20th century cosmology

- **1920s – 1990s (from Friedmann to Freedman)**
  - **theoretical technology available, but no data**
  - **20th century: birth of observational cosmology**
    - Hubble's law ~1930
    - Development of astrophysics 1940s – 1950s
    - Discovery of the CMB 1965
    - Inflation 1981
    - CMB anisotropies: COBE ~1990

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- **1920s – 1990s (from Friedmann to Freedman)**
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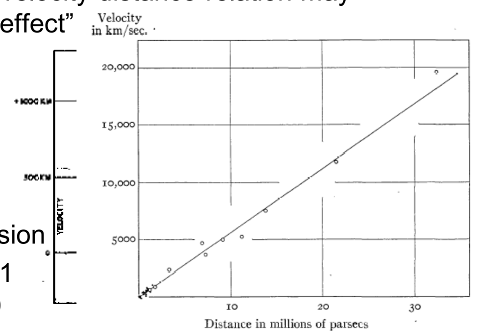
  - **20th century: birth of observational cosmology**
    - Hubble's law ~1930
      - – from antiquity Universe had been assumed to be static
      - – relativity naturally expects universe to expand or contract, but very few people took this literally
        - Alexander Friedmann
        - Georges Lemaître
        - not Einstein!
    - expansion eventually discovered by observation

The expanding universe

- **At $z << 1$ all cosmological models expect a linear behaviour, $z \propto d$**
  - **first evidence: Edwin Hubble 1929**
    - "the possibility that the velocity-distance relation may represent the de Sitter effect"
    - slope of graph 465±50 km/s/Mpc or 513±60 km/s/Mpc (individual vs grouped)
    - assumption of linearity
      - – no centre to expansion
      - – established by 1931 (Hubble & Humason)



Hubble's law

- **Timeline**
  - **1907: Bertram Boltwood dates rocks to 0.4 – 2.2 Gyr (U-Pb)**
  - **1915: Vesto Slipher demonstrates that most galaxies are redshifted**
  - **1925: Hubble identifies Cepheids in M31 and M33**
  - **1927: Arthur Holmes – "age of Earth's crust is 1.6 – 3.0 Gyr"**
  - **1929: Hubble's constant value of 500 km/s/Mpc implies age of Universe ~2.0 Gyr**
  - ***potential problem here…***

- **Hubble's law systematics**
  - **distances mostly depend on $m - M = 5 \log(d/10)$ (luminosity distance)**
  - **getting M wrong changes d by a factor of**

$$10^{(M - M_{\text{est}})/5}$$

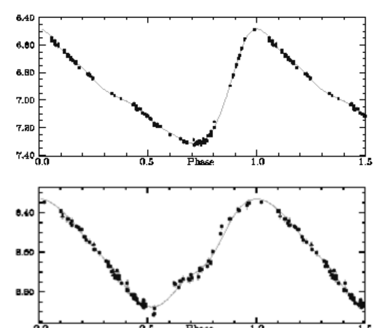
    which does not affect linearity (just changes slope)
  - **typical systematic error: very difficult to spot**
    - Jan Oort expressed doubts very quickly (1931)
    - no-one else till 1951!

Hubble's distances

- **Hubble used**
  - **Cepheid variables as calibrated by Shapley (1930)** — Wrong by factor of 2!
  - **brightest stars in galaxies as calibrated by Cepheids** — Wrong by factor of ~4!
  - **total luminosities of galaxies calibrated by Cepheids and brightest stars** — Wrong because calibration wrong

Cepheids

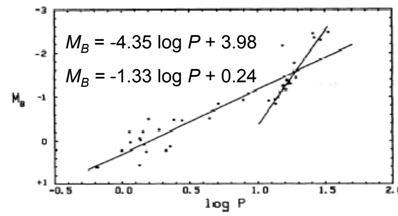
- **Shapley (1930):**
  - **calibration of extragalactic Cepheids based on assumption of consistency with RR Lyrae variables in globular clusters**
- **Baade (1952):**
  - **Cepheids in Magellanic Clouds (δ Cephei stars or classical Cepheids) are different from "Cepheids" in globular clusters (W Vir stars or Type II Cepheids)**



Typical classical Cepheid and W Vir light curves from the HIPPARCOS database

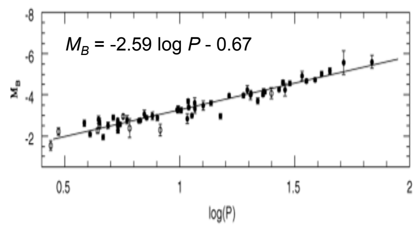
Cepheids

- **Period-luminosity relation**
  - **RR Lyrae stars**
    - period < 1 day
    - M ~ 0.7 (on horizontal branch)
    - little evidence of dependence on period (does depend on metallicity)
  - **W Vir stars**
    - period > 10 days
    - post-horizontal-branch low mass stars
  - **classical Cepheids**
    - period > 1 day
    - post-main-sequence stars of a few solar masses
- **Distance error**
  - **from +0.7 to −0.7: ~ factor 2**



DH McNamara, *AJ* **109** (1995) 2134

Ngeow & Kanbur, *MNRAS* **349** (2004) 1130

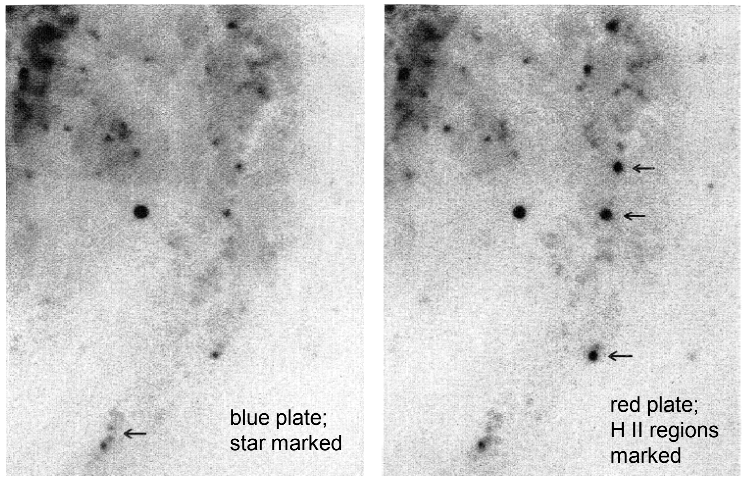


Brightest stars

- **Idea: brightest stars in all galaxies are about the same absolute magnitude**
  - **not unreasonable: tip of red giant branch is still used as distance indicator**
  - **might worry about age and metallicity effects**
  - **but first be sure you are looking at a star!**
    - Hubble wasn't: he was seeing H II regions (ionised gas around young massive stars)
    - these are much brighter than individual stars
    - difference ~2 mag

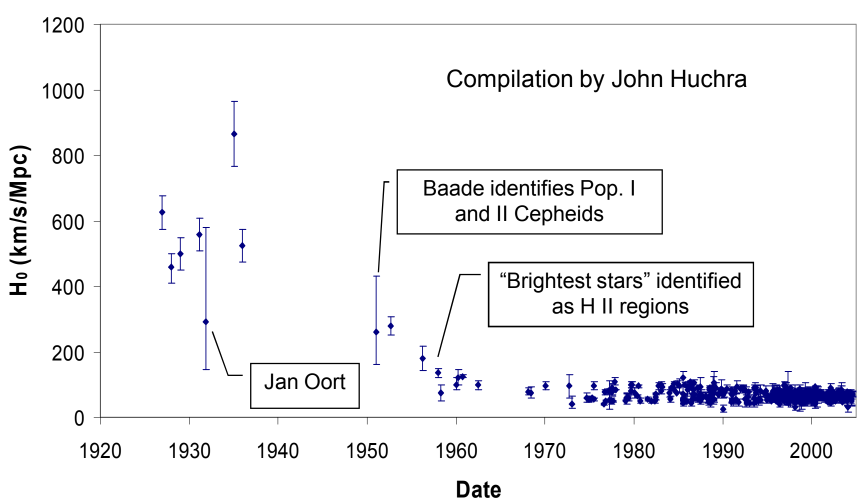
Stars and H II regions

M100 spiral arm



Allan Sandage, *ApJ* **127** (1958) 123

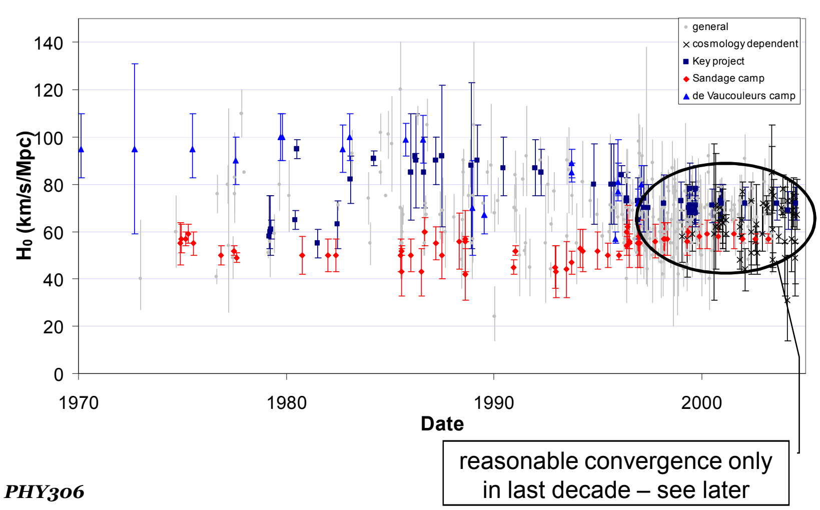
History of H_o



Hubble Wars

- **Distance indicators**
  - **Stars, clusters, etc.**
    - classical Cepheids
    - novae
    - globular clusters
    - planetary nebulae
    - supernovae Ia and II
  - **Galaxies**
    - Tully-Fisher
    - Fundamental plane
  - **Bigger things**
    - Sunyaev-Zeldovich effect
    - gravitational lensing
- **Sources of uncertainty**
  - **calibration**
    - zero point
    - dependence on age, metallicity, galaxy type, etc.
    - reddening corrections
  - **bias**
    - Malmquist bias
      - at large distances, you tend to detect brighter than average objects
    - personal biases too!
      - Allan Sandage: low
      - Gerard de Vaucouleurs: high

Hubble Wars



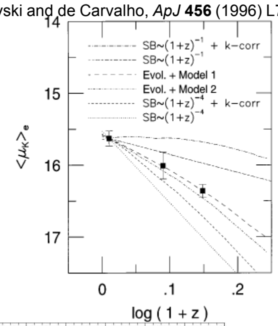
Hubble's law & expansion

- **Does Hubble's law mean universe is expanding (i.e. *a*(*t*) in RW metric not constant)?**
  - **Alternative hypotheses**
    - real explosion at some past time
      - over time *t* galaxies travel distance *d*=*vt*, so build up Hubble law
      - don't expect to be at centre of expansion, so don't expect isotropy
    - "tired light": light loses energy $\propto$ distance travelled
      - tested by looking at surface brightness:
      - tired light: object at redshift *z* has surface brightness $\propto(1+z)^{-1}$
      - expansion: object at redshift *z* has surface brightness $\propto(1+z)^{-4}$
        - 1 from energy loss, 1 from reduction in reception rate of photons, 2 from relativistic aberration

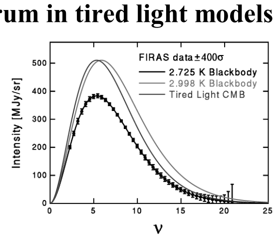
Tests of tired light

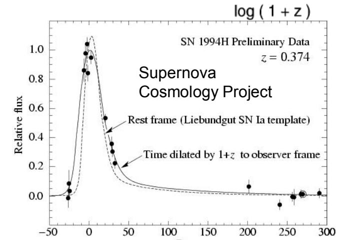
- **Surface brightness**
  - **results consistent with expansion**
    - correcting for galaxy evolution
- **Supernova light curves**
  - **effect of time dilation**
- **Cosmic microwave background**
  - **not expected to have blackbody spectrum in tired light models**

Pahre, Djorgovski and de Carvalho, *ApJ* **456** (1996) L79



Ned Wright, http://www.astro.ucla.edu/~wright/tiredlit.htm





State of Play ~1990

- **Hubble's law $v = H_0 d$ well established**
  - **actual value of H_0 uncertain by a factor of 2**
- **Interpretation of Hubble's law well established**
  - **surface brightness tests indicate expansion, not "tired light"**
- **Return of worries about age of universe**
  - **values of H_0 above ~80 km/s/Mpc looking suspiciously inconsistent with globular cluster ages**
    - in flat universe without Λ, 80 km/s/Mpc gives age 8 Gyr
    - globular cluster ages from stellar evolution ~12 Gyr