HIGHLIGHTS IN COSMOLOGY

CONSENSUS MODEL

→ WITH RELIABLE SET OF COSMO. PARAMETERS

CMB !!

MAPPING THE INFANT UNIVERSE

COSMIC SPEED UP

→ DARK ENERGY OR NEW GRAV. PHYSICS?

EVIDENCE for INFLATION

→ QUESTION IS NOW HOW MUCH OF THE TRUTH DOES IT HOLD

THE NEW COSMOLOGY

RELIABLE SET OF COSMO. PARAMETERS

$H_0 = 72 \pm 7$, $T_0 = 2.725 \pm 0.001 K$, $\Omega_0 = 1 \pm 0.03$, $\Omega_B = 0.04 \pm .01$

SPATIALLY FLAT, ACCELERATING UNIVERSE

$R_{curv} \gtrsim 5 H_0^{-1}$, $q_0 = -3/3 \pm 1/2$

NON BARYONIC DARK MATTER

$\Omega_M - \Omega_B = 0.29 \pm 0.04$ $\Omega_B = 0.04 \pm 0.01$

DARK ENERGY W/ REPULSIVE GRAVITY

$\Omega_X = 0.67 \pm 0.06$ $w \lesssim -1/2$

EARLY "INFLATIONARY EPOCH"

EVIDENCE FOR INFLATION

DEEP CONNECTIONS BETWEEN QUARKS & COSMOS MANIFEST!

KNOW MUCH, UNDERSTAND LITTLE

WHAT IS DARK MATTER? DARK ENERGY?

HOW MUCH TRUTH DOES INFLATION HAVE?

WHO IS ϕ? THE RECIPE? THE SINGULARITY?

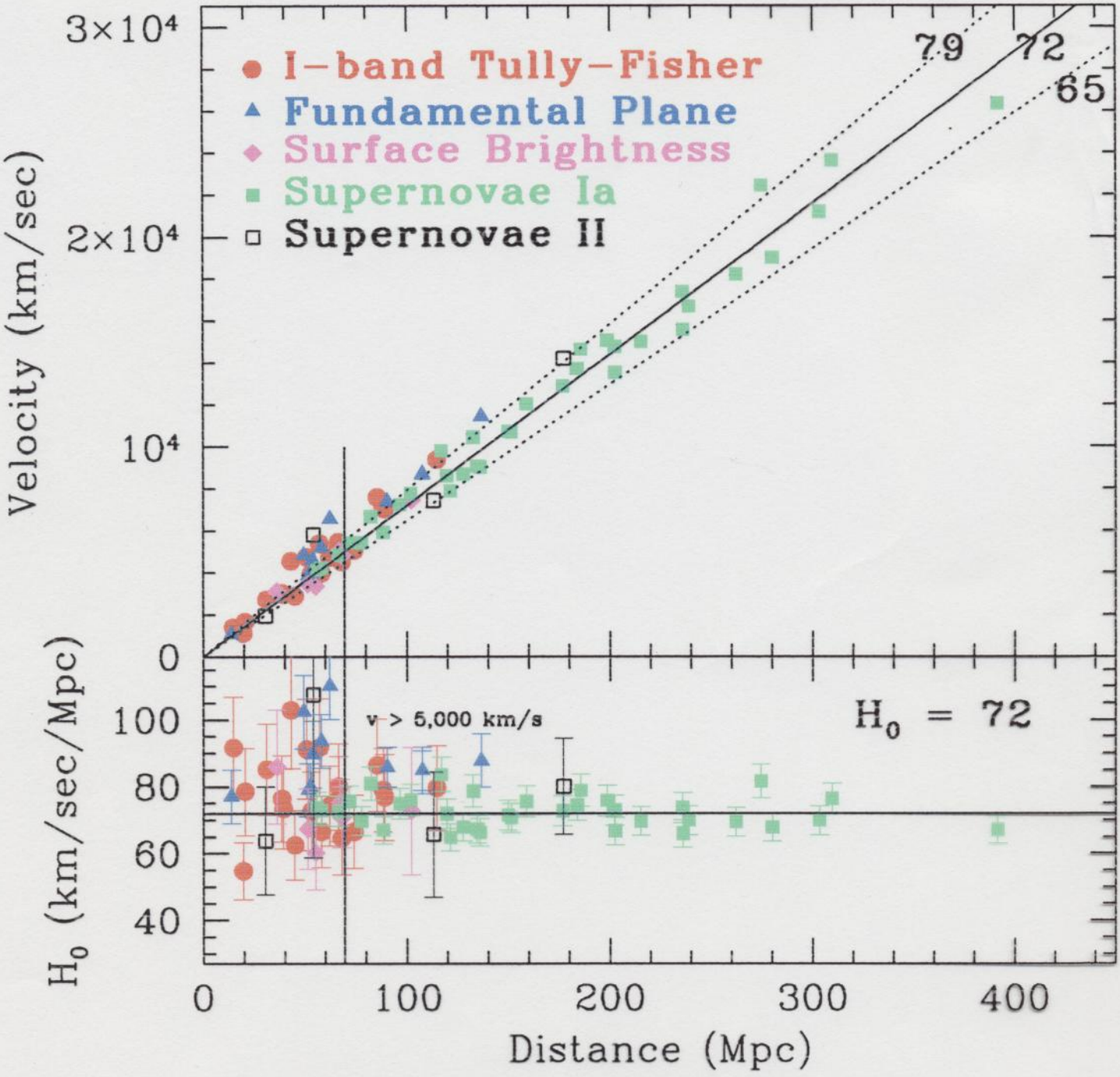
COSMOLOGICAL PARAMETERS

EXPANSION RATE	$H_0 = 72 \pm 2 \pm 7$ km s^{-1} Mpc^{-1} (70 ± 4)	HST KP
	NB: $h = H_0/100 = 0.72 \pm 0.07$ $h^2 \approx 1/2$	
DECEL. RATE	$q_0 = -0.67 \pm 0.25$	SNeIa + Ω_M
AGE	$t_0 = 13 \pm 1.5$ Gyr (13.7 ± 0.3 Gyr)	GC, H_0, CMB consensus
TEMP	$T_0 = 2.725 \pm 0.001$ K	COBE FIRAS
SHAPE	$\Omega_0 = 1.03 \pm 0.03$ (1.02 ± 0.02)	CMB
Baryons	$\Omega_B = 0.04 \pm 0.008$ (0.044 ± 0.004)	BBN, CMB, H_0, CLUSTERS
Matter	$\Omega_M = 0.33 \pm 0.035$ (0.27 ± 0.04)	
Dark Energy	$\Omega_X = 0.67 \pm 0.06$ (0.73 ± 0.04)	$\Omega_0 - \Omega_M$
EOS	$w = -1 \pm 0.2$ (< -0.8 (95%))	SNeIa, CMB, LSS
$\delta p/p$	$\sqrt{s} = 5.6^{+1.5}_{-1.0} \times 10^{-6}$	CMB-COBE
G.W.	$\sqrt{T} < \sqrt{s}$	CMB, H_0
power law indices	$n = 1.05 \pm 0.09$ (0.93 ± 0.03)	CMB
	n_T —	
running	$dn/d\ln k = -0.02 \pm 0.04$ (-0.03 ± 0.02)	CMB

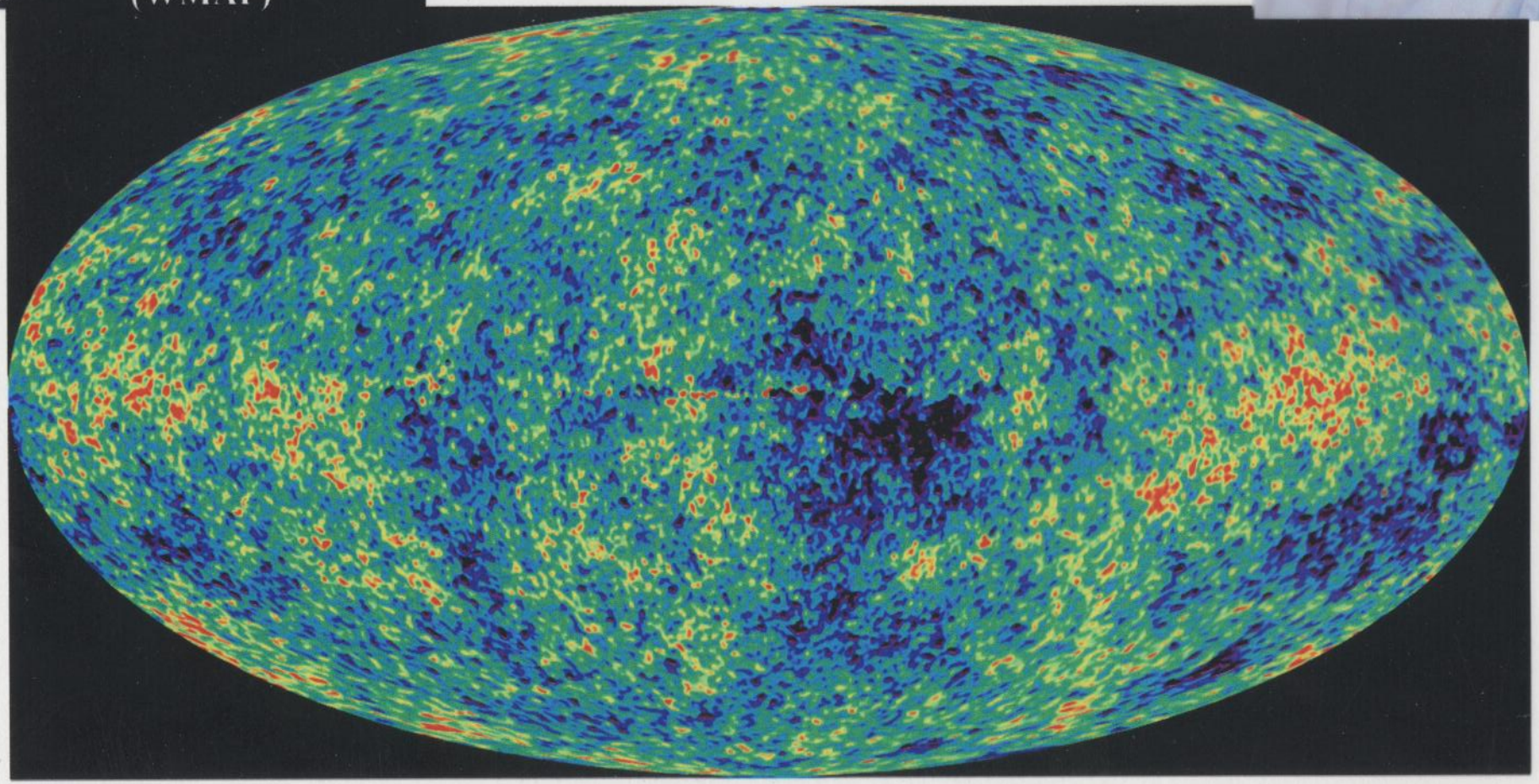
WMAP

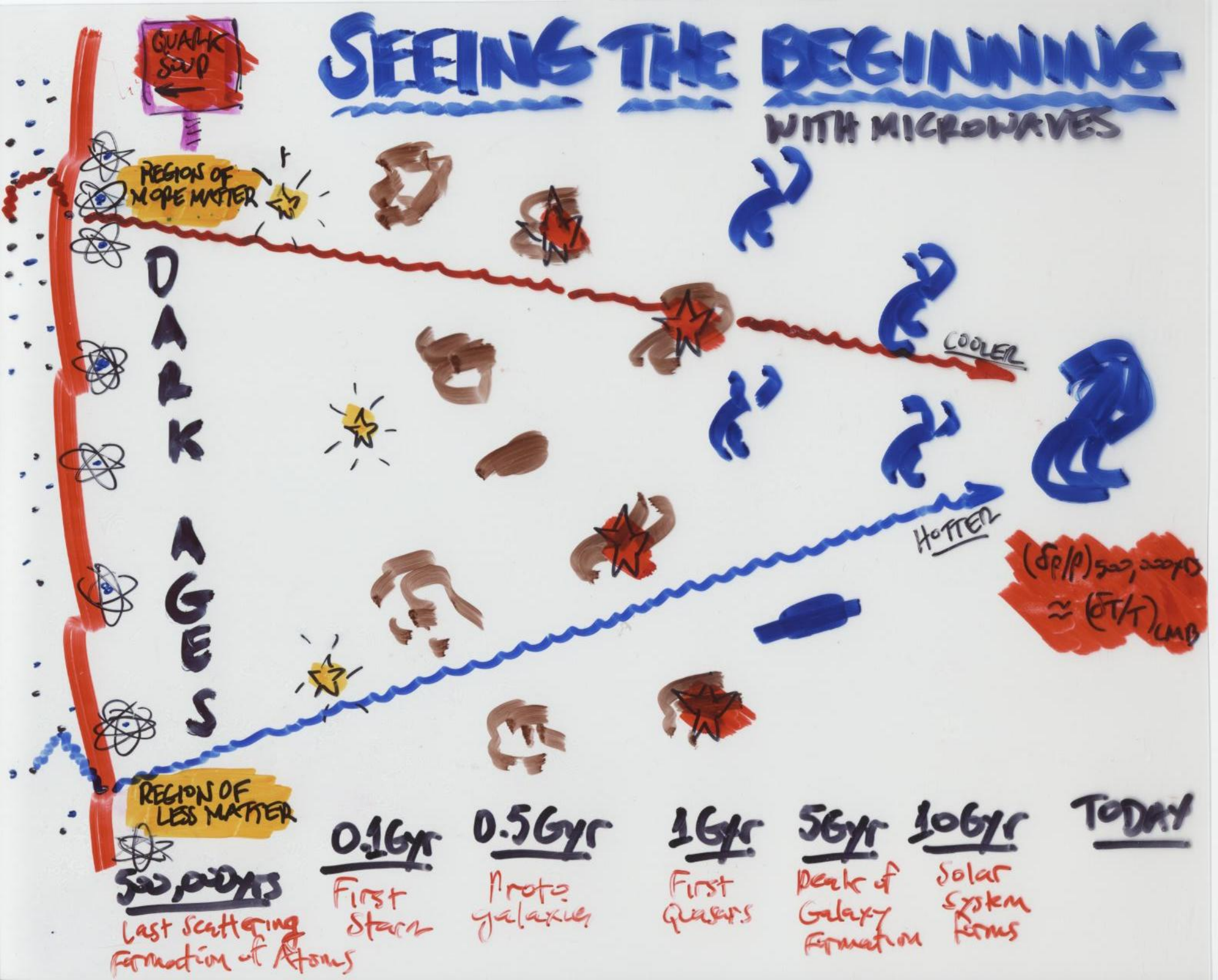
NB: RELIABLE ERROR BARS

HST Key Project
W. Freedman et al



MAP OF THE UNIVERSE AT A SIMPLER TIME (400,000 YRS)



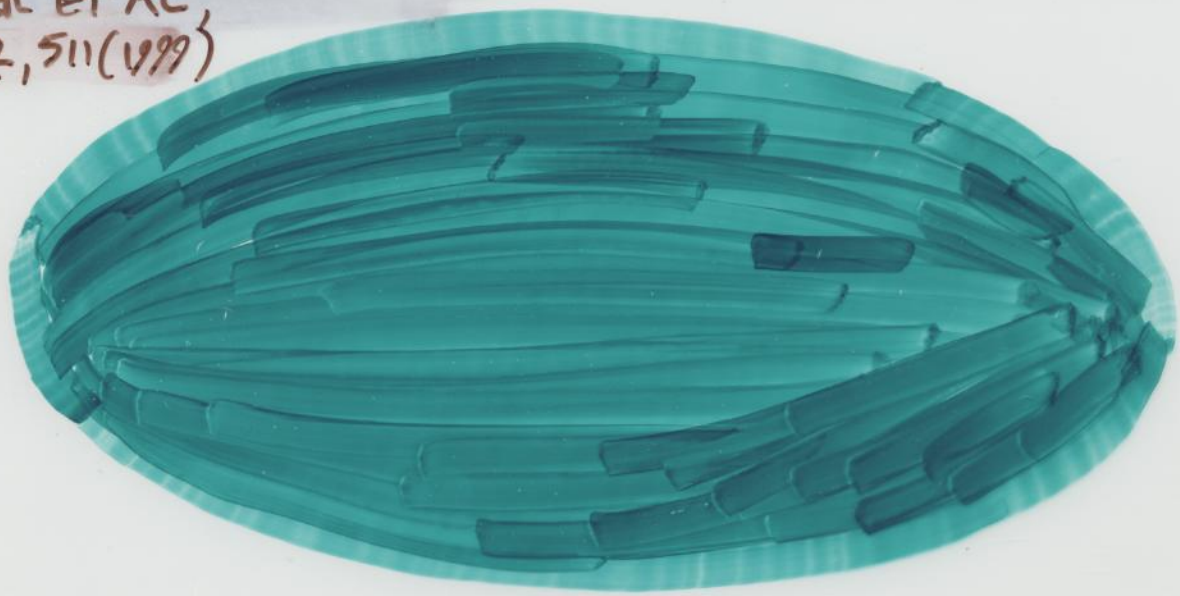

SEEING THE BEGINNING
WITH MICROWAVES
QUARK SOUP
REGION OF MORE MATTER
DARK AGES
REGION OF LESS MATTER
COOLER
HOTTER
$(\delta\rho/\rho)_{500,000} \simeq (\delta T/T)_{CMB}$
500,000yrs
Last scattering
Formation of Atoms
0.16yr
First Stars
0.5Gyr
Proto galaxies
1Gyr
First Quasars
5Gyr
Peak of Galaxy Formation
10Gyr
Solar system forms
TODAY

COBE DMR 4 YR MAP

$T = 2.725 \pm 0.001\ K$

BEST BLACK BODY IN NATURE

J. MATHER ET AL, ApJ 512, 511 (1999)



UNIFORM TO $\pm 3\ mK$

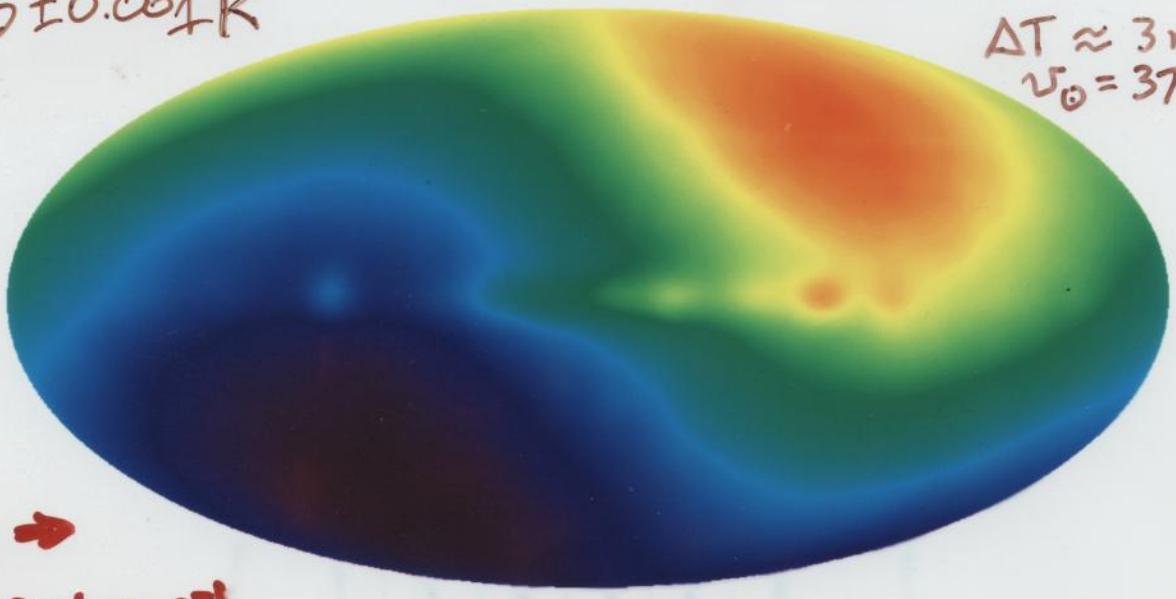
COBE DMR 4-YR

G. SMOOT et al, 1992

$T = 2.725 \pm 0.001$ K

$\Delta T \approx 3$ mK

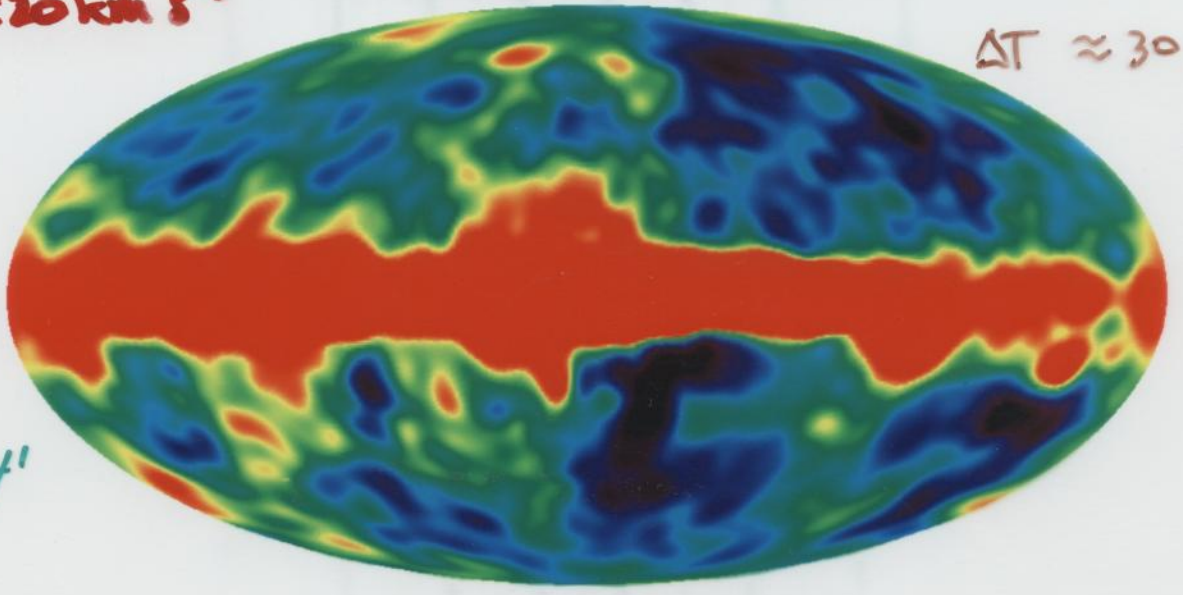
$v_\odot = 370 \pm 0.5$ km/sec



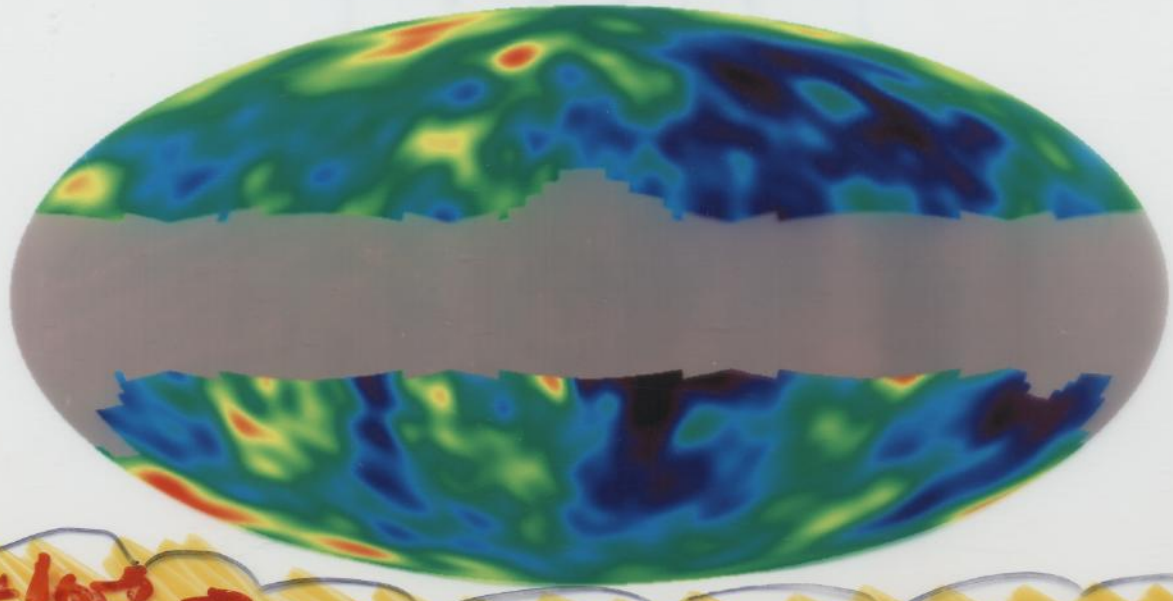
DIPOLE →

$v = 620 \pm 20$ km s^{-1}

$\Delta T \approx 30\ \mu$K

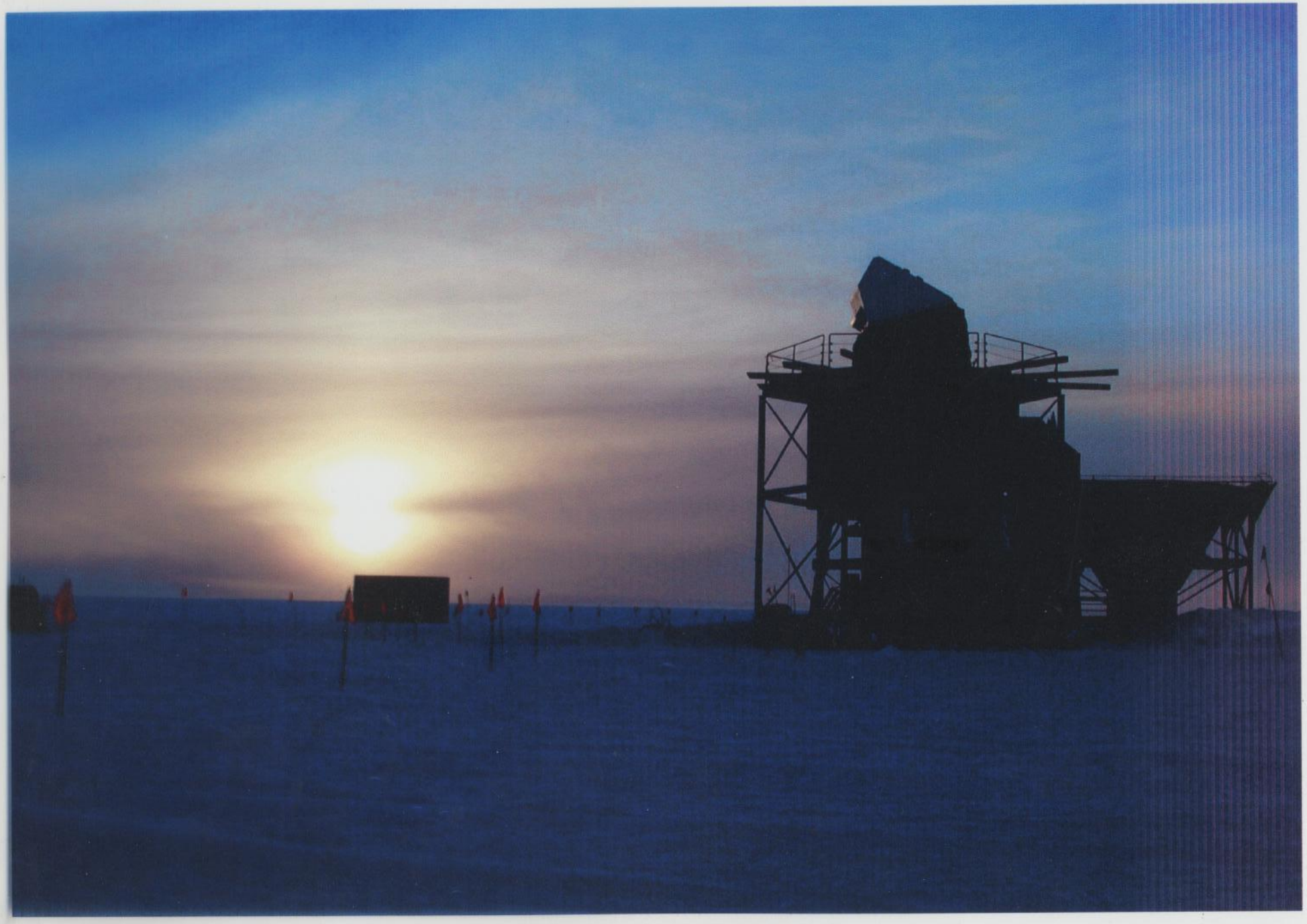


GLOW OF 'THE GALAXY'



$\delta T/T \simeq 10^{-5}$ →

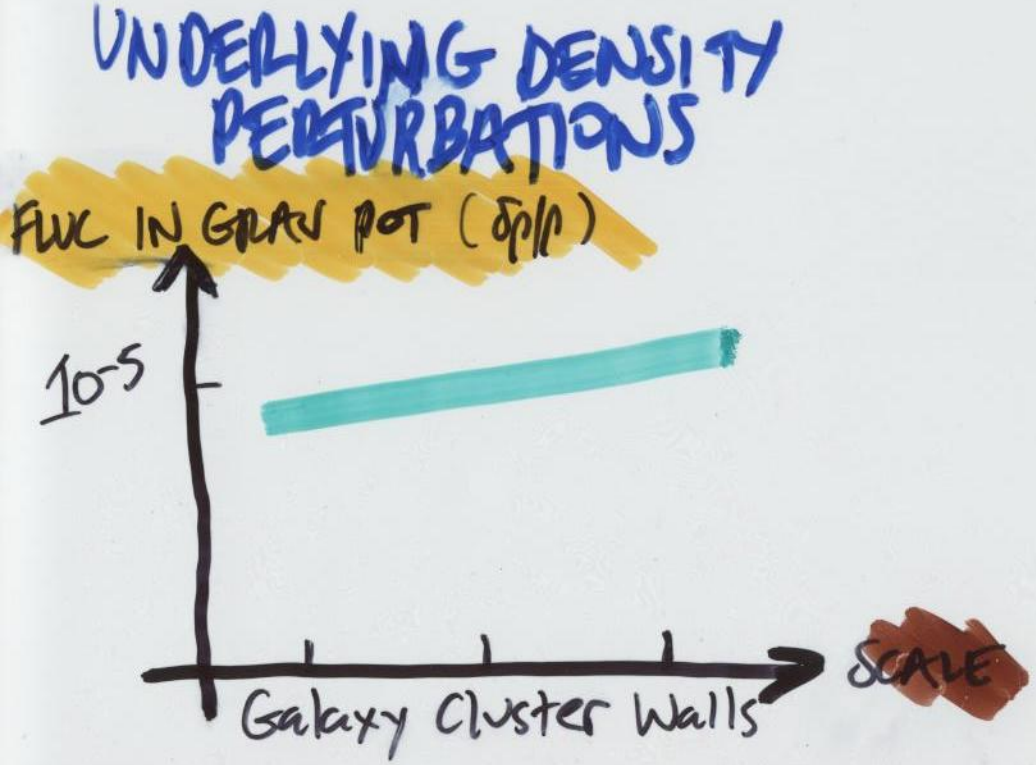
$(\delta\rho/\rho) \sim$ few 10^{-5} SEEDS FORMATION OF STRUCTURE

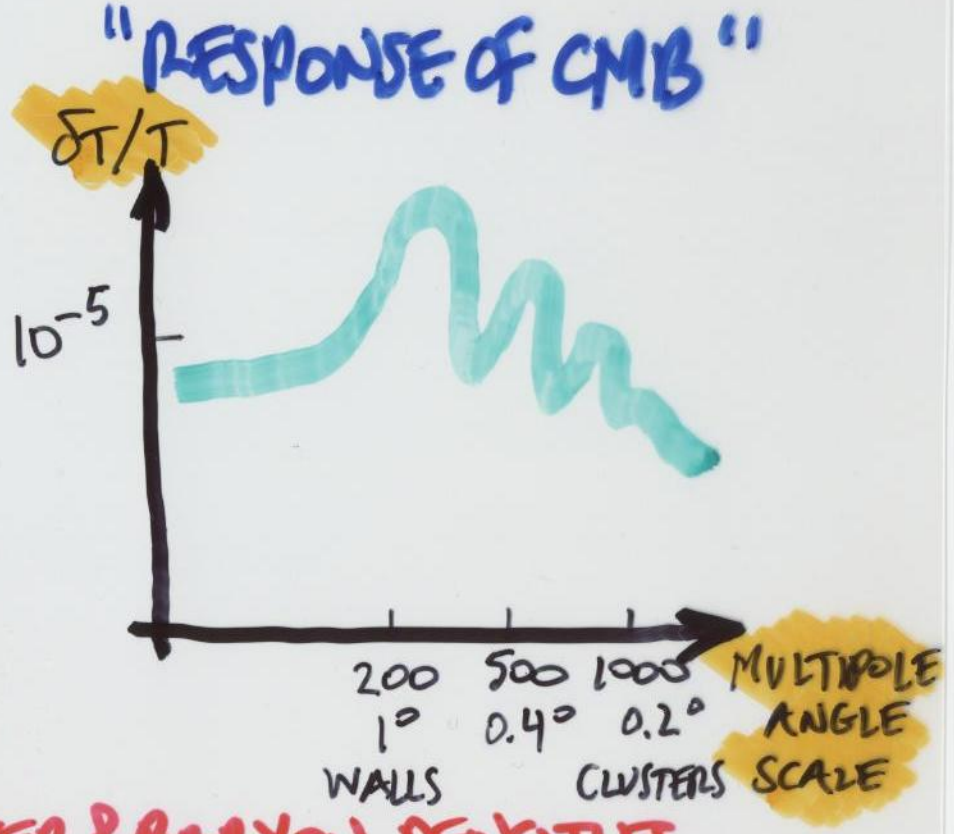


DASI AT SOUTH POLE SUNSET MAY 2000

10

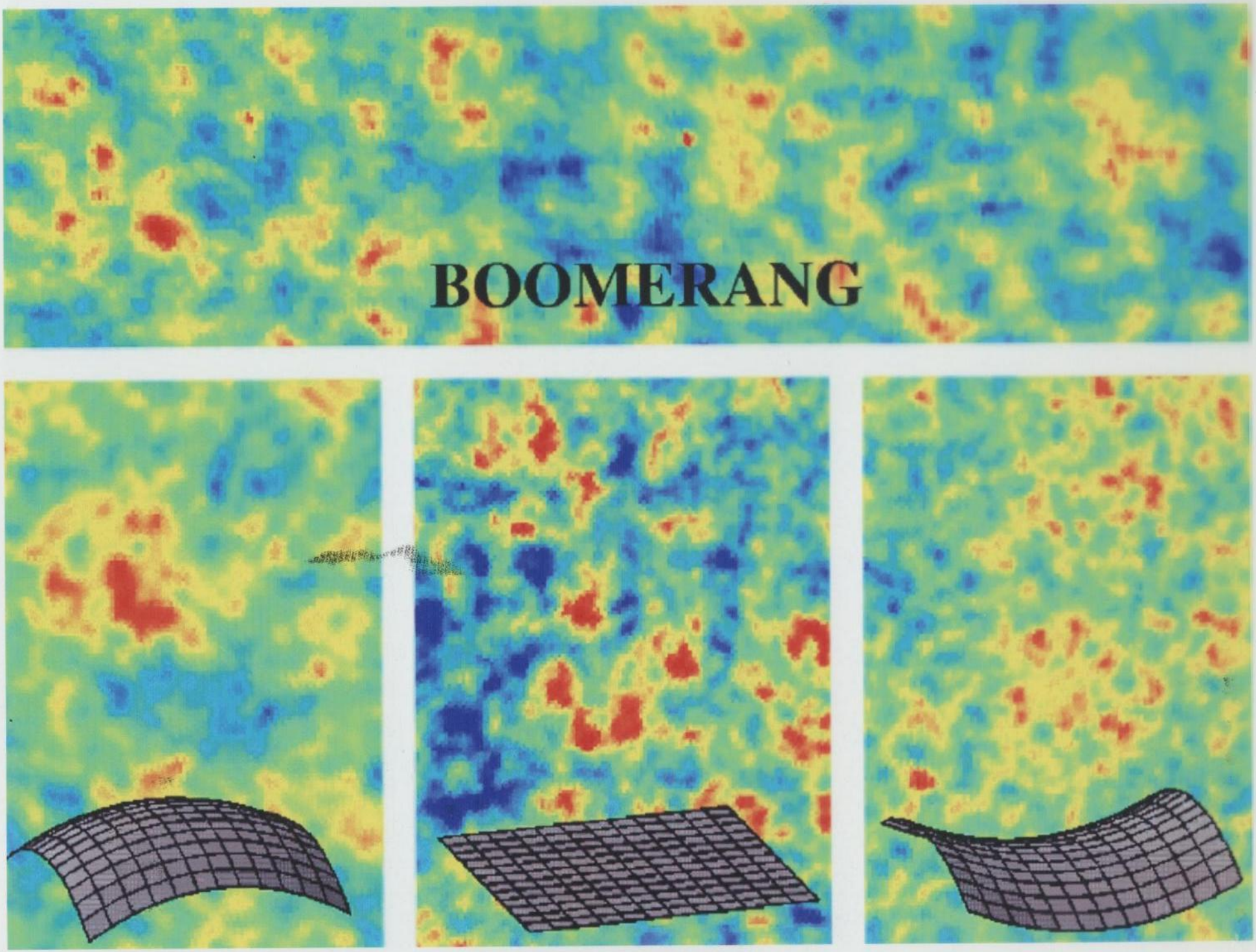
CMB IS A NON TRIVIAL PROBE OF MATTER DENSITY





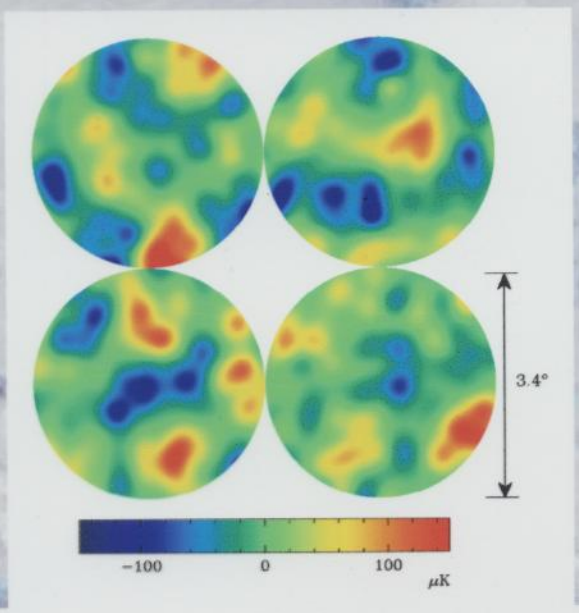
RESPONSE DEPENDS UPON: MATTER & BARYON DENSITIES, CURVATURE, DARK ENERGY ... & PRIMEVAL $\delta\phi/\phi$

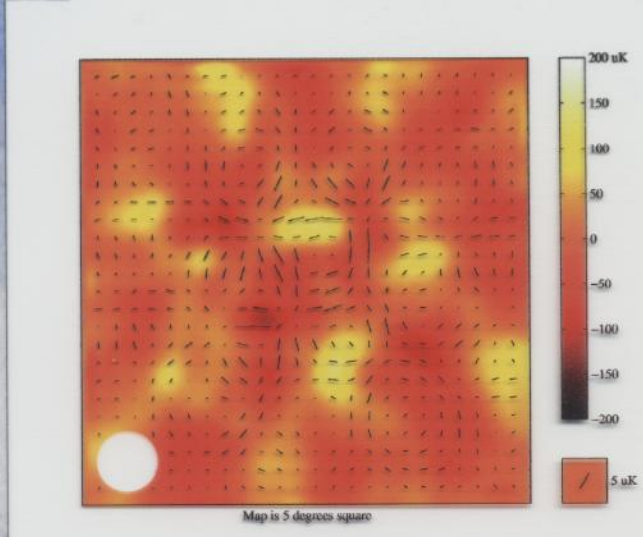
→ PROBES COSMOLOGY!

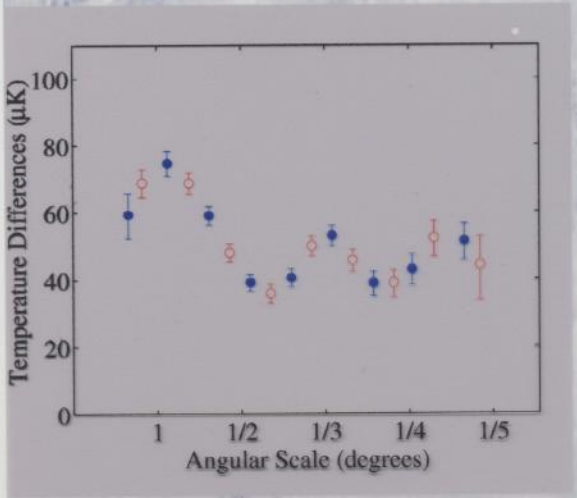

BOOMERANG

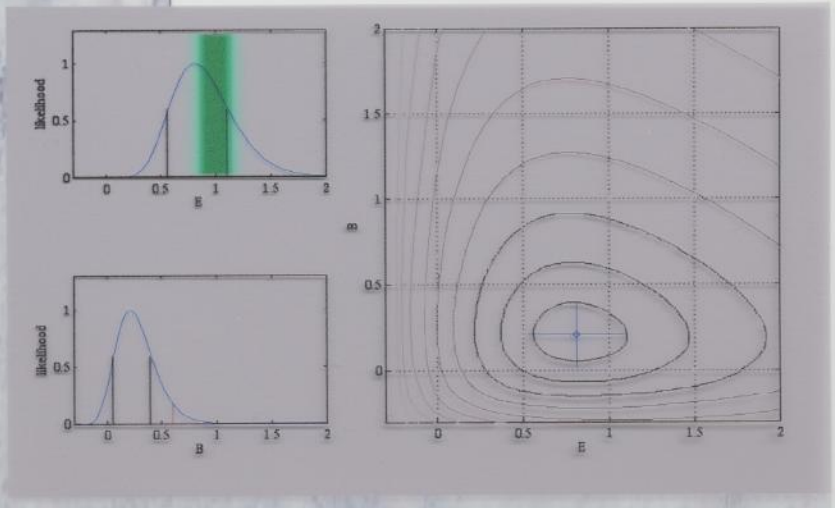
DASI

Acoustic Peaks and Polarization



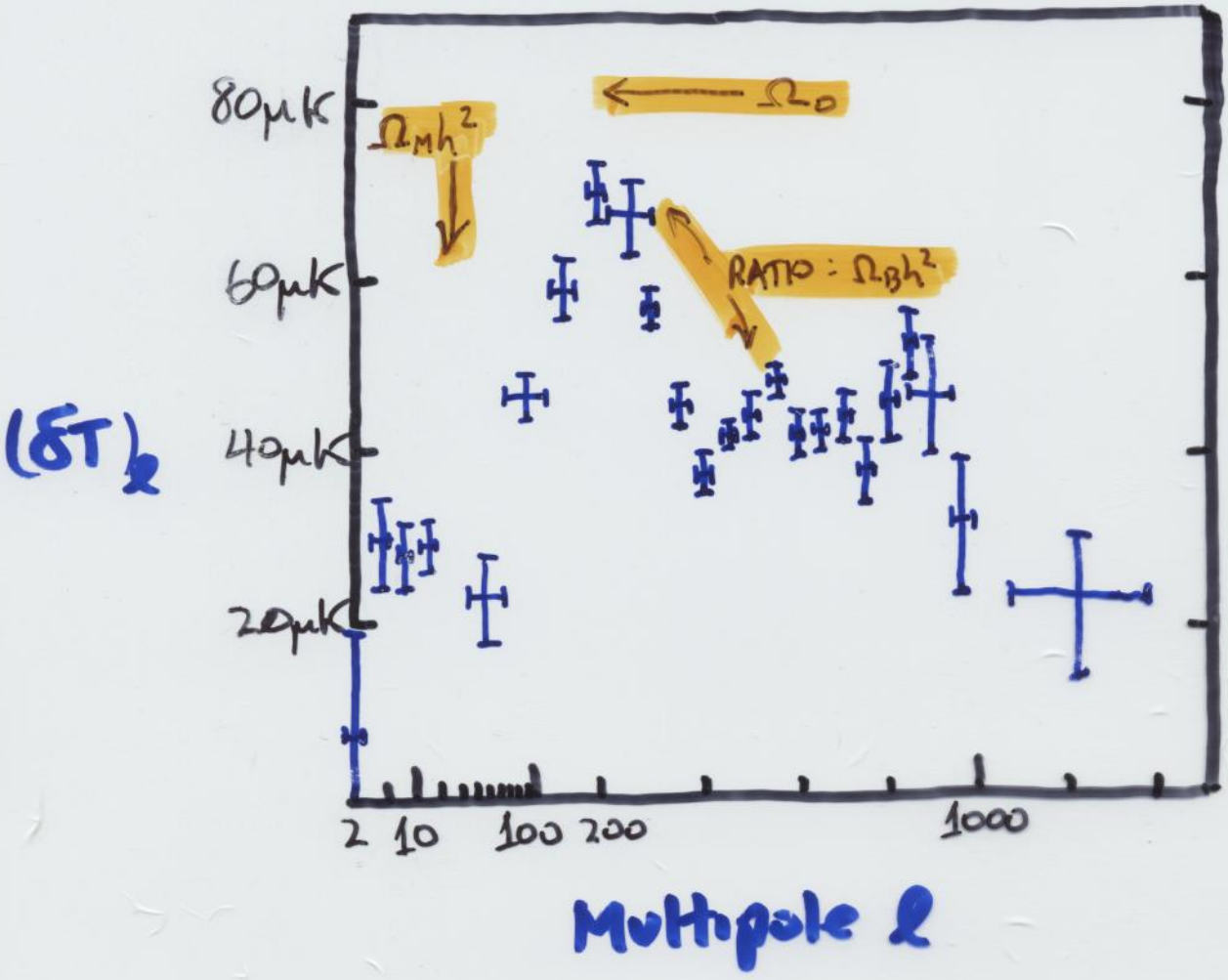






SUMMARY: CMB ANISOTROPY

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

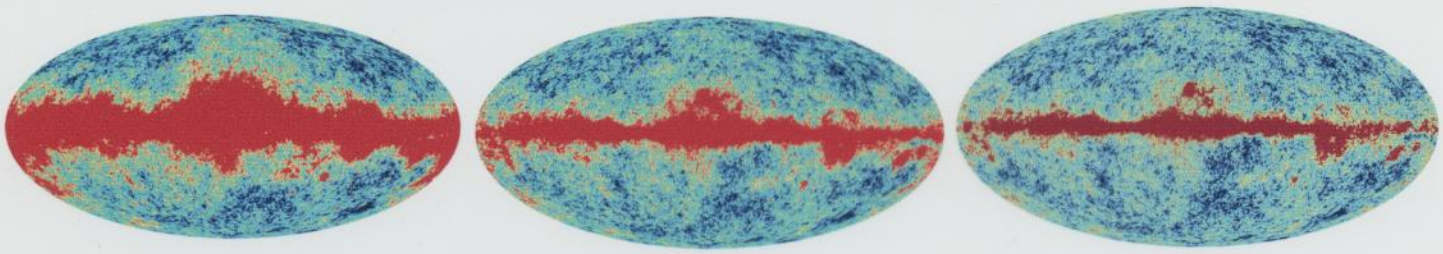


Curvature: $\Omega_0 = 1 \pm 0.03$

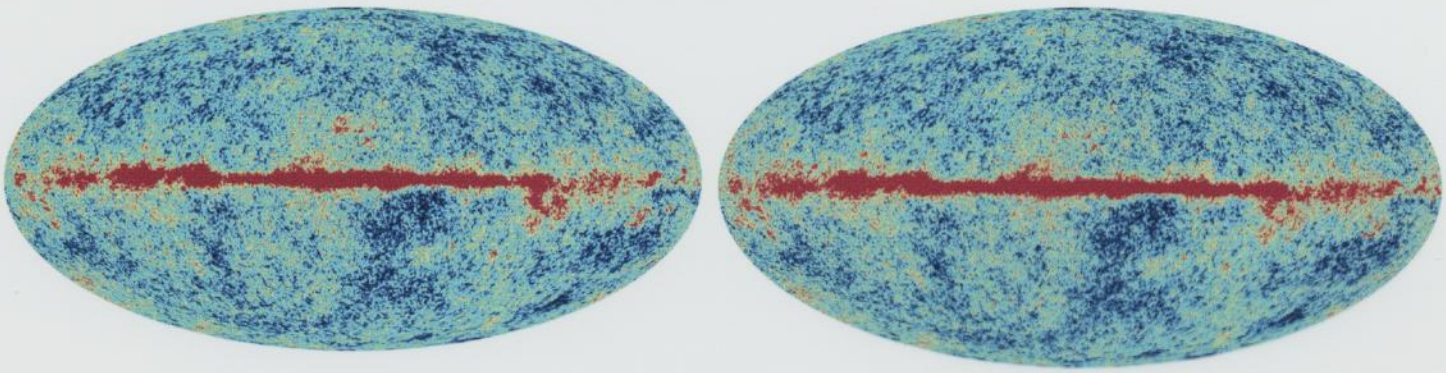
Matter density: $\Omega_M h^2 = 0.16 \pm 0.04$

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

WMAP's 6 MAPs

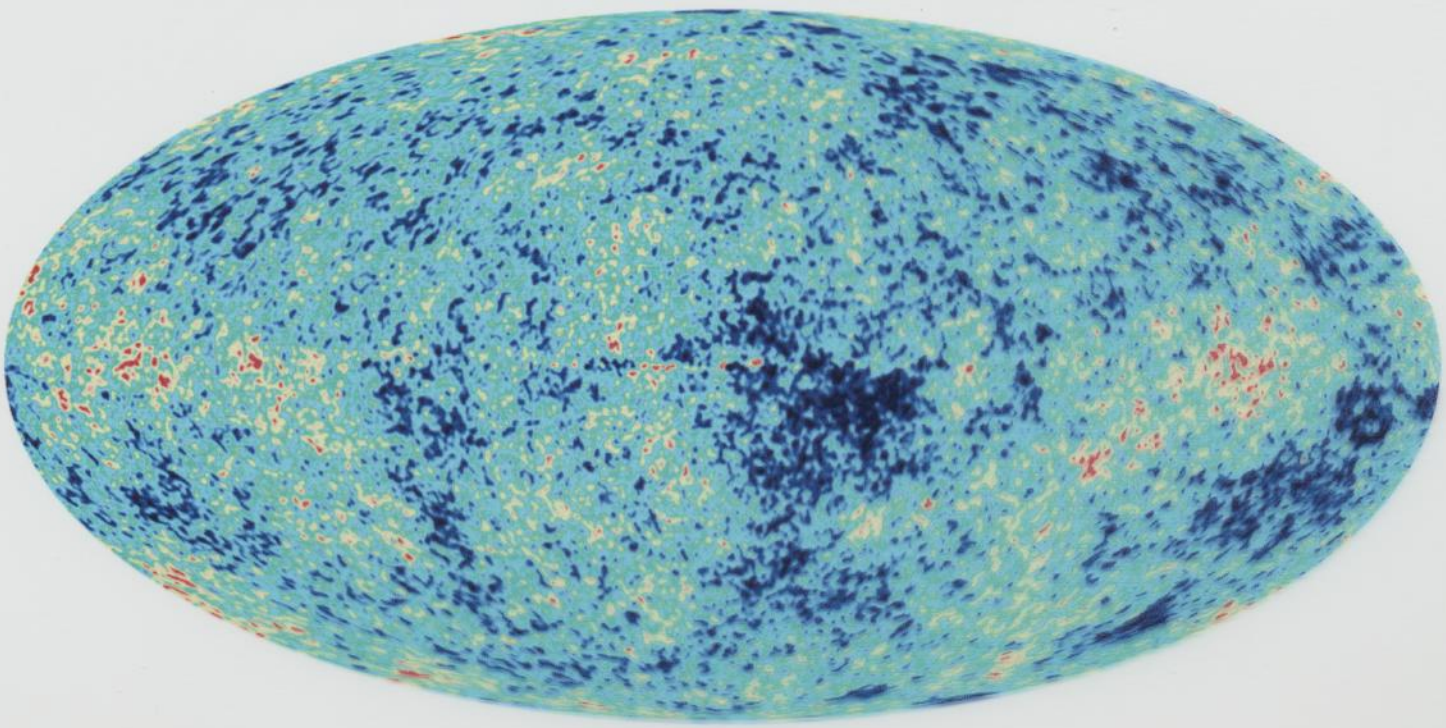


23 GHz 33 GHz 41 GHz



61 GHz 94 GHz

Cosmic Microwave Background



Foreground Subtracted

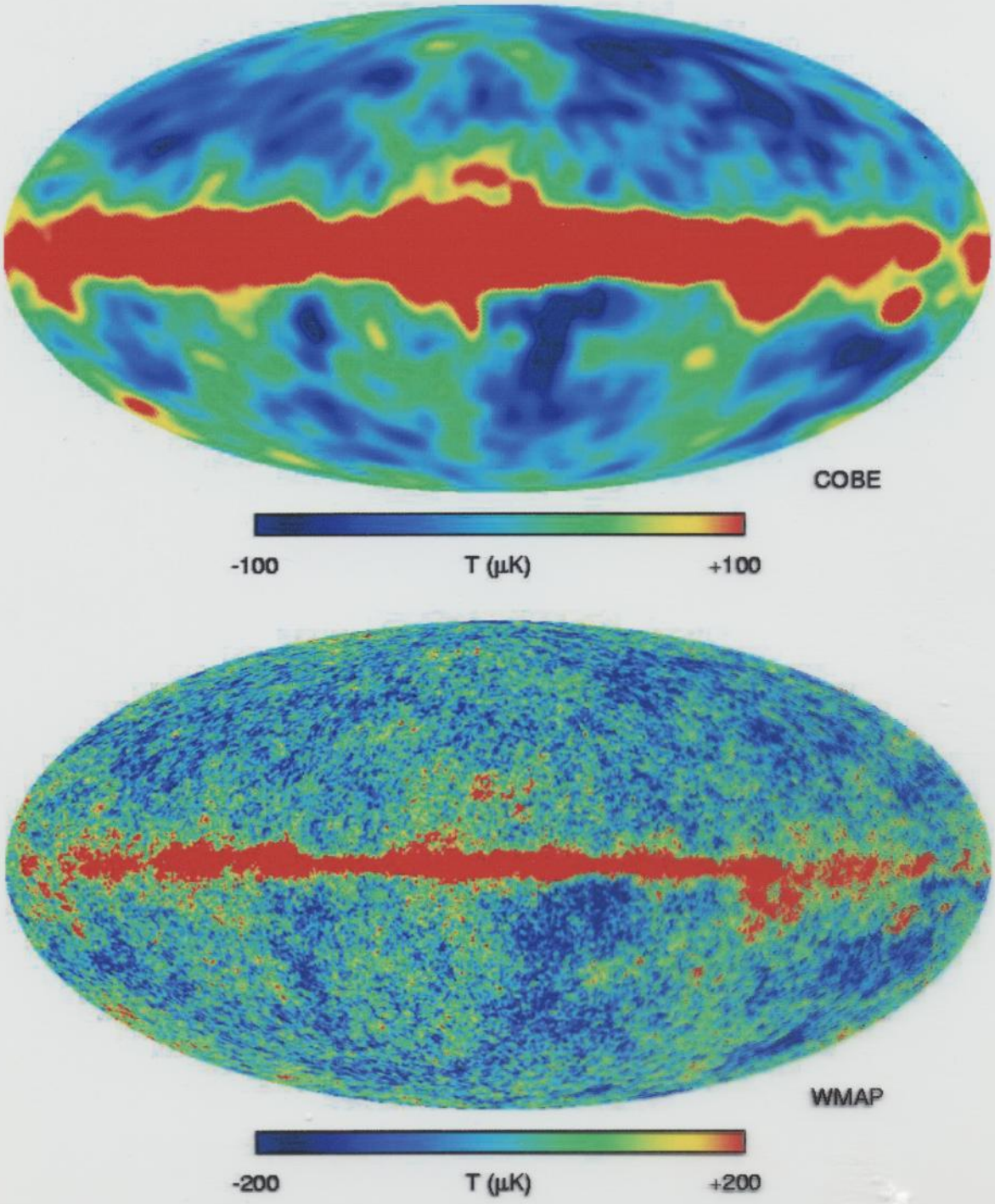
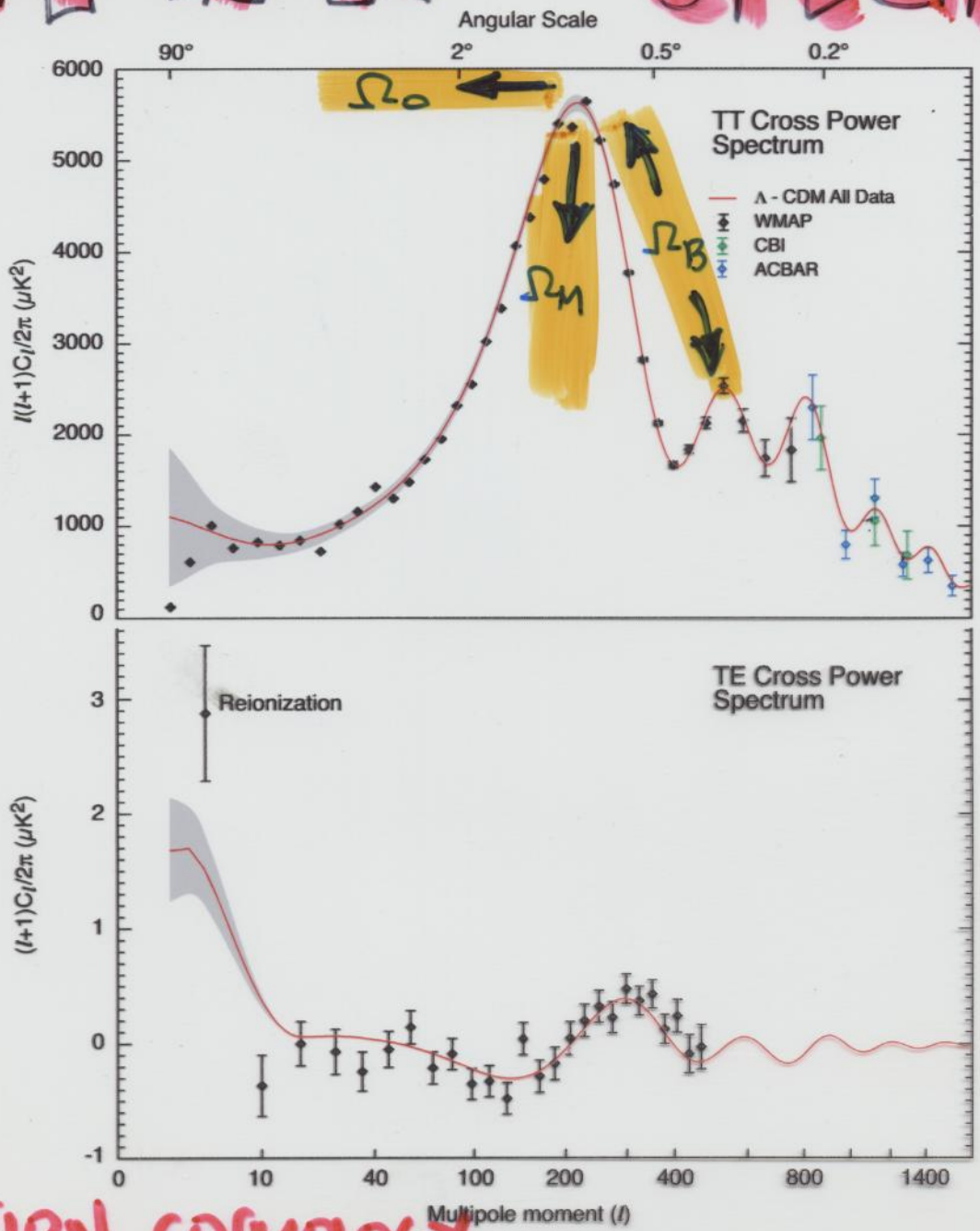


Fig. 7.— A comparison of the *COBE* 90 GHz map (Bennett et al. 1996) with the W-band *WMAP* map. The *WMAP* map has 30 times finer resolution than the *COBE* map.

WMAP POWER SPECTRUM



PRECISION COSMOLOGY

$\Omega_0 = 1.02 \pm 0.02$

$t_0 = 13.7 \pm 0.2$ Gyr

* $\Omega_M h^2 = 0.135 \pm 0.008$

$h = 0.71 \pm 0.035$

* $\Omega_B h^2 = 0.0224 \pm 0.001$

$\Omega_{D.E.} = 0.7 \pm 0.04$

$\Omega_M / \Omega_B = 6 \pm 0.4$

* $h^2 \approx \frac{1}{2}$, $h^{-2} \approx 2$

COSMIC CONSISTENCY: WMAP vs. pre-WMAP

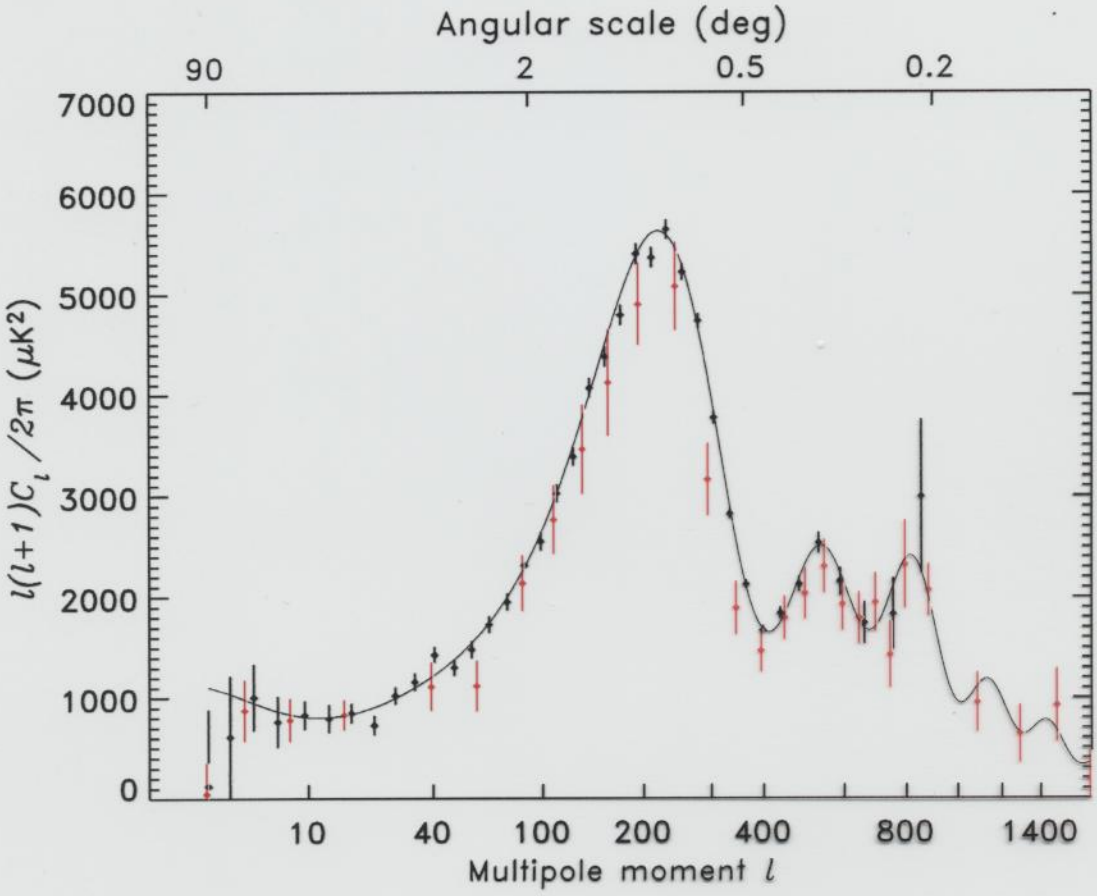


Fig. 10.— The *WMAP* combined power spectrum, in black, compared to a compilation of all CMB data published prior to *WMAP* from Wang et al. (2002a), in red. The *WMAP* data are plotted with cosmic variance plus measurement uncertainties here in order to facilitate a comparison with the compiled data which is reported in this way. The data agree well on *COBE* scales, $l < 20$, (but note that the *WMAP* cosmic variance errors are computed from the best-fit model rather than the data, thus they appear larger than the *COBE* errors at the quadrupole). However, the overall normalization of the *WMAP* spectrum is ~10% higher on smaller scales.

COSMOLOGY IS BECOMING BORING....

WMAP HIGHLIGHTS

RE-IONIZATION DUE TO 1ST GENERATION OF STARS

$z = 20 \pm 10$

AGE OF UNIVERSE

13.7 ± 0.2 Gyr

FURTHER EVIDENCE FOR DARK ENERGY & FLAT UNIVERSE

$\Omega_{DE} = 0.73 \pm 0.04$ $\Omega_0 = 1.02 \pm 0.02$

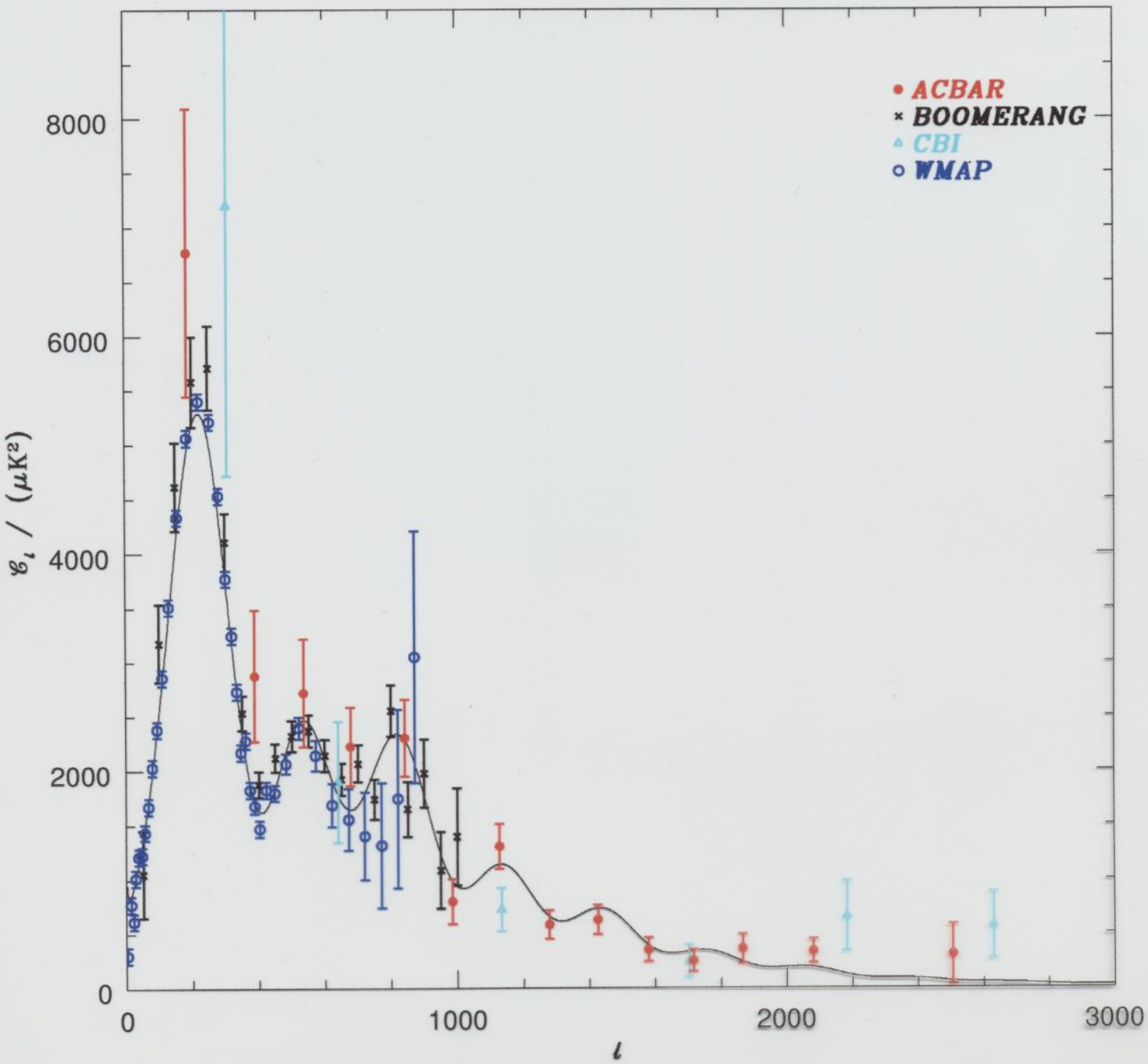
BARYON DENSITY TEST

$\Omega_B h^2 = 0.0224 \pm 0.001$ vs 0.02 ± 0.001 BBN

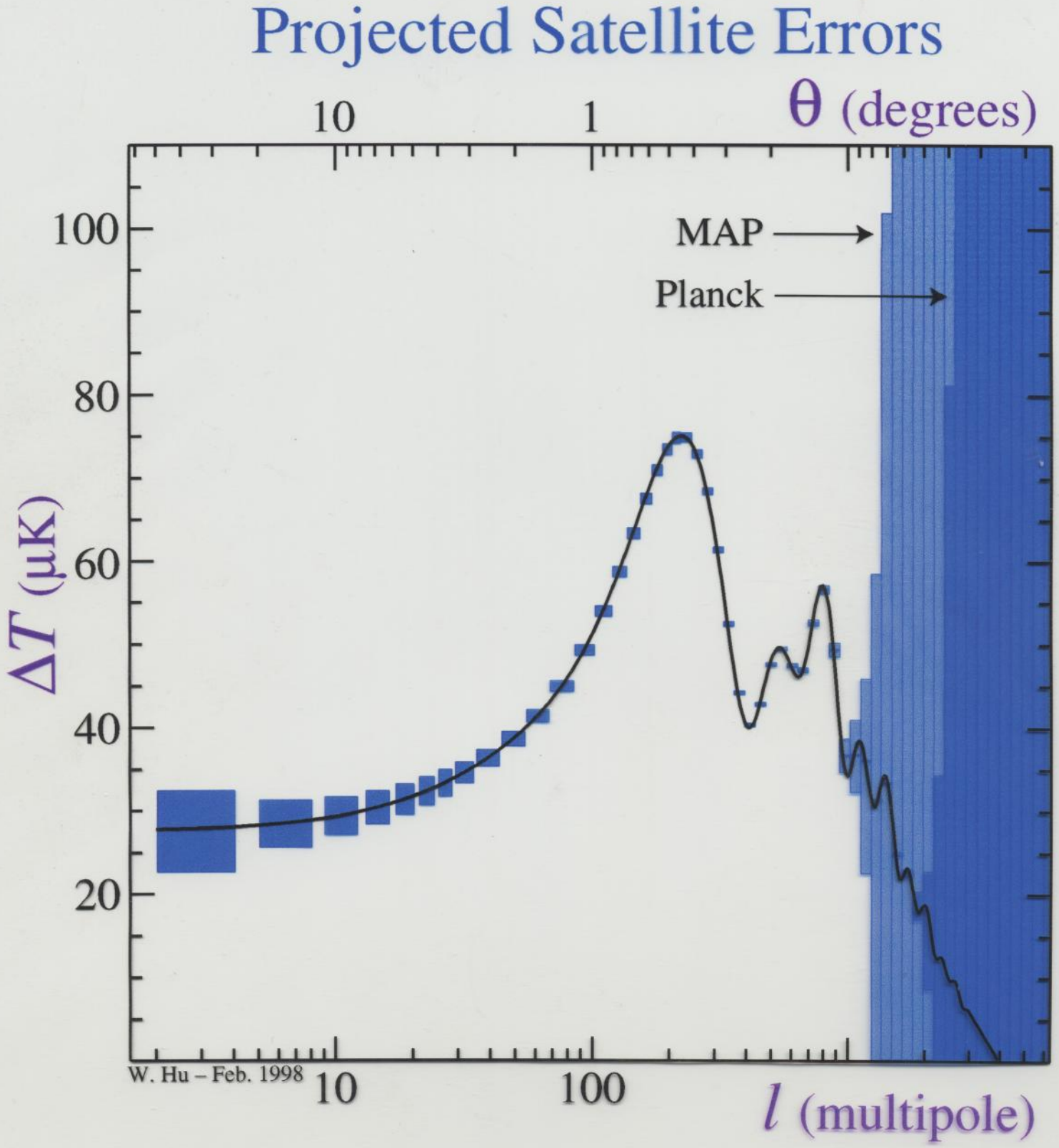
EVIDENCE FOR INFLATION & RULED OUT FIRST MODEL!

EXQUISITE CONTROL OF SYSTEMATICS & ALL-SKY

FIRMLY ANCHORS PREVIOUS RESULTS


ACBAR
BOOMERANG
CBI
WMAP
8000
6000
4000
2000
0
0
1000
2000
3000
$\mathcal{C}_l$ / (μK^2)
l

Projected Satellite Errors



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

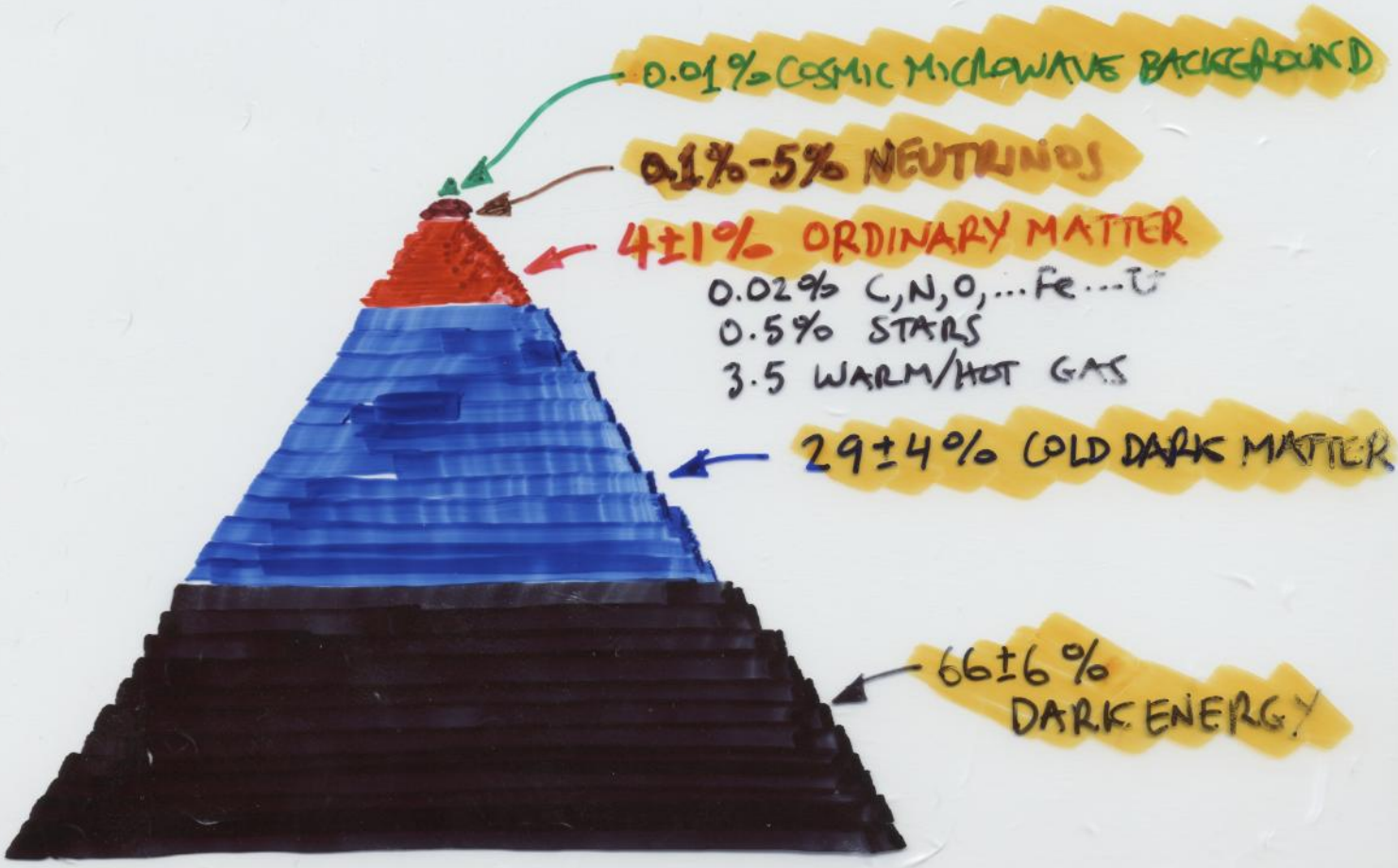
DARK ENERGY DETERMINES ITS DESTINY

COSMIC RECIPE

FLAT, CRITICAL DENSITY UNIVERSE

0.5% STARS

33% DARK MATTER + 66% DARK ENERGY

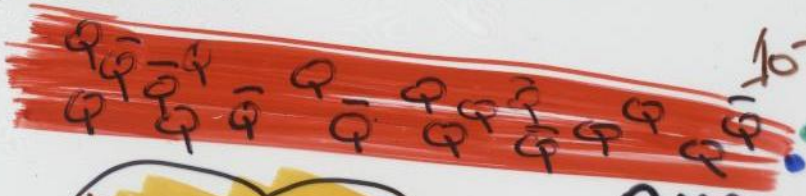


→ MORE THAN 95% IN NEW FORMS OF MATTER & ENERGY!

ORDINARY MATTER: FROM QUARKS TO US

COSMIC ACCOUNTING

BARYOGENESIS



10^{-5} sec

QUARK/HADRON TRANSITION

1 sec

BBN

Burles et al astro-ph/0010171

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

$\Omega_B h^2 = 0.02 \pm 0.001$

$\Omega_B \simeq 0.04 \pm$

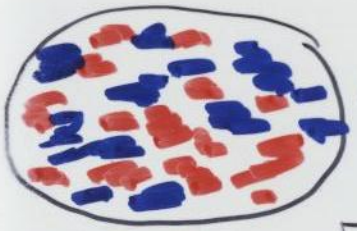
"BARYON BUMPS"

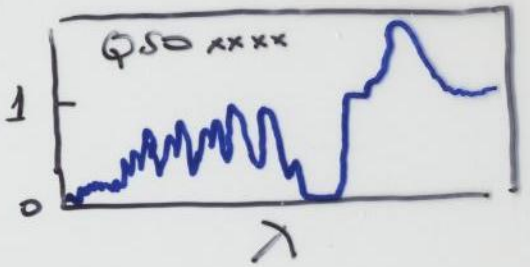
$\Omega_B/\Omega_M = 0.15 \pm 0.07$

$\Omega_B h^2 = 0.021 \pm 0.08$

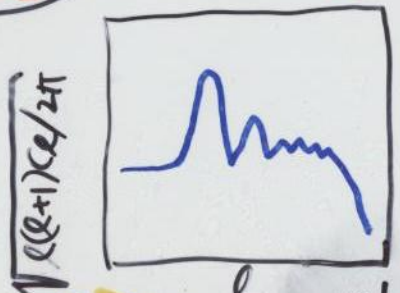
CMB

400,000 yr





$z \sim 2\text{-}5$ QSOs



astro-ph/0104490 & 0104460

$\frac{1^{st}\ PEAK}{2^{nd}\ PEAK} \simeq 2\left(\frac{\Omega_B h^2}{0.02}\right)^{2/3}$

$\Omega_B h^2 = 0.0224 \pm 0.001$

$\Omega_B \simeq 0.045$

ABSORPTION OF QSO LIGHT BY GASEOUS BARYONS @ $z \approx 2\text{-}3$

$\Omega_B h^2 \geq 0.021 \left[\frac{\Omega_M h^2}{0.3(2/3)^2}\right]^{1/4} \Gamma_{-12}^{1/2}$

McDonald et al astro-ph/0005553

LSS

Direct Inventory

MATTER CONTENT

NOW DETERMINED INDEPENDENT OF MASS/LIGHT BIAS

BARYONS: $\Omega_B h^2 =$

0.020 ± 0.001 BBN (THEORY + D/H)

$0.022^{+0.004}_{-0.003}$ CMB (DASI/BOOMERANG)

0.021 ± 0.008 Baryon Bumps (2dF)

0.0224 ± 0.001 WMAP

--- CONFIRMS SCHRAMM BBN PREDICTION

Ω_M/Ω_B:

$\frac{\Omega_M}{\Omega_B} =$

8.5 ± 1.5 CLUSTER INVENTORY

7.2 ± 2 CMB

6.6 ± 3 BARYON BUMPS

6 ± 0.5 CMB/WMAP

→ **Air tight case for nonbaryonic DM**

NB: Cross checks / consistency

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

BEST NUMBERS

M&T astro-ph/0106035

$\Omega_B = 0.04 \pm 0.008$

$\Omega_M = 0.33 \pm 0.035$

$= 0.27 \pm 0.04$ WMAP!

$\Omega_X = 0.67 \pm 0.06$ — DARK ENERGY

+ $\Omega_0 = 1 \pm 0.04$

1.02 ± 0.02 (WMAP)

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

"75 case for nonbaryonic DM"

MOOSE DIAGRAM of DARK MATTER CANDIDATES

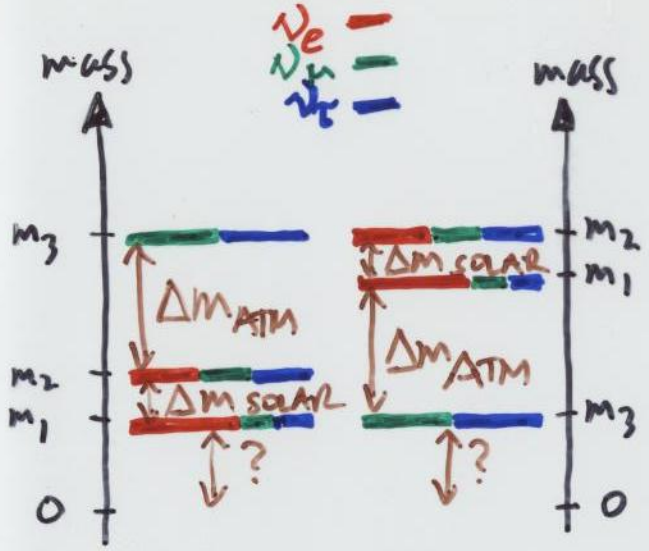
MIT '90

COMING INTO FOCUS

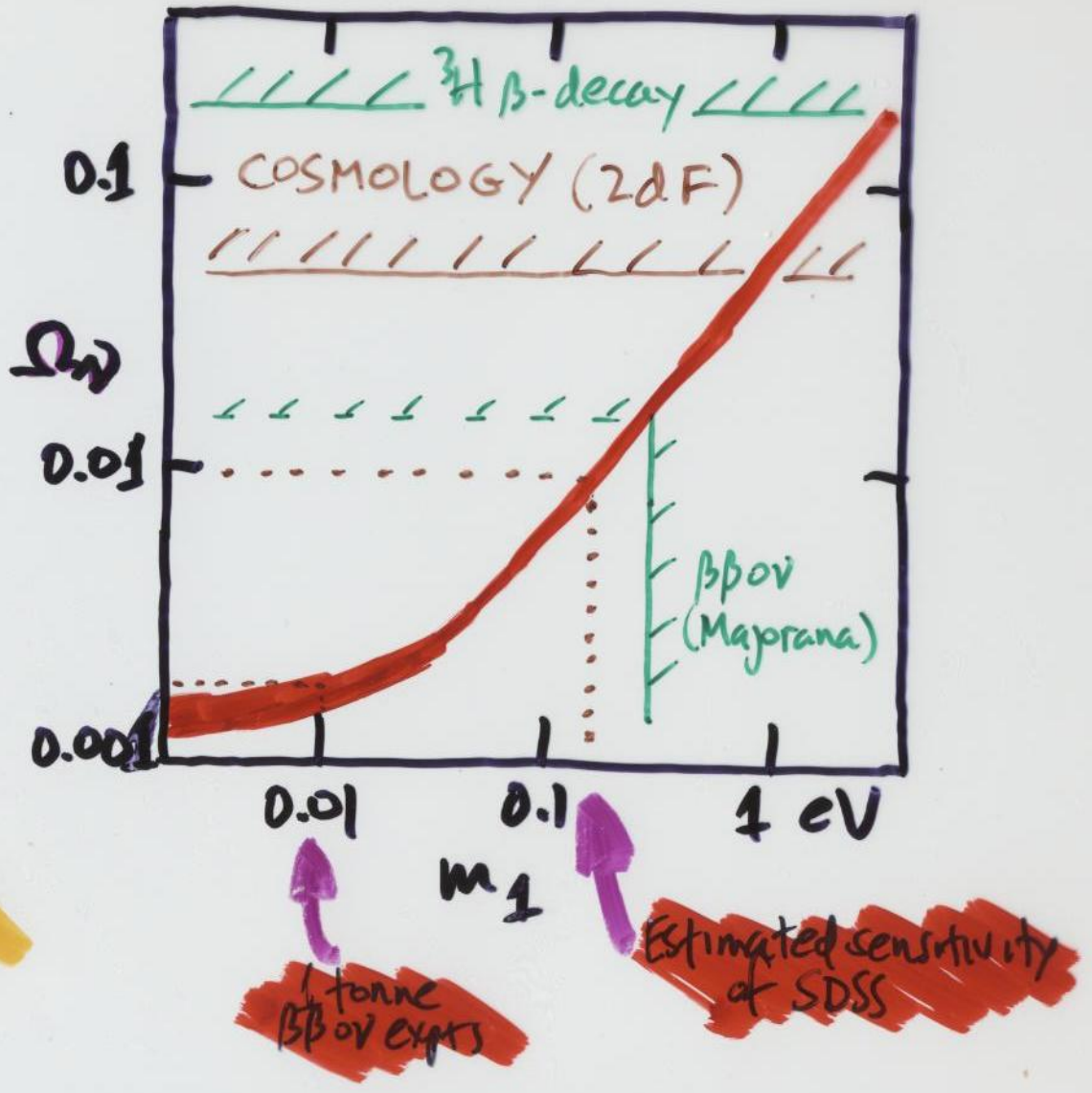
NEUTRINO DARK MATTER

Homestake, ..., SNO

TWO (MASS DIFF)^2 : $(\Delta m^2)_{Atm} = (1.6\text{-}3.9)\times 10^{-3}\,eV^2$ SuperK,... 90%cl $(\Delta m^2)_{solar} = (0.23\text{-}3.7)\times 10^{-4}\,eV^2$ 95%cl



NEED MASS SCALE & PATTERN

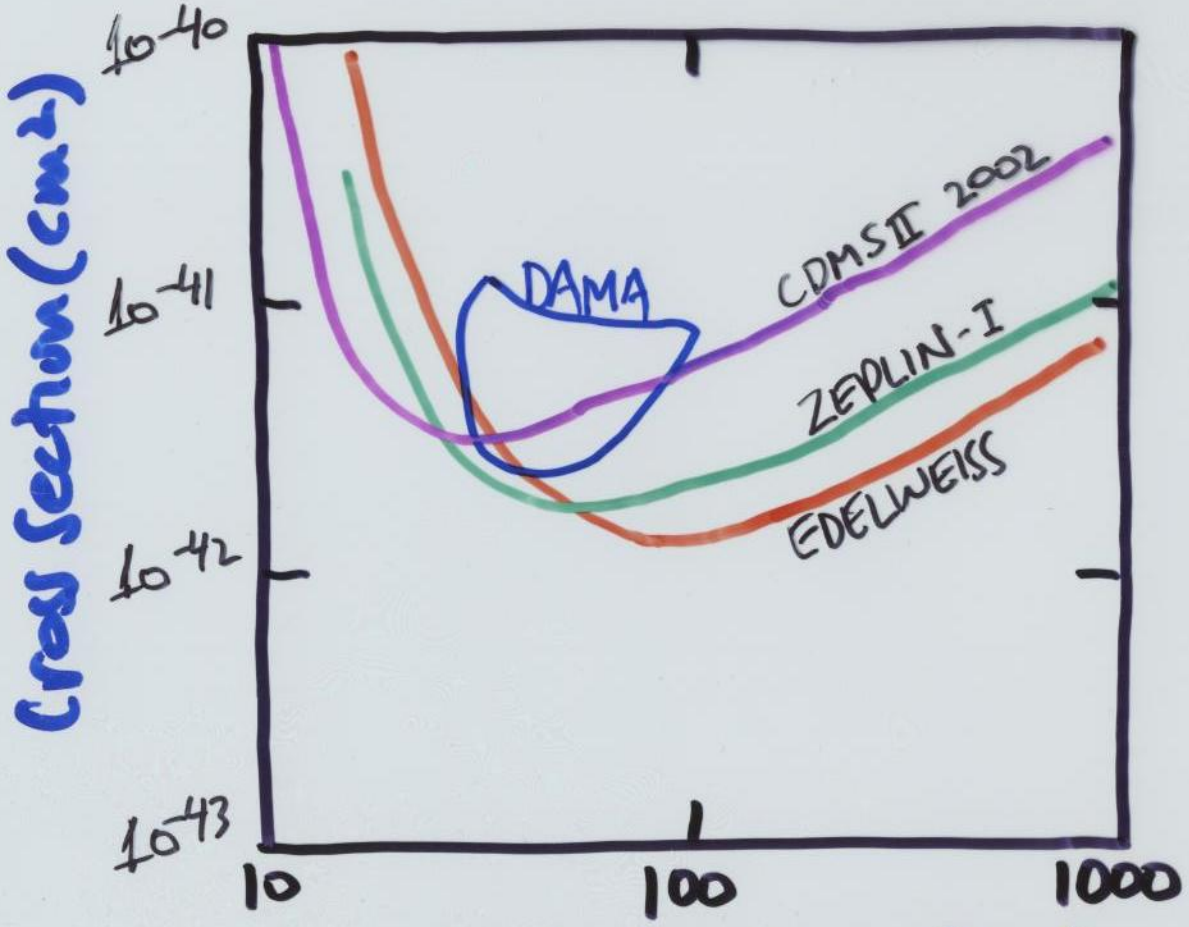


$\Omega_\nu = 0.001\text{-}0.05$

CosmicSpice

EXPT'L SUMMARY

M. DeJesus Cosmo 02



$3 \times 10^{-41}\ cm^2$

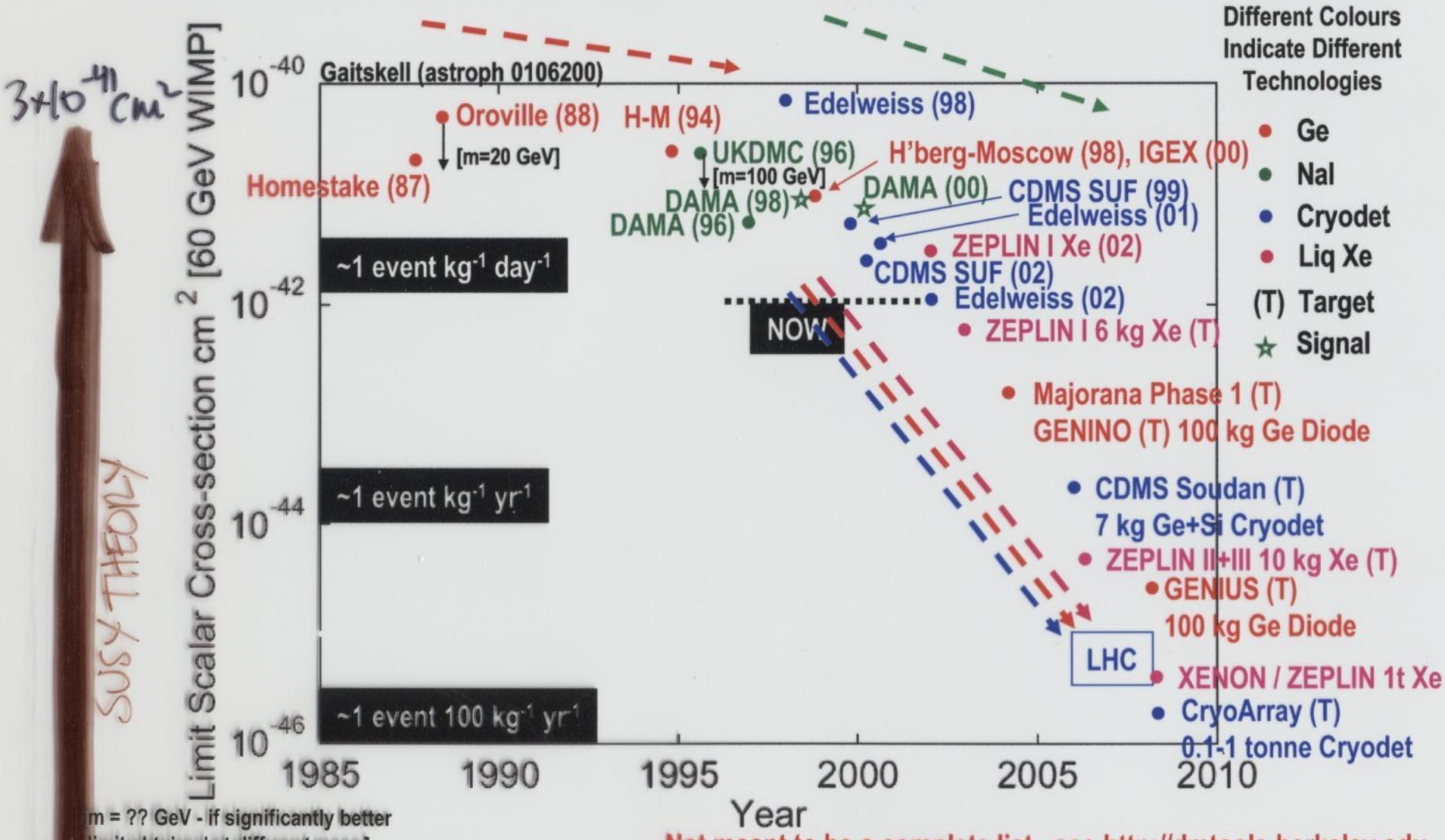
FAVORED BY SUSY MODELS

"50 - 500 GeV"

$10^{-47}\ cm^2$

Direct Detection: History & Future

90% CL Limit on Cross section for 60 GeV WIMP (scalar coupling)



m = ?? GeV - if significantly better limit obtained at different mass]

Not meant to be a complete list - see http://dmtools.berkeley.edu

NeSS Sept 2002

011211.6.rjg

Rick Gaitskell

18 December 1998

Science

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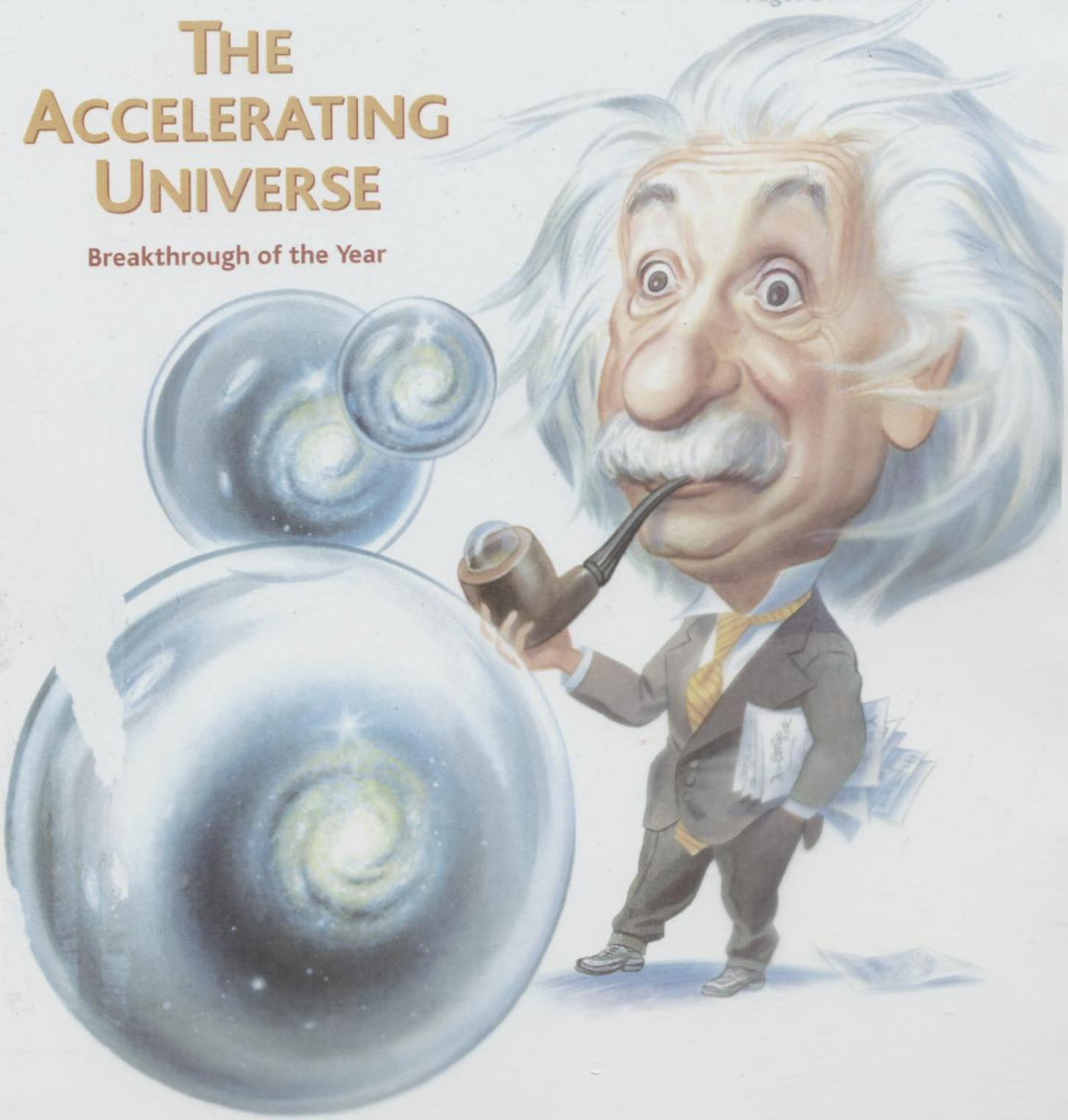
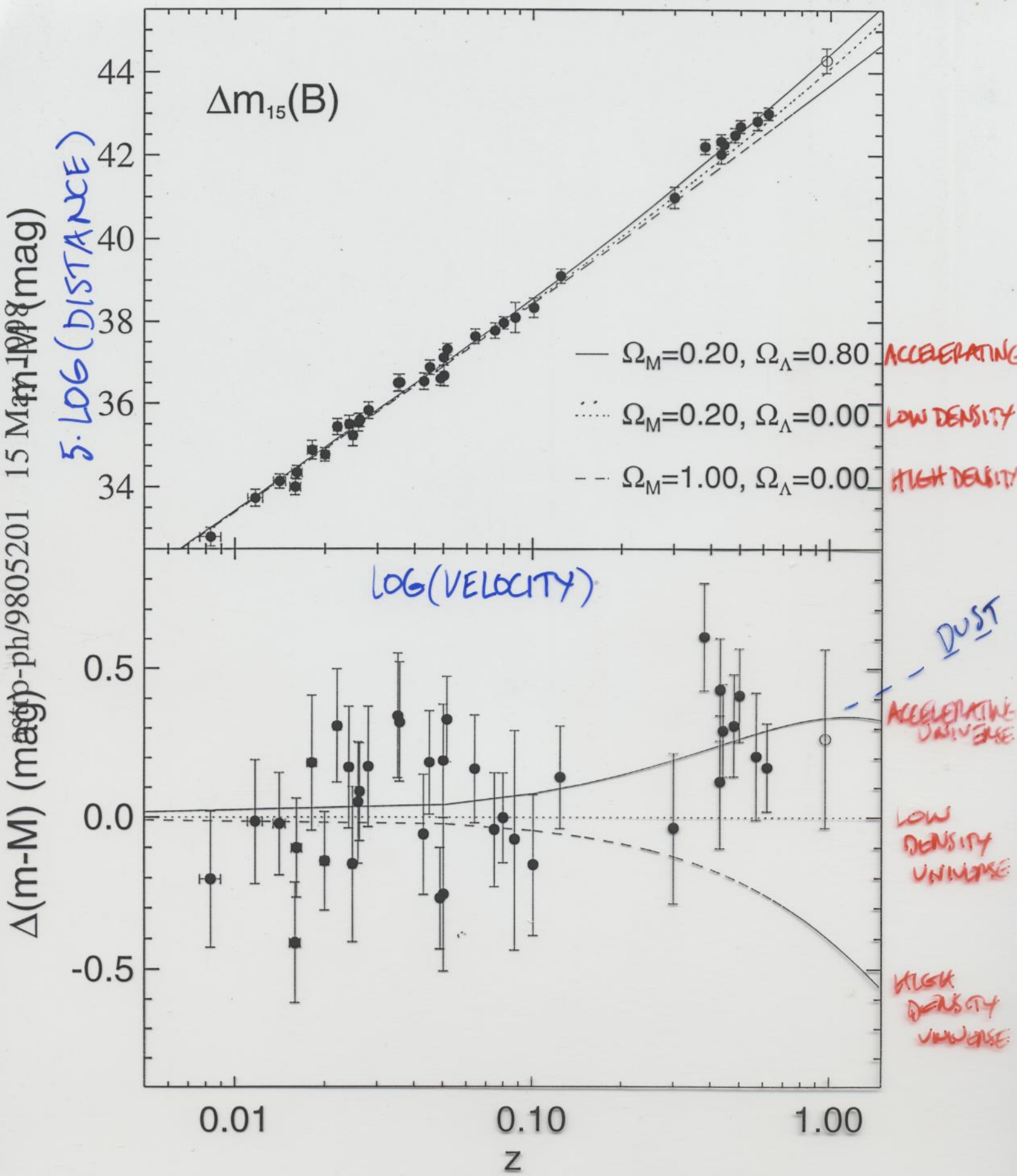
THE ACCELERATING UNIVERSE

Breakthrough of the Year



AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

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



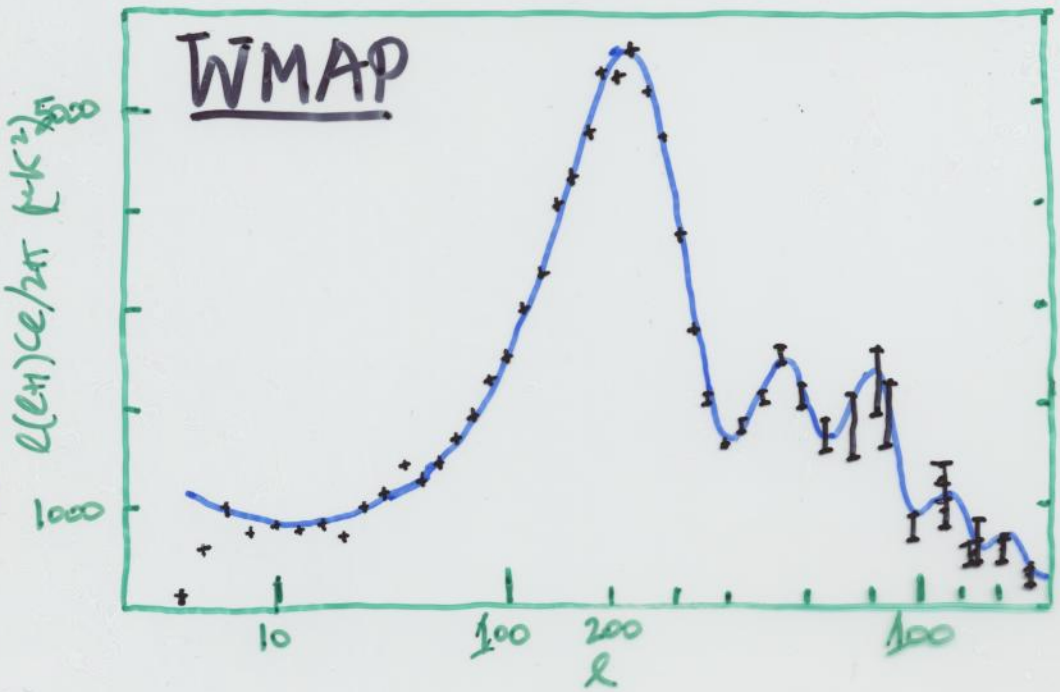
astro-ph/9805201 15 May 1998

TWO LINES OF EVIDENCE FOR DARK ENERGY

CMB → "MISSING ENERGY"

$\Omega_X = \Omega_0 - \Omega_M$

$= 0.7 \pm 0.04$

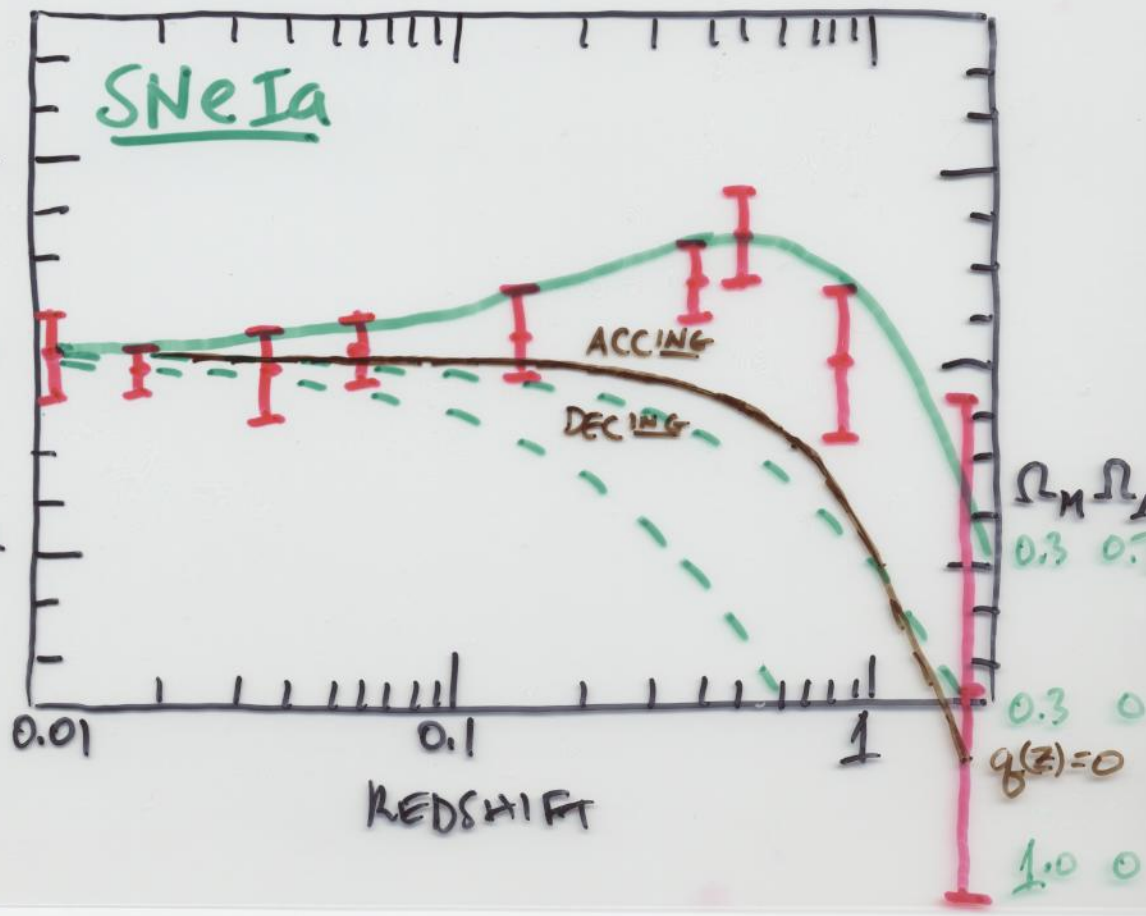


SNeIa

200 SNeIa
astro-ph/
0305008
(Tonry etal)

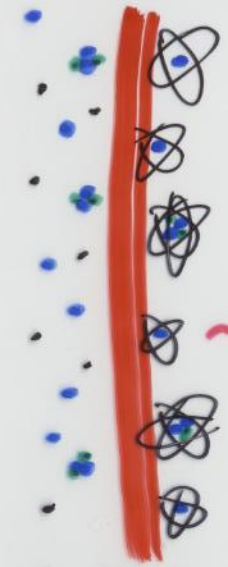
$\Omega_X = 1.4\Omega_M + 0.35 \pm 0.14$

$= 0.8 \pm 0.06$



DETECTING DARK ENERGY W/ SACHS-WOLFE EFFECT

R. Scranton et al, astro-ph/0307355



WITH DARK ENERGY

$(\Omega_M = 1/3, \Omega_{DE} = 2/3)$

$z \sim 0.5$
EVOLVING
LARGE-SCALE STRUC.

WMAP & SDSS

POSITIVE CORRELATION BETWEEN HOT SPOTS & LSS

Blueshift (falling in)

Smaller Redshift (climbing out)

$z = 1100$
$t = 400{,}000$ yrs

W/O DARK ENERGY

$(\Omega_M = 1, \Omega_{DE} = 0)$

NO CORRELATION

Blueshift (falling in)

Equal Redshift (climbing out)

GR ALLOWS FOR REPULSIVE GRAVITY:

SOURCE OF GRAVITY IN GR:

$\rho + 3p$

(SPHERICAL SYMMETRY)

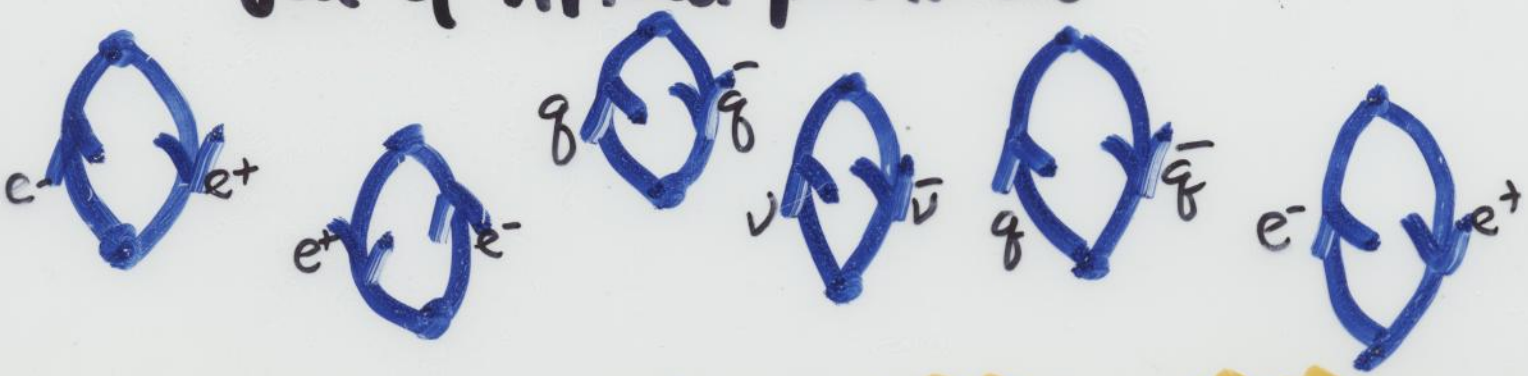
FEATURE NOT A BUG!

BLACK HOLES WHEN $p \geq \rho/3$

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

QUANTUM VACUUM IS NOT EMPTY!

sea of virtual particles



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

W. Lamb, calif.

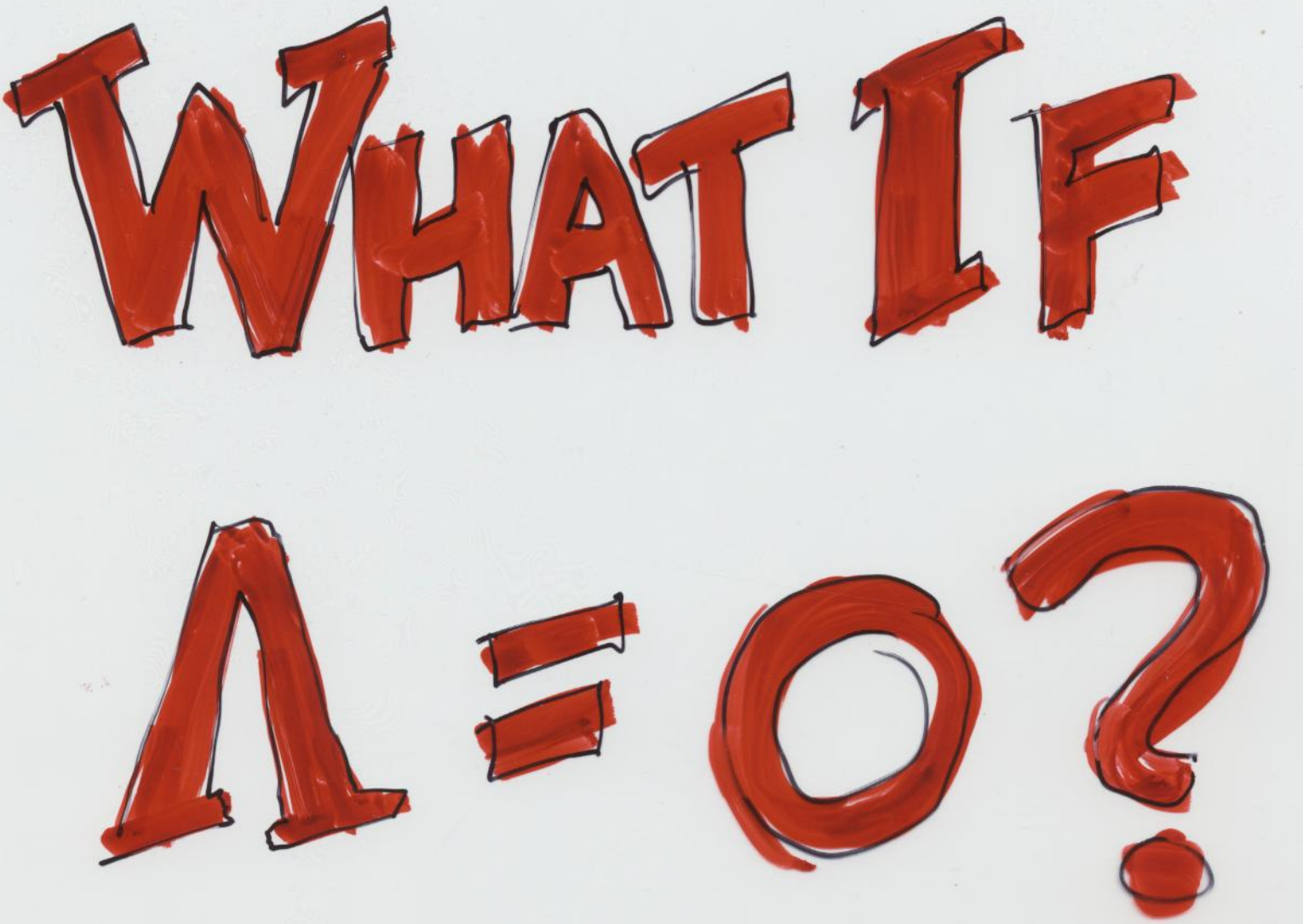
Quantum vacuum is elastic ($p = -p$)
& its Gravity is Repulsive!

JUST WHAT IS NEEDED -- BUT...

THEORETICAL ESTIMATES OF AMOUNT

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

"Houston, we have a problem"



BE CAREFUL WHAT YOU WISH FOR !!

CALL IT: DARK ENERGY

SOLVING THE DARK ENERGY PROBLEM WILL REQUIRE A CRAZY, NEW IDEA!

NB: NOT EVERY CRAZY IDEA IS A SOLUTION

COSMOLOGY IS THE BEST PROBE (ONLY?) OF DARK ENERGY

NETWORK OF (FRUSTRATED) TOPOLOGICAL DEFECTS

EG STRING

A. Vilenkin '84
Ben-Spergel '98

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

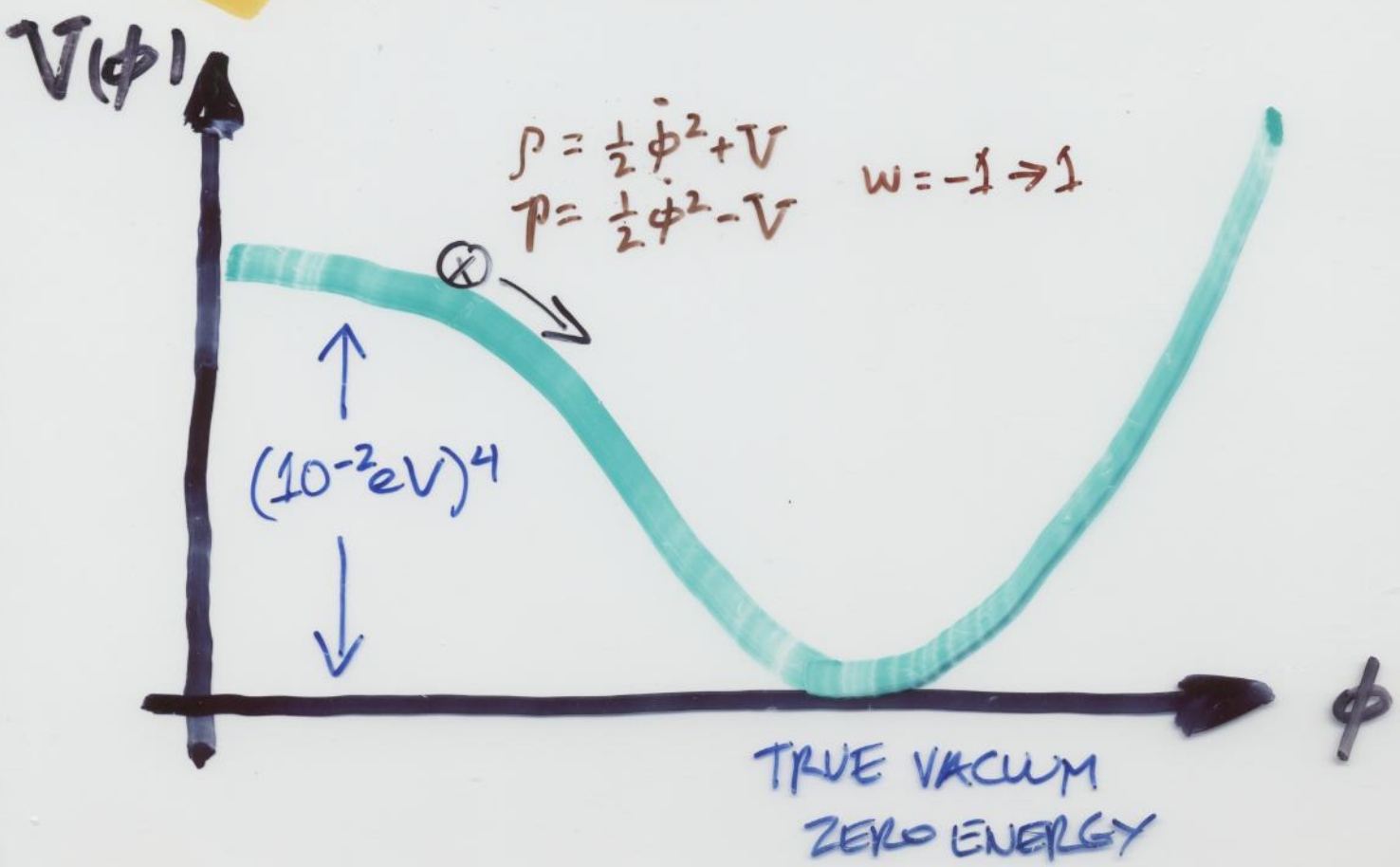
INTERMEDIATE: $p = -N/3\ \rho$

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."



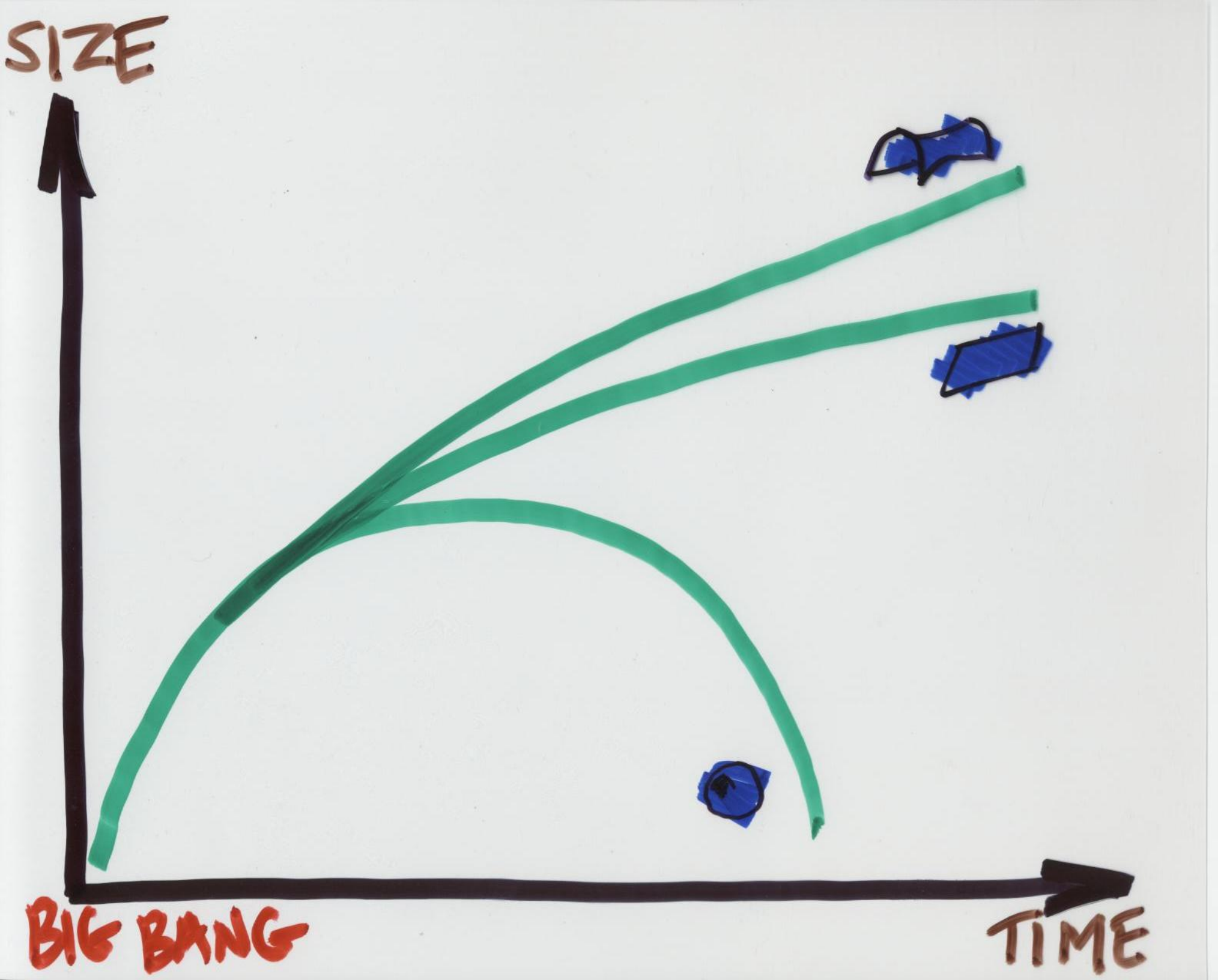
WEIRD DARK ENERGY

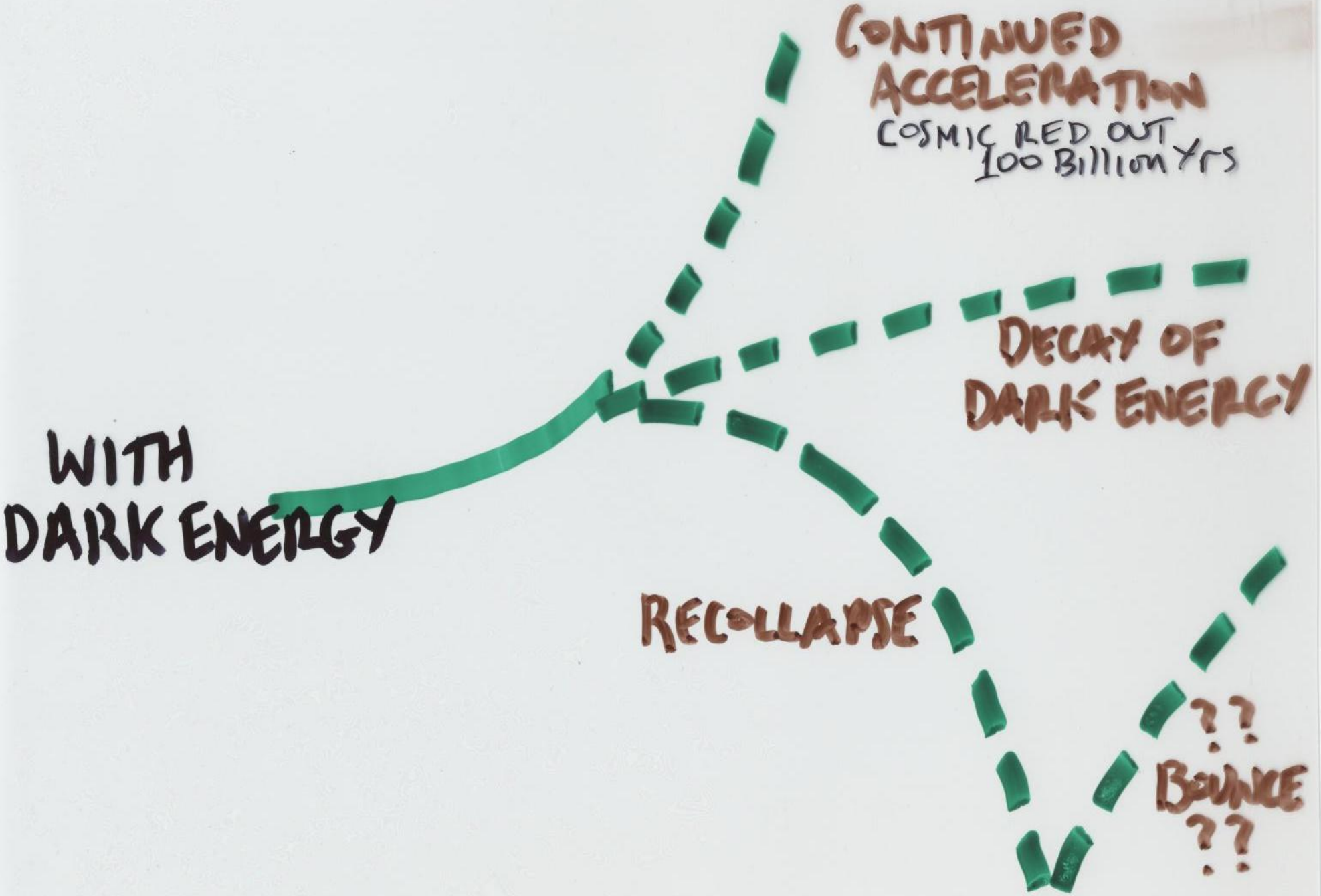
OR

NEW GRAVITATIONAL PHYSICS?

EINSTEIN'S SURPRISE: NATURAL STATE OF UNIVERSE IS EXPANSION OR CONTRACTION

NEW SURPRISE: NATURAL STATE OF "EMPTY UNIVERSE" IS ACCELERATED EXPANSION!


SIZE
BIG BANG
TIME


CONTINUED ACCELERATION
COSMIC RED OUT
100 Billion Yrs
DECAY OF DARK ENERGY
WITH DARK ENERGY
RECOLLAPSE
??
BOUNCE
??

INFLATION

- MOST INFLUENTIAL IDEA IN COSMOLOGY
- NOW BEING TESTED

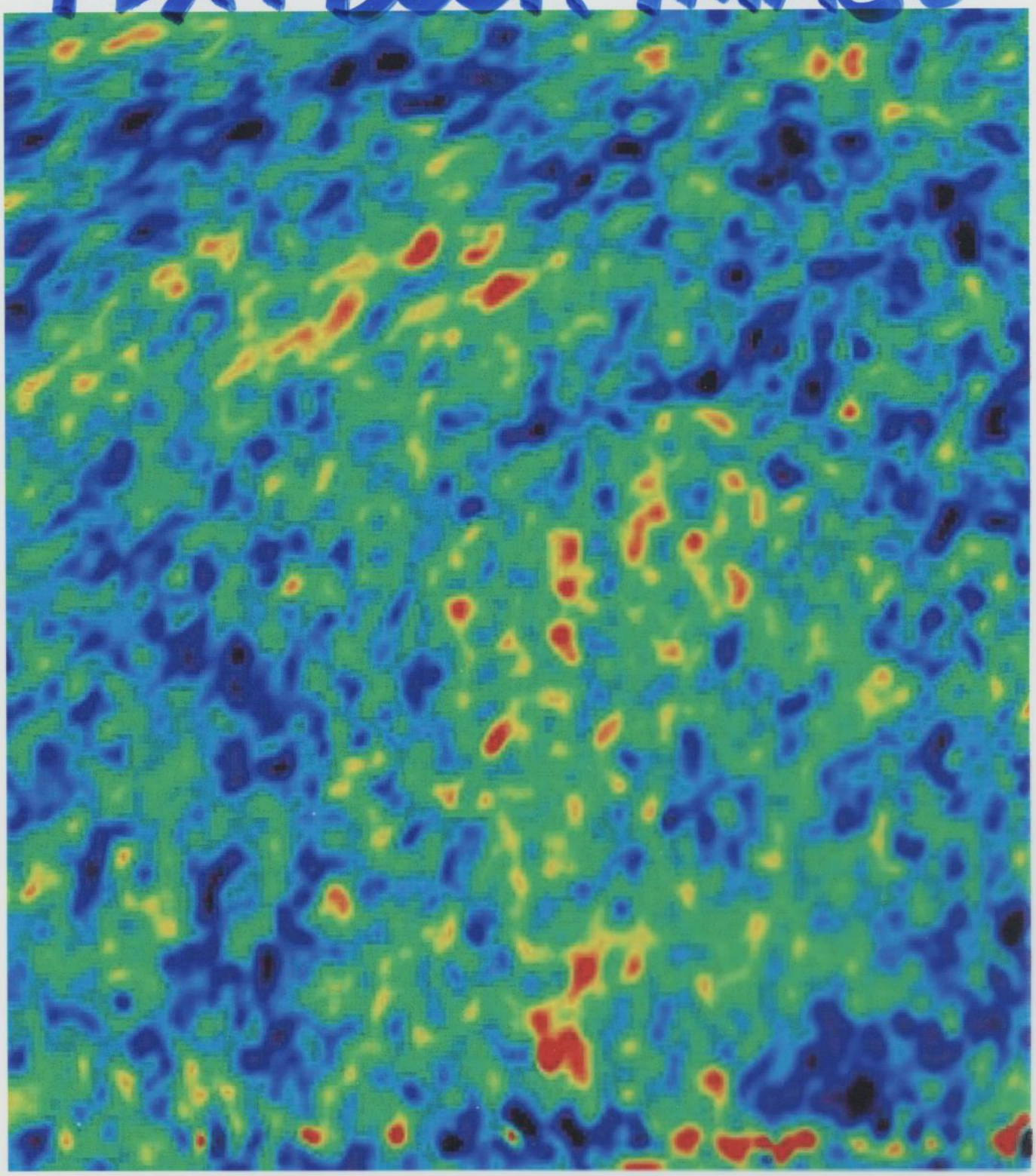
Additional Reading:

- Kolb & Turner The Early Universe Ch 8
- Liddle & Lyth Cosmological Inflation... Ch 3 & 7
- astro-ph/ 9607066, 9704062, 0006321, 0212281, 0302225, 0304370

INFLATION SCORECARD

PREDICTIONS	WMAP NOW	GRADE	GOAL
FLAT UNIVERSE			
★ $\Omega_0 = 1.000$	1.02 ± 0.02 $\Omega_0 = 1.03 \pm 0.03$	++*	± 0.001
	* FOR DOING IT THE HARD WAY		
DENSITY PERTS FROM QM FLUC			
★ ADIABATIC	≥3 ACOUSTIC PEAKS	+	≥7
★ NEARLY SCALE-INVARIANT $(n-1) \sim \mathcal{O}(\pm 0.1)$	0.93 ± 0.03 $n = 1.05 \pm 0.09$	+	± 0.001
★ NEARLY POWER-LAW $dn/d\ln k \sim \pm 10^{-3}$	-0.03 ± 0.02 $dn/d\ln k = -0.02 \pm 0.04$	✓	$\pm 10^{-3}$
★ GAUSSIAN	NO EVIDENCE AGAINST	✓	
→ **CDM**	"HAS MUCH OF THE TRUTH"	++	
GRAV WAVES FROM QM METRIC FLUC			
★ $T/S \gtrsim 10^{-3}$ (??)	$T/S \lesssim \mathcal{O}(1)$		$10^{-3}/10^{-4}$
★ NEARLY SCALE INVARIANT $n_T = -\frac{1}{5} T/S$	0.71 (95% cl)		± 0.03

TEXTBOOK IMAGE



"QUANTUM FUZZ"

WHY the TENSORS MATTER

"SMOKING GUN" SIGNATURE

FLAT UNIVERSE & SCALE-INVARIANT $\delta\rho/\rho$
PRE-DATE INFLATION

STRENGTH DIRECTLY TIED TO $V(\phi)$ & $H_{INFLATION}$

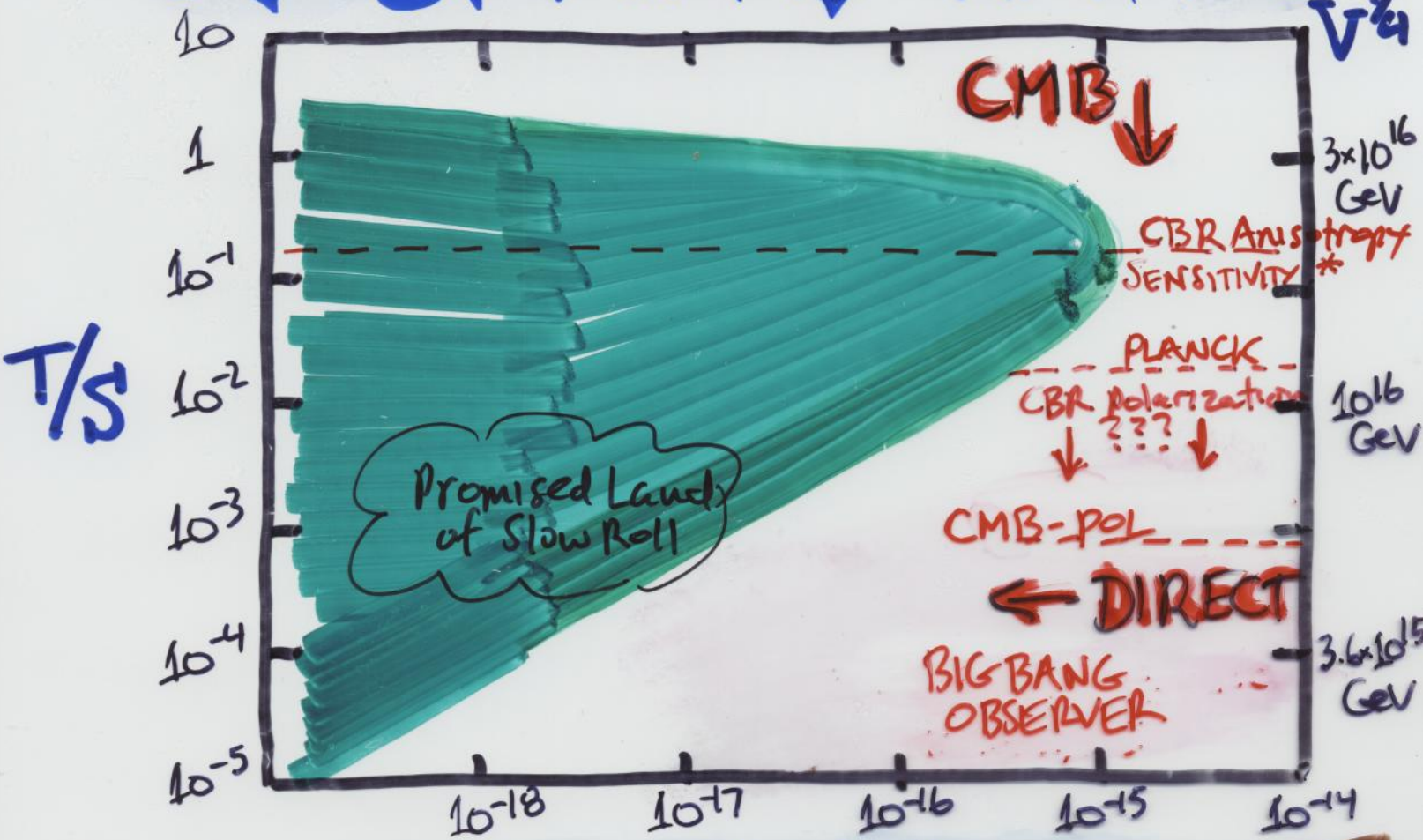
"RECONSTRUCTION OF $V(\phi)$

CONSISTENCY TEST

$T/S = -5 n_T$

... BUT NO ROBUST PREDICTION FOR AMPLITUDE

DETECTION OF GRAVITY WAVES



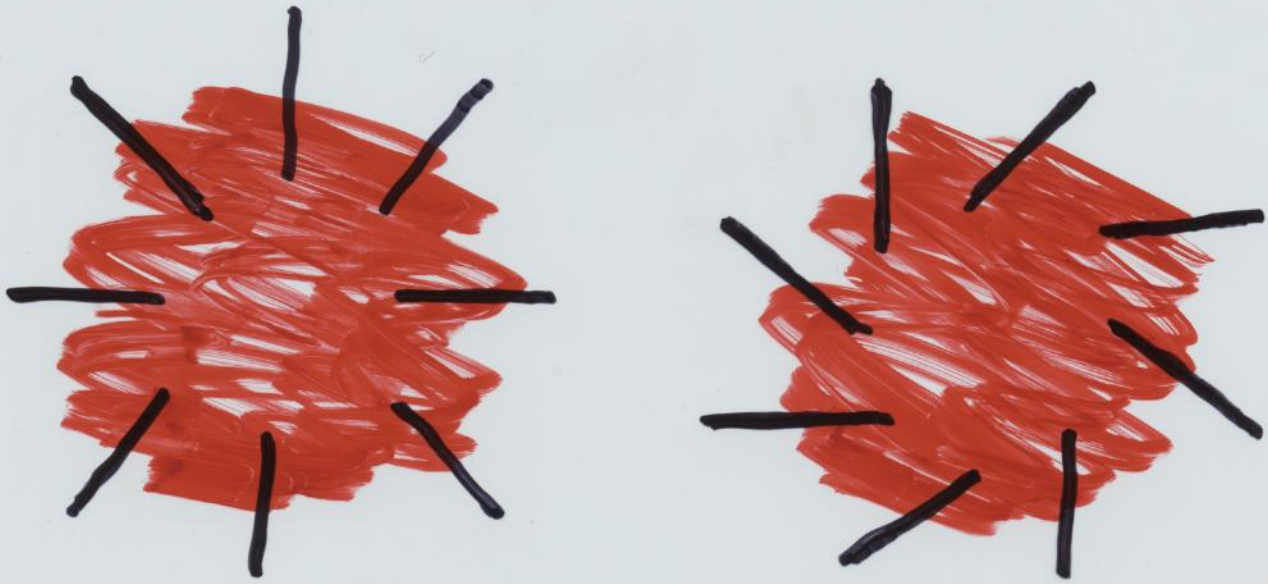
NB:

LIGO 10^{-10}

LISA 10^{-12}

VERY CHALLENGING!

"DOUBLE DETECTION" $\Rightarrow n_T$ to ± 0.03



WE KNOW MUCH

INFLATION

STRING COSMOLOGY

HOT BIG BANG MODEL

MASSIVE NEUTRINOS

DARK ENERGY

COSMIC ACCELERATION

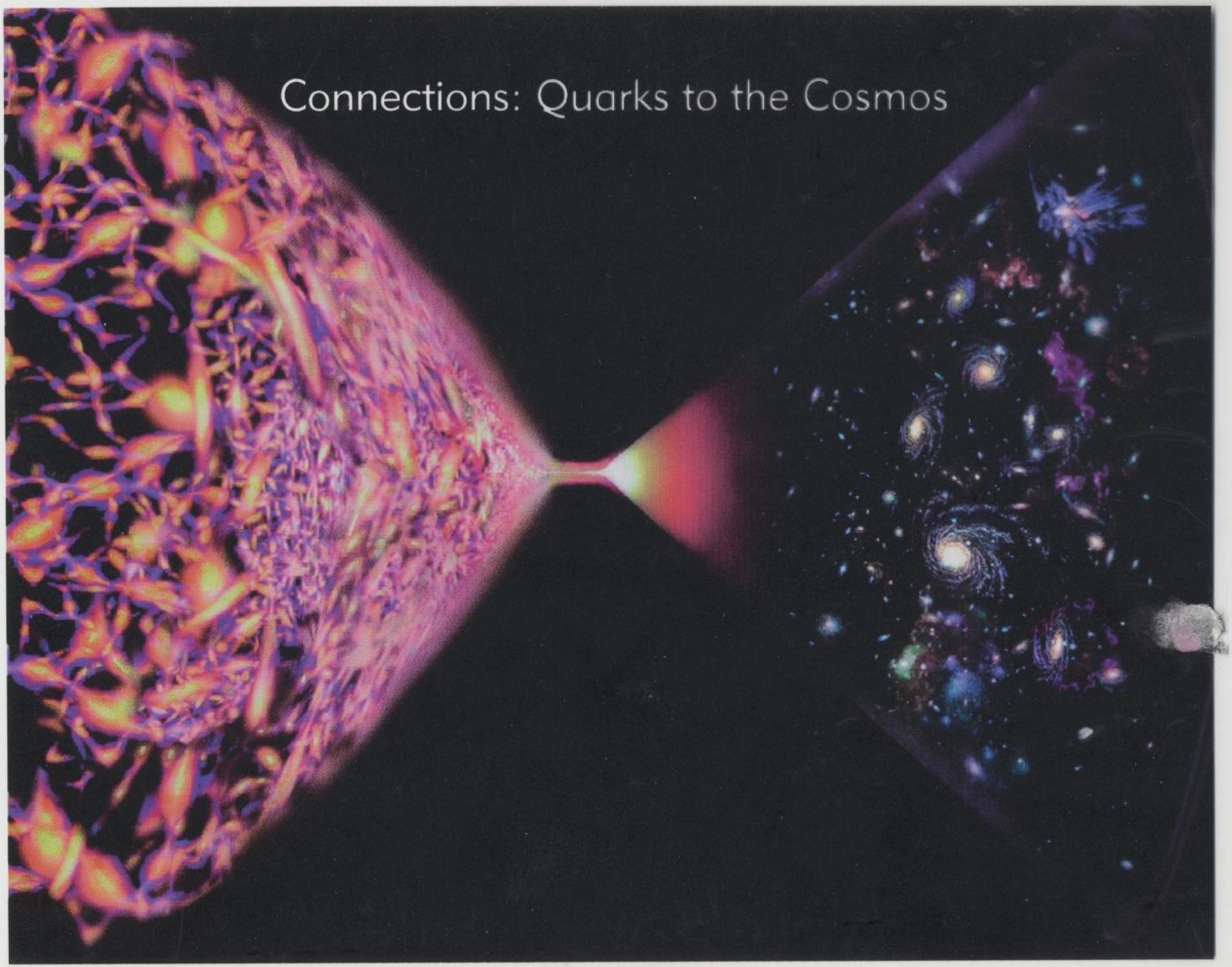
BARYONS

COLD DARK MATTER

CAN WE PUT IT ALL TOGETHER?

THE BIG PICTURE

OUR UNIVERSE


Connections: Quarks to the Cosmos