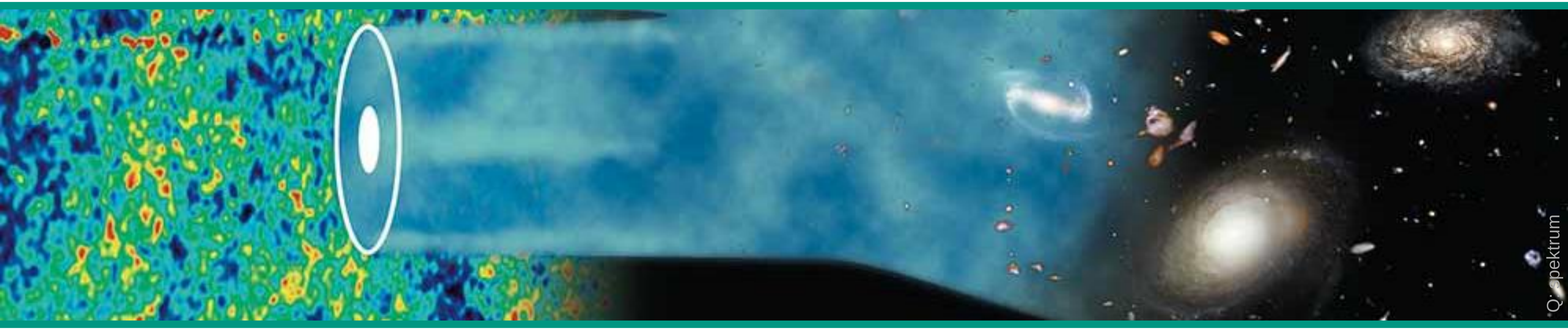
Karlsruhe Institute of Technology

Introduction to Cosmology

Winter term 22/23 Lecture 2 Nov. 8, 2022



Recap of Lecture 1

- **Cosmological distances: measurements via standard candles**

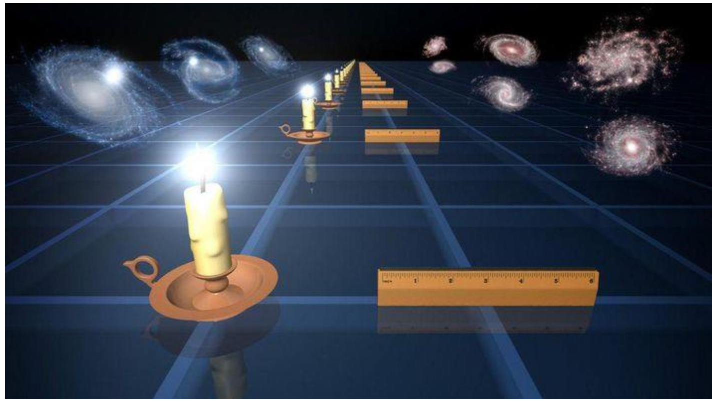
  - **distance modulus $m - M$**

$$m - M = 5 \cdot \log\left(\frac{r}{r_0}\right)$$

m: apparent brightness
M: absolute brightness ($r_0 = 10\, pc$)

  - **distance ladder:** from kpc … up to Gpc…

    1. parallax method (up to $3 - 4\ kpc$)
    2. pulsation of δ-cepheids (up to $\sim 50\ Mpc$)
    3. supernovae Type Ia (up to $\sim 3\ Gpc$)

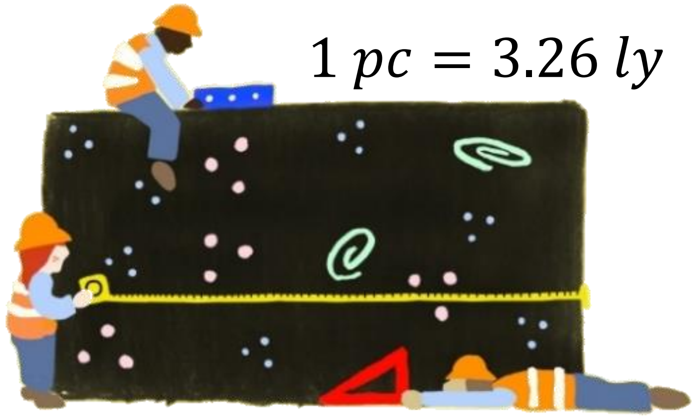


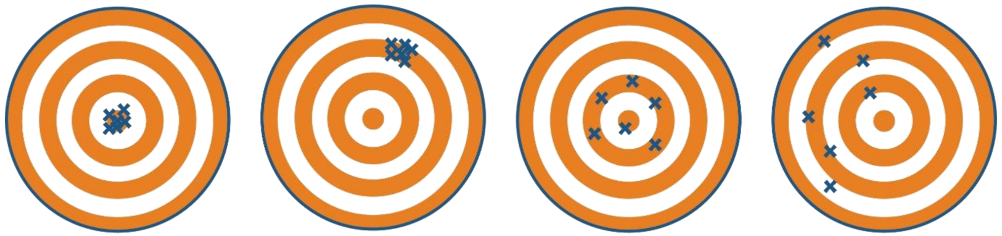
cosmological standard candles

Systematic effects in cosmology

■ Cosmological distance measurements & systematic effects

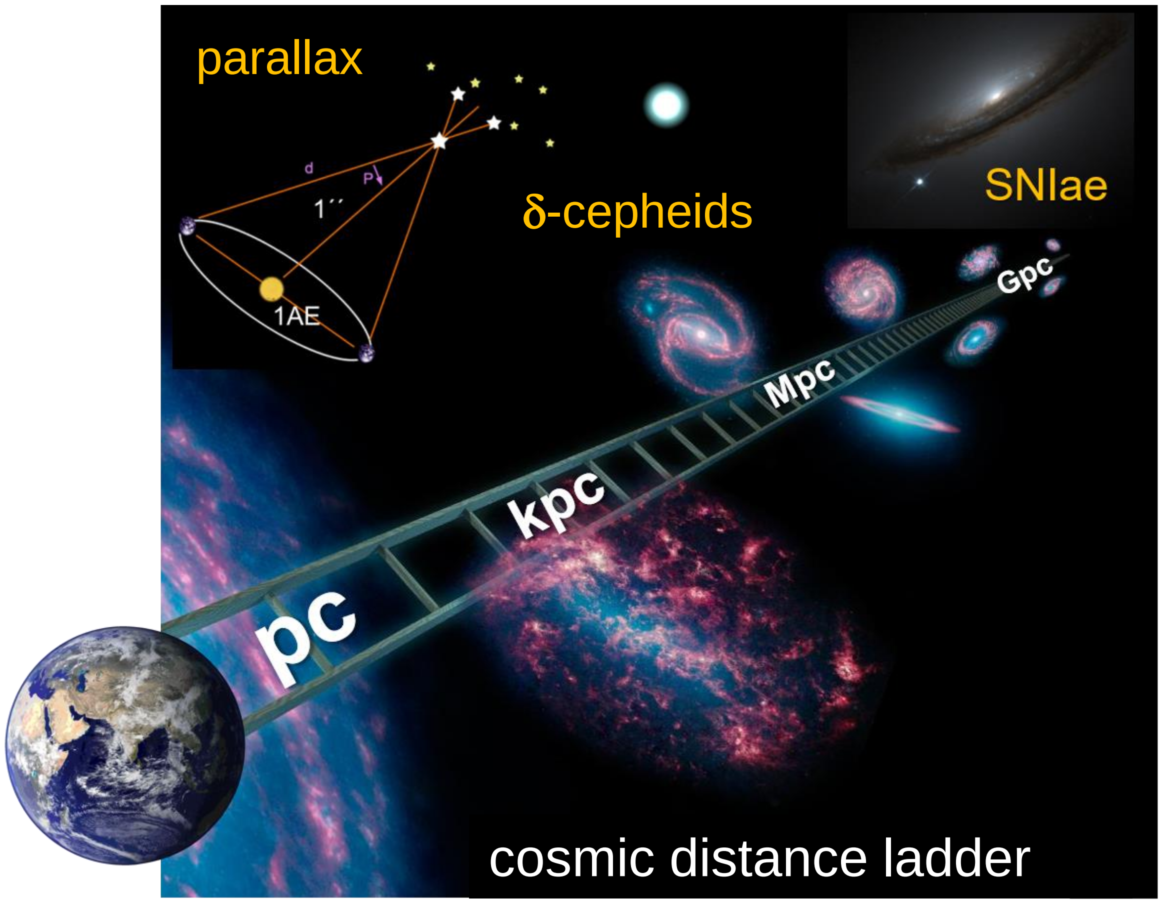
$1\ pc = 3.26\ ly$





recurring keywords in cosmology:

accuracy & precision

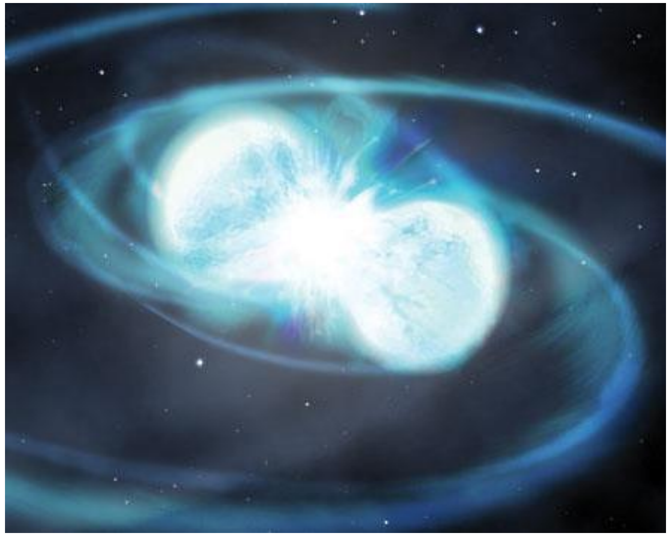


Supernovae – cosmological standard candles

- **SN Ia: thermonuclear detonation of a WD***

  - white dwarf reaches a mass of $1.4\,M_{\odot}$

  - maximum brightness of light curve: $M = -19.6\,mag$

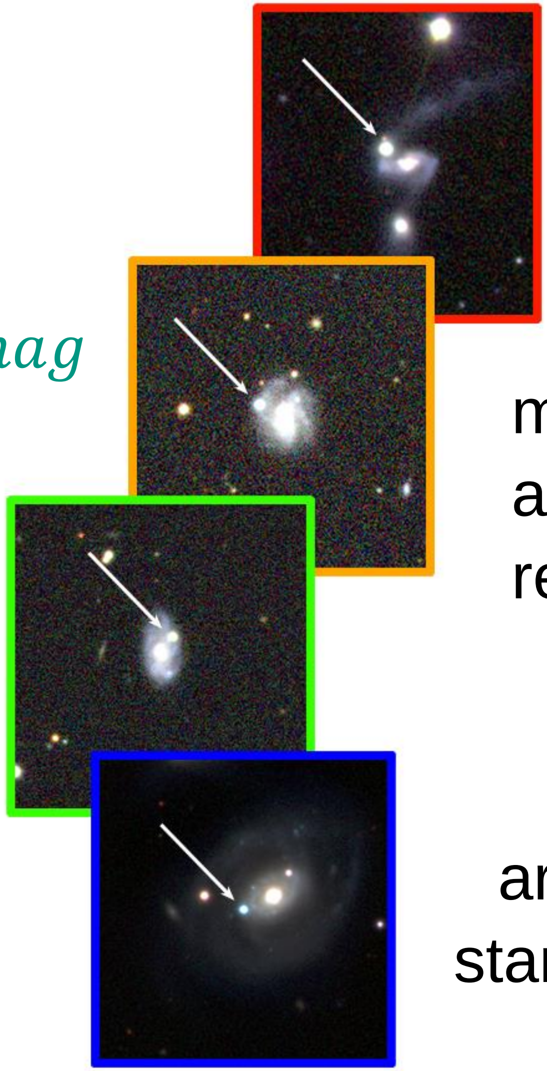


Q: Nature

1: merger scenario

Q: NASA

2: accretion scenario



measurement of a SN light curve requires weeks

are SNIae true standard candles?

*WD = White Dwarf, s. also ATP-2 (summer term 23)

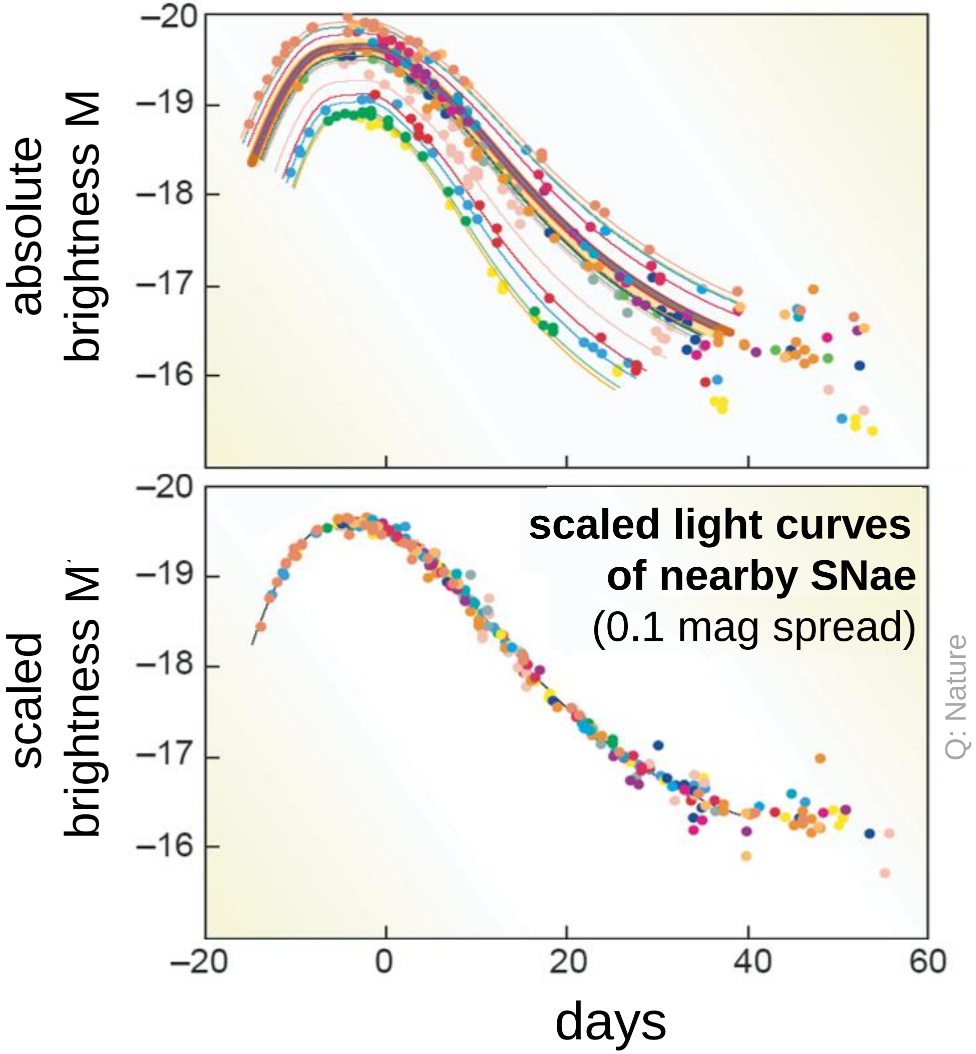
Supernovae – cosmological standard candles

- **SN Ia: thermonuclear detonation of a WD***

  - empirical **Philips relation** (scaling): the peak brightnesses of SNIae are (re-)scaled, depending on the time scale of brightening and dimming of a specific observed light curve

  - possible cause: different chemical composition of the WD prior to explosion, or different overall mass of the progenitor system

  - SNIae-explosions in $d = few\ Gpc$ reveal the accelerated expansion of the universe (**dark energy**)



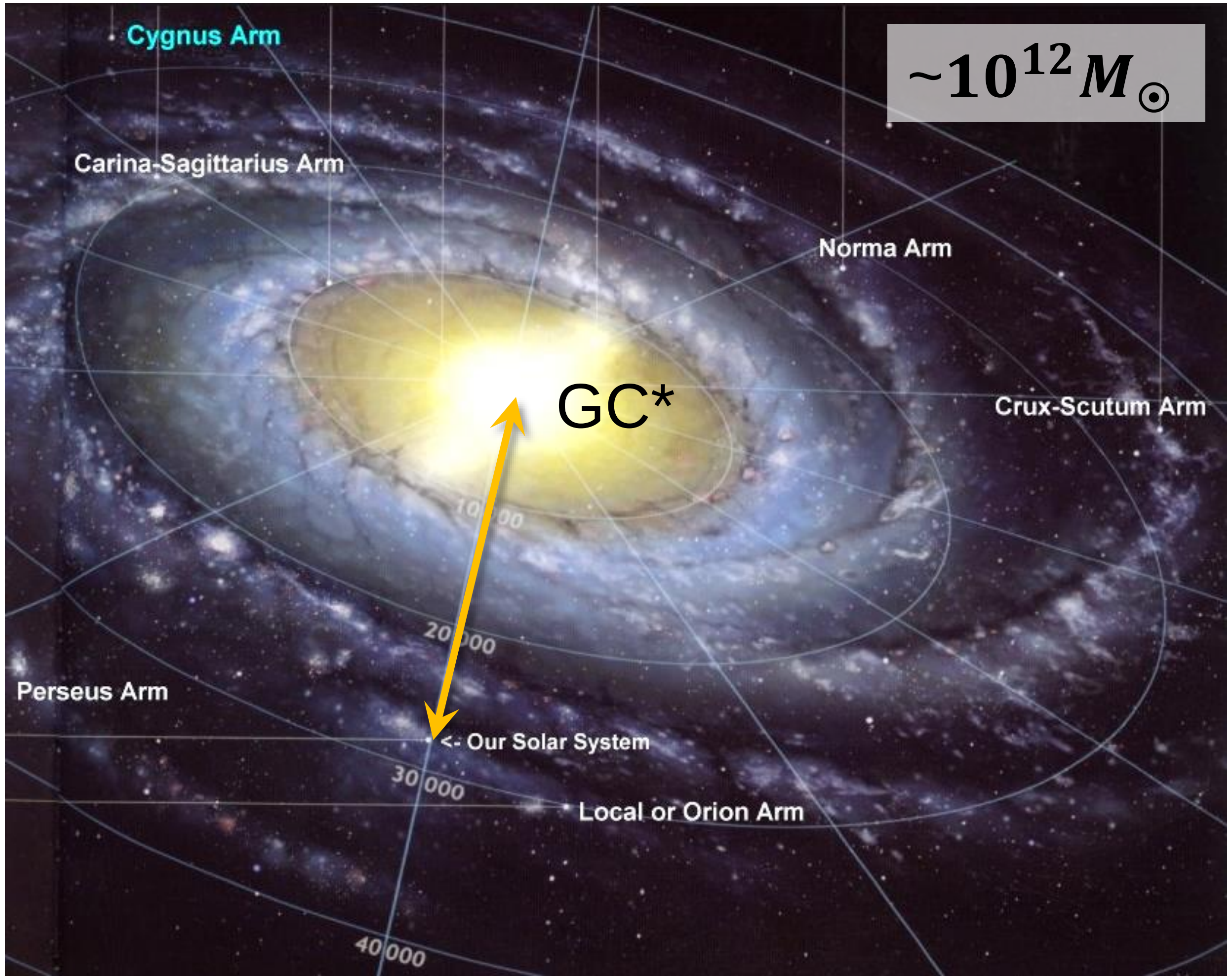
Lenght scales – visible matter in galaxies

- **size of a typical spiral galaxy:**
  Ø = 35 kpc

  - distance Sun – GC: $d = 7.8\ kpc$

  - this lenght scale is important for the „**Dark Universe**" & also for the local DM-density

    ⇨ structures on the scale of a **few tens of kpc** must not be ´washed out´ during the evolution of large-scale structures in the universe (only ´cold´ dark matter)



*Galactic Centre

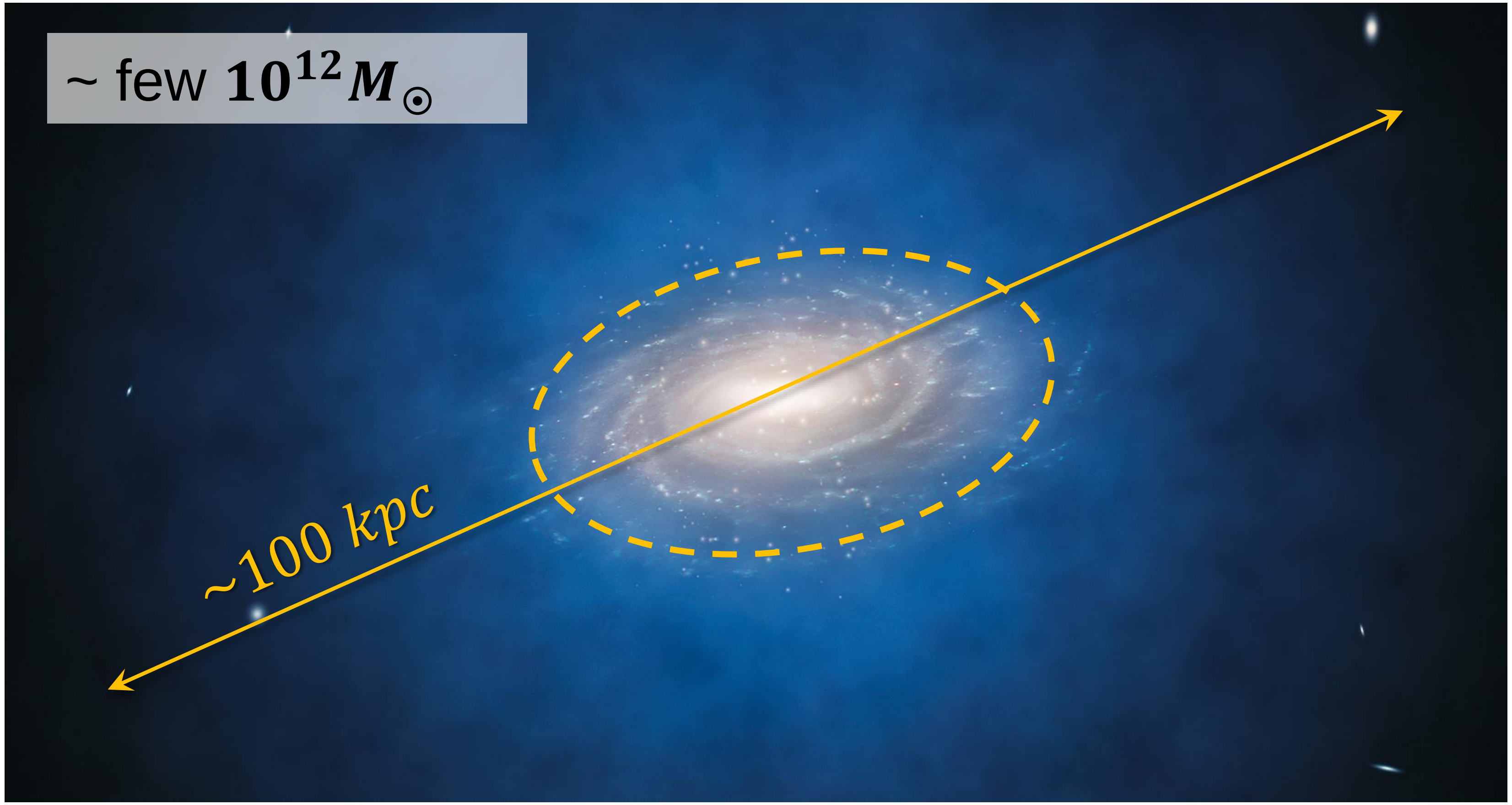
Length scales – dark matter in galaxies

- **size of a typical DM-Halo around a spiral galaxy:** Ø = 100 kpc

  - DM halo extends well beyond the visible scale of the galaxy embedded into it

  - we expect DM halos with a **tri-axial form**

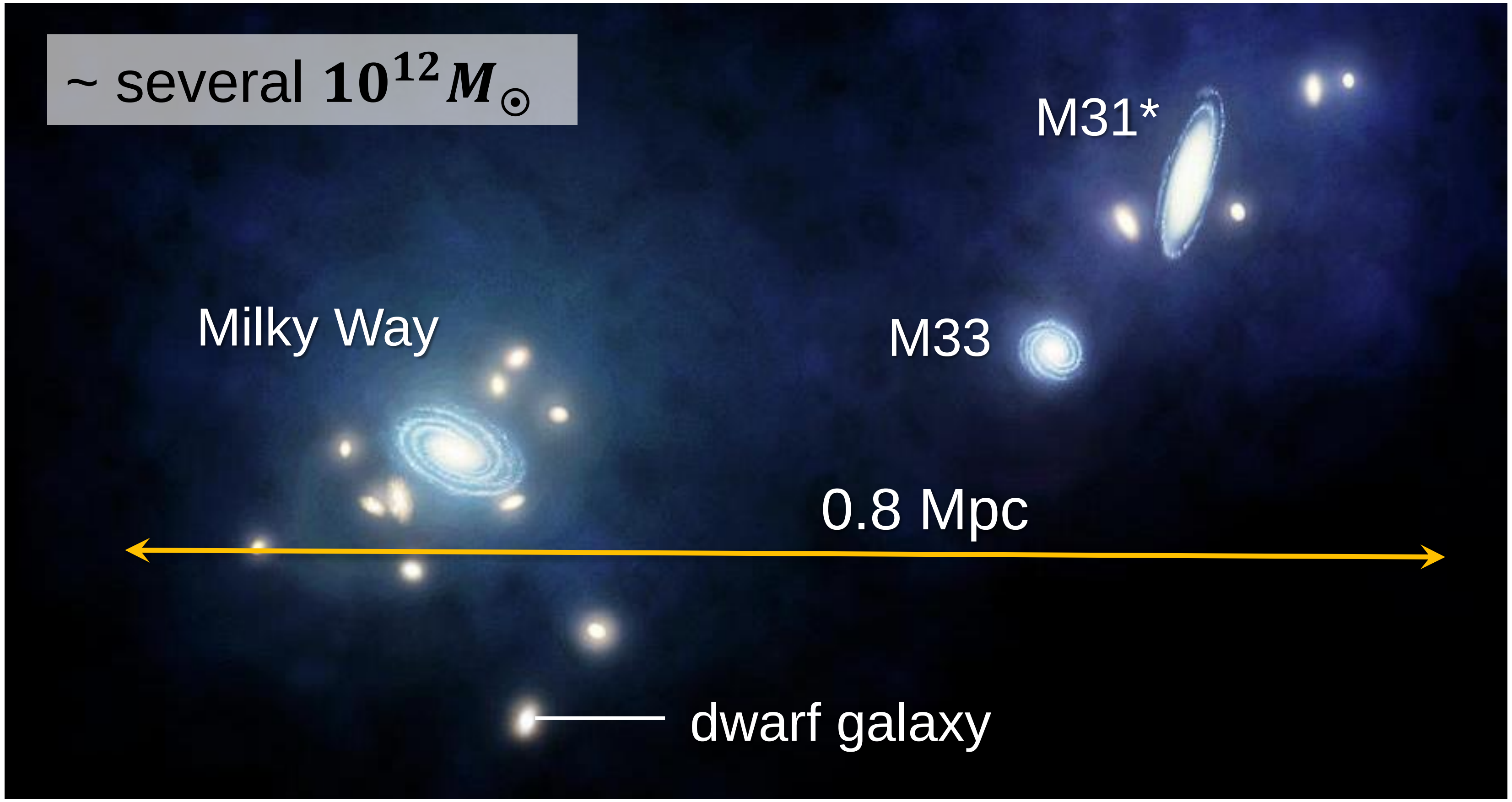
  - fundamental structure in all cosmological models (**ΛCDM**)



Length scales – our local group

- **size of a typical (small) group of galaxies:** Ø = 800 kpc (0.8 Mpc)

- gravitationally bound system of galaxies
- two large spirals (M31, Milky Way)
- ca. 60 dwarf galaxies
- this structure has to be compared with typical cosmological models (**ΛCDM paradigm**)



Q: M. Garlick

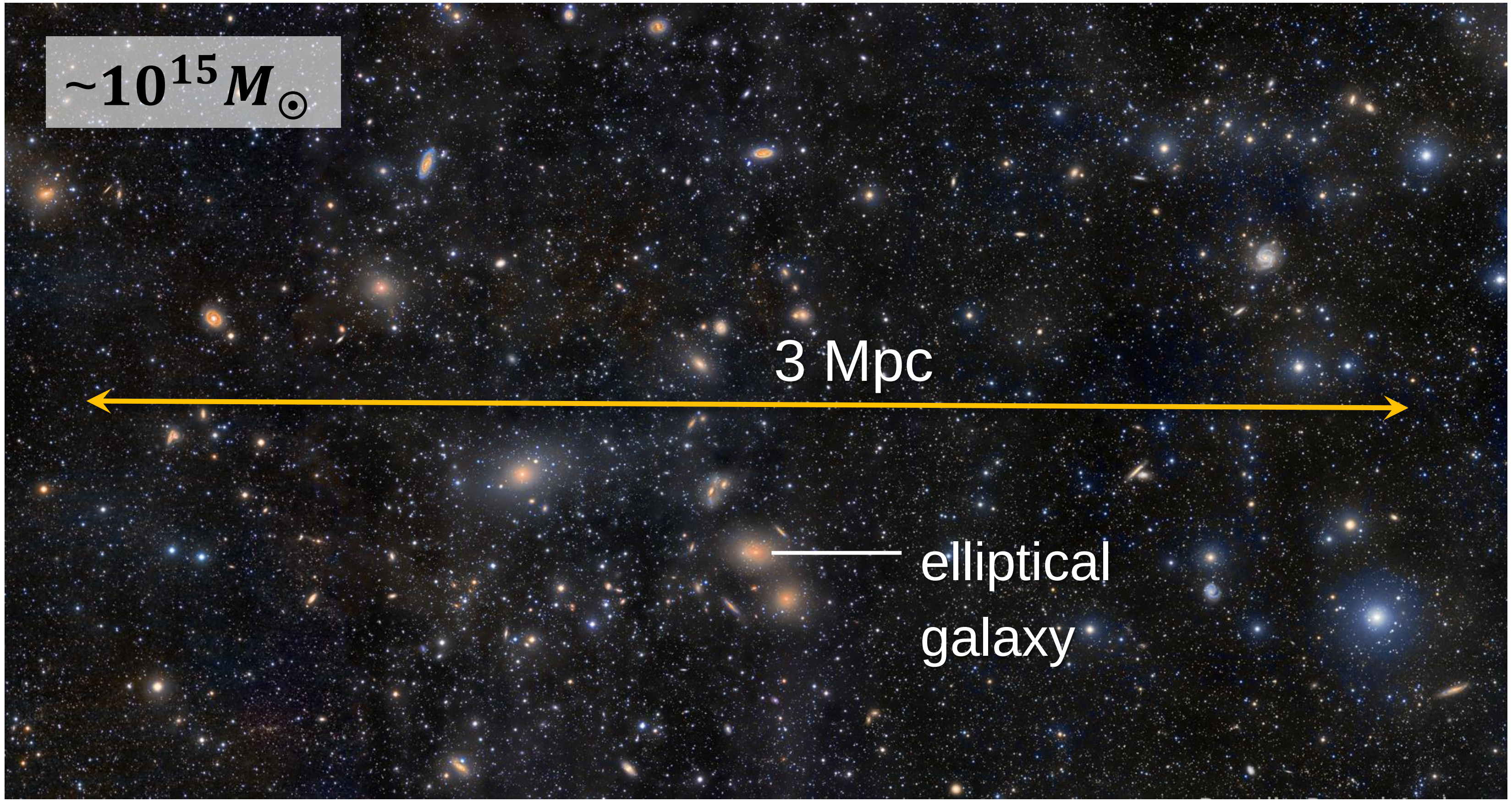
*M31 = Andromeda

Length scales – our local galaxy cluster Virgo

- **Size of a typical galaxy cluster:** Ø = 2.2 - 3 Mpc

- gravitationally bound system of galaxies
- 1300 … 2000 galaxies
- 16 Mpc distance to our local group
- largest ´virialised´ systems with relation

$$T_{kin} = -{}^{1}/_{2}\, E_{pot}$$



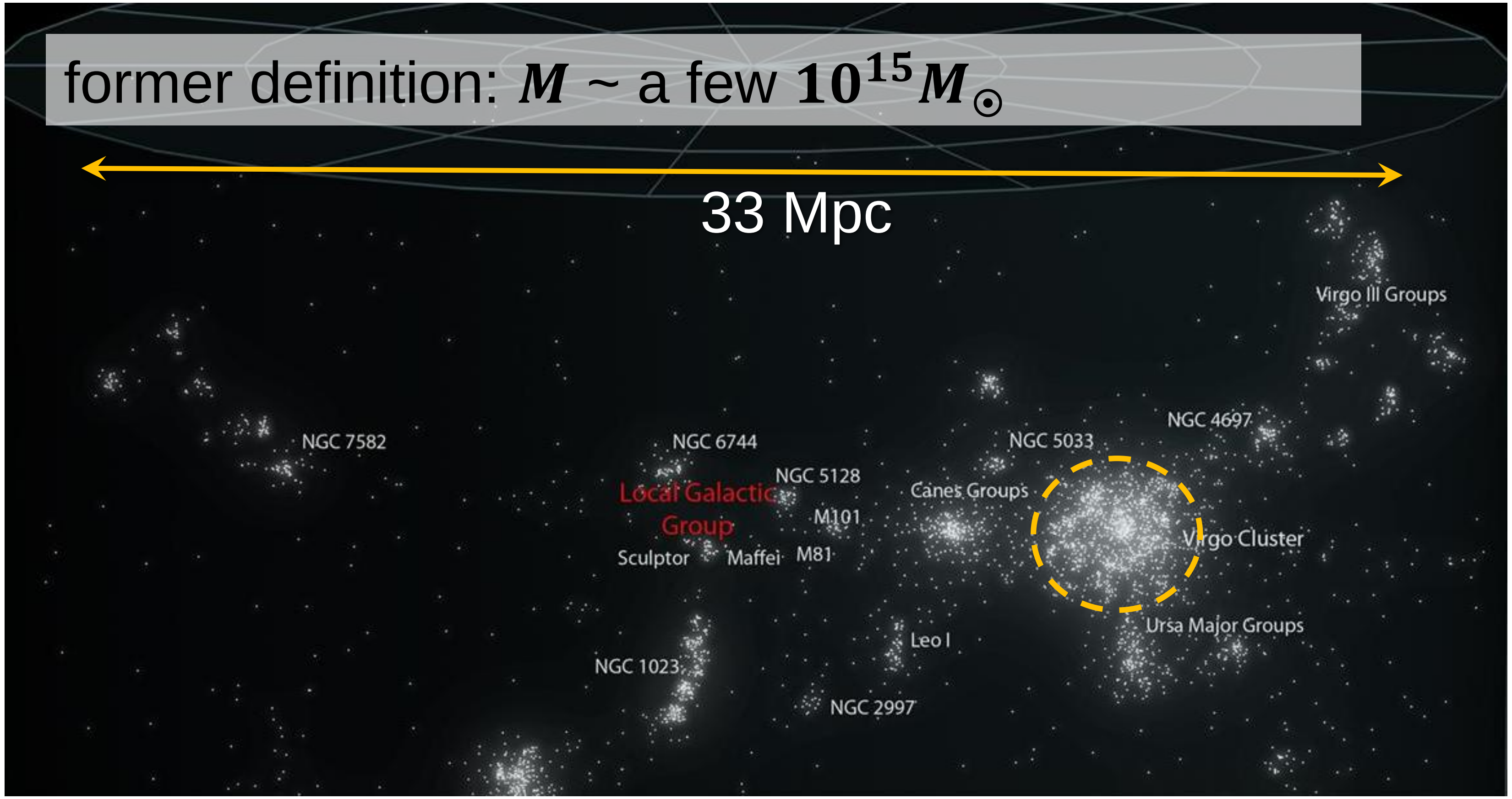
Q: M. Garlick

T_{kin} = kinet. energy E_{pot} = potential energy

Length scales – our local super cluster

- **next structure: galaxy super clusters**

  - systems gravitationally **not** bound, i.e. expand
  - 100 galaxy clusters
  - **local supercluster**: density & size are below average
  - since 2014: new definition of local supercluster



Q: M. Garlick

Length scales – our local supercluster Laniakea

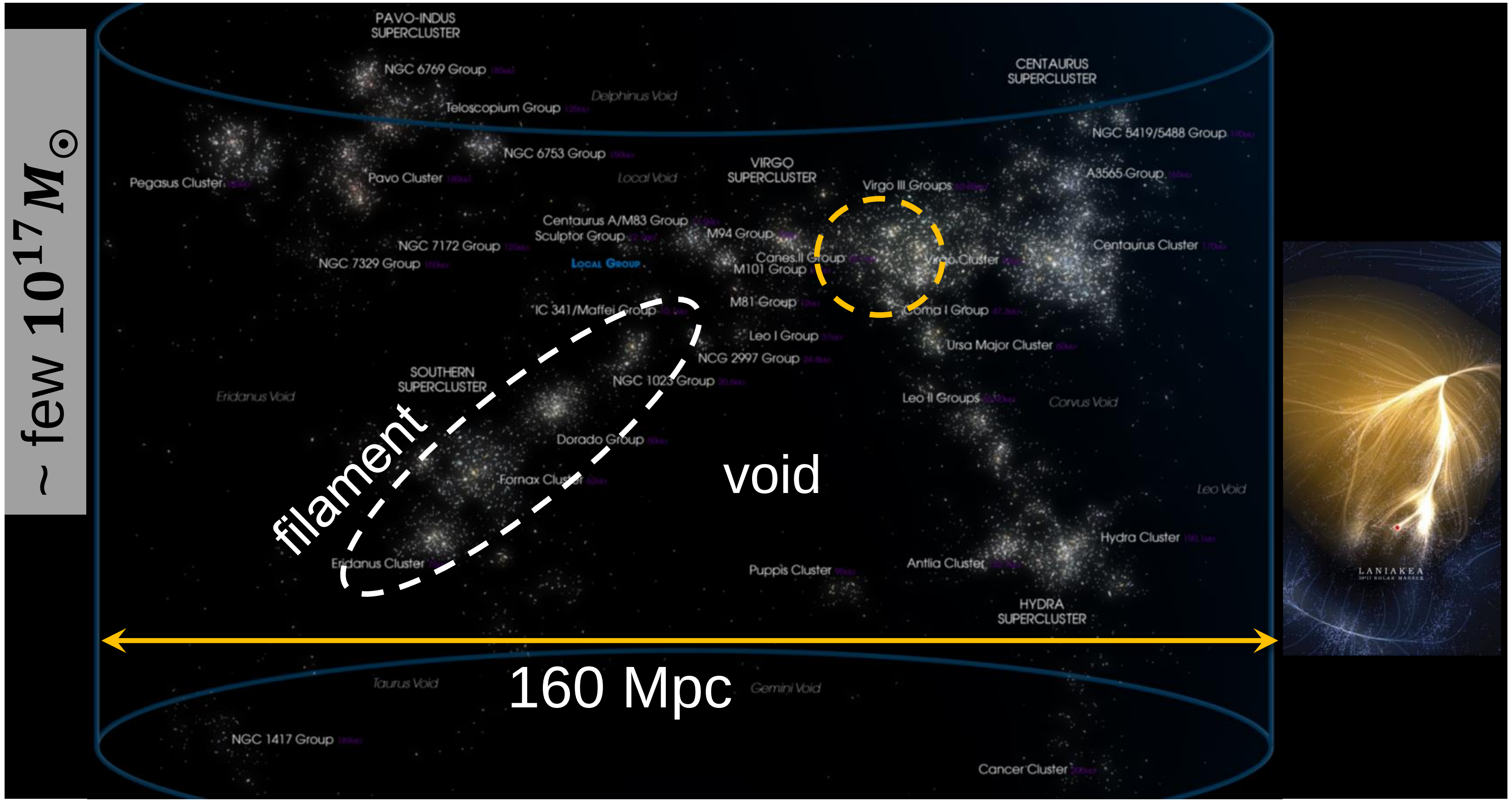
- **largest observed structures: supercluster of galaxies with Ø ~ 160 Mpc**

- gravitationally unbound

- ~ 100 000 galaxies

- 2014: definition based on relative velocities of galaxies/ groups

- **filament**-like structure with large ´**voids**´ in between



Q: wikipedia

Length scales – our local universe

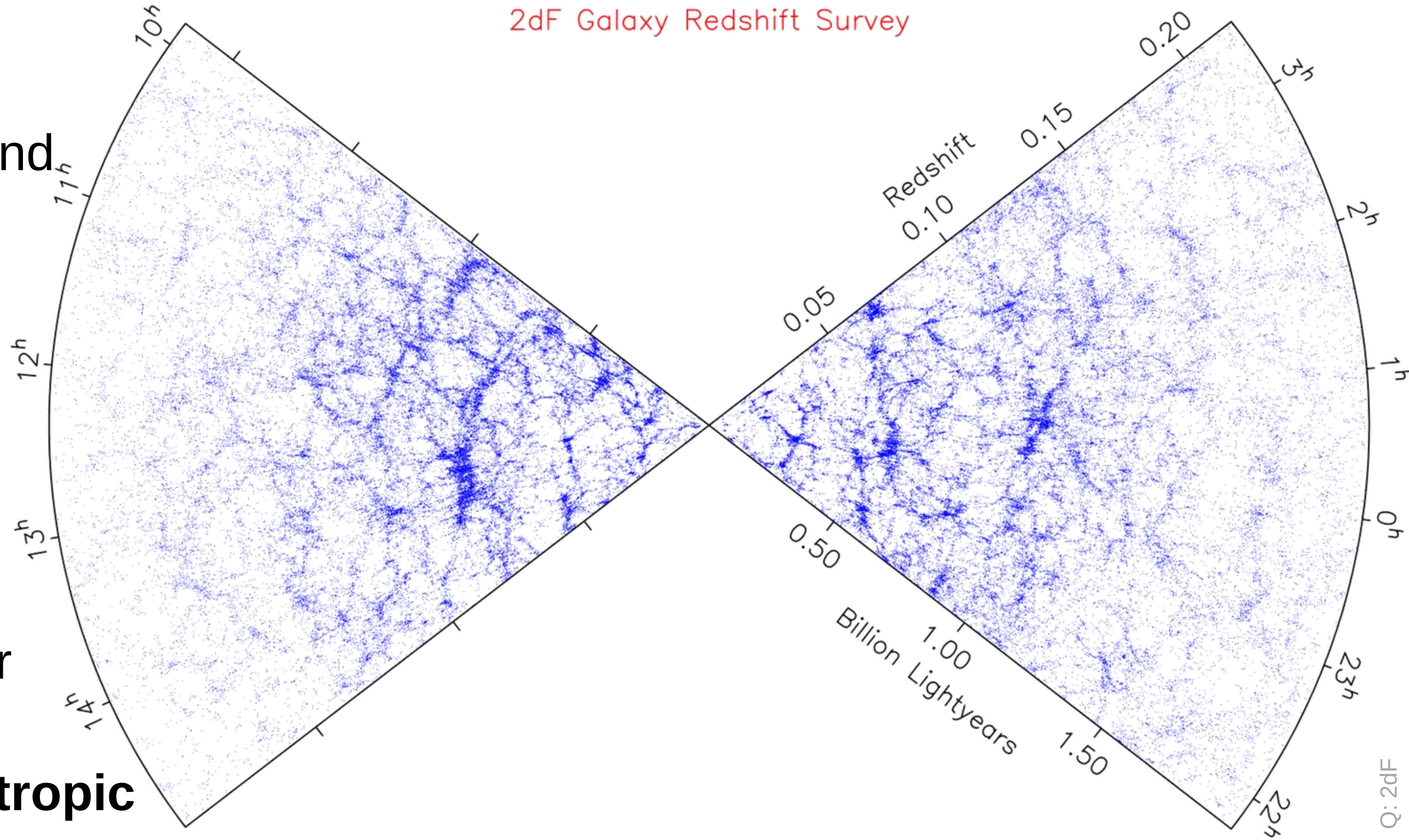
- **2dF GRS:** 500 Mpc

  - gravitationally unbound

  - participates in the cosmological expansion

  - filaments & voids

  - when averaging over large distances: **homogenous & isotropic**



Q: 2dF

Length scales – entire universe (MC)

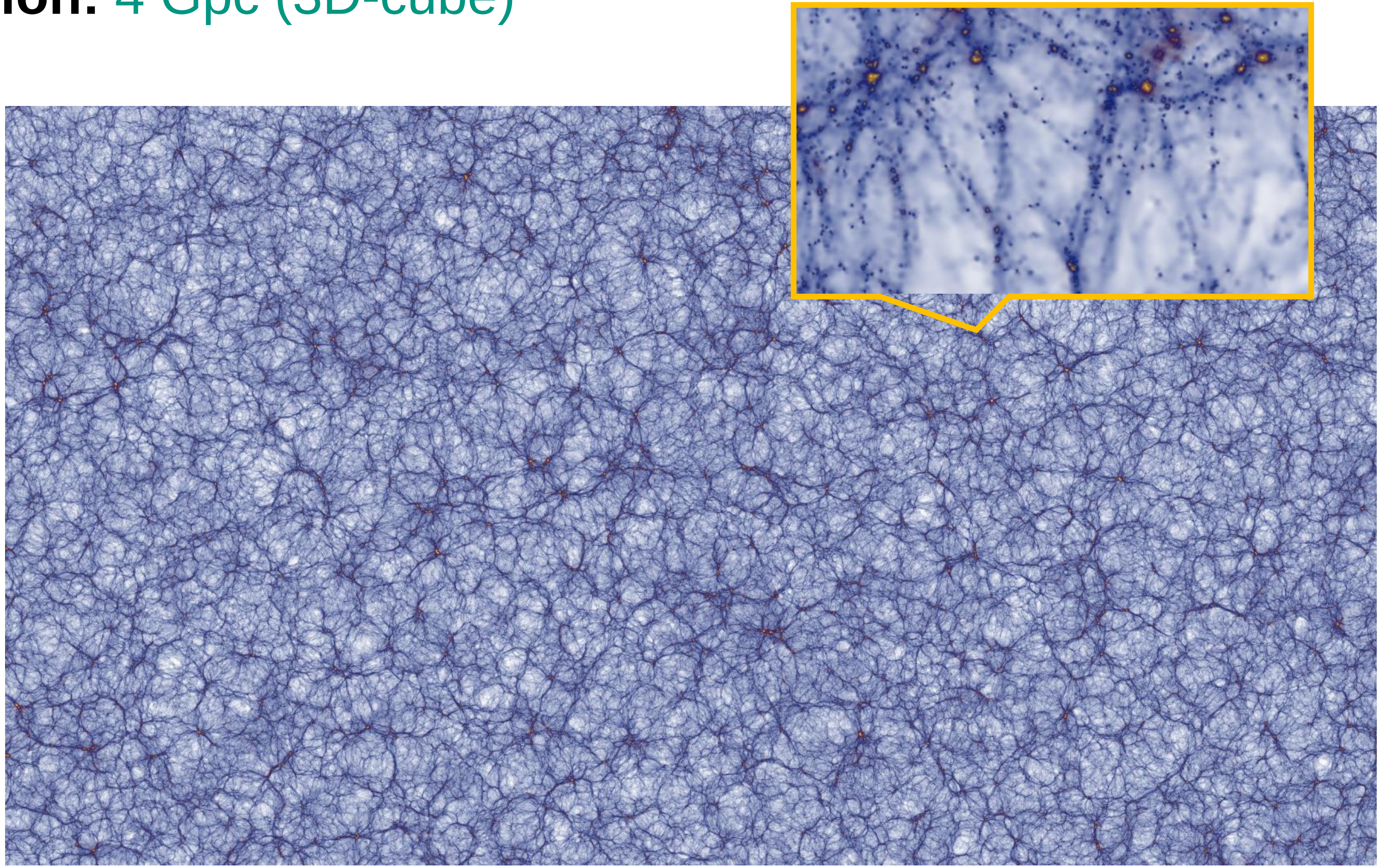
- **Millennium XXL Simulation:** 4 Gpc (3D-cube)

- result of cosmological N-body-simulations

- shows distribution of **Dark Matter**

- based on the so-called **ΛCDM model**

- when averaging over large distances: homogenous & isotropic



Q: MPG

Length scales – entire visible universe

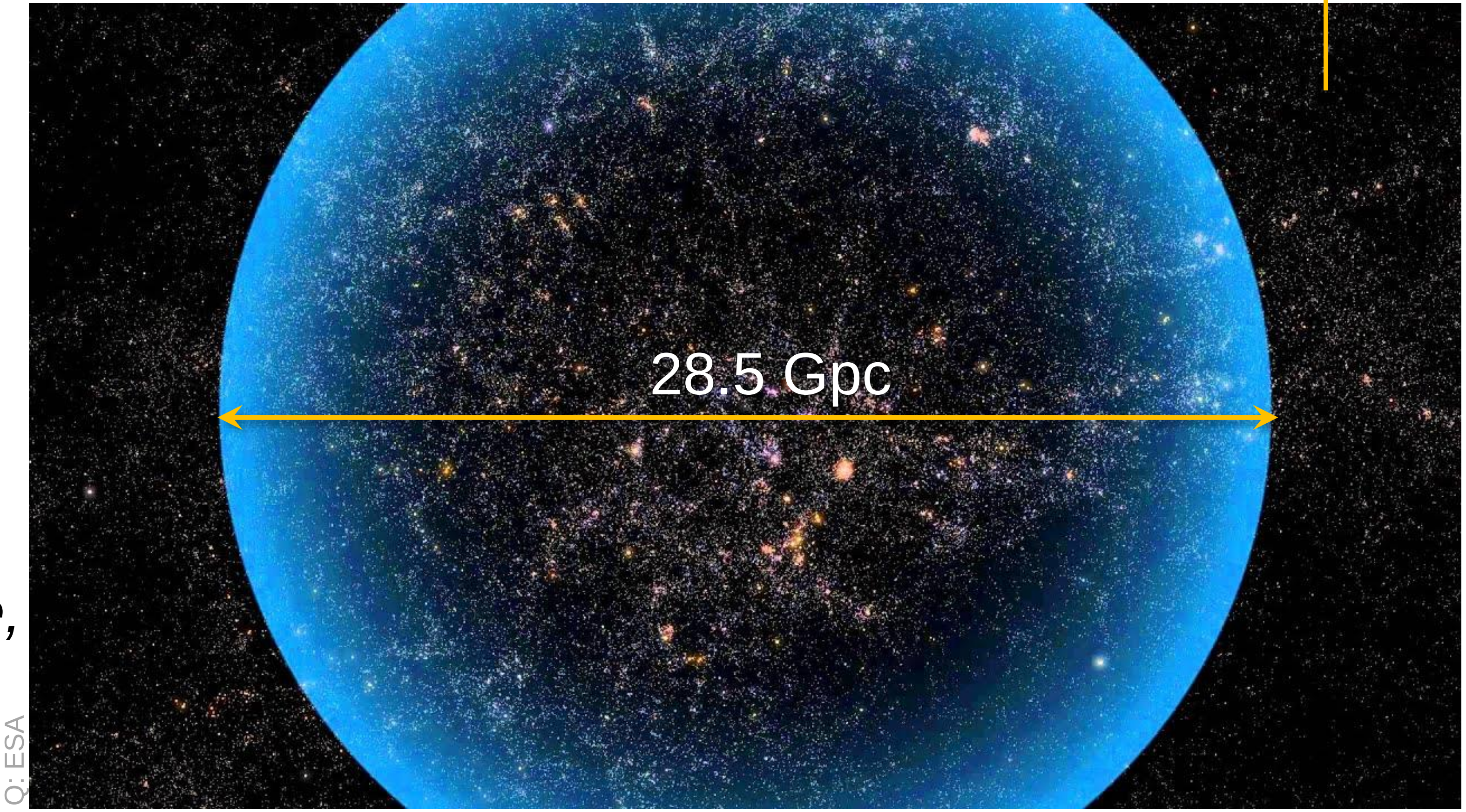
- **spherical region around Earth with** Ø = 28.5 Gpc

  - **visible region**: light from object has reached Earth

  - important fact: **acclerated expansion of space**

  - requires more precise definition of distances (see chapter 2.1): *distance via light travel time, co-moving distance -* ***redshift*** z

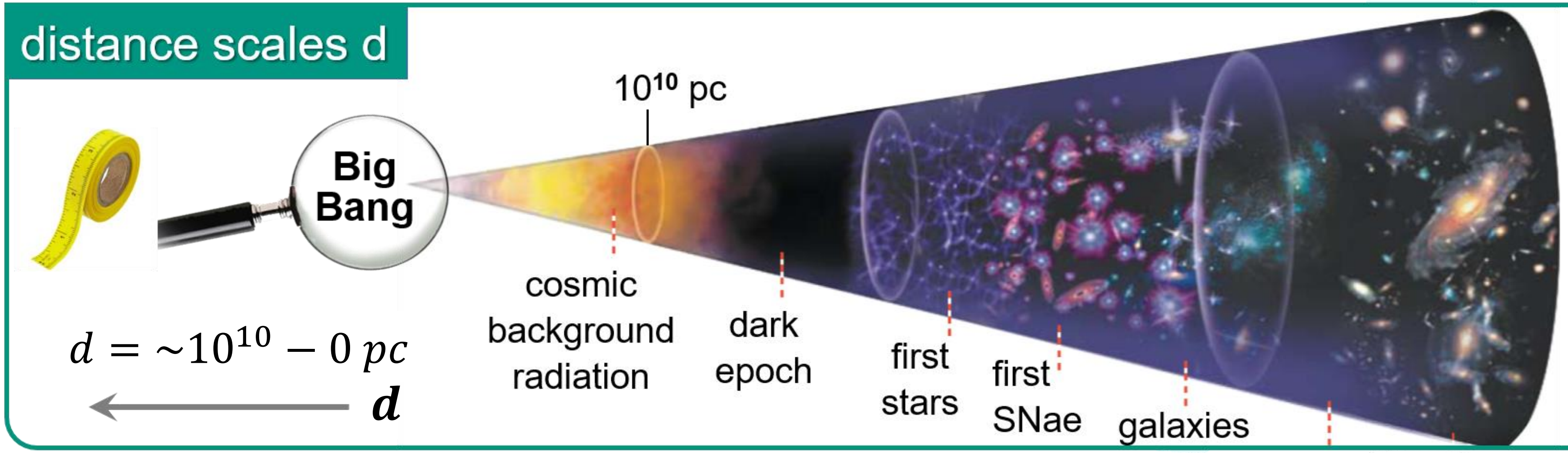
unobservable



Q: ESA

Cosmological length- & time scales are correlated

distance scales d

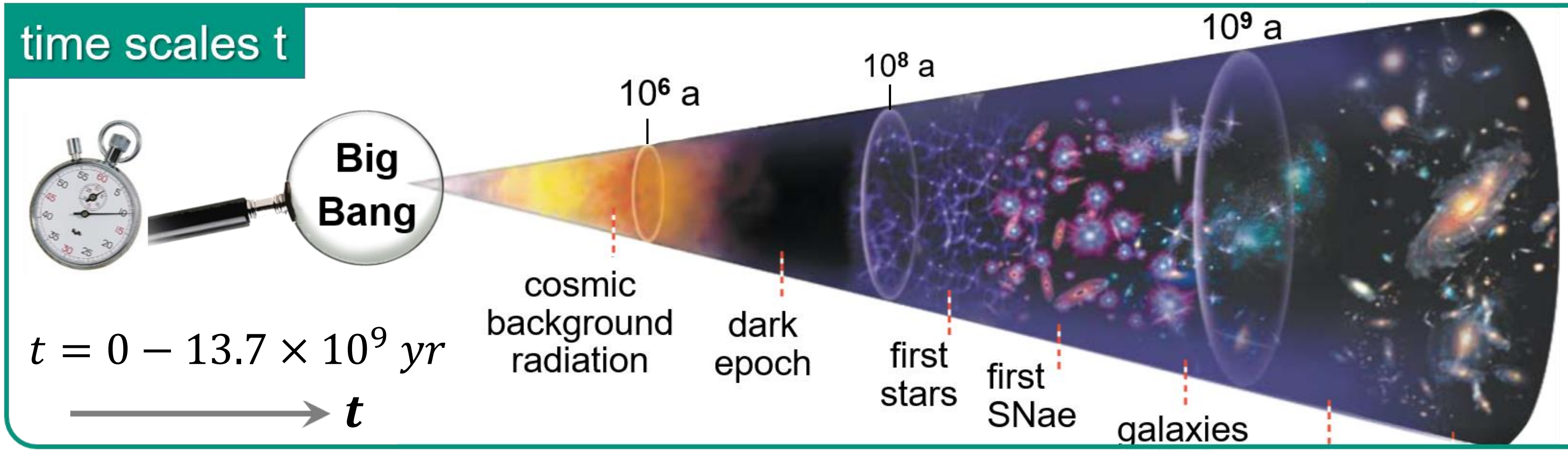


$d = \sim 10^{10} - 0 \; pc$

$\boldsymbol{d}$

here: $d = 0 \; pc$

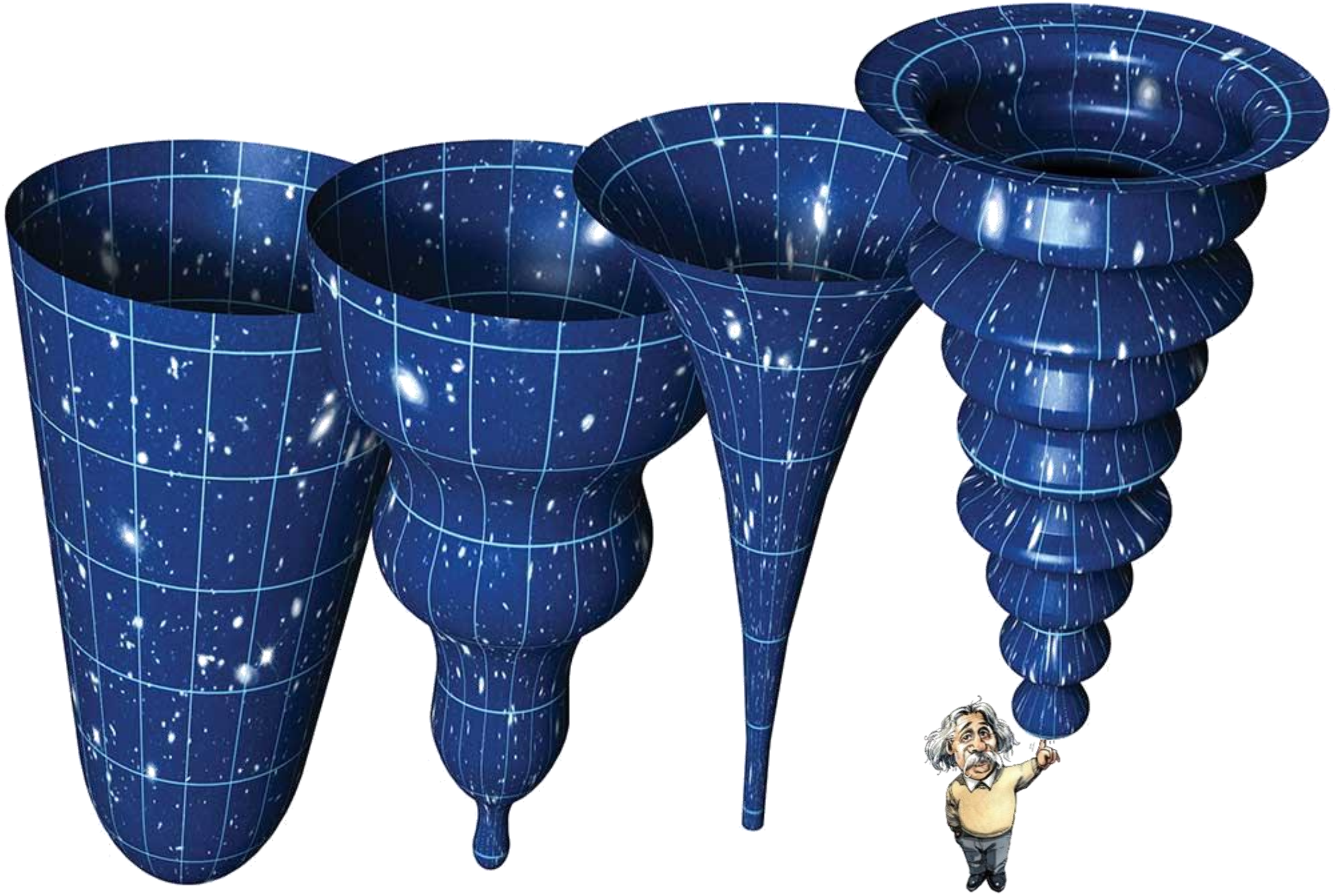
time scales t



$t = 0 - 13.7 \times 10^{9} \; yr$

$\boldsymbol{t}$

now: $t = 13.7 \times 10^{9} yr$



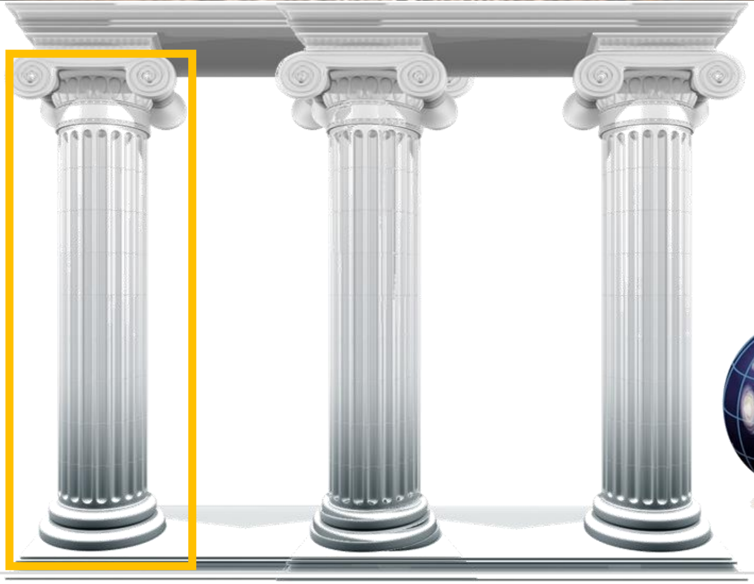
CHAPTER 2 – EXPANDING UNIVERSE

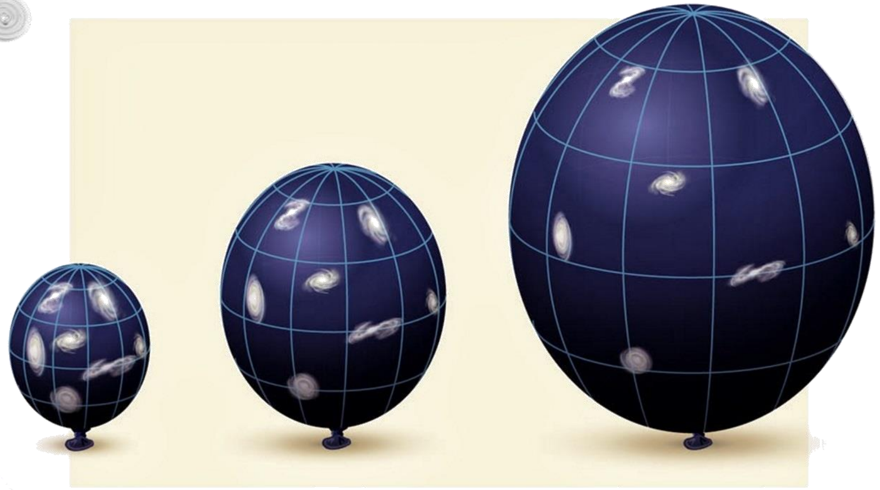
Pillars of the Big Bang: Hubble expansion

- **Key experimental evidence 1: cosmological expansion since the Big Bang**

E. Hubble

Pillar 1:
Hubble
expansion





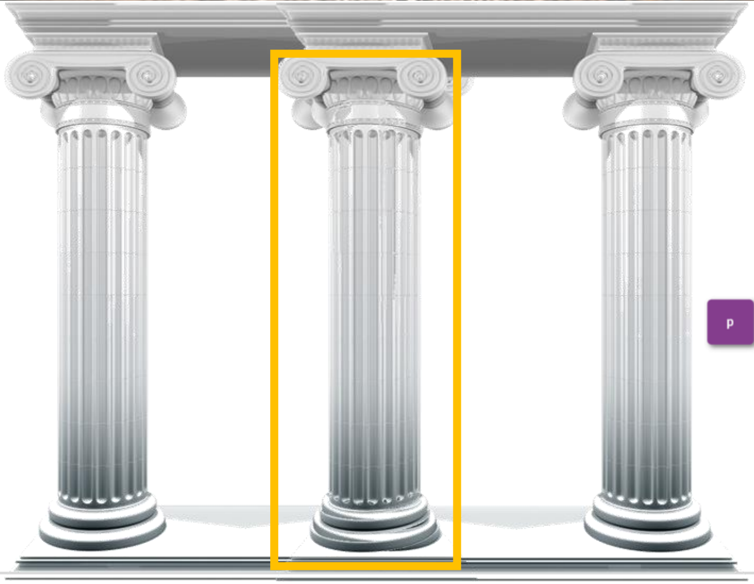
Q: R Kolb et al.

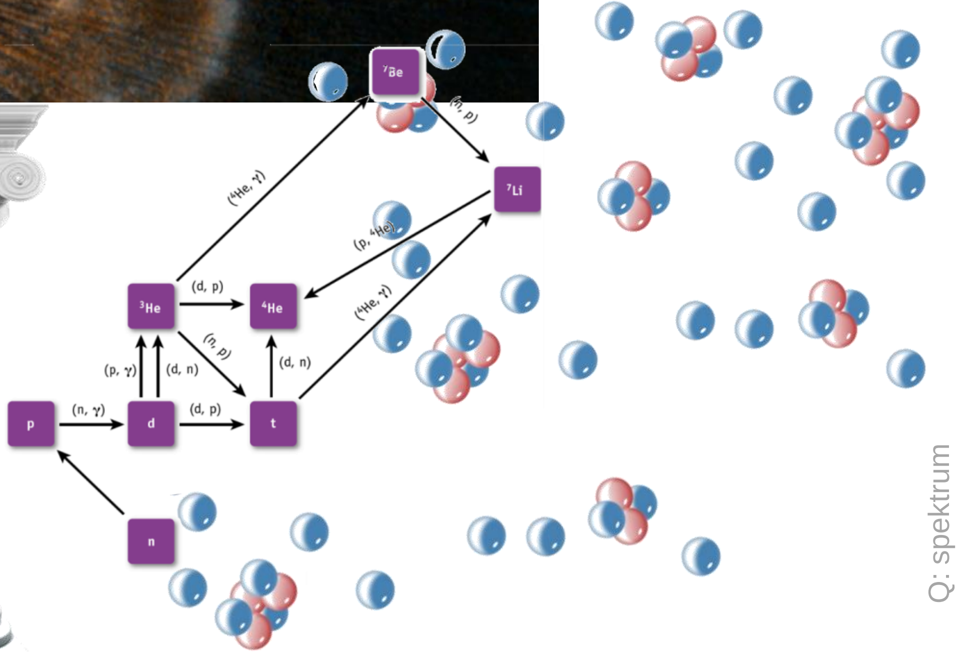
Pillars of the Big Bang: light element synthesis

- **Key experimental evidence 2: nucleosynthesis during the Big Bang (3 min.)**

G. Gamow

Pillar 2:
Big Bang
nucleo-
synthesis

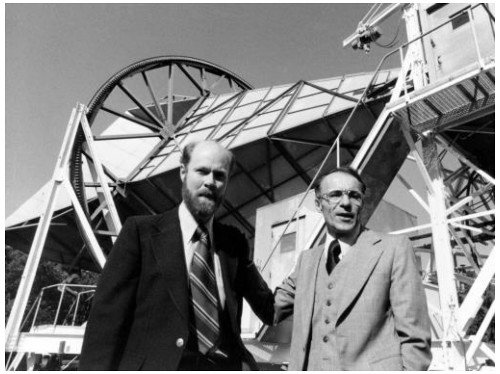




Q: spektrum

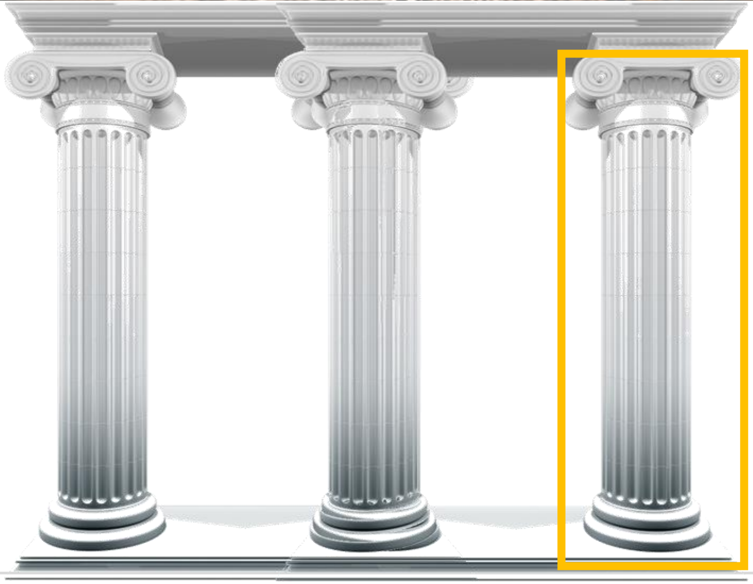
Pillars of the Big Bang: isotropic $3K$ radiation

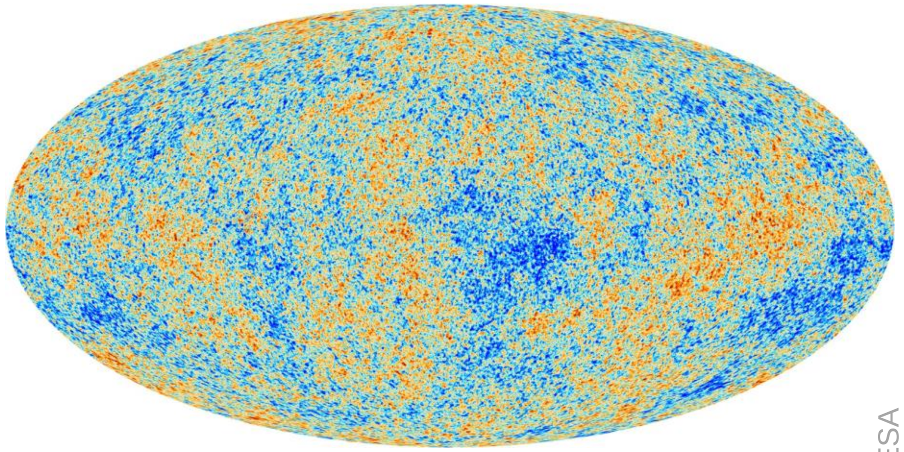
- **Key experimental evidence 3: $3K$ microwave radiation from the Big Bang**



Penzias & Wilson

Pillar 3:
$3\ K$ cosmic
background-
radiation



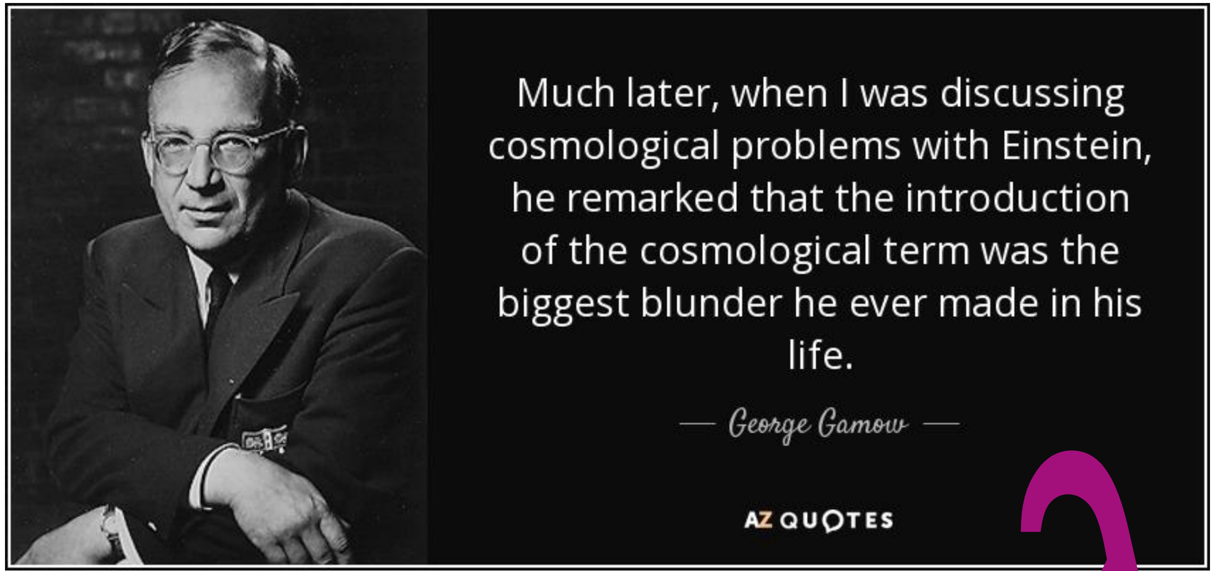


Q: ESA

2.1 Hubble Expansion

- **How can we measure the expansion rate of the universume?**

  - Edwin Hubble (1889-1953) shows, that the **universe** is **not static** (expansion)!



Q: symmetry magazine

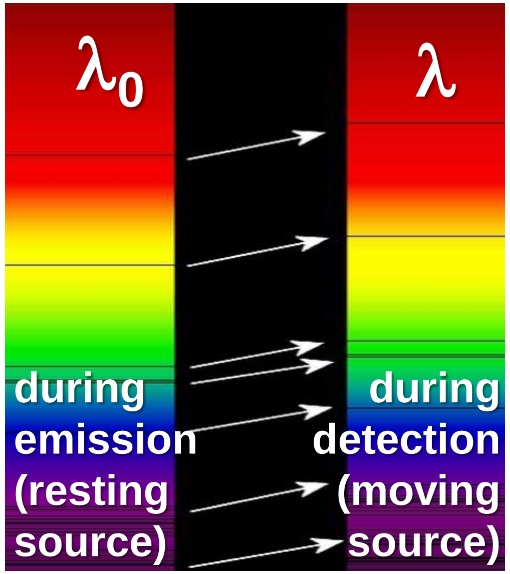
1929: observing galaxies with the
100 – inch Mount-Wilson telescope

λ

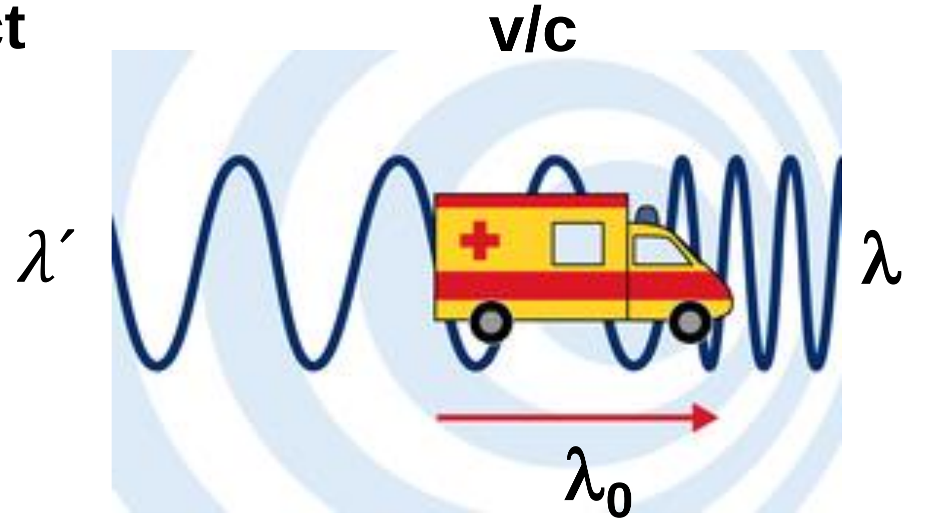
Hubble: redshift of atomic spectral lines

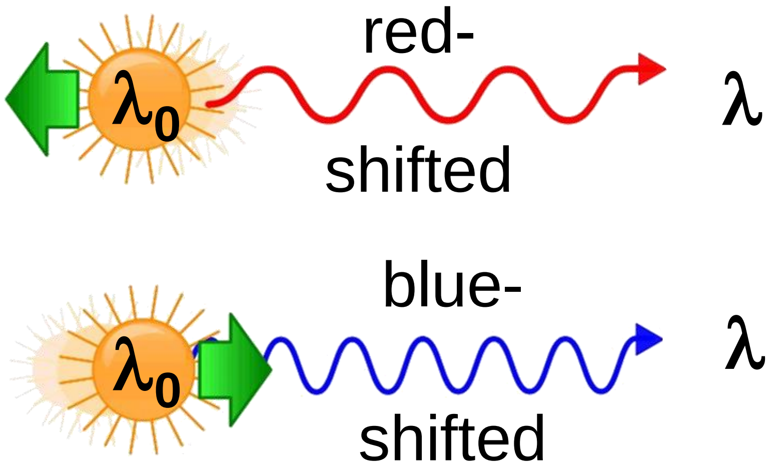
- **initial analogy: Doppler effect**

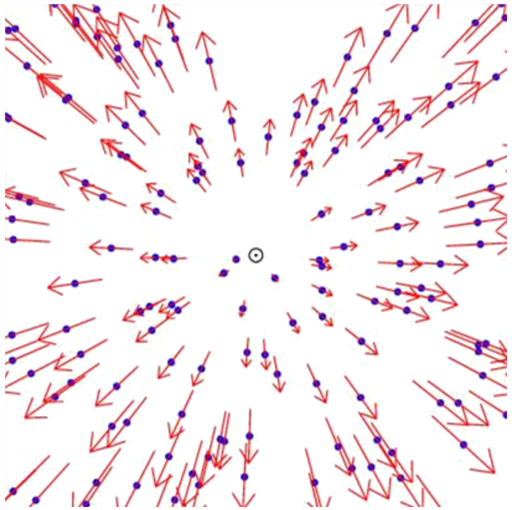
  - moving objects in space



1929: observing galaxies with the 100 – inch Mount-Wilson telescope







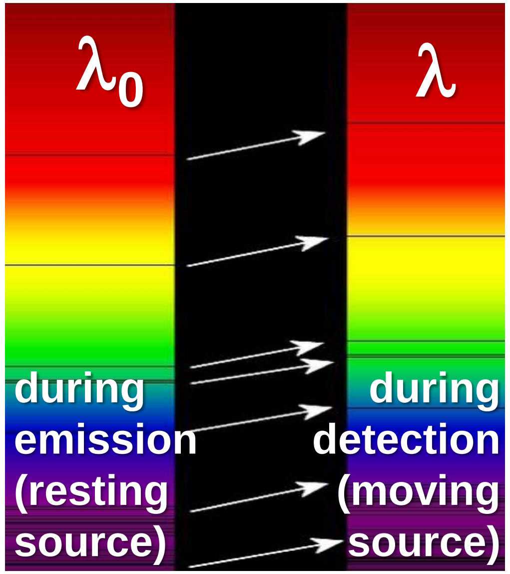
- spectra of all galaxies are **redshifted**

Hubble: escape velocity of galaxies

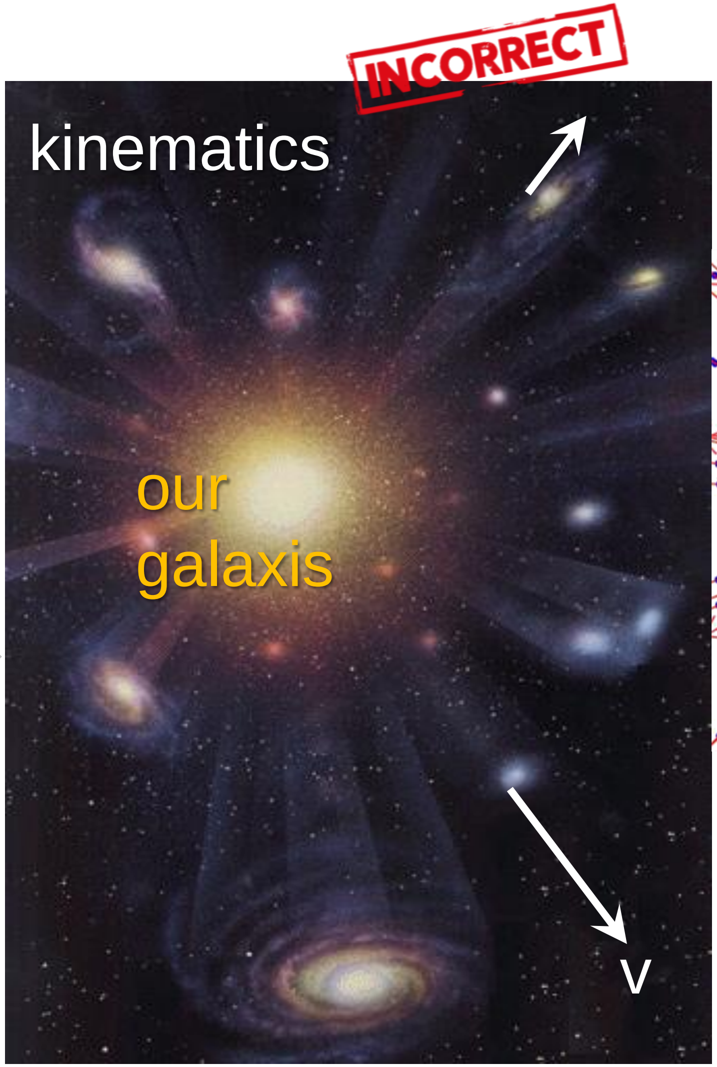
Karlsruhe Institute of Technology

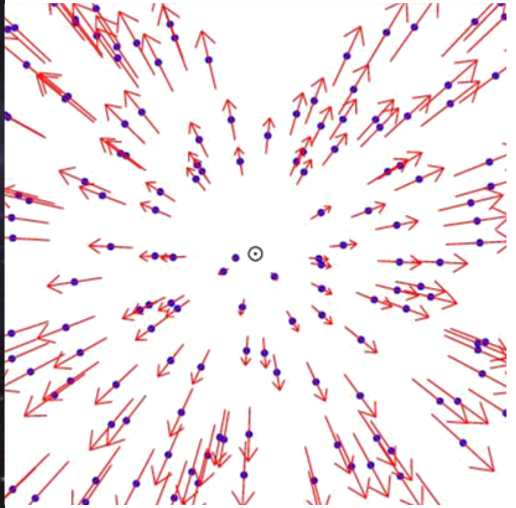
- **initial analogy: Doppler effect**

- ´moving galaxies in space´



analogy





1929: observing galaxies with the 100 – inch Mount-Wilson telescope

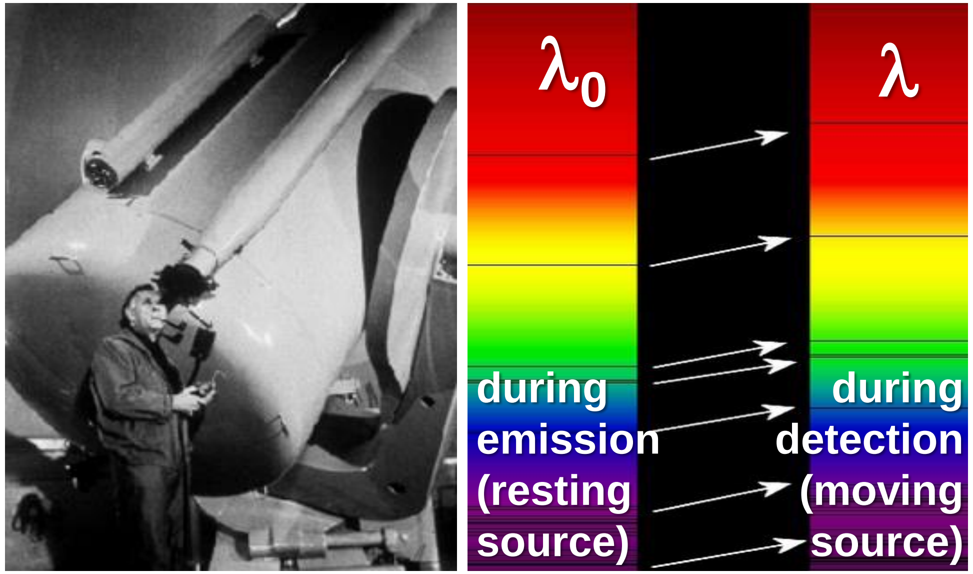
´escape velocity v´

- spectra of all galaxies are **redshifted**

redshift of spectral linies: interpretation

- **early interpretation of cosmological redshift z**

- relativistic Doppler shift along the observer´s line of sight



λ_0 = original wavelength during emission

λ = observed (redshifted) wavelength

redshift z

$$z = \frac{\lambda - \lambda_0}{\lambda_0} \qquad z = [0, \infty]$$

$$1 + z = \frac{\lambda}{\lambda_0}$$

„classical“ but incorrect interpretation

$$1 + z = \sqrt{\left(1 + \frac{v}{c}\right) \Big/ \left(1 - \frac{v}{c}\right)}$$

´escape velocity v´

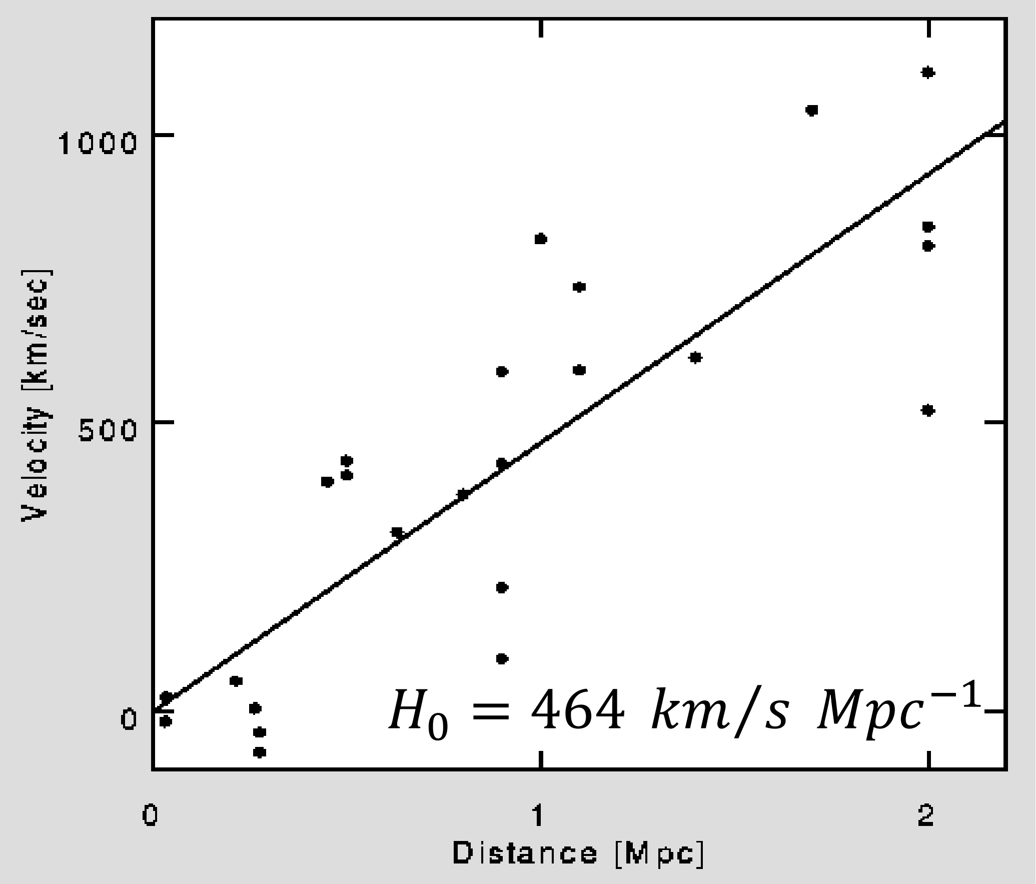
Hubble diagram: distance vs. escape velocity

- **Hubble constant $\boldsymbol{H_0}$: measures current expansion rate of the universe**

Hubble law: $v_0 = H_0 \cdot r$

- initial Hubble value was far too large (factor 6-7) due to *systematics*
- modern value $\sim 70\ km/s\ Mpc^{-1}$
  i.e. an object at a distance of 1 Mpc „is receding from Earth with an escape velocity $v = 70\ km/s$"
- **expansion rate $\boldsymbol{H(t)}$** is time-dependent over cosmological time scales

escape velocity v

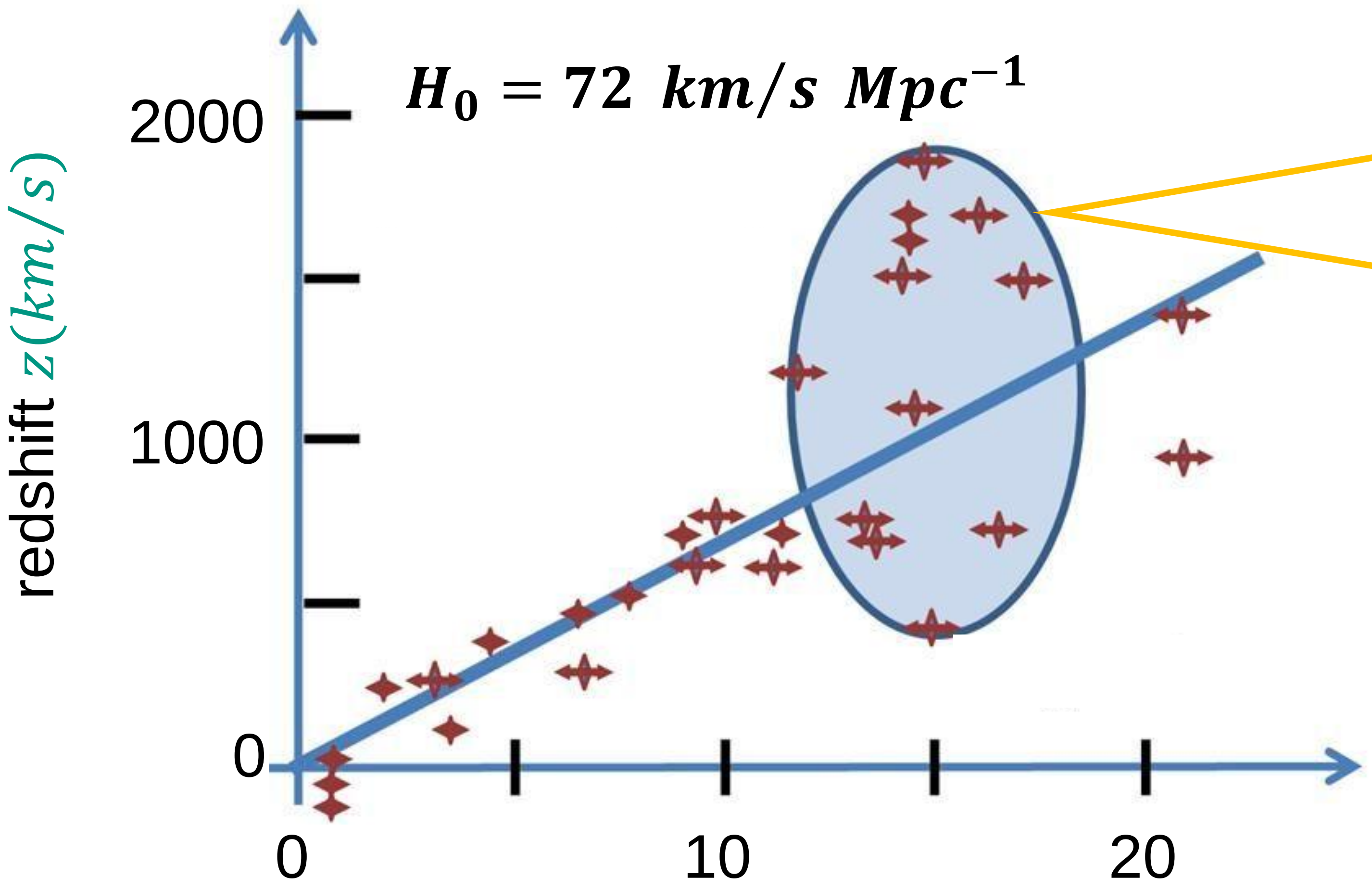


distance r

Original publication

Hubble diagram: systematic effects

- improvements: δ-Cepheids & proper motion



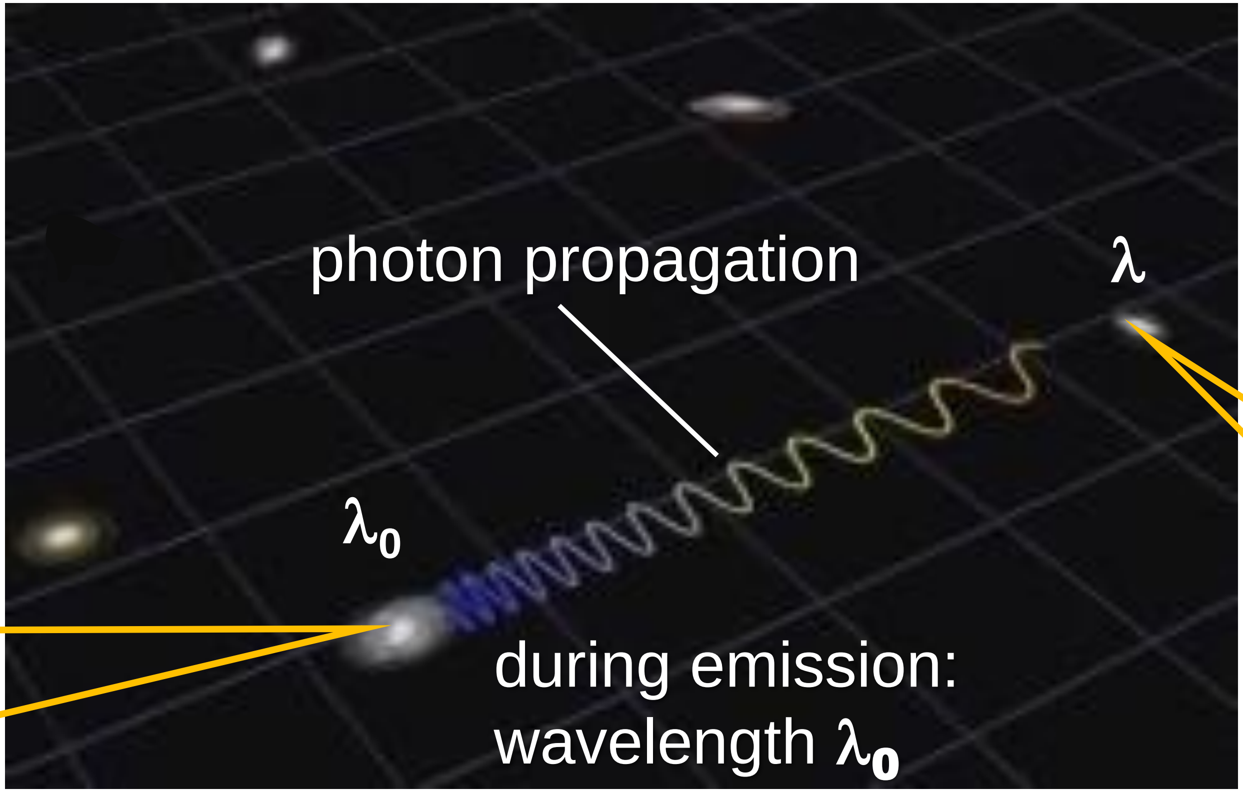
Virgo-Cluster: proper motion of galaxies (i.e motion around centre of a cluster) is super-imposed on cosmic redshift z

Q: wikipedia

Hubble expansion – todays´ correct scenario

- **redshift z** is due to the <u>stretching of the wavelength</u> of photons during propagation through cosmos: λ thus affected by cosmological expansion

emission (past):
corresponds to
lab-wavelength λ_0
(atomic physics)



detection (today):
after propagation one
measures stretched
wavelength λ

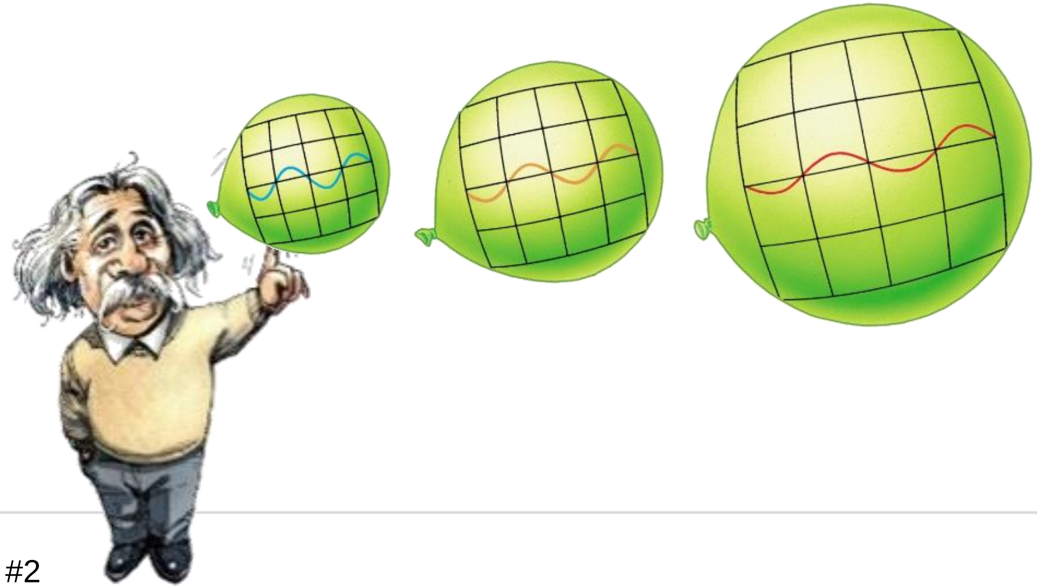
general relativity: **expansion of space-time**

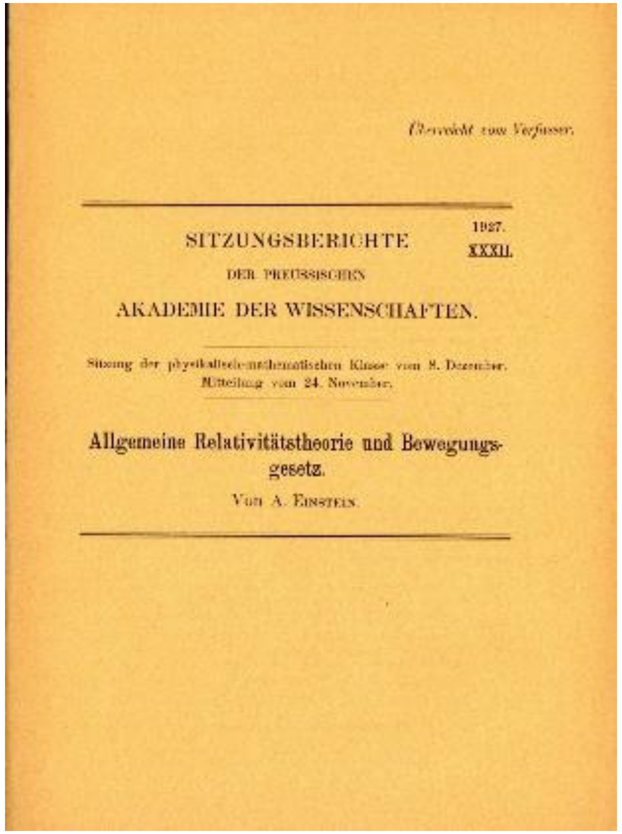
Hubble expansion – todays´ correct scenario

- **redshift** z is due to the stretching of the wavelength of photons during propagation through cosmos: λ thus affected by cosmological expansion

  - **redshift** as an ideal tool to reconstruct the expansion history of patches of spacetime since the Big Bang

  - **spectroscopy** of atomic lines is an important method to determine the actual size of the universe!




Überreicht vom Verfasser.

SITZUNGSBERICHTE 1927. XXXII.
DER PREUSSISCHEN
AKADEMIE DER WISSENSCHAFTEN.

Sitzung der physikalisch-mathematischen Klasse vom 8. Dezember.
Mitteilung vom 24. November.

Allgemeine Relativitätstheorie und Bewegungsgesetz.

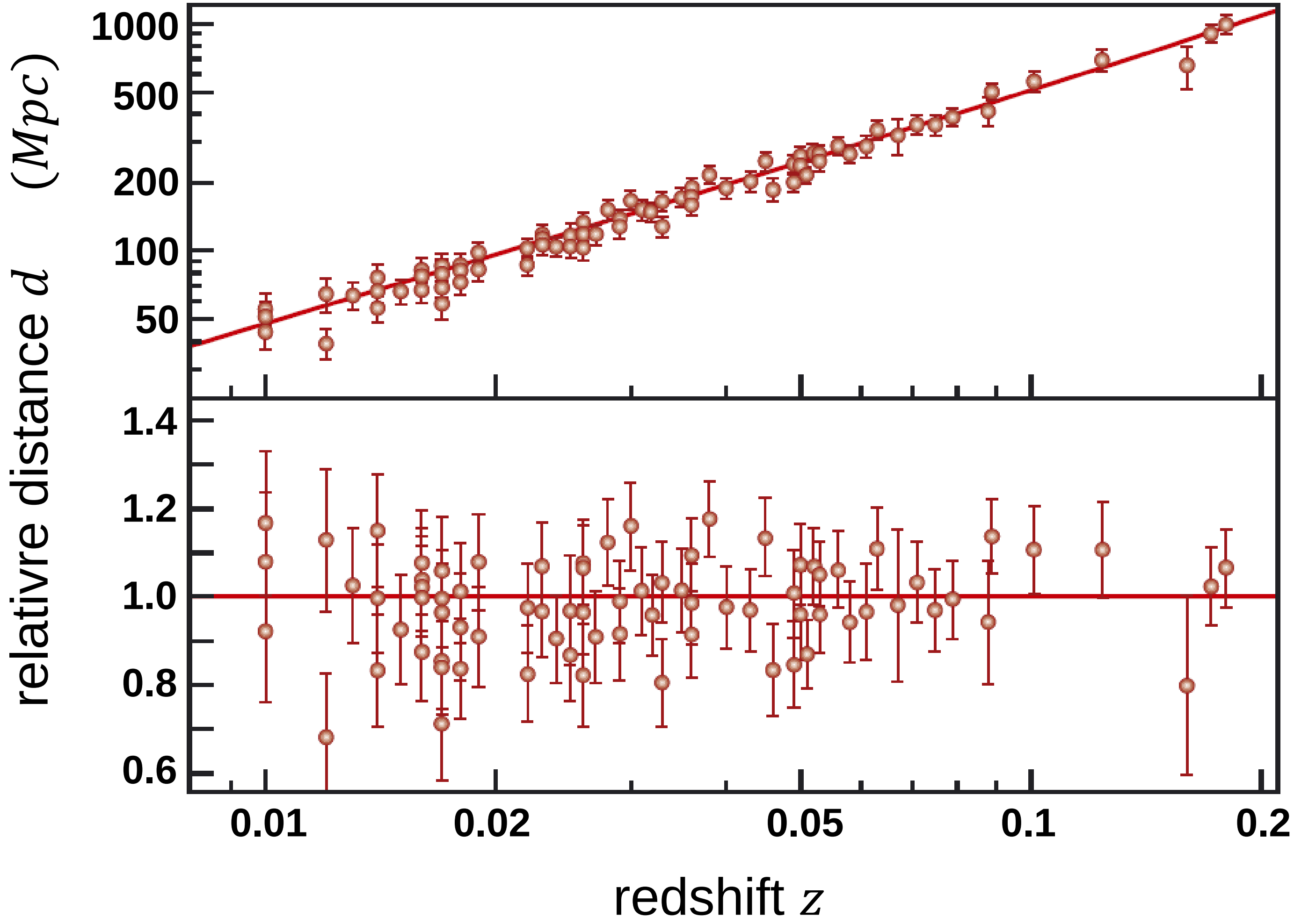
Von A. Einstein.

Up to 2015: exp. results for Hubble rate H_0

- experimental, averaged value for **Hubble constant** H_0 (HST, Chandra X-ray mission, distant SNae,…)

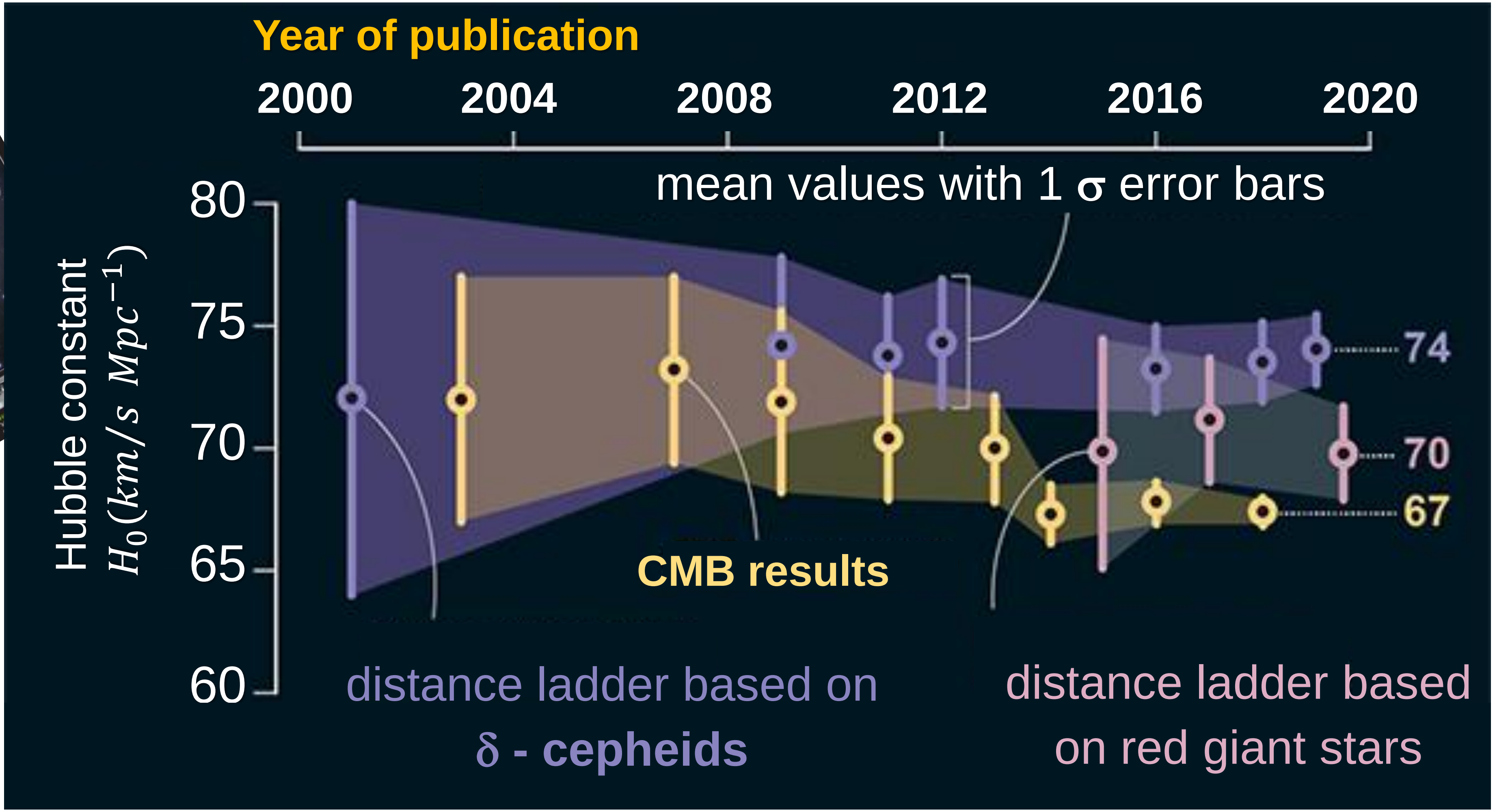
$$H_0 = \left(72 \pm 3_{\,stat} \pm 7_{\,syst}\right) \; km/s \;\; per \; Mpc$$

Q: spektrum



SNae = supernovae

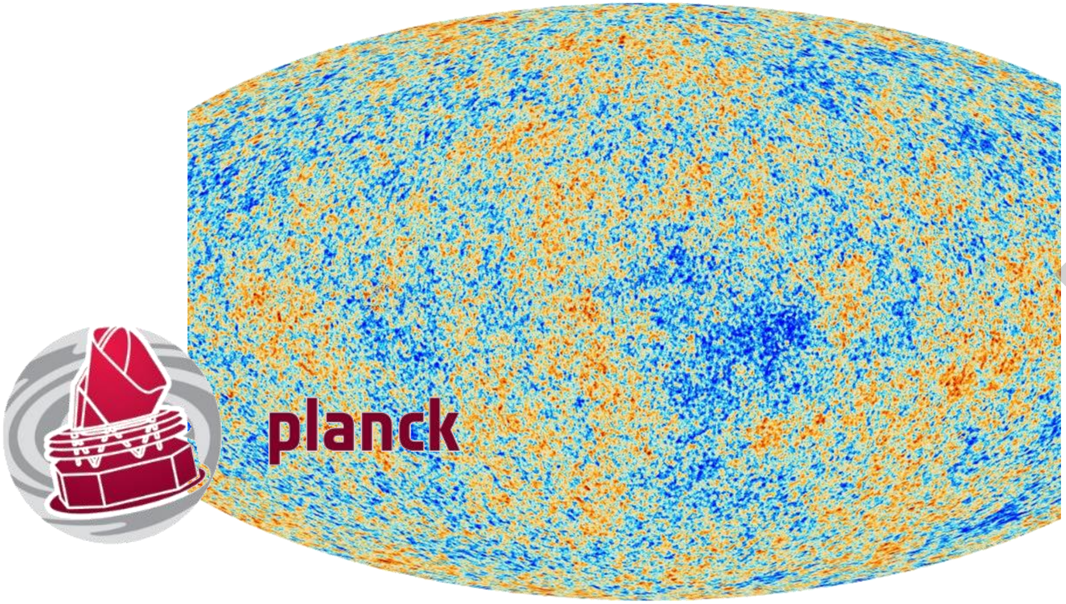
20 years of measurements of Hubble rate H_0



2021: controversy about Hubble rate H_0

- **discrepancy** observed for **Hubble-“constant“**

method-I: temperature fluctuations of CMB (see 3.3)



$(67.0 \pm 0.5)\ km/s\ Mpc^{-1}$

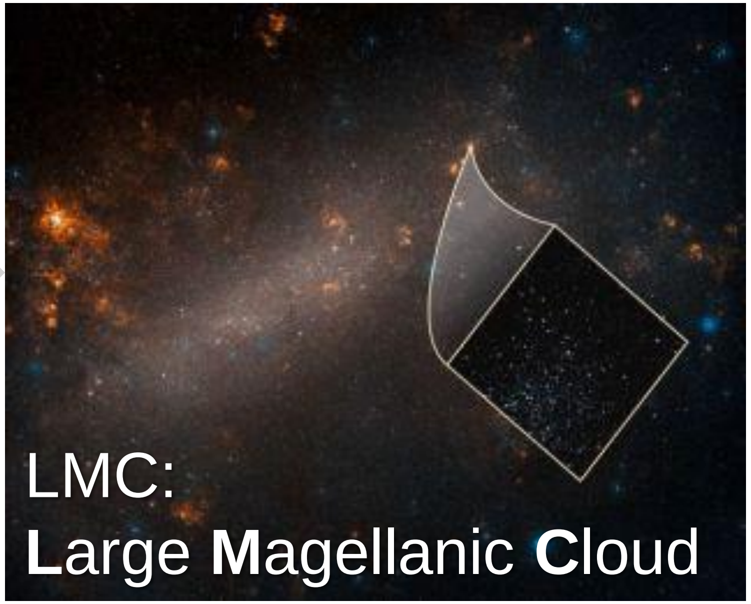
(derived H_0 for todays´ cosmic expansion)

4.4 σ

discrepancy

$\Delta H_0 = (6.6 \pm 1.5)\ km/s\ Mpc^{-1}$

method-II: δ-Cepheids in the LMC (Adam Reiss)



$(74.0 \pm 1.4)\ km/s\ Mpc^{-1}$

(measured H_0 for today)

2021: controversy about Hubble rate H_0

BREAKING NEWS

KIT Karlsruhe Institute of Technology

- **discrepancy** observed for **Hubble-“constant“**

  - early universe (**CMB**, cosmic background radiation with PLANCK)

  - present universe (**δ-cepheids** in our local neighbourhood)

  - all values of cosmological parameters depend on the value of $\boldsymbol{h}$ (dimension-less Hubble constant)

    with $H_0 = \boldsymbol{h} \cdot 100\ km/s\ Mpc^{-1}$

    $\boldsymbol{h} = 0.67 \ldots 0.74$ $(\boldsymbol{h^2 \sim 0.5})$

nature

NEWS | 17 September 2021

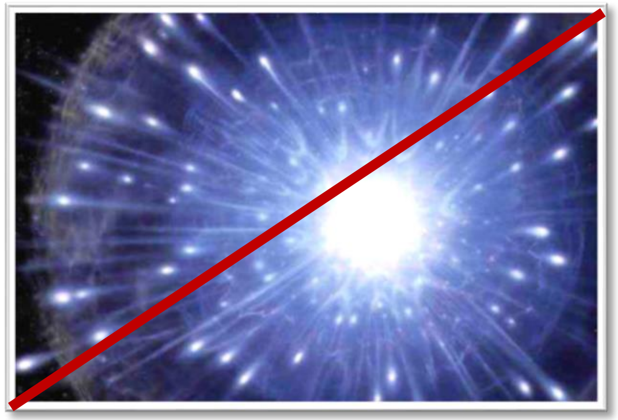
New type of dark energy could solve Universe expansion mystery

Data from the Atacama Cosmology Telescope suggest the existence of two types of dark energy at the very start of the Universe. Credit: Giulio Ercolani/Alamy

Big Bang: expansion mechanismus

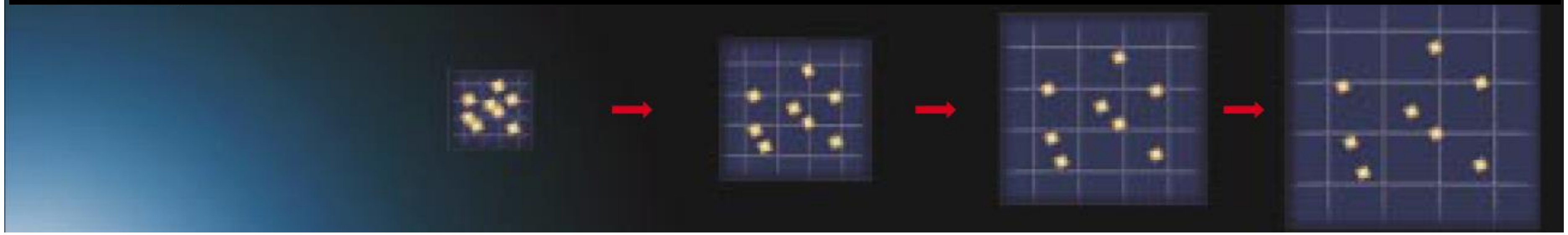
- **Big Bang** occured „every-where“

- space & time are generated simultaneously



wrong scenario: Big Bang occured at a specific location in space, from which matter expanded into empty space, driven by pressure difference

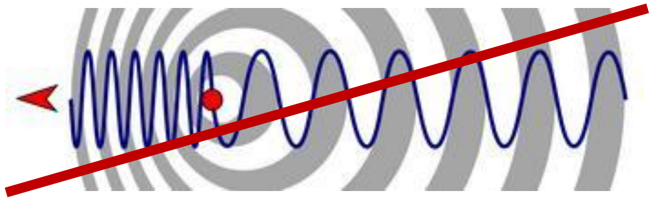
correct scenario: space & time did originate in the Big Bang, there is no explosion center, density & pressure of matter are identical everywhere



Big Bang: origin of redshift z

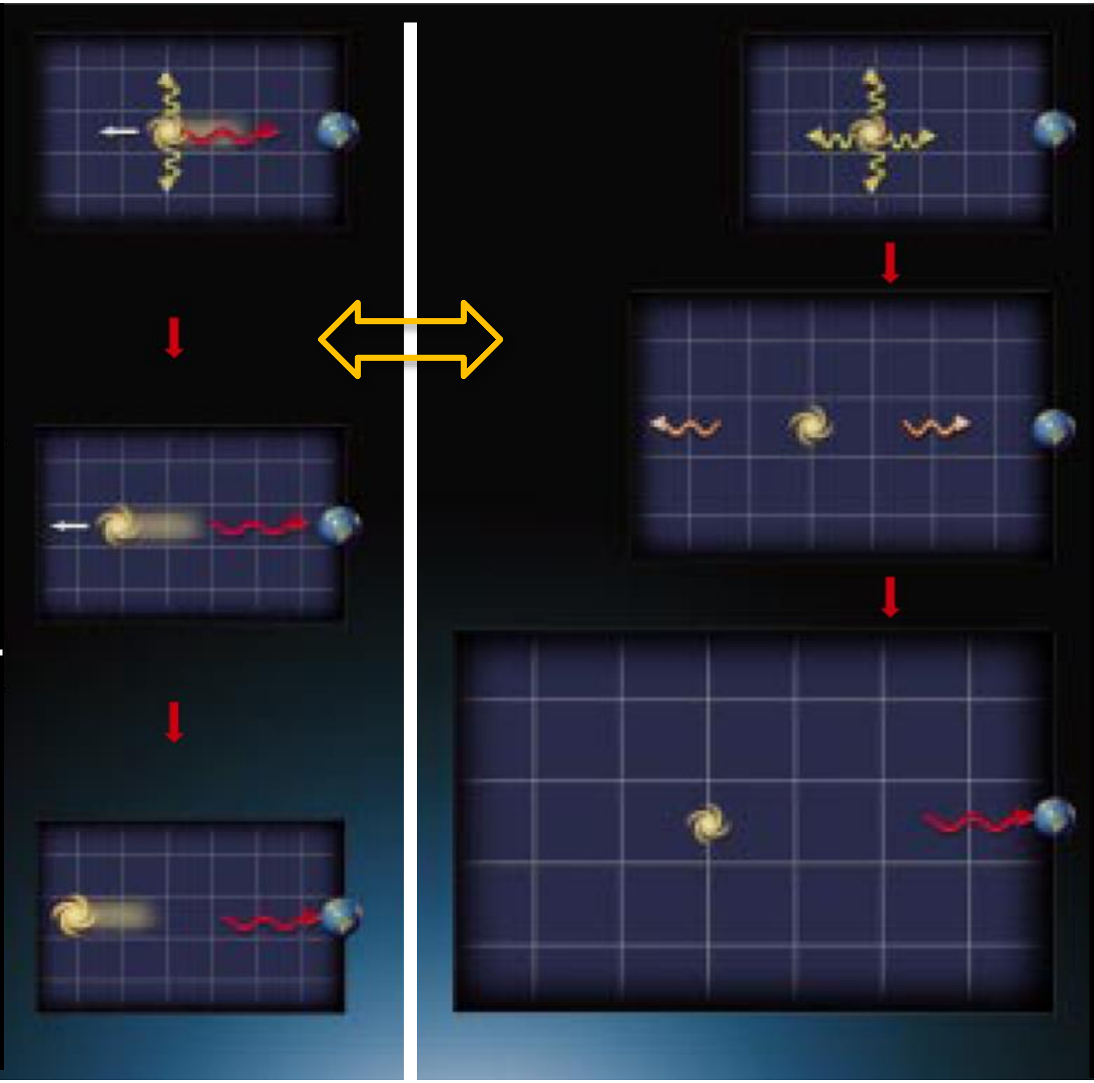
- **Space itself** expands

- galaxies are „at rest“ (i.e. they are co-moving objects over cosmological expansion)



Q: spektrum

wrong scenario: all galaxies are moving through space, so their spectral lines are Doppler-shifted to red. From z one can calculate an escape velocity for each single galaxy

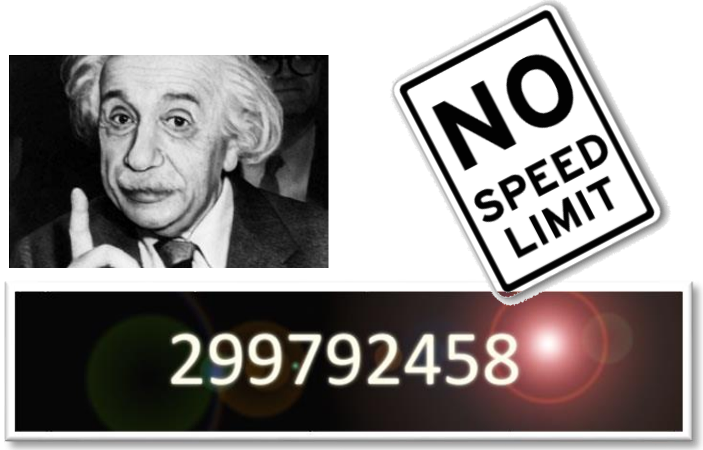


correct scenario: expanding space-time stretches the wavelength of photons, redshift z is identical in all directions. The proper motion of galaxies (& res. Doppler effect) can be neglected

Big Bang: „escape velocities“ with v > c

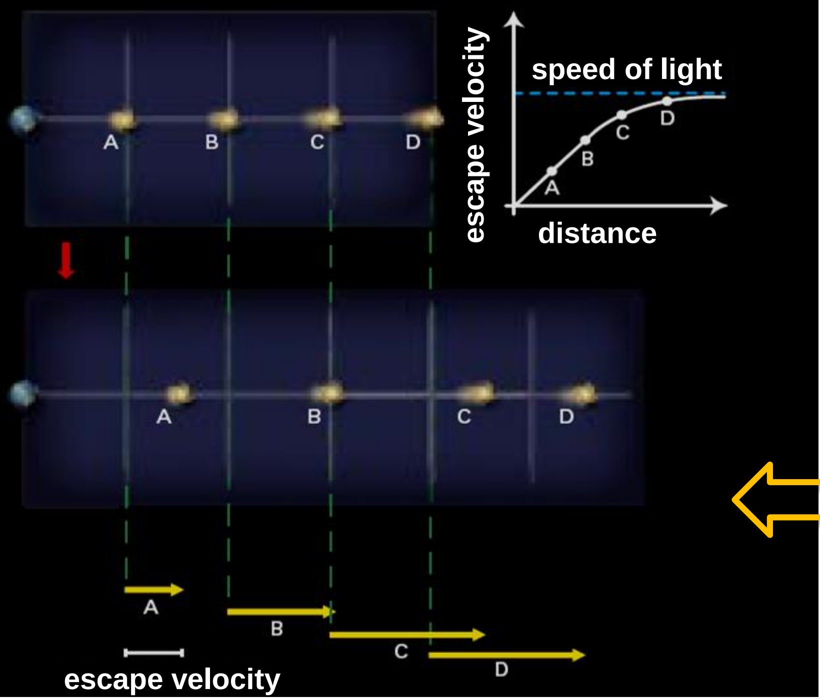
- **Escape velocity**
  has no formal limit

  - but: no transmission of information with $v > c$ due to the cosmolog. expansion

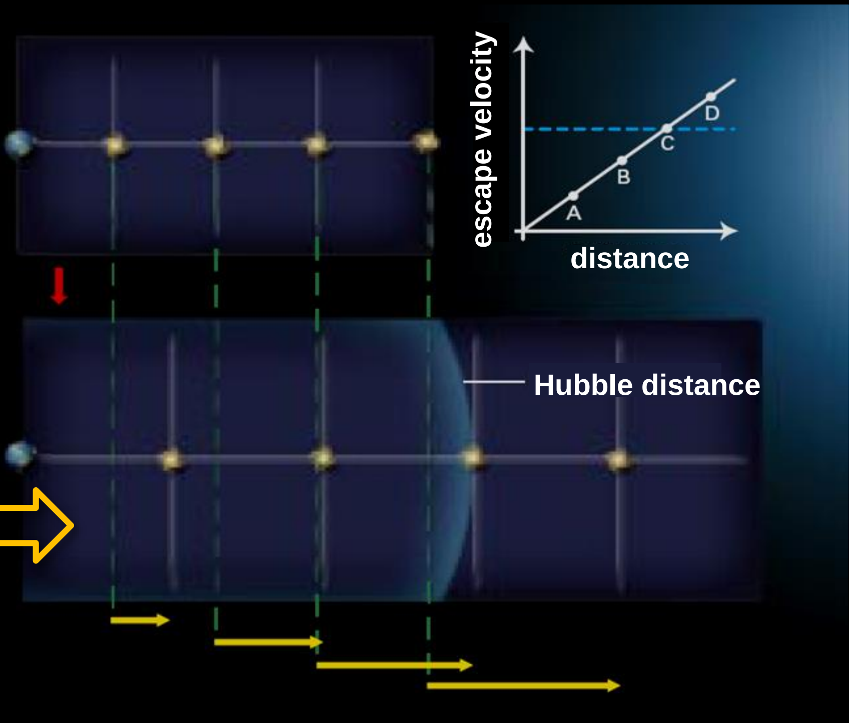


Q: spektrum

wrong scenario: galaxies moving through empty space with v < c (special relativity), thus v = c is approached asymptotically



correct scenario: space & time are expanding (with galaxies at rest), thus ´escape velicity´ will reach v > c at so-called Hubble distance



Big Bang: Light from galaxies with v > c ?

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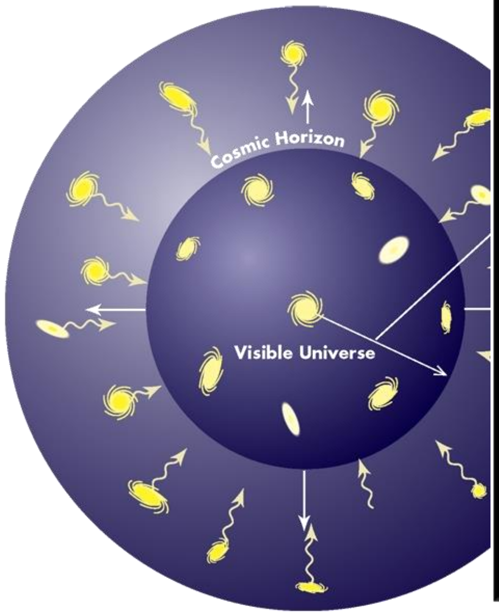
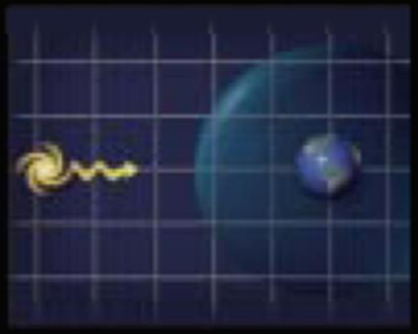
- **Hubble-radius**

- cosmological horizon changes over time

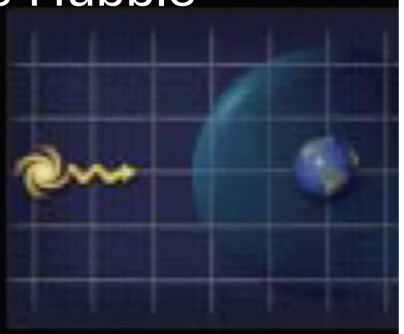


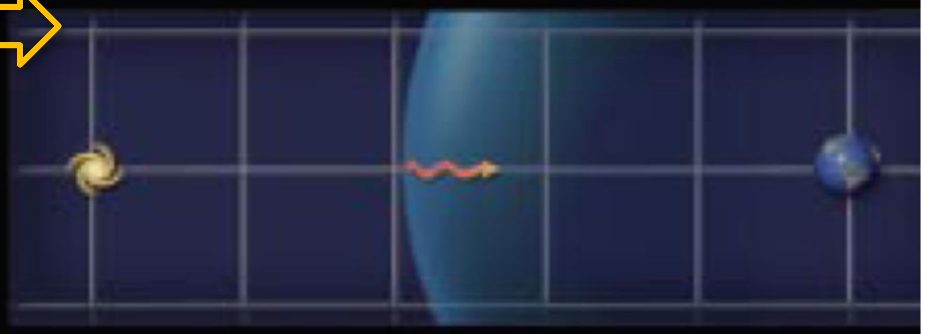
Q: spektrum

wrong scenario: light from all galaxies beyond the Hubble-scale will never reach us, as their distance relative to us is increasing faster than the speed of light c. We cannot obtain information from beyond the Hubble radius



correct scenario: expansion rate is changing over time. After an initial increase of distance, the photon can propagate into the Hubble sphere, so it can eventually reach the Earth to be detected, giving info on space beyond the Hubble radius





Big Bang: size of the observable Universe

Karlsruhe Institute of Technology

- **Space itself is expanding**

- to calculate the present size of the universe requires detailed knowledge of its expansion history

- **scale parameter** $a_0(t_0) \equiv 1$ for today ($t = t_0$)

wrong scenario:
as the age of the universe is 14 billion years, its size is 14 billion ly. The farthest galaxy is 14 billion ly away thus a photon from it reaches us just now.

$r \cong 14 \times 10^9\ ly$

$r \cong 14 \times 10^9\ pc$

correct scenario:
the universe itself expands & is larger than 14 billion ly. A photon travels through the expanding space, thus the distance from where it did emerge is now ~ 3 × the light path.

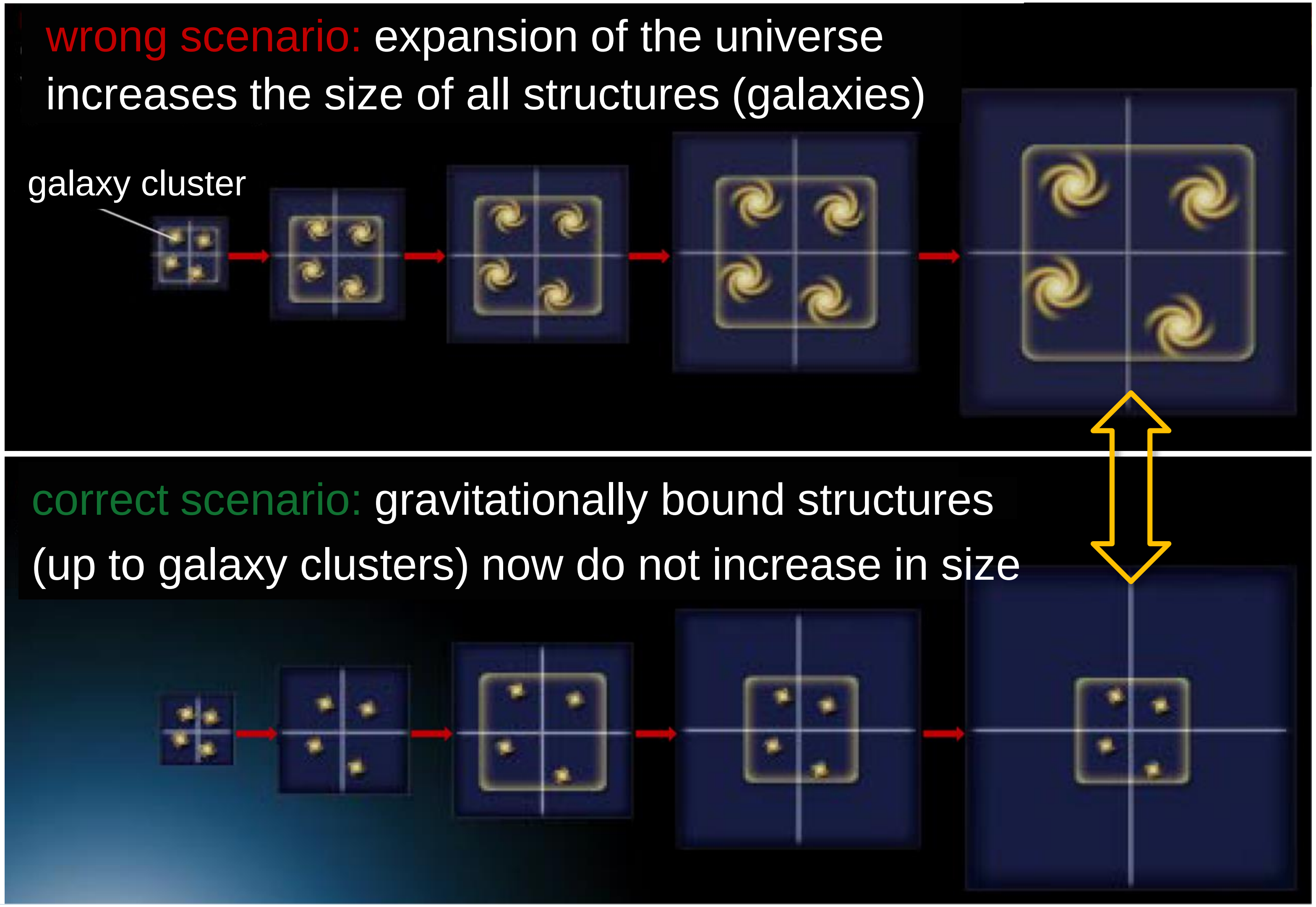
Big Bang: regions participating in expansion

- **Hubble expansion**

  - only gravitationally non-bound objects (superclusters, voids) participate in the general cosmological expansion

  - galaxy groups, -clusters, stars, atoms: stable in size over time

  - wavelength λ of a (CMB) photons increases



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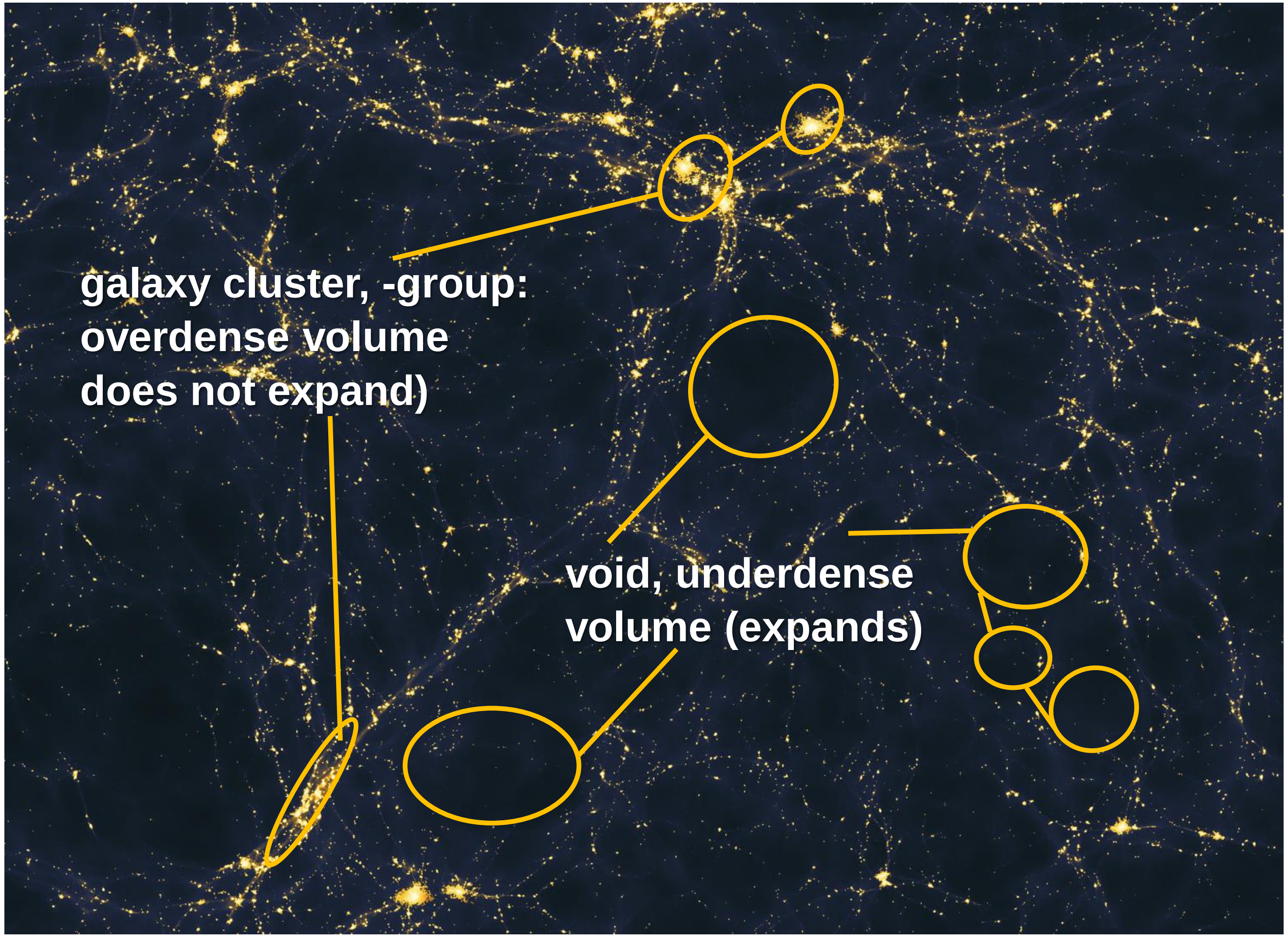
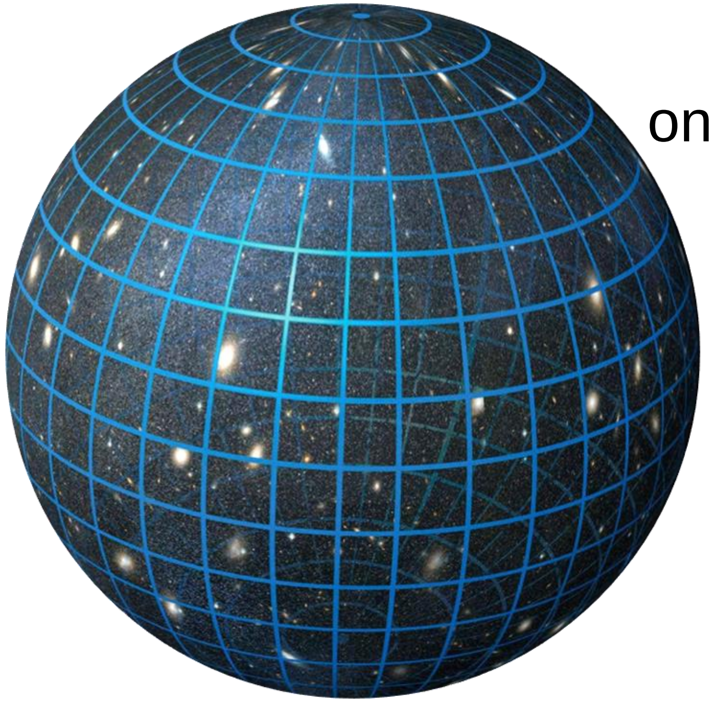


Big Bang: Hubble parameter $H(t)$

- **Hubble xpansion rate $H(t)$ of the universe is variable**

who steps on the **brake**?

gravitation



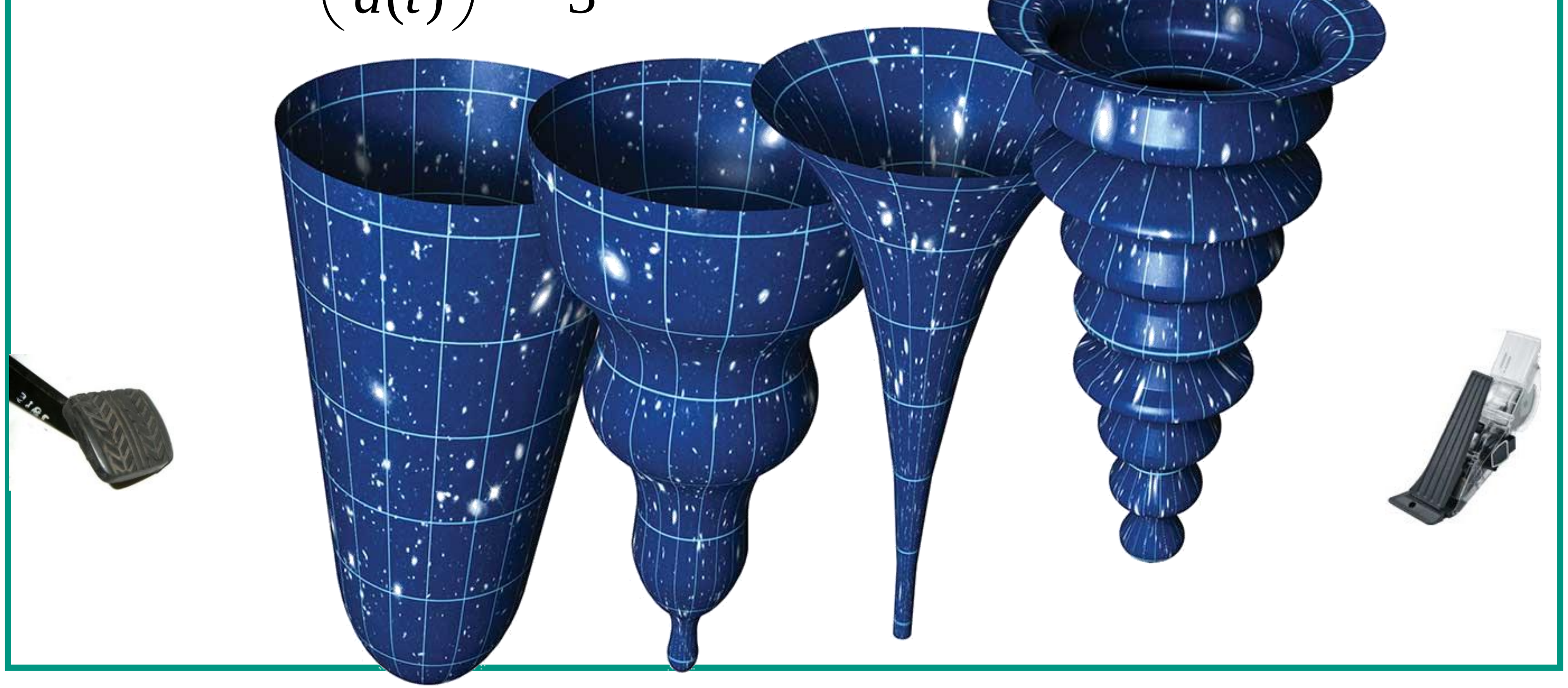
who steps on the **gas pedal**?

anti-gravitation

Big Bang: Hubble parameter $H(t)$

- **expansion rate $H(t)$ of the universe: Friedman-Lemaître equation**

$$H^2(t) = \left(\frac{\dot{a}(t)}{a(t)}\right)^2 = \frac{8}{3}\pi G \rho_{m,r,V}(t)$$



Aleksandr **Friedmann** (1888 – 1925)

Georges **Lemaître** (1894 – 1966)