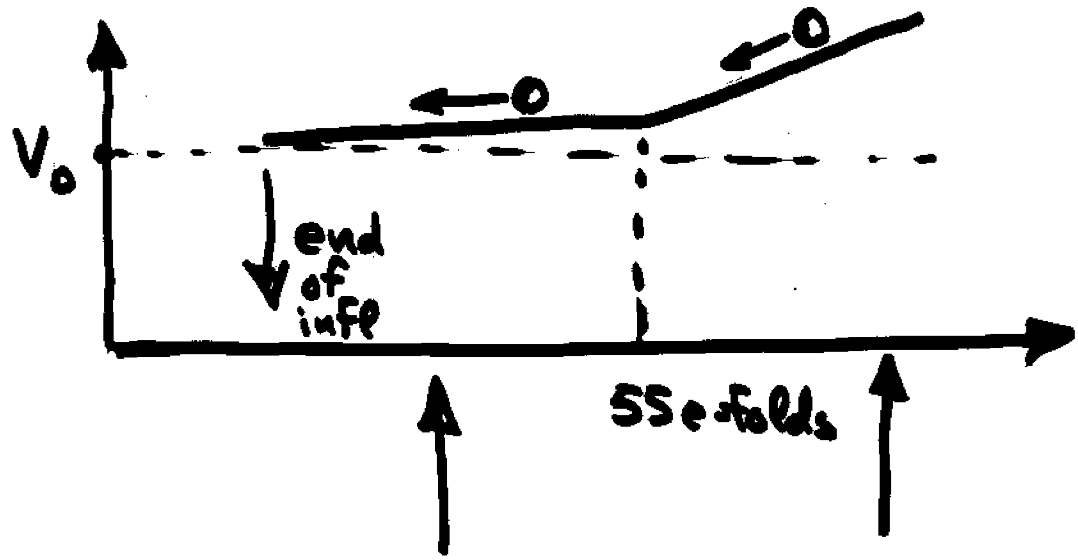
# Can we tune the spectrum?

Contaldi, Kofman, A.L., Peloso

**Example:** Hybrid inflation

$$V = V_0 + f(\varphi) \qquad f(\varphi) \ll V_0$$

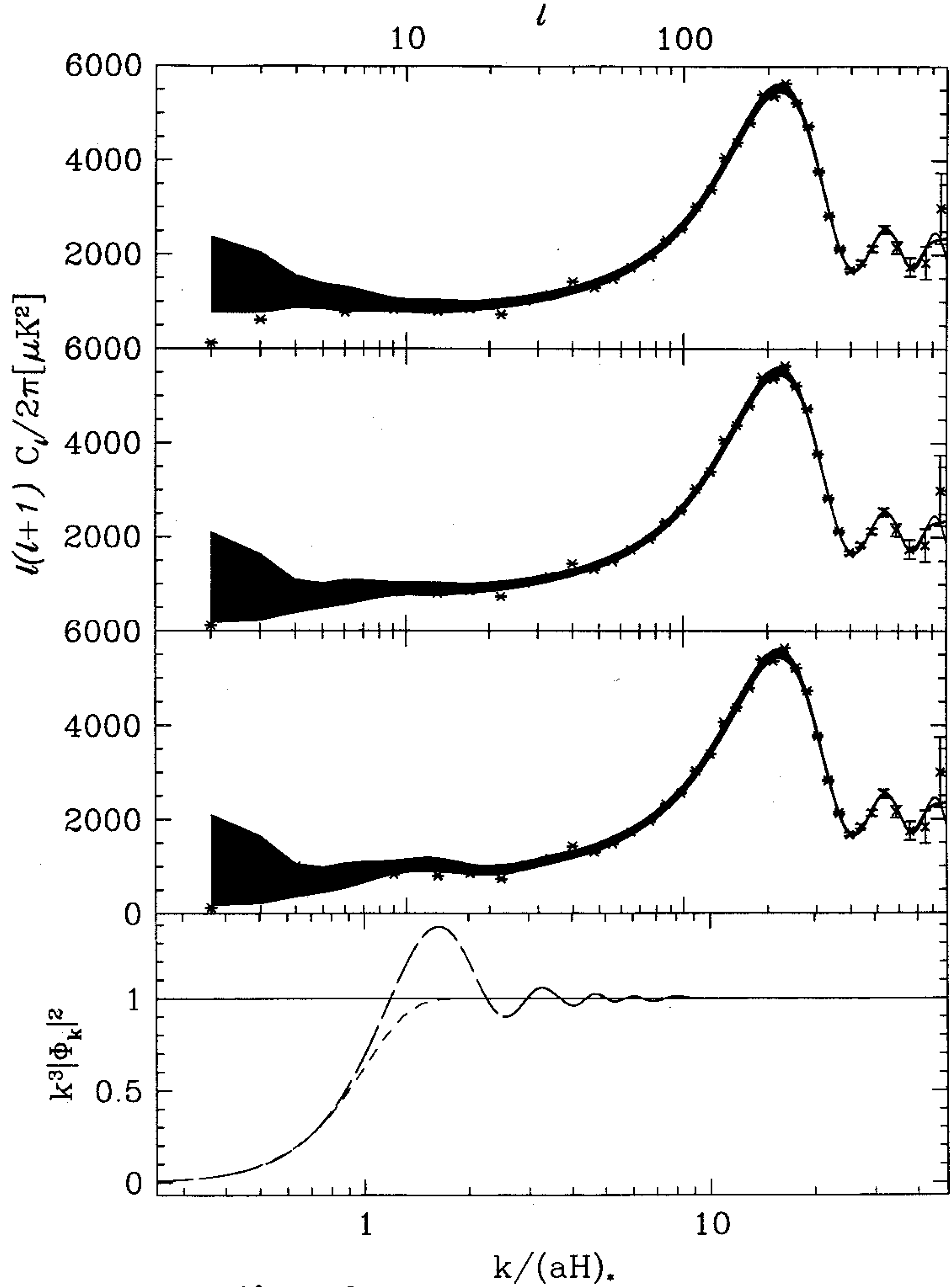
$$\frac{\delta\rho}{\rho} \sim \frac{V_0^{3/2}}{f'(\varphi)}$$




$$\frac{\delta\rho}{\rho} \sim 10^{-5} \qquad\qquad \frac{\delta\rho}{\rho} \ll 10^{-5}$$

Leads to suppression of low $\ell$ multipoles in CMB

See also A.L. and Riotto 1997 → cutoff at large lengths.




Contaldi, Kofman, A.L, Peloso

# Some history

**1.** Starobinsky model 1979, 1980

$$R + R^2 + \ldots$$

complicated, but worked!

**2.** Chibisov and Muknanov 1981

Adiabatic density perturbations with flat spectrum

This was the first paper predicting what COBE and BOOMERANG discovered

For new and chaotic inflation it was done by Hawking 82, Starobinsky 82, Guth and Pi 82, Bardeen, Turner, Steinhardt 83, Mukhanov 85

# Quantum fluctuations and a nonsingular universe

V. F. Mukhanov and G. V. Chibisov

*P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow*

(Submitted 26 February 1981; resubmitted 15 April 1981)

Pis'ma Zh. Eksp. Teor. Fiz. **33**, No. 10, 549–553 (20 May 1981)

Over a finite time, quantum fluctuations of the curvature disrupt the nonsingular cosmological solution corresponding to a universe with a polarized vacuum. If this solution held as an intermediate stage in the evolution of the universe, then the spectrum of produced fluctuations could have led to the formation of galaxies and galactic clusters.

PACS numbers: 98.80.Bp, 98.50.Eb

A nonsingular cosmological model with a polarized vacuum has been attracting particular interest recently.[1] It has been pointed out elsewhere that quantum fluctuations may prove important in cosmology at energy densities comparable to the Planck value.[2] Since these are in fact the energy densities characteristic of the nonsingular polarized-vacuum model,[1] we believe it is worthwhile to study the role of quantum fluctuations in order to determine whether there is a singularity in this model.

For an isotropic metric, the single-loop corrections describing the polarization of the vacuum of physical fields in a strong gravitational field lead to the following Einstein equations[3]:

$$R^i_k - \frac{1}{2}\,\delta^i_k = \frac{1}{H^2}\left(R^i_l R^l_k - \frac{2}{3}\,RR^i_k - \frac{1}{2}\,\delta^i_k R^l_m R^m{}_l + \frac{1}{4}\,\delta^i_k R^2\right)$$

$$- \frac{1}{6M^2}\left(2R^{;i}{}_{;k} - 2\,\delta^i_k R^{;l}{}_{;l} - 2\,RR^i_k + \frac{1}{2}\,\delta^i_k R^2\right), \tag{1}$$

where the coefficients $M^2$ and $H^2$ result from the sum over the effects of all the fields. For stability of the Minkowski space, $M^2$ must be positive. For $H^2 > 0$, Eqs. (1) have a particular solution of the "de Sitter" type,[1]

$$ds^2 = g_{ik}dx^i\,dx^k = a^2(\eta)\left(d\eta^2 - \sum_{\alpha=1}^{3}(dx^\alpha)^2\right), \tag{2}$$

$(M^2 \ll H^2)$,

$$Q(k) \approx 3tM\left(1 + \frac{1}{2}\ln\frac{H}{k}\right). \tag{9}$$

The fluctuation spectrum is thus nearly flat. The quantity $Q(k)$ is a measure of the amplitude of perturbations with scale dimensions $1/k$ at the time the universe begins the ordinary Friedmann expansion. With $Mt \sim 10^{-3}$-$10^{-5}$ and $M/H \lesssim 0.1$—these values are consistent with modern theories of elementary particles—the amplitude of the perturbations of the metric on the scale of galactic clusters turns out to be equal to $10^{-3}$-$10^{-5}$, and these perturbations can lead to the observed large-scale structure of the universe. The form of spectrum (9) is completely consistent with modern theories for the formation of galaxies.[5]

To summarize: Using a de Sitter model as an example, we have shown that quantum fluctuations (zero-point vibrations) cause the universe to spend a finite time in a state with a polarized vacuum. This result casts doubt on the possibility of a nonsingular origin for the universe. However, models in which the de Sitter stage exists only as an intermediate stage in the evolution are attractive because fluctuations of the metric sufficient for the formation of galaxies can occur. Thus we have one possible approach for solving the problem of the appearance of the original perturbation spectrum.

We thank V. L. Ginzburg, Ya. B. Zel'dovich, M. A. Markov, and A. A. Starobinskiĭ for discussions.

1. A. A. Starobinskiĭ, Phys. Lett. **91B**, 99 (1980).
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Translated by Dave Parsons
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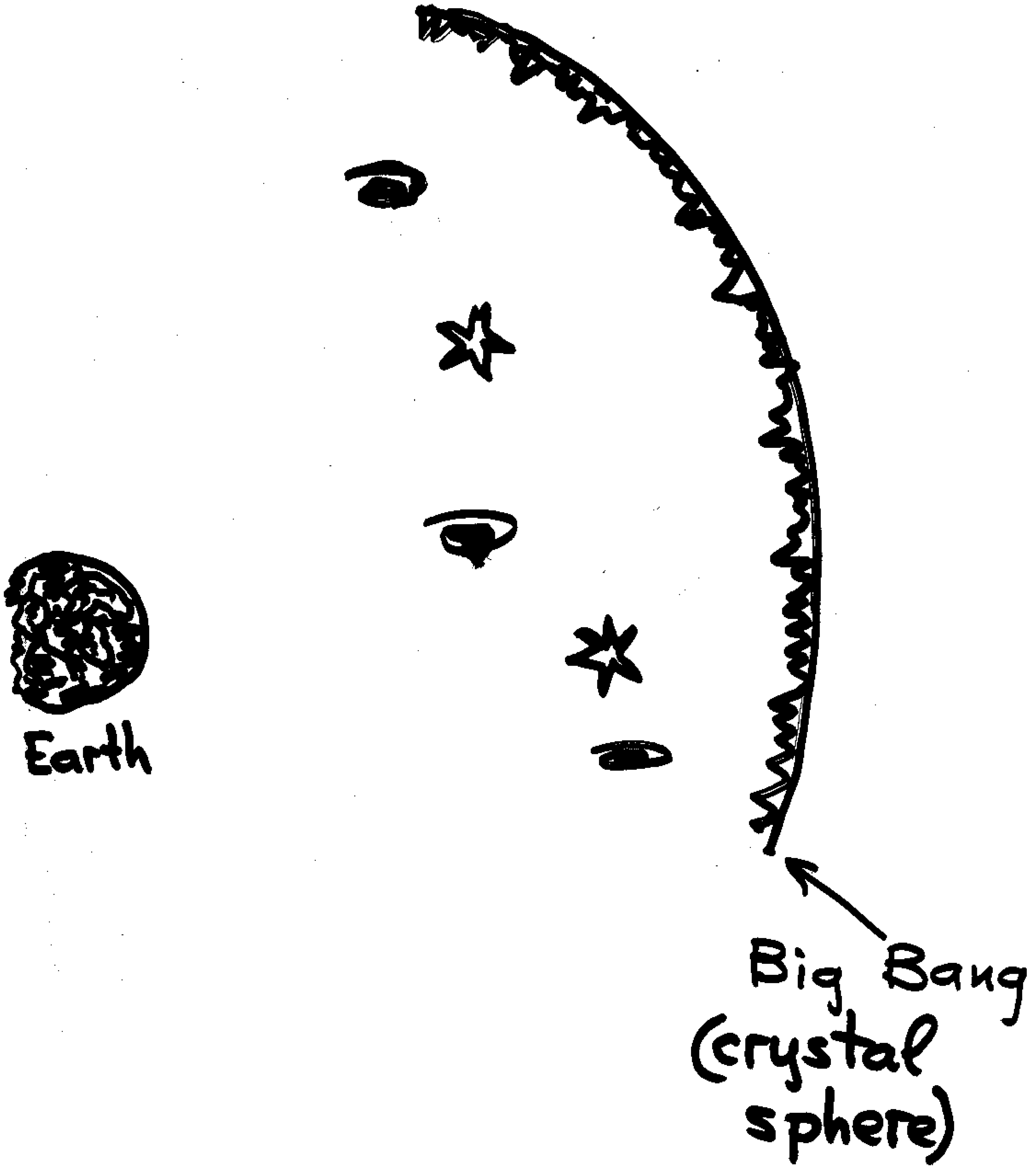

Earth
Big Bang
(crystal
sphere)

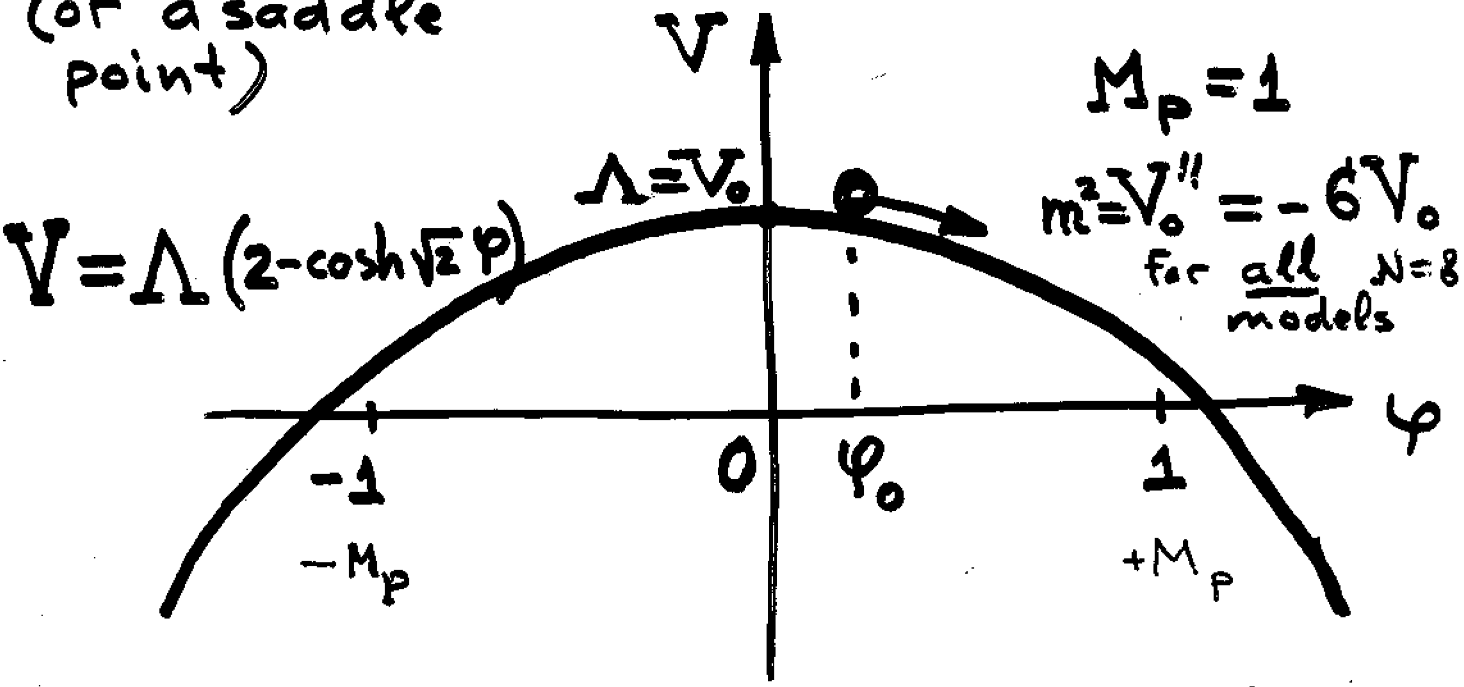
Inflation

# Supergravity, Supernova, And the future of the universe

hep-th/0208156
0208157

Kallosh, Prokushkin, Shmakova, A. L.
2001, 2002

It is possible to obtain dS space in N=8 supergravity, but in all known examples it corresponds to a maximum of $V(\varphi)$, (or a saddle point)




In all known examples $m^2(\varphi)$ is quantized in units of $H^2$

$$m^2 = 0,\ \pm 2,\ -3,\ +4,\ \pm 6\ H^2$$

Why? (+ → for N=2 SUGRA, Van Proeyen, Fre, Trigiante)

Let us assume that $N=8$ describes a hidden sector of the theory with $V_0 \sim 10^{-120} M_p^4$

present value of the „cosmological constant"

Then $|m| = |\sqrt{6}|\, H \sim 10^{-60} M_p$

It will take the field about $10^{10}$ years to fall down, depending on its initial value $\varphi_0$

Note: Typical time to fall $t_{fall} \sim m^{-1}$. Age of the universe $t_{now} \sim H^{-1}$. Since $m \sim H$, the time $t_{fall}$ remaining until the global collapse is similar to the present age of the universe.

We have $10^{10}$ years to think about it...

M/String Theory, S-branes and Accelerating Universe

M. Gutperle, R. Kallosh and A. L. hep-th/0304225

Accelerating cosmologies from compactification Compact hyperbolic extra dimensions

Townsend and Wohlfarth, Ohta, Emparan and Garriga, ...

DARK ENERGY FROM M THEORY??? Transient period of acceleration related to S-branes

Major problem: KK mass gap is practically nonexistent

$$m_{\mathrm{KK}} \sim \sqrt{V} \sim H \sim 10^{-60}$$

The Compton wavelengths of KK modes are the same as the size of the cosmological horizon, and therefore particles should be able to freely move in all 11/10 dimensions of space.

???

It would be rather sad if, after 20 years of making statements that string/M-theory is a theory of everything, this theory would fail to describe the acceleration of the universe.

# de Sitter space and inflation in string theory

No-go theorems: Maldacena & Nunez 2001
Gibbons 1985

<u>Problem</u>: In terms of canonical scalars (moduli) representing dilaton and volume of the compactified space

$$V = e^{\overset{\text{dilaton}}{\sqrt{2}\,\varphi} - \overset{\text{volume}}{\sqrt{6}\,\psi}}\ \tilde{V}(\varphi, \psi) \qquad \text{type IIB}$$

Exponents are too steep, runaway behavior

$$\varphi \to -\infty$$

$$\psi \to +\infty$$

<u>Interpretation</u>: Decompactification

$4D \Longrightarrow 10D$

# Possible solution

Kachru, Kallosh, A.L., Trivedi
hep-th/0301240

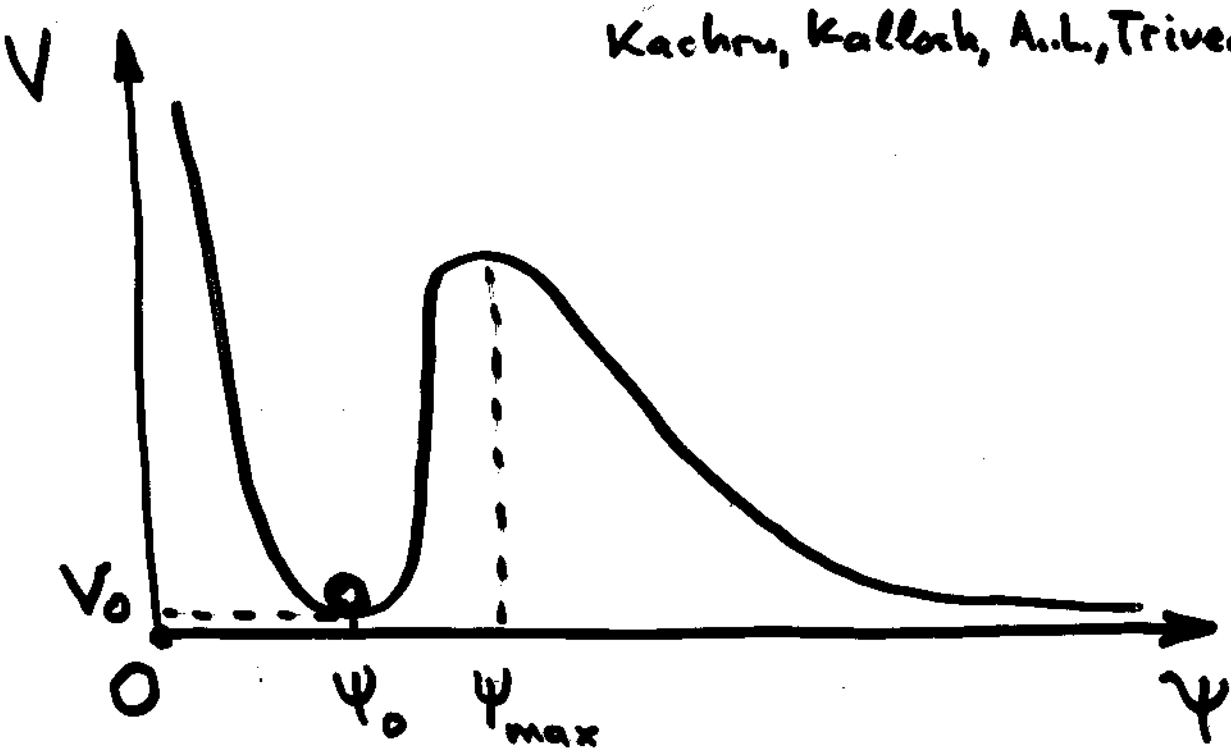
Use IIB compactifications with nontrivial NS and RR fluxes and calculate nonperturbative contributions to the moduli potential in presence of $\overline{D3}$ branes

Result: Dilaton is fixed

Giddings, Kachru, Polchinski 2002

and volume modulus is fixed as well:

Kachru, Kallosh, A.L., Trivedi



# How stable is dS?

$$P(\psi_{tunn}) = e^{-\mathcal{S}(\psi_{tunn}) + \mathcal{S}_0}$$

$\mathcal{S}(\psi_{tunn}) \leftarrow$ action on the tunn. trajectory

$\mathcal{S}_0 \leftarrow$ dS action

$$\mathcal{S}_0 = -\mathbf{S}_0 \quad \text{dS entropy}$$

$$S(\psi) = -\int d^4x\sqrt{g}\ V(\psi) < 0$$

Usually $|\mathcal{S}(\psi)| \ll |\mathcal{S}_0|$

$$P \approx e^{-\mathbf{S}_0} \approx e^{-10^{120}}$$

very stable...

But because $\mathcal{S}(\psi) < 0$ one has $e^{-S(\psi)} \gg 1$ so the tunneling occurs within time

$$t \ll t_r = e^{+\mathbf{S}_0}$$

Thus dS space is always <u>unstable</u>, as anticipated by Susskind et al, and it always <u>decays faster than the recurrence time $e^{S_0}$</u>

In case when thermodynamic appoach is applicable

$$P = e^{-S_0 + S(\varphi_{max})}$$

A.L. 98
Susskind et al
2002

In inflationary context this expression is given by Hawking-Moss instanton, 1982

$$P = \exp\left(\frac{24\pi^2}{V(\varphi_{max})}\right) \cdot \exp\left(-\frac{24\pi^2}{V(\varphi_0)}\right)$$

If it will be possible to solve the moduli stabilization problem not only in dS but also during inflation (there are some encouraging results in D3/D7 model + KKLT mechanism) then the global structure of the universe will become very rich:

1) Self reproduction during eternal inflation

2) „Thermal" jumps between various dS minima after inflation

# Towards inflation in string-theory.

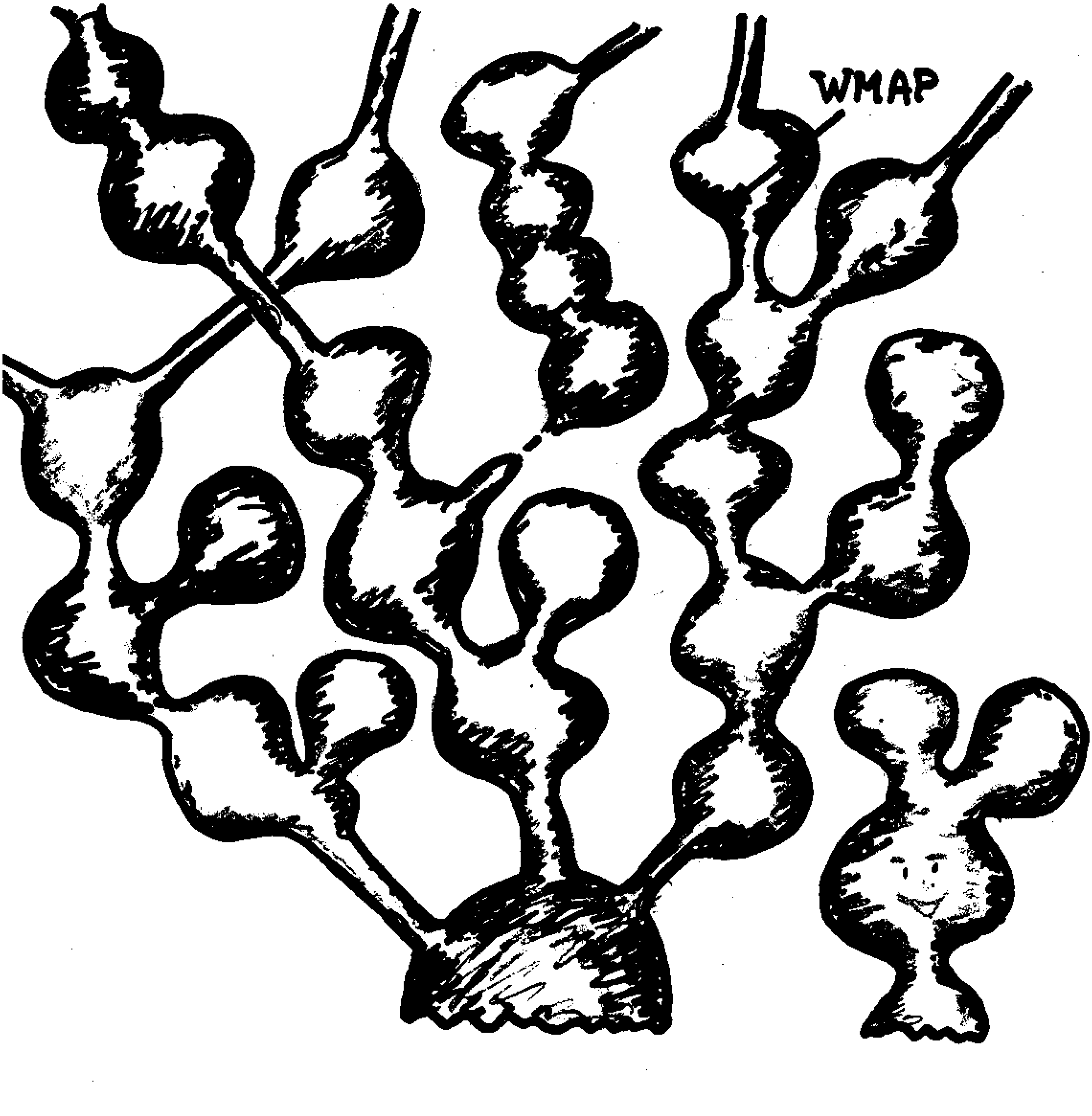
Many attempts, none of them so far had moduli stabilization

Kachru, Kallosh, Liam, A.L., Maldacena, Trivedi (in progress)

All existing models end up with the tachyon condensation $T \to \infty$.
Problematic reheating.

The only exception:
Dasgupta, Herdeiro, Hirano, Kallosh 2002

## D3/D7 Model


WMAP