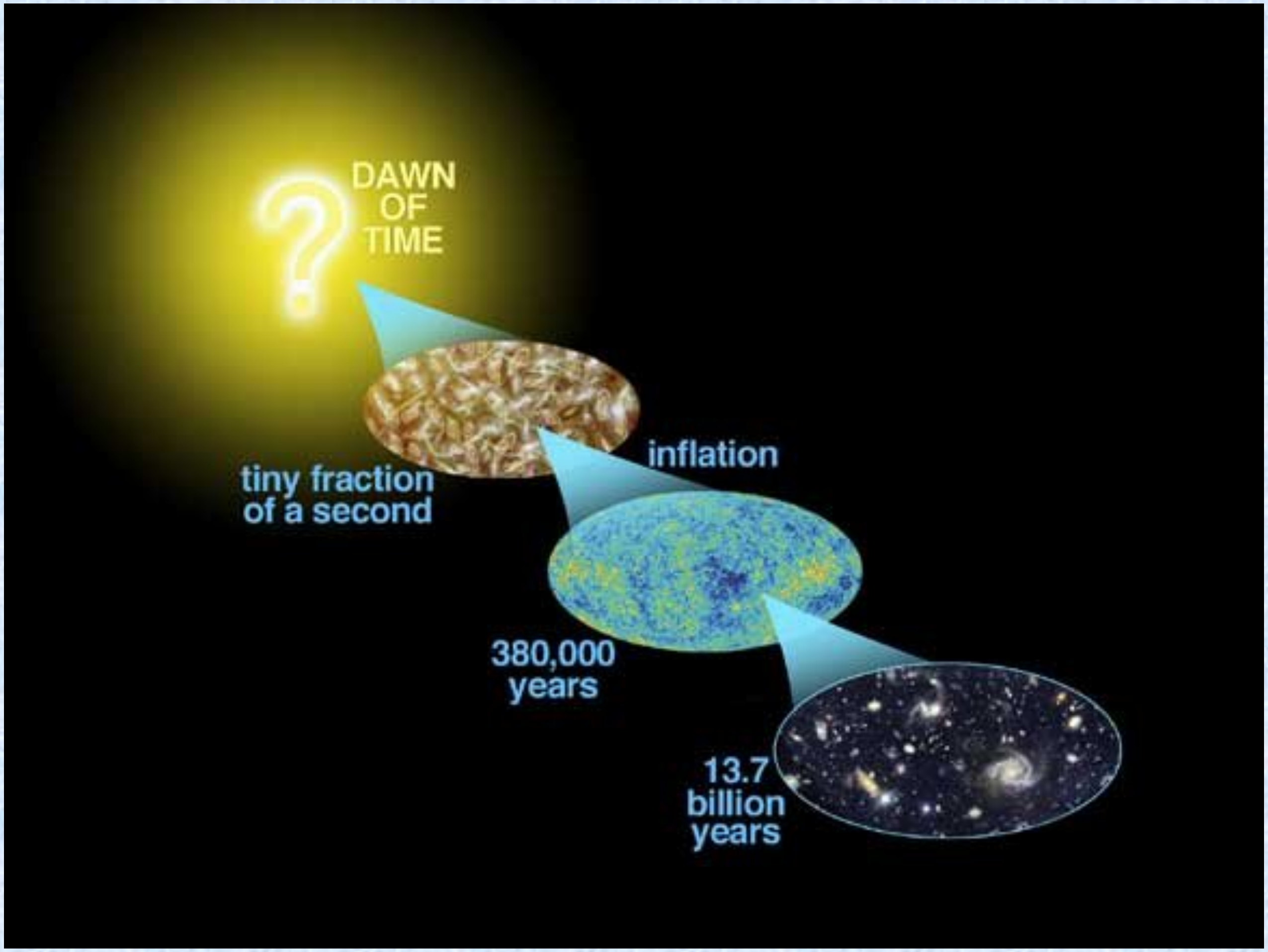
Physics 133: Extragalactic Astronomy and Cosmology



Lecture 9; February 10 2014

Previously:

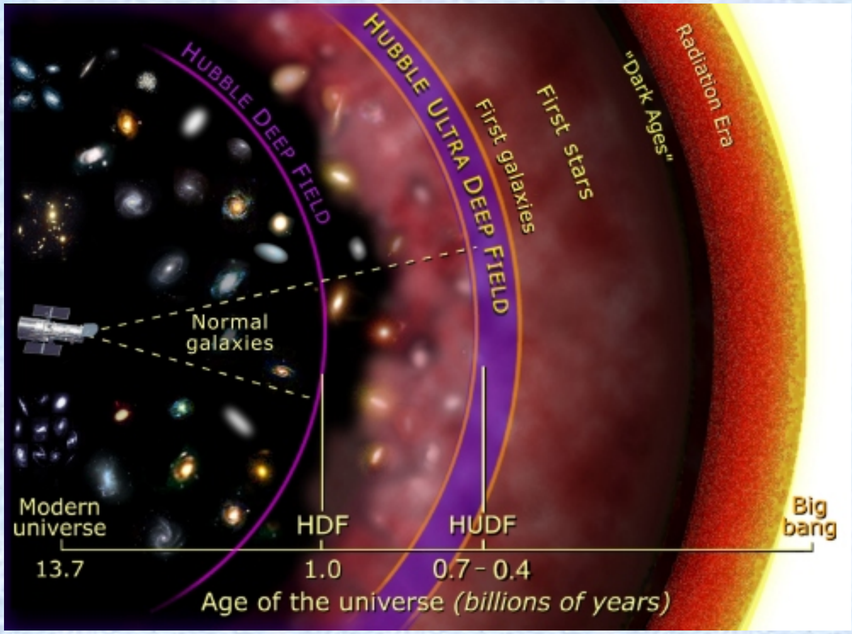
- Measuring kinematics of the universe determines cosmological parameters.
- Proper distance depends on redshift via the Hubble constant, to first order
- Higher order terms of the kinematics are needed to obtain other cosmological parameters
- Proper distance is not appropriate. We need stuff we can measure.
  - Luminosity distance ~ Proper distance (1+z) for a "flat" universe

Previously:

- Measuring cosmological parameters. II:
  - Angular Diameter Distance
  - Cosmological dimming and the Tolman Test
  - Cosmic volume
  - Cosmic time

What else? Cosmic time

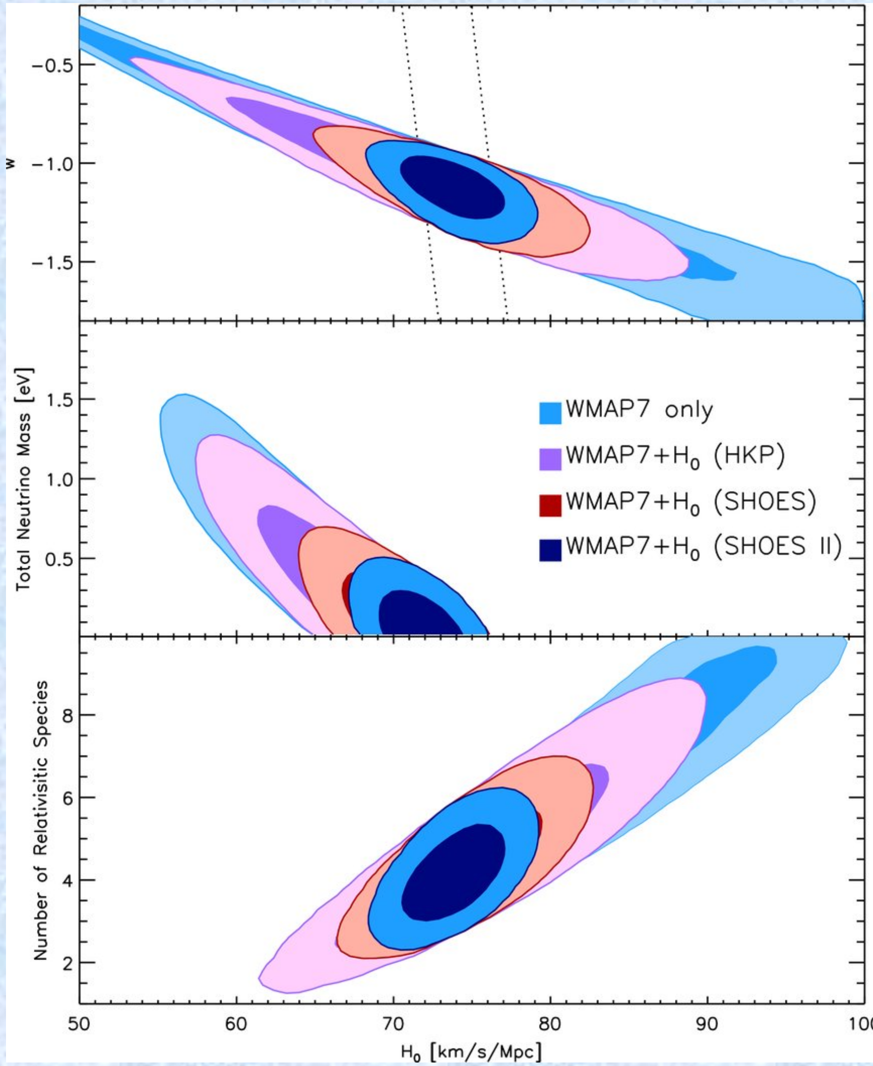
- Suppose we had a clock
- For example?
- Measuring time as a function of redshift gives us the cosmological parameters
- [Black board]



Outline:

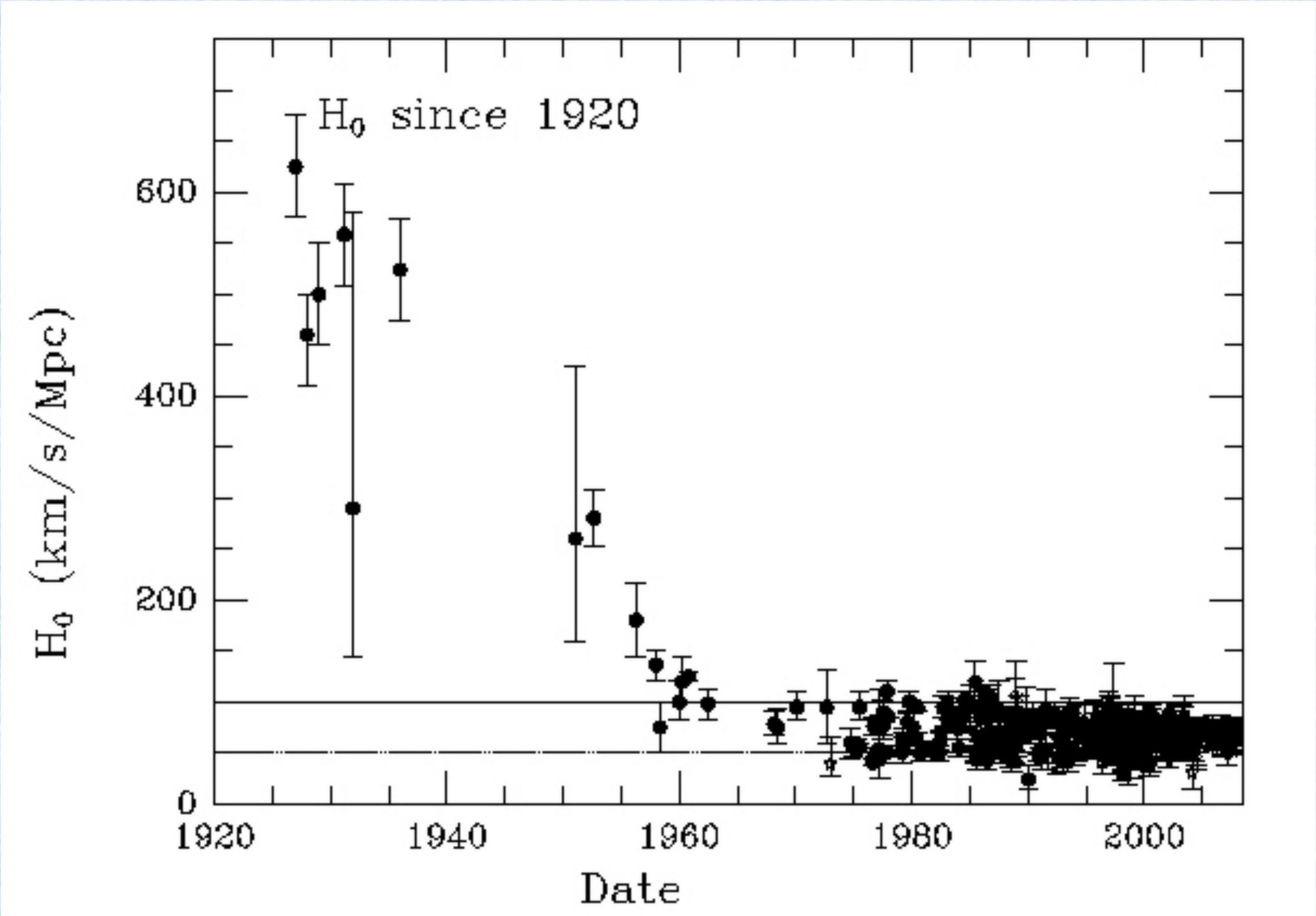
- Basic statistics
- Measuring the Hubble Constant
  - Standard Candles
    - Supernovae Ia
    - Other standard candles
- Examples of cosmography
  - Luminosity distance
  - Cosmic Clocks
  - Tolman test
- Other ways to estimate cosmological parameters:
  - Clusters and cosmology (later on)
  - Gravitational lensing (later on)

Why H_0?



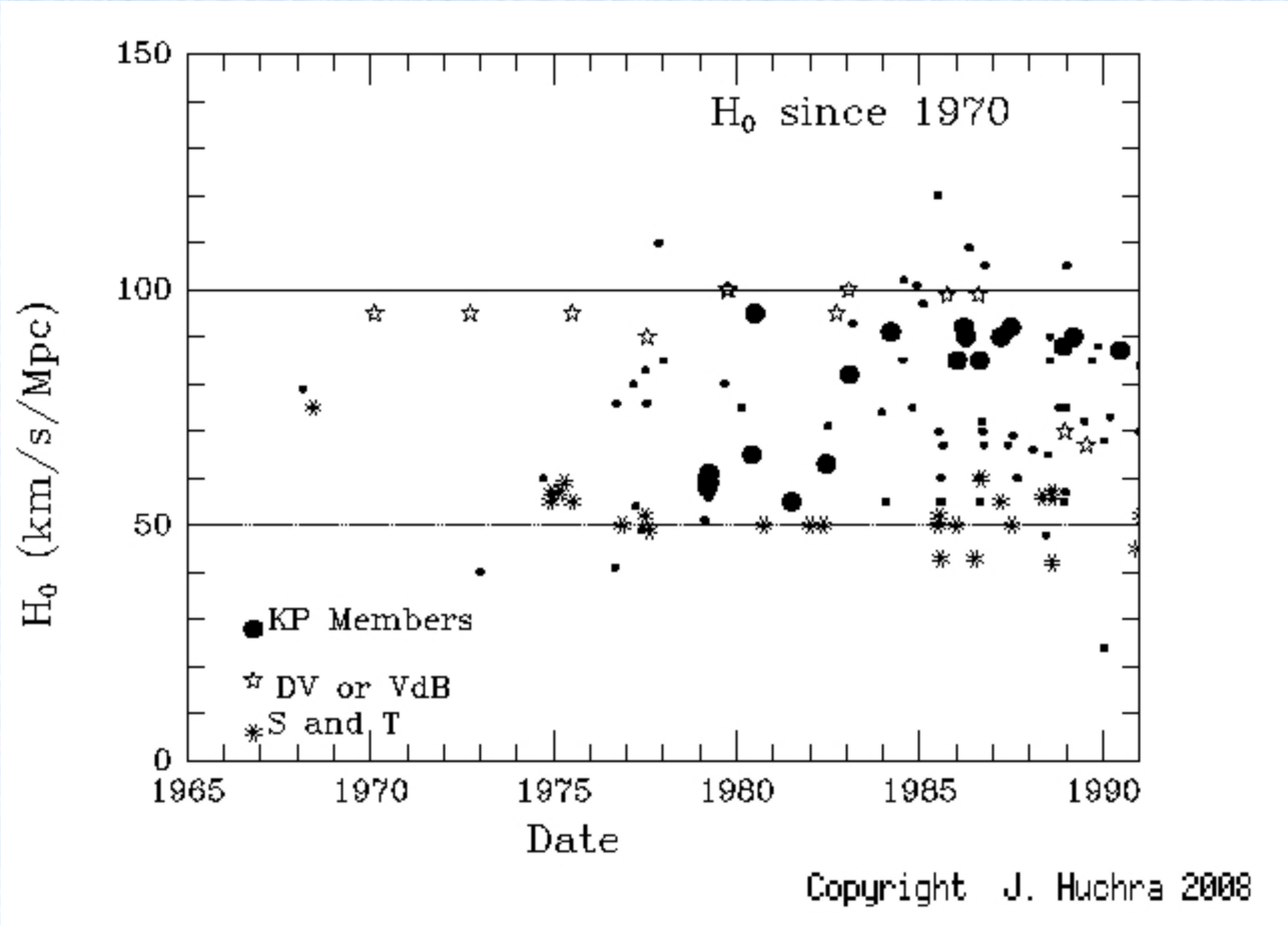
w
−0.5
−1.0
−1.5
Total Neutrino Mass [eV]
1.5
1.0
0.5
WMAP7 only
WMAP7+H0 (HKP)
WMAP7+H0 (SHOES)
WMAP7+H0 (SHOES II)
Number of Relativisitic Species
8
6
4
2
50
60
70
80
90
100
H0 [km/s/Mpc]

H_0 History



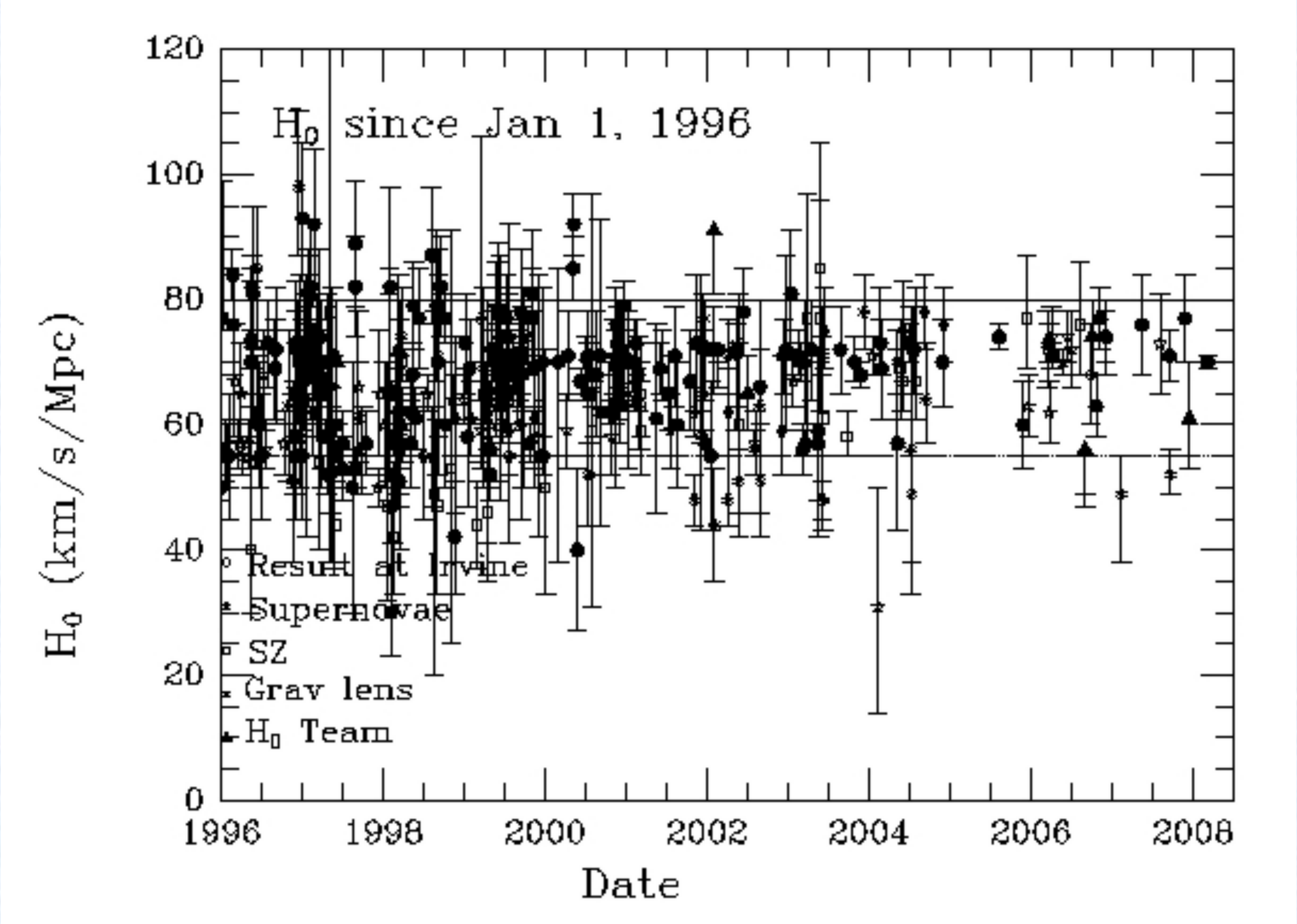
H0 since 1920
H0 (km/s/Mpc)
Date
0
200
400
600
1920
1940
1960
1980
2000

History



H0 since 1970
H0 (km/s/Mpc)
150
100
50
0
1965
1970
1975
1980
1985
1990
Date
KP Members
DV or VdB
S and T
Copyright J. Huchra 2008

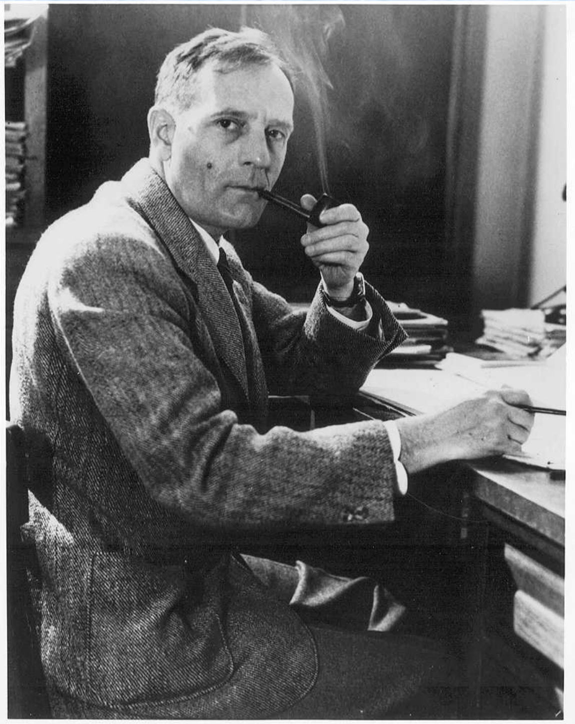
History



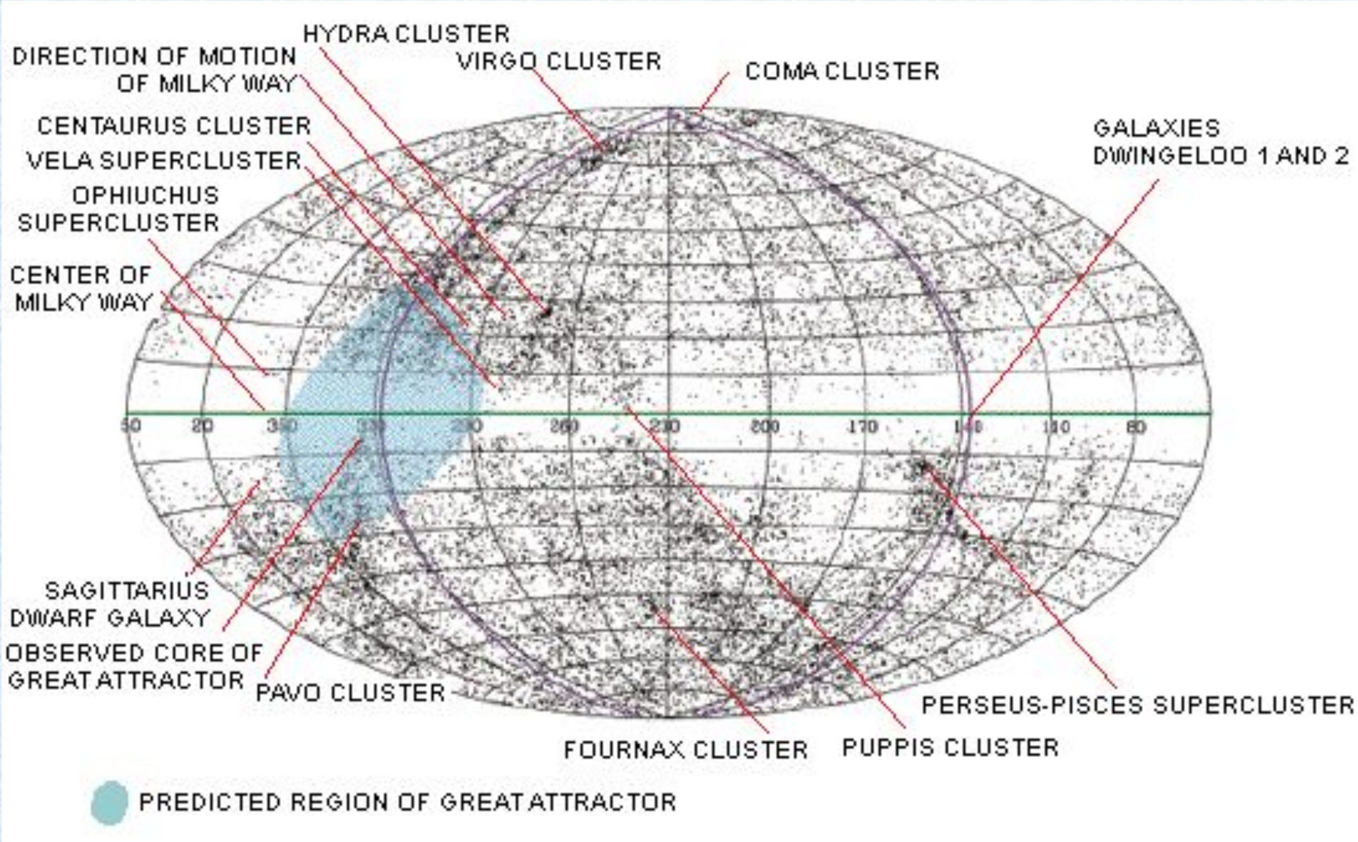
H_0 since Jan 1, 1996
H_0 (km/s/Mpc)
Date
Result at Irvine
Supernovae
SZ
Grav lens
H_0 Team
0
20
40
60
80
100
120
1996
1998
2000
2002
2004
2006
2008

The Hubble Constant

- For small z:
  - $zc=H_0 D$
  - What D?
- Easy?:
  - Measure z (v)
  - Measure D
- Problems:
  - Peculiar velocities
  - How to measure D?

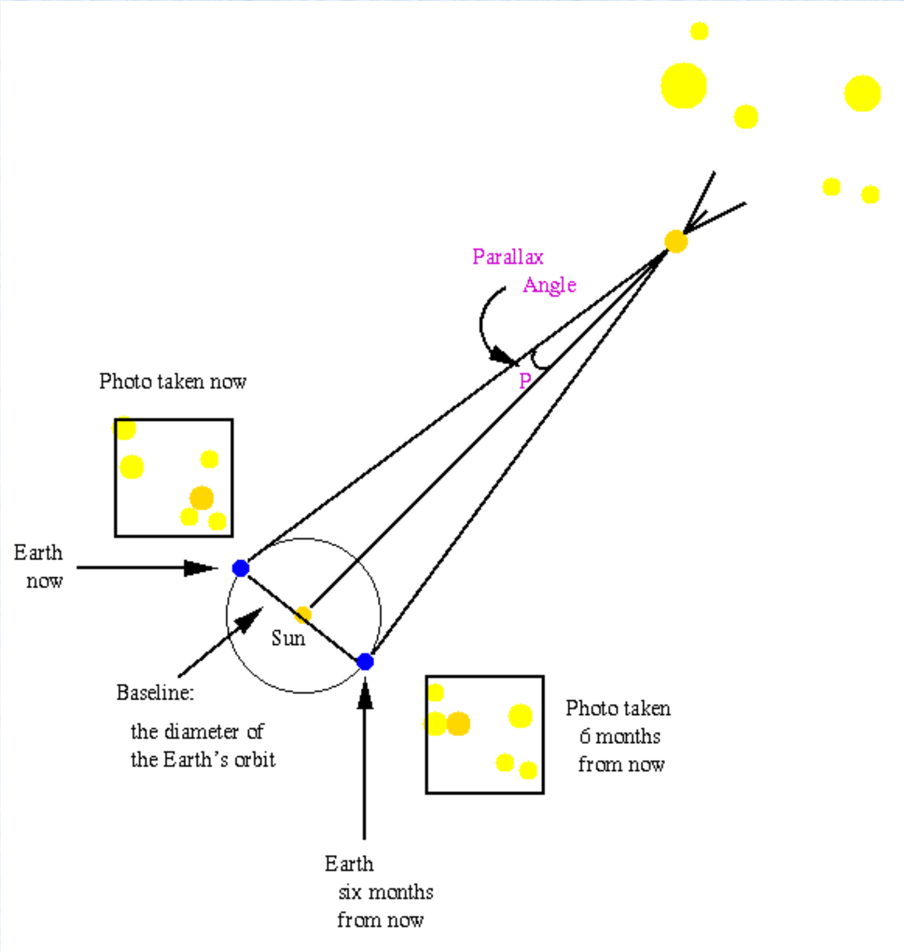


The Hubble Constant. Measuring v



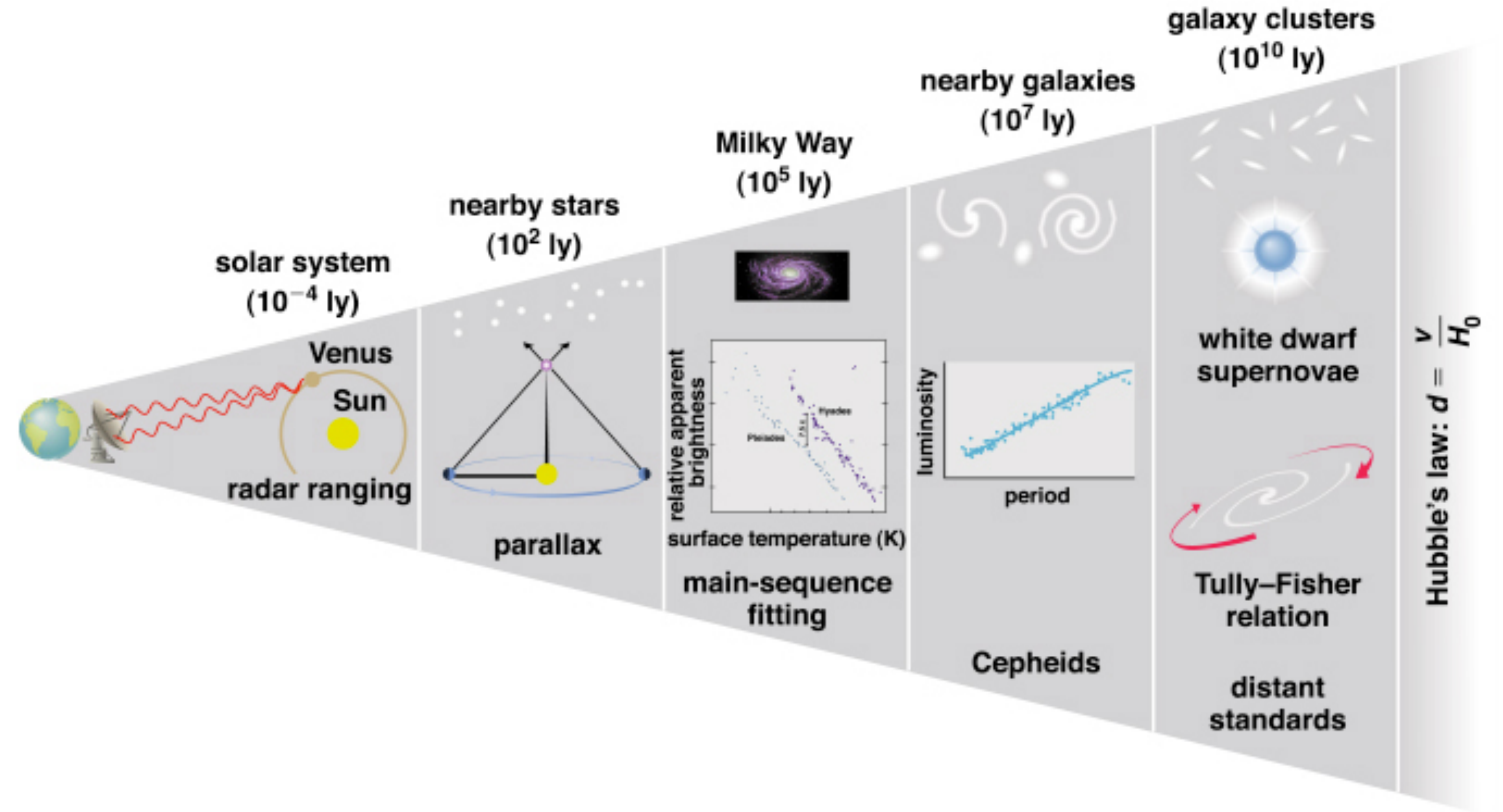
- **V=zc+vp**
- **vp~500 km/s -> zc>>500 km/s**

The Hubble Constant. Measuring D



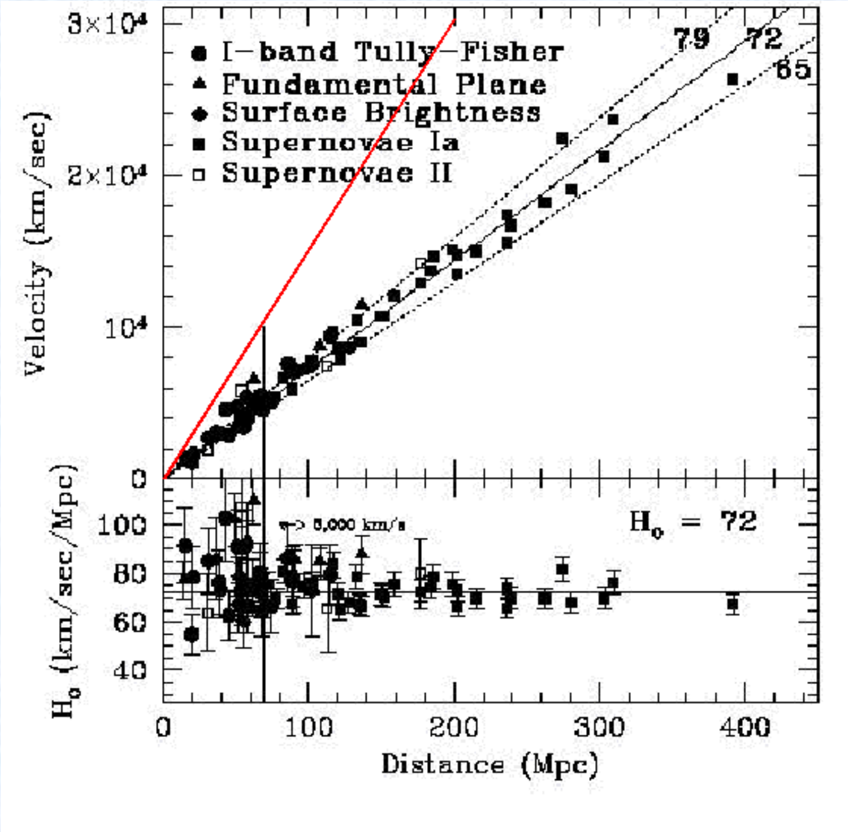
Parallax works to <kpc… not enough!

The cosmic distance ladder

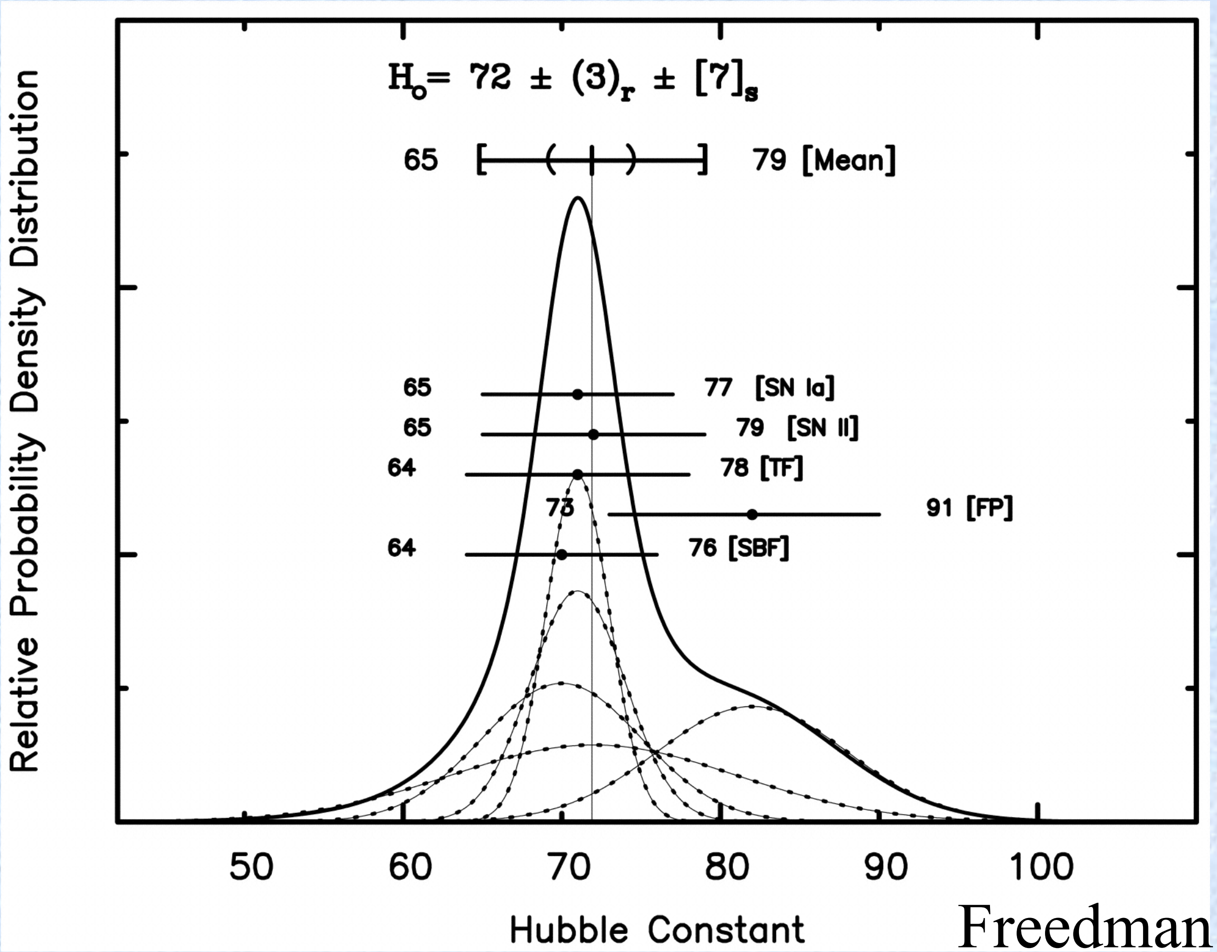


The Hubble constant. Key project strategy

- "Secondary" distance indicators calibrated with cepheids P-L relation reach into the Hubble Flow
- Cepheids P-L relation is calibrated using Cepheids in the Large Magellanic Cloud



The Hubble constant.
Key project results



Freedman et al. 2001

The Hubble constant. Problems with the distance ladder

- **Distance to the LMC**
- **Calibration of the Cepheid P-L relation (chemical composition)**
- **Most "standard candles" are not understood in terms of fundamental physics.**

From Key Project to SHOES

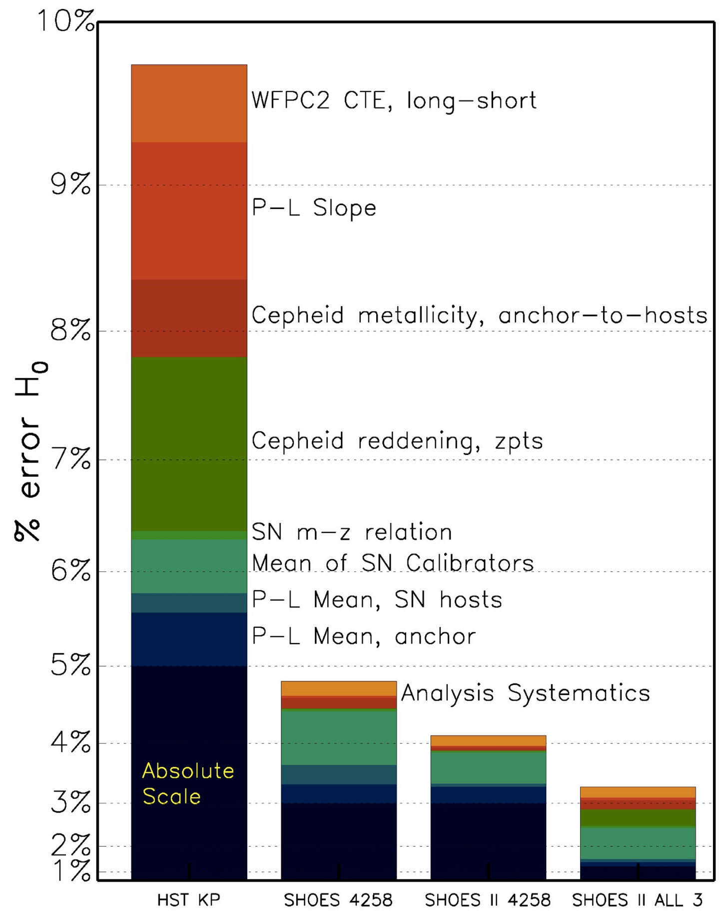
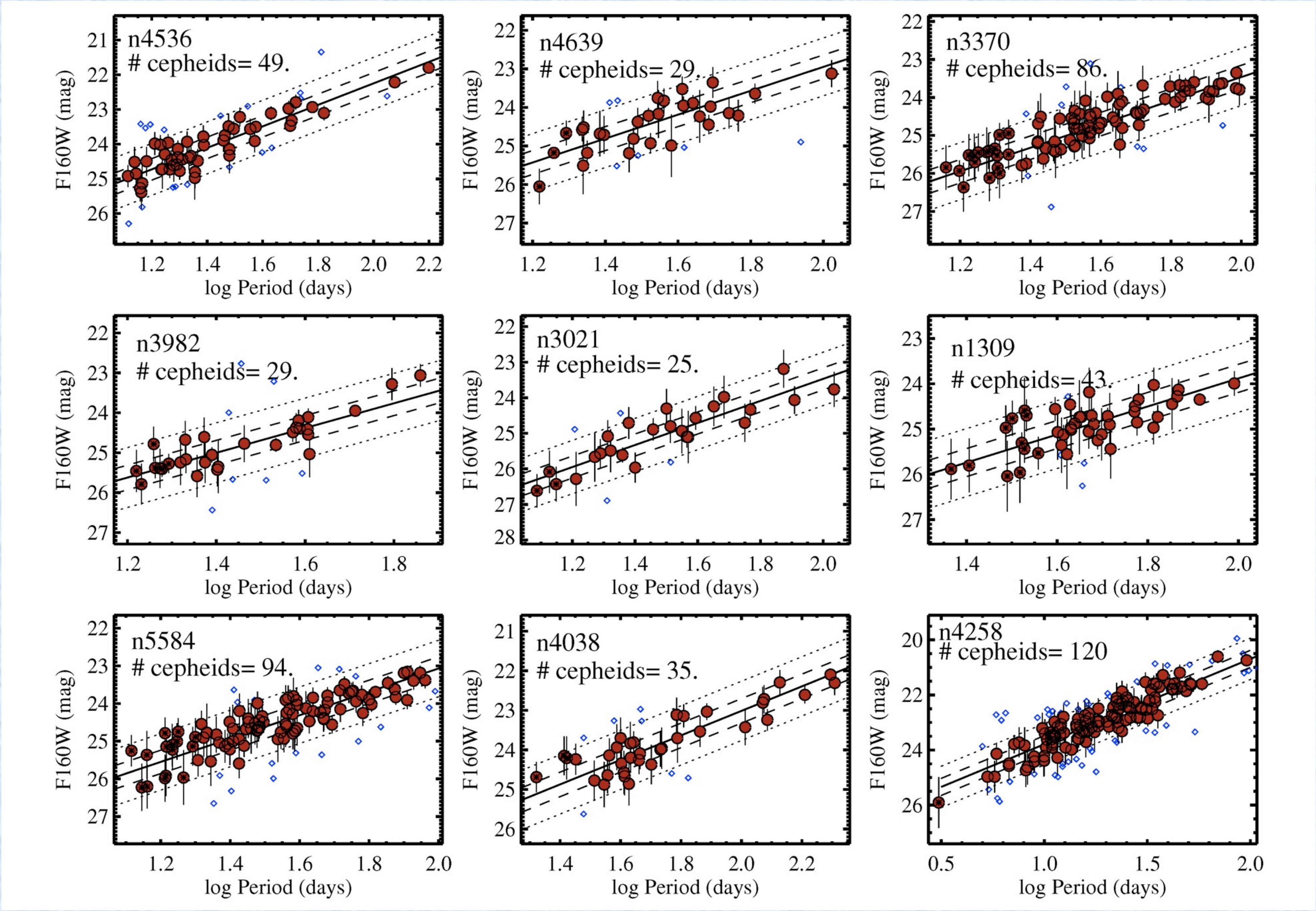


Figure 9. Uncertainties in the determination of the Hubble constant. Uncertainties are squared to show their contribution to the quadrature sum. These terms are given in Table 5.

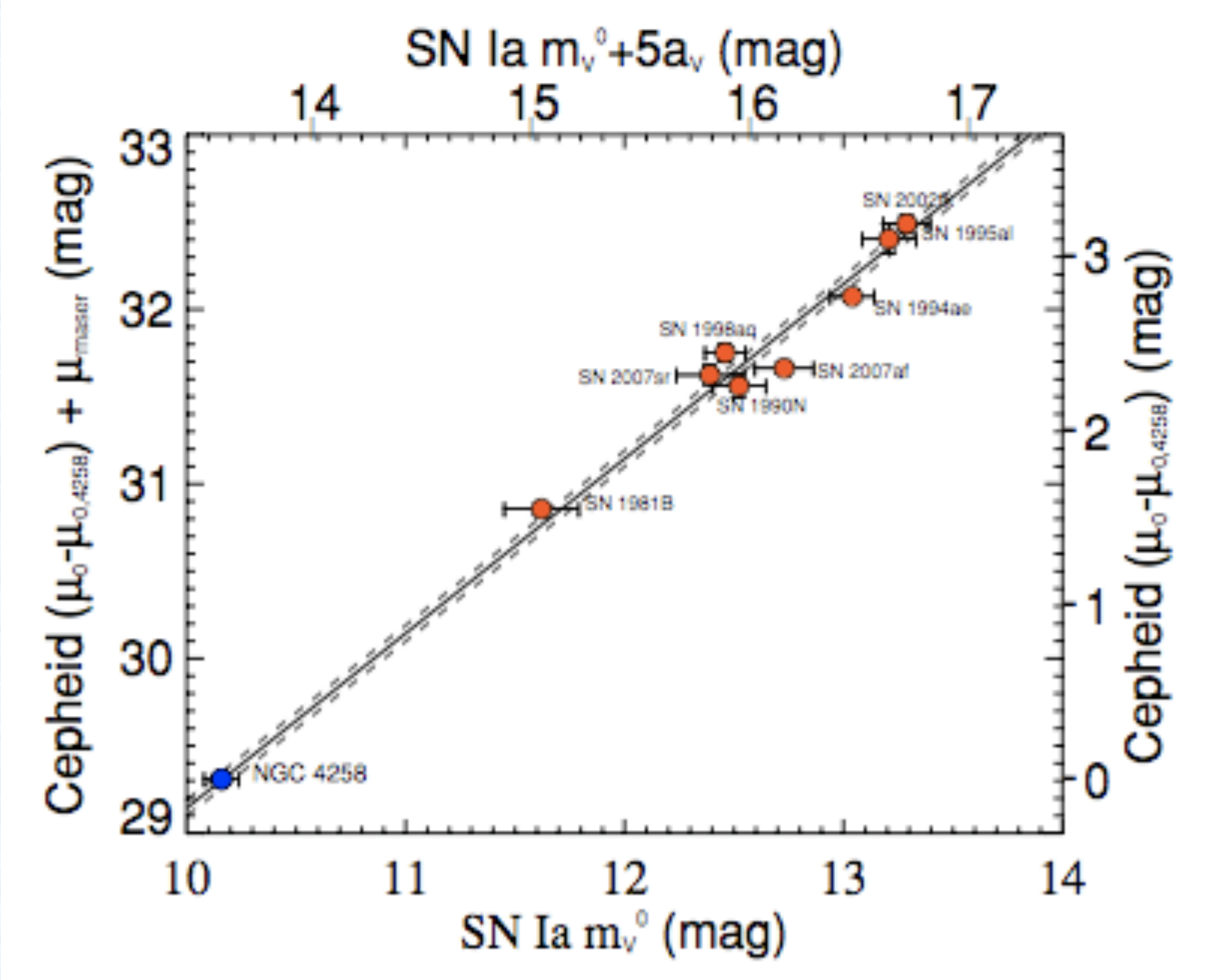
Riess et al 2011

SHOES



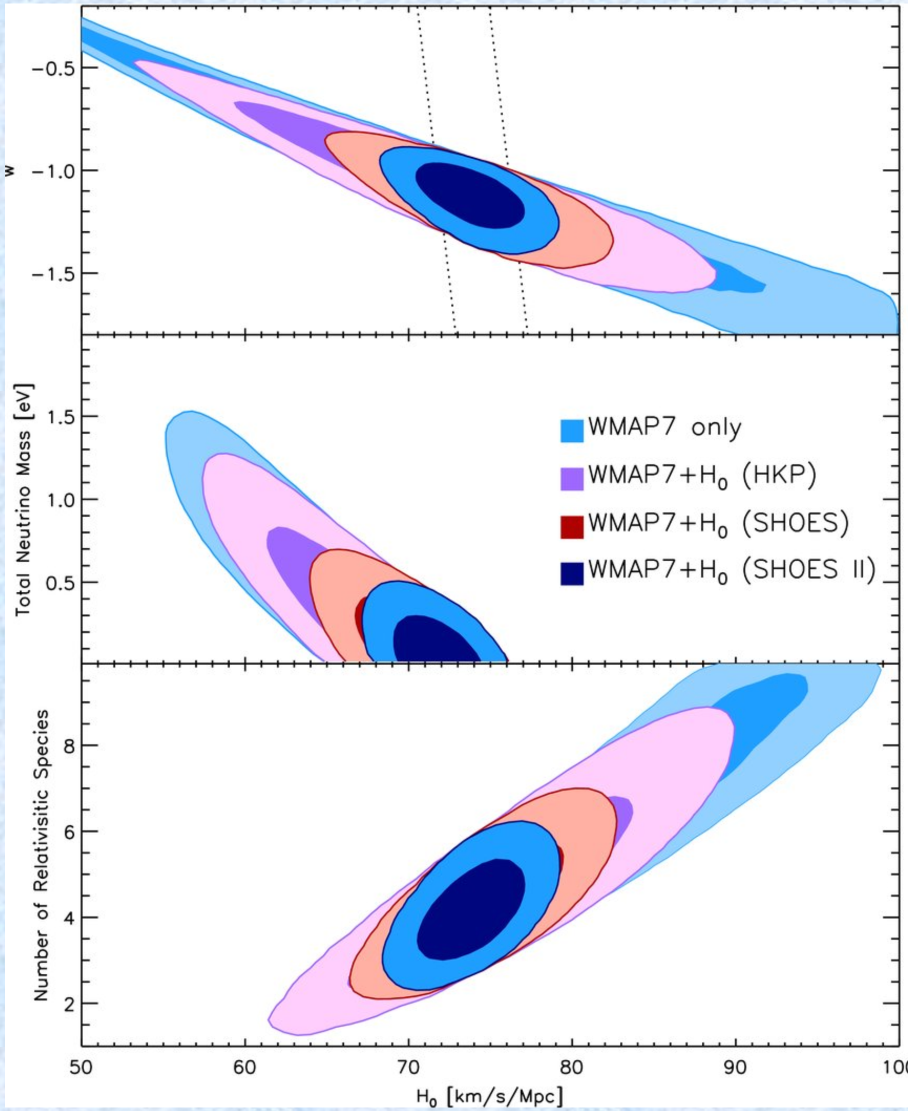
n4536
cepheids= 49.
n4639
cepheids= 29.
n3370
cepheids= 86.
n3982
cepheids= 29.
n3021
cepheids= 25.
n1309
cepheids= 43.
n5584
cepheids= 94.
n4038
cepheids= 35.
n4258
cepheids= 120
F160W (mag)
log Period (days)

SHOES



SN Ia $m_V^0 + 5a_V$ (mag)
14
15
16
17
33
32
31
30
29
10
11
12
13
14
SN Ia m_V^0 (mag)
Cepheid $(\mu_0 - \mu_{0,4258}) + \mu_{maser}$ (mag)
Cepheid $(\mu_0 - \mu_{0,4258})$ (mag)
3
2
1
0
SN 1995al
SN 1994ae
SN 1998aq
SN 2007sr
SN 2007af
SN 1990N
SN 1981B
NGC 4258

SHOES



w
−0.5
−1.0
−1.5
Total Neutrino Mass [eV]
1.5
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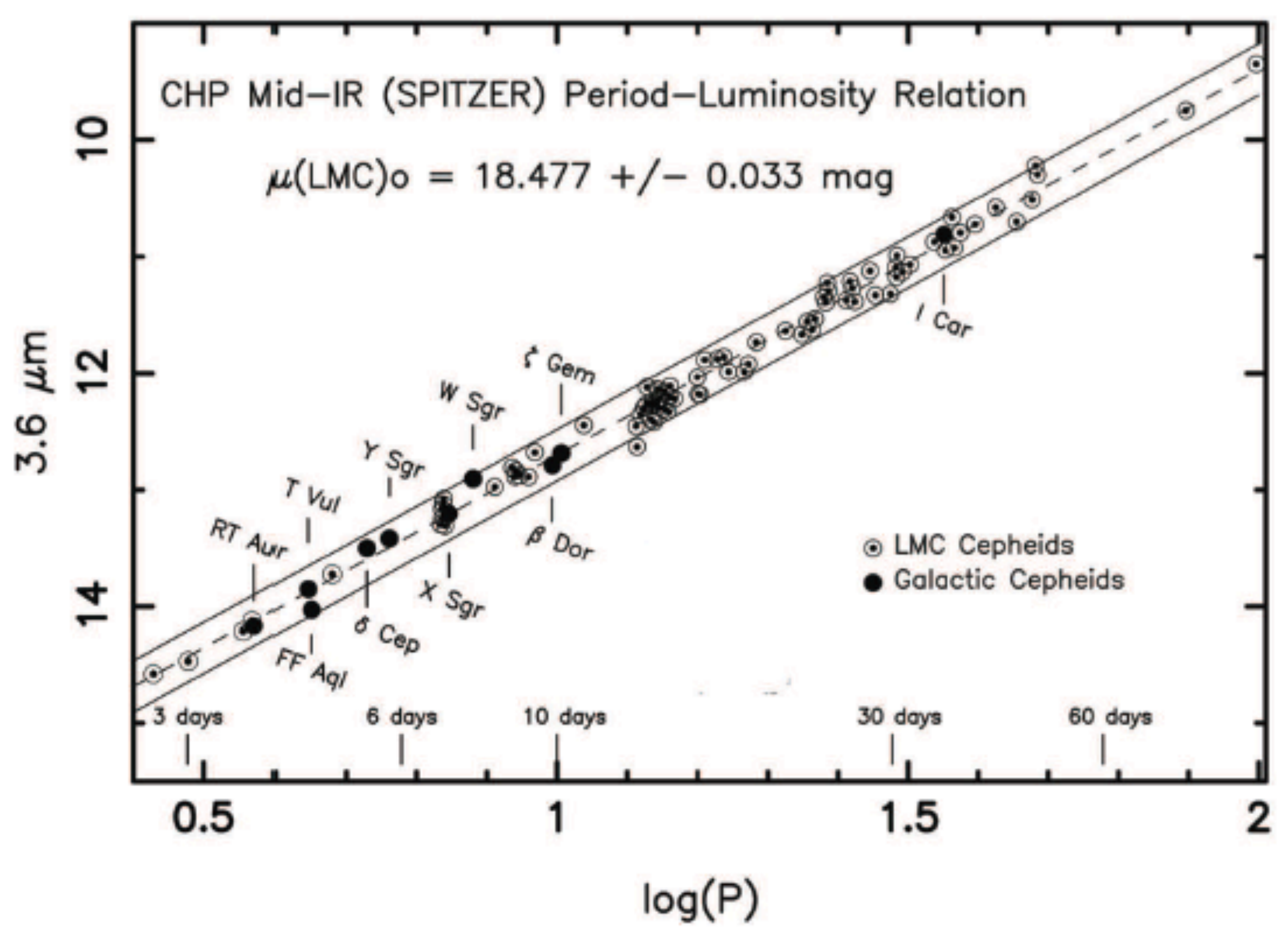
WMAP7 only
WMAP7+H0 (HKP)
WMAP7+H0 (SHOES)
WMAP7+H0 (SHOES II)
Number of Relativisitic Species
8
6
4
2
50
60
70
80
90
100
H0 [km/s/Mpc]

CHP



CHP Mid–IR (SPITZER) Period–Luminosity Relation
μ(LMC)o = 18.477 +/– 0.033 mag
3.6 μm
10
12
14
0.5
1
1.5
2
log(P)
3 days
6 days
10 days
30 days
60 days
RT Aur
T Vul
Y Sgr
W Sgr
ζ Gem
FF Aql
δ Cep
X Sgr
β Dor
l Car
LMC Cepheids
Galactic Cepheids

Ia as standard candles

$$D_L = (1+z)D$$

$$D = \frac{c}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + (1-\Omega_m-\Omega_{de})(1+z')^2 + \Omega_{de}(1+z')^{3(1+w)} + \Omega_\gamma(1+z')^4}}$$

$$D_A = D/(1+z)$$

Sn Ia as standard candles

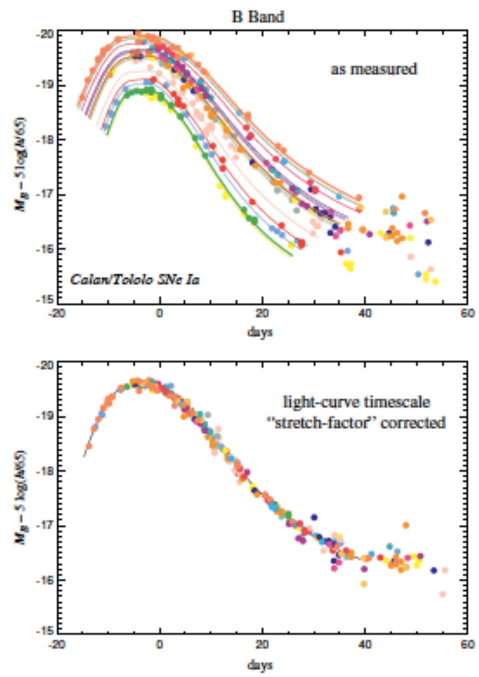


Figure 12: *Top panel:* *B*-band light curves for low-redshift SNe Ia from the Calan-Tololo survey (Hamuy et al. 1996) show an intrinsic scatter of ~ 0.3 mag in peak luminosity. *Bottom panel:* After a one-parameter correction for the brightness-decline correlation, the light curves show an intrinsic dispersion of only ~ 0.15 mag. From Kim (2004).

Ia as standard candles

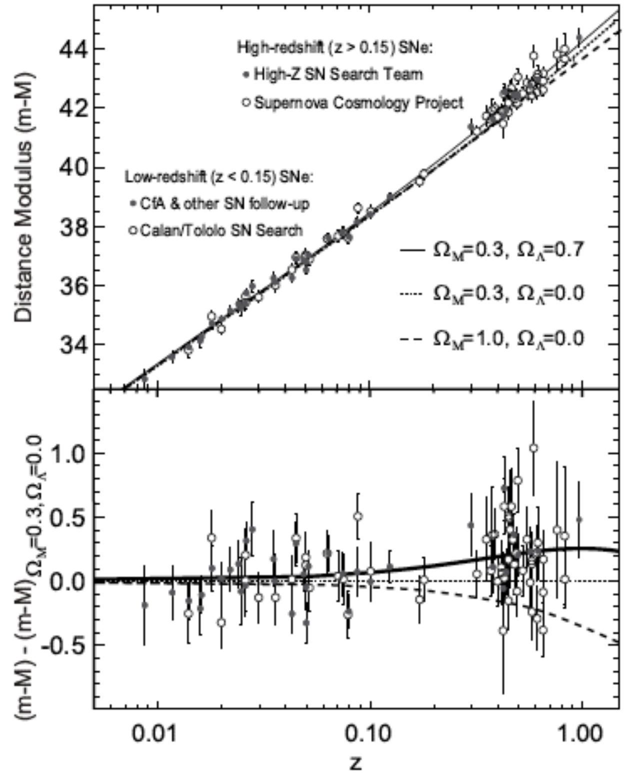
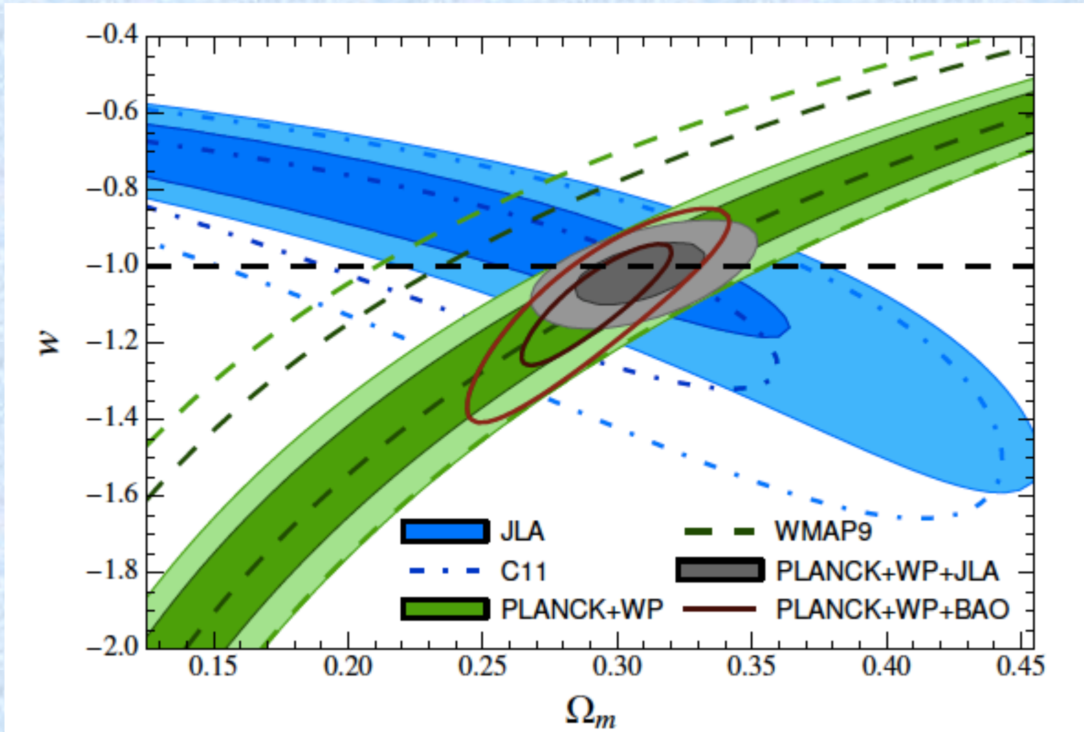


Figure 4: Discovery data: Hubble diagram of SNe Ia measured by the Supernova Cosmology Project and the High-z Supernova Team. Bottom panel shows residuals in distance modulus relative to an open universe with $\Omega_0 = \Omega_M = 0.3$. Figure adapted from Perlmutter & Schmidt (2003), Riess (2000), based on Perlmutter et al. (1999), Riess et al. (1998).

Sn Ia Concordance cosmology.

- Sn Ia most recent constraints
- Agree with and complementary with other methods
- This is called "concordance cosmology"

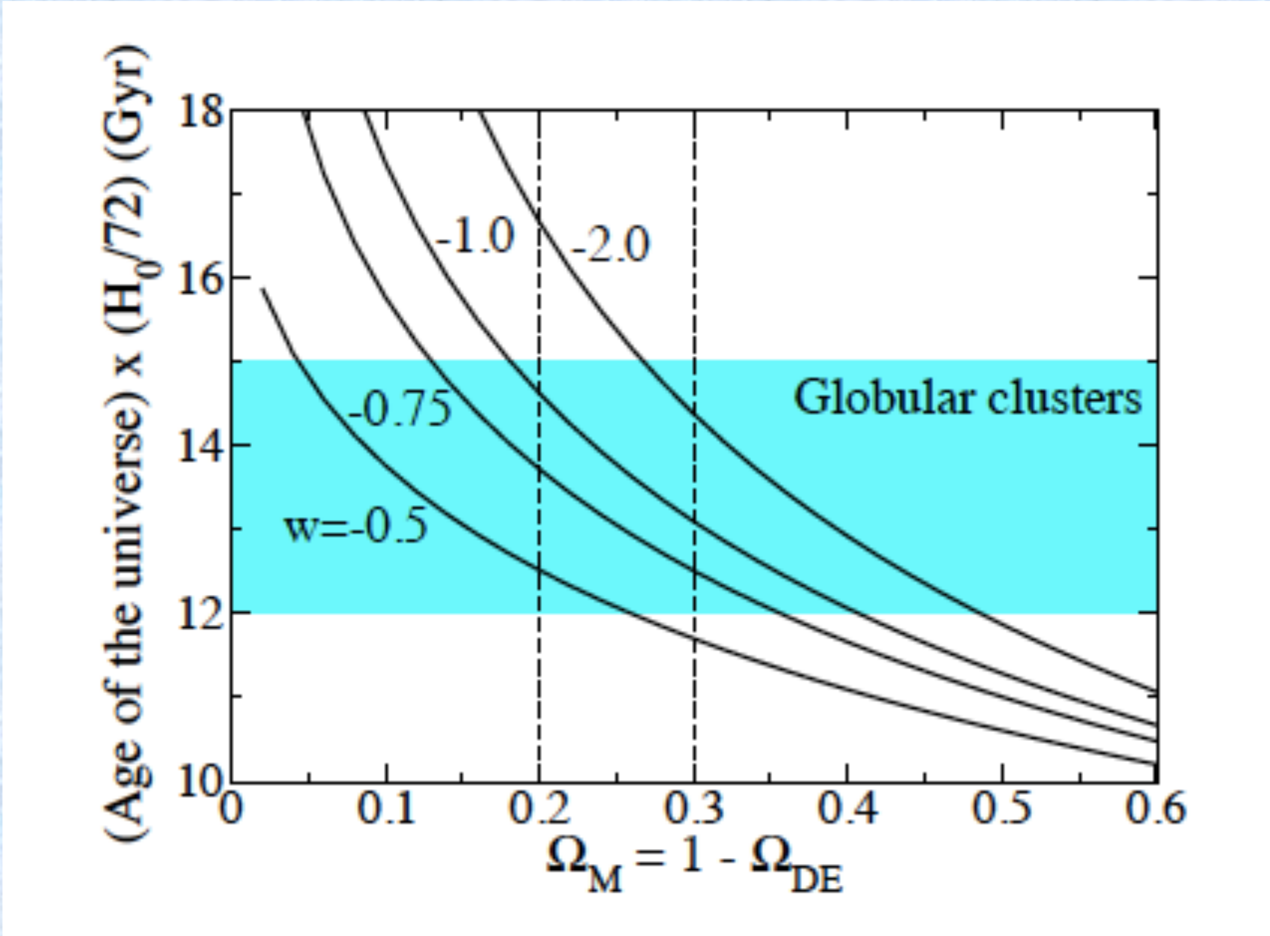


Betoule et al. 2014

SN Ia challenges

- Poorly understood physics
- Selection effects (brightness and lensing)
- Dust
- Photometric calibration is hard at extreme levels of precision

Cosmic Chronometers



Cosmic Chronometers – H(z)

$$H(z) = -\frac{1}{(1+z)}\frac{dz}{dt}.$$

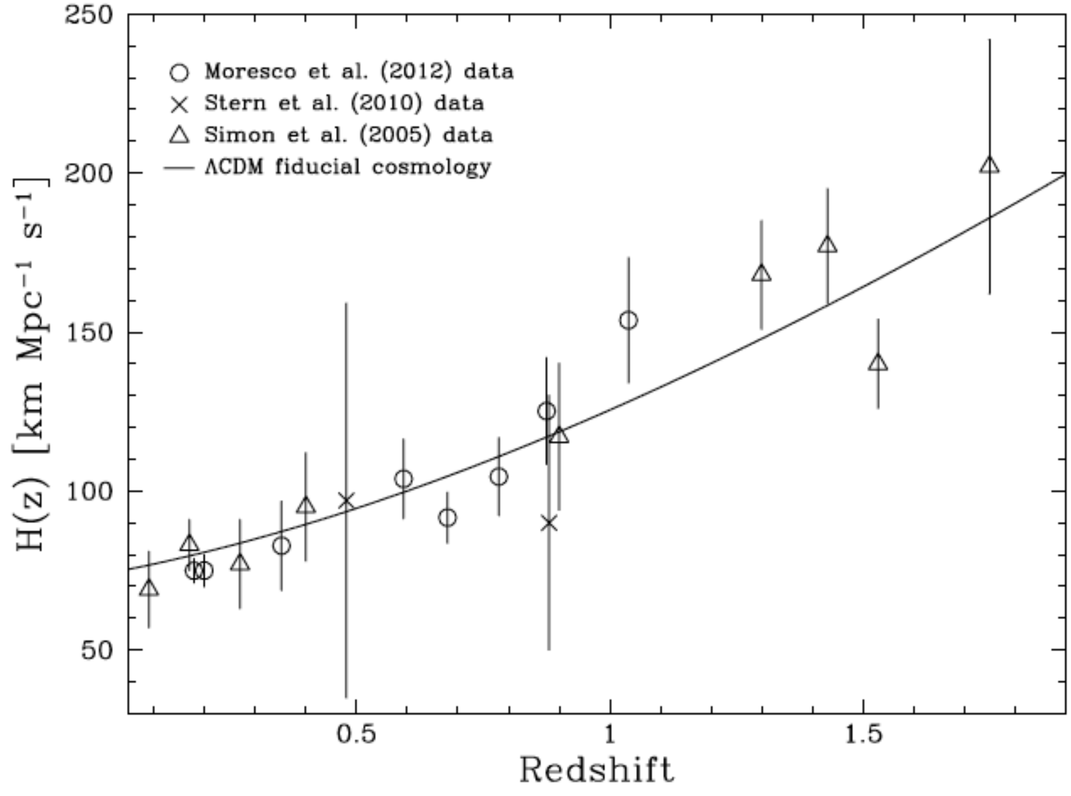


Figure 2. Hubble parameter measurements. Open circle points correspond to $H(z)$ estimates from Ref. [6], open triangle points from Ref. [17], and starred points are taken from Ref. [18]. We also show a fiducial ΛCDM cosmology, with $H_0 = 73.8$, $\Omega_{k,0} = 0$, $\Omega_{m,0} = 0.27$, $\Omega_{\rm DE,0} = 0.73$, $w_0 = -1$, $w_a = 0$.

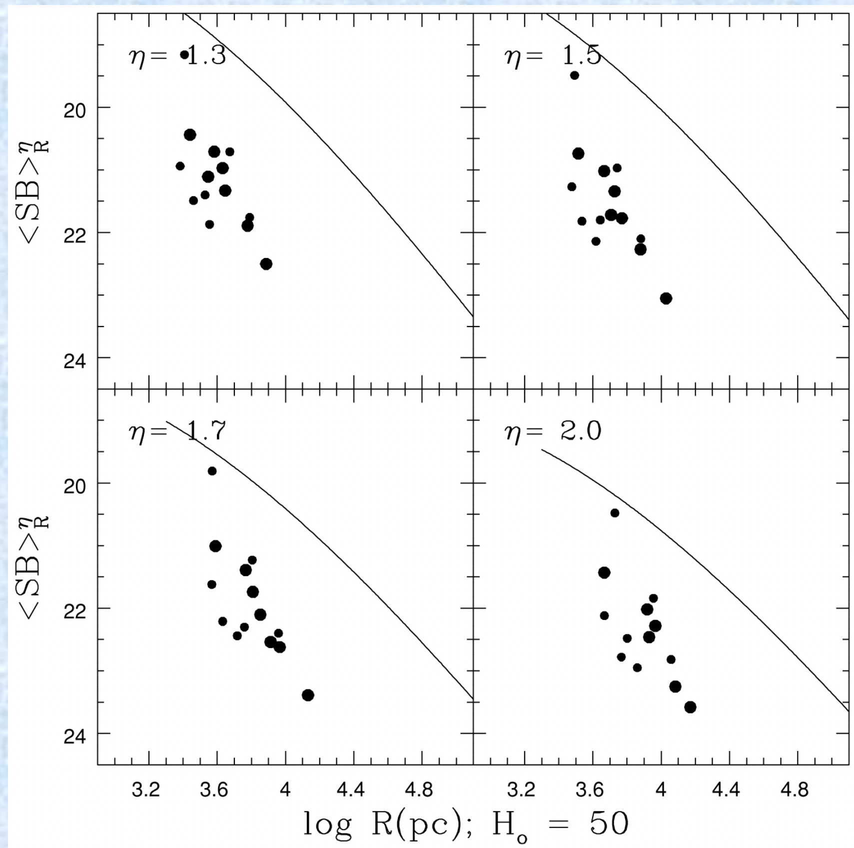
Jimenez & Loeb 2002; Moresco et al. 2012

Chronometers challenges

- Hard to measure stellar ages with high precision
- Progenitor bias: galaxies evolve
- Edge effects

Testing the expansion

- **Define a standard surface brightness**
- **Does it decline with redshift as (1+z)^4?**
- **Problems:**
  - **Stellar evolution**
  - **Scaling laws are subject to selection effects**



Lubin & Sandage, 2001a,b,c,d

The End

See you on wednesday!