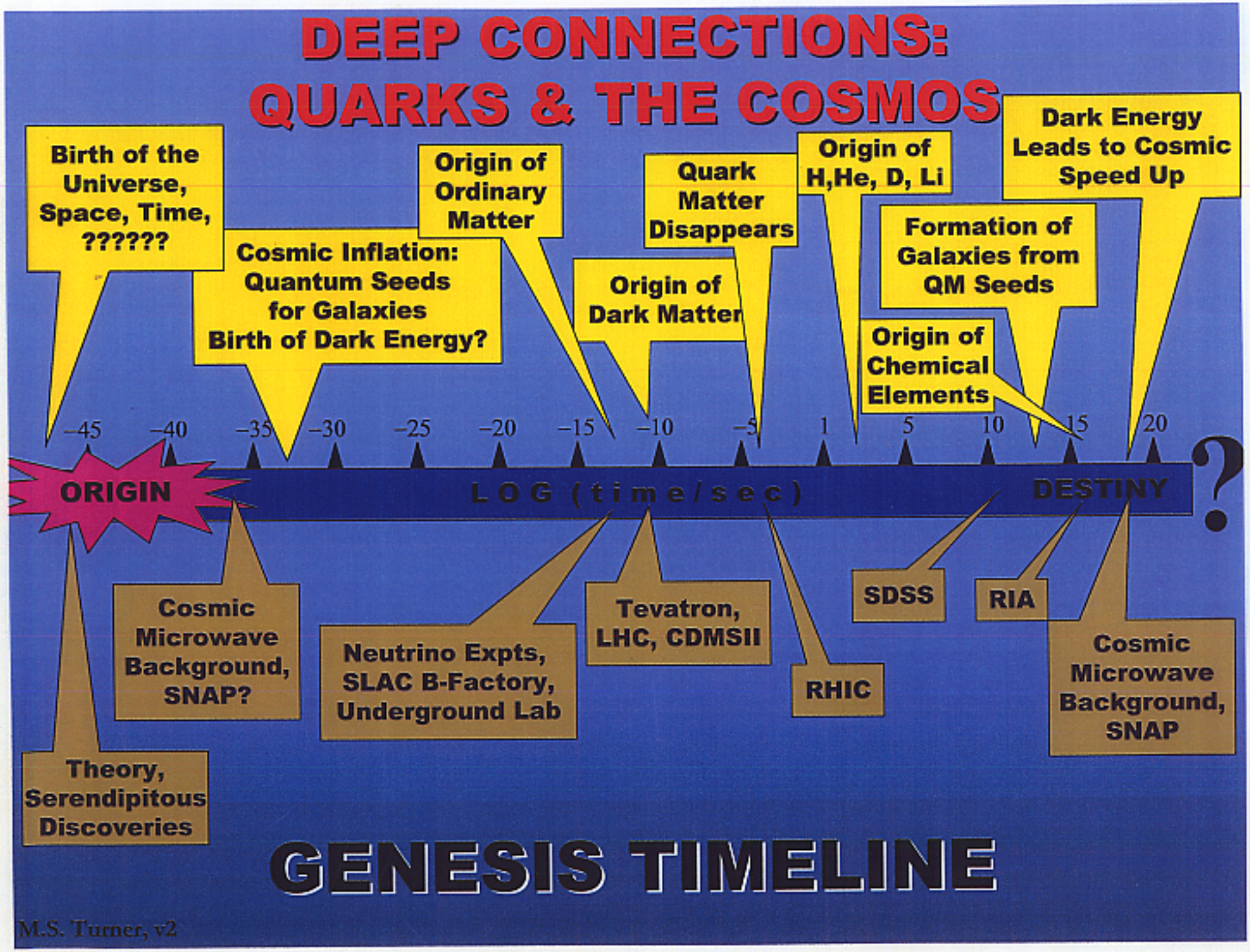
Campbell's
Quark
WITH LEPTONS AND GAUGE BOSONS
SOUP


DEEP CONNECTIONS:
QUARKS & THE COSMOS
Birth of the Universe, Space, Time, ??????
Cosmic Inflation: Quantum Seeds for Galaxies Birth of Dark Energy?
Origin of Ordinary Matter
Origin of Dark Matter
Quark Matter Disappears
Origin of H,He, D, Li
Origin of Chemical Elements
Formation of Galaxies from QM Seeds
Dark Energy Leads to Cosmic Speed Up
−45
−40
−35
−30
−25
−20
−15
−10
−5
1
5
10
15
20
ORIGIN
LOG (time/sec)
DESTINY
?
Theory, Serendipitous Discoveries
Cosmic Microwave Background, SNAP?
Neutrino Expts, SLAC B-Factory, Underground Lab
Tevatron, LHC, CDMSII
RHIC
SDSS
RIA
Cosmic Microwave Background, SNAP
GENESIS TIMELINE
M.S. Turner, v2

**Tadpole Galaxy • UGC 10214**

**Hubble Space Telescope • Advanced Camera for Surveys**

NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M. Clampin (STScI), G. Hartig (STScI) and the ACS Science Team • STScI-PRC02-11a

# DON'T LET THE BRIGHT LIGHTS FOOL YOU

# THE DARK SIDE CONTROLS THE UNIVERSE

OUR UNIVERSE

STARS: 0.5%

DARK MATTER: 33%

DARK ENERGY: 66%

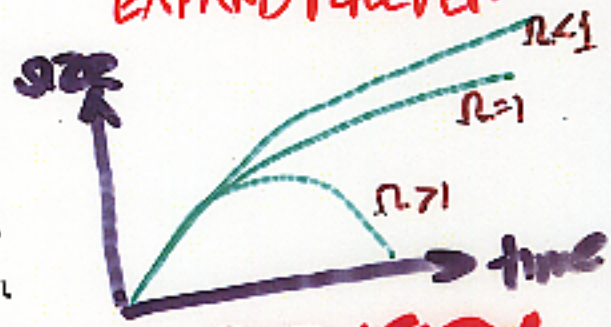
## DARK MATTER HOLDS IT TOGETHER

## DARK ENERGY DETERMINES ITS DESTINY

# EINSTEIN: CURVATURE-DENSITY CONNECTION

ALWAYS TRUE

| | | FATE IF MATTER ONLY |
|---|---|---|
| HIGH DENSITY | $\Omega_0 > 1$ | RECOLLAPSE |
| CRITICAL DENSITY | $\Omega_0 = 1$ | EXPAND FOREVER (BARELY) |
| LOW DENSITY | $\Omega_0 < 1$ | EXPAND FOREVER |




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

$= 1.88h^2 \times 10^{-29}\ g\,cm^{-3}$

$= 3H_0^2/8\pi G \approx 10^{-29}\ g/cm^3$

$\approx 10^{-29}$ gram/cm$^3$ $\sim$ $\frac{\text{1 PROTON}}{\text{15 LITERS}}$

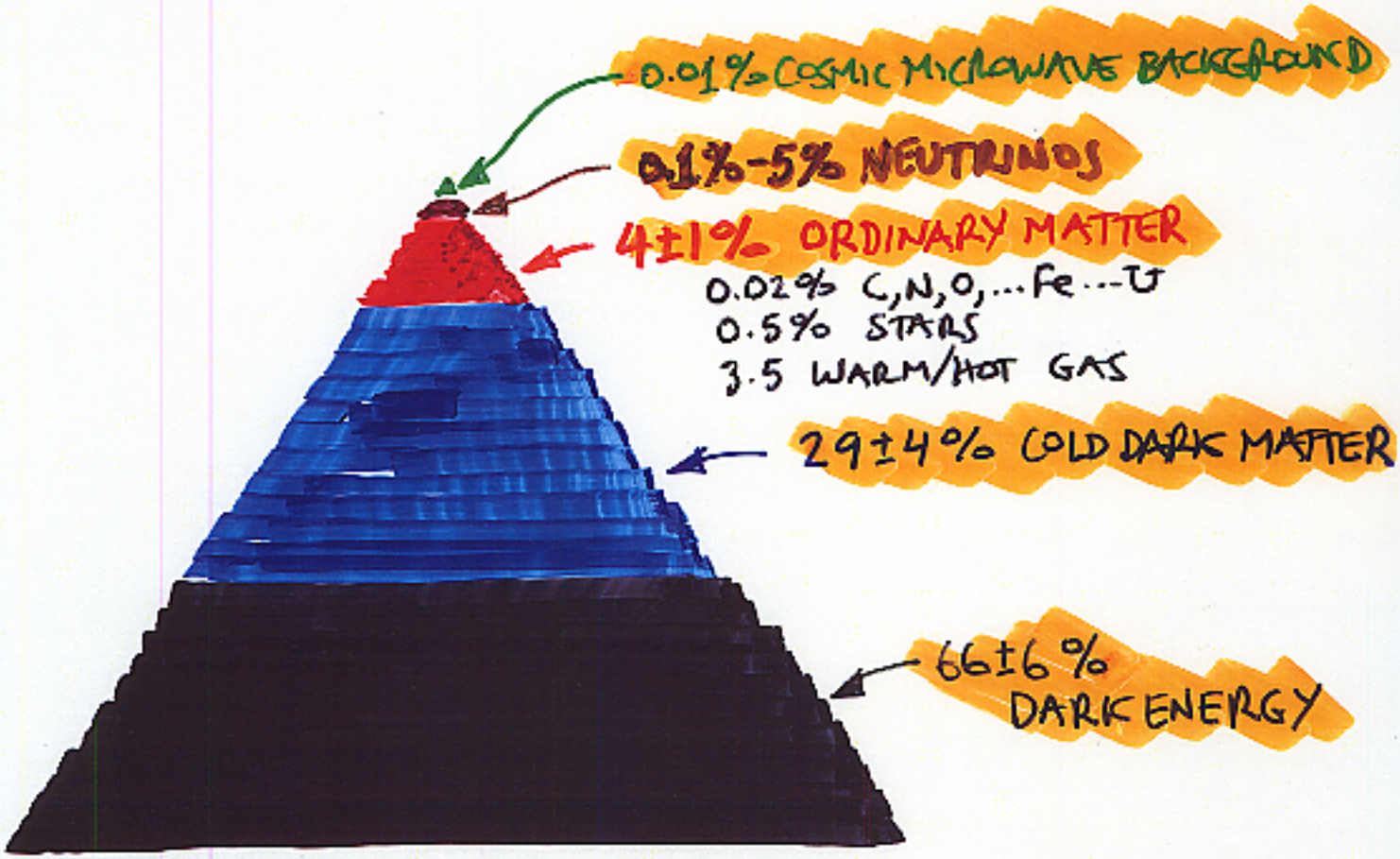
NB: $\Omega_0 = \sum_i \Omega_i$

# COSMIC RECIPE

## FLAT, CRITICAL DENSITY UNIVERSE

0.5% STARS

33% DARK MATTER + 66% DARK ENERGY




→ MORE THAN 95% IN NEW FORMS OF MATTER & ENERGY!

# CURVED SPACE

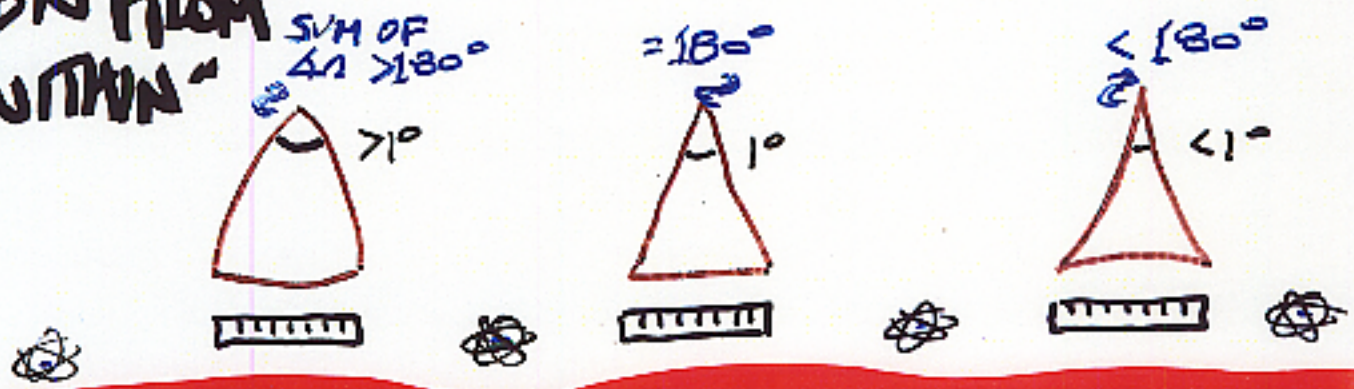
for flatlanders

## "VIEW FROM ABOVE"

3d LOOKING AT 2d

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

## "VIEW FROM WITHIN"




Universe at 450,000yr

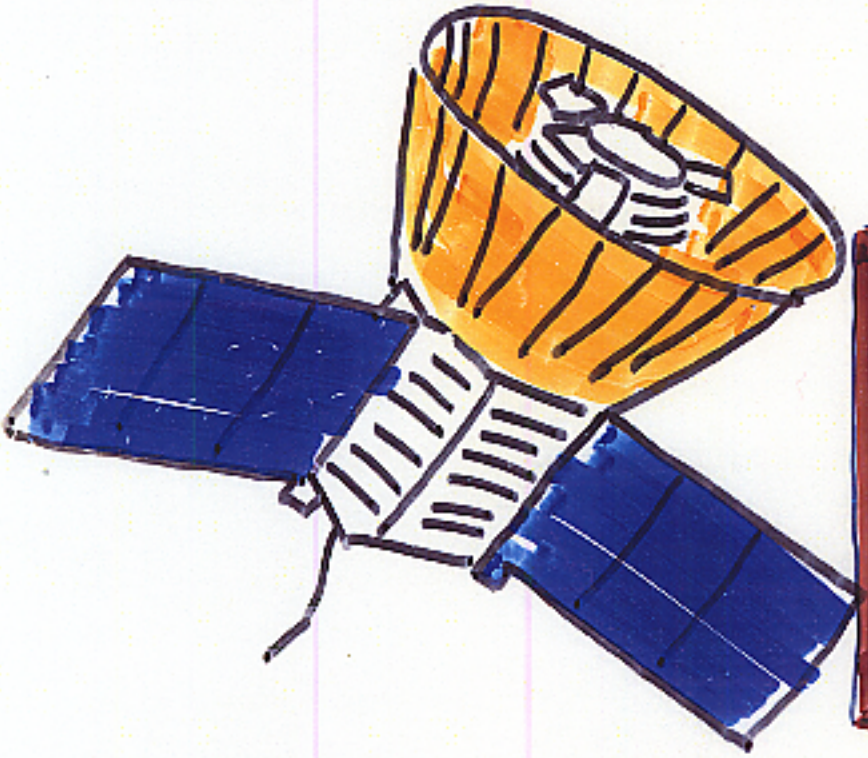
RULER: "STANDARD LUMP" OF MATTER

CMB

OUR UNIVERSE

# COBE

23 April 1992

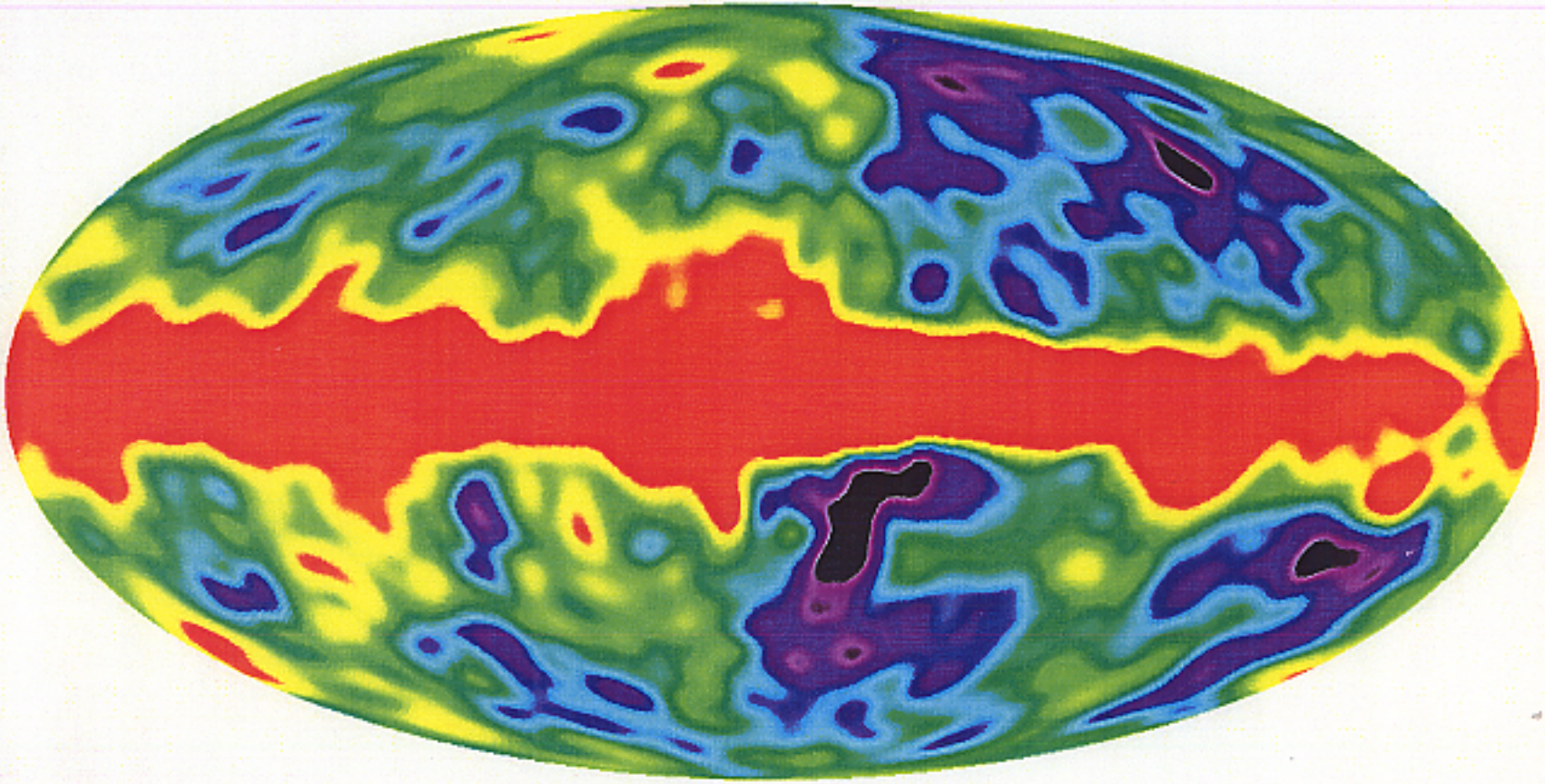


$$\frac{\delta T}{T} \approx 10^{-5}$$

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

# WOW!

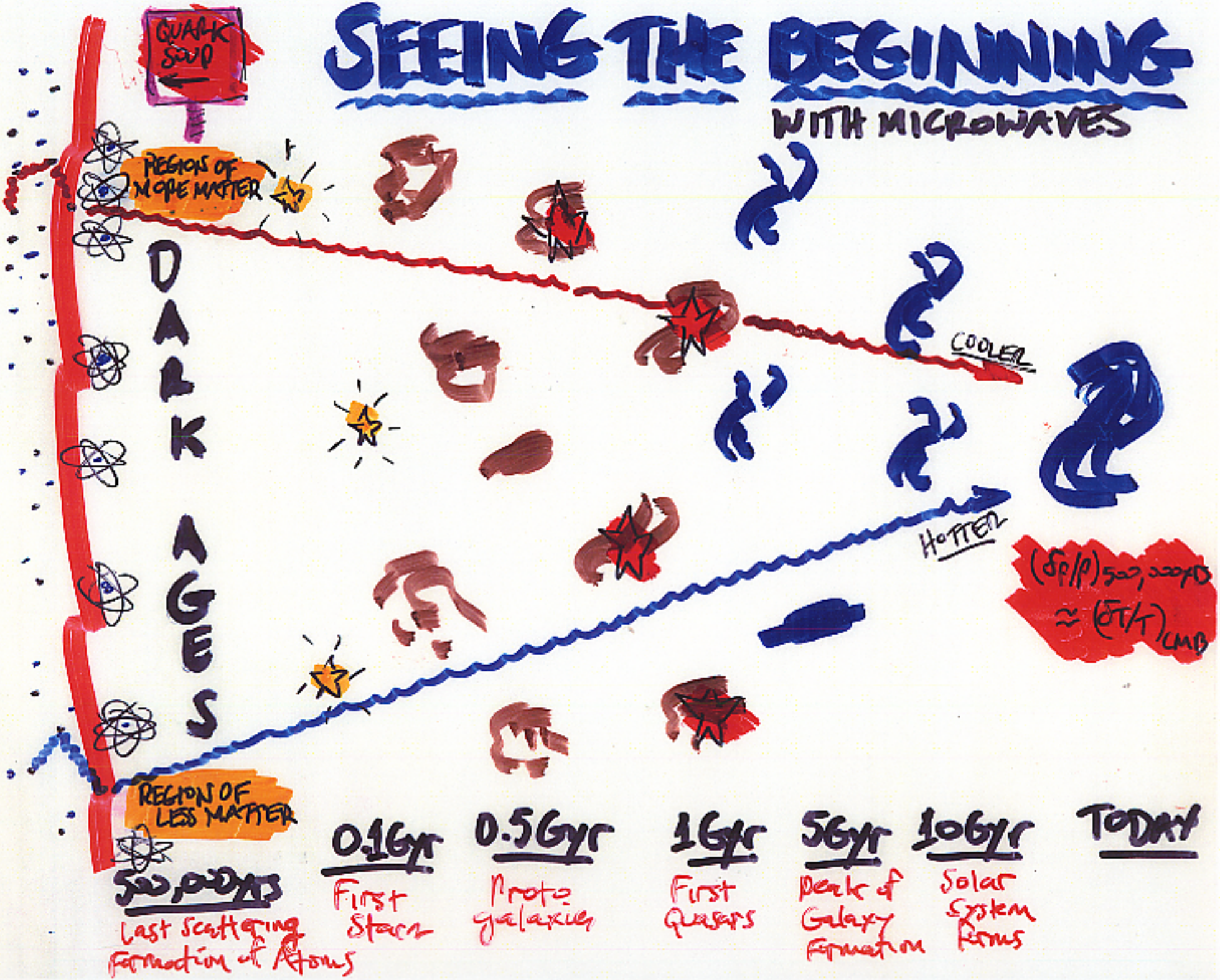
# MAP OF UNIVERSE AT 300,000 YRS



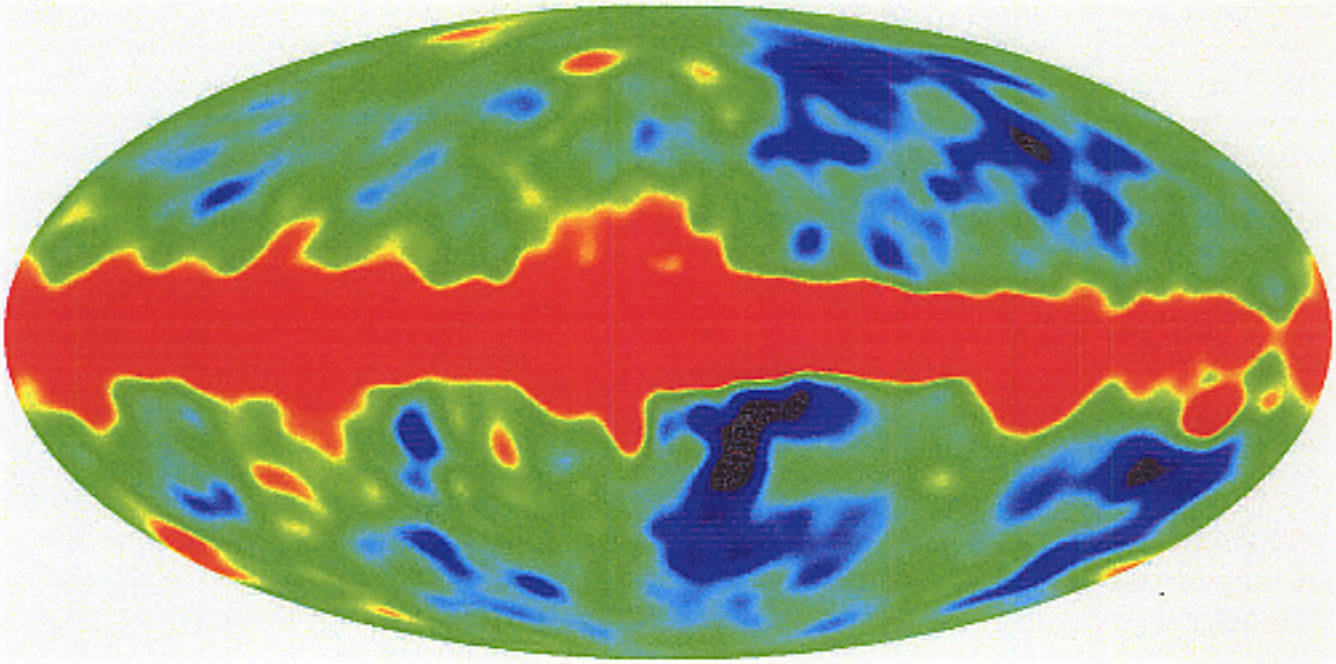
MADE BY COBE

# SEEING THE BEGINNING

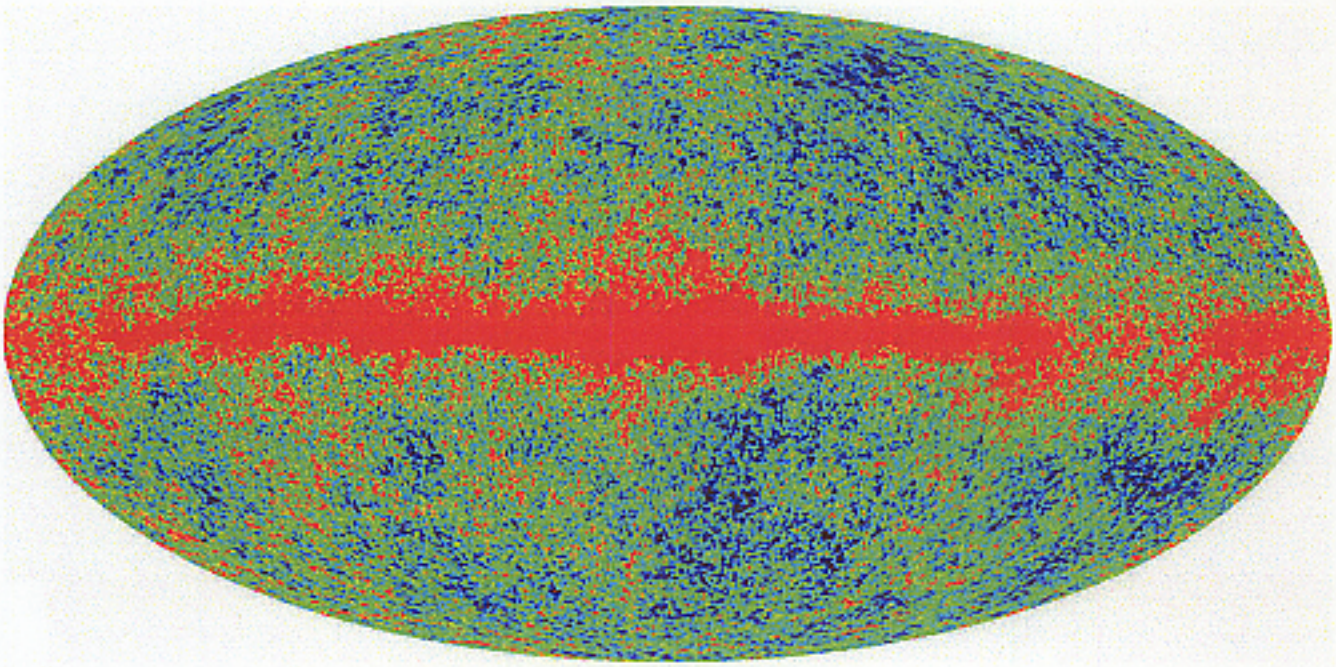
## WITH MICROWAVES

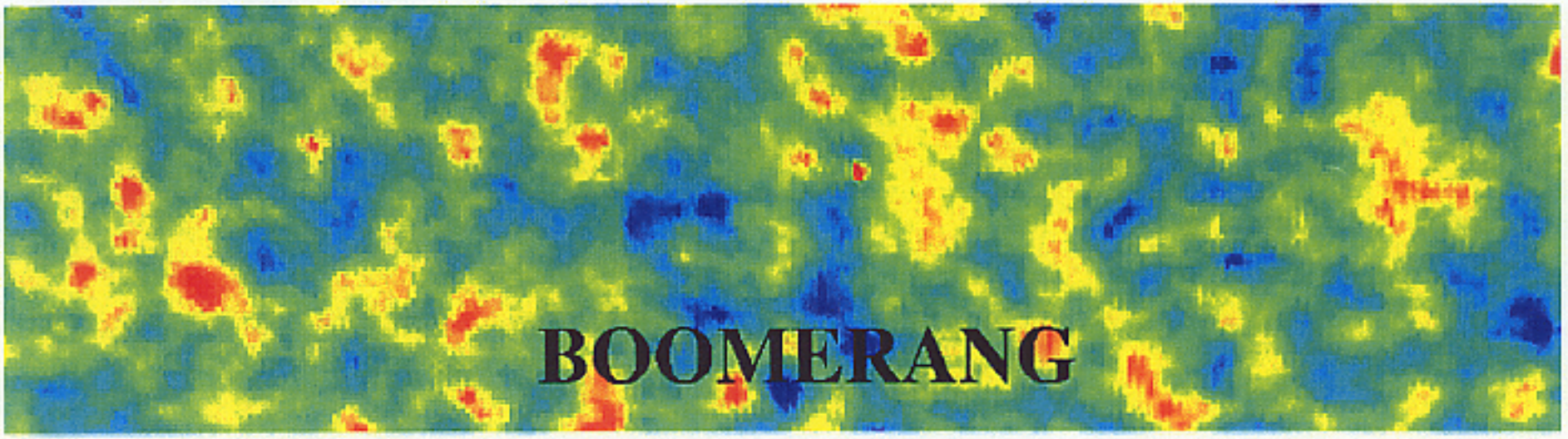


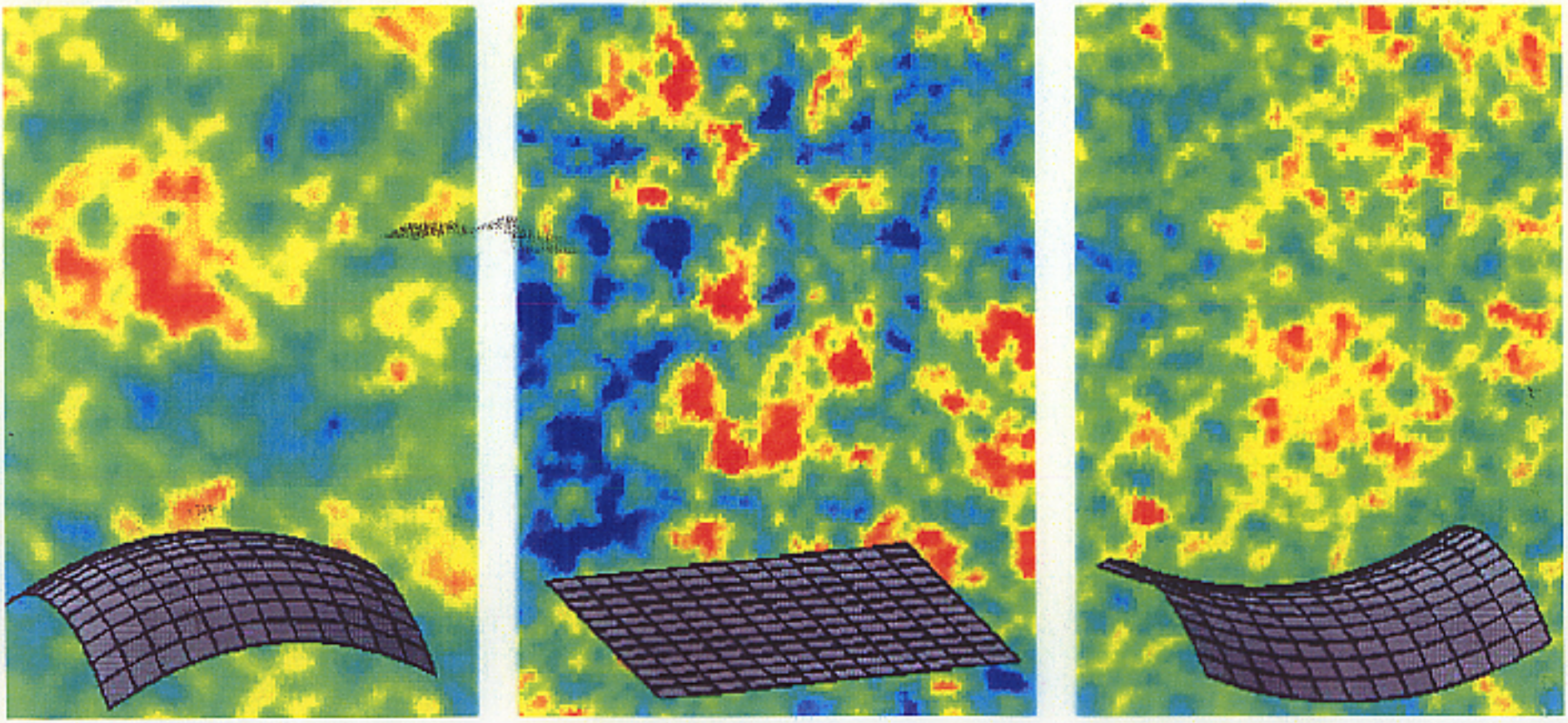
## COBE DMR 4–Year Sky Map



## MAP Simulated Sky Map

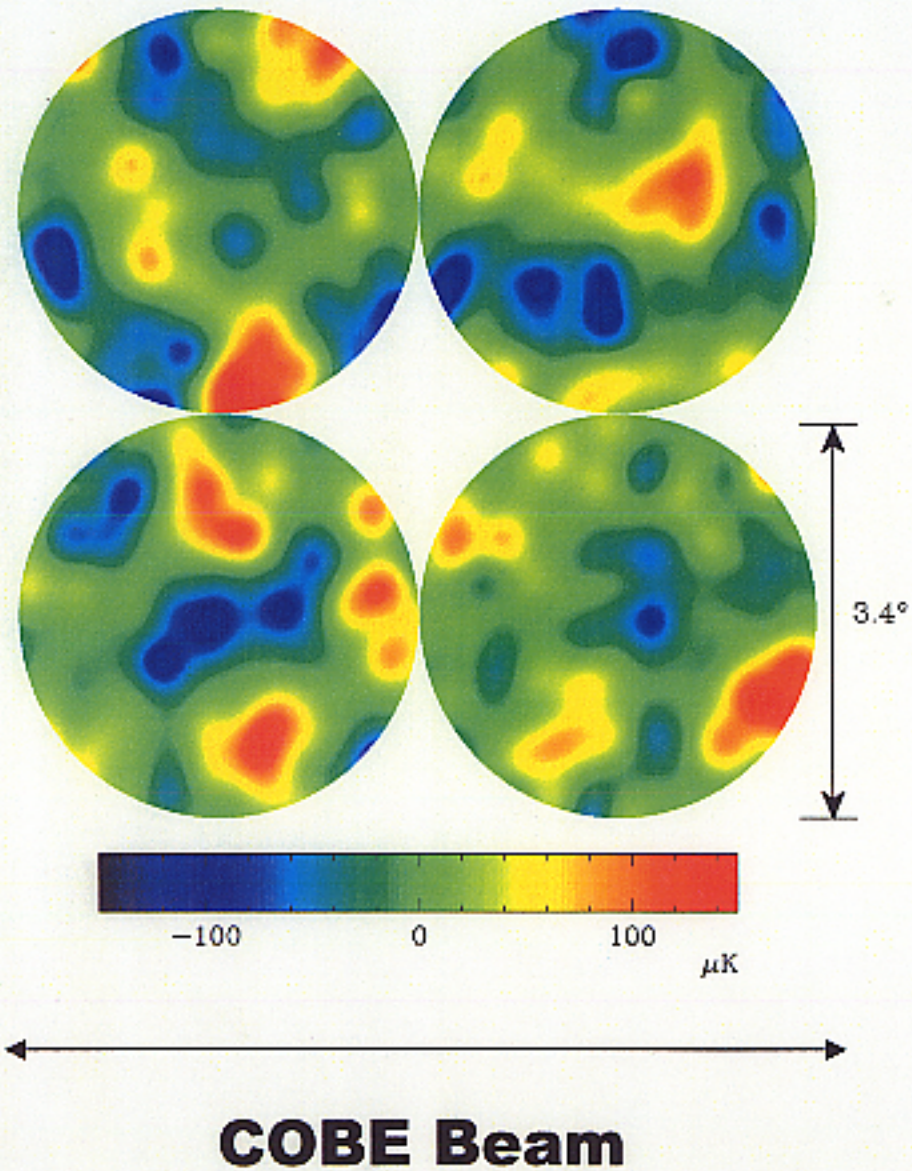



BOOMERANG



DASI AT SOUTH POLE SUNSET MAY 2000

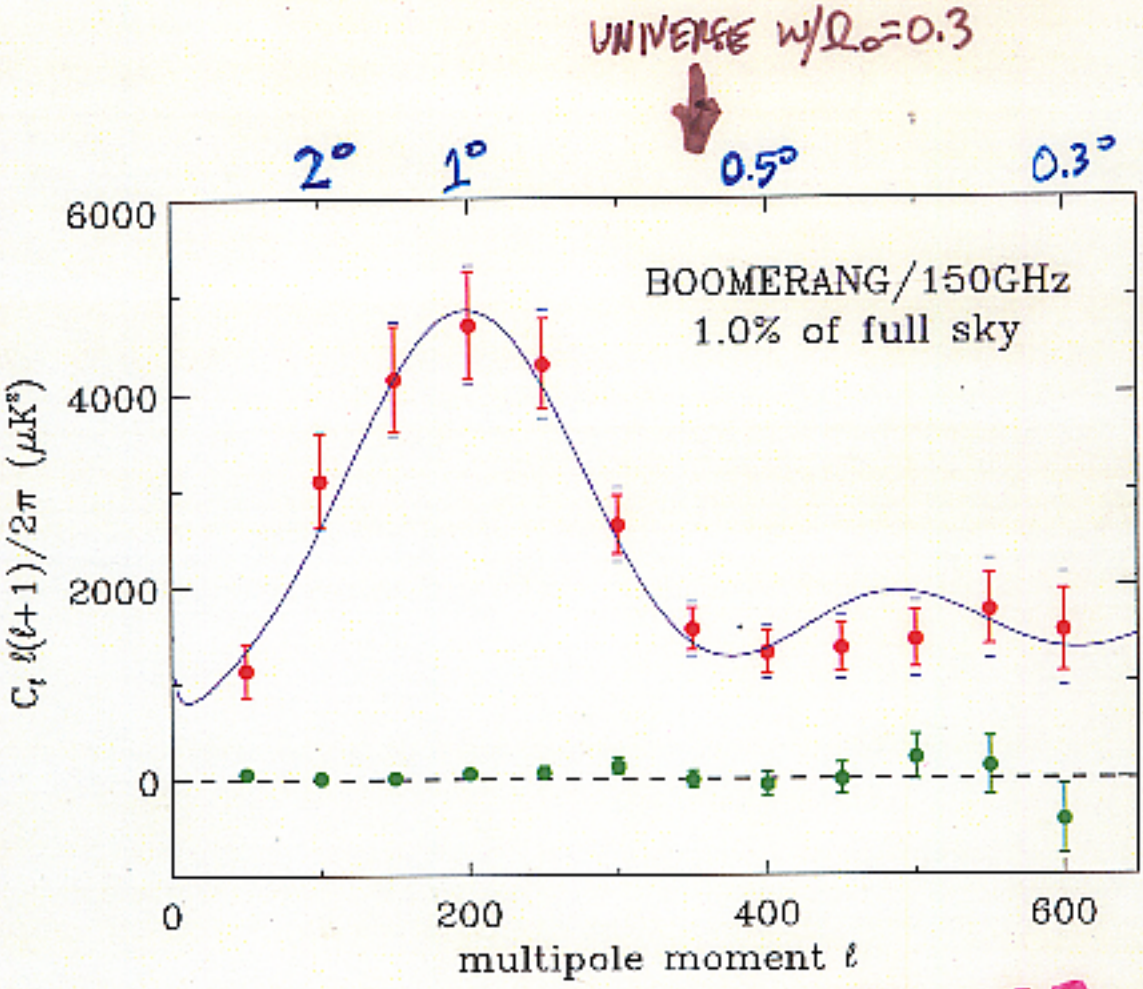
10




## DASI Revealed additional detail, which implied

- Universe is flat
- Exotic dark matter accounts for 30% of the Universe
- Ordinary Matter accounts for only 4% of the Universe
- Evidence that the seeds for the largest objects came from quantum fluctuations

**Last two confirmed predictions of UC theorists**




**CURVE:** $\Omega_0 = 1.1$

**FIT:** $\Omega_0 = 1 \pm 0.06$

$h = 0.99 \pm 0.06$

THE UNIVERSE IS FLAT!

April 2000

**NB:** FIT TO ACOUSTIC OSCILLATIONS

REDUCED $\chi^2 < 1$

# EVIDENCE for DARK MATTER

## ITS GRAVITY IS:

NEEDED TO HOLD GALAXIES TOGETHER

V. RUBIN ET AL '70s

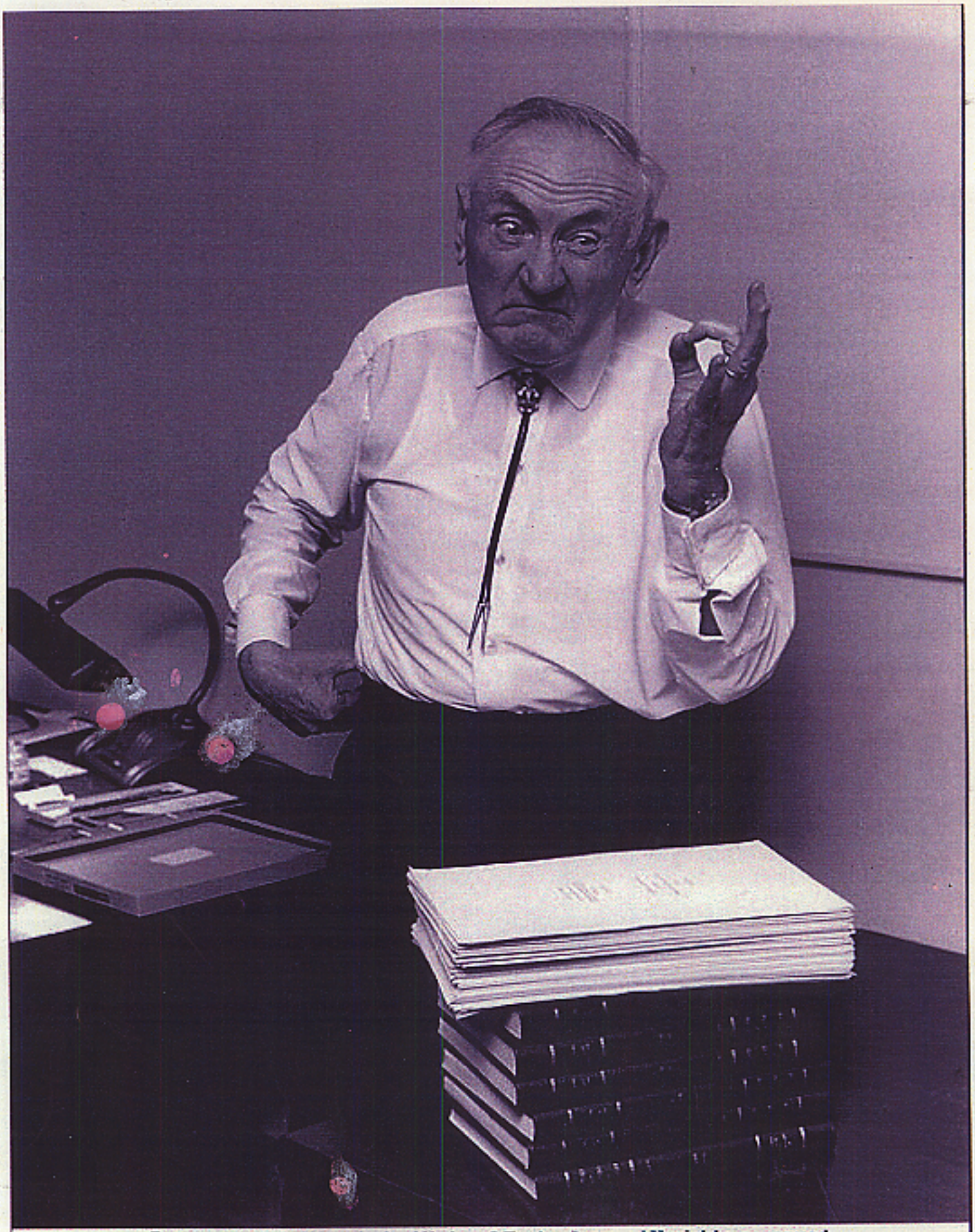
NEEDED TO HOLD CLUSTERS TOGETHER

ZWICKY '35

"LEO"

ACCELERATE OUR GALAXY TO 620 KM/SEC

DARK MATTER CONTRIBUTES 20%-50%



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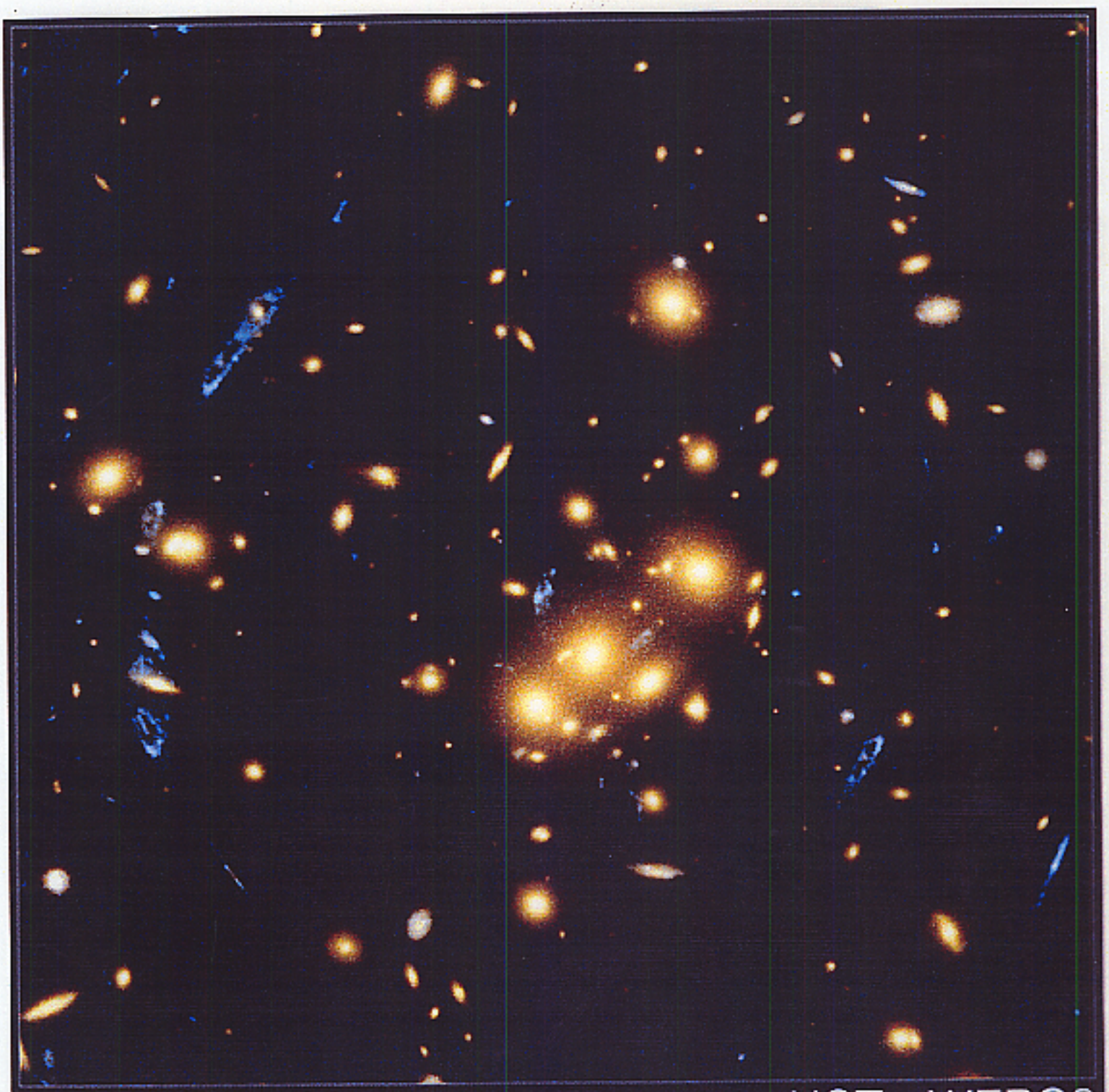
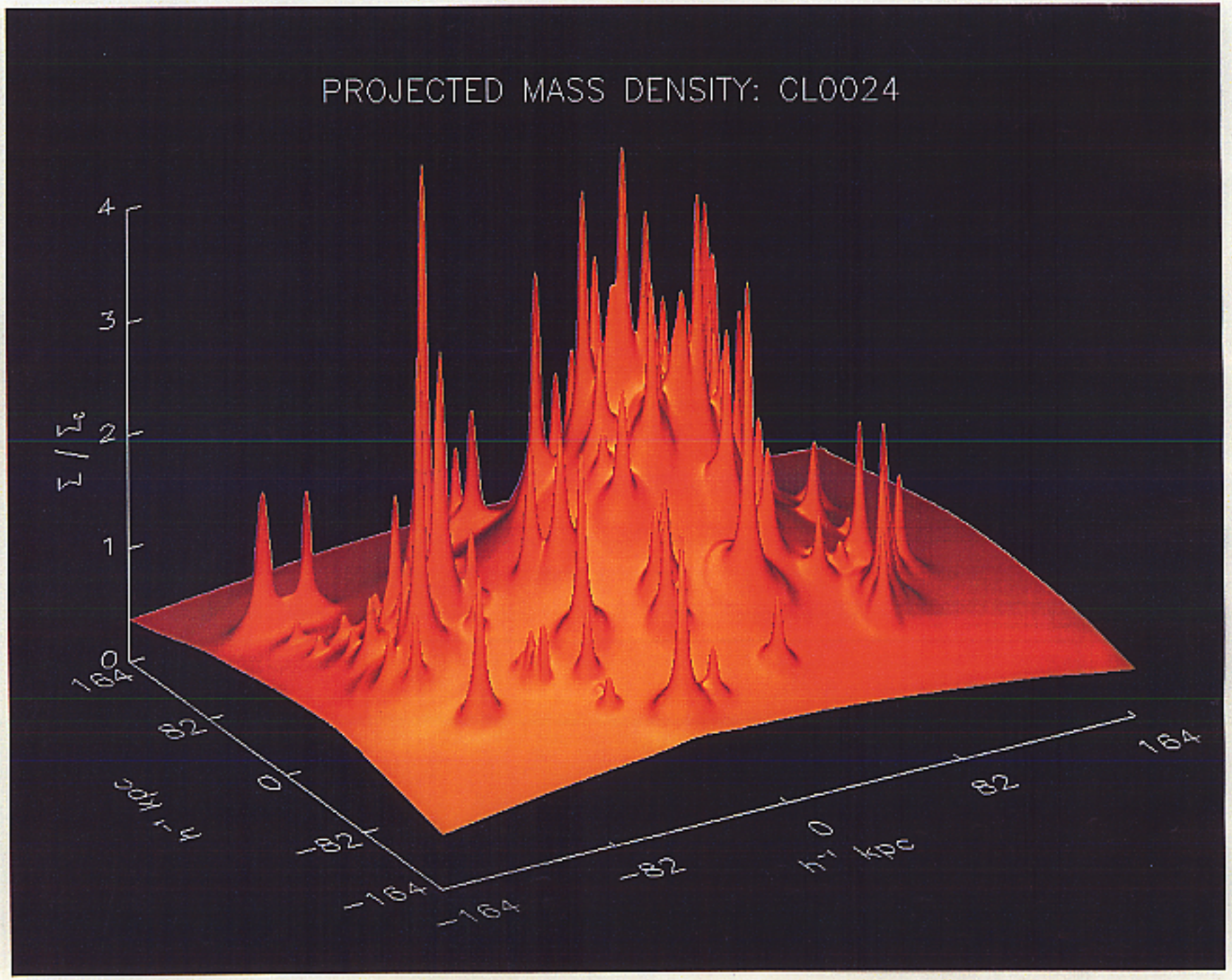


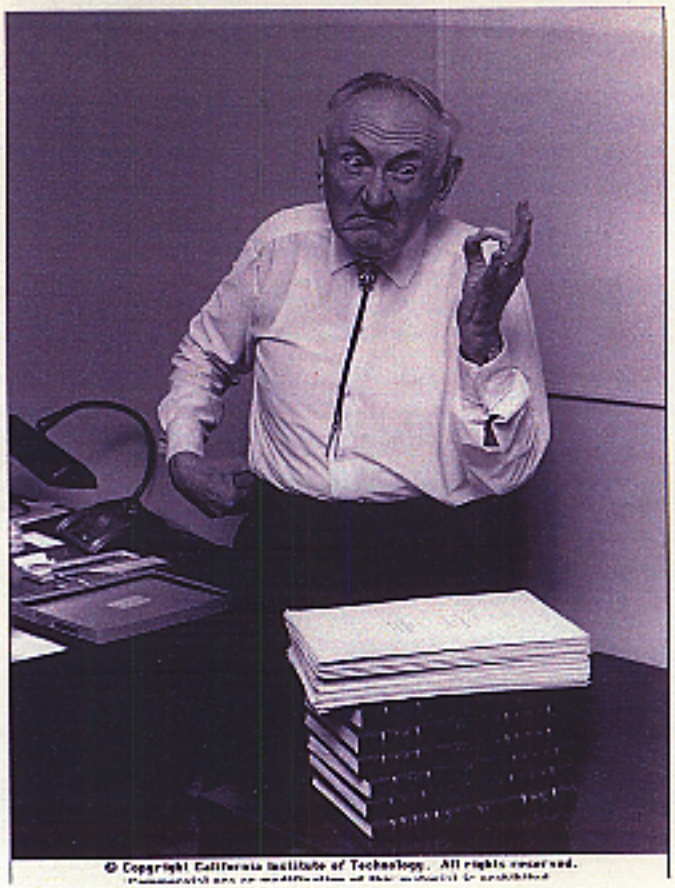
HST • WFPC2

# Gravitational Lens Galaxy Cluster 0024+1654

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


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



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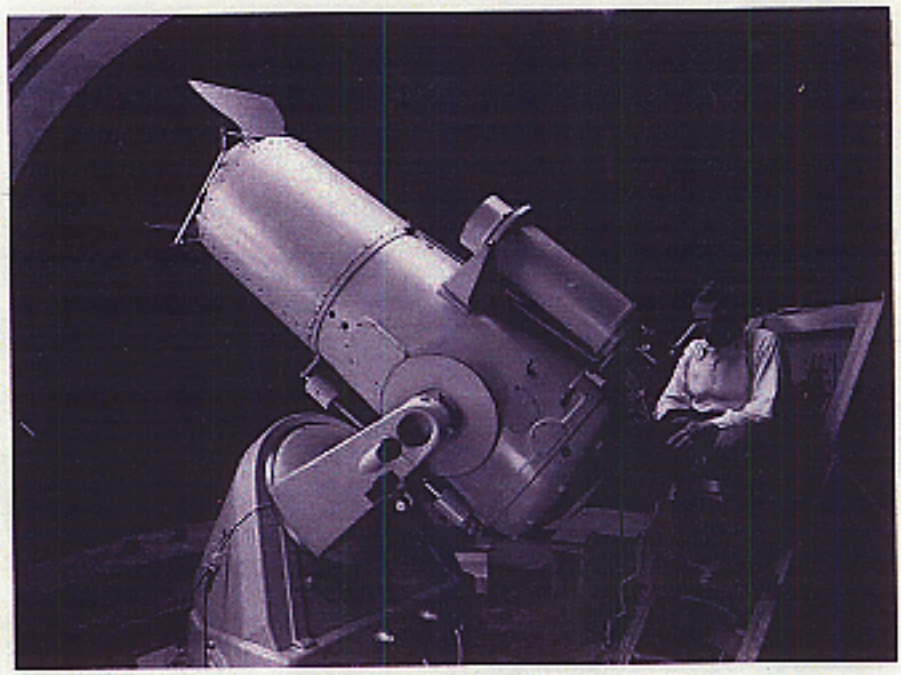
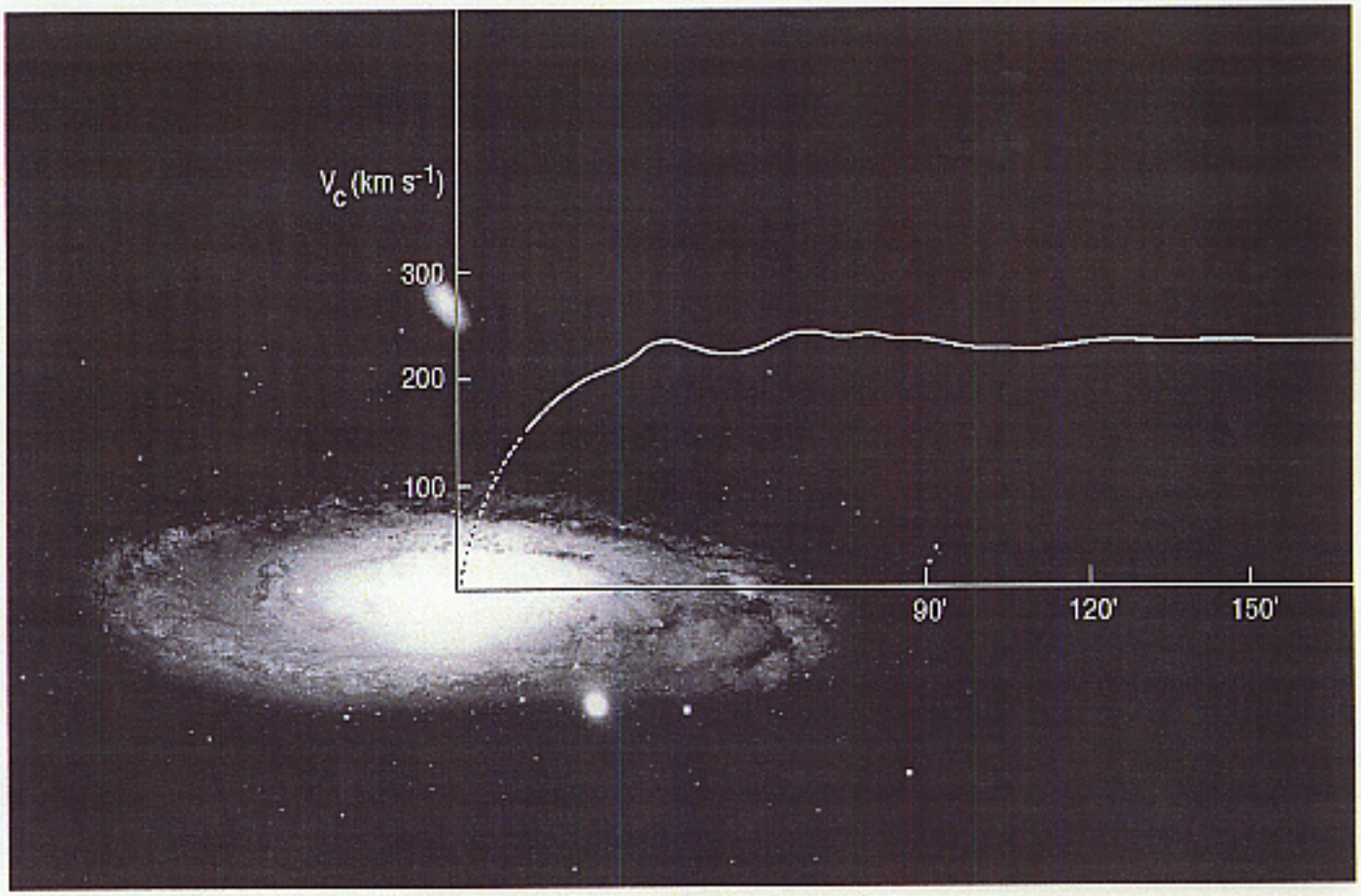


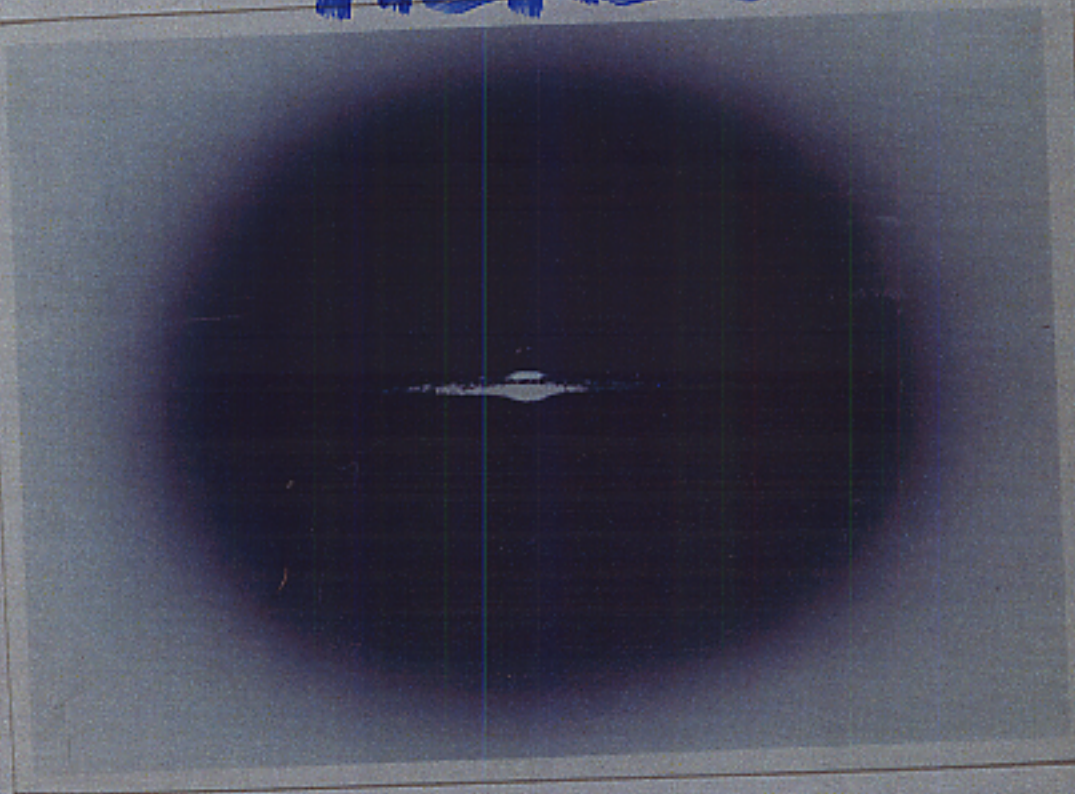
# Flat Rotation Curves: The Light Ends, but the Effect of Gravity Continues ... (hence, DARK MATTER)

Our Neighbor, The Andromeda Galaxy

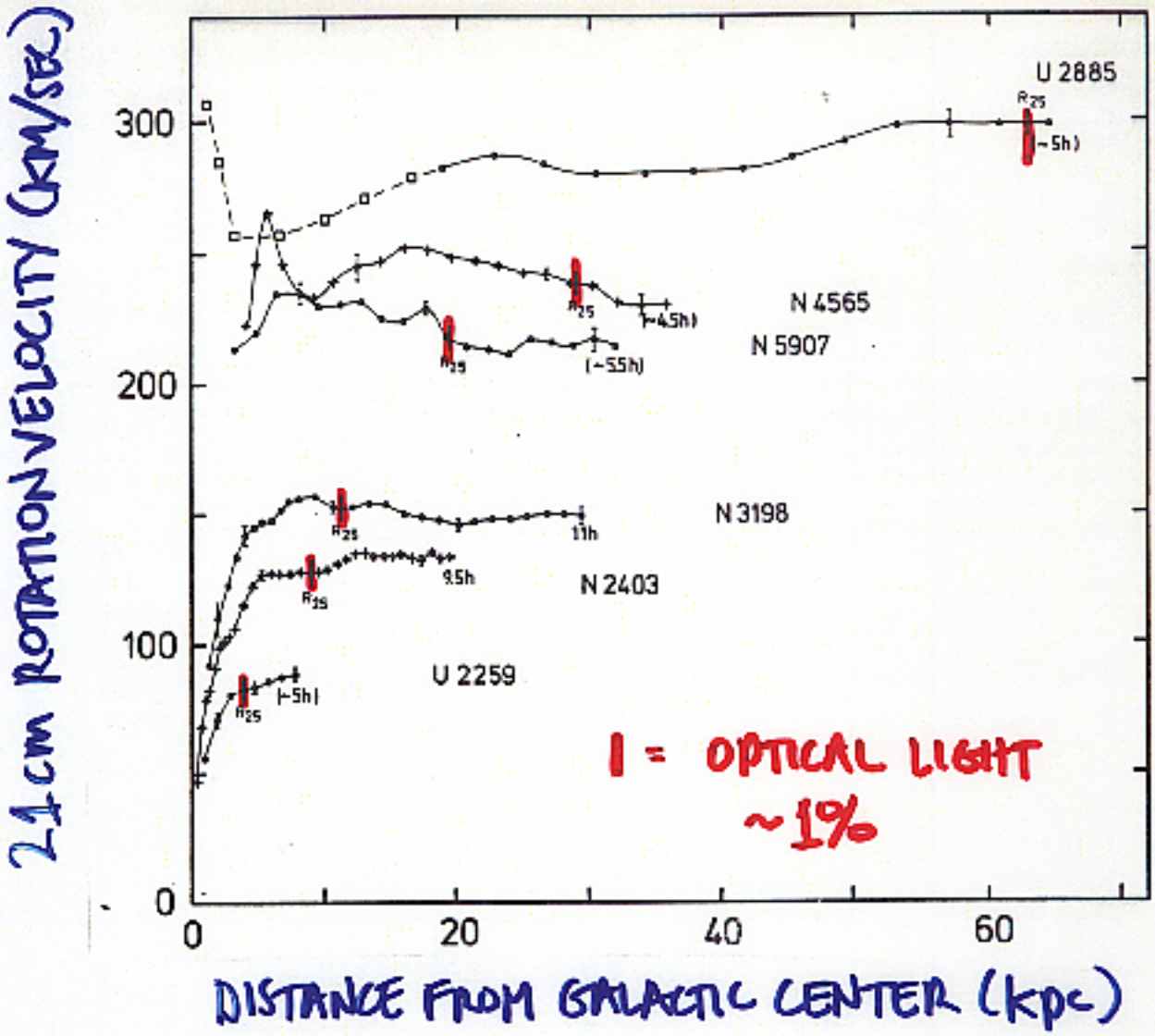



-- Courtesy of M. Roberts

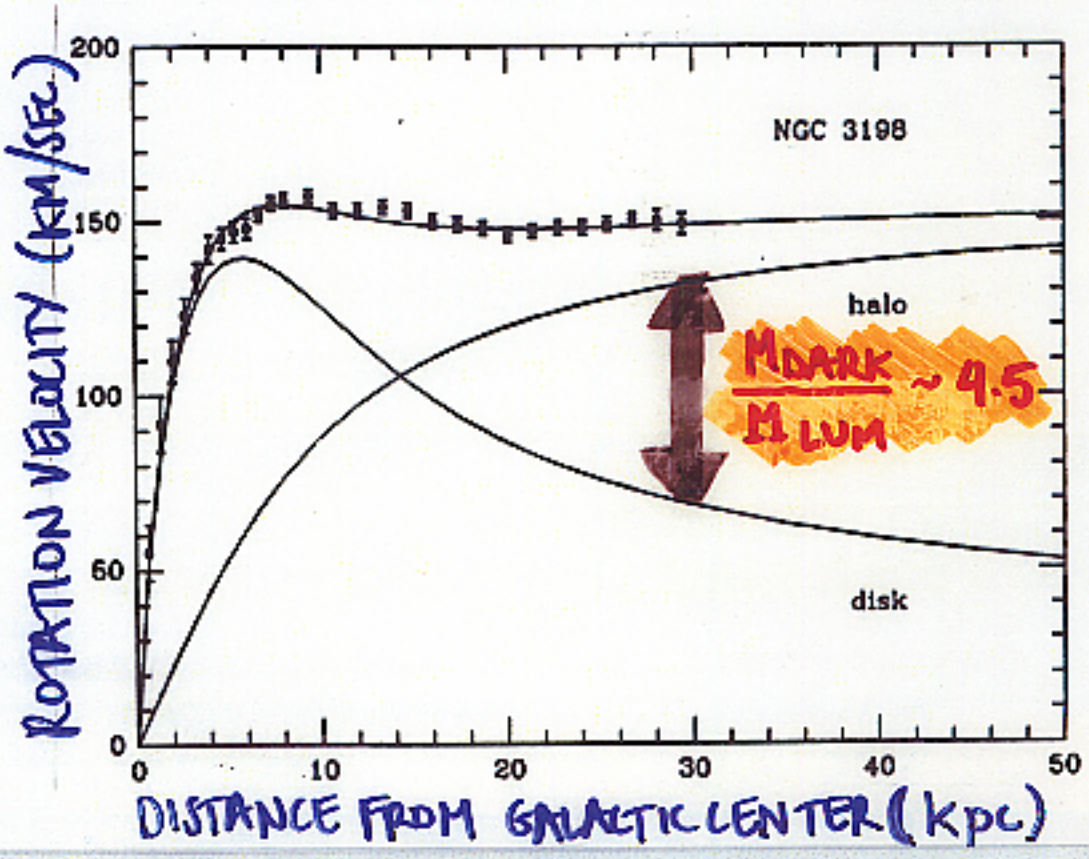
LOTS OF DARK MATTER-RIGHT HERE!



SANCISI - VAN ALBADA, IAU117

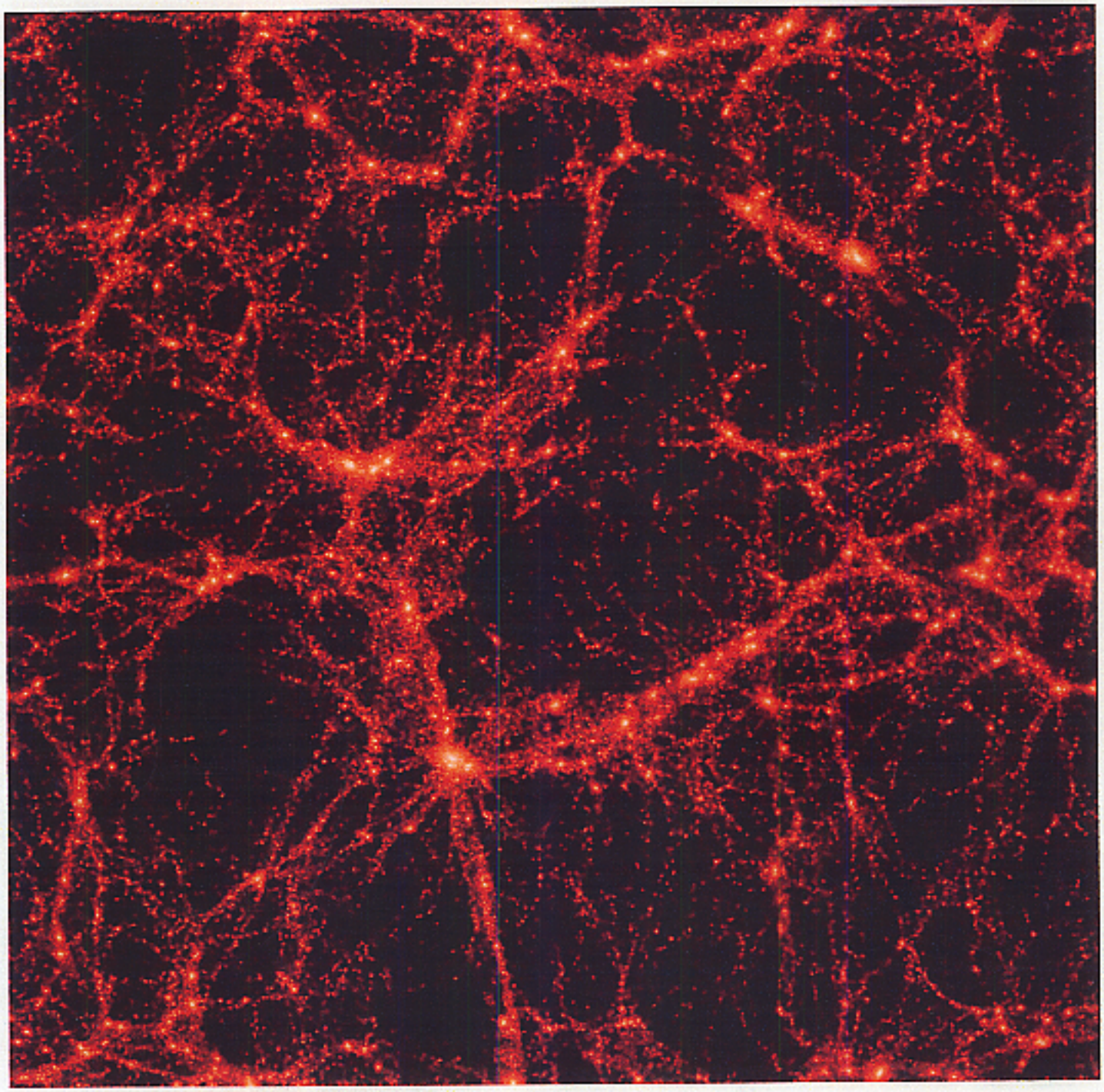



MODELLING



# COSMIC WEB OF DARK MATTER

from Virgo Project



# ORDINARY MATTER: FROM QUARKS TO US

INFLATION
BARYOGENESIS

$q\bar{q}\,Q\bar{Q}\,q\bar{q}\,\bar{Q}q\,q\bar{q}\,\bar{Q}q\,Q\bar{Q}\,q\bar{q}$

$10^{-5}$ SEC

TRANSITION FROM QUARKS → NEUTRONS, PROTONS

100 SEC

BIG-BANG NUCLEOSYNTHESIS

Formation of H, D, He, He-3, Li

BBN

$D/H = (3 \pm 0.2) \times 10^{-5}$

$\Downarrow$

$\Omega_B = 0.04 \pm 0.002$

FORMATION OF ATOMS

COSMIC MICROWAVE BACKGROUND

400,000 YRS

QSO LIGHT

1 BILLION YRS

FIRST QUASARS

$(\delta\rho/\rho)^2$ TODAY

$\Omega_B/\Omega_M = 0.15 \pm 0.07$

$\Omega_M h = 0.20 \pm 0.03$

$\Omega_B = 0.04 \pm 0.02$

CMB

CMB

RATIO OF FIRST-TO-SECOND PEAKS: 2/1

$\Downarrow$

$\Omega_B = 0.045 \pm 0.006$

INTERGALACTIC GAS

ABSORPTION OF QUASAR LIGHT BY HYDROGEN:

$\Omega_B \geq 0.04$

HERE & NOW

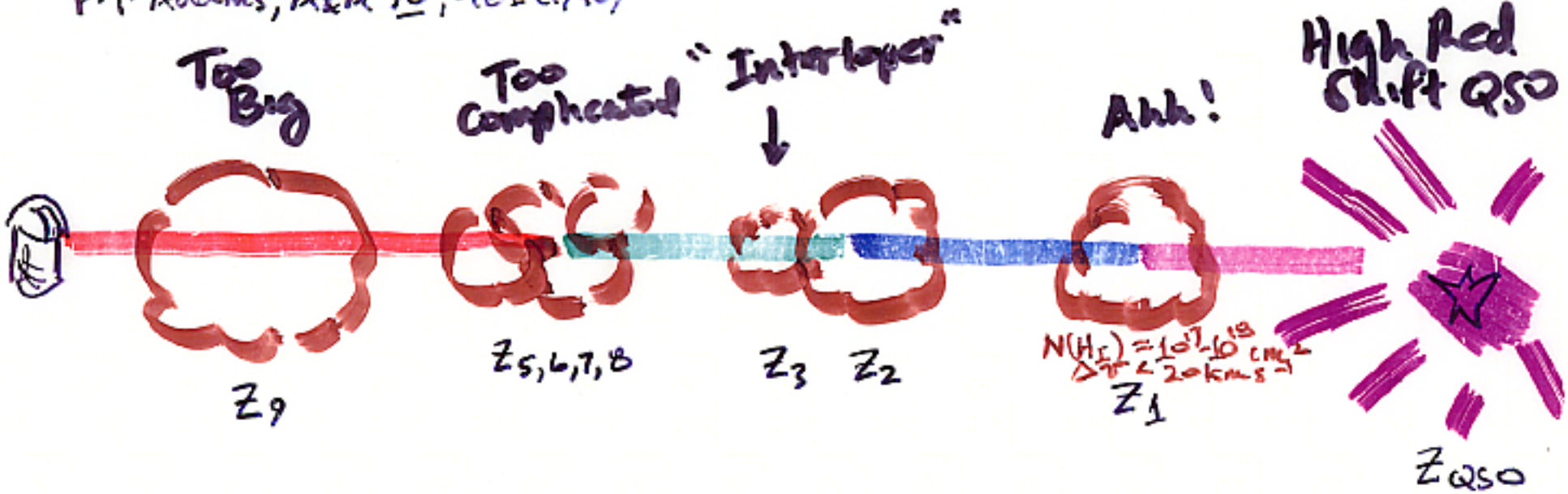
14 Billion YRS

stars, gas, dust, ...

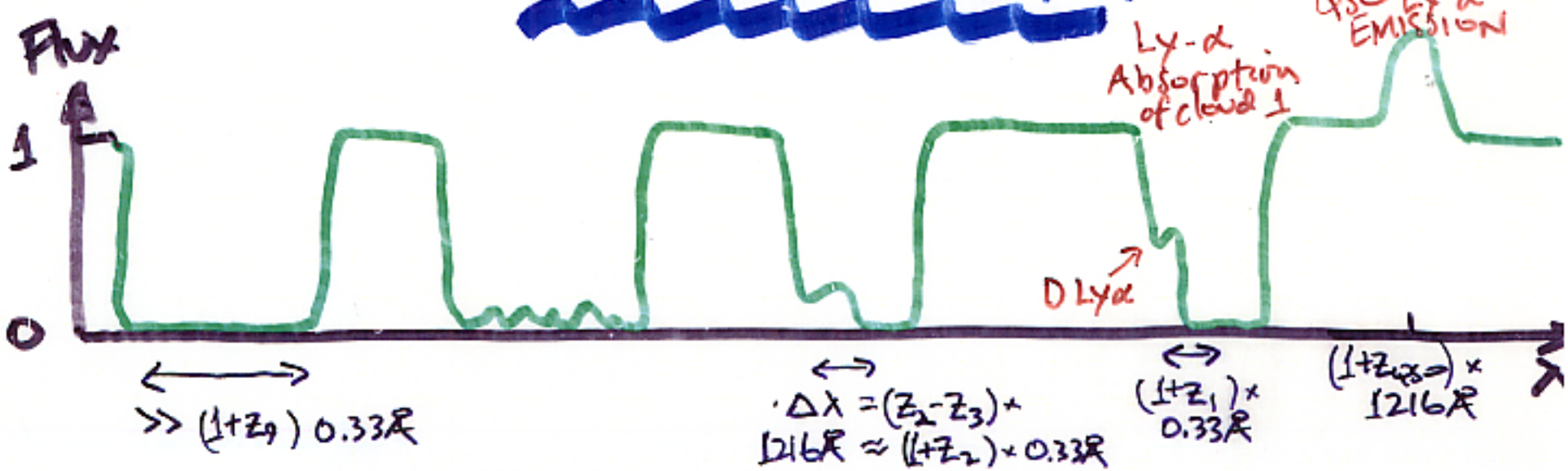
BHs, NSs, Pennsylvania ...

# Hi Clouds Backlit by QSO "Seen" in Absorption

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

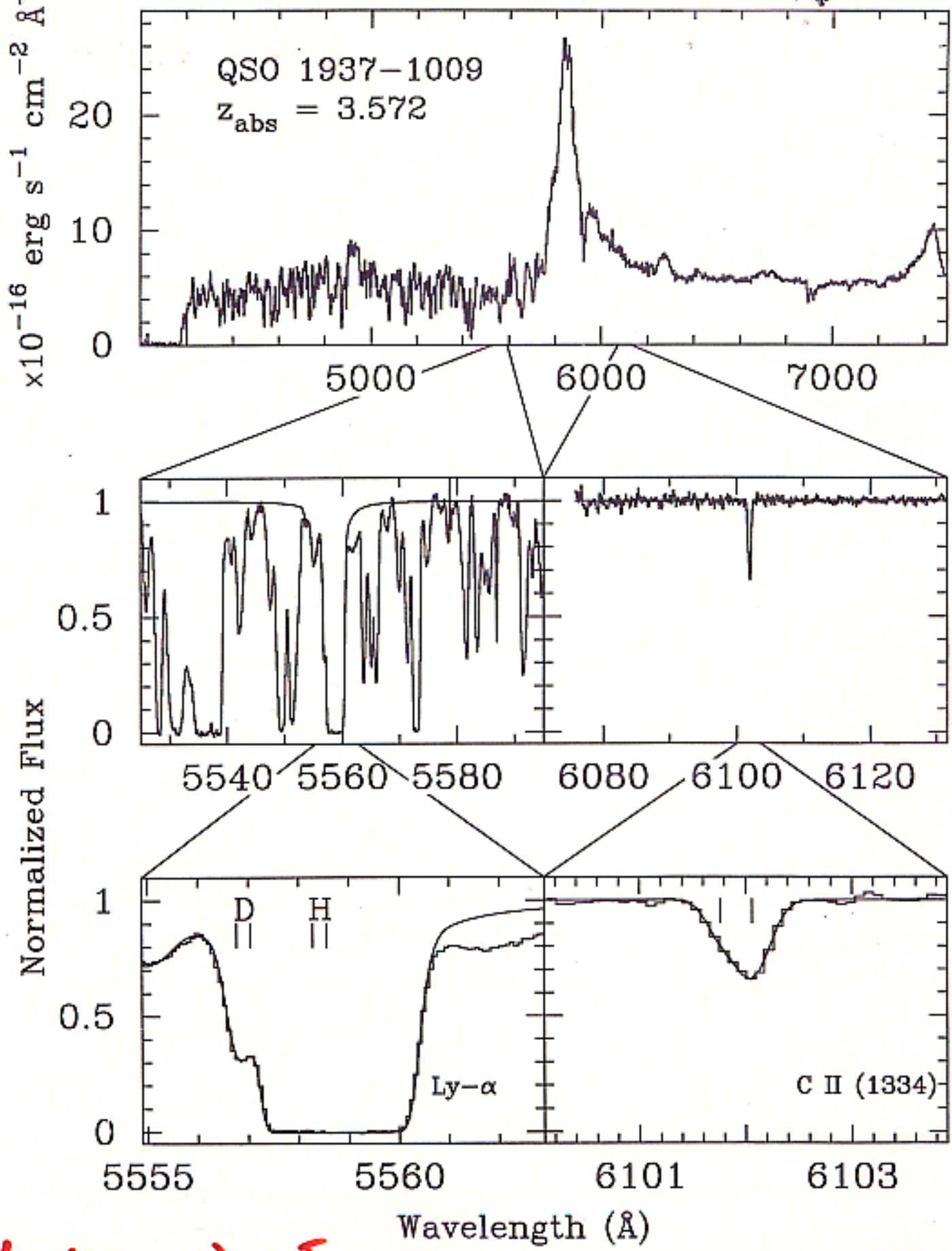



# SPECTRUM



# 10m KECK TELESCOPE

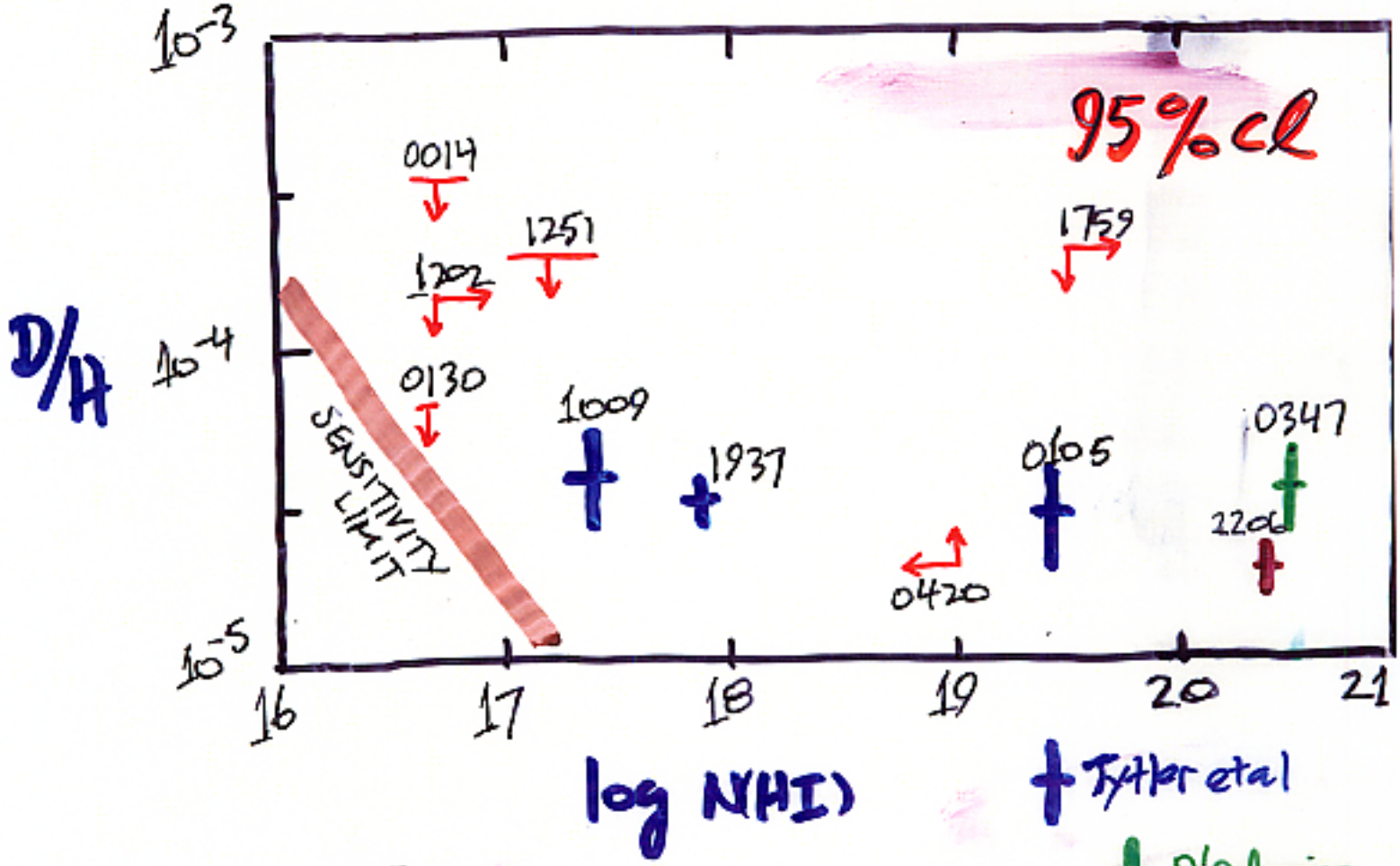
D. Tytler, S. Burles
Ap. J. 98




$D/H = (3.4 \pm 0.3) \cdot 10^{-5}$

NB: FOUR OTHER SYSTEMS SUPPORT THIS CONCLUSION

# DEUTERIUM



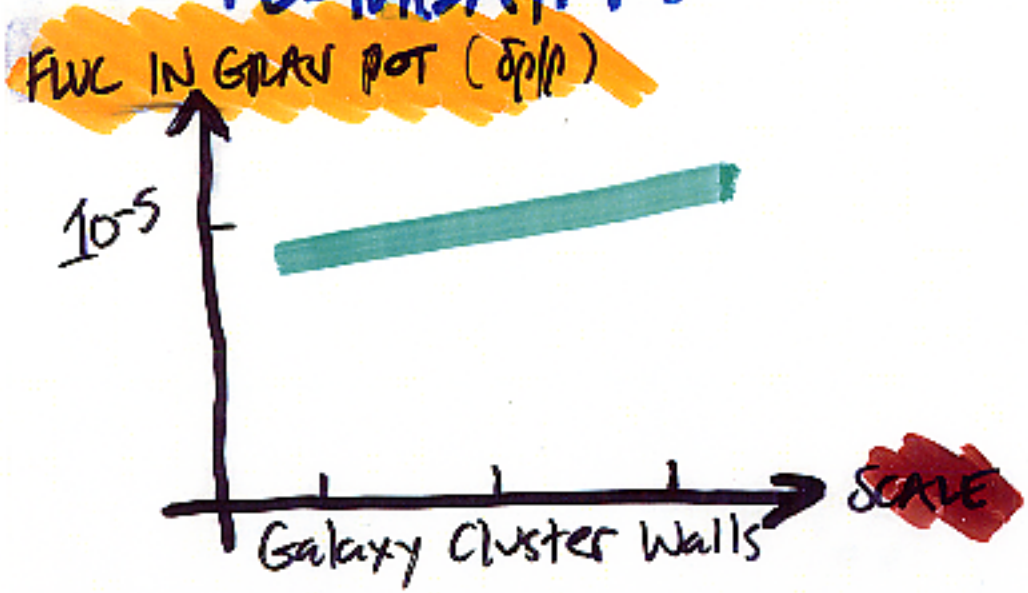

~~FOUR~~ 5 DETECTIONS

... MORE COMING

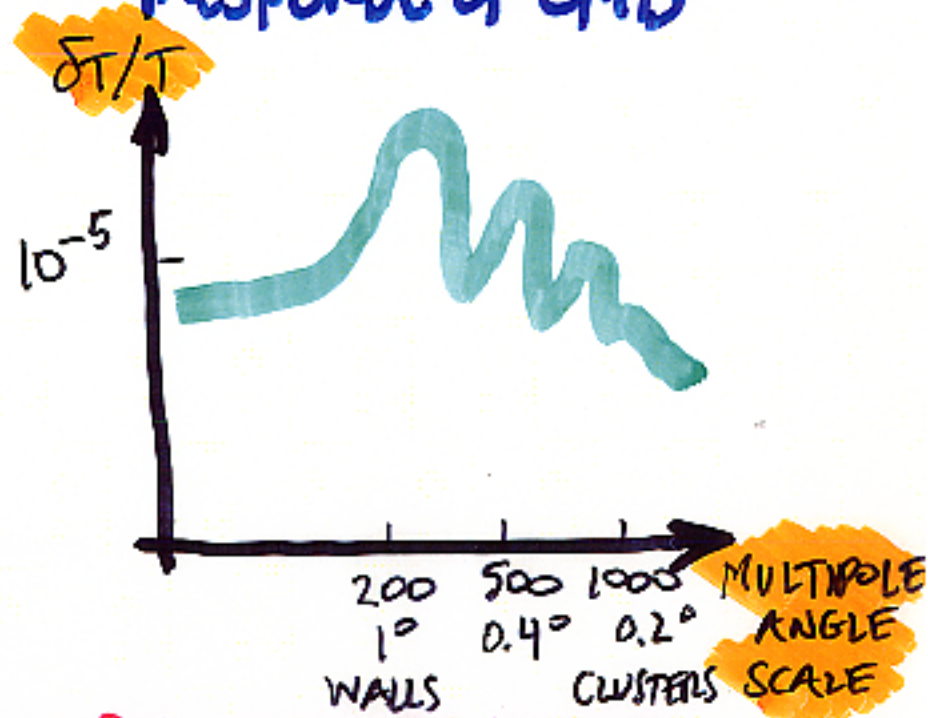
$$(D/H)_p = (3.0 \pm 0.4) \times 10^{-5} \quad (95\% \text{ cl})$$

# CMB IS A NON TRIVIAL PROBE OF MATTER DENSITY

UNDERLYING DENSITY PERTURBATIONS




"RESPONSE OF CMB"

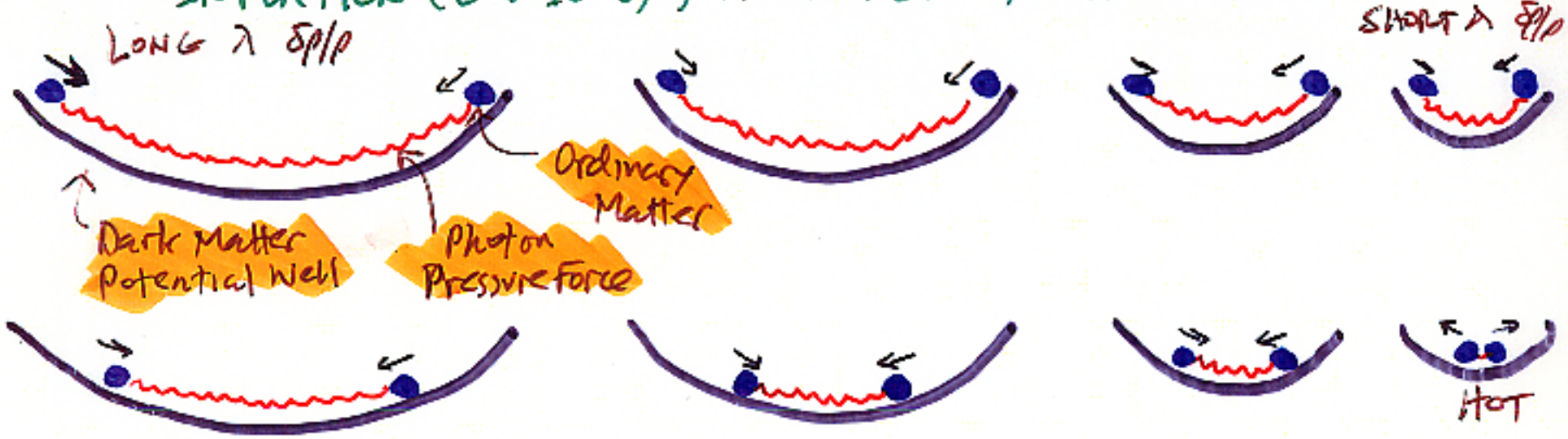



RESPONSE DEPENDS UPON: MATTER & BARYON DENSITIES, CURVATURE, DARK ENERGY ... & PRIMEVAL $\delta\rho/\rho$

→ PROBES COSMOLOGY!

# GRAVITY DRIVEN ACOUSTIC OSCILLATIONS

(1) SPECTRUM OF DENSITY PERTURBATIONS, CREATED DURING INFLATION ($t \ll 10^{-2}$ s); ALL MODES SYNCHRONIZED




(2) ORDINARY MATTER FALLING IN, RESISTED BY PHOTON PRESSURE

(3) CMB: SNAPSHOT AT 400,000 YRS

First Peak ≈1° L

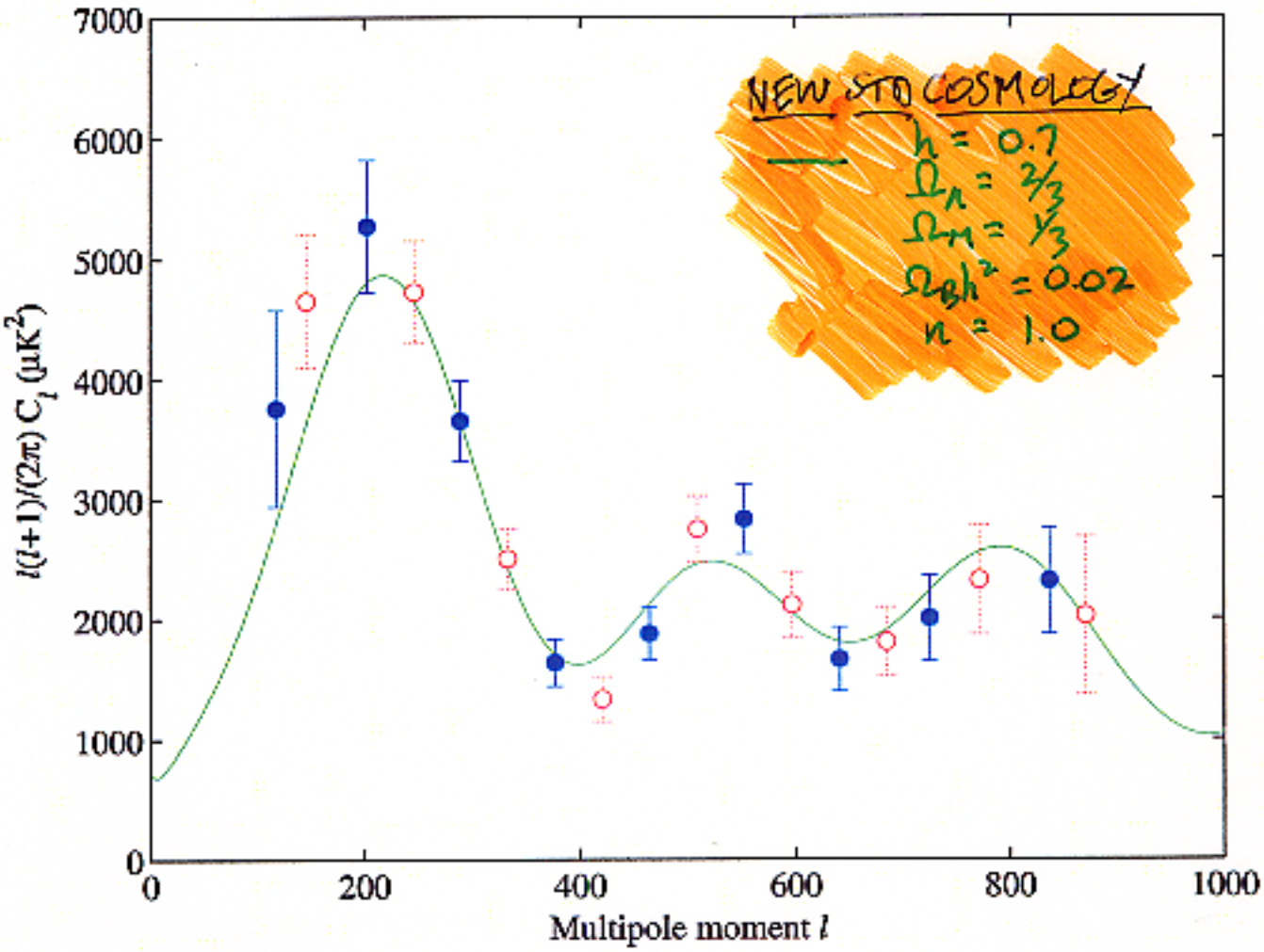
3/4 L

2nd Peak L/2 ≈½°

3rd Peak L/3 ≈⅓°

# DASI 2001

C. Pryke et al astro-ph/0104490
N. Halverson et al 0104489
E. Leitch et al 0104488



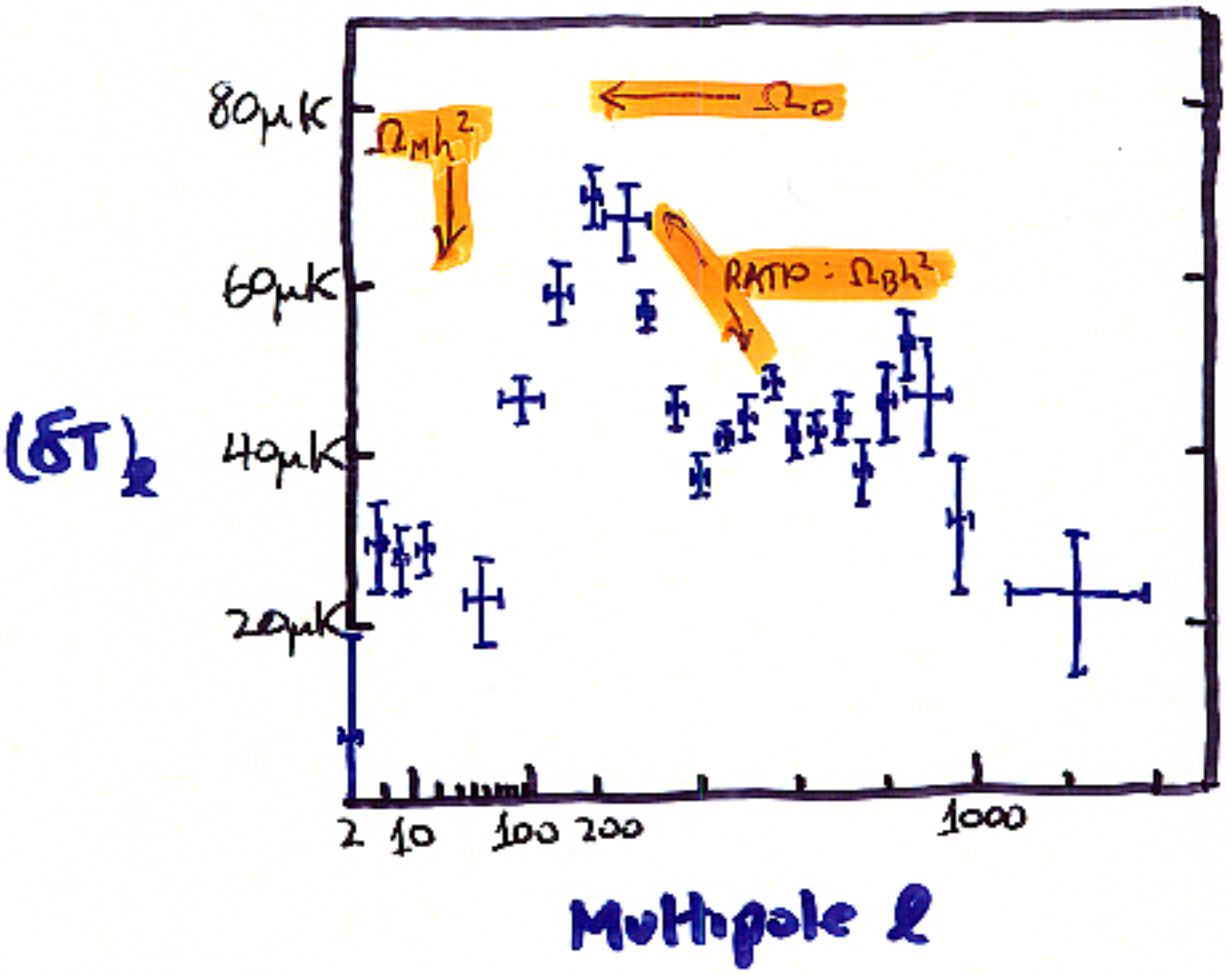

$\Omega_B h^2 = 0.022 \pm 0.004 \pm 0.003$
$\Omega_M h^2 = 0.16 \pm 0.04$
$\Omega_0 = 1 \pm 0.04$
$n = 1.01 \pm 0.08 \pm 0.06$

$+\ h = 0.72 \pm 0.07$

$\Omega_M = 0.32 \pm 0.1$
$\Omega_X = \Omega_0 - \Omega_M = 0.68 \pm 0.1$

# SUMMARY: CMB ANISOTROPY

COBE, BOOMERanG, MAXIMA, DASI, CBI, ... 1/2002




Curvature: $\Omega_0 = 1 \pm 0.03$

Matter density: $\Omega_M h^2 = 0.16 \pm 0.04$

Baryon density: $\Omega_B h^2 = 0.022^{+0.004}_{-0.003}$

# MATTER CONTENT

**BARYONS:** $\Omega_B h^2 =$

| | |
|---|---|
| $0.020 \pm 0.001$ | BBN (THEORY + D/H) |
| $0.022^{+0.004}_{-0.003}$ | CMB (DASI/BOOMERANG) |
| $0.021 \pm 0.008$ | Baryon Bumps (2dF) |

-- CONFIRMS SCHRAMM BBN PREDICTION

**$\Omega_M/\Omega_B$:** $\frac{\Omega_M}{\Omega_B} =$

| | |
|---|---|
| $8.5 \pm 1.5$ | CLUSTER INVENTORY |
| $7.2 \pm 2$ | CMB |
| $6.6 \pm 3$ | BARYON BUMPS |

→ **Air tight case for nonbaryonic DM**

+ $h = 0.72 \pm 0.07$ (Hubble Key Project Final)

**BEST NUMBERS**
M&T astro-ph/0106035

$\Omega_B = 0.04 \pm 0.008$

$\Omega_M = 0.33 \pm 0.035$

+ $\Omega_0 = 1 \pm 0.04$ → $\Omega_X = 0.67 \pm 0.06$ — DARK ENERGY

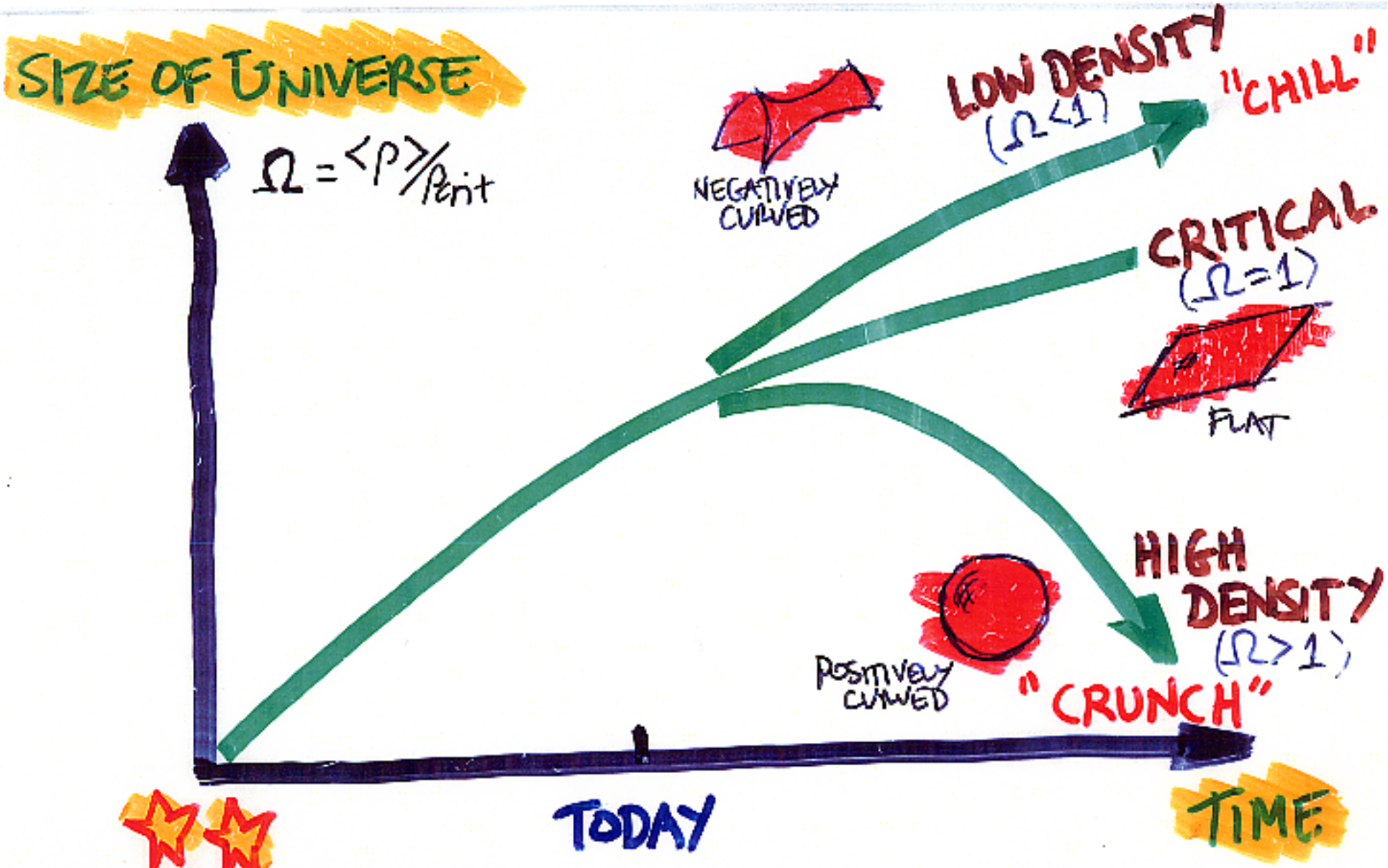
$\Omega_{\text{EXOTIC DM}} = 0.29 \pm 0.04$

NOT ENOUGH ORDINARY MATTER 4% OF CRITICAL

TO ACCOUNT FOR

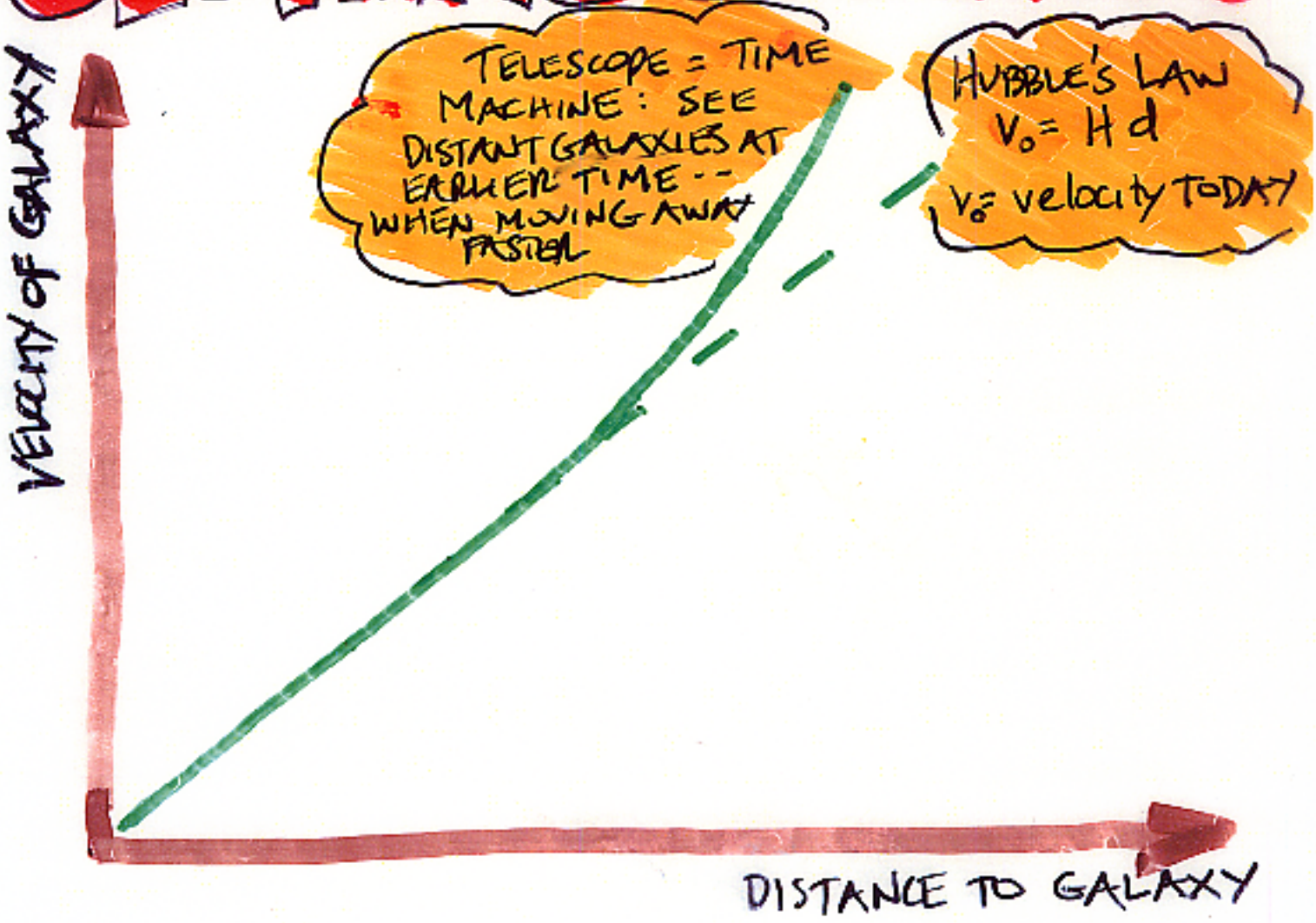
THE AMOUNT OF DARK MATTER 33% OF CRITICAL

DARK MATTER IS A NEW FORM OF MATTER! "COLD DARK MATTER"

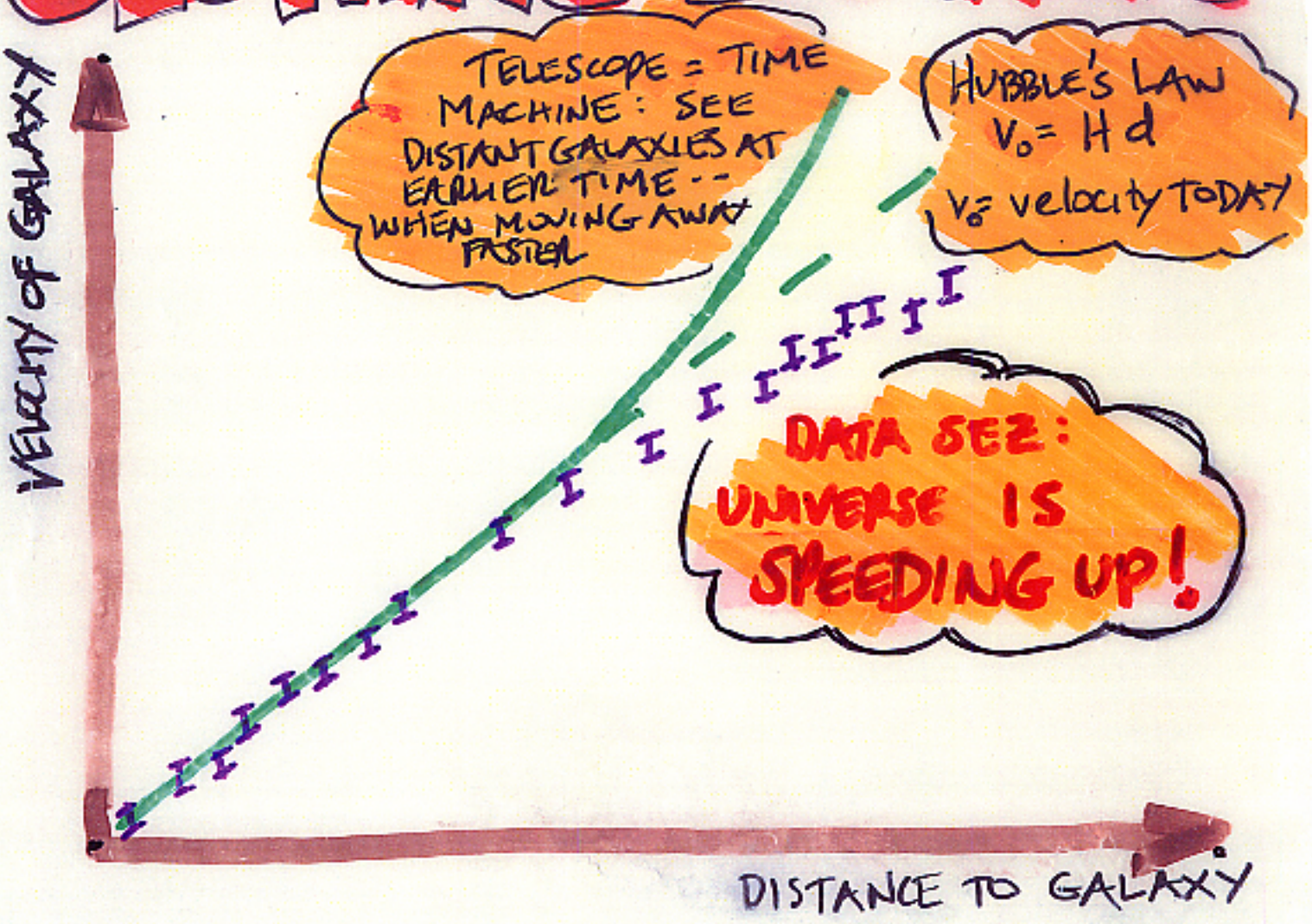



# FATE OF UNIVERSE

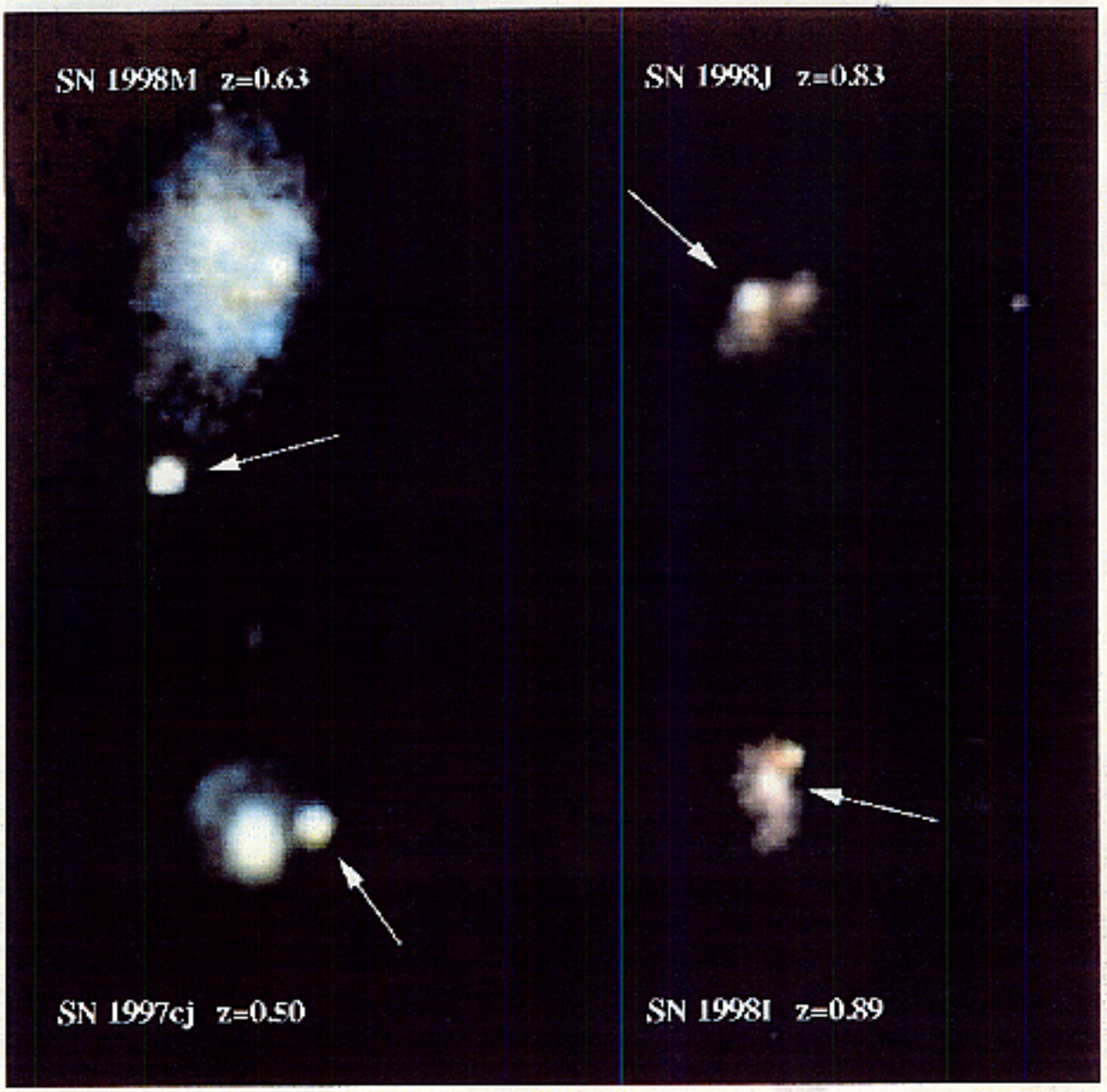
# IS THE UNIVERSE SLOWING DOWN?



# IS THE UNIVERSE SLOWING DOWN?

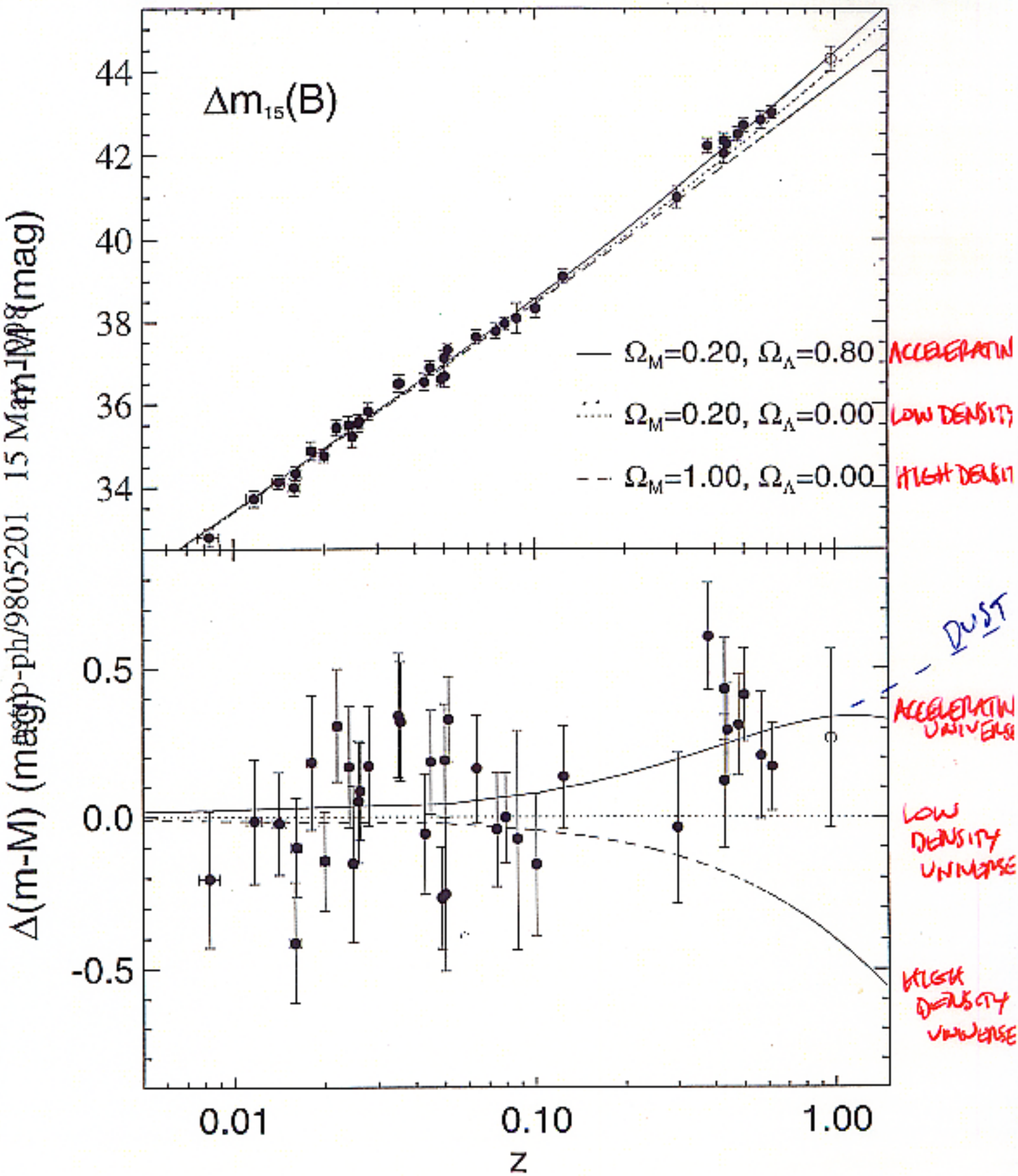


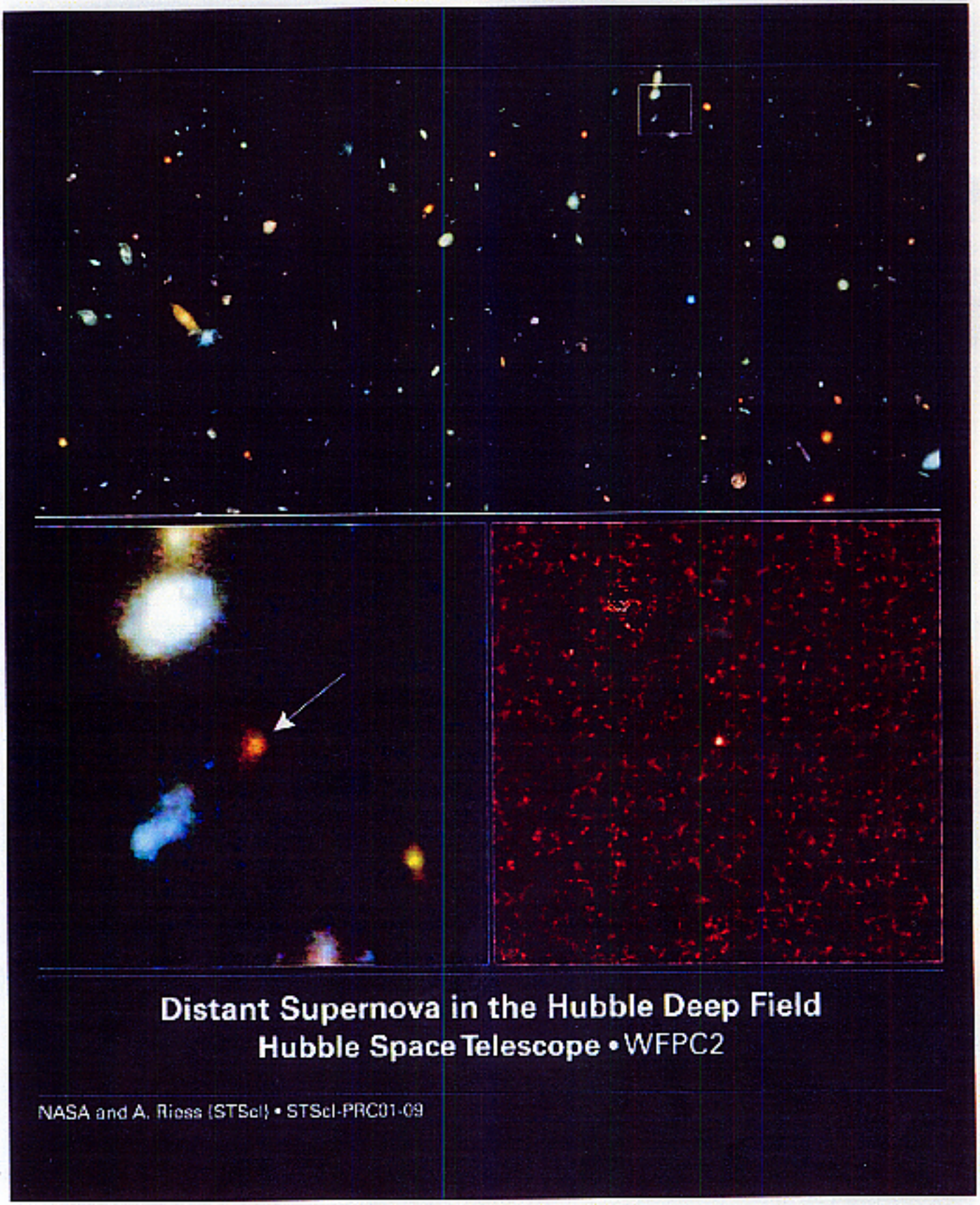

## UNIVERSE IS SPEEDING UP!? & WHY?


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

High Z SN Team

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

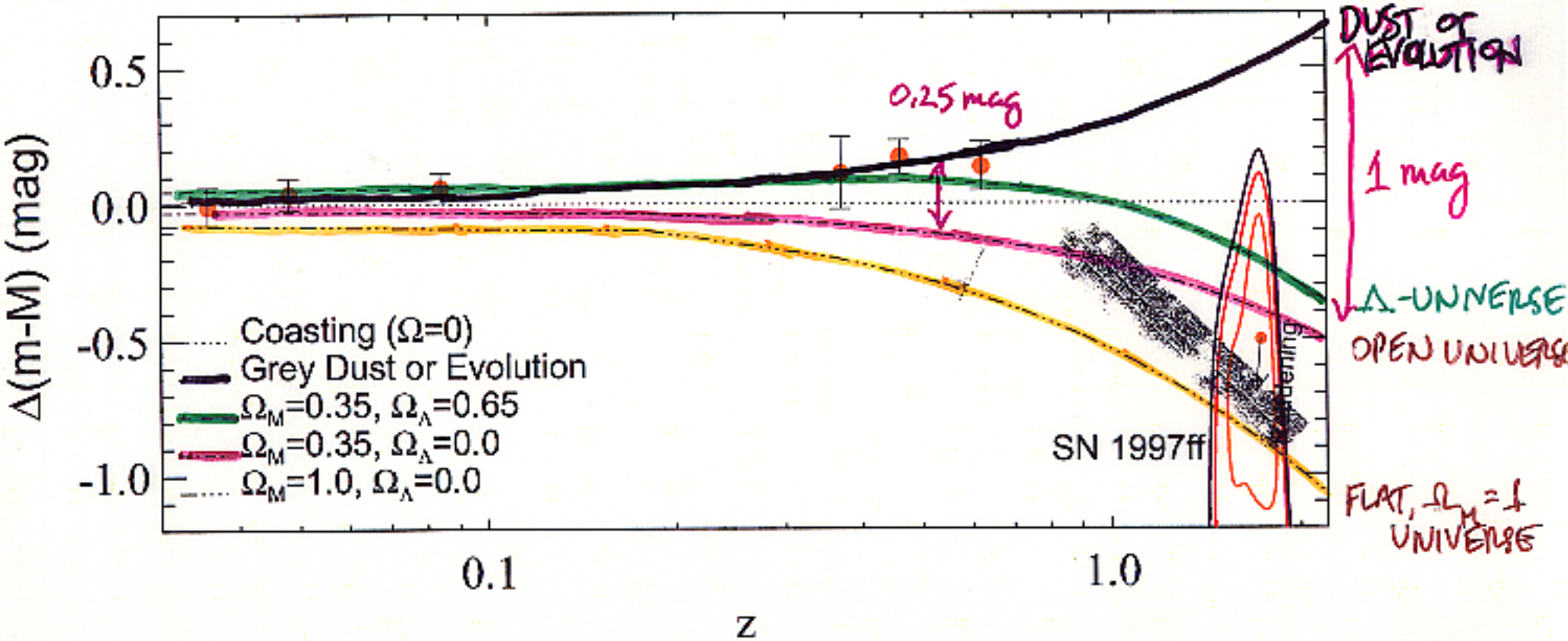





Riess et al astro-ph/0104455

# Differential Hubble Diagram

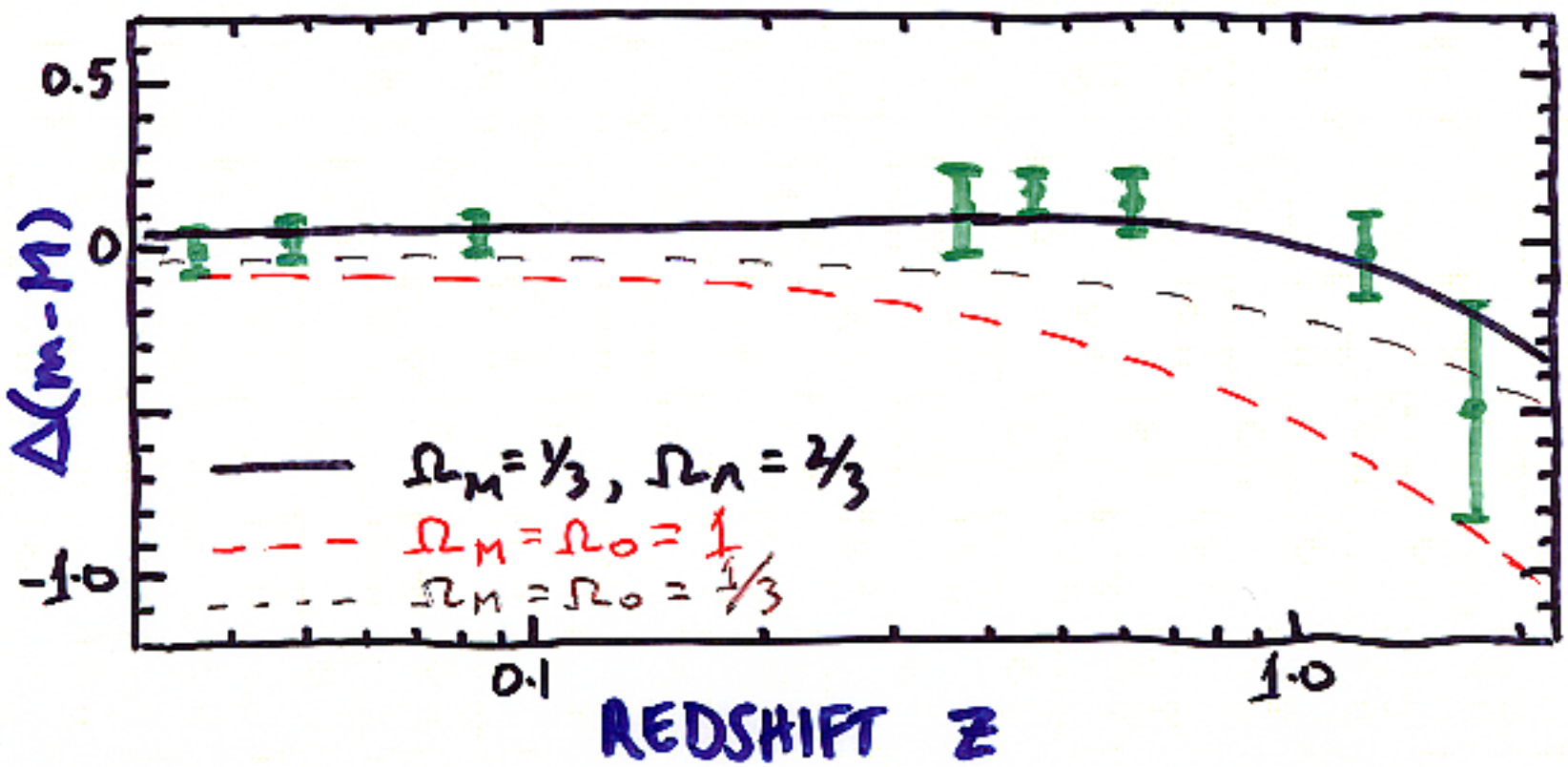
... relative to empty Universe ($\Omega_0 = 0$)




Riess et al astro-ph/0104455

# BINNED, DIFFERENTIAL HUBBLE DIAGRAM

relative to empty Universe ($\Omega_0 = 0$)



# INDIRECT EVIDENCE for DARK ENERGY

MISSING ENERGY:

$$\Omega_X = \Omega_0 - \Omega_M \simeq 0.67 \pm 0.06$$

CMB: $1 \pm 0.04$ $\quad$ $0.33 \pm 0.04$

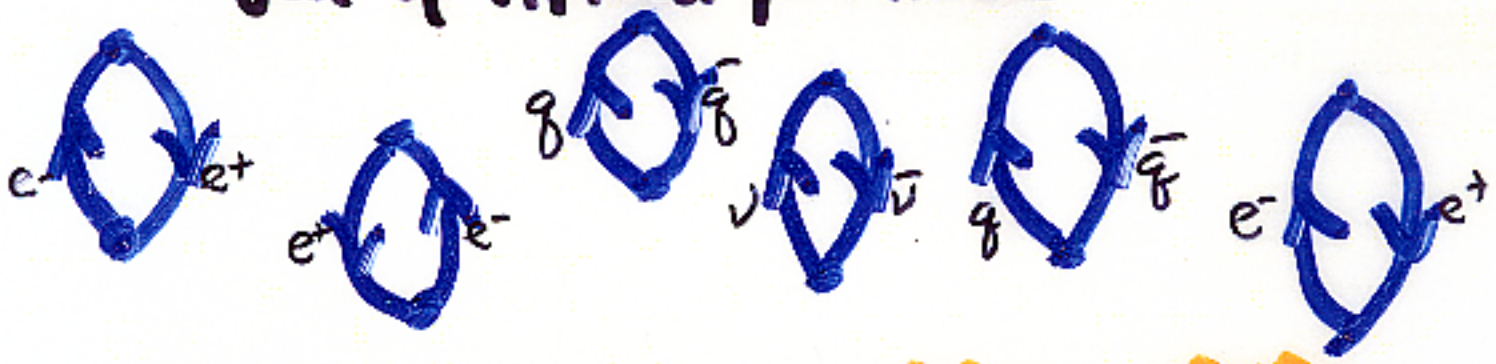
IN ORDER NOT TO INTERFERE W/ STRUC. FORMATION:

MUST EVOLVE MORE SLOWLY THAN MATTER: $w \equiv P/\rho \lesssim -1/2$

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

# QUANTUM VACUUM IS NOT EMPTY!

sea of virtual particles




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

W. Lamb, ca 1950

Quantum vacuum is elastic ($p = -\rho$)
& its Gravity is Repulsive!

JUST WHAT IS NEEDED -- BUT...

THEORETICAL ESTIMATES OF AMOUNT

$10^{55}$ x what is needed to
explain accelerating Universe

"Houston, we have a problem"

GR ALLOWS FOR REPULSIVE GRAVITY:

# SOURCE OF GRAVITY IN GR:

$$\rho + 3p$$

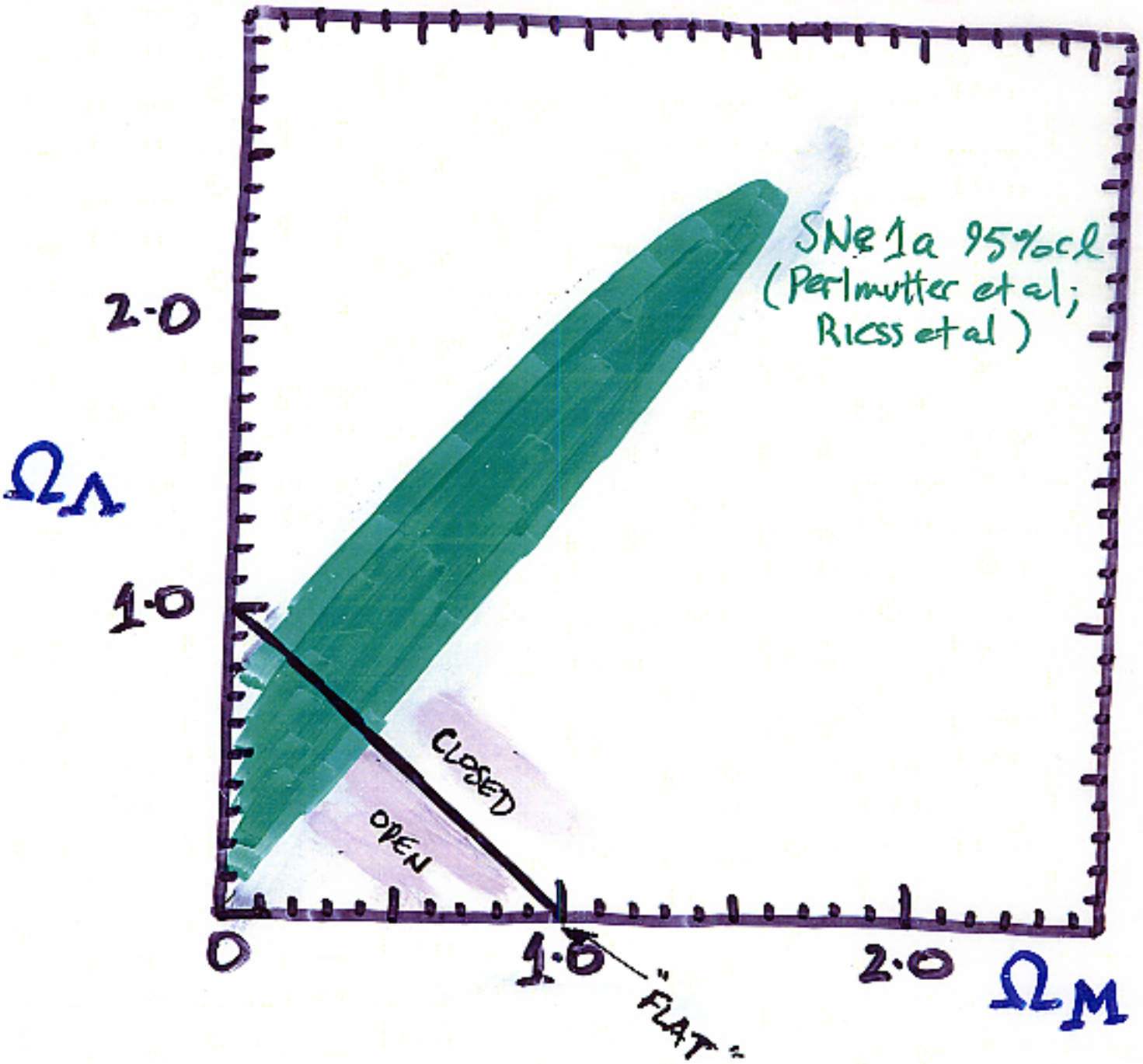
(SPHERICAL SYMMETRY)

FEATURE NOT A BUG!

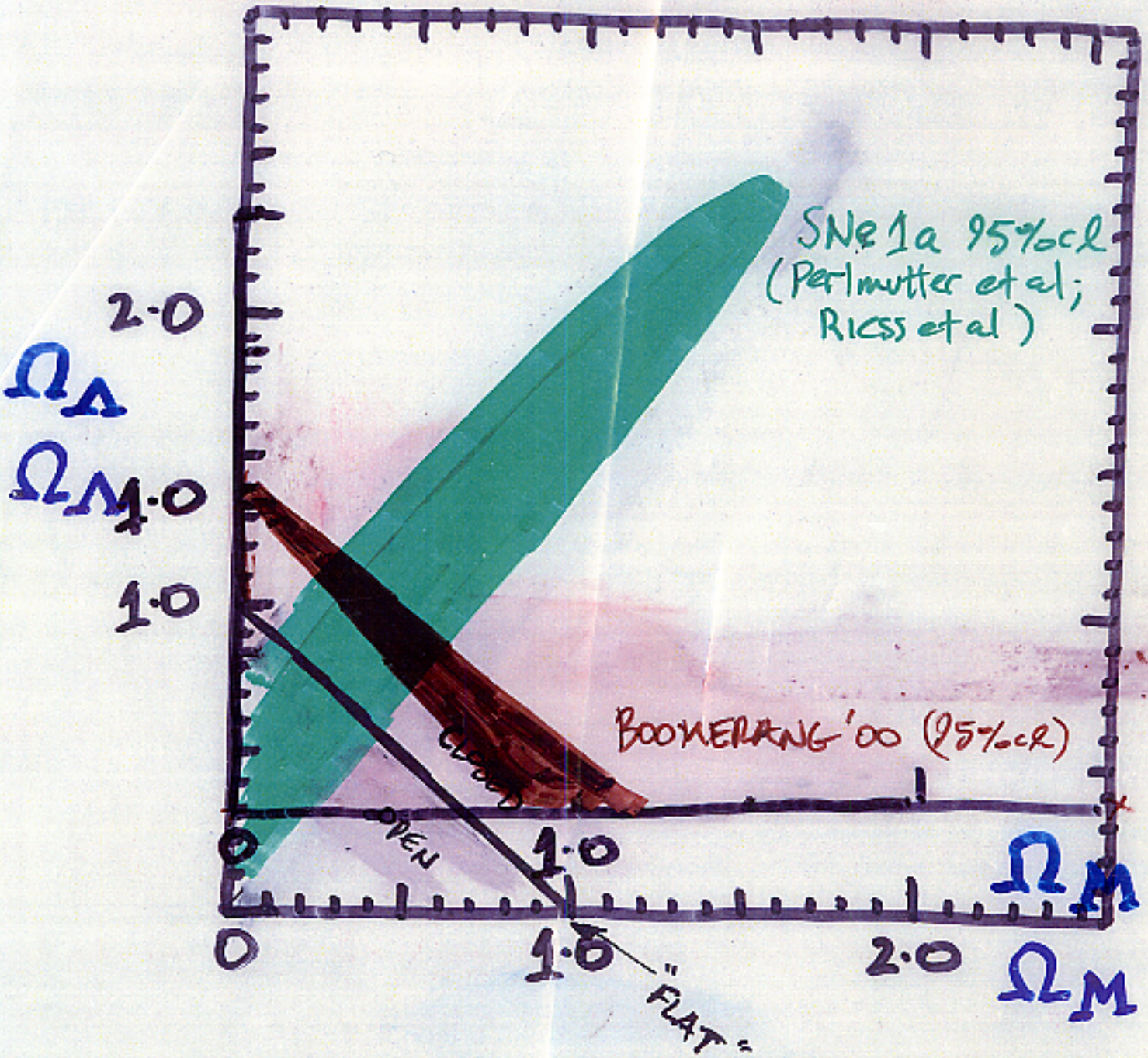
→ BLACK HOLES WHEN $p \gtrsim \rho/3$

→ REPULSIVE GRAVITY WHEN $p < -\rho/3$

# "THE BIG PICTURE"



# "THE BIG PICTURE"



# DARK QUESTIONS

## Neutrino Contribution

$0.1\% \lesssim \Omega_\nu \lesssim 5\%$

0.05eV 2eV

## Constituent of CDM

Axion
Direct Search (ADMX)

Neutralino ??
"Direct search" (CDMS II, ...)
Accelerators (Tevatron, LHC)
Annihilation products

## Dark Horse Dark Matter

- WIMP-Zilla ($m \gg$ TeV)
- keV sterile neutrino
- problem w/ gravity theory

## Dark Energy

Heavenly Lab

$w \equiv p/\rho = -1$ ?
$\dot{w} = 0$ ?
spatially const?

FEATURES OF VACUUM ENERGY
(aka "COSMOLOGICAL CONST")

# 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 $\chi_{HALO} + A \rightarrow \chi + A + keV$

* (0.1 GeV) PHOTINO Farrar-Kolb

## NEUTRINO $\sim 10 - 30$ eV

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

# WHAT DO WE KNOW ABOUT DARK ENERGY

Dark Energy (därk en´ ər jē)

non luminous; energy-like; most of the stuff in the Universe; diffuse; MYSTERIOUS

**LOTS OF IT:** $\Omega_X = \Omega_0 - \Omega_M \approx 0.67 \pm 0.06$

CMB: $1 \pm 0.04$ $\quad 0.33 \pm 0.04$

**DOESN'T CLUMP SIGNIFICANTLY:**

$$T^\mu{}_\nu \approx \begin{pmatrix} \rho_x & & & 0 \\ & -p_x & & \\ & & -p_x & \\ 0 & & & -p_x \end{pmatrix}$$

EQN OF STATE

write: $p_x \equiv w \rho_x \Rightarrow \rho_x \propto R^{-3(1+w)}$

IF $w$ = CONST

**REPULSIVE GRAVITY:**

<u>In GR</u>: source of gravity $\propto (\rho + 3p)$

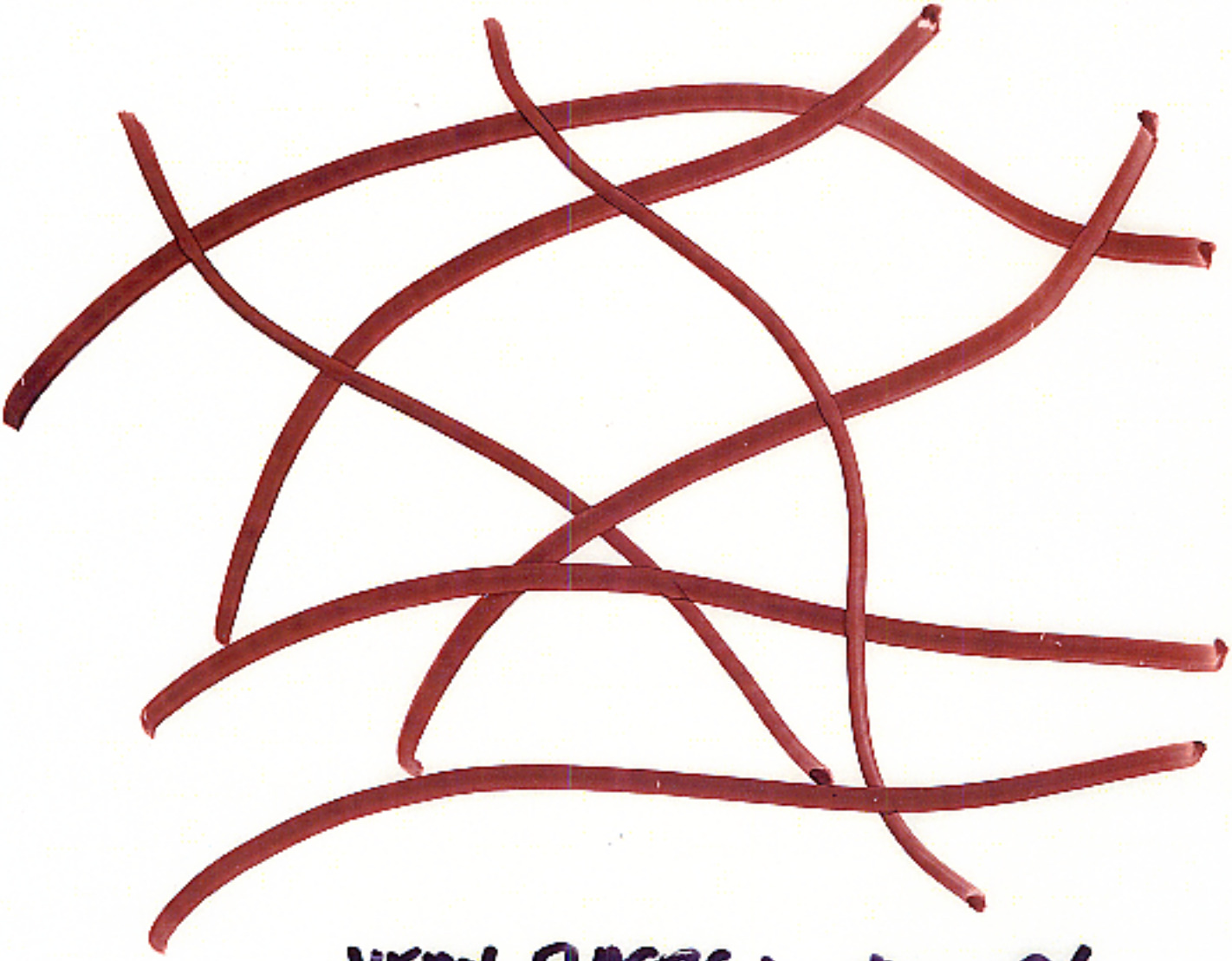
$\propto \rho_x (1+3w) < 0$ if $w < -1/3$

NB: Relativists call something w/ $|p| \sim |\rho|$ "energy-like"

# NETWORK OF (FRUSTRATED) TOPOLOGICAL DEFECTS

EG STRING

A. Vilenkin '84
Pen-Spergel '98



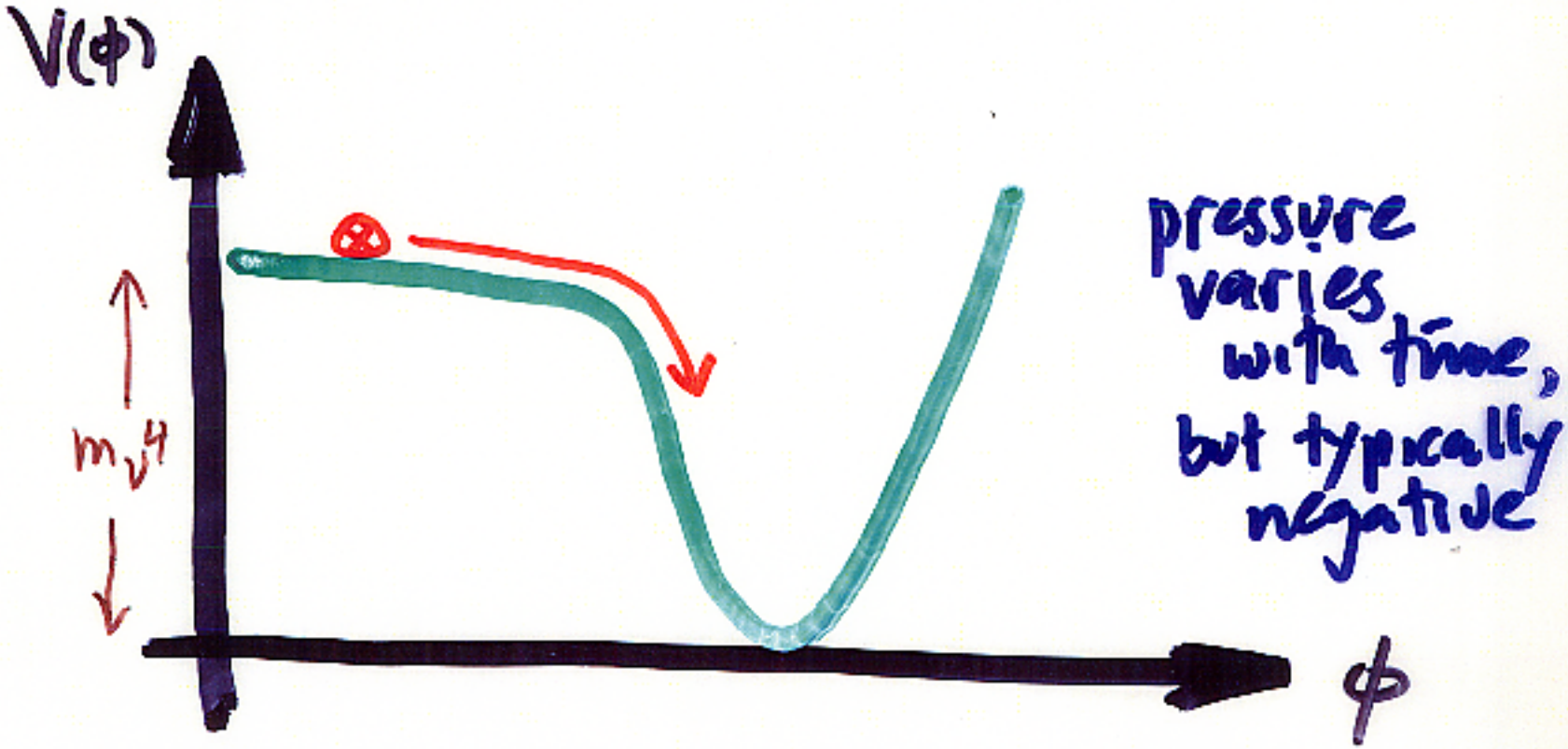
VERY ELASTIC: $p = -\rho/3$

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

# A BRIEF EPISODE OF INFLATION

(aka decaying cosmological constant, quintessence, rolling scalar field)

"...mild episodes of inflation are unavoidable" A. GREENSPAN

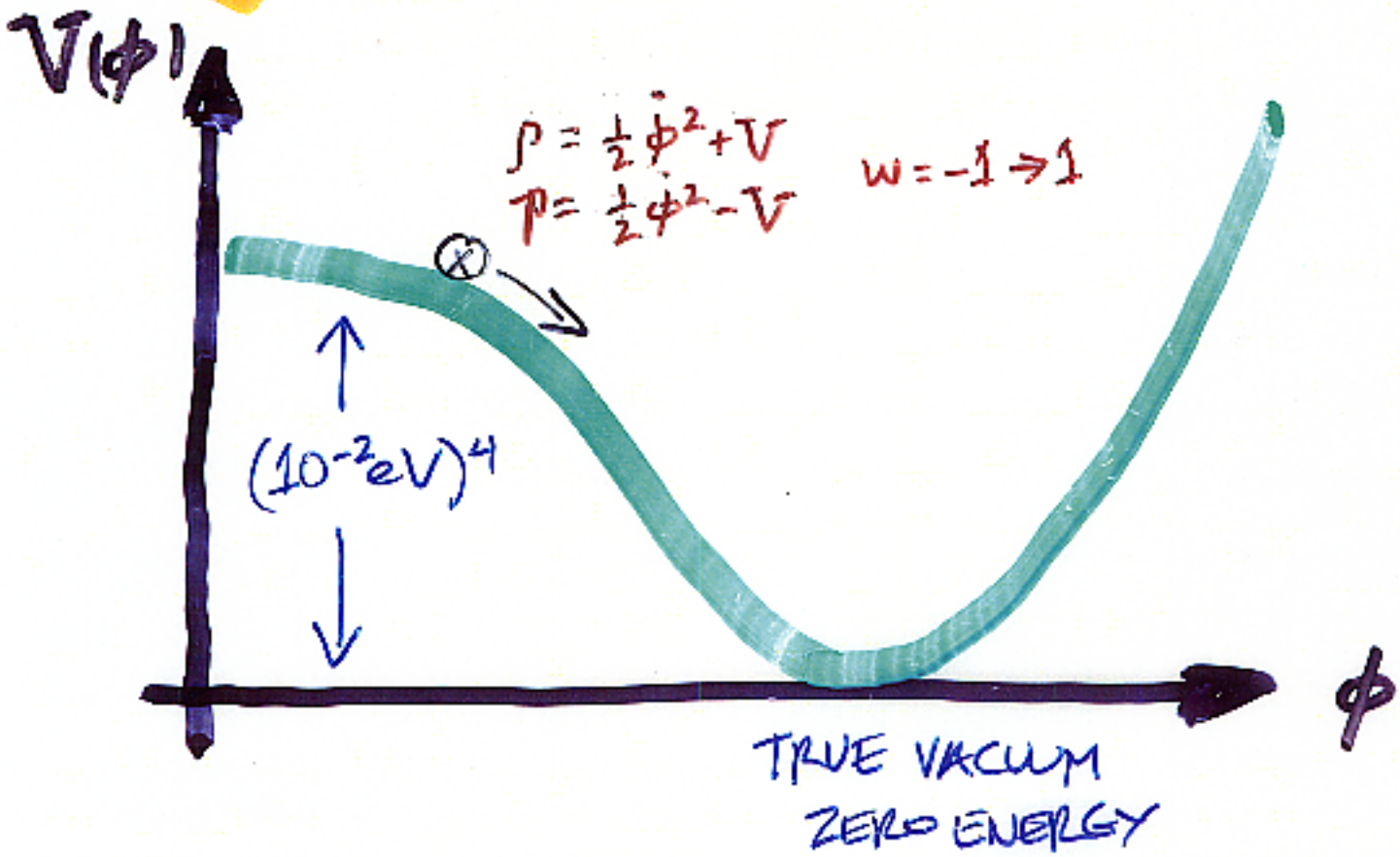


# ROLLING SCALAR FIELD

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

Bronstein 1933 (executed by Stalin 1935)
Hull 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."**



# THE DARK ENERGY PROBLEM

"DON'T HAVE A CLUE AS TO WHAT THE DARK ENERGY IS!"

"RIGHT NOW, NOT ONLY FOR COSMOLOGY BUT ALSO FOR ELEM. PART. THEORY, THIS IS THE BONE IN OUR THROAT" – S. WEINBERG

IT IS SMOOTH, HAS REPULSIVE GRAVITY, & INDICATES FUND PHYSICS

CHARACTERIZE IT BY $w_x \equiv p_x/\rho_x$, $w_x(t)$ AS A START

TURNER-WHITE PRD 56, 4439 (9

| CANDIDATE | $w$ | $\dot{w}$ |
|---|---|---|
| COSMOLOGICAL CONSTANT ($\Lambda$) | $-1$ | $0$ |
| FRUSTRATED DEFECTS $N=1$ (string), 2 (walls) | $-N/3$ | $\approx 0$ |
| FALSE VACUUM STATE | $-1$ | $\approx 0$ |
| ROLLING SCALAR FIELD "QUINTESSENCE" | $-1 \to 1$ | $= \dfrac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$ |
| "THE BULK", BREAKDOWN OF FRW COSMOLOGY, ... | ? | ? |

# HOW CAN WE LEARN MORE?

D. HUTERER-TURT, PRD 64, 123527 (2001)

LARGELY FROM COSMOLOGY

## DARK ENERGY CONTROLS THE EXPANSION OF THE UNIVERSE

NB: 2 PARAMETER PROBLEM OF 1 PARAMETER + 1 FN

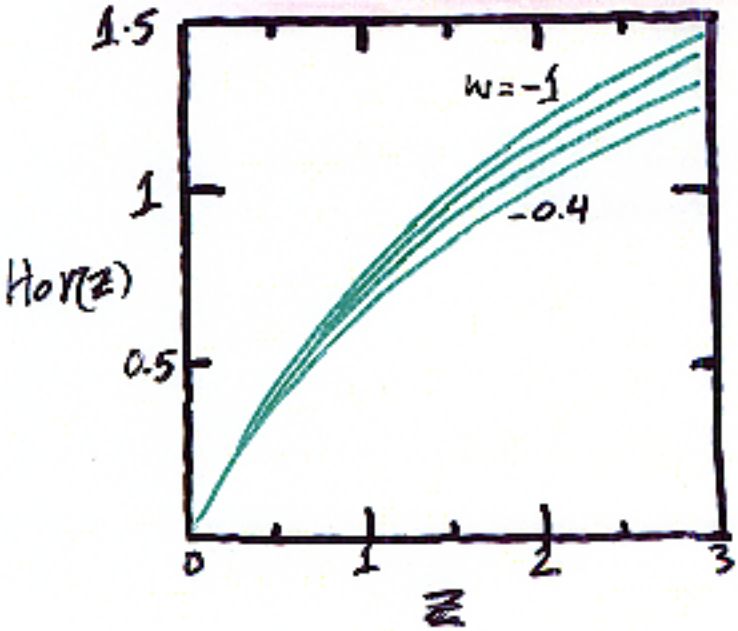
$$H^2 = \frac{8\pi G\rho}{3} = \frac{8\pi G}{3}(\rho_M + \rho_X)$$

$$H^2 = H_0^2\left[\Omega_M(1+z)^3 + \Omega_X(1+z)^{3(1+w)}\right]$$

$\Omega_X = 1 - \Omega_M$

## INFLUENCES:

### DISTANCE TO AN OBJECT AT REDSHIFT z:




$$r(z) = \int_0^z \frac{dz}{H(z)}$$

LUMINOSITY DISTANCE

$$d_L(z) \equiv (1+z)\, r(z)$$

$$= (\mathcal{L}/4\pi F)^{1/2}$$

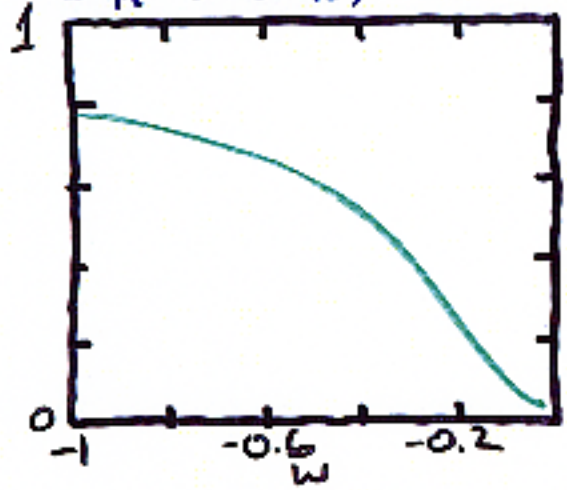
# GROWTH OF STRUCTURE:

$$\ddot{\delta} + \underbrace{2H\dot{\delta}} - 4\pi G \rho_M \delta = 0$$

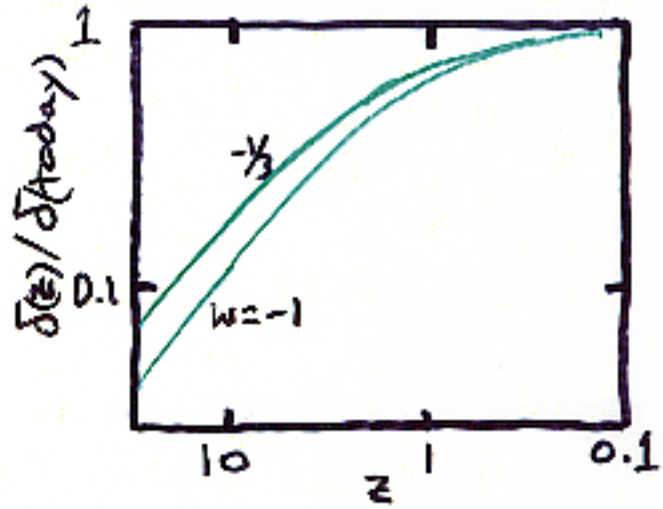
$\delta\rho/\rho$

EXPANSION ACTS LIKE FRICTION THAT SLOWS THE GROWTH OF STRUCTURE

TOTAL GROWTH RELATIVE TO $\Omega_M = 1$ (EdS)



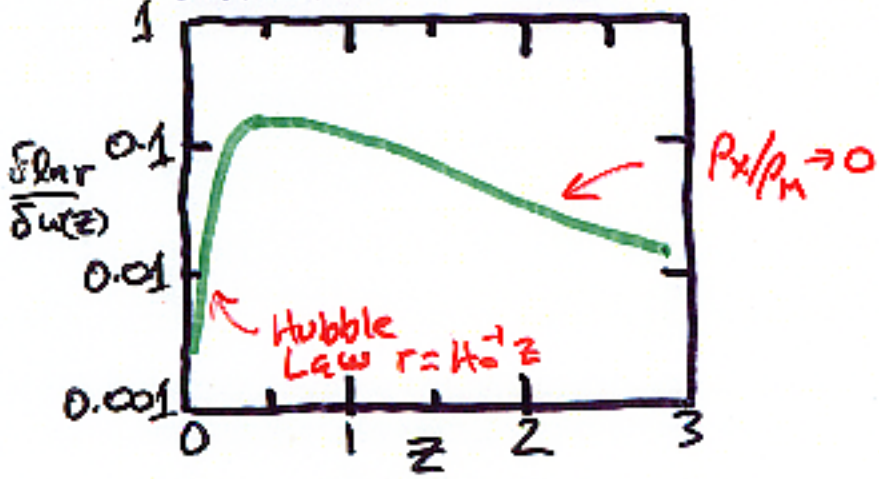

RECENT GROWTH




## DARK ENERGY INFLUENCES HOW STRUCTURE DEVELOPS

# SENSITIVITY OF COSMOLOGY TO $w(z)$

SENSITIVITY TO $w(z)$




## SWEET SPOT

$z = 0.2 \rightarrow 2$

## AGE OF UNIVERSE

$$t_0 = \int_0^\infty \frac{dz}{(1+z)H(z)}$$

LESS POTENTIAL

# COSMIC PROBES OF DARK ENERGY

| METHOD | ASSUMPTIONS | MEASURES | SYSTEMATICS | ESTIMATED POTENTIAL |
|---|---|---|---|---|
| SUPERNOVAE | SN Ia = "STD CANDLE" | $r(z)$ | EVOLUTION<br>SN DIVERSITY<br>DUST | $\sigma_w = 0.05$<br>$\sigma_{w'} = 0.15$ |
| WEAK-LENSING "SHEAR" | NON-LINEAR CDM POWER SPECTRUM $= f(\Omega_i, n, \sigma_8, \ldots)$ | $r(z)$,<br>$\delta(z)$,<br>$H(z)$ | ANISOTROPY OF P.S.F. DUE TO SKY + OPTICS | $\sigma_w = 0.03$<br>$\sigma_{w'} = 0.1$ |
| COUNT CLUSTERS<br>W-L<br>X-ray, SZ | CDM POWER SPECTRUM<br>GAUSSIANITY | $r(z)^2/H(z)$ | SEE ABOVE<br>M vs. T | $\sigma_w = 0.05 - 0.10$<br>$\sigma_{w'} = 0.2$ |
| GALAXY COUNTS | CDM PARADIGM | $r(z)^2/H(z)$ | GALAXY MASSES<br>EVOLUTION | $\sigma_w = 0.1$ |
| CMB | CDM PARADIGM | $r(z=1100)$ | $\Omega_M - w$ DEGENERACY | $\sigma_w = 0.2$ |

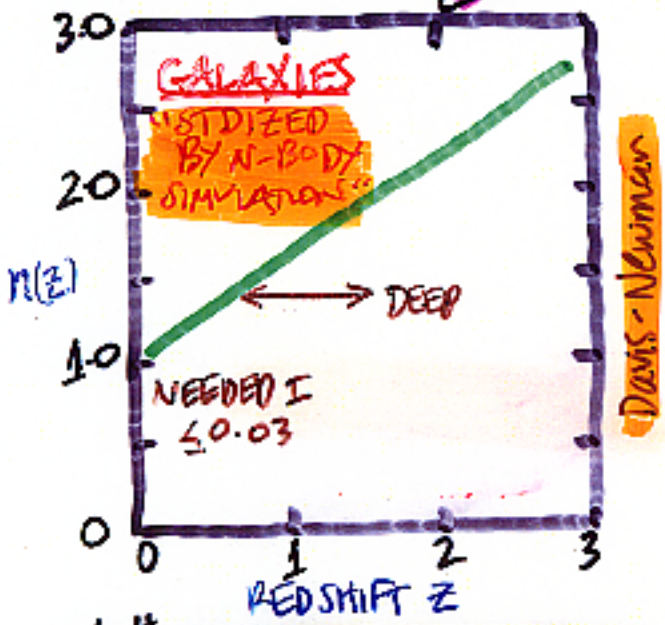
# ANOTHER APPROACH: COUNTING STANDARDIZABLE OBJECTS

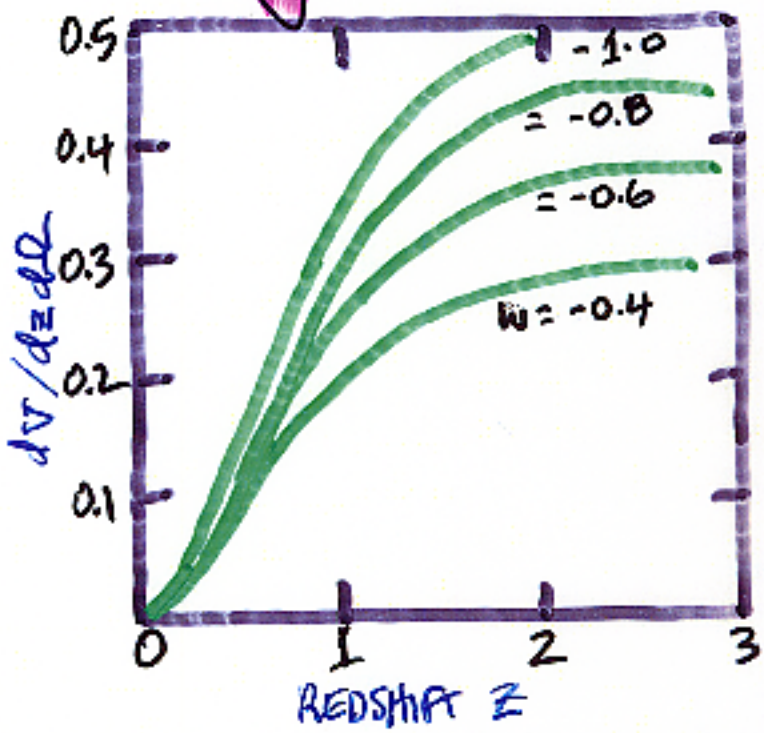
$$\frac{dN}{d\Omega\, dz} = n(z) \times \frac{dV}{d\Omega\, dz}$$

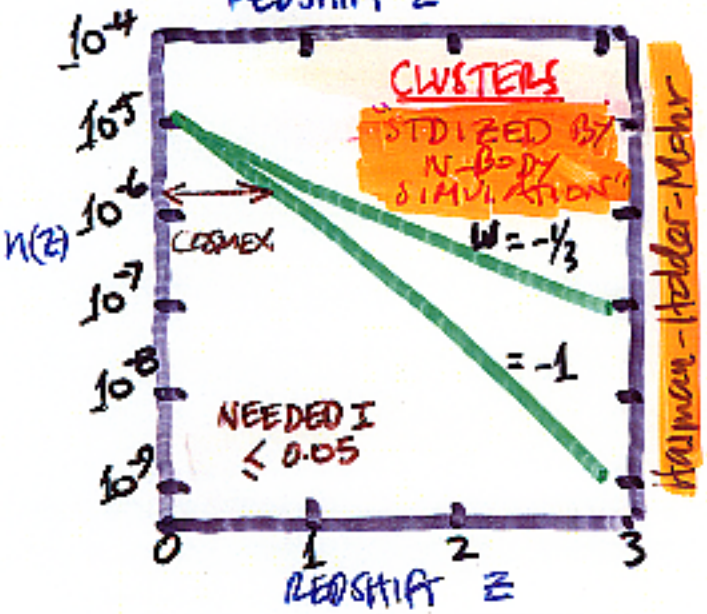
OBSERVABLE

ASTRO-PHYSICS "EVOLUTION"

VOLUME ELEMENT "COSMOLOGY" $= r(z)^2/H(z)$




## KEY SYSTEMATIC: EVOLUTION $n(z)$

IE. STANDARDIZING THE OBJECTS