Cosmology

TUM WS 2019/2020

Lecture 3

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(http://www.eso.org/~bleibund/Cosmology)

Recap: 'Equation of motion' of a homogenous and isotropic Universe

- Einstein Equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Robertson-Walker metric

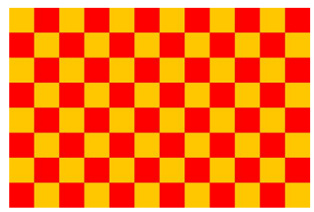
$$ds^2 = -c^2 dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right]$$

- Friedmann equation

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{kc^2}{a^2} - \frac{8\pi G}{3}\Lambda c^2 = \frac{8\pi G}{3}\rho$$

The cosmological principle

- Homogeneous: the universe looks the same everywhere on large scales
  $\Rightarrow$ there is no special place (center)
- Isotropic: the universe looks the same in all directions on the sky
  $\Rightarrow$ there is no special direction (axis)

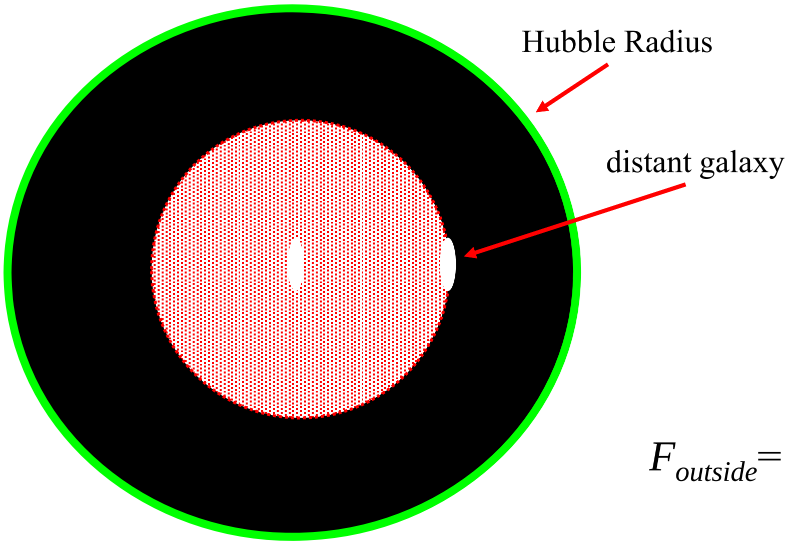


Homogeneity and Isotropy

Isotropy + Copernican Principle $\Rightarrow$ Homogeneity

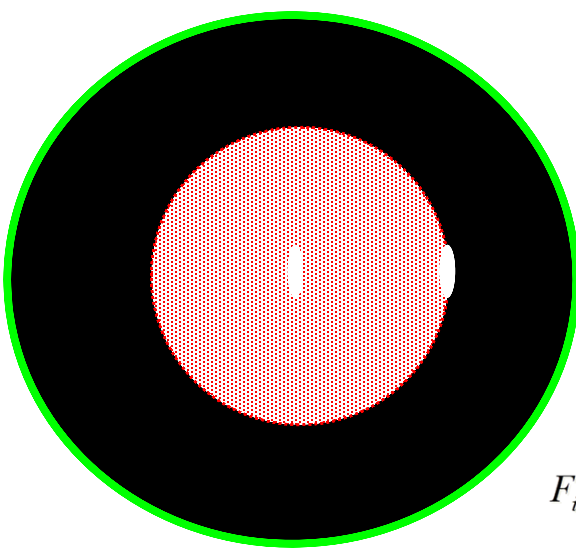
Isotropy + Isotropy around another point $\Rightarrow$ Homogeneity

a(t) in Newtonian physics



$$F_{outside} = 0$$

a(t) in Newtonian physics



$$F_{inside} = -G\frac{M_{inside} m_{gal}}{R^2}$$

What is the future of that galaxy ?

- Critical velocity: escape speed

$$v_{esc} = \sqrt{\frac{2GM_{inside}}{a}}$$

- $v<v_{esc}$: galaxy eventually stops and falls back
- $v>v_{esc}$: galaxy will move away forever

Let's rewrite that a bit ...

$$v^2 = \frac{2GM_{inside}}{a} + 2\varepsilon_\infty$$

- $\varepsilon_\infty<0 \Rightarrow v<v_{esc}$: galaxy eventually stops and falls back
- $\varepsilon_\infty>0 \Rightarrow v>v_{esc}$: galaxy will move away forever

Let’s rewrite that a bit ...

- Homogeneous sphere of density ρ :

$$M_{inside} = \frac{4\pi}{3}\rho\, a^3$$

- so for the velocity:

$$v^2 = \frac{8\pi G}{3}\rho a^2 + 2\varepsilon_\infty$$

- but what is ε_∞?

Let’s switch to general relativity

- Friedmann equation

$$v^2 = \frac{8\pi G}{3}\rho a^2 - kc^2$$

- same *k* as in the Robertson-Walker metric

Let's switch to general relativity

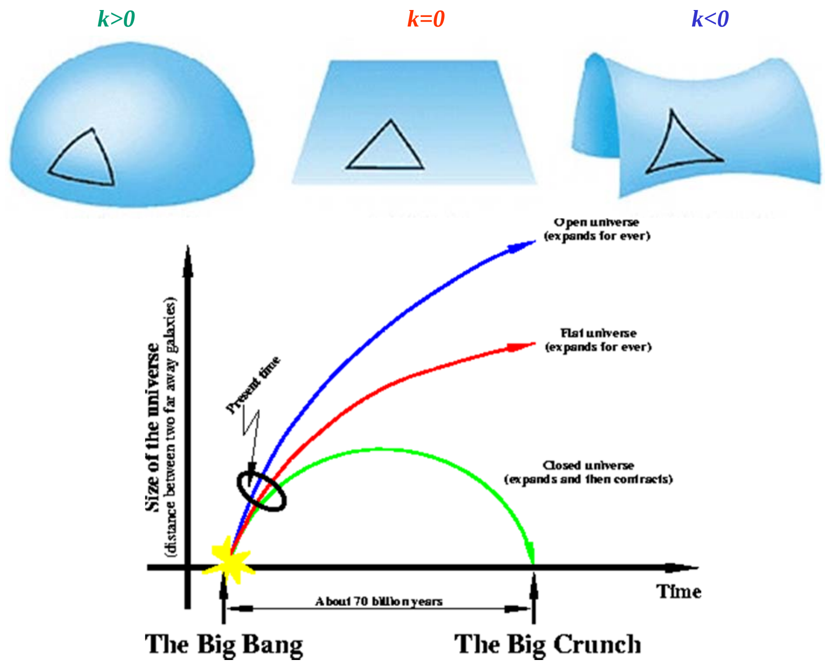
- Friedmann equation

$$v^2 = \frac{8\pi G}{3}\rho a^2 - kc^2$$

  - *k=0*: flat space, forever expanding
  - *k>0*: spherical geometry, eventually recollapsing
  - *k<0*: hyperbolic geometry, forever expanding

Note:

This is all without a Cosmological Constant!



Hubble's 'law'

$$v = H_0 d$$

v = recession velocity in km/sec

d = distance in Mpc

H_0 = expansion rate today (*Hubble Parameter*)

In words:

The more *distant* a galaxy, the *faster* its recession velocity.

<u>Problem:</u> How to measure d?

(Hubble got it wrong by more than a factor of 10!)

Hubble constant

- In the local universe (z<<1) the linear expansion law applies

$$D_L = D_A = \frac{zc}{H_0} = \frac{v}{H_0}$$

ere and in the next interval to
ch embraces the M81–NGC 2403
950; Tammann and Sandage 1968)
ar Group (de Vaucouleurs 1959).
ansion velocity at this distance is
s^{-1}. The Hubble constant cannot
by using such nearby galaxies.
nce indicators, such as brightest
-10) and the size of H II regions,
late-type giant spiral galaxies to
$n - M \simeq 32$. The apparent magni-
is $B \simeq 22$, and the angular size of
tion ($D \simeq 400$ pc derived later) is
s are then just above plate limit
n at this distance the expansion
1500 km s^{-1} (if $H_0 \simeq 50$ km s^{-1}
ater), which again is too small.
vilight zone between $m - M \simeq 32$

Paper II.
3. The H II region sizes are
distances to 50 late-type field gal
interval $m - M < 32$ (Paper IV)
absolute magnitudes of the galaxi
sample, as a function of luminosi
follows from these data.
4. Redshifts of newly identifie
with $m - M > 35$ have been m
step. Combining the redshifts and
tudes of step 3 gives H_0. Becaus
pendent of the redshifts for g
$m - M = 35$ (Paper VI), the loca
not enter the problem. Any supp
the local kinematic field is a separa
that does not affect the value of H
way.
Our final value of the expansi

Sandage & Tammann 1974

Hubble constant

- Three different methods
  1. distance ladder
     - calibrate next distance indicator with the previous
  2. physical methods
     - determine either luminosity or length through physical quantities
       - Sunyaev-Zeldovich effect (galaxy clusters)
       - Expanding photosphere method in supernovae
       - Physical calibration of thermonuclear supernovae
       - geometric methods, e.g. masers
  3. global solutions
     - Use knowledge of all cosmological parameters
       - Cosmic Microwave Background

Primary and Secondary Distance Calibrators

- Primaries are used to calibrate the secondary distance indicators to step out into the Hubble flow
- LMC as the anchor for most methods
- Use galaxies or similarly bright objects to measure the Hubble flow

Classical distance ladder

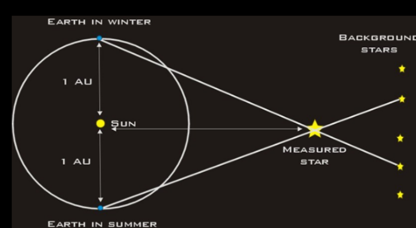
- Primary distance indicators (within Milky Way)
  - trigonometric parallax
  - proper motion
  - apparent luminosity
    - main sequence
    - red clump stars
    - RR Lyrae stars
    - eclipsing binaries
    - Cepheid stars

Classical distance ladder

- Secondary distance indicators (beyond the Milky Way)
  - Important checks
    - Large Magellanic Cloud
    - Local Group
  - Tully-Fisher relation
  - Fundamental Plane
  - Supernovae (mostly Type Ia)
  - Surface Brightness Fluctuations

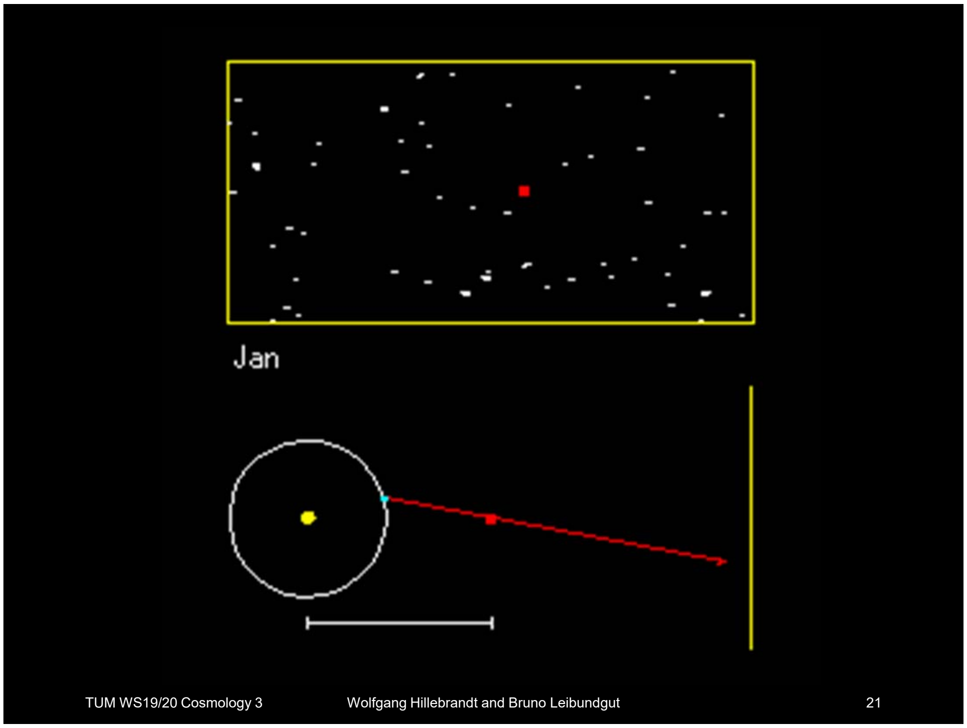
Cosmic distances

Trigonometric parallax: geometric projection of the Earth's orbit around the Sun on the sky.



1 parsec (pc) equals the distance of an angle of 1 arcsecond

$$1\,pc = \frac{\text{Sun-Earth distance}}{\text{1 arcsecond}} = \frac{1AU}{1''} = 149.6 \cdot 10^{6}\,km \,/\, \frac{\pi}{180 \cdot 3600} = 3.086 \cdot 10^{13}\,km$$
$$= 3.26 \text{ light years}$$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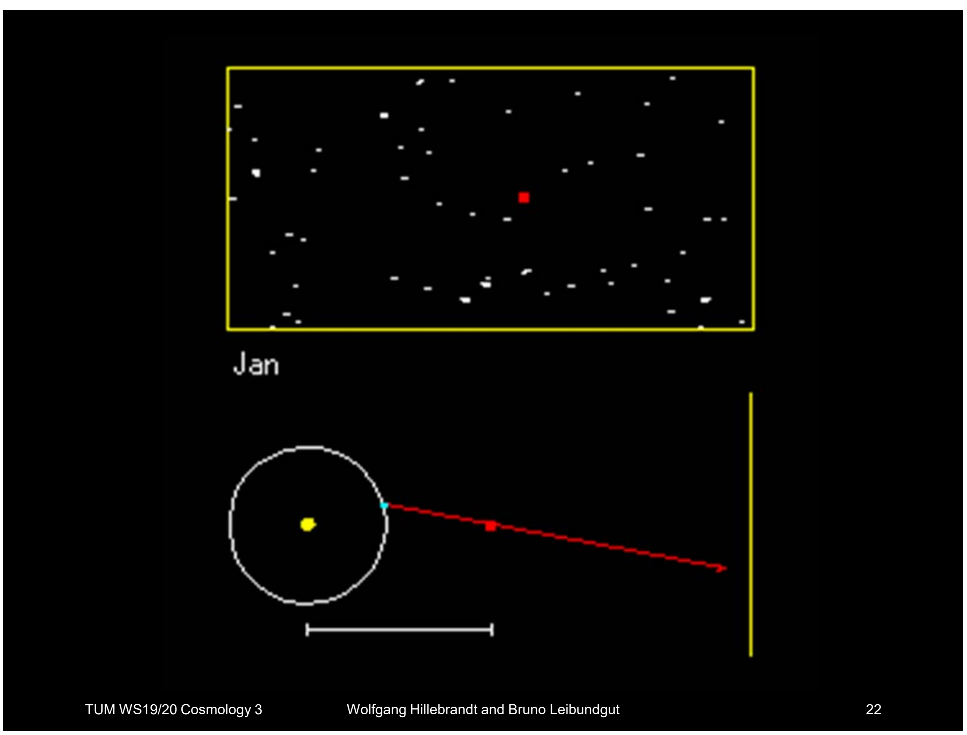
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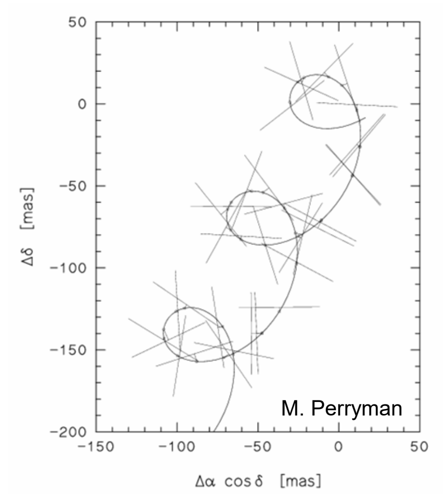
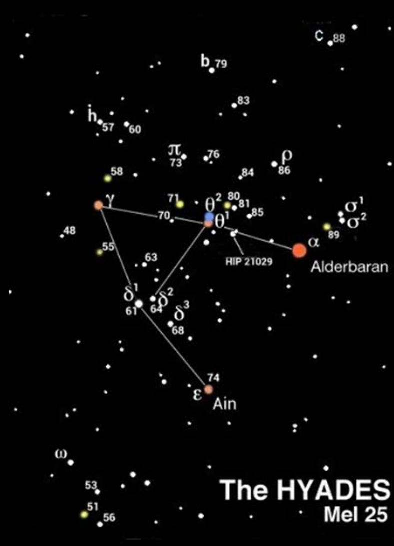
Stellar Parallax

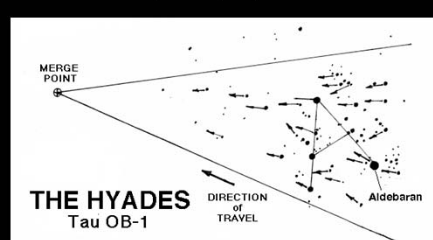
Apparent motion on the sky of a nearby star. The figure shows the combined effect of parallax, i.e. the circular motion reflecting the orbit of Earth on the sky, and the proper motion, the transverse movement of the star relative to the Sun.



Hyades Open Cluster

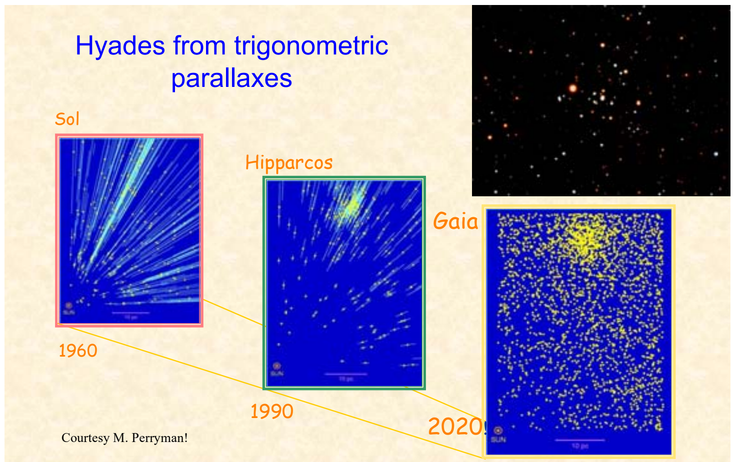


(Common) Proper Motion of the stars in the Hyades cluster of stars. The transversal velocity should match statistically the radial velocity and hence give a distance (~46pc)

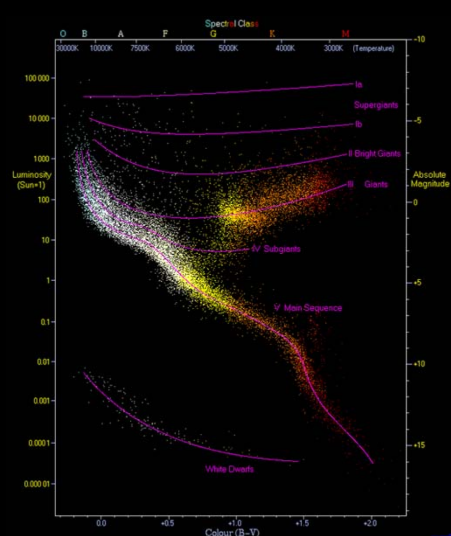


Hyades Open Cluster

- Direct distance through parallaxes



Hertzsprung-Russell Diagram

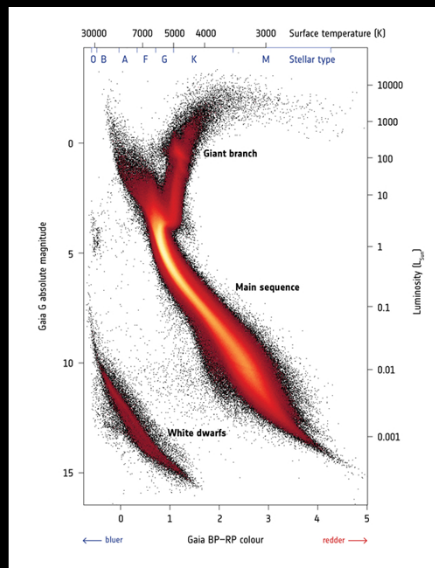


HIPPARCOS

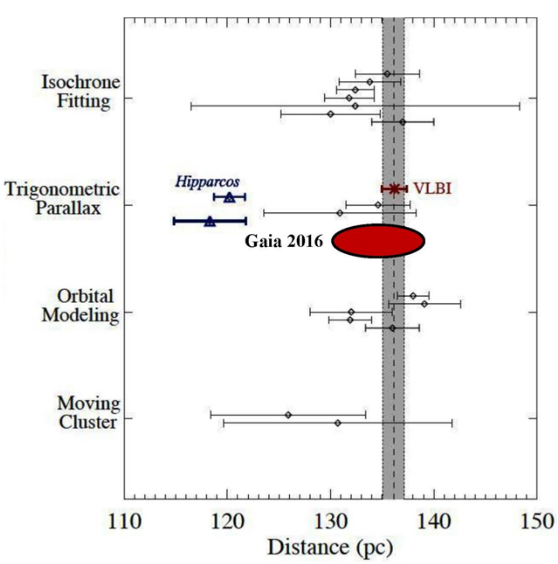
Main Sequence and Red Clump can be discerned

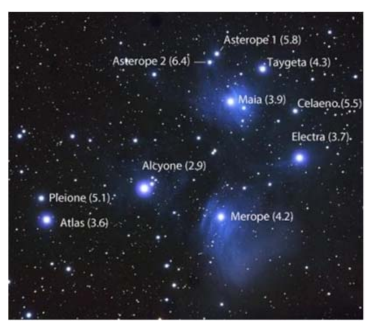
Calibrate Main Sequence (or Red Clump) of nearby clusters with parallaxes. Get distances to clusters further out.

Gaia's HR Diagram



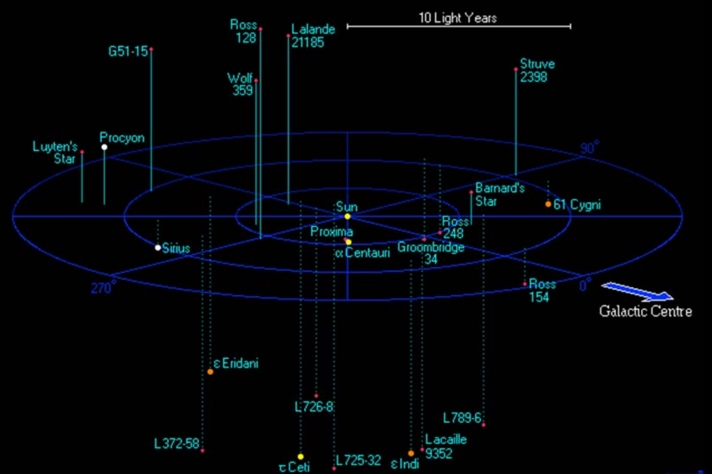
Distances to the Pleiades





Nearby stars

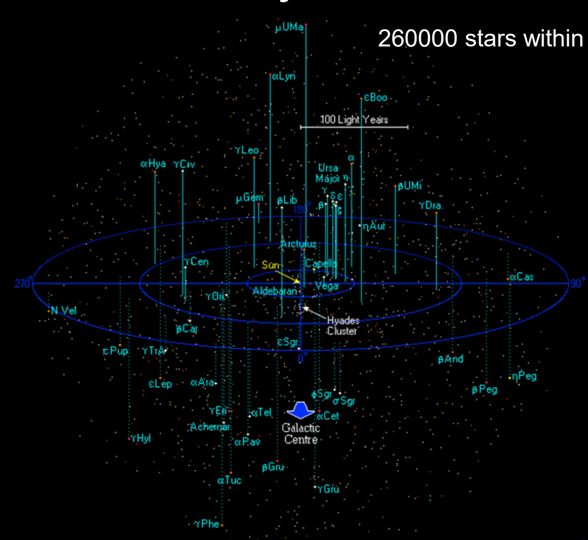
33 stars within 12 light years



www.atlasoftheuniverse.com

Nearby stars

260000 stars within 250 light years



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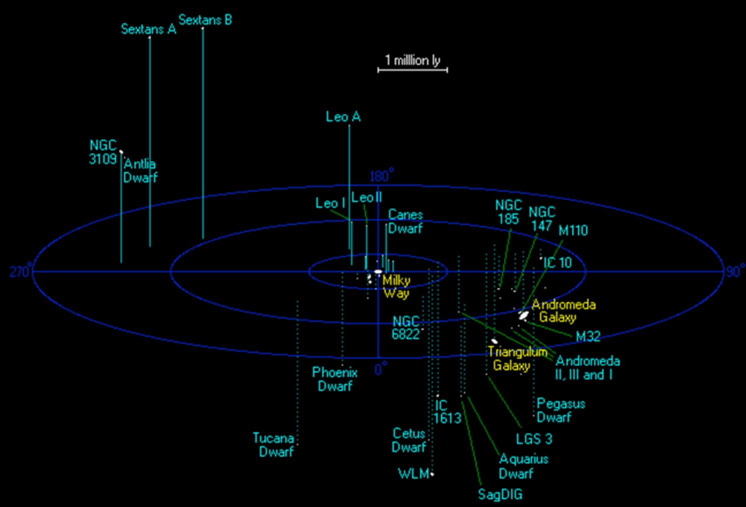
Local Group of Galaxies



Cepheid stars

- Henrietta Swan Leavitt (1912)
  - Cepheid stars in the Small Magellanic Cloud show a regular period luminosity relation

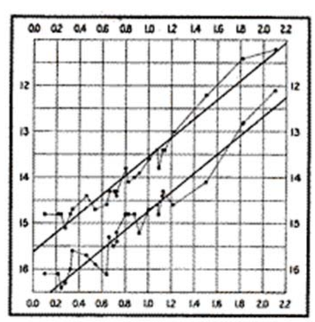
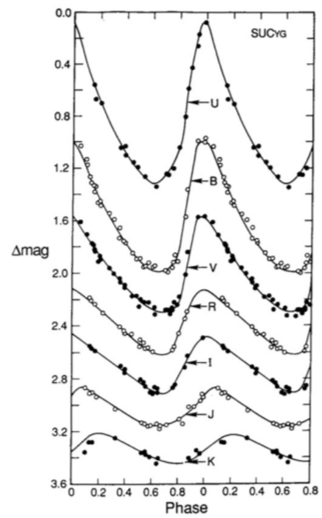


FIG. 2.

Cepheid stars

- Pulsationally variable stars
- Are observed in the solar neighbourhood and in distant galaxies

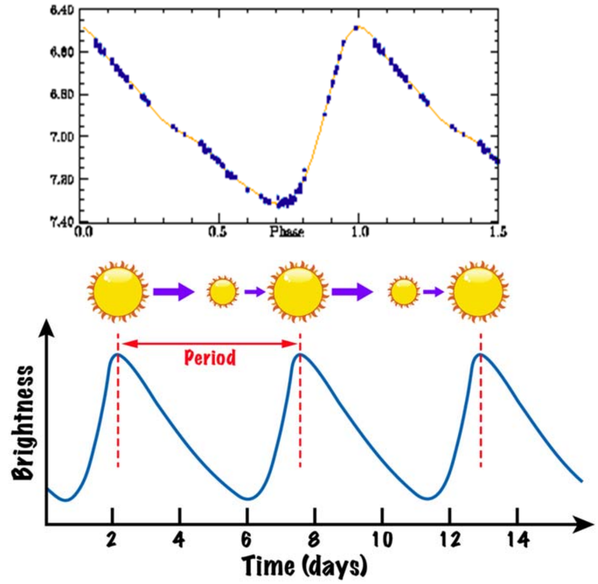


Madore & Freedman (1991)

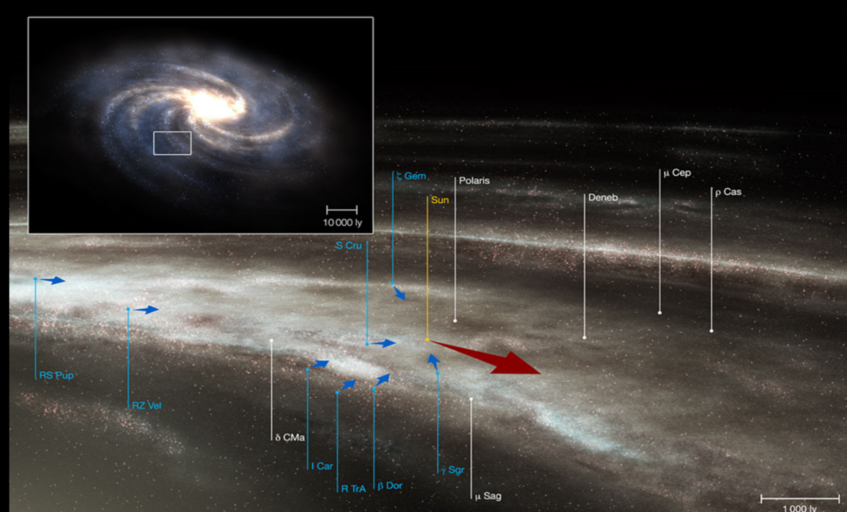
Cepheid stars

- Radial pulsators
  - star expands and shrinks on a regular basis
  - operated by the “Eddington” valve (also referred to as opacity valve)
    - a layer of ionised Helium heats up and the ionisation increases, which also increases the opacity → star expands
    - as it expands the outer layer start to cool again, Helium recombines, the opacity decreases → star shrinks again

Cepheid stars

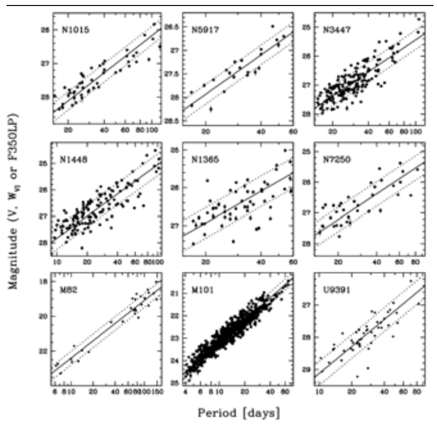


Solar Neighbourhood

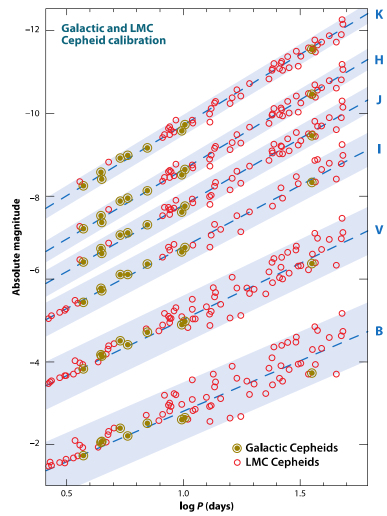


Cepheid stars

- Period-luminosity relation



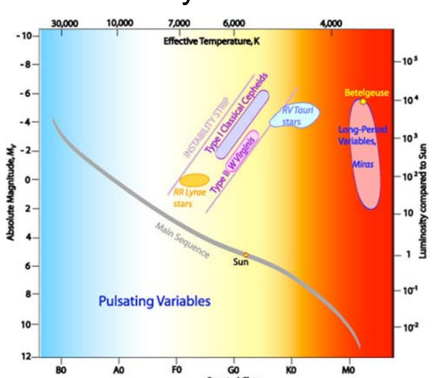
Riess et al. 2011

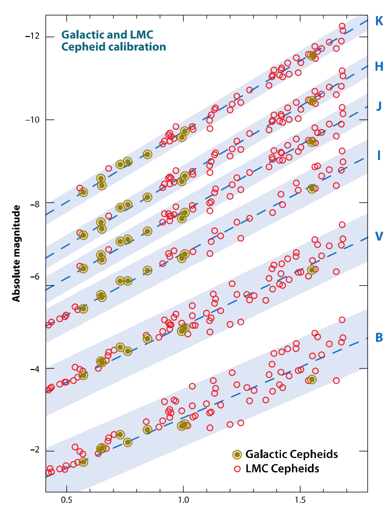


Freedman & Madore 2010

Cepheid stars

- Period-luminosity relation
  - also depends on the colour and probably metalicity





Freedman & Madore 2010

Parallax calibration of Cepheids

- Direct parallax available only for a handful

Table 1 Galactic cepheids with geometric parallaxes Freedman & Madore 2010

Cepheid	P(days)	log P	μ (mag)	σ (%)	Distance (pc)
RT Aur	3.728	0.572	8.15	7.9	427
T Vul	4.435	0.647	8.73	12.1	557
FF Aql	4.471	0.650	7.79	6.4	361
δ Cep	5.366	0.730	7.19	4.0	274
Y Sgr	5.773	0.761	8.51	13.6	504
X Sgr	7.013	0.846	7.64	6.0	337
W Sgr	7.595	0.881	8.31	8.8	459
β Dor	9.842	0.993	7.50	5.1	316
ζ Gem	10.151	1.007	7.81	6.5	365
ℓ Car	35.551	1.551	8.56	9.9	515

- HST Programme under way to observe out to 4 kpc (Riess et al. 2011) (results: see later)
- Gaia observes ~9000 Cepheids to 5-8 kpc with 1% uncertainty

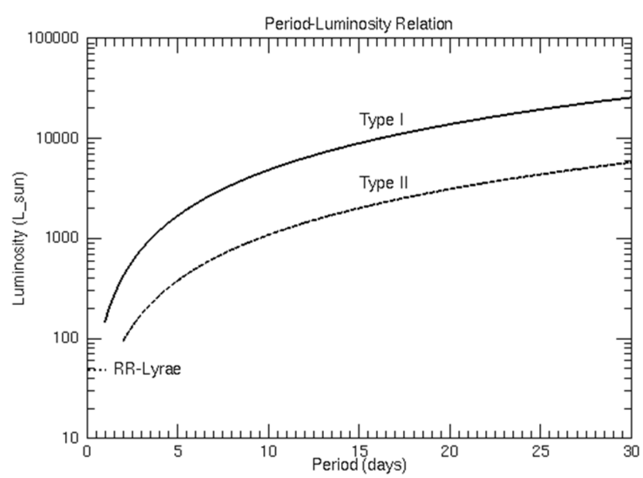
Why was Hubble's original measurement so far off ?

- Distance measurement based on the period-luminosity relation of Cepheid stars

Why was Hubble's original measurement so far off ?

- there are two populations of Cepheids (but Hubble was not aware of that)
  - –type I: metal rich stars (disk of galaxies)
  - –type II: metal poor stars (halo of galaxies)
  - –type II Cepheids ("W Virginis") are less luminous than type I Cepheids ("δ Cephei")

Why was Hubble's original measurement so far off ?



Consequence

- Distance scale was calibrated based on type II Cepheids
- Distances to other galaxies were measured using type I Cepheids
- "yard stick" was systematically too small

⟶ ***H_0 too large!***