The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2234-10

Meeting of Modern Science and School Physics: College for School Teachers of Physics in ICTP

27 April - 3 May, 2011

Cosmic inflation: Conjectures vs. facts

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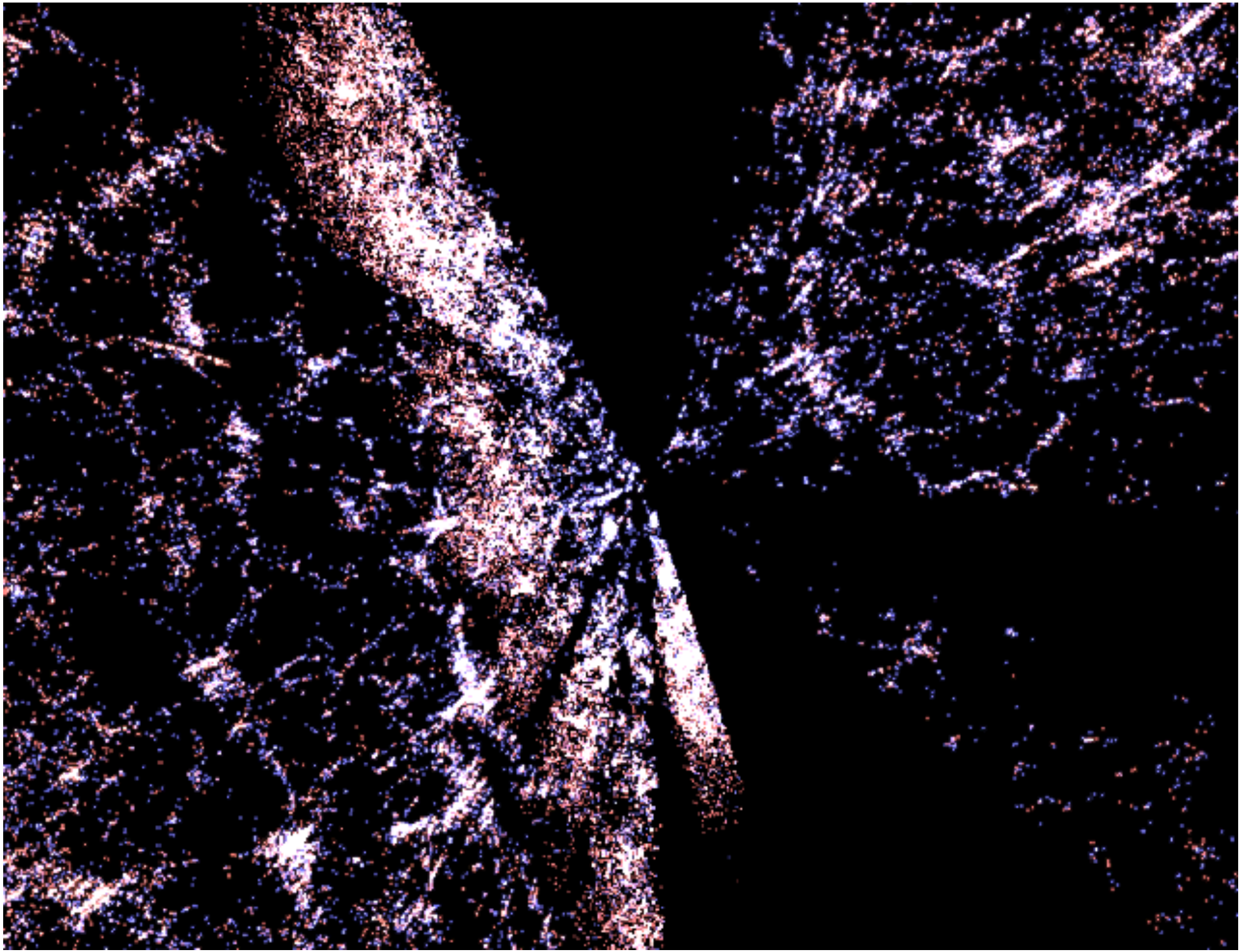
Ludwig Maximilians Universitat
Munich
Germany

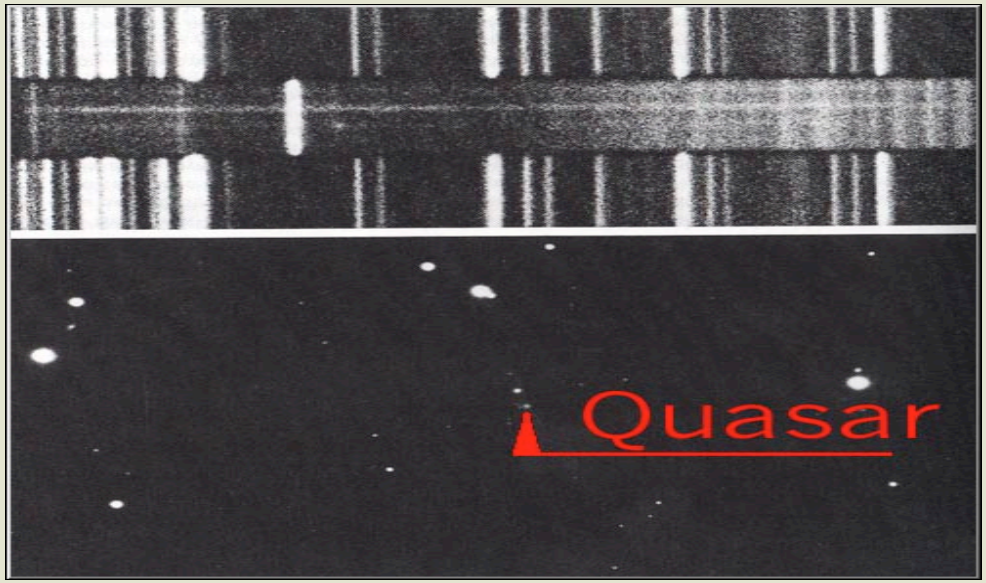
The Origin of the Universe

V. Mukhanov

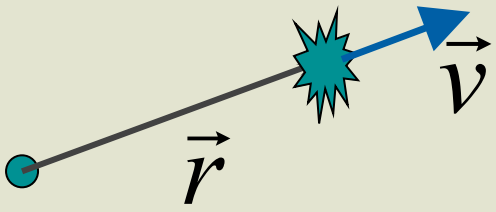
Sektion Physik, LMU, München



The Universe expands



Hubble law



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

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

Rate of expansion

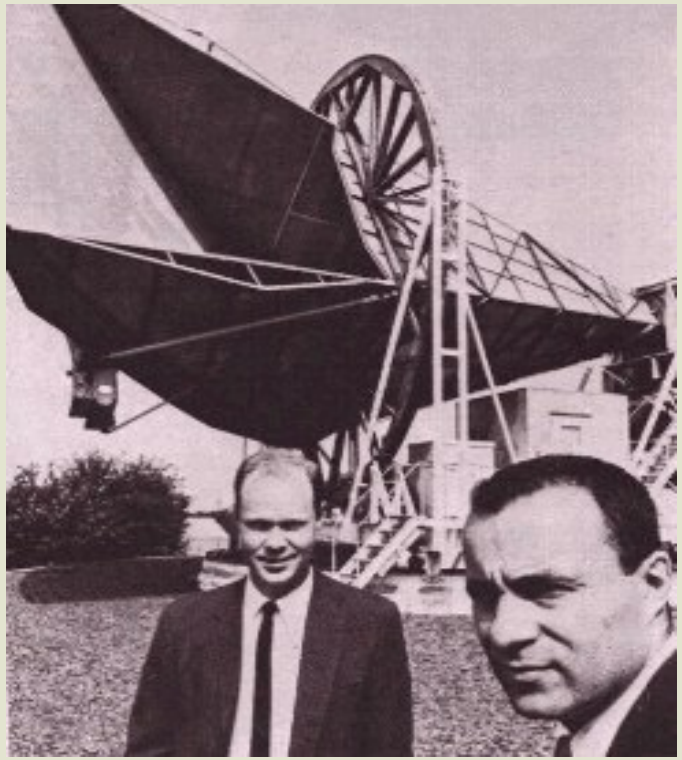
$$t \sim \frac{r}{v} \sim 13{,}7\, bil.\, years$$

Expanding Universe: Facts

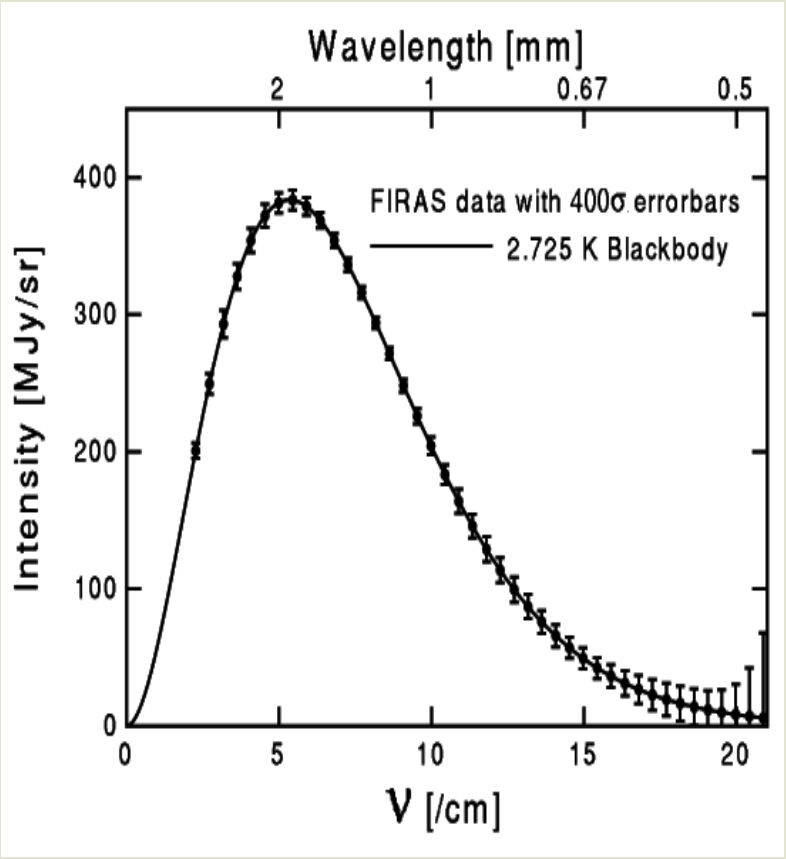
- Today: The Universe is homogeneous and isotropic on scales from 300 millions up to 13 billions light-years
- There exist structure on small scales: Planets, Stars, Galaxies, Clusters of galaxies Superclusters ....
- There is $\sim 75\% H$, $\sim 25\% He$ and heavy elements in very small amounts

- In past the Universe was VERY hot
- There exist Dark Matter and Dark Energy
- When the Universe was about 1000 times smaller, it was extremely homogeneous and isotropic in all scales $\frac{\delta\varepsilon}{\varepsilon} \sim 10^{-5}$

- There exists background radiation with the temperature $T = 2.725°K$



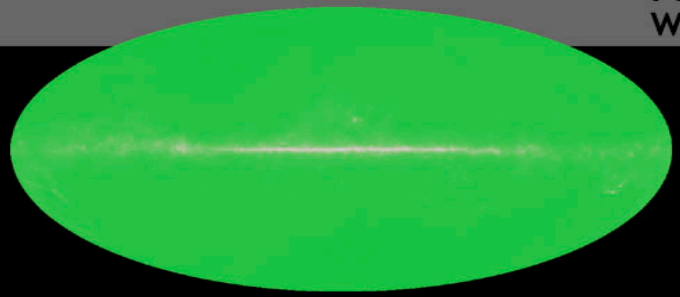
Penzias, Wilson 1965



2.725K Blackbody
Spectrum of the CMB

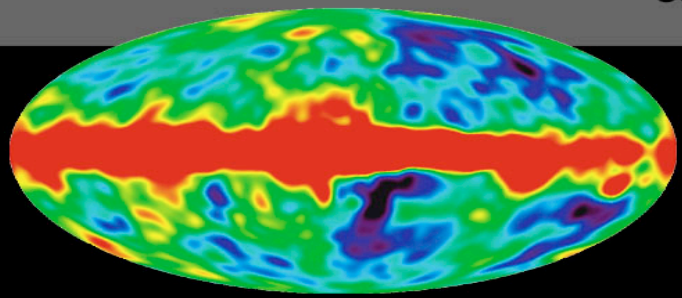
1965

Penzias and Wilson



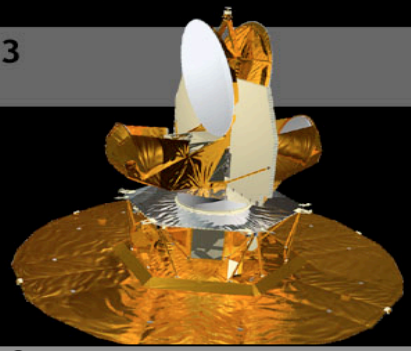
1992

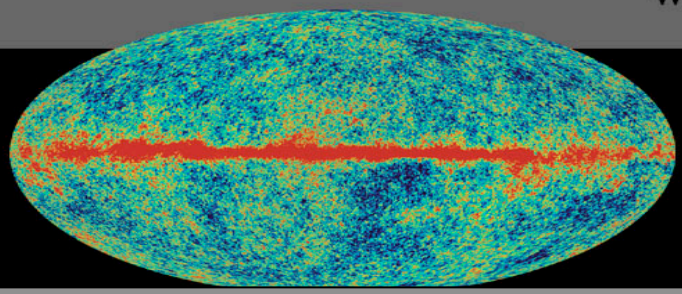
COBE



2003

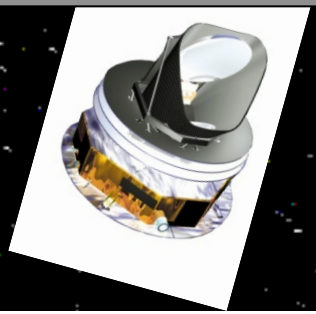
WMAP





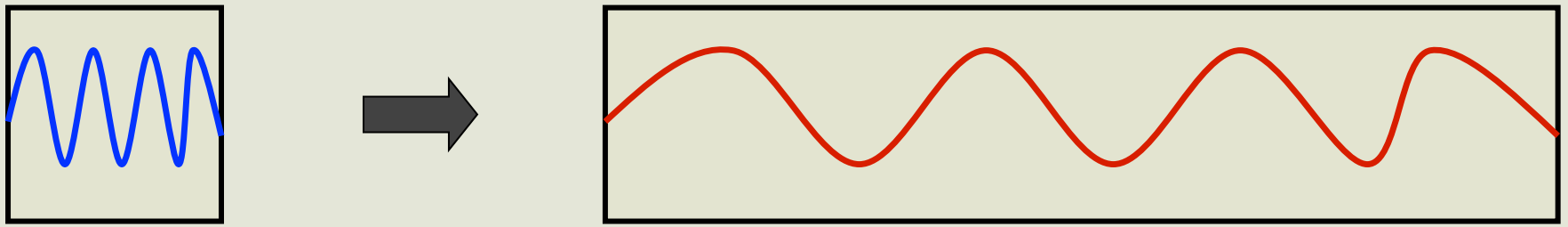
2009

Planck



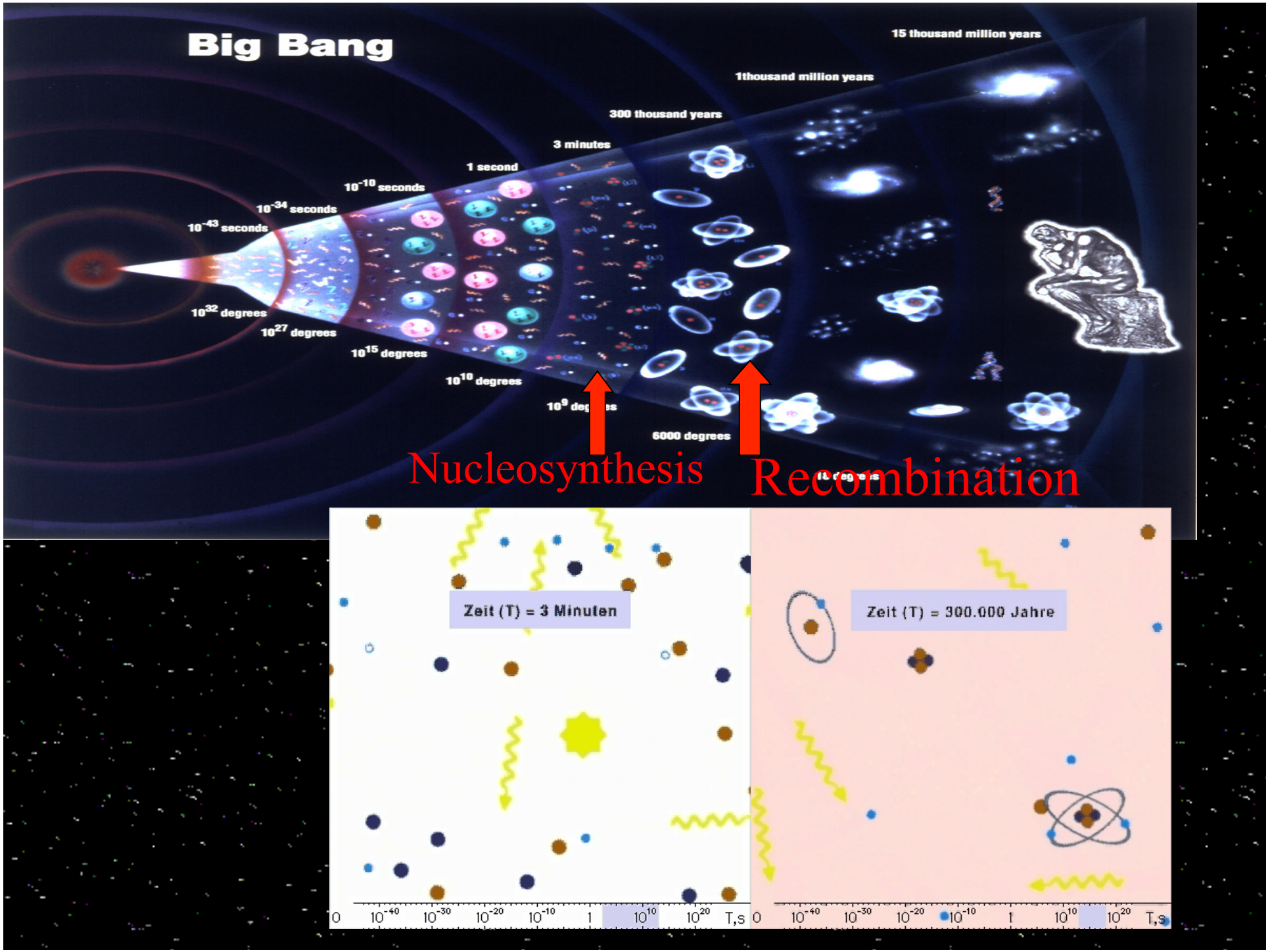
???

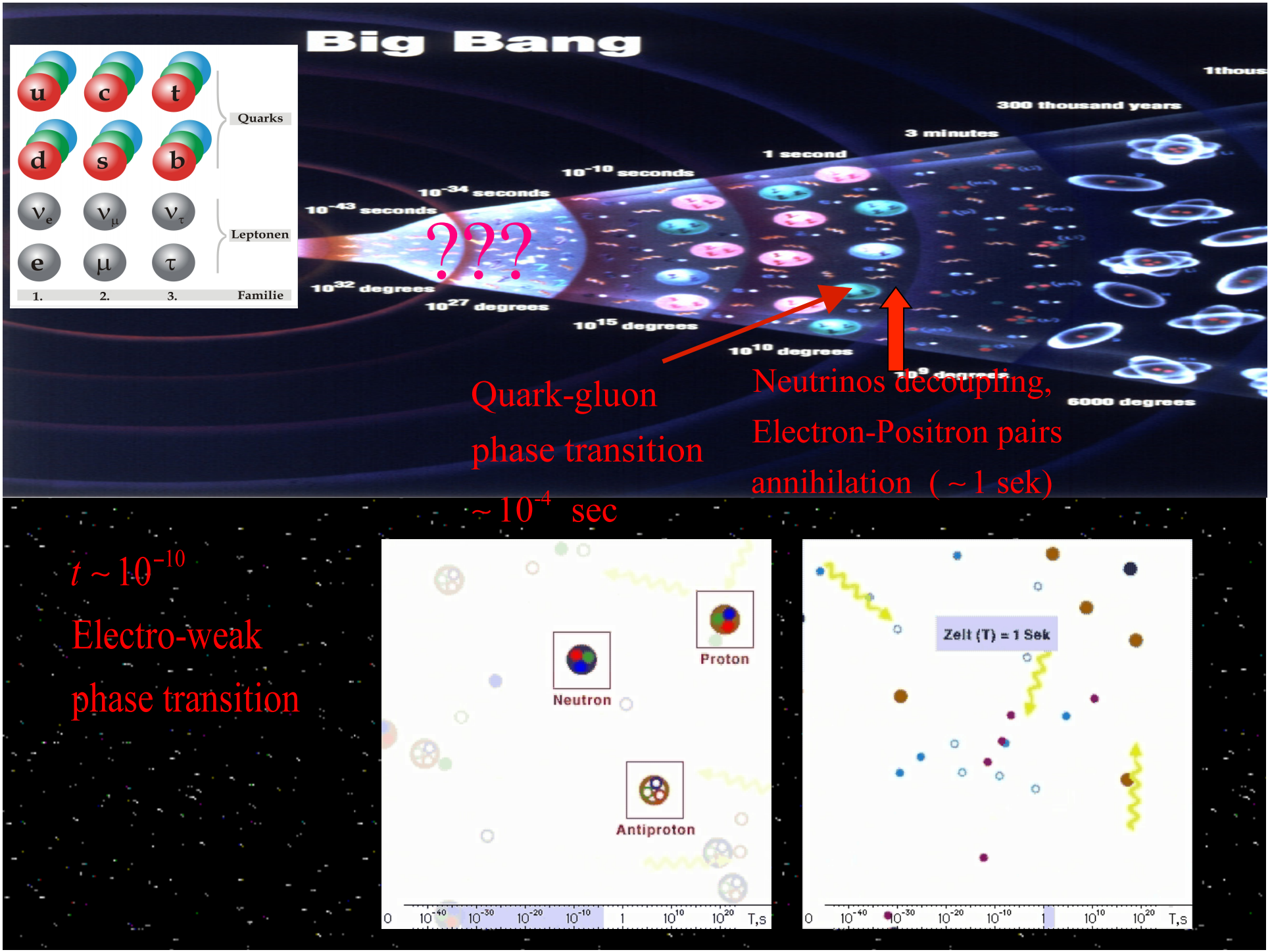
End 2012

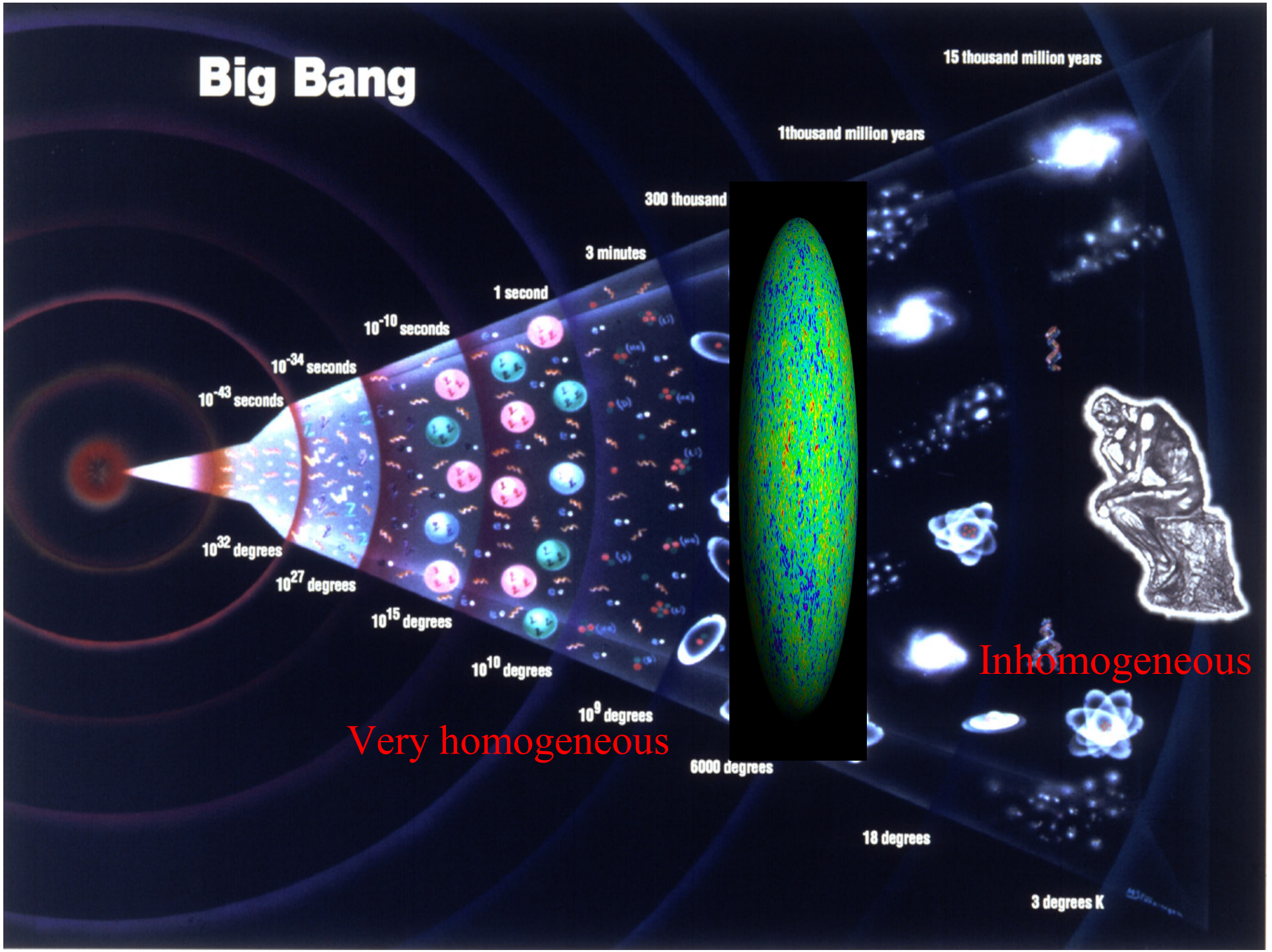


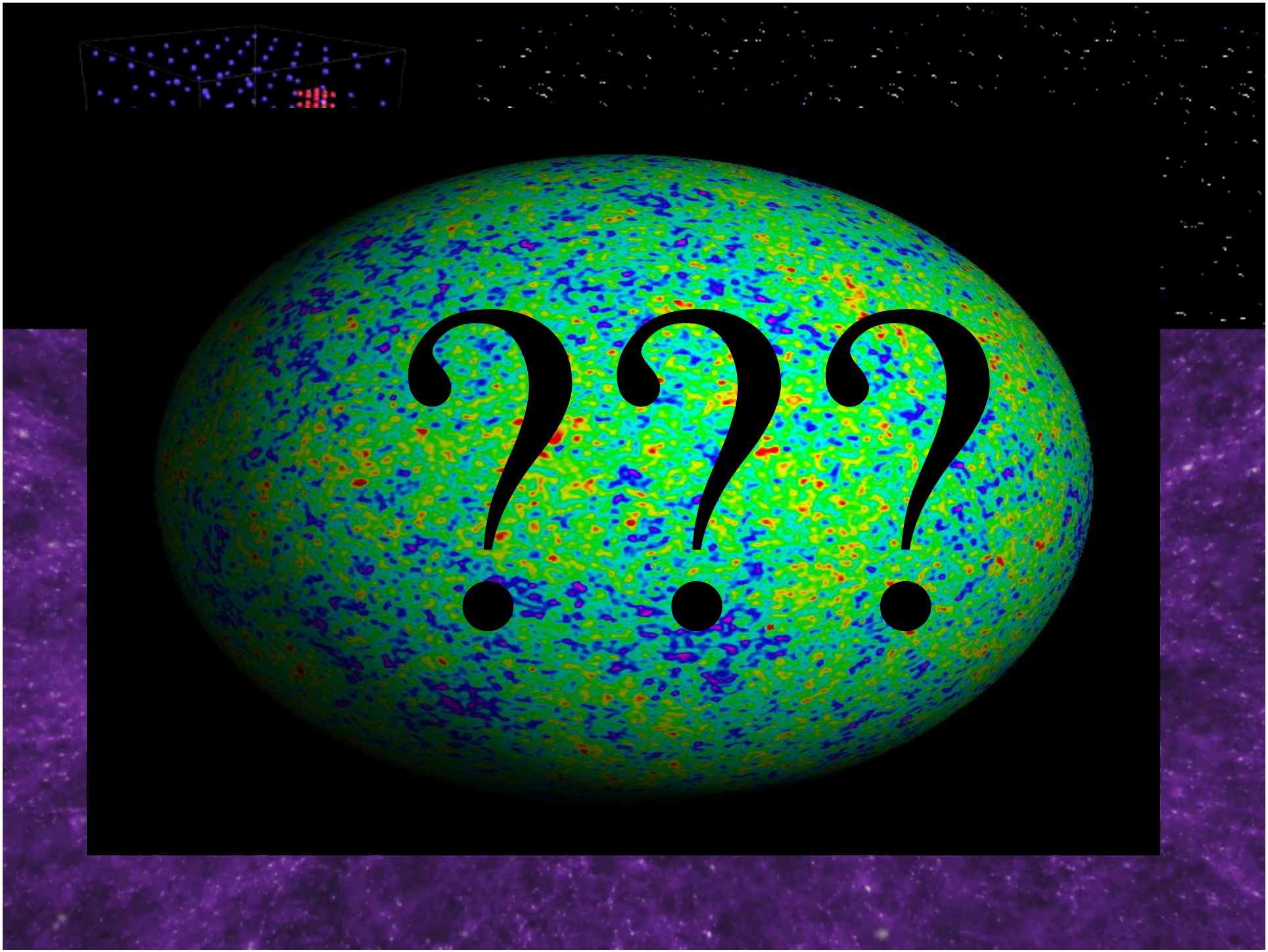
$$\lambda \propto a \qquad \Rightarrow \qquad T \propto \frac{1}{a}$$

When the Universe was 1000 times smaller its temperature was about $2725°K$


Big Bang
15 thousand million years
1thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
Nucleosynthesis
Recombination
Zeit (T) = 3 Minuten
Zeit (T) = 300.000 Jahre
0
10^{-40}
10^{-30}
10^{-20}
10^{-10}
1
10^{10}
10^{20}
T,s


Big Bang
u
c
t
d
s
b
Quarks
ν_e
ν_μ
ν_τ
e
μ
τ
Leptonen
1.
2.
3.
Familie
???
10^{-43} seconds
10^{-34} seconds
10^{-10} seconds
1 second
3 minutes
300 thousand years
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
6000 degrees
Quark-gluon
phase transition
~ 10^{-4} sec
Neutrinos decoupling,
Electron-Positron pairs
annihilation (~ 1 sek)
$t \sim 10^{-10}$
Electro-weak
phase transition
Proton
Neutron
Antiproton
0
10^{-40}
10^{-30}
10^{-20}
10^{-10}
1
10^{10}
10^{20}
T,s
Zeit (T) = 1 Sek

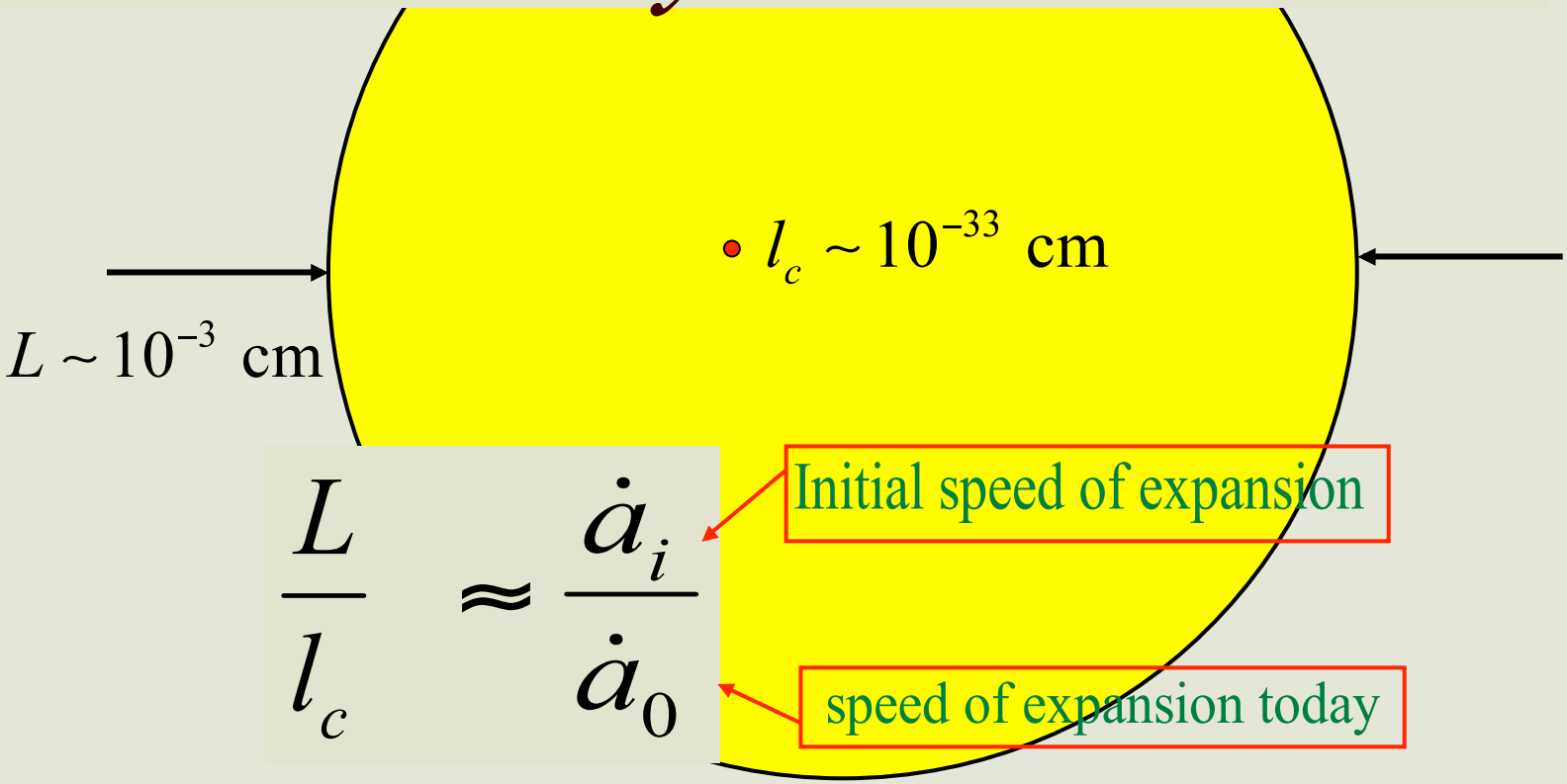

Big Bang
15 thousand million years
1thousand million years
300 thousand
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
Very homogeneous
Inhomogeneous



INFLATION

In 10^{90} causally disconnected regions $\delta\varepsilon / \varepsilon \leq 10^{-5}$!!!

Why?

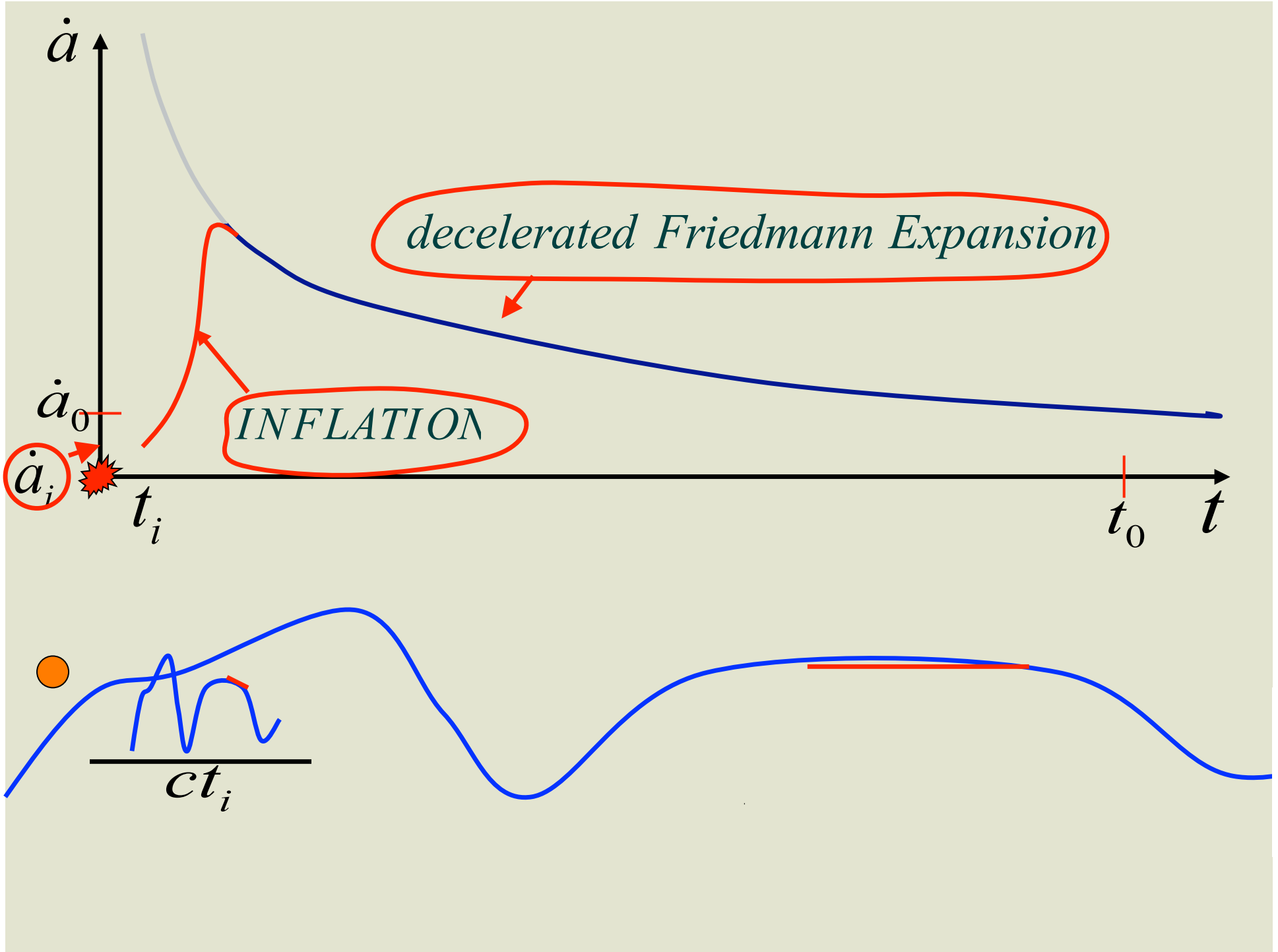


- Reason: Gravitation is attractive force $\Rightarrow \frac{\dot{a}_i}{\dot{a}_0} << 1$

- Assumption: Gravity was REPULSIVE during during some time interval in very early Universe

  $\Rightarrow \dot{a}_i / \dot{a}_0 \leq 1 \Rightarrow NO$ Problem

INFLATION is the stage of accelerated expansion in the very early Universe


$\dot{a}$
$\dot{a}_0$
$\dot{a}_i$
t_i
t_0
t
decelerated Friedmann Expansion
INFLATION
ct_i

$$\dot{a}_i << \dot{a}_0 \longrightarrow \Omega_0 \equiv \frac{\left|E_0^{\,pot}\right|}{E_0^{\,kin}} = 1 + O(1)\left(\frac{\dot{a}_i}{\dot{a}_0}\right)^2 = 1$$

Prediction of inflation !

- How gravity can become "repulsive"?

$$\ddot{a} = -\frac{4\pi G}{3}\varepsilon a$$

$$\underset{\text{acceleration}}{\ddot{a}} = -\frac{4\pi G}{3}\left(\underset{\substack{\text{energy}\\\text{density}}}{\varepsilon} + 3\underset{\text{pressure}}{p}\right)a$$

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

Scenarios

??

Energy density ε, pressure p

$p(\varepsilon)$ – equation of state

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

$$p \approx -\varepsilon$$

Which concrete scenario was realized ???

Quantum Fluctuations and Galaxies

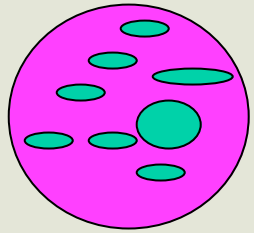
- Inflation "wash out" all existing classical inhomogeneities and leaves classical desert

Where the ihhomogeneities come from?

$$\Delta p \Delta x \geq h$$

There always exist unavoidable

Quantum Fluctuations



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

only in extremely small scales (~ 10^{-33} cm),

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

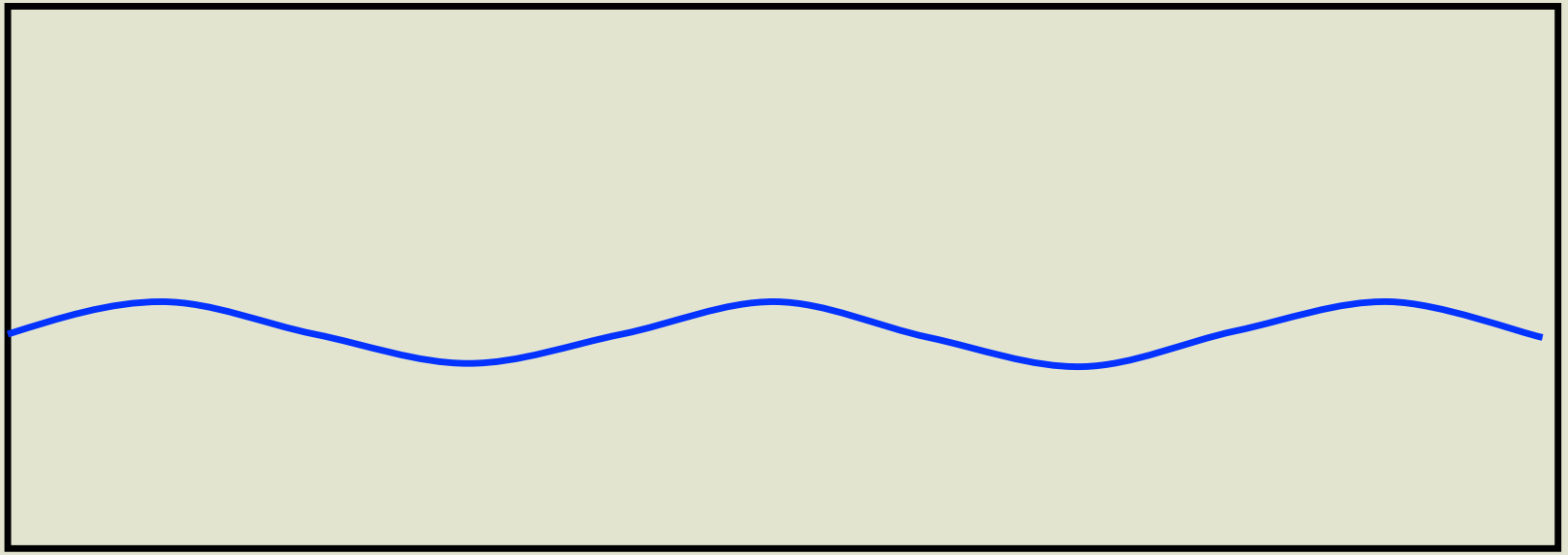
Can we transfer the large fluctuations from extremely small scales to large scales???

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

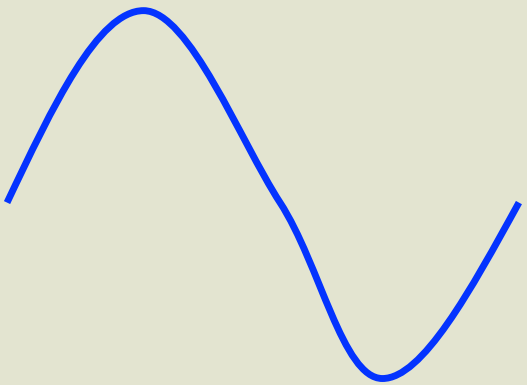
- Consider plane wave perturbation: $\delta\varphi, \Phi \propto \exp\left(i\vec{k}_{com}\vec{x}\right)$

  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) $H^{-1} = a/\dot{a}$

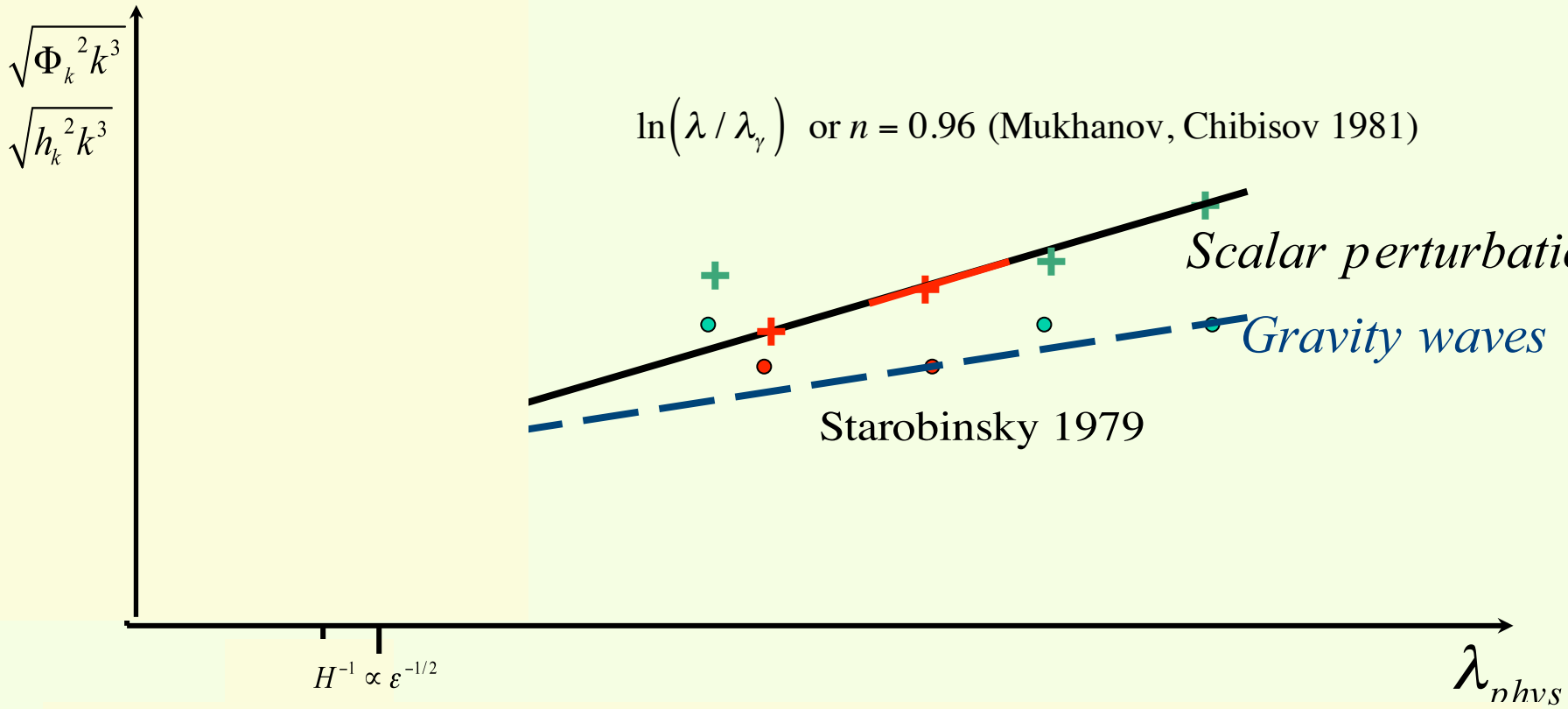
H^{-1}



H^{-1}

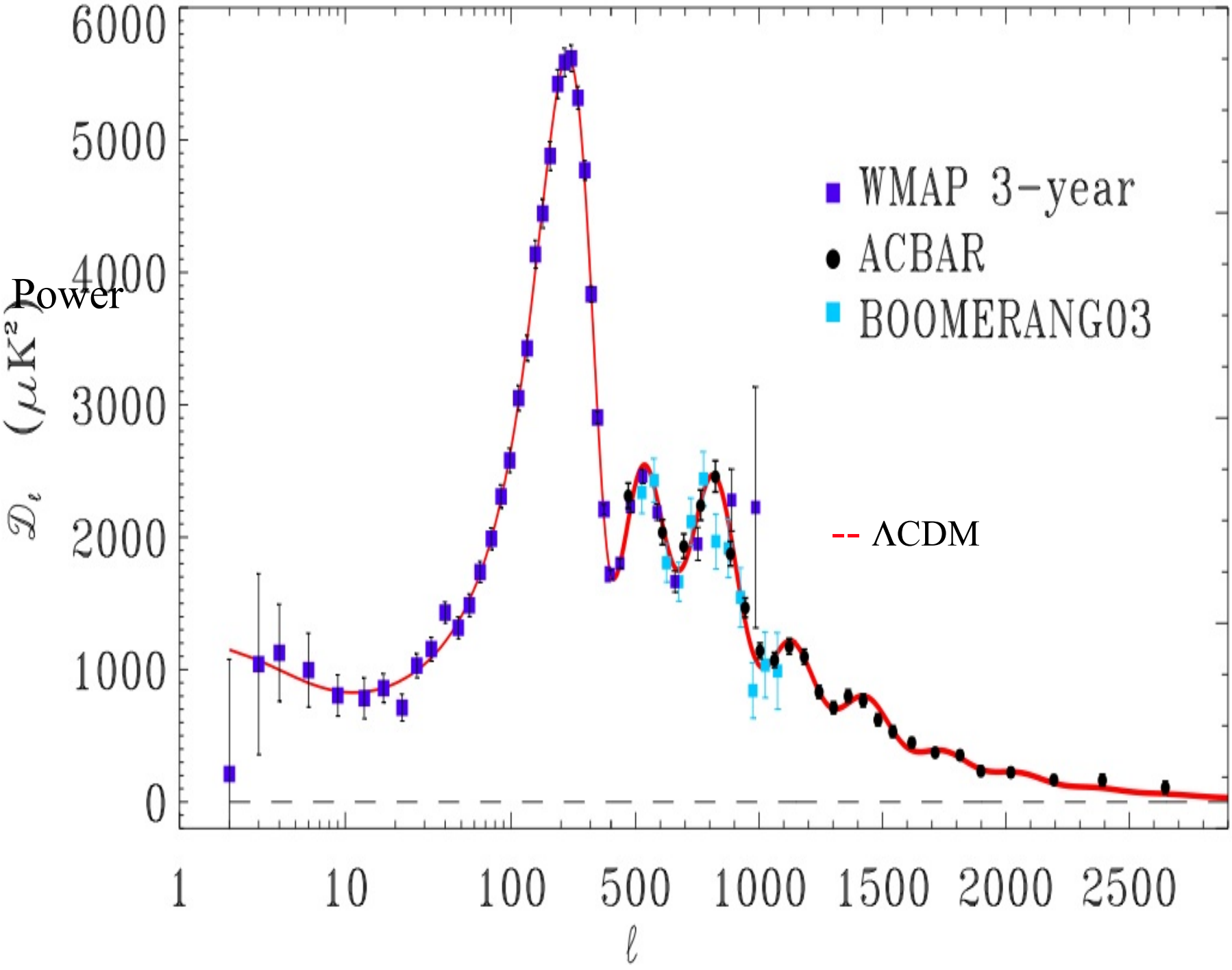


H^{-1}



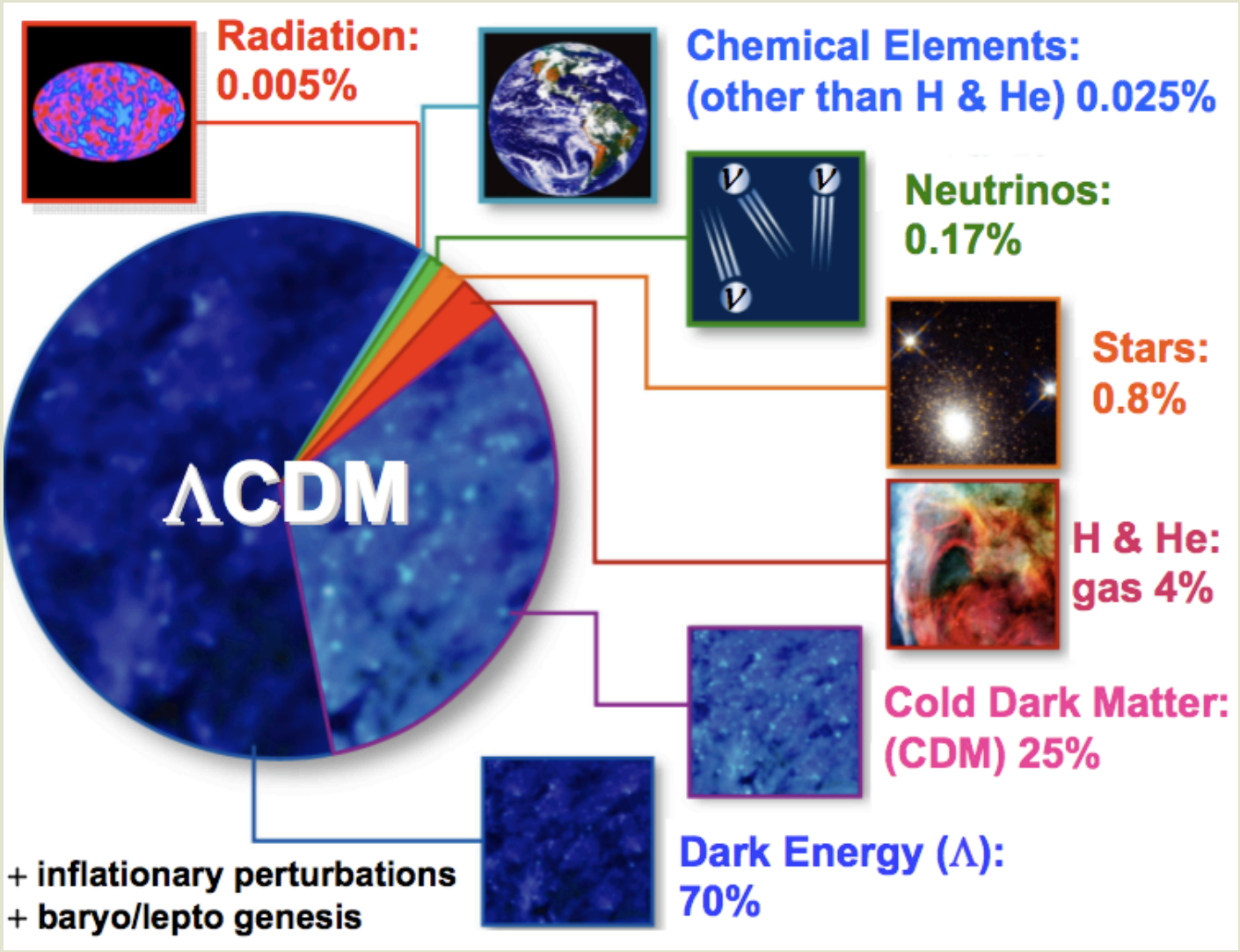
$$0.95 < n_S < 0.97$$

$$\frac{T}{S} = O(1)\left(1 + \frac{p}{\varepsilon}\right)^{1/2} \qquad k \approx Ha$$


Power
$\mathcal{D}_\ell$ (μK^2)
6000
5000
4000
3000
2000
1000
0
1
10
100
500
1000
1500
2000
2500
ℓ
WMAP 3-year
ACBAR
BOOMERANG03
-- ΛCDM

$\Omega = 1 \pm 0.02$

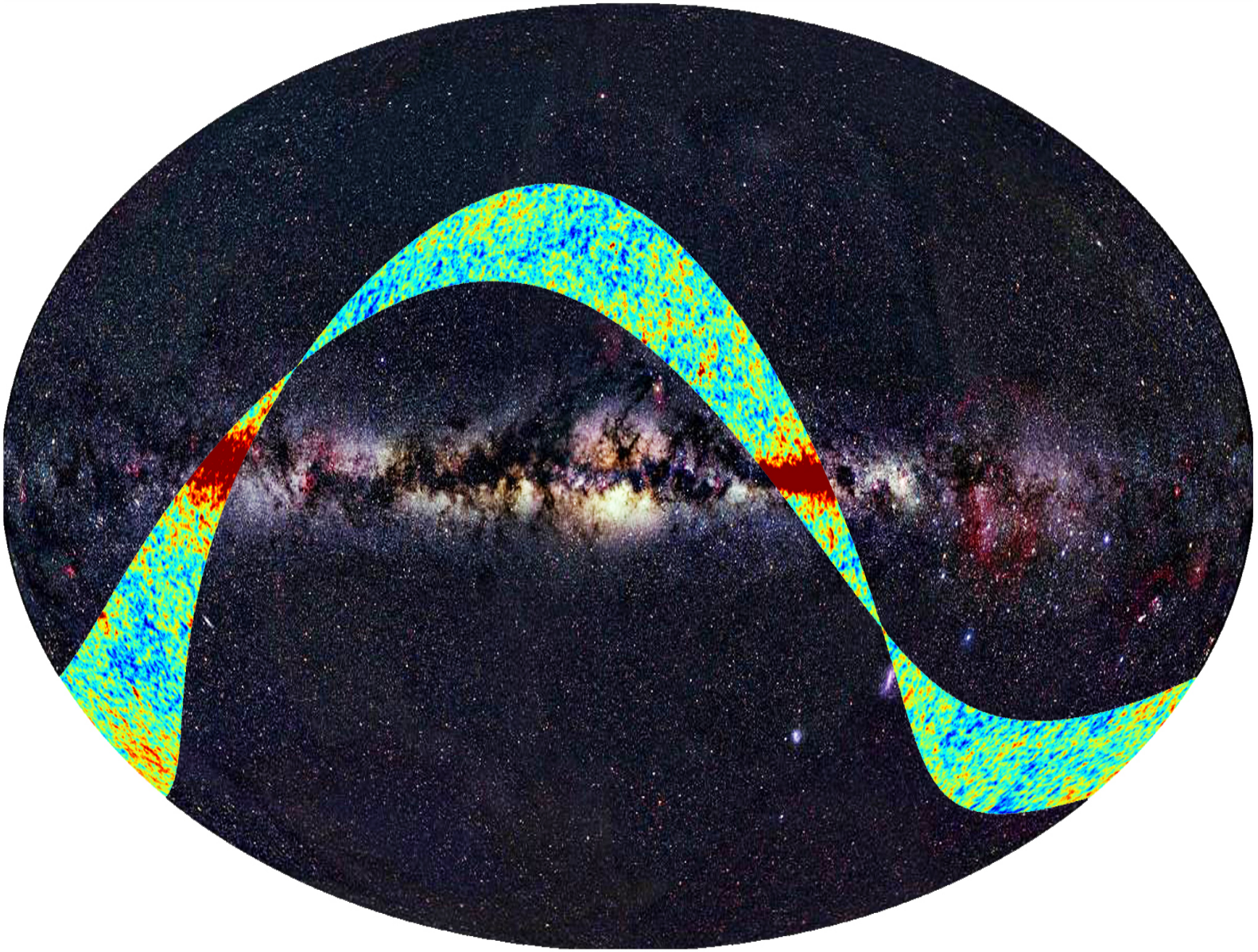
Dark Matter & Dark Energy

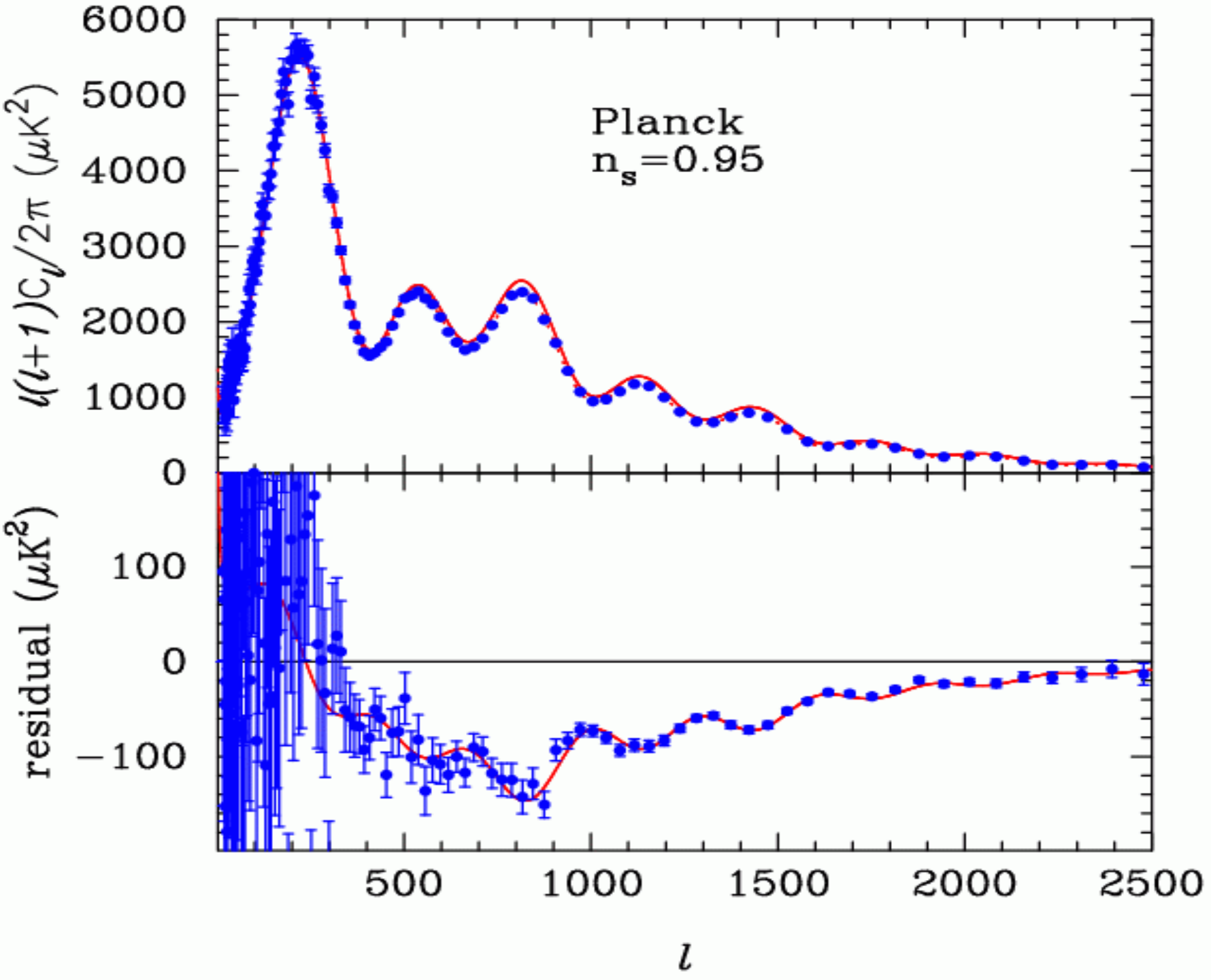


$$n_S = 0.963^{+0.011}_{-0.011}$$

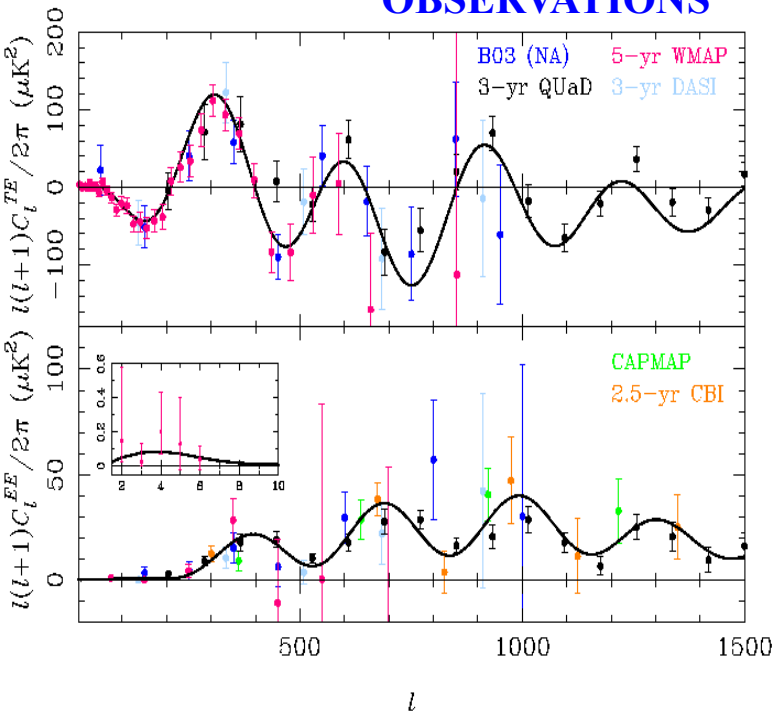
In terms of my own money, I'd bet a lot (many thousands and a few beers)

"In models with the initial superdense de Sitter state ... such a large amount of relic gravitational waves is generated
...that ... the very existence of this state can be experimentally" verified in the near future.
(Starobinsky, 1980)

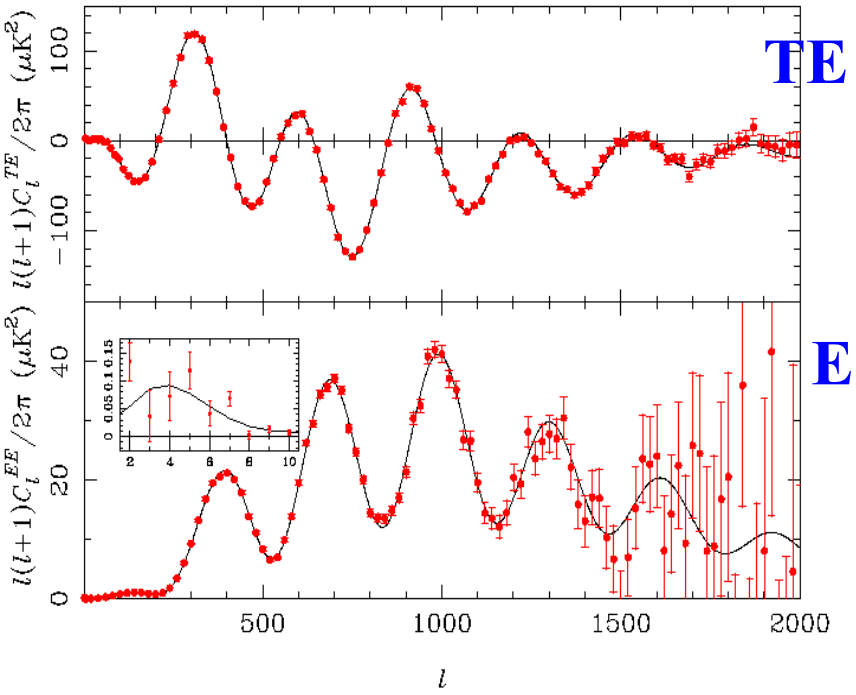



Planck
n_s=0.95
$l(l+1)C_l/2\pi$ (μK^2)
residual (μK^2)
6000
5000
4000
3000
2000
1000
0
100
0
−100
500
1000
1500
2000
2500
l

CURRENT OBSERVATIONS



PLANCK FORECAST



"What really interests me, is whether
God had any choice when he created the World"

A. Einstein

Inflation was inavoidable!!! (it is unique chance to create Universe from complete chaos without special efforts)