Introduction and Preparations

Block Course Introduction to Astronomy and Astrophysics

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Introduction to cosmology and galaxies

Cosmology:

- Fairly simple basis: homogeneous models (FLRW)
- Physics-based in hot Big Bang phase (thermodynamics)
- structure formation (homogeneous $\rightarrow$ inhomogeneous)

Galaxies:

- Bewildering variety of data, concepts, examples
- Eventual goal: Understand how the diversity of galaxies comes about
- Guidelines: Basic concepts, properties, morphology, spectra

What this part of the course is about 2

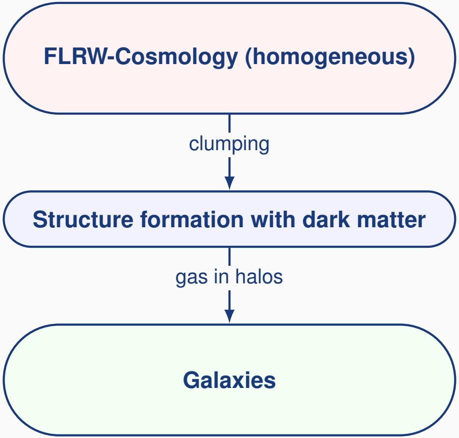
Overall goal of this course: understand basic concepts, learn the basic vocabulary

If you pick up a paper on the subject, you should be able to

- Understand the context and motivation
- Superficially understand the arguments made
- Later: Intelligently listen to talks outside your own specialty

More details and differentiation plus deeper digging can come later, in:

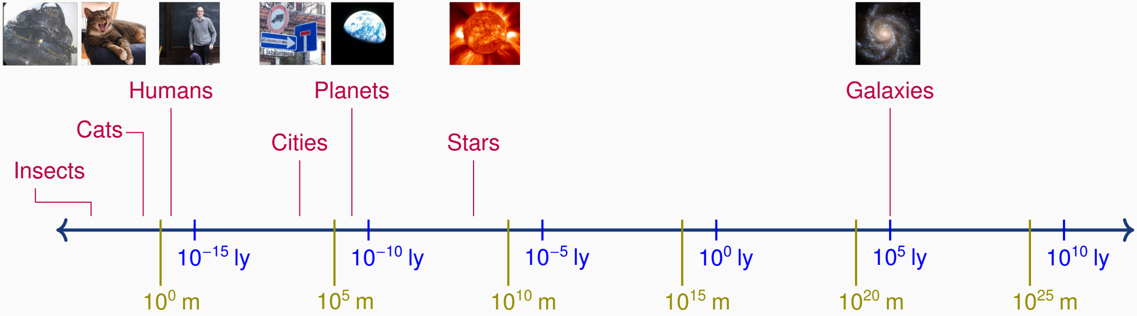
- MVASTRO3: Galactic and Extragalactic Astronomy
- MVASTRO4 or MKTP5: Cosmology
- MVSpec “Observing the Big Bang”



- basic concepts
- dynamics
- distances in cosmology
- hot Big Bang phase

- basics, morphology, spectra
- stellar dynamics, scaling relations
- galaxy types, AGN, groups/clusters
- gravitational lensing
- galaxy evolution

Distance scales



Fundamental observational facts about our universe

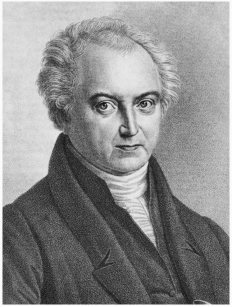
Some fundamental observational facts cosmological models need to accommodate:

- Olbers' Paradox
- Age determination for oldest objects
- Fundamental matter content, including dark matter
- Cosmography (needs distance measurements) $\Rightarrow$ on-average homogeneity
- Hubble-Lemaître-Relation

. . . and of course that is not all, but it's a start!

Olbers' paradox (1823)

Heinrich Wilhelm Matthias Olbers (1758-1840) and others:
The universe cannot be infinite, infinitely old, and stationary



If it were:

- every line-of-sight would end in a star
- area within given solid angle goes with r^2
- flux goes with $1/r^2$

$\Rightarrow$ every patch of sky as bright as the Sun's surface!

(Dust/absorption? If stationary, thermal equilibrium would give dust the same surface brightness!)

In-depth analysis: E. Harrison, *Darkness at night*. Harvard University Press 1987

Age determinations 1: lower age limit from metal-poor stars

Metal-poor halo star HE 1523-0901:

- Heavier elements from first Type II SN
- Calculate initial r-process elements abundances
- U-238 ($Z = 92$) vs. Th-232 ($Z = 90$) similar, promising
- Half-life U 4.5 Gyr, Th 14 Gyr
- Different chronometers:
  - U against all r elements
  - Th against all r elements
  - U against T
- Resulting age: 13.2 ± 0.7 Gyr

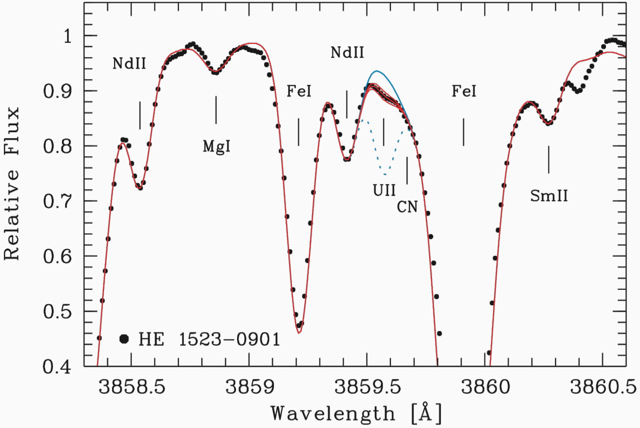


Fig. 2 (left part) from Frebel, Christlieb et al. 2007

For star clusters:

- Create color-magnitude diagram
- main-sequence turn-off (MSTO)
- $L \sim M^{3.5}$ and $\tau \sim M/L \Rightarrow \tau \sim M^{-2.5}$
- Oldest globular clusters:
  13.2 ± 2 Gyr (Carretta et al. 2000)

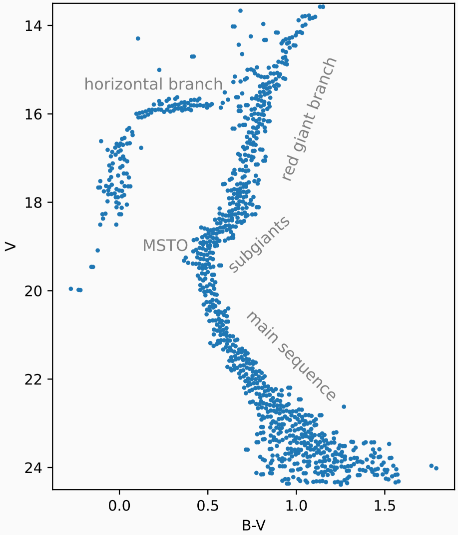
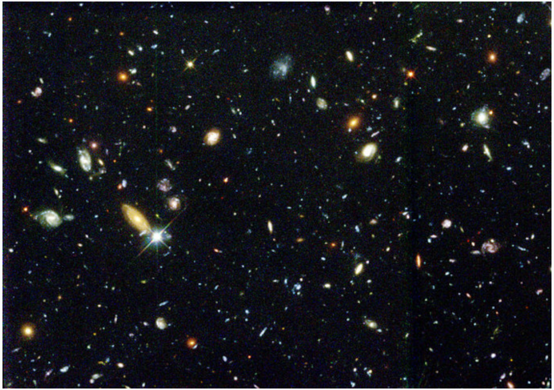
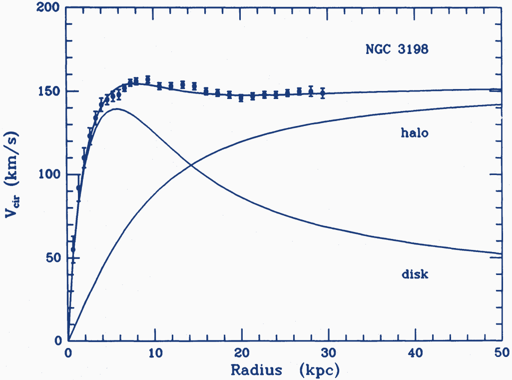


Diagram on the right after Fig. 7
in Durrell & Harris 1993



R. Williams (STScI), the Hubble Deep Field Team and NASA



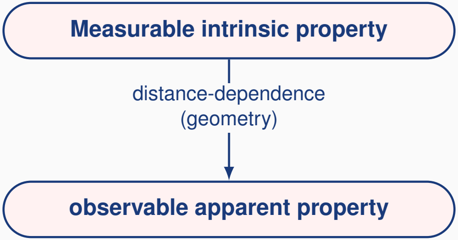
van Albada et al. 1985

Luminous baryonic matter: viscosity, electromagnetic interactions, hot Big Bang phase, star formation. . .

Interacts only via gravity: dark matter, backbone for structure formation, galaxies grow in dark matter halos

Cosmography: Mapping our universe in 3D

Distance determinations beyond parallax: standard objects:



Standard candle:	luminosity	$\Rightarrow$	apparent brightness
Standard ruler:	size	$\Rightarrow$	angular size
Standard siren:	gw amplitude	$\Rightarrow$	observed amplitude

Standard candle: from luminosity to flux

Luminosity = energy radiated per unit time

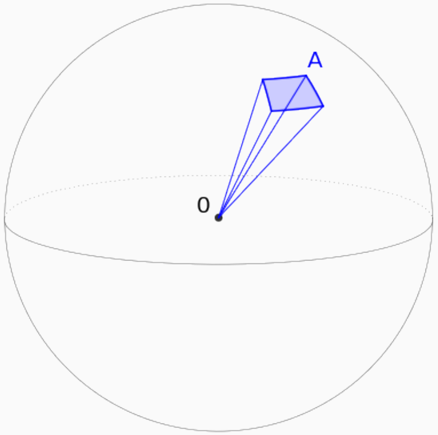
Constant luminosity: energy per unit time flowing through spherical shell with radius d is L

Isotropic radiation: fraction of energy that passes through detector area A in unit time is

$$\Delta E = \frac{A}{4\pi d^2} \cdot L$$

which is equal to the area A times the flux F,

$$F = \frac{L}{4\pi d^2}$$



Standard candle: object, where we know/can deduce L, measure the flux F, calculate

$$d = \sqrt{\frac{L}{4\pi F}}$$

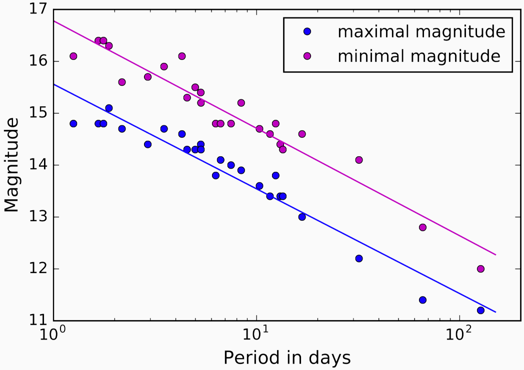
Link with astronomical magnitude system:

$$m_1 - m_2 = -2.5 \cdot \log\left(\frac{F_1}{F_2}\right)$$

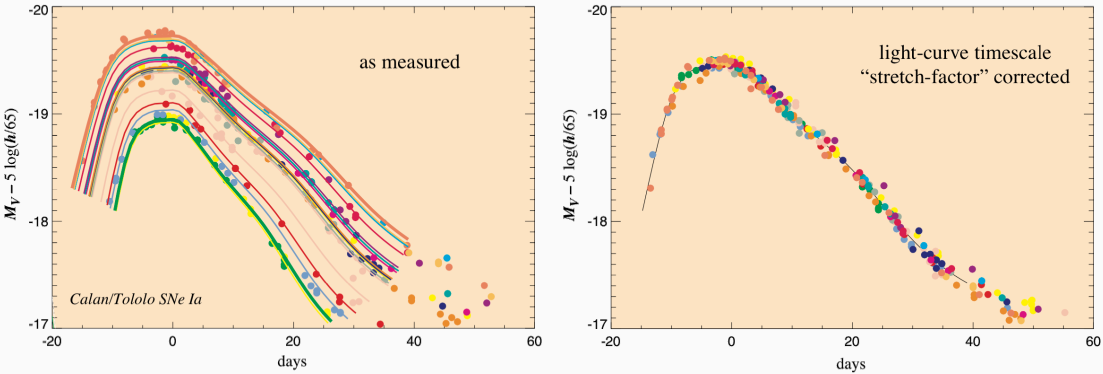
leads to distance modulus

$$m - M = -2.5 \cdot \log\left(\frac{L/(4\pi d^2)}{L/(4\pi[10\ \mathrm{pc}]^2)}\right) = 5 \cdot \log\left(\frac{d}{10\ \mathrm{pc}}\right)$$

- Cepheids = pulsating phase of medium-mass stars
- Relation pulsation period and maximal/minimal/avg. *L*
- Realized first heuristically by Henrietta Swan Leavitt, 1908–1912
- Crucial for first extra-galactic distances (Hubble)
- Modern standard candles often use extinction-corrected magnitudes (e.g. *Wesenheit magnitudes*)

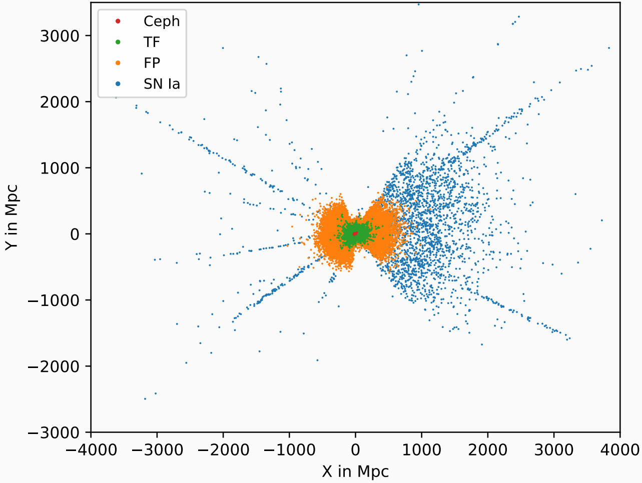


Standard candles example 2: Supernovae vom Typ Ia



Perlmutter et al. 1998, Supernova Cosmology Project

- SN Ia: binary with White Dwarf ⇒ H captured ⇒ thermonuclear explosion
- Phillips relation: fading rate (peak vs. 15 days later) allows calibration
- Standard tool for most distant extragalactic distance measurements



Not that easy: 26441 data points for galaxies from NED-D distance catalogue

Systematic redshift-distance relation: Hubble-Lemaître relation

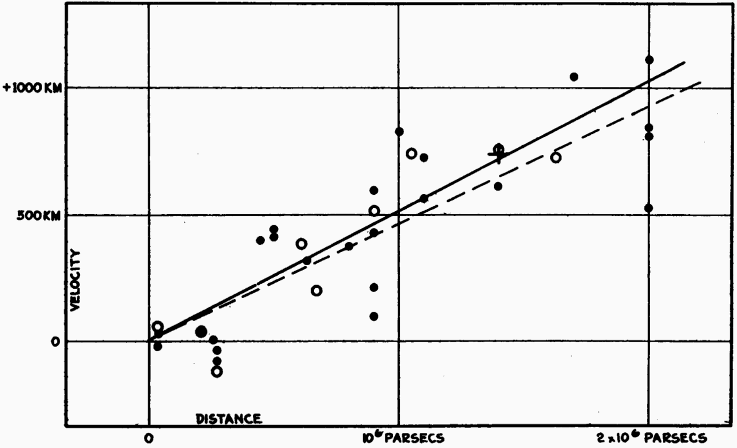


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble 1929: “A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae” in PNAS 15(3), p. 168ff.

Some fundamental observational facts cosmological models need to accommodate:

- Olbers' Paradox
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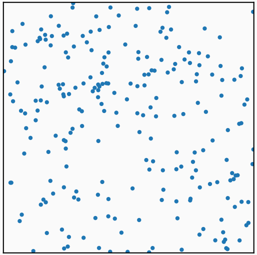
...so where do we go from here?

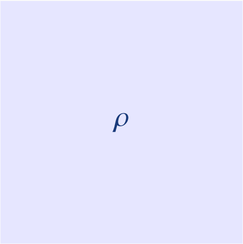
Simplest model: homogeneous, isotropic universe

Cosmological principle: The universe presents the same aspect from every point except for local irregularities (Bondi 1952)
$\Leftrightarrow$ Copernican principle: We occupy no special location in the universe.

Two complementary views of the model we will use:



"Galaxy dust" with separate, pointlike galaxies



Continuum with uniform density ρ

Our framework for model-building: general relativity

Dominant large-scale force in the cosmos: gravity!

(Electromagnetism much stronger, but astronomical objects are electrically neutral.)

Modern description of gravity:
Einstein's general theory of relativity (1915)

Gravity linked to distortion of space and time

Matter tells spacetime how to curve,
spacetime tells matter how to move
(John Wheeler)

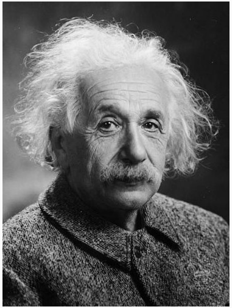
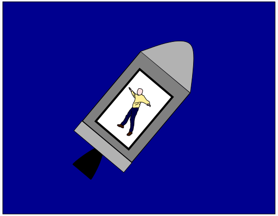


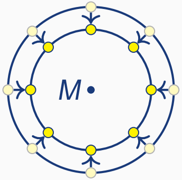
Foto via Library of Congress

What we will use later on:

- **Equivalence principle:** In free fall, special relativity is valid locally
- **Newtonian limit:** Small tidal forces are Newtonian
- **Energy-momentum:** Source terms contain energy, pressure



Equivalence principle



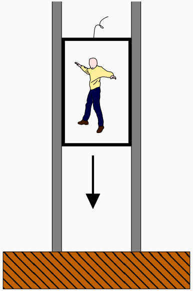
Tidal forces around source

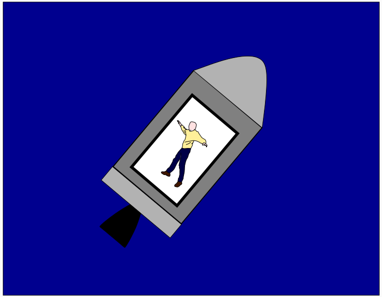
These are general relativity's "interfaces" with its precursor theories: special relativity and Newtonian gravity

General relativity: Equivalence principle

Part of gravity "vanishes" if an observer lets go, falls freely (left)

No local difference to gravity-free situation (right):
laws of special relativity hold



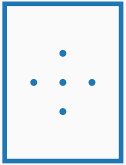


Famous example: astronauts on the International Space Station!

What remains even in free fall? Tidal forces!

External view:

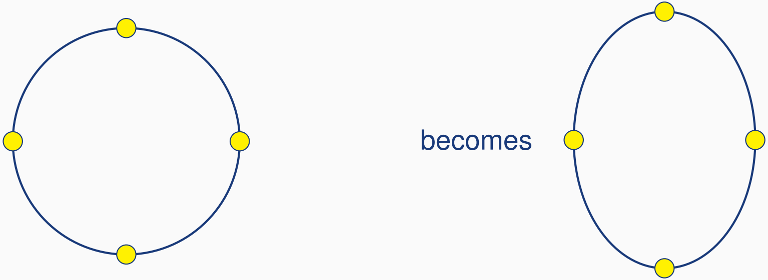
View from inside the cabin:



What do tidal forces do? 1/2

Tidal forces *distort* swarms of free-falling particles:
direction effects and distance effects

If attracting mass is below:



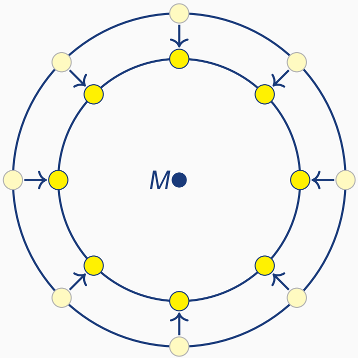
with

$$\ddot{V}\Big|_{t=0} = 0$$

(Newtonian calculation, still valid in general relativity)

What do tidal forces do? 2/2

Attracting central mass: particles initially at rest accelerate inwards



Newton:

$$\left.\frac{\ddot{V}}{V}\right|_{t=0} = -4\pi G\,\rho,$$

with $\rho \equiv M/V$ average density within sphere

Einstein's equation (simplest form):

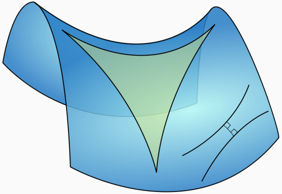
$$\left.\frac{\ddot{V}}{V}\right|_{t=0} = -4\pi G\left(\rho + [p_x + p_y + p_z]/c^2\right)$$

where ρ now includes energy plus extra pressure terms

(must-read: Baez & Bunn 2005)

From homogeneity, isotropy, derive Ansatz for the metric:

$$\mathrm{d}s^2 = -c^2\mathrm{d}t^2 + a(t)^2\left[\frac{\mathrm{d}r^2}{1-Kr^2} + r^2\mathrm{d}\Omega\right], \quad \mathrm{d}\Omega = \mathrm{d}\vartheta^2 + \sin^2\vartheta\,\mathrm{d}\varphi^2$$

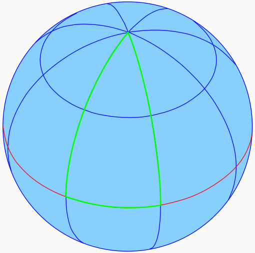


From metric follows:

- light propagation
- free-fall properties
- geometry of space

Einstein's field equation(s)

$$G_{\mu\nu} = \frac{8\pi G}{c^4}\,T_{\mu\nu}$$



...yield Friedmann equations for $a(t)$ in terms of matter content

- Introduce scale-factor expansion from homogeneity/isotropy
- Galaxy in an expanding universe are in free fall
  $\Rightarrow$ equivalence principle e.g. for light propagation
- Density is low $\Rightarrow$ use Newtonian gravity as approximation
- By hand, substitute $\rho \to \rho + 3p/c^2$ for relativistic source term

This will give us the right relations and equations for an expanding universe *except* the connection between energy density and local geometry (spherical, flat, hyperbolical)

Helpful text books

For Chapters 1 to 6: Lecture notes are in the Moodle!

Liddle, Andrew R.: *An introduction to modern cosmology*. Wiley 2015

Ryden, Barbara: *Introduction to cosmology.* 2nd edition. Cambridge University Press 2017

Schneider, Peter: *Extragalactic astronomy and cosmology: an introduction*, Springer 2006

Sparke, Linda S. & John S. Gallagher, III: *Galaxies in the Universe. An Introduction*. 2nd edition. Cambridge University Press 2007

. . . all of which are in the Lehrbuchsammlung Neuenheimer Feld

For the homogeneous cosmology part: Markus Pössel, *The expanding universe: an introduction*, arXiv:1712.10315