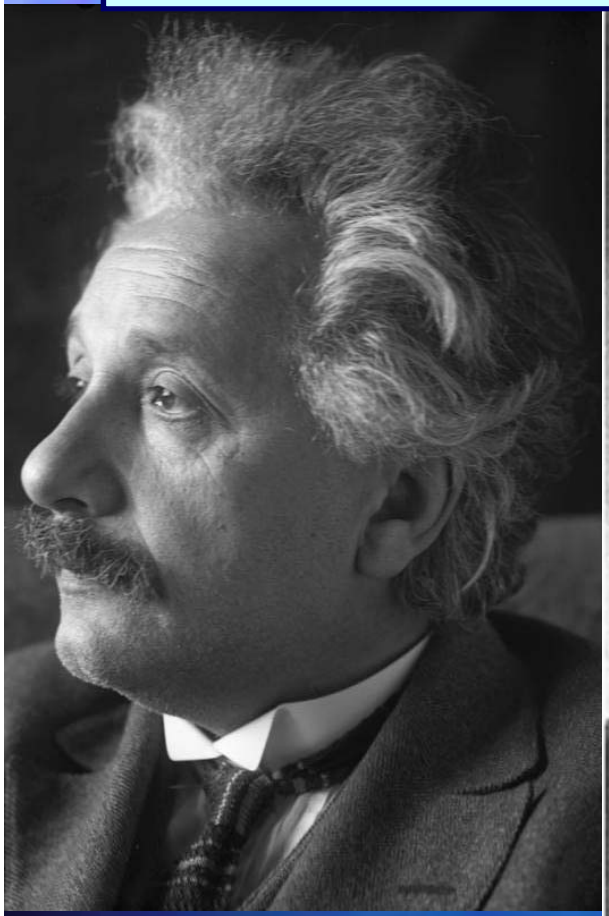
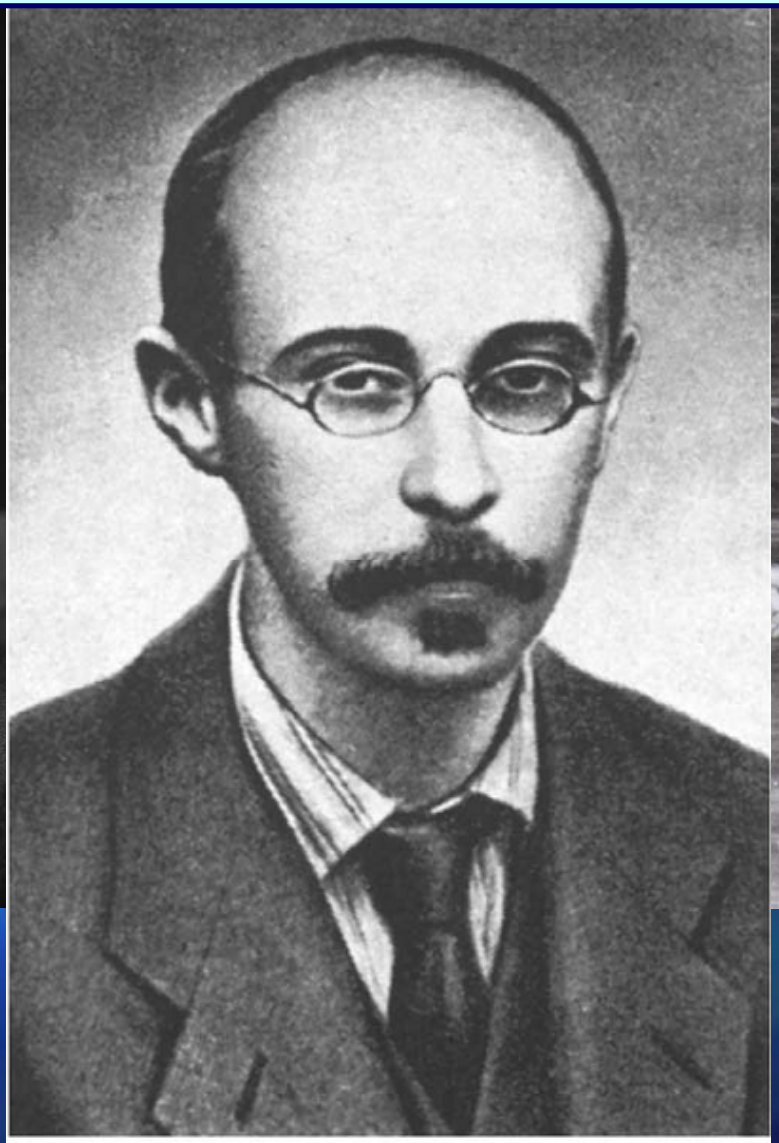
The Dark Universe

A.V. Ivanchik
Ioffe Physical-Technical Institute

2009

Principles of modern Cosmology





А. Фридман

The first observational basis of the modern cosmology

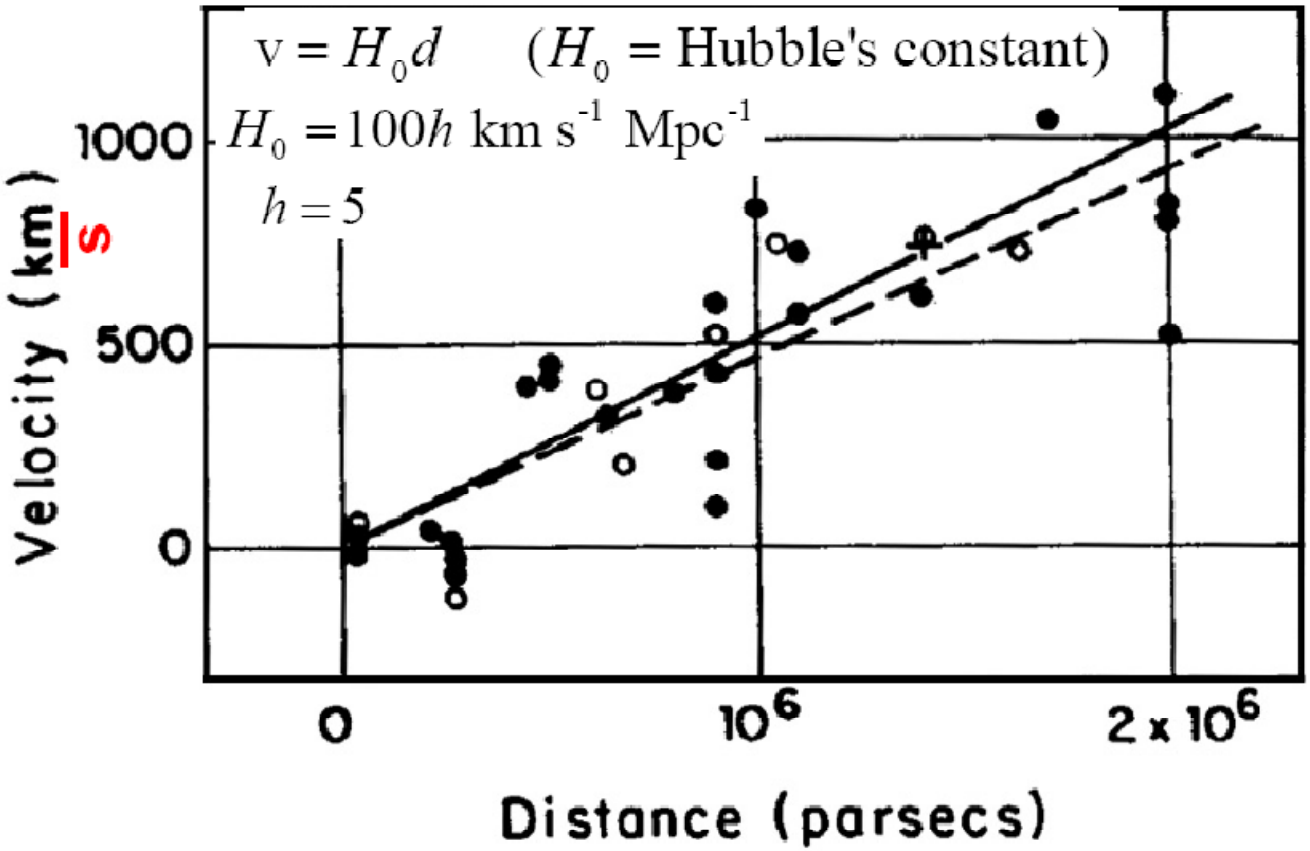
1929

Hubble's Law

1929: Edwin Hubble

$$v = H \times r$$

Hubble's Discovery Paper – 1929



1929

$H_0 \approx 500$ km/c/Mpc

Precision Cosmology

$\Omega_{tot} = 1.02^{+0.02}_{-0.02}$

$w < -0.78$ (95% CL)

$\Omega_\Lambda = 0.73^{+0.04}_{-0.04}$

$\Omega_b h^2 = 0.0224^{+0.0009}_{-0.0009}$

$\Omega_b = 0.044^{+0.004}_{-0.004}$

$n_b = 2.5 \times 10^{-7} {}^{+0.1\times10^{-7}}_{-0.1\times10^{-7}}$ cm^{-3}

$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$

$\Omega_m = 0.27^{+0.04}_{-0.04}$

$\Omega_\nu h^2 < 0.0076$ (95%CL)

$m_\nu < 0.23$ eV (95% CL)

$T_{cmb} = 2.725^{+0.002}_{-0.002}$ K

$n_\gamma = 410.4^{+0.9}_{-0.9}$ cm^{-3}

$\eta = 6.1 \times 10^{-10} {}^{+0.3\times10^{-10}}_{-0.2\times10^{-10}}$

$\Omega_b \Omega_m^{-1} = 0.17^{+0.01}_{-0.01}$

$\sigma_8 = 0.84^{+0.04}_{-0.04}$ Mpc

$\sigma_8 \Omega_m^{0.5} = 0.44^{+0.04}_{-0.05}$

$A = 0.833^{+0.086}_{-0.083}$

$n_s = 0.93^{+0.03}_{-0.03}$

$dn_s/d\ln k = -0.031^{+0.016}_{-0.018}$

$r < 0.71$ (95% CL)

$z_{dec} = 1089^{+1}_{-1}$

$\Delta z_{dec} = 195^{+2}_{-2}$

$h = 0.71^{+0.04}_{-0.03}$

$t_0 = 13.7^{+0.2}_{-0.2}$ Gyr

$t_{dec} = 379^{+8}_{-7}$ kyr

$t_r = 180^{+220}_{-80}$ Myr (95% CL)

$\Delta t_{dec} = 118^{+3}_{-2}$ kyr

$z_{eq} = 3233^{+194}_{-210}$

$\tau = 0.17^{+0.04}_{-0.04}$

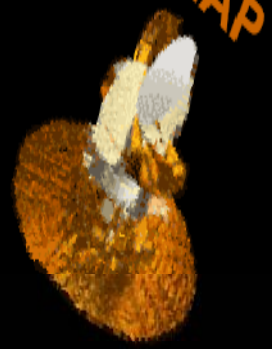
$z_r = 20^{+10}_{-9}$ (95% CL)

$\theta_A = 0.^\circ598^{+0.002}_{-0.002}$

$d_A = 14.0^{+0.2}_{-0.3}$ Gpc

$l_A = 301^{+1}_{-1}$

$r_s = 147^{+2}_{-2}$ Mpc



There is very interesting phenomenon:

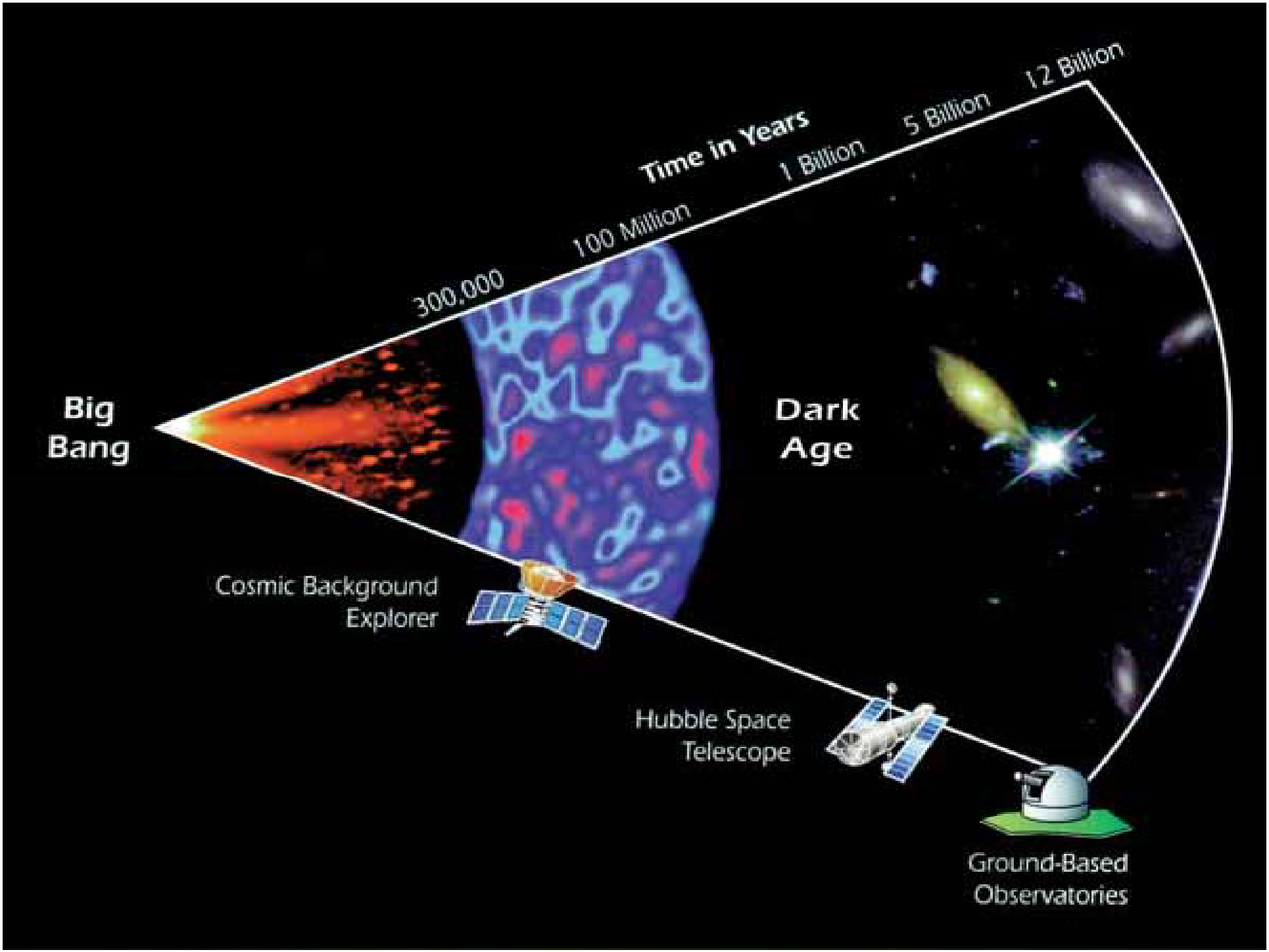
the more we know about the Universe

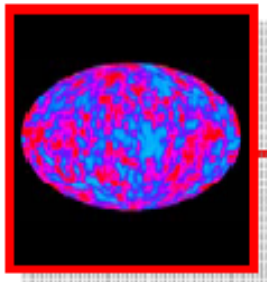
than more and more
it is getting **dark**

Dark Energy

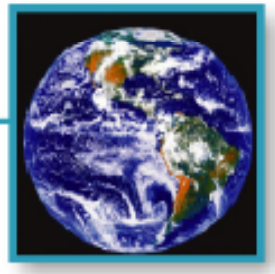
Dark Matter

Dark Ages


Time in Years
300,000
100 Million
1 Billion
5 Billion
12 Billion
Big Bang
Dark Age
Cosmic Background Explorer
Hubble Space Telescope
Ground-Based Observatories



Radiation:
0.005%

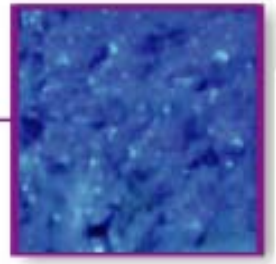


Chemical Elements:
(other than H & He) 0.025%

Neutrinos:
0.17%

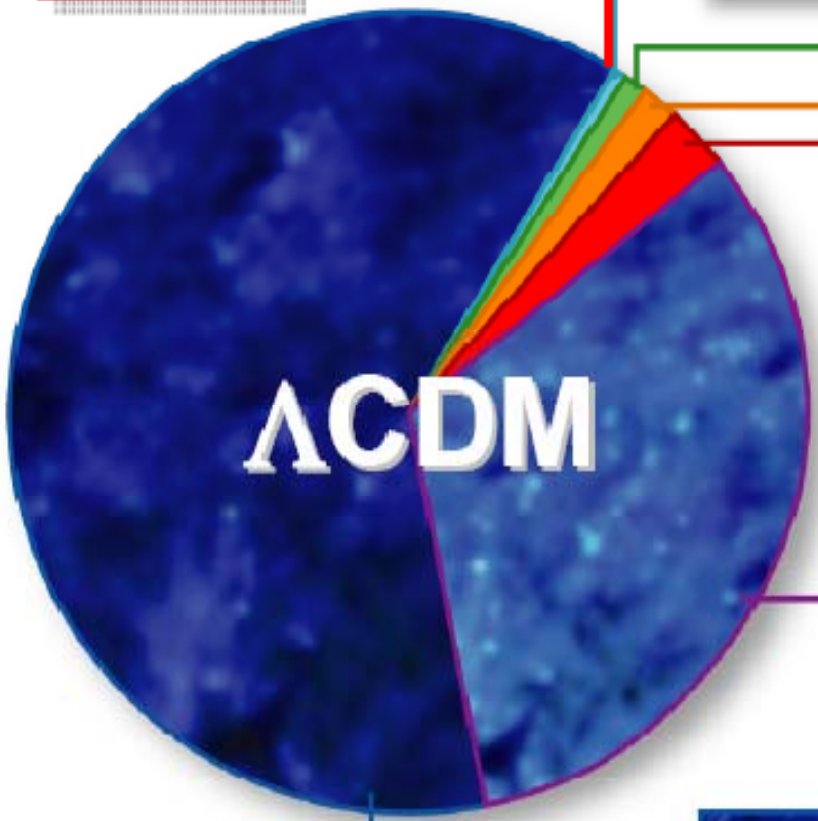
Stars:
0.8%

H & He:
gas 4%



Cold Dark Matter:
(CDM) 25%

Dark Energy (Λ):
70%



+ inflationary perturbations
+ baryo/lepto genesis

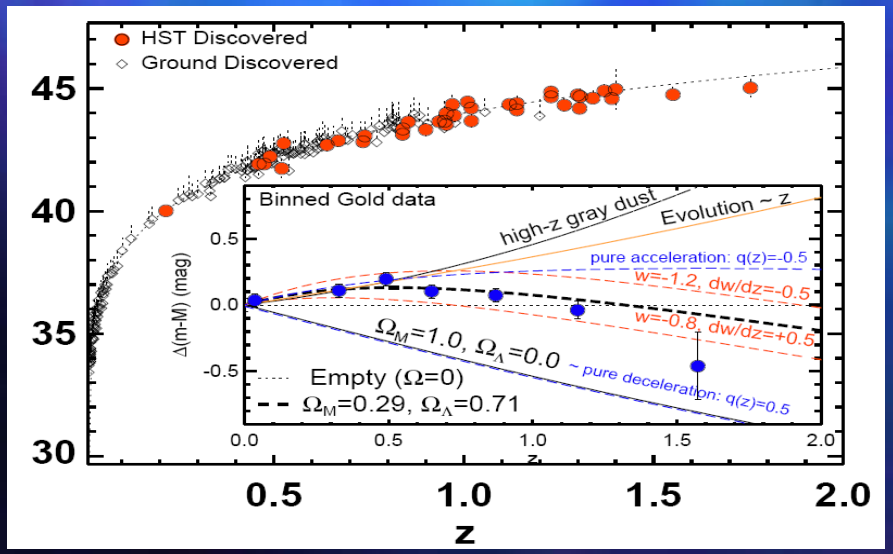
Dark Energy

Astrophysical observations

Non-clustering matter with unique Equation of State

$$p = -\varepsilon$$

which leads to accelerating expansion of the Univesre



Physical Nature ?

Λ-Term of Einstein

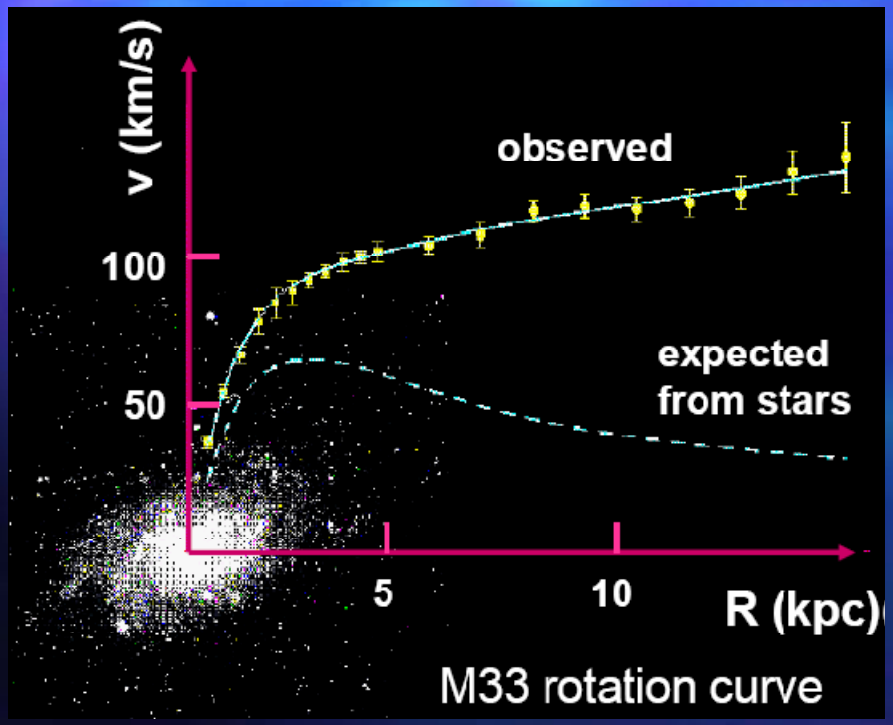
Quintessence

Scalar Fields

Dark Matter

Astrophysical observations

1. Rotation Curve of Galaxies
2. Gravitational Lensing
3. Dynamics of Galaxy Clusters
4. Large Scale Structure



Physical Nature ?

MOND
(Modified Newtonian Dynamics)

or

Relic Particles
beyond the Standard Model

Particle Relic From The Bang

- neutrinos (hot dark matter)
- sterile neutrinos, gravitinos (warm dark matter)
- LSP (neutralino, axino, …) (cold dark matter)
- LKP (lightest Kaluza-Klein particle)
- axions, axion clusters
- solitons (Q-balls; B-balls; Odd-balls, ….)
- supermassive wimpzillas

Mass range	Interaction strength range
10^{-6} eV (10^{-40} g) axions	Noninteracting: wimpzillas
$10^{-8}\,M_{\odot}$ (10^{25} g) axion clusters	Strongly interacting: B balls

The key experiment
which gives us
the most precise cosmological
information

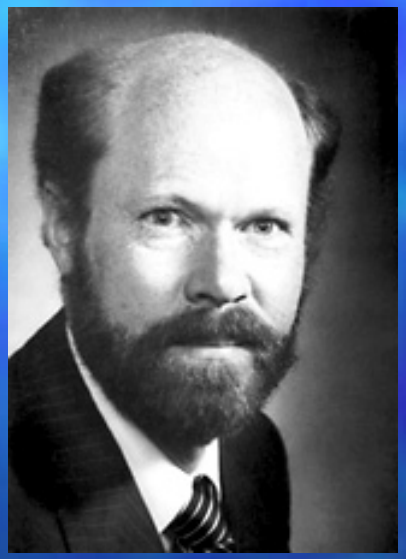
...

The Nobel Prize in Physics

1978

for their discovery of the cosmic microwave background radiation

Arno A. Penzias
1/4 of the prize
USA



Robert W. Wilson
1/4 of the prize
USA

2006

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

John C. Mather
1/2 of the prize
USA

George F. Smoot
1/2 of the prize
USA

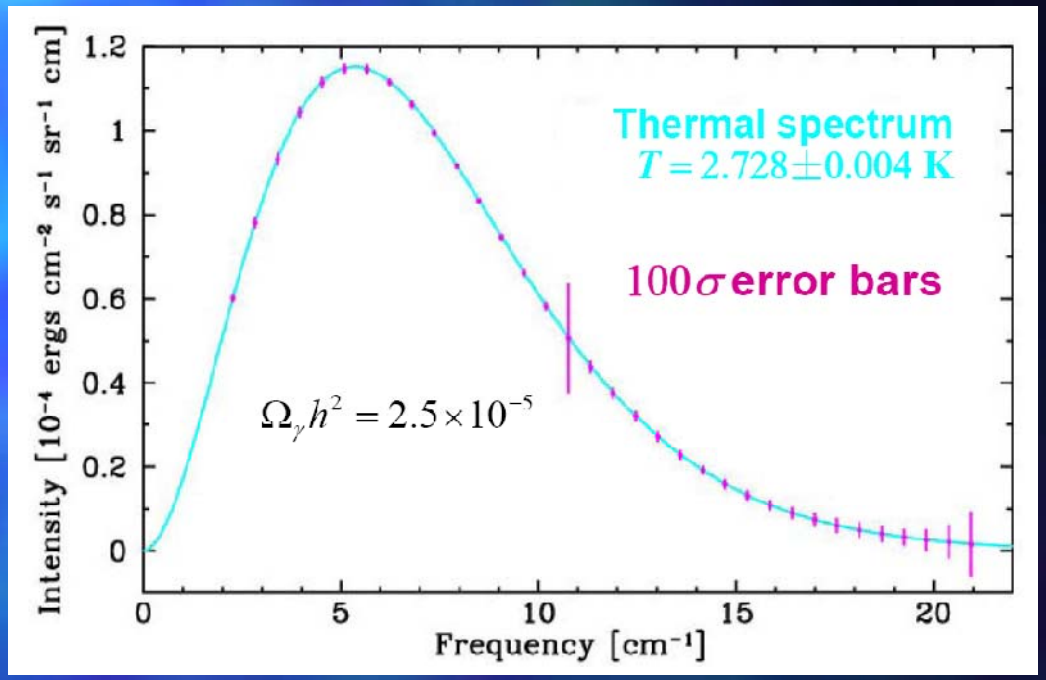
Cosmic Microwave Background Radiation

$$B_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

$$T = 2.725 \pm 0.002\ \mathrm{K}$$

$$T = T_0(1+z)$$

$$\eta = \frac{n_\gamma}{n_b} \cong 10^9$$



$$\nu \in 400\ \mathrm{MHz} \div 300\ \mathrm{GHz}$$

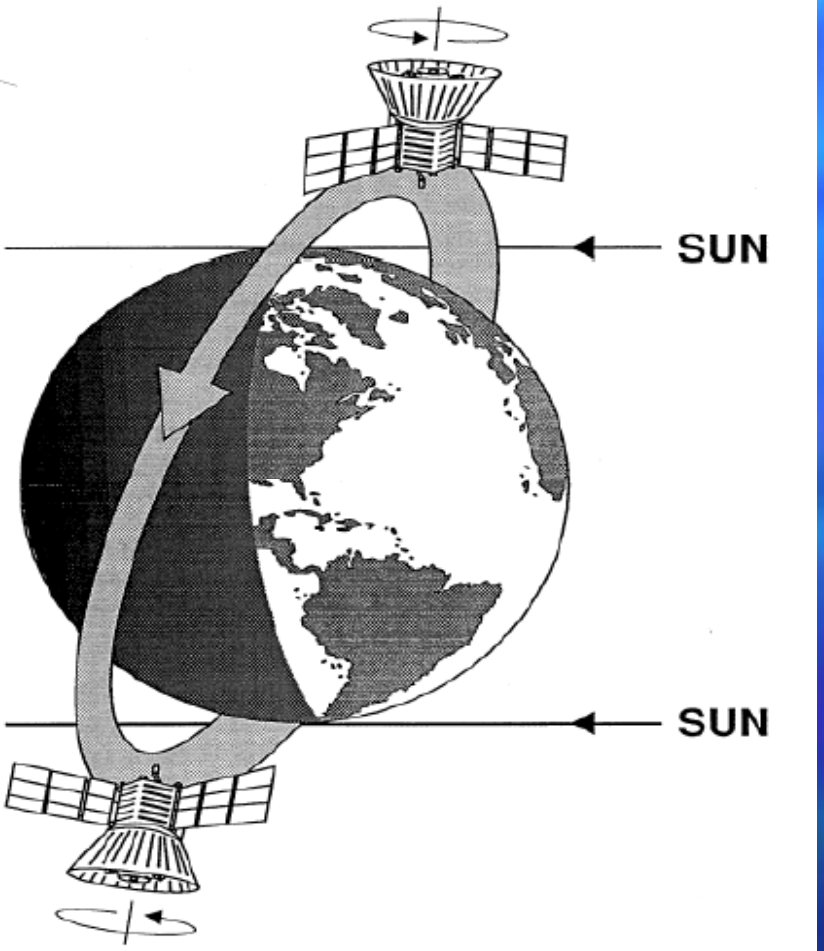
$$\lambda \in 0.1 \div 74\ \mathrm{cm}$$

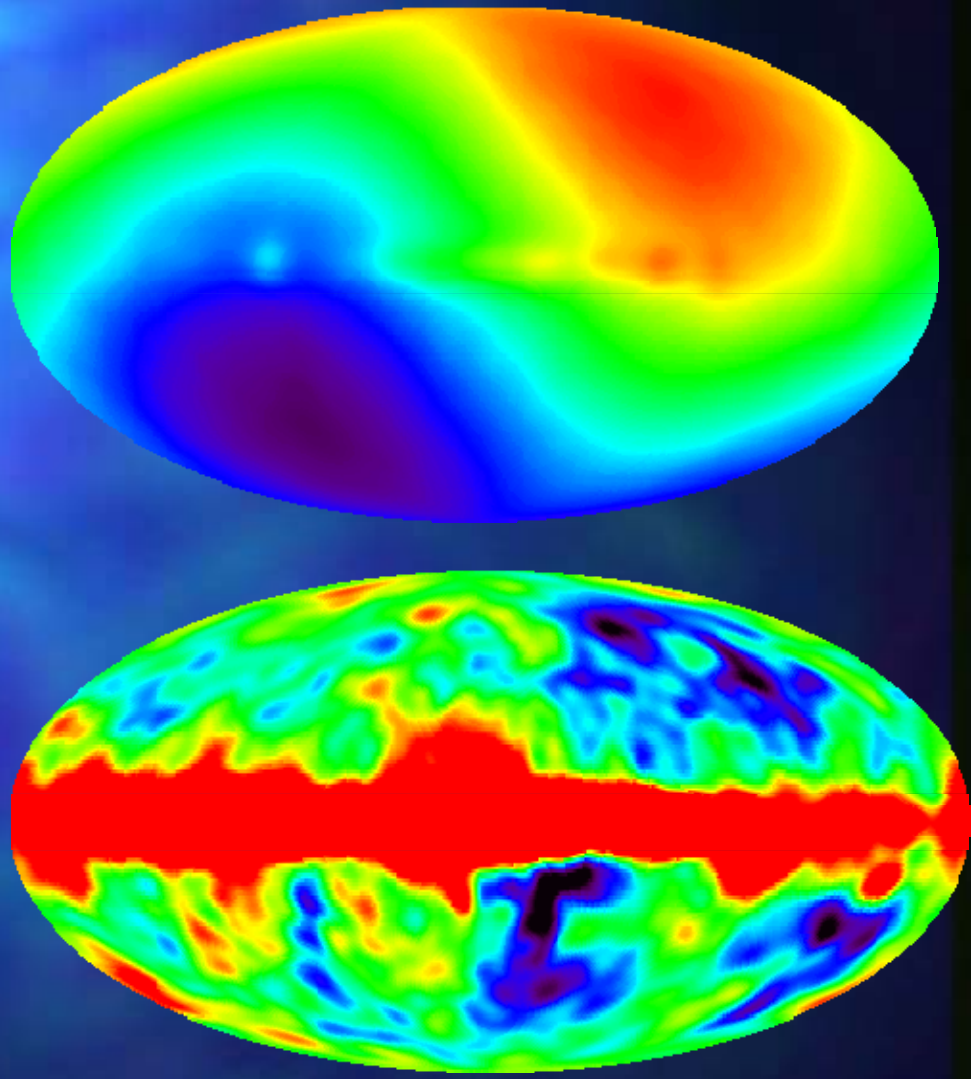
$$n_\gamma \cong 412\ \mathrm{cm}^{-3} \qquad \varepsilon_\gamma \cong 0.25\ \mathrm{eV/cm}^{-3}$$

COBE (the first results 1992)

$\Delta T_{dip} = 3.346 \pm 0.017$ mK

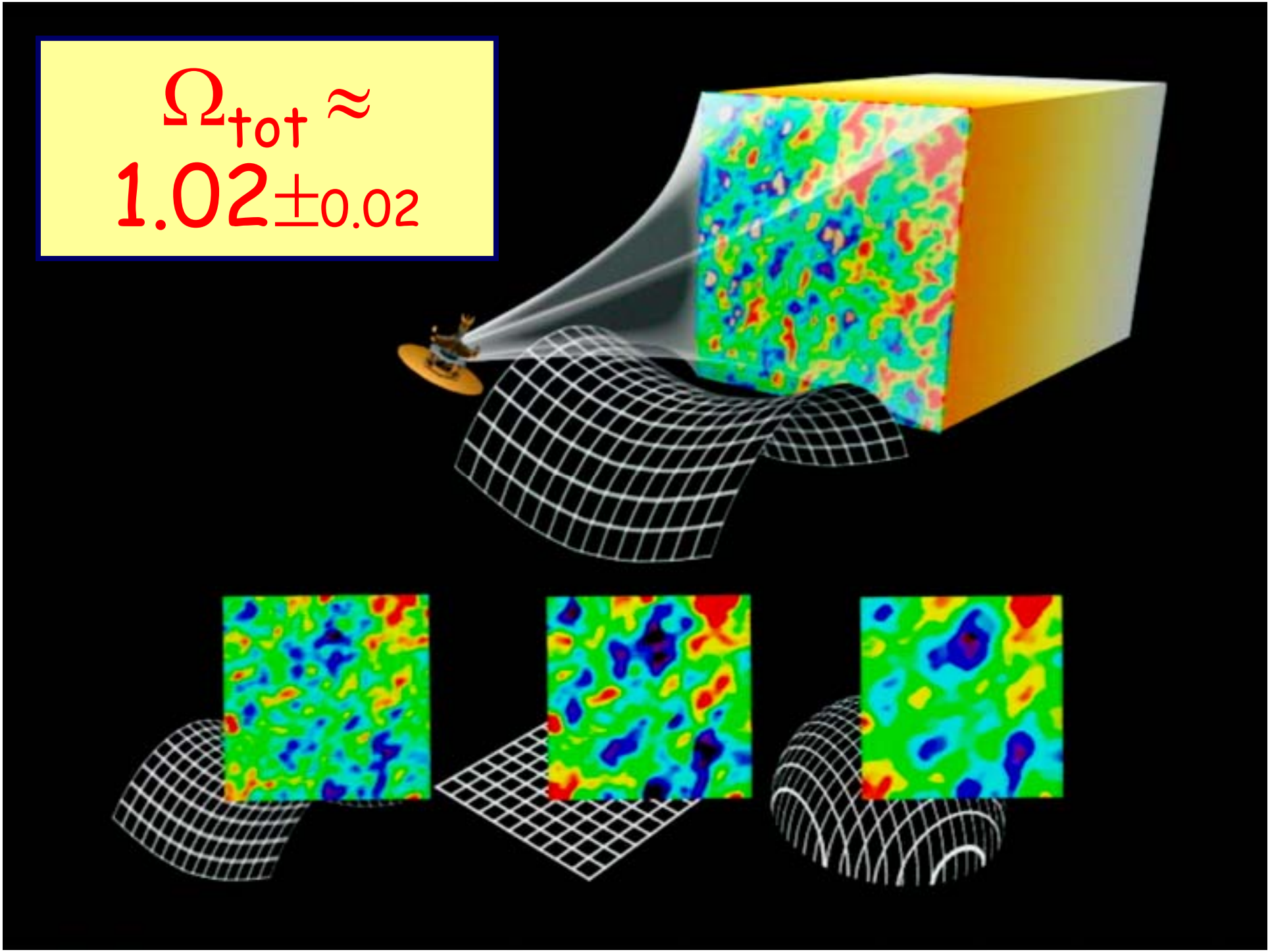
$V = 368 \pm 2$ km/sec

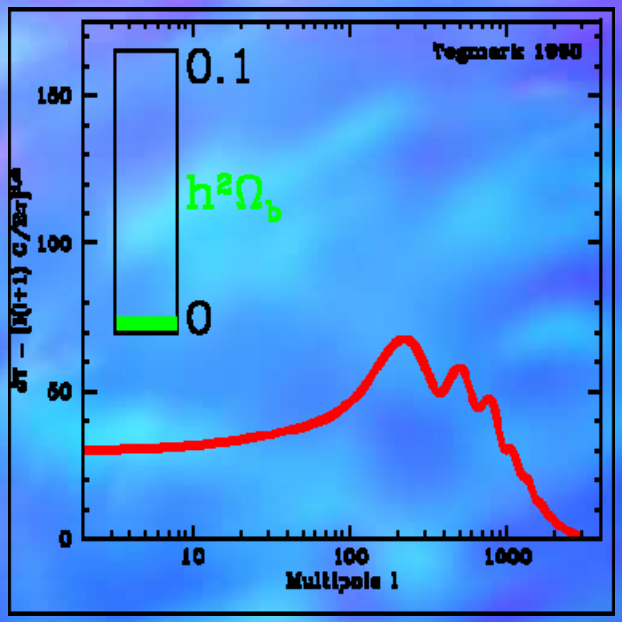


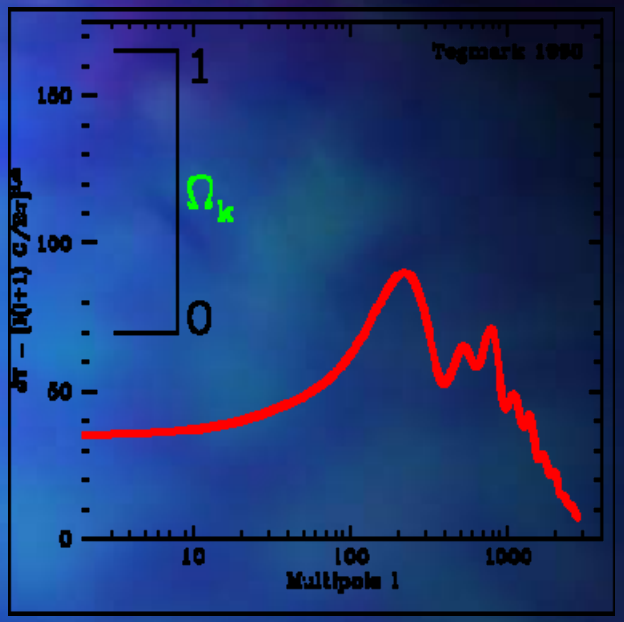


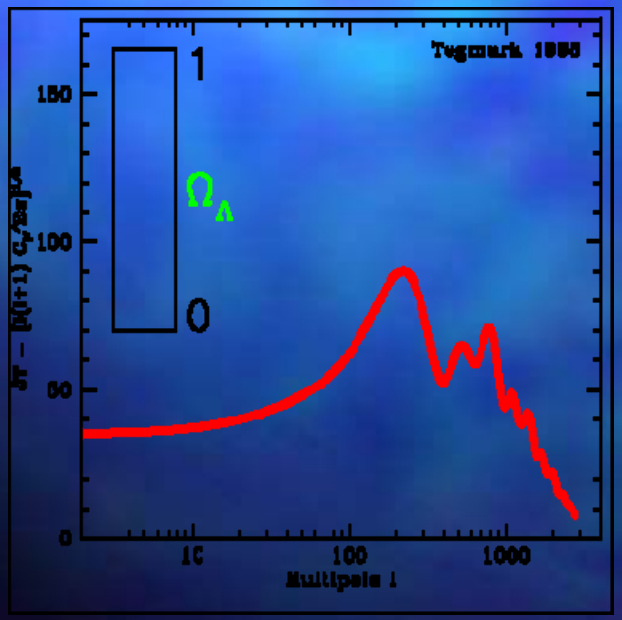
$\Delta T = 0.018\,\mu$K

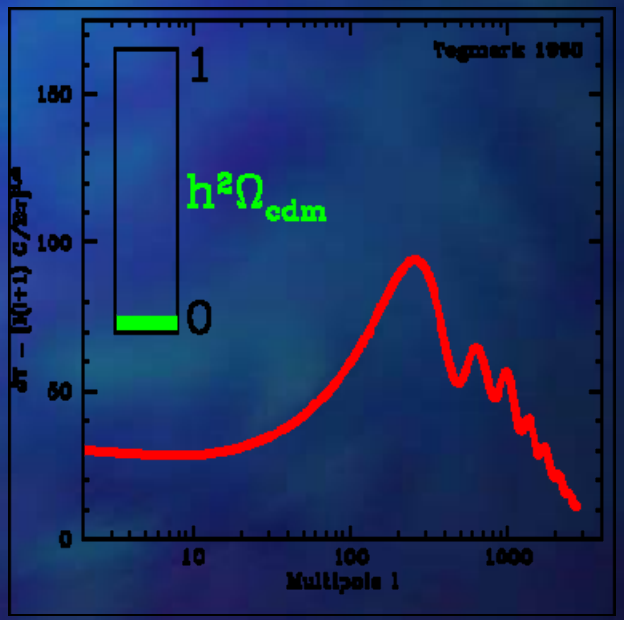
$\Omega_{tot} \approx 1.02 \pm 0.02$

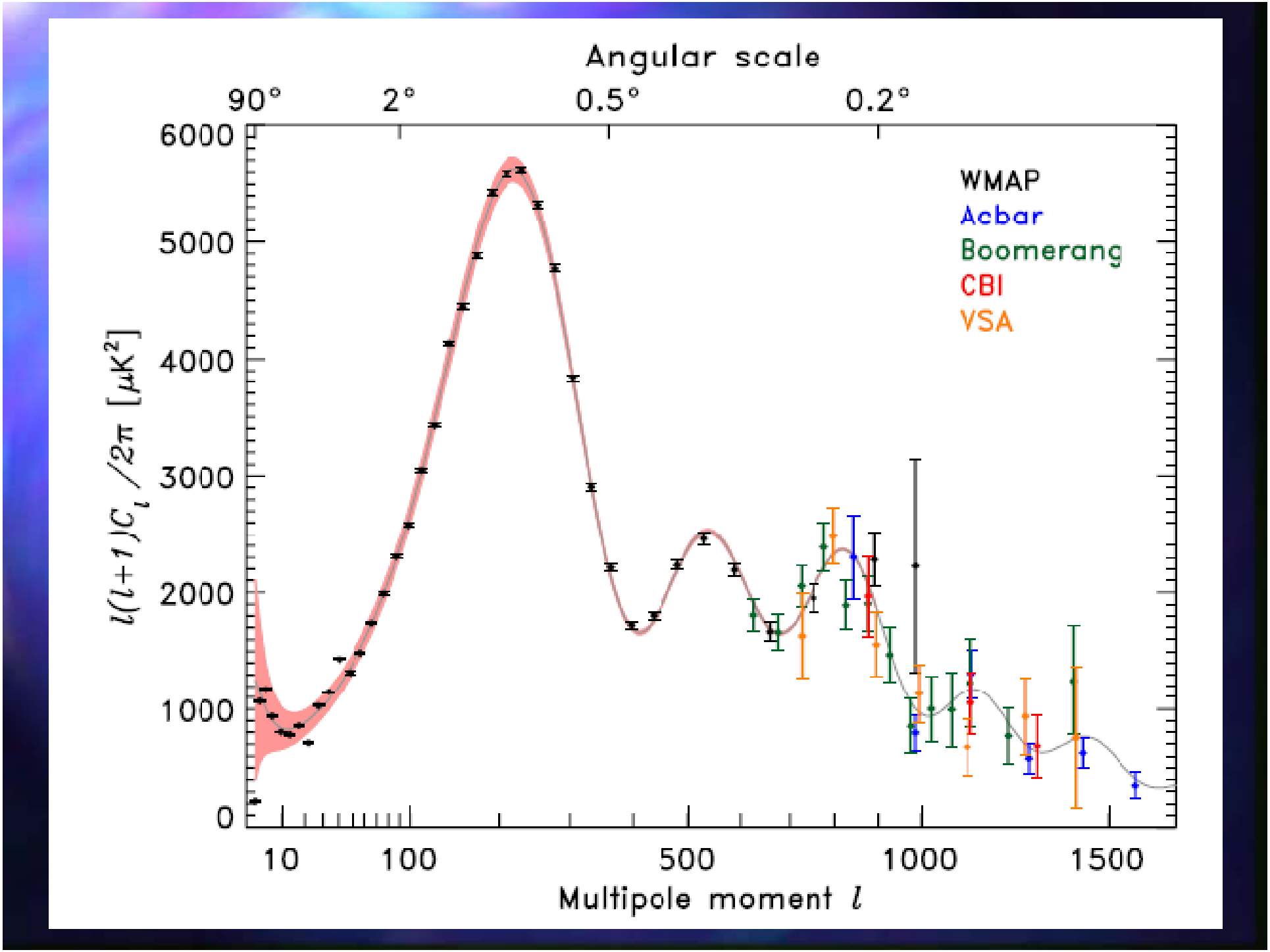



Tegmark 1995
0.1
$h^2\Omega_b$
0
150
100
50
0
10
100
1000
Multipole l


Tegmark 1995
1
Ω_k
0
150
100
50
0
10
100
1000
Multipole l


Tegmark 1995
1
Ω_Λ
0
150
100
50
0
10
100
1000
Multipole l

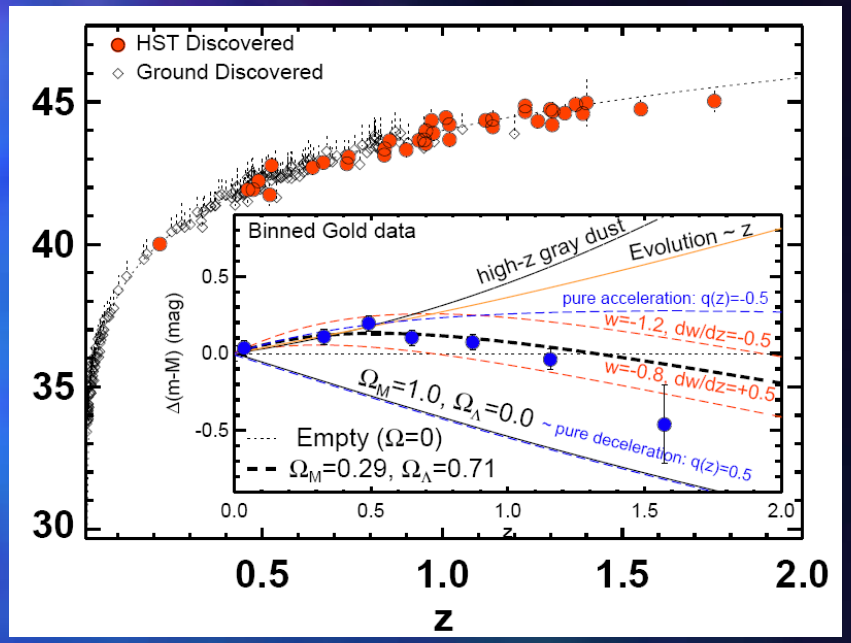

Tegmark 1995
1
$h^2\Omega_{cdm}$
0
150
100
50
0
10
100
1000
Multipole l

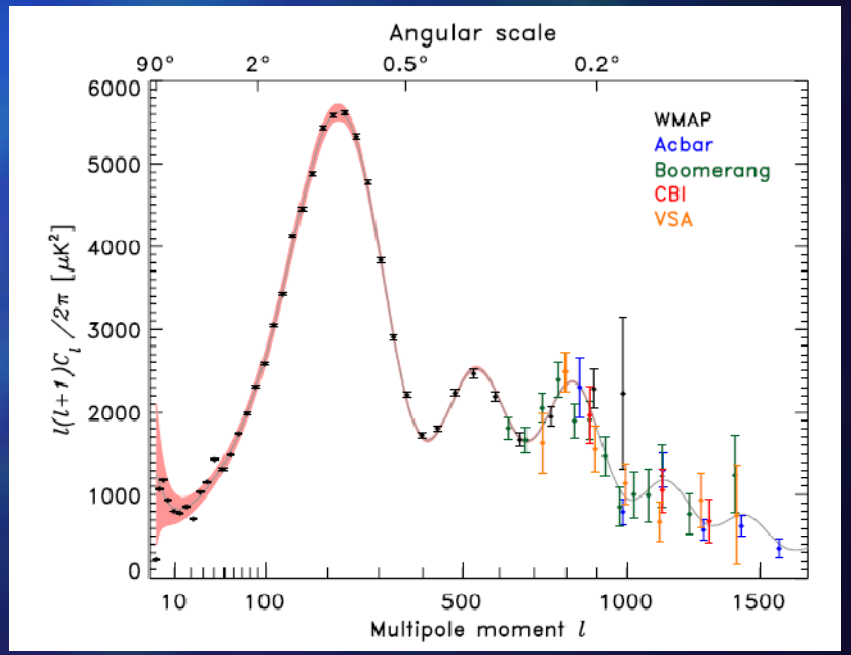

Angular scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ [μK^2]
WMAP
Acbar
Boomerang
CBI
VSA
10
100
500
1000
1500
Multipole moment l

The most precise experiments

$\Omega_{DE} \approx 70\%$

$\Omega_{DM} \approx 27\%$





What is Dark Energy ?
What is Dark Matter ?

Great expectation are concerned with two launched mission

...

Precision Cosmology

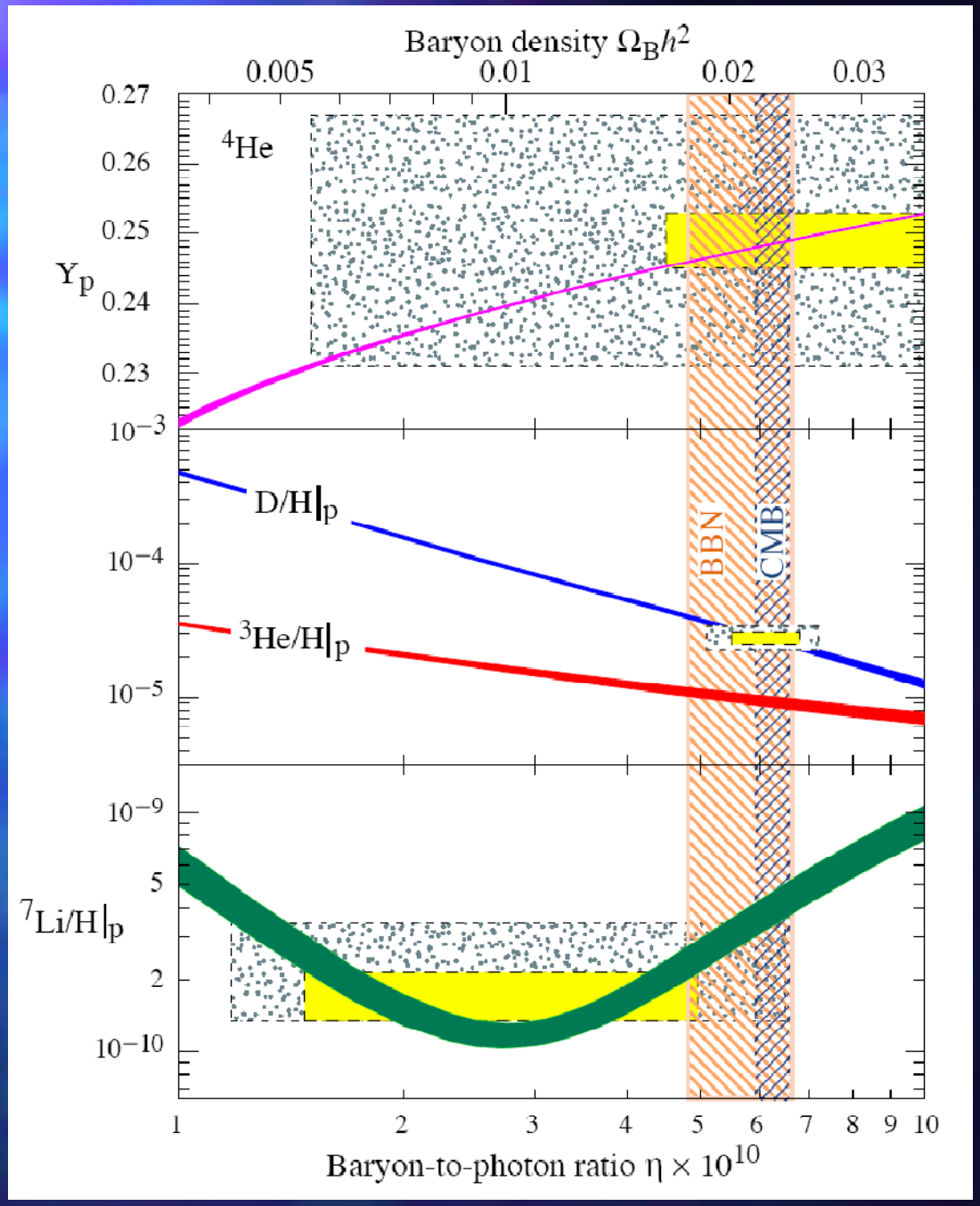
Large Hadron Collider

Fundamental Fields and Particles

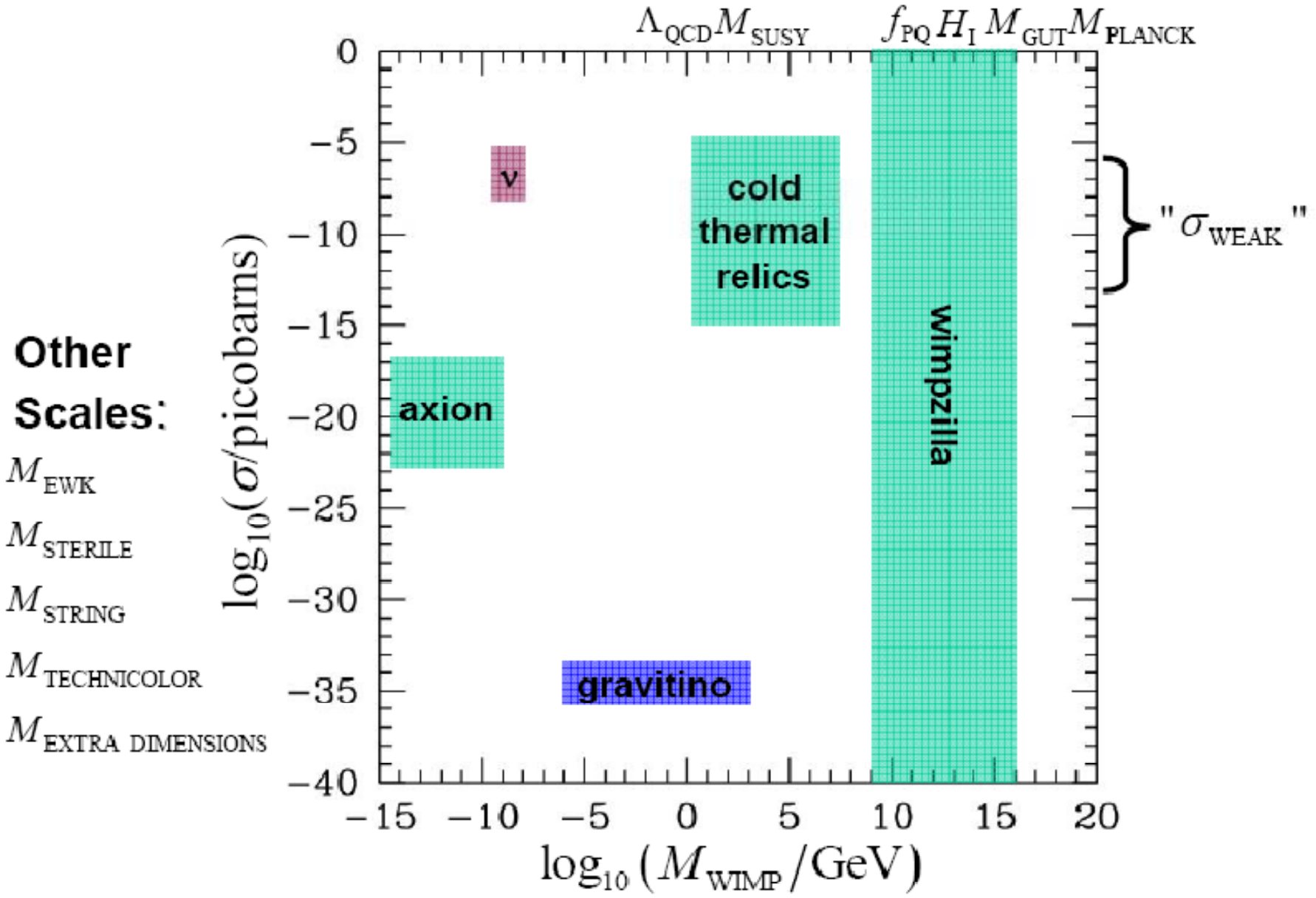
Thank you
for
your attention

BBN & CMB

$\Omega_b \approx 0.044$



Particle Dark Matter Candidates



Other Scales:

M_{EWK}

$M_{STERILE}$

M_{STRING}

$M_{TECHNICOLOR}$

$M_{EXTRA\ DIMENSIONS}$