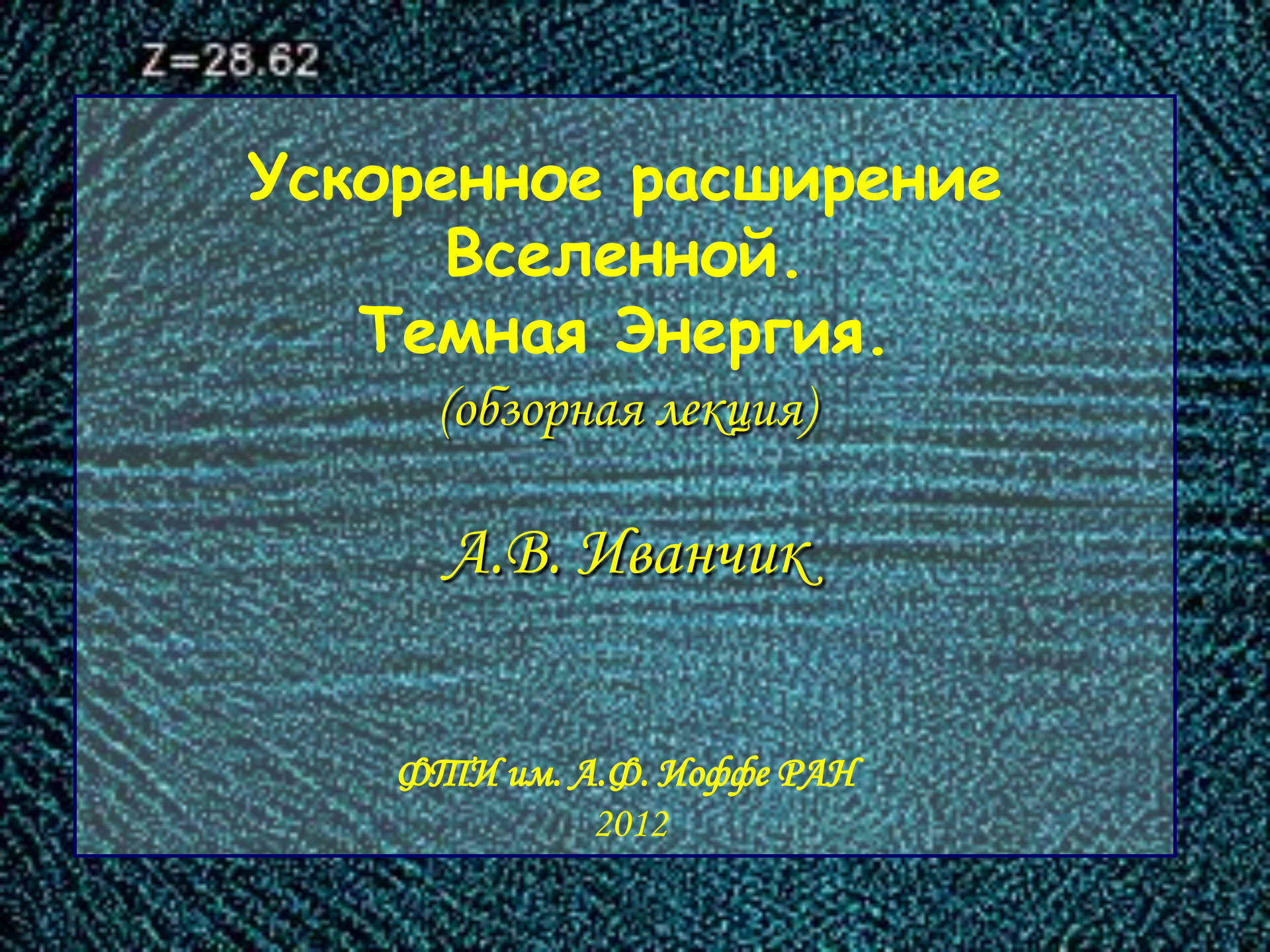


Ускоренное расширение Вселенной. Темная Энергия.

(обзорная лекция)

А.В. Иванчик

ФТИ им. А.Ф. Иоффе РАН

2012

The Nobel Prize in Physics

1978

За открытие космического микроволнового фонового излучения

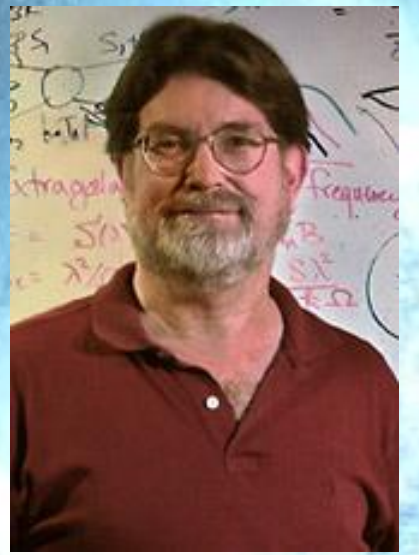
Arno A. Penzias
1/4 of the prize
USA

Robert W. Wilson
1/4 of the prize
USA

2006

За открытие чернотельной формы и анизотропии CMBR

John C. Mather
1/2 of the prize
USA



George F. Smoot
1/2 of the prize
USA

The Nobel Prize in Physics 2011

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

«за открытие ускоренного расширения Вселенной по наблюдениям удаленных сверхновых»

Saul Perlmutter

Lawrence Berkeley National Laboratory

1/2

Brian P. Schmidt **Adam G. Riess**

Australian National University

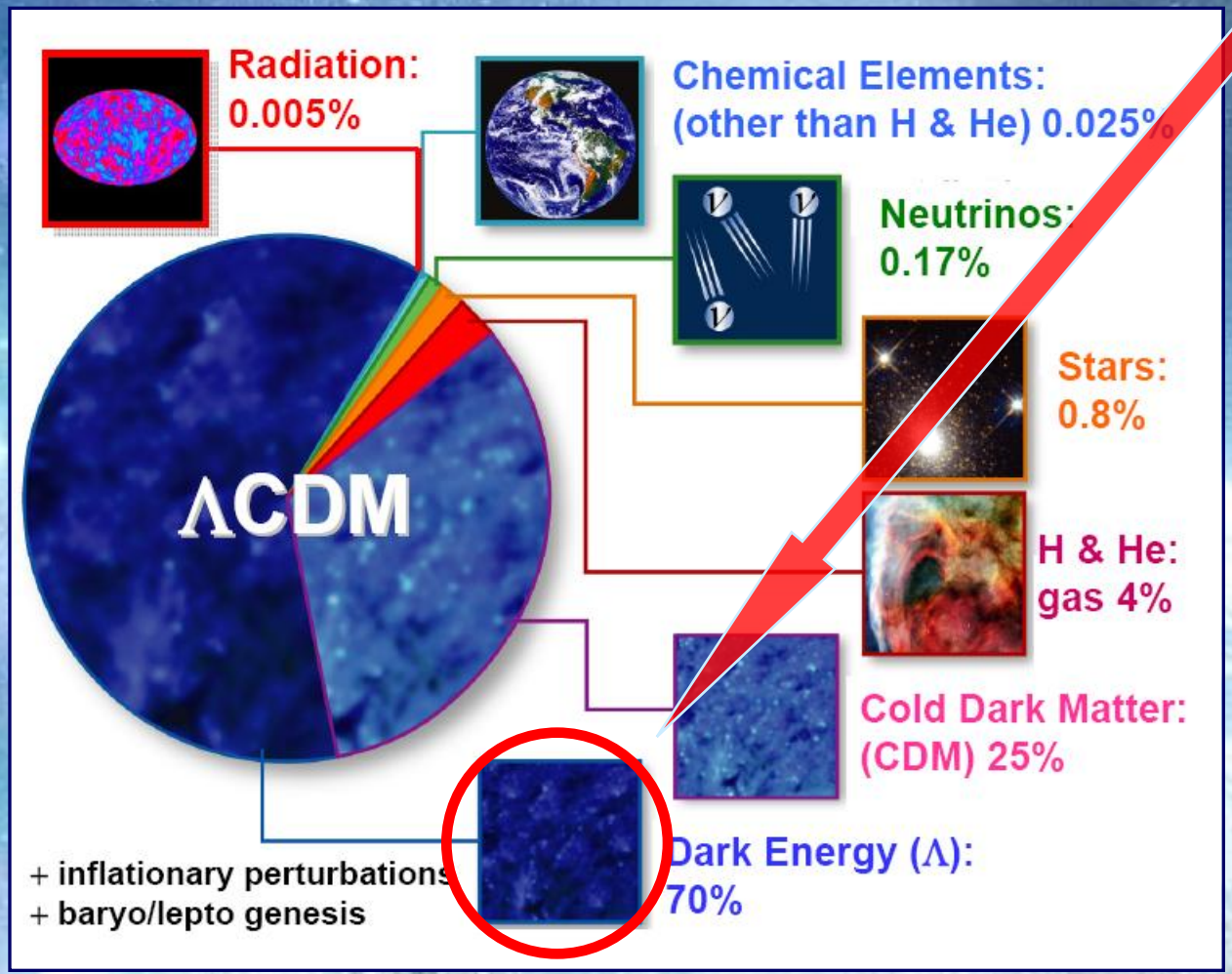
1/2

Универсальность и «знаки» Фундаментальных взаимодействий

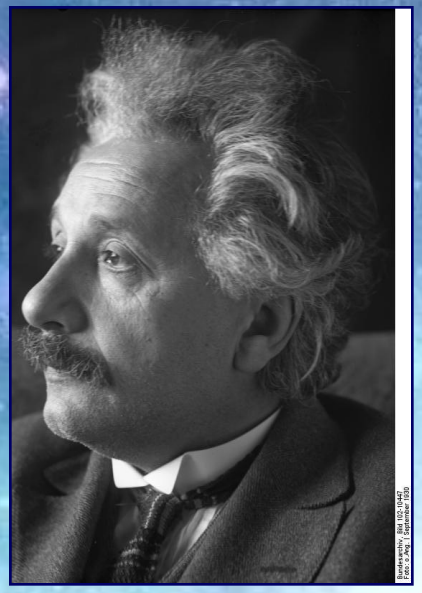
Сильное	(+/-) кварки и глюоны
Электромагнитное	(+/-) электрически заряженные частицы, фотоны
Электросалабое	(+/-) Барионы и лептоны
Гравитационное	(+) все существующие частицы (известные и неизвестные)

Формы материи во Вселенной

$\Omega_\Lambda \sim 70\ \%$



Начальные этапы современной космологии



Эйнштейн

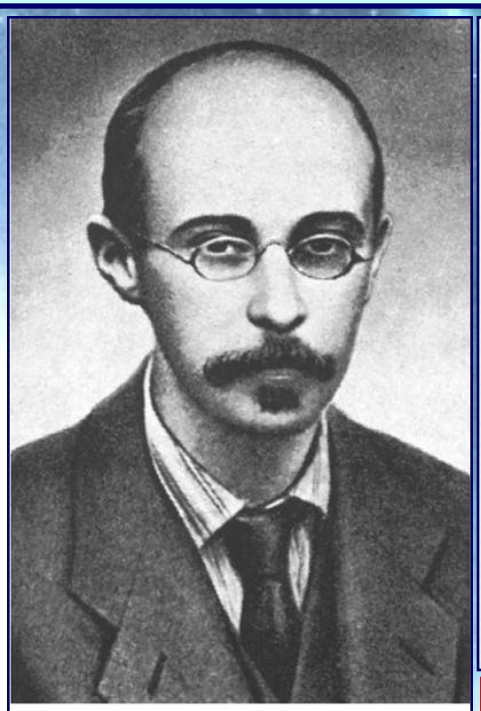
1916 ОТО
1917 Ст.Вс.

де Ситтер (1917)

Слайфер (1910-1924)

Вейль

Эддингтон



Фридман

1922
Нестационарная Вселенная

Хаббл

1929
Закон расширения

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Уравнения Фридмана

Космологический Принцип

$$ds^2 = dt^2 - a^2(t)\left[dr^2/(1-kr^2) + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right]$$

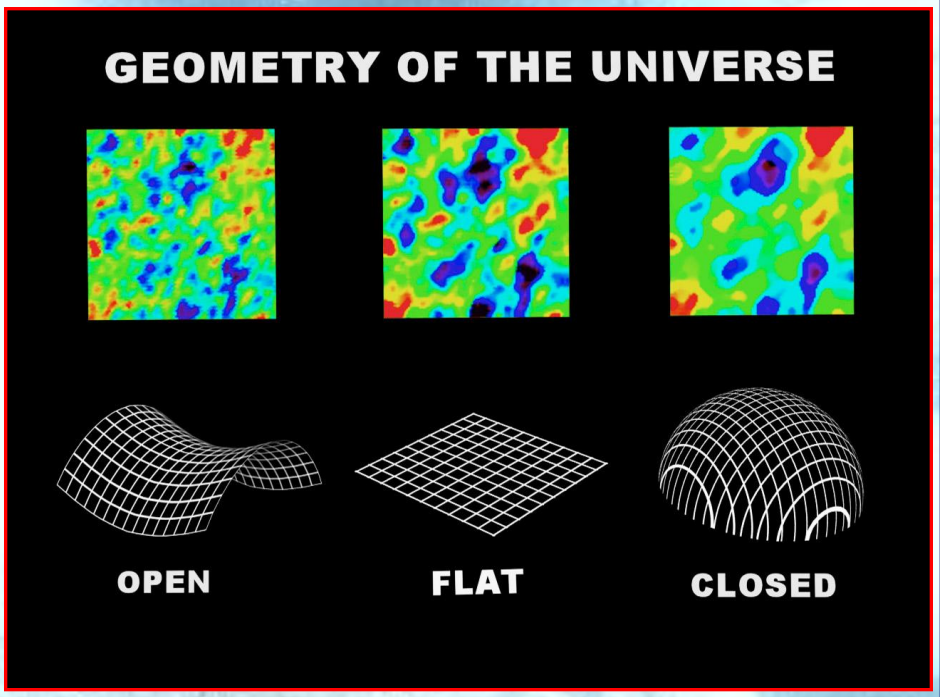
ОТО

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Уравнения Фридмана

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

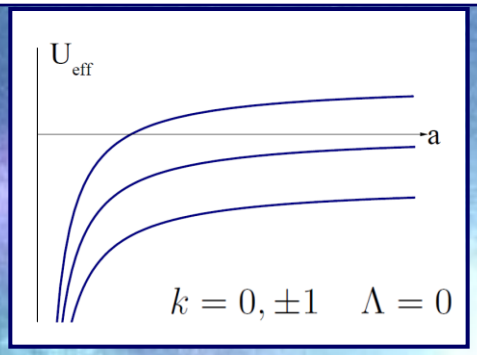
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3},$$

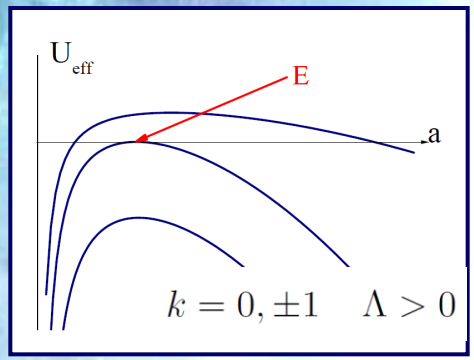


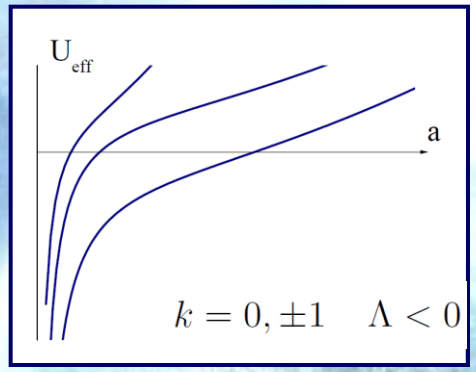
Классификация решений Фридмана

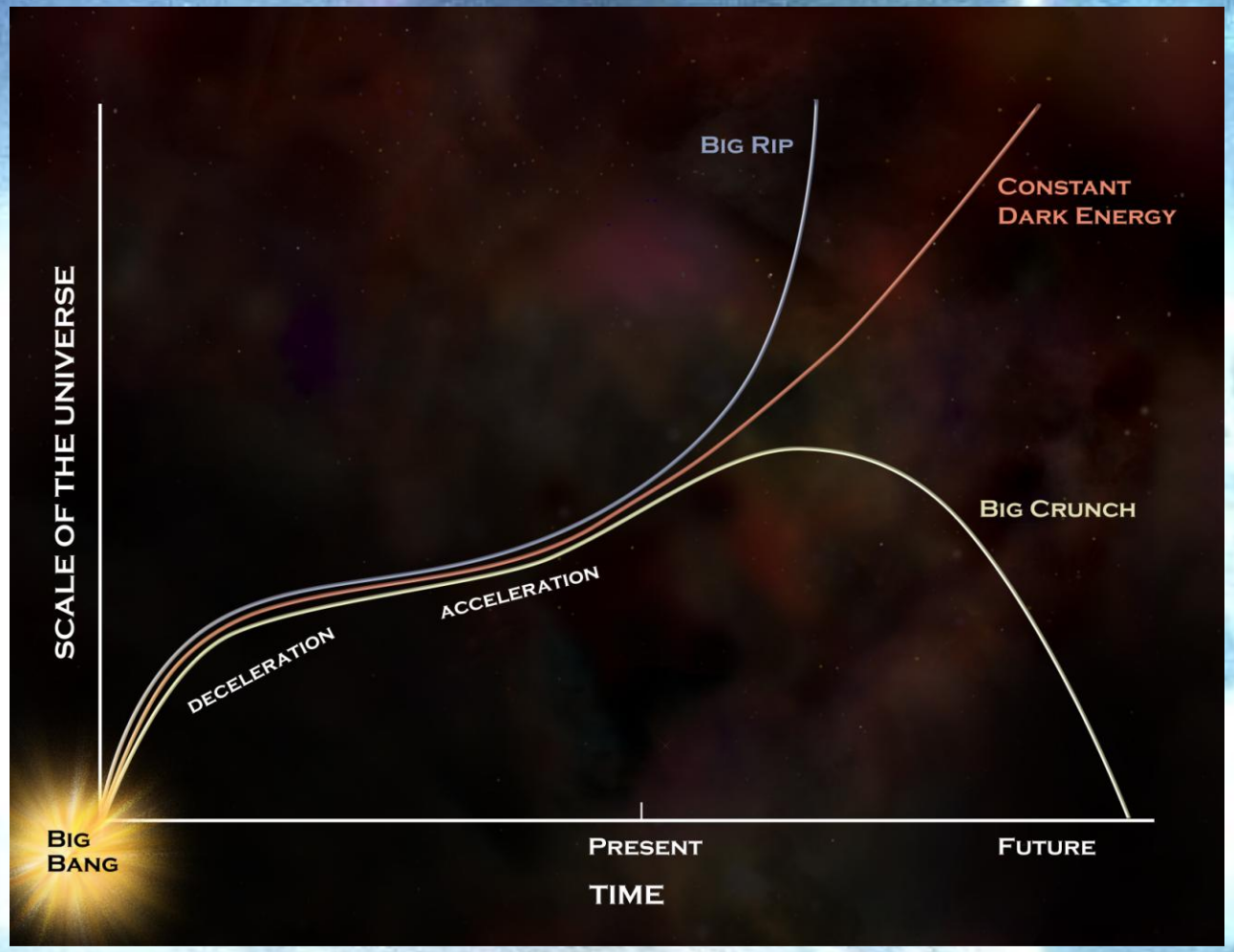
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$\dot{a}^2 + U_{eff}(a) = 0, \qquad U_{eff} = k - \frac{8\pi G}{3}\frac{\rho_0}{a^3}a^2 - \frac{\Lambda}{3}a^2$$

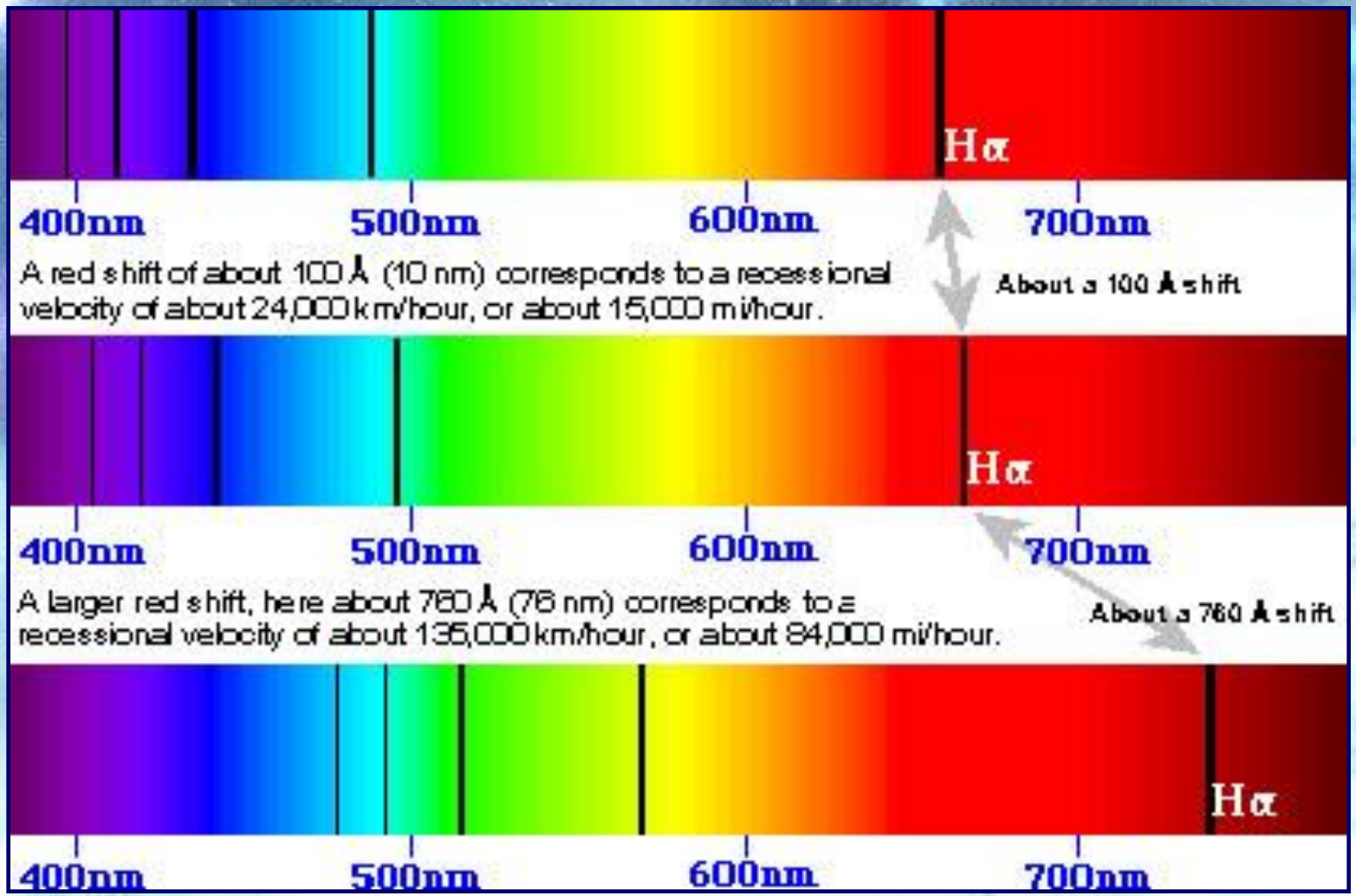








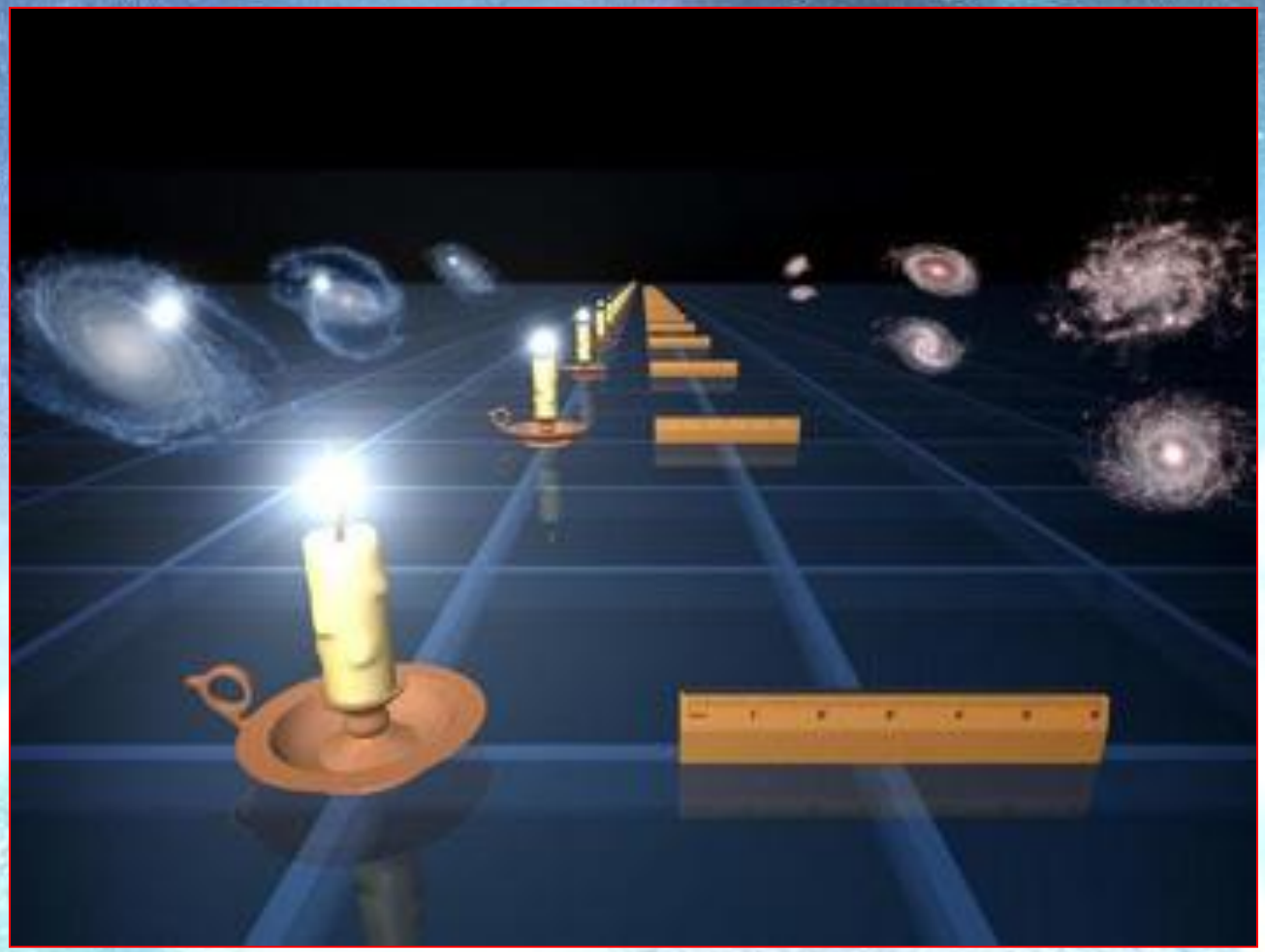
Как измерять скорость расширения ?



$$\lambda_{obs} = \lambda_0(1+z)$$

Стандартные свечи

ЦЕФЕИДЫ



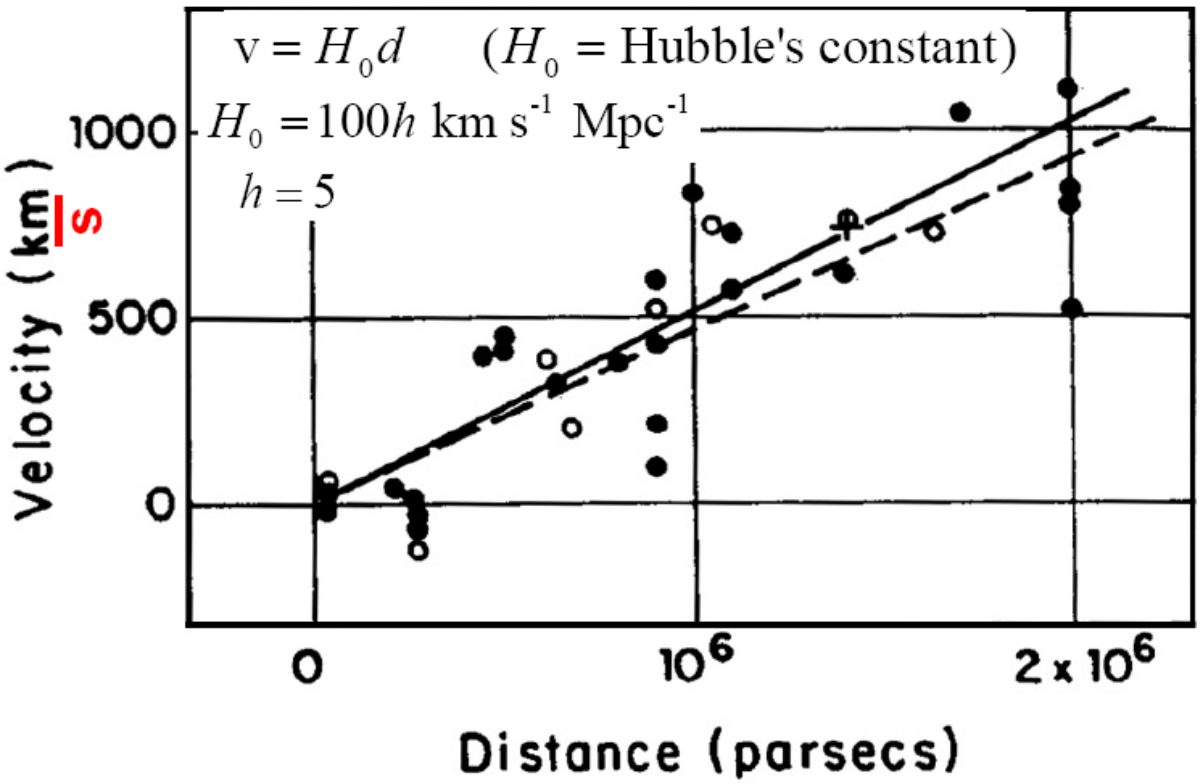
SNe Ia

Первый наблюдательный базис современной космологии

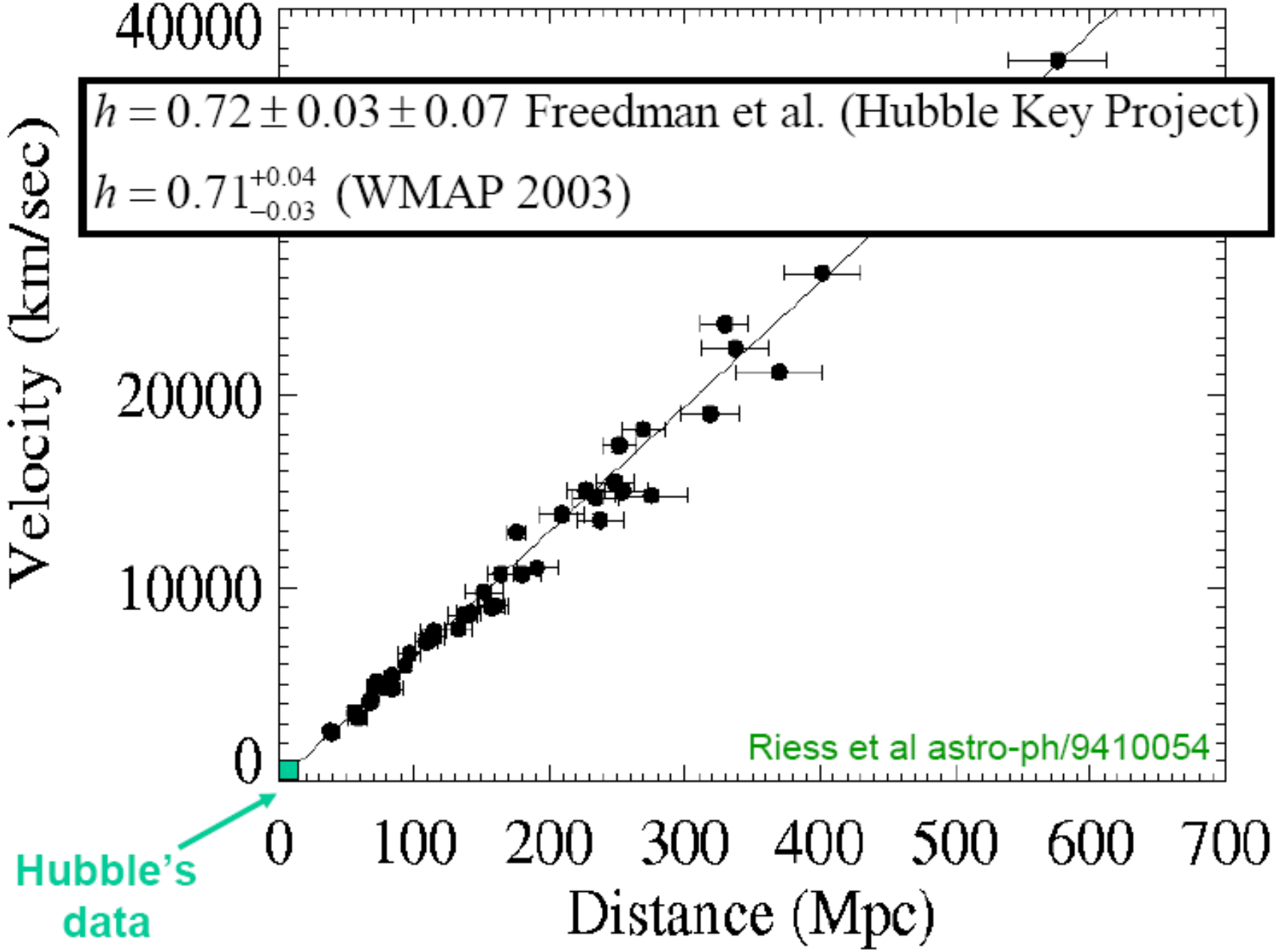
1929: Edwin Hubble

$$v = H \times r$$

Hubble's Discovery Paper – 1929



$$H_0 d_L = z + \frac{1}{2}(1 - q_0)z^2 + \dots, \qquad q_0 \equiv -\frac{\ddot{a}}{aH^2}$$


$h = 0.72 \pm 0.03 \pm 0.07$ Freedman et al. (Hubble Key Project)
$h = 0.71^{+0.04}_{-0.03}$ (WMAP 2003)
Velocity (km/sec)
40000
20000
10000
0
0
100
200
300
400
500
600
700
Distance (Mpc)
Riess et al astro-ph/9410054
Hubble's data

«Если не существует
квазистатического Мира,
то долой
космологический член»
(1923, 1982)

«the greatest blunder»
(~1940, 1970)

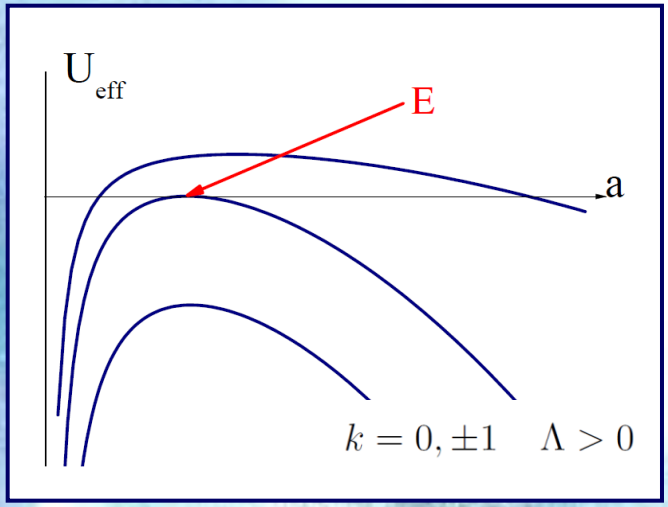
...

Вакуум как гравитация вакуумных флуктуаций

1960

Квазары

Z ~ 2



1965 – Э.Б. Глинер (ФТИ им. А.Ф. Иоффе)

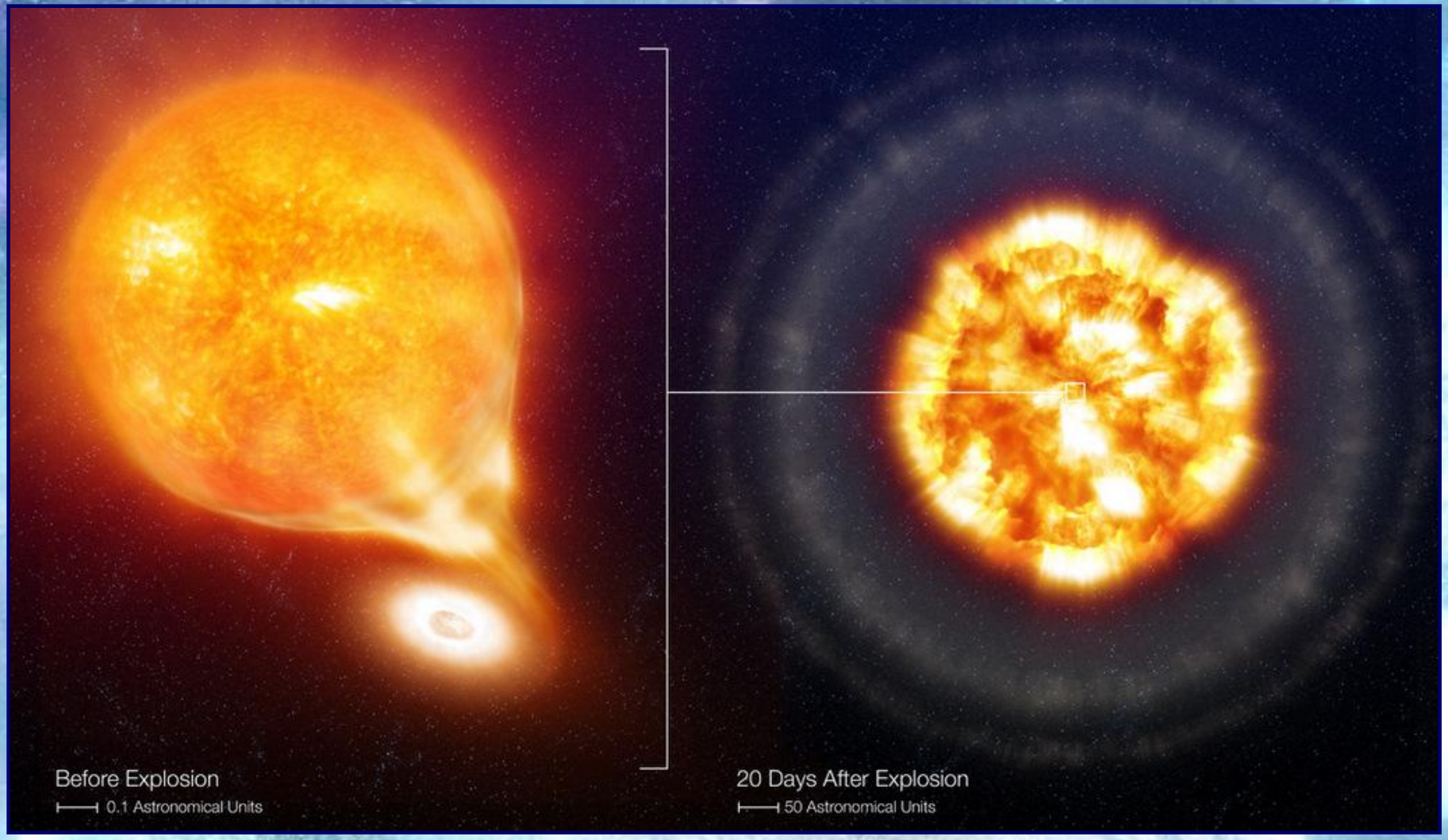
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G \left(\sum_a T_{\mu\nu}^{(a)} + T_{\mu\nu}^{DE} \right)$$

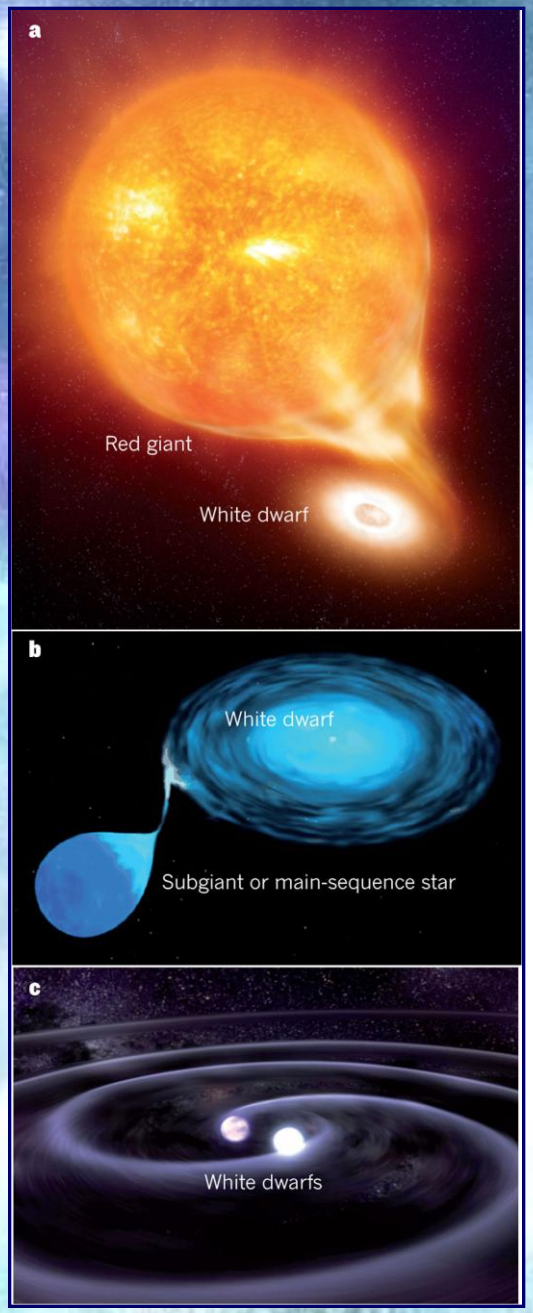
1968 – Я.Б. Зельдович

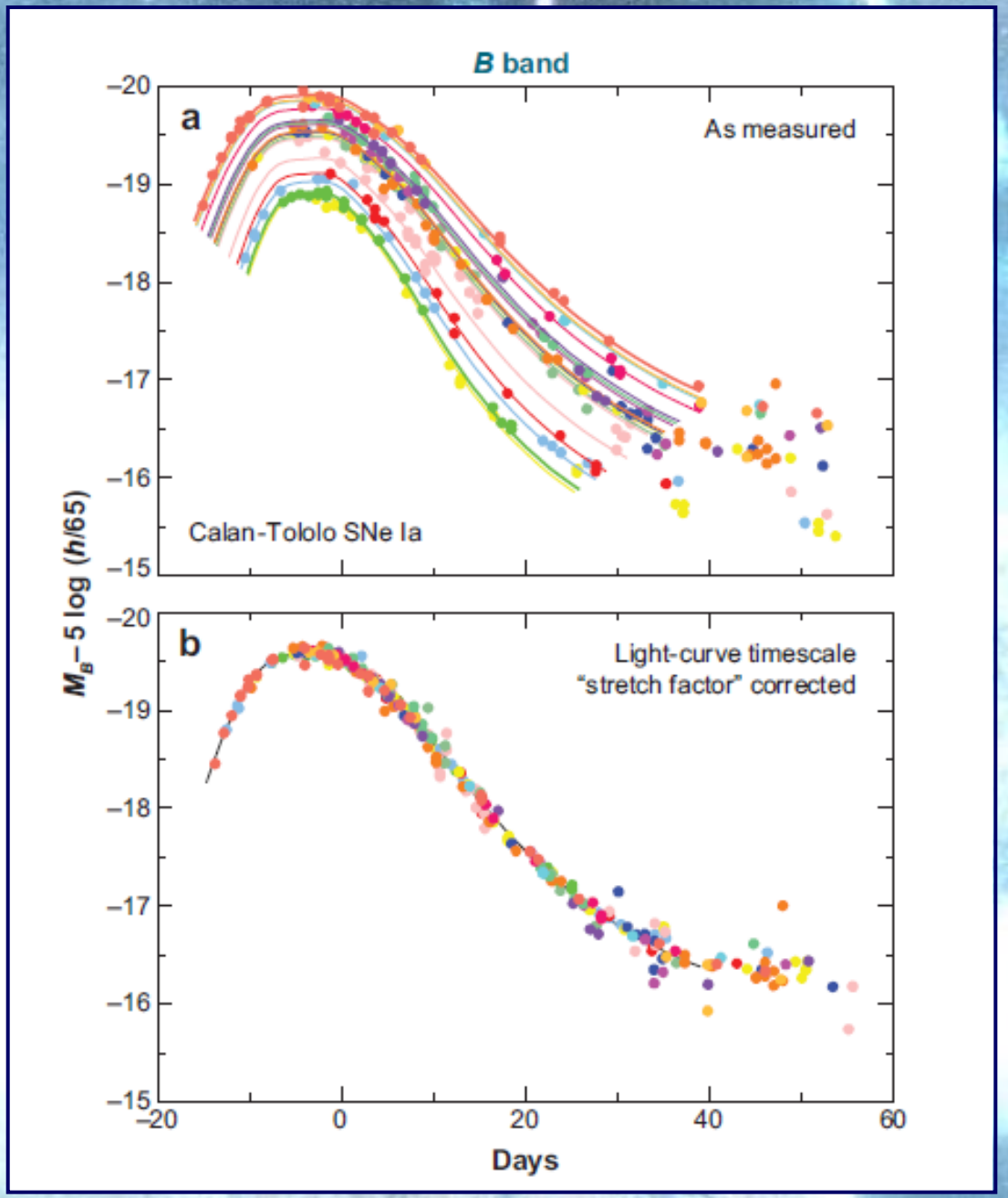
$$\rho_{\mathrm{VAC}} = \frac{1}{2} \sum_{\text{fields}} g_i \int_0^\infty \sqrt{k^2 + m^2} \, \frac{d^3 k}{(2\pi)^3} \simeq \sum_{\text{fields}} \frac{g_i k_{\max}^4}{16\pi^2}$$

Сверхновые звезды Ia – новые стандартные свечи.



Сверхновые звезды Ia – стандартные свечи.



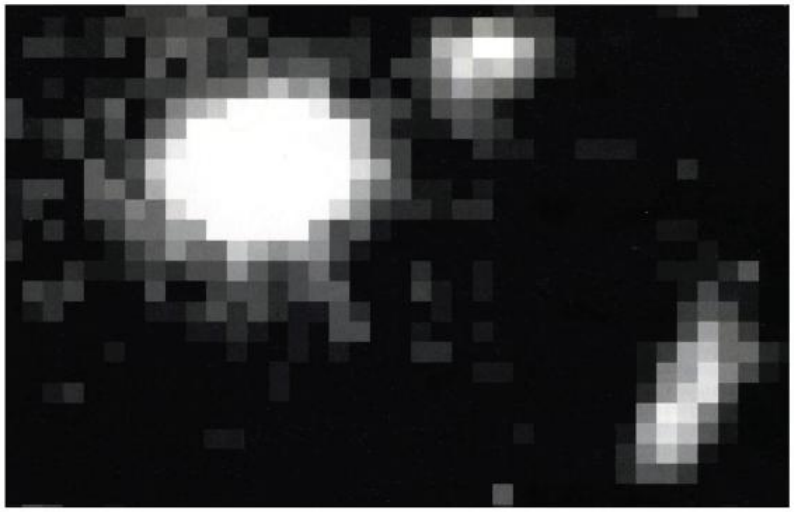


The Supernova Cosmology Project (SCP) was initiated in 1988 by **Saul Perlmutter** of the Lawrence Berkeley National Laboratory (LBNL), USA, with the aim of measuring the presumed **deceleration** of the Universe - using SNe Ia as standard candles.

$$q_0 \equiv -\frac{\ddot{a}}{aH^2}$$

Prompted by the success of the *Supernova on Demand* strategy and motivated by the importance of the quest for q_0, **Brian Schmidt** of the Mount Stromlo Observatory in Australia and Nicholas Suntzeff of the Cerro Tololo Inter-American Observatory in Chile founded, in 1994, a competing collaboration, consisting of supernova experts, backed by the renowned scientist Robert Kirshner – the High-z Supernova Search Team (HZT). Over the following years, the HZT led by Schmidt and the SCP led by Perlmutter independently searched for supernovae, often but not always at the same telescopes.

Практические измерения



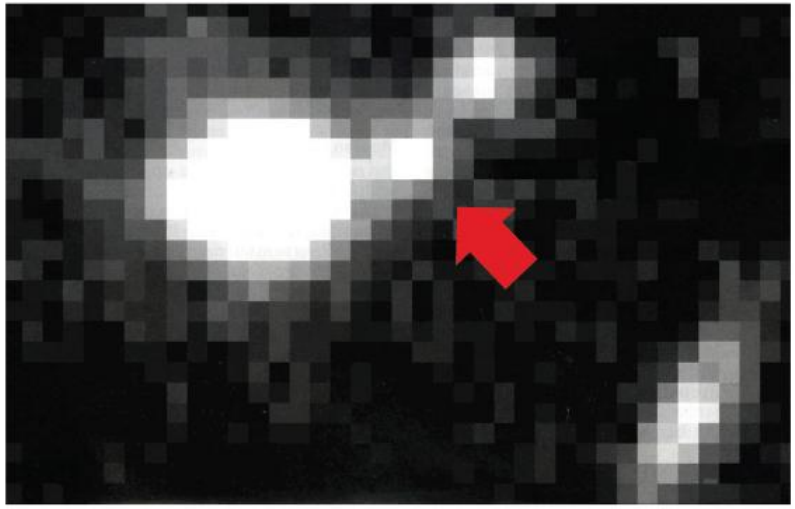
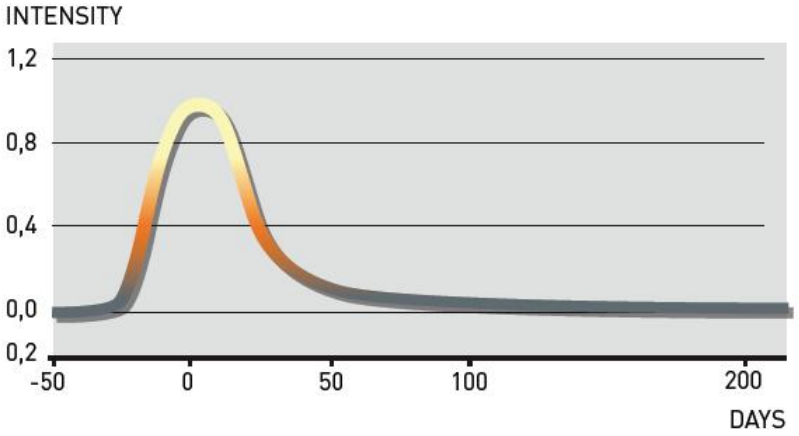
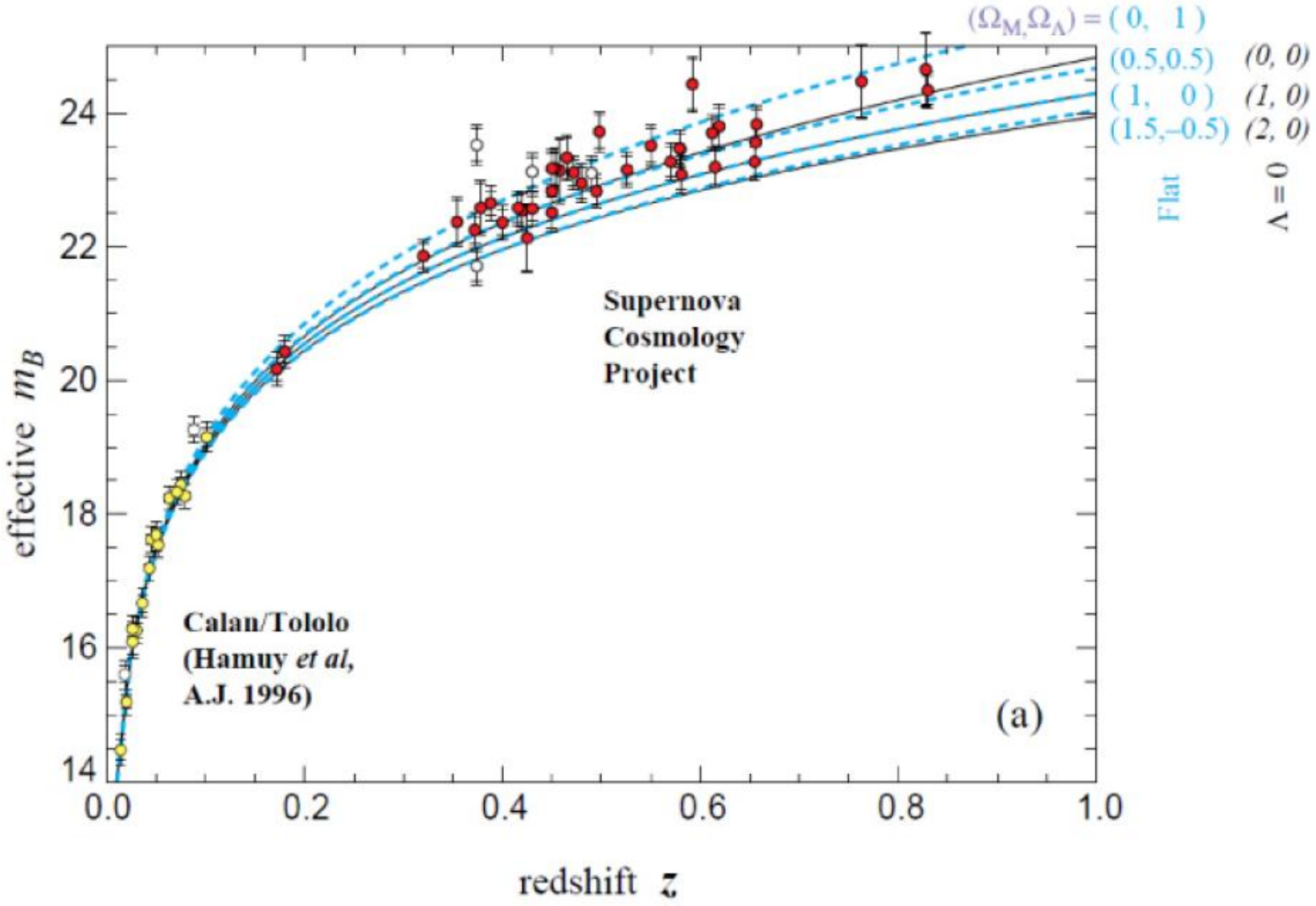


Figure 4. Supernova 1995ar. Two images of the same small piece of the sky taken three weeks apart were compared. Then, on the second image, a small dot of light was discovered! Its status as a type Ia supernova was established after further observations of its light curve. A type Ia supernova can emit as much light as an entire galaxy.The light curve is the same for all type Ia supernovae. Most light is emitted during the first few weeks (see diagram to the right).



Crucial were the light-sensitive digital imaging sensors – charged-coupled devices or CCD – the invention by Willard Boyle and George Smith who were awarded Nobel Prize in Physics in 2009.

Первые результаты



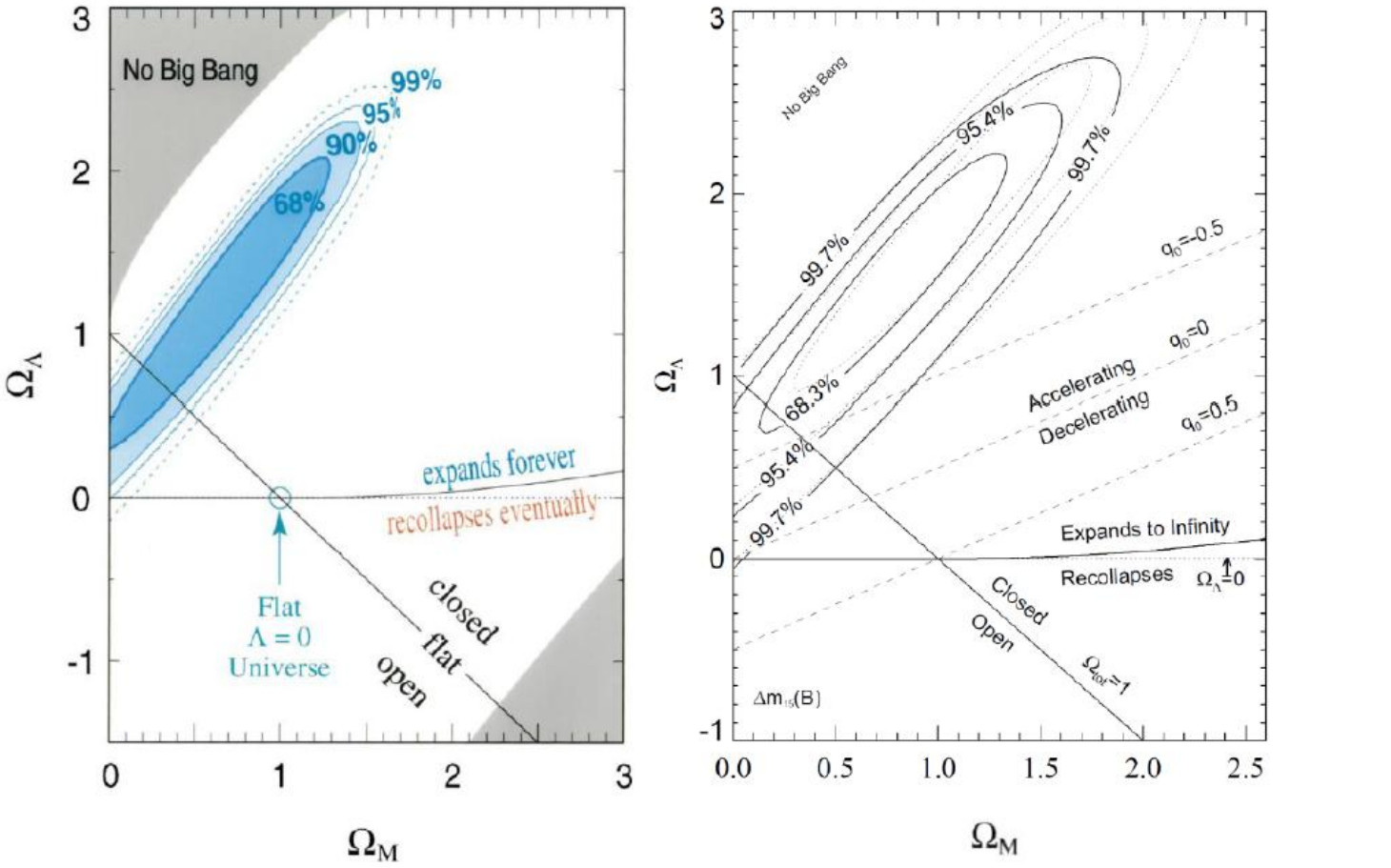
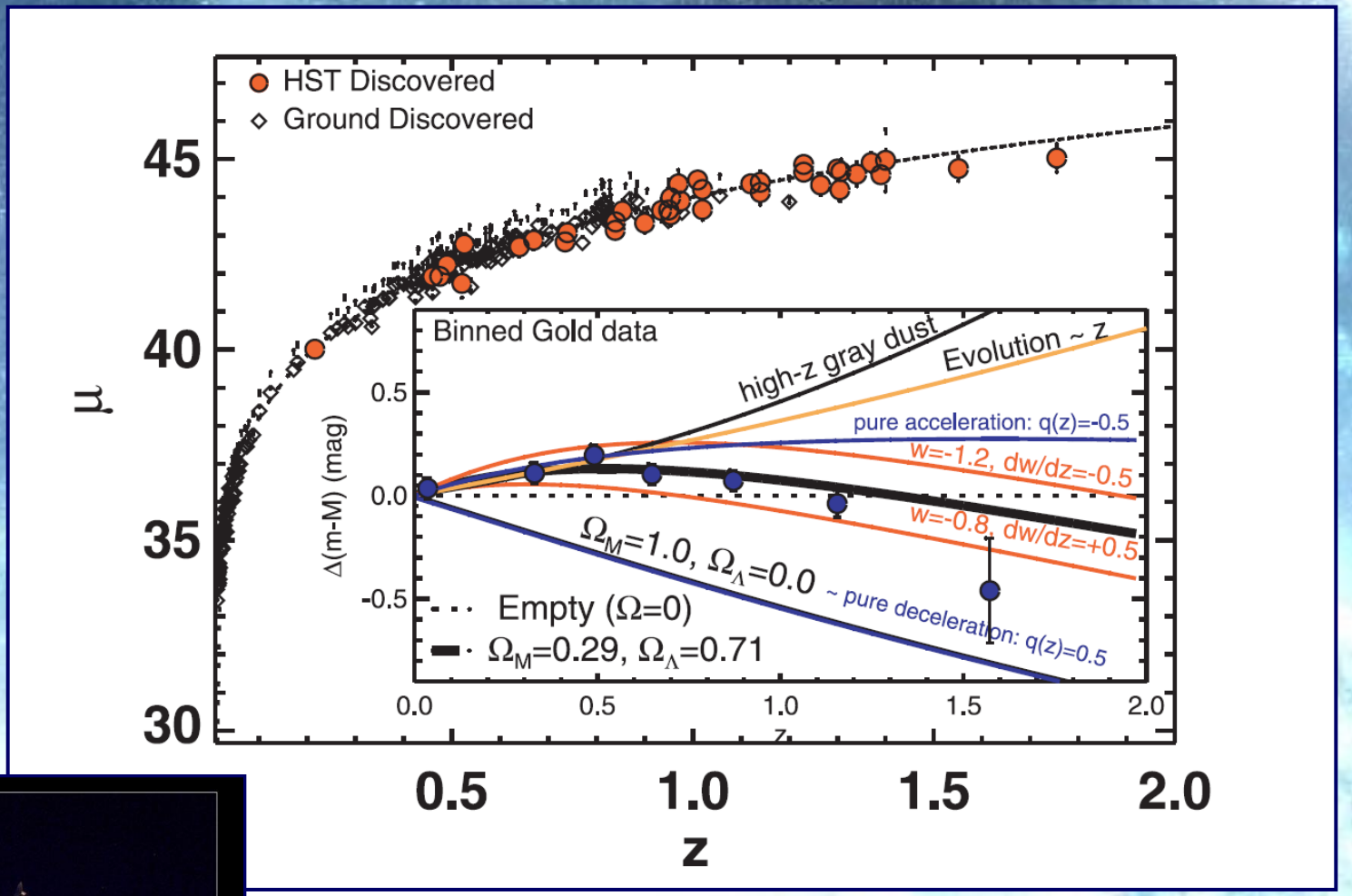
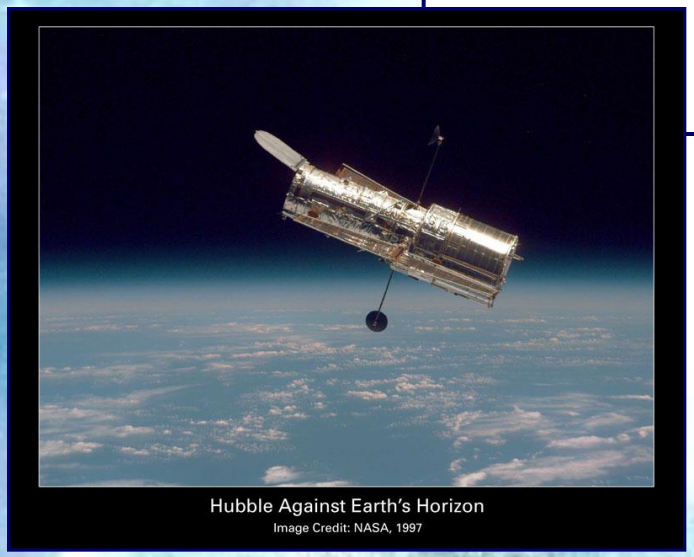
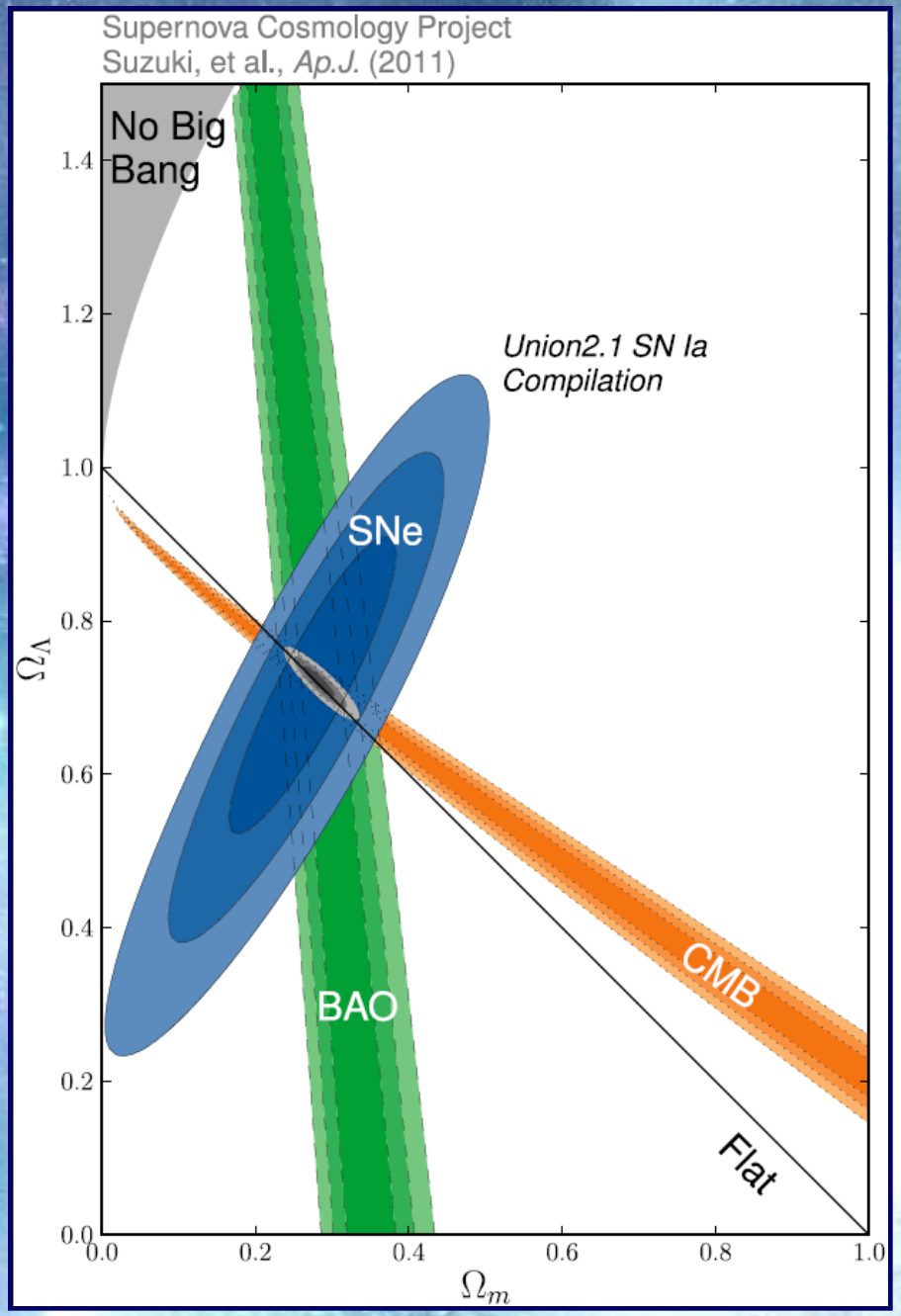
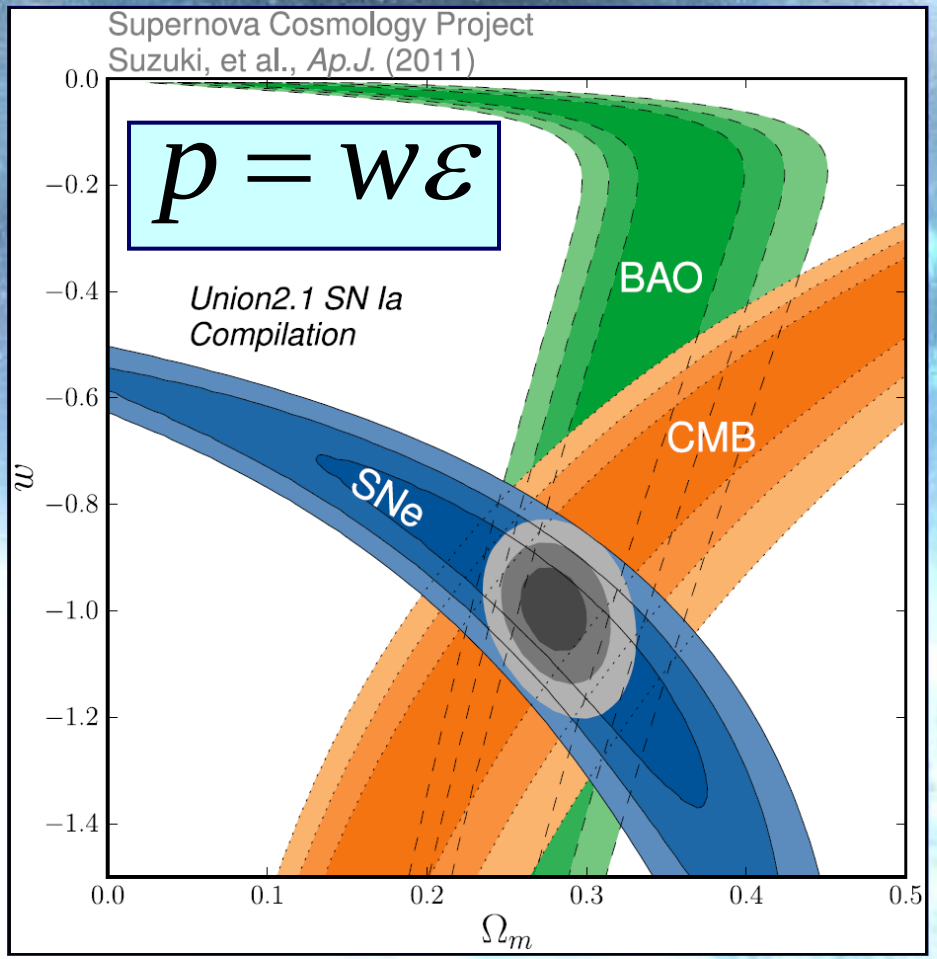


Figure 2. The left-hand panel shows the results of fitting the SCP supernova data to cosmological models, with arbitrary Ω_M and Ω_Λ [28]. The right-hand panel shows the corresponding results from HZT [27].


HST Discovered
Ground Discovered
μ
45
40
35
30
0.5
1.0
1.5
2.0
z
Binned Gold data
Δ(m-M) (mag)
0.5
0.0
-0.5
high-z gray dust
Evolution ~ z
pure acceleration: q(z)=-0.5
w=-1.2, dw/dz=-0.5
w=-0.8, dw/dz=+0.5
Ω_M=1.0, Ω_Λ=0.0
~ pure deceleration: q(z)=0.5
Empty (Ω=0)
Ω_M=0.29, Ω_Λ=0.71
0.0
0.5
1.0
1.5
2.0
z


Hubble Against Earth's Horizon
Image Credit: NASA, 1997





$$H^2(z) = H_0^2\left[\Omega_R(1+z)^4 + \Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

$$\Omega_R = 8.4\cdot 10^{-5} \quad \Omega_M = 0.27 \quad |\Omega_k| < 10^{-2} \quad \Omega_\Lambda = 0.73$$

$$\Omega_M + \Omega_\Lambda = 1$$

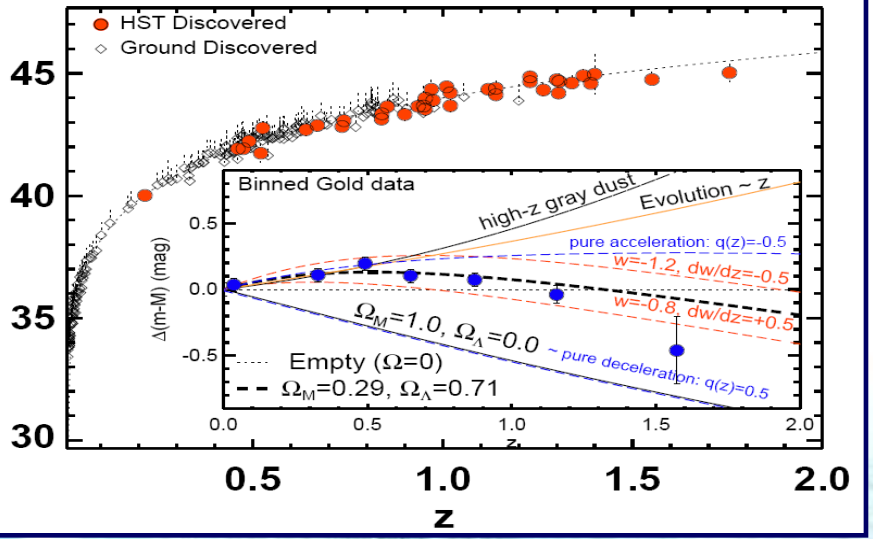
Дальнейшие перспективы …

Астрономические наблюдения

Некластаризуемое вещество с уникальным уравнением состояния,

$$p = -\varepsilon$$

приводящим к ускоренному расширению Вселенной



Физическая Природа

$w = ?$

Λ-слагаемое Эйнштейна ($w=-1$)

Скалярные поля, Квинтэссенция ($w > -1$)

Фантомная Энергия ($w < -1$)

…

Почему значение

$\rho_{Vac} \sim \rho_{tot}$?

(антропный принцип)

Начало XX века

Начало XXI века

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

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

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

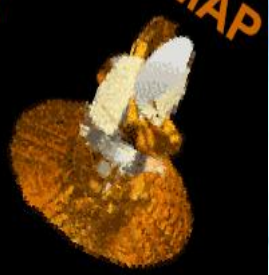
$z_r = 20^{+10}_{-9}$ (95% CL)

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

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

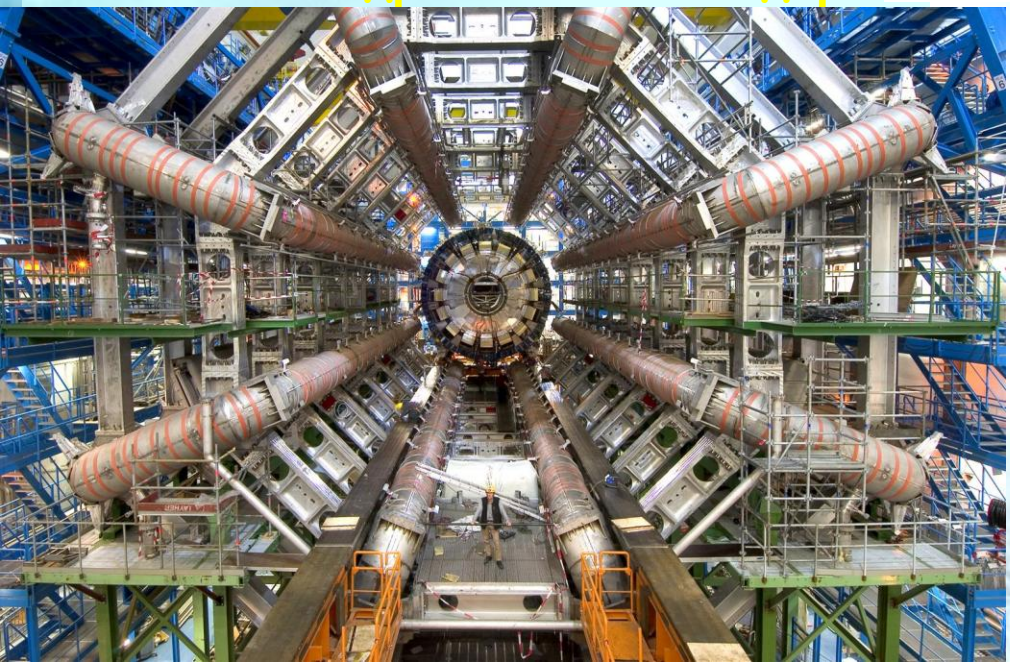
$l_A = 301^{+1}_{-1}$

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



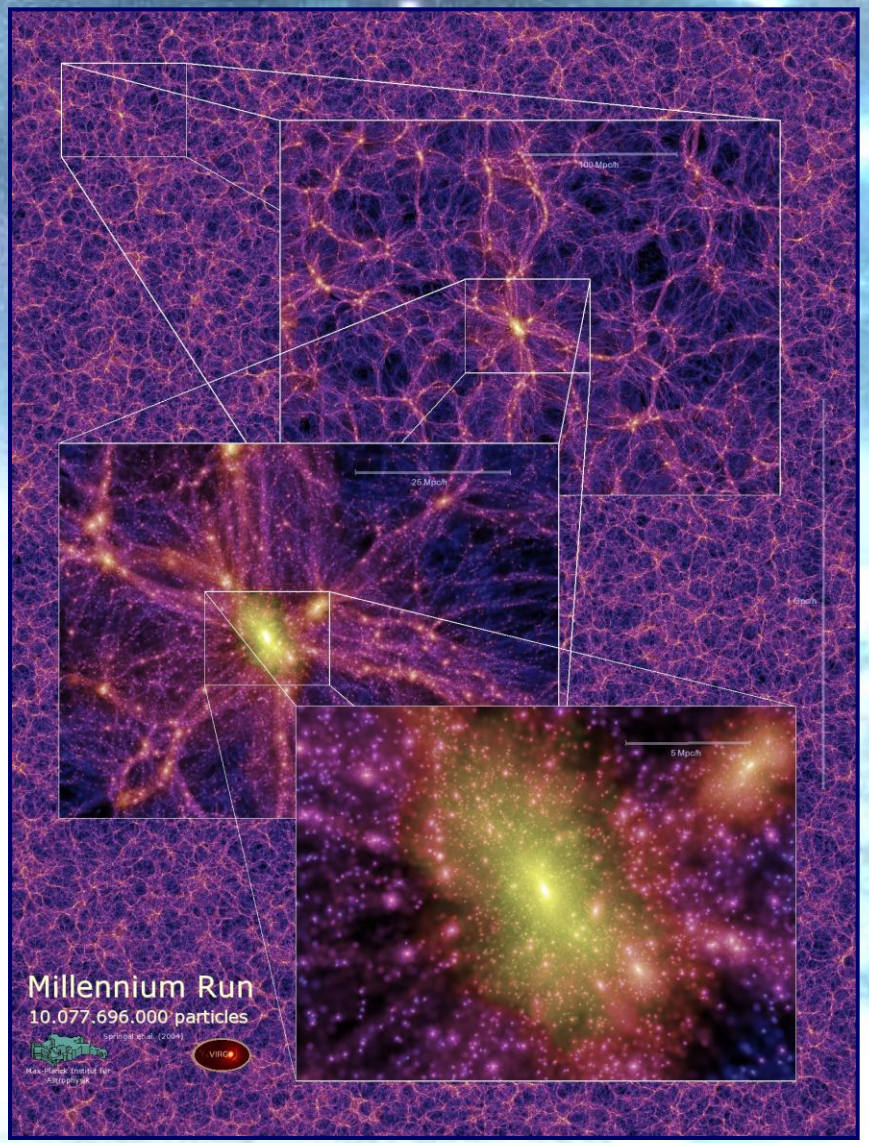
Прецизионная Космология

Большой адронный коллайдер



Физика элементарных частиц фундаментальных взаимодействий

Благодарю за внимание


100 Mpc/h
25 Mpc/h
5 Mpc/h
Millennium Run
10.077.696.000 particles
Springel et al. (2004)
Max-Planck-Institut für Astrophysik
VIRGO

Ускоренное расширение Вселенной. Темная Энергия.

(обзорная лекция)

А.В. Иванчик

ФТИ им. А.Ф. Иоффе РАН

2012