The Big Questions, Accelerators, Telescopes, the LHC and the Future

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Elementary Particle Physics Has Something Money Cannot Buy

The Greatest Opportunities for Profound Discovery in at Least 50 Years

Spelled Out in the Quantum Universe

QUANTUM UNIVERSE

THE REVOLUTION IN 21ST CENTURY PARTICLE PHYSICS

DOE / NSF

HIGH ENERGY PHYSICS ADVISORY PANEL

QUANTUM UNIVERSE COMMITTEE

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What does "Quantum Universe" mean?

To discover what the universe is made of and how it works is the challenge of particle physics. Quantum Universe presents the quest to explain the universe in terms of quantum physics, which governs the behavior of the microscopic, subatomic world. It describes a revolution in particle physics and a quantum leap in our understanding of the mystery and beauty of the universe.

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EINSTEIN'S DREAM OF UNIFIED FORCES

1

ARE THERE UNDISCOVERED PRINCIPLES OF NATURE : NEW SYMMETRIES, NEW PHYSICAL LAWS?

The quantum ideas that so successfully describe familiar matter fail when applied to cosmic physics. Solving the problem requires the appearance of new forces and new particles signaling the discovery of new symmetries–undiscovered principles of nature's behavior.

2

HOW CAN WE SOLVE THE MYSTERY OF DARK ENERGY?

The dark energy that permeates empty space and accelerates the expansion of the universe must have a quantum explanation. Dark energy might be related to the Higgs field, a force that fills space and gives particles mass.

3

ARE THERE EXTRA DIMENSIONS OF SPACE?

String theory predicts seven undiscovered dimensions of space that give rise to much of the apparent complexity of particle physics. The discovery of extra dimensions would be an epochal event in human history; it would change our understanding of the birth and evolution of the universe. String theory could reshape our concept of gravity.

4

DO ALL THE FORCES BECOME ONE?

At the most fundamental level all forces and particles in the universe may be related, and all the forces might be manifestations of a single grand unified force, realizing Einstein's dream.

THE PARTICLE WORLD

5

WHY ARE THERE SO MANY KINDS OF PARTICLES?

Why do three families of particles exist, and why do their masses differ so dramatically? Patterns and variations in the families of elementary particles suggest undiscovered underlying principles that tie together the quarks and leptons of the Standard Model.

6

WHAT IS DARK MATTER? HOW CAN WE MAKE IT IN THE LABORATORY?

Most of the matter in the universe is unknown dark matter, probably heavy particles produced in the big bang. While most of these particles annihilated into pure energy, some remained. These remaining particles should have a small enough mass to be produced and studied at accelerators.

7

WHAT ARE NEUTRINOS TELLING US?

Of all the known particles, neutrinos are the most mysterious. They played an essential role in the evolution of the universe, and their tiny nonzero mass may signal new physics at very high energies.

THE BIRTH OF THE UNIVERSE

8

HOW DID THE UNIVERSE COME TO BE?

According to cosmic theory, the universe began with a singular explosion followed by a burst of inflationary expansion. Following inflation, the universe cooled, passing through a series of phase transitions and allowing the formation of stars, galaxies and life on earth. Understanding inflation requires breakthroughs in quantum physics and quantum gravity.

9

WHAT HAPPENED TO THE ANTIMATTER?

The big bang almost certainly produced equal amounts of matter and antimatter, yet the universe seems to contain no antimatter. How did the asymmetry arise?

OPPORTUNITIES FOR DISCOVERY

We live in an age when the exploration of great questions is leading toward a revolutionary new understanding of the universe.

"Opportunities have emerged for discovery about the fundamental nature of the universe that we never expected," Presidential Science Advisor John Marburger said recently. "Technology places these discoveries within our reach, but we need to focus efforts across widely separated disciplines to realize the new opportunities."

Quantum Universe is a response to that challenge. It serves as a guide to where the search for understanding has taken us so far, and to where it is going. The chapters that follow articulate how existing and planned particle physics experiments at accelerators and underground laboratories, together with space probes and ground-based telescopes, bring within reach new opportunities for discovery about the fundamental nature of the universe.

Cosmic Complementarity: Accelerators and Telescopes

- Heavenly Lab: Extreme Dynamical Range
- Terrestrial Accelerators: Controlled Reproducible Conditions
- Examples: past and future
  - Quarks and Gauge Theory: Opened Early Universe
  - Discovery of CP Violation: Baryogenesis
  - Existence of Dark Matter: Evidence for New Physics
    - Direct Detection of Halo Neutralinos or their Annihilation Products
    - Discovery of Dark Matter Particle (closing the circle)

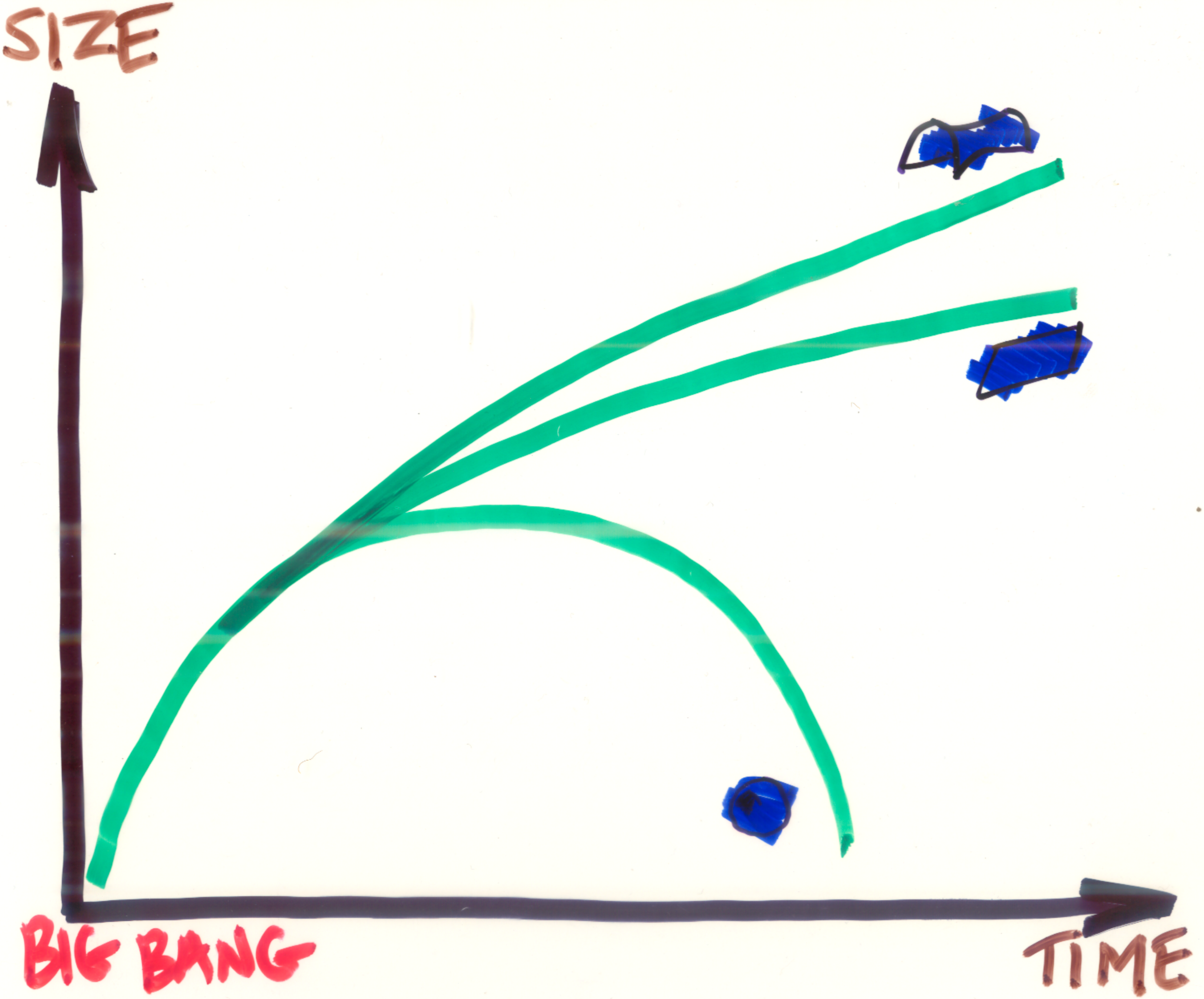
Realizing This Opportunity Will Require Physicists & Astronomers, Telescopes and Accelerators, Working Together

Discovery Potential at the LHC

- ☆Dark Matter
  - ☆Produce the DM Particle
- ☆Inflation
  - ☆Discover Fundamental Scalars
- ☆Cosmic Acceleration
  - ☆Supersymmetry
- ☆Nature of Space & Time
  - ☆Discover extra dimensions

The LHC Must Be Successful!

- Realize the Potential of a Big Investment of Human and Fiscal Capital
- Make Great Discoveries that Show Elementary Particle Physics is on the Verge of Answering Grand Questions
- Solidify the Case for a Linear Collider


SIZE
BIG BANG
TIME

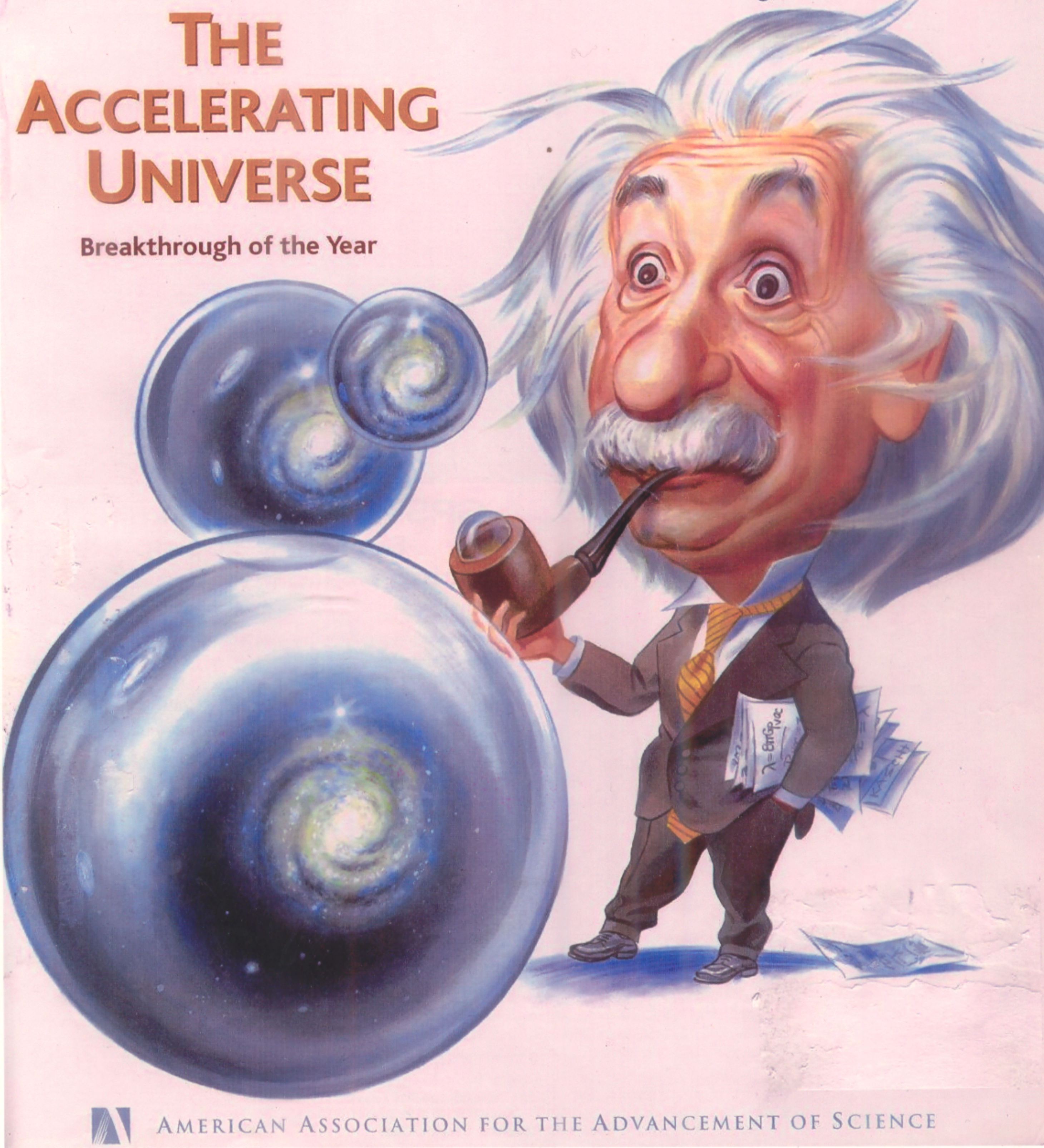
18 December 1998

Science

Vol. 282 No. 5397
Pages 2141–2336 $7

The Accelerating Universe

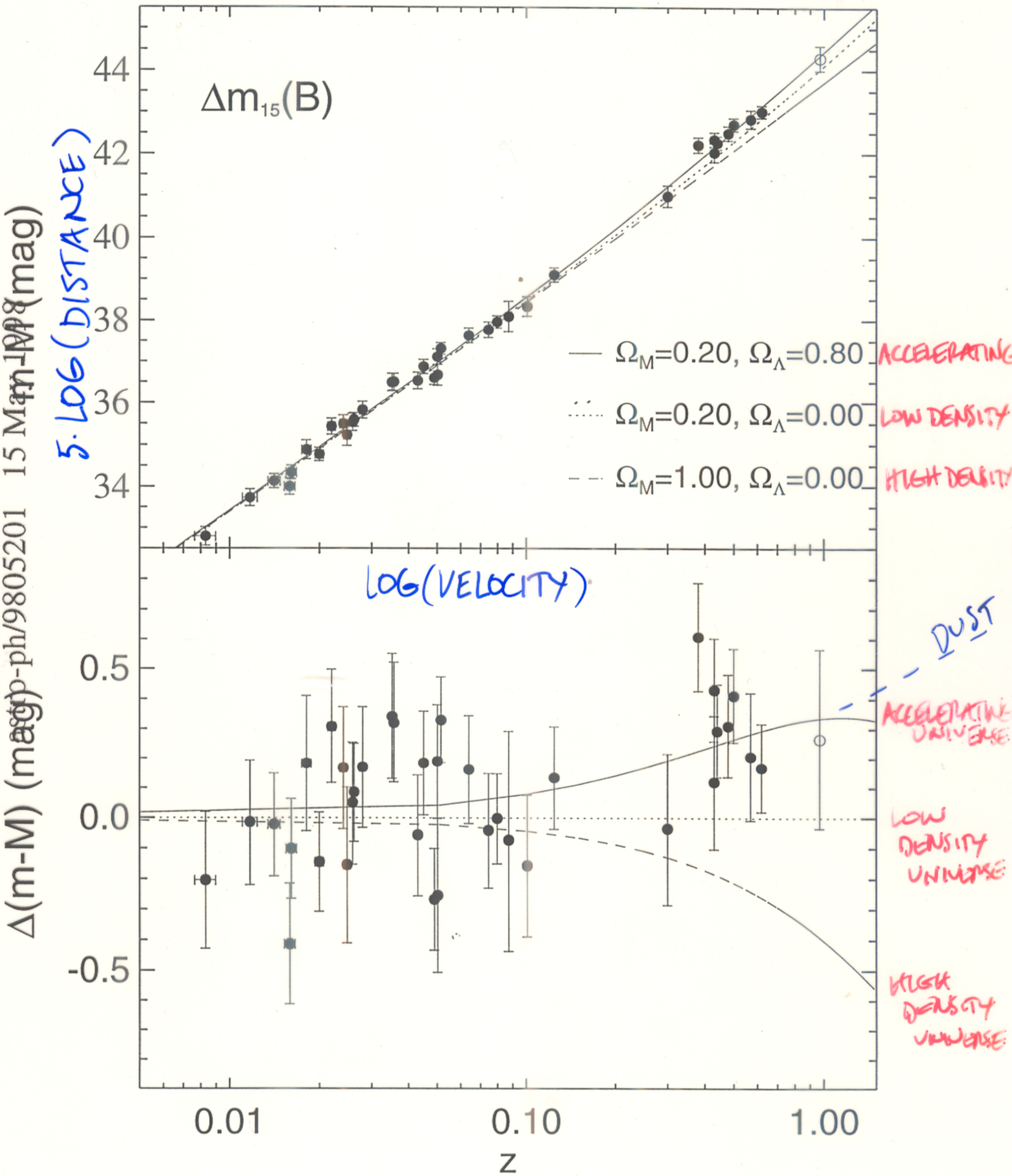
Breakthrough of the Year



American Association for the Advancement of Science

High Z SN Team

A. RIESS et al 98,
A.J. in press (astroph/9805201)



S. Perlmutter et al
Astrophys. J. 98

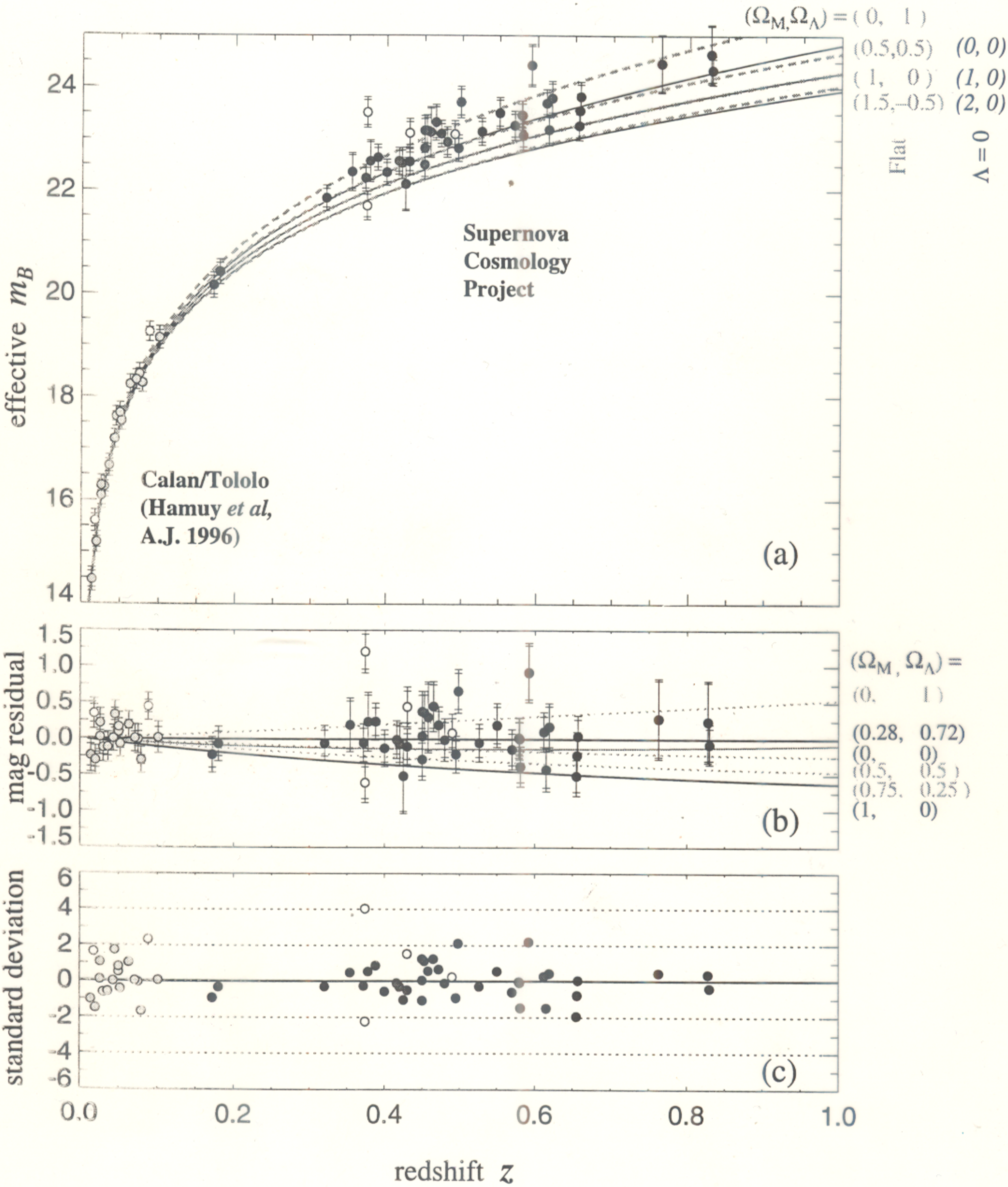
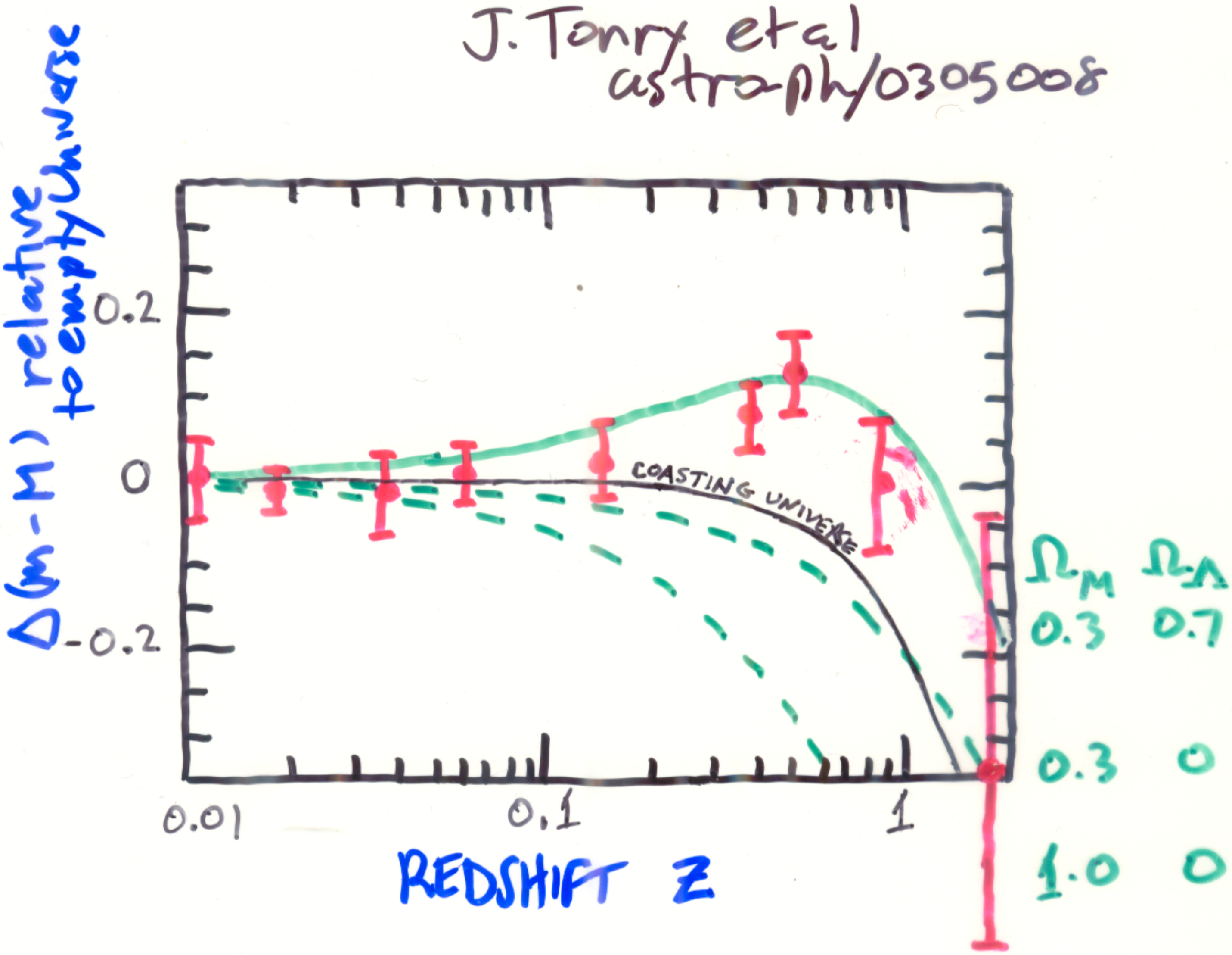


Fig. 2.—

~200 SNeIa . . .

J. Tonry et al
astroph/0305008

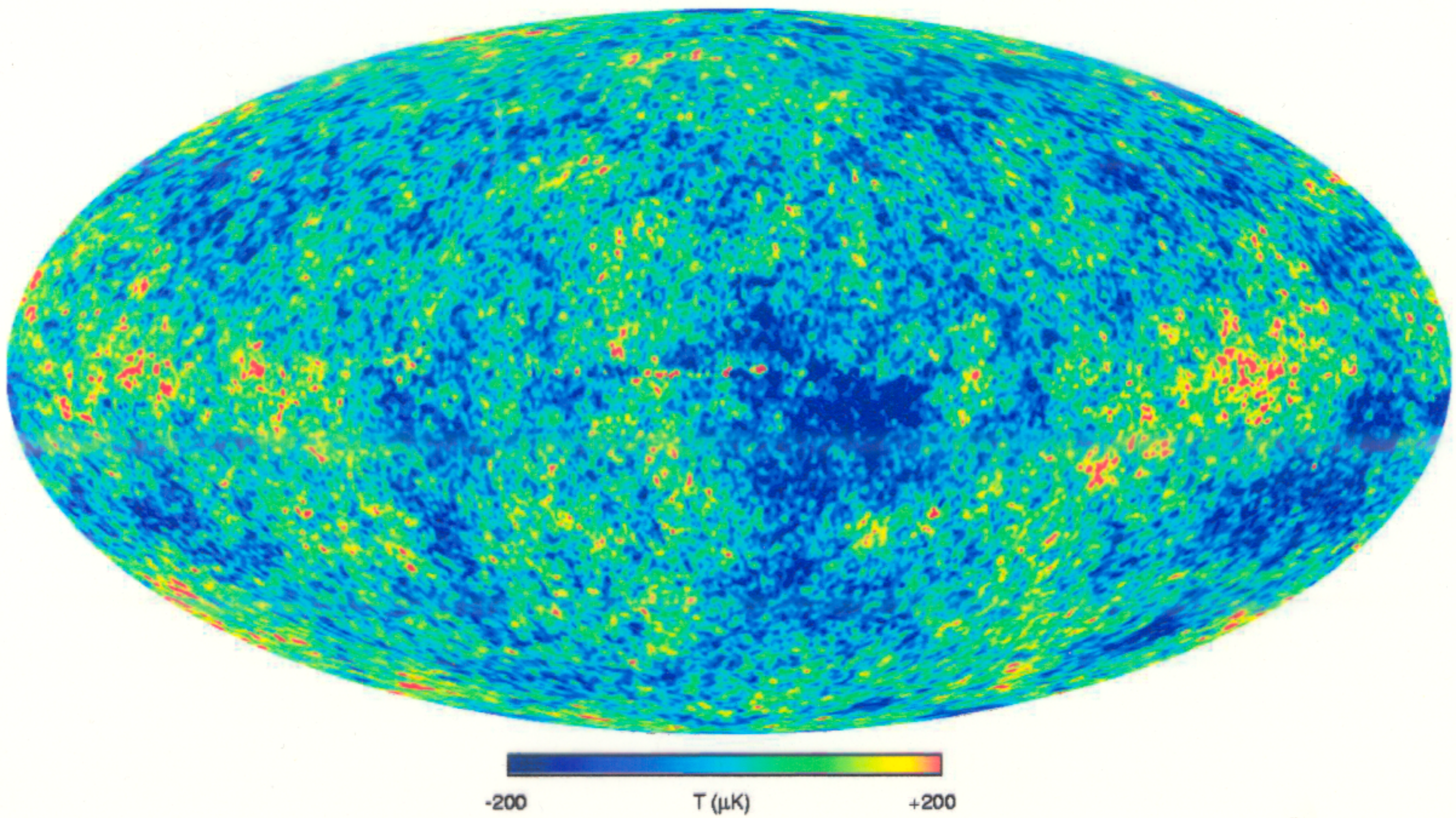


. . . still accelerating

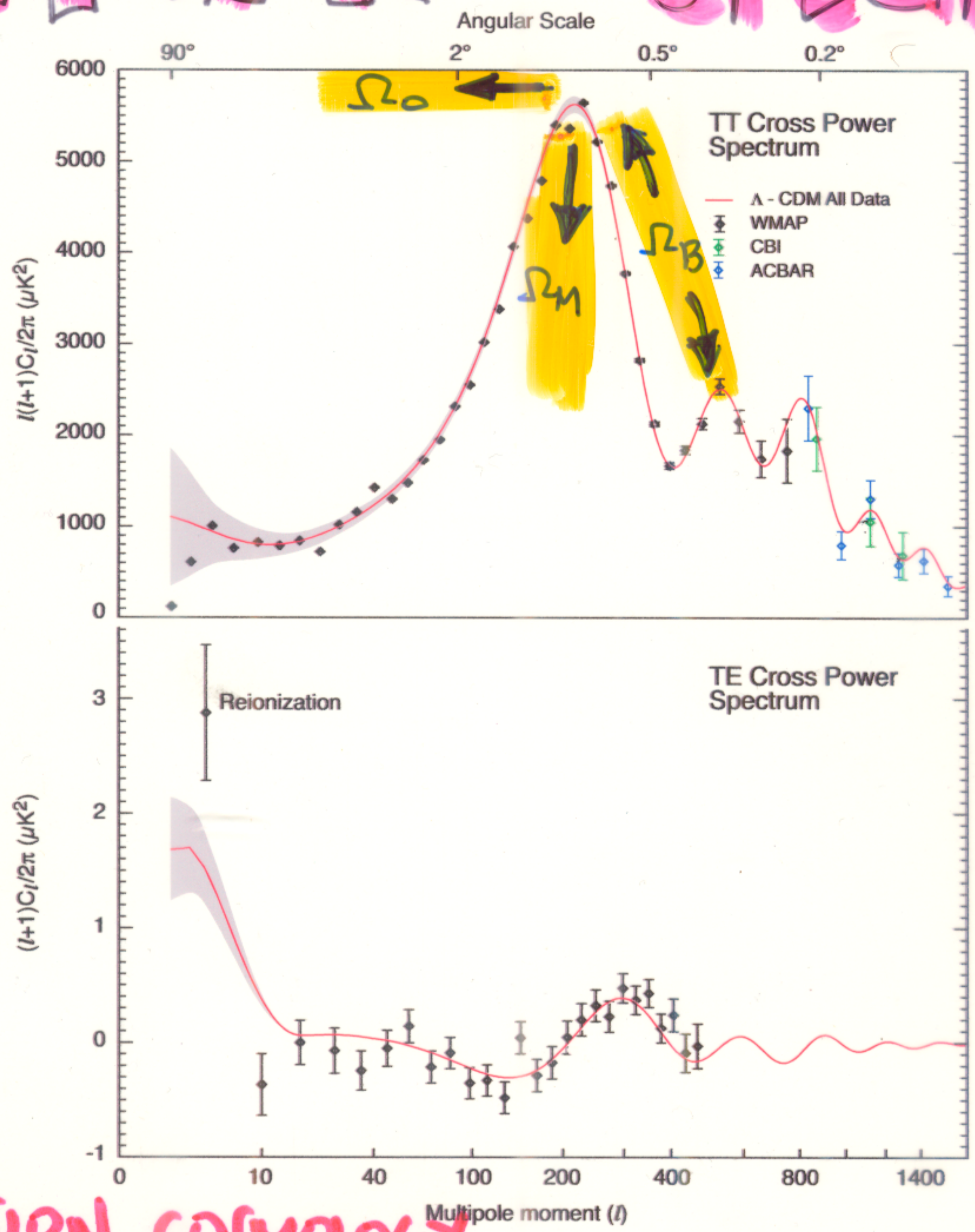
COSMIC ACCELERATION IS NOT GOING AWAY!

ANONYMOUS COSMOLOGIST (EWK):

"THIS TOO WILL PASS"


-200
T (μK)
+200

WMAP POWER SPECTRUM



PRECISION COSMOLOGY

$\Omega_0 = 1.02 \pm 0.02$

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

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

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

$t_0 = 13.7 \pm 0.2$ Gyr

$h = 0.71 \pm 0.035$

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

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

MORE EVIDENCE FOR DARK ENERGY FROM WMAP

"MISSING ENERGY"

FLAT UNIVERSE → CRITICAL DENSITY

DARK MATTER → 1/3 CRITICAL DENSITY

→ 2/3 CRITICAL DENSITY UNACCOUNTED FOR

DARK ENERGY

SUPERNOVA COSMOLOGY PROJECT

KNOP ET AL, ApJ 598, 102 (2003)

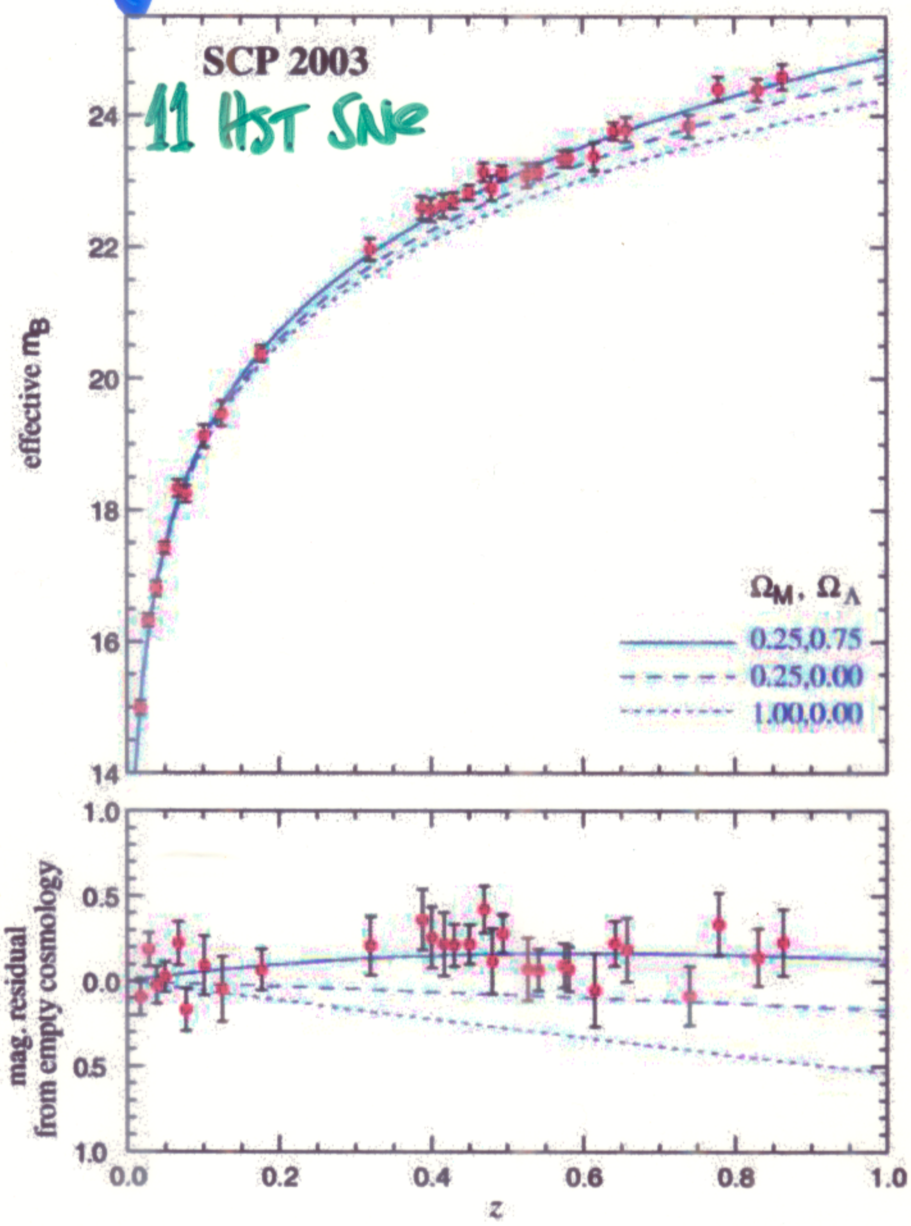
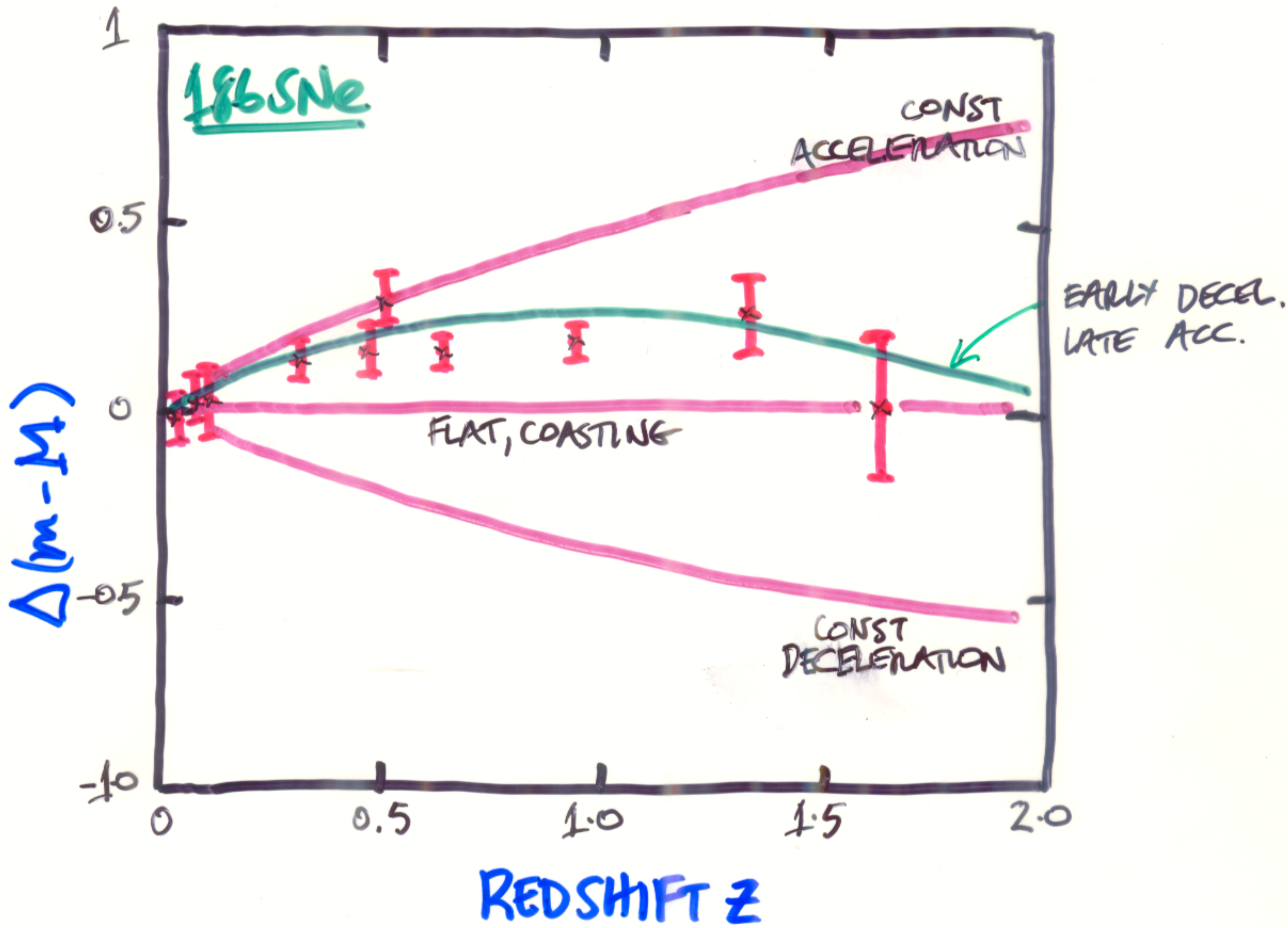


Fig. 6.— Upper panel: Averaged Hubble diagram with a linear redshift scale for all supernovae from our low-extinction subsample. Here supernovae within $\Delta z < 0.01$ of each other have been combined using a weighted average in order to more clearly show the quality and behavior of the dataset. (Note 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 8). 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 Hi-z, HST SNe

A.G. RIESS ET AL
astro-ph/0402512



EARLY PERIOD OF DECELERATION?

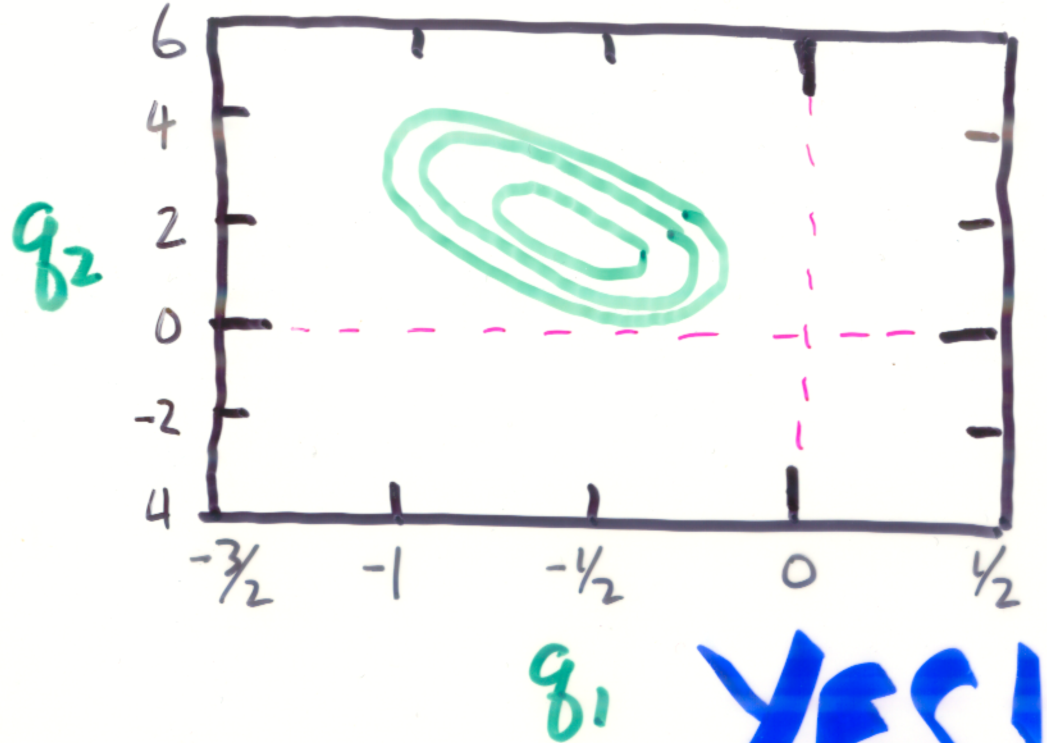
BEFORE SPEED UP

TURNER-RIESS 2001
RIESS ET AL 2003

>10 HST SNe $z \approx 0.9 - 1.8$

q_1 = AVERAGE DECELERATION SINCE $z = 1/2$ (LAST 5 Gyr)

q_2 = AVERAGE DECELERATION EARLIER THAN $z = 1/2$ (FIRST 9 Gyr)



$z_{transition} = 0.46 \pm 0.13$

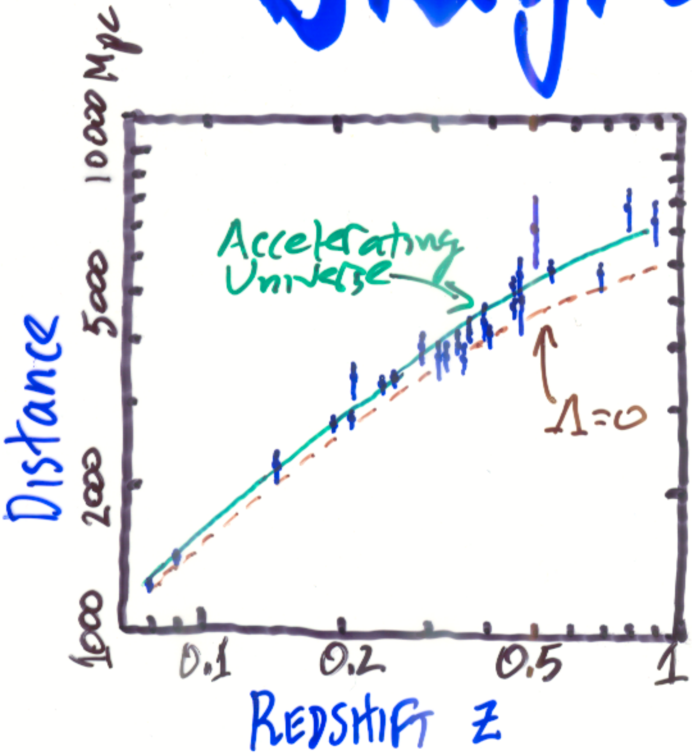
$q_1 \approx -2/3$ RECENT ACC.

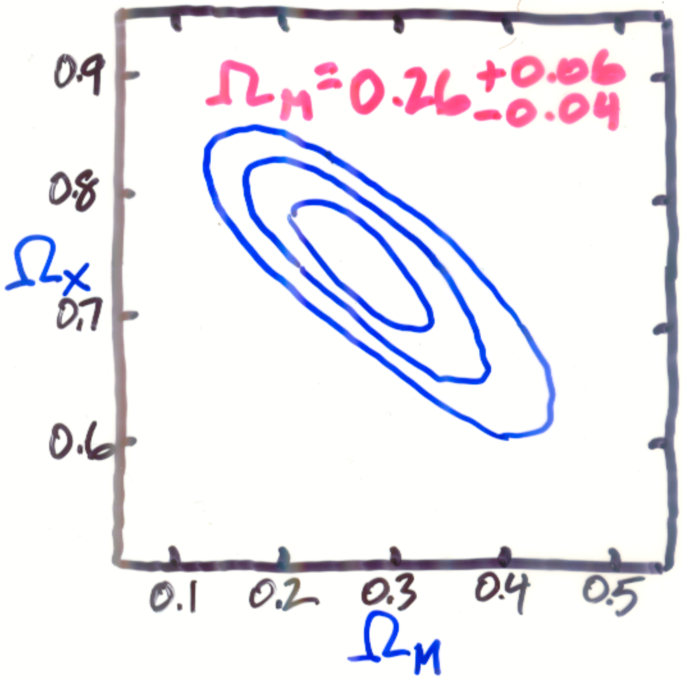
$q_2 \approx 1$ PAST DECEL.

YES!

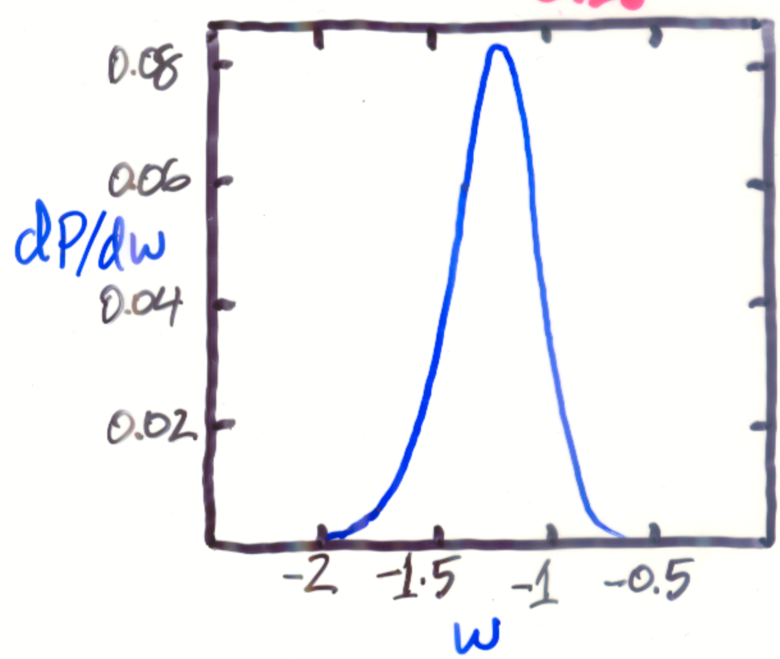
X-ray Cluster Hubble Diagram

S.W. Allen et al, MNRAS astro-ph/0405340





- 26 Clusters
- Distances inferred from gas fraction

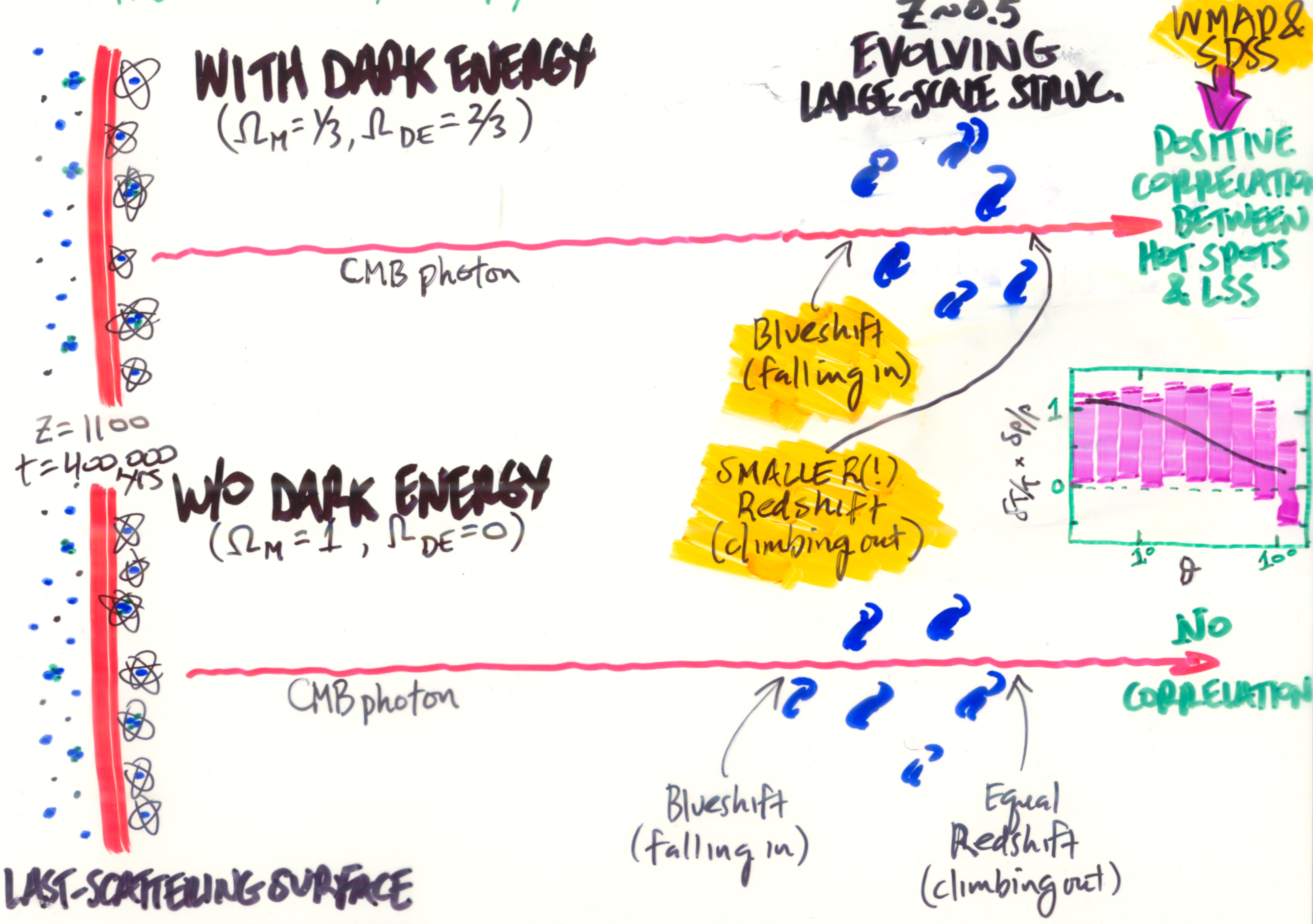


INFERRED GAS FRACTION $\propto$ DISTANCE$^{-3/2}$

⇒ USE UNIVERSALITY OF GAS FRACTION ($= \Omega_B/\Omega_M$) TO INFER DISTANCE

DETECTING DARK ENERGY W/ SACHS-WOLFE EFFECT

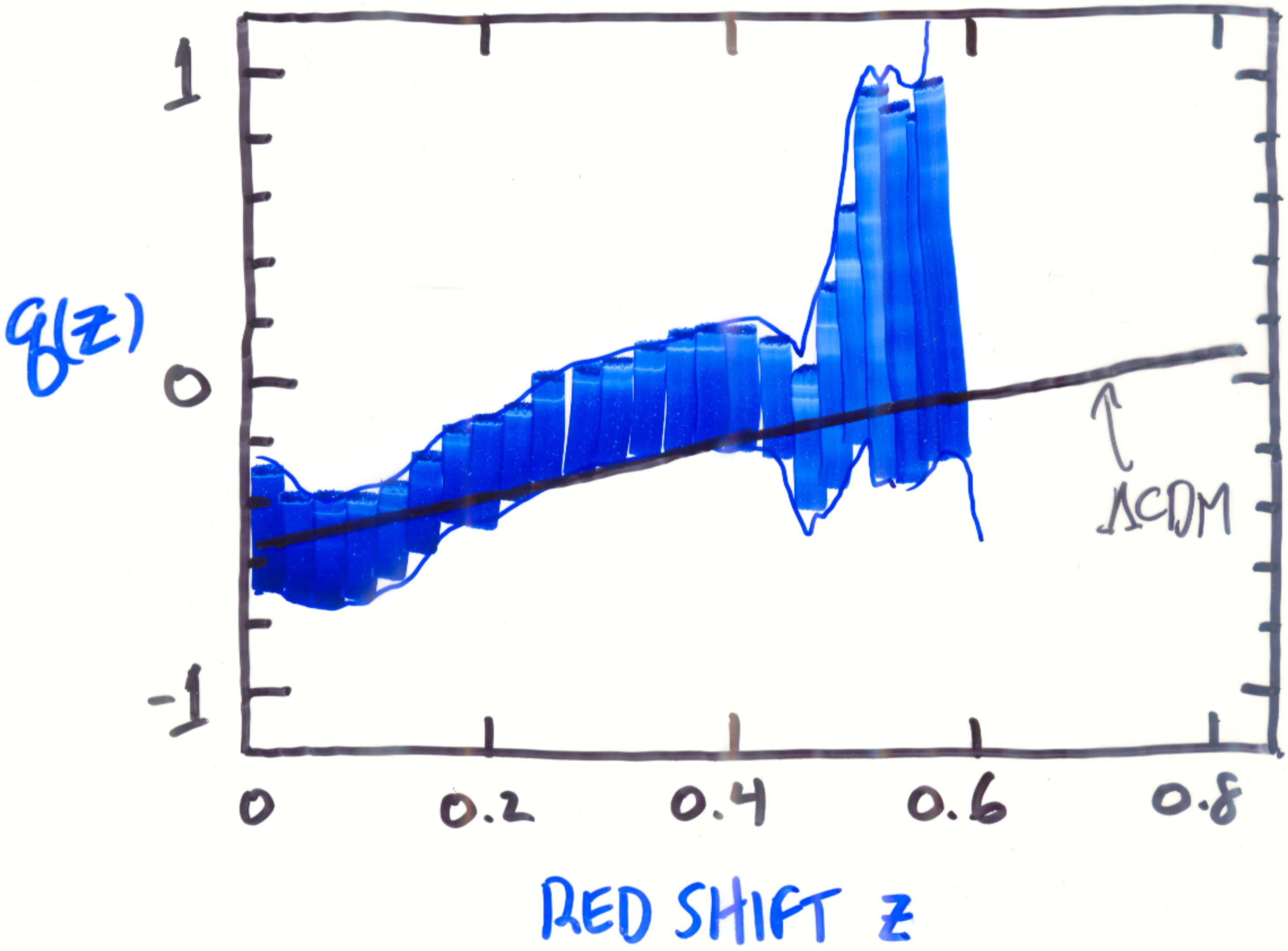
R. Scranton et al, astro-ph/0307355



RADIO GALAXIES

DALY & DJORGOVSKI, ApJ 597, 9 (2003)

$q_0 = -0.35 \pm 0.15$



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!

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

$\Rightarrow$ 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 ($p = -\rho$)

& its Gravity is VERY Repulsive! ($\rho + 3p = -2\rho$)

JUST WHAT IS NEEDED -- BUT...

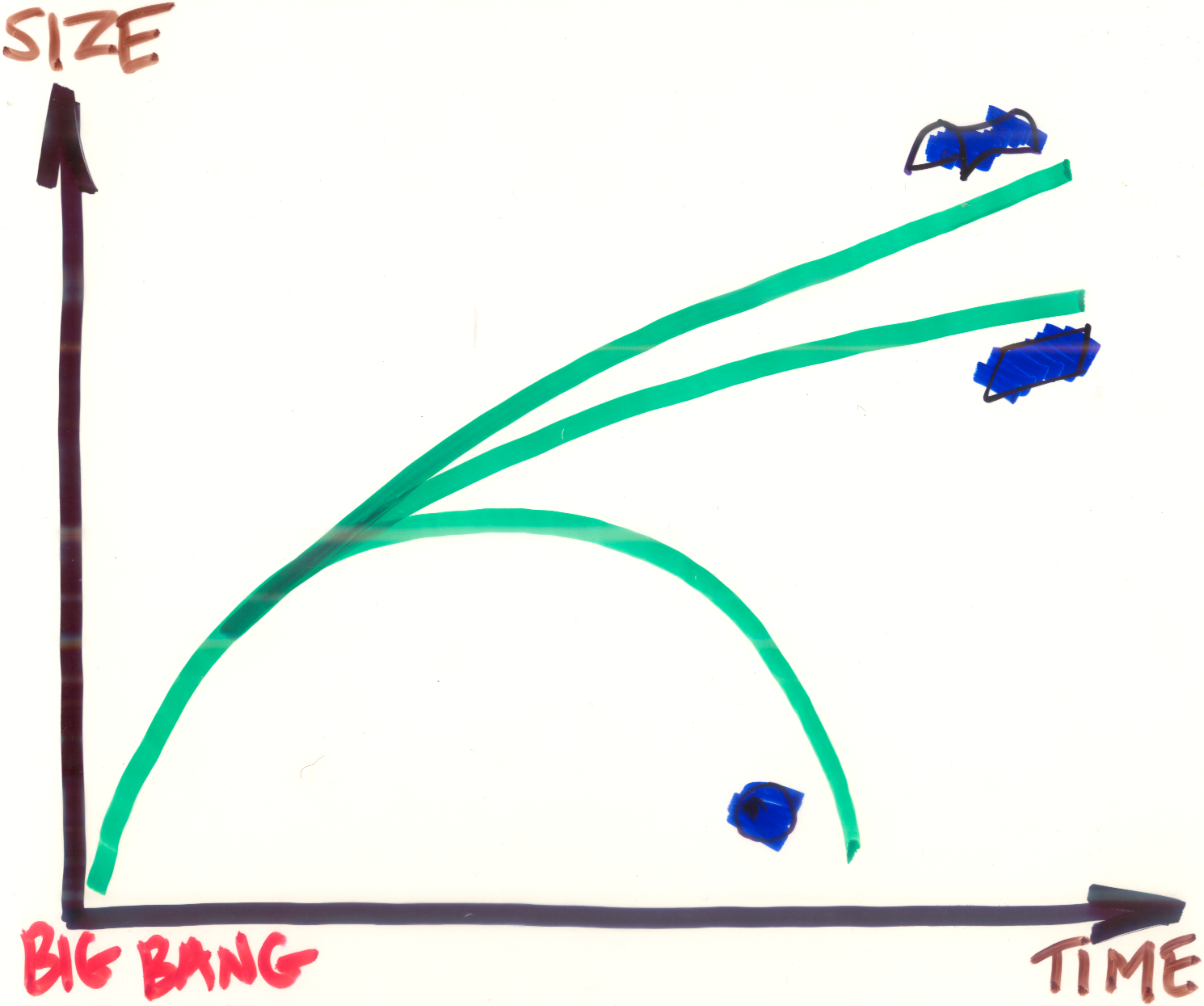
THEORETICAL ESTIMATES OF AMOUNT

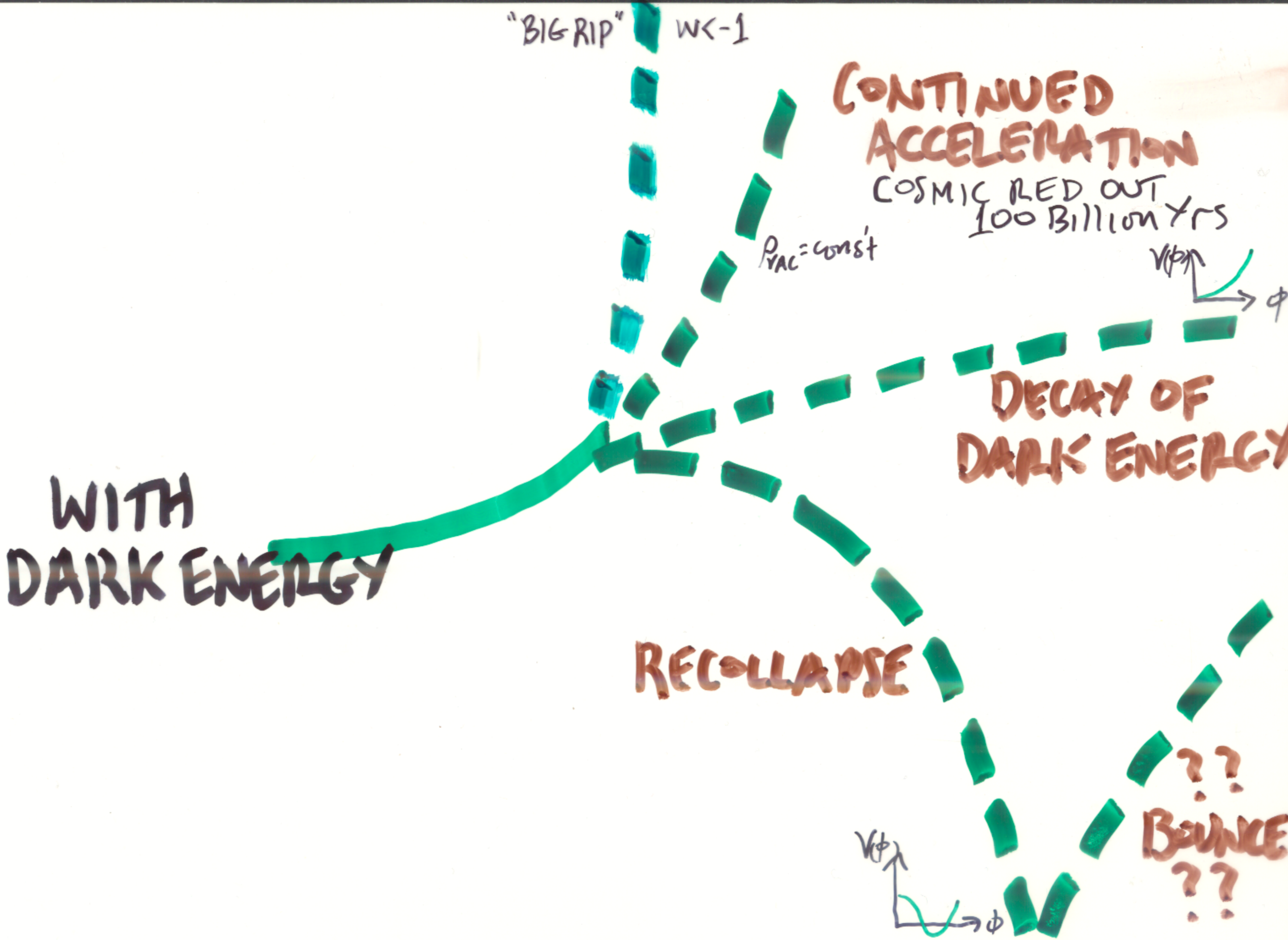
10^{55} x what is needed to explain accelerating Universe

"Houston, we have a problem"

THE BIG QUESTIONS

- WHY DOES NOTHING WEIGH SO LITTLE?
- WHY NOW?
- COSMIC DESTINY?


SIZE
BIG BANG
TIME


"BIG RIP"
w<-1
CONTINUED ACCELERATION
COSMIC RED OUT
100 Billion yrs
ρVAC = const't
V(φ)
φ
DECAY OF DARK ENERGY
WITH DARK ENERGY
RECOLLAPSE
?? BOUNCE ??
V(φ)
φ

NANCY KERRIGAN PROBLEM

WHY ME?

WHY NOW?

MYSTERIOUS, BUT CRUCIAL

SOLVING THE COSMIC ACCELERATION PROBLEM WILL REQUIRE A CRAZY, NEW IDEA!

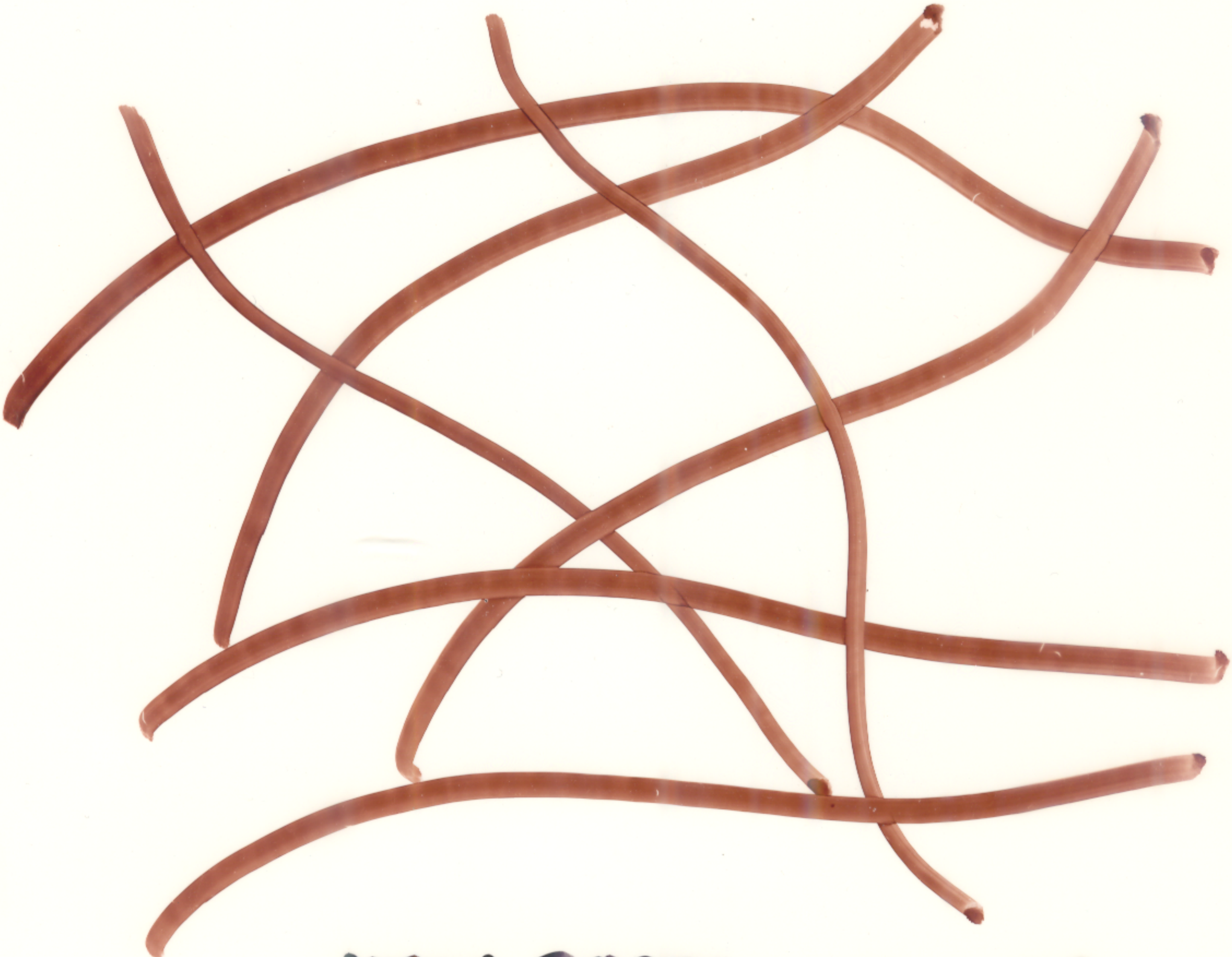
NB: NOT EVERY CRAZY IDEA IS A SOLUTION TO A PROFOUND PROBLEM ... SOME ARE ONLY? JUST CRAZY

COSMOLOGY is the BEST PROBE OF DARK ENERGY

NETWORK OF (FRUSTRATED) TOPOLOGICAL DEFECTS

EG STRING

A. Vilenkin '84
Pen-Spergel '98



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

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

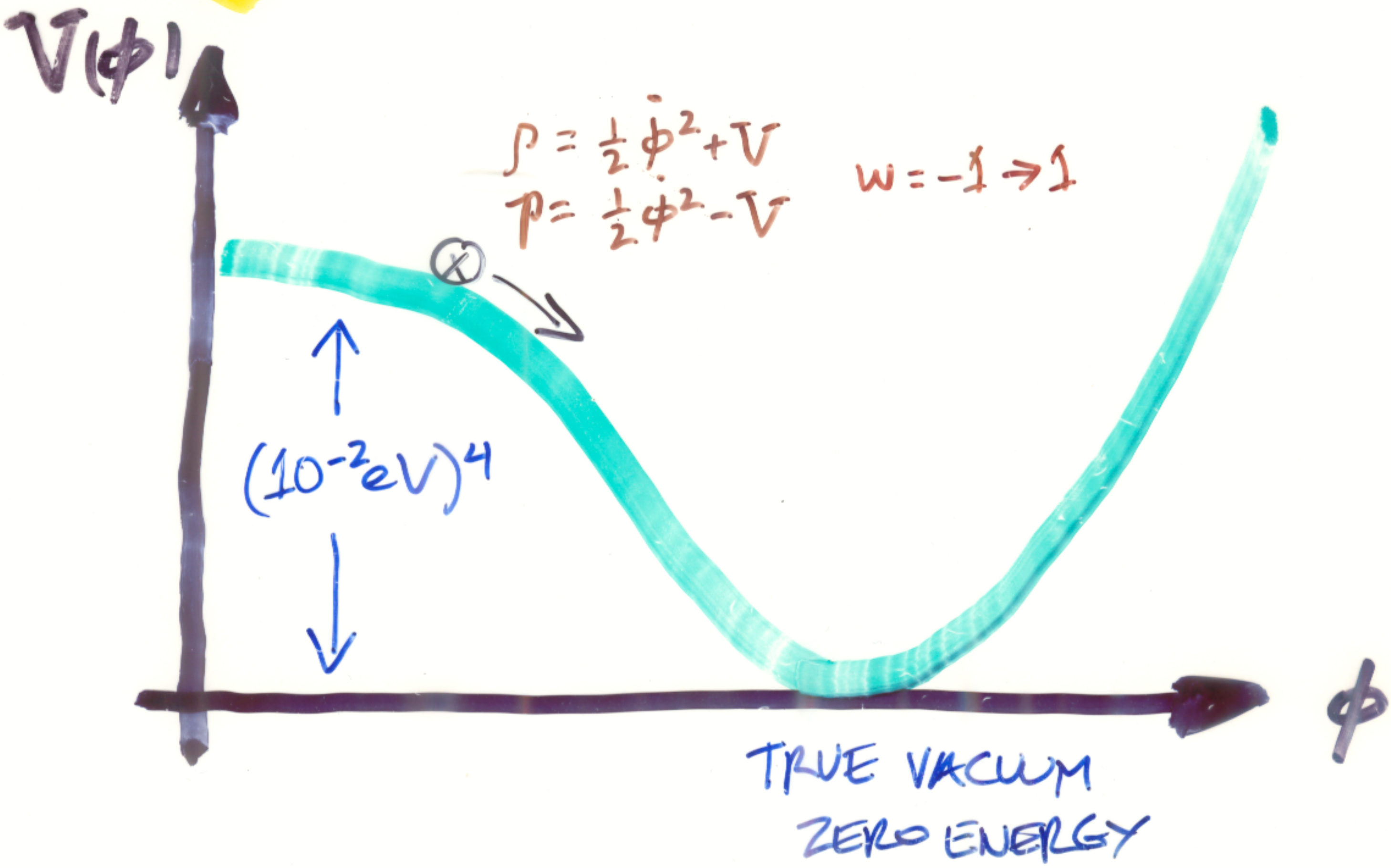
ROLLING SCALAR FIELD

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

Bronstein 1933 (executed by Stalin 1935)
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."



NO DARK ENERGY

NEW ASPECT OF GRAVITY

→ "EMPTY" UNIVERSE UNDERGOES ACCELERATED EXPANSION!

AVERAGE MATTER DENSITY TODAY $\approx 10^{-29}$ g/cm³

$\approx 10^{-100}$ × DENSITY AFTER INFLATION

NEW GRAVITATIONAL PHYSICS

BECAUSE GR DOES NOT MARRY QM & GRAVITY EXPECT A THEORY BEYOND EINSTEIN'S

BUT ... ALSO EXPECT NEW GRAV PHYSICS TO APPEAR AT SHORT DISTANCES

SURPRISE?

INFLUENCE OF EXTRA DIMENSIONS

DEFFAYET, DVALI & GABADADZE

$$H^2 = \frac{8\pi G \rho_M}{3} + H/r_c$$

$r_c \sim H_0^{-1} \sim 10^{28}\,\mathrm{cm}$

SMALL CORRECTION TO GR

DUVVURI, CARROLL, TRODDEN, MST

$$S = \frac{1}{16\pi G}\int d^4x \sqrt{-g}\left(R - \mu^4/R\right)$$

$\mu \sim H_0$

STAR TREK -- WARP CORRECTIONS

Cardassian Model K. FREESE et al

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

LEARNING ABOUT DARK ENERGY

CAN BE DESCRIBED BY

$w \equiv p_x / \rho_x$

Pronounced "Dubya"

NB: w may vary with time

current data: $w = -1 \pm 0.2$

CANDIDATE	w	$\dot{w}$
VACUUM ENERGY	-1	0
TANGLED DEFECT	$-1/3$	0
ROLLING FIELD	$-1 \Rightarrow 1$	$\neq 0$
GHOSTLY FIELD	<-1	$\neq 0$
NEW GRAV PHYSICS	<0, IMAG	$\neq 0$, 0

COSMIC EFFECTS

$$H(z)^2 = \Omega_M (1+z)^3 + \Omega_X (1+z)^{3(1+w)}$$

DISTANCES

$$r(z) = \int_0^z dz / H(z)$$

GROWTH OF STRUCTURE

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

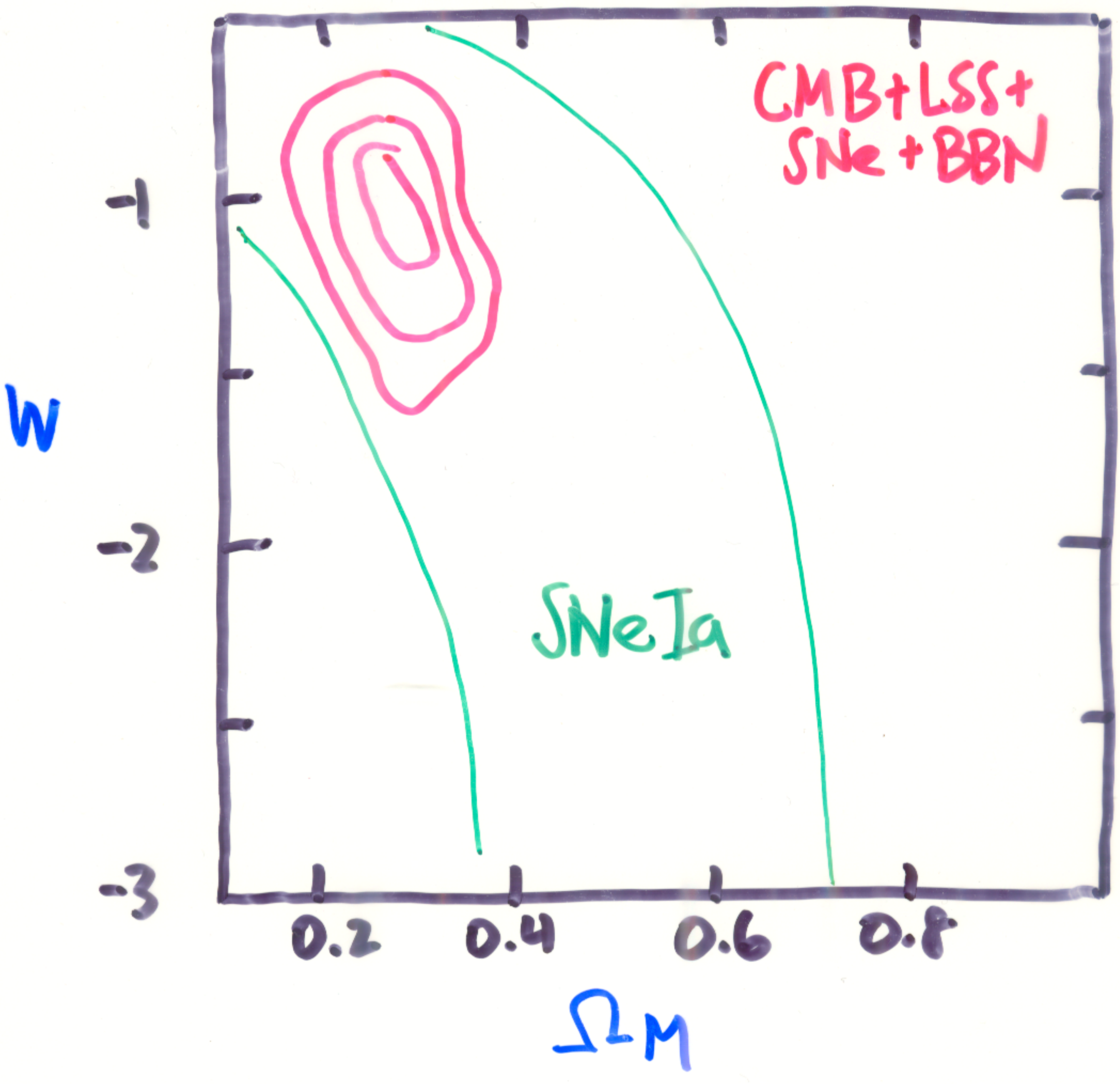
HEAVENLY MEASUREMENTS

$\sigma_w \sim 0.05$ $\quad\quad$ $\sigma_{w'} \sim 0.1$

... AND DON'T FORGET ACCELERATORS

CURRENT CONSTRAINTS

$-1.4 < w < -0.8$ (95% cl)



...very limited knowledge
no redundancy

COSMIC PROBES OF DARK ENERGY

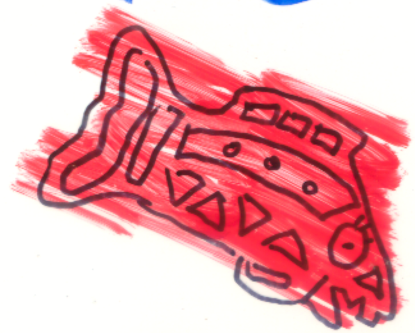
METHOD	ASSUMPTIONS	MEASURES	SYSTEMATICS	ESTIMATED POTENTIAL
SUPERNOVAE r(z) vs z	SN Ia = "STD CANDLE"	$r(z)$	EVOLUTION SN DIVERSITY DUST	$\sigma_w = 0.05$ $\sigma_{w'} = 0.15$
WEAK-LENSING "SHEAR" EVOL. OF STRUCTURE	NON-LINEAR CDM POWER SPECTRUM $= f(\Omega_i, n, \sigma_8, \ldots)$	$\delta(z)$ $r(z), H(z)$	ANISOTROPY OF P.S.F. DUE TO SKY + OPTICS	$\sigma_w = 0.03$ $\sigma_{w'} = 0.1$
S-Z, X-RAY, W-L COUNT CLUSTERS	CDM POWERSPECTRUM GAUSSIANITY	$r(z)^2/H(z)$ $\delta(z)$	SEE ABOVE M vs. T	$\sigma_w = 0.05\text{-}0.10$ $\sigma_{w'} = 0.2$
DEEP RED SHIFT SURVEYS COUNT GALS, CLUSTERS	CDM PARADIGM	$r(z)^2/H(z)$ $\delta(z)$	GALAXY MASSES EVOLUTION	$\sigma_w = 0.1$
CMB FIRST PEAK	CDM PARADIGM	$r(z=1100)$ NB: Best "Ω_m prior"	$\Omega_M - w$ DEGENERACY	$\sigma_w = 0.2$

NB: DARK ENERGY DESCRIBED BY $P/\rho \equiv w(z) = w + w' \frac{dw}{dz}$

COSMIC ACCELERATION

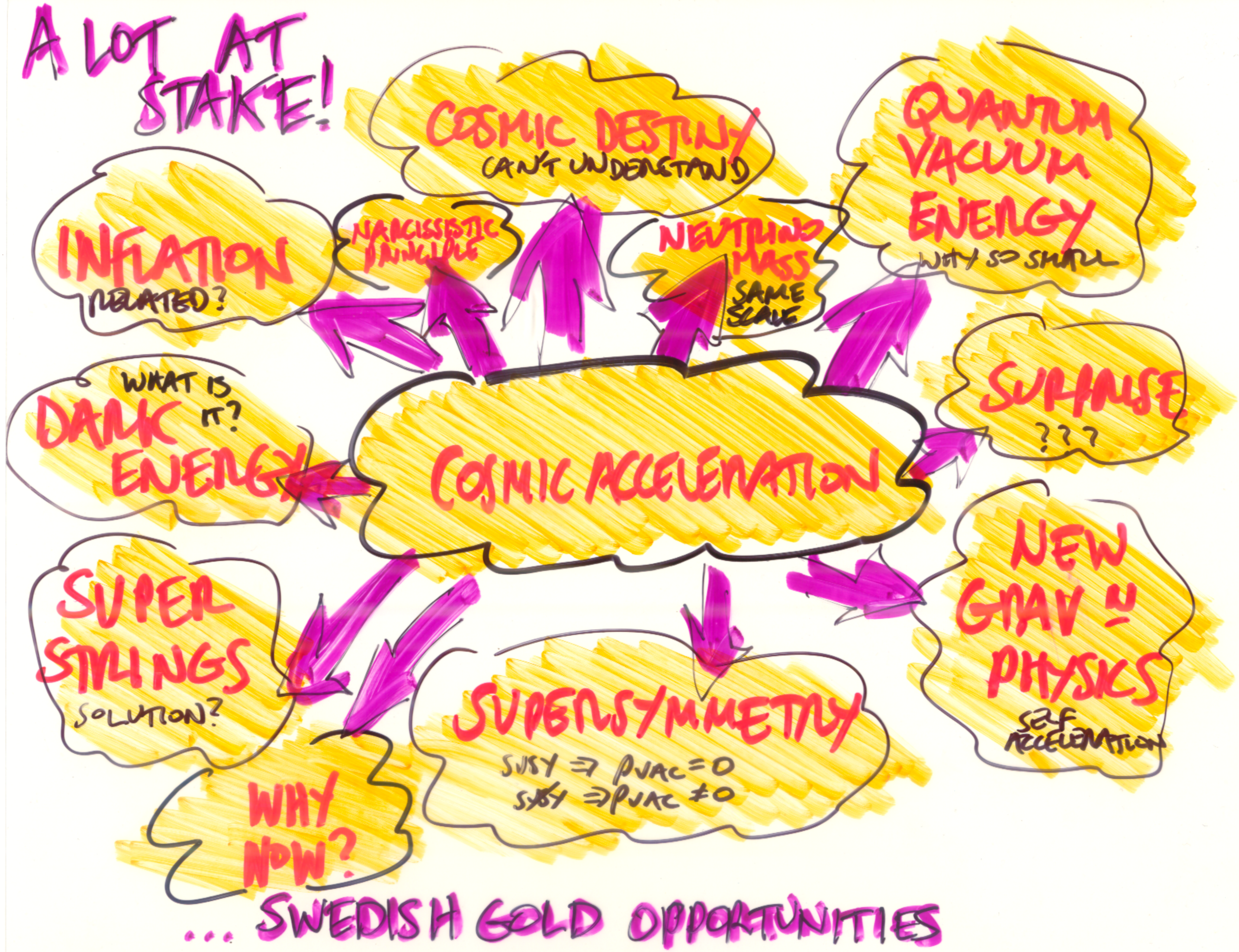
MOST PROFOUND MYSTERY

IN ALL OF SCIENCE TODAY



DARK ENERGY or

NEW GRAVITATIONAL PHYSICS


A LOT AT STAKE!
COSMIC DESTINY
(CAN'T UNDERSTAND)
QUANTUM VACUUM ENERGY
WHY SO SMALL
INFLATION
RELATED?
NARCISSISTIC PRINCIPLE
NEUTRINO MASS
SAME SCALE
DARK ENERGY
WHAT IS IT?
SURPRISE
???
COSMIC ACCELERATION
NEW GRAV'N PHYSICS
SELF ACCELERATION
SUPER STRINGS
SOLUTION?
SUPERSYMMETRY
SUSY $\Rightarrow \rho_{vac} = 0$
SUSY $\Rightarrow \rho_{vac} \neq 0$
WHY NOW?
... SWEDISH GOLD OPPORTUNITIES