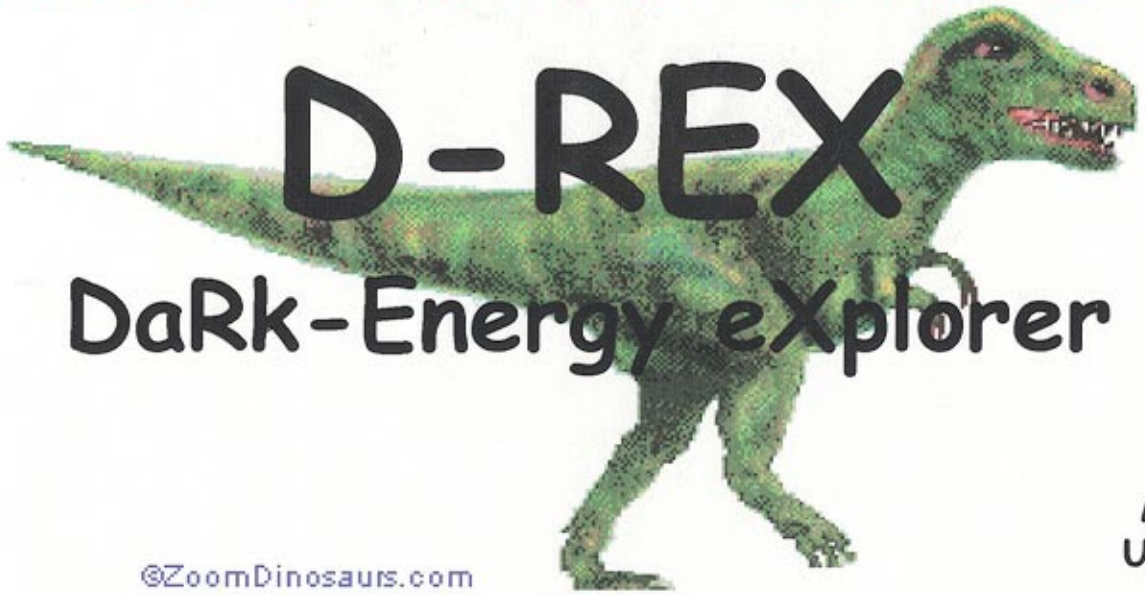
Theoretical Case for

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

EVIDENCE FOR DARK ENERGY

DEF^{N}: 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 $\Rightarrow$ $q_0 < 0$ $\Rightarrow$ $w_x \Omega_x < -1/3$

"INDIRECT"

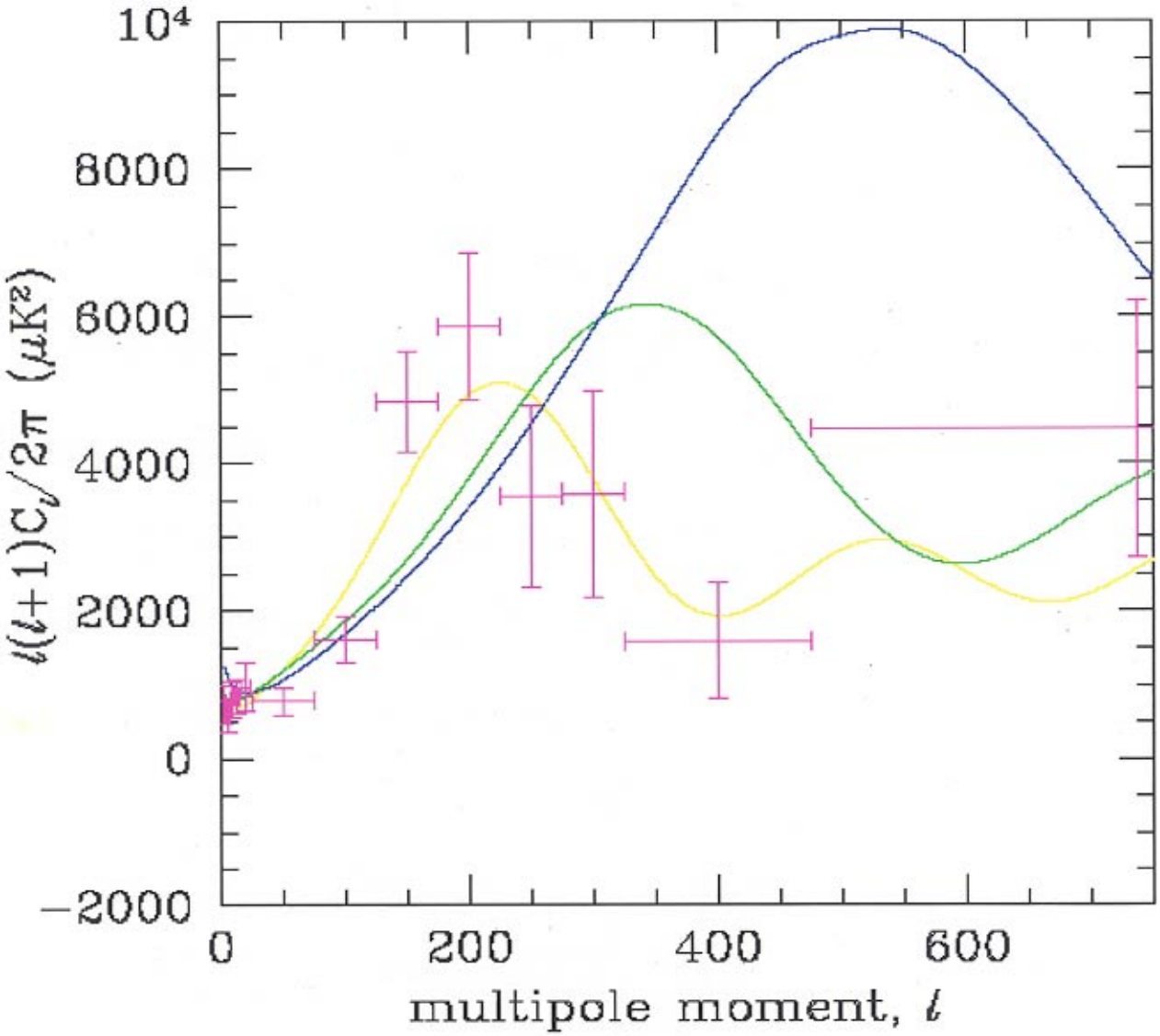
$$\underset{\text{CMB}}{\Omega_0 \approx 1 \pm 0.1} > \underset{\text{CLUSTERS etc}}{\Omega_m \approx 0.35 \pm 0.1} + \text{structure formation}$$

- MUST BE SMOOTH (NOT IN Ω_m)
- MUST HAVE NEGATIVE PRESSURE (DO NOT INTERFERE W/ S.F.)

$\Omega_x \approx 0.65 \pm 0.10 \quad w_x \lesssim -1/2$

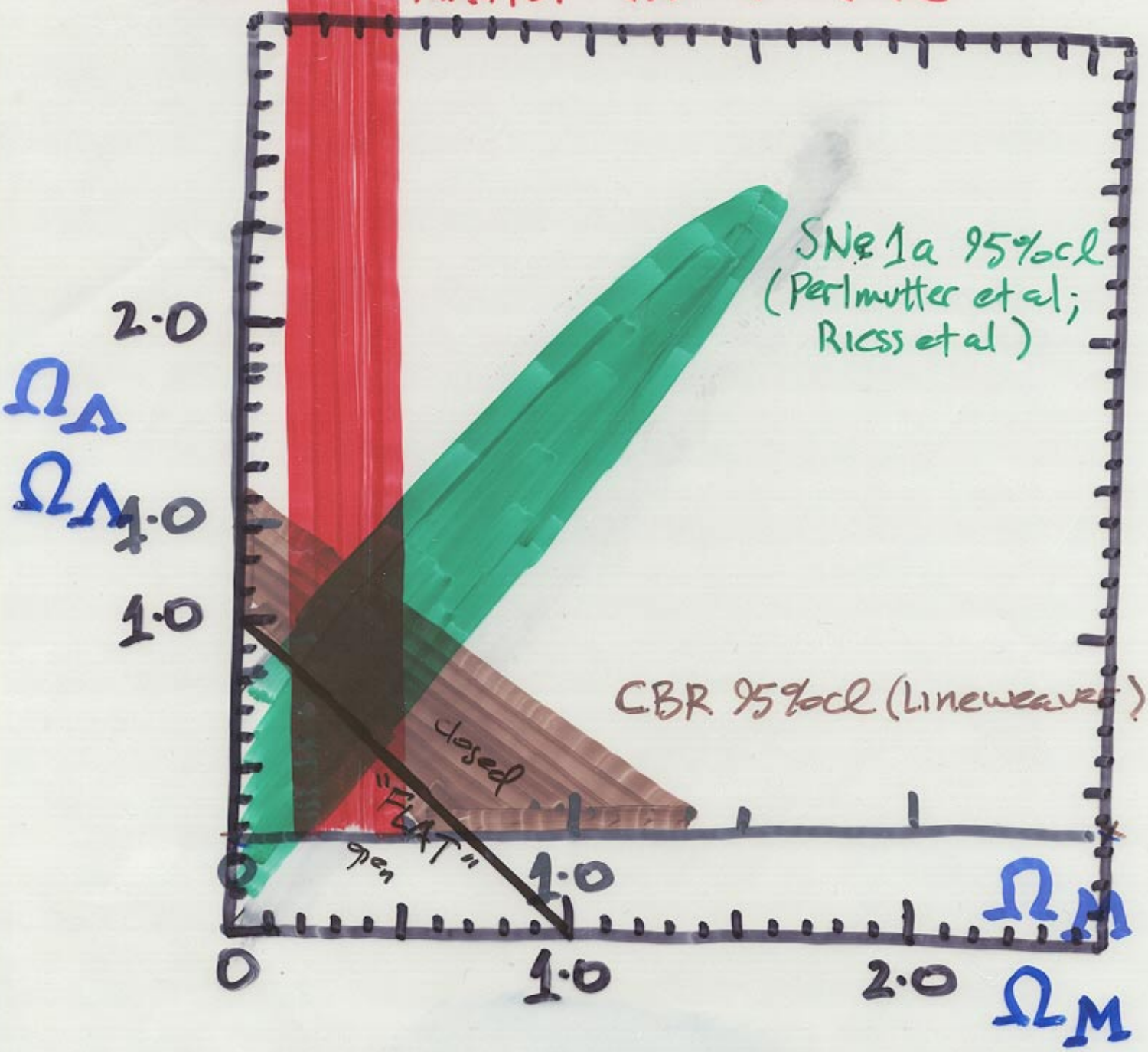
CONCORDANCE OF DIRECT & INDIRECT

Compilation of Current Data (ca 12/1999)



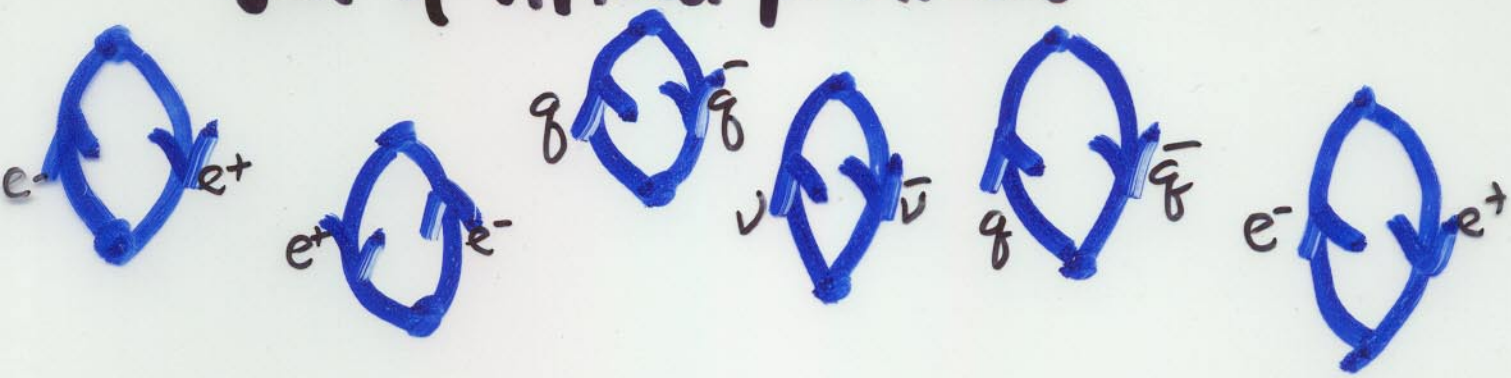
Knox 1999

"THE BIG PICTURE"



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?

<u>theoretical estimates</u>

'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

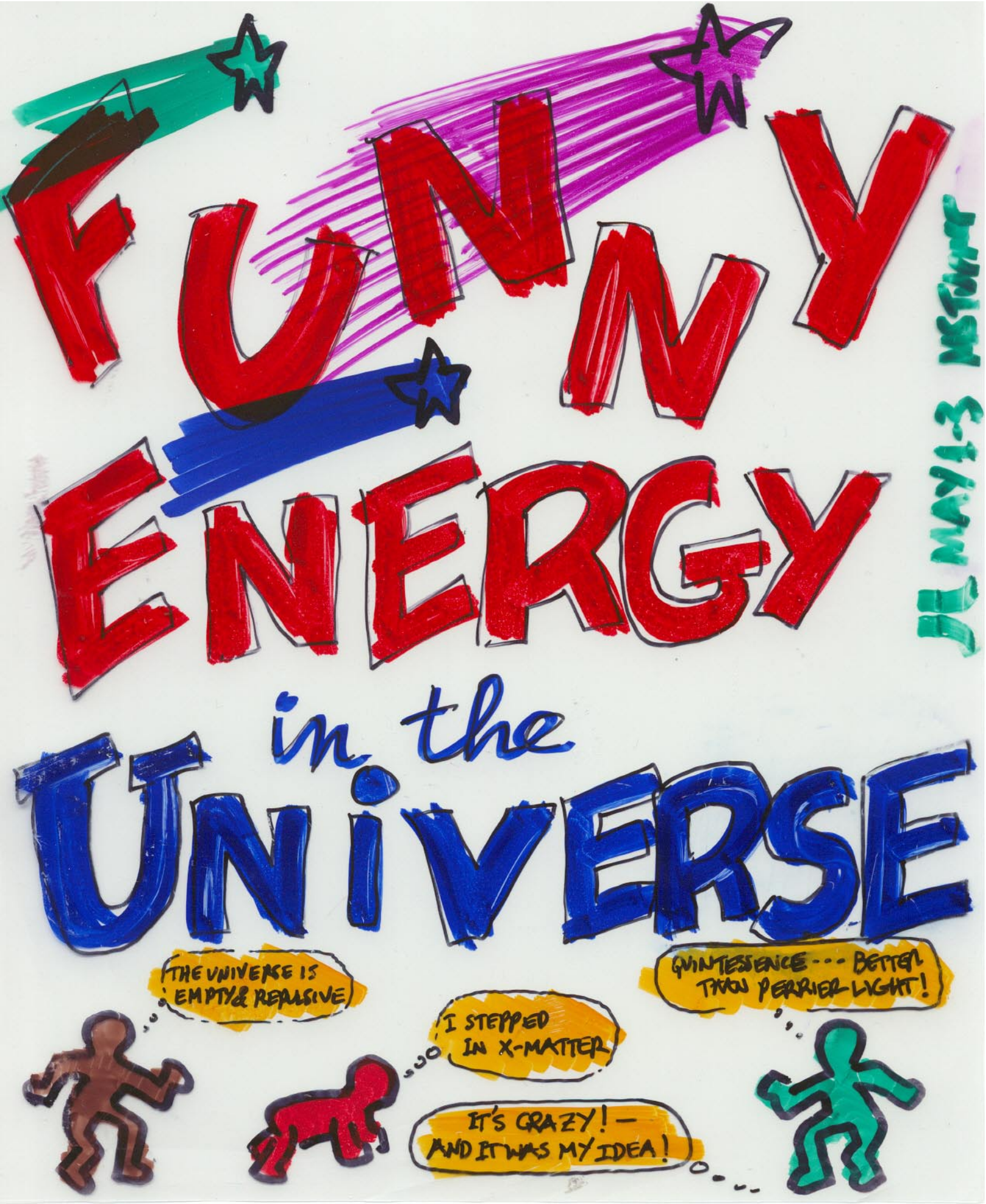
Science Times, 30 November 1999 (J. Glanz)

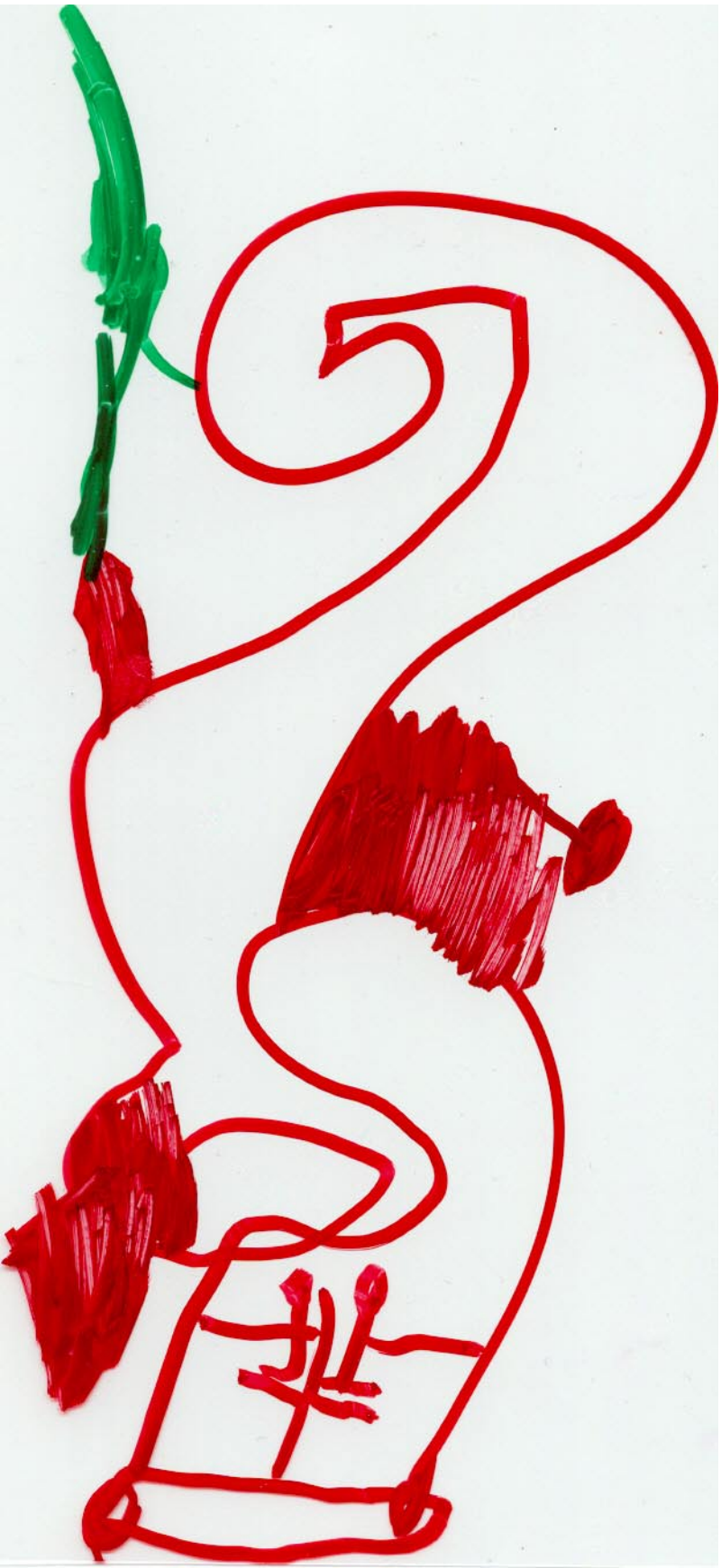
J. Harvey: Basically, people don't have a clue as to how to solve this problem.

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.


FUNNY ENERGY in the UNIVERSE
JL MAY 1-3 MSTOWER
THE UNIVERSE IS EMPTY & REPULSIVE
I STEPPED IN X-MATTER
QUINTESSENCE --- BETTER THAN PERRIER LIGHT!
IT'S CRAZY! — AND IT WAS MY IDEA!

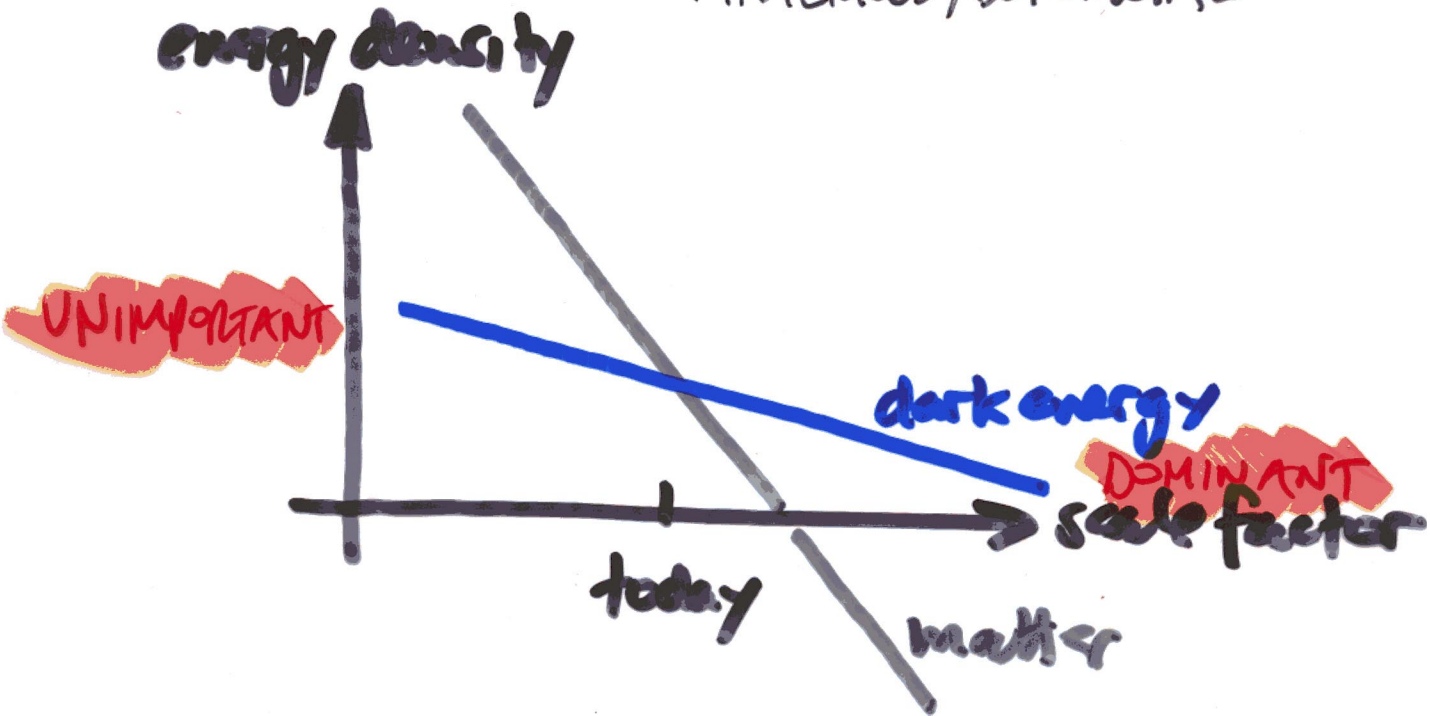


NANCY KERRIGAN PROBLEM

WHY ME?

WHY NOW?

MYSTERIOUS, BUT CRUCIAL



ACCELERATING UNIVERSE

$\Rightarrow$ $\rho + 3p < 0$

source of gravity in GR

$\Rightarrow$ $\rho_x \sim 2/3\, \rho_{crit}$ $\quad p_x < -\rho_x/3$

POSSIBILITIES:

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

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

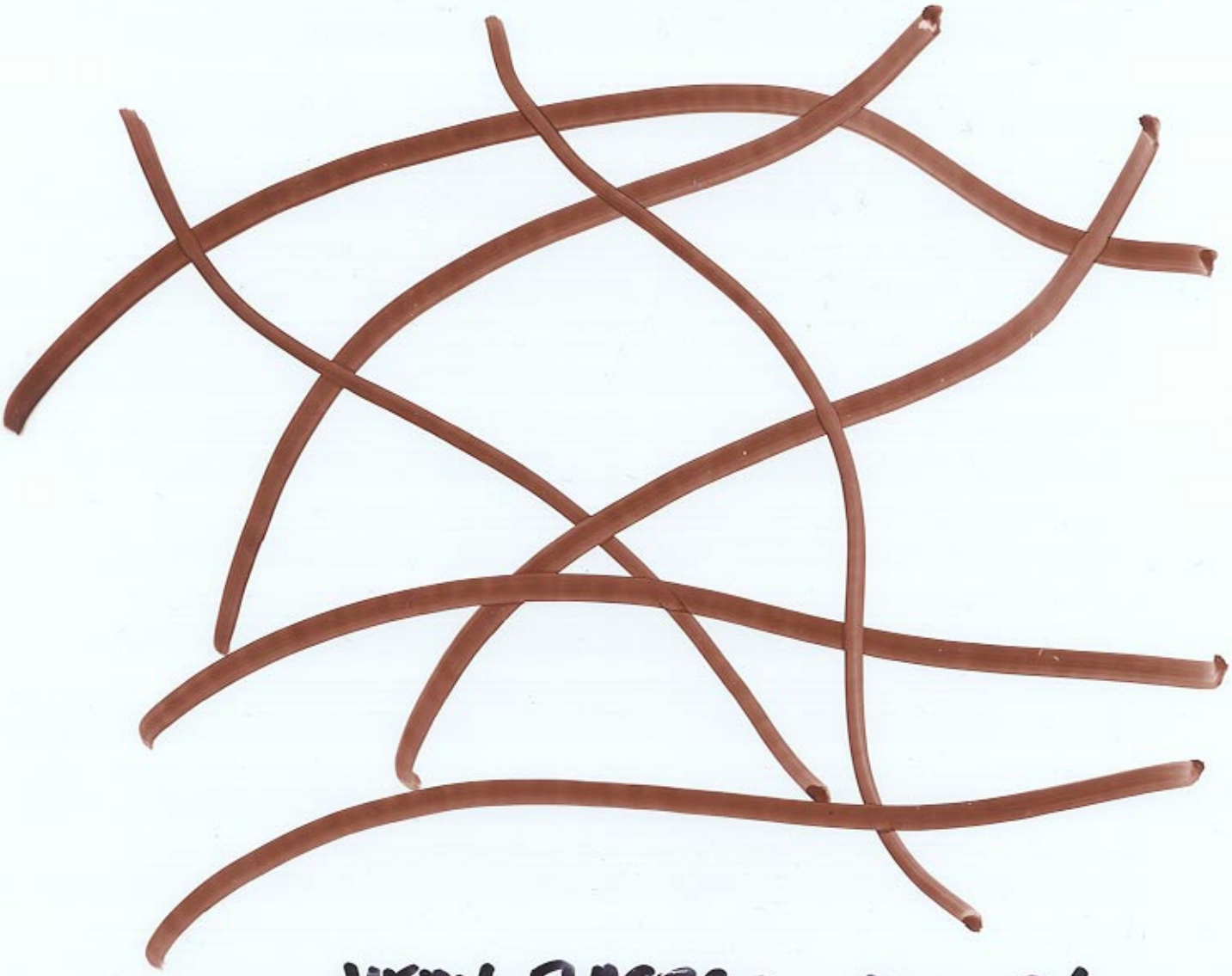
ROLLING SCALAR FIELD $\quad p = -\rho/3 \rightarrow -\rho$

AKA "QUINTESSENCE"

NETWORK OF (FRUSTRATED) TOPOLOGICAL DEFECTS

EG STRING

A. Vilenkin '84
Pen-Spergel '98



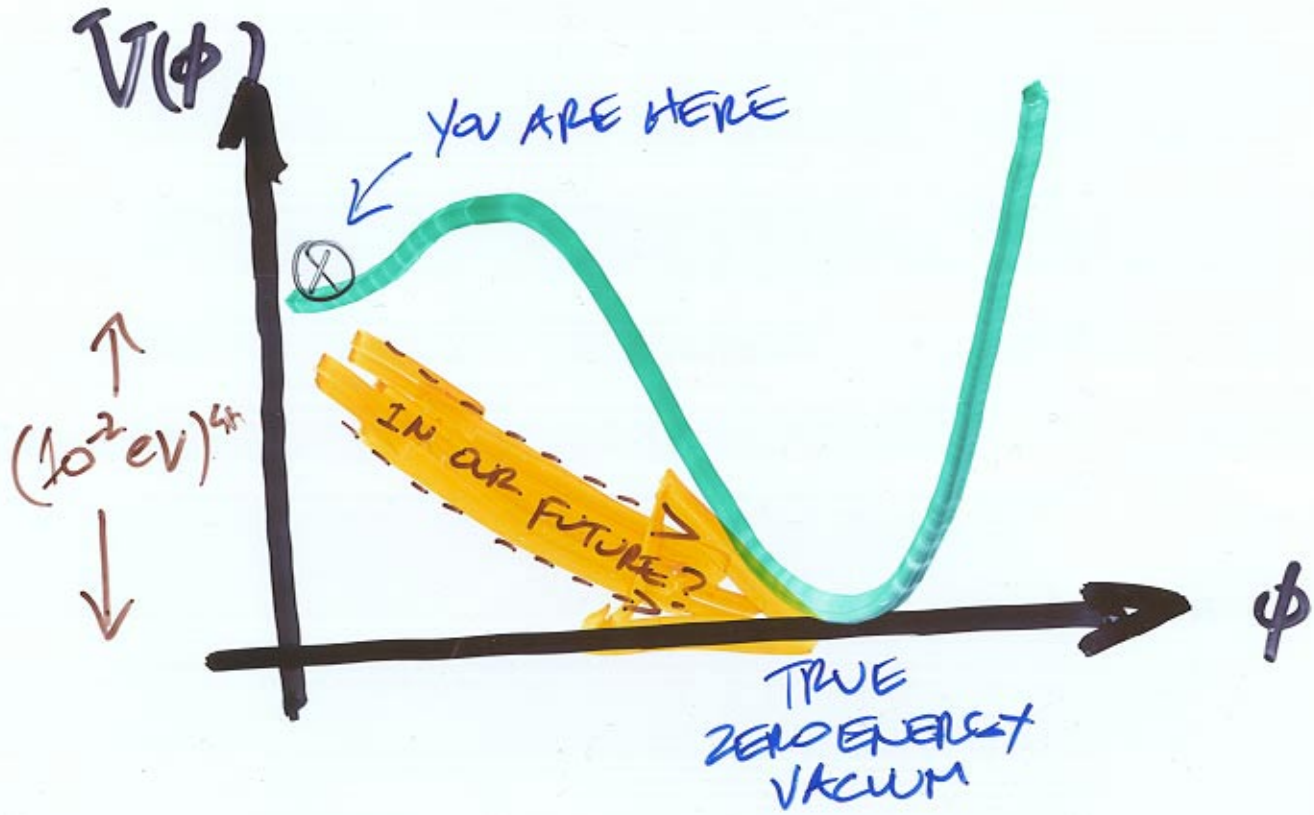
VERY ELASTIC: $p = -\rho/3$

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

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



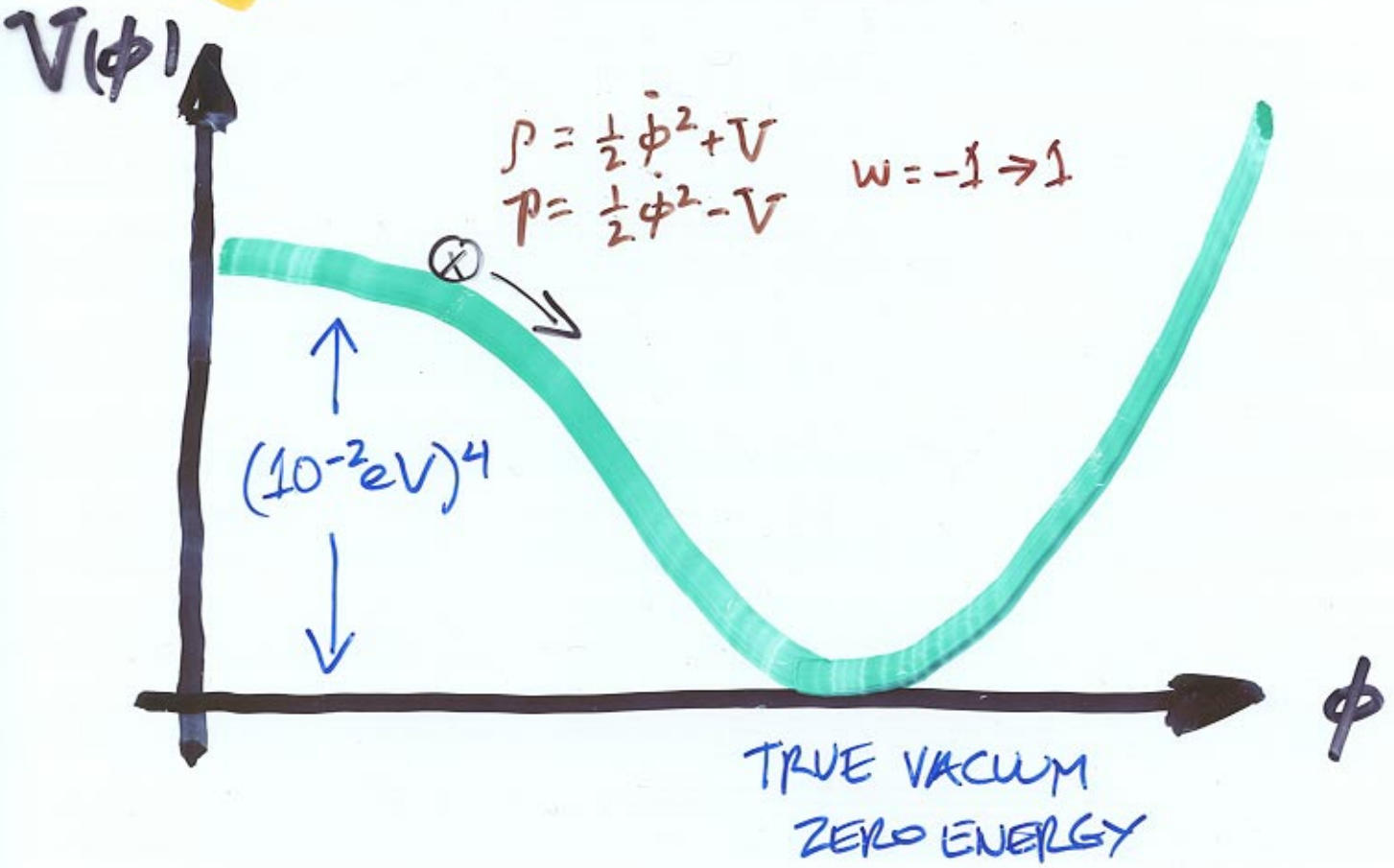
ROLLING SCALAR FIELD

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

Bronstein 1933 (executed by Stalin)
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."



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, & INVOLVES FUND PHYSICS

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

TURNER-WHITE PRD 56, 4439 (9

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"	$-1 \to 1$	$= \dfrac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$
"THE BULK", BREAKDOWN OF FRW COSMOLOGY, ...	?	?

PROBING THE Mysterious DARK ENERGY

Perlmutter-White-MST
astro-ph/9901052

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

COMPLEMENTARITY

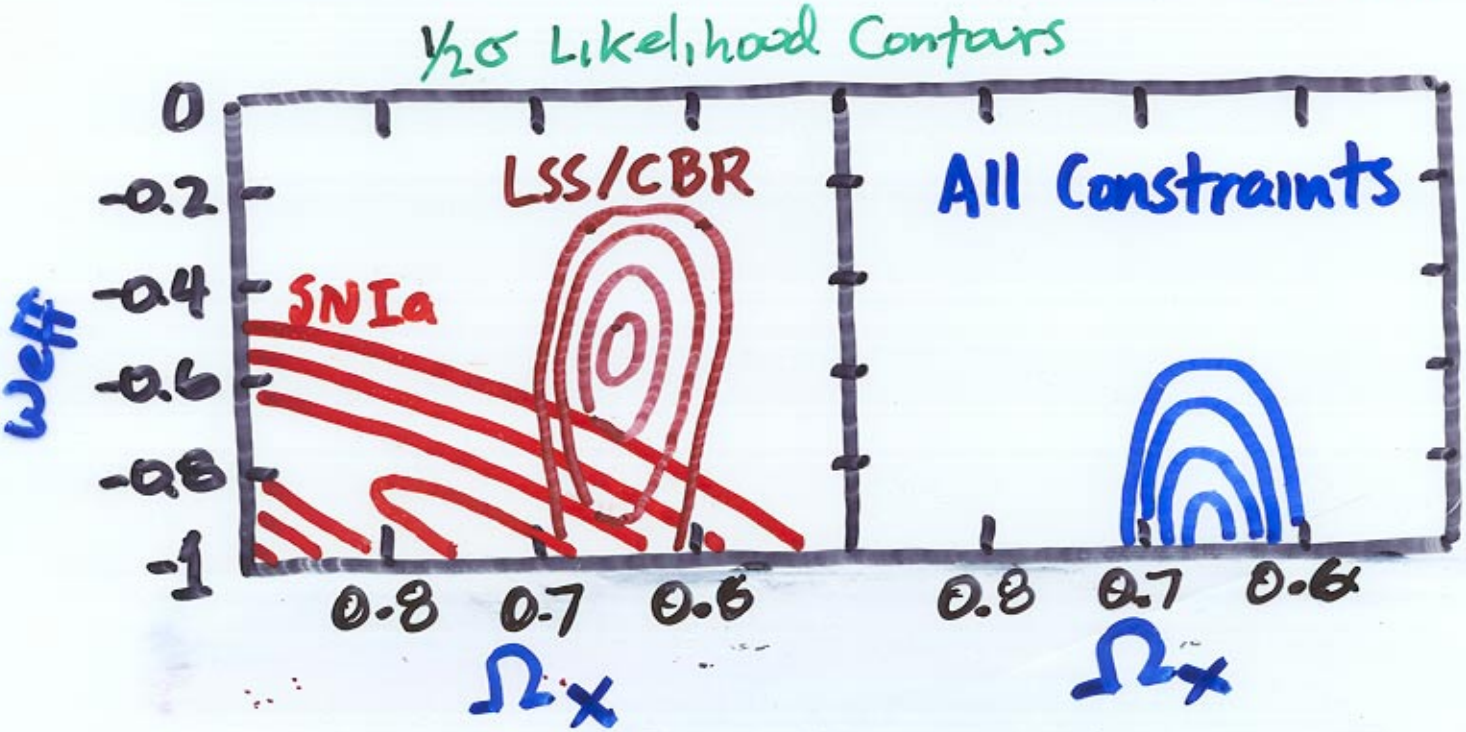
SN Ia

LSS/CBR

CONSISTENCY

AGE OF UNIVERSE
GRAV. LENSING

Ω_M (direct measures)



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

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

GETTING AT THE DARK ENERGY

COSMIC COMPARISONS

(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_{Ω_M}	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:

$$\sigma \propto (N/2200)^{-1/2}\,\sigma_{sys}$$

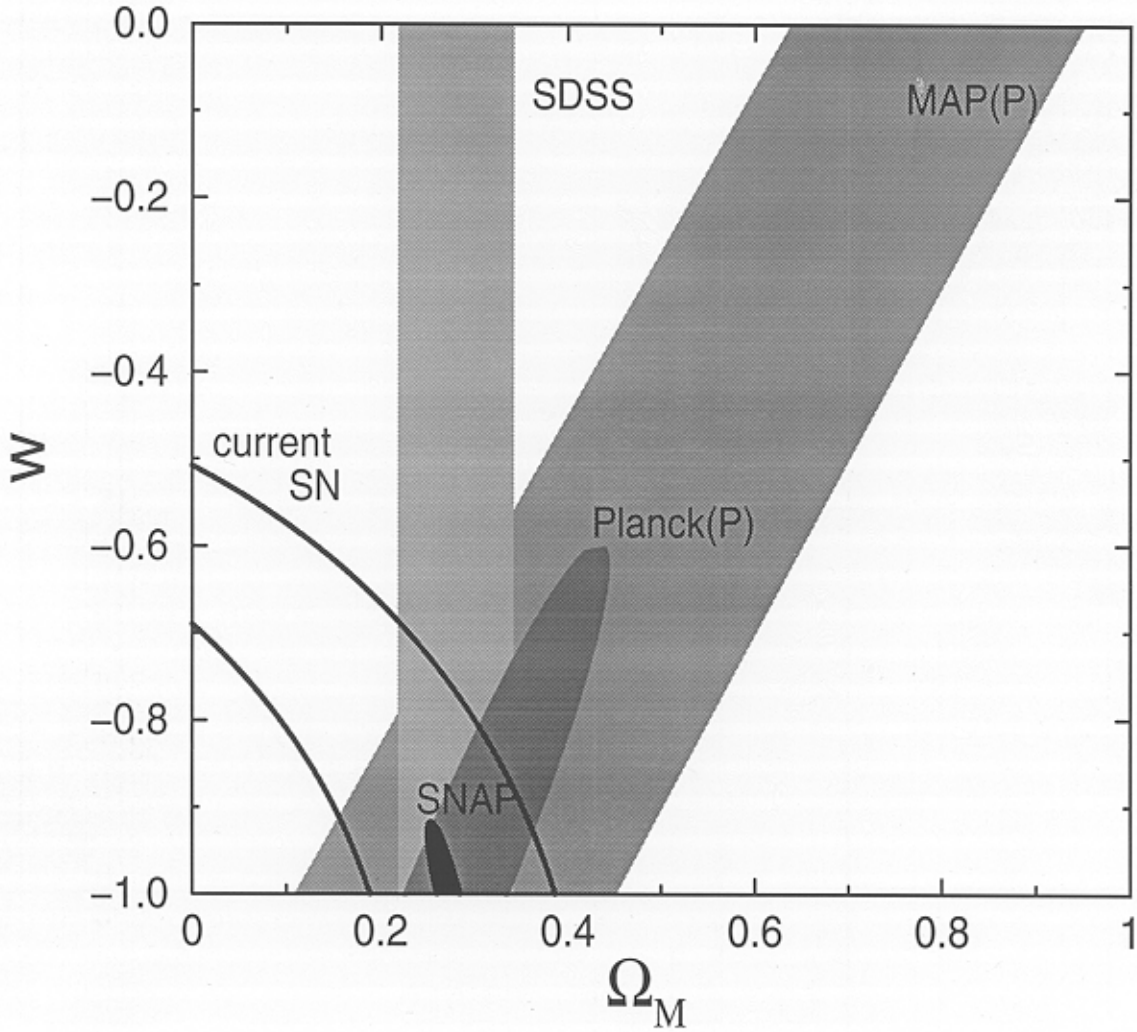
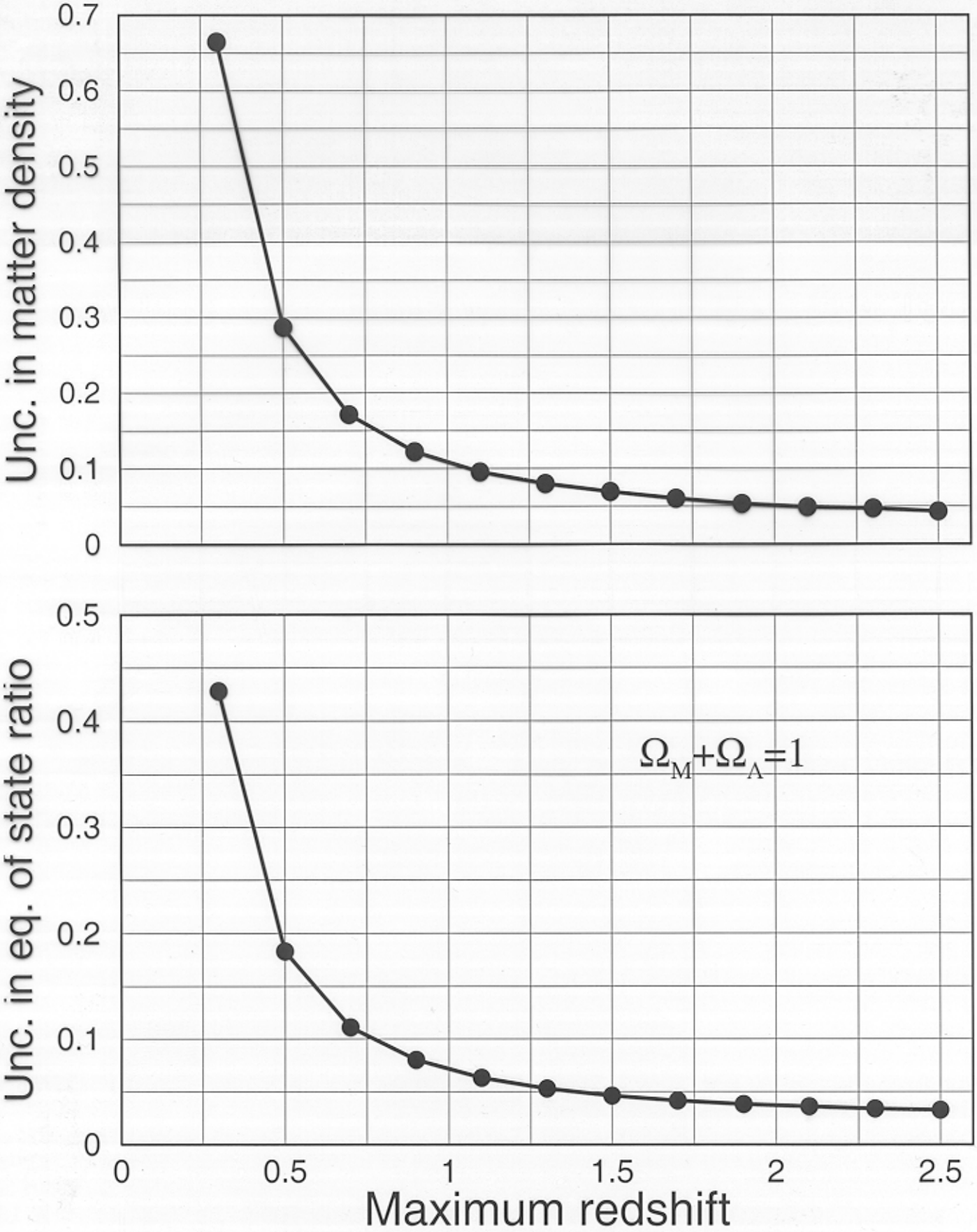


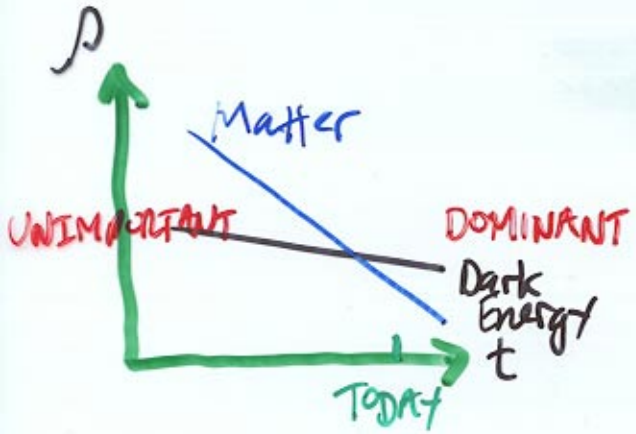
Figure 3: SNAP constraint on parameters Ω_M and w compared to those of MAP and Planck both with polarization information, and SDSS (MAP, Planck and SDSS constraints are from [?]). Also shown are the present constraints using a total of 54 SN. All constraints are 1-σ and include statistical uncertainties 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.

How unc. decrease with going to higher redshift



KEY ADVANTAGE OF SNe Ia

CAN PROBE <u>RECENT</u> EXPANSION HISTORY WELL



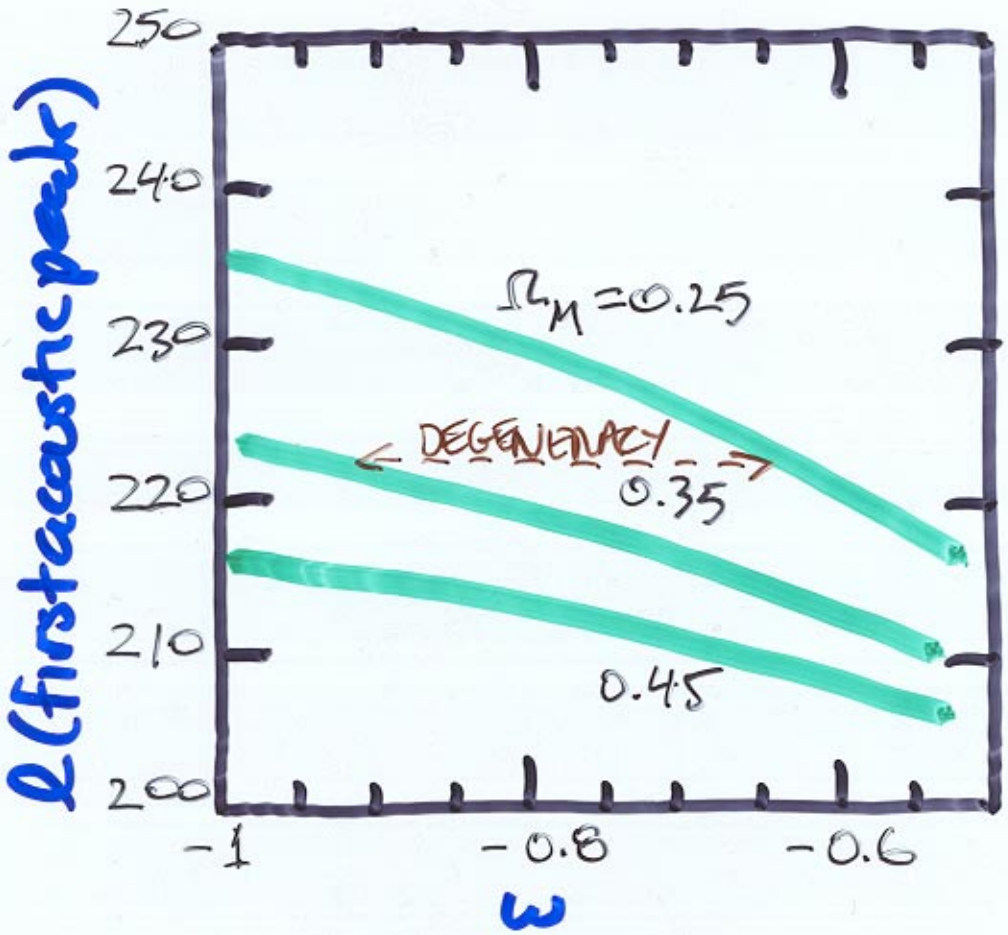
$$\rho_X/\rho_M = \frac{\Omega_X}{\Omega_M}(1+z)^{3w_X}$$

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

NB: CMB EPOCH

WHEN THE DARK ENERGY IS DOMINANT

Pattern of CMB anisotropy



ANGULAR POSITION OF "FEATURES"

$\propto$ 1/distance to LSS

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

$\Omega_M - w$ degeneracy

CMB NEEDS HELP

SNeIa CAN GET AT THE NATURE OF DARK ENERGY

SNe DETERMINE EXPANSION HISTORY THRU

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

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

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

DETERMINE FROM SNeIa DATA

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

RECONSTRUCT $w(z)$:

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

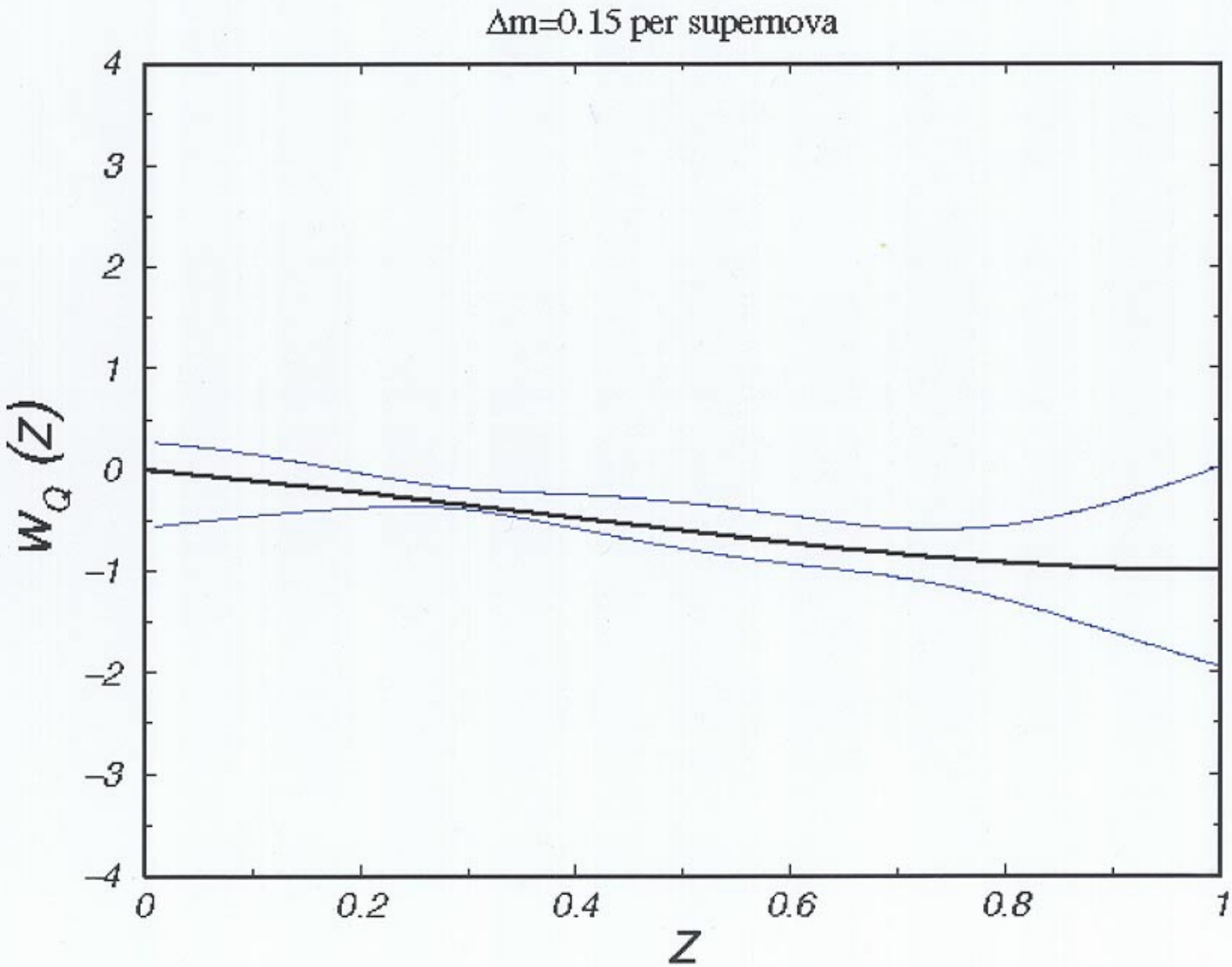
($k=0$)

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

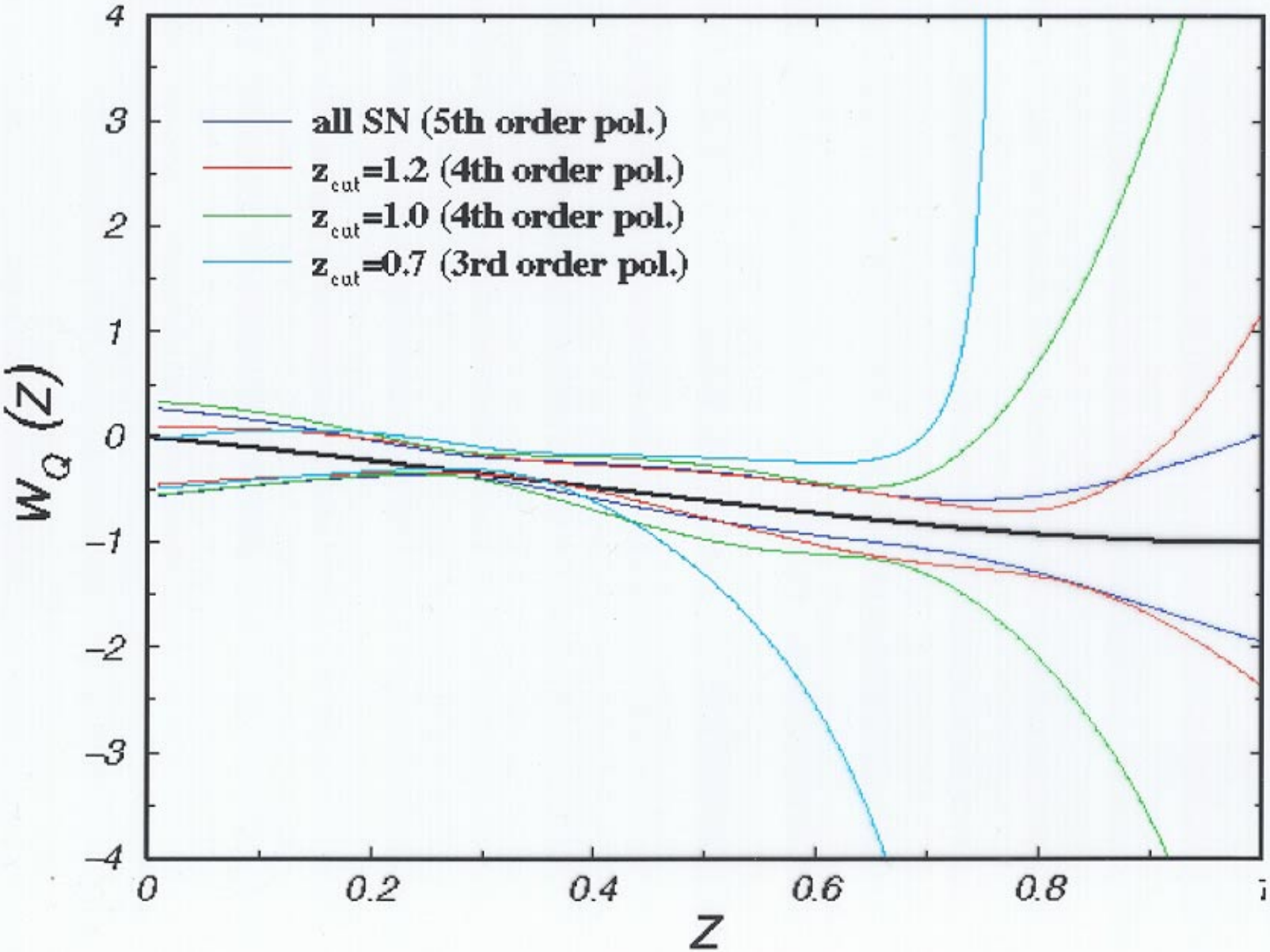
$$V(\phi) = \frac{1}{8\pi G}\left[\frac{3}{(dr/dz)^2} + (1+z)\frac{d^2r/dz^2}{(dr/dz)^3}\right] - \frac{3\Omega_M H_0^2(1+z)^3}{16\pi G}$$

NEED QUALITY DATA SET!

RECONSTRUCTING w(z) w/D-REX



PULL OF HIGH REDSHIFT SNe



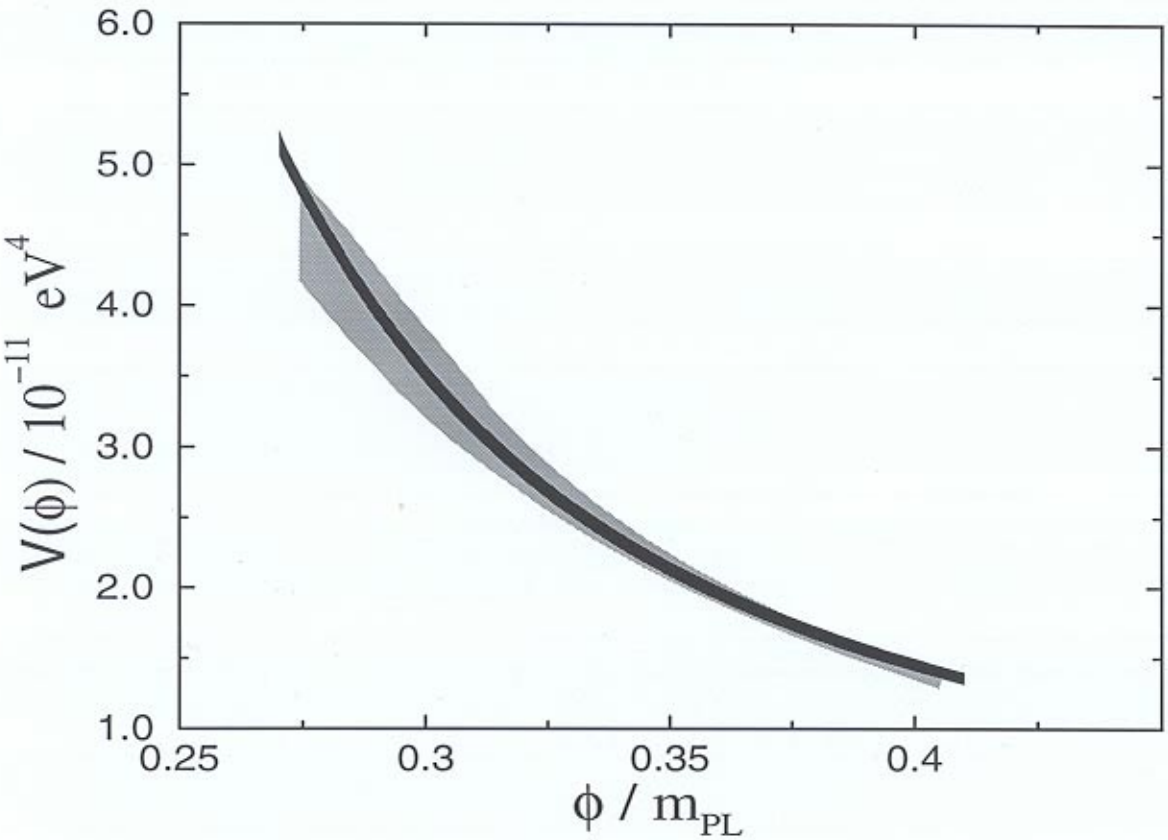


Figure 1: The 68% confidence interval for the reconstructed potential assuming SNAP's data set (shaded area) and the original potential (heavy line). The quintessence potential is $V = V_0\,[\exp(m_{PL}/\phi) - 1]$ with $V_0 = 1.3 \times 10^{-12}\ (\mathrm{eV})^4$ and $\Omega_{\mathrm{dark}} = 0.52$. 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.

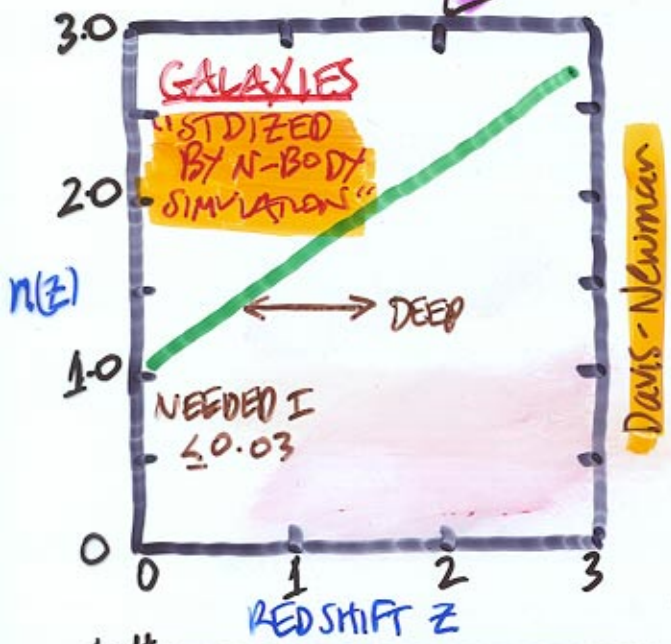
ANOTHER APPROACH: COUNTING STANDARDIZABLE OBJECTS

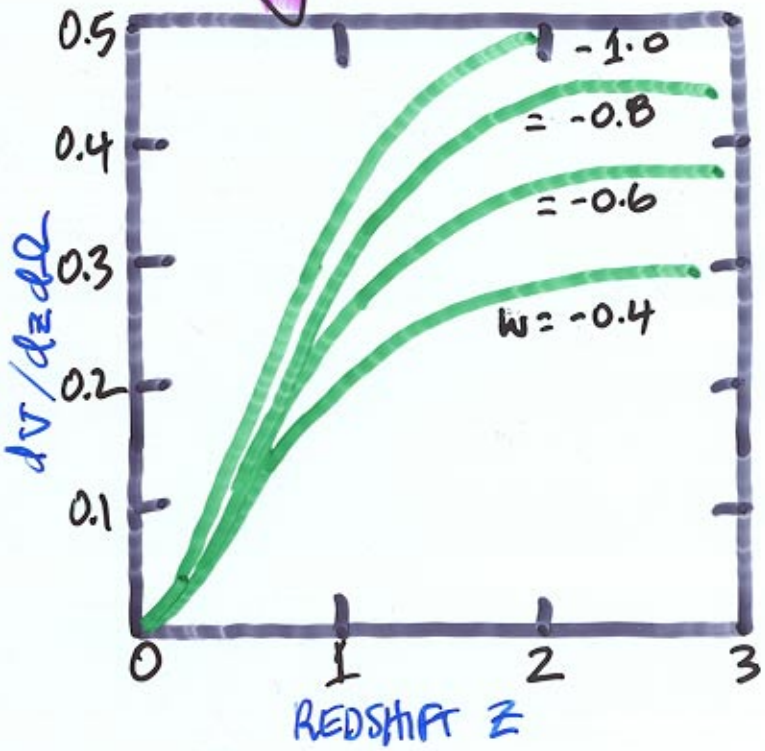
$$\frac{dN}{d\Omega\, dz} = n(z) \times \frac{dV}{d\Omega\, dz}$$

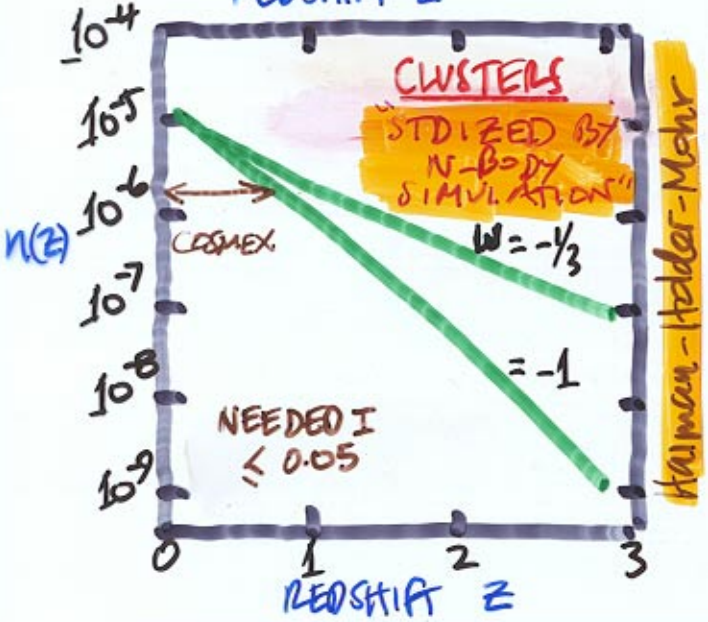
OBSERVABLE

ASTRO-PHYSICS "EVOLUTION"

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







KEY SYSTEMATIC: EVOLUTION $n(z)$

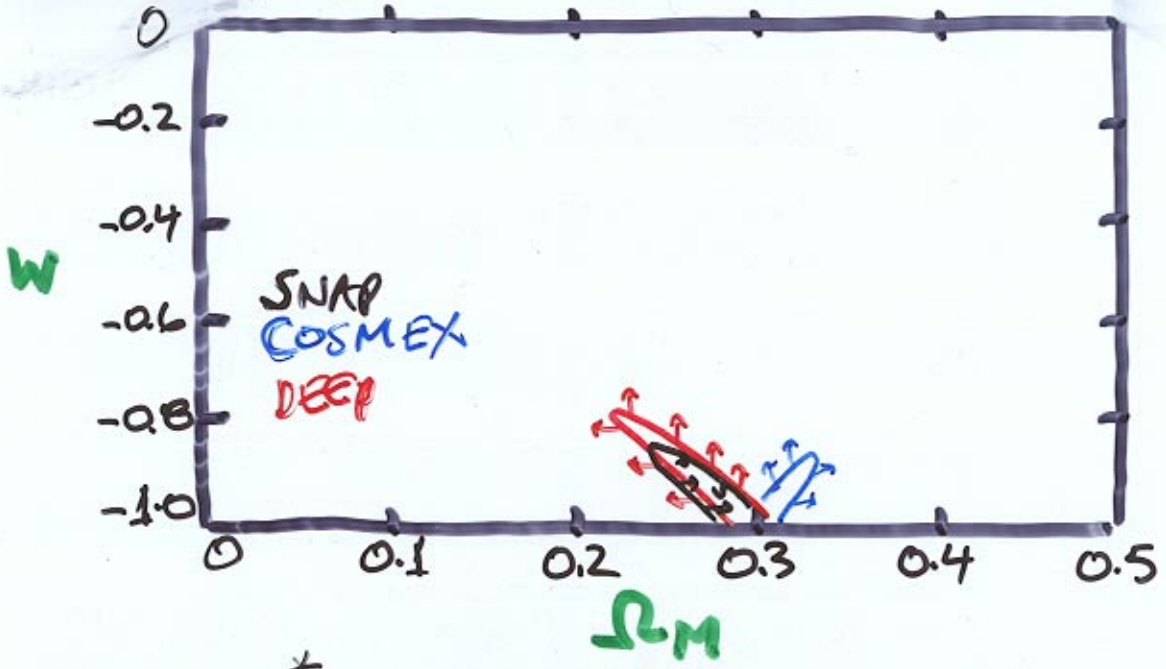
I.E. STANDARDIZING THE OBJECTS

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"

* SMECS PROPOSAL

If we knew that the Dark Energy had to be vacuum energy the case for a dedicated space mission would be debatable.

However, we do not; we do know that the Dark Energy is truly fundamental. Because SNe are the best way to probe its nature the case for a dedicated mission is compelling.

Michael S. Turner
Cosmologist