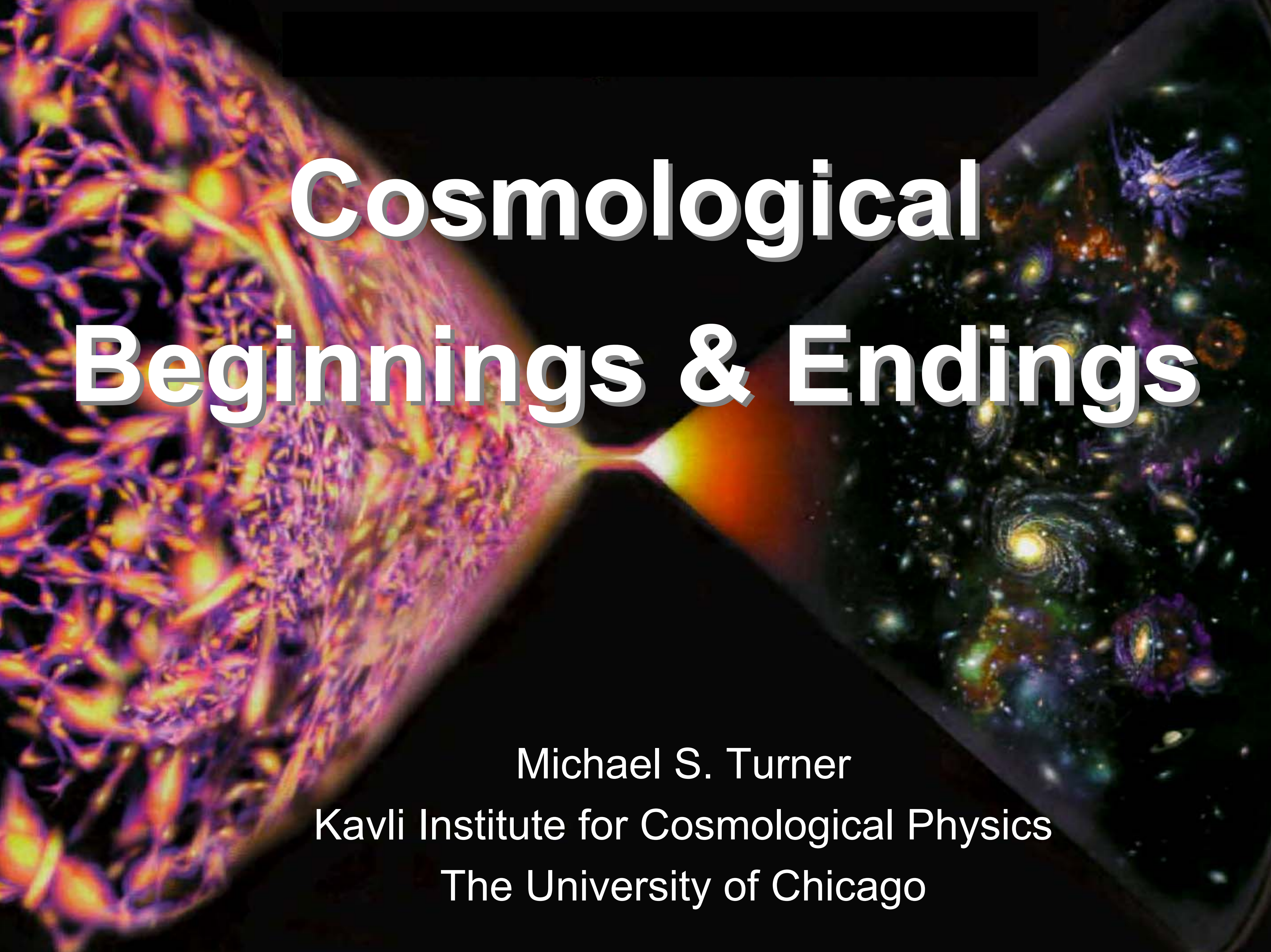


Cosmological Beginnings & Endings

Michael S. Turner
Kavli Institute for Cosmological Physics
The University of Chicago

“The New Cosmology”

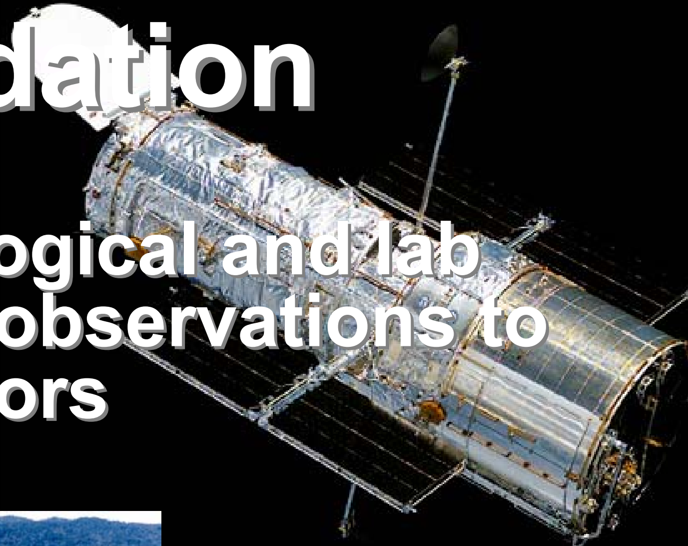
(aka Concordance Model)

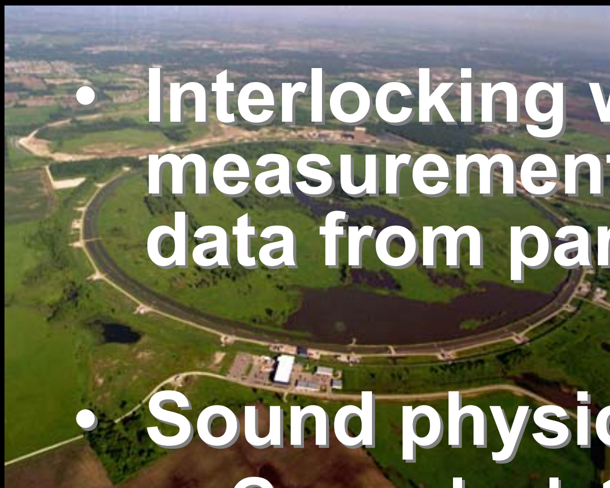
- Flat, accelerating Universe
- Composition
  - 4% baryons (0.5% stars!)
  - 26% cold dark matter (~0.1% neutrinos)
  - 70% “dark energy”
  - < 4% secret ingredients & sauces
- Inflation-produced, nearly scale-invariant density perturbations

<u>… Consistent with large & growing body of observations</u>

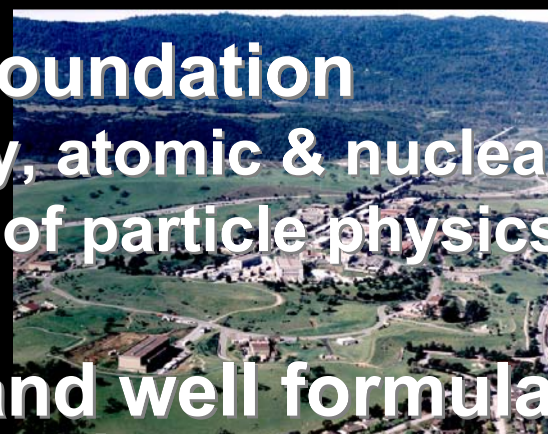
ORDINARY MATTER: FROM QUARKS TO US

Strong Foundation

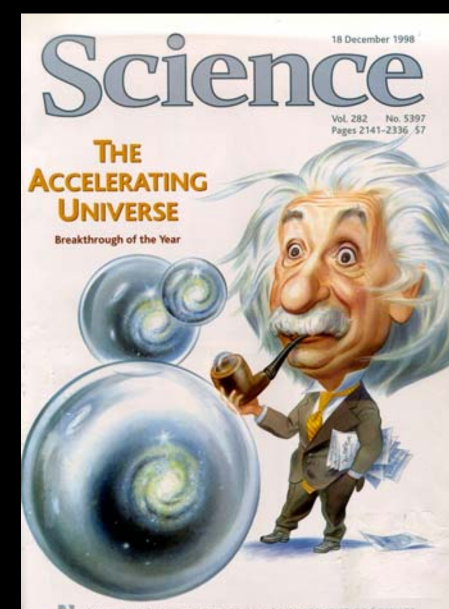




- Interlocking web of cosmological and lab measurements: from CMB observations to data from particle accelerators

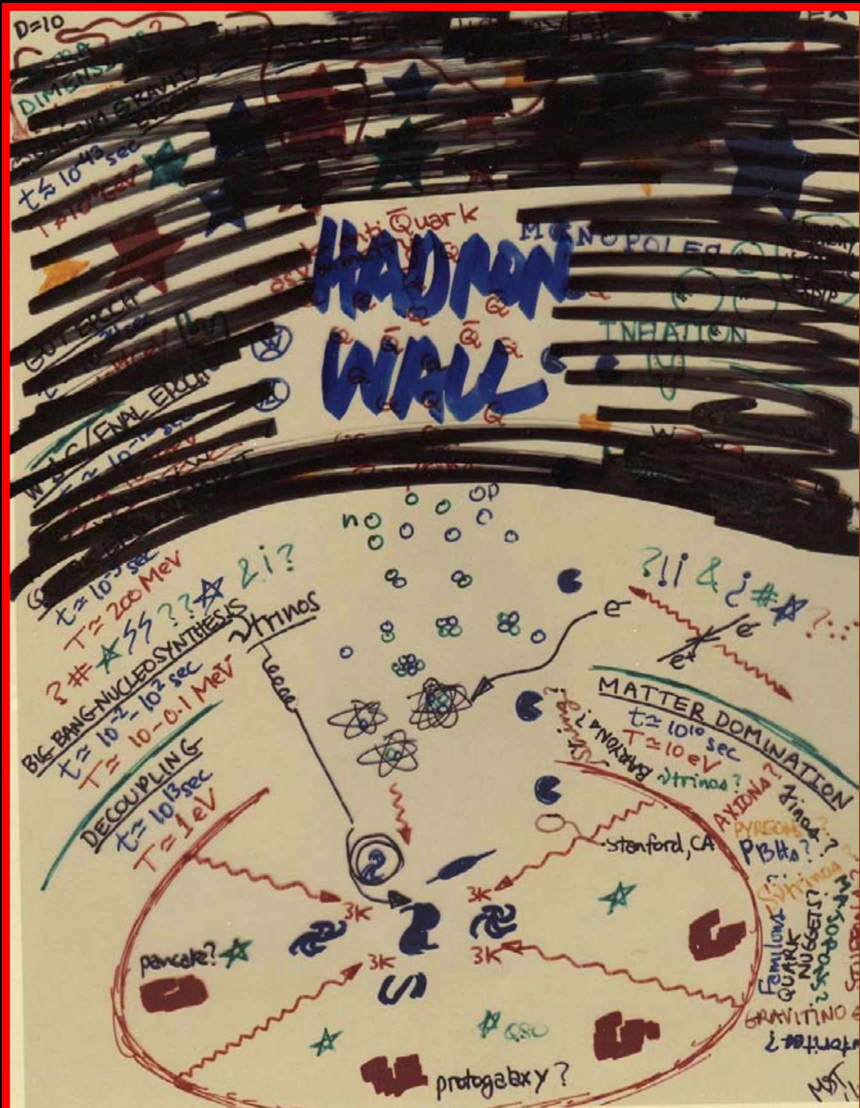


- Sound physics foundation
  - General relativity, atomic & nuclear physics
  - Standard model of particle physics



- Well motivated and well formulated speculations based upon
  - Gauge theory and grand unification
  - Supersymmetry
  - Superstring theory

The Hadron Wall



S. Weinberg in *Gravitation & Cosmology*

11 The Very Early Universe

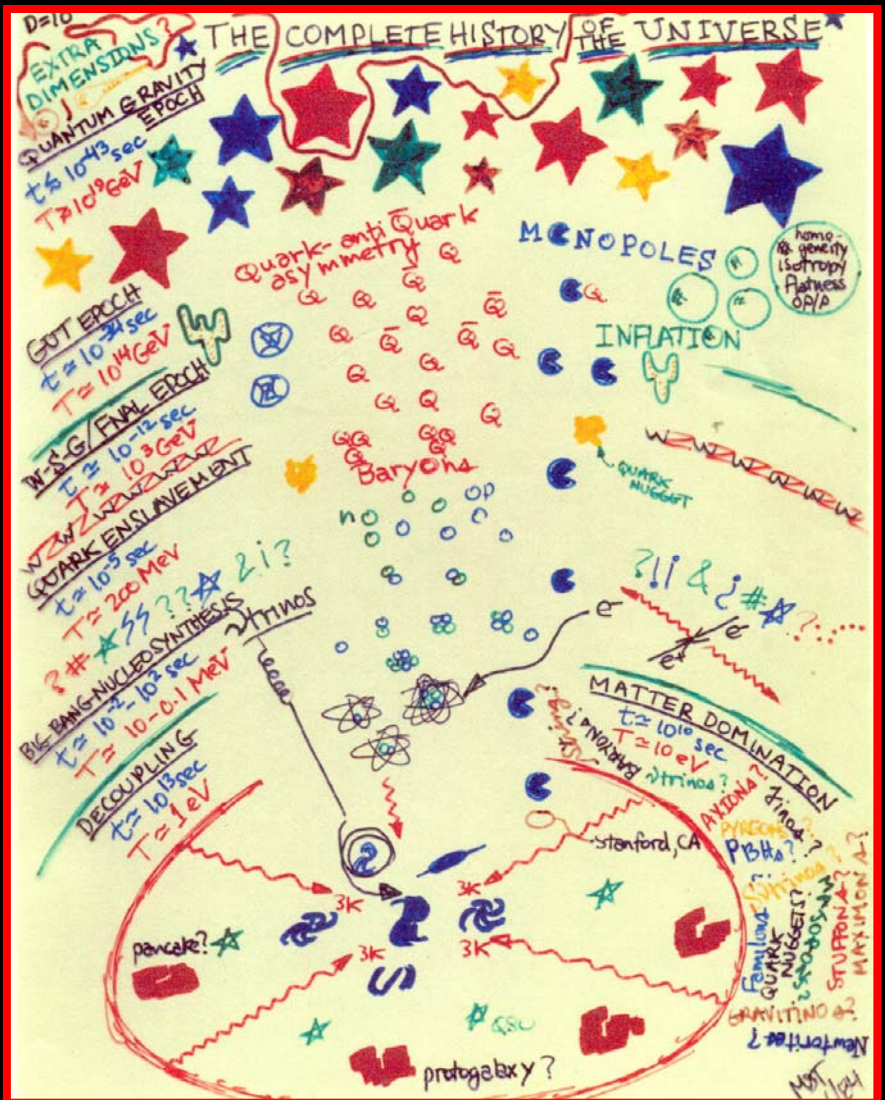
The thermal history of the universe was traced in Section 15.6 back to an era when the temperature was about 10^{12}°K. At this early time, the universe was filled with particles—photons, leptons, and antileptons—whose interactions are hopefully weak enough to allow this medium to be treated as a more or less ideal gas. However, if we look back a little further, into the first 0.0001 sec of cosmic history when the temperature was above 10^{12}°K, we encounter theoretical problems of a difficulty beyond the range of modern statistical mechanics. At such temperatures, there will be present in thermal equilibrium copious numbers of strongly interacting particles—mesons, baryons, and antibaryons—with a mean interparticle distance less than a typical Compton wavelength. These particles will be in a state of continual mutual interaction, and cannot reasonably be expected to obey any simple equation of state.

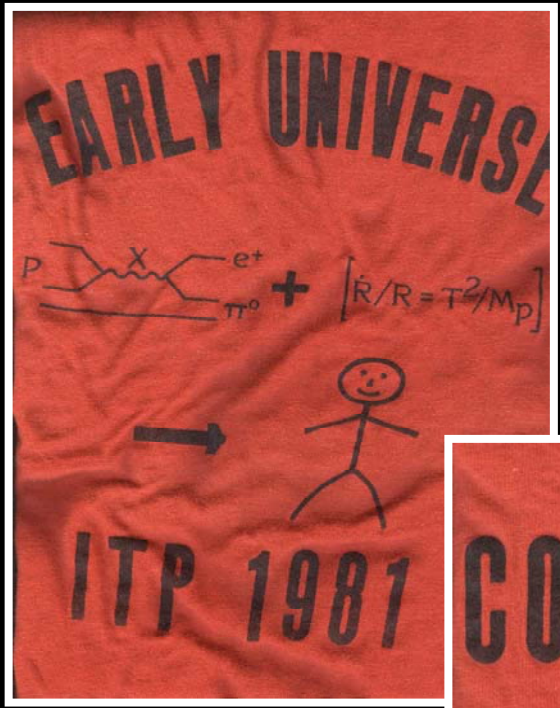
However, the temptation to try to construct some sort of model of the very early universe is irresistible. There are in fact two extremely different simple models that have been widely considered in recent years, and that reflect two divergent views of the nature of the strongly interacting particles. Although neither model can be taken seriously in detail, the hope is that one or the other of these models may come close enough to reality to lead to useful insights about the very early universe.

The first of these two pictures may be called the *elementary particle model*. It is supposed that all particles are made up of a small number of elementary

The Fall of the Hadron Wall

The 1970s: Gauge Theory, Asymptotic Freedom and GUTs





Precision Cosmology!

with no apologies!

Some Cosmological Parameters

error bars decreasing, consistency holding

- $T = 2.725 \pm 0.001$ K — COBE FIRAS
- $H_0 = 70 \pm 7$ km/s/Mpc — HST, SZ, CMB, …
- $\Omega_0 = 1.01^{+0.009}_{-0.016}$ — WMAP, H_0
  - $\Omega_M = 0.27 \pm 0.04$ — WMAP, SDSS, SNe, Clusters
  - $\Omega_{DE} = 0.65 \pm 0.05$ — WMAP, SDSS, SNe
  - $\Omega_B = (0.022 \pm 0.001)/h^2$ — WMAP, BBN
  - $0.001 < \Omega_\nu h^2 < 0.01$ — WMAP, SDSS, SuperK, K2K, …
- $t_0 = 13.7^{+0.13}_{-0.17}$ Gyr — WMAP, GC, WDs, H_0
- $n = 0.961 \pm 0.017$ — WMAP, SDSS
- $\tau = 0.093 \pm 0.03$ — WMAP
- $w = -1 \pm 0.1$ — WMAP, SDSS, SNe

Hubble Constant has been constant for 5+ years!

HST Key Project: $H_0 = 72 \pm 7$ km/s/Mpc

WMAP: $H_0 = 73^{+3}_{-4}$ km/s/Mpc

SZ: $H_0 = 74 \pm 4 \pm 10$ km/s/Mpc

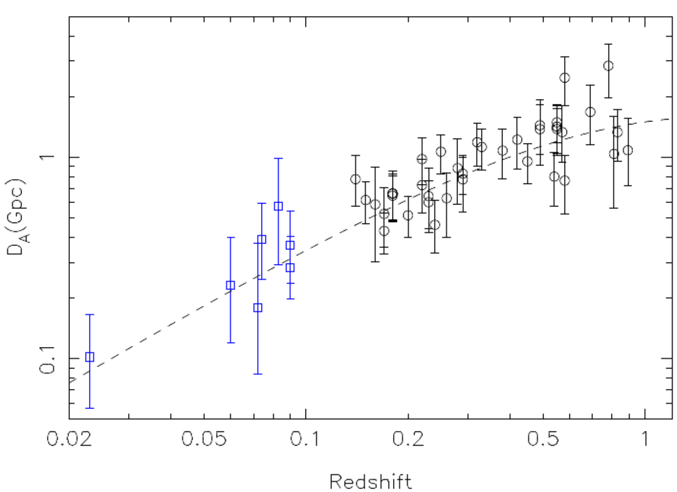
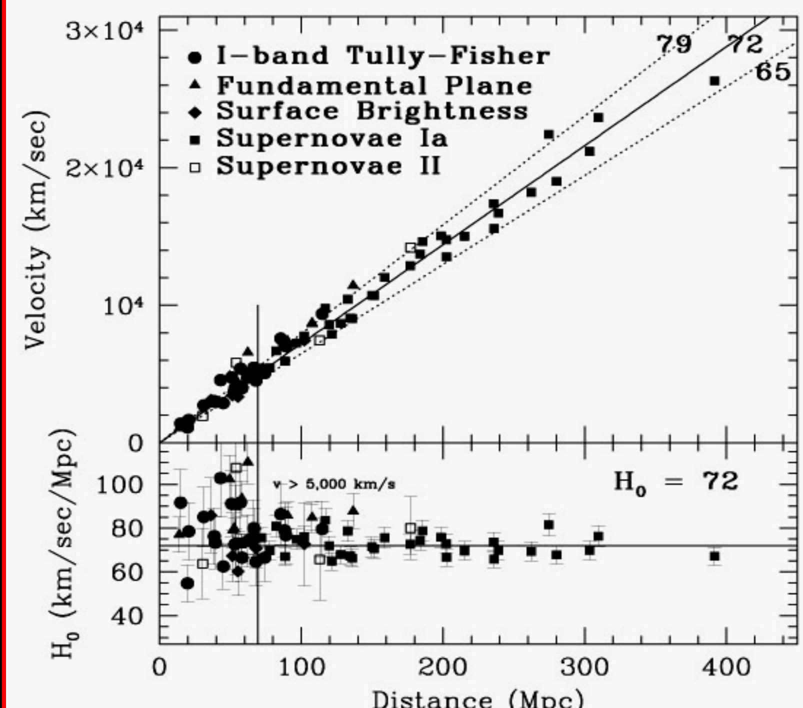
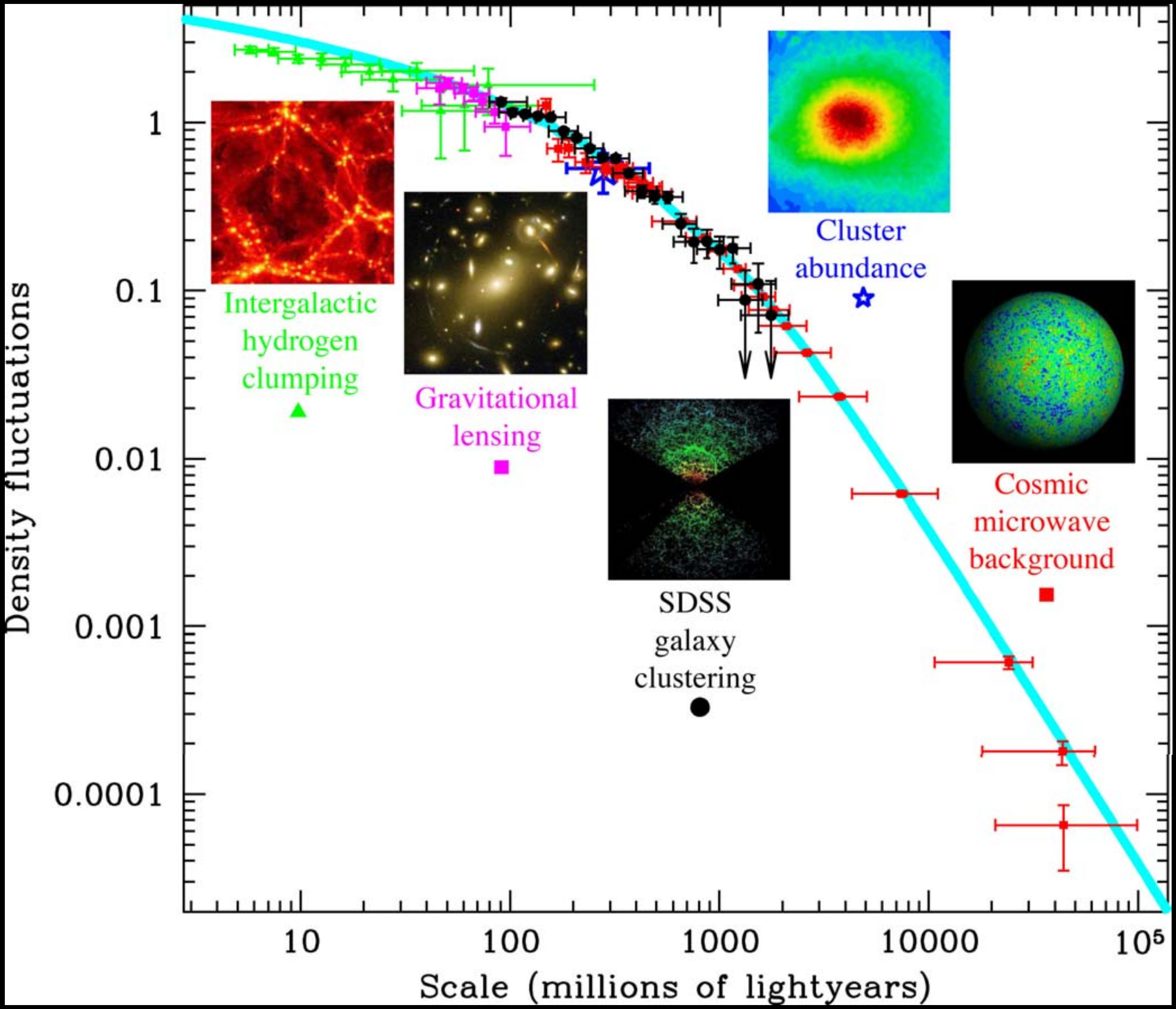


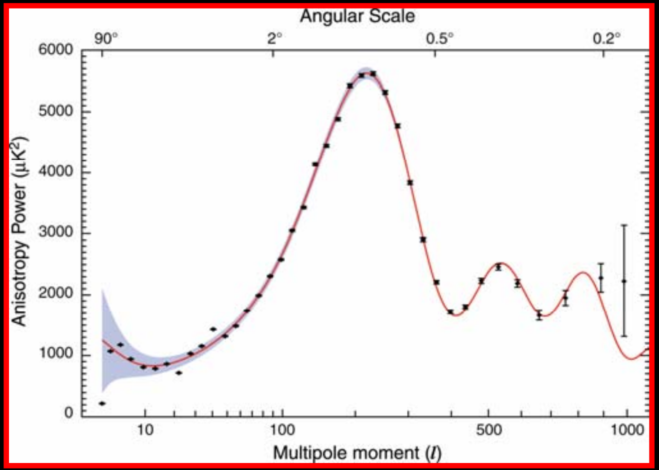
Fig. 3.— Angular diameter distances of the 38 clusters (open circles). The error bars are the total statistical uncertainties, obtained by combining the X-ray and SZE data modelling uncertainties (Table 2) and the additional sources of random error described in Section 3.3 and Table 3. The systematic errors of Table 3 are not shown. Dashed line is the angular diameter curve using the best-fit Hubble constant H_0=76.9 km s^{-1} Mpc^{-1} and $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$. The open squares are from the low redshift sample of Mason et al. (2001), and they are not included in the fit.



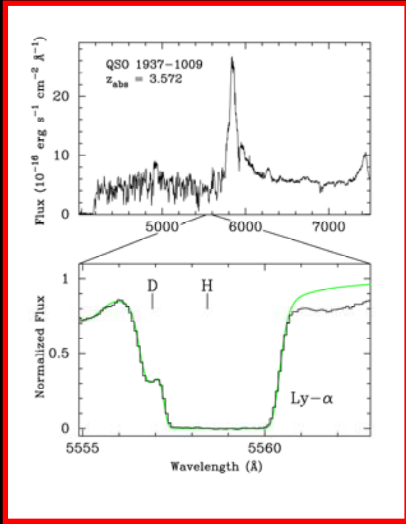
The CDM Power Spectrum



Baryon Density



- CMB: $\Omega_B h^2 = 0.022 \pm 0.001$



- D/H and BBN: $\Omega_B h^2 = 0.021 \pm 0.002$

  started with "Alpha, Beta, Gamma"

- Mean absorption of IGM: $\Omega_B \sim 0.04$

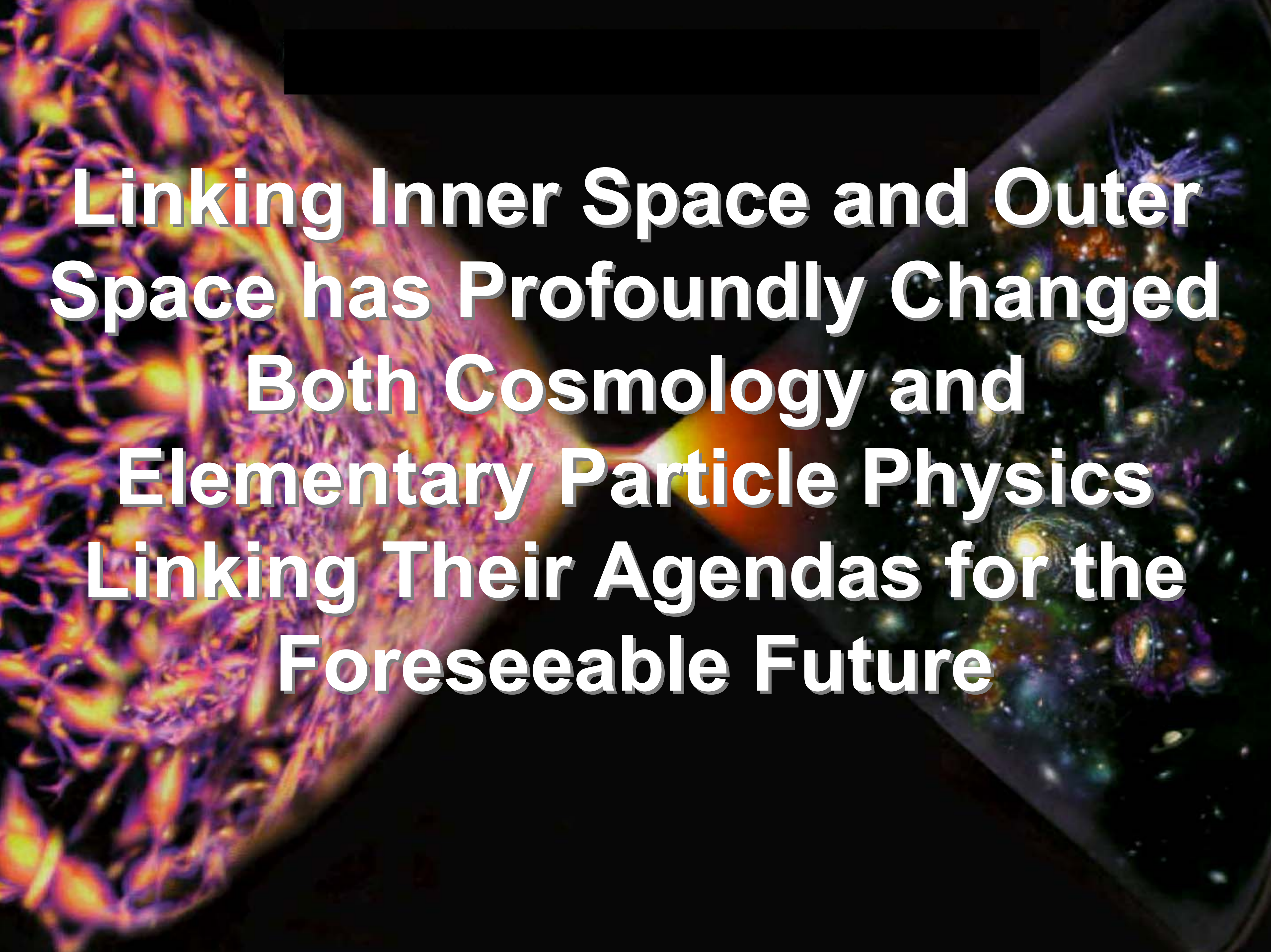
… much
more than
quark soup
beginning

Deep, Profound Connections

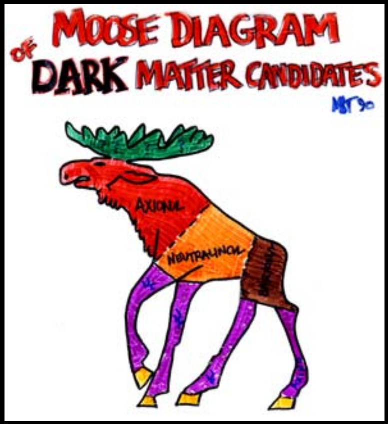
- Existence of Atoms
- Dark Matter
- Cosmic Acceleration
- Seeds for Structure
- Chemical Elements
- Longlived Stars & Life
- Multiverse

- ➢Baryogenesis/Leptogenesis
- ➢Axions, Neutrinos, Neutralinos
- ➢Dark Energy, New Grav Phys
- ➢Inflation
- ➢Neutrinos
- ➢Hierarchy of Weak/Planck
- ➢Superstrings

[redacted]


Linking Inner Space and Outer Space has Profoundly Changed Both Cosmology and Elementary Particle Physics Linking Their Agendas for the Foreseeable Future

The Big Cosmic Questions



- What is the cold dark matter?
- How much of the dark matter is neutrinos?
- How did atoms originate?

WHAT POWERED THE BIG BANG?

Inflation is a modest start

WHAT IS THE DARK ENERGY THAT CONTROLS OUR COSMIC DESTINY?

Validity of general relativity, variation of the constants, … "precision heavenly lab"

COSMIC BEGINNINGS & ENDINGS

The Middle is in Pretty Good Shape

SPACE-TIME GEOMETRY

our initial geometry

smooth, small ripples

15 Gyr

generic initial geometry

10^{-43} sec

Black holes, anisotropy, ...

"A MESS"

Collins & Hawking '7

NOT LOGICAL INCONSISTENCY!

DILEMMA OF INITIAL DATA (WHY SO SPECIAL?)

Promise of INFLATION*:

- TO LESSEN DEPENDENCE OF PRESENT STATE UPON INITIAL STATE
- "GRANDER" BIG BANG MODEL -- FROM 10^{-2} sec → 10^{-32} sec

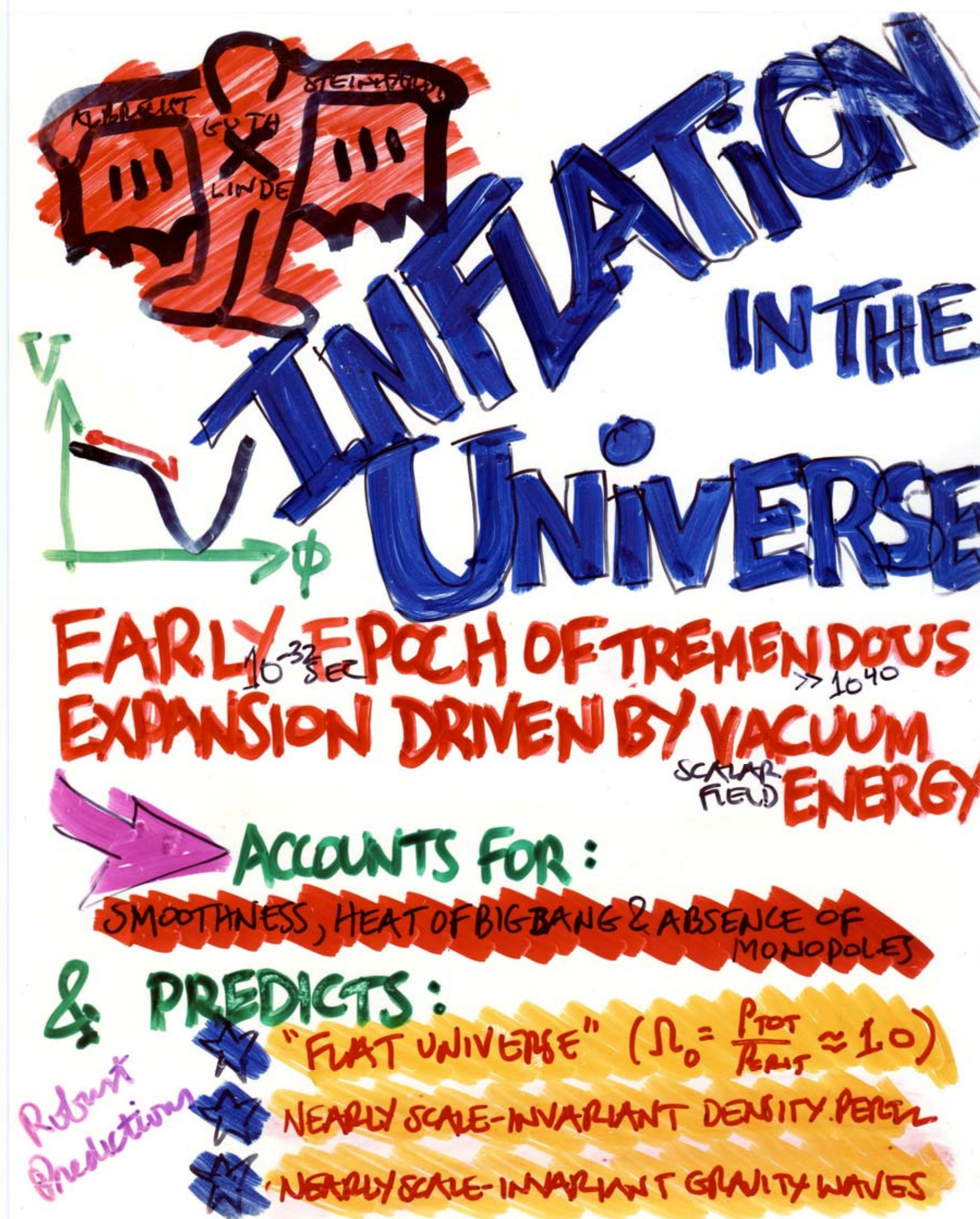
Underlying Physics

- SPECULATIVE --- <u>BUT WELL DEFINED</u> ((Classical Field Theory motivated by grand unification, superstrings, supersymme

***NOTE:**
"Modest Promise"

All models based upon scalar field dynamics

$$\ddot{\phi} + 3H\dot{\phi} + V' \;=\; 0$$



Density Perturbations

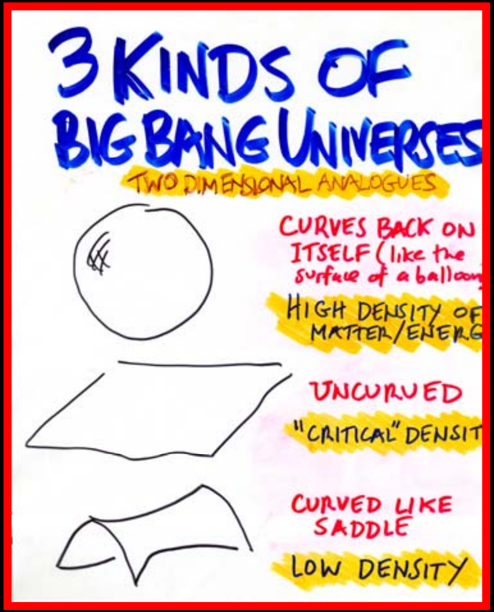
$$
\begin{aligned}
P(k) &= \frac{1024\pi^3}{75}\frac{k}{H_0^4}\frac{V_*^3}{{m_{\rm Pl}}^6 V_*'^2}\left(\frac{k}{k_*}\right)^{n-1} T^2(k) \\
n-1 &= -\frac{1}{8\pi}\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)^2 + \frac{m_{\rm Pl}}{4\pi}\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)' \\
\frac{dn}{d\ln k} &= -\frac{1}{32\pi^2}\left(\frac{{m_{\rm Pl}}^3 V_*'''}{V_*}\right)\left(\frac{m_{\rm Pl}V_*'}{V_*}\right) \\
&\qquad +\frac{1}{8\pi^2}\left(\frac{{m_{\rm Pl}}^2 V_*''}{V_*}\right)\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)^2 - \frac{3}{32\pi^2}\left(m_{\rm Pl}\frac{V_*'}{V_*}\right)^4 \\
T(q) &= \frac{\ln\left(1+2.34q\right)/2.34q}{\left[1+3.89q+(16.1q)^2+(5.46q)^3+(6.71q)^4\right]^{1/4}},
\end{aligned}
$$

Gravitational Waves

$$
\begin{aligned}
P_T(k) &\equiv \langle |h_k|^2\rangle = \frac{8}{3\pi}\frac{V_*}{{m_{\rm Pl}}^4}\left(\frac{k}{k_*}\right)^{n_T-3} T_T^2(k) \\
n_T &= -\frac{1}{8\pi}\left(\frac{m_{\rm Pl}V_*'}{V_*}\right)^2 \\
\frac{dn_T}{d\ln k} &= \frac{1}{32\pi^2}\left(\frac{{m_{\rm Pl}}^2 V''}{V}\right)\left(\frac{m_{\rm Pl}V'}{V}\right)^2 - \frac{1}{32\pi^2}\left(\frac{m_{\rm Pl}V'}{V}\right)^4 = -n_T[(n-1)-n_T] \\
T_T(k) &\simeq \left[1+\frac{4}{3}\frac{k}{k_{\rm EQ}}+\frac{5}{2}\left(\frac{k}{k_{\rm EQ}}\right)^2\right]^{1/2},
\end{aligned}
$$

Signatures of Inflation

- "Flat," smooth Universe

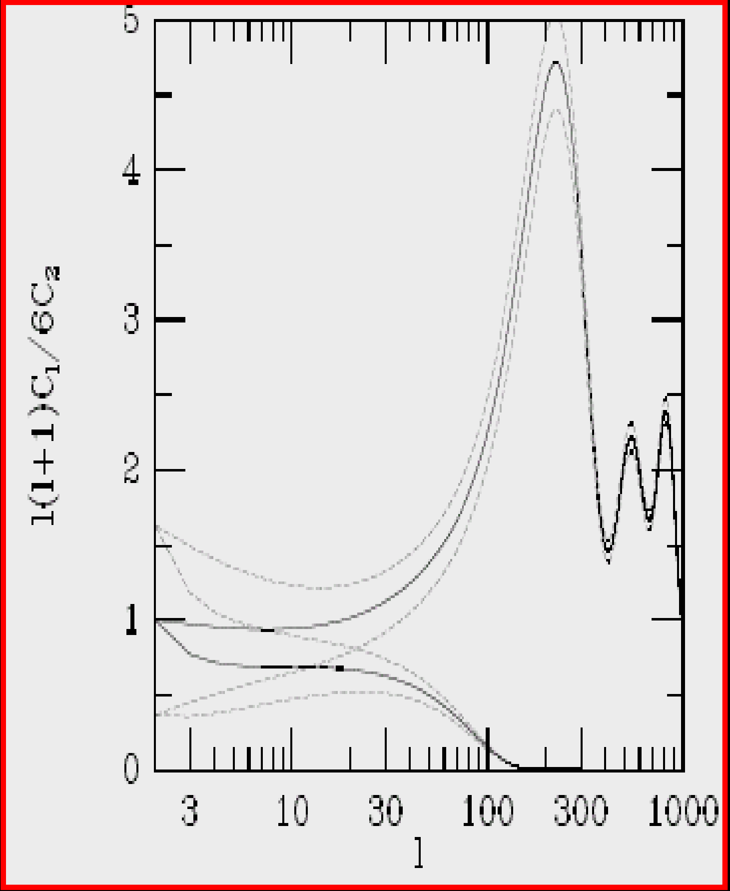


- With tiny lumpiness arising from Quantum Fluctuations

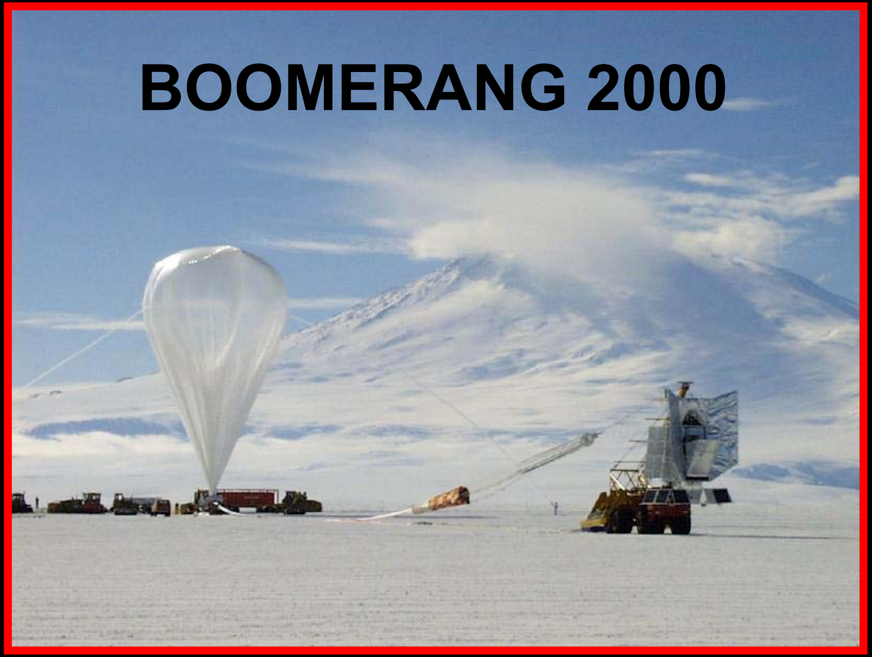
- Hot quark soup from decay of vacuum energy

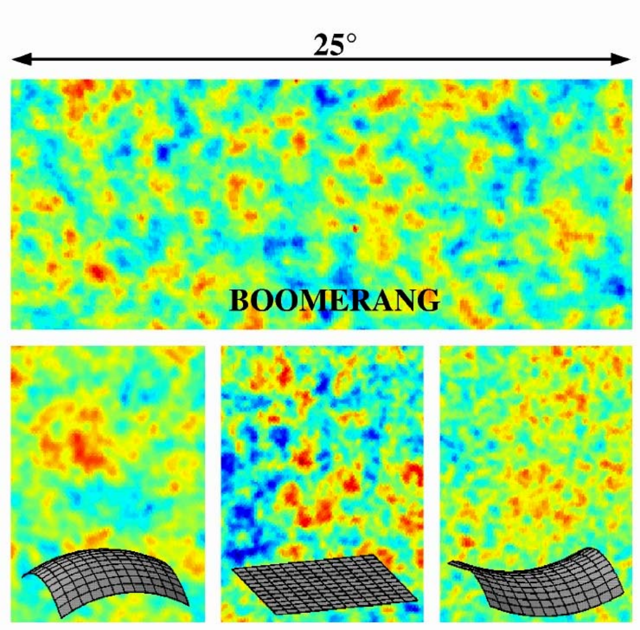
CMB is Key to Testing Cosmic Inflation

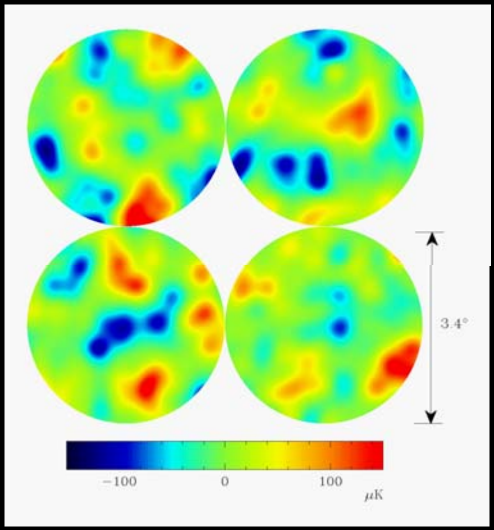
- Uncurved (flat) Universe
  - "Spot size"
- Lumpiness from "Quantum Fluctuations"
  - Acoustic peaks, relative heights
- Evidence for inflation produced gravitational waves
  - Polarization (and Anisotropy)



First Evidence for Flat Universe








"All the News That's Fit to Print"

The New York Times

VOL. CL . . . . No. 51,739 — MONDAY, APRIL 30, 2001

Listen Closely: From Tiny Hum Came Big Bang

Scientists Hear the Tiny Hum They Say Ignited the Big Bang

By JAMES GLANZ

'Listening' to the Origin of the Universe

THE MEASUREMENT

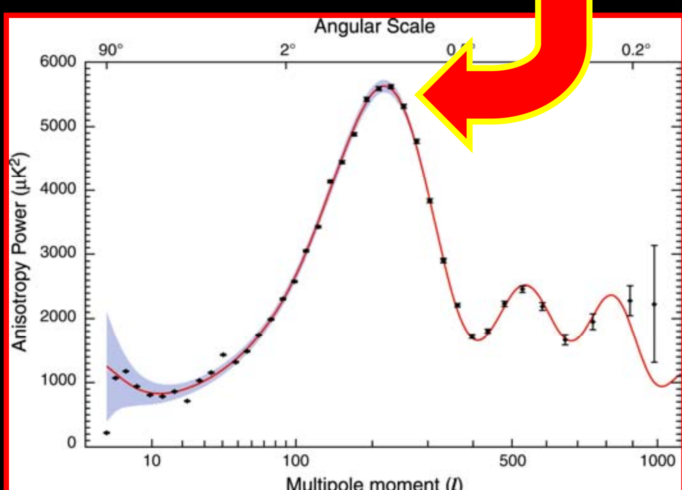
INFLATION THEORY AND THE BIG BANG

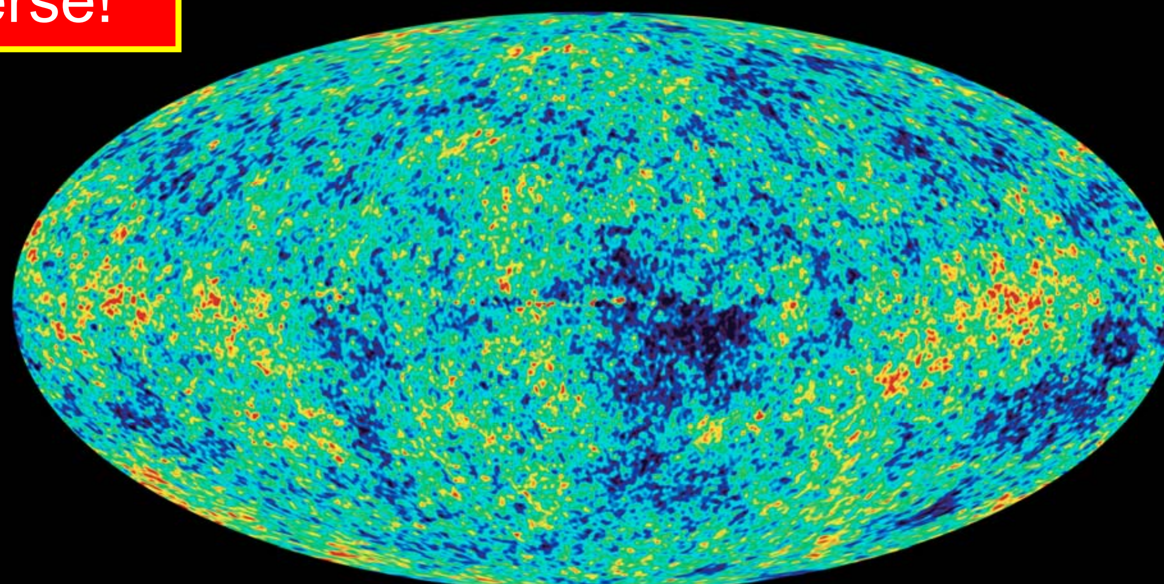
WMAP

all sky maps
large angular scales
2003, 2006

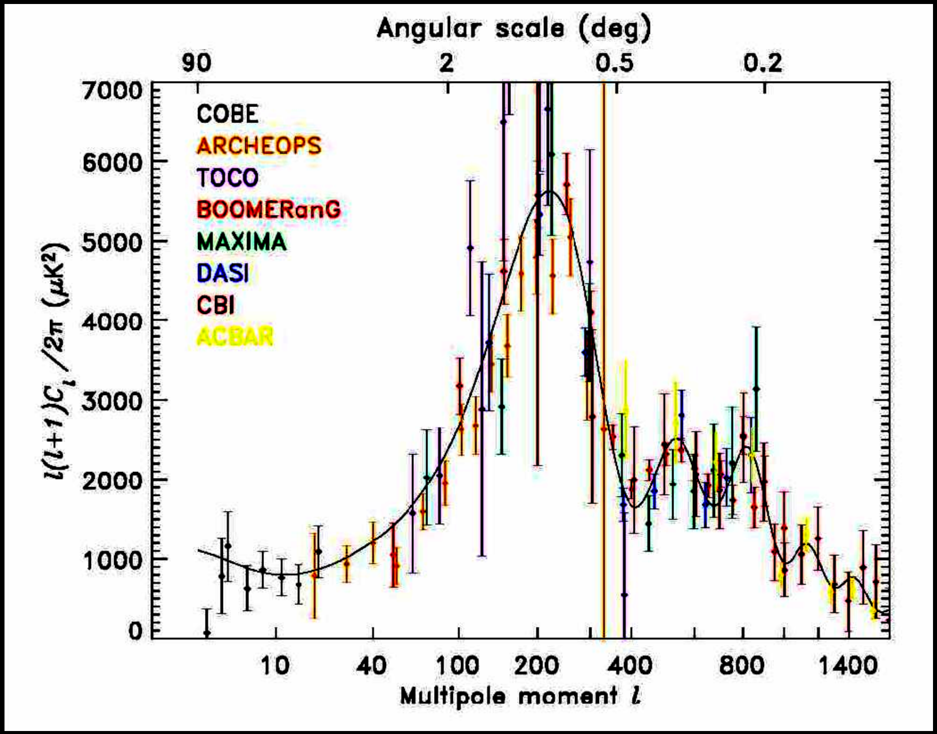
MAP990389

You Live in a Flat Universe!

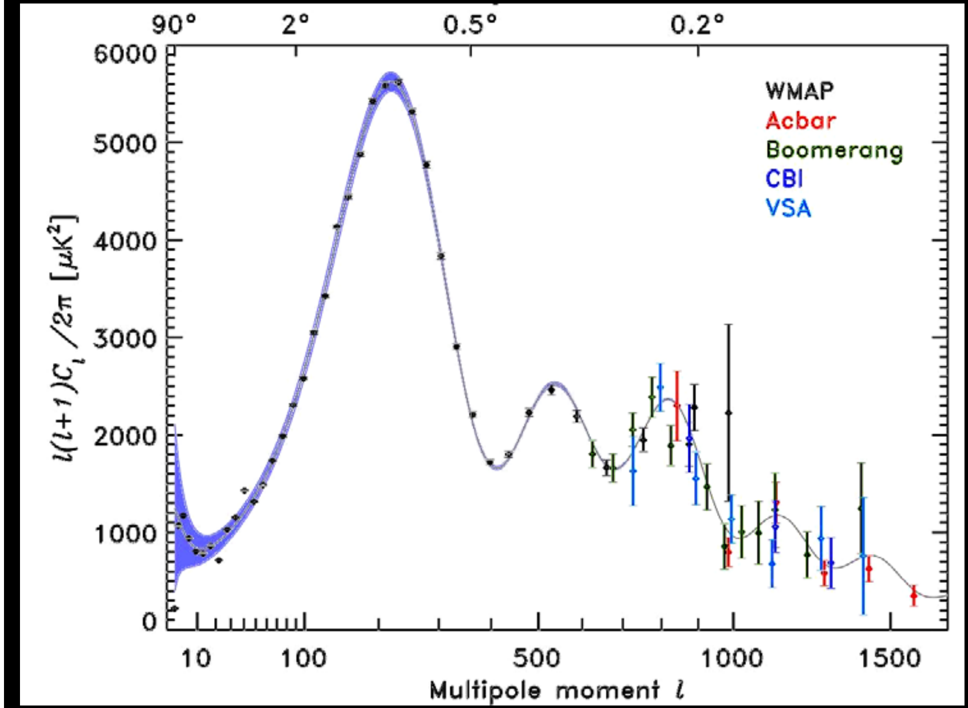




WMAP Sea Change



BEFORE WMAP



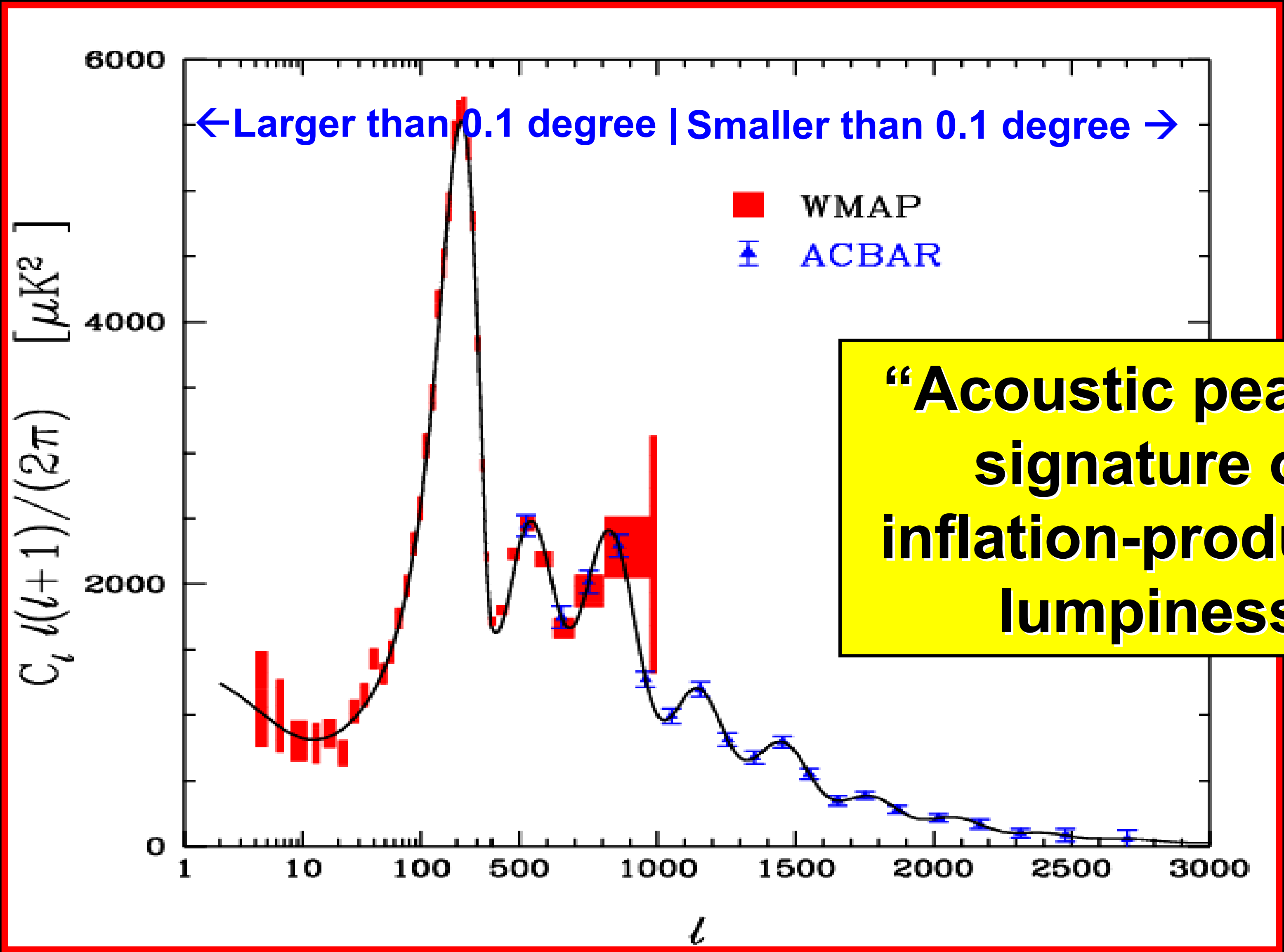
AFTER WMAP

ACBAR on Viper 2.1 m Telescope

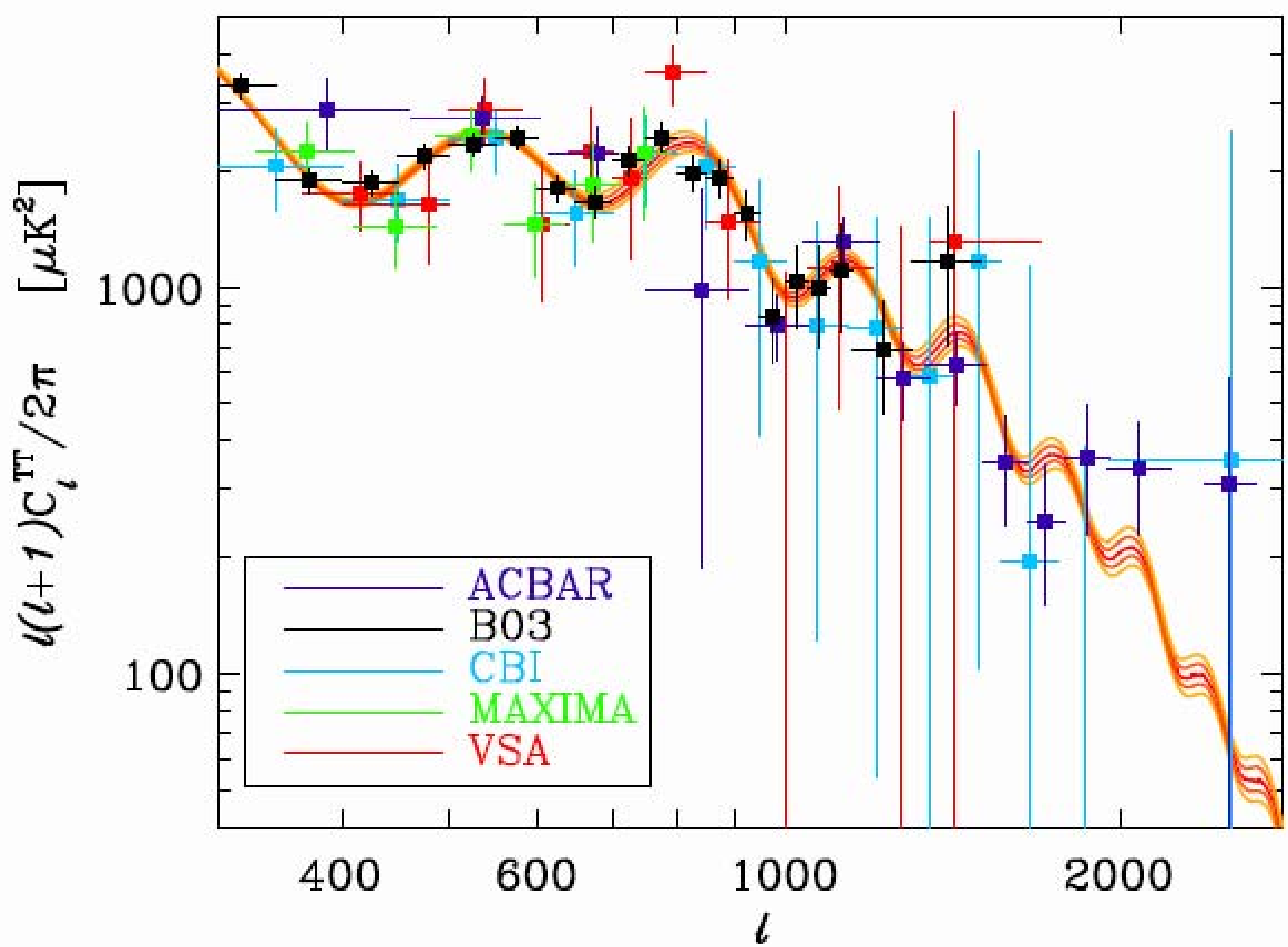
UC Berkeley/Case Western

Probe small angular scales
Complementary to WMAP

ACBAR & WMAP Complementary: Different Technology & Different Angular Scales

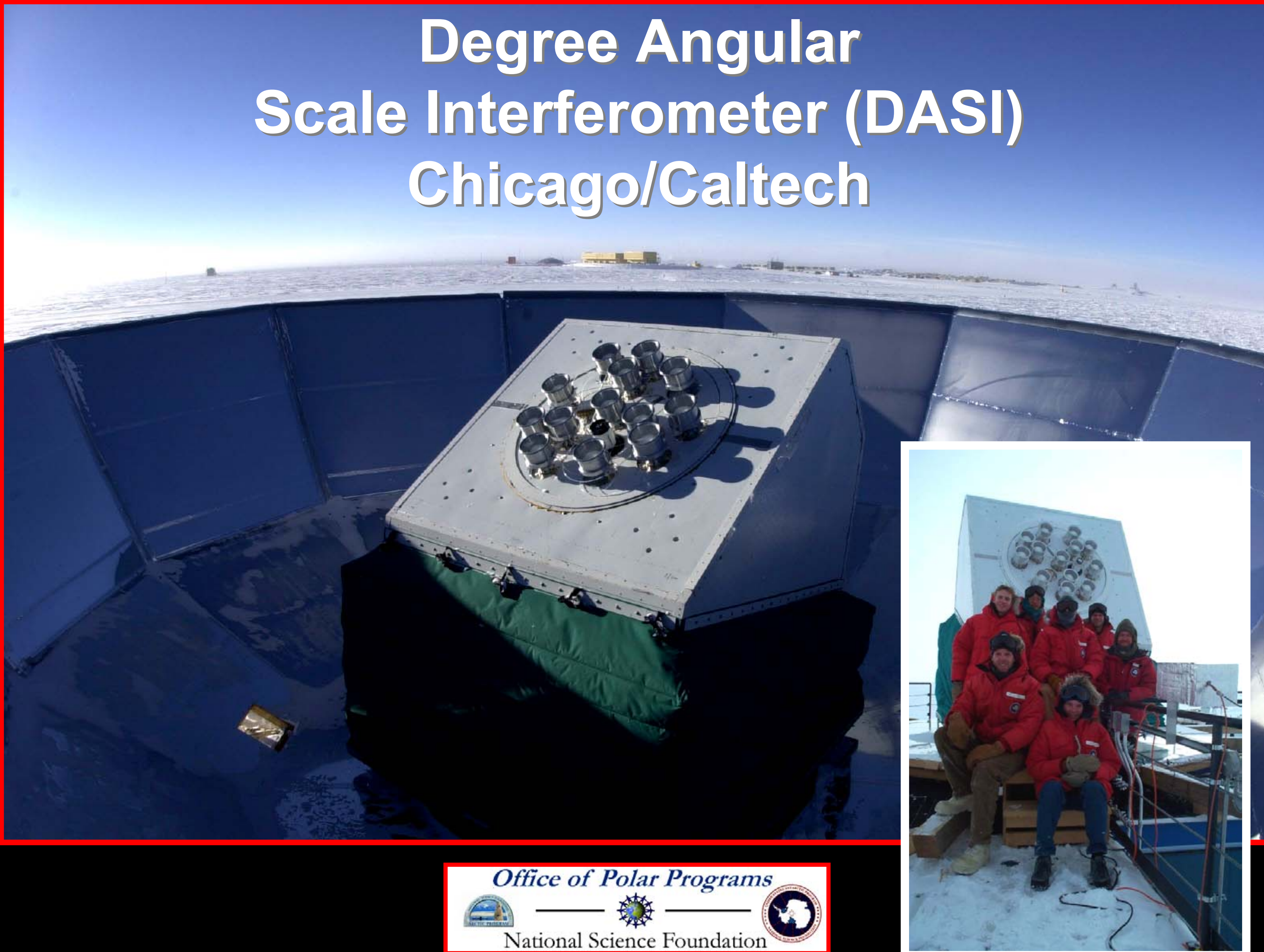


"Acoustic peaks": signature of inflation-produced lumpiness



$\ell(\ell+1)C_\ell^{TT}/2\pi \quad [\mu K^2]$
1000
100
400
600
1000
2000
ℓ
ACBAR
B03
CBI
MAXIMA
VSA

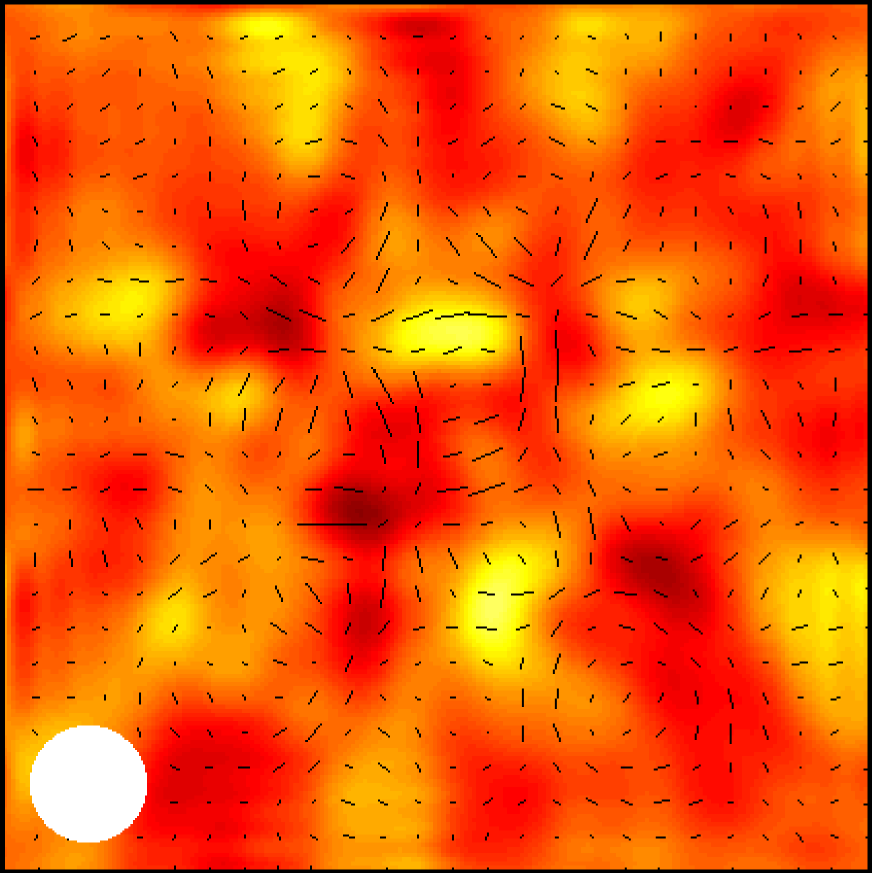
Degree Angular Scale Interferometer (DASI) Chicago/Caltech



Office of Polar Programs

National Science Foundation

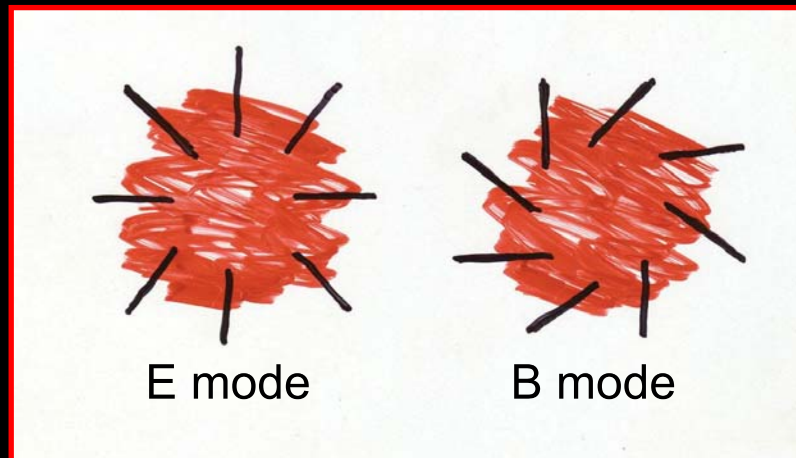
DASI Discovers CMB Polarization



- Key Test of Hot Big Bang
- Open Door for the Big Test of Inflation

The Big Prize

"B-Mode" Polarization

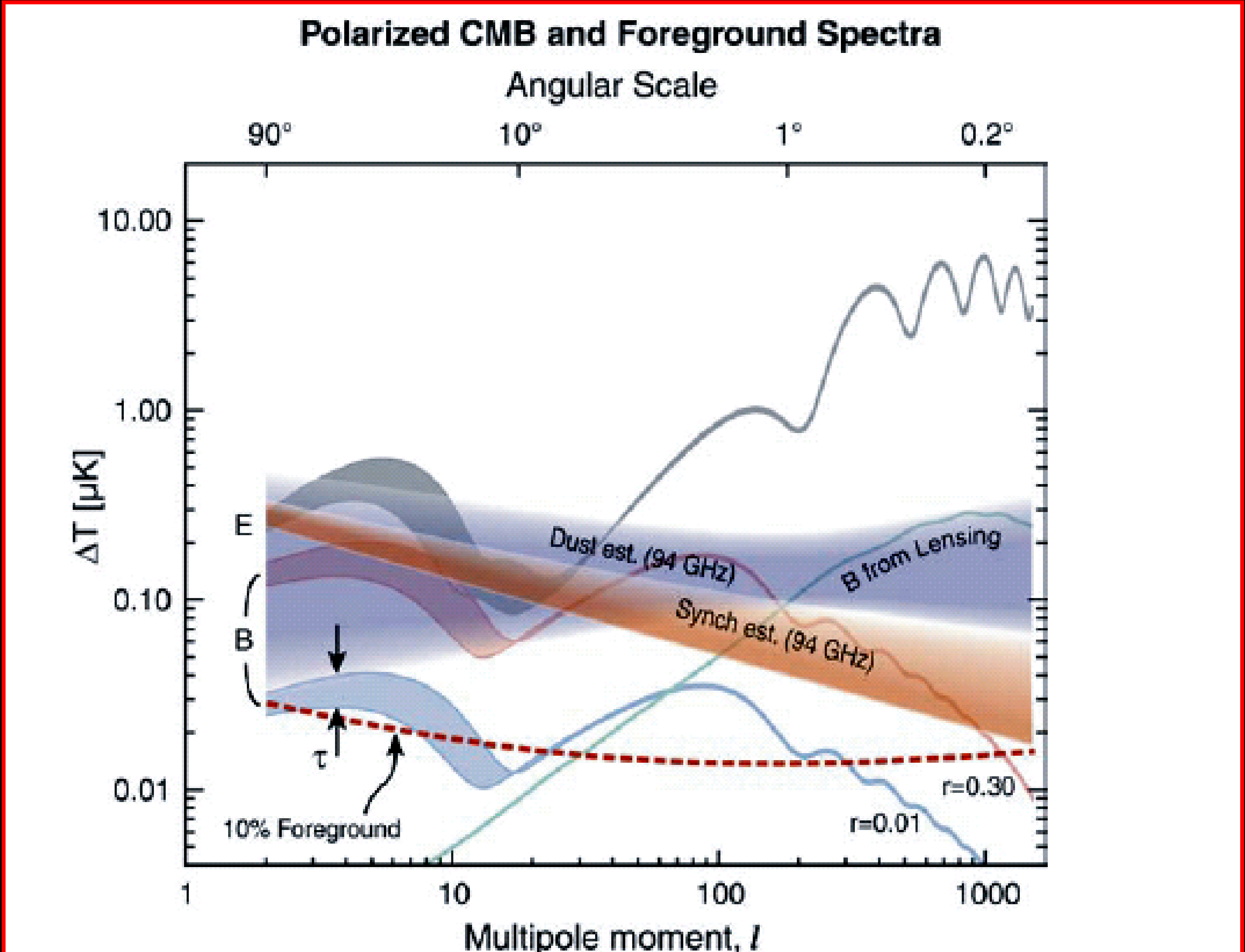


Third Critical Test of Inflation (Gravitational Waves)

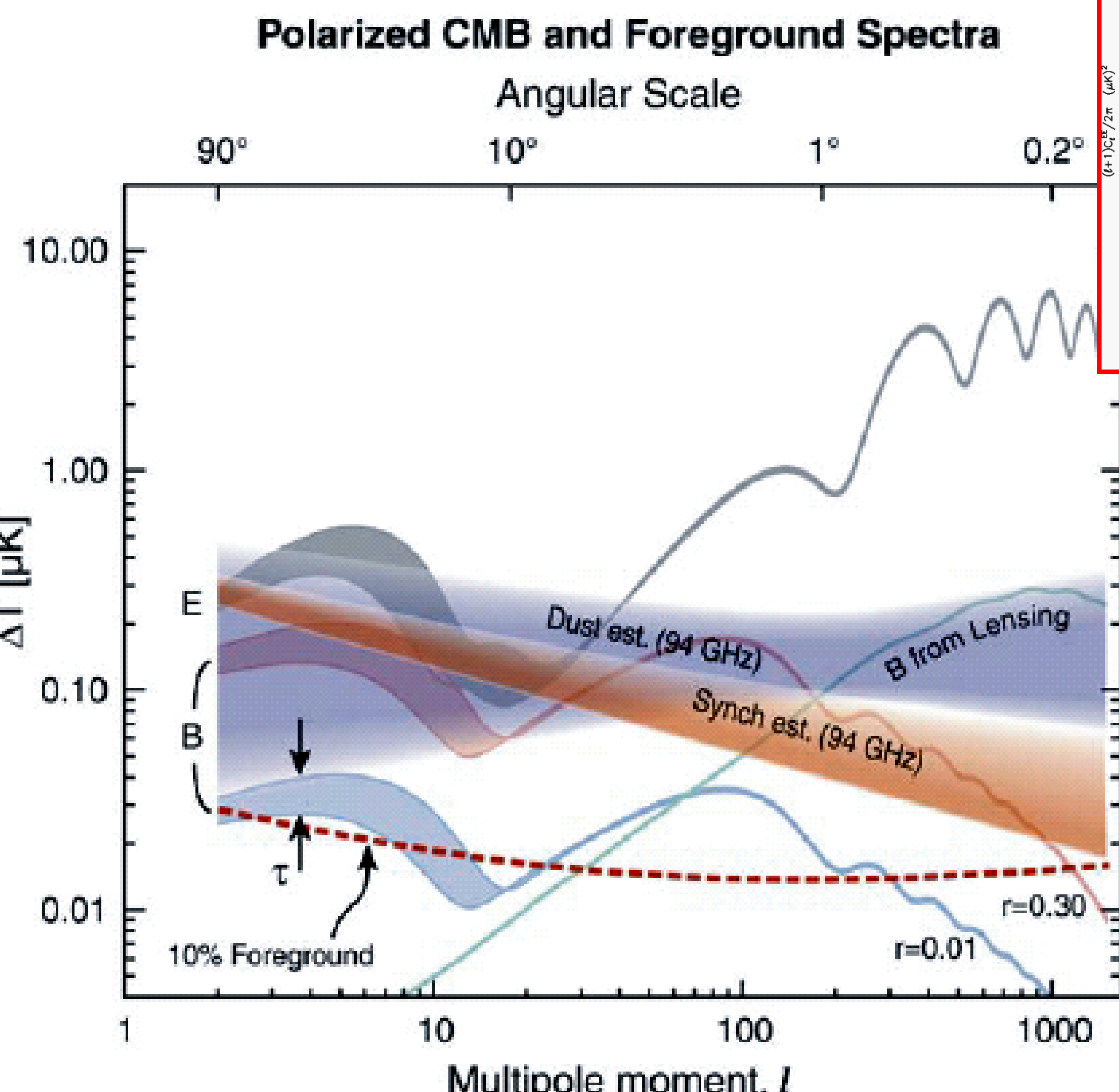
Pin Down Energy Scale/Time of Inflation

$V = 3.5 \times 10^{16}\ \mathrm{GeV}\ (r=T/S)^{1/4}$ or $H^{-1} = 2 \times 10^{-38}\ \mathrm{sec}/(r=T/S)^{1/2}$

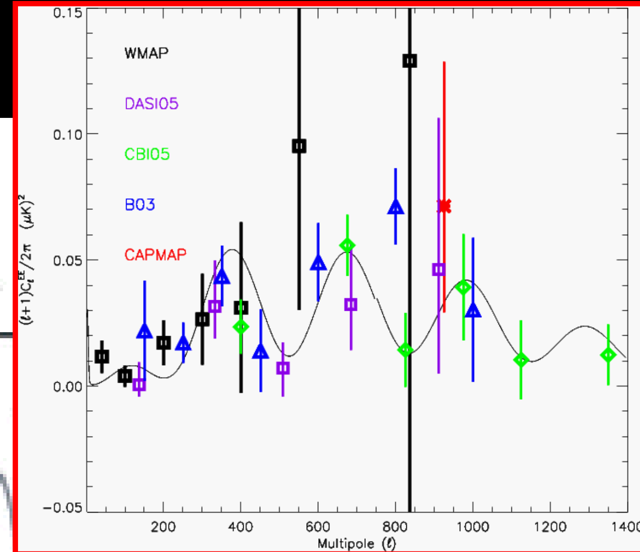
Reveal Cause of Inflation



Polarized CMB and Foreground Spectra
Angular Scale
90°
10°
1°
0.2°
10.00
1.00
0.10
0.01
ΔT [μK]
E
B
τ
Dust est. (94 GHz)
Synch est. (94 GHz)
B from Lensing
r=0.30
r=0.01
10% Foreground
1
10
100
1000
Multipole moment, l

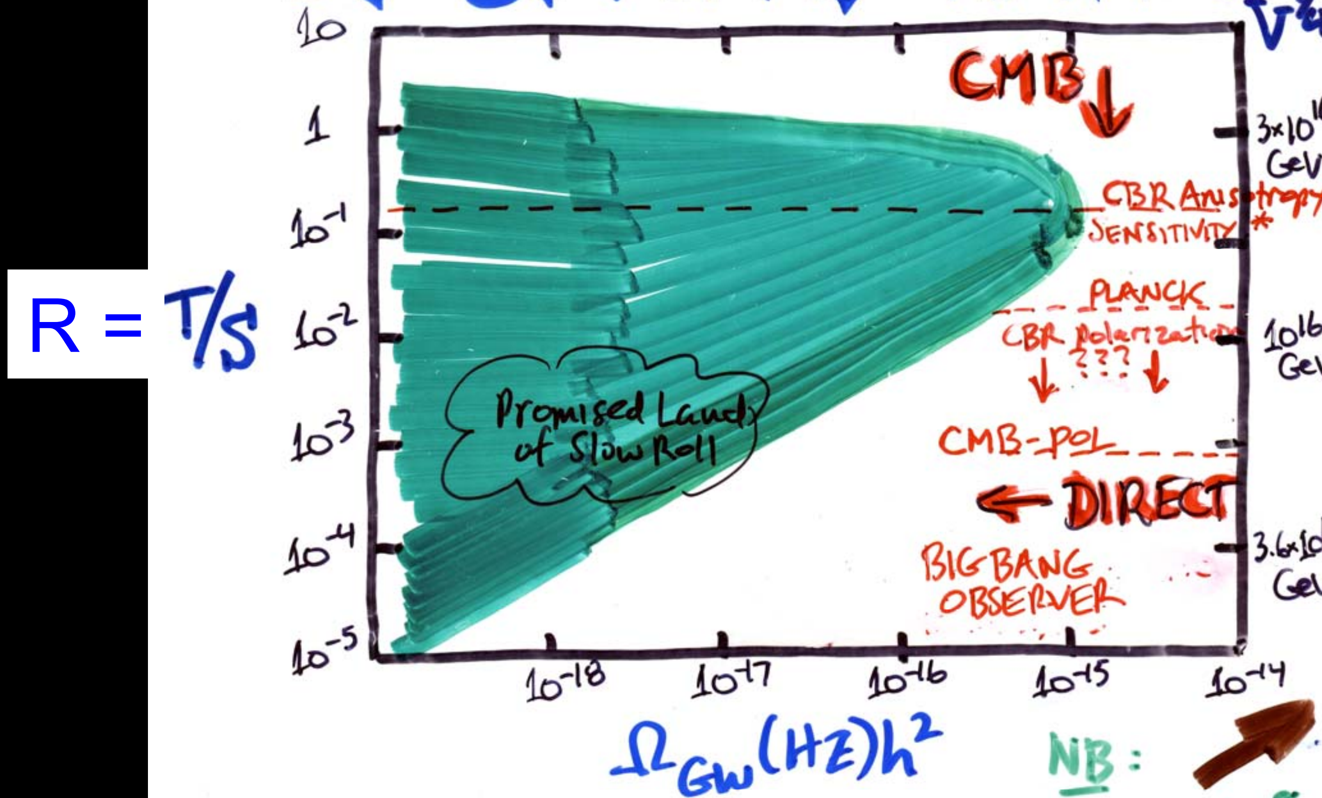


Polarized CMB and Foreground Spectra
Angular Scale
90°
10°
1°
0.2°
10.00
1.00
0.10
0.01
ΔT [μK]
E
B
τ
10% Foreground
Dust est. (94 GHz)
Synch est. (94 GHz)
B from Lensing
r=0.30
r=0.01
1
10
100
1000
Multipole moment, l



WMAP
DASI05
CBI05
B03
CAPMAP
0.15
0.10
0.05
0.00
−0.05
200
400
600
800
1000
1200
Multipole (ℓ)

DETECTION OF GRAVITY WAVES



NB:

LIGO: 10^{-8}

LISA: 10^{-13}

VERY CHALLENGING!

"DOUBLE DETECTION" ⇒ n_T to ± 0.03

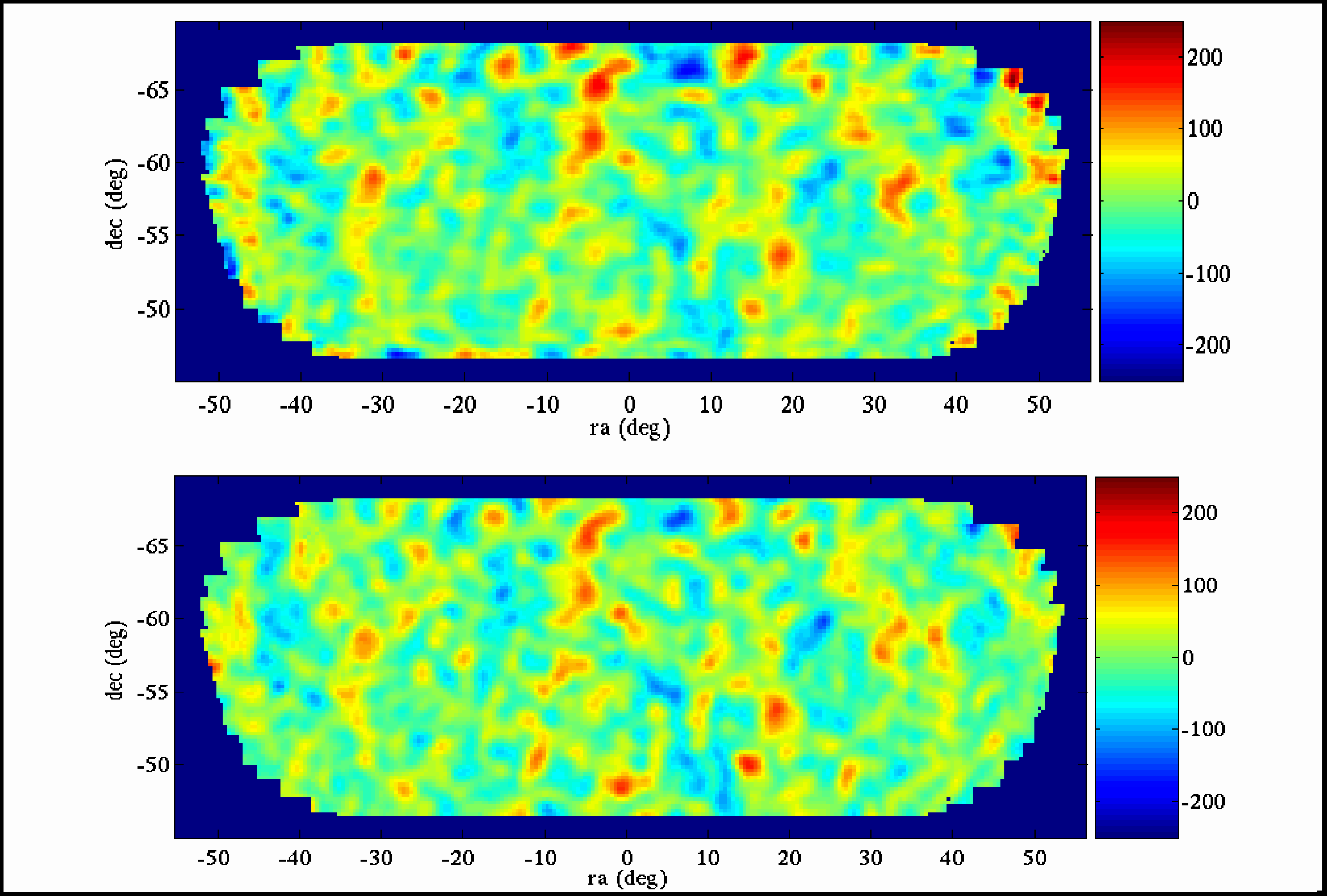
BICEP* Polarization Experiment

Caltech/JPL, UCSD, UC Berkeley, IAS (Paris), CEA (Grenoble), Cardiff

Optimized for angular scales greater > 1 degree

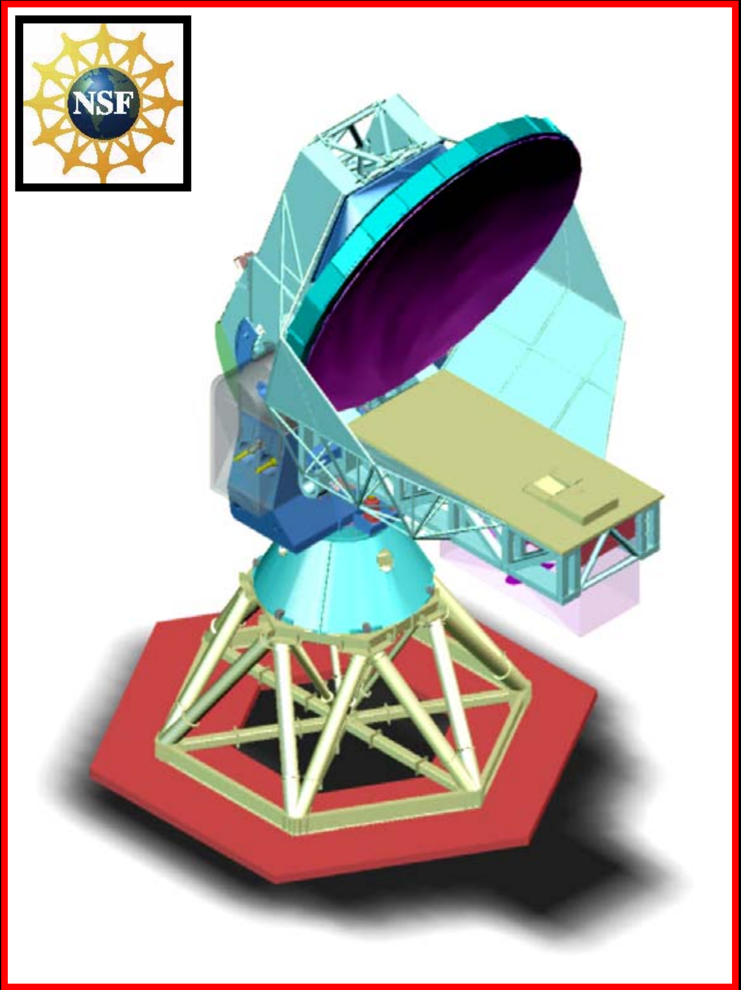
*Background Imaging of Cosmic Extragalactic Polarization

9 hours BICEP vs. 3 years WMAP
Which is which?



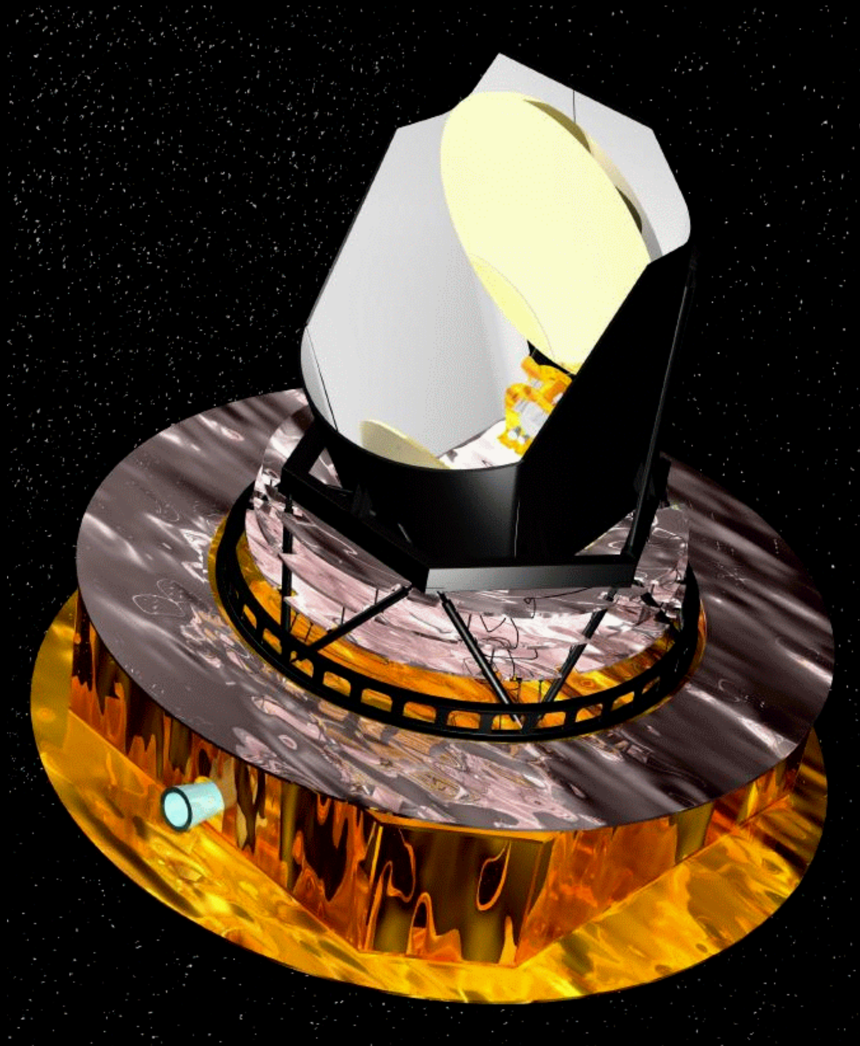
10 m South Pole Telescope (SPT)

Chicago/UC Berkeley/UIUC/Case Western/SAO



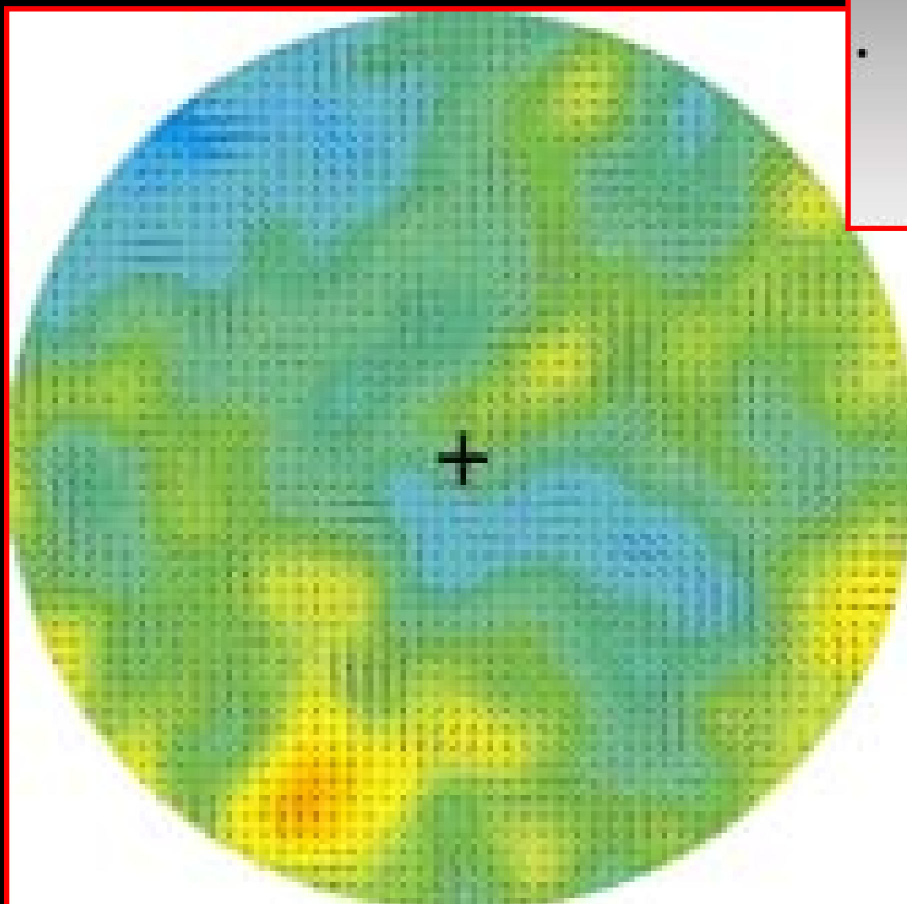
Nov 06/Jan 07 Deployment

Planck 2008



$r = 10^{-2}$?

CMB Polarization Satellite?



$r = 10^{-3}$?

Serious testing of Inflation has ***begun***

Key Predictions

1. Flat Universe
2. *Almost* scale-invariant, Gaussian perturbations: $(n-1) \sim \pm 0.1$ and $dn/d\ln k \sim \pm 0.001$
3. Gravity waves: spectrum, amplitude not predicted

Key Results (WMAP)

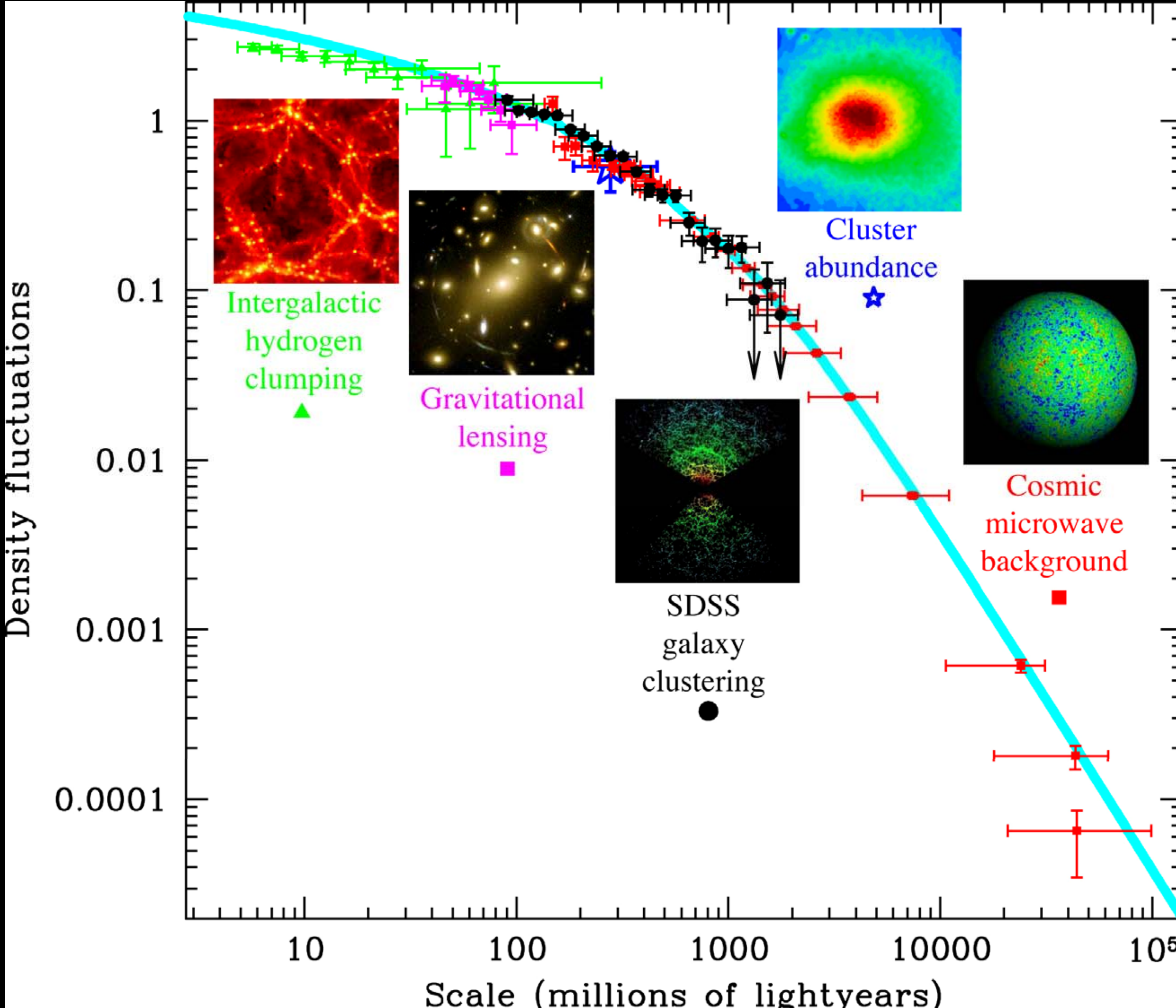
1. $\Omega_0 = 1.0 \pm 0.01$
2. $n = 0.96 \pm 0.017$*; $dn/d\ln k = -0.1 \pm 0.05$; no evidence for nonGaussianity
3. $r < 0.55$ (95% cl)*

*Depends significantly upon the priors assumed

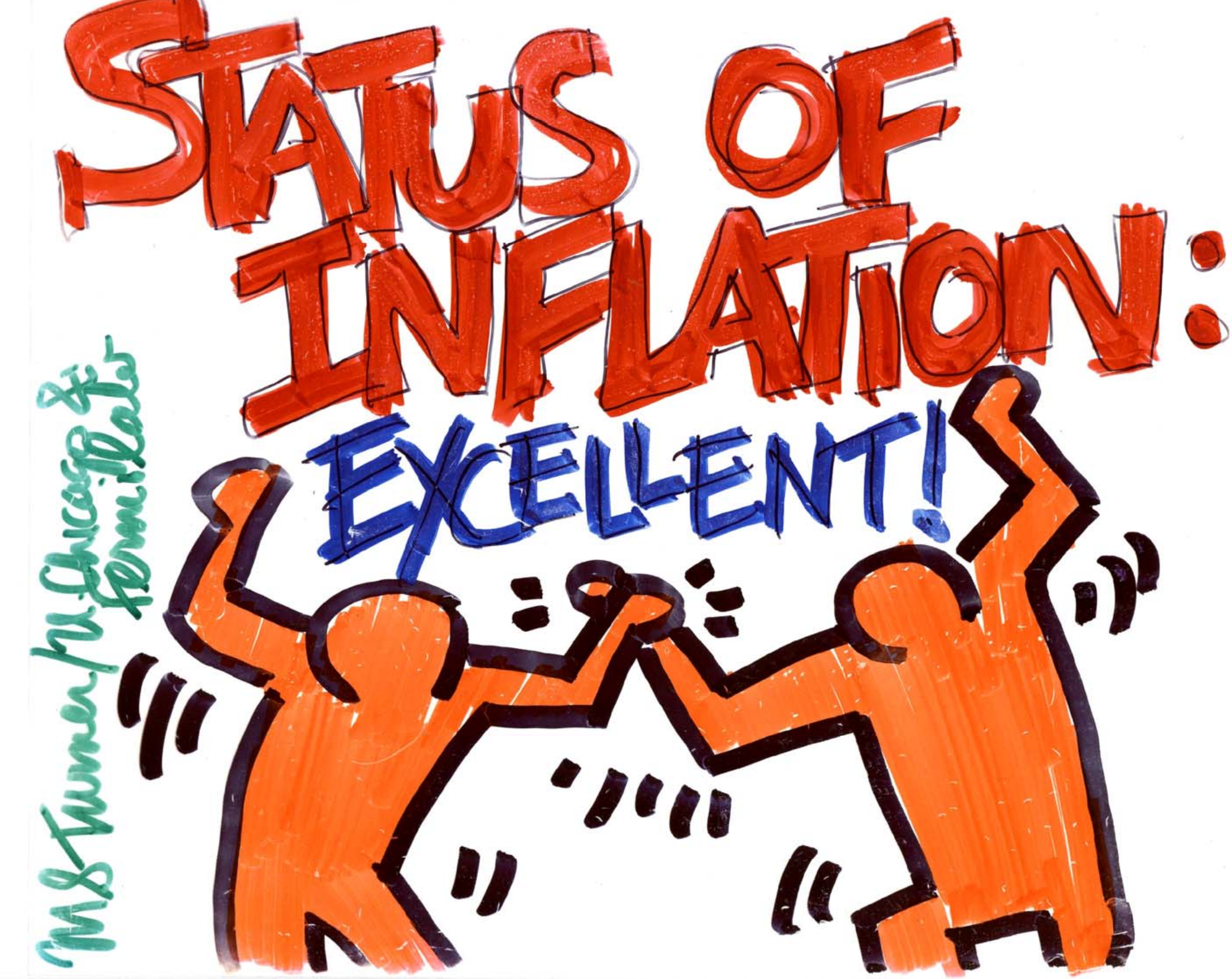
INFLATION SCORECARD

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		?	
★ $T/S \gtrsim 10^{-3}$ (??)	$T/S \leq \mathcal{O}(1)$ 0.71 (95% cl)		$10^{-3}/10^{-4}$
★ NEARLY SCALE INVARIANT $n_T = -\frac{1}{5} T/S$			± 0.03

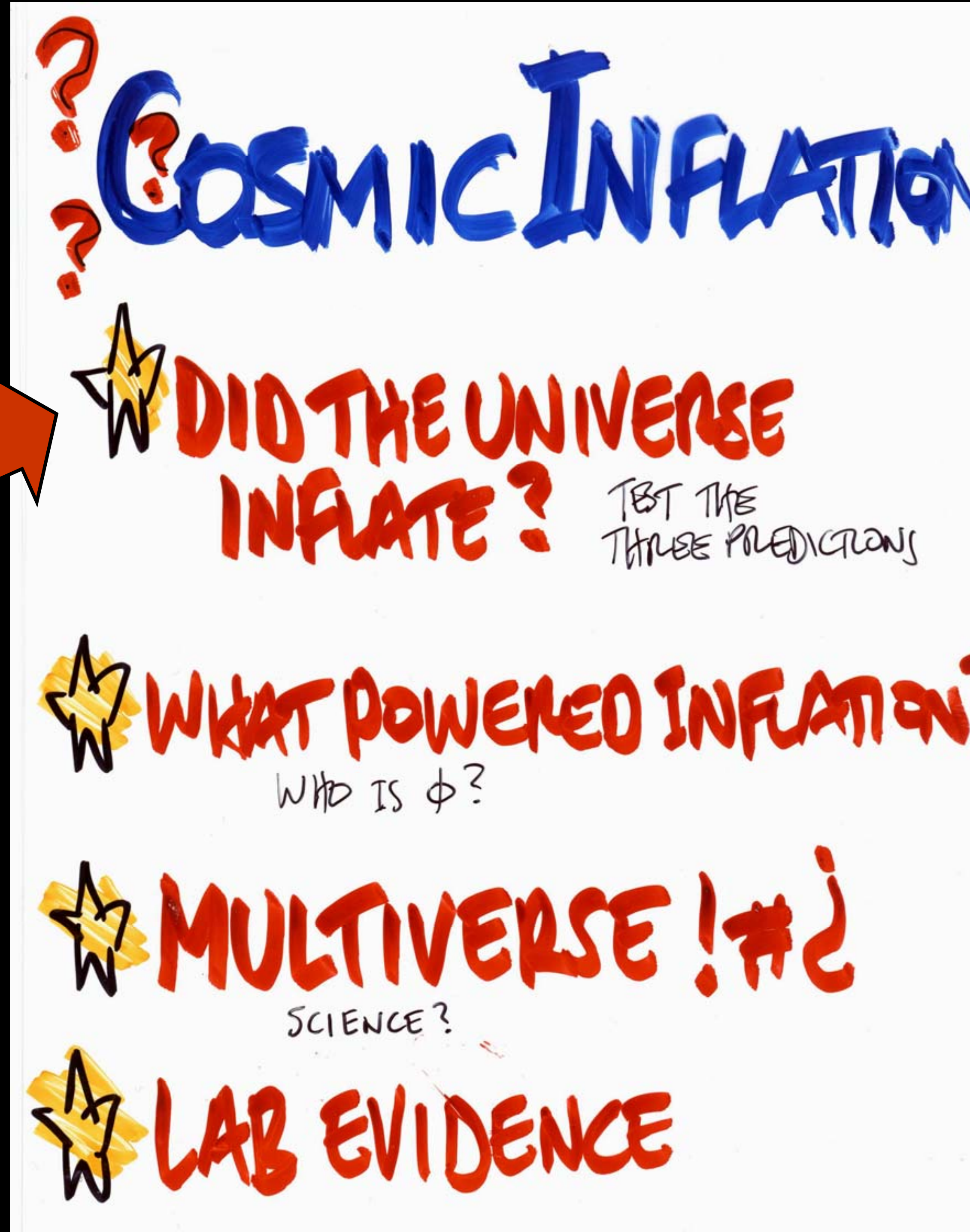
* FOR DOING IT THE HARD WAY



Density fluctuations
Scale (millions of lightyears)
1
0.1
0.01
0.001
0.0001
10
100
1000
10000
10^5
Intergalactic hydrogen clumping
Gravitational lensing
SDSS galaxy clustering
Cluster abundance
Cosmic microwave background


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

HOW MUCH TRUTH DOES INFLATION HAVE?

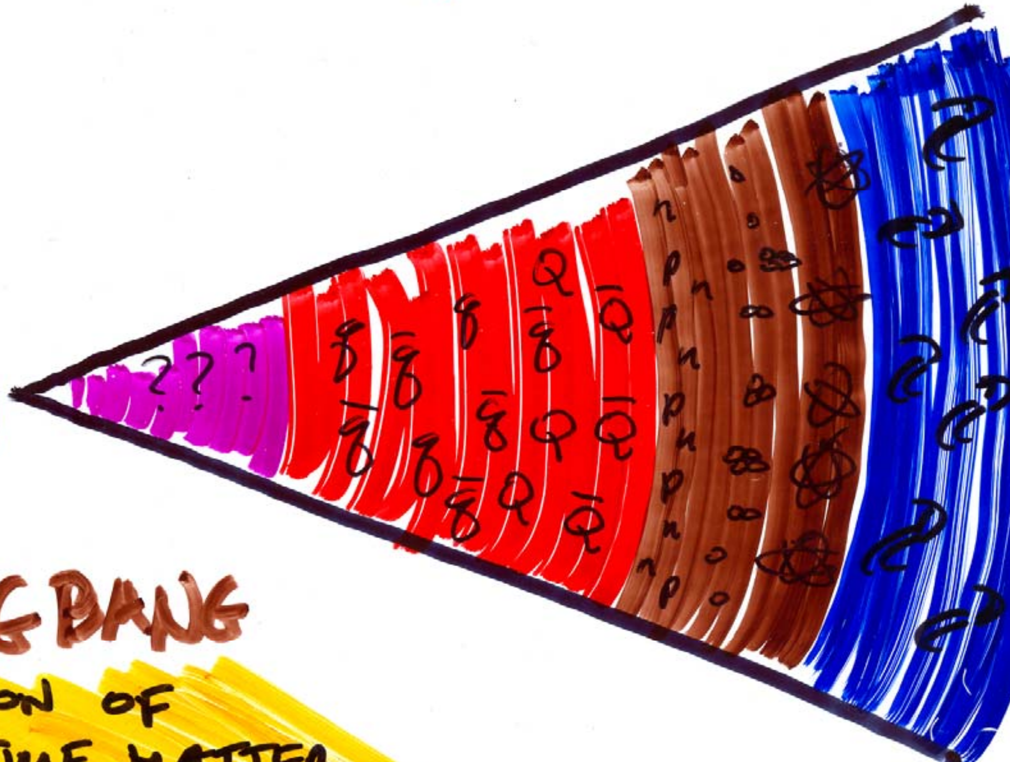


Inflation is Modest – More Like Duct Tape

BEFORE THE BIG BANG

Three Ideas – All Probably Wrong

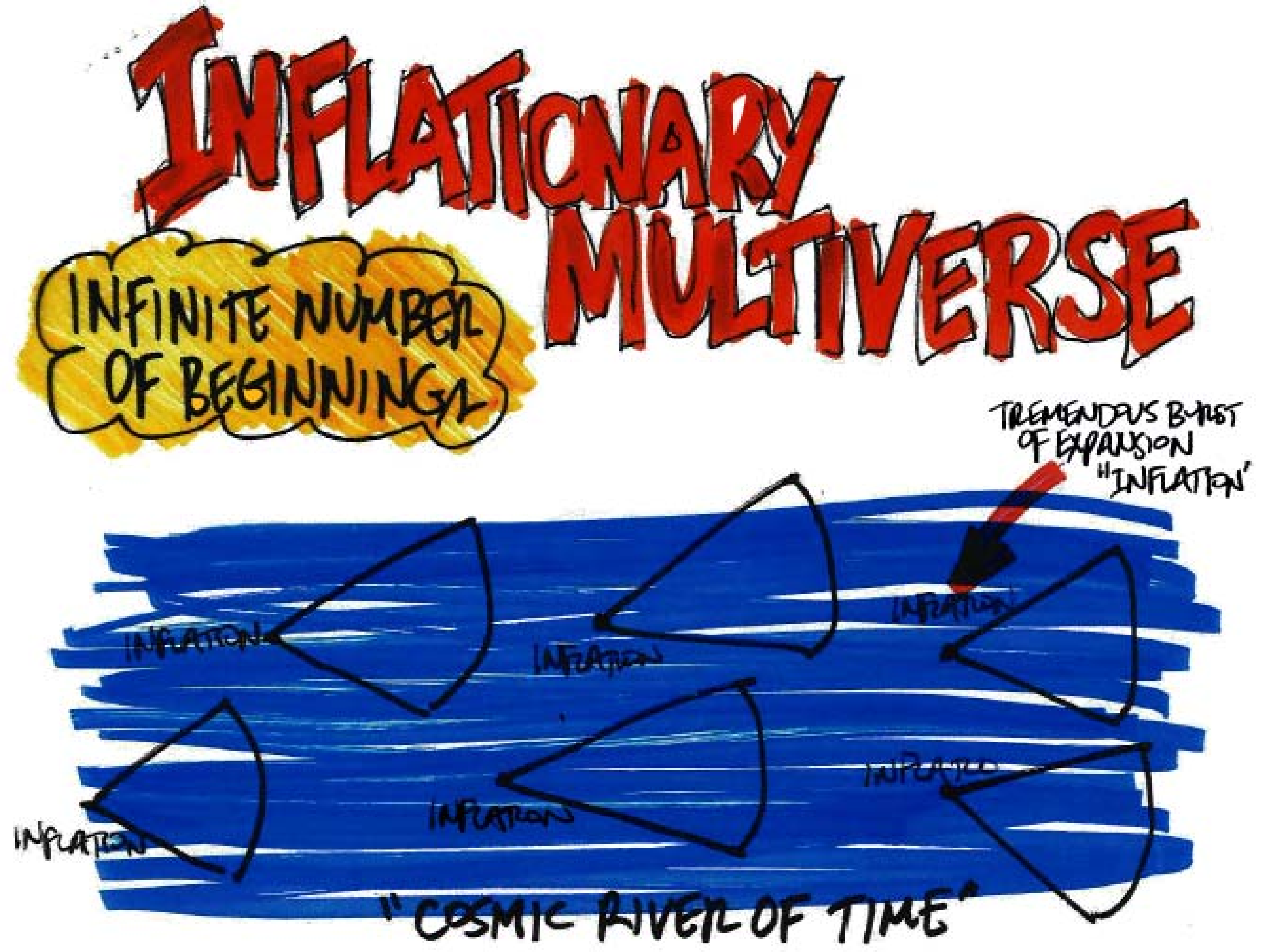
EINSTEIN'S BIG BANG



THE BIG BANG

CREATION OF SPACE, TIME, MATTER & ENERGY

- NO BEFORE THE BIG BANG



INFLATIONARY MULTIVERSE
INFINITE NUMBER OF BEGINNINGS
TREMENDOUS BURST OF EXPANSION "INFLATION"
INFLATION
INFLATION
INFLATION
INFLATION
INFLATION
"COSMIC RIVER OF TIME"

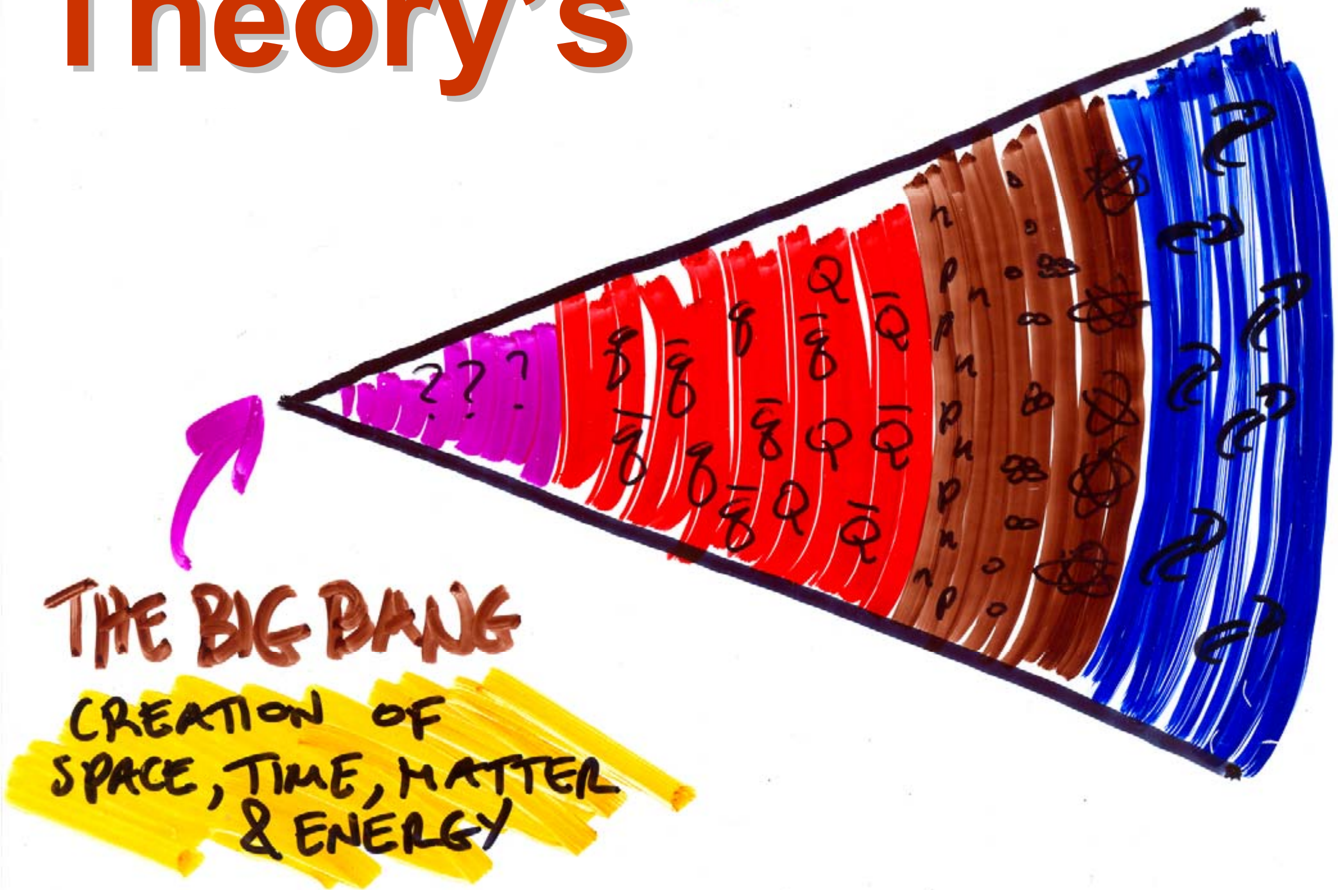
Some Features of String Theory

- Extra "dimensions" (big & small)
- Multiple vacua (landscape, etc)
- Variable constants (moduli field)
- Unification of particles and forces
- Strings

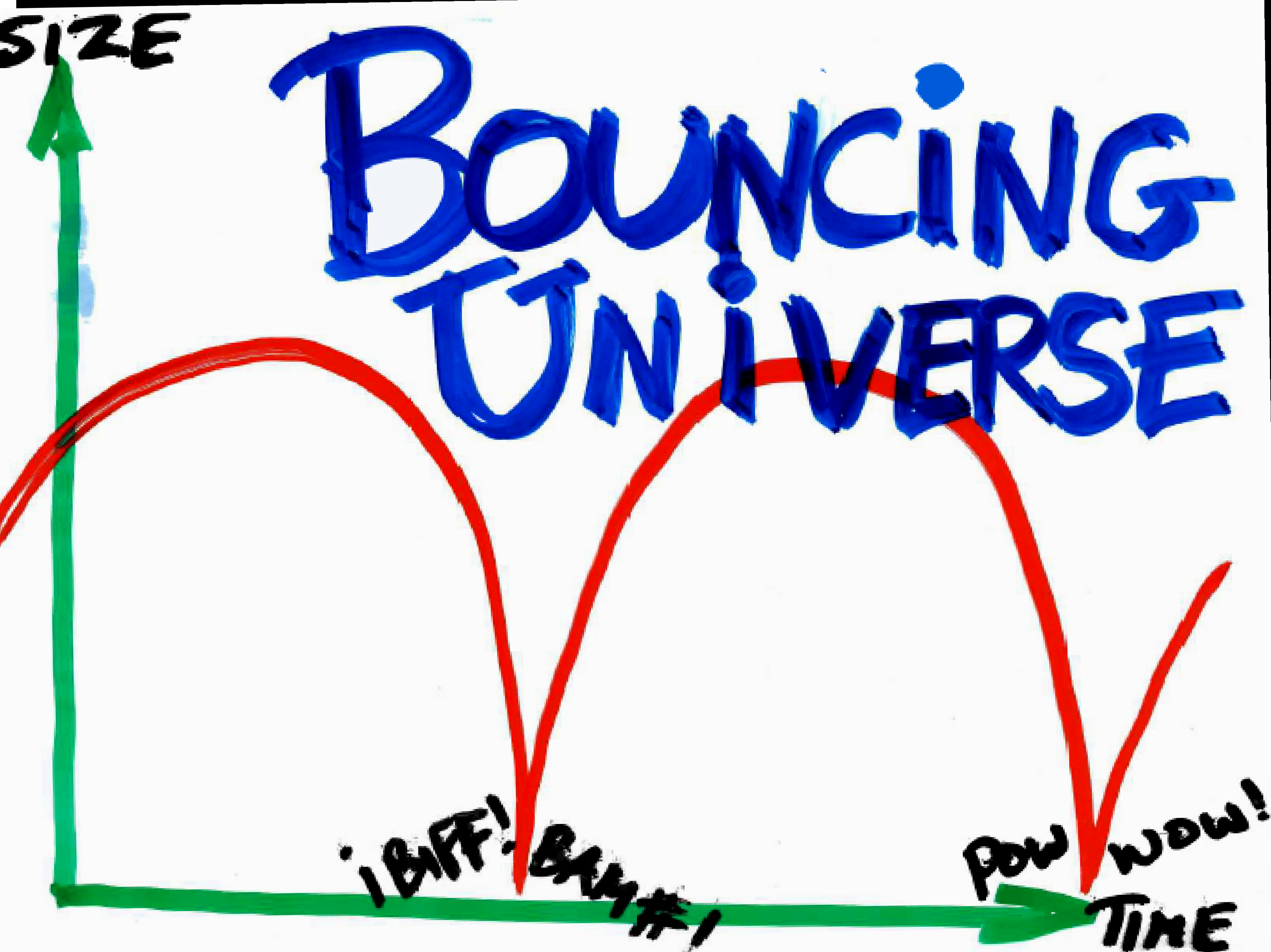
Some Cosmic Aspirations of String Theory

- Fundamental theory of inflation
- Explanation of cosmic acceleration
- Emergent space and time
- Variable constants (moduli field)
- Foundation for multiverse

String Theory's BIG BANG

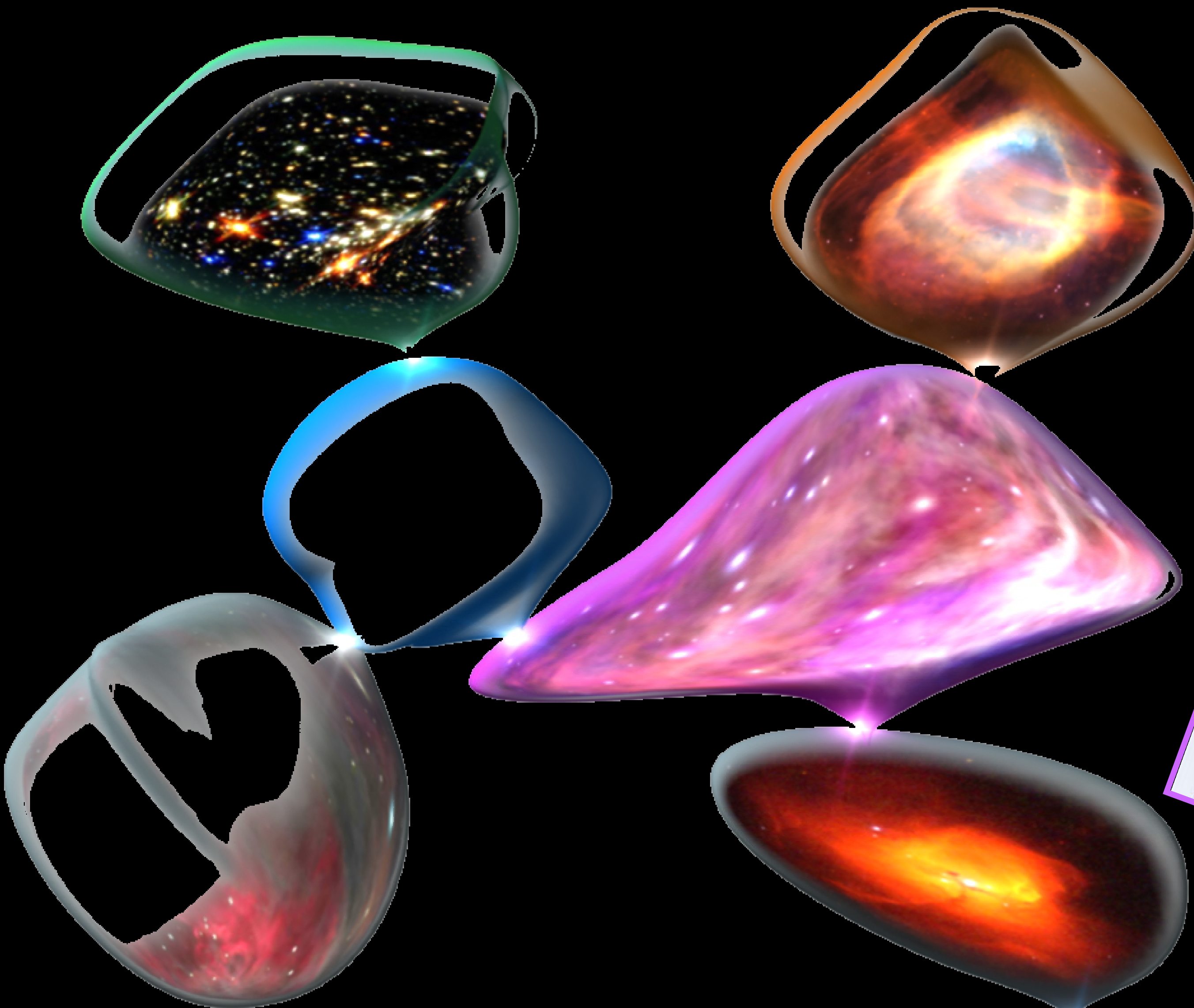


- NO BEFORE THE BIG BANG



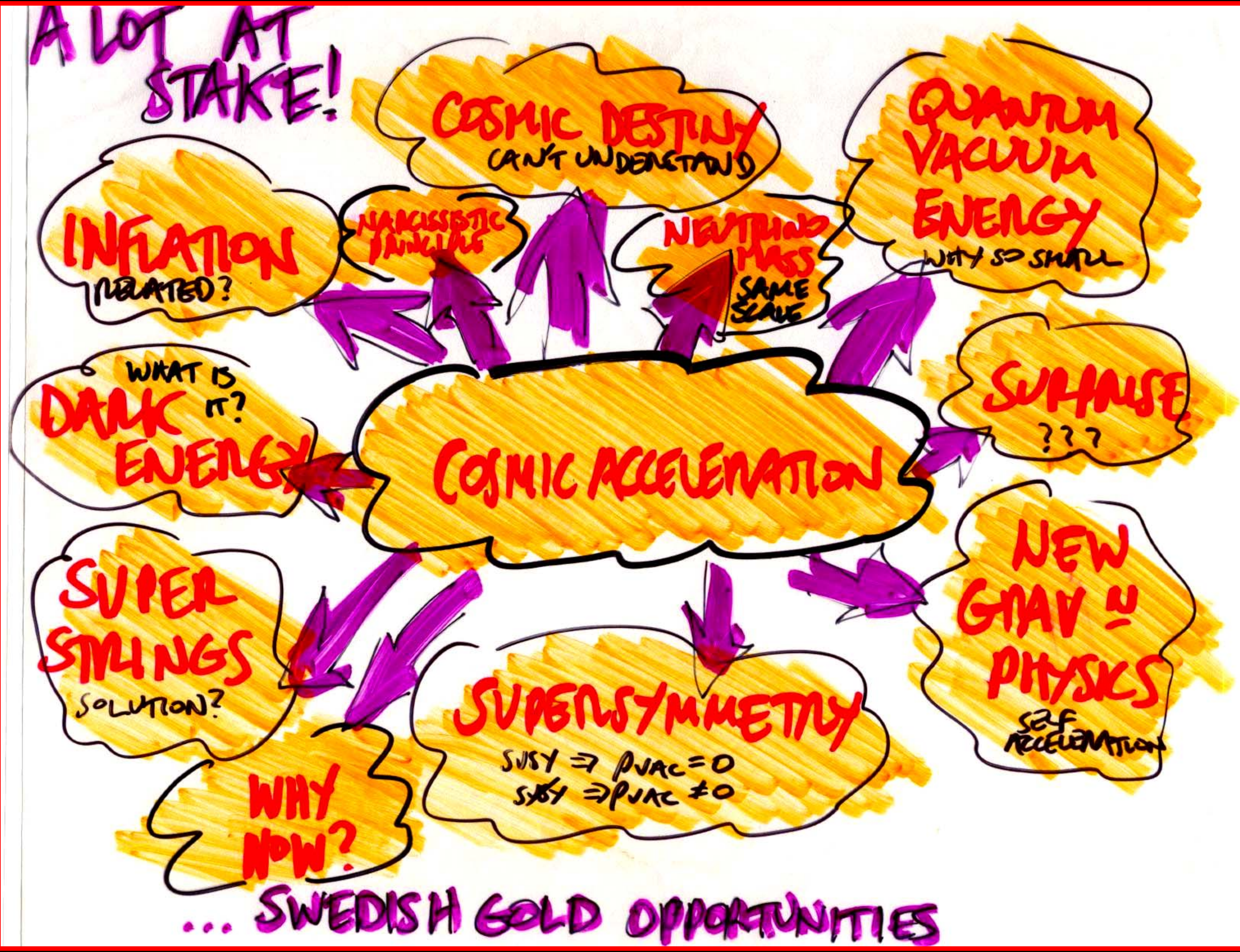
BOUNCING UNIVERSE
SIZE
TIME
¡BIFF!
BAM!
POW
WOW!

THE MULTIVERSE



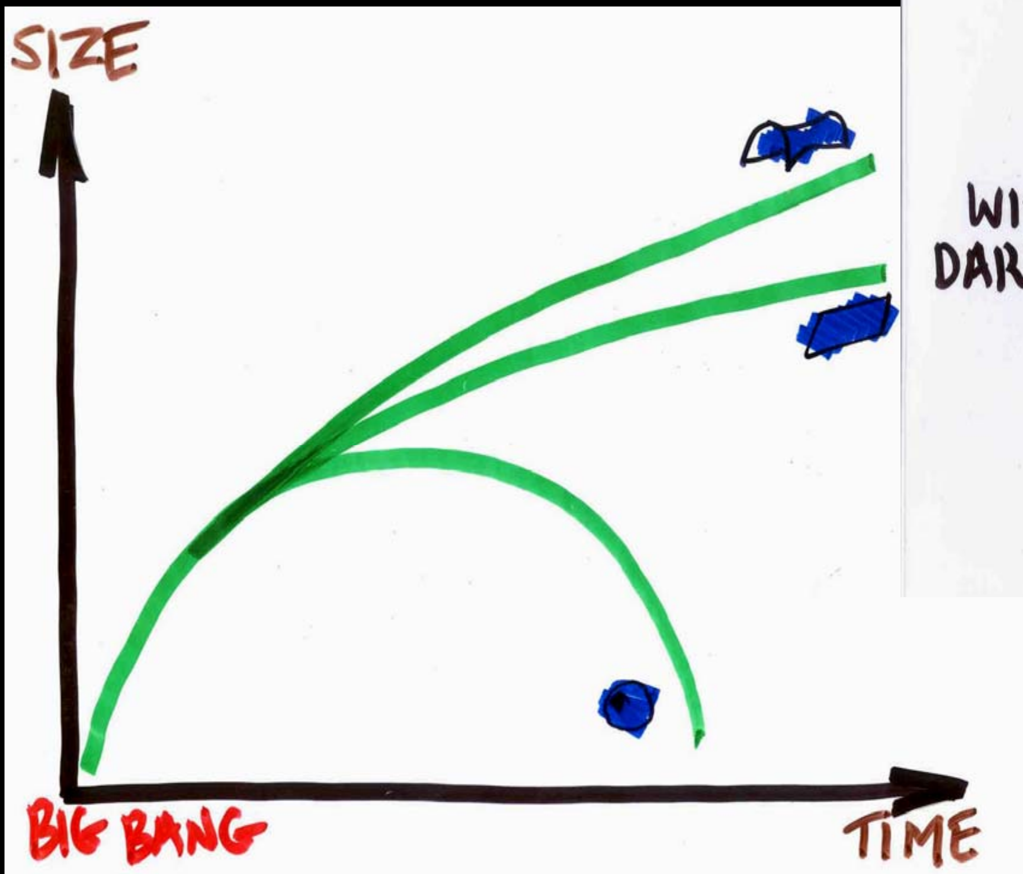
DARK ENERGY

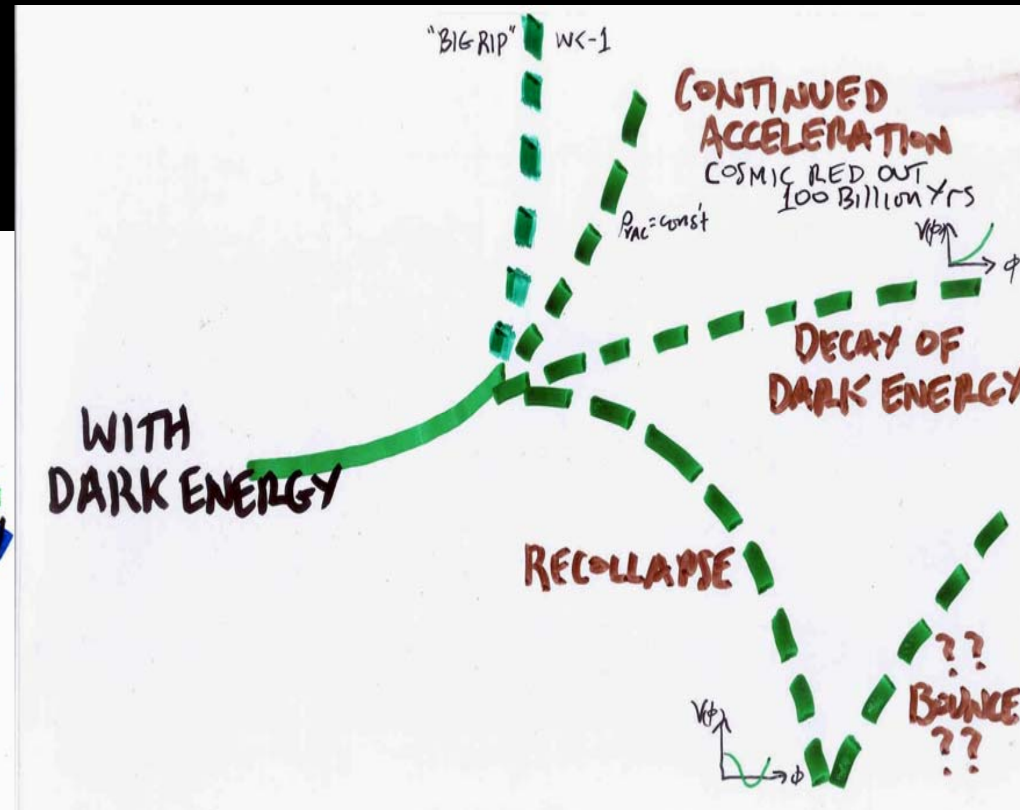
MAY BE THE MOST PROFOUND PROBLEM IN ALL OF SCIENCE TODAY



A LOT AT STAKE!
COSMIC DESTINY
CAN'T UNDERSTAND
QUANTUM VACUUM ENERGY
WHY SO SMALL
INFLATION
RELATED?
NARCISSISTIC
NEUTRINO MASS
SAME SCALE
WHAT IS IT?
DARK ENERGY
COSMIC ACCELERATION
SURPRISE
???
NEW GRAV & PHYSICS
self acceleration
SUPER STRINGS
SOLUTION?
SUPERSYMMETRY
SUSY ⇒ $\rho_{VAC} = 0$
SUSY ⇒ $\rho_{VAC} \neq 0$
WHY NOW?
... SWEDISH GOLD OPPORTUNITIES

In the Presence of Dark Energy, a Flat Universe Can Expand Forever, Re-collapse, or Even Experience a Big Rip!





Cannot Understand Our Cosmic Destiny Until We Understand What Dark Energy Is!

Cosmic Acceleration Dark Energy

- Evidence for cosmic acceleration has gotten stronger (HST, CFHTLS, Essence, WMAP, XMM/Chandra…)
- Still no understanding – “theorists continue to explore phase space”
- No evidence that dark energy is not the energy of the quantum vacuum
- Very significant probes on the horizon

GR ALLOWS FOR REPULSIVE GRAVITY:

SOURCE OF GRAVITY IN GR:

$$\rho + 3p$$

(SPHERICAL SYMMETRY)

FEATURE NOT A BUG!

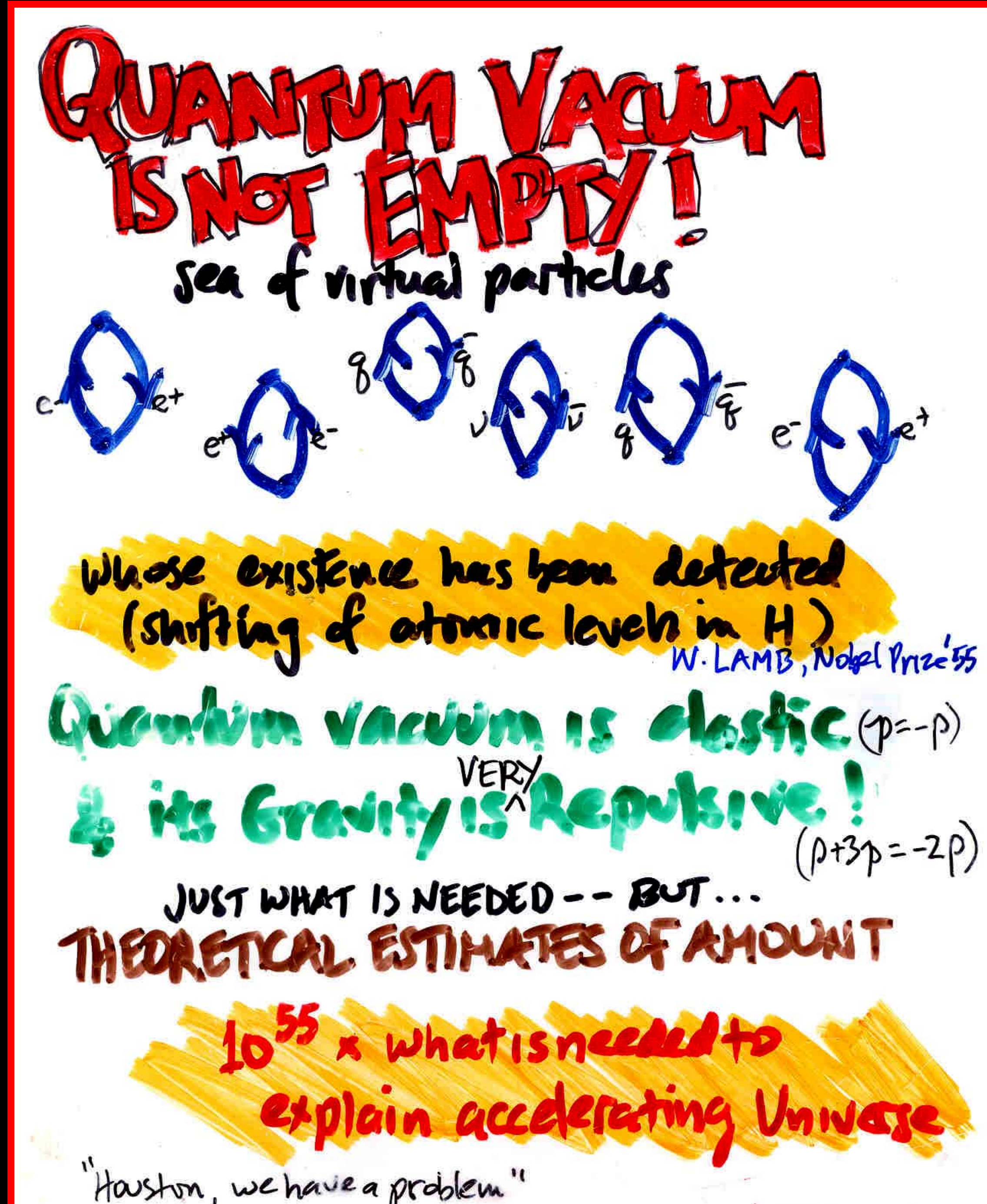
→ BLACK HOLES WHEN $p \gtrsim \rho/3$

→ REPULSIVE GRAVITY WHEN $p < -\rho/3$

The Gravity of Nothing Is Repulsive

… But How Much Does Nothing Weigh?

Apparently, Way Too Much or Possibly Nothing



Dark Energy Theory

SOLVING THE COSMIC ACCELERATION RIDDLE WILL REQUIRE A CRAZY, NEW IDEA!

NB: NOT EVERY CRAZY IDEA IS A SOLUTION TO A PROFOUND PROBLEM!

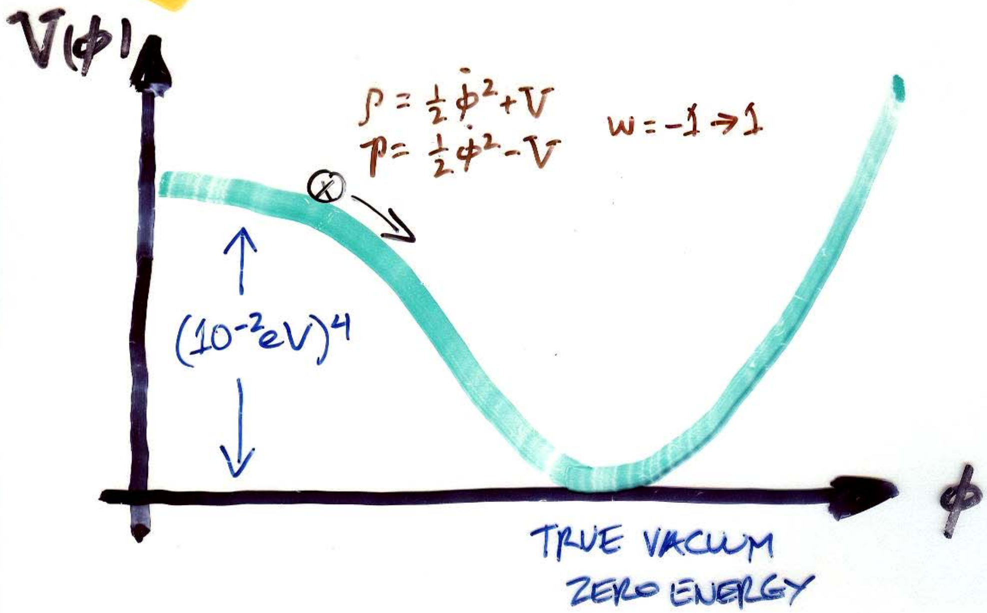
ROLLING SCALAR FIELD

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

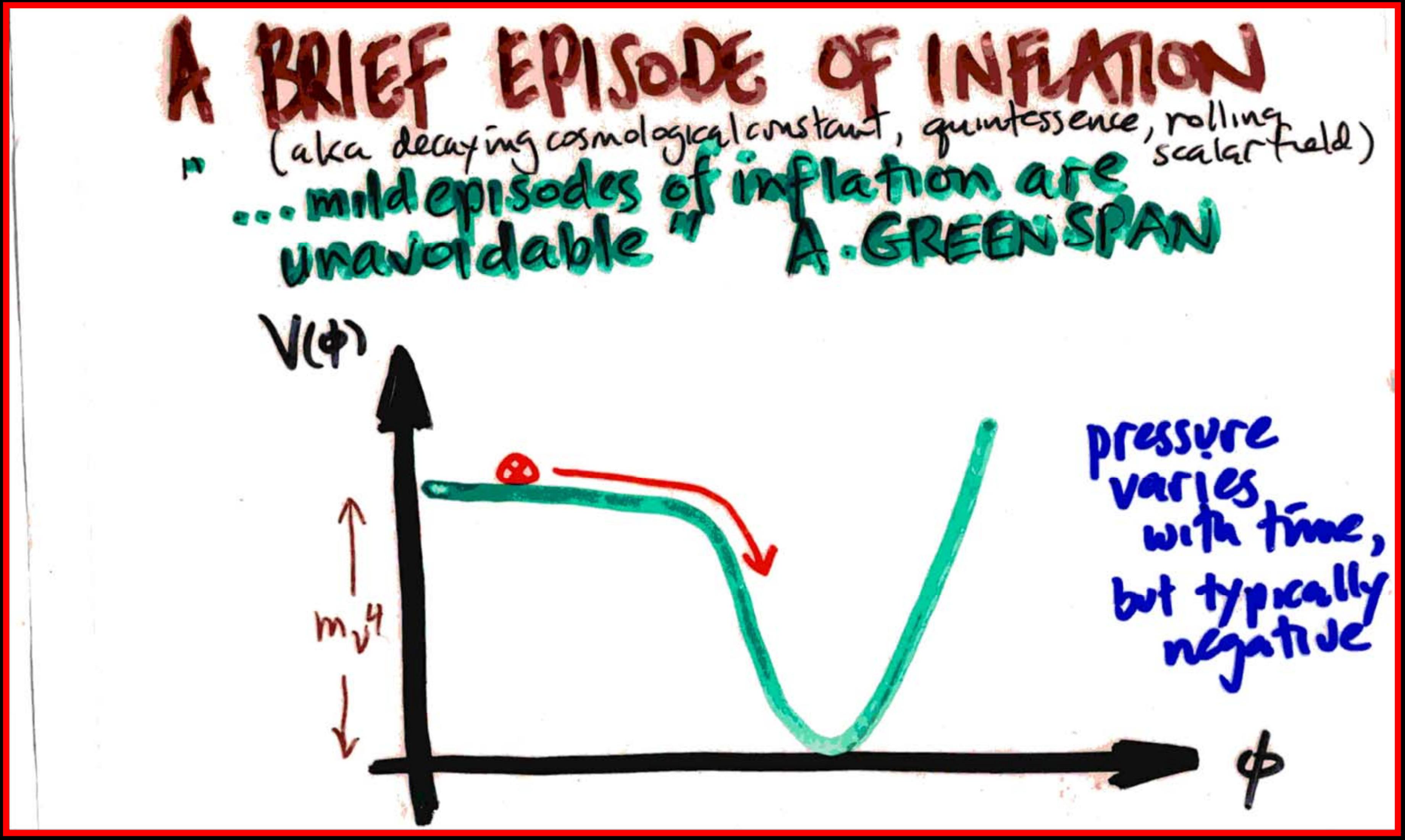
Bronstein 1933 (executed by Stalin 1935)
Hill Schramm Fry 1986
Freese et al 1987
Ratra-Peebles 1988
Frieman et al 1995
Caldwell et al 1998

& others

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



Everyone Wants to Play!



NETWORK OF (FRUSTRATED) TOPOLOGICAL DEFECTS

EG STRING

A. Vilenkin '84
Pen-Spergel '98

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

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

NO DARK ENERGY

NEW ASPECT OF GRAVITY

→ "EMPTY" UNIVERSE UNDERGOES ACCELERATED EXPANSION !

AVERAGE MATTER DENSITY TODAY $\approx 10^{-29}$ g/cm^3

$\approx 10^{-100} \times$ DENSITY AFTER INFLATION

Summary of Dark Theory

- No compelling model (to say the least)
- Current Menu
  - Quantum Vacuum Energy
    - + it exists (!)
    - \- 55 orders-of-magnitude discrepancy (or more!)
  - Quintessence
    - + temporary, related to cosmic inflation, great variety of models
    - \- doesn't solve vacuum energy, coupling to the world
  - Modified Gravity
    - + Einstein didn't get last word, superstring inspired, no dark energy
    - \- No workable/compelling model
  - "Conventional solution" (Riotto et al)
    - \- Doesn't work?, no fun!

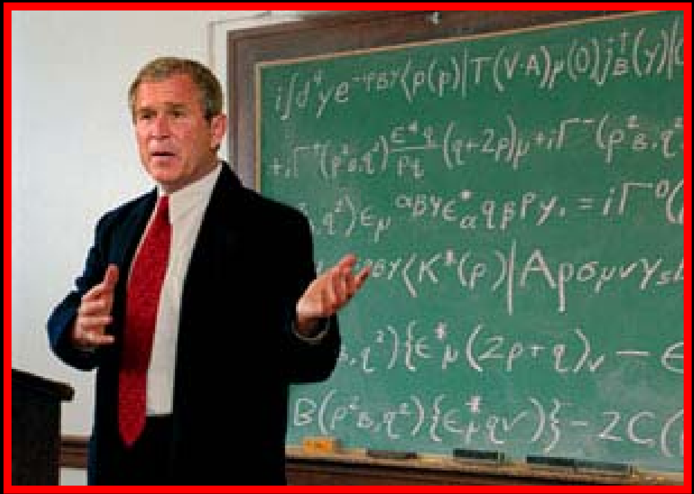
Describing Dark Energy

all about dubya

- Defining feature of dark energy: negative pressure, smooth distribution
- w, not perfect, but nothing is better, connects to the physics

$$w \quad = \quad \text{pressure/energy density}$$

$$\rho_{DE} \sim (1 + z)^{3(1+w)}$$



1. Not necessarily constant
2. Vacuum energy = -1
3. Quintessence -1 to 1
4. Ghostly quintessence < -1
5. Modified gravity, w can be imaginary

Probing Dark Energy

- **Primary effect is on the expansion and it controls :**
  - **<u>cosmic distances</u>**
  - **<u>evolution of cosmic structure</u>**
- **Powerful Probes:**
  - Supernovae, baryon acoustic oscillations
  - Clusters, large-scale structure
- Where we are: w = 1 ± "0.1"; no evidence for variation
- Where we could be by the end of next decade:
  - w = xx ± 0.03 and dw/dz = yy ± 0.1
  - Multiple complementary techniques
  - Evidence for supersymmetry (from LHC)

Baryon Acoustic Oscillations as a Standard Ruler

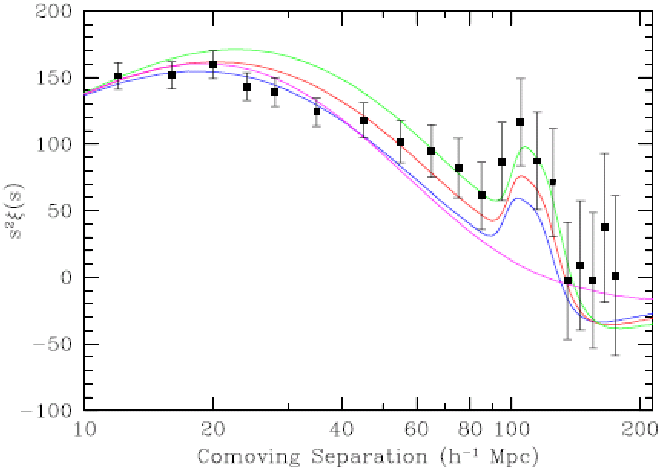


FIG. 3.— As Figure 2, but plotting the correlation function times s^2. This shows the variation of the peak at $20h^{-1}$ Mpc scales that is controlled by the redshift of equality (and hence by $\Omega_m h^2$). Varying $\Omega_m h^2$ alters the amount of large-to-small scale correlation, but boosting the large-scale correlations too much causes an inconsistency at $30h^{-1}$ Mpc. The pure CDM model (magenta) is actually close to the best-fit due to the data points on intermediate scales.

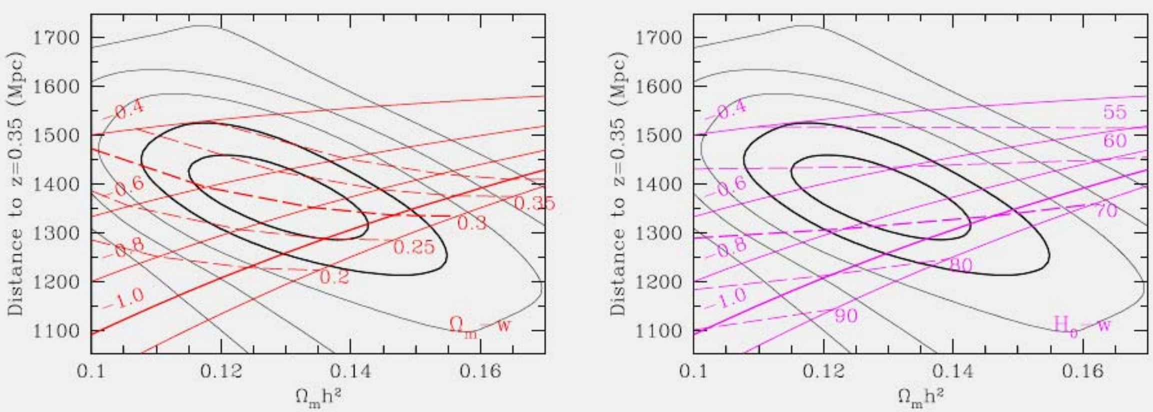
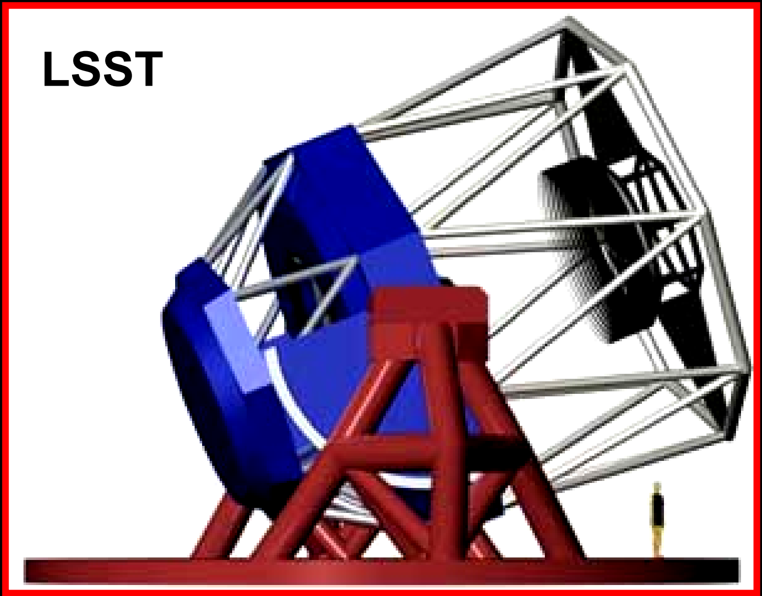
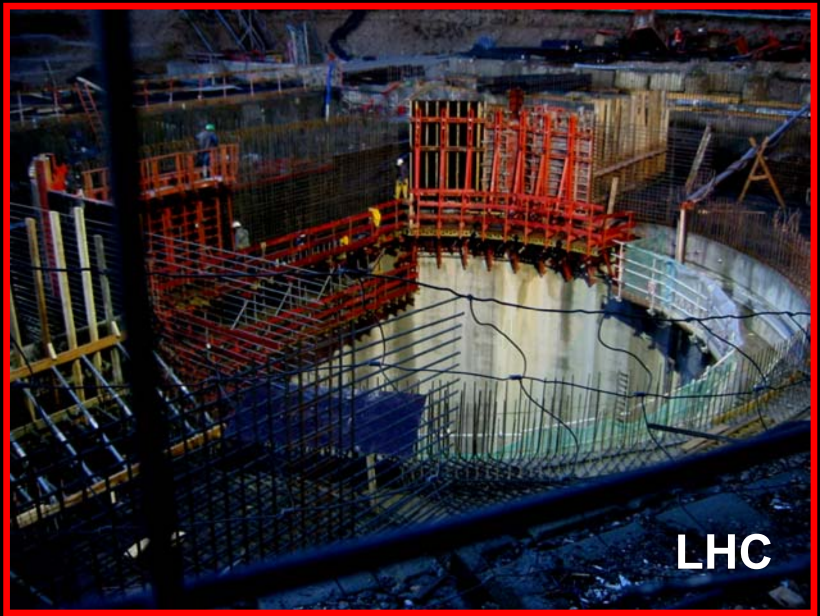


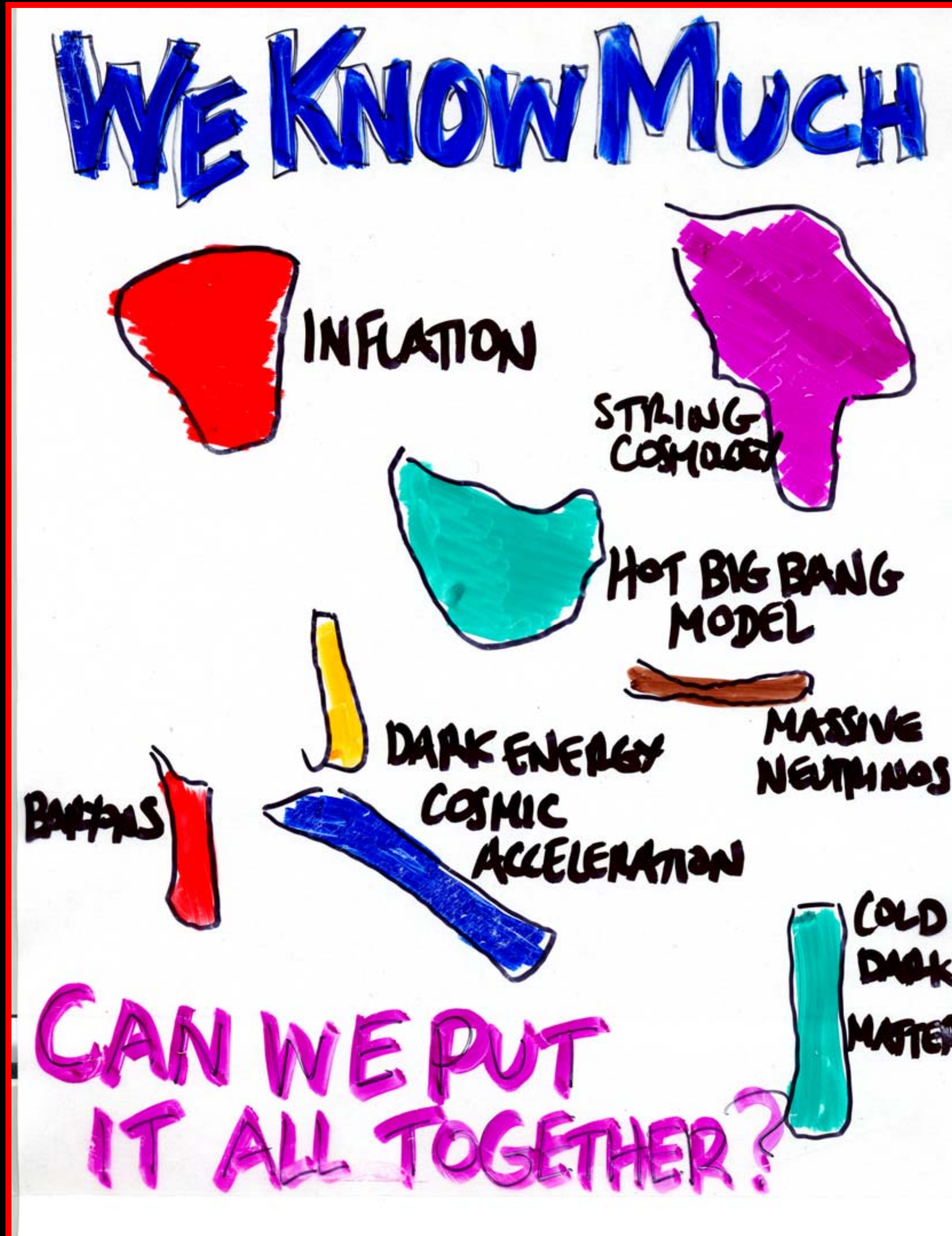
FIG. 10.— a) As Figure 7, but overplotted with model predictions from constant w flat models. For a given value of $\Omega_m h^2$ and w, the angular scale of the CMB acoustic peaks (known to 1%) determines Ω_m and H_0. Of course, the required Ω_m is a function of w and $\Omega_m h^2$. The solid red lines show lines of constant w; the dashed lines show lines of constant Ω_m. Our knowledge of $\Omega_m h^2$ still limits our inference of w. b) As (a), but the dashed lines are now lines of constant H_0.

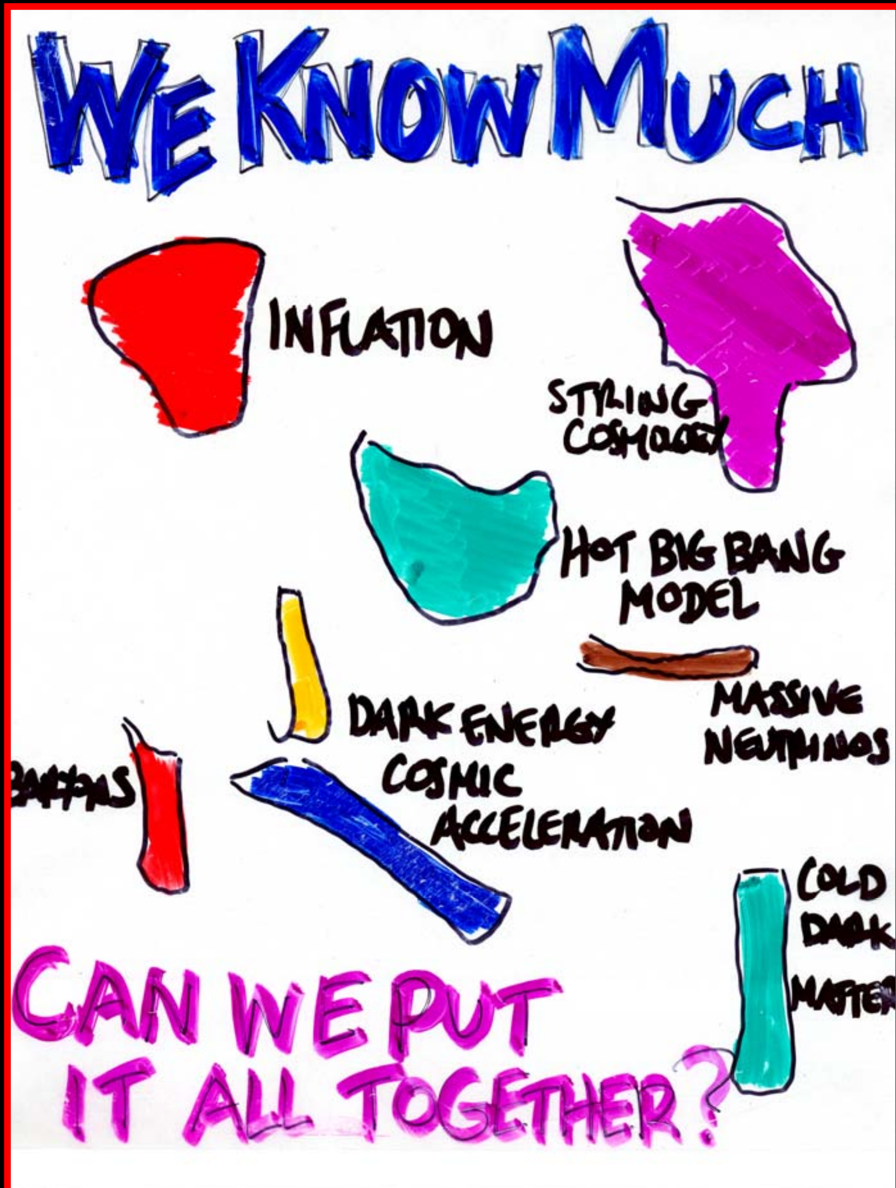
Eisenstein et al, 2005





3 Critical Probes of Dark Energy


WE KNOW MUCH
INFLATION
STRING COSMOLOGY
HOT BIG BANG MODEL
MASSIVE NEUTRINOS
DARK ENERGY
COSMIC ACCELERATION
BARYONS
COLD DARK MATTER
CAN WE PUT IT ALL TOGETHER?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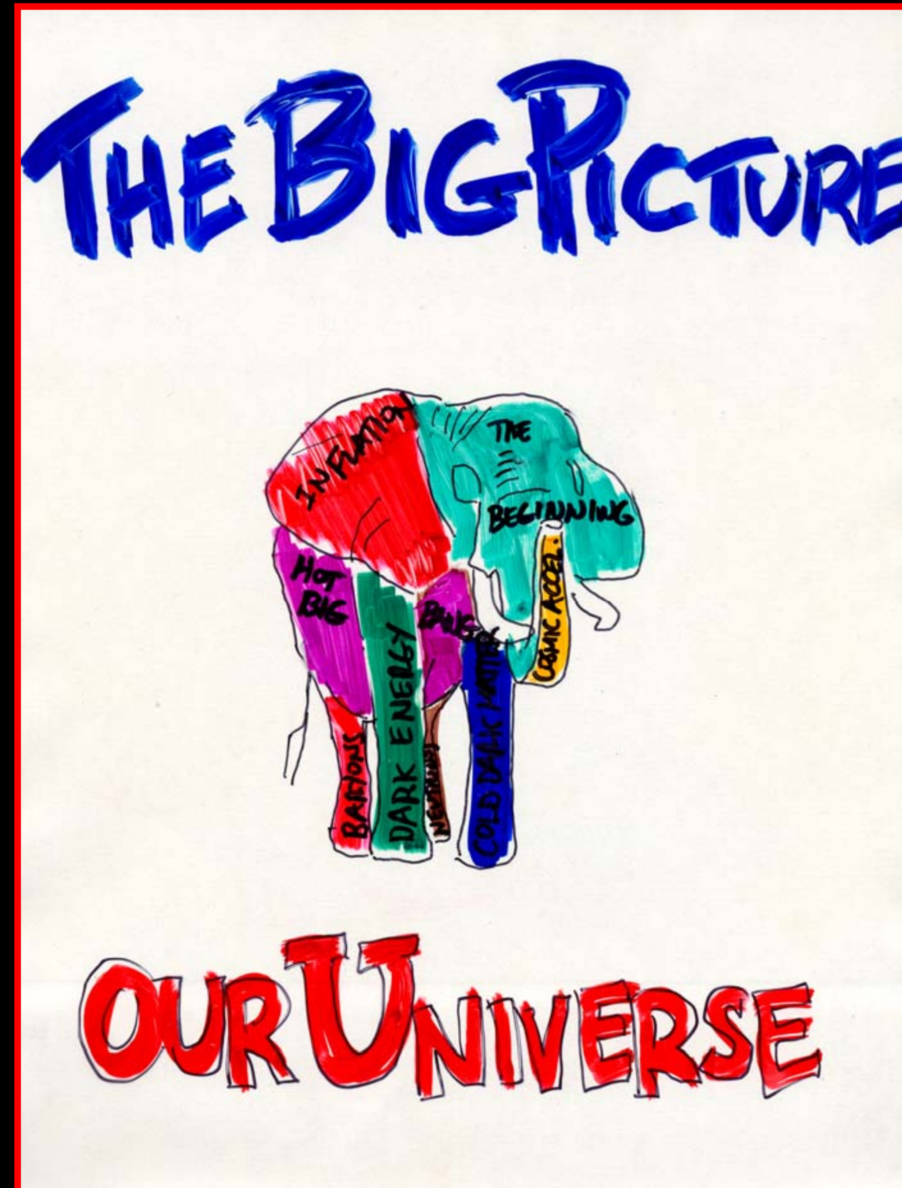
THE BIG PICTURE
INFLATION
THE BEGINNING
HOT BIG BANG
COSMIC ACCEL.
DARK ENERGY
BARYONS
NEUTRINOS
COLD DARK MATTER
OUR UNIVERSE