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INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SMR.996 - 23

Lecture I & II

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

2 June - 4 July 1997

INFLATION AND THEORY OF COSMOLOGICAL PERTURBATIONS

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Lecture ...   std cosmology puzzles

"   tests

"   problems

inflation as a solution

obtaining inflation

models of inflation

old

new

→ chaotic

reheating

Lecture 2:   data on LSS & CMB

key questions

formation of structure problem

solution in the context of inflation

summary / preview: fluct. growth in infl. cosmology

↳ fluctuation problem

Newtonian theory of cosm. pert.

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Lecture 3: relativistic theory of cosmological perturbations

quantum analysis

CMB anisotropies

problems of inflation

Lecture 4: problems reviewed

nonsingular cosmology

back-reaction in infl. cosmology

Inflation & Theory of Cosmological Perturbations

1. The Inflationary Universe Scenario

    standard cosmology : pillars, tests & problems
    inflation as a solution
    models of inflation
    reheating in inflationary Universes

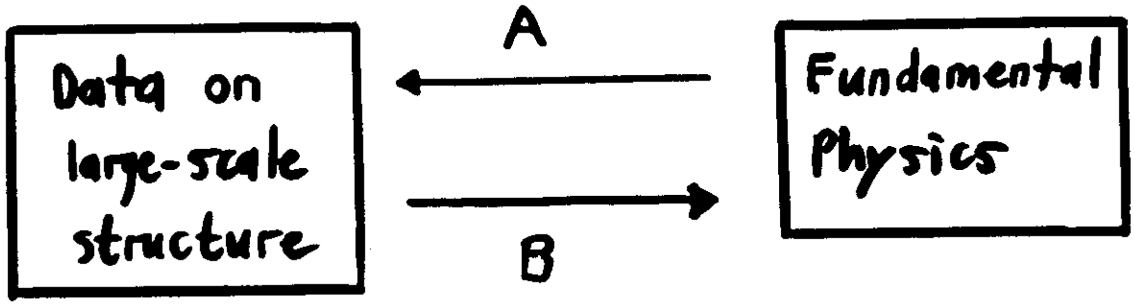
2. Newtonian Theory of Cosmological Perturbations

3. Relativistic Theory of Cosmological Perturbations

4. Problems of Inflation

    & some recent attempts to solve them ....

Questions



A: Are there theories based on fundamental physics which explain the observed structure of the Universe?

B: Can we learn something about physics at very high energies from cosmological data?

Basic References on Inflation

A. Guth, Phys. Rev. **D23**, 347 (1981)

A. Linde, Phys. Lett. **129B**, 177 (1983)

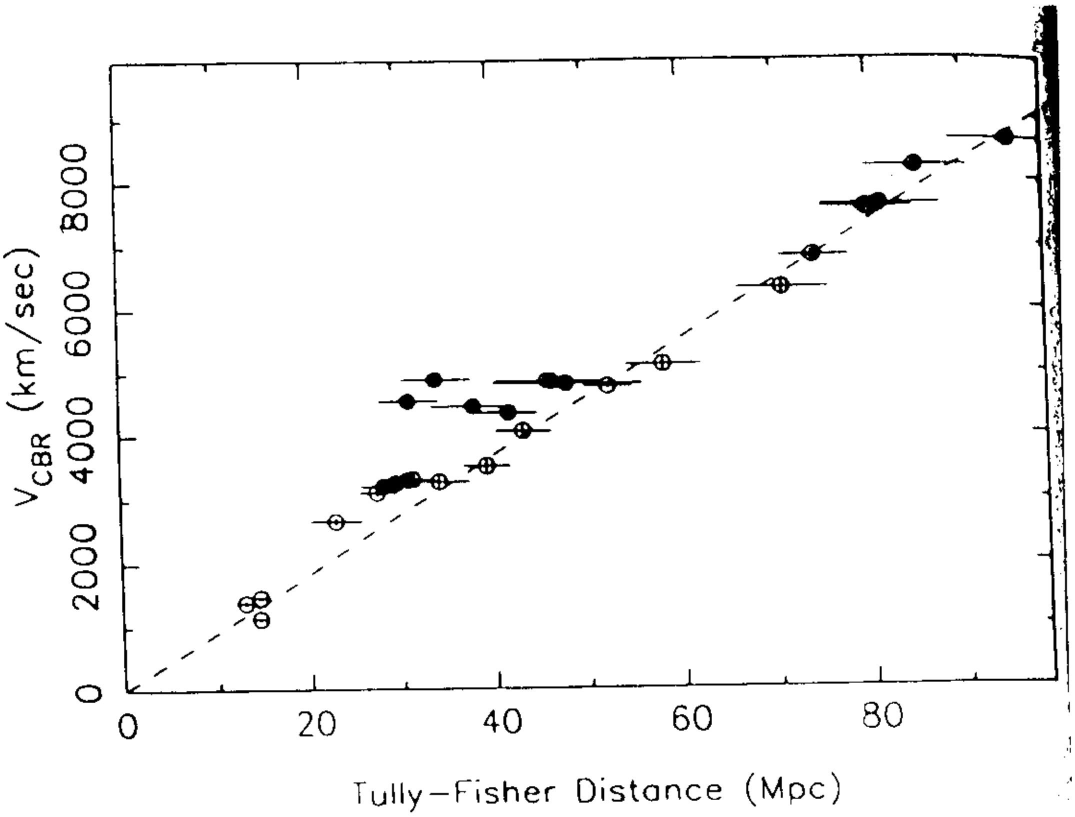
R. B. Rev. Mod. Phys. **57**, 1 (1985)

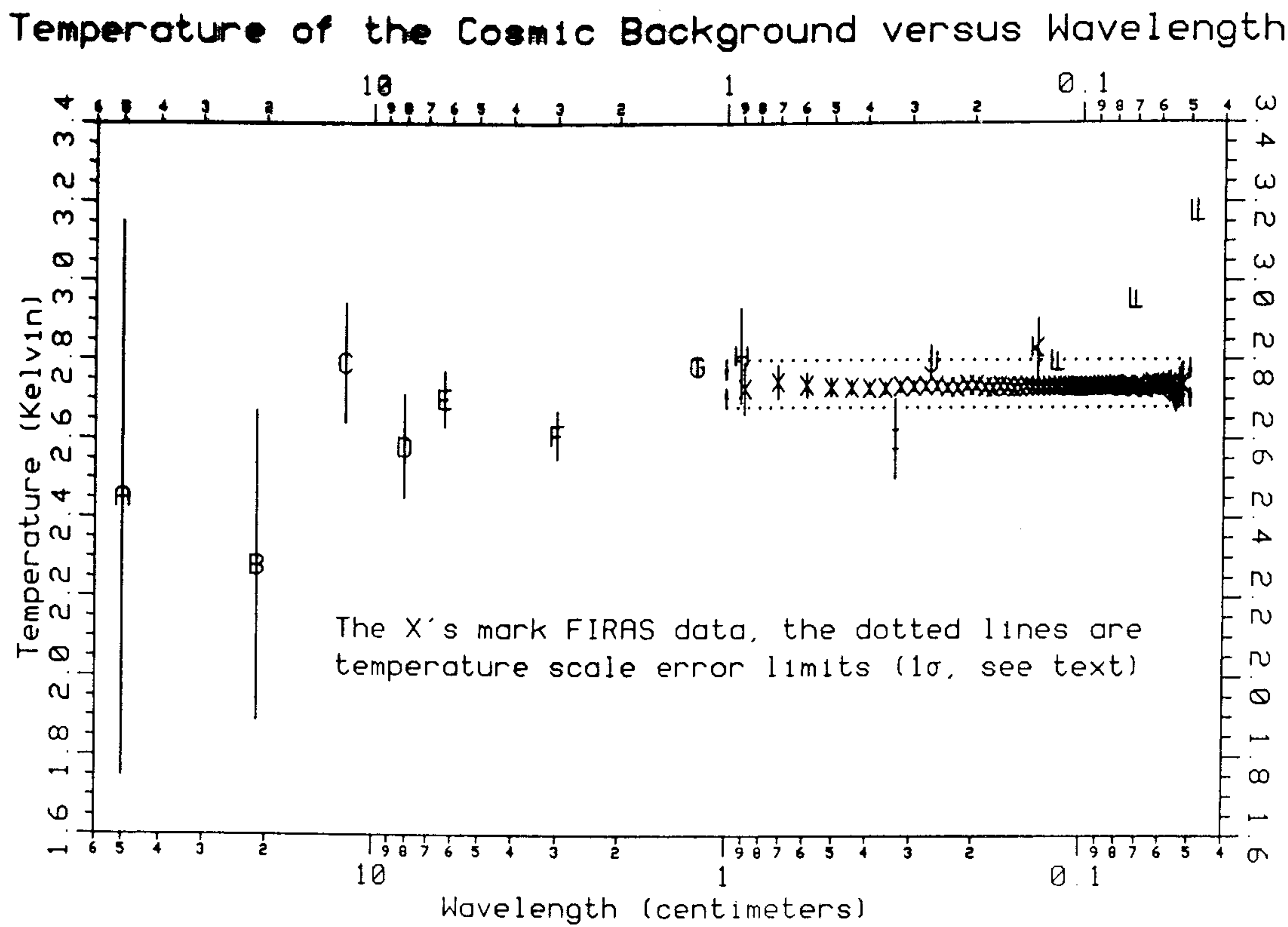
A. Linde, Particle Physics & Infl. Cosmology (Harwood, Chur, 1990)

A. Guth & S. Blau, in '300 Years of Gravitation' (Cambridge Univ. Press, Cambridge 1987)

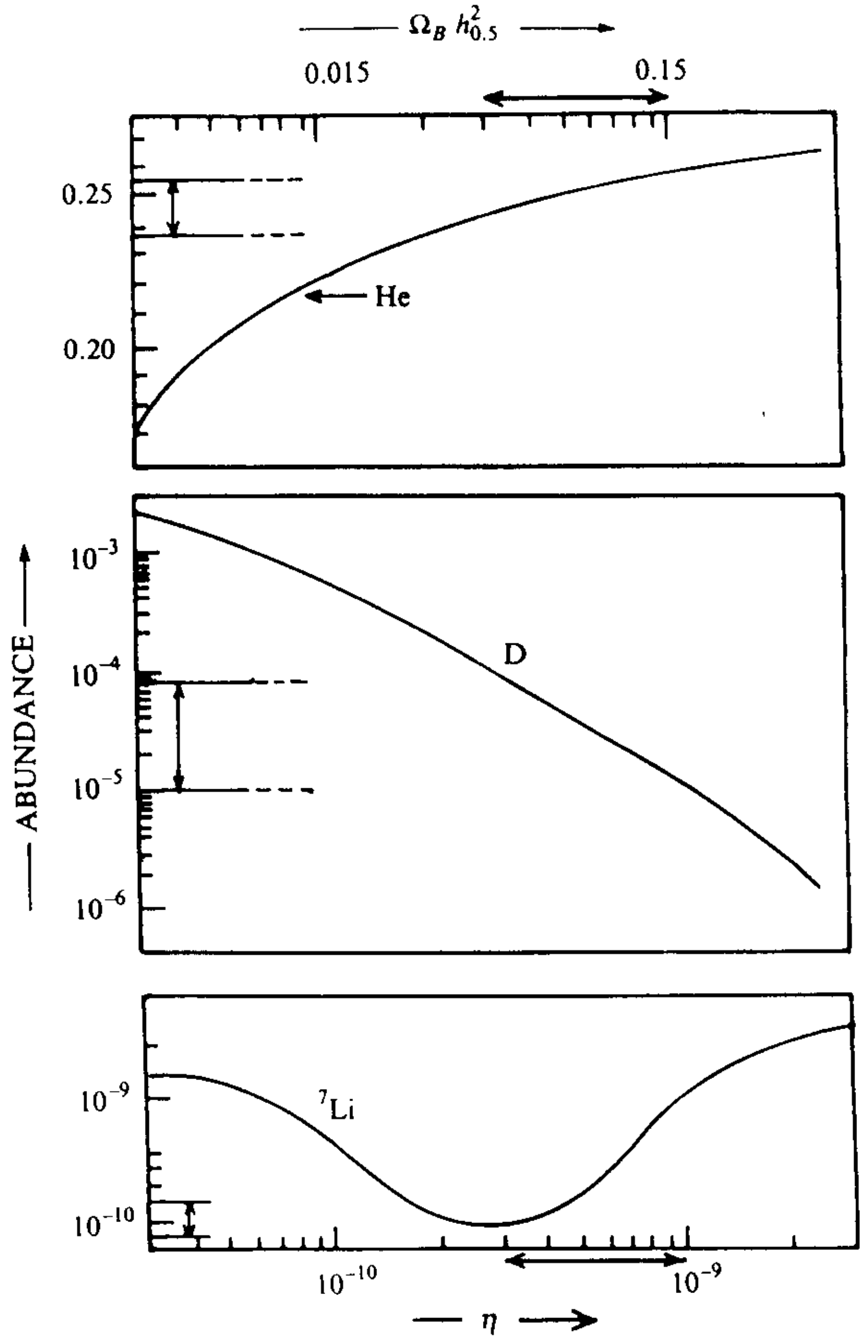
K. Olive, Phys. Rep. **190**, 307 (1990)

R.B. hep-ph/9701276
'Particle Physics Aspects of Modern Cosmology'


V_{CBR} (km/sec)
0
2000
4000
6000
8000
0
20
40
60
80
Tully–Fisher Distance (Mpc)


Temperature of the Cosmic Background versus Wavelength
Temperature (Kelvin)
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
Wavelength (centimeters)
10
1
0.1
A
B
C
D
E
F
G
H
J
K
L
The X's mark FIRAS data, the dotted lines are
temperature scale error limits (1σ, see text)

8



T. Padmanabhan

Basis of Standard Cosmology

Cosmological Principle

Universe is spatially homogeneous
on large scales

+ Einstein eqs.
+ perfect fluid matter

$\downarrow$

Big Bang Cosmology

but: observations

$\downarrow$

inhomogeneities on "small" scales

Framework I

Metric : $ds^2 = dt^2 - a(t)^2(dx^2 + dy^2 + dz^2)$

$a(t)$: scale factor

Dynamical equations of space-time :

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

$$\dot{\rho} = -3H(\rho + p)$$

H : Hubble parameter

ρ : energy density

p : pressure

Equation of state : $p = w\rho$

e.g. radiation : $p_r = \frac{1}{3}\rho_r$

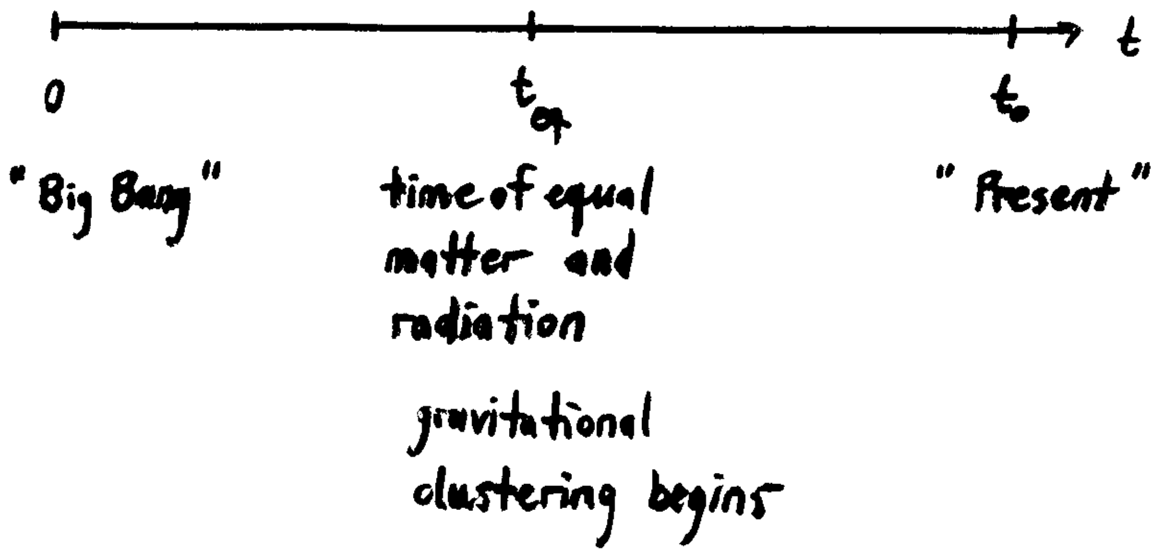
cold matter : $p_m = 0$

in cosmology : $p = p_r + p_m$

$\rho = \rho_r + \rho_m$

Framework II

FRWL cosmology, expanding Universe



$$x_p(t) = a(t)\, x_c$$

comoving distance

physical distance

scale factor

$t < t_{eq}$: $\quad p = \frac{1}{3}\rho \qquad a(t) \sim t^{1/2}$

$t > t_{eq}$: $\quad p = 0 \qquad a(t) \sim t^{2/3}$

$H \equiv \frac{\dot{a}}{a}$ Hubble expansion rate

$\;\; = h \; 100 \text{ km s}^{-1} \text{Mpc}^{-1}$

Successes of Standard Cosmology

1. Hubble expansion

$$z = H d$$

redshift distance

2. Existence of CMB

t_{rec} : time of last scattering

$t < t_{rec}$: photons in thermal equilibrium

CMB : remnant of hot early Universe

Note: $z(t_{rec}) \sim 10^3$

$z(t_{eq}) \simeq 4^{-1} h^{-2} 10^4 = h_{60}^{-2} 10^4$

3. Nucleosynthesis

abundances of light elements

$t_{NS} \sim 1$ minute

Problems of Standard Cosmology

1. Horizon problem

   observation: near isotropy of CMB $\quad \frac{\Delta T}{T} \ll 10^{-4}$

   cosmic microwave background

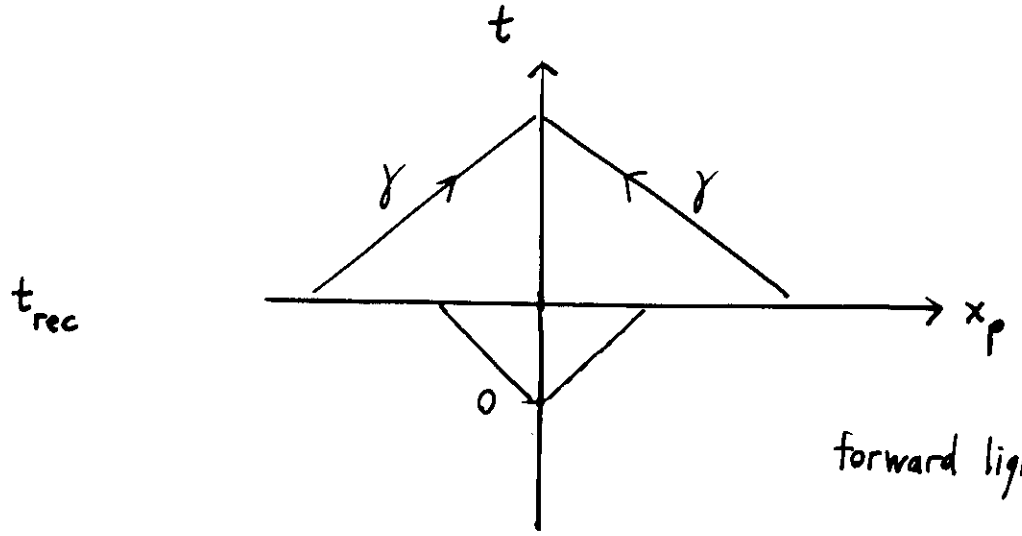
2. Flatness problem

   observation: $\Omega \equiv \frac{\rho}{\rho_c} \sim 1 \quad \{\in [0.3, 1]\}$

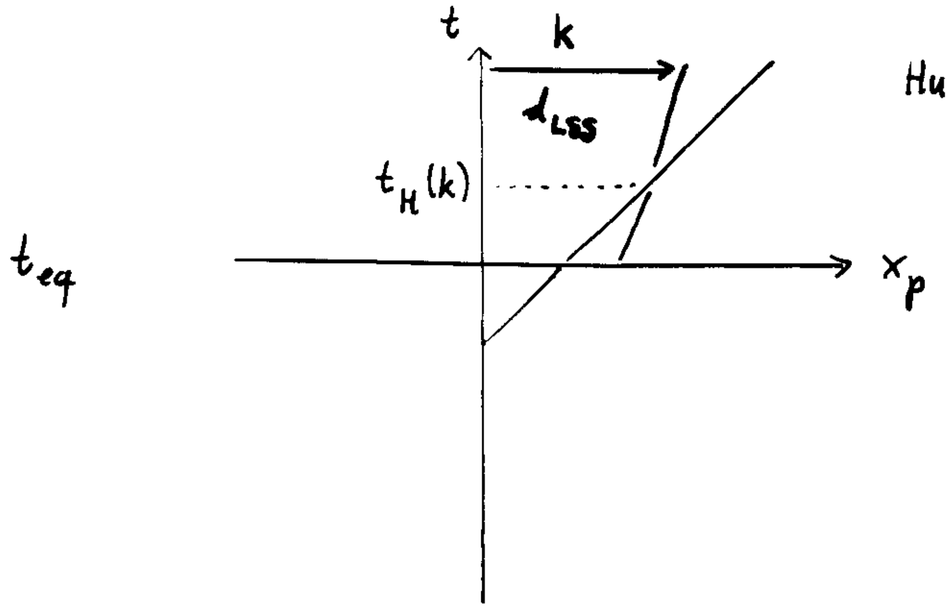
   but: $\Omega = 1$ is unstable fixed point in an expanding Universe

3. Formation of structure problem

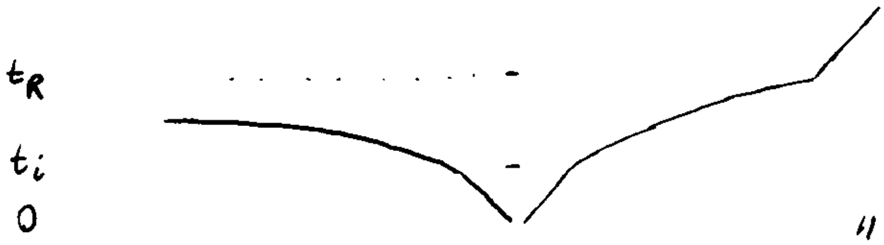
   observation: nonrandom distribution of galaxies on large scales



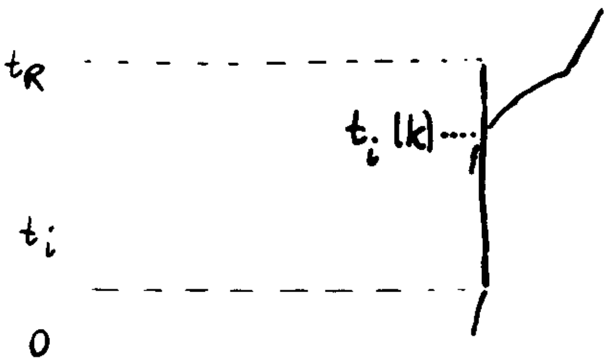
forward light cone (std. cos.)



Hubble radius (std. cos.)



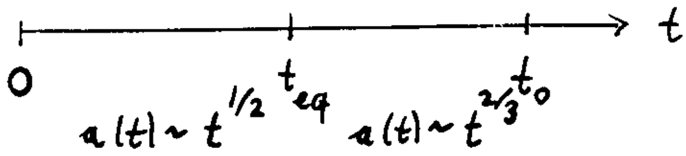
" " " (infl. cos.)



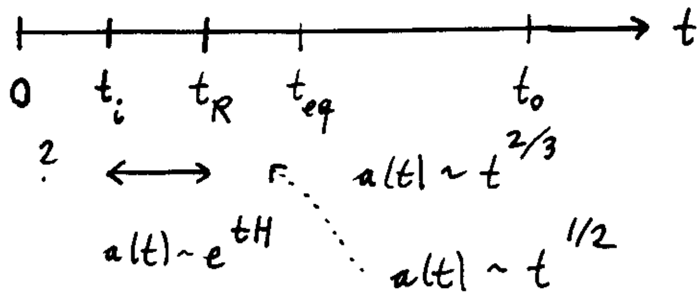
Hubble radius (infl. cos.)

1. Inflationary Universe Scenario

Idea : standard cosmology



inflationary cosmology



Success : 1. homogeneity problem

inflation explains isotropy of CMB

2. flatness problem

inflation explains why $\Omega \simeq 1$

$\Omega \equiv \rho / \rho_c$

3. formation of structure problem

inflation → mechanism for producing density fluctuations

Importance:

- 1^{st} causal theory of structure formation

  explains: distribution of galaxies

  CMB anisotropies

- specific predictions
  - scale invariant spectrum of $\delta M/M$
  - specific link between $\frac{\delta M}{M}$ & $\frac{\delta T}{T}$

- link between fundamental (high energy) physics & data

How to obtain inflation? Scalar fields!

φ : scalar field

$$\mathcal{L} = \frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - V(\varphi)$$

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

$$p = \frac{1}{2}\dot{\varphi}^2 - \frac{1}{6}a^{-2}(\nabla\varphi)^2 - V(\varphi)$$

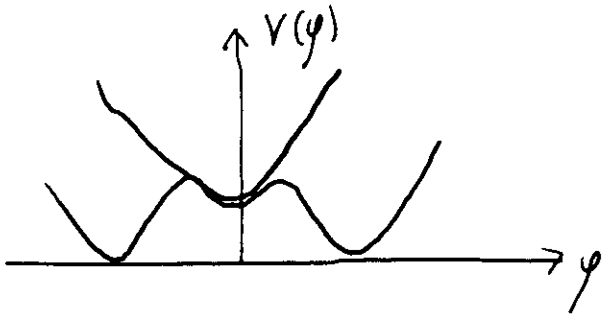
$$\dot{\varphi} = \nabla\varphi = 0 \ \ \& \ \ V(\varphi) > 0 \Rightarrow p = -\rho$$

$\Rightarrow$ inflation

How to obtain $\dot{\varphi} = \nabla\varphi = 0$, $V(\varphi) > 0$?

Idea: Spontaneous symmetry breaking

False vacuum $\rightarrow$ inflation



false vacuum : $\varphi = 0$

Why start out in false vacuum ?

Idea: Finite temperature effects !

$$V_T(\varphi) = V(\varphi) + \alpha T^2 \varphi^2$$

$\rightarrow$ symmetry restoration at large T

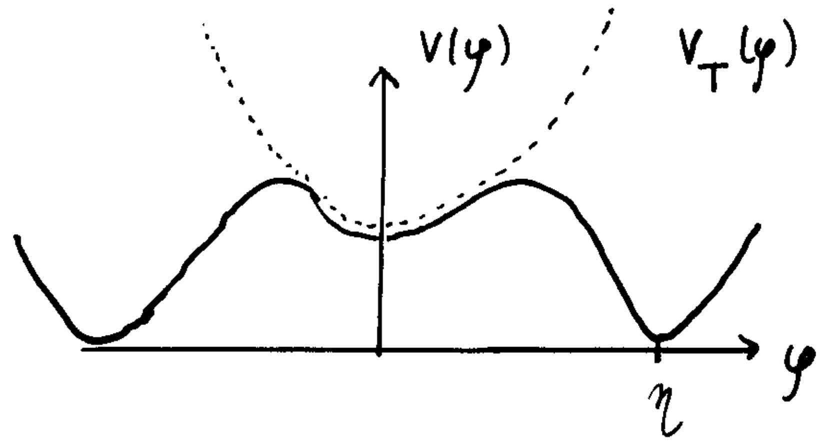
Note: $\mathcal{L} = \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\varphi)$ $\qquad T = 0$

$$S = \int d^4x \sqrt{-g}\,\mathcal{L}$$

$\downarrow$ EOM

$$\ddot{\varphi} + 3H\dot{\varphi} - a^{-2}\nabla^2\varphi = -V'(\varphi)$$

Old Inflationary Universe (Guth 1981)



$\varphi \overset{?}{=}$ Higgs

Scenario: $\varphi = 0$ metastable

$t < t_i$: universe dominated by radiation

$t > t_i$: $V(\varphi=0)$ dominates $T_{\mu\nu}$

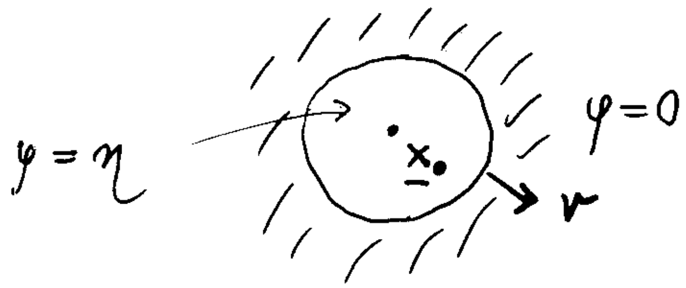
$\rightarrow$ inflation

$t = t_R$: decay of metastable state

$\varphi(\underline{x}_0) \rightarrow \eta$

$\rightarrow$ end of inflation

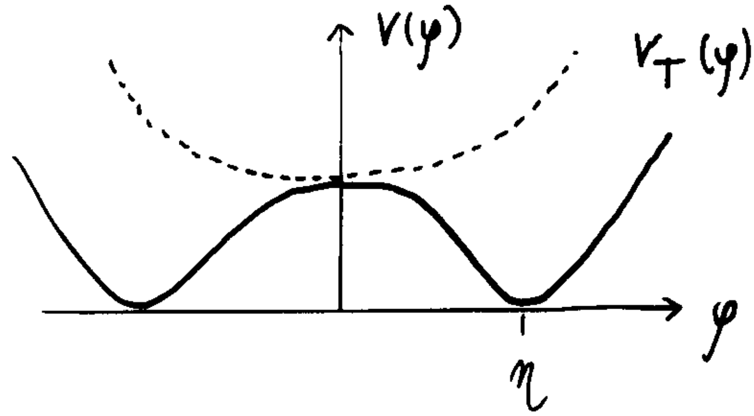
bubble nucleation



Problem: graceful exit problem

(bubbles do not percolate)

New Inflationary Universe (Linde 1982, Albrecht & Steinhardt 1982)



$\varphi \overset{?}{=}$ Higgs

Scenario: $\varphi = 0$ unstable

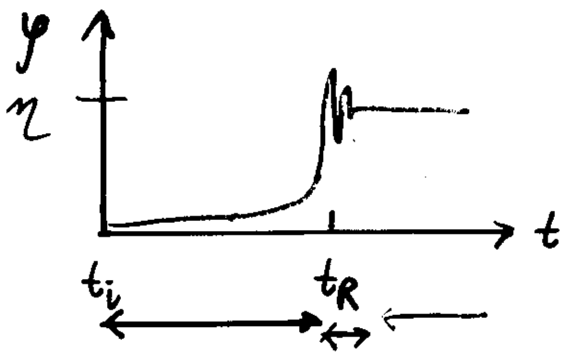
$t < t_i$: Universe radiation dominated

$t > t_i$: $V(\varphi=0)$ dominates $T_{\mu\nu}$

$\varphi(t_i) \simeq 0$ by thermal effects

Ass: slow rolling, i.e. $\dot{\varphi}^2(t_i) \ll V(\varphi(t_i))$

$\rightarrow$ inflation

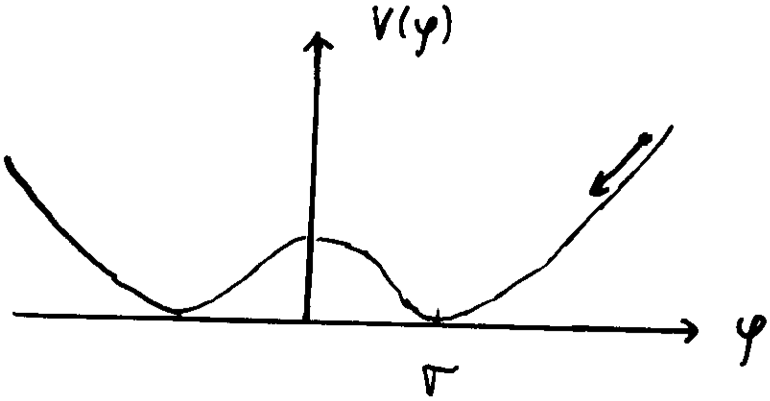


N.B. homogeneous evolution

inflation reheating standard evolution

Problem: initial conditions not justified

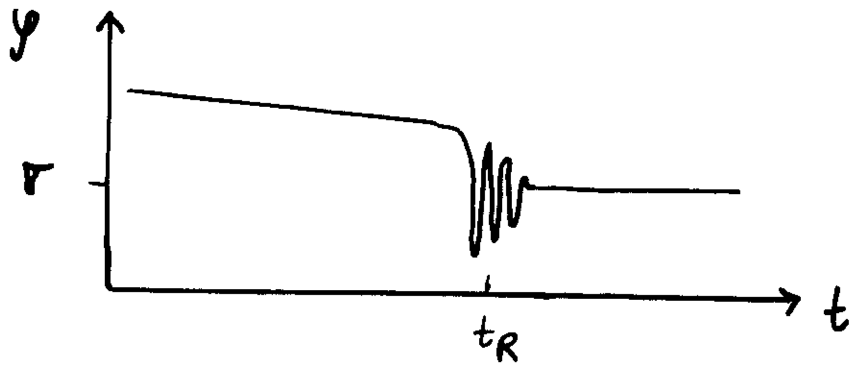
Chaotic inflationary Universe (A. Linde 1983)



$\varphi \neq$ Higgs

$$\ddot{\varphi} + 3H\dot{\varphi} - a^{-2}\nabla^2\varphi = -V'(\varphi)$$

$$V(\varphi) = \lambda(\varphi^2 - \sigma^2)^2$$



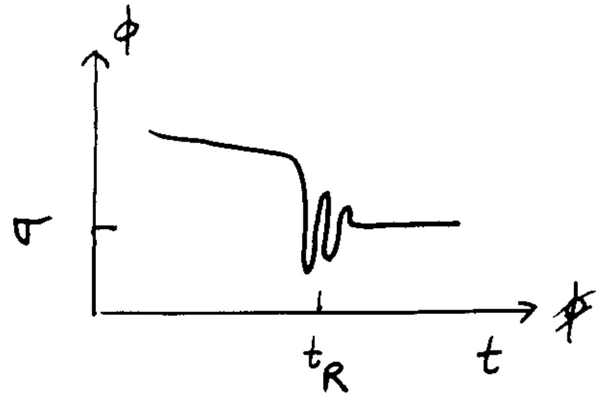
slow rolling   reheating   std. cosmolog. evol.

energy transfer

c) reheating

t_R : energy transfer scalar field → radiation / matter

Scenario:

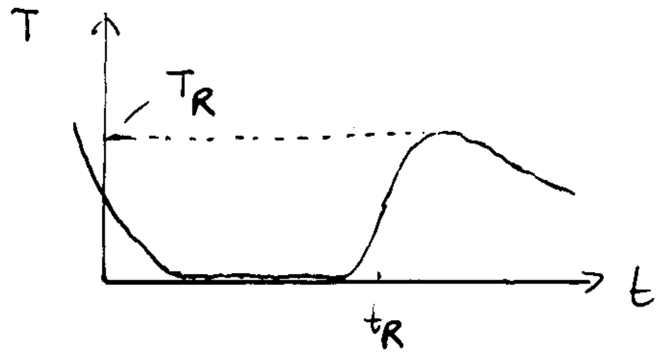


vacuum energy → oscillations of ϕ → radiation / matter

ϕ field dynamics

decay / particle production

Questions: how?
how fast?
reheating temperature?



Relevance: baryogenesis
topological defects
matter content at t_0

3. Elementary Theory of Reheating

A. Dolgov & A. Linde
L. Abbott, E. Farhi & M. Wise

Scenario: oscillation of ϕ
coherent state of $\underline{k}=0$ particles
decay
$\rightarrow$ particle production

1^{st} order perturbation theory (Born approx.)

Model: $$\mathcal{L}_0 = \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - \lambda(\phi^2-\sigma^2)^2\frac{1}{4}$$

$$\mathcal{L}_I = \frac{1}{2}g^2\phi^2\chi^2$$

change of variables: $\phi = \tilde{\phi} + \sigma$

$$\mathcal{L}_I = g^2\sigma\tilde{\phi}\chi^2 + \frac{1}{2}g^2\tilde{\phi}^2\chi^2$$

$\tilde{\phi}$: oscillates with frequency ω

$$\omega = m_{\tilde{\phi}} = \lambda^{1/2}\sigma$$

Feynman rules $\rightarrow$ Γ decay rate

$$\Gamma_B = \frac{g^4\sigma^2}{8\pi m_{\tilde{\phi}}}$$

leads to decay of $\tilde{\phi}$

$$\tilde{\phi}(t) \simeq \tilde{\phi}(t_R)\exp\left(-\frac{1}{2}\Gamma_B(t-t_R)\right)\sin(mt+\alpha)$$

effective EOM : $\ddot{\phi} + 3H\dot{\phi} + \Gamma_B \dot{\phi} = -V'(\phi) = -m^2 \phi$

reheating complete : $H = \Gamma_B$

$\Rightarrow$ reheating temperature T_R

$$H^2 = \frac{8\pi G}{3}\rho \qquad \rho = \frac{\pi^2}{30} g_* T^4$$

$$\Rightarrow T_R \sim (\Gamma_B M_p)^{1/2}$$

Result : "Naturalness" $\Rightarrow g^2 = \mathcal{O}(\lambda)$

$$\Rightarrow \Gamma_B \sim \lambda^{3/2} \sigma (8\pi)^{-1}$$

$$\Rightarrow T_R \sim \underbrace{\lambda^{3/4} (8\pi)^{-1/2}}_{\sim 10^{-9}} \underbrace{\left(\frac{\sigma}{M_{pl}}\right)^{1/2}}_{<1} M_{pl}$$

$$\Rightarrow \boxed{T_R < 10^{10}\, \text{GeV}}$$

Consequences :

no GUT scale defects

no GUT baryogenesis

if $T_R < m_{3/2} \Rightarrow$ no gravitino problem

4. Modern Theory of Reheating

R.B. & J. Traschen, PR D 42, 2491 (90)

Y. Shtanov, J. Traschen & R.B. PR D51, 5438 (95)

L. Kofman, A. Linde & A. Starobinski, PRL 73, 3195 (94)

a) Qualitative considerations

$$\mathcal{L}_I = g^2 \sigma \phi \chi^2$$

Consider EOM for χ

$$\ddot{\chi} + 3H\dot{\chi} - \left(\left(\frac{\nabla}{a}\right)^2 - m_\chi^2 - g^2\sigma\phi\right)\chi = 0$$

EOM for Fourier mode:

$$\ddot{\chi}_k + 3H\dot{\chi}_k + (m_\chi^2 + k_p^2 + g^2\sigma\phi)\chi_k = 0$$

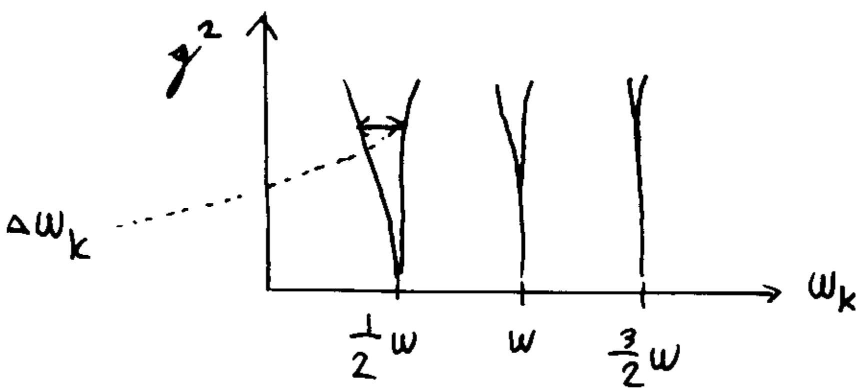
Ass: rapid reheating

→ neglect expansion of Universe

→ Mathieu equation

→ parametric resonance

→ explosive particle production



instability bands

$$\omega_k^2 = m_\chi^2 + k_p^2$$

width: $\Delta\omega_k \sim g\sigma^{1/2}\varphi_0^{1/2}$

growth: $\chi_k \sim e^{\mu t}$ $\quad \mu \sim \frac{g^2\sigma\varphi_0}{\omega}$

N.B. no divergence since amount of time a mode is in band finite

particle production : $\dot{\rho} \sim \mu\, \omega_{res}^2\, \Delta\omega_k\, H\, e^{\mu t}$

using initial condition for χ_k

$\chi_k(t_R) \sim H$

justification: quantum zero point value

$\dot{\rho}/\rho = \Gamma$

resonance criterium: $\mu H^{-1} \gg 1$

If $\mu H^{-1} \gg 1$ then $\Gamma \gg \Gamma_B$

b) Improved analysis (Y. Shtanov, J. Traschen & R.B.)
(L. Kofman, A. Linde, A. Starobinsky)

- exact solution for background evolution
- reduction of mode equation to Mathieu eq.
- no need for artificial initial conditions

  χ quantized
  in background classical ϕ field
  QFT in curved background
  Bogoliubov mode mixing techique
- back reaction: included at energetic level

background evolution

$$V(\phi) = \lambda \mu^{4-q} |\phi|^q$$

turn-over scale $\phi_c^2 = \frac{q^2}{24\pi} M_{pl}^2$

$\phi > \phi_c$: slow rolling

$\phi < \phi_c$: quasi-periodic oscillations

$$\phi(t) = \phi_c(t) \cos \int W(t)\, dt$$

$$W \simeq \left(\frac{2[\rho - V(\phi)]}{\phi_0^2 - \phi^2} \right)^{1/2}$$

$p = \frac{q-2}{q+2} \rho$ equation of state during quasi-periodic oscillations

Mode equation :

$$L_{int} = -(\sigma\phi + h\phi^2)\chi^2$$

$$\ddot{\chi}_k + 3H\dot{\chi}_k + \left(m_\chi^2 + \left(\frac{k}{a}\right)^2 + 2\sigma\varphi + 2h\phi^2\right)\chi_k = 0$$

$$Y_k = a^{3/2}\chi_k$$

$$\ddot{Y}_k + [\omega_k^2(t) + g(\omega t)]\,Y_k = 0$$

$$\omega_k^2(t) = \left(\frac{k}{a}\right)^2 + m_\chi^2 - \frac{9}{4}H^2 - \frac{3}{2}\dot{H} + 2h\bar{\phi}^2$$

where $\bar{\phi}^2$ = average of ϕ^2 over rapid oscillations

$$g(\omega t) = 2\sigma\phi + 2h(\phi^2 - \bar{\phi}^2)$$

a $\frac{2\pi}{\omega}$ periodic fct. in t

leading freq.: ω, 2ω

focus on leading frequency

Resonance bands

$$\omega_k^2 - \left(\frac{1}{2}\omega\right)^2 = \Delta \lesssim g$$

$$\omega = \frac{\sqrt{\rho}}{\varphi_0}$$

N.B. both ω_k & ω are in general t dependent

c) Parametric resonance

classical analysis

$$\ddot{Y}_k + \left[\omega_k^2 + \varepsilon g(\omega t)\right] Y_k = 0$$

$$g(\omega t) = g\cos(\omega t + \alpha)$$

$$\omega_k^2 = \left(\tfrac{1}{2}\omega\right)^2 + \varepsilon\Delta$$

Ansatz: $y = a\cos\psi + \varepsilon\cdot\text{periodic}$ $\left[\psi = \omega t + \vartheta\right]$

insert into mode equation

$$\Rightarrow \quad \ddot{a}(t) \sim \left(\frac{\varepsilon}{\omega}\sqrt{g^2-\Delta^2}\right)^2 a(t)$$

→ exponential growth with rate μ

$$\mu = \frac{\varepsilon}{\omega}\sqrt{g^2-\Delta^2}$$

semiclassical analysis (Bogoliubov)

$$\mathcal{H}_k = \frac{1}{2}\left[P_k^2 + \Omega_k^2(t)\, Q_k^2\right]$$

Find time dependent basis of creation & annihilation operators

$$a(t) = \alpha(t)\, a_0 + \beta^*(t)\, a_0^+$$

$$a^+(t) = \beta(t)\, a_0 + \alpha^*(t)\, a_0^+$$

$$|\alpha(0)| = 1 \qquad \beta(0) = 0$$

$\rightarrow \quad N(t) = |\beta(t)|^2$ # of particles at time t in initial vacuum state

$\chi(t)$ satisfies Mathieu equation

$\Rightarrow$ classical parametric resonance

$$\Rightarrow \underline{|\beta_k|^2} = N_k \simeq \boxed{\sinh^2 \int \mu\, dt}$$

d) Application

$$V(\phi) = \frac{1}{2} m^2 \phi^2$$

$$\omega = m$$

$$\omega_{res} = \frac{1}{2} m$$

$$\Delta \omega_k = \omega_k - \omega_{res}$$

general equation for energy gain of χ :

$$\dot{\rho}_\chi = \omega_{res}\, N_{res}\, \underbrace{\frac{\omega_{res}^2}{2\pi^2} \frac{d\,\Delta\omega_k}{dt}}\Big|_{\Delta\omega_k = 0}$$

energy per particle

# of particles in the mode produced by the time the mode has passed outside band

rate at which modes enter resonance band

$$N_{res} \simeq \sinh^2(\mu\, \Delta t)$$

time in band

Evaluation :

$$N_{res} \simeq \sinh^2\left(\frac{\pi}{8}\,\frac{g^2}{H\,\omega_{res}^3}\right)$$

using $\dfrac{d\,\Delta\omega_k}{dt} = H\,\omega_{res}$

Parametric resonance condition :

$$\frac{g^4 \sigma^2 \varphi_0^2}{\omega_{res}^3\, H} \gg 1$$

(after replacing the general $g(\omega t)$ by the expression for our $V(\phi)$)

Express H in terms of φ_0, M_{pl}

" $\omega_{res} \simeq m$ in terms of σ

Criterium : $\dfrac{\varphi_0 M_{pl}}{\sigma^2} > 1$ o.k.

N.B. similar to condition obtained from heuristic parametric resonance analysis

5. Discussion

a) Reheating in inflationary cosmology

$T_R \gg T_R^{Born}$

$T_R \sim 10^{17}$ GeV possible

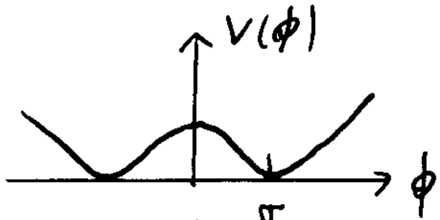
$\Rightarrow T_R > T_{GUT}$ "

$\Rightarrow$ defects after inflation

GUT baryogenesis

b) State after "pre-heating" : nonthermal

$\Rightarrow$ large fluctuations



$\lambda m_{pl}^4 \sim \omega^2 \varphi_k^2 = \lambda \sigma^2 \varphi_k^2$

$\Rightarrow \varphi_k \sim \frac{m_{pl}}{\sigma} m_{pl}$

vs. thermal flucts.: $T_R \sim \lambda^{1/4} m_{pl}$

$\Delta\varphi_{th} \sim \lambda^{1/4} m_{pl}$

$\Rightarrow$ symmetry restoration ?

nonthermal production of topol. defects ?

(L. Kofman, A. Linde & A. Starobinsky 1996)

c) New form of dark matter

$$\frac{\sigma^2 \varphi_0^2}{m^3 H} = 1 \quad \Rightarrow \text{ decoupling of } \phi$$

remnant coherent ϕ oscillations

$\Rightarrow$ dark matter

$$\left.\begin{aligned} \rho_\phi &= \frac{1}{2}\varphi_0^2 m^2 \\ \rho_{rad} &\sim M_{pl}^2 H^2 \end{aligned}\right\} \text{ at decoupling}$$

$$\left.\frac{\rho_\phi}{\rho_{rad}}\right|_{T_{eq}} = \left.\left(\frac{T}{T_{eq}}\frac{\rho_\phi}{\rho_{rad}}\right)\right|_{decoupling}$$

$$\sim \frac{(HM_{pl})^{1/2}}{T_{eq}} \frac{\lambda}{2} \frac{m^3}{HM_{pl}^2} \sim \lambda \frac{m}{T_{eq}} \frac{m}{M_{pl}} \frac{m}{(HM_{pl})^{1/2}}$$

$$\sim 1$$

d) Other applications:

moduli field cosmology

parametric resonance $\Rightarrow$ moduli decay

axions in cosmology

parametric resonance $\Rightarrow$ loss of coherence

$\Rightarrow p \neq 0$

e) Future work

study thermalization

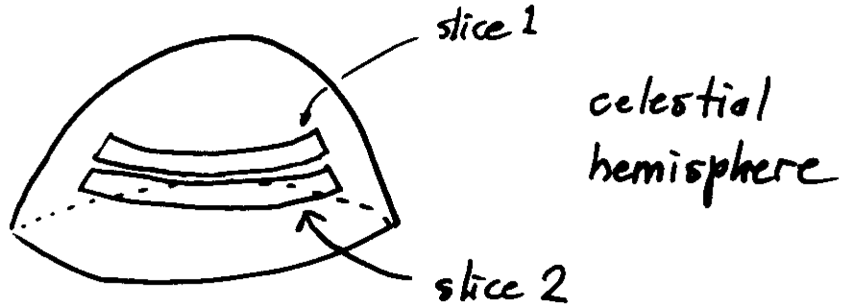
Methods for quantifying inhomogeneities :

1. Power spectrum

$$\bar{\rho}^{-1} \rho(\underline{x}) = \int d^3k \, e^{i\underline{k}\cdot\underline{x}} \delta_{\underline{k}} \frac{V}{(2\pi)^3}$$

$$P(k) = \langle |\delta_k|^2 \rangle$$

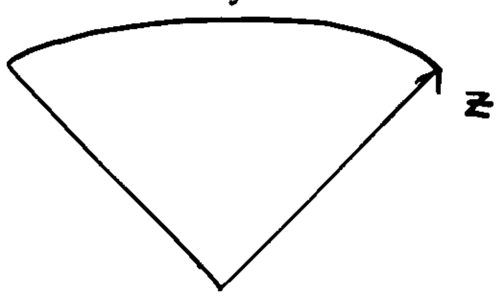
2. Systematic redshift surveys



measure redshifts of all galaxies in slice

$\downarrow$

cone diagrams



Power Spectrum

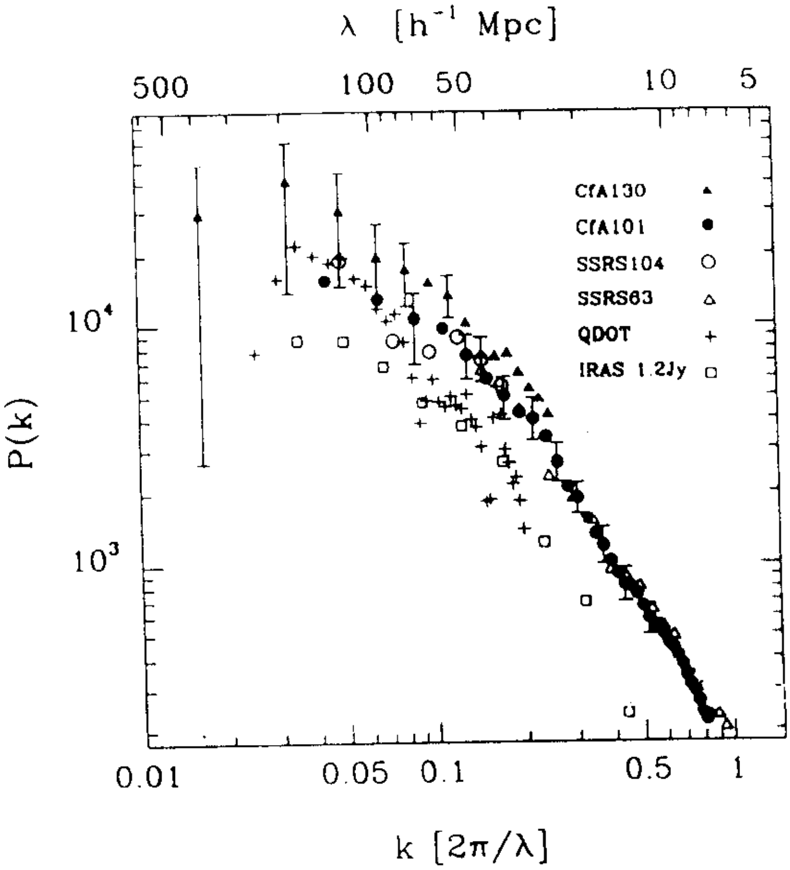
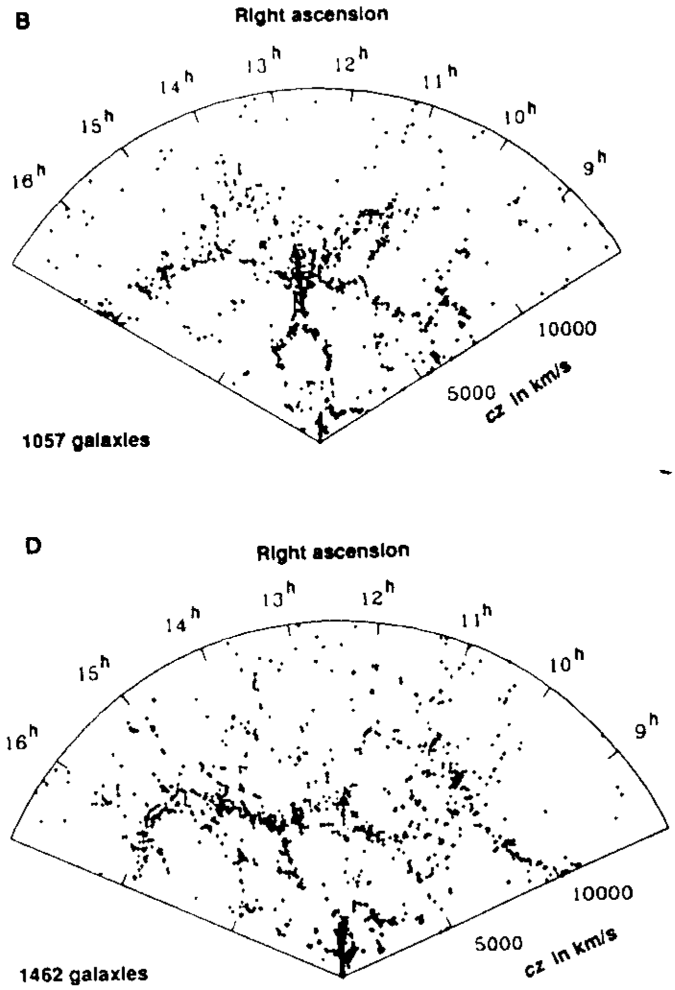


FIG. 9.—Comparison of the PS of the CfA130 (*filled triangles*) and CfA101 (*filled circles*) samples with the PS for diameter-limited SSRS104 (*open circles*) and SSRS63 (*open triangles*) samples, the *IRAS* QDOT survey (*stars*), and the *IRAS* 1.2 Jy survey (*open squares*). The PS for optical-galaxy samples (CfA and SSRS) agree quite well. The *IRAS* 1.2 Jy PS has similar shape to the PS of optical galaxies, but has smaller amplitude The QDOT PS is steeper than the other PS, with an apparent turnover on large scales.

C. Park et al. Ap. J. 431, 569 (94)



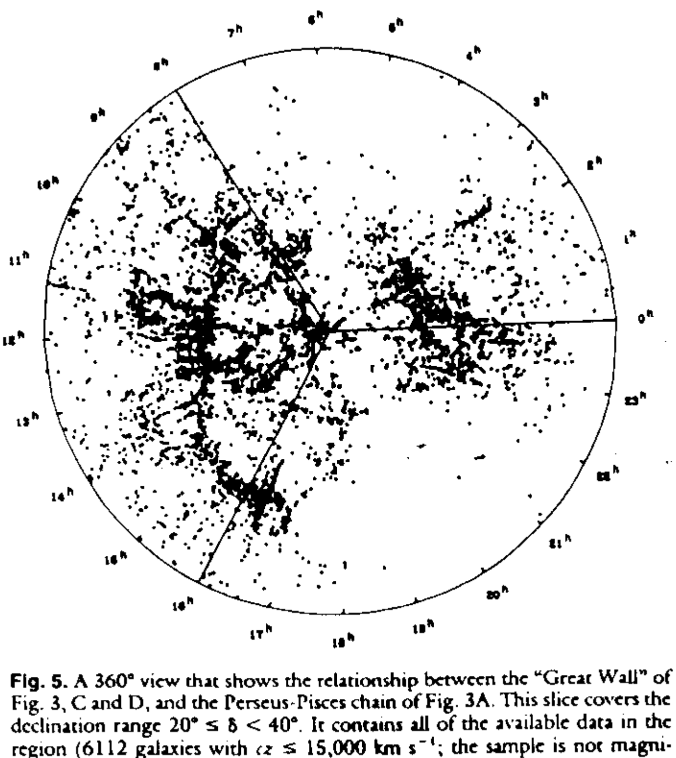


Fig. 5. A 360° view that shows the relationship between the "Great Wall" of Fig. 3, C and D, and the Perseus-Pisces chain of Fig. 3A. This slice covers the declination range $20° \leq \delta < 40°$. It contains all of the available data in the region (6112 galaxies with $cz \leq 15{,}000$ km s^{-1}; the sample is not magnitude limited). The blank regions are obscured by the galactic plane.

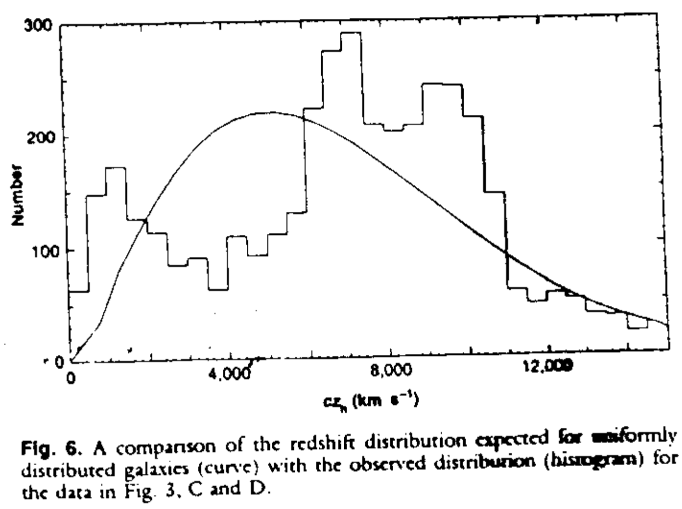
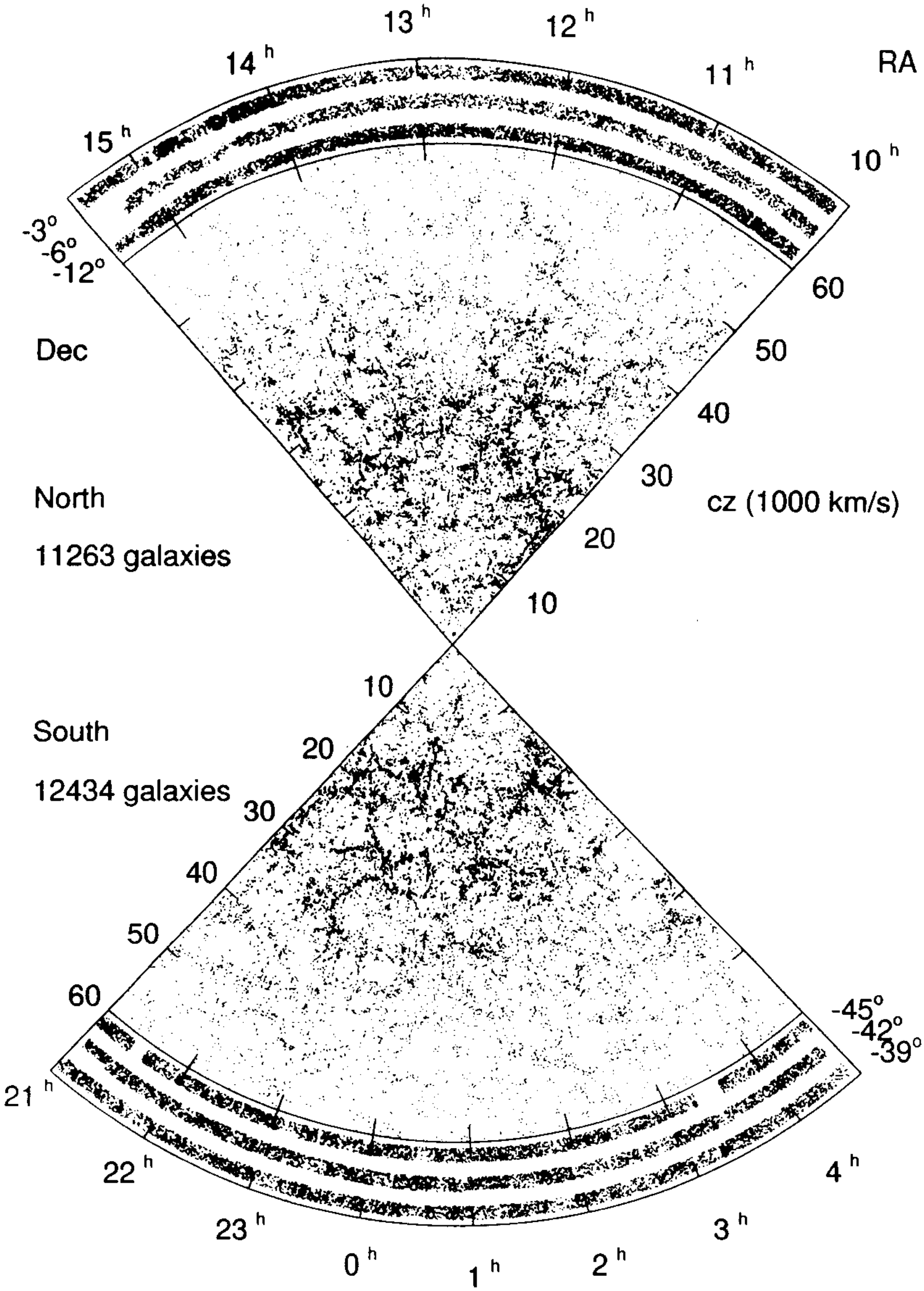


Fig. 6. A comparison of the redshift distribution expected for uniformly distributed galaxies (curve) with the observed distribution (histogram) for the data in Fig. 3, C and D.

M. Geller & J. Huchra, Science
246, 897 (89)



RA
13 h
12 h
14 h
11 h
15 h
10 h
-3°
-6°
-12°
Dec
North
11263 galaxies
60
50
40
30
20
10
cz (1000 km/s)
South
12434 galaxies
-45°
-42°
-39°
21 h
22 h
23 h
0 h
1 h
2 h
3 h
4 h

LCRS (96)

Questions

1. Origin of correlations of galaxy positions.

2. Topology of Large-Scale Structure
   (sheets ?)

3. Distinguished scale for large-scale structure
   ($50 h^{-1}$ Mpc ?)

Basic Reading

- T. Padmanabhan — Structure Formation in the Universe, Cambridge Univ. Press, 1993
- P. J. E. Peebles — Principles of Physical Cosmology, Princeton Univ. Press, 1993

A. Linde — Particle Physics & Inflationary Cosmology, Harwood 1990

A. Vilenkin & E.P.S. Shellard — Cosmic Strings & Other Topol. Defects, Cambridge Univ. Press, 1994

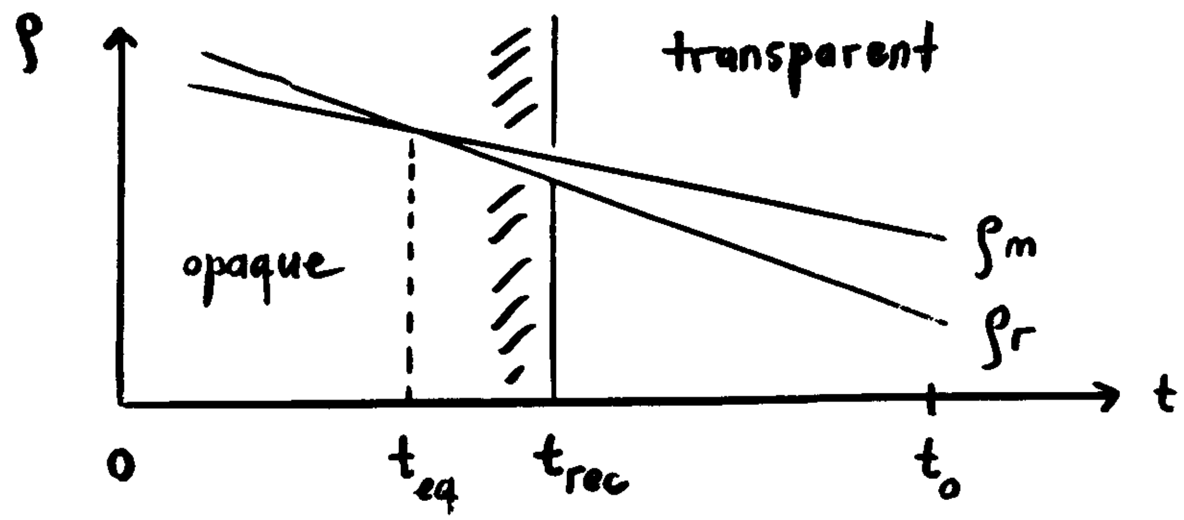
G. Börner — The Early Universe, Springer, 1988

E. Kolb & M. Turner — The Early Universe, Addison-Wesley, 1990

R. Brandenberger — Modern Cosmology & Structure Formation, BROWN-HET-964 1994

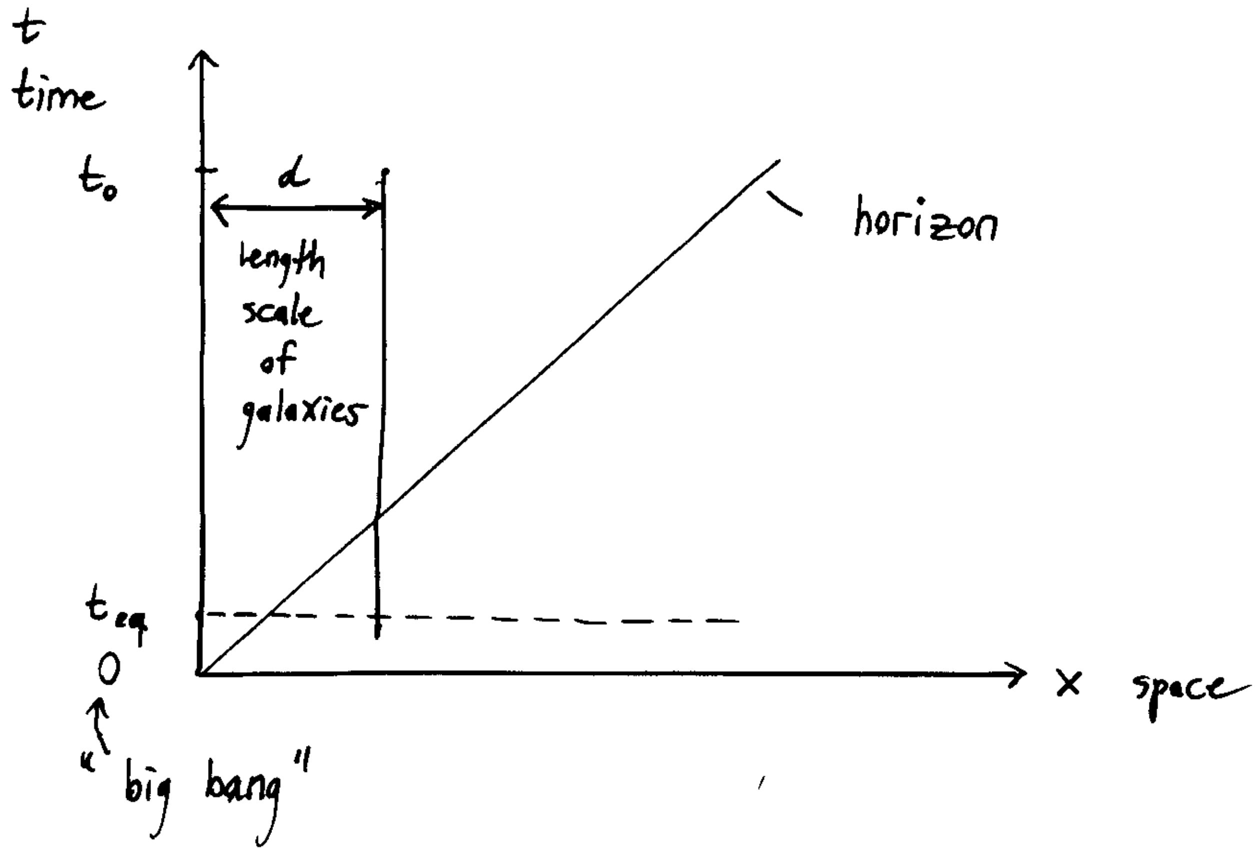
1. Introduction

Standard Big Bang Cosmology



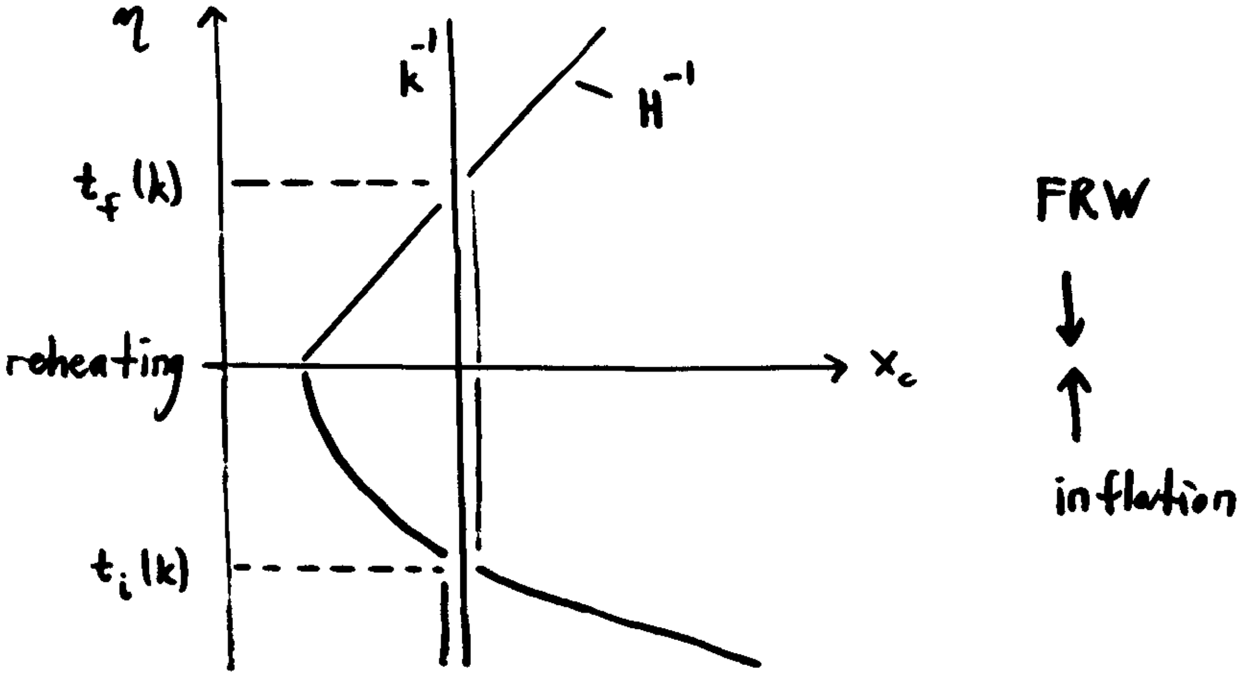
radiation dominated	matter dominated
$a(t) \sim t^{1/2}$	$a(t) \sim t^{2/3}$
perturbations frozen	perturbations grow

Formation of Structure Problem



Problem: No mechanism obeying the principles of physics (causality) exists which can produce nonrandom distribution of seeds at early times.

Issues :

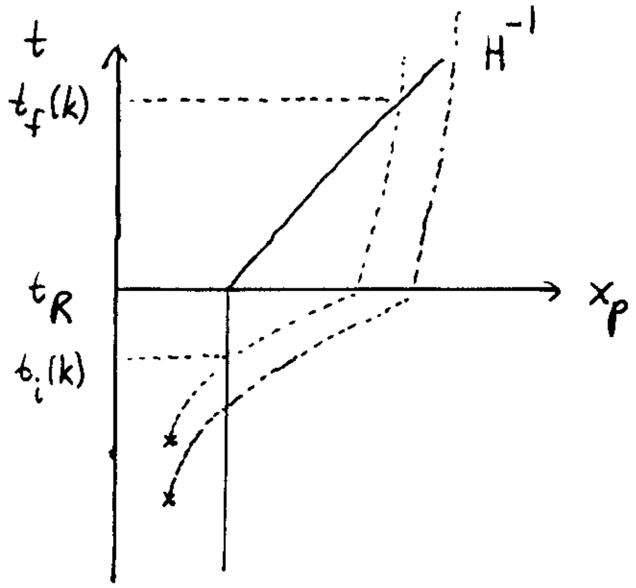


k wave number of fluctuation

H^{-1} Hubble radius

1. classical evolution of perturbation
2. quantum generation " "
3. quantum → classical transition

First Prediction from Inflation :



$$\frac{\delta M}{M}(k, t_i(k)) = \text{const}$$

$$\Rightarrow \frac{\delta M}{M}(k, t_f(k)) = \text{const}'$$

scale invariant (Harrison-Zel'dovich) spectrum

$$\Leftrightarrow \underline{P(k) \sim k} \qquad \text{(primordial spectrum)}$$