

Theoretical Case for

D-REX

DaRK-Energy explorer

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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

★ "DIRECT"

SNe Ia

$$q_0 \equiv -\frac{(\ddot{R}/R)_0}{H_0^2} = \frac{1}{2} \sum_i (1+w_i) \Omega_i \quad w_i \equiv \frac{\dot{w}_i}{w_i}$$

$$= \frac{\Omega_0}{2} + \frac{3}{2} w_X \Omega_X$$

$$\text{SNe Ia} \Rightarrow q_0 < 0 \Rightarrow w_X \Omega_X < -\frac{1}{3}$$

$$\star \text{"INDIRECT"} \quad \Omega_0 > \Omega_m + \text{structure formation}$$

CMB CUSTERS etc

- MUST BE SMOOTH (NOT IN Ω_m)
- MUST HAVE NEGATIVE PRESSURE
(\Rightarrow NOT INTERFERE w/ S.F.)

$$\Omega_X \approx 0.65 \pm 0.10, \quad w_X \leq -\frac{1}{2}$$

★ CONCORDANCE OF DIRECT & INDIRECT

CANDIDATES/ REQUIREMENTS

PER. PERTURBATION

very light
matter
much

fragmented
matter
etc.
etc.

scale
rad
"gravitational"
vacuum

$\omega = \gamma_3$

$\omega = 0$

$\omega = -\gamma_3, 2\gamma_3$

$\omega = -1 \rightarrow ?$

X

$\omega = -1$

$\omega = -1$



* HERE TODAY, GONE YESTERDAY!
TO AVOID INTERFERENCE WITH GROWTH
OF STRUCTURE

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

EQN OF STATE: $w = \frac{p}{\rho}$

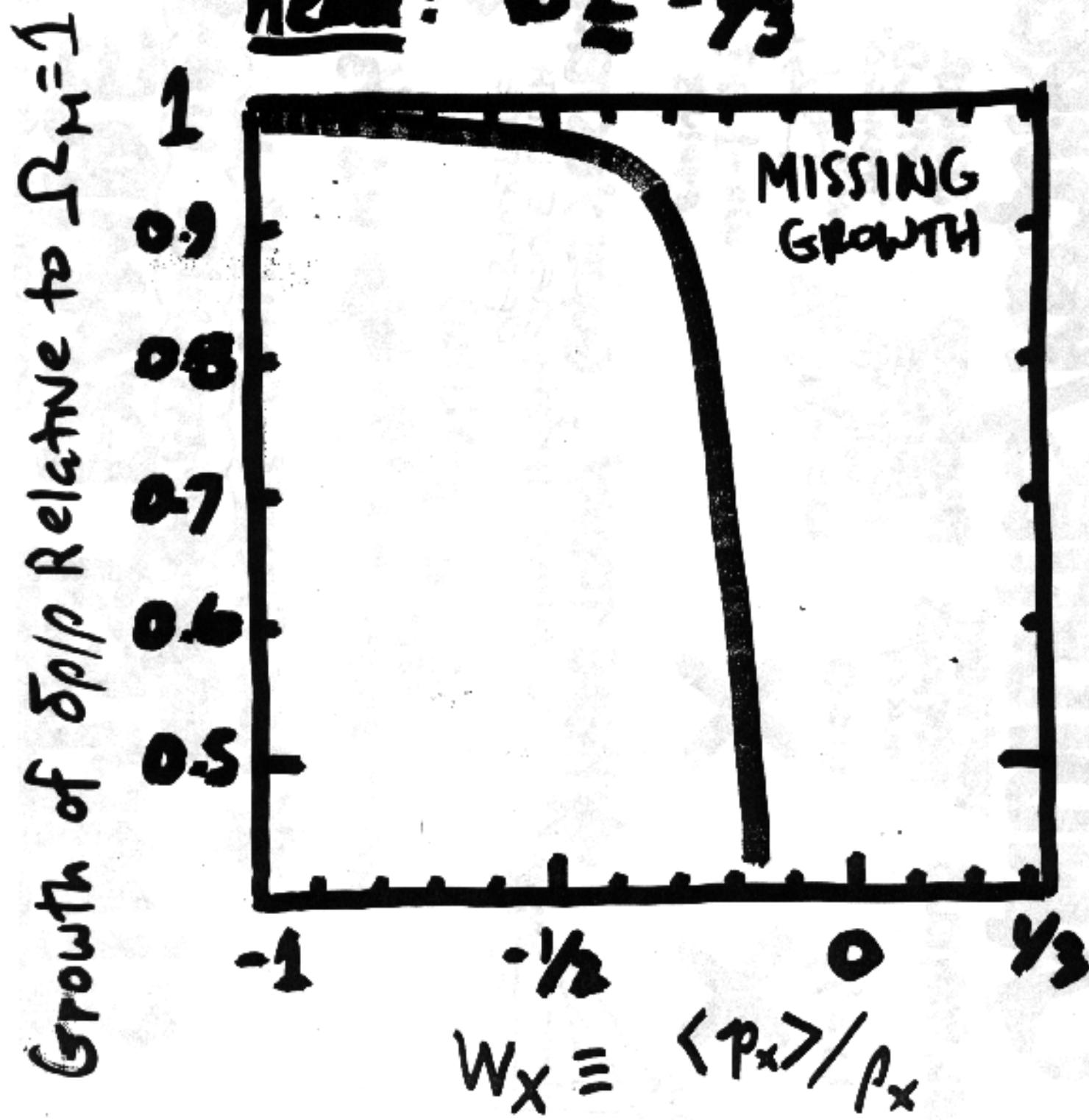
* OF DECKY
DEMONSTRATED

* ACE FALCON'S SHREWD W
ON USE: $w = -1$

SIMPLIFIED EXAMPLE

Growth of $\delta\rho/\rho$

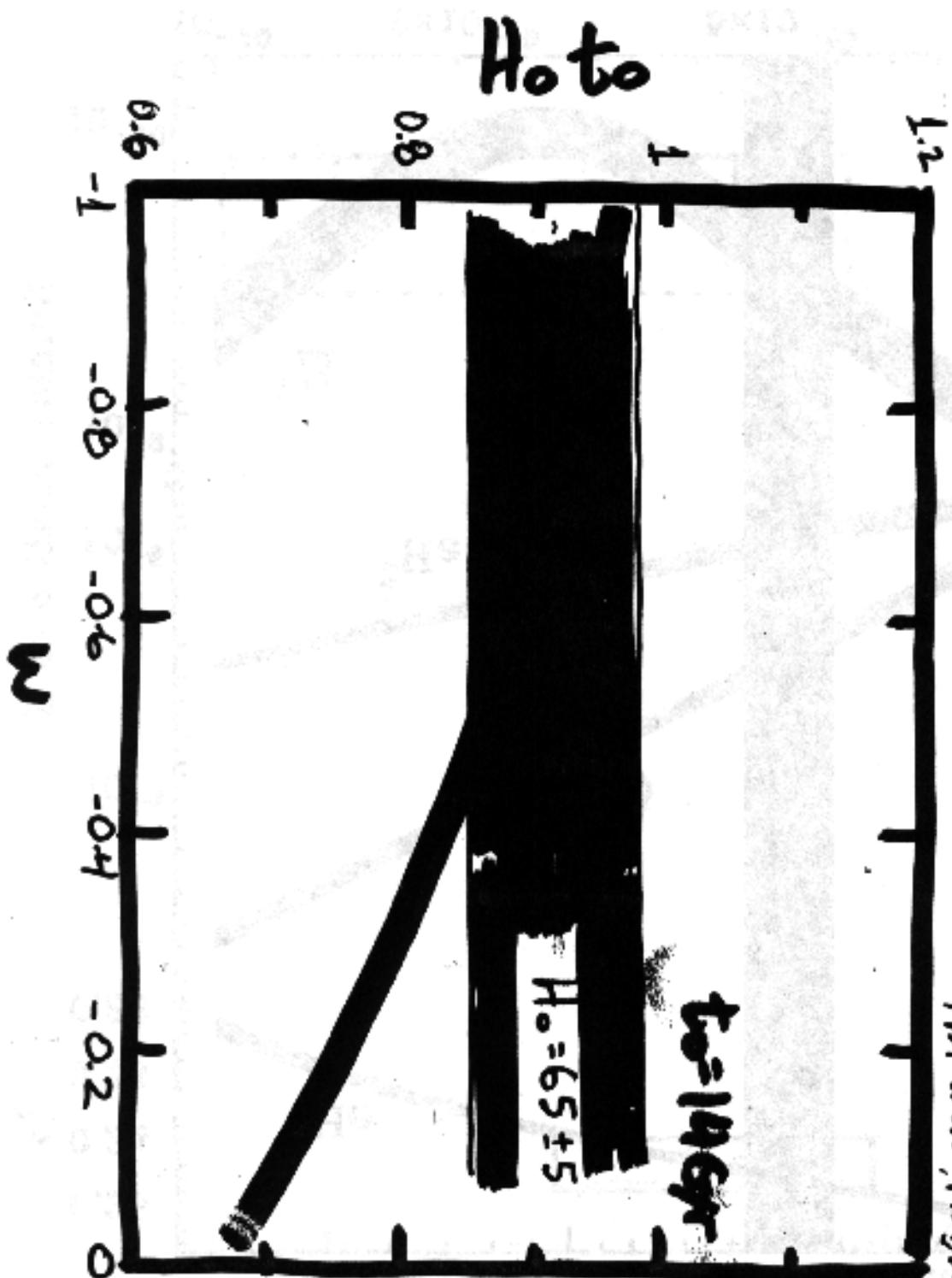
less growth \rightarrow larger $\delta T/T$
need: $w \leq -\gamma_3$

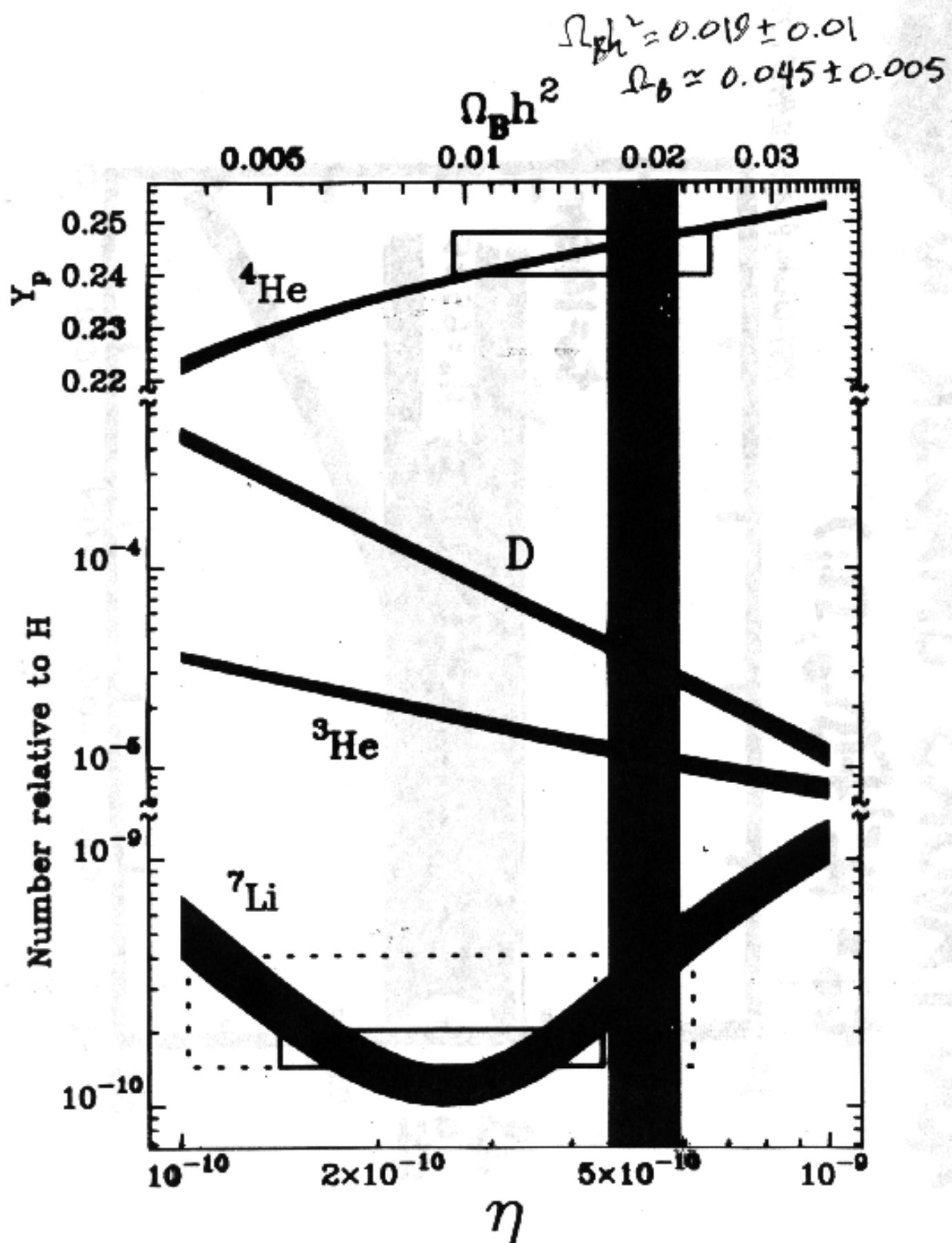


AGE FAVORS SMALLER W

$$t_0 = H_0^{-1} f(\Omega_0, \Omega_i)$$

MST-White, Pg 56, R 4439 (7)





CLUSTER BARYON FRACTION + $\Omega_B \rightarrow \Omega_M$



Wittels et al., Nature 334, 449 (93)

HOT SAMMIS HYPOTHESIS:

$$\frac{f_{\text{bar}}}{\Omega_m} = \frac{M_{\text{gas}}}{M_{\text{tot}}} \quad \begin{matrix} \leftarrow \text{x-ray flux, S-Z} \\ \leftarrow \text{x-ray temp, Grav.} \\ \leftarrow \text{Lensing, Virial Thm} \end{matrix}$$

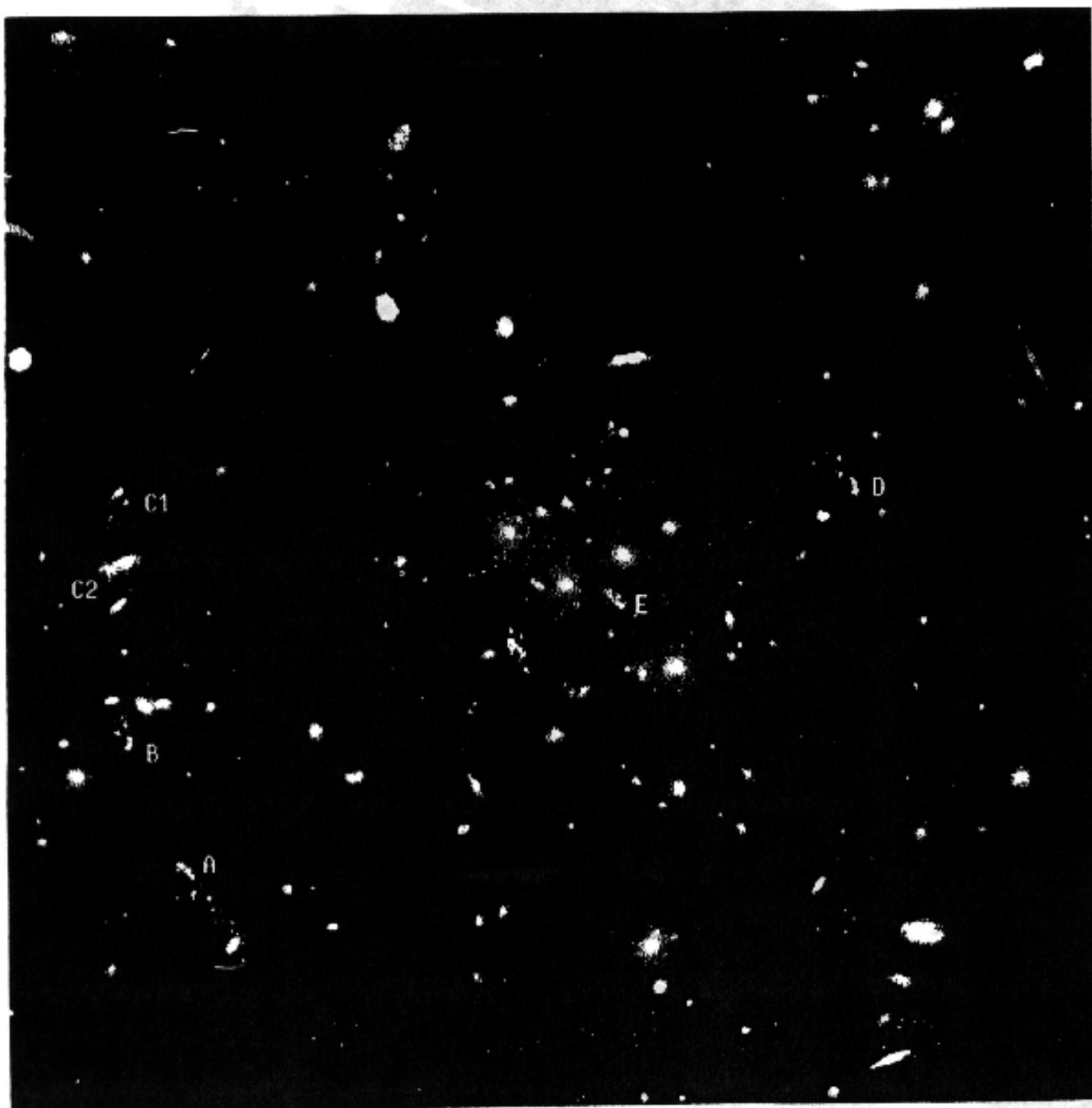
Evrard '97

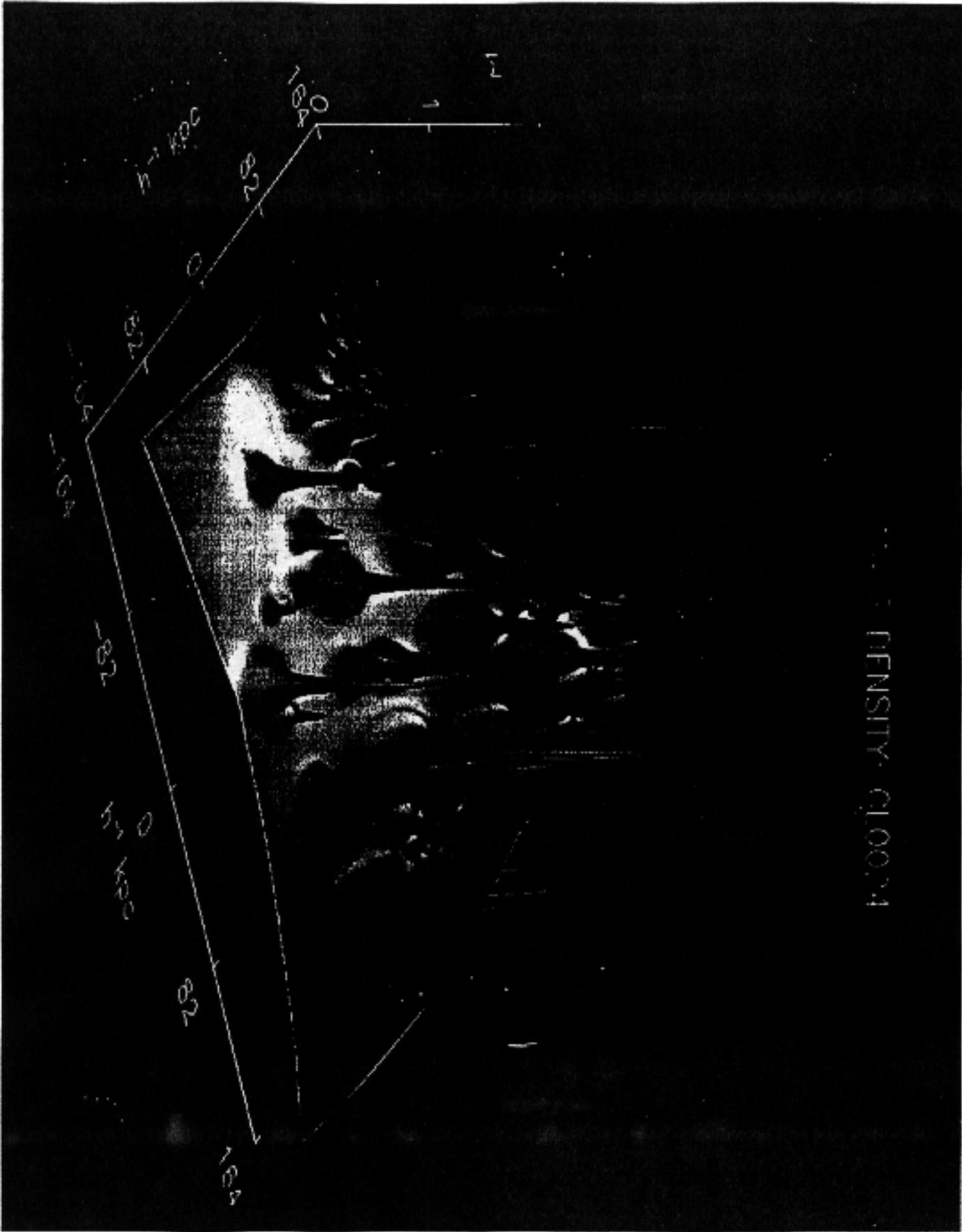
$$\langle M_{\text{gas}}/M_{\text{tot}} \rangle = (0.07 \pm 0.007) h^{-3/2},$$

$(0.06 \pm 0.006) h^{-1}$
Carlstrom '98 S-Z

$$\Omega_M = (0.3 \pm 0.05) h^{-1}, \quad (0.25 \pm 0.04) h$$

X-ray S-Z





DEC (J2000)

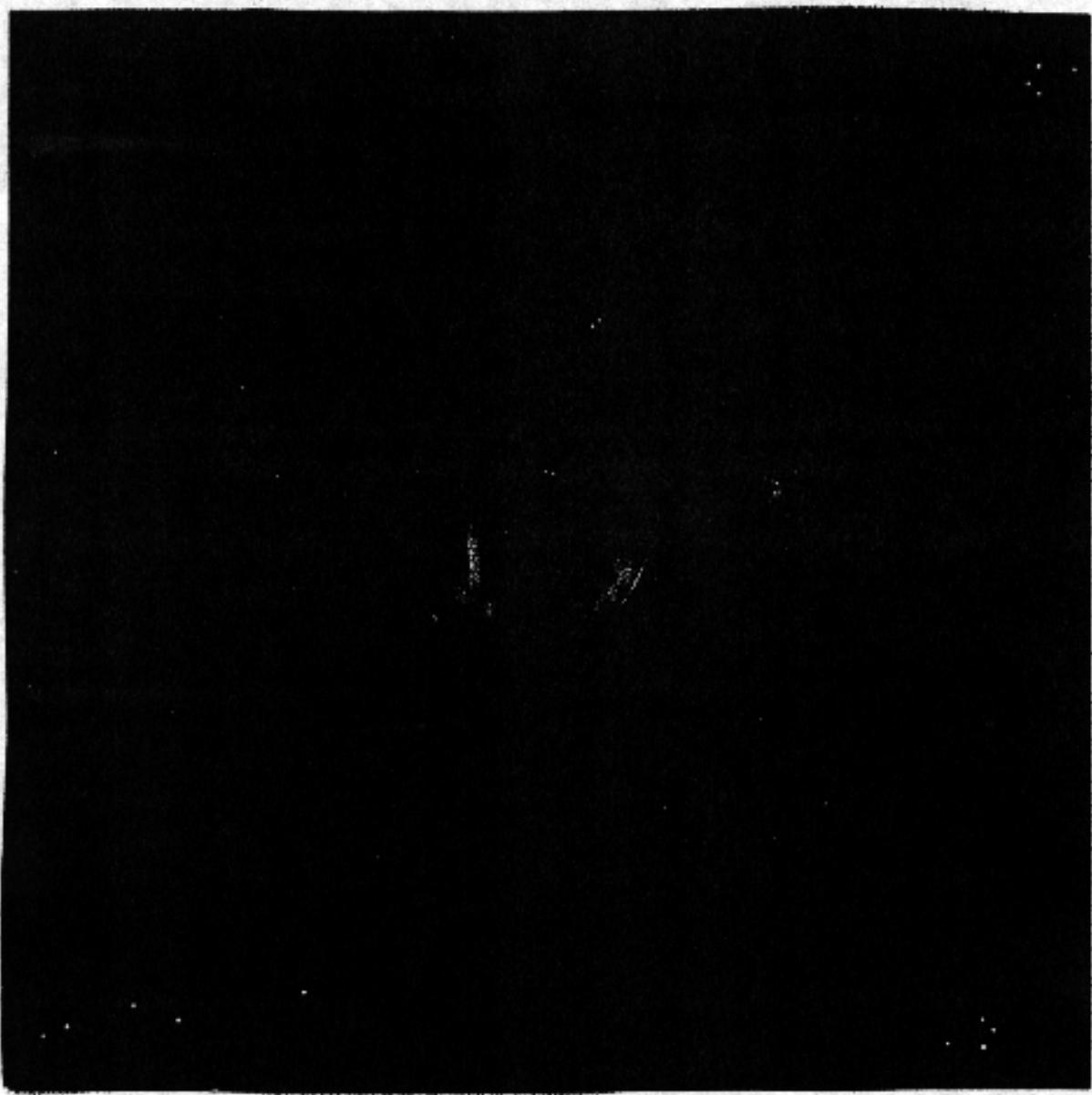
16°24'

25

26

27

28



0°18'44"

40°

36°

DRA (J2000)

32°

28°

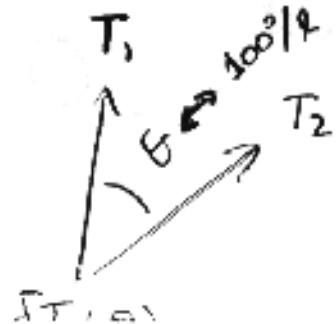
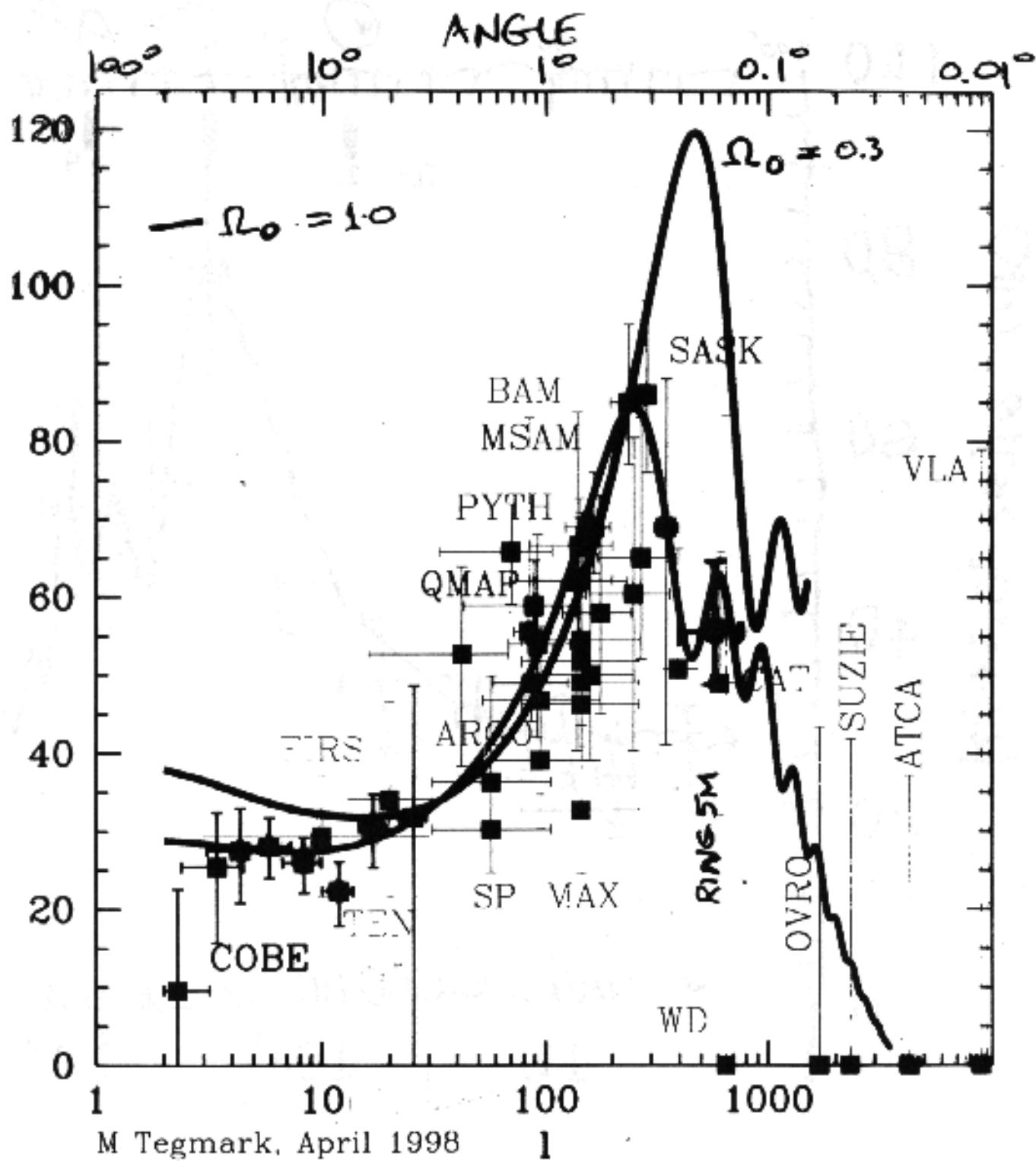
24°

+22°
+18°

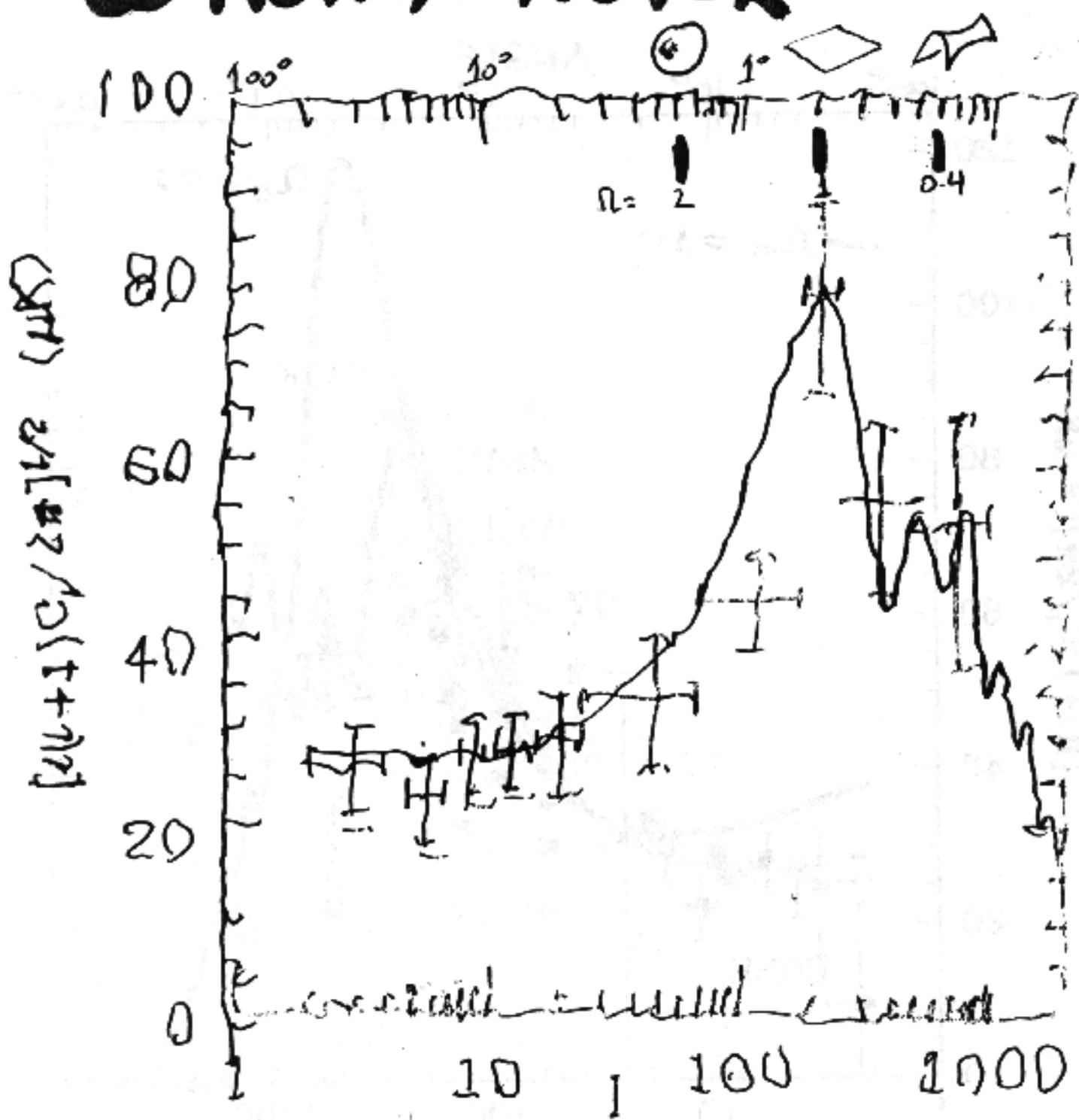
+21°

TEMPERATURE DIFFERENCE BETWEEN TWO DIRECTIONS

$$[(1+1)C_l/2\pi]^{1/2} \mu\text{K}$$



"COMBUSTION-METER"



Way KNOX and
TOE TURNER

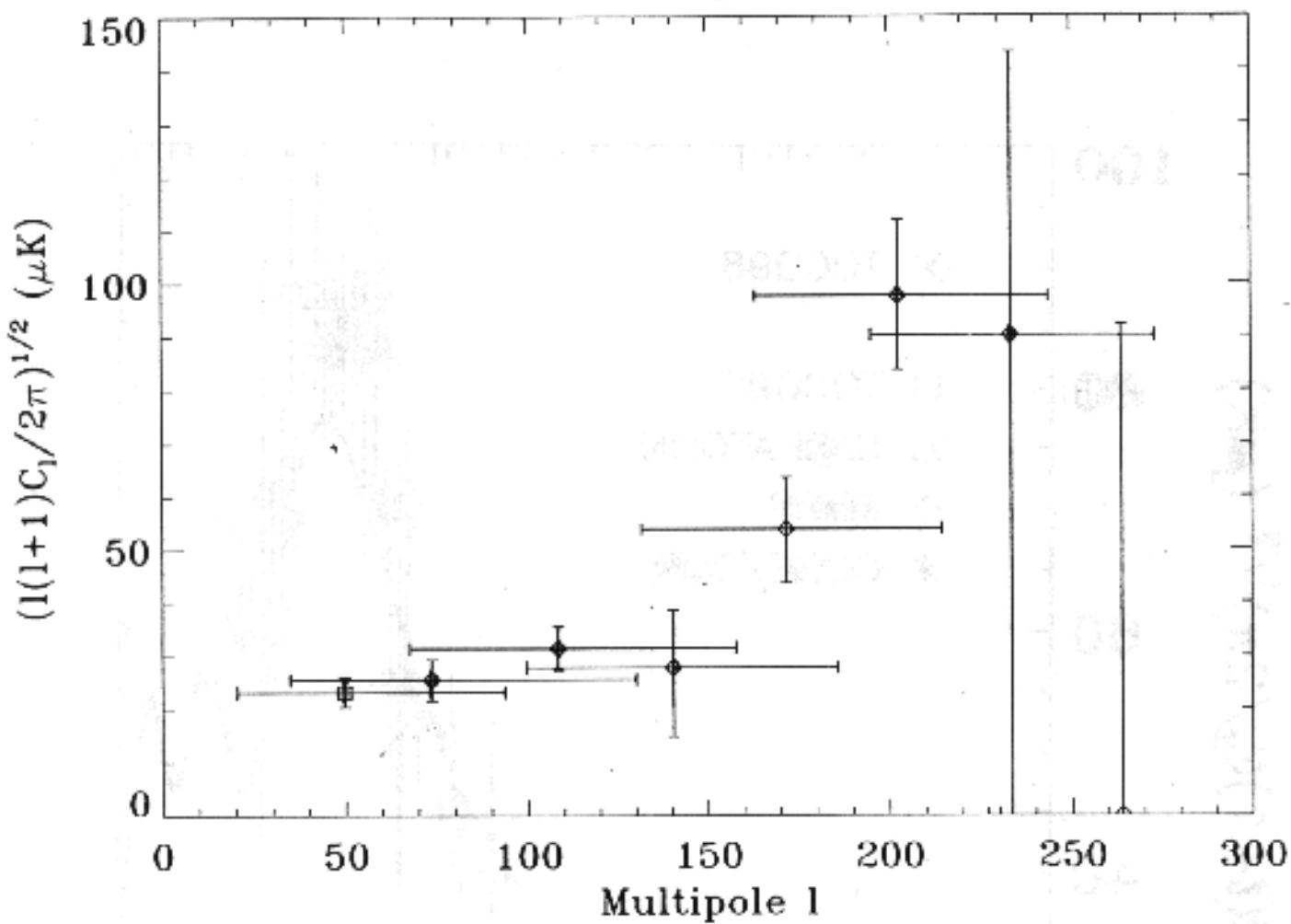
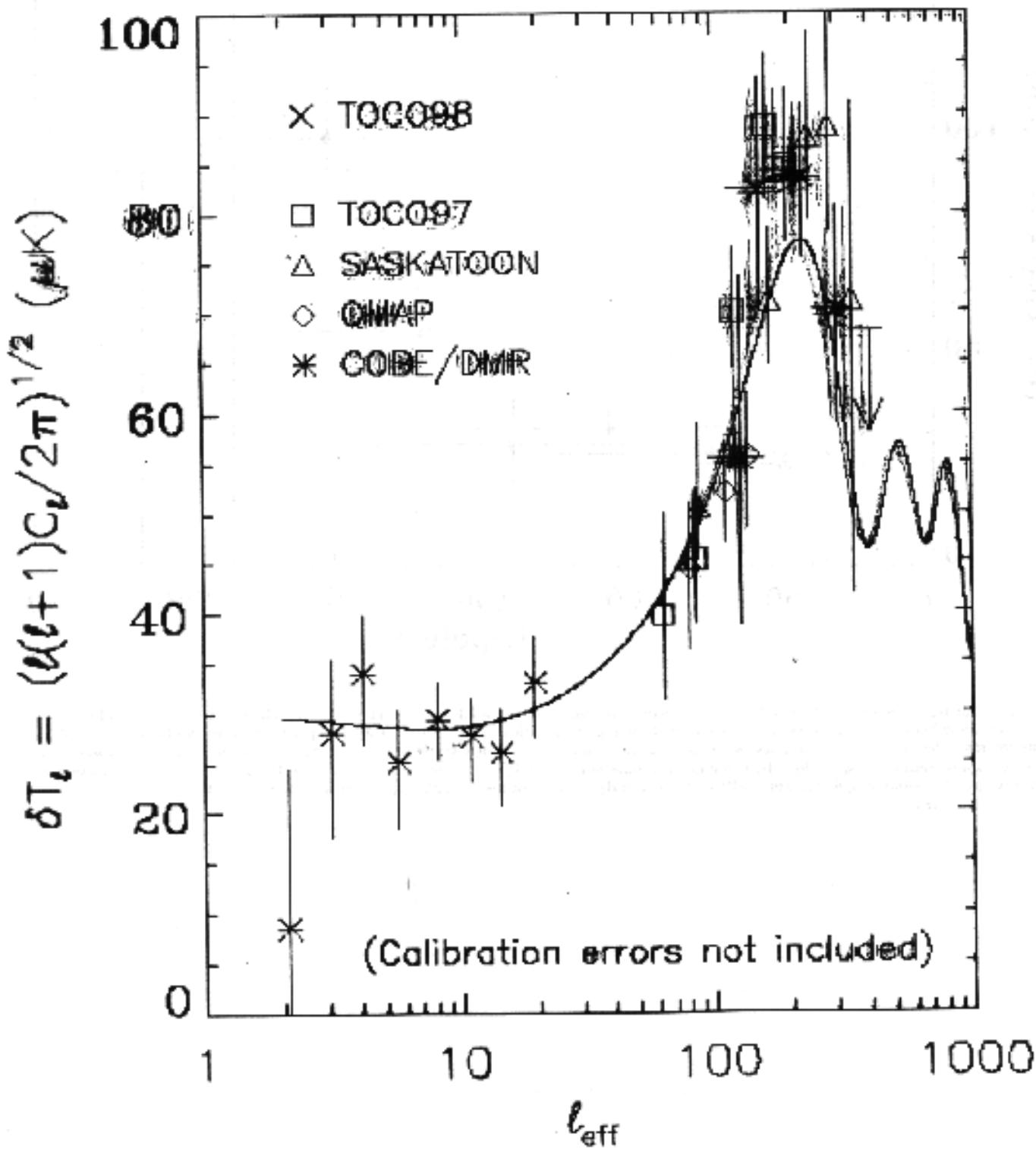
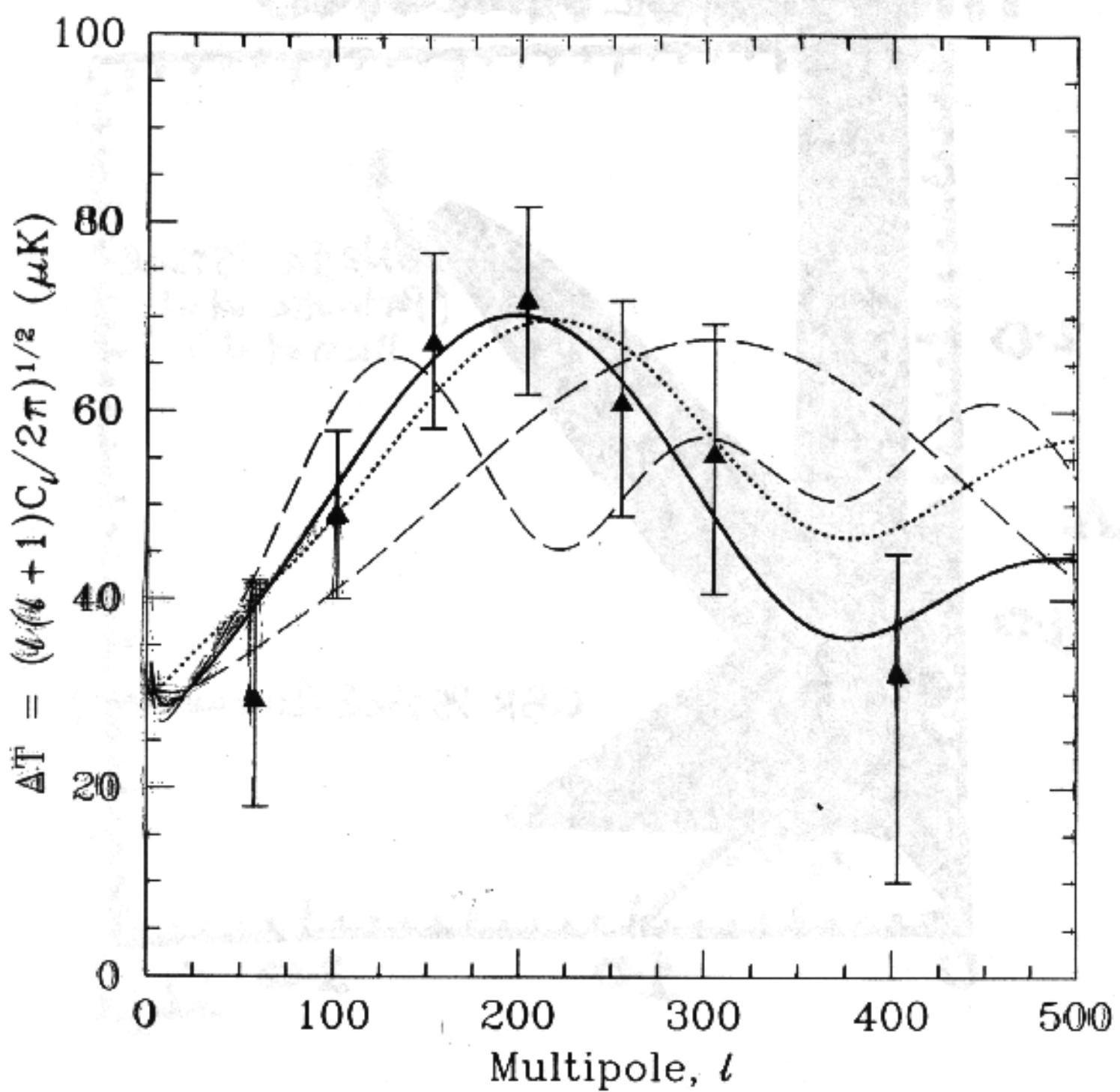


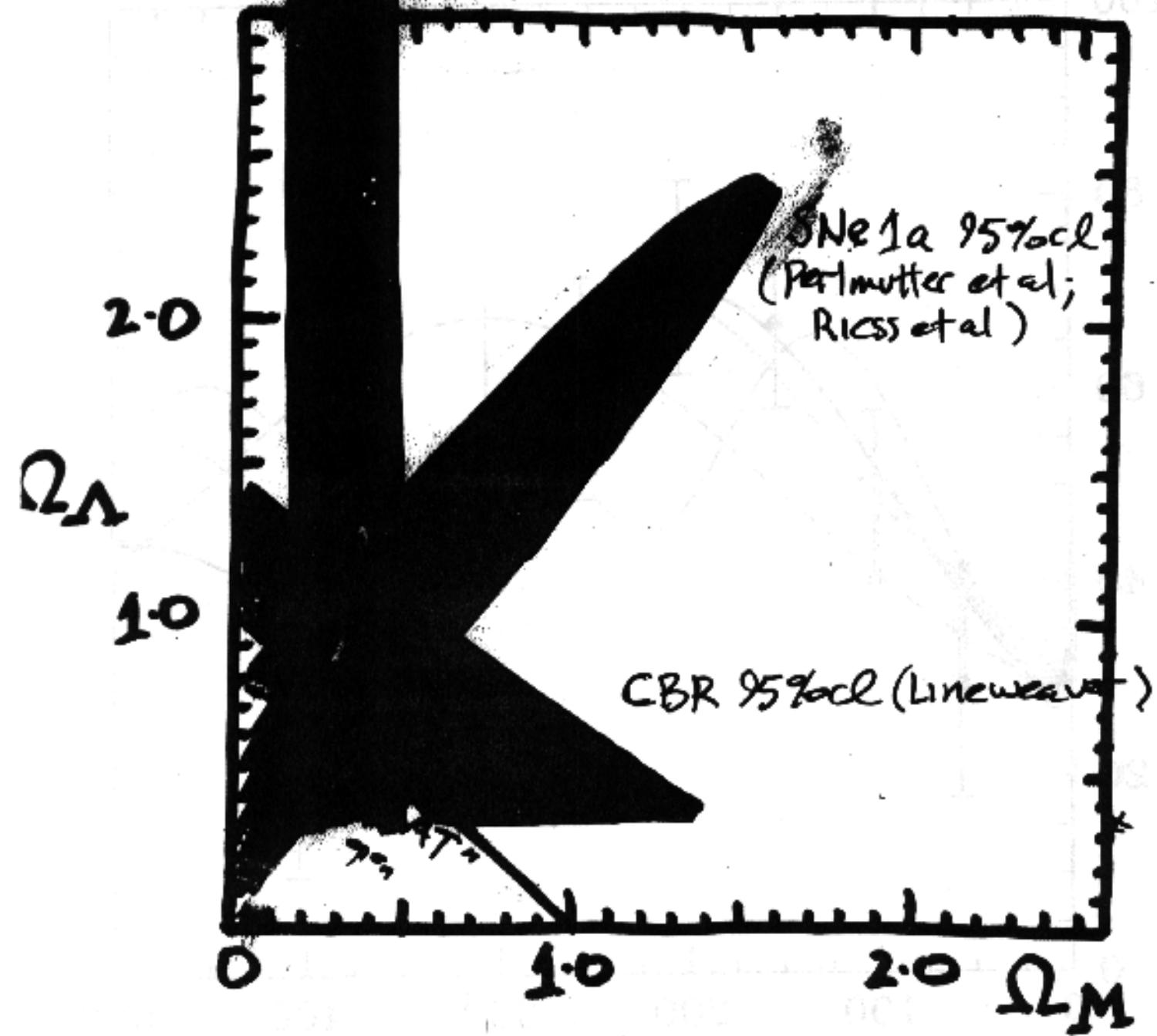
FIG. 3.— Flat band power, $(l(l+1)C_l/2\pi)^{1/2}$, vs. multipole l for all of the modulations. The detections have 1σ error bars and the upper limit has 2σ error bars. The unapodized cosine modulation is plotted with an open square and the apodized cosine modulations are plotted with diamonds. The error bars include statistical uncertainties only and do not include uncertainties in the calibration or beam size. The l range of each modulation is determined by the half-maximum points of $(W_l)^{1/2}$. Low l values correspond to large angular scales and high l values correspond to small angular scales. CMB power is clearly rising from low to high l up to the sensitivity cutoff of PyV.

Its Looking Flat to Me!





"THE BIG PICTURE"



THE DARK ENERGY "DON'T HAVE A CLUE PROBLEM AS TO WHAT THE DARK ENERGY IS!"

"RIGHT NOW, NOT ONLY FOR COSMOLOGY,
BUT ALSO FOR ELEM. PART. TODAY, THIS IS
THE BONE IN OUR THROAT" - S. WEINBERG

IT IS SMOOTH, HAS REPULSIVE
GRAVITY, & INFLUENCES FUTURE FRAMES
CHARACTERIZE IT BY $w_x = P_x/\rho_x$, $w_x(t)$
AS A START

CANDIDATE	w	\dot{w}
COSMOLOGICAL CONSTANT (Λ)	-1	0
FLUCTUATED DEFECTS $N=1$ (string), 2 (walls)	$-\frac{N}{3}$	≈ 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 FLRW COSMOLOGY, ...	?	?

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 is 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.

ACCELERATING UNIVERSE

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

$$\rightarrow \rho_x \sim 2/3 \rho_{\text{crit}} \quad p_x < -\rho_x/3$$

POSSIBILITIES:

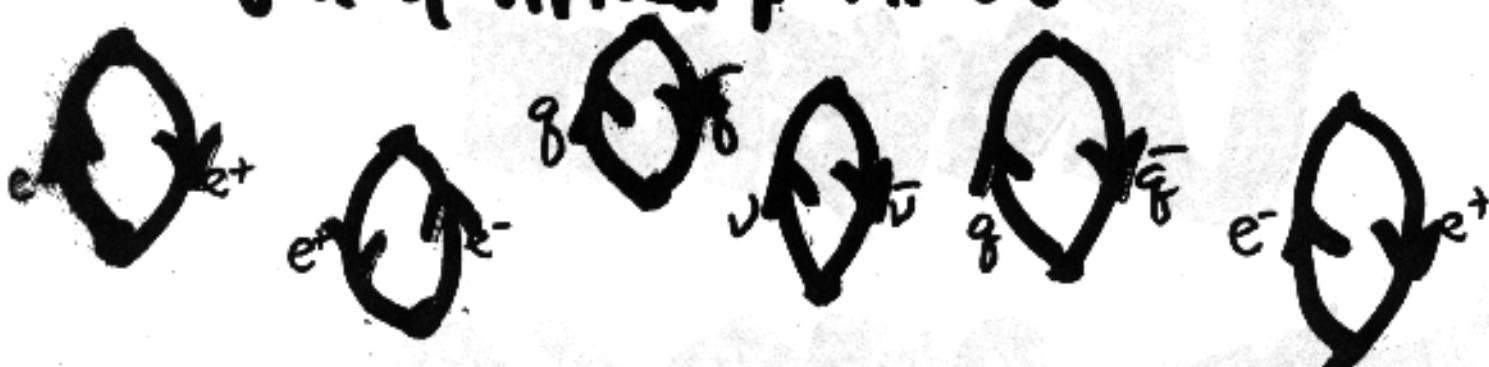
Einstein's COSMOLOGICAL CONST' (VACUUM ENERGY) $p = -\rho$

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
(splitting of atomic levels in H)

Quantum vacuum is elastic
 $\mathbf{T} = -\mathbf{P}$, but how much does
it weigh?

numerical estimates

$$\Omega_{VAC} = \frac{P_{vac}}{P_{crit}} = \infty$$

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

$$\Omega_{VAC} = 10^{122}$$

cut off at m_p

$$'98 \Omega_{VAC} \approx 0.6 ?$$

Harvey; Silverstein-Harvey

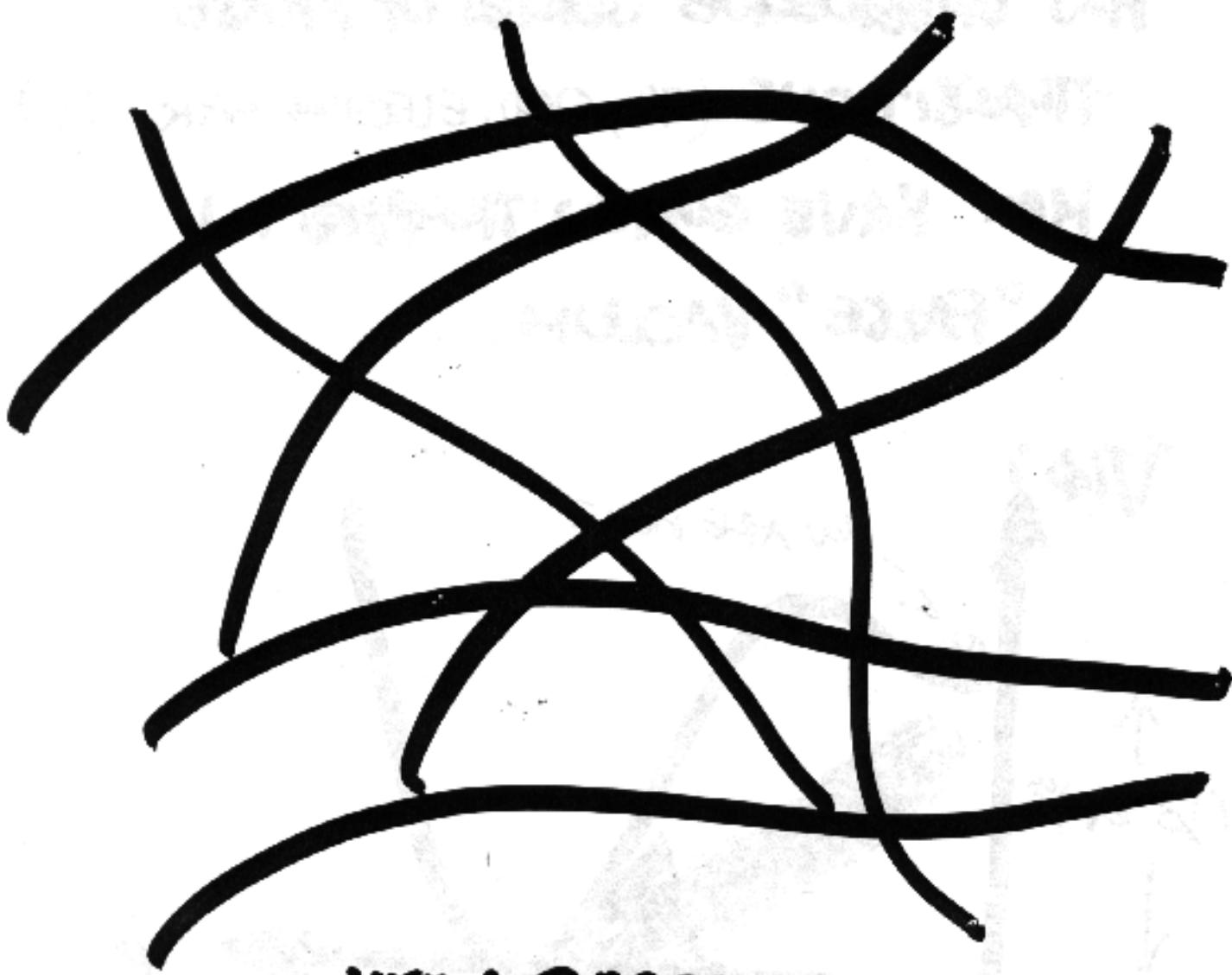
$$?? \Omega_{VAC} = 0^2$$

pre-'98 "guess" of most particle theorists

NETWORK OF (FLUSTRATED) TOPOLOGICAL DEFECTS

EG STRING

A. Vilenkin '84
Pen-Sazgol '93

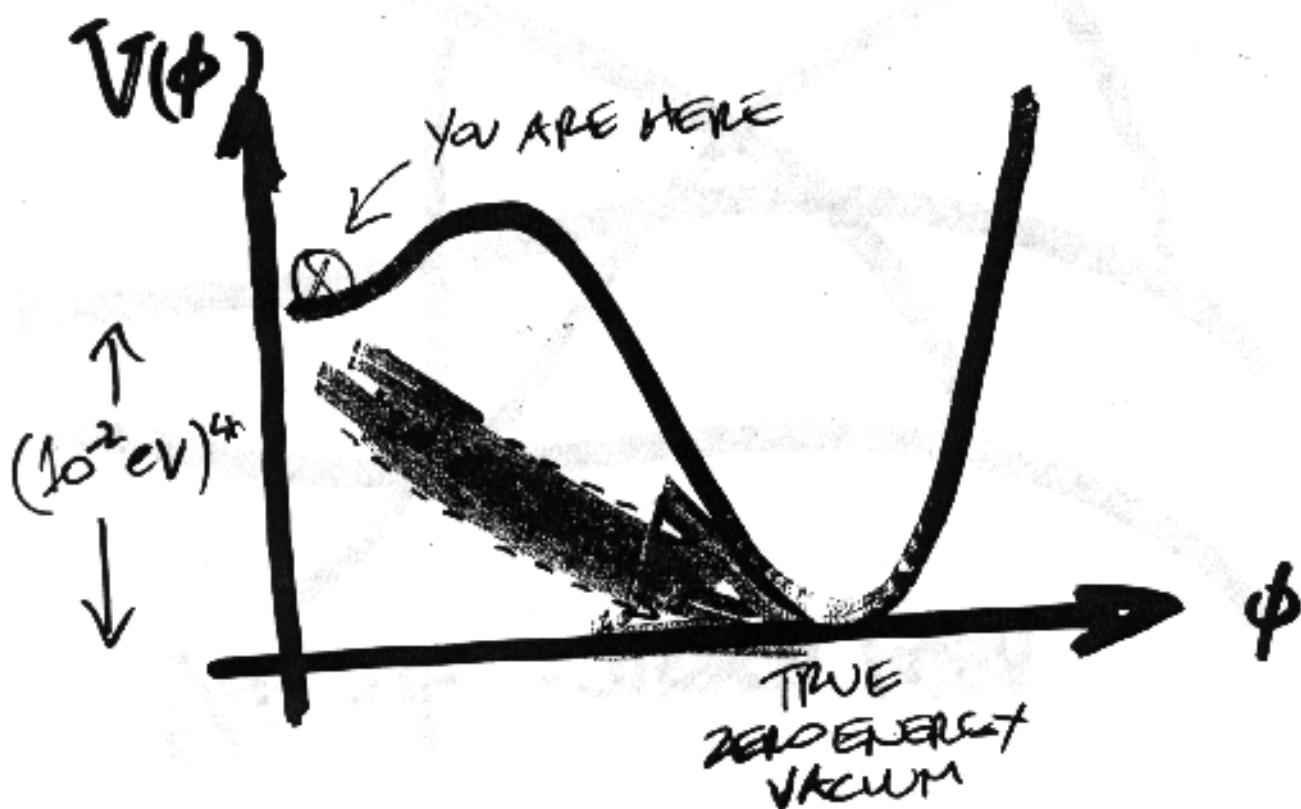


VERY ELASTIC: $\tau = -\rho/3$

YOUTHFUL IDISCRETION

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,
~~dark energy~~)

Bronstein 1933 (executed by Stalin)

Hill Schramm Fry 1986

Freese et al 1987

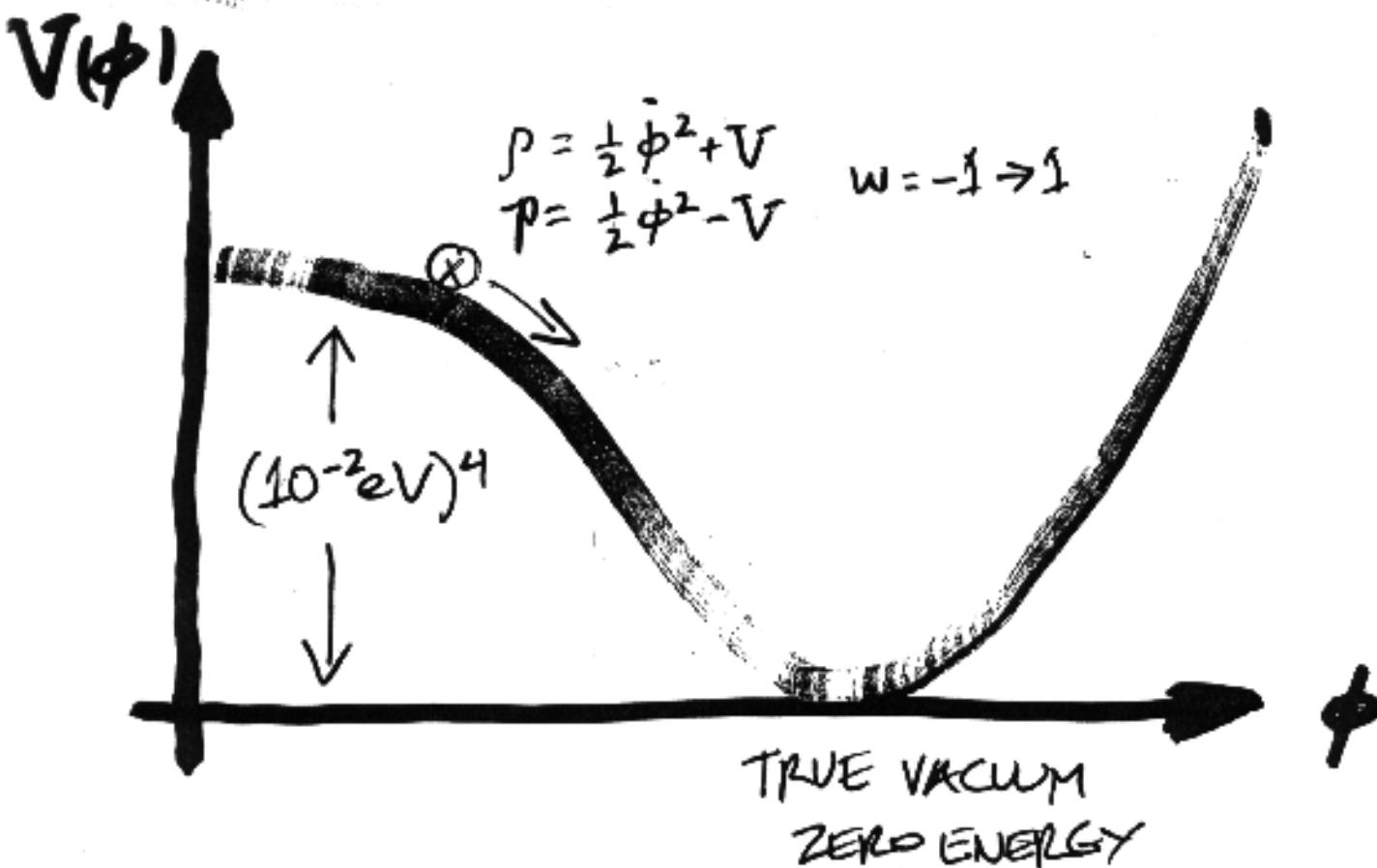
Petra-Peebles 1988

Frieman et al 1995

Caldwell et al 1998

& others

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



$$\tau_{\mu\nu} = \left(\begin{array}{c} \text{LARGE} \\ \text{NEGATIVE PRESSURE} \\ + \text{ANISOTROPIC} \\ \text{STRESS} \end{array} \right)$$

"SOLID DARK MATTER"

Bucher & Spergel

PLD60, 043505 (99)

"GENERALIZED DARK MATTER"

Hu *Astrophys.J.*
506, 405 (90)

Sketch CONCEPT OF THE NATURE OF DARK ENERGY

SNe DETERMINING EXPANSION HISTORY THRU

$\Delta m = m_B - m_V$

$$r(z) = \int_0^z \frac{dx}{H(x)}$$

$$H^2 = H_0^2 [1 + \Omega_m(1+z)^3 + \Omega_X(1+z)^{3(1+w_X)}]$$

($k \approx 0, w = \text{const}$)

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

↑

DETERMINE FROM
SNe DATA

RECONSTRUCT $w(z)$:

$$w_X(z) = -1 + \frac{4z}{3} \frac{3H_0^2 \Omega_m (1+z)^2 + 2(d^2 r / dz^2) / (dr / dz)^3}{H_0^2 \Omega_m (1+z)^3 - 1 / (dr / dz)^2}$$

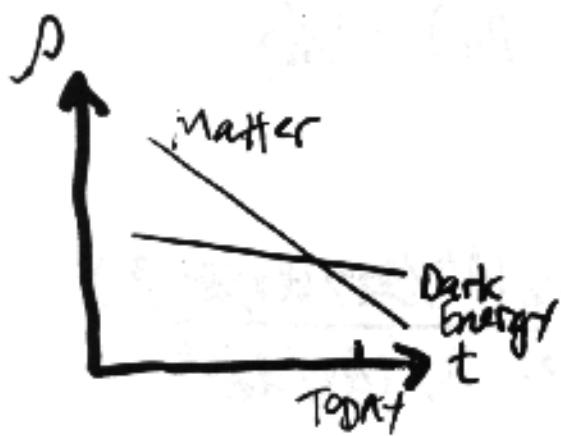
or $V(\phi)$ for scalar field model:

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

NEED QUALITY DATA SET!

KEY ADVANTAGE OF SNe Ia

CAN PROBE RECENT EXPANSION
HISTORY WELL



$$\rho_x/\rho_m = \frac{\Omega_x}{\Omega_m} (1+z)^{3w_x}$$

$$\approx \begin{cases} \text{TODAY} & \approx 1.5 \\ z=2 & \approx 0.05 \\ z=1000 & < 3 \times 10^{-5} \end{cases}$$

WHEN THE DARK ENERGY IS DOMINANT

COSMIC COMPANIONS

GETTING AT DARK ENERGY

(1) ASSUME Λ

	σ_{Ω_m}	σ_{w_0}	σ_{w_k}
MAP*	0.04	0.04	0.02
PLANCK*	0.03	0.02	0.005
D-MEX	0.03	0.05	0.06

* w/SDSS + POLARIZATION
+ AKA SNAP

COMPARABLE & COMPLEMENTARY
& REDUNDANT

(2) ASSUME CONST w_x

	σ_{Ω_m}	σ_{w_x}
MAP*	0.9	2
PLANCK*	0.1	0.3
D-MEX	0.03	0.05

POLARIZATION, $\Omega_k = 0$

D-MEX WINS BY WIDE MARGIN

(3) DO NOT ASSUME CONST w_x

ONLY D-MEX HAS
SUFFICIENT POWER TO
ATTACK THIS PROBLEM

PROBING THE MYSTERIOUS DARK ENERGY

$$w_{\text{eff}} = \langle P_x/P_y \rangle \quad \Delta = -1$$

$$\text{STRINGS: } -\frac{1}{3}$$

Perlmutter-White-MST
[astro-ph/990152](#)

COMPLEMENTARITY

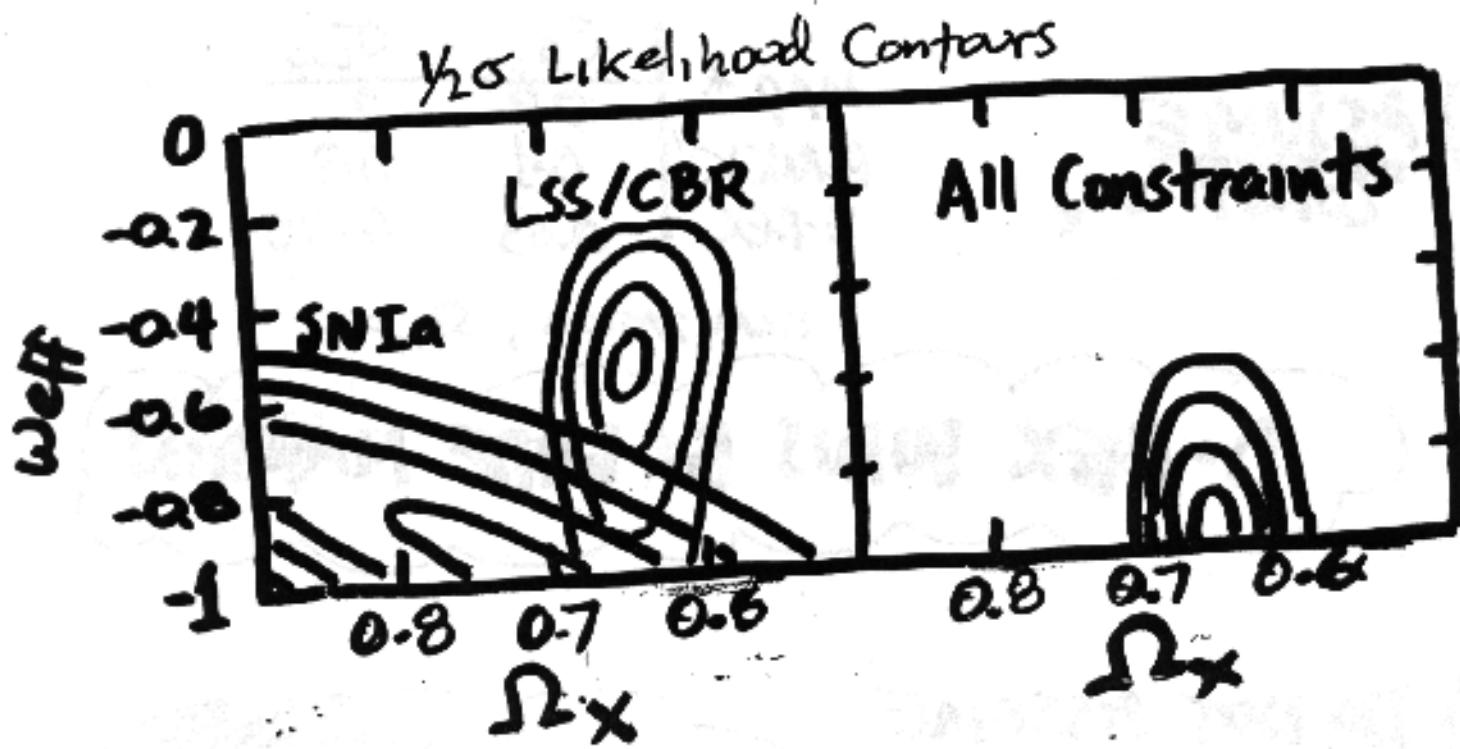
SN Ia

LSS/CBR

CONSISTENCY

AGE OF UNIVERSE
GRAT. LENSING

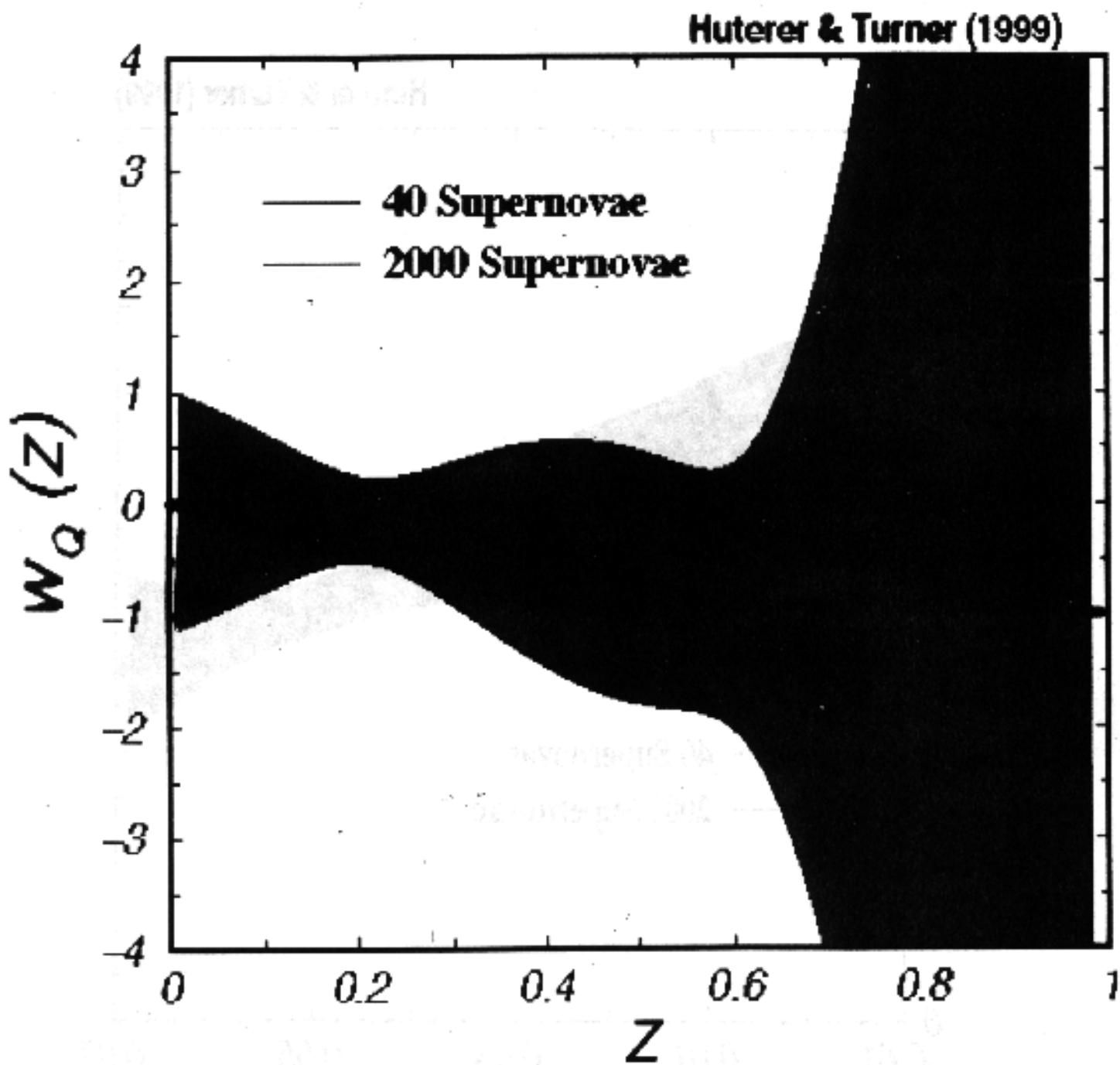
Ω_M (direct
measures)



AT 95% CL: $w_{\text{eff}} < -0.6 \quad 0.6 < \Omega_X < 0.7$

N.B.: Also see, L.Wang et al [astro-ph/9901303](#) for similar but different conclusions.

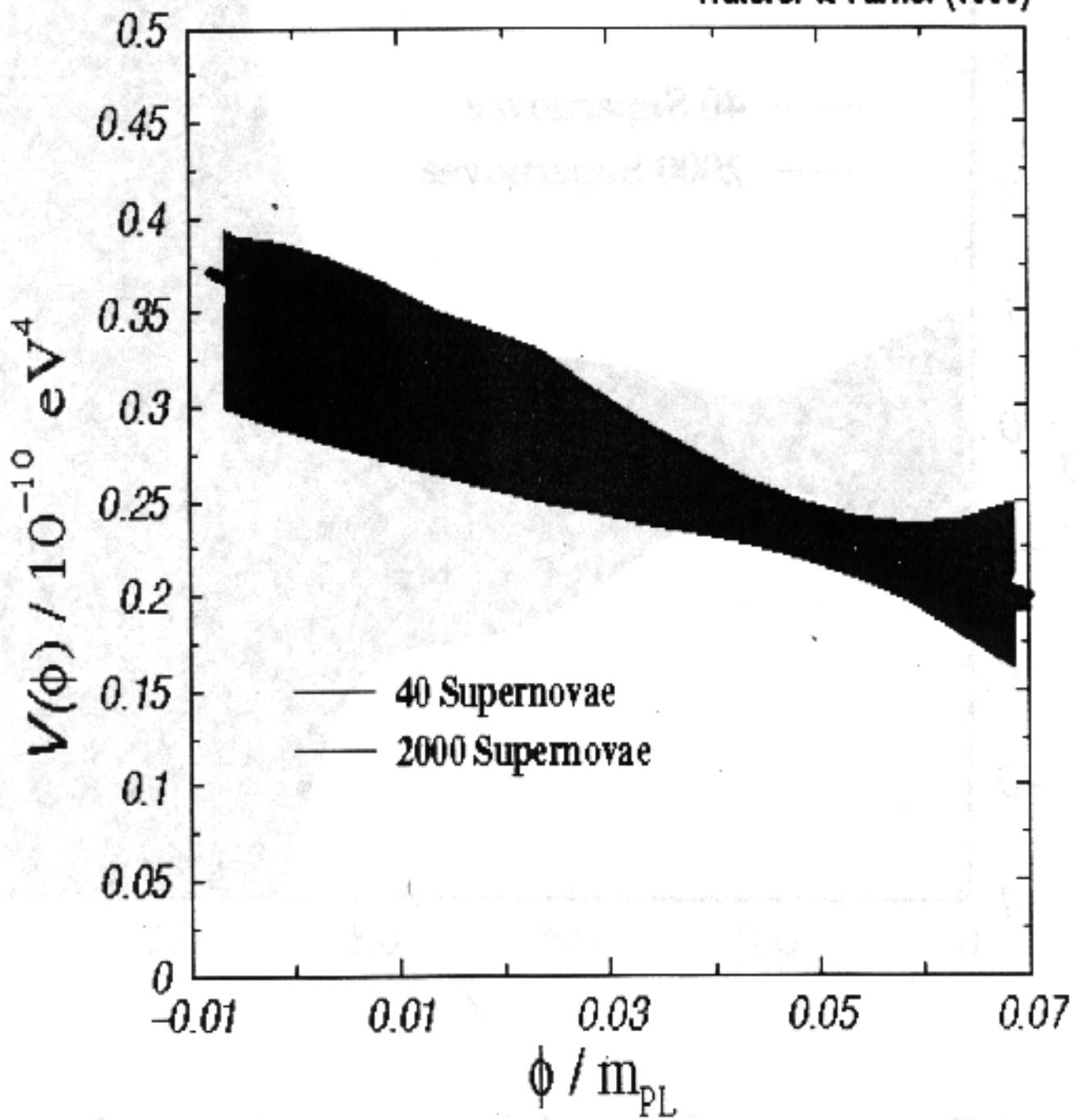
Probing Dark Energy with SNe Ia



NB: Lost of sensitivity about $z = 0.8$

Probing Dark Energy with SNe Ia

Huterer & Turner (1999)



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