Quantum origin of structure

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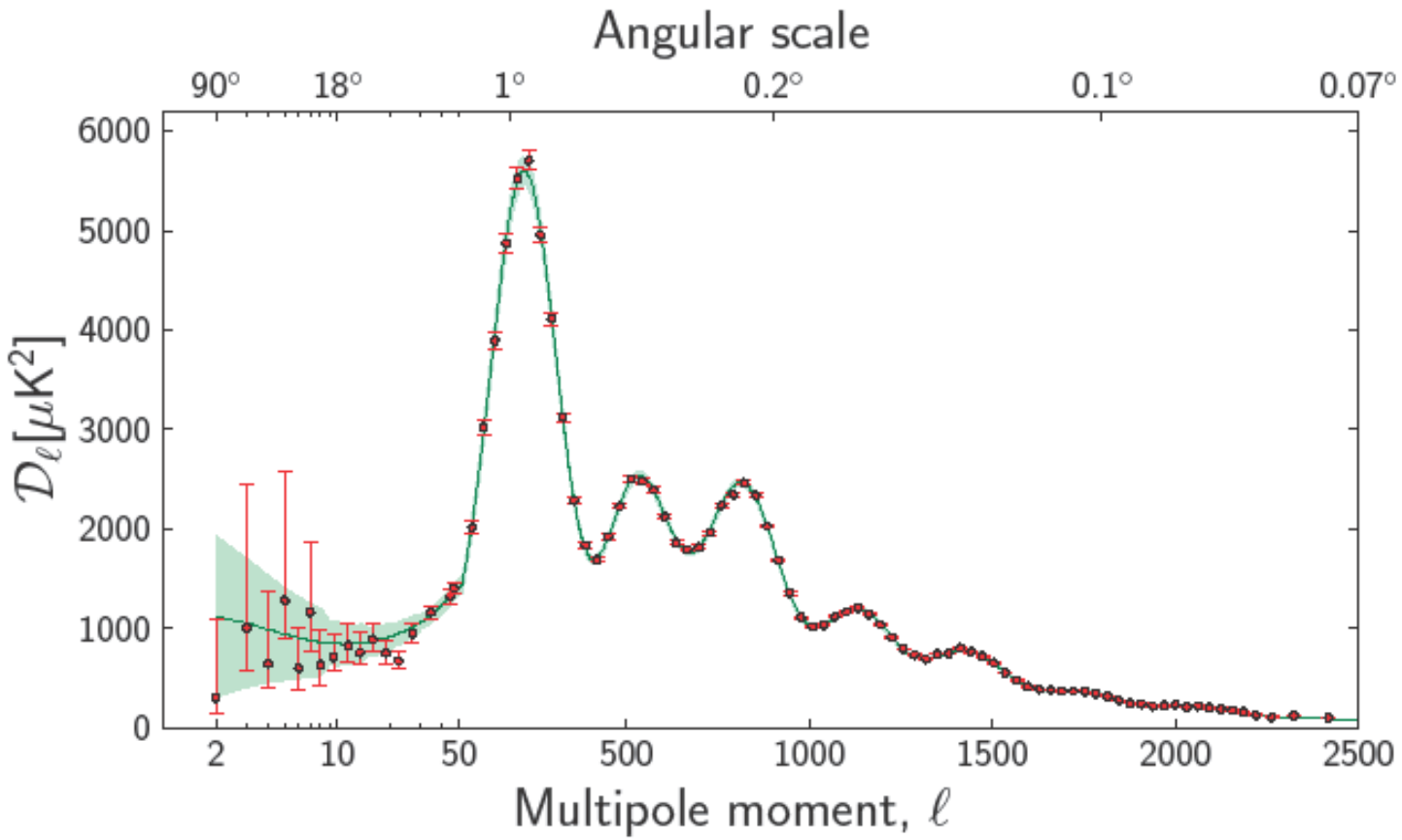
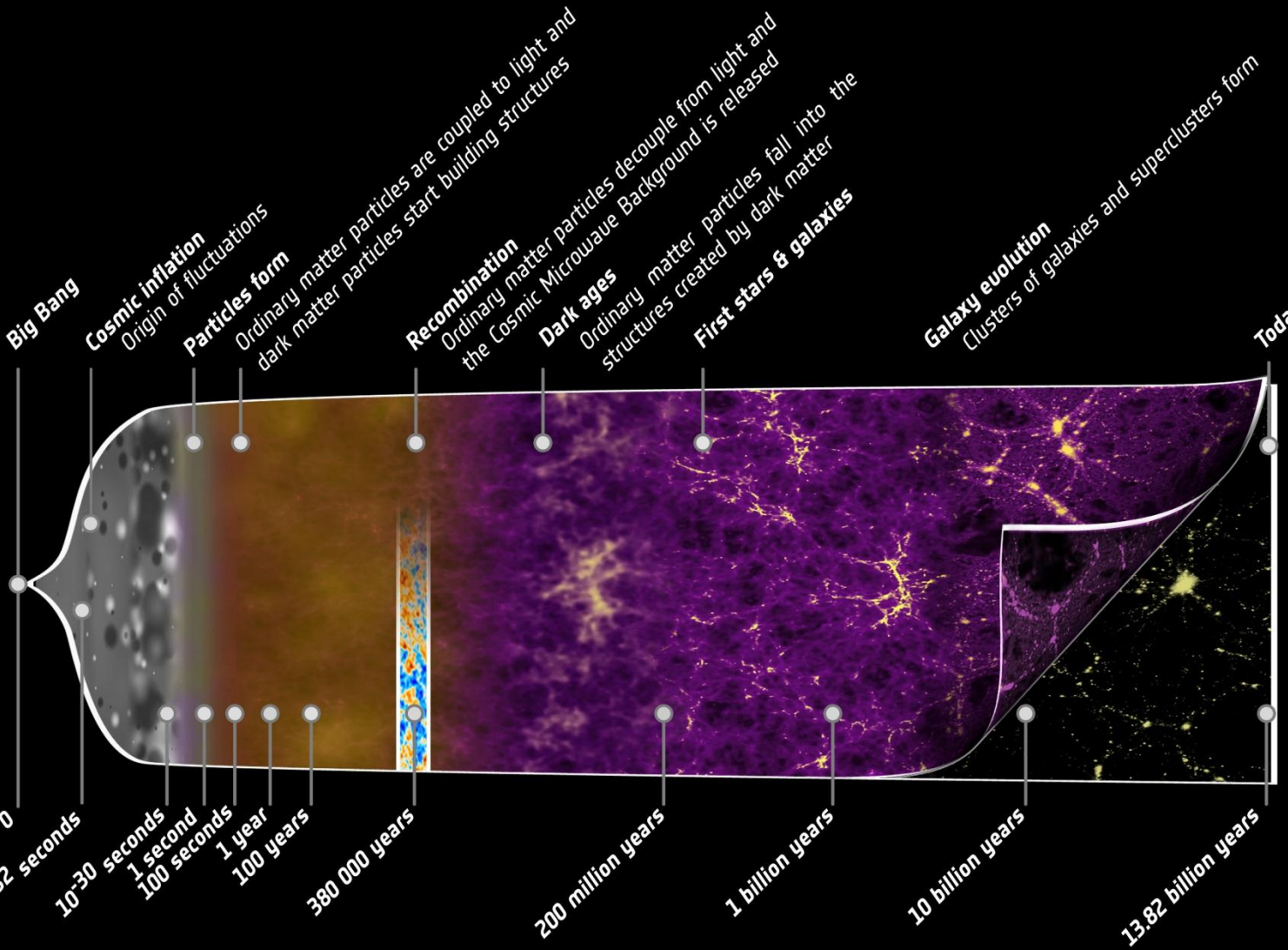
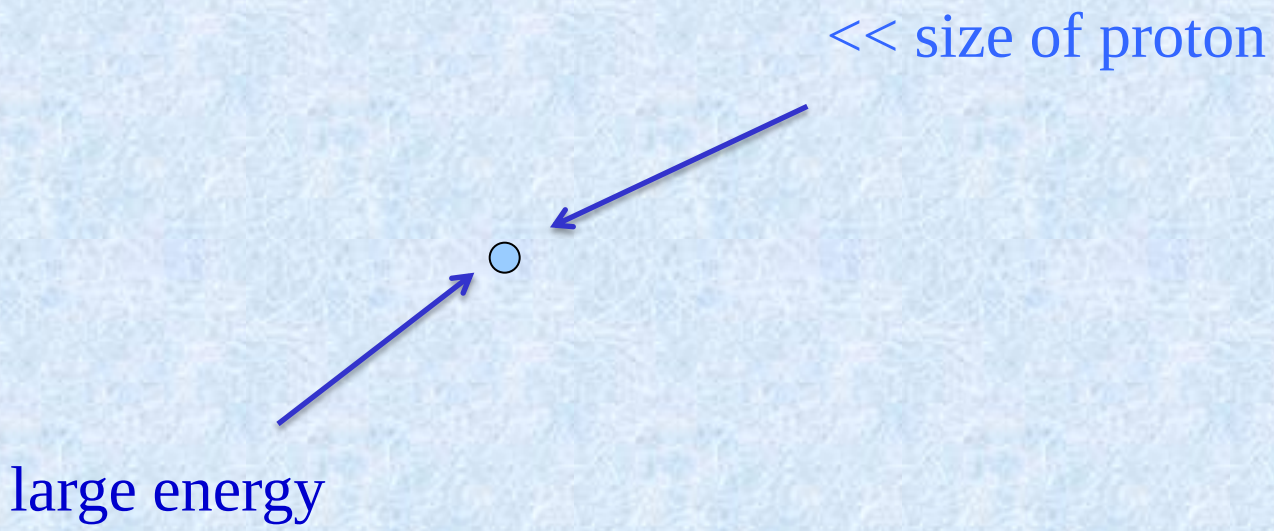
Planck CMB spectrum

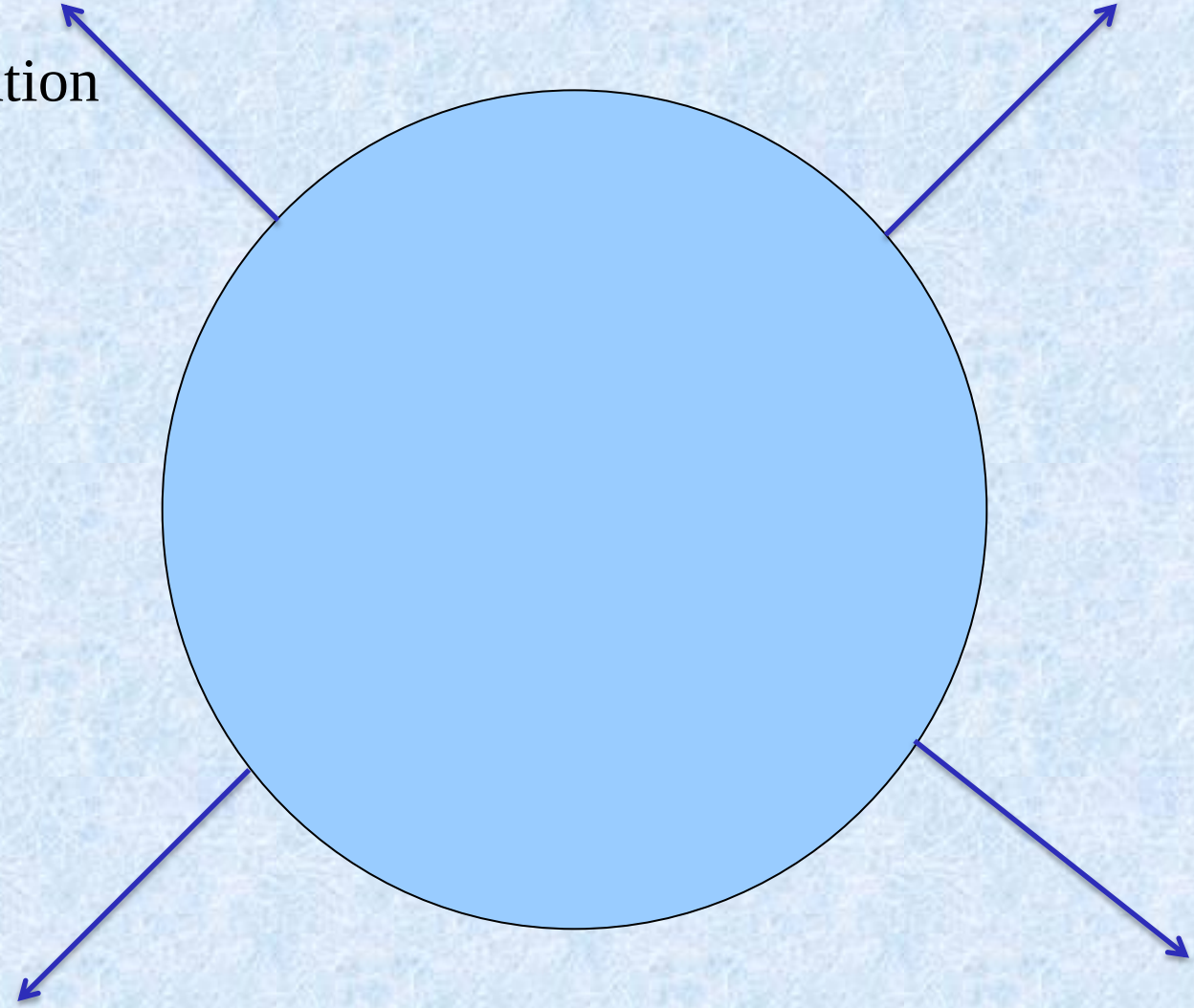


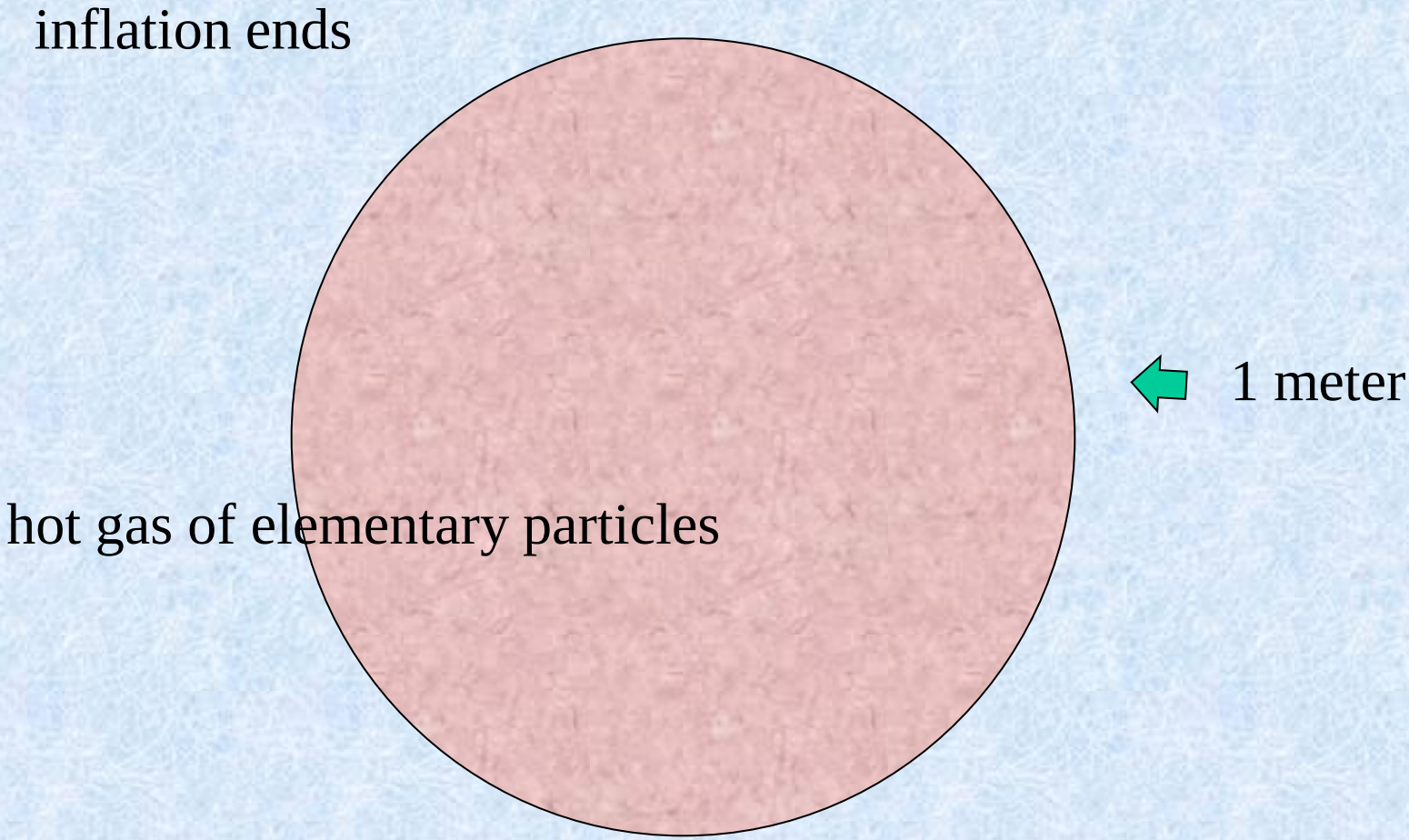

Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles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


<< size of proton
large energy

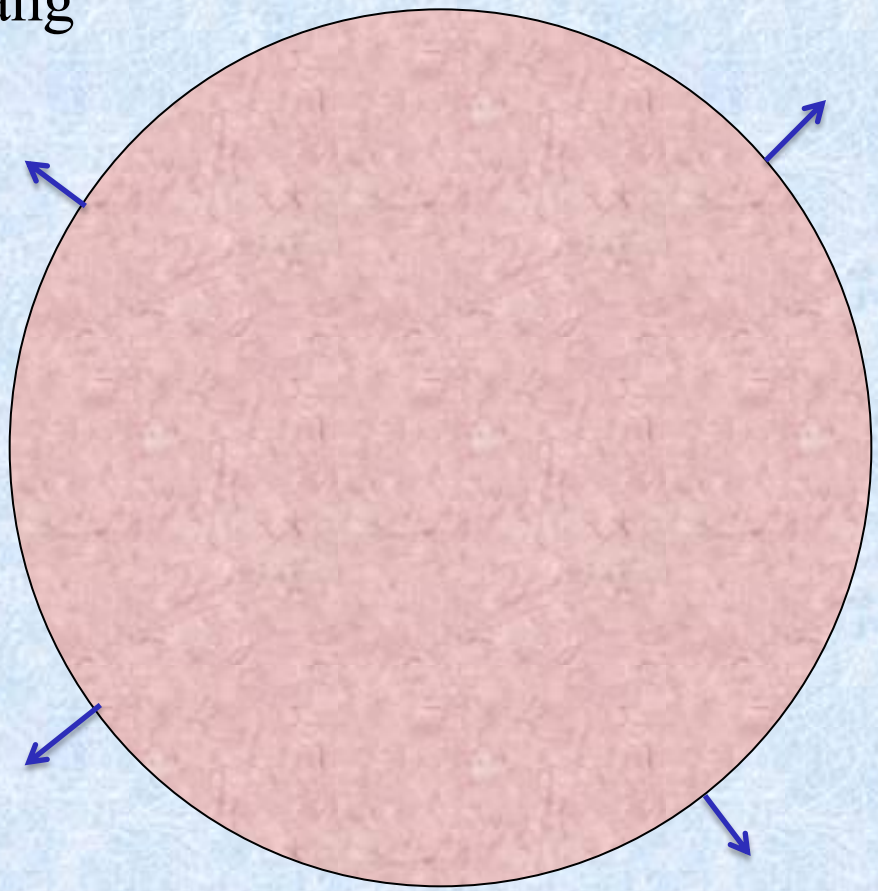
space expands exponentially

inflation




inflation ends
hot gas of elementary particles
1 meter

”hot big bang”



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

$$H = \frac{\dot{a}}{a}$$

Inflaton:

Homogenous scalar field φ responsible for superluminal expansion

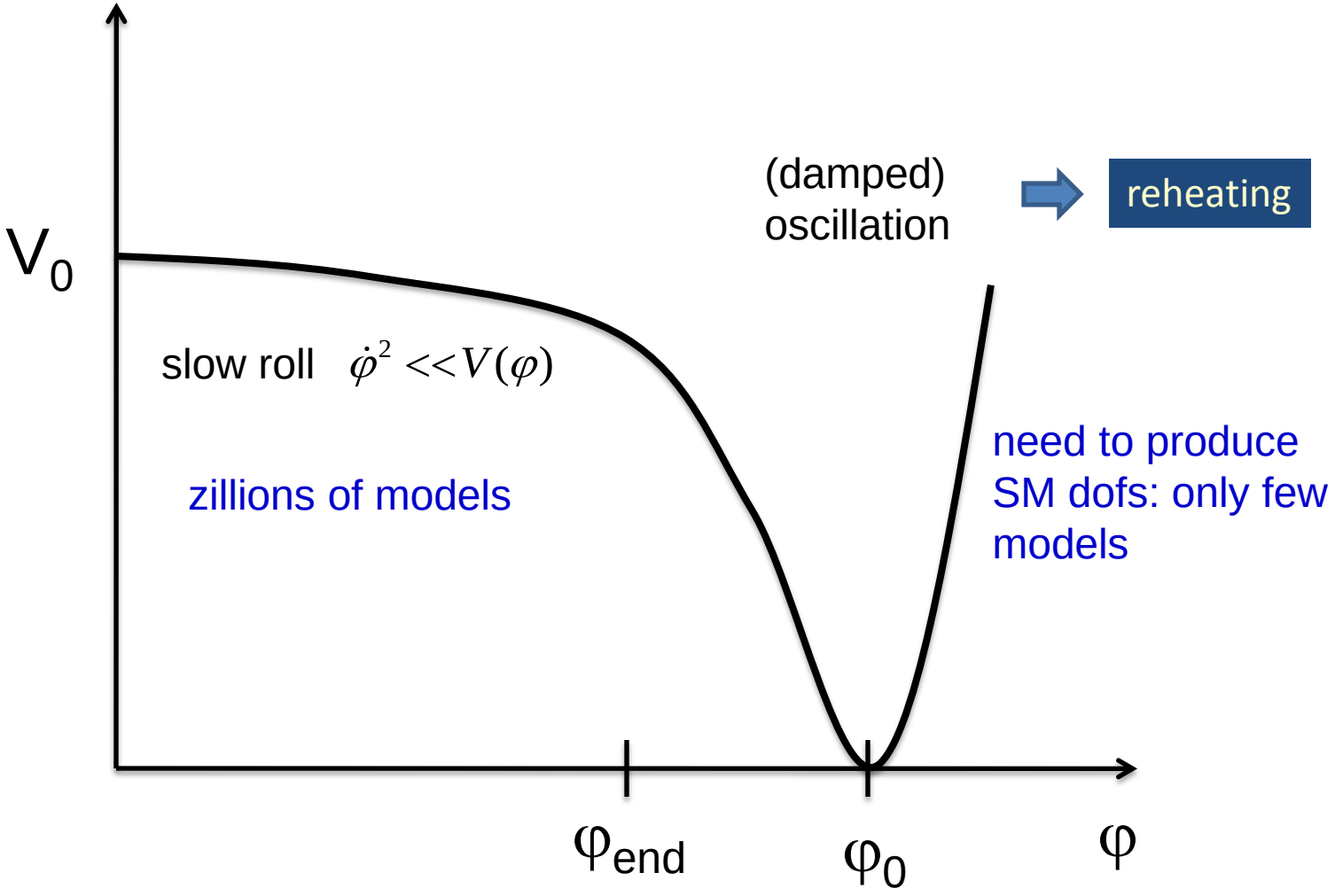
$$\rho = \tfrac{1}{2}\dot{\varphi}^2 + V(\varphi)$$

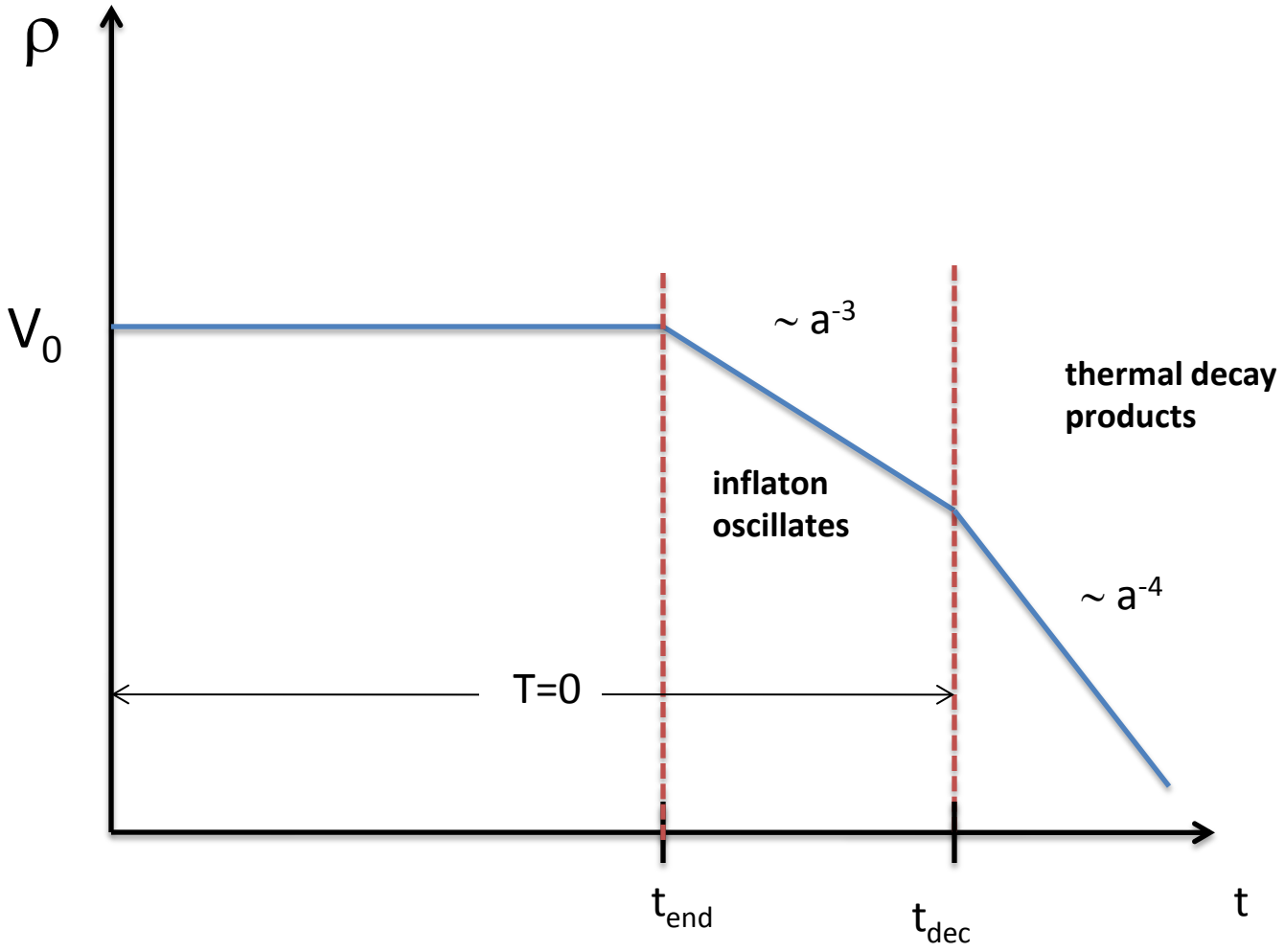
FRW: $3M_P^2 H^2 = \rho$

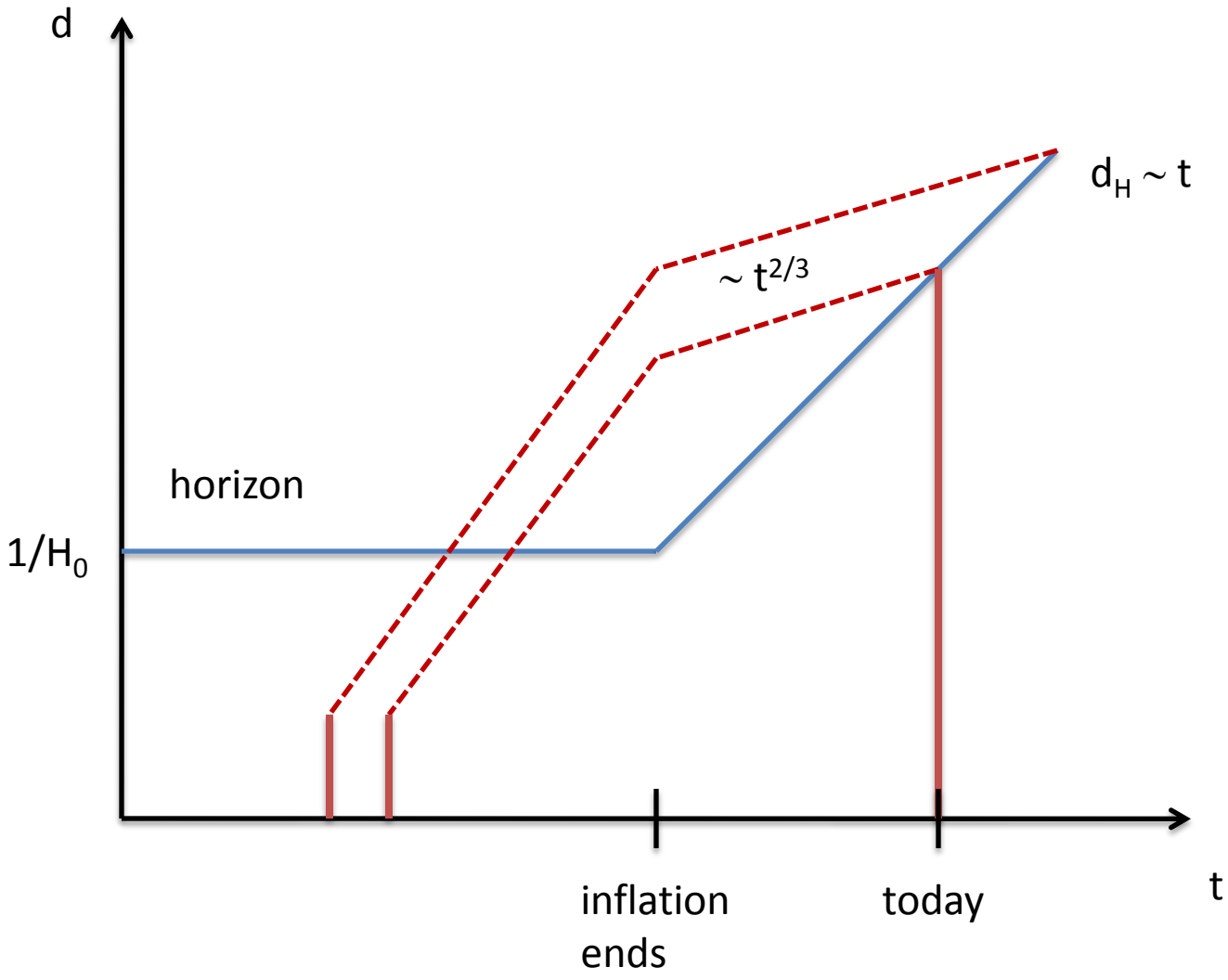
→ constant Hubble if φ in slow roll $\dot{\varphi}^2 << V(\varphi)$

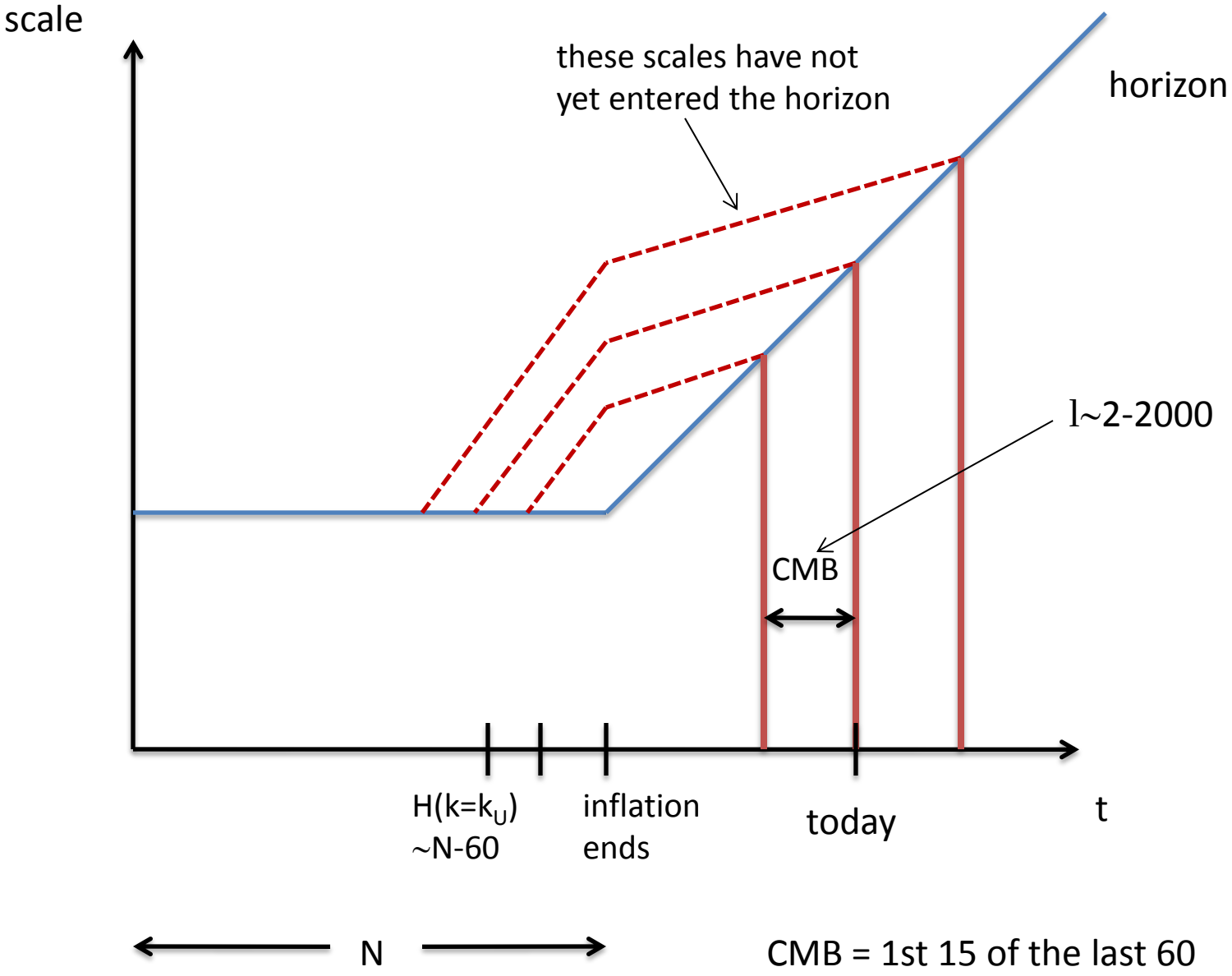
→ equation of motion in FRW $3H\dot{\varphi} + V'(\varphi) = 0$

slow roll inflation




ρ
V_0
~ a^{-3}
thermal decay products
inflaton oscillates
~ a^{-4}
T=0
t_{end}
t_{dec}
t


d
$d_H \sim t$
$\sim t^{2/3}$
horizon
$1/H_0$
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

during inflation fields quantum fluctuate

$$\varphi = \varphi_0(t) + \delta\varphi(t,x)$$

homogeneous background

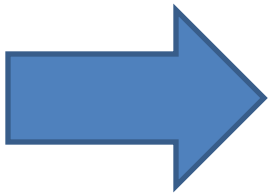
quantum fluctuation

locally Minkowski

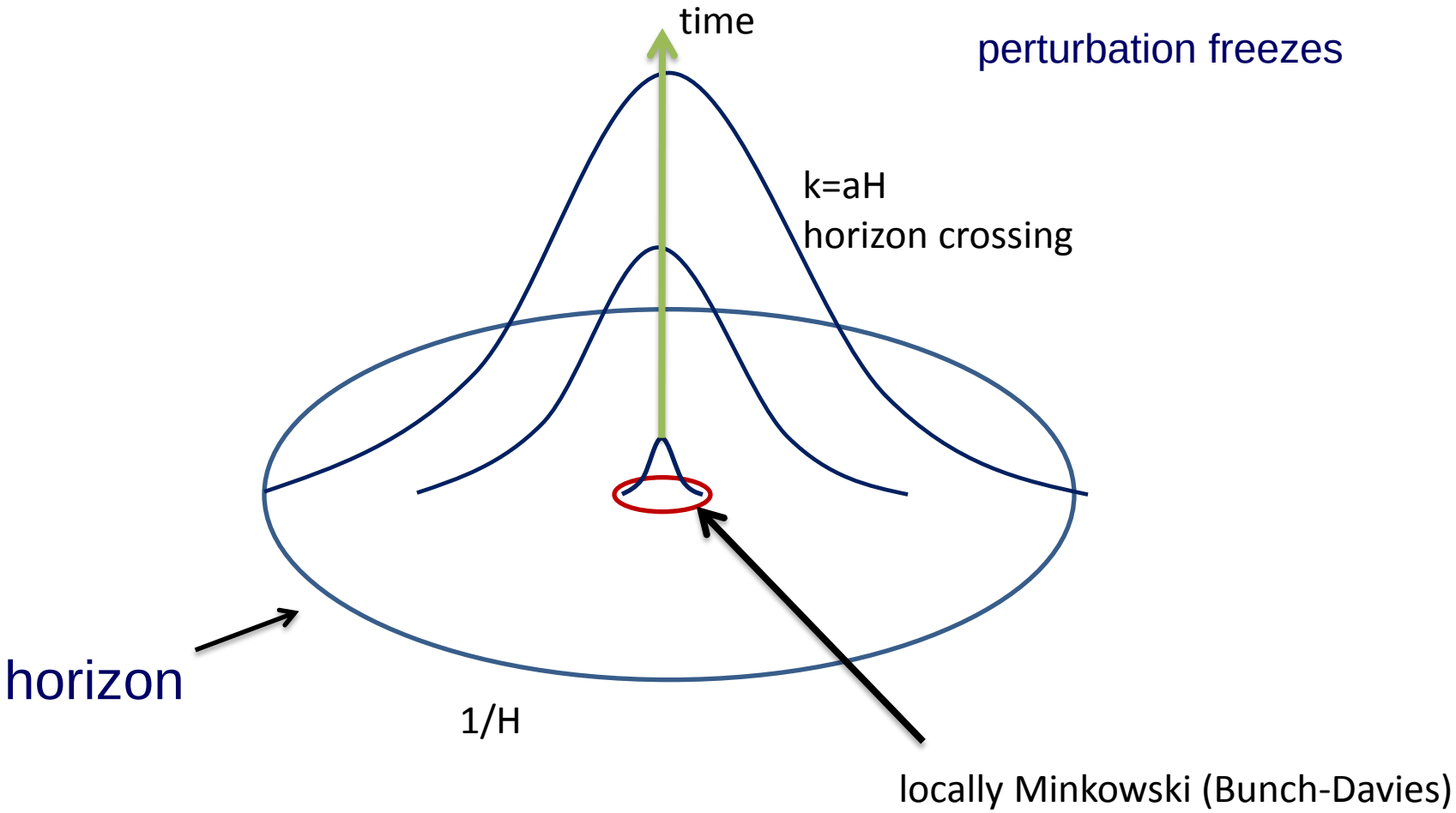
$$\langle \delta\varphi(t,x) \rangle = 0 \quad \textbf{but} \quad \langle \delta\varphi(t,x)^2 \rangle \neq 0$$

→ classical field perturbation

insert into equations of motion and solve



during inflation fields quantum fluctuate



slow roll ⇒ almost scale invariant spectrum of perturbations

From field perturbation to temperature fluctuation

during slow roll $3M_P^2 H_*^2 = \rho \approx V(\phi)$

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

→ $g_{\mu\nu} \to g_{\mu\nu} + \delta g_{\mu\nu}$ metric perturbation

general coordinate invariance: $g_{\mu\nu} \to g'_{\mu\nu}$

→ need gauge invariant measure: curvature perturbation ζ

at large scales $\zeta \propto \frac{\delta T}{T}$

origin of the dominant curvature perturbation

1) during inflation

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

2) after inflation

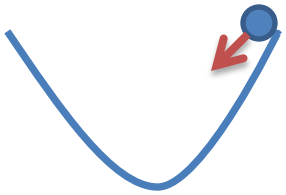
- curvaton models
- modulated reheating
- modulated end of inflation

but require a period of inflation

Large number of inflaton models

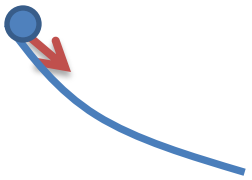
$$V = \lambda M_P^4 \left(\frac{\varphi}{M_P} \right)^p$$

chaotic inflation



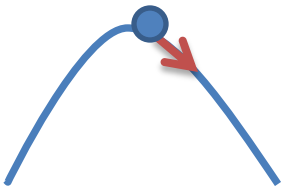
$$V = \Lambda^4 \exp\left(-\lambda \frac{\varphi}{M_P} \right)$$

power law inflation

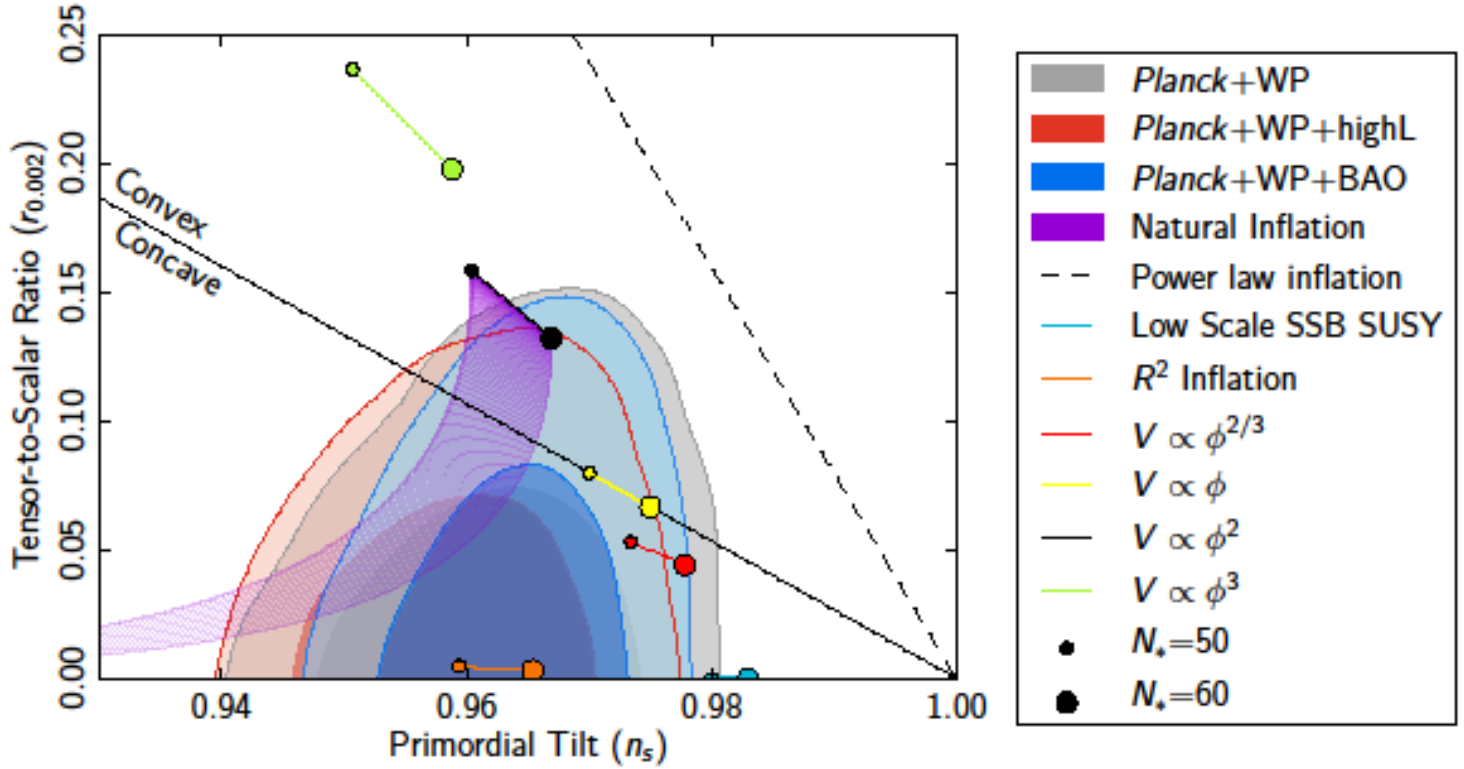


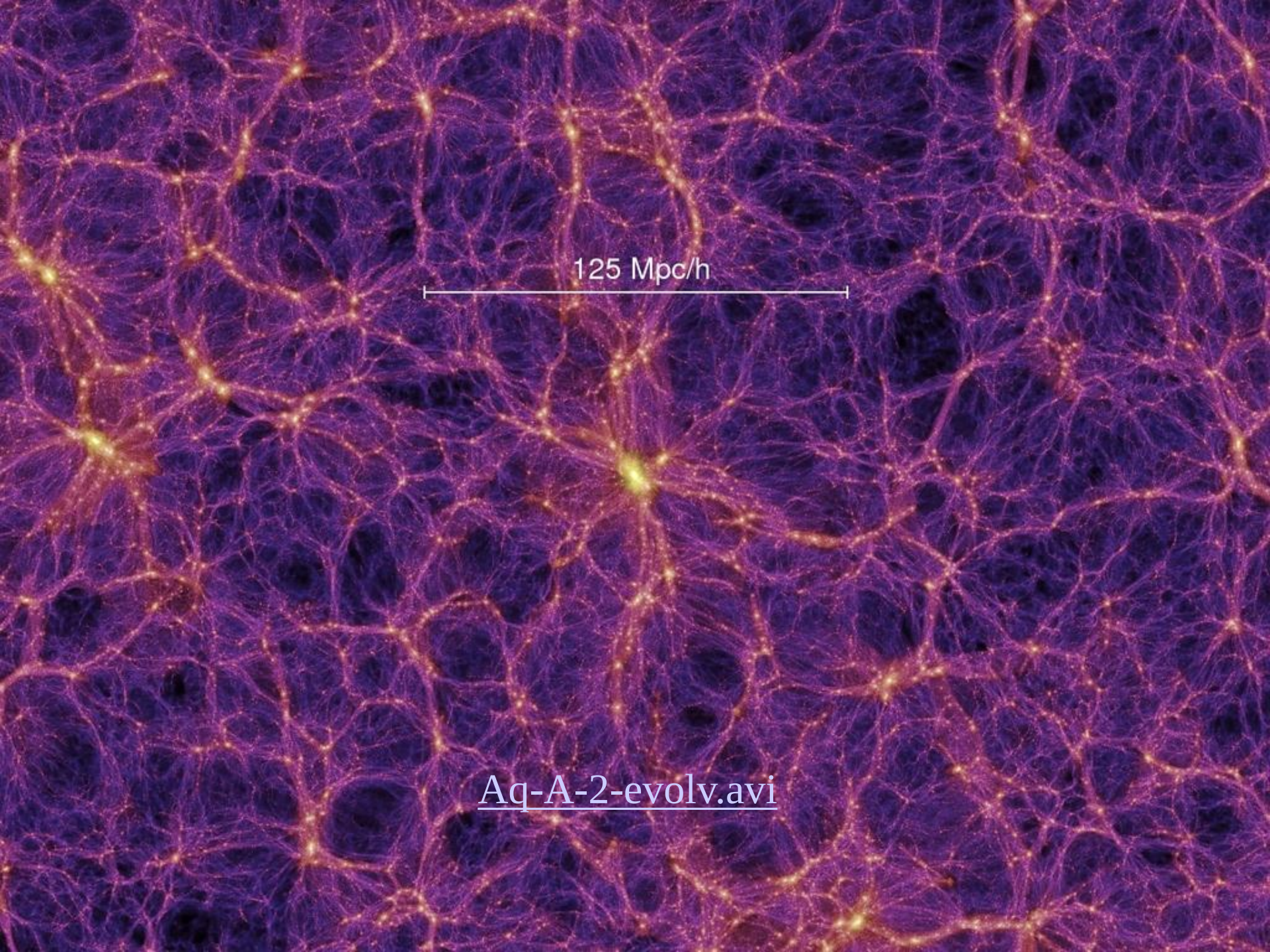
$$V = \Lambda^4 \left(1 - \frac{\varphi^p}{m^p} + \ldots \right)$$

hilltop inflation



etc


Tensor-to-Scalar Ratio ($r_{0.002}$)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00
Primordial Tilt (n_s)
Convex
Concave
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



Aq-A-2-evolv.avi

CONCLUSION

- **origin of structure: inflation**
- **no specific model**
- **primordial perturbation could be generated during or after inflation**