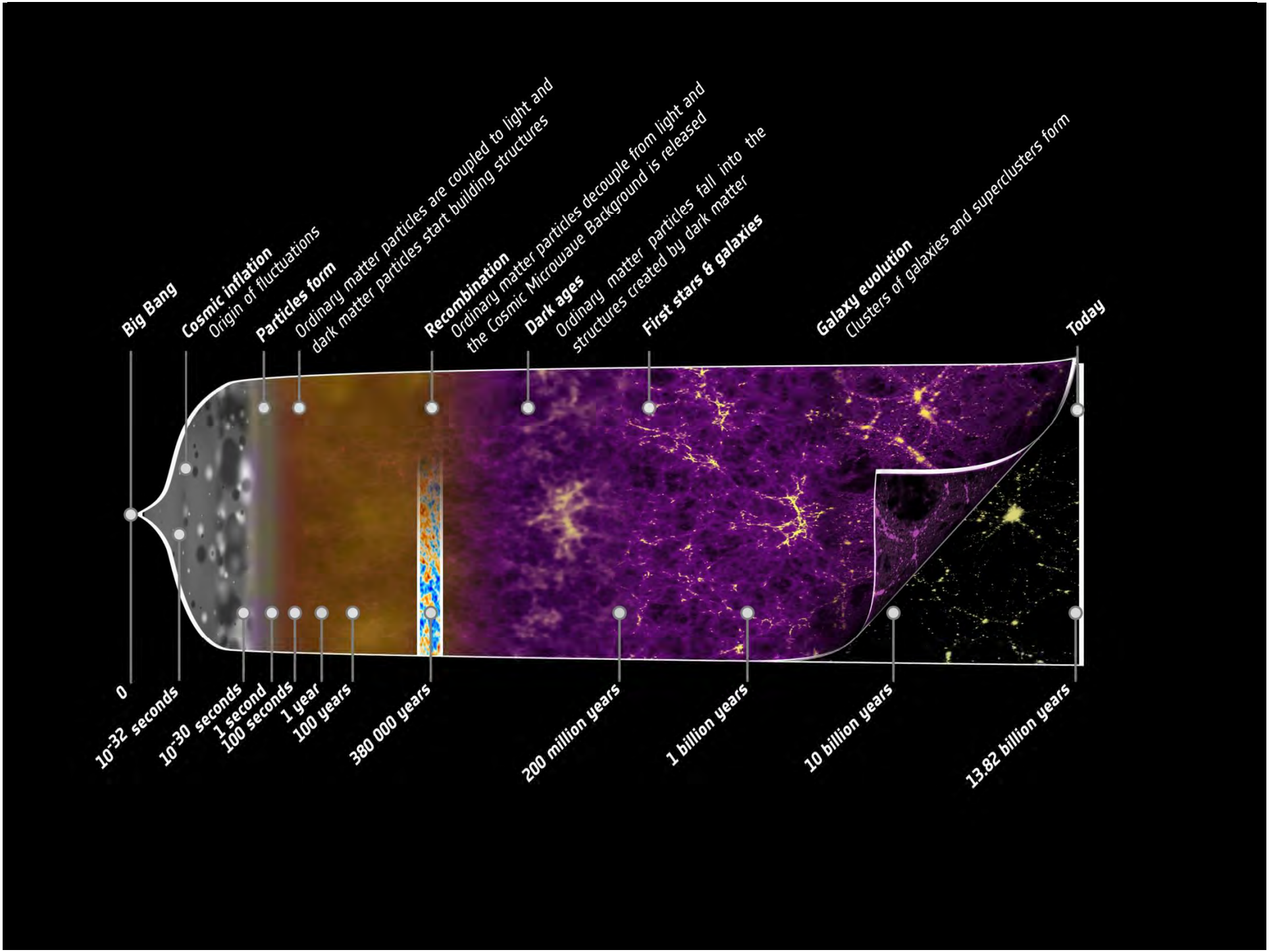
Origin of structure in the universe

Kari Enqvist

Helsinki University

and

Helsinki Institute of Physics


Big Bang
0
Cosmic inflation
Origin of fluctuations
10-32 seconds
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
10-30 seconds
1 second
100 seconds
1 year
100 years
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
380 000 years
Dark ages
Ordinary matter particles fall into the structures created by dark matter
200 million years
First stars & galaxies
1 billion years
Galaxy evolution
Clusters of galaxies and superclusters form
10 billion years
Today
13.82 billion years

Inflation:

a period of superluminal expansion
of space in the early universe

$$ds^2 = -dt^2 + a^2(t)d\mathbf{x}^2$$

FRW universe

$$a(t) = \exp(H_0 t)$$

H_0 = Hubble rate during inflation
~ constant

Inflaton:

Homogeneous scalar field φ responsible for superluminal expansion

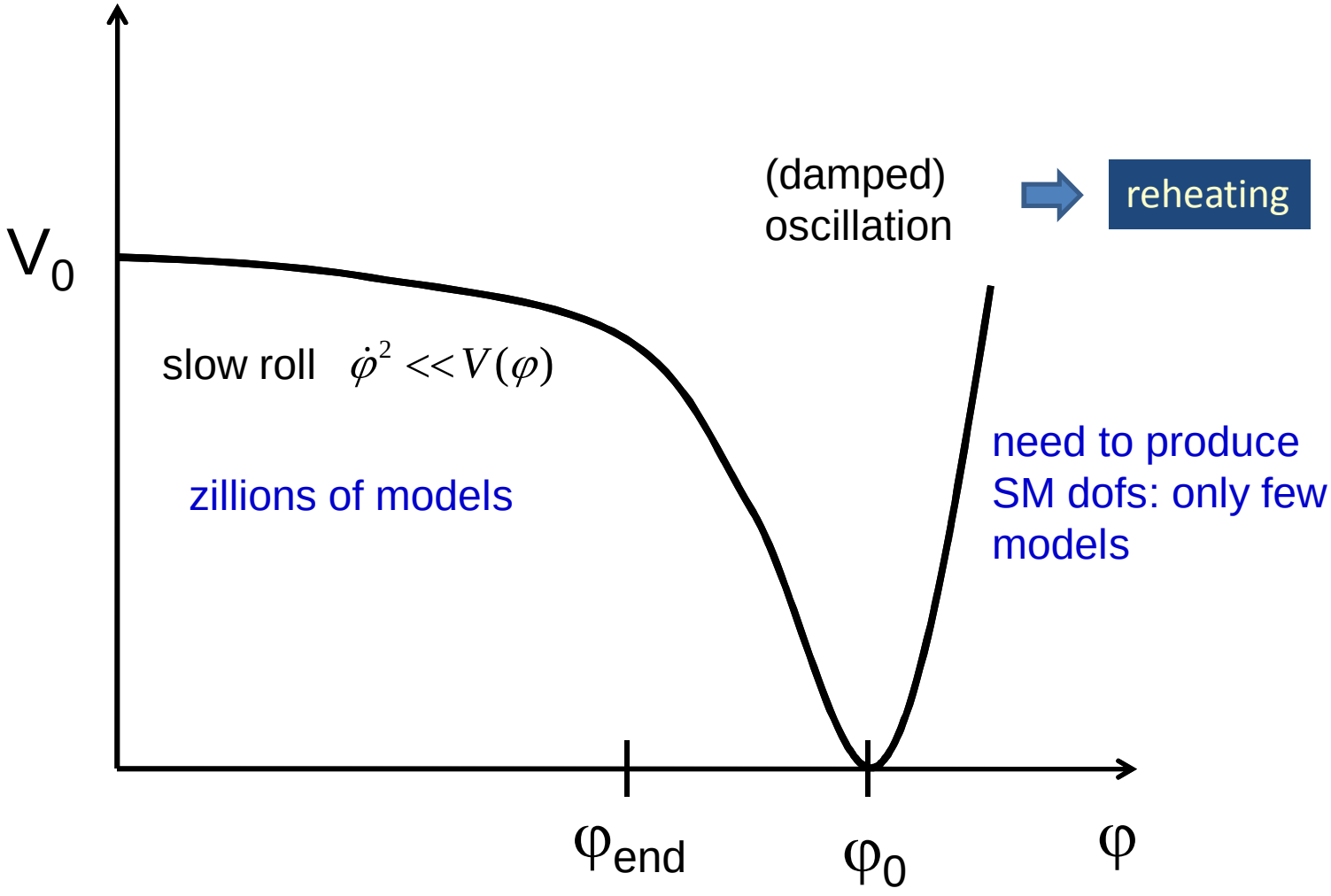
$$\rho = \tfrac{1}{2}\dot{\varphi}^2 + V(\varphi)$$

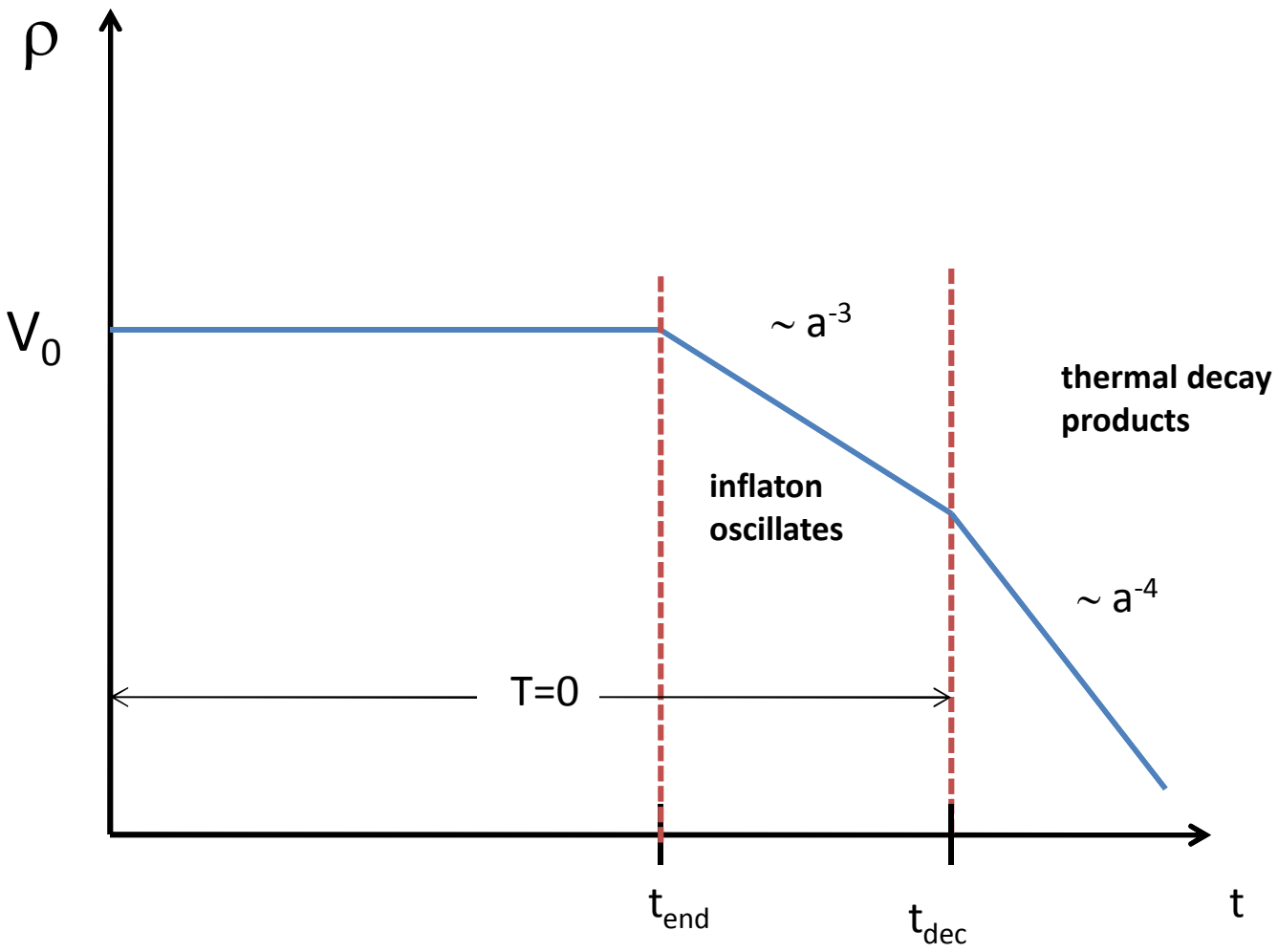
FRW: $$3M_P^2 H^2 = \rho$$

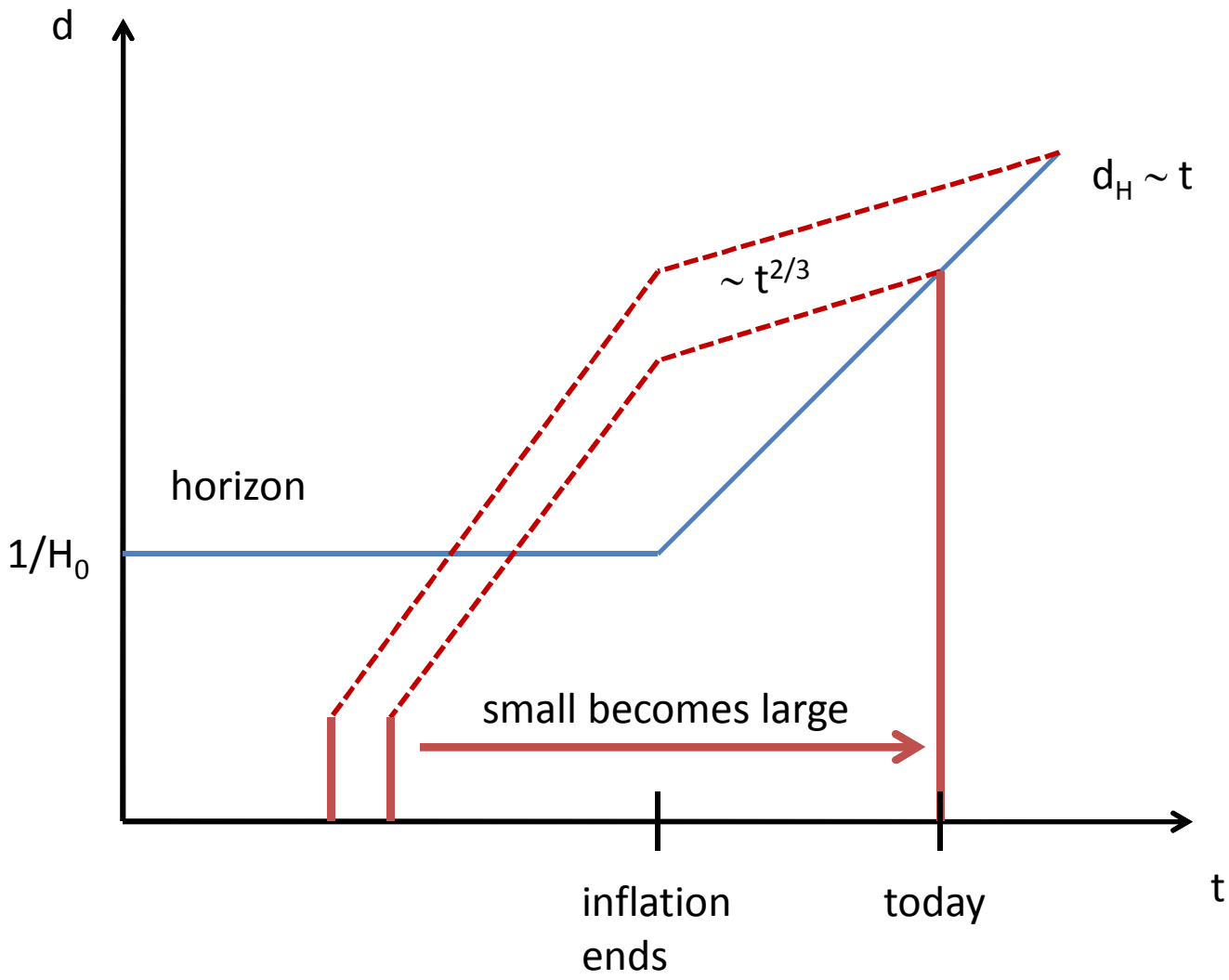
→ constant Hubble if φ in slow roll $$\dot{\varphi}^2 << V(\varphi)$$

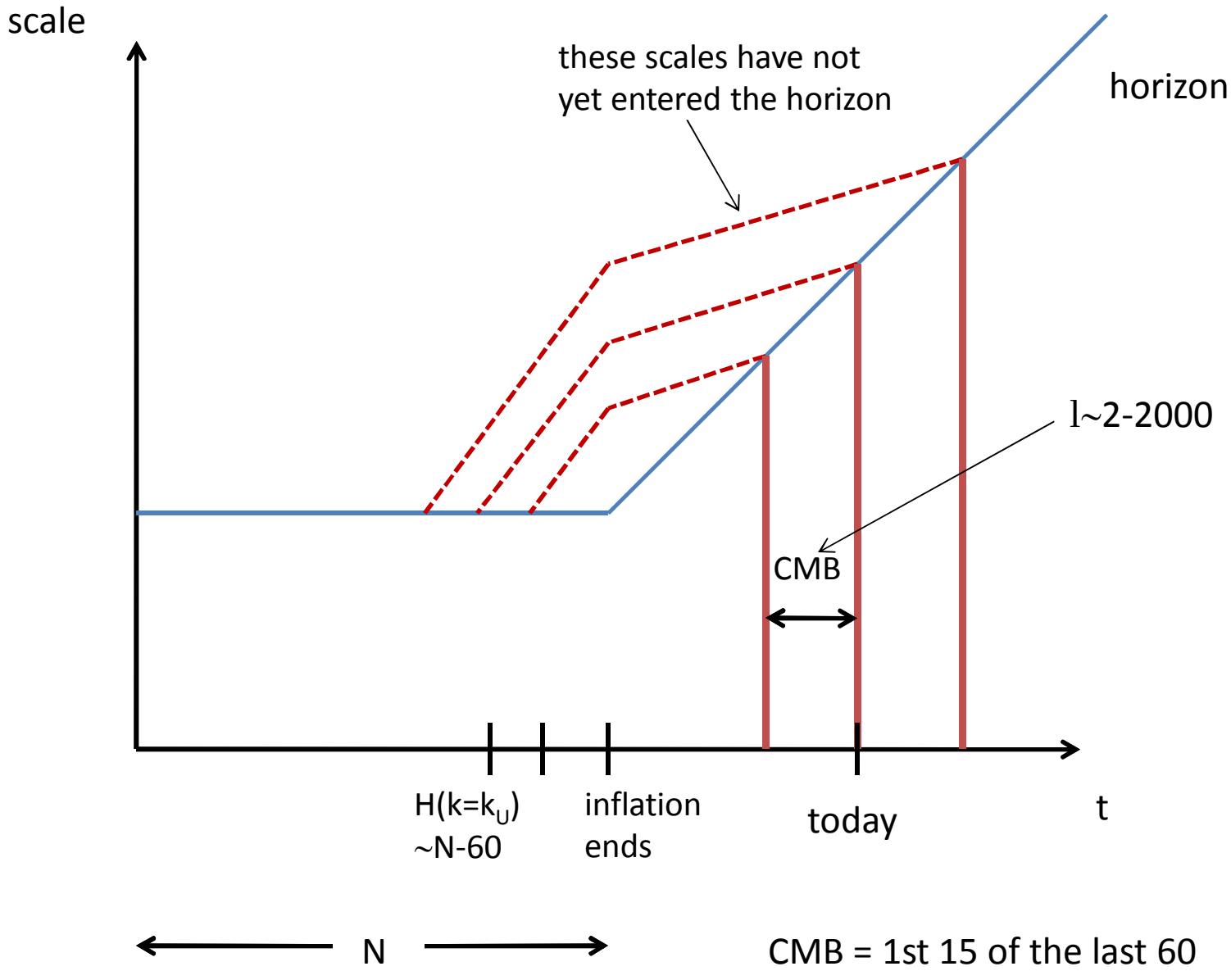
→ equation of motion in FRW $$3H\dot{\varphi} + V'(\varphi) = 0$$

slow roll inflation




ρ
V0
~ a-3
thermal decay
products
inflaton
oscillates
~ a-4
T=0
tend
tdec
t


d
$d_H \sim t$
$\sim t^{2/3}$
horizon
$1/H_0$
small becomes large
inflation
ends
today
t


scale
these scales have not
yet entered the horizon
horizon
l~2-2000
CMB
H(k=k$_U$)
~N-60
inflation
ends
today
t
N
CMB = 1st 15 of the last 60

quantum fields fluctuate

field = collection of oscillators, labeled by momenta *k*

$$\phi(x,t) = \phi_0(t) + \delta\phi(x,t)$$

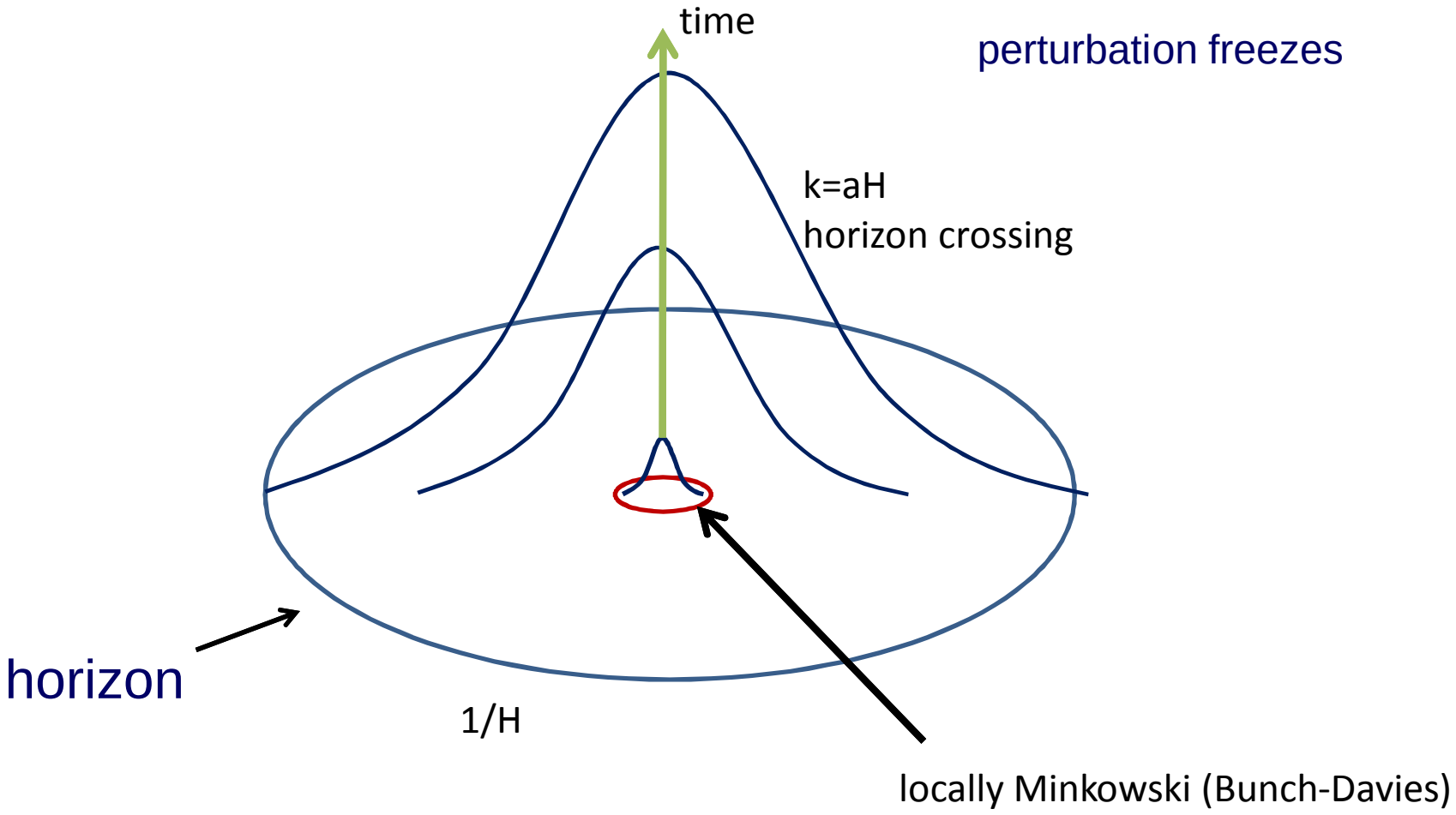
perturbation $\left\langle \delta\phi(x,t) \right\rangle = 0$

with $\left\langle \delta\phi(x,t)^2 \right\rangle \neq 0$

can compute

initial condition for evolution of (classical) wave in expanding universe

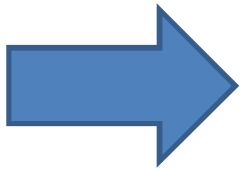
inflaton fluctuations



slow roll ⇒ almost scale invariant spectrum of perturbations

From field perturbation to temperature fluctuation

during slow roll $\rho \approx V(\phi)$

field perturbation  $\delta\rho \approx V'(\phi)\delta\phi$ density perturbation

(but need to worry about gauge invariance)

When the dust has settled ...

slow roll single field inflation predicts the primordial spectrum of density perturbations

SLOW ROLL SINGLE FIELD INFLATION

spectral index

$$n_s - 1 = \frac{d \ln P(k)}{d \ln k} = 2\varepsilon - 6\eta$$

slow-roll parameters << 1:

$$\varepsilon = \frac{M}{2}\left(\frac{V'}{V}\right)^2$$

$$\eta = M^2 \frac{V''}{V}$$

primordial gravitational waves

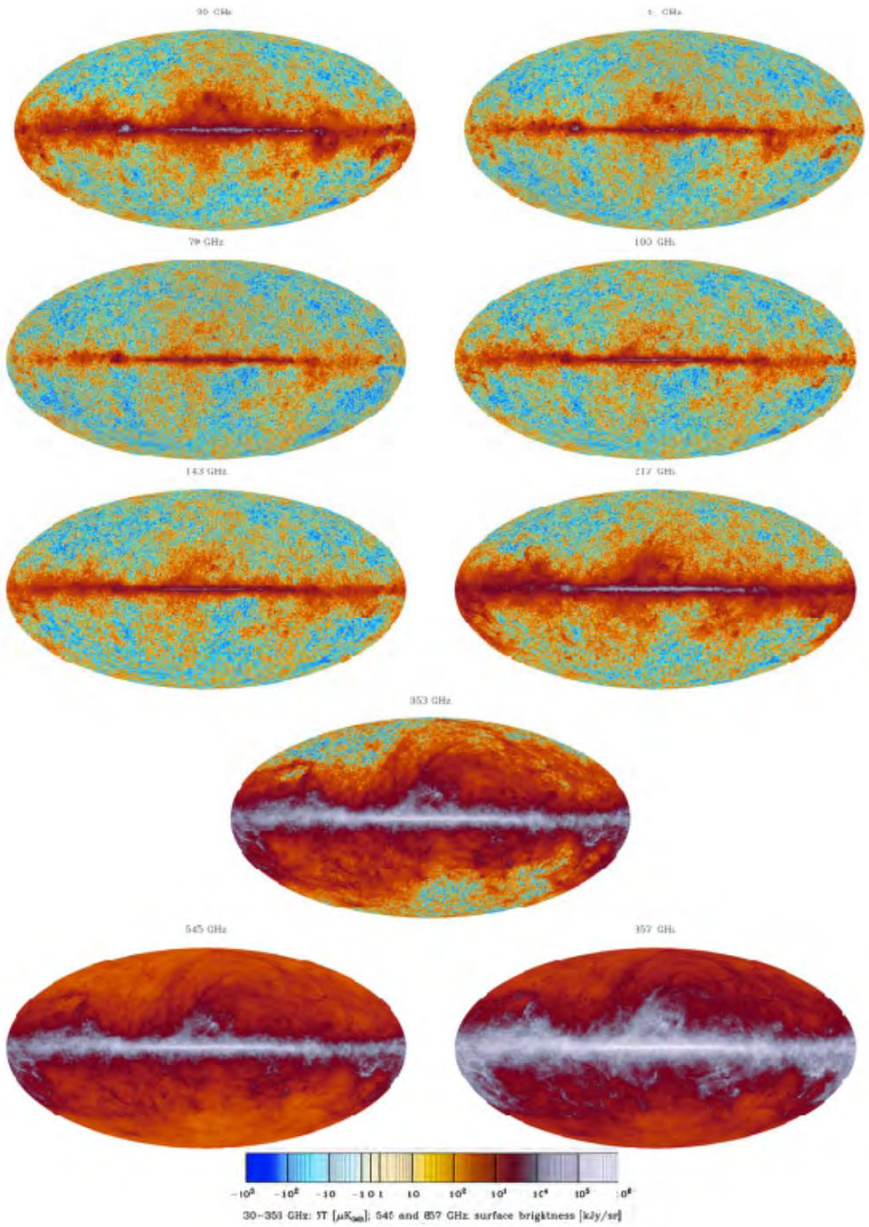
$$\frac{P_{grav}}{P} \equiv r = 12\varepsilon$$

gravity + plasma physics in the early universe

slow roll single field inflation predicts the spectrum of observable CMB temperature fluctations

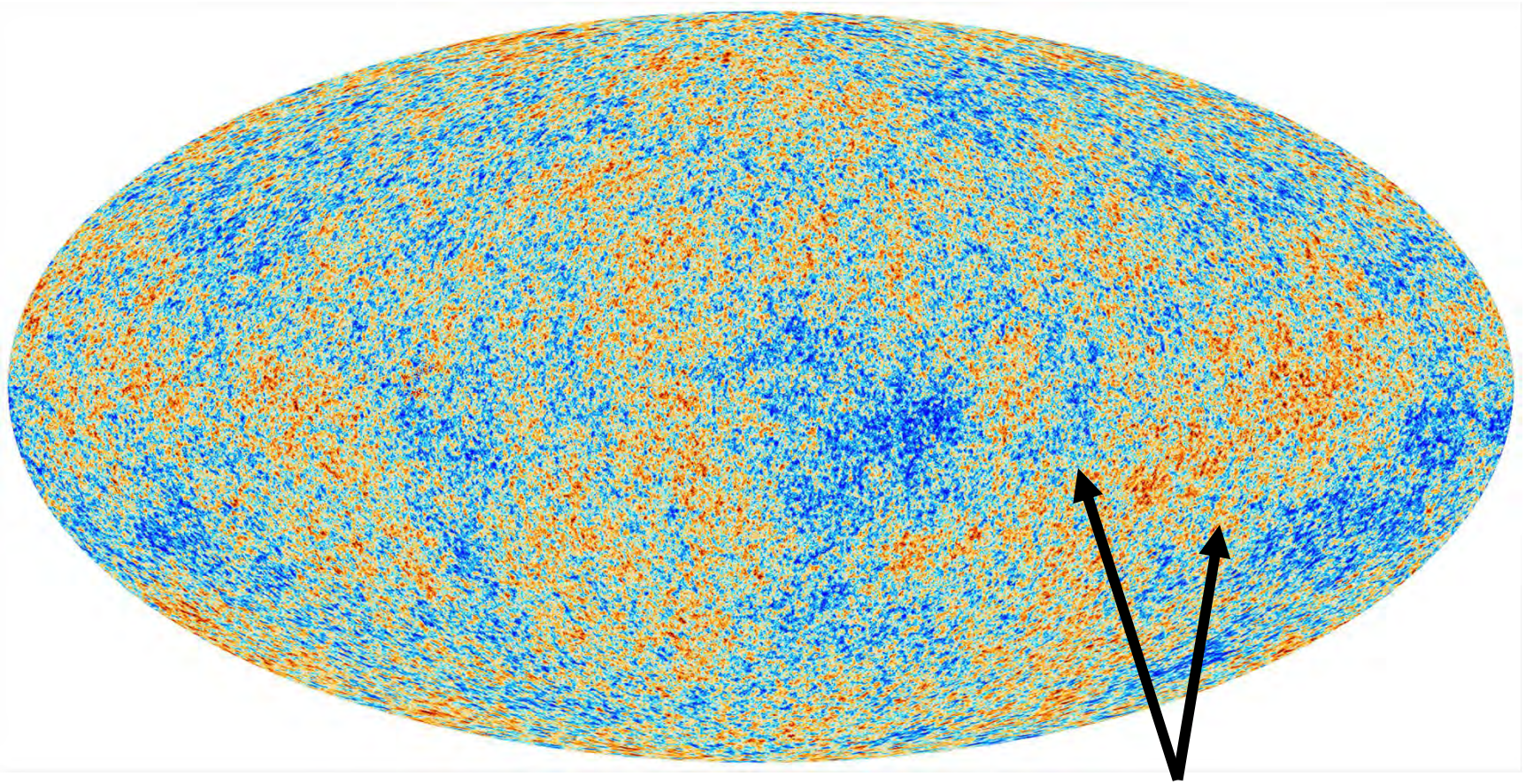
Planck: channels

Finns



Planck-satellite temperature map of 380 000 yr old universe

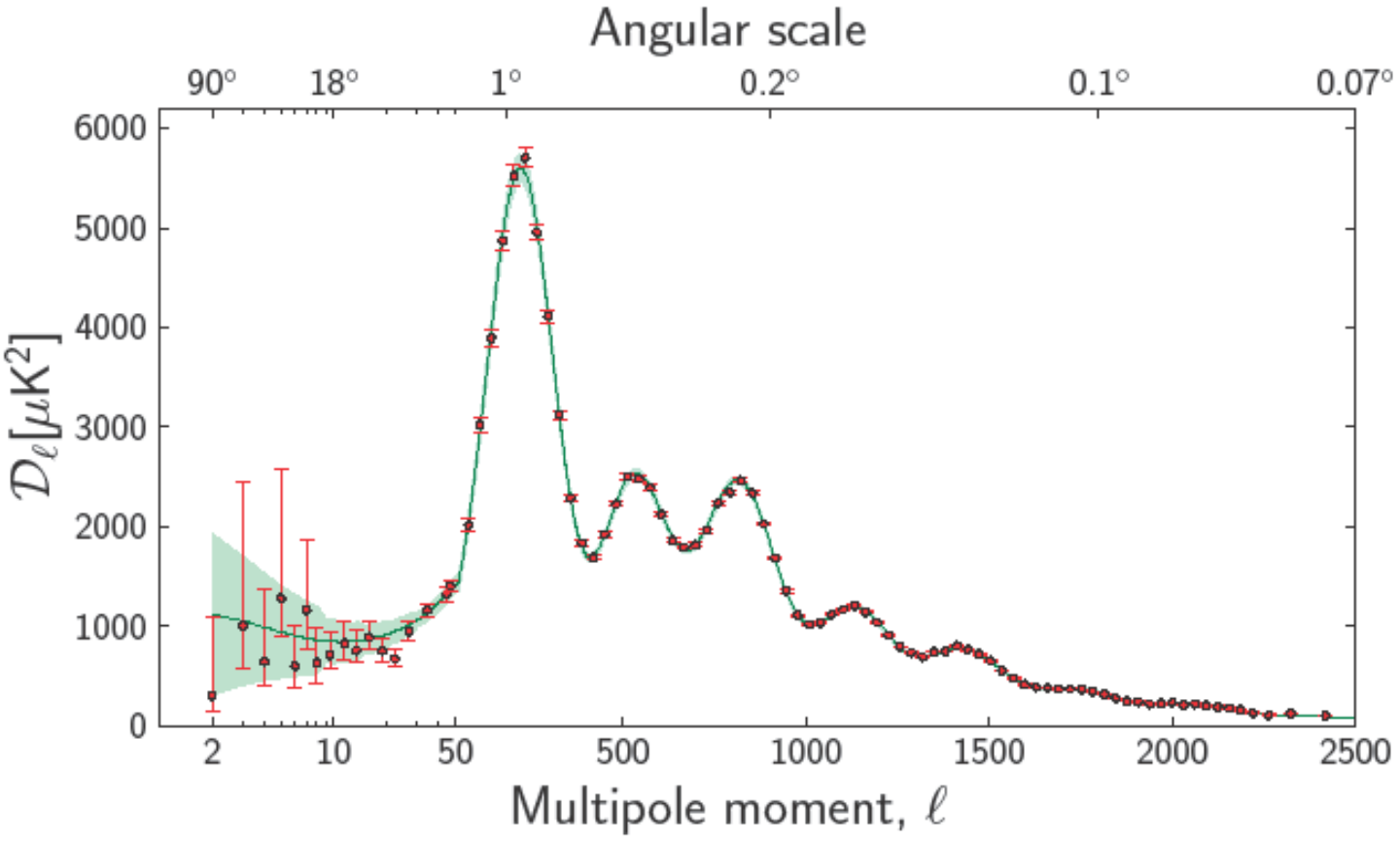
$\langle T \rangle = 2.725\ \mathrm{K} \pm O(10^{-5})\ \mathrm{K}$



differences of order few 10^{-5} K

hot* and *cold regions

Planck CMB spectrum



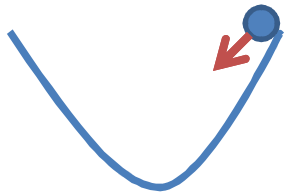
fit to data: $n_s = 0.9603 \pm 0.0073$

scale invariance ruled out at 5σ

Large number of inflaton models

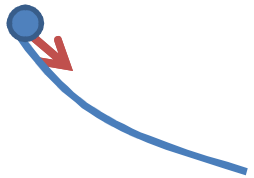
$$V = \lambda M_P^4 \left(\frac{\varphi}{M_P} \right)^p$$

chaotic inflation



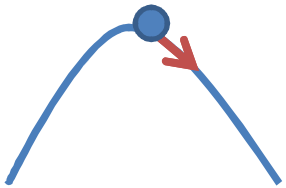
$$V = \Lambda^4 \exp\left(-\lambda \frac{\varphi}{M_P} \right)$$

power law inflation

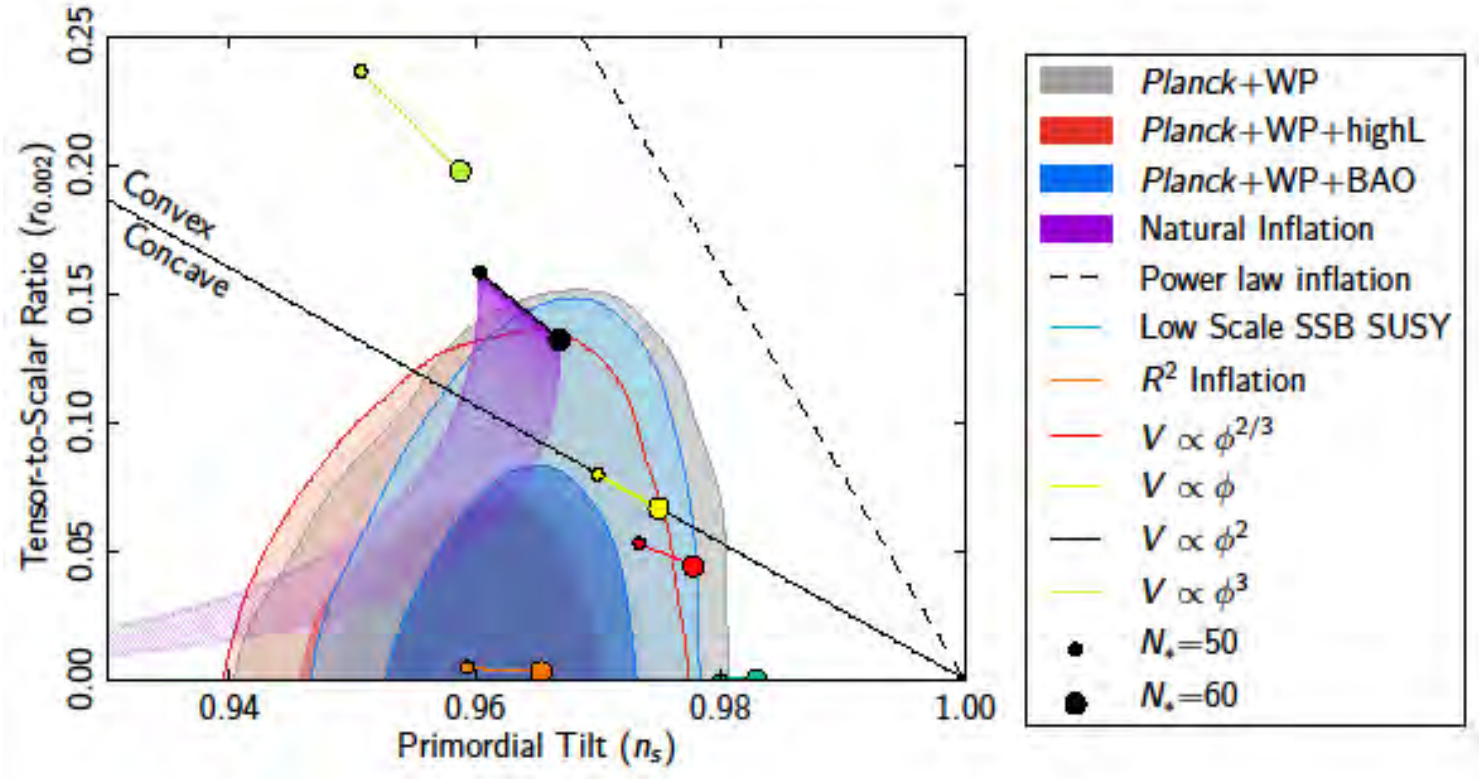


$$V = \Lambda^4 \left(1 - \frac{\varphi^p}{m^p} + \ldots \right)$$

hilltop inflation



etc


Tensor-to-Scalar Ratio ($r_{0.002}$)
0.00
0.05
0.10
0.15
0.20
0.25
Convex
Concave
0.94
0.96
0.98
1.00
Primordial Tilt (n_s)
Planck+WP
Planck+WP+highL
Planck+WP+BAO
Natural Inflation
Power law inflation
Low Scale SSB SUSY
R^2 Inflation
$V \propto \phi^{2/3}$
$V \propto \phi$
$V \propto \phi^2$
$V \propto \phi^3$
N_*=50
N_*=60

inflation: massless slow rolling scalar $m << H_*$

other massless scalars ?

Higgs

several inflatons

spectators $\rho_\sigma << \rho_\phi$

can play a dynamical role after inflation

inflation ⇒ **all light fields fluctuate**

perturbation $\delta\sigma \approx H_*$

origin of the dominant curvature perturbation:

1) during inflation

- single field inflation
- multifield inflation
  2 field ... Nflation

2) after inflation

- curvaton models
- modulated reheating
- modulated end of inflation

NO THEORY OF INFLATION - YET