From Quantum Fluctuations to Galaxies

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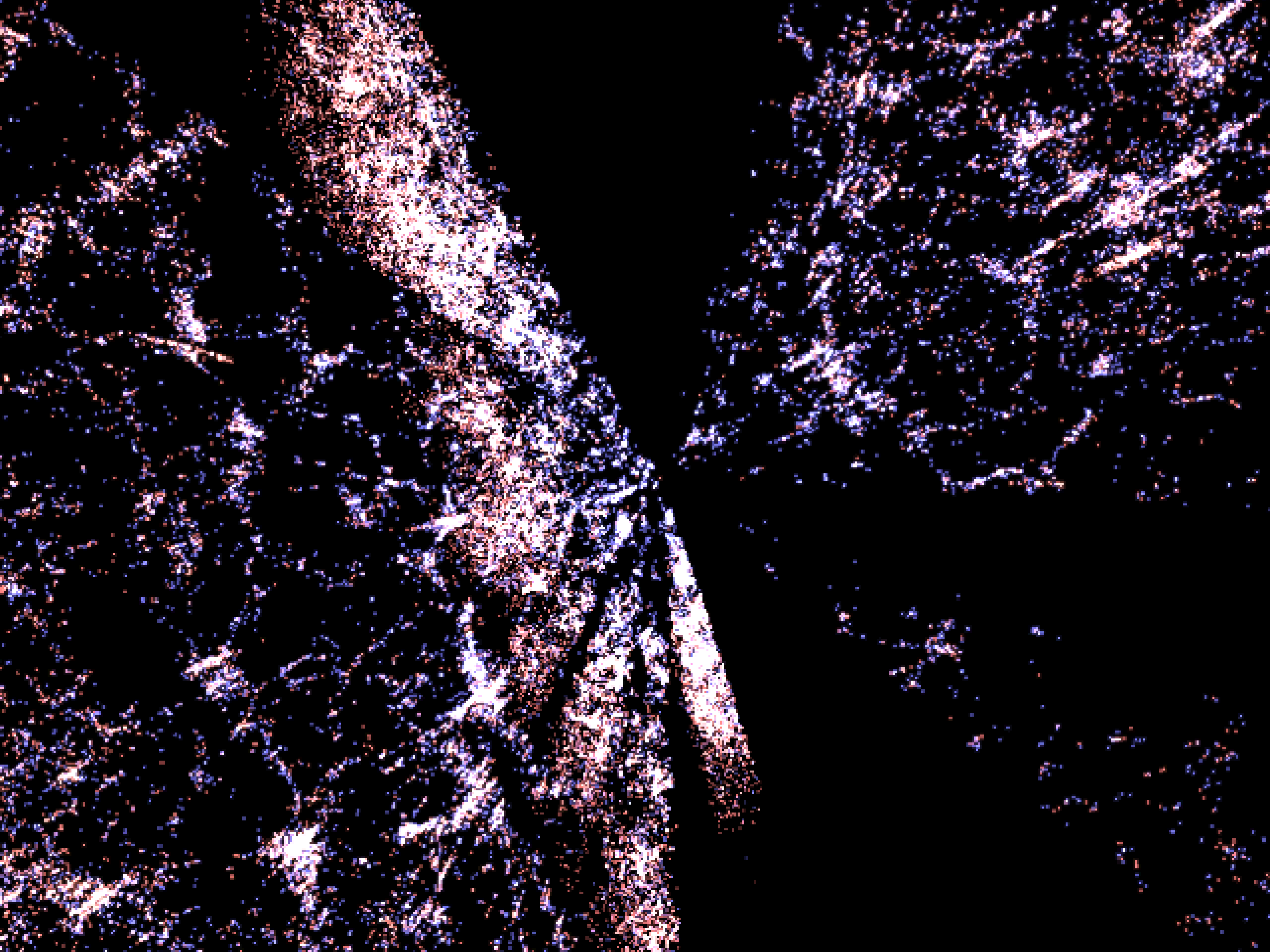
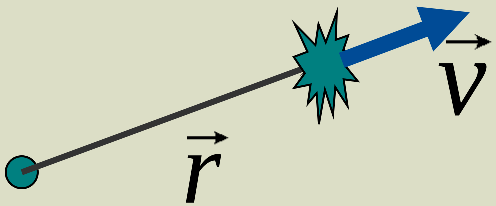


"...our mistake is not that we take our theories too seriously, but that we do not take them seriously enough. It is always hard to realize that these numbers and equations we play with at our desks have something to do with the real world..."

S. Weinberg, "The first three minutes"

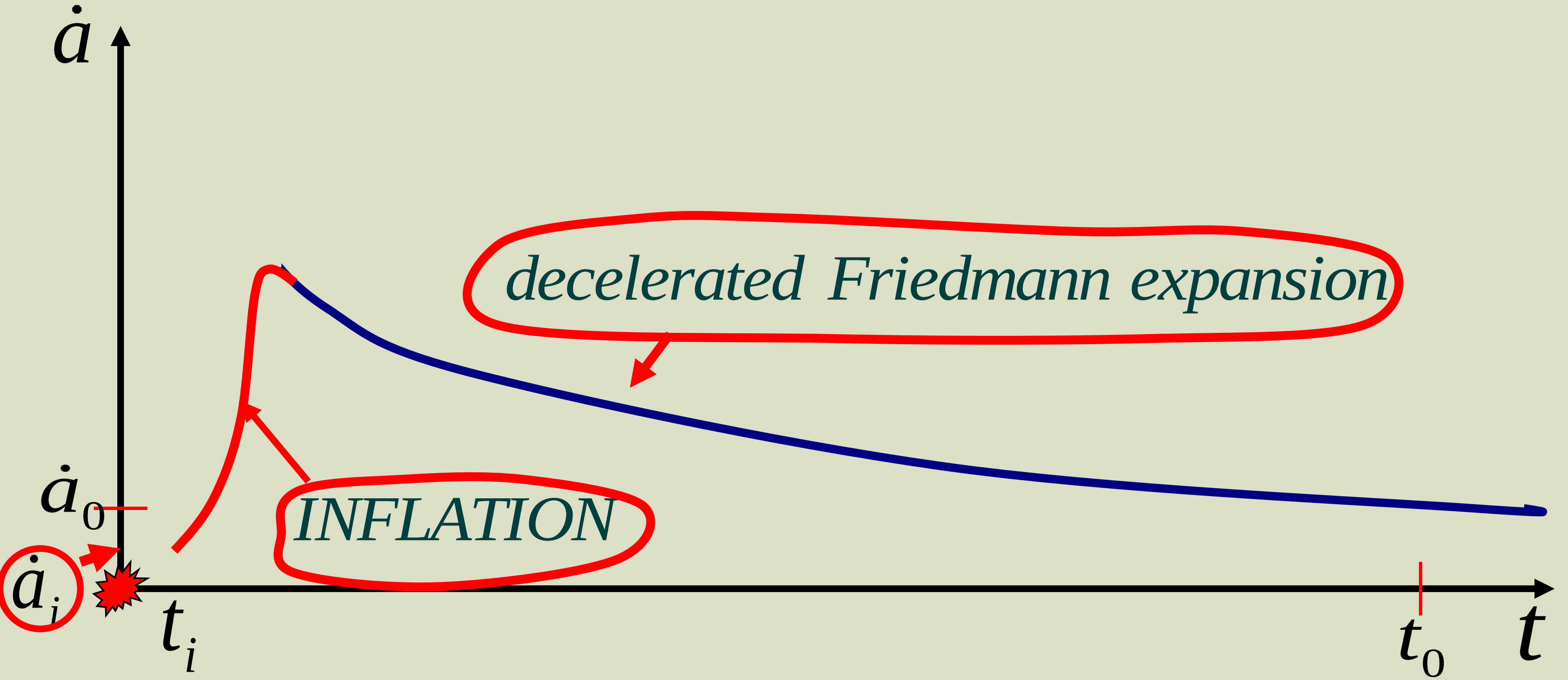
- Hubble law



$$\vec{r} = a(t)\,\vec{\chi}_{com}$$

$$\vec{v} = \dot{a}\,\vec{\chi}_{com}$$

rate of expansion



Necessary conditions for successful inflation:

- $\dot{a}_i << \dot{a}_0 \longrightarrow \Omega_0 \equiv \frac{|E_0^{pot}|}{E_0^{kin}} = 1$ — Prediction of inflation!

- Transition from inflation to Friedmann era should be "smooth"

- How gravity can become "repulsive"?

$$\ddot{a} = -\frac{4\pi G}{3}\left(\varepsilon + 3p\right)a$$

acceleration — energy density — pressure

Only if $\varepsilon + 3p < 0 \Rightarrow \ddot{a} > 0 \equiv$ "antigravity"

Scenarios

???

> Simplicity is the ultimate sophistication.
>
> Leonardo da Vinci

Energy density ε, pressure p

$p(\varepsilon) -$ equation of state

$p + \varepsilon \ll \varepsilon$ for inflation

⬇

$$p \approx -\varepsilon$$

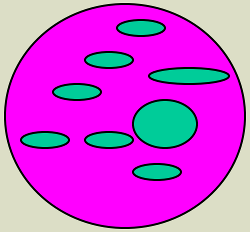
Which concrete scenario was realized ???

$\rightarrow \quad \Delta p \Delta x \geq h$

$\downarrow$

There alwayz exist unavoidable

Quantum Fluctuations



Quantum fluctuations in the densitz distribution are large (10^{-5})

only in extremely small scales ($\sim 10^{-33}$ cm),

but very small ($\sim 10^{-58}$) on galactic scales ($\sim 10^{25}$ cm)

Can we transfer the large fluctuations from extremely small scales to large scales???

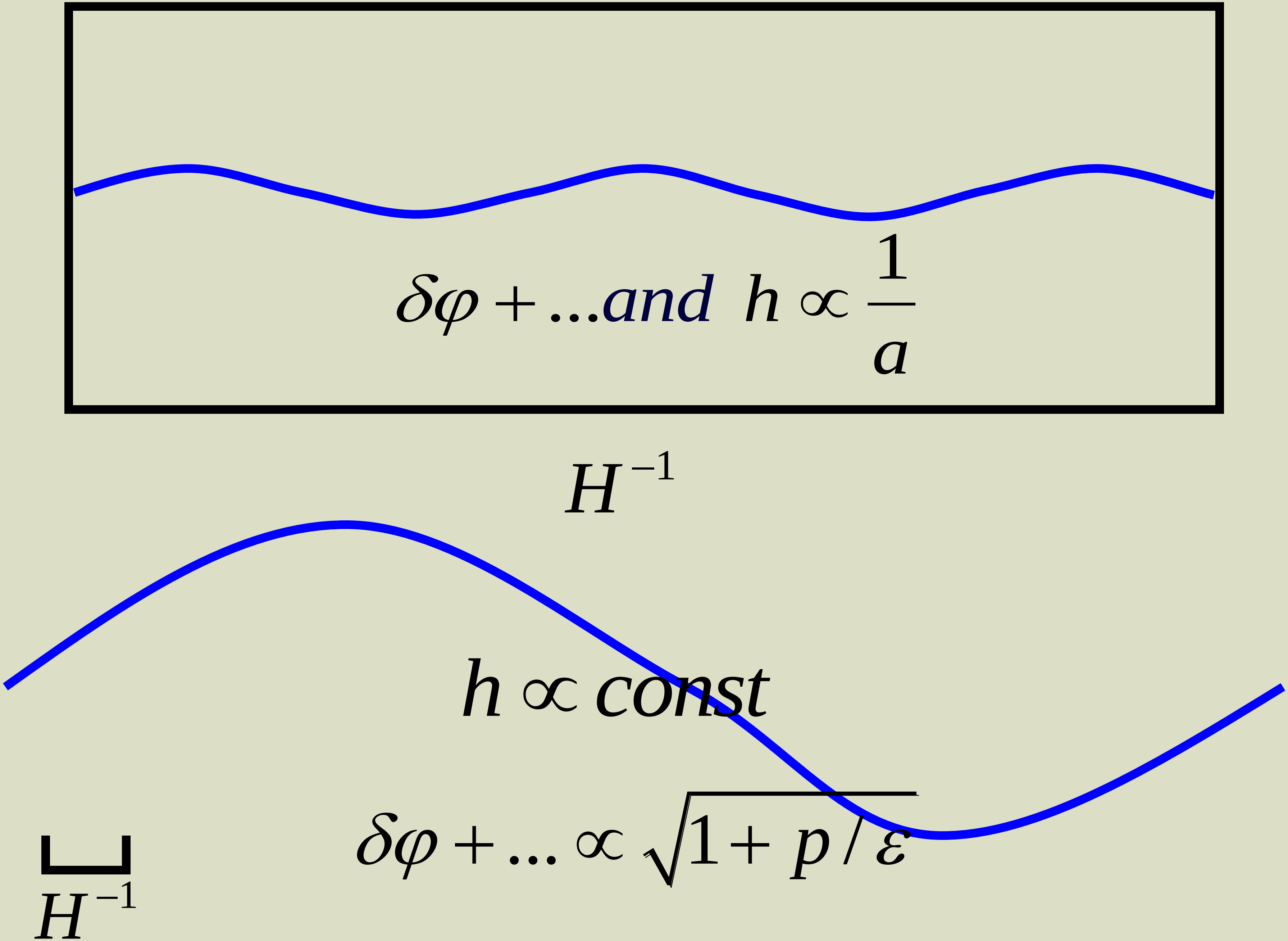
Yes!!! but only if in past the Universe went through the stage of accelerated expansion (inflation)

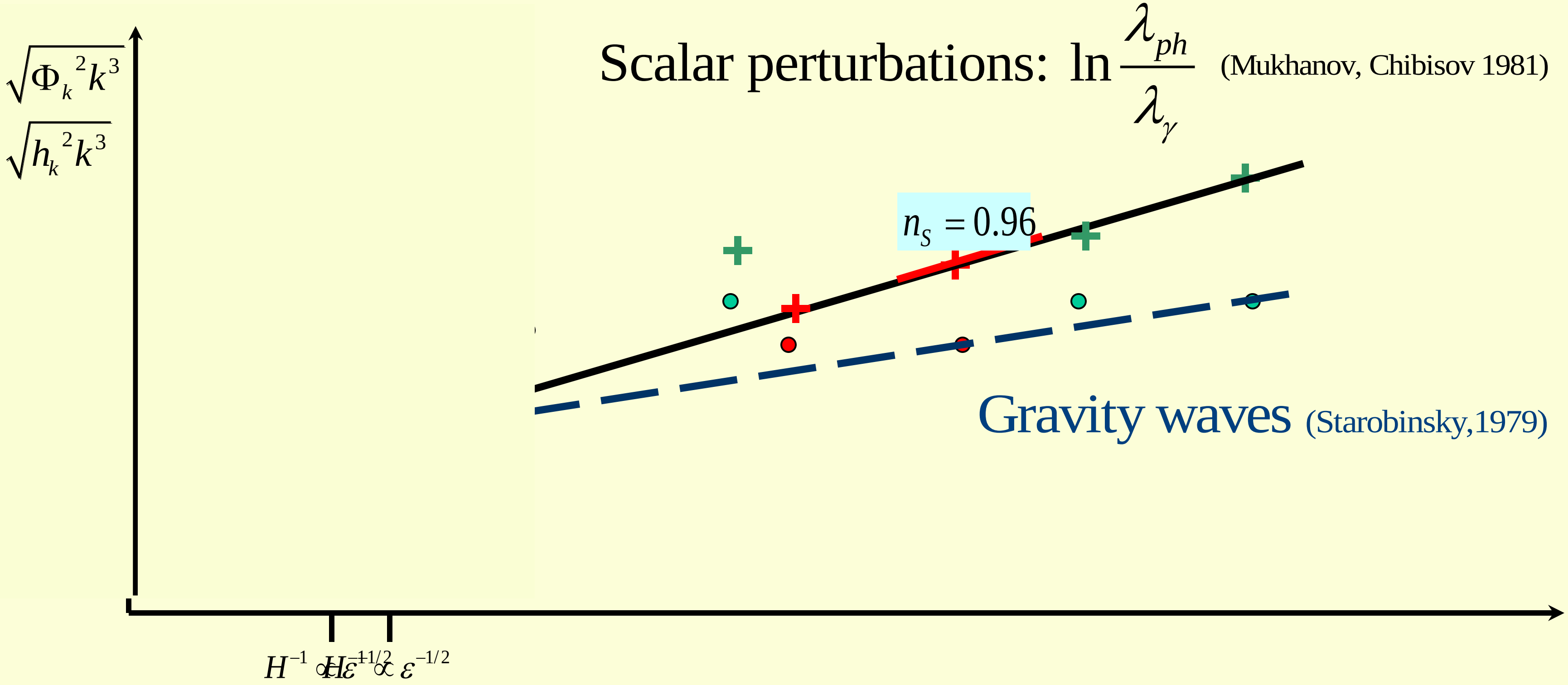
Quantum metric fluctuations are big enough (10^{-5}) only in the scales close to the Planckian scale ($10^{-33}cm$)

Purpose : Transfer these fluctuations to galactic scales ($10^{28}cm$)

- Consider plane wave perturbation: $\delta\varphi, \Phi \propto \exp\left(i\vec{k}_{com}\vec{x}\right)$

For given k_{com}, $\lambda_{ph}(cm) \propto a / k_{com} \propto a(t)$ and the change of the amplitude with time depends on how big is λ_{phys} compared to the curvature scale (size of Einstein lift) $H^{-1} = a / \dot{a}$


δφ + …and h ∝ 1/a
H^−1
h ∝ const
δφ + … ∝ √(1 + p/ε)
H^−1



$\sqrt{\Phi_k^2 k^3}$
$\sqrt{h_k^2 k^3}$
Scalar perturbations: $\ln \frac{\lambda_{ph}}{\lambda_\gamma}$ (Mukhanov, Chibisov 1981)
$n_S = 0.96$
Gravity waves (Starobinsky,1979)
$H^{-1} \propto \varepsilon^{-1/2}$

$$0.92 < n_S < 0.97$$

Summary

Input from HEP

???

Idea and basic properties of inflation are established:
Inflation is the stage of accelerated expansion of the universe with graceful exit to Friedmann stage

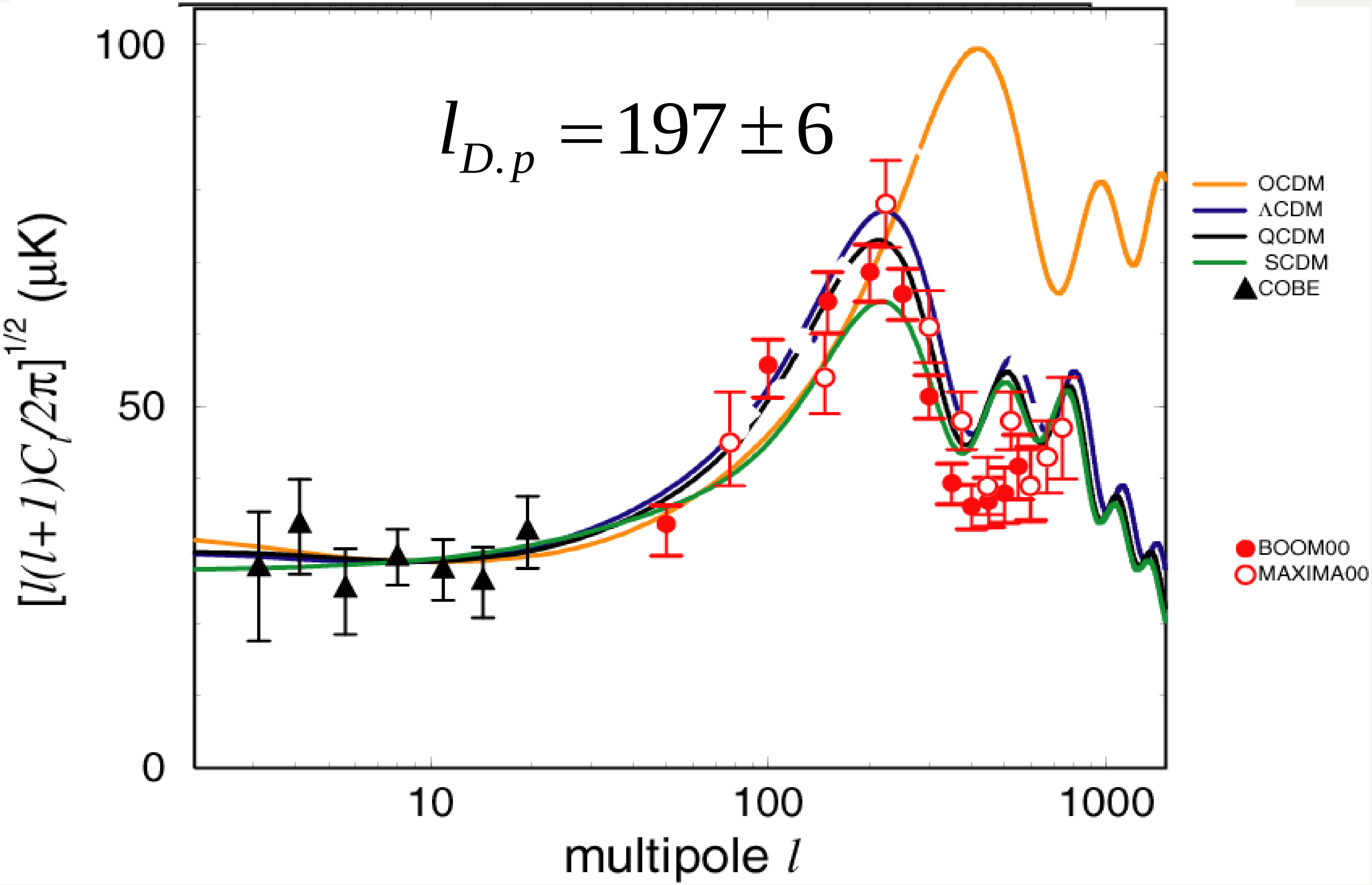
SCENARIO ???

???

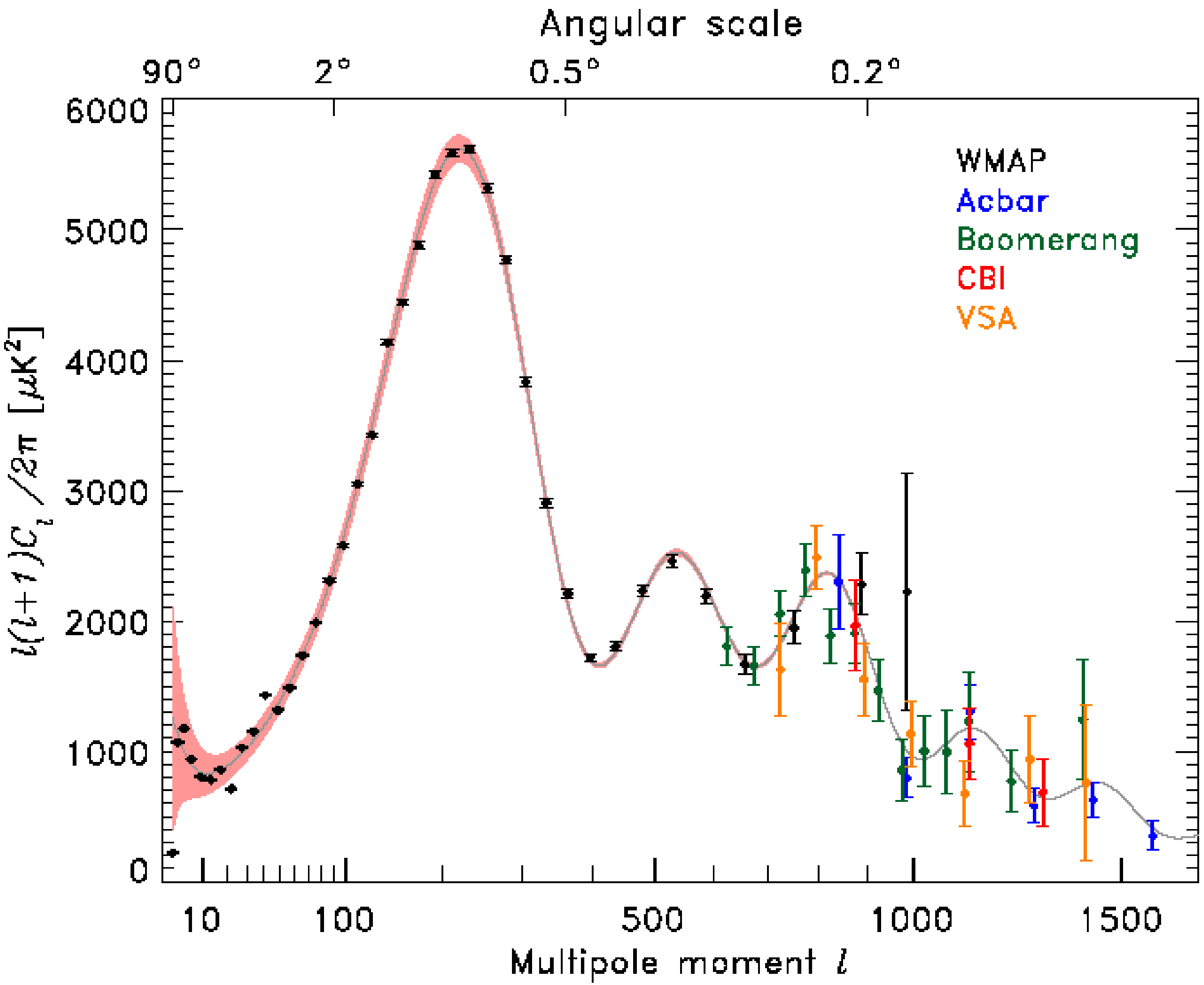
- Robust predictions:
  - –Spatially flat Universe: $\Omega_{total} = 1 \pm 10^{-5}$
  - –Sligtly red-tilted spectrum of scalar perturbations $(0{,}92 < n_S < 0{,}97)$
  - –Perturbations are Gaussian
  - –Gravity waves

- Energy scale of inflation → prediction of the perturbations amplitude, concrete n_s
- Transition from inflation to Friedmann, reheating mechanism
- The origin of small number 10^{-5} characterizing perturbations

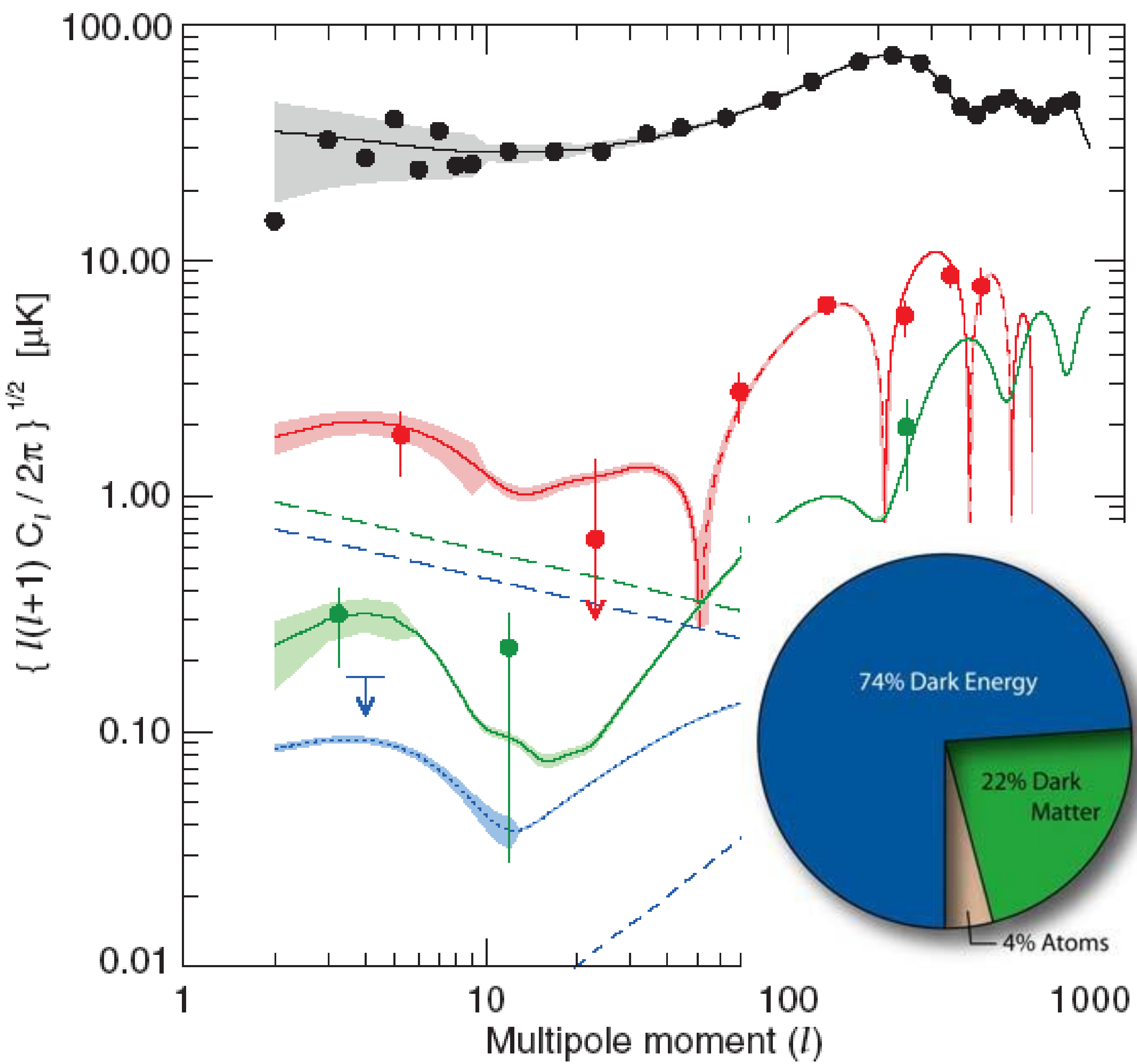
$$l_{D.p} = 197 \pm 6$$



100
50
0
10
100
1000
multipole l
$[l(l+1)C_l/2\pi]^{1/2}$ (μK)
OCDM
ΛCDM
QCDM
SCDM
COBE
BOOM00
MAXIMA00



Angular scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ [μK^2]
WMAP
Acbar
Boomerang
CBI
VSA
10
100
500
1000
1500
Multipole moment l


100.00
10.00
1.00
0.10
0.01
{ l(l+1) C_l / 2π }^{1/2} [μK]
1
10
100
1000
Multipole moment (l)
74% Dark Energy
22% Dark Matter
4% Atoms

"A finite duration of the de Sitter stage does not by itself rule out the possibility that this stage may exist as an intermediate stage in the evolution of the universe. An interesting question arises here: Might not perturbations of the metric , which would be sufficient for the formation of galaxies and galactic clusters, arise in this stage?..........

$$Q(k) \approx 3lM\left(1+\frac{1}{2}\ln\frac{H}{k}\right)$$

The fluctuation spectrum is. $n_s = 0.96$ y flat...."

(Mukhanov, Chibisov,1981)

$n_s = 0.951$

In terms of my own money, I'd bet a lot (many thousands)