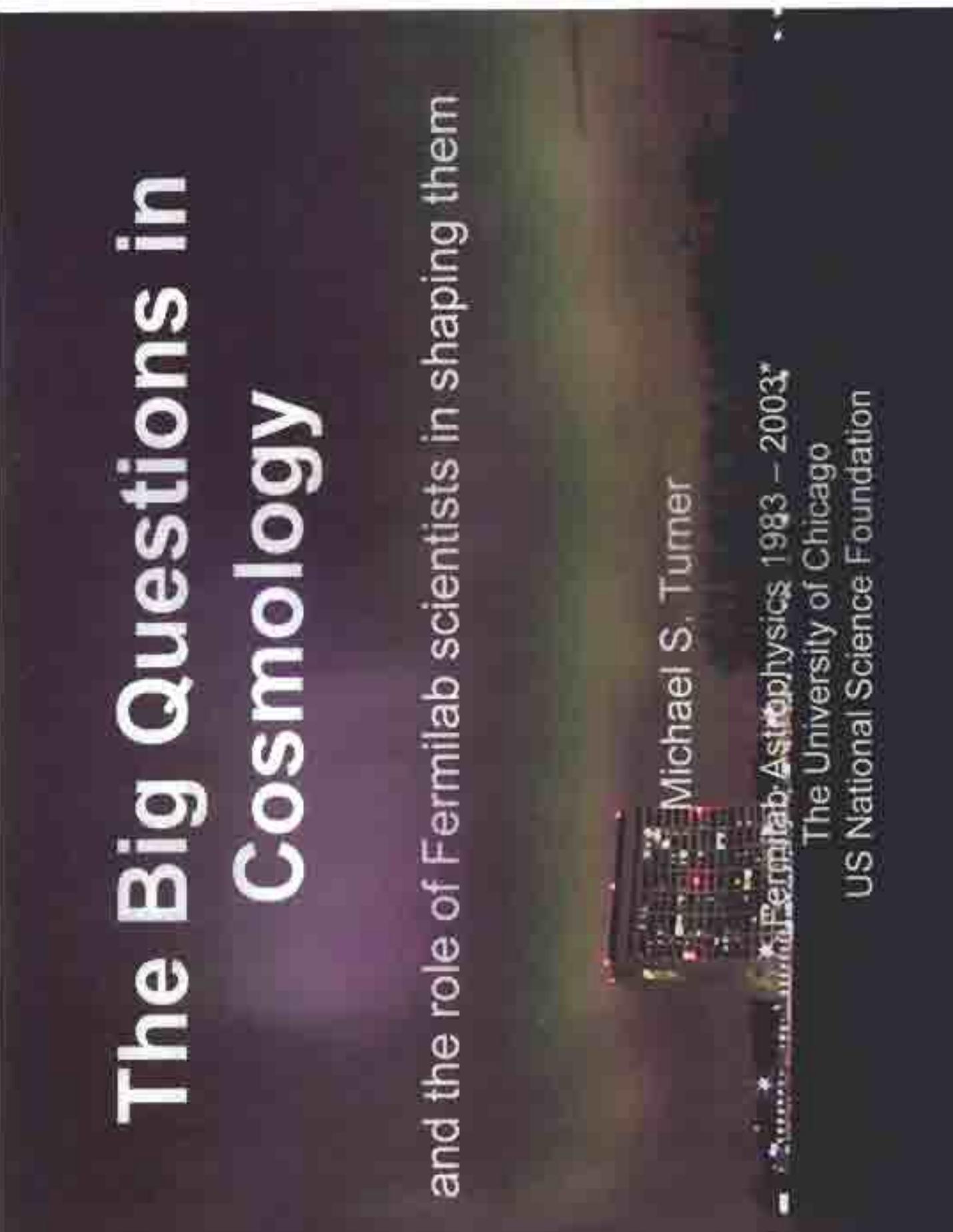


The Big Questions in Cosmology

and the role of Fermilab scientists in shaping them

Michael S. Turner

*Fermilab Astrophysics 1983 – 2003*

The University of Chicago

US National Science Foundation

BIG QUESTIONS

NEW IDEAS, CONTROVERSIES

1970

Allan Sandage:

"COSMOLOGY IS THE SEARCH FOR TWO NUMBERS, H_0 & q_0 "

$H_0 = \dot{R}/R$ expansion rate $q_0 = -\frac{\ddot{R}/R}{H_0^2}$ deceleration parameter

'77

BBN NEUTRINO LIMIT



'78

NEUTRINO DARK MATTER



'79

BARYOGENESIS



'80

MONOPOLE PROBLEM

GALACTIC DM (V. RUBIN)



'81-
'83

INFLATION

COLD DARK MATTER



CMB
1983

H_0, Ω_0
Hot DM vs Cold DM
MONOPOLES

COSMOLOGY CIRCA 1980

HIGH REDSHIFT $z_{980} \leq 3.5$ z_{64} TODAY
 $z_{64} \leq 1$ z_7

CMB $T = 2.96 \pm 0.06$ 2.725 ± 0.001
 $\delta T_{DIPOL} \sim 3 \text{ mK}$
 $\delta T/T < 10^{-4}$ $\sim 10^{-5}$

LSS Shane-Wirtanen Catalogue ~ 1000 REDSHIFTS
 500K + REDSHIFTS

BBN $N_{\nu} < 4$

"CONCORDANCE MODEL"

$\Omega_{\star} \approx 0.005$
 $\Omega = \Omega_M = \Omega_B = 2\Omega_0 \approx 0.01$
 $H_0 \sim 60 \text{ km s}^{-1} \text{ Mpc}^{-1}$
 "An Unbound Universe"



GROWING EVIDENCE FOR "DARK" MATTER

- Flat rotation curves V. Rubin et al
- Clusters Zwicky ...
- Hot x-ray emitting clusters accounts for DM?

Ω
 Age, BBN, Dynamic Measurements of Mass, Ω_0, H_0
 Evidence for ...

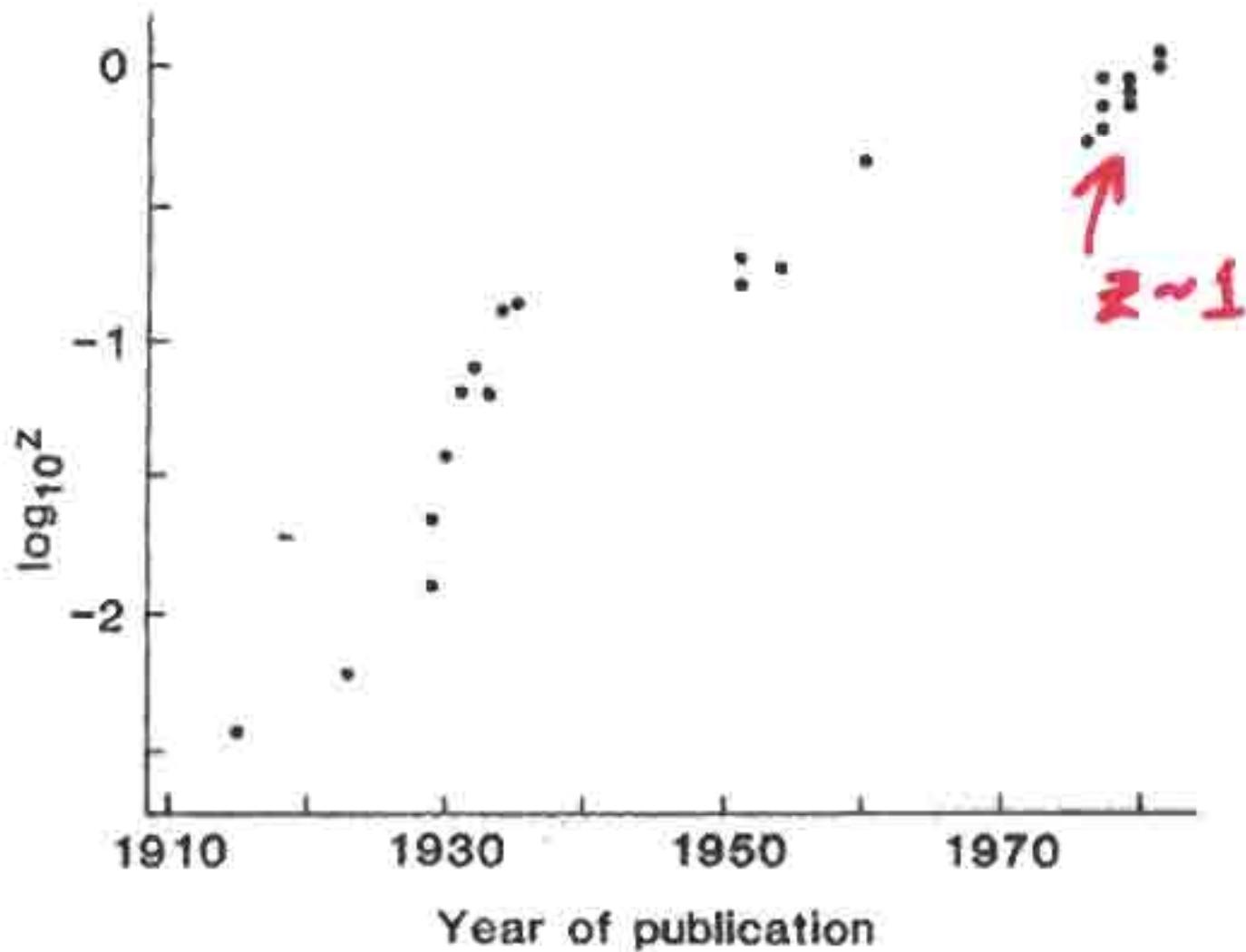
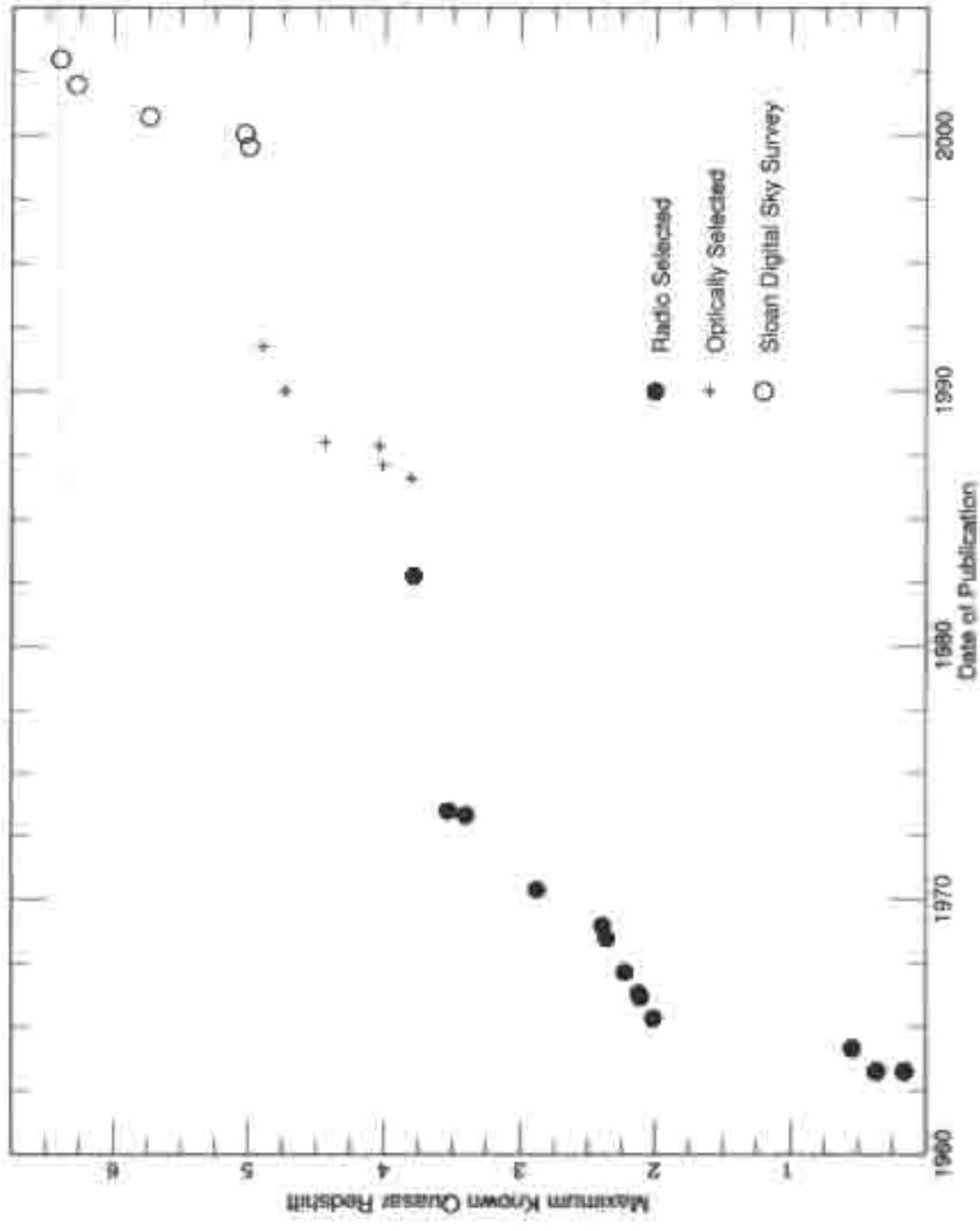


Fig. 1. Published highest spectroscopic redshifts for galaxies, illustrating the relative gains in observational sophistication. See text for sources of points plotted.

R. Kron, *Science* 1980



D. Schneider

- '84 DEATH OF HDM
 Λ CDM
 COSMIC STRINGS
 "DEFECTS w/ INFLATION"
 DECAYING DM
- '84 SUCHEP "CONFIRM" BBN $N_{\nu} < 4$
- '92 COBE!
- '95 CMB PARAMETER ESTIMATION
- FLAVORS OF CDM: Λ CDM,
 LHC-CDM, ν CDM, DCDM,
- '96 B-MODES (CMB-POL)
- '97 "W- DARK ENERGY"
- '98 COSMIC ACCELERATION,
 NEUTRINO MASS
- '00 FLAT UNIVERSE, SDCS BEGINS
- '01 CMB CONFIRMS BBN Ω_B
- '01 EKAHYLOTIC / CYCLIC
- '03 WMAP / SDCS "SCIENCE COVER"
- '04 CDMS-13

SEMICONDUCTORS



Breakthrough of the Year

THE NEW COSMOLOGY

★ RELIABLE SET OF COSMO. PARAMETERS

$$H_0 = 72 \pm 7, T_s = 2.725 \pm 0.001 \text{ K}, \Omega_0 = 1 \pm 0.03, \Omega_B = 0.04 \pm 0.01$$

★ SPATIALLY FLAT, ACCELERATING UNIVERSE

$$R_{\text{curv}} \gtrsim 5 H_0^{-1}, q_0 = -\frac{2}{3} \pm \frac{1}{4}$$

★ NON BARYONIC DARK MATTER

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

★ DARK ENERGY W/ REPULSIVE GRAVITY

$$\Omega_X = 0.67 \pm 0.06 \quad w \lesssim -\frac{1}{2}$$

★ EARLY "INFLATIONARY EPOCH"

EVIDENCE FOR INFLATION

DEEP CONNECTIONS BETWEEN QUANTUM & 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	$H_0 = 72 \pm 2 \pm 7 \text{ km s}^{-1} \text{ Mpc}^{-1}$ NB: $h = H_0/100 = 0.72 \pm 0.07$ $h^2 \approx 1/2$	70 ± 4 HST KP
DECEL RATE	$q_0 = -0.67 \pm 0.25$	SNe Ia + Ω_M
AGE	$t_0 = 13 \pm 1.5 \text{ Gyr}$	GC, H_0 , CMB consensus
TEMP	$T_0 = 2.725 \pm 0.001 \text{ K}$	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	$\Omega_0 - \Omega_M$
Dark Energy	$\Omega_X = 0.67 \pm 0.06$ 0.73 ± 0.04	SNe Ia, CMB, LSS
EoS	$w = -1 \pm 0.2$ < -0.8 (95%)	

$\delta\%$ $\sqrt{S} = 5.6^{+1.5}_{-1.0} \times 10^{-6}$

G.W. $\sqrt{T} < \sqrt{S}$

power law indices $n = 1.05 \pm 0.09$
 0.93 ± 0.03

running $n_T -$
 $dn/dlnk = -0.02 \pm 0.04$
 -0.03 ± 0.02

CMB-COBE

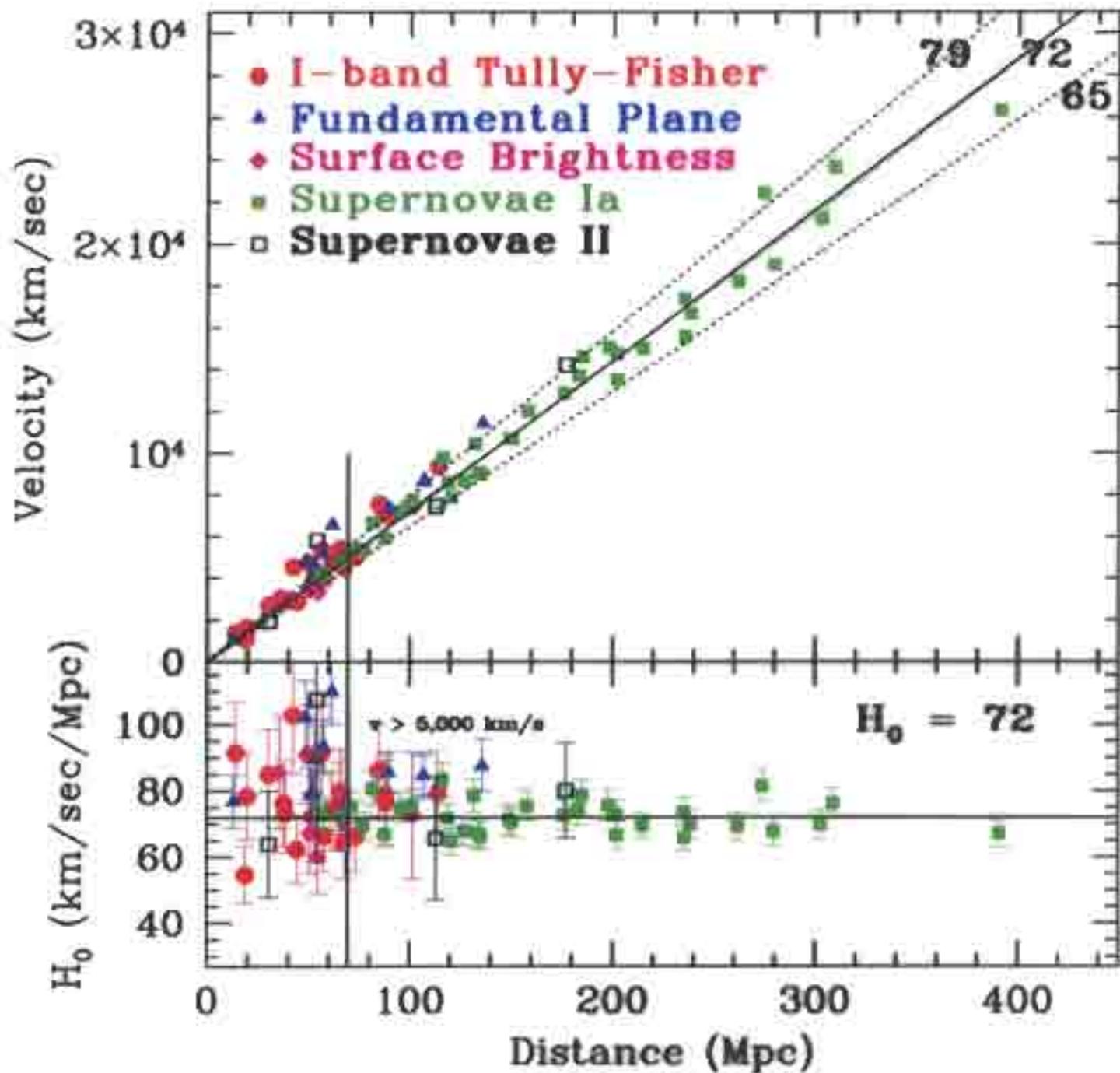
CMB, H_0

CMB

CMB

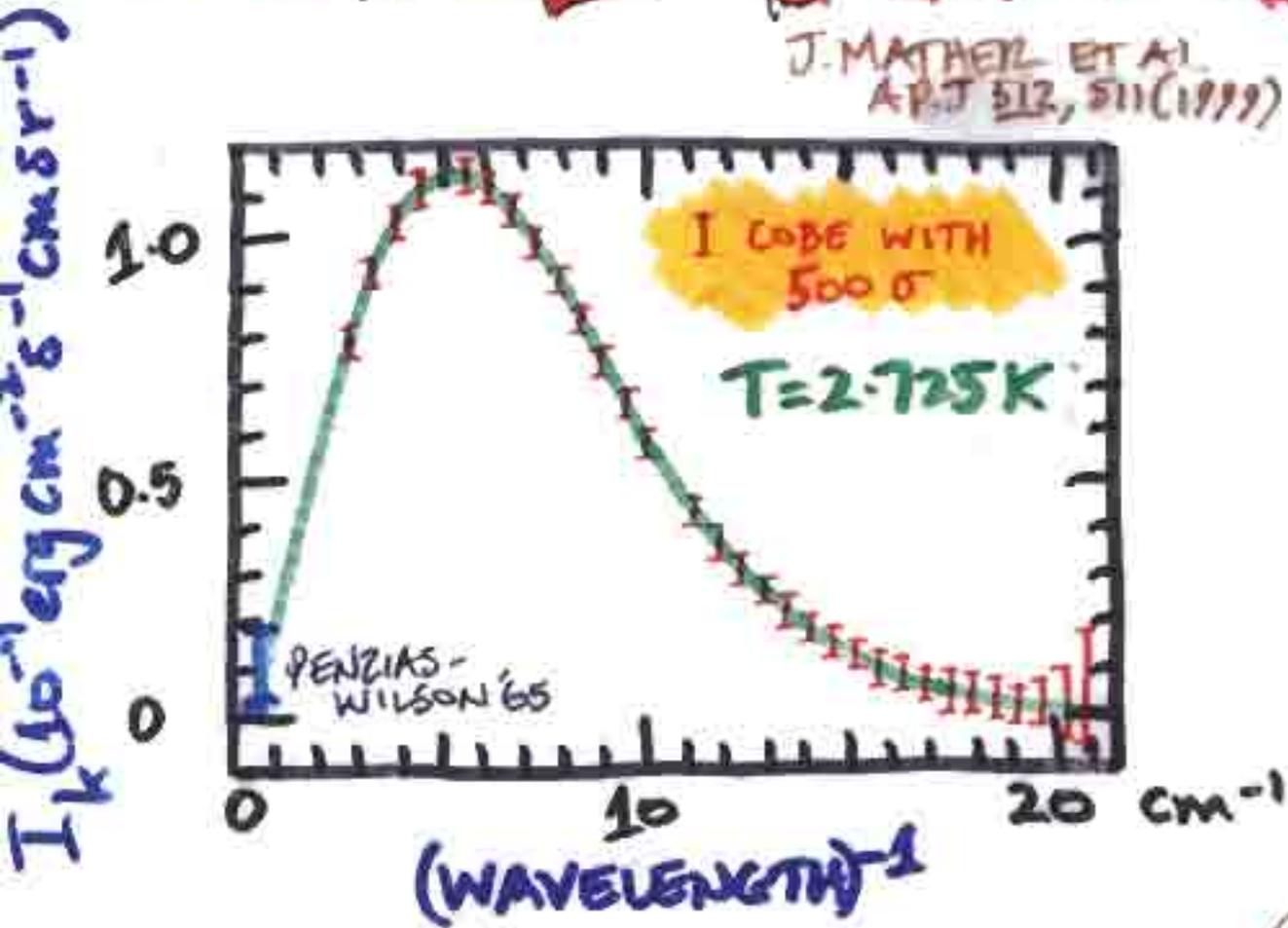
post-WMAP

NB: RELIABLE ERROR BARS



COBE FIRAS

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



★ $T = 2.725 \text{ K} \pm 0.00001 \text{ K}$
 $\pm 0.001 \text{ K}$

$\Delta I / I_{\text{max}} < 0.005 \%$

$|m/kT| < 3.3 \times 10^{-4} \quad y < 2.5 \times 10^{-5} \quad (95\% \text{ cl})$

"BEST BLACK BODY KNOWN"

NECESSARY OF MEASUREMENT

TEMP. SCALE

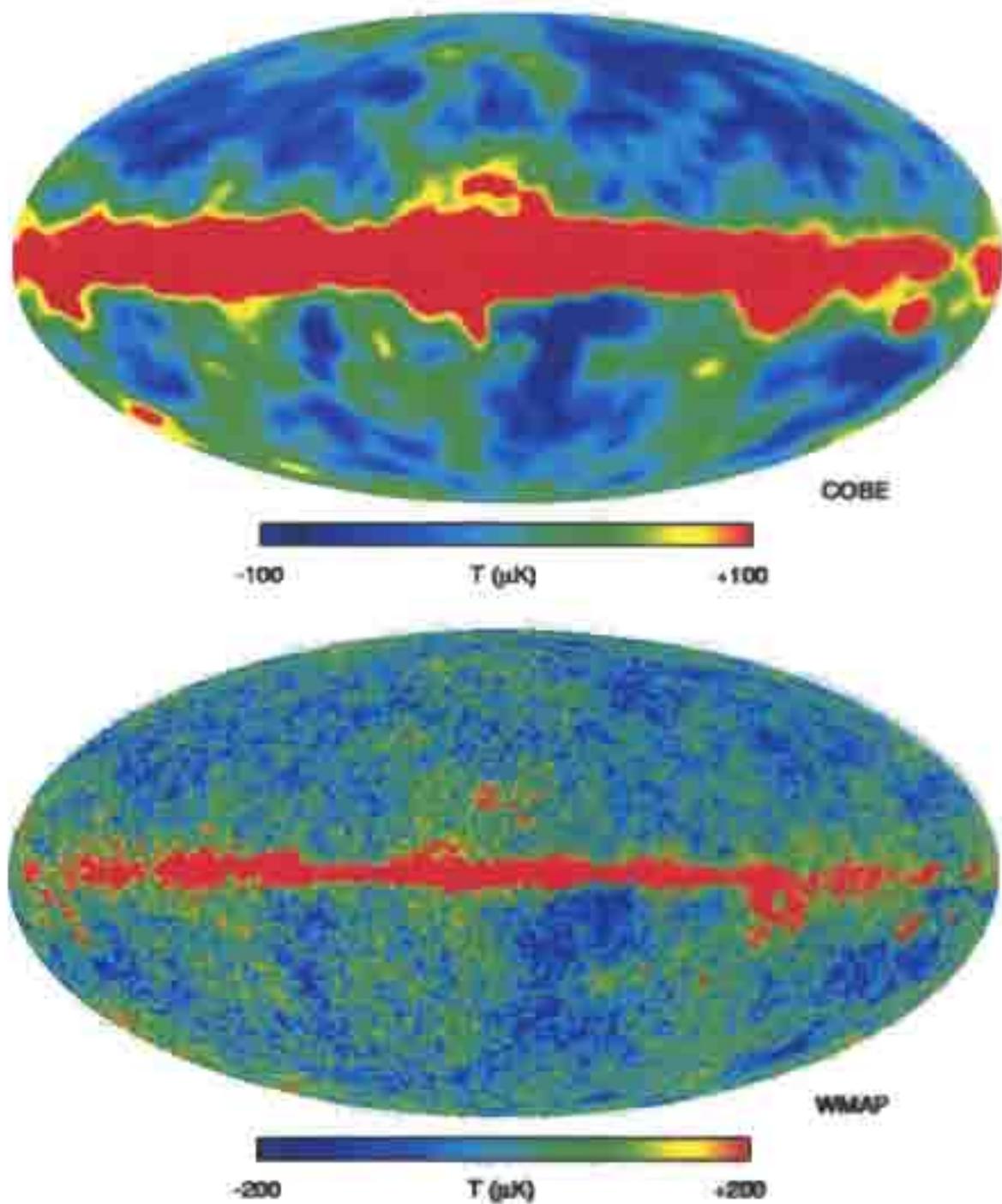
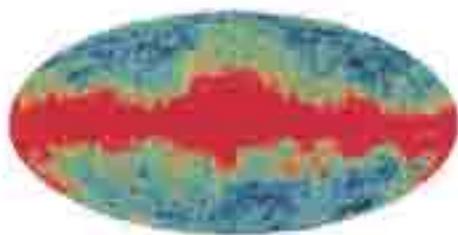
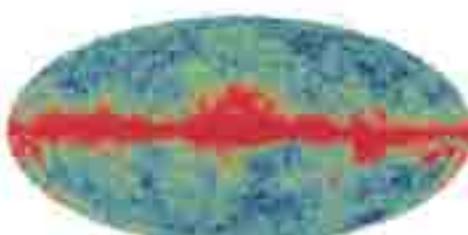


Fig. 7.— A comparison of the COBE 90 GHz map (Bennett et al. 1996) with the W-band WMAP map. The WMAP map has 30 times finer resolution than the COBE map.

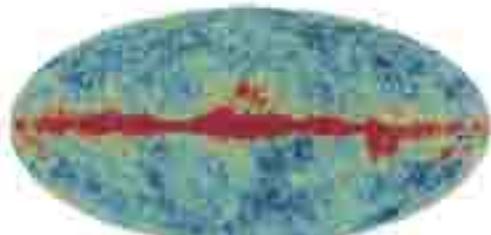
WMAP's 6 MAPs



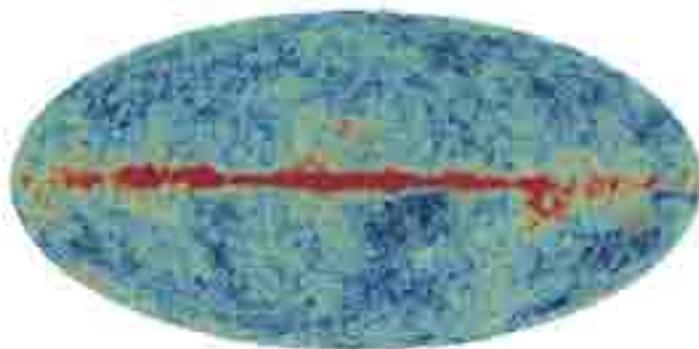
23 GHz



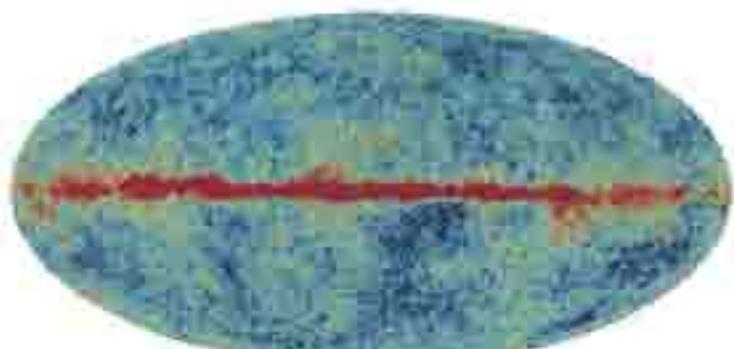
33 GHz



41 GHz

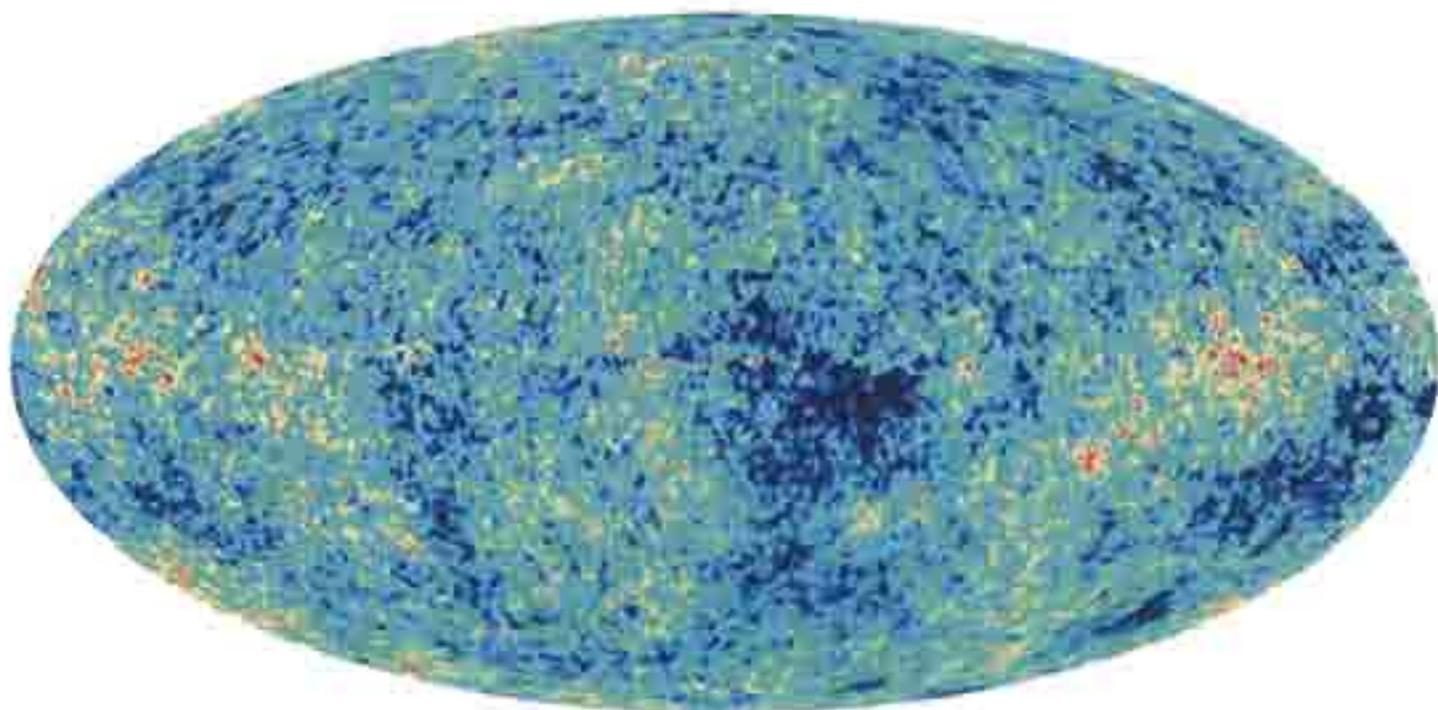


61 GHz

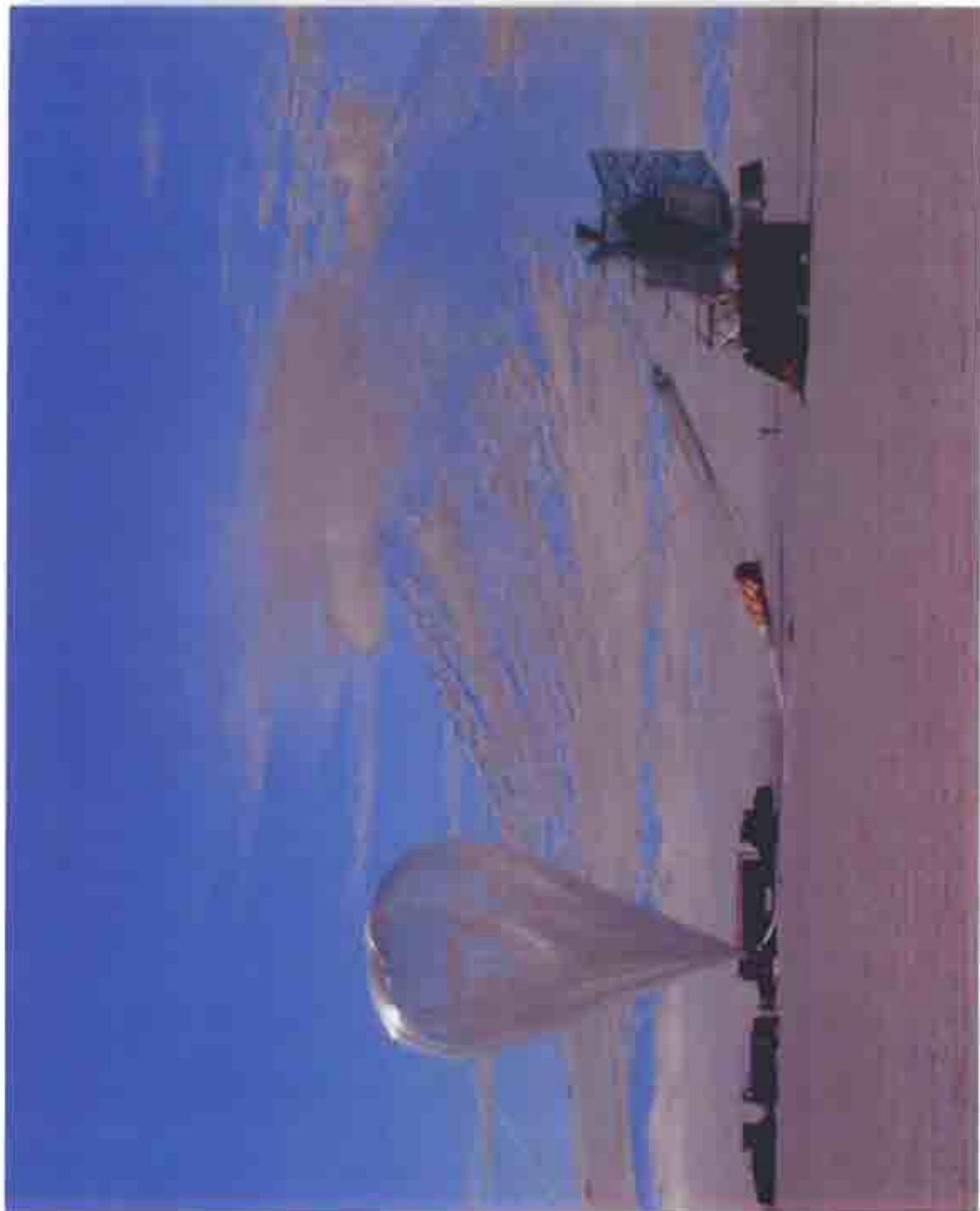


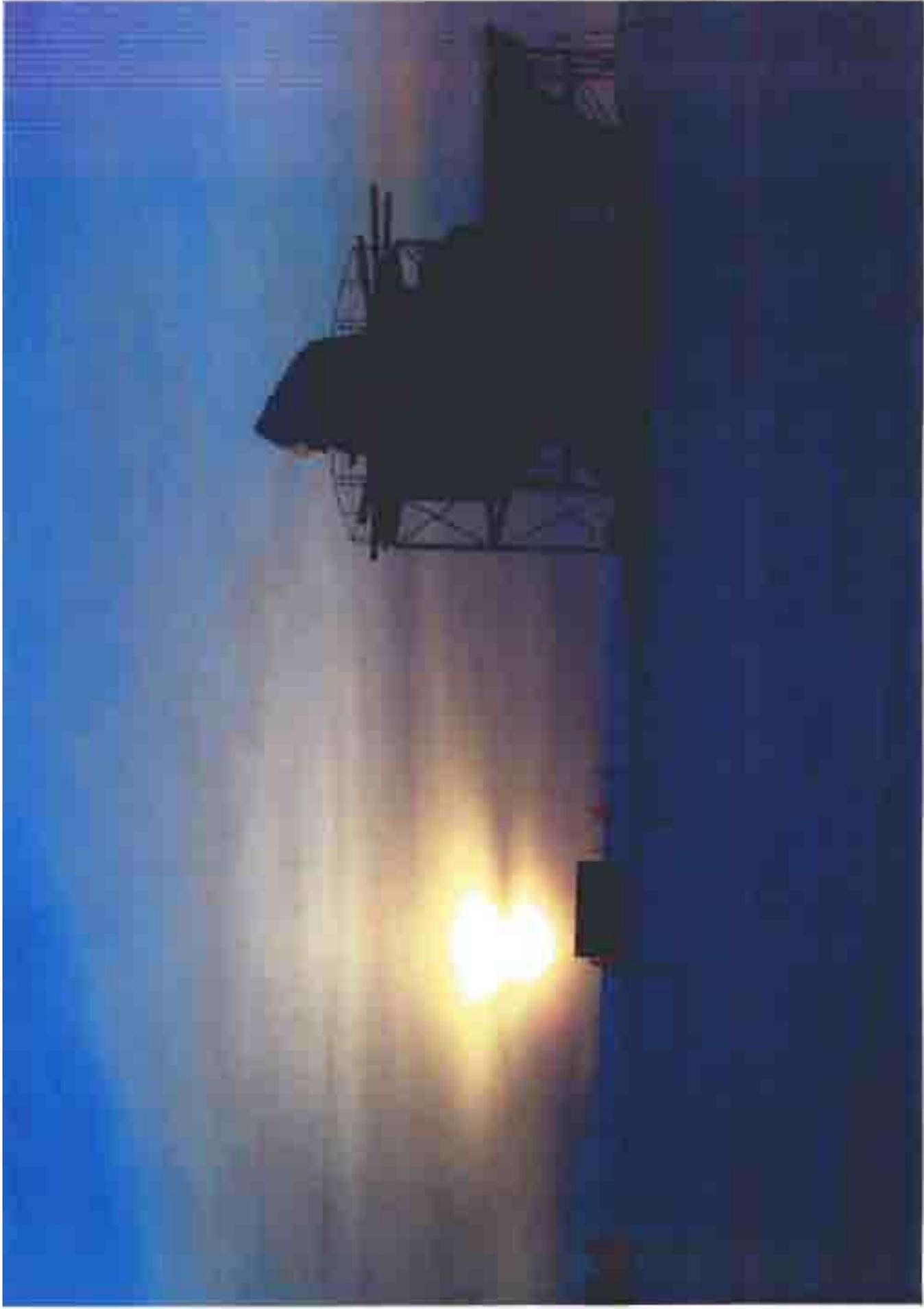
94 GHz

Cosmic Microwave Background

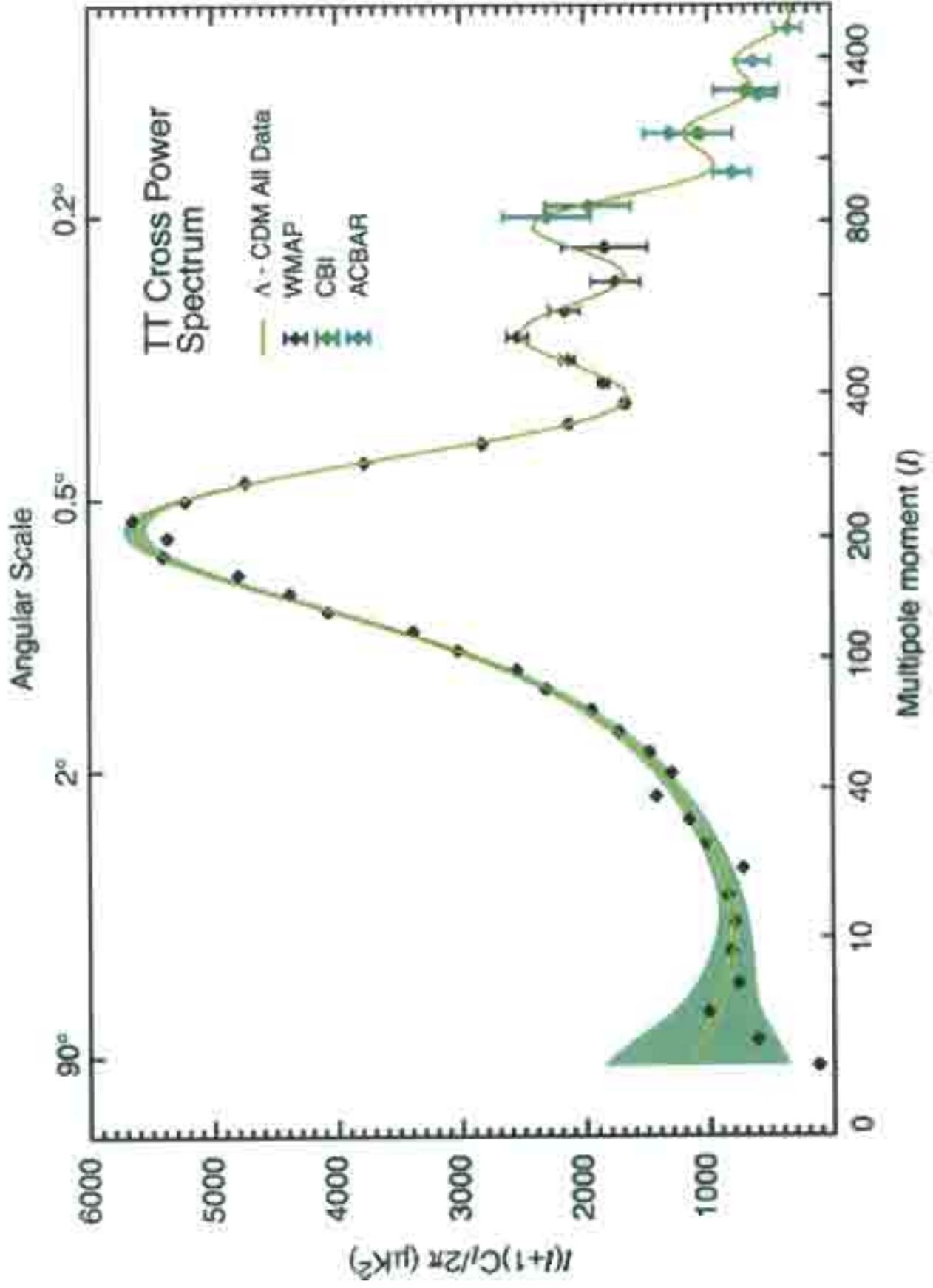


Foregound Subtracted



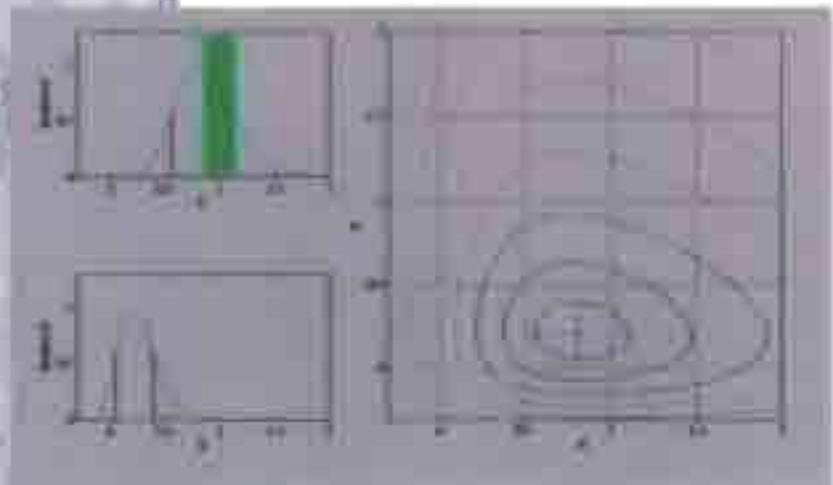
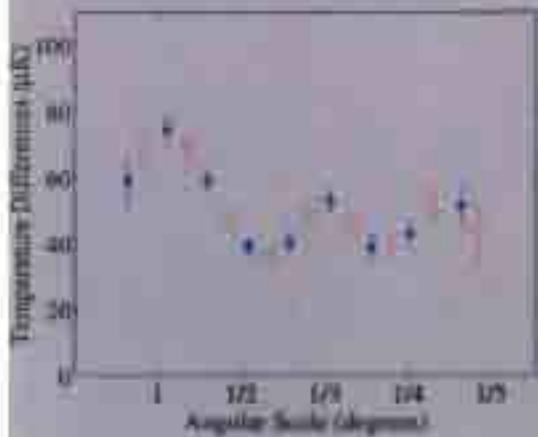
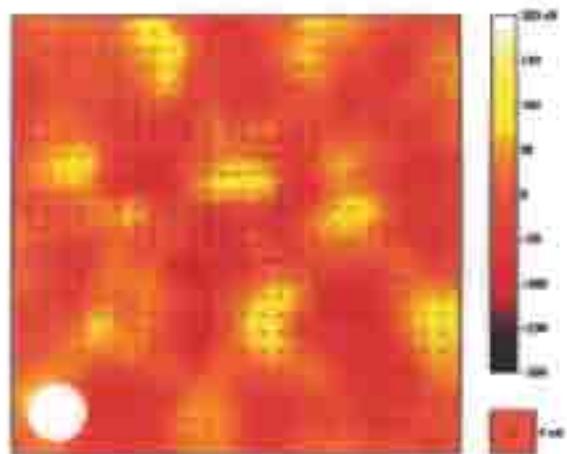
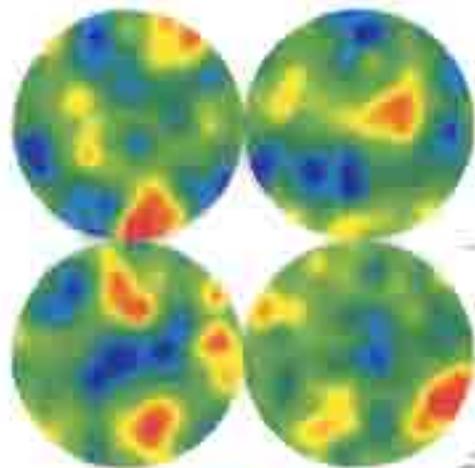
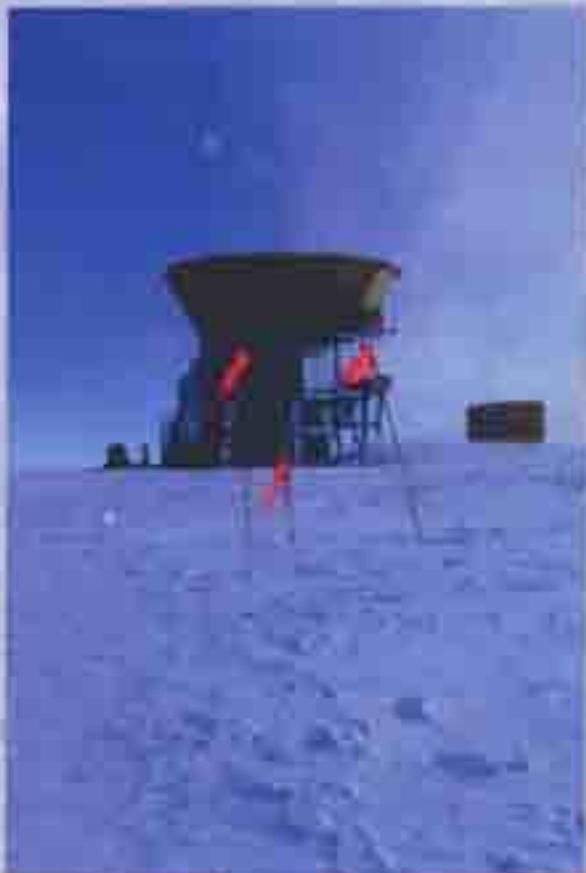


DASI AT SOUTH POLE SUNSET MAY 2000



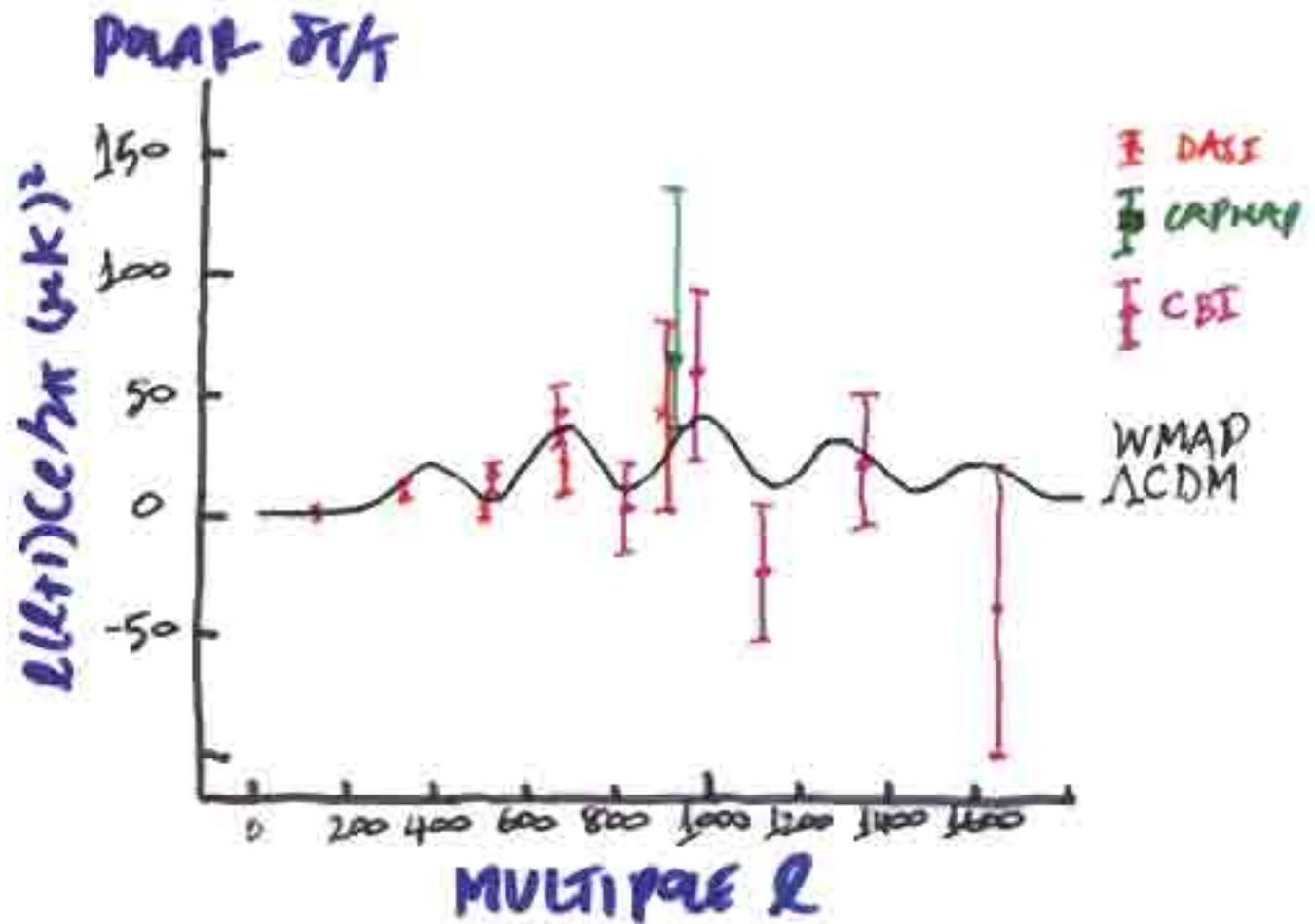
DASI

Acoustic Peaks and Polarization



POLARIZATION: THE NEXT FRONTIER!

3 DIRECT DETECTIONS + WMAP INDIRECT



SMALL θ (5 μK)!



CONSISTENT



2X INFO + WINDOW TO GWs FROM INFLATION!

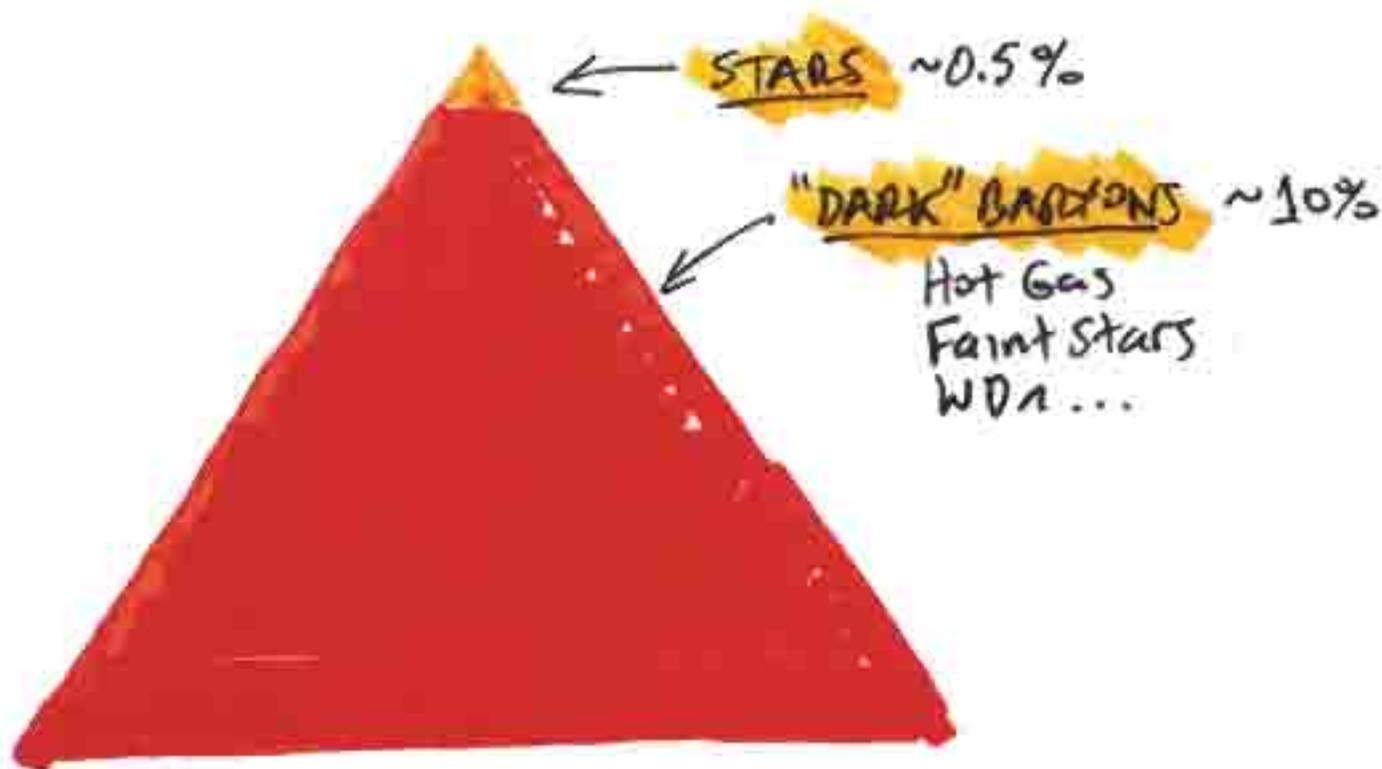
DARK SECTOR

CIRCA 1979

~~HYPERBOLIC~~, UNBOUND UNIVERSE

0.5% STARS + 10% DARK ATOMS

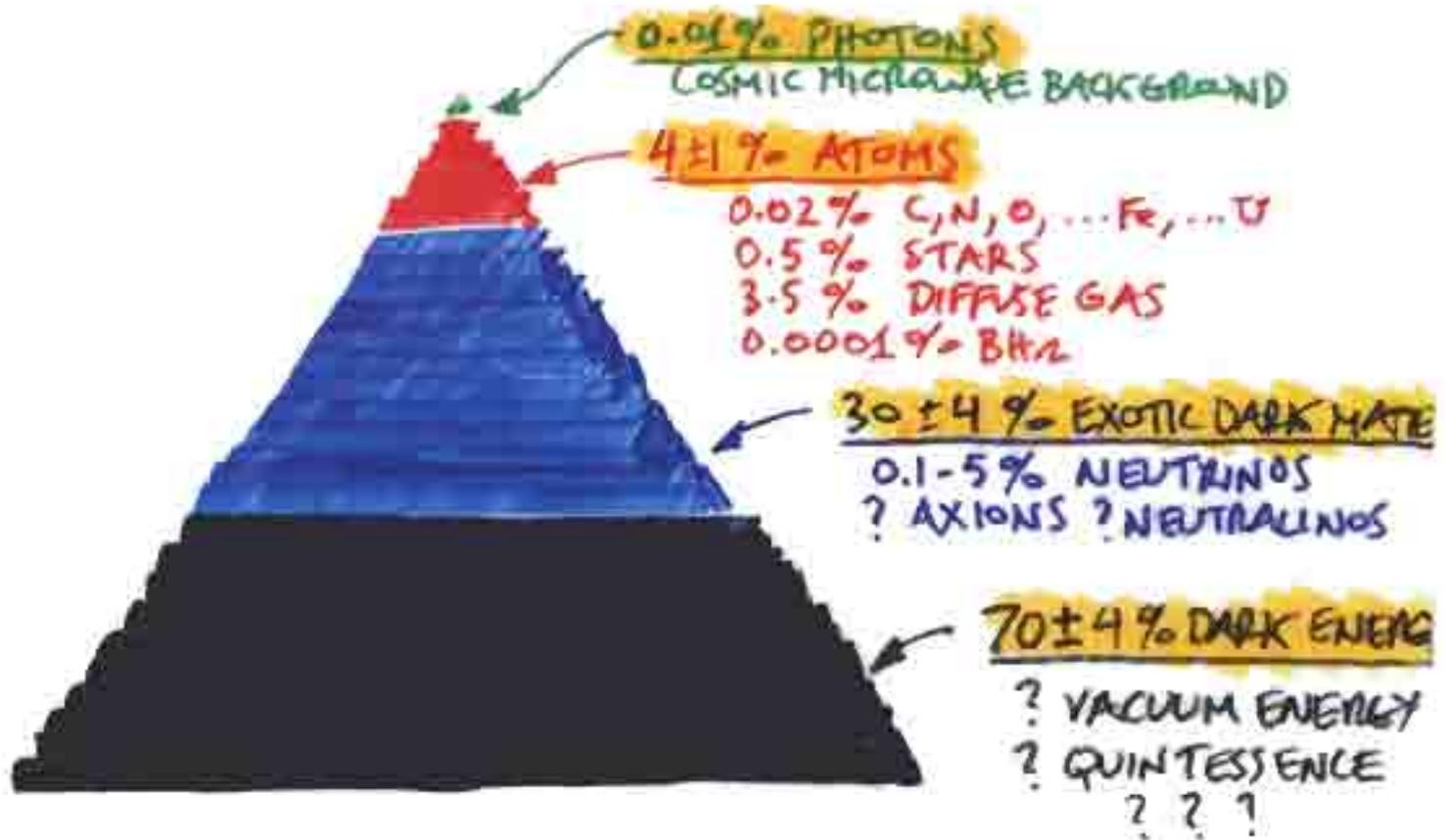
(RELATIVE TO CRITICAL DENSITY)



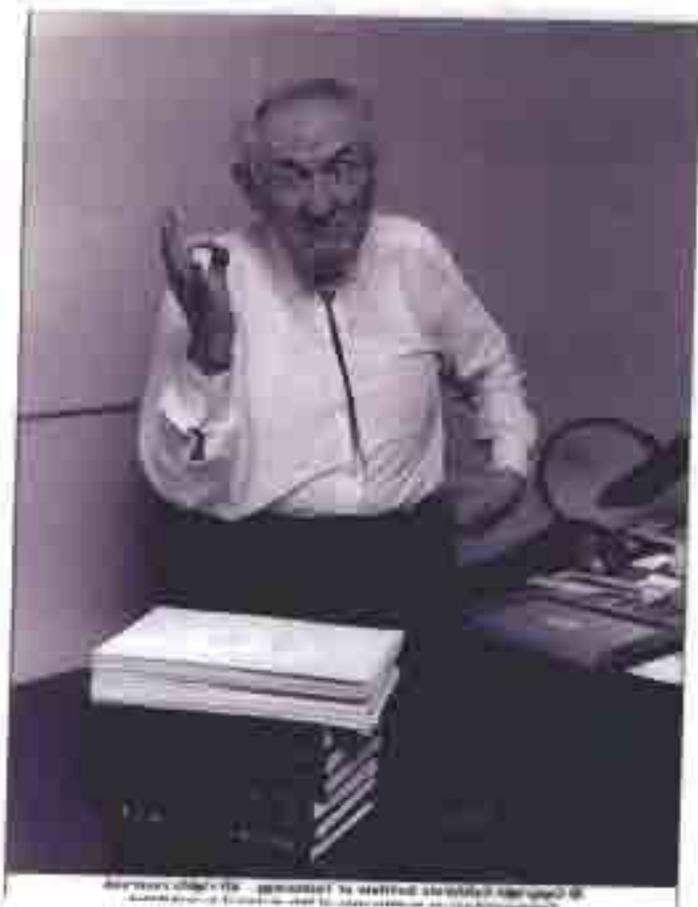
SIMPLE UNIVERSE

COSMIC STUFF

0.5% STARS + 30% DARK MATTER + 70% DARK ENERGY

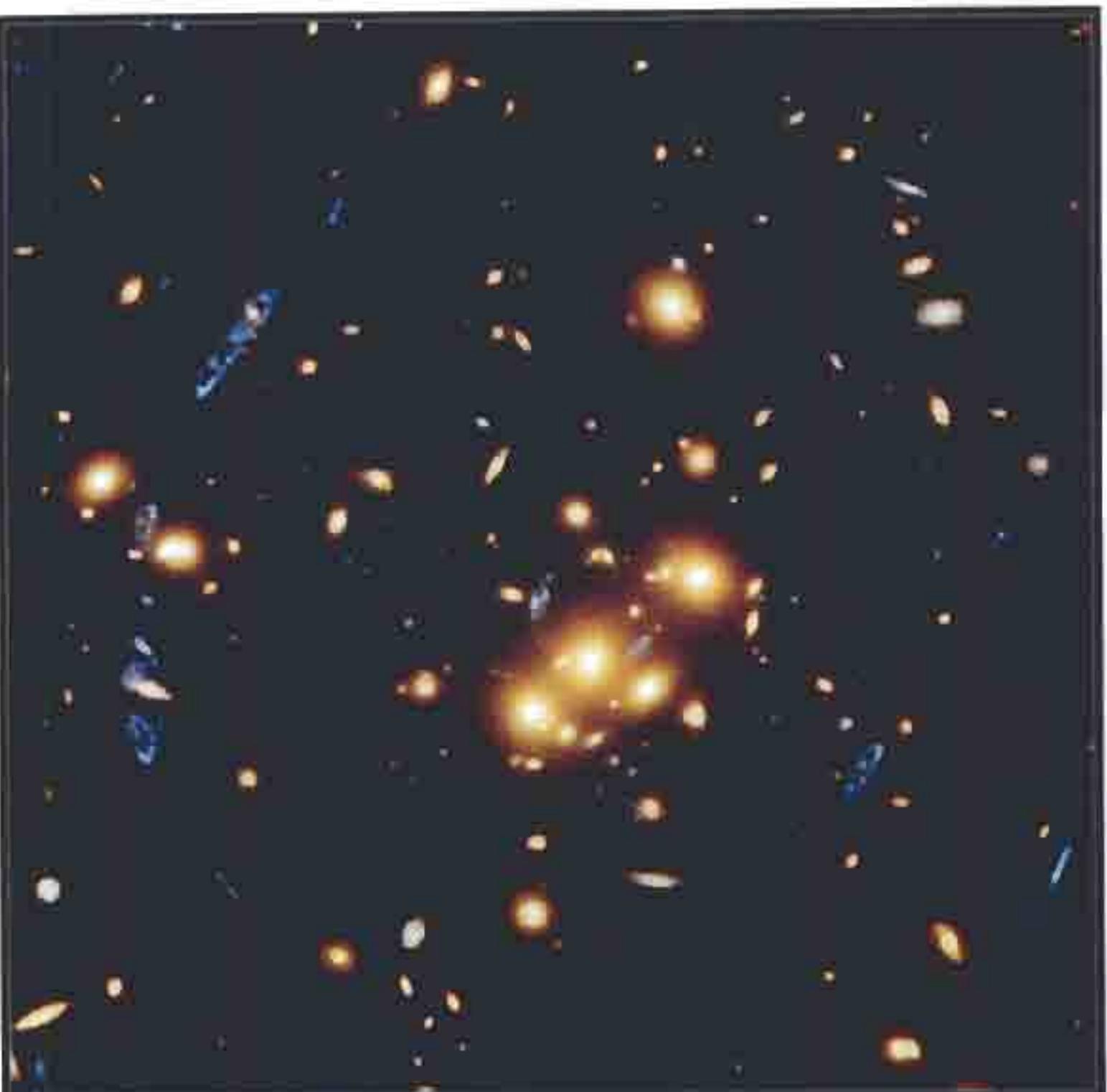


➡ 96% IN NEW FORMS
OF MATTER & ENERGY



Dr. [Name] is shown in his laboratory at the University of [Name].





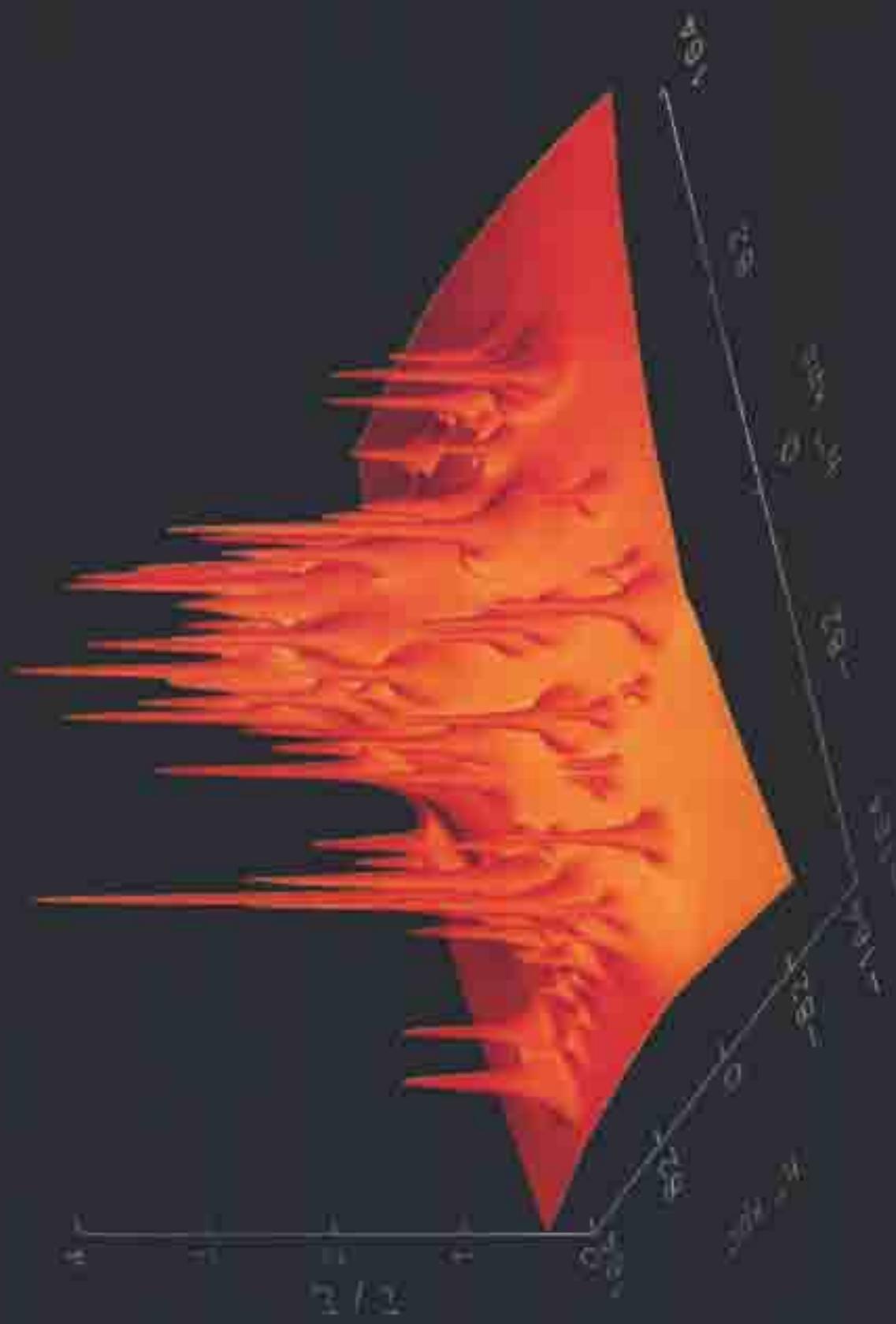
Gravitational Lens
Galaxy Cluster 0024+1654

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

PROJECTED MASS DENSITY: G10024



LOTS OF DARK
MATTER-RIGHT
HERE!



ORDINARY MATTER: FROM QUARKS TO US

INFLENTION ELEMENTS



10⁻⁵ SEC

TRANSITION FROM QUARKS → NEUTRONS, PROTONS



DENSITY OF MATTER

BIG-BANG NUCLEOSYNTHESIS

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

BBN

$D/H = (3.1 \pm 0.2) \times 10^{-5}$
 $\Omega_B = 0.04 \pm 0.002$

FORMATION OF ATOMS

COSMIC MICROWAVE BACKGROUND



400,000 YRS



950 LIGHT



1 BILLION YRS
FIRST QUANTA

CMB

RATIO OF FIRST TO SECOND PEAKS: 2/1

$\Omega_B = 0.045 \pm 0.006$

180/10 YEARS

$\Omega_B / \Omega_M = 0.15 \pm 0.07$
 $\Omega_{bh} = 0.20 \pm 0.03$
 $\Omega_B = 0.09 \pm 0.02$



INTERCOSMETIC GAS

ABSORPTION OF QUASAR LIGHT BY HYDROGEN

$\Omega_B > 0.04$

HERE & NOW

44 BILLION YRS
 stars, gas, dust, ...
 BBN, NS, ...
 ...

MATTER CONTENT

Now determined independent of mass/light B

NB: Cross checks / consistency

BARYONS:

$$\Omega_b h^2 = \begin{matrix} 0.020 \pm 0.001 \\ 0.022 \pm 0.004 \\ \quad \quad -0.003 \\ 0.021 \pm 0.008 \\ \underline{0.0224 \pm 0.001} \text{ WMAP} \end{matrix}$$

BBN (THEORY + D/H)
CMB (DATA / MEASUREMENT)
Baryon Bumps (2dF)

-- CONFIRMS SCHRAMM BBN PREDICTION

Ω_M / Ω_B :

$$\frac{\Omega_M}{\Omega_B} = \begin{matrix} 8.5 \pm 1.5 \\ 7.2 \pm 2 \\ 6.6 \pm 3 \\ \underline{6 \pm 0.5} \end{matrix}$$

CLUSTER INVENTORY
CMB
BARYON BUMPS
CMB/WMAP



Air tight case for nonbaryonic DM

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

BEST NUMBERS

MST ustraph/106035

$$\Omega_B = 0.04 \pm 0.008$$

$$\Omega_M = 0.33 \pm 0.035$$

$$\Omega_X = 0.67 \pm 0.06$$

$$+ \Omega_\Lambda = 1 \pm 0.04$$

$$1.02 \pm 0.02 \text{ (WMAP)}$$



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

"75 case for nonbaryonic DM"

DARK ENERGY

OF MOOSE DIAGRAM DARK MATTER CANDIDATES

MT 90



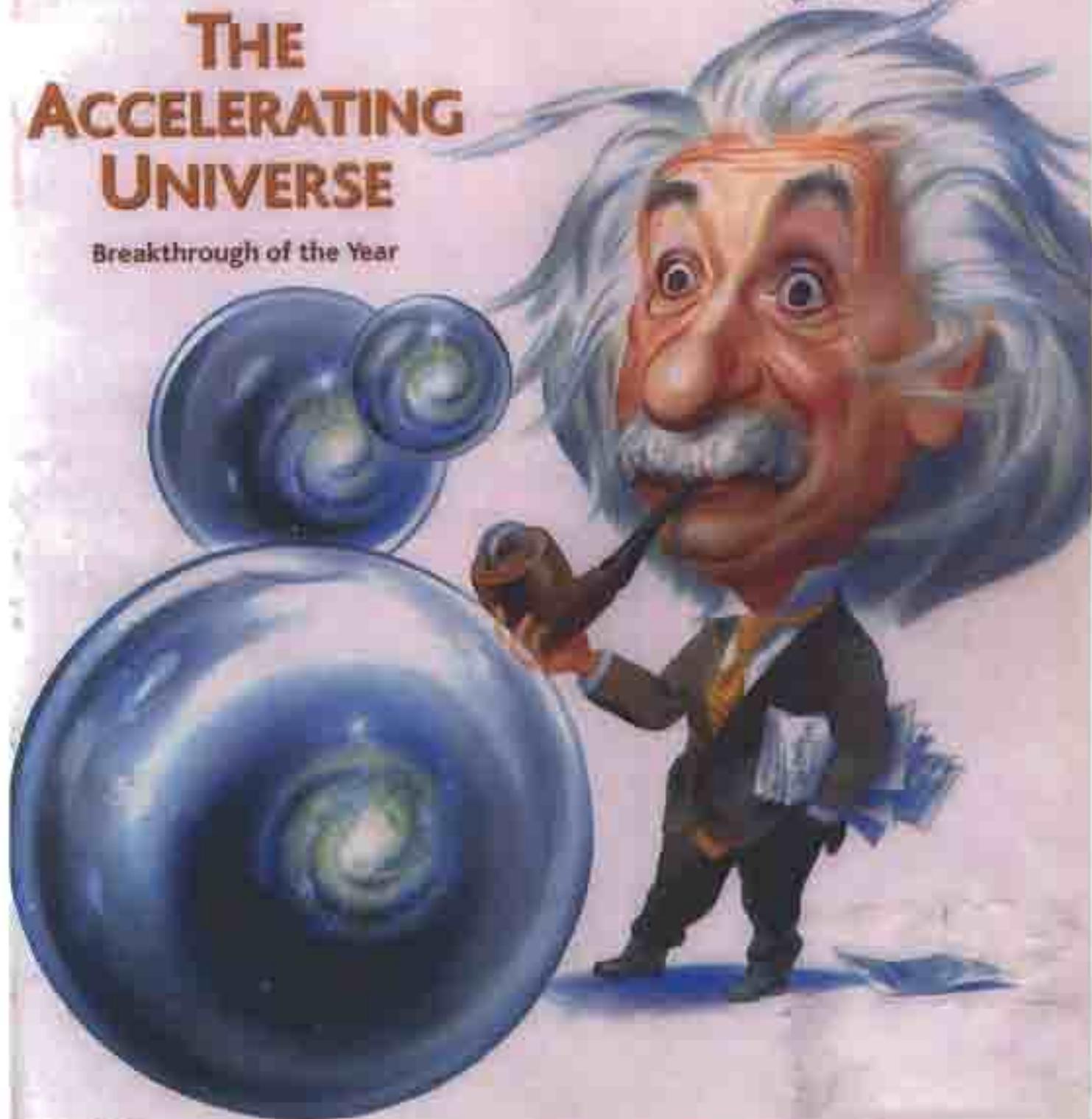
18 December 1998

Science

Vol. 282 No. 5397
Pages 2141-2336 \$7

THE ACCELERATING UNIVERSE

Breakthrough of the Year



AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

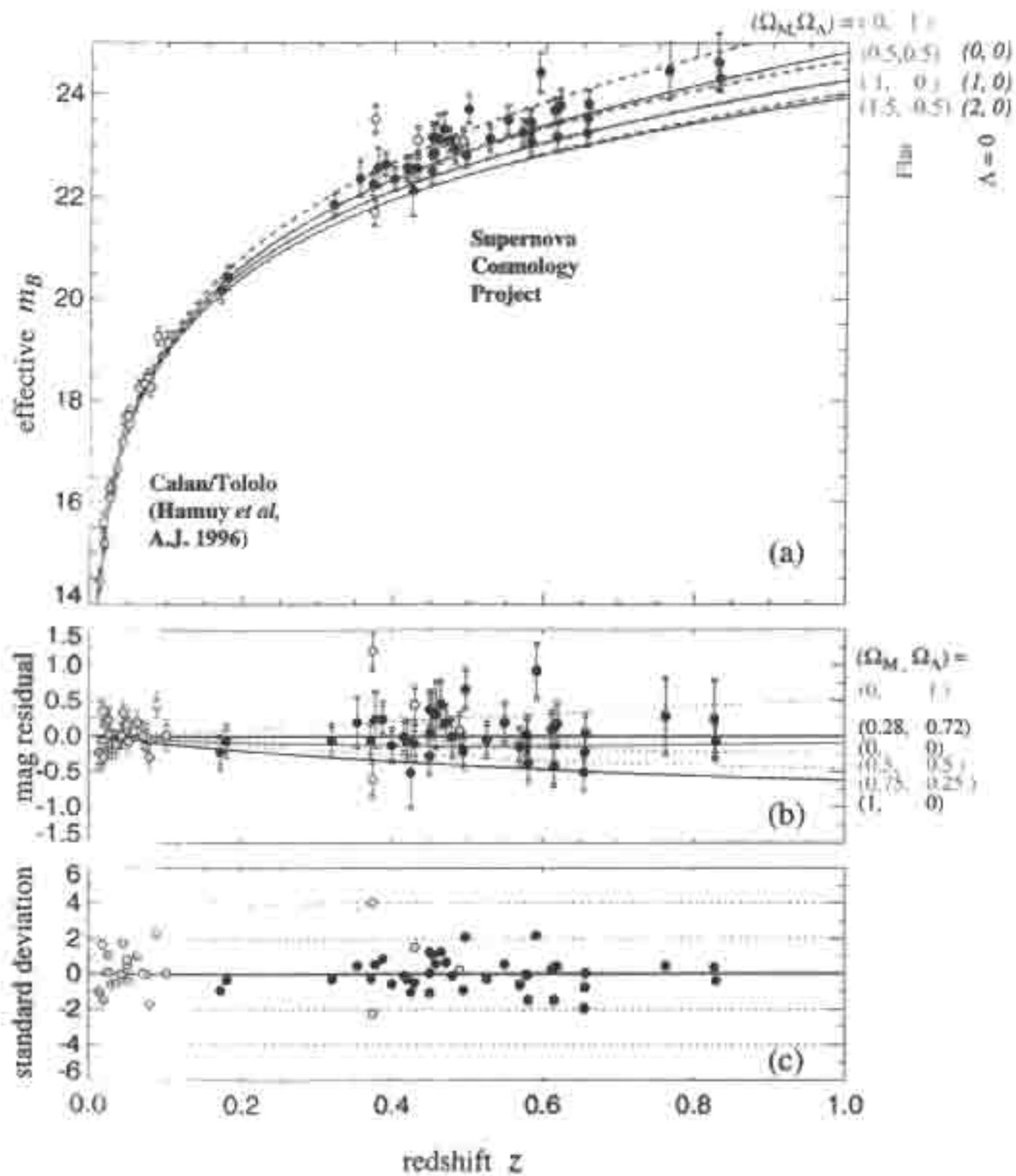


FIG. 2.

**COSMIC ACCELERATION
IS NOT GOING AWAY!**

ANONYMOUS COSMOLOGIST (ENK):

"THIS TOO WILL PASS"

**BETTER DATA:
SIGNAL HAS GOTTEN STRONGER!**

SUPERNOVA COSMOLOGY PROJECT

KNOP ET AL, APJ 598, 102 (2003)

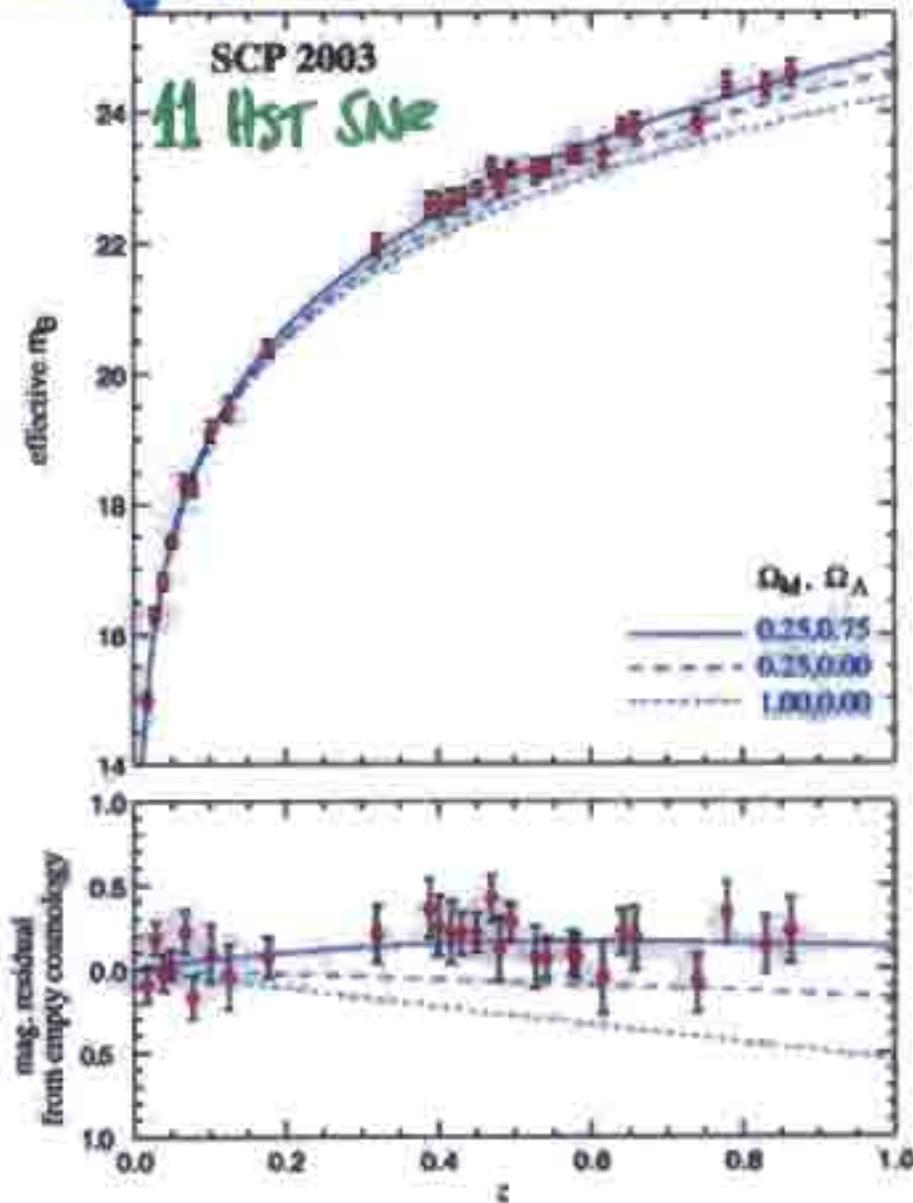
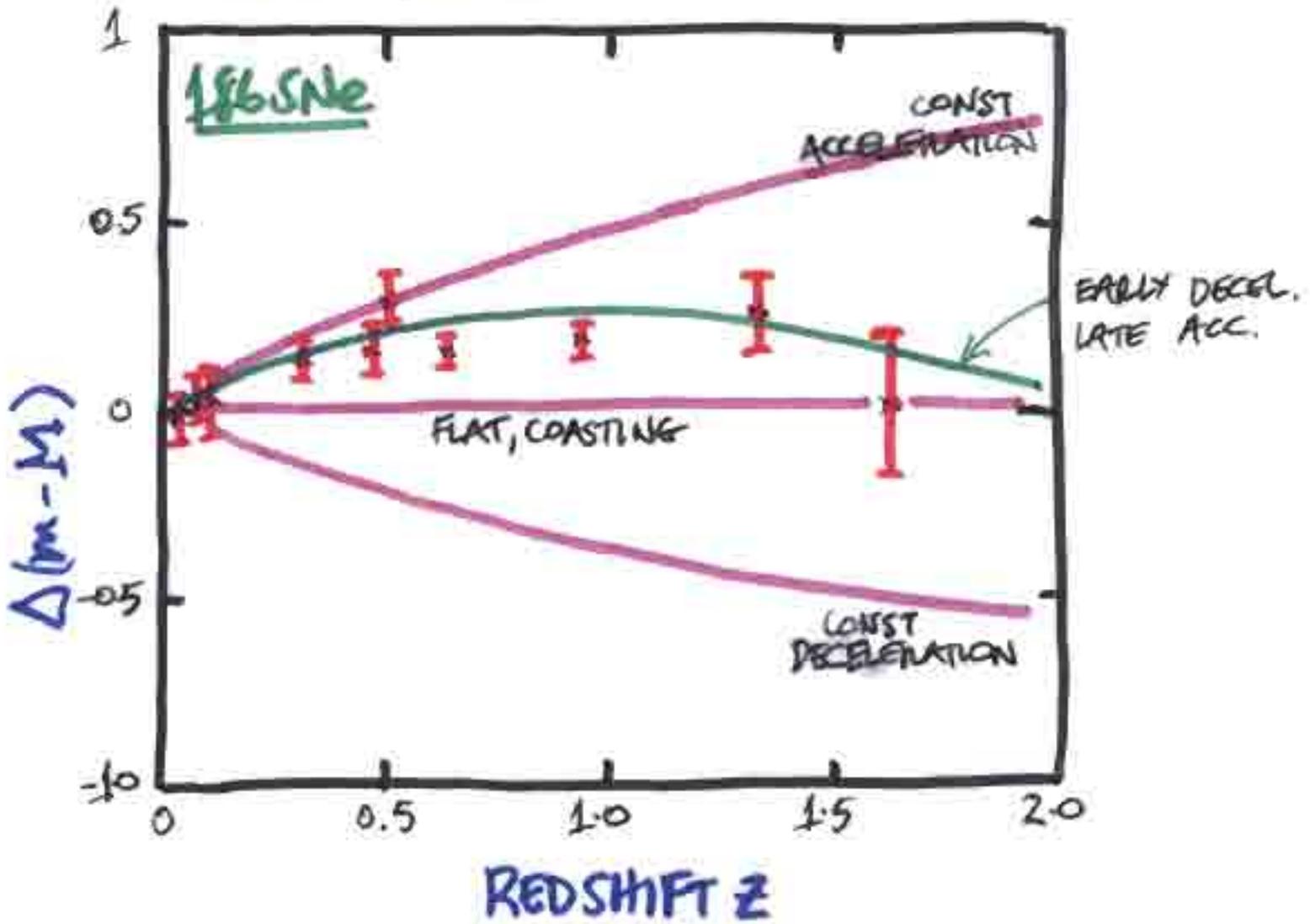


Fig. 6.— Upper panel: Averaged Hubble diagram with a linear redshift scale for all supernovae from our low-extinction subsample. Here supernovae within $\Delta z < 0.01$ of each other have been combined using a weighted average in order to more clearly show the quality and behavior of the dataset. (Note that these averaged points are for display only, and have not been used for any quantitative analyses.) The solid curve overlaid on the data represents our best-fit flat-universe model, $(\Omega_M, \Omega_\Lambda) = (0.25, 0.75)$ (Fit 3 of Table 6). Two other cosmological models are shown for comparison: $(\Omega_M, \Omega_\Lambda) = (0.25, 0)$ and $(\Omega_M, \Omega_\Lambda) = (1, 0)$. Lower panel: Residuals of the averaged data relative to an empty universe, illustrating the strength with which dark energy has been detected. Also shown are the suite of models from the upper panel, including a solid curve for our best-fit flat-universe model.

EVIDENCE FOR ^{EXPECTED} PAST DECELERATION

16 H_I-z, HST SNe

AG. NIESS ET AL
astro-ph/0402512



INDIRECT EVIDENCE for DARK ENERGY

MISSING ENERGY:

$$\Omega_x = \Omega_0 - \Omega_M \approx 0.67 \pm 0.06$$

CMB: 1 ± 0.04
 0.02 0.33 ± 0.04

IN ORDER NOT TO INTERFERE
W/STRUC. FORMATION:

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

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

DETECTING DARK ENERGY W/ SACHS-WOLFE EFFECT

R. Scranton et al, astro-ph/0307355

WMAP & SXS
 POSITIVE CORRELATION BETWEEN HOT SPOTS & LSS

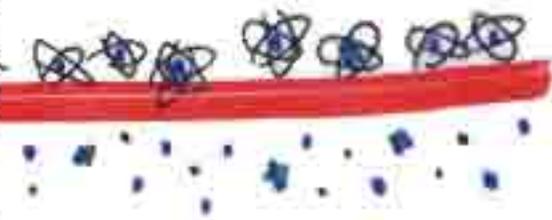
$Z=0.5$
 EVOLVING LARGE-SCALE STRUK

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



$Z=1100$
 $t=400,000$ yrs

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

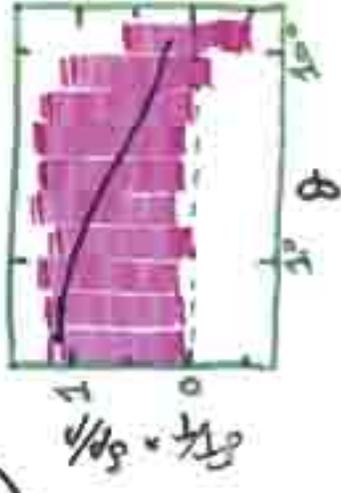


LAST-SCATTERING SURFACE



Blueshift (falling in)

SMALLER(!) Redshift (climbing out)



Blueshift (falling in)

Equal Redshift (climbing out)

No CORRELATION

NOT TOO GOOD TO
BE TRUE!

EDDINGTON:

"NO EXPERIMENTAL RESULT
SHOULD BE ACCEPTED UNTIL
CONFIRMED BY THEORY"

GR ALLOWS FOR REPULSIVE GRAVITY:

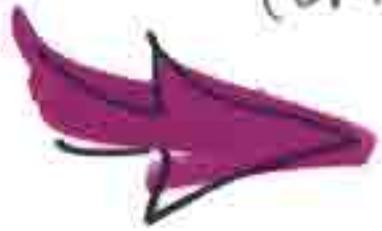
SOURCE OF GRAVITY

IN GR:

$$\rho + 3p$$

(SPHERICAL SYMMETRY)

FEATURE NOT A BUG!



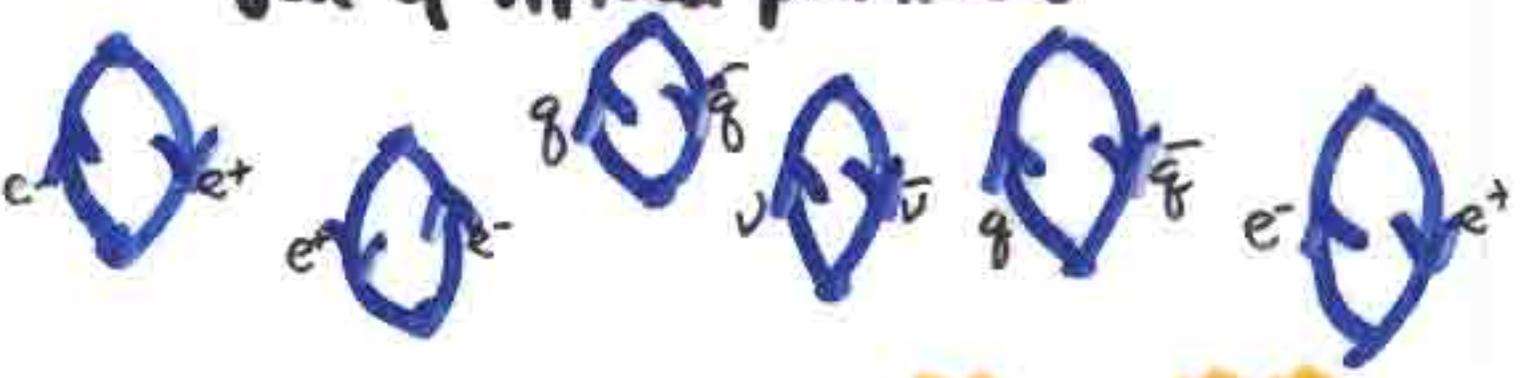
BLACK HOLES WHEN $p \geq \rho/3$



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, Nobel Prize '55

Quantum vacuum is elastic ($p = -p$)
& its Gravity is ^{VERY} Repulsive! ($p + 3p = -2p$)

JUST WHAT IS NEEDED -- BUT...
THEORETICAL ESTIMATES OF AMOUNT

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

"Houston, we have a problem"

INFLATION IN THE UNIVERSE



EARLY EPOCH OF TREMENDOUS EXPANSION DRIVEN BY VACUUM ENERGY

10^{-32} sec $\rightarrow 10^{40}$

SCALAR FIELD ENERGY

ACCOUNTS FOR:
SMOOTHNESS, HEAT OF BIG BANG & ABSENCE OF MONOPOLES

& PREDICTS:

- "FLAT UNIVERSE" ($\Omega_0 = \frac{\rho_{TOT}}{\rho_{CRIT}} \approx 1.0$)
- NEARLY SCALE-INVARIANT DENSITY PERTURBATIONS
- NEARLY SCALE-INVARIANT GRAVITY WAVES

Robust Predictions

Inflation Scoreboard

Predictions

FLAT UNIVERSE

$\Omega_0 = 1.000$

NOW

$\Omega_0 = 1.03 \pm 0.03$

GRADE



GOAL

± 0.001

DENSITY PERTURB FROM QM FLUC

ADIBATIC

NEARLY SCALE-INVARIANT $(n_s) \sim \mathcal{O}(\pm 0.1)$

NEARLY POWER LAW $dn/dlnk \sim 10^{-3}$

GAUSSIAN

≥ 3 ACOUSTIC PEAKS

0.93 ± 0.03

$n = 1.05 \pm 0.09$

-0.03 ± 0.02

$dn/dlnk = -0.02 \pm 0.04$

NO EVIDENCE AGAINST

\gg

± 0.001

$\pm 10^{-3}$

* See POINT AT THE ROADWAY



CDM

" HAS MUCH OF THE TRUTH

GRAN WAVES FROM QM METRIC FLUC

$T/S \approx 10^{-3}$ (??)

NEARLY SCALE INVARIANT $n_s = \frac{1}{2} T/k$

$T/S \leq 841$

$0.71 (95\% CL)$

$10^{-3}/10^{-4}$

± 0.03

CDM Predictions



"Bottom Up"

first stars	$z \sim 10-20$	✓
galaxies	$z \sim 2-5$	✓✓
clusters	$z \sim 0-1$	✓✓✓
superclusters	$z \sim 0$	✓✓✓✓



Large-scale Structure

voids, filaments, sheets



"Power Spectrum"

$$P(k) \propto k^{-2}$$

FROM CMB & REDSHIFT SURVEYS (2dF, SDSS)



Properties of clusters

number, distribution,
X-ray temp



"Lots of Recent Evolution"

merging, relaxing, ...



PROVIDED $\Omega_{mh} \approx 0.25 \pm 0.05 \Rightarrow \Omega_m \approx 0.4$



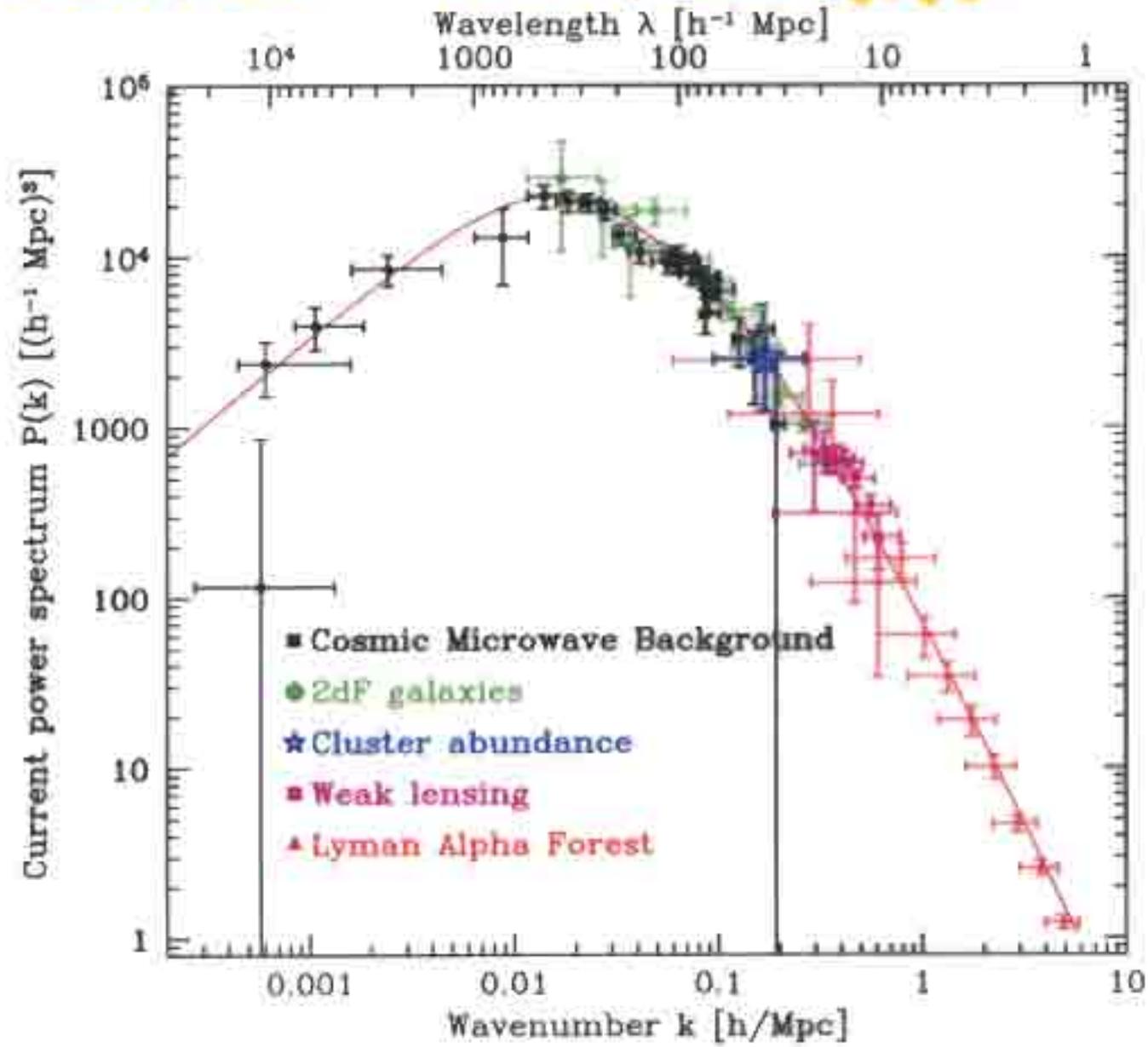
Hubble Deep Field

HST - WFPC

96-01a · ST ScI OPO · January 15, 1996 · R. Williams (ST ScI), NASA

CDM POWER SPECTRUM v. OBSERVATIONS

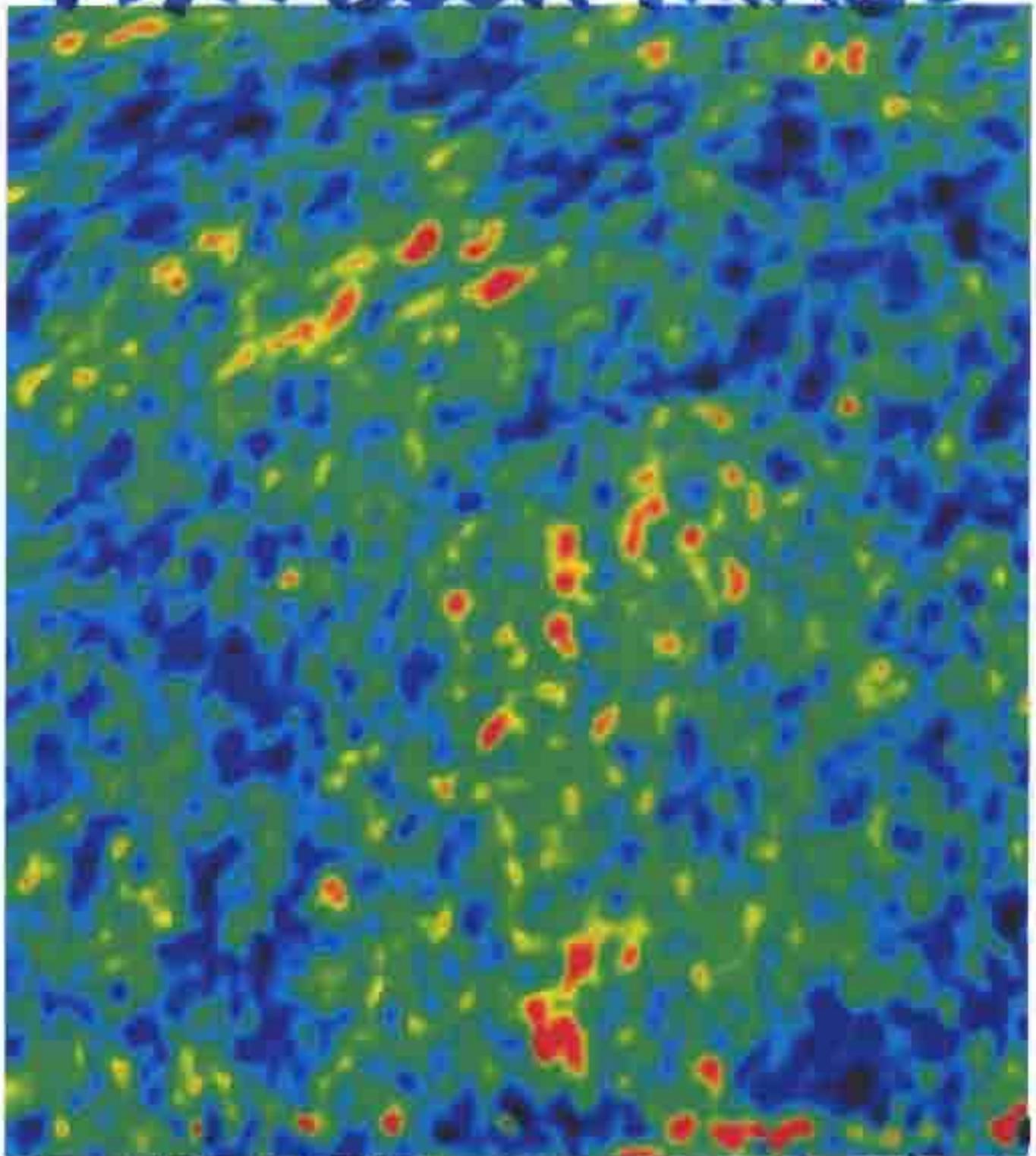
from the Ly- α Forest to the Hubble Scale
w/ a decade of overlap (CMB & LSS)



Tegmark-Zaldarriaga astroph/0207047 v3

NB: Baryon only, HDM, ...,
cannot make a similar claim

TEXTBOOK IMAGE ^{of 1}



← ONE BILLIONTH THE SIZE OF A MICRON →
"QUANTUM FUZZ"

Fluctuations:

Burdeen-Steinhardt-MST, Guth-Pi,
Hauking, Starobinski, 1982



$\ll 10^{-8} \text{ cm}$



MORE MATTER

LESS MATTER

\ll LIGHT \gg

MICRO TO MACRO

QUANTUM FLUCTUATIONS
ON SUBATOMIC SCALE

"LUMPY" DISTRIBUTION OF
MATTER ON

MACRO SCALE

? ? ? COSMIC INFLATION



DID THE UNIVERSE
INFLATE?

TEST THE
THREE PREDICTIONS



WHAT POWERED INFLATION?

WHO IS ϕ ?



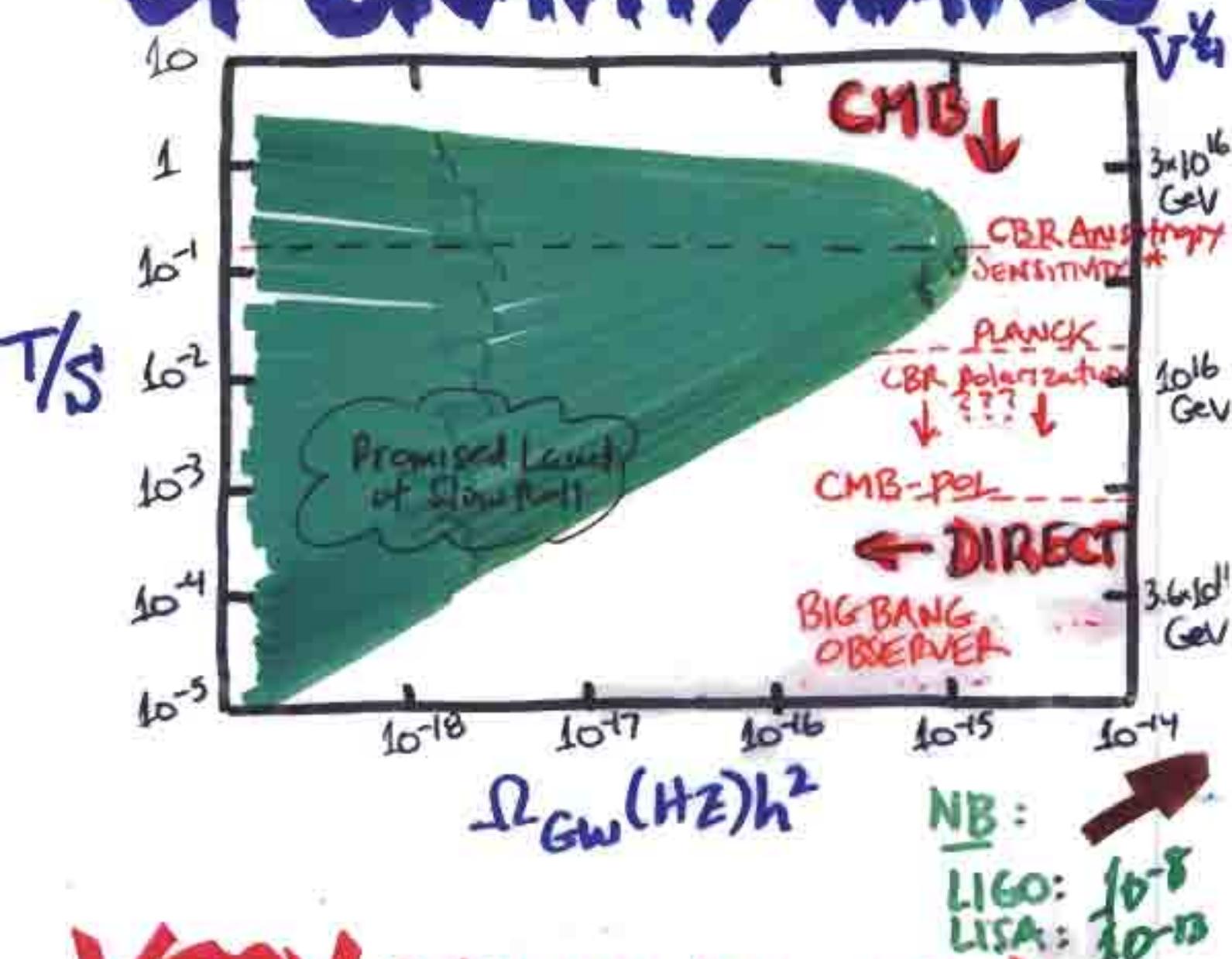
MULTIVERSE! #1?

SCIENCE?



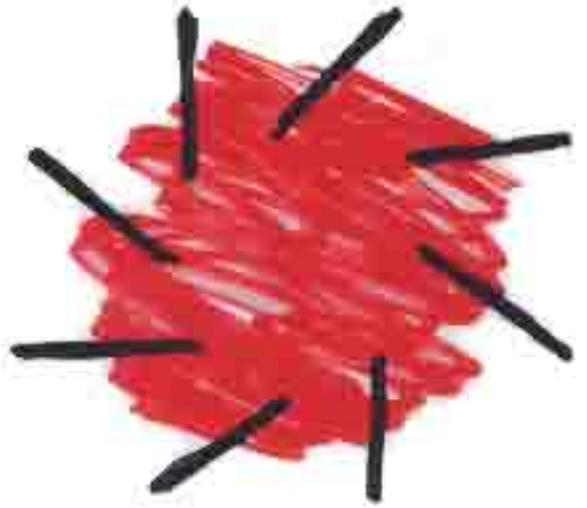
LAB EVIDENCE

DETECTION OF GRAVITY WAVES



VERY CHALLENGING!

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



?? Cosmic Acceleration

★ DARK ENERGY OR NEW GRAVITATIONAL PHYSICS?

★ WHAT IS DARK ENERGY?

★ WHAT IS OUR COSMIC DESTINY?

**COMIC
ACCELERATION**

SOLVING THE

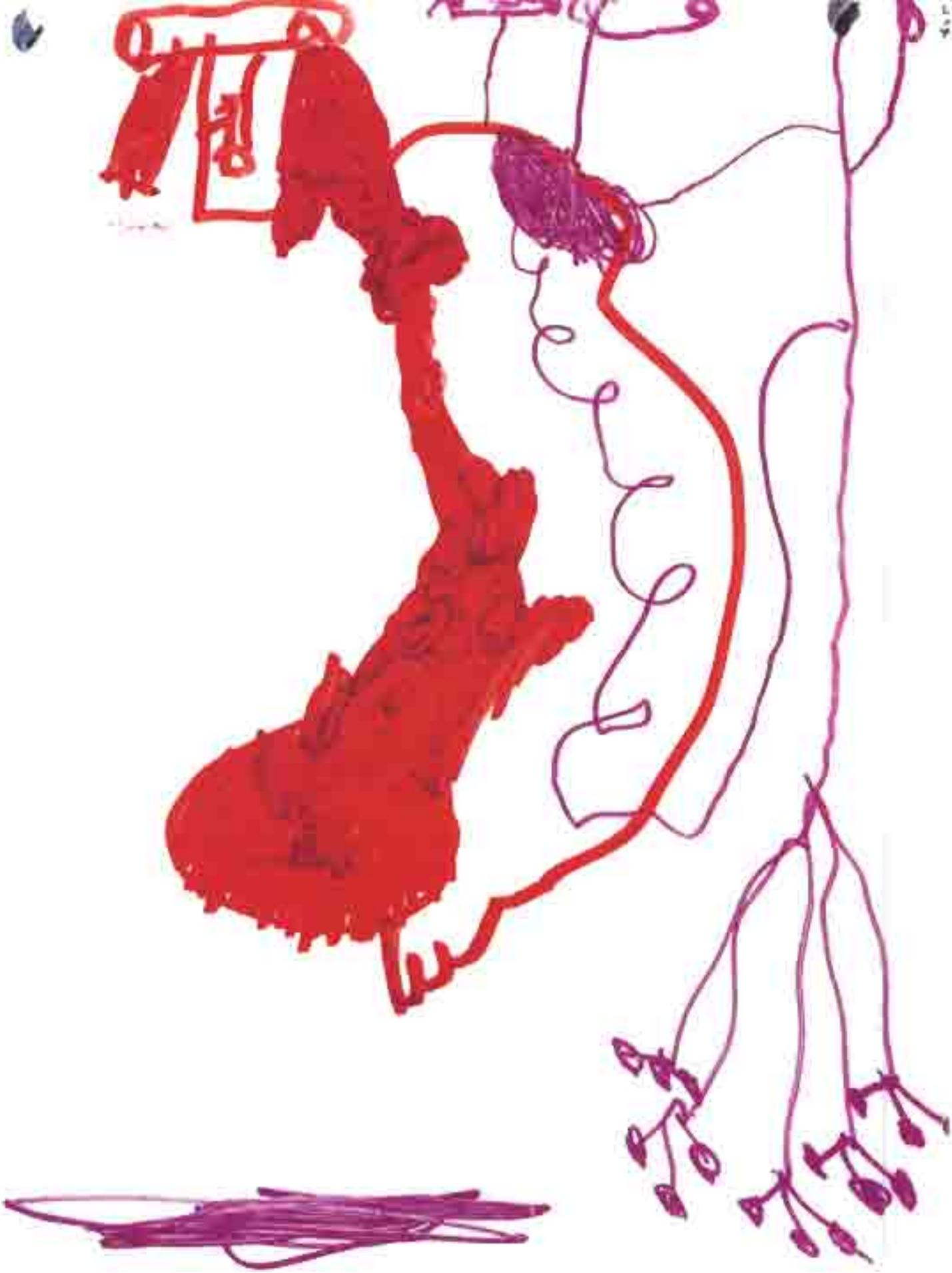
PROBLEM WILL REQUIRE

ACRAZY, NEW IDEA!

**NB: NOT EVERY CRAZY IDEA IS A SOLUTION
TO PROBLEMS. ONLY THE BEST**

COSMOLOGY IS THE BEST PROBE

OF DARK ENERGY



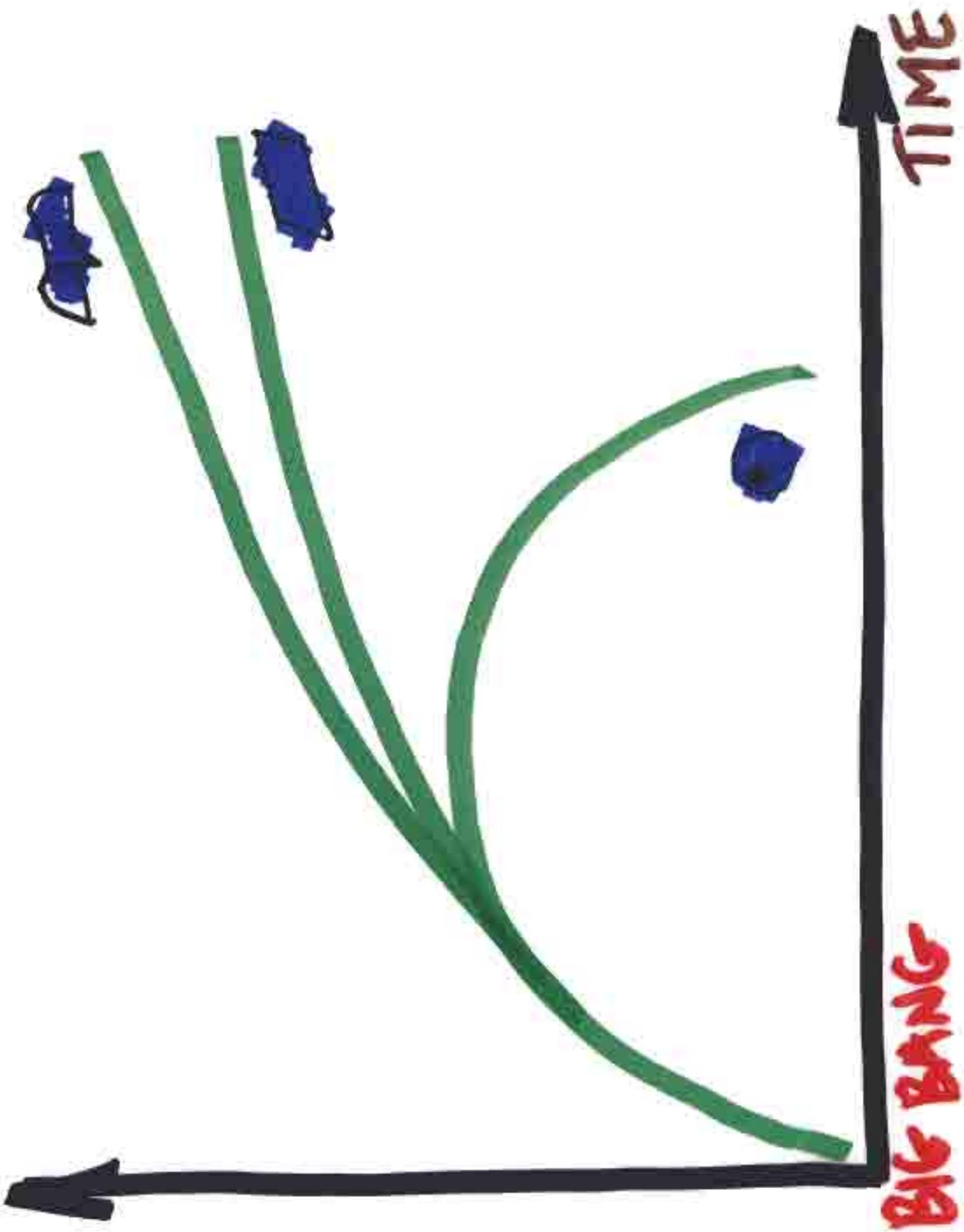
NO DARK ENERGY

NEW ASPECT OF GRAVITY

 **"EMPTY" UNIVERSE
UNDERGOES ACCELERATED
EXPANSION!**

**AVERAGE MATTER-DENSITY TODAY $\rho \approx 10^{-24} \text{ g/cm}^3$
 $\approx 10^{-100} \times$ DENSITY AFTER INFLATION**

SIZE



BIG BANG

TIME

"BIG RIP" $w < -1$

CONTINUED ACCELERATION

COSMIC RED OUT 100 Billion YRS

$p_{rac} = const$



DECAY OF DARK ENERGY

WITH DARK ENERGY

RECOLLAPSE

??
Balance
??



IT'S ALL ABOUT w !

$$w \equiv p/\rho$$

RECALL: GRAVITY $\propto (\rho + 3p) = \rho(1 + 3w)$



CHARACTERIZES DIFFERENT MODELS/IDEAS

	w	\dot{w}
VACUUM ENERGY	-1	0
TANGLED DEFECTS	-1/3	0
ROLLING FIELD	-1 \rightarrow 1	$\neq 0$
GHOSTLY FIELDS	< -1	$\neq 0$
NO DARK ENERGY (NEW GRAVITATIONS)	< 0 , EVEN IMAGINARILY!	



CAN MEASURE w !

SNe, SZ, Grav Lensing, LSS

$$\sigma_w \sim \pm 0.05 \quad \sigma_{\dot{w}} \sim \pm 0.15$$

DES, SPT, LSST, SNAP/JDEM, ...

?? DARK MATTER? ??

★ How much ^{IS IN} NEUTRINOS?

★ WHAT IS THE COLD DARK MATTER?

★ LAB EVIDENCE!

BEFORE THE BIG BANG

NOW, A SCIENTIFIC QUESTION

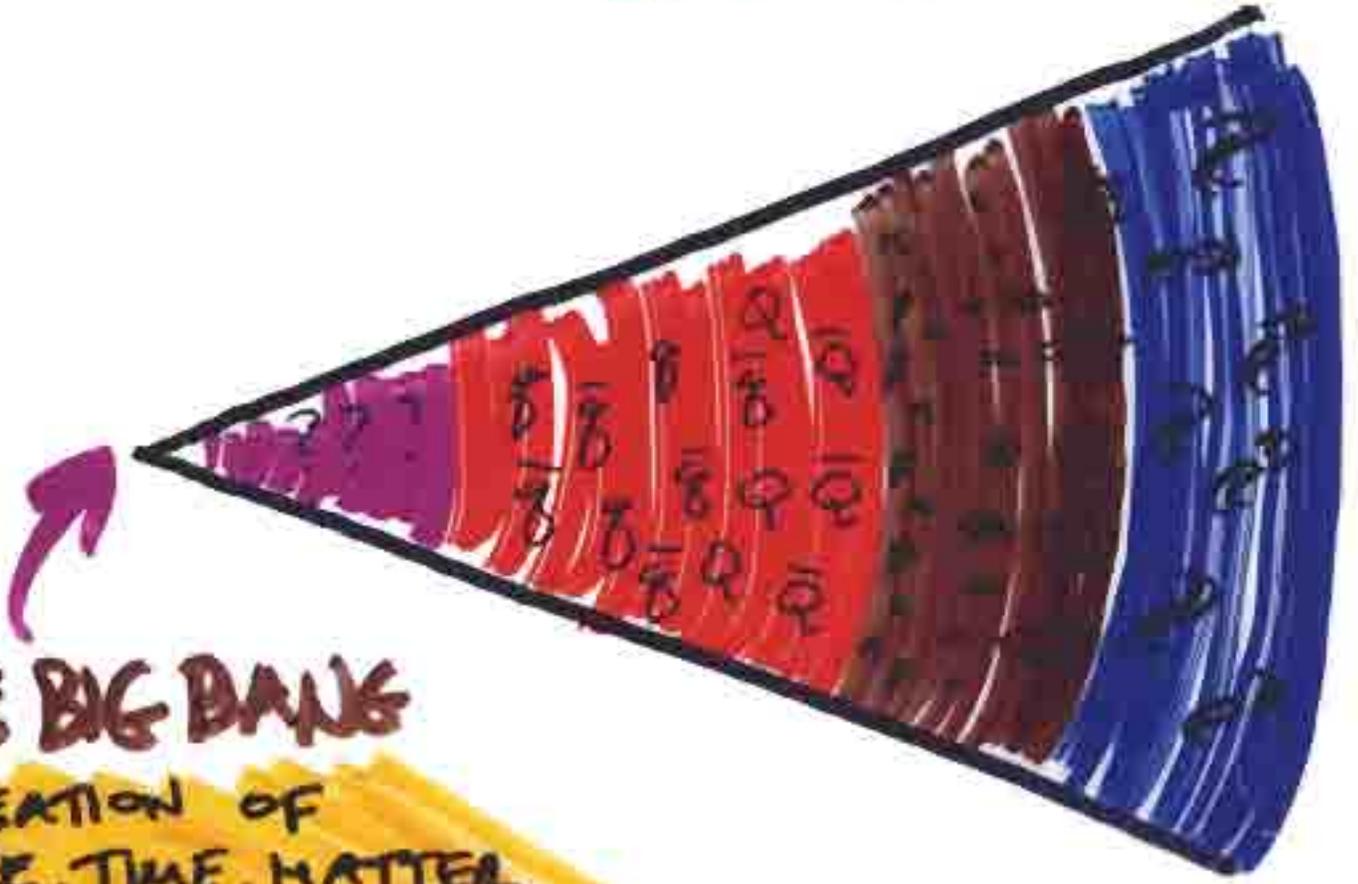
★ BIG BANG SINGULARITY?

★ MULTIVERSE?

★ CYCLIC ?

??

EINSTEIN'S BIG BANG



THE BIG BANG
CREATION OF
SPACE, TIME, MATTER
& ENERGY

- NO BEFORE THE BIG BANG
- NEAT & TIDY
- SATISFIES ST. AUGUSTINE'S PRINCIPLE

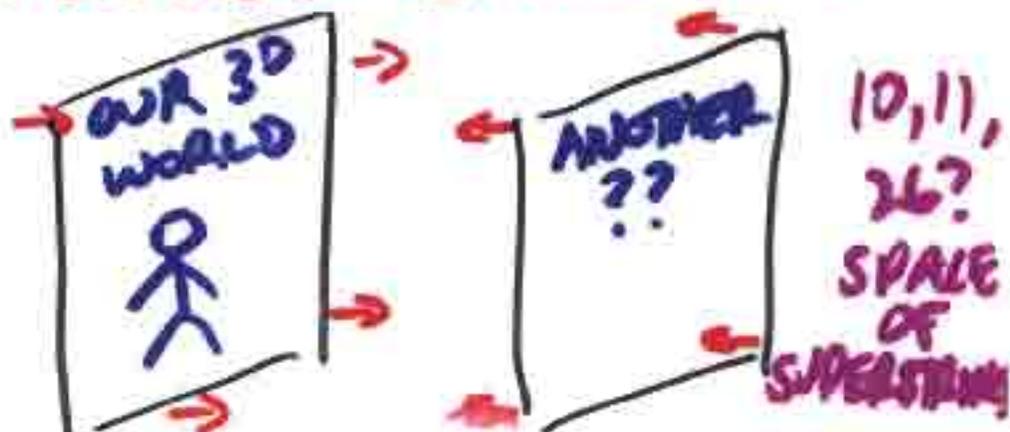
... but Einstein's theory is incomplete!

THE BOUNCING UNIVERSE



... BUT HOW TO MAKE A UNIVERSE BOUNCE?

LATEST IDEA:
COLLIDING BRANES





THE INFLATIONARY MULTIVERSE

INFINITE NUMBER OF big bangs
Issue of a beginning is black hole
...we are but one of an infinite number
of distinct inflationary bubbles!



"RIVER of COSMIC TIME"

ORIGIN OF ATOMS

WHAT PROVIDED EXCESS OF MATTER?

★ BARYOGENESIS?

★ NEUTRINO-GENESIS?

★ LAB EVIDENCE?

W LARGE-SCALE STRUCTURE OF SPACE-TIME?

★ # OF DIMENSIONS

★ MULTIVERSE

★ SINGULARITIES, RIPS

★ BEGINNINGS, ENDS, ..

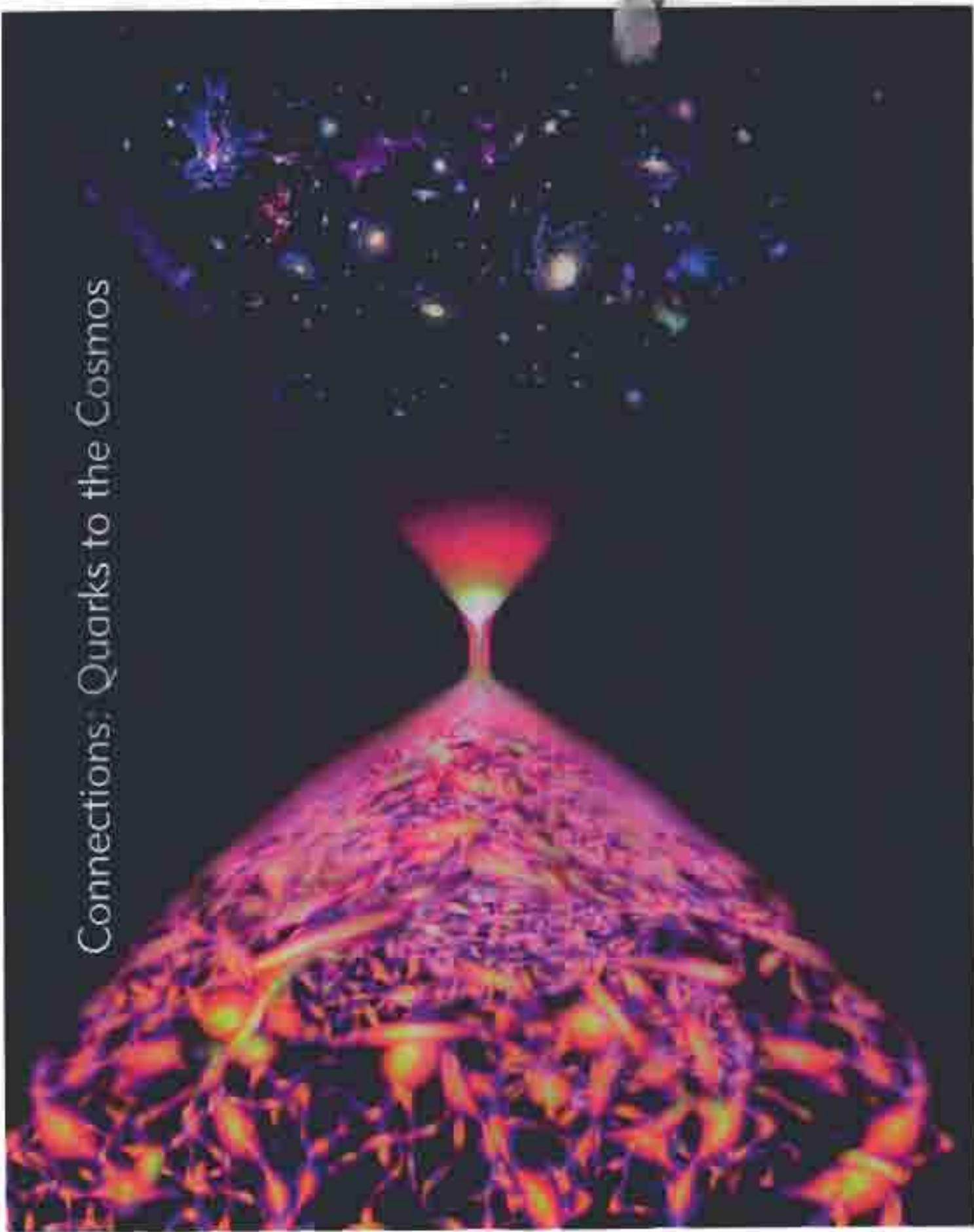
MORE RELICS, ?
? NEW SURPRISES, ...

★ SOURCE OF HIGHEST
ENERGY COLL

★ TOPOLOGICAL DEFECTS

★ SACLED SYMMETRY VIOLATED

Connections: Quarks to the Cosmos



A LOT AT
STAKE!

INFLATION
RELATED?

WHAT IS
IT?

DARK
ENERGY

SUPER
STINGS

SOLUTIONS?

WHY
NOW?

COSMIC DESTRUCTION
CAN'T UNDERSTAND

NEUTRINO
MASSES
SAME
SCALE

SYMBIOTIC
PARTICLES

COGNIC ACCELERATION

SUPERSYMMETRY

$SWY \Rightarrow p_{vac} = 0$
 $SWY \Rightarrow p_{vac} \neq 0$

QUANTUM
VACUUM
ENERGY

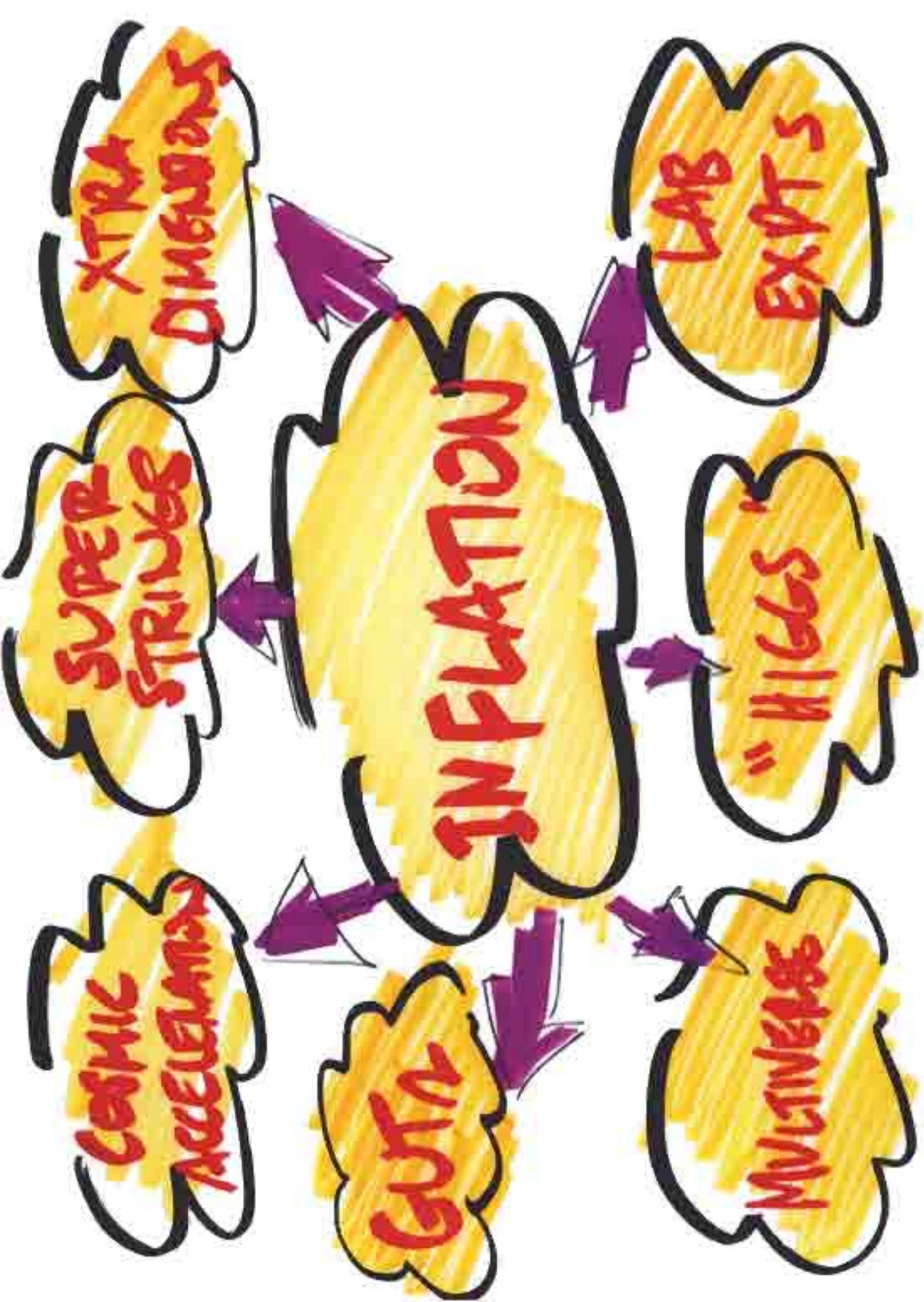
WHY SO SMALL

SUPRAUSE
???

NEW
GRAV IN
PHYSICS

SELF
ACCELERATION

... SWEDISH GOLD OPPORTUNITIES



SUPER STRINGS

XTRA DIMENSIONS

LAB EXPTS

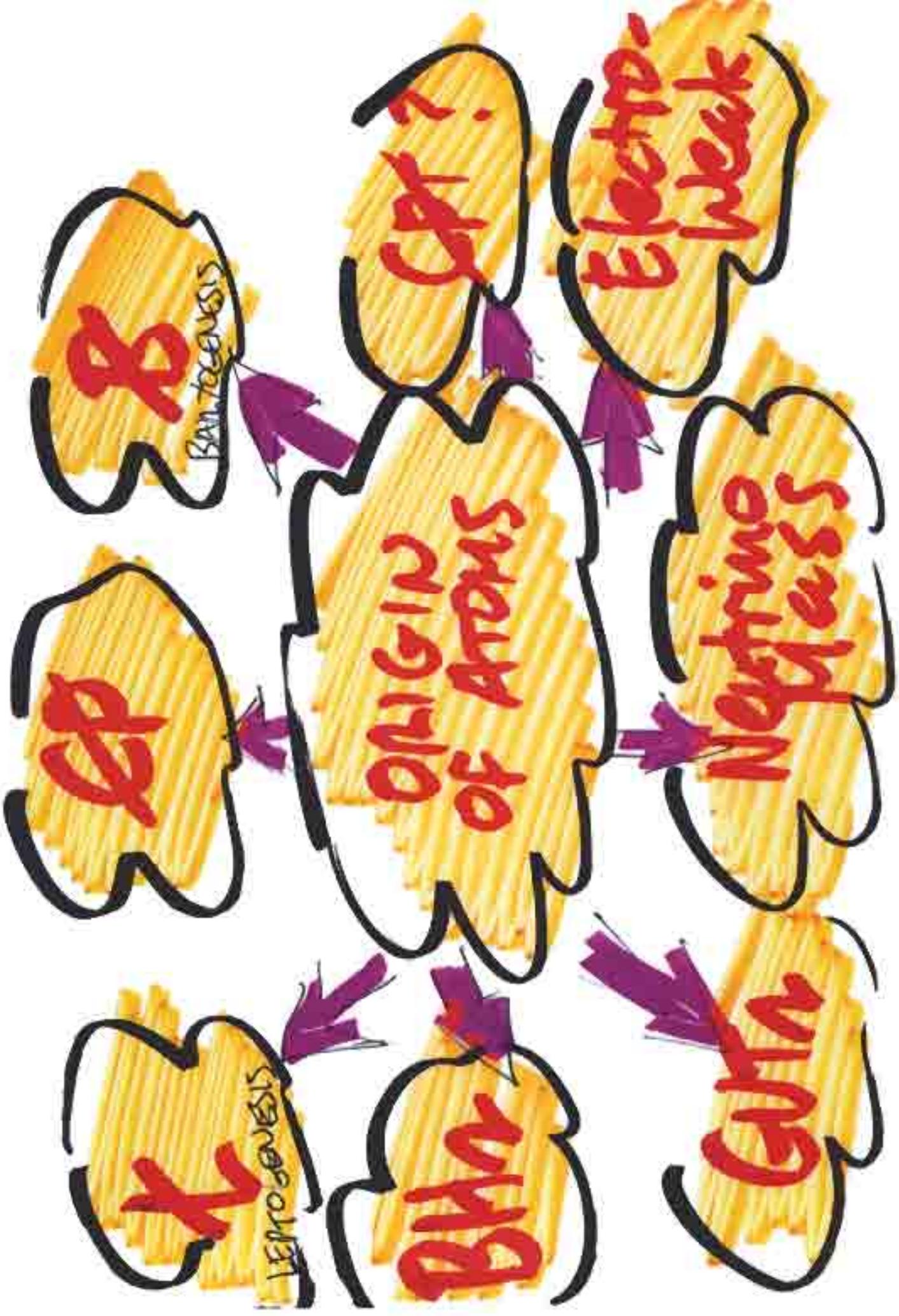
"WIGGS"

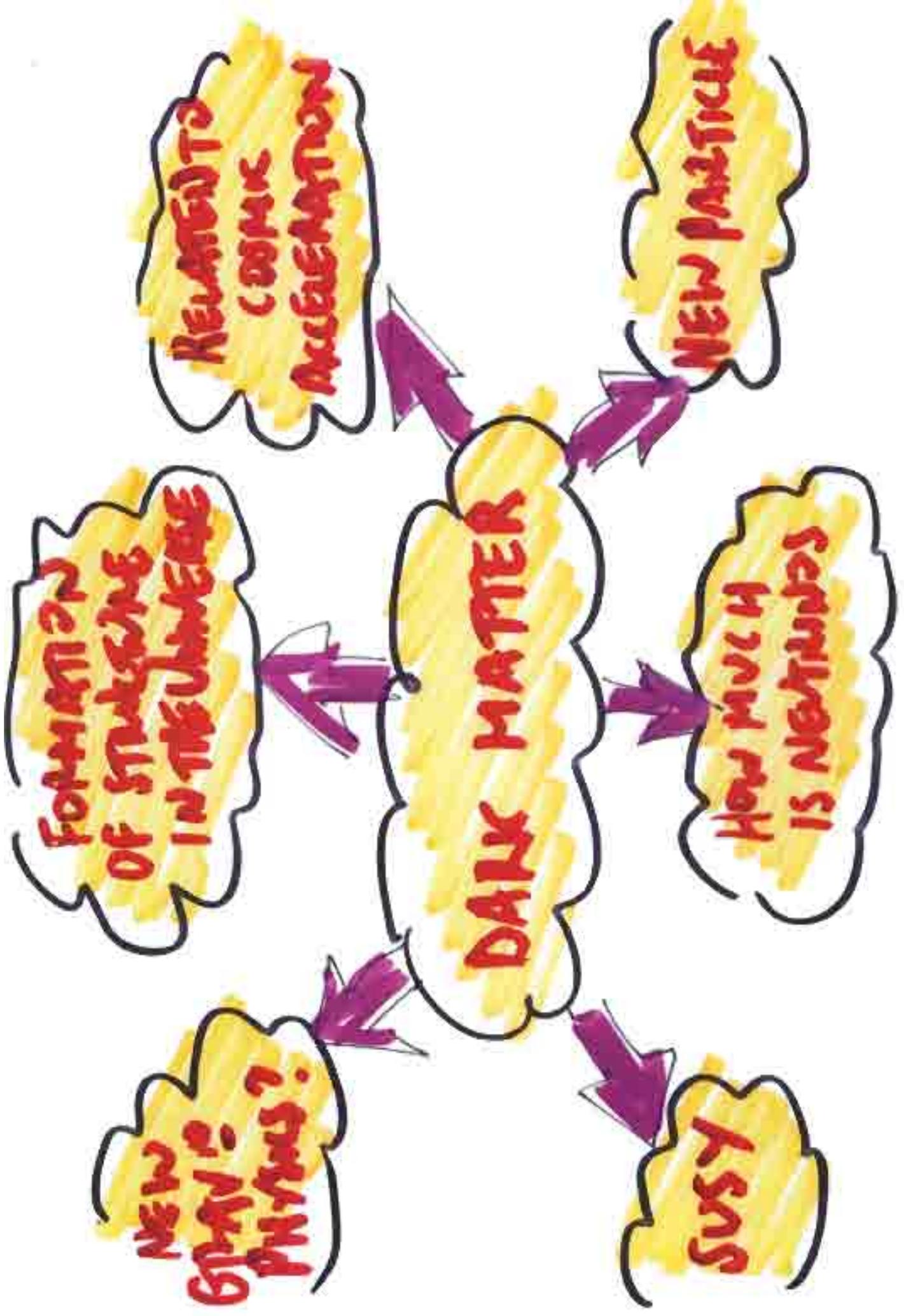
MULTIVERSE

GUTS

COSMIC ACCELERATIONS

INFLATION





ORIGIN OF
HIV ELEMENTS

SN
EXPLAINS
NS

LARGE-SCALE
STRUCTURE

NEUTRINO MS

CLUES TO
MULTIPLYING
UNIFICATION

ORIGIN OF
ATOMIC MATTER
*PROTOGENESIS?
LEPTOGENESIS?*

WE KNOW MUCH



INFLATION



STRING
COSMOLOGY



HOT BIG BANG
MODEL



DARK ENERGY
COSMIC
ACCELERATION



MASSIVE
NEUTRINOS



BARIONS



COLD
DARK
MATTER

CAN WE PUT
IT ALL TOGETHER?

THE BIG PICTURE



OUR UNIVERSE