Trends in High Energy Physics

13 June 2012, Primorsko

The Early Universe Processes and Relics

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Outline

Early Universe processes.

Relics: CNB, BBN, CMB.

Universe Riddles:

Matter Content of the Universe:

DM.DE.BAU

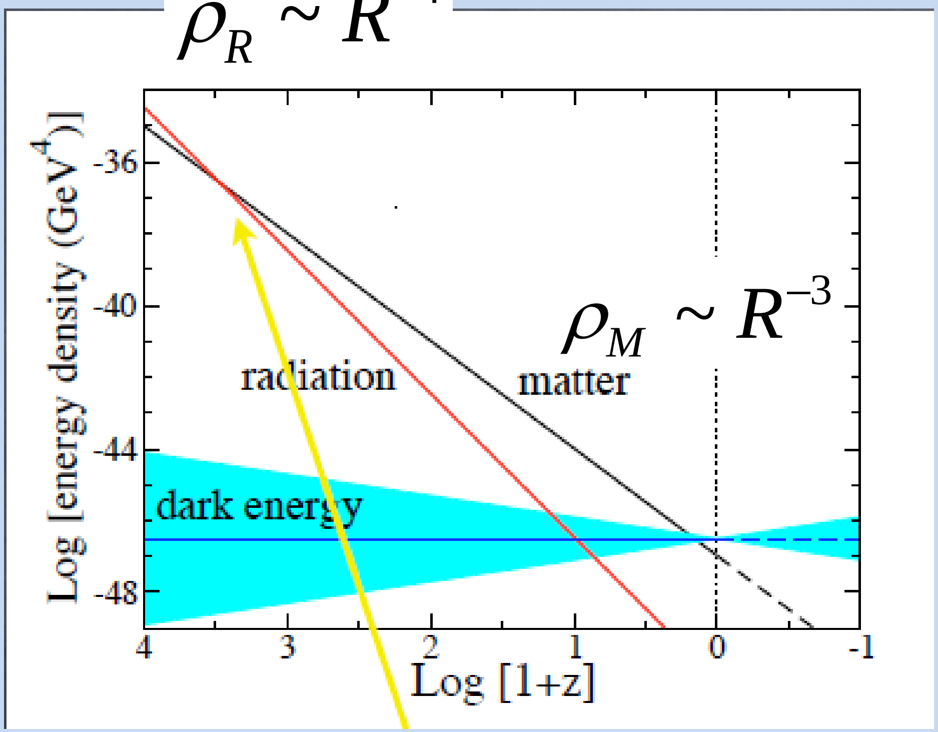
Initial conditions of SCM:

inflation

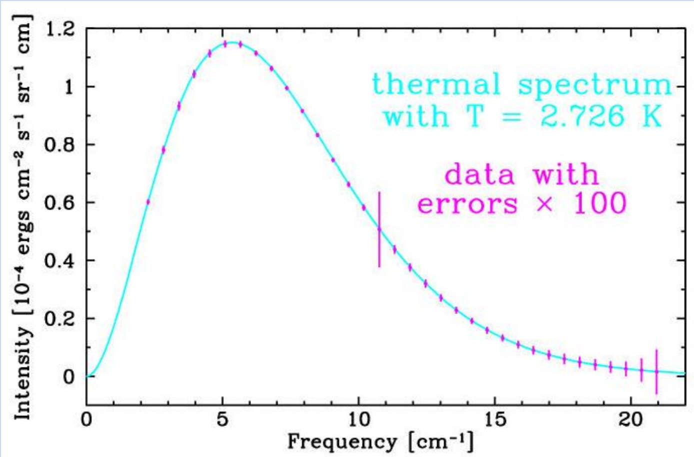
CMB and BBN abundances point to RD Universe:

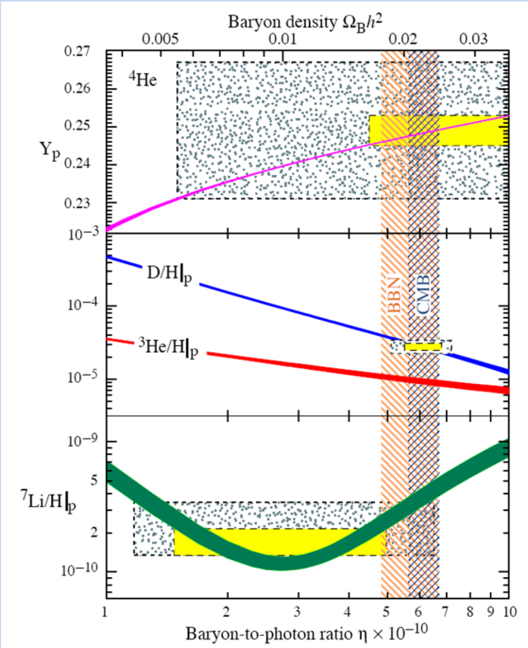
$$\rho \propto R^{-3(1+w)}$$

$$\rho_R \sim R^{-4}$$



$$\rho_M \sim \rho_R$$





No matter how small is the radiation component today, having in mind the different dependence of radiation and matter density on R(t) and T~ 1/R, radiation dominated at early stage .

RD stage:

Thermodynamic relations for the energy density, S and number densities n:

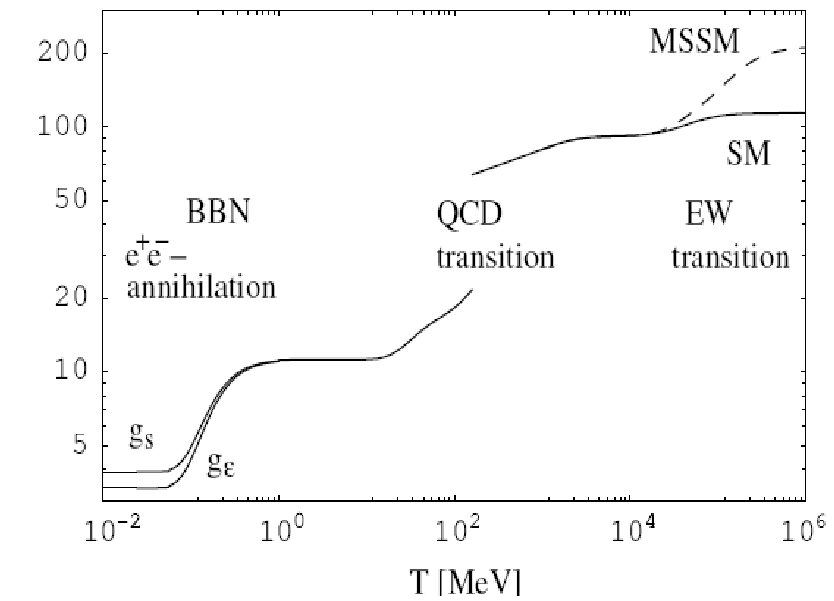
$$\rho = \frac{\pi^2}{30} g_* T^4 ,$$
$$n = \frac{\zeta(3)}{\pi^2} \left(g_B + \frac{3}{4} g_F\right) T^3 ,$$

$$g_* = \sum_{i=\text{bosons}} g_i + \frac{7}{8} \sum_{j=\text{fermions}} g_j \equiv \left(g_B + \frac{7}{8} g_F\right)$$

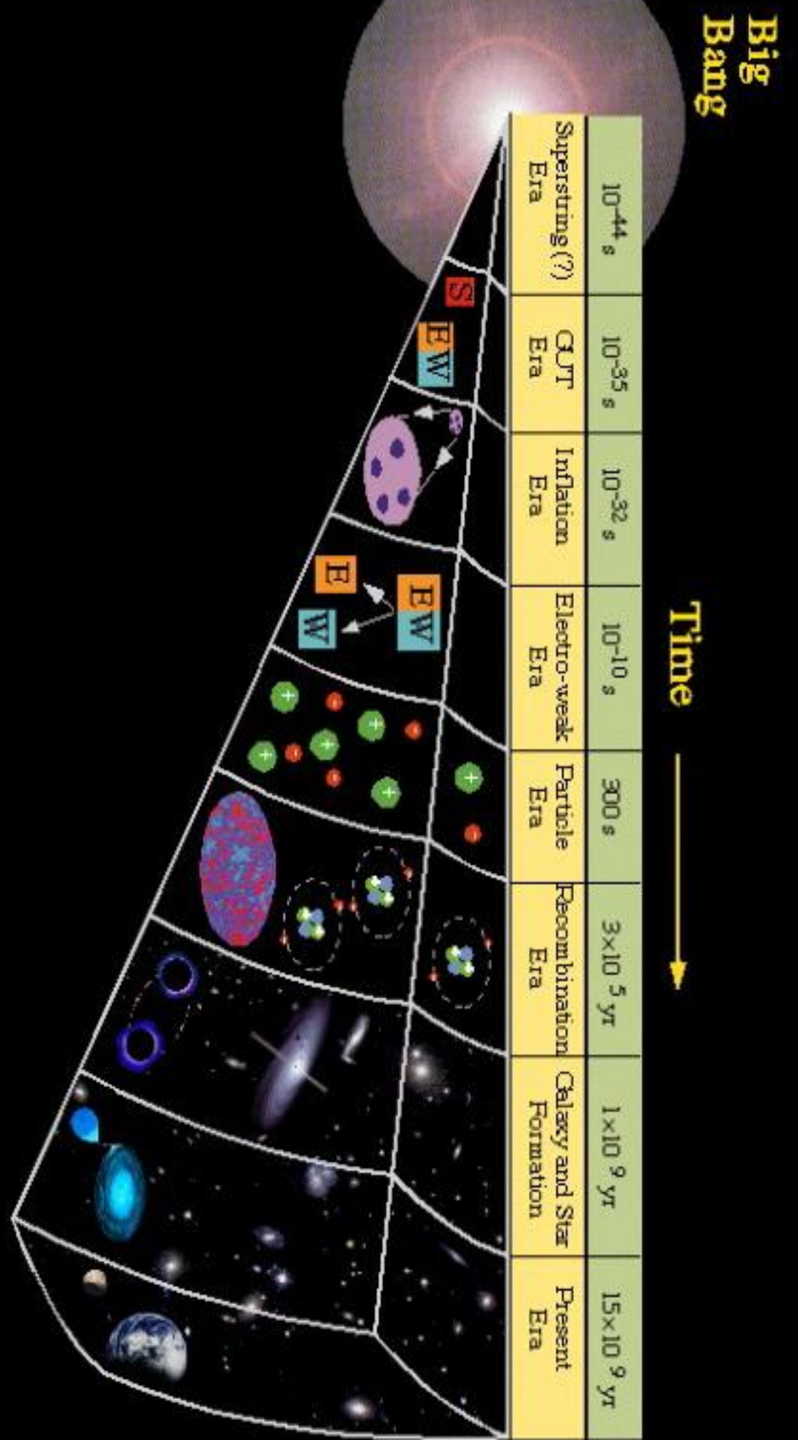
$$R(t) \propto t^{\frac{2}{3(1+w)}} = \sqrt{t}; \quad \text{rad } (w = 1/3)$$

Radiation era:

$$t[\text{s}] \approx \frac{2.4\times 10^{-6}}{\sqrt{g(t)}\, T^2[\text{GeV}]}$$



Number of relativistic degrees of freedom g as a function of T



UNIVERSE HISTORY

Processes	cosmic time	T
GUT	10^{-35} s	10^{15} GeV
Inflation		
BA generation		
EW symmetry breaking	10^{-10} s	100 GeV
QCD	10^{-5} s	0.3 GeV
CNB formation	1 s	3 - 1 MeV
BBN	1 s – 3 m	1 - 0.1 MeV
CMB formation	300 000 y	0.3 eV
Galaxy formation	$\sim 10^{9}$ y	
Today	13.7 10^{9} y	0.0003 eV ~ 3K

Relic Neutrino

Thermodynamical Equilibrium. Decoupling.

Thermodynamical equilibrium.Particle Decoupling

T>1 MeV

$\nu_\alpha \nu_\beta \leftrightarrow \nu_\alpha \nu_\beta$

$\nu_\alpha \bar{\nu}_\beta \leftrightarrow \nu_\alpha \bar{\nu}_\beta$

$\nu_\alpha e^- \leftrightarrow \nu_\alpha e^-$

$\nu_\alpha \bar{\nu}_\alpha \leftrightarrow e^+ e^-$

$T_\nu = T_e = T_\gamma$

$$\rho_r = \rho_\gamma + \rho_\nu + \rho_x = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] \rho_\gamma$$

At RD stage neutrinos are important component, influence considerably H, n-p kinetics, etc.

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

$$\frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3}(\rho + 3p),$$

T ~1 MeV

As the Universe cools the rate of interaction decrease and could no longer keep neutrino in equilibrium.

$$\Gamma \sim G_F^2 E_\nu^2 N_\nu \leq H \sim \sqrt{g_{eff} G} T^2$$

$T_{dec}(\nu_e) \sim 2$ MeV $\quad T_{dec}(\nu_{\mu,\tau}) \sim 3$ MeV

$T \sim m_e$, $\quad e^+e^- \rightarrow \gamma\gamma \quad T_\nu = (4/11)^{1/3} T_{cmb}$

$$f_\nu(p,T) = \frac{1}{e^{p/T_\nu} + 1}$$

$N_\nu = 3.046$ not 3 because of partial heating. $\quad N_\nu = 2.984 \pm 0.008$ (LEP)

$T_0 \sim 2.7$ K

RELIC NEUTRINO BACKGROUND

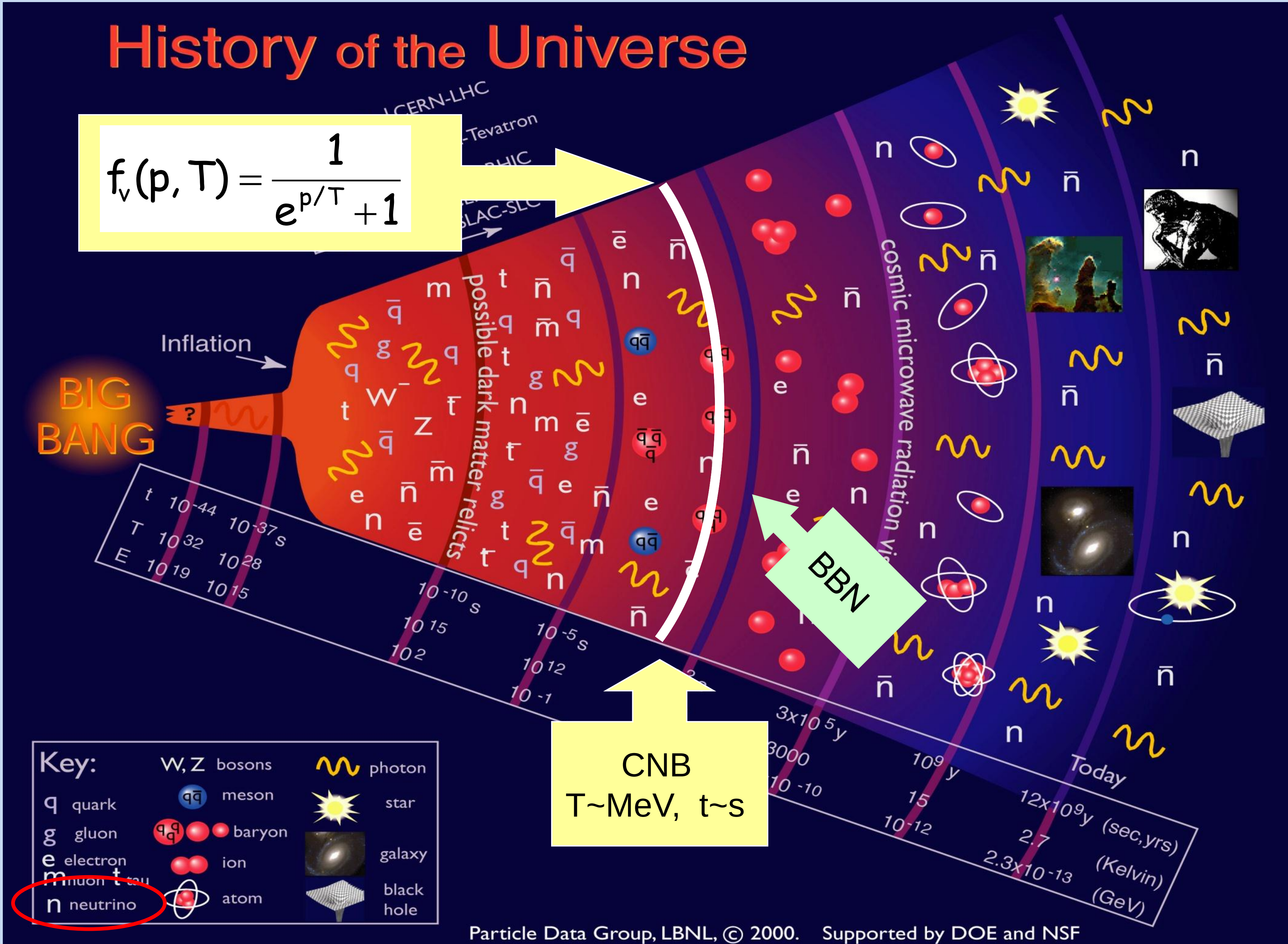
$T_{\nu 0} \sim 1.9$ K.

$n_\nu = 339.3\ \text{cm}^{-3}$

$n_\nu = 112\ \text{cm}^{-3} \quad n_{cmb} = 411\ \text{cm}^{-3}$

$$\Omega_\nu = \frac{3m_0}{93.14 h^2\ \text{eV}^2}$$

Neutrinos from CNB are expected to be the most numerous particles after CMB photons.



History of the Universe
$f_\nu(p,T) = \frac{1}{e^{p/T}+1}$
CERN-LHC
Tevatron
RHIC
SLAC-SLC
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation
BBN
CNB
T~MeV, t~s
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
3x10 5 y
3000
10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Relic Neutrino Background

Neutrinos decoupled at T~MeV, keeping a spectrum as that of a relativistic species

$$f_\nu(p,T) = \frac{1}{e^{p/T_\nu}+1}$$

- Number density

$$n_\nu = \int \frac{d^3p}{(2\pi)^3} f_\nu(p,T_\nu) = \frac{3}{11} n_\gamma = \frac{6\zeta(3)}{11\pi^2} T_{CMB}^3$$

- Energy density

$$\rho_{\nu_i} = \int \sqrt{p^2 + m_{\nu_i}^2} \frac{d^3p}{(2\pi)^3} f_\nu(p,T_\nu) \to \begin{cases} \frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{4/3} T_{CMB}^4 & \text{Massless} \\ m_{\nu_i} n_\nu & \text{Massive } m_\nu \gg T \end{cases}$$

Decoupling of neutrino is a continuous process:

	$T^{\gamma}_{fin} / T^{\gamma}_{0}$	$\delta\rho_{\nu e}$(%)	$\delta\rho_{\nu\mu}$(%)	$\delta\rho_{\nu\tau}$(%)	N_{eff}
Instantaneous decoupling	1.40102	0	0	0	3
SM	1.3978	0.94	0.43	0.43	3.046
+3v mixing (θ_{13}=0)	1.3978	0.73	0.52	0.52	3.046

ΔN_{eff} ~ 3 (WMAP)

ΔN_{eff} ~ 0.2 (Planck)

Dolgov, Hansen & Semikoz, 1997
Mangano et al, 2005

Today neutrino density (3 degenerate masses)

$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{3m_0}{94.12h^2\ \mathrm{eV}^2} \rightarrow \Omega_\nu = \frac{3m_0}{93.14h^2\ \mathrm{eV}^2}$$

$$n_\nu = 335.7\ \mathrm{cm}^{-3} \rightarrow n_\nu = 339.3\ \mathrm{cm}^{-3}$$

Relic neutrino is the most numerous particle after CMB photons.

Though numerous, CNB has not been detected. Its detection is difficult because of its weak interactions and the extremely low energy expected for neutrinos background today, i.e. relic neutrinos.

$$n_\nu = 339.3\ \mathrm{cm}^{-3} \qquad \Omega_\nu = \frac{3m_0}{93.14h^2\ \mathrm{eV}} \qquad 0.001 < \Omega_\nu < 0.02$$

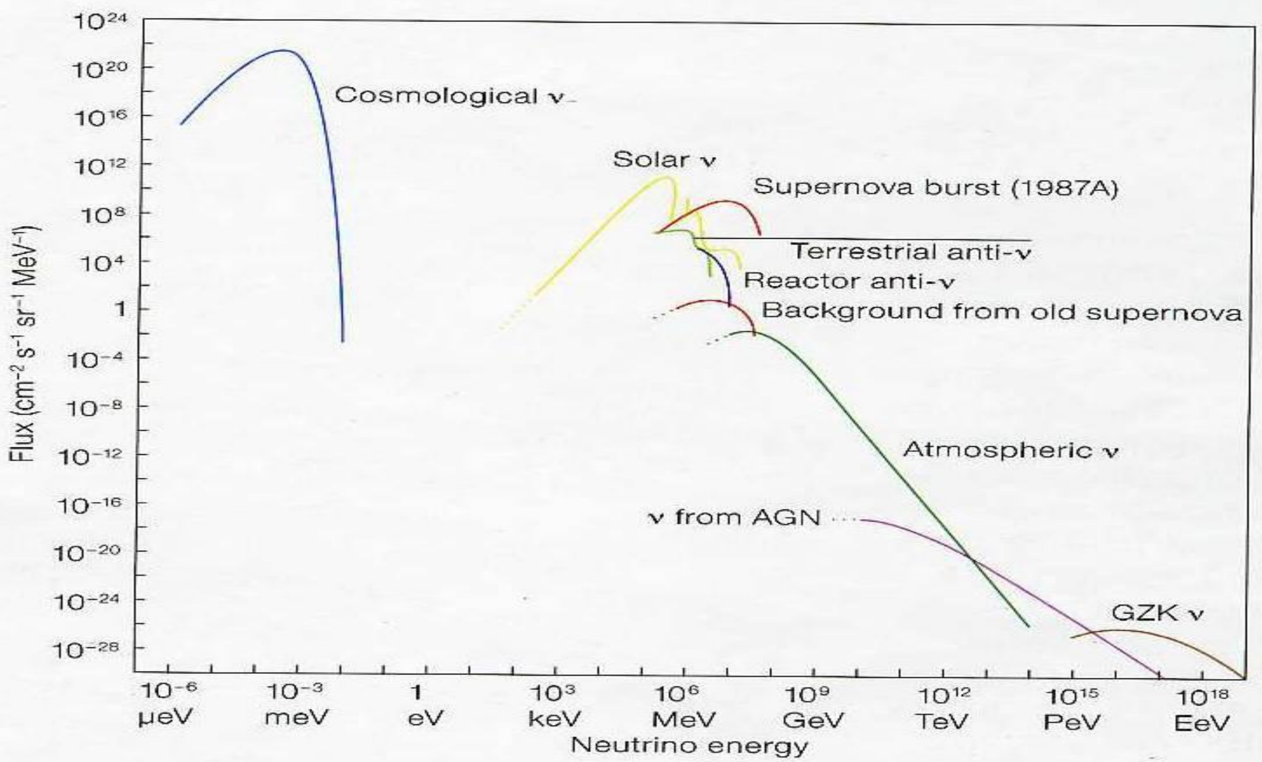


Figure 2: The 'grand unified' neutrino spectrum.

Figure from ASPERA roadmap

Indirect CNB detection is possible due to its effect on BBN,CMB, LSS.

CMB&LSS feel the total neutrino density. BBN is precise probe also of neutrino energy distribution, mass differences and mixing, chemical potential, etc.

Neutrinos in the Universe:

Effect the energy density
expansion rate
of the Universe

Constraints on number
of neutrino species N<5

Matter/radiation equality shift

Constraints on neutrino masses
and number densities < 0.6 eV

DM candidate

Effect BBN kinetics

Spectrum distortion
asymmetry constraints

Constraints on
oscillation parameters
Constraints on
sterile neutrino population

baryogenesis through
leptogenesis

Effect on CMB and LSS

Feel total energy density
stored in neutrinos

Constraints on neutrino masses
Constraints on lepton asymmetry

not sensitive to different species
or spectrum distortions

OSCILLATING NEUTRINOS

$\nu_m = U_{mf}\, \nu_f$, $(f = e, \mu, \tau)$ P $(\theta, \delta m^2, E, t)$

Evidence for oscillations of neutrino were obtained at the greatest neutrino experiments: solar, atmospheric and terrestrial **LSND, KAMLAND, K2K…..**

Solar neutrino problem, atmospheric neutrino anomaly and the results of terrestrial neutrino oscillations experiments can be resolved by the phenomenon of neutrino oscillations.

It has been observationally and experimentally proved that neutrinos oscillate . Then

- ✓ non-zero neutrino mass and mixing
- ✓ LA may be non-zero
  Initially present, or generated in resonant active-sterile oscillations
- ✓ Relic neutrino n(E) may differ from the equilibrium form

$$n_\nu^{cnb} \neq n_\nu^{eq} = \exp(-E/T)/(1+\exp(-E/T))$$

$N_e < N_{eq}$

Solar neutrino anomaly: $\nu_e \leftrightarrow \nu_\mu, \nu_\tau$

$\delta m^2 \sim 7.6 \cdot 10^{-5}\ eV^2$ $\sin^2\theta \sim 0.3$

Atmospheric neutrino anomaly: $\nu_\mu \leftrightarrow \nu_\tau$

$\delta m^2 \sim 2.4 \cdot 10^{-3} eV^2$ nearly maximal mixing

$\delta m^2 \neq 0 \Longrightarrow$ at least 2 neutrino with $m_\nu \neq 0$

$$\Omega_\nu = \frac{3m_0}{93.14 h^2\ \mathrm{eV}}$$

$$0.001 < \Omega_\nu$$

Flavor neutrino does not play an important role for DM and the formation of structure.

$$0.001 < \Omega_\nu < 0.02$$

Eventual sterile neutrino may be a good DM representative.

Neutrino oscillations effects

❖ **Flavor Matter Oscillations** corresponding to the regions favored by the atmospheric and solar neutrino data establish an equilibrium between active neutrino species before BBN epoch. No considerable influence on BBN, CMB, CNB.

Account for flavour oscillations : 113 per cubic cm instead 112 in SCM.

❖ **Active-sterile oscillations** may have considerable cosmological influence!

✓ BBN with fast $\nu_a \leftrightarrow \nu_s$: $H \sim \sqrt{g_{eff} G} T^2$ increase $g_{eff} = 10.75 + \frac{7}{4}\delta N_s$ $\delta N_s = N_\nu - 3$

effective before ν_a decoupling - effect BBN and CMB

He-4 mass fraction is a strong function of the effective number of light stable particles at BBN epoch $\delta Y_d \sim 0.013\ \delta N_s$ (the best speedometer). δN_s

✓ BBN with $\nu_a \leftrightarrow \nu_s$ $\delta m^2 \sin^4 2\theta \leq 10^{-7}$ ν_e spectrum distortion

effective after ν_a decoupling and $\delta N_s < 1$ BBN, CNB effect

Effect both expansion rate and the weak interactions rates, may distort ν_e energy spectrum, causing ν_e depletion, neutrino-antineutrino asymmetry generation and influences the neutrino involved processes in Universe, like BBN Kinetics, CMB, etc.

He-4 depends also on the ν_e characteristics $\Gamma \sim G_F^2 E_\nu^2 N_\nu$

decrease $\rightarrow$ n/p freezes earlier $\rightarrow$ ^{4}He is overproduced

Dolgov 81. DK 88, Barbieri, Dolgov 90, Kainulainen 91, Enqvist et al.,92, Foot&Volkas 95,96; D.K&Chizhov,96-98,2000-01, Dolgov&Villante 03; DK 04, DK&Panayotova 06, DK 07,08

Neutrino oscillations indications

Evidence for neutrino mixing and oscillations were obtained at the greatest neutrino experiments. Solar neutrino problem, atmospheric neutrino anomaly and the positive results of terrestrial experiments were resolved by the phenomenon of neutrino oscillations.

Recent analysis of global neutrino data within 3flavour framework: SKI+SKII+SKIII, MINOS, Kamland

Schwetz, Tortola, Valle, arXiv: 1103.0734; Mention 1101.2755

$$\delta m^2_{12} \sim (7.6 \pm 0.2) 10^{-5} eV^2, \sin^2\theta_{12} < 0.3$$

$$\delta m^2_{31} \sim (2.4 \pm 0.1) 10^{-3} eV^2, \quad 0.007 < \sin^2\theta_{13} < 0.03$$

$$\sin\theta_{23} \sim 0.5 \pm 0.06$$

Recent analysis 3+1 and 3+2 : Hint of oscillations with 2 ν_s with sub-eV mass

Reactor experiments+LSND+MiniBooNe+Gallium expt

Kopp, Maltoni,Schwetz, arXiv: 1103.4570

$$\delta m^2_{41} \sim 0.5 eV^2,$$

$$\delta m^2_{51} \sim 0.9 eV^2$$

Neutrino oscillations effect early Universe processes. Does cosmology allow 2 light ν_s?

Does cosmology favour non-zero ν_s ?

Excess radiation density

$$\rho_r = \rho_\gamma + \rho_\nu + \rho_x = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

ΔN_{eff} measures any relativistic component, including iner neutrino brought into equlibrium, oscillations, LA, decays, etc.

- ✓ Cosmological indications about the presence of additional relativistic density:

  N_{BBN}=3.8+0.8-0.7 N_{CMB}=4.34+/- 0.87 N_{SDS}=4.8+1.9-1.8

  WMAP7+BAO+HST Komatsu et al. 2011

  WMAP7+BAO+HST+ACT Keisler et al. 2011: 3.86+/-0.42 *+SPT Dunkley et al. 2011* 4.56+/-0.75

- ✓ Combined neutrino oscillations data (including MiniBoone and LSND):

  require 1 or 2 additional light sterile neutrino (in eq. before BBN),
  participating into oscillations with flavor neutrinos with higher mass differences values, than the ones required by solar and atmospheric neutrino oscillations experiments.

- ➢ Were these inert neutrinos brought into equilibrium by oscillations? Does cosmology allow them?

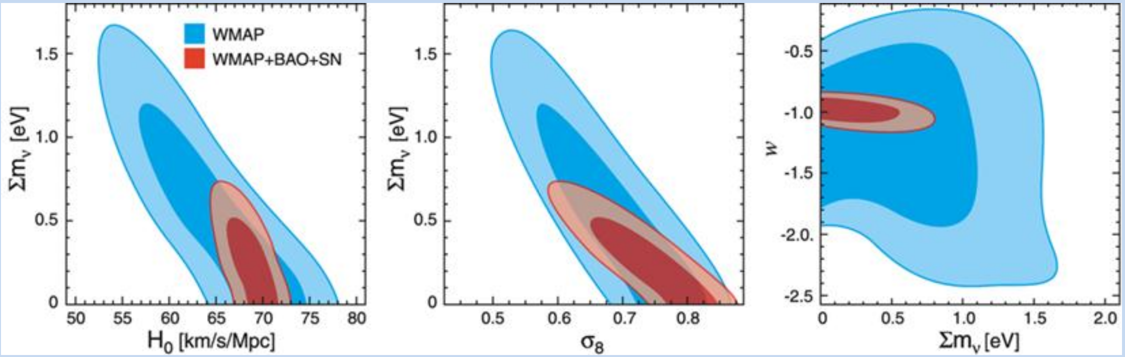
CMB, galaxy clustering and and SNIa data allow 3+2 models
BBN is more restrictive. Modfied BBN may be necessary.

The role of massive neutrino

- Contribution of neutrinos to total energy density today (3 degenerate masses)

$$\Omega_\nu = \frac{3m_0}{93.14h^2 \text{ eV}}$$

$$n_\nu = 339.3 \text{ cm}^{-3}$$



In case neutrino masses are in the eV range they can constitute several % of the DM, they can influence matter clustering (suppressing small-scale power of the matter power spectrum) providing better correspondence between models and observational data (from SDSS, cluster abundance, weak lensing, Lyman Alpha forest, CMB).

Fast moving neutrinos must not play any major role in the evolution of structure in the universe. They would have prevented the early clumping of gas in the universe, delaying the emergence of the first stars, in conflict with the new WMAP data.

How comparing the CMB and galaxy surveys constrains the neutrino mass:

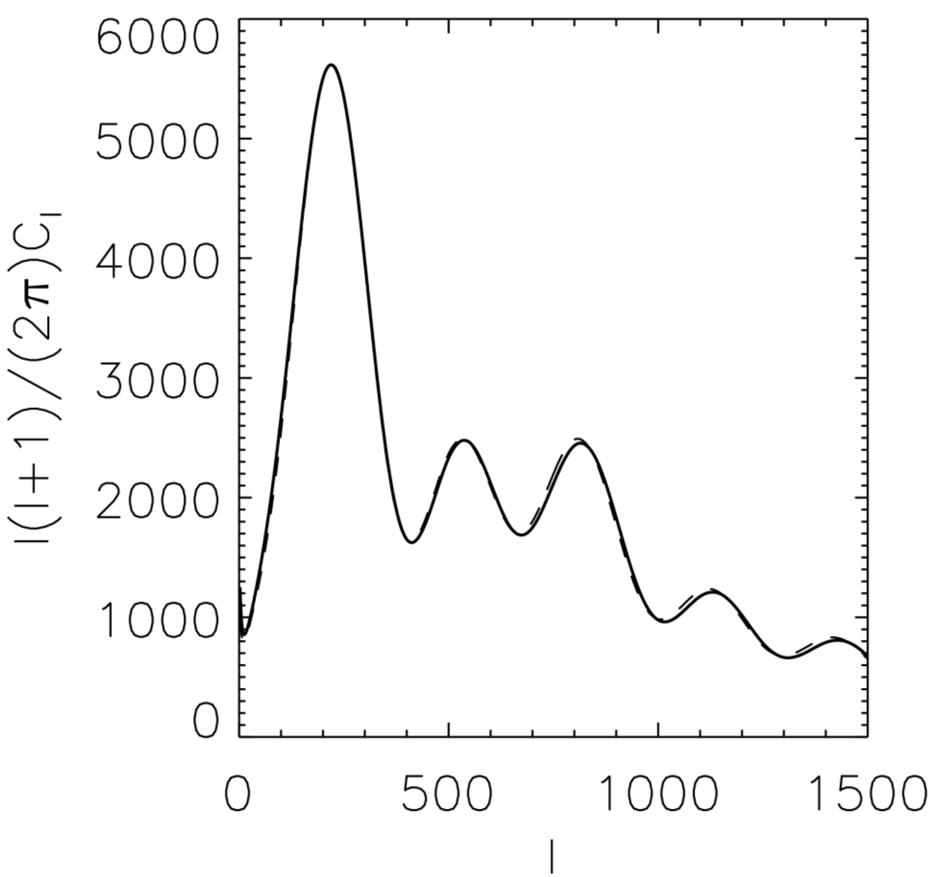
CMB +LSS: total neutrino mass < 0.6 eV

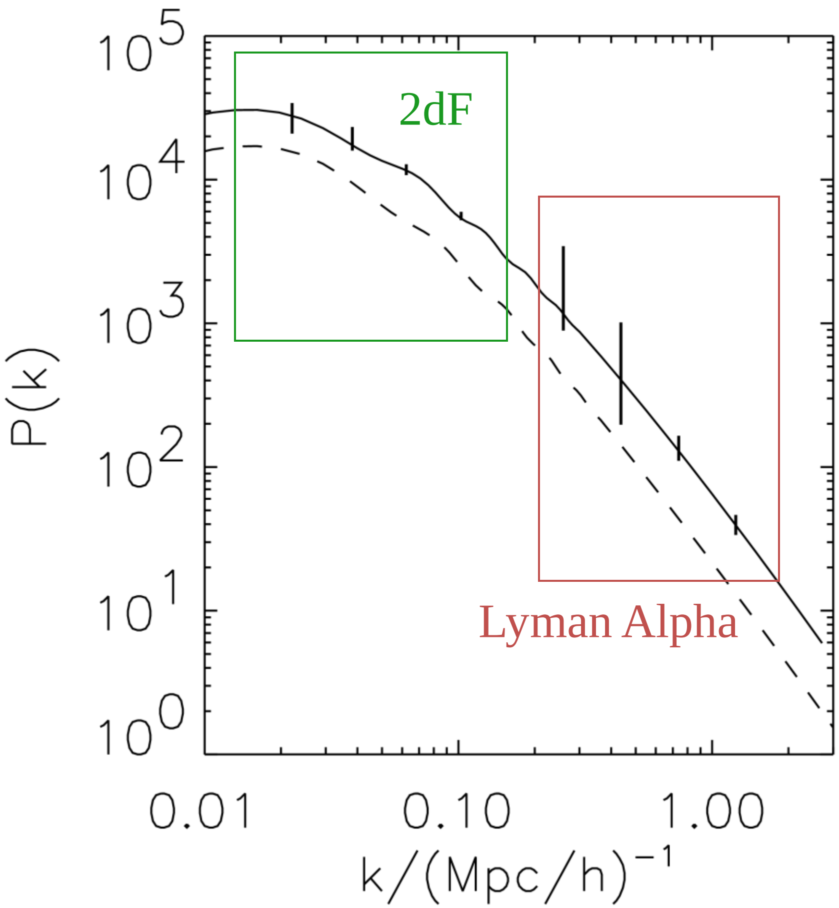
Massive neutrinos can hide in the CMB…

… but at low redshift they are no longer relativistic and have a big effect on galaxy clustering.

Solid: h=0.71 neutrino density=0

Dashed: h=0.60 neutrino density=0.02





Sterile Neutrinos Status

Wellcomed by cosmology:

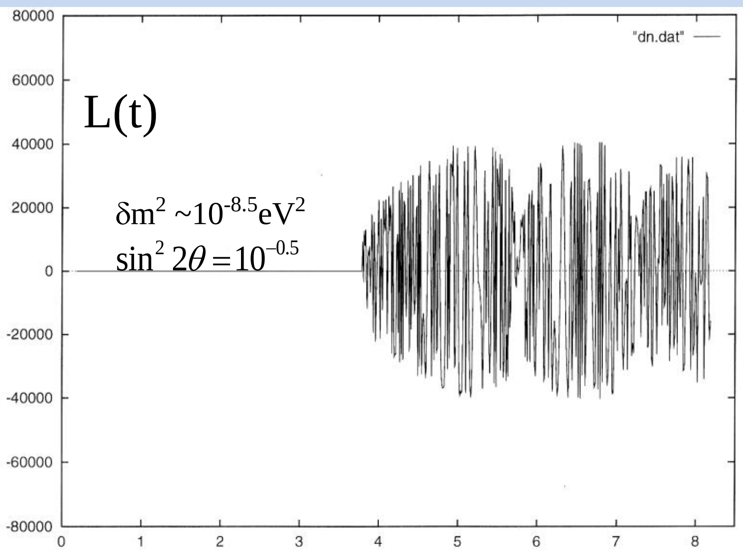
- may play subdominant role as DM component (eV, KeV)
- may play a role in LSS formation (when constituting few % of the DM it suppresses small scale power in the matter power spectrum and better fits the observational data from SDSS, cluster abundance, weak lensing, Lyman Alpha forest, CMB)
- plays major role in natural baryogenesis through leptogenesis
- The X ray photons from sterile neutrino decays may catalize the production of molecular H and speed up the star formation, causing earlier reionization – observational feature predicted
- CMB feels the increase in the density due to additional particles
- Sterile neutrino is constrained by BBN, because it increases the expansion rate and hence dynamically influences He production, in case it is brought into equilibrium. Its decoupling temperature must be $T_R > 130$ MeV.
- In case of oscillations with active neutrino it exerts major effect on nucleons kinetics during pre-BBN and its mixing parameters are constrained by BBN+CMB
- Et cetera…..

Oscillations generated LA and BBN

For $\delta m^2 \sin^4 2\theta < 10^{-7} eV^2$ evolution of LA is dominated by oscillations and typically LA has rapid oscillatory behavior.
The region of parameter space for which large generation of LA is possible:

$$|\delta m^2| \sin^4 2\theta \leq 10^{-9.5} eV^2$$

Generation of LA up to 5 orders of magnitude larger than β is possible, i.e. $L \sim 10^{-5}$



DK, PNPP,2010; 2011

❖ In BBN with $\nu_e \leftrightarrow \nu_s$ neutrino spectrum distortion and asymmetry generation lead to different nucleon kinetics, and modified BBN element production.

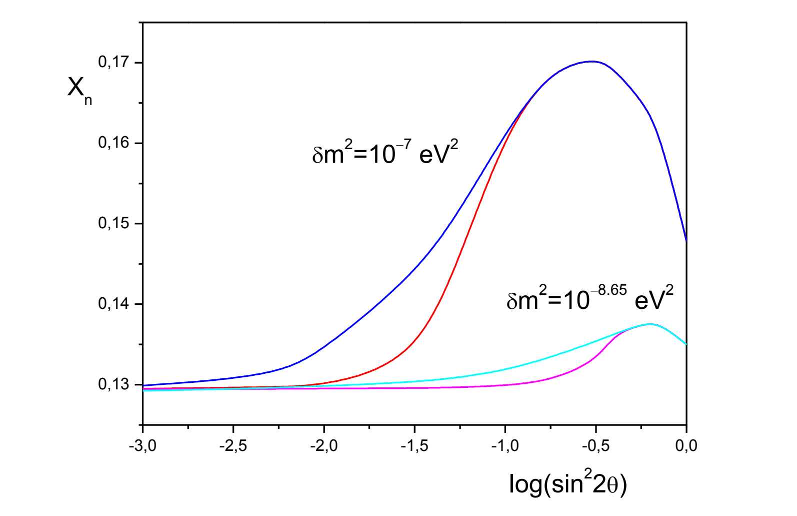
$$\frac{\partial n_p}{\partial t} = Hp_n \frac{\partial n_n}{\partial p_n} + \int d\Omega(e^-, p, \nu) \left| A(e^- p \to \nu n) \right|^2 (n_{e^-} n_p - n_n \rho_{LL})$$

$$- \int d\Omega(e^+, p, \tilde{\nu}) \left| A(e^+ n \to p \tilde{\nu}) \right|^2 (n_{e^+} n_n - n_p \bar{\rho}_{LL})$$

$$\delta m^2 \leq 10^{-7} eV^2 \qquad all\ mixing\ angles\ \theta \qquad 0 \leq \delta N_s \leq 1$$

$$2\ MeV \geq T \geq 0.3\ MeV$$

X_n and correspondingly the primordially produced He-4 decreases at small mixing parameters values due to asymmetry growth.



Primordial Nucleosynthesis

George Gamow

1904 – 1968

In 1946–1948 develops BBN theory.
In the framework of this model
predicts CMB and its T.

Big Bang Nucleosynthesis

Theoretically well established
Precise data on nuclear processes rates
from lab expts at low E (10 KeV – MeV)
Precise data on D, He, Li
Baryon fraction measured by CMB

COSMOLOGY

ASTROPHYSICS → **MICROPHYSICS**

Most early and precision probe for physical conditions
in early Universe and for new physics at BBN energies.

The Universe Baryometer
BAU – local or global
The Best Speedometer at RD Stage
BBN probes neutrino
BBN and neutrino oscillations
The Most Exact Leptometer

The Abundances of Light Elements

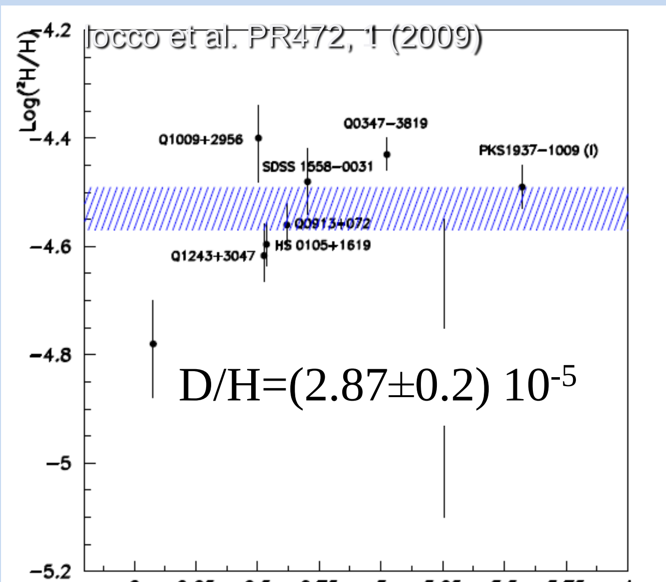
Main problem: Primordial abundances are not observed directly (chemical evolution after BBN).

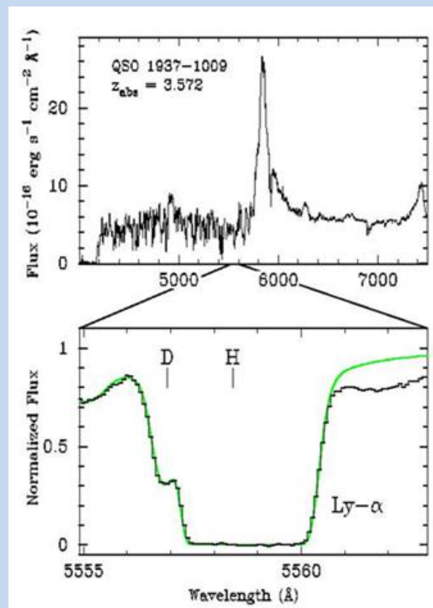
Observations

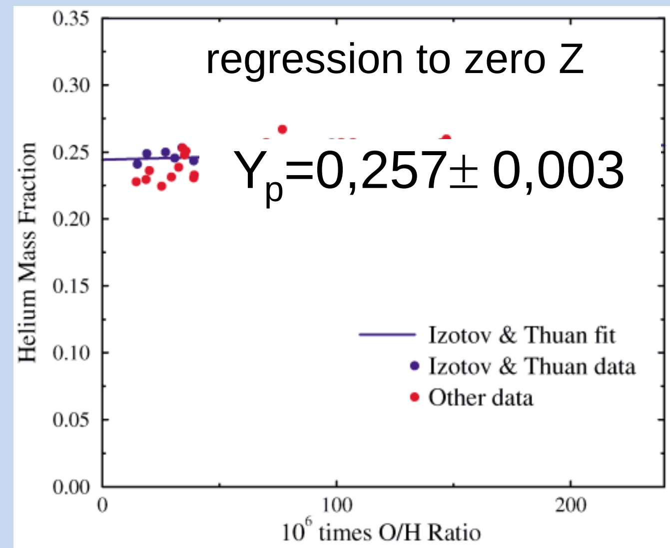
in systems least contaminated by stellar evolution.

- D is measured in high z low-Z H-rich clouds absorbing light from background QSA.

- He in clouds of ionized H (H II regions), the most metal-poor blue compact galaxies.







Account

for galactic chemical evolution

- Li in Pop II (metal-poor) stars in the spheroid of our Galaxy, which have $Z<1/10\,000\, Z_{\odot}$).

$$\mathrm{Li/H}|_{\mathrm{p}} = (1.7 \pm 0.02^{+1.1}_{-0}) \times 10^{-10}.$$

Determinations of Primordial He-4

Small statistical error but large systematics (interstellar reddening, clouds T, e density):

$Y_p = 0.250 \pm 0.003$ *Iocco et al. PR472, 1 (2009)*

$Y_p = 0.2565 \pm 0.0010(\mathrm{stat}) \pm 0.0050(\mathrm{syst})$ *Izotov & Thuan 2010*

$Y_p = 0.2561 \pm 0.0108$ *Aver et al. 2010*

$Y_p = 0.2573 \pm 0.0033$ *Aver et al. 2011*

2001: Observations with Far Ultraviolet Spectroscopic Explorer provided first direct observations of primordial He.

CMB anisotropies sensitive to reionization, thus to baryons in form of He. But uncertainty, even with Planck, will be larger than the present systematic spread.

Density fluctuations in the intergalactic gas (H and He) grow under gravity's pull. The densest clumps form galaxies and QSA whose radiation reionizes the gas.

The FUSE observations were accomplished by collecting the light from a distant quasar, at 10 billion ly from Earth, for twenty days. Along the trajectory to Earth intervening clouds containing hot helium gas modified the quasar's light, He atoms absorb in the far-ultraviolet range of the spectrum. Simultaneous observations using Hubble Space Telescope showed the brightness of the quasar at longer ultraviolet wavelengths where the spectrum is unaffected by He.

According to BBN 4 light elements: D, He-3, He-4, Li-7 produced during the hot stage of the Universe evolution, 1 s – 3 m 1 - 0.1 MeV.

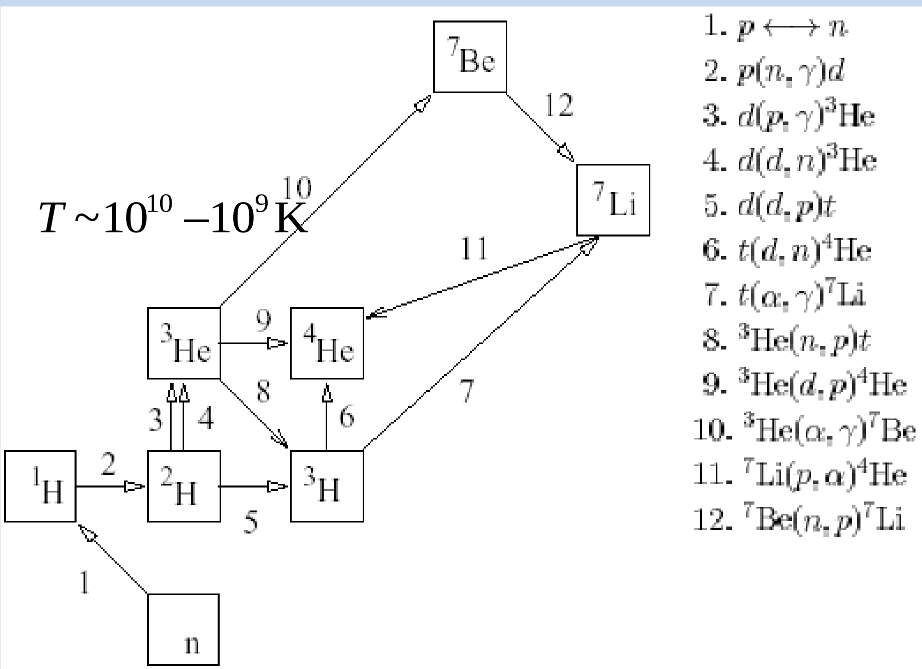
The primordially produced abundances depend on:

- ✓ baryon-to-photon ratio (CMB measured now),
- ✓ relativistic energy density (effective number of nu)

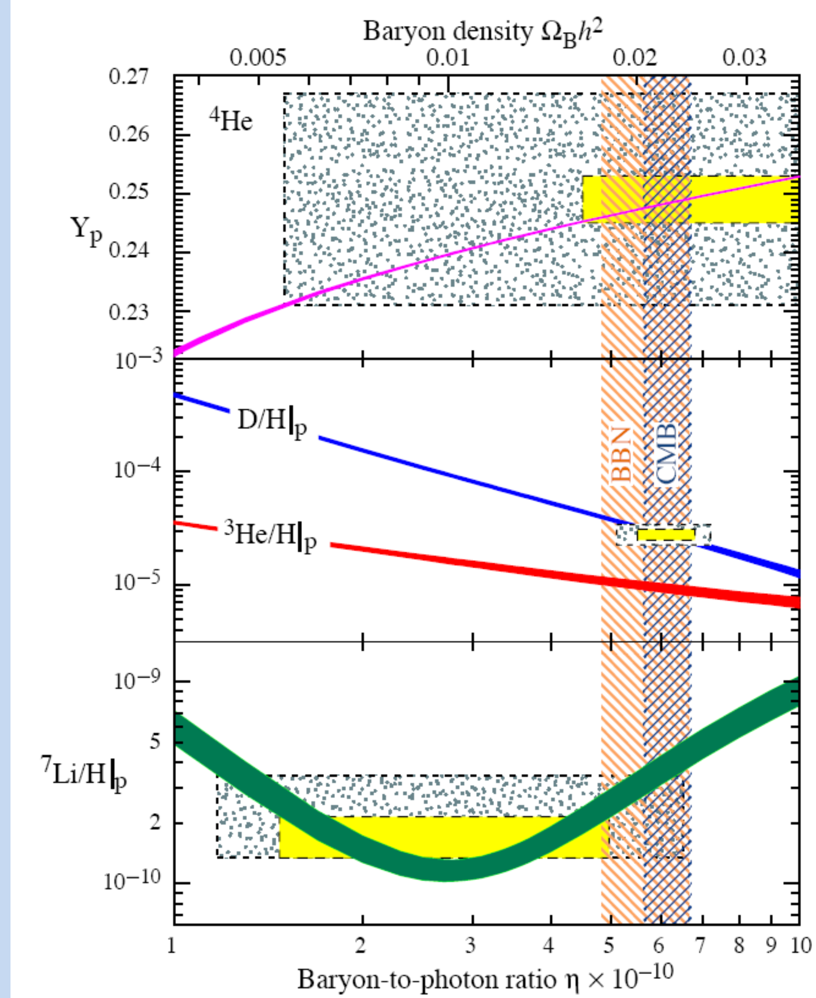
(nonst interactions, extra rel degrees of freedom, exotic physics)

$$\rho_\nu + \rho_X(?) \equiv N_\nu \; \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma$$

- ✓ n lifetime: 885.7±0.8; 878.5±0.8s *(Serebrov et al. 2005)*



$$H_0, \Omega_B, \Omega_\nu, N_{eff}, L, etc$$



Observational data in yellow (2σ statistical error), bigger boxes (2σ statistical+systematic error). Vertical band give baryon density measured by CMB and BBN.

BBN predictions are in agreement with observational data for $\Omega_B \sim 0.05$.

Solving numerically BBN dynamics

1. Weak interactions freeze out at T ~1 MeV
2. Deuterium forms via p n →D γ at T ~ 0.1 MeV
3. Nuclear chain

$$\frac{\dot a}{a} = H = \sqrt{\frac{8\,\pi G_N}{3}\,\rho}$$

$$\frac{\dot n_B}{n_B} = -\,3\,H \quad ,$$

$$\dot\rho = -\,3\,H\,(\rho + P) \quad ,$$

$$\dot X_i = \sum_{j,k,l} N_i \left(\Gamma_{kl\to ij} \frac{X_k^{N_k}\,X_l^{N_l}}{N_k!\,N_l!} \,-\, \Gamma_{ij\to kl} \frac{X_i^{N_i}\,X_j^{N_j}}{N_i!\,N_j!} \right) \equiv \Gamma_i \quad ,$$

$$n_B \,\sum_j Z_j\,X_j = n_{e^-} - n_{e^+} \equiv L\left(\frac{m_e}{T}, \phi_e\right) \equiv T^3\,\hat L\left(\frac{m_e}{T}, \phi_e\right) \quad ,$$

$$\left(\frac{\partial}{\partial t} - H\,|\mathrm{p}|\frac{\partial}{\partial|\mathrm{p}|}\right) f_{\nu_\alpha}(|\mathrm{p}|,t) = I_{\nu_\alpha}\left[f_{\nu_e}, f_{\bar\nu_e}, f_{\nu_x}, f_{\bar\nu_x}, f_{e^-}, f_{e^+}\right] ,$$

•Run BBN code (PArthENoPE) to get $Y_P(N_\nu,\eta)$, $X_D(N_\nu,\eta)$ *Miele et al. 2011*

$$^2\mathrm{H/H} = 2.87^{+0.22}_{-0.21} \times 10^{-5}, \qquad \mathrm{Y}_p = 0.247 \pm 0.002_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}}$$

Neutrino decoupling can be computed independently of nuclear abundances

BBN Baryometer

$$\eta = n_b / n_\gamma \sim 6.10^{-10}$$

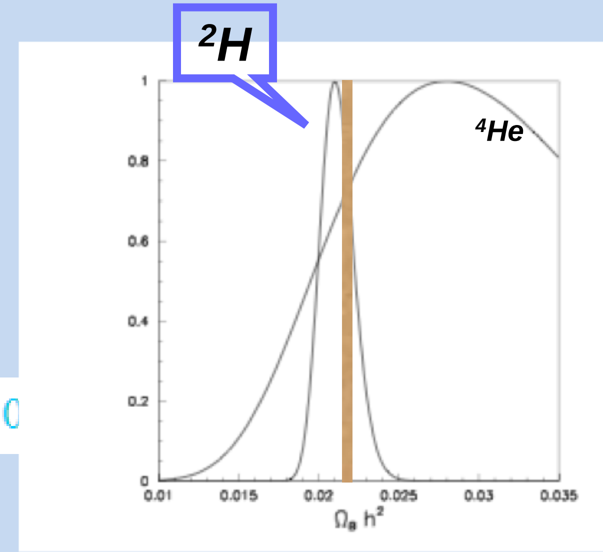
- The baryon density is measured with very high precision.
  Among light elements D is the best baryometer.
  BBN + D measurements: towards QSA with big z and low Z.

$$\Omega_b h^2 = 3.65\times10^7\eta,\quad \Omega_b = \frac{\rho_b}{\rho_c},\quad \rho_c = \frac{3H^2}{8\pi G_N}$$

$$\Omega_b h^2 = 0.021 \pm 0.001$$

$$\eta = (5.7\pm0.3)\times10^{-10}$$

$5.1 \times 10^{-10} < \eta_{BBN} < 6.5 \times 10^{-10}$ 95%



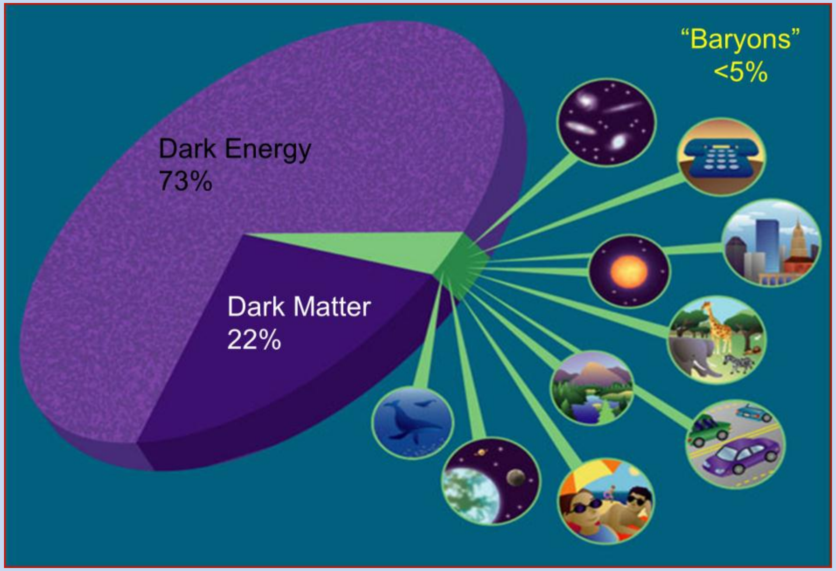
Iocco et al. 2009

- CMB anisotropy measurements-WMAP7: $\Omega_b h^2 = 0.0226 \pm 0.000$

$\eta_{WMAP}=6.16\pm0.16 \times 10^{-10}$ at 68% CL

Compatible at 1.5σ

Baryonic matter building the planets, the stars , etc. is a negligible fraction <5% !

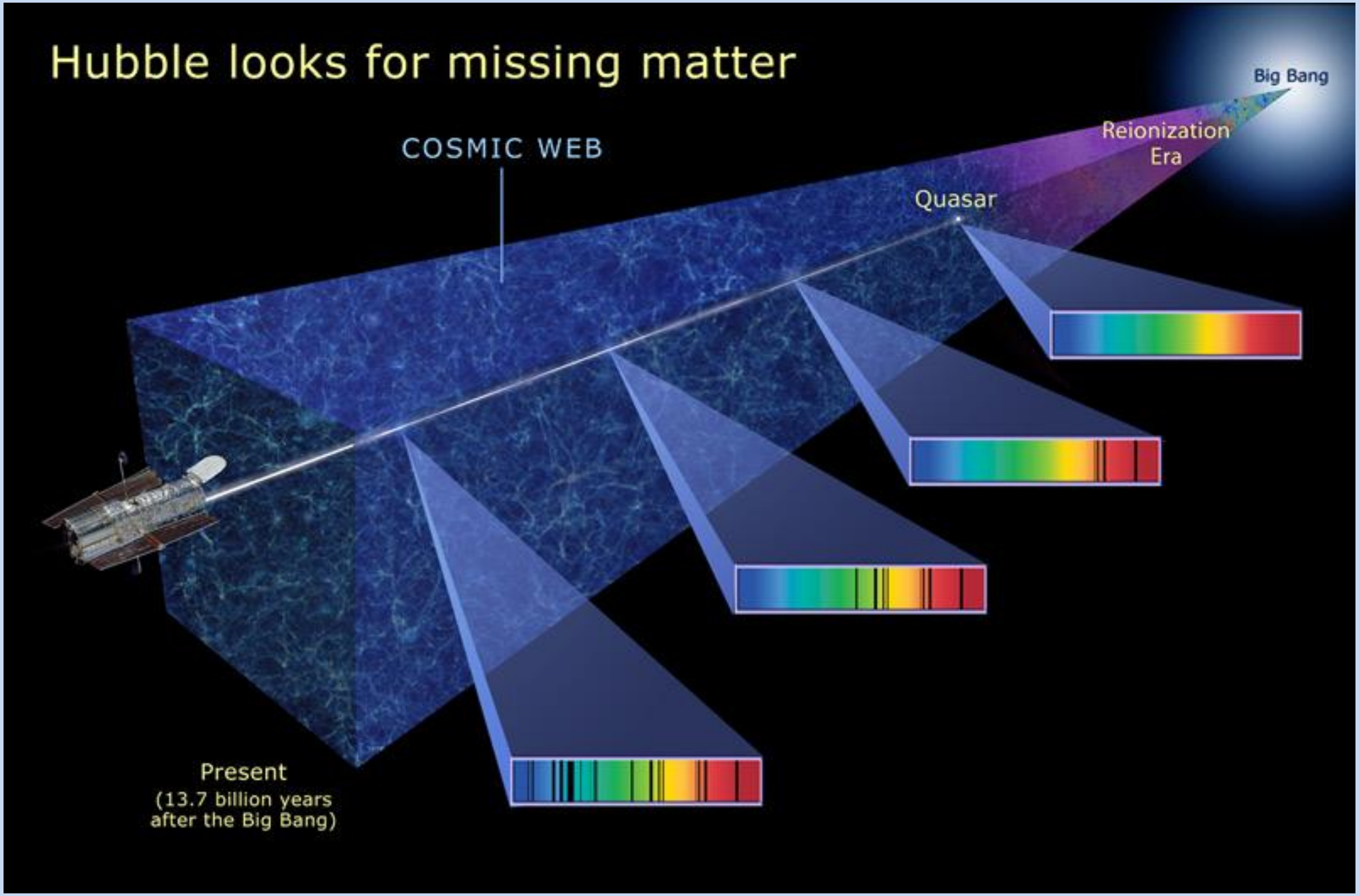


Baryon density is ~ 0.05 of the total density,
i.e. much bigger than the luminous matter (0.005),
but considerably less than the gravitating matter (0.3

Baryons are not enough to close the Universe.
Most of the baryons are optically dark.
There exists nonbaryonic DM.

Where are the dark baryons?

Half of the dark baryons are in the space between galaxies



In the spectra of the light from distant quasars (several billion ly away) the absorption lines of ordinary baryonic matter were found.

Where is the other half of dark baryons? MACHOS, BH,..

C. Danforth & M. Shull, ApJ, 2008

The analysis of HST FUSE observations taken along sight-lines to 28 quasars represents how the intergalactic medium looks within 4 billion ly of Earth.

Combined Results of Hubble ST + WMAP + clusters
BBN points to the existence of DM > baryon density.
What is nonbaryonic matter?

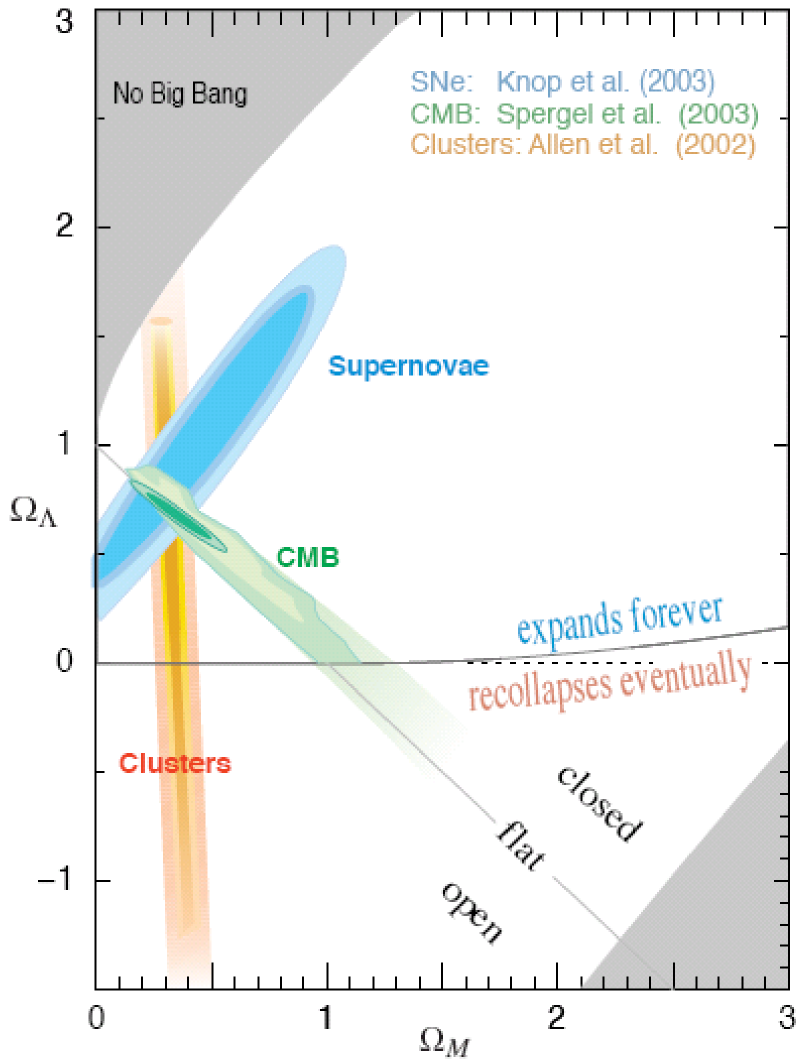


Figure 21.1: This shows the preferred region in the Ω_m–Ω_Λ plane from the compilation of supernovae data in Ref. 18, and also the complementary results coming from some other observations. [Courtesy of the Supernova Cosmology

Where are the antibaryons?

SBBN predicts equal quantities at the hot stage and now the relic density should be:

$$\beta \sim 10^{-18}$$

However $$\beta = (n_b - n_{\bar{b}})/n_\gamma \sim \eta = n_b / n_\gamma \sim 6.10^{-10}$$

Why baryon density is so big?

Where is the antimatter?

Is the asymmetry local or global?

How and when the asymmetry was produced? -baryogenesis models (GUT, SUSSY, BTL, SCB..) *Dolgov 99,2011; DK, 99; DK, NPB2002; DK, Panayotova, 2007*

If the symmetry is local what were the separation mechanisms? *Dolgov, DK 99; DK, Chizhov*

Missions searching for traces of antimatter: anti p, anti nuclei, annihilation radiation:

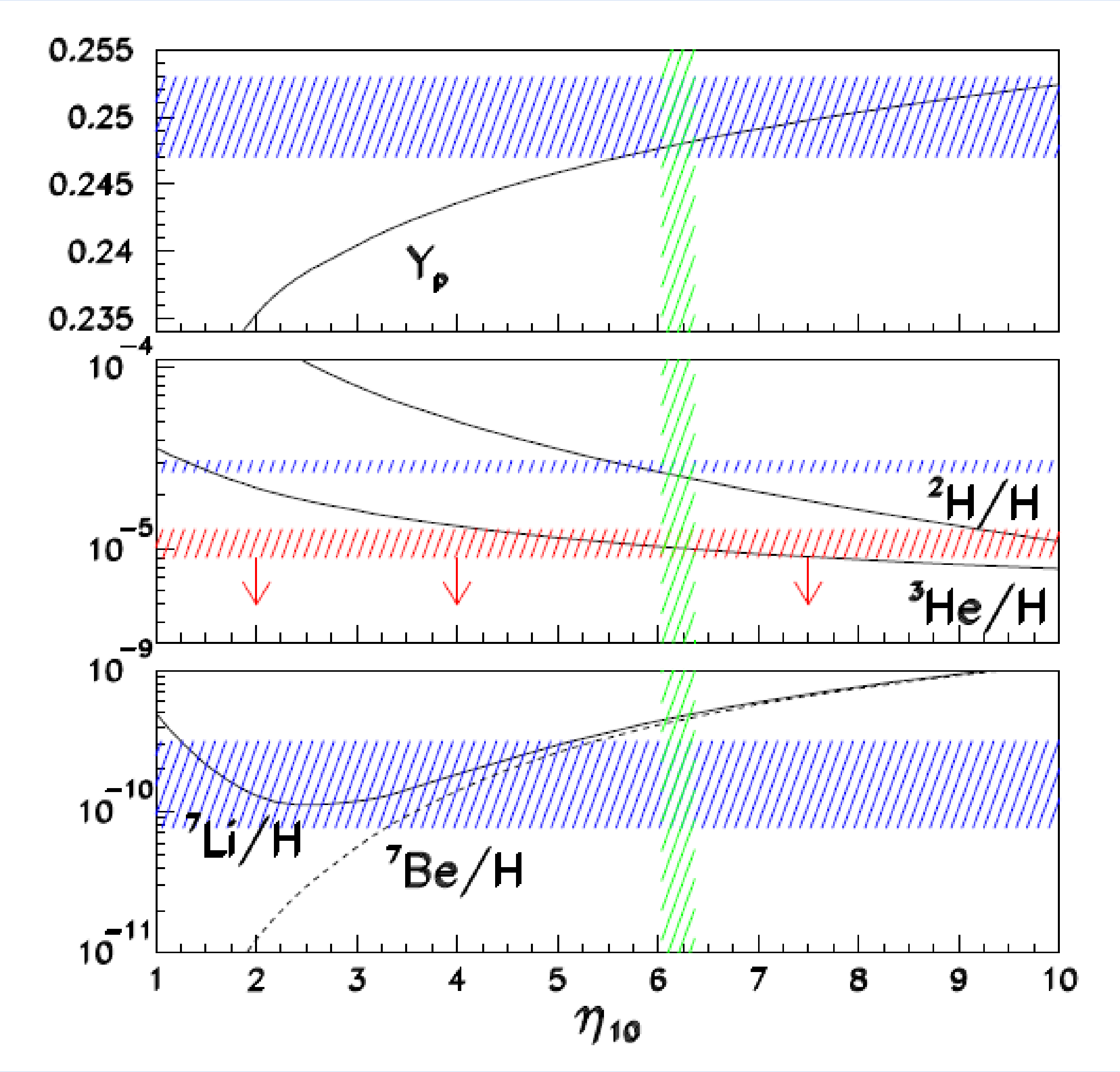
PAMELA, BESS, AMS, AMS 2, PEBS(2010), etc

- CR data from search of antip, positrons and antinuclei indicate that there is no significant quantity of antimatter objects within a radius 1 Mpc.
- Gama ray measurements significant amounts of antimatter up to galaxy cluster scales ~ 10 -20 Mpc.

Locally up to ~10-20 Mpc the Universe is made of matter. Steigman 79, Stecker 85

Both theory and observations allow astronomically significant antimatter .

BBN Speedometer



$2.8 \leq N_\nu \leq 3.6$ (95% CL)

Iocco et al, 2009

Using Y from IT10:

$3.0 \leq N_\nu \leq 4.5$ (95% CL)

^{4}He – the best speedometer

$Y_T = (H(\rho(g)), \Gamma) = 0{,}2482 \pm 0{,}0007$ $Y_o = 0{,}257 \pm 0{,}003$

- T > 1 MeV

$$\nu_e + n \leftrightarrow p + e^-$$
$$e^+ + n \leftrightarrow p + \tilde{\nu}_e$$
$$n \rightarrow p + e^- + \tilde{\nu}$$

$$\frac{n}{p} \sim e^{-\frac{\Delta m}{T}} \qquad \Delta m = 1.293 MeV$$

- T < 1 MeV

$$\Gamma \sim G_F^2 T^5 \qquad H \sim \sqrt{g_{eff} G} T^2 \qquad g_{eff} = \frac{11}{2} + \frac{7}{4} N_\nu = 10{,}75$$

$$T_f \sim \left(\frac{g_{eff} G}{G_F} \right)^{1/6} \sim 0{,}7 MeV \qquad \left(\frac{n}{p} \right)_f \sim e^{-\frac{\Delta m}{T_f}} \sim \frac{1}{6}$$

- T < 80 KeV

$$p + n \rightarrow D + \gamma \qquad D + D \rightarrow {}^4He + \gamma$$

$$(X_n)_f = \left(\frac{N_n}{N_{nuc}} \right)_f = \frac{\left(\frac{n}{p} \right)_f}{1 + \left(\frac{n}{p} \right)_f}$$

$$Y_p = 2(X_n)_f e^{-\frac{t}{\tau_n}} \sim 0.24 \qquad \tau_n = 885{,}7 s$$

He-4 most abundantly produced (25%), most precisely measured (3-5 %) and calculated element (0.1% error) with simple post-BBN evolution.

BBN – the best speedometer

- **Constrains the effective number of relativistic species**

$$\rho_r = \rho_\gamma + \rho_\nu + \rho_x = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_\gamma$$

$\delta Y_{KH} \sim 0.013\ \delta N_{eff}$

Non-zero ΔN_{eff} will indicate extra relativistic component, like sterile neutrino, neutrino oscillations, lepton asymmetry, neutrino decays, nonstandard thermal history, etc

$\Delta N_{eff} < 1.6$

$\Delta N_{eff} \sim 3$ (WMAP)

$\Delta N_{eff} \sim 0.4$ (Planck) (2 sigma)

- **Constrains chemical potentials**

$$\Delta N_{eff} = 15/7[([\mu/T)/\pi]^4 + 2[(\mu/T)/\pi]^2$$

ξ_e >0 favour n→p, causes He decrease

nu oscillations equilibrate ξ_e with other flavors for θ_{13}

Dolgov et al. 2002

$\xi < 0.07$ BBN + LMA

→ BBN restricts chemical potential of all neutrino flavors

- **Constrains sterile neutrino decoupling** T_R > 130 MeV **production, right handed bosons**

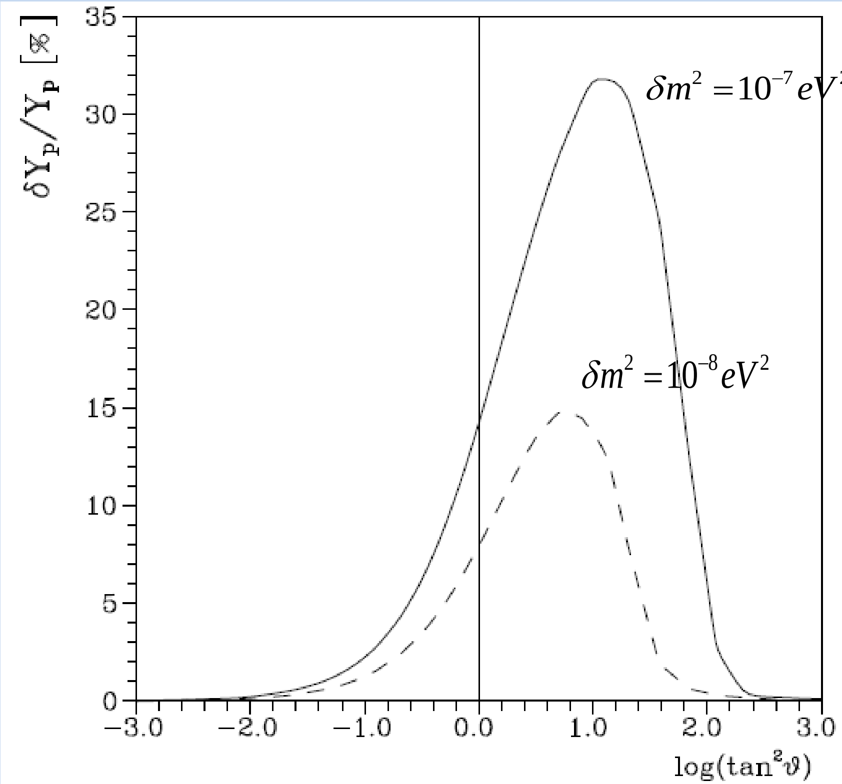
$$\frac{\Gamma_R}{H} = \left(\frac{T_R}{T_L}\right)^3 \left(\frac{G_T}{G_F}\right)^2 \sim 1; \quad G_T \le 10^{-2} G_F$$

- **Constrains neutrino magnetic moment** $\mu_\nu < 310^{-10}\mu_B$
- **Constrains neutrino oscillations parameters** BBN with $\nu \leftrightarrow \nu_s$ neutrino spectrum and densities differ, thus influencing kinetics of nucleons in BBN epoch, reducing weak processes rates overproducing He-4.

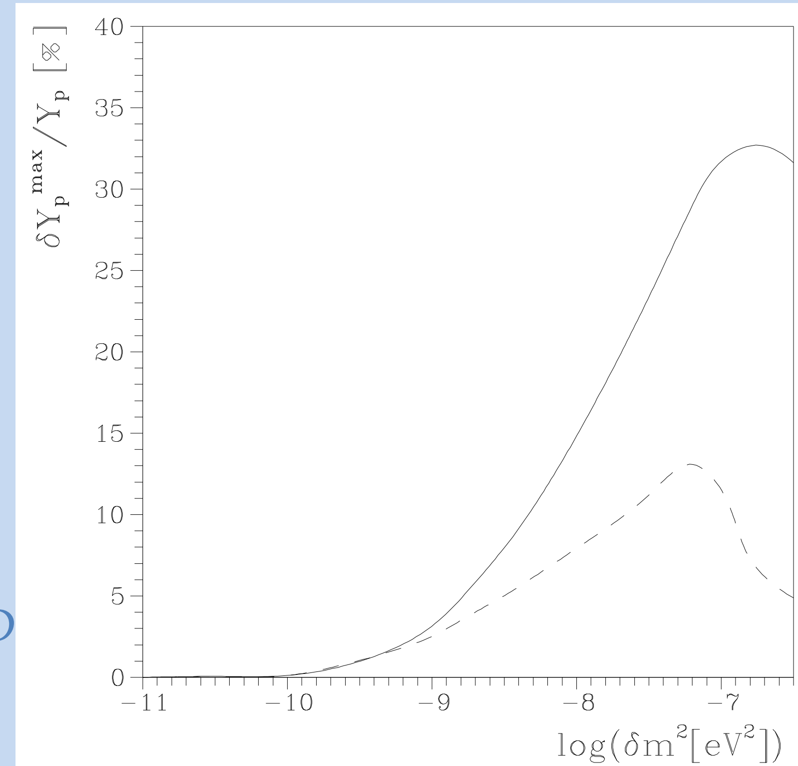
The abundance of helium is known with 5% accuracy. This allows to constrain $\nu \leftrightarrow \nu_s$

Maximum He-4 overproduction in BBN with oscillations due to spectrum distortion

Dependence of max overproduction on mixing



Max overproduction on mass difference



DK, Astrop.Phys.,2003

For BBN with $n_e \leftrightarrow n_s$ the maximal overproduction of ^{4}He is 32% in the resonant case and 13% in the non-resonant, i.e. 6 times stronger effect than the dynamical oscillations effect.

BBN with nonequilibrium $\nu_e \leftrightarrow \nu_s$ allows to constrain ν oscillation parameters for He-4 uncertainty up to32% (14%) in resonant (non-resonant) case.

BBN constraints on $\nu_e \leftrightarrow \nu_s$ oscillation parameters

He-4 is the preferred element:

✓ abundantly produced,

✓ precisely measured

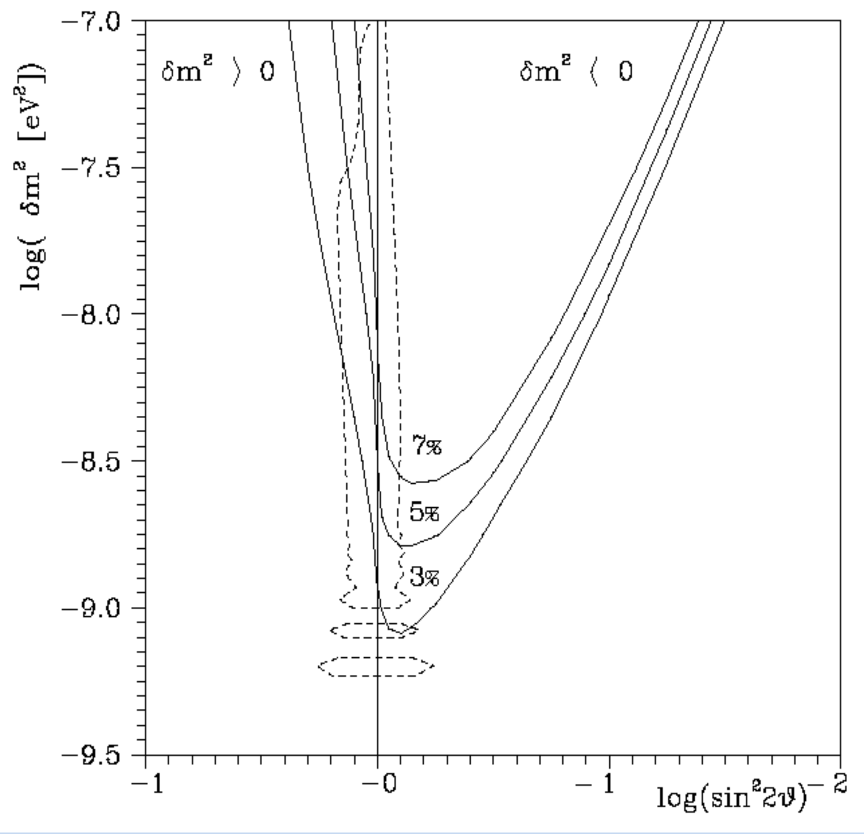
✓ precisely calculated (0.1% uncertainty)

Y_p=0,2482± 0,0007

✓ has a simple post-BBN chemical evolution

✓ best speedometer and leptometer

✓ sensitive to neutrino characteristics (n, N, sp,LA..)



Fit to BBN constraints ($\delta Y_p/Y_p$=3%) at smaller δm^2 (re-population of active neutrino slow, spectrum distortion considerable) :

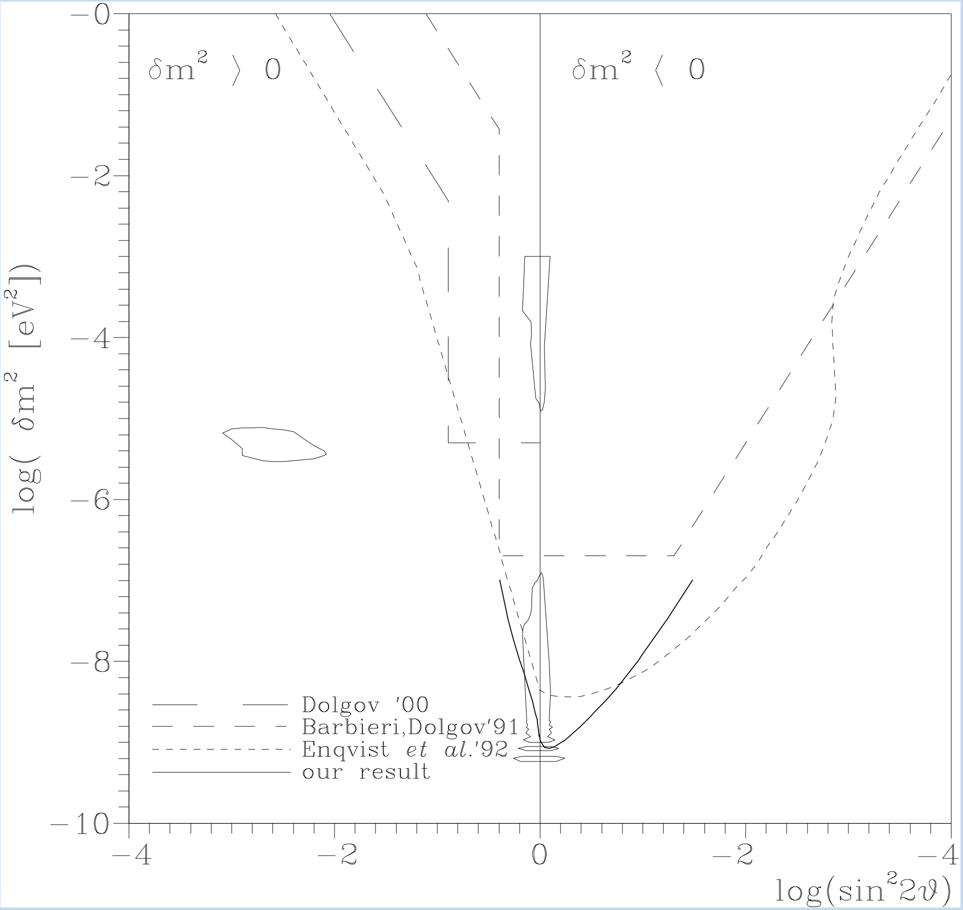
$$\delta m^2 \left(\sin^2 2\theta\right)^4 \leq 1.5\times 10^{-9} eV^2 \quad \delta m^2 > 0$$

DK, Chizhov NPB2000,2001

$$\delta m^2 < 8.2\times 10^{-10} eV^2 \quad \text{large } \theta,\ \delta m^2 < 0$$

BBN constraints on oscillations

BBN with neutrino oscillations between initially empty ν_s and ν_e



BBN constraints on $\nu_e \leftrightarrow \nu_s$:

Barbieri, Dolgov 91 – depletion account
Dolgov 2000 – dashed curve;
DK, Enqvist et al. 92 – one p approx.
Dolgov, Villante, 2003 - spectrum distortion

$\delta m^2 > 10^{-6}$ eV^2

$$\delta m^2_{es} \sin^4 2\theta_{es} \leq 3.16\times10^{-5} eV^2 \left(\Delta N_\nu\right)^2$$

$$\delta m^2_{\mu s} \sin^4 2\theta_{\mu s} \leq 1.74\times10^{-5} eV^2 \left(\Delta N_\nu\right)^2$$

$$\delta m^2 \sin^4 2\theta \leq 10^{-7}$$

DK.,Chizhov 2001 – distortion and asymmetry growth account

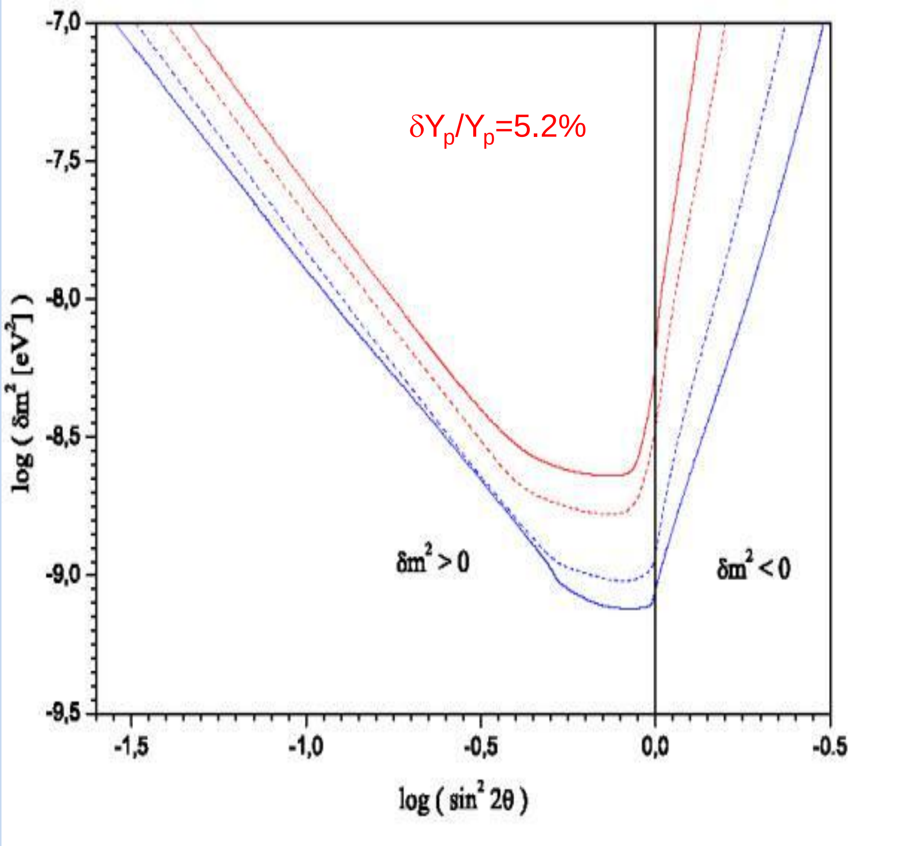
$$\delta m^2 \left(\sin^2 2\theta\right)^4 \leq 1.5\times10^{-9} eV^2 \quad \delta m^2 > 0$$

$$\delta m^2 < 8.2\times10^{-10} eV^2 \quad \text{large } \theta,\ \delta m^2 < 0$$

- ✓ BBN constraints are by 4 orders of magnitude more stringent than experimental ones
- ✓ Excluded 2 LMA and LOW active-sterile solutions (1990, 1999) years before experimental results.

BBN constraints relaxed or strengthened?

Additional ν_s population may strengthen or relax BBN constraints.



DK&Panayotova JCAP 2006;DK IJMPD 07

Y_p=0,2565 ± 0.001(stat)± 0,005(syst)

Izotov&Thuan, 2010 *93 Sp of 86 low Z HII*

✓Y_{th}=0,2482± 0,0007

Due to interplay b/n the effects of non-zero initial population of ν_s on BBN, BBN bounds change non-trivially with δN_s:

In case the dynamical effect dominates, He-4 overproduction is enhanced and BBN constraints strengthen.

In case the kinetic effect dominates He-4 overproduction decreases with δN_s increase and BBN constraints relax.

Dotted blue (red) contour presents $\delta Y_p/Y_p$=3% ($\delta Y_p/Y_p$=5.2%) for δN_s=0, solid - δN_s=0,5.

Cosmological constraint on new coupling constant

- Constrains sterile neutrino decoupling, new coupling constant strength

From $\Delta N_\nu < 1$ at BBN epoch, and entropy conservation, we can calculate T_R decoupling of right-handed neutrino production:

$$\left(\frac{g_*(T_R)}{g_*(T_L)}\right)^{4/3} > 3; \quad g_*(T_R) > 2.28 \times 10.75 = 24.5,$$

which corresponds to $T_R > 130$ MeV. On the other side T_R depends on G_T :

- (in case of 3 light right-handed neutrinos) $$\frac{\Gamma_R}{H} = \left(\frac{T_R}{T_L}\right)^3 \left(\frac{G_T}{G_F}\right)^2 \sim 1; \quad G_T \leq 10^{-2} G_F$$

DK&Chizhov, 2009

Lepton Asymmetry

Lepton asymmetry of the Universe

$$L = (n_l - n_{\bar{l}}) / n_\gamma$$

$$L = \sum_i \frac{1}{12\zeta(3)} \frac{T_{\nu_i}{}^3}{T_\gamma{}^3} (\xi_{\nu_i}^3 + \pi^2 \xi_{\nu_i})$$

$$\xi = \mu / T$$

may be orders of magnitude bigger than the baryon one, $\beta = (n_b - n_{\bar{b}}) / n_\gamma \sim 6.10^{-10}$

Though usually assumed $L \sim \beta$, big LA may reside in the neutrino sector (universal charge neutrality implies $L_e = \beta$) .

$$L \sim \sum_i L_{\nu_i}$$

CNB has not been detected yet, hence LA may be measured/constrained only indirectly through its effect on other processes, which have left observable traces in the Universe:

light element abundances from Big Bang Nucleosynthesis

Cosmic Microwave Background

LSS, etc.

BBN Leptometer

Lepton Asymmetry Effects

- Dynamical - Non-zero LA increases the radiation energy density

$$\Delta N_{eff} = 15/7((\xi/\pi)^4 + 2(\xi/\pi)^2)$$

$$\rho_r = \rho_\gamma + \rho_\nu + \rho_x = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

leading to faster expansion $H=(8/3\pi G\rho)^{1/2}$, delaying matter/radiation equality epoch …

⇒ influence BBN, CMB, evolution of perturbations i.e. LSS

Lesgourgues&Pastor, 99

$$\nu_e + n \leftrightarrow p + e^-$$

$$e^+ + n \leftrightarrow p + \tilde{\nu}_e$$

$$n \rightarrow p + e^- + \tilde{\nu}$$

- Direct kinetic - $|L_{\nu e}|> 0.01$ effect neutron-proton kinetics in pre-BBN epoch

⇒ influence BBN, outcome is L sign dependent

Simha&Steigman, 2008:

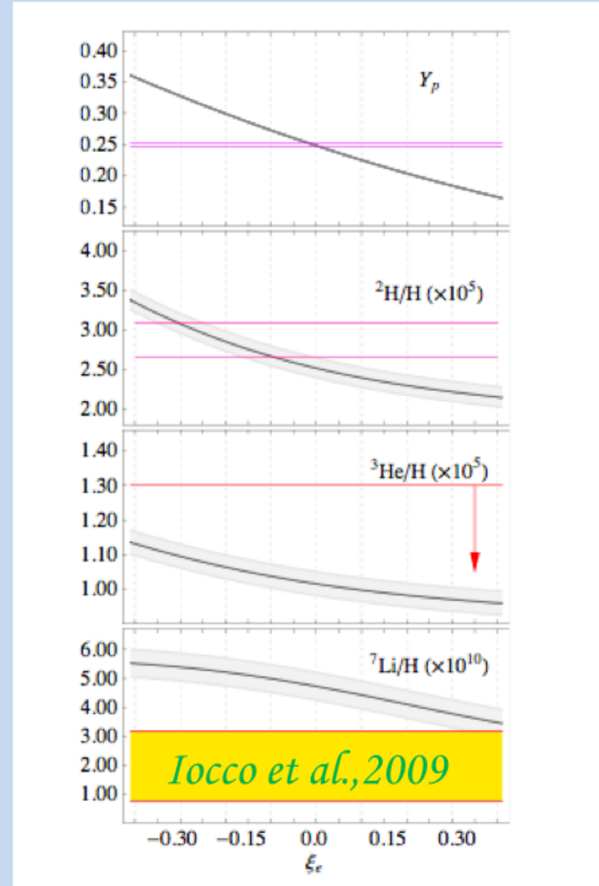
$$Y_p \sim (0.2482 \pm 0.0006) + 0.0016\eta_{10} + 0.013\Delta N_{eff} - 0.3\xi_{\nu_e}$$

- Indirect kinetic - $L \geq 10^{-8}$ effects neutrino evolution, its number density, spectrum distribution, oscillations pattern and hence n/p kinetics and BBN

DK&ChizhovNPB98,2000; DK PNPP, 2010, JCAP2012

- LA changes the decoupling T of neutrino

Lepton Asymmetry Constraints



❖ BBN provides the most stringent constraint on L in case of combined variation of chemical potentials

In case neutrino oscillations degeneracies equilibrate due to oscillations before BBN

$$|\xi_\nu| < 0.1$$

Dolgov et al., NPB, 2002

Serpico&Raffelt,2005

Iocco et al.,2009

$$-0.021 \leq \xi_\alpha \leq 0.005$$

Recent Y measurements and WMAP7 data relax the constraints:

$$-0.4 < \xi_{\nu e} < 0.12$$

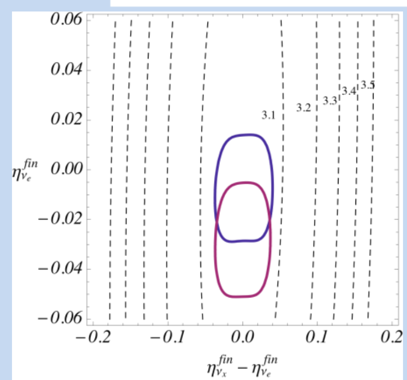
❖ Accounting for flavor oscillations and nu decoupling and $\sin^2\theta_{13} > 0.03$ $L < 0.1$

otherwise the bound may be relaxed for $\theta_{13} = 0$ $-0.7 < L < 0.6$

CMB and LSS provide much looser bounds

❖ Recent measurement $\theta_{13} > 0.1$ $|L| < 0.1$

→ extra d.o.f. during BBN !

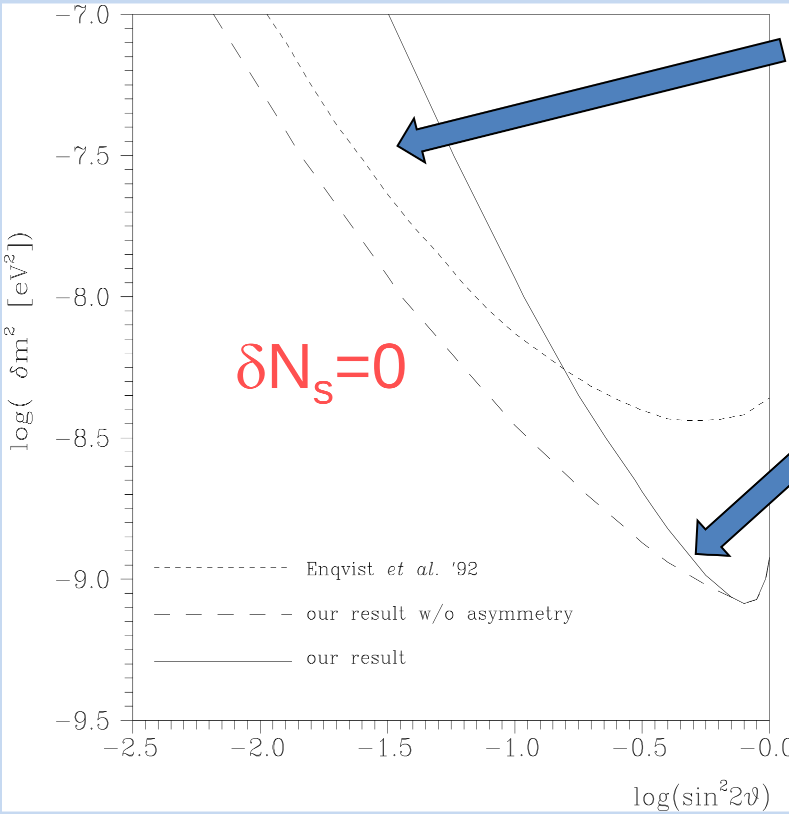


BBN with L and $\theta_{13} = 0$ allows $\Delta N < 1.4$

Mangano et al.,2011

Effects of neutrino-antineutrino asymmetry and distortion of spectrum

❖LA changes energy spectrum distribution and the number densities of ν_e from standard BBN case. This influences the kinetics of nucleons during BBN and changes the produced light element abundances.



❖ The account of the neutrino-antineutrino asymmetry growth caused by resonant oscillations leads to relaxation of the BBN constraints for small mixings.

❖ The spectrum distortion leads to a decrease of the weak rates, to an increase of the n/p freezing T and He overproduction. Correspondingly the account of spectrum distortion leads to strengthening of BBN constraints at large mixings.

Initial LA and BBN with oscillations

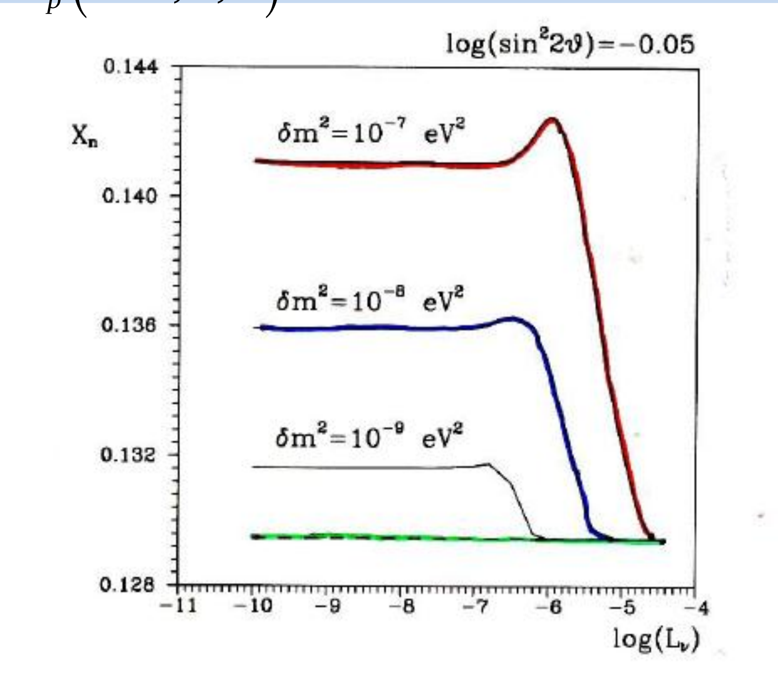
DK, JCAP2012

$L > 0.1(\delta m^2)^{2/3}$ suppresses oscillations

$L > (\delta m^2)^{2/3}$ inhibit oscillations.

L change primordial production of He
by enhancing or suppressing oscillations.

$Y_p\left(\delta m^2, \theta, L\right)$



LA may strengthen, relax or eliminate BBN constraints on oscillations.

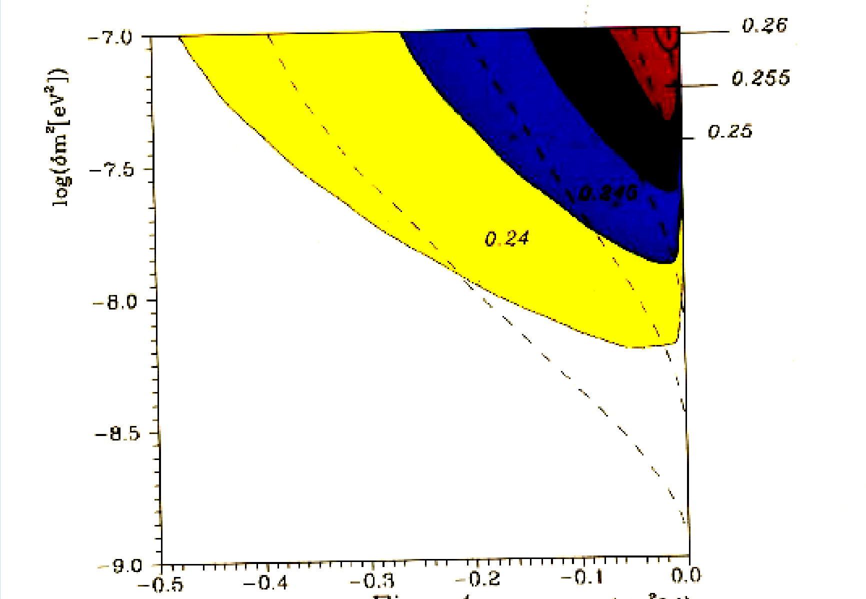


Fig. 4

Lepton asymmetry may relax BBN constraints at large mixings and strengthen them at small mixing.

DK&ChizhovNPB98

DK JCAP 2012

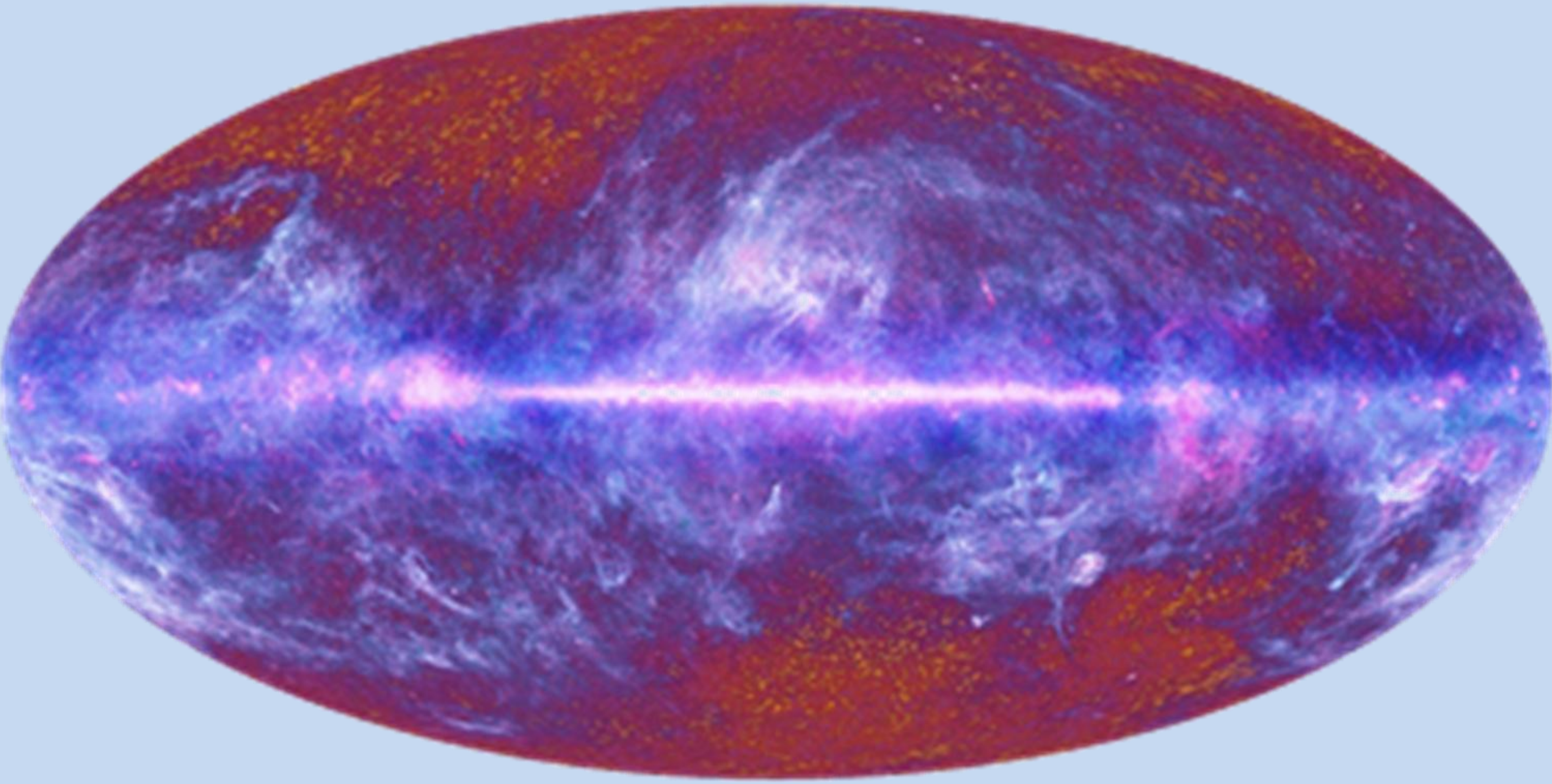
Cosmic Microwave Background

The direct evidence for the hot early Universe

Discovery
Formation of CMB
Characteristics
COBE, WMAP, Planck
Cosmological Parameters

$$H_0, q_0, \Omega_i(\Omega_0, \Omega_\Lambda, \Omega_M, \Omega_B, \Omega_\gamma, \Omega_\nu, \ldots), t_0, T_0, P(k), C_l$$

The sky as seen by Planck



Observational Milestones of Hot Big Bang Cosmology

- Homogeneity and isotropy and structures in the Universe
- The expansion of the Universe

$$H_0, \Omega_B, \Omega_\nu$$

- The abundance of the light elements
- The cosmic microwave background radiation

The cosmic microwave background radiation is the remnant heat left over from the Big Bang. It is an evidence for a hot early Universe.

Points to a flat LambdaCDM dominated Universe now.

$$H_0, q_0, \Omega_i(\Omega_0, \Omega_\Lambda, \Omega_M, \Omega_B, \Omega_\gamma, \Omega_\nu, \ldots), t_0, T_0, P(k), C_l$$

Исторически бележки

Теорията на Големия взрив предсказва горещ и плътен стадий на Вселената, на който в резултат от бързи взаимодействия на лъчението с веществото се установява ТДР.
В резултат на разширението на Вселената тя се охлажда. Днес тя е изпълнена с лъчение "космичен микровълнов фон", което е реликт от ранния горещ стадий.

- Още през 1940 някои измервания указват радиационно поле, необходимо за обяснение на преходите между енергетичните нива на междузвездни молекули (McKellar 1941)
- G. Gamov (1946) предсказва КМФ и пресмята неговата T. По-точно определяне на T се прави по-късно от неговите сътрудници Ralph Alpher и Robert Herman през1948-50.
- През 1964 Дорошкевич и Новиков предлагат област за детектиране на КМФ на базата на неговите характеристики.
- R. Dicke, P. Peebles, P. Roll, D. Wilkinson, (1964) Princeton University: подготвят експеримент за детектиране на КМФ.
- 1964 A. Penzias & R.Wilson детектират КМФ. *Нобеловата награда за 1978*
- След 1964 измервания с използуване на инструменти върху балони, спътници и наземни инструменти.
- РЕЛИКТ (1983-84), COBE (1989-93) – измерен Планковски спектър, детектиране на анизотропията. *2006 Нобелова награда* (G. Smoot, J.Mather)

CMB Formation

Big Bang theory predicts hot and dense early Universe and cooling as it expands. Thus it is filled with radiation that is the remnant heat left over from the Big Bang, called the "cosmic microwave background radiation", or CMB.

CMB first predicted by G. Gamow and collaborators R. Alfer and R. Herman in 1948.

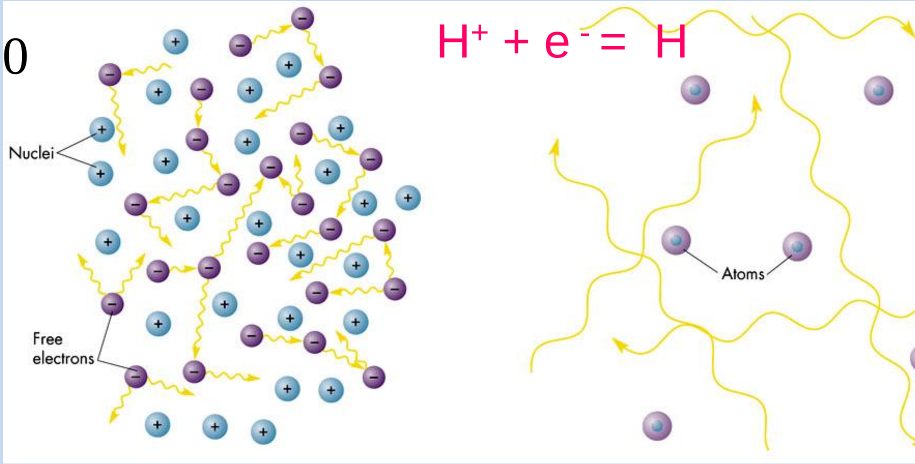
T>3000 K : thermodynamical equilibrium

Photons interact with electrons.

CMB photons easily scatter off electrons (Thompson scattering) . This process of multiple scattering and the electromagnetic interactions produced a blackbody spectrum of photons.

Sound waves: The radiation pressure - gravitation interplay lead to accustic oscillations, resulting in spatial variations of CMB T with time.

T=3000 K : Recombination 380,000 y, z=1100



The expanding Universe cools T~1/R(t) and nuclei capture electrons to form neutral atoms.

The radiation stops to interact.

The energy of photons decrease and is insufficient to ionize H, photons "decoupled" move through Universe essentially unimpeded.

Universe becomes **transparent** to radiation.

CMB emitted detectable now by radio telescopes.

The cooling blackbody radiation in an expanding Universe retains its blackbody form (Tolman 1934) .

Photon-baryon system stops oscillating at recombination. The modes caught in max represent the max in CMB power spectrum. Spatial variations of T are observed as angular variations.

CMB Detection and Characteristics

1964 A. Penzias & R.Wilson

detected noise in the radio antenna,
not dependent on the direction.

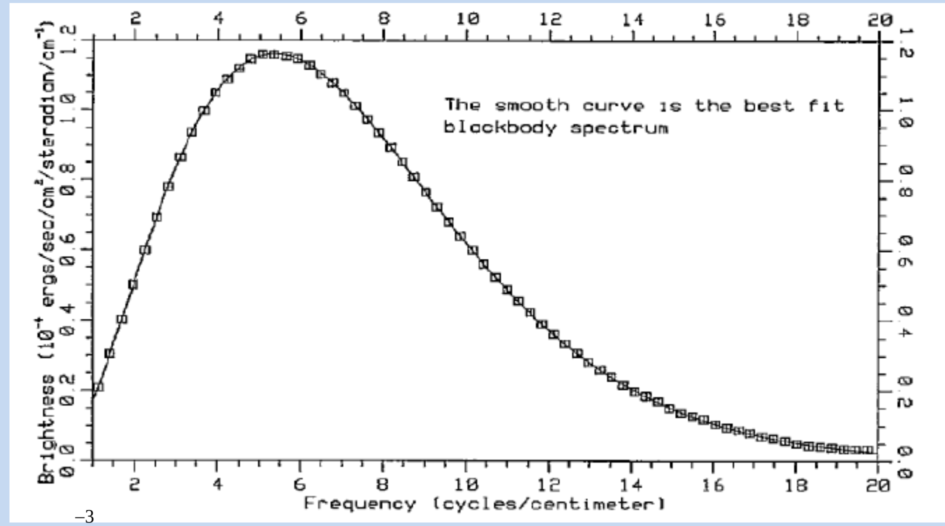
2.7 K blackbody

Isotropic (<1%)

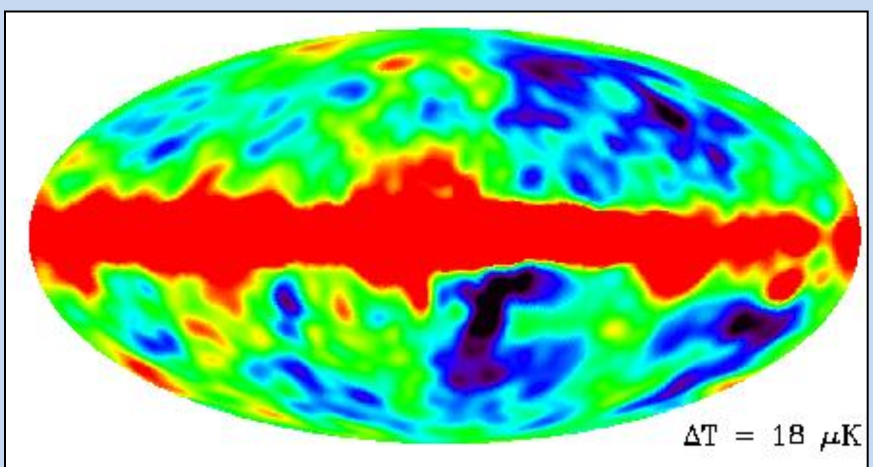
1970's and 1980's

3 mK dipole (local Doppler) due to
the Earth movements towards
Hydra Centaurus superclusters v=600 km/s.

$\delta T/T < 10^{-5}$



Maximum at 1 mm where the absorption of the atmosphere is big, hence studied by cosmic missions



RELIKT (1983-84) 1992: $\delta T/T \approx 5.10^{-6}$

COBE (1989-93) T= 2.725 K

WMAP T= 2.725 ± 0.001 K 411cm^{-3}

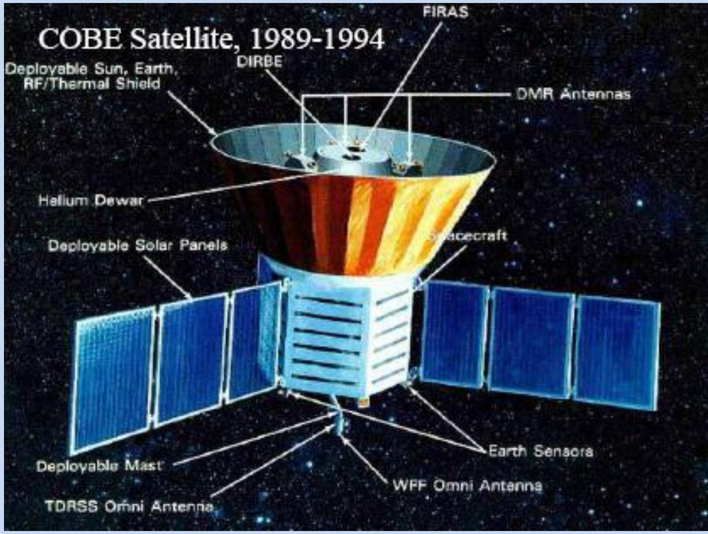
T fluctuations 13 ± 4 μK $\ell < 30 : \delta T/T \approx 10^{-5}$

2006 Nobel Prize in Physics (G. Smoot, J.Mather)

"for their discovery of the blackbody form and anisotropy of the Cosmic microwave background radiation"

Precise measurements of Universe characteristics: density, age, geometry, reionization , ...

COBE



COsmic Background Explorer 1989-94

COBE was launched November 18, 1989 and carried three instruments covering the wavelength range 1 µm to 1 cm to measure the anisotropy and spectrum of the CMB as well as the diffuse infrared background radiation

John Mather was the COBE Principal Investigator and the project leader from the start.

Diffuse Infrared Background Experiment to search for the cosmic infrared background radiation, Mike Hauser

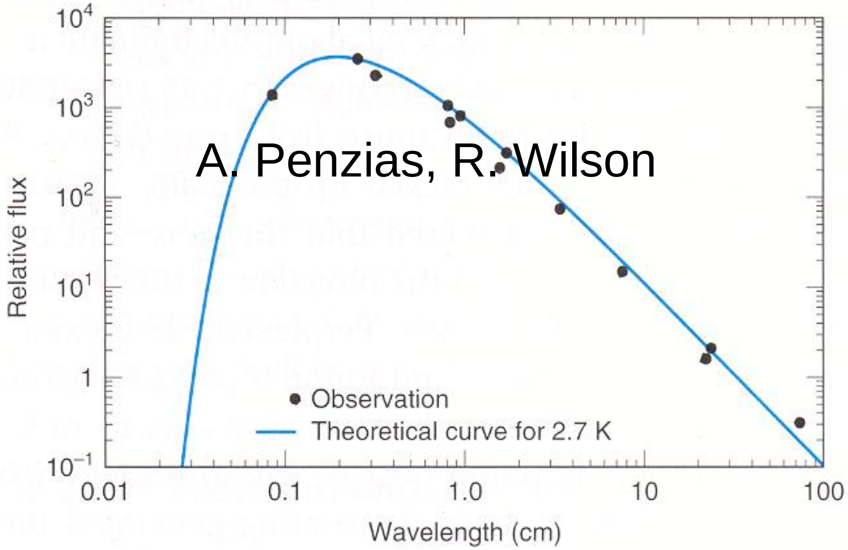
Differential Microwave Radiometers (DMR) to map the cosmic radiation sensitively principal investigator George Smoot
The objective was to search for anisotropies at three wavelengths, 3 mm, 6 mm, and 10 mm in the CMB with an angular resolution of about 7°.

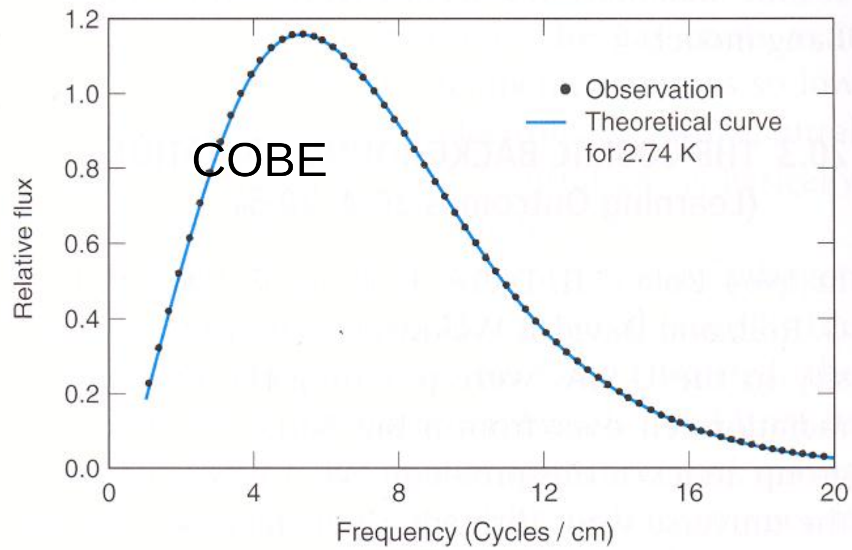
Far Infrared Absolute Spectrophotometer (FIRAS) to measure the spectral distribution of the CMB in the range 0.1 – 10 mm and compare it with the blackbody form expected in the Big Bang , John Mather

Characteristics: Blackbody Sp

T= 2.725 ± 0.001 K

411cm^{-3}



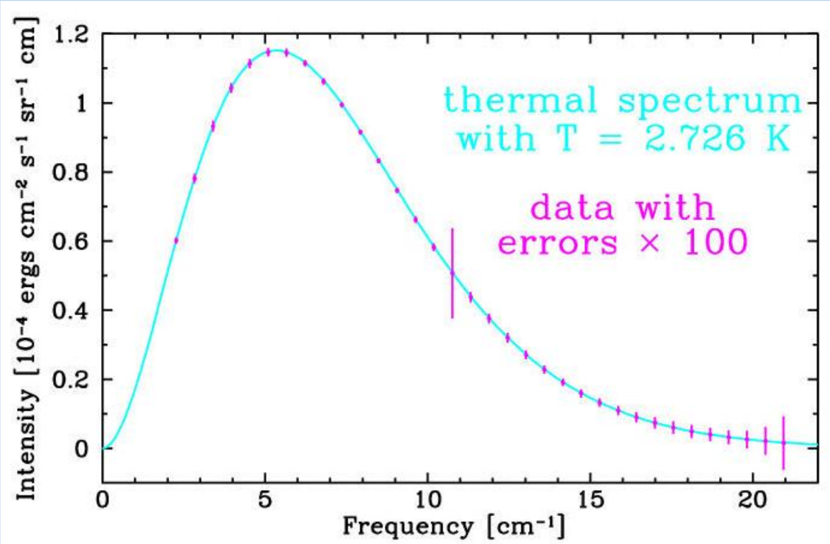


2.7 K bb sp with high isotropy (<1%)

The maximum is at 1 mm (the absorption of atmosphere).

CMB is a direct evidence for an early hot stage of the Universe:

The spectrum measured by COBE in the range 0.1 – 10 mm is extremely uniform, with less than 1 % deviation from that of a blackbody.
T= 2.725 ± 0.002 K

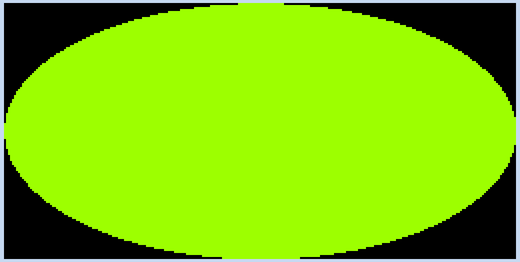


No alternative theory predicts this energy spectrum. The accurate measurement of its shape was another important test of the Big Bang.

WMAP : T= 2.725 ± 0.001 K
particle density of 411cm^{-3}
energy density 4.64 10^{-34} g/cm^3

CMB has the best recorded blackbody spectrum.

Properties of the CBR



- Isotropic, except for the motion of the earth

(together with the local cluster) towards Hydra

and Centaurus super-cluster with velocity of v=600 km/s.

dipole temperature anisotropy $dT/T = 10^{-3}$

(*Conklin 1969, Henry 1971, Corey and Wilkinson 1976 and Smoot, Gorenstein and Muller 1977*)

- Anisotropy: to explain LSS in the form of galaxies and clusters observed today, small anisotropies should exist.

$$\frac{\delta T}{T} \sim \frac{\delta\rho}{\rho}$$

$$\rho = \overline{\rho} + \delta\rho$$

1990 – first detected by РЕЛИКТ

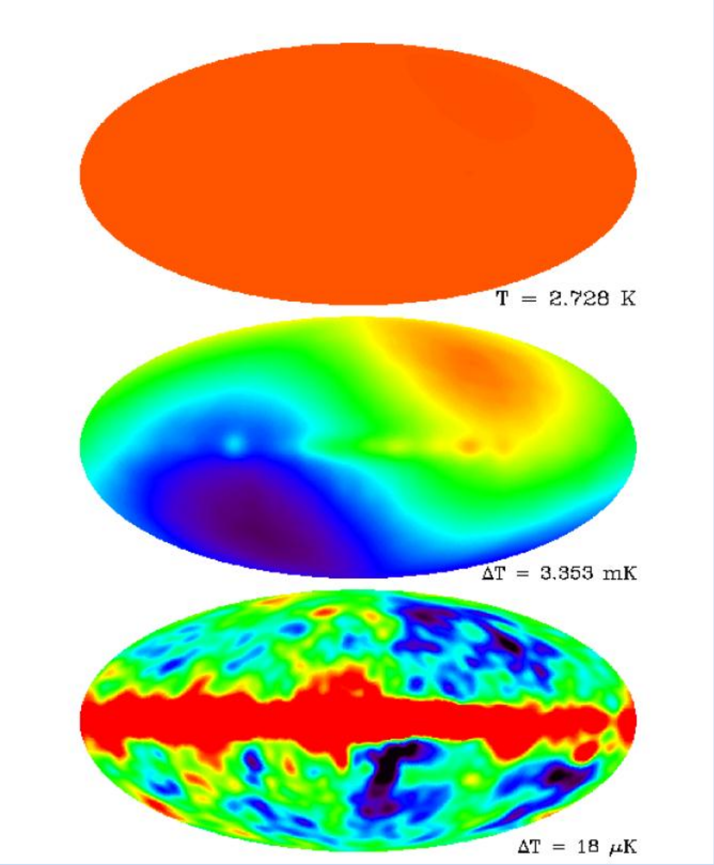
1992-- CMB Explorer at 90, 53 and 31.5 GHz (wavelengths 3.3, 5.7 and 9.5 mm), near the CMB intensity max and where the galactic background was low.

The RMS cosmic quadrupole amplitude was estimated at 13 ± 4 μK ($\Delta T/T = 5\times10^{-6}$) with a systematic error of at most 3 μK.

- Most models for structure formation predict that temperature variations have Gaussian distribution for large angles (corresponding to DMR measurements). In inflation models the Gaussian distribution originates from primordial quantum fluctuations.

COBE's DMR data showed Gaussian, near scale-invariant temperature fluctuations and support inflation models

DMR results: Isotropy and Anisotropy of CMB

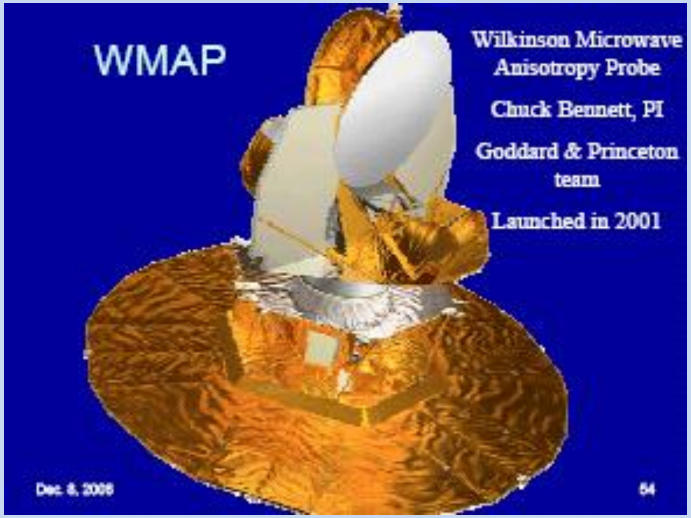


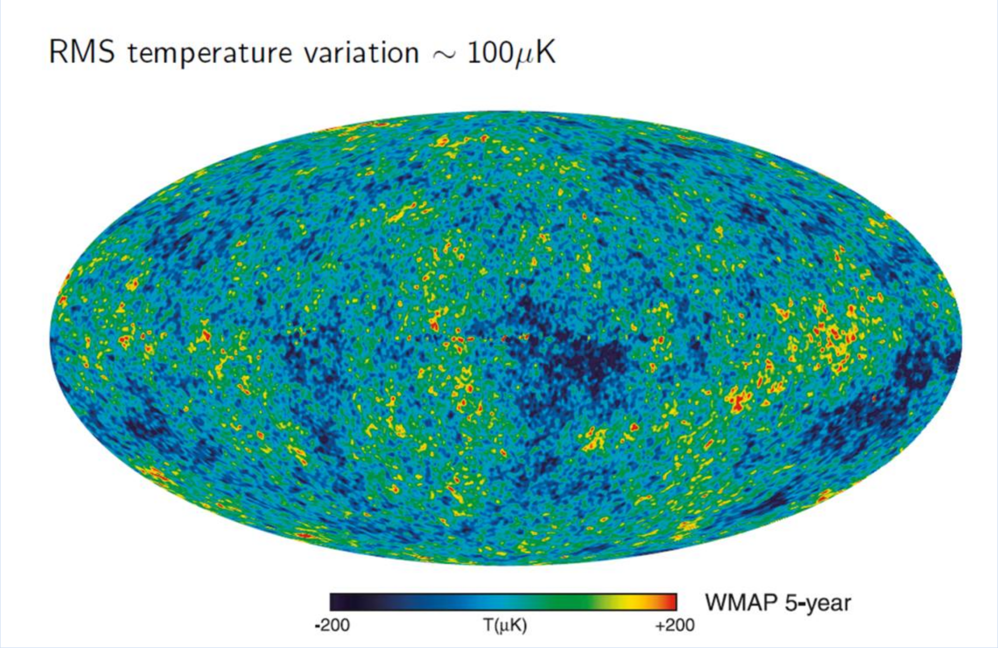
DMR results (Smoot et al. 1992, http://lambda.gsfc.nasa.gov/product/cobe/) in galactic coordinates

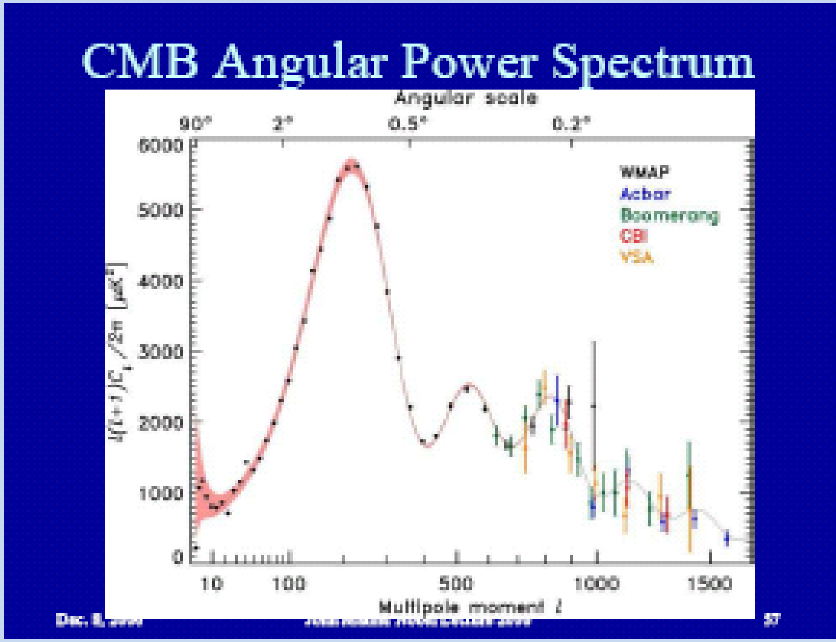
The data from the 53 GHz band (6 mm wavelength) showing the near uniformity of the CMB (top), the dipole (middle) and the quadrupole and higher anisotropies with the dipole subtracted (bottom). The relative sensitivities from top to bottom are 1, 100 and 100,000. The background from the Milky Way, not following a blackbody spectrum (visible as a horizontal red band in the bottom panel), has not been subtracted.

WMAP

COBE's results were confirmed by a number of balloon-borne experiments, and, more recently, by the 1° resolution WMAP (Wilkinson Microwave Anisotropy Probe) satellite, launched in 2001 (Bennett et al. 2003).



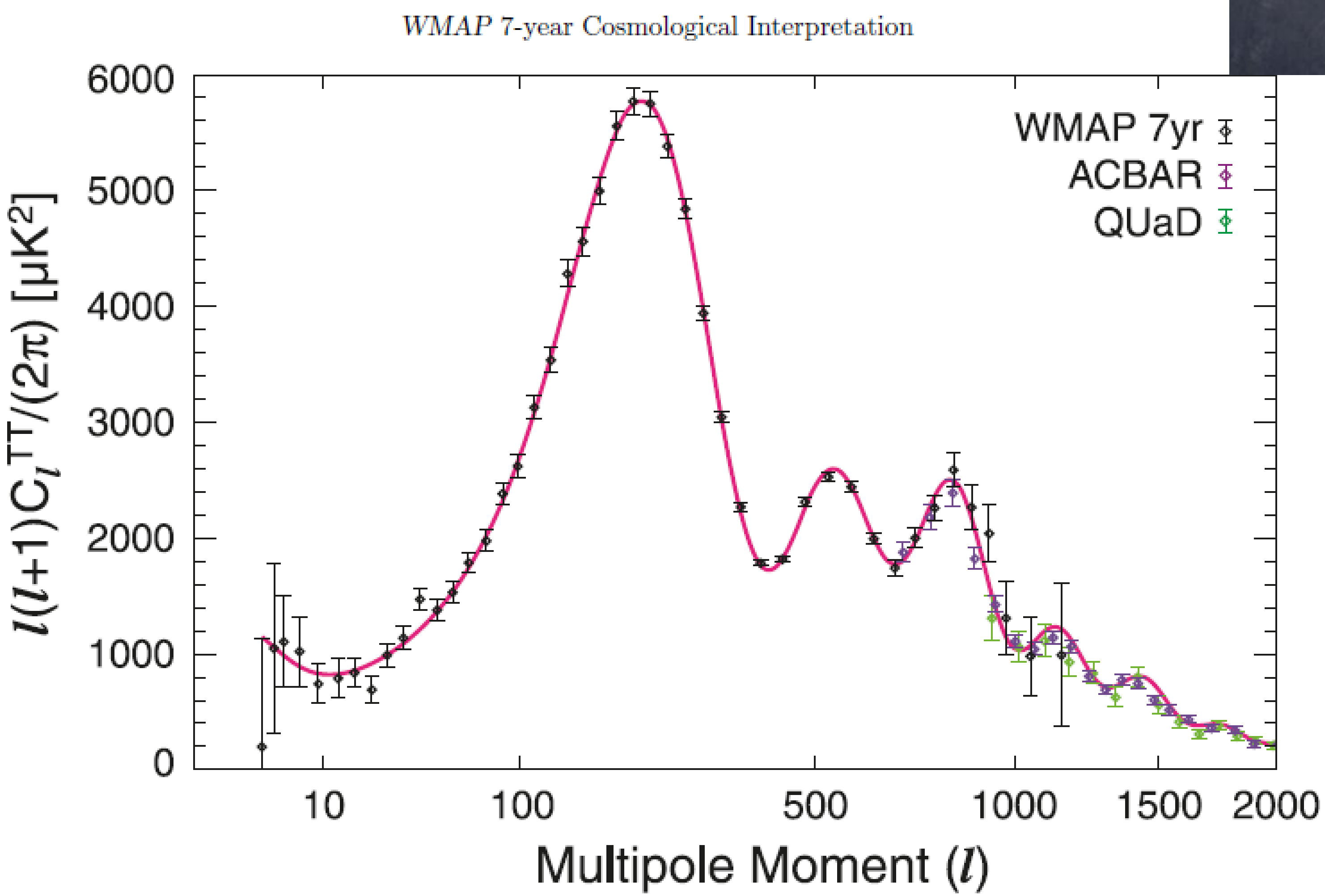




CMB Angular Power Spectrum

$$\frac{\Delta T}{T} = \sum_{lm} a_{lm} Y_{lm}(\theta, \phi)$$

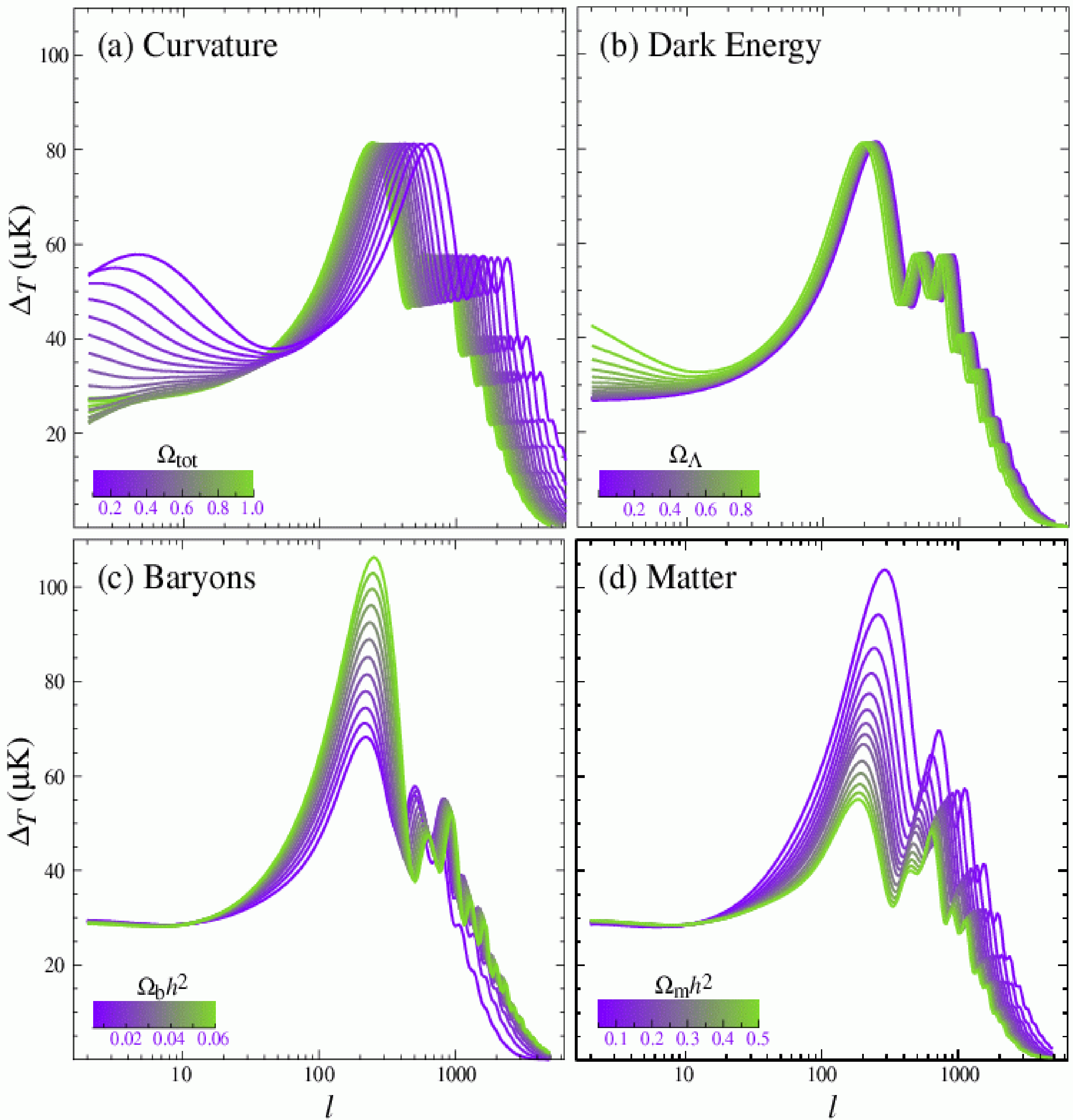
$$C_l = \langle |a_{lm}|^2 \rangle$$



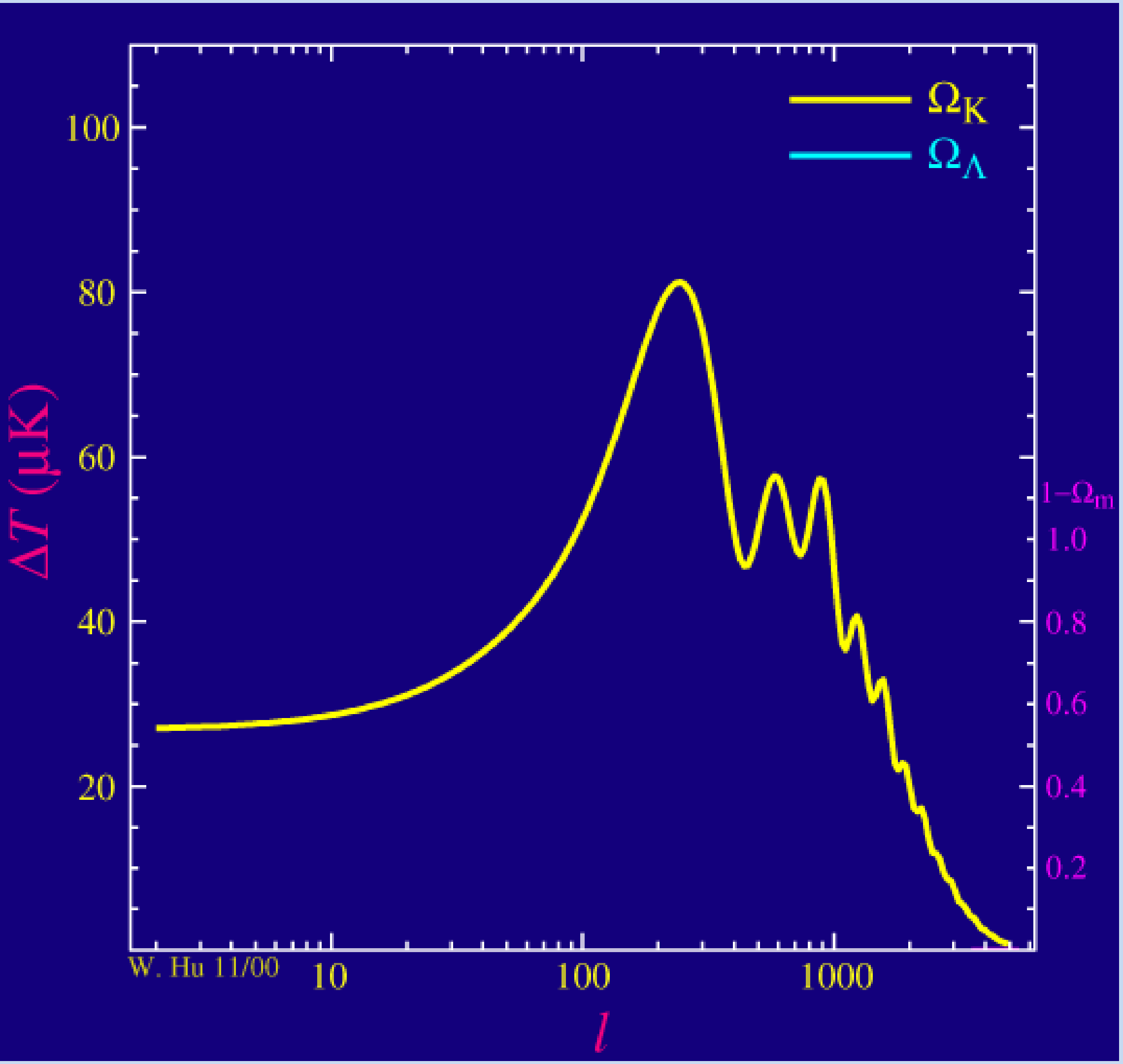
Location and height of acoustic peaks determine the values of cosmological parameters.

Relevant parameters

- curvature (e.g. open, flat, closed)
- dark energy (e.g. cosmological constant)
- amount of baryons (e.g. electrons & nucleons)
- amount of matter (e.g. dark matter)


(a) Curvature
(b) Dark Energy
(c) Baryons
(d) Matter
Δ_T (μK)
Ω_{tot}
0.2 0.4 0.6 0.8 1.0
Ω_Λ
0.2 0.4 0.6 0.8
$\Omega_b h^2$
0.02 0.04 0.06
$\Omega_m h^2$
0.1 0.2 0.3 0.4 0.5
100
80
60
40
20
10
100
1000
l

Геометрия на Вселената

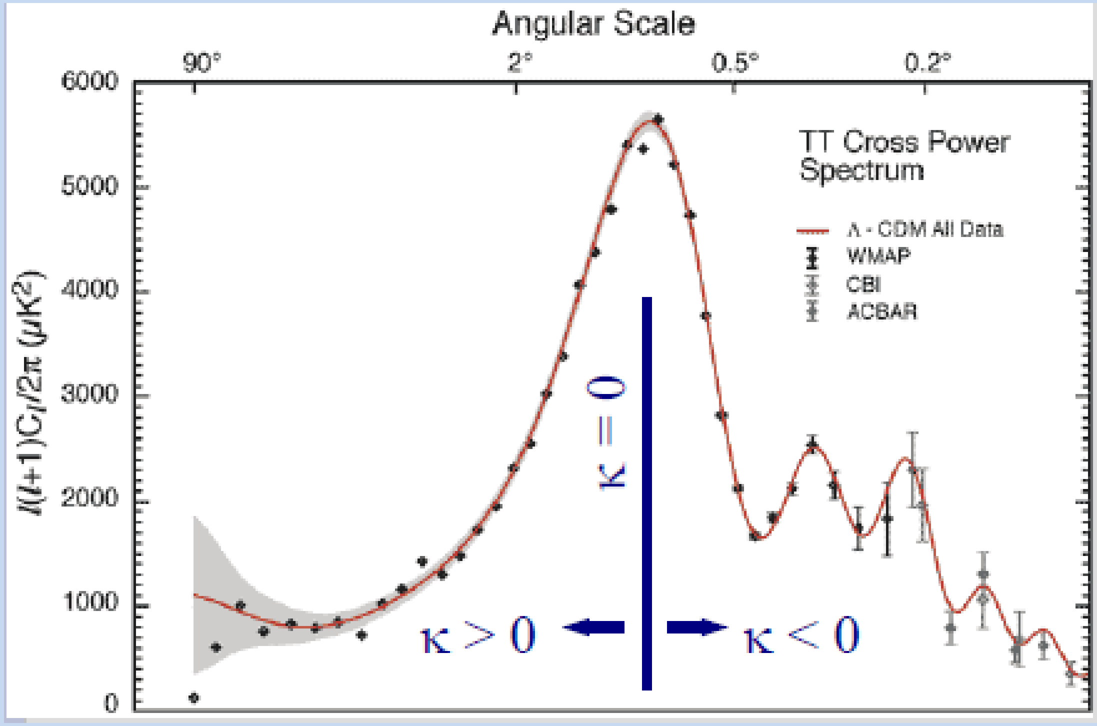


Изменението на разстоянието до z =1100 изменя спектъра

- Мястото и височината на акустичните пикове
  - Определя величините на космологичните параметри
- Параметри
  - Кривина (отворена, плоска, затворена)
  - ТЕ(космол.константа)
  - бариони
  - тъмно вещество

Courtesy Wayne Hu – *http://background.uchicago.edu*

Determining the total density $\Omega = 1 + k / H^2R^2$



Position of CMB max of fluctuations measures k. $\theta_{peak} = 1^{o}$

$\Omega = 1.0$

LSS: $\Omega_M \sim 0.3$

Hence $\Omega_{DE} \sim 0.7$

- Existence of DE in correspondence with SN results.

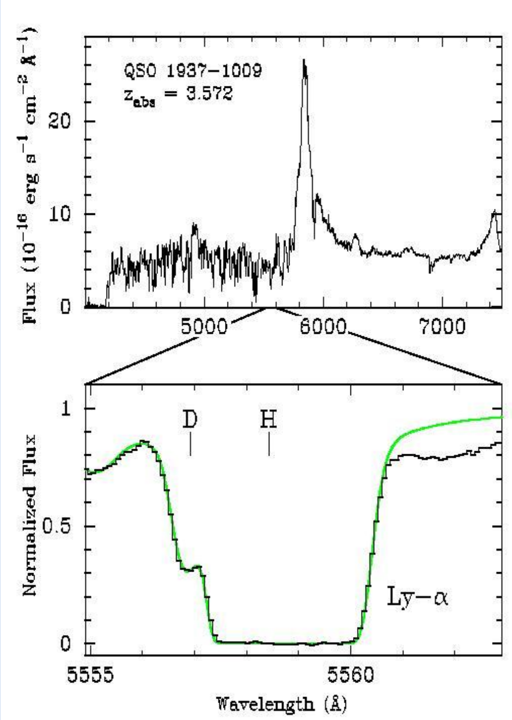
Baryon Density

$$\eta = n_b / n_\gamma \sim 6.10^{-10}$$

η_{WMAP}=6.16±0.16 x 10^{-10} at 68% CL

$$\Omega_b h^2 = 0.0226 \pm 0.0005$$

β is measured precisely by different independent means - BBN and CMB



measuring abundances of light elements

DASI, BOOMERANG, MAXIMA, WMAP

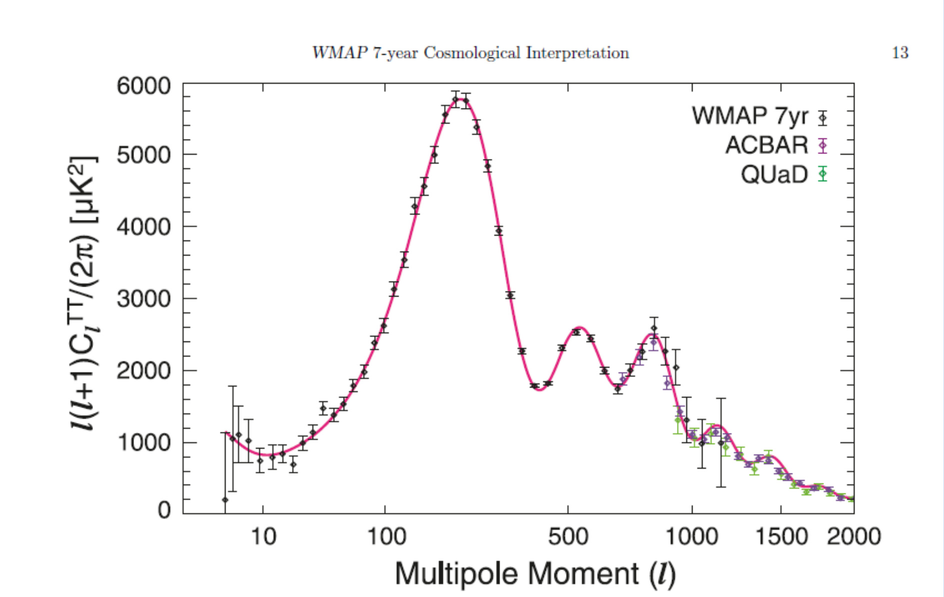


FIG. 7.— The *WMAP* 7-year temperature power spectrum (Larson et al. 2010), along with the temperature power spectra from the ACBAR (Reichardt et al. 2009) and QUaD (Brown et al. 2009) experiments. We show the ACBAR and QUaD data only at $l \geq 690$, where the errors in the *WMAP* power spectrum are dominated by noise. We do not use the power spectrum at $l > 2000$ because of a potential contribution from the SZ effect and point sources. The solid line shows the best-fitting 6-parameter flat ΛCDM model to the *WMAP* data alone (see the 3rd column of Table 1 for the maximum likelihood parameters).

from CMB anisotropy measurements

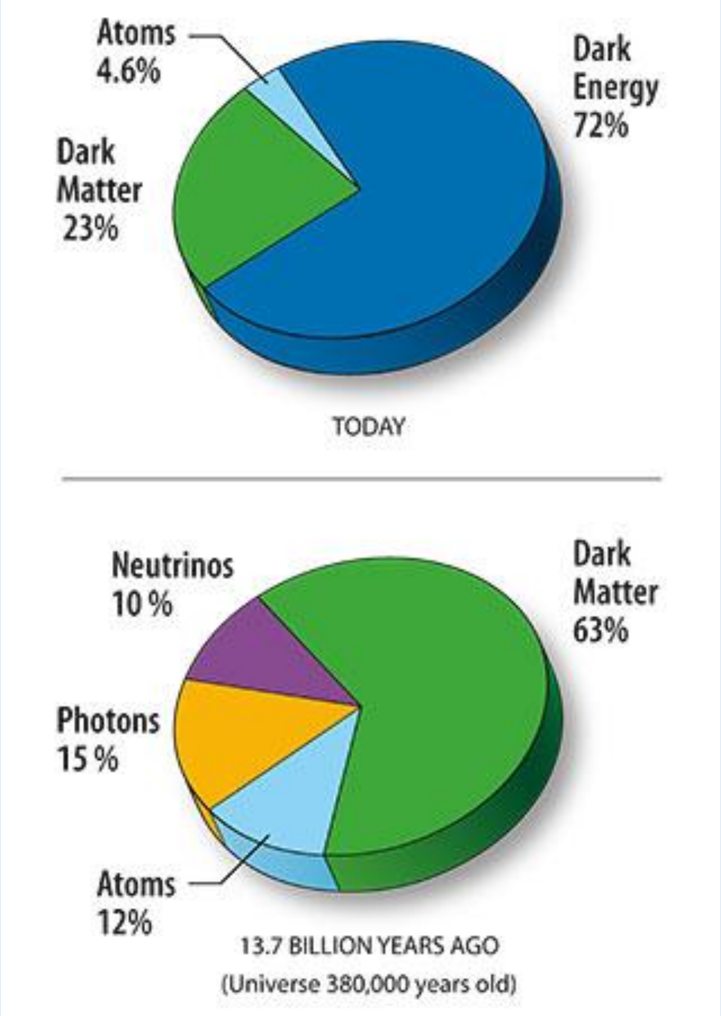
Baryons are not enough to close the Universe.
Most of the baryons are optically dark. There exists nonbaryonic DM.

WMAP

96% of the Universe density is in form undetected in the laboratory ..!?

CMB – baryometer 4.6% (5% acc.)
Visible baryons (0.1%)
DM 23.3% (1.3%)
DE 72.1% (1.5%); ω= -1.1 ± 0.14

- constraints on the DE. It seems more like a "cosmological constant" than "quintessence". But quintessence is not ruled out.



- Full map of the sky in microwaves, resolution 0.2 degrees
- polarization of the microwave radiation
- reionization epoch – earlier than expected – info about galaxy formation

Flat Euclidian space – 1% accuracy
Close to critical density 9.9 x 10-30 g/cm3
(5.9 p в m3) (2% accuracy)

- Universe age 13.73 bln y, 1% accuracy (0.12 млрд. г.)

WMAP7+H+BAO: 13.75+/- 0.11

Higher and higher precision

Improvements in $N_{\rm eff}$: 7-year versus 5-year

Parameter	Year	*WMAP* only	*WMAP*+BAO+SN+*HST*	*WMAP*+BAO+H_0	*WMAP*+LRG+H_0
$z_{\rm eq}$	5-year	3141^{+154}_{-157}	3240^{+99}_{-97}		
	7-year	3145^{+140}_{-139}		3209^{+85}_{-89}	3240 ± 90
$\Omega_m h^2$	5-year	$0.178^{+0.044}_{-0.041}$	0.160 ± 0.025		
	7-year	$0.184^{+0.041}_{-0.038}$		0.157 ± 0.016	$0.157^{+0.013}_{-0.014}$
$N_{\rm eff}$	5-year	> 2.3 (95% CL)	4.4 ± 1.5		
	7-year	> 2.7 (95% CL)		$4.34^{+0.86}_{-0.88}$	$4.25^{+0.76}_{-0.80}$

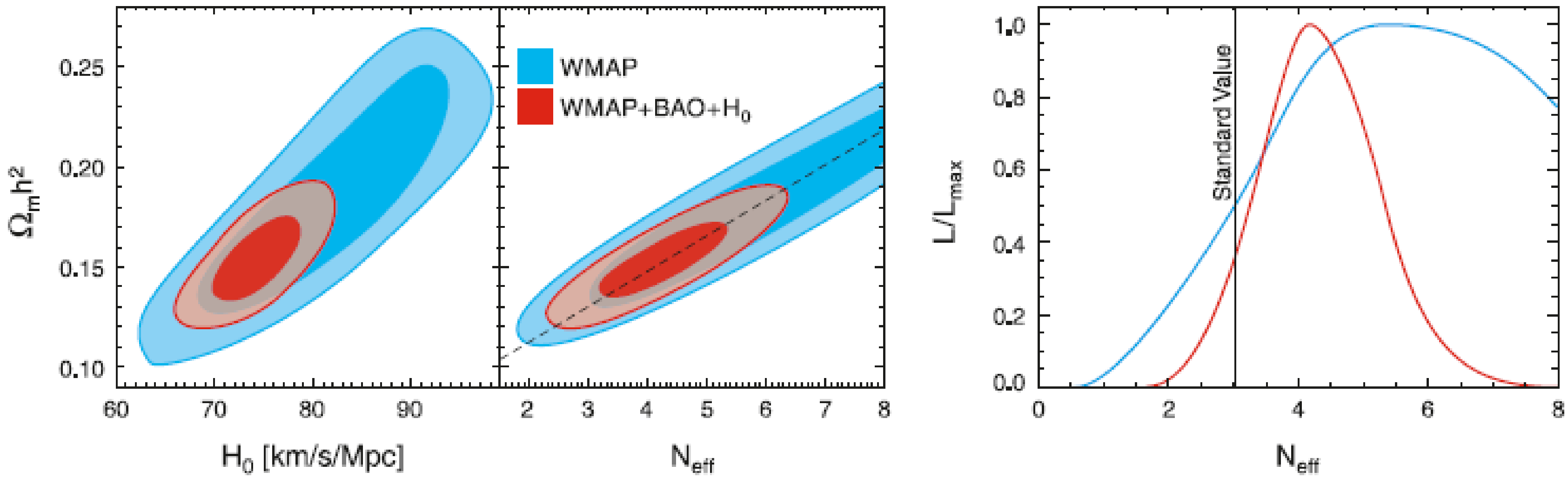


FIG. 9.— Constraint on the effective number of neutrino species, $N_{\rm eff}$. (Left) Joint two-dimensional marginalized distribution (68% and 95% CL), showing how a better determination of H_0 improves a limit on $\Omega_m h^2$. (Middle) A correlation between $N_{\rm eff}$ and $\Omega_m h^2$. The dashed line shows the line of correlation given by equation (58). A better determination of H_0 improves a limit on $\Omega_m h^2$ which, in turn, improves a limit on $N_{\rm eff}$. (Right) One-dimensional marginalized distribution of $N_{\rm eff}$ from *WMAP*-only and *WMAP*+BAO+H_0. The 68% interval from *WMAP*+BAO+H_0, $N_{\rm eff} = 4.34^{+0.86}_{-0.88}$, is consistent with the standard value, 3.04, which is shown by the vertical line.

Cosmological parameters after WMAP7

Class	Parameter	*WMAP* 7-year ML[a]	*WMAP*+BAO+H_0 ML	*WMAP* 7-year Mean[b]	*WMAP*+BAO+H_0 Mean
Primary	$100\Omega_b h^2$	2.270	2.246	$2.258^{+0.057}_{-0.056}$	2.260 ± 0.053
	$\Omega_c h^2$	0.1107	0.1120	0.1109 ± 0.0056	0.1123 ± 0.0035
	Ω_Λ	0.738	0.728	0.734 ± 0.029	$0.728^{+0.015}_{-0.016}$
	n_s	0.969	0.961	0.963 ± 0.014	0.963 ± 0.012
	τ	0.086	0.087	0.088 ± 0.015	0.087 ± 0.014
	$\Delta^2_{\mathcal{R}}(k_0)$[c]	2.38×10^{-9}	2.45×10^{-9}	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.441^{+0.088}_{-0.092}) \times 10^{-9}$
Derived	σ_8	0.803	0.807	0.801 ± 0.030	0.809 ± 0.024
	H_0	71.4 km/s/Mpc	70.2 km/s/Mpc	71.0 ± 2.5 km/s/Mpc	$70.4^{+1.3}_{-1.4}$ km/s/Mpc
	Ω_b	0.0445	0.0455	0.0449 ± 0.0028	0.0456 ± 0.0016
	Ω_c	0.217	0.227	0.222 ± 0.026	0.227 ± 0.014
	$\Omega_m h^2$	0.1334	0.1344	$0.1334^{+0.0056}_{-0.0055}$	0.1349 ± 0.0036
	$z_{\rm reion}$[d]	10.3	10.5	10.5 ± 1.2	10.4 ± 1.2
	t_0[e]	13.71 Gyr	13.78 Gyr	13.75 ± 0.13 Gyr	13.75 ± 0.11 Gyr

[a] Larson et al. (2010). "ML" refers to the Maximum Likelihood parameters.

[b] Larson et al. (2010). "Mean" refers to the mean of the posterior distribution of each parameter. The quoted errors show the 68% confidence levels (CL).

[c] $\Delta^2_{\mathcal{R}}(k) = k^3 P_{\mathcal{R}}(k)/(2\pi^2)$ and $k_0 = 0.002$ Mpc^{-1}.

[d] "Redshift of reionization," if the universe was reionized instantaneously from the neutral state to the fully ionized state at $z_{\rm reion}$. Note that these values are somewhat different from those in Table 1 of Komatsu et al. (2009b), largely because of the changes in the treatment of reionization history in the Boltzmann code CAMB (Lewis 2008).

[e] The present-day age of the universe.

Summary of the 95% confidence limits on deviations from the simple (flat, Gaussian, adiabatic, power-law) ΛCDM model except for dark energy parameters

Sec.	Name	Case	*WMAP* 7-year	*WMAP*+BAO+SN[a]	*WMAP*+BAO+H_0
§ 4.1	Grav. Wave[b]	No Running Ind.	$r < 0.36$[c]	$r < 0.20$	$r < 0.24$
§ 4.2	Running Index	No Grav. Wave	$-0.084 < dn_s/d\ln k < 0.020$[c]	$-0.065 < dn_s/d\ln k < 0.010$	$-0.061 < dn_s/d\ln k < 0.017$
§ 4.3	Curvature	$w = -1$	N/A	$-0.0178 < \Omega_k < 0.0063$	$-0.0133 < \Omega_k < 0.0084$
§ 4.4	Adiabaticity	Axion	$\alpha_0 < 0.13$[c]	$\alpha_0 < 0.064$	$\alpha_0 < 0.077$
		Curvaton	$\alpha_{-1} < 0.011$[c]	$\alpha_{-1} < 0.0037$	$\alpha_{-1} < 0.0047$
§ 4.5	Parity Violation	Chern-Simons[d]	$-5.0^\circ < \Delta\alpha < 2.8^\circ$[e]	N/A	N/A
§ 4.6	Neutrino Mass[f]	$w = -1$	$\sum m_\nu < 1.3$ eV[c]	$\sum m_\nu < 0.71$ eV	$\sum m_\nu < 0.58$ eV[g]
		$w \neq -1$	$\sum m_\nu < 1.4$ eV[c]	$\sum m_\nu < 0.91$ eV	$\sum m_\nu < 1.3$ eV[h]
§ 4.7	Relativistic Species	$w = -1$	$N_{\rm eff} > 2.7$[c]	N/A	$4.34^{+0.86}_{-0.88}$ (68% CL)[i]
§ 6	Gaussianity[j]	Local	$-10 < f_{NL}^{\rm local} < 74$[k]	N/A	N/A
		Equilateral	$-214 < f_{NL}^{\rm equil} < 266$	N/A	N/A
		Orthogonal	$-410 < f_{NL}^{\rm orthog} < 6$	N/A	N/A

[a] "SN" denotes the "Constitution" sample of Type Ia supernovae compiled by Hicken et al. (2009b), which is an extension of the "Union" sample (Kowalski et al. 2008) that we used for the 5-year "*WMAP*+BAO+SN" parameters presented in Komatsu et al. (2009b). Systematic errors in the supernova data are not included. While the parameters in this column can be compared directly to the 5-year *WMAP*+BAO+SN parameters, they may not be as robust as the "*WMAP*+BAO+H_0" parameters, as the other compilations of the supernova data do not give the same answers (Hicken et al. 2009b; Kessler et al. 2009). See Section 3.2.4 for more discussion. The SN data will be used to put limits on dark energy properties. See Section 5 and Table 4.

[b] In the form of the tensor-to-scalar ratio, r, at $k = 0.002$ Mpc^{-1}.

[c] Larson et al. (2010).

[d] For an interaction of the form given by $[\phi(t)/M]F_{\alpha\beta}\tilde{F}^{\alpha\beta}$, the polarization rotation angle is $\Delta\alpha = M^{-1}\int \frac{dt}{a}\dot{\phi}$.

[e] The 68% CL limit is $\Delta\alpha = -1.1^\circ \pm 1.3^\circ$ (stat.) $\pm 1.5^\circ$ (syst.), where the first error is statistical and the second error is systematic.

[f] $\sum m_\nu = 94(\Omega_\nu h^2)$ eV.

[g] For *WMAP*+LRG+H_0, $\sum m_\nu < 0.44$ eV.

[h] For *WMAP*+LRG+H_0, $\sum m_\nu < 0.71$ eV.

[i] The 95% limit is $2.7 < N_{\rm eff} < 6.2$. For *WMAP*+LRG+H_0, $N_{\rm eff} = 4.25 \pm 0.80$ (68%) and $2.8 < N_{\rm eff} < 5.9$ (95%).

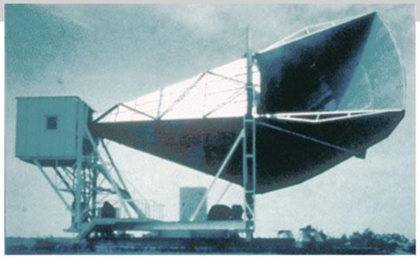
[j] V+W map masked by the *KQ75y7* mask. The Galactic foreground templates are marginalized over.

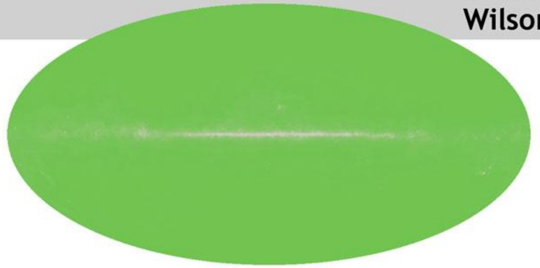
[k] When combined with the limit on $f_{NL}^{\rm local}$ from *SDSS*, $-29 < f_{NL}^{\rm local} < 70$ (Slosar et al. 2008), we find $-5 < f_{NL}^{\rm local} < 59$.

Cosmic Microwave Background Radiation Overview

The oldest light in universe

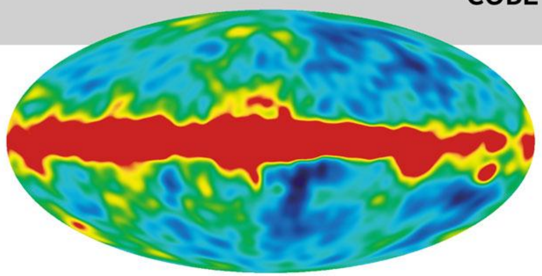
1965 — Penzias and Wilson





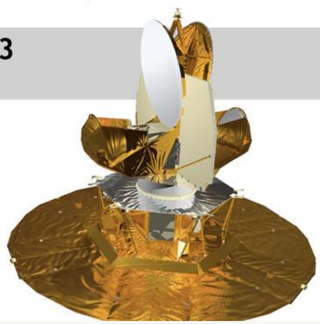
Discovered the remnant afterglow from the **Big Bang**
→ **2.7 K**

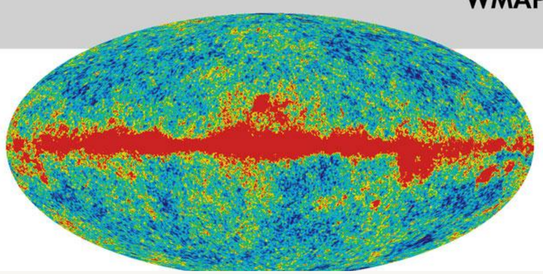
1992 — COBE



Blackbody radiation, Discovered the patterns (**anisotropy**) in the afterglow.
→**angular scale ~ 7°** at a level $\Delta T/T$ of 5.10^{-5}

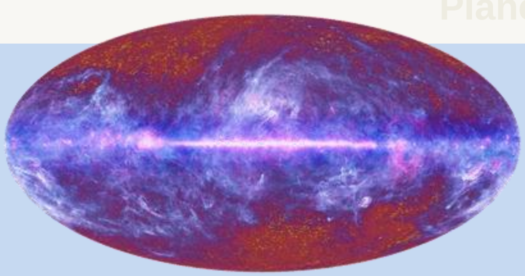
2003 — WMAP





(Wilkinson Microwave Anisotropy Probe):
→ **angular scale ~ 15'**

2009 — Planck



→ **angular scale ~ 5',**
$\Delta T/T \sim 2\times10^{-6}$, 30~867 Hz

- Planck to study CMB anisotropy with higher sensitivity and angular resolution: 5’ ;
- To test the inflationary models; to measure H, the amplitude of CMB structures
- Better sensitivity – to measure polarization of CMB

Wide range of frequencies

3 times better accuracy of determination of Universe characteristics

- with an uncertainty on the temperature limited by “natural causes” (foreground fluctuations, cosmic variance) rather than intrinsic or systematic detector noises

Wide range of frequencies

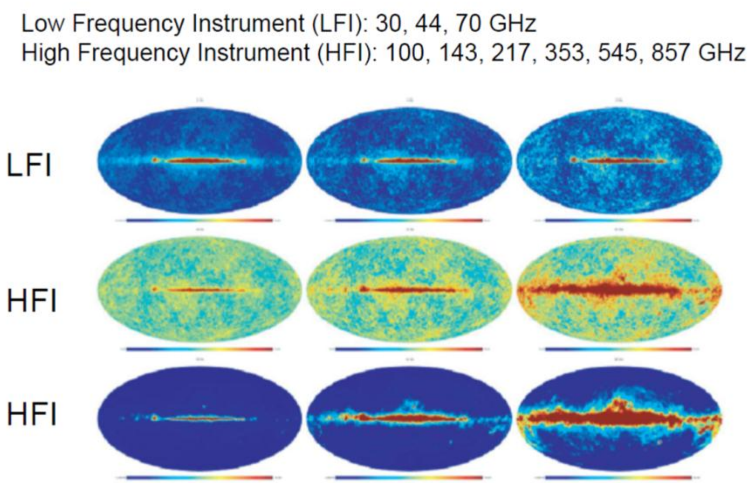


FIG 5.1.— False colour images of the simulated sky in the nine frequency channels of *Planck*, after subtraction of the monopole and dipole CMB components. From top left to bottom right: 30, 44, 70, 100, 143, 217, 353, 545, and 857 GHz channels.

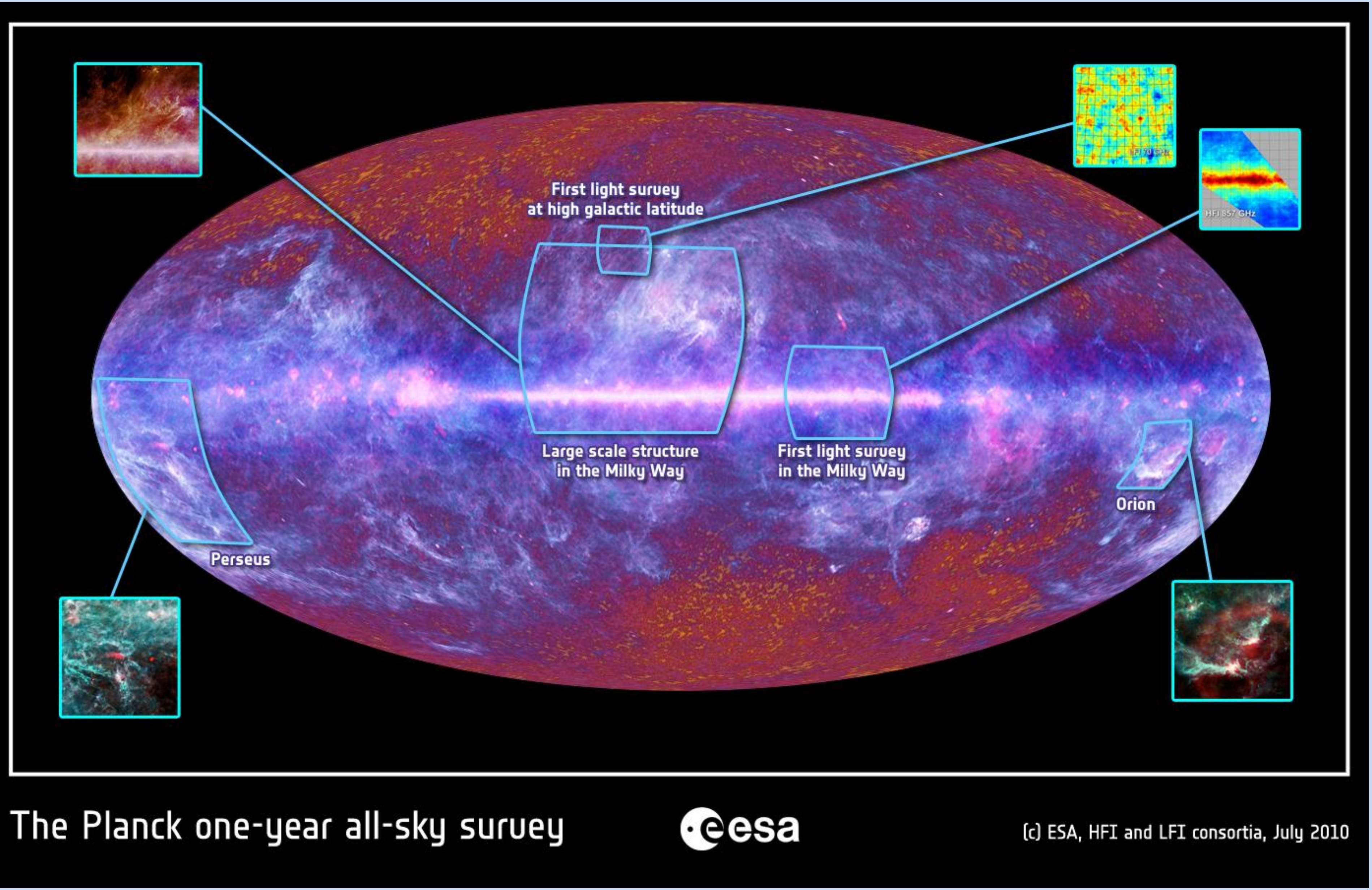
4 of the LambdaCDM prameters are known with better than 10% accuracy, while the optical depth with 20%.

Bad accuracy of n_s

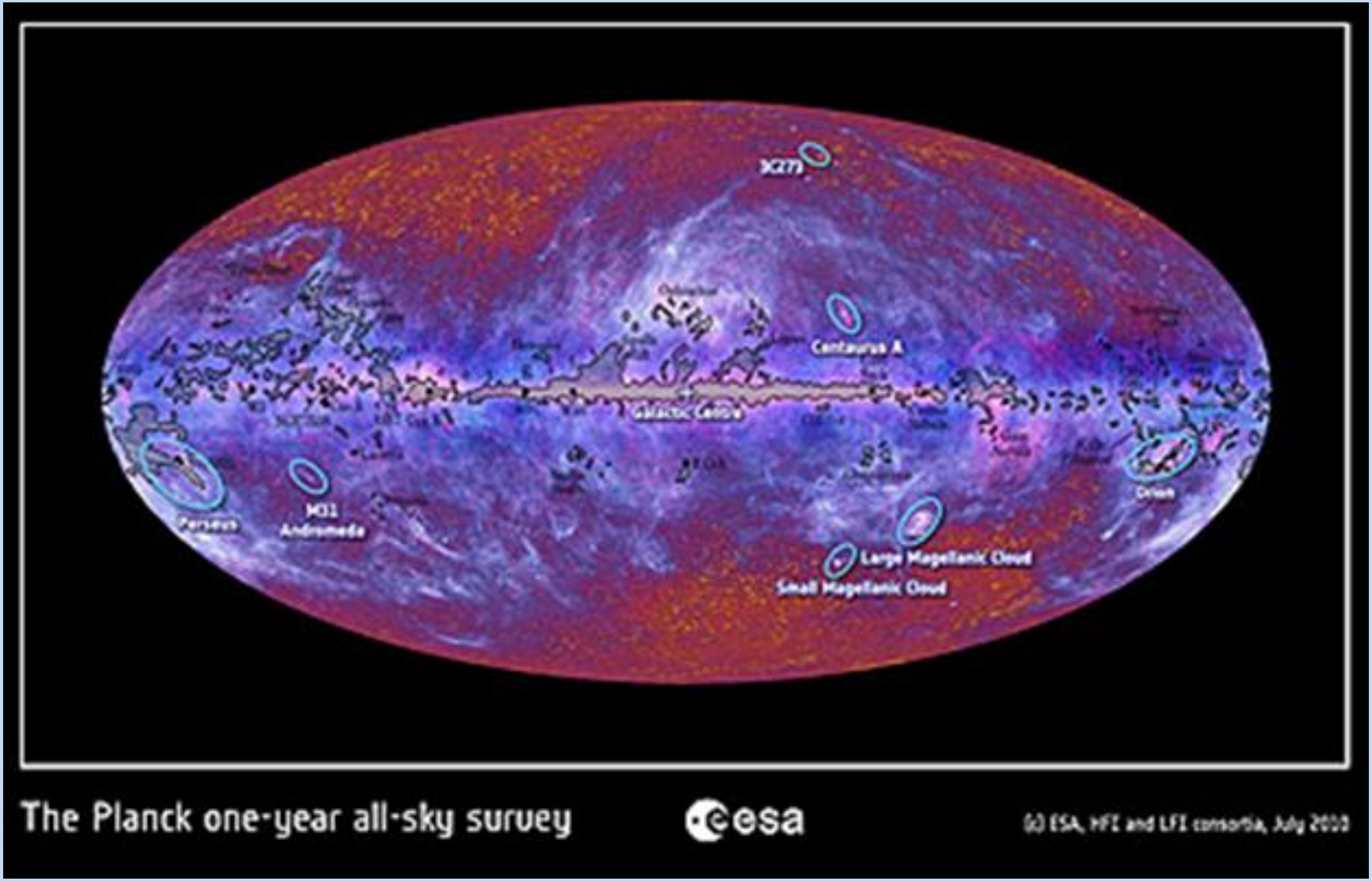
$$1 - n_s = 0.037 \pm 0.014$$

Info about:
primordial fluctuations (about inflation)
adiabaticity of primordial fluctuations;
Non-gausianity of the distribution
Primordial grav waves;
Tensor perturbations; Reionization
Large-scale WMAP anomalies

Sky in microwaves as seen by Planck



Това изображение на цялото небе в микровълни е получено чрез композиране на данните от Planck покриващи електромагнитния спектър от 30 GHz до 857 GHz. Структурата на CMBR, с нейните финни температурни флуктуации отразяващи първичните флуктуации на плътността, от които днешните структури са възникнали, се вижда ясно в областите отдалечени от галактичната плоскост на картата.
Централната ивица е плоскостта на Галактиката. Голяма част от изображението е доминирано от дифузни емисии на прах и газ. Изображението е получено от данни получени от Planck по време на първият пълен небесен обзор, който бе завършен в резултат на 12 месеца наблюдения.
В дясно на основното изображение, под галактичната равнина, е показан голям облак от газ в нашата Галактика. Дъгата от светлина, който го заобикаля е Barnard’s Loop – разширяващ се bubble на избухнала звезда. Planck изучава и други галактики. Спиралната галактика Andromeda, 2.2 милиони ly от Земята, изглежда като обломък от микровълни, излъчени от най-студения газ в нея. Други, по-отдалечени галактики със свръхмасивни черни дупки се виждат като точки на изображението.
Получено от изображения които са направени между август 2009 и юни 2010, това изображение е изображение с ниска резолюция (в сравнение с получените изображения на базата на пълните данни).
Credits: ESA, C. Carreau



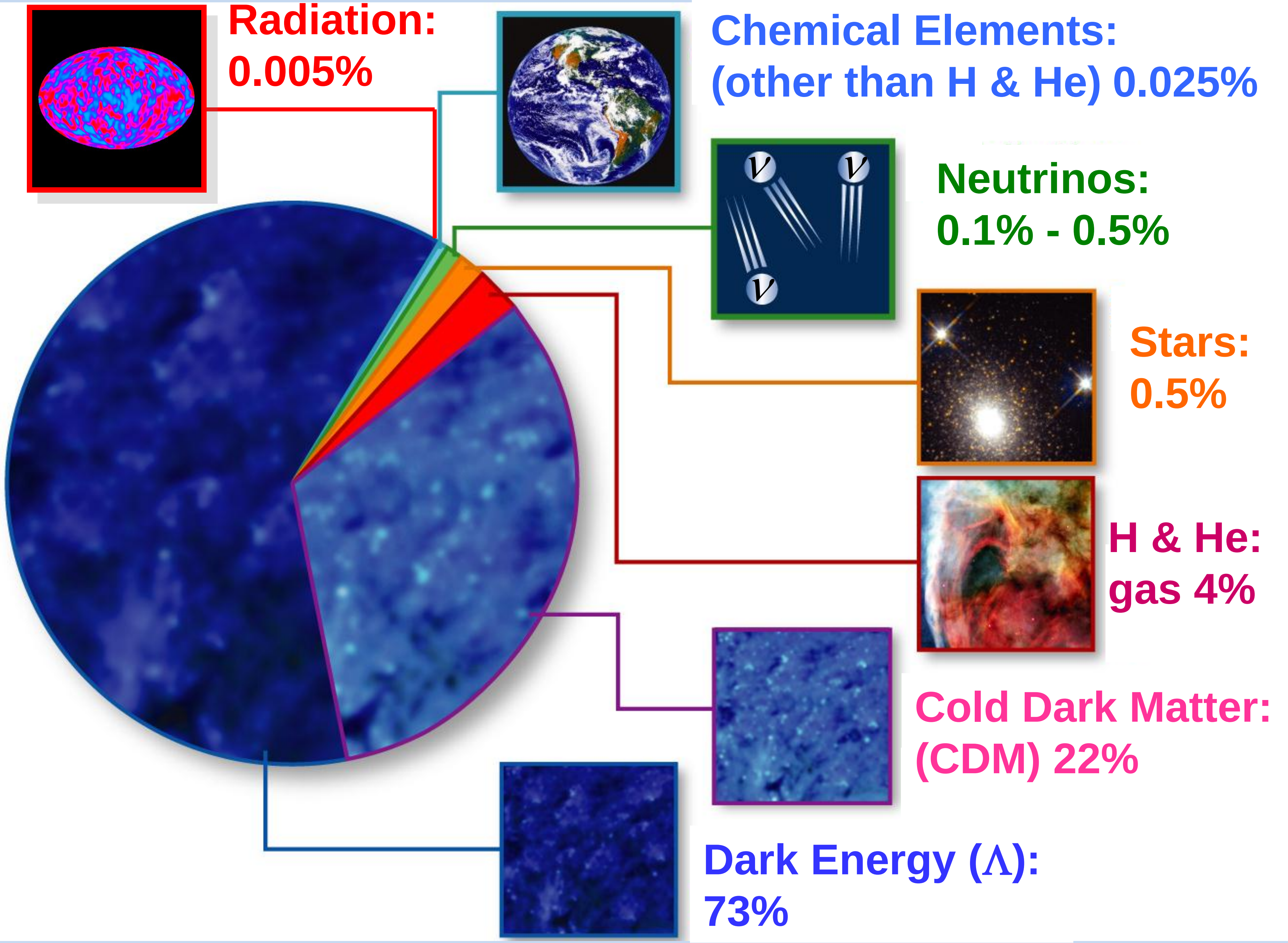
This multi-frequency all-sky image of the microwave sky by Planck from 30 GHz to 857 GHz.
The image was derived from data collected by Planck during its first all-sky survey, and comes from about 12 months of observations (August 2009 and June 2010).
The central band is the plane of our Galaxy. A large portion of the image is dominated by the diffuse emission from its gas and dust. To the right of the main image, below the plane of the Galaxy, is a large cloud of gas in our Galaxy. The obvious arc of light surrounding it is Barnard’s Loop – the expanding bubble of an exploded star. Planck has seen other galaxies. The great spiral galaxy in Andromeda, 2.2 million light-years from Earth, appears as a sliver of microwave light, released by the coldest dust in its giant body. Other, more distant, galaxies with supermassive black holes appear as single points of microwaves dotting the image.

The Universe Secrets

Dark Matter, Dark Energy

matter-antimatter asymmetry

inflation


Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.1% - 0.5%
Stars:
0.5%
H & He:
gas 4%
Cold Dark Matter:
(CDM) 22%
Dark Energy (Λ):
73%

Dark Matter

Independent observational evidences from different epochs:
BBN, CMB, structures, SNIa, H_0

Observations at different scales
with different methods

Evidence from combined data CMB, BAO, SN, H_0, Universe age, ...

Theoretical indications – growth of fluctuations, evolution of structures

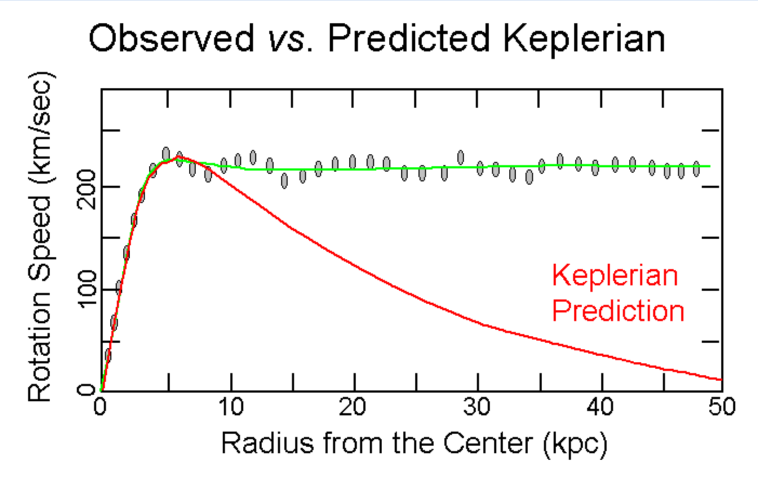
Observational indications concerning DM type:
structures – baryon matter is insufficient, CDM

BBN - dark baryons also are not enough to account for clustering matter
CMB - dark baryons are insufficient

Dark Matter

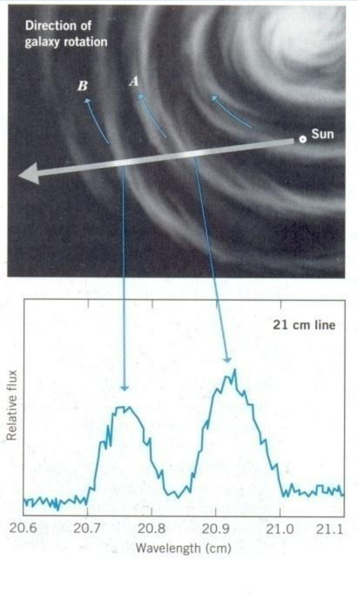
Observational Indications

Rotation Curves: The dependence of the velocity of rotation of an object on its distance from the galactic center.



The mass inferred for galaxies is roughly ten times larger than the mass that can be associated with stars, gas and dust in a Galaxy.

$\Omega_{DM} \gtrsim 0.1,$



Radio and optical observations of gas and stars in galaxies enable us to determine the distribution of mass in these systems

DM at galactic and galaxy cluster scale

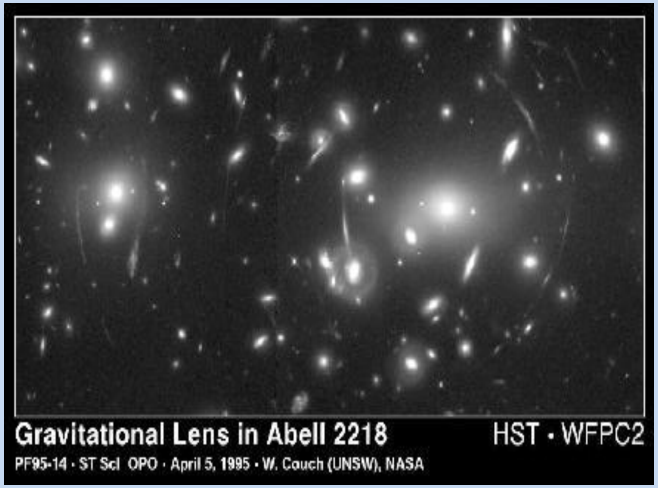
F. Zwicky discovered the presence of DM on a much larger scale through his studies of large velocitieas in galactic clusters. Recent measurements:

galaxy clusters (and binary galaxies) have M/L ratios up to 300.

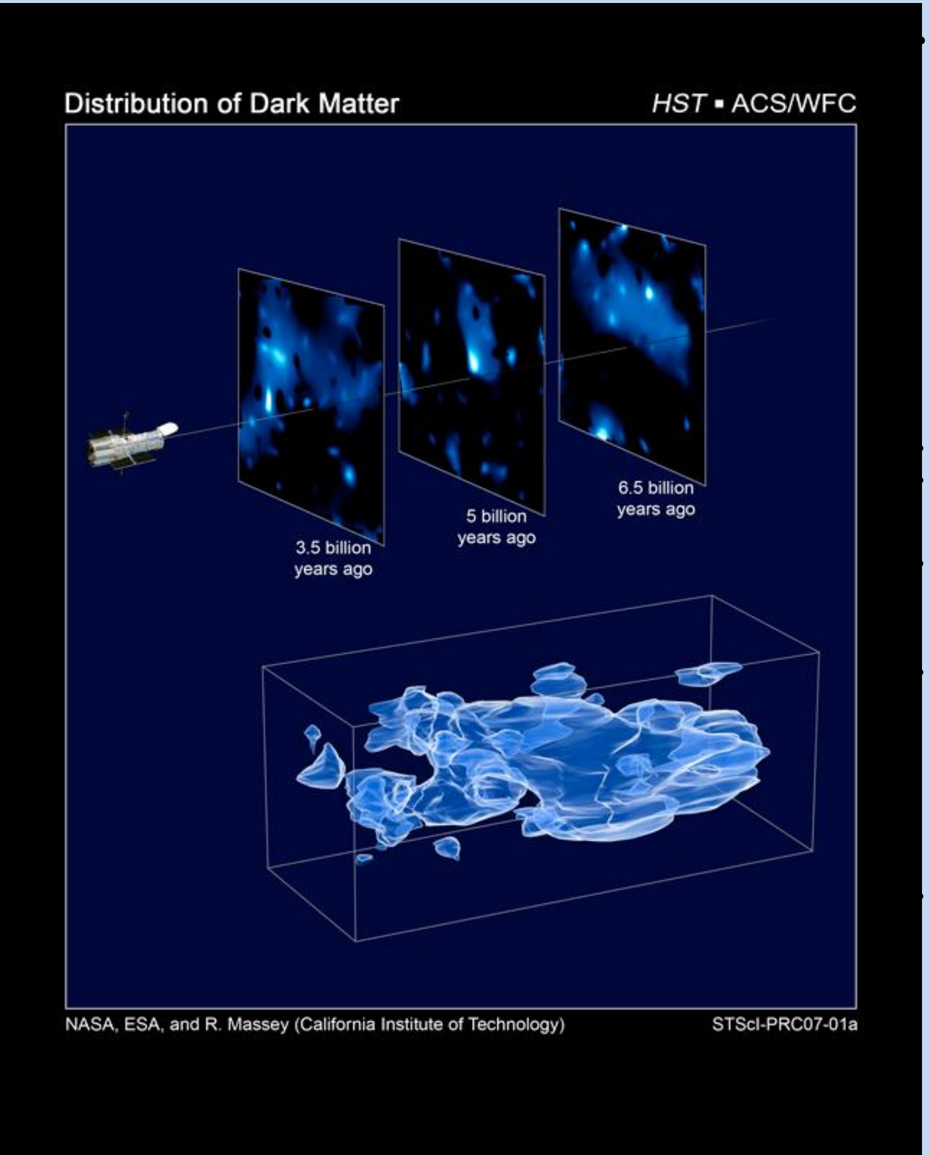
Gravitational Lensing

This mass discrepancy confirmed by gravitational lensing.

By measuring how the background galaxies are distorted by the foreground cluster the cluster mass is measured. It is more than ten times larger than the inferred mass in visible stars, gas and dust. $\Omega_{DM} \simeq 0.2$



A 3D map of DM in the Universe

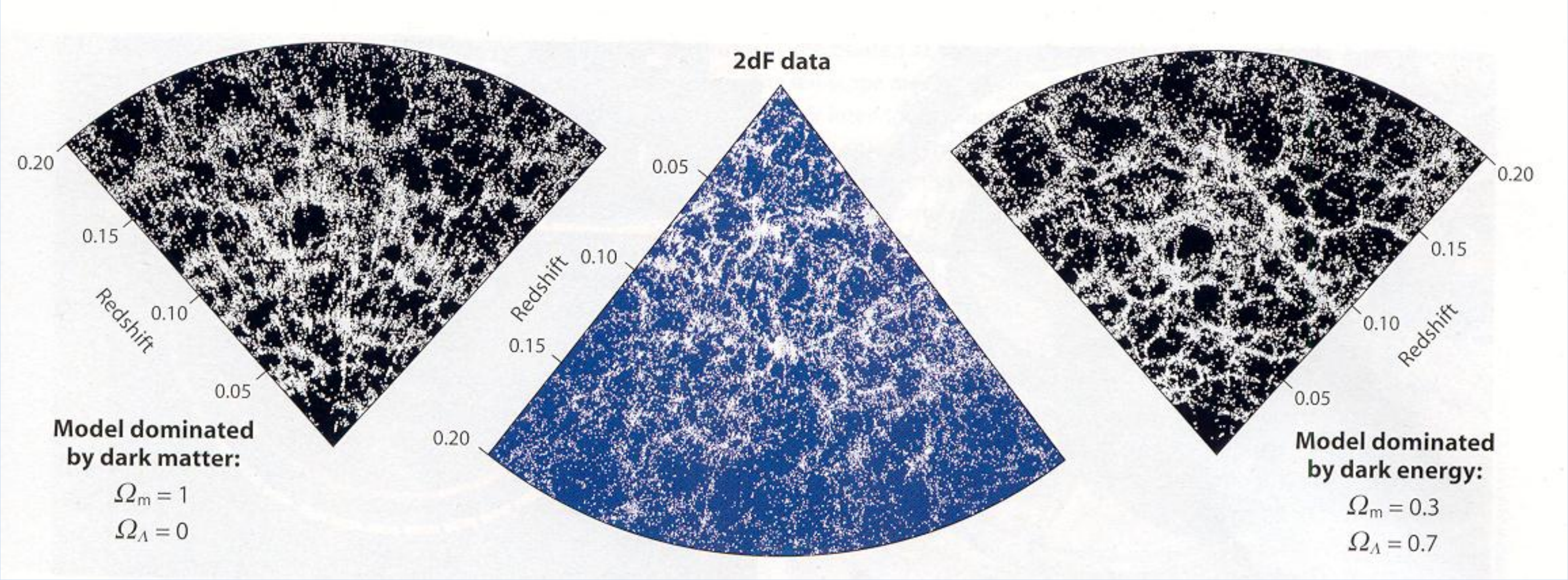


- The map reveals a loose network of dark matter filaments, gradually collapsing under the relentless pull of gravity, and growing clumpier over time. This confirms theories of how structure formed in our evolving universe, which has transitioned from a comparatively smooth distribution of matter at the time of the big bang. The dark matter filaments began to form first and provided an underlying scaffolding for the subsequent construction of stars and galaxies from ordinary matter. Without dark matter, there would have been insufficient mass in the universe for structures to collapse and galaxies to form.

- [Top] - Three slices through the evolving distribution of DM.
- This is calibrated by measuring the cosmological redshift of the lensing galaxies used to map the dark matter distribution, and binning them into different time/distance "slices".
- Each panel represents an area of sky nine times the angular diameter of the full Moon. Note that this fixed angle means that the survey volume is a really a cone, and that the physical area of the slices increases (from 19 Mpc on a side to 31 Mpc on a side) from left to right.
- [Bottom] - When the slices across the universe and back into time are combined, they make a 3D map of DM in the universe. The three axes of the box correspond to sky position (in right ascension and declination), and distance from the Earth increasing from left to right (as measured by cosmological redshift). Note how the clumping of the DM becomes more pronounced, moving right to left across the volume map, from the early universe to the more recent universe.

- The DM distribution was mapped with Hubble Space Telescope's survey of the universe, the Cosmic Evolution Survey ("COSMOS"). To compile the COSMOS survey, Hubble photographed 575 adjacent and slightly overlapping views of the universe using the Advanced Camera for Surveys' (ACS) Wide Field Camera onboard Hubble. It took nearly 1,000 hours of observations. The distances to the galaxies were determined from their spectral redshifts, using the Subaru telescope in Hawaii.

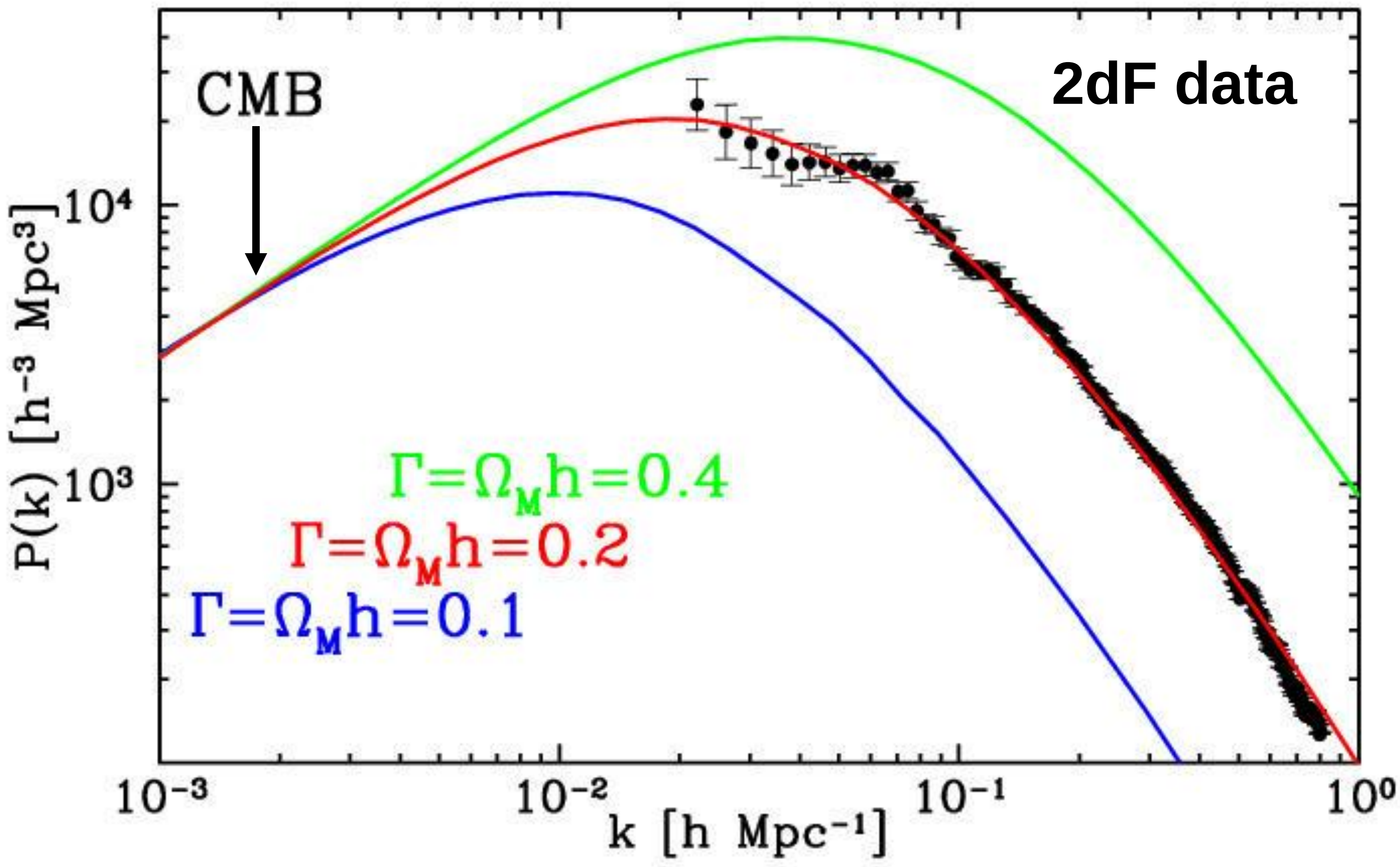
Galaxies' Distribution vers Theoretical Simulations



CDM is required in order to enable gravity to amplify the small fluctuations in CMB enough to form the large-scale structures that we see in the universe today.

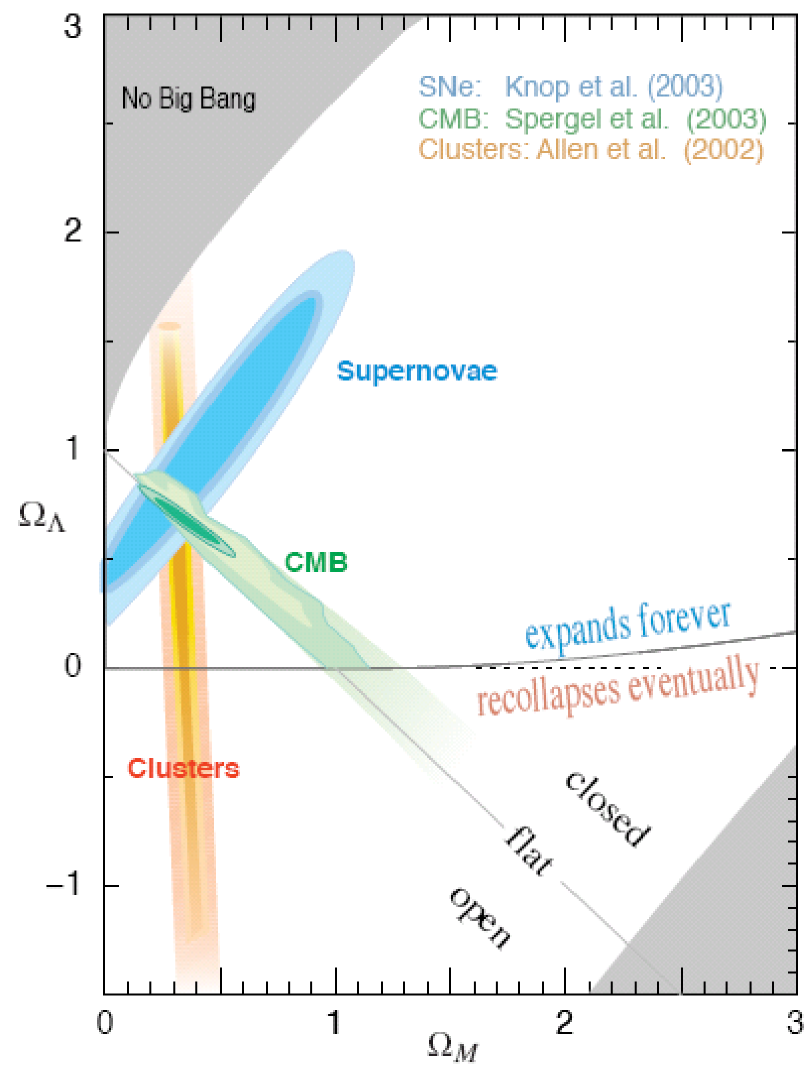
$$\Gamma \propto \Omega_M h \propto 0.25 \pm 0.05$$

$\Omega_M h$	Ω_M	h
0.25	1	0.25
0.25	0.35	0.70



Combined Results

Hubble ST + WMAP + clusters
point to the existence of DM and DE:



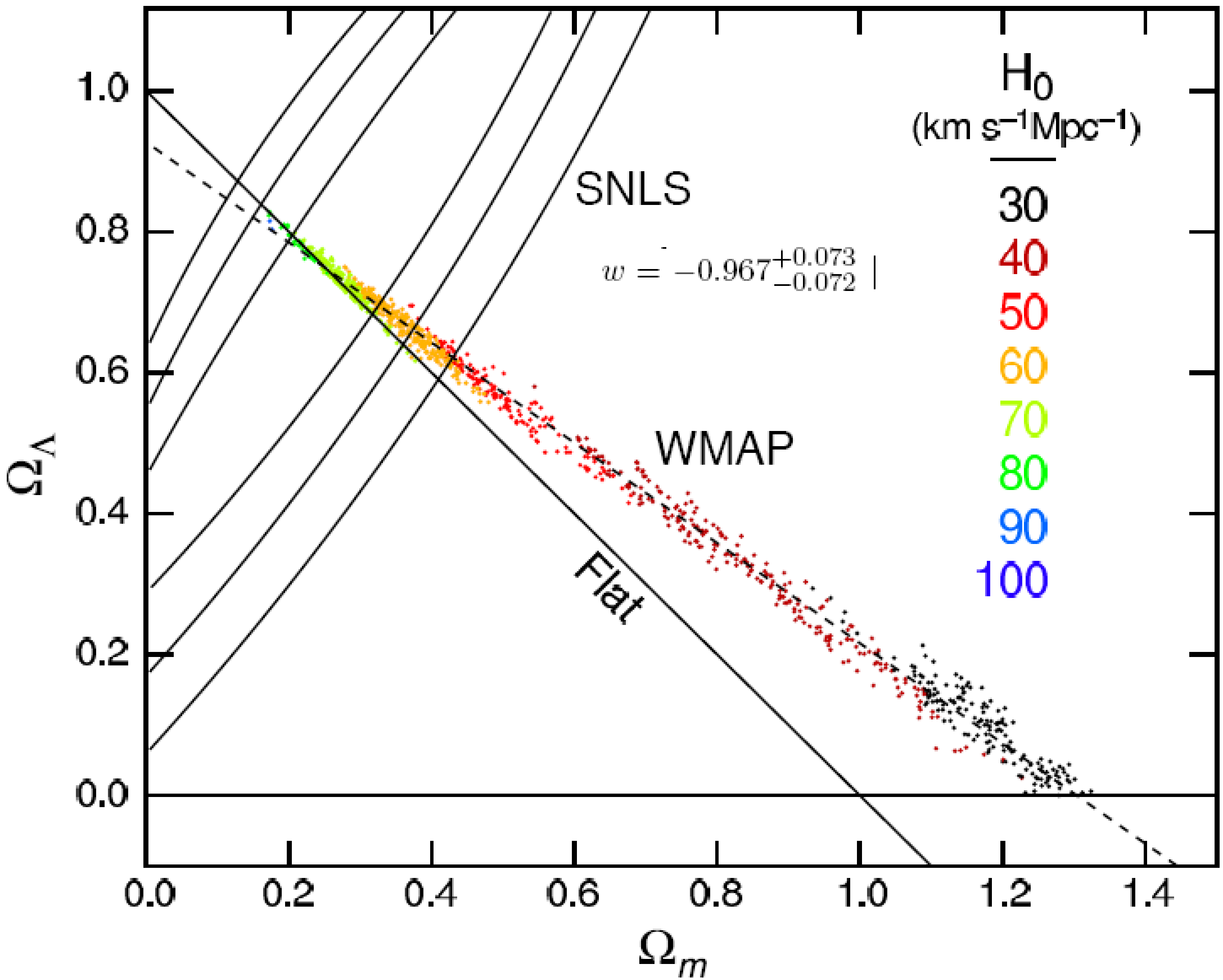


Figure 19.2: Likelihood-based probability densities on the plane Ω_Λ (*i.e.*, Ω_v assuming $w = -1$) vs Ω_m. The colored Monte-Carlo points derive from WMAP [22] and show that the CMB alone requires a flat universe $\Omega_v + \Omega_m \simeq 1$ if the Hubble

Dark Matter Candidates

Baryonic

MACHOS MAssive Compact Halo Objects

Brown Dwarfs and similar objects, not luminous enough to be observed, have been nicknamed MACHOs

Supermassive Black Holes, thought to power distant quasars.

detection by gravitational lensing

Non baryonic (CDM and HDM)

WIMPs (Weakly Interacting Massive Particles) or non-baryonic matter , produced shortly after the Big Bang

neutrino - HDM

sterile neutrino with KeV masses WDM

axion - CDM,

neutralino, gravitino, axino

Modified gravity models able to explain the dynamics of the LSS

without DM but have problems at Solar system scales.

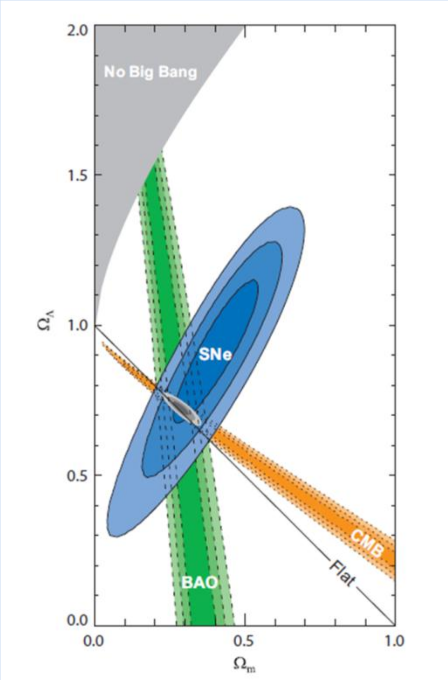
DARK ENERGY

Accelerated Expansion

LSS $\Omega_M = 0.3$

Flatness

$\Omega_0 = 1$
$\Omega_M = 0.3$
$1 - 0.3 = 0.7$



DE density $$\rho \propto 10^{-30}\ \mathrm{g\ cm^{-3}}$$

Nature of Dark Energy

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

$$\frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3}(\rho + 3p),$$

- ✓ **cosmological constant** $R(t) \propto e^{\sqrt{\Lambda/3}t}$

- ✓ **an energy of empty space**

  Why space should contain the observed amount of energy and not, say, much more or much less? Multi universes with different vacuum?

$$\rho_{vac} = E_{Pl}/L_{Pl}{}^3 = 10^{120}\,\rho_{vac}{}^{(obs)}$$

- ✓ **quintessence** (time varying cosmological constant)

  Unlike the energy of space envisioned by Einstein, quintessence would have the property that it could vary from place to place and moment to moment. Existing evidence tends to disfavor quintessence.

- ✓ **Accelerating universe signals a new aspect of the law of gravity**.
- ✓ **An effect of extra dimensions of space**

  One of the extra dimensions (predicted by supersymmetry of space can mimic the effect of a dark energy by causing the expansion of our three-dimensional space to accelerate.

How did the observed locally asymmetry b/n matter and antimatter occur?

What plays the role of the inflaton?

What is the nature of 95% of Universe matter?

Is there cosmological constant or scalar field representing DE?

New exotic physical theories are to propose the DM candidate.

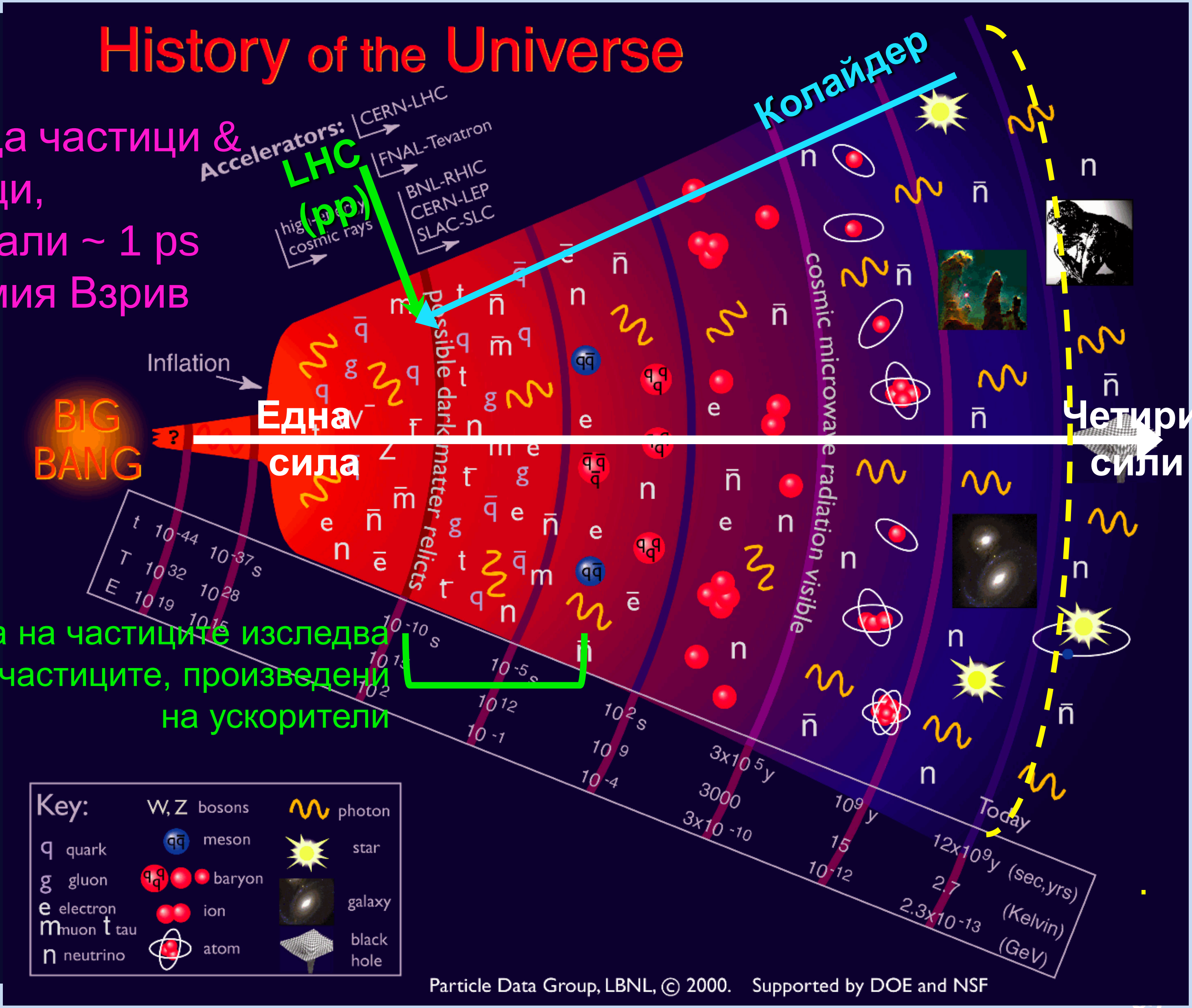
OR

DM and DE are signatures for necessity of alternative gravitational theory?

…………………….

Future observations and experimental studies, and in particular LHC, are expected to answer part of the Universe puzzles.

Произвежда частици & античастици, съществували ~ 1 ps след Големия Взрив



Физиката на частиците изследва свойствата на частиците, произведени на ускорители

Mosaics of our knowledge about Universe

homogeneous and isotropic at large scales

flat, with negligible curvature

expanding, during the last 5 billion y accelerated expansionот

Its energy density is dominated by DE ~ 73% with characteristics of Λ.

The light elements D, He-3, He-4 and Li-7 have been produced during cosmological nucleosynthesis.

The matter is mostly dark and non-baryonic, its density is under-critical ~ 0.27 , the baryons constitute <5%!

Today's Universe is filled with reli photons and relic neutrino

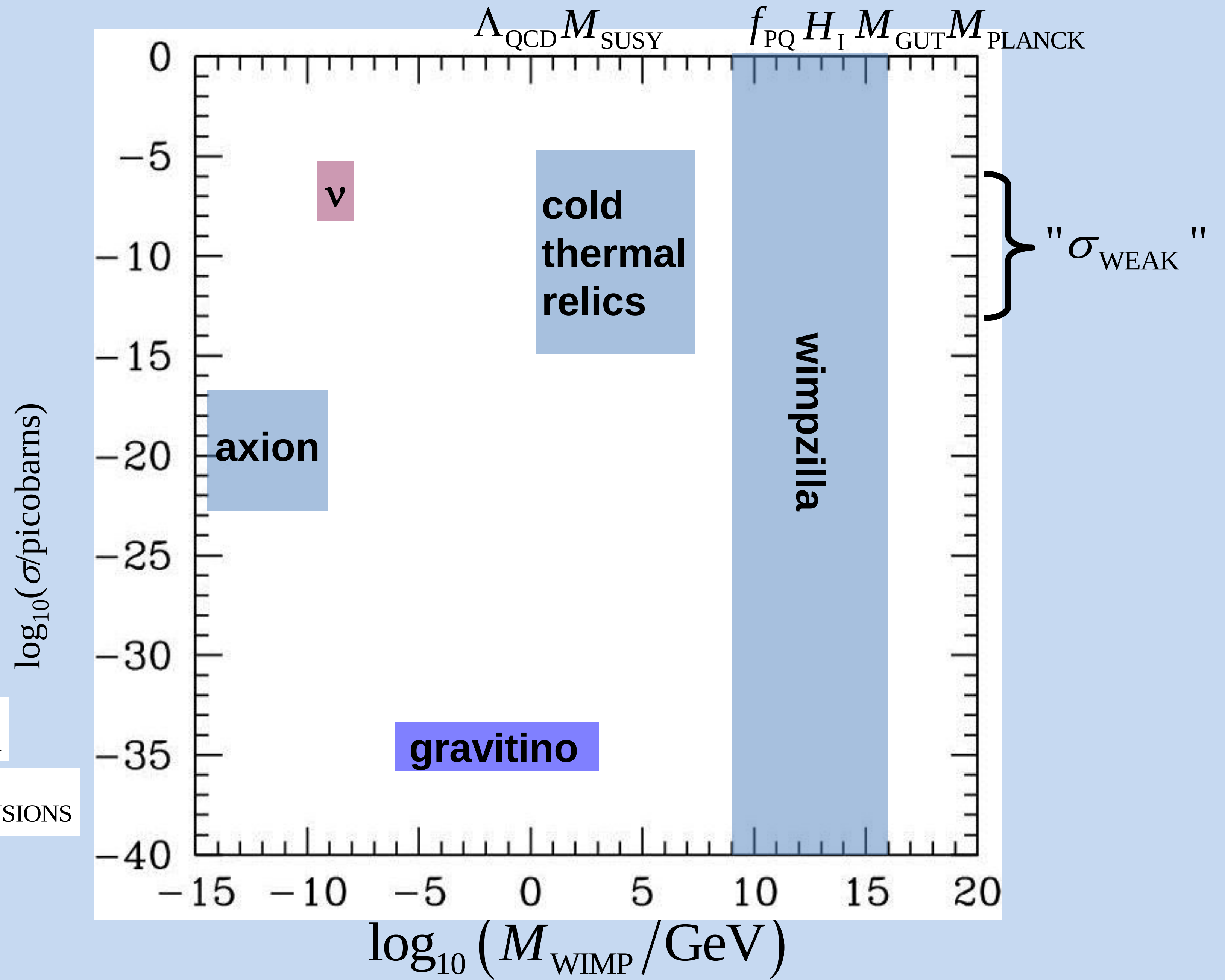
CMB+LSS sensitive to the total energy density , they put the most stringent constraints to the sum of neutrino masses < 0.6 eV.
BBN is the most sensitive baryometer, speedometer and leptometer. It is
Very sensitive to neutrino characteristics.
Planck mission will strengthen our knowledge about CMB considerably.

Observational evidences from different epochs of Universe evolution:
light elements abundances from the first minutes, CMB from 300 000 y of the Big Bang,
Structures from the first billion years, give valuable information about Universe characteristics and constrain physics beyond the standard model.

Благодаря за вниманието!

Thanks for the attention!

Particle Dark Matter Candidates



Other Scales:

M_{EWK}

$M_{STERILE}$

M_{STRING}

$M_{TECHNICOLOR}$

$M_{EXTRA\ DIMENSIONS}$

Matter Content in the Universe

To solve the Friedmann equations, one has to specify the Universe matter content and the equation of state for each of the constituents. Current observations point to at least four components:

$\Omega_r = 2.47 \times 10^{-5} h^{-2}$

$\Omega_\nu h^2 \leq 0.0076 \quad 95\%\ \text{CL}$

Radiation (relativistic degrees of freedom) ~0.002%

Today this component consists of the photons and neutrino and gives negligible contribution into total energy density. However, it was a major fraction at early times.

Baryonic matter ~4% $\Omega_b h^2 = 0.022 \pm 0.001$

Dark matter ~23% $\Omega_{nbm} h^2 = 0.106 \pm 0.008$

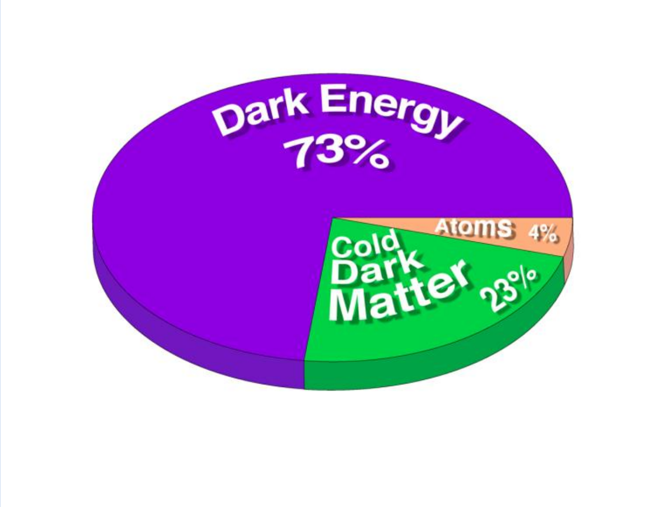
Was not directly detected yet, but should be there.

Constitutes major matter fraction today.

Dark energy ~73%

It provides the major fraction of the total energy density.

Was not anticipated and appears as the biggest surprise and challenge for particle physics, though conceptually it can be very simple, being just a `cosmological constant' or vacuum energy. $\Omega_m + \Omega_v = 1.011 \pm 0.012$



- 4% - H+He, 0.0025% heavy elements, 0.8% stars, 0.005% CMB
- 23% - DM, 73% DE, 0.17% neutrino