from QUARK SOUP to the EXPANDING UNIVERSE

HOT BIG-BANG COSMOLOGY

TESTED BACK TO: 10^{-5}s → 14 Gyr

... and now possibly back to

QUANTUM FLUCTUATIONS

BOLD IDEAS -- INFLATION + COLD DARK MATTER --
BORN OF THE INNER-SPACE/OUTER-SPACE CONNECTION

BEGINNING TO BE TESTED BY A FLOOD OF DATA

PRECISION COSMOLOGY

THE HOT BIG BANG

IT REALLY HAPPENED!

RELIABLE & TESTED ACCOUNTING:

$t \simeq 10^{-2}$ sec $\rightarrow$ 15 Gyr

$T \simeq 10$ MeV $\rightarrow$ 2.73 K

UNIVERSAL EXPANSION

$t \gtrsim 1$ Gyr

$H_0 = 65 \pm 7$ km s^{-1} Mpc^{-1}

COSMIC MICROWAVE BACKGROUND

$t \simeq 300{,}000$ yrs

$T_0 = 2.728 \pm 0.002$ K

3½ Decades in wavelength

PRIMORDIAL NUCLEOSYNTHESIS

^{4}He, D, ^{3}He, ^{7}Li

$t \simeq 10^{-2}$ sec - 100 sec

$T \simeq 10$ MeV - 0.1 MeV

BBN: $\Omega_B = 0.05 \pm 0.01$

$N_\nu < 3.2$

LEP: $N_\nu = 2.991 \pm 0.016$

STRUCTURE FORMATION --

GALAXIES, CLUSTERS, SUPERCLUSTERS, VOIDS, WALLS

GENERAL FRAMEWORK: Jeans Instability

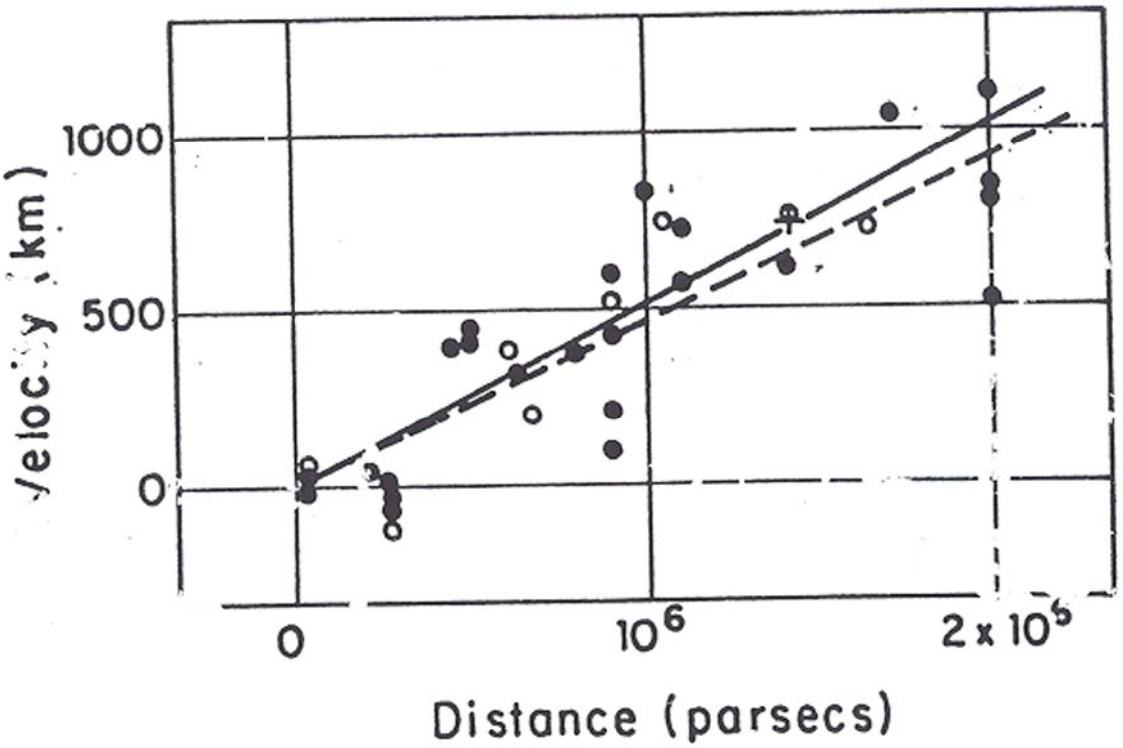
$(\delta T/T) \simeq 10^{-5}$ $t \gtrsim 1000$ yrs

E. HUBBLE

PROC. NAT. ACAD. SCI. 15, 168 (1929).

$H_0 = 550 \text{ km sec}^{-1} \text{ Mpc}^{-1}$

"HUBBLE'S LAW"

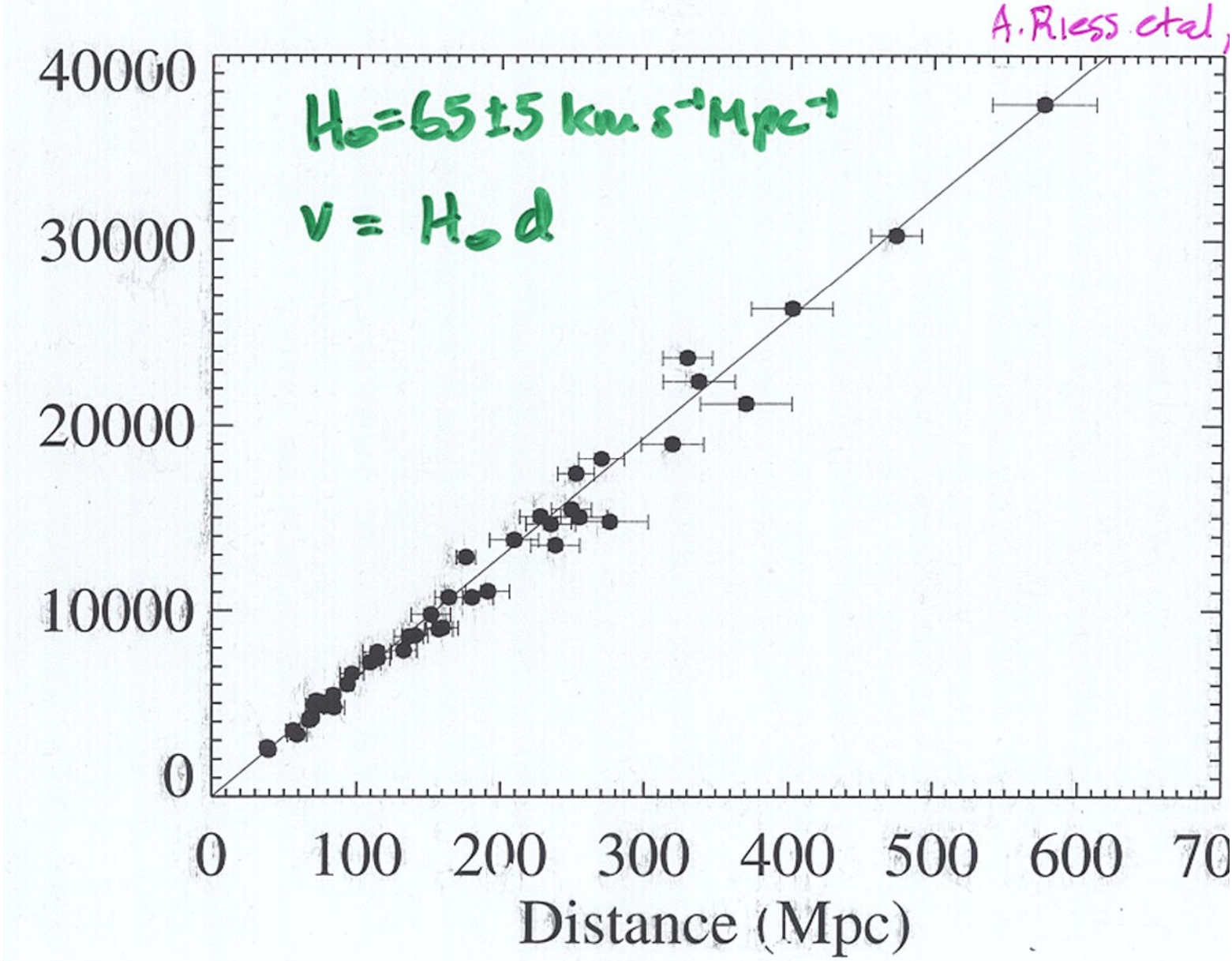


$$H_0 = \frac{\text{velocity}}{\text{distance}} = [T]^{-1}$$

Velocity-Distance Relation among Extragalactic Nebulae.

Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean dis-

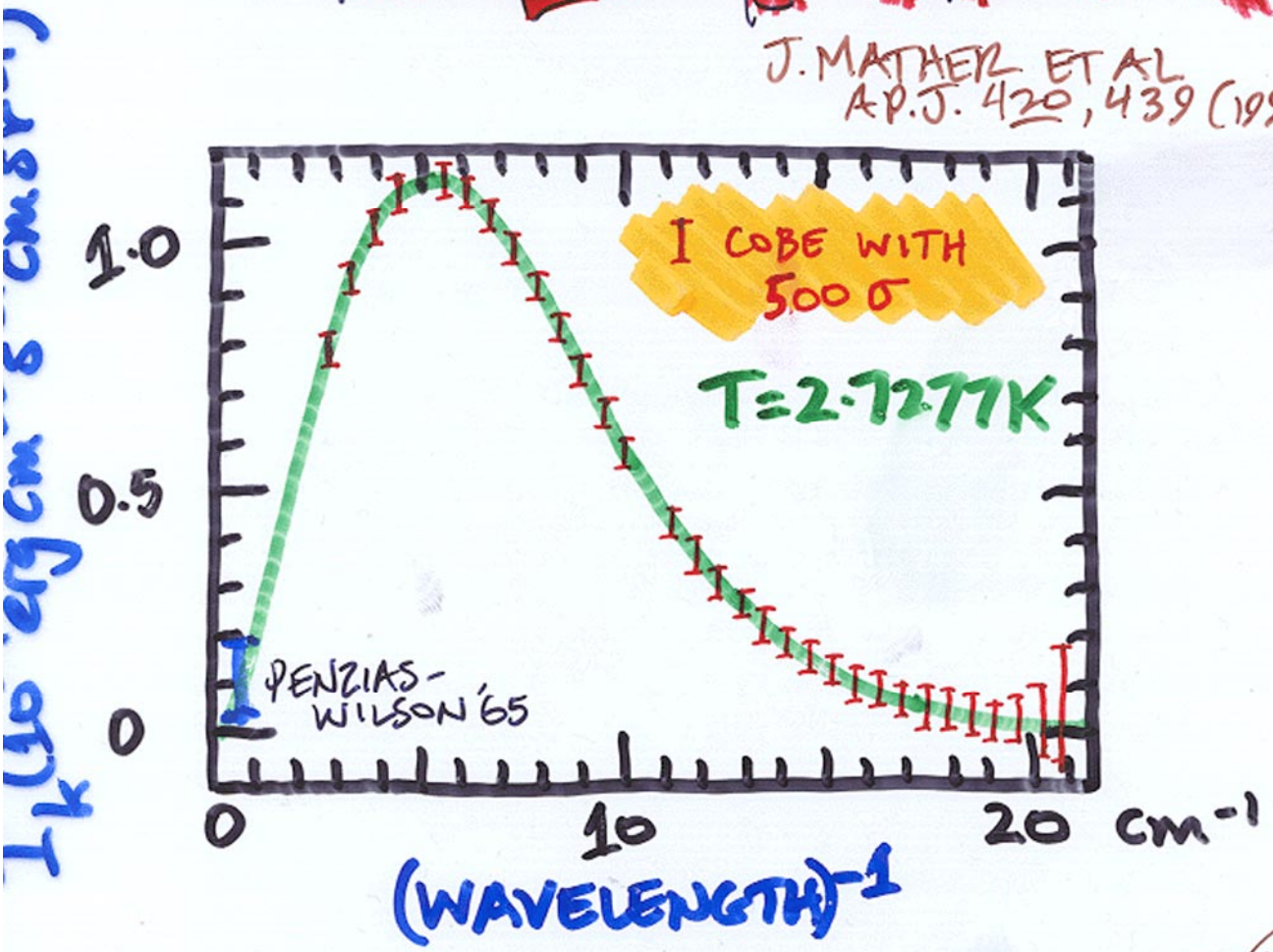
AL" HUBBLE DIAGRAM



65's reputation ±10 family pet ±15 child ±20 first b

COBE FIRAS

J. MATHER ET AL
A.P.J. 420, 439 (1994)



ACCURACY OF MEASUREMENT

$T = 2.7277\,K \pm 0.00001\,K \pm 0.002\,K$

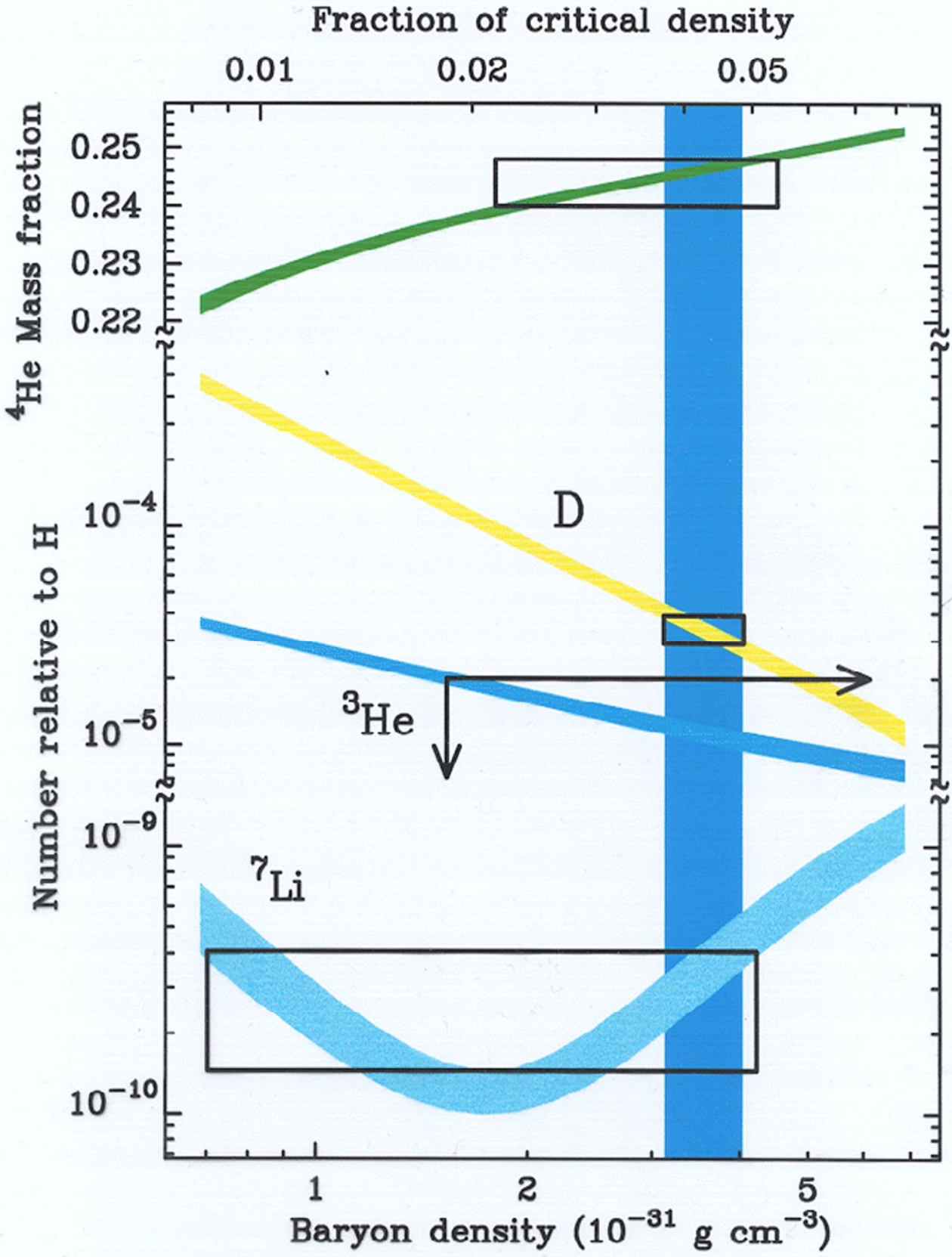
D.J. FIXSEN, ET AL, ApJ 473, 576 (96)

TEMP. SCALE

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

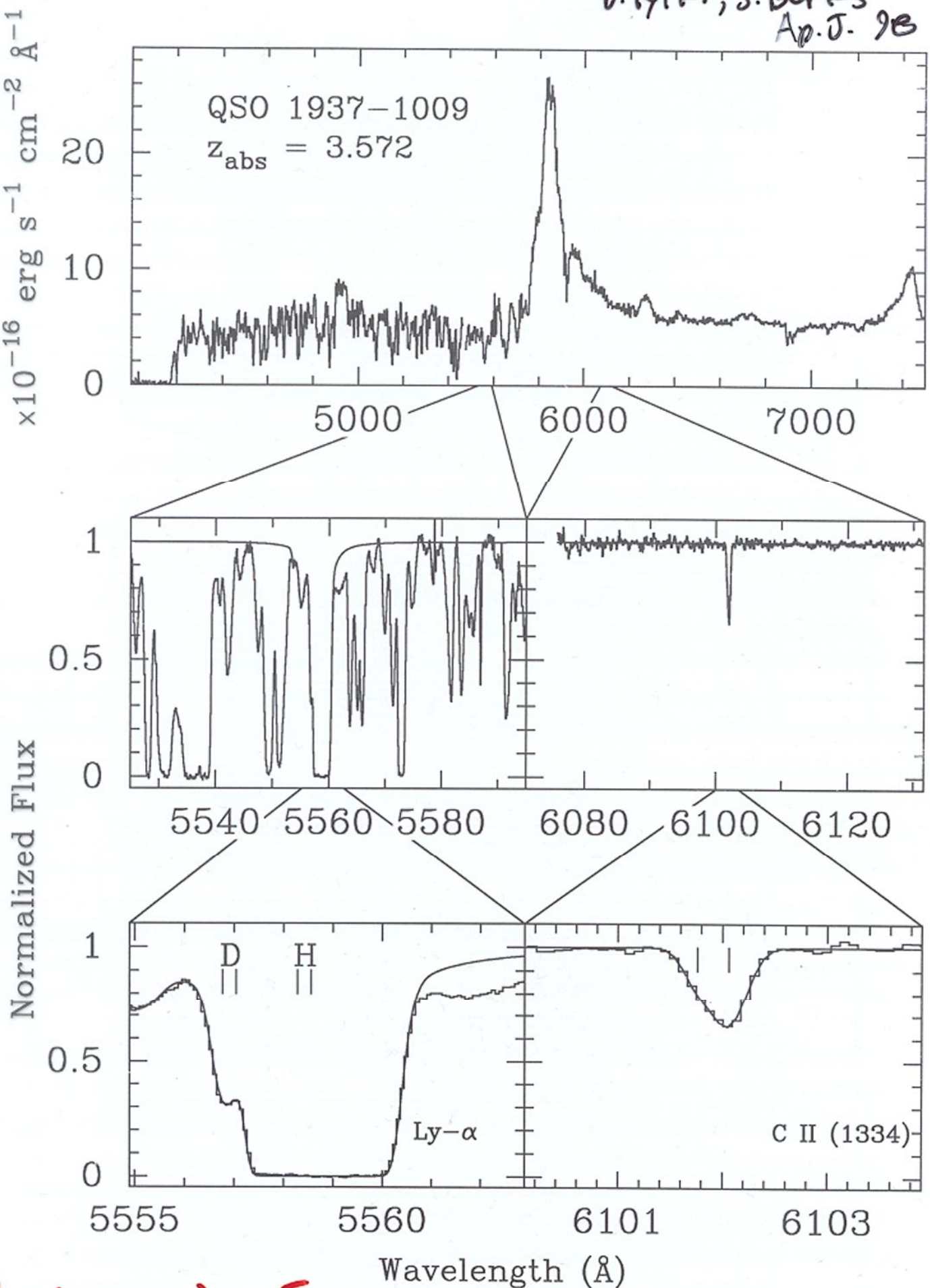
$|\mu/kT| < 3.3 \times 10^{-4}$ $\quad y < 2.5 \times 10^{-5}$ (95% cl)

"BEST BLACK BODY KNOWN"



INVENTORY OF ORDINARY MATTER AT A

D. Tytler, S. Burles
Ap. J. 98



D/H = (3.4 ± 0.3) · 10^{-5}

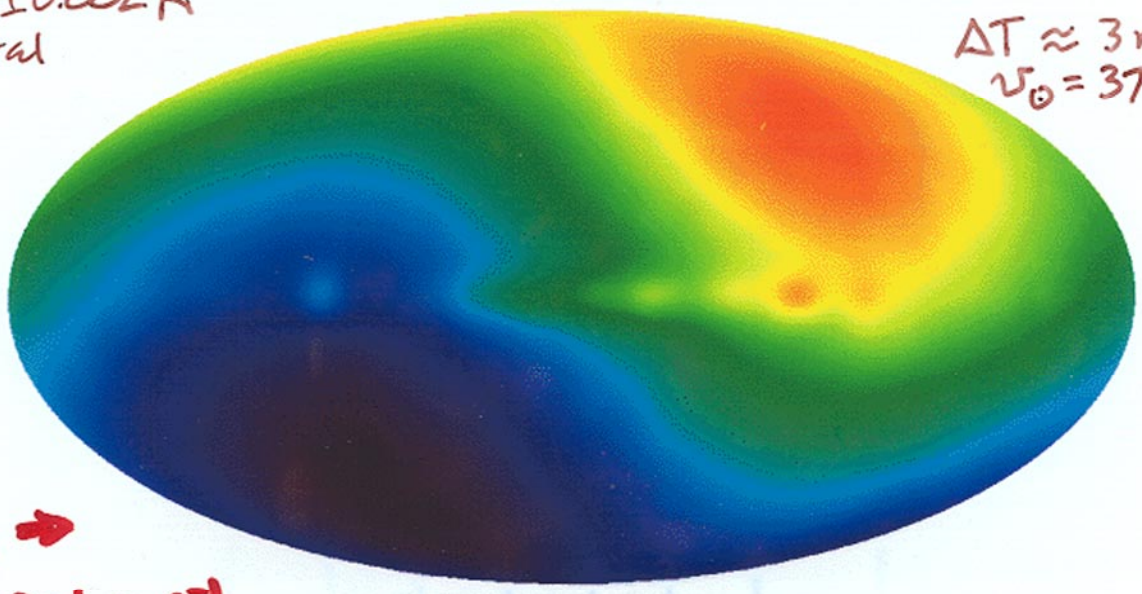
NB: FOUR OTHER SYSTEMS SUPPORT

COBE DMR 4-YR

G. SMOOT et al.

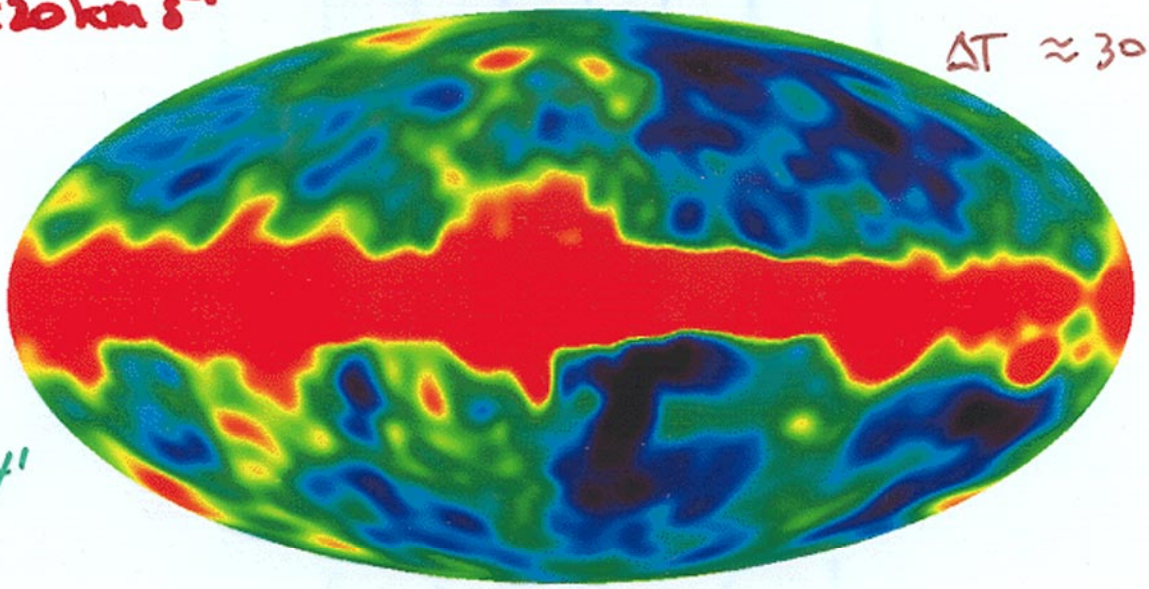
$T = 2.728 \pm 0.002$ K
J. Mather et al

$\Delta T \approx 3$ mK
$v_\odot = 370 \pm 0.5$ km/sec

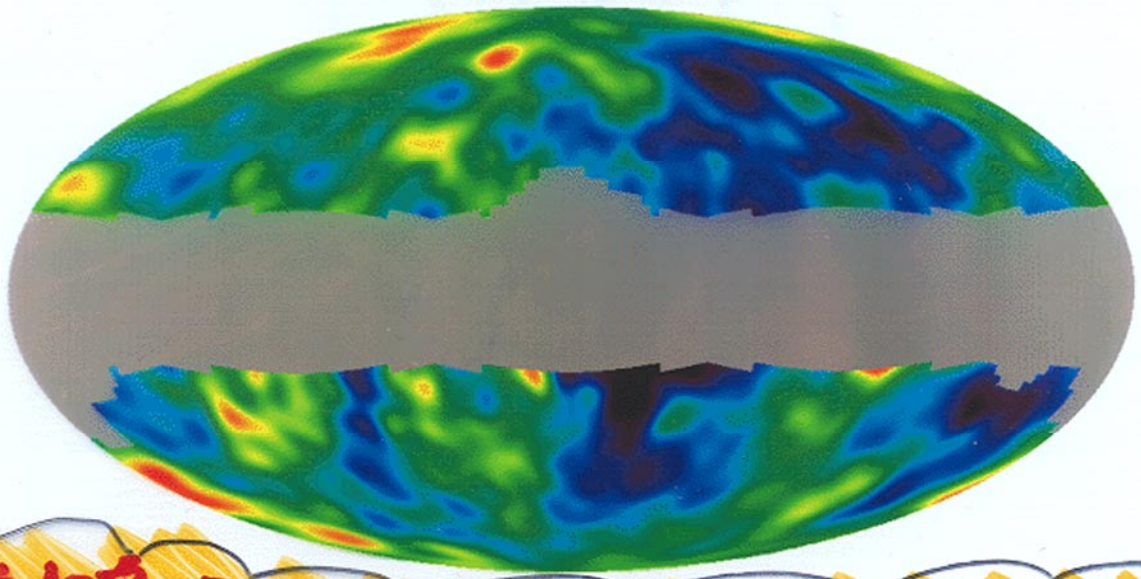


DIPOLE →
$v = 620 \pm 20$ km s^{-1}

$\Delta T \approx 30\ \mu$K

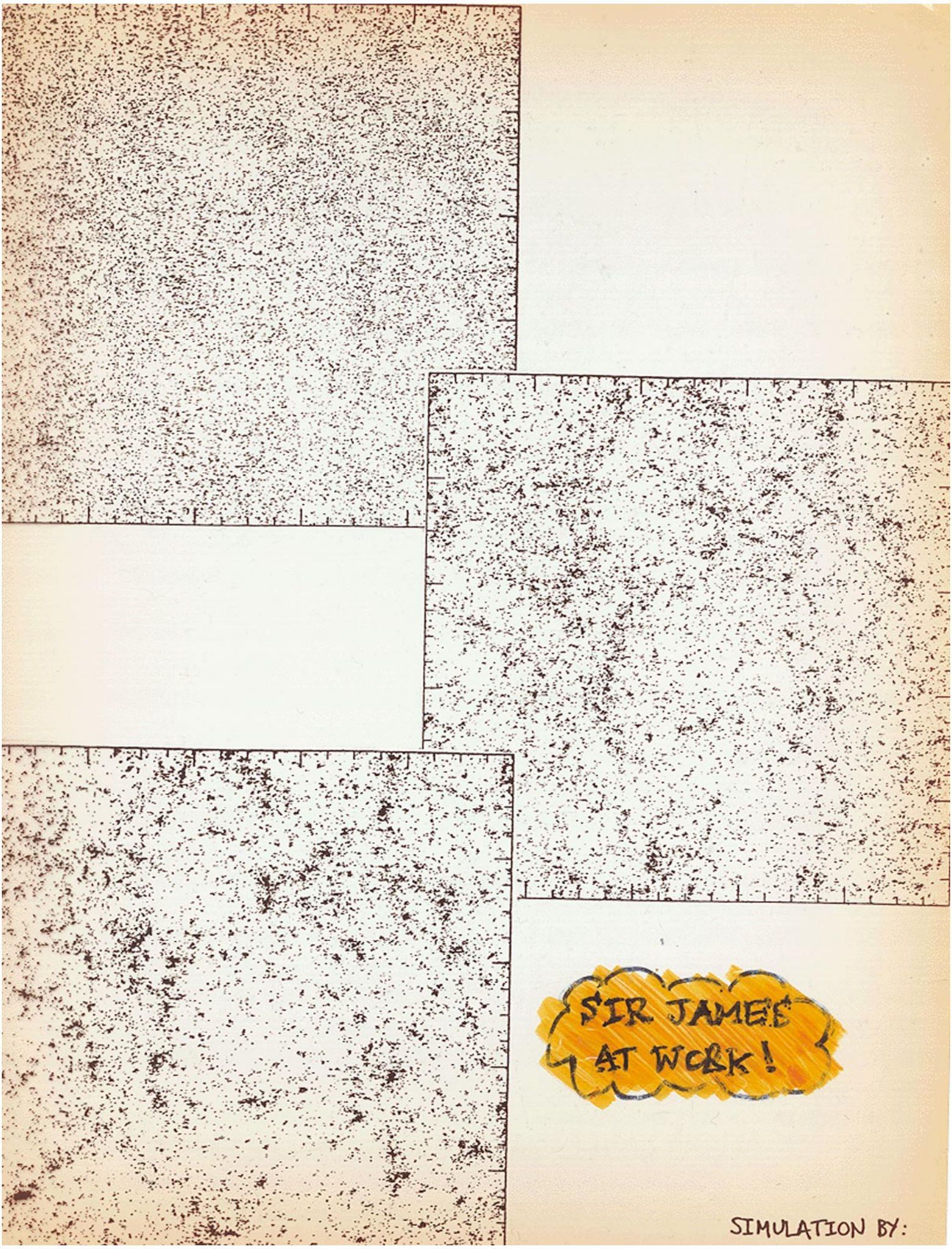


GLOW OF THE GALAXY!



$\delta T/T \approx 10^{-5}$ →

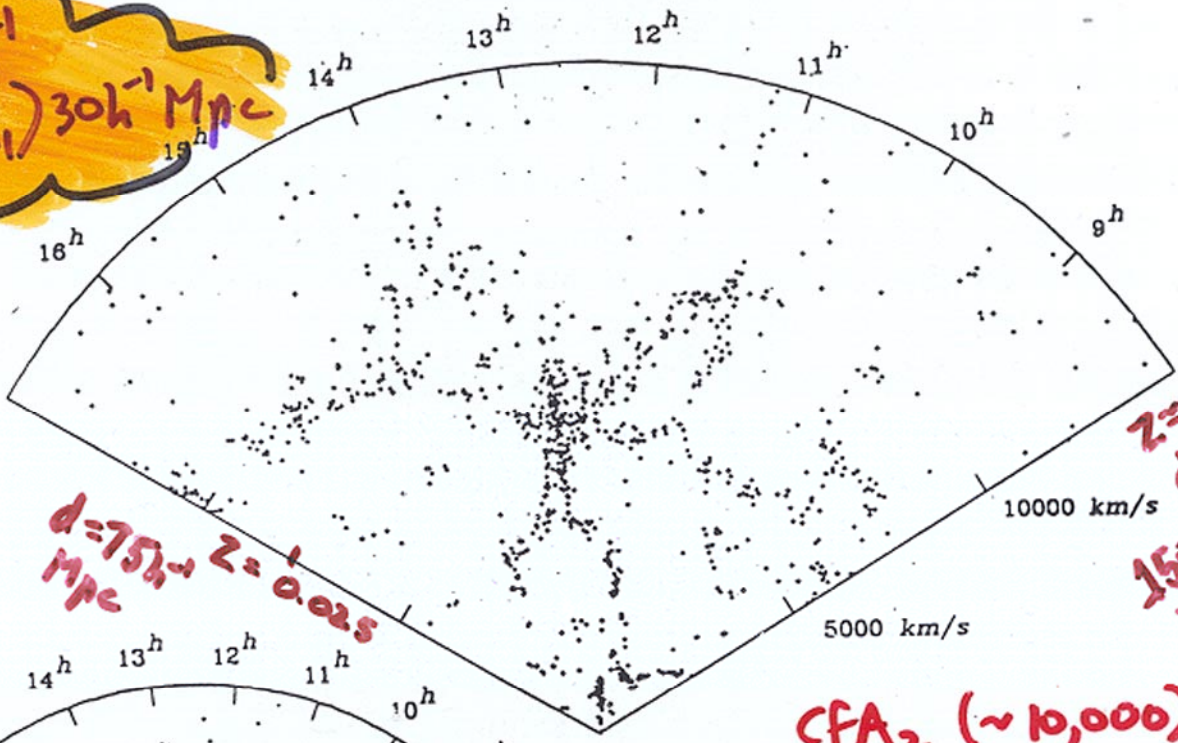
SEEDS FOR METRIC OF STRUCTURE


SIR JAMES
AT WORK!
SIMULATION BY:

CfA SLICES OF THE UNIVERSE

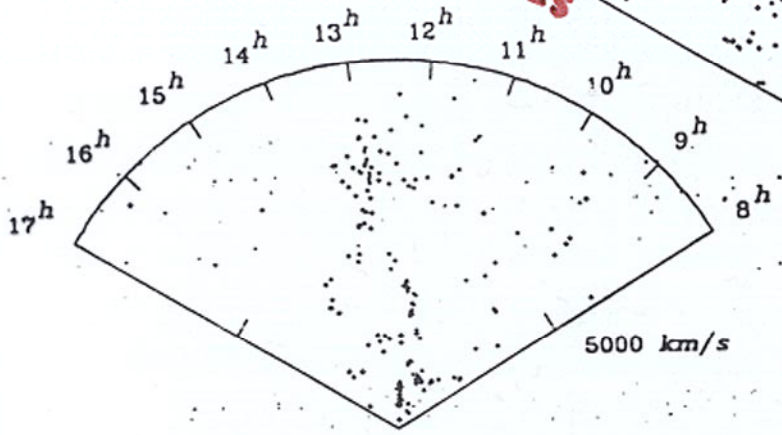
MEASURE RED SHIFT
GET DISTANCE:

$d = z H_0^{-1}$
$\approx (z/0.01)\, 30h^{-1}$ Mpc



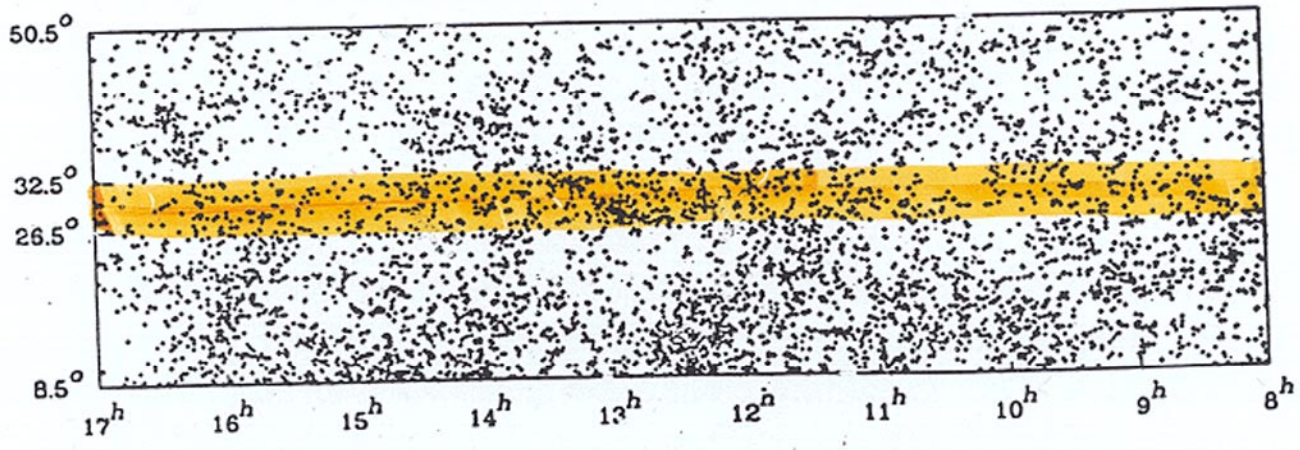
$z = 0.05$
$d \simeq 150h^{-1}$ Mpc

$d = 75h^{-1}$ Mpc $z = 0.025$



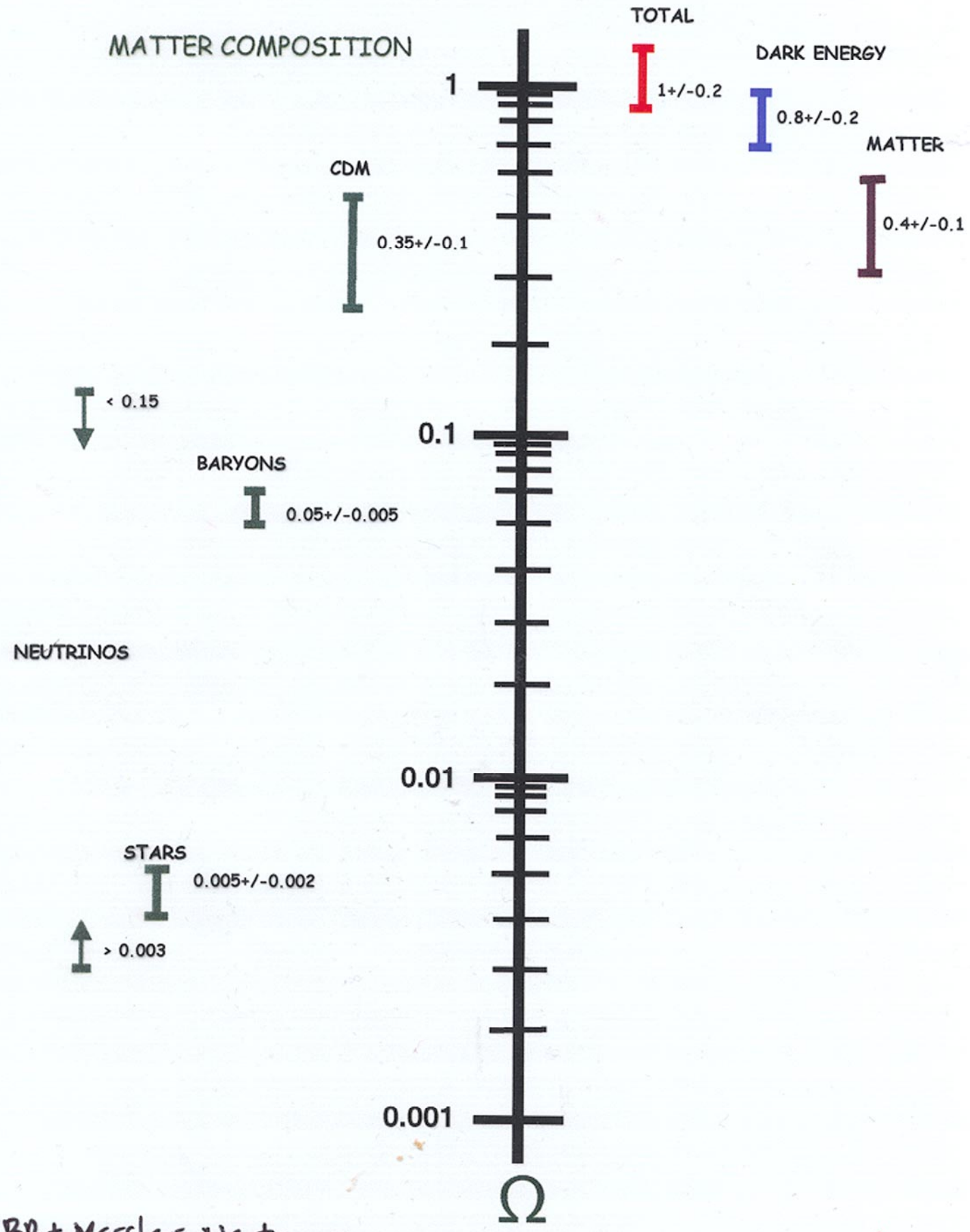
CfA$_2$ (~ 10,000)
de Lapparent - Geller - Huchra
(1986 → 1990)

CfA$_1$ (1982)



ZWICKY Catalogue

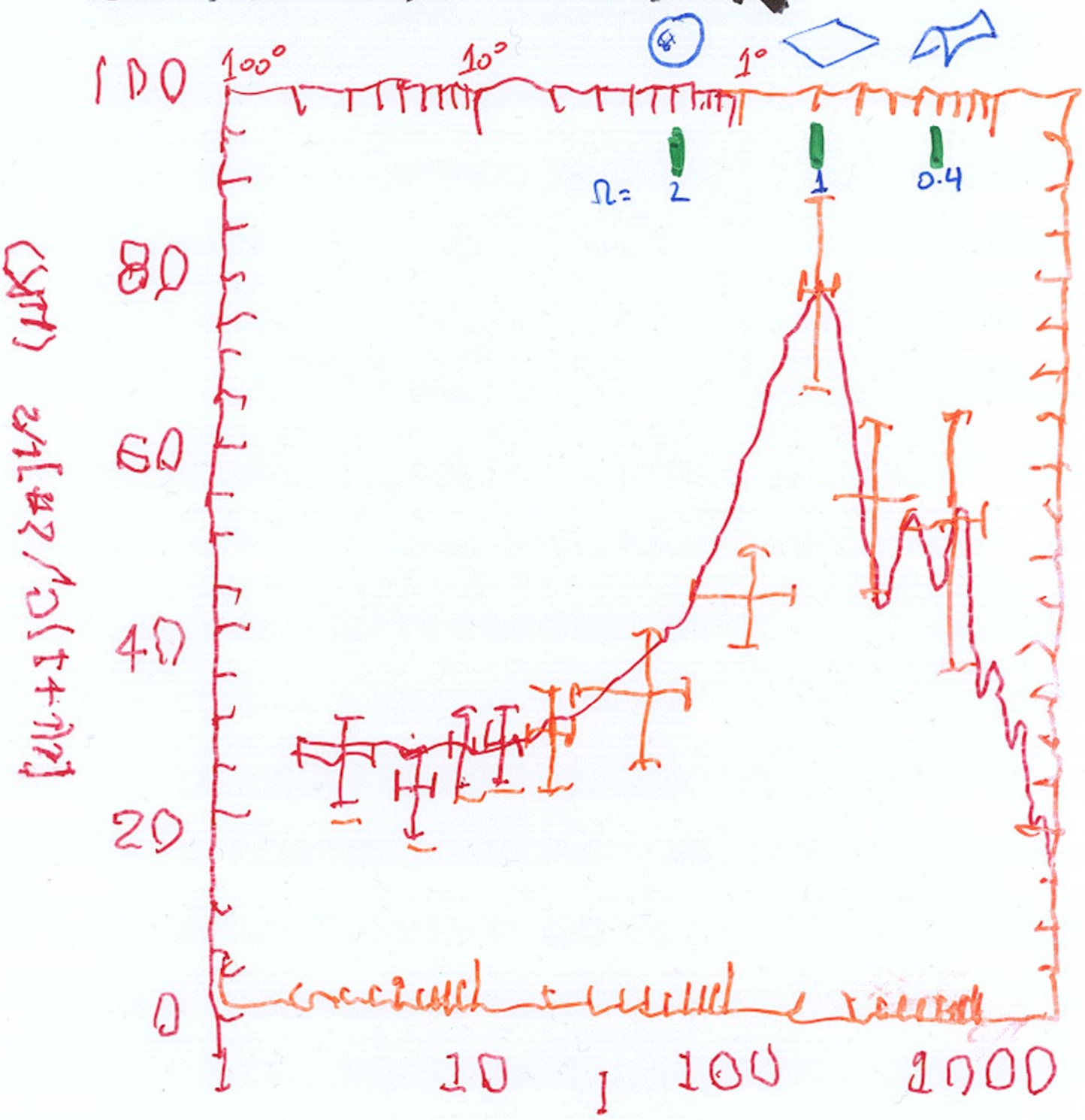
MATTER / ENERGY in the UNIVERSE



CBR + Massless Neutrinos :

version 1.0

"GEOMETRY-METER"



Lloyd KNOX and TOE TURNER

CLUSTER BARYON FRACTION + Ω_B → Ω_M

MOST BARYONS ARE IN THE HOT X-RAY EMITTING GAS

White et al, Nature 366, 429(93)

FAIR SAMPLE HYPOTHESIS:

$$\frac{\Omega_B}{\Omega_M} = \frac{M_{GAS}}{M_{TOT}}$$

$\frac{\Omega_B}{\Omega_M}$ ← BBN: $(0.02 \pm 0.002)h^{-2}$

M_{GAS} ← X-ray Flux, S-Z

M_{TOT} ← X-ray temp, Grav. Lensing, Virial Thm

Evrard '97

$$\langle M_{GAS}/M_{TOT} \rangle = (0.07 \pm 0.007)h^{-3/2}, \quad (0.06 \pm 0.006)h^{-1}$$

Carlstrom '98 S-Z

$$\Omega_M = \underbrace{(0.3 \pm 0.05)h^{-1/2}}_{\text{X-ray}}, \quad \underbrace{(0.25 \pm 0.04)h^{-1}}_{\text{S-Z}}$$

THE LEADING Particle Dark Matter CANDIDATES for Master of the Universe

MOTIVATED BY PARTICLE PHYSICS
$\Omega \sim 1$ "THE COSMOLOGICAL BONUS"

AXION $\sim 10^{-5}$ eV

- PART OF SOL^N TO STRONG CP-PROBLEM
- "COLD" DARK MATTER
- DETECTABLE $a_{HALO} + \vec{B} \rightarrow \gamma_{microwave}$

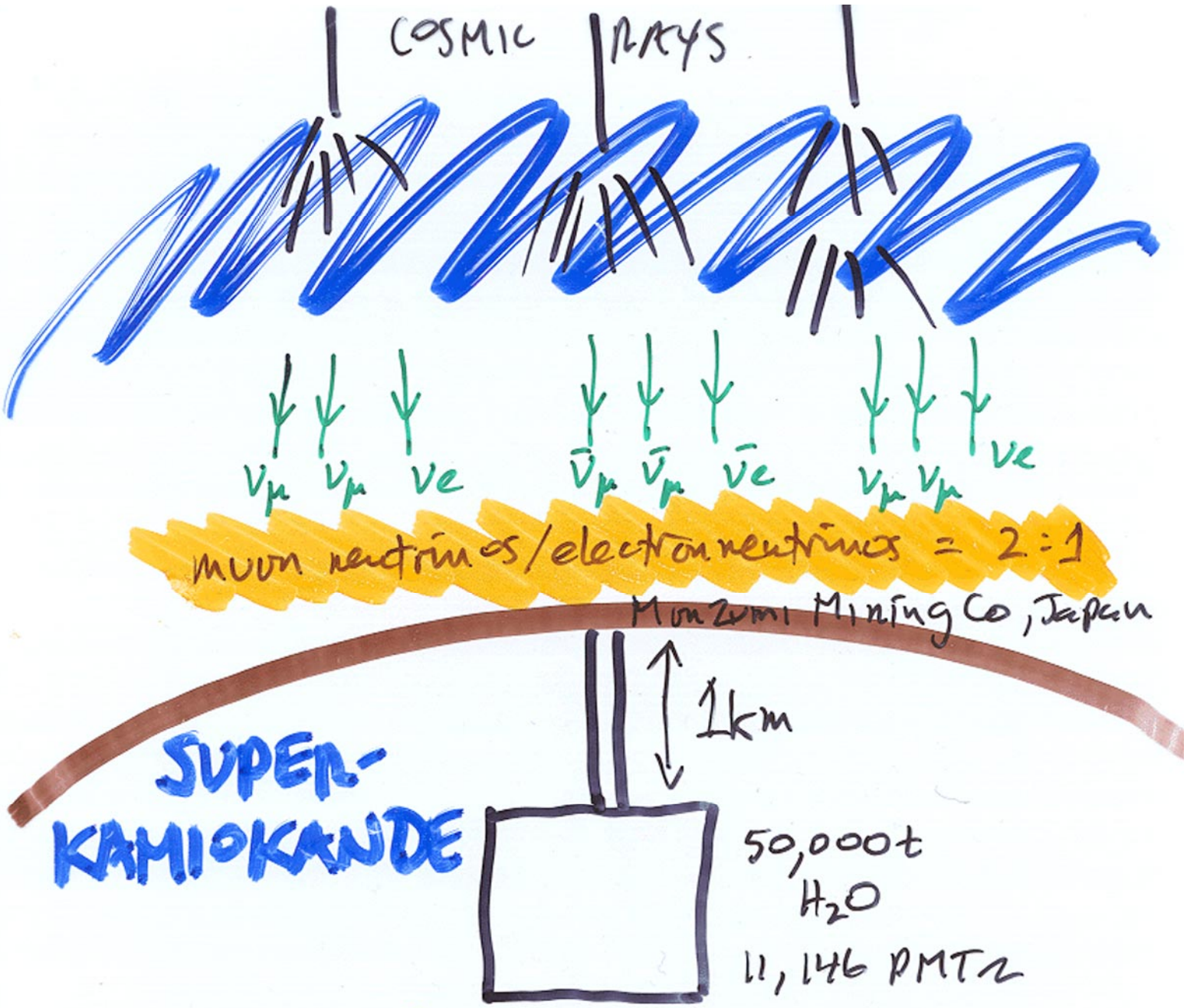
NEUTRALINO $\sim 10 - 1000$ GeV*

- LIGHTEST SUPERSYMMETRIC PARTICLE
- COLD DARK MATTER
- DETECTABLE $\chi_{HALO} + A \rightarrow \chi + A + keV$

*0(1 GeV) PHOTINO farrar-Kolb

NEUTRINO $\sim 10 - 30$ eV

- KNOWN TO EXIST!
- "HOT" DARK MATTER
- GAERT "ADDITIVE"

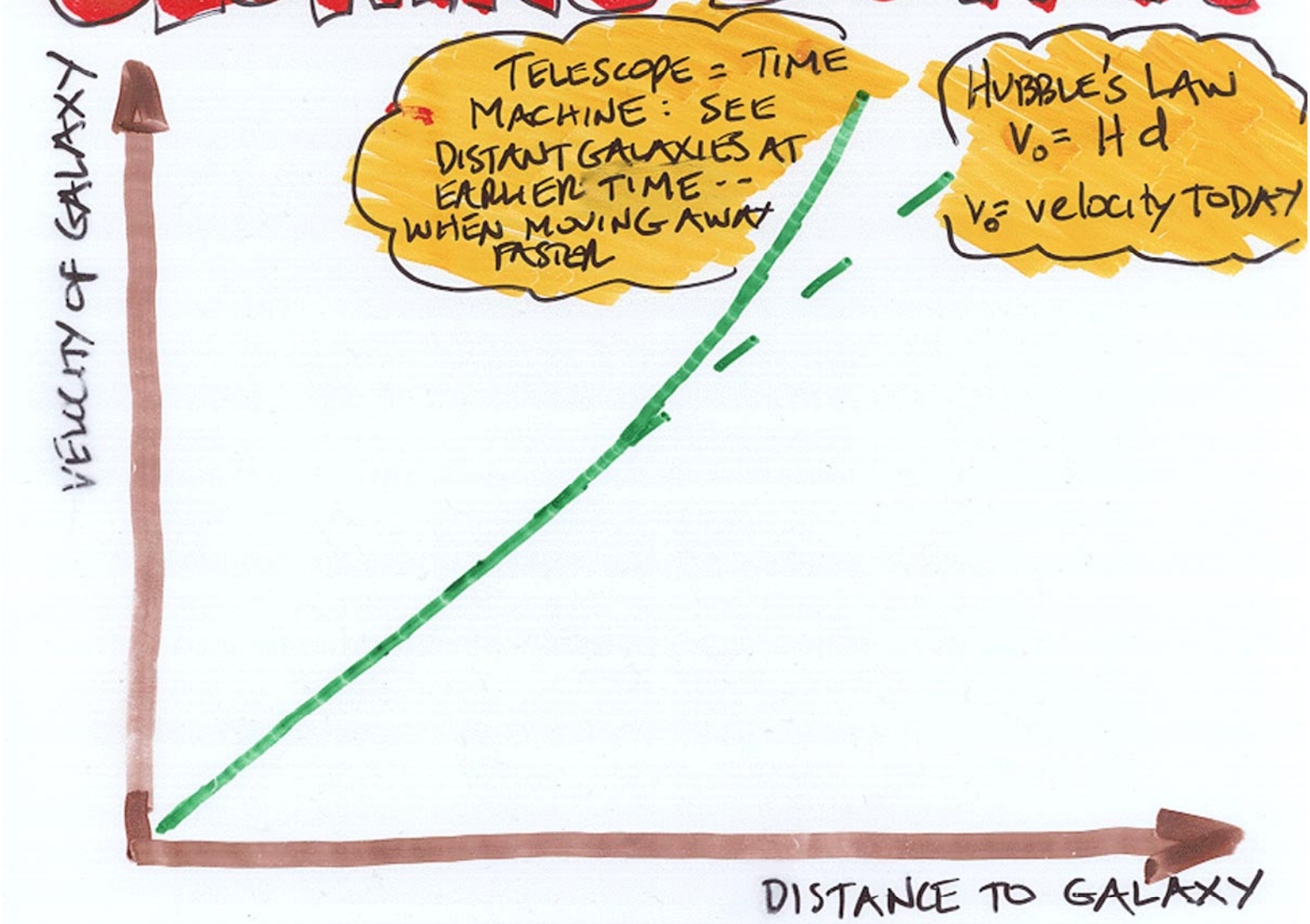


DETECT EQUAL NUMBERS OF ν_e, ν_μ
NEUTRINO OSCILLATIONS

→ AT LEAST ONE NEUTRINO SPECIES HAS A MASS $\geq 0.1 eV$
(PROBABLY MUON NEUTRINO)

UNIVERSE IS SPEEDING UP!?# WHY?

Is the Universe Slowing Down?



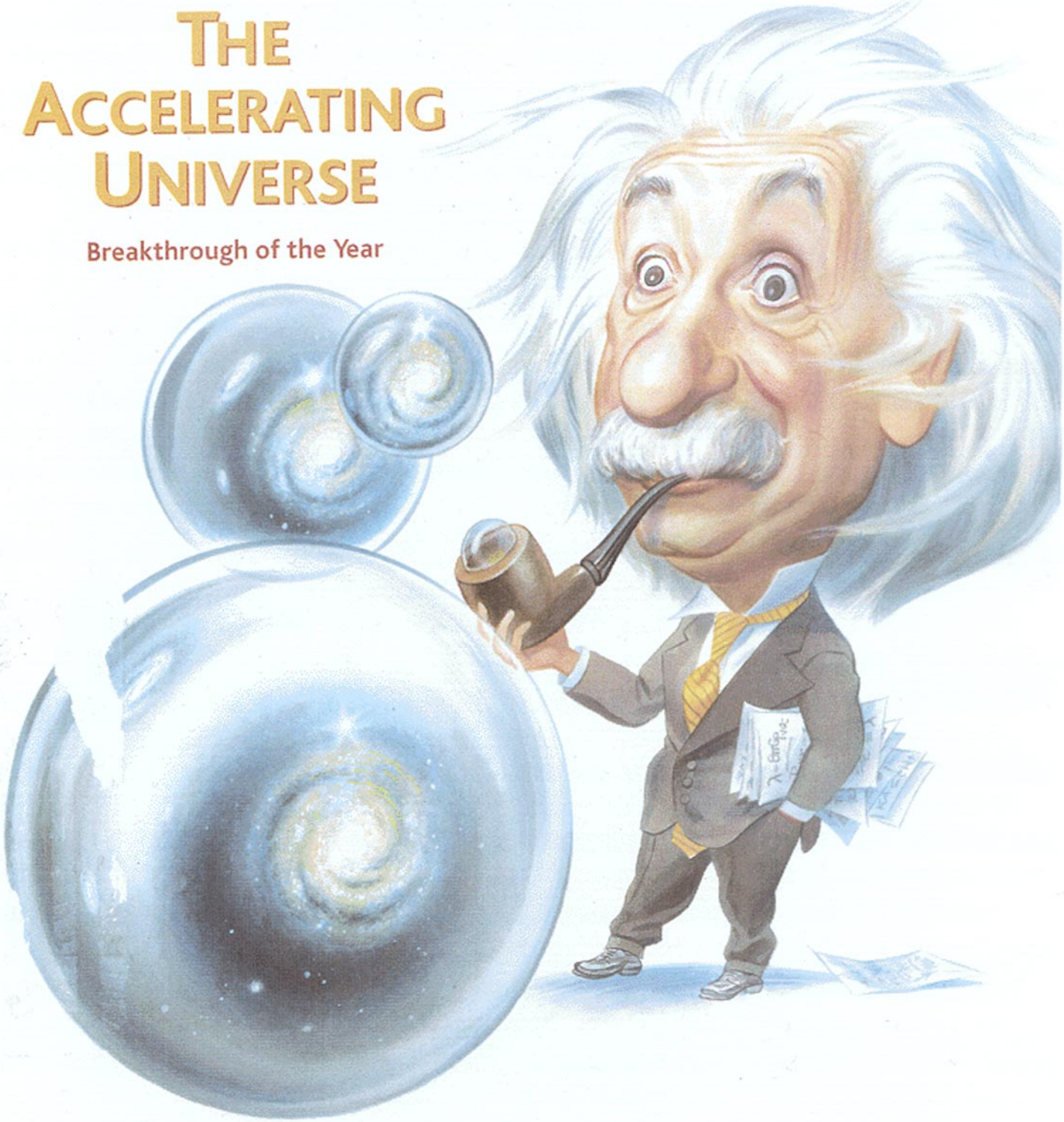
18 December 1998

Science

Vol. 282 No. 5397
Pages 2141–2336 $7

THE ACCELERATING UNIVERSE

Breakthrough of the Year



AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

ACCELERATING UNIVERSE

$\rho + 3p < 0$

source of gravity in GR

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

POSSIBILITIES:

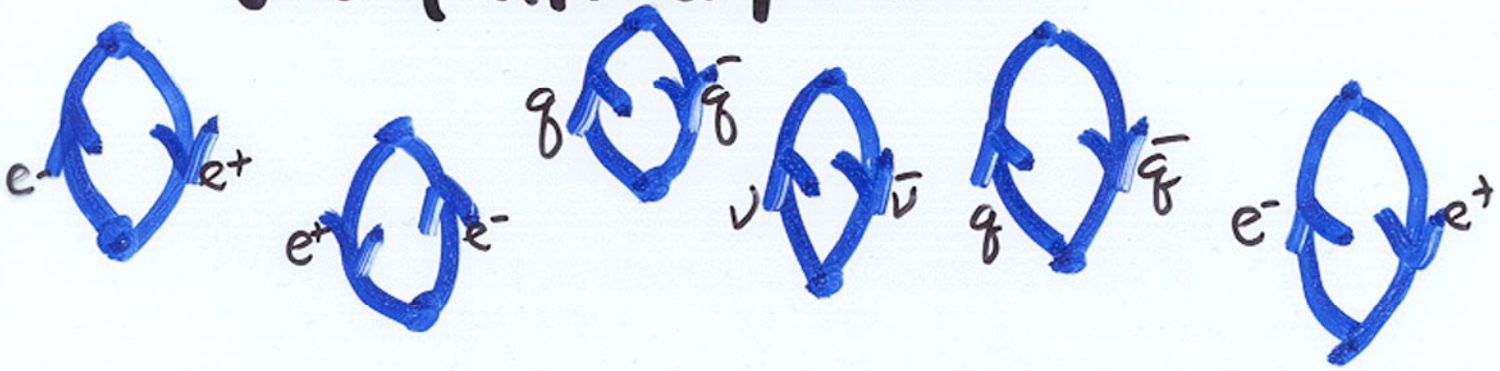
Einstein's COSMOLOGICAL CONST'T (VACUUM ENERGY) $\quad p = -\rho$

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

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

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

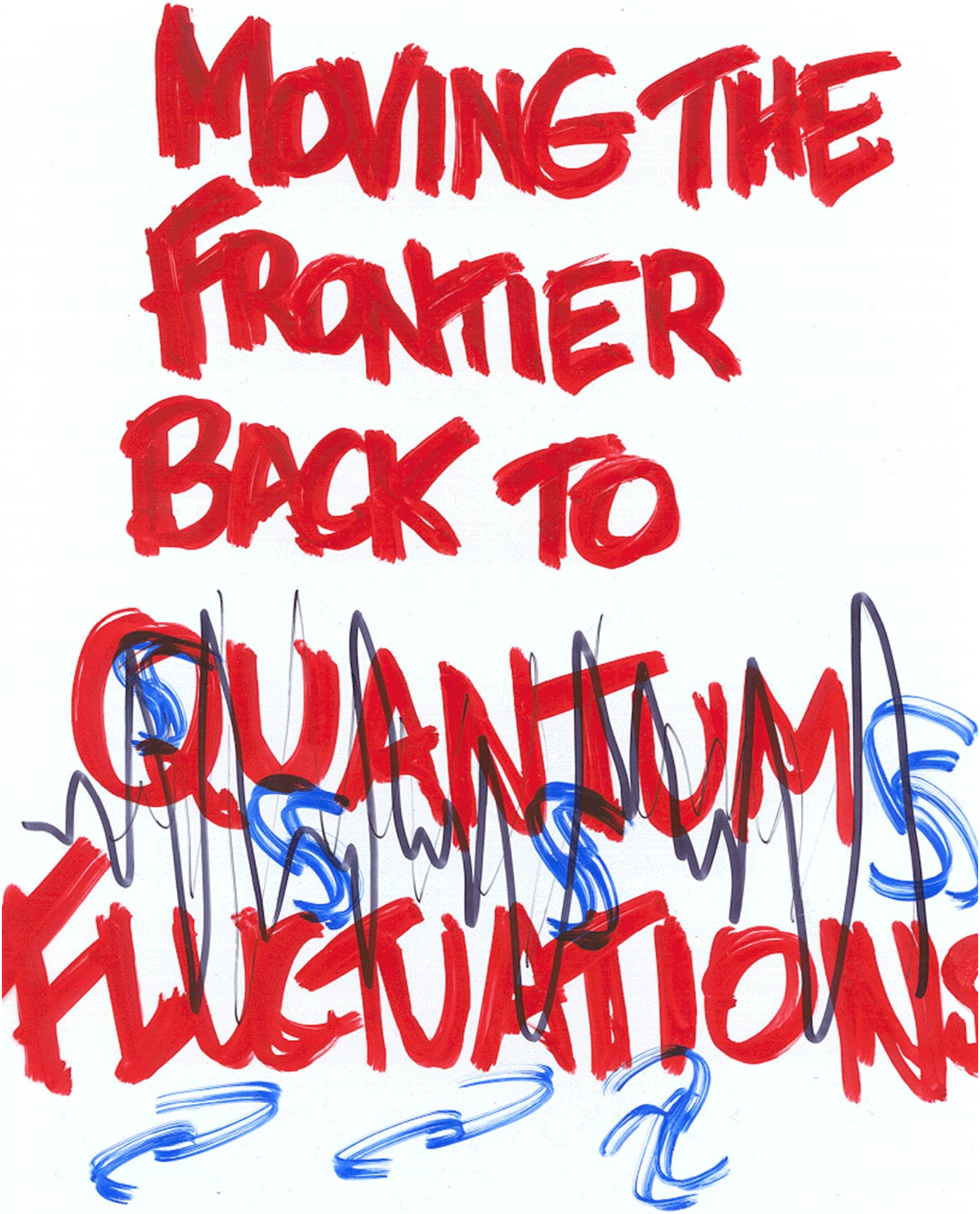
'30 $\Omega_{VAC} = \frac{\rho_{VAC}}{\rho_{crit}} = \infty$

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

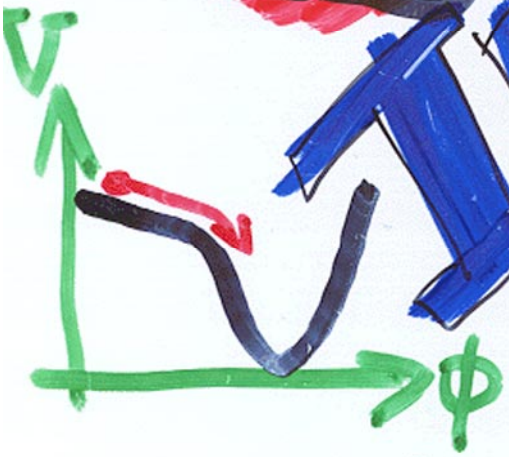
'84 $\Omega_{VAC} = 10^{55}$ susy

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

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


MOVING THE
FRONTIER
BACK TO
QUANTUM
FLUCTUATIONS

INFLATION IN THE UNIVERSE



EARLY EPOCH OF TREMENDOUS EXPANSION DRIVEN BY VACUUM ENERGY

10^{-32} SEC

$>> 10^{40}$

SCALAR FIELD

"EXPLAINS": FLATNESS, SMOOTHNESS, & HEAT

PREDICTS:

Robust Predictions

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

TOWARD A "GRANDER" BIG BANG THEORY:

THE COLD DARK MATTER COSMOGENY

MOTIVATED BY INFLATION

CRITICAL UNIVERSE

mostly ^

ORDINARY MATTER 5%

"SLOW MOVING" RELICS 95%

(AXIONS or NEUTRALINOS or ?)

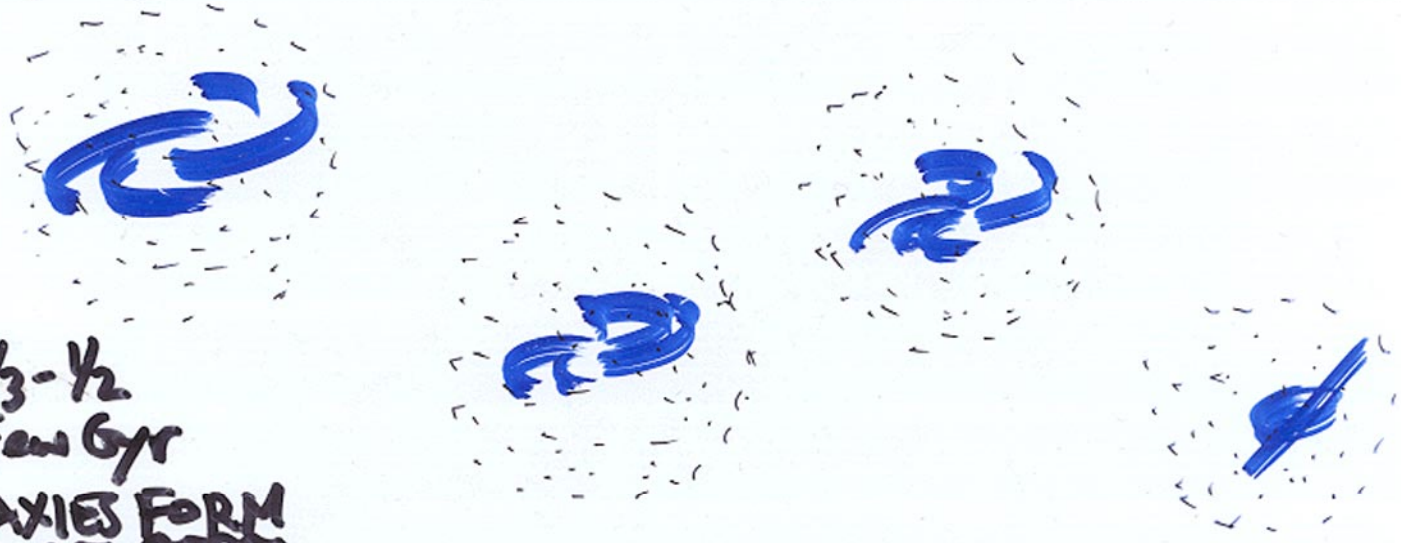
INFLATION-PRODUCED LUMPINESS

NEARLY SCALE-INVARIANT, GAUSSIAN ϕ/p

(+ GRAVITY WAVES)

COLD DARK MATTER

EQ!:
$z \sim 3 \times 10^3$
$t \sim 1000\,yr$
$\delta\rho/\rho \sim 10^{-5}$



$R \sim 1/3 - 1/2$
$t \sim$ few Gyr
GALAXIES FORM!
Dark halos, baryons dissipate

TODAY
Formation of larger structures (superclusters) continues...

SUCCESSES

(at least so far!)

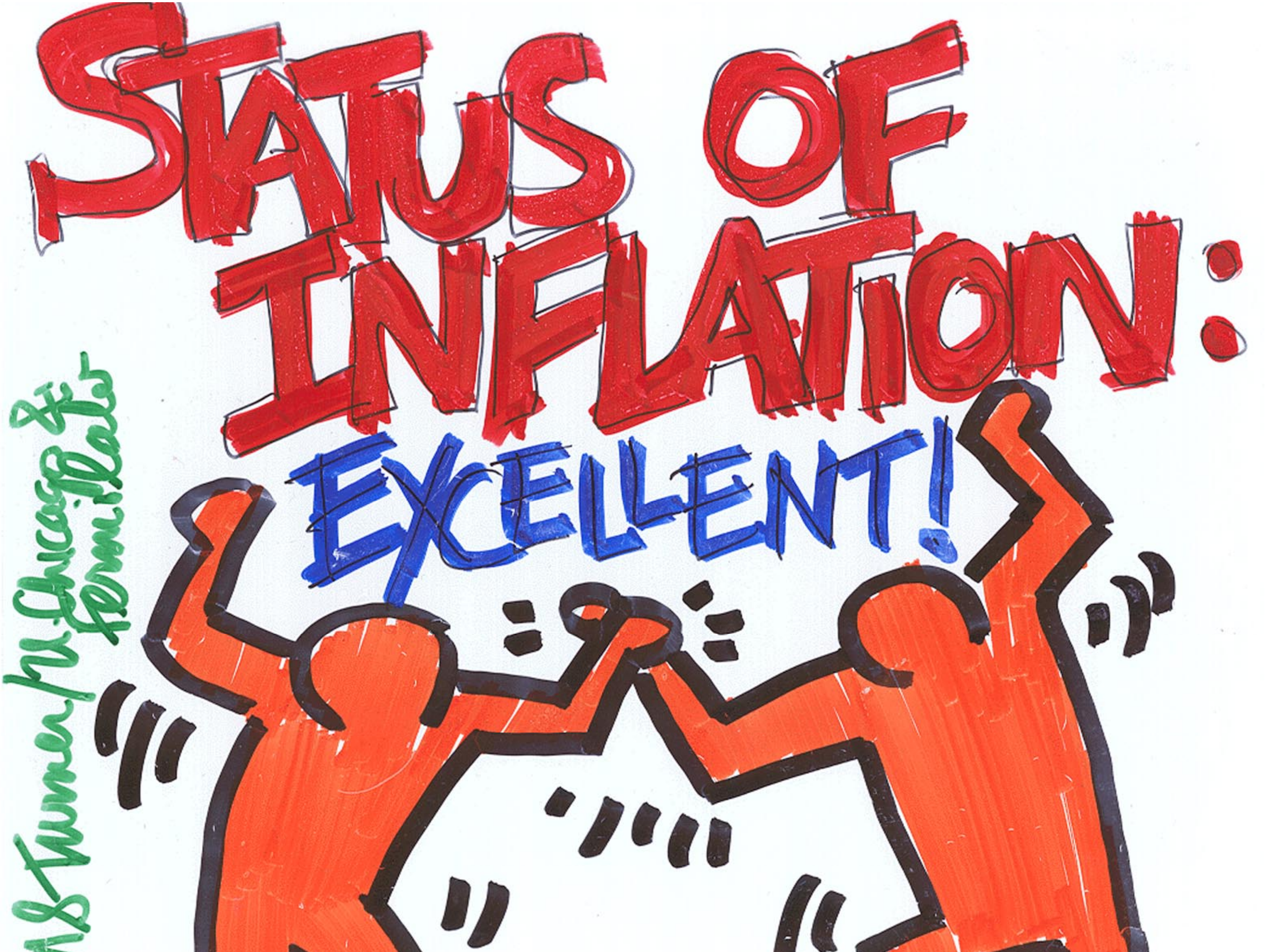
FLATNESS ✓

- $(\Omega_0 = 1 \pm 0.2) = (\Omega_M = 0.4 \pm 0.1) + (\Omega_\Lambda = 0.8 \pm 0.2)$

QUANTUM ORIGIN OF LUMPINESS ✓

- Gaussian — no evidence to the contrary
- Adiabatic — acoustic peak(s)
- Nearly scale-invariant — $n_s = 0.95 \pm 0.07$

ΛCDM ✓


STATUS OF INFLATION:
EXCELLENT!
MS Turner U. Chicago &
Fermilab

COSMOLOGY ENTERING A GOLDEN AGE

BOLD IDEAS TESTED BY PRECISION MEASUREMENTS

HST KECK GEMINI NGST
OPTICAL

SOFIA ALMA SIRTF
INFRARED/RADIO

COBE .. MAP ... PLANCK
CMBR

CHANDRA XMM ...
X-RAY

TEVATRON B-FACTORY . LHC ...
ACCELERATORS

2dF SDSS
MAPS OF THE UNIVERSE

LIGO ... LISA ...
GRAVITY WAVES

DM SEARCHES
AXIONS, NEUTRALINOS

EGRET ... GLAST
γ-RAYS

SNO KAMIOKANDE SOUDAN
AMANDA FLYS EYE AUGER
NEUTRINOS COSMIC RAYS

& MORE

GREAT PROGRAM IN PLACE

GWs ARE CRUCIAL NEXT ~~STEP~~ LEAP

CHALLENGING, EVEN BY LIGO STANDARDS!

GRAVITY WAVES from the EARLY UNIVERSE

... PREACHER ... PHYSICIST ... PRAGMATISM ...

INFLATION

PHASE TRANSITIONS

FOCUS ON

"ROBUST PREDICTIONS"

FLAT UNIVERSE

$$\Omega_0 \equiv \rho_{TOTAL}/\rho_{CRITICAL} = 1.0$$

$$\rho_{TOT} = \rho_B + \rho_{CDM} + \rho_{VAC} + \rho_{\nu\bar{\nu}} + \rho_{RAD} + \cdots$$

ALMOST SCALE-INVARIANT SPECTRUM OF DENSITY PERTR

(SCALAR) A_s

↑ "GAUSSIAN"

ALMOST SCALE-INVARIANT SPECTRUM OF GRAVITY WAVES

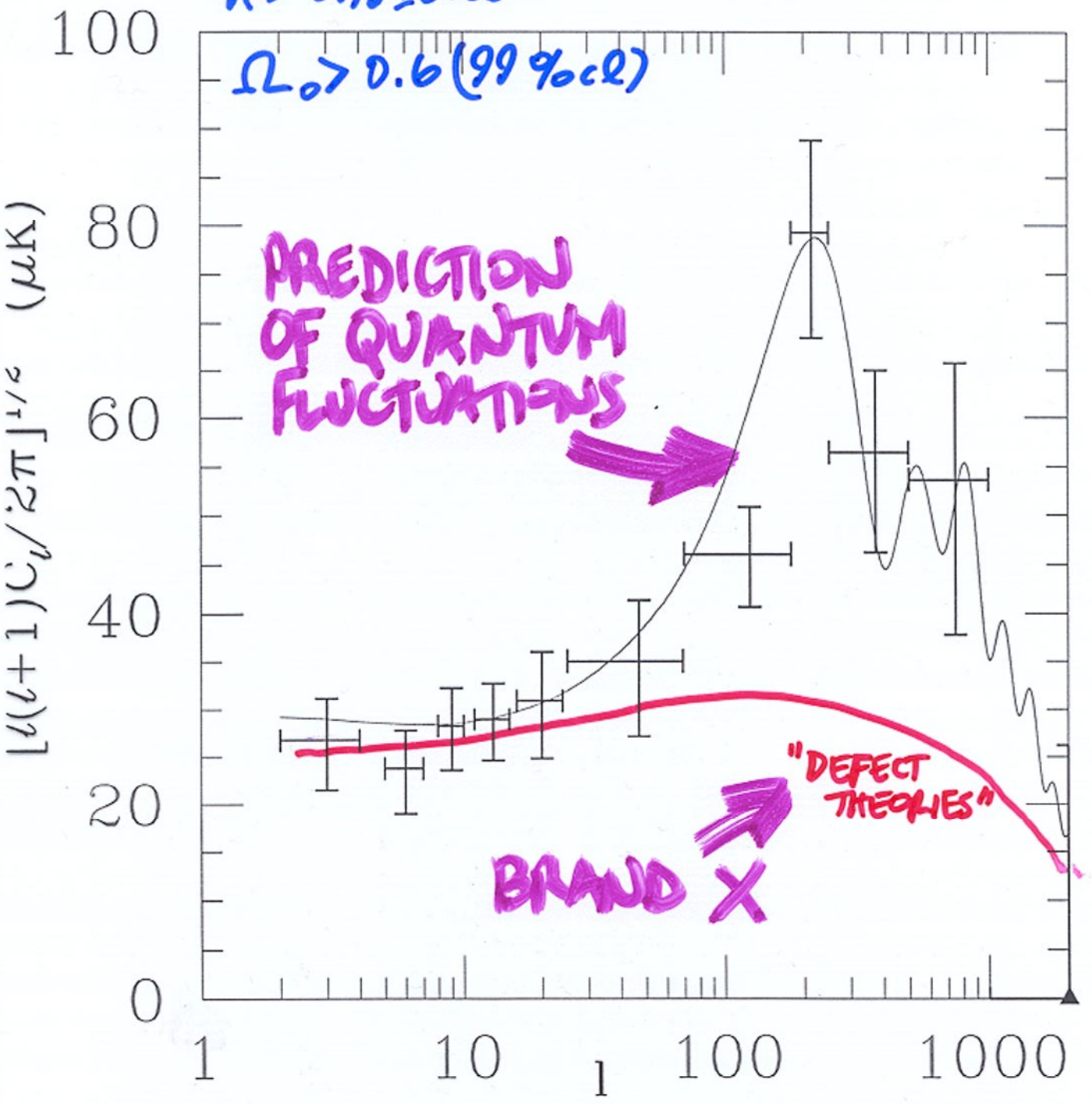
(TENSOR A_t)

(+ sharply peaked spectrum of gravity waves in first-order inflation)

Bond, Jaffe and Knox 1998

$n = 0.95 \pm 0.06$

$\Omega_0 > 0.6$ (99 % cl)



$h = 0.65$

$\Omega_M = 0.4$

$\Omega_\Lambda = 0.6$

"PREDICTIONS OF ANY SENSIBLE SCENARIO"

CRUCIAL TEST OF INFLATION

GRAVITY WAVES

(1) Direct detection
limited by sensitivity

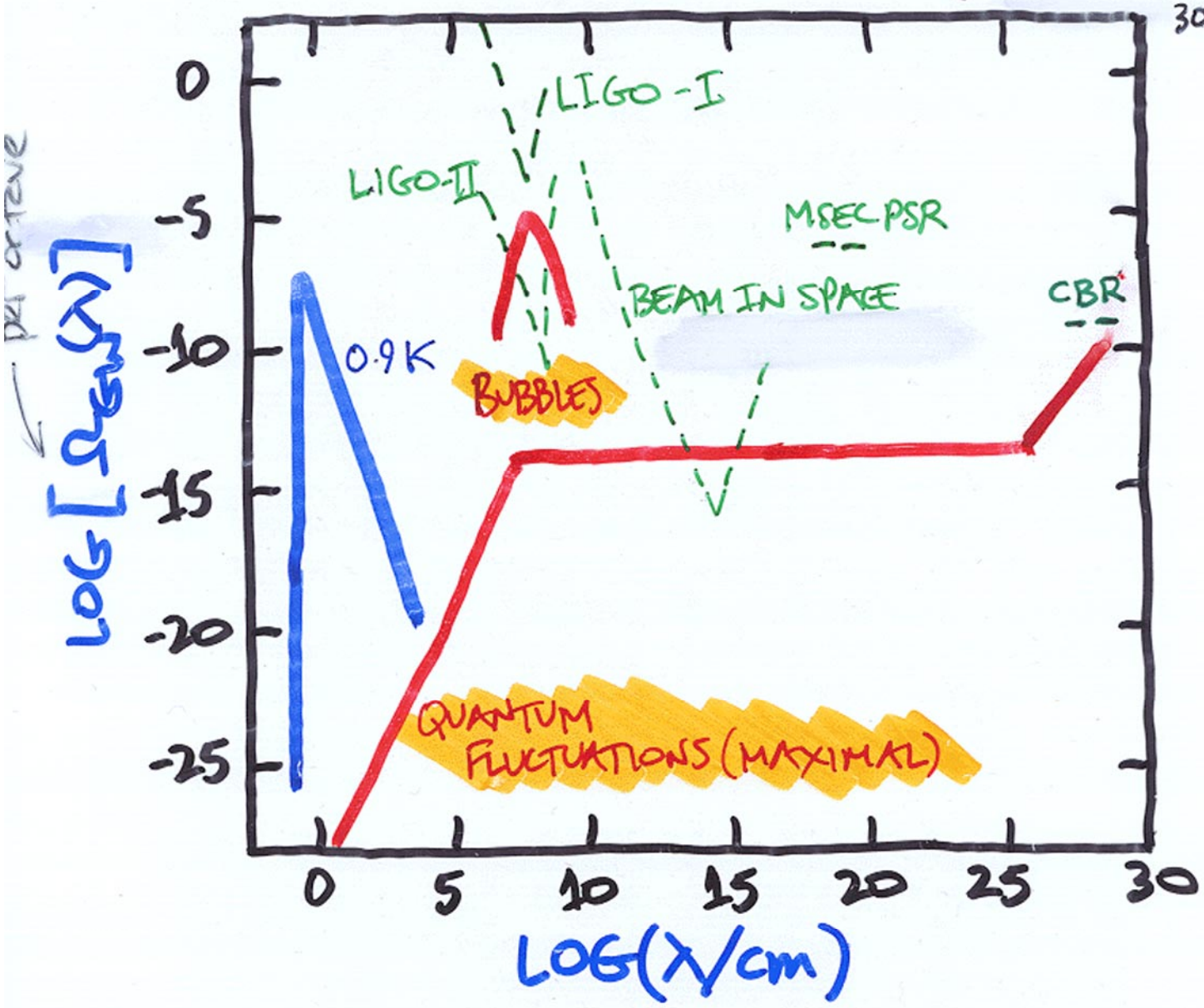
(2) CBR anisotropy $T/S \gtrsim 0.1$
limited by sampling variance

(3) CBR polarization ??
limited by sensitivity?
(& not cosmic variance)
↑
Tensor excites different pattern of polarization
(Kamionkowski, Kosowsky, Stebbins astro-ph/9609 ...)

VERY IMPORTANT TEST OF INFLATION & PROBE OF INFLATIONARY PHYSICS
WORTH SERIOUS THOUGHT

GRAVITY WAVES FROM INFLATION

(MST-Wilczek PRL 65, 3033 ('90))

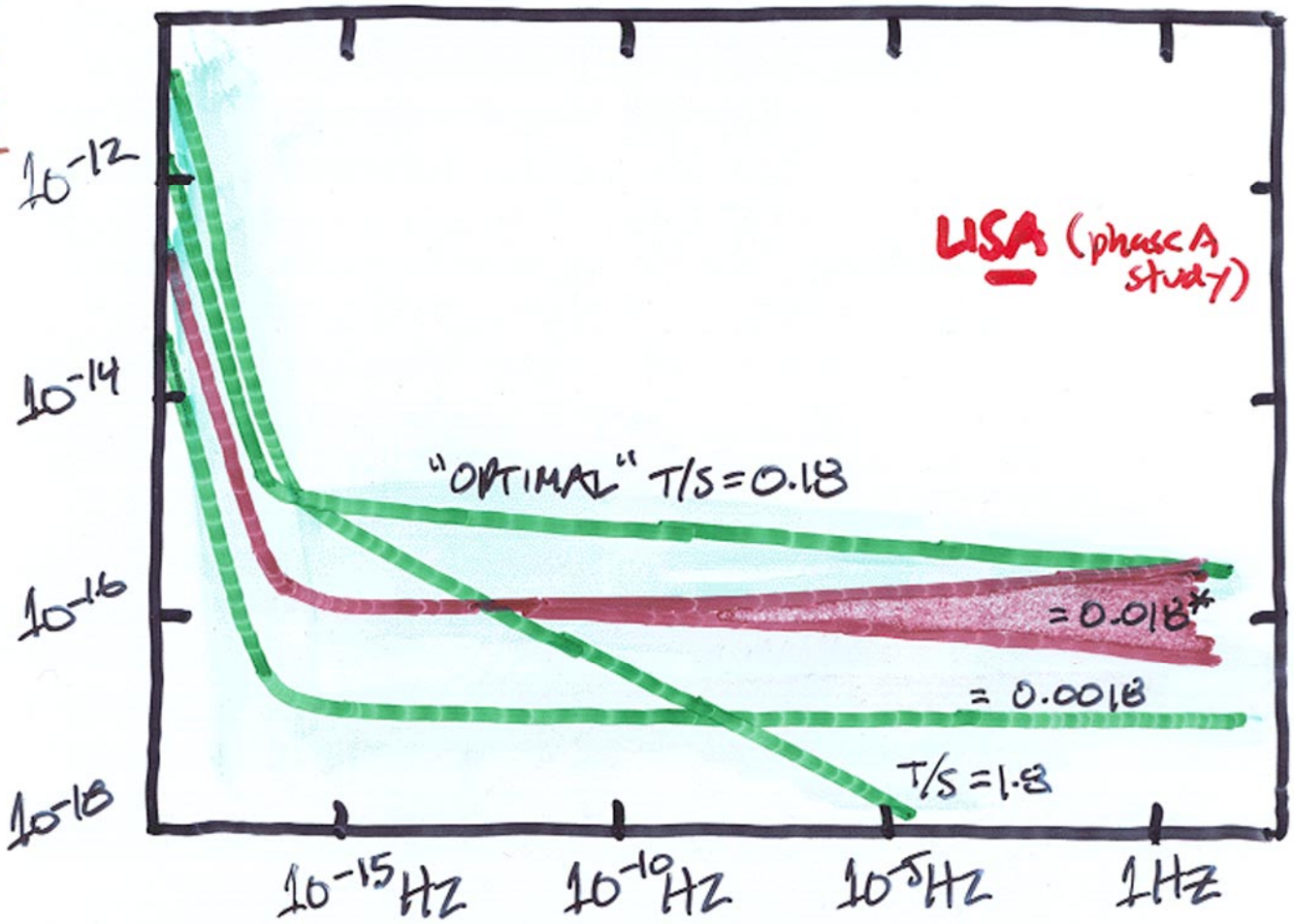


NB: "Astrophysical Background" Not Shown

ENERGY DENSITY IN INFLATION PRODUCED GWs

MST PRD55 ('97)

LIGO-II



* INCLUDES UNCERTAINTY DUE TO "RUNNING" OF POWER LAW IND

COBE normalized: $\delta+T = Q_{rms-ps} \approx 4\times10^{-11}$

$\Rightarrow T = Q/(1+S/T)$

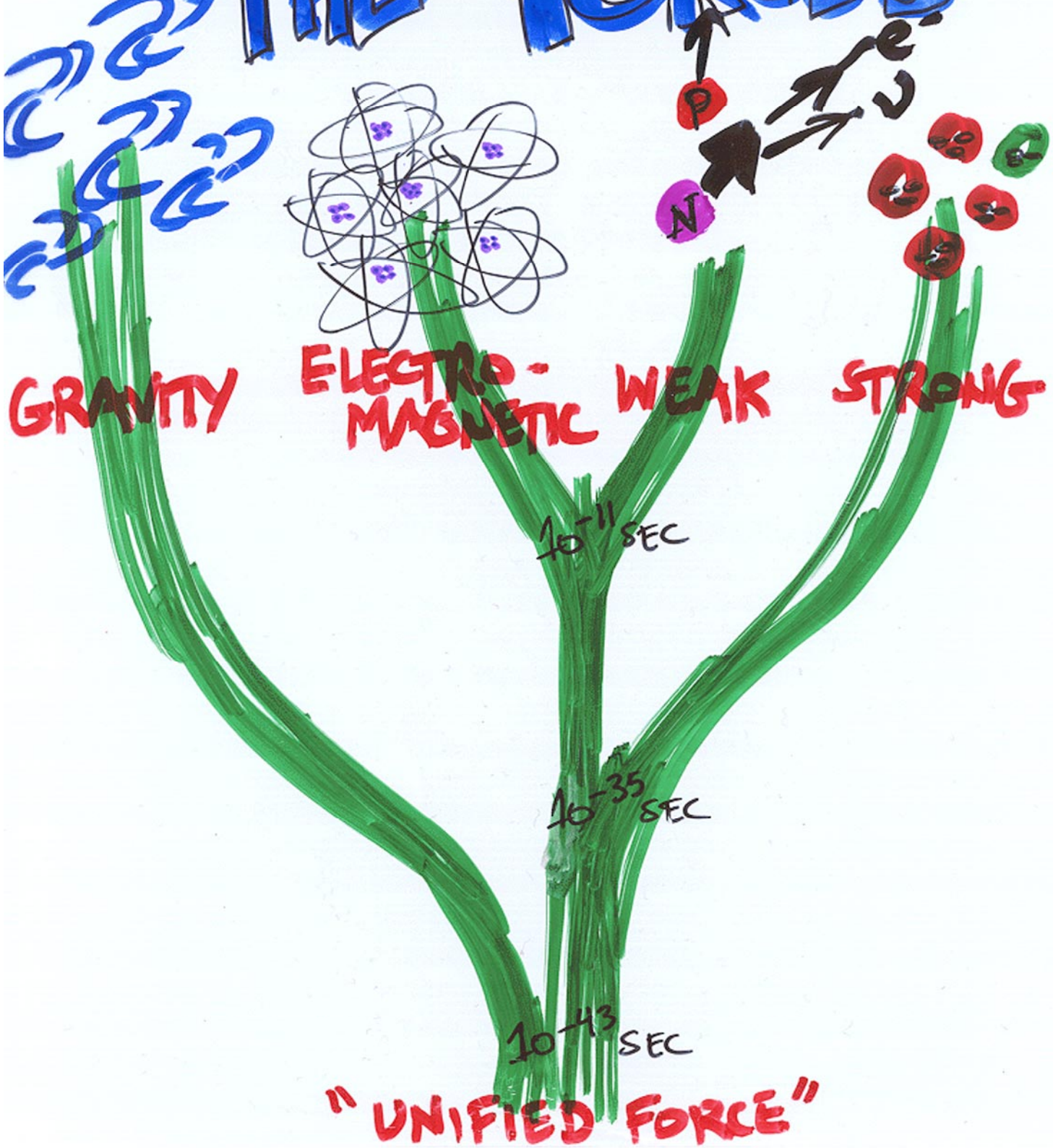
$$\Omega_{GW}(f)h^2 = 5.1\times10^{-15}\,\frac{n_T}{n_T - y_7}\cdot e^{N n_T + \frac{1}{2}N^2\, dn/d\ln f}$$

$\Omega_{GW}(f)h^2 \equiv \frac{1}{\rho_{crit}(H_0=100)} \times \frac{d\rho_{GW}}{d\ln f}$

$N = 33 + \ln(f/\mathrm{Hz})$

$$\frac{dn_T}{d\ln f} = -n_T[(n-1) - n_T] \approx \pm 10^{-3}$$

BLOSSOMING OF THE FORCES

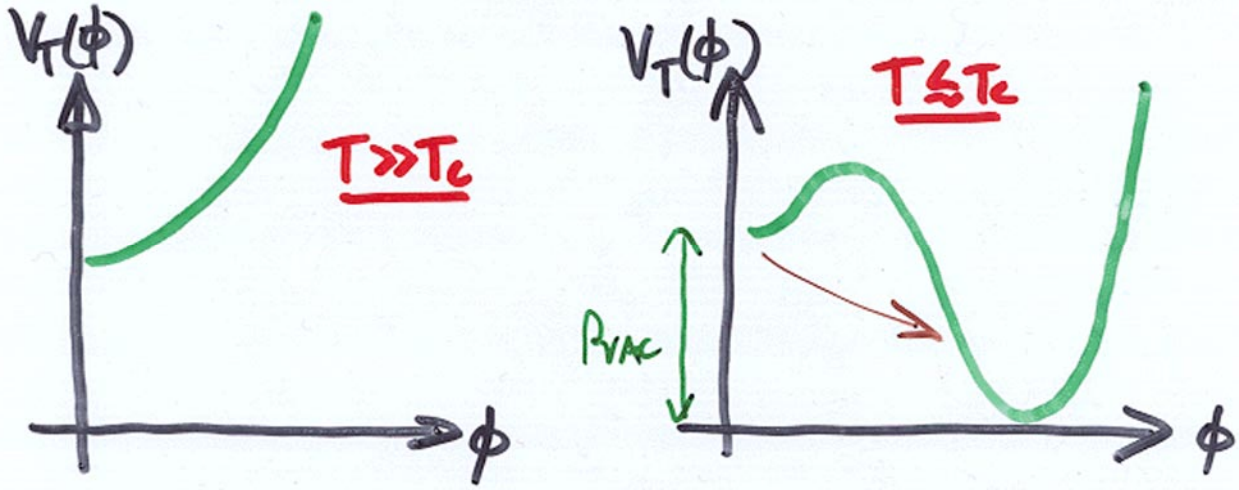


WHY VACUUM BUBBLES?

Very strongly

FIRST-ORDER PHASE TRANSITION

E.G. INFLATION, ELECTROWEAK, QCD ..., ??

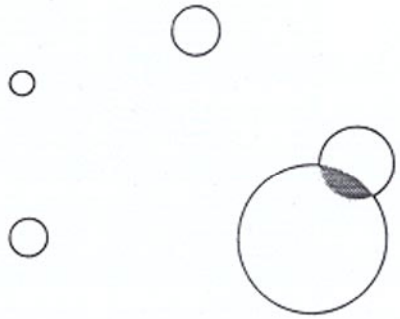


- proceeds thru nucleation & percolation of vacuum bubbles
- large energy (entropy) release

ρ_{vac}/ρ_{rad} = latent heat / thermal energy $\gg 1$

- "violent collisions" (vacuum popping)

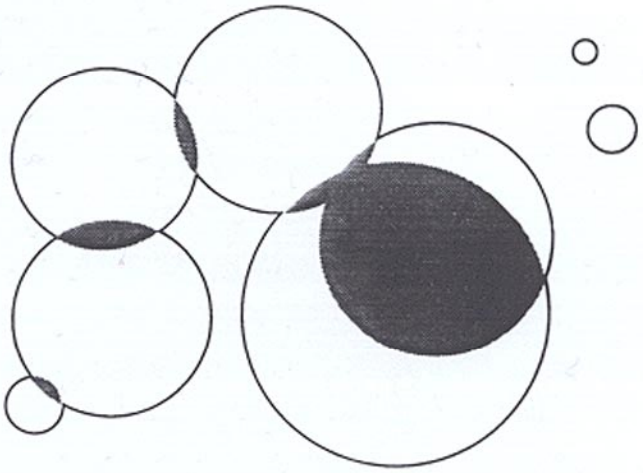
→ POTENT SOURCE OF GW's



(a)

ENVELOPE APPROXIMATION:

IGNORE INTERACTION (OVERLAP) REGIONS: fine-scale motion radiation adds incoherently



(b)

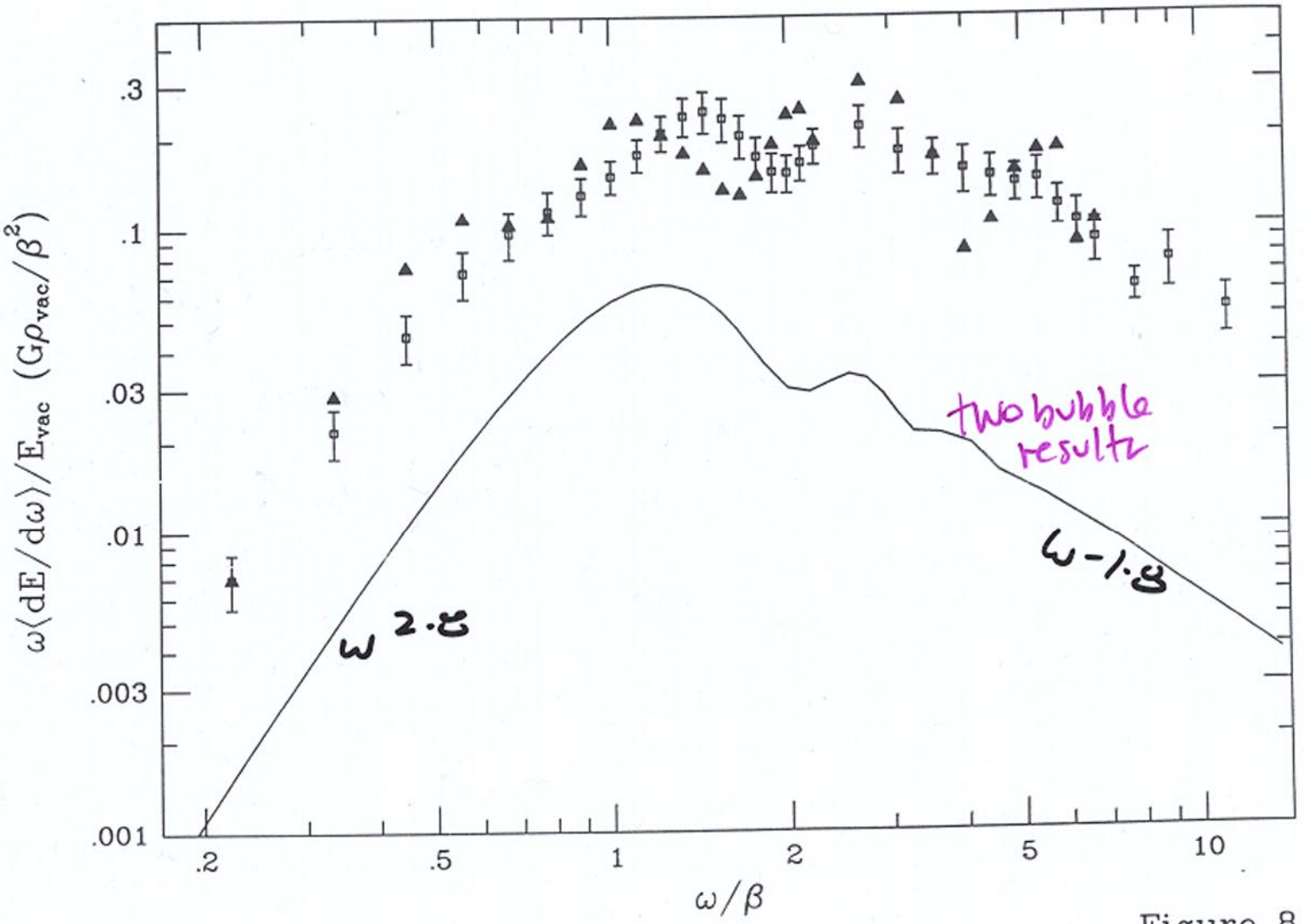


Figure 8

▲ 180 bubbles

I average over 6 directions × 5 simulations

$E_{GW}/E_{VAC} \approx 0.06\,(H/\beta)^2$

≈ 5 × 2 bubble result

Kosowsky et al '91, '92

TODAY

$$f_{max} \simeq 5\times10^{-8}\,\text{Hz}\left(\frac{\beta}{H_*}\right)\left(\frac{g_*}{100}\right)^{1/6}\left(\frac{T_*}{\text{GeV}}\right) \qquad 1 \to 100$$

$$\Omega_{GW}h^2 \simeq 10^{-6}\,(H_*/\beta)^2\left(\frac{100}{g_*}\right)^{1/3} \qquad 10^{-4} \to 1$$

$$\bar{h} \simeq 1.3\times10^{-18}\sqrt{\Omega_{GW}h^2}\,/(f/\text{Hz})$$

↑ DIMENSIONLESS STRAIN $\approx \frac{\Delta x}{x}$

$k^{3/2}h^{1/2}/2\pi$

Ph. Tr.	T_*	g_*	$\Omega_{GW}h^2$	f_{max}	$\bar{h}$
QCD	0.2 GeV	30	8×10^{-11}	7×10^{-7} Hz	7×10^{-18}
EW	300 GeV	100	$\boxed{7\times10^{-11}}$	1×10^{-3} Hz	4×10^{-21}
GUT	$10^{15\pm1}$ GeV	1000	6×10^{-10}	$1\times10^{8\pm1}$ Hz	$10^{-32\mp1}$
?	$10^{7\pm1}$ GeV	300	10^{-10}	$3\times10^{1\pm1}$ Hz	$2\times10^{-25\mp1}$

NB: $(H_*/\beta) = [\ln(m_{pl}/T_*)]^{-1}$ ◀ SM: 10^{-22}

GWs: Scientific Challenge of 21st Century

Crucial New Window on Early Universe

- Test inflation
- Determine scale of inflation
- Listen to Cosmological Phase Transitions
- ??? (eg, detect presence of extra dimensions by index of refraction for GWs!)

LIGO is first step toward this ambitious goal

Bon Voyage

Note 1, Linda Turner, 12/06/99 02:37:46 PM
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