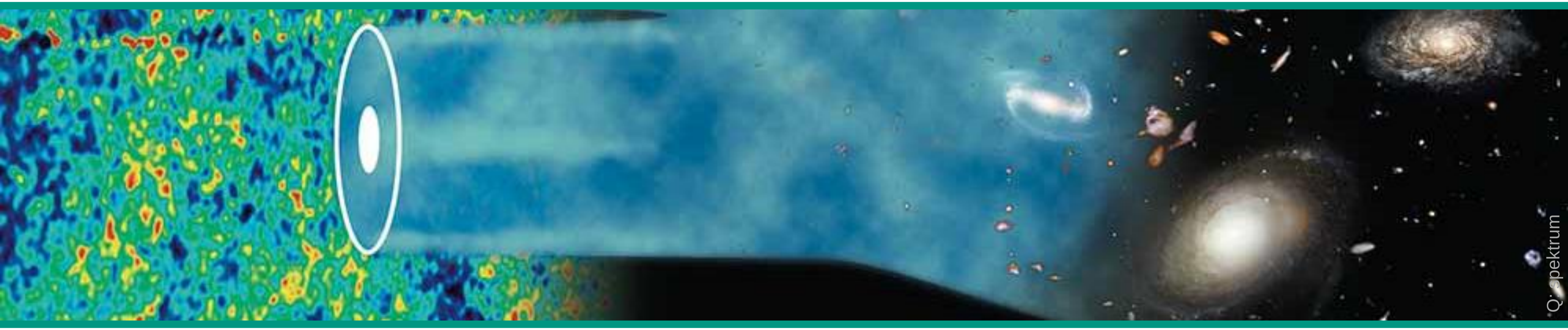
Karlsruhe Institute of Technology

Introduction to Cosmology

Winter term 23/24 Lecture 2 Oct. 31, 2023



Recap of Lecture 1

- **Cosmological distances: measurements based on three ´standard candles´**

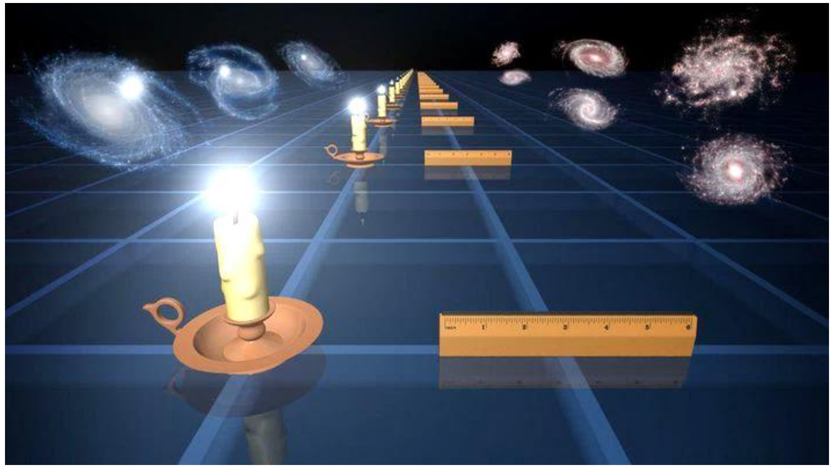
  - **distance modulus $m - M$**

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

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

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

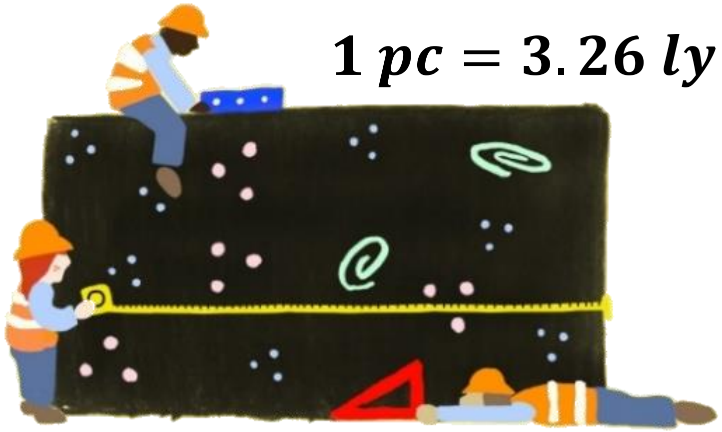
    1. parallax method (up to $3 \ldots 4\ kpc$)
    2. pulsation of δ – Cepheids (up to ~ $50\ Mpc$)
    3. supernovae $Type\ Ia$ (up to ~ $3\ Gpc$)

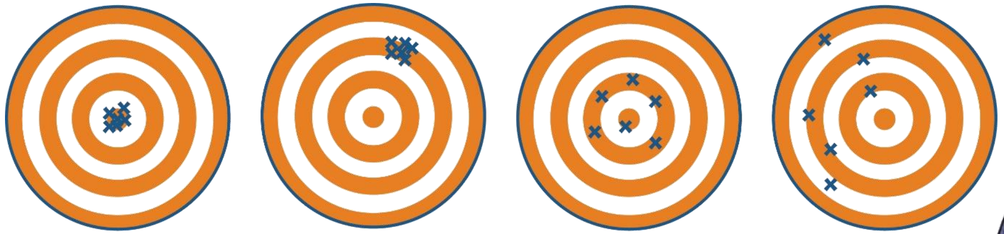


cosmological standard candles

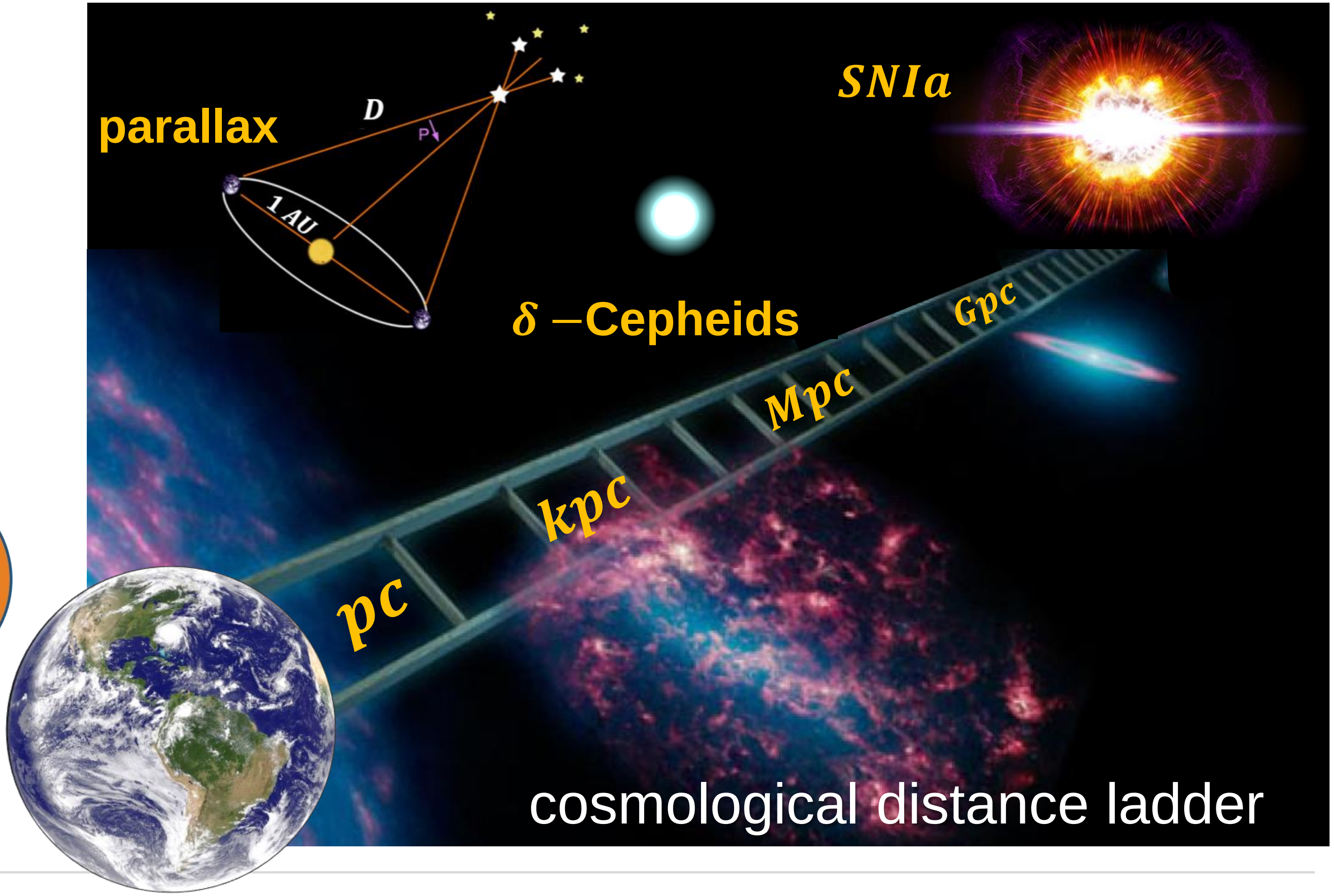
Systematic effects in cosmology

- **Cosmological distance measurements** & **systematic effects**





recurring keywords in cosmology:
accuracy & precision



Supernovae – cosmological standard candles

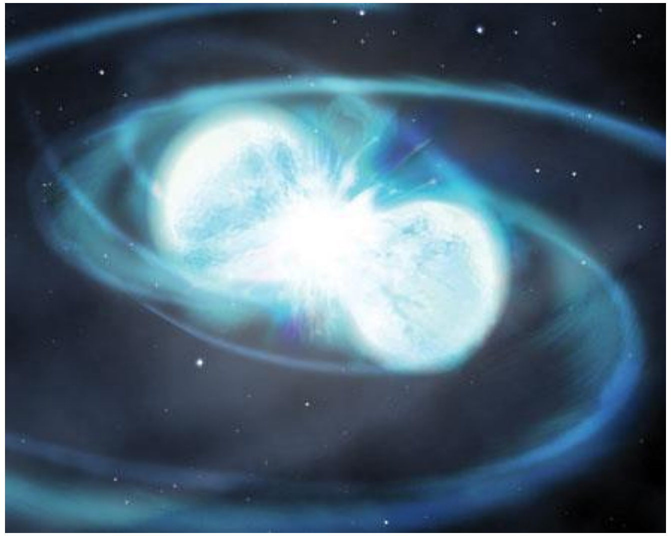
Karlsruhe Institute of Technology

- $SN\ Ia$: **thermonuclear detonation of a** WD*
  - White Dwarf reaches a mass of $M = 1.4\ M_\odot$
  - maximum brightness light curve: $M = -19.6\ mag$

measurement of a SN light curve requires weeks

are $SNIae$ true standard candles?

Q: Nature



1: merger scenario

Q: NASA

2: accretion scenario

*WD = White Dwarf, see $ATP - 2$ (summer term 24)

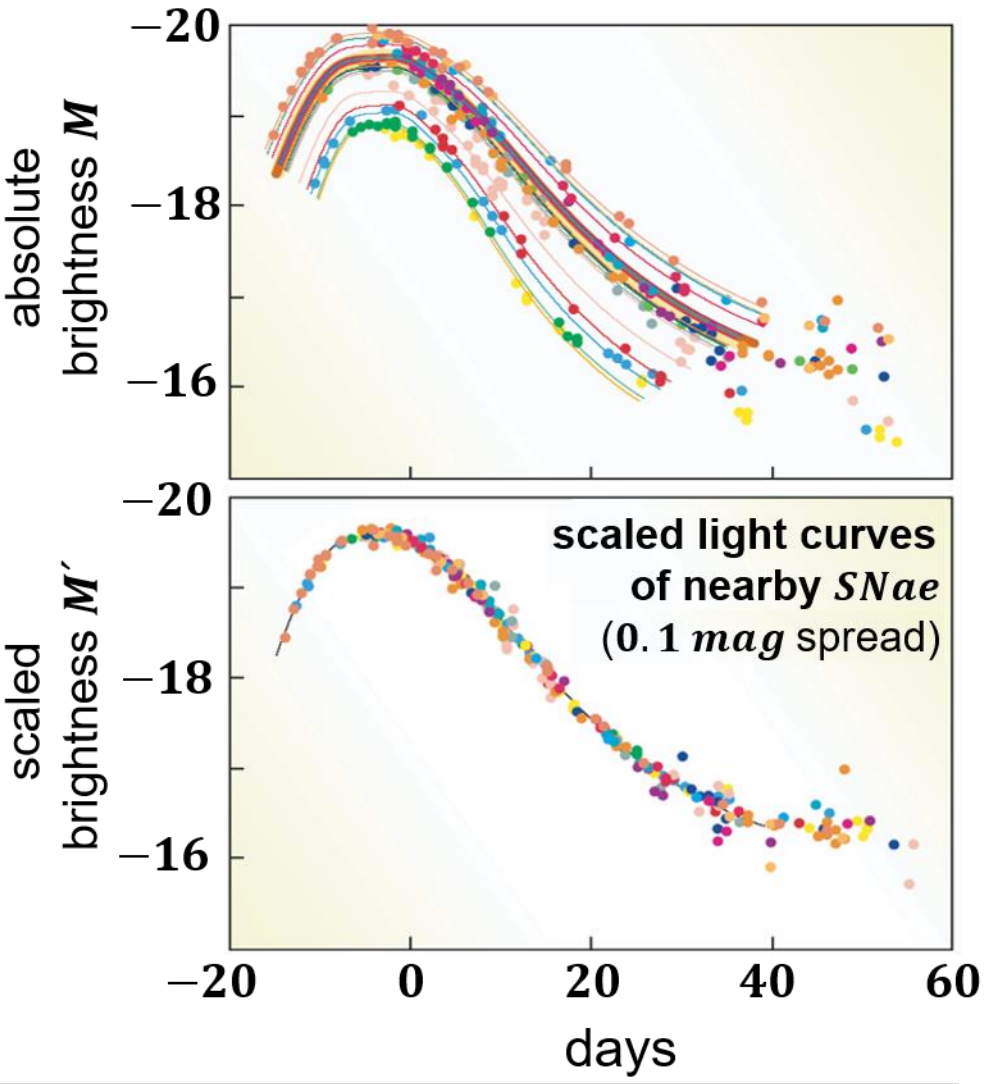
Supernovae – cosmological standard candles

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

  - empirical **Philips relation** (scaling):
    peak brightnesses of $SNIae$ are **re–scaled**,
    depending on the time scale of brightening
    & 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 at $D = few\ Gpc$ crucial for our understanding of **accelerated expansion** of the universe (& of **dark energy**)



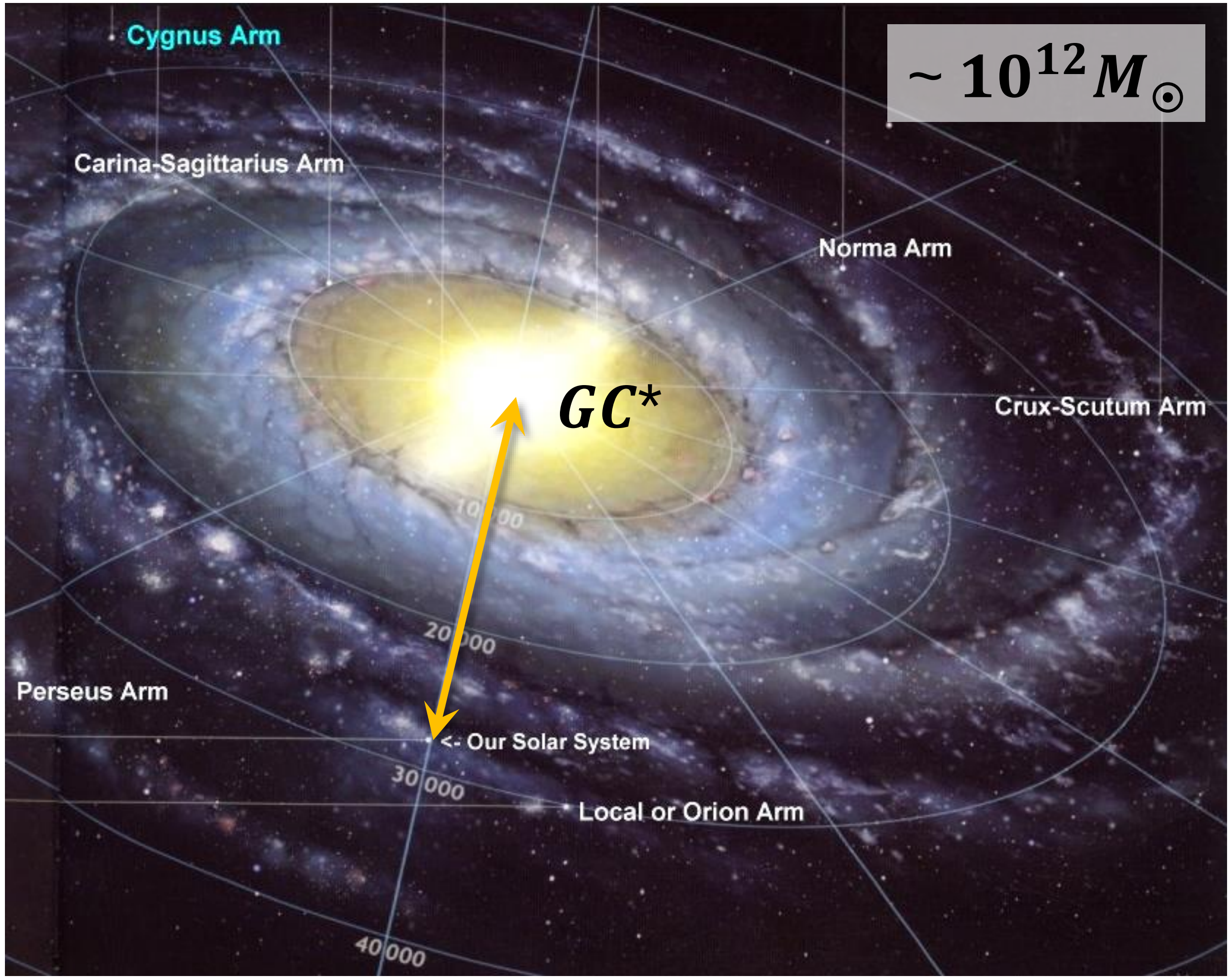
Length scales – visible matter in galaxies

- **size of a typical spiral galaxy:**
  $\varnothing = 35\ kpc$

  - distance **Sun** – GC: $D = 7.8\ kpc$

  - this length scale is important for the ´**Dark Universe**´ & also to calculate the local DM – density

    ⇨ structures on the scale of a **few tens of** kpc must not be ´**washed out**´ during evolution of large–scale structures in the universe (⇨ ´**Cold**´ Dark Matter)



 ***G**alactic **C**entre

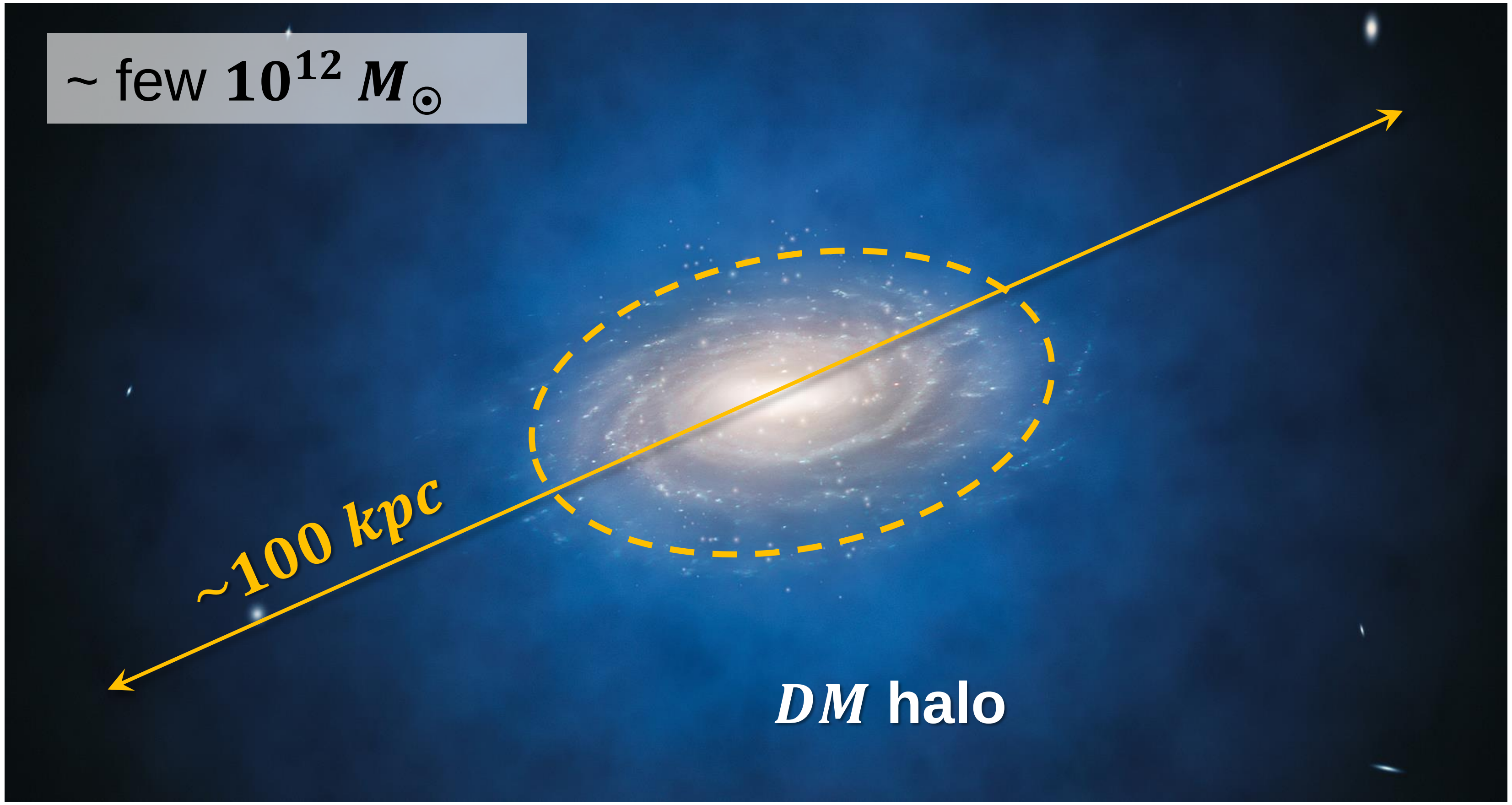
Length scales – Dark Matter in galaxies

- **size of a typical DM – halo around a spiral galaxy: $\varnothing = 100\ kpc$**

- DM – **halo** extends well beyond the visible scale of the central galaxy that it is embedded into

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

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



Length scales – our local group

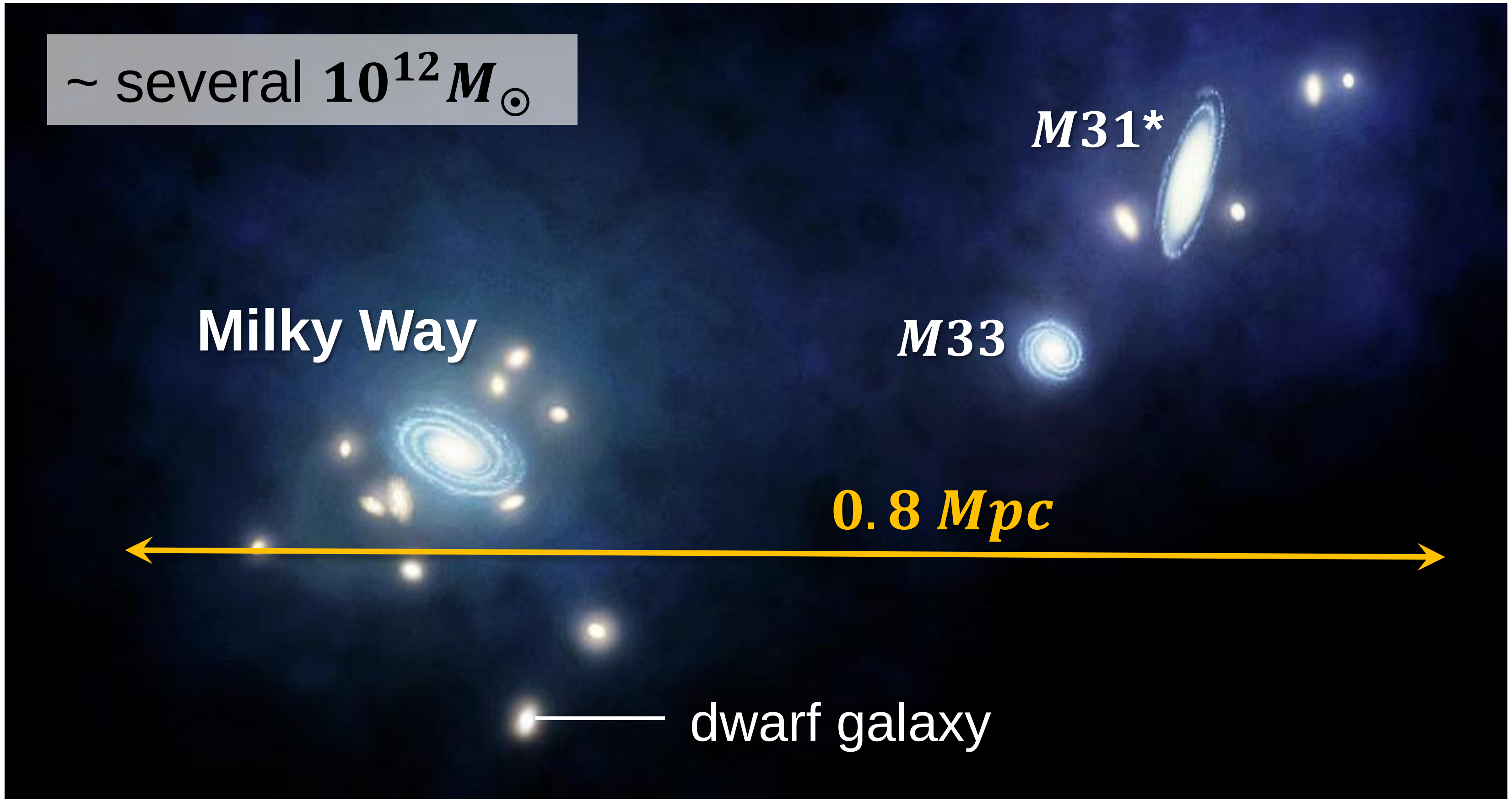
- **size of a typical (small) group of galaxies: $\varnothing = 800\ kpc\ \ (0.8\ Mpc)$**

- **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

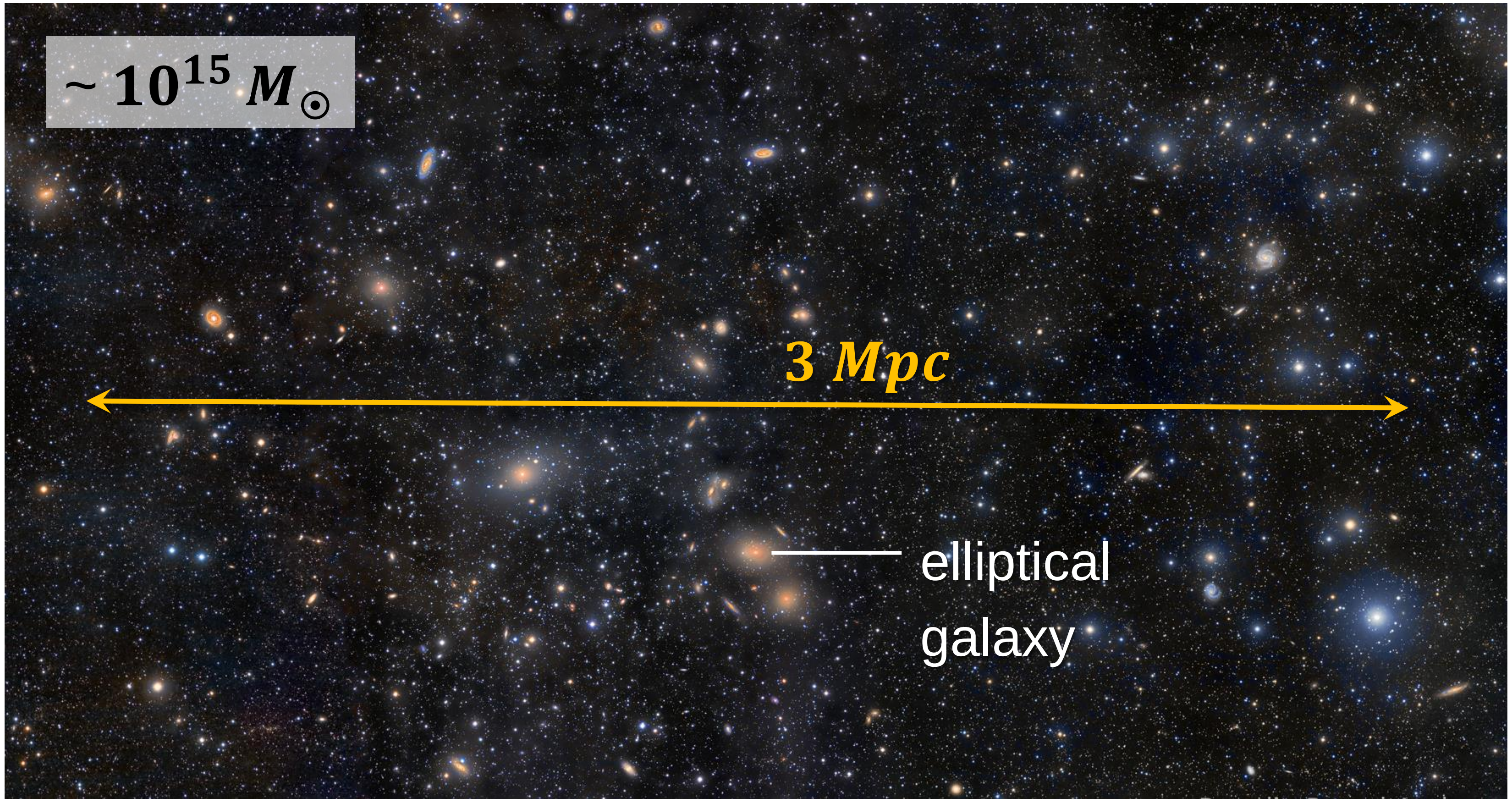
$^*M31$ = Andromeda galaxy

Length scales – our local galaxy cluster Virgo

- size of a typical galaxy cluster: $\varnothing = 2.2 \ldots 3\ Mpc$

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

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

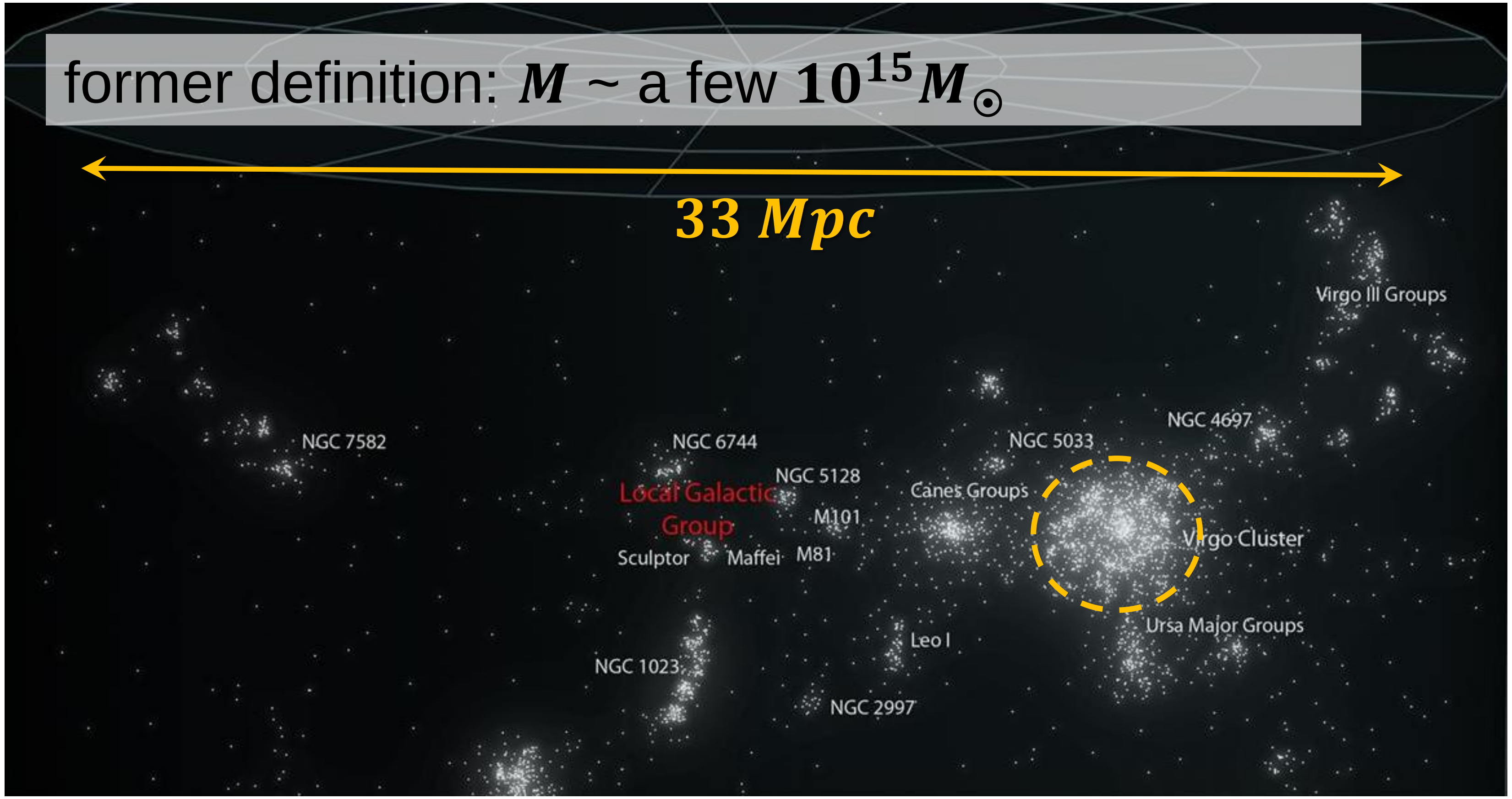


T_{kin} = kinetic energy E_{pot} = potential energy

Length scales – our local supercluster

- **next structure: galaxy super clusters**

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



Q: M. Garlick

Length scales – our local supercluster *Laniakea*

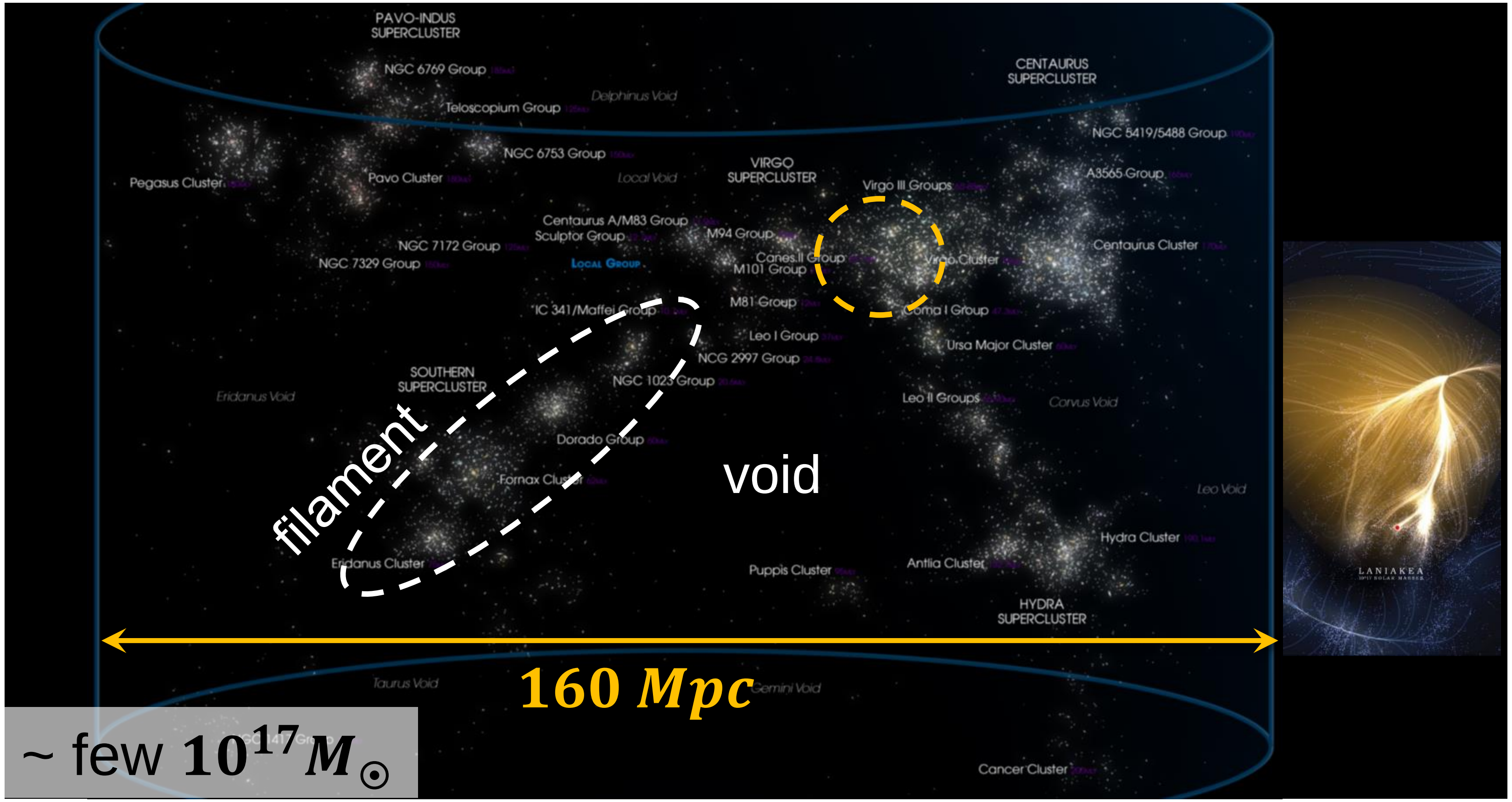
- **largest observed structures: supercluster of galaxies with $\varnothing \sim 160\ Mpc$**

  - gravitat. not **bound**

  - $\sim \mathbf{100\,000}$ galaxies

  - $\mathbf{2014}$: definition based on **relative velocities** of galaxies / groups

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



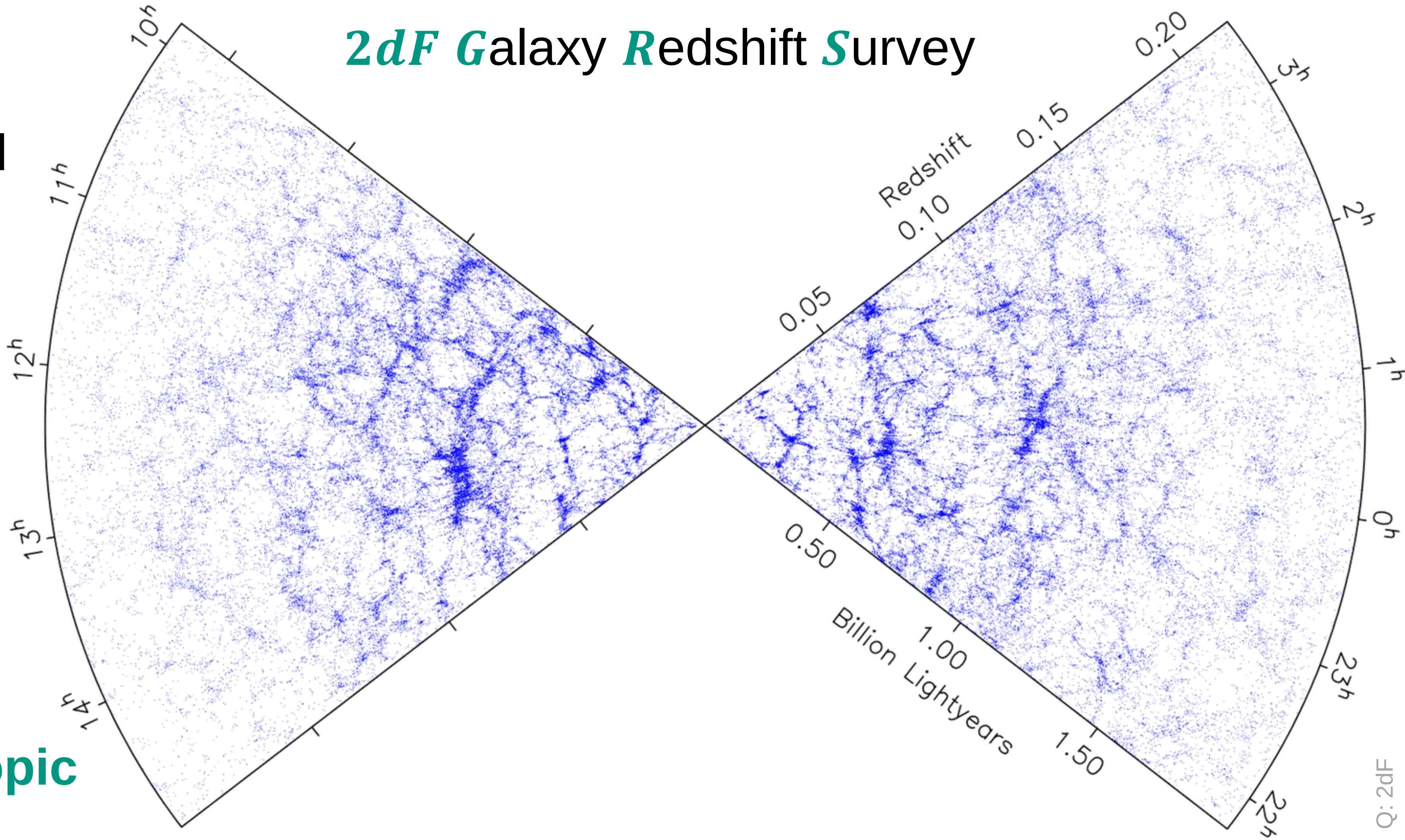
$\sim$ few $\mathbf{10^{17}}\,\boldsymbol{M_\odot}$

Q: wikipedia

Length scales – our local universe

- $2dF\ GRS$: $500\ Mpc$

2dF Galaxy Redshift Survey



- gravitationally unbound

- participates in the **cosmological expansion**

- filaments & voids

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

Q: 2dF

Length scales – entire universe (MC)

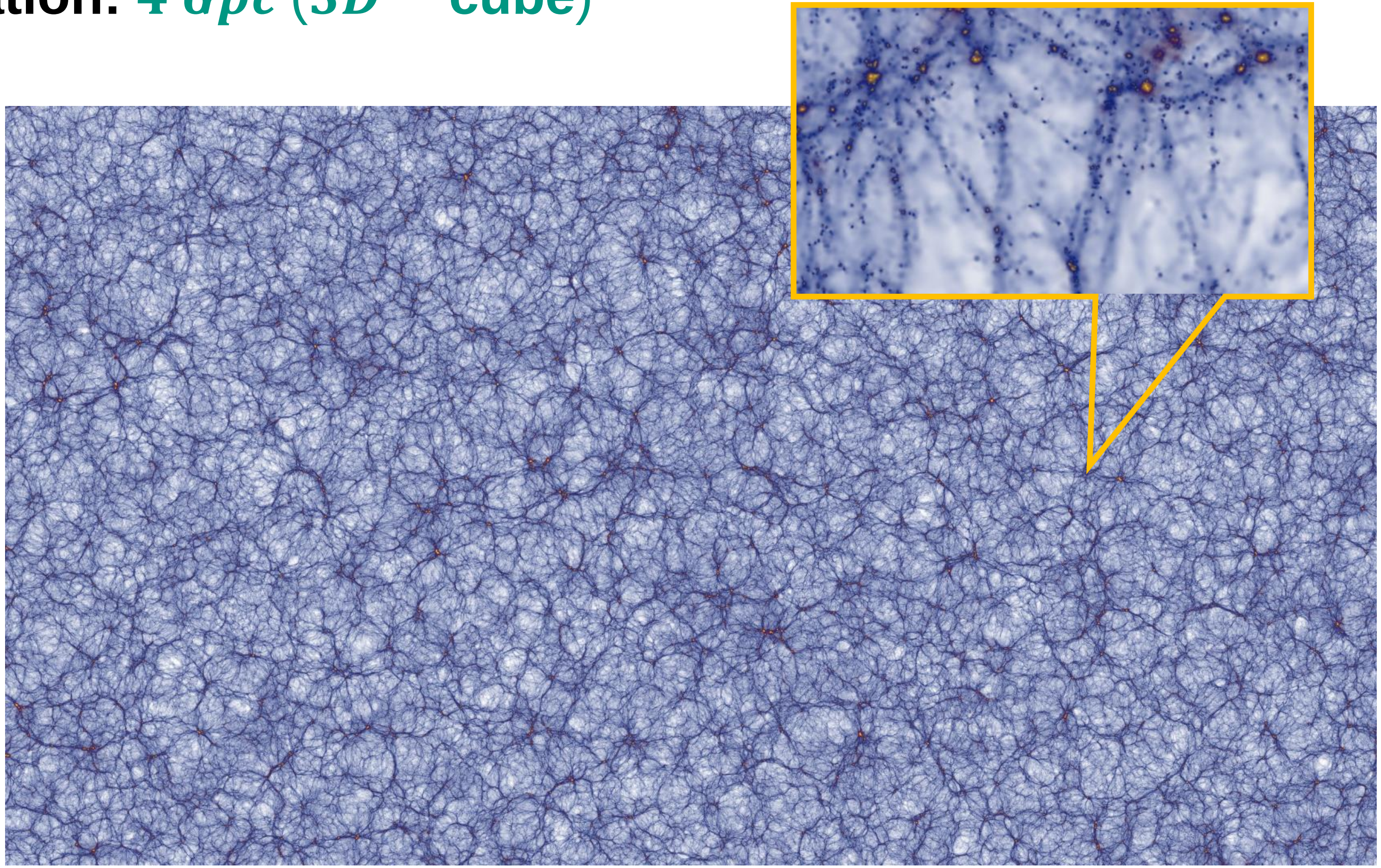
- $\boldsymbol{Millennium\ XXL}$ **simulation:** $4\ Gpc\ (3D-$ cube)

- result of cosmological
  $\boldsymbol{N}$ **–body–simulations**

- shows distribution of
  Dark Matter only

- underlying assumption:
  $\boldsymbol{\Lambda CDM}$ **model** *

- when averaging over
  large distances:
  homogenous & isotropic



Q: MPG

* $\Lambda CDM = \Lambda$ vacuum energy + CDM

Length scales – entire visible universe

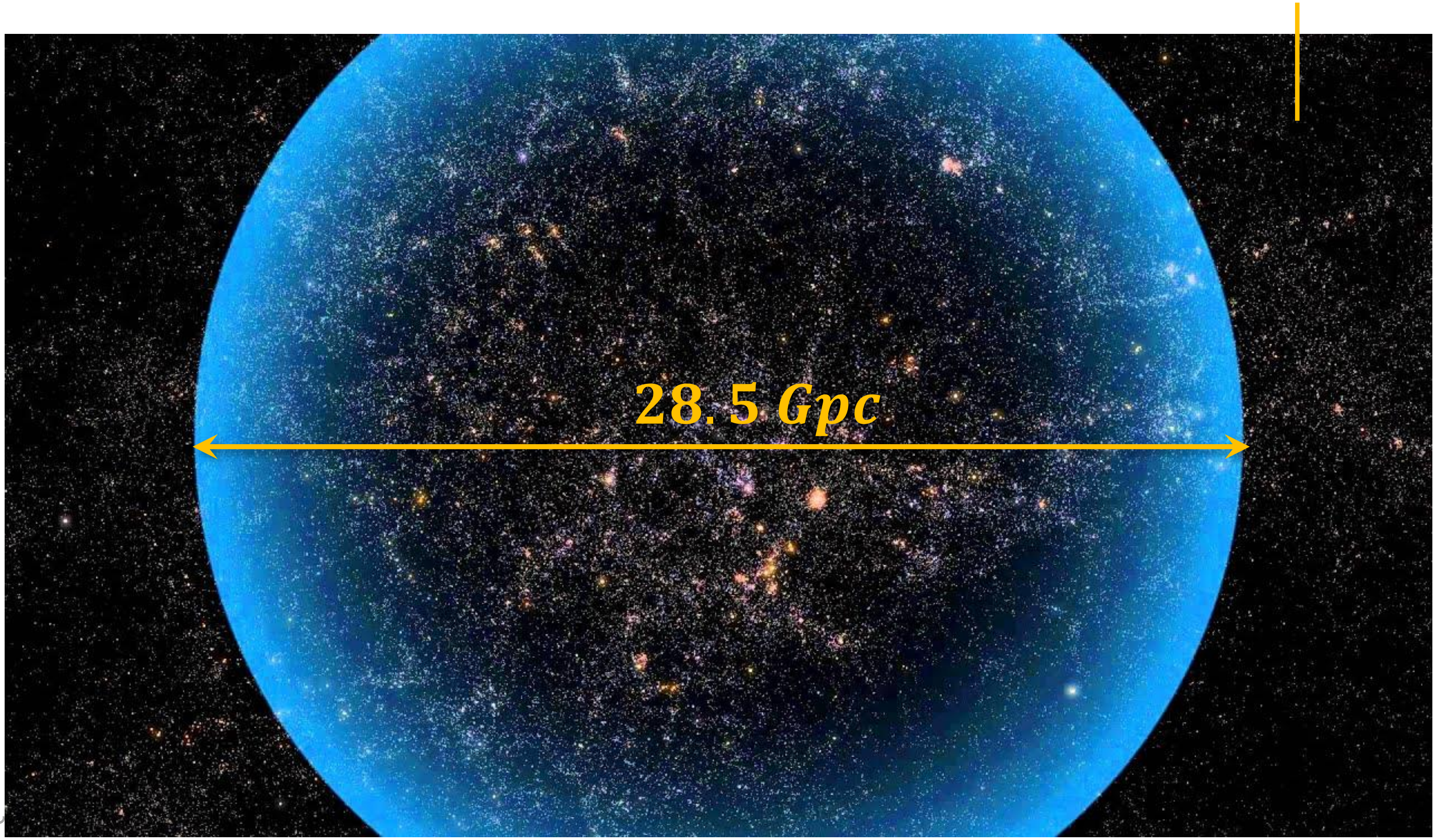
- **spherical region around Earth with $\varnothing = 28.5\ Gpc$**

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

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

  - requires more precise definition of distances $\boldsymbol{D}$ (see chapter $\mathbf{2.1}$)
    distance via light travel time, *co–moving distance* : ***redshift*** $\boldsymbol{z}$

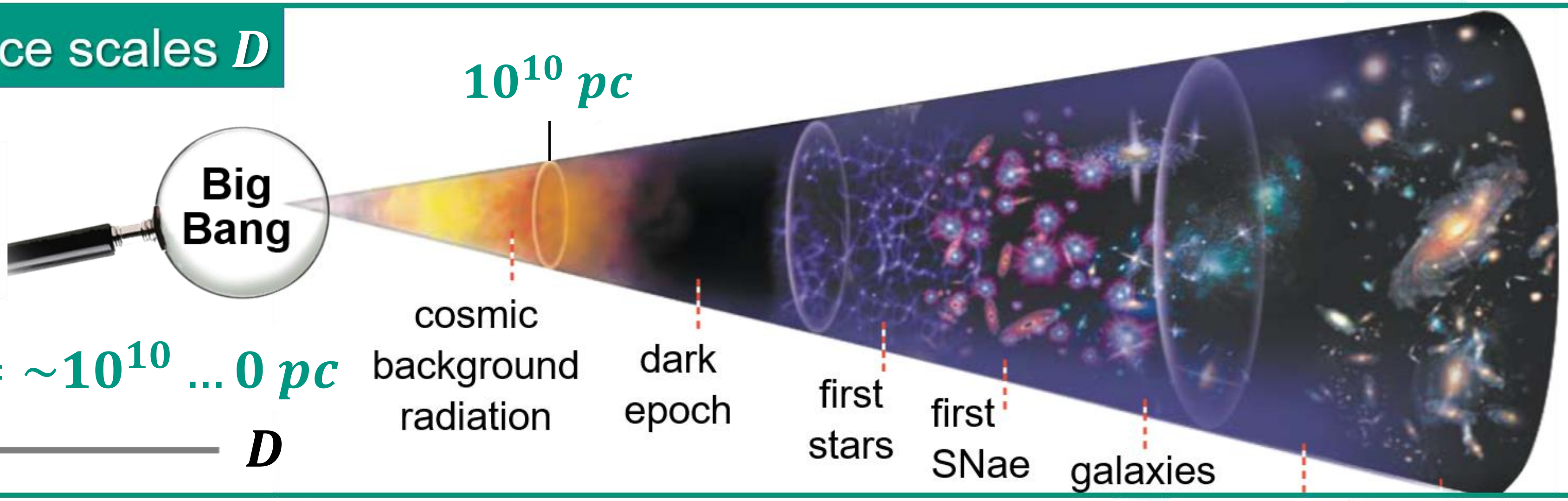
unobservable



Q: ESA

Cosmological length– & time scales: correlated

distance scales D

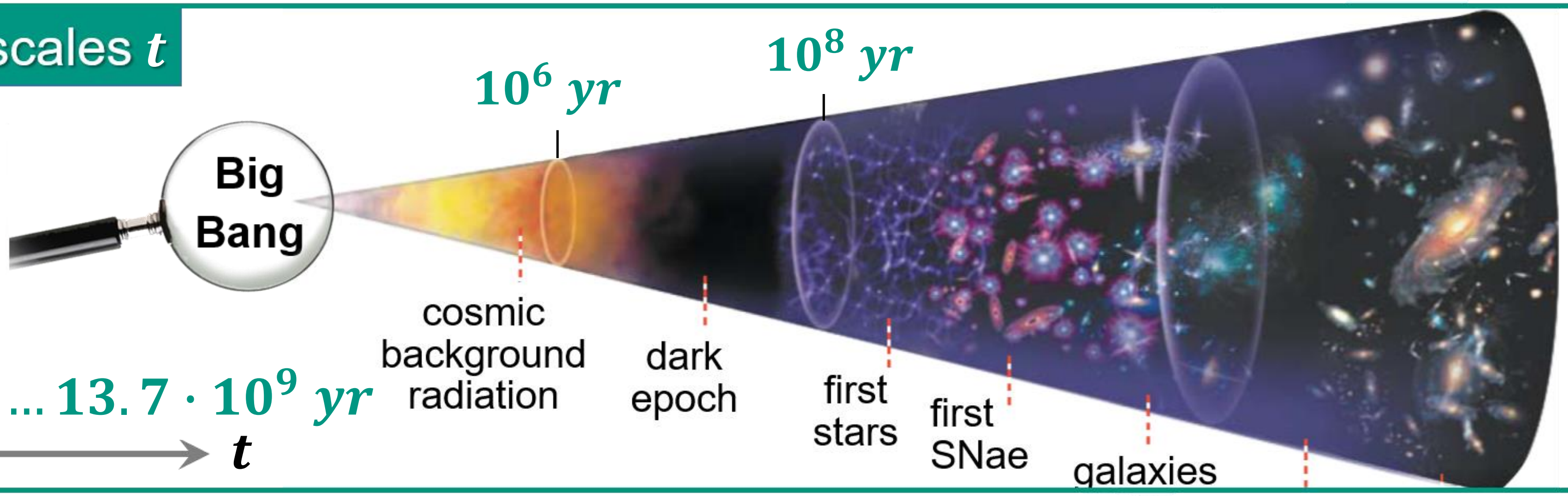


$D = \sim 10^{10} \ldots 0\ pc$

$\longleftarrow D$

here:
$D = 0\ pc$

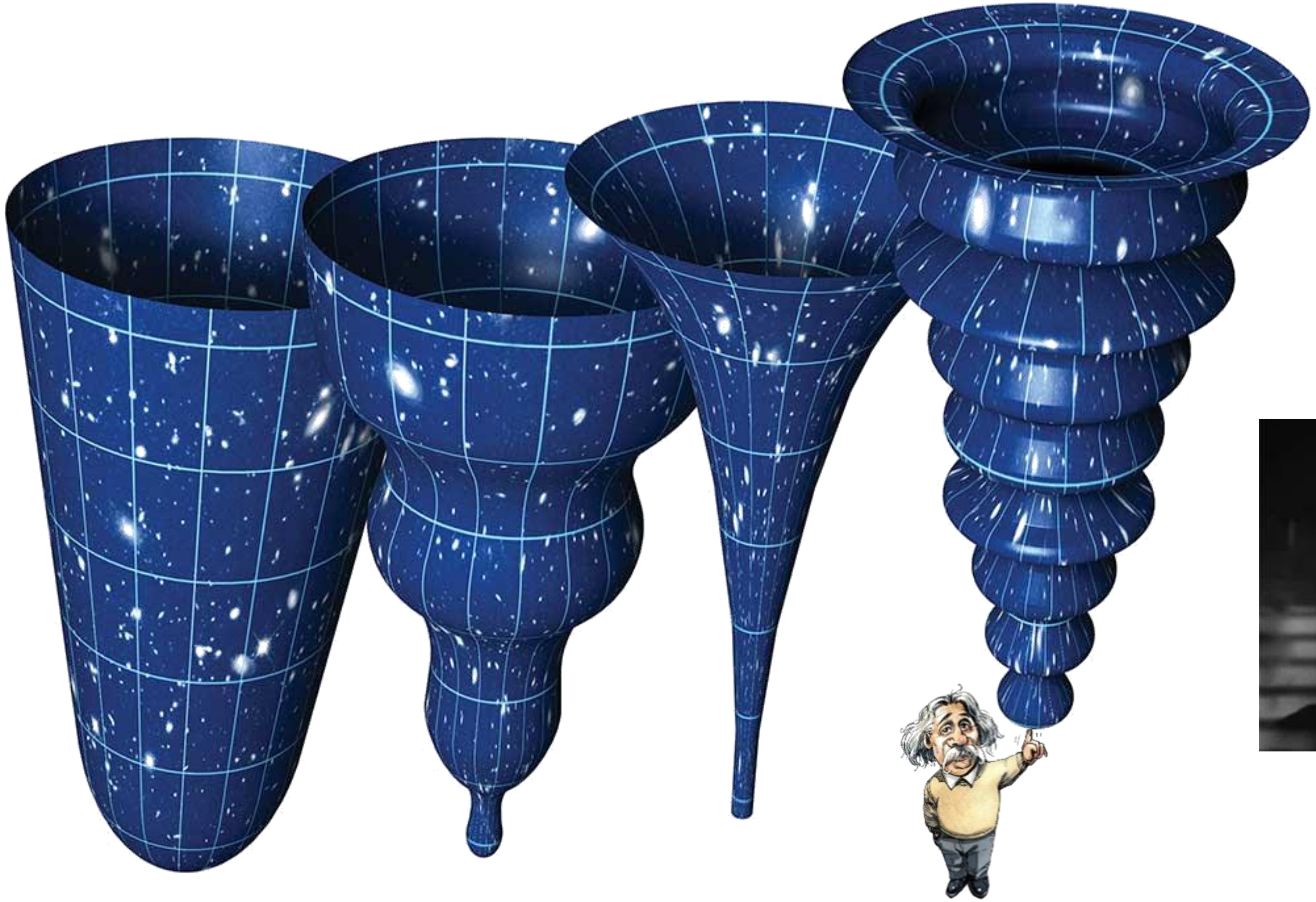
time scales t



$t = 0 \ldots 13.7 \cdot 10^{9}\ yr$

$\longrightarrow t$

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



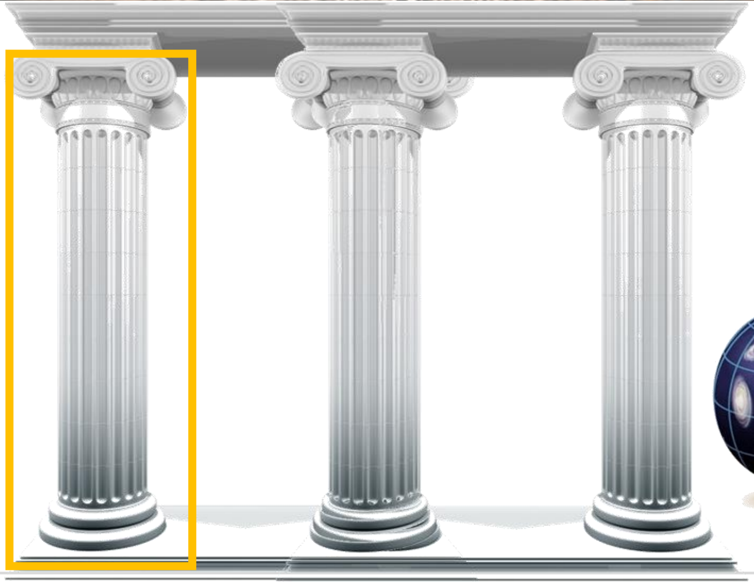
CHAPTER 2 – EXPANDING UNIVERSE

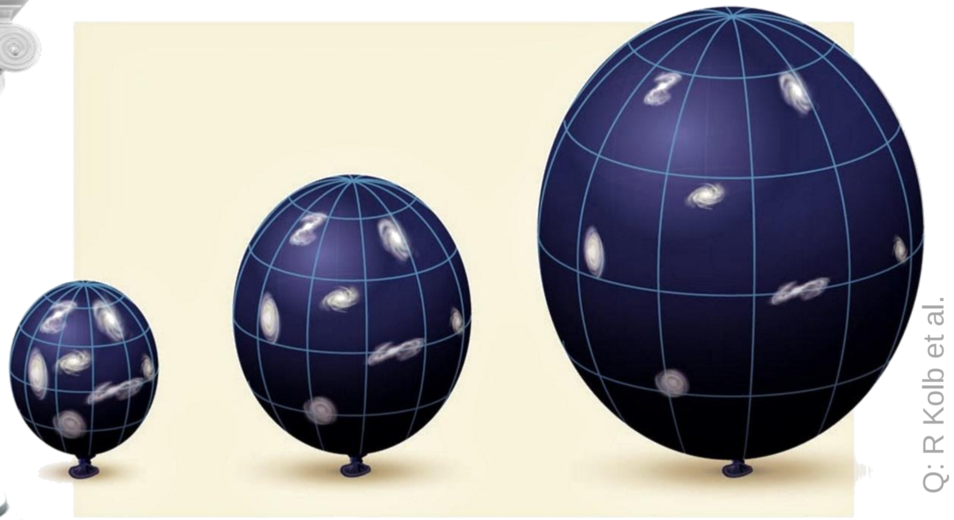
Pillars of the Big Bang: Hubble expansion

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

E. Hubble

Pillar 1:
Hubble
expansion





Q: R Kolb et al.

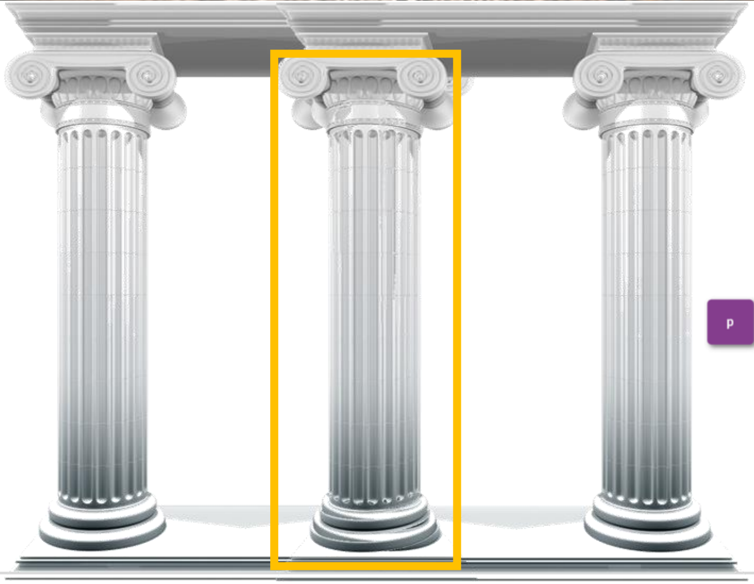
Pillars of the Big Bang: light element synthesis

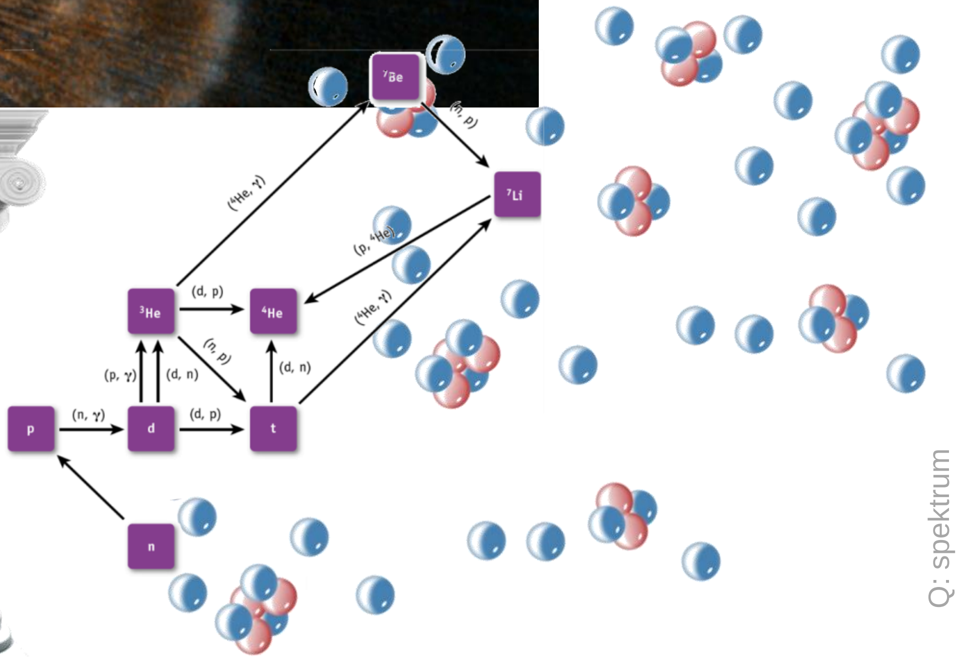
Karlsruhe Institute of Technology

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

G. Gamow

Pillar 2:
Big Bang
nucleo-
synthesis

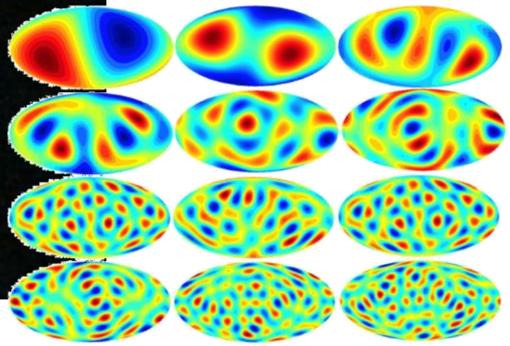


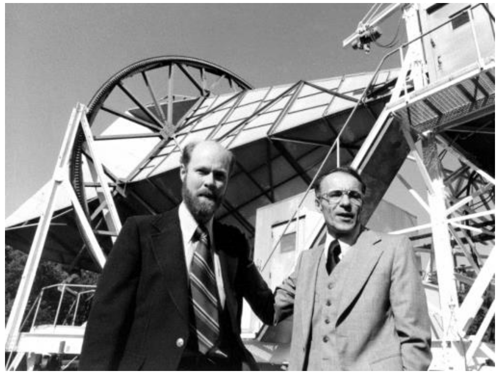


Q: spektrum

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

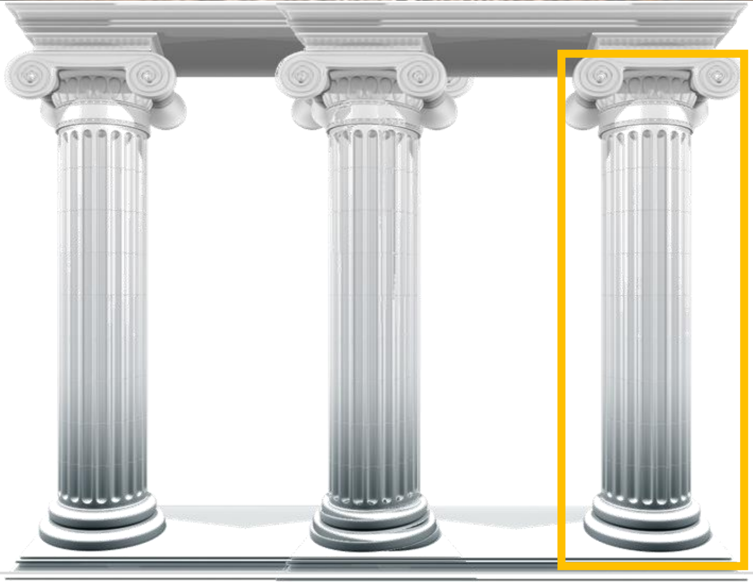
- **Key experimental evidence 3: $3K$ microwave radiation from the Big Bang**

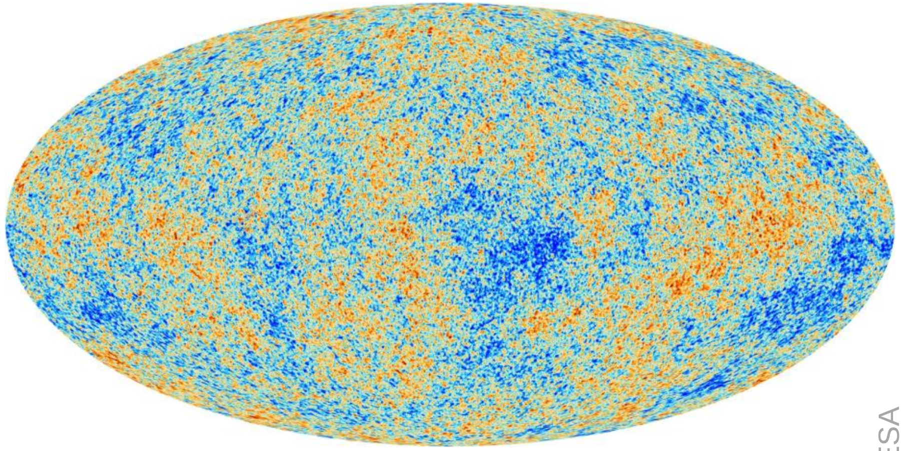




Penzias & Wilson

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



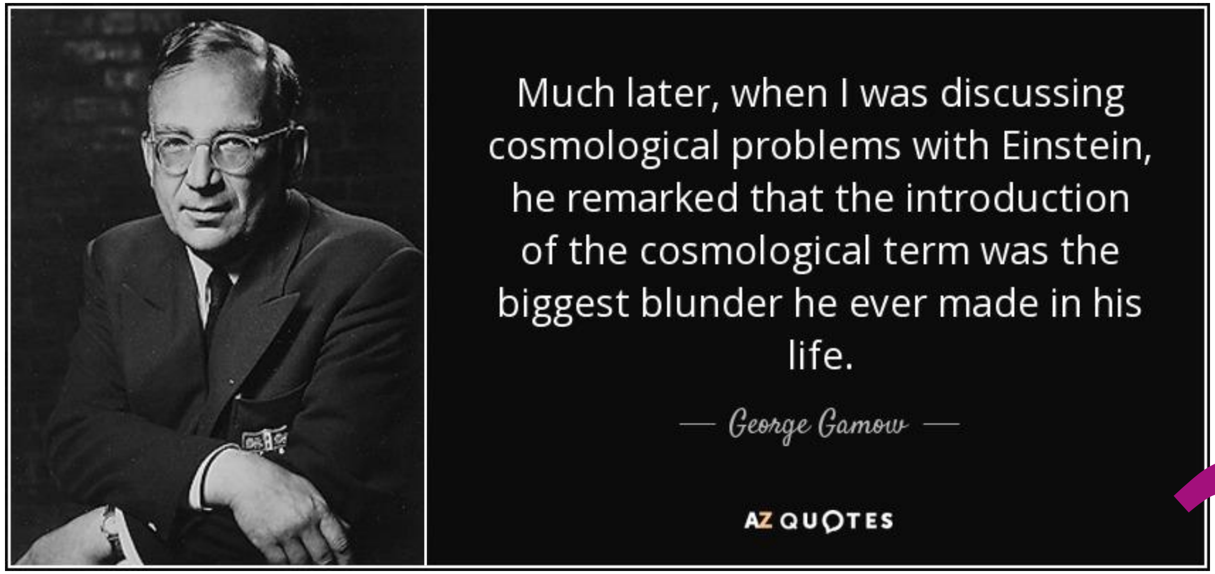


Q: ESA

2.1 *Hubble* Expansion

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

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



Q: symmetry magazine

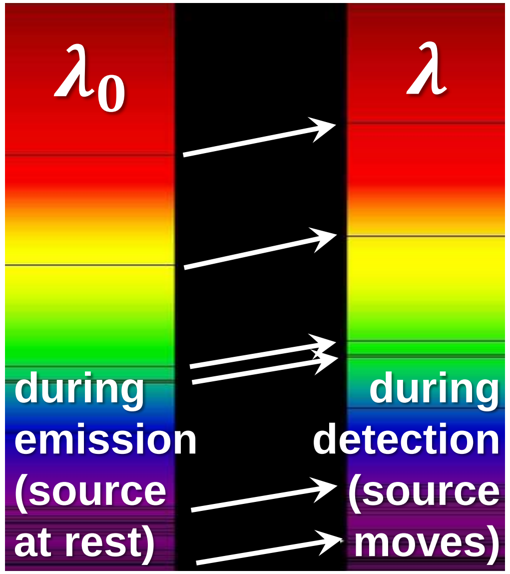
λ

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

Hubble: redshift of atomic spectral lines

- initial analogy: Doppler effect

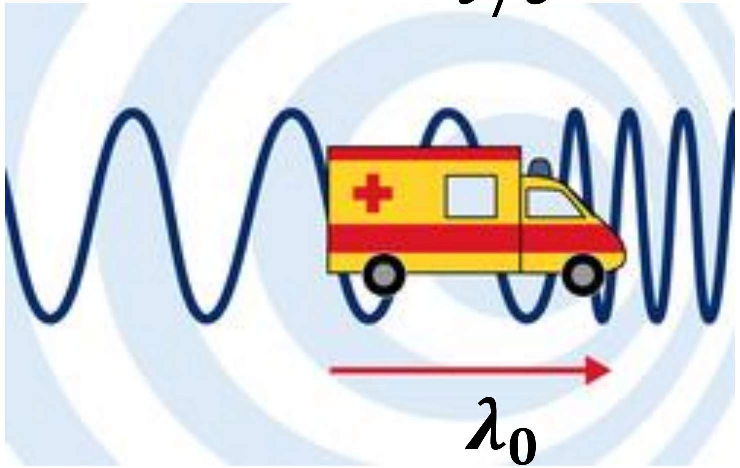
  - **moving** objects in space



$\mathbf{1929}$: observing many galaxies with the
$\mathbf{100 - \textit{inch}}$ Mount–Wilson telescope

v/c

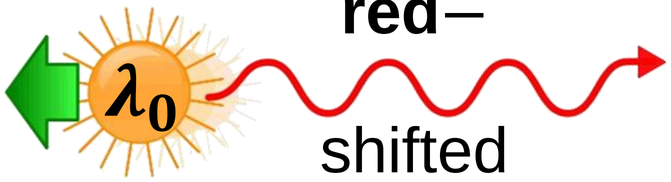
λ'



λ

λ_0

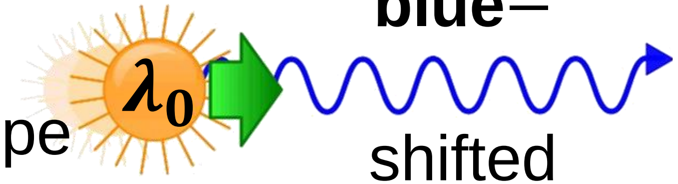
red–



λ

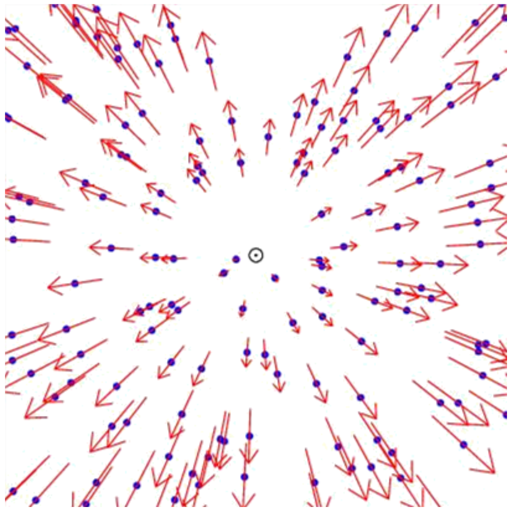
shifted

blue–



λ

shifted

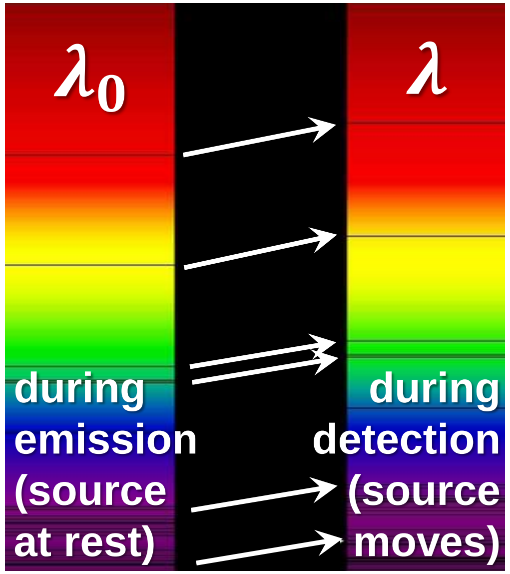


- spectra of ***all*** galaxies are **redshifted**

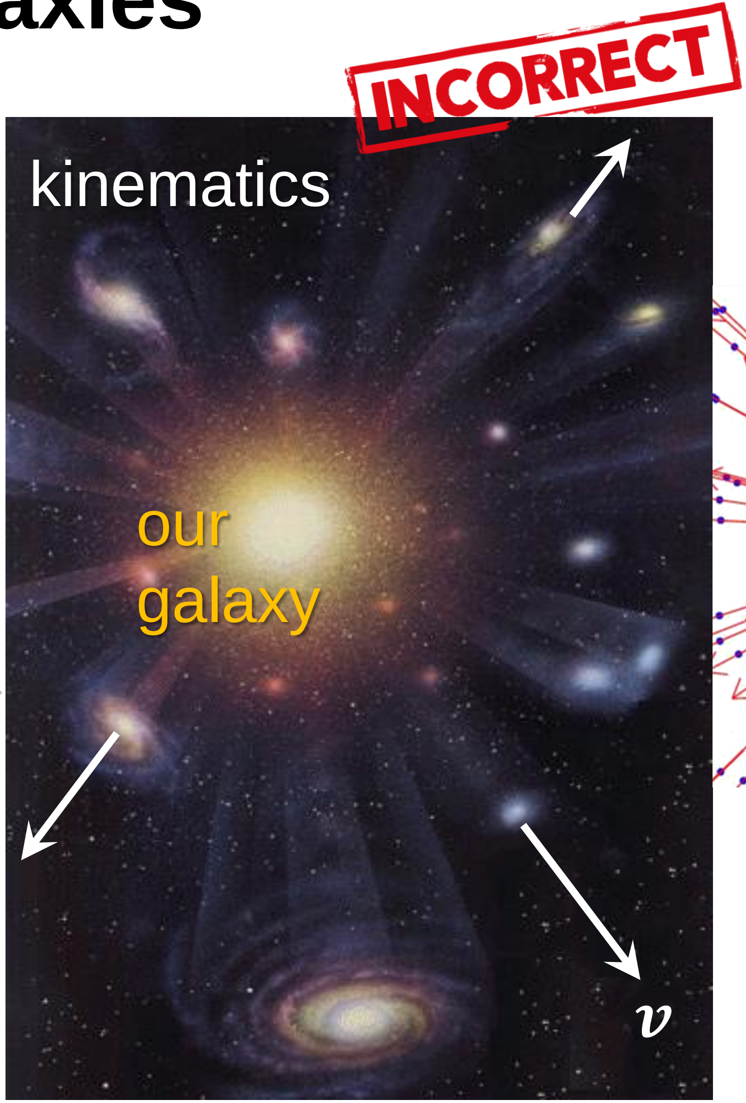
Hubble: escape velocity of galaxies

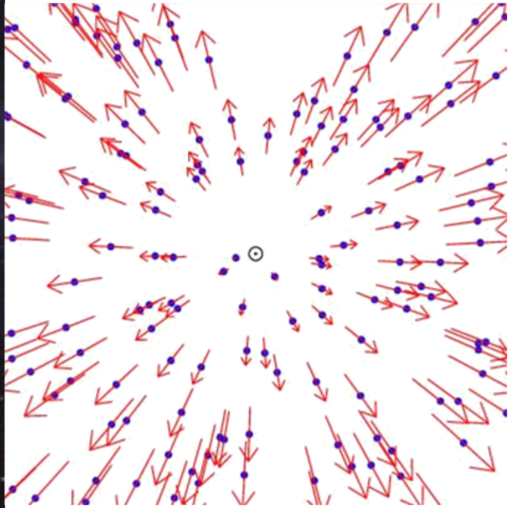
- **initial analogy: Doppler effect**

  - ´**moving** galaxies in space´



analogy





1929: observing many galaxies with the $\mathbf{100 - \mathit{inch}}$ Mount–Wilson telescope

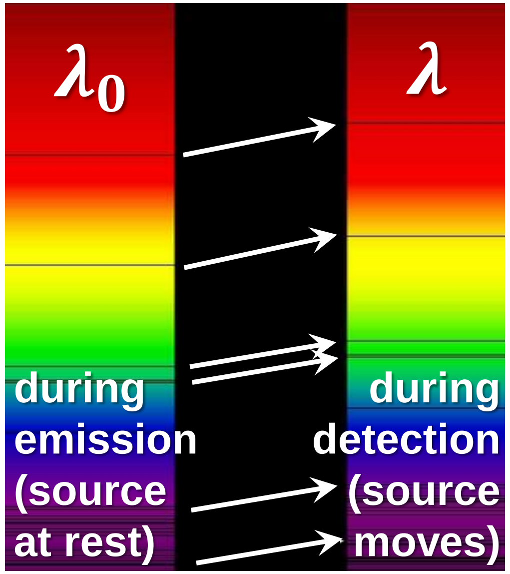
´escape velocity $\boldsymbol{v}$´

- spectra of ***all*** galaxies are **redshifted**

redshift of spectral linies: interpretation

■ cosmological redshift z : definition & early interpretation

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



λ_0 = original wavelength during emission

λ = observed (**redshifted**) wavelength

redshift z

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

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

´classical´ but **incorrect** interpretation

$$1 + z = \sqrt{(1 + v/c)/(1 - v/c)}$$

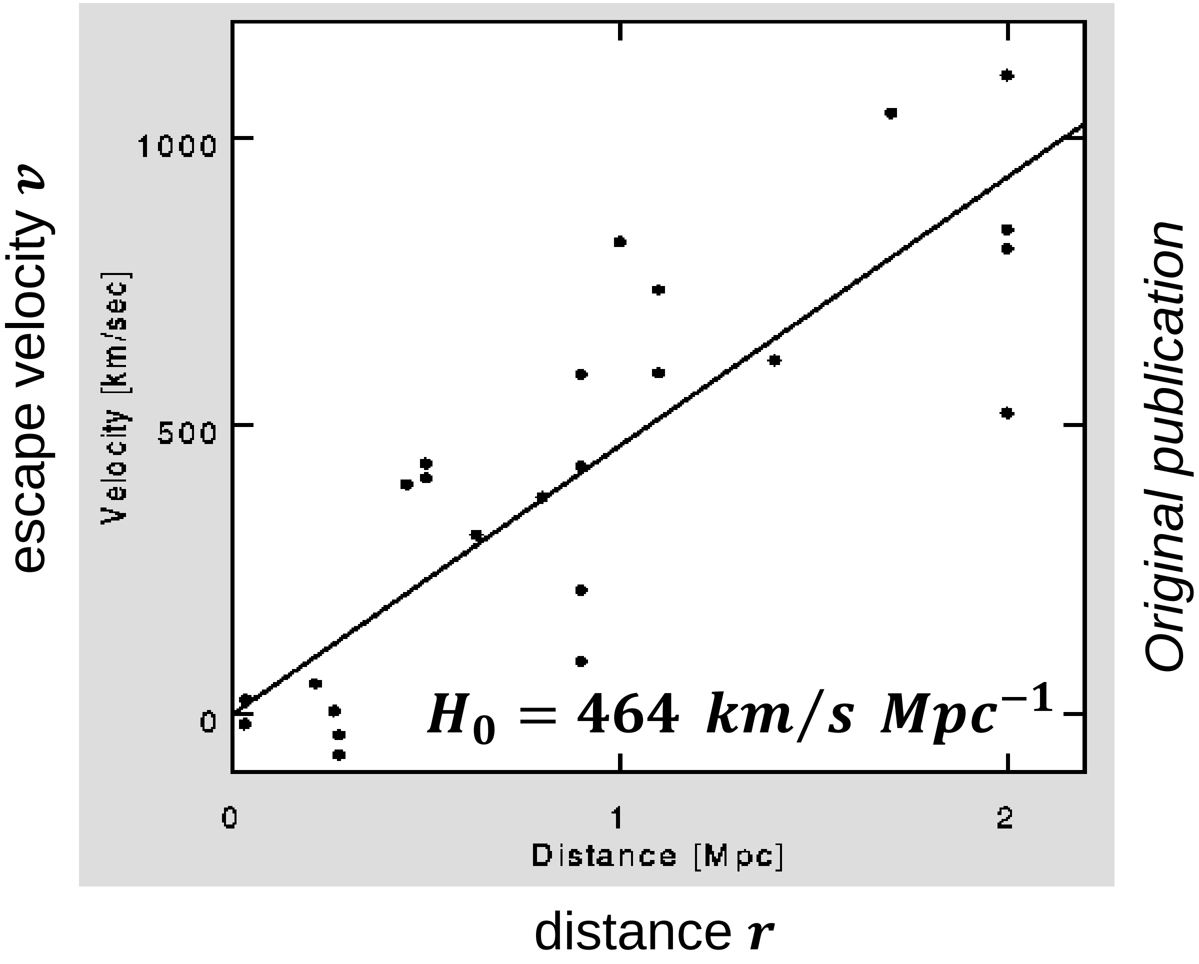
´escape velocity v´

Hubble diagram: distance vs. escape velocity

- **Hubble constant H_0 : measures current expansion rate of the universe**

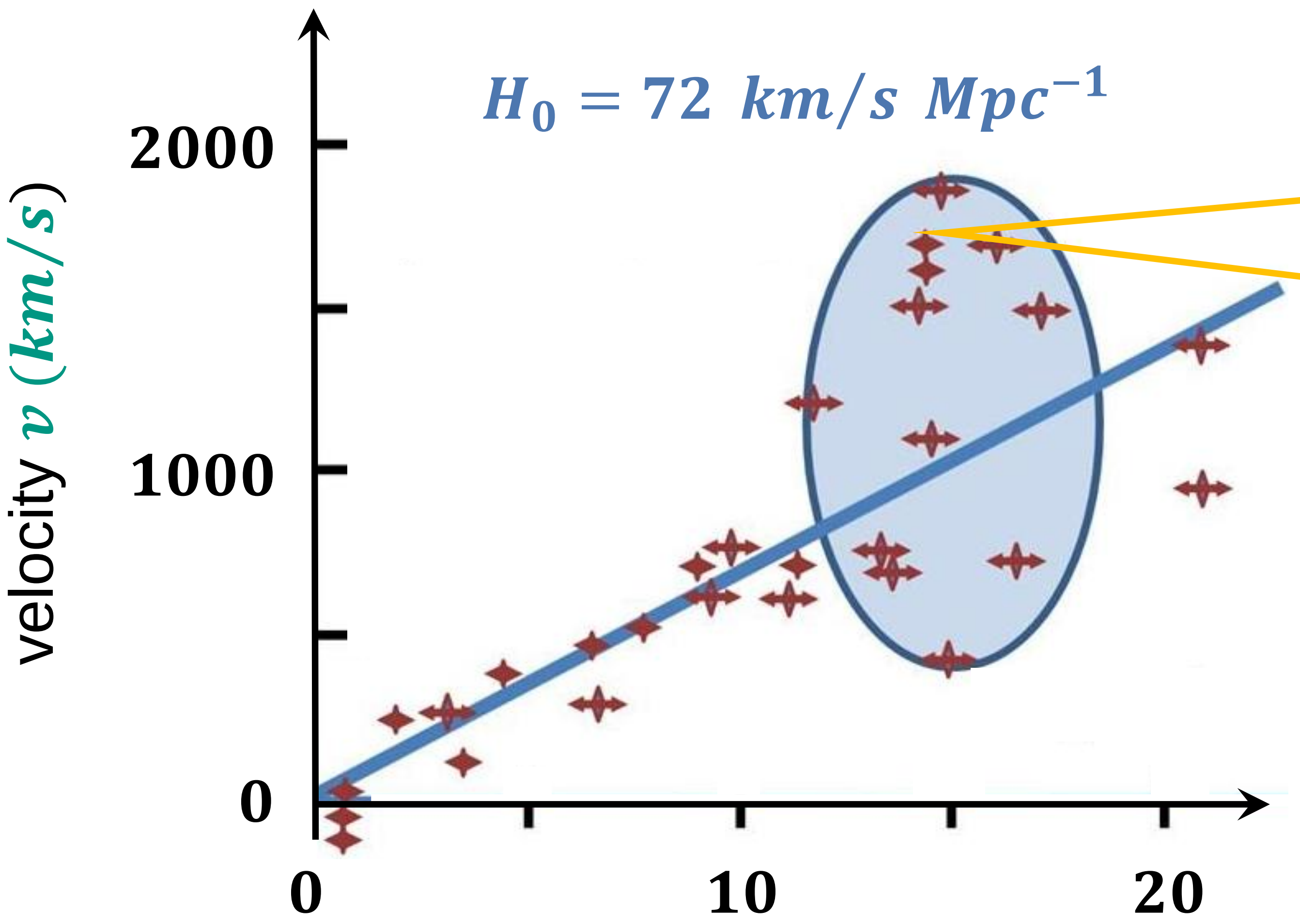
Hubble law: $\boxed{v_0 = H_0 \cdot r}$

- initial Hubble value was far too large (factor $6 \dots 7$) 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 $H(t)$**: time–dependent value over cosmological time scales



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 onto cosmic redshift z

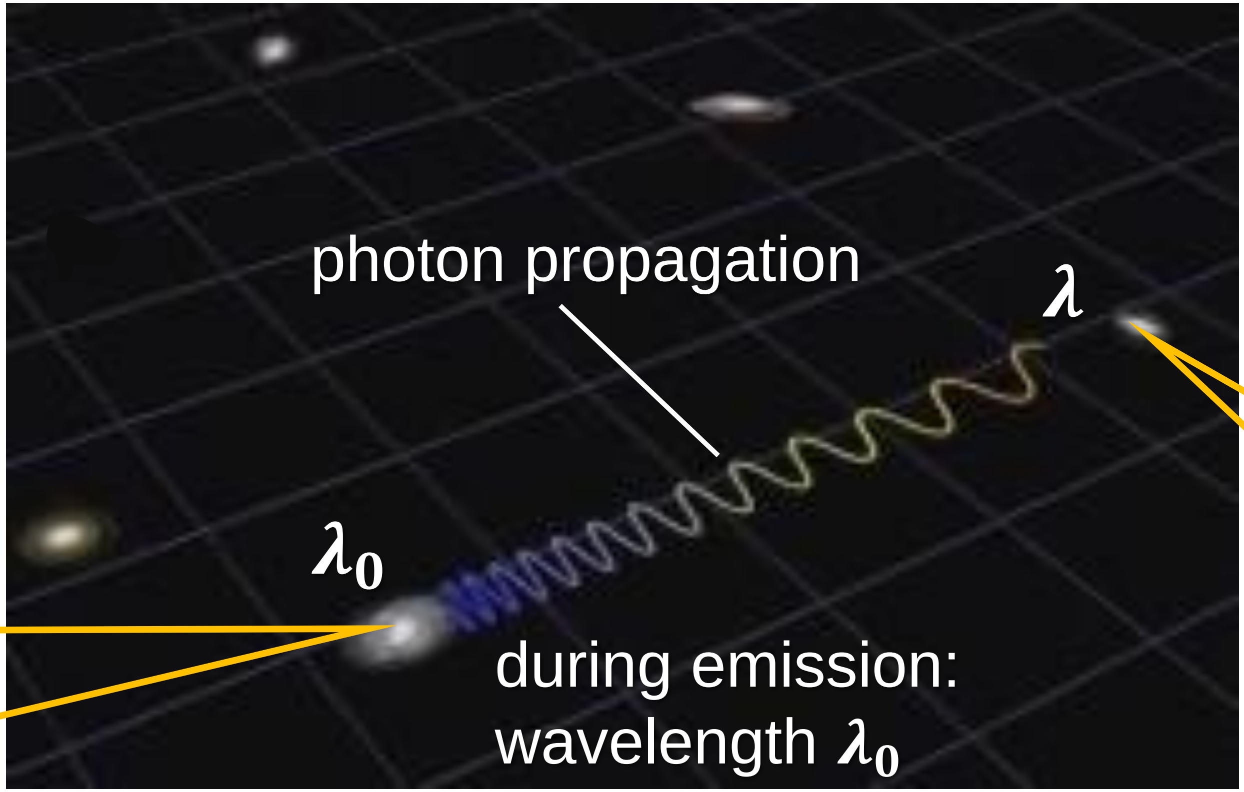
distance $r\ (Mpc)$

Q: wikipedia

Hubble expansion – todays´ correct scenario

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

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



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

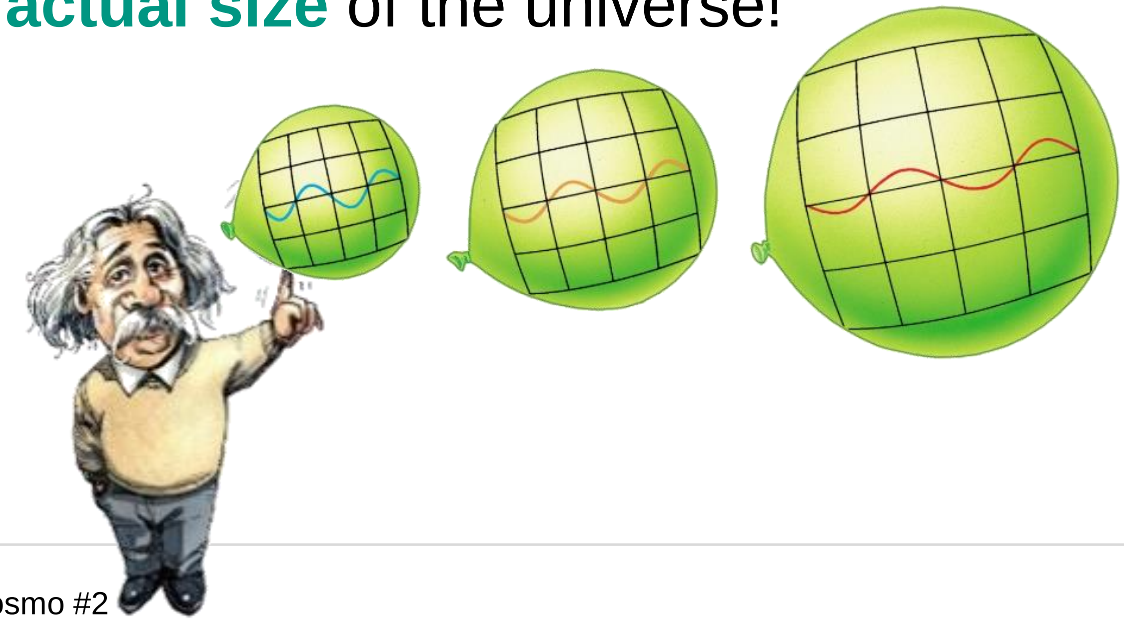
general relativity: **expansion of space–time**

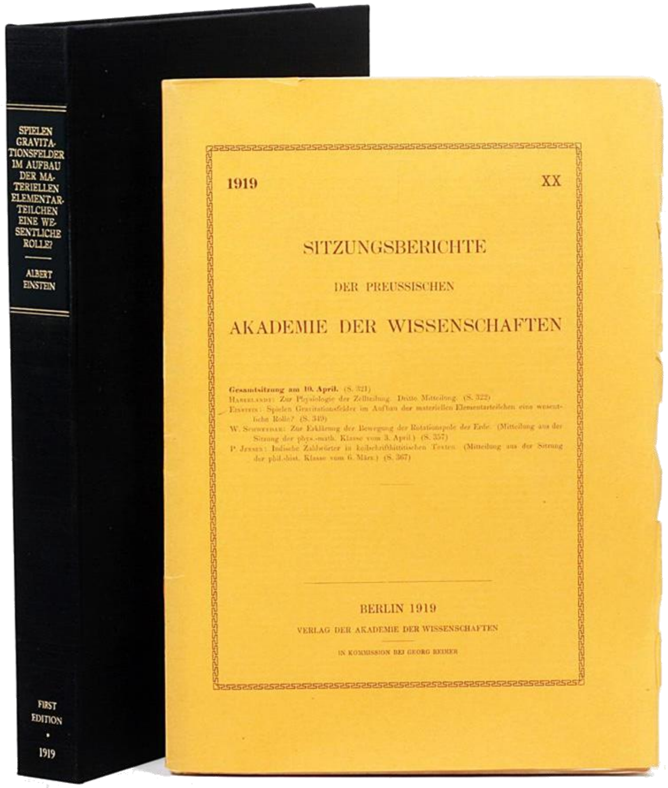
Hubble expansion – todays´ correct scenario

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

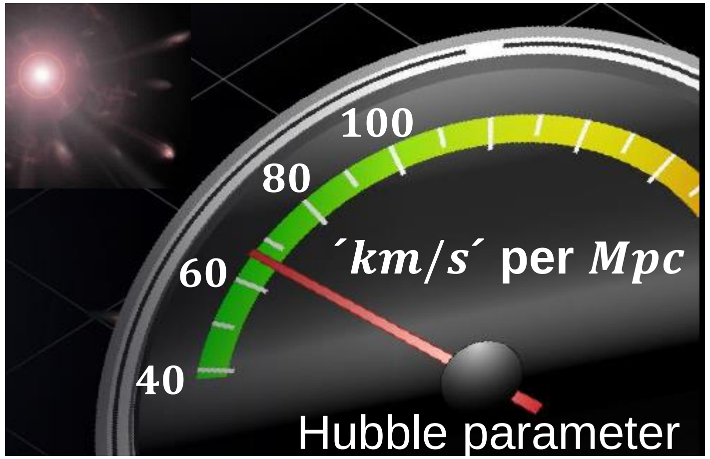




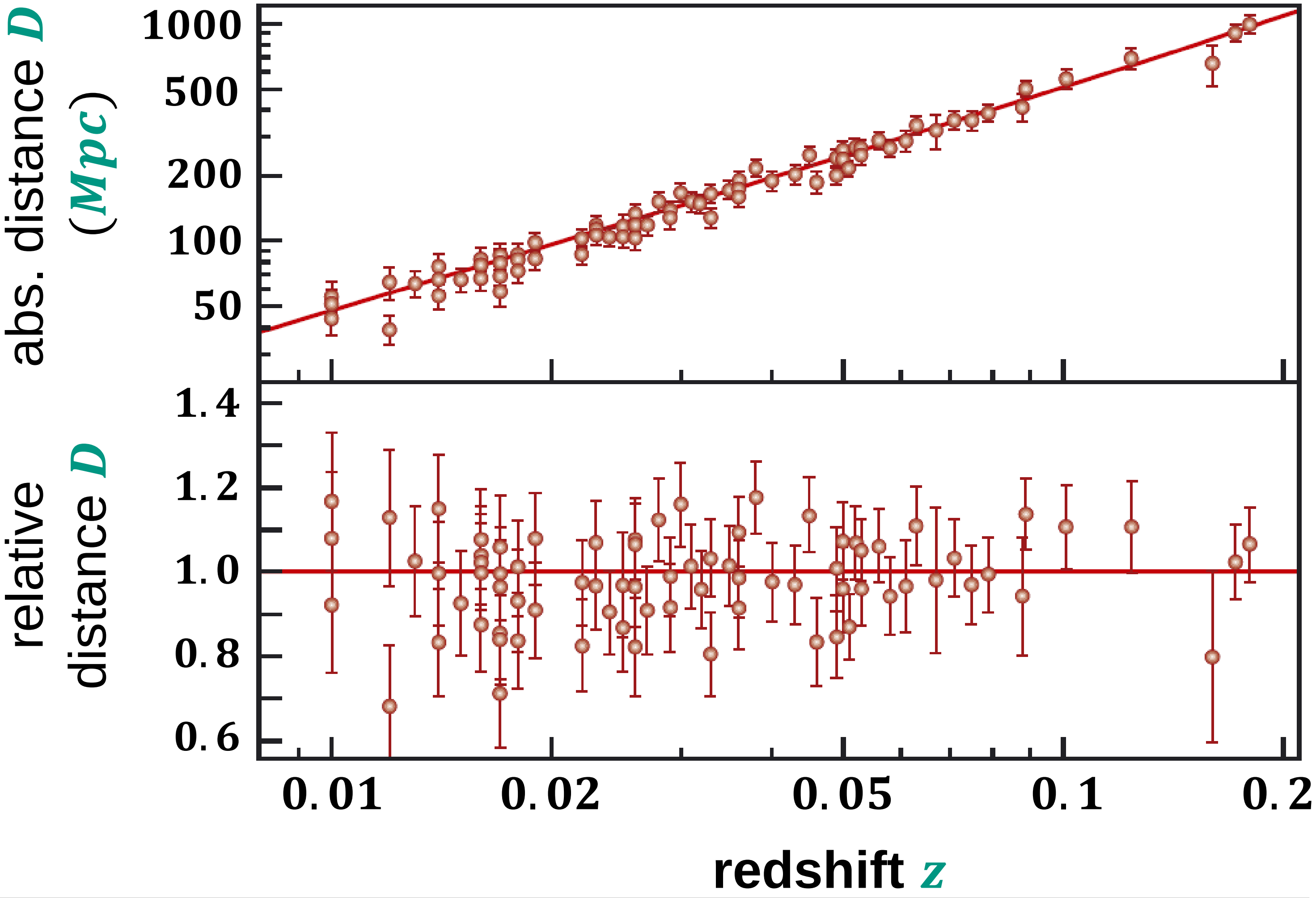
Up to 2015: experimental results Hubble rate H_0

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

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

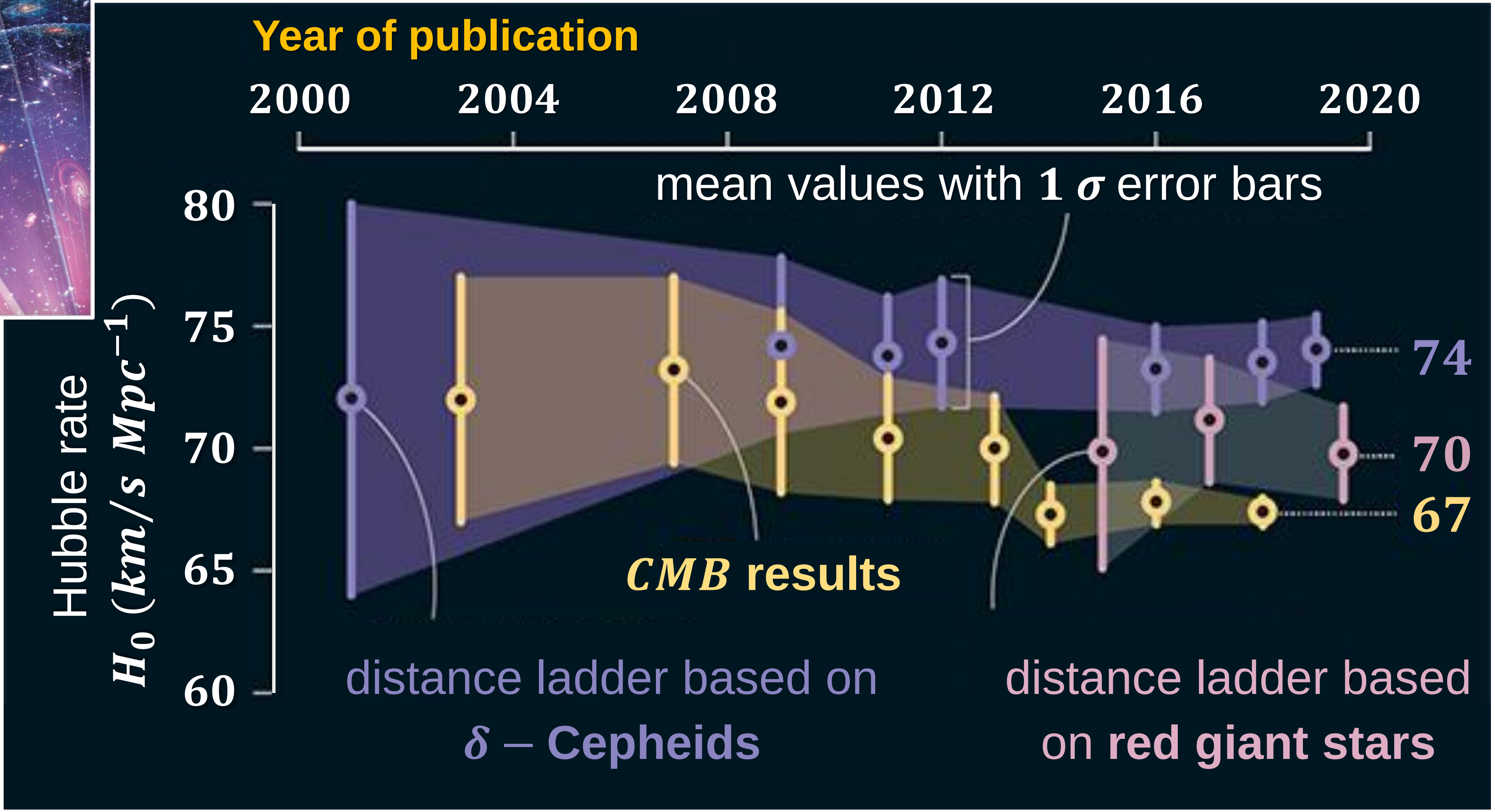


Q: spektrum



$SNae$ = supernovae

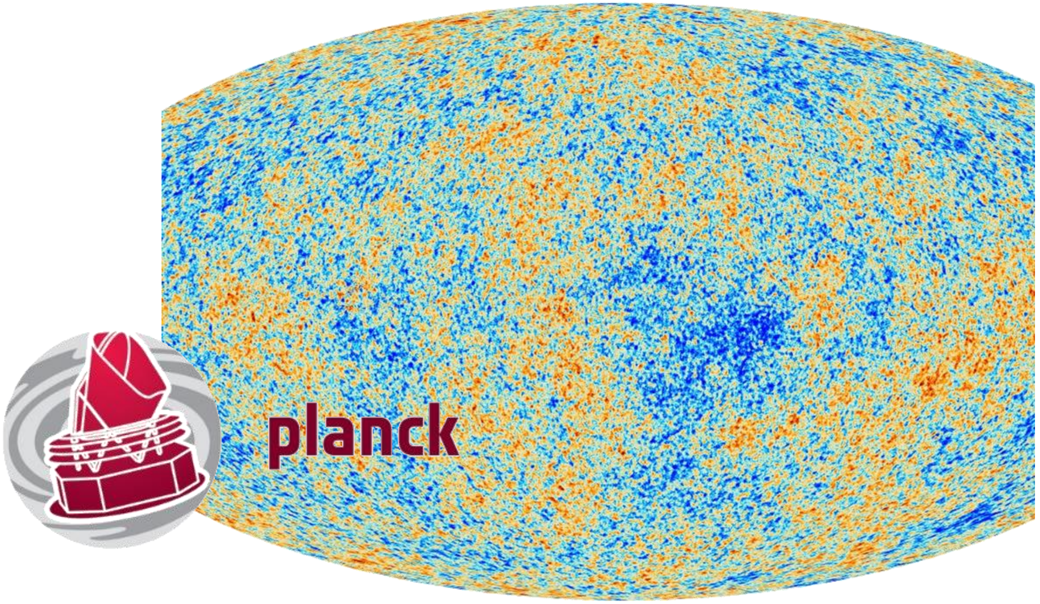
20 years of measurements of Hubble rate H_0



2021: controversy about Hubble rate H_0

- discrepancy observed for Hubble–´constant´

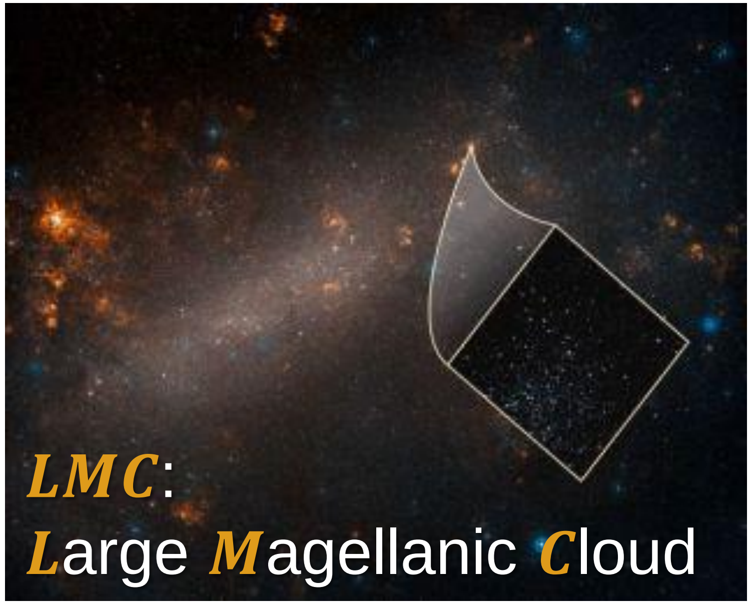
method–I: temperature fluctuations of CMB (see 3.3)



$(67.0 \pm 0.5)\ km/s\ Mpc^{-1}$
(derived H_0 for todays´ cosmic expansion)

$\sim 4.6\,\sigma$
discrepancy
$\Delta H_0 = (7.0 \pm 1.5)\ km/s\ Mpc^{-1}$

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

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 h (**dimension–less Hubble constant**)

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

  $h = 0.67 \dots 0.74\ (h^2 \sim 0.5)$

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

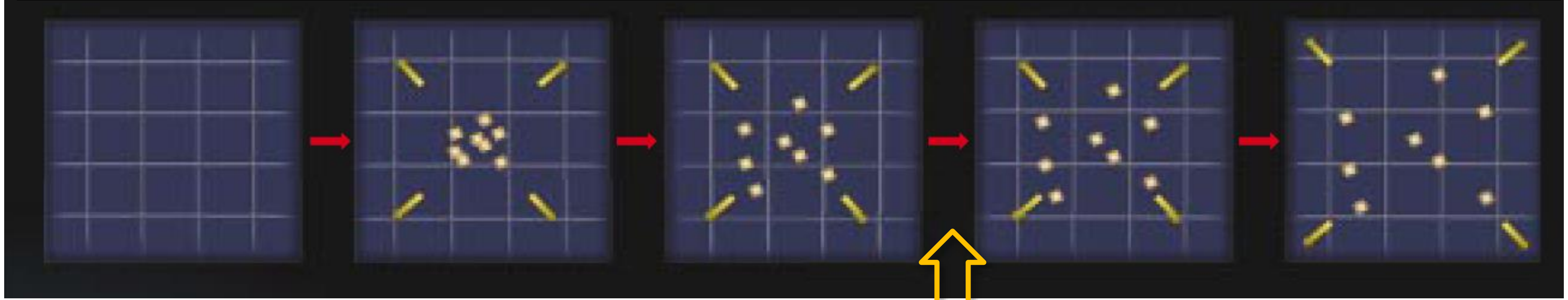
Big Bang: underlying expansion mechanismus

- **Big Bang**
  occured ´**every-where**´

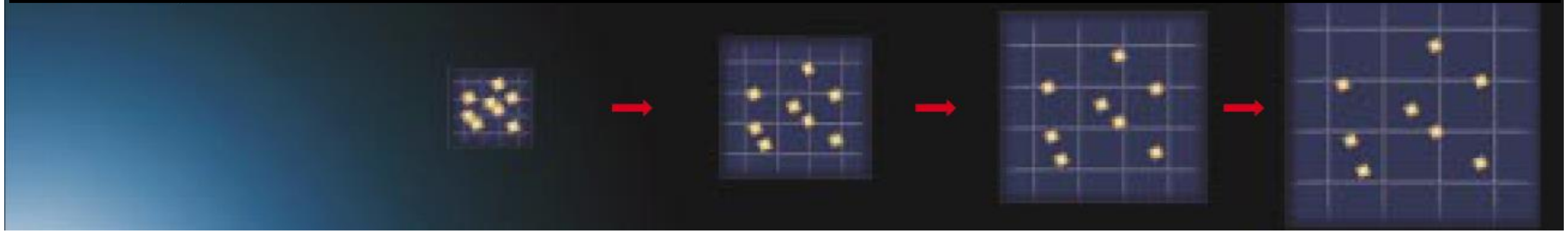
\- space & time are generated **simultaneously**

Q: spektrum

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



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



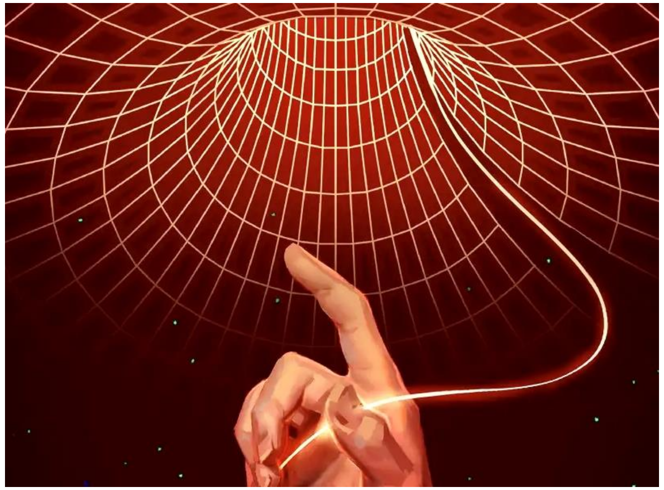
Big Bang: underlying expansion mechanismus

Karlsruhe Institute of Technology

- **Big Bang**
  occured ´**every-where**´

By Lyndie Chiou

25 October 2023

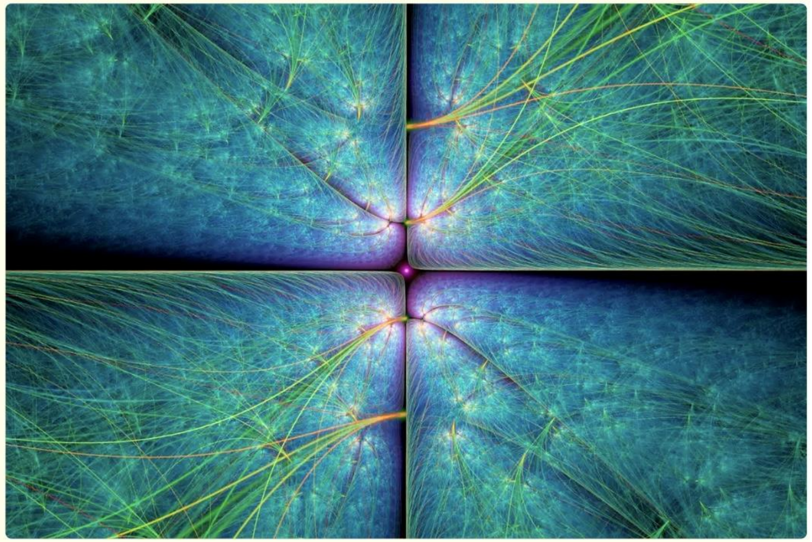


Q: new scienticst

Physics

Is space-time quantum? Six ways to unpick the fabric of the universe

One of the biggest questions in physics asks whether space-time is classical or quantum in nature. From slow neutrinos to quantum foam, these experiments are hoping to finally answer it



Rethinking reality: Is the entire universe a single quantum object?

In the face of new evidence, physicists are starting to view the cosmos not as made up of disparate layers, but as a quantum whole linked by entanglement

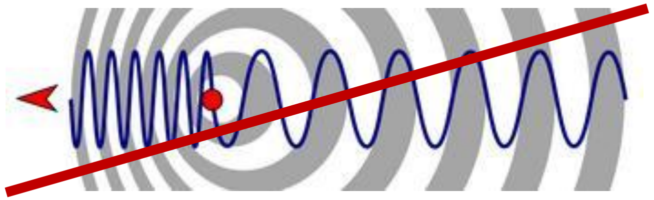
The physicist trying to create space-time from scratch

Monika Schleier-Smith is testing the idea that space-time emerges, like a hologram, from quantum interactions by attempting to make it in the lab

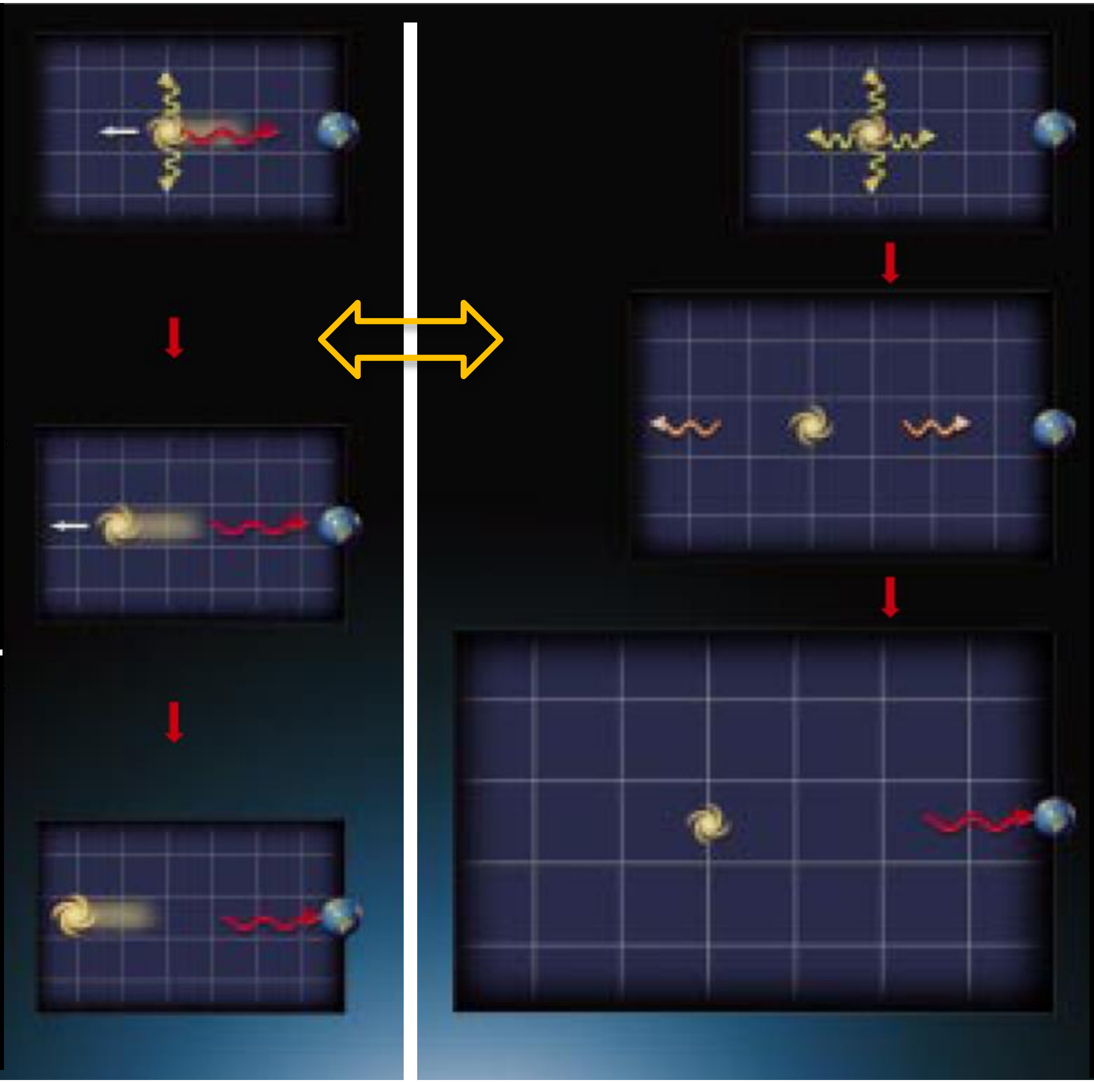
Big Bang: origin of redshift z

- **Space itself** expands

- galaxies are ´**at rest**´ (*i.e.* they are **co–moving** objects over cosmological expansion)



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



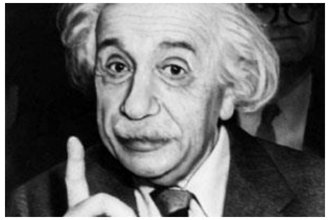
correct scenario: expanding space–time stretches the wavelength of photons, redshift z is identical in all directions. The proper motion of galaxies (& corr. Doppler effect) can be neglected

Q: spektrum

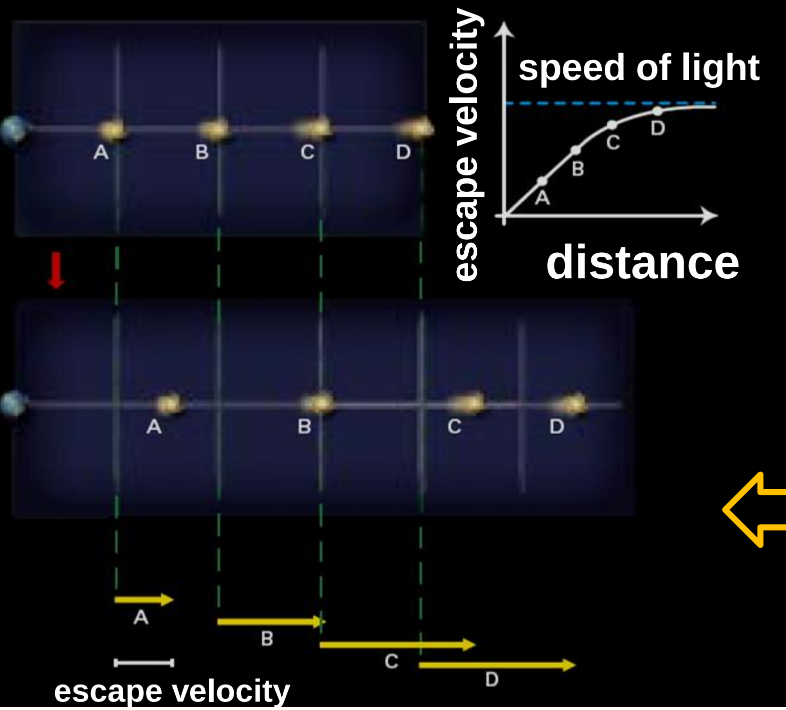
Big Bang: ´escape velocities´ with $v > c$

- **Escape velocity** has no formal limit

- but: <u>**no**</u> transmission of information with $v > c$ due to the cosmological expansion

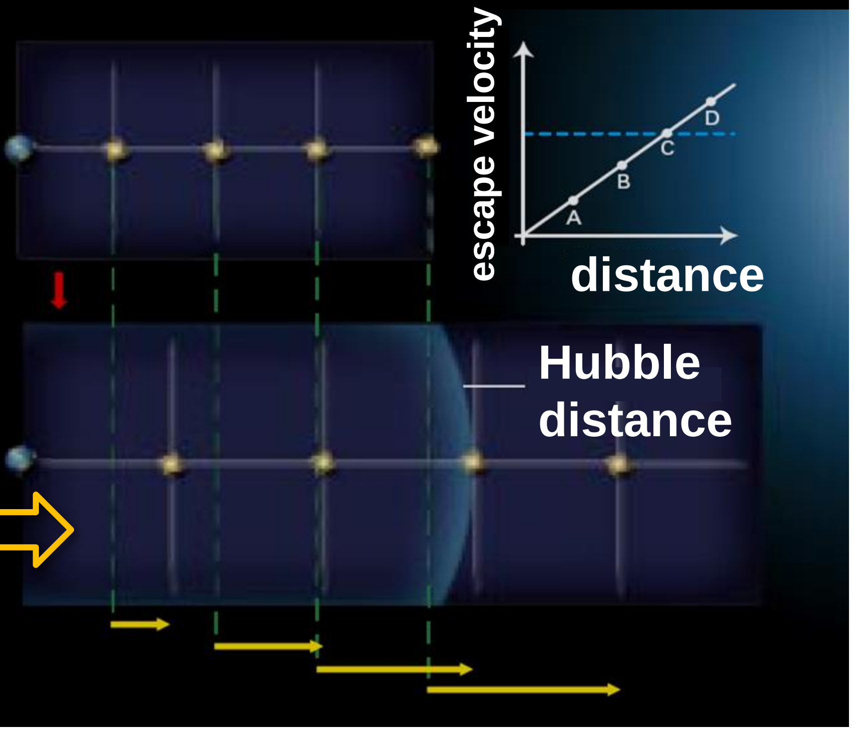


wrong scenario: galaxies moving through empty space with $v < c$ (special relativity), thus $v = c$ is approached only asymptotically



Q: spektrum

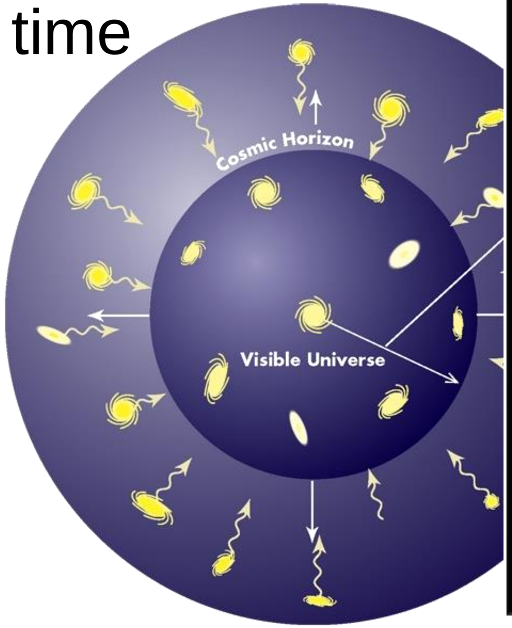
correct scenario: space & time are expanding (galaxies at rest), thus ´escape velocity´ will reach $v > c$ at the **Hubble distance**



Big Bang: light from galaxies with $v > c$?

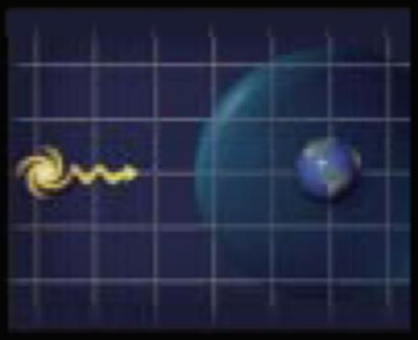
Karlsruhe Institute of Technology

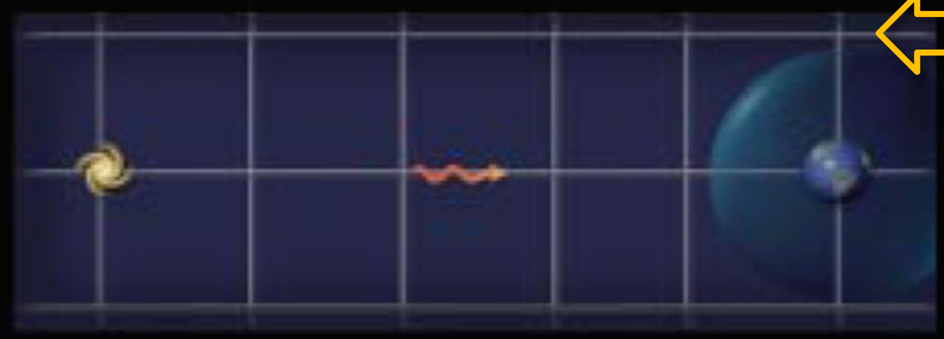
- **Hubble−radius**
  - cosmological **horizon** will change over time



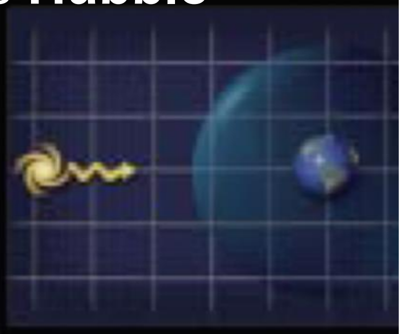
Q: spektrum

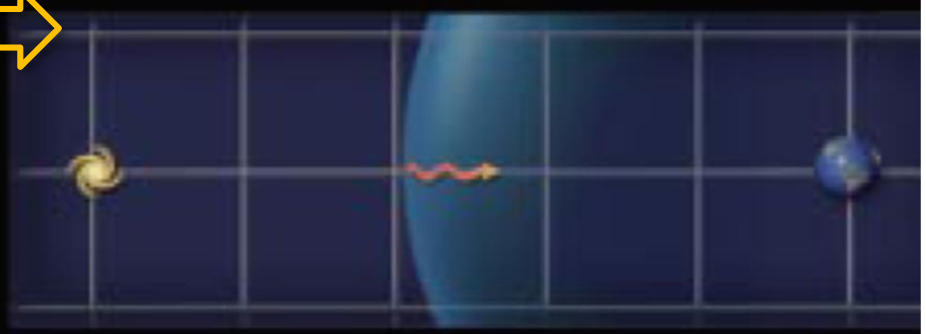
wrong scenario: light from all galaxies beyond the Hubble−scale will never reach us, as their distance relative to us is increasing faster than the speed of light c. We cannot obtain information from beyond the Hubble radius





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

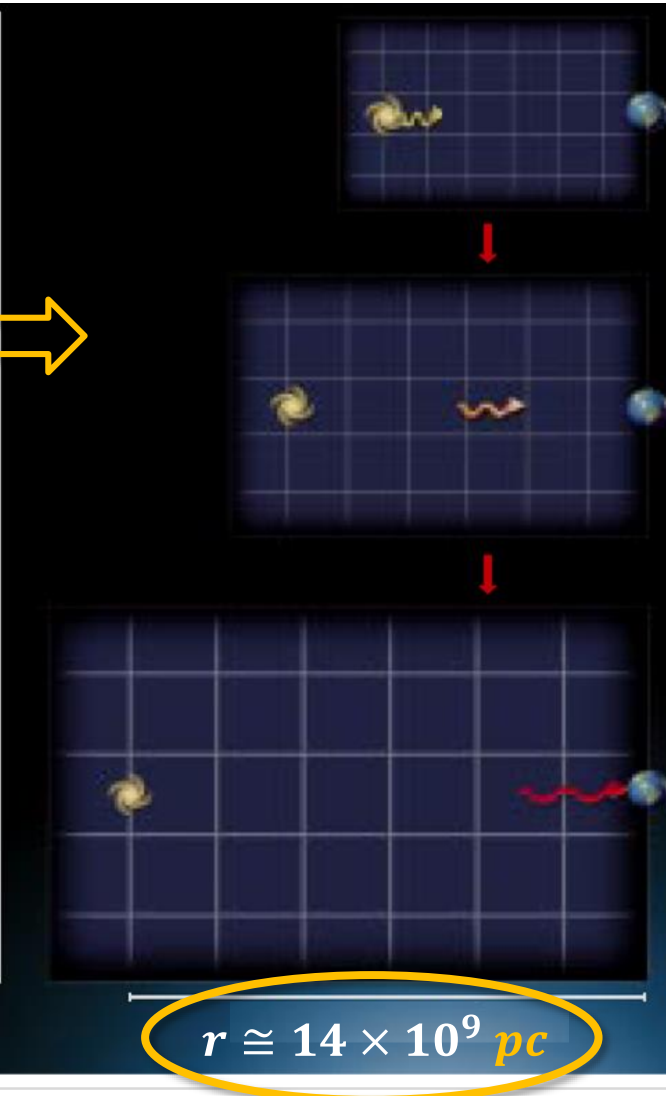
Karlsruhe Institute of Technology

- **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 the edge reaches us just now.



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 $\sim 3 \times$ the light path.

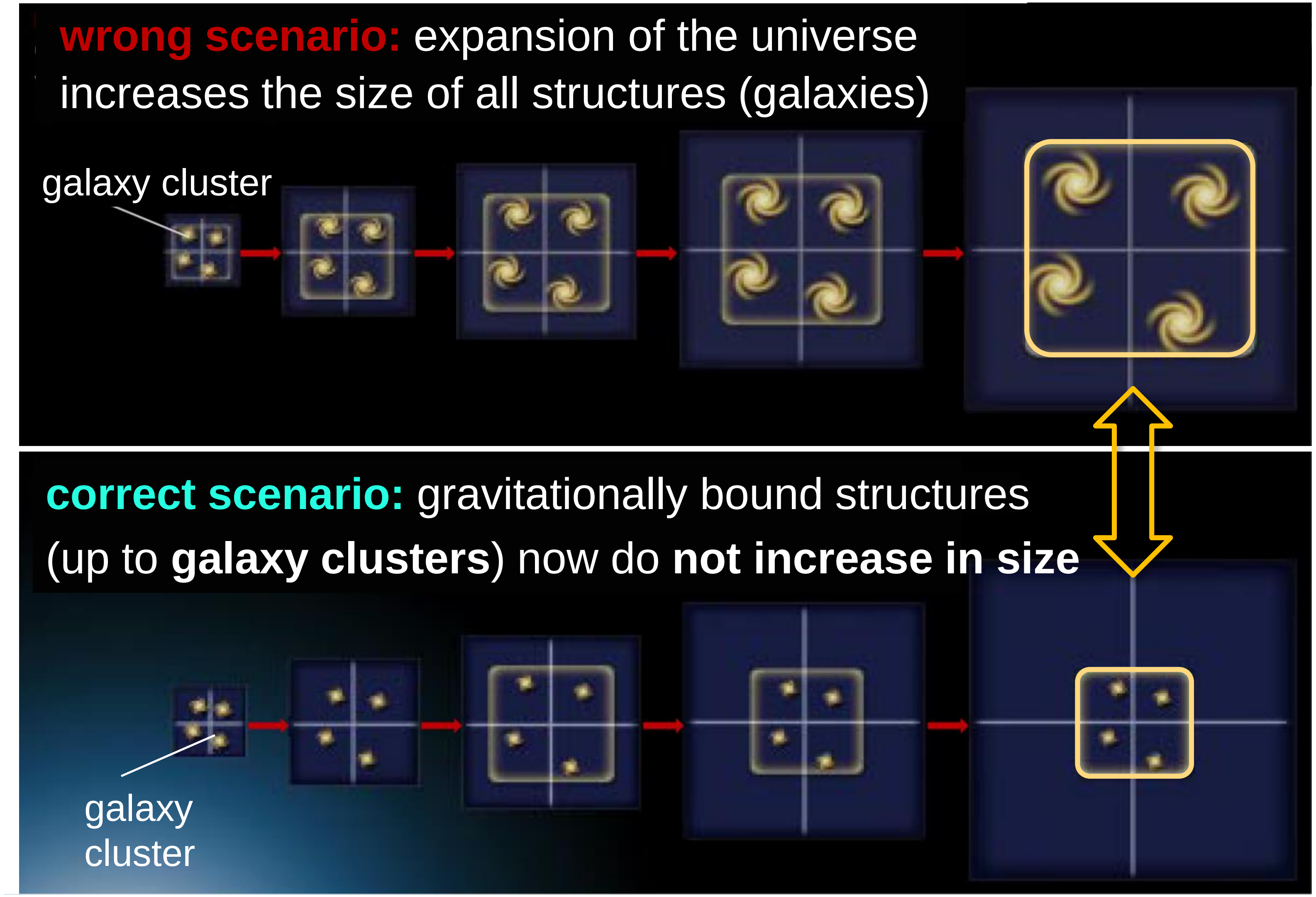
Big Bang: regions participating in expansion

- **Hubble expansion**

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

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

- wavelength λ of a (CMB) photon will **increase**



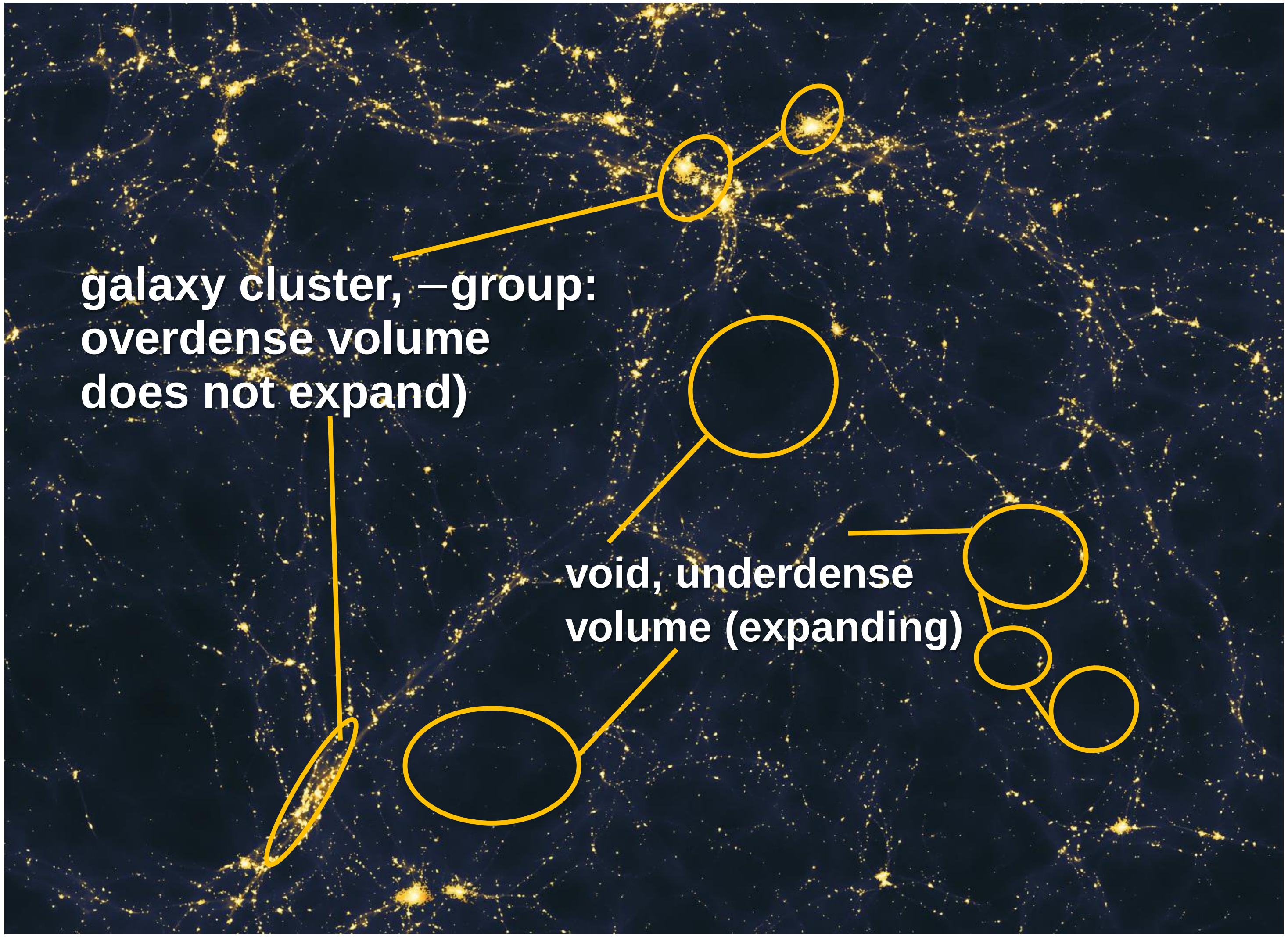
Big Bang: regions participating in expansion

- **Hubble expansion**

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

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

- wavelength λ of a (CMB) photon will **increase**



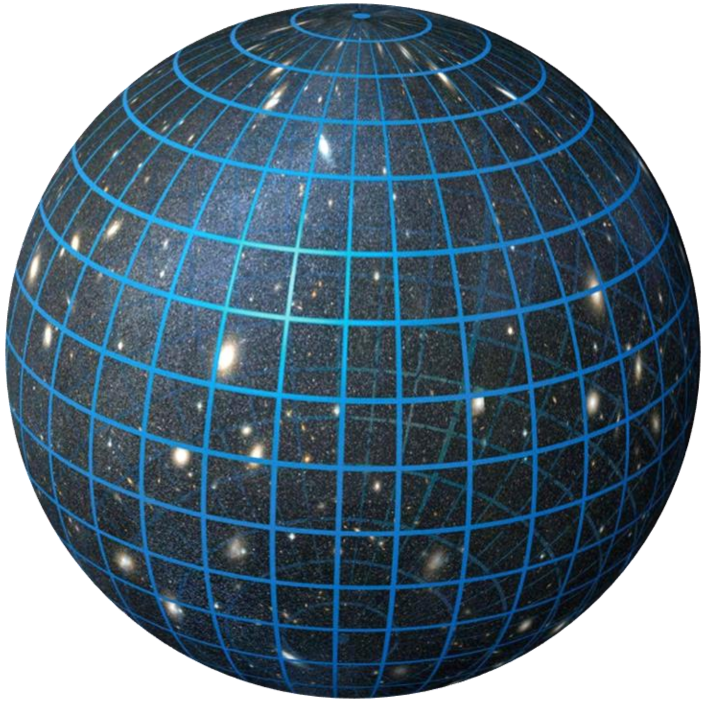
Big Bang: Hubble parameter $H(t)$

Karlsruhe Institute of Technology

- Hubble expansion rate $H(t)$ of the universe is not constant but variable

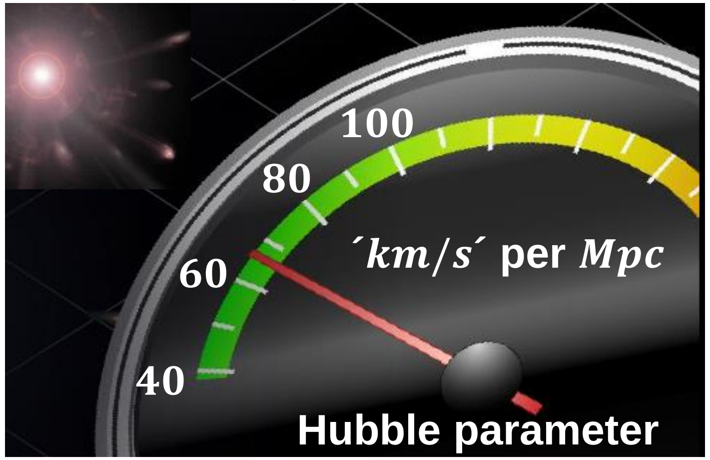
who is stepping
on the **brake** ?

gravity



who is stepping
on the **gas pedal** ?

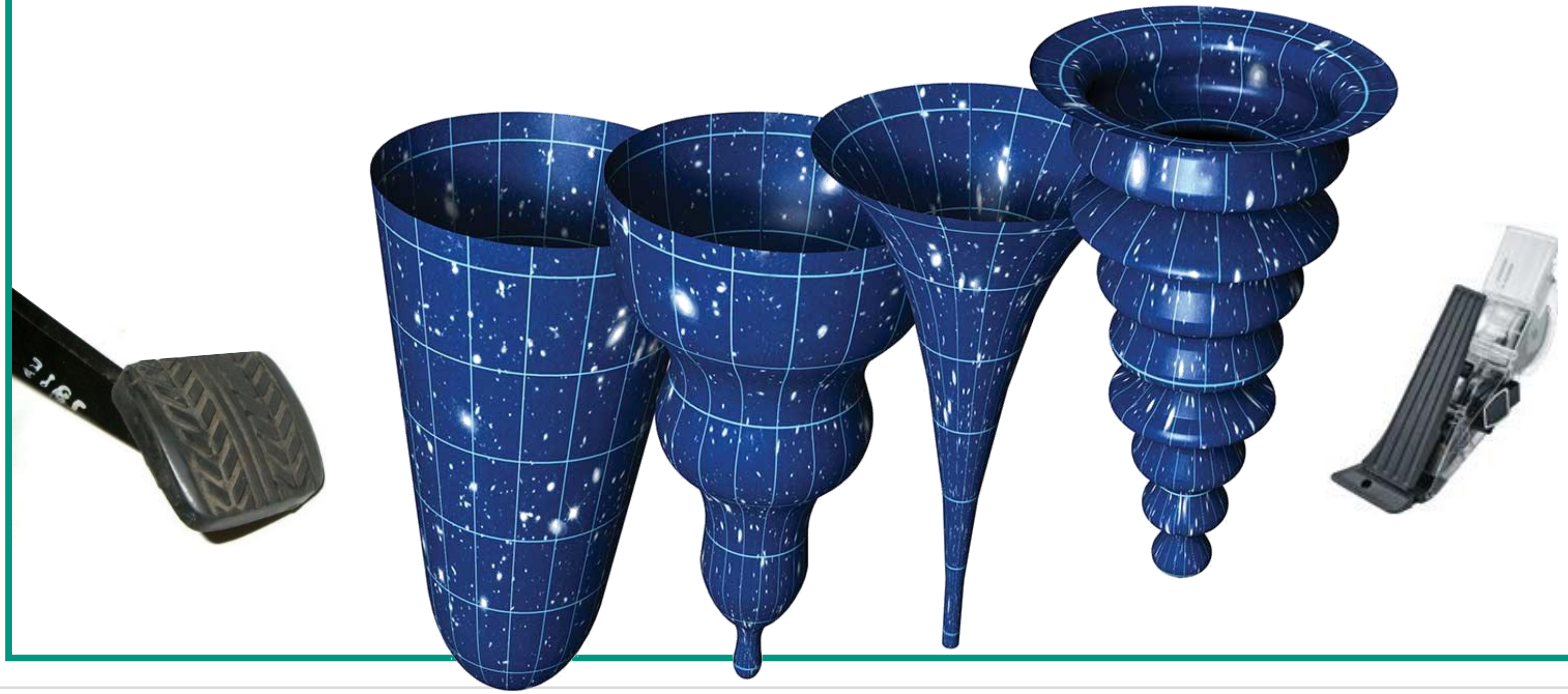
anti–gravity



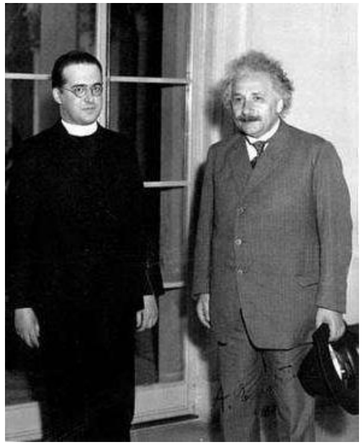
Big Bang: Hubble parameter $H(t)$

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

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



Aleksandr ***Friedmann*** **(1888 – 1925)**



Georges ***Lemaître*** **(1894 – 1966)**