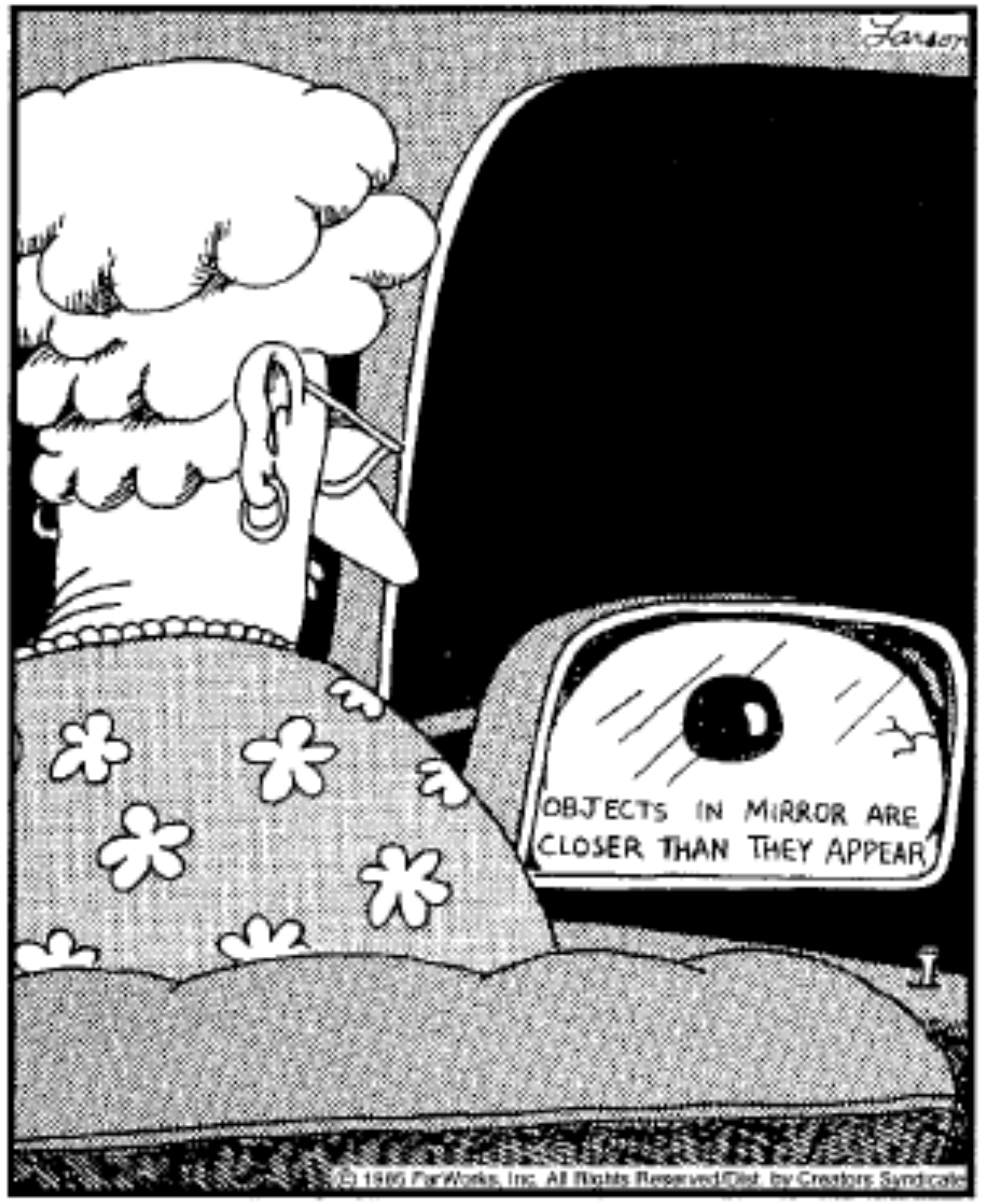
Measuring Distances

ASTR/PHYS 4080: Intro to Cosmology
Week 6



HWs 1-3 graded and returned
Midterm 1 grading in progress

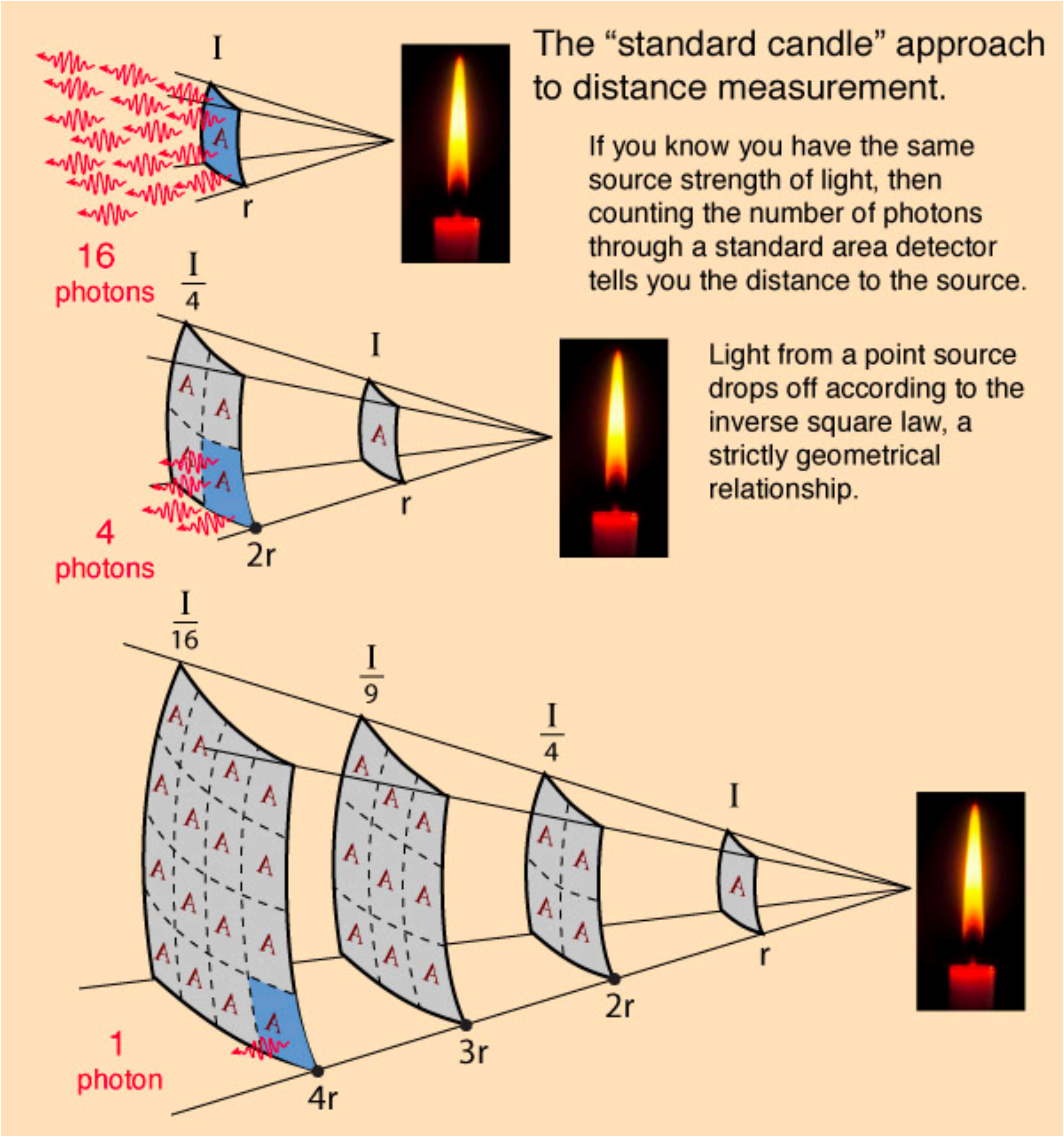
HW 4 due on Thursday

Today:
Different Model Universes (finish Ch. 5)
Measuring Cosmological Parameters (start Ch. 6)

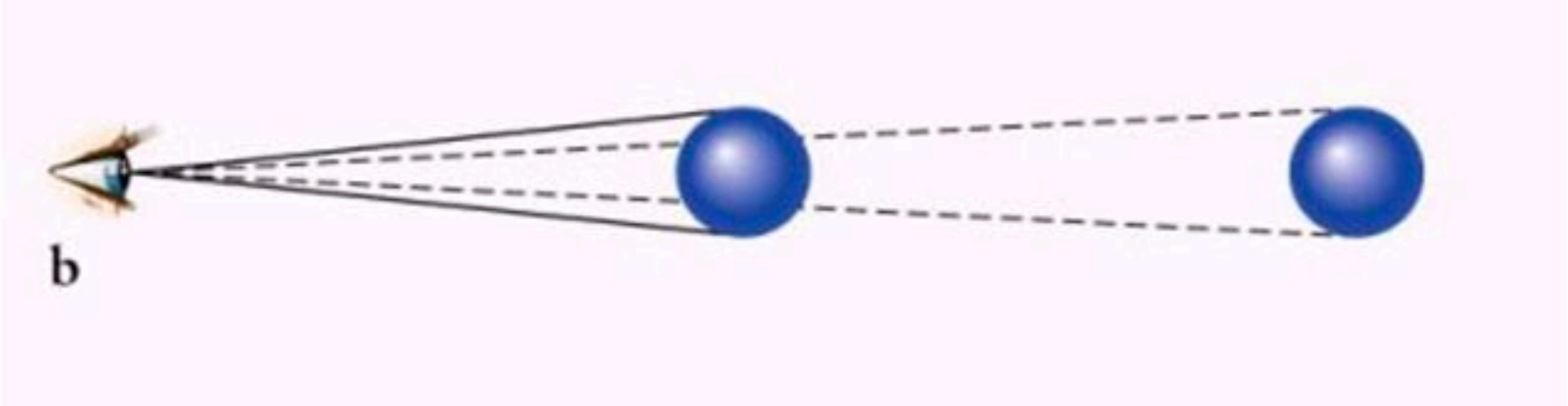
How do we measure the distances to astronomical objects?

Practical Distance Measures

Luminosity Distance



Angular Diameter Distance



d_L and d_A in a universe with curvature

Robertson-Walker Metric

$$ds^2 = -c^2 dt^2 + a(t)[dr^2 + S_\kappa(r)^2 d\Omega^2]$$

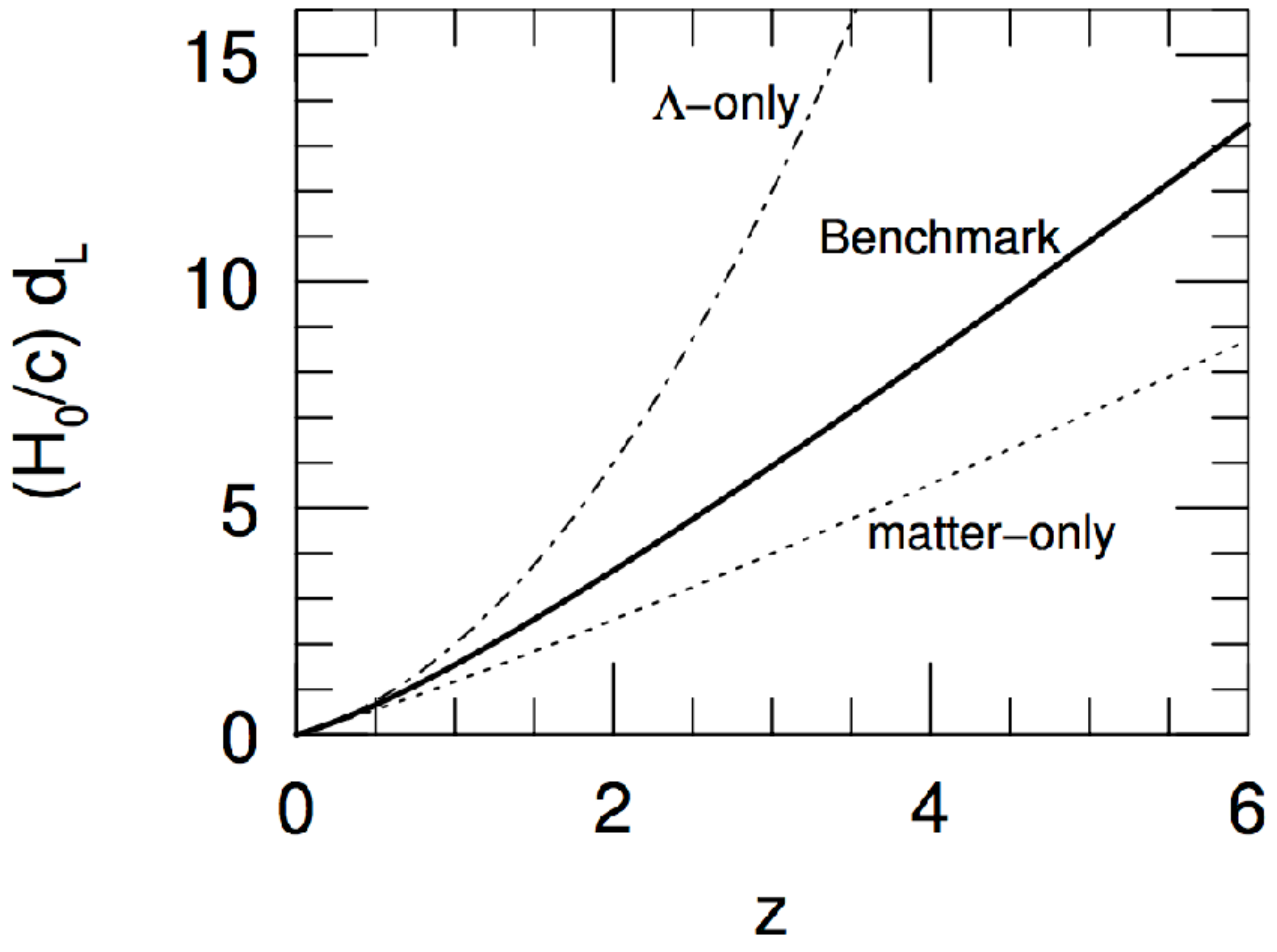
$$S_\kappa(r) = \begin{cases} R \sin \frac{r}{R} & (\kappa = +1) \\ r & (\kappa = 0) \\ R \sinh \frac{r}{R} & (\kappa = -1) \end{cases}$$

flux affected by area of expanding shell of light

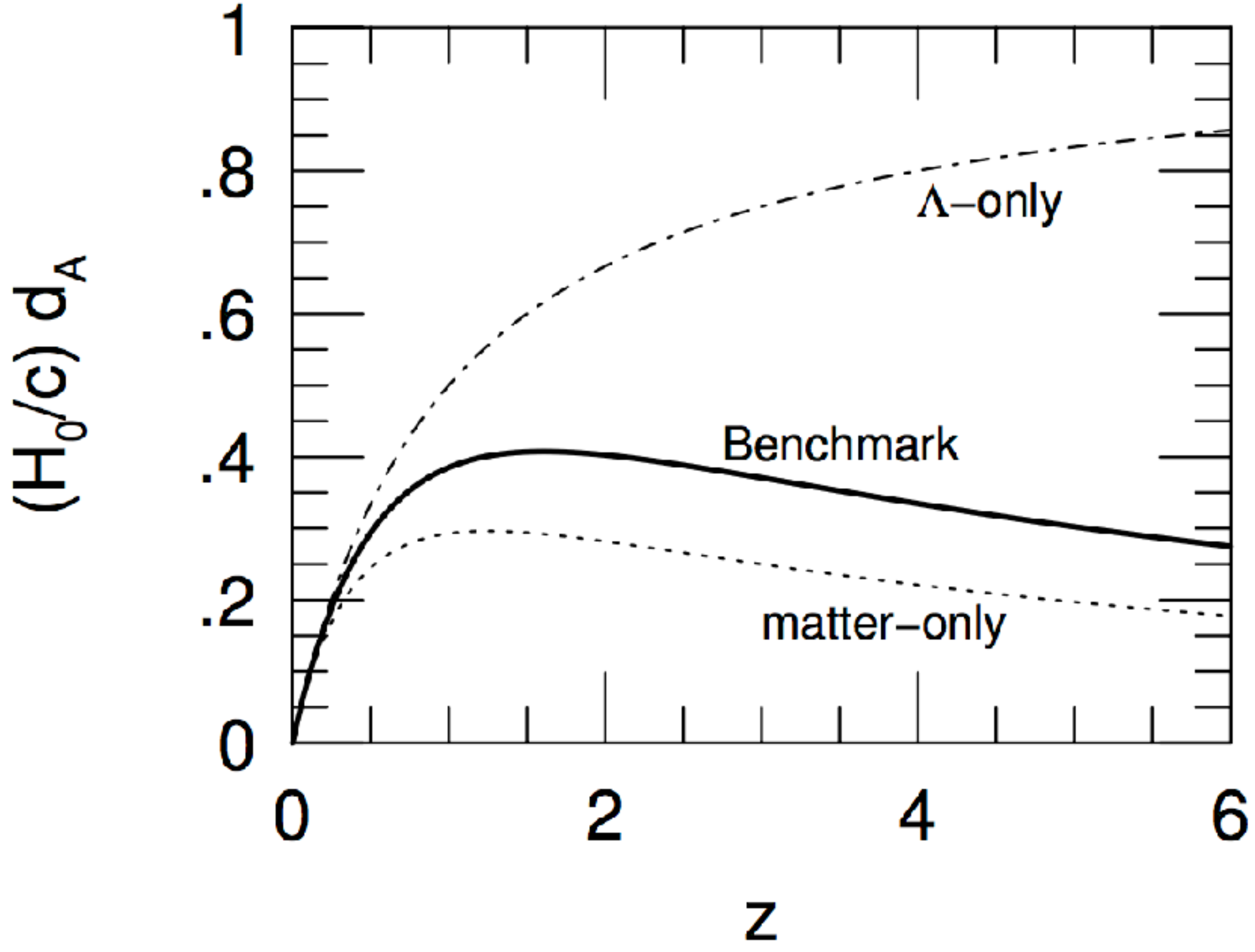
angular extent affected by curvature of geodesics

How distances are affected by underlying cosmology

Luminosity Distance



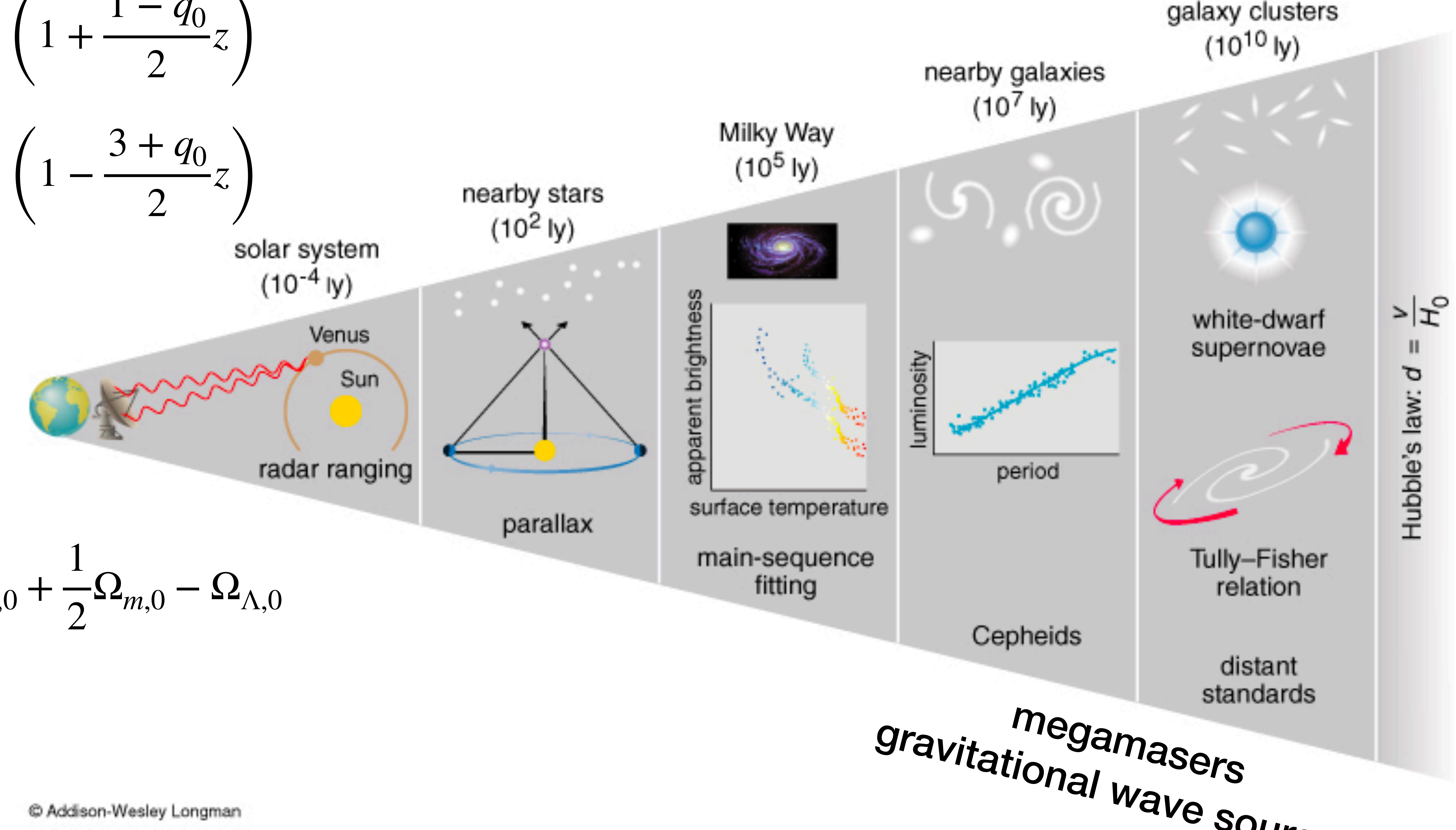
Angular Diameter Distance



Distance Ladder

$$d_L \approx \frac{cz}{H_0}\left(1 + \frac{1-q_0}{2}z\right)$$

$$d_A \approx \frac{cz}{H_0}\left(1 - \frac{3+q_0}{2}z\right)$$



$$q_0 = \Omega_{r,0} + \frac{1}{2}\Omega_{m,0} - \Omega_{\Lambda,0}$$

megamasers
gravitational wave sources

Magnitudes (alternative units of flux)

$$m \equiv -2.5 \log_{10}(f/f_{\rm ref}) \qquad f_{\rm ref} = 2.53 \times 10^{-8}\ \mathrm{W\ m^{-2}}$$

$$M \equiv -2.5 \log_{10}(L/L_{\rm ref}) \qquad L_{\rm ref} = 78.7\ L_{\odot}$$

$m = M$ at 10 pc

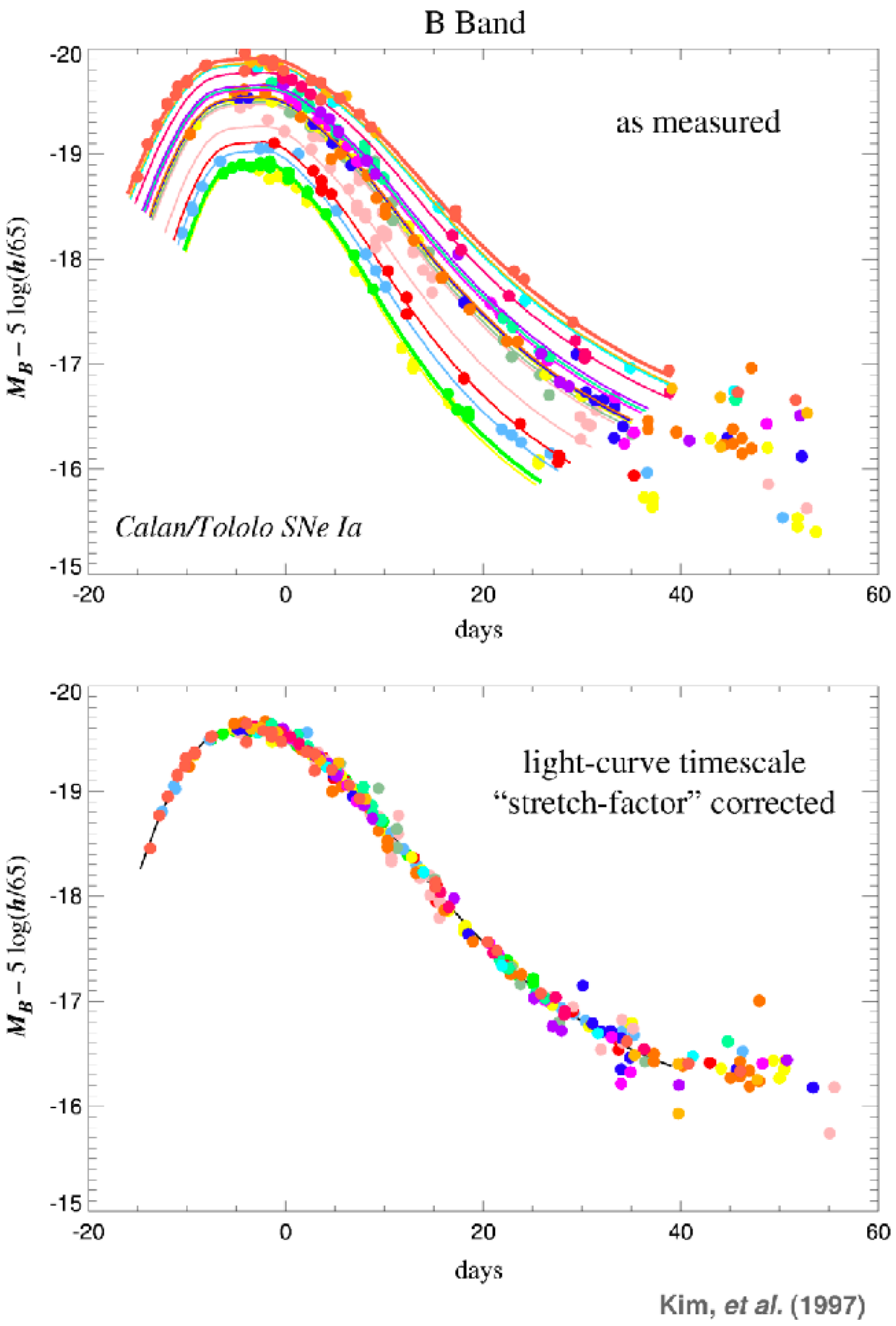
Combine:

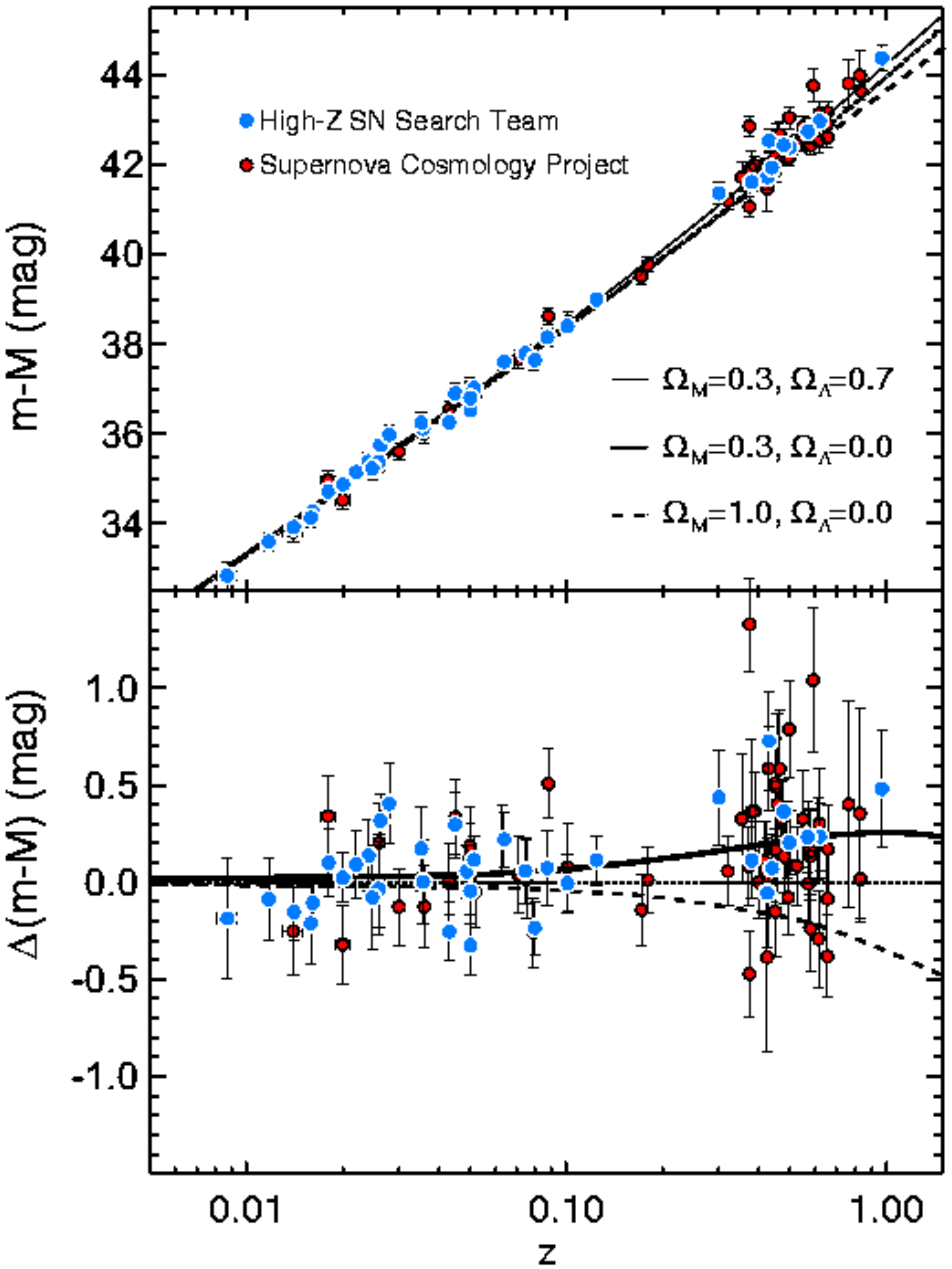
$$M = m - 5\log_{10}\left(\frac{d_L}{10\ \mathrm{pc}}\right) = m - 5\log_{10}\left(\frac{d_L}{1\ \mathrm{Mpc}}\right) - 25$$

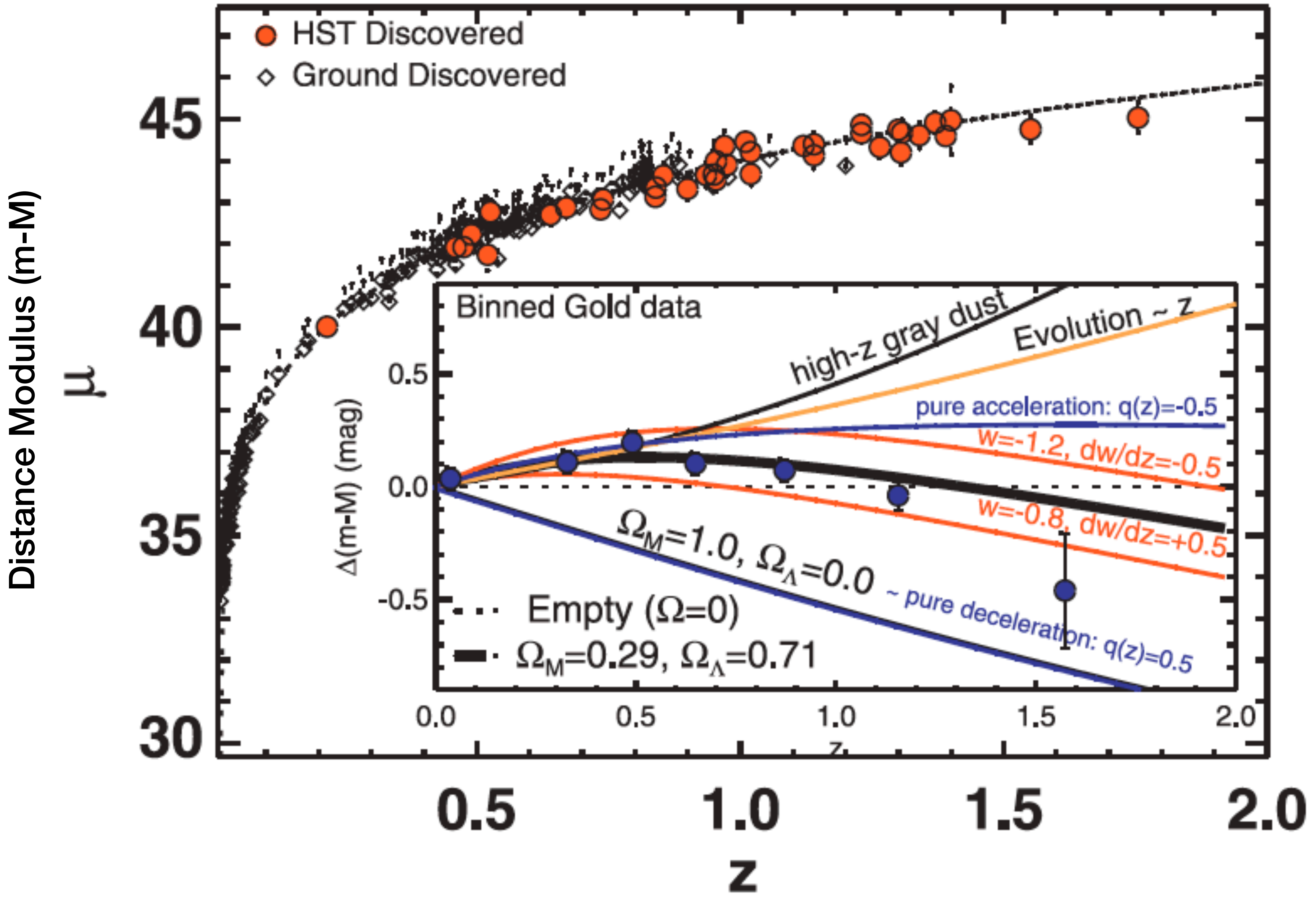
$$h = \frac{H_0}{68\ \mathrm{km\ s^{-1}\ Mpc^{-1}}}$$

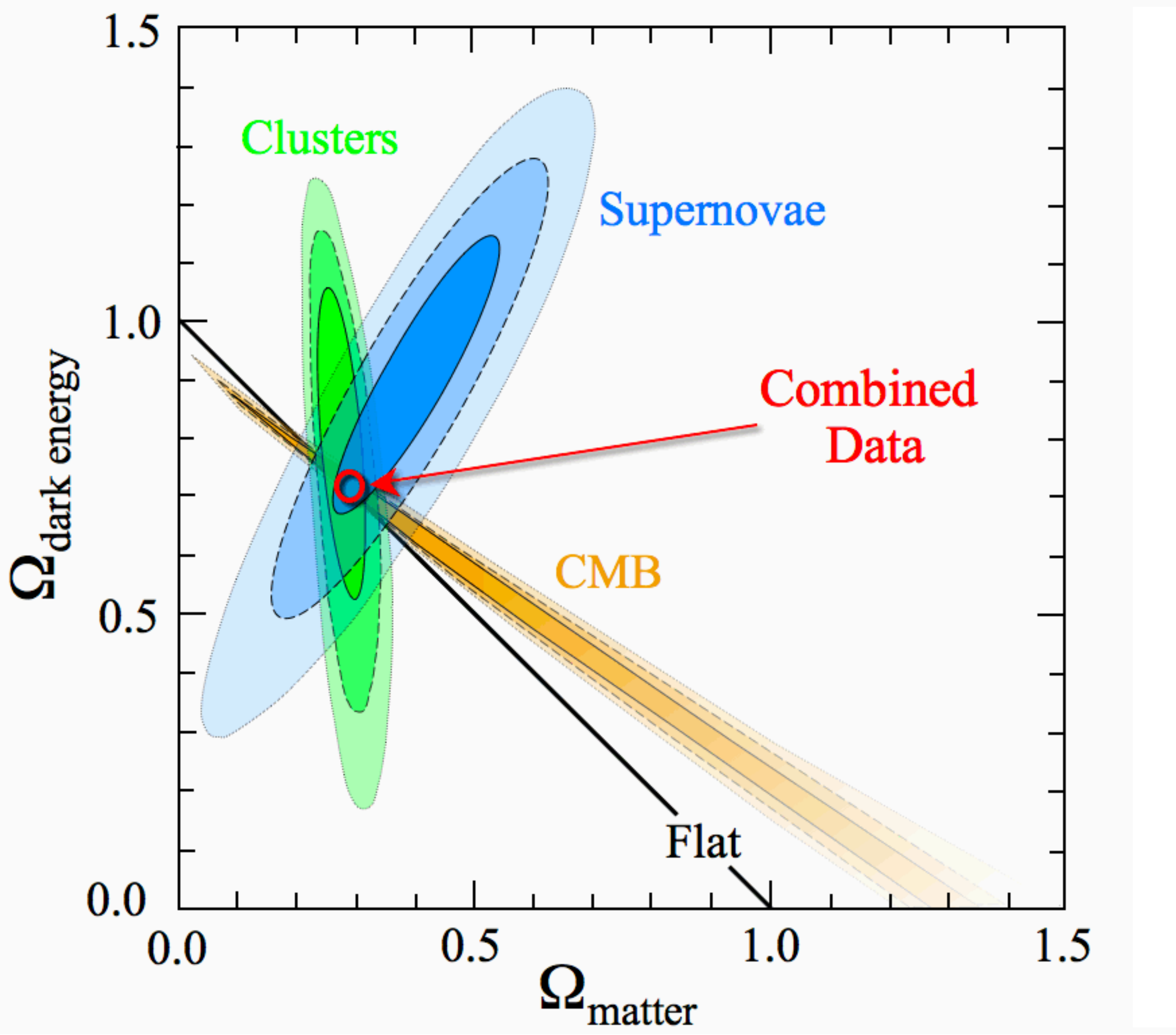
Substitute expression for d_L:

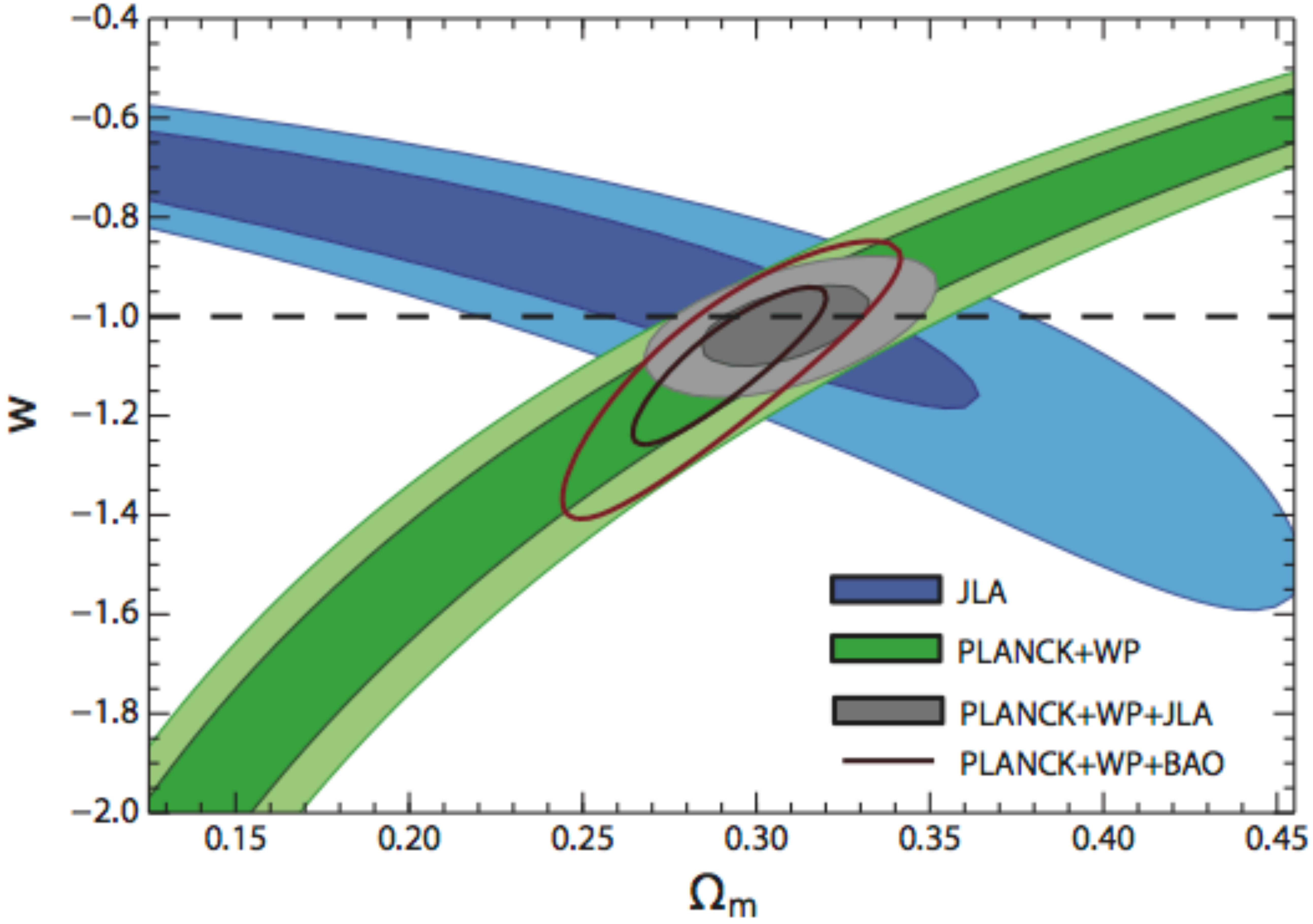
$$m - M \approx 43.23 - 5\log_{10} h + 5\log_{10} z + 1.086(1 - q_0)z$$


B Band
as measured
Calan/Tololo SNe Ia
$M_B - 5\log(h/65)$
days
light-curve timescale
"stretch-factor" corrected
Kim, et al. (1997)


High-Z SN Search Team
Supernova Cosmology Project
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
m-M (mag)
Δ(m-M) (mag)
z


HST Discovered
Ground Discovered
Distance Modulus (m-M)
μ
45
40
35
30
0.5
1.0
1.5
2.0
z
Binned Gold data
high-z gray dust
Evolution ~ z
pure acceleration: q(z)=-0.5
w=-1.2, dw/dz=-0.5
w=-0.8, dw/dz=+0.5
Ω_M=1.0, Ω_Λ=0.0
~ pure deceleration: q(z)=0.5
Empty (Ω=0)
Ω_M=0.29, Ω_Λ=0.71
Δ(m-M) (mag)
0.5
0.0
-0.5
0.0
0.5
1.0
1.5
2.0
z


1.5
1.0
0.5
0.0
Clusters
Supernovae
Combined
Data
CMB
Flat
0.0
0.5
1.0
1.5
$\Omega_{\text{dark energy}}$
Ω_{matter}

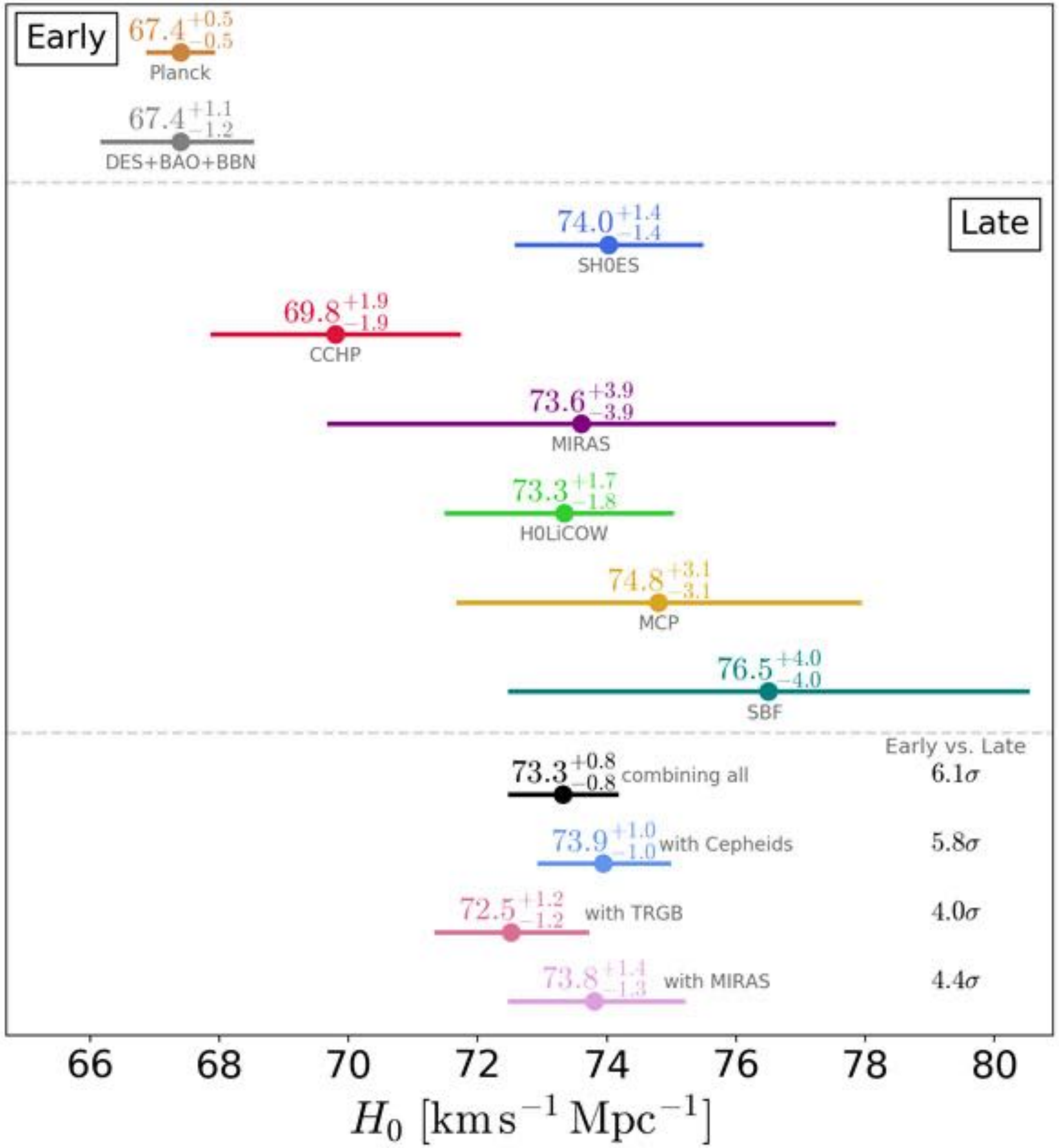

−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6
−1.8
−2.0
w
0.15
0.20
0.25
0.30
0.35
0.40
0.45
Ω_m
JLA
PLANCK+WP
PLANCK+WP+JLA
PLANCK+WP+BAO

Measurements of H_0

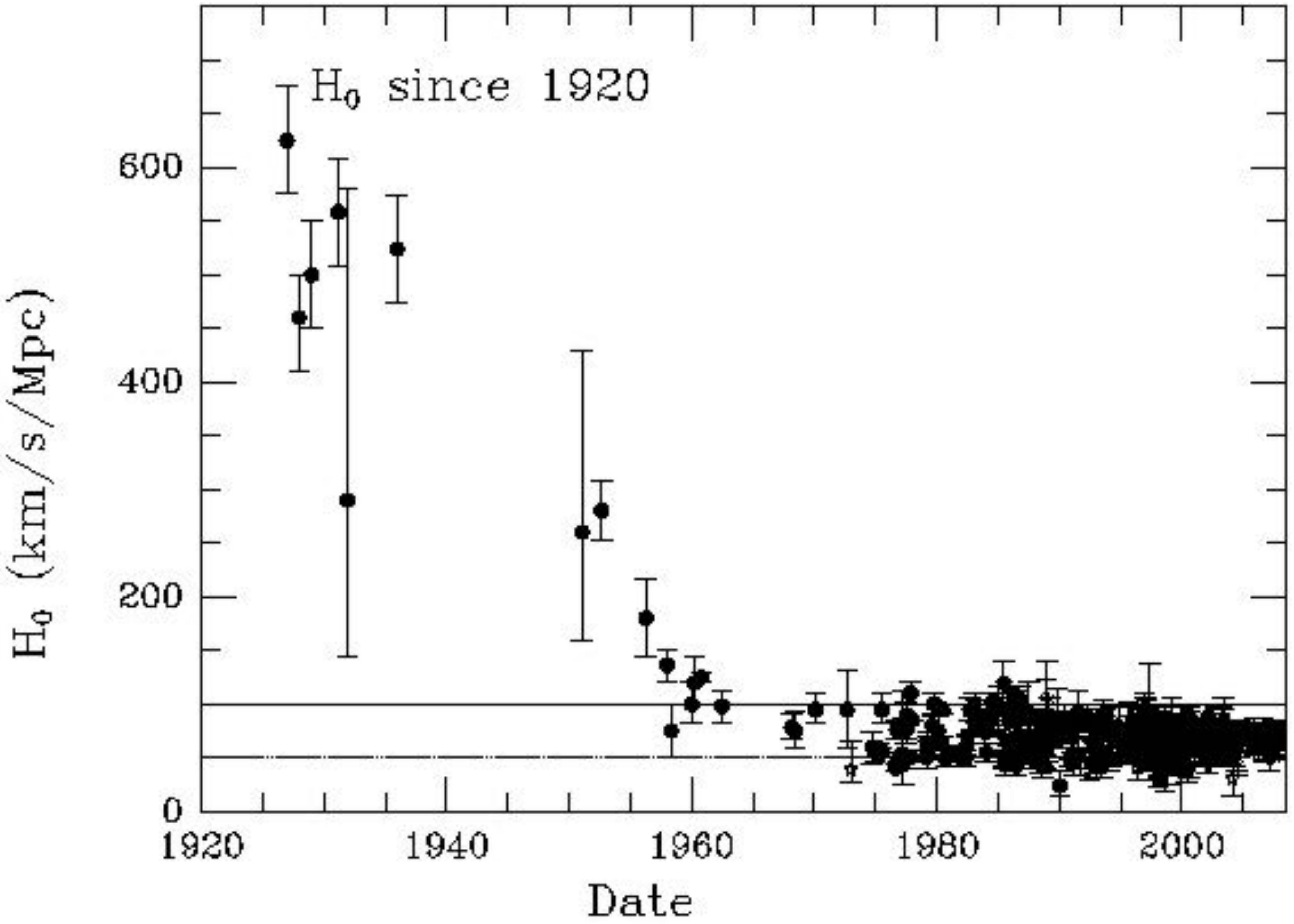
Supernovae Luminosity Distances

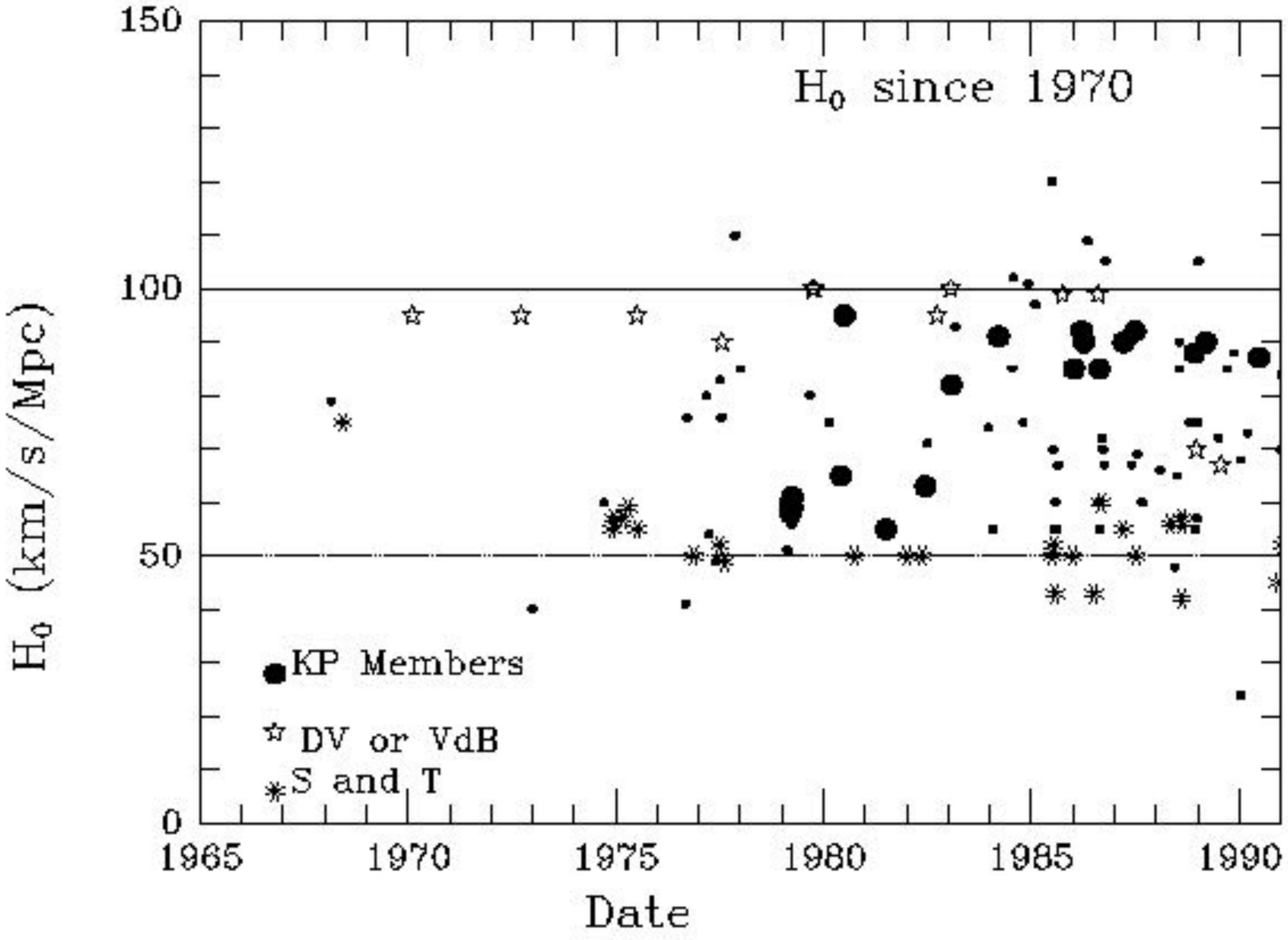
Megamaser Potential

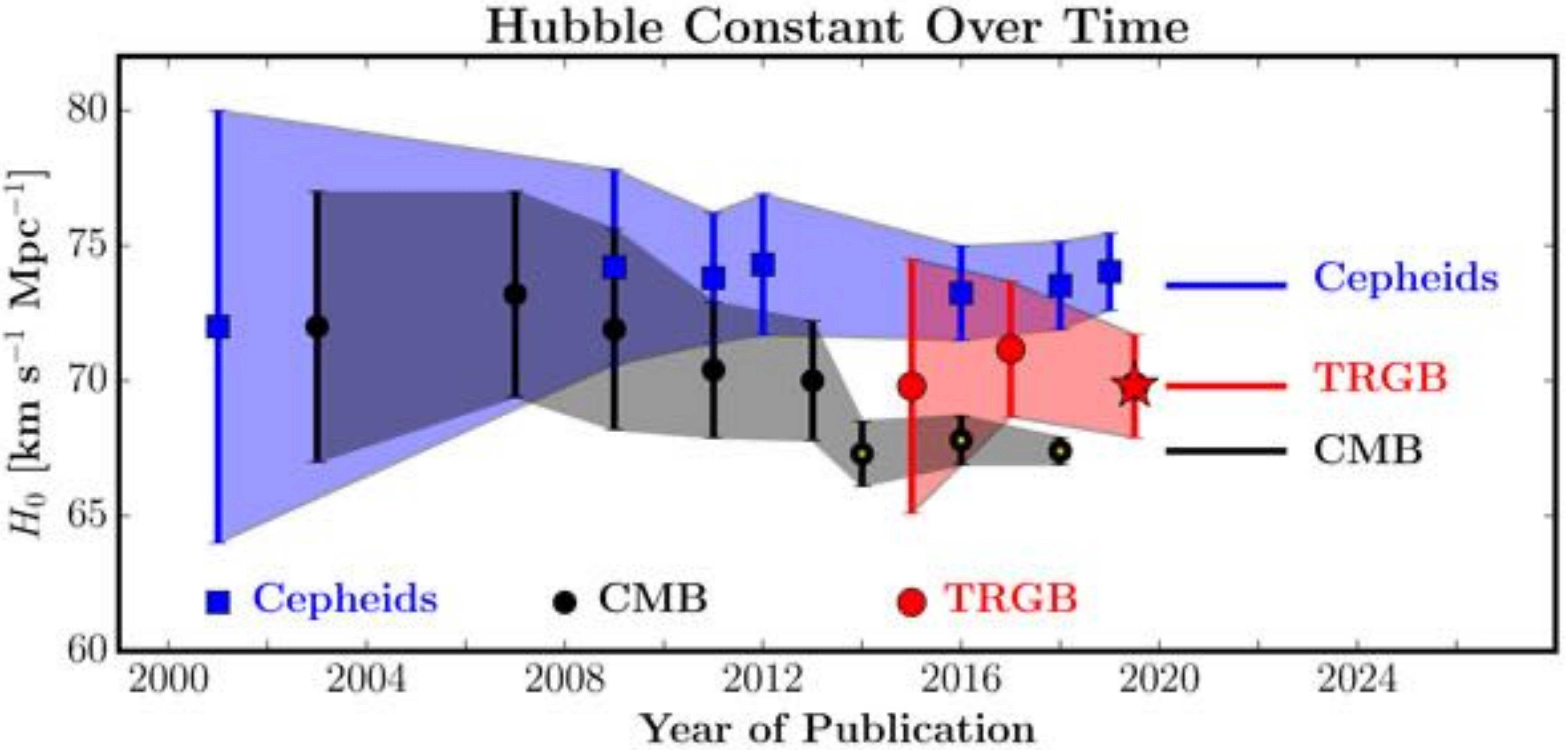
Promise of GW sources as
“standard sirens”



Distances are hard, estimating H_0 is hard

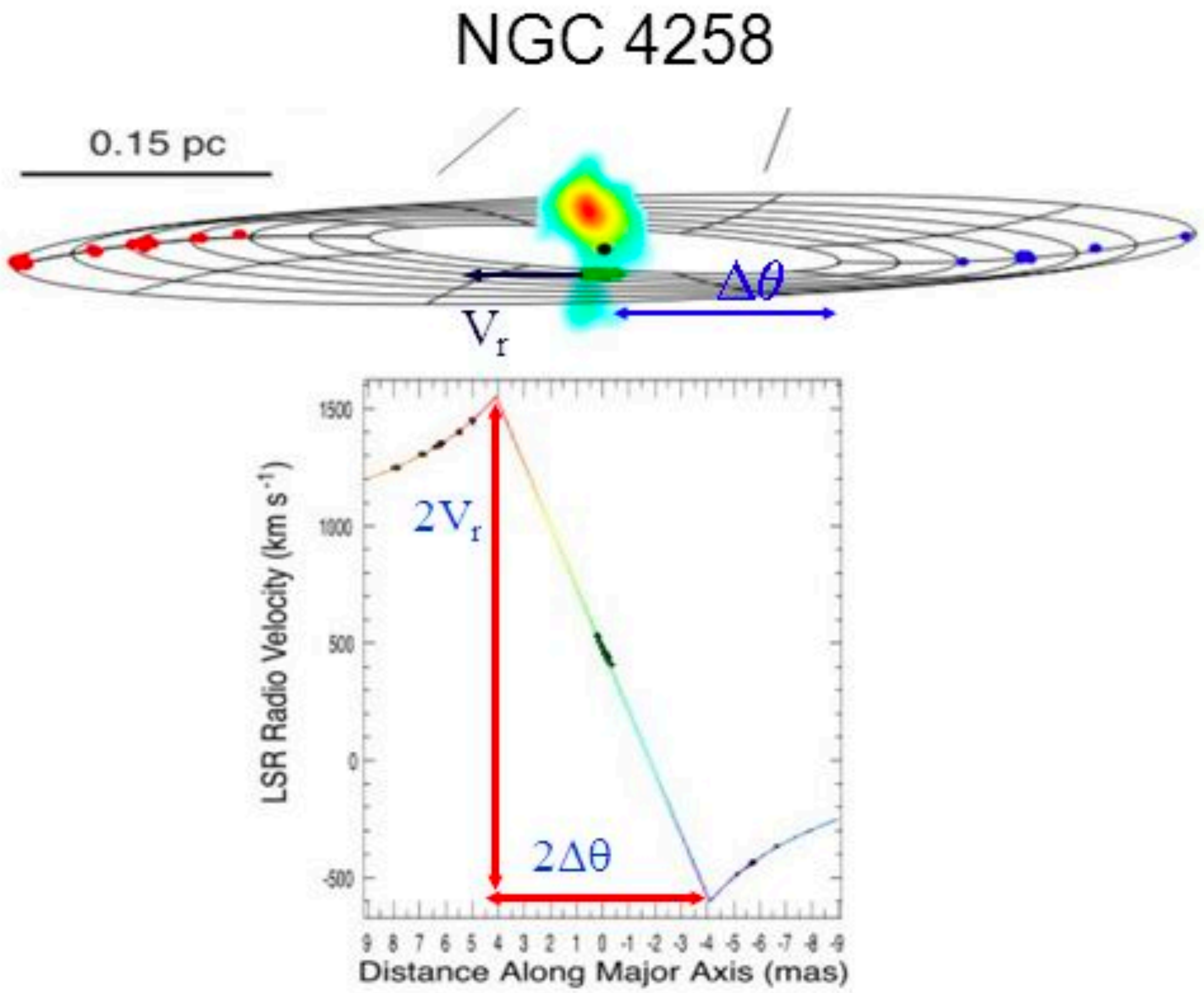






Hubble Constant Over Time
80
75
70
65
60
H_0 [km s^{-1} Mpc^{-1}]
2000
2004
2008
2012
2016
2020
2024
Year of Publication
Cepheids
TRGB
CMB
Cepheids
CMB
TRGB

Measuring Distances to H_2O Megamasers



7.2 ± 0.5 Mpc : Herrnstein et al. (1999))

Thin-ring model:

$$D = a^{-1}\, k^{2/3}\, \Omega^{4/3}$$

a = acceleration

$v = k\, r^{-1/2}$

Ω = slope of sys features

$$\frac{\sigma_{Da}}{D_a} \simeq \sqrt{\left(\frac{\sigma_a}{a}\right)^2 + \frac{4}{9}\left(\frac{\sigma_k}{k}\right)^2 + \frac{16}{9}\left(\frac{\sigma_\Omega}{\Omega}\right)^2}.$$

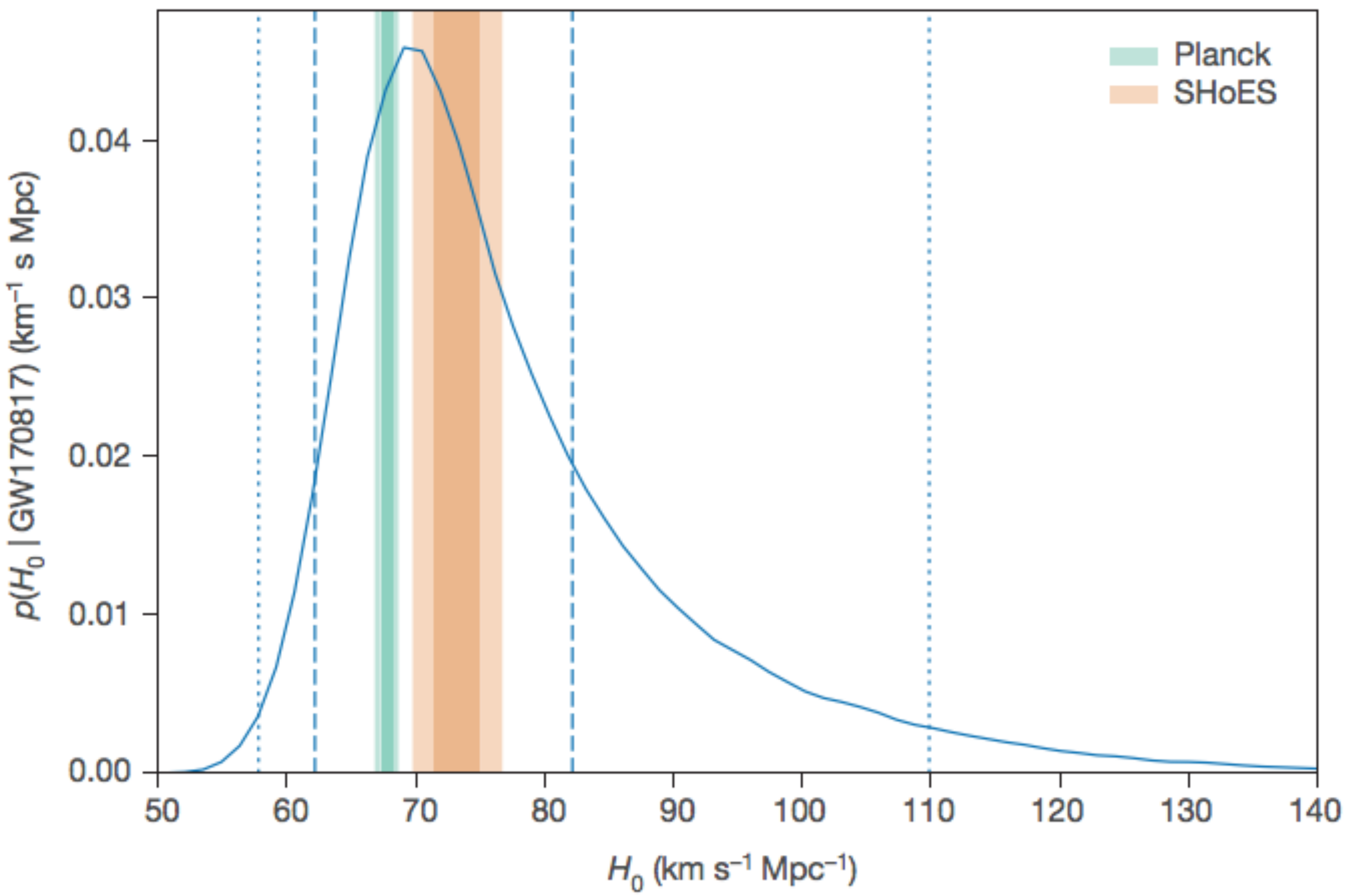


Figure 1 | GW170817 measurement of H_0. The marginalized posterior density for H_0, $p(H_0 \mid \text{GW170817})$, is shown by the blue curve. Constraints at 1σ (darker shading) and 2σ (lighter shading) from Planck[20] and SHoES[21] are shown in green and orange, respectively. The maximum a posteriori value and minimal 68.3% credible interval from this posterior density function is $H_0 = 70.0^{+12.0}_{-8.0}\,\text{km s}^{-1}\text{Mpc}^{-1}$. The 68.3% ($1\sigma$) and 95.4% ($2\sigma$) minimal credible intervals are indicated by dashed and dotted lines, respectively.

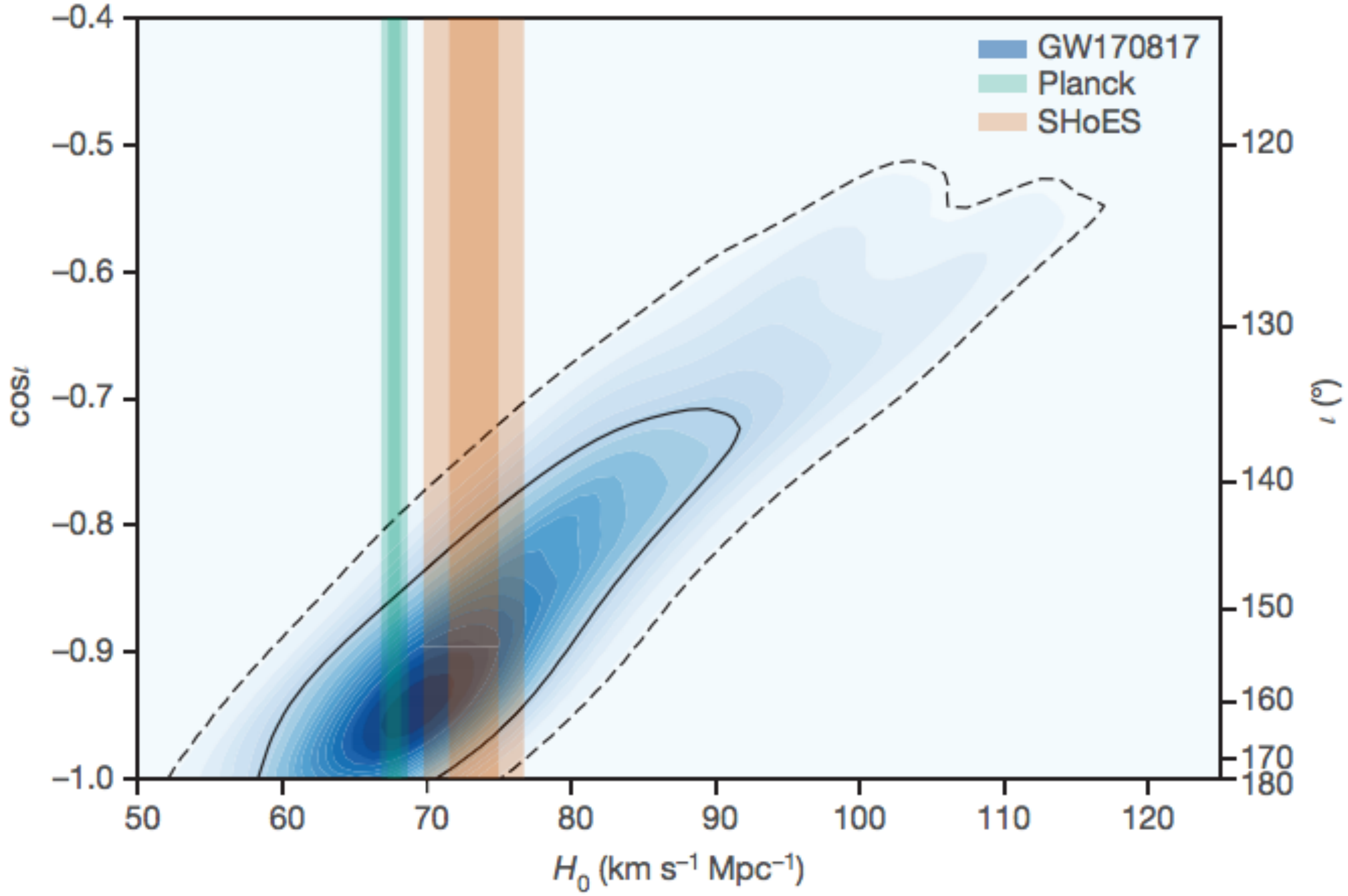
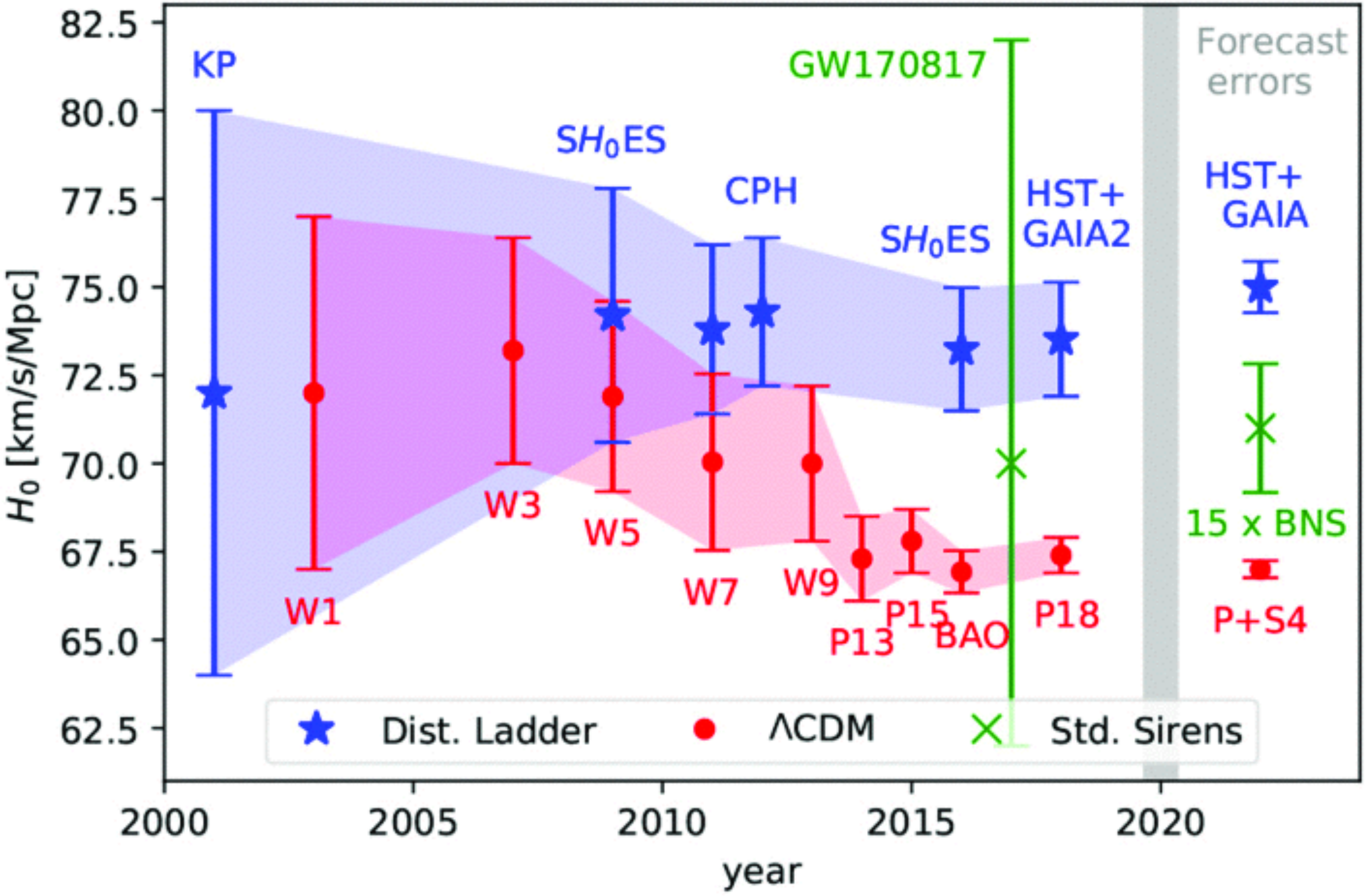


Figure 2 | Inference on H_0 and inclination. The posterior density of H_0 and $\cos\iota$ from the joint gravitational-wave–electromagnetic analysis are shown as blue contours. Shading levels are drawn at every 5% credible level, with the 68.3% (1σ; solid) and 95.4% (2σ; dashed) contours in black. Values of H_0 and 1σ and 2σ error bands are also displayed from Planck[20] and SHoES[21]. Inclination angles near 180° ($\cos\iota = -1$) indicate that the orbital angular momentum is antiparallel to the direction from the source to the detector.



82.5
80.0
77.5
75.0
72.5
70.0
67.5
65.0
62.5
H_0 [km/s/Mpc]
2000
2005
2010
2015
2020
year
KP
SH_0ES
CPH
SH_0ES
HST+ GAIA2
HST+ GAIA
GW170817
Forecast errors
W1
W3
W5
W7
W9
P13
P15
BAO
P18
P+S4
15 x BNS
Dist. Ladder
ΛCDM
Std. Sirens