Introduction to Cosmology

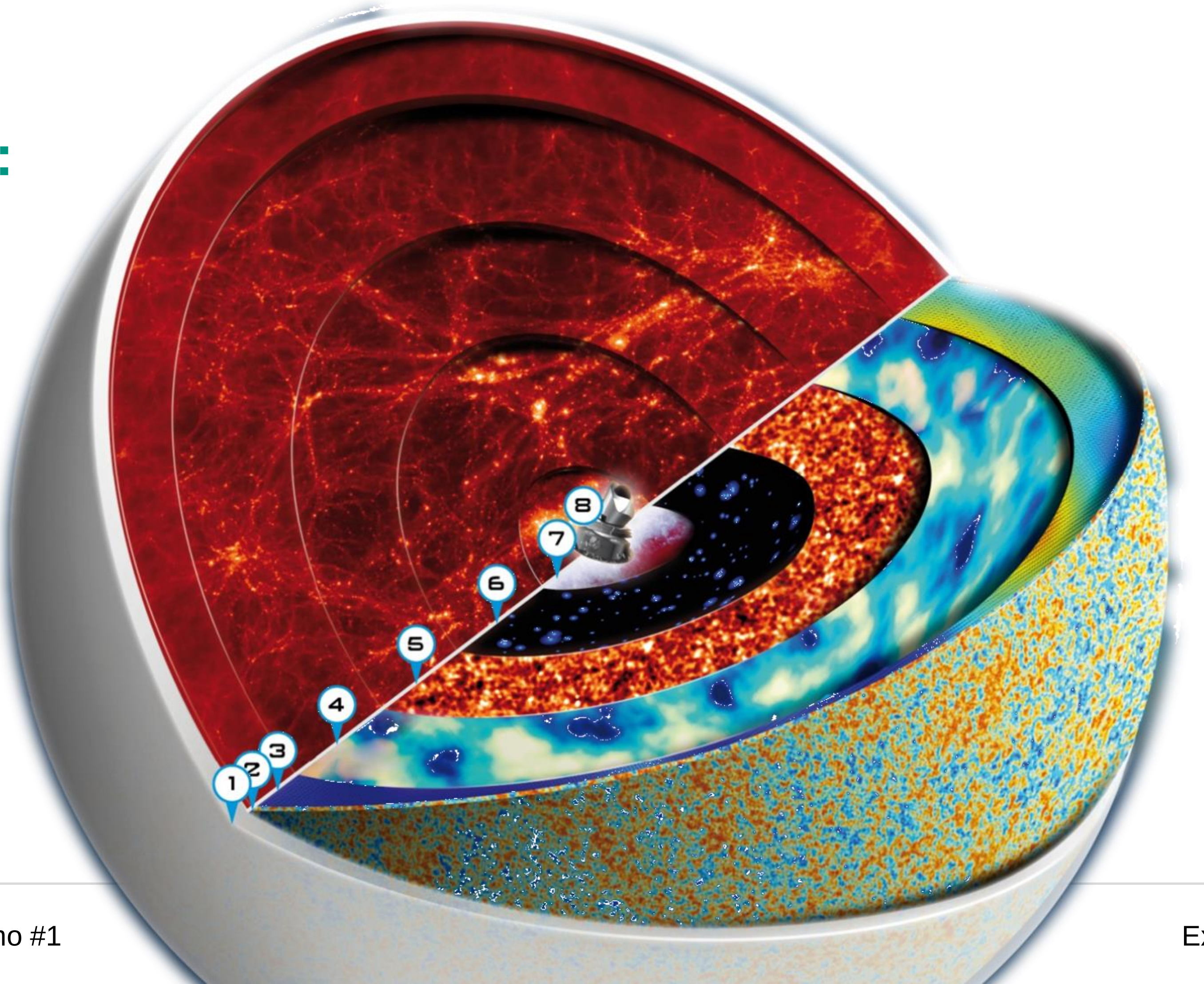
Winter term 22/23 Lecture 1 Oct. 25, 2022

Cosmology – Definition

- **Evolution & Structure of the Universe from the Big Bang to now**

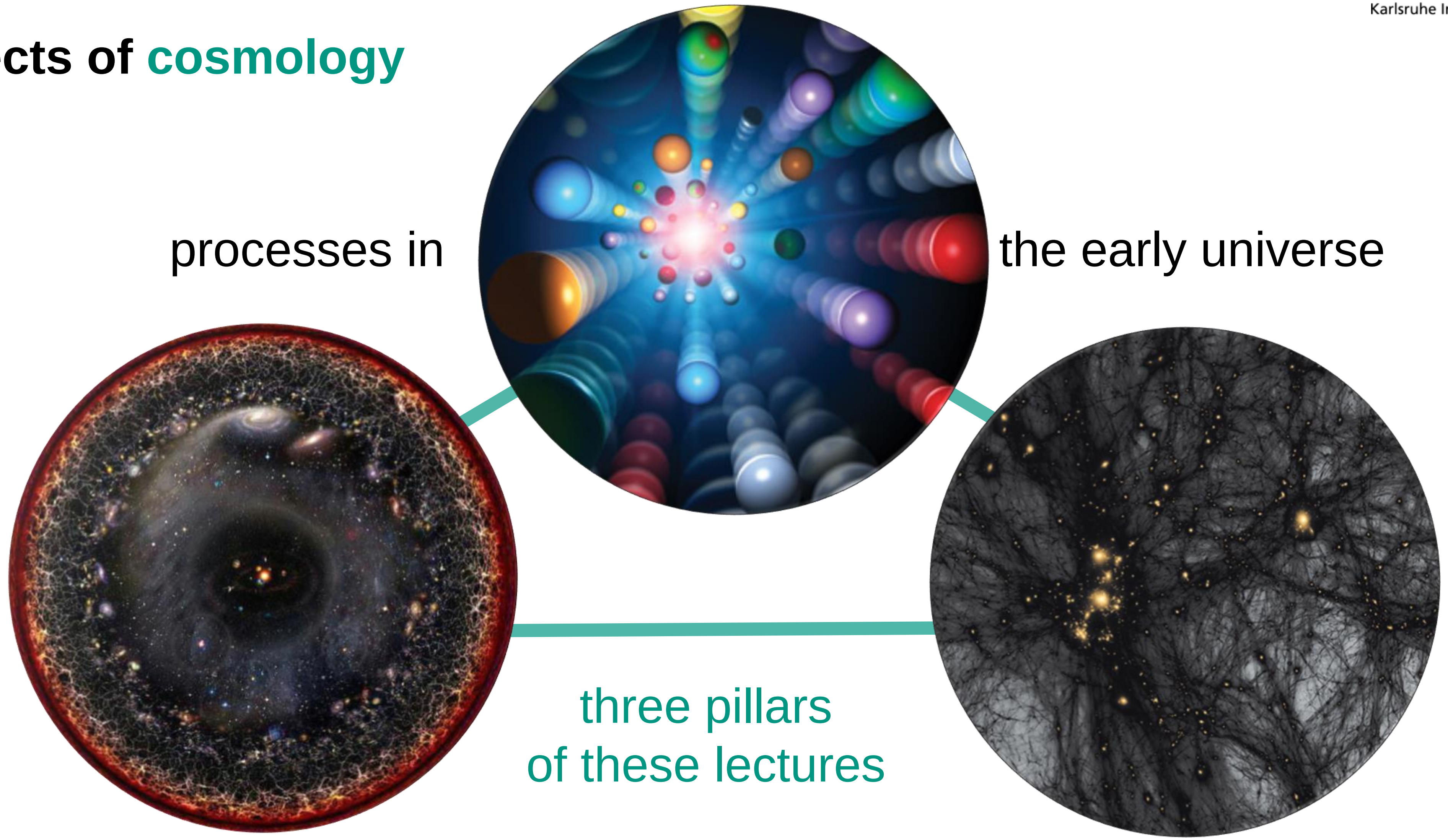
important stopovers:

1 – Big Bang
2 – CMB (3K)
3 – reionisation
4 – dark ages
5 – first stars
6 – first galaxies
7 – Milky Way
8 – today



Cosmology – range of subjects

- **subjects of cosmology**



processes in the early universe

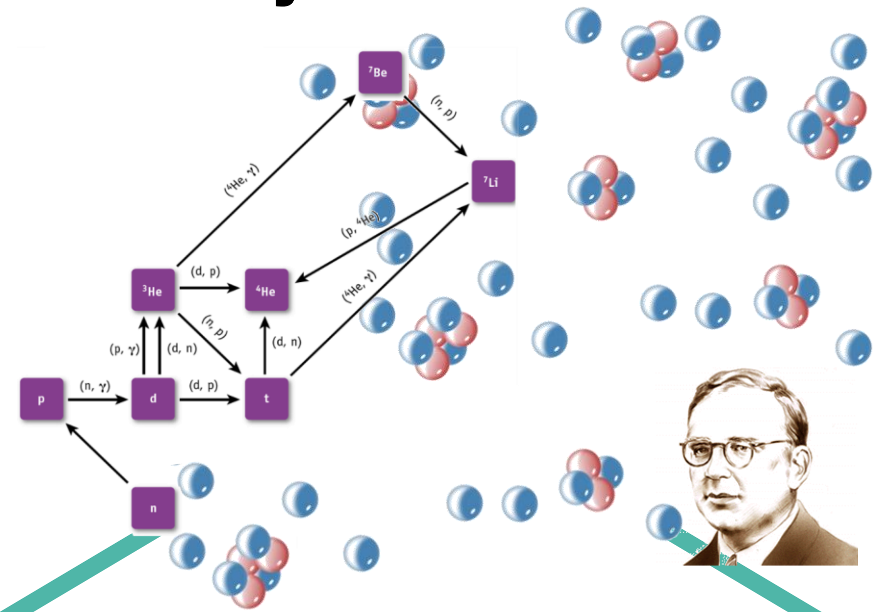
strucuture formation

dark universe

three pillars
of these lectures

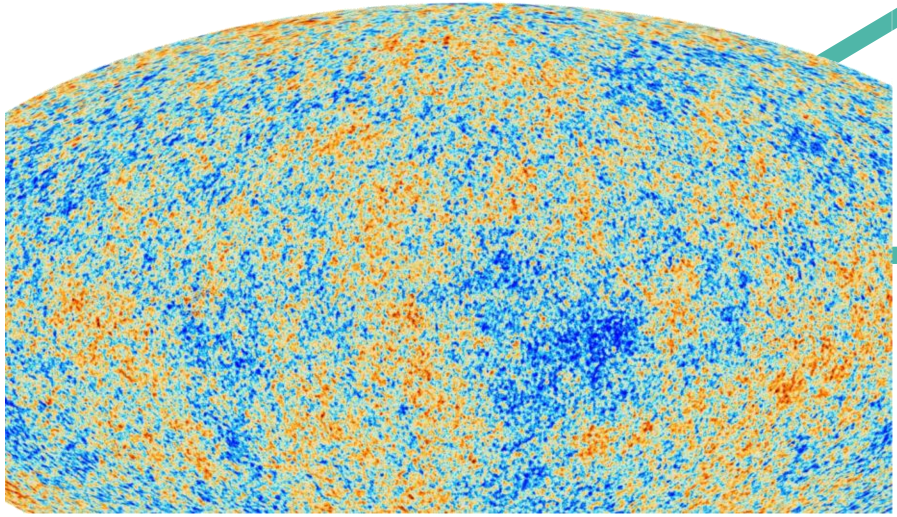
Cosmology – range of subjects

- **example:**
  thermal processes



formation of elements
during Big Bang

CMB*-
temperature



neutrino
properties

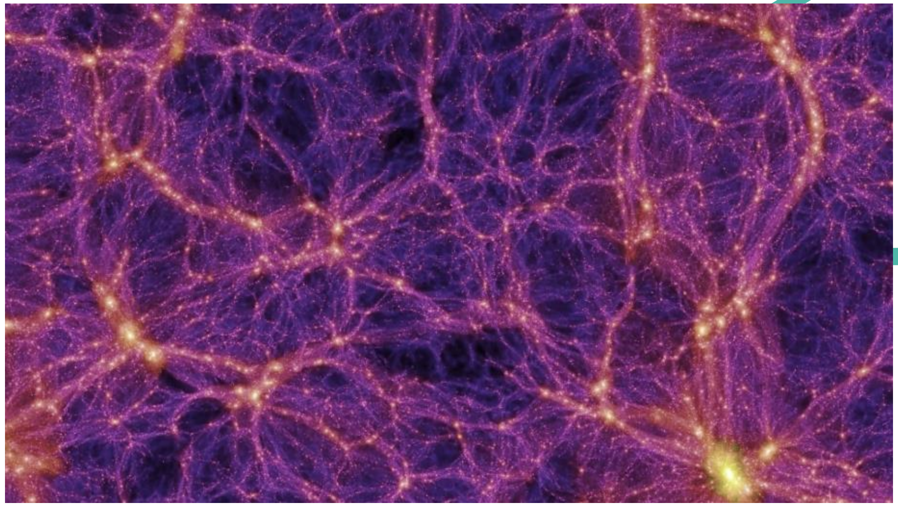
*Cosmic Microwave Background

Cosmology – range of subjects

- **example:**
  Dark Matter (DM)

DM-particle candidates:
HDM*, WDM**, CDM***

DM in
structure formation

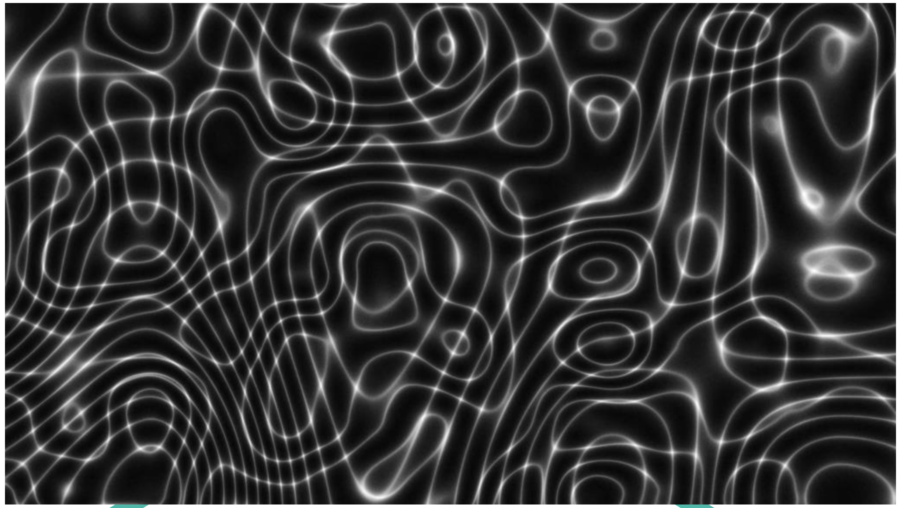


galactic
DM-
halos

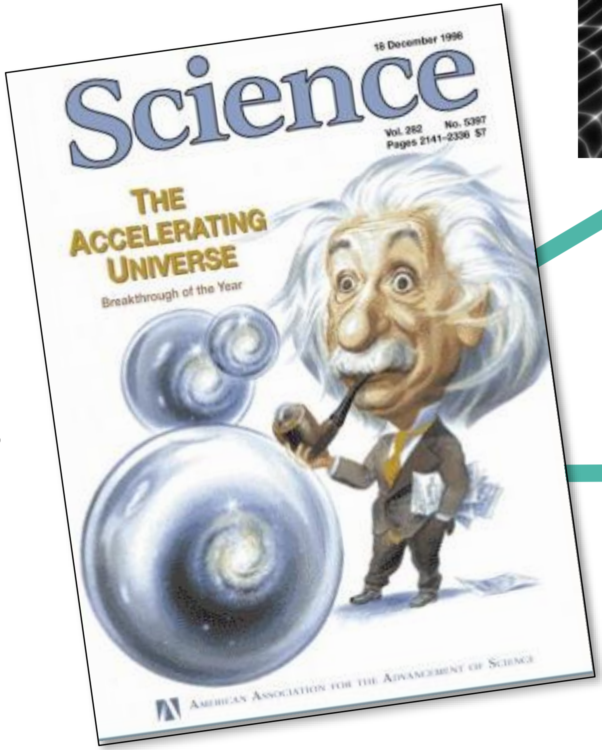
*Hot Dark Matter
*Warm Dark Matter
*Cold Dark Matter

Cosmology – range of subjects

- **example:**
  Dark Energy (DE)



nature of DE:
cosmological constant?

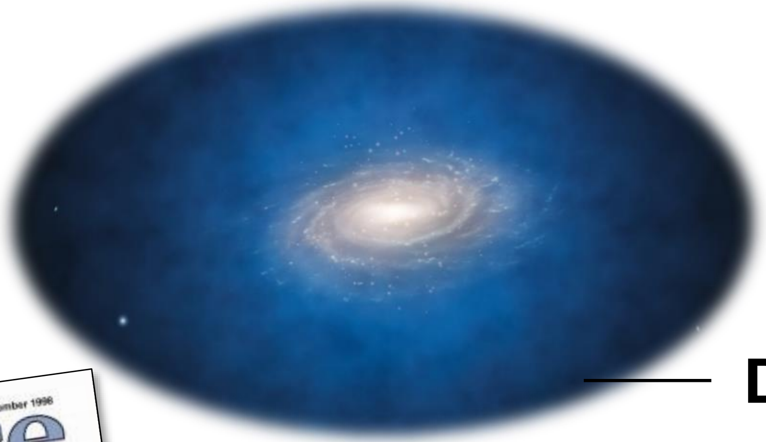


evidences for DE

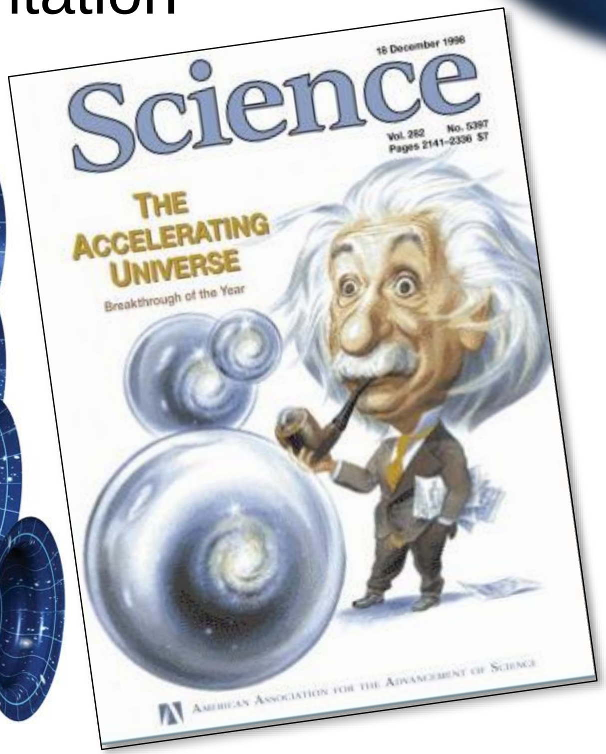
DE & expansion rate of the universe

Cosmology – new concepts

- **classification**



Antigravitation



Dark Matter

Bachelor Studies

gravitation

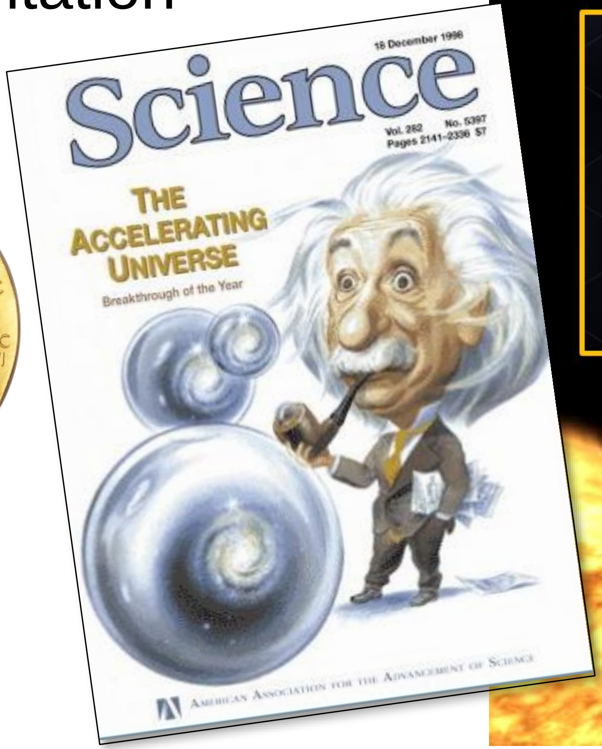
nuclear physics
thermodynamics
optics

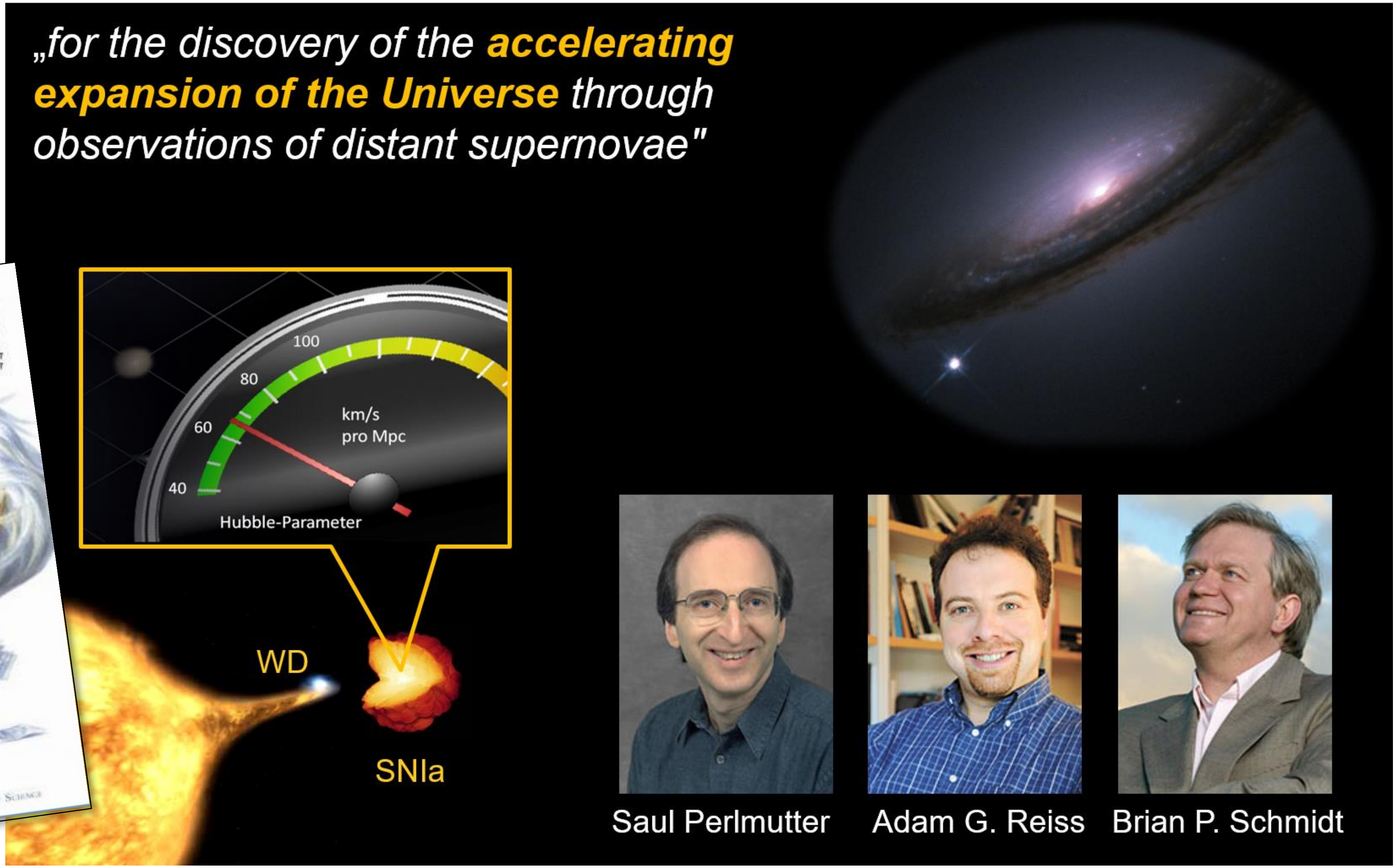
condensed matter, atoms, molecules

Cosmology – modern observations

- **Nobel Prize 2011**

Antigravitation





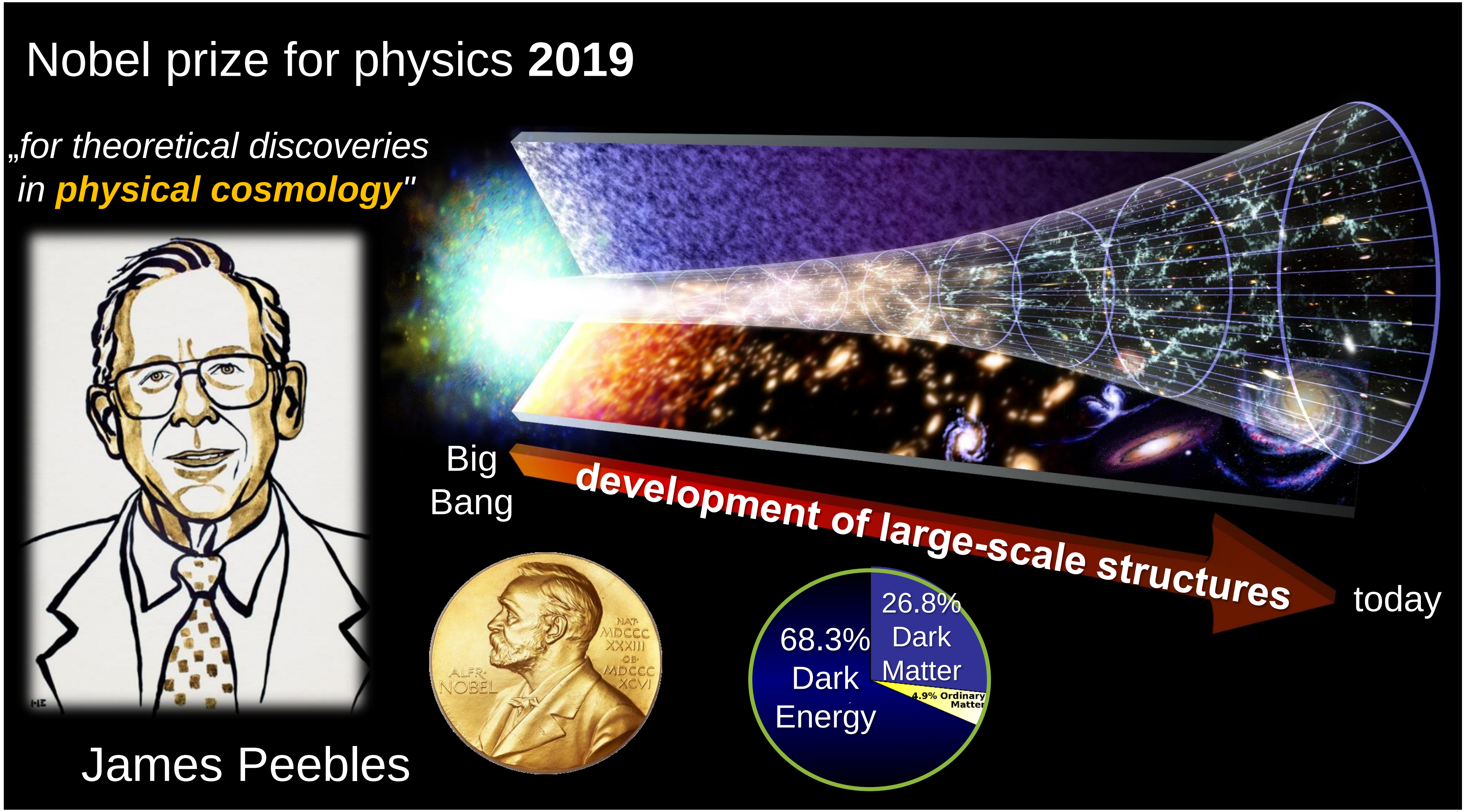
Cosmology – modern theories

- **Nobel Prize 2019**

structure formation

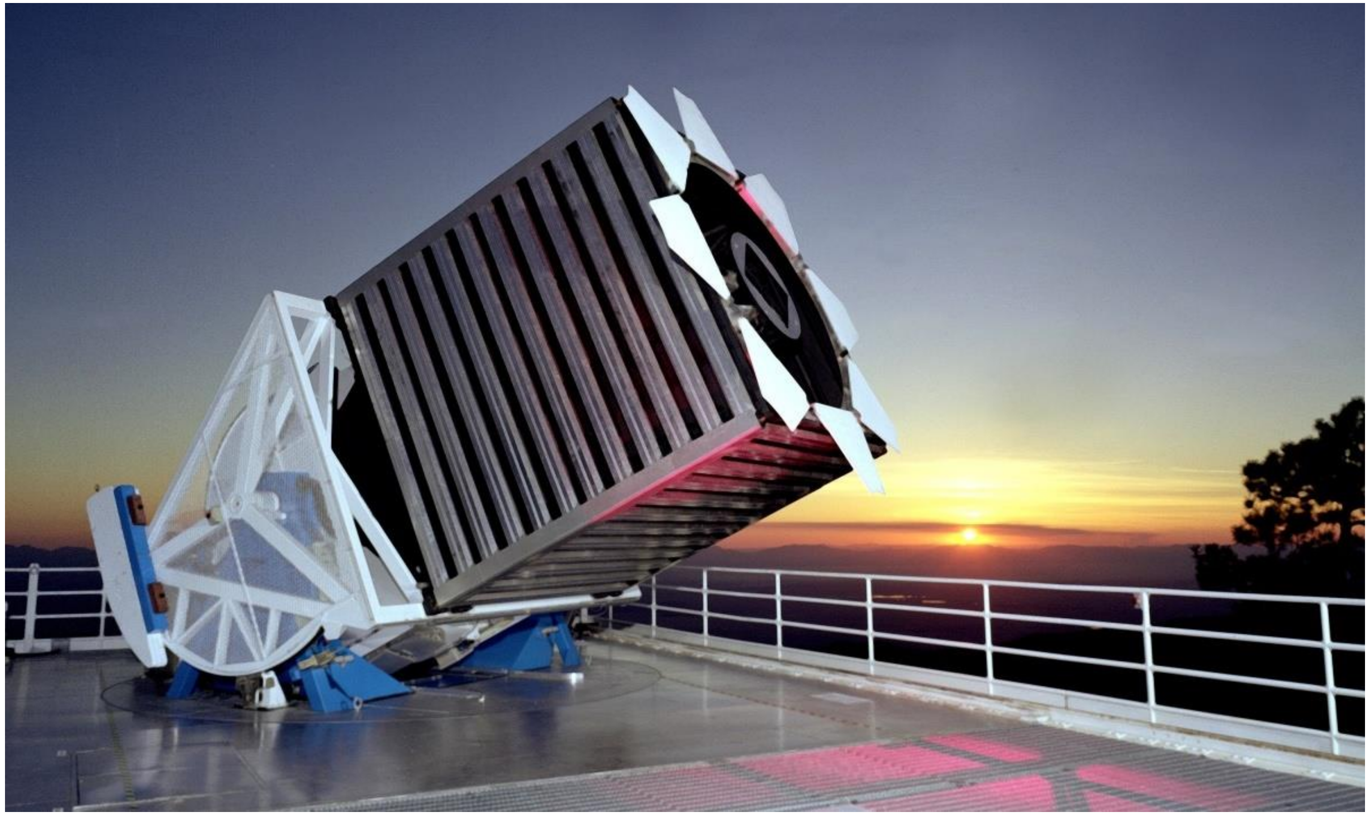
50%

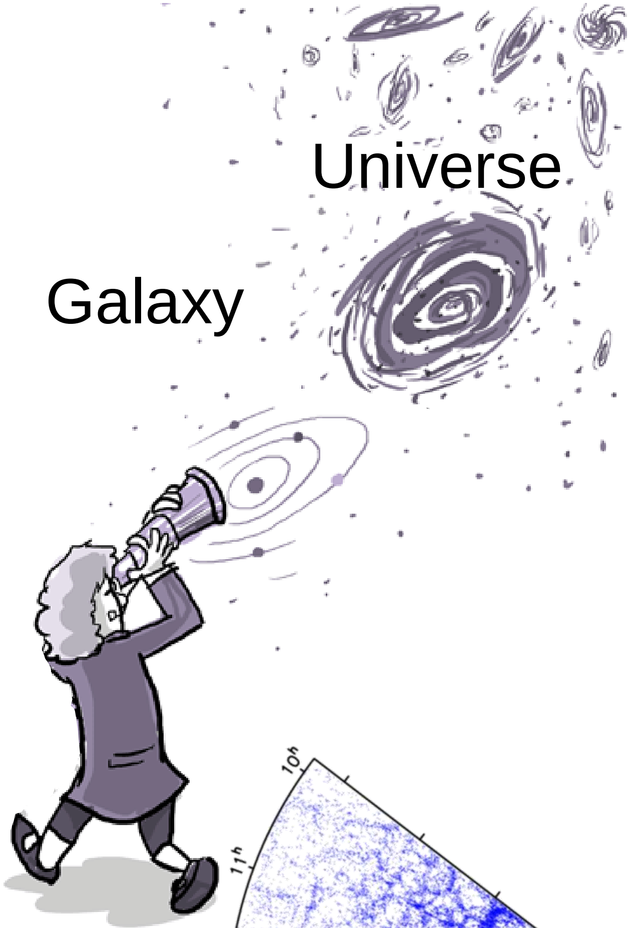
$$\delta(\vec{r}) = \frac{\rho(\vec{r}) - \langle \rho \rangle}{\langle \rho \rangle}$$

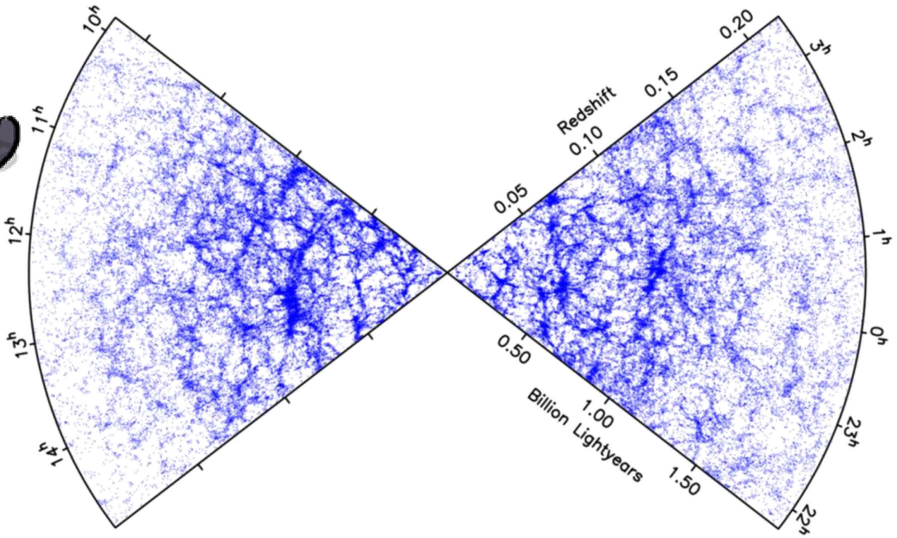


Cosmology – observations

- **example: galaxy redshift surveys**

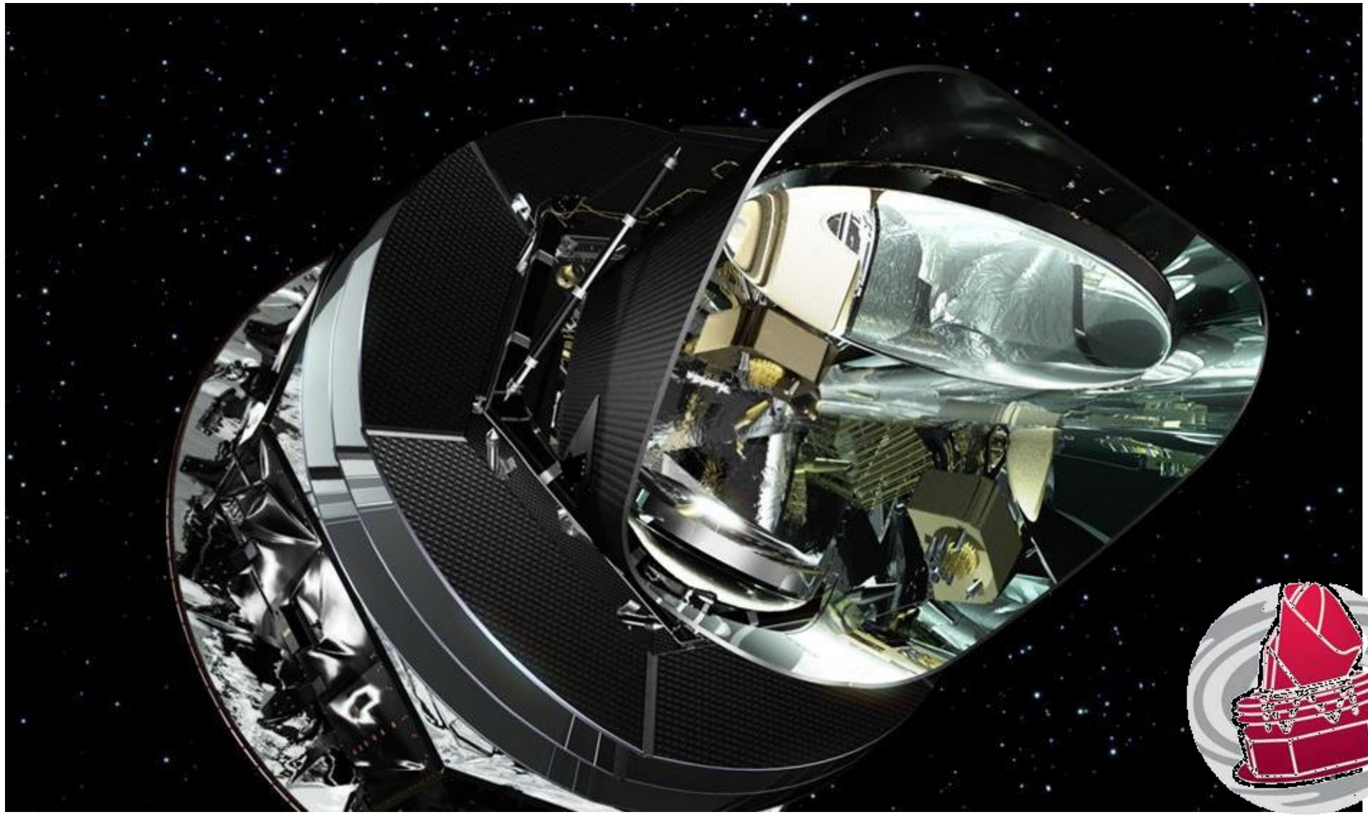


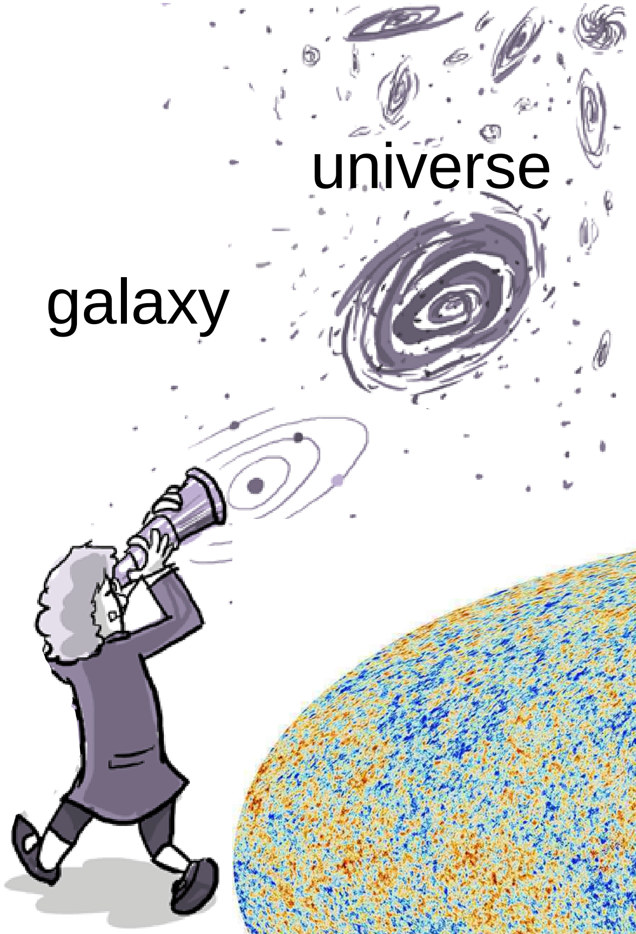


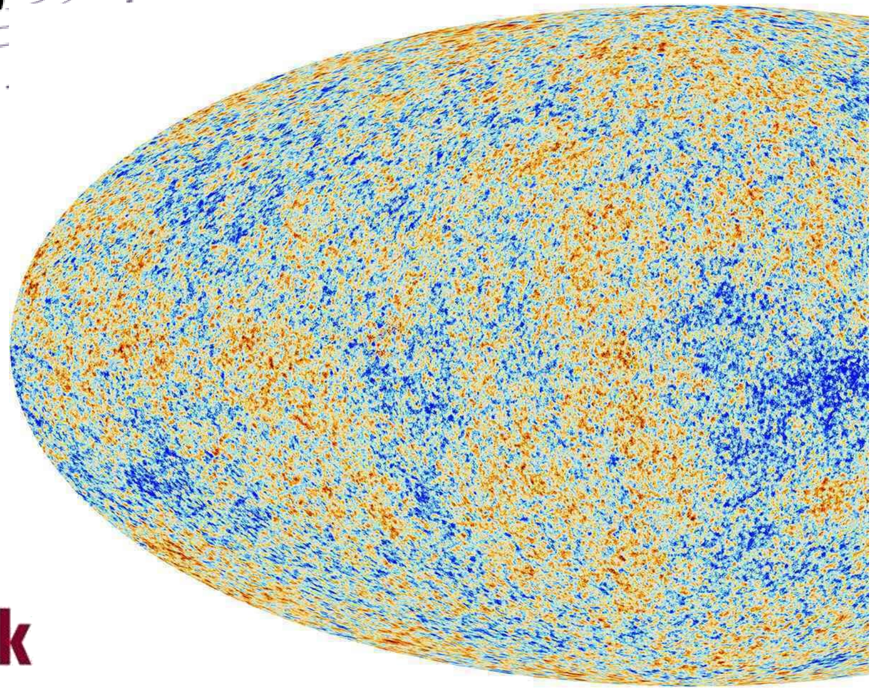


Cosmology – observations

- **example:** **temperature fluctuations of the CMB (cosmic microwave background radiation)**



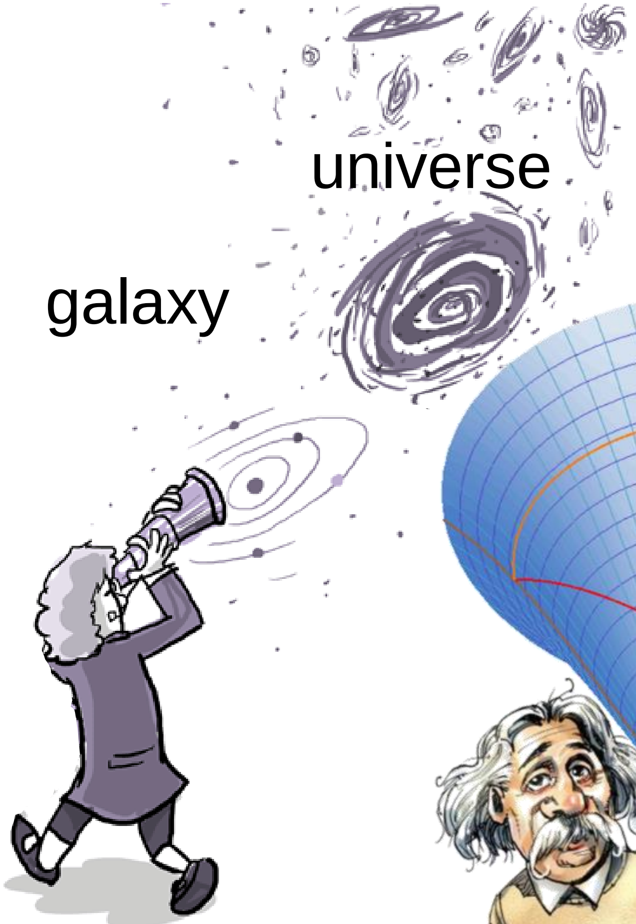


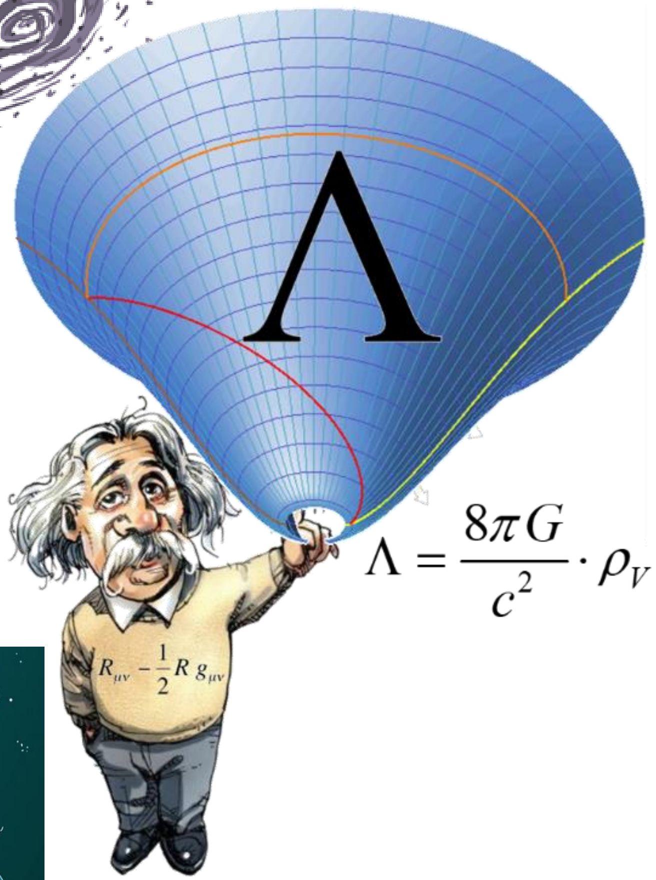


planck

Cosmology – open questions

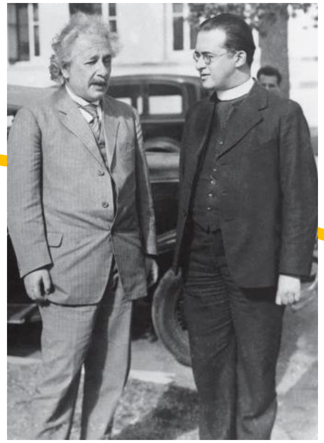
- **what is the intrinsic nature of**
  Dark Matter & Dark Energy ?





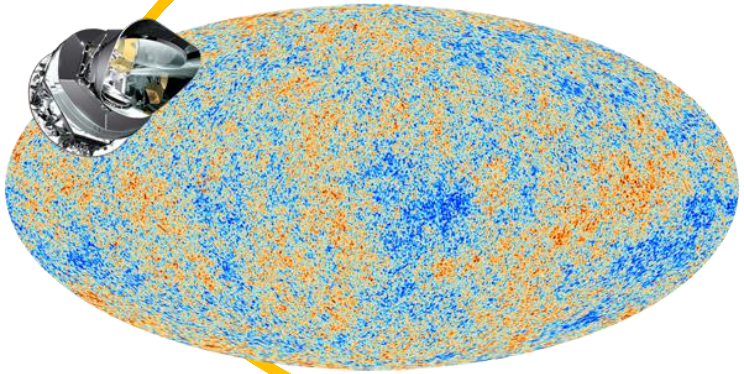
$$\Lambda = \frac{8\pi G}{c^2} \cdot \rho_V$$

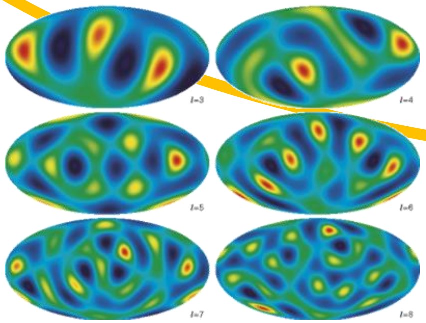
I can learn the following in this lecture series:

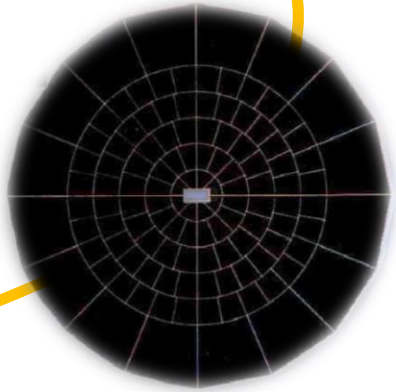


$$\left(\frac{\dot{H}(t)}{H(t)}\right)^2 \sim 1+\frac{7\Delta N_\nu}{43}$$

...new tools for discoveries…



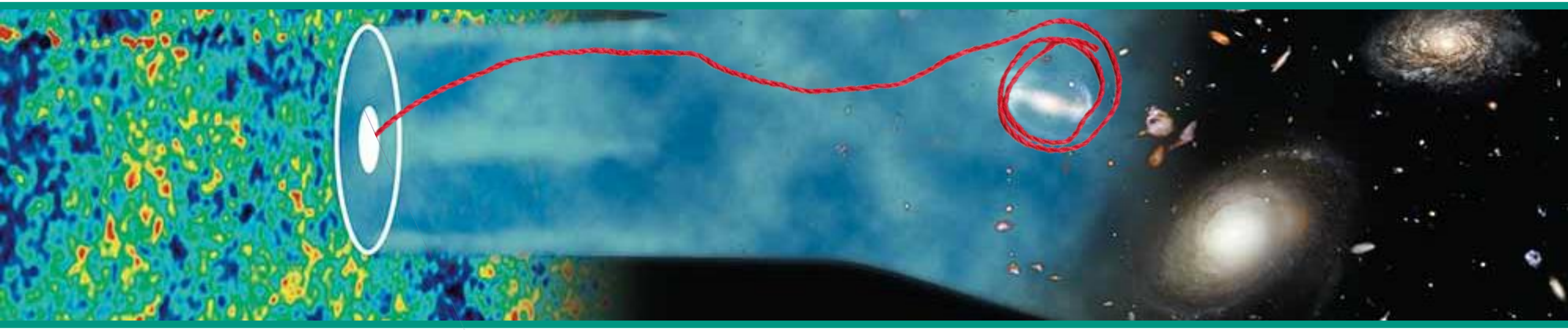




hands-on TRAINING

...modern analysis methods…

...advanced experimental methods…



OUTLINE

Cosmology: Outline

Cosmology: Outline

3. Thermal Universe

3.1 **primordial nucleosynthesis (BBN)**
the first three minutes

3.2 **cosmic microwave background radiation – essentials:**
formation, black body radiation, fluctuations

3.3 **cosmic microwave background radiation – experiments:**
COBE, WMAP & Planck

3.4 **cosmological ΛCDM concordance model**

Cosmology: Outline

4. Structure Formation in the Universe

4.1 **Inflation & Early Universe**

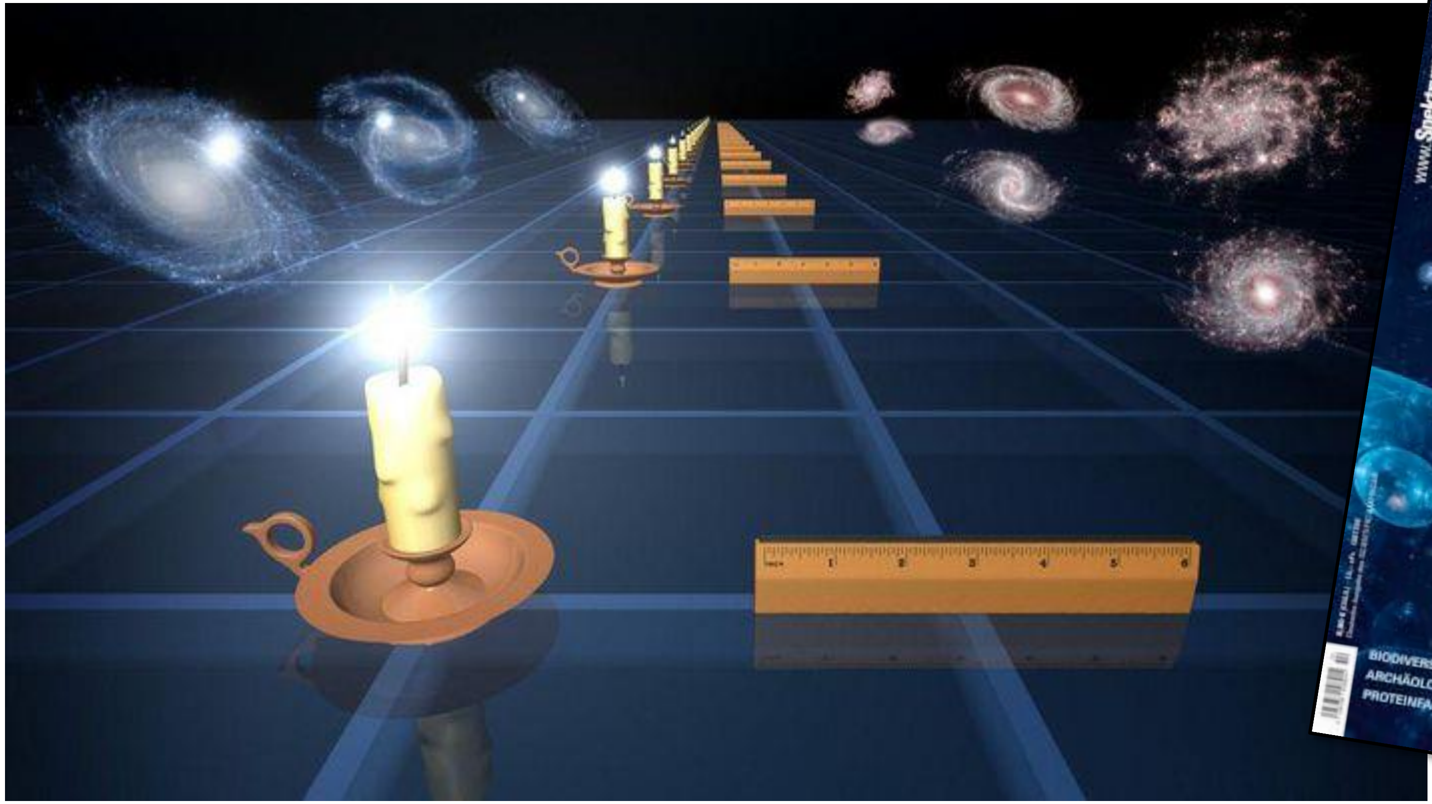
4.2 **BAO – Baryon Acoustic Oscillations :**
formation & relevance in the present universe

4.3 **Large-scale Galaxy Surveys:**
the matter power spectrum

4.4 **Evolution of Large-Scale Structures:**
hot, warm & cold Dark Matter

Cosmology: Outline

5. Dark Universe



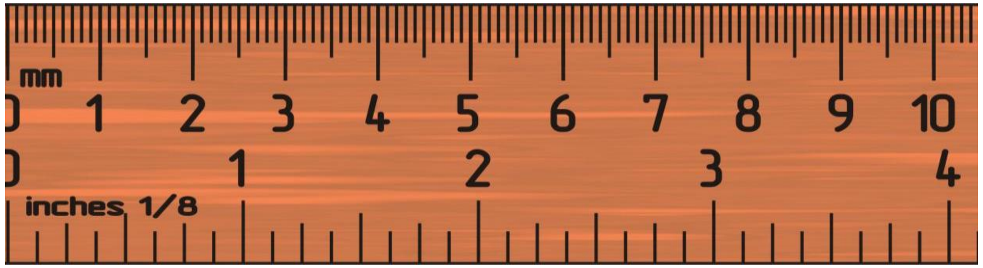
Q: NASA

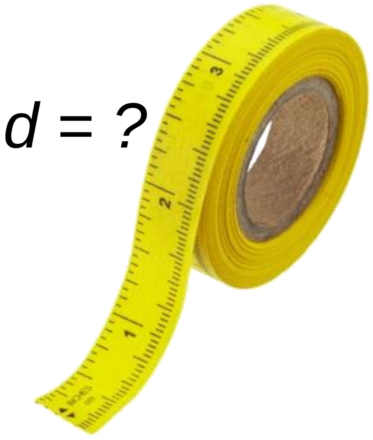
CHAPTER 1 - INTRODUCTION

cosmological distances and time scales

Measurement of distances

- cosmological standard candles up to *d* = ?

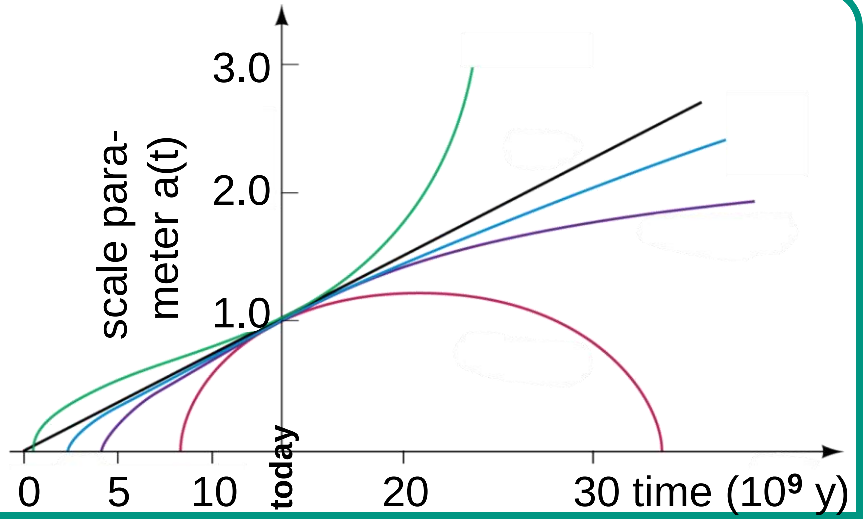




Q: NASA; maqns

Measurement of cosmological time scales

- cosmological standard time scale up to *t* = ?



Q: symmetricom, duoer

Cosmology: typical time- and distance-scales

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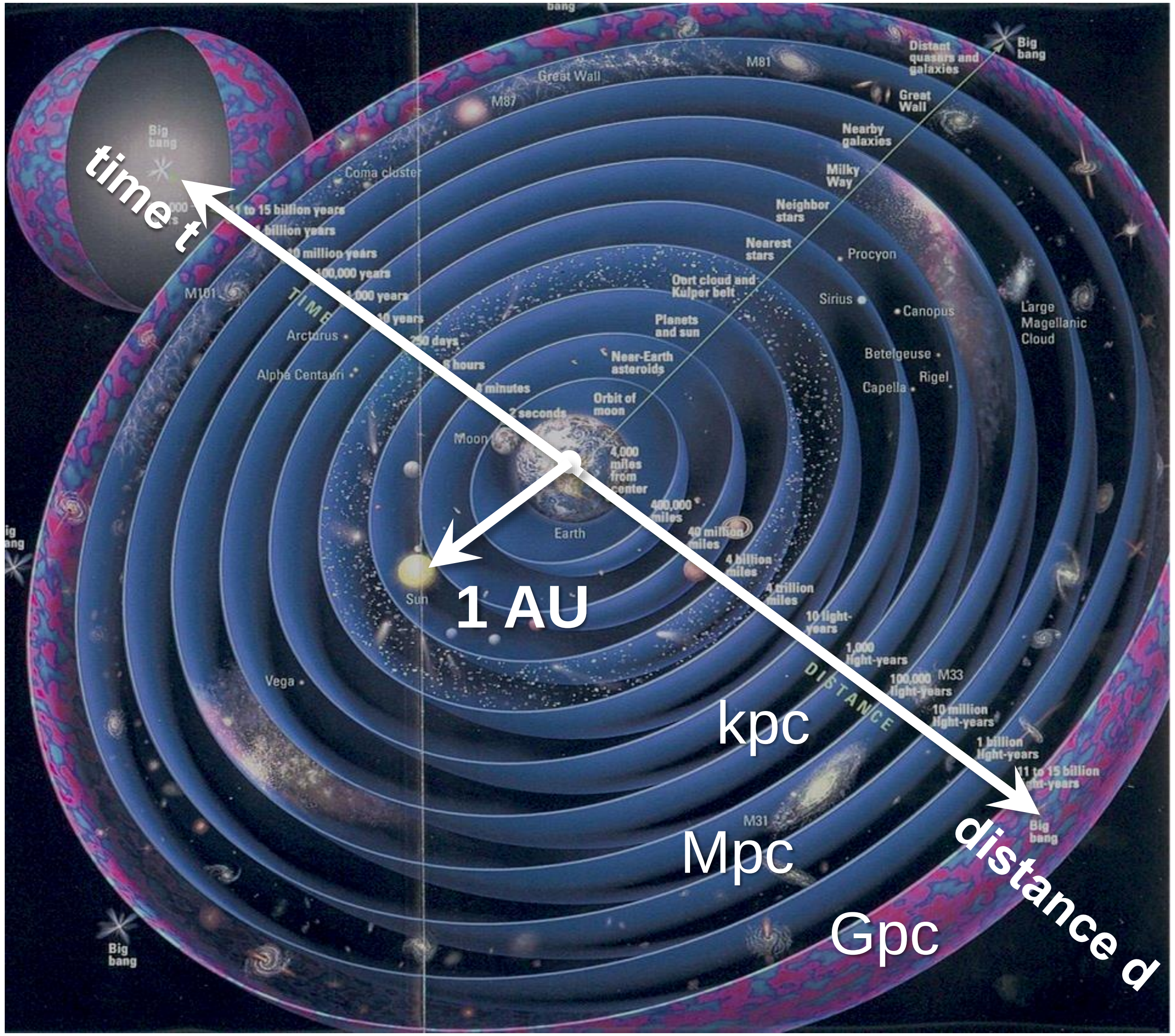


Q: NASA

astronomical scales	
1 AU	1.496×10^{11} m
1 ly	9.461×10^{15} m
	= 63 240 AU
	= 0.3066 pc
1 pc	3.086×10^{16} m
	$= 2.06 \times 10^{5}$ AU
	= 3.262 ly

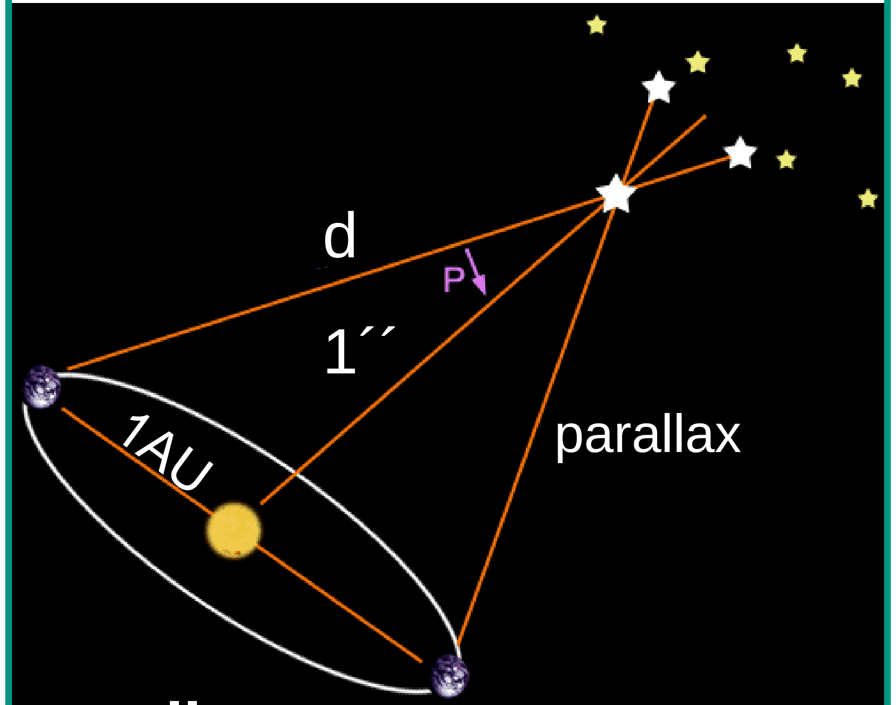
AU: Astronomical **U**nit
major semi-axis of Earth around Sun

ly: light-year light trajectory in t = 1 a

pc: parsec parallax of 1 arc-sec

Cosmology: typical time- and distance-scales

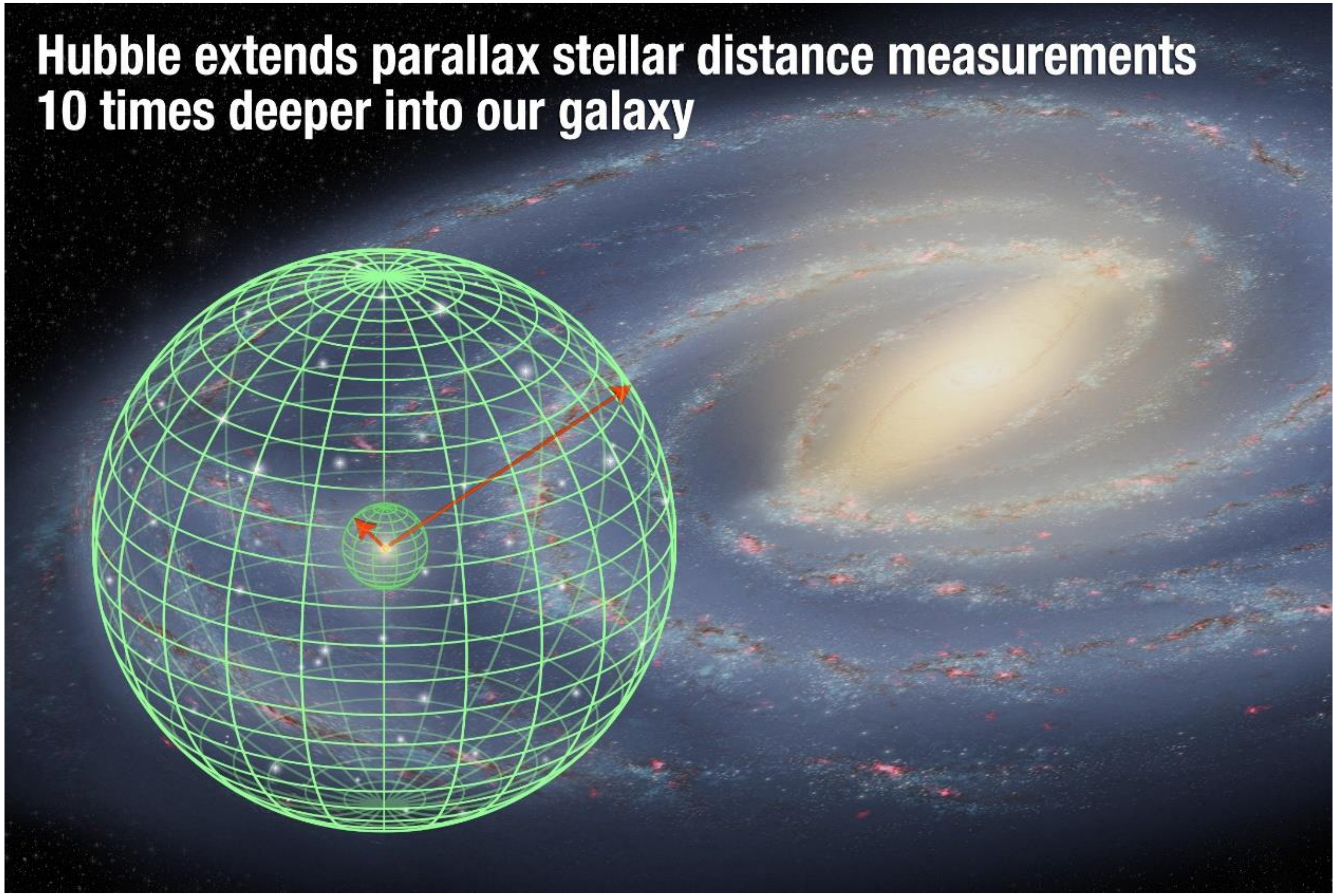
Definition of „parallax“



parallax:

1 pc = 1 AU subtends to 1´´

= 1 AU · 180 · (3600 / π)



Q: NASA

2014 - range of parallax measurements now: 3-4 kpc

1 ´´ = 1 arcsec = 1 arcsecond

Cosmology: typical time- and distance-scales

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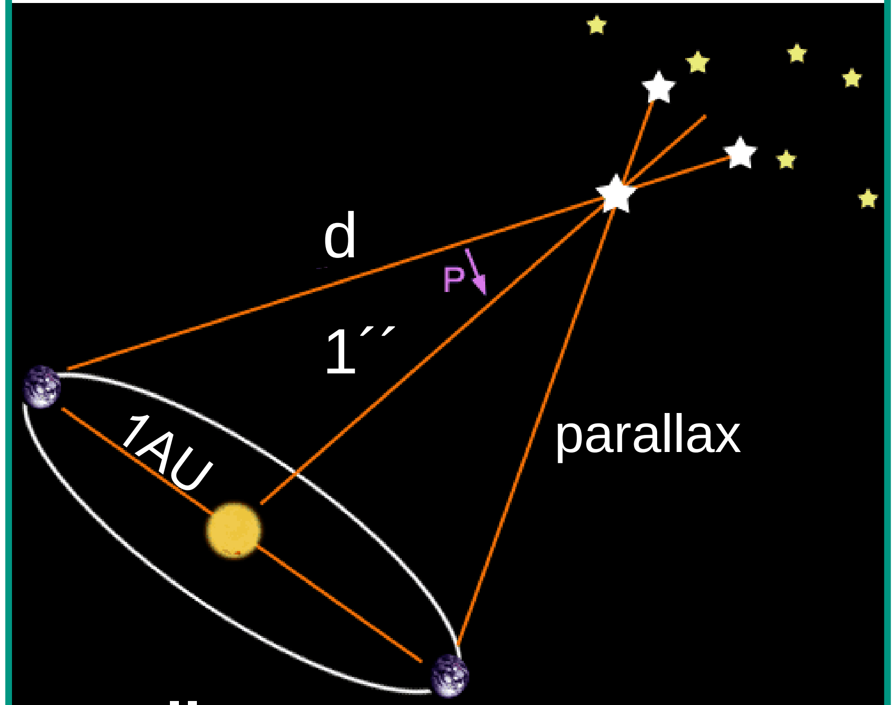
Definition of „parallax“



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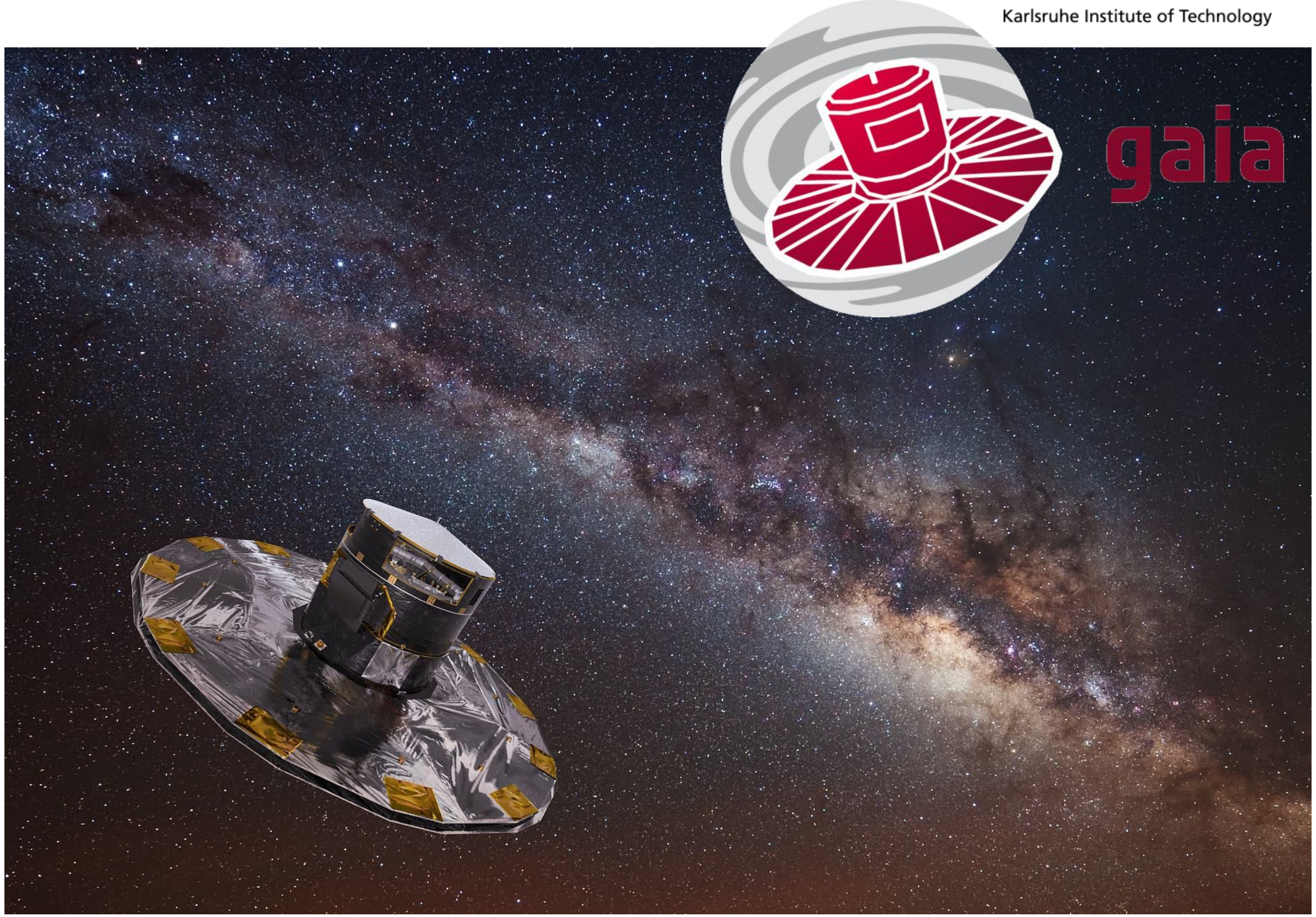


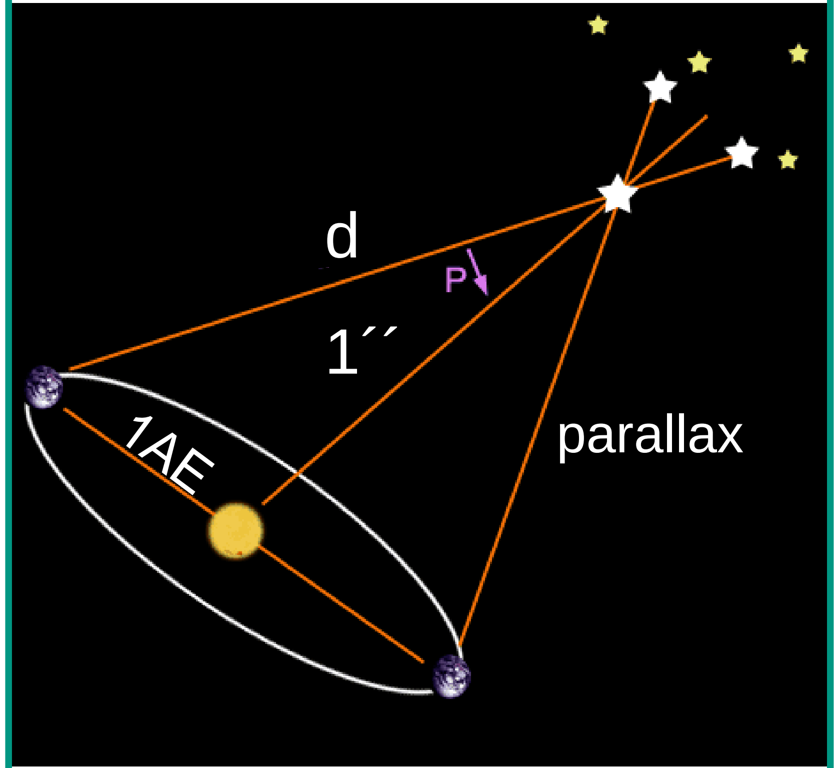
Q: ESA

measurements of GAIA with µas-precision*

*GAIA DR3 = 3. Data Release (June 2022)

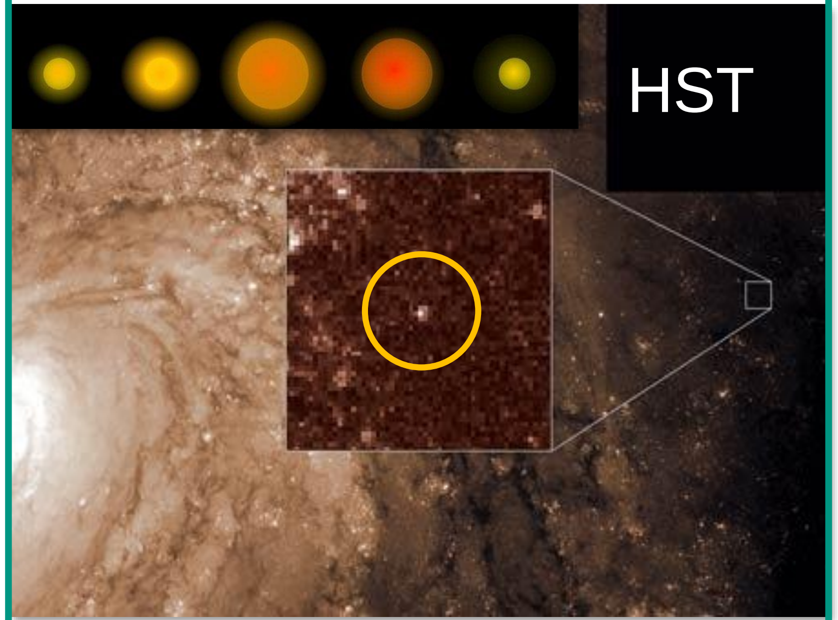
Cosmology: typical time- and distance-scales

parallax method



Parallax method: reach to
d = few kpc (Milky Way)

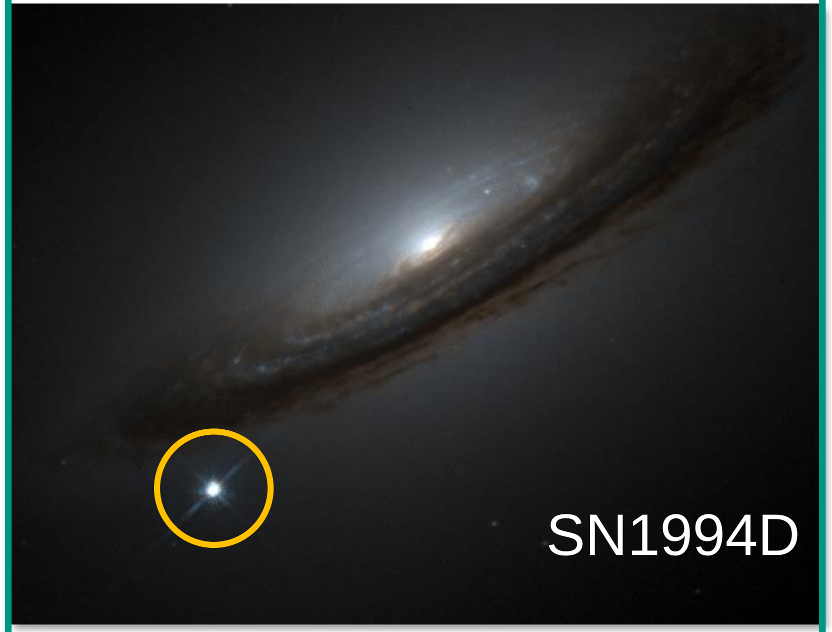
δ-Cepheids



δ-Cepheids: absolute luminosity $L_{abs} \sim 10^4 L_{\odot}$

d = 1 kpc - 50 Mpc

SN-Ia-brightness curve



Supernovae Type Ia: luminosity $L_{abs} \sim 10^9 L_{\odot}$

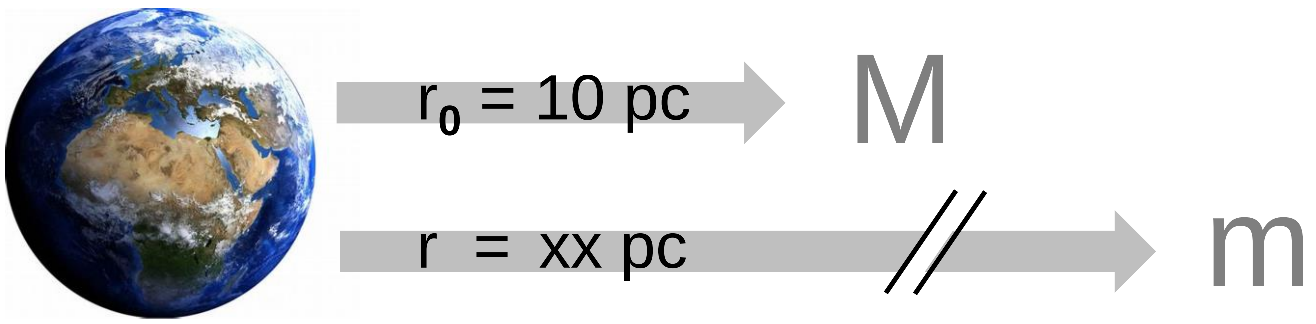
d = 30 Mpc – 3 Gpc

luminosity of the sun: $L_{\odot}$

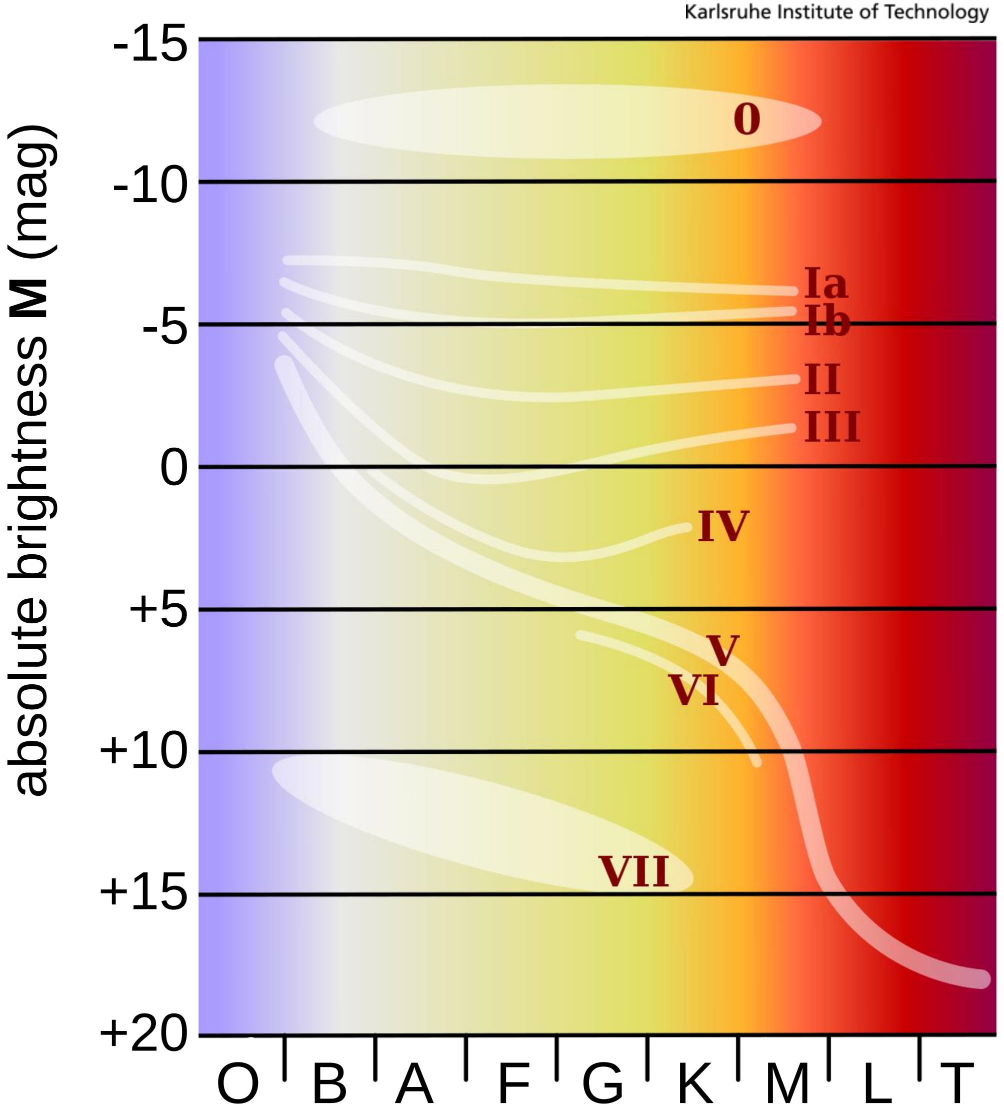
Brightness – definition in astronomy

absolute & relative brightness

- brightness of objects is measured in **magnitudes (mag)** = logarithmic scale
- absolute brightness **M**: defined at unit distance r_0 = 10 pc
- apparent brightness **m**: object as it appears here on Earth



Q: NASA



Q: wikipedia

Brightness – cosmological standard candles

absolute & apparent brightness: magnitude

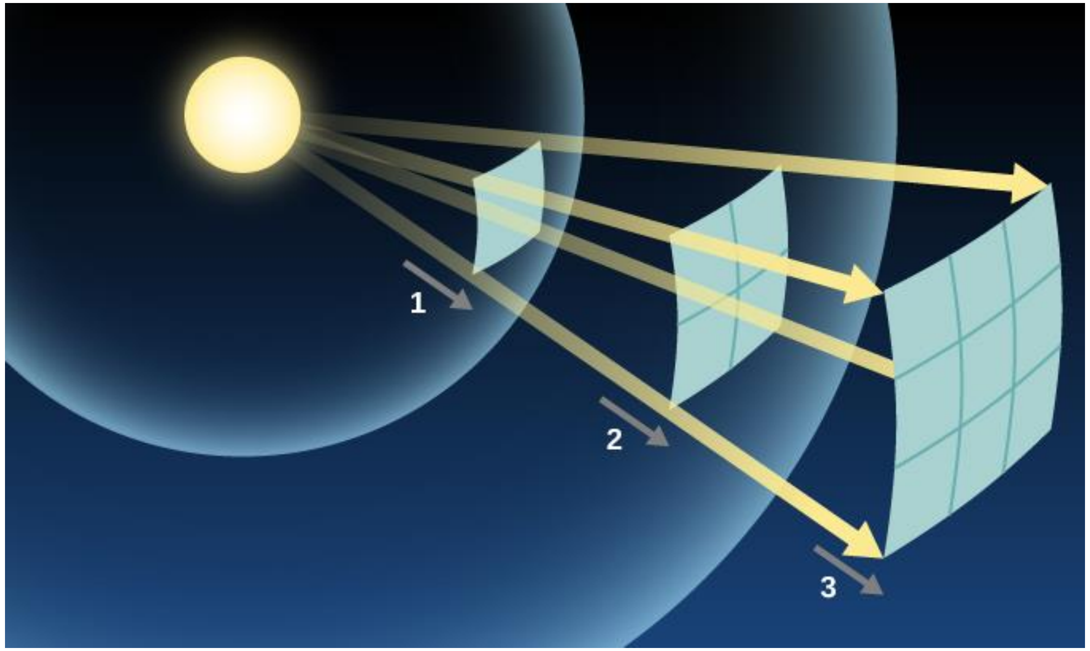
- reference: m ≡ 0 is defined for the nearby star Wega (α Lyrae)

- mag = logarithmic unit: difference of 5 mag ≡ factor 100 in brightness
  per magnitude: factor = $\sqrt[5]{100} = 2.512$

- **Distance modulus $\boldsymbol{m - M}$:**

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

quadratic distance law



Q: BCcampus

Cepheids – cosmological standard candles

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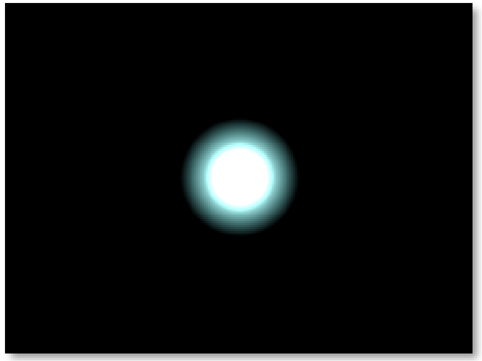
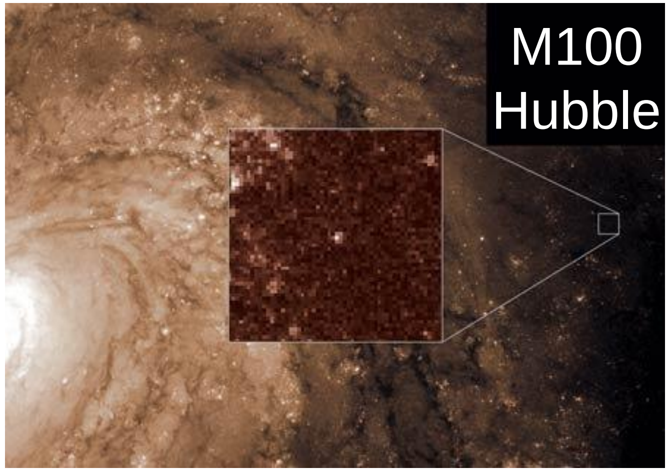
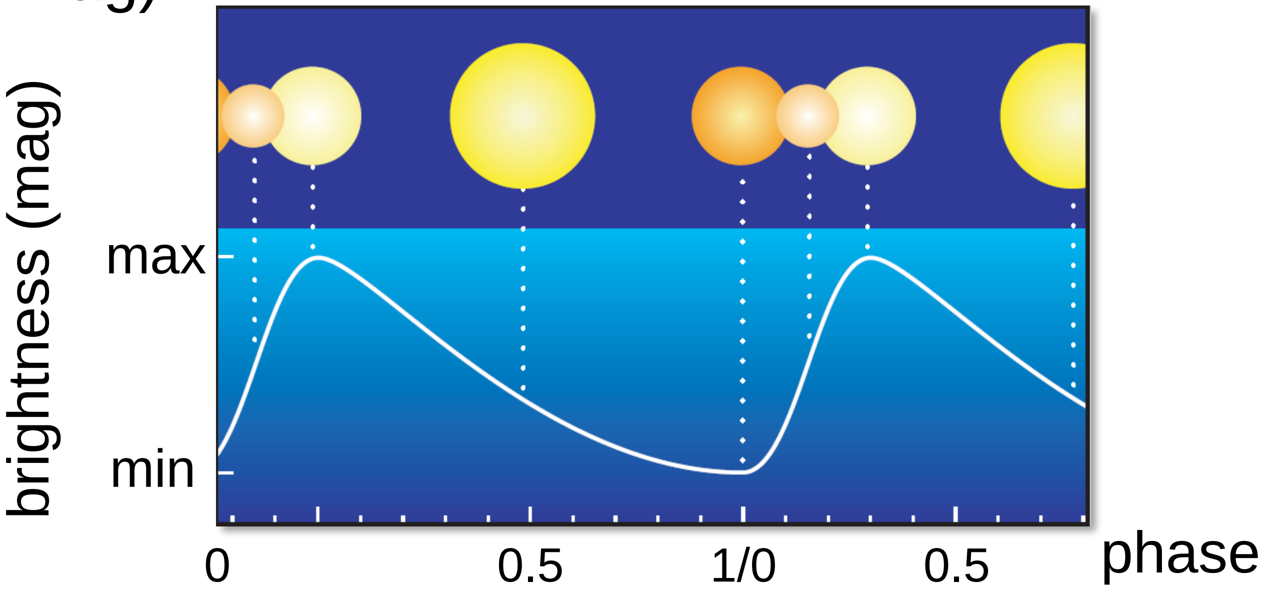
- **Cepheids:**
  - giant stars with radial pulsations (´super-giants´)
  - allows to determine **absolute brightness from period T_0**
  - mass range: $M = 5 – 15\ M_\odot$ (⇨ very rare stars)
  - spectral class: F, G (white, yellow)
  - brightness class: Ia, II (M_V = -2 … -7 mag)
  - period: T_0 < 100 days

period of a δ-Cepheid



Q: NASA





M_V = visual brightness

Cepheids – cosmological standard candles

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- „Kappa mechanism“ causes the radial pulsations of Cepheids

changes in the opacity $\kappa(p, T)$ of a specific stellar layer

- important: hot stellar core causes an He-ionisation layer with He^{++} & He^{+} - ions

- **cycle of stellar pulsation:**

increasing T:

more He^{++} & free electrons

↳ larger opacity

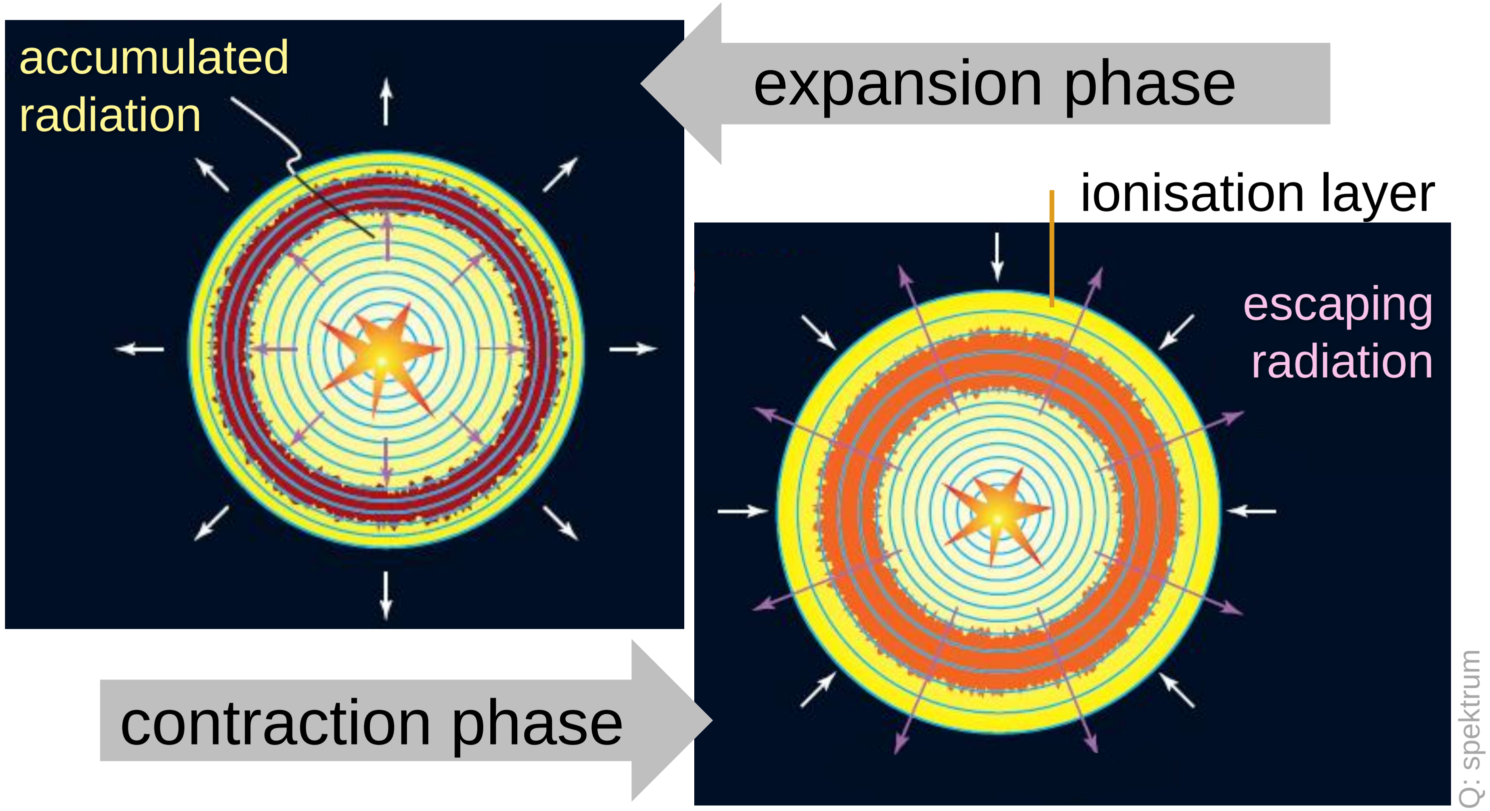
↳ increase of rad. pressure

↳ expansion of outer shell

decreasing T:

gravitational contraction

↳ recombination to He^{+}



Cepheids – cosmological standard candles

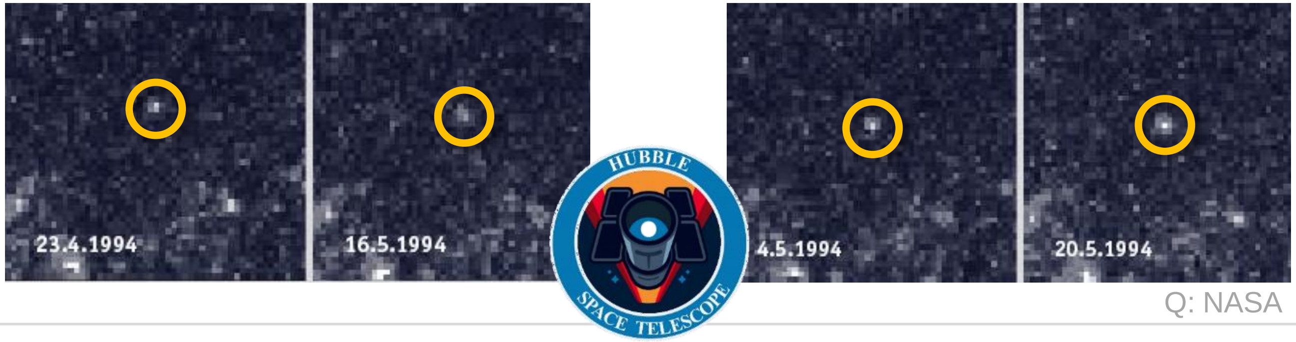
- **pulsation time scale of outer stellar shell**

  - very massive, very bright cepheids are pulsating more slowly, **period $T_0 \sim L^{3/4}$**

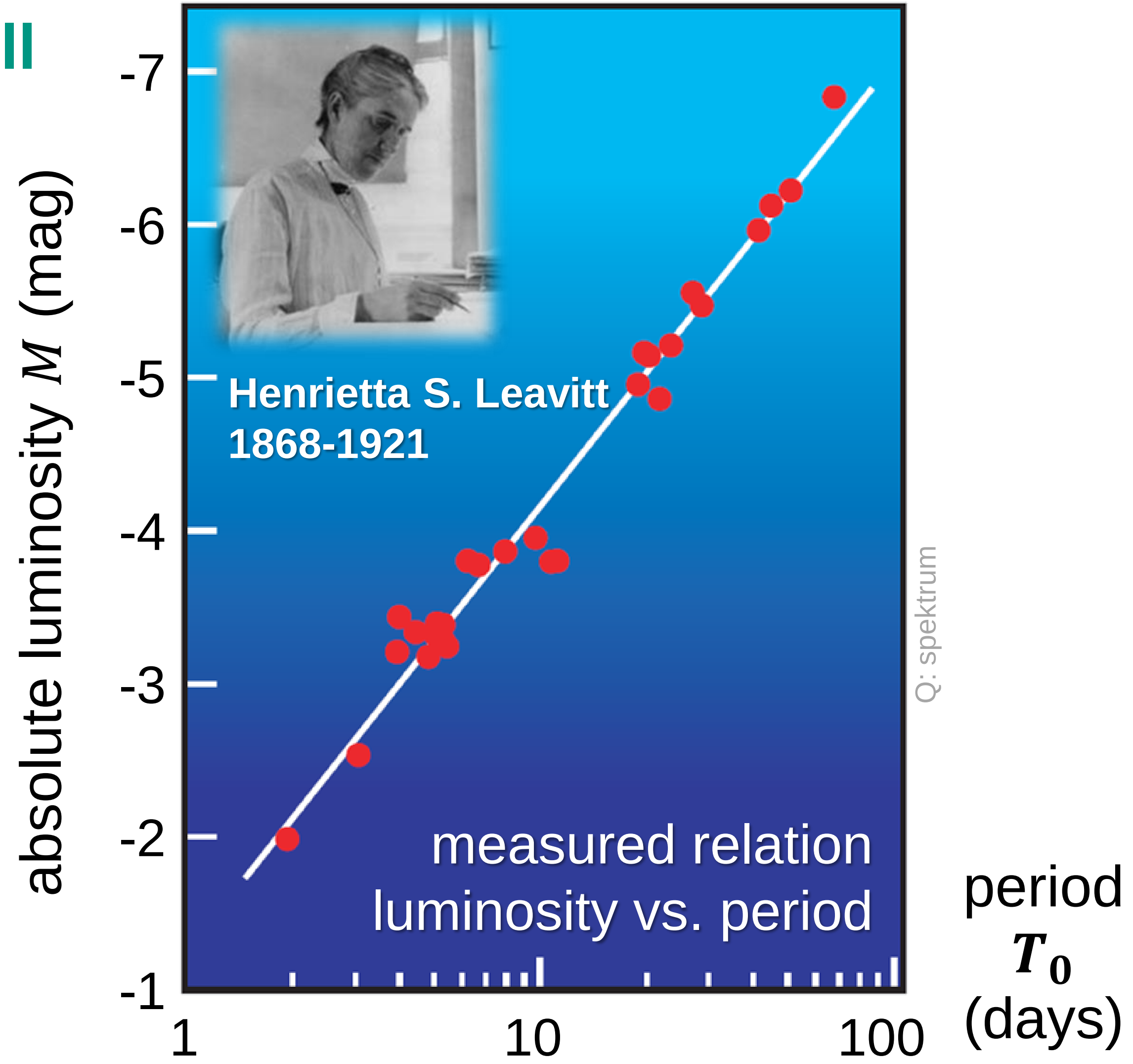
pulsation period - luminosity relation

$$M = -2.81 \cdot \log(T_0) - (1.43 \pm 0.1)$$

T_0: pulsation period (days)
M: absolute brightness (mag)



Q: NASA



Supernovae – cosmological standard candles

SN Ia: thermonuclear detonation*

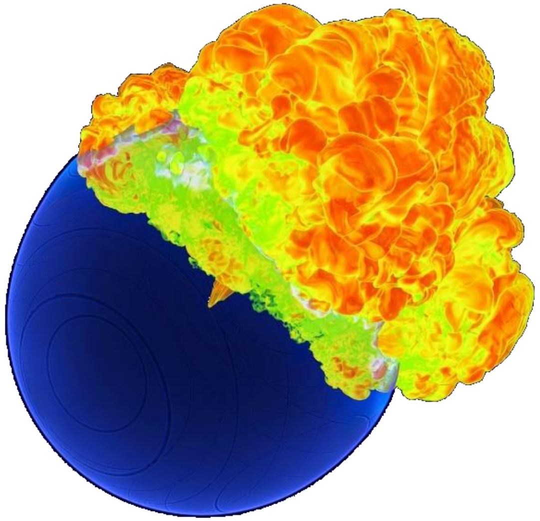
- a white dwarf reaches a mass of $M \geq 1.4\ M_{\odot}$

Q: Nature

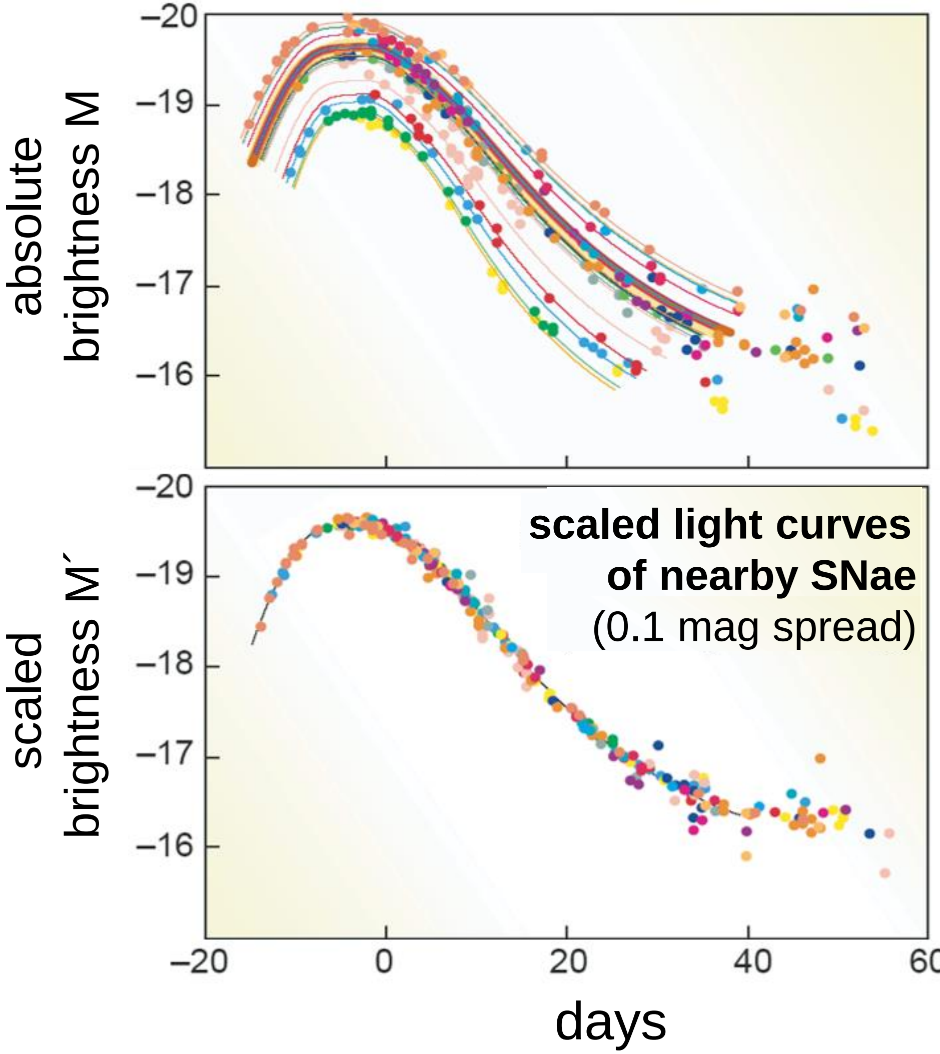
merger scenario

or

Q: U of chicago



accretion scenario



Q: Nature

*s. also ATP-2 lectures (summer term 23)