Obsew. support for Hot Big-Bang scenario

- Hubble expansion

$$H(t)\Big|_{t=t_0} = \frac{\dot{a}(t)}{a(t)}\Big|_{t=t_0} \equiv H_0 > 0$$

- Element abundance

Hydrogen	75%	primordial nucleosynthesis
Helium	24%	
Other	1%	

- Cosmic microwave background (CMB)

photons once in thermal equilibrium with charges further decoupled and formed thermal background radiation of $T = 2{,}7\,^{\circ}K$ (blackbody)

- Imprint of information in CMB

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

temperature fluctuations — density fluctuations

spherical harmonics decomposition

$$\frac{\delta T}{T} = \sum_{l,m} a_{lm} Y_{lm}(\theta, \phi)$$

power spectrum of fluctuations

$$C_l = \langle |a_{lm}|^2 \rangle$$

peak structure related to angular scale in the sky

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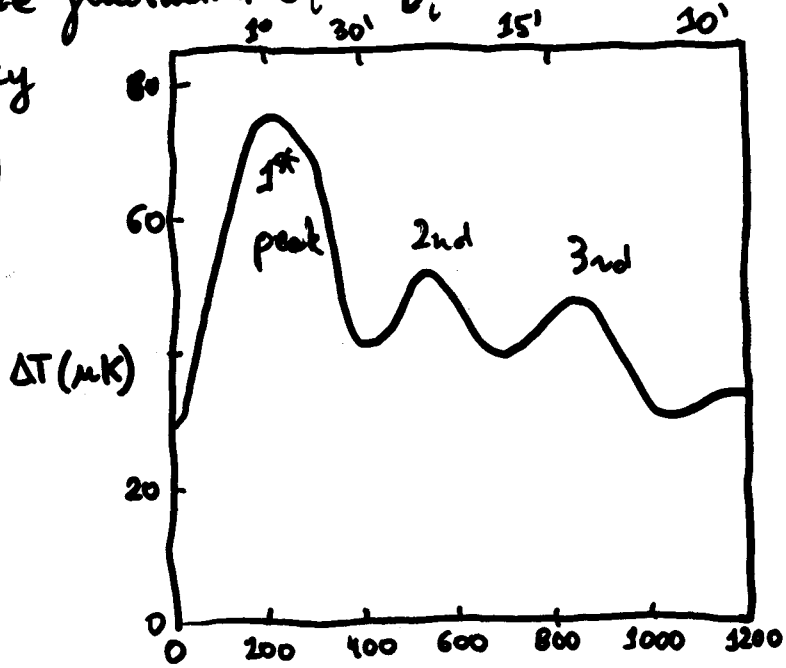
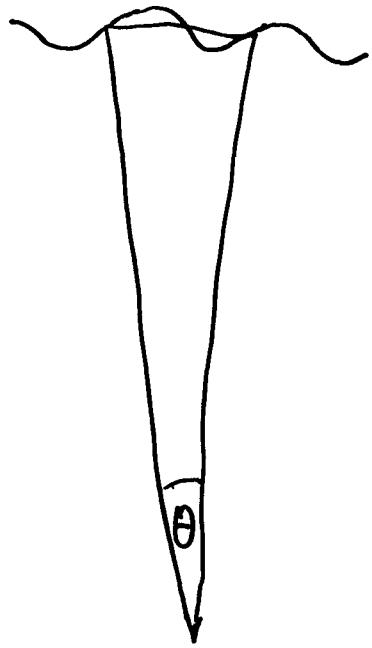
peak structure related to angular scale in the sky

the angle we can see fluctuation in the sky today $\theta_i = \frac{\pi}{l_i}$





peaks give hints about cosmological parameters (k, Ω, Λ)

density parameter $\Omega = \sum_i \frac{\rho_i}{\rho_{crit}}$ $\qquad \rho_{crit} = \frac{3H^2}{8\pi G}$

$$\Omega = \Omega_m + \Omega_r + \Omega_\Lambda + \Omega_d + \ldots = 1 + \frac{k}{a^2 H^2}$$

Ω_m ↓ matter $\qquad$ Ω_r ↓ radiation etc.

1st peak gives <u>strong evidence for $\Omega = 1$</u>

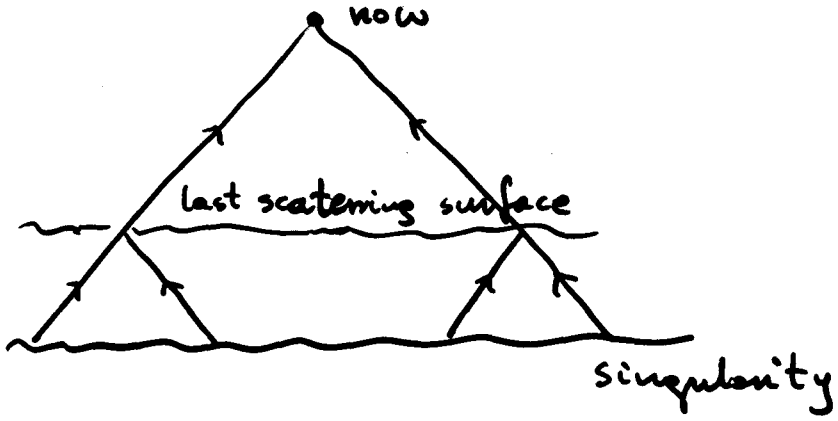
(<u>flat universe</u>)

$(k = 0)$

THE PUZZLES of Hot Big-Bang

1. the problem of <u>singularity</u> $t = 0$ (people assumed $t \geq 0$ only)
   (what was before?)

2. the <u>horizon</u> problem



CMB radiation isotropic ($\frac{\delta T}{T} \sim 10^{-5}$)
though it was not in causal contact

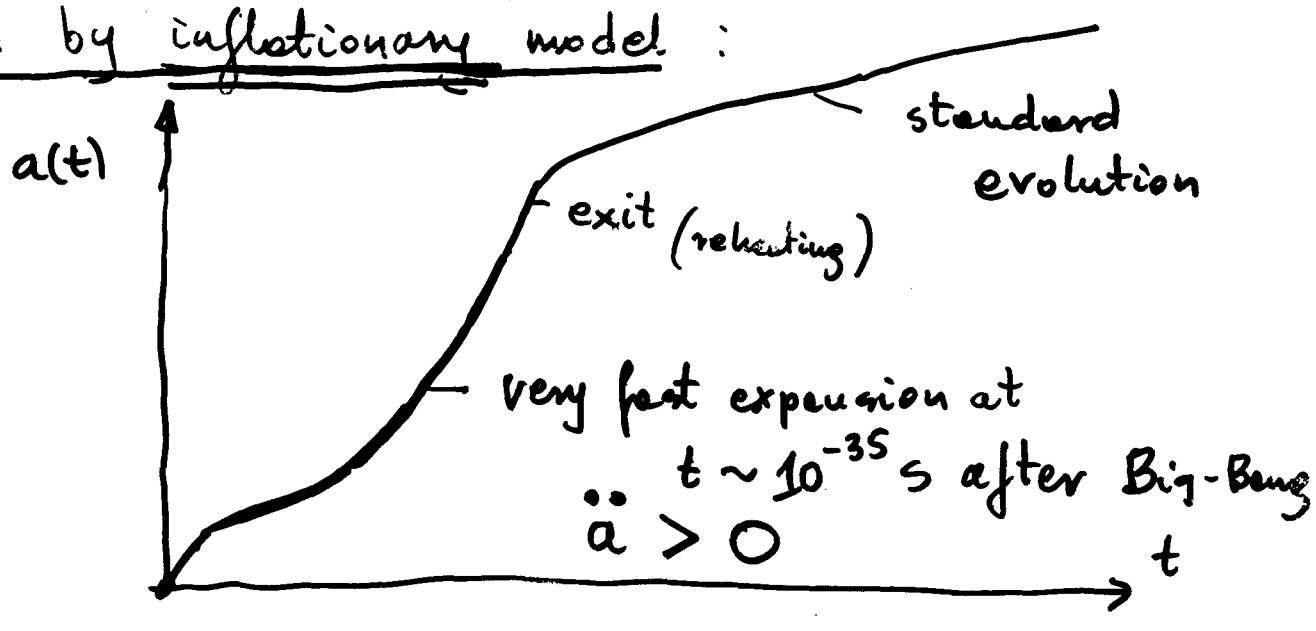
3. the <u>origin</u> of anisotropies of CMB which could give observed structures in the universe

4. <u>flatness</u> problem

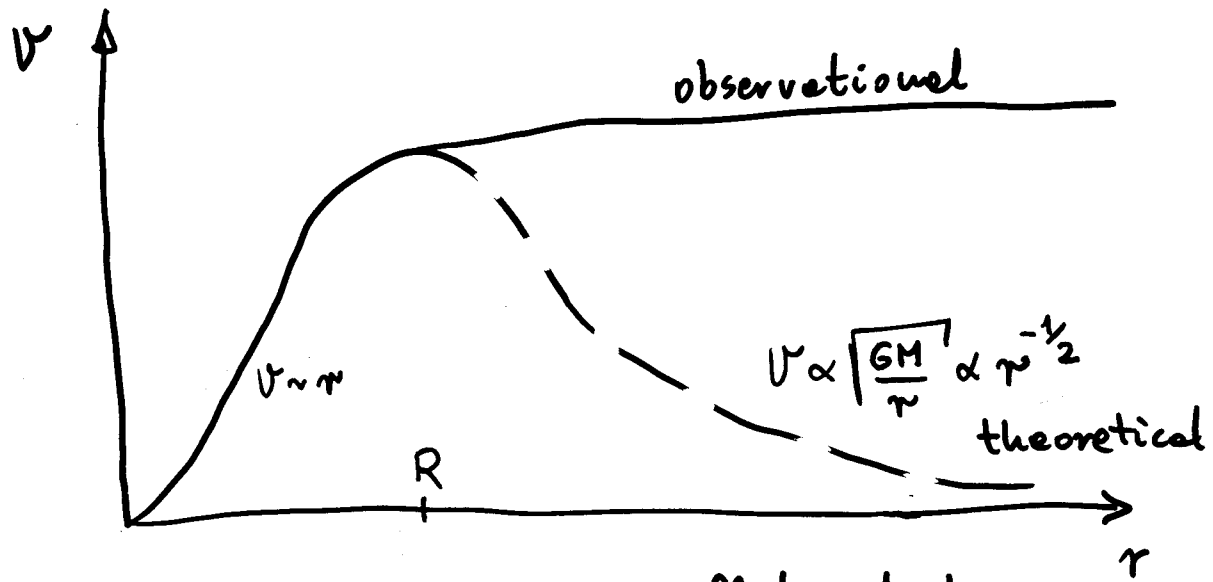
strong evidence for $\Omega \sim 1$ — evolving to the past (~singularity) $\Omega = 1$ at the very high precision

Problems 2-4

<u>Solved by inflationary model</u> :



5. dark matter problem



Galaxies rotation curves flat outside

$\Rightarrow$ there must be some matter which is <u>not visible</u> - dark matter

6. dark energy problem

2nd Einstein equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

accelerated expansion/inflation requires

$$p < -\frac{1}{3}\rho$$

a scalar field potential energy for example

<u>Pressure must be negative</u> !

Deceleration parameter

$$q = -\frac{\ddot{a}\,a}{\dot{a}^2} < 0$$

This does not seem to be a problem since it <u>refers</u> to the <u>early universe</u> $t \sim 10^{-35}$ s.

Supernovae Ia "revolution" (as standard "candles")

A redshift-magnitude test (generalized Hubble evolution law)

observed magnitude

$$m(z) = M(z) + 25 + 25 \log cz - 5 \log_{10} H_0 + 1.086\,(1 - q_0)\,z + O(z^2)$$

$M(z)$: absolute magnitude; z: redshift

for nearby galaxies ($z \ll 1$) – Hubble law

$$D = \frac{cz}{H_0}$$

does not include q_0 – not enough

Strong evidence that

$$\boxed{q_0 < 0}$$

or

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

or

$$\boxed{p < -\frac{1}{3}\varepsilon}$$

at the current moment of evolution !

At least 70% of matter in the universe has negative pressure now – dark energy.

What is the source of dark energy?

cosmological constant Λ ? $p = -\Lambda$

a scalar field / scalar fields

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

$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi) \quad ?$$

$\dot{\phi} \approx 0$ ← → $V(\phi) \approx 0$

$p = -\rho = -\Lambda$ $\qquad$ $p = \rho$

more puzzle

$\rho + p < 0$ (phantom requires negative kinetic energy, for example)

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

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

tuning other cosm. parameters requires more sophisticated

$$\phi = \phi(t)$$

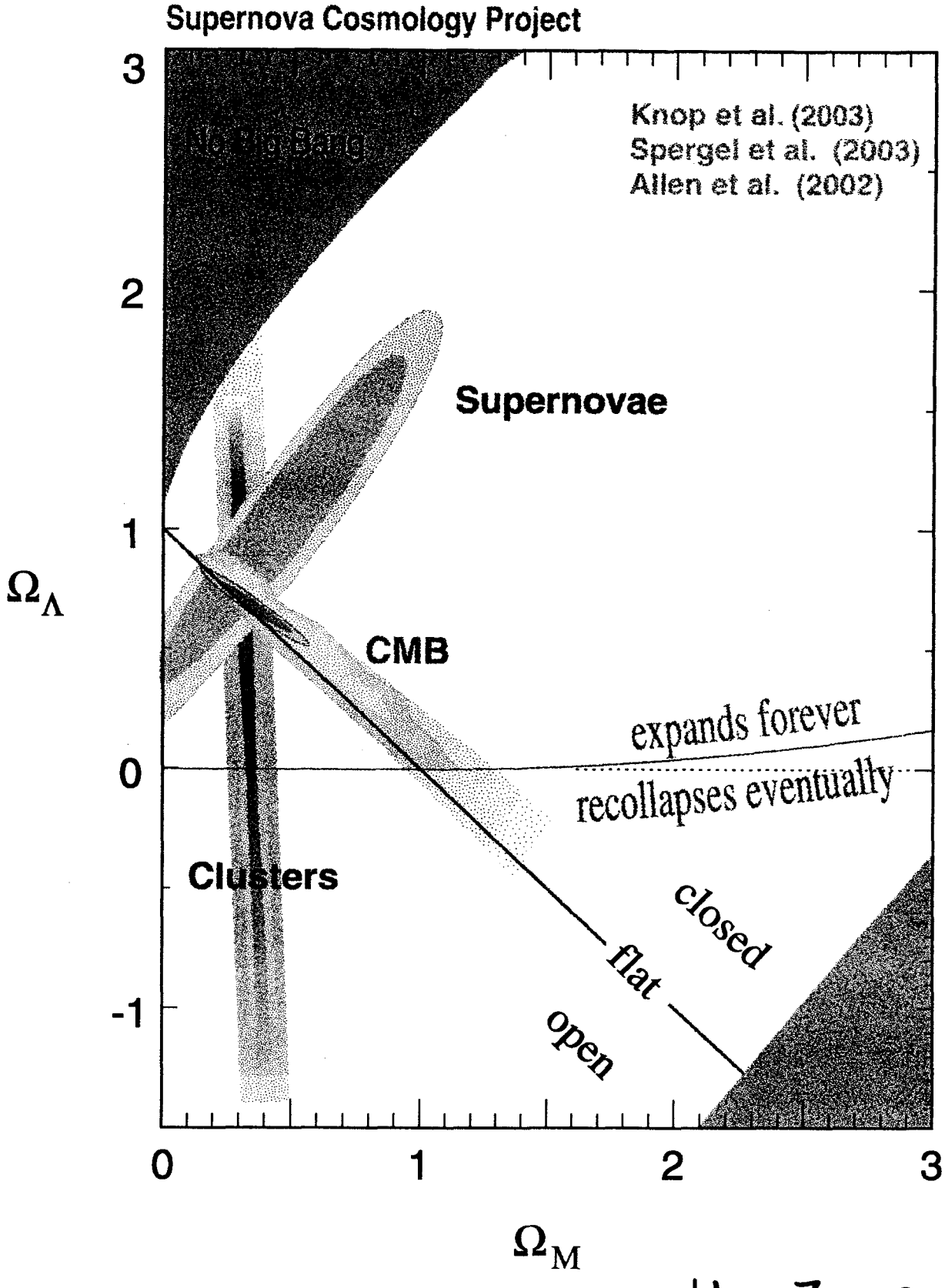
and $$V = V(\phi(t))$$

which makes equation of state

$p = p(\rho)$ time-dependent !

Independent check : CMB
clusters

$\Omega_\Lambda = 0.75$ best fit



$H_0 = 73 \pm 3 \frac{km}{s\,Mpc}$

What is the source of dark matter?

unknown light particles?

Is there a way to avoid singularity?

was the Universe evolving before?

How about unification of interactions*?

(gauge + gravity)

requires running gravitational "constant"

$G \propto \frac{1}{\Phi}$ - dilaton

Is there a quantum theory of gravity?

These questions are addressed in more fundamental framework than Einstein's theory

i.e.

superstring &

M-theory (brane)

* extra dimensions –

moduli fields

III. SUPERSTRING COSMOLOGIES

Unification requires "running" of grav. constant

$$G(t) = \frac{1}{\Phi(t)} = \frac{\lambda_s^2}{e^{-\phi(t)}} = \frac{1}{M_{pl}^2(t)} \qquad \left[\frac{1}{\text{Energy}^2}\right]$$

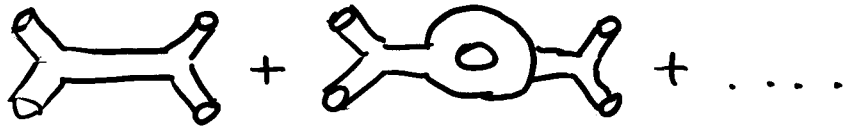
λ_s ← fundamental string length (= const.)

$\Phi(t)$ ← Brans-Dicke field

$\phi(t)$ ← dilaton field

$M_{pl}(t)$ ← Planck mass

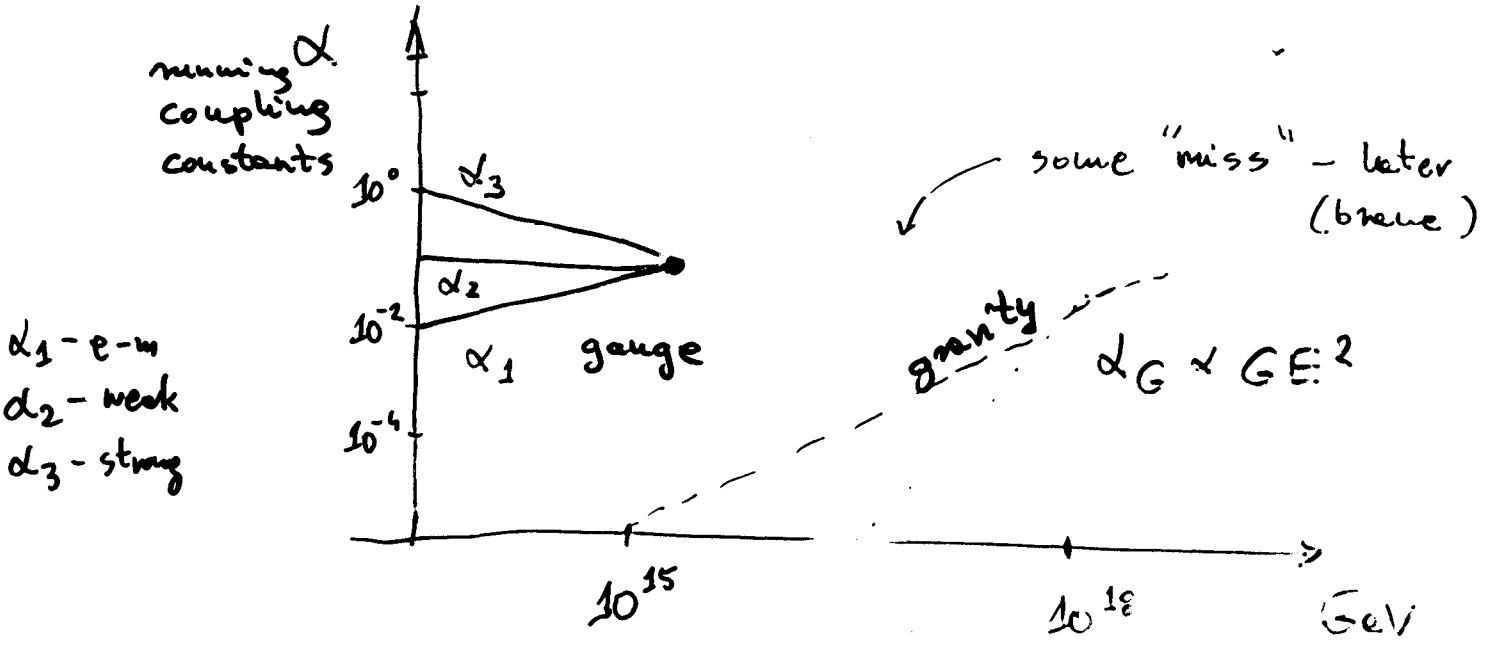
String theory interpretation



$$g_s \propto \langle e^{\phi/2} \rangle$$

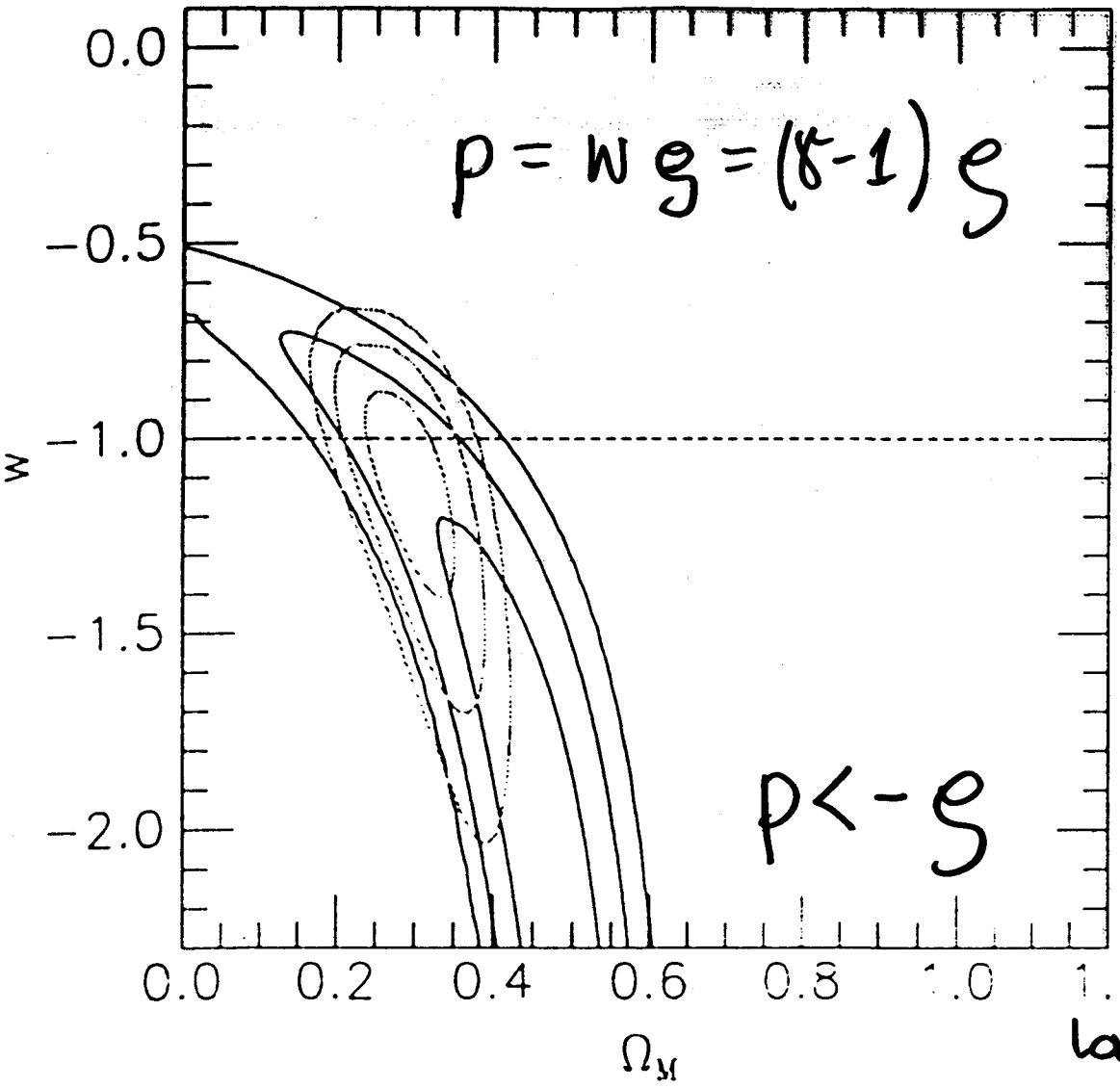
↑ string coupling constant

1. $\phi \to \infty$ strong coupling
2. $\phi \to -\infty$ weak coupling (perturbative)



New data

Tonry et al. astro-ph/0305008 (Ap.J. 2003)



strong evidence for very large negative pressure "phantom" (violates weak energy condition of Hawking Penrose)

Fig. 13.— Probability contours for dark energy parameter w versus Ω_m are shown at 1σ, 2σ, and 3σ when $\Omega_{tot} = 1$. We also give 1σ, 2σ, and 3σ contours when we adopt a prior of $\Omega_M h = 0.20 \pm 0.03$ from the 2dF survey (Percival et al. 2001). This sample includes all 172 SN Ia with $z > 0.01$ and $A_V < 0.5$ mag.

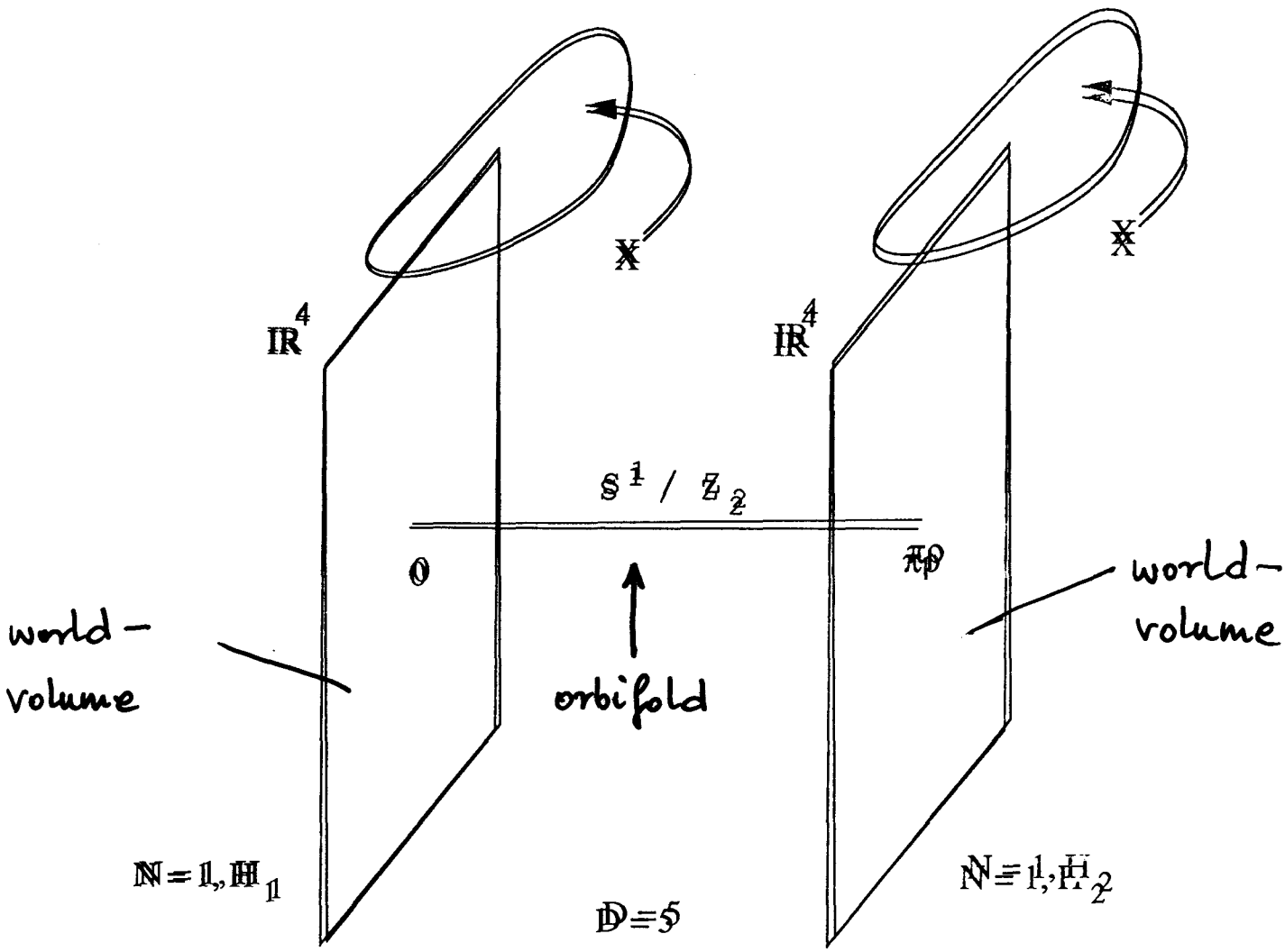


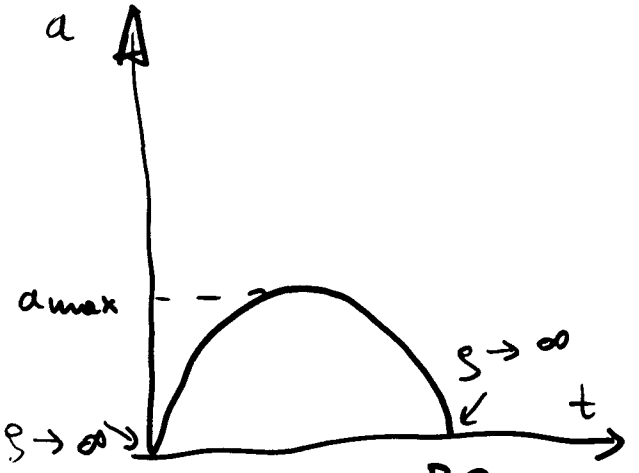
Figure 5: Hořava-Witten model compactified on Calabi-Yau manifold.

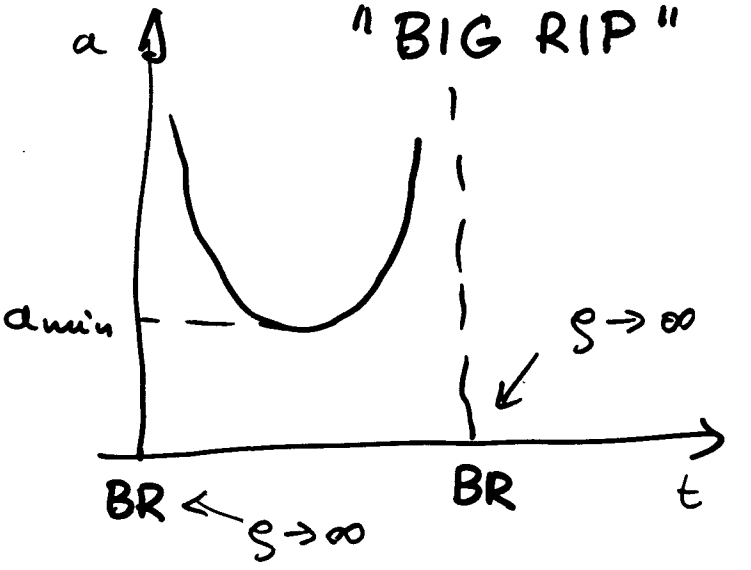
similarity - (Pre-big-bang) scale factor duality
& phantom duality

For phantom barotropic index

$\gamma < 0$ assume $|\gamma| = -\gamma > 0$

so that $\rho \propto a^{3|\gamma|}$ the bigger the Universe the denser it is - future curvature singularity "BIG RIP"



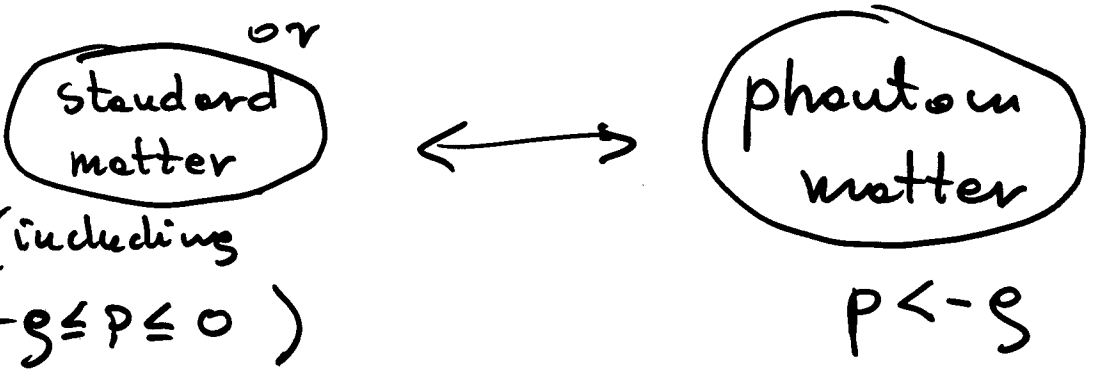


Phantom Duality
(field equations invariant w.r.t)

$a \leftrightarrow \frac{1}{a}$

or

$\gamma \leftrightarrow -\gamma$



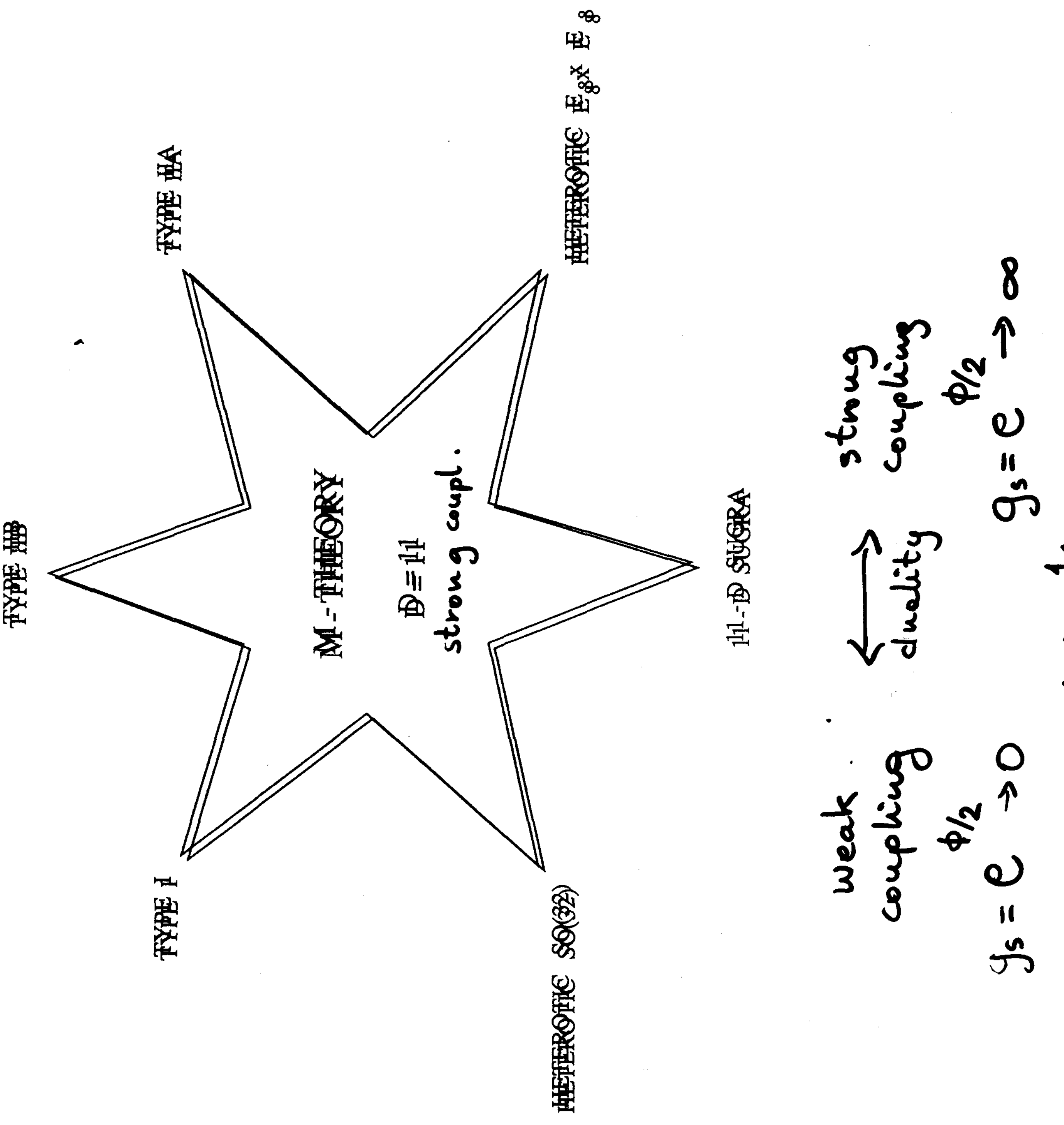


Figure 1.1: Moduli space of superstring theories.

Prediction :

Modification of Newton's potential in a 4-dimensional world

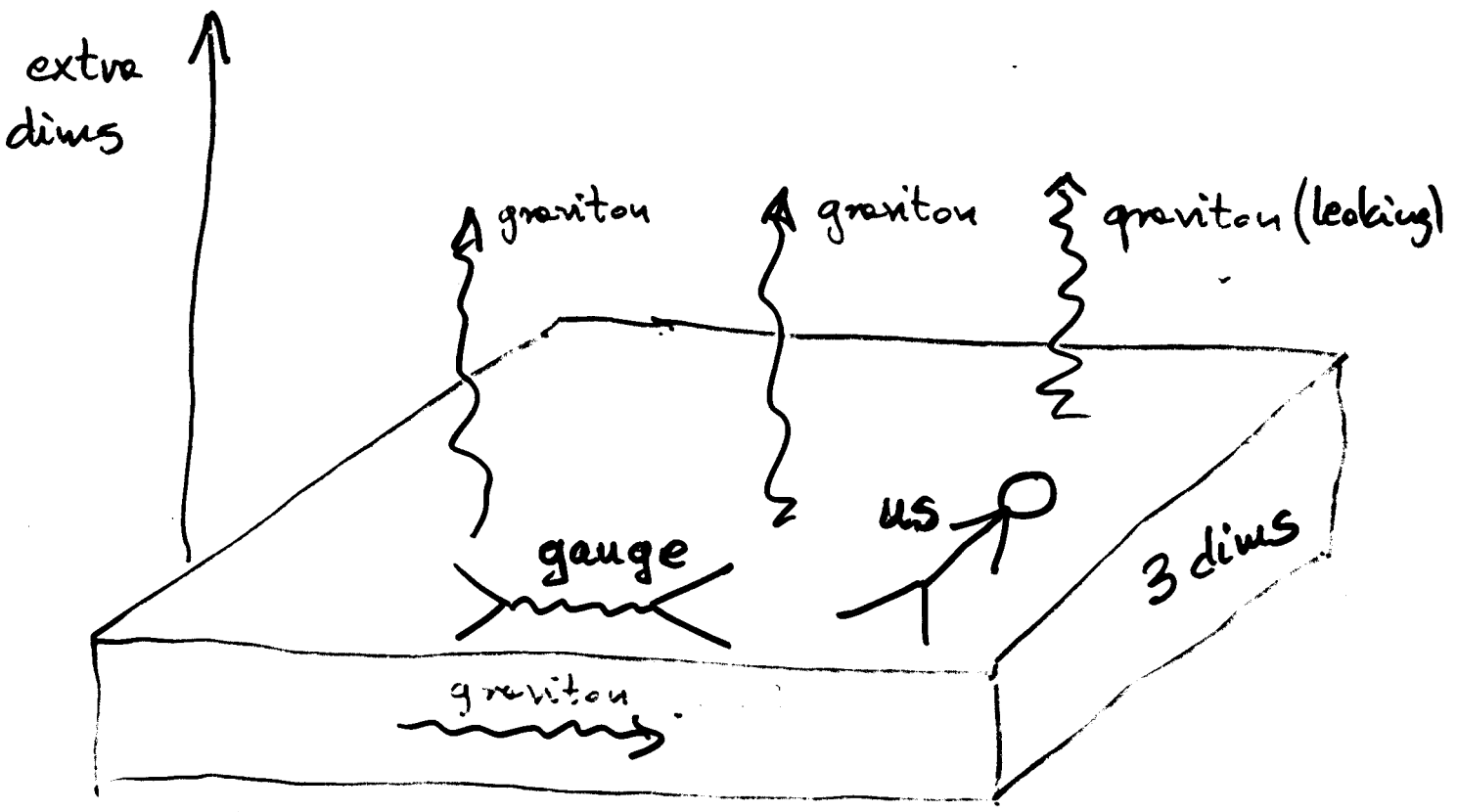
$$V(r) = \frac{GM}{r}\left(1 + \frac{2L^2}{3r^2}\right)$$

L ← ~ size of an extra dimension

in a submillimeter scale

$$r \lesssim 1\ \text{mm}$$

Explanation :



Basic cosmological solutions based on the modified Friedmann equation

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}\rho + \frac{8\pi G}{6\lambda}\rho^2 - \frac{k}{a^2} + \frac{2}{\lambda}\frac{U}{8\pi G}$$

ρ^2: a unique contribution from brane

U: dark radiation (gravitons leaking or flowing into the brane)

$U \lesssim 0$

$\left(\rho^n - \text{Cordasian generalization}\right)$

λ - brane tension

Einstein limit for $\lambda \to \infty$! (in fact nucleosynth. restr. $\lambda > (100\,\text{GeV})^4$)

Types of cosmologies similar qualitatively but not quantitatively

For example: inflation requires fluid with much stronger negative pressure

$$\gamma < \frac{1}{3}\frac{\rho + 2\lambda}{\rho + \lambda}$$

$\lambda \to \infty$ (Einstein) $p < -\frac{1}{3}\rho$

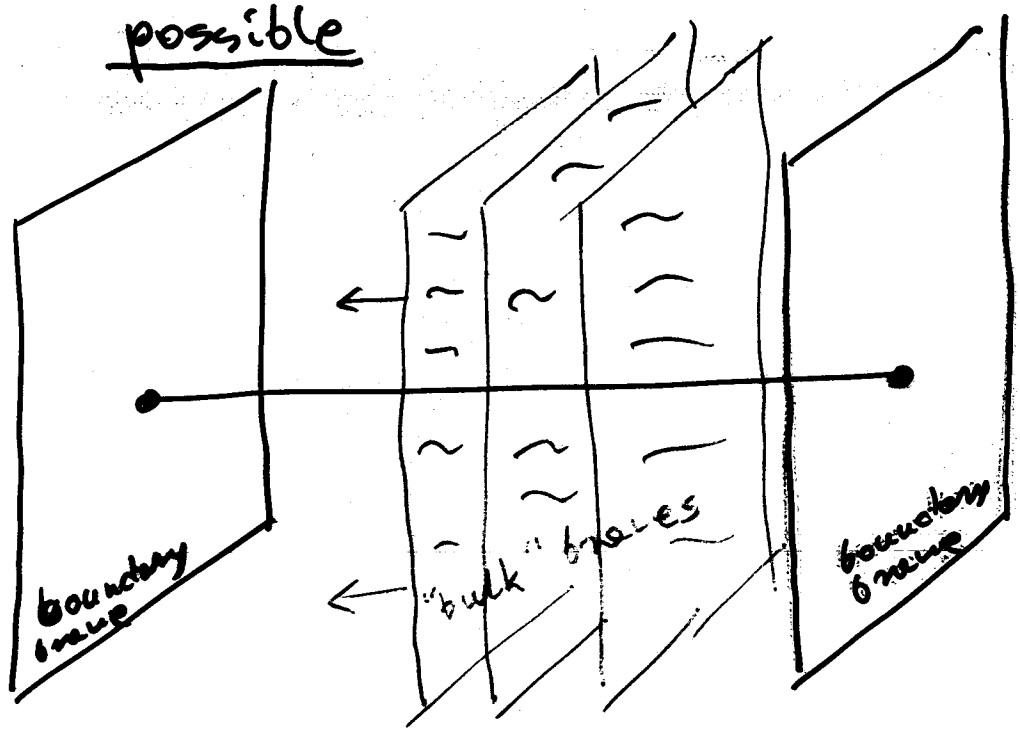
λ small (brane) $p < -\frac{2}{3}\rho$

e.g. phantom required to adapt supernovae data

Ekpyrotic / cyclic framework

* Hořava-Witten theory

additional branes called "bulk" branes which move between boundary branes possible



a bulk brane hits a boundary brane and "produces" Big-Bang

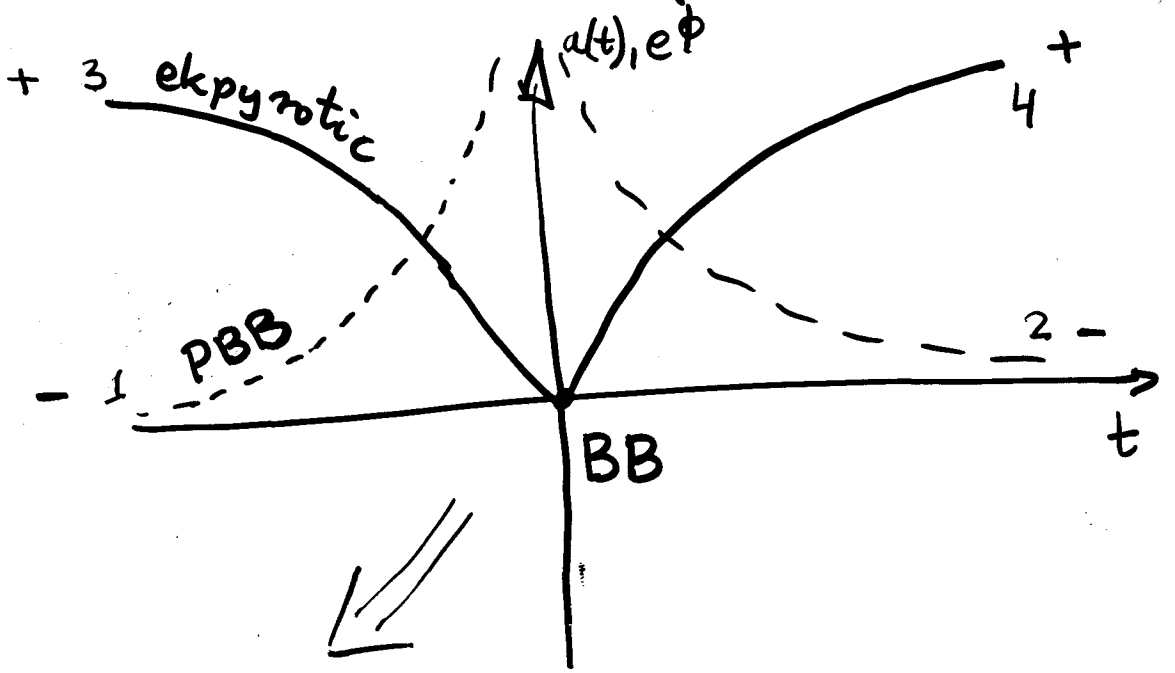
Effective 4-dim description as in pre-big-bang, so 4 branches possible

$$a(t) = |t|^{\pm \frac{1}{\sqrt{3}}}$$

$$\phi(t) = \left(\pm\sqrt{3} - 1\right) \ln|t|$$

However,

one makes use of a different branch in a pre-big-bang phase



Big-Bang has <u>no strong coupling singularity</u> since now

$$g_s = e^{\phi} = |t|^{\sqrt{3}-1} \to 0$$

at $t = 0$

it is beneficial

but

still Big-Bang curvature singularity is present

apparently - no way to go from

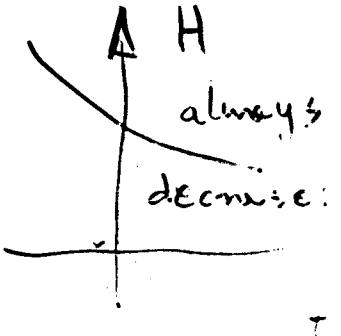
contraction $H = \frac{\dot{a}}{a} < 0$

to expansion $H = \frac{\dot{a}}{a} > 0$

through singularity in 4-dim theory (H should have a minimum)

$$\dot{H} = \left(\frac{\dot{a}}{a}\right)^{\cdot} = -4\pi G(\rho + p)$$

$$= -4\pi G \dot{\phi}^2 \leqslant 0$$



unless one violates

the weak energy condition $\rho + p \geqslant 0$

in fact, phantom does

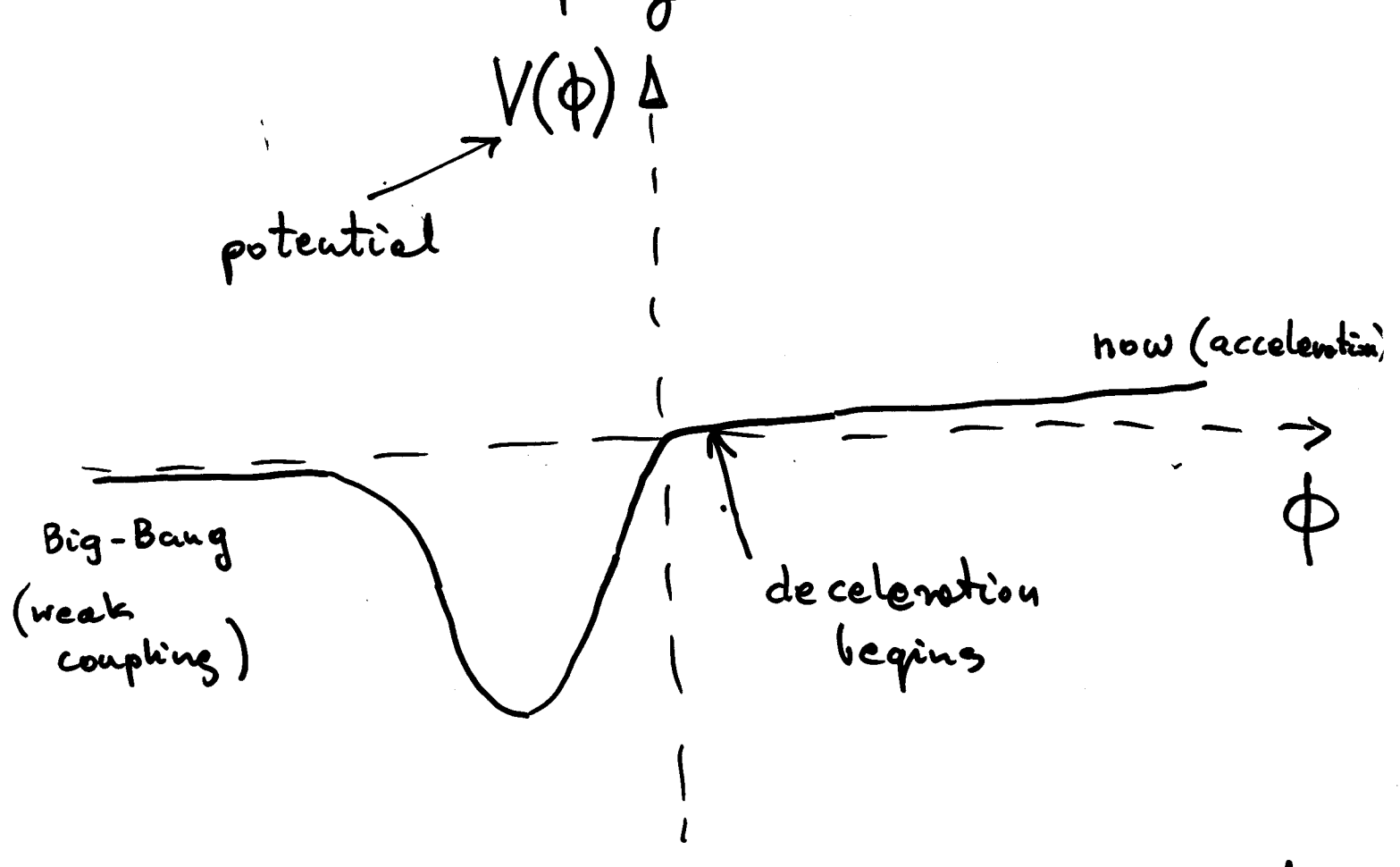
and, in principle, possible

Denying phantom, still the singularity avoidance possible due to a special choice of the potential and coupling to an energy-momentum tensor

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{16\pi G} R - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) + \right.$$

$$\left. + \beta^4(\phi) \left(\varrho_R + \varrho_m \right) \right]$$

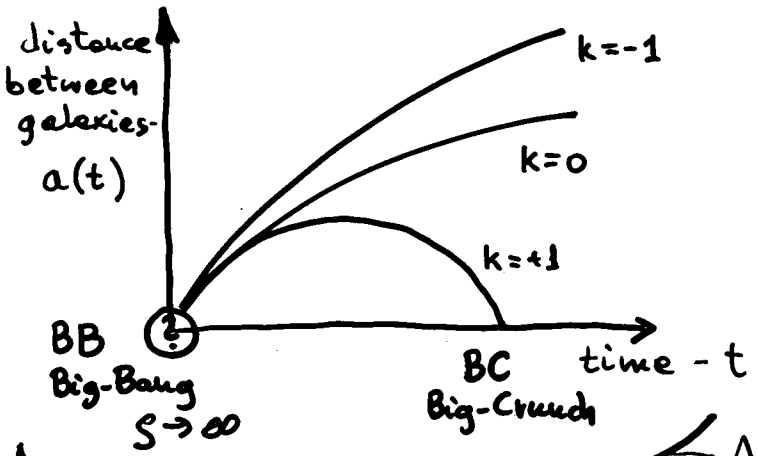
coupling — radiation — matter



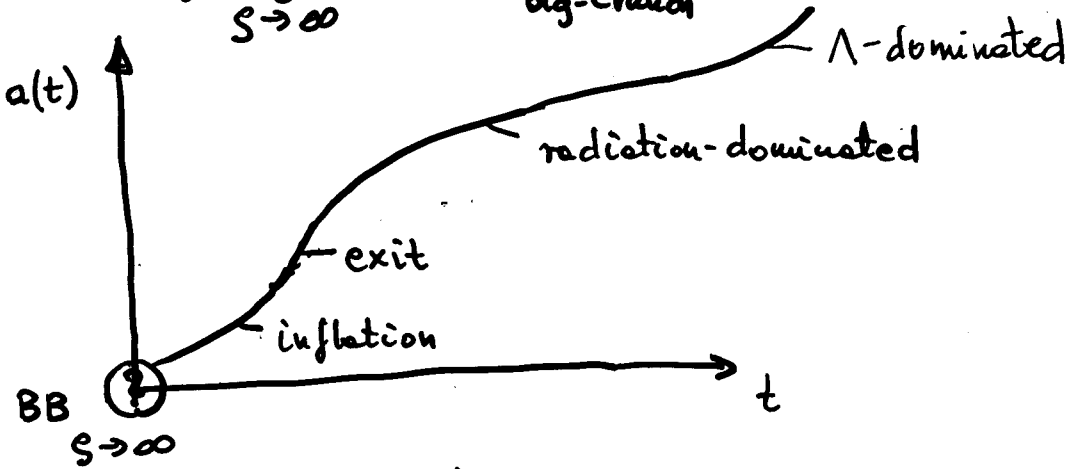
$$V(\phi) = V_0 \left(1 - e^{-c\phi} \right) F(\phi) \quad , \quad F(\phi) \propto e^{-\frac{1}{g_s}}$$

BASIC COSMOLOGIES

Standard

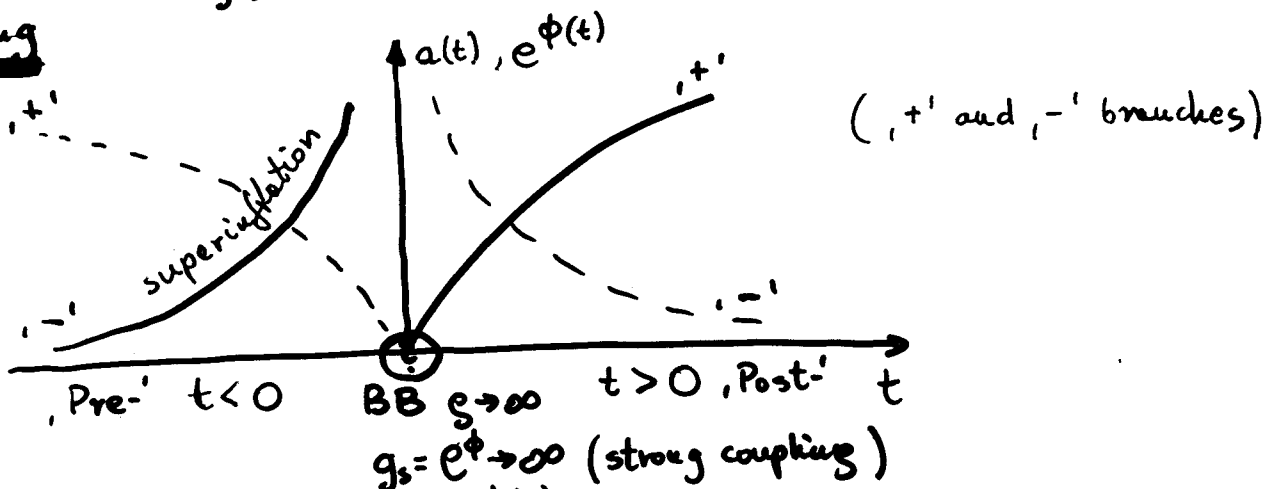


Inflationary



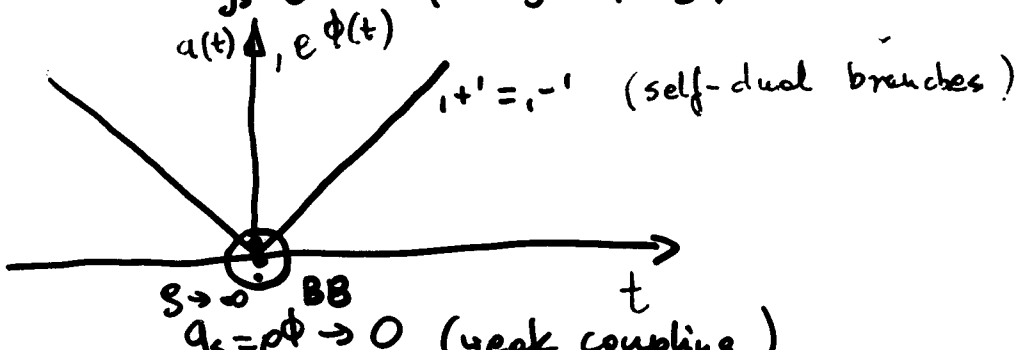
Pre-Big-Bang

(superstring)
$\omega = -1$



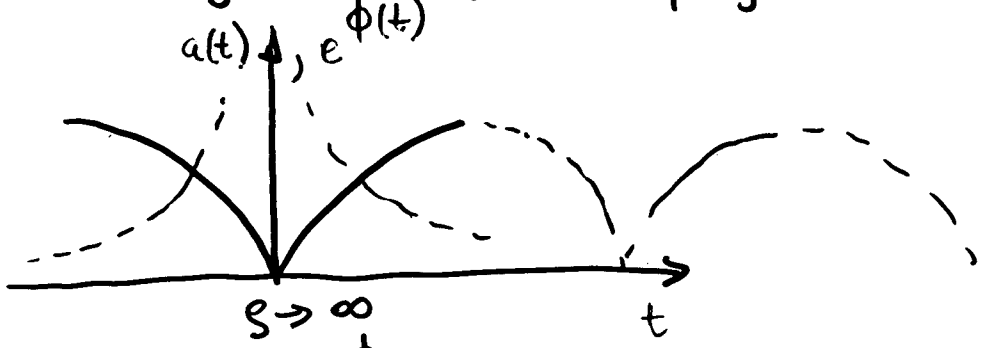
Conformal Relativity

$\omega = -\frac{3}{2}$

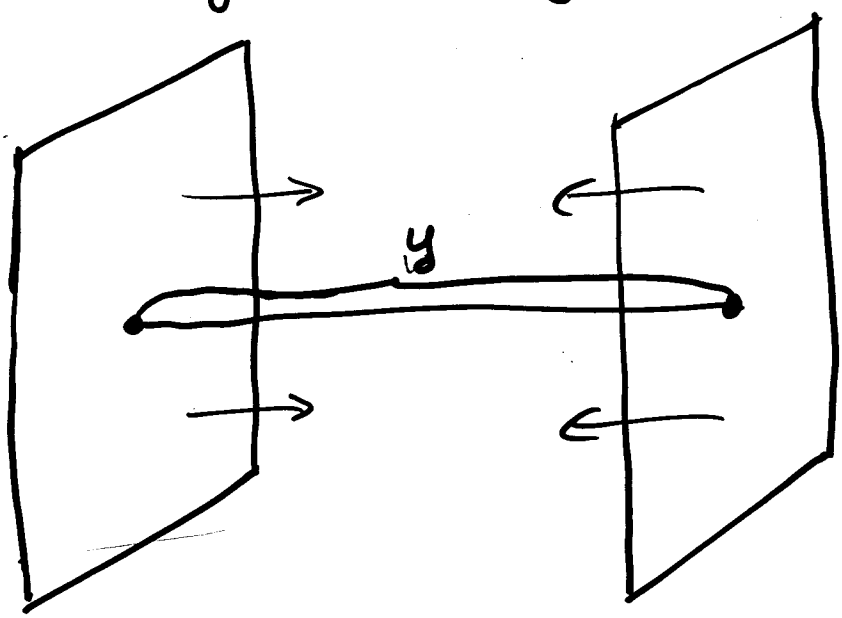


Cyclic

(M-theory)



Scenario admissible only for collision of boundary branes (not bulk branes)



The 5th dimension y (orbifold) collapses but 4-dim theory has no singularity

generalized Friedman

$$H^2 = \frac{8\pi G}{3}\left(\frac{1}{2}\dot{\phi}^2 + V + \beta^4 \rho_R + \beta^4 \rho_m\right)$$

$$\frac{\ddot{a}}{a} = -\frac{8\pi G}{3}\left(\dot{\phi}^2 - V + \beta^4 \rho_R + \frac{1}{2}\beta^2 \rho_m\right)$$

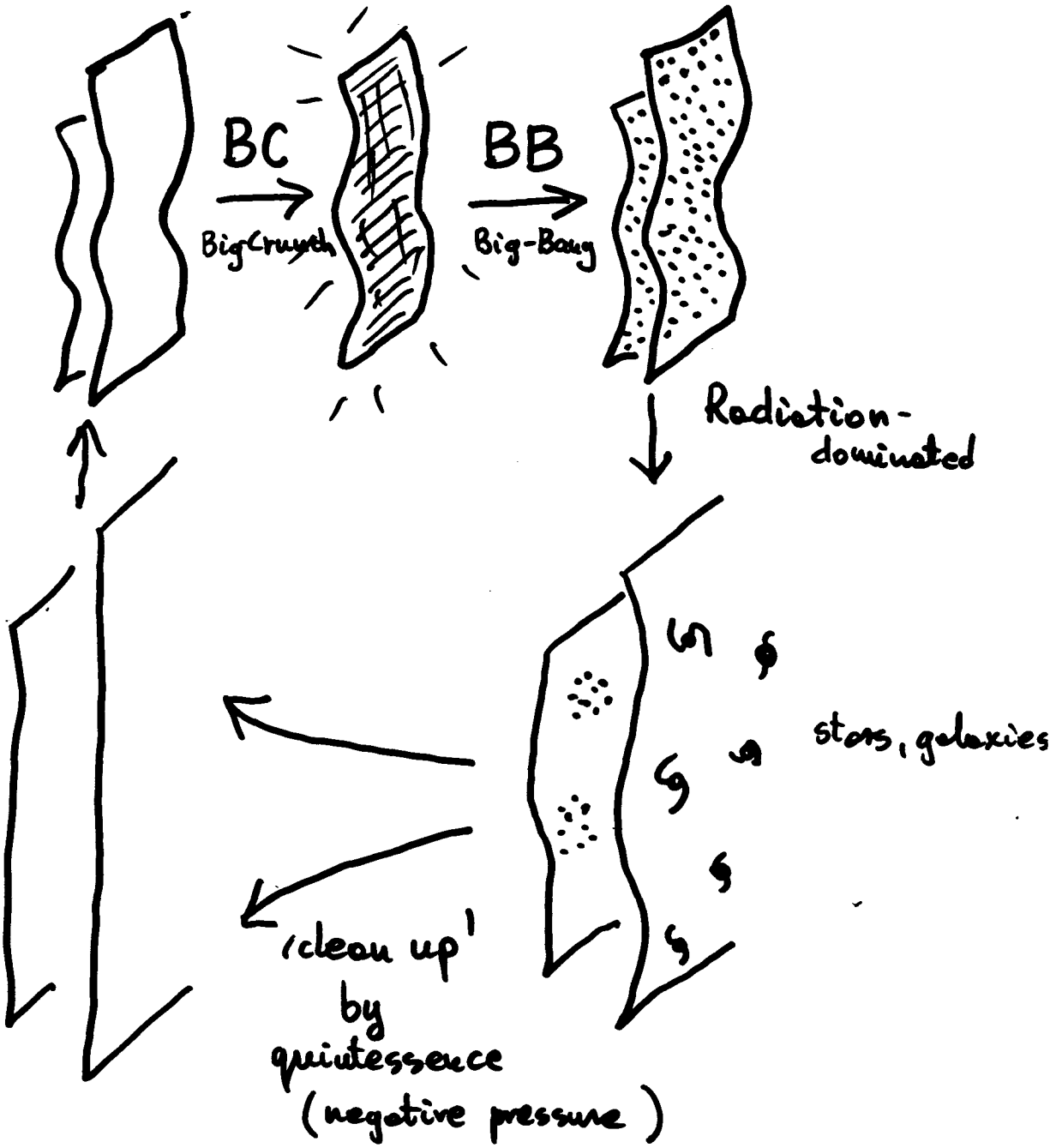
since

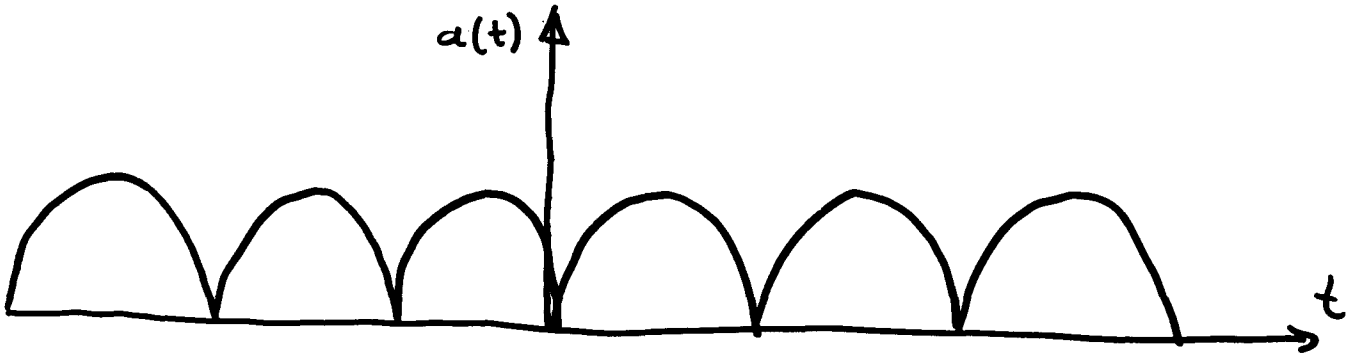
$$\rho_R \sim \frac{1}{[a\beta(\phi)]^4} \overset{a\to 0}{\sim} \frac{1}{\left(a\frac{1}{a}\right)^3} \sim \text{const.}$$

$$\rho_m \sim \frac{1}{[a\beta(\phi)]^3} \overset{a\to 0}{\sim} \frac{1}{\left(a\frac{1}{a}\right)^3} \sim \text{const}$$

CYCLIC (RECYCLING) UNIVERSE

Based on M-theory - colliding 3-branes in 5-dimensional spacetime.



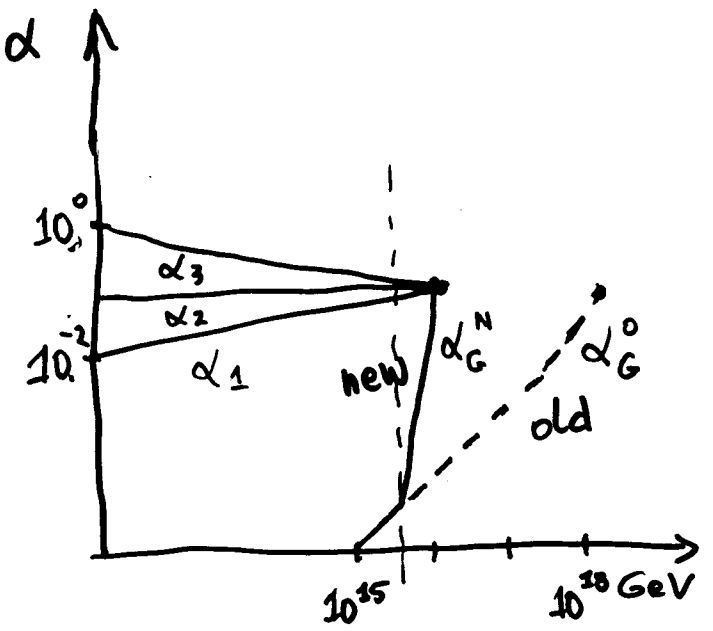


1

world

$\frac{2L^2}{3r^2}$ ← ~ size of an extra dimension

scale



meet

provided

one admits gravity propagates in a different number of dimensions than gauge interactions

unification at 10^{16} GeV

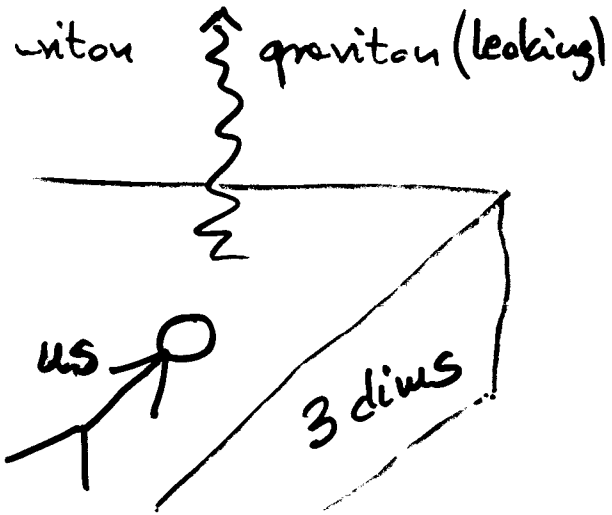
Randall-Sundrum ('99) framework

Arkani-Hamed, Dvali '98 & others

the scale of unification of gravity can even be lowered to electroweak

1 TeV

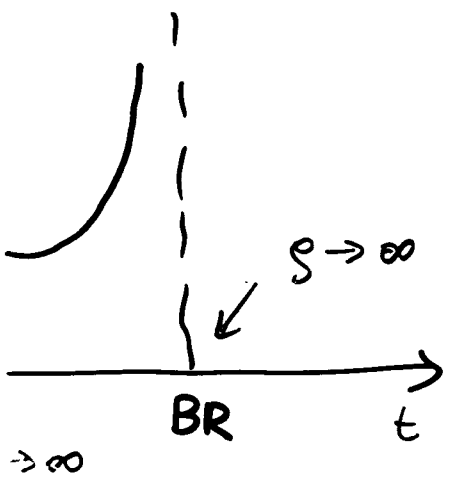
energy scale



GRAVITY IS WEAK NOW COMPARED TO OTHER INTERACTIONS SINCE SOME

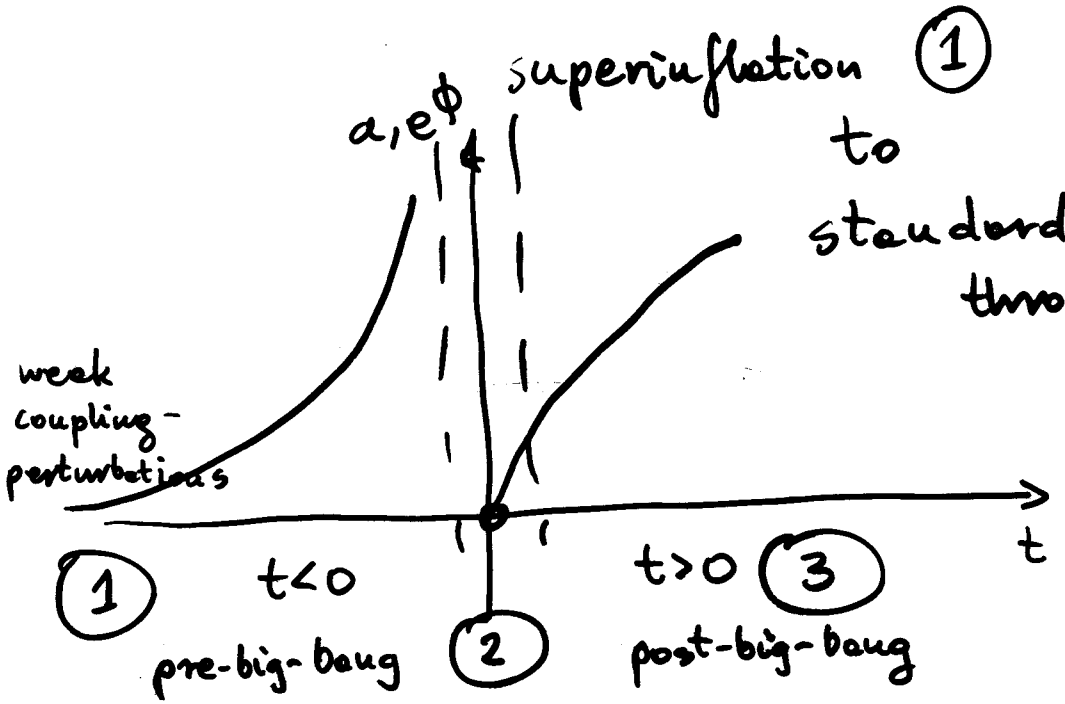
$|\dot{\gamma}| = -\dot{\gamma} > 0$

the bigger the Universe the denser it is - future curvature singularity "BIG RIP"



„Graceful-exit" problem

How to transit from superinflation (1) to standard evolution through singularity (3)? 2



Possible solutions:

1. Regularize singularity in sense of string theory
   - λ_s effects
   - loops effects

2. Quantum mechanical tunneling through singularity

phantom

V. CONCLUSIONS

Hot points:

- Universe accelerates -
all "exotics" admissible
to explain this

  - quintessence
  - phantom
  - cardassian
  - Chaplygin gas etc

- theories which move
"before" Big-Bang under studies

- non-singular/cyclic universes
possible

(cf. no black hole
claim of
yesterday)