Cosmology Course

Classical Cosmology:

The Age and Distance Scales

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- *Astronomical Background*
- *The Distance Scale and the Age of the Universe*
- *Methods for Age Determination*
- *The Local Distance Measurements*
- *Large-scale Distance Measurements*
- *Direct Distance Determinations*

Bibliography

- Galactic Astronomy, Binney and Merrifield (1998)
- Cosmological Physics, John Peackock (1999)
- Gravitation and Cosmology, Steven Weinberg (1972)
- The Cosmological Distance Scale, Michael Rowan-Robison (1985)

Astronomical Background

The *energy flux* f received at the Earth from a star depends on both its *intrinsic Luminosity* L and its *distance* D

$$f = \left(\frac{L}{4\pi D^2}\right)$$

From the standard *Robertson-Walker metric* this *luminosity distance* D for a source at z is given by

$$D = \frac{cz}{H_0} \frac{2}{\Omega(1+z)} \left[\Omega z + (\Omega - 2)\left(\sqrt{1+\Omega z} - 1\right)\right]$$

Alternatively, one can define the *angular diameter distance* $\mathcal{D}$ such that a source of intrinsic size d subtends an angle $\delta\theta = \tan^{-1}(d/\mathcal{D}) \approx d/\mathcal{D}$

$$\mathcal{D} = (1+z)^{-2} D$$

2 Some Jargon and Units.

Parsec (pc)		$=$	$3.08567802(2) \times 10^{16}\text{m}$
Hubble constant	H_0	$=$	$100\ h\ \text{km Mpc}^{-1}$
Solar mass	$M_\odot$	$=$	$1.982(2) \times 10^{30}$ kg
Jansky (flux)	Jy	$=$	$10^{-26}\text{W m}^{-2}\ \text{Hz}^{-1}$
Galaxy		$\sim$	30 kpc
		$\sim$	$10^{11}\ M_\odot$
Cluster		$\sim$	2 Mpc
		$\sim$	$10^{14}\ M_\odot$
Critical density	ρ_C	$=$	$1.879\ h^2 \times 10^{-32}\text{kg cm}^{-3}$
	Ω	$=$	ρ/ρ_C

Astronomers do not usually work with L and f.

$$m_2 - m_1 = 2.5 \log_{10}\left(\frac{f_1}{f_2}\right) = -5 \log_{10}\left(\frac{D_1}{D_2}\right)$$

The *absolute magnitude* M of a star is *the apparent magnitude* of a star placed *absolute magnitude* @ 10 pc away

$$M = m - 5 \log_{10}\left(\frac{D}{10\ \mathrm{pc}}\right)$$

The Distance Scale and the Age of the Universe

The age of the universe is largely determined by the rate at which it expands, and the current value of the Hubble 'constant' fixes the Hubble time

$$H_0^{-1} = 9.78\, h^{-1}\mathrm{Gyr}$$

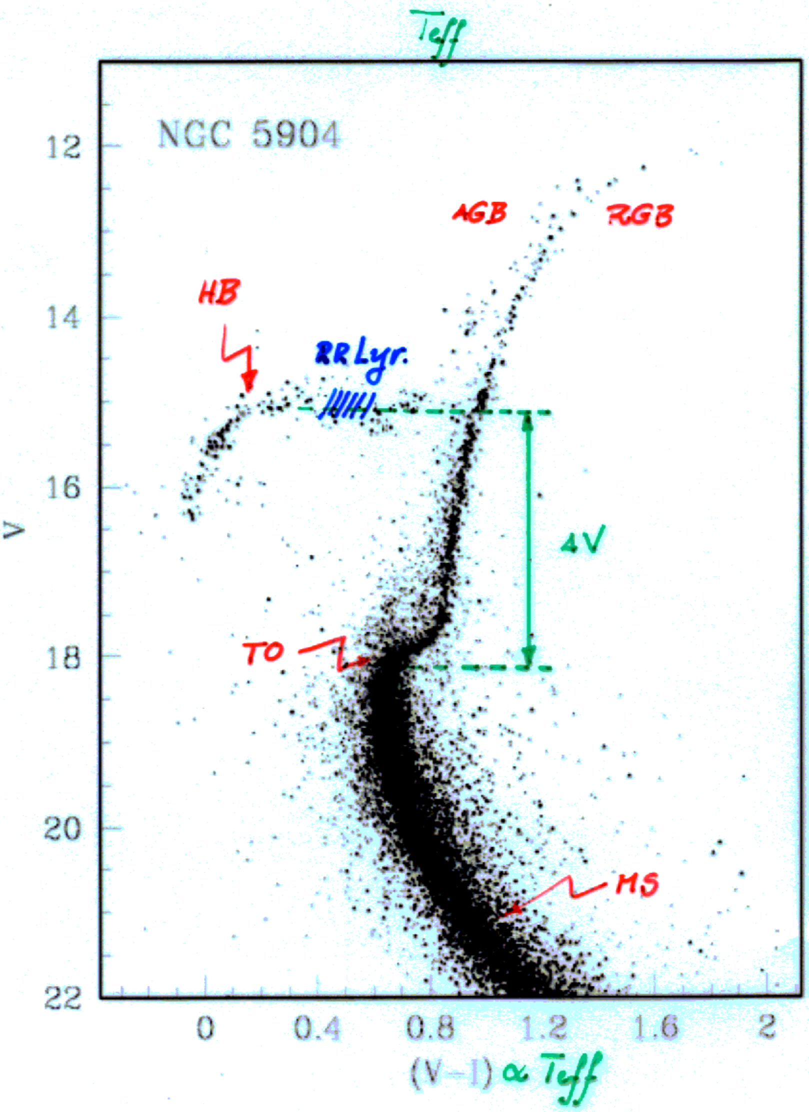
If the expansion did not decelerate, the Hubble time would be the exact age of the Universe.

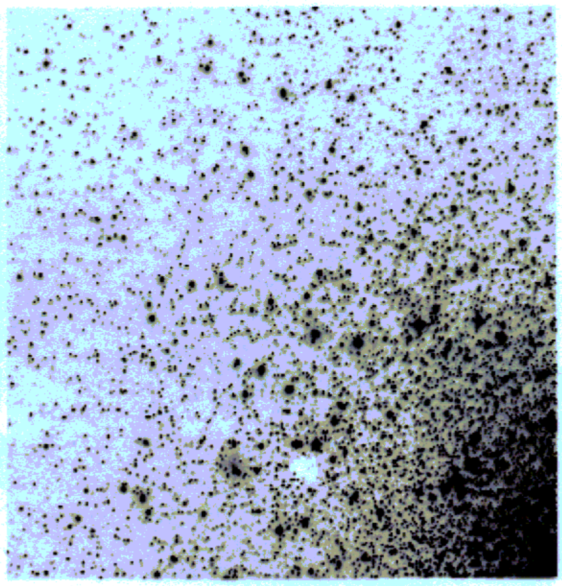
Manipulating the Friedmann equations one gets:

$$H_0^{-1} t_0 = \int_0^\infty \frac{(1+z)^{-1} dz}{\sqrt{(1+z)^2(1+\Omega_m z) - 2(2+z)\Omega_v}}$$

GLOBULAR CLUSTERS

- $\sim 10^5$ STARS
- OUTER PARTS OF GALAXIES
- OLD POPULATIONS





- $M_V(TO) = 2.70 \log_{10}(t/Gyr) + 0.30\,[Fe/H] + 1.41$

TIPICAL G.C. $\left\{ \begin{array}{l} [Fe/H] \simeq -1.5 \\ M_V(TO) = 4 \end{array} \right.$ $\Rightarrow t \sim 13\,Gyr$

- ΔV METHOD $\Delta V = 2.70 \log_{10}(t/Gyr) + 0.13\,[Fe/H] + 0.59$

$\Rightarrow t \sim (15 \pm 1)\,Gyr$

NUCLEAR COSMOCHRONOLOGY:

- $^{238}U \rightarrow {}^{206}Pb$ 6.45 Gyr

  $^{235}U \rightarrow {}^{207}Pb$ 1.02 Gyr

  $\underbrace{^{232}Th}_{\text{'PARENT'}} \rightarrow \underbrace{^{208}Pb}_{\text{'DAUGHTER'}}$ 20.27 Gyr

- $D = D_0 + P_0\left[1-\exp(-t/\tau)\right] = D_0 + P\left[\exp(t/\tau)-1\right]$

- $D/S = D_0/S + (P/S)\left[\exp(t/\tau)-1\right]$

- $\underbrace{D/S}_{\text{RANGES WITH } T} = \underbrace{D_0/S}_{\text{const.}} + \underbrace{(P/S)}_{\text{RANGES WITH } T}$

★)

$t_{f,\text{METEO.}} = 4.57$ Gyr (~1%)

$t_{f,\text{EARTH}} = 3.7$ Gyr

★★) $^{235}U / {}^{238}U \simeq 0.33$

$^{232}Th / {}^{238}U \simeq 2.3$

- r-process

RATE EQUATIONS $^{235}U / {}^{238}U \simeq 1.3$ (~10%) (1

$^{232}Th / {}^{238}U \simeq 1.7$ (~10%) (2

(1) => 1.6 Gyr

(2) => 2.9 Gyr

[HOW OLD THE ELEMENTS WERE WHEN THE SOLAR SYSTEM FORMED.]

AGE OF THE MILKY WAY ~ 10.5 Gyr (± 1.5 Gyr)

[= (4.57 + 5.4) Gyr]

Large-scale Structure Measurements

Using methods based on the global properties of galaxies: Standard Candles

Ellipticals

Their brightness profiles are well fitted by

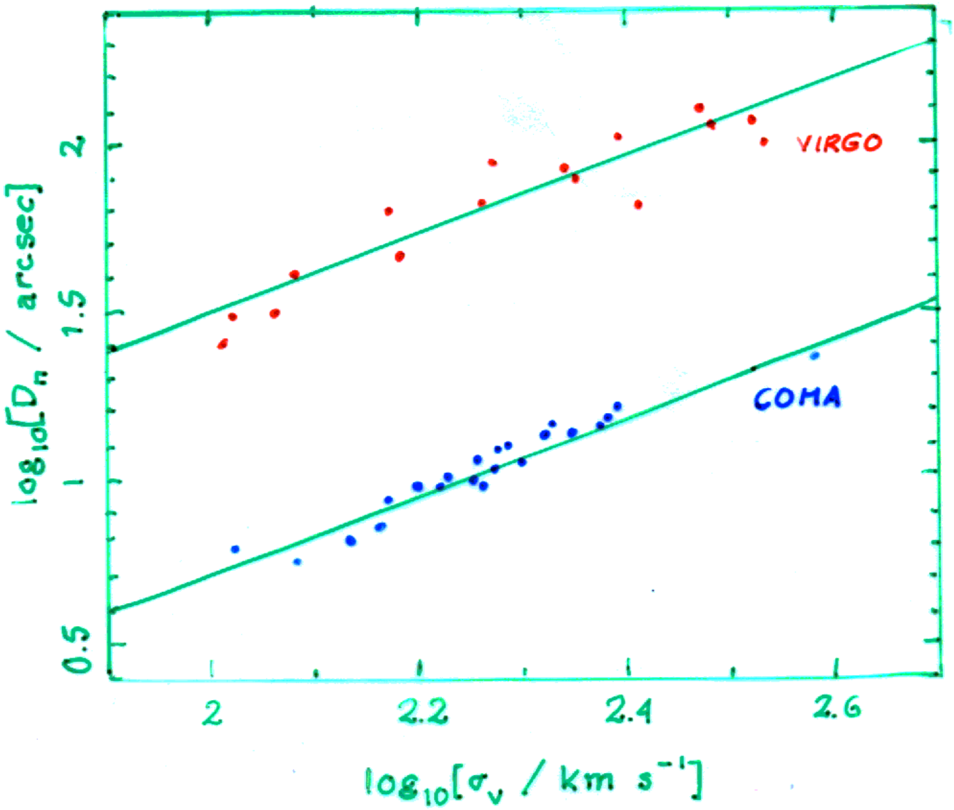
$$I(r) = I_0 \exp\left[-(r/r_0)^{1/4}\right]$$

Another observable is the *velocity dispersion* σ_v

Empirically these three observables are closely correlated, with the ellipticals lying on the *fundamental plane*:

$$L^{1+\alpha} \propto \sigma_v^{4-4\alpha} I_0^{\alpha-1}$$

M87 © Anglo-Australian Observatory
Photo by David Malin



• $D_{VIRGO} = D_{COMA} \times 5.82$

• $cz_{VIRGO} = \frac{D_{VIRGO}}{D_{COMA}} \cdot cz_{COMA}$

$$\begin{cases} z_{COMA} = 0.0240 \\ cz_{COMA} = 72000 \text{ Km/} \end{cases}$$

⇓

$cz_{VIRGO} = 1186$ Km/

$$h = \frac{11.9 \text{ Mpc}}{D_{VIRGO}} \qquad (\sim 5\% \text{ rms})$$

Spirals

There is a very similar relation for spiral galaxies. The correlation is now between a measure of the *luminosity* and a measured *rotational velocity* of the spiral v_r

$$L \propto v_r^\alpha ,$$

known as the *Tully-Fisher* relation.

M 51 (NGC 5194

HST

Intermediate Distances

- T-F to measure relative distances between Virgo and more nearby galaxies
- HST to look for Cepheid variable stars.
- Surface-Brightness Fluctuations The brightness presents fluctuations (white noise) caused by the discreteness of the image.

MEAN NUMER OF STARS $\bar{N} = n\,(D\,\delta_\theta)^2$

FLUX PER STAR $f = L\,/\,(4\pi D^2)$

$$\left.\begin{array}{l} \bar{N} = n\,(D\,\delta_\theta)^2 \\ f = L\,/\,(4\pi D^2) \end{array}\right\} \quad F = \bar{N} f = \frac{n L \delta_\theta^2}{4\pi}$$

$$\Downarrow$$

$$\sigma_F = \bar{N}^{1/2} f = \frac{n^{1/2} \delta_\theta L}{4\pi D}$$

$$\Downarrow$$

$$\frac{\sigma_F^2}{F} = f = \frac{L}{4\pi D^2}$$

- 2 GALAXIES MADE UP FROM INTRINSICALLY IDENTICAL STARS $\Rightarrow$ WE CAN INFER REL. DISTANCES !

$D_{VIRGO} / D_{M31} = 20.65 \pm 6\%$

The Local Distance Scale

- CEPHEID VARIABLES $(L \propto P^{1.3})$

$$D_{M31} / D_{LMC} = 15.28 \pm 5\%$$

LMC IS A DWARF GALAXY OF LOW METAL CONTENT RELATIVE TO THE SUN. IT IS CONCEIVABLE THAT THERE COULD BE A SYSTEMATIC EFFECT !!!

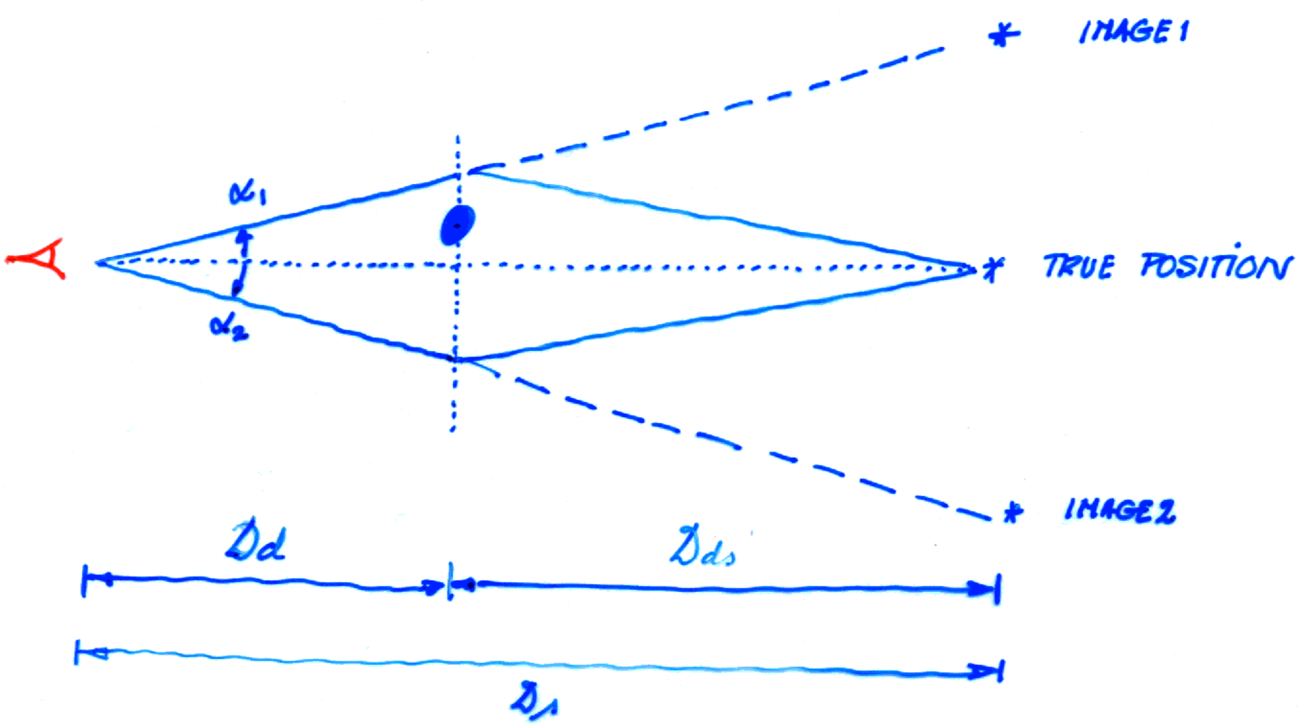
- WITHIN THE GALAXY: ★ TRIGONOMETRIC PARALAAXES (HIPPARCUS) DISTANCE TO HYADES

★★ M-S FITTING TO FURTHER CLUSTERS

★★★ CEPHEID + RR Lyr.

$$D_{LMC} = 50.1 \text{ Kpc} \pm 6\%$$

LENSING



$$ct^{(i)} = (1+z_L)\left[\frac{\alpha_i^2}{2}\underbrace{\frac{D_d D_s}{D_{ds}}}_{\propto \frac{c}{H_0}} - \underbrace{\frac{2}{c^2}\int ds\,\phi(s)}_{\simeq 0\ (?)}\right]$$

QSO 0957+561 $\quad H_0 = (64 \pm 13)\ \mathrm{Km\,s^{-1}}/\mathrm{Mpc^{-1}}$

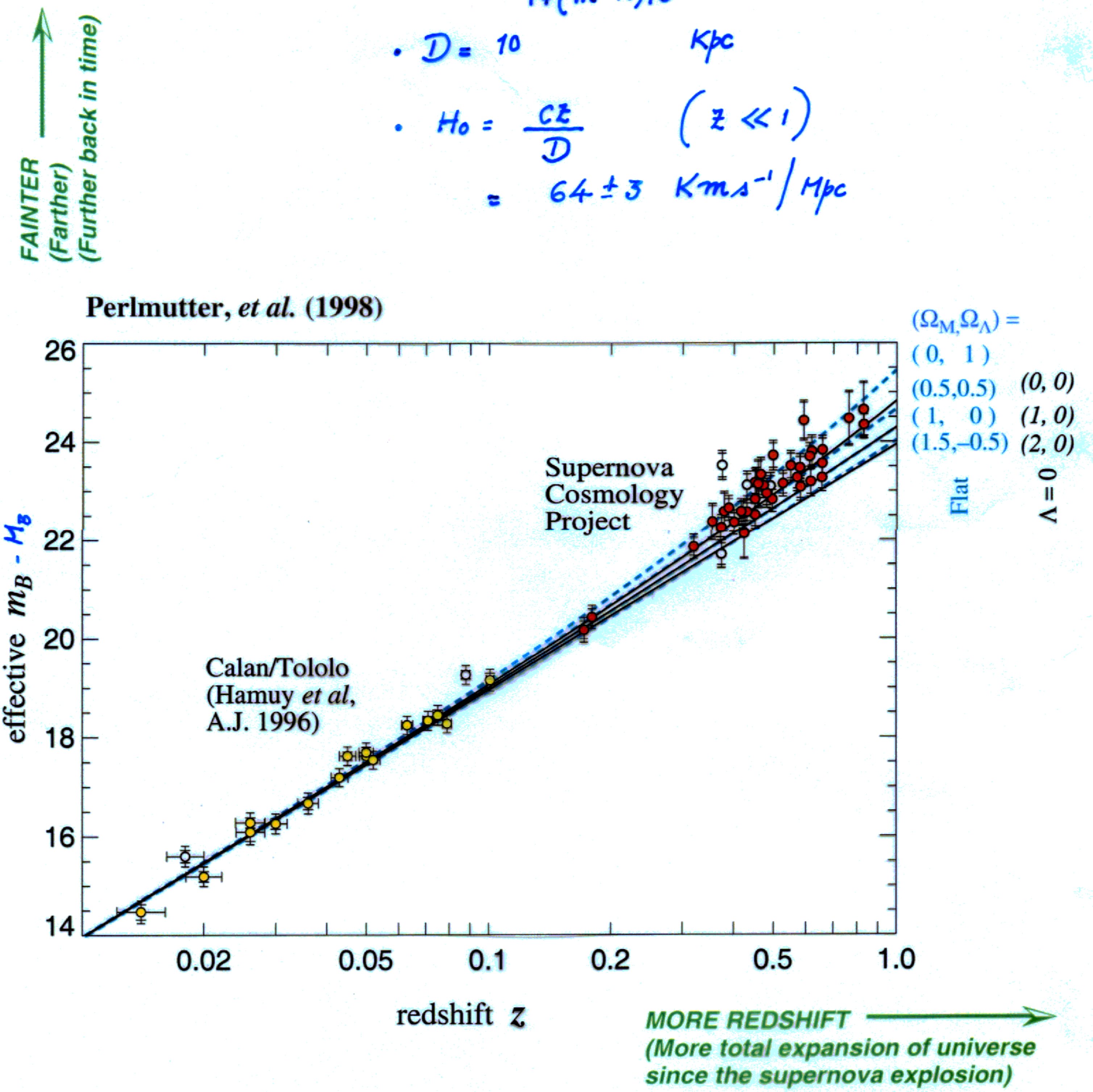
$$H_0 = \left(79 \pm 7\ \mathrm{Km\,s^{-1}\,Mpc^{-1}}\right)\left(\frac{\sigma_v}{300}\right)^2\left(\frac{\Delta t}{yr}\right)^{-1}$$

- $D = 10^{1+(m-M)/5}$ Kpc

- $H_0 = \dfrac{cz}{D} \quad (z \ll 1)$

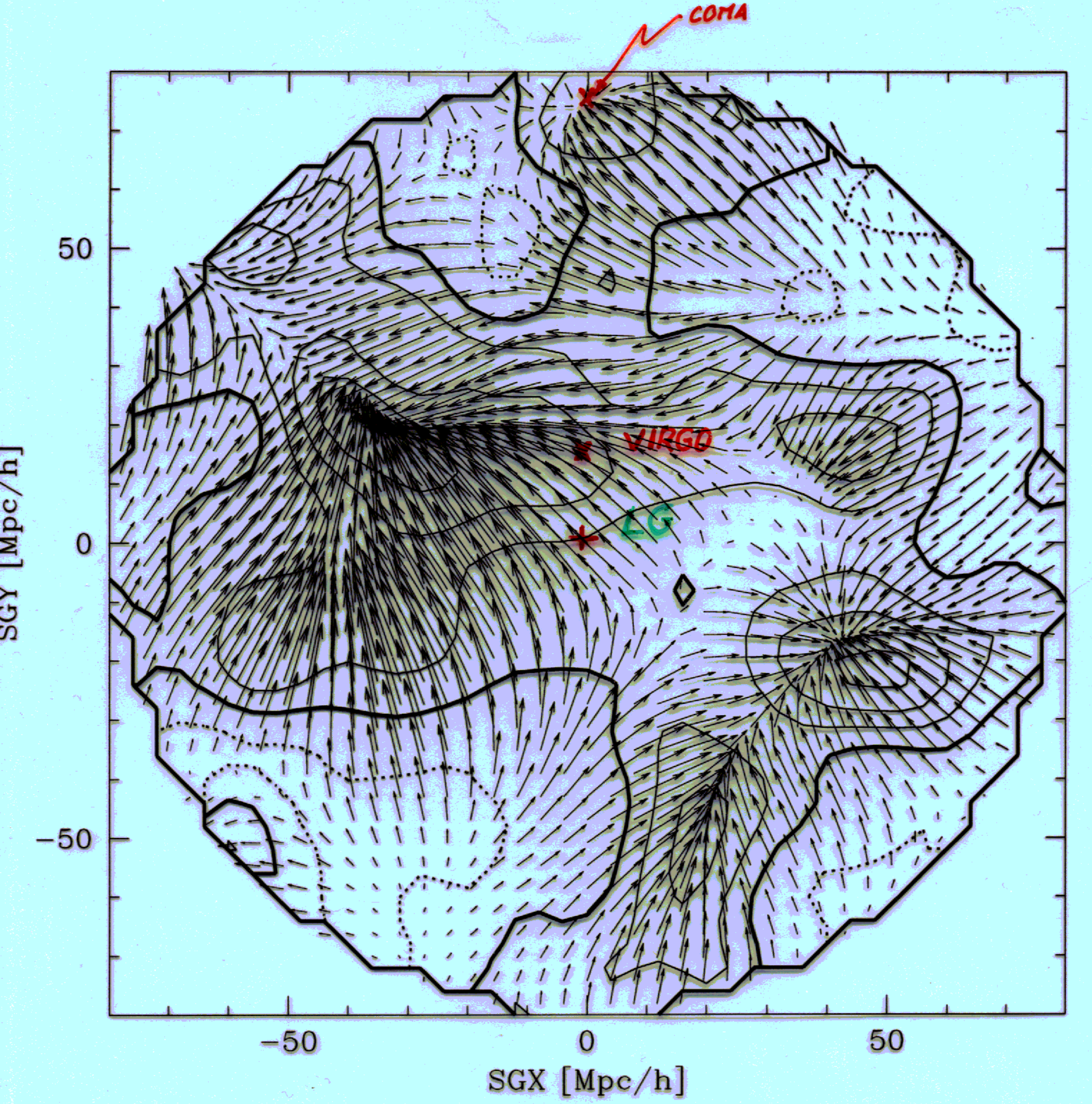
$= 64 \pm 3$ $Km s^{-1} / Mpc$

Perlmutter, *et al.* (1998)

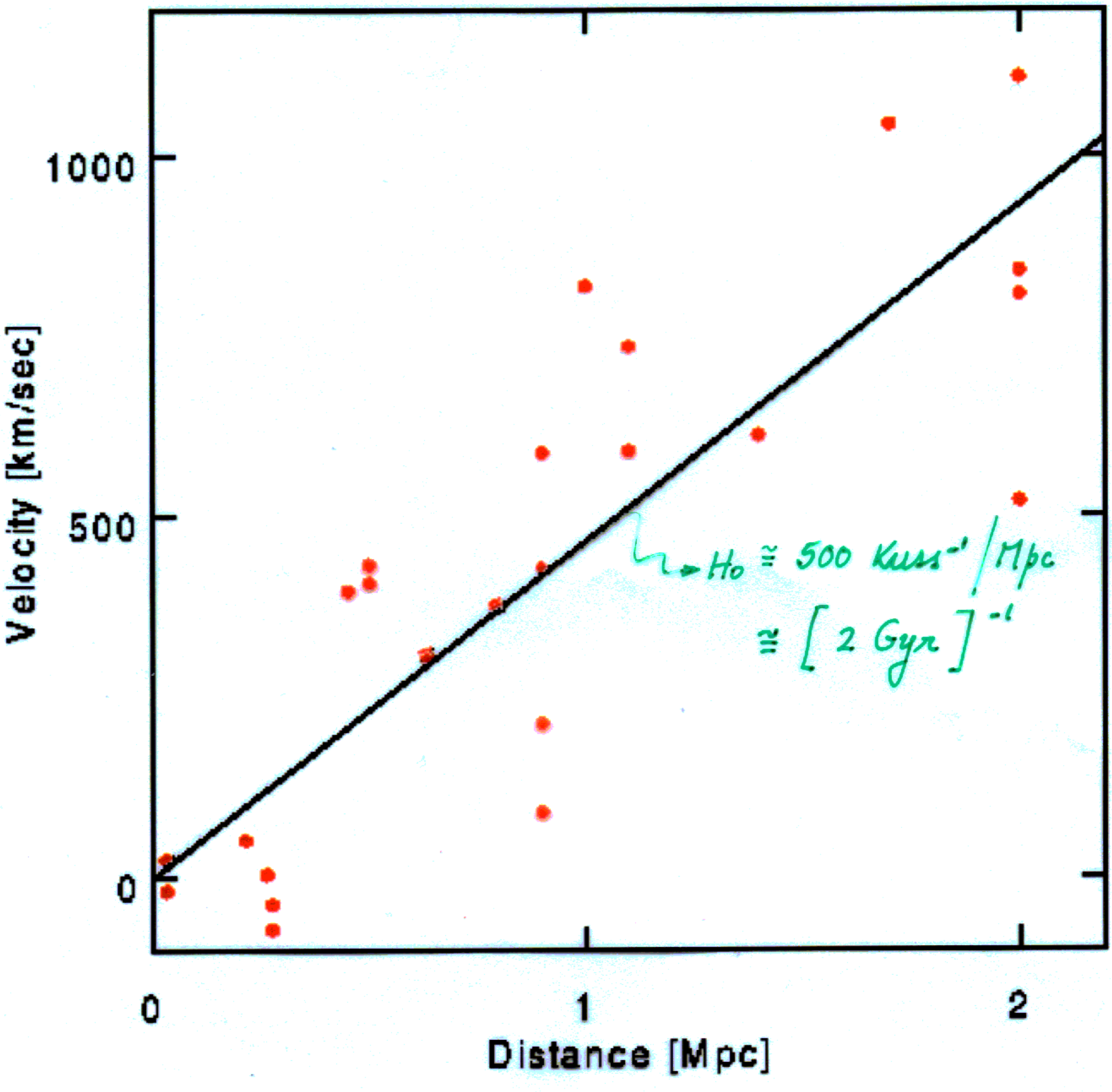


In flat universe: $\Omega_M = 0.28$ [± 0.085 statistical] [± 0.05 systematic]

Prob. of fit to $\Lambda = 0$ universe: 1%



COMA
VIRGO
LG
50
0
−50
SGY [Mpc/h]
SGX [Mpc/h]



* LG IS A BOUND OBJECT!

** VELOCITY FIELD!

BIASES

- SAMPLE INCOMPLETENESS
- SCOTT EFFECT — $V_R \longleftrightarrow L$ [BRIGHT GALAXIES]
- MALMQUIST BIAS — MORE OBJECTS SCATTERED IN THAN OUT DUE TO DISTANCE MEASUREMENT ERRORS
- K CORRECTION — REDSHIFT DISTORS THE ν DISTRIBUTI… OF LIGHT
-
- ABSORPTION — GALAXY ABSORBS PART OF THE LIGH…
- GALAXY ROTATION
- PEC. VELOCITY FIELD
- EVOLUTION