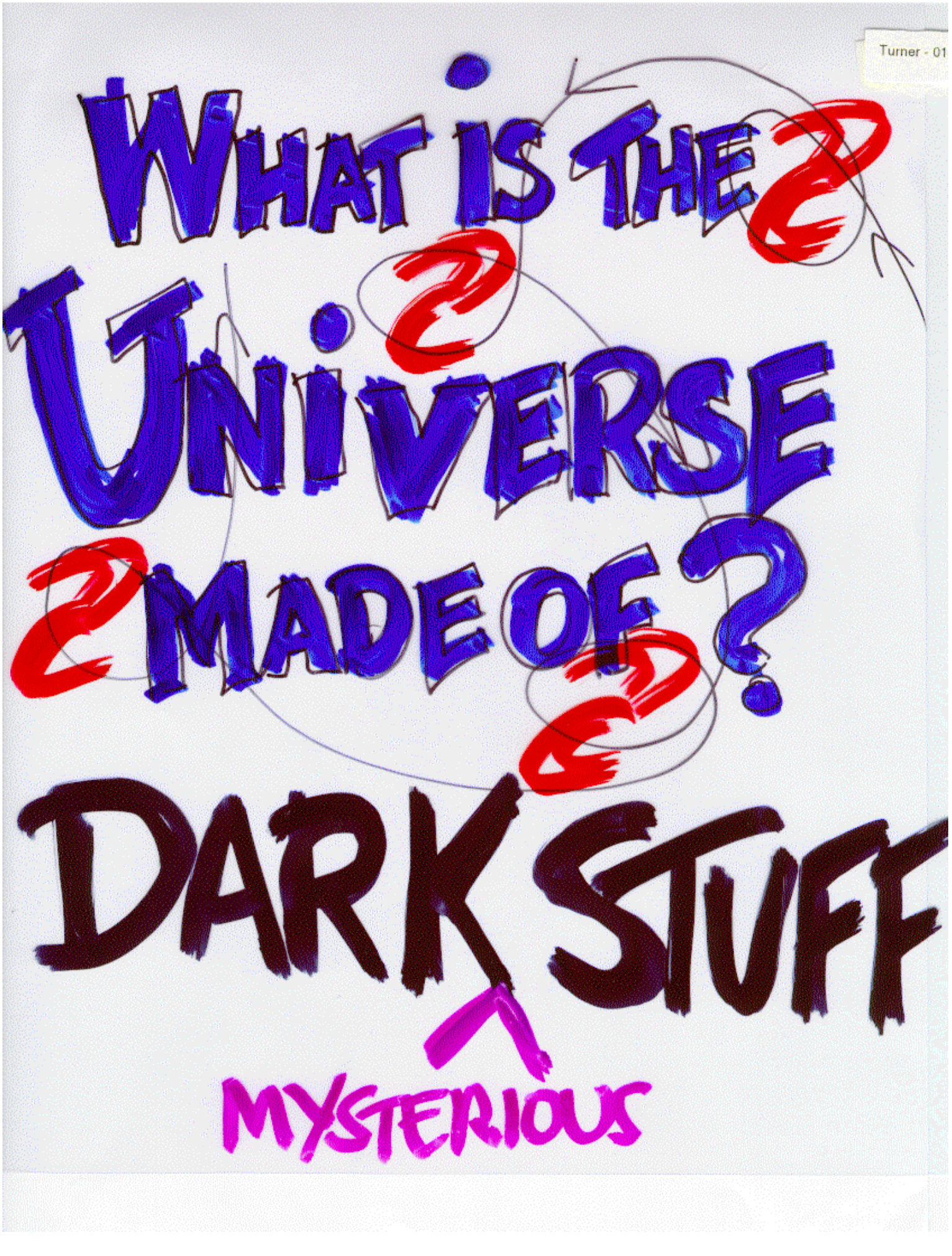

WHAT IS THE UNIVERSE MADE OF?
DARK STUFF
MYSTERIOUS

DARK SIDE of the UNIVERSE

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

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

COSMIC RECIPE

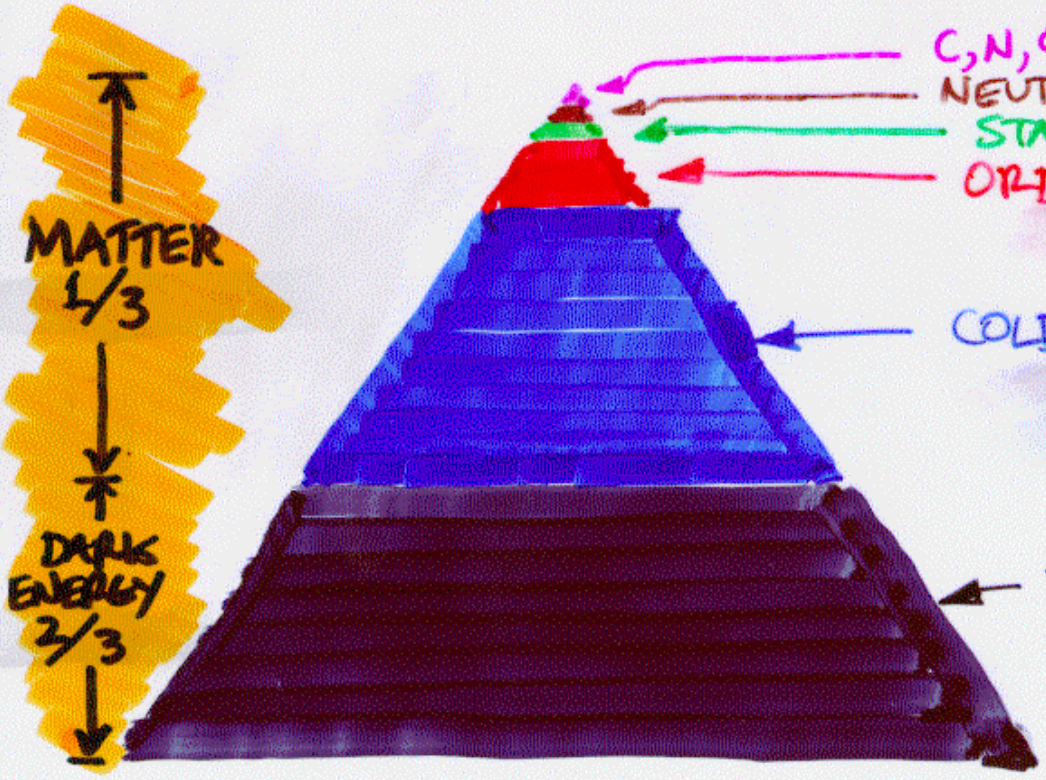
Turner - 03

FLAT UNIVERSE

AVERAGE DENSITY

= CRITICAL DENSITY ±6%

= ⅓ DARK MATTER + ⅔ DARK ENERGY



"COSMIC FOOD CHAIN"

DARK ENERGY in the Universe

AS INTERESTING & MYSTERIOUS AS NEUTRINOS & JUST AS FUNDAMENTAL

UNIVERSE IS ACCELERATING: TWO INDEPENDENT LINES OF EVIDENCE

ACCELERATION PARAMETER $q_0 = \frac{\Omega_0}{2} + \frac{3}{2}\sum w_i \Omega_i < 0 \Rightarrow w_x \Omega_x \lesssim -\frac{1}{3}$

$w_i \equiv p_i/\rho_i$

CAUSED BY DARK ENERGY: FUNDAMENTAL & VERY IMPORTANT BUT NOT UNDERSTOOD !!

NB: DARK MATTER $w \equiv p/\rho \approx 0$ (Nonrelativistic, clumpy)
DARK ENERGY $w_x \equiv p_x/\rho_x \lesssim -1/2$ (Relativistic, pushy)

COSMOLOGY OFFERS KEY TO UNDERSTANDING NATURE OF DARK ENERGY

ESPECIALLY SNeIa
also galaxies + clusters

EVIDENCE FOR DARK ENERGY

DEFN: SMOOTH ENERGY COMPONENT WITH $p \lesssim -\rho/2$

"DIRECT" SNe Ia

$$q_0 \equiv \frac{-(\ddot{R}/R)_0}{H_0^2} = \frac{1}{2}\sum_i (1+w_i)\Omega_i \qquad w_i \equiv p_i/\rho_i$$

$$= \frac{\Omega_0}{2} + \frac{3}{2} w_x \Omega_x$$

SNe Ia $\Rightarrow$ $q_0 < 0$ $\Rightarrow$ $w_x \Omega_x < -\frac{1}{3}$

"INDIRECT"

$\approx 1 \pm 0.1$ $\approx 0.35 \pm 0.1$

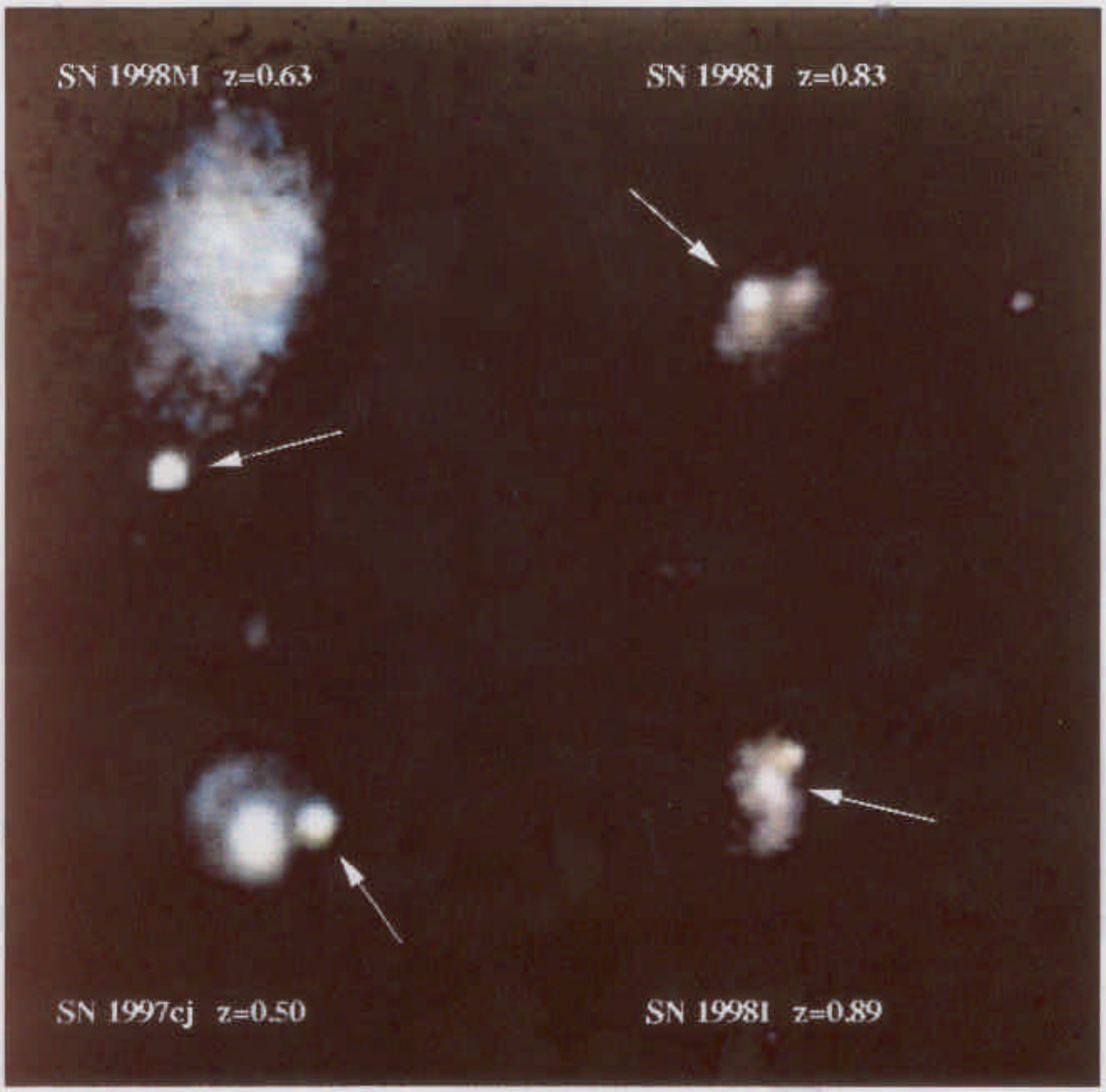
$\Omega_0 > \Omega_m$ + structure formation

CMB, clusters, etc

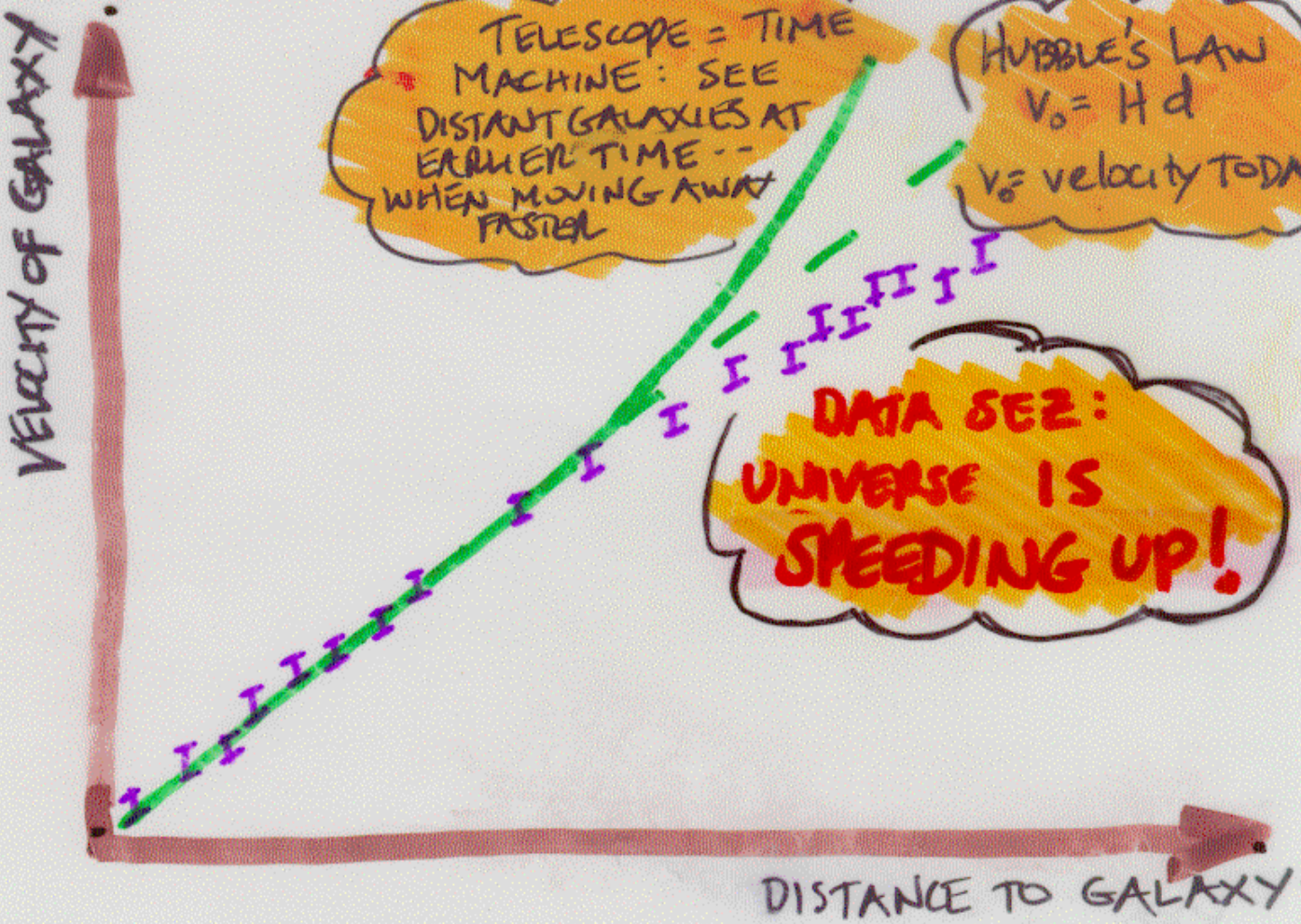
- $\Omega_x \approx \frac{2}{3}$
- MUST BE SMOOTH (NOT IN Ω_m)
- MUST HAVE NEGATIVE PRESSURE (DO NOT INTERFERE W/ S.F.)

$\Omega_x \approx 0.65 \pm 0.10$ $\quad w_x \lesssim -\frac{1}{2}$

CONCORDANCE OF DIRECT & INDIRECT


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

IS THE UNIVERSE SLOWING DOWN?



UNIVERSE IS SPEEDING UP!? # WHY?

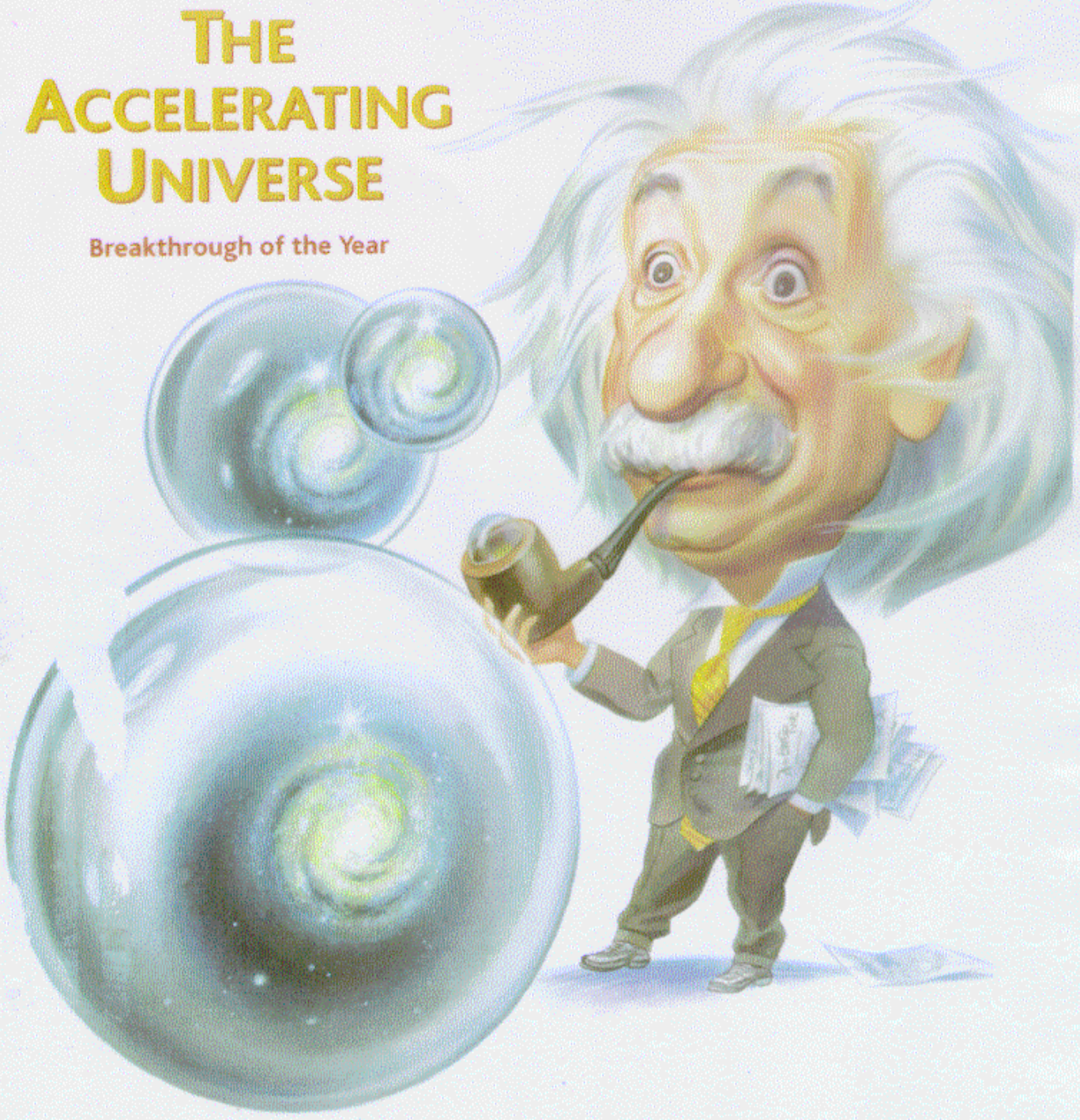
18 December 1998

Science

Vol. 282 No. 5397
Pages 2141–2336 $7

THE ACCELERATING UNIVERSE

Breakthrough of the Year



AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

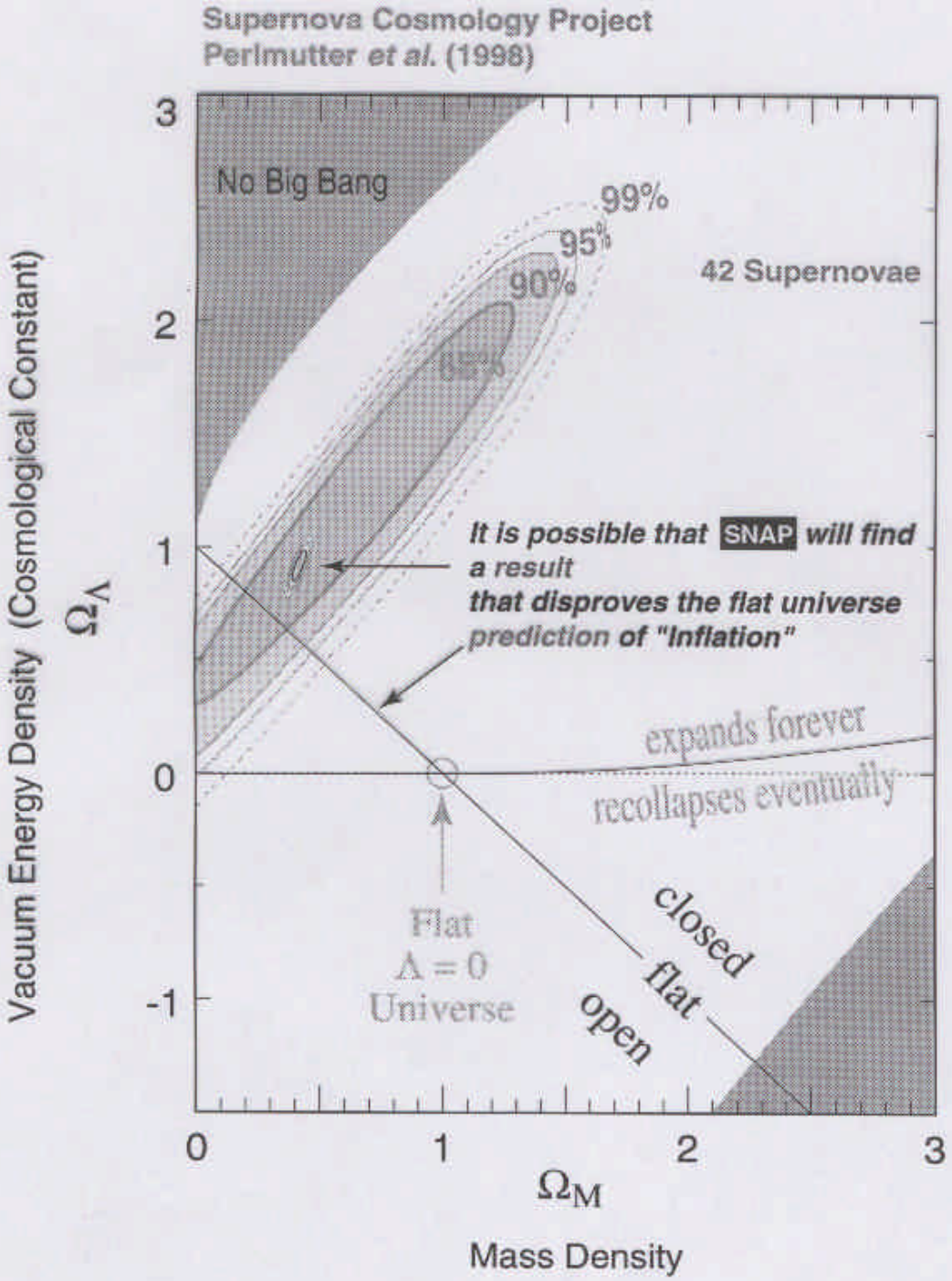
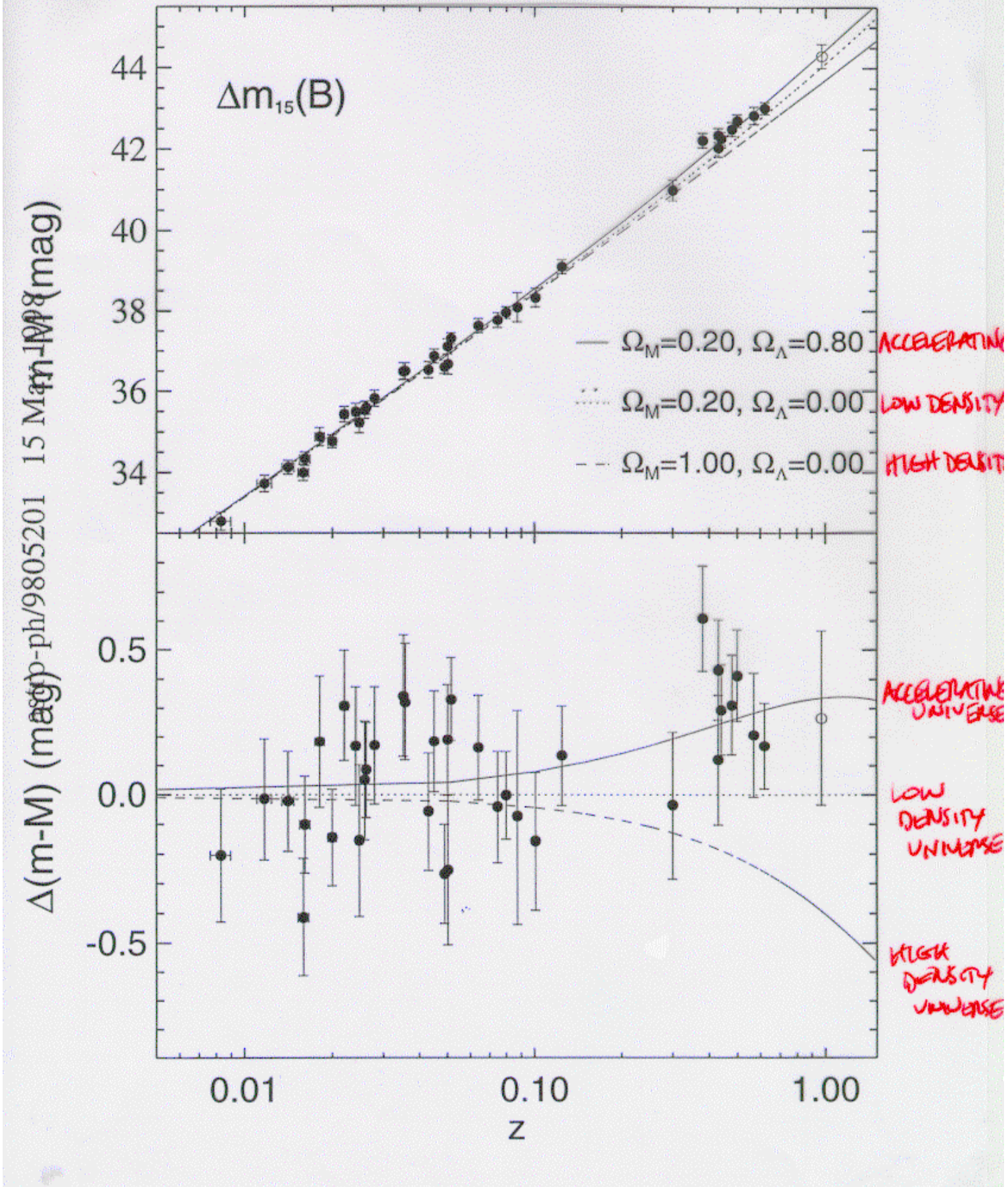


Figure 2: Constraints on Ω_M and Ω_Λ expected from the proposed experiment compared to current SN Ia constraints. This figure shows the case of a closed universe.

High Z SN Team

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



S. Perlmutter et al
Astrophys. J. 98

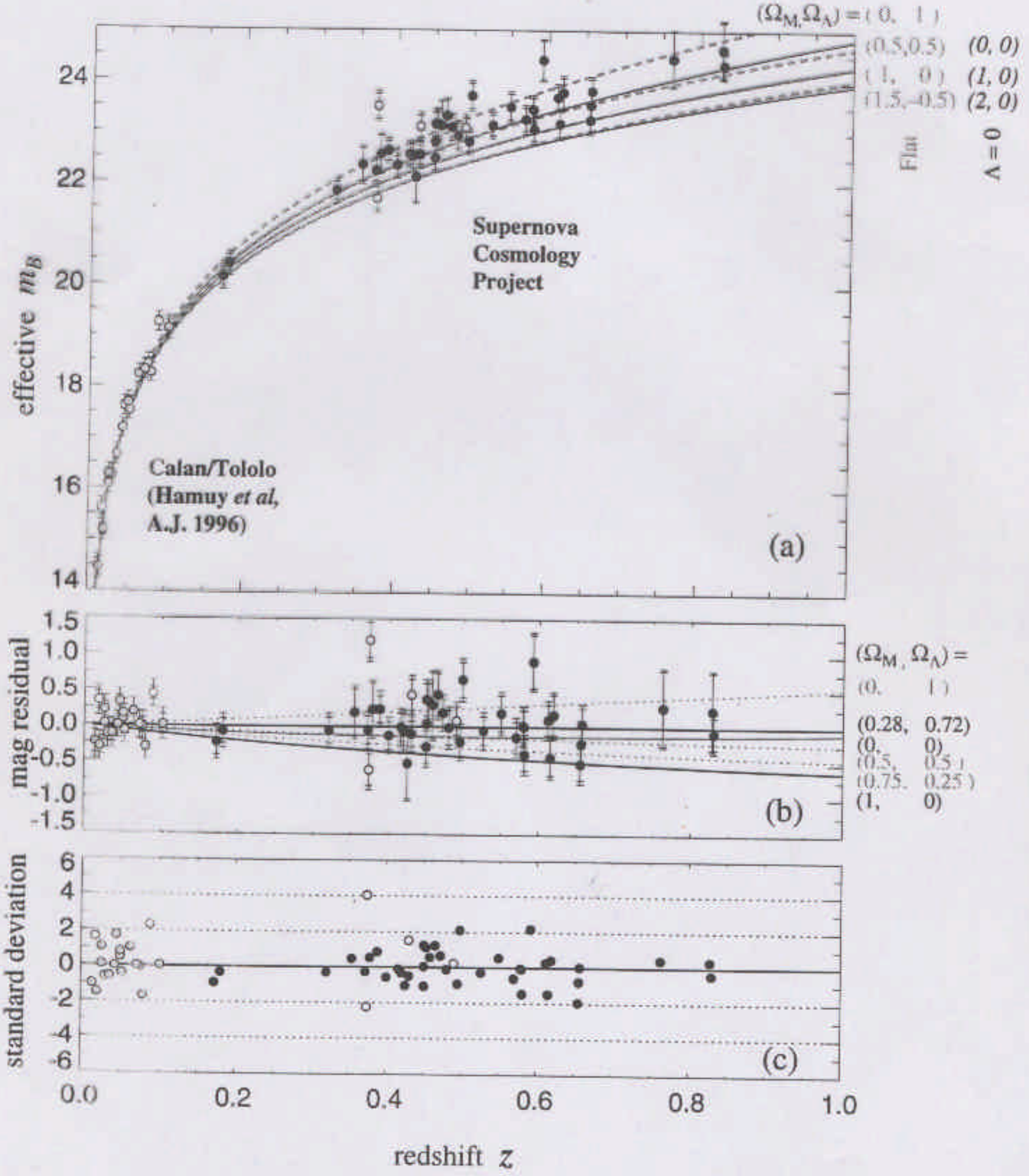


Fig. 2.

CANDIDATES/REQUIREMENTS

REL. PARTICLES

$w = 1/3$

NO

VERY LIGHT PARTICLES

$m \ll eV$

$w = 0$

NO

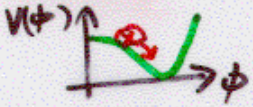
FRUSTRATED DEFECTS

E.G. strings, walls

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

SCALAR FIELD

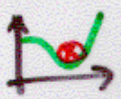
"EVOLVING Λ"



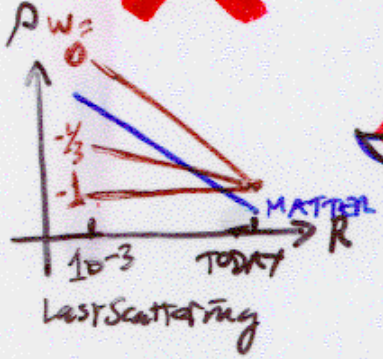
$w = -1 \Rightarrow$? evolves

Λ

VACUUM ENERGY



$w = -1$



★ **HERE TODAY, GONE YESTERDAY!**

TO AVOID INTERFERENCE WITH GROWTH OF STRUCTURE

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

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

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

EQN OF STATE: $w \equiv p/\rho$ ⇒ $w \lesssim -1/3$

★ **OR DECAY PRODUCED**

NO! BAD CBR

★ **AGE FAVORS SMALLER w**

BOTTOM LINE: $w \lesssim -1/2$

SIMPLEST EXAMPLE Λ

GOOD STARTING POINT

WORRIES:

Dust dims $z \sim 0.5$ SNeIa

- DON'T SEE REDDENING, INCREASED DISPERSION
- NEED LOTS OF "GREY" DUST (UNSEEN)

Evolution dims $z \sim 0.5$ SNeIa

- $z \sim 0.5$ & $z \sim 0.05$ SNeIa LOOK THE SAME
- BULK OF METAL PRODUCTION, STAR FORMATION @ $z > 0.5$

Don't understand SNeIa, Phillips relation

- CONSENSUS MODEL: THERMONUCLEAR DETONATION (RAPID DEFLAGRATION) OF 1.4 $M_\odot$ WD (FORMED BY ACCRETION)

IN PROGRESS

More Spectra IR turnover at $z \sim 1.5$

Increase "local sample" More Spectra

More observations More theory

& DON'T FORGET "CONFIRMING EVIDENCE" IN ENERGY MISSING

DARK ENERGY

AFFECTS EVOLUTION OF SCALE FACTOR

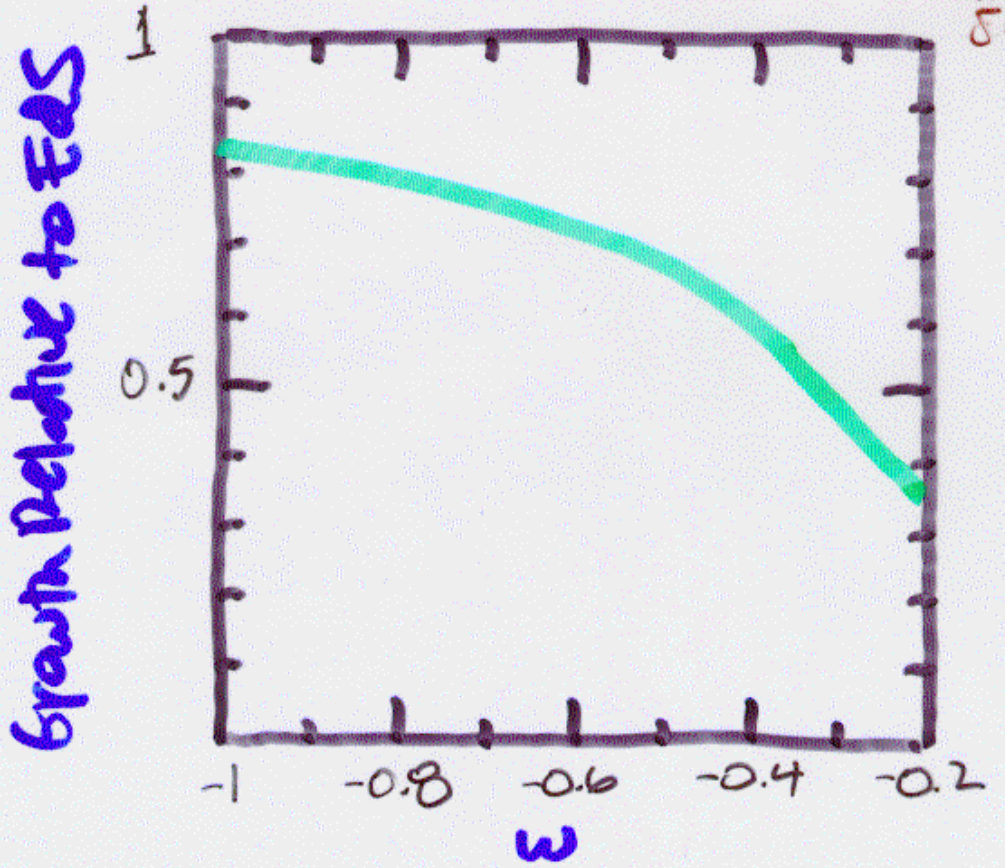
$H^2 = \frac{8\pi G}{3}(\rho_M + \rho_X)$

$\rho_X = \rho_X(\text{today})\, e^{3\int (1+w(z))\, d\ln z}$

& LITTLE ELSE SINCE IT DOES CLUMP

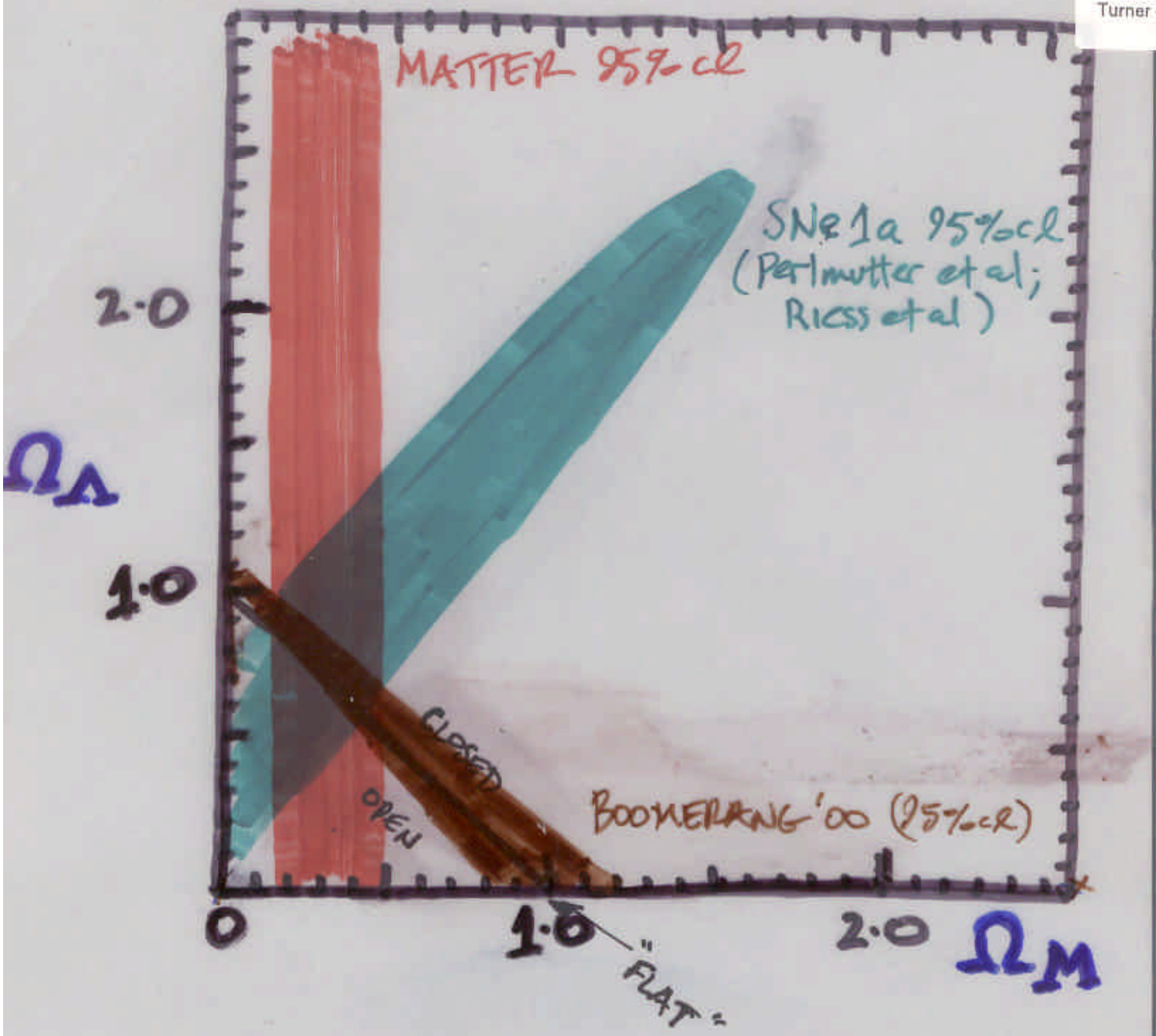
DENSITY PERTURBATIONS

$\ddot{\delta} + 2H\dot{\delta} - \frac{3}{2}H^2\Omega_M(z)\delta = 0$



σ_8 normalization $\Rightarrow$ $w \lesssim -1/3$

"THE BIG PICTURE"



ACCELERATING UNIVERSE

$\rho + 3p < 0$

source of gravity in GR

$p_x \sim \frac{1}{3} \rho_{crit}$ $p_x < -\rho_x/3$

POSSIBILITIES:

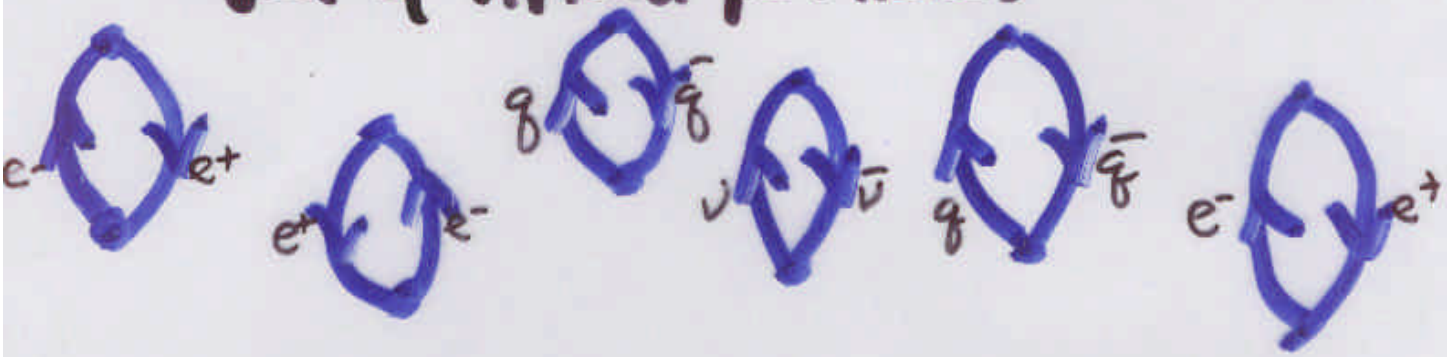
Einstein's COSMOLOGICAL CONST'T (VACUUM ENERGY) $p = -\rho$

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

ROLLING SCALAR FIELD AKA "QUINTESSENCE" $p = -\rho/3 \Rightarrow -\rho$

QUANTUM VACUUM IS NOT EMPTY!

sea of virtual particles



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

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

theoretical estimates

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

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

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

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

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

Comments About Dark Energy

Science Times, 30 November 1999 (J. Glanz)

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

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

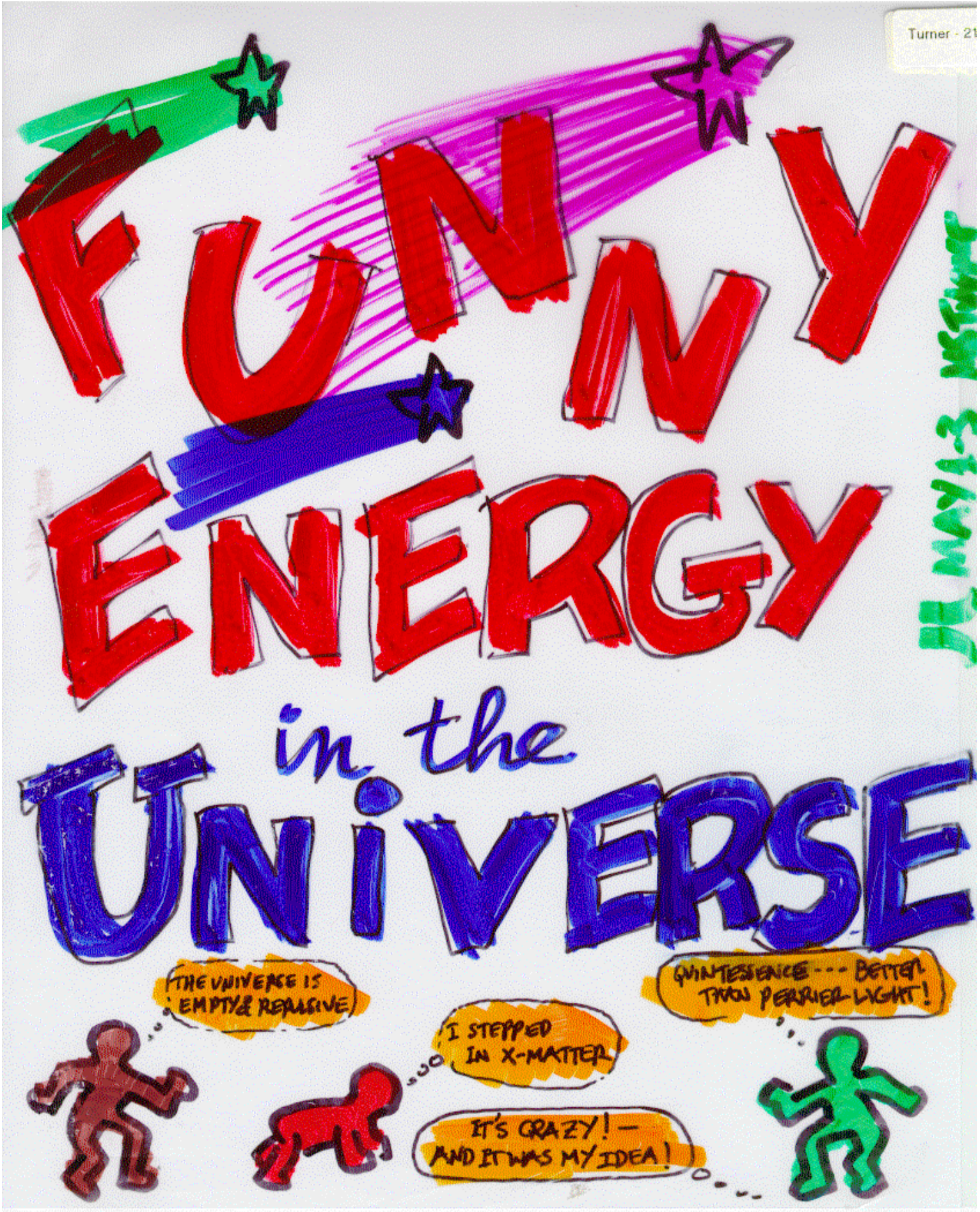
F. Wilczek: ...maybe the most fundamentally mysterious thing in all of basic science.

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

WHAT IF

$\Lambda = 0$?

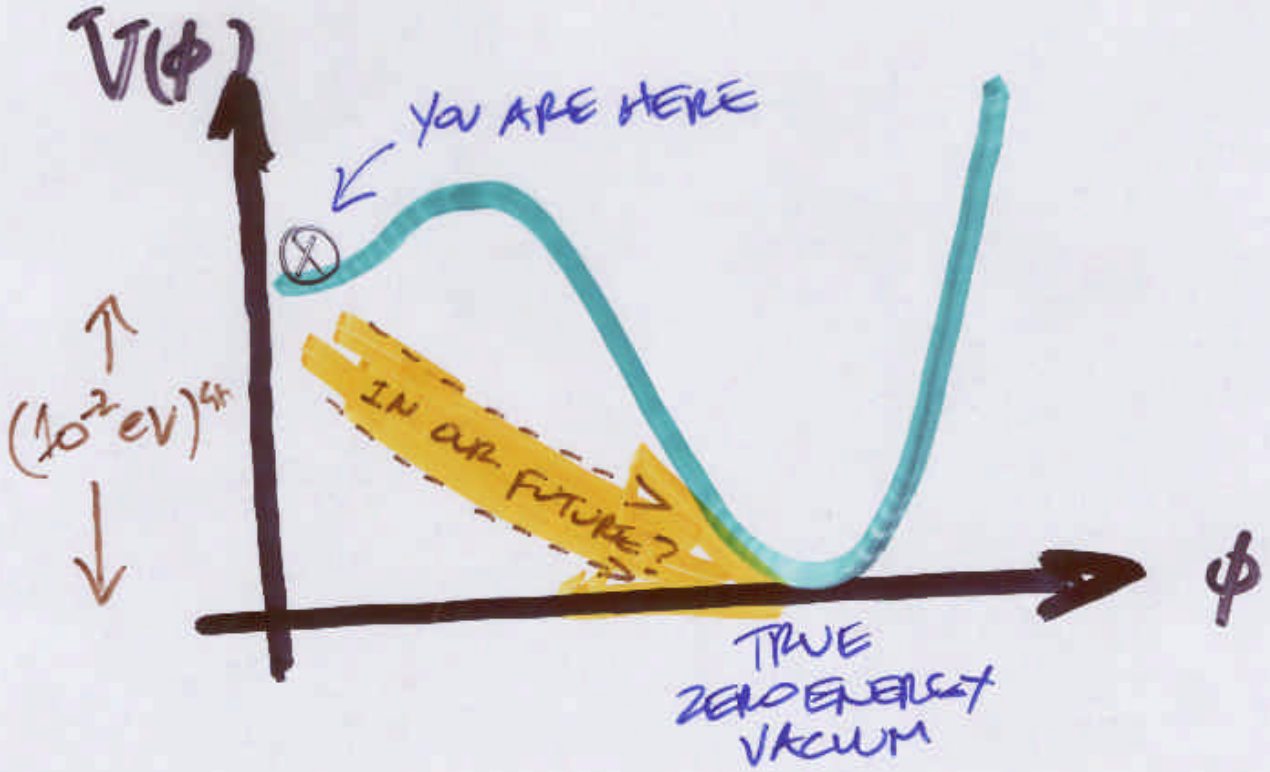
BE CAREFUL WHAT YOU WISH FOR !!


FUNNY
ENERGY
in the
UNIVERSE
THE UNIVERSE IS EMPTY & REPULSIVE!
I STEPPED IN X-MATTER!
IT'S CRAZY! — AND IT WAS MY IDEA!
QUINTESSENCE --- BETTER THAN PERRIER-LIGHT!

YOUTHFUL INDISCRETION

MST-WILCZEK '82
Nature 298, 633

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

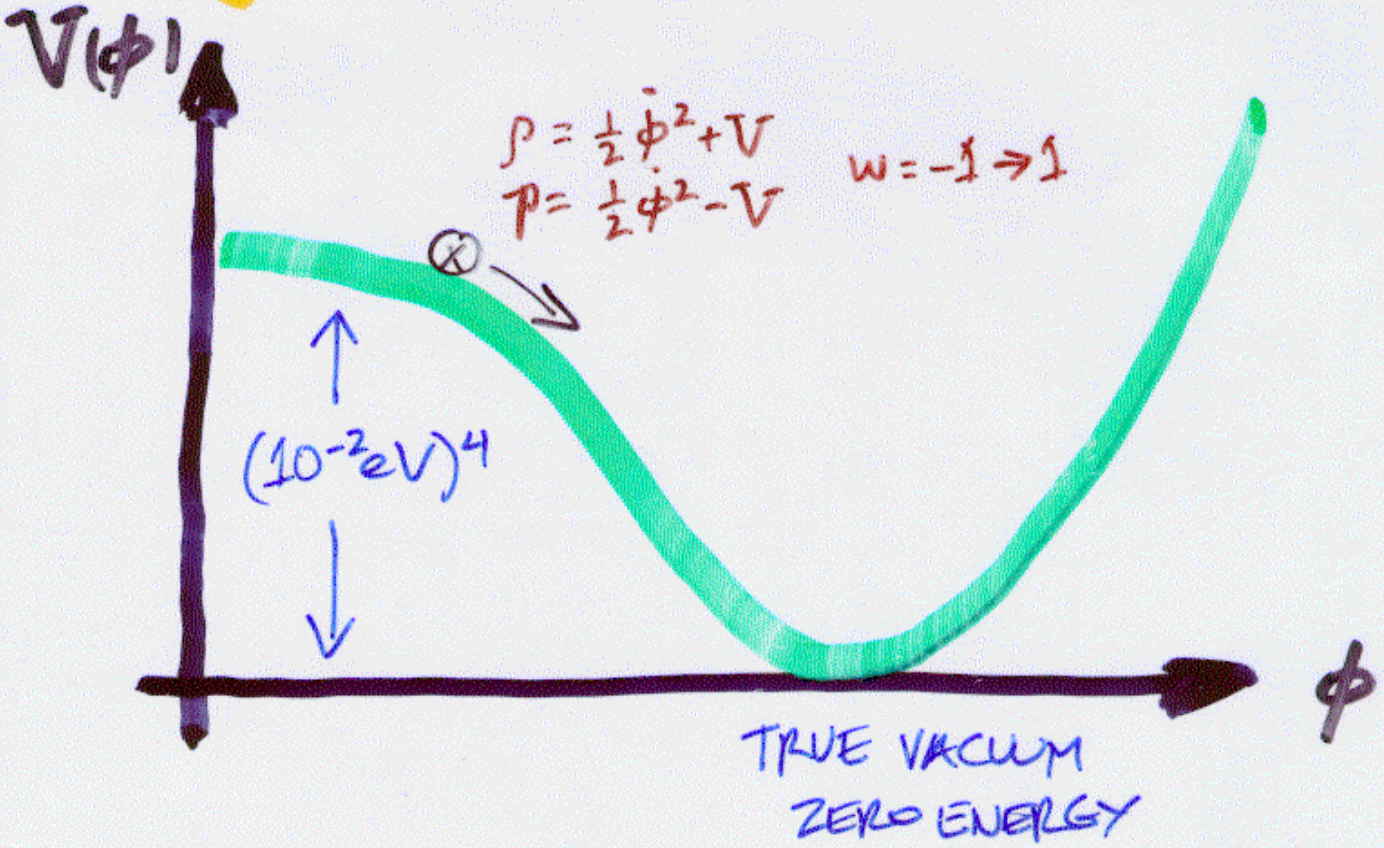


ROLLING SCALAR FIELD

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

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

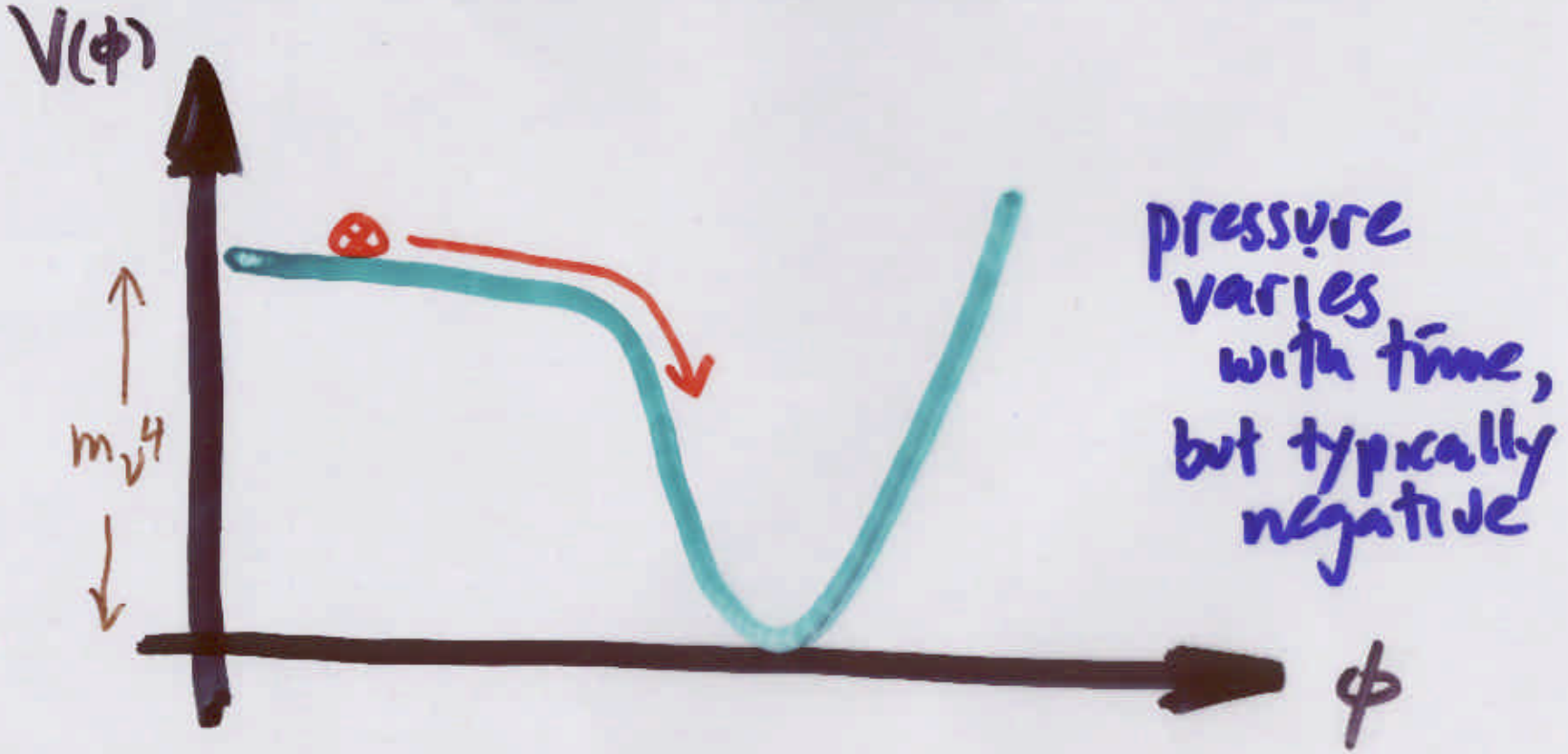
A. GREENSPAN 1998: "... Brief Episodes of Inflation Are Unavoidable."



A BRIEF EPISODE OF INFLATION

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

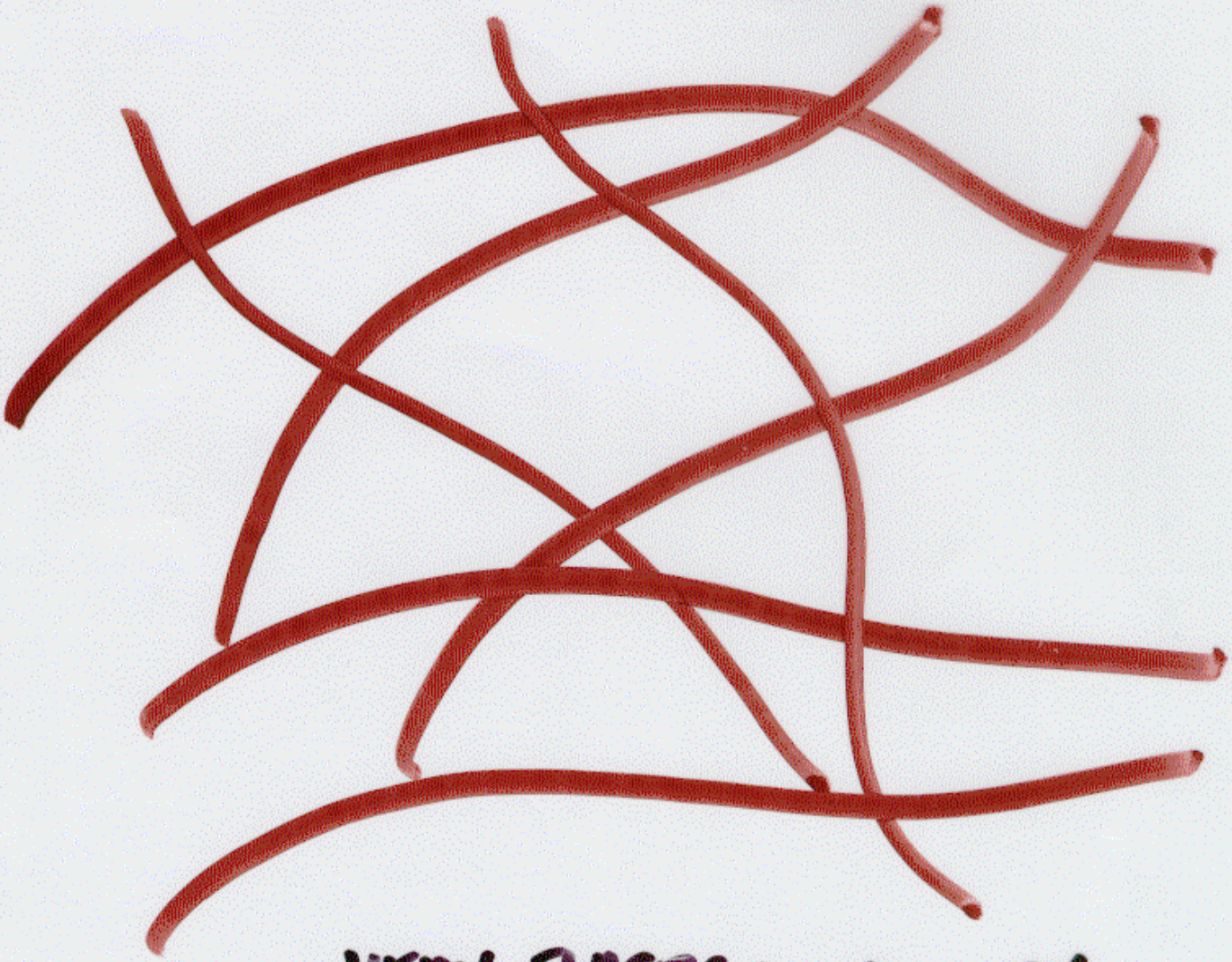
"...mild episodes of inflation are unavoidable" A. GREENSPAN



NETWORK OF (FLUSTRATED) TOPOLOGICAL DEFECTS

EG STRING

A. Vilenkin '84
Pen-Spergel '98



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

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

$T_{\mu\nu} =$ (LARGE NEGATIVE PRESSURE + ANISOTROPIC STRESS)

"SOLID DARK MATTER" Bucher & Spergel PRD60, 043505 (99)

"GENERALIZED DARK MATTER" Hu Astrophys. J. 506, 485 (98)

Joe's Model for Dark Energy

NANCY KERRIGAN PROBLEM

WHY ME?

WHY NOW?

MYSTERIOUS, BUT CRUCIAL

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, & UNDERMINES FUND PHYSICS

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

TURNER-WHITE PRD 56, 4439 (97)

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

PROBING THE Mysterious DARK ENERGY

Perlmutter-White-MST
astro-ph/9904152

$w_{eff} = \langle P_x/\rho_x \rangle$ Λ: -1
STRINGS: $-1/3$

COMPLEMENTARITY

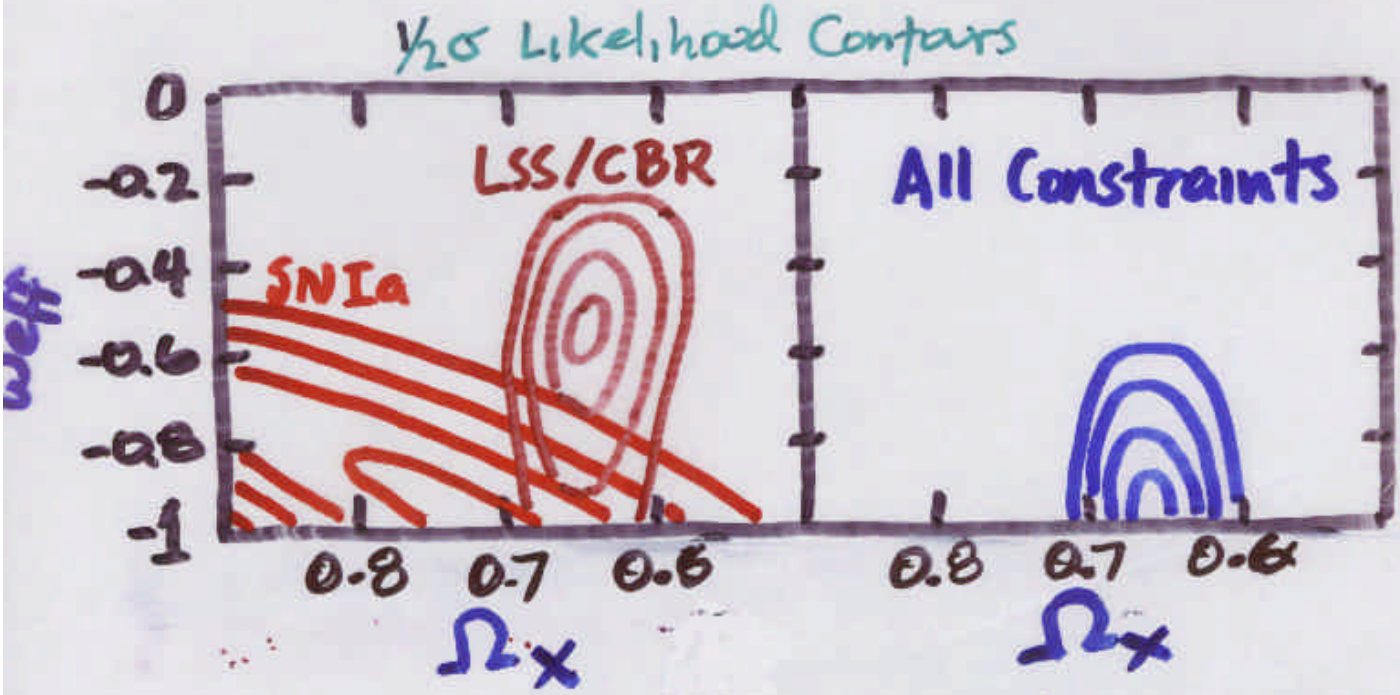
SN Ia

LSS/CBR

CONSISTENCY

AGE OF UNIVERSE
GRAV. LENSING

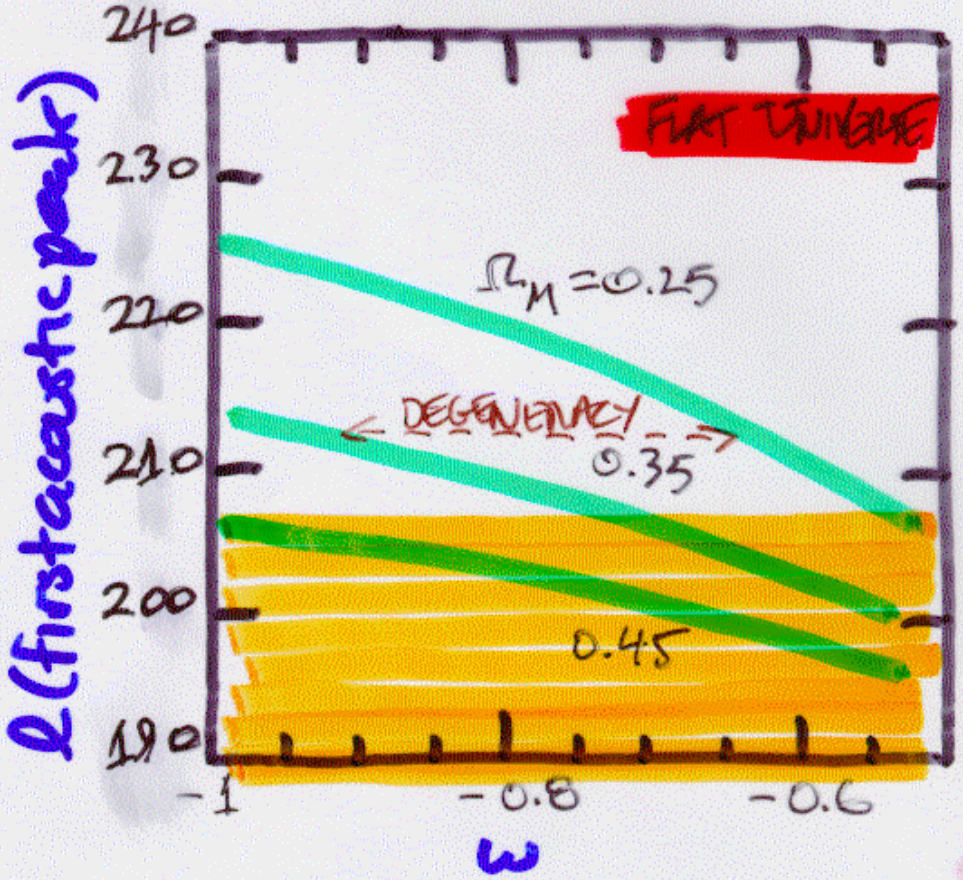
Ω_M (direct measures)



AT 95% CL: $w_{eff} < -0.6$ $0.6 < \Omega_x < 0.7$

B: Also see, L. Wang et al astro-ph/9901388 for similar & but different conclusions.

Pattern of CMB anisotropy



ANGULAR POSITION OF "FEATURES"

$\propto$ 1/distance to LSS

$\uparrow \int_0^{z=1100} \frac{dz}{H(z)} \equiv r(z=1100)$

Ω_M - w degeneracy

CMB NEEDS HELP

SNeIa CAN GET AT THE NATURE OF DARK ENERGY

SNe DETERMINE EXPANSION HISTORY THRU

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

"LUMINOSITY DISTANCE": $d_L = \left(\frac{L}{4\pi F}\right)^{1/2}$

$$r(z) = \int_0^z \frac{dx}{H(x)} \qquad H^2 = H_0^2\left[\Omega_M (1+z)^3 + \Omega_X (1+z)^{3(1+w_X)}\right]$$

($k=0$, $w=$ const)

DETERMINE FROM SNeIa DATA

$$= \frac{8\pi G}{3}(\rho_M + \rho_X) - k/R^2$$

RECONSTRUCT $w(z)$:

$$w_X(z) = -1 + \frac{1+z}{3}\,\frac{3H_0^2\Omega_M(1+z)^2 + 2\left(d^2r/dz^2 / (dr/dz)^3\right)}{H_0^2\Omega_M(1+z)^3 - 1/(dr/dz)^2}$$

($k=0$)

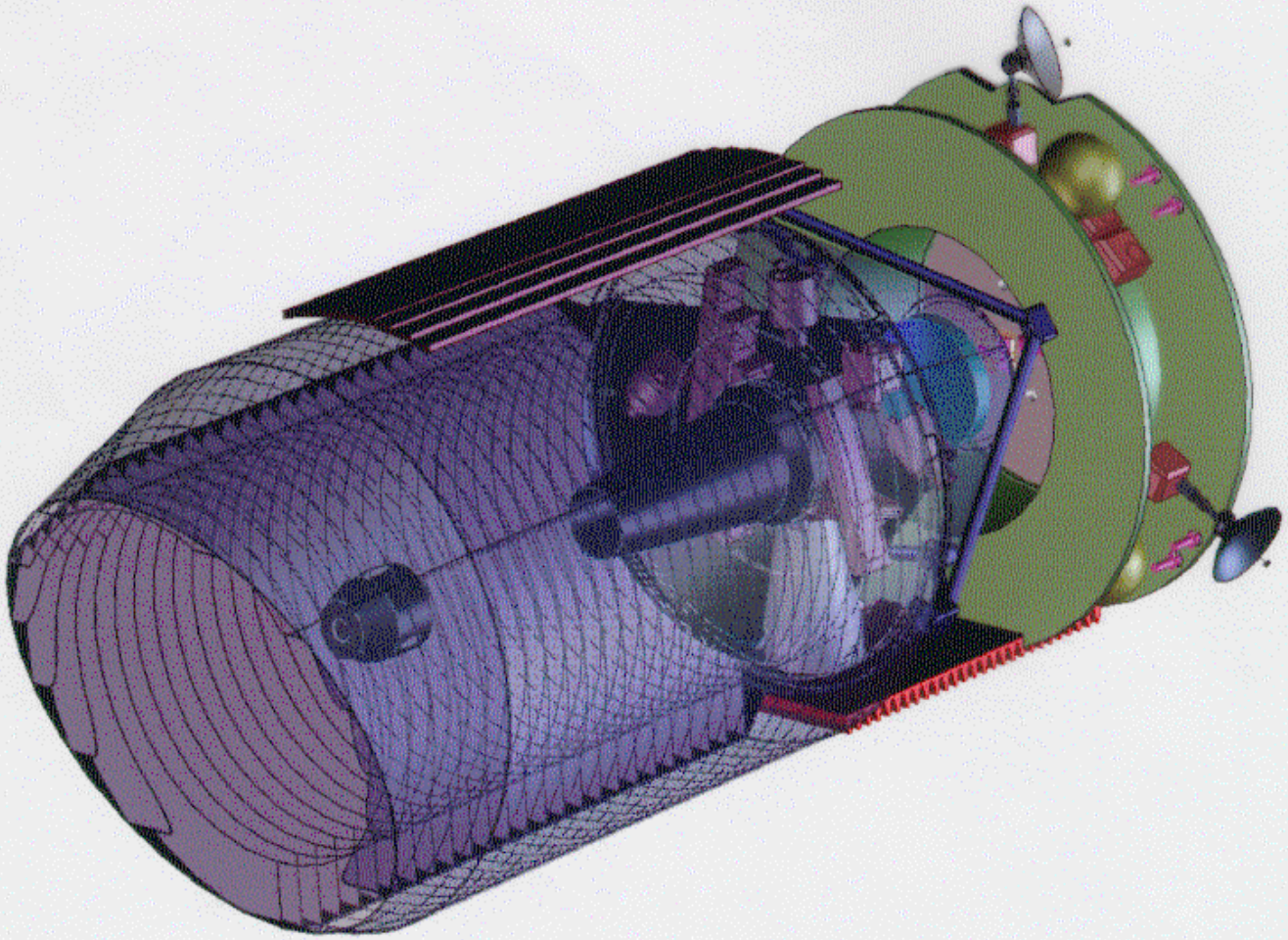
OR $V(\phi)$ FOR SCALAR FIELD MODEL:

$$V(\phi) = \frac{1}{8\pi G}\left[\frac{3}{(dr/dz)^2} + (1+z)\frac{d^2r/dz^2}{(dr/dz)^3}\right] - \frac{3\Omega_M H_0^2 (1+z)^3}{16\pi G}$$

NEED QUALITY DATA SET!

DEDICATED 2-meter SPACE TELESCOPE TO STUDY DARK ENERGY

SNAP SuperNova Acceleration Probe



~ 5000 SNeIa $z \lesssim 1.7$!

"precision sample"

Theoretical Case for

D-REX

DaRk-Energy eXplorer

Michael S. Turner
U. Chicago/Fermilab
12/1/99

- Strong Evidence for Dark Energy
  - smooth energy component with large negative pressure
- The Dark Energy Problem
  - don't have a clue to what it is, except that it involves fund physics
- SNe Ia Are the Best Probe
  - most powerful approach to getting at ***the nature*** of the dark energy

SNAP SuperNova Acceleration Probe

satellite overview

Instruments:

- **~2 m aperture telescope**
  Can reach very distant SNe.
- **1 square degree mosaic camera, 1 billion pixels**
  Efficiently studies large numbers of SNe.
- **3-channel spectroscopy, 0.3um -- 1.7um**
  Detailed analysis of each SN.

Satellite:

Dedicated instrument.

Designed to repeatedly observe an area of sky.

Essentially no moving parts.

4-year construction cycle.
3-year operation for experiment
(lifetime open-ended).

GETTING AT THE COSMIC COMPARISONS DARK ENERGY

1) ASSUME Λ

	σ_{Ω_Λ}	σ_{Ω_M}	σ_{Ω_K}
MAP +	0.04	0.04	0.02
PLANCK +	0.02	0.03	0.005
D-REX	0.05	0.02	0.06

+ SDSS & POLARIZATION

COMPARABLE & COMPLEMENTARY

2) ASSUME CONST w_x

	σ_{w_x}	σ_{w_x}
MAP +	0.9	2
PLANCK +	0.1	0.3
D-REX	0.02	0.05

D-REX WINS BY FACTOR OF 6

3) ASSUME $w_x = w_0 + w'z$

	σ_{w_0}	$\sigma_{w'}$
D-REX	0.08	0.12

4) NON PARAMETRIC RECONSTRUCTION

≫ SEE FIGS ≪

NB: errors for D-REX scale as:
$\sigma \propto (N/2200)^{-1/2}\,\sigma_{sys}$

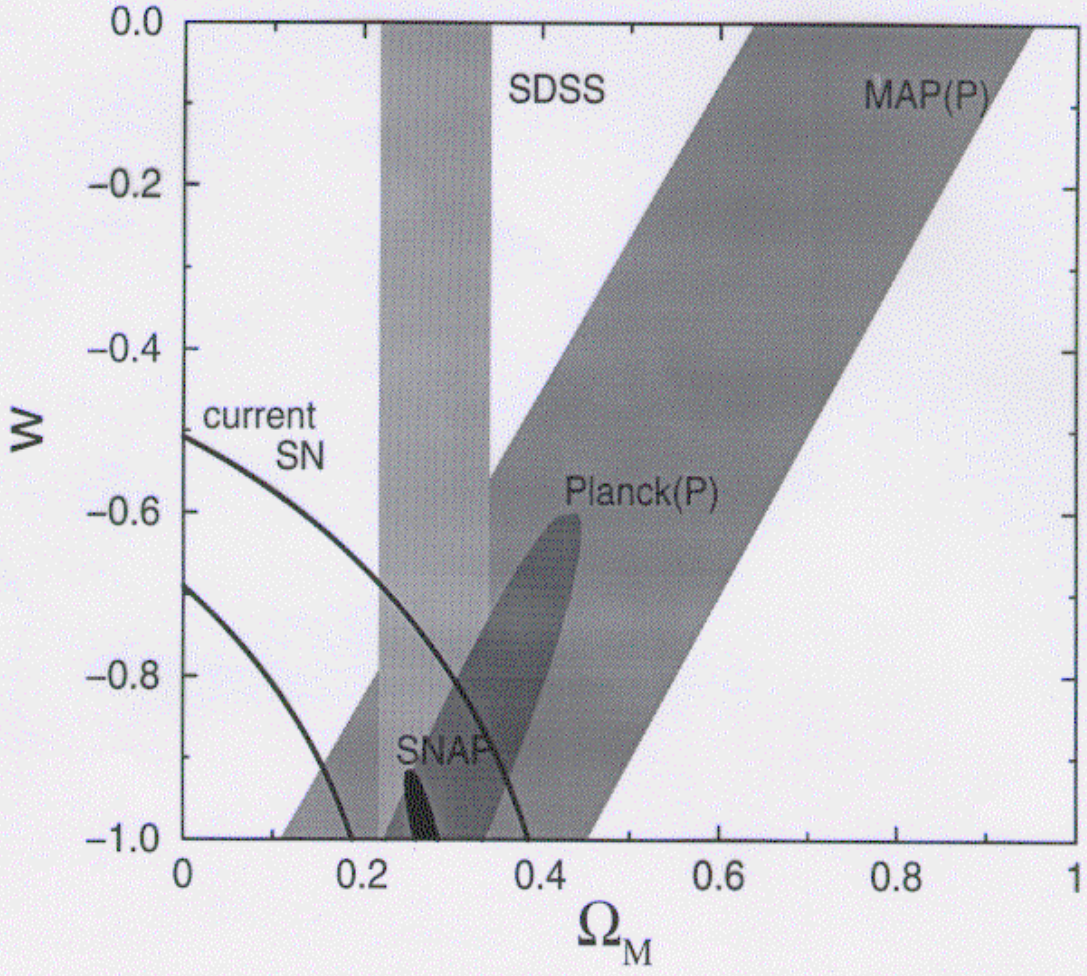
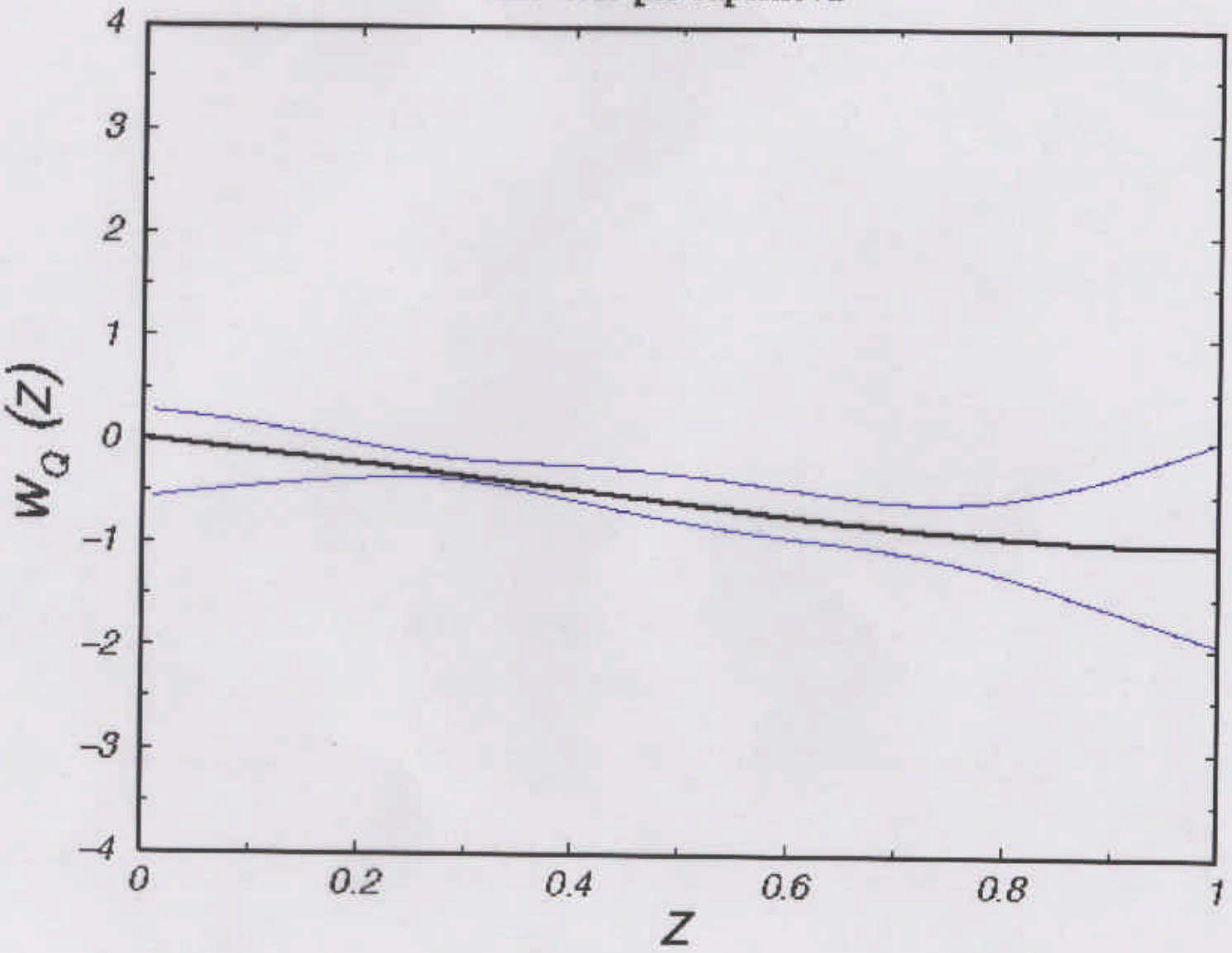


Figure 3: SNAP constraint on parameters Ω_M and w compared to those of MAP and Planck both with polarization information, and SDSS (MAP, Planck and SDSS constraints are from [?]). Also shown are the present constraints using a total of 54 SN. All constraints are 1-σ and include statistical uncertainties only. A flat universe is assumed, and fiducial values of the parameters are $\Omega_M = 1 - \Omega_{dark} = 0.28$, $w = -1$. MAP and SDSS constraint regions are obtained using a Fisher matrix analysis, while SNAP constraint is obtained using a Monte-Carlo simulation.

RECONSTRUCTING w(z) w/D-REX



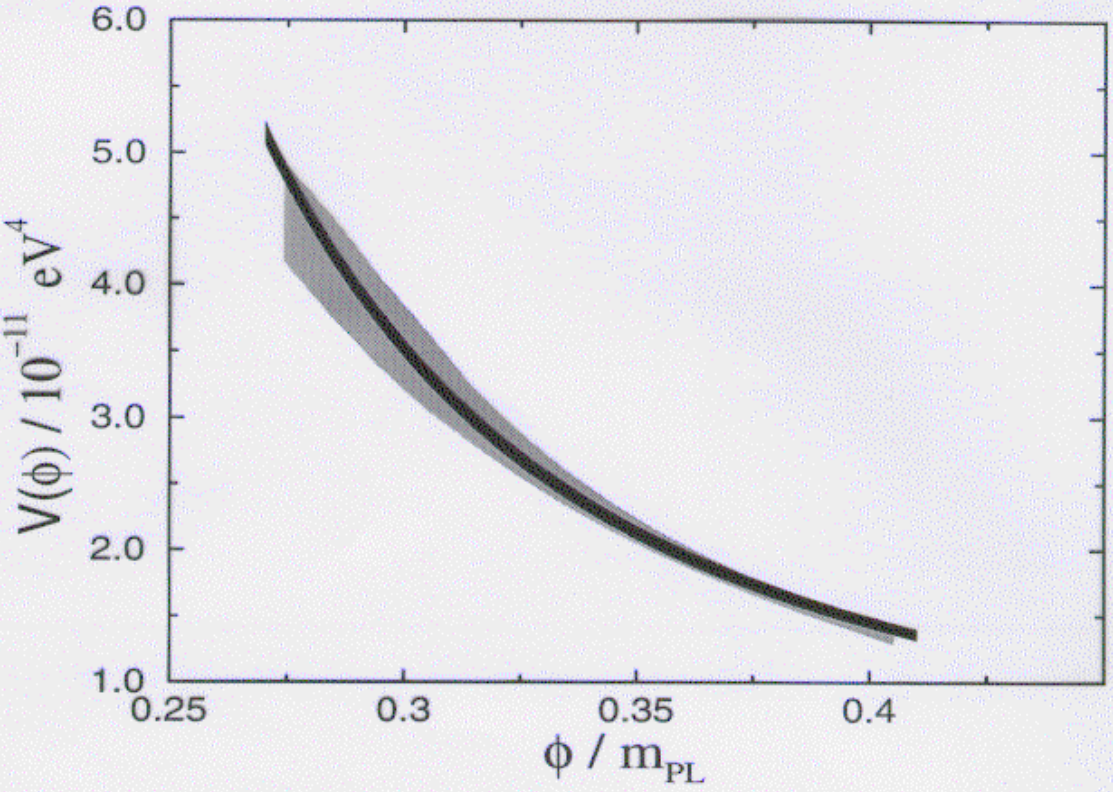
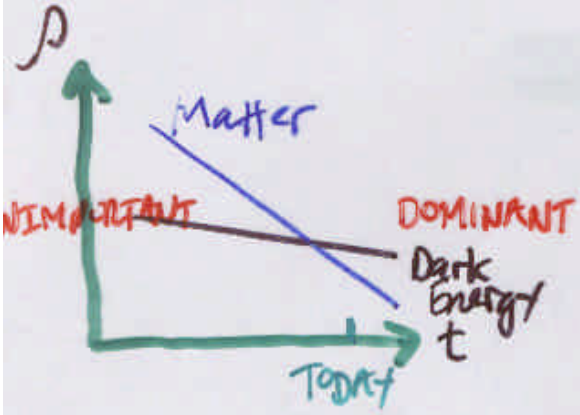


Figure 1: The 68% confidence interval for the reconstructed potential assuming SNAP's data set (shaded area) and the original potential (heavy line). The quintessence potential is $V = V_0\,[\exp(m_{PL}/\phi) - 1]$ with $V_0 = 1.3 \times 10^{-12}\ (\mathrm{eV})^4$ and $\Omega_{\mathrm{dark}} = 0.52$. The simulated distance-redshift data were fit by a three-parameter Padé approximant. Note that, for the reconstruction, no *a priori* knowledge about the potential is needed.

KEY ADVANTAGE OF SNeIa

CAN PROBE RECENT EXPANSION HISTORY WELL



$$\rho_X/\rho_M = \frac{\Omega_X}{\Omega_M}(1+z)^{3w_X}$$

$$\approx \begin{cases} \text{TODAY} & \approx 1.5 \\ z=2 & \approx 0.05 \\ z=1000 & < 3\times10^{-5} \end{cases}$$

NB: CMB EPOCH

WHEN THE DARK ENERGY IS DOMINANT

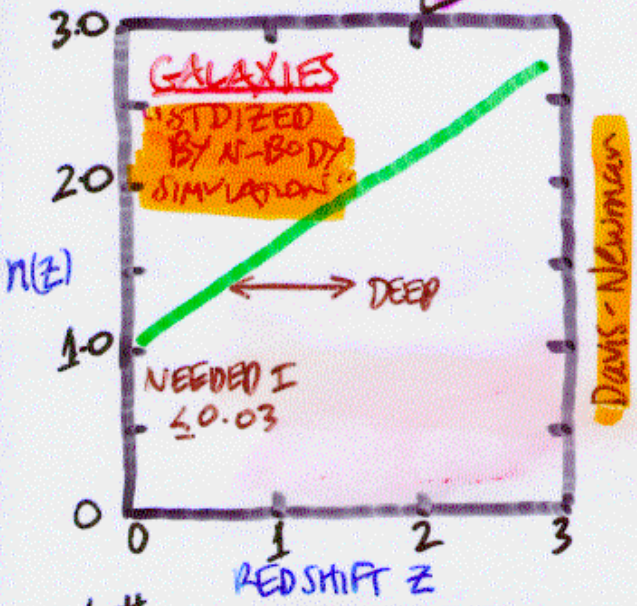
ANOTHER APPROACH: COUNTING STANDARDIZABLE OBJECTS

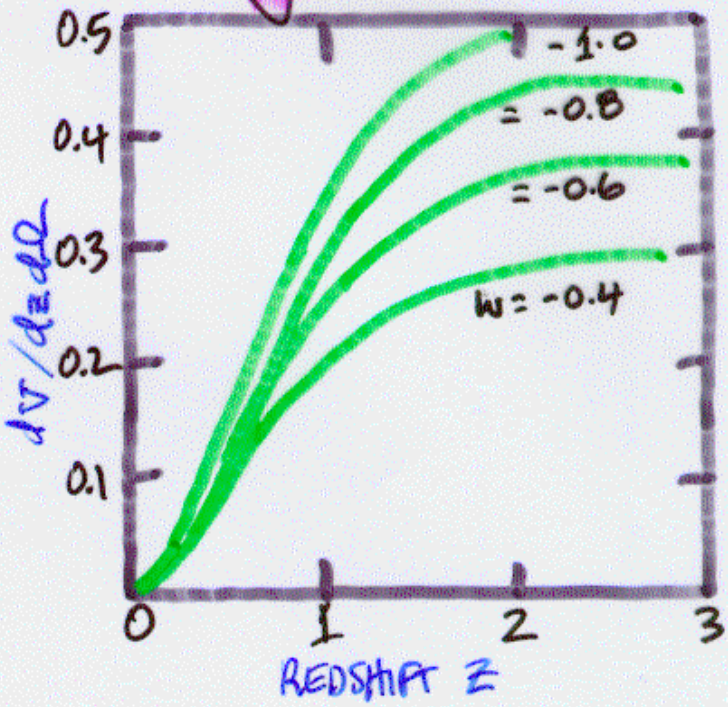
$$\frac{dN}{d\Omega\, dz} = n(z) \times \frac{dV}{d\Omega\, dz}$$

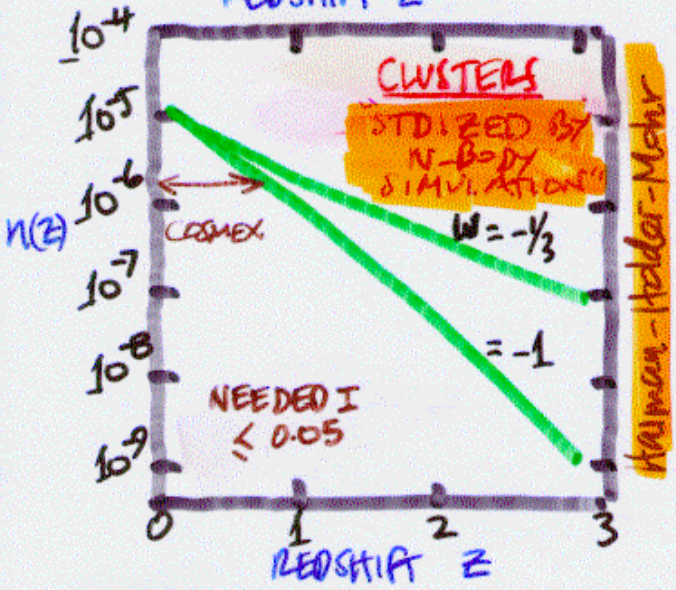
OBSERVABLE

ASTRO-PHYSICS "EVOLUTION"

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







KEY SYSTEMATIC: EVOLUTION $n(z)$

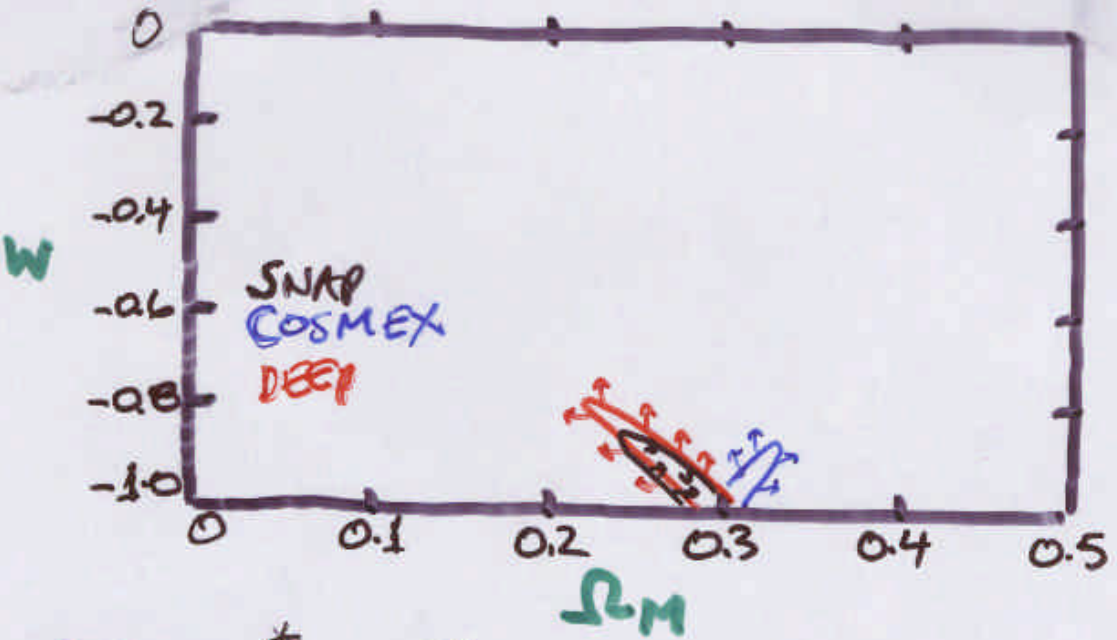
IE. STANDARDIZING THE OBJECTS

SNe1a vs. COUNTING

NB: SNe1a include systematic $\Delta m = 0.15$; clusters + galaxies do not include systematics

SNAP: 1 yr + $\Delta m = 0.15$ "upper limit"

DEEP: 10^4 Galaxies, $z = 0.7$-1.5
requires $\Delta n/n \leq 0.03$ "lower limit"



COSMEX*: 10^4 Clusters $z \to 1/2$
requires $\Delta n/n \leq 0.05$ "lower limit"

*SMEIS PROPOSAL