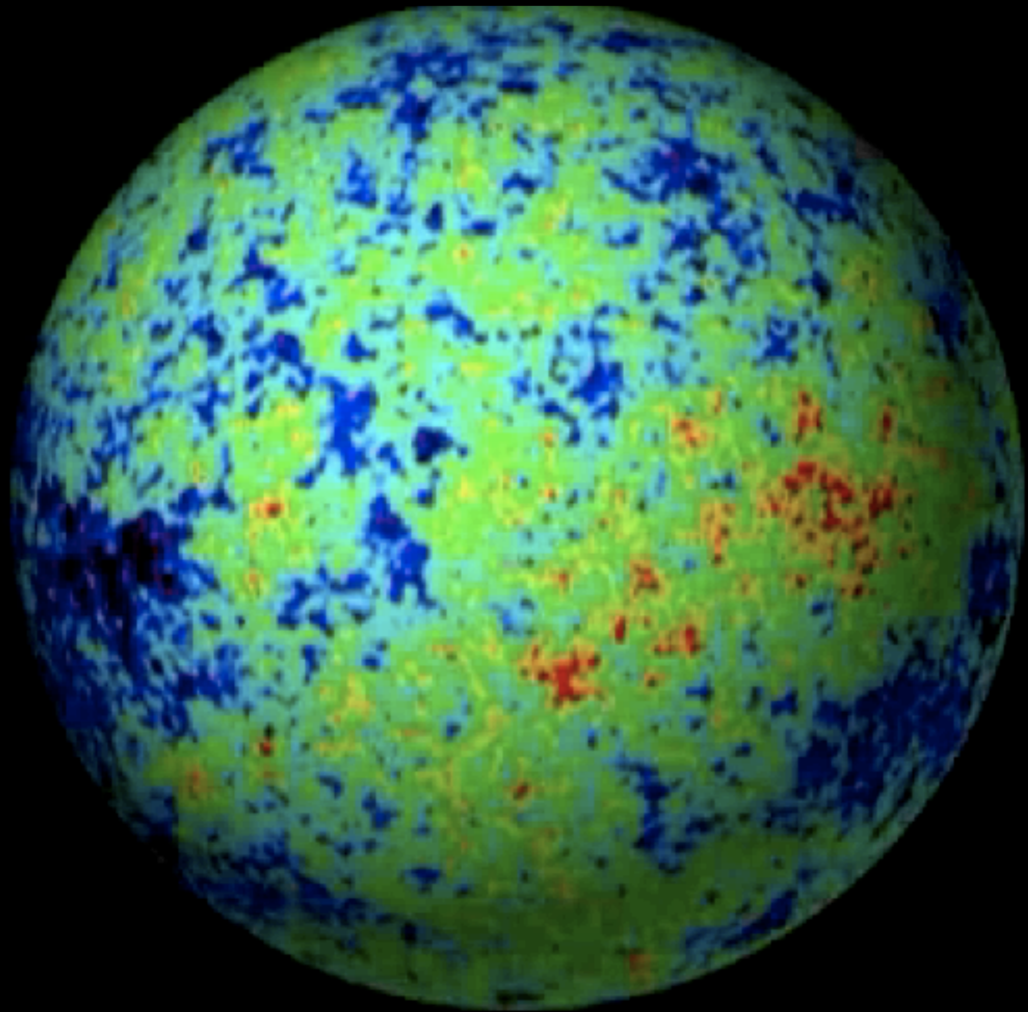
Cosmology & Particle Physics



John Ellis
King's College London & CERN

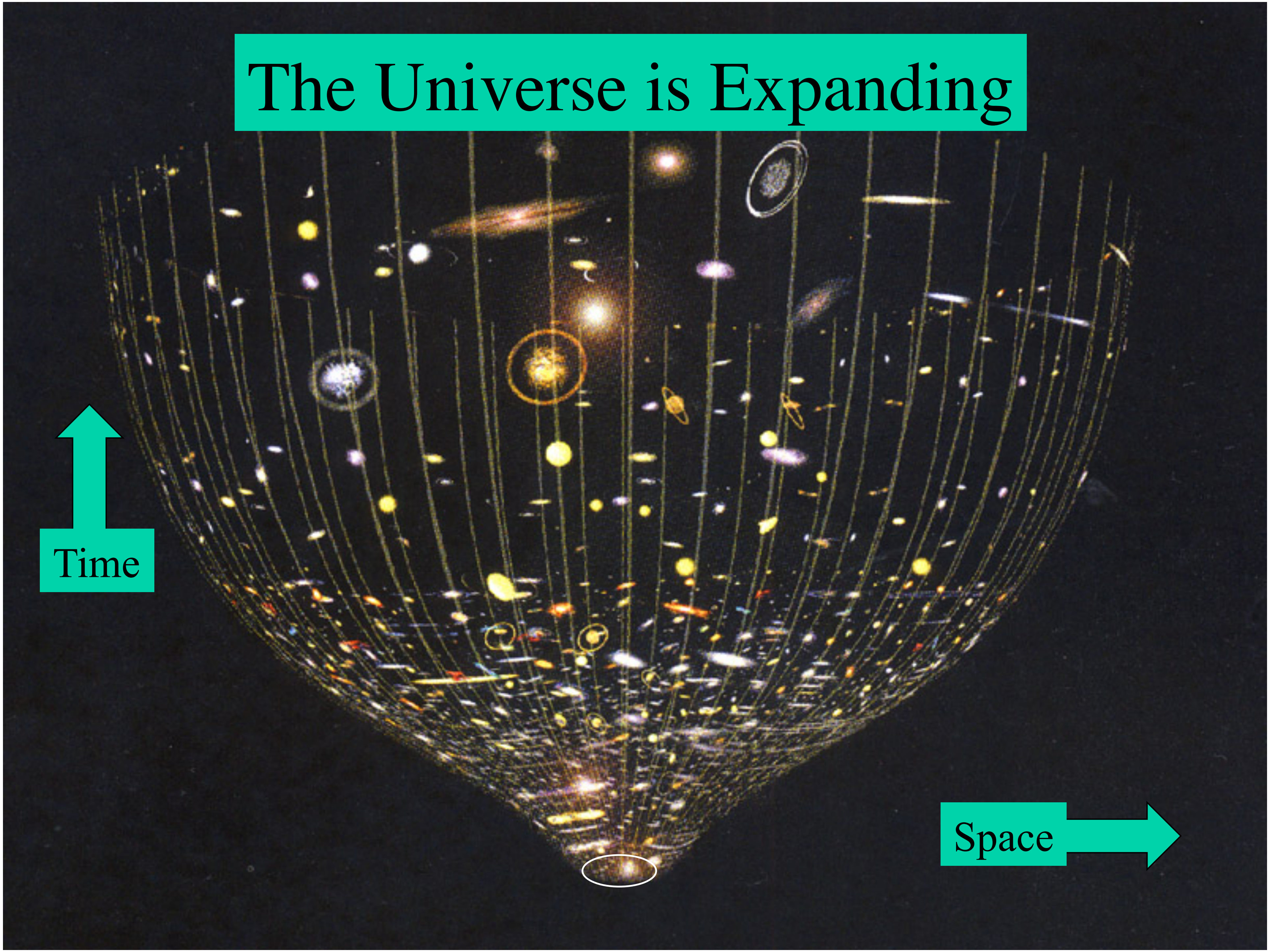
Plan of Lectures

1 - The Big Picture

- Introduction to Big Bang cosmology
- Dark matter and dark energy
- The role of particle physics in the early Universe

2 – Particle candidates for dark matter and dark energy

- The Higgs boson and cosmology
- Supersymmetry
- Searching for supersymmetry at the LHC
- Searches for supersymmetric dark 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

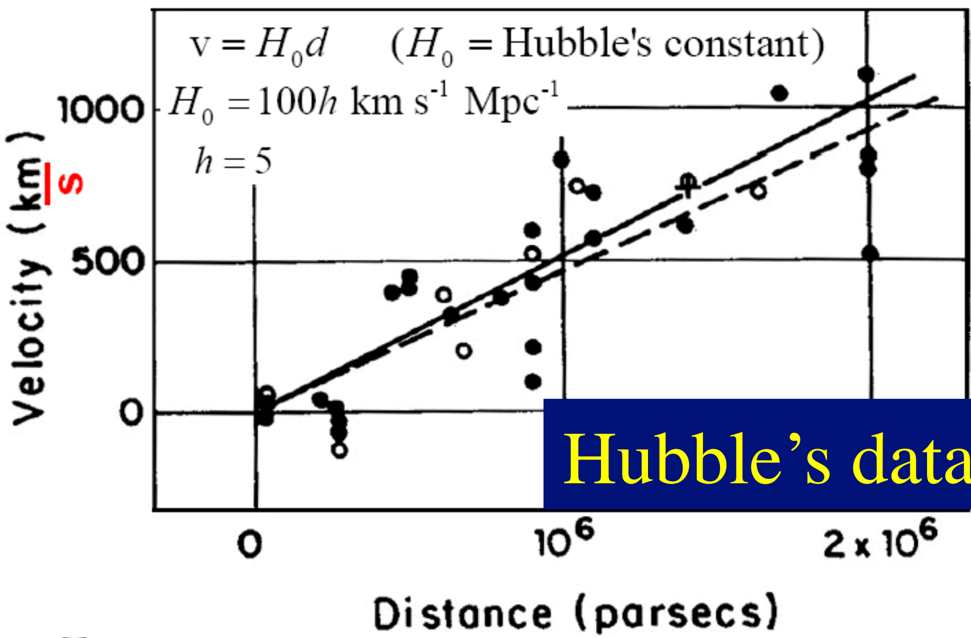
- Galaxies are receding from us

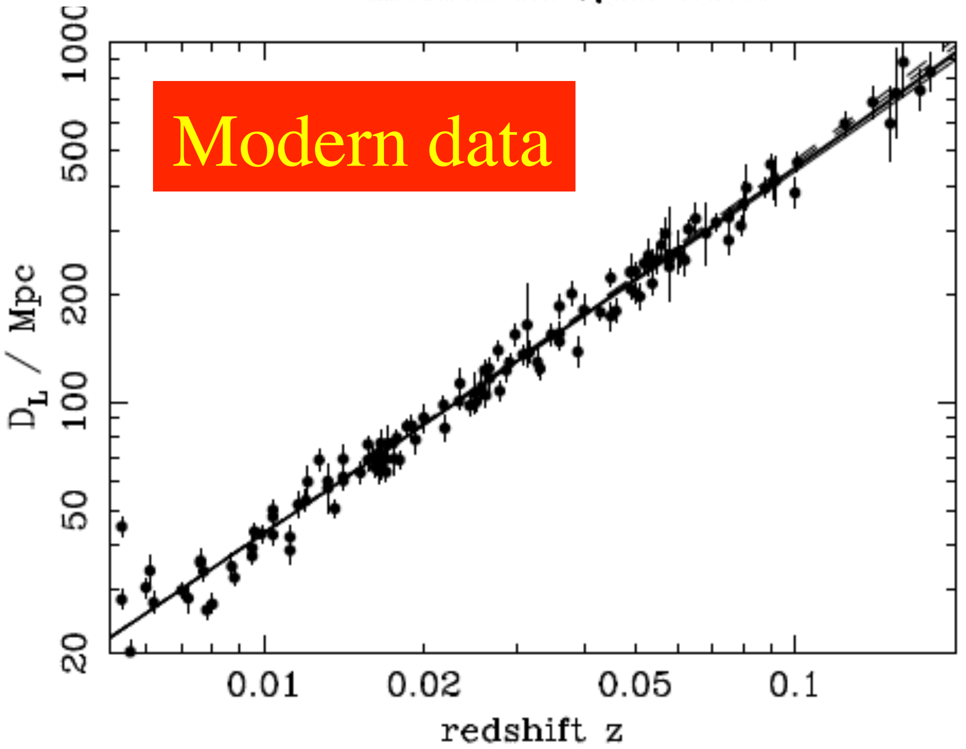
    Hubble expansion law: galactic redshifts

The expansion of the Universe

Hubble, basketball player

University of Chicago 1909 National Champions





The Universe is expanding

- Galaxies are receding from us

  Hubble expansion law: galactic redshifts

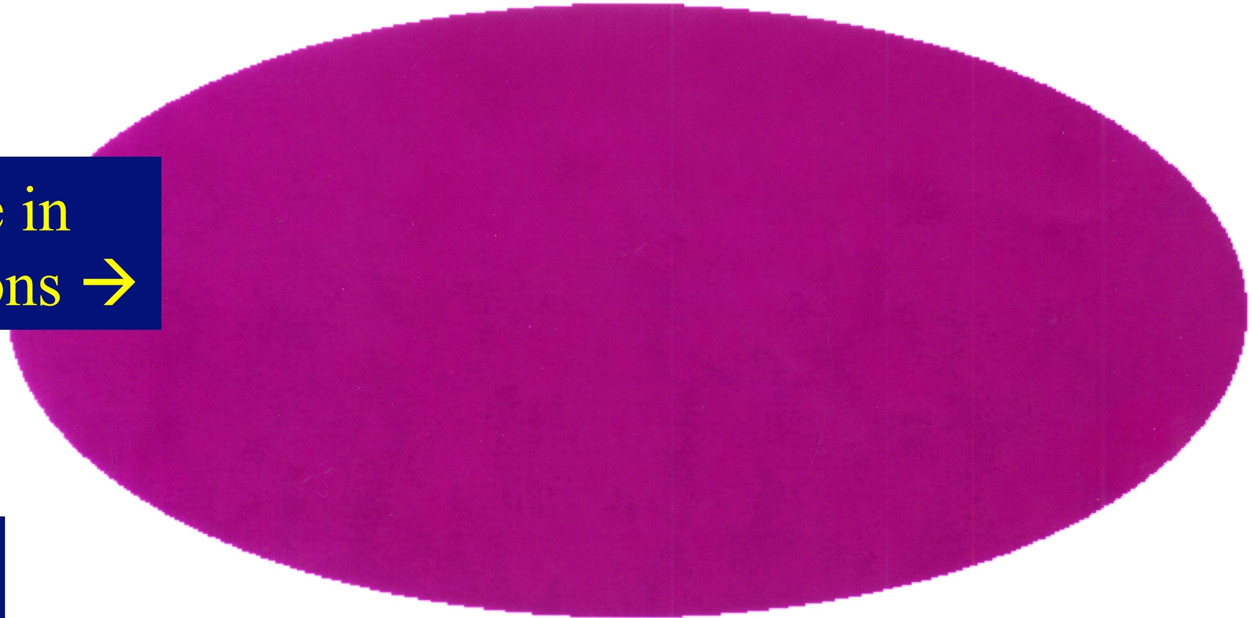
- The Universe was once 3000 smaller, hotter than today

  cosmic microwave background radiation

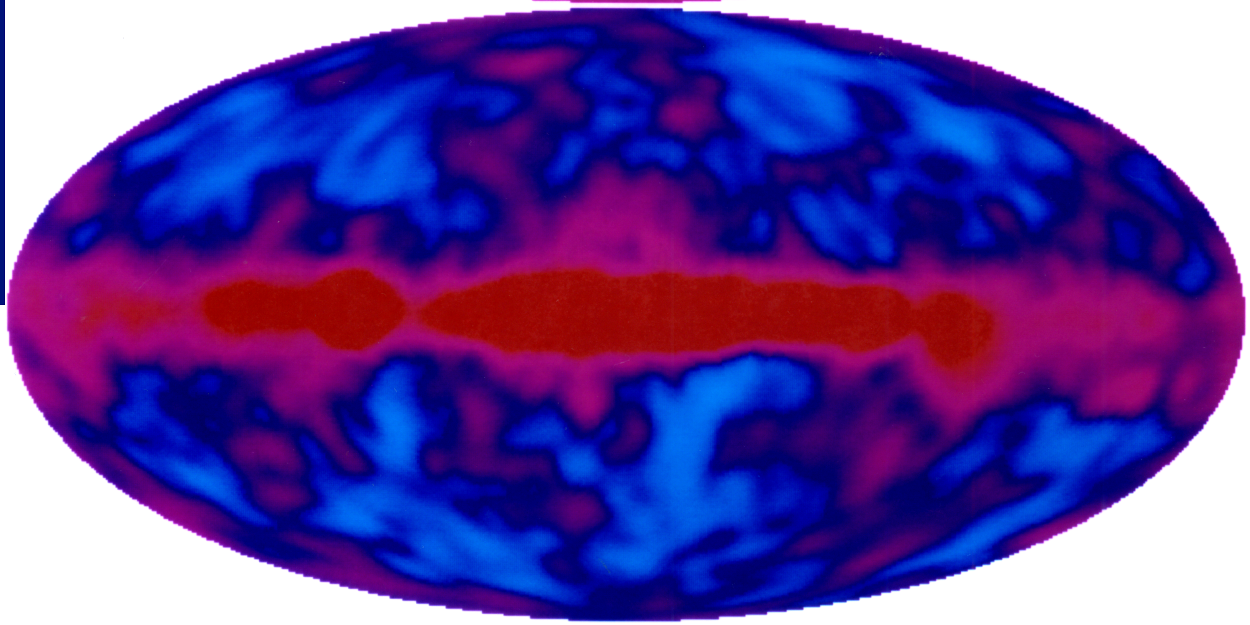
  emitted from the primordial plasma

Cosmic Microwave Background

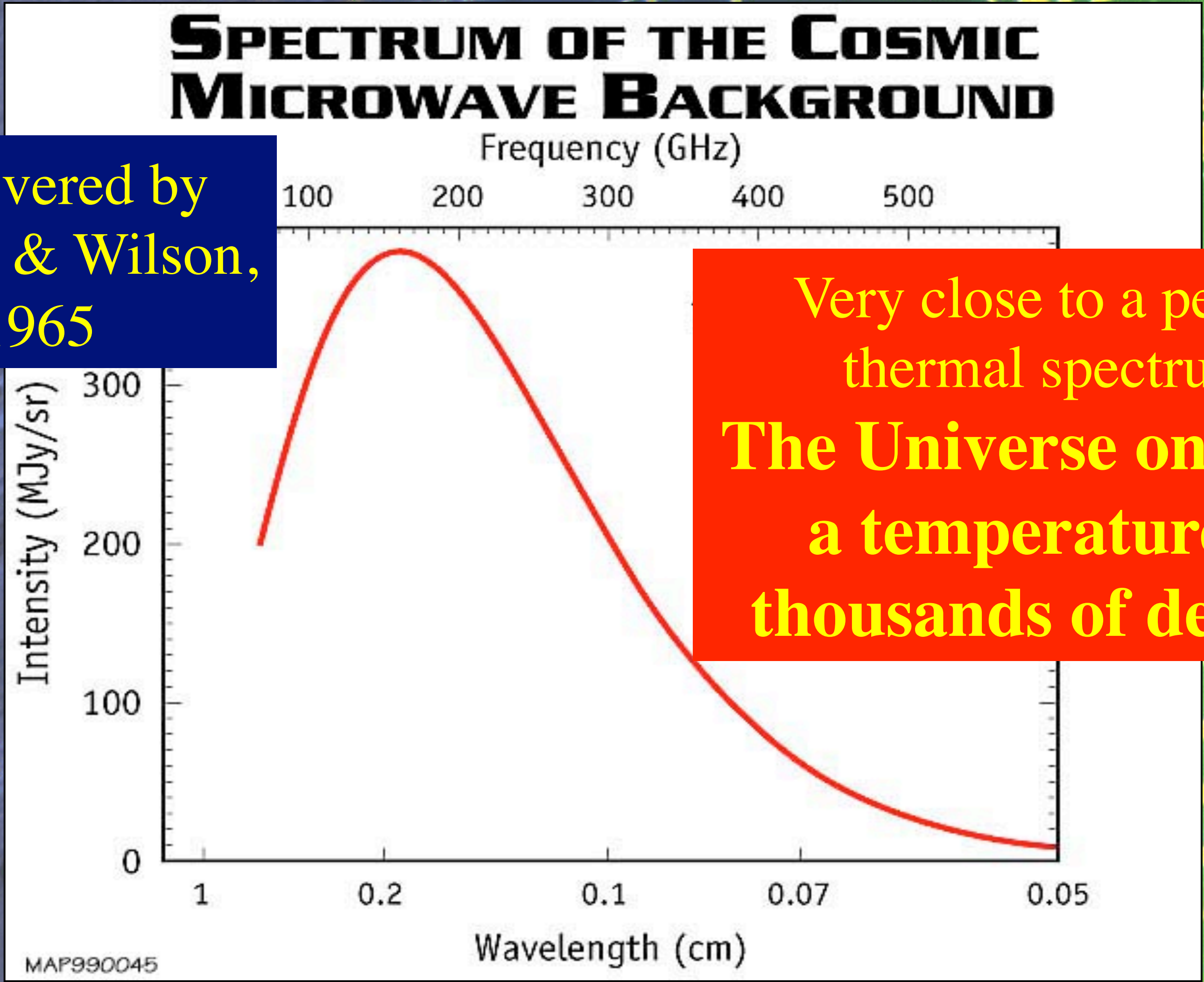
Almost the same in different directions →



Small variations discovered by COBE satellite →



The Cosmic Microwave Background Radiation



Discovered by Penzias & Wilson, 1965

Very close to a perfect thermal spectrum:

The Universe once had a temperature of thousands of degrees

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

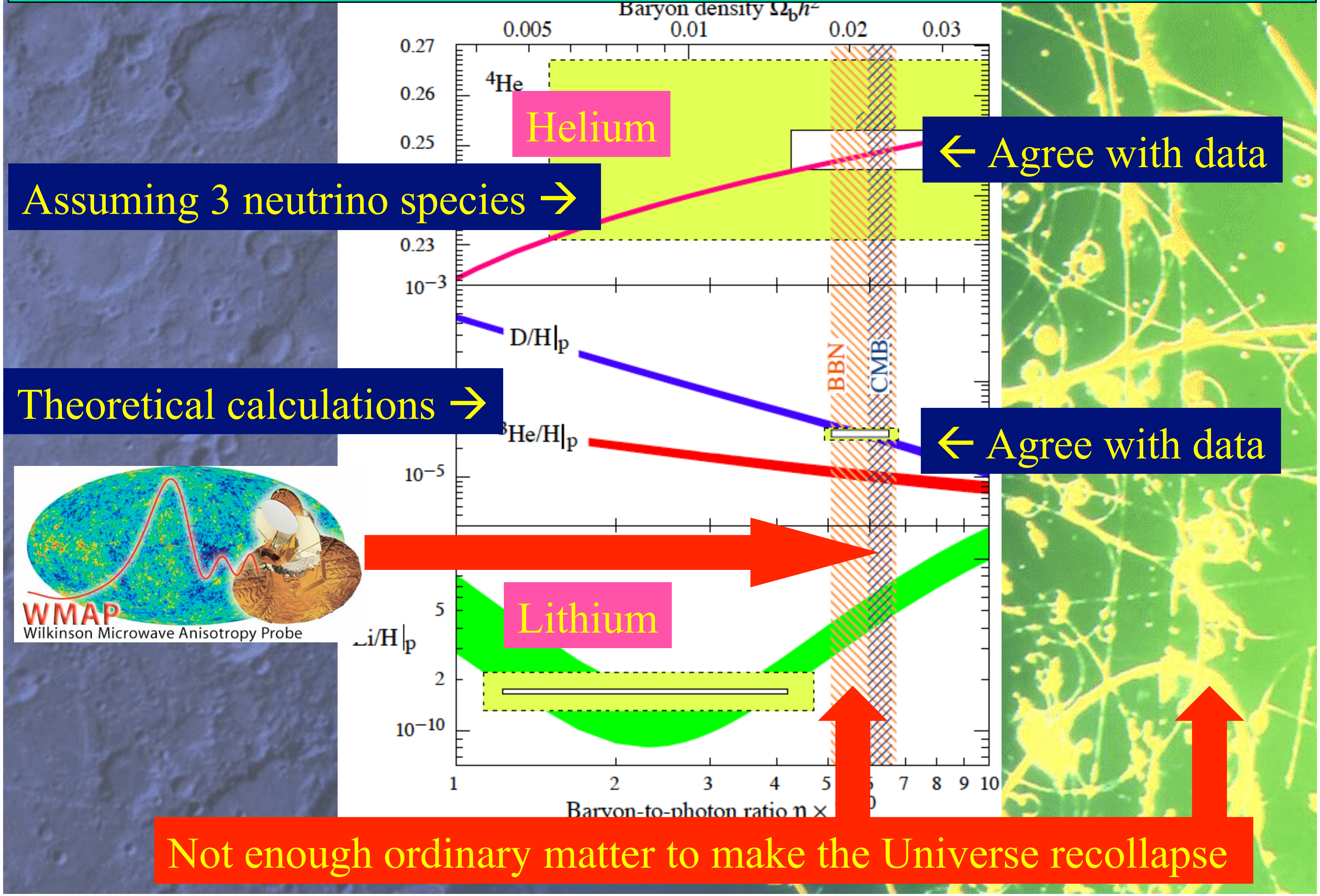
- The Universe was once a billion times smaller, hotter than today

    light elements cooked in the Big Bang

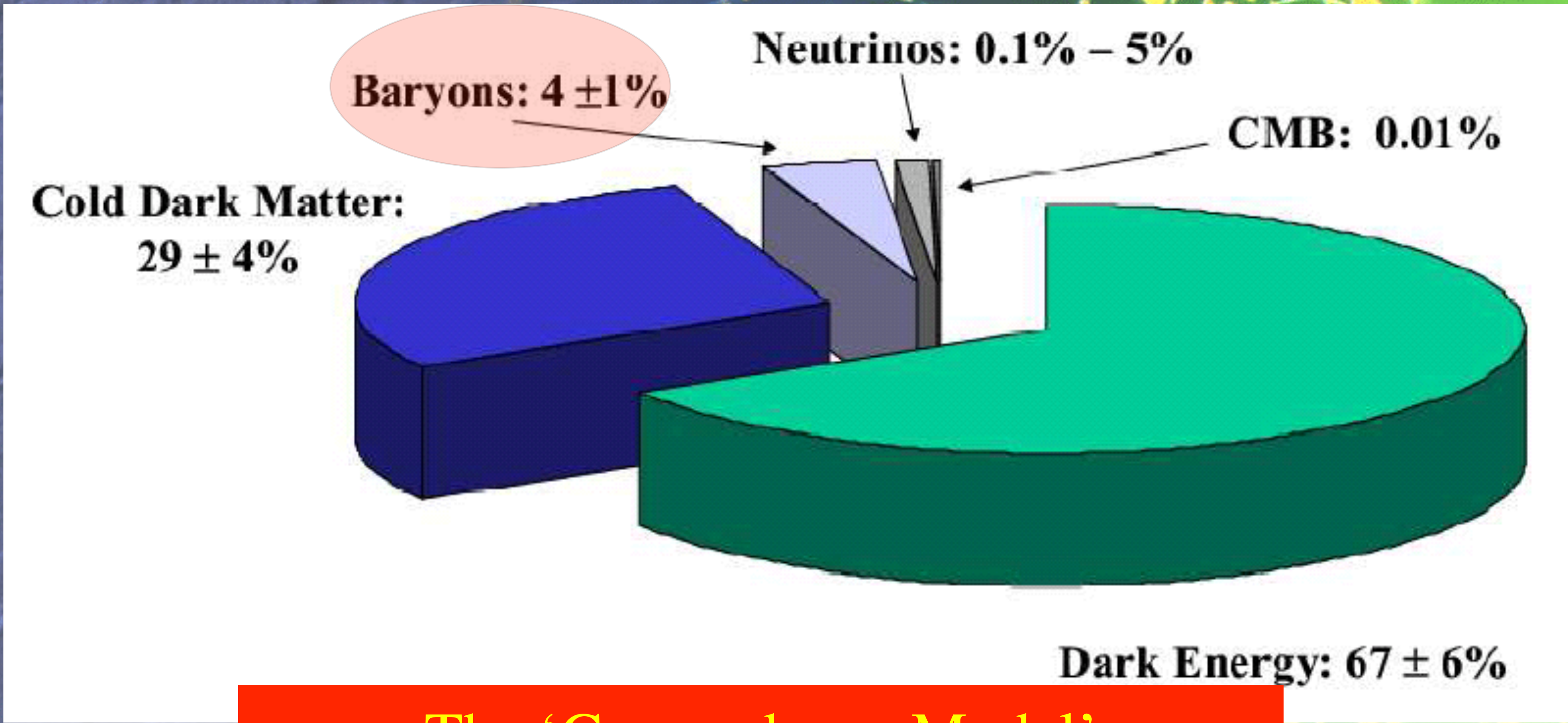
Making Elements in the Early Universe

- 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



A Strange Recipe for a Universe



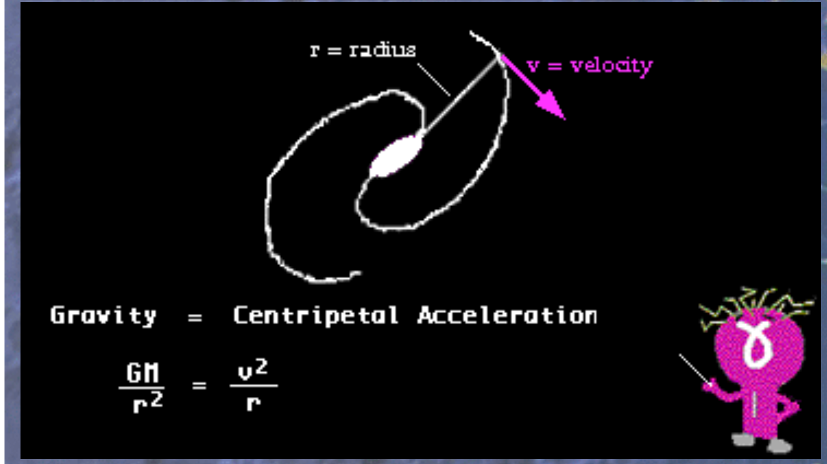
The ‘Concordance Model’
prompted by astrophysics & cosmology

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

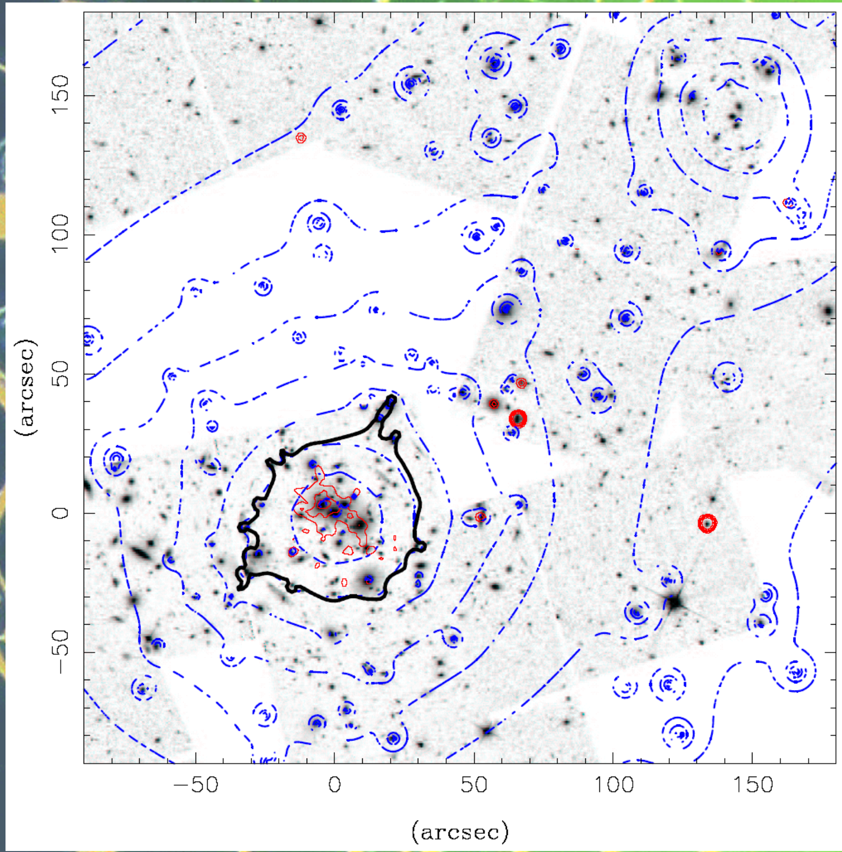
Even a 'dark galaxy' without stars



Evidence for Dark Matter from Gravitational Lensing

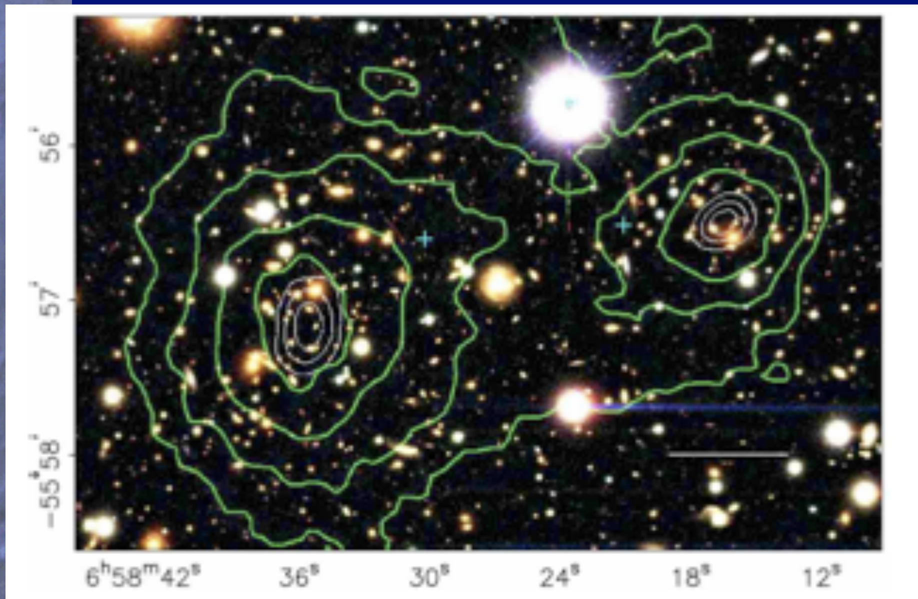
Light bent by gravitational field of dark matter

Contours of mass density

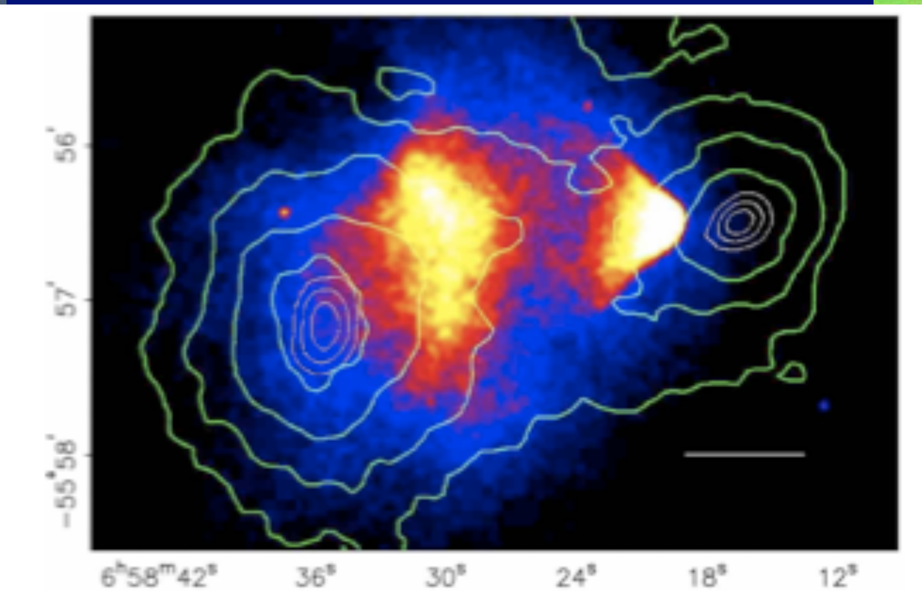


Direct Evidence for Collisionless Dark Matter

Collision of two galaxies:
dark matter lumps pass through



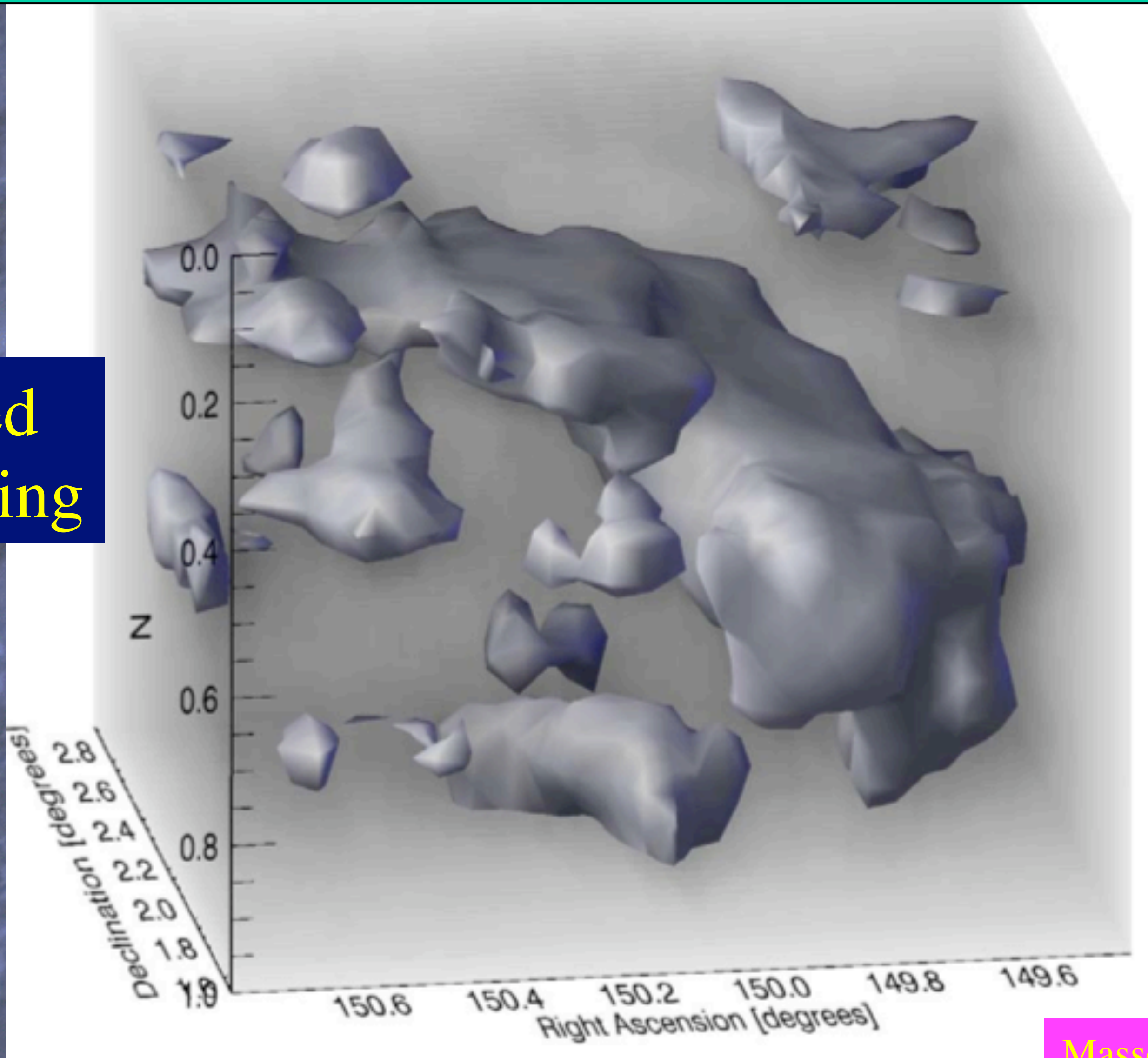
Collision of two galaxies:
gaseous matter stuck in between



Clowe et al, 2006

The Dark Matter Scaffolding

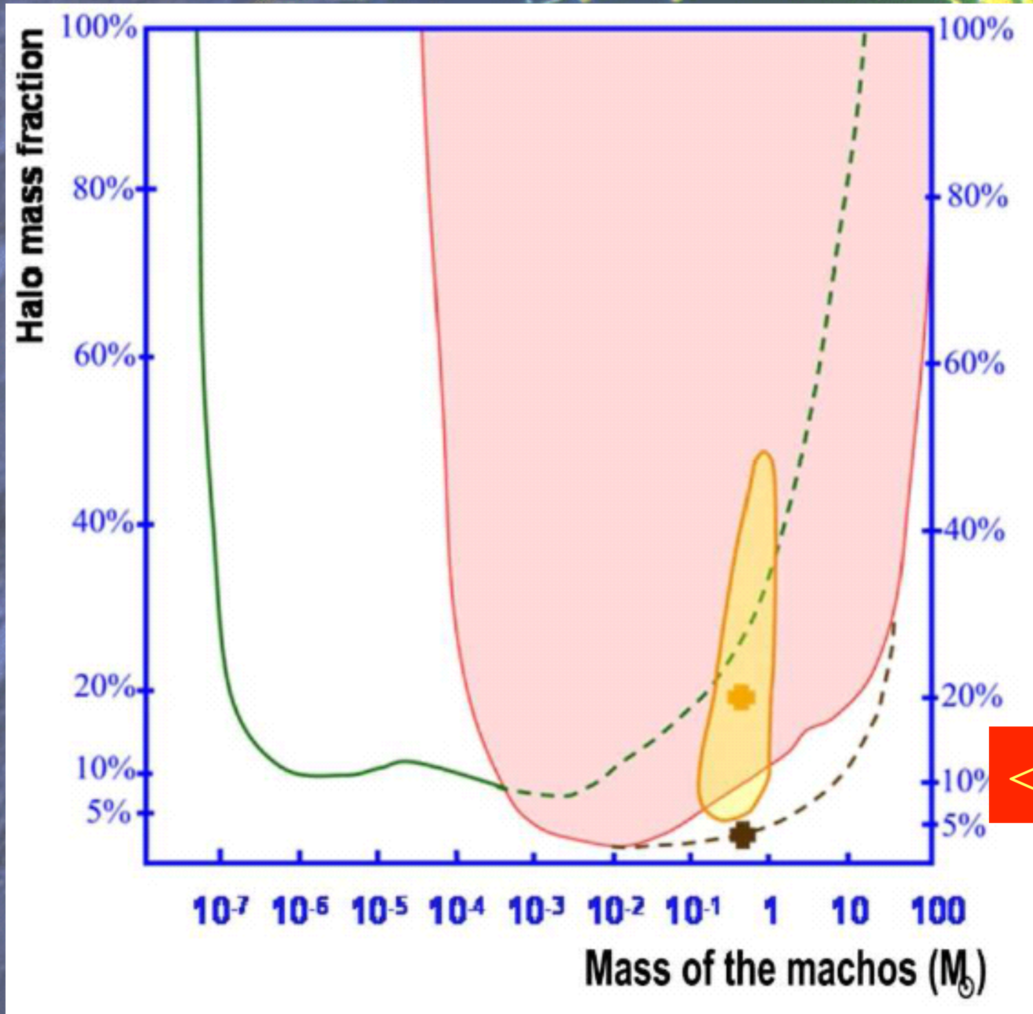
As measured
by weak lensing



Massey et al, 2007

Could our galactic halo be ordinary matter?

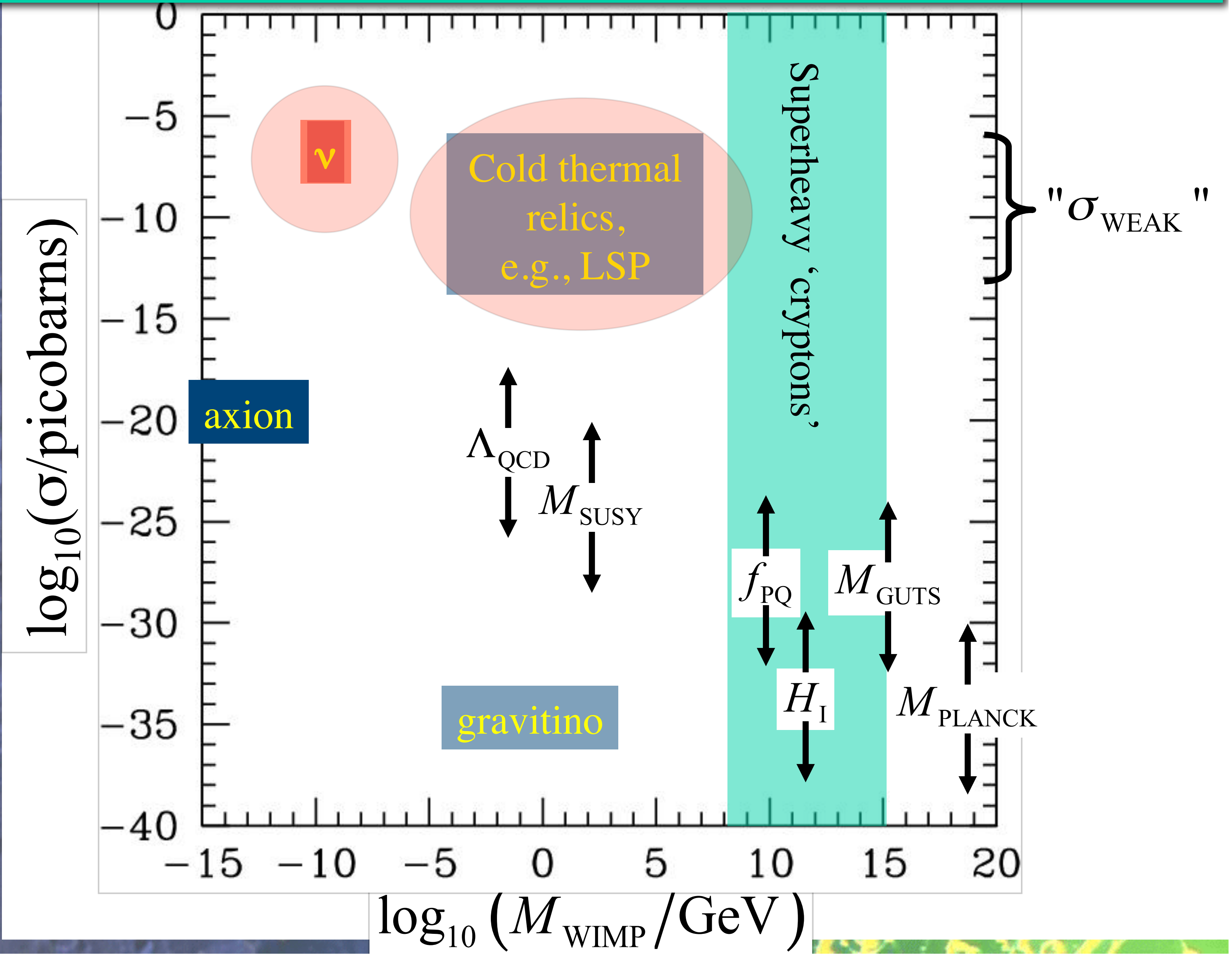
Our Halo is not made of Machos



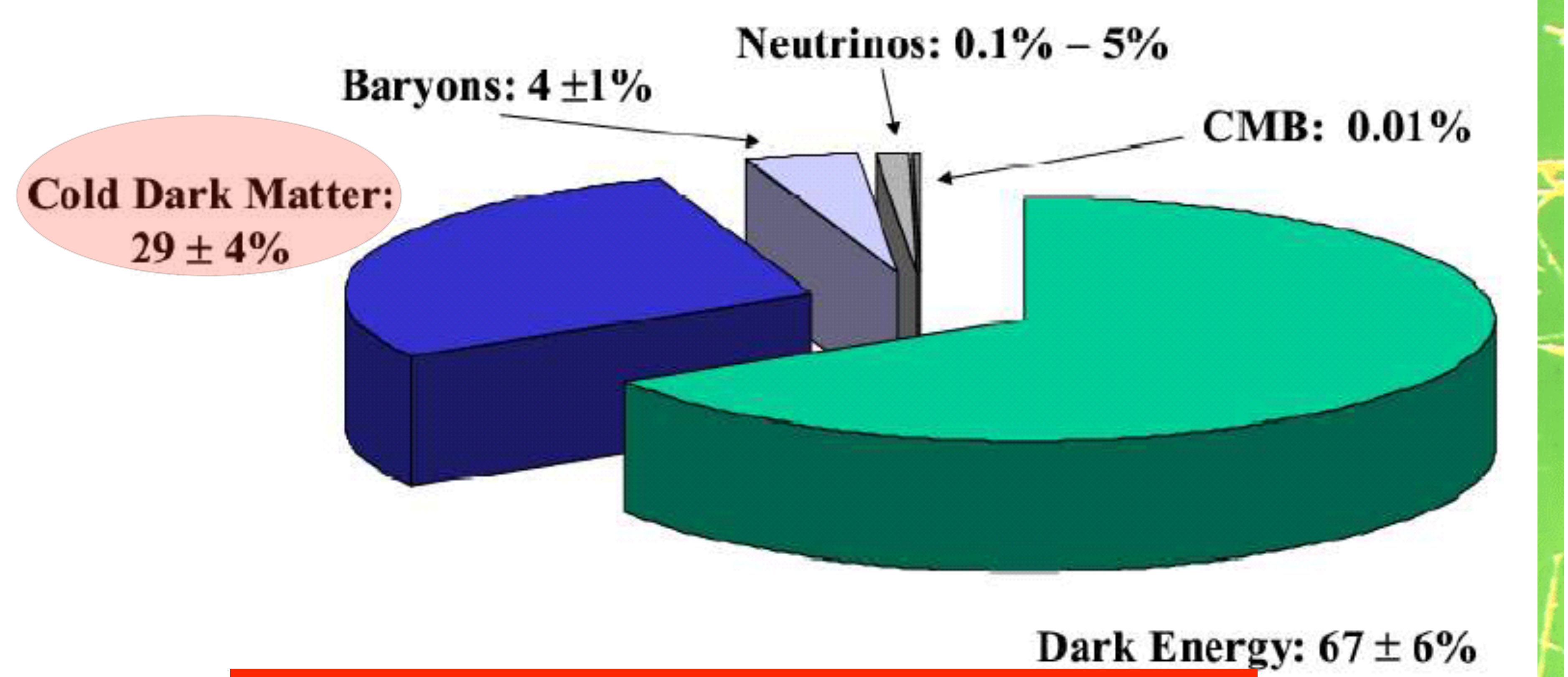
= MAssive
Compact
Halo
Objects
= dead stars
or black holes

< 10 % of our halo

Particle Dark Matter Candidates



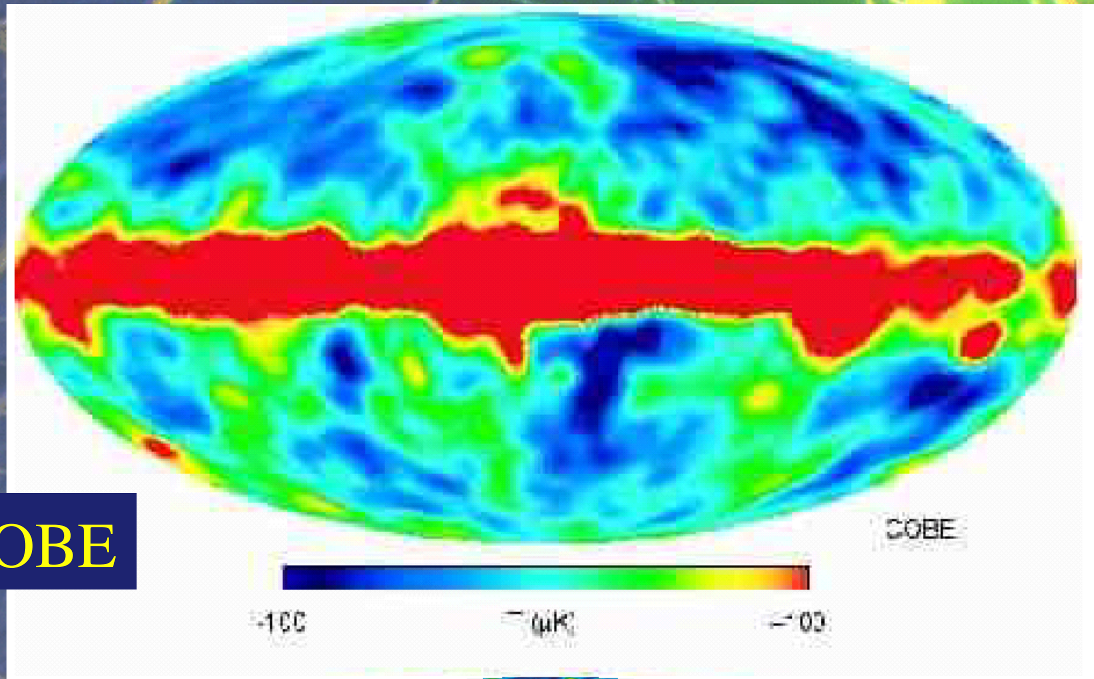
A Strange Recipe for a Universe

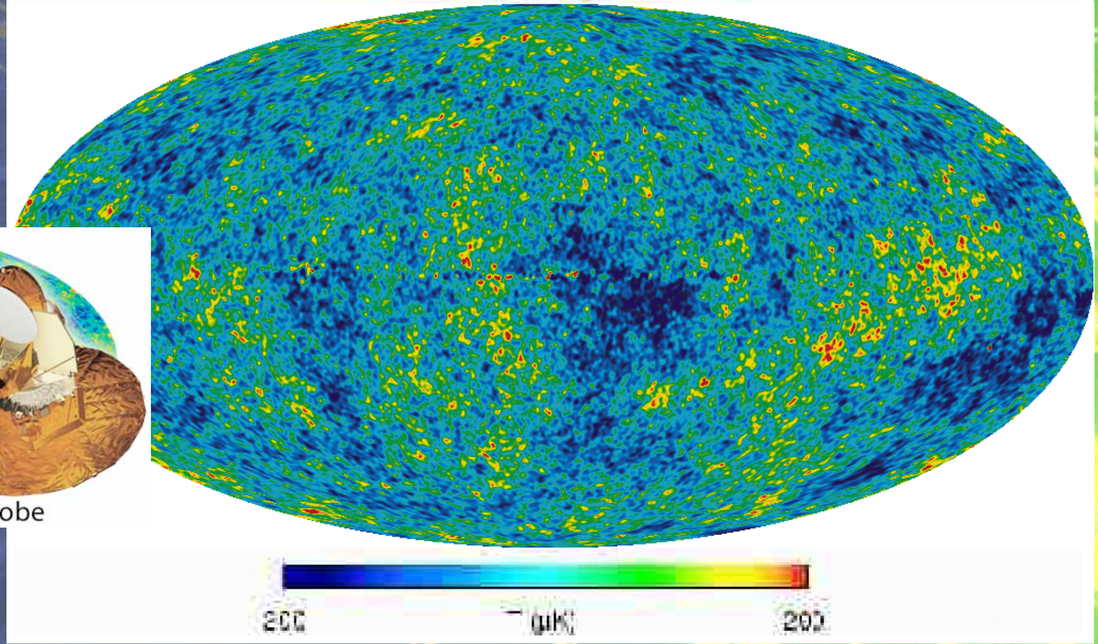


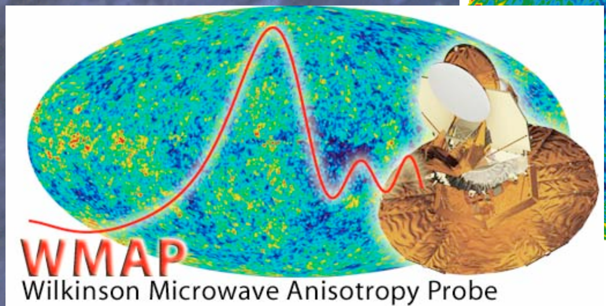
The 'Concordance Model'
prompted by astrophysics & cosmology

The Cosmic Microwave Background

According to COBE



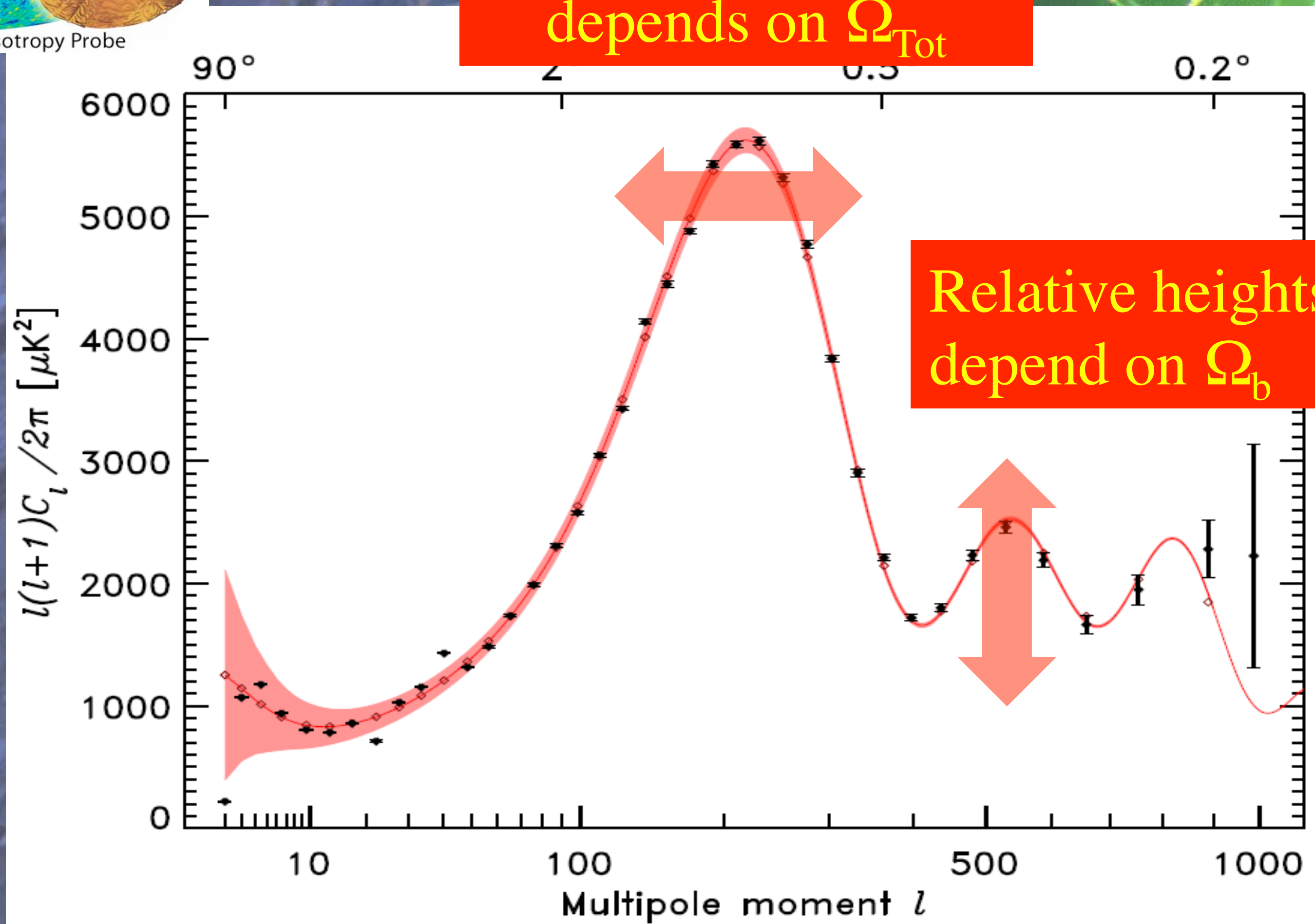




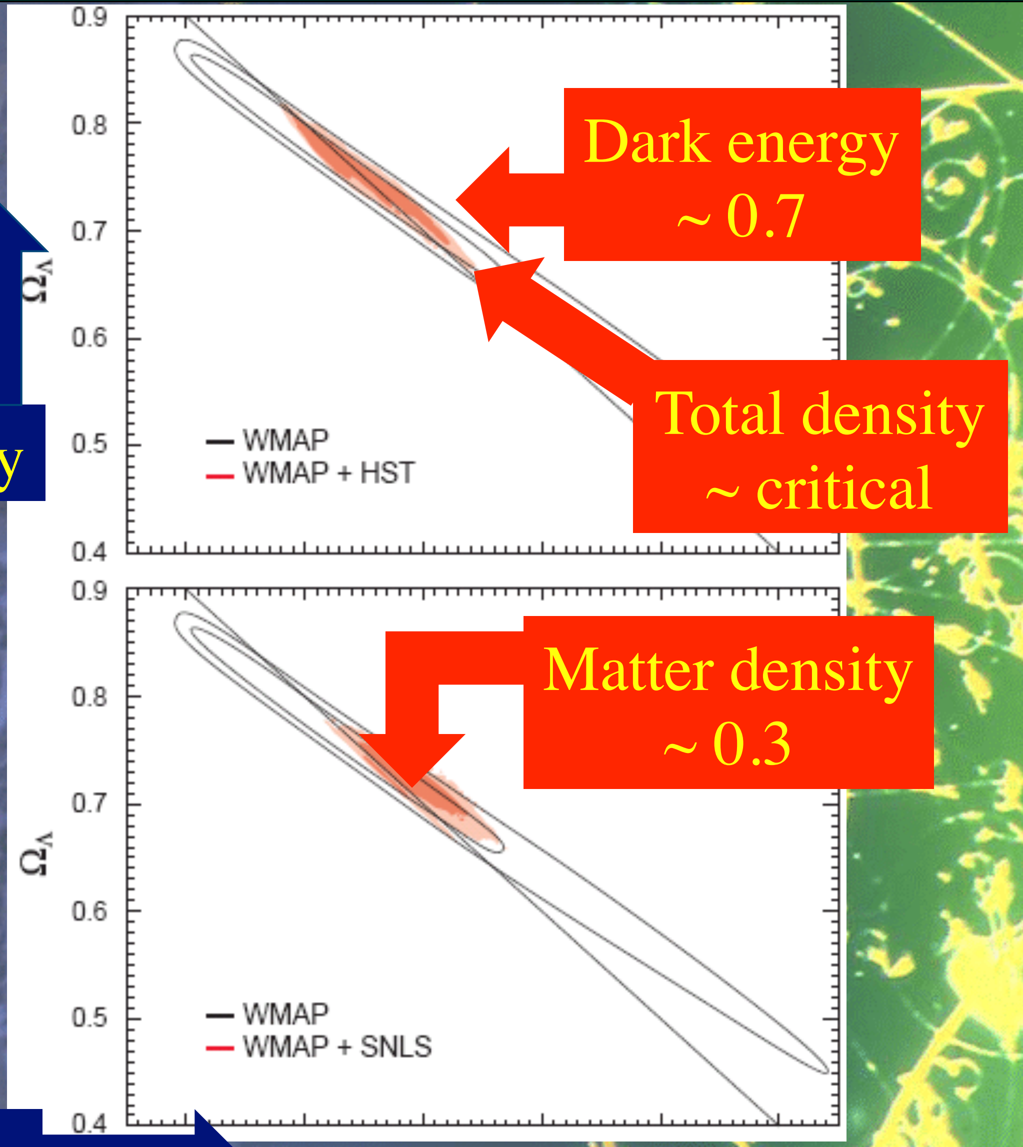
The CMB Power Spectrum

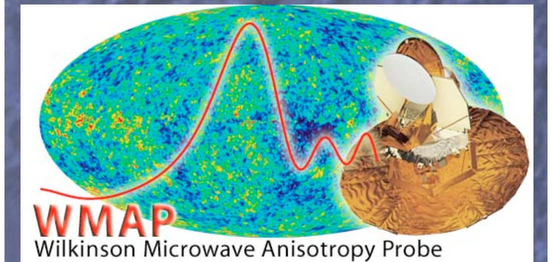
Location of first peak depends on Ω_{Tot}

Relative heights depend on Ω_b

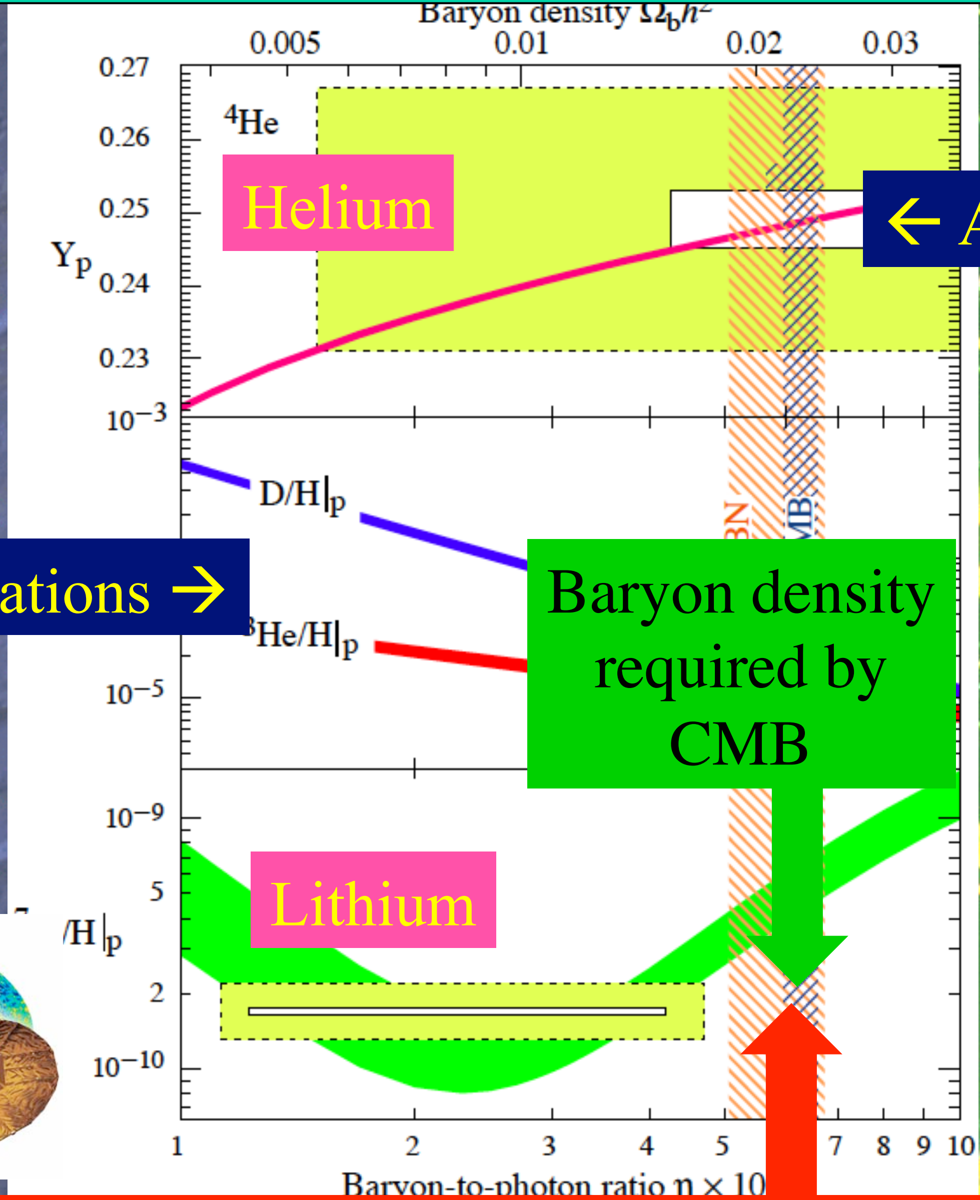


WMAP Constraints on Density





Abundances of light elements in the Universe



Helium

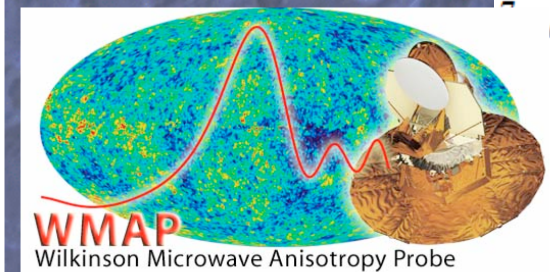
← Agree with data

Theoretical calculations →

Lithium

Baryon density required by CMB

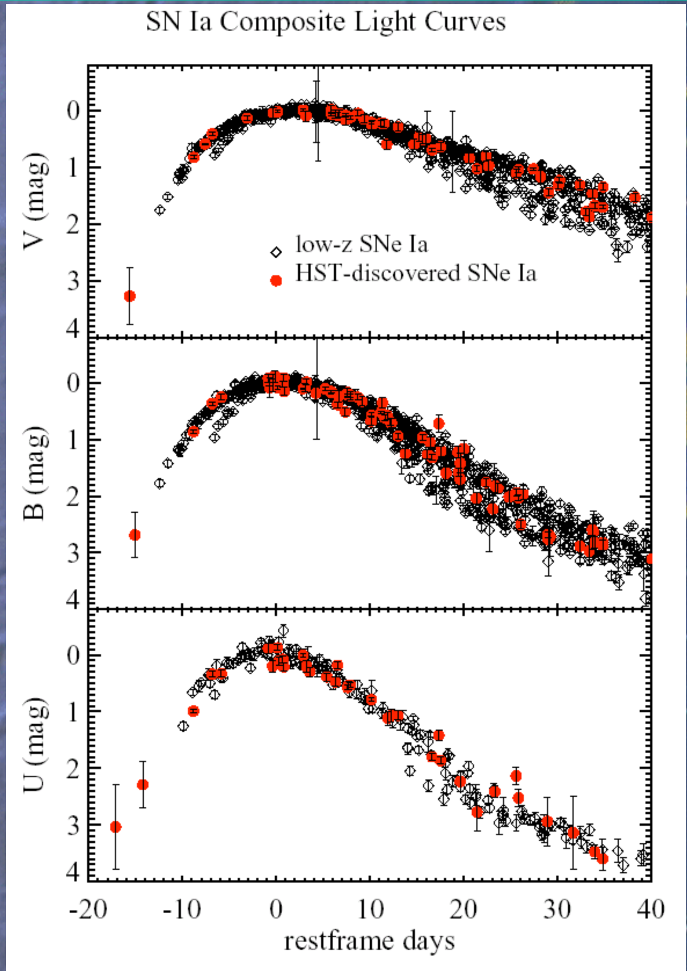
Total density required by CMB



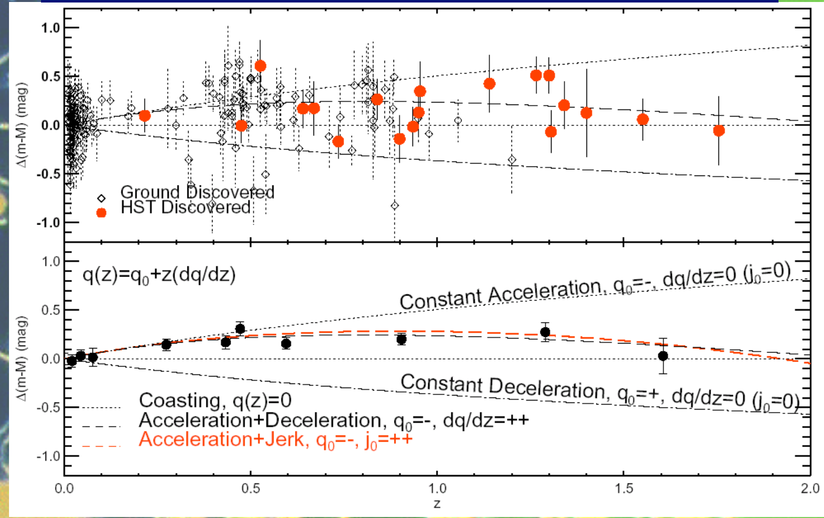
Not enough ordinary matter to make the Universe recollapse

Direct evidence for dark energy

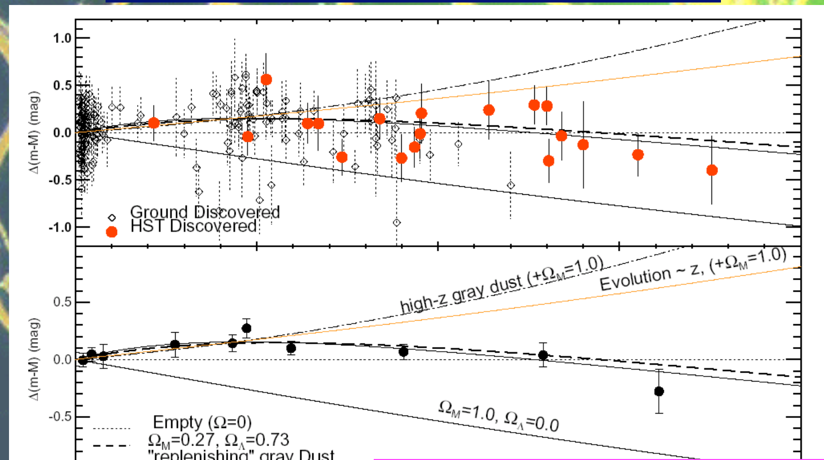
High-redshift supernovae are standard candles



Universe now accelerating, previously decelerating



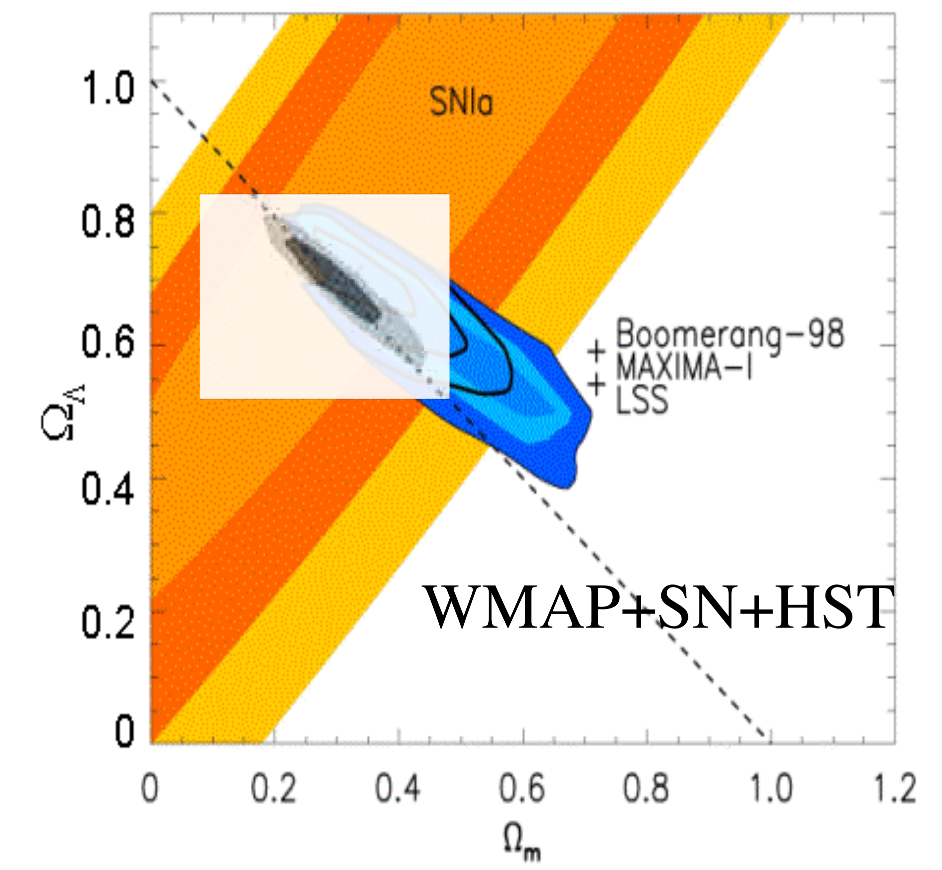
not dust, not evolution



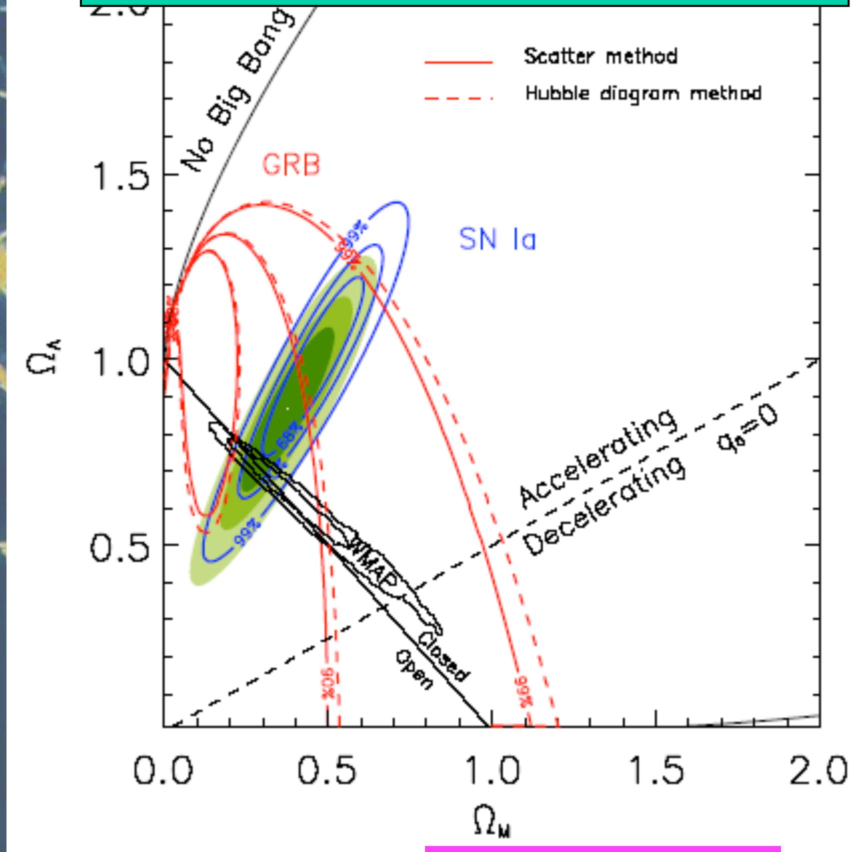
Riess et al, Perlmutter et al

Concordance Cosmological Model

WMAP, Supernovae,
Large-scale structures …

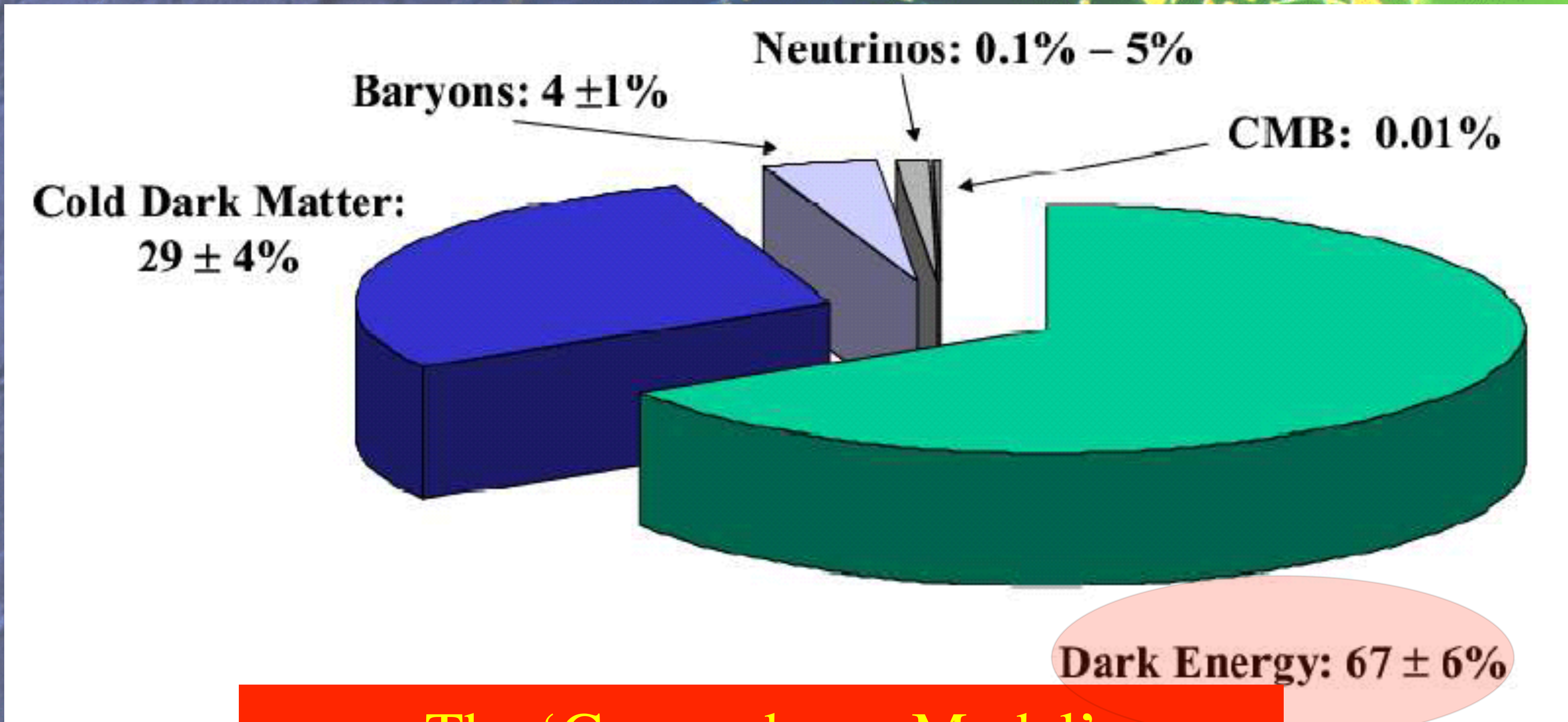


… and gamma-ray bursters?



Ghirlanda et al

A Strange Recipe for a Universe

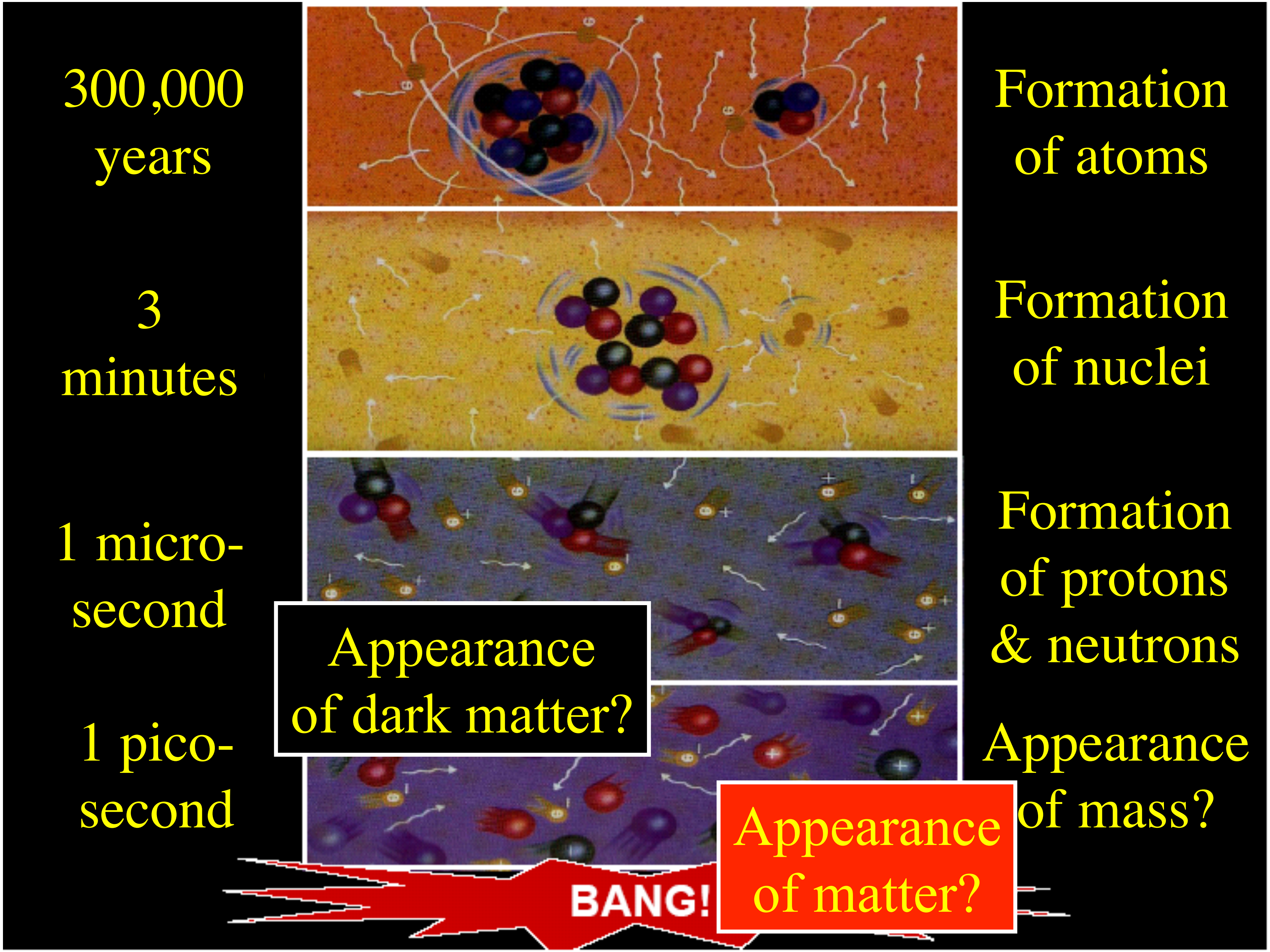


The 'Concordance Model'
prompted by astrophysics & cosmology

Open Cosmological Questions

- Where did the matter come from?
  - 1 proton for every 1,000,000,000 photons
- What is the dark matter?
  - Much more than the normal matter
- What is the dark energy?
  - Even more than the dark matter
- Why is the Universe so big and old?
  - Mechanism for cosmological inflation

Need particle physics to answer these questions


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?
BANG!
Appearance of matter?

The Very Early Universe

- Size: $a \rightarrow$ zero
- Age: $t \rightarrow$ zero
- Temperature: $T \rightarrow$ 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:

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

  – 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:

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

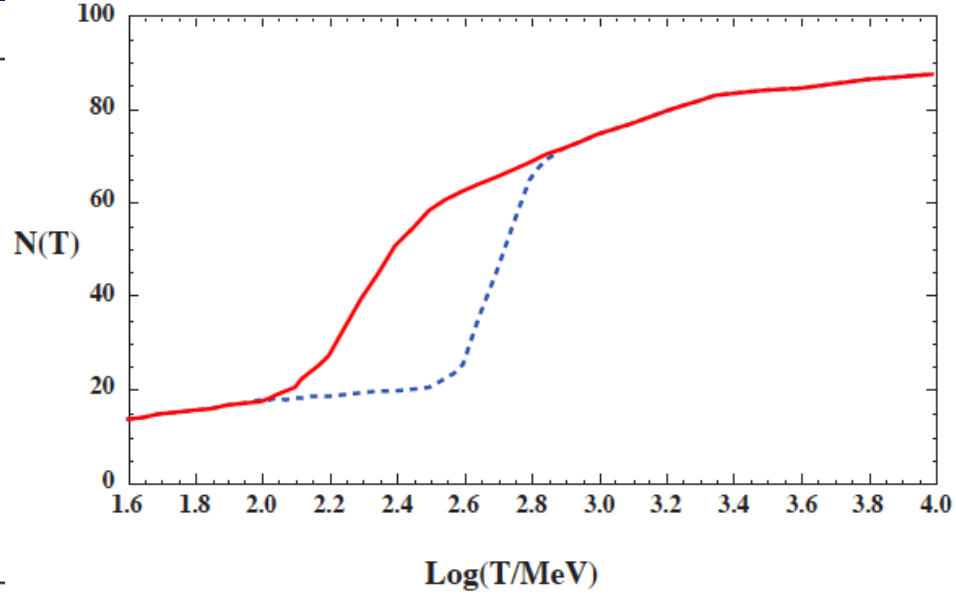
Relativistic Particles

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

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
$m_b < T < m_{\text{W,Z}}$	$b, \bar{b}$	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



How Flat is the Universe?

- Measure density relative to critical value:

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

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

  where critical density

$$\rho_c \equiv \frac{3H^2}{8\pi G_N} = 1.88 \times 10^{-26}\, h^2 \text{ kg m}^{-3}$$
$$= 1.05 \times 10^{-5}\, h^2 \text{ GeV cm}^{-3}$$

- And Hubble expansion rate: $H \equiv 100\, h \text{ km s}^{-1} \text{ Mpc}^{-1}$
- Exponential expansion if Λ dominates:

$$R(t) \propto e^{\sqrt{\Lambda/3}t}$$

Age of the Universe

- Integrating Hubble expansion rate:

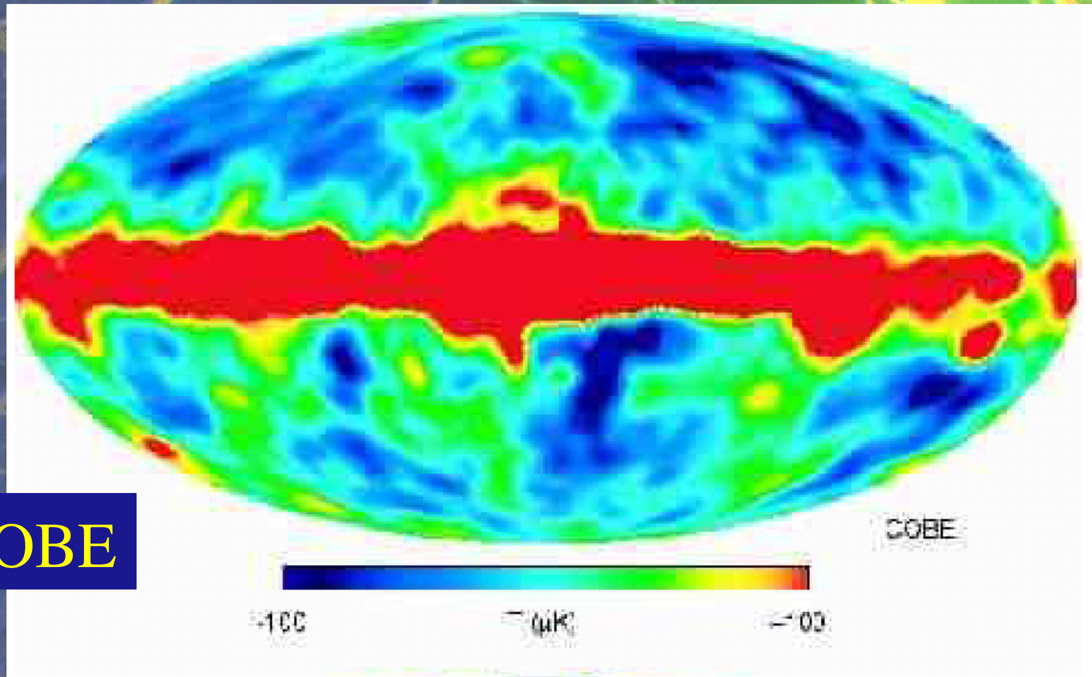
$$H_0 t_0 = \int_0^\infty \frac{dz}{(1+z)H(z)}$$
$$= \int_0^\infty \frac{dz}{(1+z)\,[(1+z)^2(1+\Omega_m z) - z(2+z)\Omega_v]^{1/2}}$$

- Approximate solution:

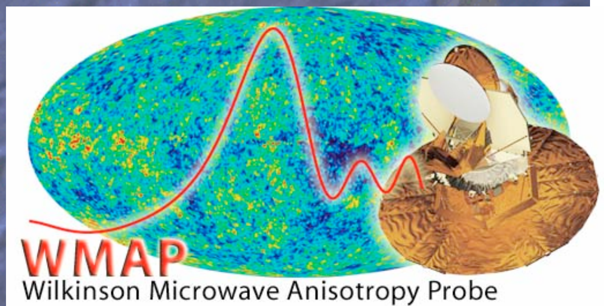
$$H_0 t_0 \simeq \tfrac{2}{3}\,(0.7\Omega_m + 0.3 - 0.3\Omega_v)^{-0.3}$$

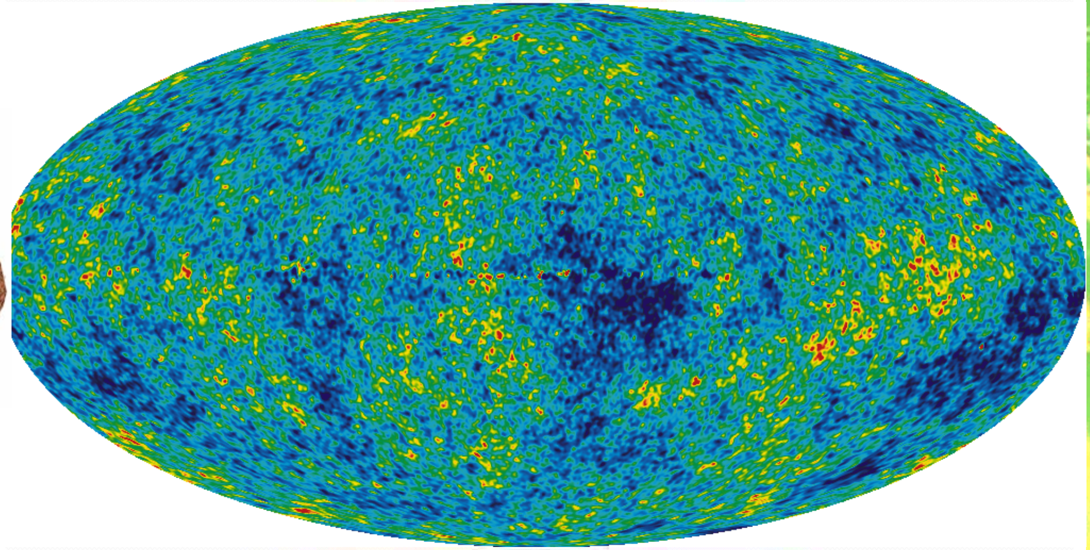
- Estimated age: **13.7 billion years**

The Cosmic Microwave Background



According to COBE





What is the origin of the fluctuations in the CMB?

Scalar Fields & Inflation

- Energy-momentum tensor for scalar field:

$$T_{\mu\nu} = \partial_\mu \phi \partial_\nu \phi - \frac{1}{2} g_{\mu\nu} \partial_\rho \phi \partial^\rho \phi - g_{\mu\nu} V(\phi)$$

- Density & pressure:

$$\rho = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2} R^{-2}(t)(\nabla\phi)^2 + V(\phi)$$

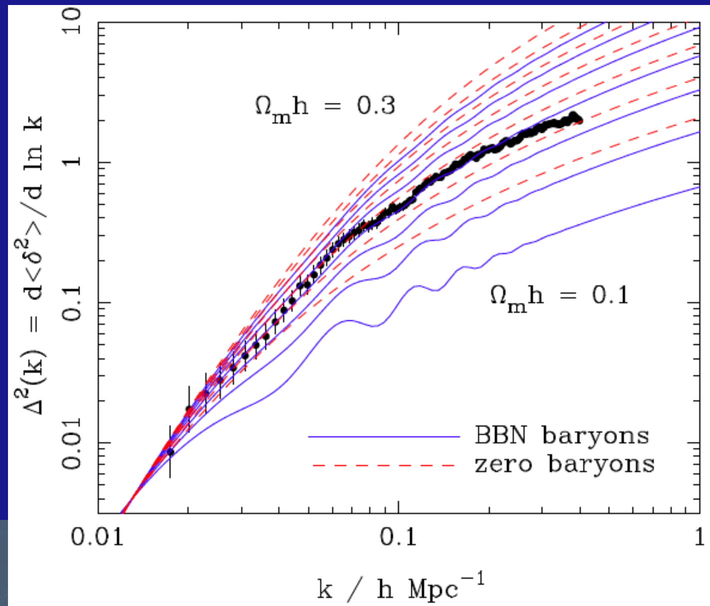
$$p = \frac{1}{2}\dot{\phi}^2 - \frac{1}{6} R^{-2}(t)(\nabla\phi)^2 - V(\phi) \, ,$$

- Evolution of scalar field: $\ddot{\phi} + 3H\dot{\phi} = -\partial V/\partial\phi$
- Slow-roll parameters: $\epsilon \equiv \frac{M_{\rm P}^2}{16\pi}(\frac{V'}{V})^2 \qquad \eta \equiv \frac{M_{\rm P}^2}{8\pi}(\frac{V''}{V})$
- If these are small, near-exponential expansion:

$$R(t) \propto e^{\sqrt{\Lambda/3}t}$$: **$\Lambda = V(\phi)$**

Density Perturbations

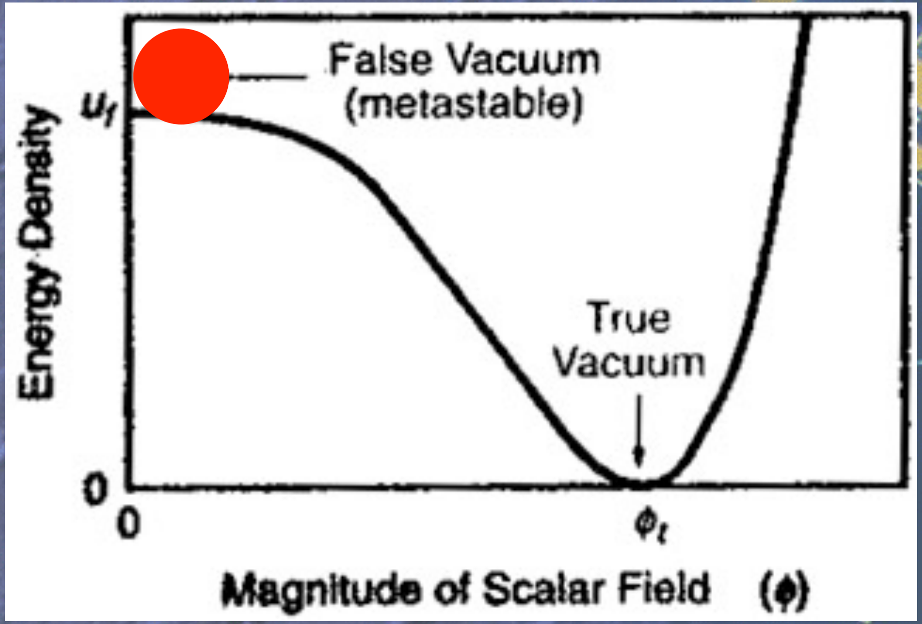
- Generated by quantum fluctuations in inflaton field
- Density perturbations: $\delta(\mathbf{x}) \equiv \frac{\rho(\mathbf{x}) - \langle\rho\rangle}{\langle\rho\rangle}$ $\delta(\mathbf{x}) = \sum \delta_{\mathbf{k}} e^{-i\mathbf{k}\cdot\mathbf{x}}$
- Power spectrum: $\langle\delta^2\rangle = \sum |\delta_{\mathbf{k}}|^2 \equiv \sum P(k)$
- Evolution depends on equation of state
- Measured in CMB, galaxy distributions

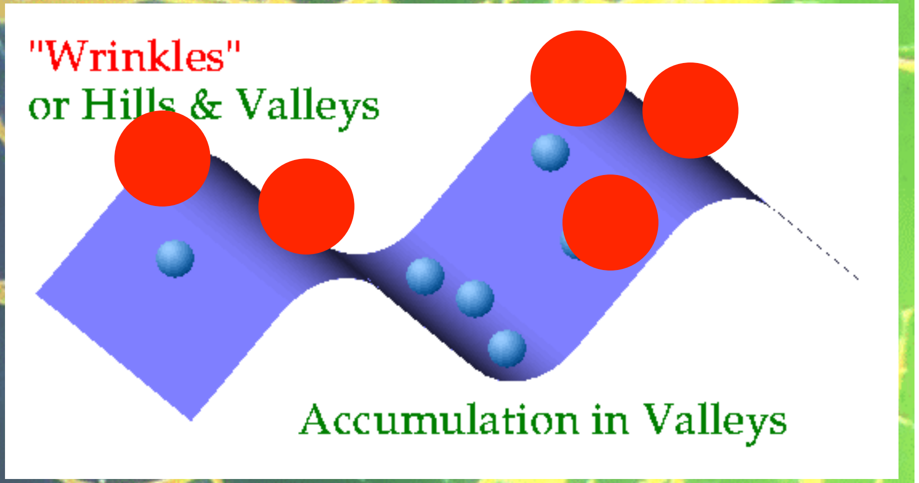


Origin of Structures in Universe

Small primordial fluctuations:
one part in 10^5

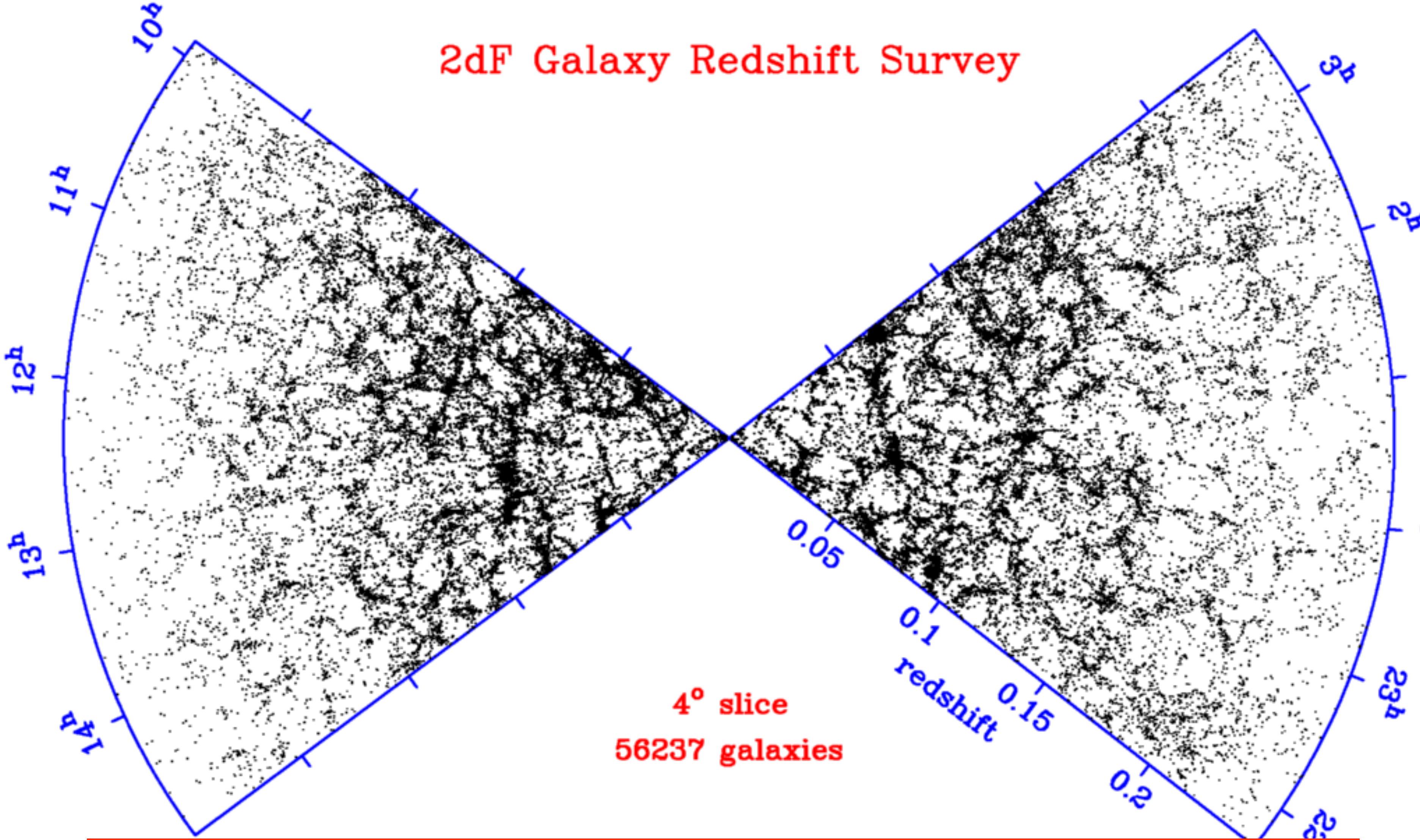
Gravitational instability:
Matter falls into
the overdense regions





Convert into matter with varying density

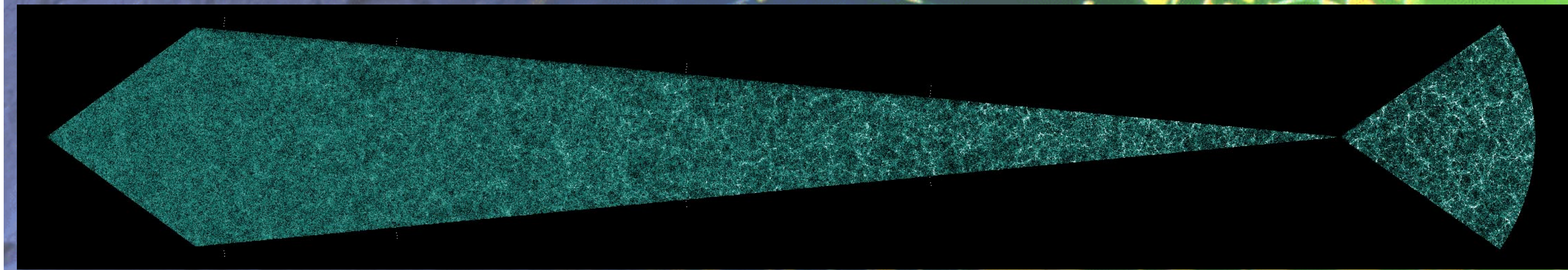
Structures observed in the Universe



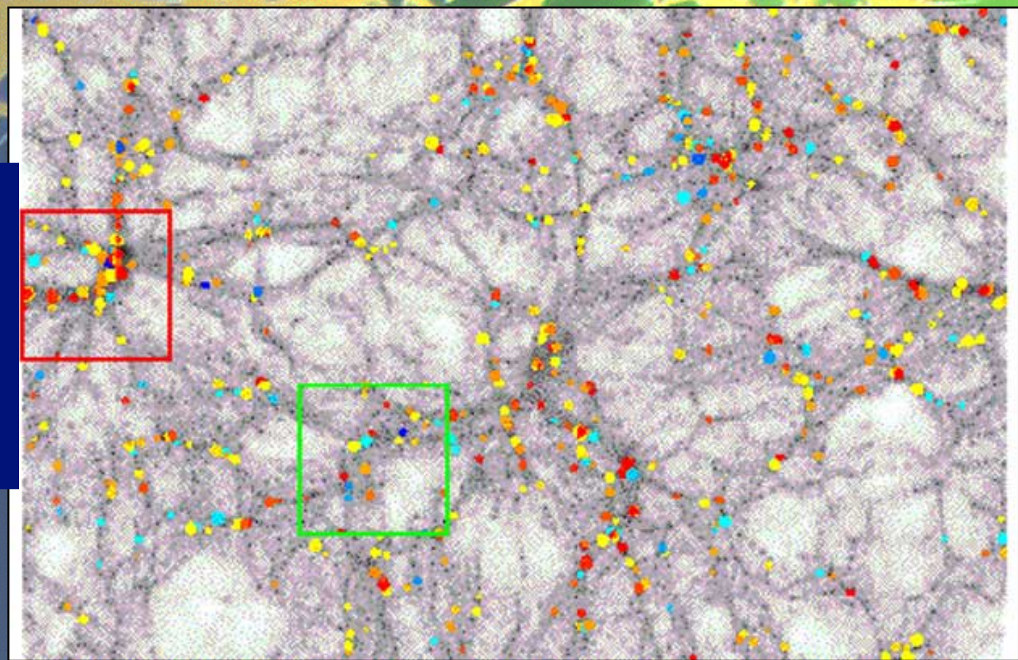
Galaxies → Clusters → smooth at largest scales

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



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:

$\Omega_\Lambda \sim 0.7$