COSMOLOGY AND EXTRA DIMENSIONS

INFLATION
BRANEWORLDS
OTHER IDEAS
OBSERVABLES

COSMO-02

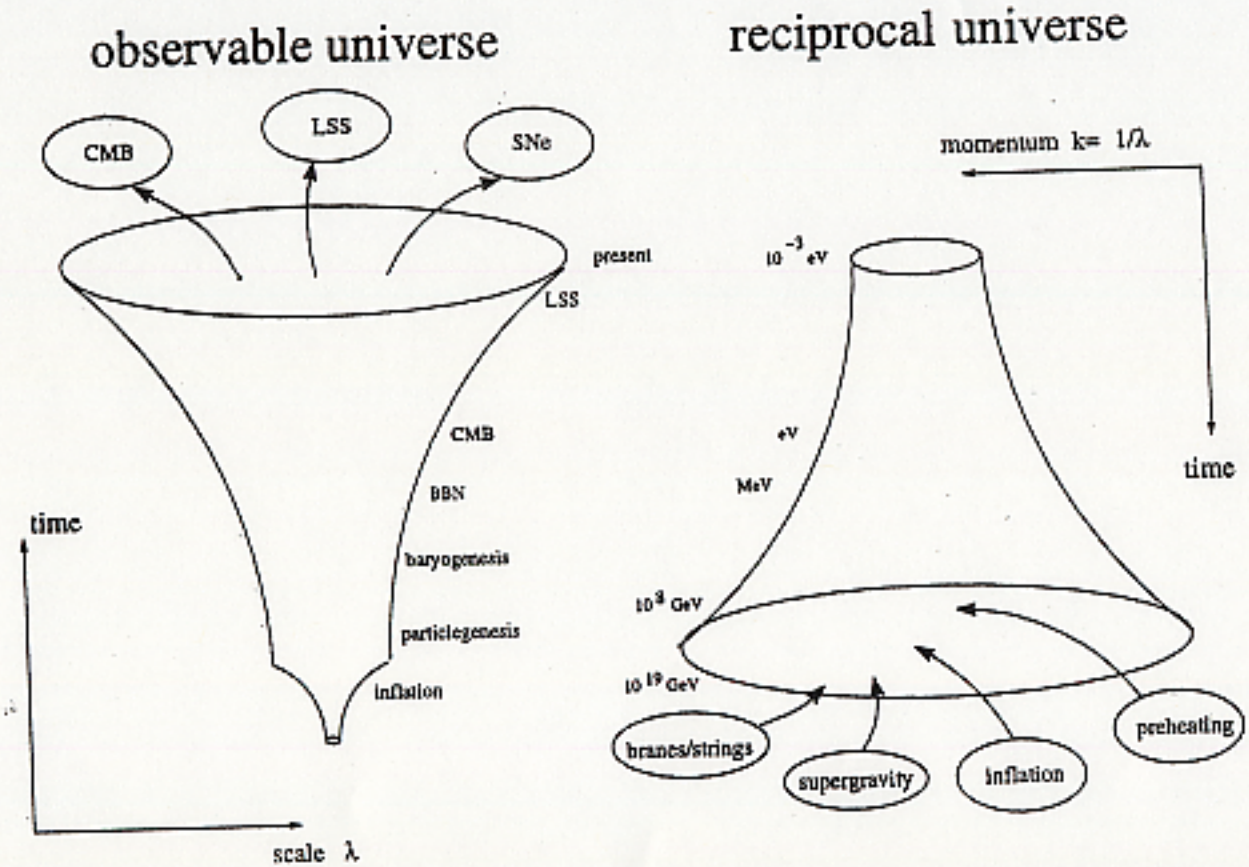


Fig. 1. Sketch of an expanding universe where the wavelengths $\lambda(t)$ are proportional to a scale factor $a(t)$ and "reciprocal" universe where the momenta $k(t) \sim 1/\lambda(t)$ are inversly proportional to $a(t)$.

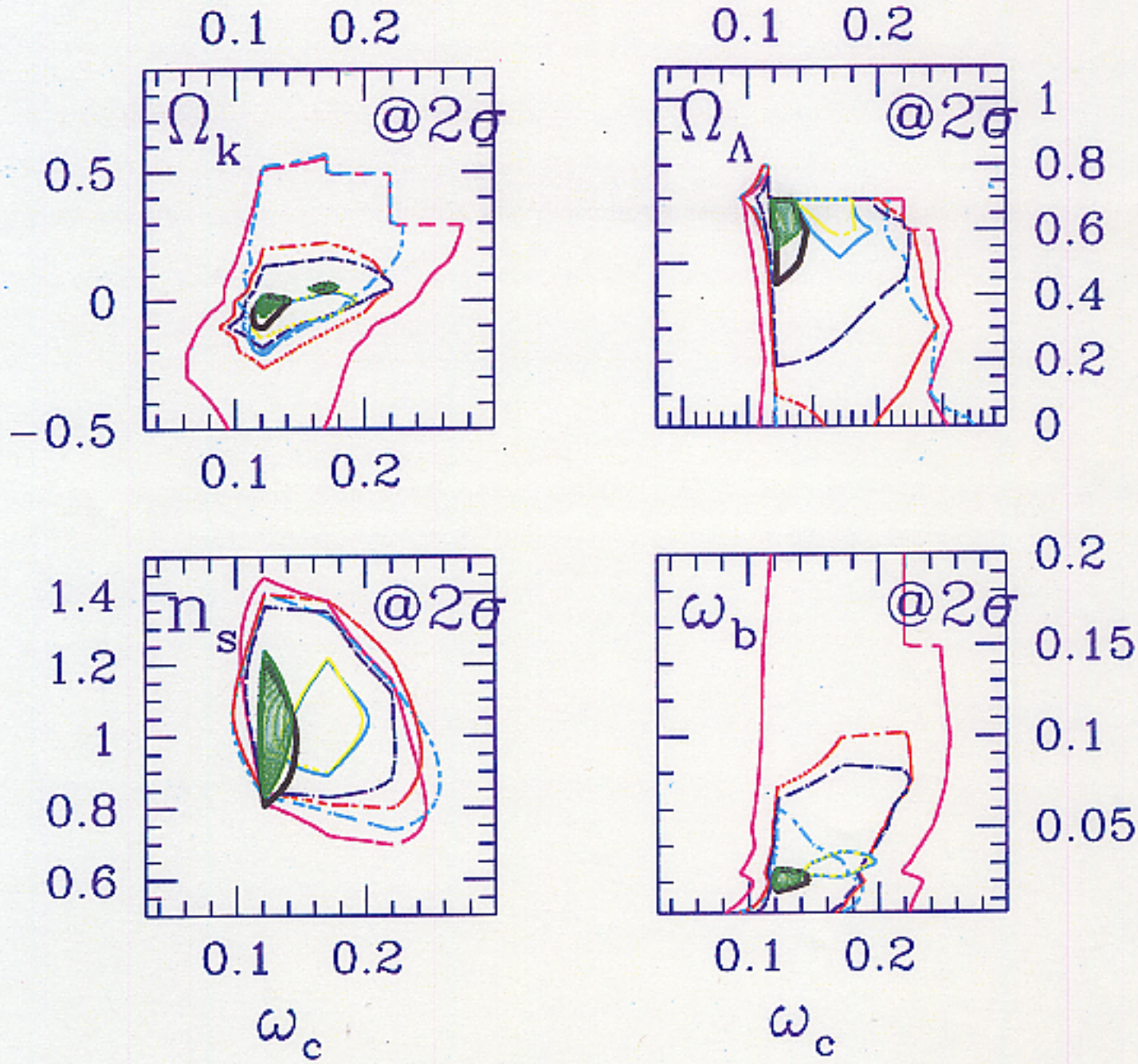
Inflation predicts

- $\Omega_{tot} = 1$

- scale-free $n=1$ gaussian scalar fluctuations

- scale-free gaussian gravitational waves

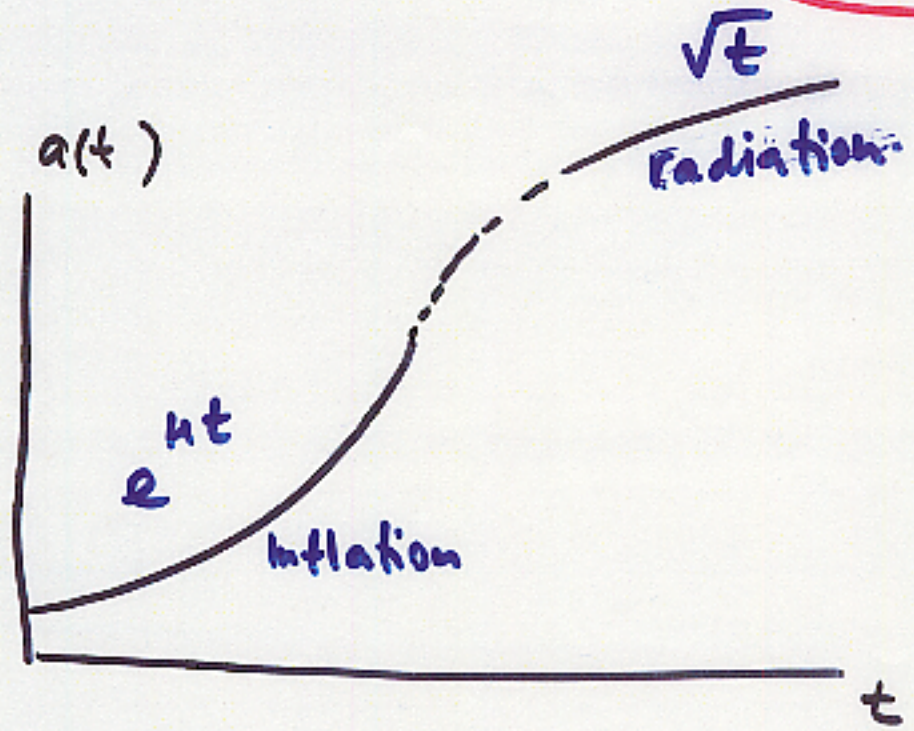
- creation of all particles



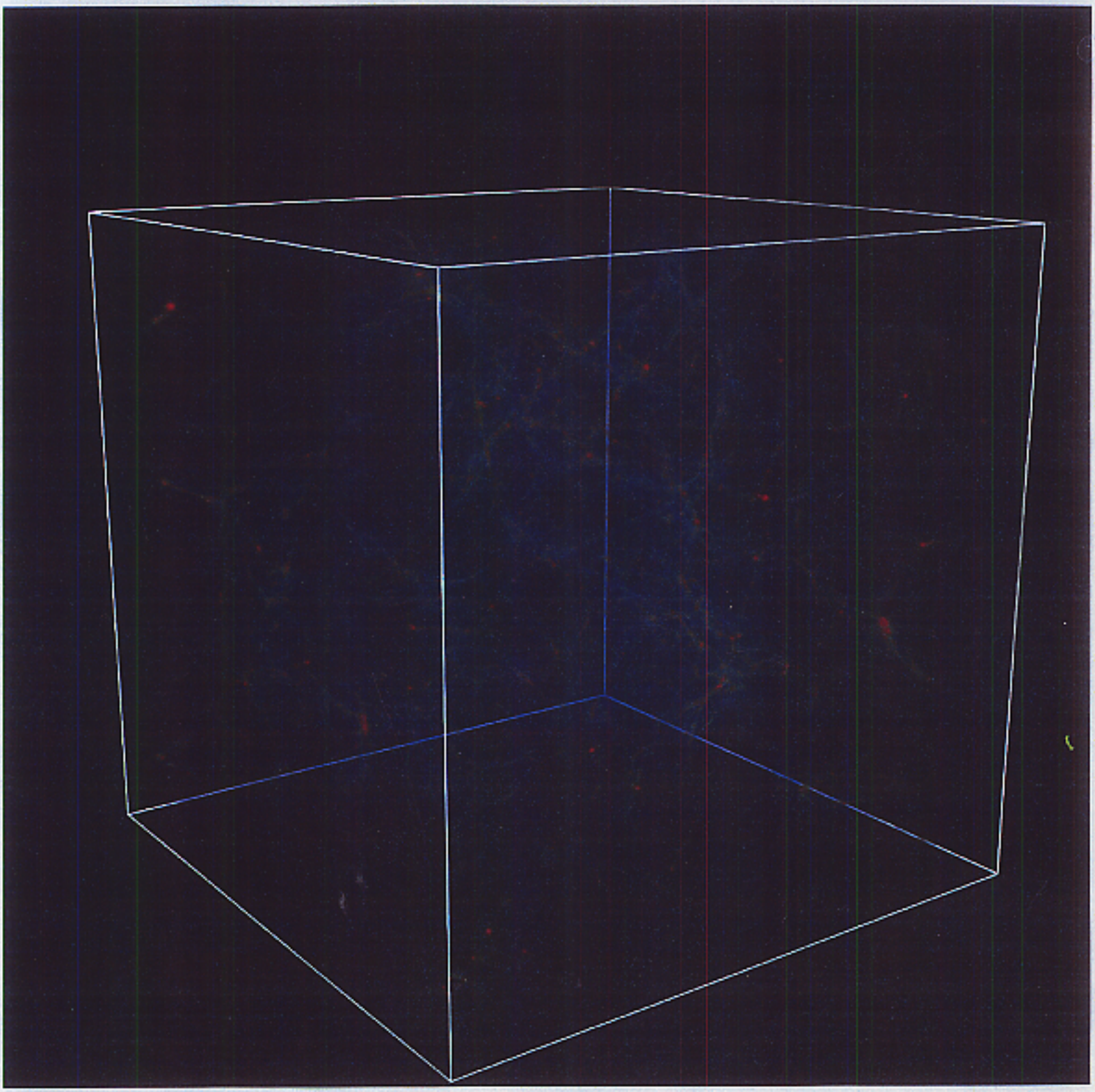
$\omega = \Omega h^2$

COSMIC INFLATION

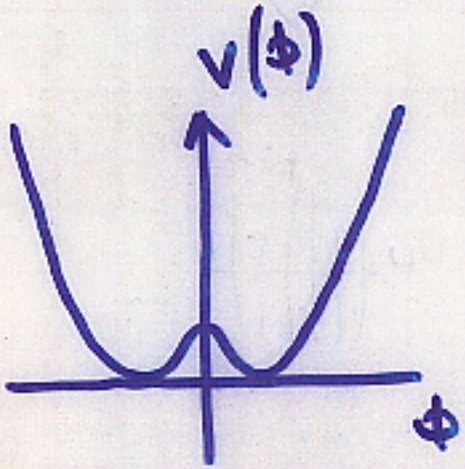
Equation of State $p \approx -\varepsilon$

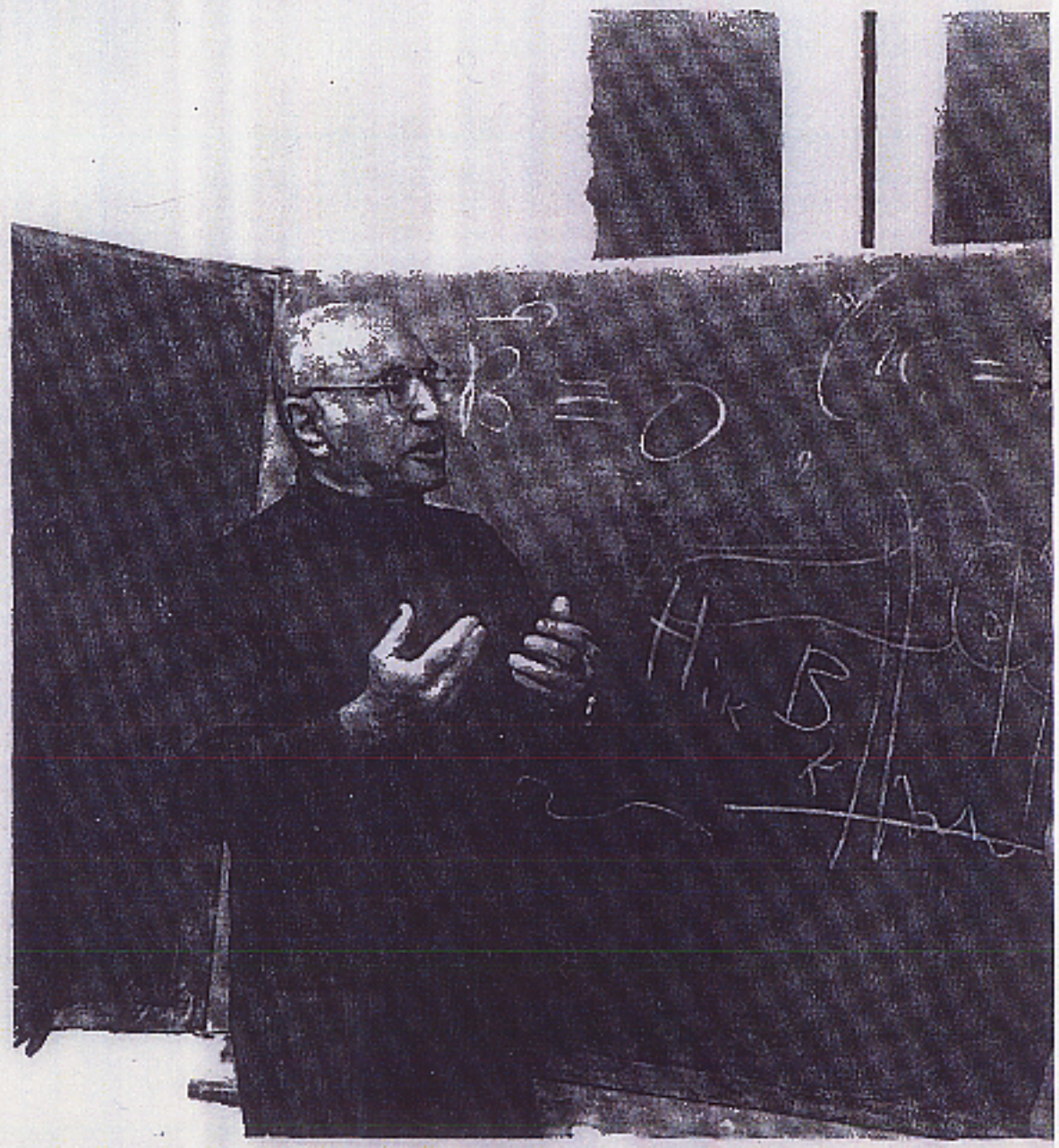


$p \approx 0$



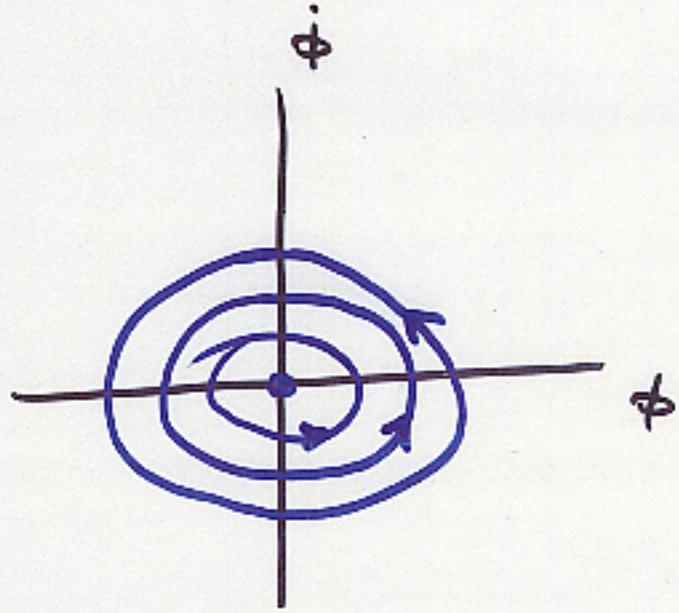
SUMMER 1980

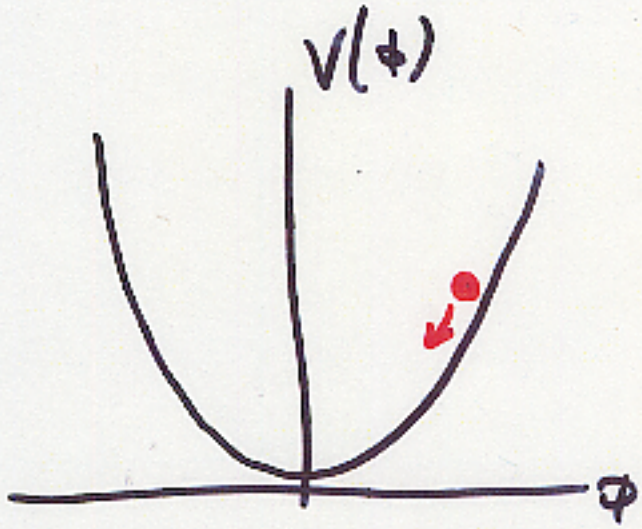




HARMONIC OSCILLATOR

$$\ddot{\phi} + m^2\phi = 0$$





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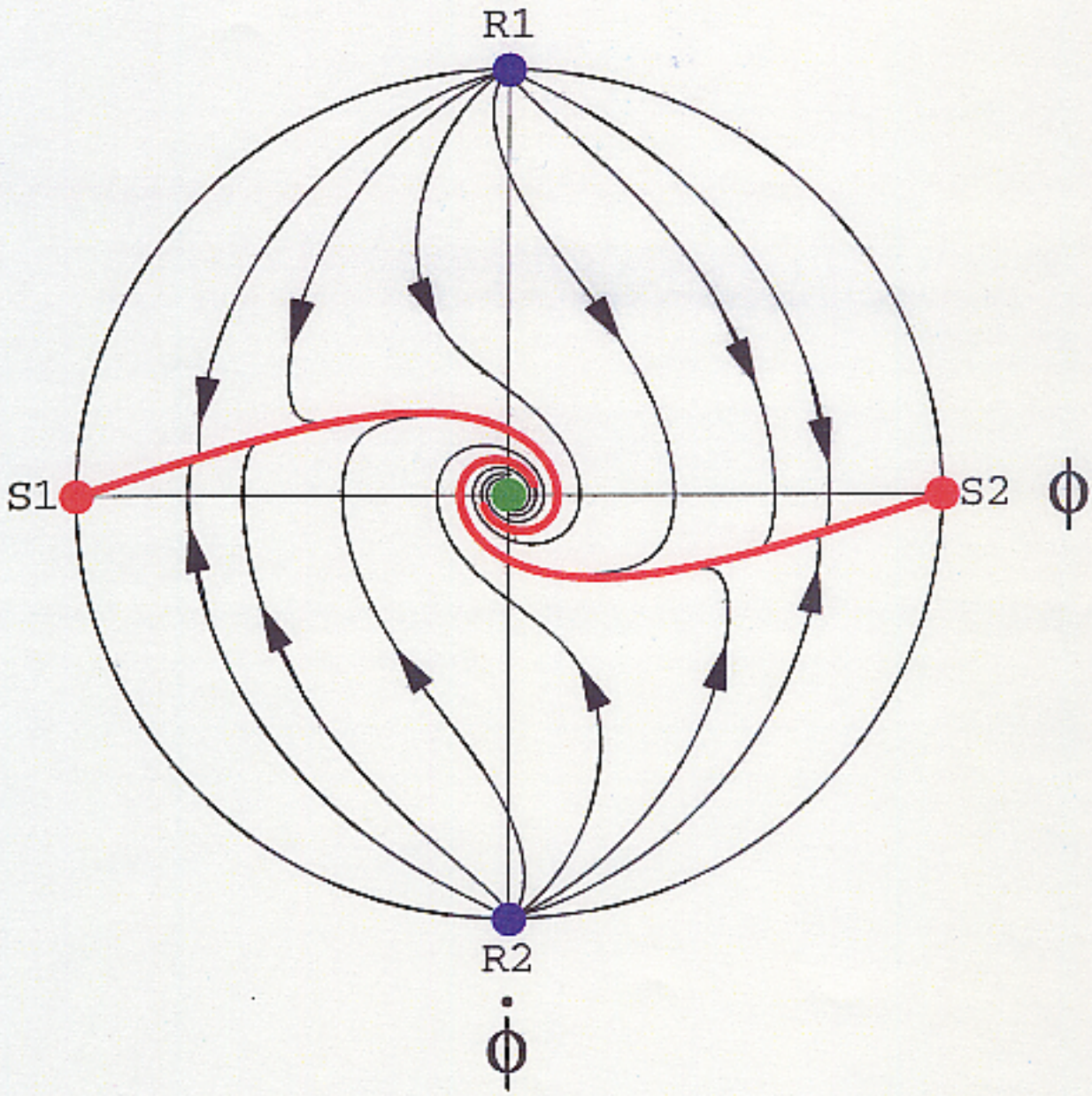
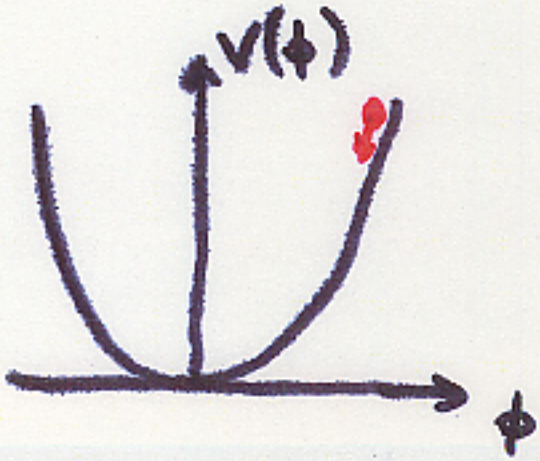
Expanding Universe

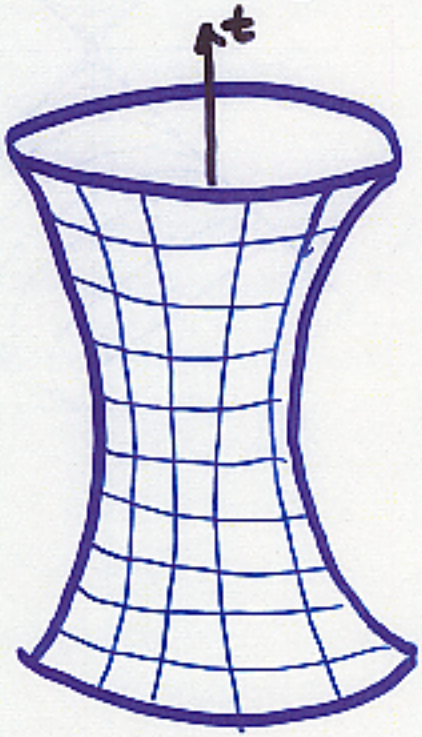




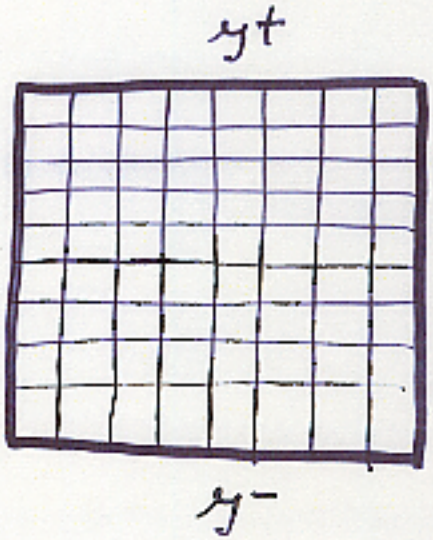
GLOBAL GEOMETRY WITH INFLATION

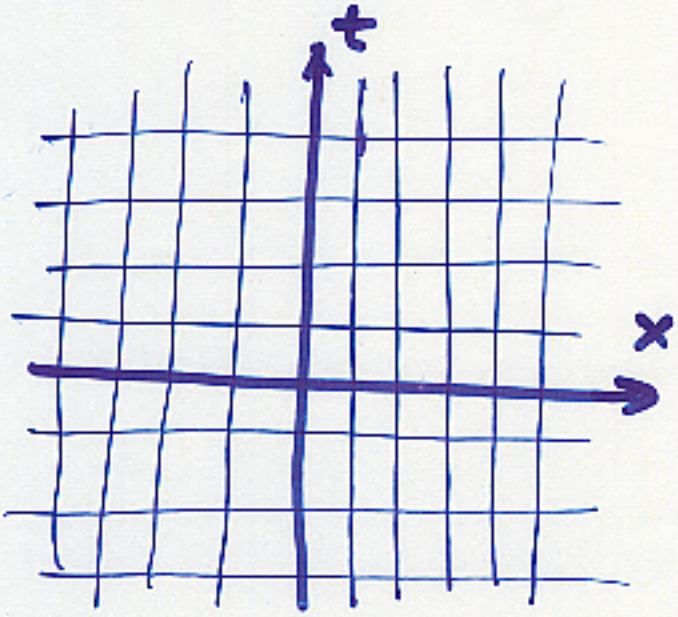
Penrose diagrams

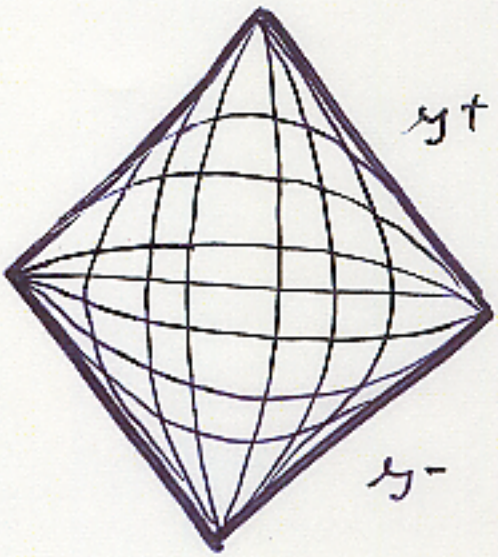
dS

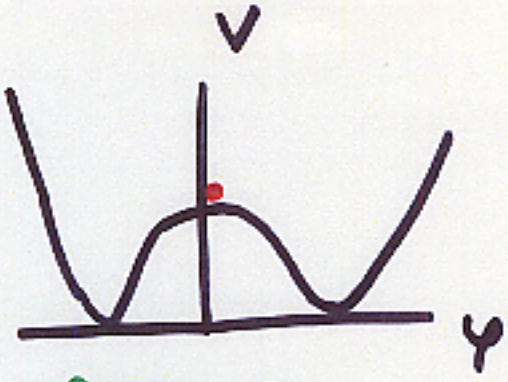


$\Rightarrow$



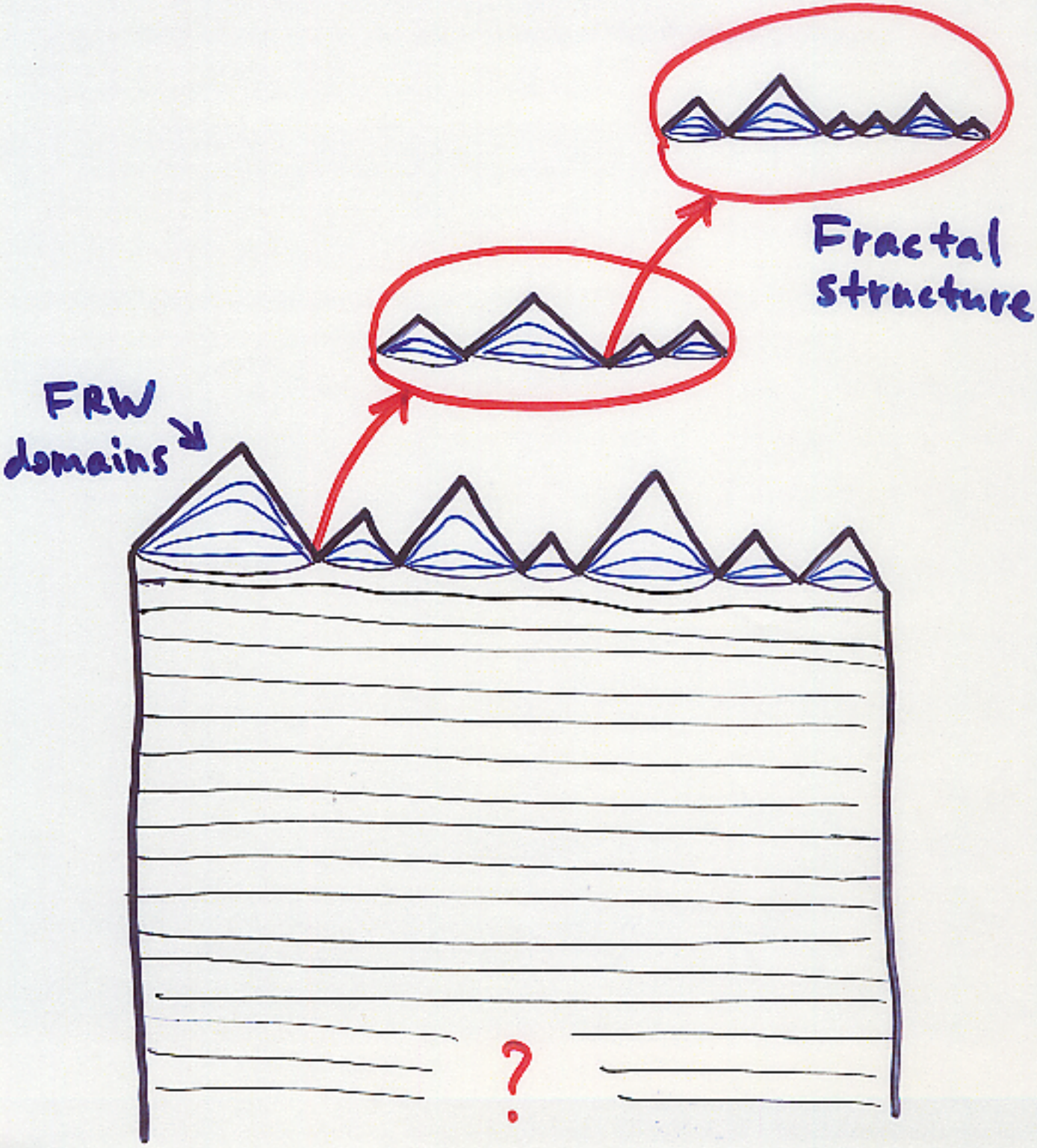




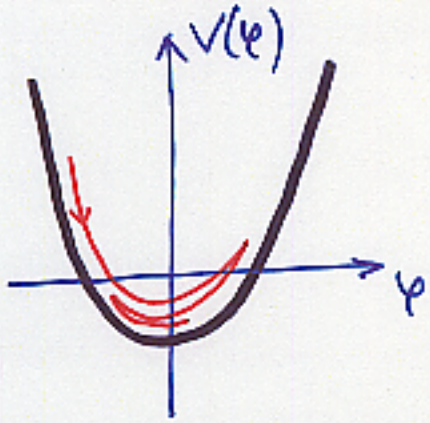


example

ds/CFT ?



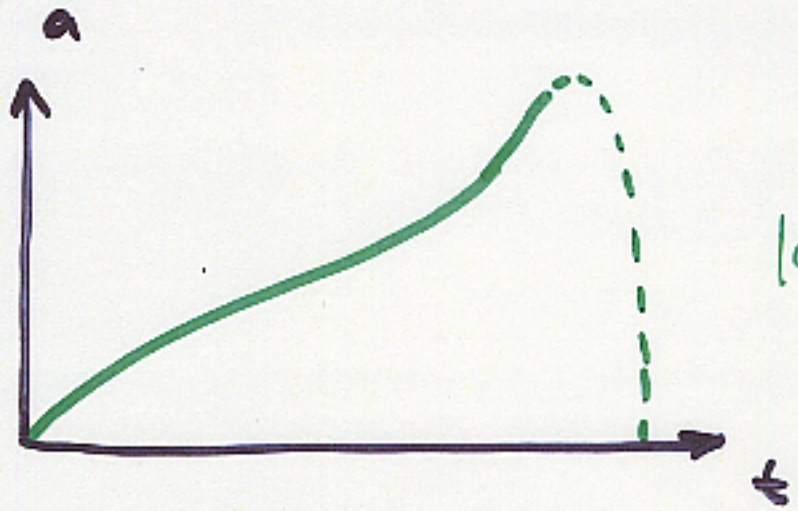
COSMOLOGY WITH NEGATIVE POTENTIAL



$$H^2 = \frac{8\pi}{M_p^2}\left(\frac{1}{2}\dot{\varphi}^2 + V\right)$$

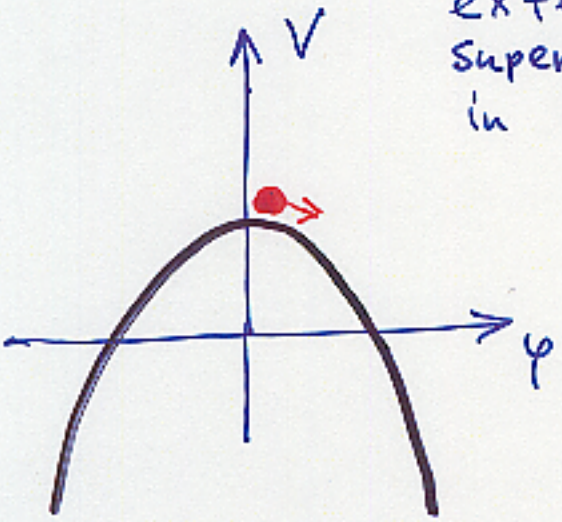
$$\ddot{\varphi} + 3H\dot{\varphi} + V_{,\varphi} = 0$$

Felder, Frolov
L.K., Linde



$\Omega = 1$

$$|out\rangle = \begin{cases} R^4 \\ dS_4 \\ \text{collapse} \end{cases}$$



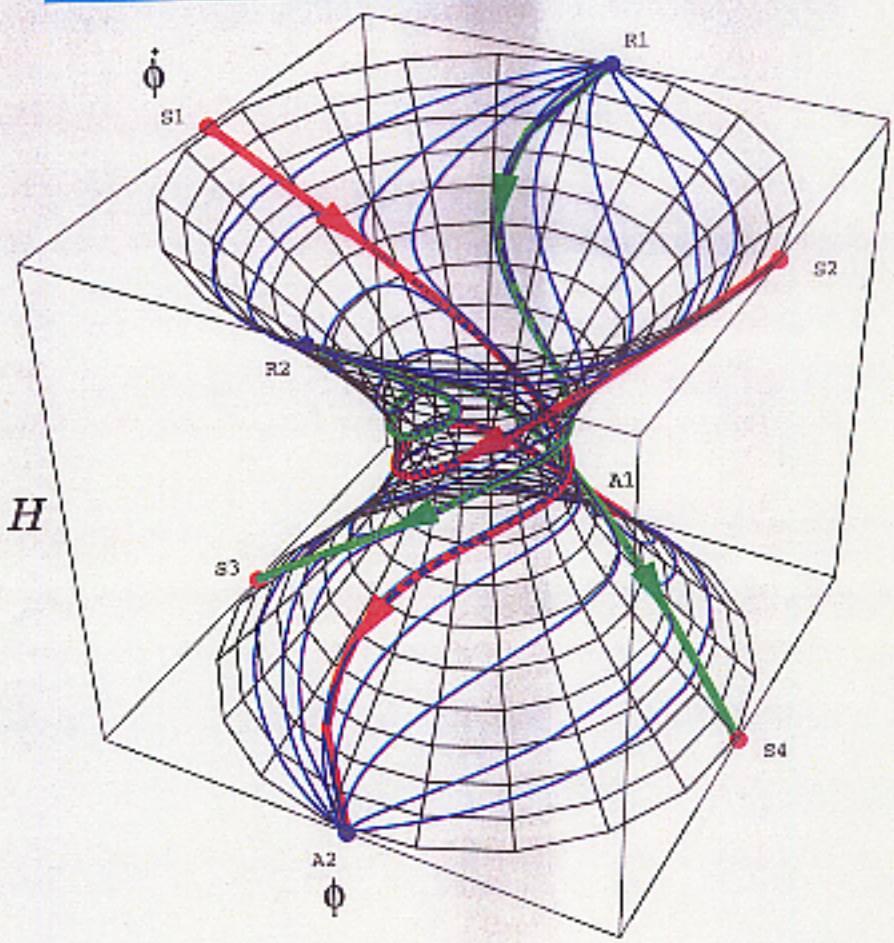
extended gauged supergravity originated in M-theory

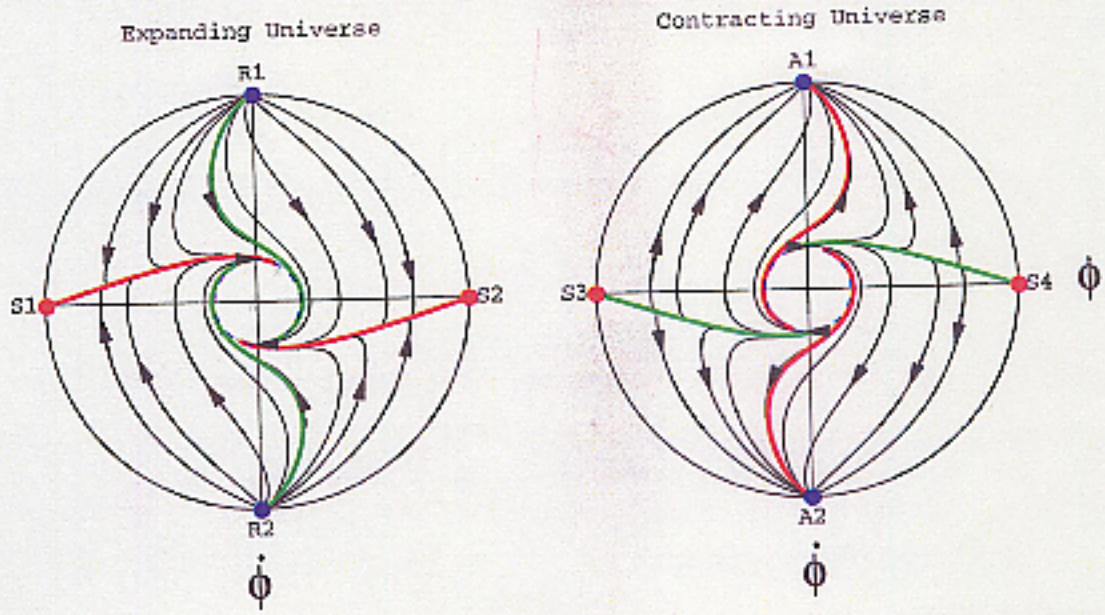
Kallosh, Linde
Prokushkin, Shmakova

$$\frac{V}{M_p^2 H^2} \simeq \Omega_\Lambda$$

$$T \sim H^{-1}$$

$$V(\phi) = \frac{1}{2}m^2\phi^2 + \Lambda, \quad \Lambda < 0$$





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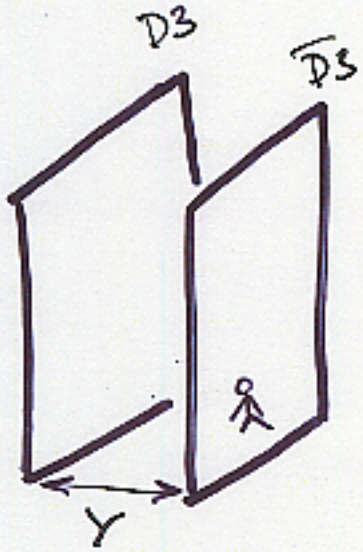
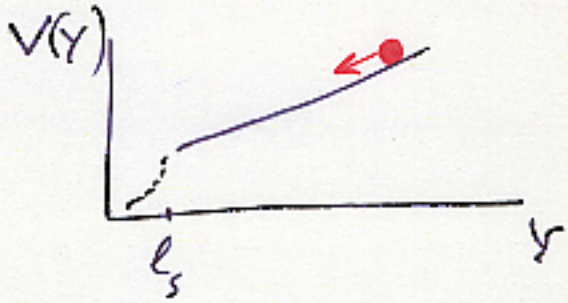
- ✓ NEW IDEAS ABOUT INFLATON(S)
- ✓ NEW IMAGES IN EARLY UNIVERSE THEORIES
- ✓ LINK BETWEEN STRING THEORY AND OBSERVATIONS
- ✓ NEW IDEAS ABOUT 4D GRAVITY

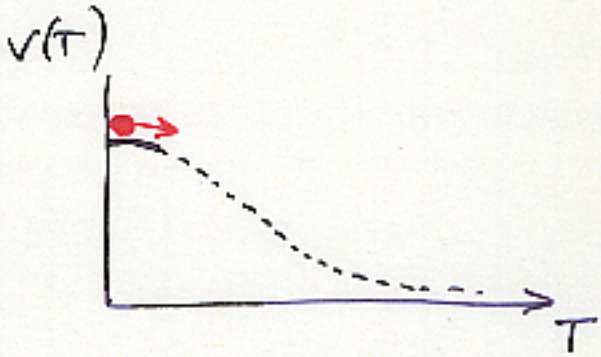
SEARCH FOR INFLATION

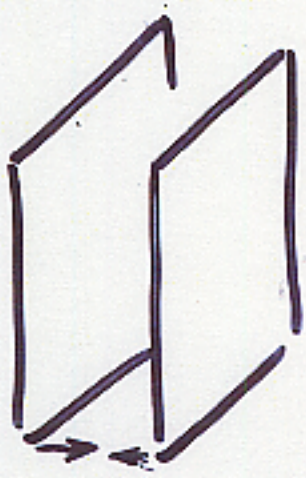
NEW IMAGES



$$\ddot{Y} + 3H\dot{Y} + V_{,Y} = 0$$







colliding branes

without inflation tuning $\frac{\Delta\theta}{\theta} \lesssim 10^{-60}$

FLUCTUATIONS FROM INFLATION AND EXTRA DIMENSIONS

- Fluctuations of scalars
- Gravitational waves h_{AB}

$D = 3+1$
two TT tensor components
$$h_k = \frac{H}{M_p} \cdot \frac{1}{k^{3/2}}$$

- in general $\frac{D(D-3)}{2}$ components
- 4D appearance as 2 tensor + V + S modes
- more scales (M_s, M_p, R, H) to amplitude ?
- KK modes

Inner space is not inflating

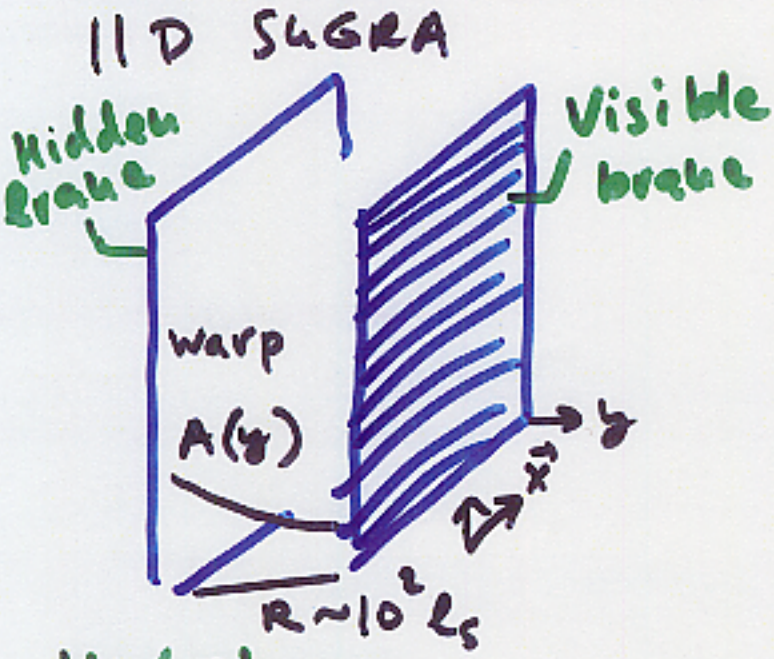
Inner space is inflating

HOW ONE CAN HEAR THE SHAPE OF A DRUM?

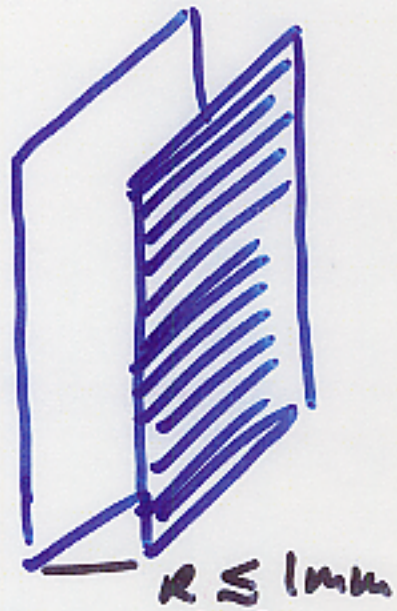
$$\Box h = 0$$

BRANE WORLDS

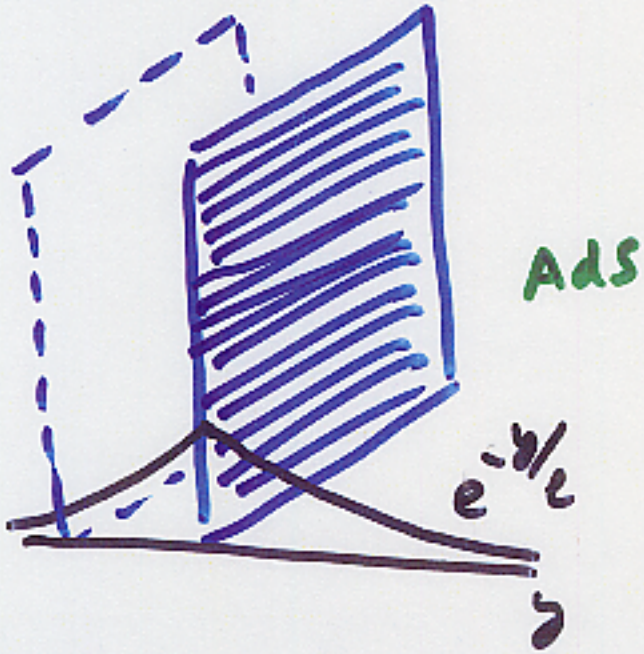
$G_D = R^{D-4} G_4$



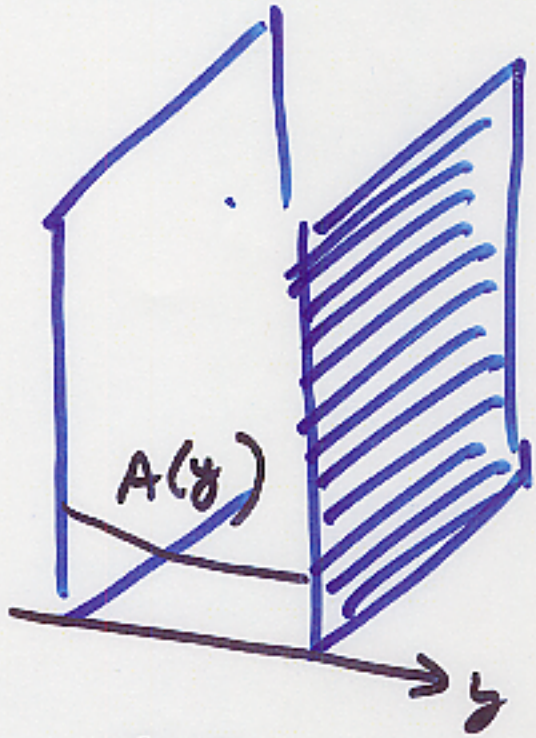
HW Theory



ADD model

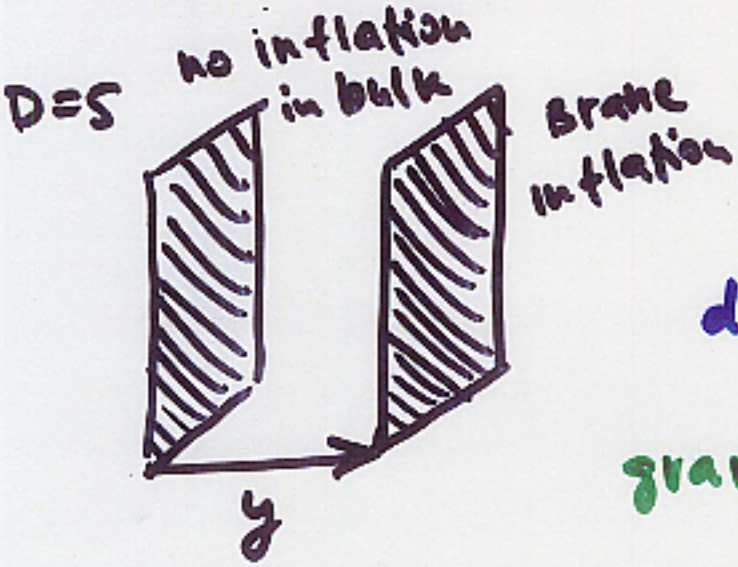


RS models



bulk scalars $\varphi(y)$
warp geometry $A(y)$

Braneworld INFLATION



$$ds^2 = dy^2 + A^2(y)\left(-dt^2 + e^{2Ht} d\vec{x}^2\right)$$

grav. waves $h_{AB}(y, \vec{x}, t)$

$$h_{\mu\nu} = A^{1/2} h_m(y)\, Q^{(m)}_{\mu\nu}(t, \vec{x})$$

$$h_{yA} = h_{yy} = 0$$

$$\boxed{\Box_{ds} Q^{(m)}_{\mu\nu} = m^2 Q^{(m)}_{\mu\nu}}$$

$$\boxed{h_m'' + (m^2 - V_{eff})\, h_m = 0}$$

$$V_{eff} = \frac{3}{2}\frac{A''}{A} + \frac{A'^2}{2A}$$

$$x = \int \frac{dy}{A(y)}$$

NO-GO RESULTS

for arbitrary $A(y)$, $V(\varphi)$

- massive KK graviton modes are not generated from inflation due to the gap

$$\Delta m \geq \sqrt{\frac{3}{2}}\, H$$

- massless scalar and vector projections of the bulk gravitons are absent

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AMPLITUDE OF GRAV. WAVES FROM BRANEWORLD INFLATION

$$k^{3/2} h_k = \frac{H}{M_p} f(H, \ell, M_p)$$

$$k^{3/2} h_k = \frac{H}{\tilde{M}_p}$$

$$\tilde{M}_p^2 = M_s^{D-2} V_{D-4}$$

$$\tilde{M}_p \neq M_p$$

$D=5$

$$\tilde{M}_p^2 = M_s^3 \int_{y_1}^{y_2} dy\, A^2(y)$$

- $k^{3/2} h_k = \mathcal{O}\, \frac{V}{M_p}$

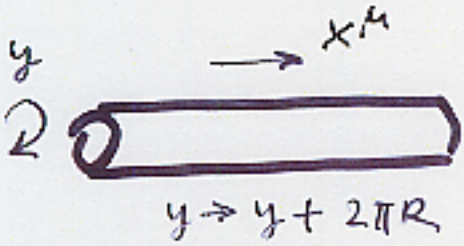
- $\frac{\text{tensor}}{\text{scalar}}$ = model-dependent

Kaluza-Klein REDUCTION AND BULK GRAVITONS

$$S = \int d^D x \sqrt{-g}\, R$$

$\frac{1}{2}D(D-3)$ components of bulk graviton

$$\Box\left(h_{AB} - \frac{1}{2}\eta_{AB} R\right) = 0$$



$$h_{AB} = \left(\begin{array}{c|c} h_{\mu\nu} + h_{\mu\nu}\varphi & A_{\mu i} \\ \hline A_{\nu i} & \varphi_{ij} \end{array}\right)$$

$$S = \int d^4 x \sqrt{-g}\left(\underset{2}{R} - \underset{2(D-4)}{\frac{1}{4}F^{\mu\nu}F_{\mu\nu}} + \underset{\frac{1}{2}(D-4)(D-3)}{\frac{1}{2}\varphi_{,\mu}\varphi^{,\mu}}\right)$$

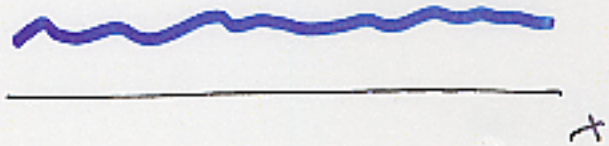
$$\boxed{\begin{aligned} &({}^4\Box + m_n^2)\left(h_{\mu\nu} - \tfrac{1}{2}\eta_{\mu\nu} h\right) = 0 \\ &({}^4\Box + m_n^2)\, A_{\mu i} = 0 \\ &({}^4\Box + m_n^2)\, \varphi_i = 0 \end{aligned}}$$

$$m^2 = \frac{4\pi^2 n^2}{R^2}$$

Long wave length fluctuations of any light scalars and grav. waves are generated from Inflation

$h \simeq \frac{H}{M_P}$

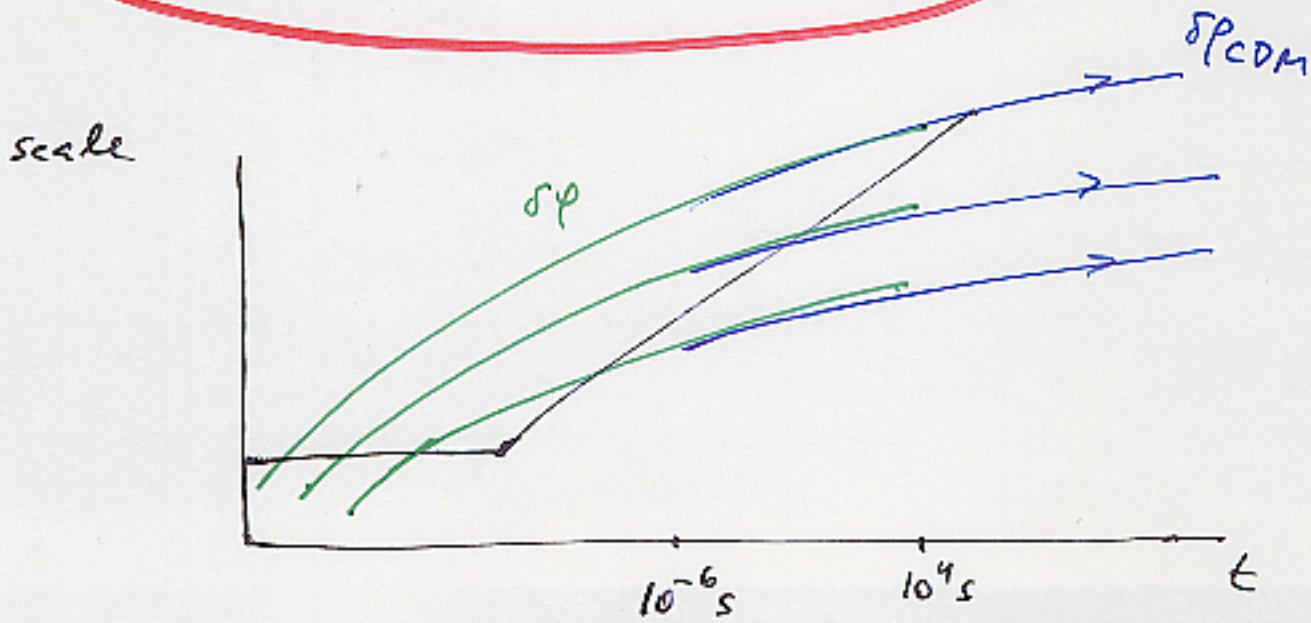
moduli $\frac{\delta\varphi}{\varphi} \sim \frac{H}{M_P} \sim h$



$$\frac{\delta\varphi}{\varphi} \rightarrow \frac{\delta\alpha}{\alpha}$$

coupling constant spatial variations

$$\frac{\delta\rho_{CDM}}{\rho_{CDM}} \sim \frac{\delta\rho_B}{\rho_B} \sim \frac{\delta Y}{Y} \sim h$$



BULK INFLATION

$$ds^2 = -dt^2 + e^{2Ht}\left(dx_1^2 + dx_2^2 + dx_3^2 + \underbrace{dy_1^2 + \cdots dy_N^2}_{\text{compact}}\right)$$

$$h_k = \frac{\sqrt{\pi}}{2} H^{\frac{N-1}{2}} \tau^{N/2} H^{(1)}_{N/2}(p\tau)\, e^{-ikx} \sin ny$$

$$p^2 = k^2 + \frac{n^2}{(2\pi R_0)^2}$$

$$\boxed{h \simeq \frac{H}{M_p}\left(H^{\frac{D-3}{2}} R^{\frac{(D-4)(D-1)}{2(D-2)}} \ell_p^{\frac{1}{D-2}}\right)}$$

$\ell_p \simeq 10^{-33}$ cm

$R \sim 10^{-4}$ mm

$H \sim 10^{13}$ GeV

$h \sim 10^{7}$

Difficult to have bulk inflation