MATTER IN THE UNIVERSE

WHAT DO WE KNOW?

	$\Omega_{\nu/\gamma} \sim 10^{-5}$	—	RAD. BKGND.
	$\Omega_{LUM} \sim 5 \times 10^{-3}$	—	LUM STARS
	$\Omega_{\nu_m} \sim 3 \times 10^{-3}$	—	SUPER K / SNO
★ (BARYONIC DARK MATTER)	$\Omega_b \sim 5 \times 10^{-2}$	—	BBN
★ (NONBARYONIC DARK MATTER)	$\Omega_{DYN} \sim 0.35$	—	CLUSTERS ETC.
★ (DARK ENERGY)	$\Omega_{DE} \sim 0.65$	—	SN Ia

$$\boxed{\sum_i \Omega_i \simeq 1 \pm (5\text{-}10\%) \qquad \text{CMB}}$$

- ORDINARY STUFF: WHAT'S OUT THERE & WHAT DOES IT TELL US ABOUT THE MATTER DISTRN.
- WHAT WE KNOW IS OUT THERE BUT DON'T KNOW WHAT IT IS
- PROBES OF DARK MATTER AND DARK ENERGY
- COSMOLOGICAL PROBES OF PARTICLE PHYSICS (FUNDAMENTAL CONSTITUENTS OF MATTER)

MASS-ENERGY IN THE UNIVERSE

THE GLOBAL PICTURE:

COSMIC OPTION A

AESTHETICS ✓ $\Omega = 1$

REALITY ? $\Lambda = 0$

$\Omega_{NB} \simeq 0.95$

- LENSING ✗
- LARGE SCALE FLOWS ✓
- LSS ✓
- CLUSTERS ✗
- CMB ✓
- AGE ✓
- SN Ia ✗

COSMIC OPTION B

AESTHETICS ? $\Omega = 1$

REALITY ✓ $\Omega_\Lambda \simeq 0.7$

$\Omega_{NB} \simeq 0.3$

- LENSING ✓
- LARGE SCALE FLOWS ✓
- LSS ✓
- CLUSTERS ✓
- CMB ✓
- AGE ✓
- SN Ia ✓

COSMIC OPTION C

AESTHETICS ✗ $\Omega < 1$

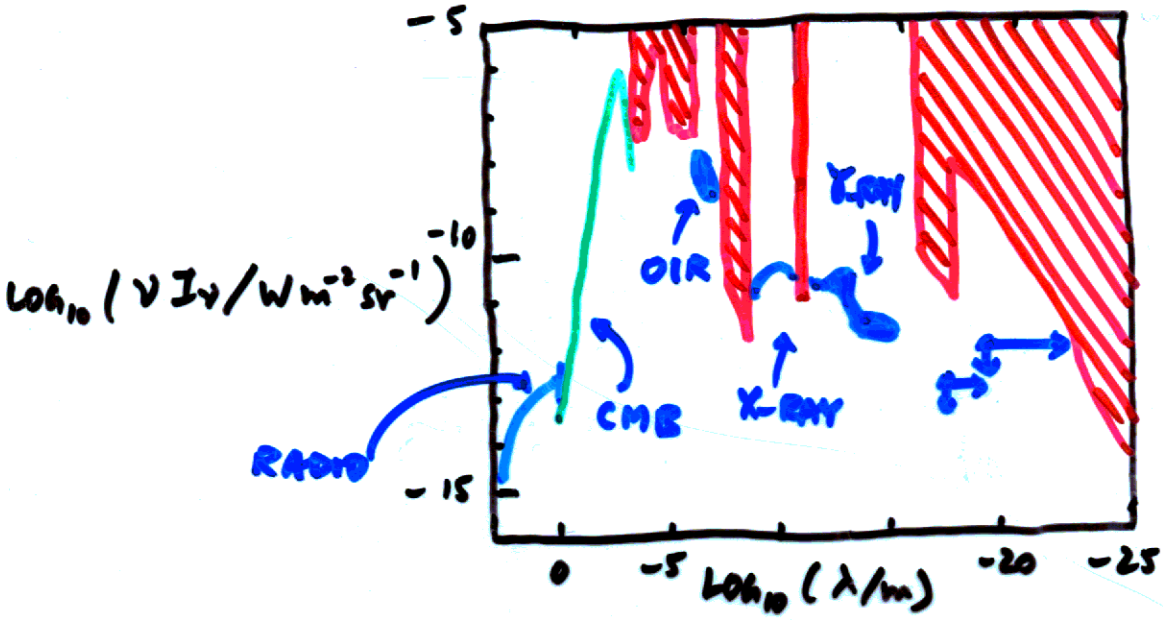
REALITY ✗ $\Lambda = 0$

$\Omega_{NB} \simeq 0.3$

- LENSING ✓
- LARGE SCALE FLOWS ✗
- LSS ?
- CLUSTERS ✓
- CMB ✗
- AGE ✓
- SN Ia ?

[IN ALL 3 OPTIONS $\Omega_B \simeq 0.05$]

THE ELECTROMAGNETIC SPECTRUM



BY ITSELF RADIATION IS $\boxed{\Omega_{REL}(\nu/\gamma) \simeq 10^{-5}}$ NOT AN IMPORTANT COMPONENT TODAY BUT IT IS A USEFUL PROBE OF WHAT'S OUT THERE. ESPECIALLY THE CMB!

USE BOTH BACKGROUNDS & DISCRETE SOURCES $\longmapsto$ TWO EXAMPLES:

- X-RAY BACKGROUND
- Lyα SYSTEMS WITH 'SEARCHLIGHT' QUASARS

(i) NOT POINT QUASARS (SPECTRUM)
(ii) NOT IGM NO GOOD (CORE)
(iii) CLUMPY SOURCES EXCLUDED (SMOOTHNESS)
(iv) MOST LIKELY FROM LOW-LUMINOSITY ACTIVE GALAXIES

③

CONTRIBUTION FROM LUMINOUS BARYONS

SUPPOSE LIGHT TRACES MASS → DETERMINE LIGHT DENSITY, ASSUME A UNIVERSAL M/L EXISTS, THEN FIND 'L × M/L'.

REDSHIFT SURVEYS GIVE GOOD DETERMINATION OF LUMINOSITY DENSITY (MODULO 50% OVERALL NORMALIZATION DIFFERENCES IN SURVEYS). IN THE B BAND

$$\rho_L \simeq 2 \pm 0.7 \times 10^8 \, h \, L_\odot \, \mathrm{Mpc}^{-3}$$

SINCE

$$\rho_{CRIT} \simeq 2.78 \times 10^{11} \Omega h^2 M_\odot \, \mathrm{Mpc}^{-3}$$

$$\Rightarrow \quad \langle M/L \rangle \Big|_{\substack{\text{SOLAR} \\ \text{UNITS}}} \simeq 1390 \, h \Omega \simeq 900 \Omega \; (\pm 600 \Omega)$$

OBSERVED M/L IN CENTERS OF GALAXIES OR IN OPEN/GLOBULAR STAR CLUSTERS ON SCALES OF 1-100 pc IS ~ 1-10. THESE SYSTEMS ARE KNOWN TO BE BARYON-DOMINATED

THUS FOR BARYONS,

$$\boxed{\Omega_{LUM} \sim \frac{5}{900} \sim 5 \times 10^{-3}}$$

SCALE-DEPENDENCE OF M/L

SYSTEM	METHOD	SCALE	$M/L \times h$	Ω
SOLAR NEIGHBORHOOD, STAR CLUSTERS	VELOCITIES OF STARS	1-3 kpc	1-4	.001-.004
LUMINOUS PARTS OF GALAXIES	v_{ROT}, STAR VELOCITIES	10 kpc	3-10	.003-0.01
GALAXIES	GLOB. CLUSTER VELOCITIES ETC.	100 kpc	10-30 ↑	.01-.03 ↑
GROUPS OF GALAXIES	VELOCITIES OF GALAXIES	1 Mpc	30-100	.03-.1
CLUSTERS	" , X-RAY GAS	10 Mpc	100-300	0.1-0.3
UNIVERSE	CMB ETC.	10^4 Mpc	~ 1000	1

AFTER TRIMBLE 2000

EVIDENCE FOR <u>DARK</u> MATTER

Ω_{BARYON}

FOLLOWING BBN & PRIMEVAL D ABUNDANCE,

$$\Omega_b h^2 = 0.02 \pm .002$$ BURLES ET AL 2000

$$\Rightarrow \Omega_b \simeq 0.047 \quad \text{FOR } h \simeq 0.65$$

ERRORS APPEAR OPTIMISTIC (FAIR FOR THE COURSE FOR BBN), E.G., NEWER D SYSTEM GIVES $\Omega_b h^2 = 0.023$ O'MEARA ET AL 2001

IN ANY CASE, THIS VALUE IS BROADLY CONSISTENT WITH LATEST CMB RESULTS FROM BOOMERANG, DASI, & MAXIMA (CANNOT MAKE PRECISE STATEMENTS DUE TO CALIBRATION UNCERTAINTIES & STATISTICAL LIMITATIONS)

MAIN MESSAGE 1 IF $\Omega_M \gtrsim .05$ SUBSTANTIALLY THEN THE MAJOR COMPONENT IS NOT BARYONS (MACHOS ARE OUT)

MAIN MESSAGE 2 SINCE $\Omega_{LUM} \sim 5 \times 10^{-3}$, WHERE ARE THE BARYONS HIDING?

DARK MATTER & Ω_{DYN}

KEPLERIAN BEHAVIOR [ROTATION CURVES]

$$v_c \propto \frac{1}{\sqrt{r}}$$

PREDOMINANTLY FOR SPIRALS BUT ALSO FOR ELLIPTICALS

BUT SEE INSTEAD

$$v_c \sim \text{CONST.}$$

$\Rightarrow$ $M(r) \sim r$ or $\rho \propto r^{-2}$

MORE PRECISELY,

$$M(r) = \frac{v_c^2 r}{G}$$

[$M(r)$: MASS ENCLOSED TILL r]

THEN WITH $v_c \simeq 220$ km/s

$$M(r) = 1.1 \times 10^{10}\, r(\text{kpc})\, M_\odot$$

IN CLUSTERS, MEASURE VELOCITY DISPERSION

$$M \sim \frac{v^2 R}{G}$$

TO GET ROUGH ESTIMATE OF MASS

ZWICKY / COMA

SMITH / VIRGO

GALACTIC ROTATION CURVES

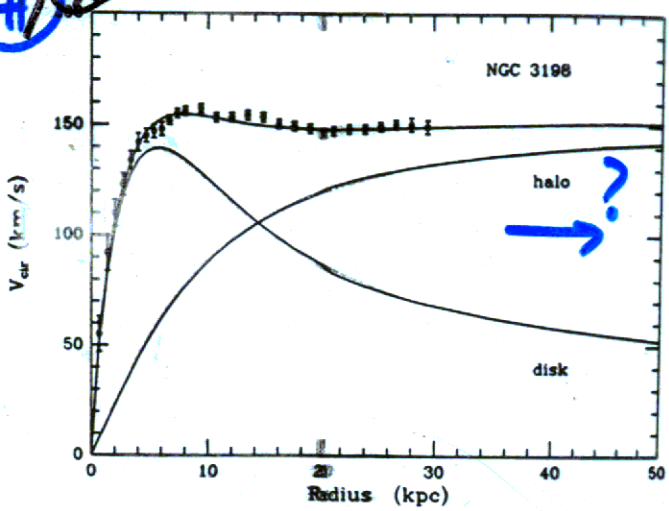
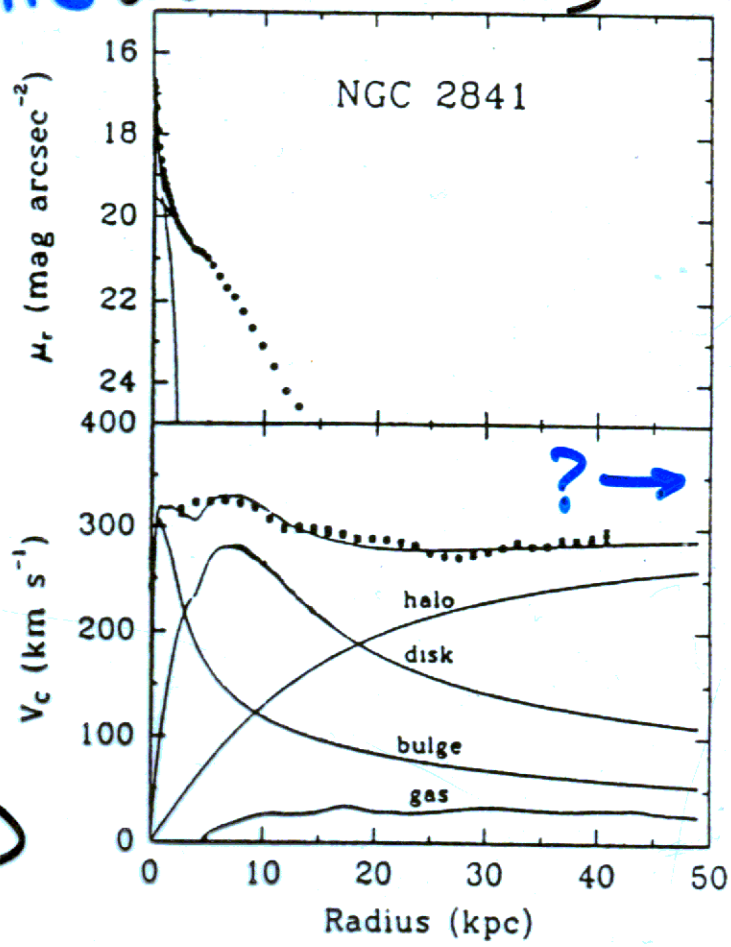


Figure 10-2. The Sc galaxy NGC 3198. Top: neutral hydrogen column density contours superimposed on an optical photograph. Bottom: circular-speed curve plus model fits using an exponential disk with constant mass-to-light ratio and the halo density profile (10-11). The model curve is for the maximum possible disk mass-to-light ratio. The horizontal scale assumes $h = 0.75$. Reprinted from van Albada et al. (1985), by permission of *The Astrophysical Journal*.



CLUSTER (VELOCITY DISPERSION)

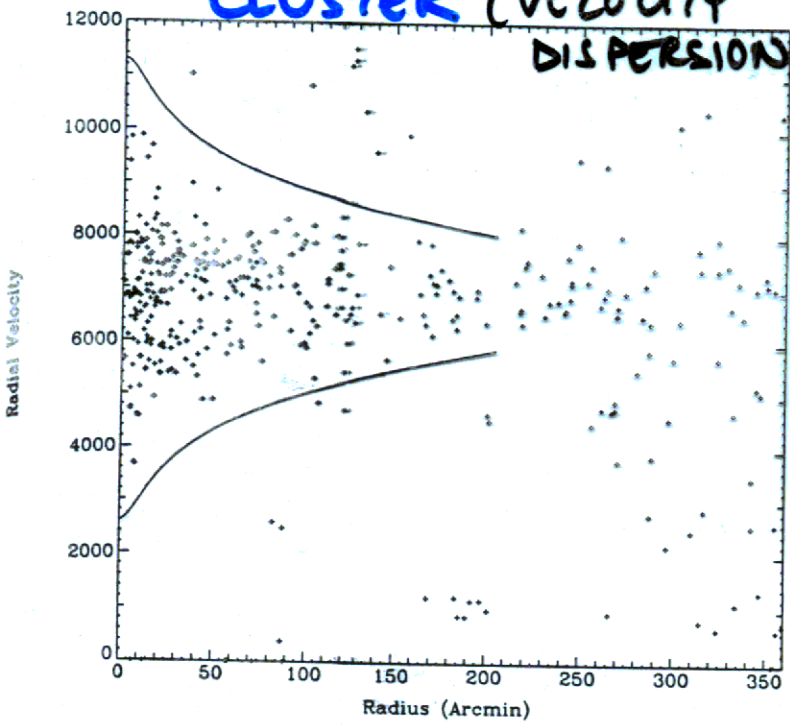


Figure 10-4. Line-of-sight velocities of galaxies in the Coma cluster (in km s^{-1}) as a function of distance from the cluster center in minutes of arc (Kent & Gunn 1982). The curves mark the authors' estimate of the boundary between cluster members and interlopers. At the distance of Coma 1 arcmin = $20h^{-1}$ kpc. Reprinted by permission from *The Astronomical Journal*.

ZWICKY '33

- LENSING : EVIDENCE FOR $r_g \sim 100\,h^{-1}$ kpc
- SATELLITE GALAXIES CONSISTENT WITH $\sim 100\,h^{-1}$ kpc

[$r_{opt.} \sim 15$ kpc
GAS ~ 25 kpc]

M_G ("STANDARD") $\sim 10^{11} M_\odot$

CAN NOW EASILY BE $\sim 10^{12} M_\odot$

$M/L|_G \sim 10-30h$ CAN GO UP TO

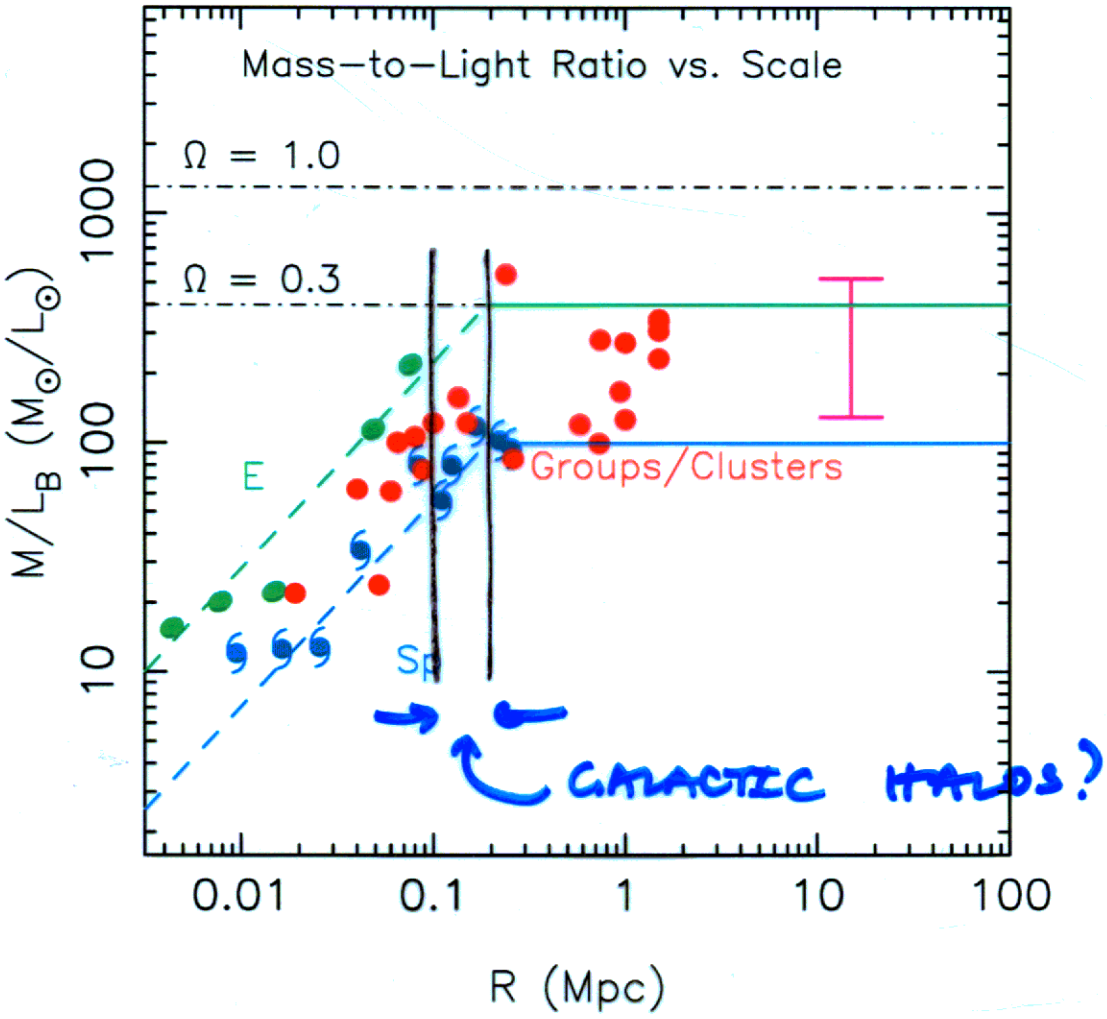
$M/L|_{Cluster} \sim 100-300h$

FLASH

IN FACT $5\times10^{12} M_\odot$ FROM SDSS & $r_g \sim 275\,h^{-1}$

8

DOES M/L SATURATE ?



HMMM...

BAHCALL ET AL 00

BAHCALL/FAN '9

Figure 1.The dependence of mass-to-light ratio, M/L_B, on scale, R, for average spiral galaxies (blue symbols), elliptical galaxies (green), and groups and clusters (red). (From Bahcall, Lubin and Dorman 1995)(11). The large scale point at $\sim 15h^{-1}$ Mpc represents Virgo cluster infall motion results (11). The location of $\Omega_m = 1$ and $\Omega_m = 0.3$ are indicated by the horizontal lines. A flattening of M/L_B is suggested at $\Omega_m \simeq 0.2 \pm 0.1$.

STILL ONE SHOULD BE CAREFUL RE BIAS --
BUT LATEST RESULTS (OBSERVATIONS VS. SIMULATIONS)
SHOW NO PROBLEM & ARGUE $\Omega_{CLUSTER} \sim 0.16$

HISTORICAL RECAP

ALL MASS IS NOT LUMINOUS

- LATE 18TH CENTURY: BLACK HOLES (LAPLACE ...)
- EARLY 20TH CENTURY: KAPTEYN/JEANS DETERMINE MASS DENSITY IN SOLAR NEIGHBORHOOD VIA DISTRN. OF STARS ABOVE GALACTIC PLANE & THEIR VELOCITIES. CONCLUDE

$$M_{DARK} : M_{BRIGHT} = 3:1$$

- 1930s ZWICKY / COMA
- 1936 SMITH / VIRGO
- 1940s-50s OORT
- 1940s-50s CLUSTERS: $M/L \sim 100 - 1000$
- 1970s GALACTIC ROTATION CURVES FREEMAN, RUBIN, ..
- 1973 OSTRIKER/PEEBLES: WITHOUT DM, DISKS UNSTABLE
- MID-70s M/L INCREASES WITH SCALE
- THE 'GREAT ATTRACTOR' 50 Mpc BEYOND VIRGO, $10^{15} - 10^{16} M_\odot$
- POLAR RING GALAXIES REQUIRE DM FOR STABILIZATION
- LENSING

60s NO BELIEF IN GALACTIC DM!

PARTICLE DARK MATTER EXISTS: MASSIVE NEUTRINOS

PRESENT DENSITY OF NEUTRINOS PLUS PARTNERS IN ONE FAMILY FIXED BY T_{CMB} TO BE

$$n_\nu \simeq 113 \,/\, cm^3$$

AS FRACTION OF CRITICAL DENSITY

$$m_\nu = 93\, \Omega_\nu h^2 \, eV$$

FOR $\Omega_\nu \simeq 1 \Rightarrow m_\nu \simeq 40\, eV$

$\Omega_\nu \simeq 0.2 \Rightarrow m_\nu \simeq 8\, eV$

$\Omega_\nu \simeq 0.15$ ($m_\nu \simeq 6\, eV$) IS THE UPPER LIMIT FROM STRUCTURE FORMATION

LATEST SUPERK/SNO RESULTS PROVIDE LOWER BOUND FOR Ω_ν

NEW RESULTS GIVE $0.05\, eV < m_\nu < 0.18\, eV$

i.e.

$$.0013 < \Omega_\nu < .0046$$

OR

$$\Omega_\nu \sim .003$$

WHICH IS ROUGHLY THE SAME AS $\Omega_{LUMINOUS}$!

DARK ENERGY

SNIa AS STANDARD CANDLES TO PROBE EXPANSION HISTORY OF THE UNIVERSE.

- BRIGHT SOURCES HENCE HIGH Zs
- APPARENTLY (?) GOOD CONTROL OF SYSTEMATICS

RESULTS NO LONGER LIMITED BY STATISTICS --

BUT QUESTIONS ABOUT SYSTEMATICS LINGER. (WRIGHT 2001)

- EVOLUTION
- DIMMING VIA AXIONS
- DUST

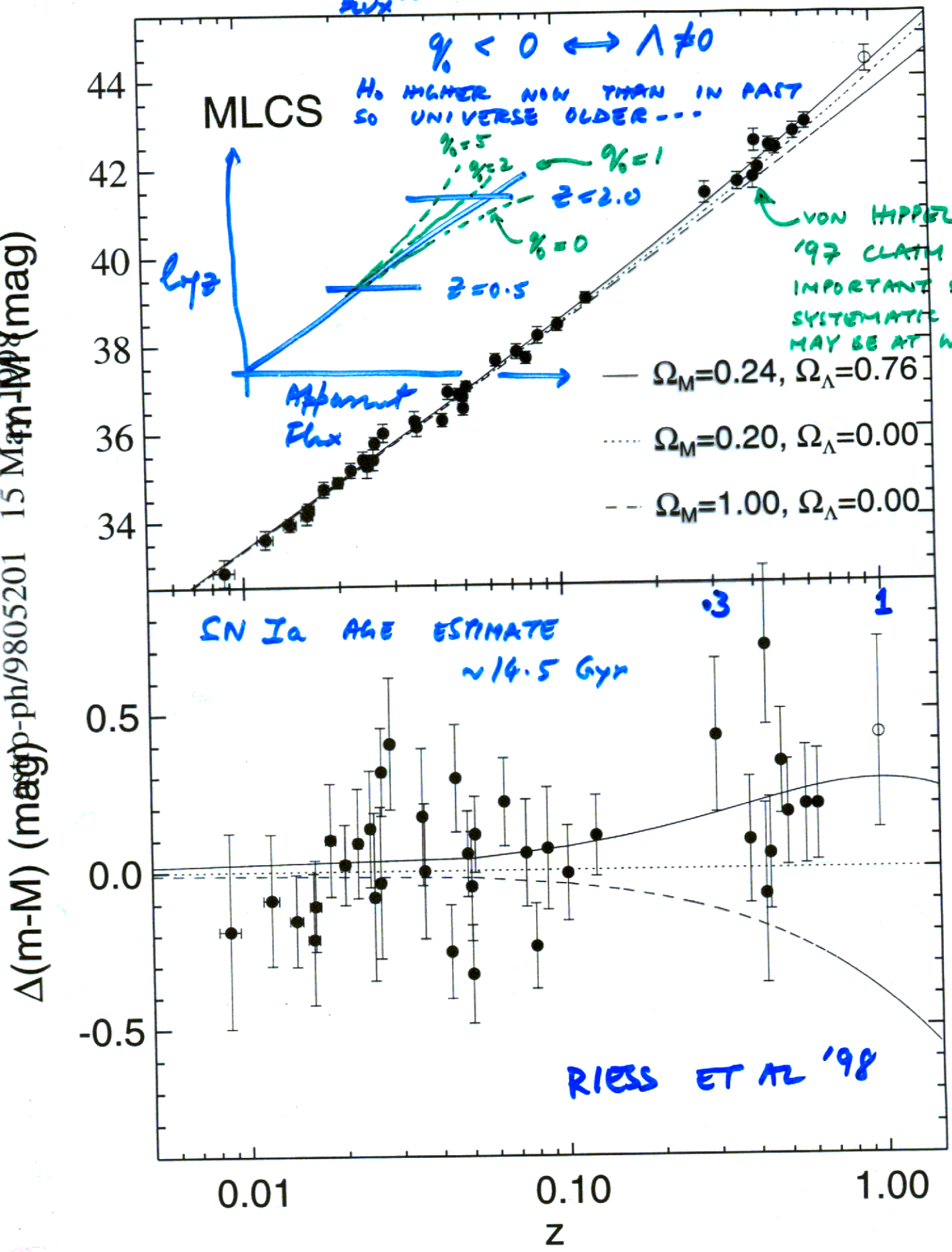
SNIa BY THEMSELVES INSUFFICIENT TO PROVIDE IRON-CLAD EVIDENCE FOR ACCELERATION.

UNFORTUNATELY CMB NOT A VERY GOOD DIRECT PROBE EITHER

(12)

$l_d \sim \sqrt{\frac{L}{F}}$ → INTRINSIC LUMINOSITY [HARD...]
→ MEASURED FLUX

$H_0 l_d = z + 0.5(1-q_0)z^2 + \cdots$



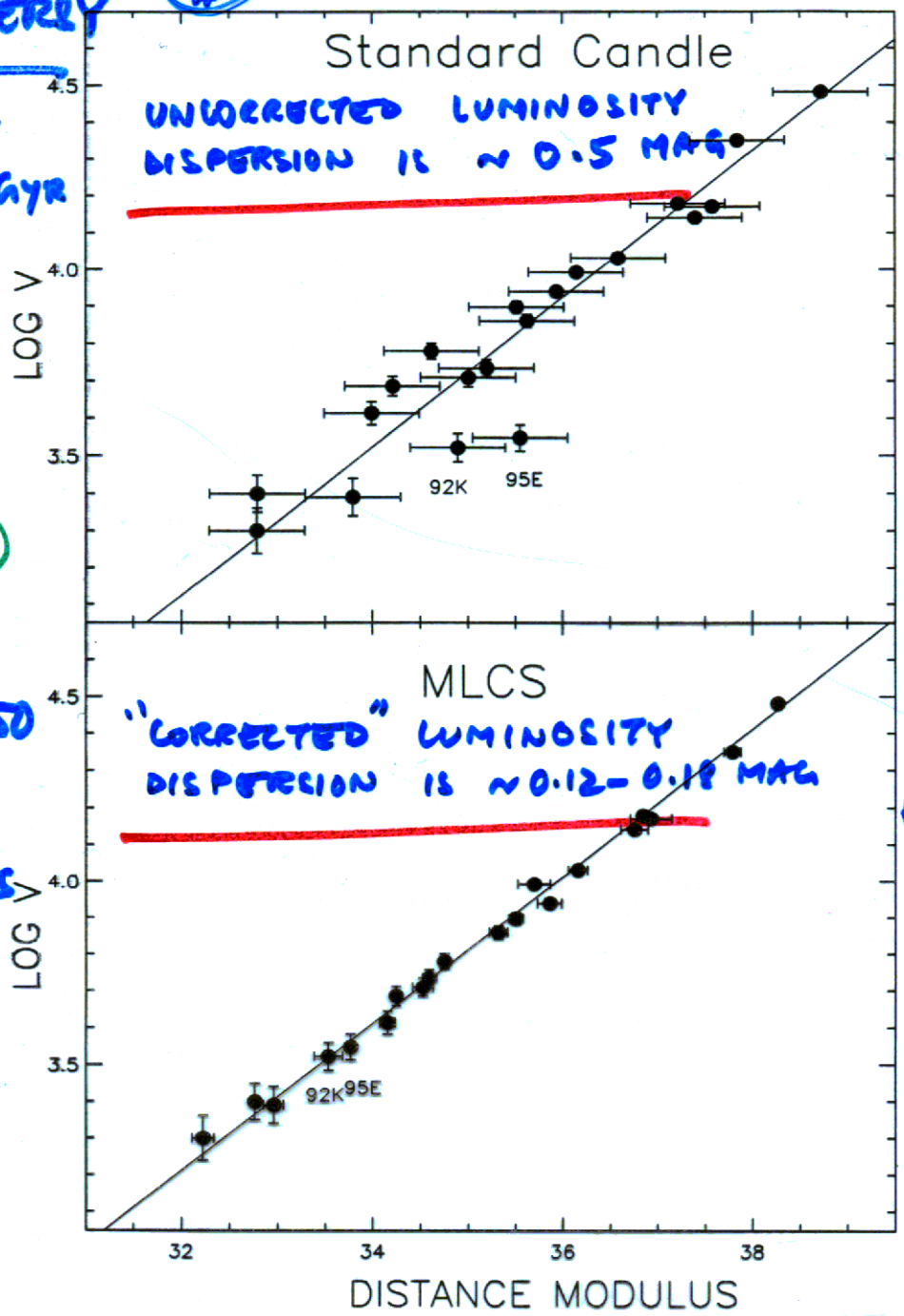
astro-ph/9805201 15 May 1998

DIGRESSION:
H_0 CONTROVERSY

100 ⇒ AGE
↓ ≈10 GYR
80
↓
65
↓
? (YES!)

SANDAGE ~50
(55 ± 10)

SYSTEMATICS
STILL
TRICKY!



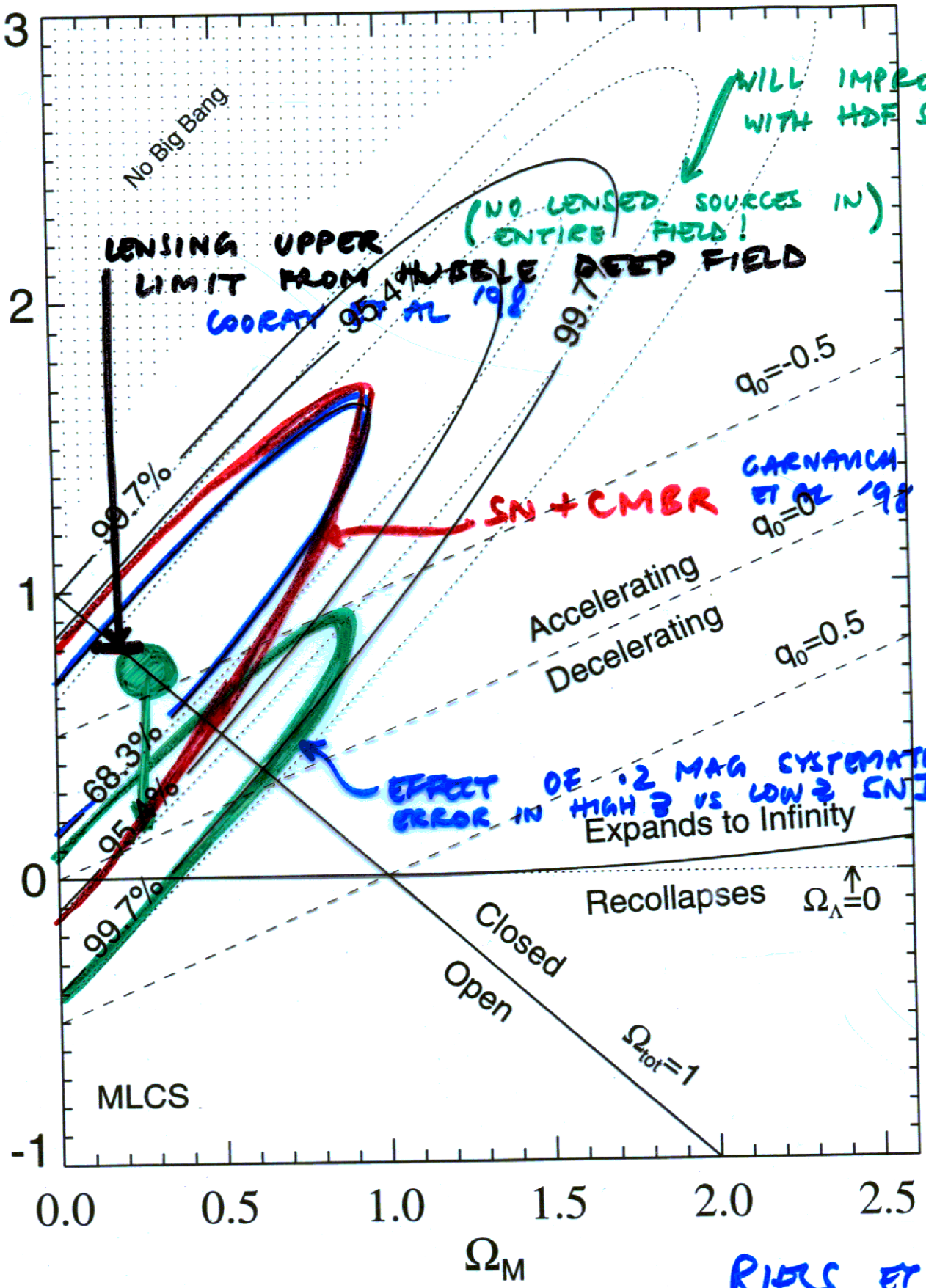
52 ± 8 km/s/Mp

65 ± 6 km/s/Mp

Figure 6: Hubble Diagrams for SN Ia with velocities in the COBE rest frame on the Cepheid distance scale (Sandage et al 1994, 1996). All velocity errors are 300 km s^{-1} reflecting a plausible estimate of random velocities with respect to the Hubble flow. (a) Distances estimated with a standard luminosity assumption and no correction for extinction. This method yields σ_v=0.52 and H_0=52 ± 8 (statistical) km s^{-1} Mpc^{-1}(b) Distances from the MLCS method which makes a correction for intrinsic luminosity variation and total extinction as determined from the light and color curve shapes. This method yields σ_v=0.12 and H_0=65 ± 3 (statistical) km s^{-1} Mpc^{-1}.

REISS, PRESS, KIRSHNER '96

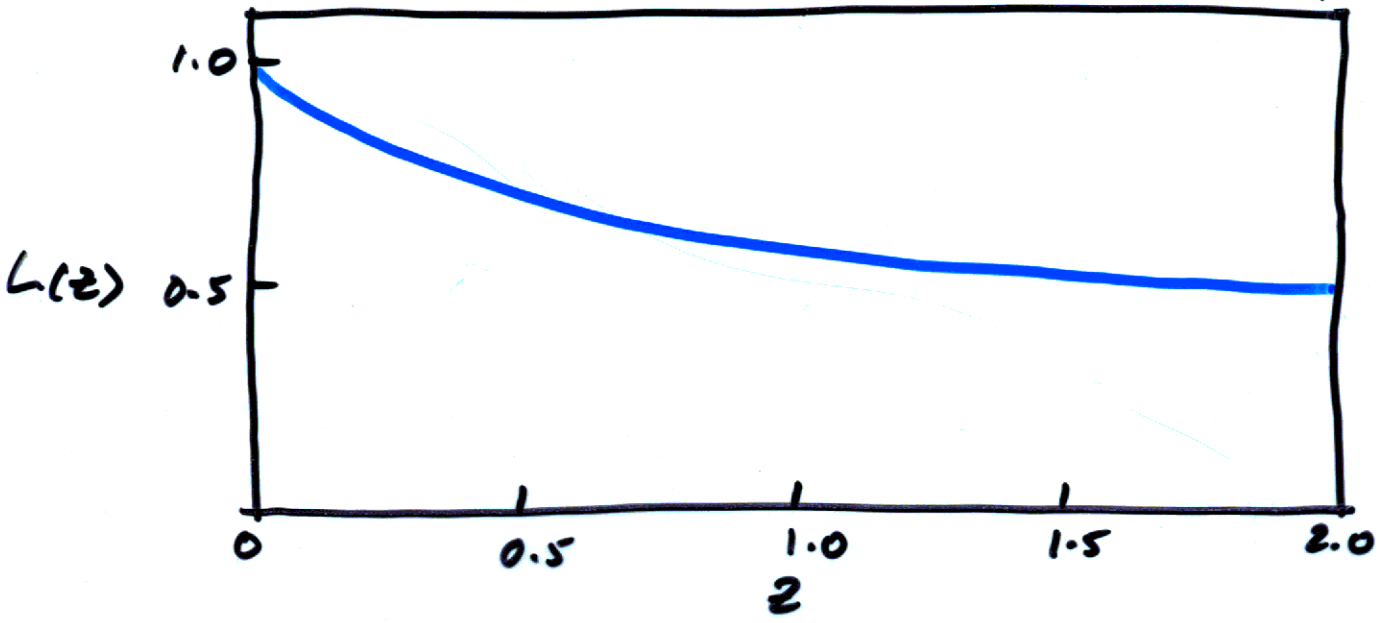
astro-ph/9805201 15 May 1998

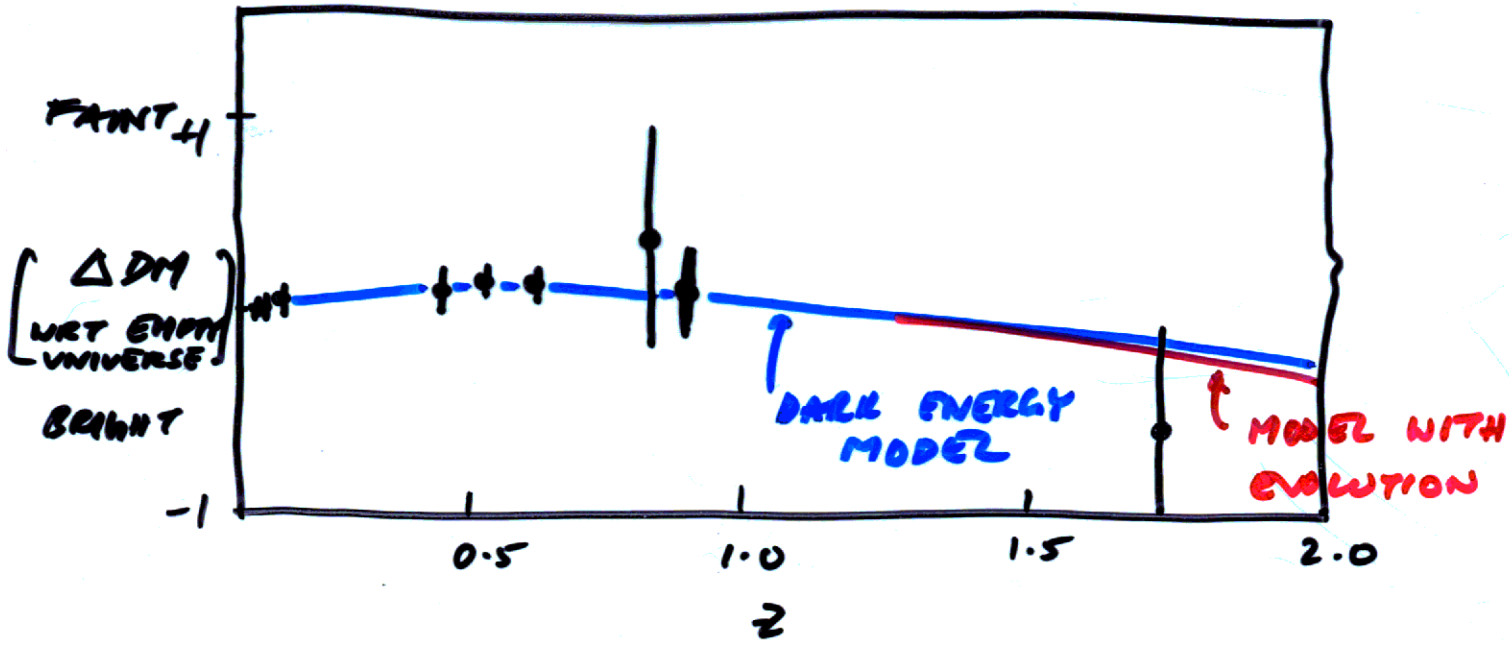


RIESS ET AL '98

SYSTEMATICS:

REQUIRED $L(z)$ TO MAKE $\Omega_M = 1$ LOOK LIKE $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$





WRIGHT 2001

BACK TO CLUSTERS

RICH CLUSTERS – LARGEST VIRIALIZED SYSTEMS IN THE UNIVERSE; TYPICAL SEPARATION $\sim 50\, h^{-1}$ Mpc. (100s – 1000s OF GALAXIES)

- OBSERVED VELOCITY DISPERSIONS:

$$500 - 1500 \text{ km/s}$$

COMBINE THIS WITH $\ell \sim 1\, h^{-1}$ Mpc

$$\Rightarrow M/L \sim 200 - 400\, h$$

$$\text{OR } \Omega_{DYN} \sim 0.15 - 0.30$$

- CLUSTERS ARE HOT:

$$T \sim 10^7 - 10^8 \text{ K} \quad \text{or} \quad 1 - 10 \text{ keV}$$

(H & He FULLY STRIPPED)

IMAGE THERMAL X-RAY FROM HOT GAS THEN INFER MASS DENSITY FROM LUMINOSITY & TEMPERATURE PROFILE.

CLUSTER BARYON FRACTION

$$\frac{\Omega_B}{\Omega_D} \gtrsim \underbrace{0.06\, h^{-1.5}}_{\text{GAS}} + \underbrace{0.02}_{\text{STARS}}$$

WITH $h \simeq 0.15$

$$\Rightarrow \frac{\Omega_B}{\Omega_D} \simeq 1.3$$

CONSISTENT WITH $\Omega_D \simeq 0.3$

ASSUMING $\Omega_B|_{BBN} \simeq 0.045$!

MANY THINGS NOT COVERED:

- LENSING → SEPARATE LECTURE
- FUTURE PROBES → SEE REFS. ON WEBSITE
- MORE STUFF ON CLUSTERS → DITTO
- CMB CONSTRAINTS → SEPARATE LECTURE
- LSS CONSTRAINTS → SEPARATE LECTURE PLUS REFS.
- NATURE OF DARK BARYONS & DARK NONBARYONS → DITTO
- NATURE OF DARK ENERGY → REFS. PLUS LECTURE (?)