What are we?

Where do we come from?

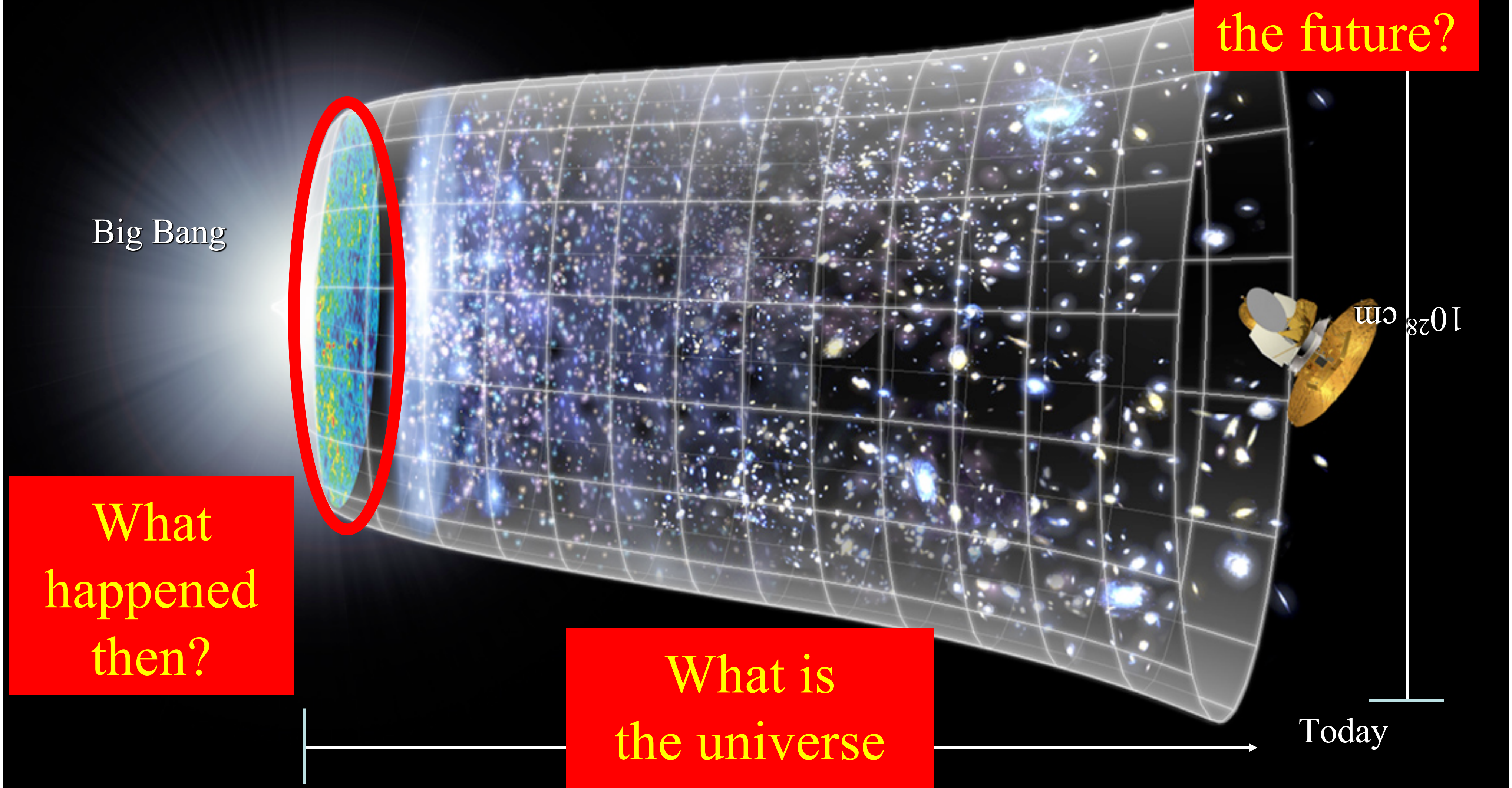
Where are we going?

The aim of particle physics:
What is matter in the Universe made of?

John Ellis

KING'S College LONDON

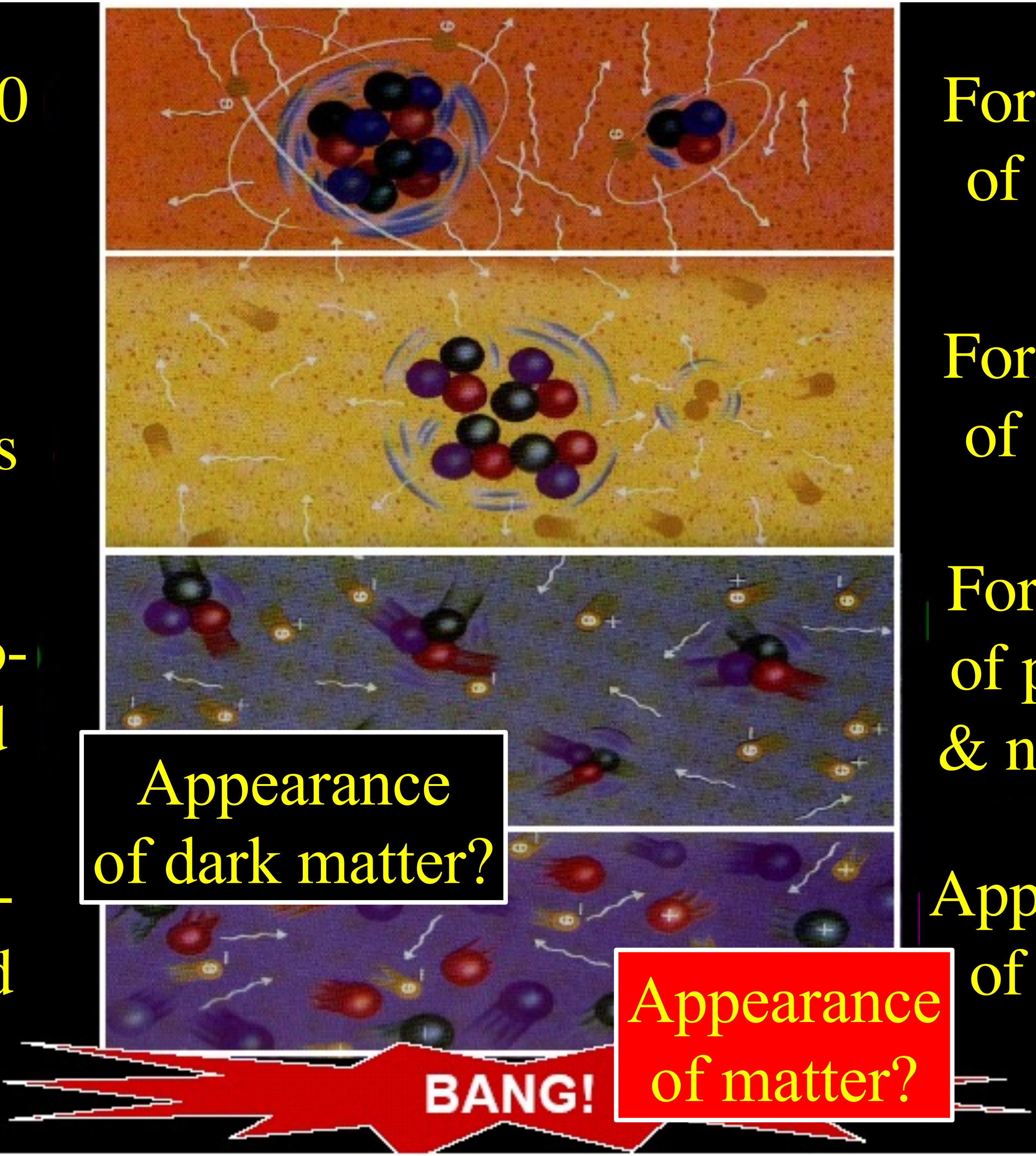
Evolution of the Universe



What will happen in the future?

What happened then?

What is the universe made of?



300,000 years

Formation of atoms

3 minutes

Formation of nuclei

1 micro-second

Formation of protons & neutrons

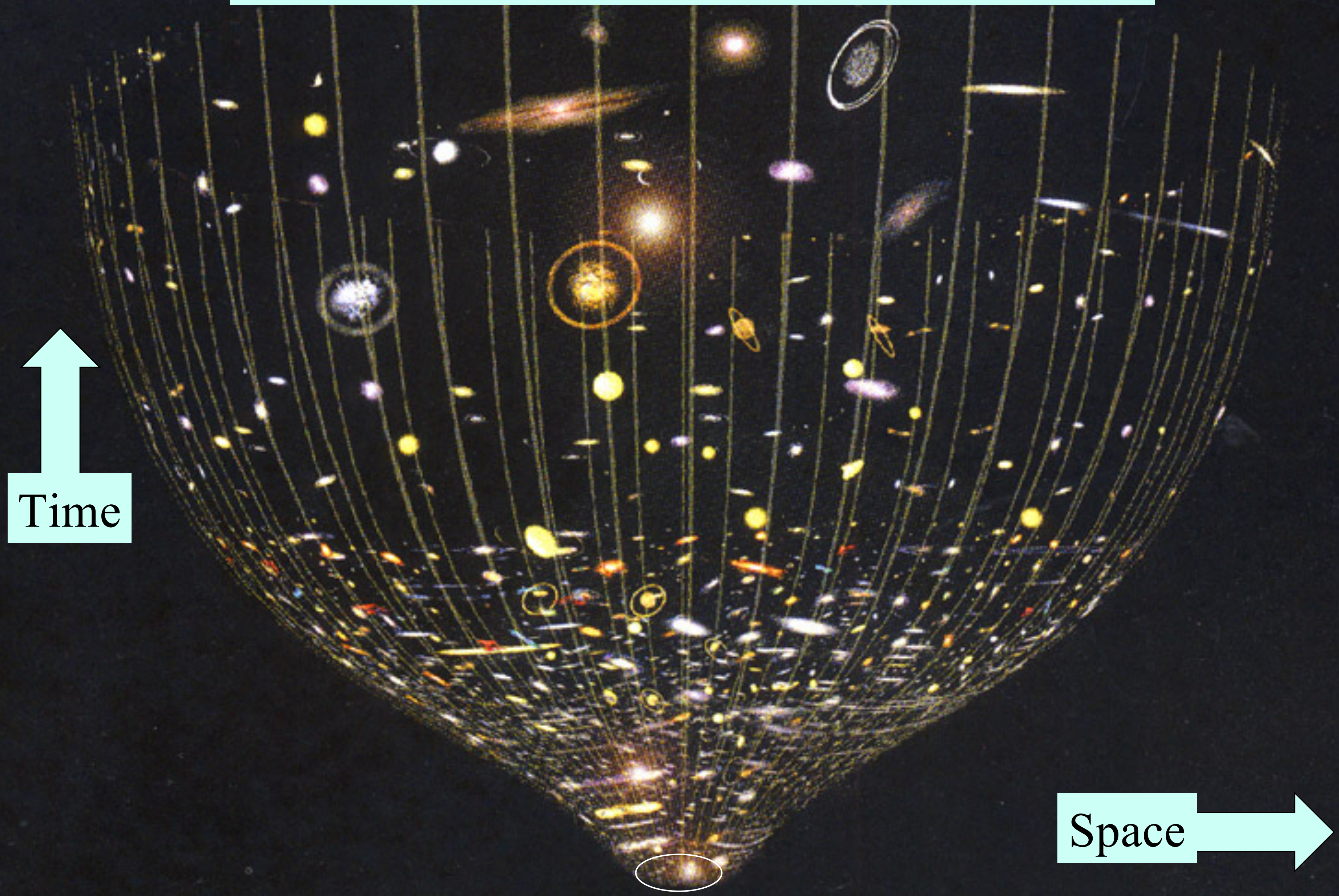
Appearance of dark matter?

1 pico-second

Appearance of mass?

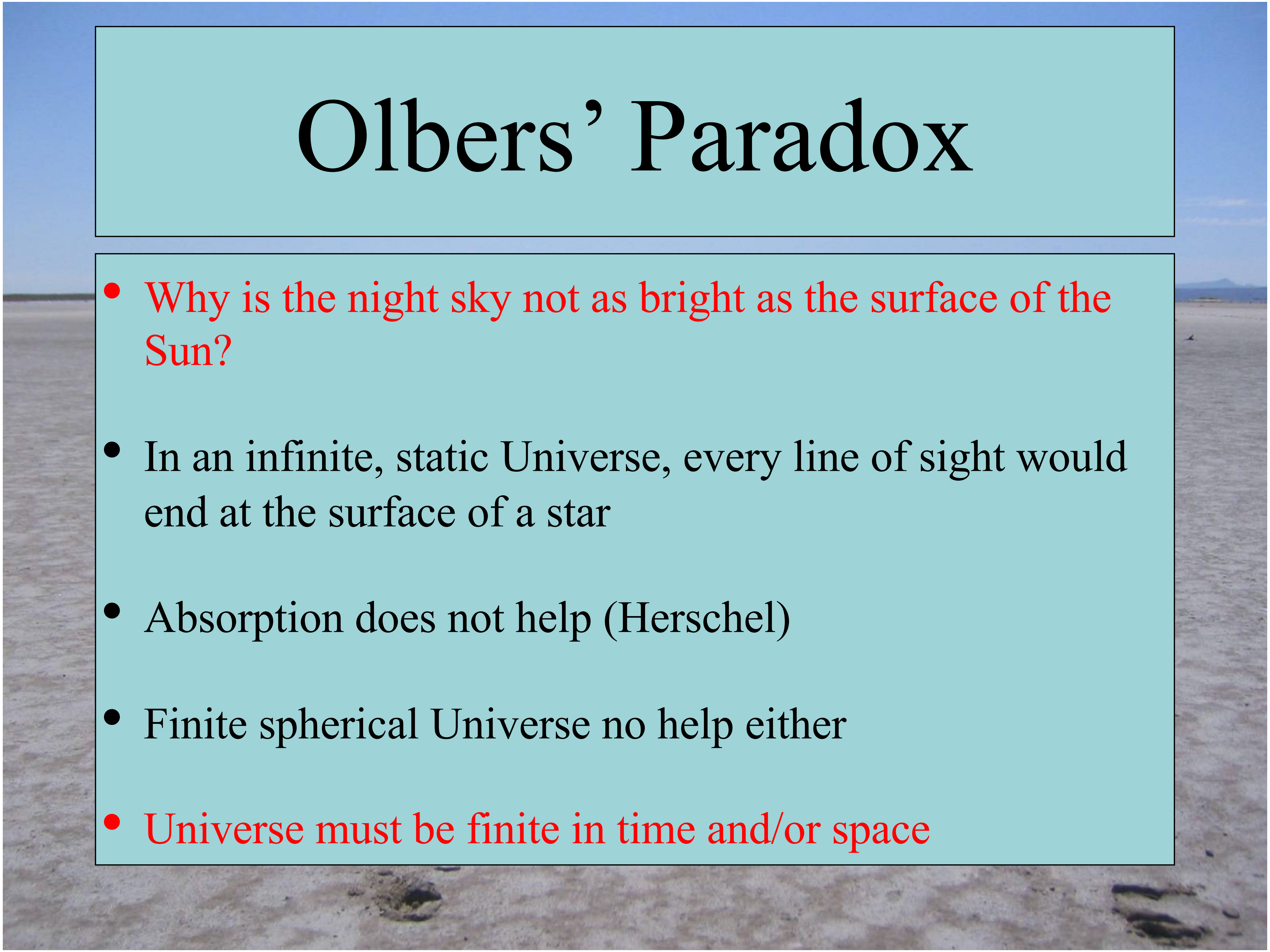
Appearance of matter?

The Universe is Expanding



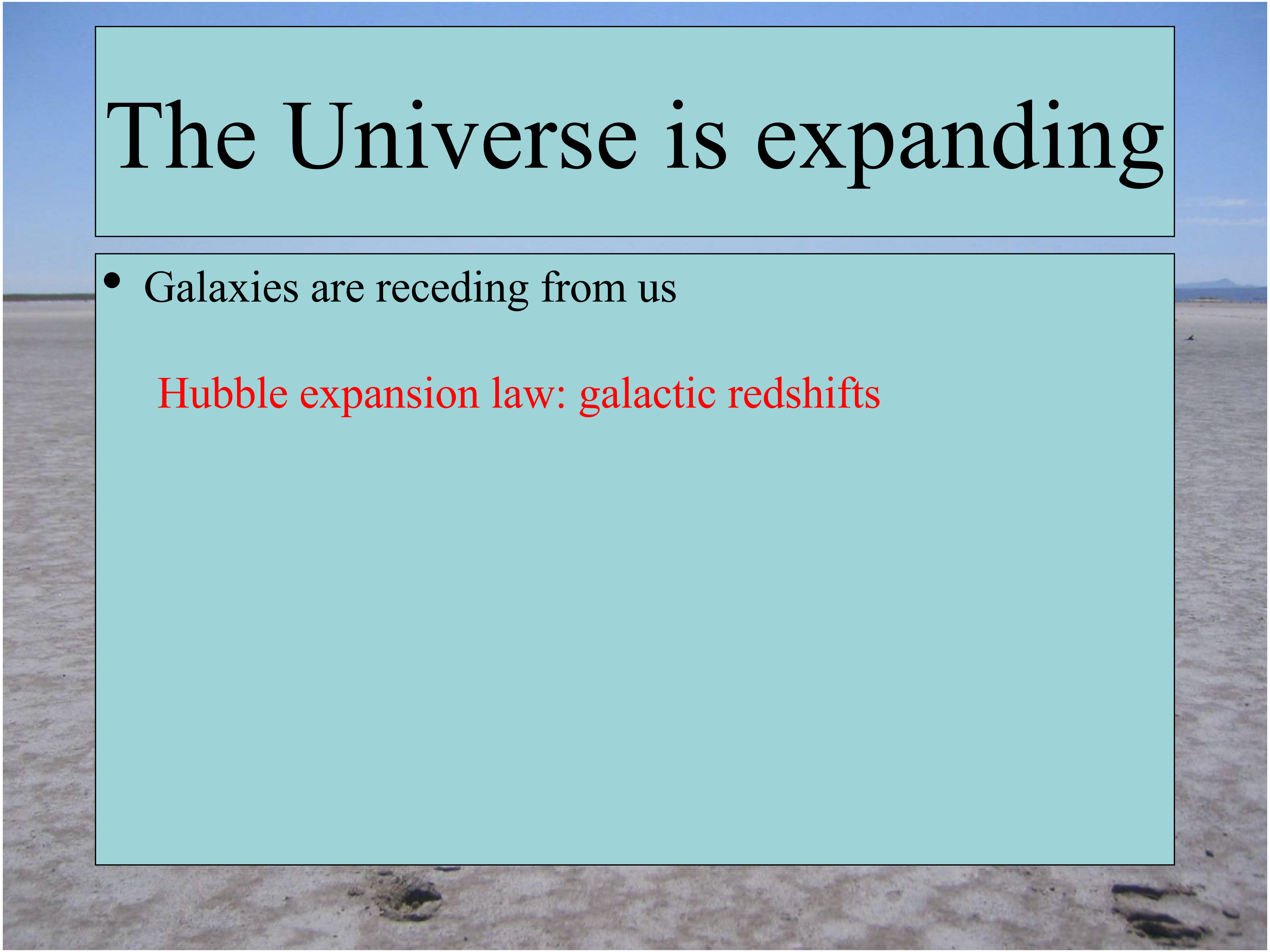
Time

Space



Olbers' Paradox

- Why is the night sky not as bright as the surface of the Sun?
- In an infinite, static Universe, every line of sight would end at the surface of a star
- Absorption does not help (Herschel)
- Finite spherical Universe no help either
- Universe must be finite in time and/or space



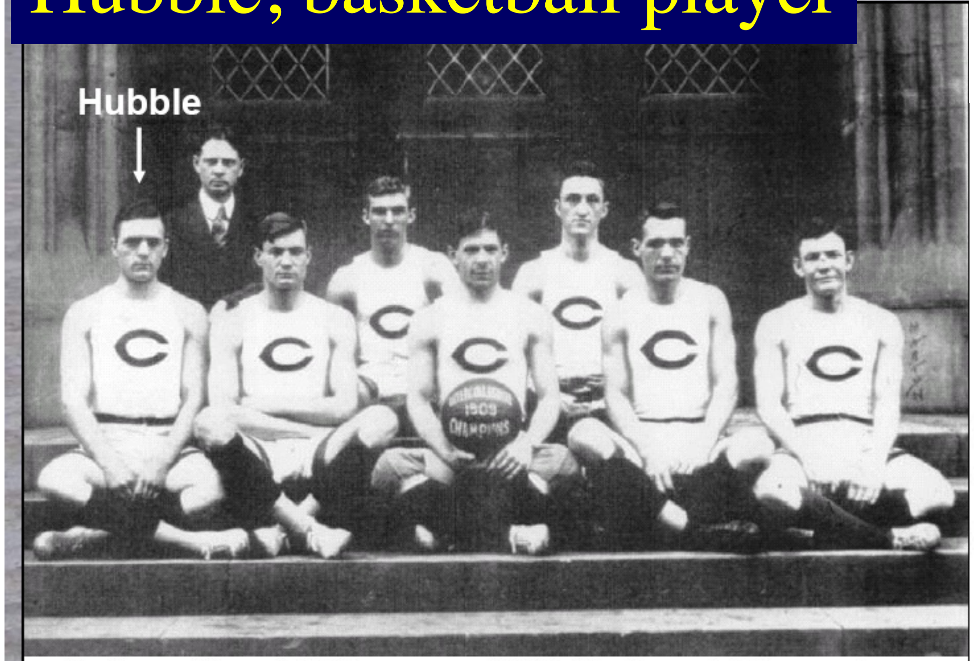
The Universe is expanding

- Galaxies are receding from us

Hubble expansion law: galactic redshifts

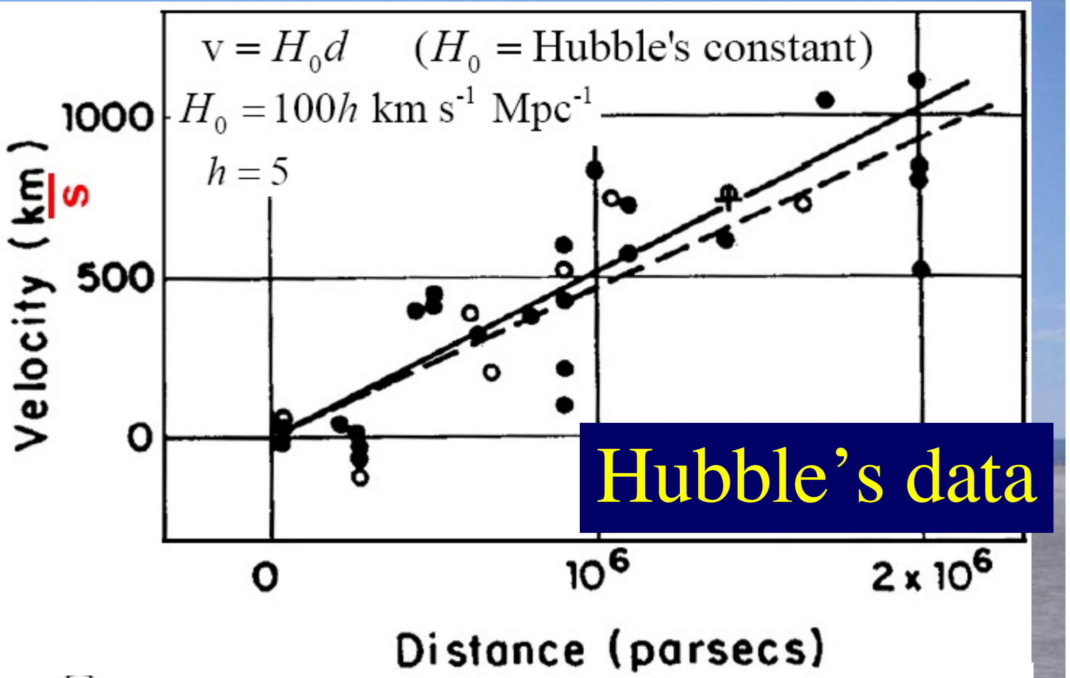
The expansion of the Universe

Hubble, basketball player

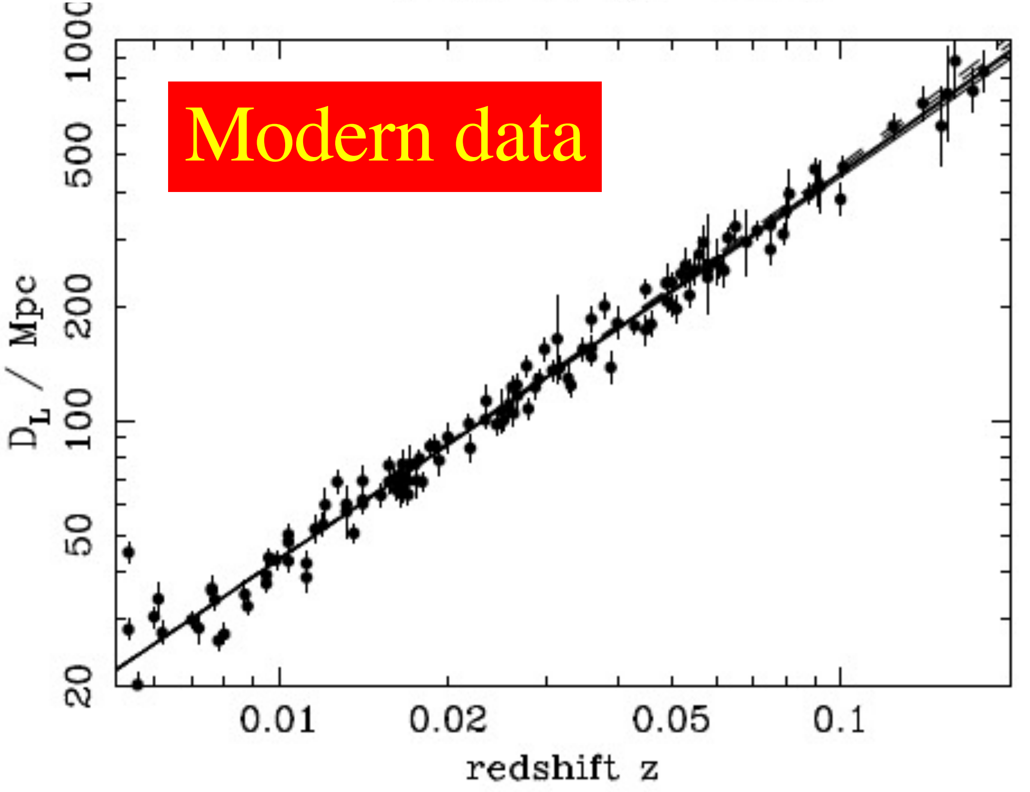


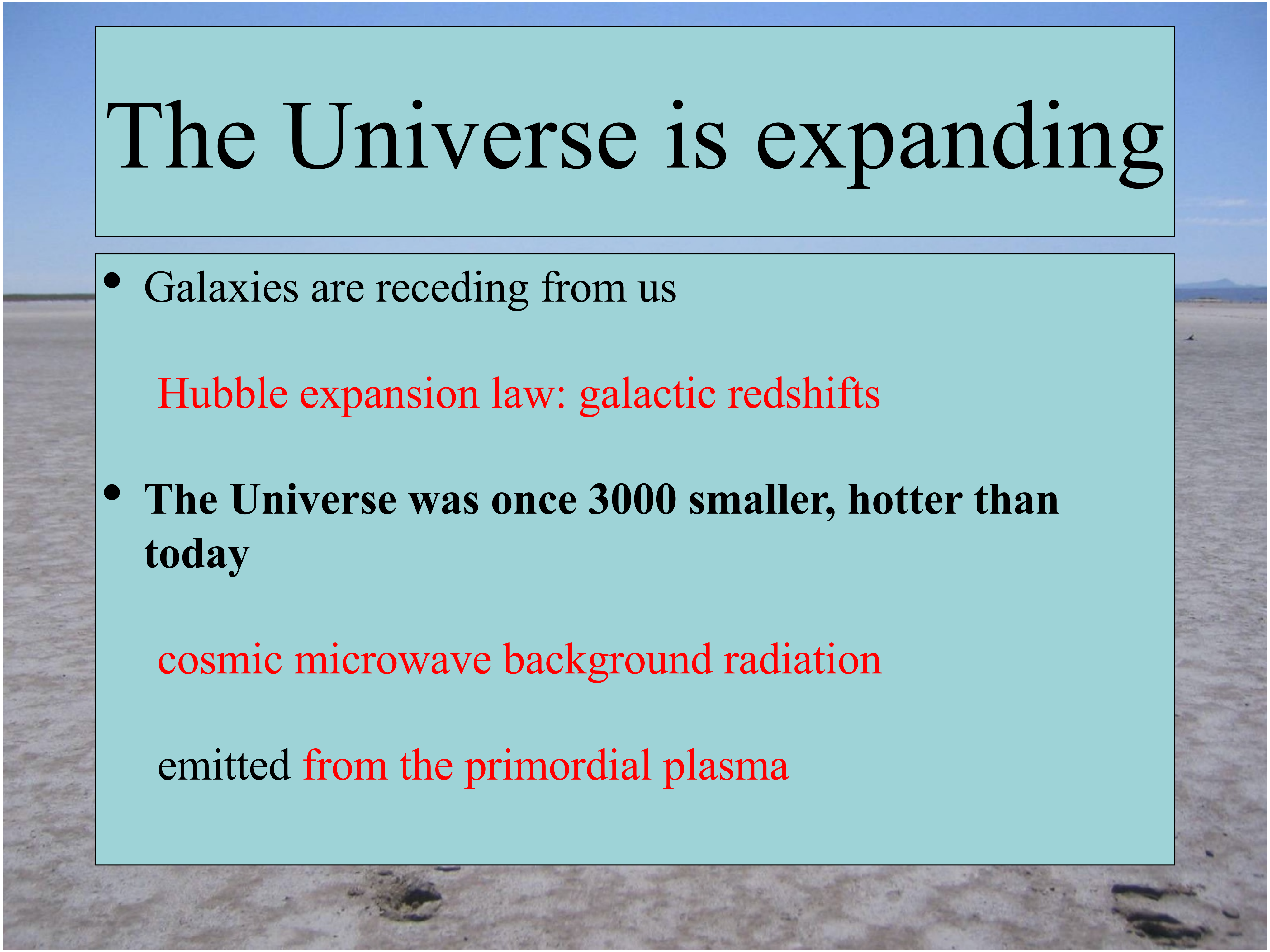
University of Chicago 1909 National Champions

Hubble's data



Modern data





The Universe is expanding

- Galaxies are receding from us

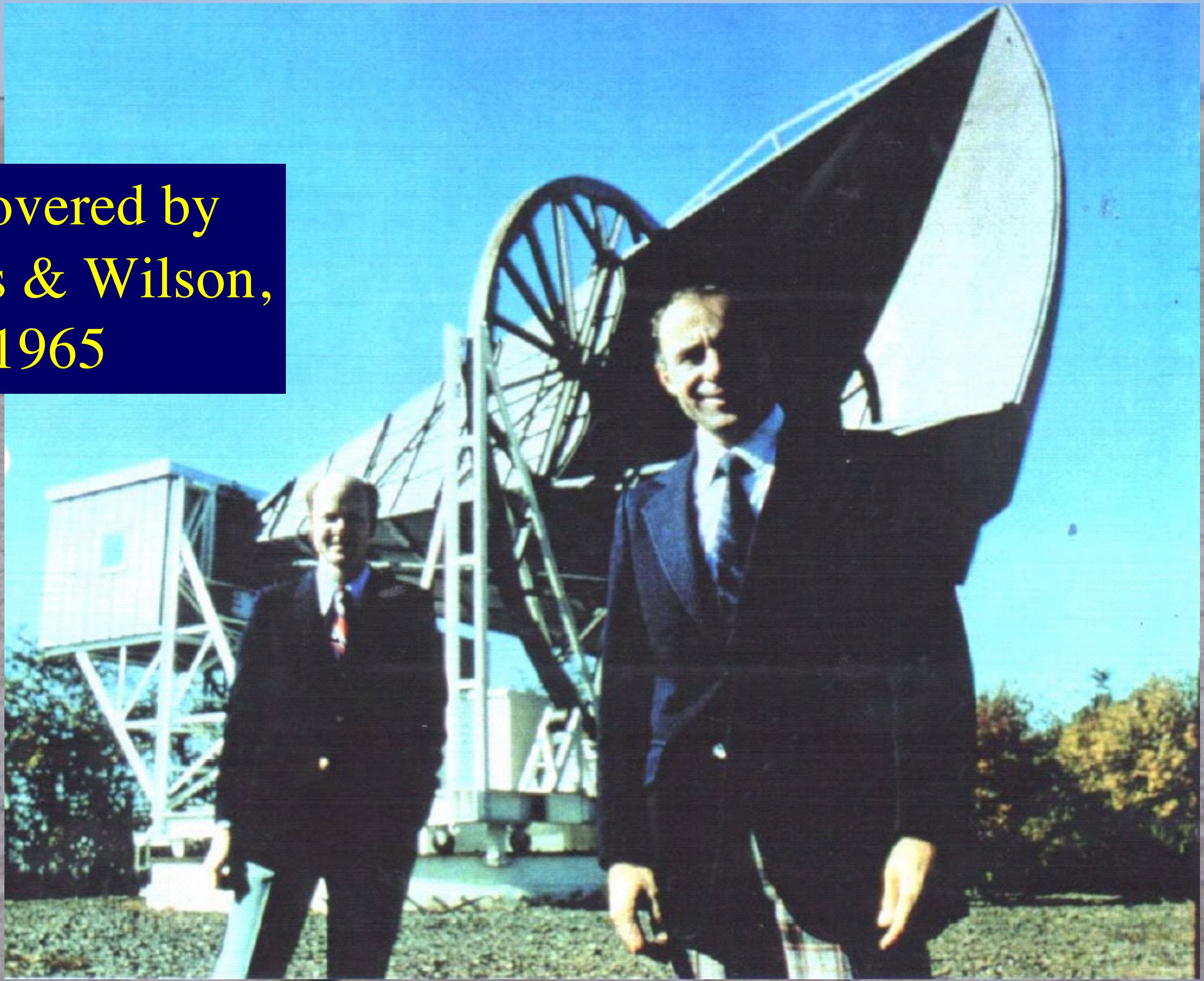
  Hubble expansion law: galactic redshifts

- **The Universe was once 3000 smaller, hotter than today**

  cosmic microwave background radiation

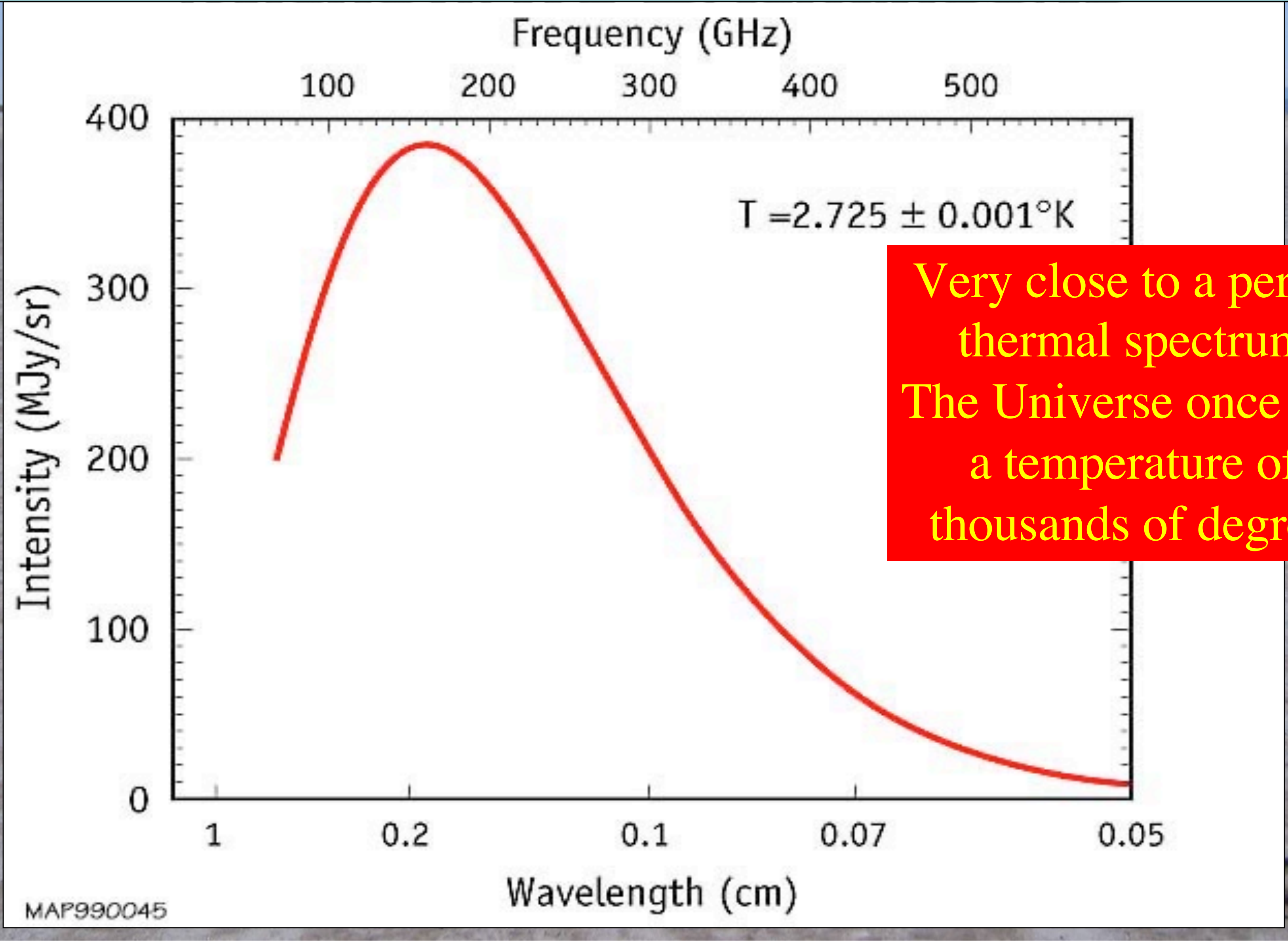
  emitted from the primordial plasma

The Cosmic Microwave Background Radiation



Discovered by
Penzias & Wilson,
1965

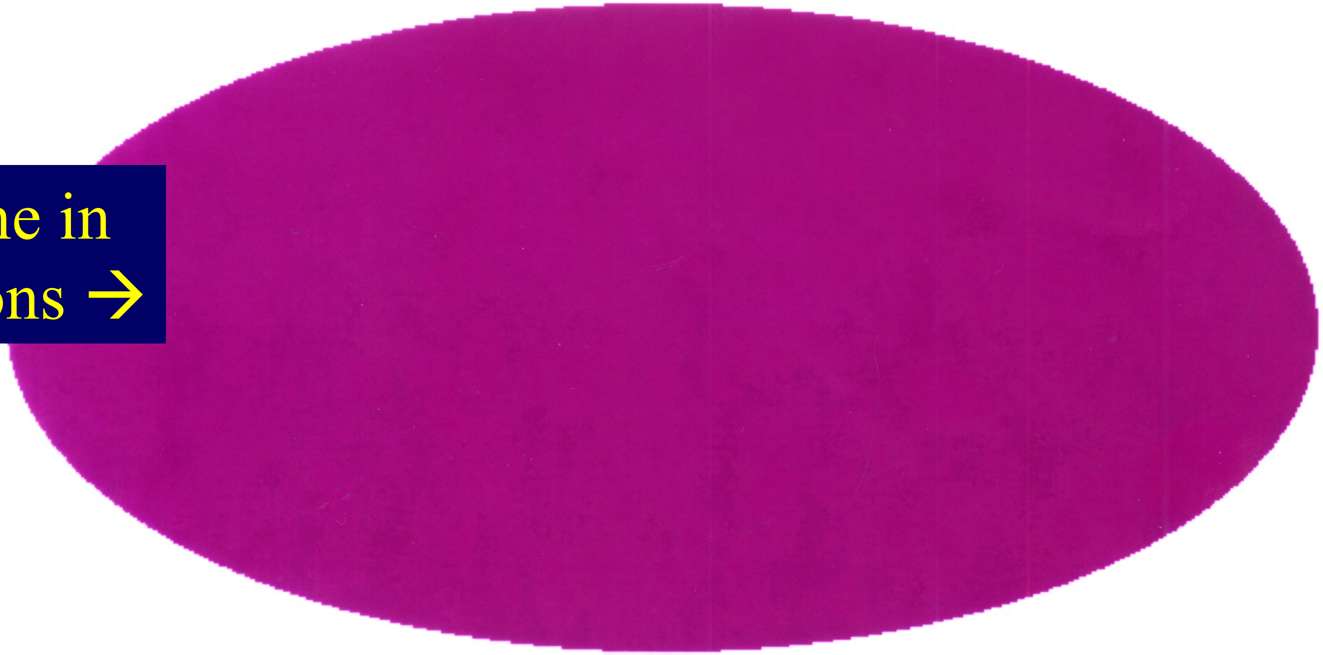
The Cosmic Microwave Background Radiation



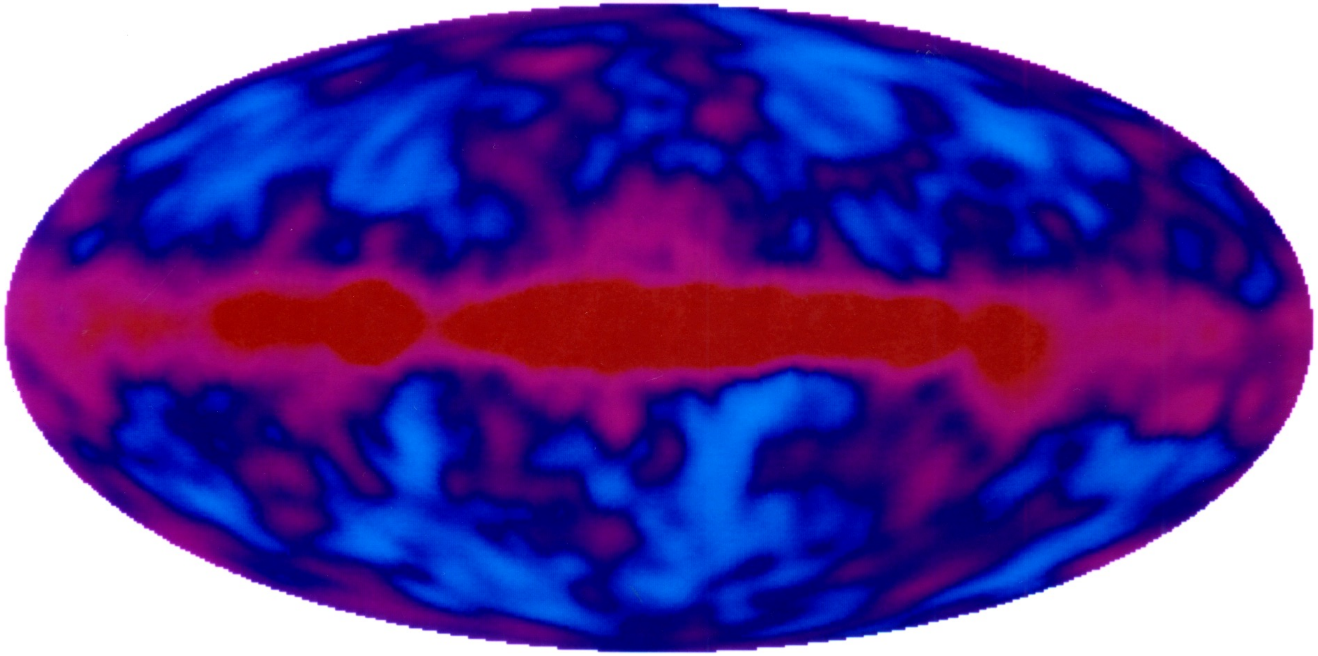
Very close to a perfect thermal spectrum:
The Universe once had a temperature of thousands of degrees

Cosmic Microwave Background

Almost the same in different directions →



Small variations discovered by COBE satellite →



The Universe is expanding

- Galaxies are receding from us

  Hubble expansion law: galactic redshifts

- The Universe was once 3000 smaller, hotter than today

  cosmic microwave background radiation

- **The Universe was once a billion times smaller, hotter than today**

  light elements cooked in the Big Bang

Making Elements in the Early Universe

- Universe contains about 24% Helium 4

  and less Deuterium, Helium 3, Lithium 7

- Could only have been cooked by nuclear reactions in dense early Universe

  when Universe billion times smaller, hotter than today

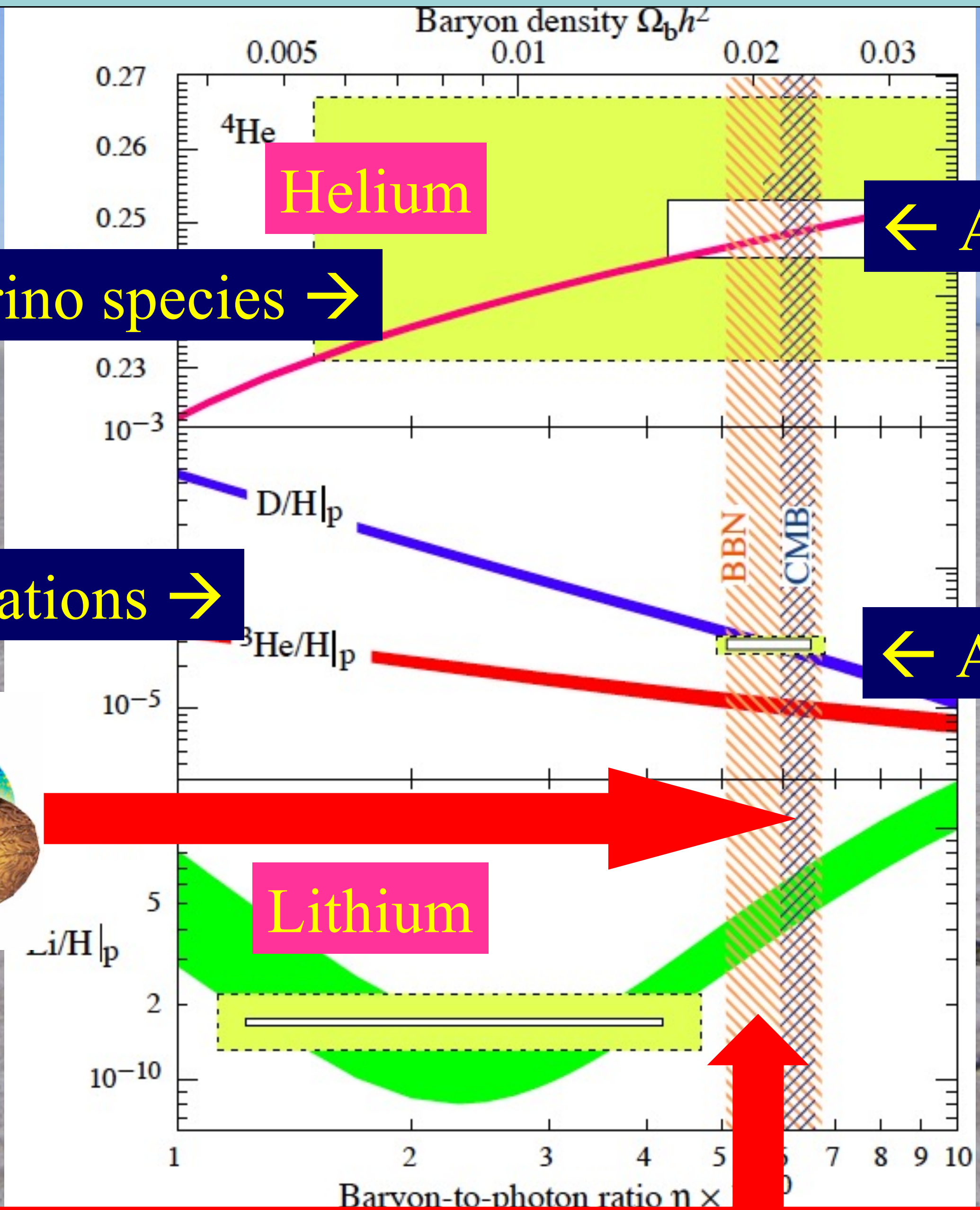
- Dependent on amount of matter in Universe

  not enough to stop expansion, explain galaxies

- Dependent on number of particle types

  number of different neutrinos measured at accelerators

Abundances of light elements in the Universe



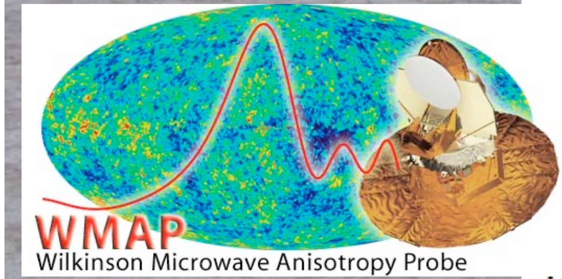
Helium

← Agree with data

Assuming 3 neutrino species →

Theoretical calculations →

← Agree with data



Lithium

Not enough ordinary matter to make the Universe recollapse

The Very Early Universe

- Size: a → zero
- Age: t → zero
- Temperature: T → large

  $T \sim 1/a$, $t \sim 1/T^2$

- Energies: $E \sim T$
- Rough magnitudes:

  T ~ 10,000,000,000 degrees

  E ~ 1 MeV ~ mass of electron

  t ~ 1 second

Need particle physics to describe earlier history

Mathematical Description

- Large-scale universe ~ isotropic & homogeneous
- Only possible form of metric (Robertson-Walker)

$$ds^2 = dt^2 - R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right]$$

- Redshift: $z \equiv \frac{\nu_1 - \nu_2}{\nu_2} \simeq \frac{v_{12}}{c}$
- Related to expansion rate:

$$\frac{v_{12}}{c} = \dot{R}\,\delta r = \frac{\dot{R}}{R}\,\delta t = \frac{\delta R}{R} = \frac{R_2 - R_1}{R_1} \qquad 1 + z = \frac{\nu_1}{\nu_2} = \frac{R_2}{R_1}$$

- **No Einstein yet!**

General-Relativistic Description

- Einstein's equations:

$$\mathcal{R}_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \mathcal{R} = 8\pi G_{\mathrm{N}} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

Cosmological constant Λ part of $T_{\mu\nu}$

- Treat matter & radiation as fluid:

$$T_{\mu\nu} = -p g_{\mu\nu} + (p + \rho)\, u_\mu u_\nu \qquad \dot{\rho} = -3H\,(\rho + p)$$

- Friedman-Lemaître equations:

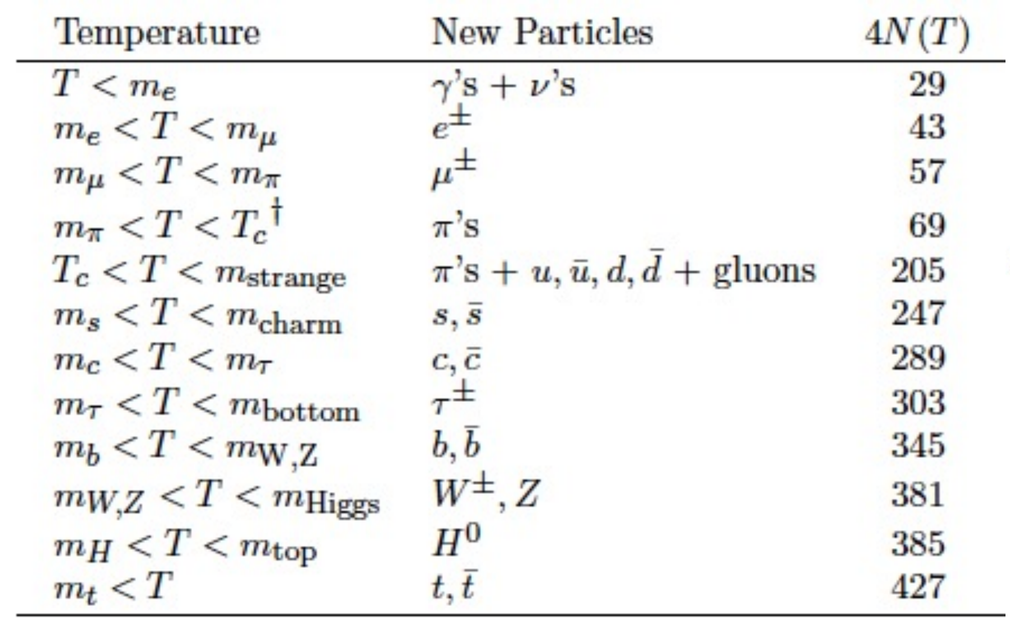
$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi\, G_{\mathrm{N}}\, \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3} \qquad \frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G_{\mathrm{N}}}{3}\,(\rho + 3p)$$

Relativistic Particles

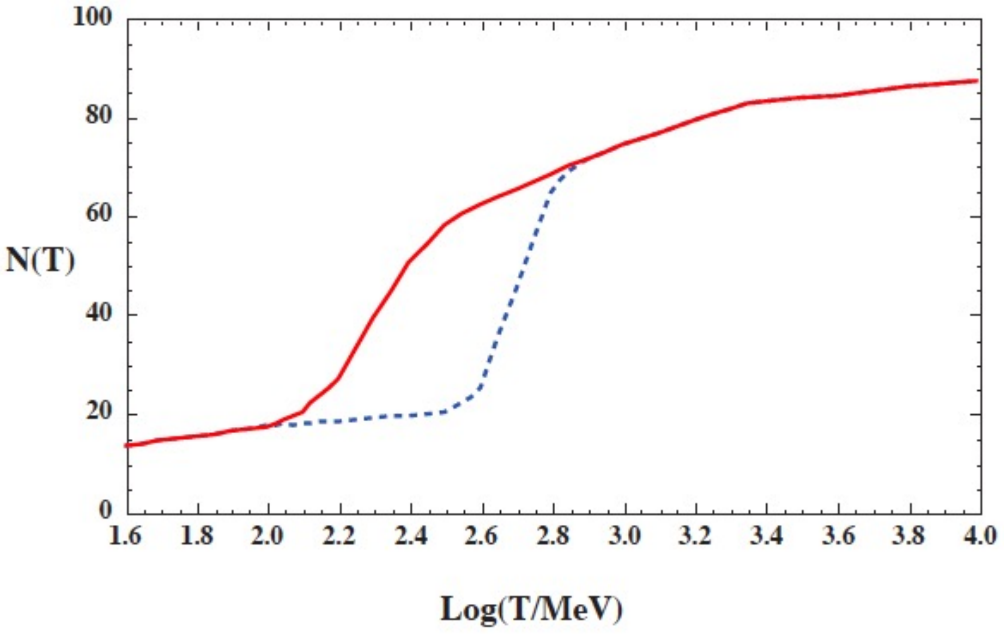
- Relativistic degrees of freedom:

$$\rho = \left(\sum_B g_B + \frac{7}{8} \sum_F g_F \right) \frac{\pi^2}{30} T^4 \equiv \frac{\pi^2}{30} N(T) T^4$$

- Degrees of freedom in Standard Model:



Temperature	New Particles	$4N(T)$
$T < m_e$	γ's + ν's	29
$m_e < T < m_\mu$	$e^\pm$	43
$m_\mu < T < m_\pi$	$\mu^\pm$	57
$m_\pi < T < T_c{}^\dagger$	π's	69
$T_c < T < m_{\text{strange}}$	π's + $u, \bar{u}, d, \bar{d}$ + gluons	205
$m_s < T < m_{\text{charm}}$	$s, \bar{s}$	247
$m_c < T < m_\tau$	$c, \bar{c}$	289
$m_\tau < T < m_{\text{bottom}}$	$\tau^\pm$	303
$m_b < T < m_{W,Z}$	$b, \bar{b}$	345
$m_{W,Z} < T < m_{\text{Higgs}}$	$W^\pm, Z$	381
$m_H < T < m_{\text{top}}$	H^0	385
$m_t < T$	$t, \bar{t}$	427



- Expansion rate: $R(t) \propto t^{1/2}$; $H = 1/2t$

How Flat is the Universe?

- Measure density relative to critical value:

$$\Omega_{\rm tot} = \rho/\rho_c$$

- Curvature: $k/R^2 = H^2(\Omega_{\rm tot} - 1)$

  where critical density $\rho_c \equiv \dfrac{3H^2}{8\pi G_N} = 1.88 \times 10^{-26}\, h^2 \ \mathrm{kg\ m^{-3}}$

$$= 1.05 \times 10^{-5}\, h^2 \ \mathrm{GeV\ cm^{-3}}$$

- And Hubble expansion rate: $H \equiv 100\, h \ \mathrm{km\ s^{-1}\ Mpc^{-1}}$

- Exponential expansion if Λ dominates: $R(t) \propto e^{\sqrt{\Lambda/3}t}$

Age of the Universe

- Integrating Hubble expansion rate:

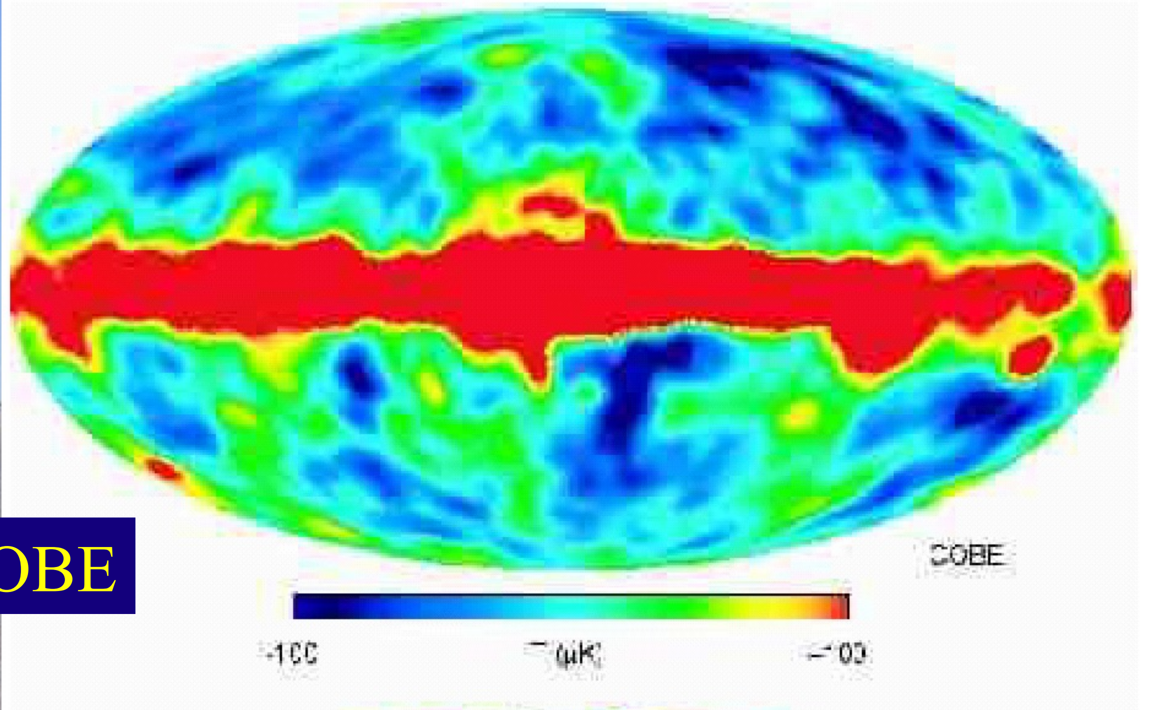
$$H_0 t_0 = \int_0^\infty \frac{dz}{(1+z)H(z)}$$
$$= \int_0^\infty \frac{dz}{(1+z)\left[(1+z)^2(1+\Omega_{\mathrm{m}} z) - z(2+z)\Omega_{\mathrm{v}}\right]^{1/2}}$$

- Approximate solution:

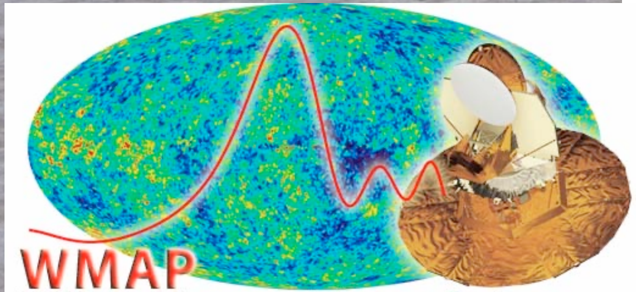
$$H_0 t_0 \simeq \tfrac{2}{3}\left(0.7\Omega_{\mathrm{m}} + 0.3 - 0.3\Omega_{\mathrm{v}}\right)^{-0.3}$$

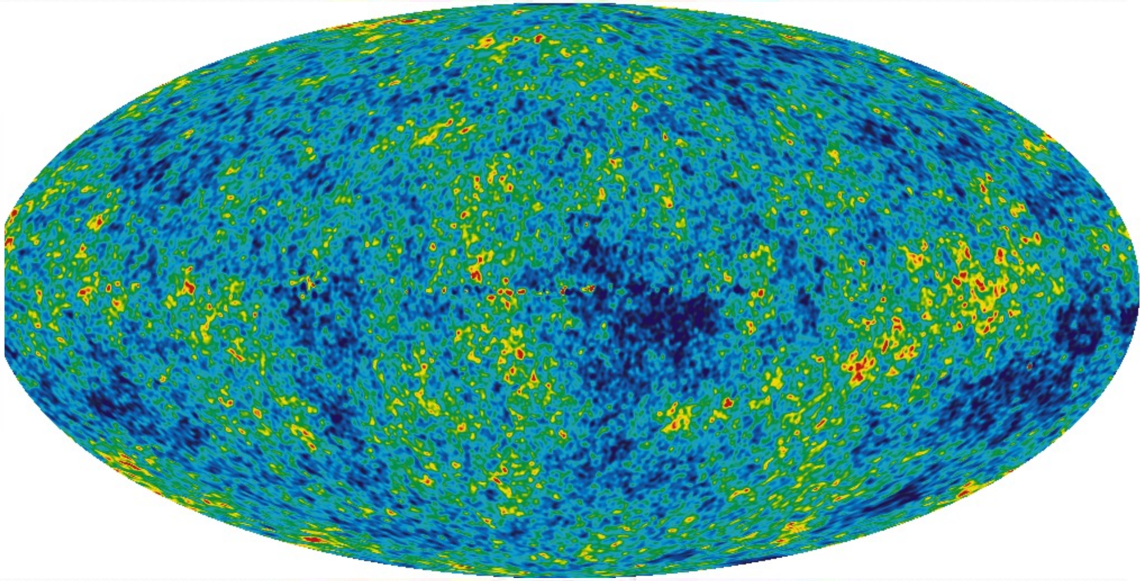
- Estimated age: **13.8 billion years**

The Cosmic Microwave Background



According to COBE





What is the origin of the fluctuations in the CMB?

The Hypothesis of Cosmological Inflation

- Why is the Universe so big?
- Why is the Universe so homogeneous (on large scales)?
- Why is geometry (approximately) Euclidean **($\Omega_{Tot} \sim 1$)?**
- What is the origin of the structures in the Universe?
- **A possible answer:**
- The Universe grew very rapidly just after the Big Bang
- Pushed by energy in empty space, similar to the Higgs field

  (Perhaps it was the Higgs field itself?)
- Structures due to quantum fluctuations?

Cosmological Inflation

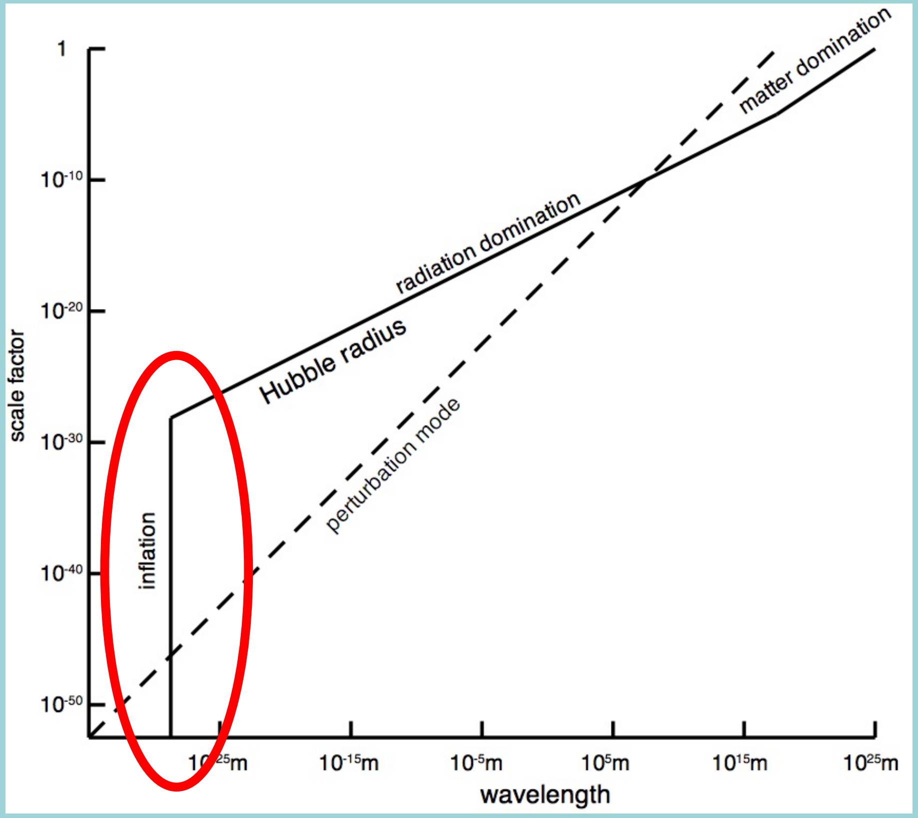
- Expansion driven by cosmological constant: (a = scale size)

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda}{3}$$

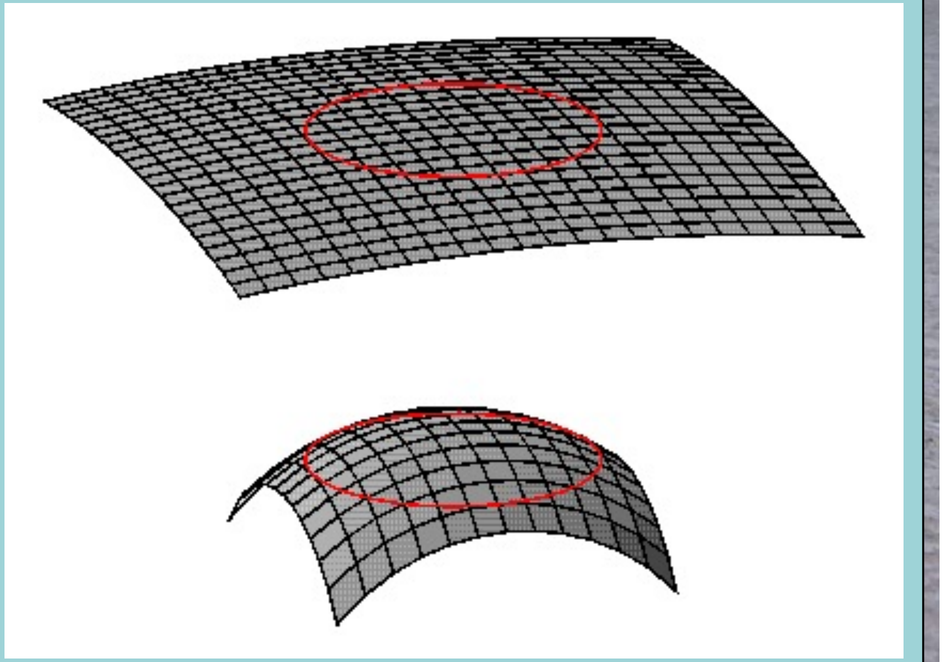
- Exponential expansion
- All the visible Universe

  was once very small
- In close contact:

  (almost) homogeneous
- Geometry ~ flat



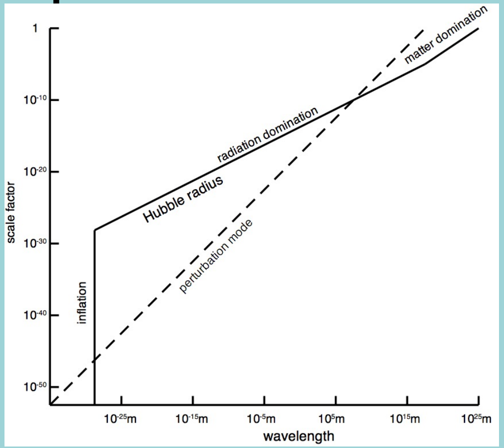
The Hypothesis of Cosmological Inflation

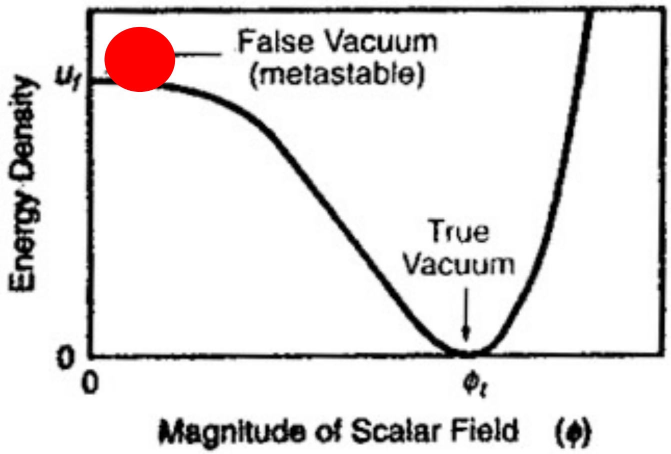


- All the visible Universe started in very small region
- Then it blew up very quickly, like a kid’s balloon
- In this way its geometry became almost flat
- Structures originated from quantum fluctuations

Primordial Perturbations

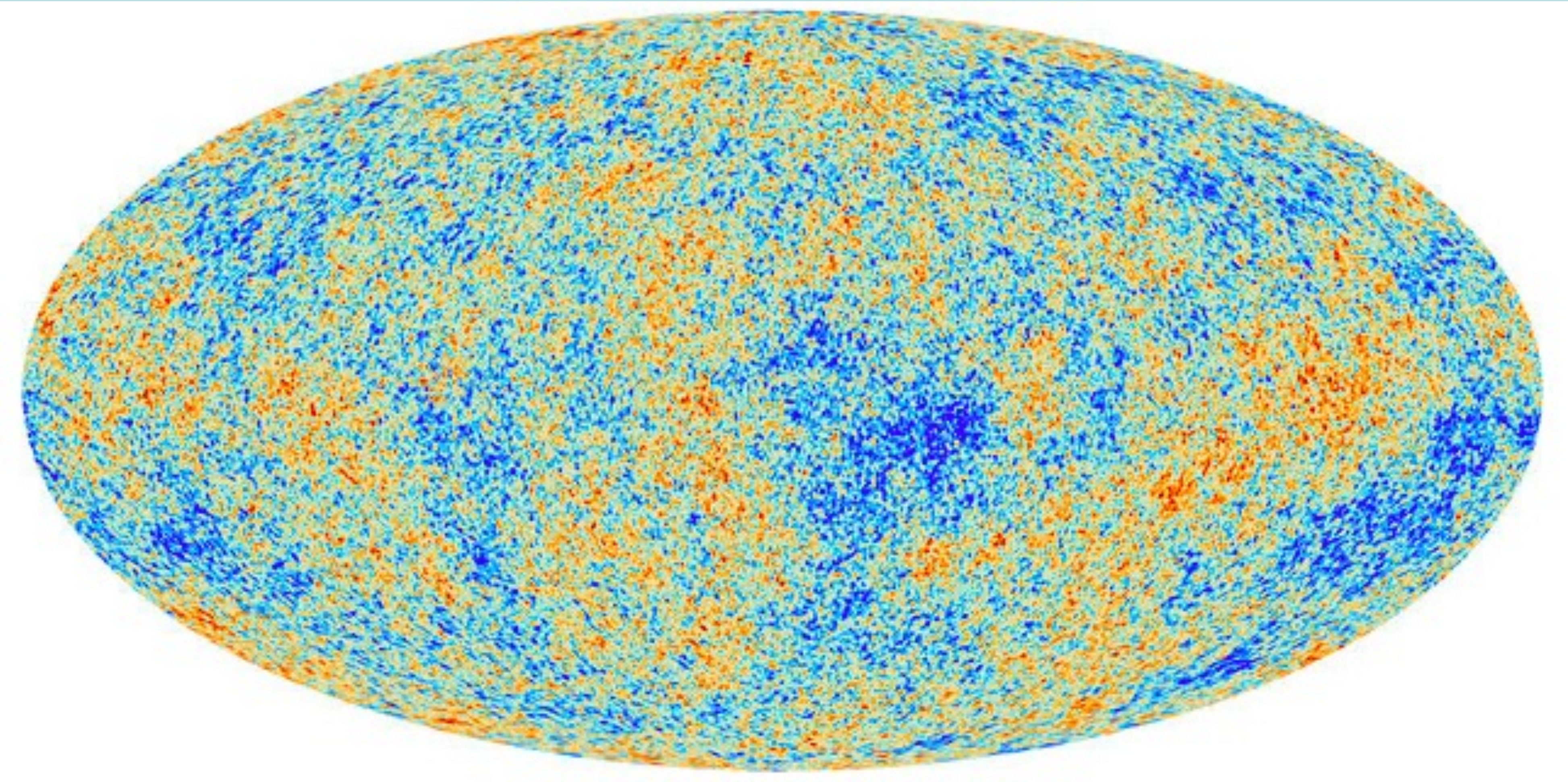
- “Cosmological constant” due to vacuum energy in “inflaton” field ϕ: $\Lambda \sim V(\phi) \neq 0$
- Quantum fluctuations in ϕ cause perturbations in energy density (scalar) and metric (tensor)
- (Almost) independent of scale size



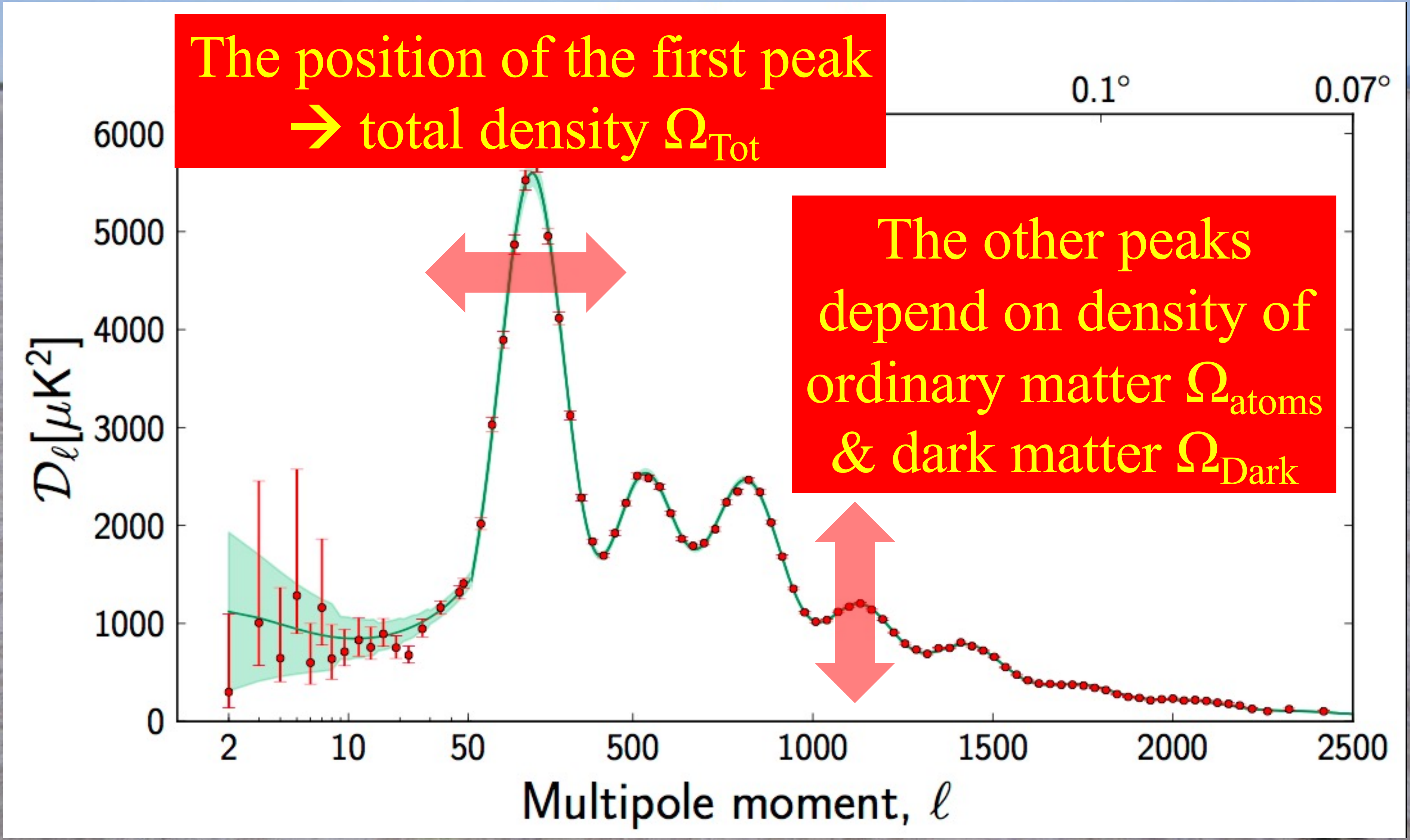


- Visible in cosmic microwave background (CMB)

Cosmological Inflation in Light of Planck



The Spectrum of Fluctuations in the Cosmic Microwave Background

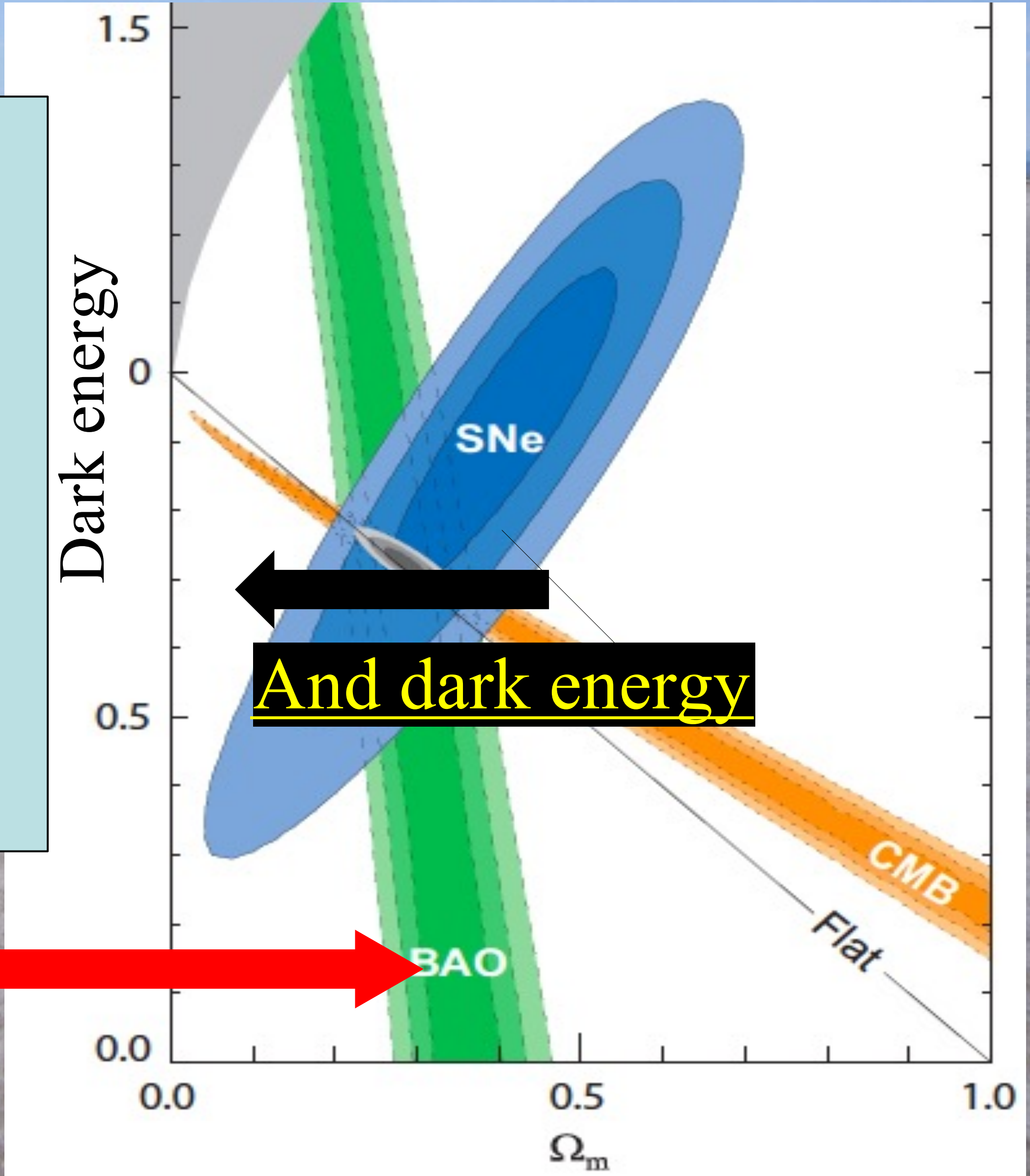


The position of the first peak
→ total density Ω_{Tot}

The other peaks
depend on density of
ordinary matter Ω_{atoms}
& dark matter Ω_{Dark}

The Content of the Universe

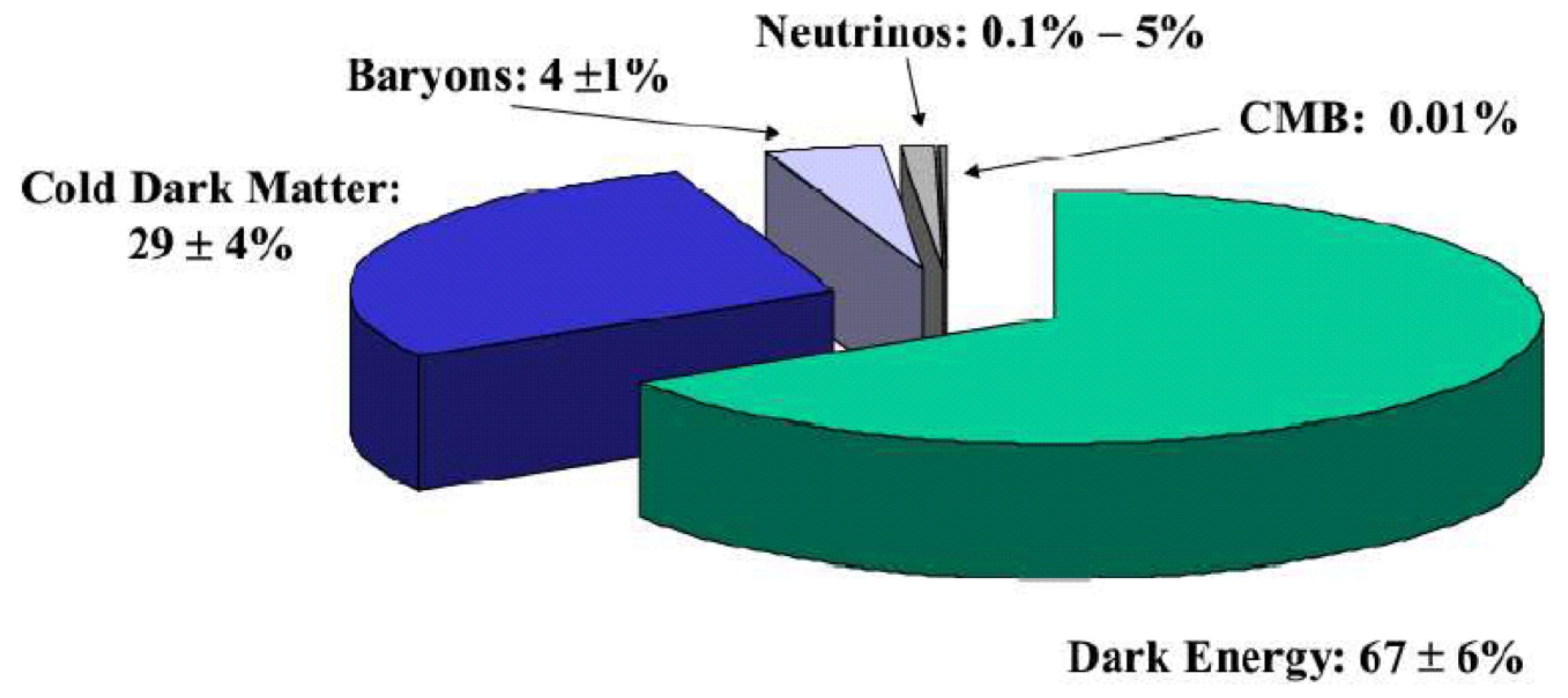
- According to
  - **Microwave background**
  - **Supernovae**
  - **Structures (galaxies, clusters, …) in the Universe**



And dark energy

There is dark matter

Strange Recipe for a Universe



The 'Standard Model' of the Universe indicated by astrophysics and cosmology

Slow-Roll Inflation

- Expansion driven by cosmological constant:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda}{3}$$

- Getting small density perturbations requires a "small" potential:

$$\left(\frac{V}{\epsilon}\right)^{\frac{1}{4}} = 0.0275 \times M_{Pl}$$

- That is almost flat: small $\epsilon = \frac{1}{2} M_{Pl}^2 \left(\frac{V'}{V}\right)^2$, $\eta = M_{Pl}^2 \left(\frac{V''}{V}\right)$

so as to get sufficient e-folds of expansion:

$$N = \frac{v^2}{M_{Pl}^2} \int_{x_i}^{x_e} \left(\frac{V}{V'}\right) dx$$

Main CMB Observables

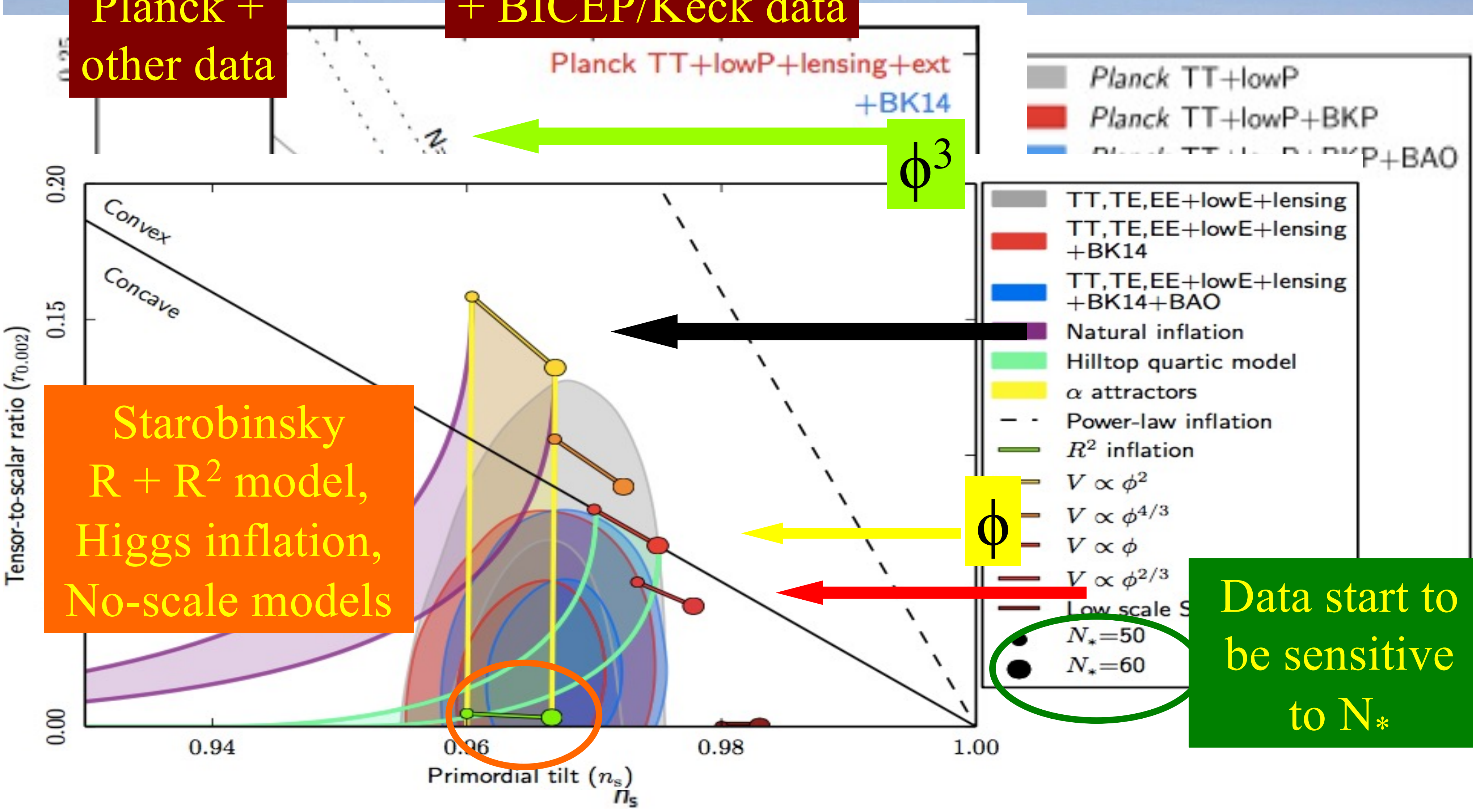
- Scalar and tensor perturbations
- Tilt in scalar spectrum (running down hill)

$$\boxed{n_s = 1 - 6\epsilon + 2\eta}$$

- Tensor perturbations = gravitational waves of quantum origin
- Tensor/scalar ratio: $\boxed{r = 16\epsilon}$
- Are perturbations ~ Gaussian?
  - Look for deviations, e.g., $\boxed{f_{NL}}$
- Expected to be small in slow-roll models

Inflationary Landscape

Monomial Single-field potentials



Planck + other data

+ BICEP/Keck data

ϕ^3

ϕ

Starobinsky
$R + R^2$ model,
Higgs inflation,
No-scale models

Data start to be sensitive to N_*

Challenges for Inflationary Models

- Links to low-energy physics?
  - Only SM candidate for inflaton is Higgs
    - **BUT** negative potential, ….
- Link to other physics?
- Links to Planck-scale physics?
  - Inflaton candidates in string theory?

Starobinsky Model

- Non-minimal general relativity (singularity-free cosmology):
- **No scalar!?**

$$S = \frac{1}{2}\int d^4x\sqrt{-g}\left(R + R^2/6M^2\right)$$

Starobinsky, 1980

- **Conformally equivalent to scalar field model:**

$$S = \frac{1}{2}\int d^4x\sqrt{-\tilde{g}}\left[\tilde{R} + (\partial_\mu\varphi')^2 - \frac{3}{2}M^2\left(1 - e^{-\sqrt{2/3}\varphi'}\right)^2\right]$$

Stelle; Whitt, 1984

- Inflationary interpretation, calculation of perturbations:

Mukhanov & Chibisov, 1981

$$\delta S_b = \frac{1}{2}\int d^4x\left[\phi'^2 - \nabla_a\phi\nabla^a\phi + \left(\frac{a''}{a} + M^2a^2\right)\phi^2\right]$$

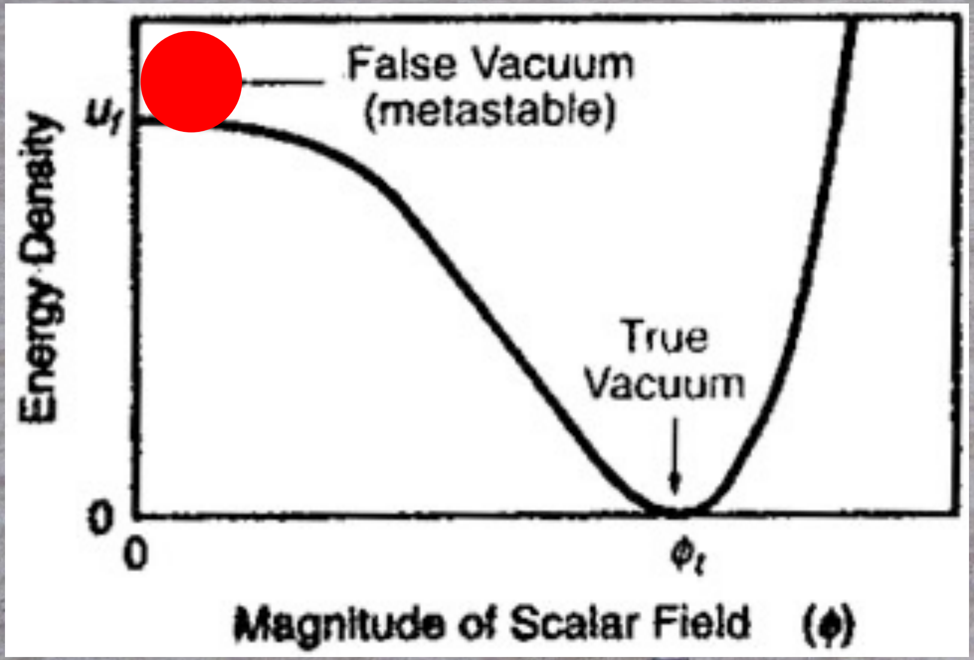
CMB: Opportunity & Challenge

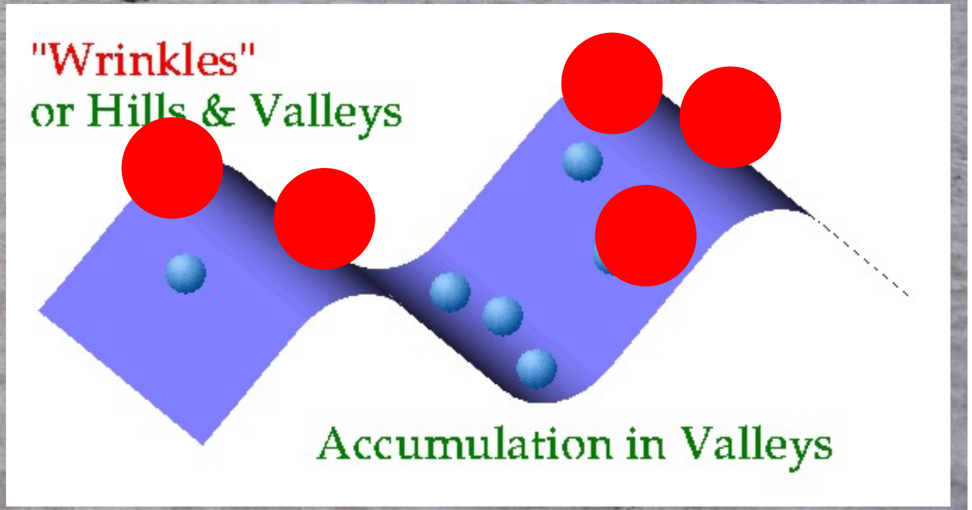
- Unique probe of (very) high-energy scale
- Close to string scale?
- Detailed measurements
  - ➔ Many probes of models of inflation
- Connection with collider physics via pattern of inflaton decay?
- Use string-motivated framework to construct models of inflation
- **No-scale supergravity (+ flipped unification)**

Origin of Structures in Universe

Small primordial fluctuations:
one part in 10^5

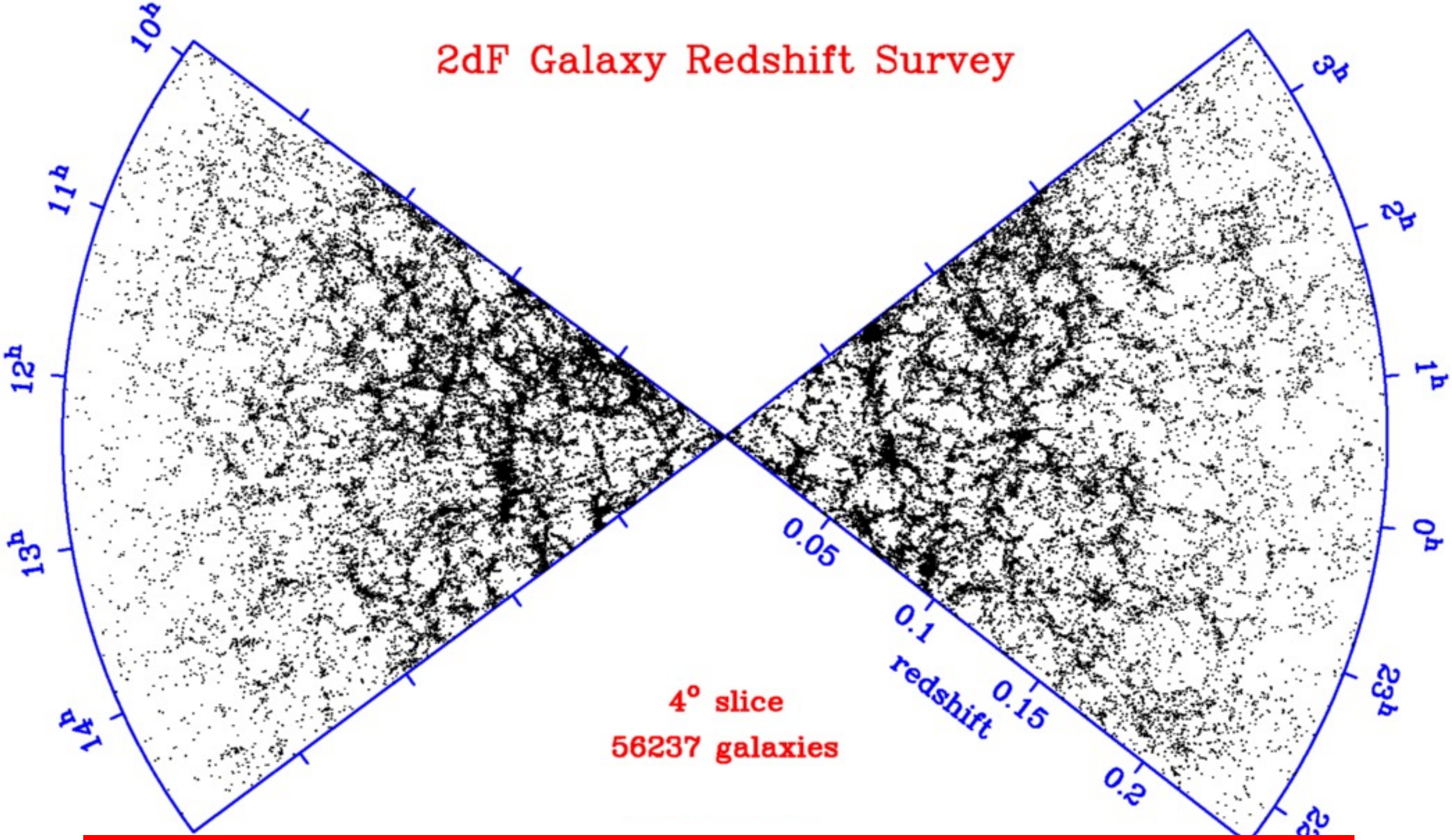
Gravitational instability:
Matter falls into
the overdense regions





Convert into matter with varying density

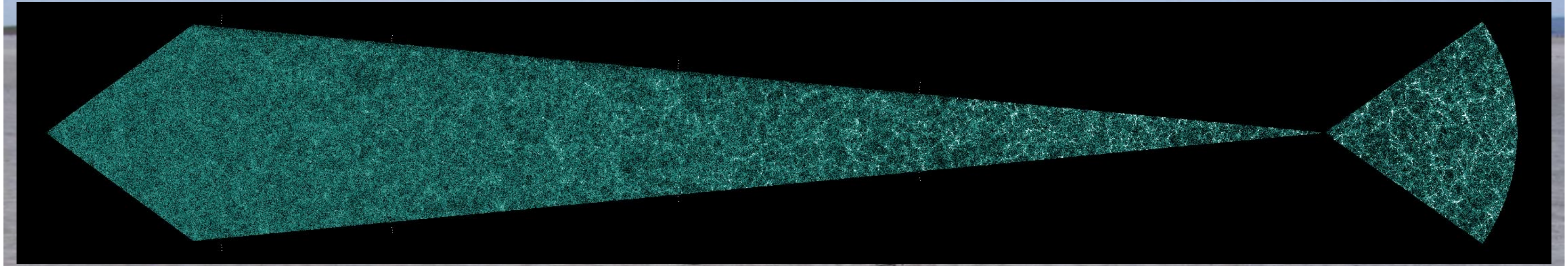
Structures observed in the Universe



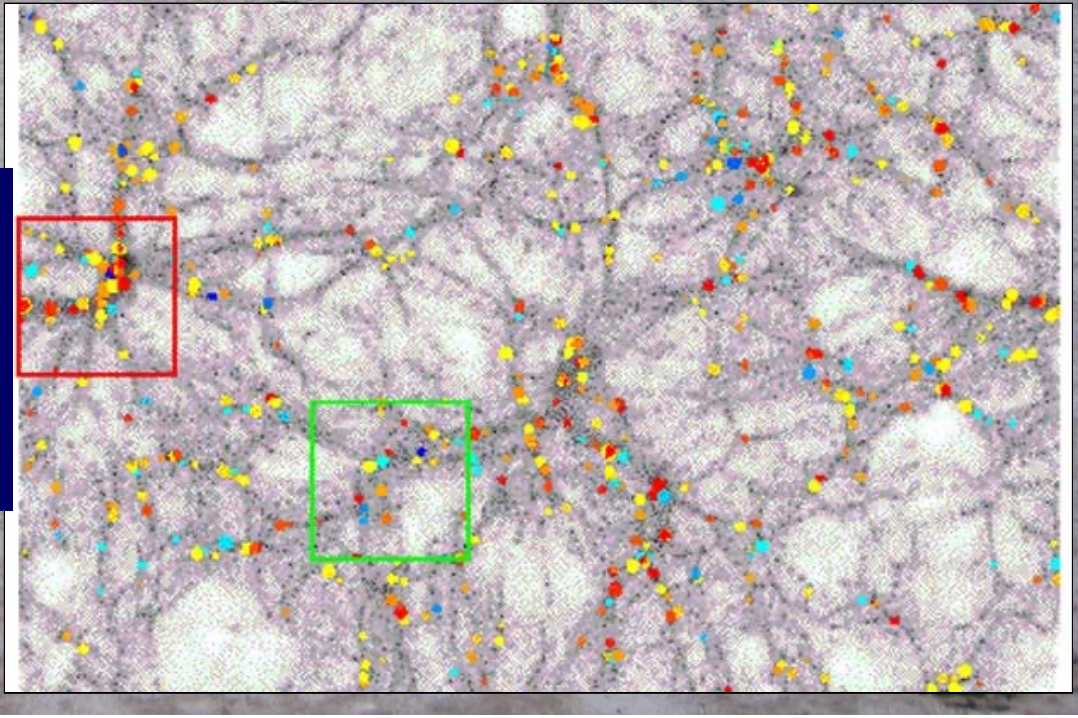
Galaxies → Clusters → smooth at largest scales

Simulation of Cold Dark Matter

Initially quite homogeneous: gravity → structures form → today



Simulation of present-day Universe:
- Filaments of dark matter,
- Clusters of galaxies at nodes



A Successful Theory of the Formation of Structures in the Universe

Dark matter:

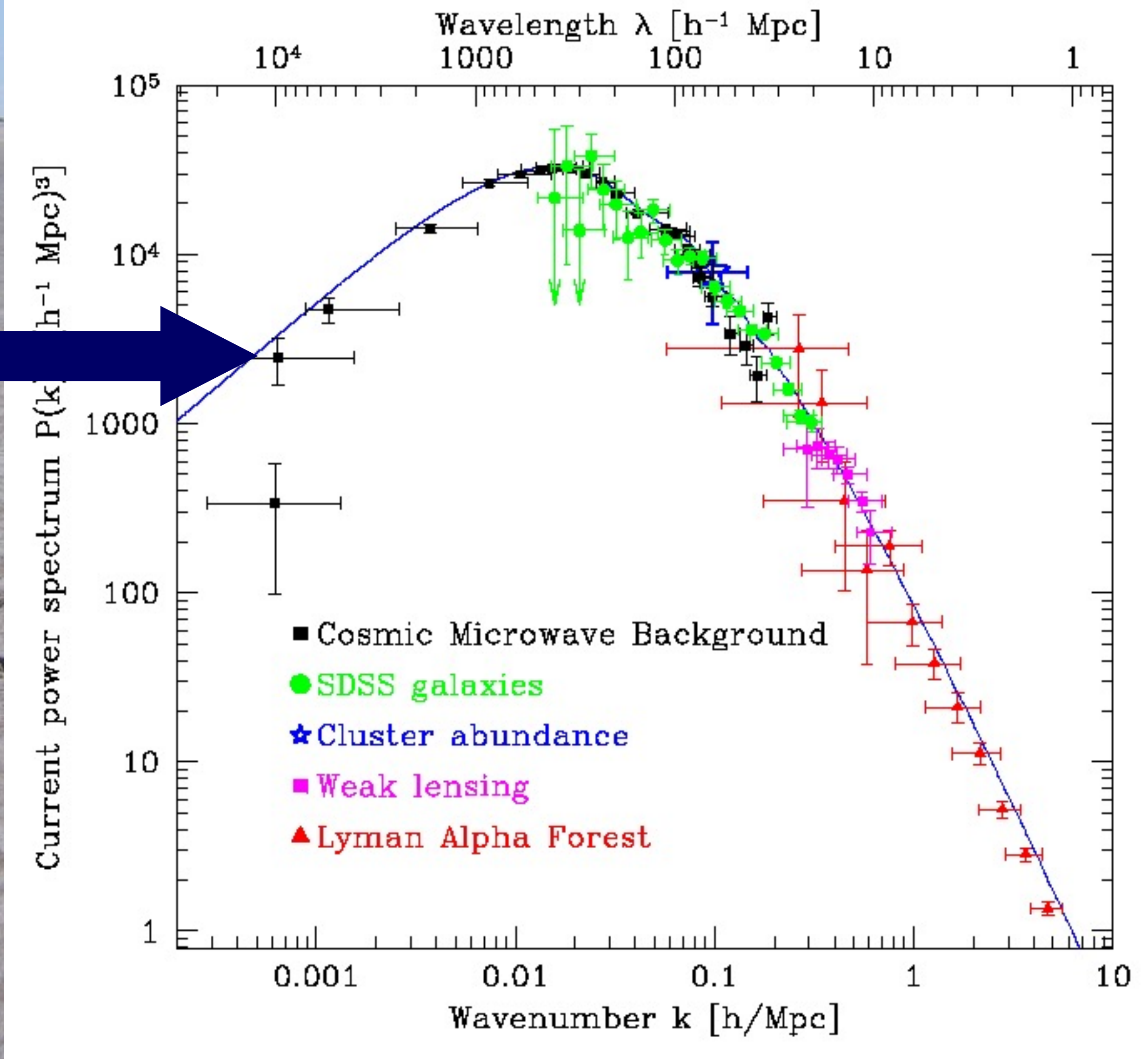
$\Omega_{CDM} \sim 0.25$,

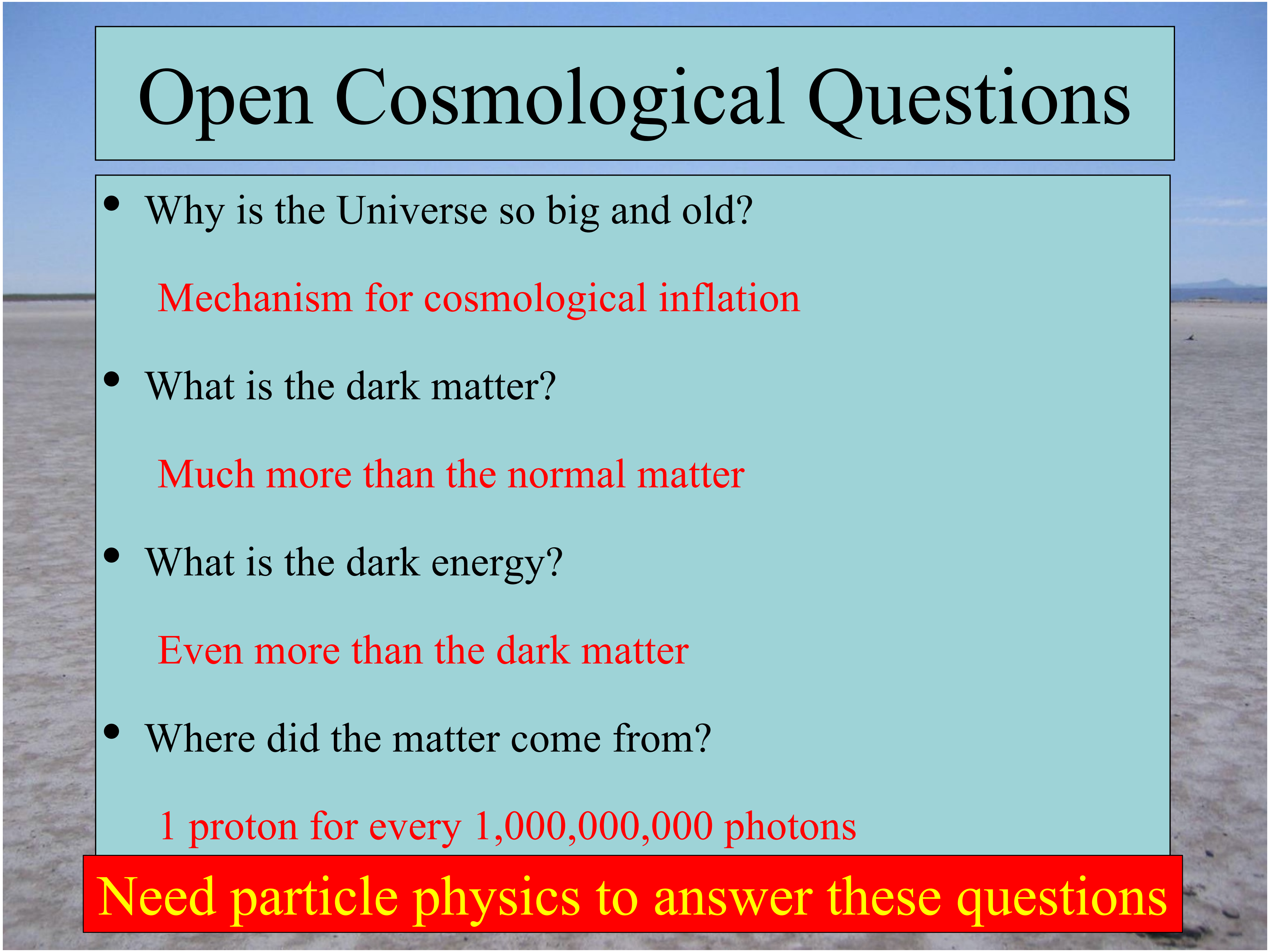
Visible matter:

$\Omega_b \sim 0.05$,

Dark energy:

$\Omega_\Lambda \sim 0.7$





Open Cosmological Questions

- Why is the Universe so big and old?

  Mechanism for cosmological inflation

- What is the dark matter?

  Much more than the normal matter

- What is the dark energy?

  Even more than the dark matter

- Where did the matter come from?

  1 proton for every 1,000,000,000 photons

Need particle physics to answer these questions

Comments on Dark Energy

- Many orders of magnitude smaller than expected contributions from ‘known’ physics: today: 10^{-48} GeV^4

QCD: $\Lambda_{QCD}{}^4 \sim 10^{-4}$ GeV^4

Higgs: $m_W{}^4 \sim 10^8$ GeV^4

Broken susy: $m_{susy}{}^4 \sim 10^{12}$ GeV^4

GUT: $m_{GUT}{}^4 \sim 10^{64}$ GeV^4

Quantum Gravity: $m_P{}^4 \sim 10^{76}$ GeV^4

- Need new physics!
- A great challenge for string theory

General Interest in Antimatter Physics

Physicists cannot make enough for
Star Trek or Dan Brown!

How do Matter and Antimatter Differ?

Dirac predicted the existence of antimatter:
same mass
opposite internal properties:
electric charge, …
Discovered in cosmic rays
Studied using accelerators
Used in PET scanners

Matter and antimatter not quite equal and opposite: WHY?

Why does the Universe mainly contain matter, not antimatter?

Experiments at LHC and elsewhere looking for answers

How to Create the Matter in the Universe?

Sakharov

- Need a difference between matter and antimatter

  observed in the laboratory

- Need interactions able to create matter

  predicted by theories

  not yet seen by experiment

- Need the expansion of the Universe

  a role for the Higgs boson?

Will we be able to calculate using laboratory data?