Kolloquium-english.ppt

J. Jersák,

Technical Univ. Aachen

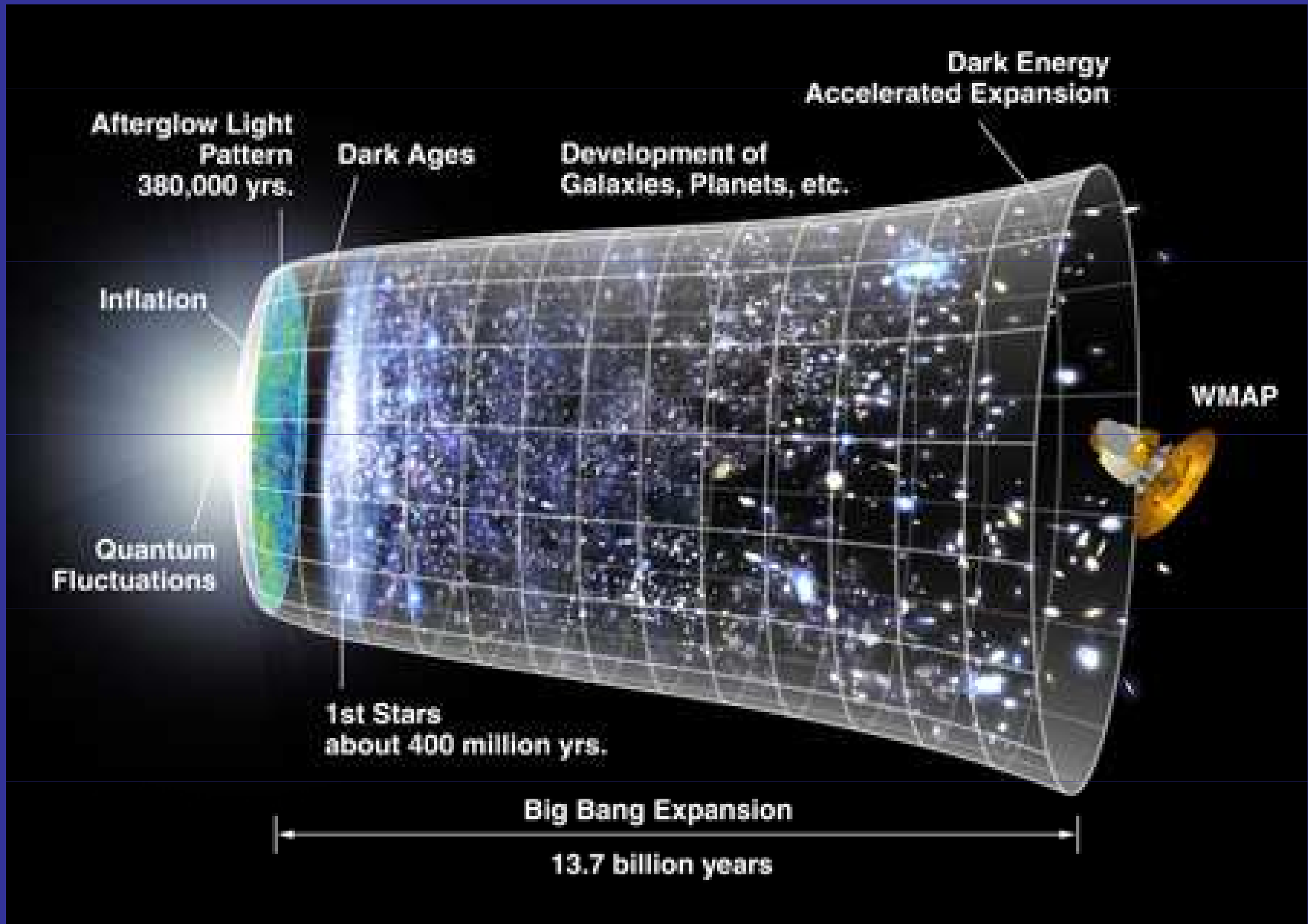
Theoretical Physics

Kaiserslautern, May 2009

Expansion of space in contemporary cosmology

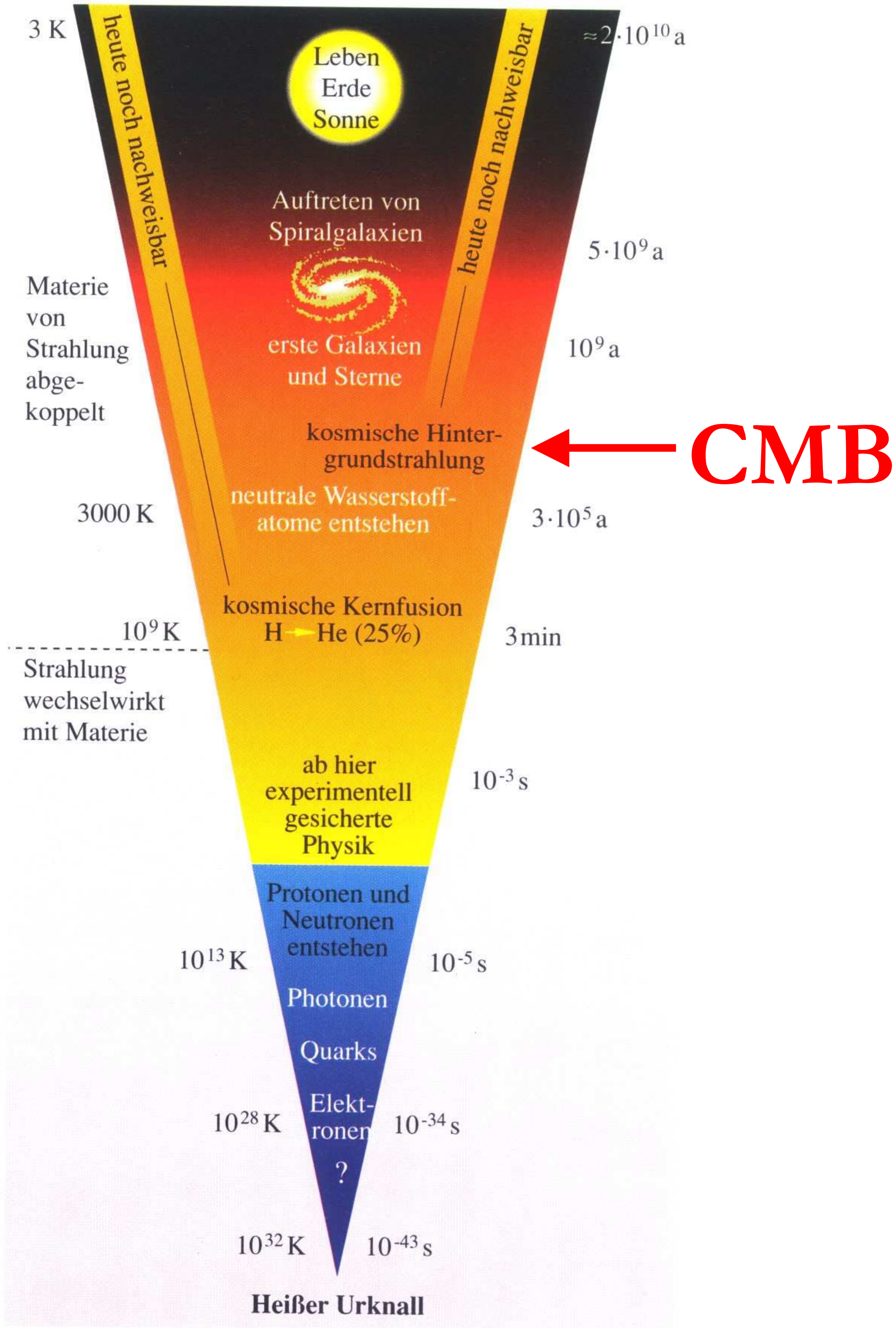
- In the general theory of relativity the elastic space can not only be curved but it can also expand.
- This makes the expansion of the Universe qualitatively easily understandable.
- However, one should keep in mind that the special theory of relativity and conservation of energy have a limited validity.
- Quantitatively, the observed expansion speed is not understood.
- Nevertheless, a remarkably simple phenomenological model, the ΛCDM model, describes the expansion of the Universe quite well and explains many observations.

One of numerous sophisticated illustrations



History of the Universe from a German **Schulbuch**

(Dorn-Bader)



History of the expansion paradigm (I)

- Known theoretically since 1920´s (after GR 1915) before Hubble
- **Original theory of expansion**

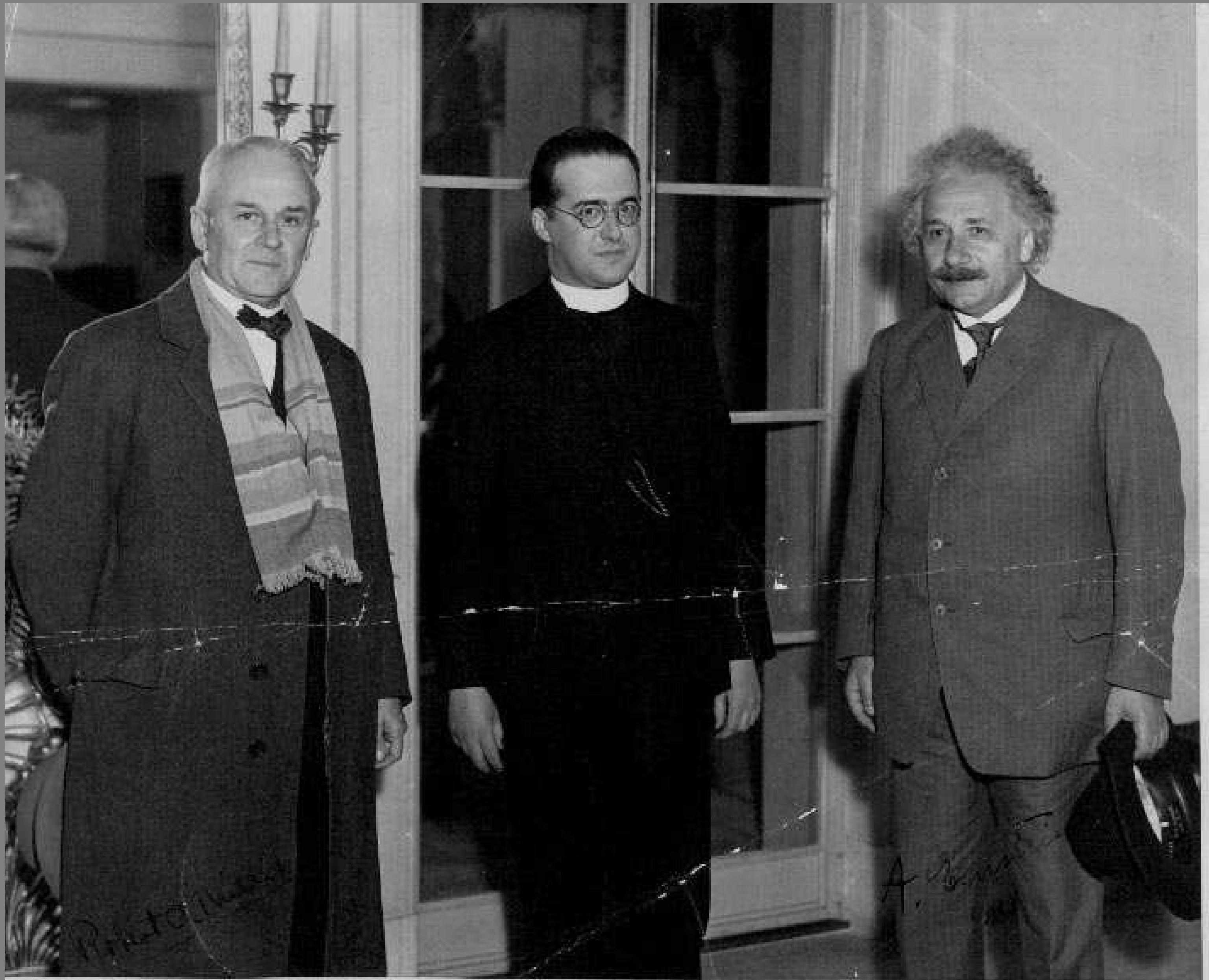
  based on general relativity (GR)

  Friedmann (Russia),

  Lemaître (Belgium, *L'Hypothèse de l'Atome Primitif*),

  …

Millikan, Lemaître, Einstein



History of the expansion paradigm (II)

- **First observations in 1920´s** **(Slipher, …)**
- Redshift of **close Galaxies**

  increases with their distance

⇒ **Evidence of the expansion:**

Hubble (USA)

- **Since 1998: Distant supernovae**

⇒ **Evidence of an**

accelerated expansion

Understanding of the expansion

- 1920-1990´s:

„simple“ explanations of the expansion without GR

(bomb-like explosion in a rigid space,
using Newtonian mechanics or SR only,
evoking Doppler-effect,
assuming energy conservation, etc.)

were applicable only at small distances (locally)

- Today: observations at large distances require use of

general relativity

+ cosmological constant Λ

both introduced into cosmology by Einstein

Universe on cosmological time-scales (Giga…)

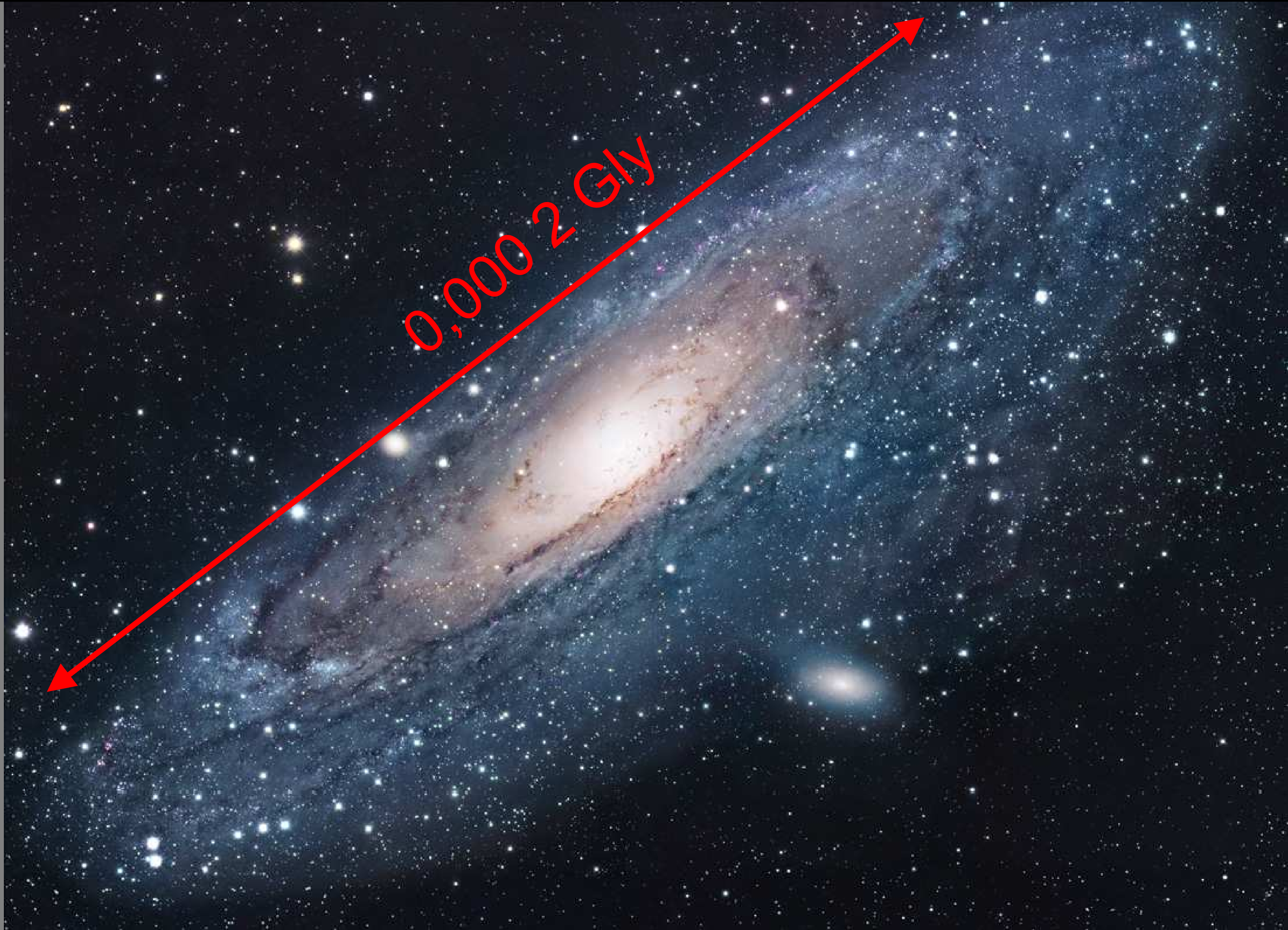
- 1 Gy = **1 000 000 000** y = billion years
- Solar system age 4,5 Gy
- Our galaxy age ≈ 10 Gy
- Universe since the big bang t_0 = 14 Gy
- Cosmic microwave background (CMB) origin 400 000 y = 0.000 4 Gy
- Maximum density *(?)* $t \approx 0$
- Big Bang = a process! (3 min*?*) $t > 0$

Universe on cosmological length-scales (Giga…)

- 1 Gly = **1 000 000 000** ly = 1 billion light years

- Galaxies („dust particles“) 0,000 1 Gly
- Galaxy clusters 0,001 Gly

- Uniform mass distribution
  (*no structures)* from 1 Gly
- Observable Universe 46 Gly
  (source of CMB, radius today)



Andromeda, APOD

Sombrero Galaxy • M104

Hubble Heritage

D

NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope ACS • STScI-PRC03-28

Dark matter
in halo around
some galaxy

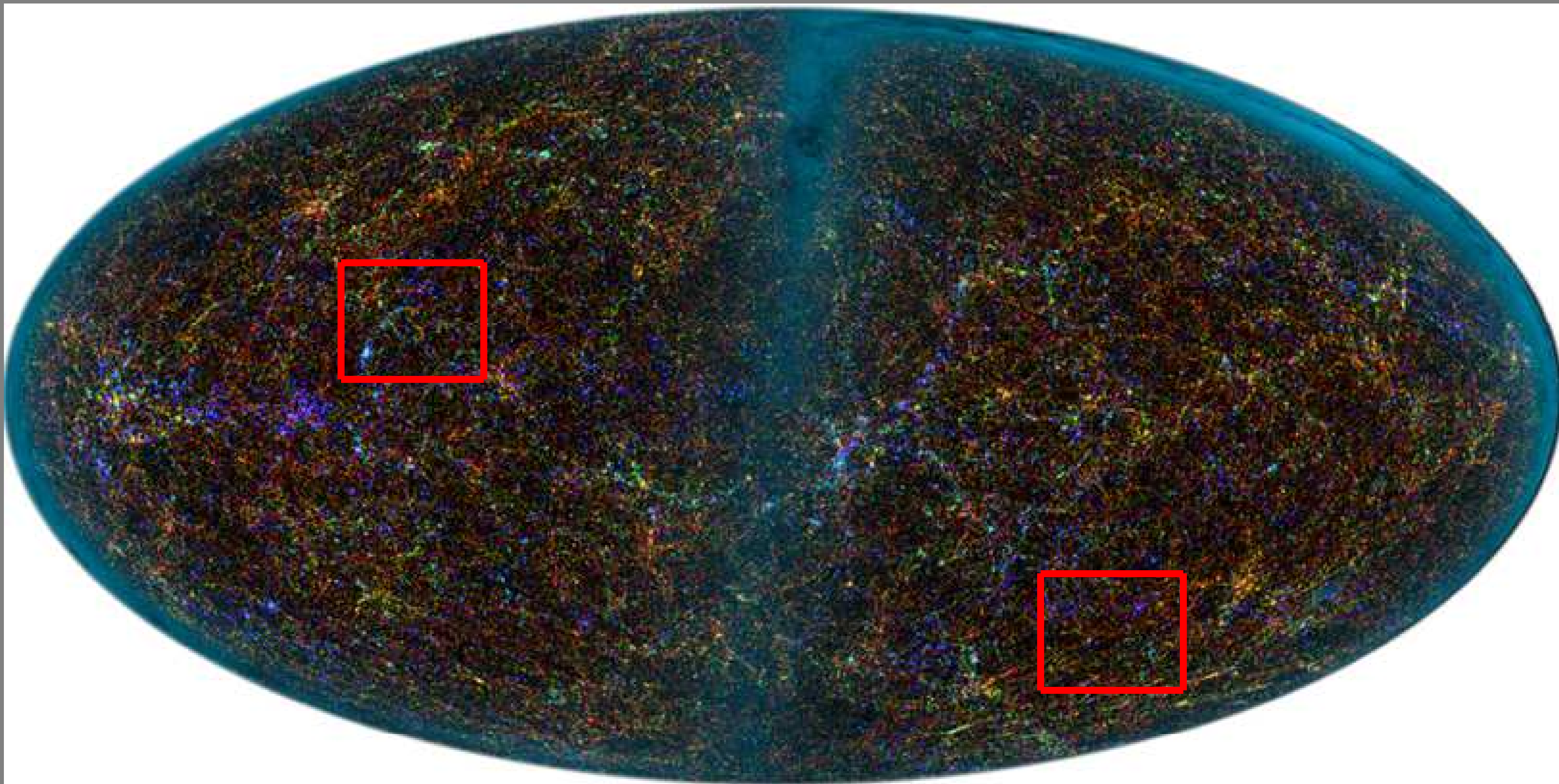
dark matter
≈ 10x
visible matter

RELEVANT

Artist‘s view

D.B.Cline, SciAm March 03

Distribution of galaxies over the whole sky

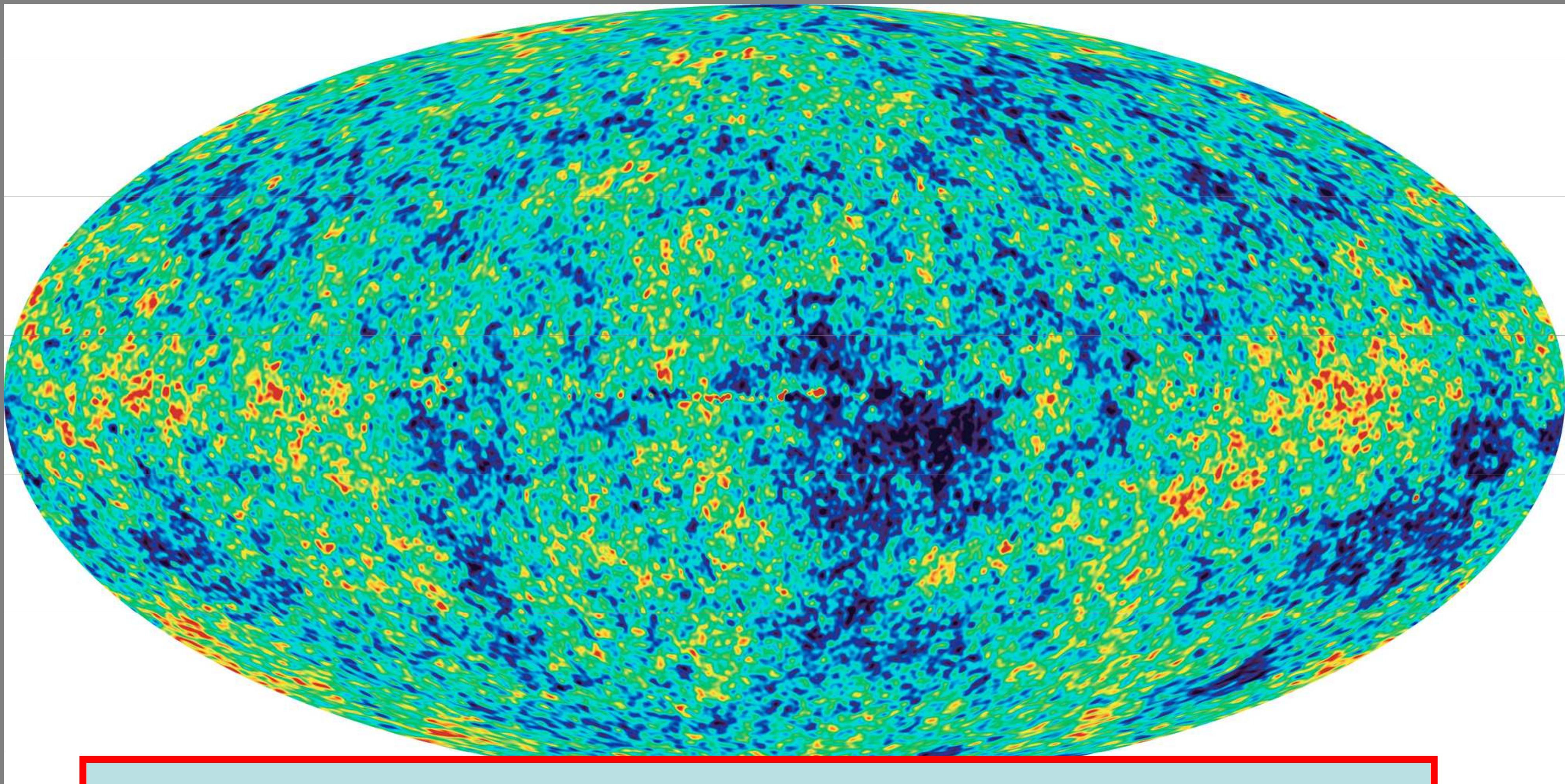


http://spider.ipac.caltech.edu/staff/jarrett/papers/LSS/

Cosmic microwave background (CMB)

averaged over all sky directions T_0 = 2,730+/-0,001 ° (COBE)

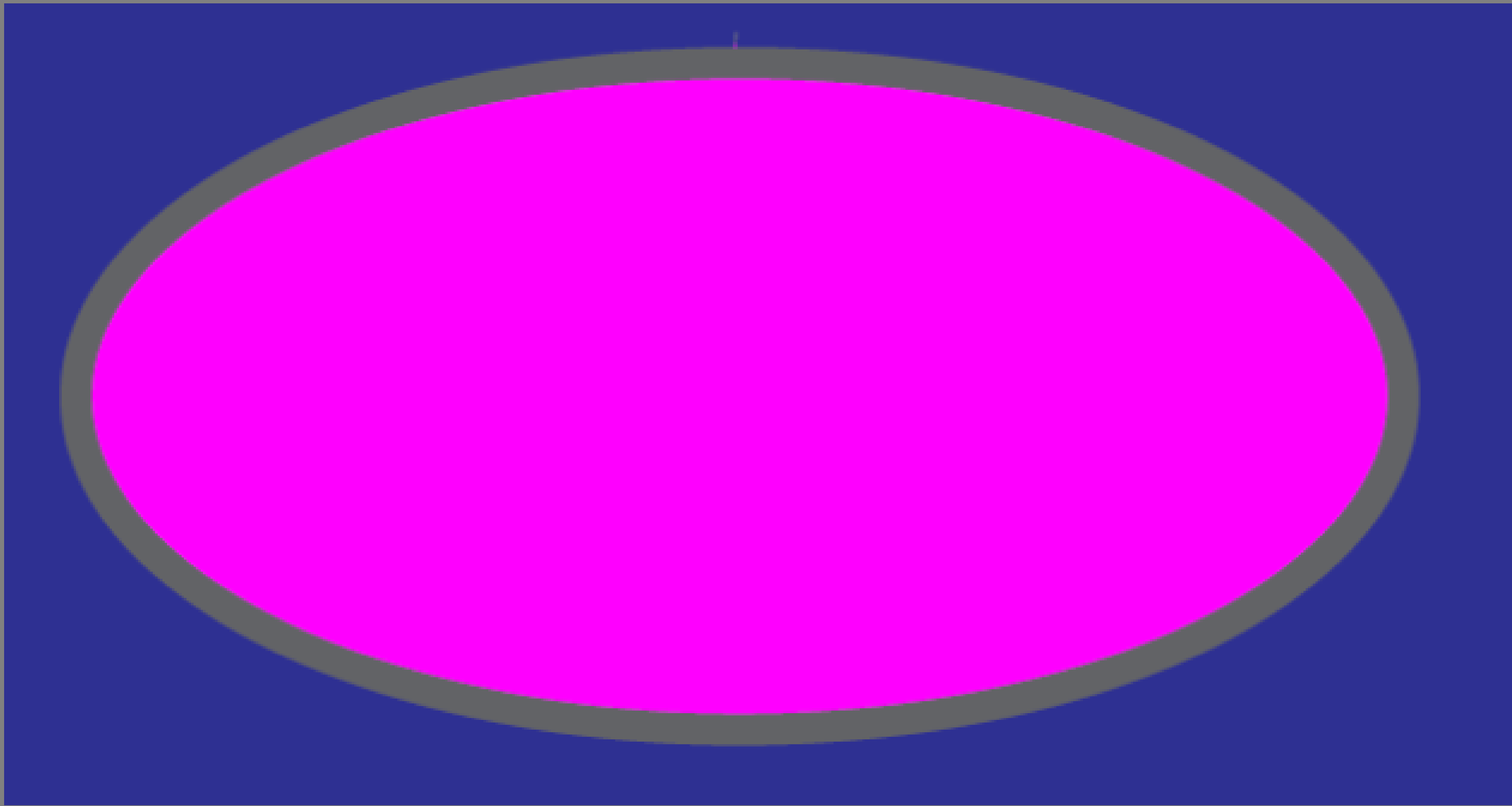
T-fluctuations only very fine 0,000 02 °K (COBE and WMAP satellites)



COBE 1989: Mather, Smoot, Nobel prize 2006

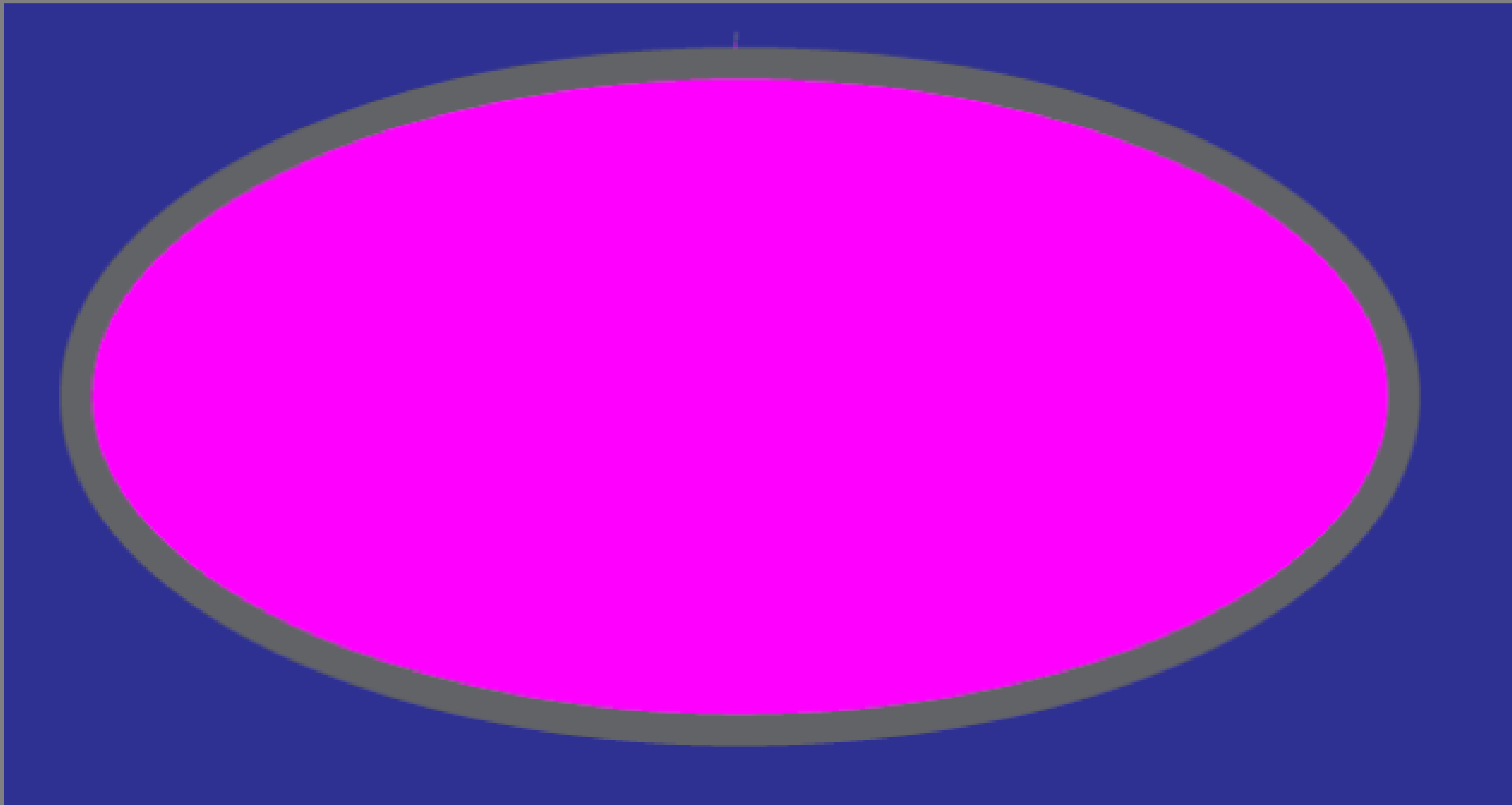
Cosmic microwave background (CMB)

From all sky directions at lower T-resolution: T_0 = 2,7..°K



W. Hu, http://background.uchicago.edu/%7ewhu/beginners/introduction.html

On cosmological scales is the observable Universe everywhere the same



(uniform matter distribution)

The observable Universe is equal everywhere.

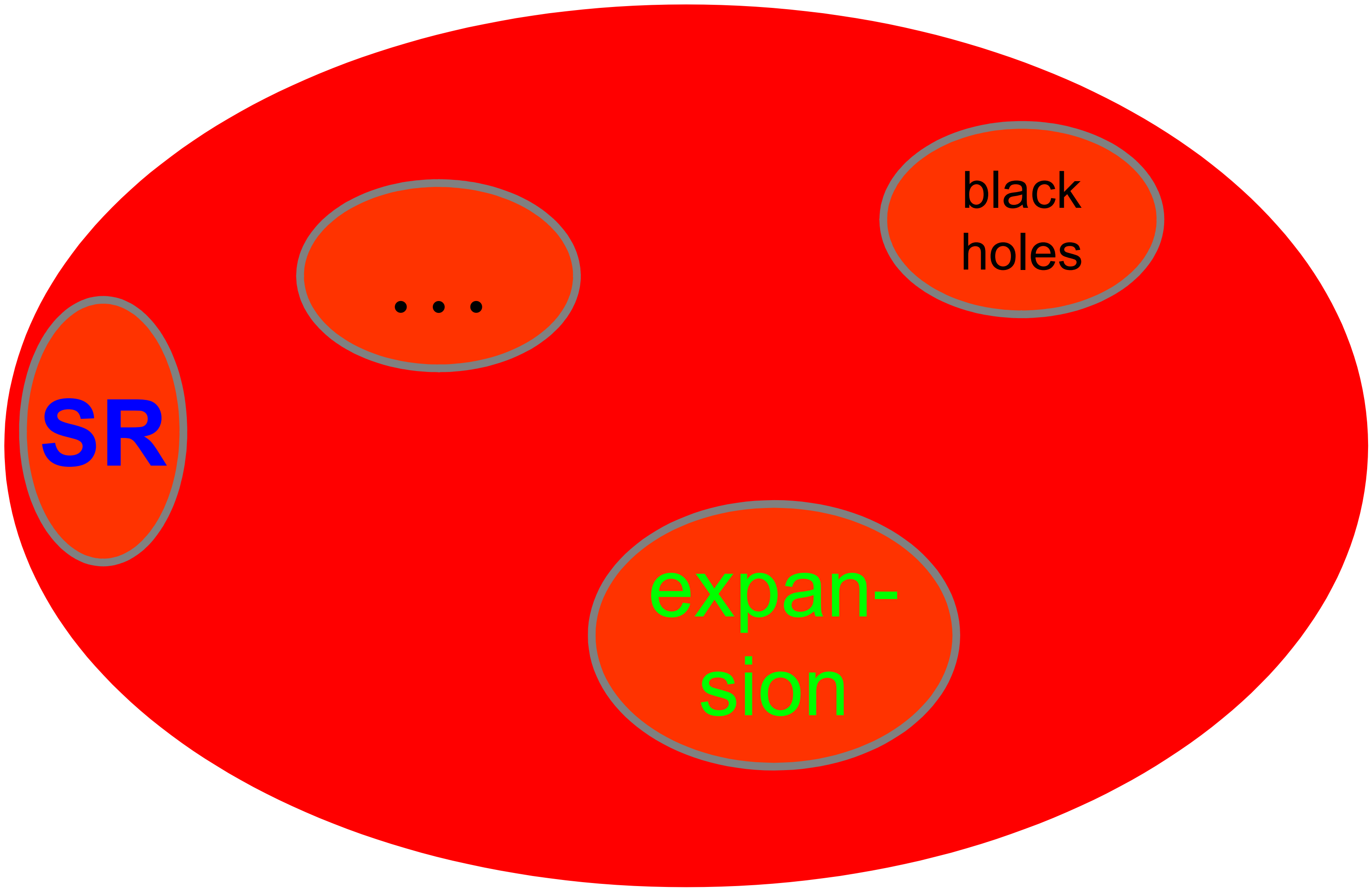
Thus it expands everywhere, at all observable distances.

For an understanding of the expansion at large distances is the general theory of relativity (**GR**) with elastic space necessary

The special theory of relativity (**SR**) with rigid space is NOT applicable, since a rigid space can approximate an elastic space only locally.

Correct theory of spacetime is GR

SR, black holes, …, expansion



Cosmic time t

applicable in the whole observable Universe

GR => no global inertial system is required

(different from SR)

Since the Universe is equal everywhere,

it has also the same age everywhere

$\Rightarrow$ Cosmic age t

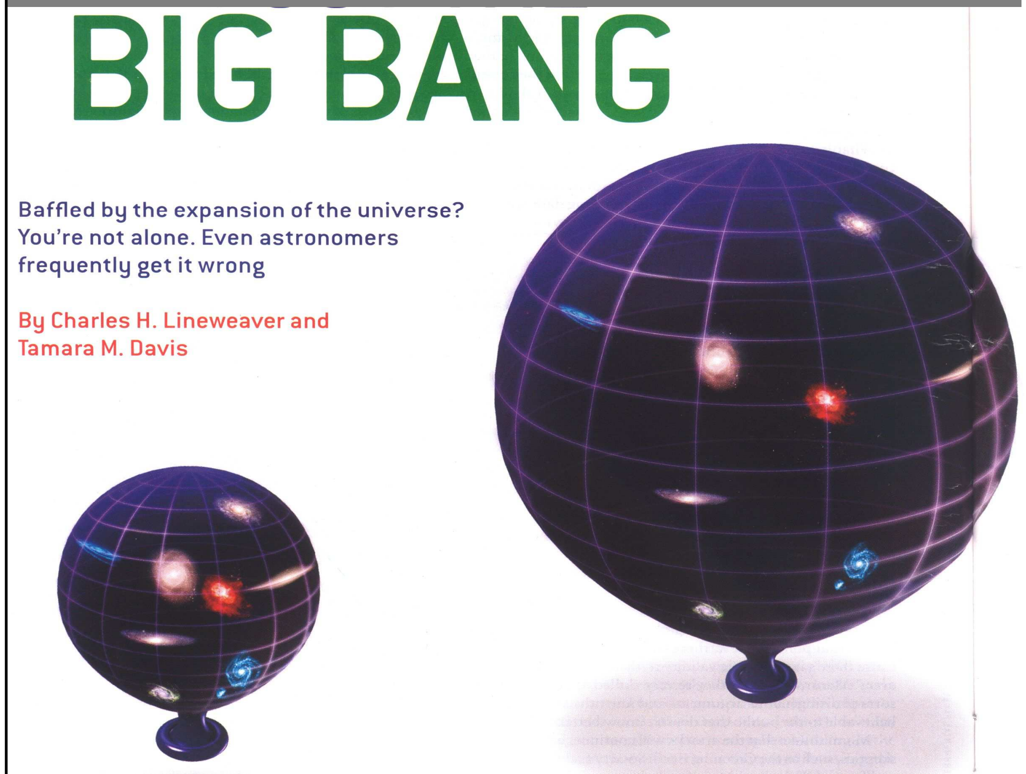
Defined by the expansion as by a sandglass

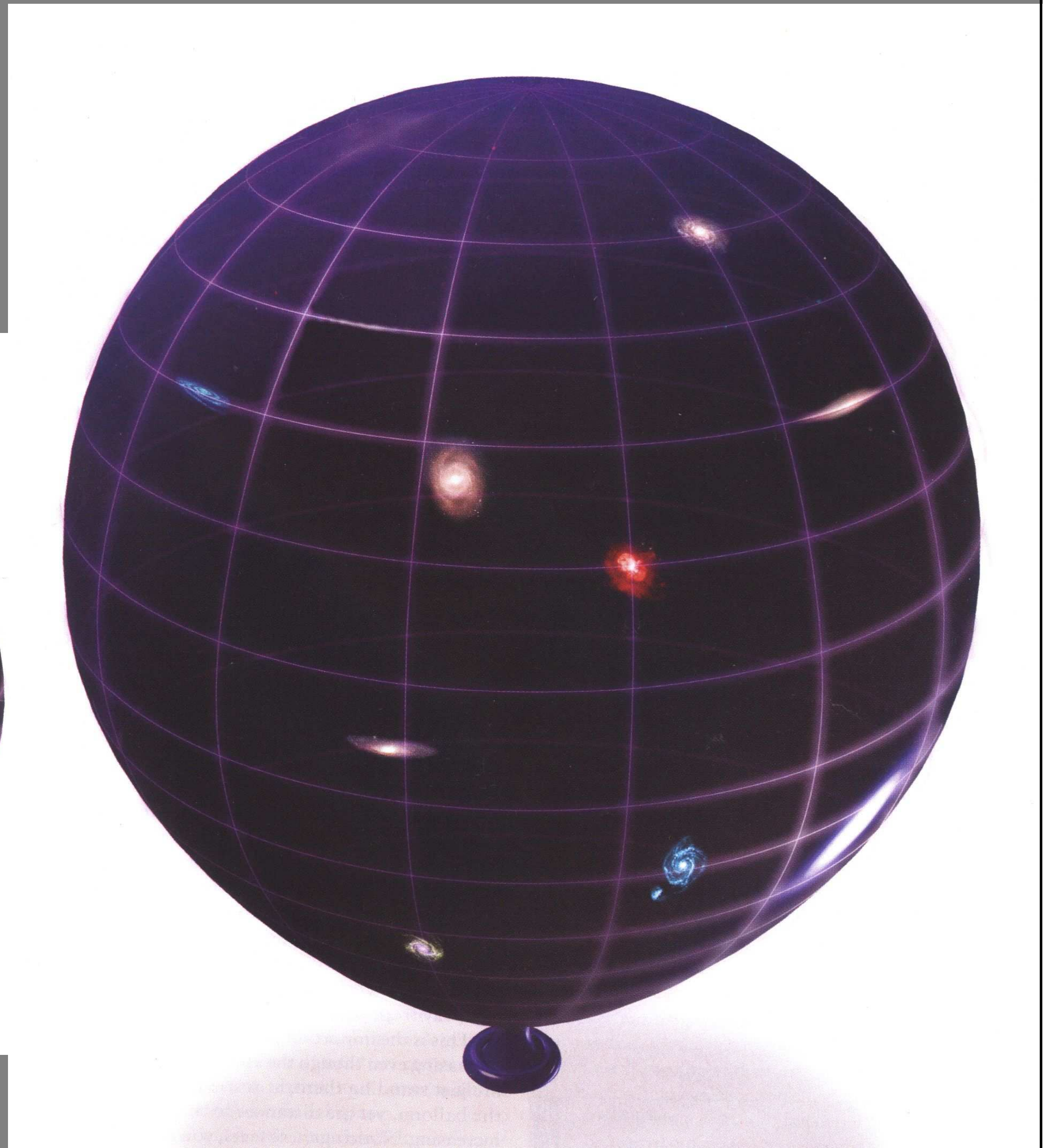
Now (today): $t = t_0$ (= 14 Gy)

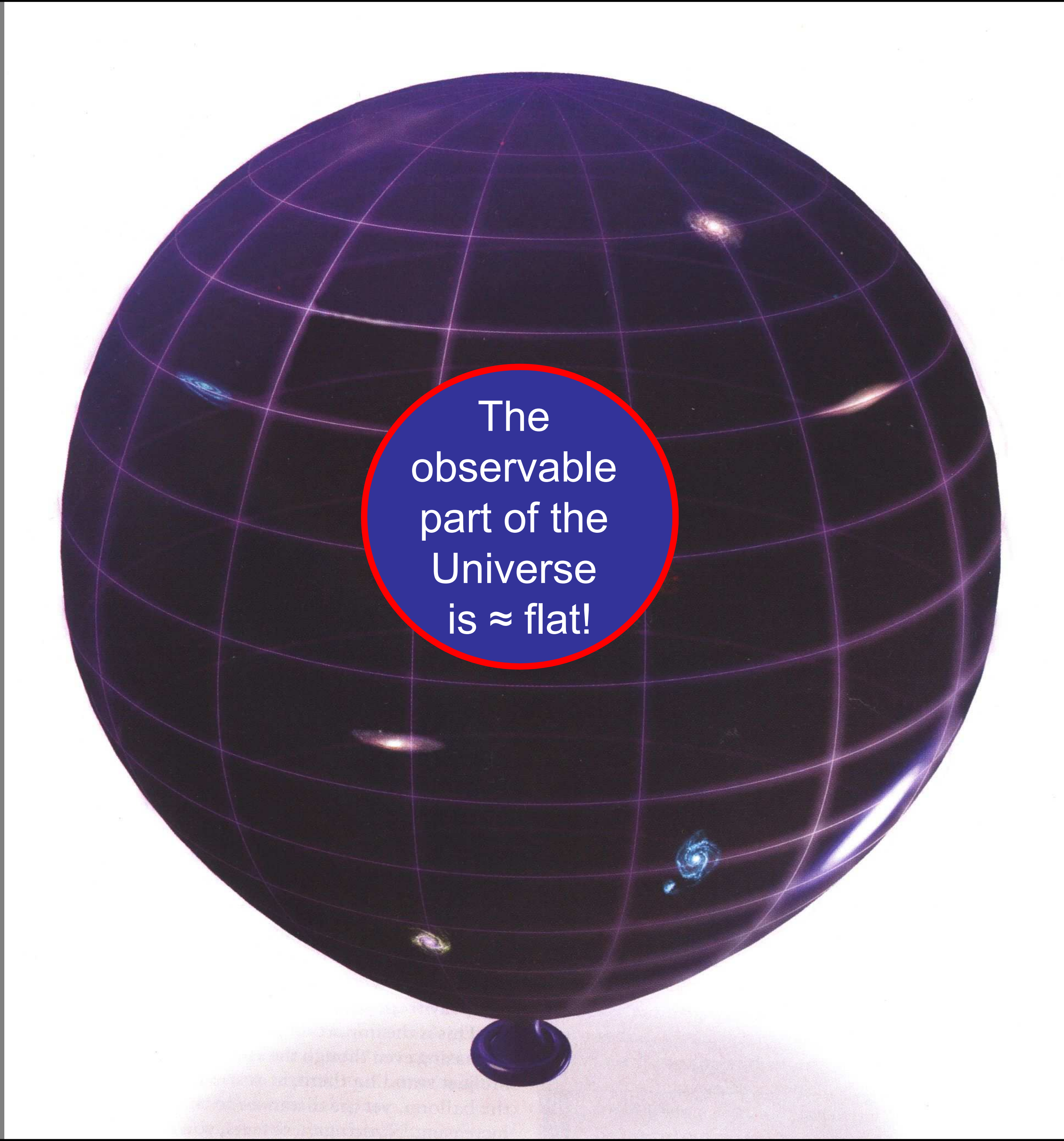
2-dim model of expansion

C.H.Lineweaver and T.M.Davis,
Scientific American, March 2005

Read, please







A curved
2-dim surface of
an air balloon
is a model of the
whole Universe,

not of the
observable part of
the Universe

Cosmic („proper“) distance $D(t)$

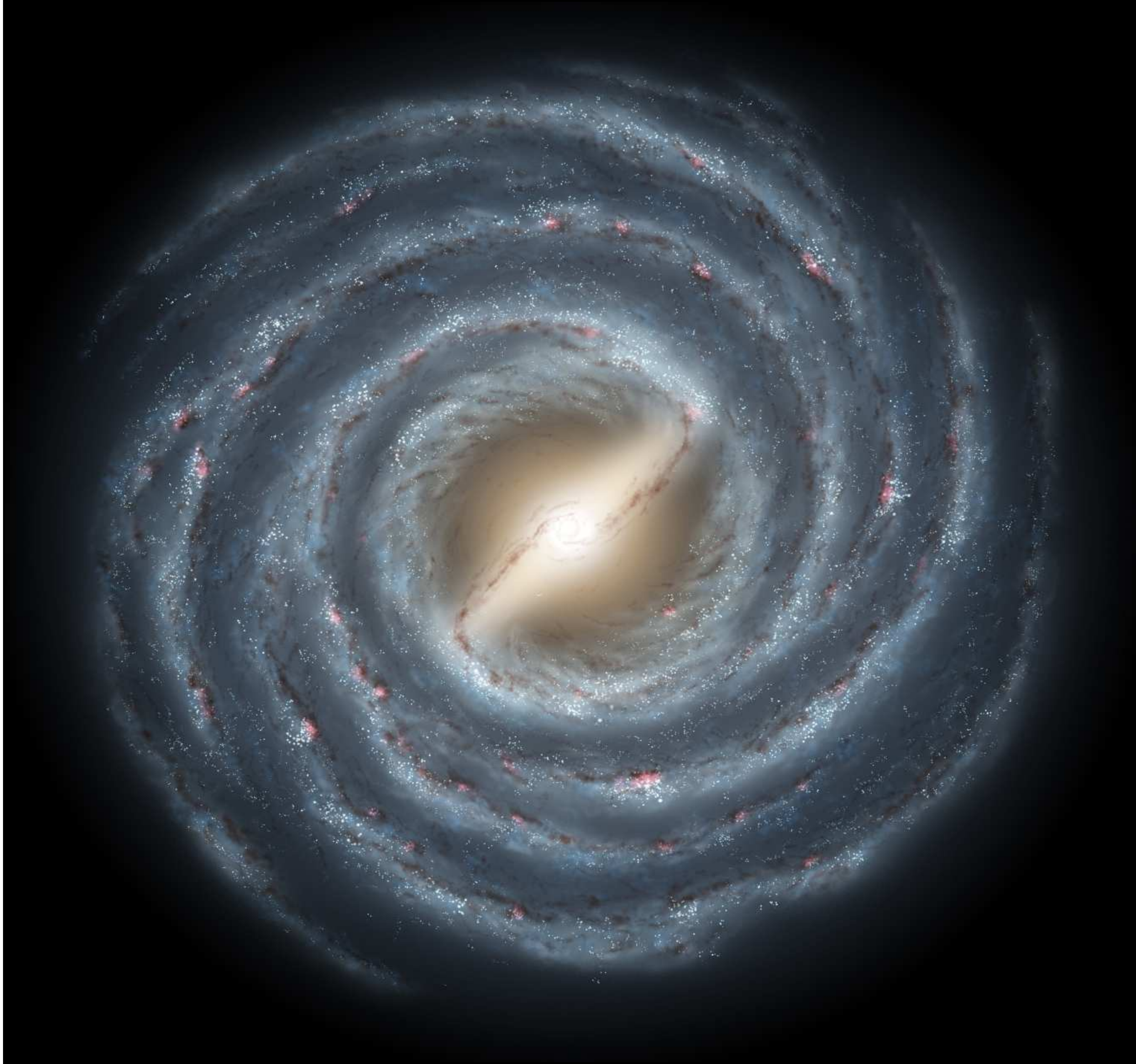
All directions are equal:

It suffices to consider the distance $D(t)$ between pairs of distant galaxies in arbitrary directions

Space is flat:

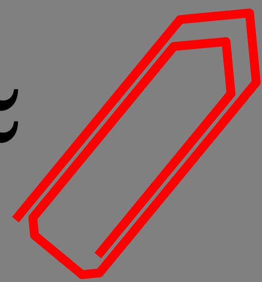
A Euclidean model of elastic space is suitable

- 1-dim GR-space: a straight rubber band



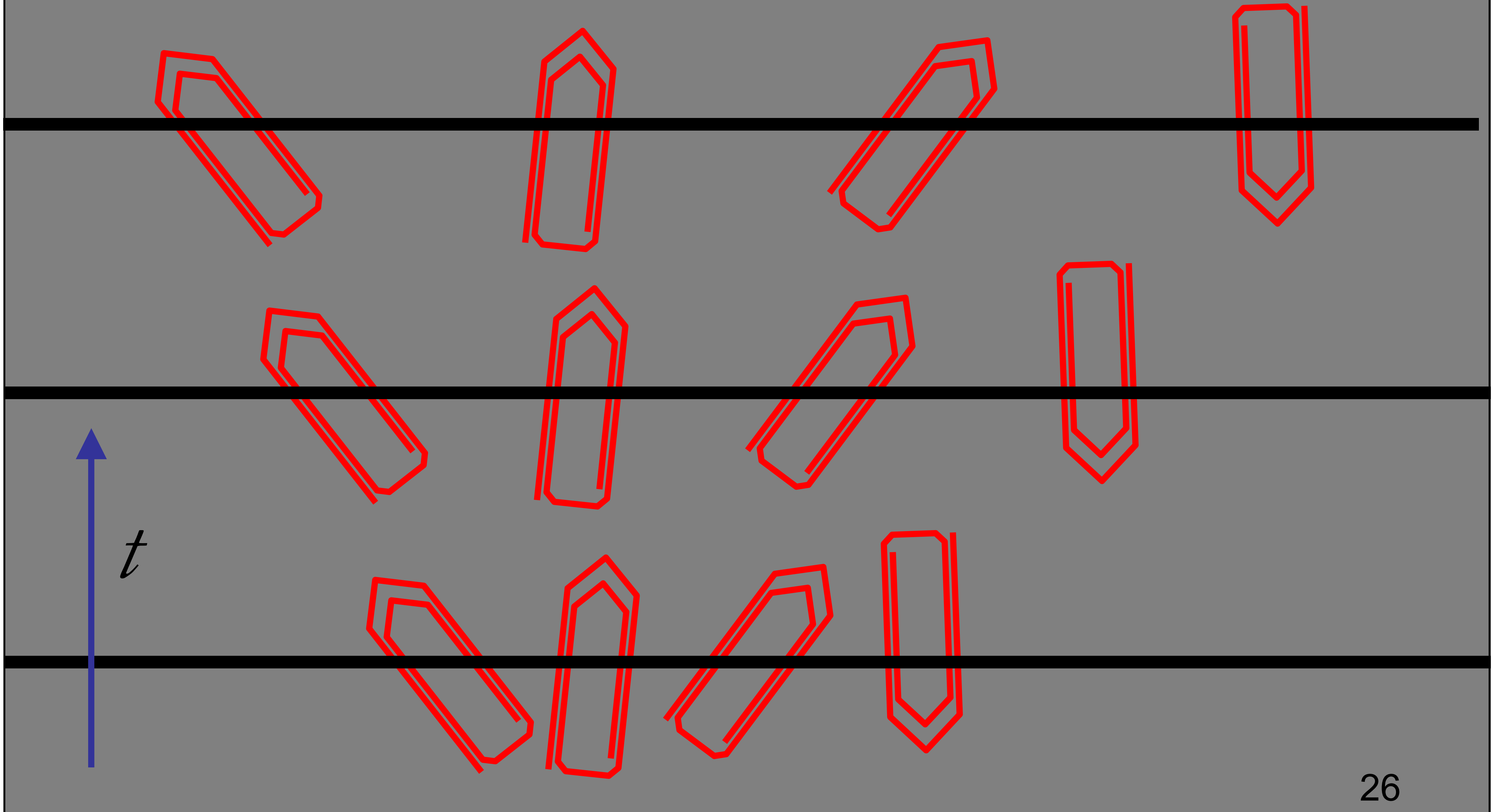
good approxi-mation:

≈



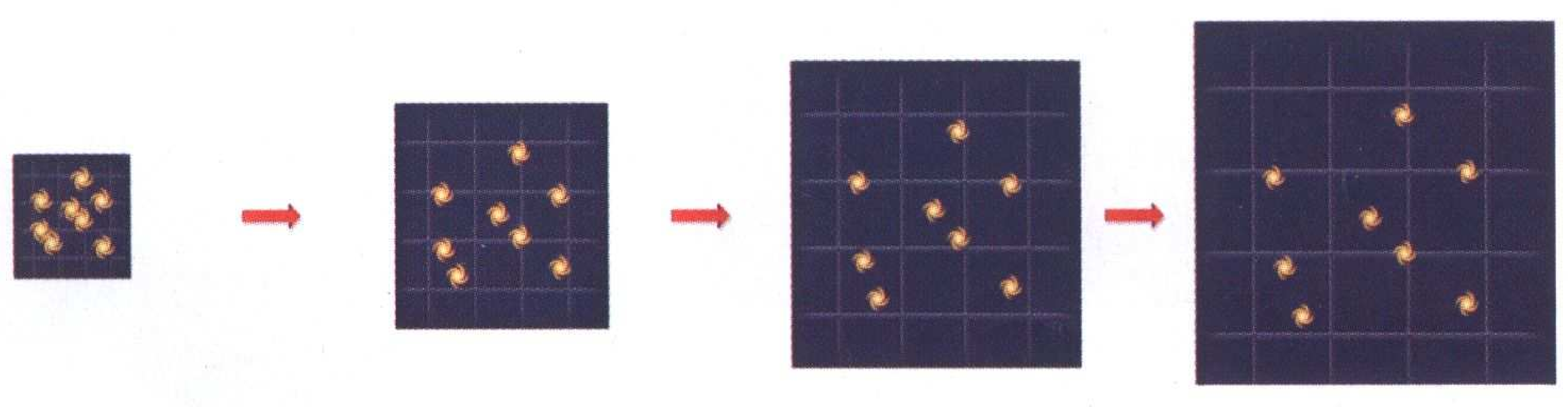
APOD

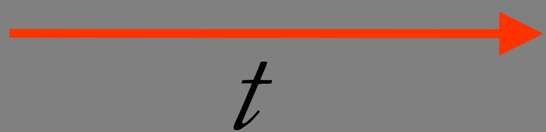
The space expands,
but remains locally always the same.
Galaxies recede from each other,
but they are at rest in space and do not expand.



The distance between galaxies grows, since the **space between them expands**

A flat elastic membrane model:





What is the expansion:

- Expansion =

  stretching of elastic space

  Therefore galaxies recede from each other

- Recession velocity u

  of the galaxies at rest

  is not a mechanical motion

  of the galaxies through the space!

The Hubble law

(in a modern form)

Recession velocity u of galaxies

is **rigorously** proportional to their **distance** D

$$u(t) = H(t) \cdot D(t)$$

$H(t)$ … Hubble expansion parameter

measures the expansion velocity of the space

Hubble distance $D_H(t)$:

$$H(t)\, D(t) = u(t) = c$$

$$D_H(t) = c/H(t)$$

For $D(t) > D_H(t)$ is

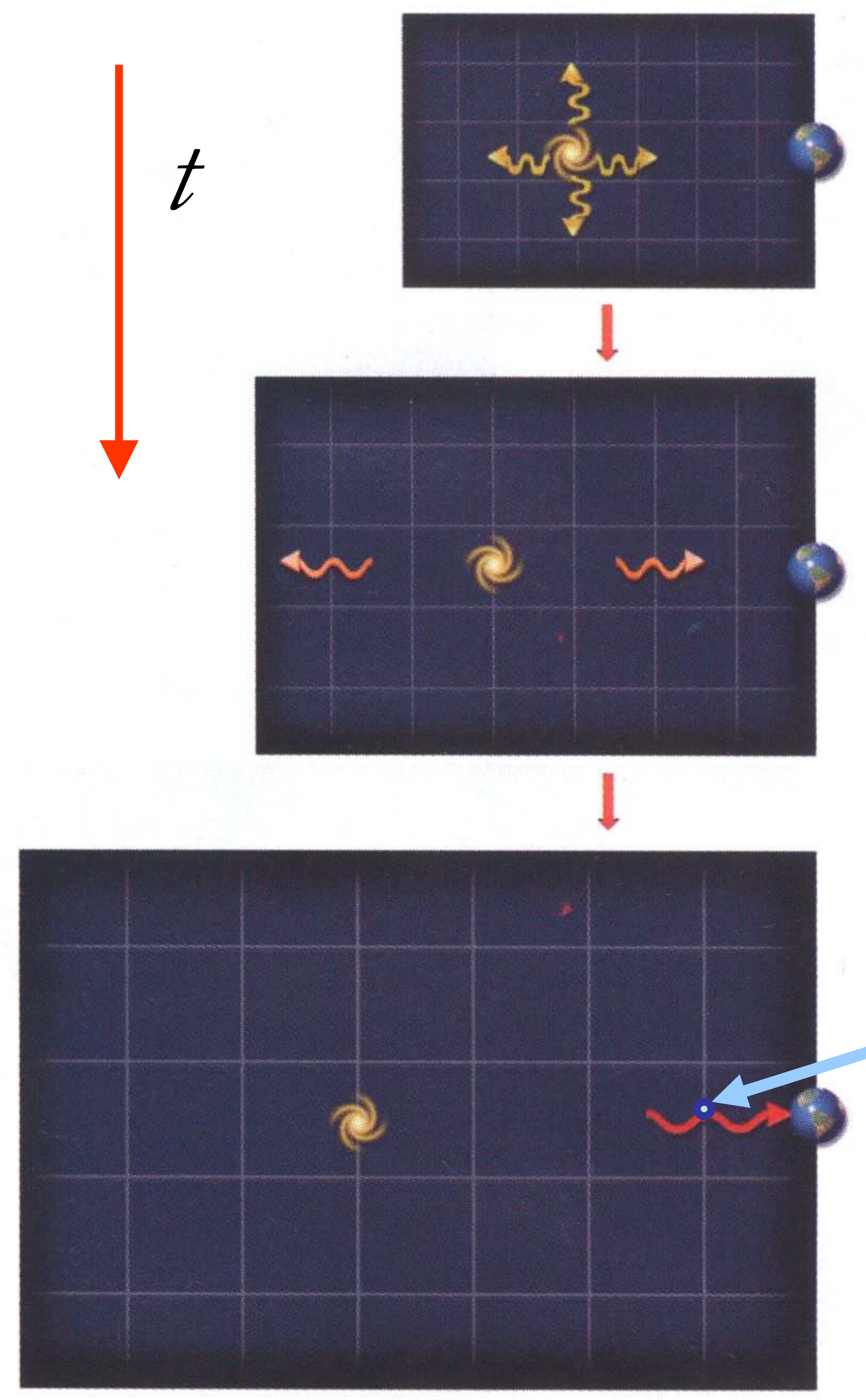
$$u(t) > c \quad !!!$$

It is in no contradiction with SR

- Expansion cannot transmit a signal
- SR holds around any place

. = locally (in any galaxy)

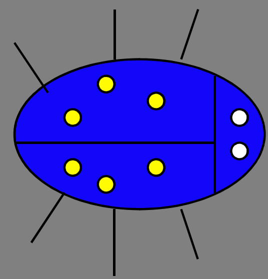
- Locally, the light velocity is always c
- Locally, c is the maximal velocity
- **At large distances (nonlocally), SR is not applicable**



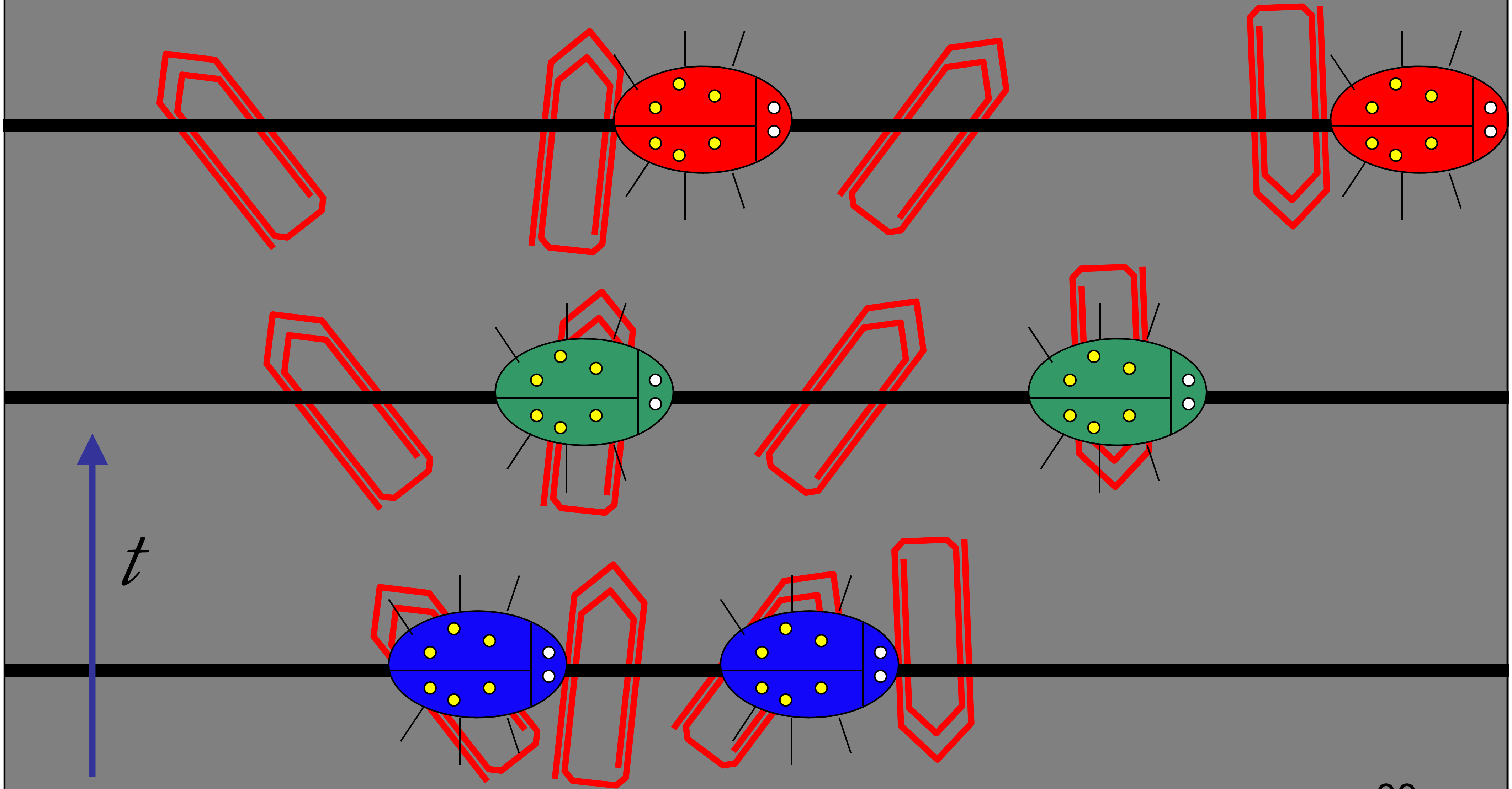
Cosmological redshift

z

Wave-crest $\approx$



The distance between wave crests of light increases



Cosmological redshift z

- Expansion of the wave length λ of the light during ist travel to us through the expanding space
- It has NOTHING to do with the motion of the source

=> NOT the Doppler effect!

- Energy of redshifted photons decreases without any compensation (Universe cools down)

$$1 + z = \frac{\lambda_{obs}}{\lambda_{emis}}$$

Typical observed values of z

- Observations by Hubble 1929:

  $D <$ 0,04 Gly $z <$ 0,0003

- Galaxies at the Hubble distance

  $D = D_H =$ 14 Gly $u = c$ $z =$ 1,5

- Quasars up to $u = 2c$ $z \approx$ 6,4

- CMB source: $u = 3c$ $z =$ 1090

Universe on cosmological velocity scales

c = 1 Gly/Gy = 300 000 km/s

Mechanical velocities through the space:

- Earth around Sun 0,0001c
- Typical motion of galaxies 0,003c

Large recession velocities u:

- Galaxies with z > 1,5 (thousands observed!) > c
- Source of CMB today (z = 1090) 3c
- Source of CMB „then“ 50c

Cosmic scale factor $a(t)$

- Distances normalized with respect to the present ones

$$a(t) = \frac{D(t)}{D(t_0)}$$

- All length scales in cosmology are proportional to the cosmic scale

$$D(t) = D(t_0) \cdot a(t)$$

$a(t)$ determines the expansion at all distances simultaneously

$a(t)$ describes the expansion

- $a(t_0) = 1$ — $D(t_0)$ today
- $a(t') = 2$ — $D(t') = 2D(t_0)$
- $a(t'') = 1/1000$ — $D(t'') = D(t_0)/1000$

$$H(t) = \frac{\dot{a}(t)}{a(t)}$$

z-$a(t)$ relation

Rigorous:

$$1 + z = \frac{1}{a(t)}$$

- t … time of emission ($t < t_0$)
- 1+ z measures the expansion of space between t and t_0
- **$z > 0$ is an evidence of the expansion**

Empirical properties of $H(t)$:

- Hubble-law: $v(t) = H(t)\, D(t)$
- $H(t)$ is t-dependent
- After the big bang it decreased for ≈ 7 Gy

$$H(t) \sim 1/t \Rightarrow \text{decelerated expansion}$$

- Since ≈ 7 Gy

$$H(t) \approx \text{const} \Rightarrow \text{accelerated expansion}$$

- The present value („Hubble-constant“):

. $H(t_0) = 70$ km/s Mpc (1Mpc = 0,003 Gly)

… and a THEORY ???

Qualitative description of changes of the expansion velocity:

Matter decelerates the expansion

$$\ddot{a}(t) < 0$$

Einstein´s cosmological constant Λ accelerates the expansion

$$\ddot{a}(t) > 0$$

A. Friedmann

THEORY of space expansion

- Simplified eqs. of the Einstein´s general relativity

(Friedmann-Lemaître eqs. without radiation and the pressure term)

$t > 0.000\,1$ Gy

$$H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho_{matter}(t) + \frac{1}{3}\Lambda - (curvature)$$

$$\ddot{a}(t) = \frac{1}{3}\left(-4\pi G \cdot \rho_{matter}(t) + \Lambda\right)a(t)$$

„Cold“ matter

- Negative contribution to the acceleration
- Decelerates the expansion
- Ist density decreases during the expansion:

$$\rho_{matter}(t) \propto \frac{1}{a^3(t)} \xrightarrow[a \to \infty]{} 0$$

Cosmological constant Λ

- Positive contribution to the acceleration,
  accelerates the expansion
- Remains constant with t
- Tension of space („negative pressure“)
- The second greatest discovery by Einstein
  (next to GR)
- $\Lambda \neq 0$ is generic in GR

($\Lambda g_{\mu\nu}$ term in E. eqs., but ist value ???)

Willem de Sitter

De Sitter Universe

- Universe without matter, only Λ
- De Sitter (the Netherlands) 1917:

$$\ddot{a}(t) = \frac{\Lambda}{3} \cdot a(t)$$

$$a(t) \propto e^{H_\infty \cdot t}$$

$$H_\infty = \sqrt{\Lambda / 3} = const$$

Exponentially accelerated expansion

Discovery during the last 10 years:

- Distant supernovae observations =>

The expansion accelerates!

Some accelerating term like Λ is required

The cause of the acceleration?

- **New constant of Nature**

= cosmological constant **Λ** à la Einstein**?**

- **Energy of the vacuum (quantum effect)?**

To be expected, but theoreticians cannot calculate ist value

- **Quintessence? A new scalar field ≈ Λ(t)?**

Suggested first by Ch. Wetterich (Heidelberg)

Standard-model of the antic Greeks

Ch. Wetterich

Constant of Nature Λ, Quintessence, Vacuum energy, ???

Cosmologists need *something* like that:

„DARK ENERGY“

Nobody knows, what it is,

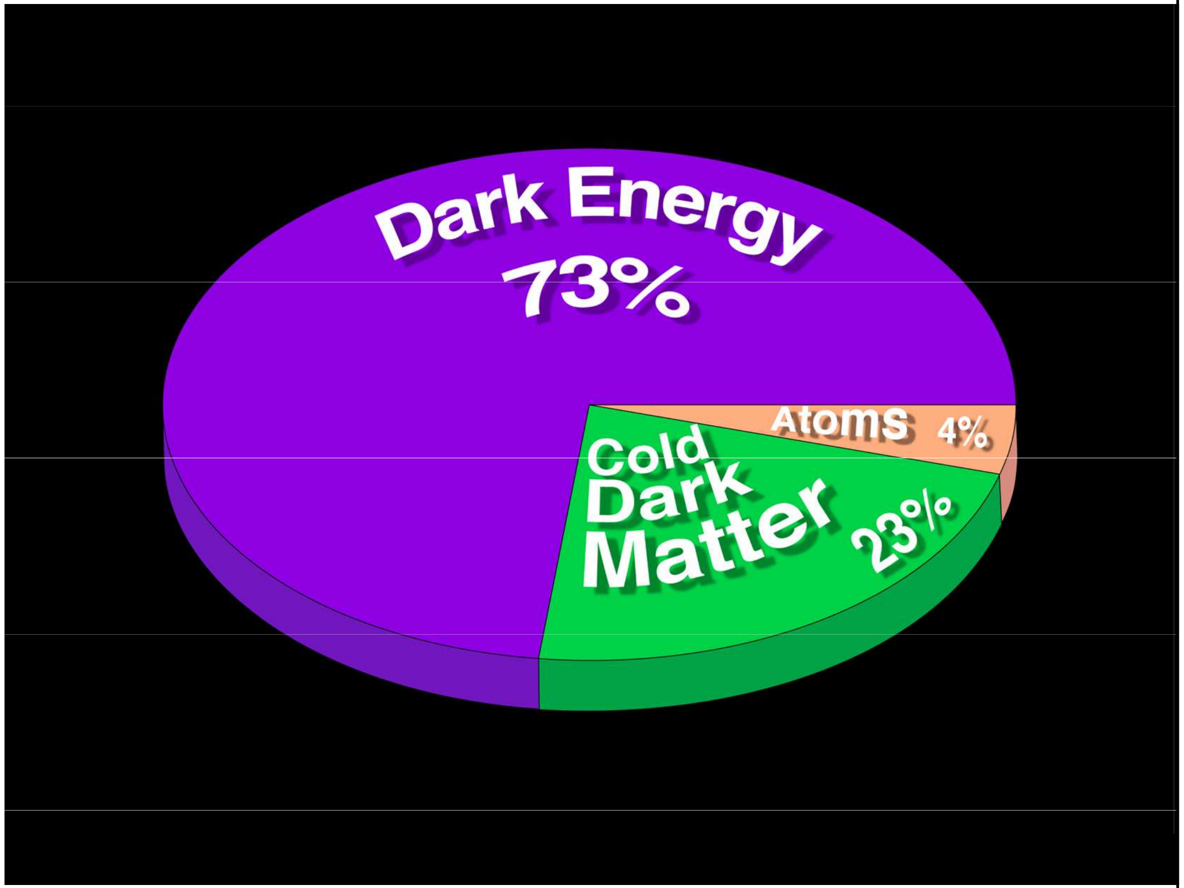
since it is transparent (unobservable)!

- A completely new category

(tension of space)?

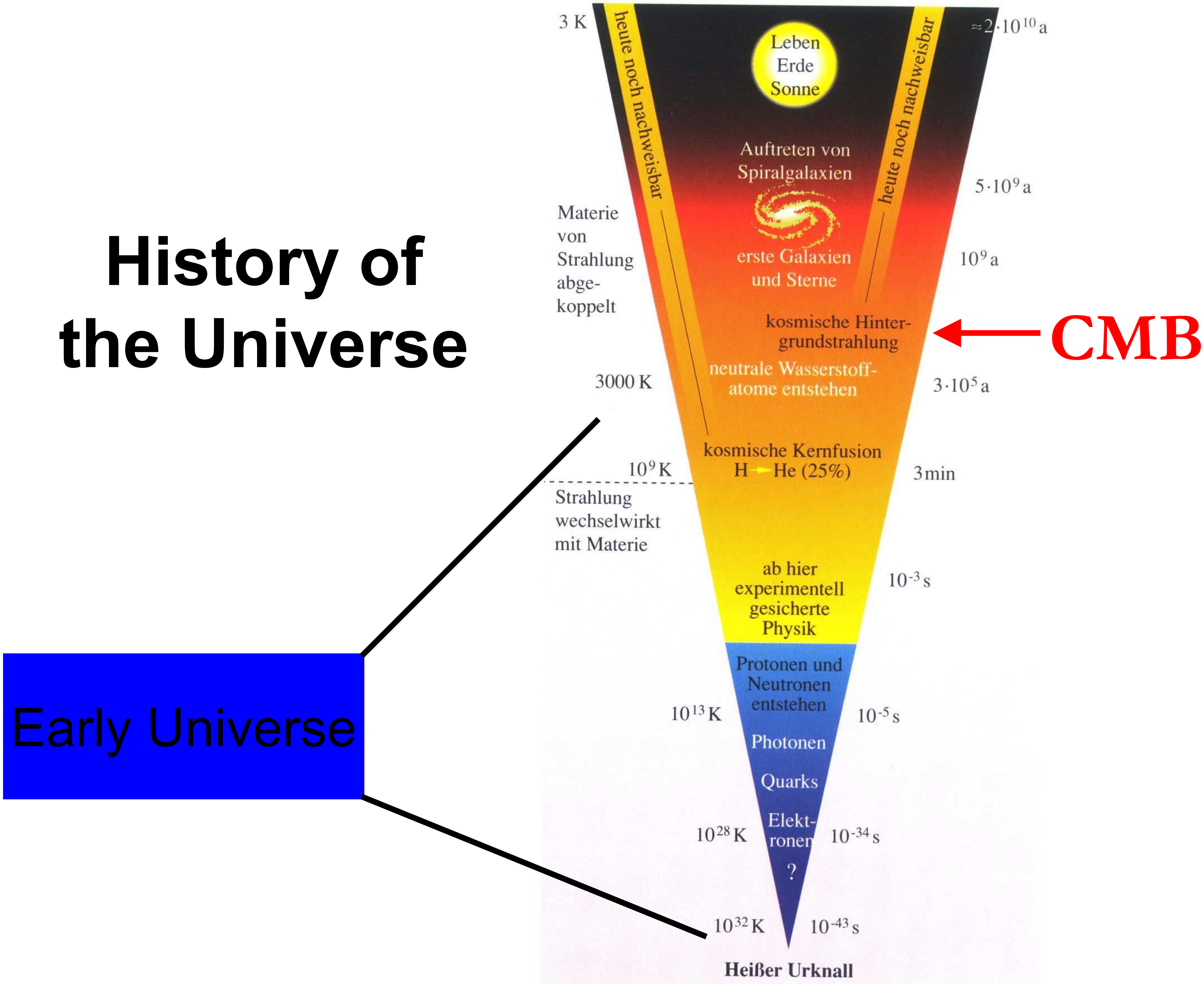
Energy in contemporary observable Universe

- 73±% dark energy **dominates**
- 23±% unknown matter („dark matter“)
- 4% known matter ≈ atoms (stars, H-gas, ourselves)
- Matter slows down, dark energy speeds up the expansion



WMAP

History of the Universe



Further components in the early Universe

- *t* < 0,000 1 Gy: **radiation** must be included (photons, neutrinos, other particles with v ≈ c) [phys. straightforward, but math. more complex].
- **Seeds of inhomogeneities** must be included [models].

- *t* < 0,0…01 sec: **big speculations about big bang** (inflation, quantum gravity, big bounce, pre-big bang universe, ekpyriotic universe, strings, branes, multiverse, baby universes, …)
- „Cosmologists are often wrong, but never in doubt“

. L.D. Landau

- I am not cosmologist
- New ideas and surprises to be expected!

_t_ > 0,000 1 Gy: simplified ΛCDM model is reliable on cosmological scales

(above the scales of inhomogeneities)

Λ**CDM** model of our Universe

Assumptions on cosmological scales:

(1) Observable Universe is („cosmological principle")
homogeneous and isotropic

(2) CMB ((1) → isotropic, observable everywhere)

(3) Expanding space is flat

(4) Simplified GR eq. of motion for $a(t)$

(5) Evolution of $a(t)$ is determined (t > 0.000 1Gy) by

- cold dark matter (**CDM**) (dominates earlier epoch)
- cosmological constant Λ (dominates later epoch)

(1) → Hubble law

- Recession velocity of distant points

$$D(t) = a(t)D(t_0)$$

$$u(t) = \dot{D}(t) = \dot{a}(t)D(t_0) = \frac{\dot{a}(t)}{a(t)}D(t)$$

$$H(t) = \frac{\dot{a}(t)}{a(t)}$$

Thus linear dependence on the distance at fixed *t*

$$u(t) = H(t)D(t)$$

(1) → Cosmological redshift z

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

$$D(t) = a(t)D(t_0) \qquad t = t_{em}$$

$$1 + z(t_{em}) = 1/a(t_{em})$$

(1)-(5) $\rightarrow$ Eq. of motion for $a(t)$

- Conveniently reparameterized form:

$$\ddot{a}(t) = H_0^2 \left(-\frac{1}{2}\Omega_M \frac{1}{a^2(t)} + \Omega_\Lambda a(t) \right)$$

$$\Omega_M = 0.24, \quad \Omega_\Lambda = 0.76$$

$$H_0 = 73 \frac{km}{s.Mpc} = 0.075 \frac{c}{Gly}$$

$$H_0^2 = \frac{1}{3}\left(8\pi G \rho_M(t_0) + c^2\Lambda\right),$$

$$\Omega_M = \frac{8\pi G}{3H_0^2}\rho_M(t_0), \quad \Omega_\Lambda = \frac{c^2\Lambda}{3H_0^2}$$

Exact solution

$$a(t) = \left(\frac{\Omega_M}{\Omega_\Lambda}\right)^{1/3} \sinh^{2/3}\left(3\sqrt{\Omega_\Lambda}H_0 t/2\right)$$

Small *t*:

$$a(t) \propto t^{2/3}, \quad \ddot{a}(t) \propto -t^{-4/3}, \quad H(t) \propto t^{-1}, \quad D_H(t) \propto t$$

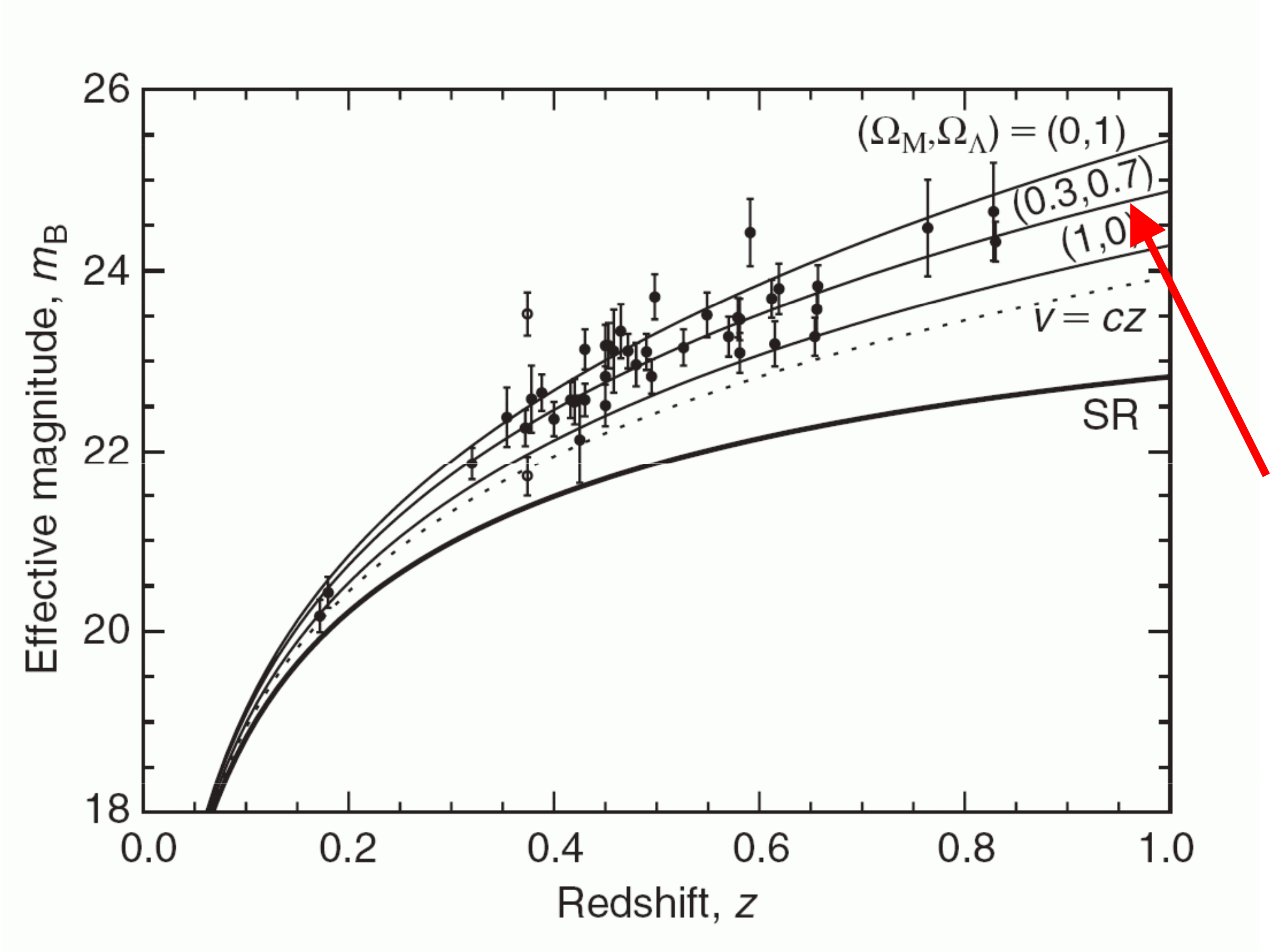
Large *t*:

$$\ddot{a}(t) \propto a(t) \propto \exp\left(H_\infty t\right)$$

$$H_\infty = H(t=\infty) = H_0\sqrt{\Omega_\Lambda}$$

Some models

(Fig.5 from: http://www.mso.anu.edu.au/~charley/papers/DavisLineweaver04.pdf)



ΛCDM model

Our light cone

- World lines of light we observe today
- Emitted

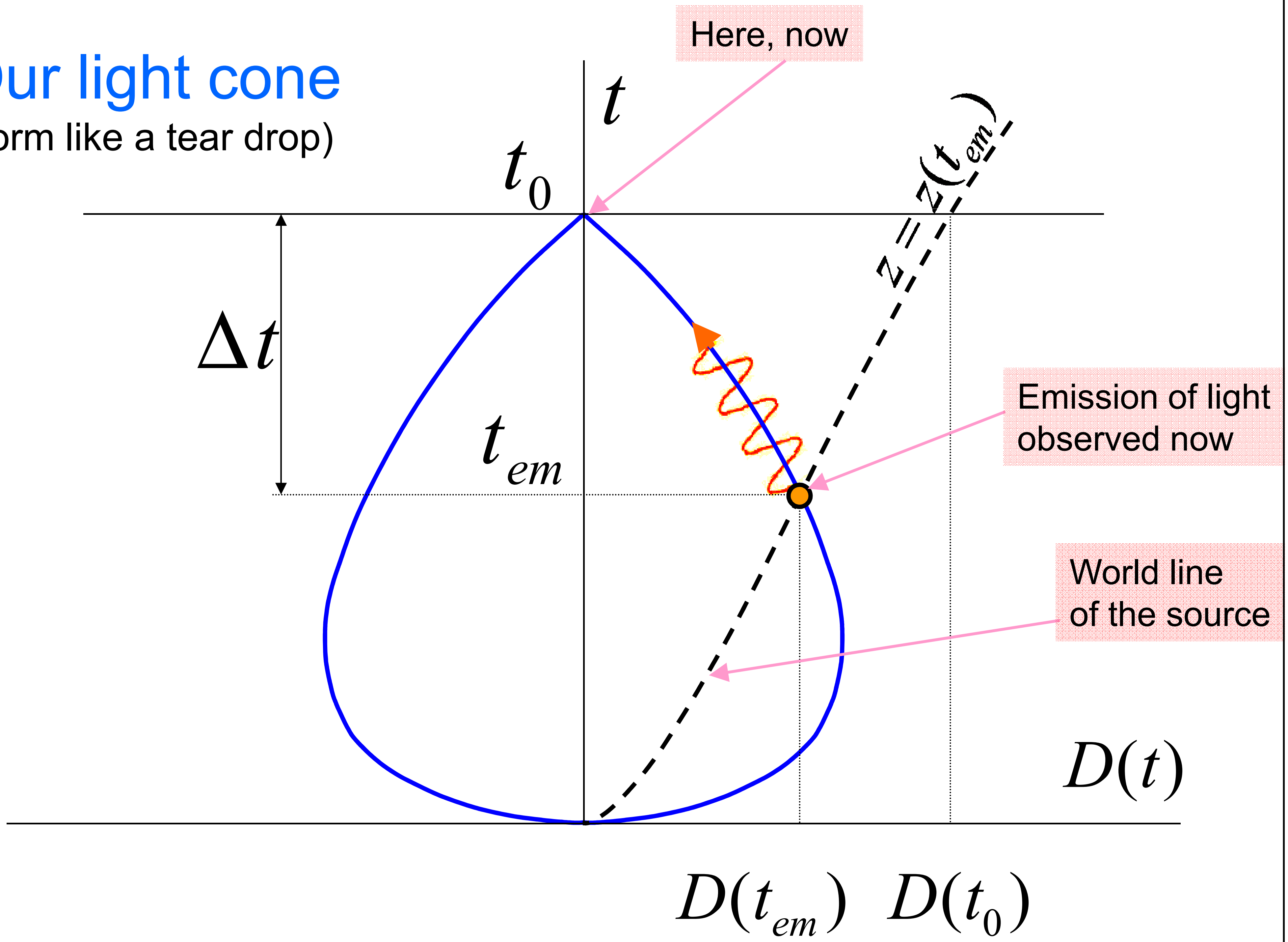
  at various times t_{em}

  at distances $D(t_{em})$

$$D(t_{em}) = a(t_{em})c \int_{t_{em}}^{t_0} \frac{dt'}{a(t')}$$

Our light cone

(form like a tear drop)

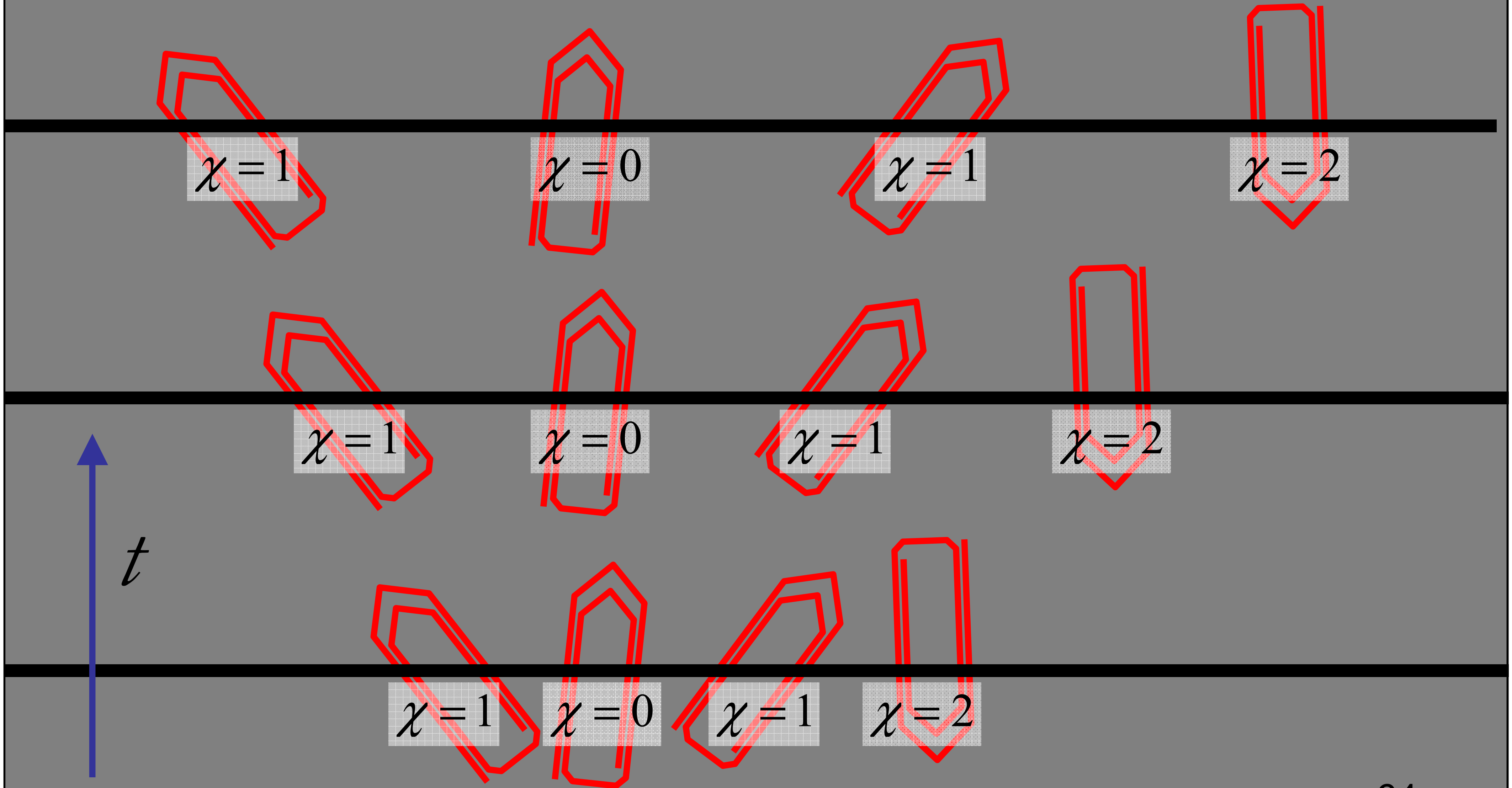


(1)(2) → Fixed points in space

- Origins of local reference frames in which
  . CMB is isotropic
- Defined by a global method (SR not applicable!)
- Such points are in absolute rest with respect to the surrounding space
- They obey the Hubble law rigorously
- Distant galaxies can be in good approximation identified with fixed points

  (recession velocities >> peculiar velocities)
- Clocks at rest at fixed points
  define the absolute cosmic time *t*

Comoving coordinates of fixed points (galaxies) χ



Comoving coordinate χ

- Dimensionles coordinates of fixed points (galaxies) in space
- Defined by the present distances of these points

$$D(t_0) = R_0 \chi$$

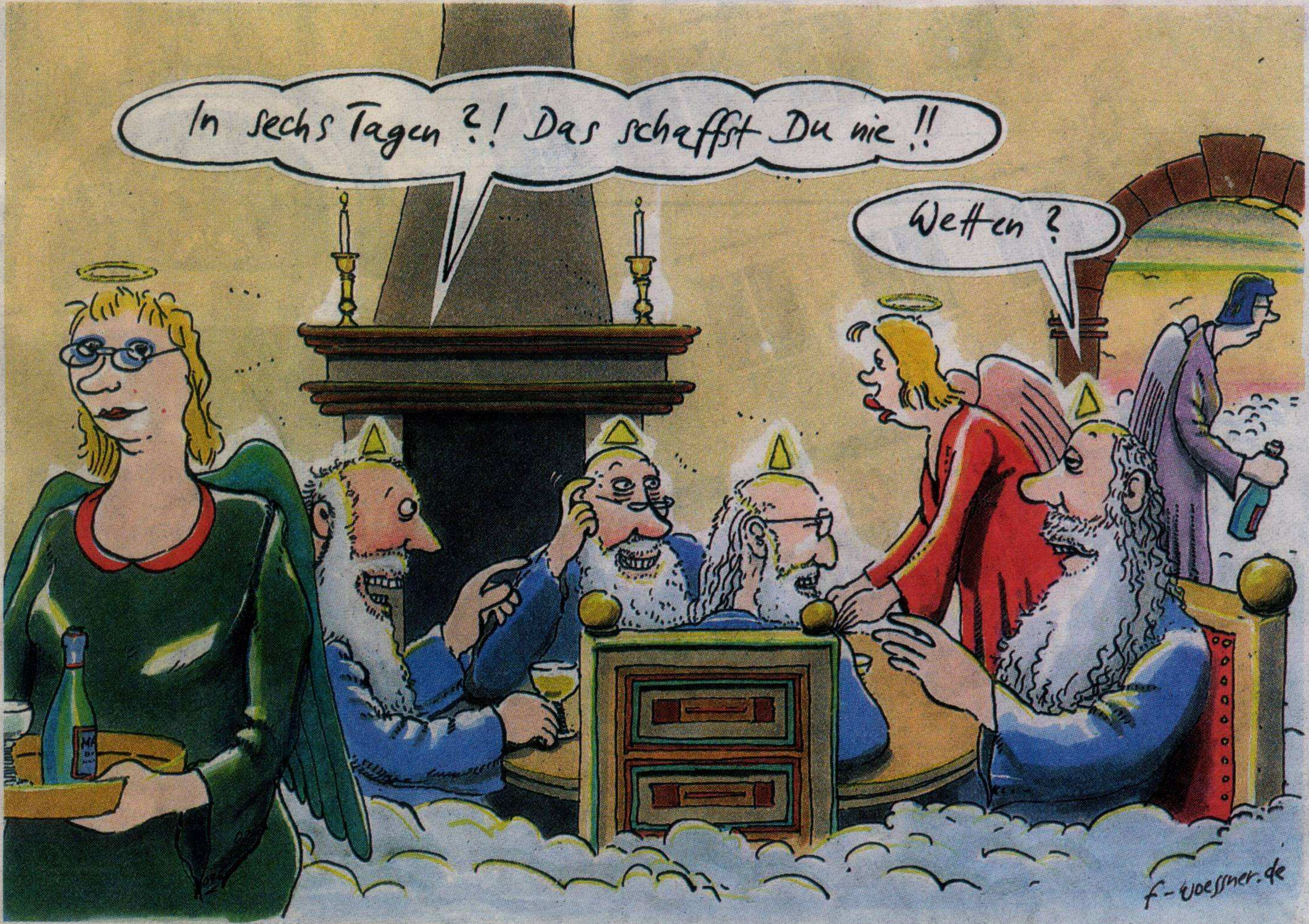
- t -independent
- R_0 … distance of a point with $\chi = 1$

$$D(t) = a(t) D(t_0) = a(t) R_0 \chi$$

Suitable internet adresses

- http://tpe.physik.rwth-aachen.de/jersak/expansion.html
- http://www.mso.anu.edu.au/~charley/papers/LineweaverDavisSciAm.pdf
  http://www.mso.anu.edu.au/~charley/papers/DavisLineweaver04.pdf
  http://www.astro.virginia.edu/class/whittle/astr553/Topic16/t16_light_cones.html
  http://www.astro.ucla.edu/~wright/cosmolog.htm
  http://en.wikipedia.org/wiki/Expansion_of_space#Overview_of_metrics
  http://www.talkorigins.org/faqs/astronomy/bigbang.html#misconceptions
  http://en.wikipedia.org/wiki/Georges_Lema%C3%AEtre

Kosmologie mal anders



Warum unsere Welt so unvollkommen geworden ist.

Illustration: Freimut Wössner für DIE ZEIT