Introduction of the Cosmological Constant

The years before the inauguration of the Cosmological Constant

(Retrospect)

Masataka Fukugita

Cosmology as of 1980's

Hubble constant $H_0 = 50 \quad \text{or} \quad 90$

Sandage vs deVaucouleurs

Age of the Universe $t_0 \simeq 14 - 18 \text{ Gyr}$

Cosmological mass density $\Omega_m = 1$ (by belief)

noise $\Omega_\mathrm{m} \sim 0.2$

Friedman(n) Universe is the prime basis of our thinking

(not verified)

$$t_0 = 13.0 \text{ Gyr} \left(\frac{50}{H_0}\right) \qquad (\text{with } \Omega = 1)$$

CMB

theory $\Delta T/T > 10^{-4}$

observation $\Delta T/T < 10^{-4}$

Our line of thought may be fundamentally wrong!

(Friedmann Universe, gravitational instability)

Distance indicators

Only reliable method:

Cepheids limited to <3Mpc

Tully-Fisher (1977) method = 21cm line width $\propto L^\alpha$

generally gives $H_0 \approx 80$

Criticisms by Sandage & Tammann

How to get $H_0 \sim 50$?

Distance to Coma cluster (1988-1990)

surface photometry to study Sandage's criticism

Ended up with $H_0 \approx 90 \quad > 70$ MF,Okamura,Rood,...

(local distance 10% longer than today)

$\Lambda \neq 0$ is compelling if we stick to the Friedmann Universe

C. Hayashi "There's no reason to exclude Λ from the beginning"

Around the same time

PNLF (Jacoby et al. 1989)

Surface Brightness Fluctuation (Tonry et al. 1988)

errors are empirically mutually documented

Virgo “centre” 15 Mpc

(Sandage-Tammann 22Mpc)

COSMOLOGY

High H_0?

M. Fukugita and C. Hogan

EVER since Hubble discovered the linear relationship between the velocity v of recession of a galaxy and its distance r — the relation $v = H_0 r$ which shows that the Universe is expanding — astronomers

candles all at a single distance; this is why spotting the Virgo Cepheids is a top priority for the Hubble Space Telescope.

The link from the nearby galaxies to the Virgo cluster and beyond has thus mostly

stant, in the range 75–100 km s^{-1} Mpc^{-1}. Such a rapid rate of expansion implies that the Universe is surprisingly young and small. In a universe without a cosmological constant (a kind of repulsive gravity) this rate is not consistent with conventional age estimates based on stellar evolution and nuclear-decay chronometers. The option of having a cosmological constant is anathema to theorists who both abhor fine tuning and free parameters in the grand design of the Universe, and like to believe in their chronometers.

Hayashi: There's no reason to exclude the cosmological constant !

- 4. FEB. 1991

THE OBSERVATORIES

OF THE CARNEGIE INSTITUTION OF WASHINGTON

January 30/1991

Dr. Fukugita:

I was so very sorry to see your paper with Professor Hogan in Ap.J. Letters of February 10, 1991. Enclosed is a different point of view. I am astounded you place so much emphasis on the PN calibration when the theoretical zero point jump by ~1 mag for (1) a difference of only 0.02 $M_\odot$ in the parent object, & (2) whether the CPNS is burning He or H.

Sincerely,

Allan Sandage

THE OBSERVATORIES - 5. AUG. 1991

OF THE CARNEGIE INSTITUTION OF WASHINGTON

July 24/1991

Dear Herbert:

You were the last person in the world I would have imagined could have written what is written in Ap.J. 376, 8, 1991. Once we agree that the

Fukugita, Okamura, Rood, ...
Coma distance 1991

Mon. Not. R. astr. Soc. (1991) **251,** 128–136

Dynamical effects of the cosmological constant

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1 INTRODUCTION

The Cosmological constant Λ has had a chequered past. Einstein introduced a positive Λ (universal spatial repulsion) to counterbalance the gravitational attraction of matter in order to get a static universe (Einstein 1917; Kerszberg 1989). Eddington–Lemaître cosmologies, which have large spatial volume interval at some intermediate redshift range (the coasting period), were invoked to explain the abundance of quasars at $z \sim 2-3$ (e.g. Petrosian, Salpeter & Szekeres 1967). Although these previous appeals to Λ are now thought to be misguided, Λ is becoming popular in cosmology again in order to help resolve a number of problems.

(i) There is a conflict between globular cluster estimates of the age of the Universe (Sandage & Cacciari 1990) and the age estimated for $\Lambda = 0$ and a large value of the Hubble parameter $H_0 \approx 75$ km s^{-1} Mpc^{-1}, that seems increasingly to be favoured by observations (see, e.g. Fukugita & Hogan 1990).

THE ASTROPHYSICAL JOURNAL, 402:3–14, 1993 January 1

$H_0 = 43 \pm 11$ km s^{-1} Mpc^{-1} BASED ON ANGULAR DIAMETERS OF HIGH-LUMINOSITY FIELD SPIRAL GALAXIES

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Received 1992 January 10; accepted 1992 June 30

ature for these two methods present the most severe challenge to the long distance scale. For this reason FH believe that the PN and SB results are overridingly powerful. But the adumbration of FH that "none of the [long distance scale] methods are empirically reliable" is obdurate.

1. FH neglect two analyses of the Tully-Fisher (TF) method

Tests for Λ (1991)

SNIa Hubble diagram (already advocated 1984?)

★ Number count of galaxies --- comoving volume

Gravitational lensing

Alcock-Paczynski test (1979): transversal vs depth

★ lensing statistics (1991: MF,Futamase,Kasai; Turner)

CMB viewing angle: ISW

1990

non − zero Λ?

TEST FOR THE COSMOLOGICAL CONSTANT WITH THE NUMBER COUNT OF FAINT GALAXIES

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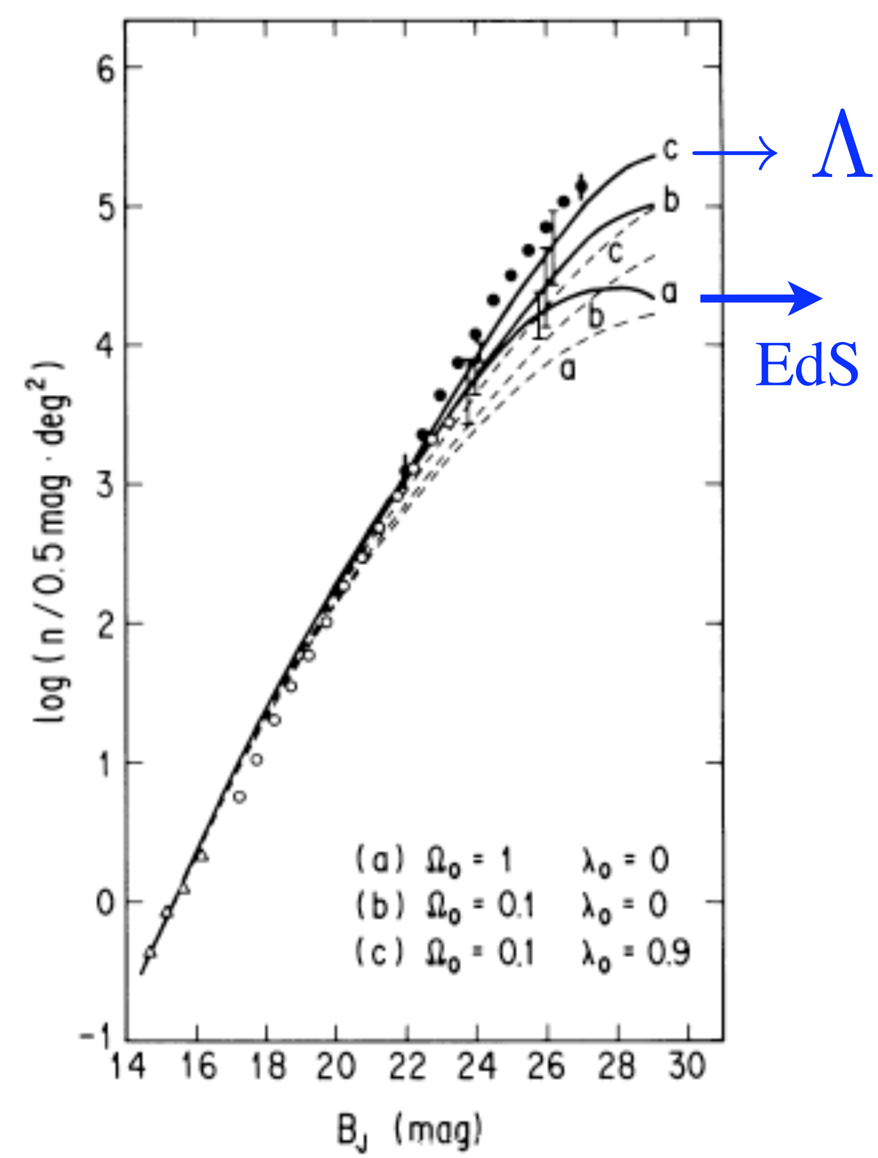
Received 1990 March 2; accepted 1990 July 2

Tyson's CCD count (1988):
cosmological depth



Importance of photometric-spectrophotometric accuracy

Mon. Not. R. astr. Soc. (1990) **246**, *Short Communication*, 24P–27P

A possible test for the cosmological constant with gravitational lenses

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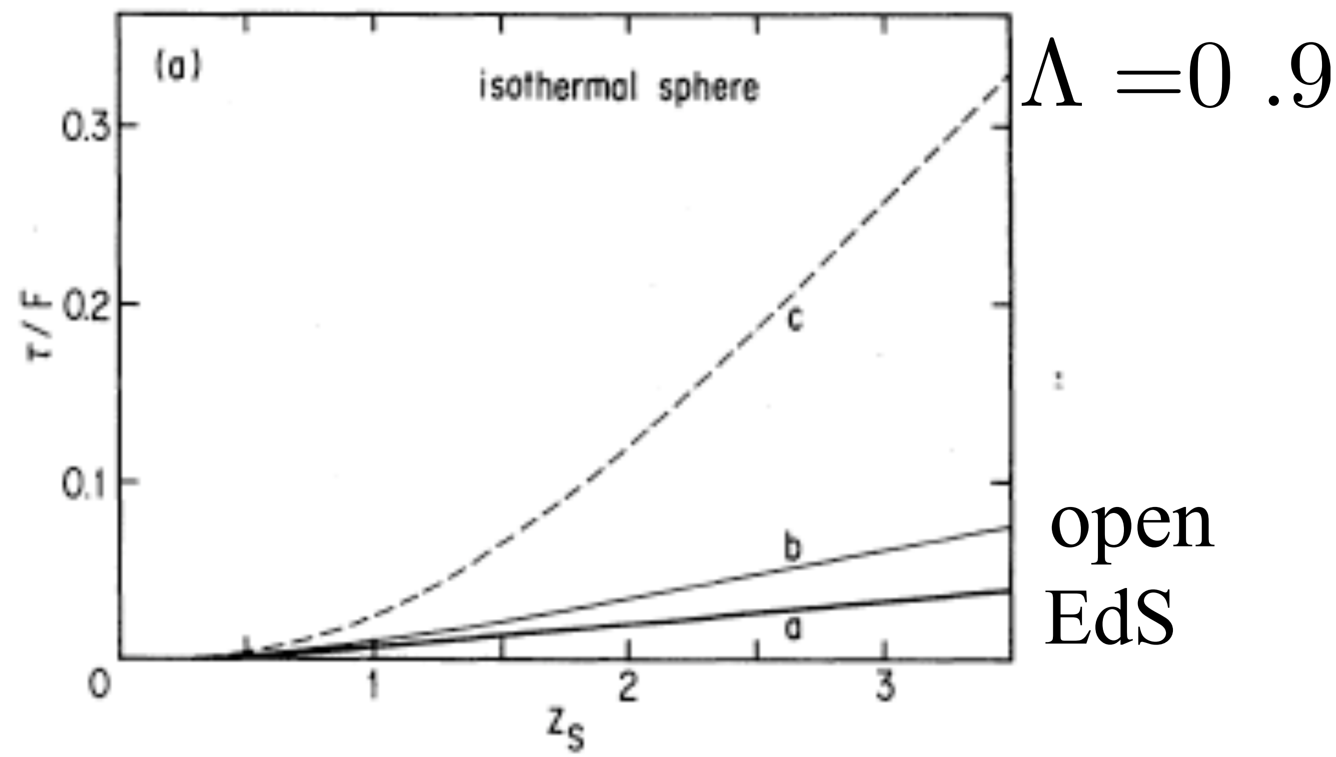
also EL Turner



Test immediately taken up by HST snapshot (Bahcall+ 1992)

$\Lambda < 0.9$

Meaningful results, finally

J. Mitchell et al. 2005 (CLASS) $\Lambda = 0.72 - 0.78$

M. Oguri et al. 2012 (SDSS) $\Lambda = 0.79 \pm 0.09$

Another indication for Λ

large scale power in $w(\theta)$ + speed of the growth

within the CDM model

Efstathiou et al. 1990

Reaction to Λ is very negative

SNIa Hubble

LNP 224, 151 (1985)

TYPE I SUPERNOVAE AS STANDARD CANDLES

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Abstract

Observations are compiled to construct a mean light curve of SNe I in different colors. Individual SNe I show generally no systematic deviations from these templet light curves, and occasional deviations are explained as photometric errors, which can be quite severe in the case of SNe. The peak luminosity of absorption-free SNe I is also uniform with an intrinsic rms scatter of <0.3 mag. The calibration of the peak luminosity yields $M_B(\max) = -20.0 \pm 0.4$, which requires $H_o = 43 \pm 10$ km s^{-1} Mpc^{-1}. SNe I are probably among the best standard candles known and hence have in view of their high luminosity important applications for distance determinations and for cosmological tests to be performed with Space Telescope.

I. Introduction

- The adopted value of $M_B(\max)$ requires a Hubble constant of 43^{+10}_{-7} km s^{-1}Mpc^{-1}. This value is freed from the effects of Virgocentric streaming velocities and reflects therefore the global expansion rate. A rounded value of $H_o = 50$ is discussed in the light of independent evidence elsewhere in this volume.
- SNe I used as standard candles have important advantages over brightest cluster galaxies, i.e. their luminosity evolution is expected to be small, they do not suffer from dynamical evolution, and their photometry is easier than for extended objects. They can play an important role in cosmology if they are observed with Space Telescope out to $z \approx 0.5$. The resulting Hubble diagram would provide a unique chance to confine the possible range of the deceleration parameter q_o and of the cosmological constant Λ (cf. Sandage and Tammann 1984), and the expected time dilation of their light curves by a factor (1+z) would provide a fundamental test for the Doppler nature of the redshifts observed in distant galaxies (cf. Tammann 1979).

The night before towards the convergence of H_0 (1993)

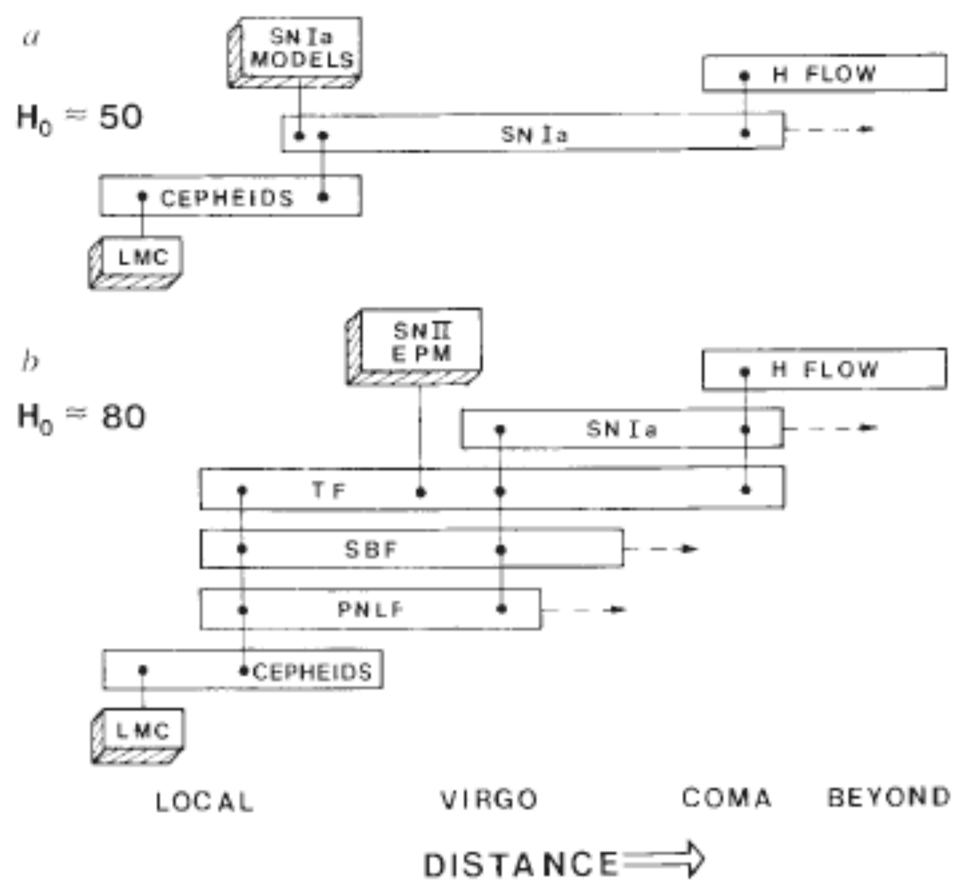
The cosmic distance scale and the Hubble constant

M. Fukugita, C. J. Hogan & P. J. E. Peebles

Although astronomers can reliably measure the relative distances of distant galaxies, attempts to calibrate the absolute cosmic distance scale remain controversial. Nevertheless, the sources of possible error are now clearly defined and a convincing result seems to be within reach.

IN a perfectly uniform and isotropic expanding universe, particles move according to the Hubble law, $v = H_0 r$, where v and r ...

to connect the local distances to the smooth large-scale Hubble flow.



THE OBSERVATORIES

OF THE CARNEGIE INSTITUTION OF WASHINGTON

March 1/93

Hogan:

What a paper! Suitable for Freshman. The open conference did, indeed, seduce you. Understand your *detailed* Malmquist-like bias applied to the T-F relation (Ap. J. 331, 605). Neither you nor Peebles have understood this paper. The *fatal* clue is that the zero point of the TF relation in flux limited samples is a *strong* function of redshift. This is a selection effect. Understand it & you will believe in the long distance scale. Both you & Peebles are making fools of yourselves. Fukugita is beyond saving.

You will shortly get a preprint on SN Ia.

A. S.

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Are SNeIa a standard candle?

giving $H_0 \approx 50$

1984 Pskovskii max brightness - decline time correlated
(AZh)

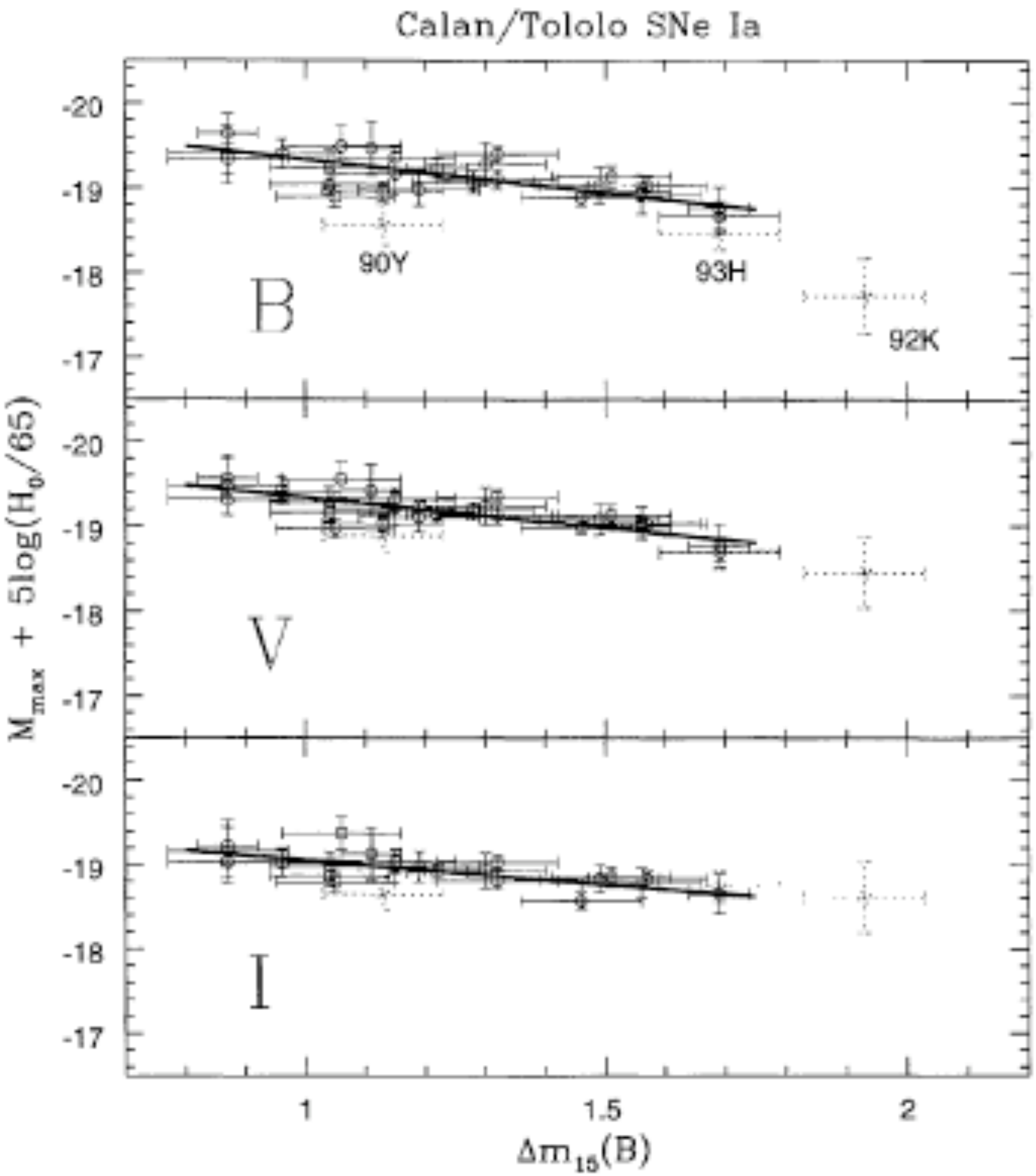
1993 Phillips

1996 implementation of the $B_{\max} - \Delta t$ relation
(Δm_{15})

Hamuy et al.

Riess, Press, Kirshner

$H_0 = 64$ for the Sandage-Tammann sample



Hamuy et al. 1996

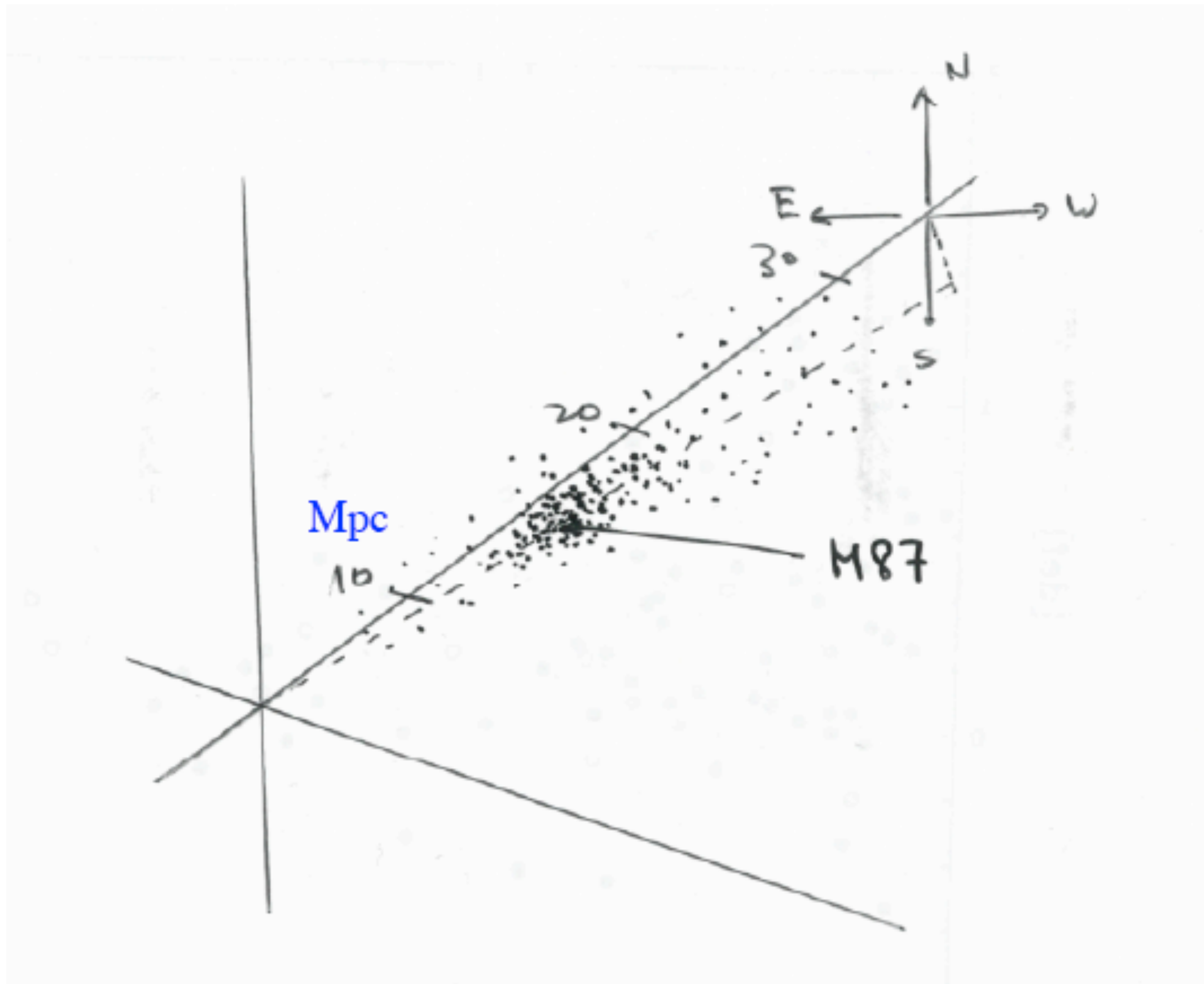
From Virgo SNe

$$H_0 = 57$$

Virgo cluster is complicated

It elongates along the line of sight

Fukugita,Okamura,Yasuda 1993



Change of the atmosphere on CMB

COBE launched in Nov 1989 (plan 1982+)

1992 Announce of $\Delta T/T = 5 \times 10^{-6}$

We are on the right track!

Structure formation: OK, but

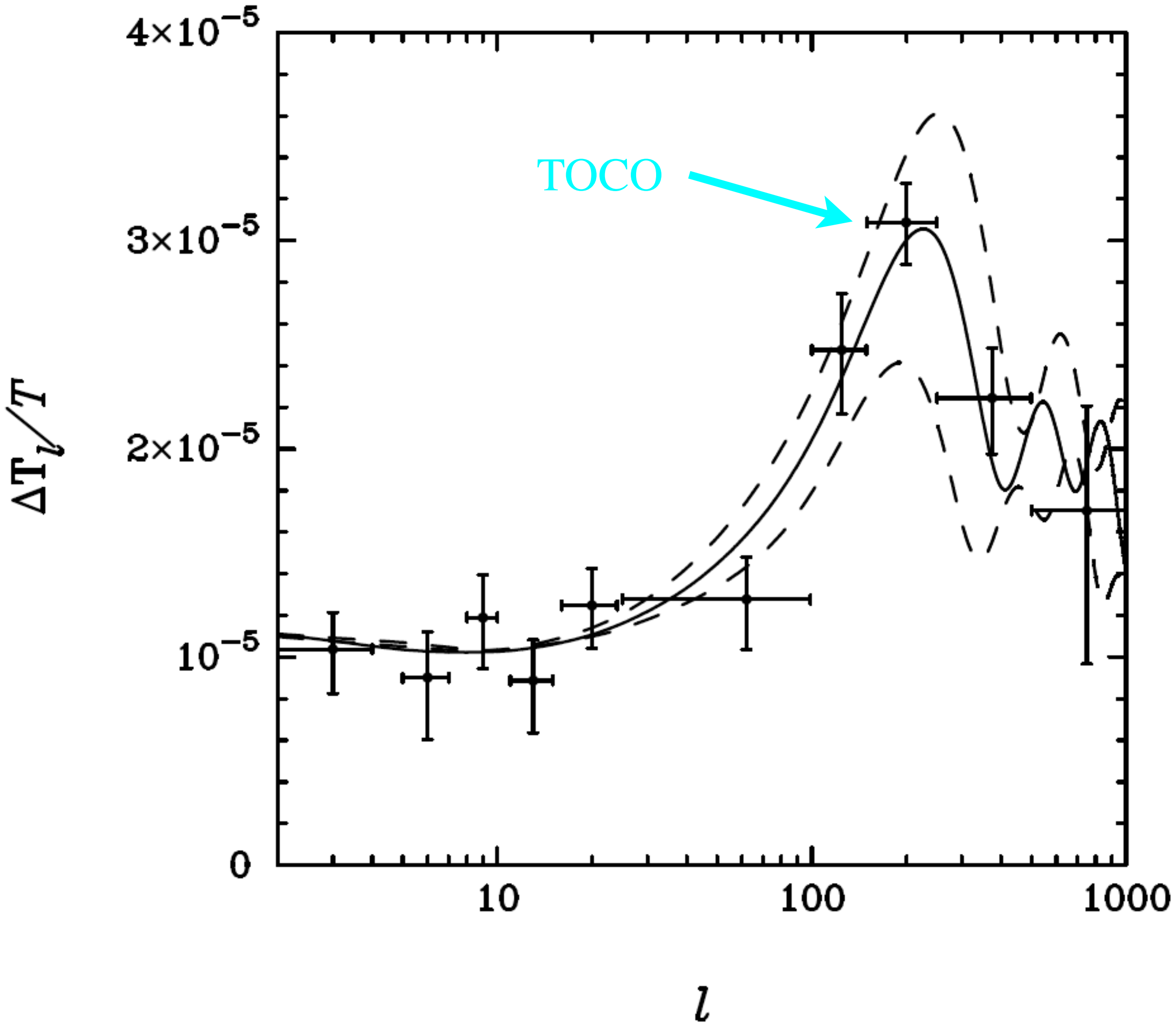
Dominance of Dark matter: it is now beyond doubt!

Λ is not yet!

CDM model is a promising candidate theory

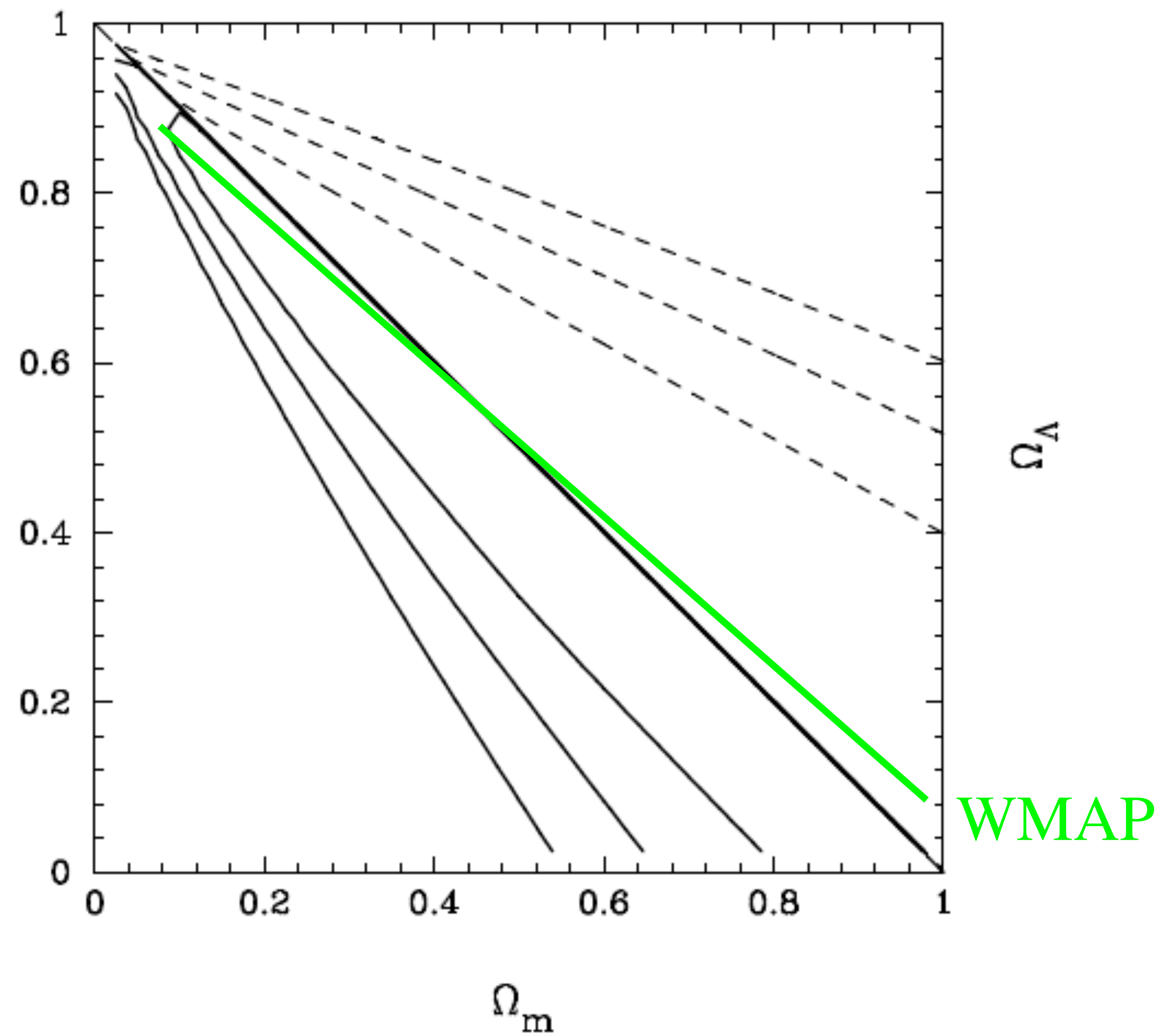
Triggered many experiments to measure $\Delta T/T$

The status before Boomerang



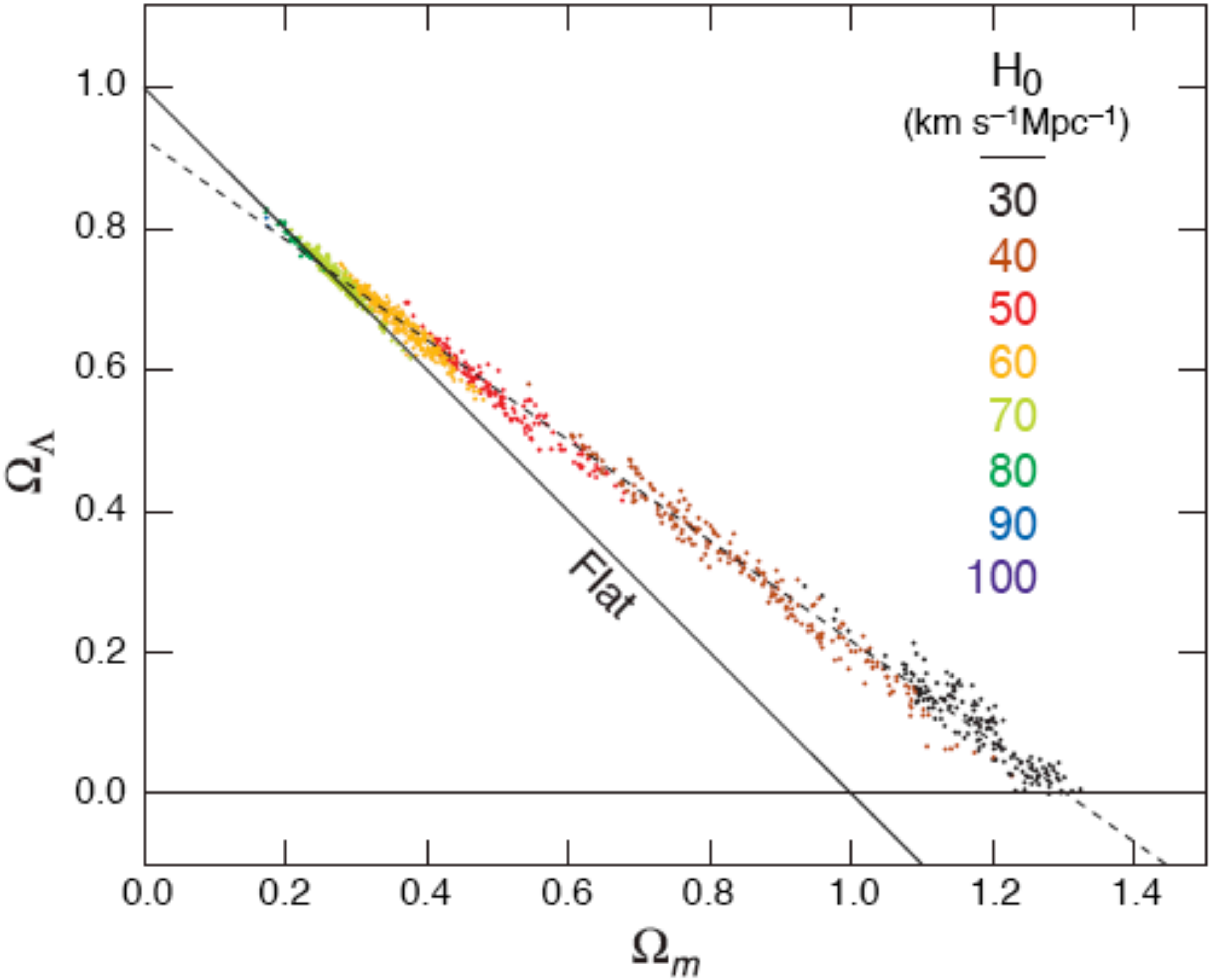
22 experiments
to 1998

Efstathiou compilation
1999



We took $\Omega + \lambda \approx 1$ before SNe or Boomerang!

WMAP



1.0
0.8
0.6
0.4
0.2
0.0
Ω_Λ
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Ω_m
Flat
H_0
(km s^{-1}Mpc^{-1})
30
40
50
60
70
80
90
100

1996/6 250-year anniversary of Princeton U symposium

'All observations are consistent with $\Lambda \neq 0$ except for

'SN Hubble diagram'

Saul claimed '$\Lambda \neq 0$ is already excluded by SN Hubble'

MF: 'Saul's band matching/K correction may be incorrect by 0.5 mag'

Perlmutter et al. 1997 (1996/Aug) $\Lambda = 0.06 \pm 0.03$

Schmidt et al. 1998 (1997/Dec) $\Lambda = 0.6 \pm 0.5$

Riess et al. 1998 (1998/March) Λ: 7-9 sigma

Perlmutter et al. 1999 (1998/Sept) $\Lambda = 0.72 \pm 0.09$

TABLE 8. Estimates of maximum brightness on SNe: 1997 vs. 1999 from Perlmutter et al. (1997; 1999).

SN	1997 value	1999 value	difference
SN1992bi	(23.26±0.24)	23.11±0.46	(0.15)
SN1994H	22.08±0.11	21.72±0.22	0.36
SN1994al	22.79±0.27	22.55±0.25	0.24
SN1994F	(21.80±0.69)	22.26±0.33	(−0.58)
SN1994am	22.02±0.14	22.26±0.20	−0.24
SN1994G	22.36±0.35	22.13±0.49	0.23
SN1994an	22.01±0.33	22.58±0.37	−0.57

Note: The numbers in the parentheses are not used in the final result of the 1997 paper.

We have been led to take ΛCDM = the paradigm

Λ Problem

zero cosmological constant was already a tough problem

progress in 1997+ has made this problem by an order of magnitude more difficult

Do you want to make it more difficult by another orders of magnitude??

Accessory:

$$\Delta V = \frac{\phi_0}{M_c} m_W^2 M_c^2 (\exp[-2\pi/\alpha_W])^2$$
$$\approx [10\mathrm{meV}]^4$$

$$M_c = M_{pl}$$

MF +Yanagida 1995