Four lectures on

COSMOLOGY

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Lecture 1: The large picture

observations, cosmological principle, Friedmann model, Hubble diagram, thermal history

Lecture 2: From quantum to classical

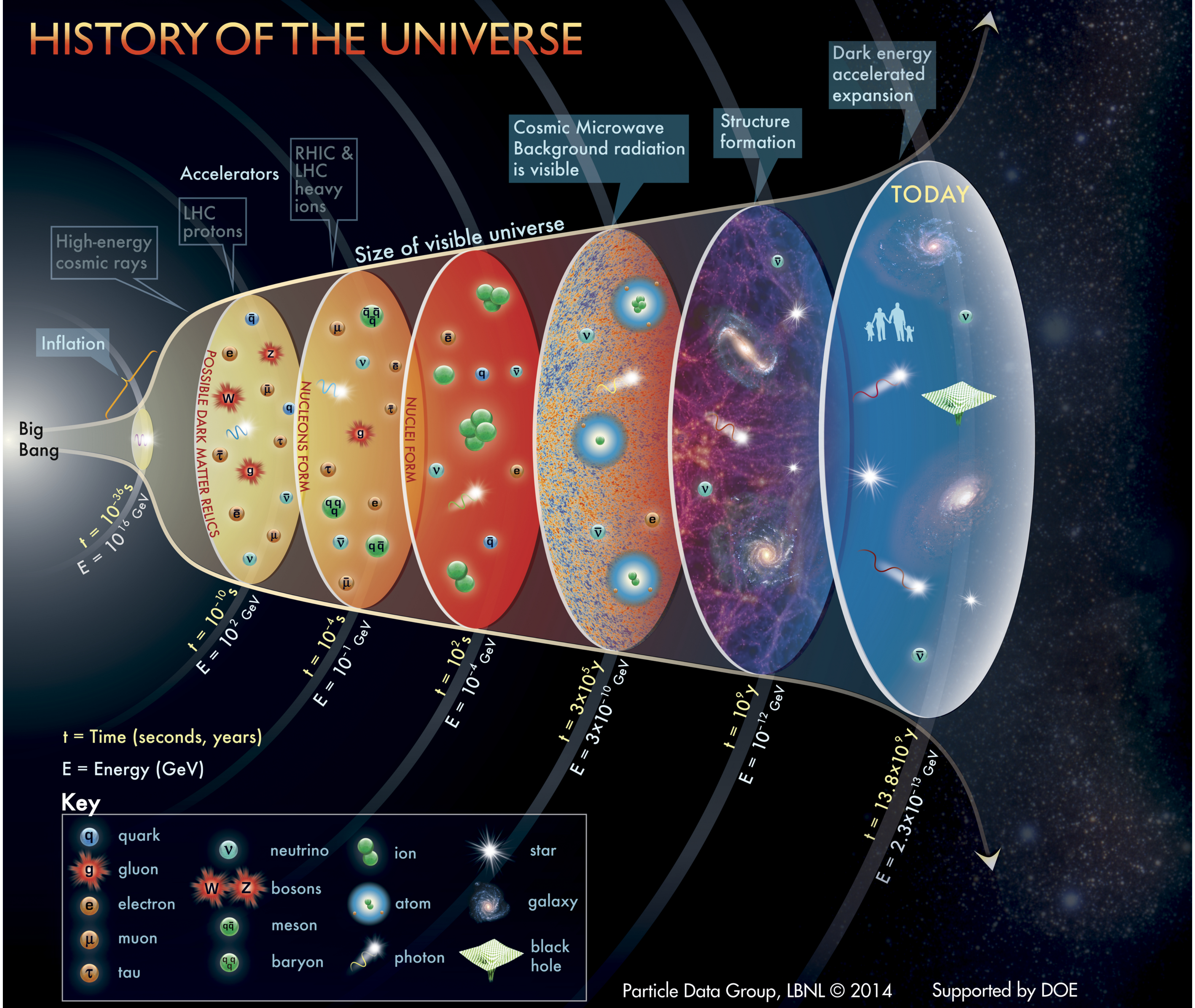
cosmological inflation, isotropy & homogeneity, causality, flatness, metric & matter fluctuations

Lecture 3: Hot big bang

radiation domination, hot phase transitions, relics, nucleosythesis, cosmic microwave radiation

Lecture 4: Cosmic structure

primary and secondary cmb fluctuations, large scale structure, gravitational instability



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^{-36} s
E = 10^{16} GeV
t = 10^{-10} s
E = 10^{2} GeV
t = 10^{-4} s
E = 10^{-1} GeV
t = 10^{2} s
E = 10^{-4} GeV
t = $3x10^{5}$ y
E = $3x10^{-10}$ GeV
t = 10^{9} y
E = 10^{-12} GeV
t = $13.8x10^{9}$ y
E = $2.3x10^{-13}$ GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
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Shortcomings of ΛCDM model

observed, but not explained:

- isotropy and homogeneity

- spatial flatness

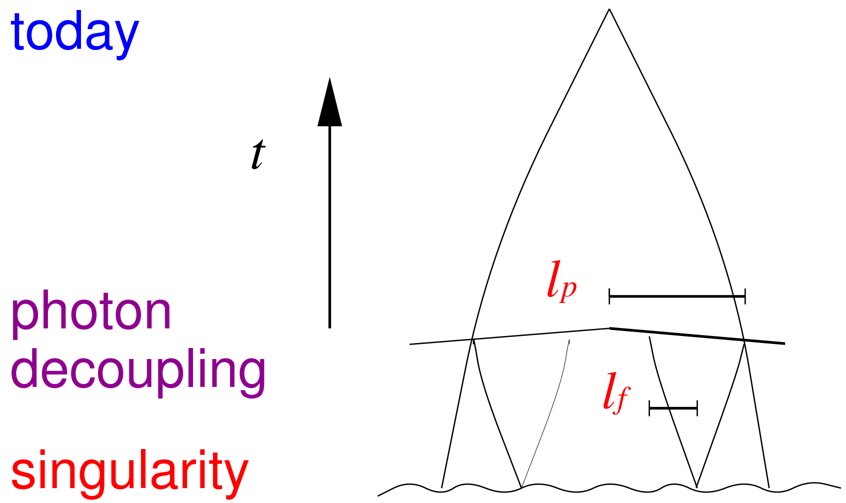
- $\Omega_\Lambda \sim \Omega_m$ today

Horizon problem

$\ell_p(t)$ past causal horizon
$\ell_f(t)$ future causal horizon

$$(\ell_p/\ell_f)(z_{\text{dec}}) \simeq \sqrt{z_{\text{dec}}} \gg 1 \quad (z_{\text{dec}} \simeq 1100)$$

10^3 causally disconnected patches have the same temperature. Why?



Flatness problem

Why is $|1 - \Omega_0| = \mathcal{O}(10^{-3})$?

$$|1 - \Omega(z)| = |1 - \Omega_0| \begin{cases} (1+z)^{-1} & \text{matter dominated} \\ (1+z)^{-2} & \text{radiation dominated} \end{cases}$$

$$\Rightarrow |1 - \Omega(z_{\rm dec})| = \mathcal{O}(10^{-6}) \ , \quad |1 - \Omega(z_{\rm GUT})| = \mathcal{O}(10^{-57}) \ \ (z_{\rm GUT} \sim 10^{29})$$

Singularity problem

singularity $(a \to 0; \epsilon \to M_{\mathrm{P}}^4)$ exists, if $\epsilon + 3p > 0$

(strong energy condition; satisfied in matter and radiation dominated universe)

proof: $\ddot{a} < 0$ from

$$-3\frac{\ddot{a}}{a} = 4\pi G(\epsilon + 3p) \qquad \text{(equation of geodesic deviation)}$$

if $\epsilon + 3p > 0$. Thus, $a \to 0$ for $t \ll t_0$. •

N.B. today's cosmological constant cannot change this conclusion

Is quantum-gravity necessary to solve the problems above?

Cosmological inflation

epoch of accelerated expansion in the very early Universe

Brout, Englert & Gunzig 1978; Starobinsky 1979; Guth 1980

$$\ddot{a} > 0 \qquad \Leftrightarrow \qquad \epsilon + 3p < 0$$

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

number of e-foldings: $N \equiv \ln \frac{a}{a_{\rm i}} = \int_{t_{\rm i}}^{t} H \mathrm{d}t$

Vacuum energy

ϵ of vacuum is constant, thus

$$\mathrm{d}U = \epsilon \mathrm{d}V = -p\mathrm{d}V \Rightarrow p = -\epsilon$$

equivalent to cosmological constant $\Lambda \equiv 8\pi G \epsilon_{\mathrm{v}}$

from $\ddot{a} - \frac{\Lambda}{3} a = 0$ and $\dot{a}_{\mathrm{i}} > 0$ follows

$$a(t) = a_{\mathrm{i}} \exp\left[\sqrt{\frac{\Lambda}{3}}(t - t_{\mathrm{i}})\right]$$

exponential growth

$H_{\mathrm{inf}} \approx \sqrt{\Lambda/3}$

$N = \sqrt{\Lambda/3}(t - t_{\mathrm{i}}) \sim (m_{\mathrm{inf}}/m_{\mathrm{Pl}})^2 (t/t_{\mathrm{Pl}}) \gg 1$ typically

Causality and flatness

horizon problem is solved:

$\ell_p/\ell_f \sim z_{\mathrm{GUT}} \exp(-N) \ll 1$

if $N \equiv H_{\mathrm{inf}} \Delta t > 65$

flatness problem disappears:

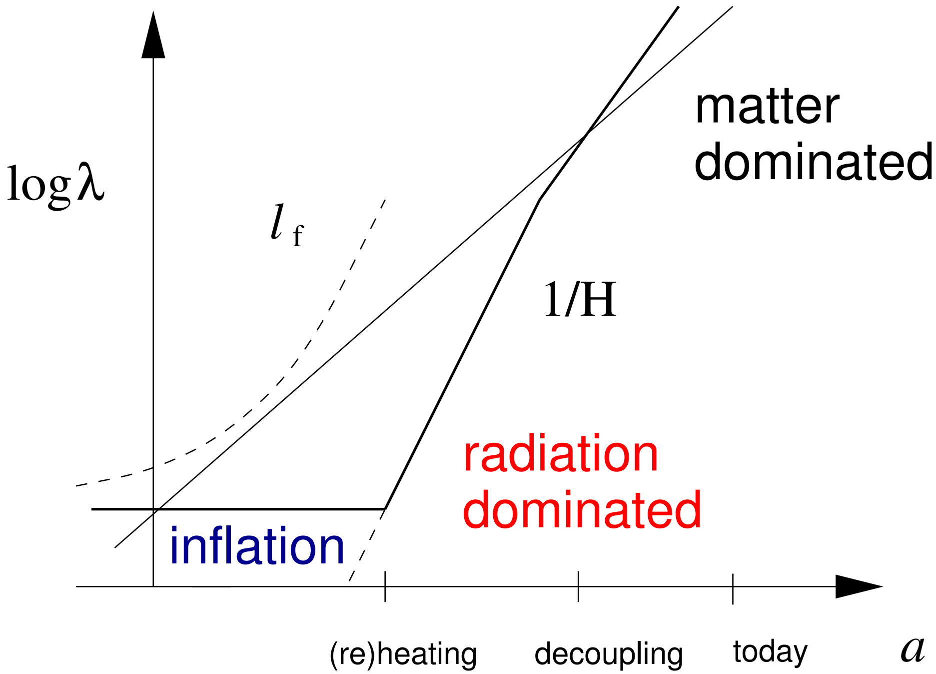
during inflation

$|1 - \Omega(t)| \propto \exp(-2H_{\mathrm{inf}} t)$

after inflation

$\Omega = 1 + \mathcal{O}(\exp[-2N])$

if inflation lasts for
at least 65 e-foldings



prediction 1: spatially flat Universe; $\Omega_0 = 1$

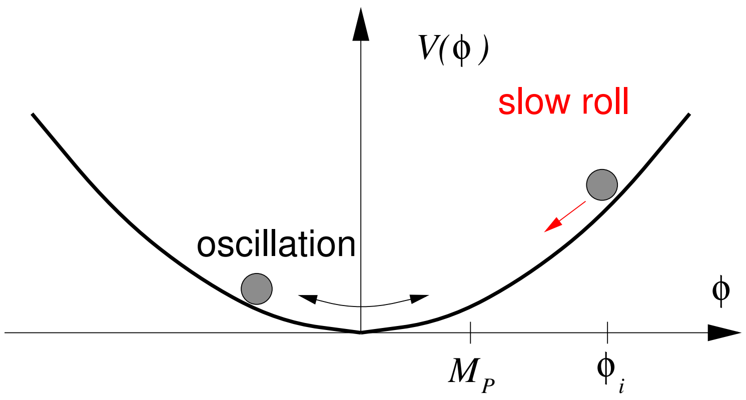
Inflation: Scenarios — History

Starobinskii 1979	R^2-inflation (quantum gravity corrections)
Guth 1980	old inflation (first order GUT transition)
	never stops, because bubbles do not merge
Linde 1982	new inflation (flat potential, slow roll)
Albrecht & Steinhardt 1982	needs special initial conditions
Linde 1983	chaotic inflation (slow roll)
	arbitrary $V(\varphi)$, random initial conditions $\varphi_i, \dot{\varphi}_i$
La & Steinhardt 1989	(hyper-)extended inflation (two scalar fields)
Linde 1993	hybrid inflation (two scalar fields)
...	

Chaotic inflation: slow roll   Linde 1983

simple example $V = \lambda\varphi^4/4,\ \lambda \ll 1$

a single scale: $M_{\rm P} \sim 10^{19}$GeV



equations of motion:

$$H^2 = \frac{8\pi}{3M_{\rm P}^2}(\frac{1}{2}\dot{\varphi}^2 + V)$$

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

generic initial conditions

at $t \sim t_{\rm P}$: $\dot{\varphi}_i^2 \sim M_{\rm P}^4$ and $V(\varphi_i) \sim M_{\rm P}^4 \Rightarrow$ $\varphi_i \sim \lambda^{-1/4} M_{\rm P} \gg M_{\rm P}$

slow roll: motion of φ is slowed down quickly by the Hubble drag ($H\dot{\varphi} \gg V_{,\varphi}$)

$\Rightarrow \frac{1}{2}\dot{\varphi}^2 \ll V$ and $\ddot{\varphi} \ll -3H\dot{\varphi}$ $\quad\Rightarrow a(t) \propto \exp(H[\varphi(t)]t)$

with $H(\varphi) \simeq [8\pi V(\varphi)/3M_{\rm P}^2]^{1/2}$ and $\varphi(t) \simeq \varphi_i \exp[-(\lambda/6\pi)^{1/2} t M_{\rm P}]$

Beyond Einstein

general relativity is incomplete at Planck scale

add higher order terms R^2, $R^{\mu\nu}R_{\mu\nu}$, etc. e.g. Starobinskii 1979

$$\mathcal{L} = \sqrt{-g}(\frac{m_{\mathsf{Pl}}^2}{2}R + \alpha R^2)$$

can be mapped on a scalar-tensor theory

add non-minimal coupling terms e.g. Bezrukov & Shaposhnikov 2008

$$\mathcal{L} = \sqrt{-g}\left[\frac{m_{\mathsf{Pl}}^2 + \xi\phi^2}{2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{\lambda}{4}\left(\phi^2 - v^2\right)^2\right]$$

conformal transformation to Einstein frame

a lot of space for models and speculations

Chaotic inflation: end and heating

Dolgov & Linde 1982; Abbott, Fahri & Wise 1982

inflation terminates at $\varphi \sim M_{\mathrm{P}}$: φ oscillates around its minimum

coherent oscillations decay into other particles

e.g. Yukawa coupling $\frac{1}{2}g^2 v\varphi\chi^2$ to a bosonic particle χ

$$\ddot{\chi}_k + 3H\dot{\chi}_k + [k_{\mathrm{ph}}^2 + m_\chi^2 + g^2 v\varphi(t)]\chi_k = 0$$

might be very efficient due to parametric resonance $\chi_k \sim \exp(\mu t)$

Traschen & Brandenberger 1990; Kofman, Linde & Starobinskii 1994

these decays produce entropy and (re)heat the Universe to T_{rh}

T_{rh} should be high enough to allow baryo-/leptogenesis

(in any case $T_{\mathrm{rh}} > T_{\mathrm{nuc}}$, i.e. 10 MeV to allow for standard BBN)

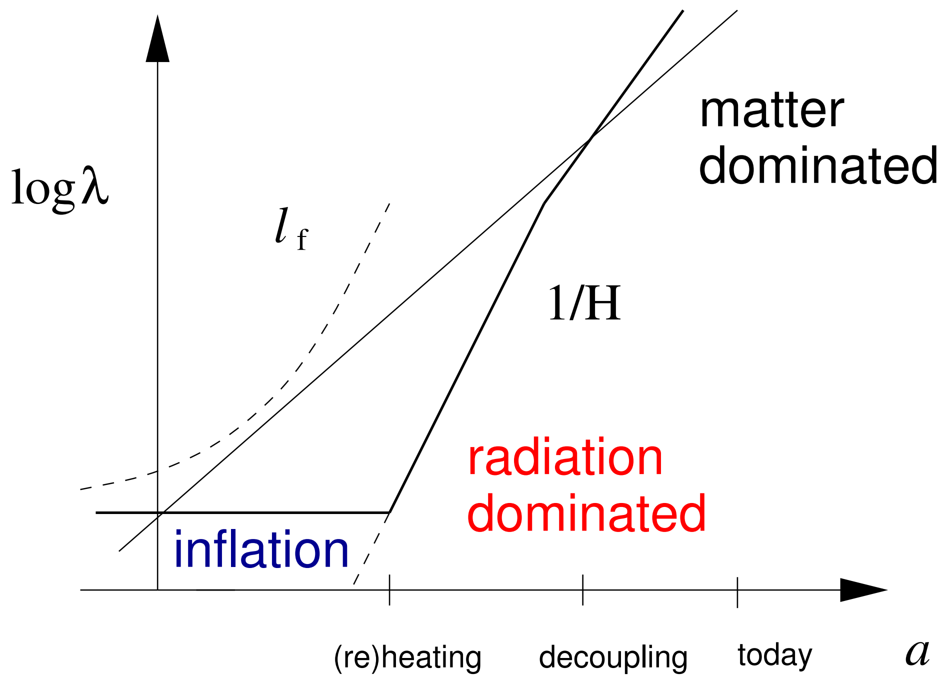
Kinematic considerations

(quantum) fluctuations of energy density and metric

Fourier modes $k = 2\pi/\lambda$

$\lambda_{\text{ph}} \equiv a\lambda$

$\lambda_{\text{ph}} \ll 1/H$ locally Minkowski
$\lambda_{\text{ph}} \gg 1/H$ no causal physics



Structure formation: quantum fluctuations

accelerated expansion provides energy to produce classical fluctuations from vacuum fluctuations

$$\hat{\varphi}(\eta,\vec{x}) = \frac{1}{a}\int \frac{\mathrm{d}^3k}{(2\pi)^{3/2}}\frac{1}{\sqrt{2k}}[\hat{c}_k f_k(\eta)\exp(\imath\vec{k}\vec{x}) + \mathrm{h.c.}]$$

with $\hat{c}_k|0\rangle = 0$ and $[\hat{c}_k, \hat{c}^\dagger_{k'}] = \delta(\vec{k}-\vec{k}')$ [$\eta \equiv \int \mathrm{d}t/a(t)$ conformal time]

$$f_k'' + (k^2 - \frac{a''}{a})f_k = 0$$

subhorizon scales $k_{\mathrm{ph}} \equiv k/a \gg H$: harmonic oscillator
superhorizon scales $k_{\mathrm{ph}} \ll H$: $f_k \simeq a$ rapid amplification of fluctuations

rms amplitude at the moment $k_{\mathrm{ph}} = H$: $\delta\varphi(k=H) \simeq \frac{H(\varphi)}{2\pi}$

power spectrum is almost scale-invariant (Harrison-Zel'dovich)

Structure formation: density perturbations

Chibisov & Mukhanov 1981; Hawking 1982; Guth & Pi 1982

fluctuations $\delta\varphi$ induce fluctuations in the metric

($\phi(\eta,\vec{x}), \psi(\eta,\vec{x})$ ... metric potentials of longitudinal sector)

$$\mathrm{d}s^2 = a^2(\eta)[-(1+2\phi)\mathrm{d}\eta^2 + (1-2\psi)\mathrm{d}\vec{x}^2] \qquad \text{(longitudinal gauge)}$$

and in the energy density

$$\delta\epsilon(\eta,\vec{x}) = \frac{1}{a^2}(\varphi'\delta\varphi' - \varphi'^2\phi) + V_{,\varphi}\delta\varphi$$

characterise them by a hypersurface-invariant quantity Bardeen 1989

$$\zeta \equiv \frac{\delta\epsilon}{3(\epsilon+p)} - \psi$$

conserved on superhorizon scales, if perturbations are isentropic (see lecture 4)

Primordial power spectra

harmonic oscillator leads to gaussian fluctuations, characterised by two-point functions

def: power spectrum $P_Q(k)$ of some observable Q

$$\langle Q(\vec{0}), Q(\vec{r})\rangle = \int \mathrm{d}(\ln k) \mathrm{j}_0(kr) k^3 P_Q(k) \quad \text{and} \quad \mathcal{P}_Q \equiv k^3 P_Q(k)$$

$Q_{\mathrm{rms}} = \sqrt{\mathcal{P}_Q}$ is the root mean square amplitude in the interval $(k, k + \mathrm{d}k)$

historic ansatz: scale-free power spectrum $\mathcal{P}_\zeta = A_\zeta (k/k_*)^{n-1}$

$n = 1$: scale-invariant Harrison-Zel'dovich, $n - 1$: spectral tilt

Density and metric fluctuations

Chibisov & Mukhanov 1981; Starobinsky 1980

prediction 2: density fluctuations are

a: gaussian distributed

b: coherent in phase (only growing mode)

c: close to scale-invariant (slow-roll models, but $n \neq 1$)

d: isentropic (simplest models, e.g. all single field models)

prediction 3: gravitational waves with properties a, b and c

prediction 4: no rotational perturbations at $k < aH$

Slow-roll inflation

attractor in many inflationary scenarios

dynamical (slow-roll) parameters: $\varepsilon_{n+1} \equiv \mathrm{d}\ln\varepsilon_n/\mathrm{d}N$ and $\varepsilon_0 \equiv H_\mathrm{i}/H$

$\varepsilon_1 = \dot{d}_\mathrm{H}$ Schwarz, Terrero-Escalante & Garcia 2001

$$\varepsilon_1 \simeq \frac{M_\mathrm{P}^2}{16\pi}(V'/V)^2, \quad \varepsilon_2 \simeq \frac{M_\mathrm{P}^2}{4\pi}\left[(V'/V)^2 - V''/V\right], \quad \ldots$$

slow-roll inflation: $|\epsilon_n| \ll 1 \ \forall n > 0$

density perturbations $\mathcal{P}_\zeta = \frac{H^2}{\pi\varepsilon_1 M_\mathrm{P}^2}\left(a_0 + a_1 \ln\frac{k}{k_*} + \frac{a_2}{2}\ln^2\frac{k}{k_*} + \cdots\right)$

gravitational waves $\mathcal{P}_h = \frac{16H^2}{\pi M_\mathrm{P}^2}\left(b_0 + b_1 \ln\frac{k}{k_*} + \frac{b_2}{2}\ln^2\frac{k}{k_*} + \cdots\right)$

with $a_i = a_i(\varepsilon_n), b_i = b_i(\varepsilon_n)$ and k_* pivot scale at which ε_n are evaluated

Stewart & Lyth 1993; Martin & Schwarz 2000;

Stewart & Gong 2001; Leach, Liddle, Martin & Schwarz 2002

Interpretation of dynamical parameters

$\varepsilon_1 = \dot{d}_\mathrm{H} > 0$ measures constancy of Hubble scale during inflation, i.e. ratio of kinetic to total energy density

if $\varepsilon_2 > 2\varepsilon_1$: kinetic energy density grows with time

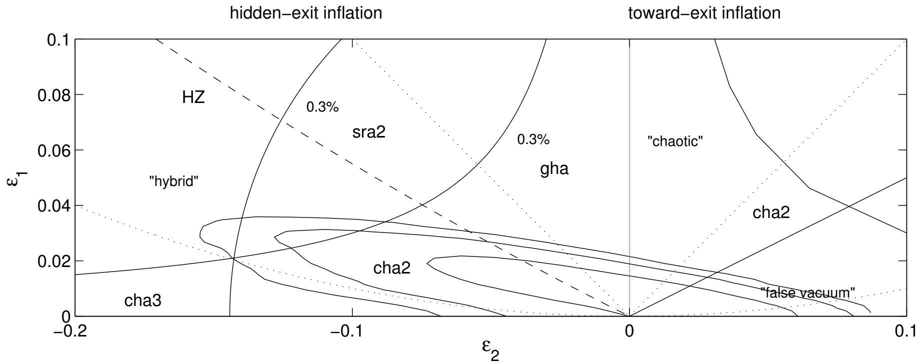
e.g. R^2 or Higgs-inflation, toward the end of inflation

if $2\varepsilon_1 > \varepsilon_2 > 0$: kinetic energy density decreases with time

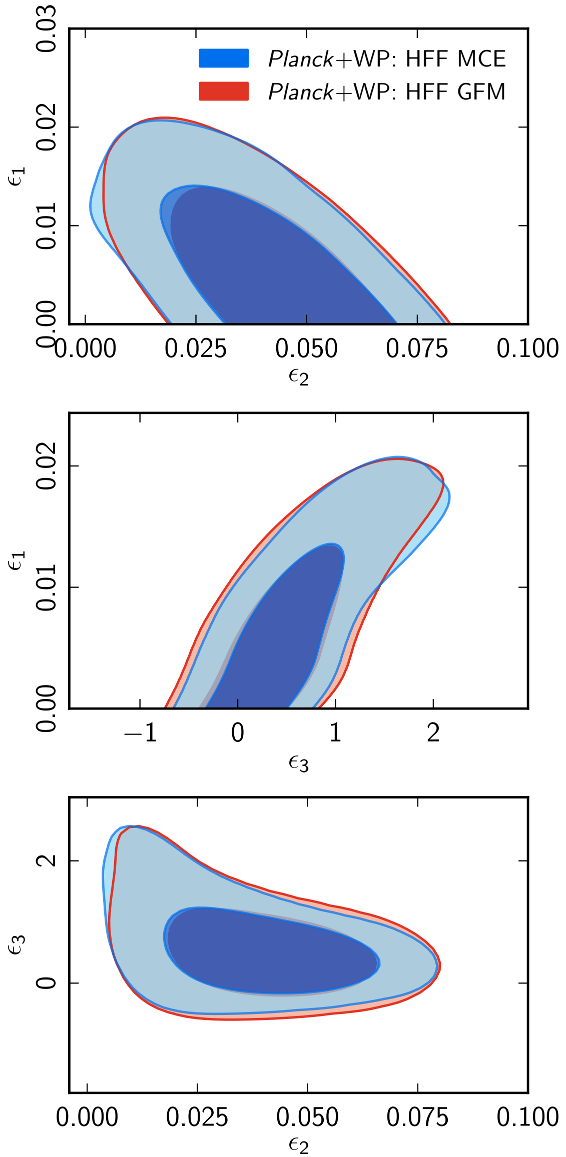
e.g. $\varphi^n, n \geq 2$, toward the end of inflation

if $\varepsilon_2 < 0$: kinetic energy density decreases w.r.t. total energy density

hybrid models, some transition is needed to end inflation



Schwarz & Terrero-Escalante 2004



Scale of inflation and slow-roll parameters

Planck collaboration, Ade et al. 2014

from upper limit on tensor perturbations and amplitude of scalar perturbations:

$H < 1.0 \times 10^{14}$ GeV $= 8.3 \times 10^{-6} M_{\mathrm{P}}$

$\varepsilon_1 < 0.013$ at 95% CL

from deviation from scale-invariance:

$\varepsilon_2 = 0.043^{+0.013}_{-0.014}$

$\varepsilon_2 > 2\varepsilon_1$: kinetic energy increases

Generic predictions of inflation vs. observations

prediction 1: $\Omega_0 = 1 + \mathcal{O}(10^{-5})$ OBS

prediction 2: existence of density fluctuations that are

a: gaussian distributed OBS

b: coherent in phase (only growing mode) OBS

c: close to scale-invariant (slow-roll models) OBS

d: isentropic (simplest models) OBS

prediction 3: gravitational waves NOT OBS (so far)

prediction 4: no rotational perturbations at $k < aH$ OBS

Summary of 2nd lecture

cosmological inflation explains or at least motivates isotropy & homogeneity, causality, spatial flatness and predicts seeds for structure formation

inflationary parameters (slow-roll):
$H_{\mathrm{inf}}, \varepsilon_1, \varepsilon_2, \ldots$ or $A, n-1, r \equiv \mathcal{P}_h/\mathcal{P}_\zeta, \ldots$

at first order slow-roll approximation: $n - 1 \simeq -2\varepsilon_1 - \varepsilon_2, r \simeq 16\varepsilon_1$
CMB: $n = 0.9603 \pm 0.0073, r < 0.11$(95% CL)
Planck collaboration, Ade et al 2014

what is the fundamental physics of inflation?
what is it's scale? is there an alternative?