8. Cosmology

Deals with the origin, evolution & structure of the Universe as a whole

[unlike astro-(particle) physics]

Here: apply GR to entire Universe!

Brief history

'early' Various conceptions, greatly varying over time and cultural background:

cyclic / (in)finite in time
(in)finite in space
geo-/ heliocentric/ "central fire" (≠ sun/earth!)
...

middle ages: finite and static

~1700 Newton: infinite, steady-state; homogeneous on large scales

➡ *grav. balanced, but unstable; Olbers Paradox*

1917 Einstein: static cosmological solution to GR (1915)

➡ *uniformly curved, finite space; unstable like Newtonian cosmology*
needs Λ ("greatest blunder of my life")

1922-35 Friedmann, Lemaitre, Robertson, Walker: solutions to GR that describe a homogeneous, isotropic and expanding universe

1929 Hubble: distant galaxies recede from us!

1948 Bond, Gold, Hoyle: "steady state universe"

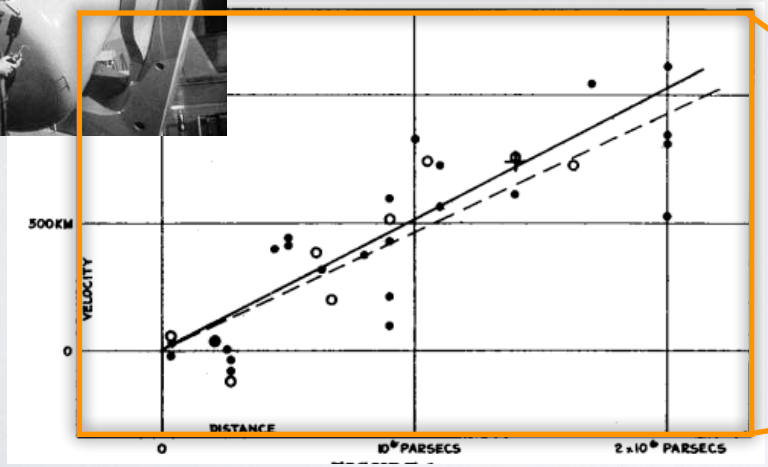
➡ *creation rate of matter ("out of nothing")*
balanced by space expansion rate

Hubble expansion

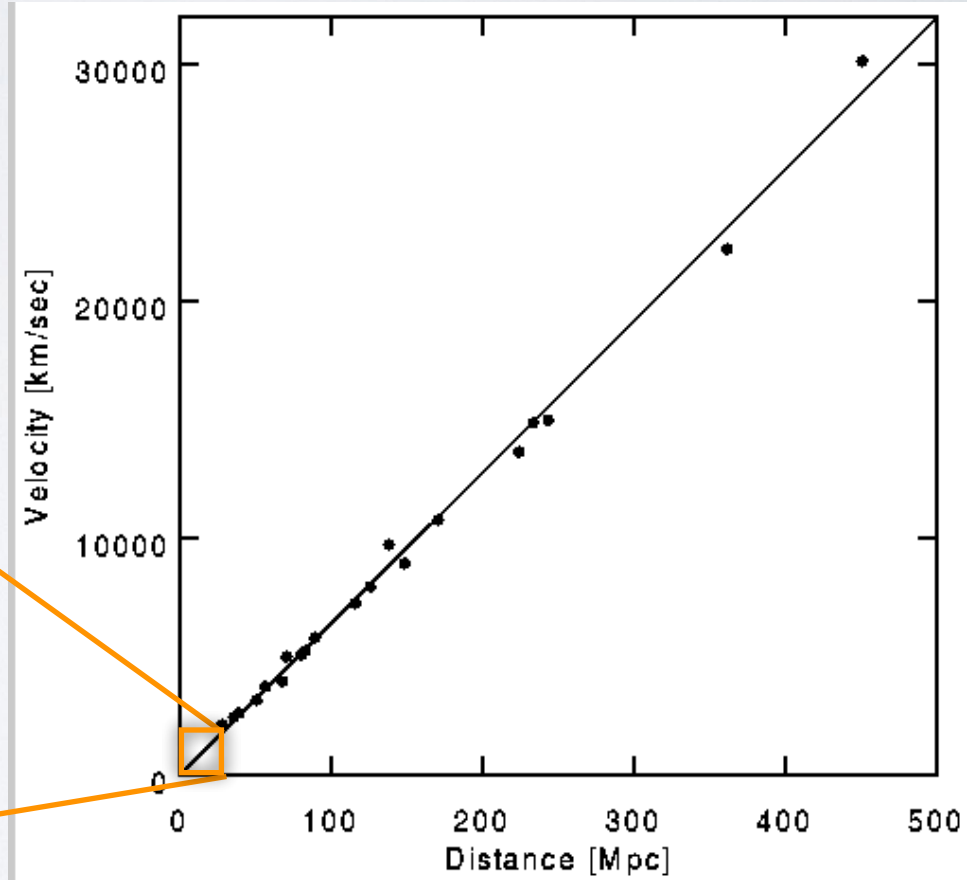
- Observation: light from distant galaxies is redshifted

$$z \equiv \frac{\Delta\lambda}{\lambda} \simeq H_0\, d$$

➡ ***All*** galaxies are receding from us!
(Doppler effect: $\Delta\lambda/\lambda = v$)



Hubble 1929



Aharony *et al.*, PR 2000

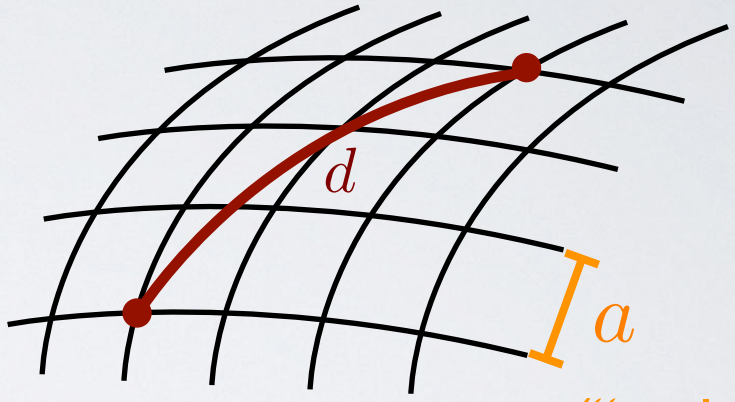
Hubble expansion

- Standard interpretation: space itself expands:

$$d(t) \simeq a(t) \cdot r$$

physical distance to distant galaxy

coordinate or "co-moving" distance



("scale factor")

- This explains why everything moves away "from us":

$$1 + z = \frac{\lambda_{\rm obs}}{\lambda_{\rm em}} = \frac{a(t_0)}{a(t_{\rm em})} = 1 + \underbrace{(t_0 - t_{\rm em})}_{d\ (c=1!)} \underbrace{\left.\frac{\dot{a}}{a}\right|_{t_0}}_{\equiv H_0} - (t_0 - t_{\rm em})^2 \left.\frac{\ddot{a}}{a}\right|_{t_0} + \ldots$$

present de-/acceleration

The transition from `philosophy' to science

1964 Penzias, Wilson: detection of isotropic CMBR

⇨ *Big Bang model "wins"; Noble prize 1978 "by accident"*

>1980 Guth, Linde, ...: "inflation" – early period of accelerated expansion

1990 COBE team: measurement of CMBR anisotropies

⇨ *Noble prize 2006*

1998 Perlmutter, Schmidt, Riess: expansion of universe currently accelerates

⇨ *Noble prize 2011*

>2001 WMAP: successor of COBE

⇨ *beginning of "precision cosmology"*

2013 first (cosmological) data from PLANCK ...

to be continued...!

Cosmology as a science is a rather young discipline which has become data driven and enormously successful during the last 2 decades!

The Cosmological Concordance model

assume tiny primordial density perturbations

➡ explains structure today

generates

Inflation

provides initial conditions

Big Bang Theory

expanding, isotropic & homogeneous universe

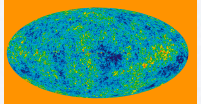
(cosmological *principle*)

QFT

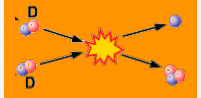
General Relativity

Hubble expansion

CMB



Abundance of light elements



theoretical frameworks

observational pillars

Very *simple* and *predictive*:

only 7 parameters needed to describe 'all' cosmological observations!

$\Omega_\Lambda, \Omega_{\rm CDM}, \Omega_{\rm b}, T_\gamma^0$

➡ **energy content & composition**

$n_s, \mathcal{P}_\mathcal{R}(k_0)$

➡ **density perturbations**

τ

➡ **star formation** $(\rightarrow z_{\rm reion})$

Cosmological Principle

- Observations:

  the universe looks the same in all directions (on large scales)

  ⇨ ***Isotropy in one point***

- "Copernican" principle:

  we do not live in a special place

  ⇨ ***Isotropy in every point***

⇨

Cosmological principle:

On large scales, the universe is homogeneous and isotropic

Translated to GR: space (not spacetime) is maximally symmetric!

[isotropy ⇝ 3 rotations; homogeneity ⇝ 3 translations; 6 = maximal number of Killing vectors in 3D!]