QUARKS-08 Sergiev Posad 25 May 2008

Dark energy in cosmology

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Structure argument (LSS+CMB) – *unambiguous evidence for DE*

$\Omega_m = \rho_m / \rho_c < 0.3 \rightarrow$ open model?

Contrarguments – inflation, age, curvature

CMB anisotropy - flat 3-geometry

More than 70% of energy of the Universe stays unclustered $\rightarrow p \approx -\rho$ (dark energy)

Other arguments – galactic peculiar velocities, lensing
X-ray gas in clusters , rotational velocities , SN , ISW


DM non-interacting with light
but light is there where DM is

Question: where is DM ?

Visible: * stars and gas in galaxies
* gas in clusters (T~ keV)

Dark baryons:
* intergalactic gas (T~ 0.01 keV)
* MACHO (BH, NS, WD, BD, jupiters)

$\rightarrow$ < 20% of halo mass in moon-star MACHOs

$\rightarrow$ > 80% of halo mass in non-baryon particles

Non-baryonic DM:

* large velocity dispersion in clusters (1930)
* flat rotation curves in spirals (1970)
* galaxy cluster masses determined (1980)

$\rightarrow$ X-ray gas (T~ keV)
$\rightarrow$ gravitational lenses

Answer: non-baryonic DM is in gravitationally bound systems

weakly interacting particles
do not dissipate as baryons

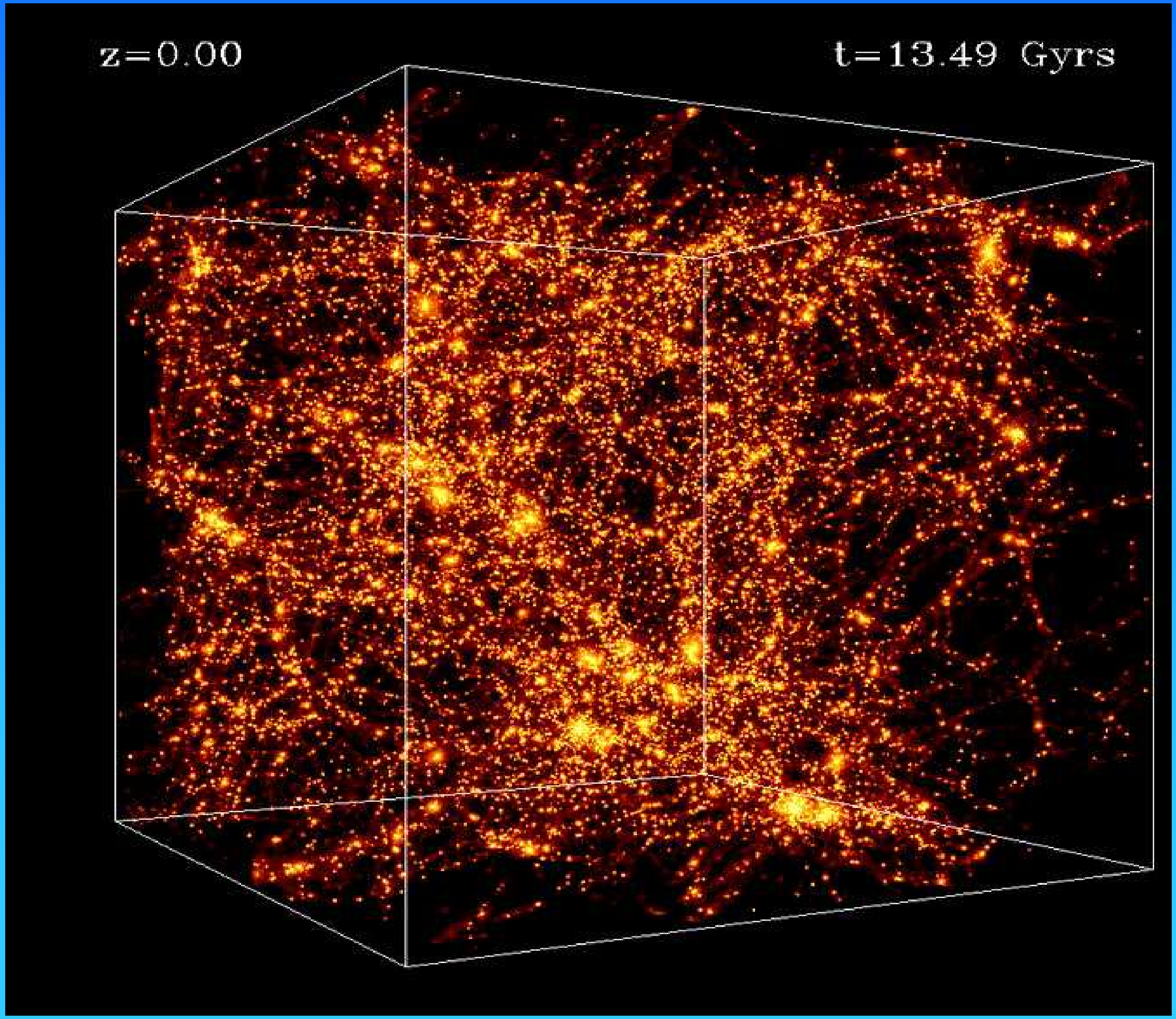
Baryons cool down radiationally and reside in centers of dark matter halos getting rotational equilibrium

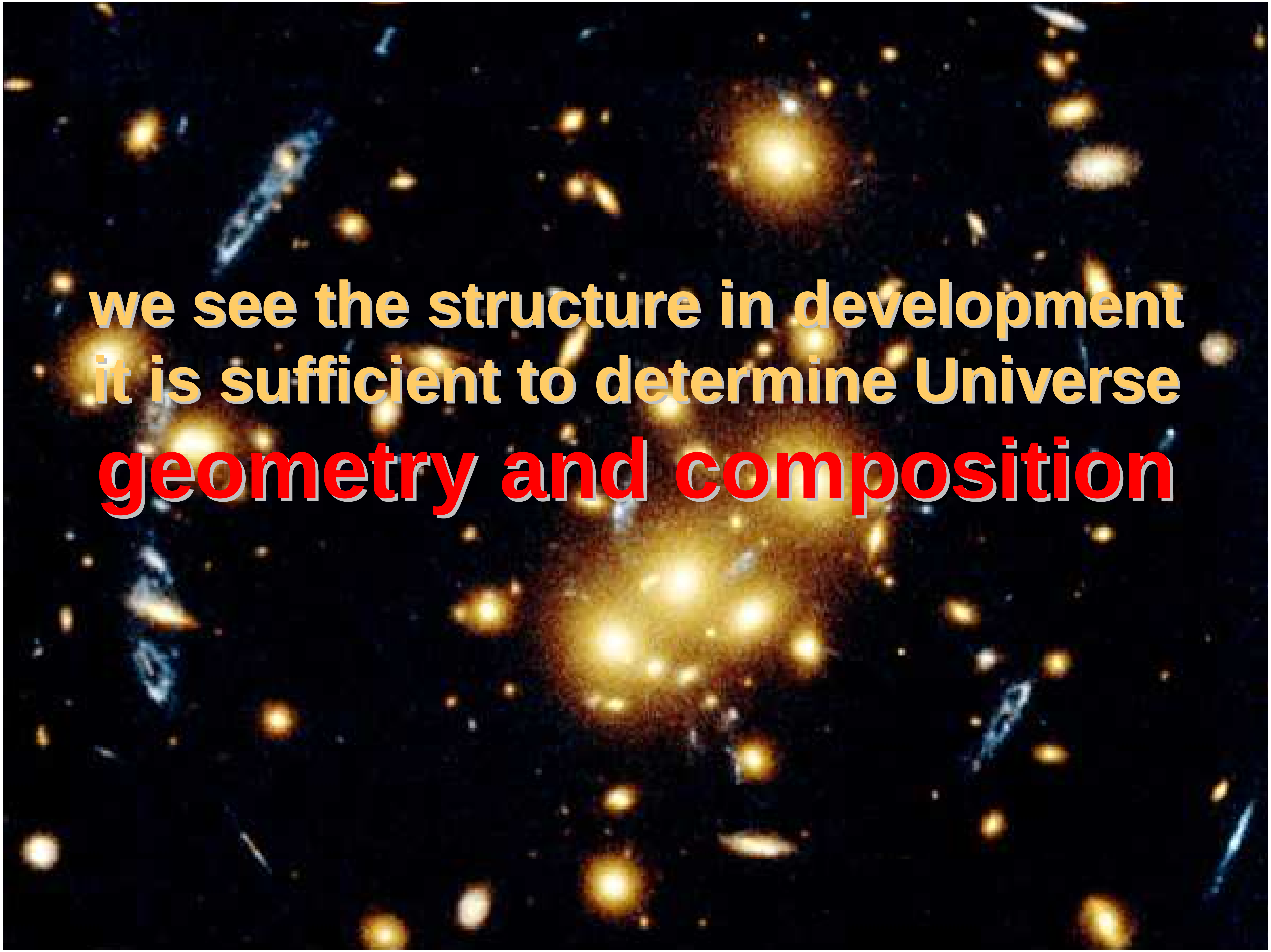
DM remains assembling around the visible matter at scale ~ 200 кpc

mass of the Local Group ~ $2 \cdot 10^{12}\ M_\odot$
(half is in Milky Way and Andromeda)

Simulations confirm this result

100 Мпк




we see the structure in development
it is sufficient to determine Universe
geometry and composition

Geometry of the Universe

- zero order   Hubble diagram $a(t)$
- first order

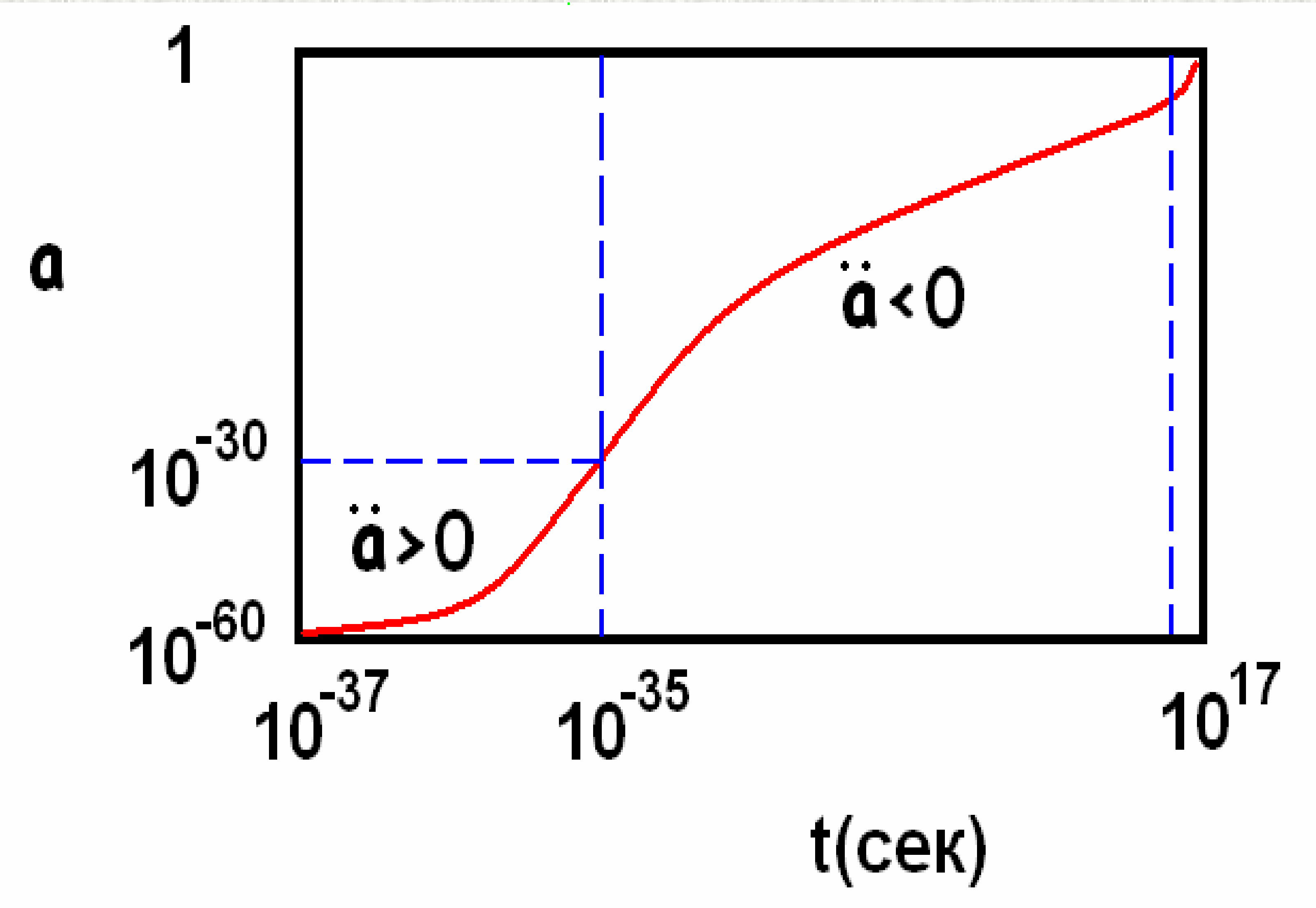
S-mode (density perturbations) $S(k)$

T-mode (gravitational waves) $T(k)$

V-mode (vortex perturbations) $V(k)$

Cosmological model in four functions
currently we know only two of them

Evolution of scale factor



Formation of the Universe is formation of Hubble outflows

$$\vec{v} = H\,\vec{r} \quad , \quad H = \dot{a} / a$$

$H_0 = 70$ km s^{-1} Mpc^{-1}, $H_0^{-1} = 14$ Gyr

$$\ddot{a} > 0$$

Formation of the structure is destruction of Hubble outflows

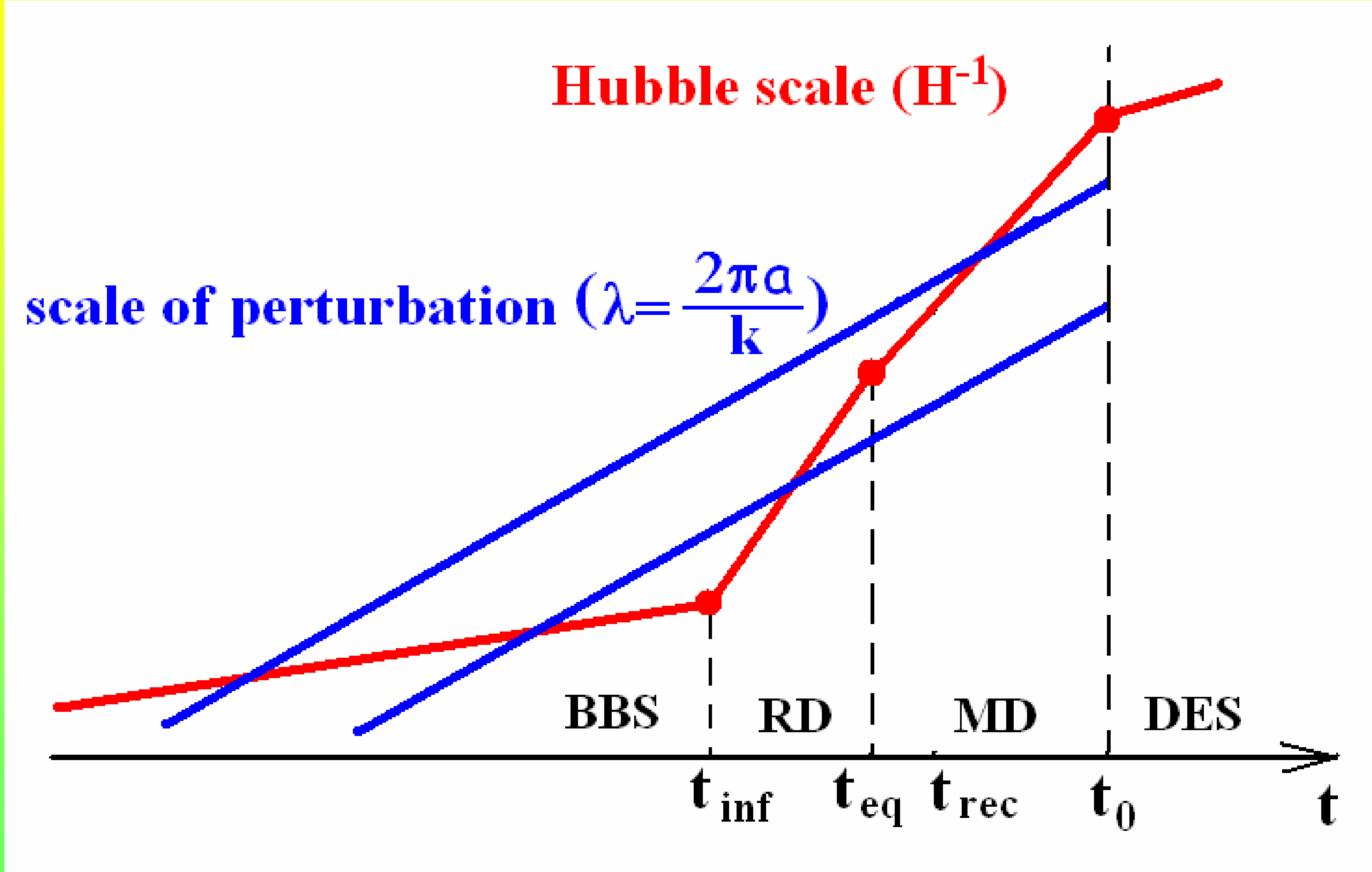
$$\ddot{a} < 0$$

lesson 1: *Universe is large*

Since the very beginning ($\ddot{a} < 0$)
the physical size of the Universe
exceeded Planck scale 10^{30} times

This big factor can be explained by existence
of preceding short stage of inflation -- BBS

lesson 2: *acausality*



lesson 3: *evidence for DE*

(structure argument: LSS + CMB)

$\Omega_m = \rho_m / \rho_c < 0.3 \rightarrow$ **open model ?**

Contrarguments – inflation, age, curvature

CMB anisotropy - flat 3-geometry

More than 70% of energy of the Universe stays unclustered → $p \approx -\rho$ (dark energy)

Other arguments – galactic peculiar velocities , lensing X-ray gas in clusters , rotational velocities , SN , ISW

Dark energy **– weakly interacting physical essence permeating space of visible Unuverse**

DE – key element of standard model

Three hypothesis of DE: vacuum, superweak field , modification of gravity

$$E_{DE} \sim 10^{-3}\ \mathrm{eV} \quad (\text{ for } \rho_{DE} = E^4)$$

New energy scale ?

Yes - if vacuum

No - if superweak field or modification of gravity

Coincidence problem: $\rho_{DM} \approx \rho_b \approx \rho_{DE}$

Scales of fundamental interactions

1 GeV	strong
100 GeV	electroweak
10^{19} GeV	gravitational

Existence of LSS is a key point for

the coincidence problem

$$\Omega_{\mathrm{rad}} << \Omega_{\mathrm{m}}\,, \qquad \Omega_{\mathrm{DE}} \leq \Omega_{\mathrm{m}}$$

-window of gravitational instability

(+ initial amplitude of perturbations)

$$\Omega_{\mathrm{rad}} << \Omega_{\mathrm{b}} \leq \Omega_{\mathrm{DE}}$$

- condition for formation of starts

DE ceases structure formation and restores Hubble outflows

lesson 4: *superweak fields*

* for 14 Gyr – **two** inflationary stages
* there could be more than two, same causes
* simple cause of inflation -- **weak massive field**
* inflation creates and restores Hubble outflows

History of the Universe is the history of origin and decay of massive fields

$$w(a) \equiv \frac{p_{DE}}{\rho_{DE}} = -1 + c_0 + c_1\alpha + \frac{1}{2}c_2\alpha^2 + \ldots$$

$$\alpha \equiv a - 1 = -\frac{z}{1+z}$$

c_n (n = 0,1,2,…) – dark energy physics

How can c_n be measured ?

Clue of DM physical nature

is precise statistical measurement of LSS formation rate in Universe

Inhomogeneous Universe

generalized Friedmann equation

$$\boxed{\left(\frac{\dot{b}}{b}\right)^2 = \frac{8\pi G}{3}\rho - \frac{\kappa}{b^2}}$$

$$b = b(t, \vec{x})$$

- volume scale factor

$$H_{\mathrm{eff}}(t, \vec{x}) \equiv \frac{\dot{b}}{b}$$

- effective Hubble parameter

$$\rho = \frac{\rho_0}{b^3} + \rho_1$$

- comoving matter density

- DE energy density

local spatial curvature

$$\kappa = \kappa(\vec{x})$$

(arbitrary small function of *x*)

Geometry of inhomogeneous Universe

$$ds^2 = dt^2 - \hat{a}^2(\delta_{ik} - 2g \cdot \hat{q},_{ik})dx^i dx^k$$

$\hat{a} = a(1 - q)$ - **effective scale factor** $\quad q = q(\vec{x})$

$\kappa = \Delta\hat{q}(\vec{x})$ – ***spatial curvature***

$\delta r_i = \hat{a}(\delta_{ik} - g \cdot \hat{q}_{ik})\delta x^k$ - **physical distance between pairs of galaxies**

$$\boxed{\delta V_i = \frac{\partial}{\partial t}\delta r_i = H_{ik}\delta r^k \,, \quad H_{ik} = H\left(\delta_{ik} - h \cdot \hat{q},_{ik}\right)}$$

Friedmann equation in dimensionless variables

$$\left(\frac{\dot{b}}{H_1}\right)^2 = \frac{c}{b} + b^2 - \kappa \equiv f^2(b) - \kappa(\vec{x})$$

$$H_1 = H_0\sqrt{\Omega_{ТЭ}} \cong 2\cdot 10^{-4}\ \text{Мпк}^{-1}\ , \quad c \equiv \frac{\Omega_m}{\Omega_{ТЭ}} \cong 0.39$$

DM Hubble constant

$$f(b) = \left(\frac{c}{b} + b^2\right)^{1/2} \geq 1$$

minimum $f_{min} = 1$ is at $b_{min}^{-1} = 1.7$

Spatial regions κ(x) < 1 expanding forever

Solution of generalized Friedmann equation

for $\kappa = 0$:

$$b = a(t) \equiv \frac{1}{1+z}, \quad H \equiv \frac{\dot{a}}{a} = H_1 \frac{f(a)}{a}$$

f(a) - ***growth factor of Hubble velocities***

$$\vec{V} = \vec{V}_H - \vec{v}_{pec}, \qquad \vec{V}_H = f \cdot H_1 \vec{x}$$

For $\kappa \neq 0$:

$$b = a\left(1 - \frac{1}{3} g(a) \cdot \kappa(\vec{x})\right)$$

$$H_{eff} \equiv \frac{\dot{b}}{b} = H\left(1 - \frac{1}{3} h(a) \cdot \kappa(\vec{x})\right), \quad h \equiv \frac{v}{f} = \frac{\dot{g}}{H}$$

Density perturbations and peculiar velocity

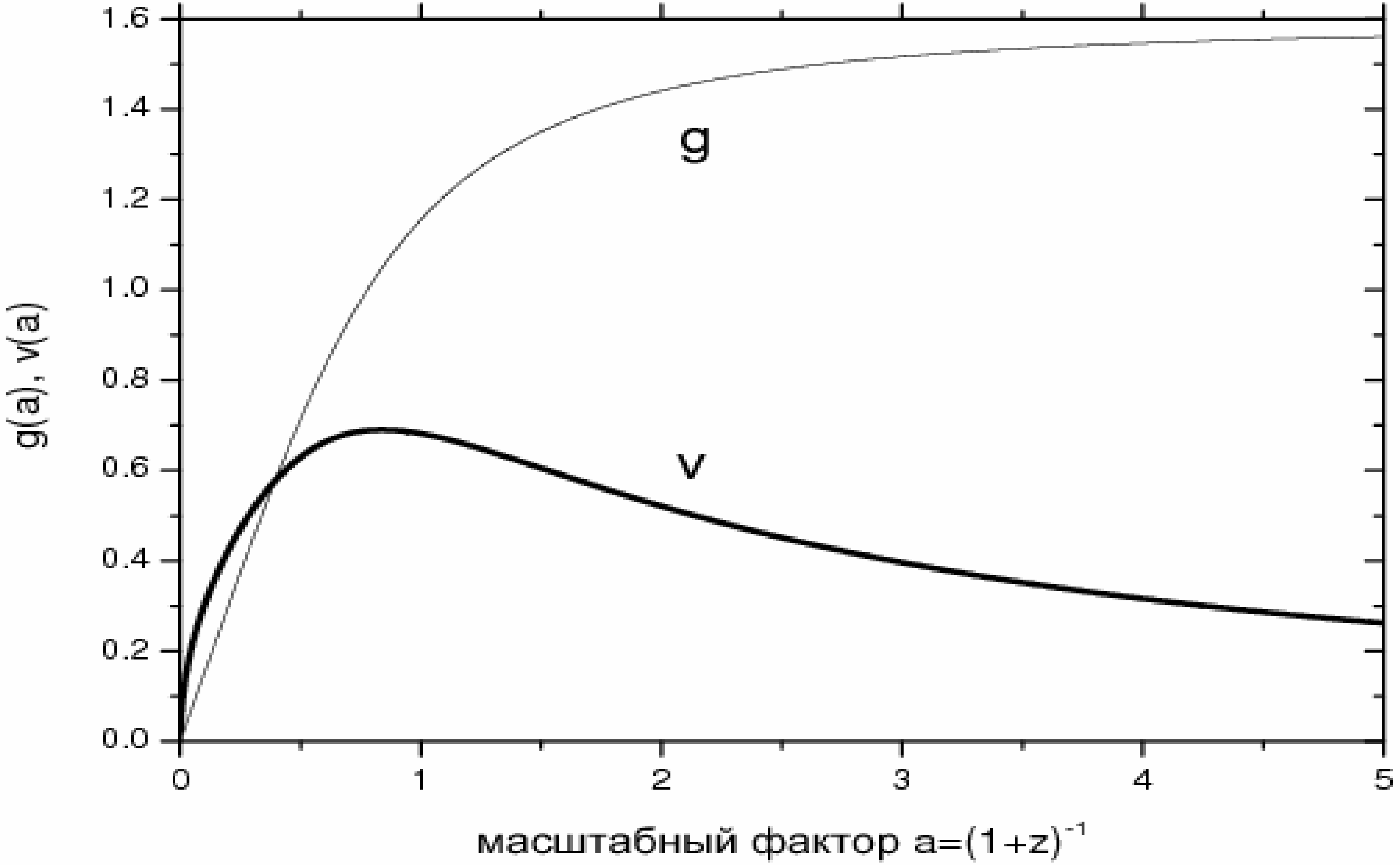
$$\delta_{\mathrm{m}} = \mathrm{g} \cdot \kappa(\vec{\mathrm{x}}), \qquad \vec{v}_{pec} = \mathrm{v} \cdot \mathrm{H}_1 \nabla \widehat{\mathrm{q}}$$

$$\kappa = \Delta\widehat{\mathrm{q}}(\vec{\mathrm{x}})$$ – ***spatial curvature***

Growth factors of density and velocity perturbations

$$\mathrm{g}(a) = \frac{1}{\mathrm{c}}\left(a - \mathrm{H}\int\frac{\mathrm{d}a}{\mathrm{H}}\right), \qquad \mathrm{v}(a) = \frac{3\mathrm{H}_1}{2a^2}\int\frac{\mathrm{d}a}{\mathrm{H}}$$

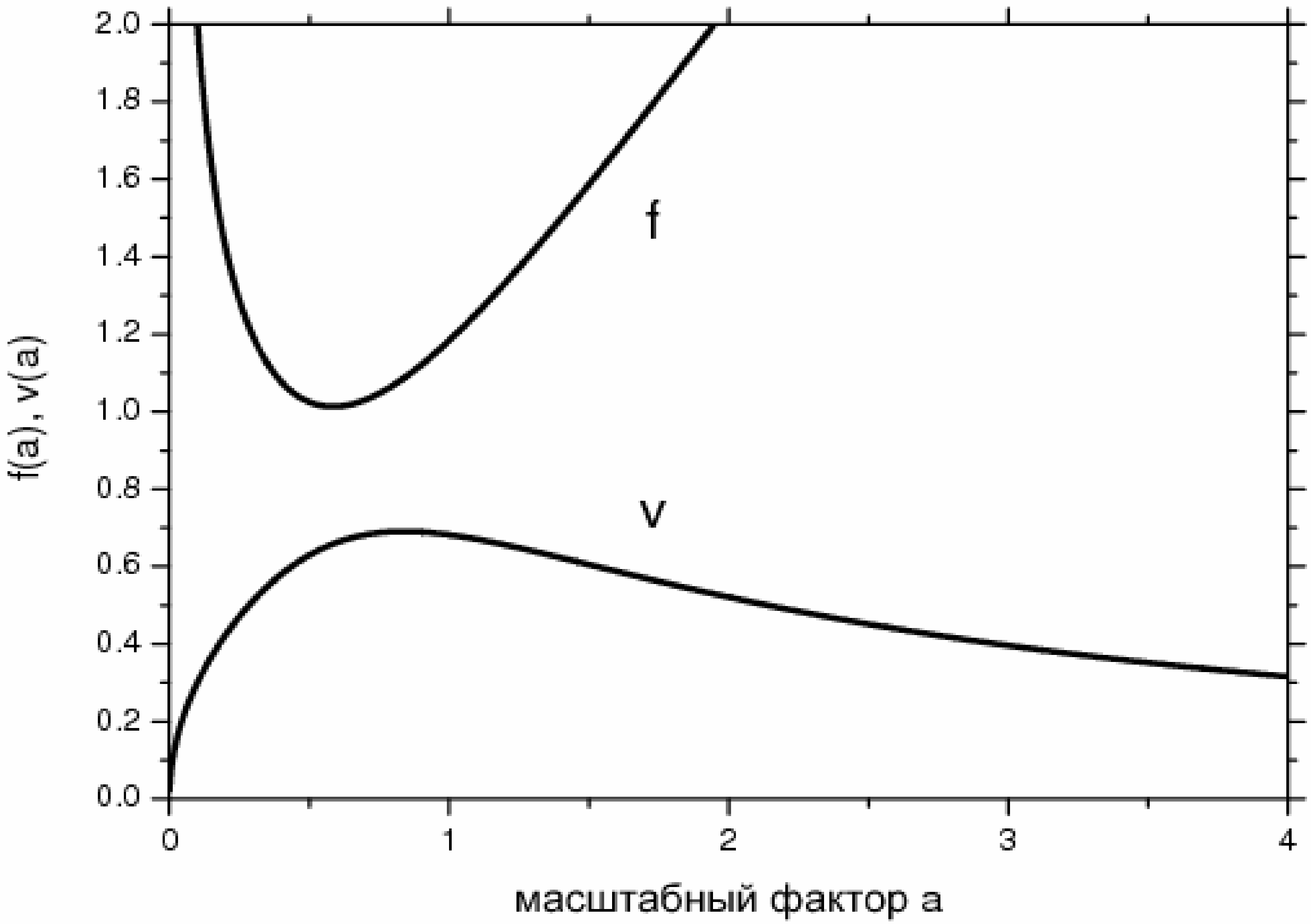
Growth factors of density and velocity perturbations



We are at maximum of structure generation

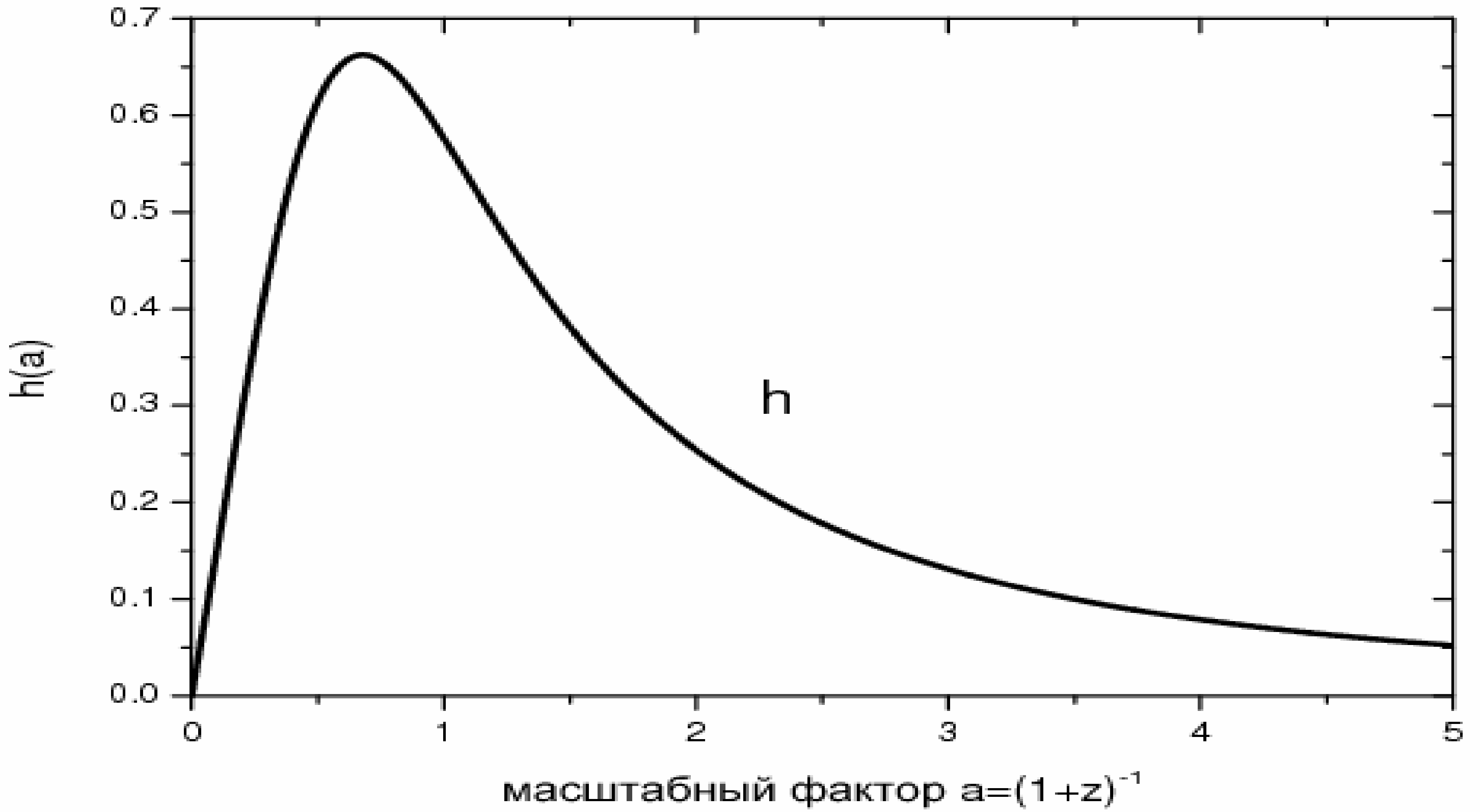
It will take 20 Gyr more to half velocity

Evolution of Hubble and peculiar velocities



$$\vec{V} = \vec{V}_H - \vec{v}_{pec}\,,\quad \vec{V}_H = f\cdot H_1\vec{x}\,,\quad \vec{v}_{pec} = v\cdot H_1\nabla\widehat{q}$$

Period $h/h_{max} > 0.5$ goes from 0.6 to 22 Gyr



$$H_{\text{eff}} = H\left(1 - \frac{1}{3} h(a) \cdot \kappa(\vec{x})\right), \quad h \equiv \frac{v}{f}$$

Where are Hubble outflows broken?

At different places at different time

Present scale of inhomogeneity 15 Mpc

Asymptotic scale of inhomogeneity 25 Mpc
(if DE preserves vacuum property)

For Local Group ~ 2(3) Mpc.

At 3-4 Mpc from LG random velocity ~ 40 km s^{-1}

Full peculiar velocity ~ 600 km s^{-1}

What had E. Hubble observed ?

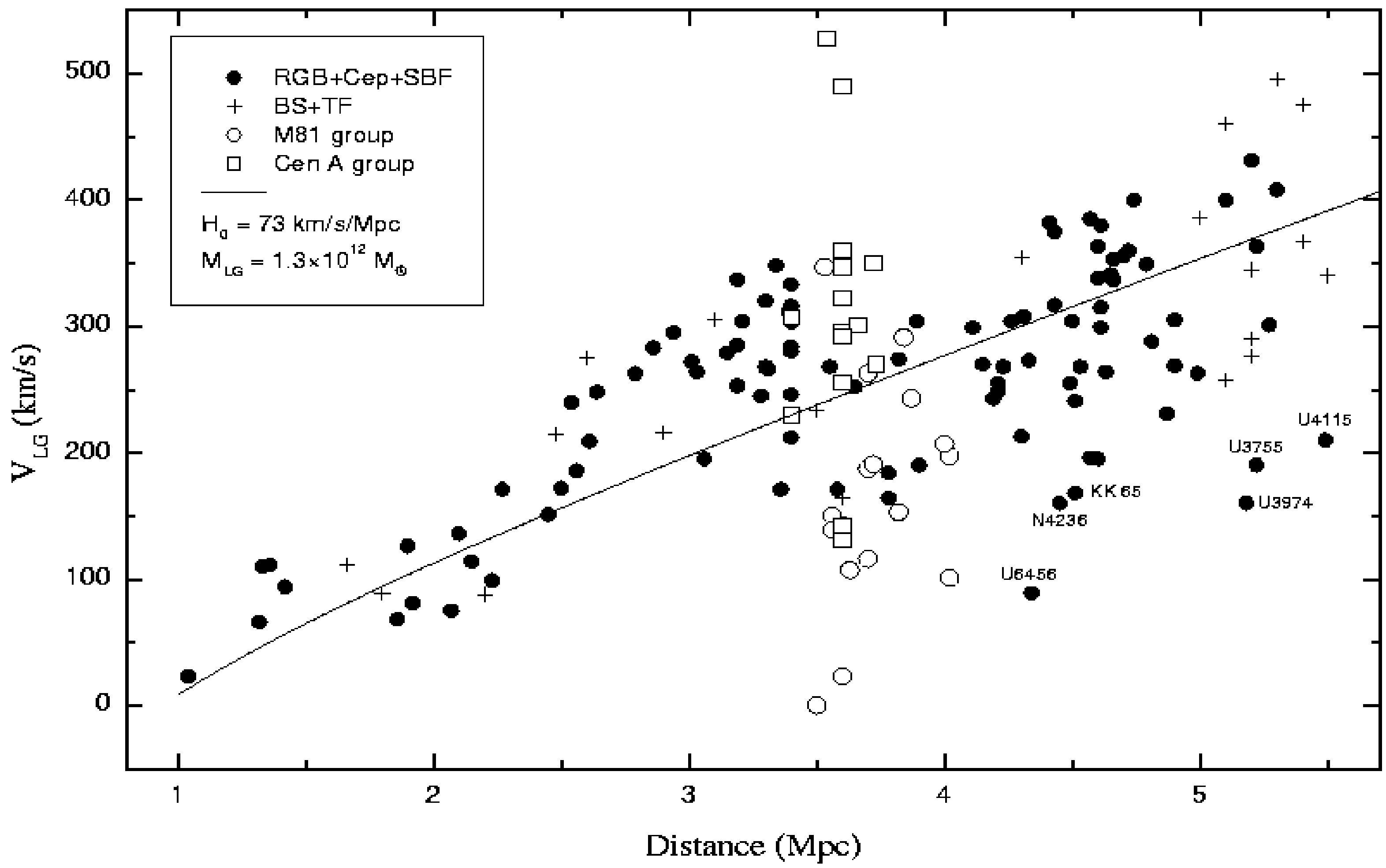
Paired galactic velocities at region $\kappa(x) < 1$ in scales < 15 Mpc (correlation length of peculiar velocity) – regular anisotropic outflows

$$\delta V_i = \frac{\partial}{\partial t}\delta r_i = H_{ik}\delta r^k\,, \quad H_{ik} = H\left(\delta_{ik} - h\cdot q,_{ik}\right)$$

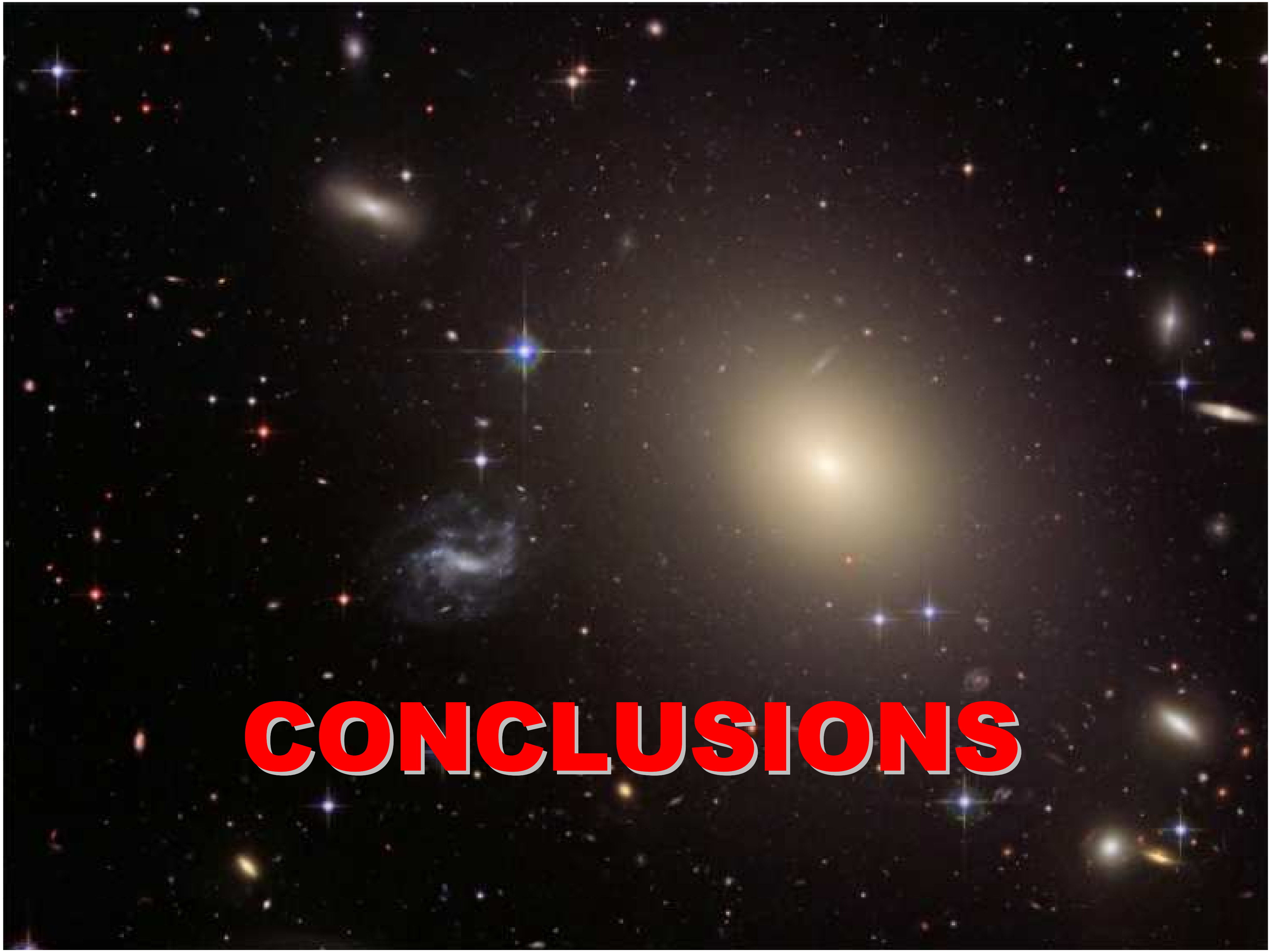
Matter peculiar velocities as well as random variations from the mean (highly correlated) velocity outflows , increase with radius and reach the maximum values at r ~15-40 Mpc

156 nearby galaxies

Radial velocity



Eigen values H_{ik}= diag (81, 62, 48) km s^{-1} Mpc^{-1}


CONCLUSIONS

Today the peculiar velocities are at maximum
This period will continue a Hubble time more
The velocity will decay by factor two in 35 Gyr

The Universe is now at period of maximum deviations from the Hubble law expansion

Hubble recovering will happen in tens Gyrs

DE affects crucially dynamics of the structure generation

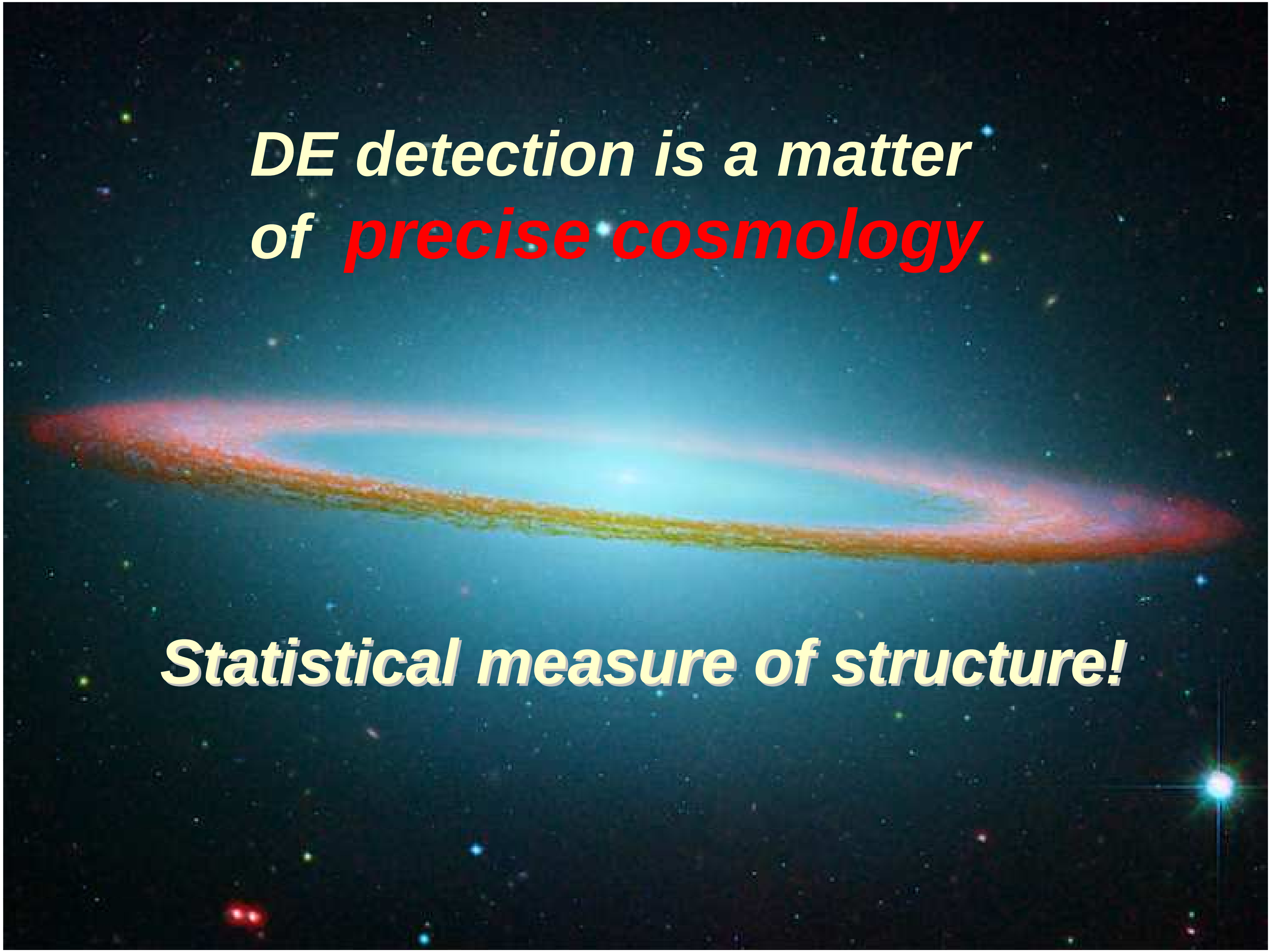
LSS is a clue of DE properties

LSS formation proceeds from 1 to 22 Gyrs since the Big Bang

We live at period of maximum LSS formation in the Universe

Use this chance:

measure DE by weighting the structure with redshift


DE detection is a matter
of precise cosmology
Statistical measure of structure!