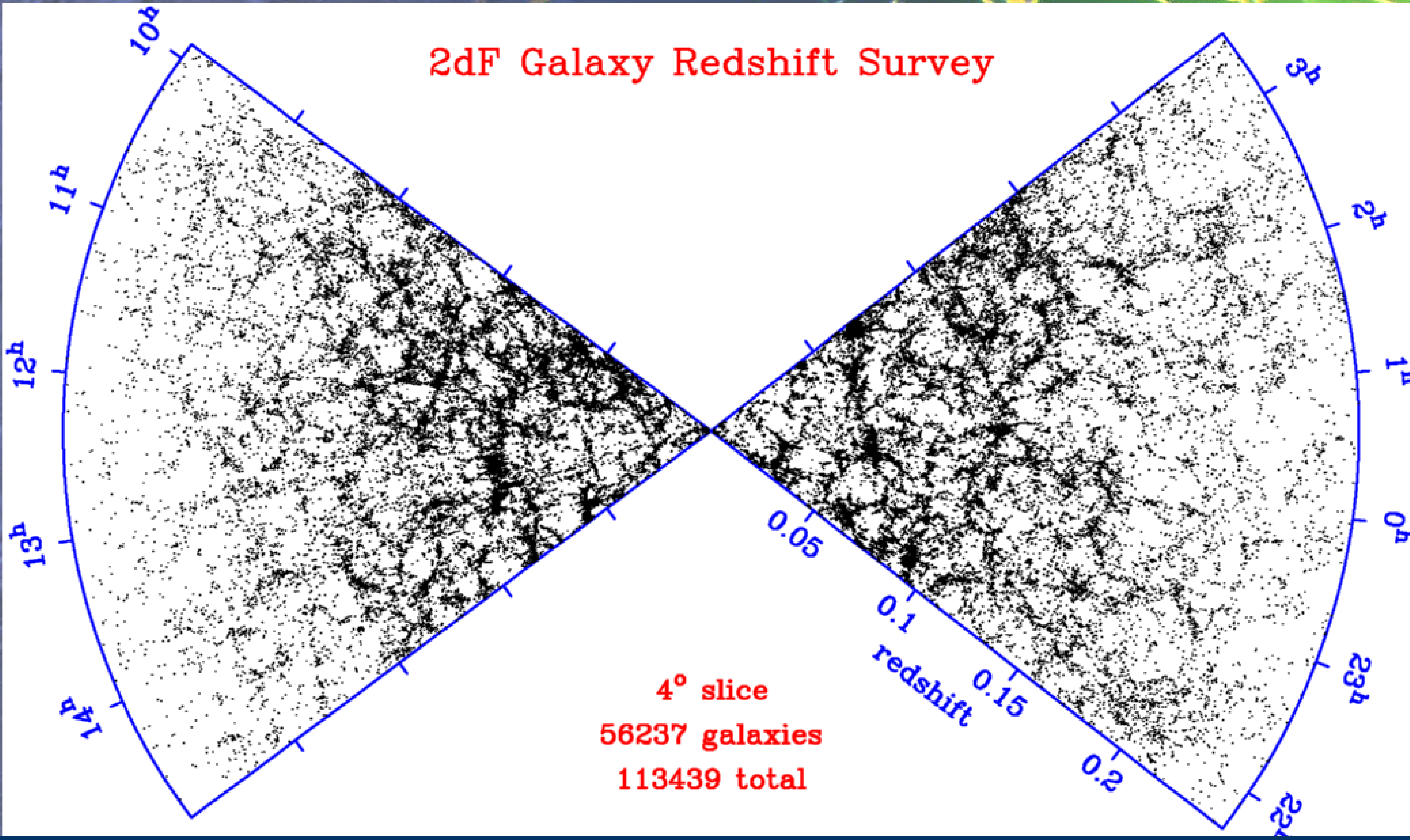
Introduction to Cosmology

from a Particle Physicist's Perspective

High-School Teachers' Programme,
CERN, July 4th & 5th, 2005

John Ellis

What we see in the Universe



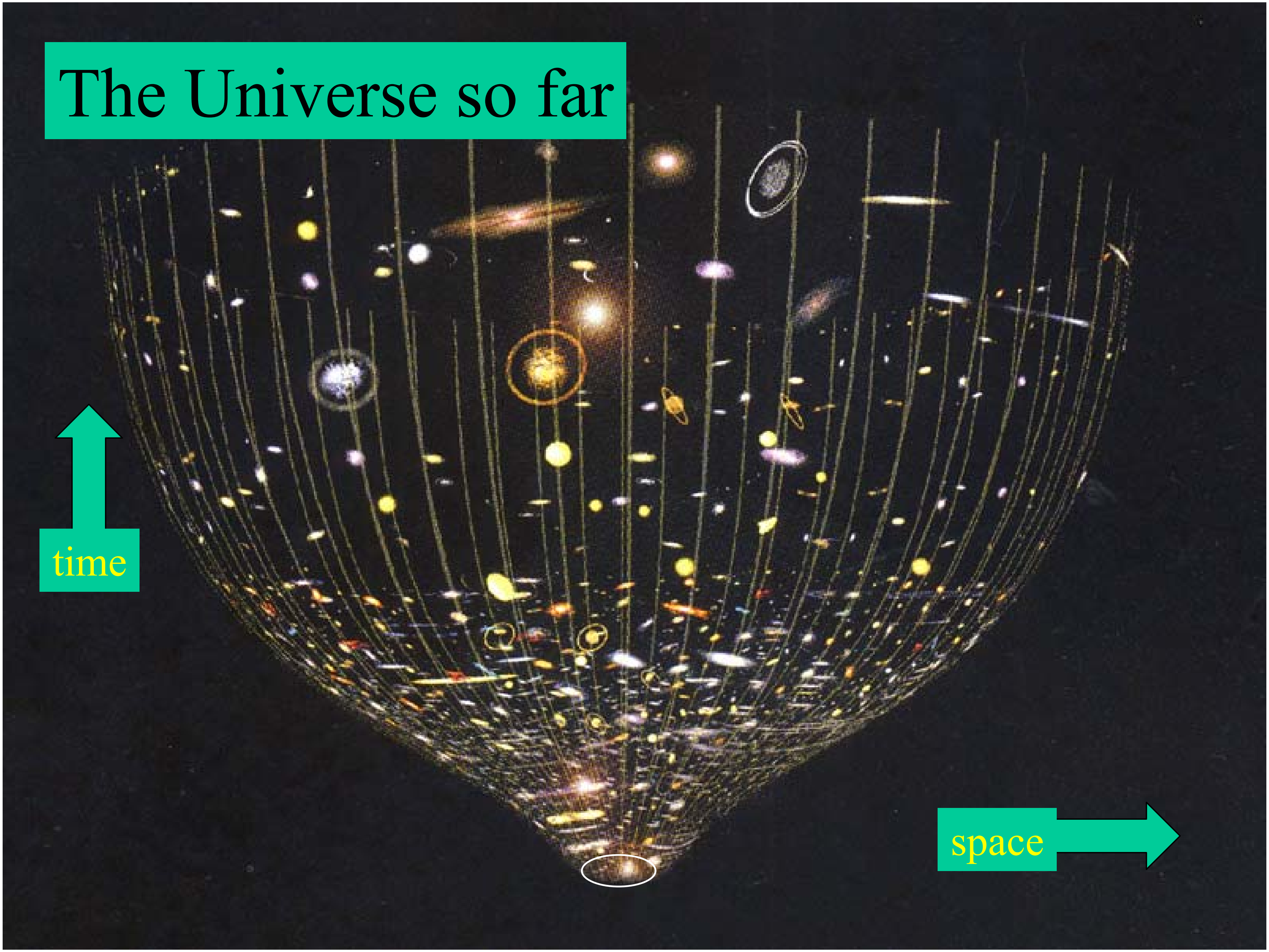
Small-scale structures → homogeneous and isotropic at large scales

Cosmological 'Principle'

- 'Universe looks the same from any point'

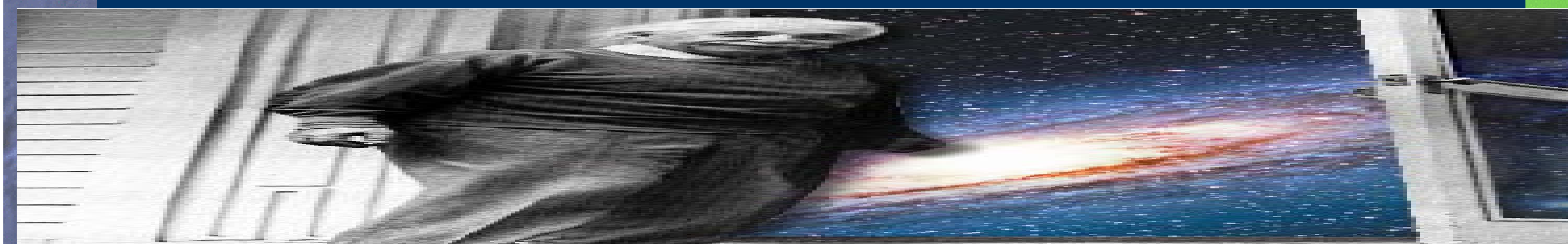
  isotropic and homogeneous
- To be interpreted in average sense
- Perfect Cosmological Principle?
- 'Universe looks same at all times and all places'
- Not correct: the Universe is expanding

The Universe so far



The Hubble Expansion

- Light arriving from distant galaxies is redshifted
- The effect increases with distance
- The effect is due to the expansion of light wave as space expands

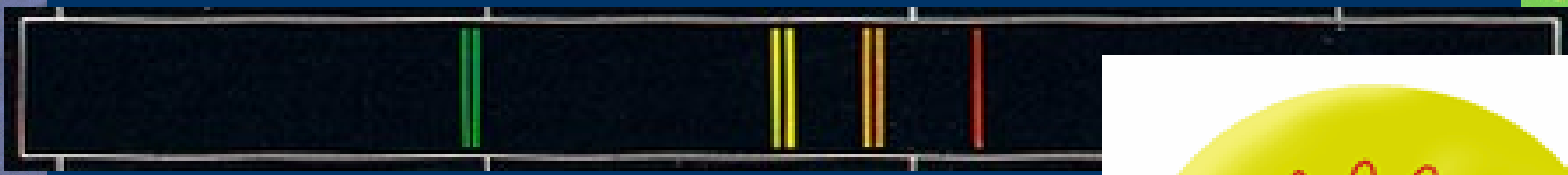


~ 10,000,000,000 light years

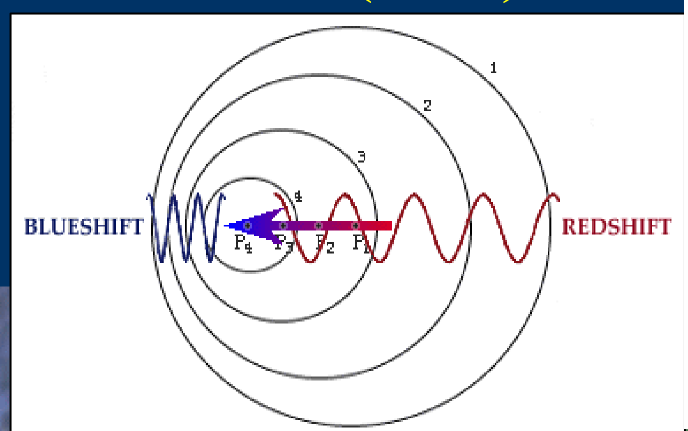
- **The same physics as in the laboratory!**

Cosmological Redshifts

- Detectable effect on spectrum ‘barcodes’ for different elements, e.g., Sodium:



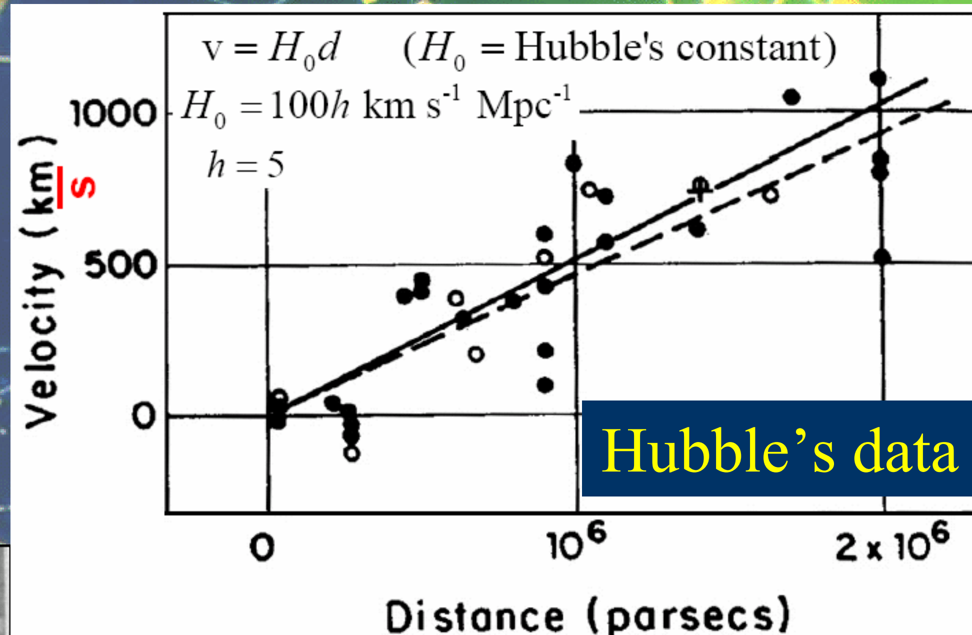
- Döppler effect: $\lambda = \lambda/(1+z)$



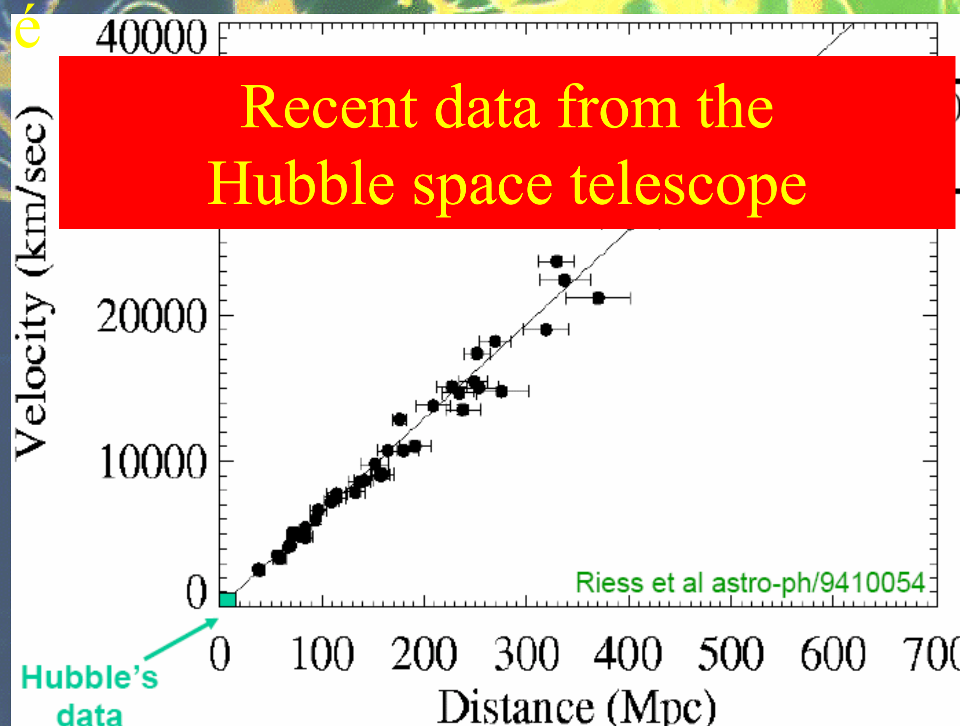
The expansion of the Universe

Hubble, basketball player

University of Chicago 1909 National Champions



Hubble's data



Recent data from the Hubble space telescope

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

Cosmological Distance Ladder

- Trigonometric parallax:

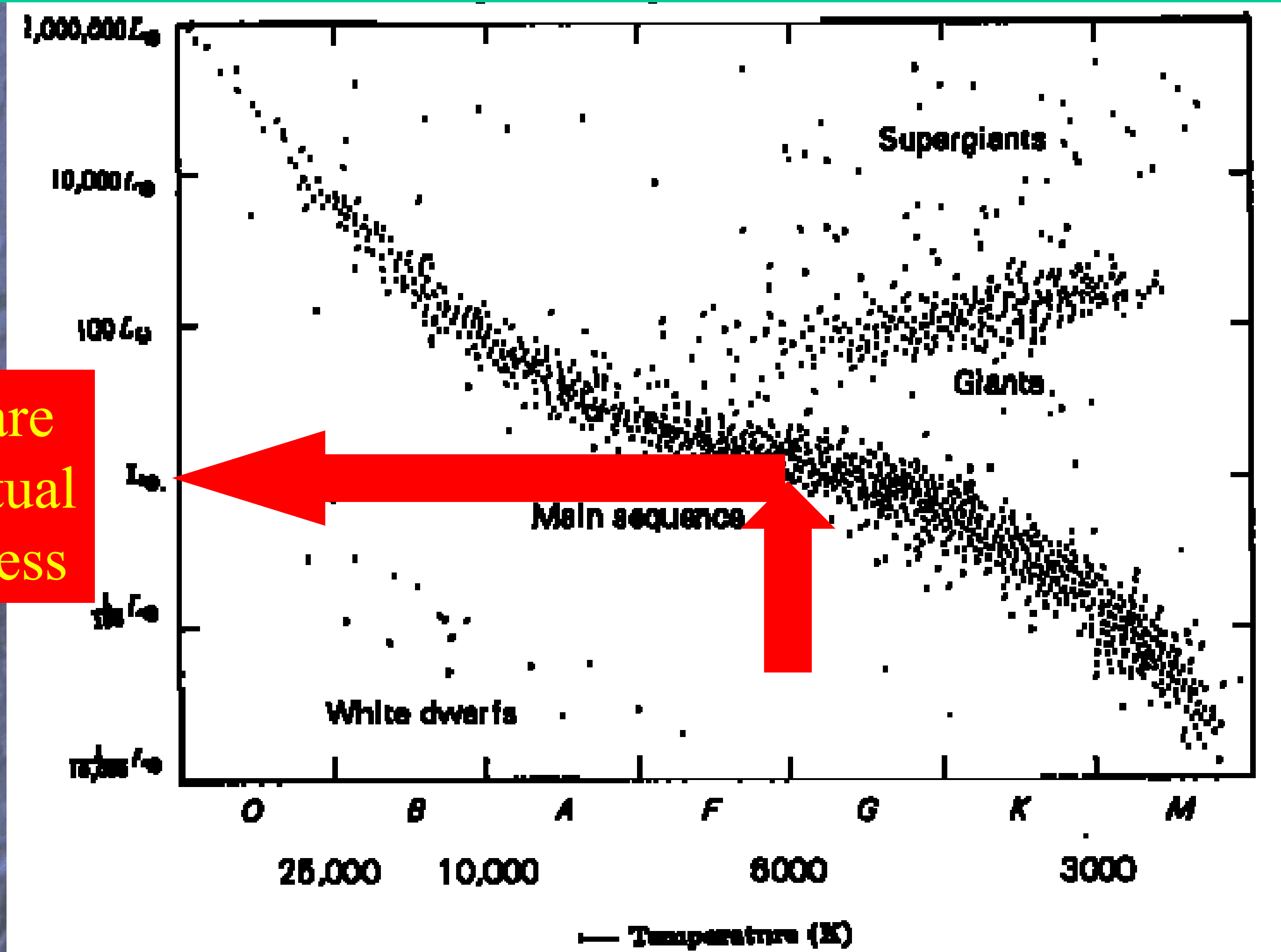
  motion of Earth around orbit → O(100) pc
- Spectroscopic Parallax:

  based on Hertzsprung-Russell diagram → 50 Kpc
- Cepheid variables: → 4 Mpc
- Other 'Standard Candles':

  clusters, galaxies, radio sources, supernovae …

  weak lensing, microwave background, …
- Hubble constant = 70 km/s/Mpc ± < 10 %

Hertzsprung-Russell Diagram for Stars in our Local Neighbourhood



Compare with actual brightness

The Universe is expanding

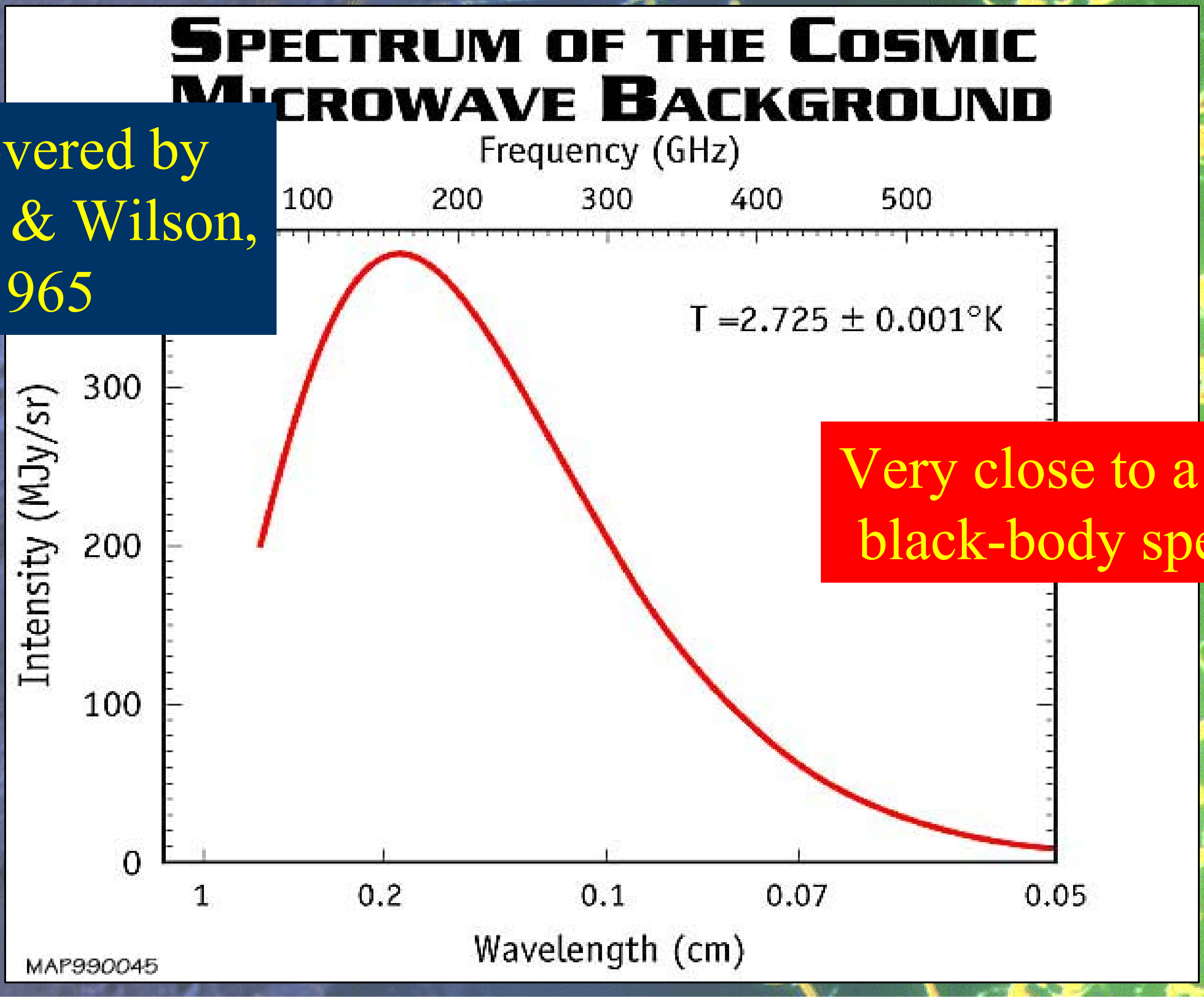
- Galaxies are receding from us

    Hubble expansion law: galactic redshifts

- The Universe was once 3000 smaller, hotter than today

    cosmic microwave background radiation

The Cosmic Microwave Background Radiation



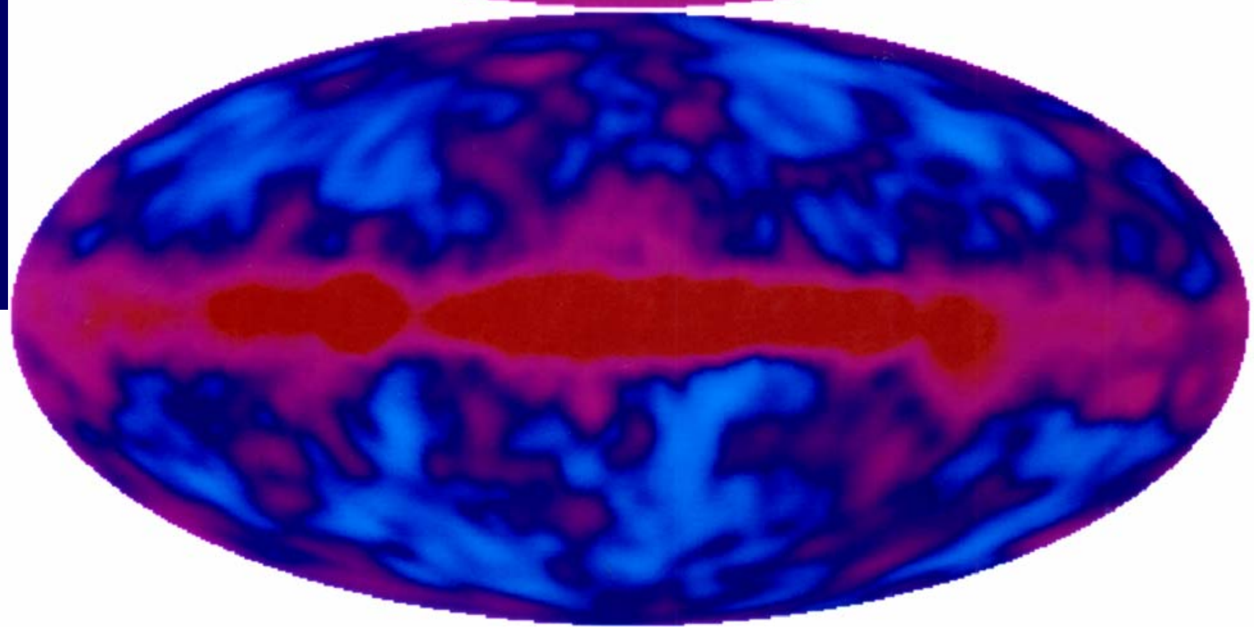
Discovered by Penzias & Wilson, 1965

Very close to a perfect black-body spectrum

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

Big-Bang Nucleosynthesis

- 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

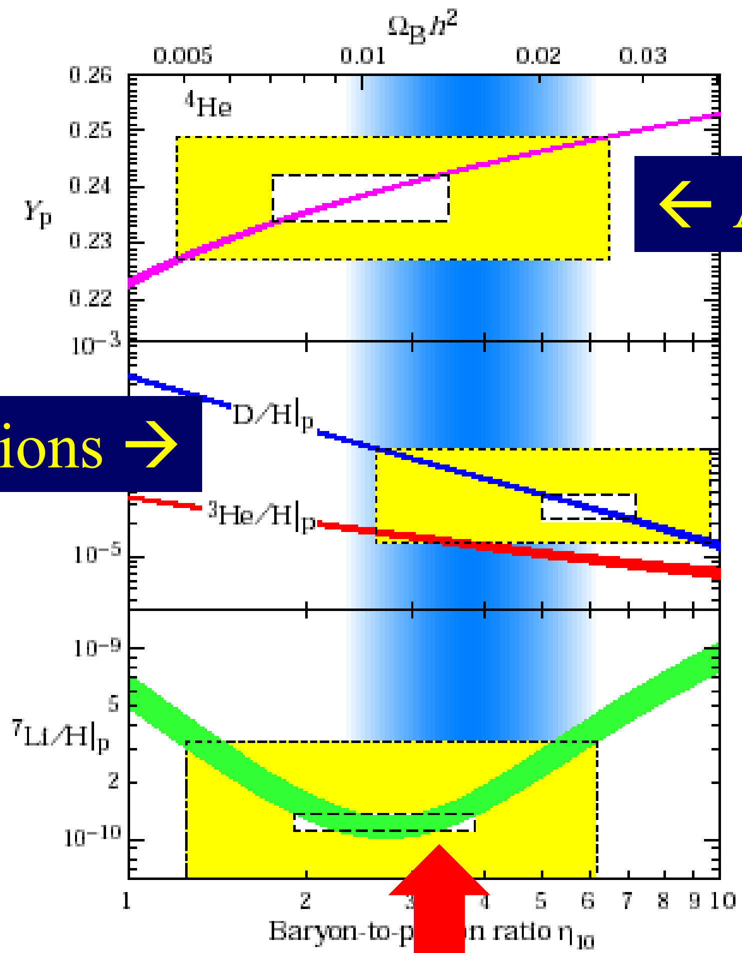
Abundances of light elements in the Universe

Helium

← Agree with data

Theoretical calculations →

Lithium



Not enough ordinary matter to make the Universe recollapse

The Very Early Universe

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

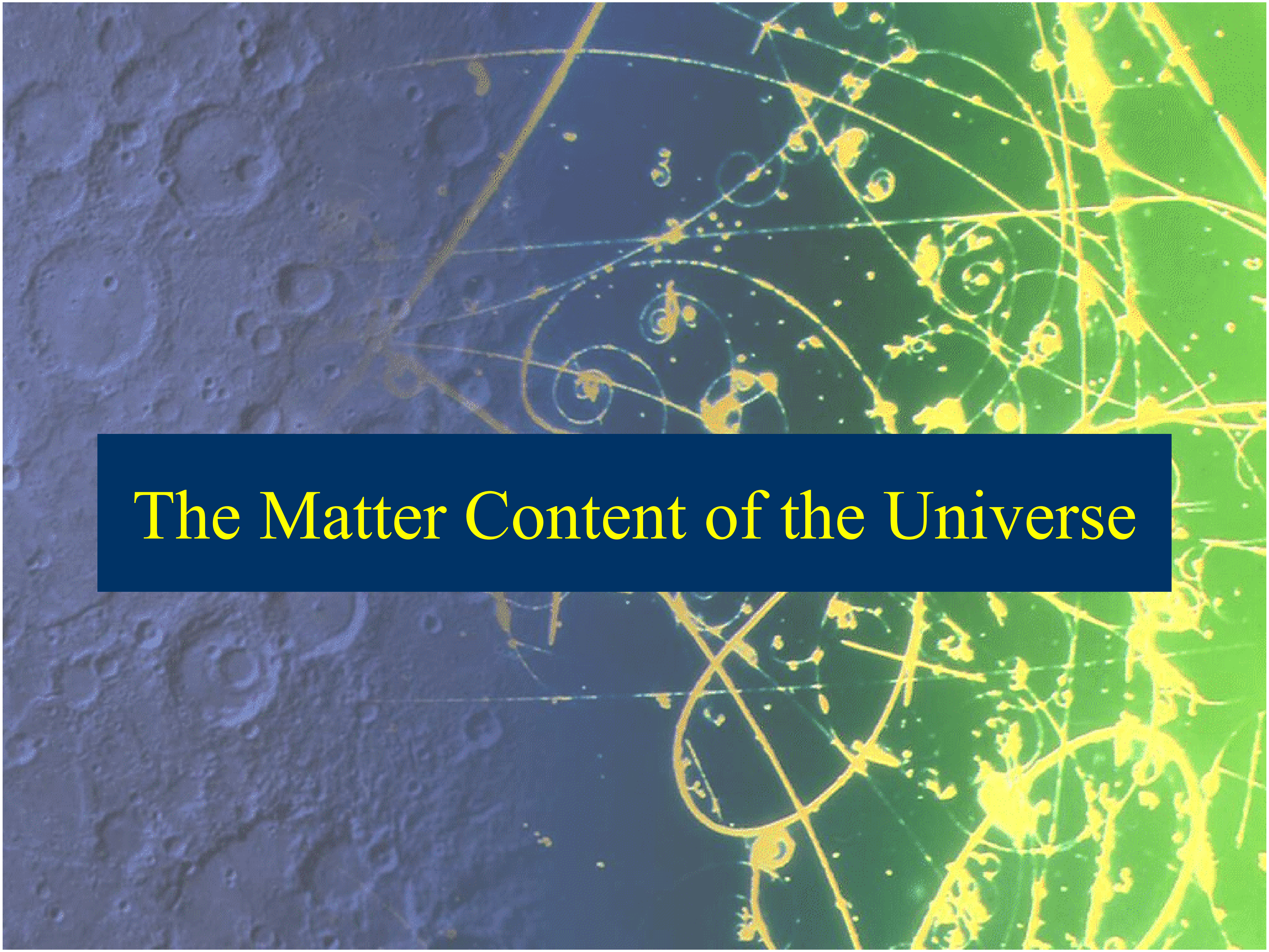
  $T \sim 1/a$, $t \sim 1/T^2$
- Energies: $E \sim T$
- Rough magnitudes:

  T ~ 10,000,000,000 degrees

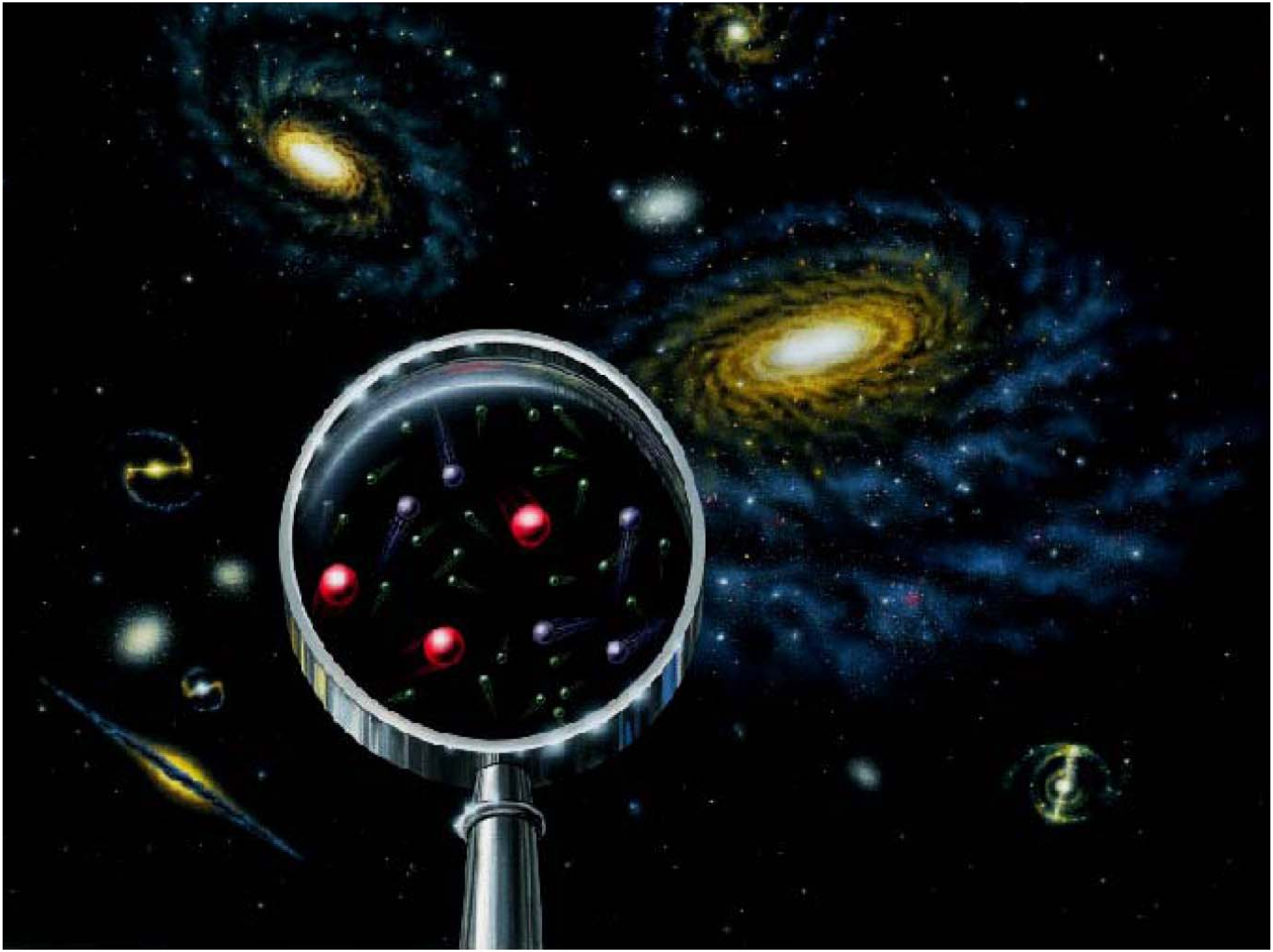
  E ~ 1 MeV ~ mass of electron

  t ~ 1 second

Need particle physics to describe earlier history



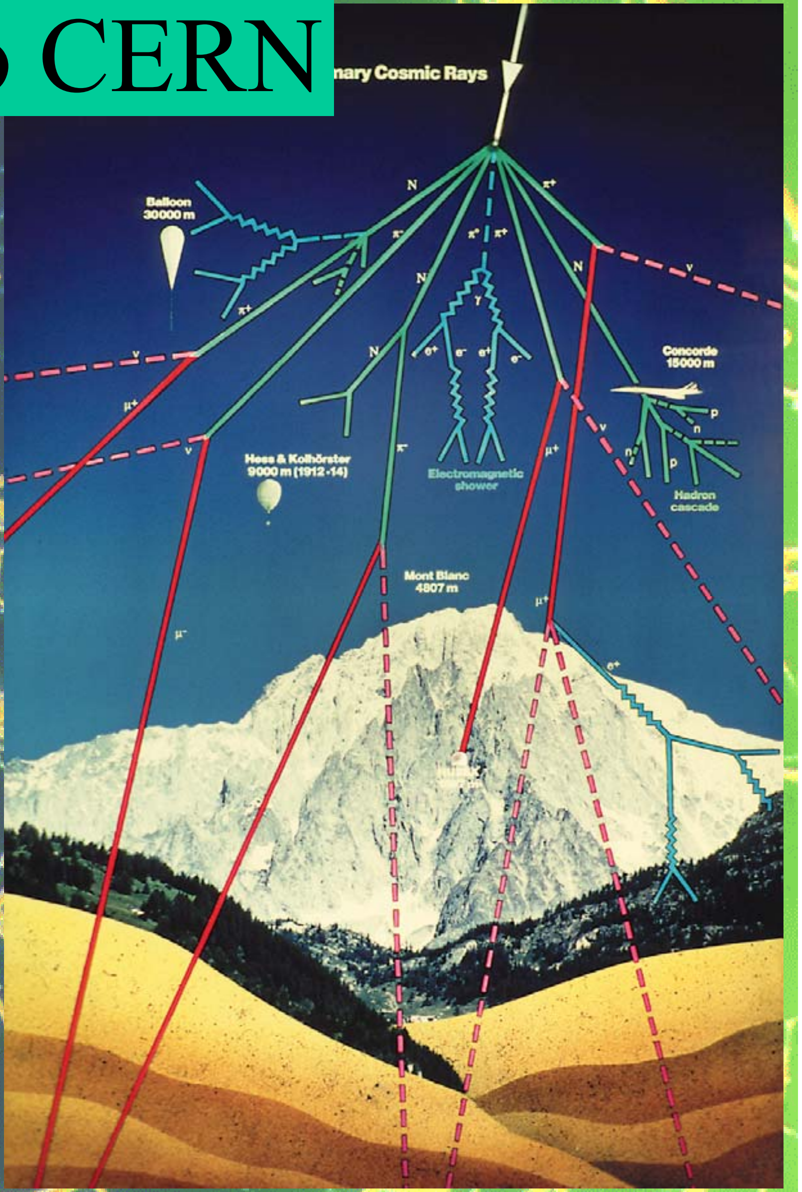
The Matter Content of the Universe



From the Cosmic Rays to CERN

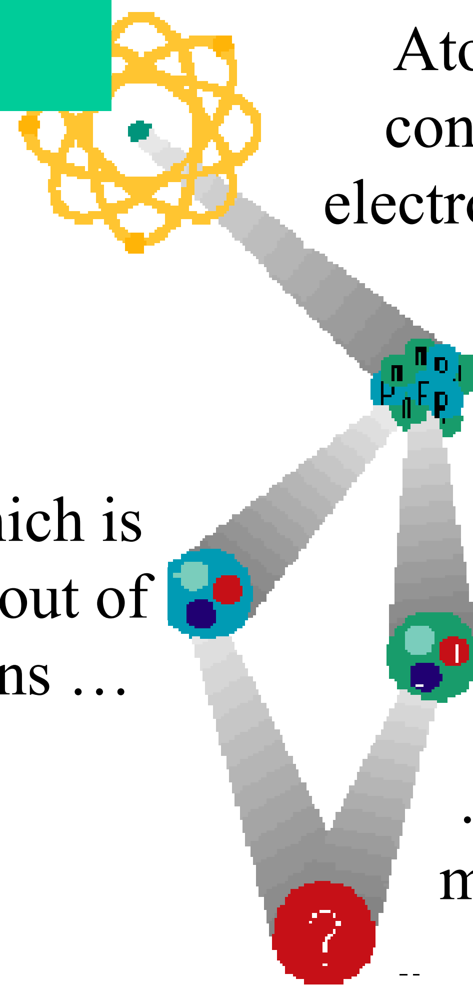
Discovered a century ago …

… cosmic rays produce various types of elementary particles …



CERN was founded in 1954 to study these particles

Inside matter

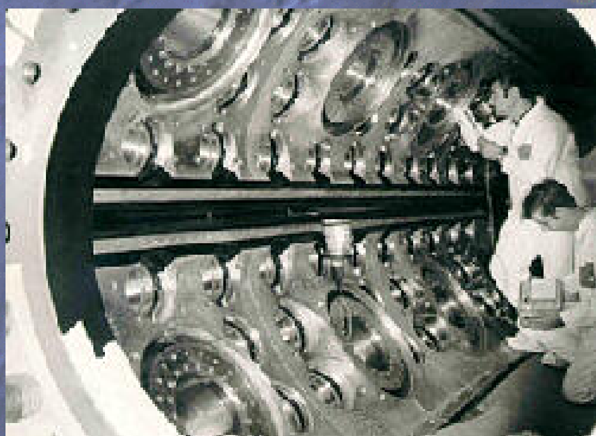


All matter is made out of the same constituents

What are the elementary particles?
How do they interact?

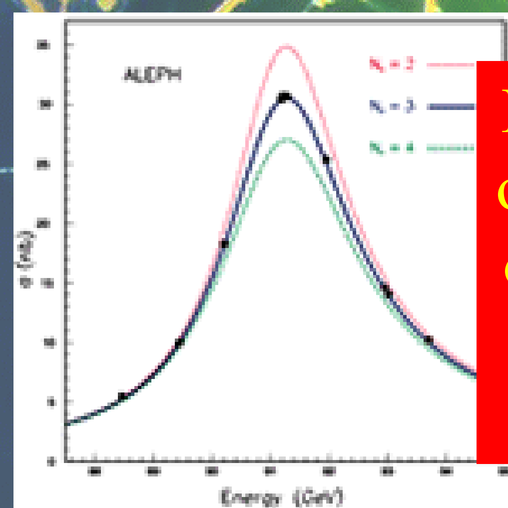
The ‘Standard Model’ of Particle Physics

Proposed by Abdus Salam, Glashow & Weinberg



Crucial tests in experiments at CERN

In agreement with all confirmed laboratory experiments

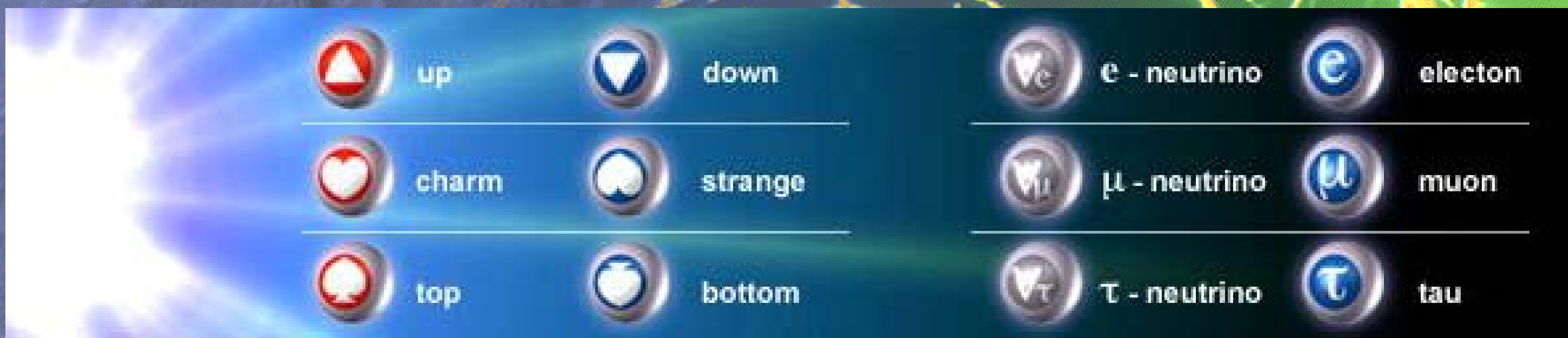


Measurement of the number of families of elementary particles: 3!

The'Standard Model'

= Cosmic DNA

The matter particles



The fundamental interactions

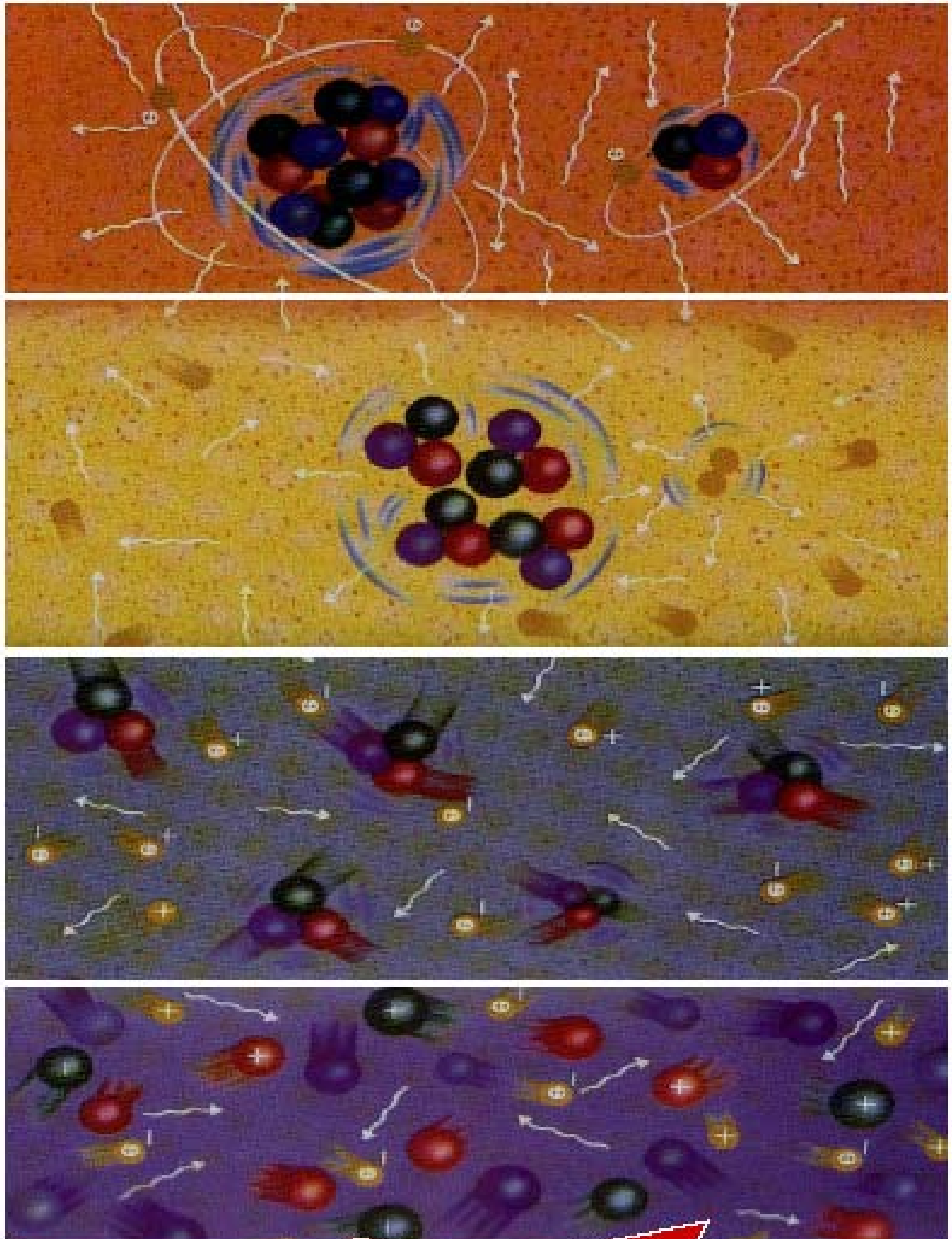
Gravitation electromagnetism weak nuclear force strong nuclear force

300,000 years — *Birth of atoms*

3 minutes — *Birth of nuclei*

1 micro-second — *Birth of protons & neutrons*

1 pico-second — Soup of quarks & gluons



How were the quarks born?

Open Cosmological Questions

- Why is the Universe so big and old?
  - ~ 13,000,000,000 years
- Why is its geometry nearly Euclidean?
  - almost flat, borderline for eternal expansion
- Where did the matter come from?
  - 1 proton for every 1,000,000,000 photons
- How did structures form?
  - ripples + invisible dark matter?
- What is the dark matter?

Need particle physics to answer these questions

The Density Budget of the Universe

- Total density ~ critical

  Theory of inflation, measurements of CMB: $\Omega_{Tot} = \sim 1$

- Baryon density small

  Big-bang nucleosynthesis, CMB:

  $\Omega_{Baryons} \sim$ few %

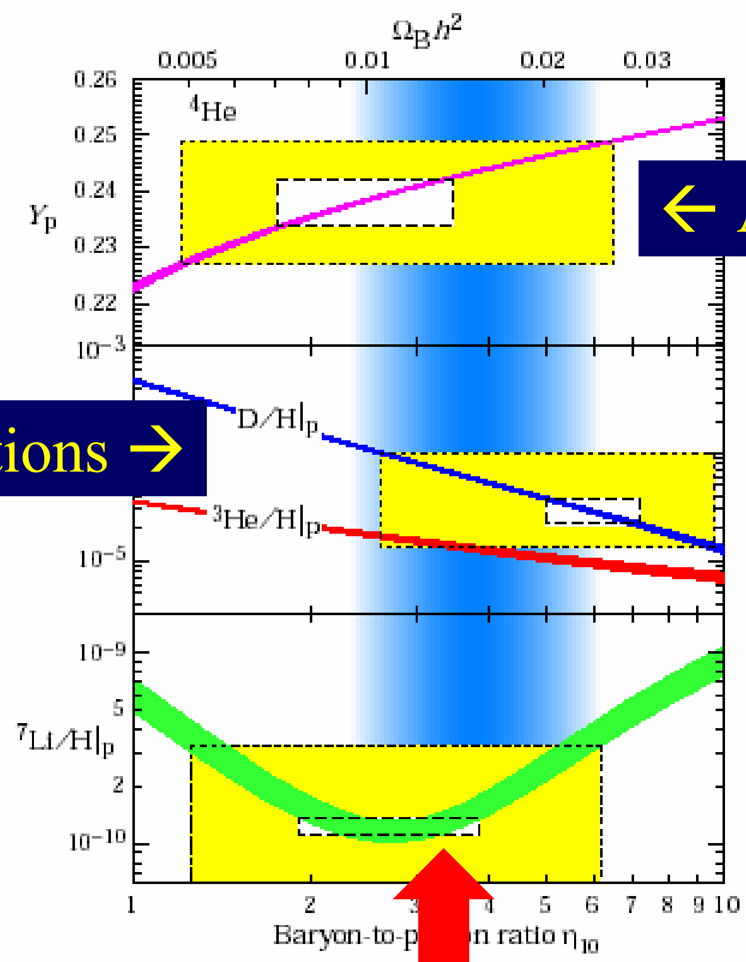
Abundances of light elements in the Universe

Helium

← Agree with data

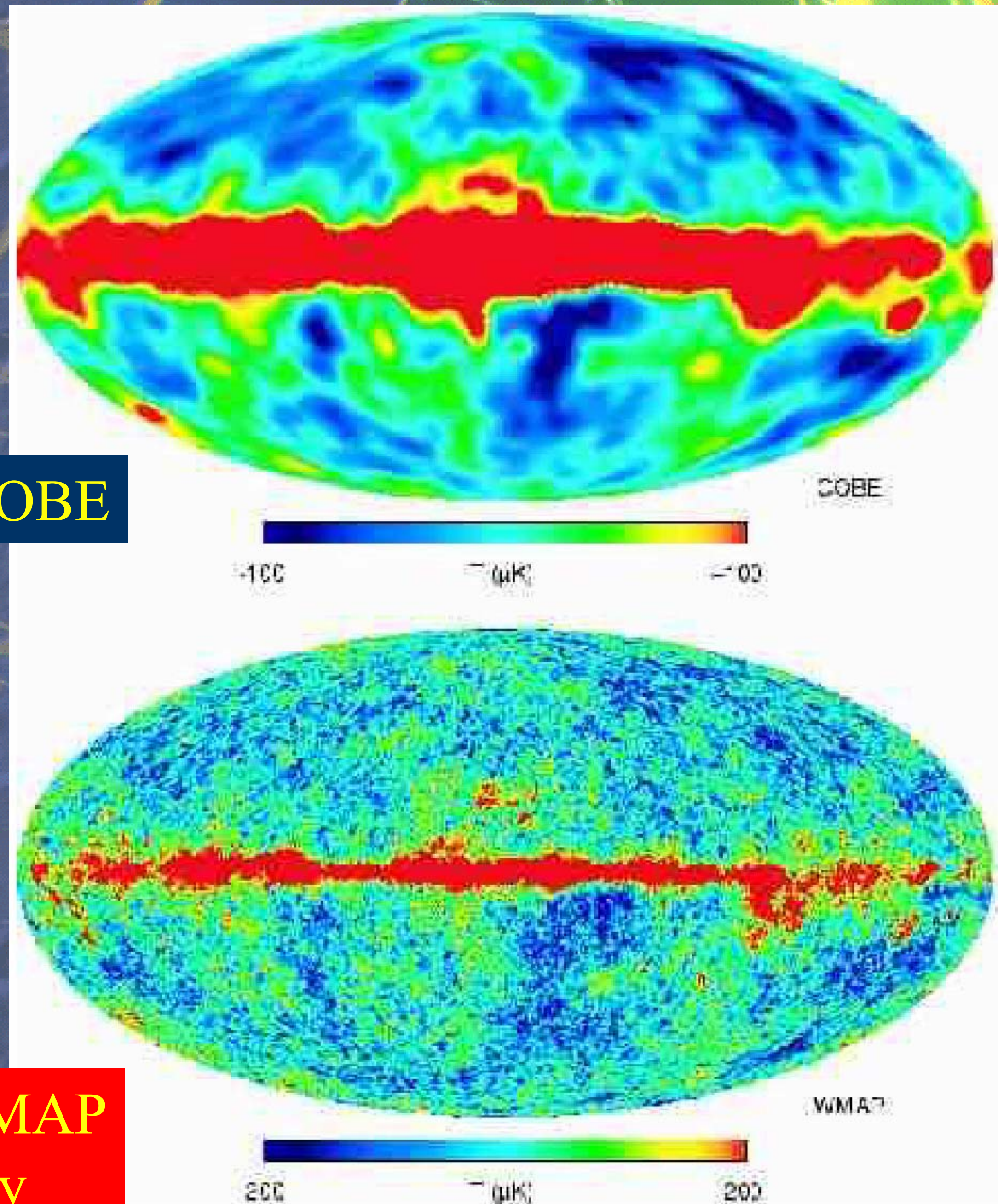
Theoretical calculations →

Lithium



Not enough ordinary matter to make the Universe recollapse

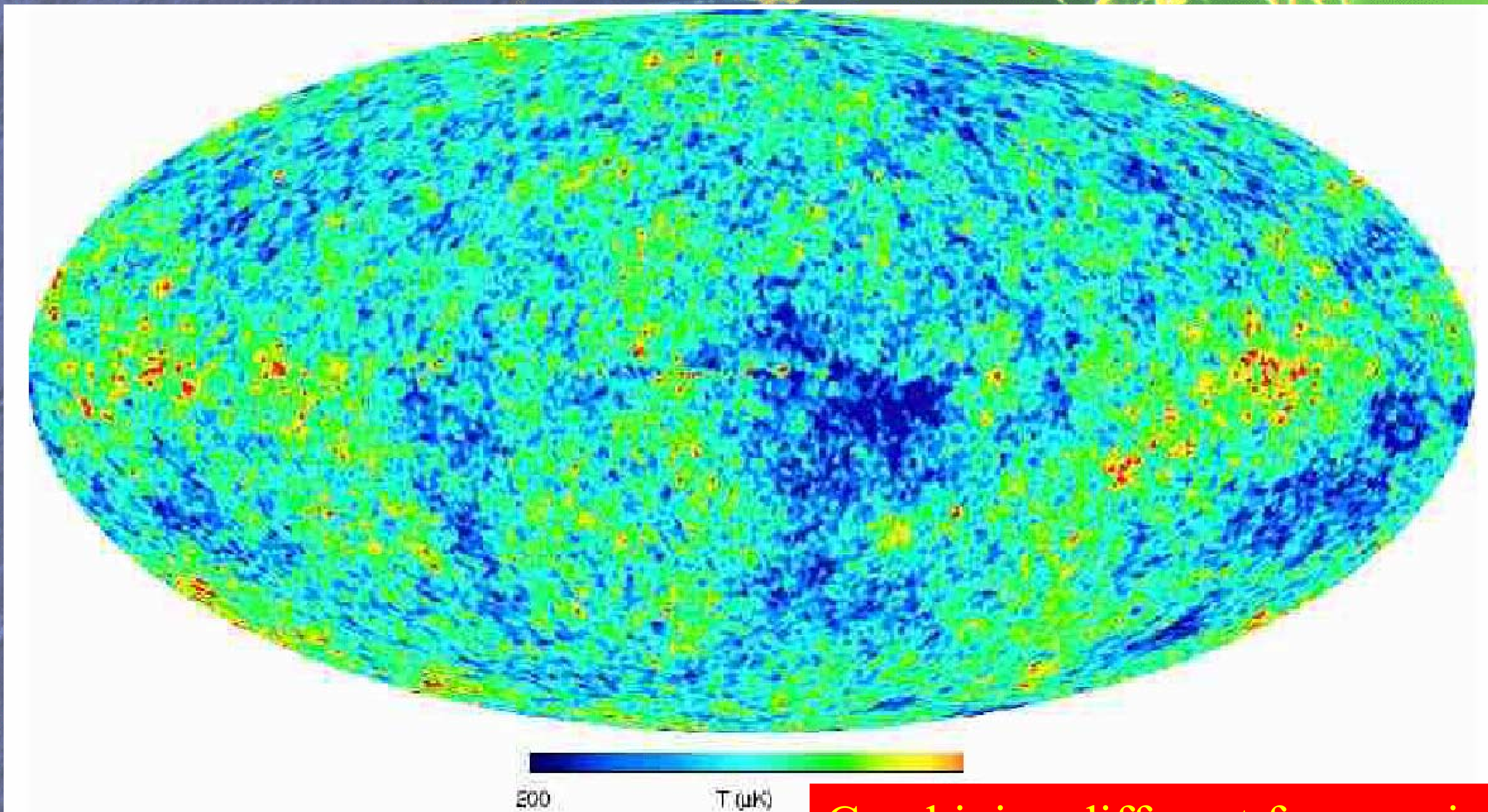
The Cosmic Microwave Background



According to COBE

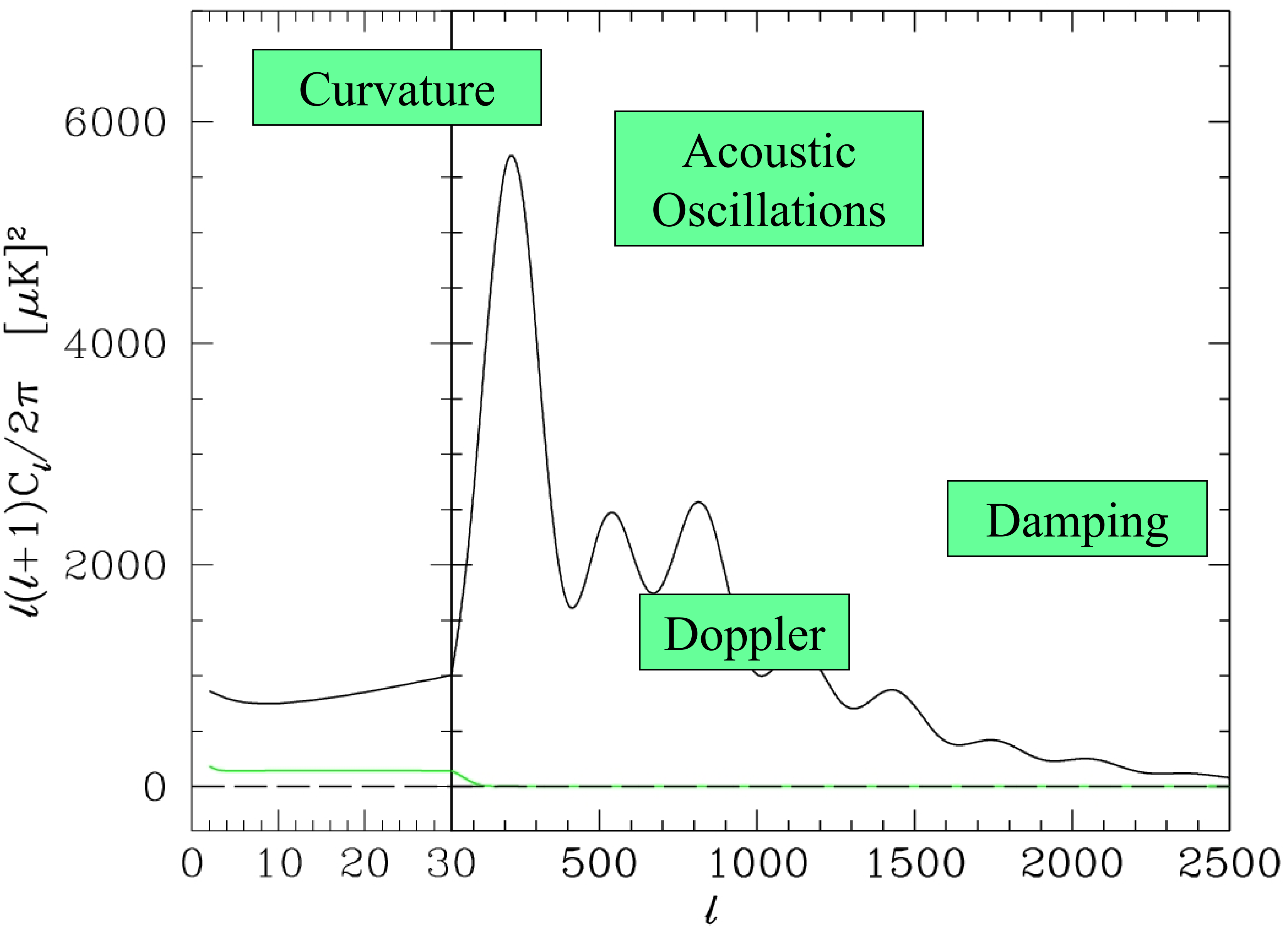
According to WMAP
- at one frequency

The CMB according to WMAP

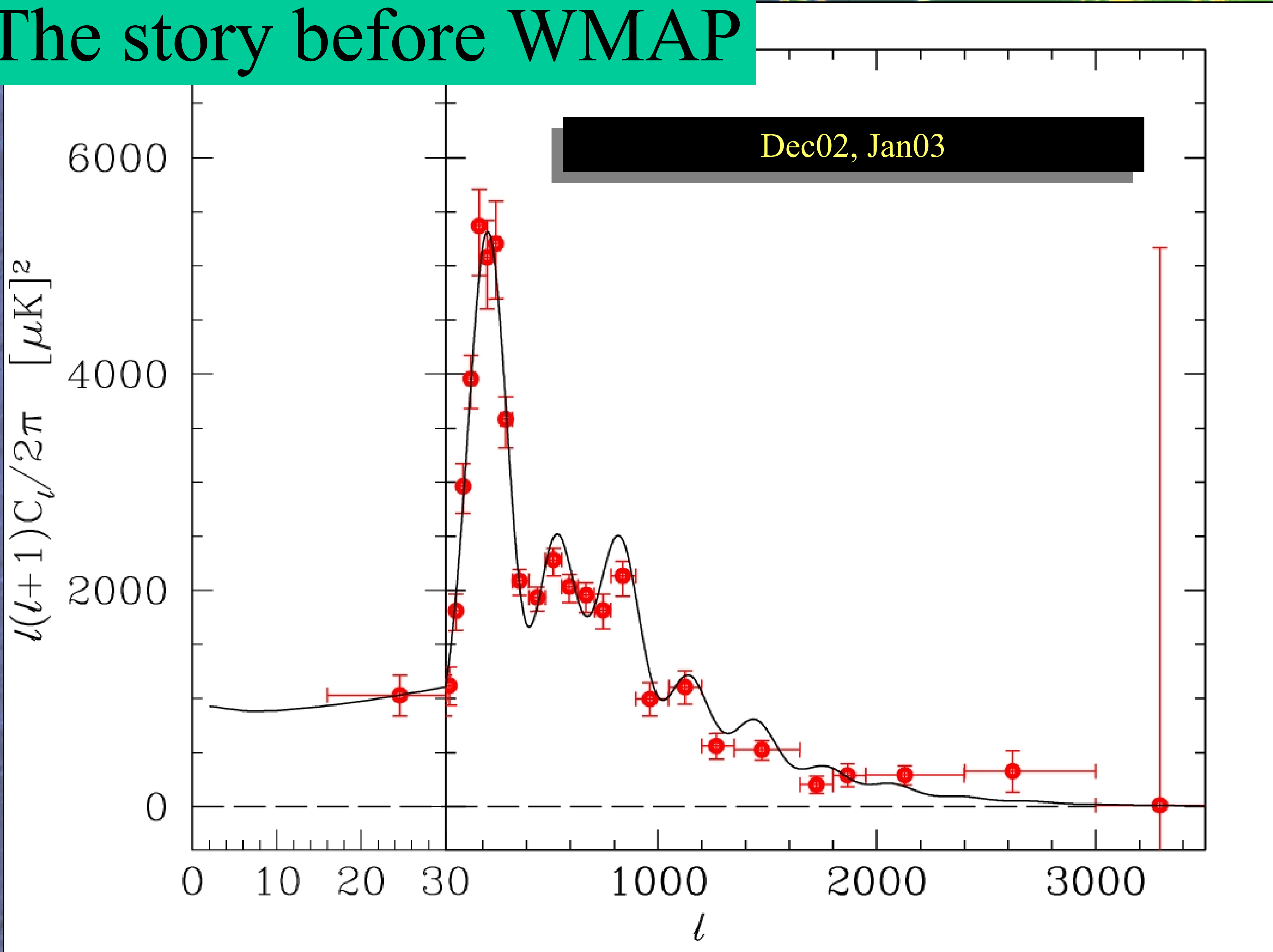


Combining different frequencies

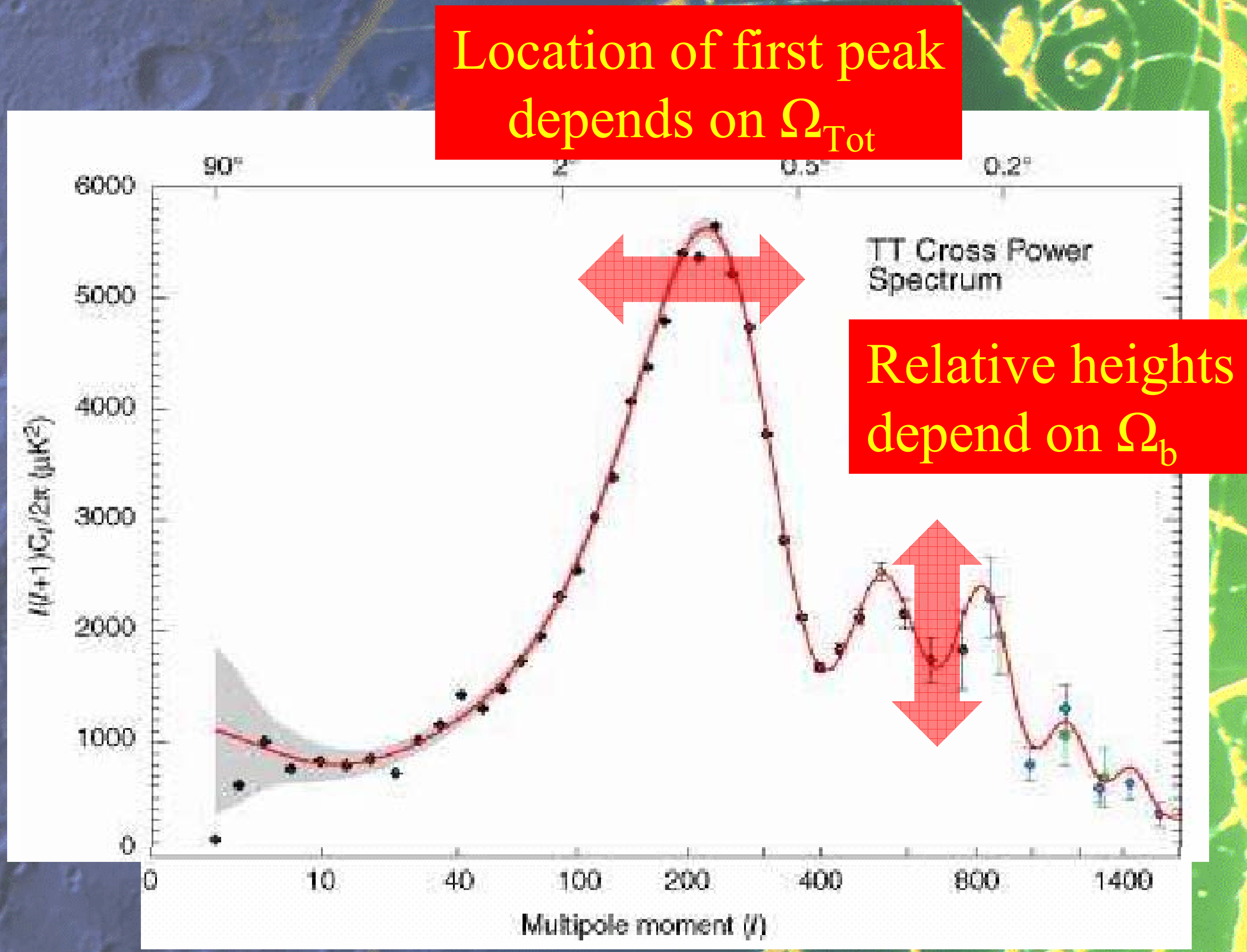
Physics of the Microwave Background



The story before WMAP



The CMB Power Spectrum



Abundances of light elements in the Universe

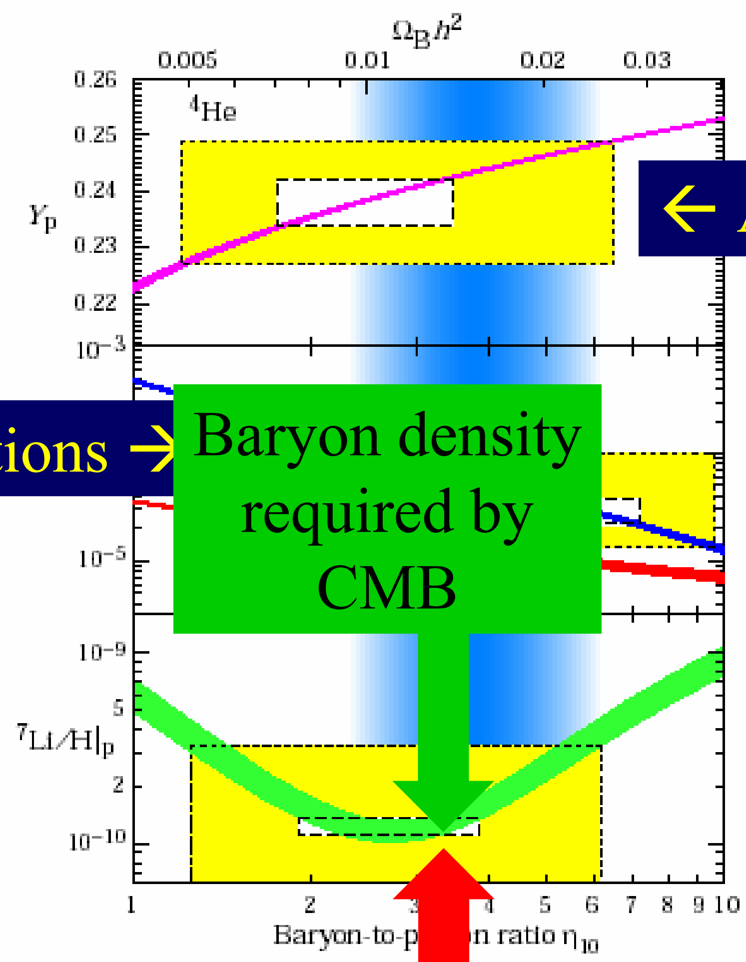
Helium

← Agree with data

Theoretical calculations →

Baryon density required by CMB

Total density required by CMB



Lithium

Not enough ordinary matter to make the Universe recollapse

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  Big-bang nucleosynthesis, CMB:

  $\Omega_{Baryons} \sim$ few %
- Total matter density much larger

  Clusters of galaxies:

  $\Omega_{Matter} \sim 25$ %
- Mainly cold dark matter

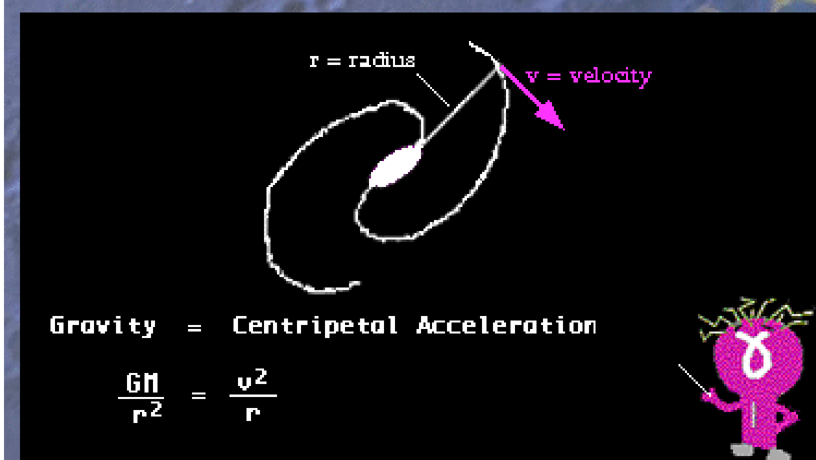
  Enables structure formation

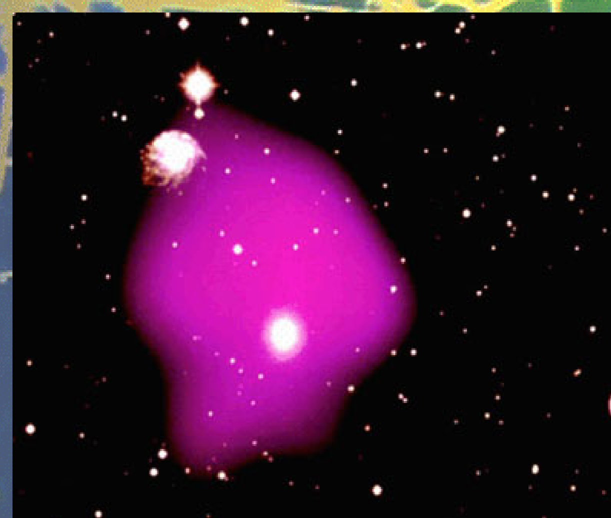
Evidence for Dark Matter

Galaxies rotate more rapidly than allowed by centripetal force due to visible matter

X-ray emitting gas held in place by extra dark matter

Even a 'dark galaxy' without stars

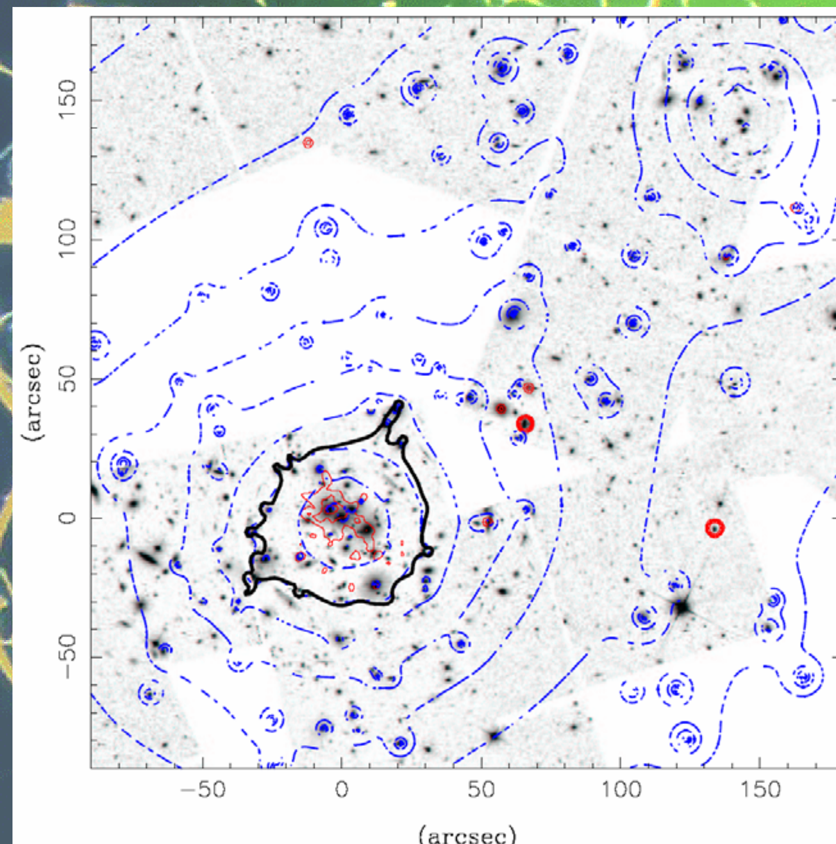




Evidence for Dark Matter from Gravitational Lensing

Light bent by gravitational field of dark matter

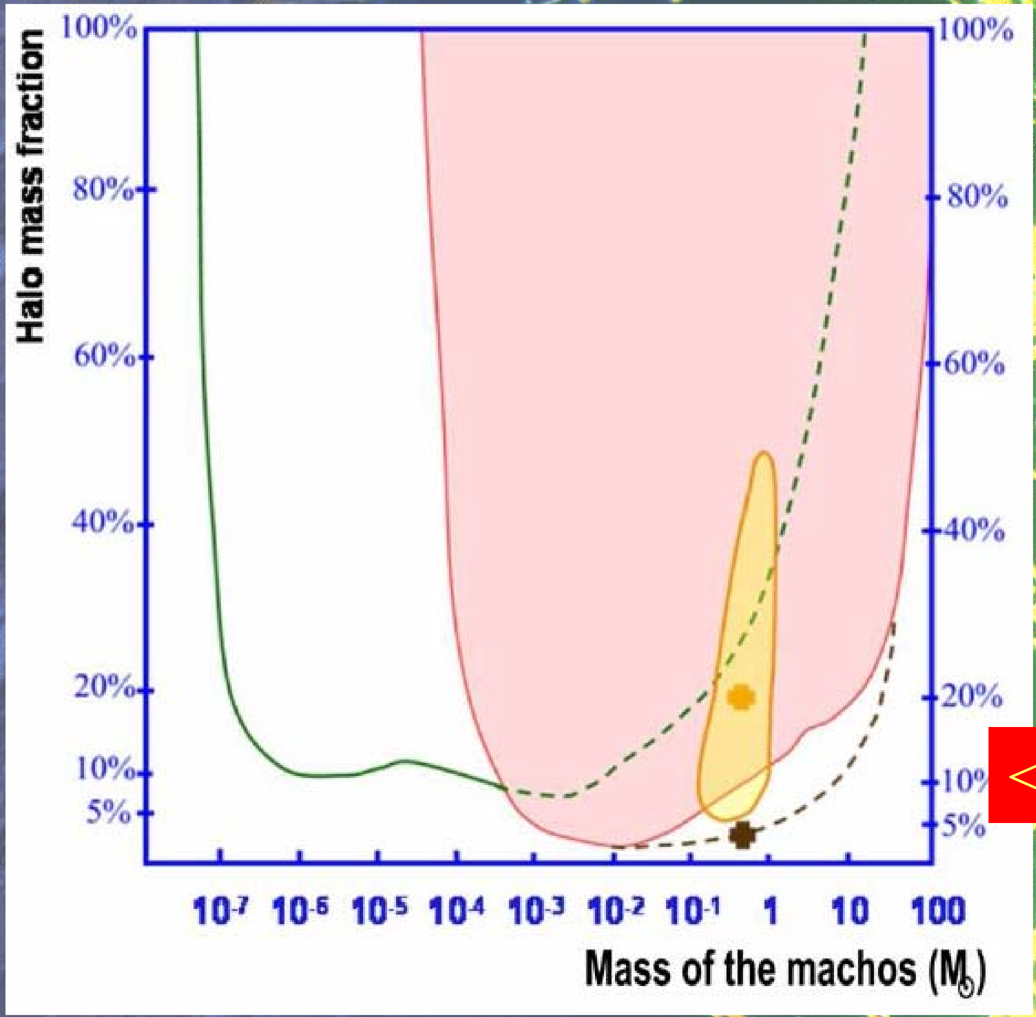
Contours of mass density



Could our galactic halo be ordinary matter?

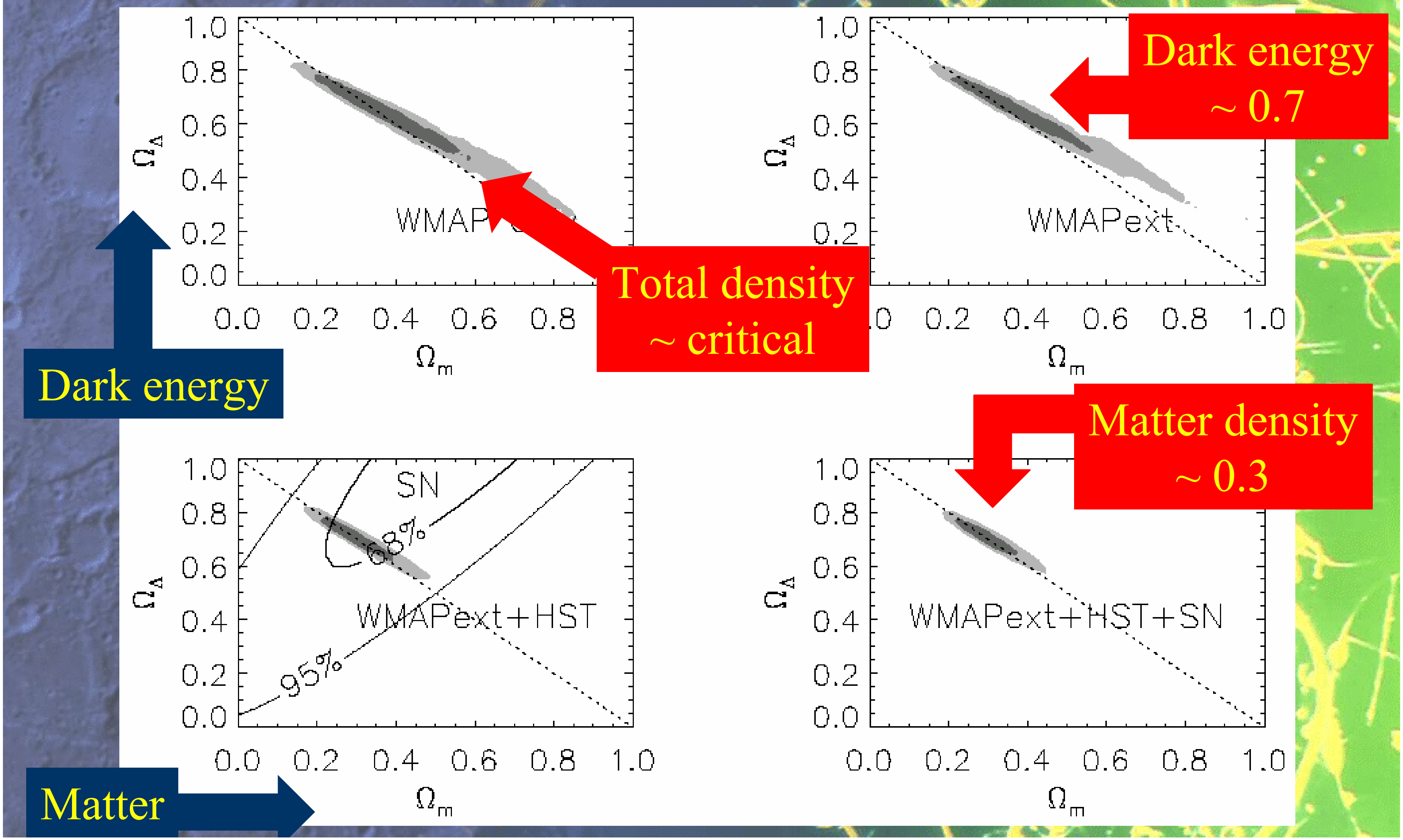
Our Halo is not made of Machos

= MAssive
Compact
Halo
Objects
= dead stars
or black holes



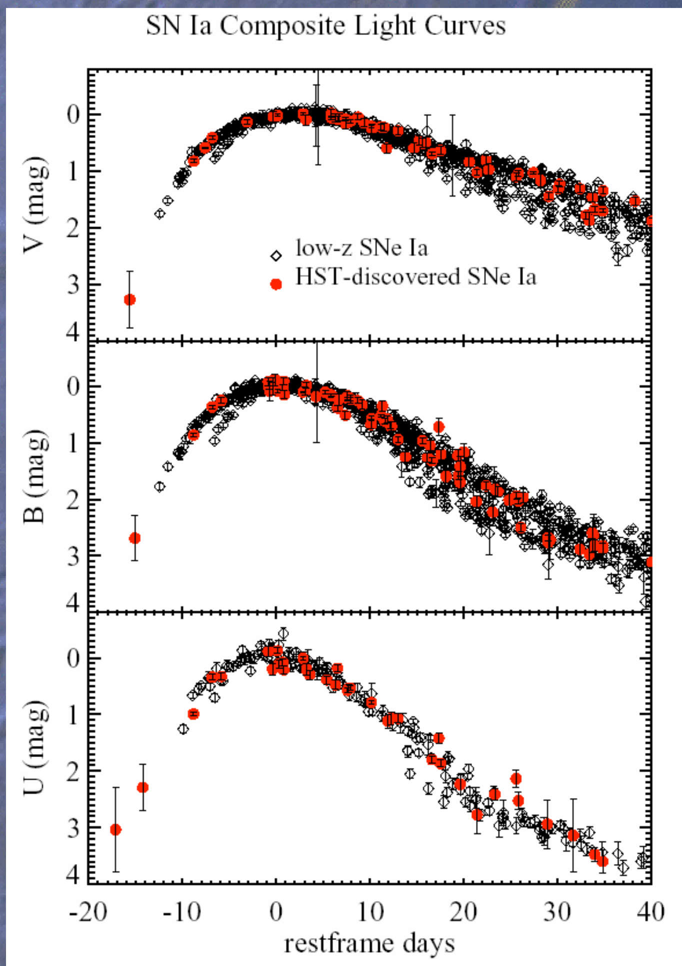
< 10 % of our halo

WMAP Constraints on Density

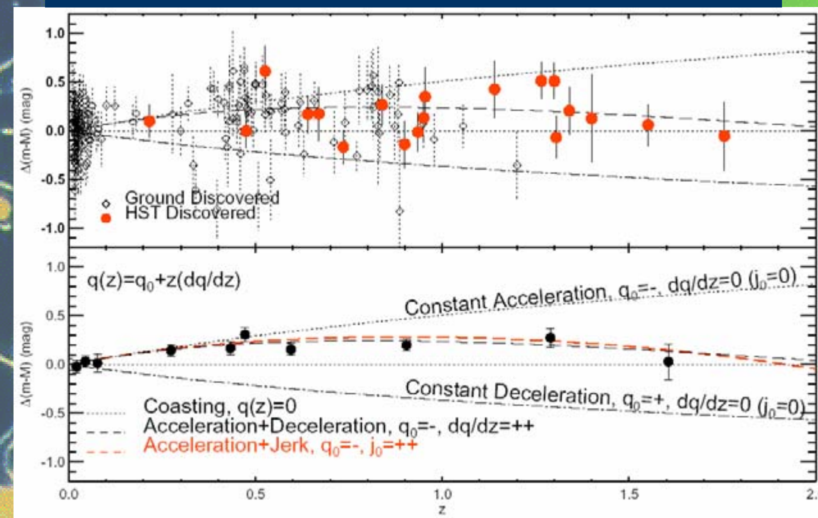


Direct evidence for dark energy

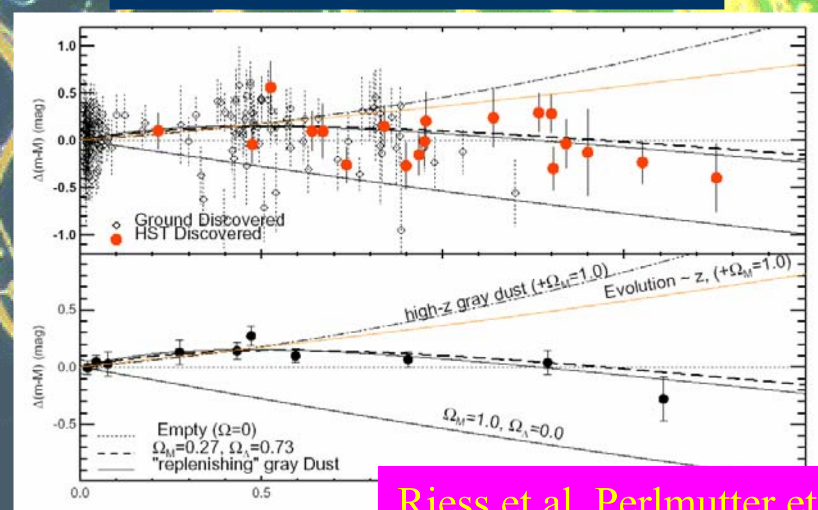
High-redshift supernovae are standard candles



Universe now accelerating, previously decelerating



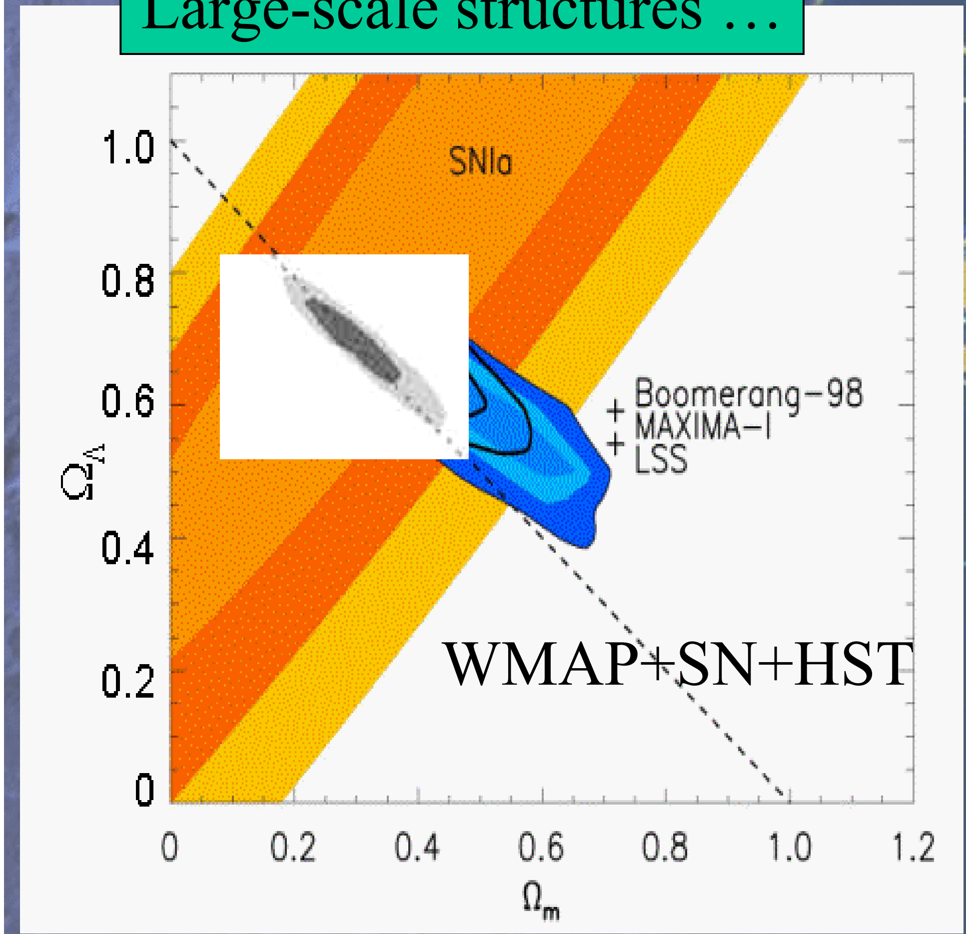
not dust, not evolution



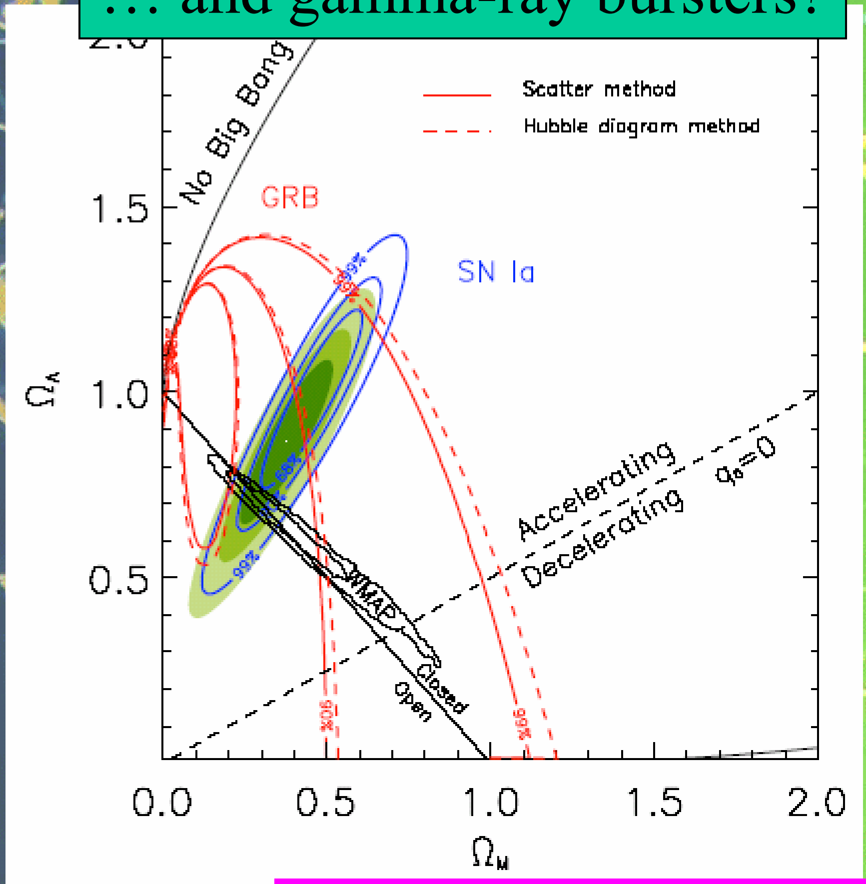
Riess et al, Perlmutter et al

Concordance Cosmological Model

WMAP, Supernovae, Large-scale structures …



… and gamma-ray bursters?

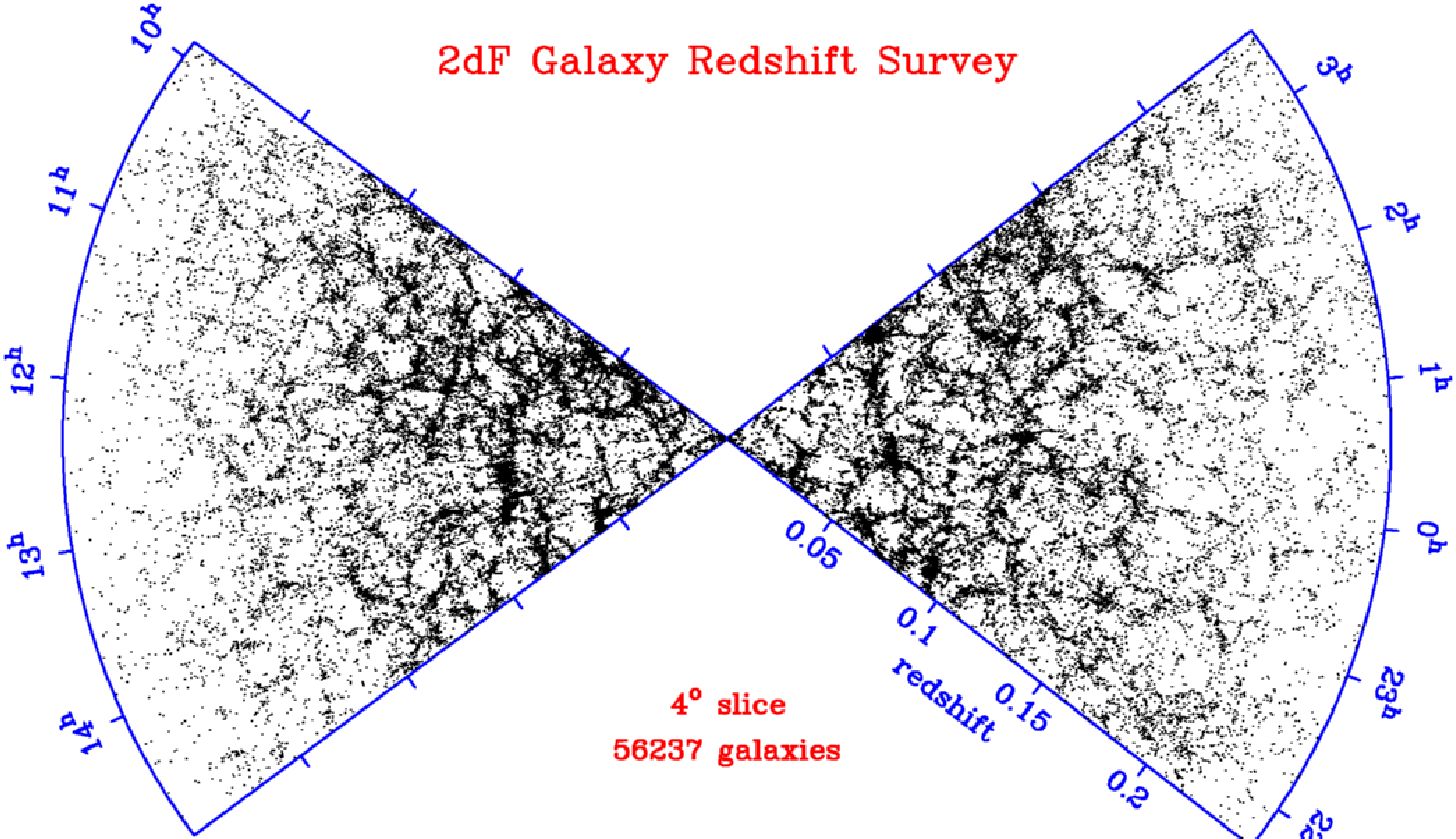


Barbiellini //, Ghirlanda et al

Formation of Structures in Universe

- Develop from CMB fluctuations
- Need amplification
- Possible with massive weakly-interacting particles
- Light neutrinos escape from smaller structures → disfavoured
- Prefer non-relativistic ‘cold dark matter’

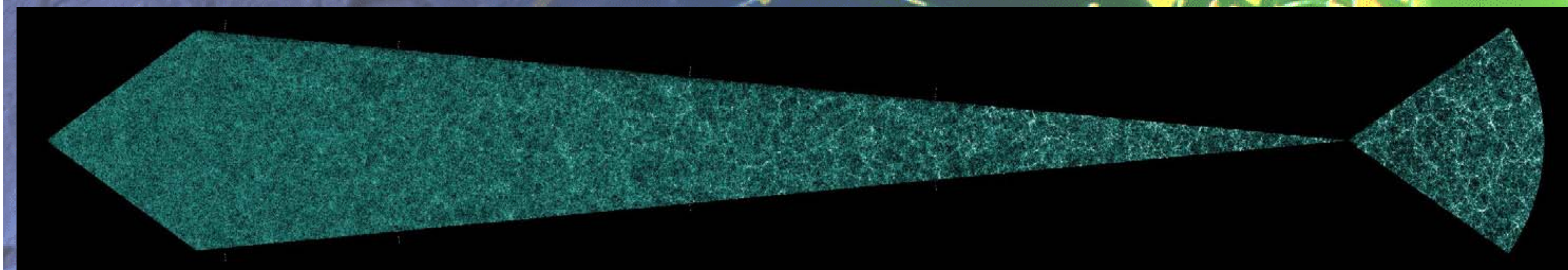
Structures observed in the Universe



Galaxies → Clusters → smooth at largest scales

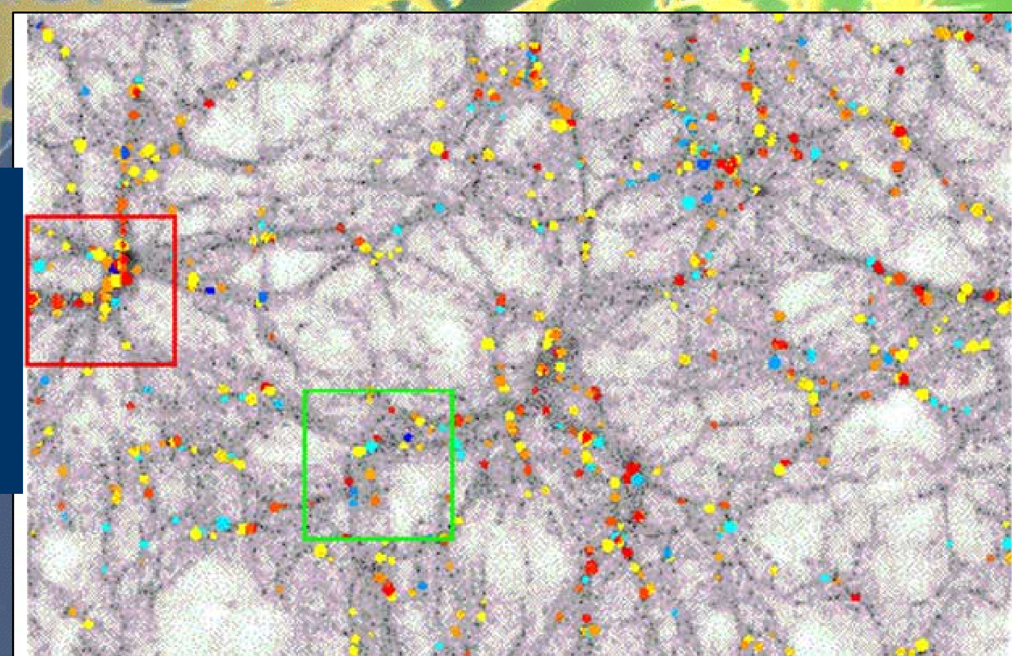
Simulation of Dark Matter

Initially quite homogeneous: gravity → structures form → today



Simulation of present-day Universe:

- Filaments of dark matter,
- Clusters of galaxies at nodes



Structures in Universe vs Concordance Model

Flat Universe:

$\Omega_{Tot} = 1$,

Cold dark matter:

$\Omega_{CDM} \sim 0.25$,

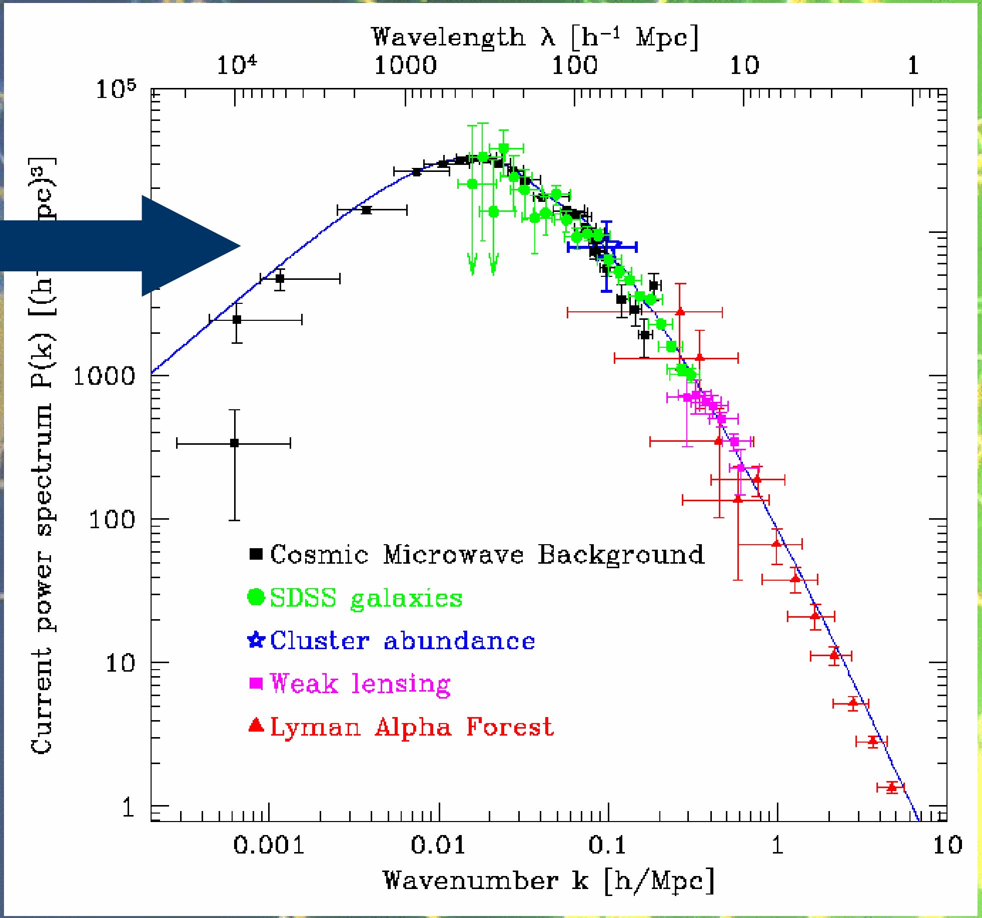
No hot dark matter,

Few baryons:

$\Omega_b \sim 0.05$,

Dark energy:

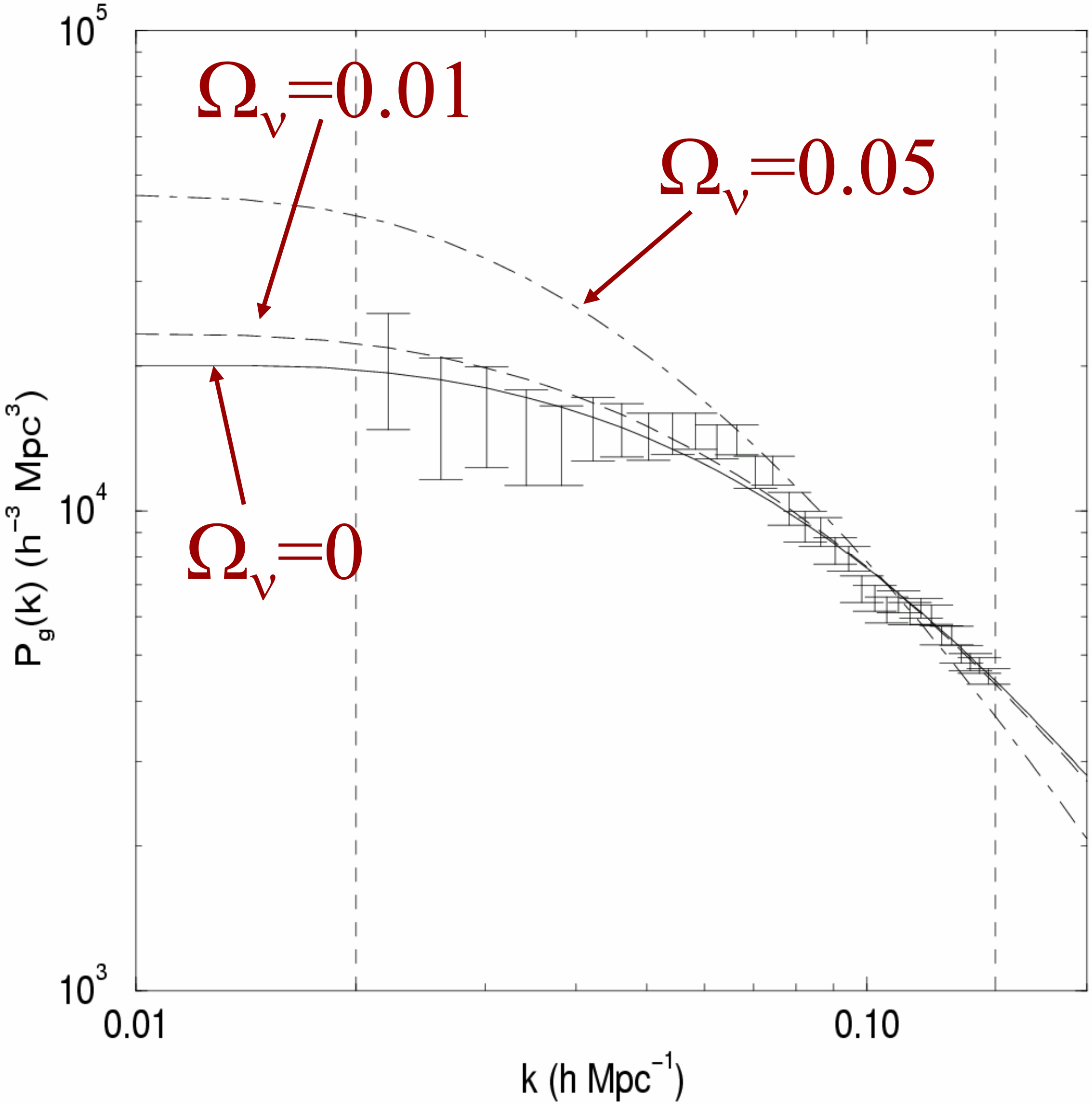
$\Omega_\Lambda \sim 0.7$



Do Neutrinos matter?

- Have very small masses
  - but non-zero – oscillation experiments
- Might make up some of dark matter
  - less than 10%?
- And would escape from galaxies
  - moving relativistically
- Also heavier neutrinos?
  - but unstable: generate matter via Sakharov?
- Need heavier stable dark matter particles
  - supersymmetric particles?

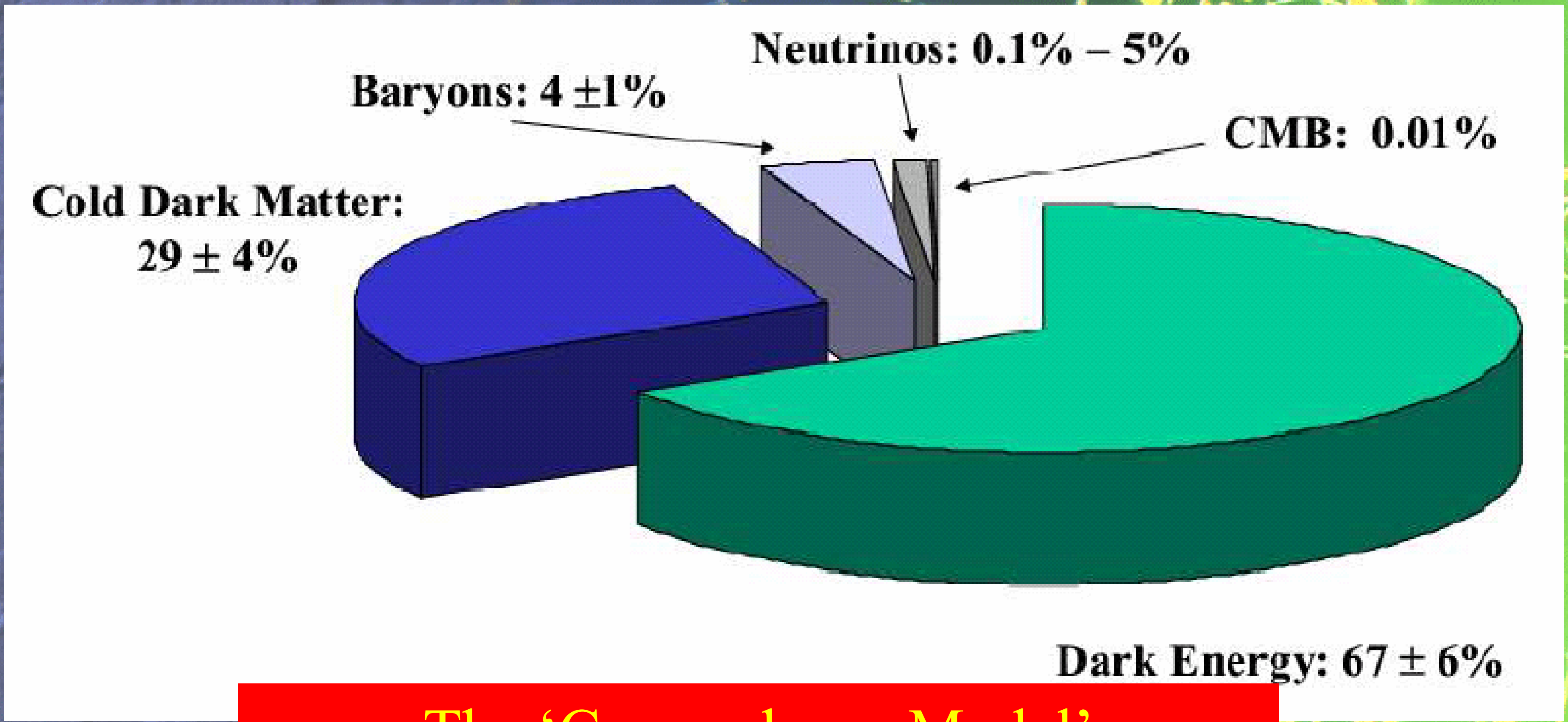
Not much neutrino mass density



2dF team: astro-ph/0204152

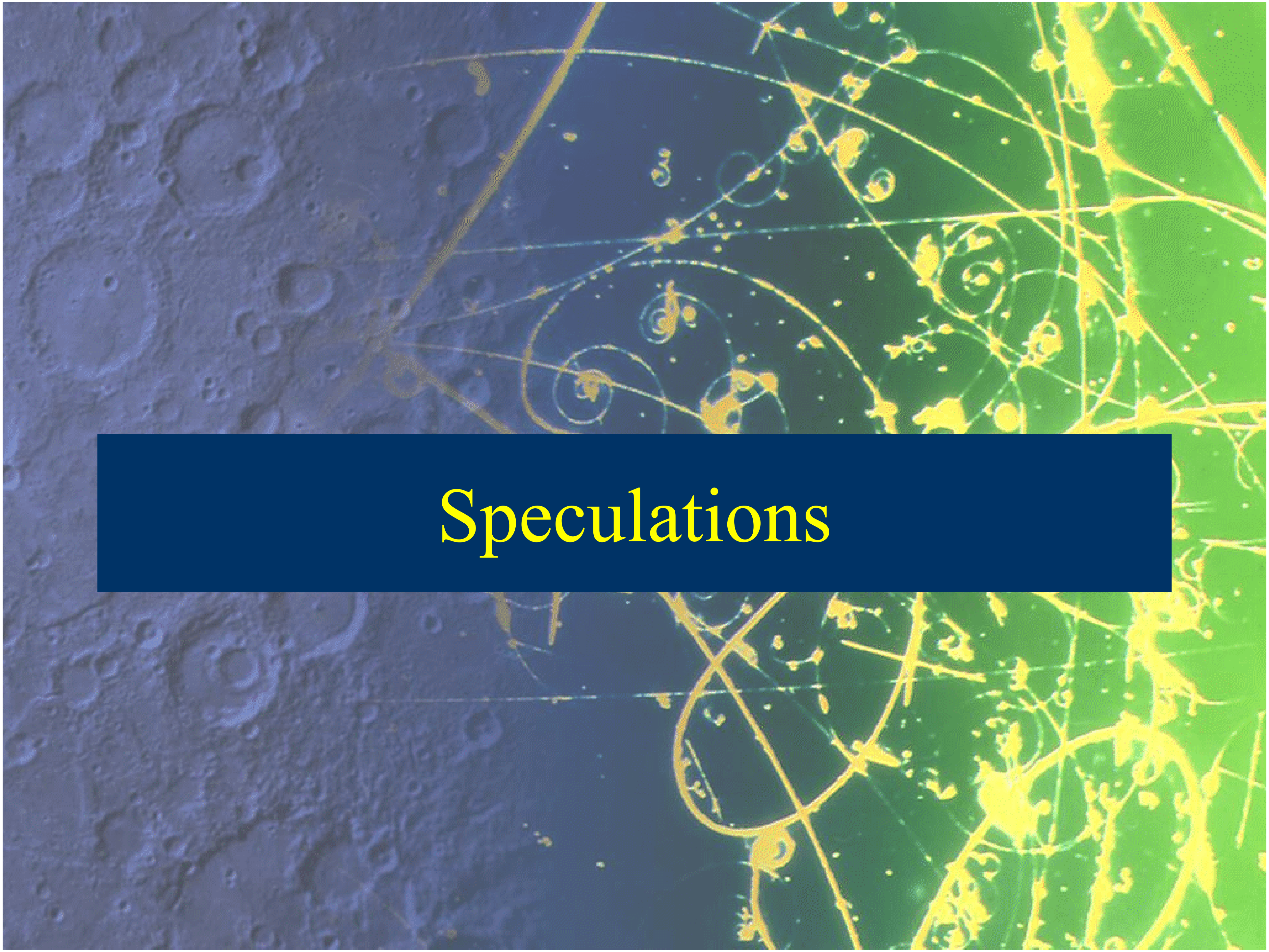
Data on large-scale structures

A Strange Recipe for a Universe



The 'Concordance Model'
prompted by astrophysics & cosmology

Speculations



The Density Budget of the Universe

- Total density ~ critical
  - Theory of inflation, measurements of CMB: $\Omega_{Tot} = \sim 1$
- Baryon density small
  - Big-bang nucleosynthesis, CMB: $\Omega_{Baryons} \sim$ few %
- Total matter density much larger
  - Clusters of galaxies: $\Omega_{Matter} \sim 25$ %
- Mainly cold dark matter
  - Enable structure formation
- Most of density is dark energy
  - Supported by high-redshift supernovae

Open Cosmological Questions

- Why is the Universe so big and old?
  ~ 13,000,000,000 years
- Why is its geometry nearly Euclidean?
  almost flat, borderline for eternal expansion
- Where did the matter come from?
  1 proton for every 1,000,000,000 photons
- How did structures form?
  ripples + invisible dark matter?
- What is the dark matter?

Need particle physics to answer these questions

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

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

Generating the matter in the Universe

Sakharov

- Need difference between matter, antimatter
  - charge symmetry broken in laboratory
- Need matter-creating interactions
  - present in unified theories – not yet seen
- Need breakdown of thermal equilibrium
  - possible during phase transition (GUT, SM?)
  - in decays of heavy particles (singlet ν_R?)

Can we calculate from laboratory measurements?

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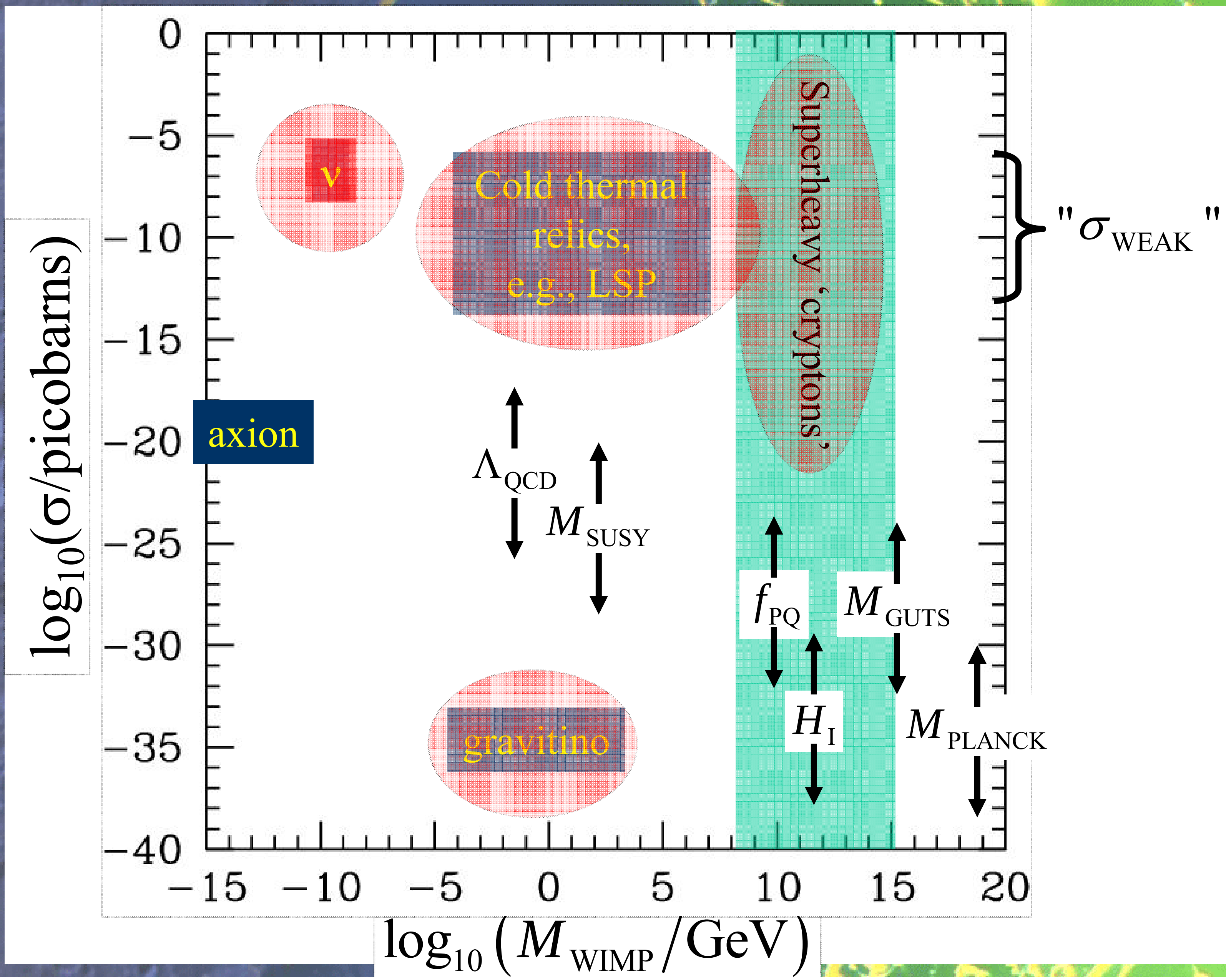
Particle Dark Matter Candidates



Dark Matter in the Universe

Astronomers say that most of the matter in the Universe is invisible

Dark Matter

‘Supersymmetric’ particles ?

We shall look for them with the LHC

‘Supersymmetric’ Dark Matter?

- Supersymmetry would relate

  fermionic ‘matter’ particles →

  bosonic ‘force’ particles
- Might help explain mass scale of particles
- Lightest supersymmetric particle stable?

  should weigh below 1000 GeV
- Density similar to required cold dark matter

Directly laboratory searches, indirect astrophysical searches

Strategies for Detecting Supersymmetric Dark Matter

- Annihilation in galactic halo

  $\chi - \chi \rightarrow$ antiprotons, positrons, …?

- Annihilation in galactic centre

  $\chi - \chi \rightarrow \gamma + \ldots ?$

- Annihilation in core of Sun or Earth

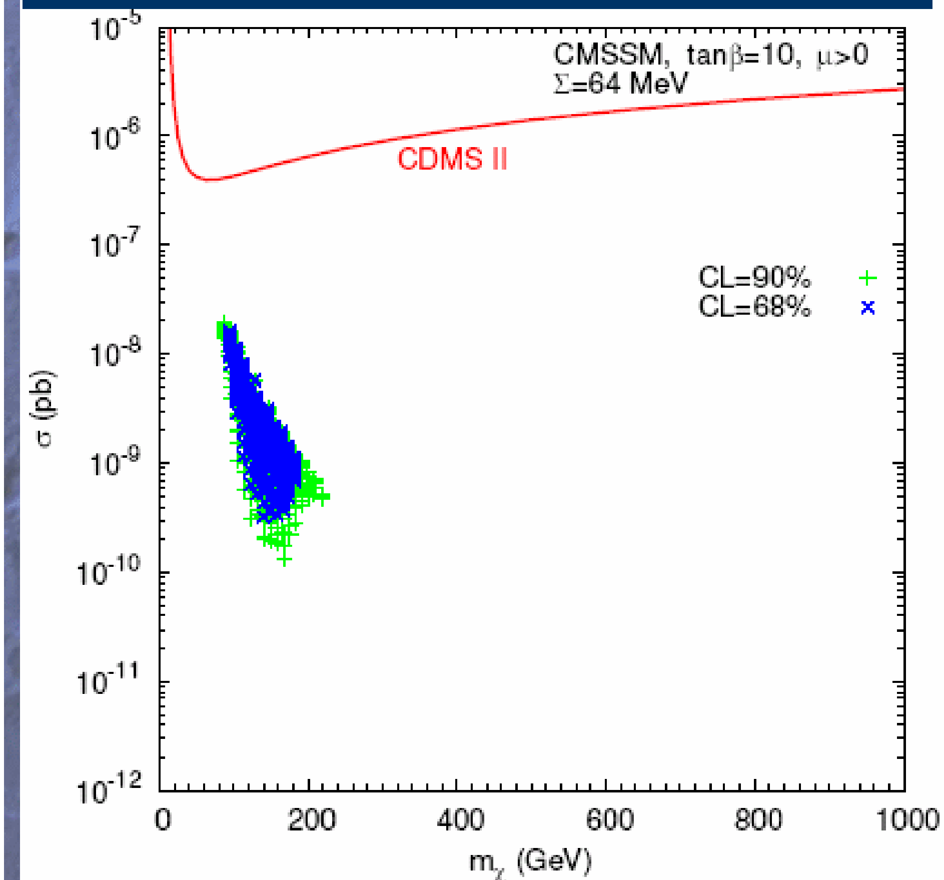
  $\chi - \chi \rightarrow \nu + \ldots \rightarrow \mu + \ldots$

- Scattering on nucleus in laboratory

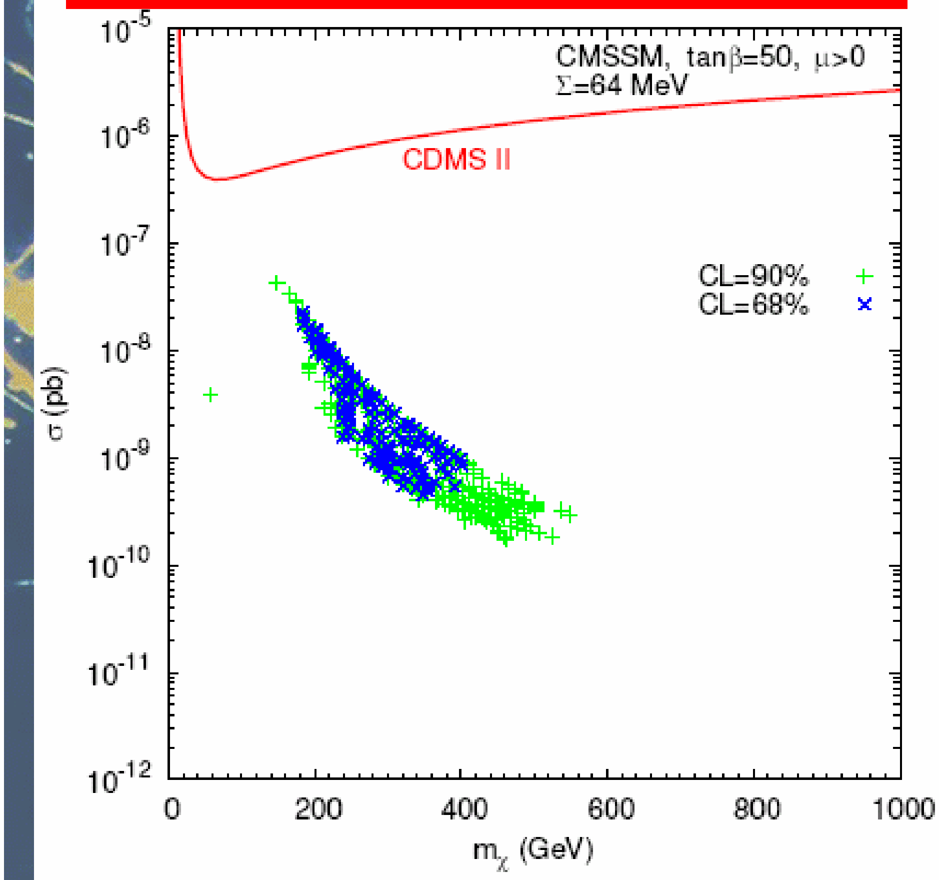
  $\chi + A \rightarrow \chi + A$

Elastic Scattering Cross Sections

From global fit to accelerator data



Latest experimental upper limit



JE + Olive + Santoso + Spanos: hep-ph/0502001

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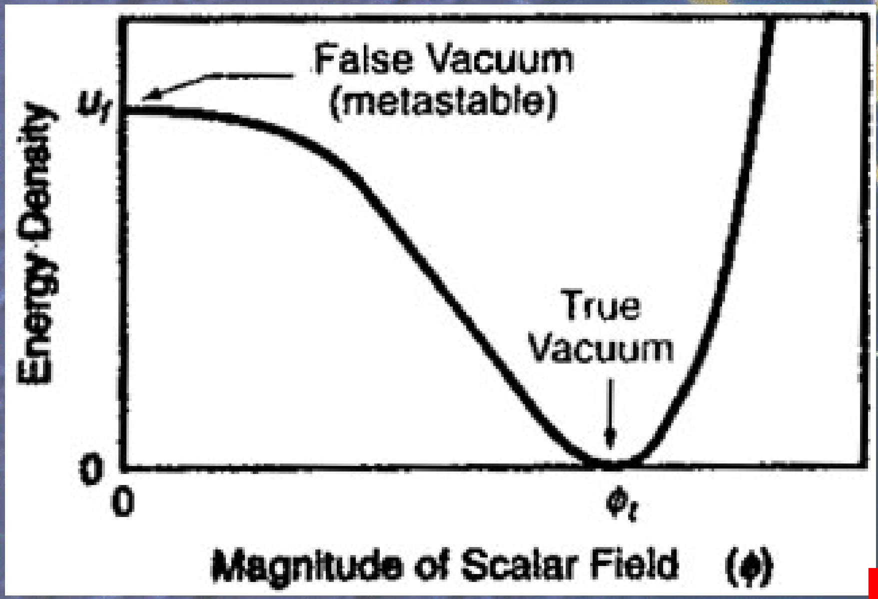
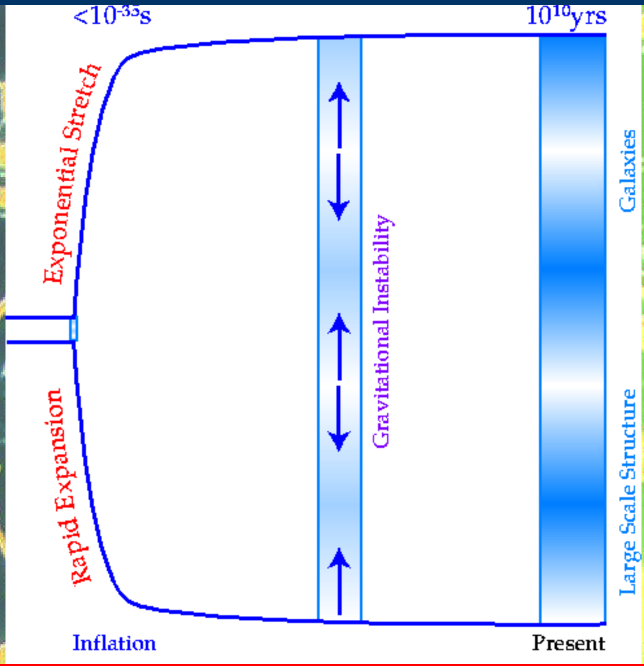
Cosmological Inflation

Basic idea: very early in the history of the Universe (10^{-35}s?) the energy density was dominated by a ~ constant piece V: would have caused ~ exponential expansion: H ~ √V

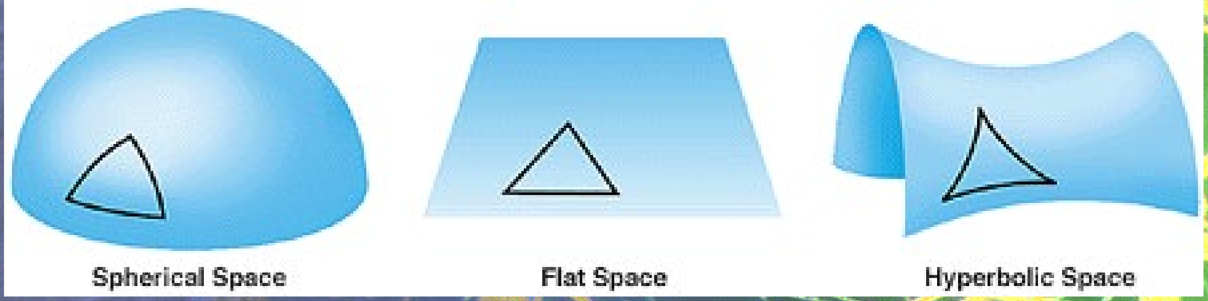




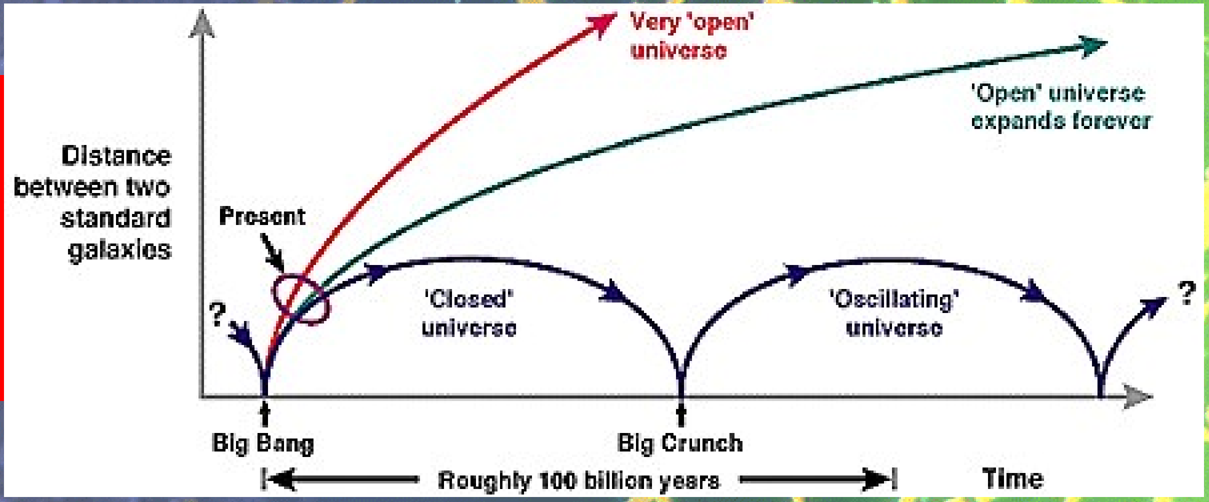
Would have expanded Universe much more than standard Big Bang

Geometry of the Universe?

Closed Universe? Flat Space? Open Universe?

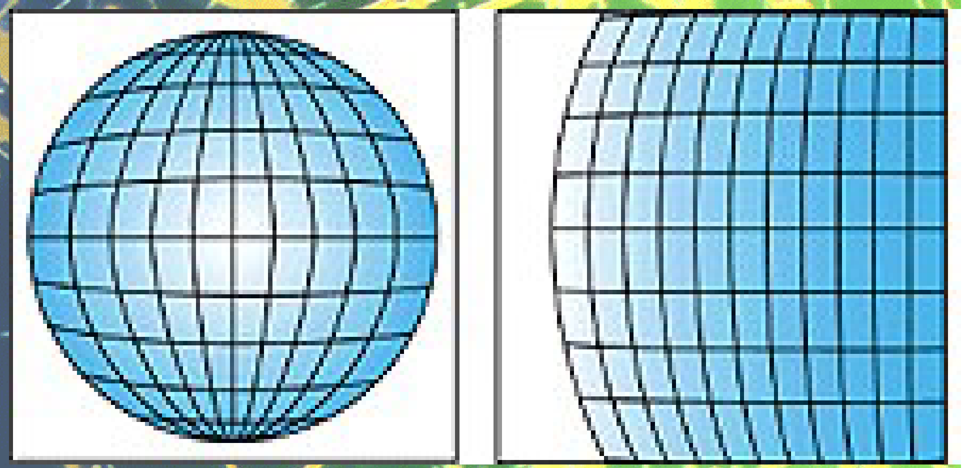


Will the expansion reverse or continue?



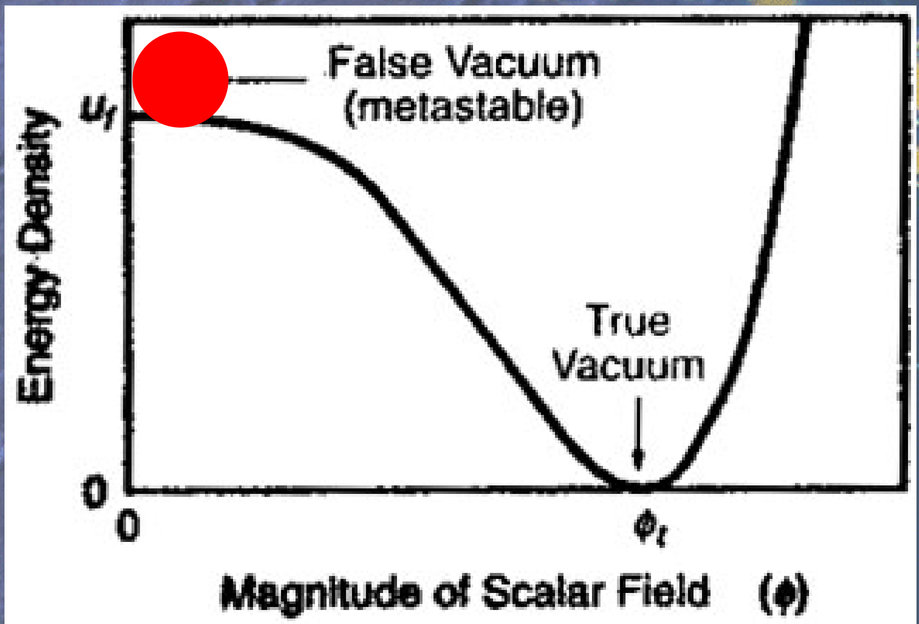
Inflation → Flat Universe

Exponential expansion makes Universe look nearly flat



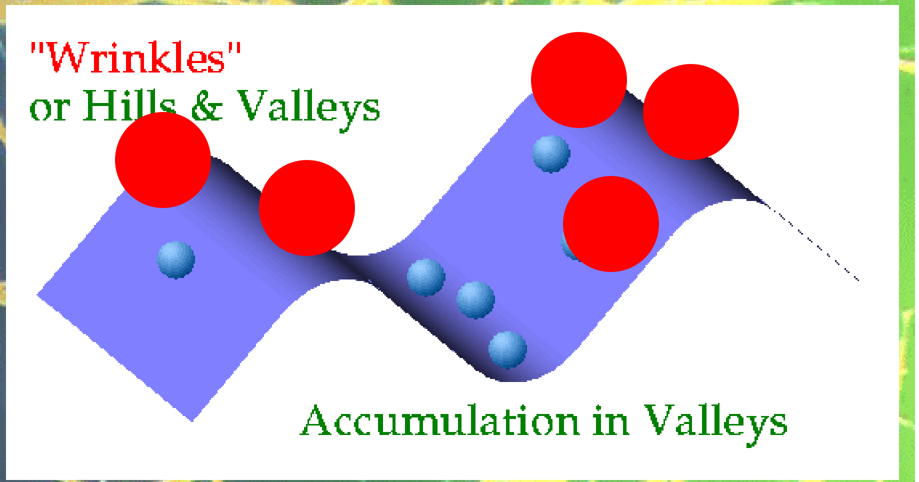
Origin of Structures in Universe

Small quantum fluctuations:
one part in 10^5

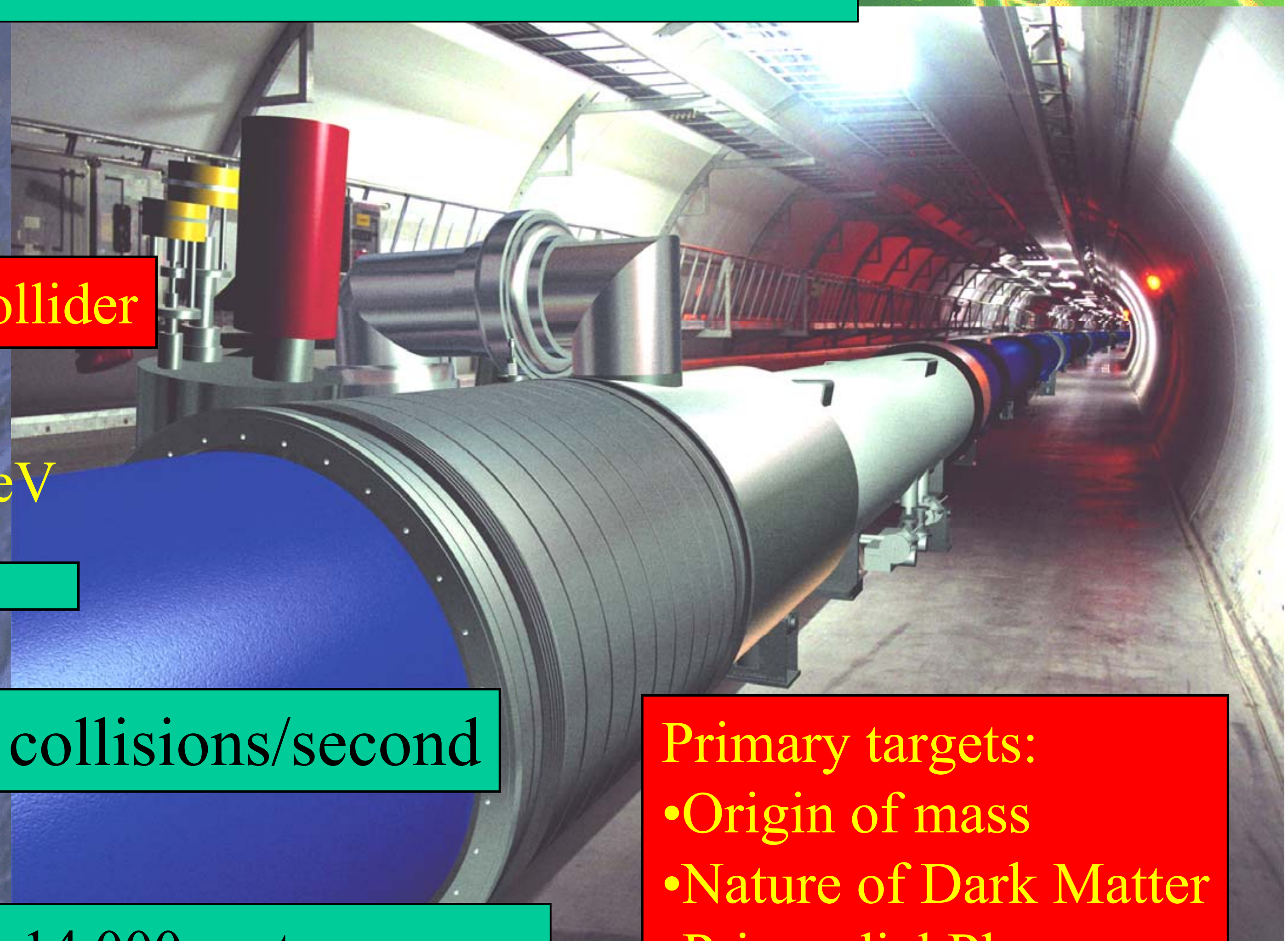


Convert into matter with varying density

Gravitational instability:
Matter falls into
the overdense regions



The Large Hadron Collider (LHC)



Proton- Proton Collider

7 TeV + 7 TeV

1,000,000,000 collisions/second

Total energy over 14,000 proton masses

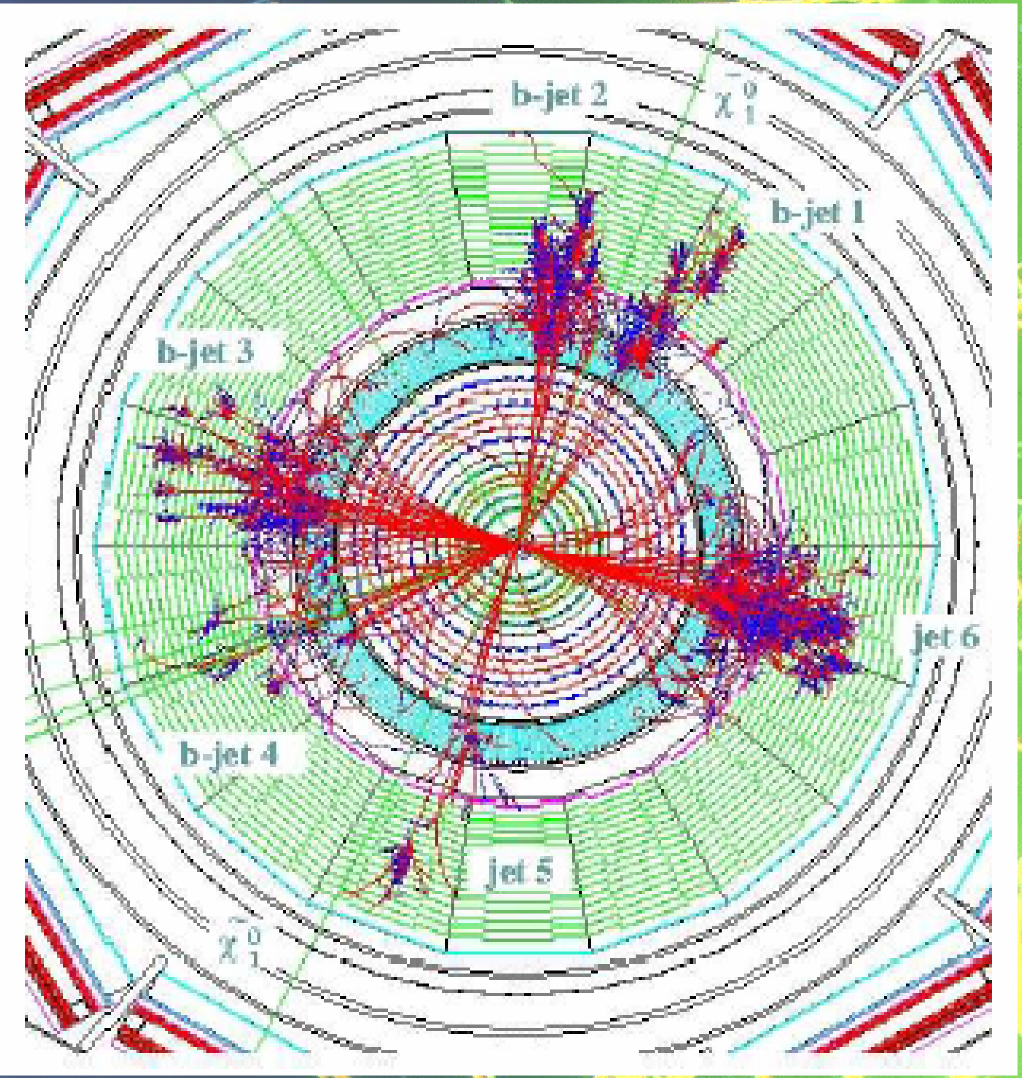
Primary targets:

- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

Supersymmetry at the LHC

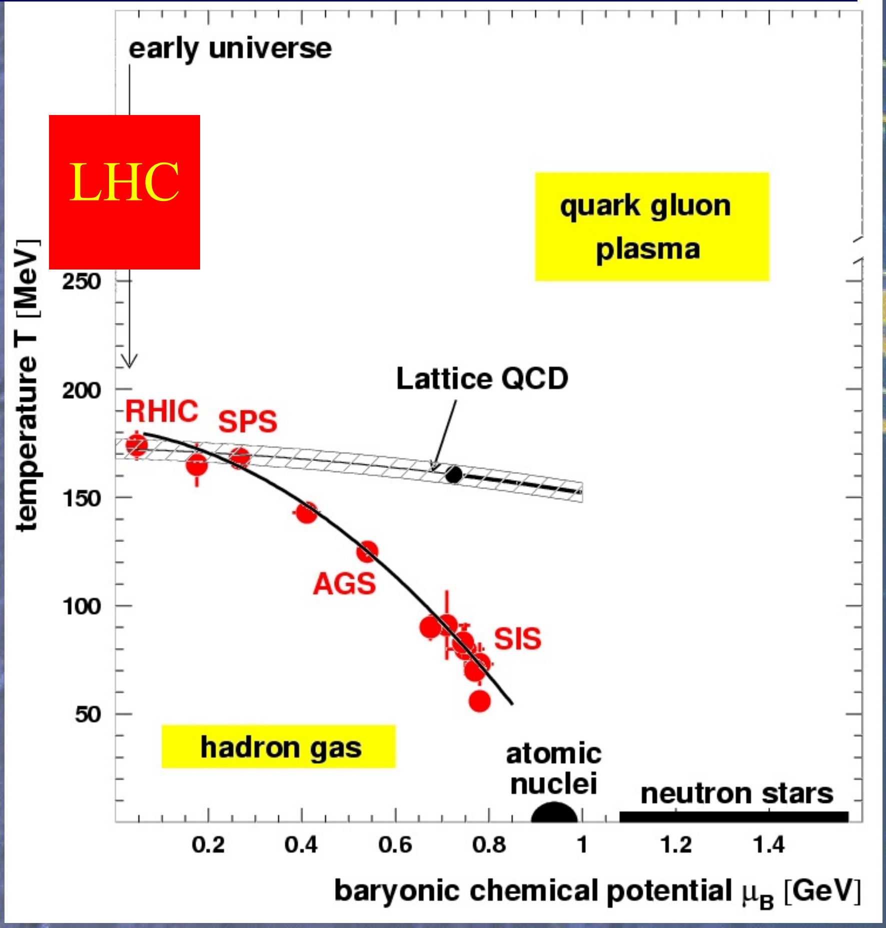
`Typical' supersymmetric Event at the LHC

Multiple jets, Electrons

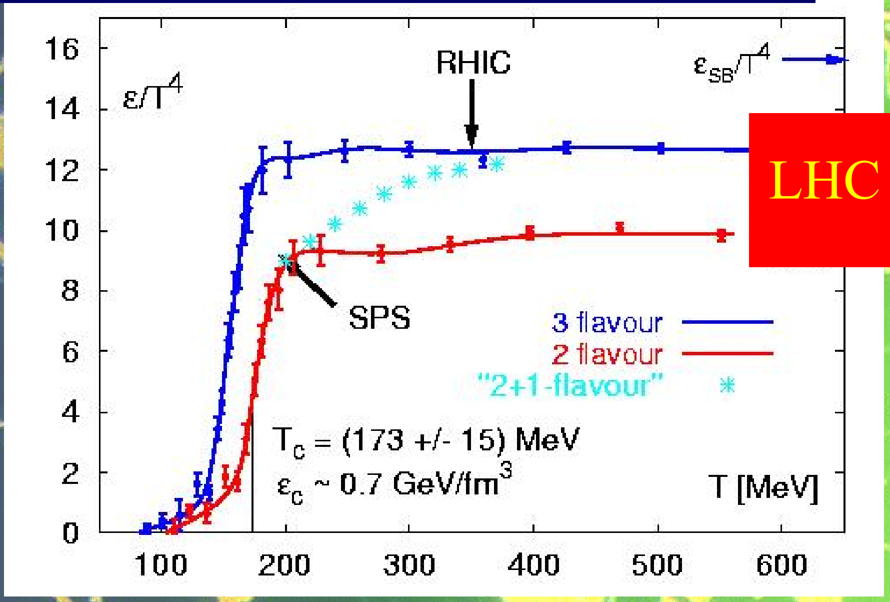


Hot and Dense Hadronic Matter

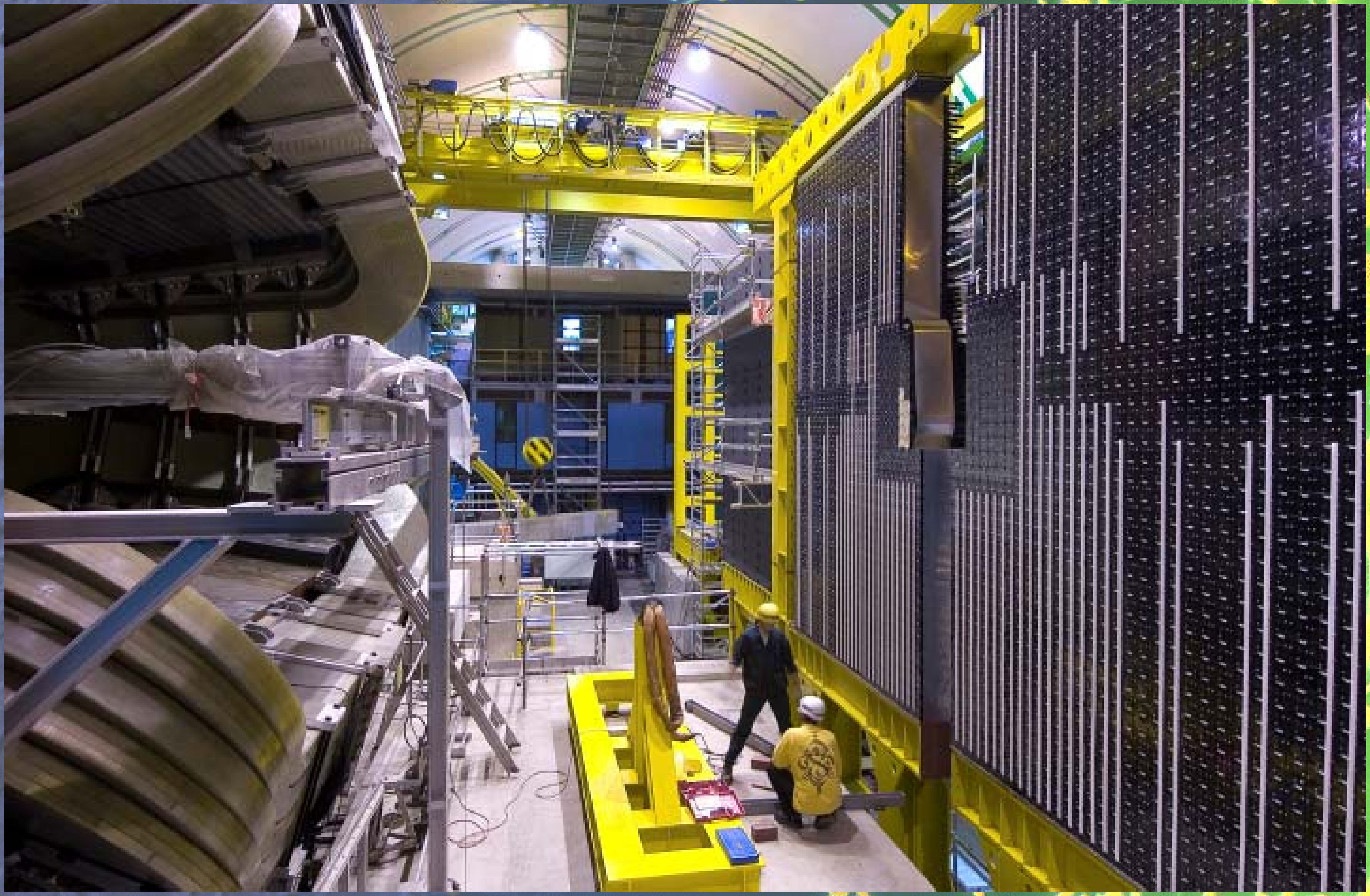
Recreate the first 10^{-6} seconds …



… and probe the quark-hadron phase transition



The LHCb Experiment:
will explore Matter and Antimatter



Big Bang ↔ Little Bangs

- The matter content of the Universe
  - Dark matter
  - Dark energy
  - Origin of matter

- Experiments at particle colliders
  - Early Universe
  - Supersymmetry
  - Matter-antimattter asymmetry

Learn particle physics from the Universe
Use particle physics to understand the Universe