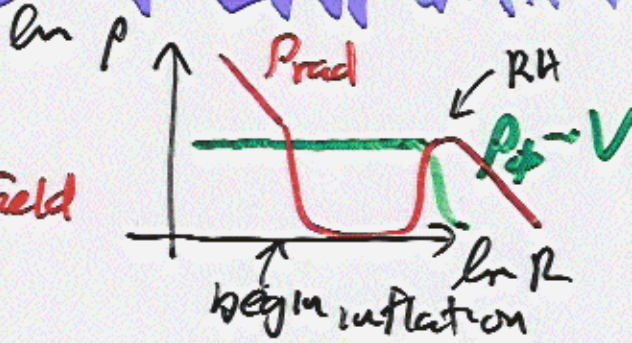
THE BEGINNING OF INFLATION

HOT BEGINNING



1: $\rho = \underset{\text{rad}^n}{aT^4} + \rho_\phi$ (scalarfield)

2: when $aT^4 \approx V(\phi_i)$ inflation starts

thereafter, $T \sim e^{-Ht}$

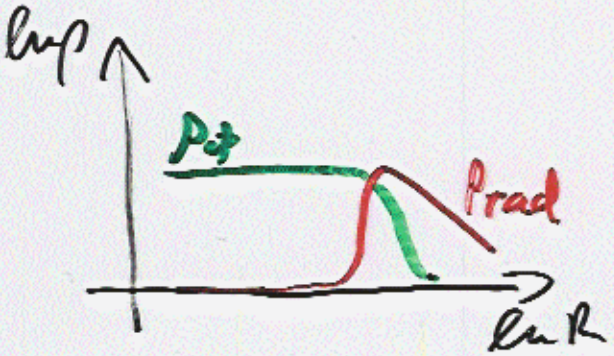
NB: $T_i \approx V(\phi_i)^{1/4}$

3: RHing: $T_f \approx V(\phi_i)^{1/4}$ (perfect)

actual: $T_{RH} = (\Gamma_\phi M_{pl})^{1/2}$

COLD BEGINNING

$\rho \approx \rho_\phi$ (no thermal bath)



SAME OUTCOME

WORKED EXAMPLE

$V(\phi) = \frac{1}{2}m^2\phi^2 \quad V' = m^2\phi$

$d\ln R = H\,dt \quad H^2 \simeq \frac{8\pi}{3m_{pl}^2}V(\phi) \quad \dot\phi \simeq \frac{-V'}{3H}$

$H \equiv \dot R/R$ — Friedmann Eqn — Slow Roll

$$N \equiv \ln R_f/R = \frac{8\pi}{m_{pl}^2}\int_0^{\phi}\frac{V\,d\phi}{V'} = 2\pi(\phi/m_{pl})^2$$

(1) $N_{Tot} > 50 \rightarrow \phi_i > (50/2\pi)^{1/2} m_{pl} \approx 3\,m_{pl}$

(2) $(\delta\rho/\rho)_{HOR} \simeq \left(\frac{V^{3/2}}{m_{pl}^3 V'}\right)_{N\sim 50} \simeq 10^{-5}$

$$\approx \left(\frac{m}{m_{pl}}\right)\left(\frac{\phi}{m_{pl}}\right)^2 = \left(\frac{m}{m_{pl}}\right)\left(\frac{N}{2\pi}\right)$$

$m/m_{pl} \approx \frac{2\pi}{N}\cdot 10^{-5} \approx 10^{-6}$

$m \approx 2\times 10^{13}\,GeV$

$h_{GW} \approx H/m_{pl} \sim \frac{V^{1/2}}{m_{pl}^2} \sim \frac{m\phi}{m_{pl}^2} \sim 10^{-6}$

(3) Initial Condx

Suppose $V(\phi_i) \approx m_{pl}^4$

"chaotic inflation"

$\rightarrow \frac{m^2 \phi_i^2}{m_{pl}^4} \sim 1$ or $\phi_i \approx \left(\frac{m_{pl}}{m}\right) m_{pl}$

$\approx 10^6 m_{pl}$

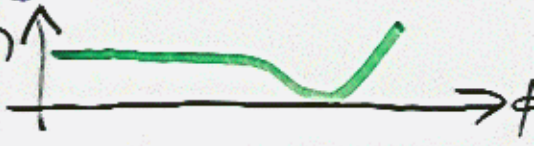
$\rightarrow N_{TOT} \approx \frac{(\phi_i/m_{pl})^2}{2\pi} \approx 10^{11}$ WOW!

EXAMPLE 2: $V = \lambda\phi^4$ ... $\lambda = 10^{-14}$

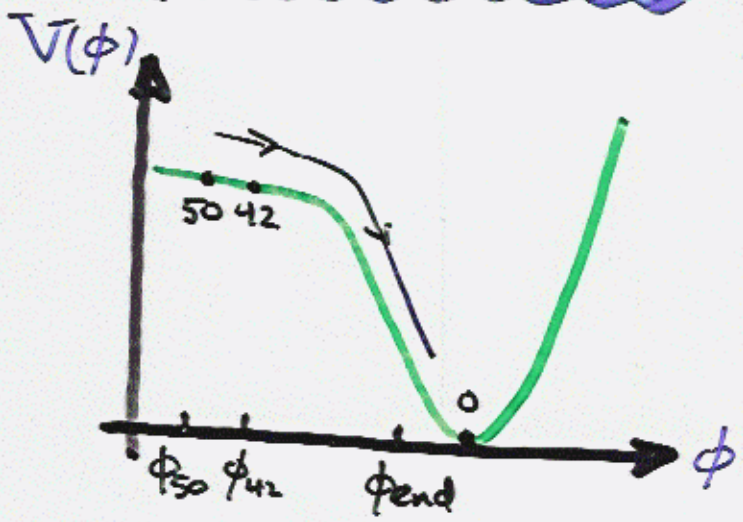
IN GENERAL:

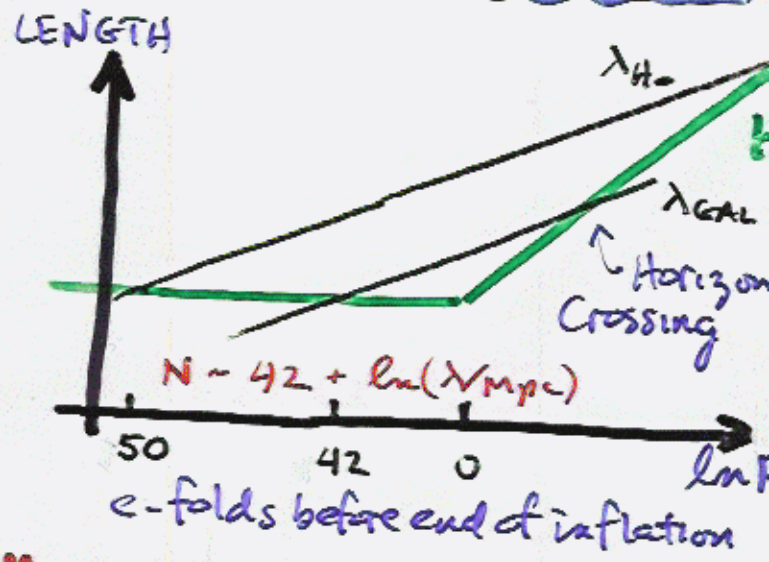
SMALL PARAMETER λ, m/m_{pl}

SQUAT POTENTIAL



QUANTUM FLUCTUATIONS





"INTERESTING SCALES" CROSS OUTSIDE "HORIZON" DURING A SMALL PORTION OF INFLATION

SLOW ROLL: $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$

$\dot{\phi} \approx -V'/3H$ $\quad N = \int H dt = \frac{8\pi}{m_{pl}^2} \int_{\phi}^{\phi_{end}} \frac{V(\phi)\, d\phi}{V'}$

DENSITY PERT (SCALAR) $\delta\rho \sim \Delta\phi V' \sim HV'$

OUTSIDE HORIZON ($\lambda > H^{-1}$) $\quad \delta\rho/(\rho+p) \approx$ const

$\rho = +\frac{1}{2}\dot{\phi}^2 + V$
$p = +\frac{1}{2}\dot{\phi}^2 - V$

$\left(\frac{\delta\rho}{\rho}\right)_{HOR} \approx \left(\frac{HV'}{\dot{\phi}^2}\right)_N \sim \frac{V_N^{3/2}}{m_{pl}^3 V_N'}$

GRAV. WAVES (TENSOR) $h_{GW} \sim H/m_{pl}$

OUTSIDE HORIZON ($\lambda > H^{-1}$) $\quad h_{GW} \approx$ const

$(h_{GW})_{HOR} \approx \left(\frac{H}{m_{pl}}\right)_N \sim V_N^{1/2}/m_{pl}$

MODELS

I.E., $V(\phi)$

GOOD NEWS: No lack of well motivated, viable models

CHAOTIC, NATURAL, NEW, SUSY, SUGR, ELECTROWEAK, GUTS, NO-SCALE, EXTENDED, HYBRID, ...

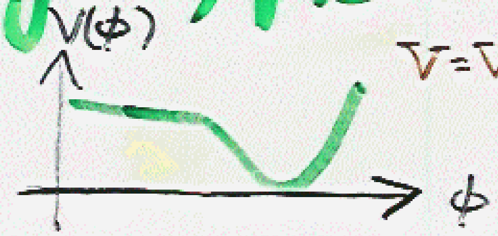
BAD NEWS: See above

i.e. NO "STANDARD" MODEL

(should be viewed in the light of our knowledge of physics at $E \gg 10^3$ GeV)

Technical point: (TO GET $\delta\rho/\rho \approx 10^{-5}$) all have a (VERY!) small number that begs explanation

"POTENTIALS" ARE VERY FLAT



$V = V_0 + \dots + \lambda\phi^4 + \dots$

$\uparrow$ 10^{-14}

MENU

Circa Aspen '93

SIMPLE (TOY) MODELS

SIMPLE POLYNOMIALS Steinhardt-MST

LINDE'S CHAOTIC INFLATION $V = \lambda\phi^4$

POWER-LAW INFLATION $V = V_0 e^{-\beta\phi}$ Abbott-Wise; Lucchin etal

COMPLICATED MODELS TIED TO PARTICLE PHYSICS

GUT Shafi-Vilenkin-Pi

SUSY GUT Holman Ramond Ross; Olive Phys Rep

Preons Pati etal Murayama etal

Electroweak Knox-MST

"NATURAL" MODELS

Natural Inflation (Nambu-Goldstone boson) Frieman-Olinto-Freese

$\lambda \propto \left(\frac{m}{M}\right)^n$ Superstring inspired, model based Banks etal

$V(\phi) = \Lambda^4 f(\phi/M)$

Lo-energy SUSY, two-field Randall etal Stewart etal

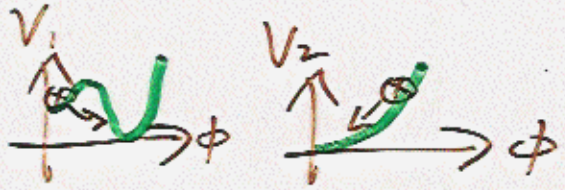
Non-STD GRAVITY

Extended (first-order) Inflation La-Steinhardt Kolb, Phys. Scripta

Induced gravity Accetta-MST-Zoller

R^2 inflation Starobinsky

Extra dimensions Shafi-Wetterich

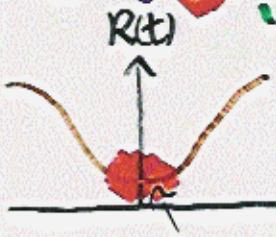


$\Omega < 1$ but not $\ll 1$

First-order (bubble), followed by "tuned" slow roll

Bucher et al
Linde et al

"Pre big-bang" (aka kinetic) Inflation



"Bounce" (Universe is big & flat because it began big & flat)

Levin
Brustein et al
Veneziano et al

Exotica

Double(...) Inflation

Silk-MST
Starobinskii
Kofman-Linde

TYPICALLY:

$V \approx (10^{14}\text{-}10^{15}\,\text{GeV})^4$, $n \simeq 0.95$, not quite scale invariant;

$|\Omega - 1| \ll 1$

EXCEPTIONS!

- $V \ll (10^{14}\,\text{GeV})^4$ & exactly scale-invariant — Knox-MST; Randall et al; Stewart et al
- $\delta\rho/\rho \approx 0$ + "blue spectrum of GWs" — Pre big-bang
- $\Omega < 1$ — Bucher et al; Linde

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 "GAUSSIAN" SPECTRUM OF DENSITY PERTS (SCALAR)

ALMOST SCALE-INVARIANT SPECTRUM OF GRAVITY WAVES (TENSOR)

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

ALL MODELS OF INFLATION BASED UPON SLOWLY ROLLING FIELD ϕ & $V(\phi)$

"LANDAU-GINZBURG DESCRIPTION"

THE OBSERVABLES: All given in terms of $V(\phi)$

AMPLITUDE² OF DENSITY PERT (CONTRIBUTION² TO CMB QUADRUPOLE)

$$S^2 = \frac{2.9(V/m_{pl}^4)}{(m_{pl}V'/V)^2} \approx 4\times10^{-11}$$

AMPLITUDE² OF GW

$$T = 0.56(V/m_{pl}^4) \approx ? \; \begin{matrix} <10^{-10} \\ \gtrsim 10^{-13}\ ? \end{matrix}$$

DEVIATION FROM SCALE INVARIANCE DENSITY PERT

$$n-1 = -\frac{1}{8\pi}\left(\frac{m_{pl}V'}{V}\right)^2 + \frac{1}{4\pi}\left(\frac{m_{pl}^2V''}{V}\right)' \approx \mathcal{O}(0.1$$

DEVIATION FROM SCALE INVARIANCE GW

$$n_T = -\frac{1}{8\pi}\left(\frac{m_{pl}V'}{V}\right)^2 \approx \mathcal{O}(0.1)$$

"RUNNING" OF n-1

$$dn/d\ln k = -\frac{1}{32\pi^2}\left(\frac{m_{pl}^3V'''}{V}\right)\left(\frac{m_{pl}V'}{V}\right) + \frac{1}{8\pi^2}\left(\frac{m_{pl}^2V''}{V}\right)\left(\frac{m_{pl}V'}{V}\right)^2 - \frac{3}{32\pi^2}\left(\frac{m_{pl}V'}{V}\right)^3 \approx \mathcal{O}(10^{-3})$$

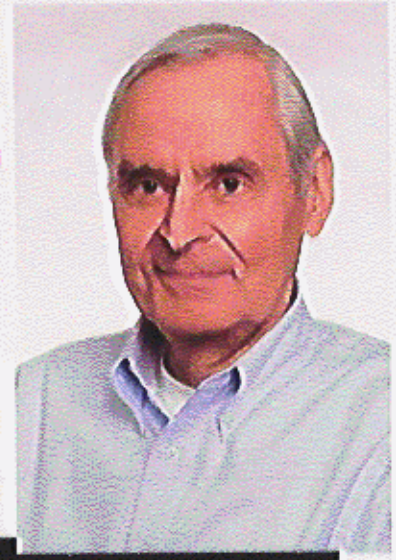
NB CONSISTENCY REL^N: $T/S = -5n_T$

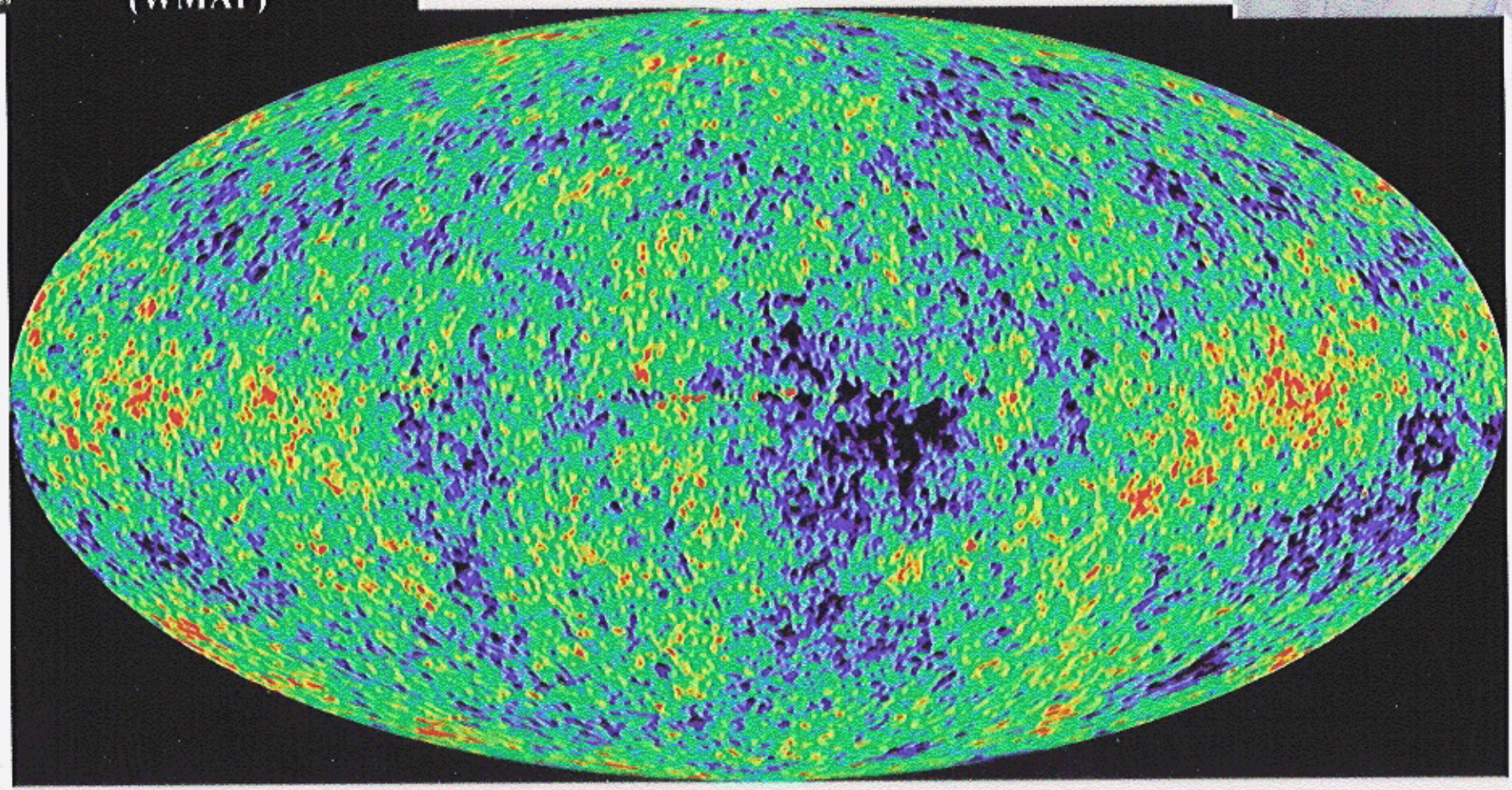
INFLATION SCORECARD

PREDICTIONS	WMAP NOW	GRADE	GOAL
FLAT UNIVERSE			
★ $\Omega_0 = 1.000$	1.02 ± 0.02 $\Omega_0 = 1.03 \pm 0.03$	++*	± 0.001
DENSITY PERTS FROM QM FLUC			
★ ADIABATIC	≥3 ACOUSTIC PEAKS	+	≥7
★ NEARLY SCALE-INVARIANT $(n-1) \sim \mathcal{O}(\pm 0.1)$	0.93 ± 0.03 $n = 1.05 \pm 0.09$	+	± 0.001
★ NEARLY POWER-LAW $dn/d\ln k \sim \pm 10^{-3}$	-0.03 ± 0.02 $dn/d\ln k = -0.02 \pm 0.04$	✓	$\pm 10^{-3}$
★ GAUSSIAN	NO EVIDENCE AGAINST	✓	
→ **CDM**	"HAS MUCH OF THE TRUTH"	++	
GRAV WAVES FROM QM METRIC FLUC			
★ $T/S \gtrsim 10^{-3}$ (??)	$T/S \lesssim \mathcal{O}(1)$		$10^{-3}/10^{-4}$
★ NEARLY SCALE INVARIANT $n_T = -\frac{1}{5} T/S$	0.71 (95% cl)		± 0.03

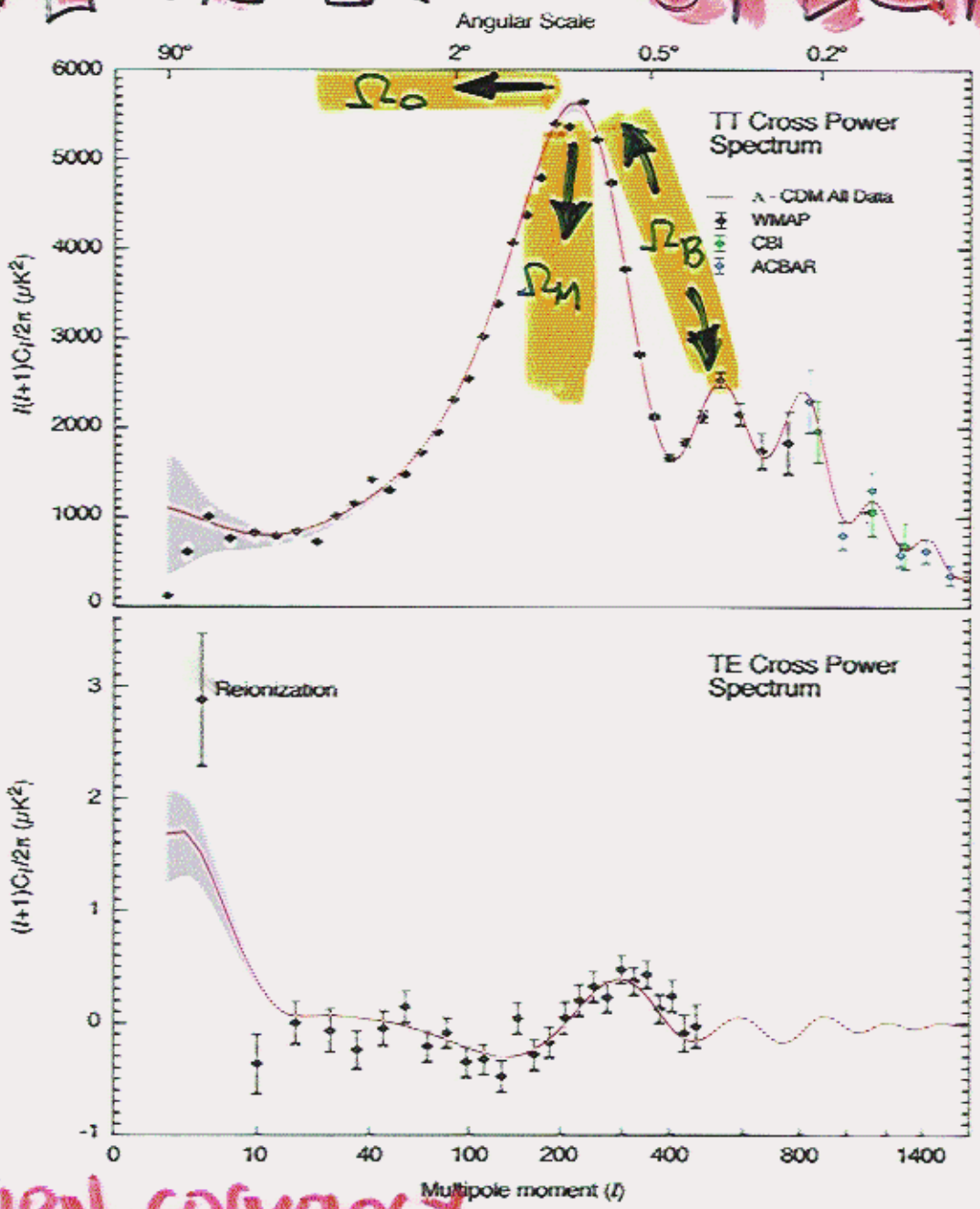
* FOR DOING IT THE HARD WAY

MAP OF THE UNIVERSE AT A SIMPLER TIME (400,000 YRS)





WMAP POWER SPECTRUM



PRECISION COSMOLOGY

$\Omega_0 = 1.02 \pm 0.02$

$t_0 = 13.7 \pm 0.2$ Gyr

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

$h = 0.71 \pm 0.035$

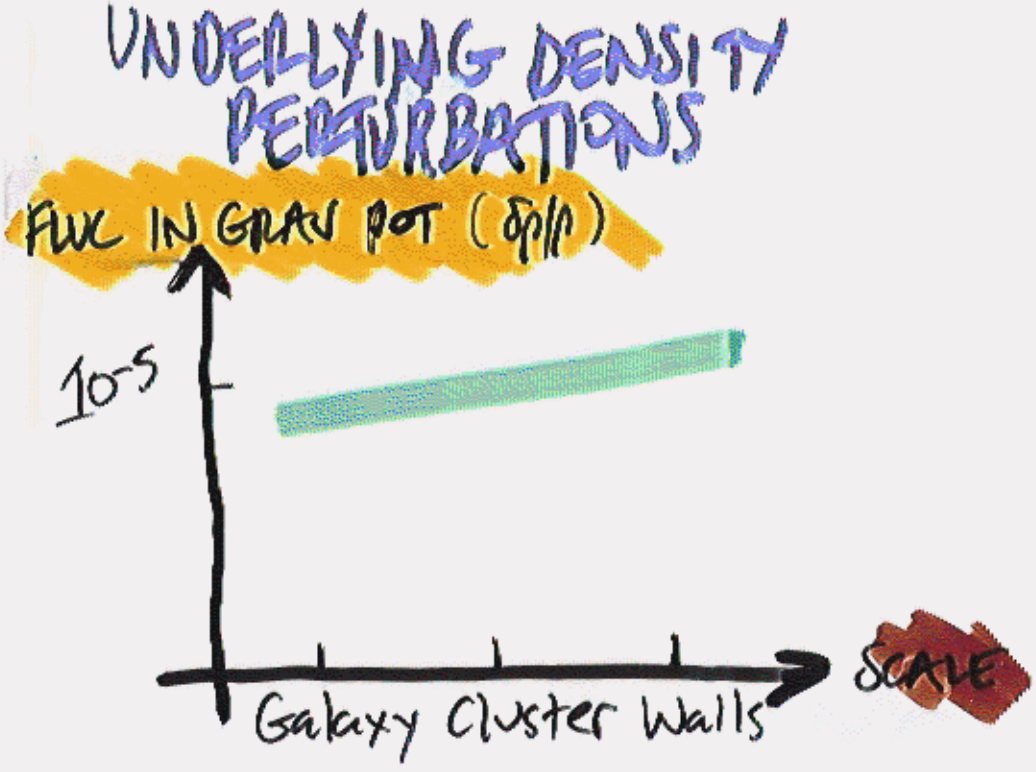
* $\Omega_B h^2 = 0.0224 \pm 0.001$

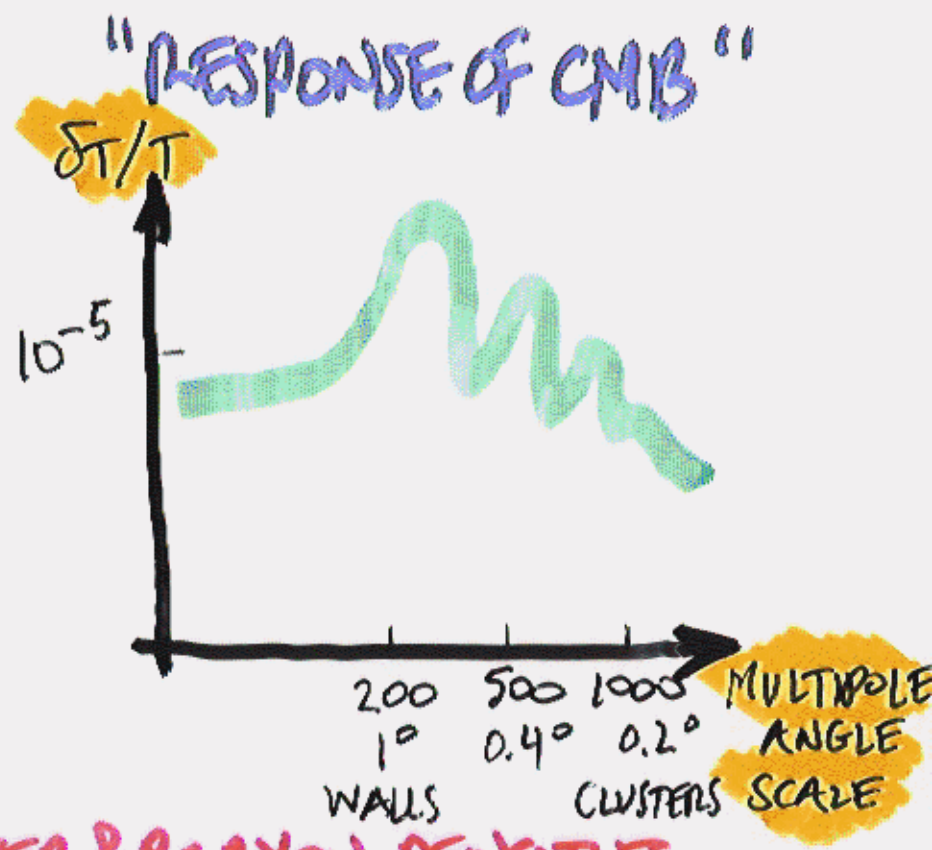
$\Omega_{D.E.} = 0.7 \pm 0.04$

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

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

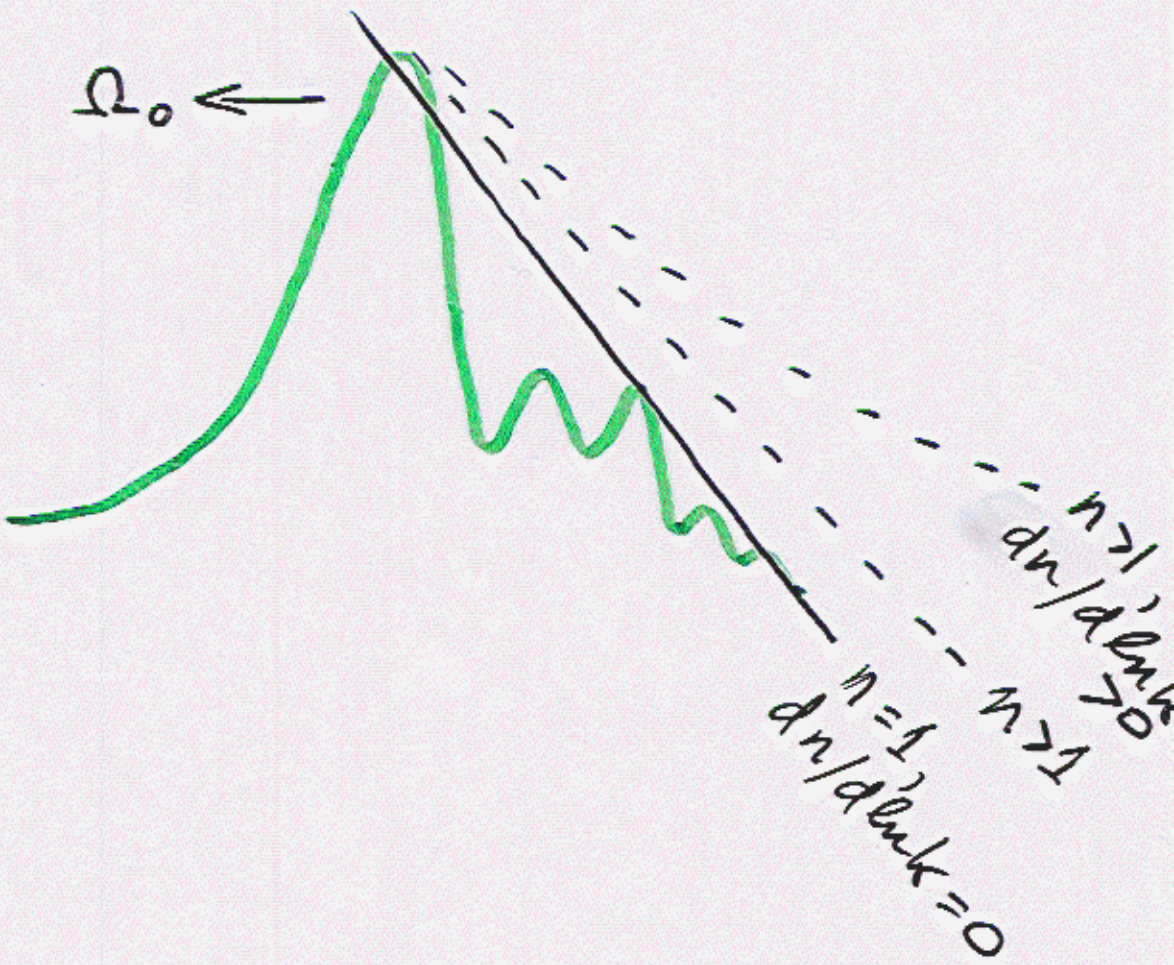
CMB IS A NON TRIVIAL PROBE OF MATTER DENSITY

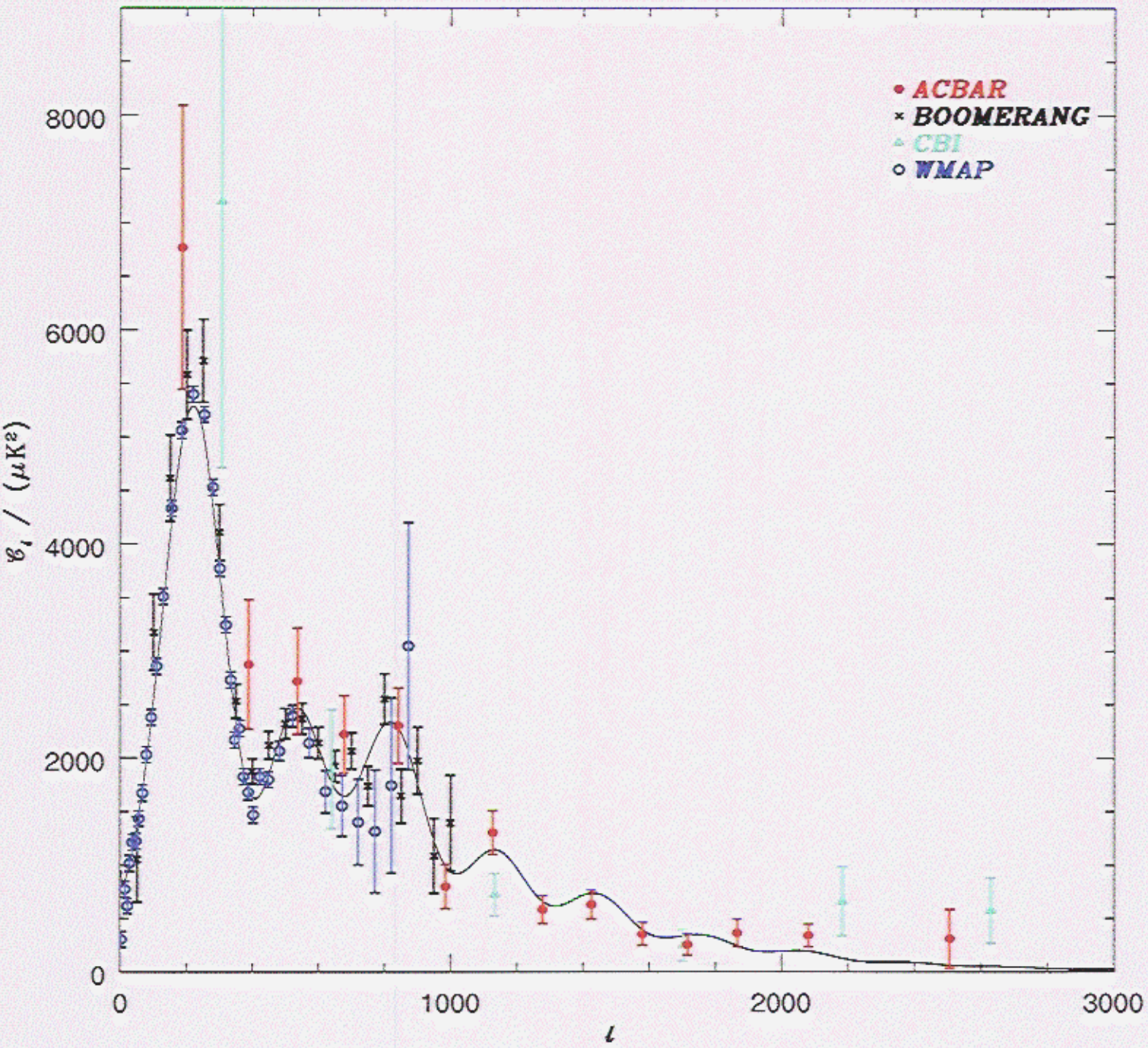


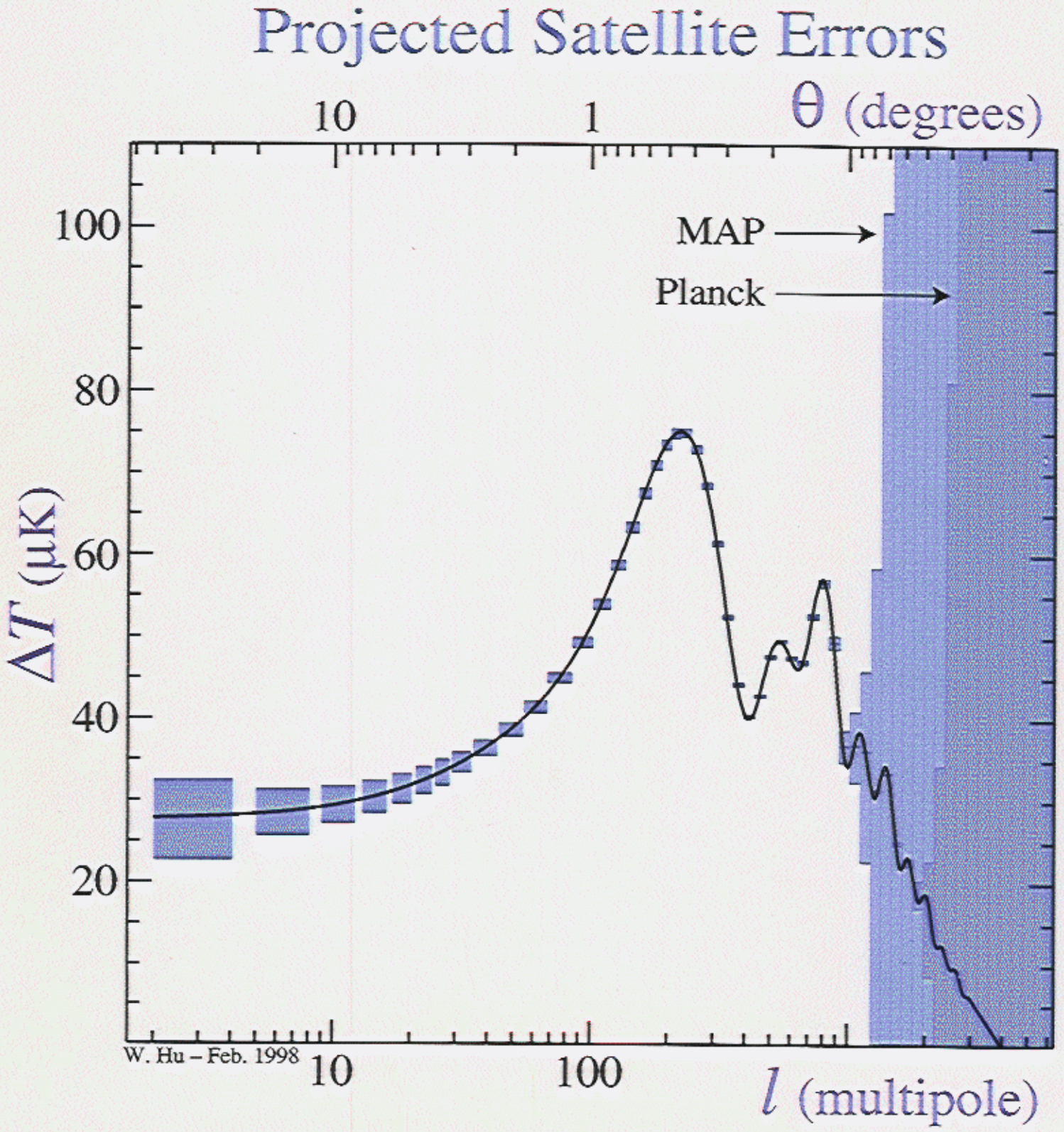


RESPONSE DEPENDS UPON: MATTER & BARYON DENSITIES, CURVATURE, DARK ENERGY ... & PRIMEVAL δφ/c

PROBES COSMOLOGY!


Ω_0
$n>1$, $dn/d\ln k > 0$
$n>1$
$n=1$, $dn/d\ln k = 0$


ACBAR
BOOMERANG
CBI
WMAP
8000
6000
4000
2000
0
0
1000
2000
3000
$\mathcal{C}_\ell$ / (μK^2)
ℓ

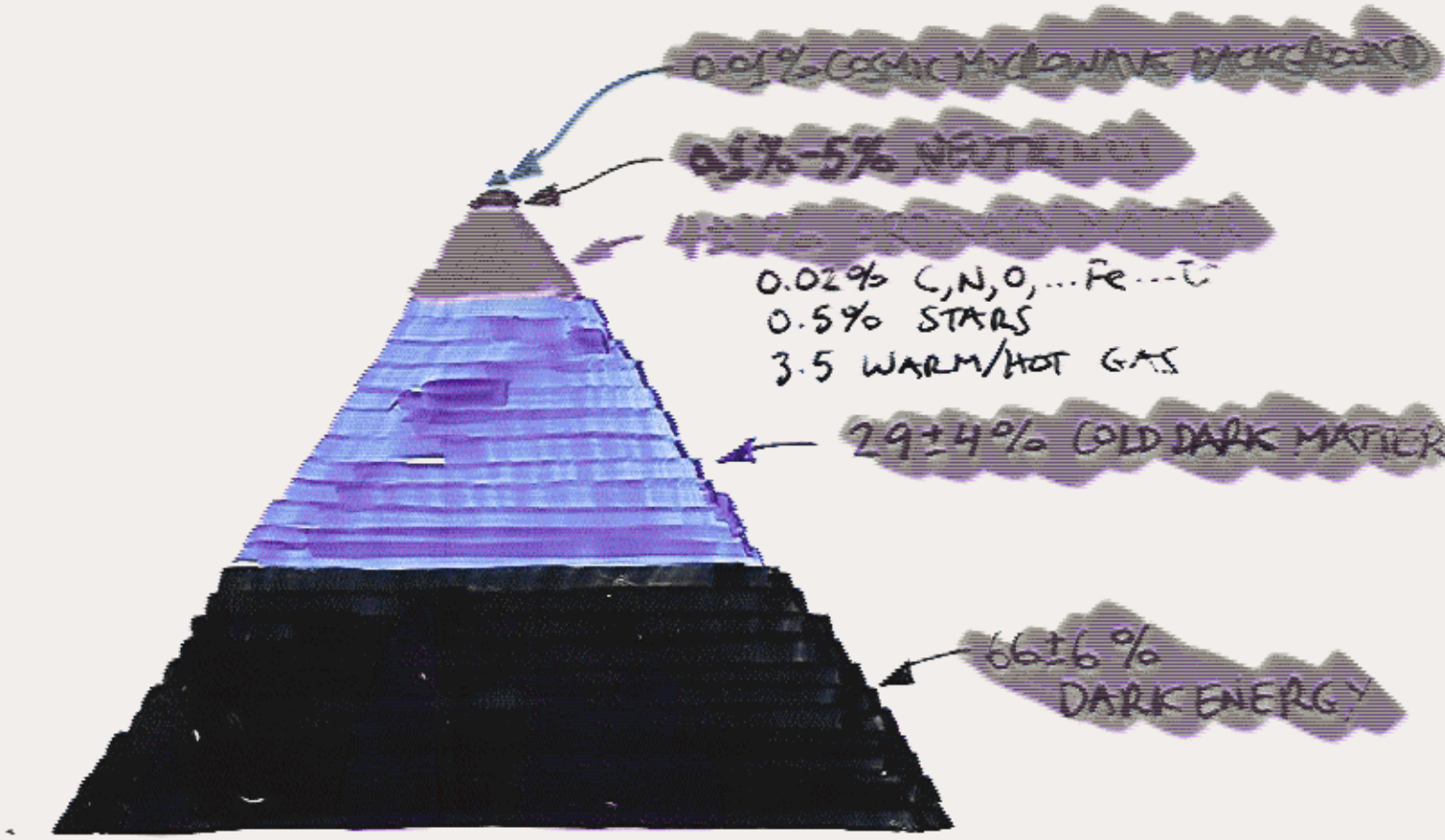

Projected Satellite Errors
θ (degrees)
10
1
100
80
60
40
20
ΔT (μK)
MAP
Planck
W. Hu – Feb. 1998
10
100
l (multipole)

COSMIC RECIPE

FLAT, CRITICAL DENSITY UNIVERSE

0.5% STARS

33% DARK MATTER + 66% DARK ENERGY



MORE THAN 95% IN NEW FORMS OF MATTER & ENERGY!

CDM Predictions

"Bottom Up"

first stars	$z \sim 10\text{-}20$
galaxies	$z \sim 2\text{-}5$ ✓
clusters	$z \sim 0\text{-}1$ ✓
superclusters	$z \sim 0$ ✓

Large-scale Structure

voids, filaments, sheets ✓

"Power Spectrum"

$P(k) = |\delta_k|^2$ ✓

FROM CBR & REDSHIFT SURVEYS (2dF, SDSS)

Properties of clusters

number, distribution, X-ray temp ✓

"Lots of Recent Evolution"

merging, relaxing, ... ✓

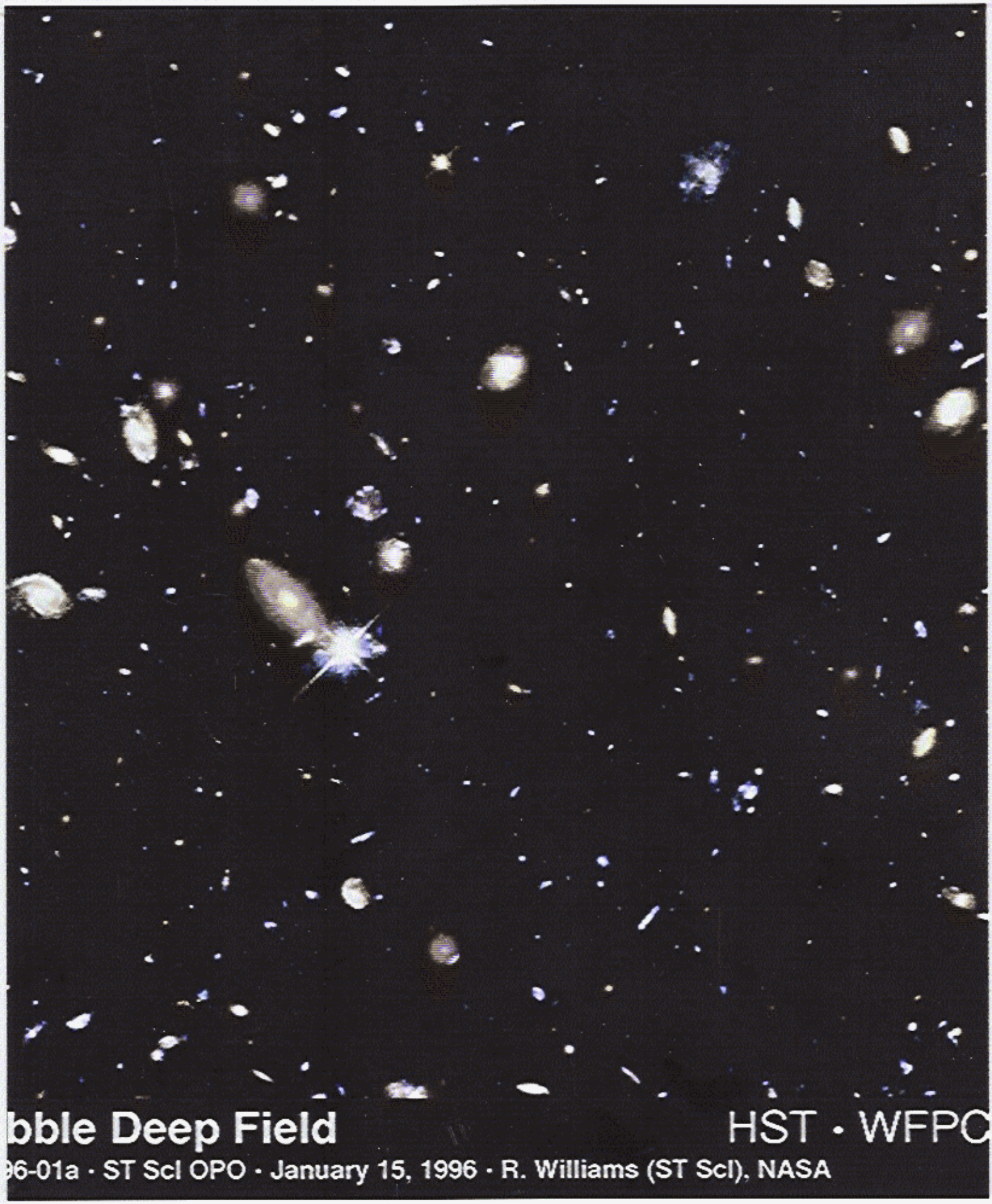
PROVIDED $\Omega_m h \simeq 0.25 \pm 0.05 \Rightarrow \Omega_m \simeq 0.4^{+}_{0.}$

COLD DARK MATTER

'EQ':
$R \sim 3 \times 10^5$
$t \sim 1000\,yr$
$\delta\rho/\rho \sim 10^{-5}$

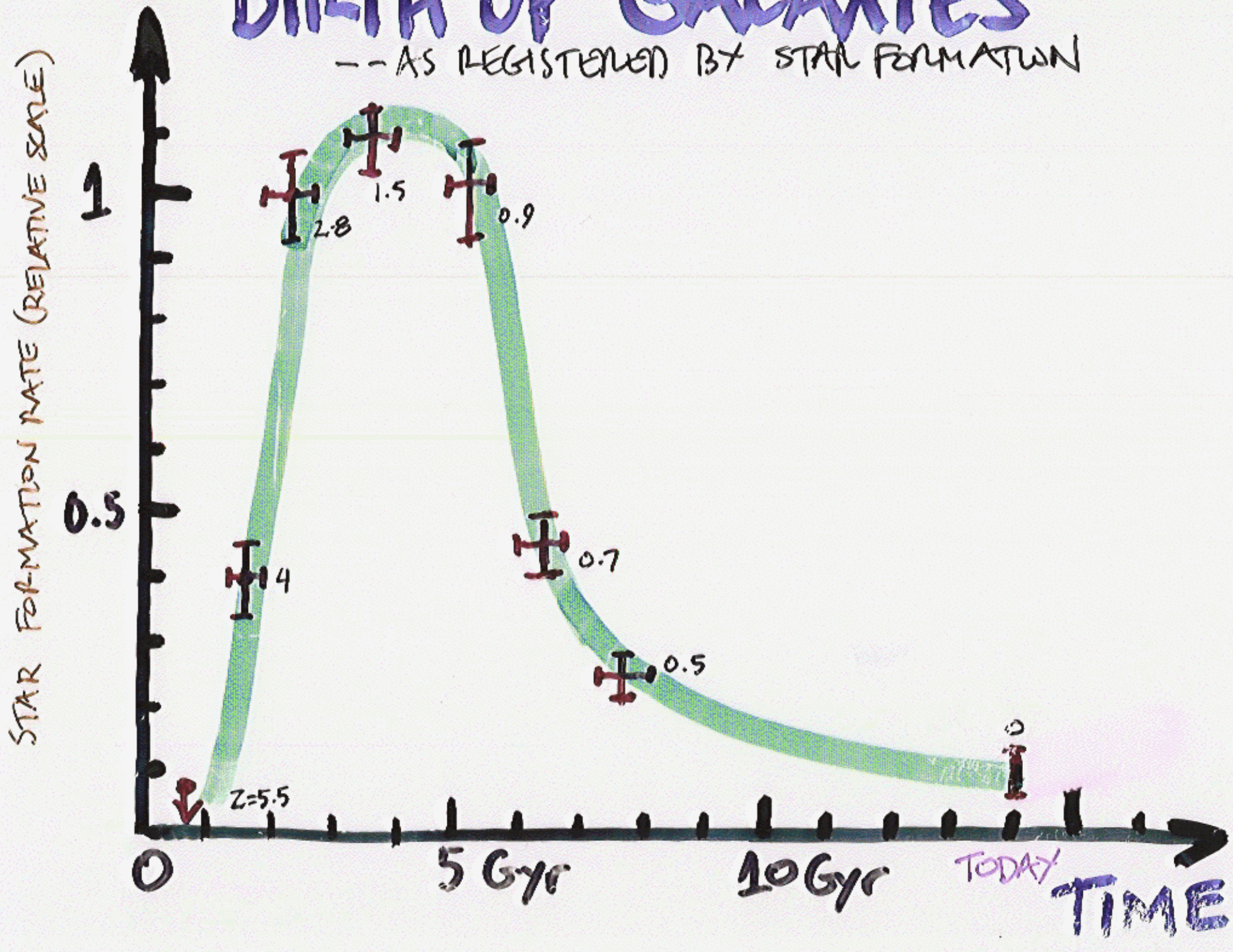
$R \sim 1/3 - 1/2$
$t \sim$ few Gyr
GALAXIES FORM!
Dark halos, baryons dissipate

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


bble Deep Field
HST · WFPC
96-01a · ST ScI OPO · January 15, 1996 · R. Williams (ST ScI), NASA

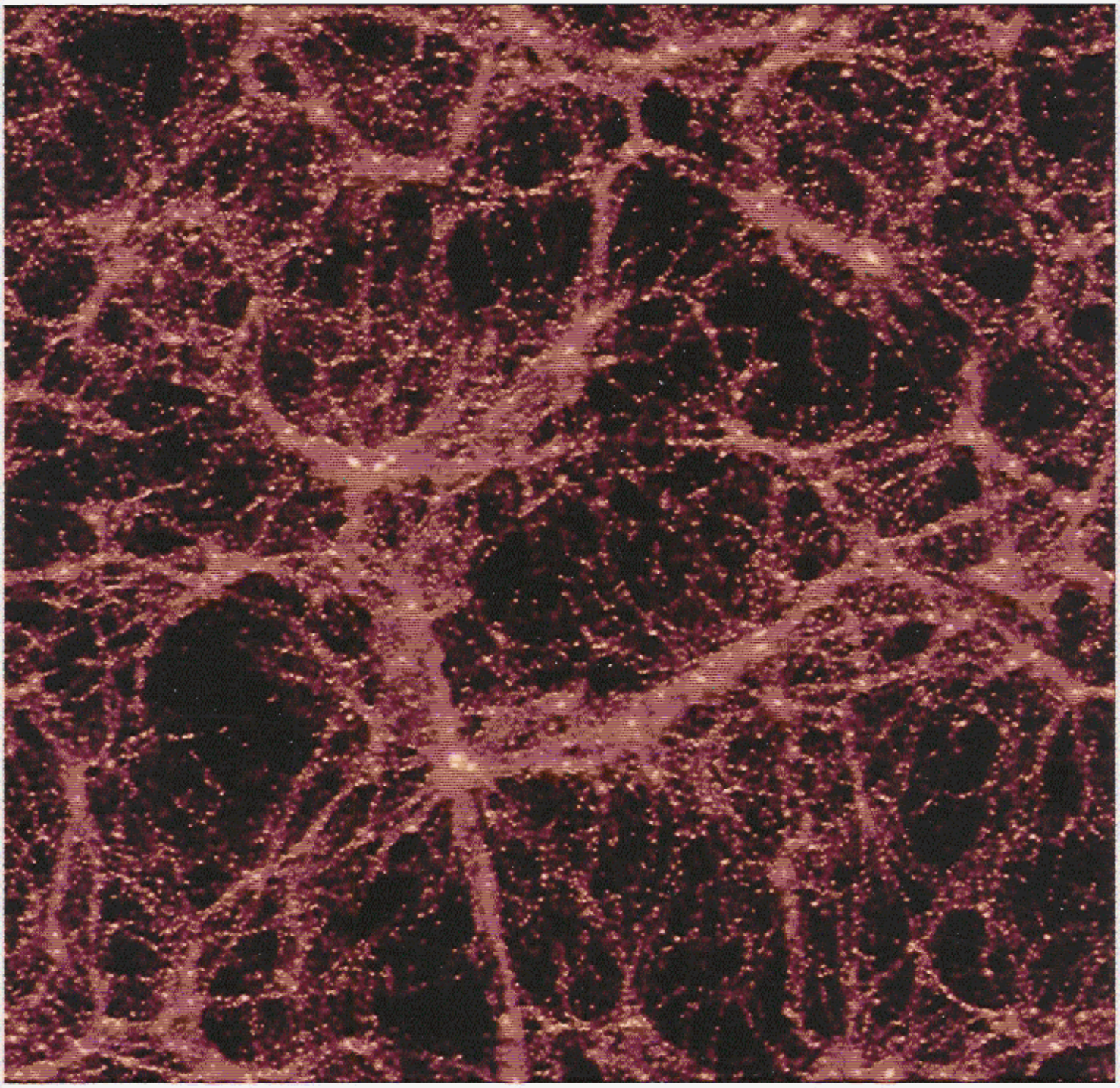
BIRTH OF GALAXIES

--AS REGISTERED BY STAR FORMATION

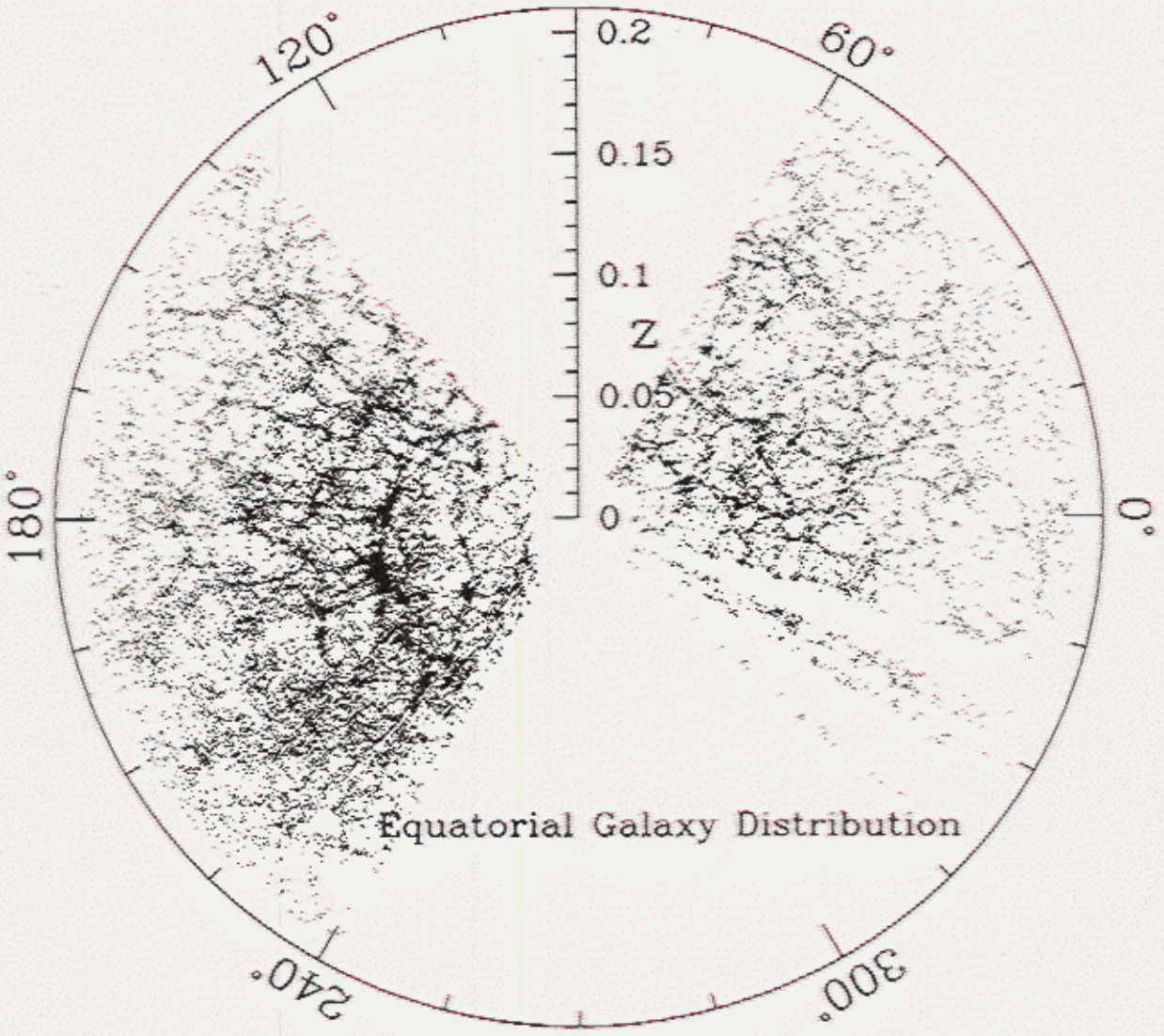


COSMIC WEB OF DARK MATTER

from Virgo Project



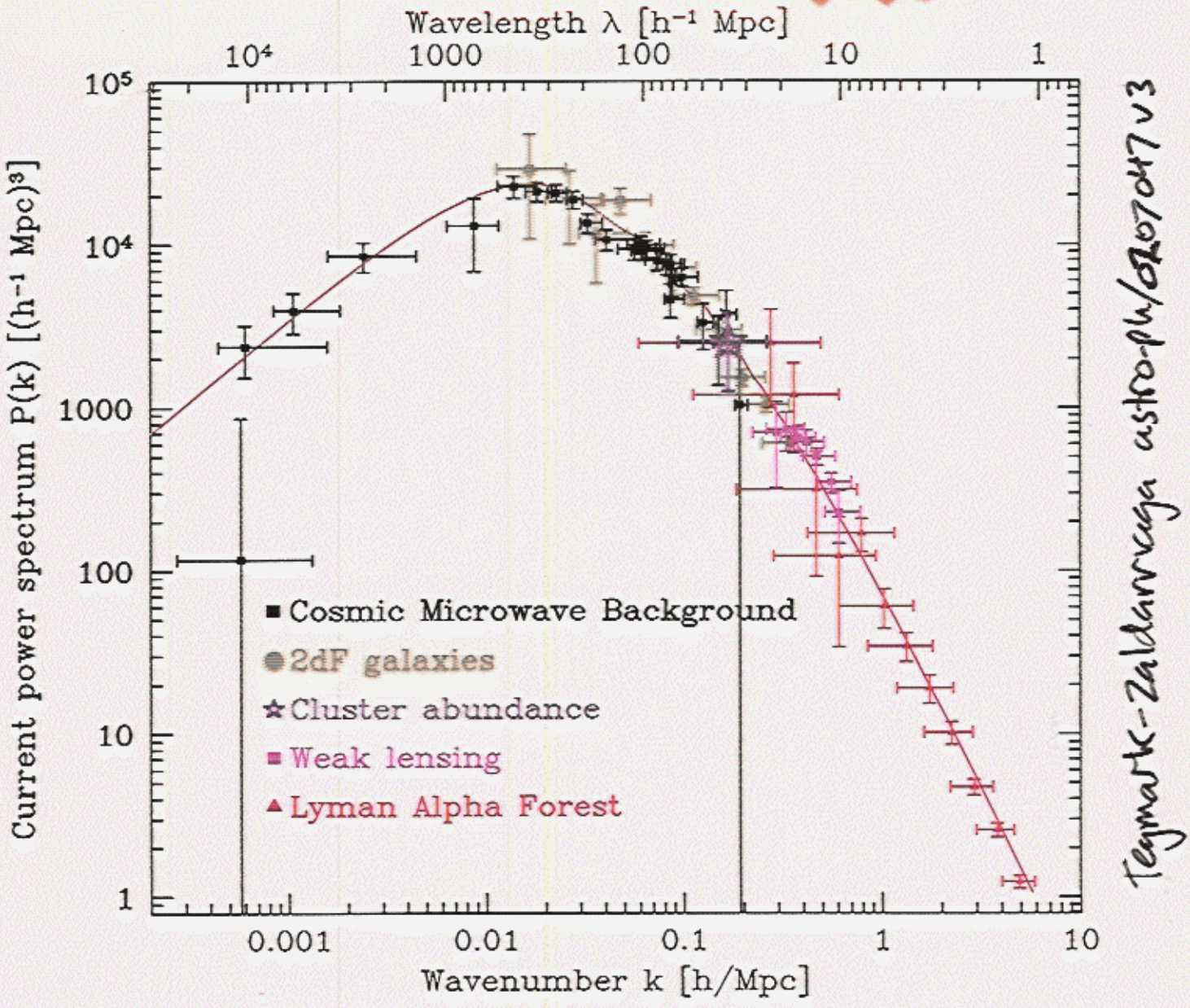
MAP of the UNIVERSE



Sloan Digital Sky Survey

CDM POWER SPECTRUM v. OBSERVATIONS

From the Ly-α Forest to the Hubble Scale
w/ a decade of overlap (CMB & LSS)



Tegmark-Zaldarriaga astro-ph/0207047 v3

NB: Baryon only, HDM, ...,
cannot make a similar claim

PRECISION TESTING HAS BEGUN

FIRST MODEL RULED OUT!

$V = \lambda\phi^4$

WMAP, 2dF, SDSS, DASI,
CAPMAP, BOOM-POL, ACT,
SPT, APEX, ... PLANCK,
LIGO, LISA, CMB-POL, BBO, ...

HOLY GRAIL: GWs

STATUS OF INFLATION:

EXCELLENT!

Mr. Turner, Mr. Chacon & Ms. Nash

WHY the TENSORS MATTER

"SMOKING GUN" SIGNATURE

FLAT UNIVERSE & SCALE-INVARIANT $\mathcal{P}_\mathcal{R}$
PRE-DATE INFLATION

STRENGTH DIRECTLY TIED TO $V(\phi)$ & $H_{INFLATION}$

"RECONSTRUCTION OF $V(\phi)$

CONSISTENCY TEST

$$T/S = -5 n_T$$

∴ BUT NO ROBUST PREDICTION FOR AMPLITUDE

RECONSTRUCTION OF $V(\phi)$

measure S, T/S, $n-1$

CMB

SCALE OF INFLATION → $V = 1.8\, T\, m_{pl}^4$

NB: $H_I^{-1} = 1.4\times10^{-34}\ \text{sec}\ (T/10^{-10})^{-1/2}$

$V' = \pm\sqrt{\frac{8\pi}{5}\frac{T}{S}}\, V/m_{pl}$

SHAPE OF POTENTIAL → $V'' = 4\pi\left[(n-1) + \frac{3}{5}\frac{T}{S}\right] V/m_{pl}^2$

also measure n_T CMB+ SUPER-LISA?

consistency test: $T/S \doteq -5\, n_T$

"PREDICTING" $n-1$ & T/S

REFORMULATE INFLATION EQ^{NS} AS "FLOW EQ^{NS}" FOR $n-1$, T/S

HOFFMAN-TURNER astro-ph/0006321

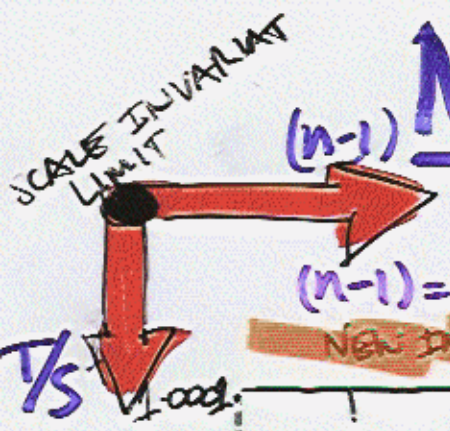
$$\frac{d(T/S)}{dN} = (n-1)\frac{T}{S} + \frac{1}{5}\left(\frac{T}{S}\right)^2$$

$$\frac{d(n-1)}{dN} = -\frac{1}{5}(n-1)\frac{T}{S} - \frac{1}{25}\left(\frac{T}{S}\right)^2 \pm \frac{dn}{d\ln k}$$

MENU OF POTENTIALS

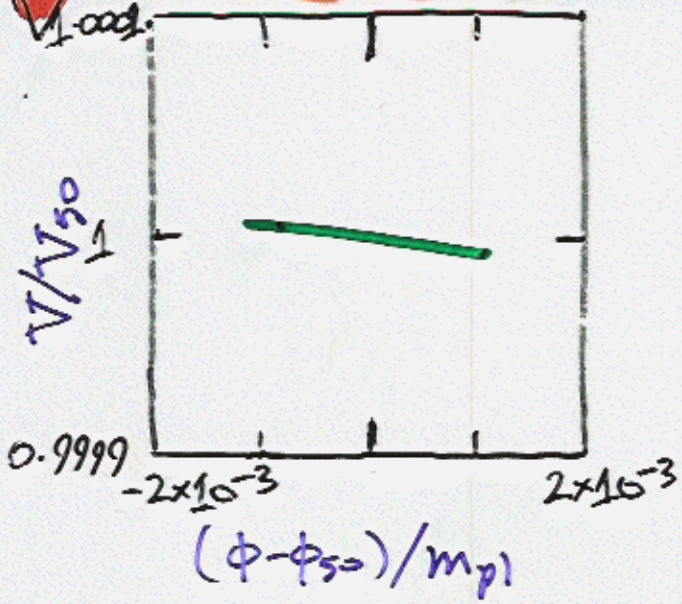
(SHAPE DETERMINED $n-1$ & $n_T = -\frac{1}{7}\frac{T}{S}$)

astro-ph/9707035



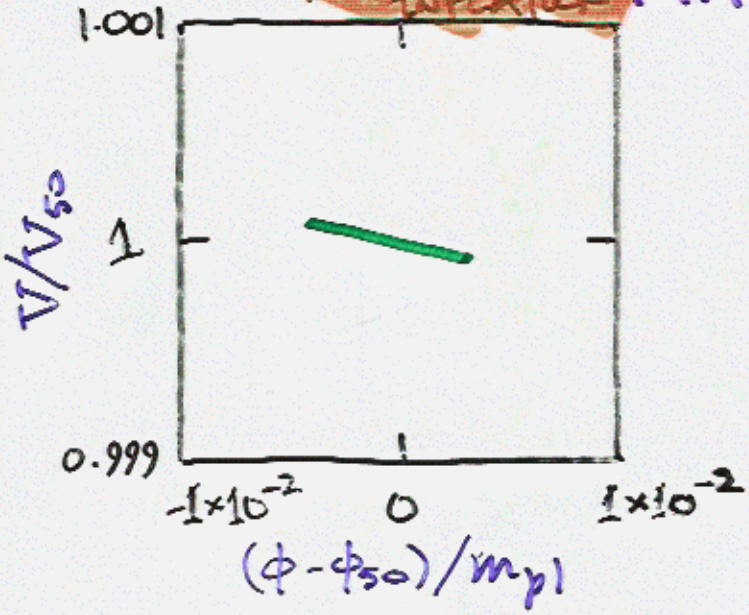
$(n-1) = -2\times10^{-6}$, $T/S = 1.4\times10^{-5}$

NEW INFLATION



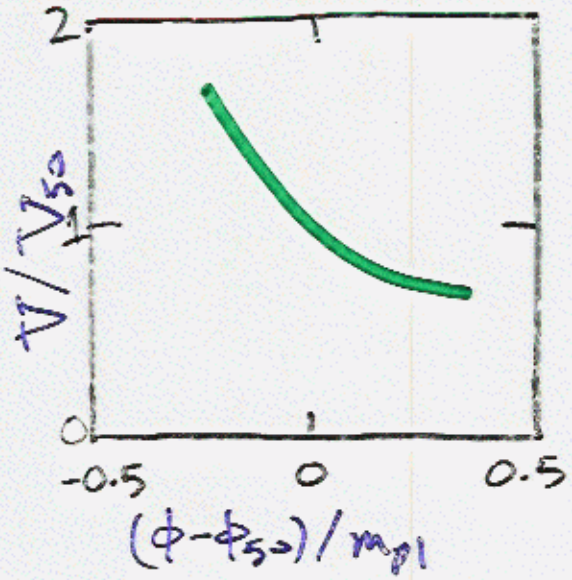
$(n-1) = -0.15$, $T/S = 1.4\times10^{-4}$

NATURAL INFLATION



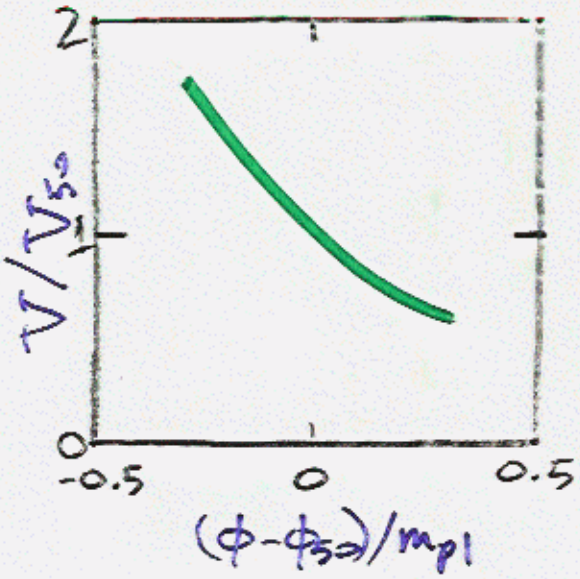
$(n-1) = 0$, $T/S = 1$

E.G. CHAOTIC INFLATION



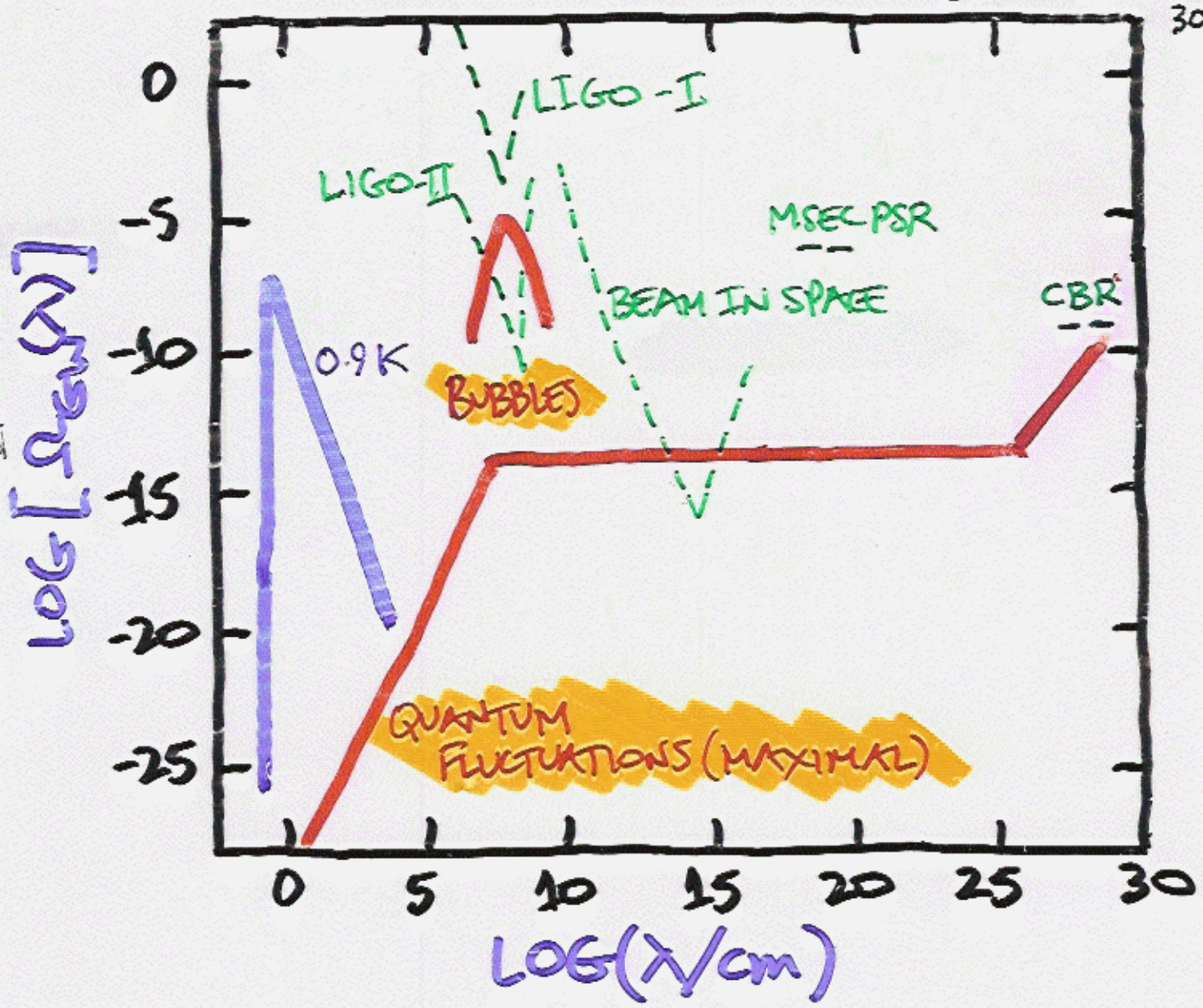
$(n-1) = -0.15$, $T/S = 1$

E.G. EXTENDED INFLATION



GRAVITY WAVES FROM INFLATION

(MST-Wilczek PRL 65, 3080 ('90))

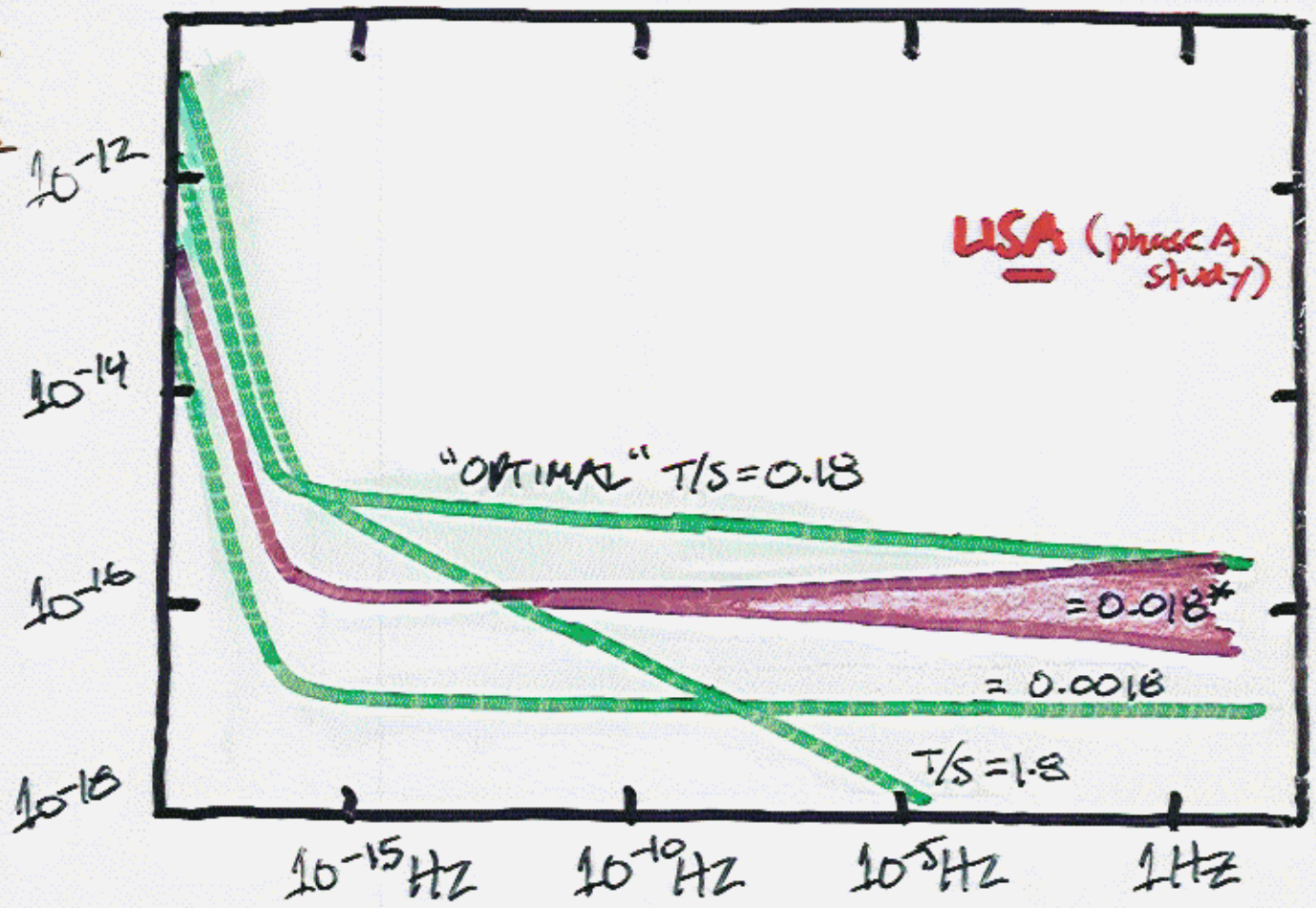


NB: "Astrophysical Background" Not Shown

ENERGY DENSITY IN INFLATION PRODUCED GWs

MST PRD55 ('97)

LIGO-II



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

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

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

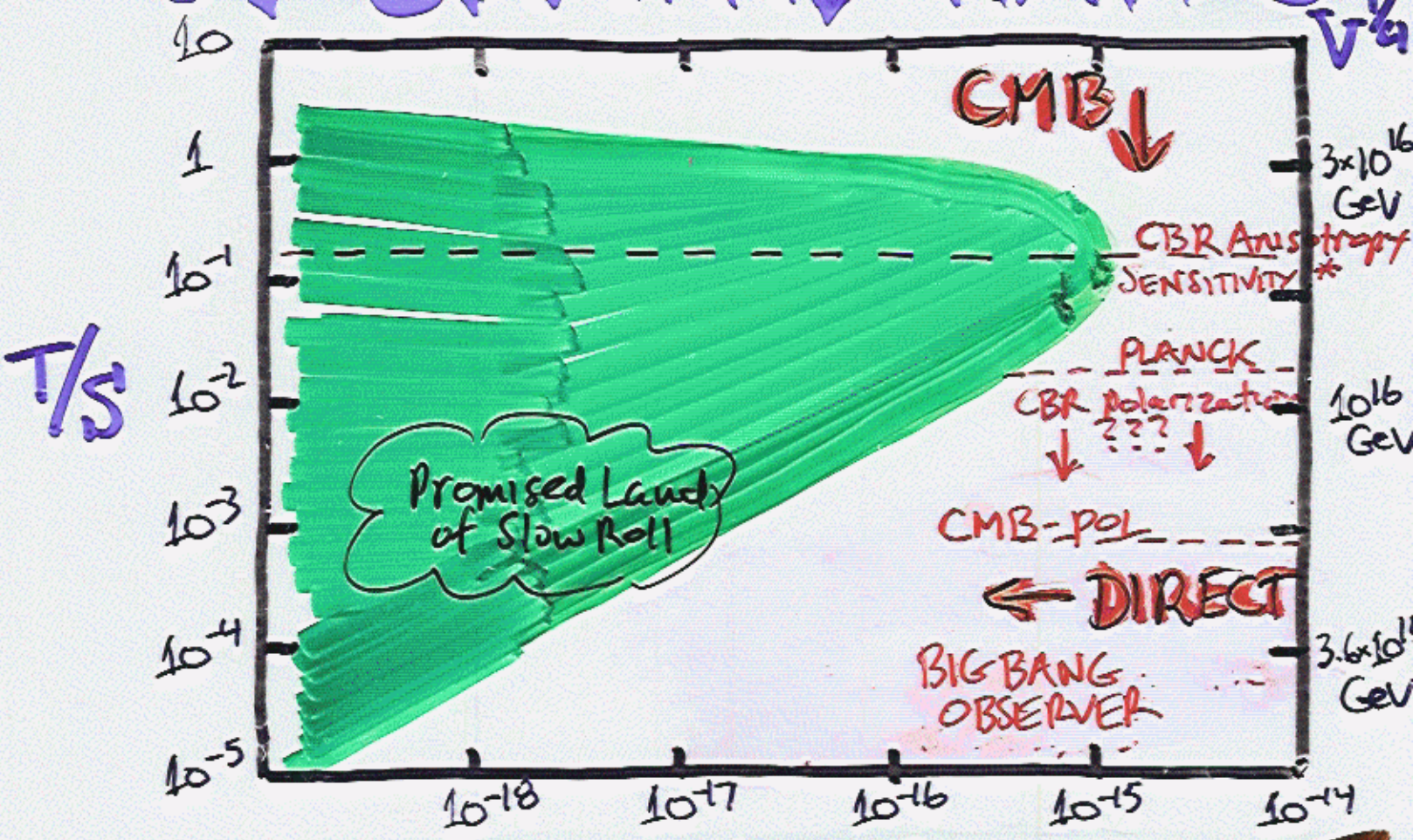
$$\Omega_{GW}(f)h^2 = 5.1\times10^{-15}\,\frac{n_T}{n_T - \gamma_T}\cdot e^{N n_T + \frac{1}{2}N^2 dn_T/d\ln f}$$

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

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

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

DETECTION OF GRAVITY WAVES



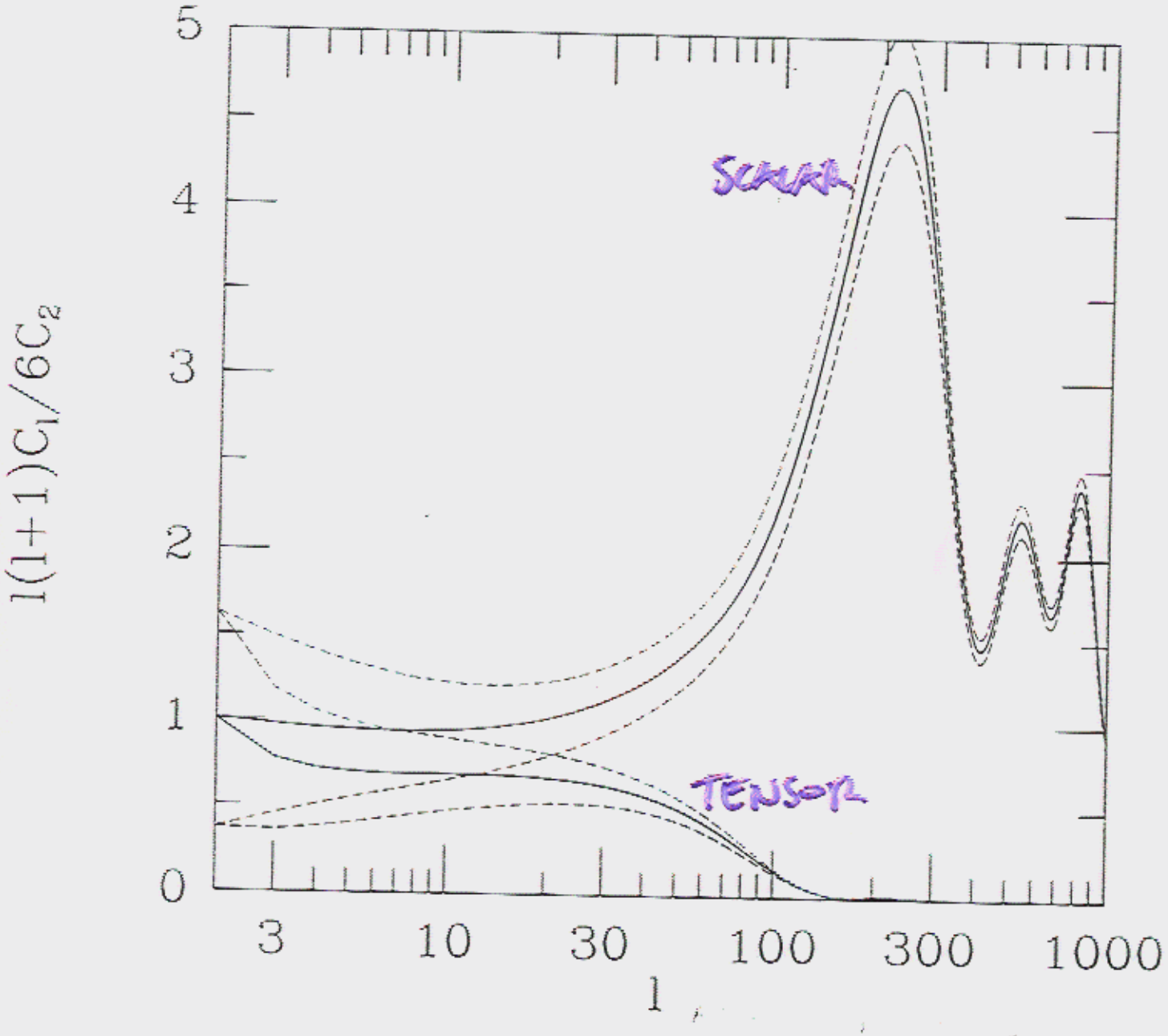
NB:

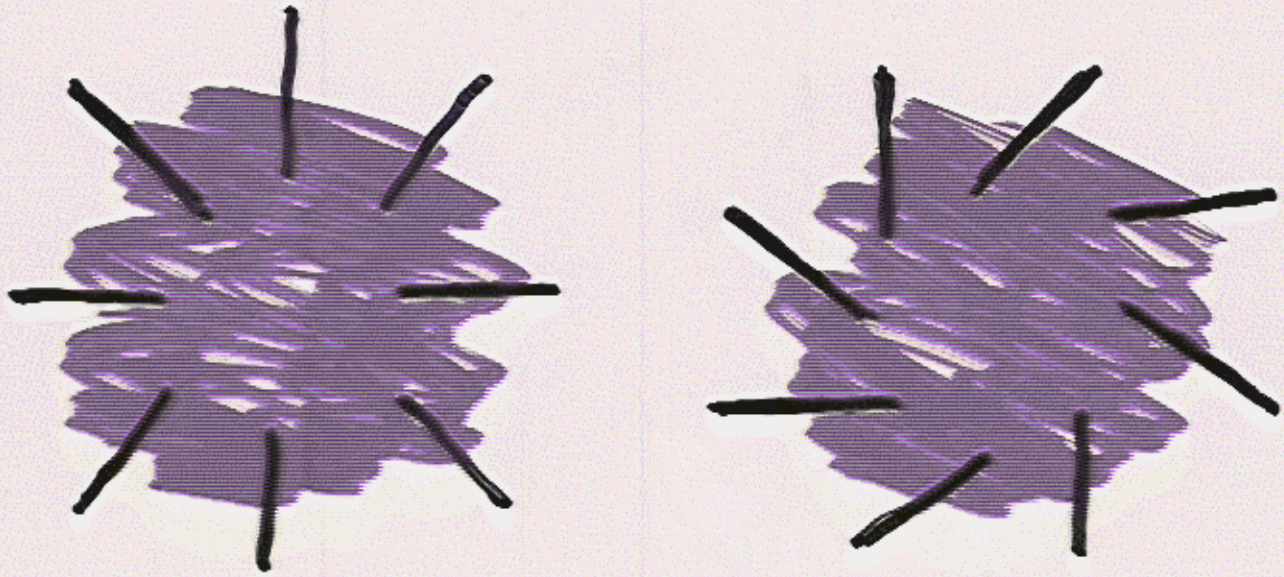
LIGO 10^{-10}

LISA 10^{-12}

VERY CHALLENGING!

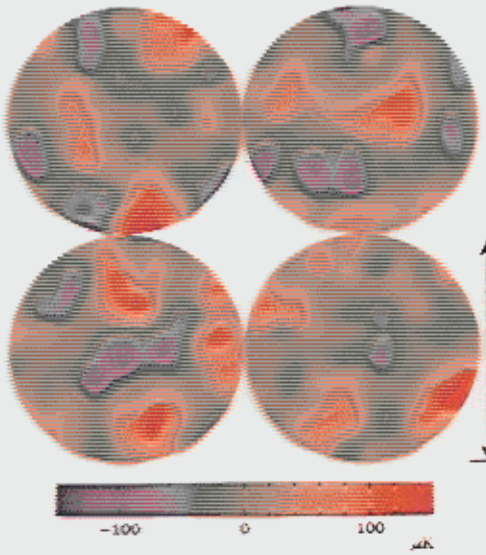
"DOUBLE DETECTION" $\Rightarrow$ n_T to ± 0.03

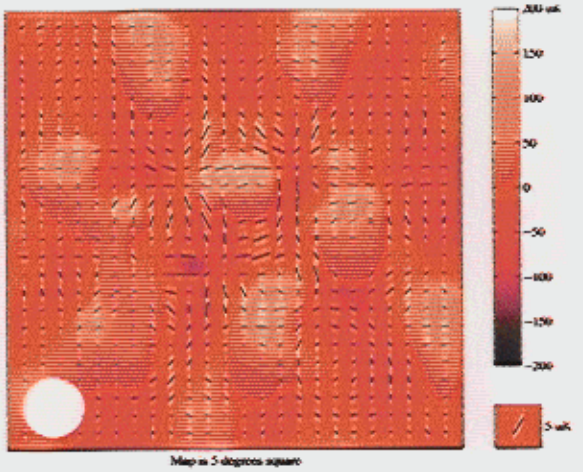

$l(l+1)C_l/6C_2$
5
4
3
2
1
0
SCALAR
TENSOR
3
10
30
100
300
1000
l

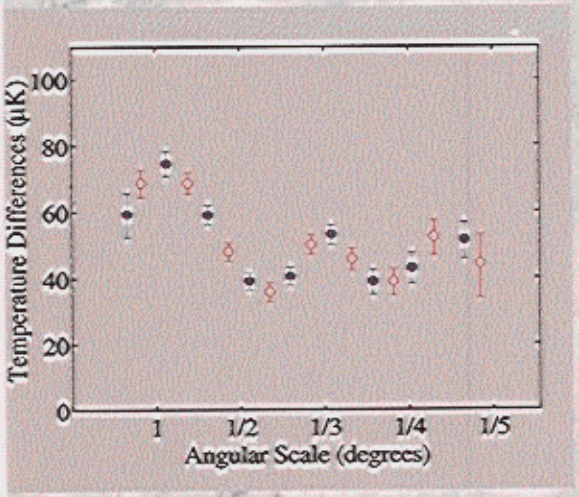


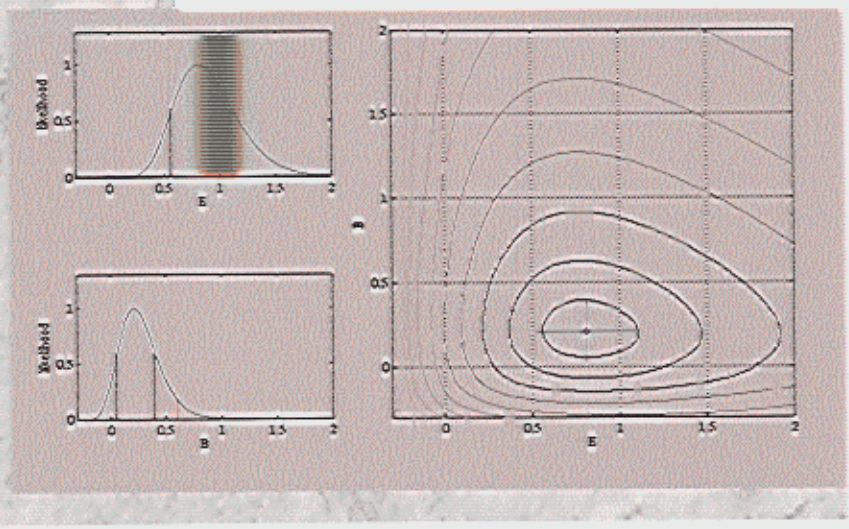
DASI

Acoustic Peaks and Polarization





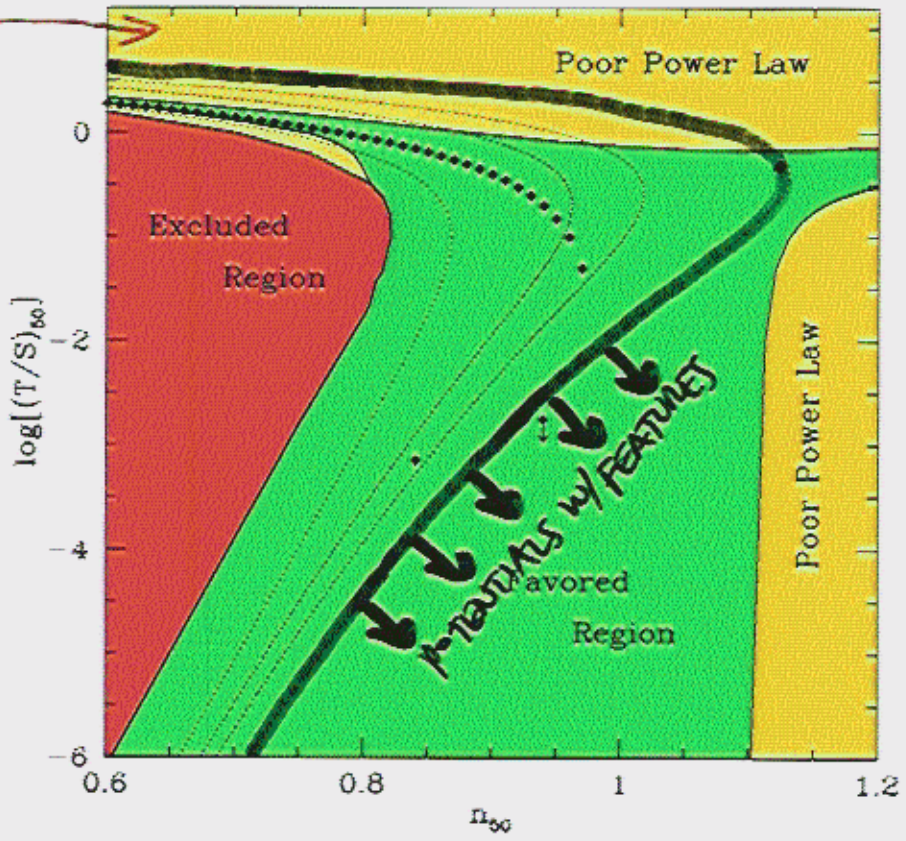




MODEL-INDEPENDENT, "KINEMATIC" CONSTRAINTS TO T/S, n

SLOW ROLLOVER INFLATION
Hoffman-MST astro-ph/0006321 (PRD64, 023506(2001))

$dn/d\ln k \geq 10^{-2}$



WMAP

PLANCK

POST-PLANCK

B-mode polarization expt

Figure 3: Same as Fig. 2, with a logarithmic scale for T/S.

for potential w/o features & $n > 0.85$ $T/S > 10^{-3}$

INFLATION RECAST AS FLOW EQN'S:

$d(T/S)/dN = (n-1)\,T/S + 1/5(T/S)^2$ $\qquad \frac{d(n-1)}{dN} = -\frac{1}{5}(n-1)\frac{T}{S} - \frac{1}{25}\left(\frac{T}{S}\right)^2$

THE FUTURE

TEST FRAMEWORK

$\Omega_0 = 1$, $(n-1) \sim \mathcal{O}(0.1)$, $dn/d\ln k \sim 10^{-3}$

PROBE UNDERLYING PHYSICS

precision measurements of $(n-1)$, $dn/d\ln k$ + TENSORS

FUNDAMENTAL MODEL

TRANSPLANCKIAN PHYSICS

... UNEXPECTED FEATURES

SOME CONNECTION TO LAB PHYSICS

THE MULTIVERSE DILEMMA

CAN IT BE MADE INTO SCIENCE

INFLATION IS A MODEST PROPOSAL

DOES NOT ADDRESS: INITIAL CONDX FOR ϕ

SINGULARITY, DISTANT FUTURE


IMPORTED
MULTIVERSE
COSMOS
BREWING

HIGH BAR TO ALTERNATIVES

SUPER HORIZON SIZE DENSITY PERT. NOT TIED TO I.C.

REQUIRES: (1) Superluminal expansion
(2) Entropy production

astro-ph/9302002

THE TWO DEFINING FEATURES OF INFLATION

DOES THAT IMPLY THAT ANY ALTERNATIVE CAN BE DESCRIBED AS SCALAR FIELD DYNAMICS?

"INFLATIONARY HEGEMONY"