Karlsruhe Institute of Technology

# Introduction to Cosmology

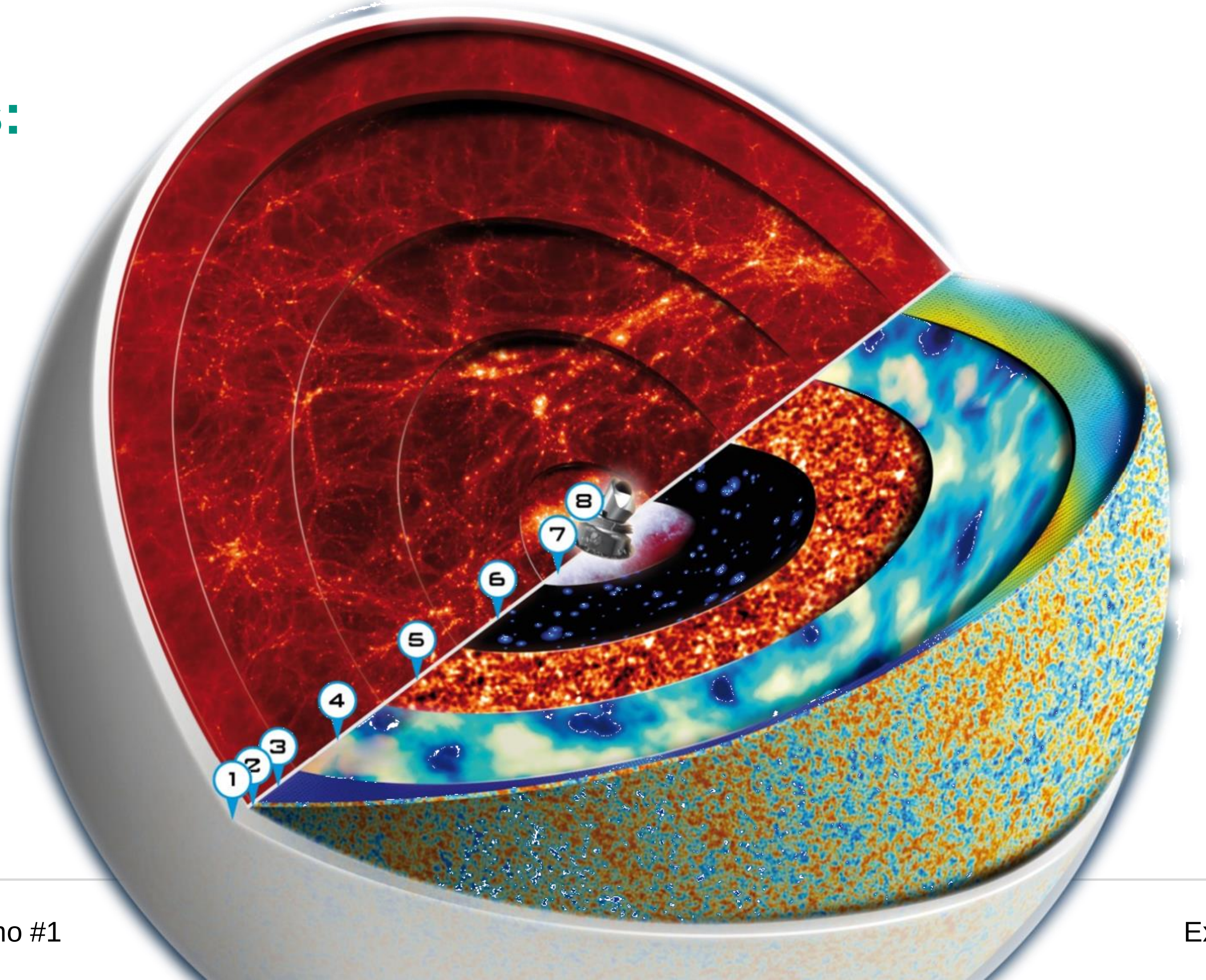
Winter term 23/24 Lecture 1 Oct. 24, 2023

# Cosmology – Definition

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

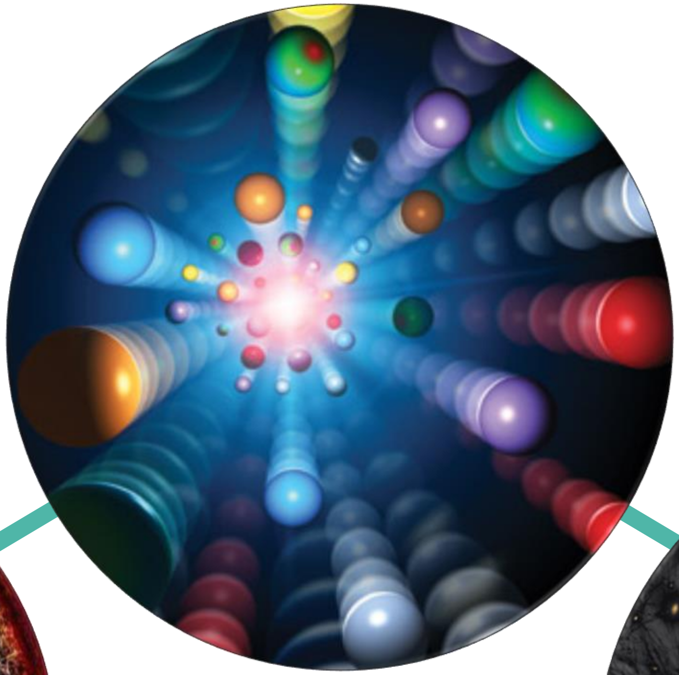
**important stopovers:**

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

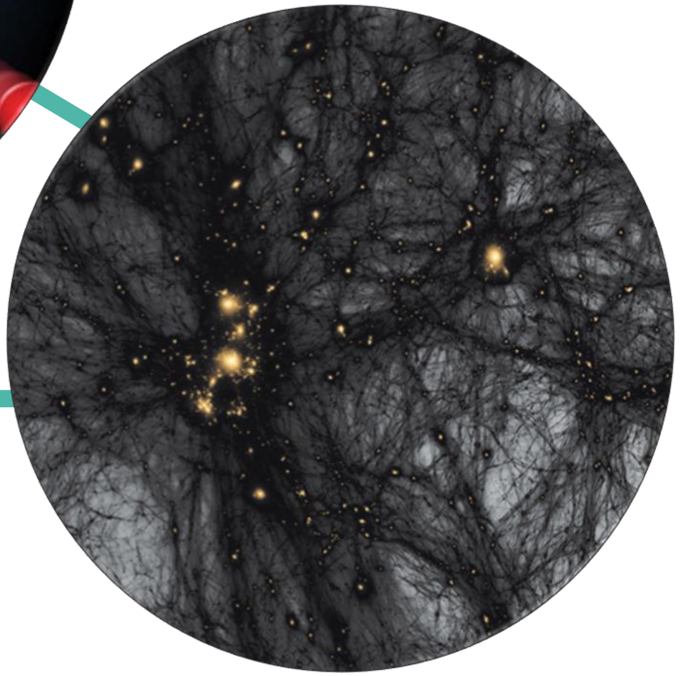


# Cosmology – range of subjects

- **subjects of cosmology**

processes in  the **Early Universe**

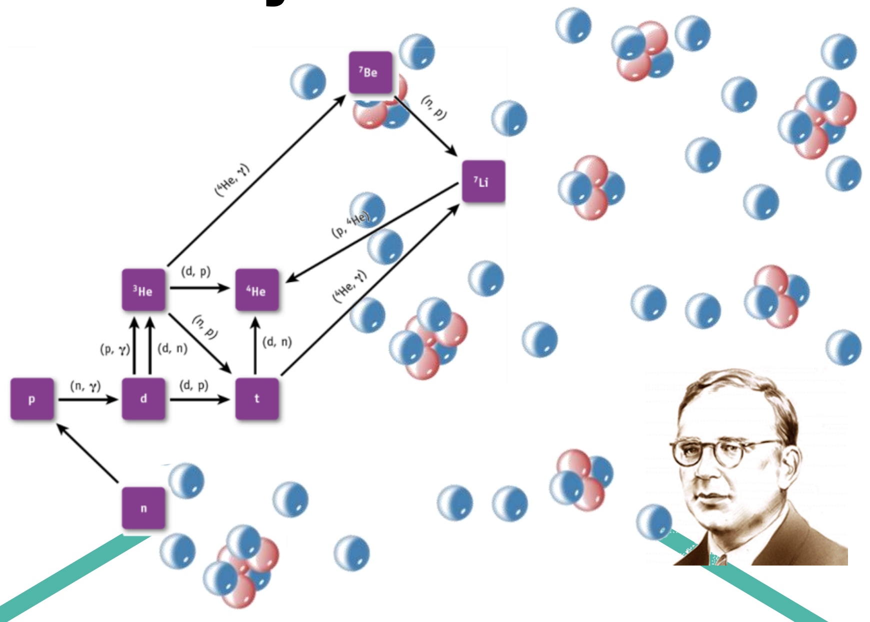
**Strucuture Formation** 

 **Dark Universe**

**three pillars of these lectures**

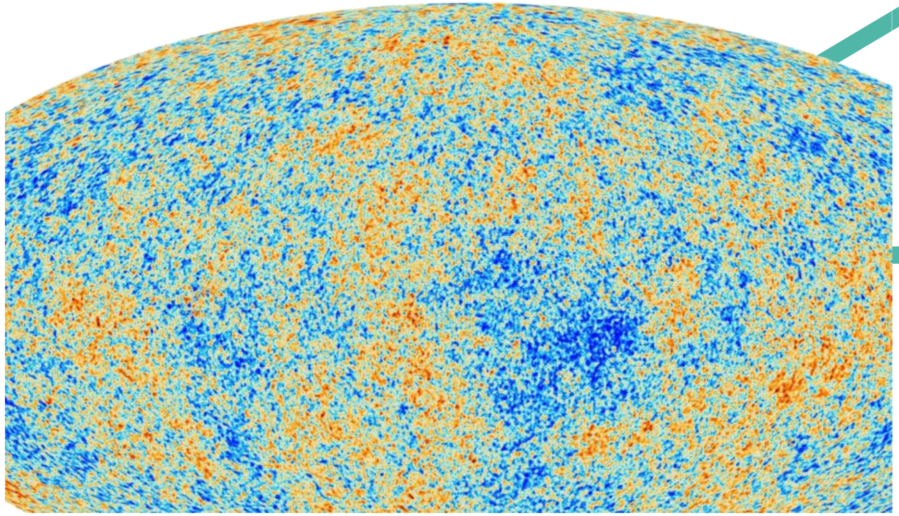
# Cosmology – range of subjects

- **example:**
  **thermal processes**




**formation of elements**
during Big Bang

$\boldsymbol{CMB^{*}}$–
temperature





neutrino properties



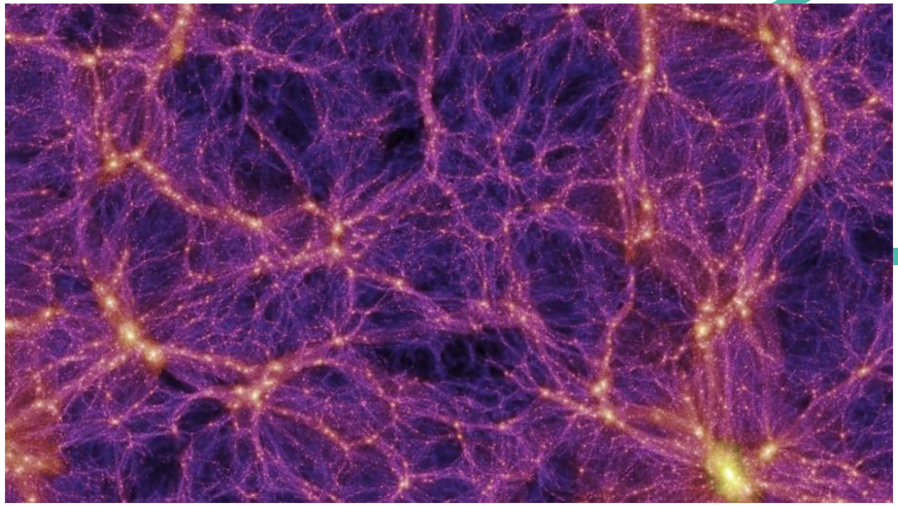
******C*osmic ***M***icrowave ***B***ackground

# Cosmology – range of subjects

- **example:**
  ***D*ark *M*atter (*DM*)**


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

***DM*** in
structure formation



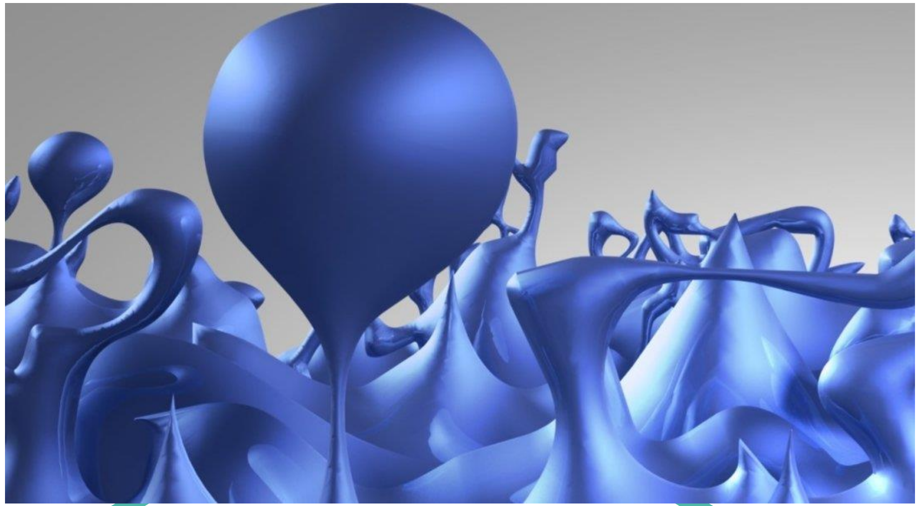
galactic
***DM*** –
halos



* ***H***ot ****W***arm *****C***old ***D***ark ***M***atter

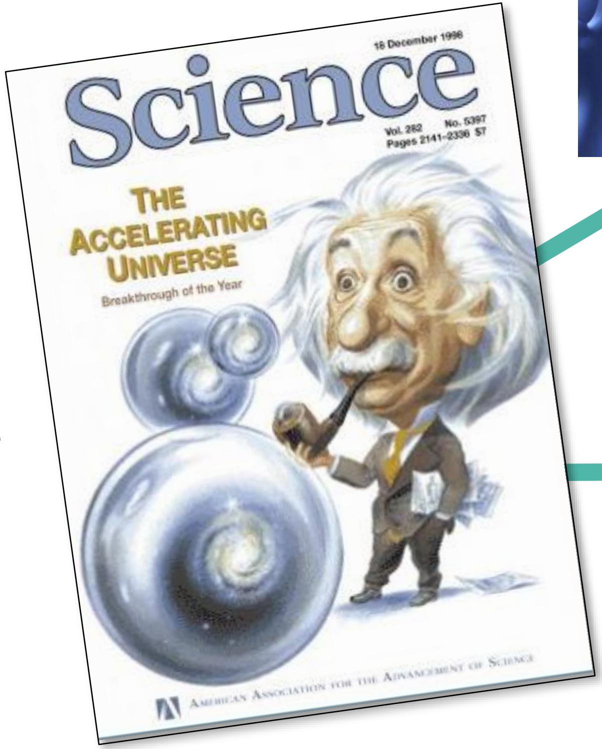
# Cosmology – range of subjects

- **example:**
  ***D*ark *E*nergy (*DE*)**



nature of ***DE***:
**cosmological constant** ?

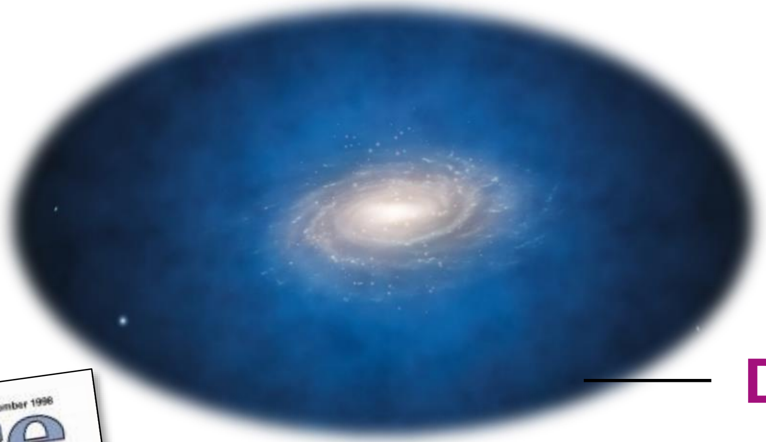
evidences for ***DE***



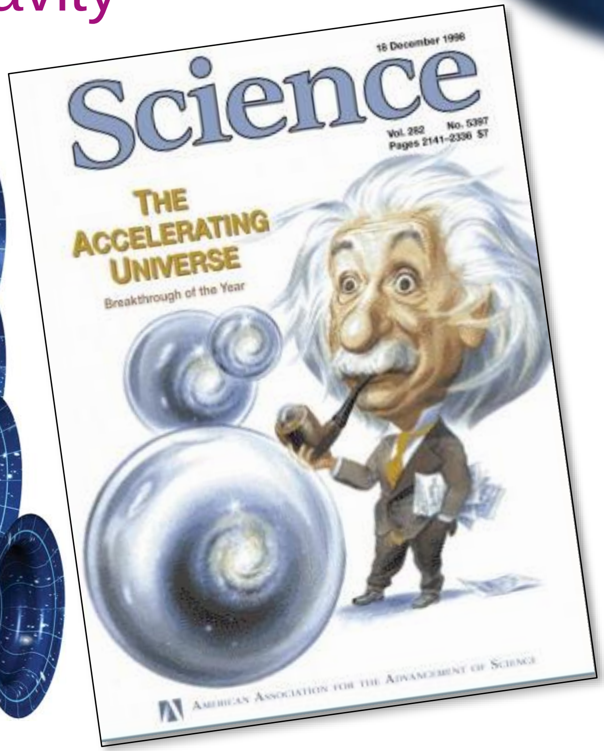

***DE*** & expansion rate of the universe

# Cosmology – new concepts

- **classification**



**Anti**–gravity




**Dark** Matter

**Bachelor Studies**

gravity

nuclear physics
thermodynamics
optics

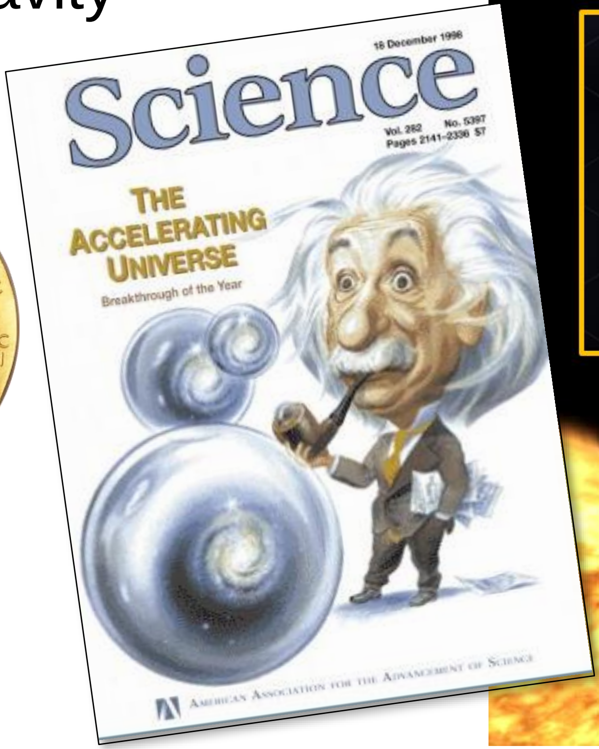
condensed matter, atoms, molecules

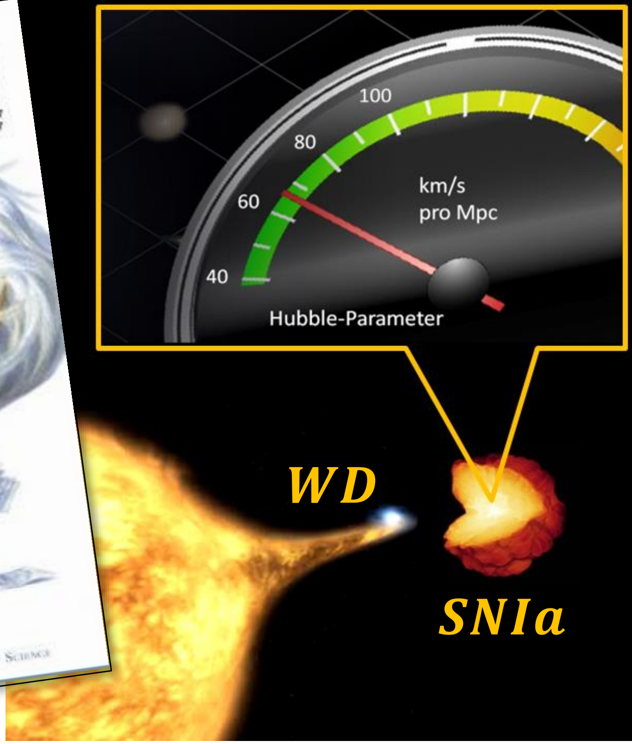
# Cosmology – modern observations

- **Nobel Prize 2011**

„*for the discovery of the* ***accelerating expansion of the Universe*** *through observations of distant supernovae*"

**Anti**–gravity



Saul Perlmutter


Adam G. Reiss


Brian P. Schmidt

# Cosmology – modern theories

- **Nobel Prize 2019**

structure formation

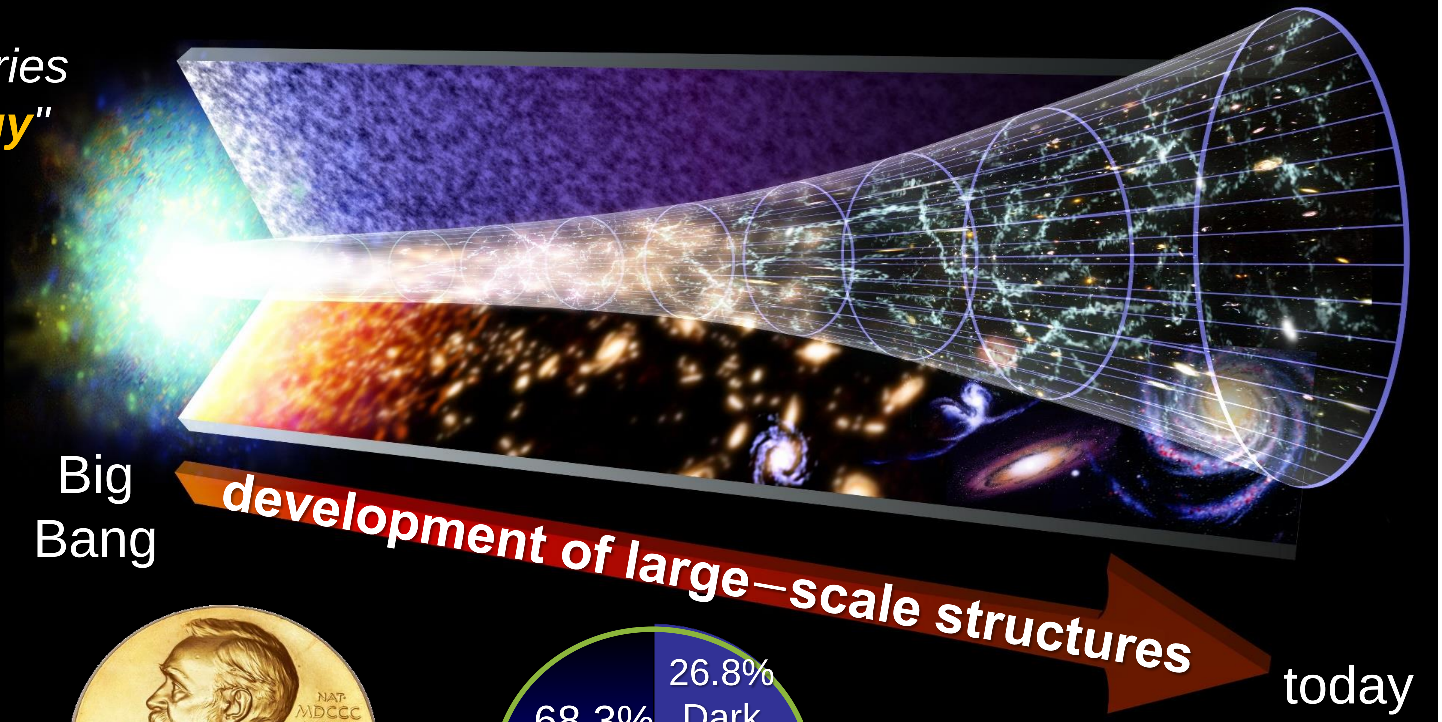

**50 %**

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

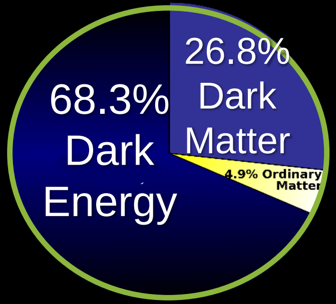
Nobel prize for physics **2019**

*„for theoretical discoveries in* ***physical cosmology***"

James Peebles



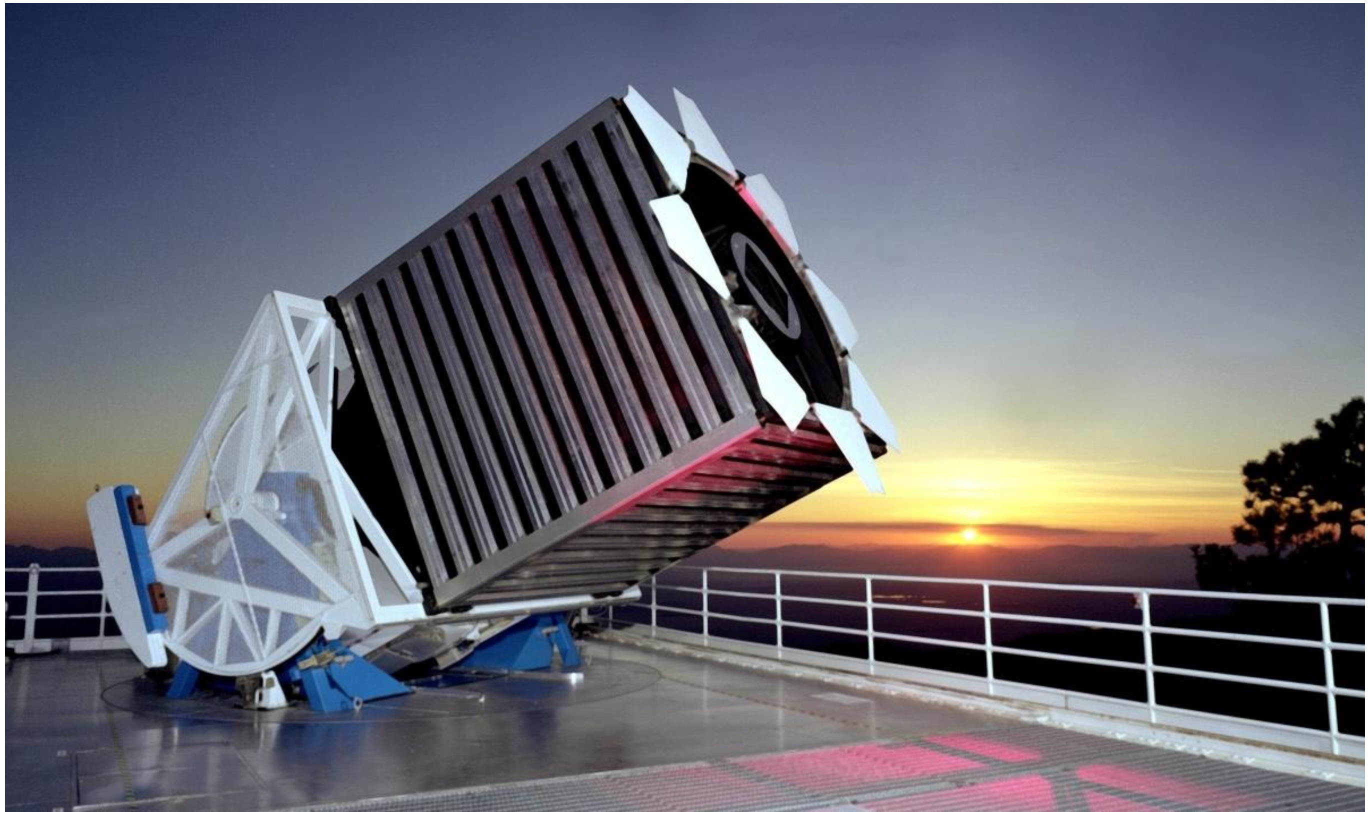


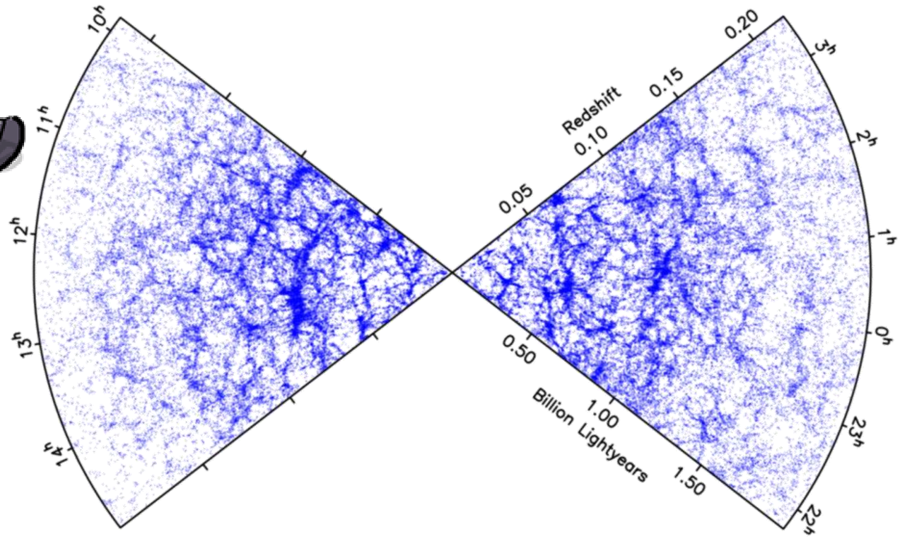


# Cosmology – observations

- example: galaxy redshift surveys

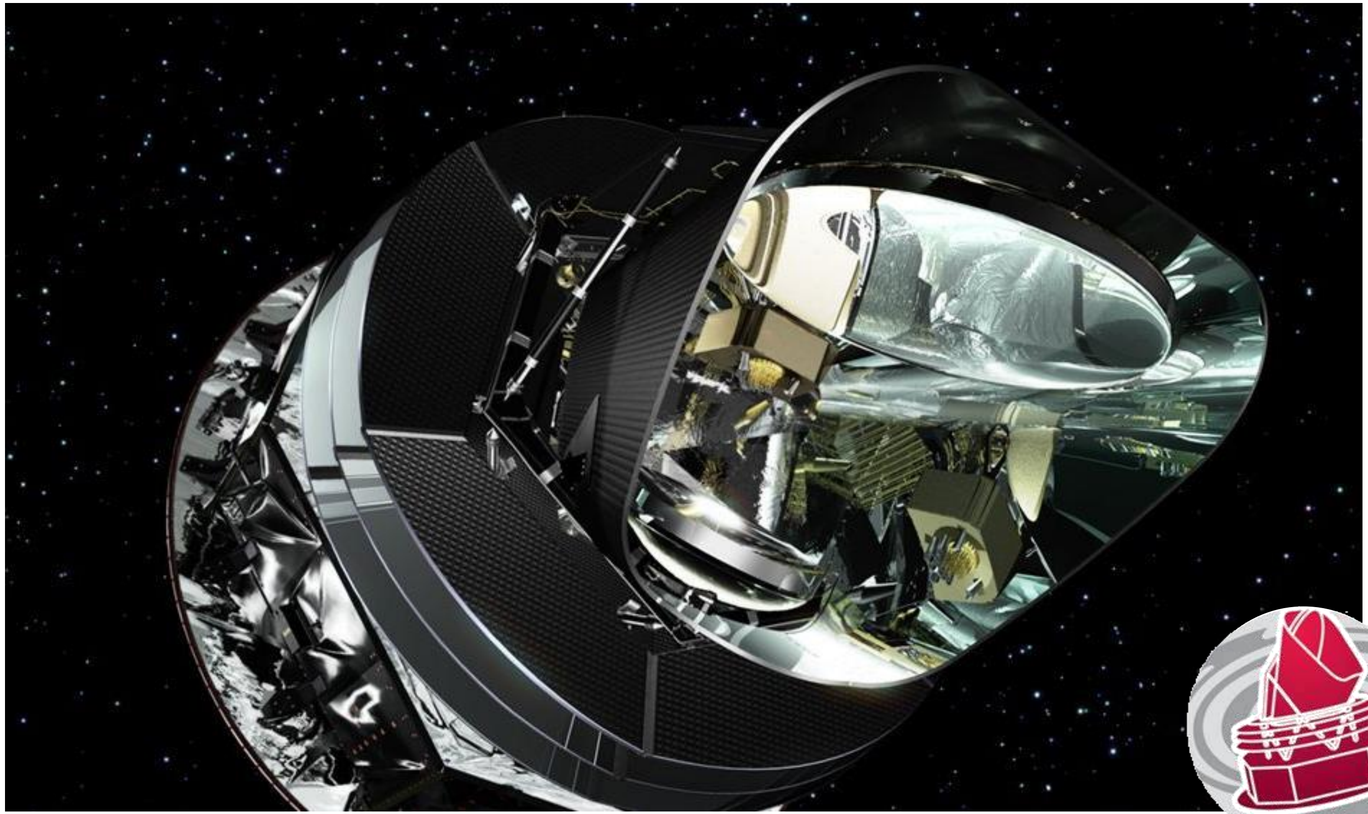
SDSS

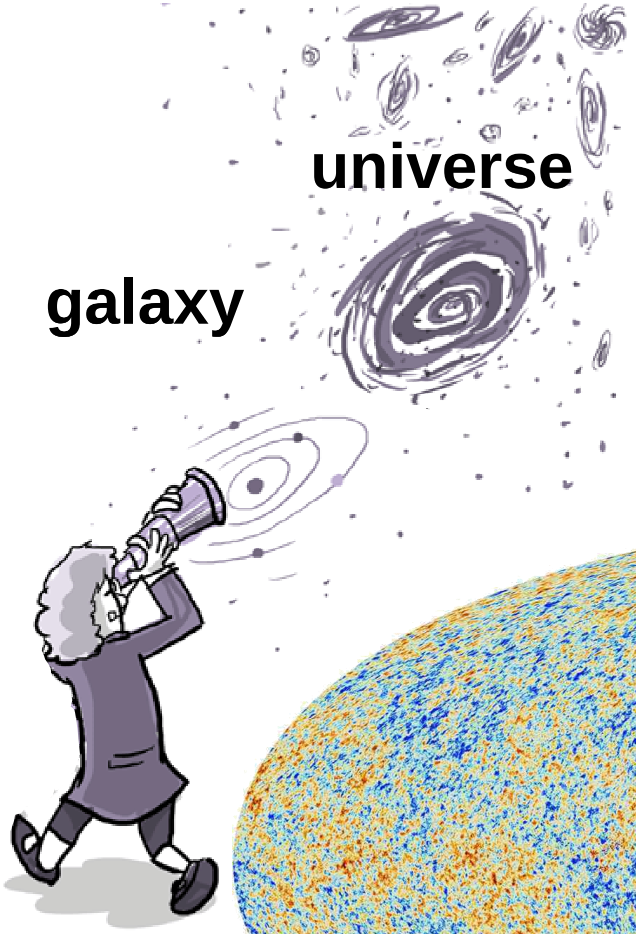


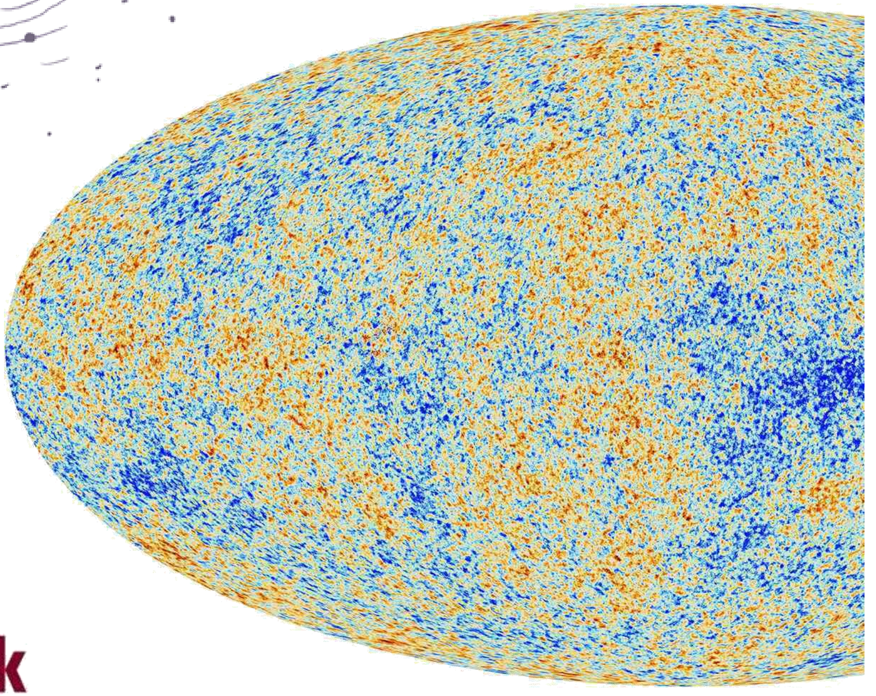



# Cosmology – observations

- **example:** **temperature fluctuations of the $CMB$ ($C$osmic $M$icrowave $B$ackground radiation)**



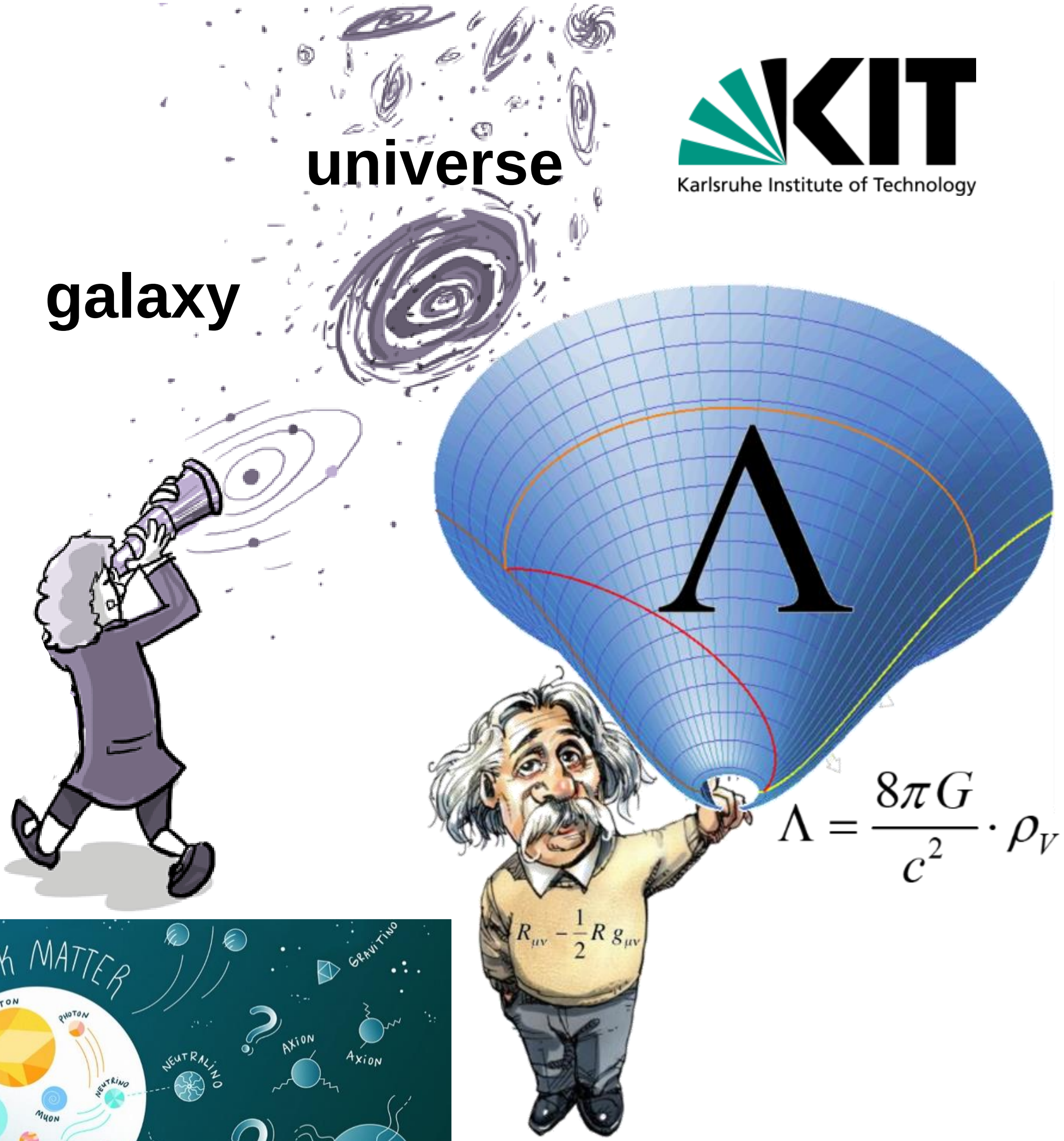


# Cosmology – open questions

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



# I can learn the following in this lecture series:

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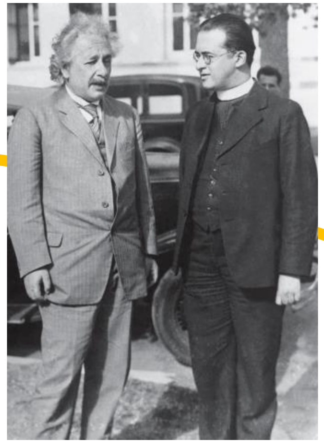
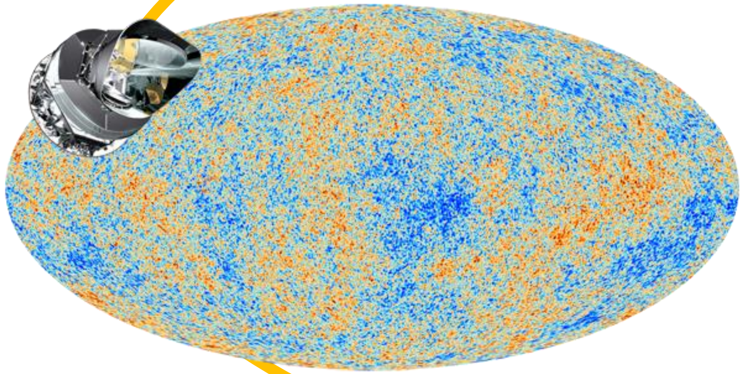
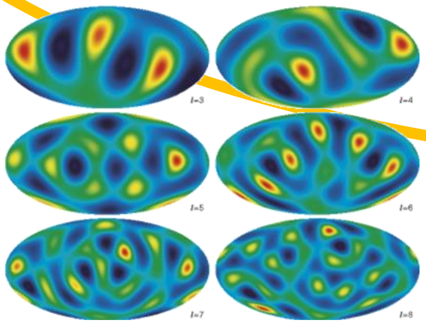


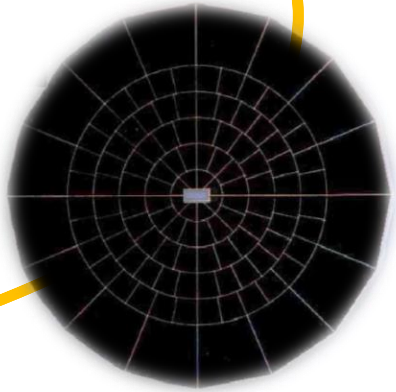
$$\left(\frac{\dot{H}(t)}{H(t)}\right)^2 \sim 1 + \frac{7\Delta N_\nu}{43}$$

...new tools for discoveries...



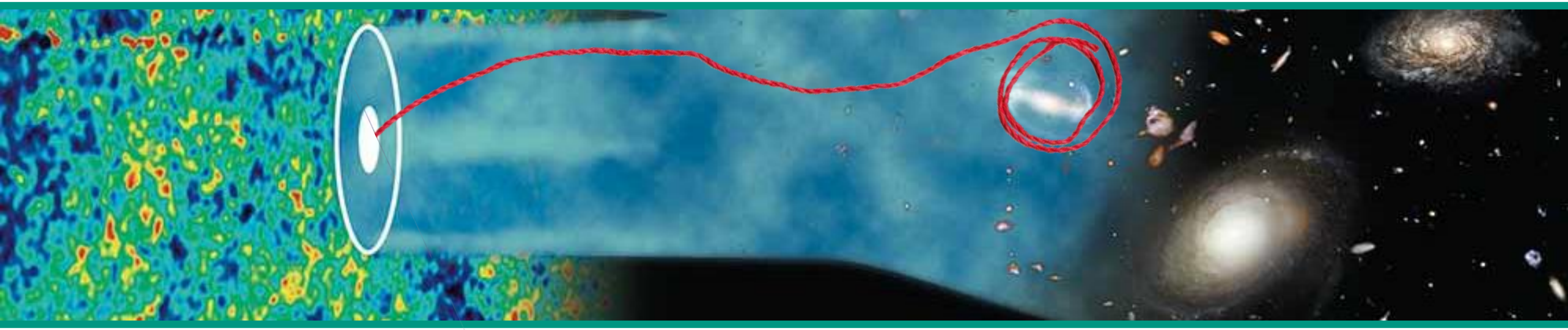
hands-on TRAINING





...modern analysis methods...

...advanced experimental methods...



# OUTLINE

# Cosmology: Outline

## 1. Introduction

1.1 fundamental principles

1.2 distance ladders for the Universe

## 2. Expanding Universe

2.1 Hubble Expansion

2.2 Friedmann–Lemaître equations

# 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 $\Lambda CDM$ 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

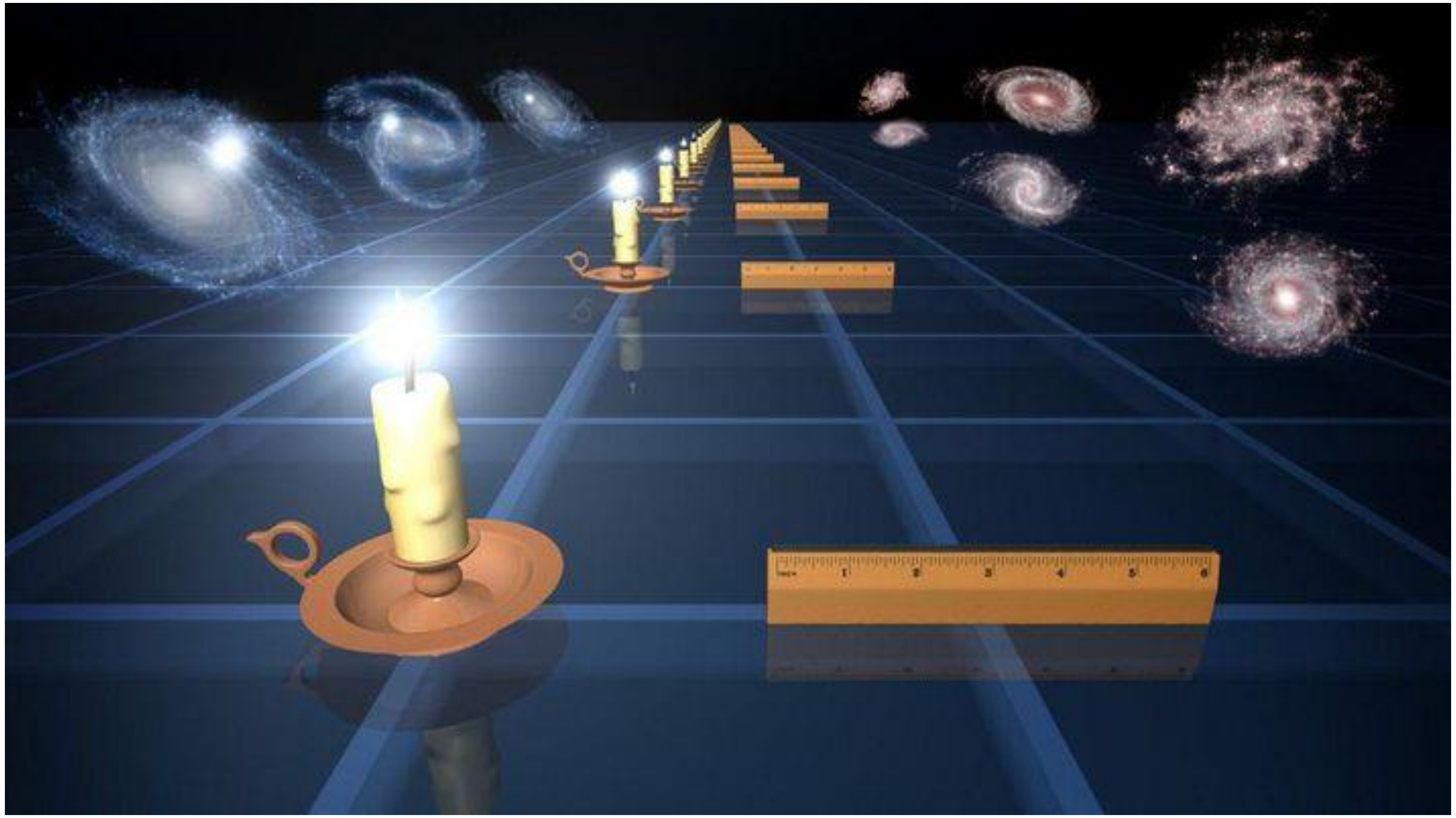
## 5. Dark Universe

**5.1** **Evidences for Dark Matter:**
from *Vera Rubin* & *Fritz Zwicky* to the Bullet–Cluster

**5.2** **Gravitational Lenses for the Dark Universe:**
strong & weak lensing

**5.3** **Dark Matter Halos: the $NFW -$ Profile**

**5.4** **Dark Energy:**
the future evolution of the Universe



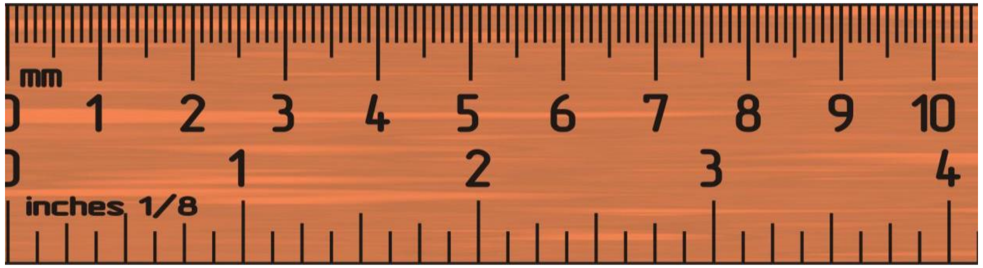

Q: NASA,S. Harris

# CHAPTER 1 – INTRODUCTION

# cosmological distances and time scales

## Measurement of distances

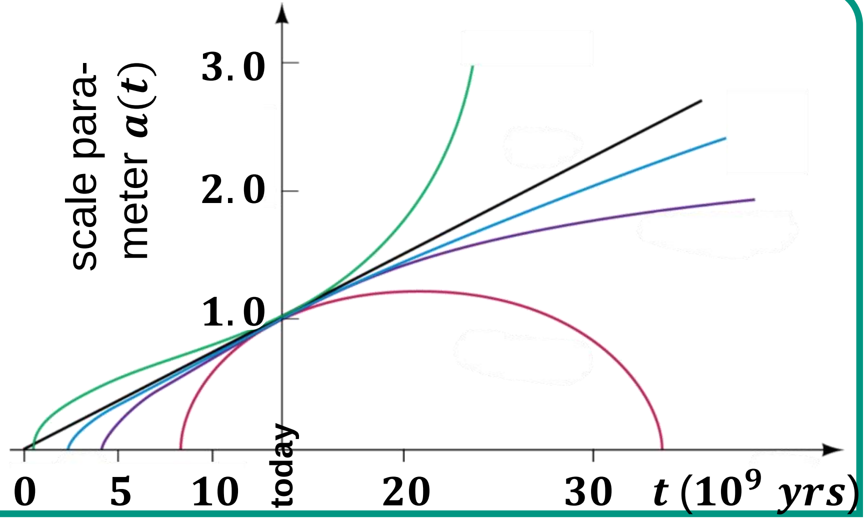
- cosmological standard candles up to $D = ?$



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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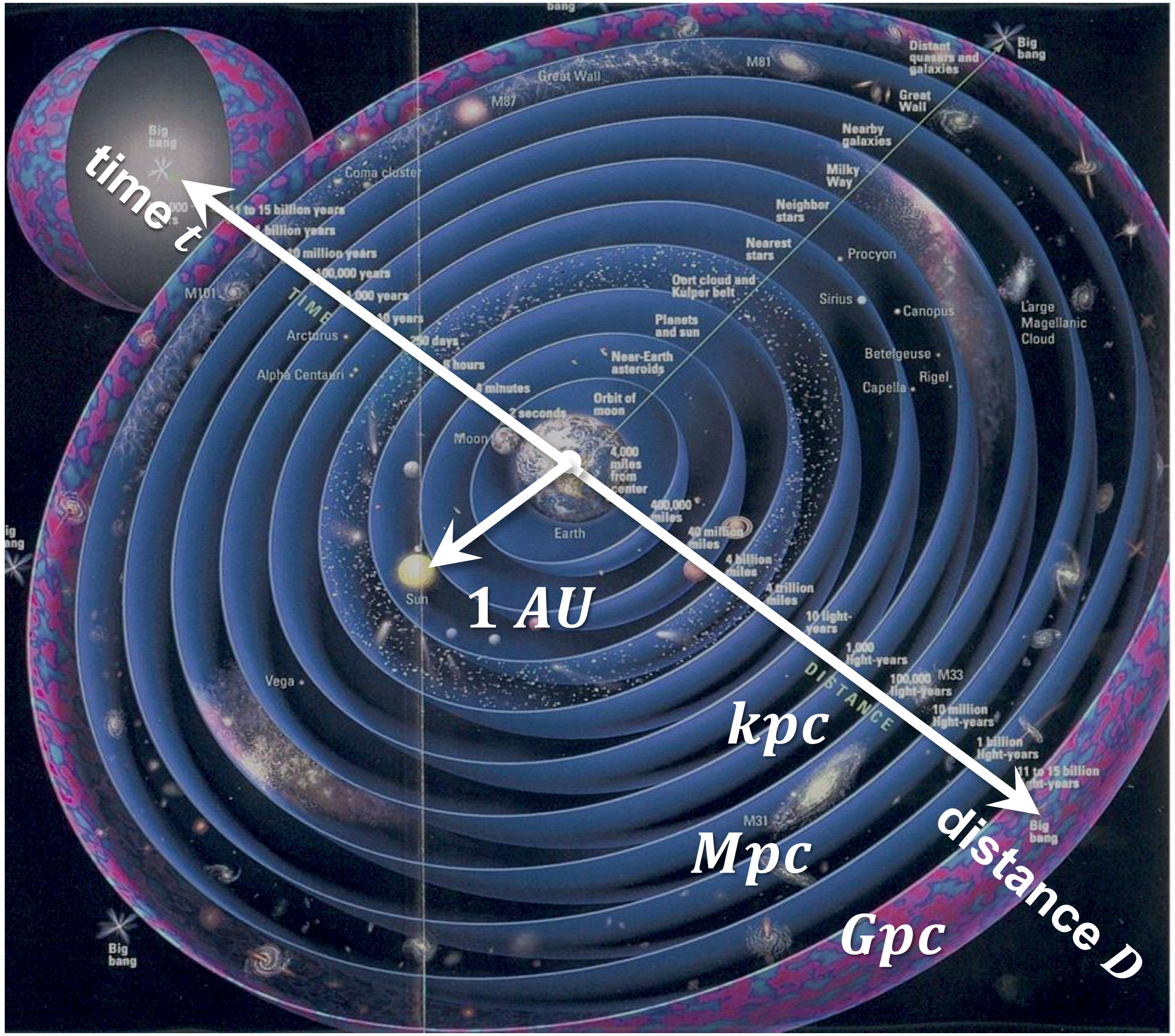



Q: NASA

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

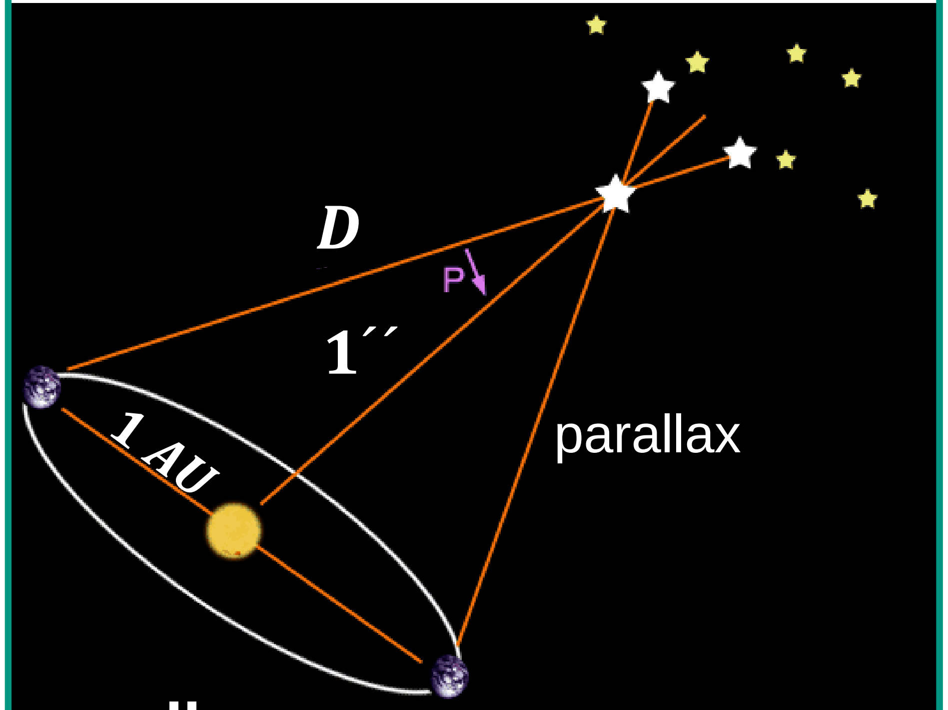
$AU$: $A$stronomical $U$nit
major semi–axis of Earth around Sun

$ly$: $l$ight–$y$ear light trajectory in $t = 1\ yr$

$pc$: $p$arse$c$ parallax of $1\ arc - sec$

# Cosmology: distance– scale $pc$

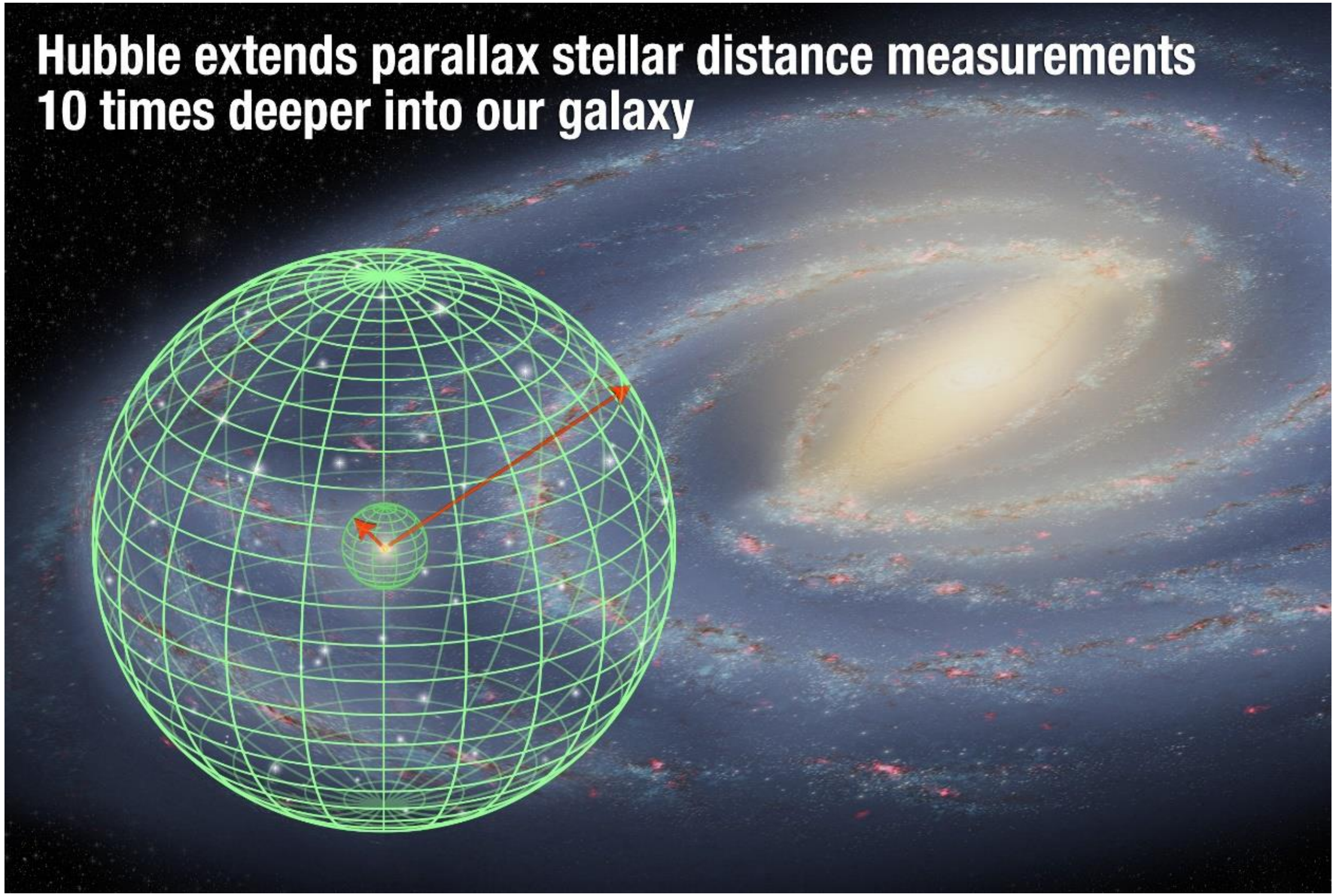
definition of ´parallax´




**parallax:**

$1\,pc = \ 1\,AU$ subtends to $1´´$

$= \ 1\,AU \cdot 180 \cdot (3600\,/\,\pi)$




Q: NASA

$\mathbf{2014}$ – parallax measurements now up to $\mathbf{3-4}\ \boldsymbol{kpc}$

$1´´ = 1\,arcsec = 1\,arcsecond$

# Cosmology: distances & $GAIA$ observatory ($ESA$)

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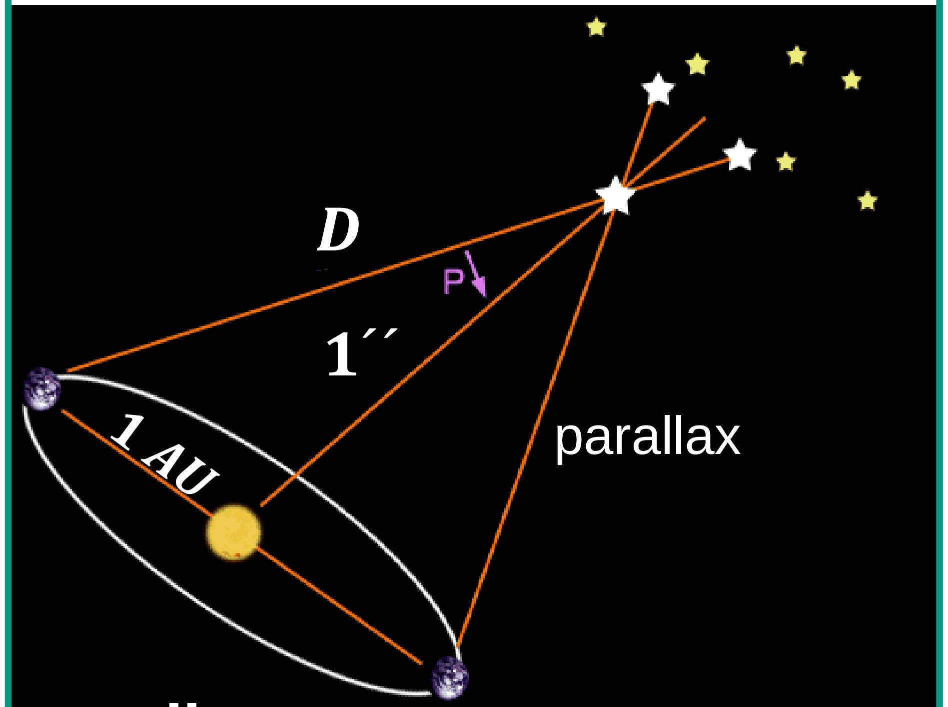
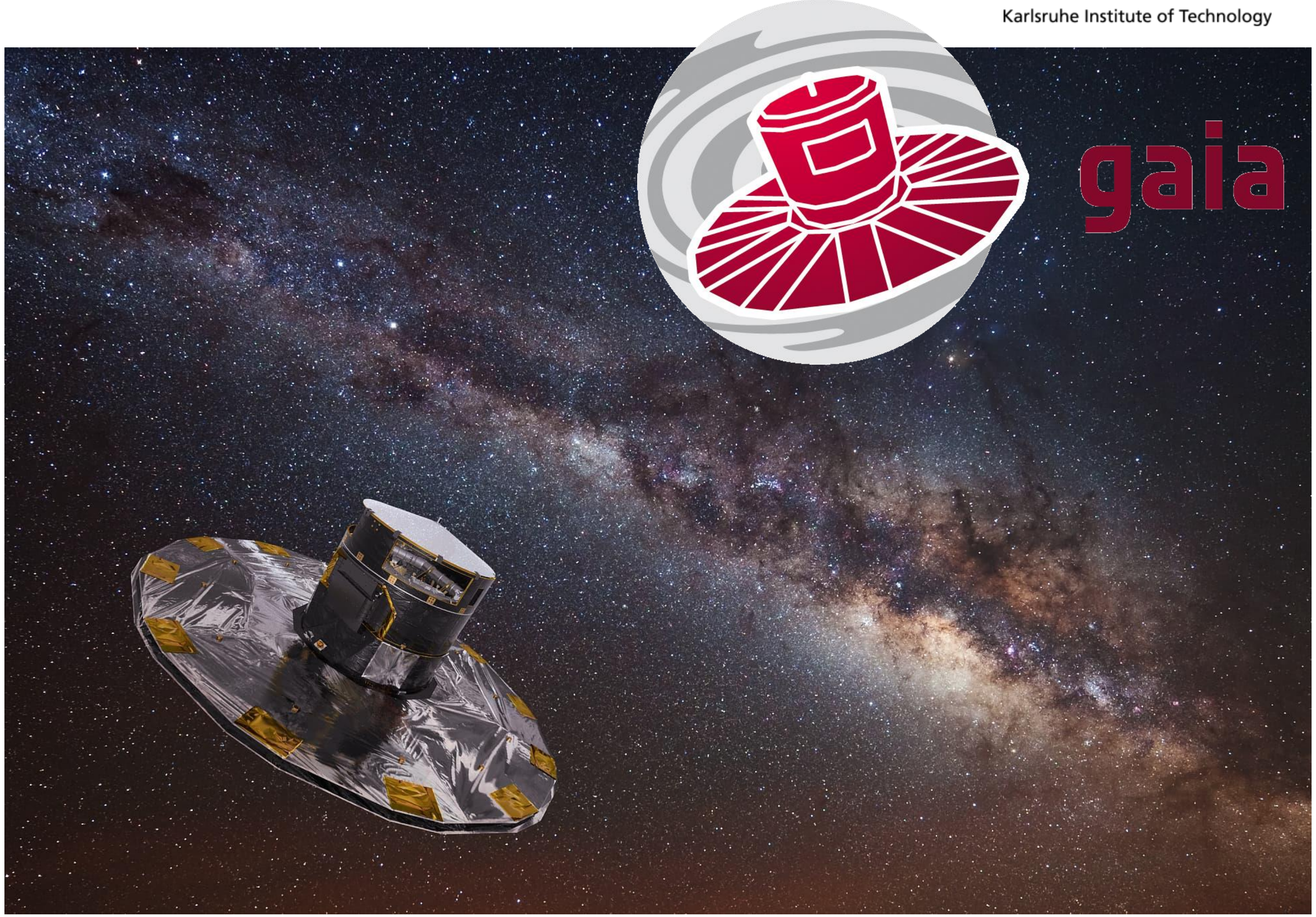
## definition of ´parallax´




**parallax:**

$$1\,pc = 1\,AU \text{ subtends to } 1''$$
$$= 1\,AU \cdot 180 \cdot (3600\,/\,\pi)$$



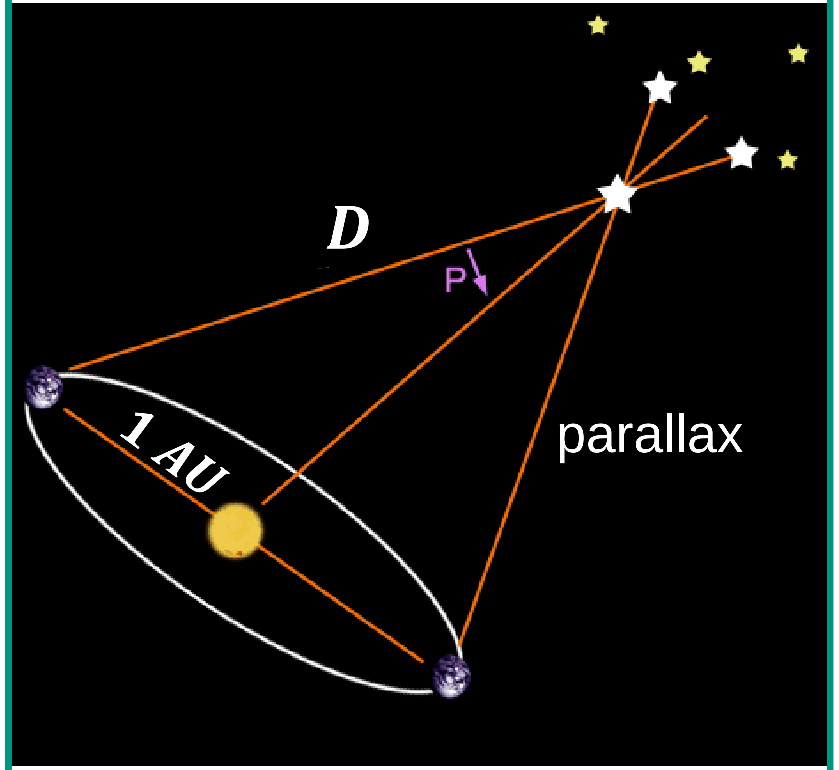

Q: ESA

measurements of $GAIA$ with $\mu as$ – precision*

*$GAIA\ DR\ 3 = 3.$ Data Release ($June\ 2022$)

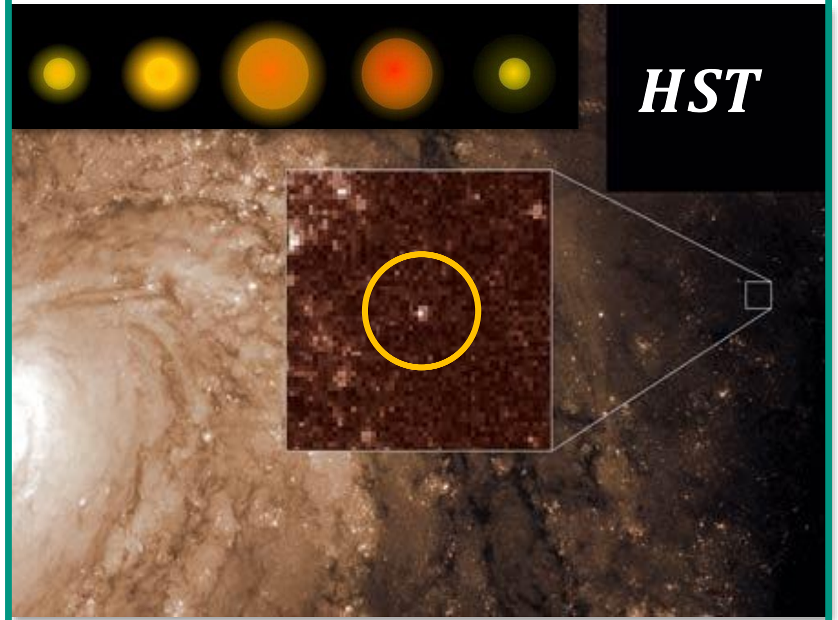
# Cosmology: the ´classical´ distance ladder

## parallax method




**Parallax method: reach to**
$D = few\ kpc$ (Milky Way)

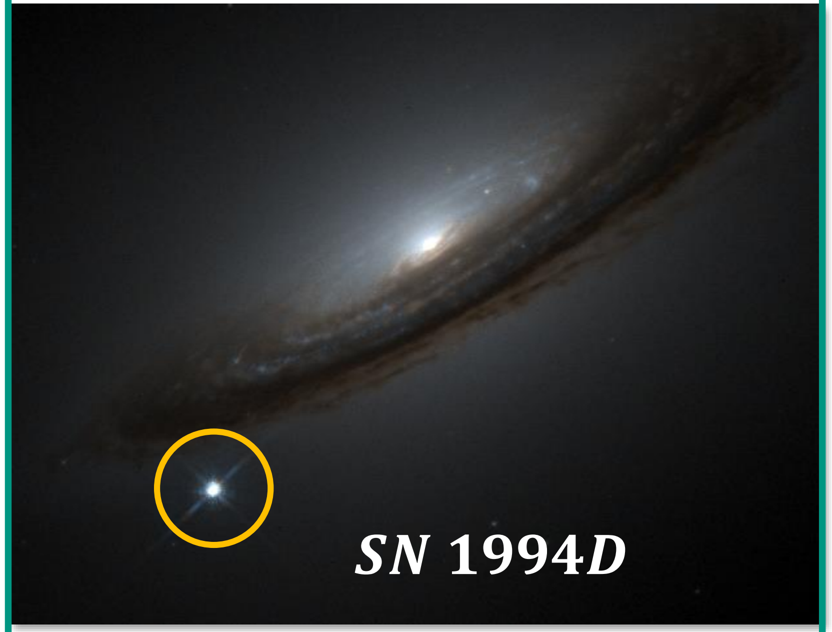
## $\delta$ – Cepheids




**$\delta$ – Cepheids:** absolute luminosity $L_{abs} \sim 10^4 L_\odot$

$D = 1\ kpc \ldots 50\ Mpc$

## $SN - Ia$ – brightness




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

$D = 30\ Mpc \ldots 3\ Gpc$

luminosity of the sun: $L_\odot$

# Brightness – definition in astronomy

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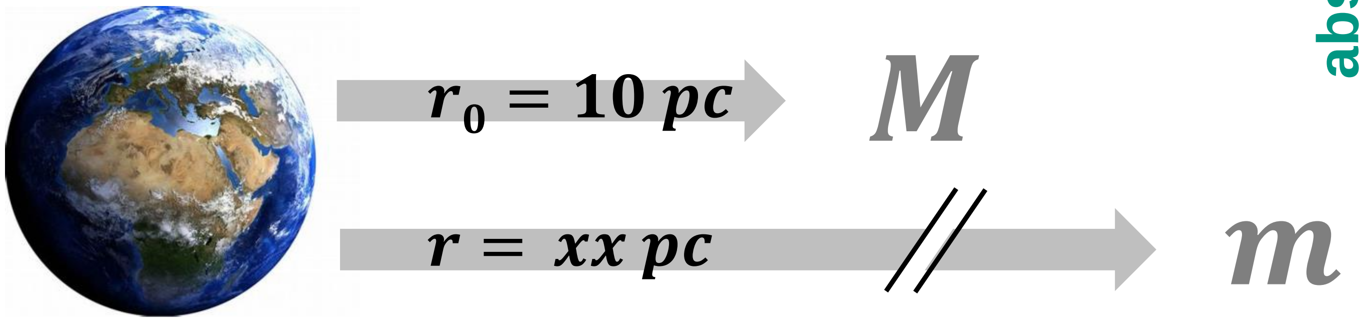
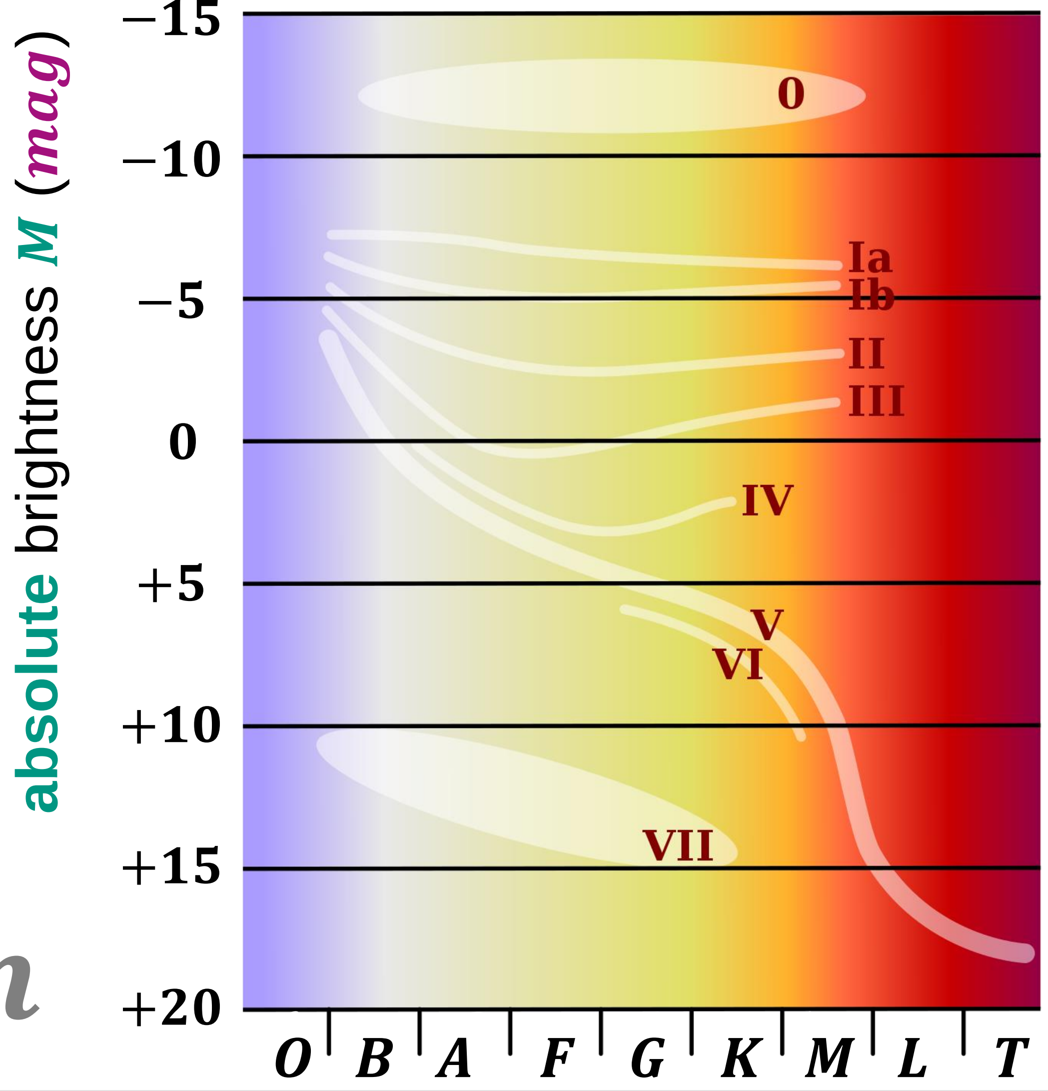
## ■ absolute & relative brightness

- 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 – definition in astronomy

- **absolute & apparent brightness: magnitude**

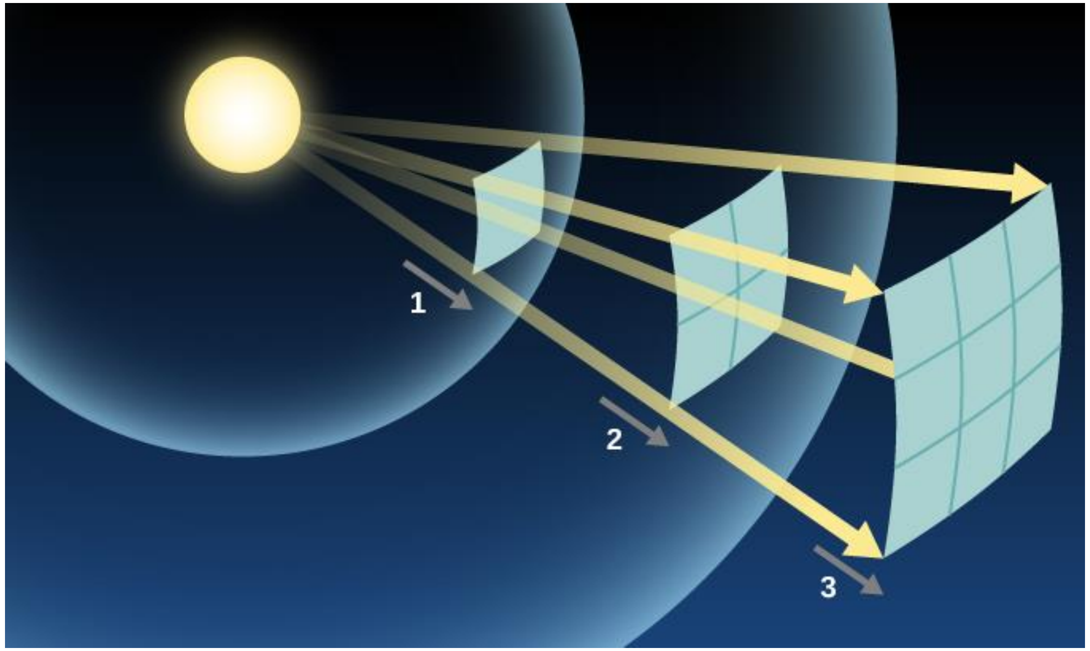
  - reference: $m \equiv 0$ is defined for the nearby star **Wega** ($\alpha$ *Lyrae*)

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

  - **Distance modulus $m - M$:**

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

quadratic distance law

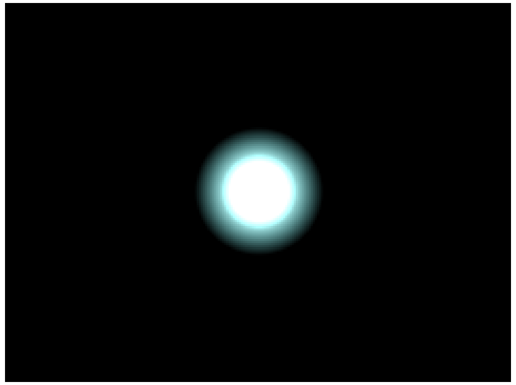



Q: BCcampus

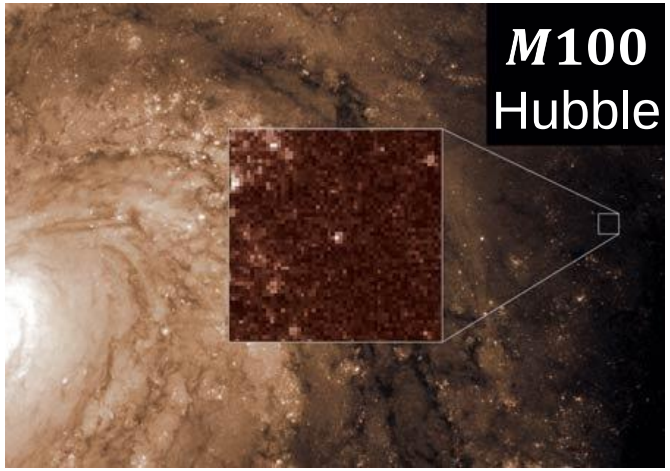
# Cepheids – cosmological standard candles #1

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

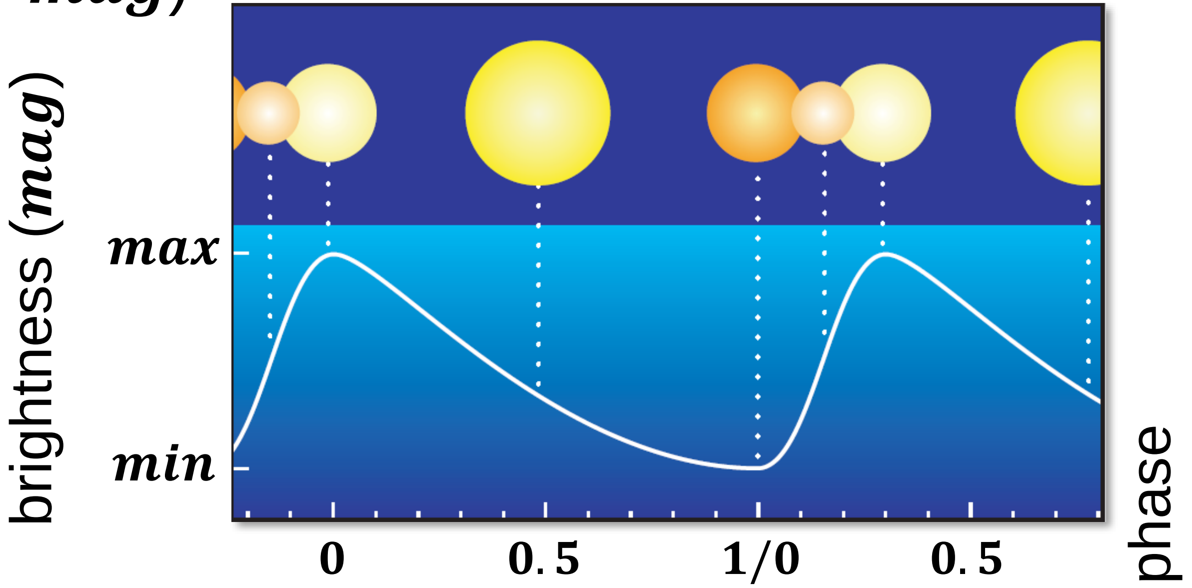
period of a $\delta$ – Cepheid



Q: NASA




distant Chepeid




* $M_V$ = visual brightness

# Cepheids – cosmological standard candles #1

- ´Kappa mechanism´ : **the underlying cause of radial pulsation**

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

  - key: hot stellar core with an $He$ – ionisation layer of $He^{++}$ & $He^{+}$ – ions

  - **cycle of stellar pulsation:**

    increasing $T$:

    more $He^{++}$ & free electrons

    ↳ larger opacity

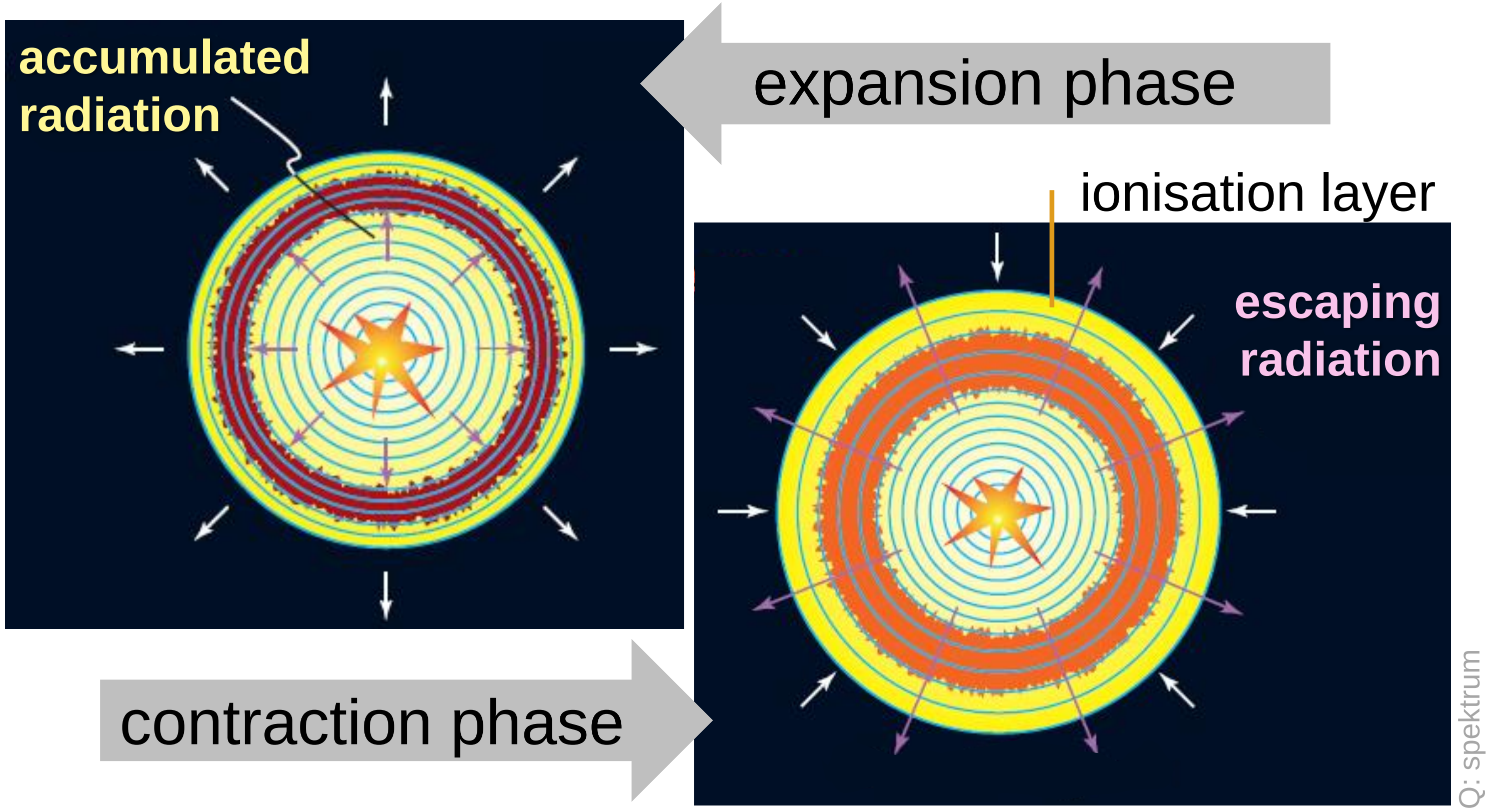
    ↳ increase of rad. pressure

    ↳ expansion of outer shell

    decreasing $T$:

    gravitational contraction

    ↳ recombination to $He^{+}$



# Cepheids – cosmological standard candles #1

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

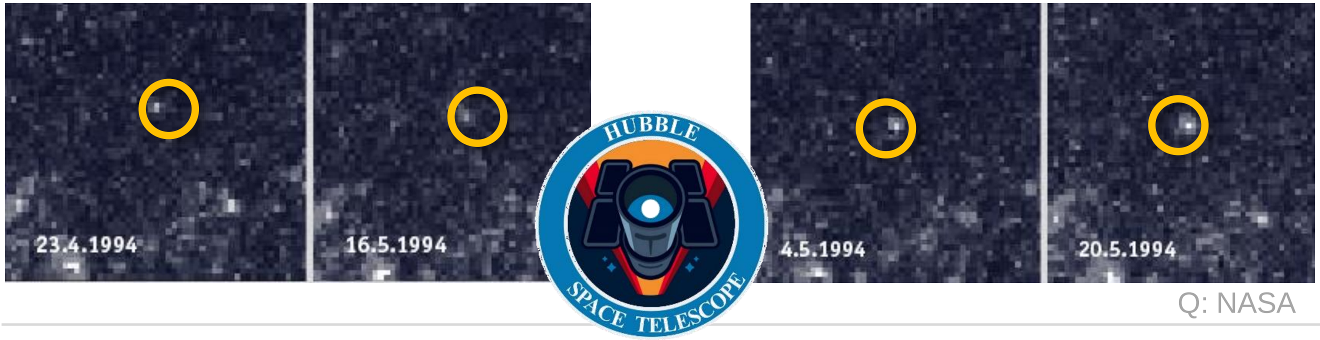
  - very massive, very bright cepheids are pulsating more slowly, **period $T_0 \sim L^{3/4}$**

**pulsation period – luminosity relation**

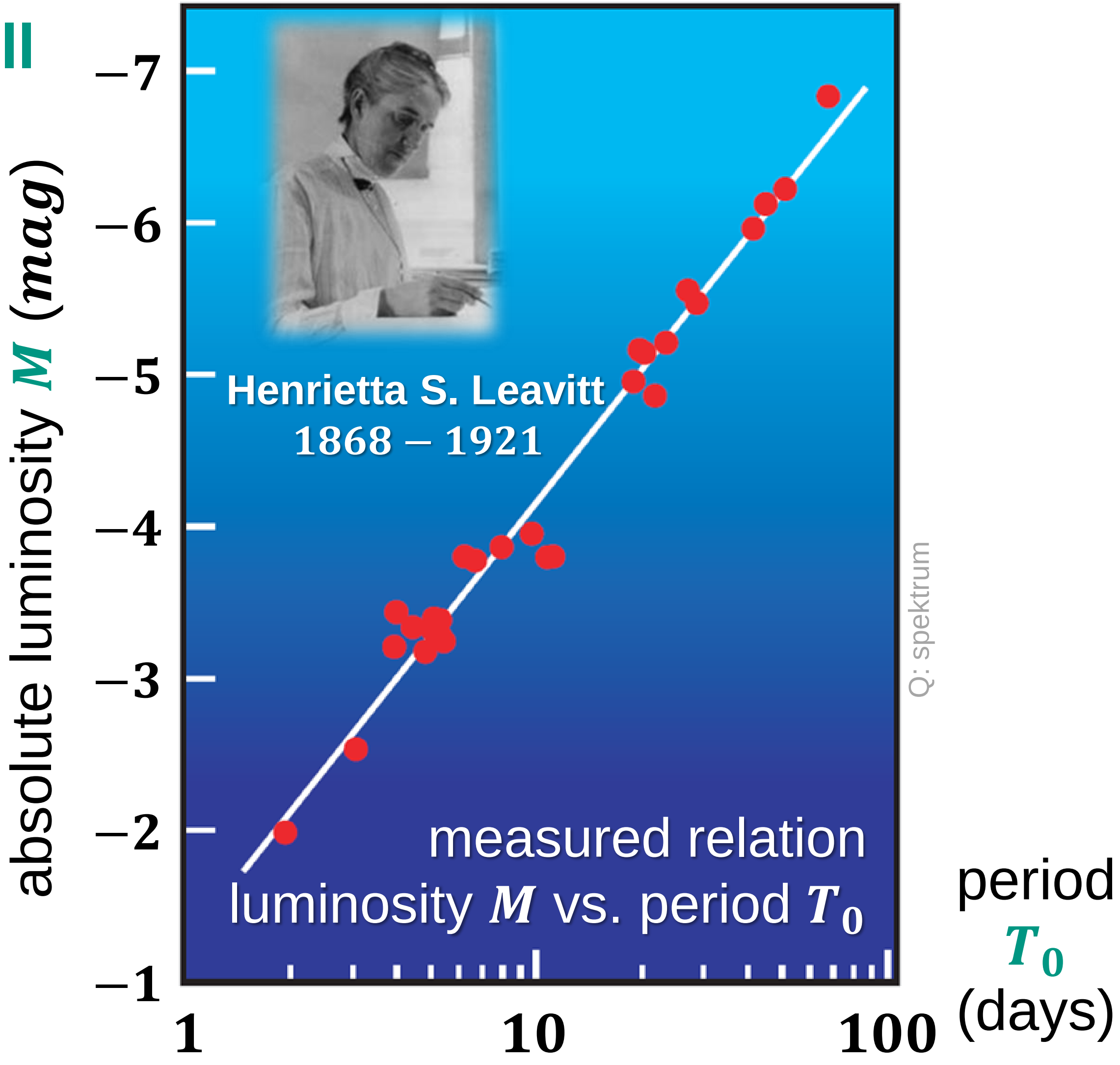
$$M = -2.81 \cdot \log(T_0) - (1.43 \pm 0.1)$$

$T_0$: pulsation period ($days$)

$M$: absolute brightness ($mag$)




Q: NASA




Q: spektrum

# Supernovae – cosmological standard candles #2

- ***SN Ia*: thermonuclear detonation***

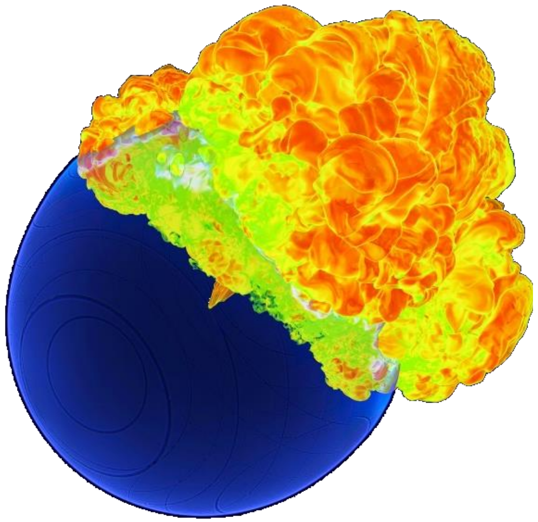
- a White Dwarf reaches a mass of $M \geq 1.4\, M_{\odot}$

Q: Nature

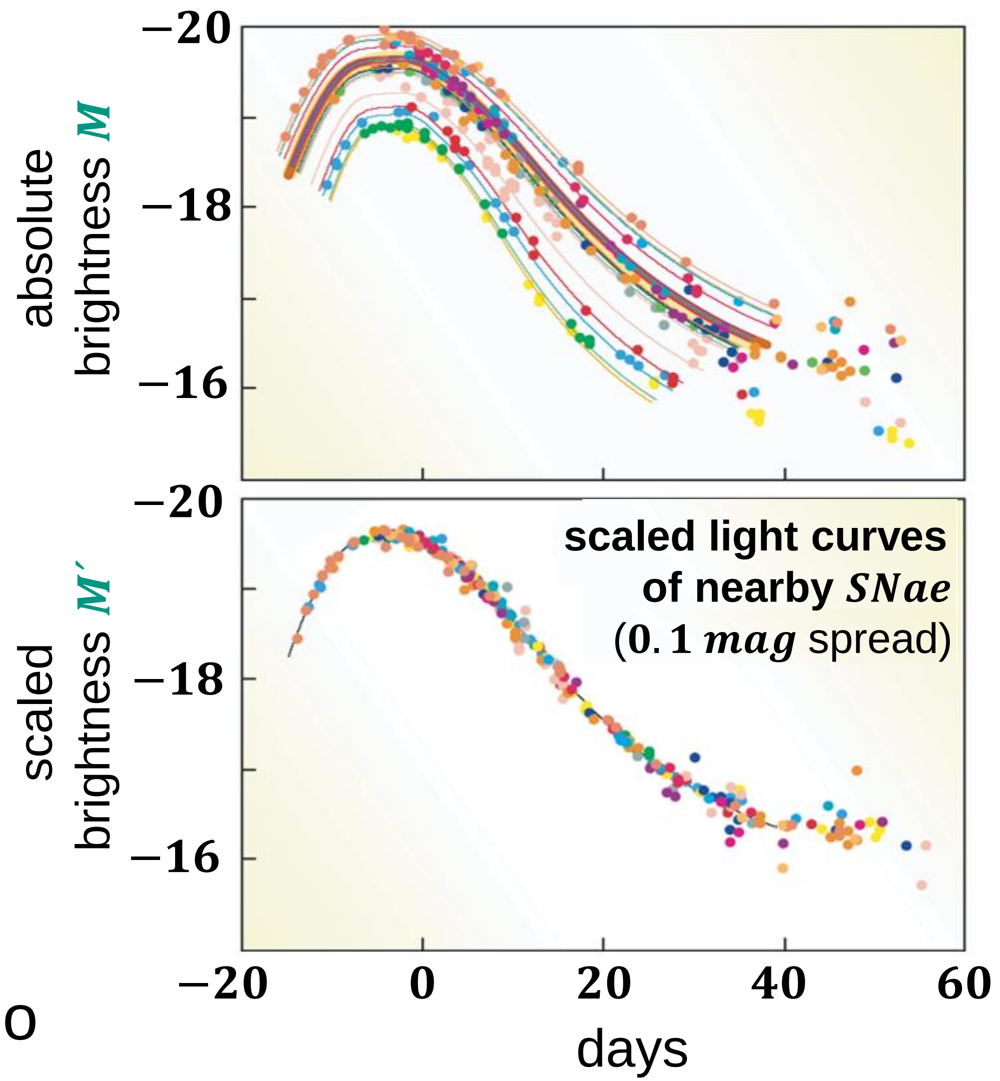
merger scenario

or

Q: U of chicago



accretion scenario




Q: Nature

*s. also $ATP-2$ lectures (summer term ´$24$)