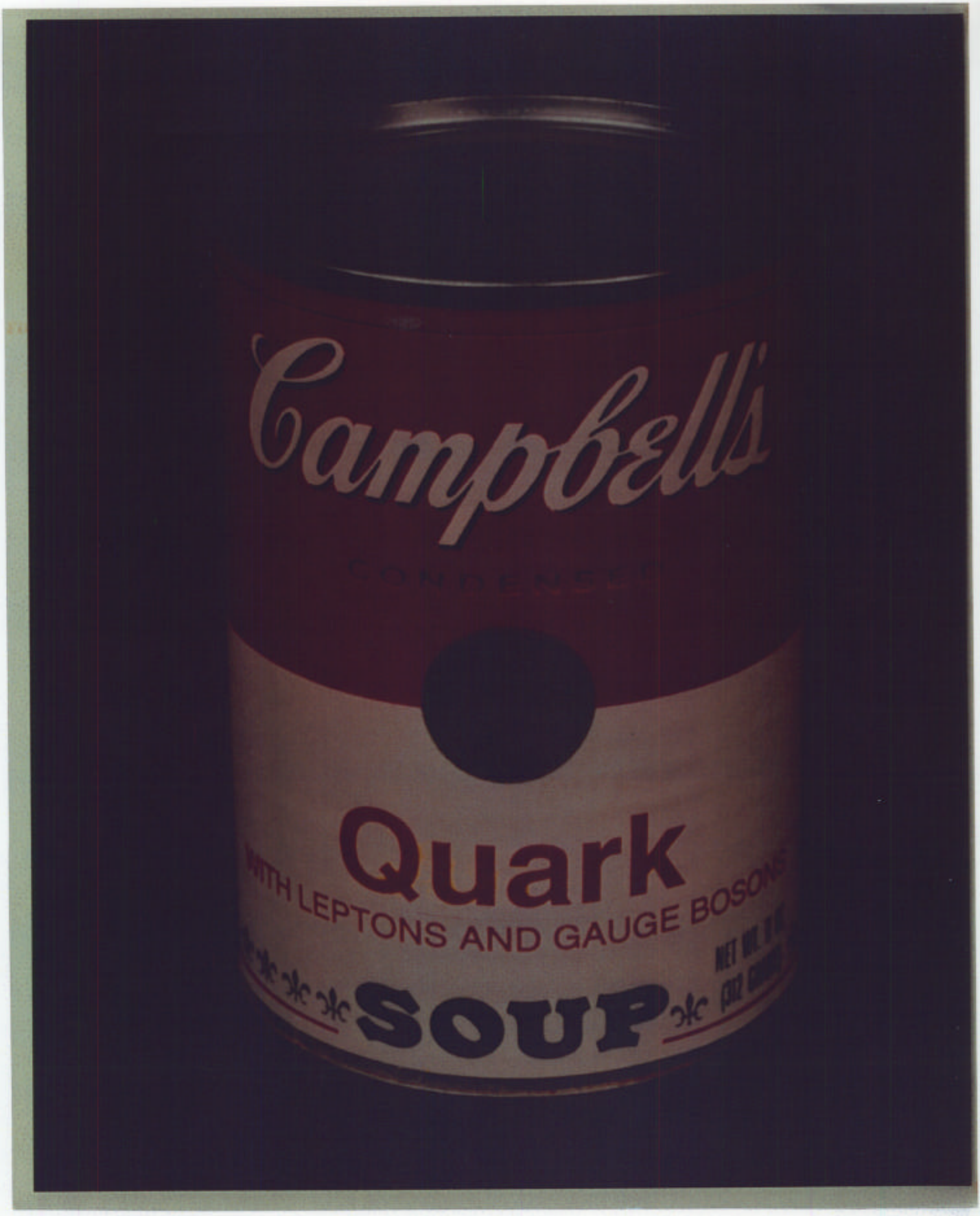
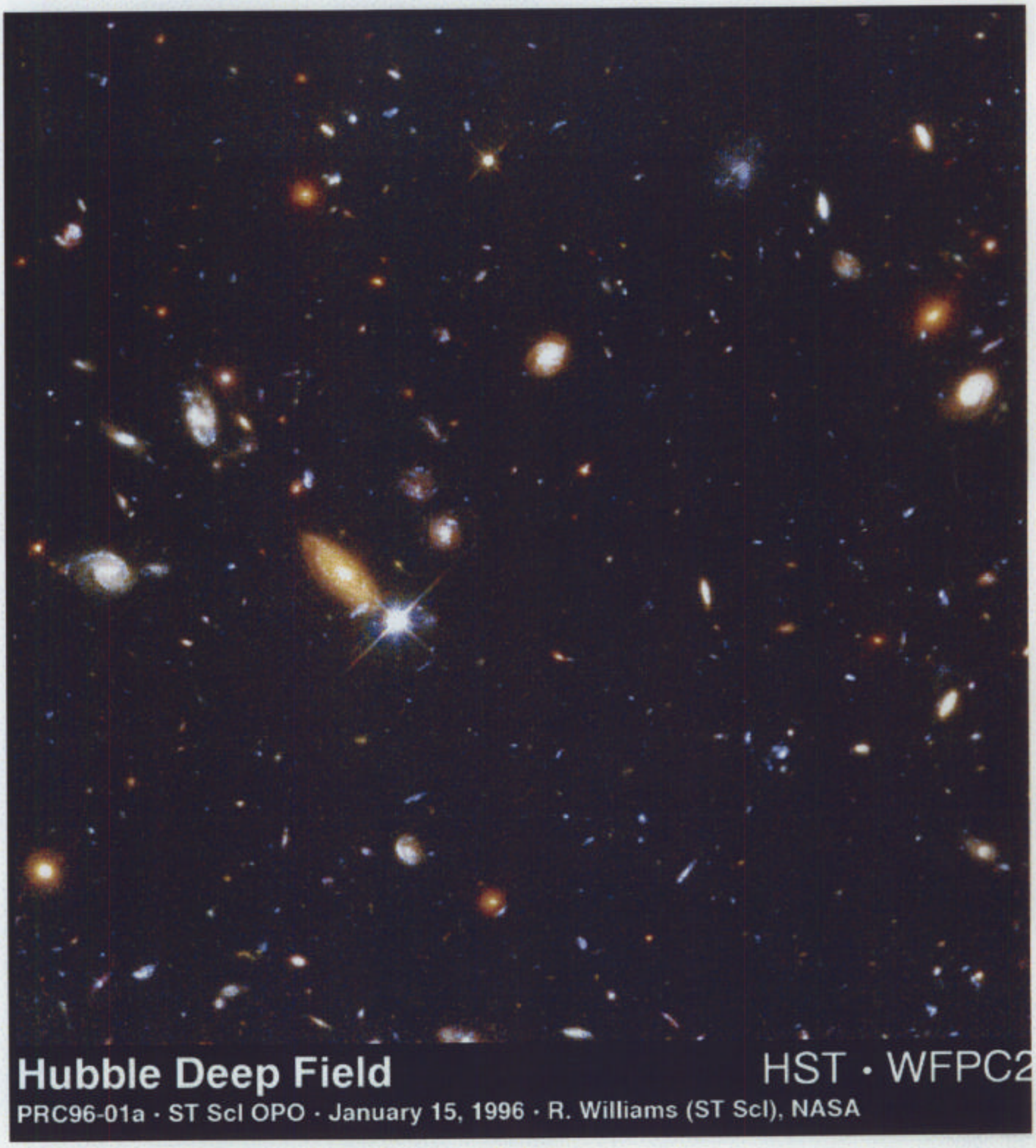
WHAT IS THE UNIVERSE MADE OF?

DARK STUFF

MYSTERIOUS

MST, Phys Rep. 333-334, 619 (2000)


Campbell's
CONDENSED
Quark
WITH LEPTONS AND GAUGE BOSONS
SOUP


Hubble Deep Field
HST · WFPC2
PRC96-01a · ST ScI OPO · January 15, 1996 · R. Williams (ST ScI), NASA

DARK SIDE of the UNIVERSE

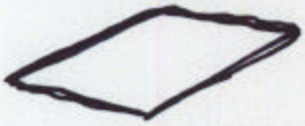
DARK MATTER HOLDS THE UNIVERSE TOGETHER.
70 YR DETECTIVE STORY
(ARREST IMMINENT?)

DARK ENERGY PUSHING UNIVERSE APART. HAVEN'T A CLUE AS TO WHAT IT IS!
STORY IS JUST BEGINNING

EINSTEIN: CURVATURE-DENSITY CONNECTION

ALWAYS TRUE

HIGH DENSITY $\Omega_0 > 1$



CRITICAL DENSITY $\Omega_0 = 1$

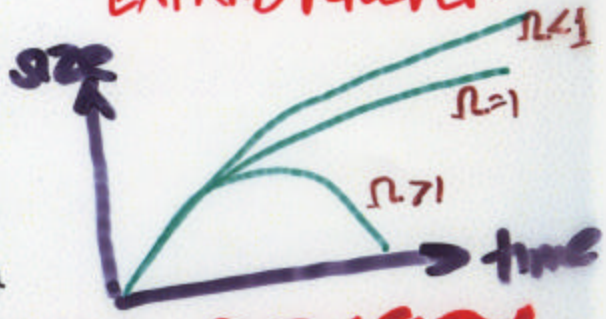
LOW DENSITY $\Omega_0 < 1$

FATE IF MATTER ONLY

RECOLLAPSE

EXPAND FOREVER (BARELY)

EXPAND FOREVER



$$\Omega_0 = \frac{\text{AVERAGE DENSITY}}{\text{CRITICAL DENSITY}}$$

$$\approx 10^{-29}\ \text{gram/cm}^3 \sim \frac{1\ \text{PROTON}}{\text{LITER}}$$

NB: $\Omega_0 = \sum_i \Omega_i$

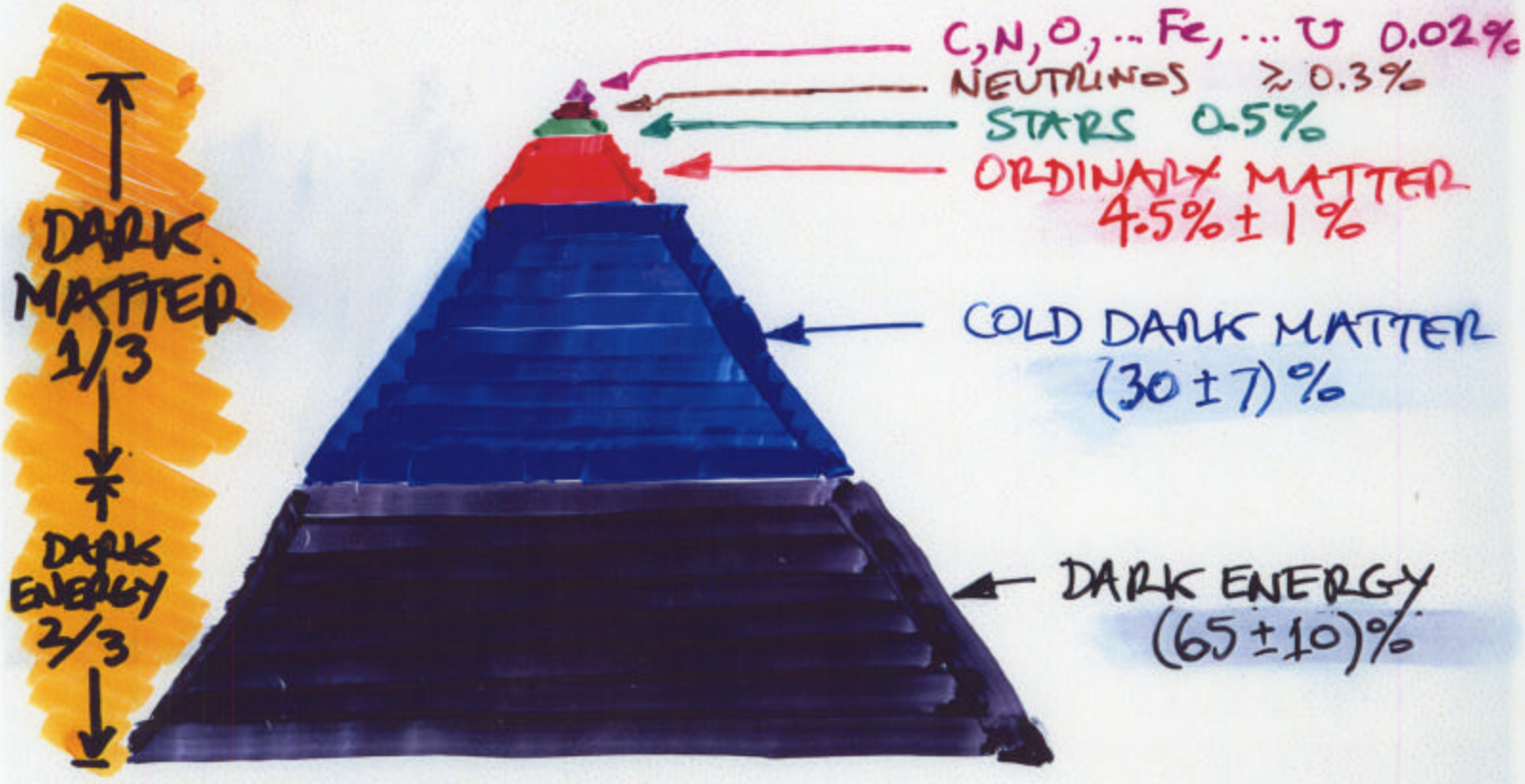
COSMIC RECIPE

FLAT UNIVERSE

→ AVERAGE DENSITY

= CRITICAL DENSITY ±6%

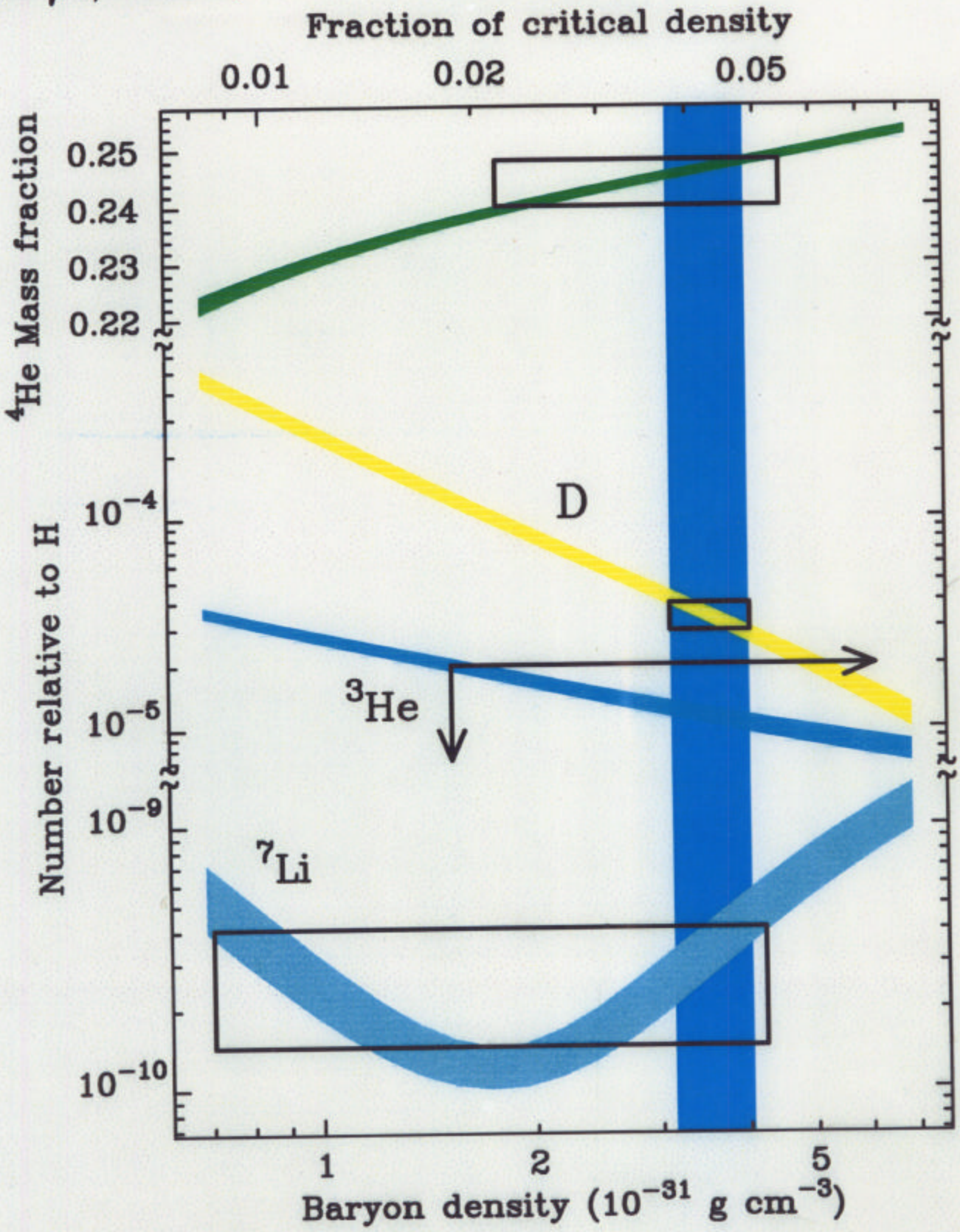
= 1/3 DARK MATTER + 2/3 DARK ENERGY



"COSMIC FOOD CHAIN"

BBN: $\Omega_B h^2 = 0.02 \pm 0.002$ (95% cl)

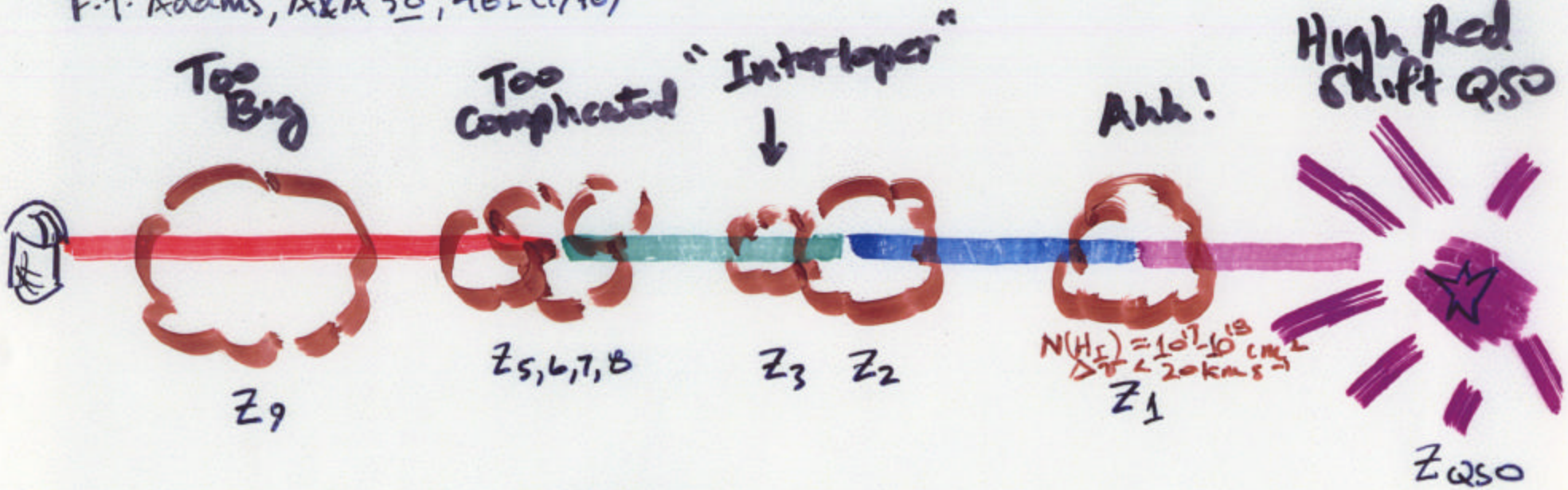
Burles-Nollett-MST, PRD
astro-ph/0008495



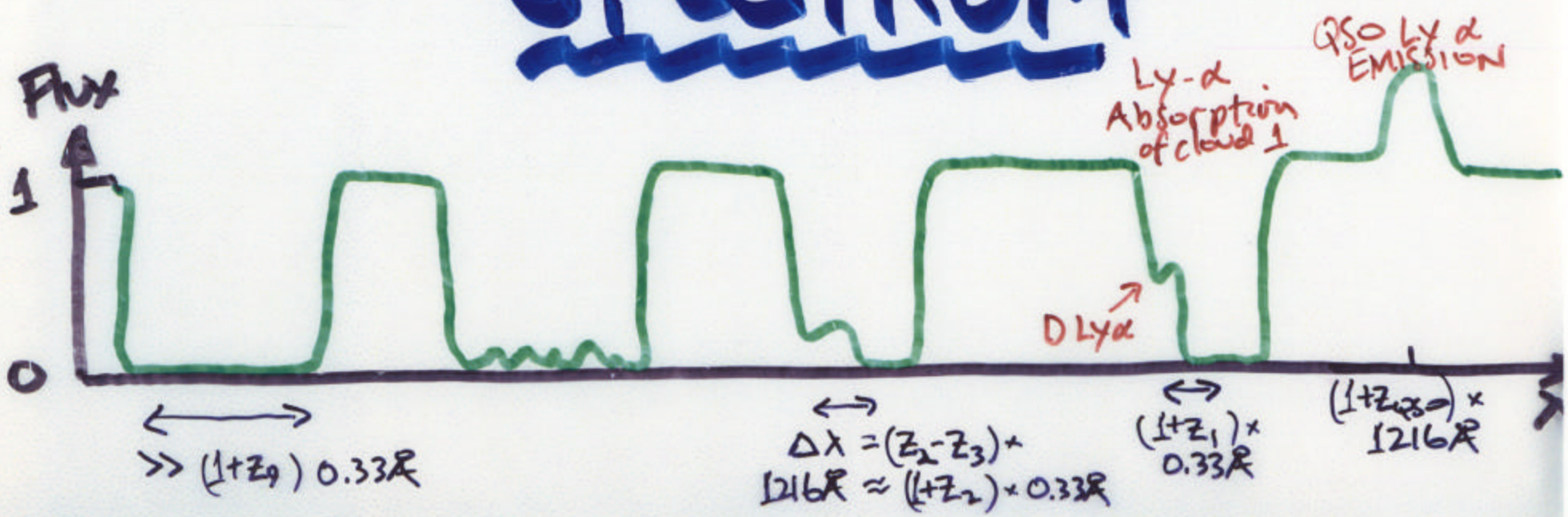
INVENTORY OF ORDINARY MATTER LATA
SIMPLER TIME

Hi z Clouds Backlit by QSO "Seen" in Absorption

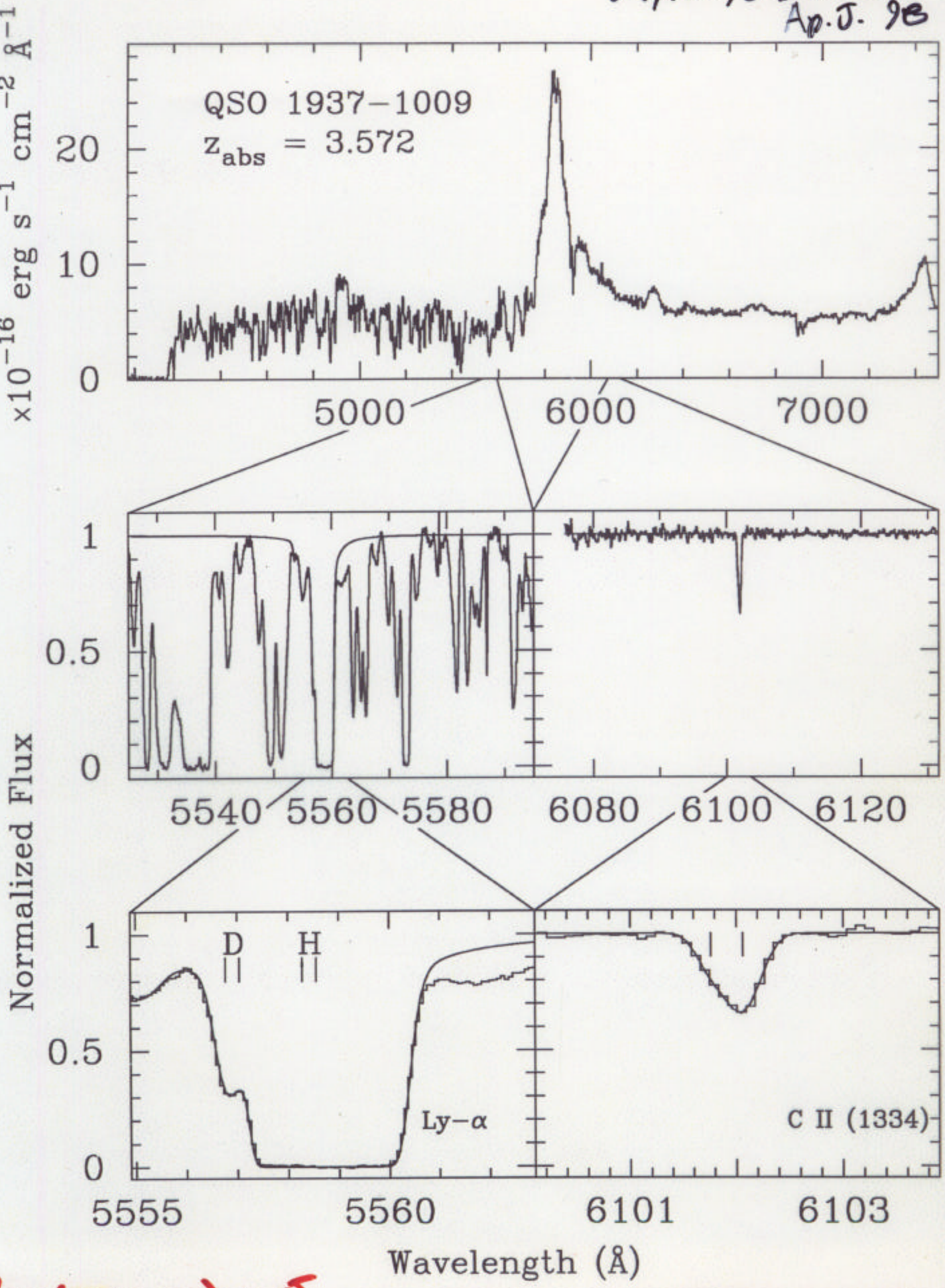
F.T. Adams, A&A 50, 461 (1976)



SPECTRUM



D. Tytler, S. Burles
Ap. J. 98

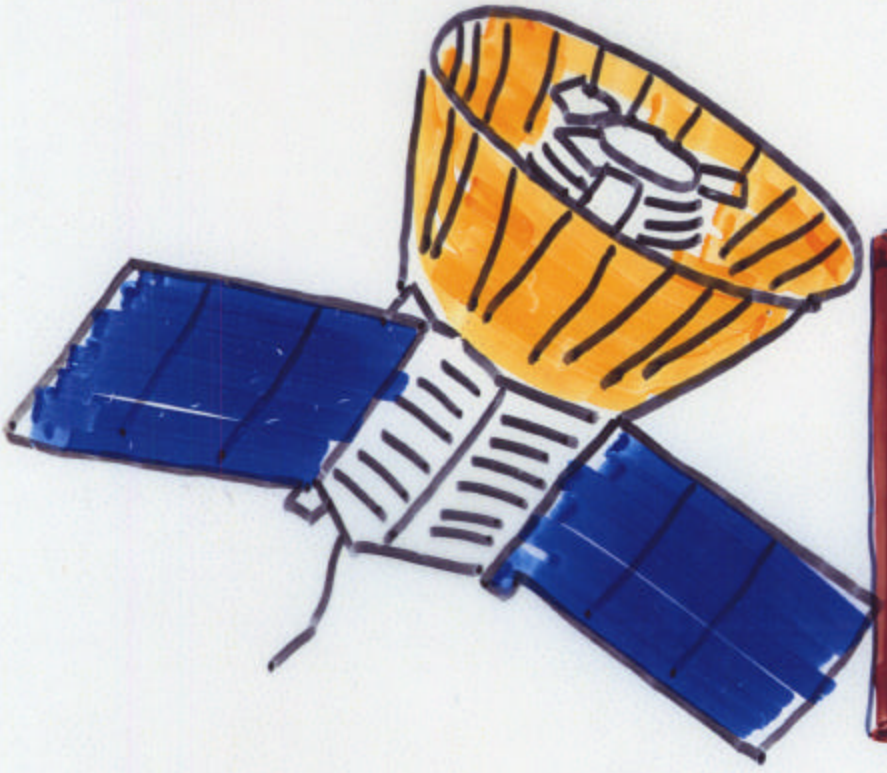


D/H = (3.4 ± 0.3) · 10^{-5}

NB: FOUR OTHER SYSTEMS SUPPORT THE CONCLUSION

COBE

23 April 1992

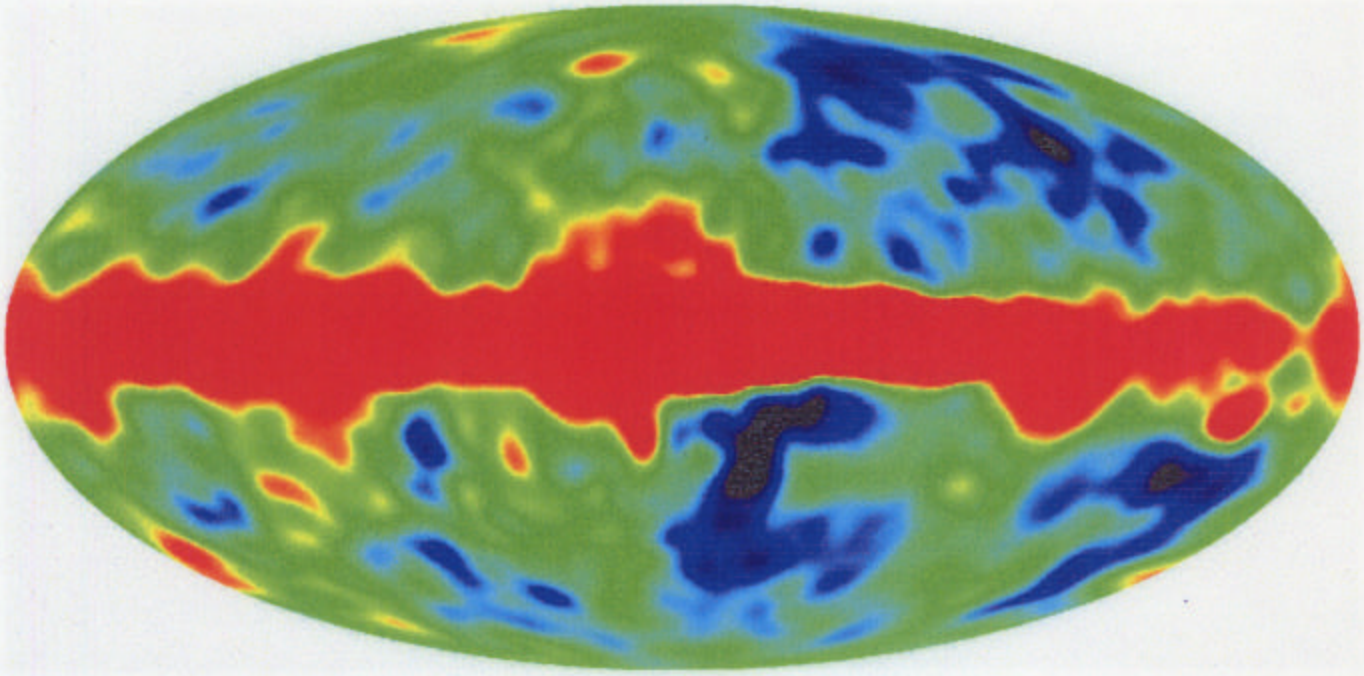


$$\frac{\delta T}{T} \approx 10^{-5}$$

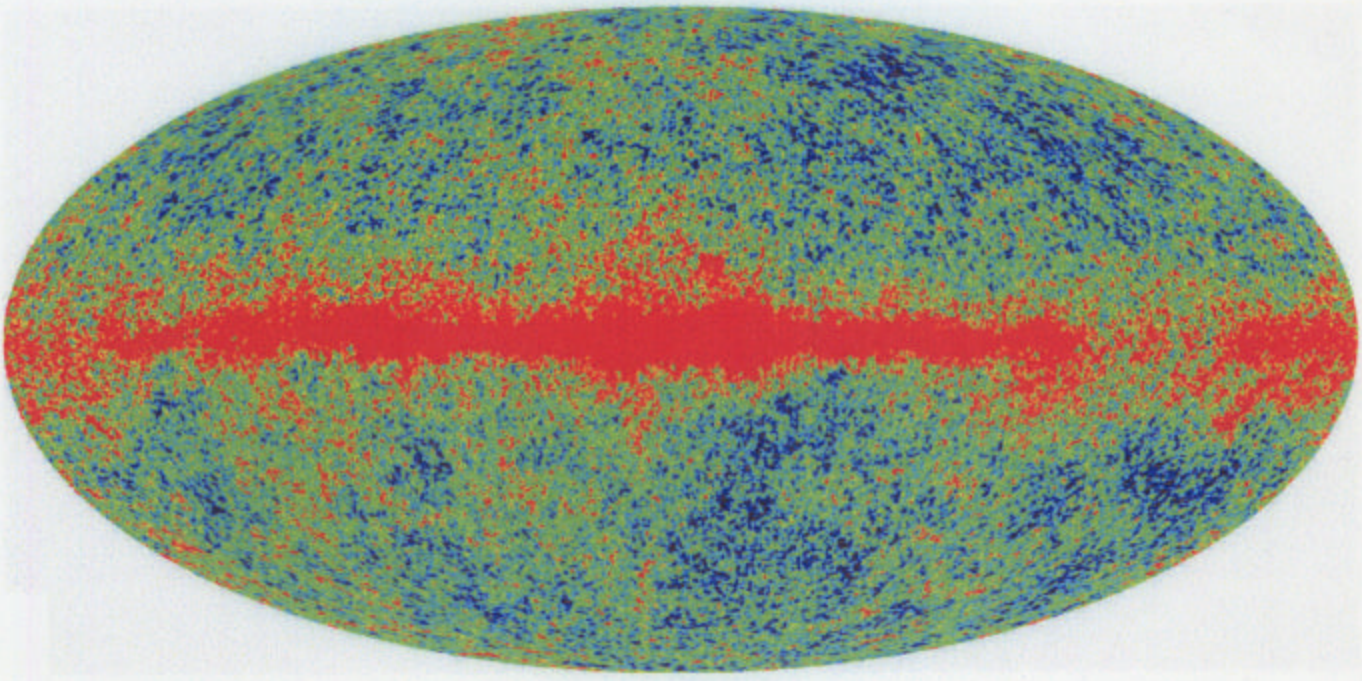
$$\theta \sim 7^\circ - 90^\circ$$

WOW!

COBE DMR 4–Year Sky Map



MAP Simulated Sky Map



CURVED SPACE

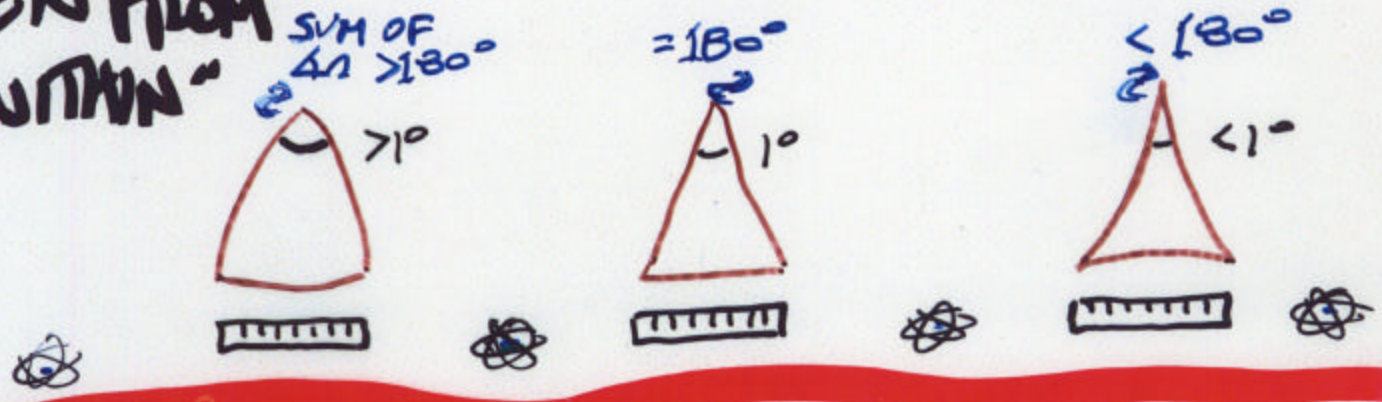
for flatlanders

"VIEW FROM ABOVE"

3d LOOKING AT 2d

CLOSED ("BALL") | FLAT ("PLANE") | OPEN ("POTATO CHIP")

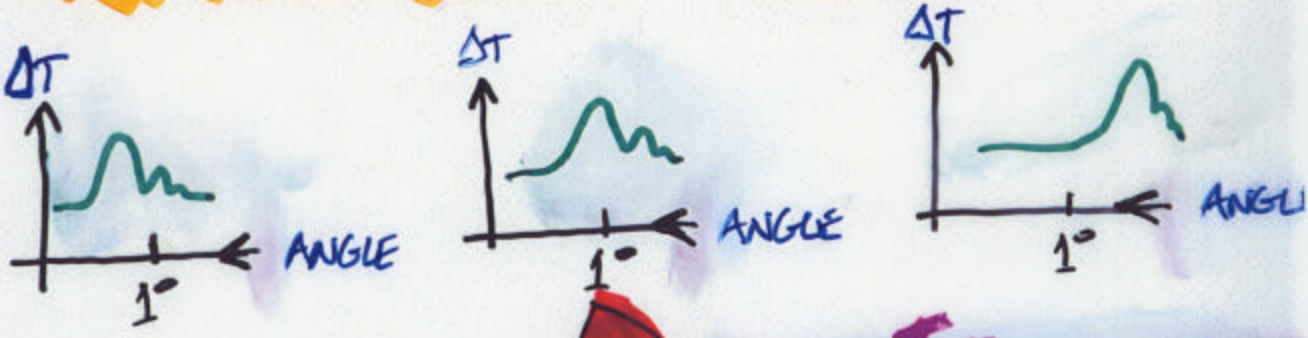
"VIEW FROM WITHIN"



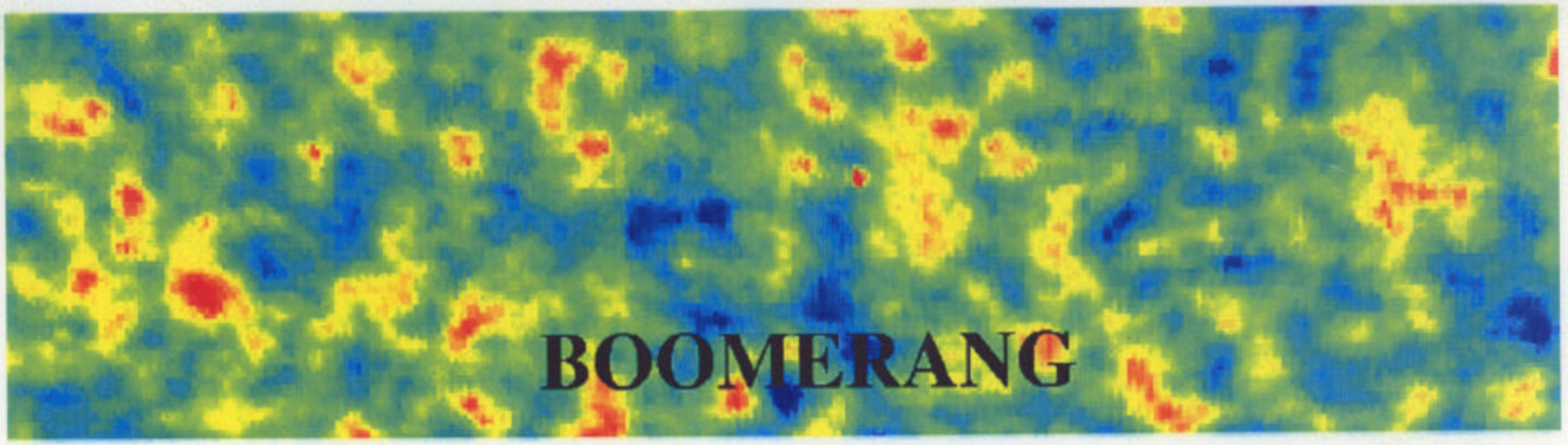
UNIVERSE at 450,000yr

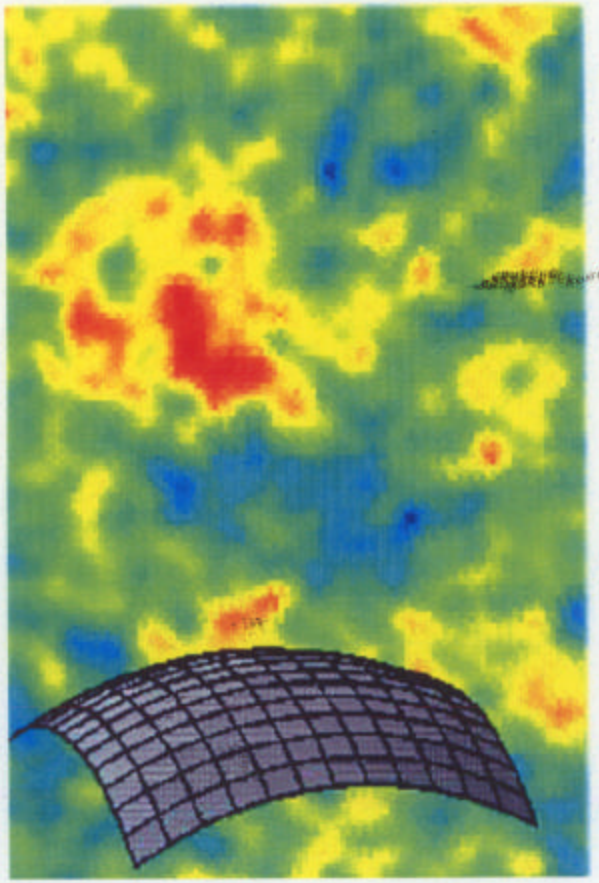
RULER: "STANDARD LUMP" OF MATTER

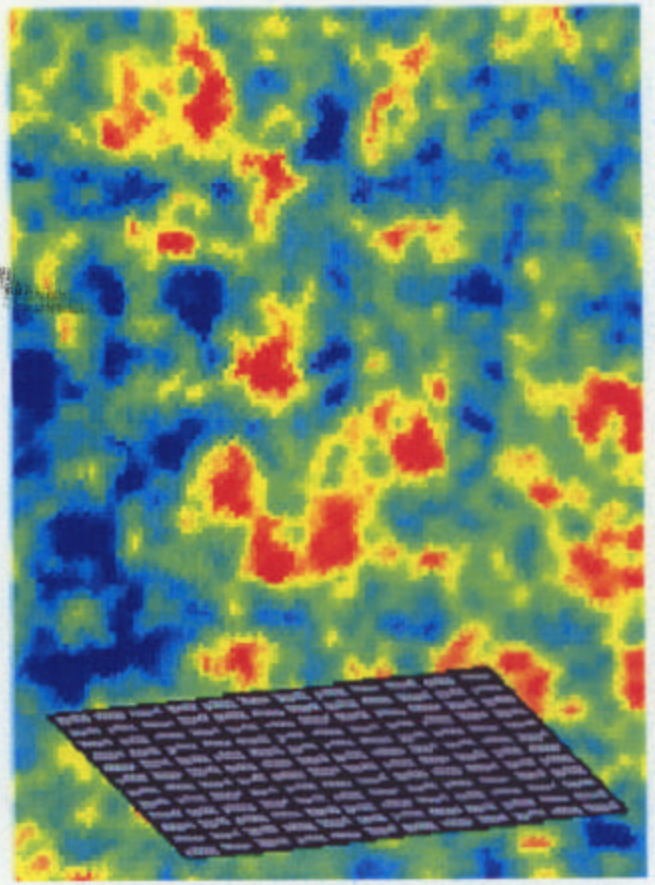
CMB

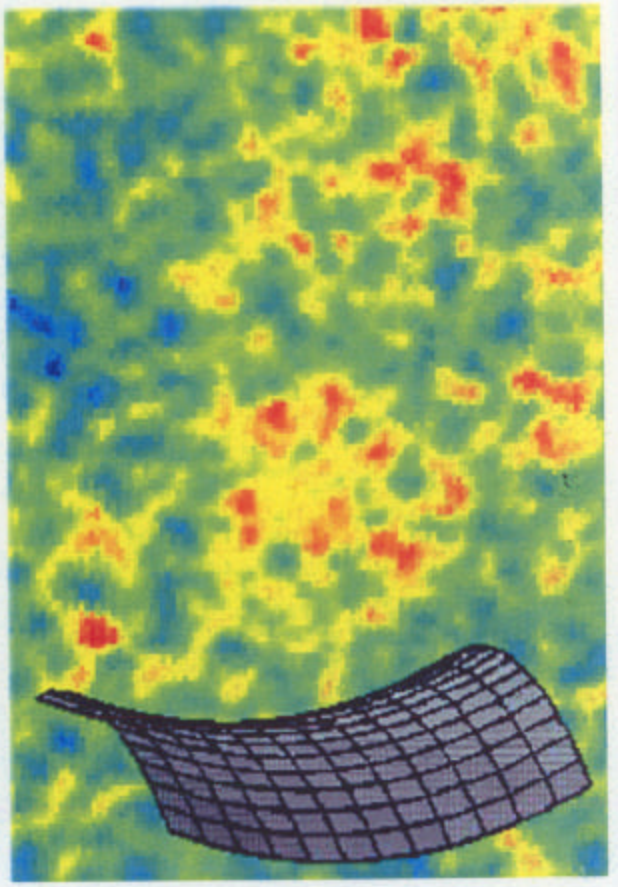


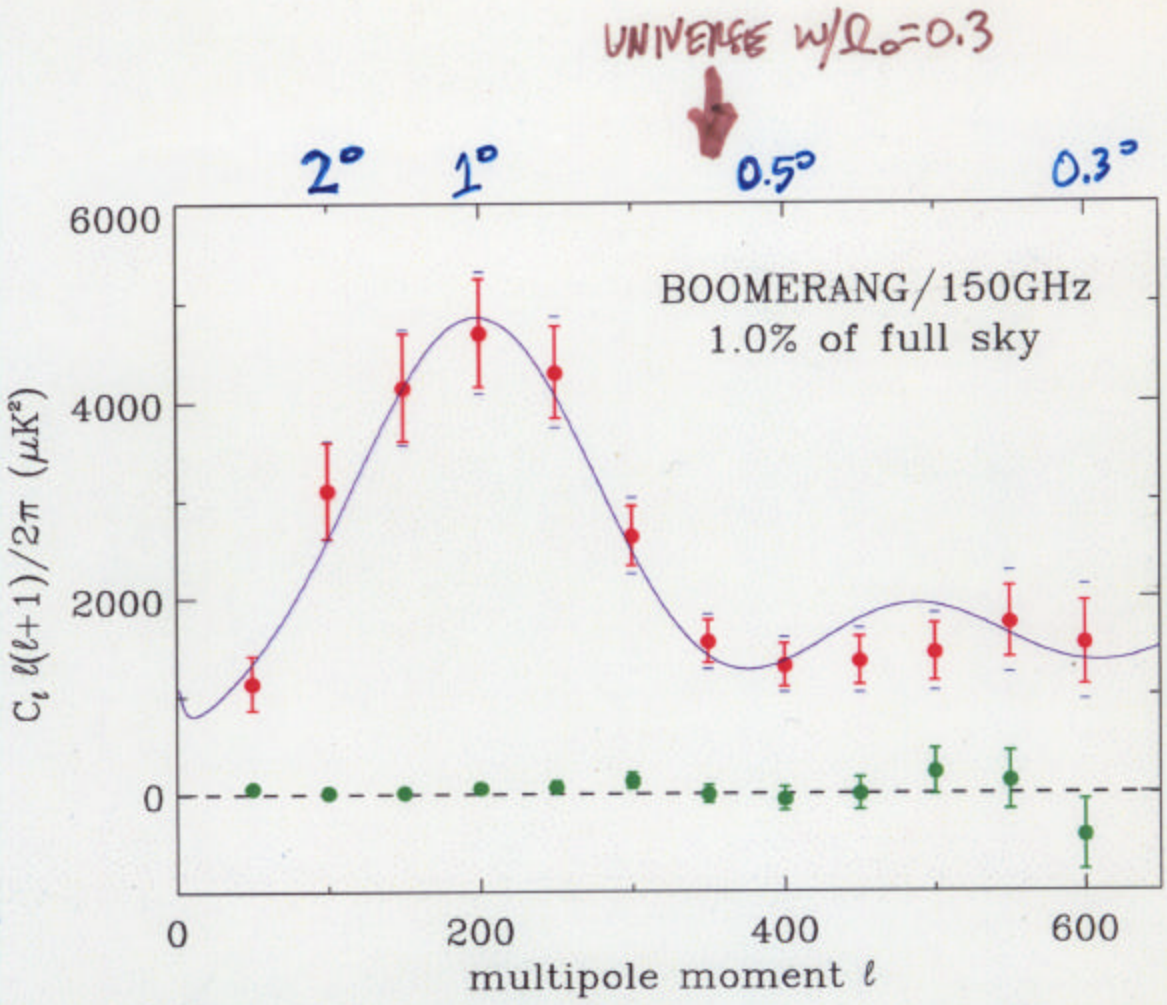
OUR UNIVERSE


BOOMERANG







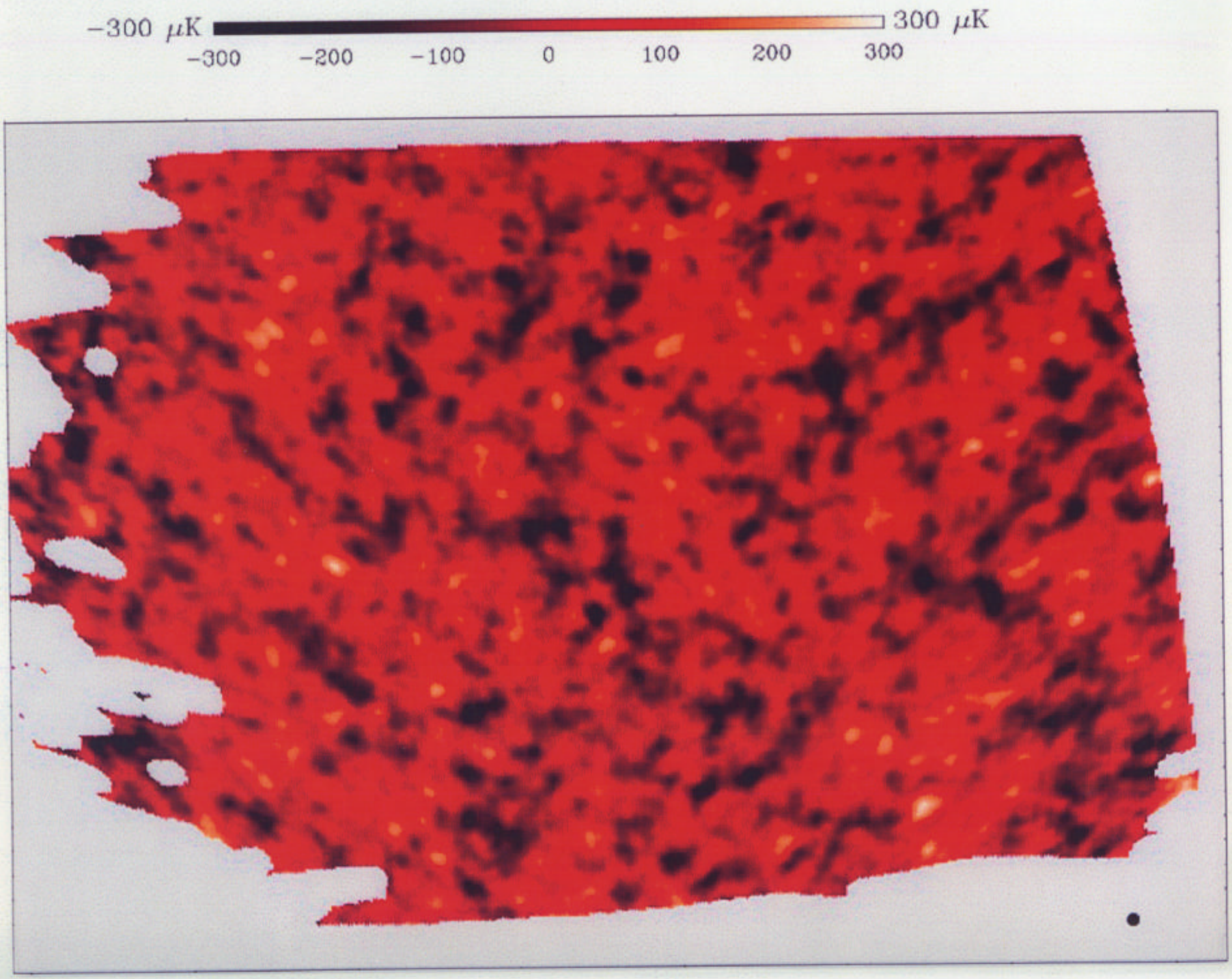


CURVE: $\Omega_0 = 1.1$

FIT: $\Omega_0 = 1 \pm 0.06$

$h = 0.99 \pm 0.06$

NB: FIT TO ACOUSTIC OSCILLATIONS
REDUCED $\chi^2 < 1$


−300 μK
300 μK
−300
−200
−100
0
100
200
300

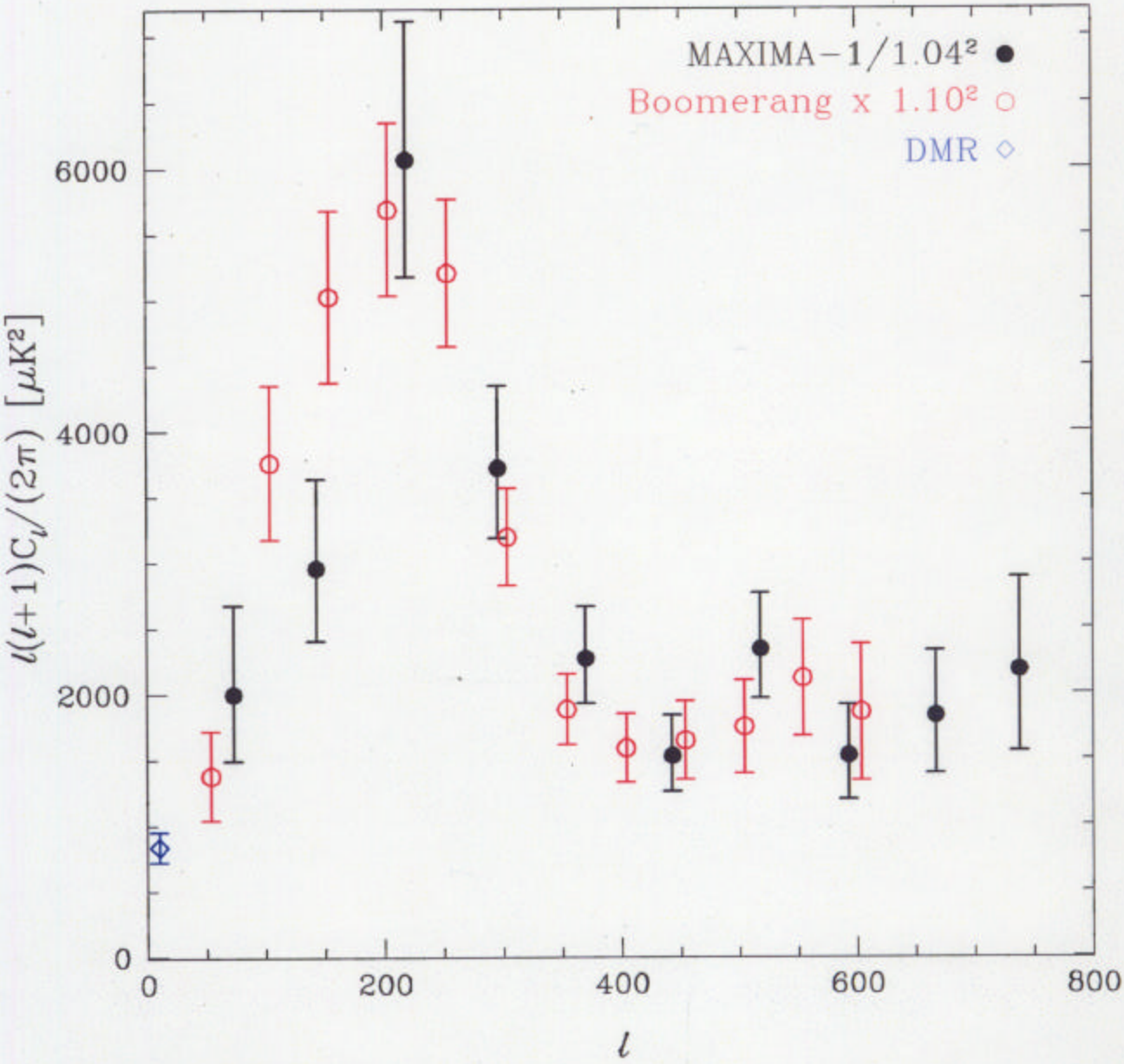


FIG. 4.— A comparison of the MAXIMA power spectrum with that of the recently reported BOOMERANG experiment (de Bernardis et al. 2000). Consistency between the power spectra has been achieved by scaling the MAXIMA-1 power spectrum down by a factor equal to its 1σ calibration uncertainty and the BOOMERANG power spectrum up by a factor equal to its 1σ calibration uncertainty (the calibration uncertainties are 4% and 10% in ΔT for MAXIMA-1 and BOOMERANG, respectively). These data show a suggestion of a peak at $\ell \sim 525$. Jaffe et al. (in preparation) give a detailed analysis of the combined MAXIMA and BOOMERANG data sets.

CONSISTENT W/BBN + NONBARYONIC DM

$\Omega_b h^2 = 0.019 \pm 0.001$

JOINT FIT:

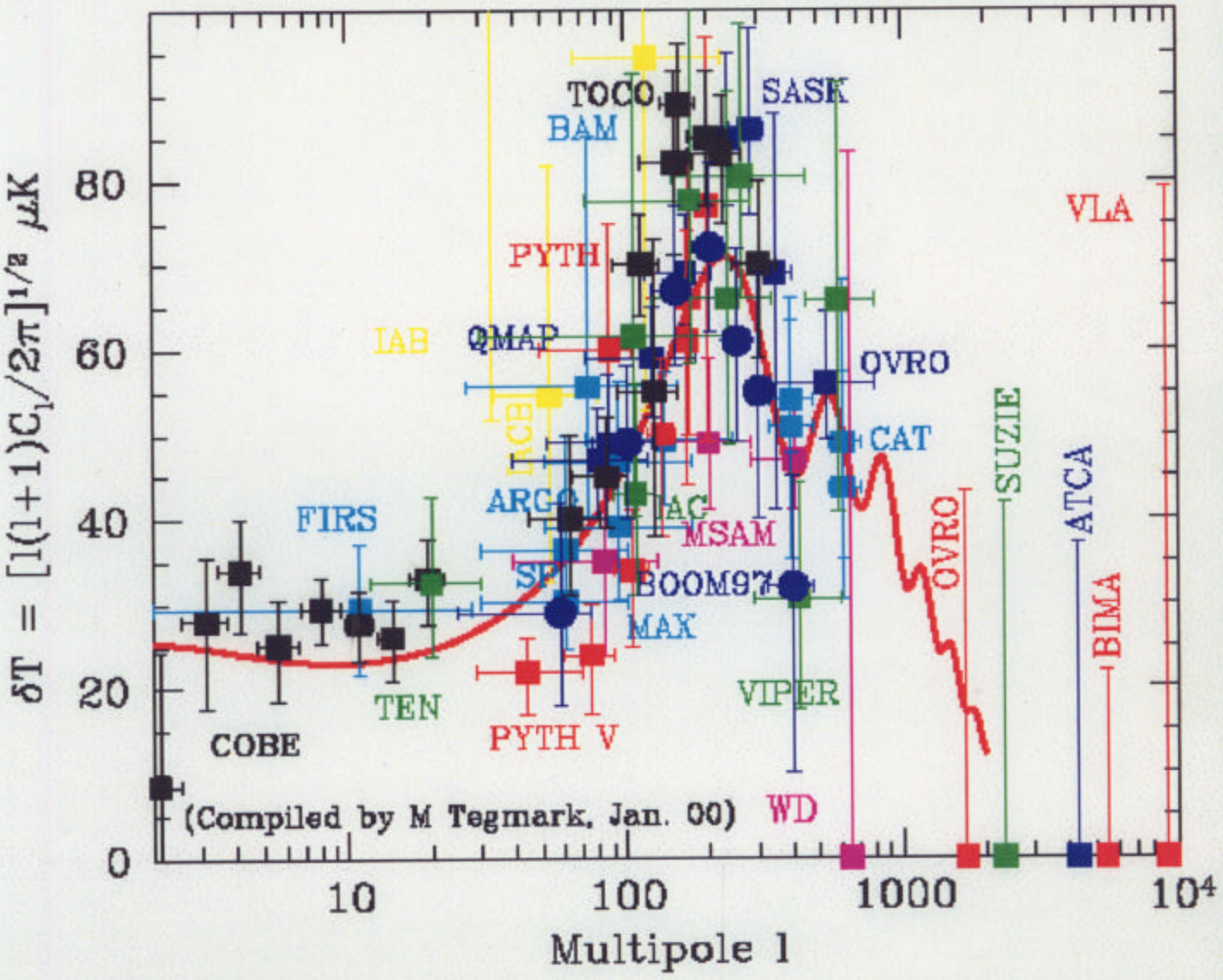
$\Omega_0 = 1.01 \pm 0.04$

$n = 0.99 \pm 0.07$

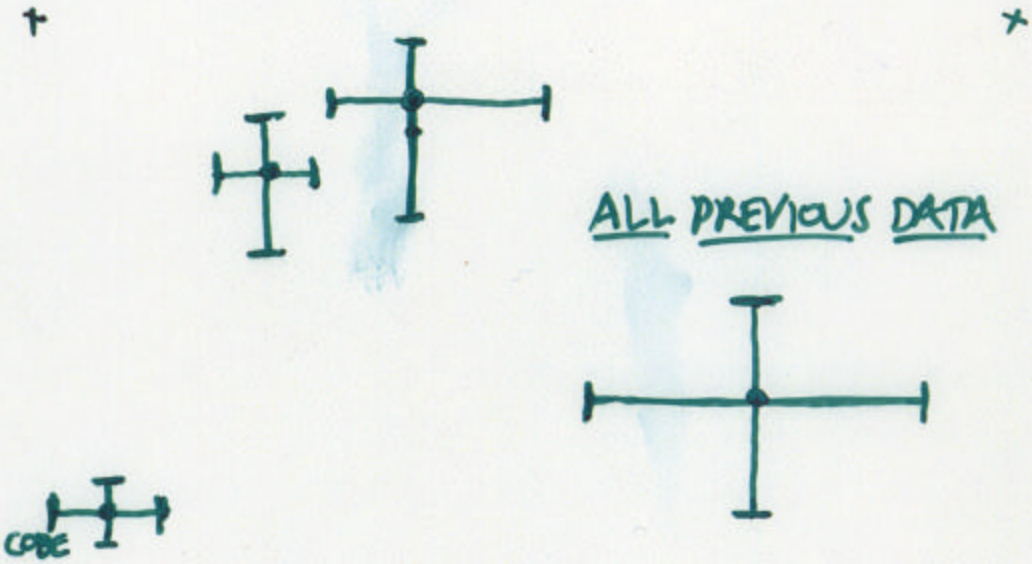
$\Omega_B h^2 = 0.03 \pm 0.005$

$\Omega_\Lambda = 0.65 \pm 0.1$

Y2K Summary of CMB Anisotropy Experiments



NB: curve is Lambda CDM


ALL PREVIOUS DATA
CODE

$\Omega_b h^2 = 0.025 \pm 0.005$ $\Omega_0 = 0.90 \pm 0.075$ $n = 0.99 \pm 0.05$
$\Omega_{CDM} h^2 = 0.13 \pm 0.05$

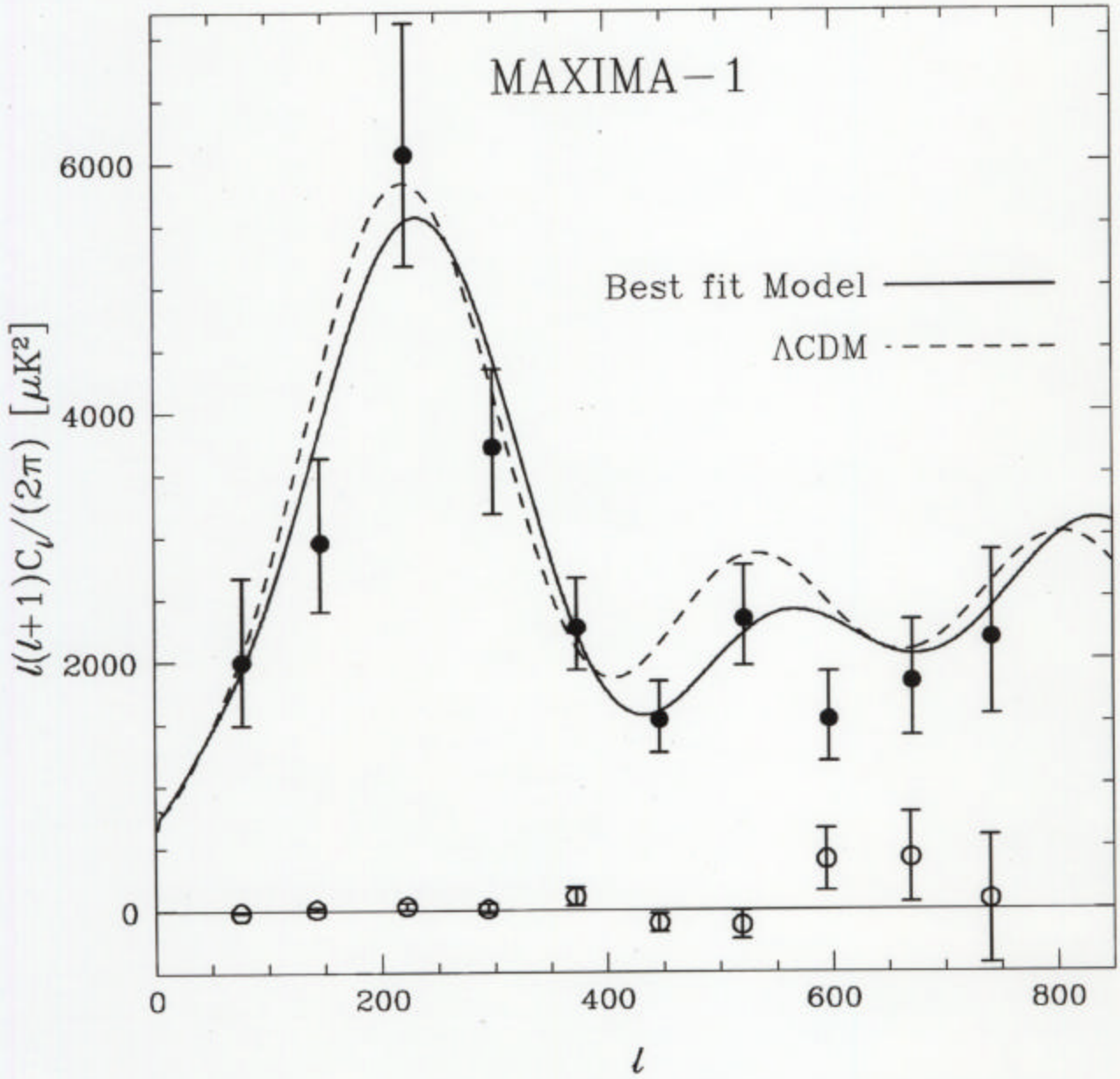
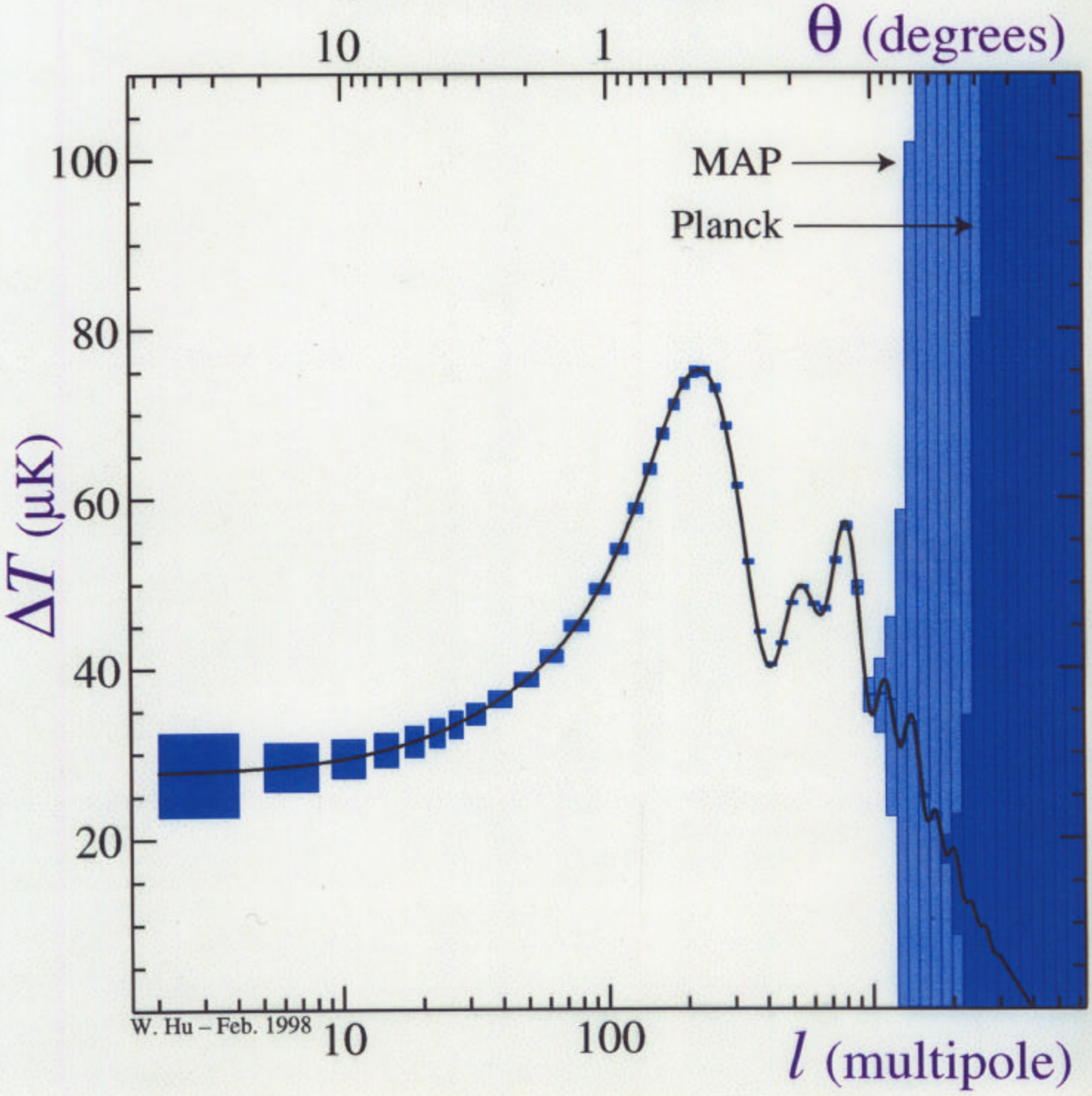


FIG. 3.— Angular power spectrum of the CMB anisotropy from the 5′-pixel MAXIMA-1 map, shown in Figure 1 (filled circles). The error bars are 68% confidence intervals calculated using the offset log-normal likelihood functions of Bond, Jaffe & Knox (2000). The solid curve is the best fit inflationary adiabatic cosmology to the MAXIMA-1 and COBE/DMR data which has (Ω_b, Ω_{cdm}, Ω_Λ, n, h) = (0.07, 0.61, 0.23, 1, 0.60), see also the companion paper by Balbi et al. (2000). The dashed curve is a ΛCDM model with (0.05, 0.35, 0.6, 1, 0.65). The open circles are the power spectrum of the difference between two independent 8′-pixel maps, each produced by a weighted-average of the maps from a pair of photometers.

Best fit: $\Omega_b h^2 = 0.024$ $\Omega_0 = 0.91$ $n = 1$ $h = 0.6$

Projected Satellite Errors



TESTING THE BBN PREDICTION FOR THE BARYON DENSITY

"SCHRAMM CHICAGO"

BBN: $\Omega_B h^2 = 0.02 \pm 0.002$ 95% cl

$\Omega_B \approx 0.04 \pm 0.008$ ($h = 0.7 \pm 0.007$)

CMB: $\Omega_B h^2 = 0.032 \begin{smallmatrix} +0.009 \\ -0.008 \end{smallmatrix}$ 95% cl

$\Omega_B \approx 0.06 \pm 0.018$

→ (1) CONFIRMS BBN PREDICTION THAT MOST OF DARK MATTER IS NONBARYONIC

(2) CONSISTENT AT "2σ" .. MORE CMB DATA ON THE WAY

"GLASS IS HALF FULL!"

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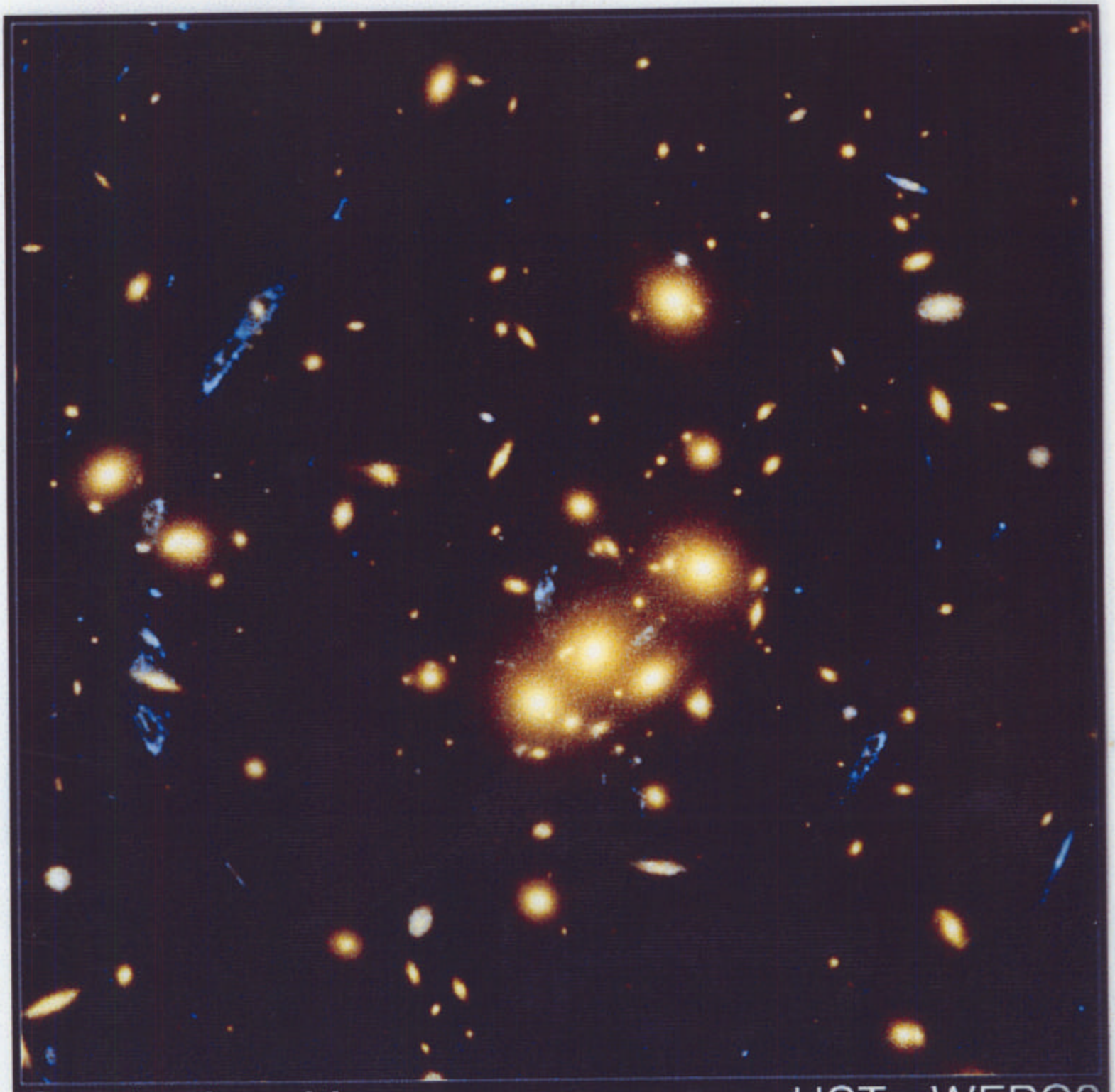
COMA CLUSTER OF GALAXIES
(KITT PEAK)

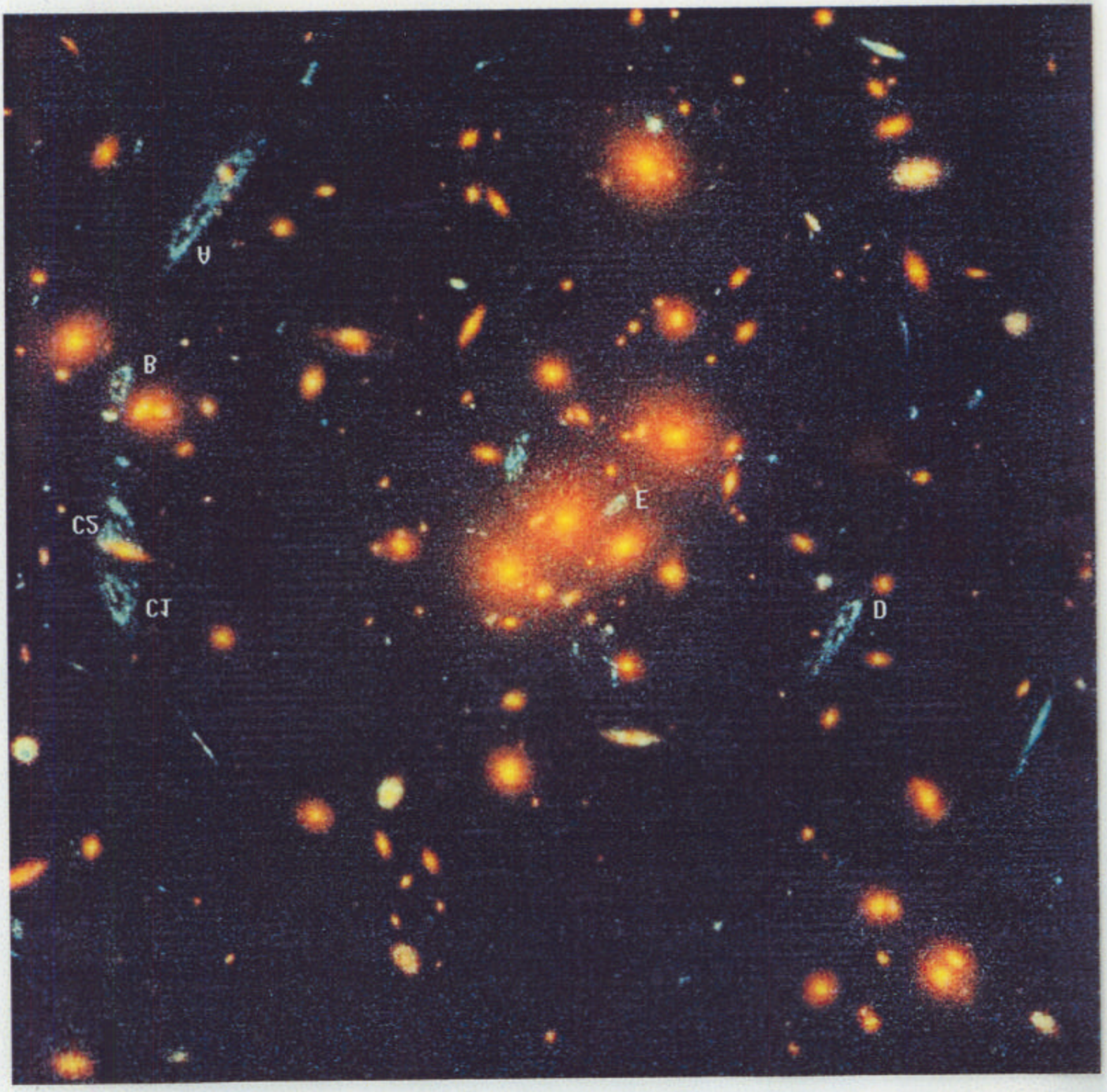


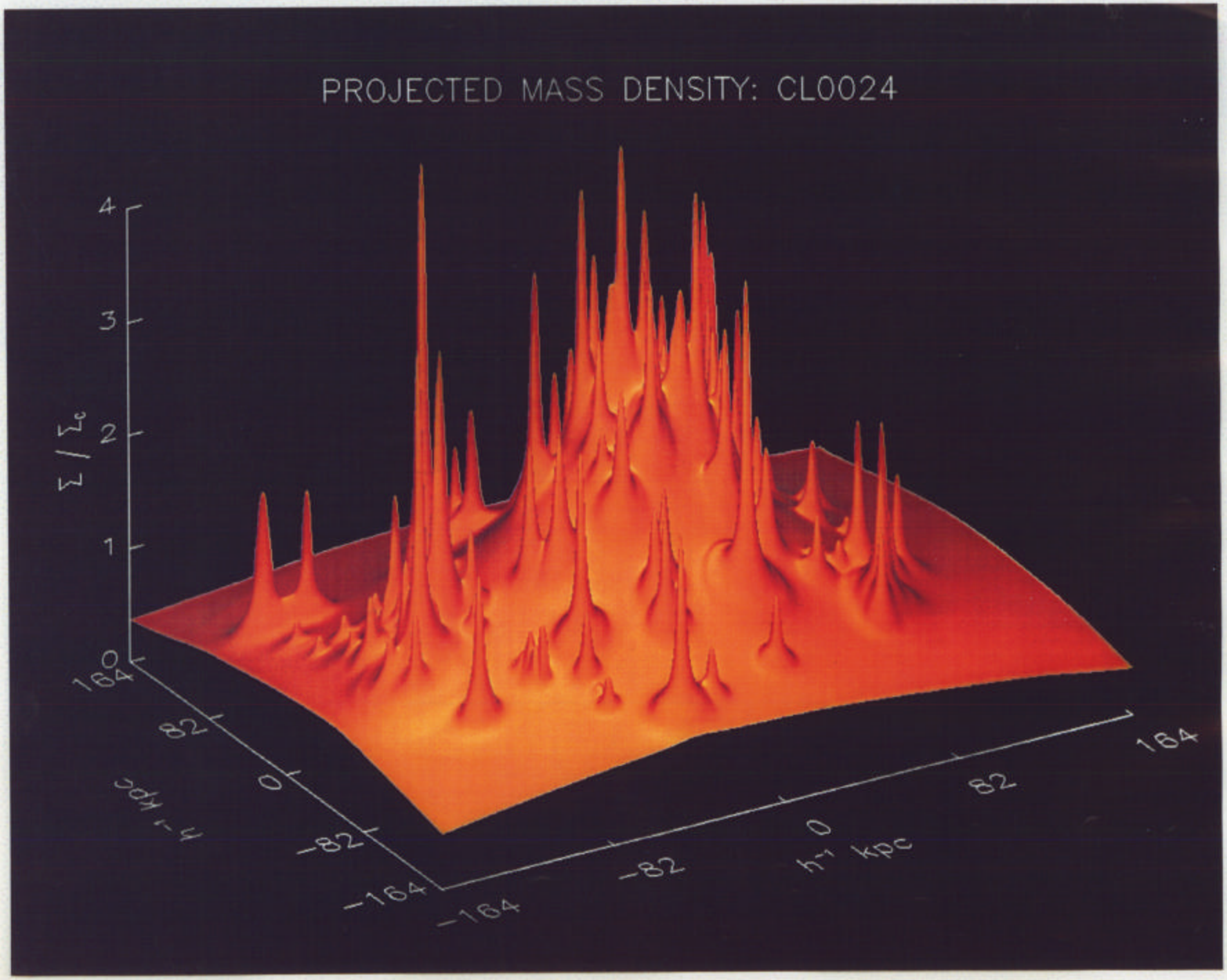
Gravitational Lens Galaxy Cluster 0024+1654

HST · WFPC2

PRC96-10 · ST ScI OPO · April 24, 1996

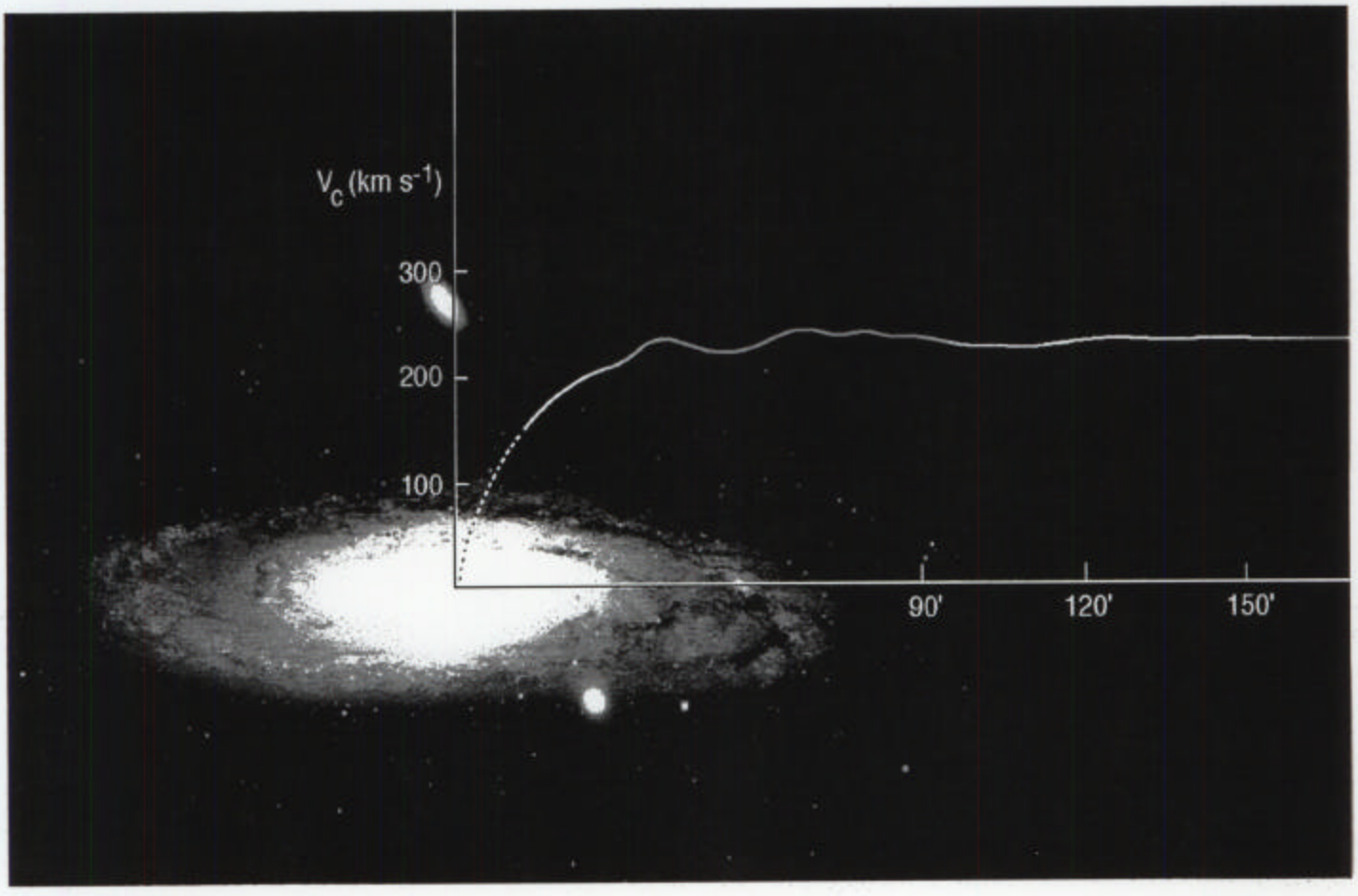
W.N. Colley (Princeton University), E. Turner (Princeton University),
J.A. Tyson (AT&T Bell Labs) and NASA


U
B
CS
CT
E
D


PROJECTED MASS DENSITY: CL0024
Σ / Σ₀
4
3
2
1
0
164
82
0
-82
-164
h⁻¹ kpc
-164
-82
0
82
164
h⁻¹ kpc

Flat Rotation Curves: The Light Ends, but the Effect of Gravity Continues ... (hence, DARK MATTER)

Our Neighbor, The Andromeda Galaxy



-- Courtesy of M. Roberts

CLUSTER BARYON FRACTION + Ω_B ➡ Ω_M

MOST BARYONS ARE IN THE HOT X-RAY EMITTING GAS

White et al, Nature 366, 429 (93)

FAIR SAMPLE HYPOTHESIS:

$$\frac{\Omega_B}{\Omega_M} = \frac{M_{BARYON}}{M_{TOT}}$$

X-ray Flux, S-Z

X-ray temp, Grav. Lensing, Virial Thm

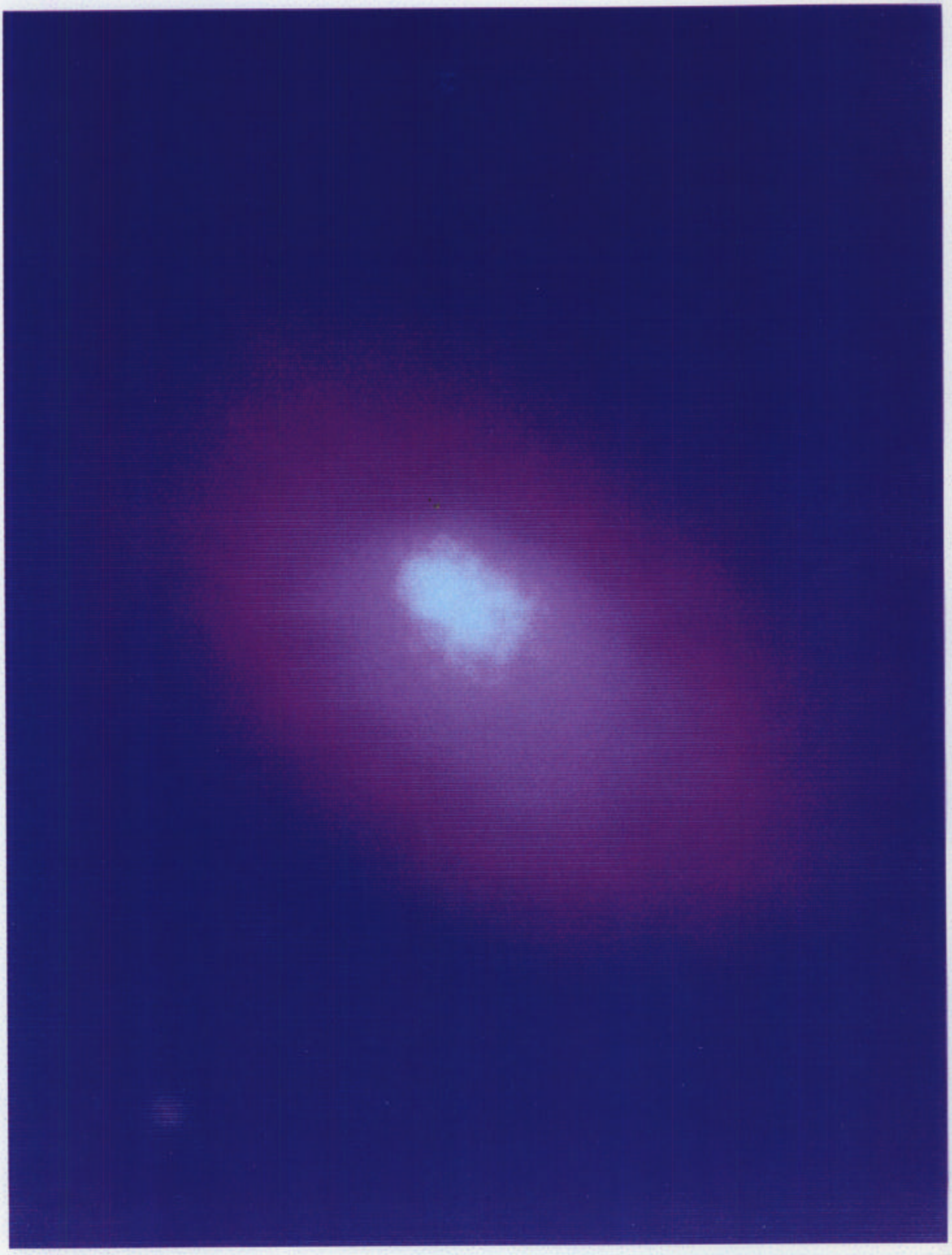
BBN: $(0.02 \pm 0.002)h^{-2}$

Evrard '97

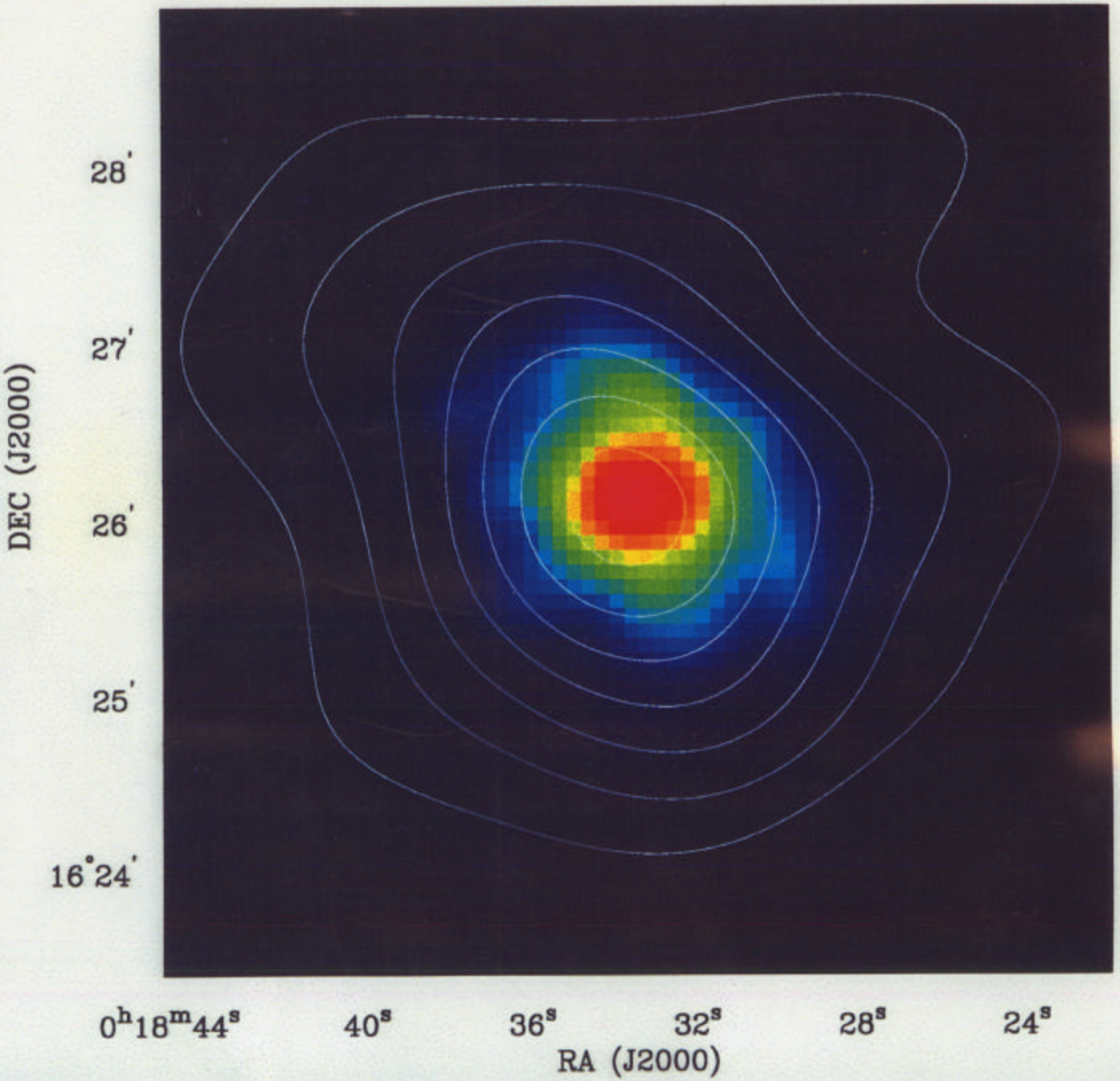
$$\langle M_{GAS}/M_{TOT} \rangle = (0.07 \pm 0.007)h^{-3/2}, \quad (0.06 \pm 0.006)h^{-1}$$

Carlstrom '98 S-Z

$$\Omega_M = (0.3 \pm 0.05)h^{-1/2} \doteq 0.35 \pm 0.07$$



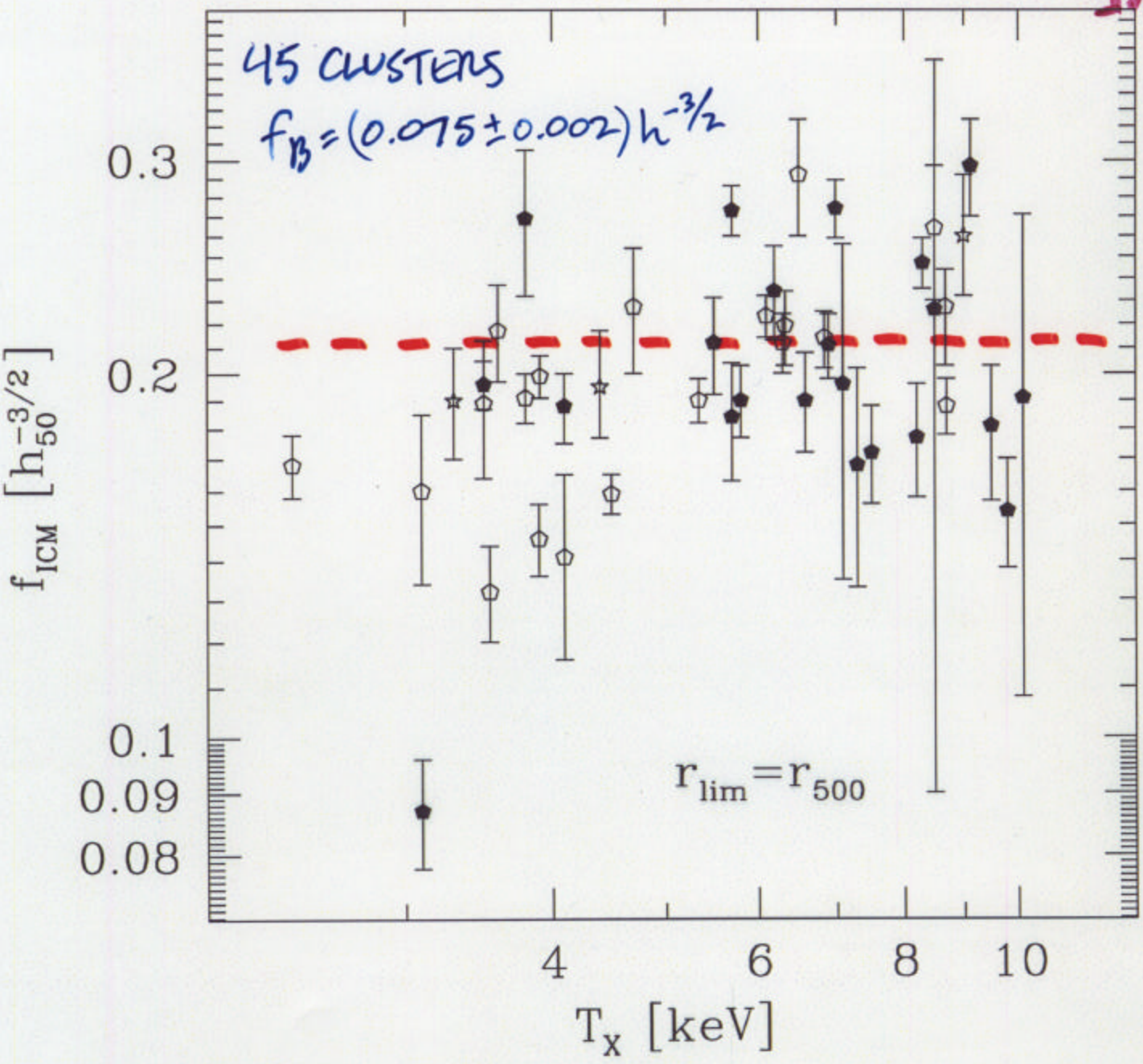
Carlstrom, Grego, Joy etal



+26
+more to come!

CLUSTER BARYON FRACTION

J. Mohr, Mathiesen, Evrard 1998



CENSUS 2000

SAMPLING OR COUNTING

CLUSTER INVENTORY

+ USE CLUSTERS AS "FAIR SAMPLE" OF MATTER IN UNIVERSE
- CLUSTERS THEMSELVES ACCOUNT FOR ~5% OF THE MATTER

$$\Omega_M = 0.35 \pm 0.07$$

EG- MST, PhysRept 333-334, 619 (2000)

DIRECT COUNT

+ COUNT MASS ASSOCIATED W/BRIGHT GALAXIES
- UNDERCOUNT FAINT GALAXIES?

$$\rho_M = \langle M/L \rangle \cdot \mathcal{L}$$

SDSS: weak lensing 28,000+ galaxies ±few %, 5 bands

SDSS PRELIM: $\Omega_M \approx 0.3 \pm$

P. Fischer et al AJ 120, 1198 (2000)

GALAXY HALOS ARE MILLION LIGHT YEARS IN EXTENT

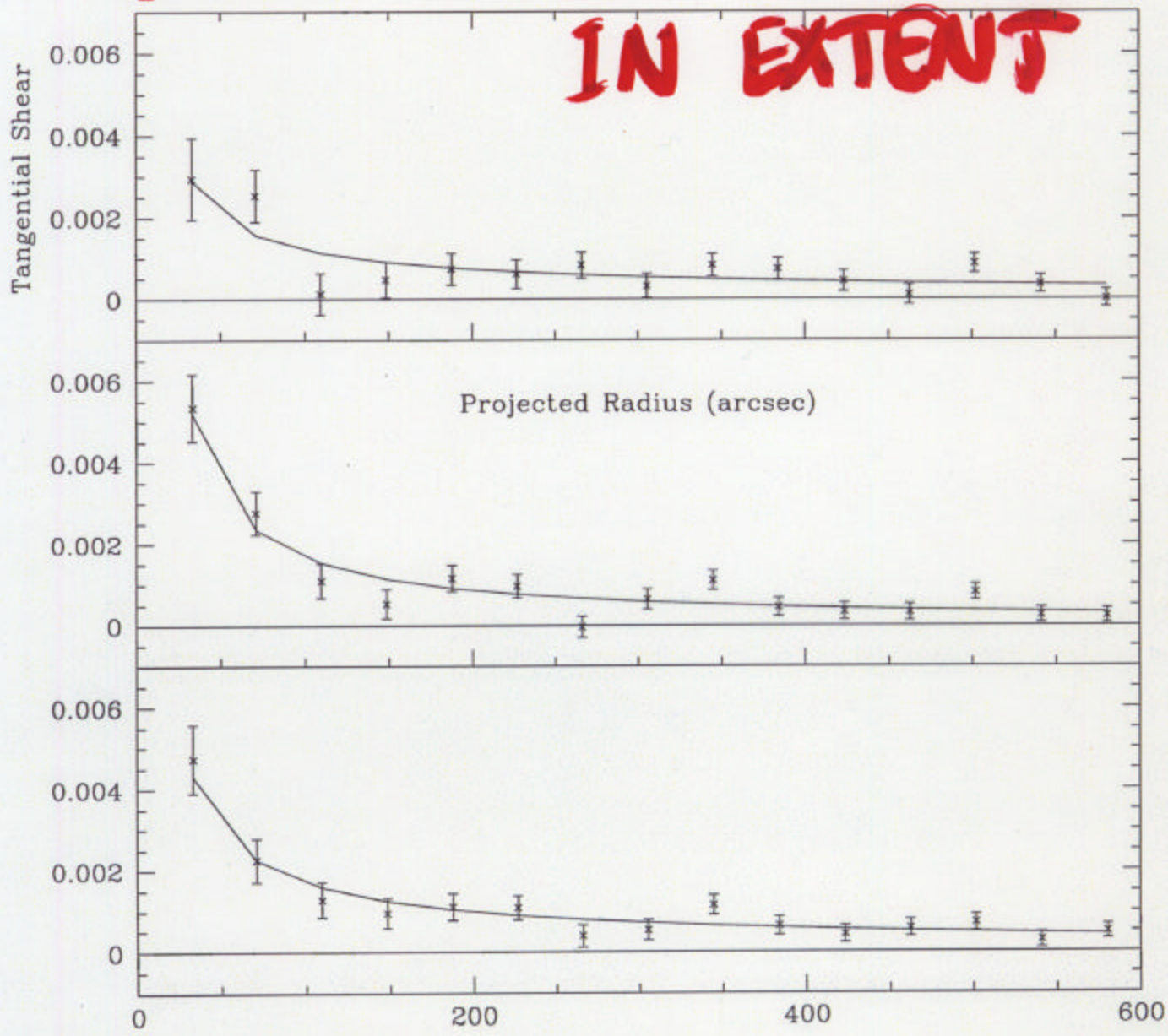


Fig. 2.— Mean shear around foreground galaxies measured from the g, $r'$and i images (top, middle, bottom). The foreground galaxies have $16 \leq r_0^* \leq 18$ and the background galaxies have $18 \leq r_0^* \leq 22$. See Table 1 for details. The solid lines are the best fit power-law models with parameters given in Table 2

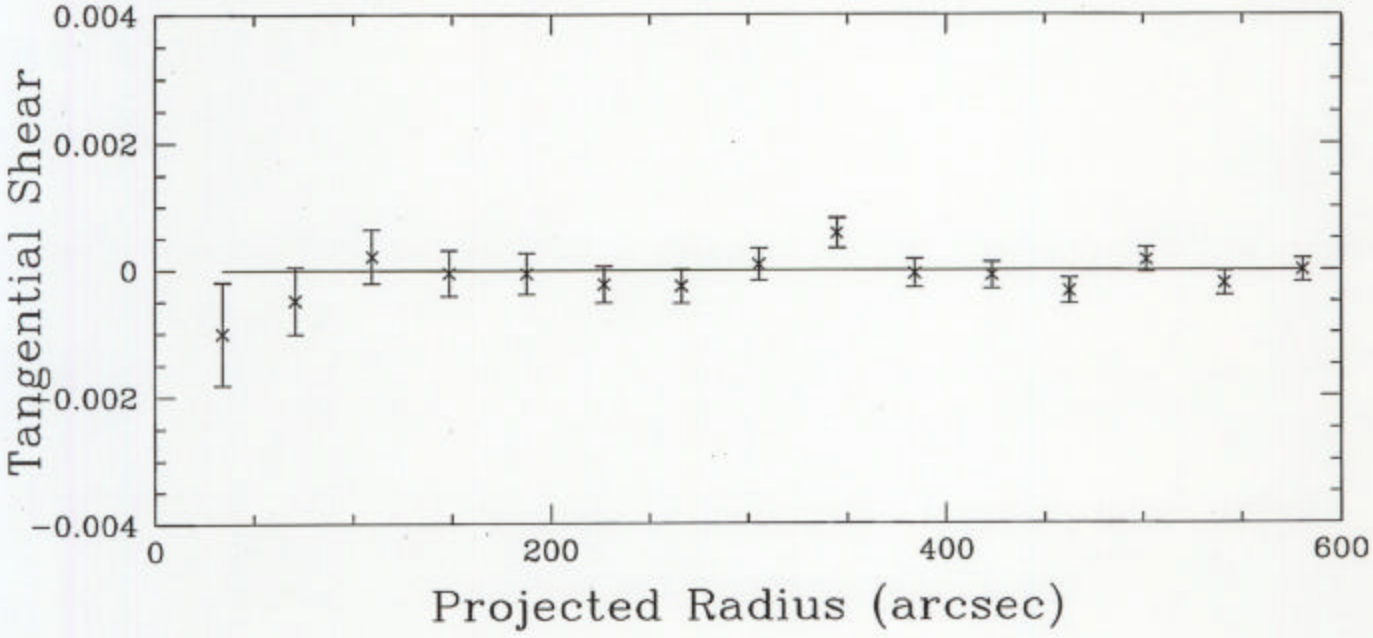
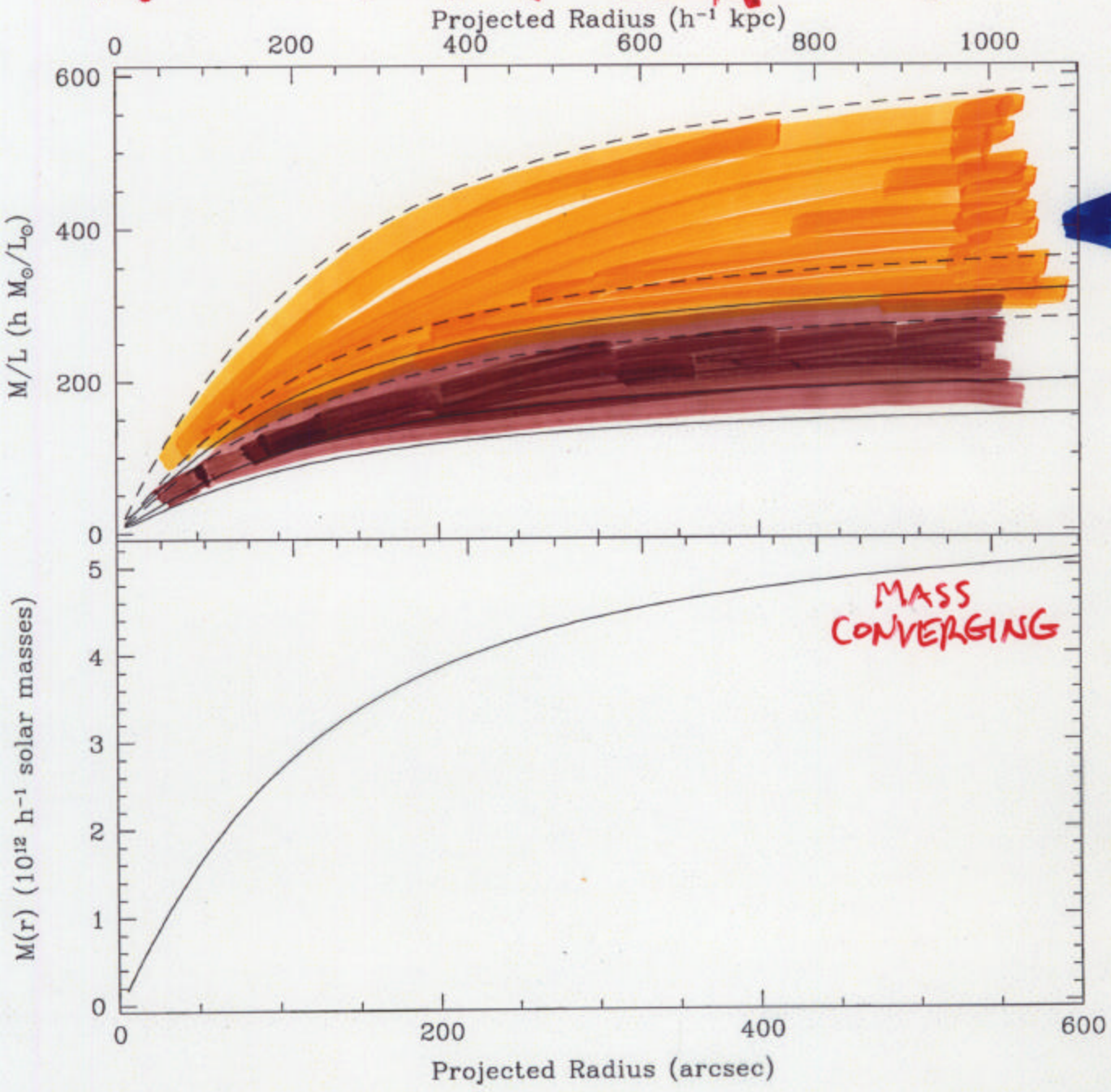


Fig. 6.— Mean shear around 26397 bright stars (r'-band). The signal is consistent with zero implying that measurements biases due to gradients in the surface brightness are not important.

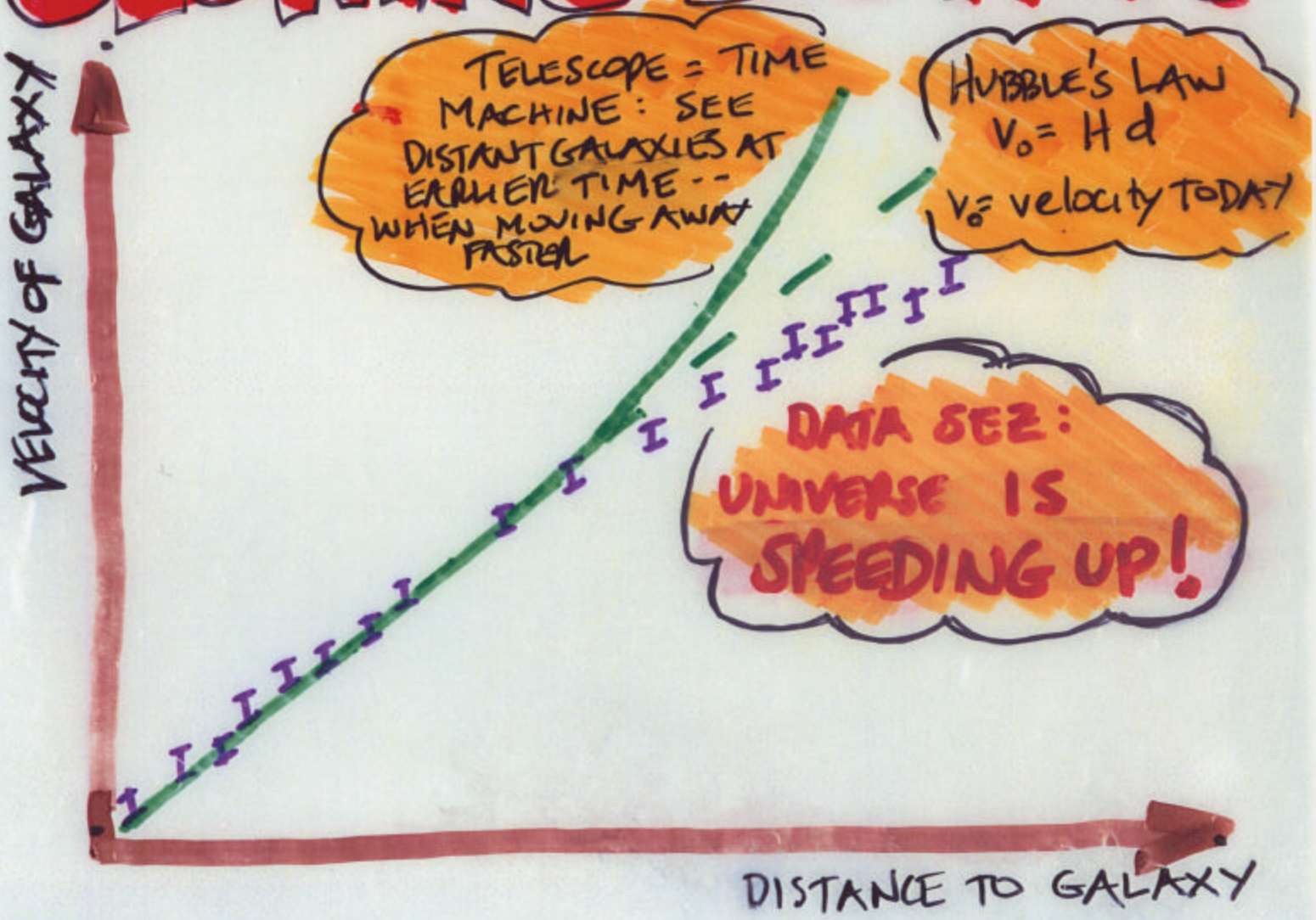
DM IN HALOS ESSENTIALLY ACCOUNTS FOR $\Omega_M \approx 1/3$



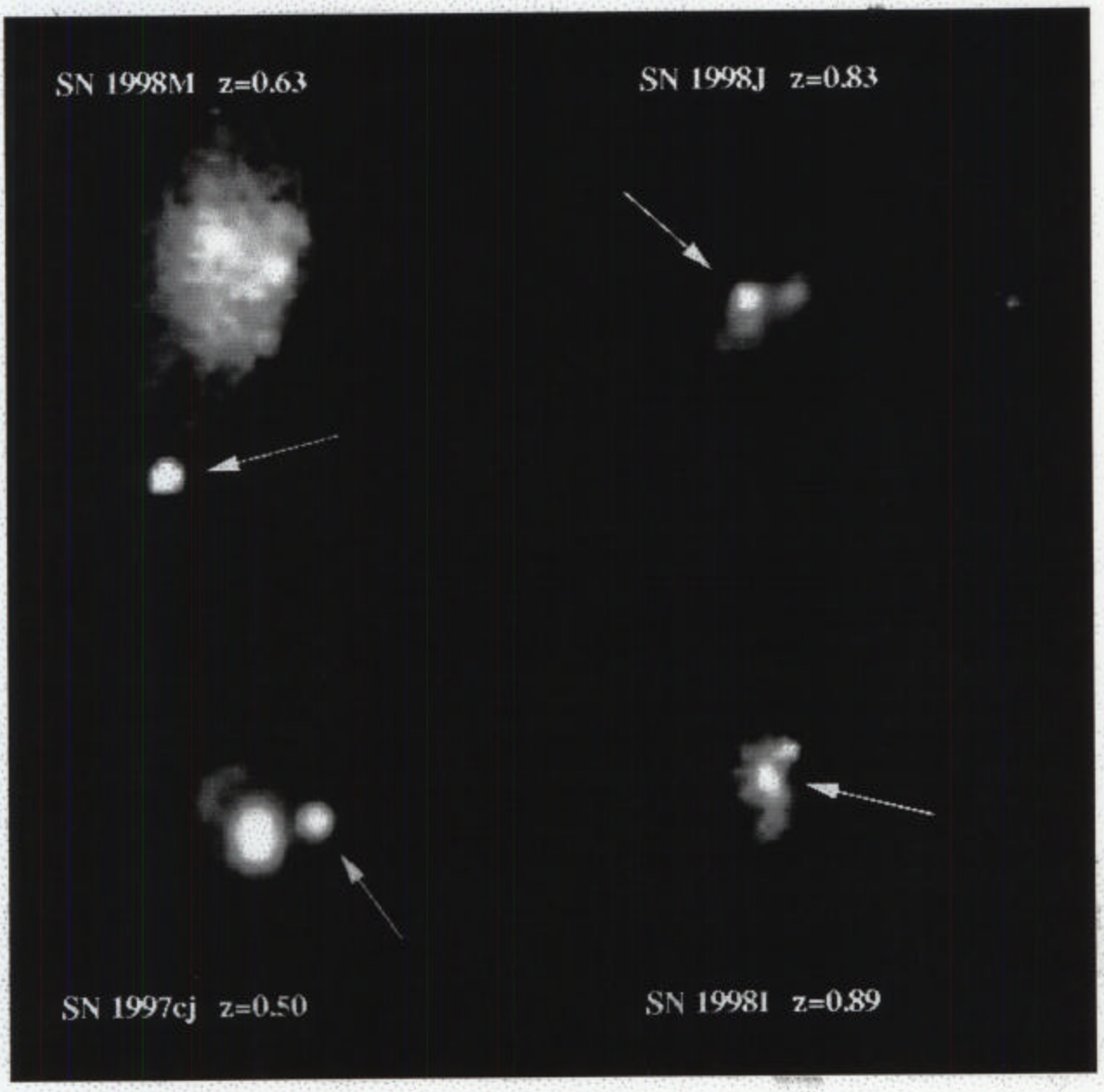
$\langle M/L \rangle$ CORRESPONDS TO $\Omega_M \approx 1/3$

Fig. 11.— Cumulative mass (lower) and mass-to-light profiles (upper) for $\sigma_v = 170$ km s^{-1} and $s = 150''$. The dashed M/L profiles assume all the galaxy light is within $5''$ of the center (as measured) while the solid lines extrpolate the light profile as described in the text. The profiles are g', r', i' from top to bottom. This represents the minimal mass model (95% lower limit on) s so the true profiles are likely to have higher values.

IS THE UNIVERSE SLOWING DOWN?



UNIVERSE IS SPEEDING UP!?# WHY?


SN 1998M z=0.63
SN 1998J z=0.83
SN 1997cj z=0.50
SN 1998I z=0.89

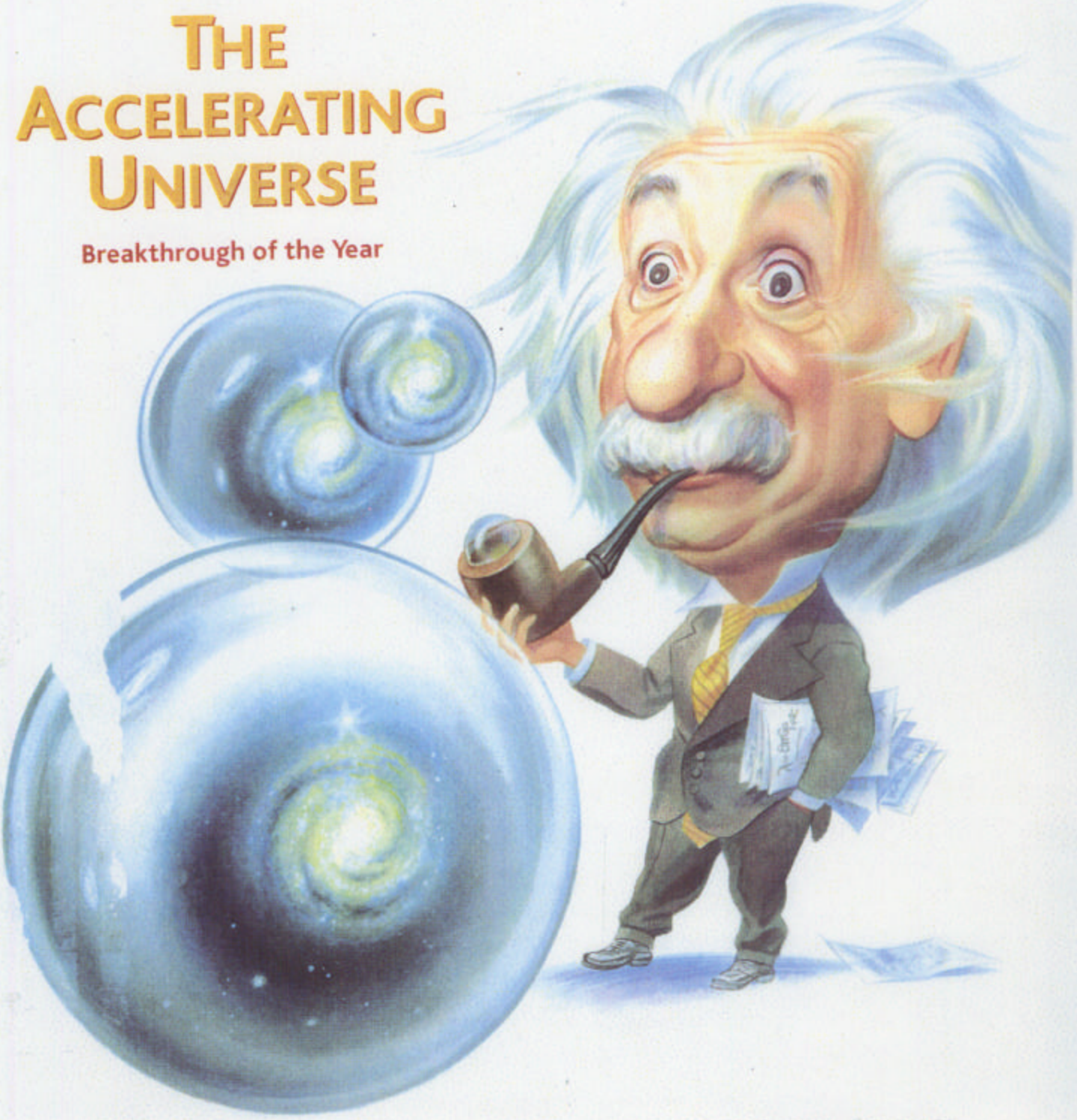
18 December 1998

Science

Vol. 282 No. 5397
Pages 2141–2336 $7

The Accelerating Universe

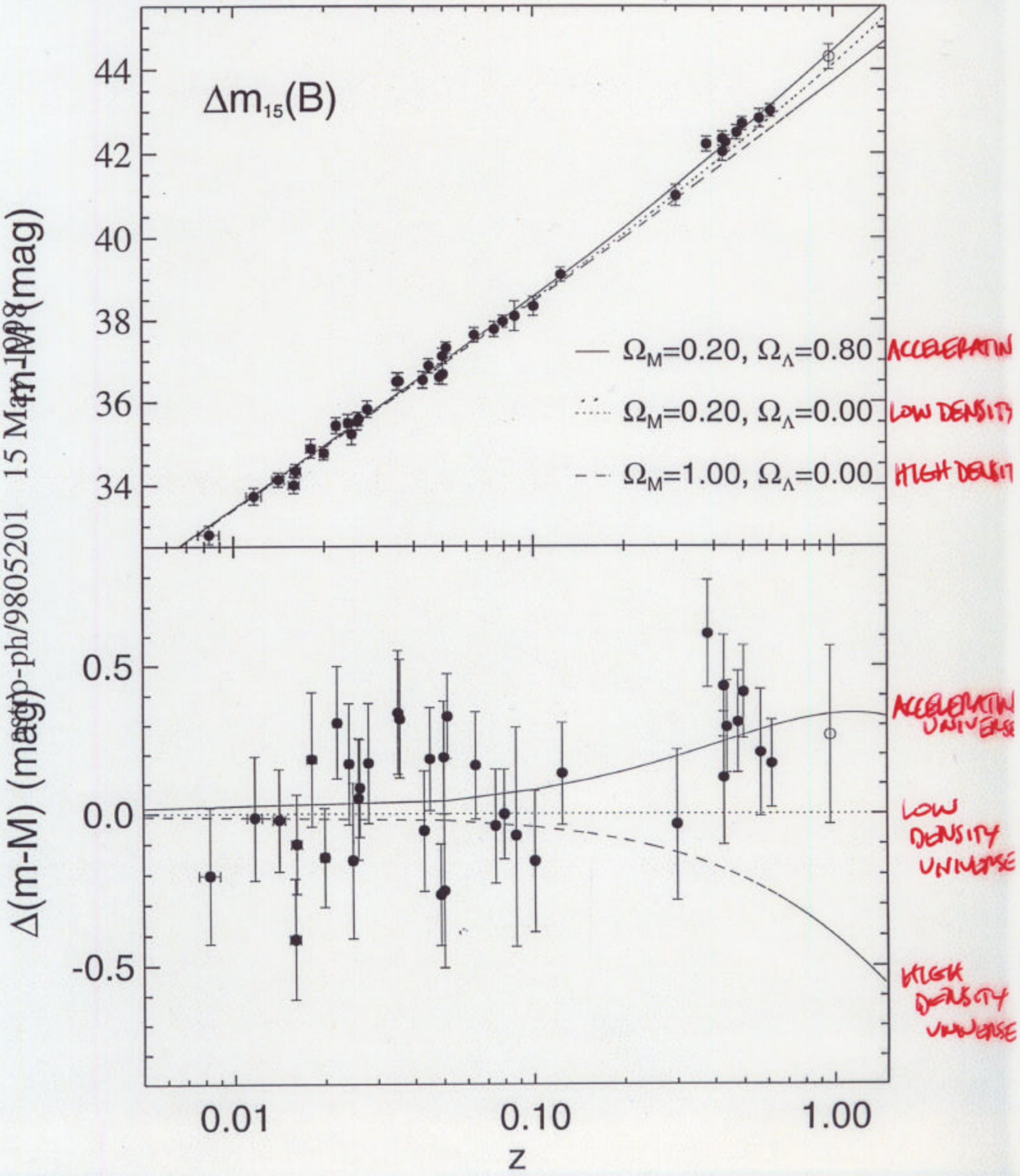
Breakthrough of the Year



American Association for the Advancement of Science

High Z SN Team

A. RIESS et al 98, A.J. in press (astro-ph/9805201)



astro-ph/9805201 15 May 1998

S. Perlmutter et al
Astrophys. J. 98

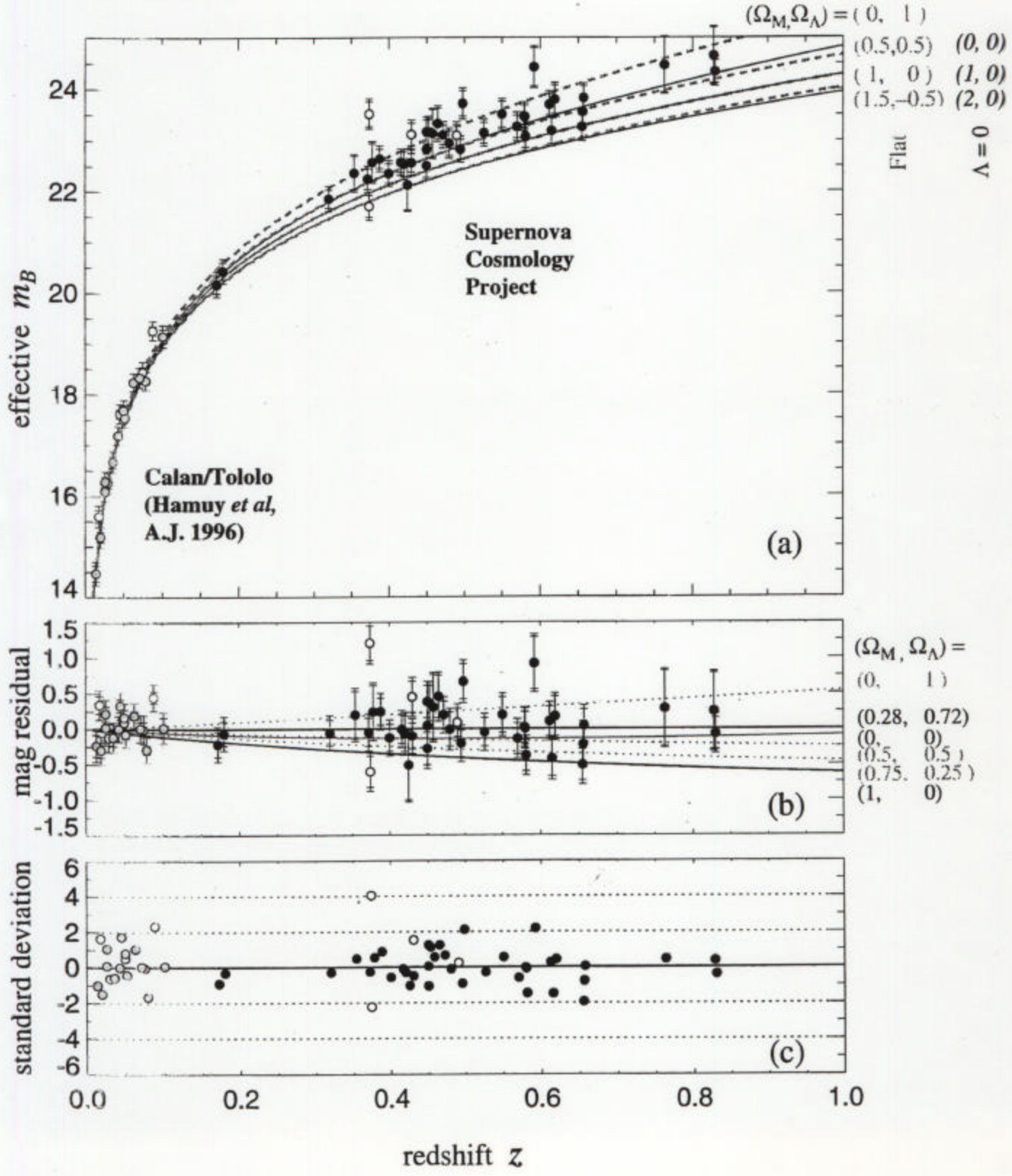
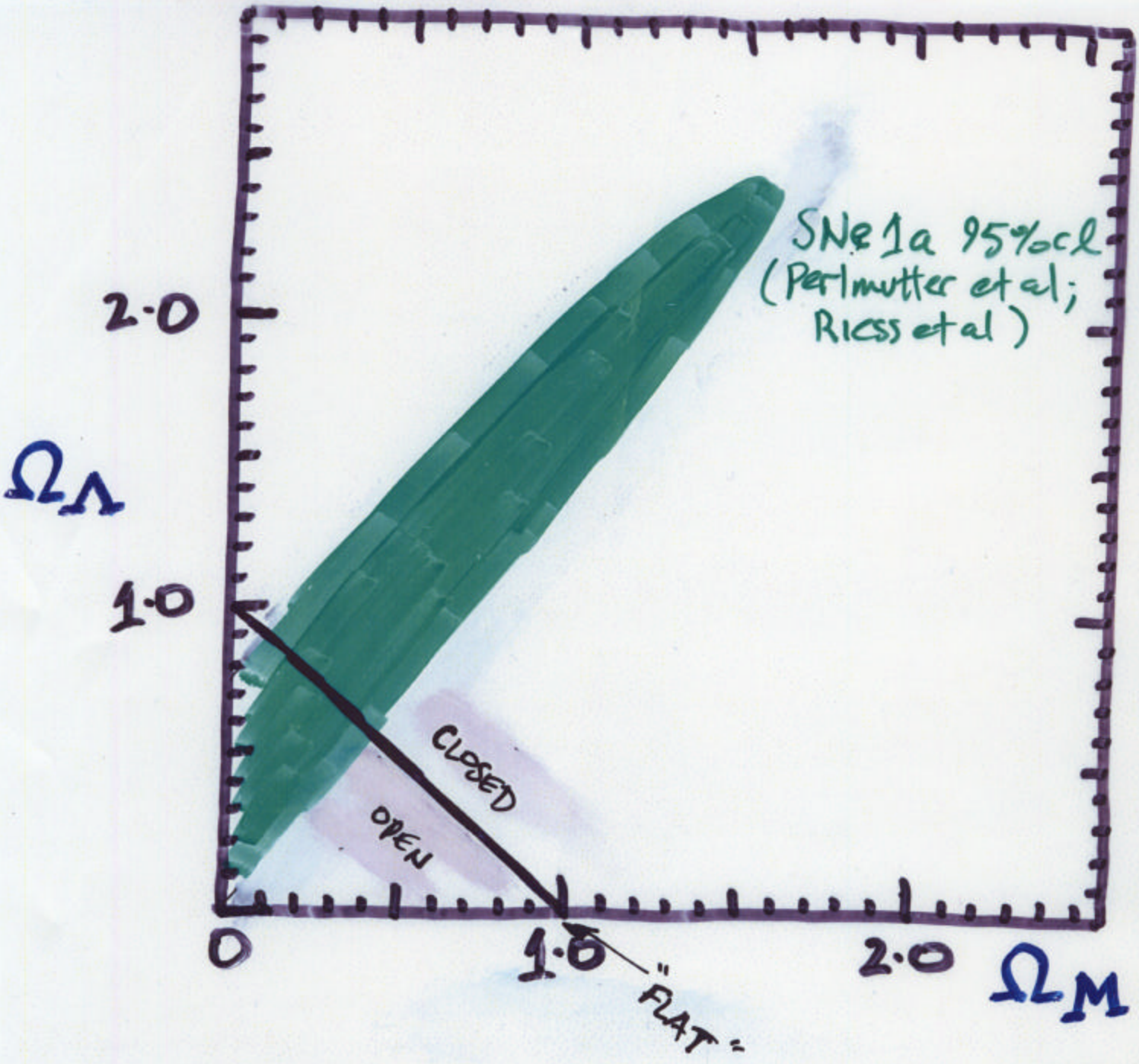
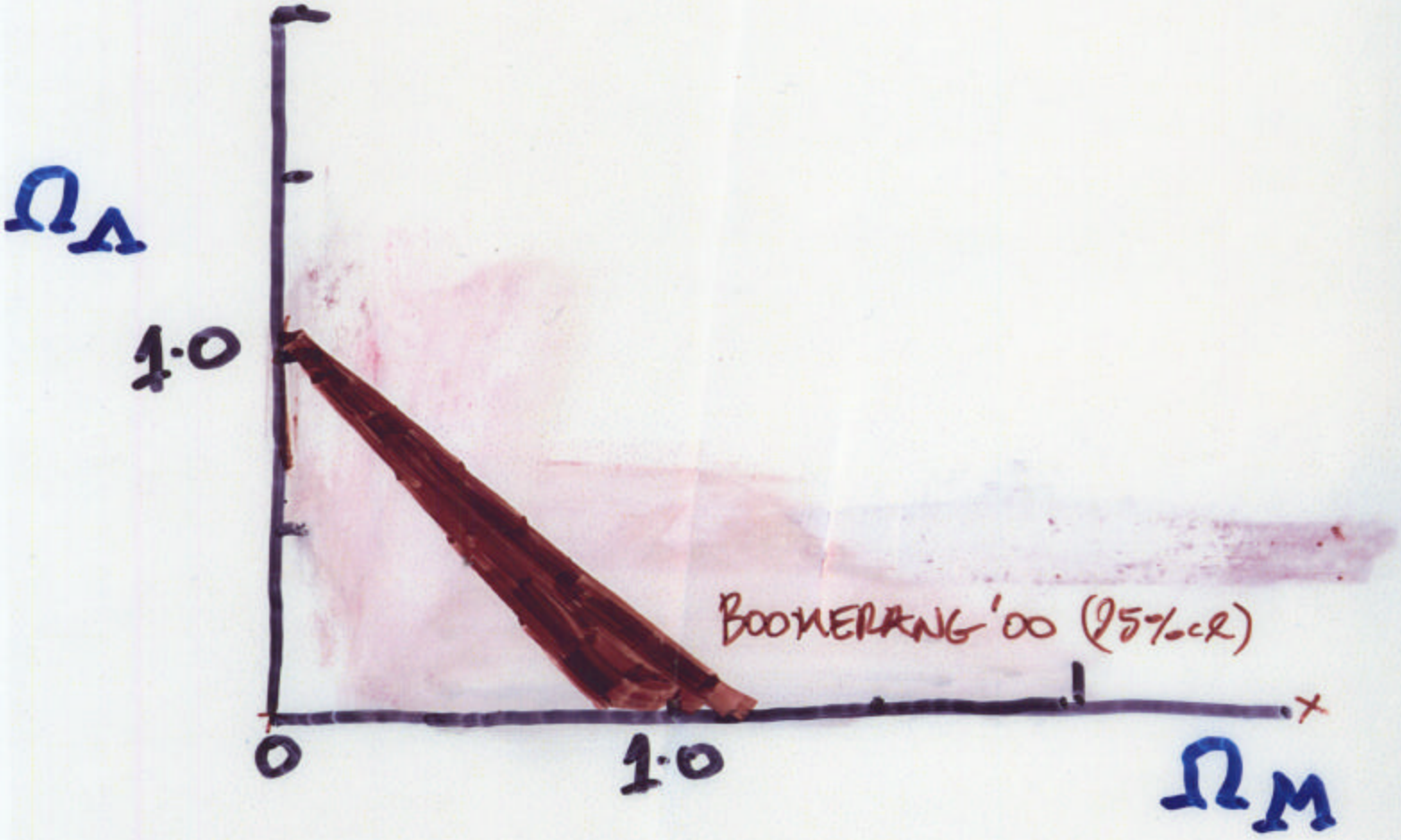


Fig. 2.

"THE BIG PICTURE"




Ω_Λ
1.0
BOOMERANG '00 (95% CL)
0
1.0
Ω_M

MATTER 95% cl

CANDIDATES/REQUIREMENTS

REL. PARTICLES

$w = 1/3$

NO

VERY LIGHT PARTICLES

$m \ll eV$

$w = 0$

NO

FRUSTRATED DEFECTS

E.G. STRINGS, WALLS

$w = -1/3, -2/3$

SCALAR FIELD

"EVOLVING Λ"

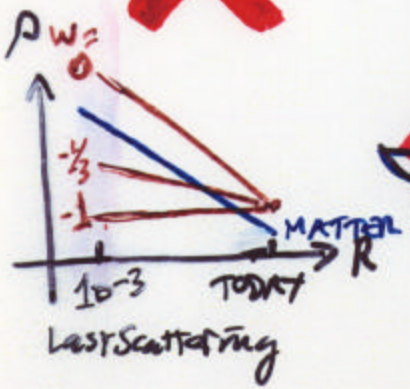
$w = -1 \rightarrow ?$

evolves

Λ

VACUUM ENERGY

$w = -1$



M-dominated: $\delta\rho/\rho \propto R$

X-dominated: $\delta\rho/\rho \sim$ const

★ HERE TODAY, GONE YESTERDAY!

TO AVOID INTERFERENCE WITH GROWTH OF STRUCTURE

$$\rho_{SM} \propto R^{-3(1+w)}$$

EQ^{N} OF STATE: $w \equiv p/\rho$ → $w \lesssim -1/3$

★ OR DECAY PRODUCED

NO! BAD CBR

★ AGE FAVORS SMALLER w

→ BOTTOM LINE: $w \lesssim -1/2$

SIMPLEST EXAMPLE Λ

GOOD STARTING POINT

3 DARK PUZZLES

WE HAVE LOTS TO DO!

- 90% OF THE ORDINARY STUFF IS "DARK"

  HOT GAS? DARK STARS?

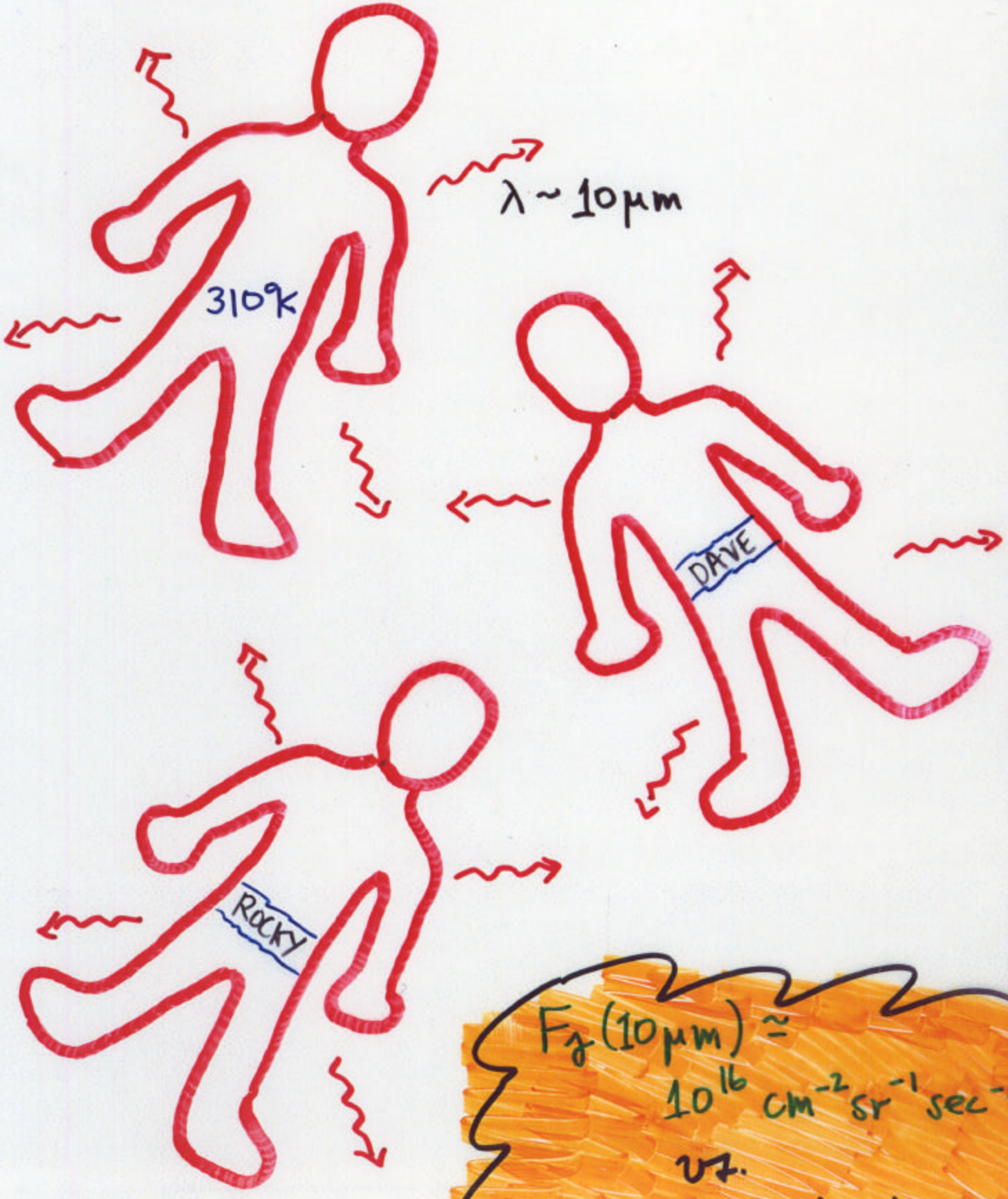
- MOST OF THE STUFF IS DARK & EXOTIC

  ELEMENTARY PARTICLES LEFT OVER FROM THE BIG BANG

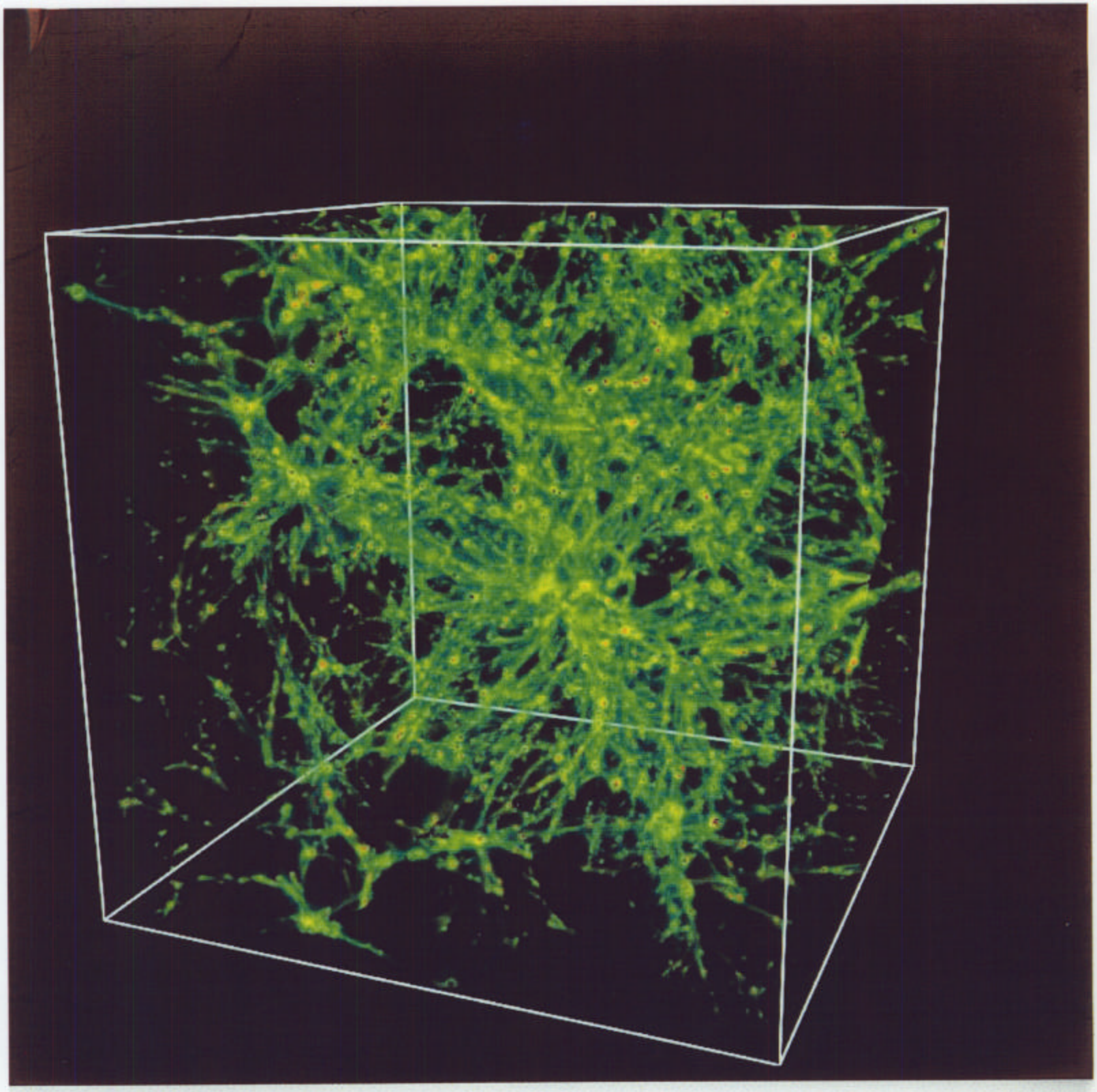
- MYSTERIOUS DARK ENERGY ACCOUNTS FOR 60% OF THE MASS/ENERGY BUDGET & IS THE UNIVERSE TO SPEED UP!

  ?

EXAMPLE: 100kg, relic cosmologists



$F_\nu(10\mu m) \simeq$
$10^{16}\ cm^{-2} sr^{-1} sec^{-1}$
vs.
$\sim 3 \times 10^{9}\ cm^{-2} sr^{-1} sec^{-1}$ (observed)



MOOSE DIAGRAM OF DARK MATTER CANDIDATES

MBT 90

THE LEADING CANDIDATES

Particle Dark Matter

for Master of the Universe

MOTIVATED BY PARTICLE PHYSICS

$\Omega \sim 1$ "THE COSMOLOGICAL BONUS"

AXION $\sim 10^{-5}$ eV

- PART OF SOL^N TO STRONG CP-PROBLEM
- "COLD" DARK MATTER
- DETECTABLE $a_{HALO} + \vec{B} \rightarrow \gamma_{MICROWAVE}$

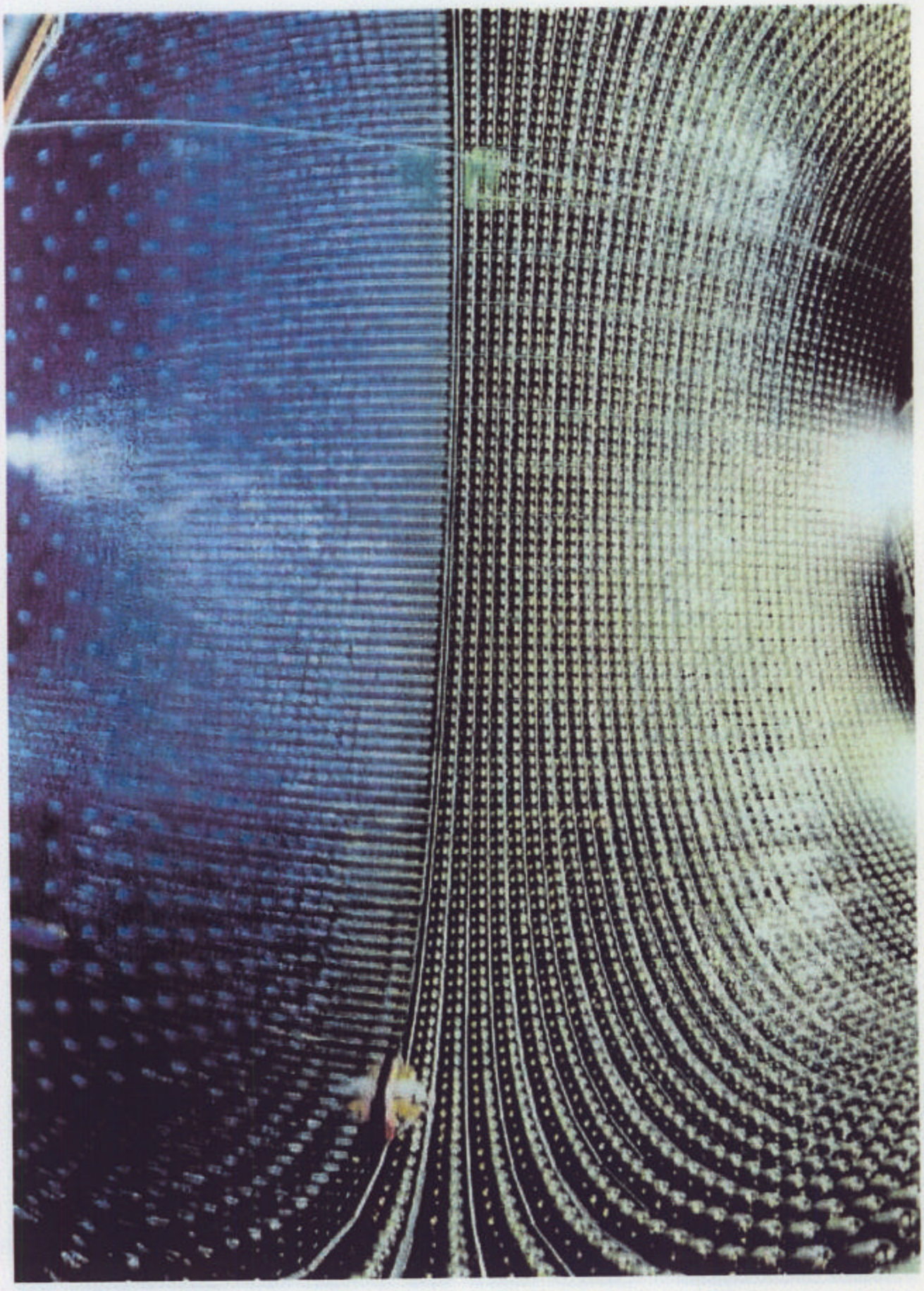
NEUTRALINO $\sim 10 - 1000$ GeV*

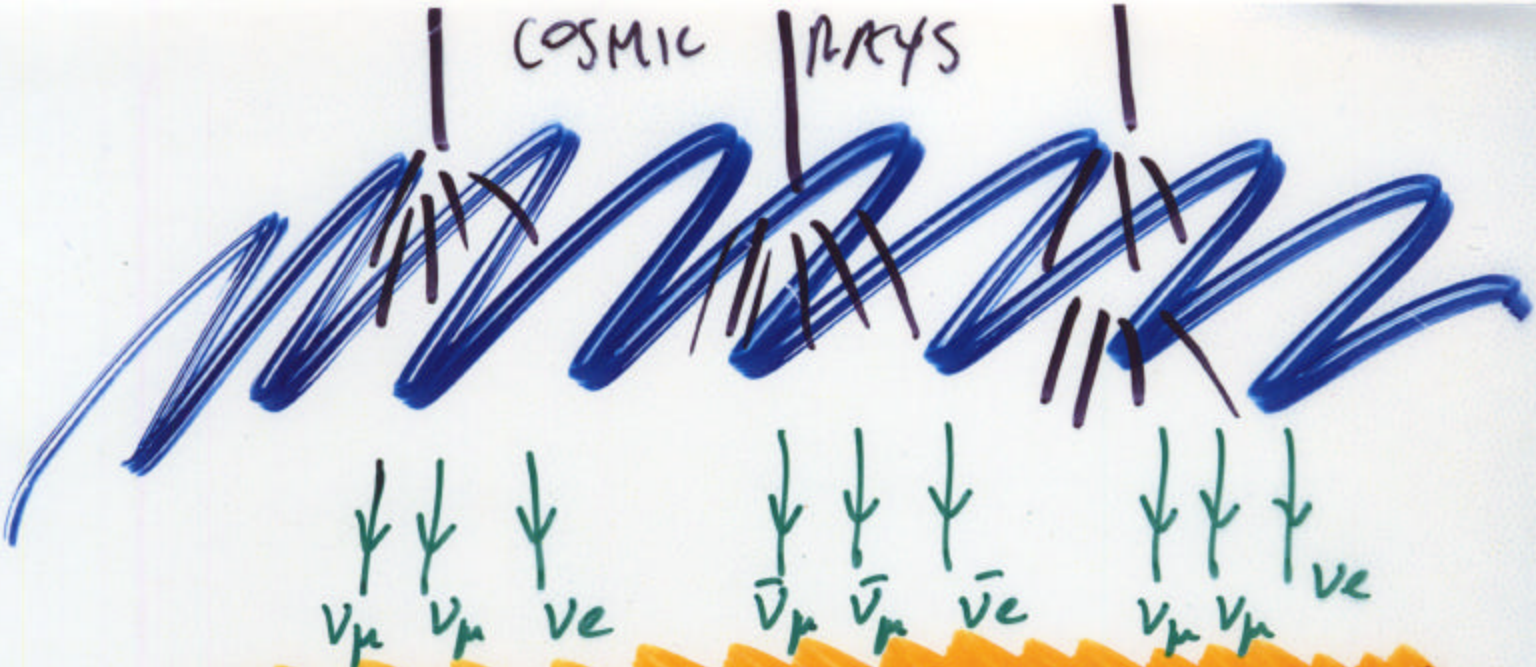
- LIGHTEST SUPERSYMMETRIC PARTICLE
- "COLD" DARK MATTER
- DETECTABLE $\chi_{HALO} + A \rightarrow \chi + A + \text{keV}$

* 0(1 GeV) PHOTINO Farrar-Kolb

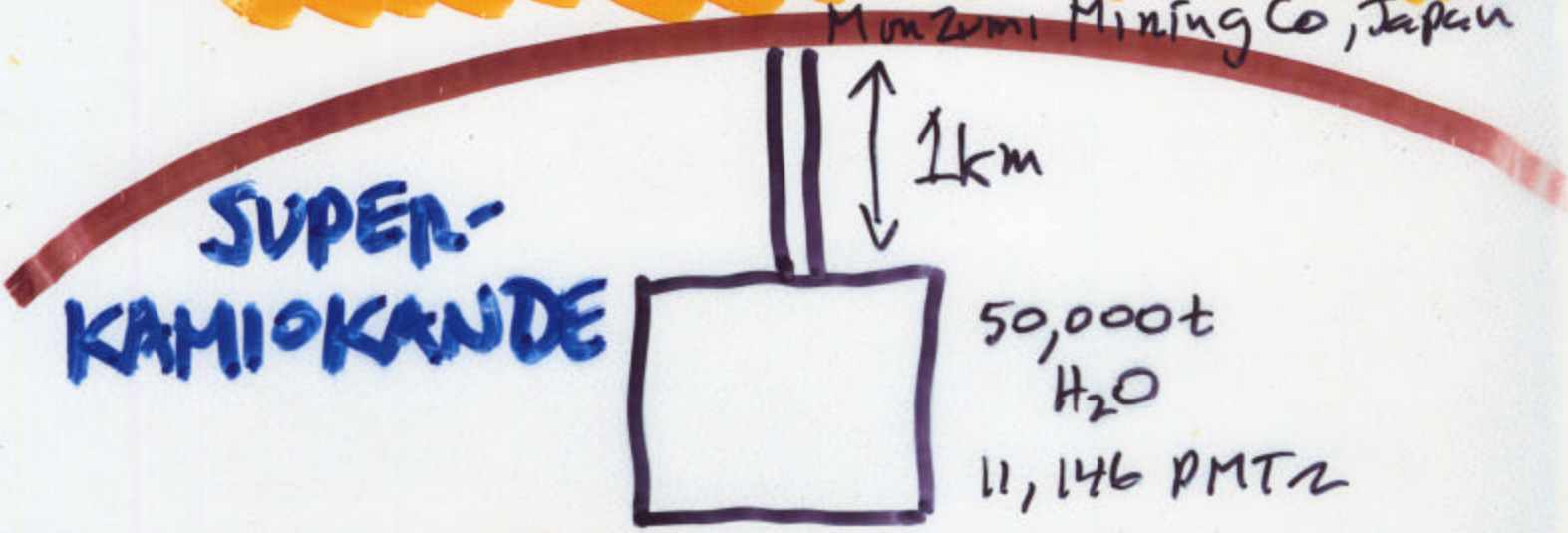
NEUTRINO $\sim 10 - 30$ eV

- KNOWN TO EXIST!
- "HOT" DARK MATTER
- GAERT "ADDITIVE"





muon neutrinos/electron neutrinos = 2:1



DETECT EQUAL NUMBERS OF ν_e, ν_μ

NEUTRINO OSCILLATIONS

⇒ AT LEAST ONE NEUTRINO SPECIES HAS A MASS $\gtrsim$ 0.1eV

(PROBABLY TAU NEUTRINO)

NB: $\Omega_\nu \approx m_i/40\text{eV} \gtrsim 0.003$

NEUTRINOS HAVE MASS

ATMOSPHERIC NEUTRINOS

$\Delta m^2_\nu \sim 3\times10^{-3}\,eV^2$ ν_μ-deficit, path length dep. ✓

- $m_\nu \gtrsim 5\times10^{-2}\,eV$
- probably $\nu_\mu - \nu_\tau$

SOLAR NEUTRINOS

$\Delta m^2_\nu \sim 10^{-5}\,eV^2$ or $10^{-10}\,eV^2$ ν_e deficit in 5 expts ✓

- $m_\nu \gtrsim 3\times10^{-3}\,eV,\ 10^{-5}\,eV$
- probably $\nu_e - \nu_\mu$

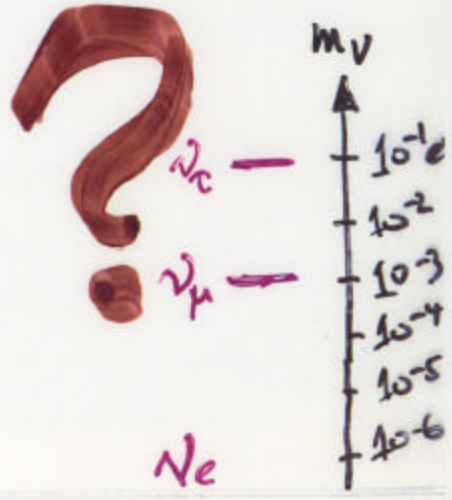
LSND/KARMEN

$\Delta m^2_\nu \sim eV^2$

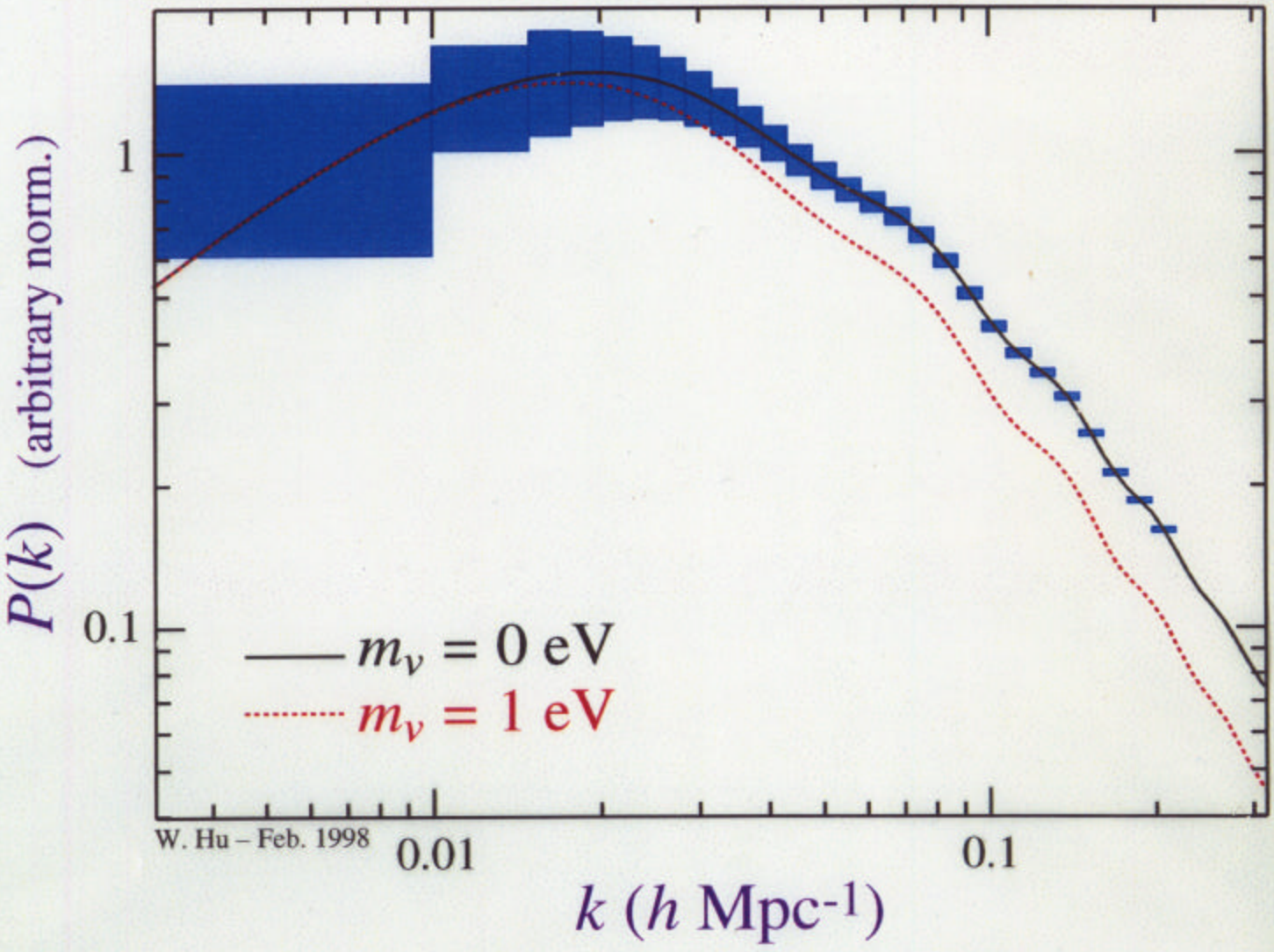
$\bar{\nu}_\mu \to \bar{\nu}_e$

$\nu_\mu \to \nu_e$

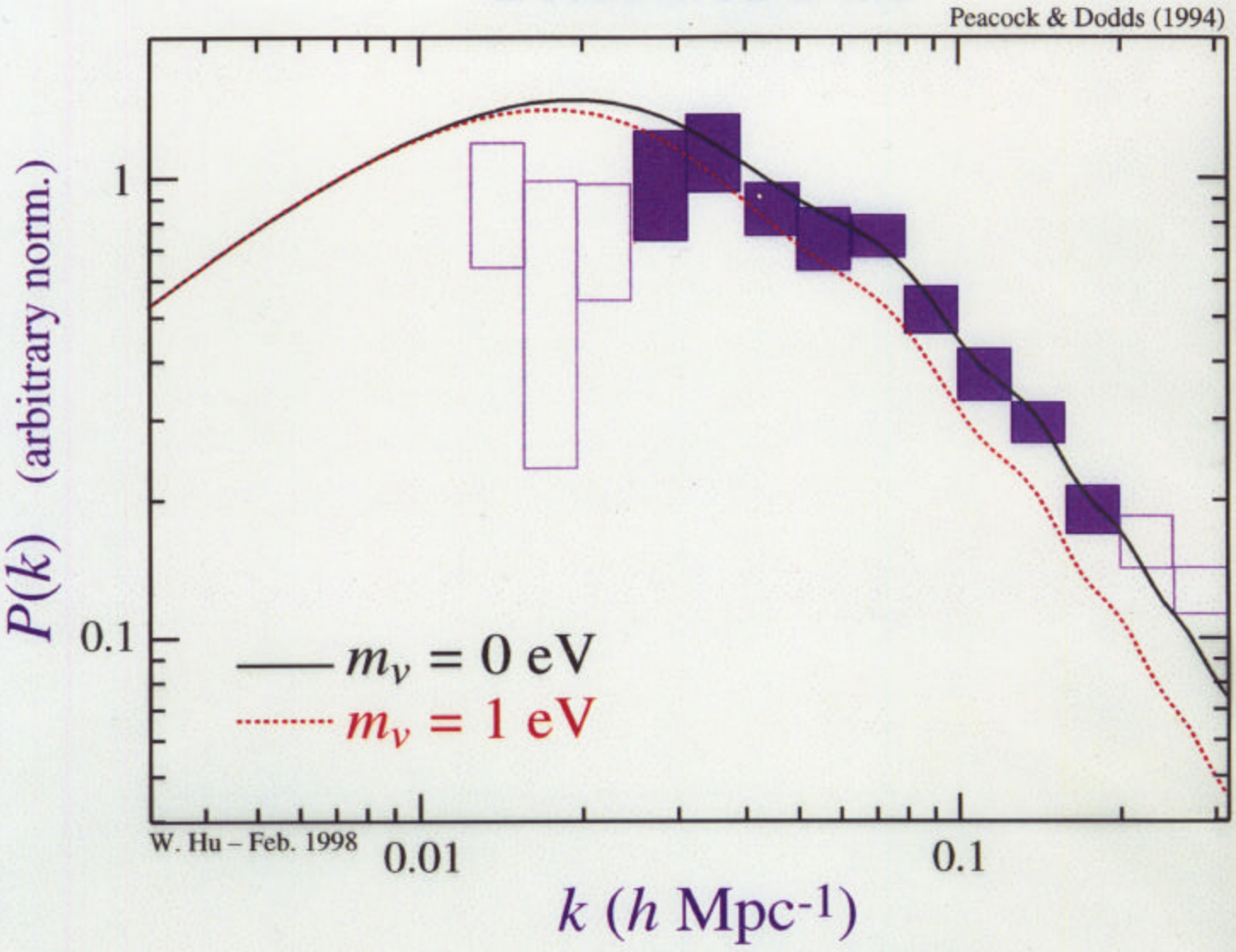
- $m_\nu \sim \mathcal{O}(0.1-1\,eV)$
- requires sterile ν for solar ν problem

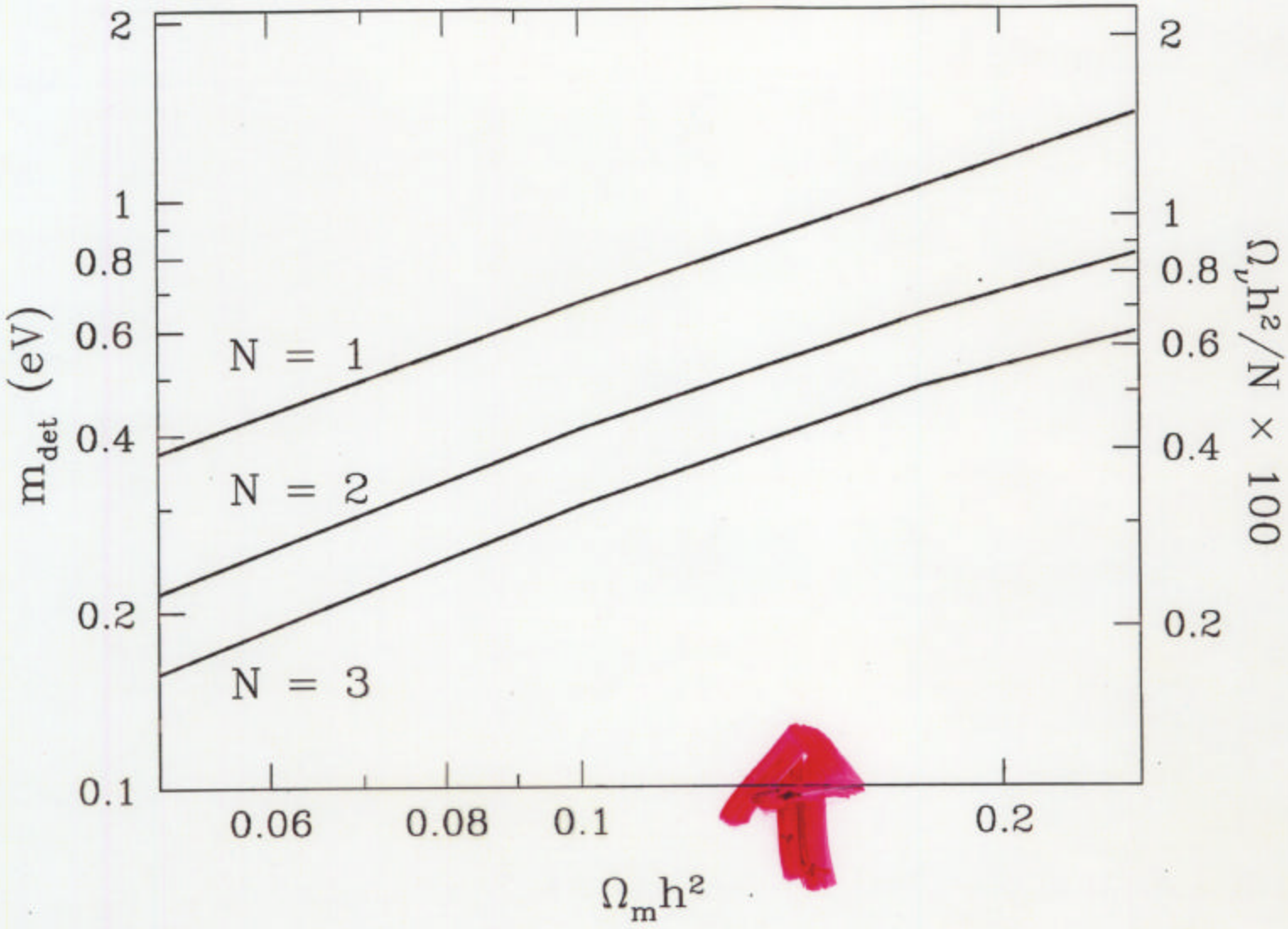


Projected SDSS BRG



Combined Data





Hu, Eisenstein, Tegmark
PRL 80, 5255 (98)

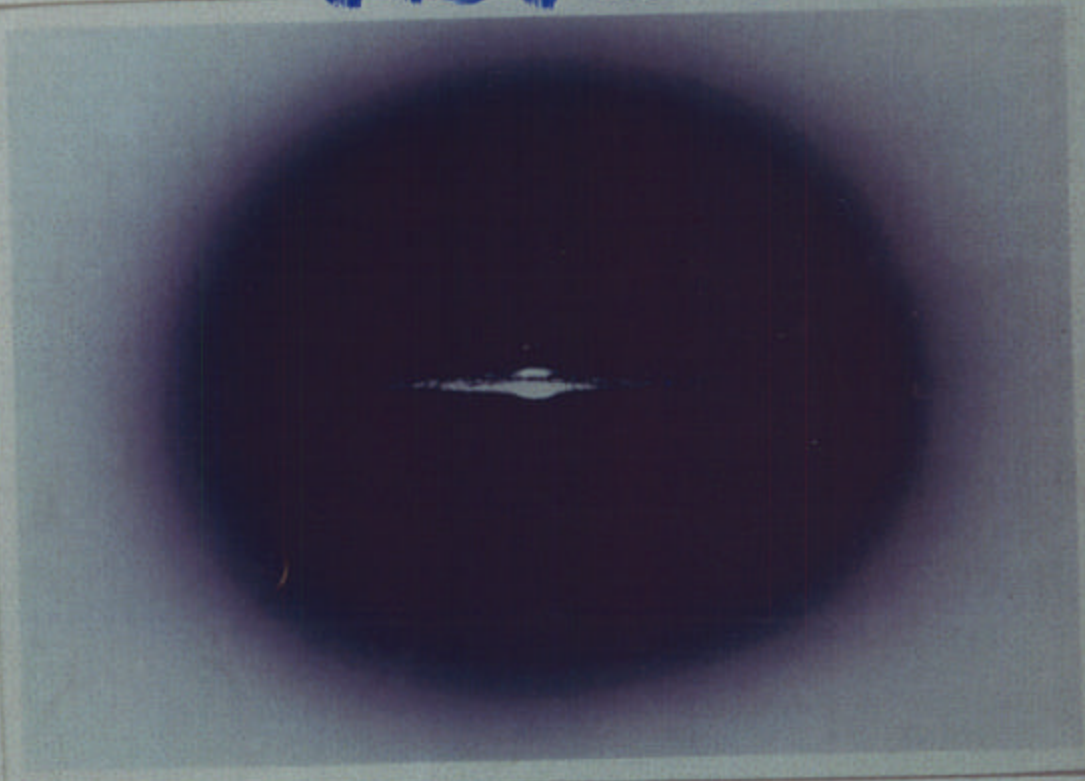
USING LSS TO PROBE NEUTRINO MASS

IN HOT PURSUIT of DARK MATTER

M.S. TURNER CHICAGO/FERMILAB

MOST OF THE MATTER IS "DARK" AND PROBABLY NOT ORDINARY MATTER — AND WE MAY KNOW SOON!

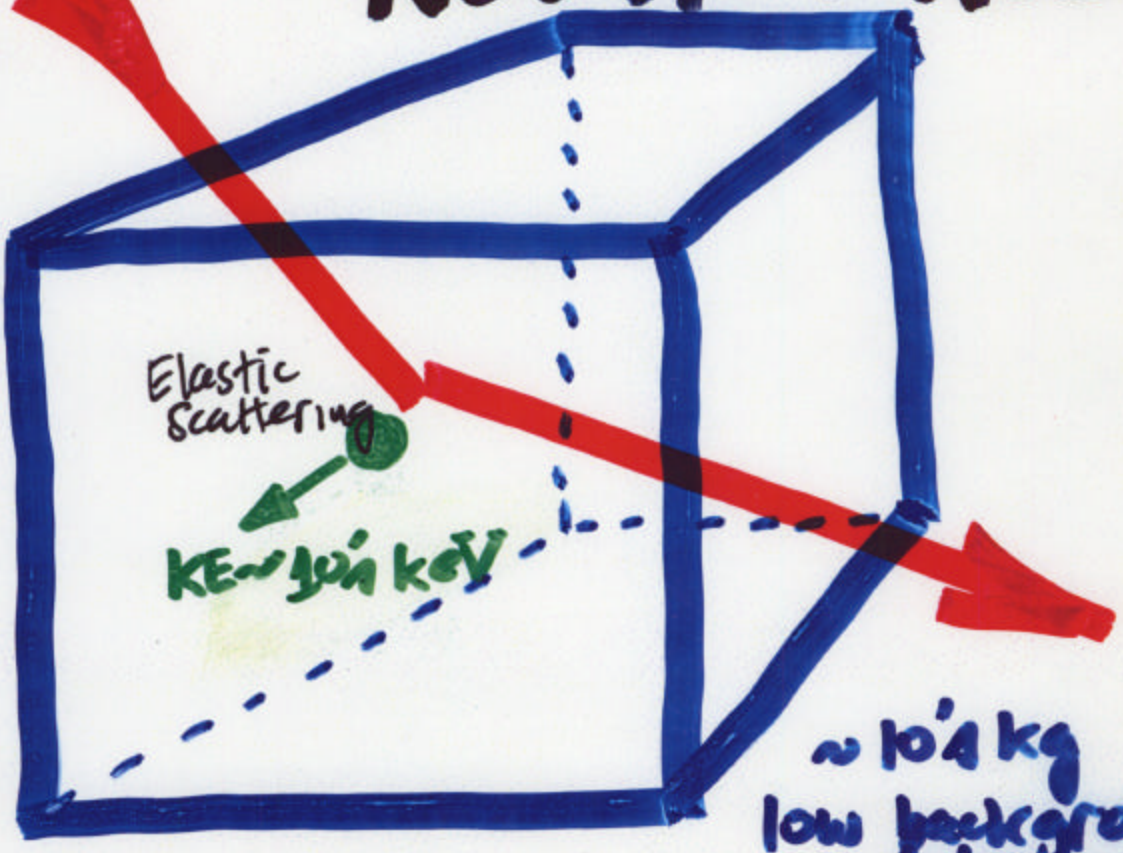
LOTS OF DARK MATTER-RIGHT HERE!



TO DETECT A NEUTRALINO

HALO NEUTRALINO

$KE = \frac{1}{2} m v^2$
$\approx 10^{-6} mc^2$
$\approx 10^{1}$ keV



~ 10^{4} kg
low background detector

Rate $\propto$ $(\sigma v)_{elastic}$ ~ $(10^{-4} - 1)\ da^{-1}\ kg^{-1}$

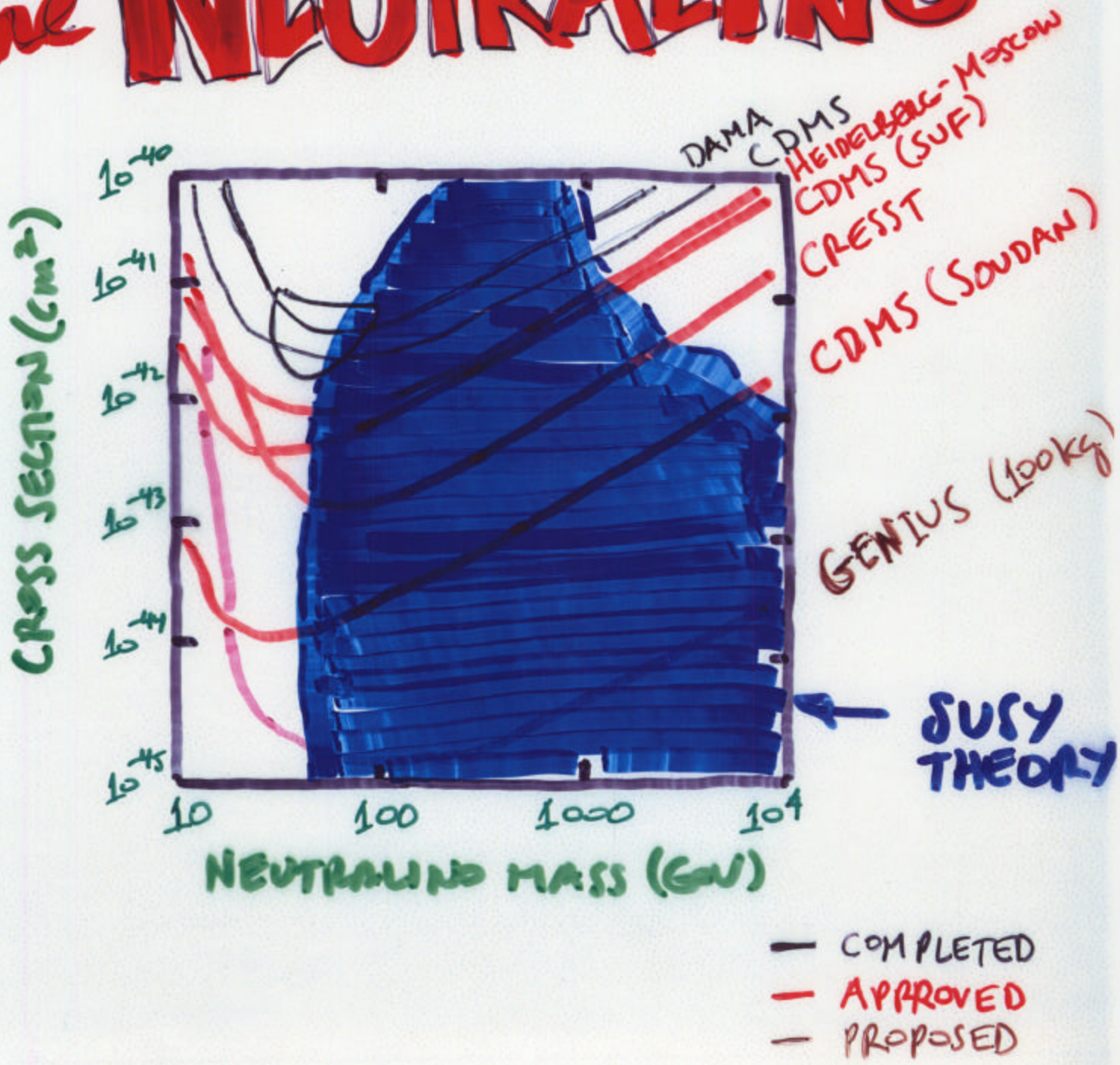
$\approx O(10^{-37} cm^2)$ fixed by $\Omega \propto \frac{1}{\langle \sigma v \rangle_{ann}} = 1$

NEED LARGE LOW-BACKGROUND, LOW-THRESHOLD DETECTORS

ESPECIALLY RADIOACTIVITY!

E.G. 10 mK bolometers, LN NaI scintillators, superheated Freon, TPC, LXe, ...

CLOSING IN on the NEUTRALINO



DEFENDER of the AXION

MS TURNER U.CHICAGO/ FERMILAB

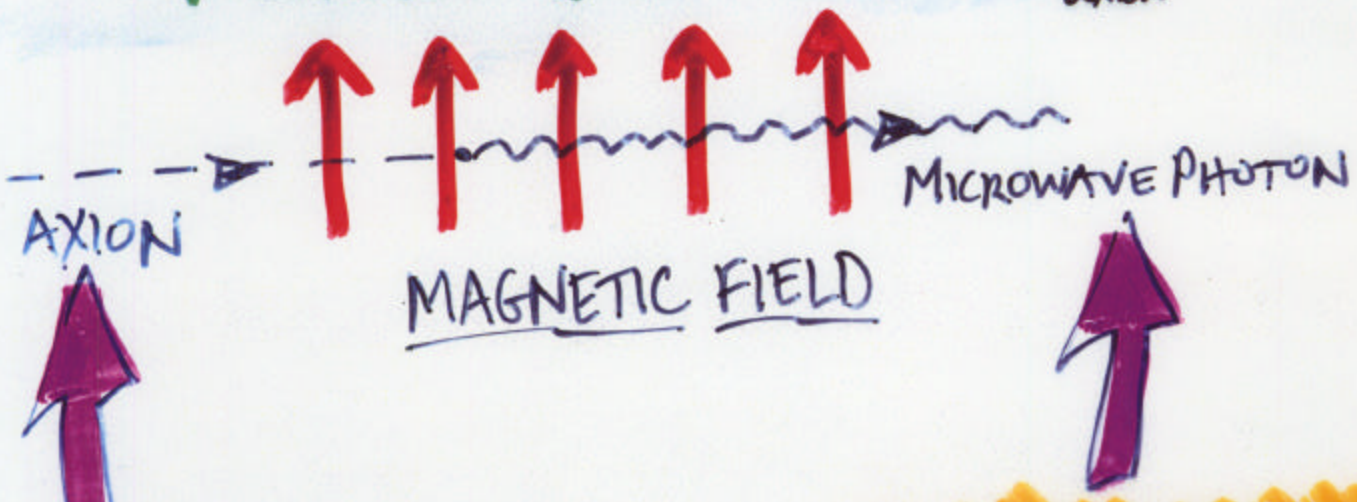
ISSUE 1
No.1
US 75¢
CAN 95¢
UK 50p

- MOTIVATION
- ASTROPHYSICAL / COSMOLOGICAL / LAB CONSTRAINTS $\Rightarrow \Omega_a \gtrsim 10^{-3}$
- DECTECTION OF RELIC AXIONS

NO TRAFFIC

TUNING IN ON COSMIC AXIONS

- P. SIKIVIE 1983

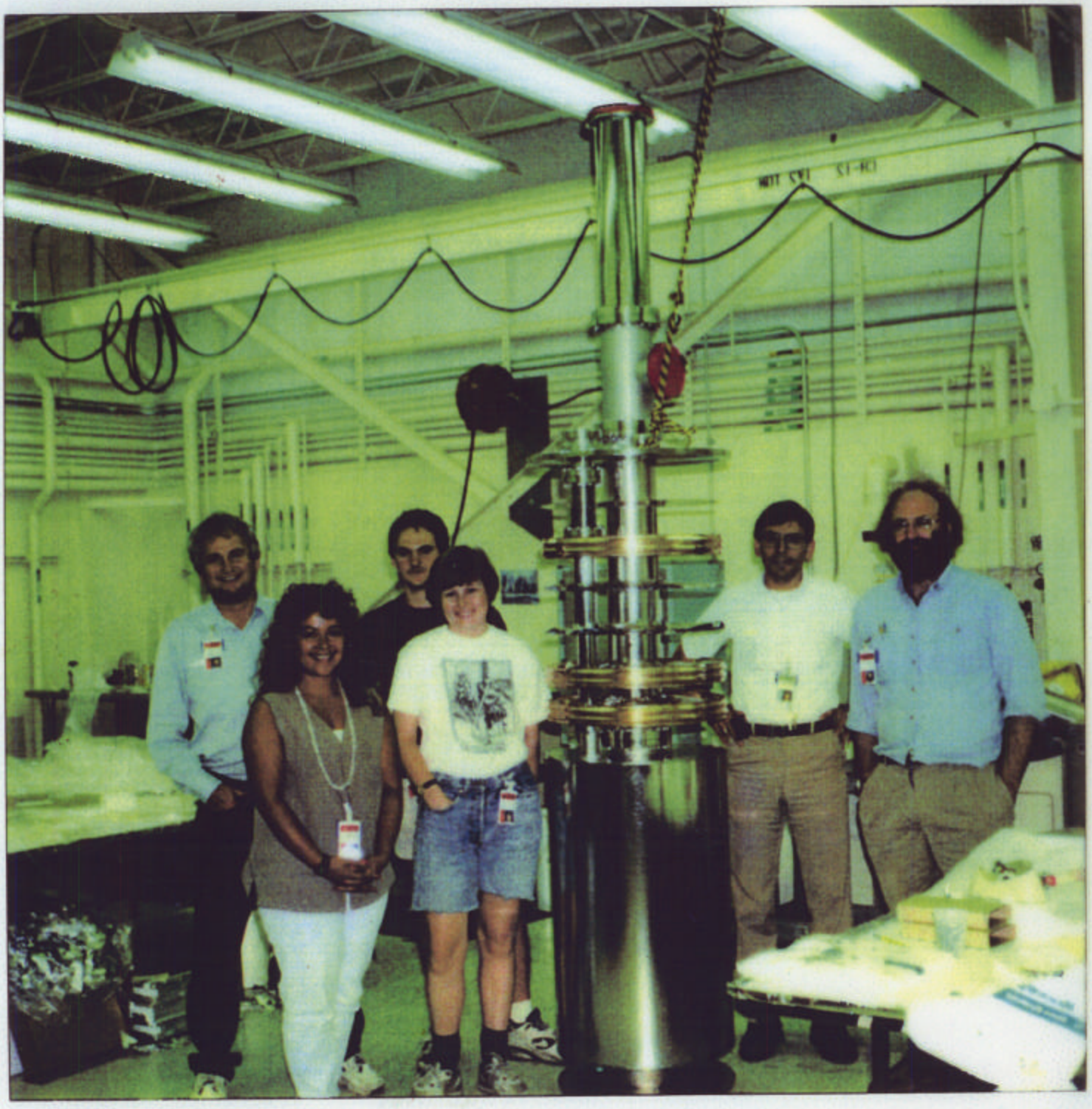


LOCALLY
10^{13} per cm^3

~30 CONVERSIONS
PER DAY
POWER ≈ 10^{-23} WATT

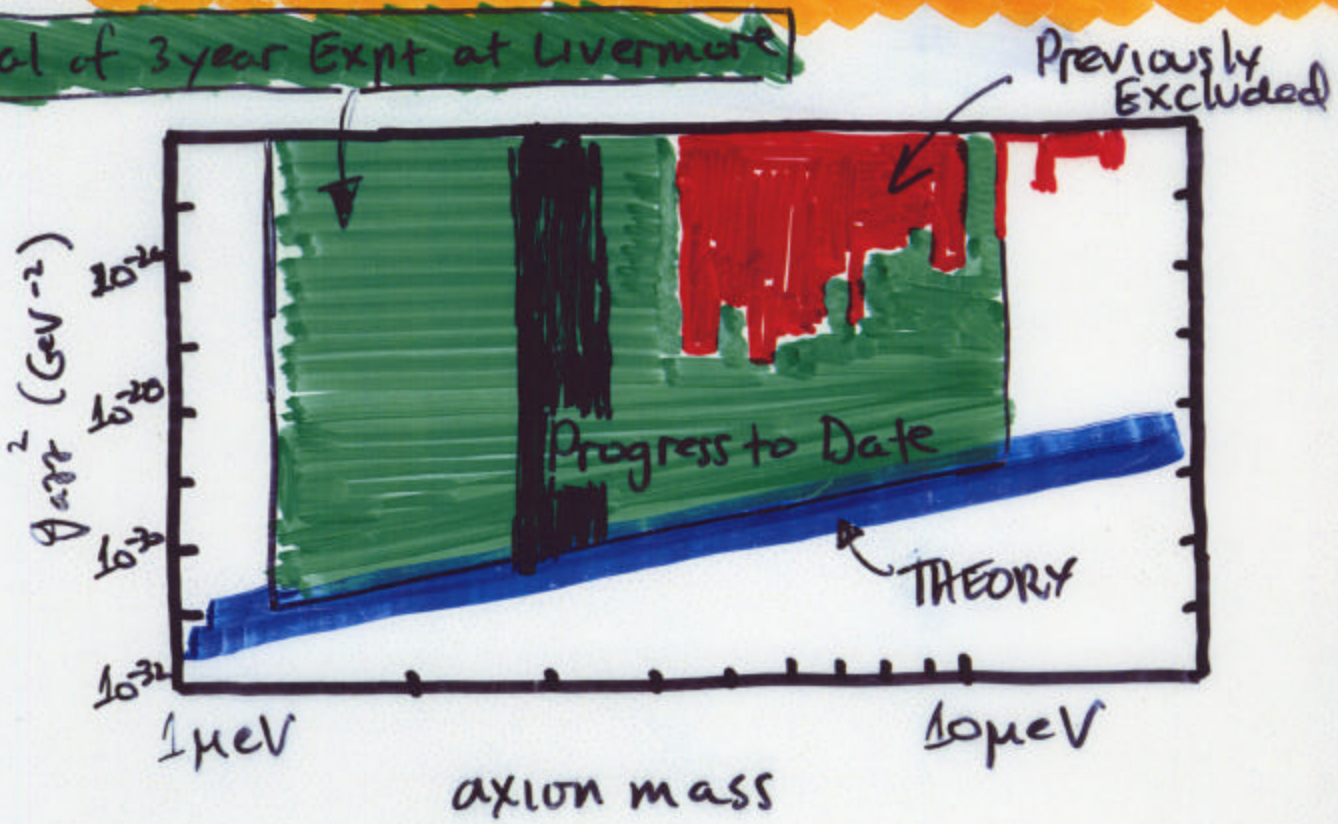
MICRO-
WAVE
CAVITY

BIG MAGNET



AXION HUNTING

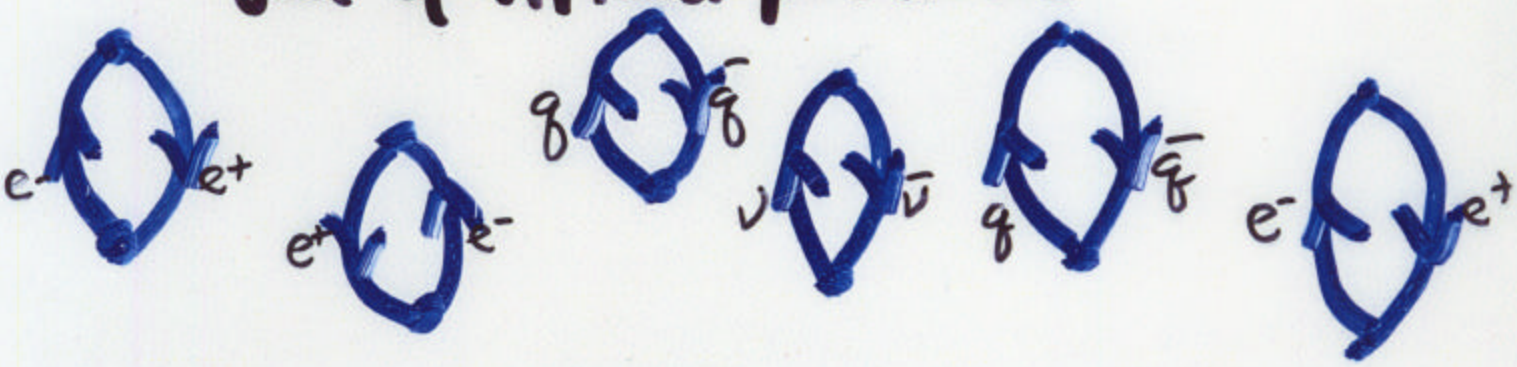
MOST SENSITIVE DARK MATTER SEARCH



$$\text{Cavity Power} = 6.5\times10^{-22}\ \text{Watt} \times \left(\frac{V}{22\,\text{liter}}\right) \times \left(\frac{B}{7.5\,T}\right)^2 \frac{C_{n\ell}}{0.56}\left(\frac{g_\gamma}{0.97}\right)^2 \left(\frac{f}{700\,\text{MHz}}\right)\left(\frac{Q}{90{,}000}\right)$$

QUANTUM VACUUM IS NOT EMPTY!

sea of virtual particles



whose existence has been detected
(shifting of atomic levels in H)

Quantum vacuum is elastic
$p = -\rho$, but how much does it weigh?

<u>theoretical estimates</u>

'30 $\Omega_{VAC} = \frac{\rho_{VAC}}{\rho_{crit}} = \infty$

'80 $\Omega_{VAC} = 10^{122}$
cut off at m_{pl}

'84 $\Omega_{VAC} = 10^{55}$ SUSY

'98 $\Omega_{VAC} \approx 0.6$?
Harvey; Silverstein-Harvey

?? $\Omega_{VAC} = 0$?
pre-98 "guess" of most particle theorists

Comments About Dark Energy

Science Times, 30 November 1999 (J. Glanz)

J. Harvey: Basically, people don't have a clue as to how to solve this problem.

S. Weinberg: Right now, not only for cosmology but for elementary particle theory, this in the bone in our throat.

F. Wilczek: ...maybe the most fundamentally mysterious thing in all of basic science.

E. Witten: ... would be number 1 on my list of things to figure out.

WHAT IF

$\Lambda = 0$?

BE CAREFUL WHAT YOU WISH FOR !!

ACCELERATING UNIVERSE

$\Rightarrow$ $\rho + 3p < 0$

source of gravity in GR

$\Rightarrow$ $\rho_x \sim 2/3\, \rho_{crit}$ $\quad p_x < -\rho_x/3$

POSSIBILITIES:

Einstein's COSMOLOGICAL CONS'T (VACUUM ENERGY) $\quad p = -\rho$

TANGLED NETWORK OF STRINGS $\quad p = -\rho/3$

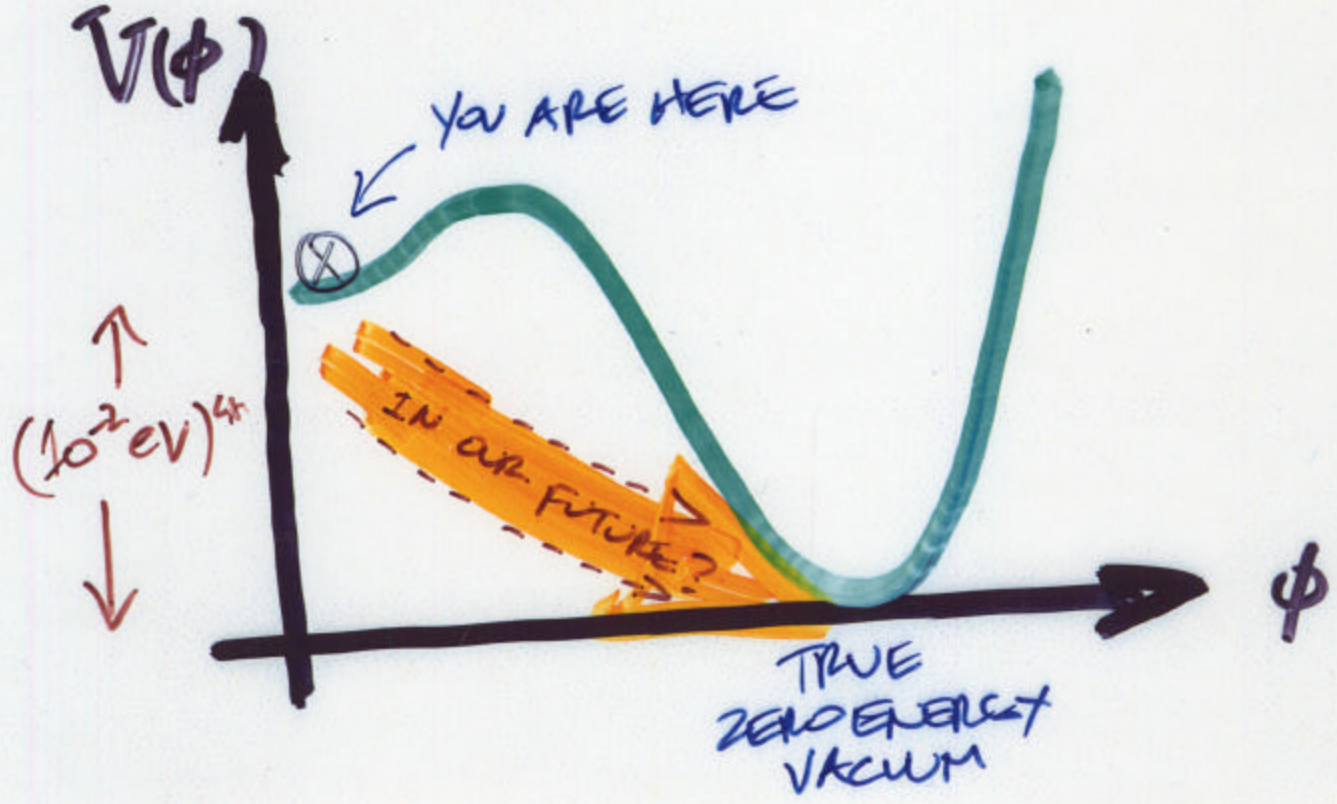
ROLLING SCALAR FIELD $\quad p = -\rho/3 \rightarrow -\rho$

AKA "QUINTESSENCE"

YOUTHFUL INDISCRETION

MST-WILCZEK '82
Nature 298, 633

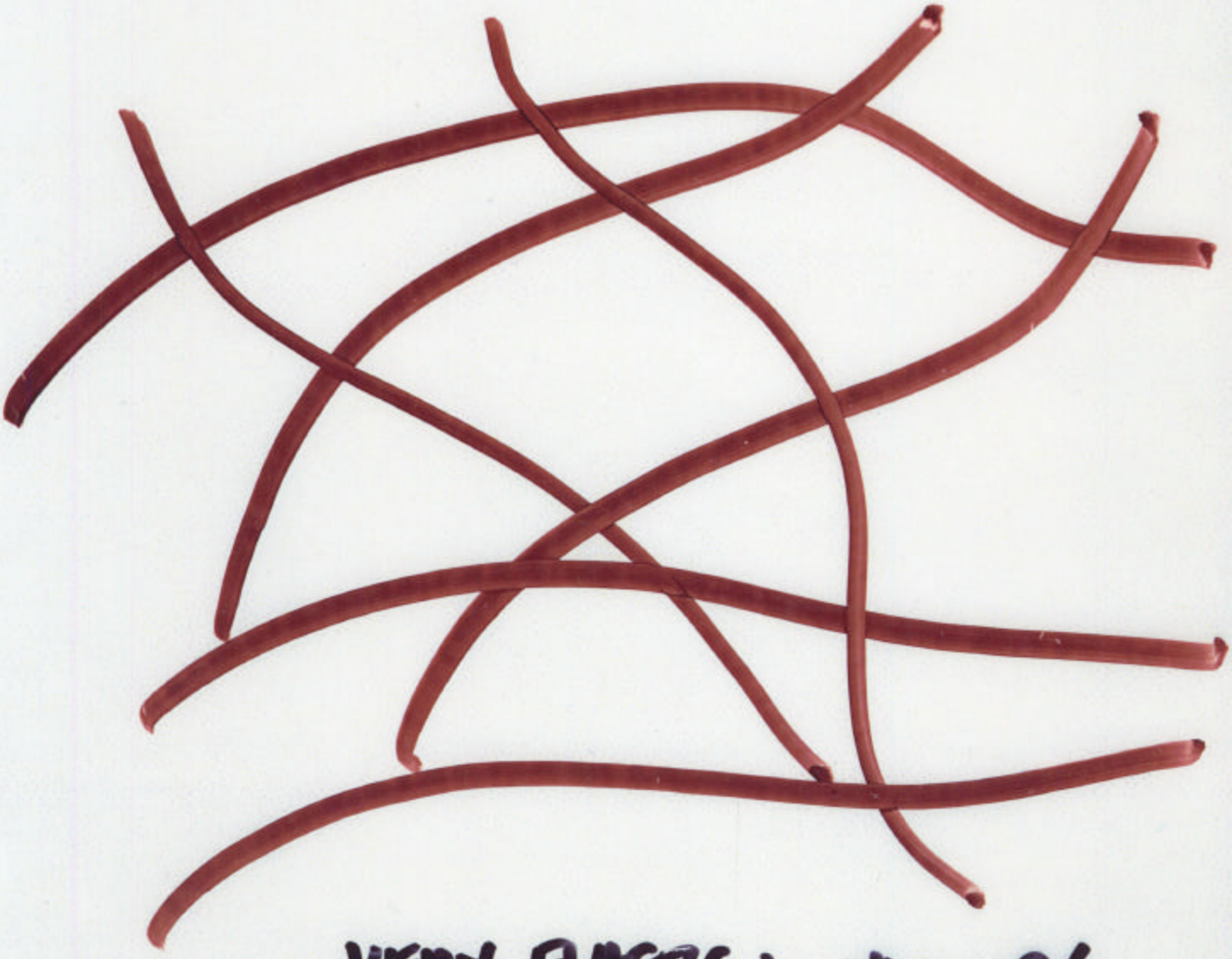
DURING ITS EVOLUTION UNIVERSE HAS UNDERGONE SERIES OF PHASE TRANSITIONS (??, QCD, ELECTROWEAK, ??) MAY HAVE GOTTEN TRAPPED IN "FALSE" VACUUM



NETWORK OF (FRUSTRATED) TOPOLOGICAL DEFECTS

EG STRING

A. Vilenkin '84
Pen-Spergel '98



VERY ELASTIC: $p = -\rho/3$

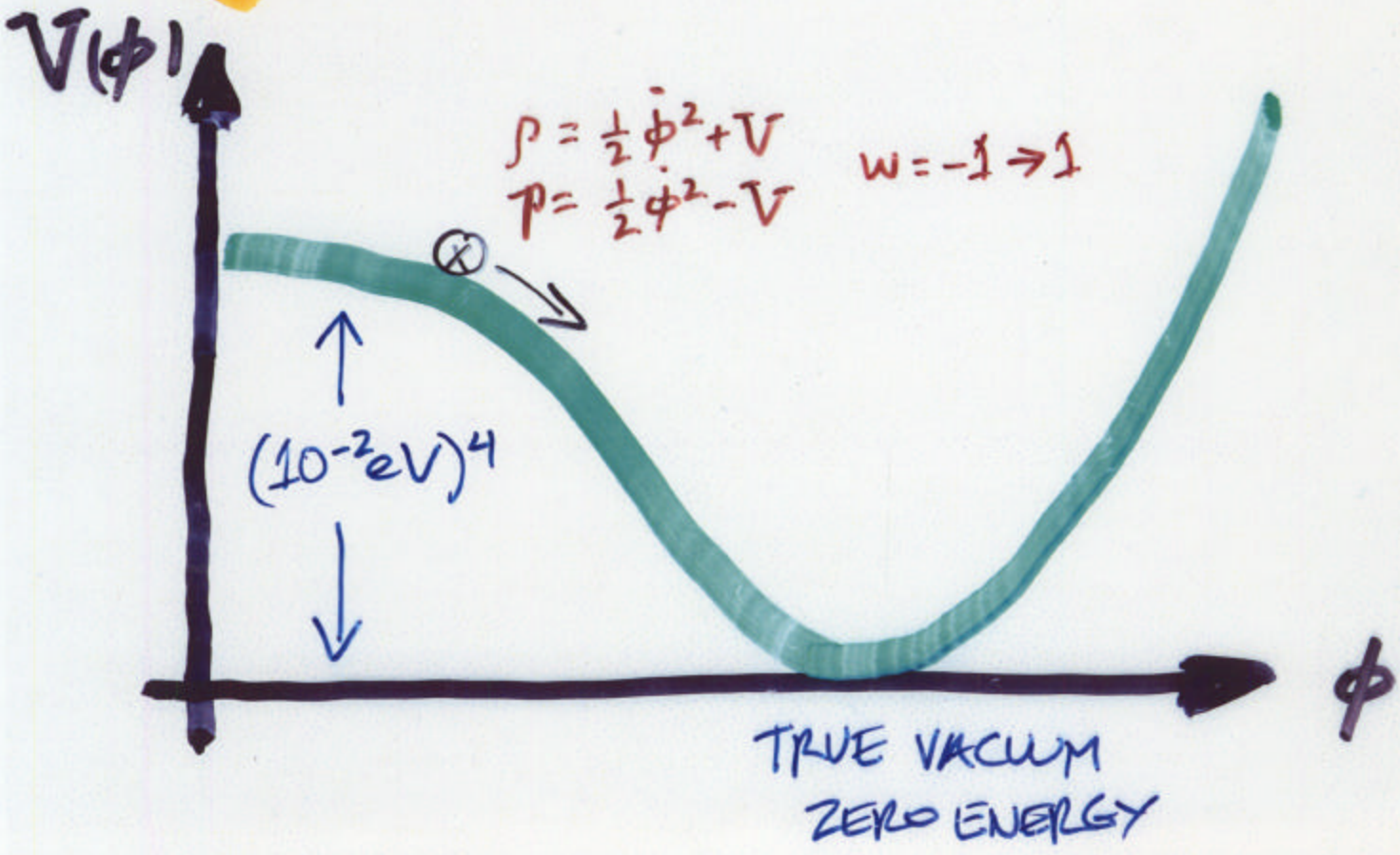
IN GENERAL: $p = -N/3\ \rho$

ROLLING SCALAR FIELD

(aka: decaying cosmological constant, pseudo Nambu Goldstone boson, quintessence, not there yet)

Bronstein 1933 (executed by Stalin 1935)
Hill Schramm Fry 1986
Freese et al 1987
Ratra-Peebles 1988
Frieman et al 1995
Caldwell et al 1998
& others

A. GREENSPAN 1998: "... Brief Episodes of Inflation Are Unavoidable."



NANCY KERRIGAN PROBLEM

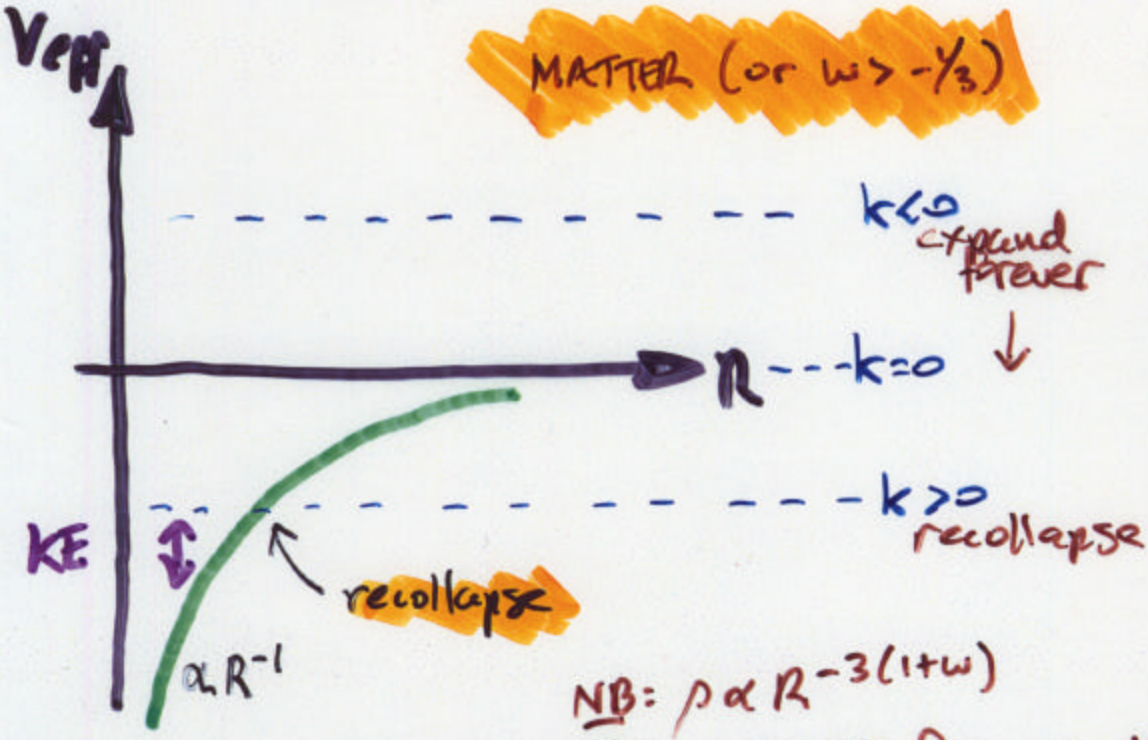
WHY ME?

WHY NOW?

MYSTERIOUS, BUT CRUCIAL

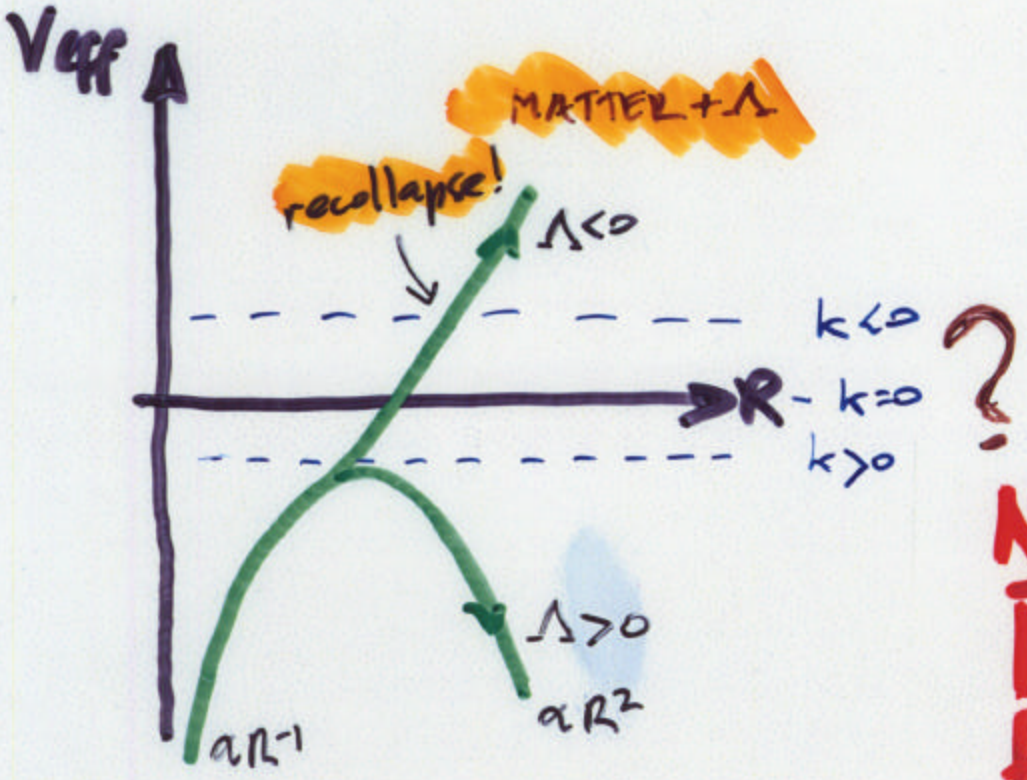
$$\dot{R}^2 - \frac{8\pi G\rho}{3} R^2 = -k$$

KE V_{eff} E_{TOT}



NB: $\rho \propto R^{-3(1+w)}$

$R^2\rho$ increases for $w > -1/3$



?

NB: Need to know EOS for all time!

DESTINY