MARCO PELOSO LECTURE 1

INFLATION & REHEATING

→ INFLATION

(MOTIVATIONS, SIMPLEST REALIZATION, PRIMORDIAL PERTURBATIONS)

→ PRODUCTION DURING REHEATING

(WHILE THE INFLATON IS DECAYING)

→ PRODUCTION DURING INFLATION

(SIGNATURES IN CMB & IN GRAVITATIONAL WAVES)

• EXPANSION IN STANDARD COSMOLOGY

DISTANCES $\propto a(t)$ SCALE FACTOR

$H \equiv \frac{\dot{a}}{a}$ HUBBLE RATE

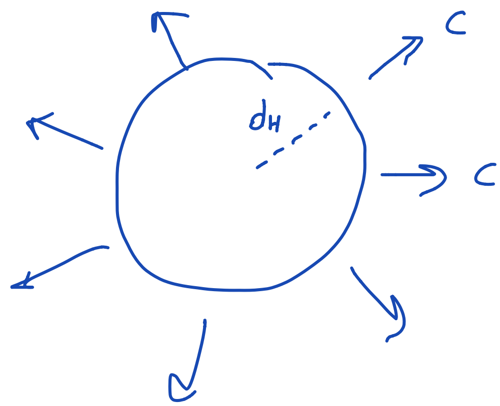
HOMEWORK

UNIVERSE DOMINATED BY

RADIATION $\quad a \propto t^{1/2}, \quad H = \frac{\dot{a}}{a} = \frac{1}{2t}$

MATTER $\quad a \propto t^{2/3}, \quad H = \frac{2}{3t}$

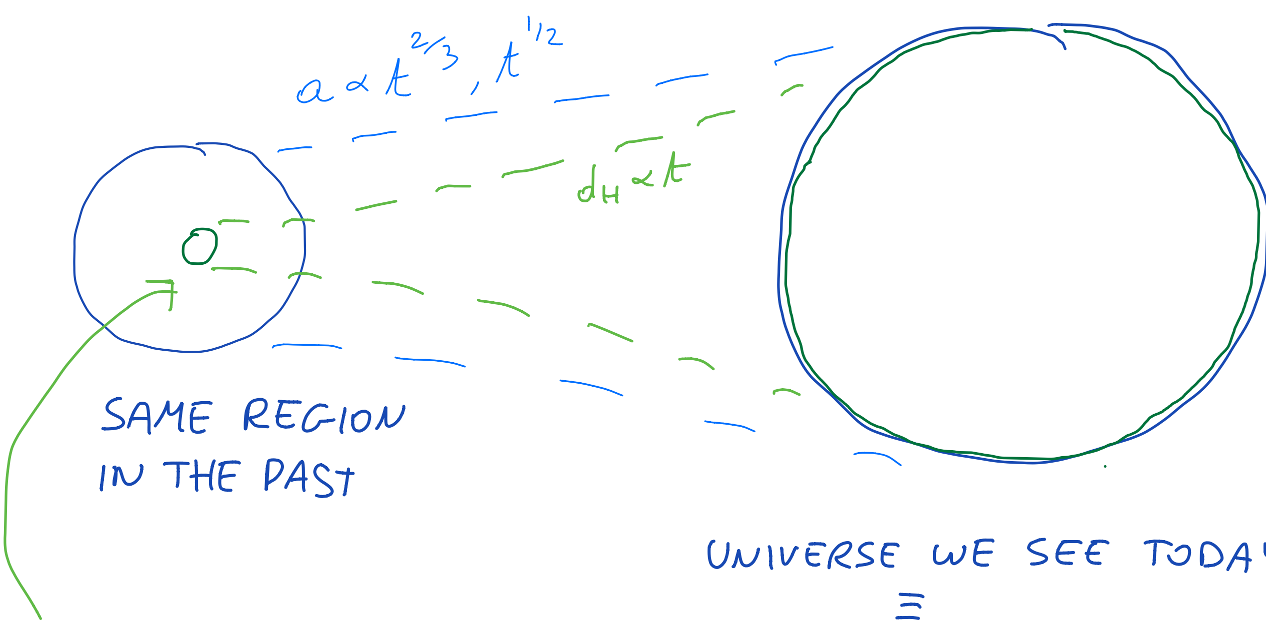
• HORIZON PROBLEM



REGION IN CAUSAL CONNECTION

$d_H \sim ct \sim \frac{1}{H}$ $\quad (c=1)$

HORIZON GROWS FASTER THAN SCALE FACTOR



SAME REGION IN THE PAST

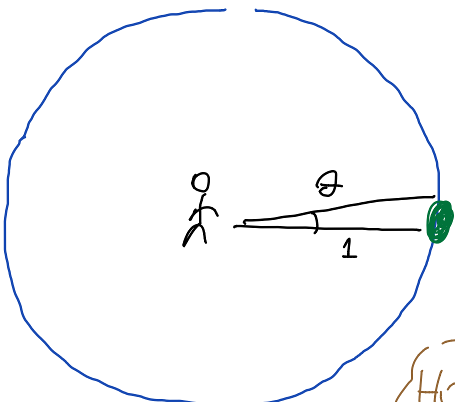
SIZE HORIZON IN THE PAST

UNIVERSE WE SEE TODAY $\equiv$ HORIZON TODAY

THE SKY WE SEE TODAY IS COMPOSED OF MANY REGIONS THAT WERE CAUSALLY DISCONNECTED IN THE PAST

EXAMPLE: CMB EMITTED WHEN $a_{CMB} \sim 10^{-3} a_0$

SUFFIX 0 MEANS TODAY



PORTION OF MY SKY OCCUPIED BY A REGION THAT WAS CAUSALLY CONNECTED WHEN CMB WAS EMITTED

$\theta \approx 2^\circ$

HOMEWORK

HOWEVER, CMB RADIATION SAME TEMPERATURE FROM ALL DIRECTIONS

PROBLEM BECAUSE $\frac{d_H}{a}$ INCREASES

$$\frac{d_H}{a} \propto \frac{t}{a} \propto \frac{1}{aH} = \frac{1}{a\frac{\dot{a}}{a}} = \frac{1}{\dot{a}}$$ ← DECREASES

$\boxed{\text{PROBLEM BECAUSE } \ddot{a} < 0 \text{ IN A MATTER + RADIATION UNIVERSE}}$

FLATNESS PROBLEM

EVOLUTION OF SCALE FACTOR GOVERNED BY

$$\frac{\dot{a}^2}{a^2} = -\frac{k}{a^2} + \frac{1}{3M_p^2}\left(\frac{\rho_M^{(0)}}{a^3} + \frac{\rho_R^{(0)}}{a^4}\right)$$

AS UNIVERSE EXPANDS, CURVATURE TERM BECOMES DOMINANT. THIS TERM IS $<0.5\%$ TODAY $\Rightarrow$ MUST HAVE BEEN $\leq 10^{-18}$ WHEN UNIVERSE $\sim 1S$ OLD

PROBLEM BECAUSE $\rho_{STANDARD} \propto a^{-P}$ WITH $P > 2$

$\Rightarrow \dot{a}^2 = a^2\left(\frac{\dot{a}^2}{a^2}\right) \propto a^{2-P}$ DECREASES $\equiv$ DECELERATION

AGAIN, PROBLEM BECAUSE MATTER & RADIATION LEAD TO DECELERATED EXPANSION

INFLATION

PROBLEMS SOLVED IF UNIVERSE UNDERWENT A PHASE OF ACCELERATED EXPANSION, $\ddot{a} > 0$. THIS MUST HAVE HAPPENED BEFORE BIG-BANG-NUCLEOSYNTHESIS (BBN), $t < 1S$.

GUTH, 1981

* DURING INFLATION, A SINGLE CAUSALLY CONNECTED REGION GROWS SO MUCH AS TO COVER ALL THE SKY WE SEE TODAY. THE SOURCE OF INFLATION DOMINATES OVER CURVATURE TERM $(P < -2)$ AND THEN DECAYS INTO $\rightarrow$ MATTER & RADIATION

WE CALL THIS SOURCE "INFLATON FIELD"

SIMPLEST ACCELERATION FROM VACUUM ENERGY

$$H^2 = \frac{\dot{a}^2}{a^2} \propto \rho \quad \text{AND} \quad \rho = \text{cost.} \longrightarrow a = e^{Ht}$$

PBM: IF $\rho = \rho_{VACUUM}$, INFLATION WILL NOT END

- SLOW ROLL INFLATION

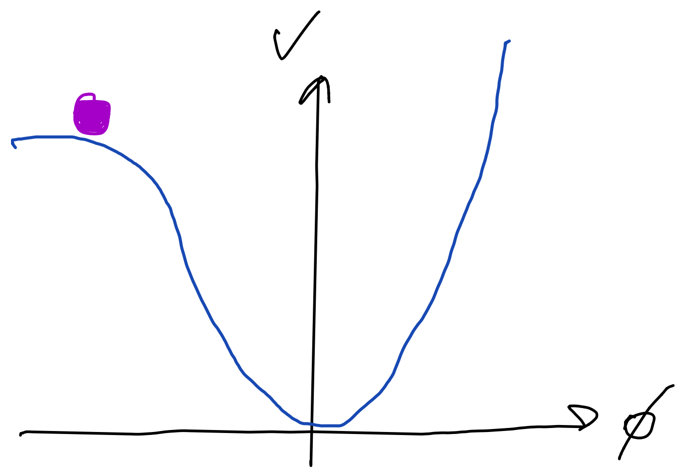
LINDE 1982

ALBRECHT, STEINHARDT 1982

→ INFLATON ON A FLAT PORTION OF $V \Rightarrow$ BEHAVES $\simeq$ VACUUM ENERGY

→ INFLATION ENDS WHEN ϕ REACHES NON-FLAT PART

THEN, OSCILLATIONS ABOUT MINIMUM AND DECAY



SLOW ROLL PARAMETERS

$$\varepsilon \equiv \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 << 1$$ THE POTENTIAL NEEDS TO BE FLAT

$$\eta \equiv \frac{M_P^2}{2}\frac{V''}{V} << 1$$ FLAT FOR LARGE SPAN OF ϕ

BYPRODUCT : MECHANISM FOR PRIMORDIAL PERTURBATIONS

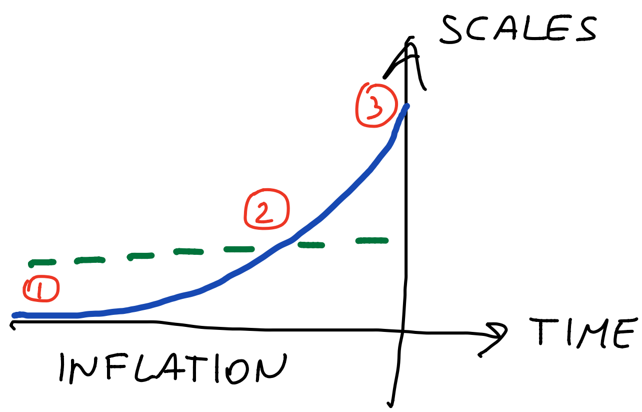
$$\delta\phi,\ \delta g \nearrow \frac{\delta\rho}{\rho} \simeq \zeta \quad \text{(SCALAR) DENSITY PERTURBATIONS}$$

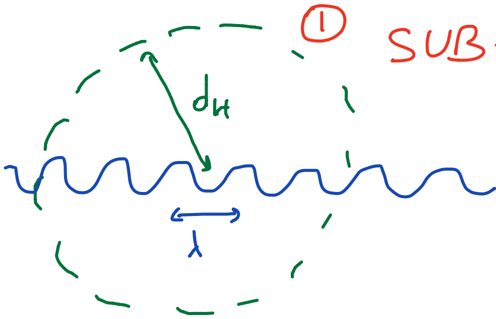
$$\delta\phi,\ \delta g \searrow h_+,\ h_\times \quad \text{(TENSOR) GRAVITATIONAL WAVES}$$

CONSIDER A PERTURBATION ON OUR SKY AND TRACE IT BACK DURING INFLATION

"HUBBLE HORIZON $d_H = H^{-1} \simeq \text{const.}$

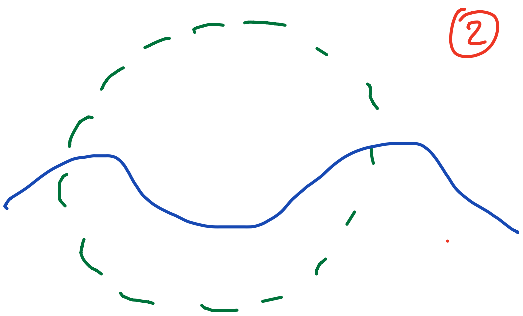
WAVELENGTH $\lambda \propto a \simeq e^{Ht}$





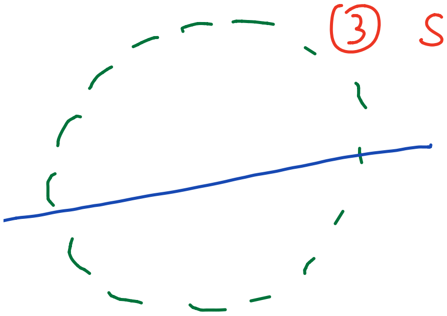
① SUB-HORIZON

QUANTUM EVOLUTION AS IN MINKOWSKI. NEGLIGIBLE EFFECT FROM GEOMETRY



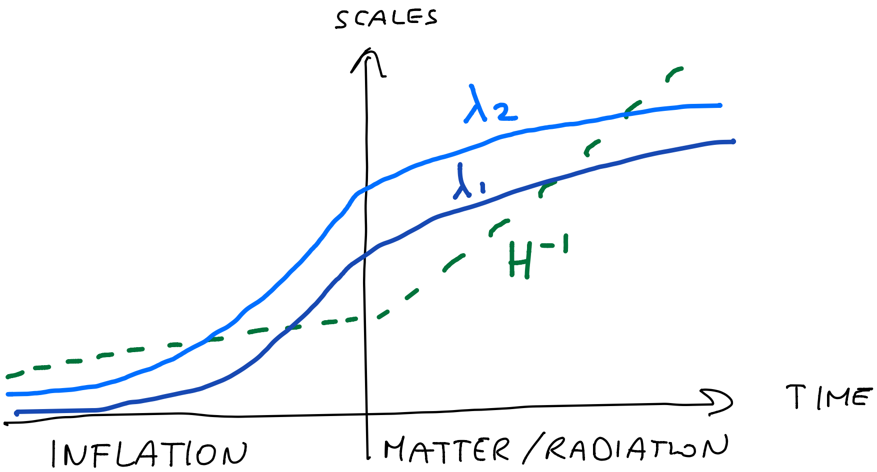
② HORIZON CROSSING

THIS IS WHEN THE MODE IS IMPRINTED. PERTURBATION PROBES CONDITION OF THE UNIVERSE AT THIS MOMENT



③ SUPER-HORIZON

MODE SEEN AS CONSTANT IN EACH HORIZON PATCH. FROZEN (NO EVOLUTION IN TIME) DUE TO CAUSALITY



MODES OF GREATER WAVELENGTH ($\lambda_2 > \lambda_1$) CROSS THE HORIZON EARLIER. THEY PROBE EARLIER TIMES OF INFLATION.

DEPARTURE FROM dS (CONSTANT V)

FROM $\varepsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2$, $\eta \equiv M_p^2 \frac{V''}{V}$

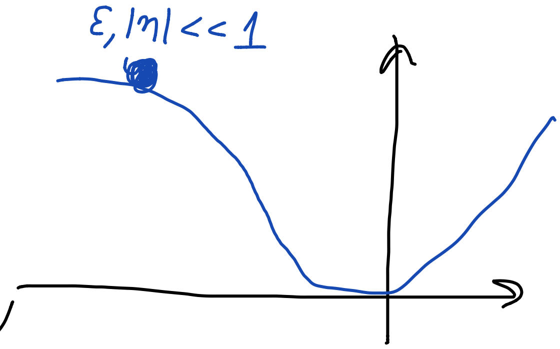
• 3 IMPORTANT PROPERTIES OF PRIMORDIAL PERTURBATIONS

1) NEAR SCALE INVARIANCE

MODES OF ≠ SIZE HAVE NEARLY THE SAME POWER,

$P_\zeta \propto \lambda^{1-n_s}$ $\quad 1-n_s \simeq 6\varepsilon - 2\eta$

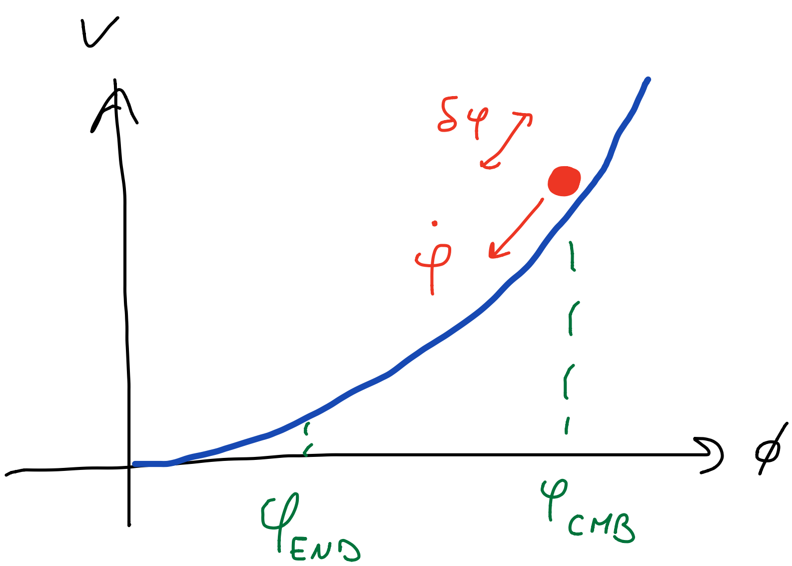
MODES OF ≠ SIZE LEAVE THE HORIZON AT ≠ TIMES, WHEN ϕ HAS MOVED DO A ≠ LOCATION IN V



BUT, FOR SLOW ROLL, $V(\phi)$ HAS CHANGED VERY LITTLE, SO NEARLY SAME POWER AT ALL SCALES

2) GW << DENSITY PERTURBATIONS

INFLATION PREDICTS $\quad r \equiv \dfrac{P_{GW}}{P_\zeta} = 16\,\varepsilon << 1$



INFLATON IS A CLOCK, MEASURING THE TIME TO THE END OF INFLATION

SMALLER / GREATER ENERGY DENSITY
≡
EARLY / LATE CLOCK

SCALAR PERTURBATIONS $\equiv \delta\varphi \equiv$ PERTURBATIONS OF THE CLOCK

$$\zeta \sim \frac{\delta\varphi}{\ell} \propto \frac{\delta\varphi}{\dot{\varphi}}$$

BACKGROUND CLOCK

THE SLOWER THE BACKGROUND CLOCK ($\equiv$ SMALL $\dot{\varphi} \equiv$ SMALL ε) THE GREATER THE EFFECT OF $\delta\varphi$ ON ζ

$$\Rightarrow \; P_\zeta \propto \frac{1}{\varepsilon} \;\Rightarrow\; r = \frac{P_{GW}}{P_\zeta} \propto \varepsilon$$

SLIDE 1

(3) HIGHLY GAUSSIAN, $\langle \zeta^3 \rangle \ll \langle \zeta^2 \rangle^{3/2}$

SMALL DEVIATIONS FROM GAUSSIANITY, PARAMETRIZED AS

$$\zeta = \zeta_g + f_{NL} * \zeta_g^2$$

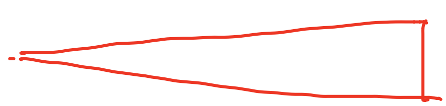
GAUSSIAN

CONVOLUTION IN MOMENTUM SPACE

$\neq$ FUNCTIONAL DEPENDENCES GIVE

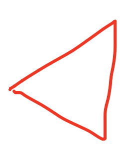
$\neq$ SHAPES

$|f_{NL,\,local}| \lesssim 10$



(RECALL $\zeta \sim 10^{-5}$)

$|f_{NL,\,EQUILATERAL}| \lesssim 100$



FREE FIELDS ARE GAUSSIAN

$$\langle \phi\phi\phi\phi \rangle = \langle \phi\phi\phi\phi \rangle + \langle \phi\phi\phi\phi \rangle + \langle \phi\phi\phi\phi \rangle$$

$$= 3 \langle \phi\phi \rangle \langle \phi\phi \rangle$$

$$\langle \phi\phi\phi \rangle = 0$$

....

$\Rightarrow$ NON-GAUSSIANITY IS A MEASURE OF ϕ INTERACTIONS

- GRAVITATIONAL INTERACTIONS ARE WEAK
- SELF INTERACTIONS PROPORTIONAL TO DERIVATIVES OF THE POTENTIAL

$$V = V_0 + \frac{V''}{2}\delta\varphi^2 + \frac{V'''}{6}\delta\varphi^3 + \frac{V^{(IV)}}{24}\delta\varphi^4 + \ldots$$

SMALL DUE TO SLOW ROLL

$\therefore$ LARGE NON-GAUSSIANITY POSSIBLE FROM INTERACTIONS WITH OTHER FIELDS, AS WE WILL SEE LATER IN THESE LECTURES.