
4th Sakharov Conference on Physics, 19 May 2009
Rise and fall of structure formation in the Universe
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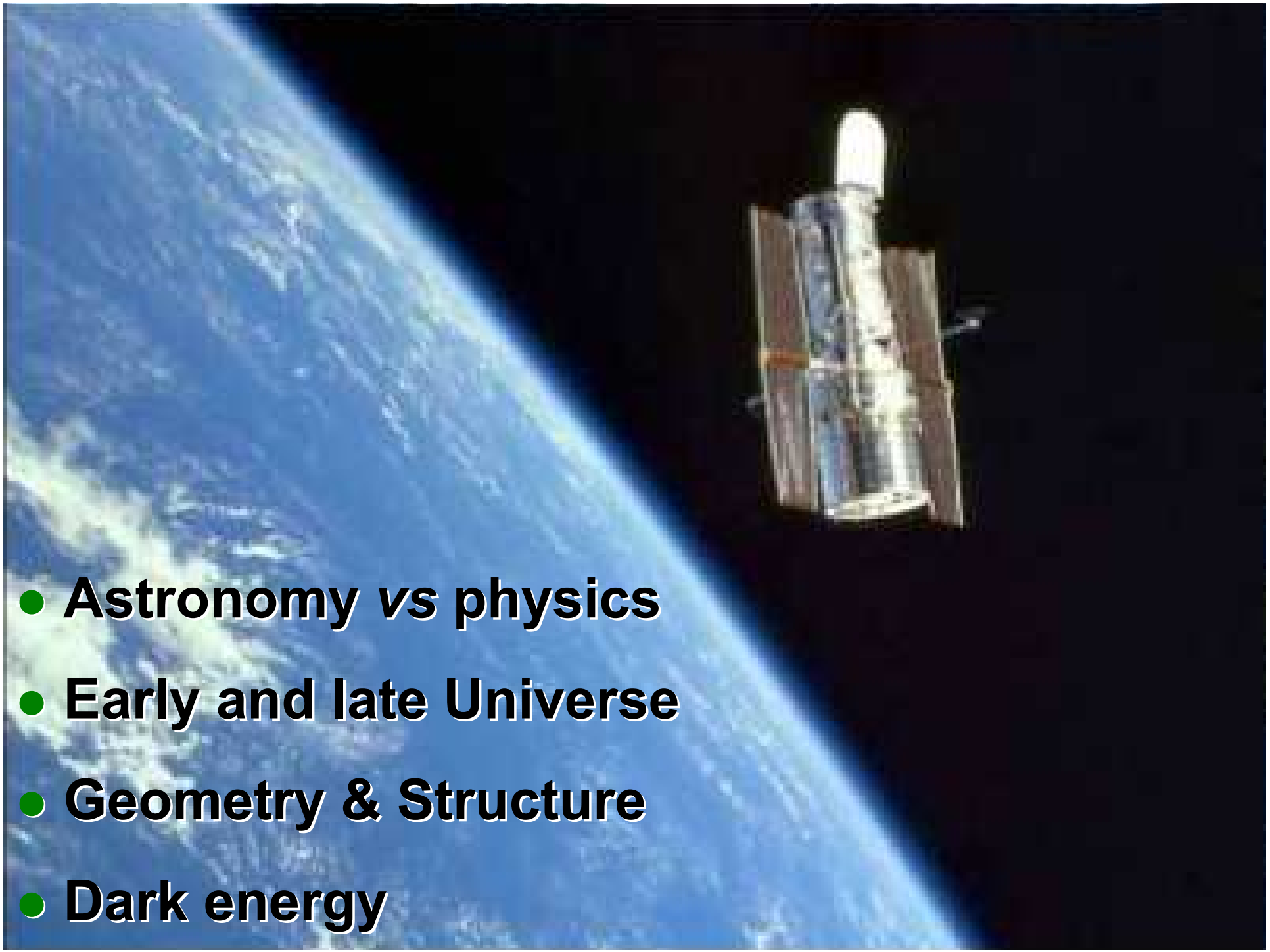
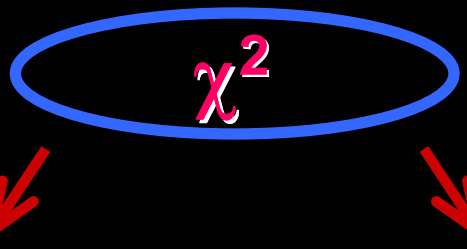

Astronomy *vs* physics
Early and late Universe
Geometry & Structure
Dark energy

Identification problem

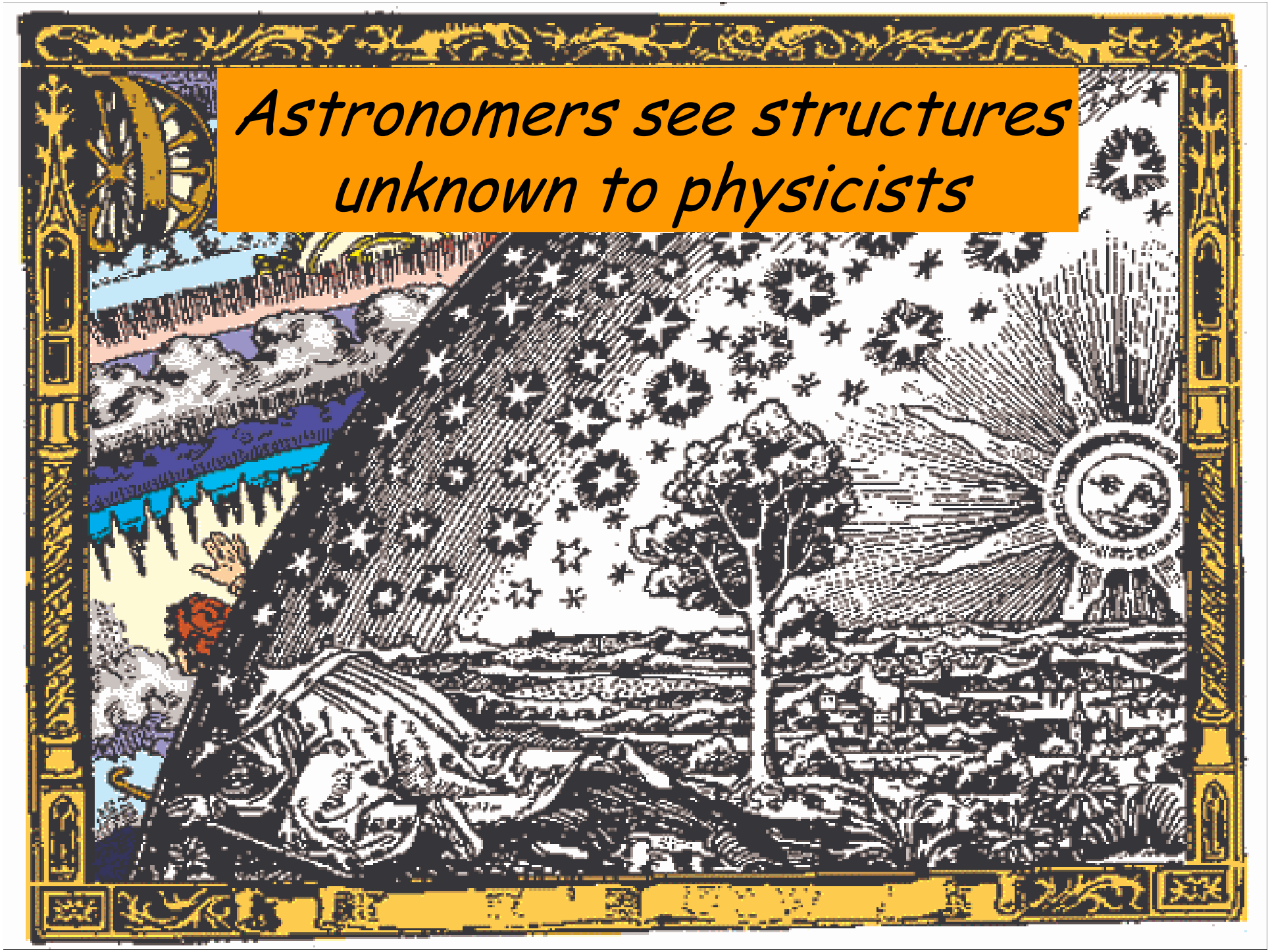
OBSERVATION → THEORY



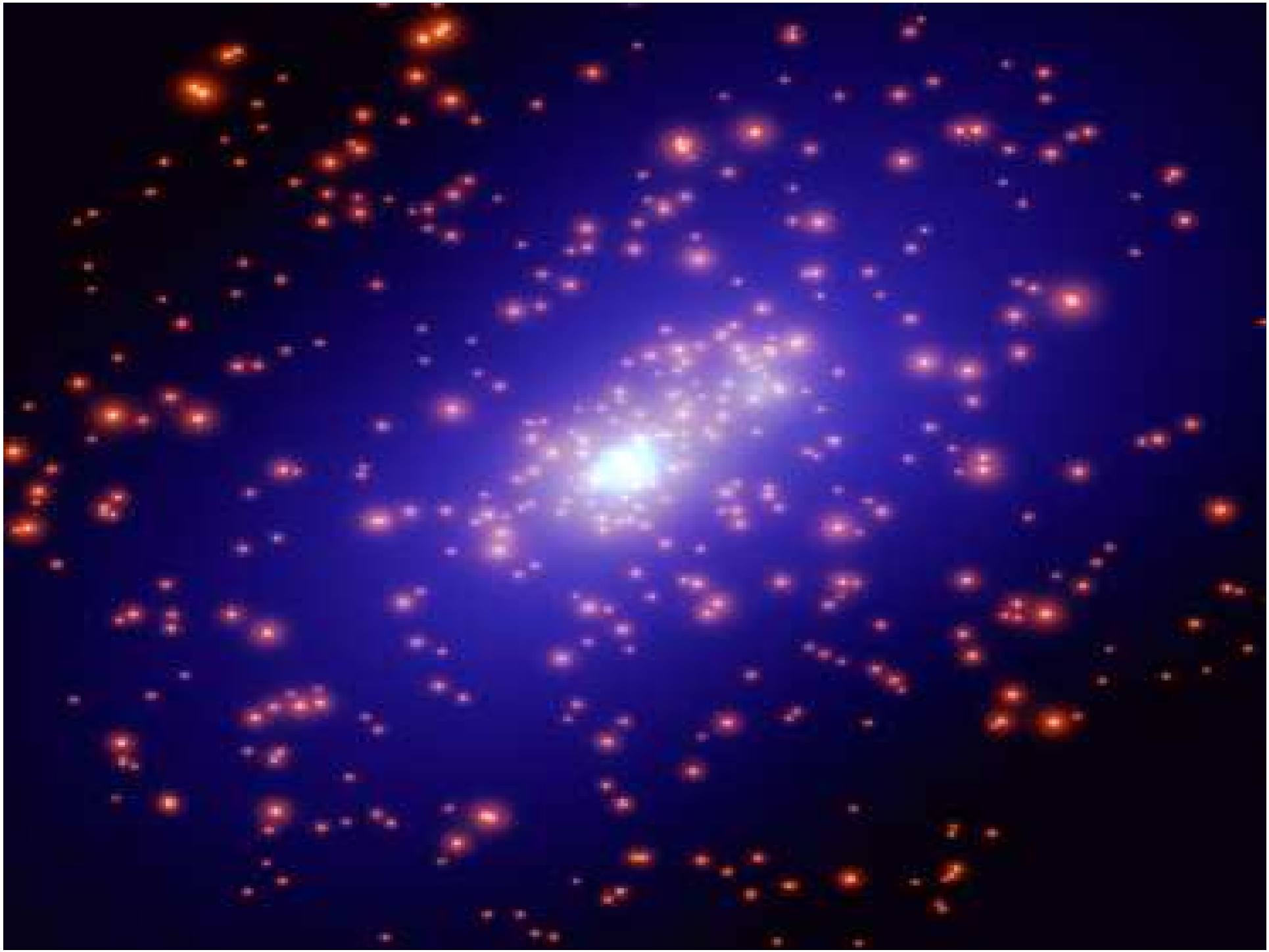
Initial conditions **development conditions**

?

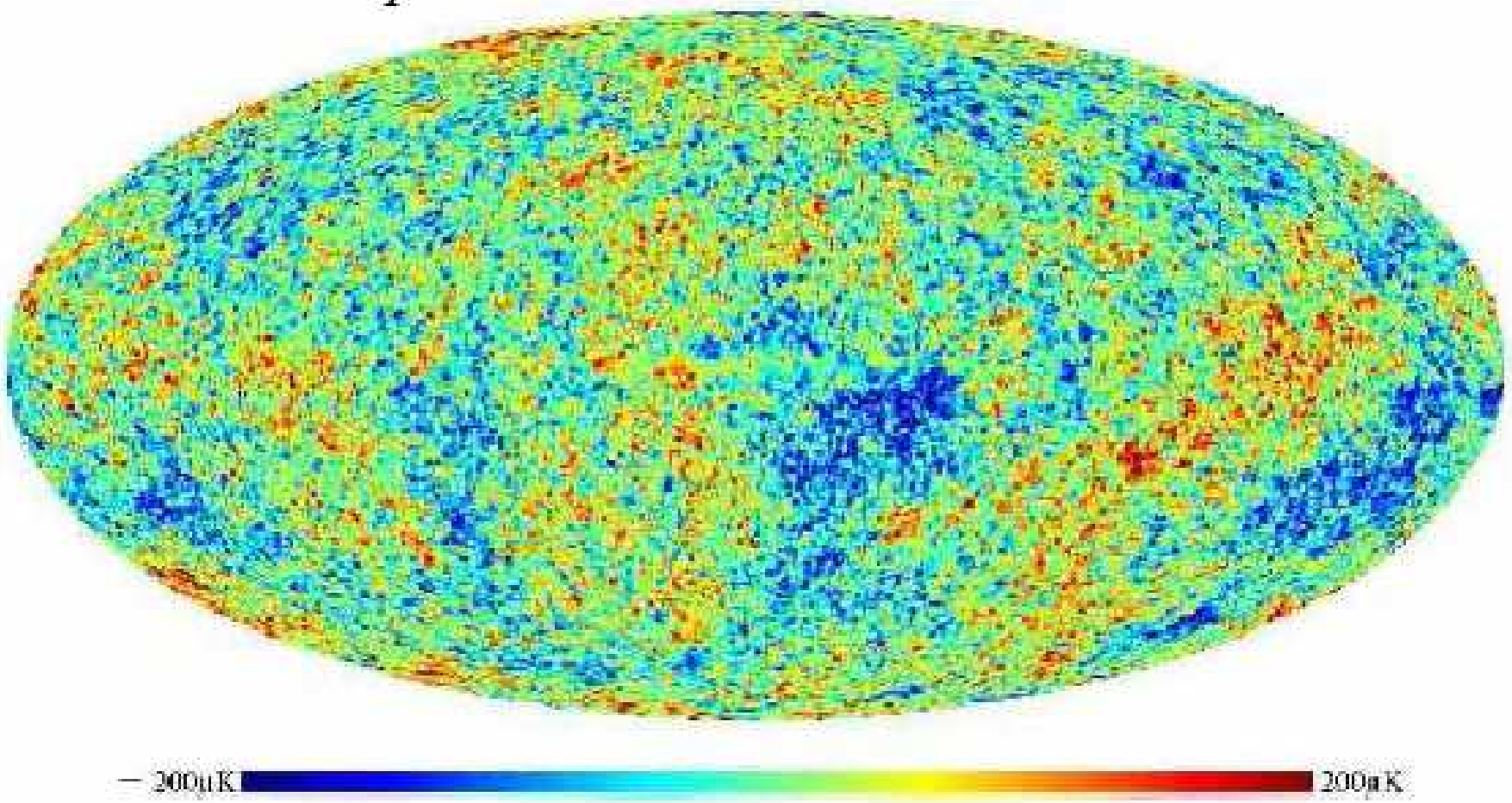
Physicists need experiment to judge things!


Astronomers see structures
unknown to physicists


DM non interacted with radiation
however light is where DM

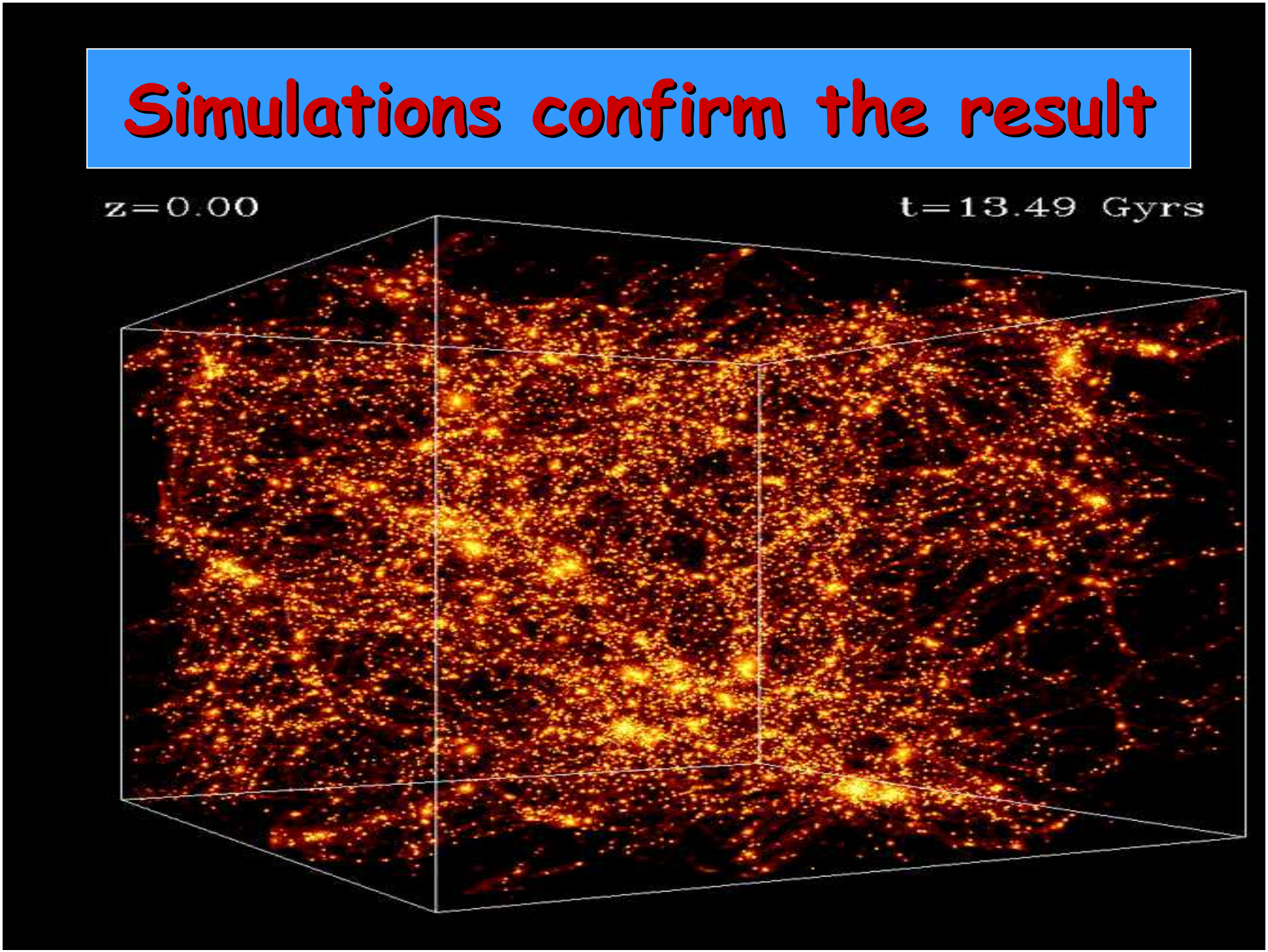


$$T = 2.725^{\circ}K, \quad \frac{\delta T}{T} \sim 10^{-5}$$



WMAP

Simulations confirm the result



What we see is structure created from initial conditions + evolution

observational separation of the early and late Universe

no model
theory of origin of initial conditions

the model
no theory of origin of matter

geometry

composition

Early Universe

- Small density perturbations
- Linear Gaussian field
- Near scale-invariant spectrum (n_S=0.96)
- Gravitational waves (T/S < 0.1)
- Theory of initial conditions

no model of the early Universe

Late Universe

- Hubble constant $h = 0.7$
- CMBR $T = 2.725\ K$
- Eucleadian space $\Omega = 1$
- Baryons $\Omega_b = 0.5$
- CDM $\Omega_{cdm} = 0.23$
- DE $\Omega_{dm} = 0.72$
- Theory of structure formation

no theory of matter origin

Geometry of the Universe

- **zero order** Hubble outflows $a(t)$
- **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

Zero order geometry

$$\frac{H}{H_0} = 10^{61}\frac{H}{M_P} = \left(\frac{10^{-4}}{a^4} + \frac{0.3}{a^3} + 0.7\right)^{1/2} \Rightarrow \frac{10^{-2}}{a^2}$$

$$\gamma \equiv -\frac{\dot{H}}{H^2} = \frac{2\times 10^{-4} + 0.4}{10^{-4} + 0.3a + 0.7a^4} \subset (2,\ 0.4)$$

$$H_0^{-1} = 14\ Gyr = 10^{33}\ eV^{-1}$$

$$M_P = 10^{19}\ GeV = 10^{33}\ cm^{-1}$$

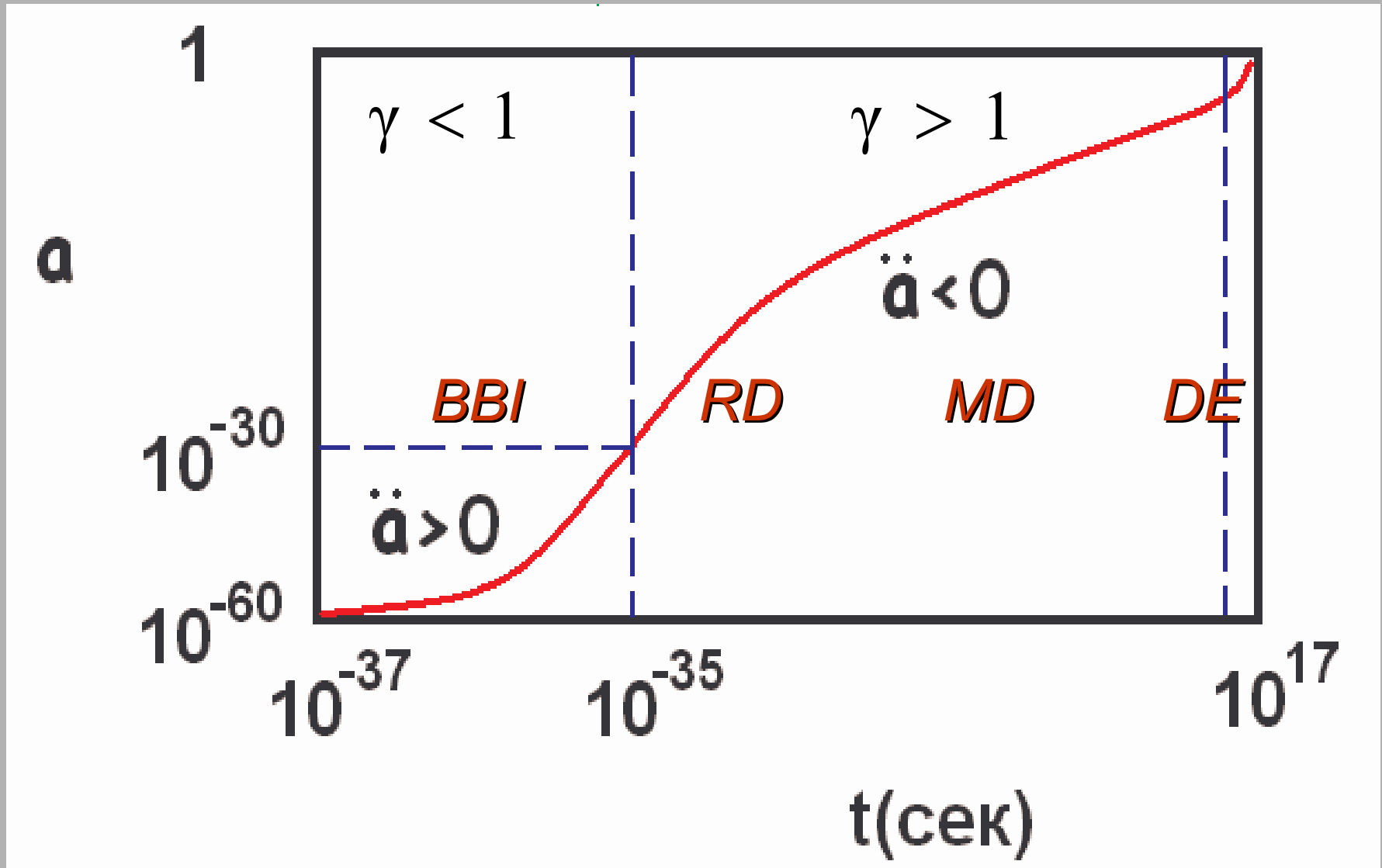
lesson 1: *large Universe*

Since the very beginning ($\gamma > 1$)
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 -- *BBI*

($\gamma < 1$)

Evolution of scale factor



Formation of the Universe is formation of Hubble outflows

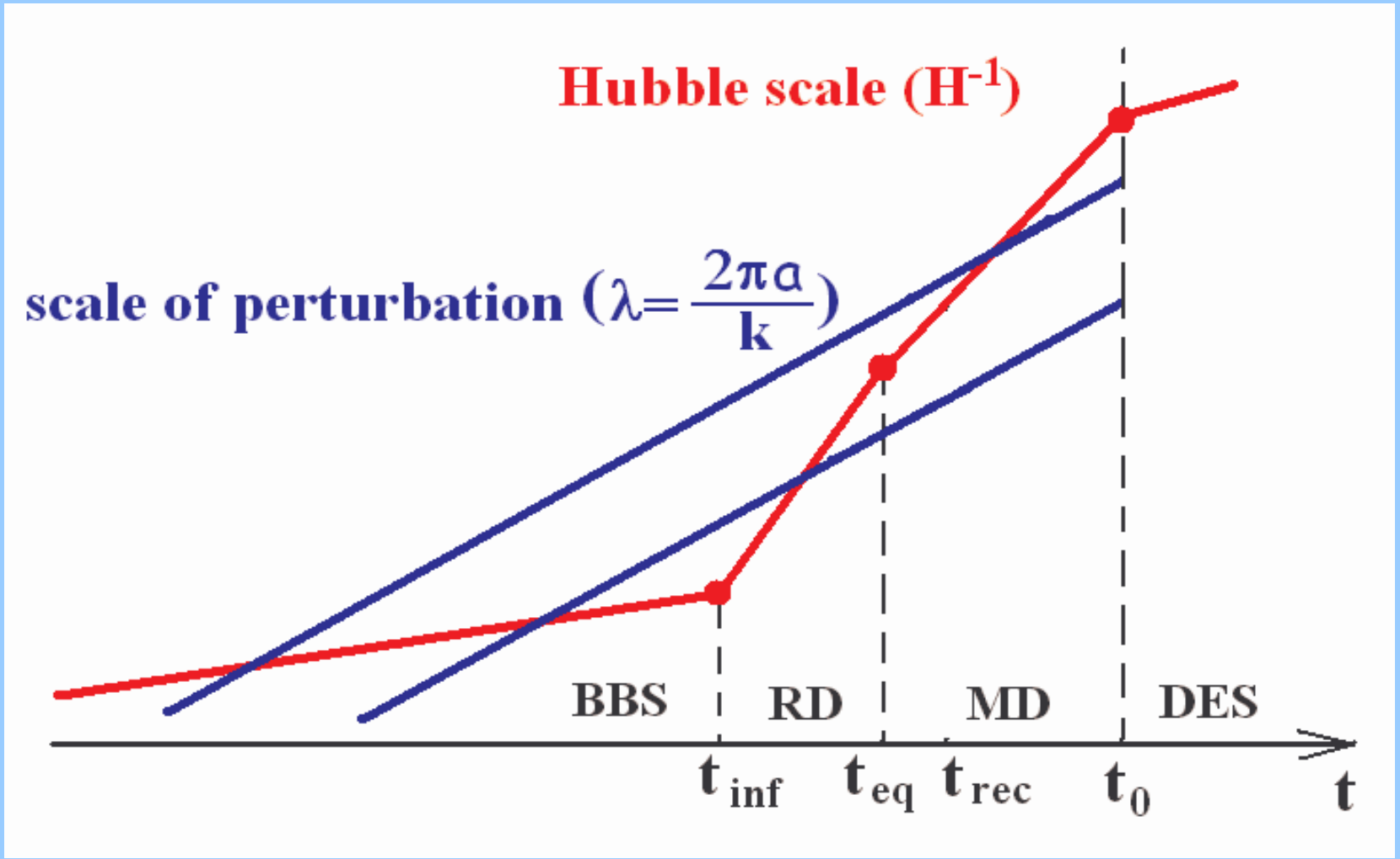
$$\vec{v} = H\vec{r} \quad , \quad H = \dot{a} / a$$

$$\ddot{a} > 0 \quad (\gamma < 1)$$

Formation of the structure is destruction of Hubble outflows

$$\ddot{a} < 0 \quad (\gamma > 1)$$

lesson 2: *acausality*



BBI is needed to explain acausality

lesson 3: *structure argument*

$\Omega_m = \rho_m / \rho_c < 0.3 \rightarrow$ 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

Superweak field ?

No principle difference with inflaton

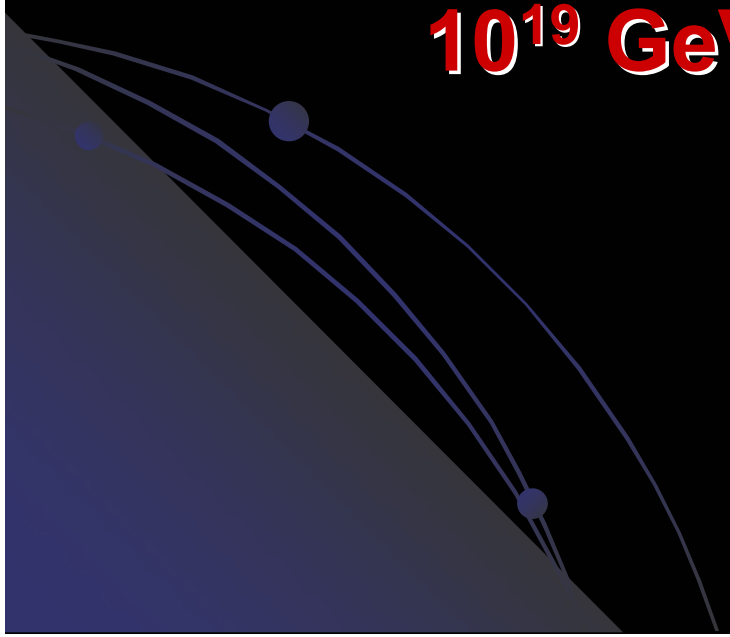
$E \sim 10^{-3}$ eV (for $\rho_E = E^4$)

New energy scale ?

Coincidence problem: $\rho_b \approx \rho_M \approx \rho_E$

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

$$\rho_r < \rho_M \,, \quad \rho_E \leq \rho_M$$

-window of gravitational instability
(+ initial amplitude of perturbations)

$$\rho_r << \rho_b \leq \rho_M$$

- condition for formation of starts

DE ceases structure formation and restores Hubble outflows

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)

→ < 20% of halo mass in moon-star MACHOs
→ > 80% of halo mass in non-baryon particles

DM (non-baryonic):

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

→ X-ray gas (T~ keV)
→ gravitational lenses

Answer: non-baryonic DM is in gravitationally bound systems

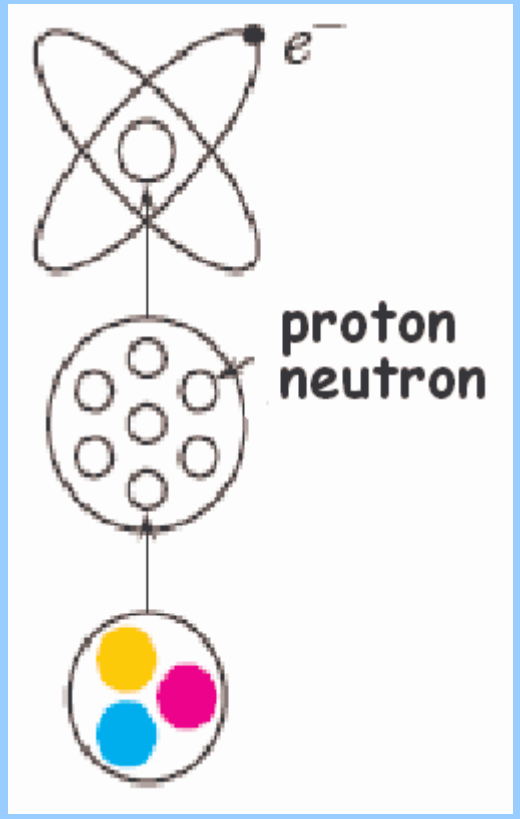
weakly interacting particles
do not dissipate as baryons

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 kpc

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

No such particles in standard model !



leptons $\begin{pmatrix} e \\ \nu_e \end{pmatrix}, \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}, \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$

three generations

quarks $\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$

+ antiparticles $e^+, \ldots$ $\bar{\nu}_e, \ldots$ $\bar{u}, \ldots$

+ particles responsible for interactions

γ, $W^\pm$, Z, gluons

Hypotheses of non-baryonic DM

candidats	mass
Gravitons	10^{-21} eV
Axions	10^{-5} eV
Sterile neutrino	10 keV
Mirror particles	1 GeV
Neutralino	100 GeV
Extra-dimensions, branes	1000 GeV
Supermassive particles	10^{13} GeV
Monopoles, defects	10^{19} GeV
Primordial black holes	10^{-16}-10^{-7} $M_\odot$

Message from the early Universe

DM mystery is related
to baryonic asymmetry

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

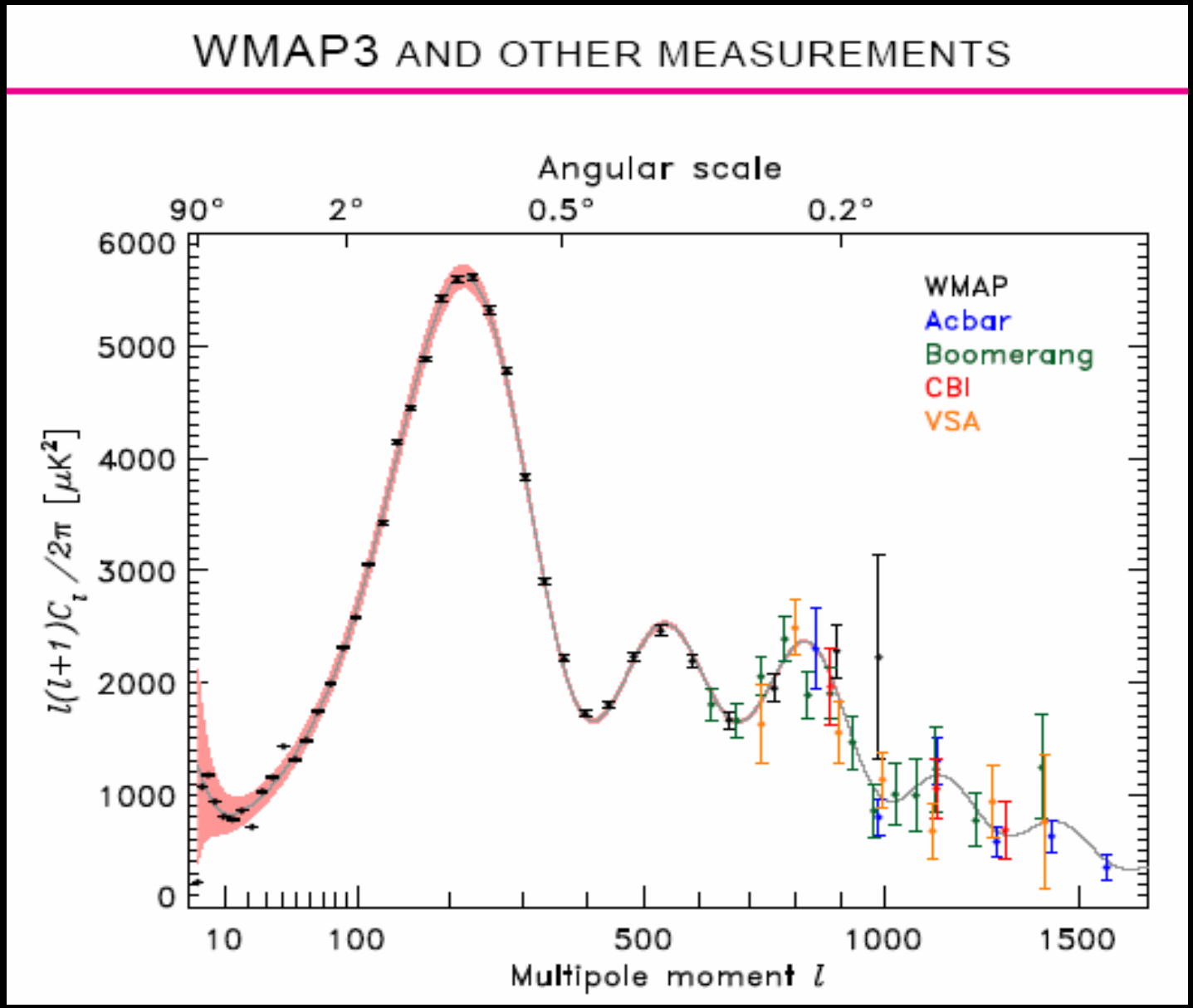
History of the Universe is the history of origin and decay of massive fields

First order geometry

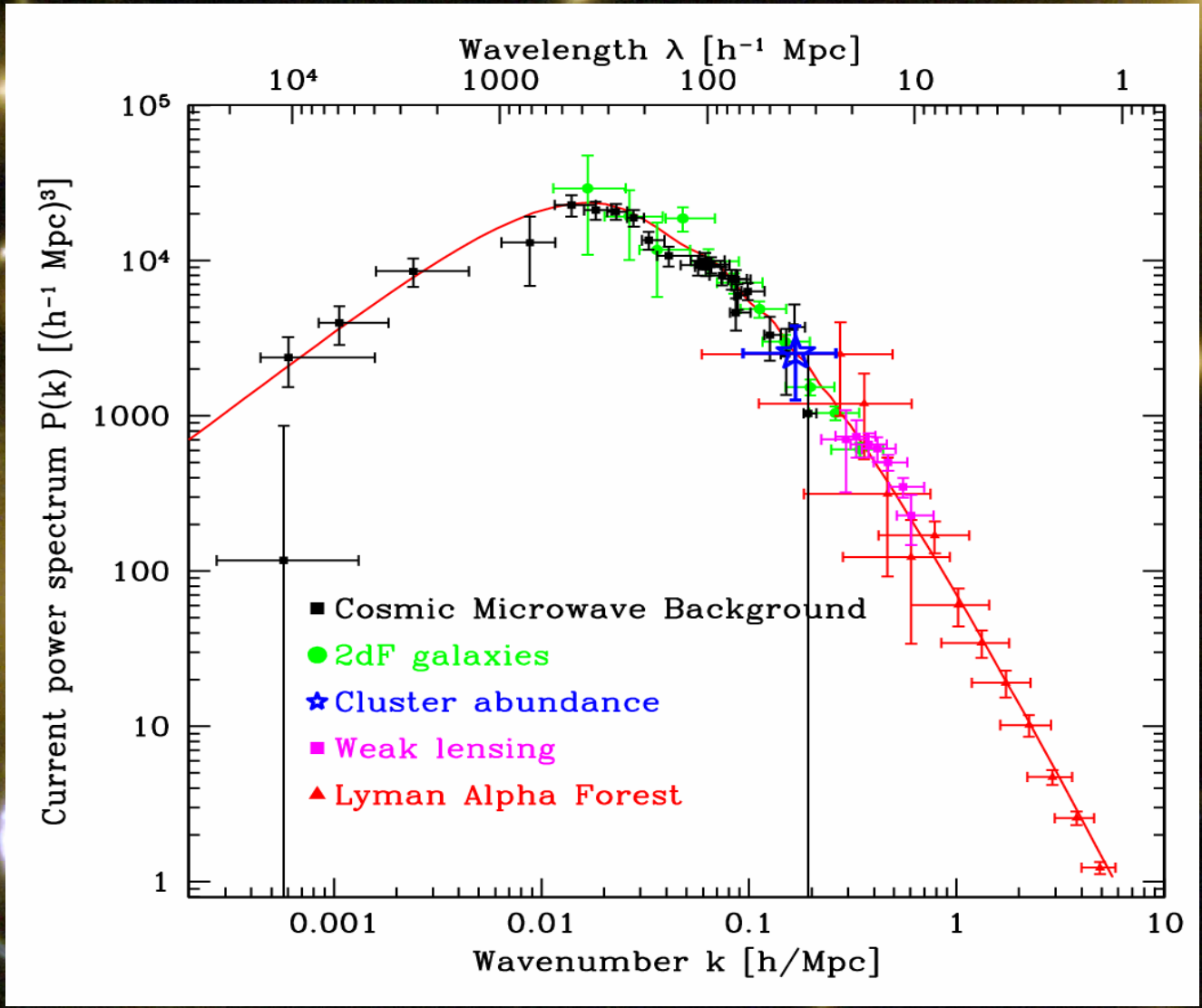
S → seeds for LSS structure
(galaxies, clusters, voids..)

S+T+V → imprinted in CMB structure
(anisotropy and polarization)

S+T+V


WMAP3 AND OTHER MEASUREMENTS
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

only S



Tegmark, Zaldarriaga 2002

We live in the Universe with small **T&V**

All values $(T+V)/S > 0.1$ *are excluded as in this case amplitude of S-mode is insufficient for the formation of the structure*

$T+S+V=10^{-10} \Rightarrow$ *fixed by CMB*

Origin of cosmological perturbations

quantum gravitational creation of massless fields under the action of non-stationary intensive gravity (external coupling), seeds – quantum fluctuations

- Creation of matter (Grib, Starobinsky…1970s)
- Generation of T-mode (Grishchuk 1974)
- Generation of S-mode (V N L 1980)

Generation of T and S modes in Friedmann cosmology is a quantum-mechanical problem of elementary oscillators $q_k(\eta)$ [$\lambda = a/k$, $\omega = \beta k$] in the Minkowski space-time in the external parametric field $\alpha = \alpha(\eta)$, $\eta = \int dt/a$

$$S_k = \int L_k d\eta, \qquad L_k = \frac{\alpha^2}{2k^3}\left(q'^2 - \omega^2 q^2\right)$$

q_T **- transverse-traceless component of gravitational field**

$$\alpha_T^2 = a^2 / 8\pi G \ , \qquad \beta = 1$$

q_S **- gauge-invariant superposition of longitudinal gravitational potential and the velocity potential of matter multiplied by the Hubble parameter**

$$\alpha_S^2 = a^2 \gamma / 4\pi G \beta^2 , \quad \beta = c_s / c$$

Evolution of elementary oscillators

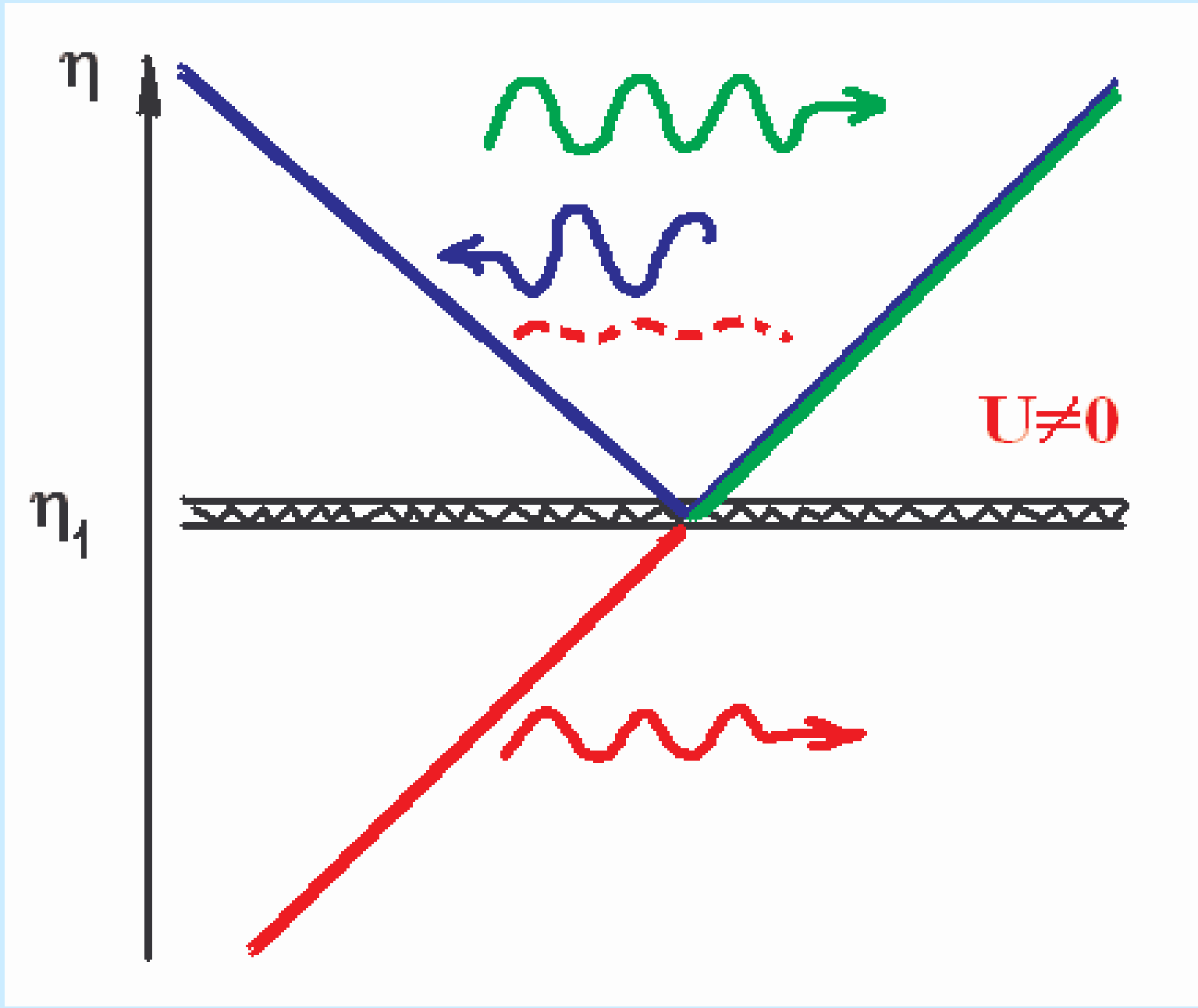
$$\overline{q} = \alpha q\,, \qquad U = \frac{\alpha''}{\alpha}$$

$$\boxed{\overline{q}'' + (\omega^2 - U)\overline{q} = 0}$$

adiabatic zone $\omega^2 > U: \quad |q| \sim 1/\alpha\sqrt{\beta}$

parametric zone $\omega^2 < U: \quad q \sim \text{const}$

creation moment $\omega^2 = U \cong (2-\gamma)\, a^2 H^2$


η
η1
U≠0

Phase information: only growing mode of perturbations is created

$U = 0$: $(a \sim \eta)$

$$q = C_1 \frac{\sin\kappa}{\kappa} + C_2 \frac{\cos\kappa}{\kappa}$$

$\kappa = \omega\eta$

growing mode

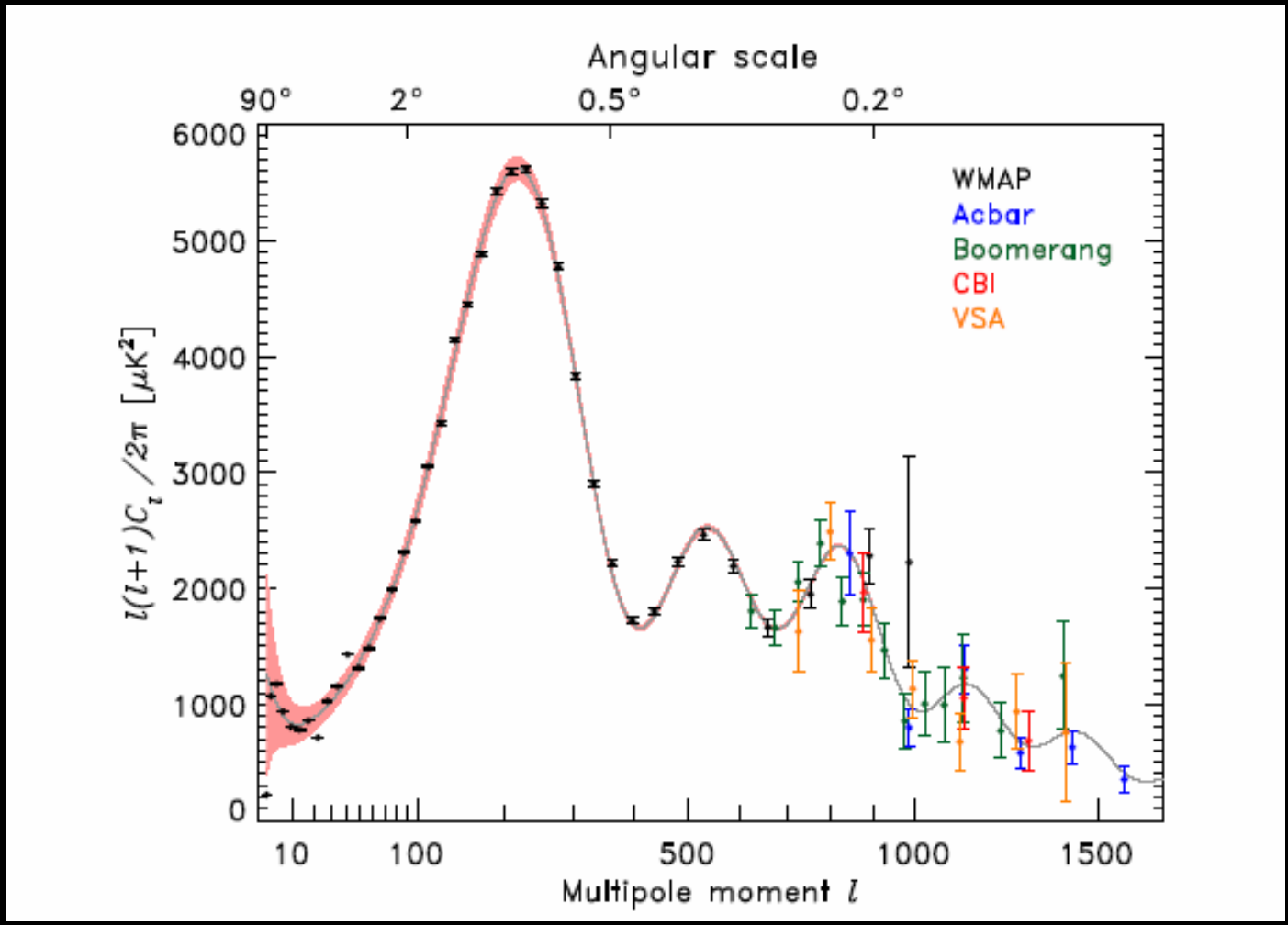
decaying mode

vacuum: $|C_1| = |C_2|$, after creation: $|C_1| >> |C_2|$

first peak: $\kappa = \pi$

$$\ell_p = \pi\eta_0 \cong \frac{\pi\sqrt{3}\eta_0}{\eta_{rec}} \cong 200$$

we see the sound !



In the beginning was sound and sound was of Big Bang

Theory of the early Universe

$$T \cong \frac{H^2}{M_P^2}, \qquad \frac{T}{S} = 4\gamma$$

$$H \equiv \frac{\dot{a}}{a} = \frac{k}{a}$$ - Hubble radius at creation moment of perturbation of wavelength $\lambda = a/k$

→ energy scale of BB = $\sqrt{M_P H}$

$$\gamma \equiv -\frac{\dot{H}}{H^2} = \frac{d \ln H^{-1}}{d \ln a} \approx \left(10^5 \frac{H}{M_P}\right)^2$$ - dynamics H

→ physical model of BBI

Universal result

$$T = \frac{H^2}{M_P^2} \quad , \qquad \frac{T}{S} = 4\gamma$$

$$H < 10^{13}\,\mathrm{Gev} \quad , \quad \gamma < 0.01$$

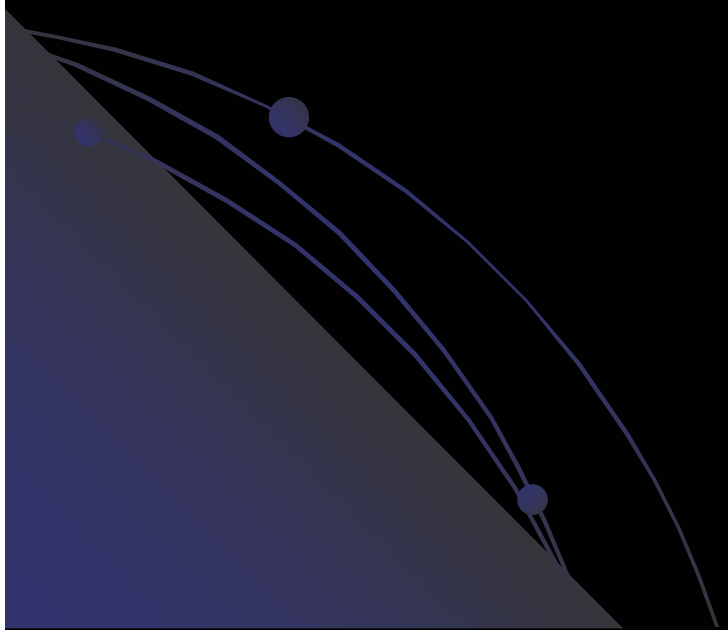
Big Bang = Inflation ($\gamma < 1$)

Power-law inflation on massive field:

the amplitude of T-mode is only five times less than amplitude of S-mode

Detection is possible !

How to measure dark Energy?



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

$$\alpha \equiv a - 1 = -\frac{z}{1+z}, \; w_0 = -1 + c_0, \; w_0' = c_1$$

c_n ($n = 0,1,2,\ldots$) – physical parameters of DE

currently all $|c_n| < 0.1$

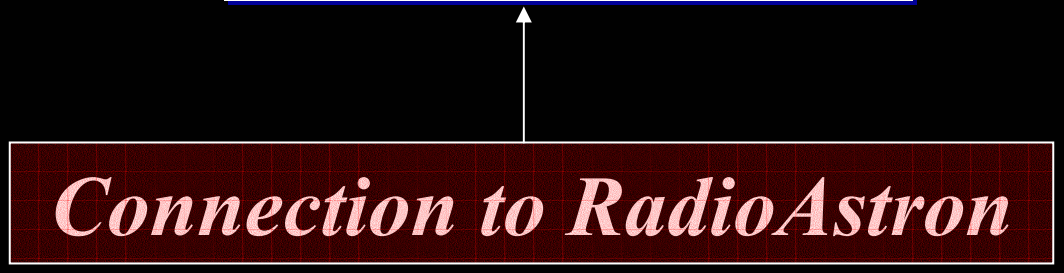
Precise statistical measurements of any cosmological parameters as function of z

Three ways to measure DE

Structural

Dynamical

Geomertrical



Structure

not entering the structure
DE affects crucially
the rate of its formation

measure DE by weighting
the structure with redshift

Structural argument: DE discovering

Still using non-linear systems

leads to non-control systematics

Just use quasilinear systems:

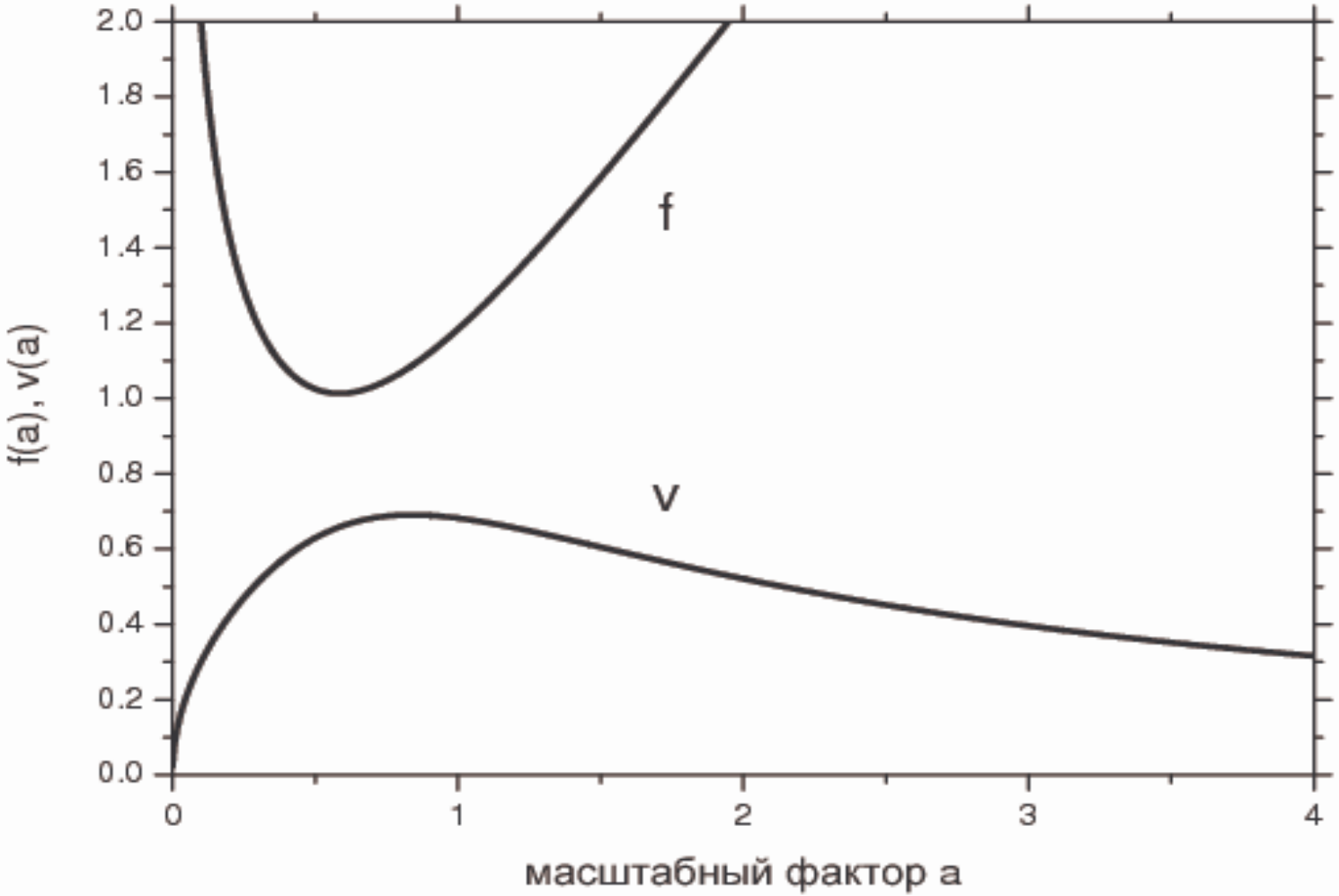
Gravitational potential,

Peculiar velocities,

Acoustic oscillations

Example: CMB

Evolution of Hubble and peculiar velocities



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

LSS formation proceeds from
1 to 22 Gyrs since Big Bang

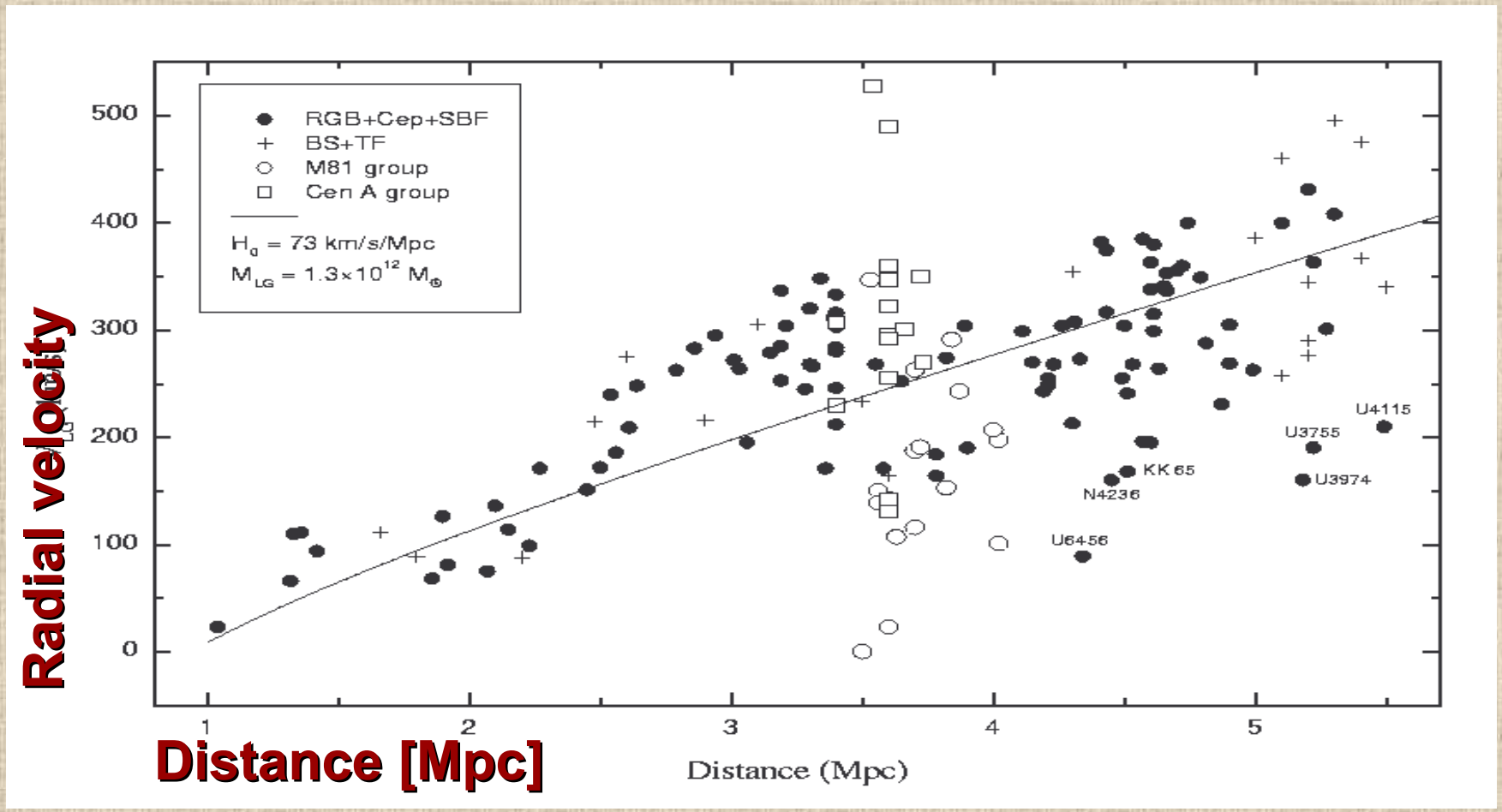
We live at period of maximum
LSS formation in the Universe

Use this chance:

measure DE by weighting
the structure with redshift

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

Nearest galaxies

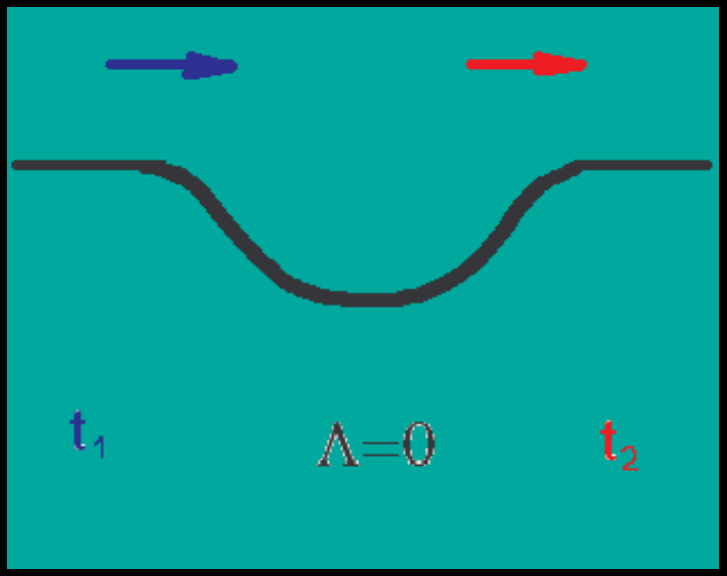


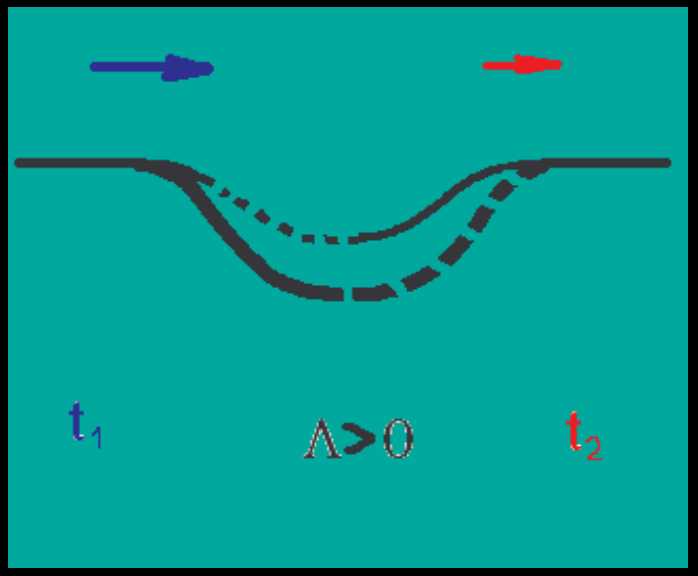
eigen values H_{ik}= *diag* (81, 62, 48) km/c/Mpc

Dynamics

cross-correlation LSS-CMB

$$\Delta\Phi = 4\pi G\rho_m a^2\delta \sim \frac{\delta}{a} \sim \begin{cases} \text{const}, & \rho_m > \rho_\Lambda \\ a^{-1}, & \rho_m < \rho_\Lambda \end{cases}$$

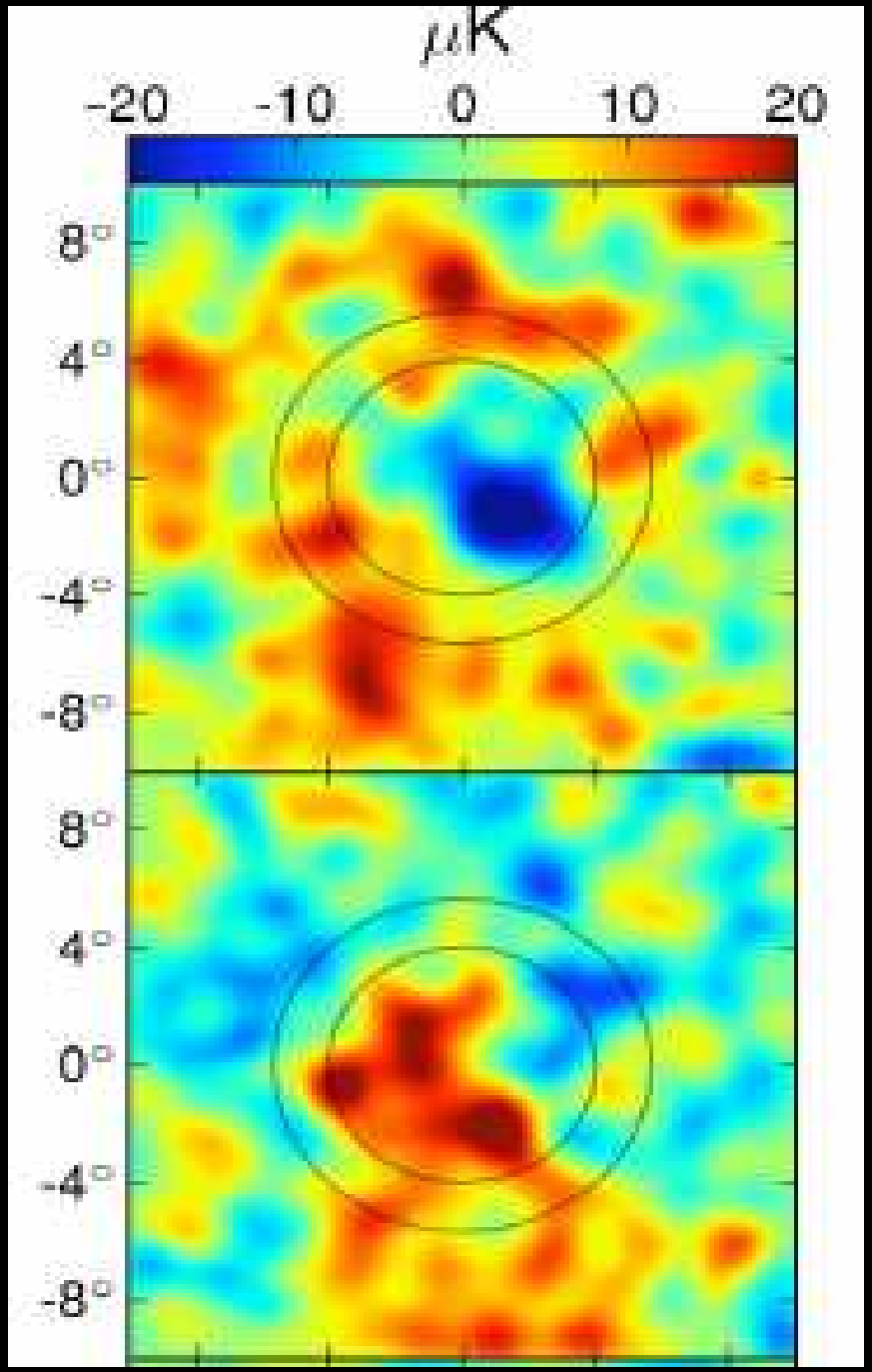




50 voids

50 superclusters

Granett et al 2008



Geometry

Apparent magnitude / redshift

$m(z)$

(SNIa, standard candle)

Angular diameter / redshift

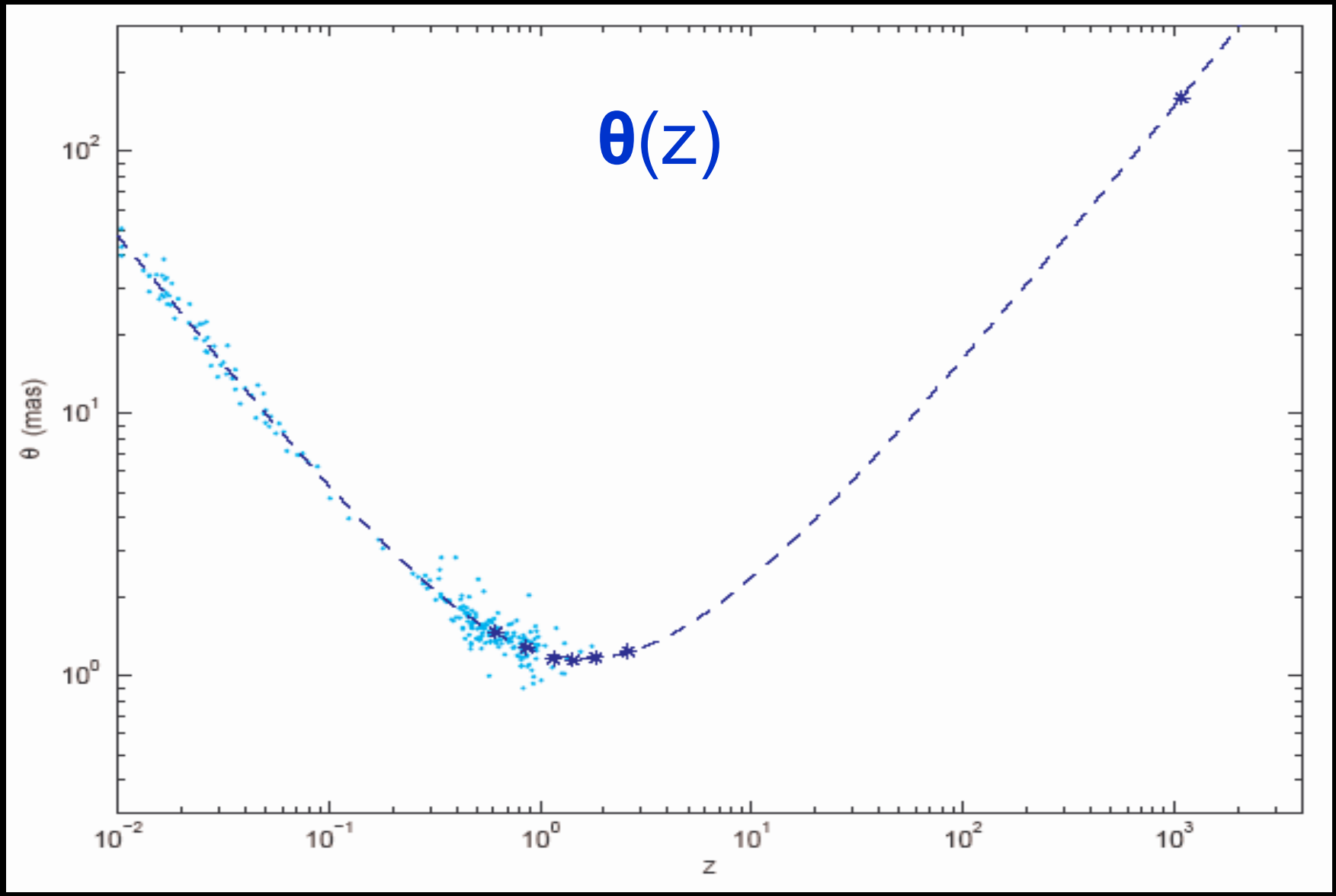
$\theta(z)$

(UCRSmas, standard rod)

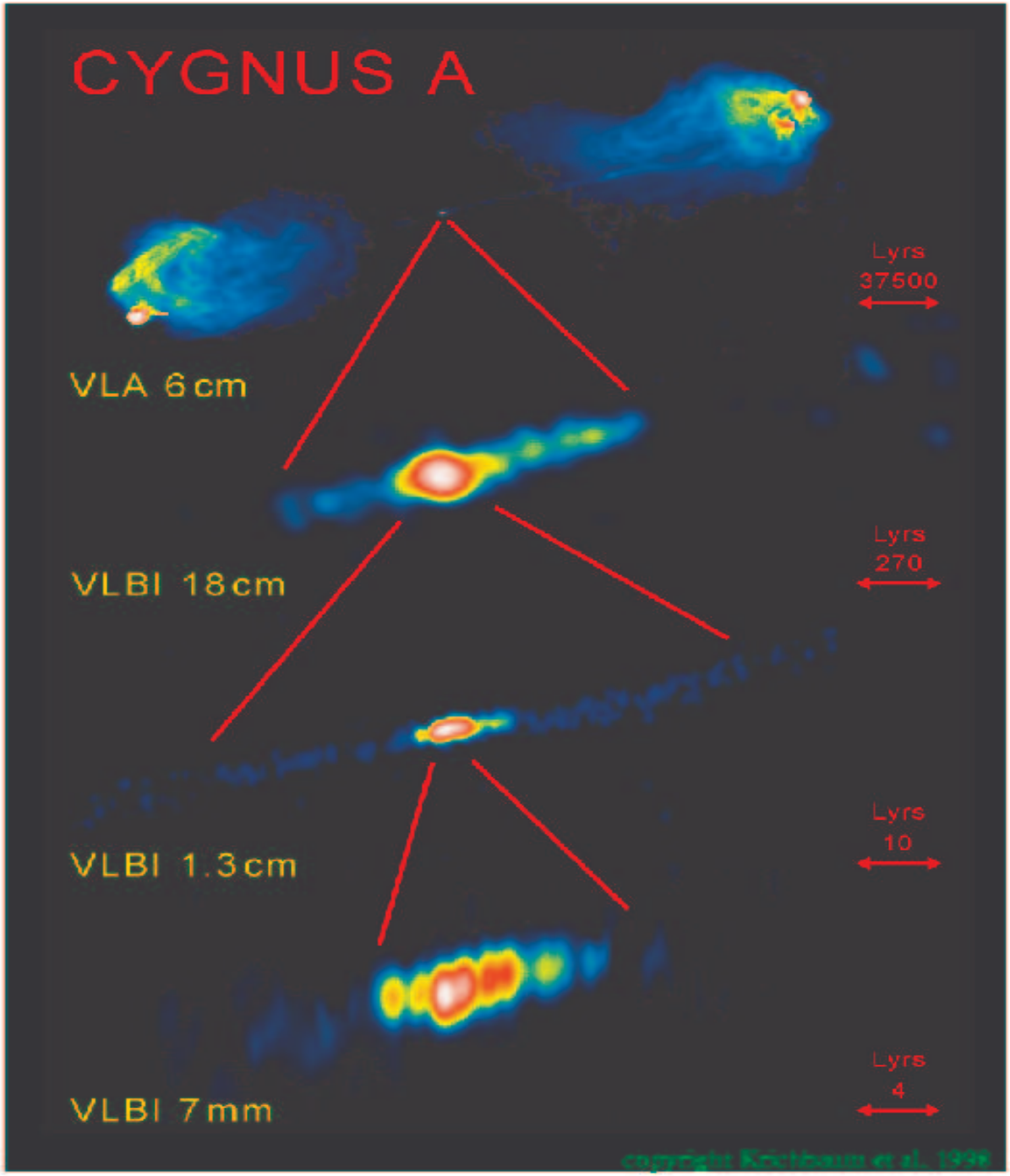
Measure geomerty with help of
$\theta(z)$ и $\dot{\theta}(z)$

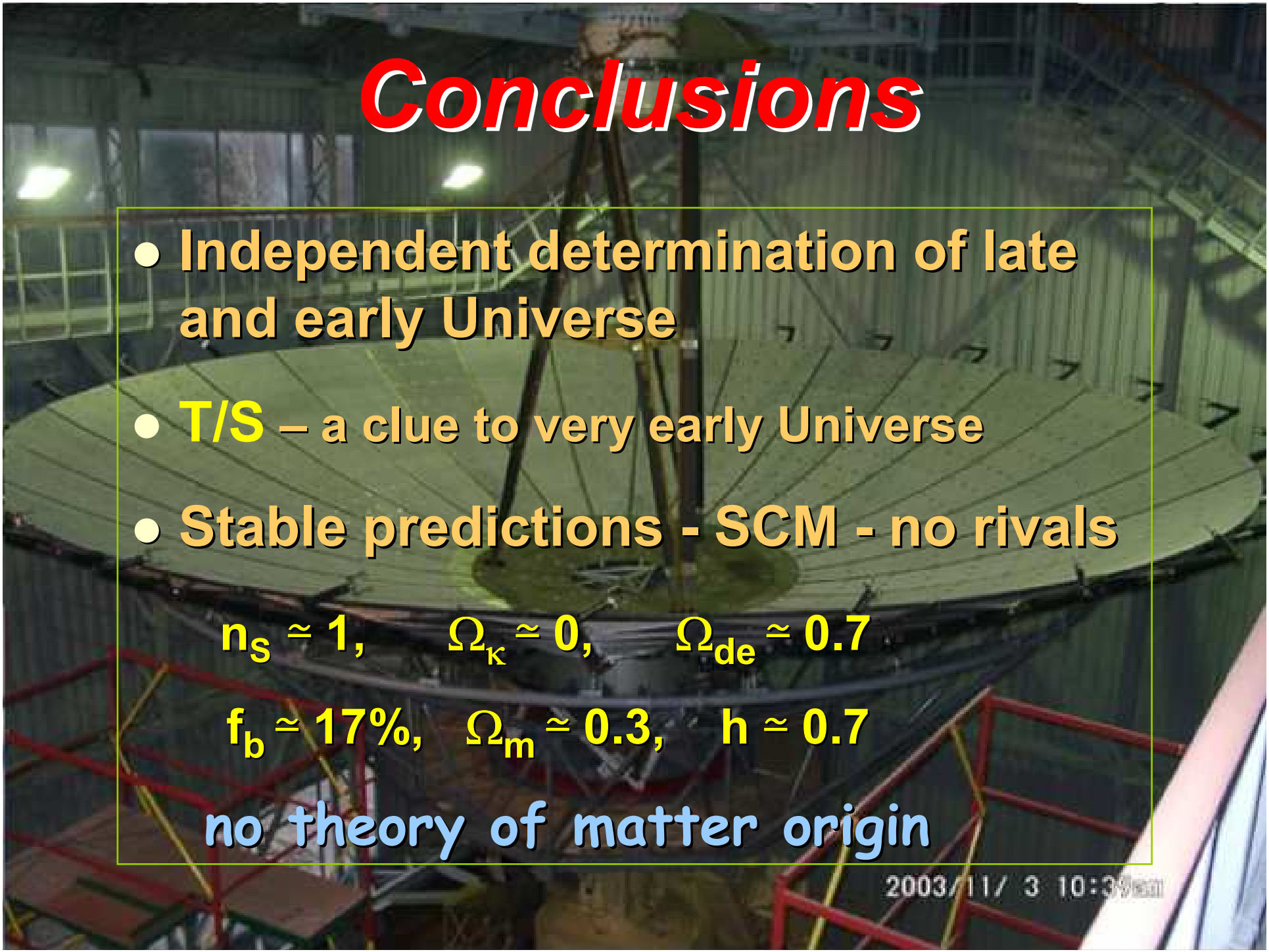
If you know the physical size of distant object,
you know the distance to it

Ultracompact radiosources



Jackson & Jannetta 2006


CYGNUS A
VLA 6cm
VLBI 18cm
VLBI 1.3cm
VLBI 7mm
Lyrs
37500
Lyrs
270
Lyrs
10
Lyrs
4
copyright Krichbaum et al. 1998



Conclusions

- Independent determination of late and early Universe
- T/S – a clue to very early Universe
- Stable predictions - SCM - no rivals

$n_S \simeq 1$, $\Omega_\kappa \simeq 0$, $\Omega_{de} \simeq 0.7$

$f_b \simeq 17\%$, $\Omega_m \simeq 0.3$, $h \simeq 0.7$

no theory of matter origin

Theory is exhausted

presenting list where/how
to search for DM and DE

Experiment's turn

The situation recalls great historical moments: quarks, W-Z-bosons, neutrino oscillations, CMB anisotropy, polarization

Why Nature is generous to us and discloses its secrets ?