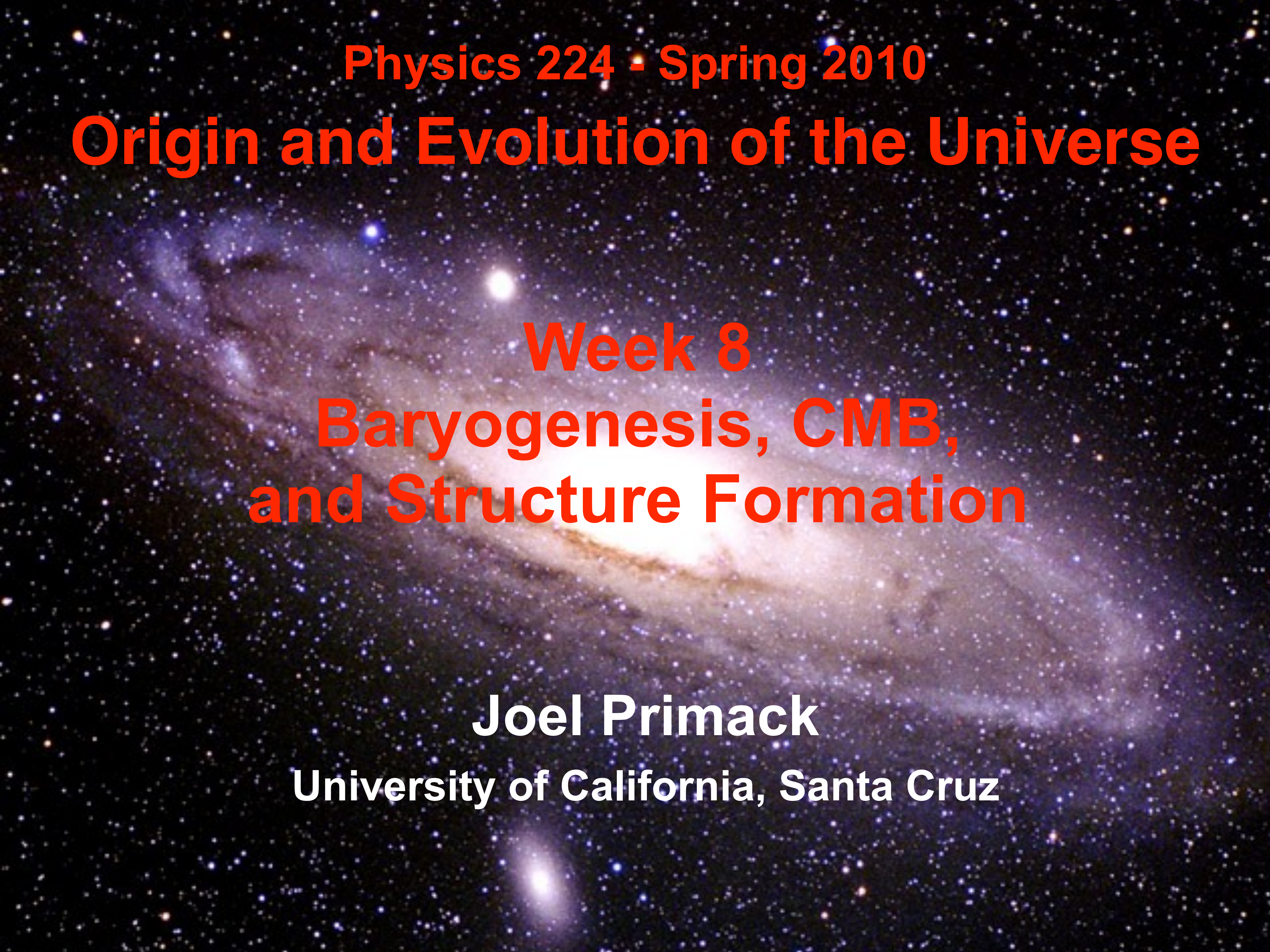

Physics 224 - Spring 2010

Origin and Evolution of the Universe

Week 8
Baryogenesis, CMB, and Structure Formation

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Physics 224 - Spring 2010

Origin and Evolution of the Universe

Week	Topics
1	Historical Introduction
2	General Relativistic Cosmology
3	Big Bang Nucleosynthesis
4	Recombination, Dark Matter
5	Dark Matter, Topological Defects
6	Cosmic Inflation
7	Before and After Cosmic Inflation
8	Baryogenesis, Cosmic Microwave Background
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Post-Inflation

Baryogenesis: generation of excess of baryon (and lepton) number compared to anti-baryon (and anti-lepton) number. In order to create the observed baryon number today

$$\frac{n_B}{n_\gamma} = \left(6.1\,^{+0.3}_{-0.2}\right) \times 10^{-10}$$

it is only necessary to create an excess of about 1 quark and lepton for every ~10^9 quarks+antiquarks and leptons +antileptons.

Other things that might happen Post-Inflation:

Breaking of Pecci-Quinn symmetry so that the observable universe is composed of many PQ domains.

Formation of cosmic topological defects if their amplitude is small enough not to violate cosmological bounds.

Baryogenesis

There is good evidence that there are **no large regions of antimatter** (Cohen, De Rujula, and Glashow, 1998). It was **Andrei Sakharov** (1967) who first suggested that the baryon density might not represent some sort of initial condition, but might be understandable in terms of microphysical laws. He listed three ingredients to such an understanding:

1. **Baryon number violation** must occur in the fundamental laws. At very early times, if baryon number violating interactions were in equilibrium, then the universe can be said to have "started" with zero baryon number. Starting with zero baryon number, baryon number violating interactions are obviously necessary if the universe is to end up with a non-zero asymmetry. As we will see, apart from the philosophical appeal of these ideas, the success of inflationary theory suggests that, shortly after the big bang, the baryon number was essentially zero.

2. **CP-violation**: If CP (the product of charge conjugation and parity) is conserved, every reaction which produces a particle will be accompanied by a reaction which produces its antiparticle at precisely the same rate, so no baryon number can be generated.

3. **Departure from Thermal Equilibrium** (An Arrow of Time): The universe, for much of its history, was very nearly in thermal equilibrium. The spectrum of the CMBR is the most perfect blackbody spectrum measured in nature. So the universe was certainly in thermal equilibrium 10^5 years after the big bang. The success of the theory of big bang nucleosynthesis (BBN) provides strong evidence that the universe was in equilibrium two-three minutes after the big bang. But if, through its early history, the universe was in thermal equilibrium, then even B and CP violating interactions could not produce a net asymmetry. One way to understand this is to recall that the CPT theorem assures strict equality of particle and antiparticle masses, so at thermal equilibrium, the densities of particles and antiparticles are equal. More precisely, since B is odd under CPT, its thermal average vanishes in an equilibrium situation. This can be generalized by saying that the universe must have an arrow of time.

Following Dine & Kusenko, RMP 2004.

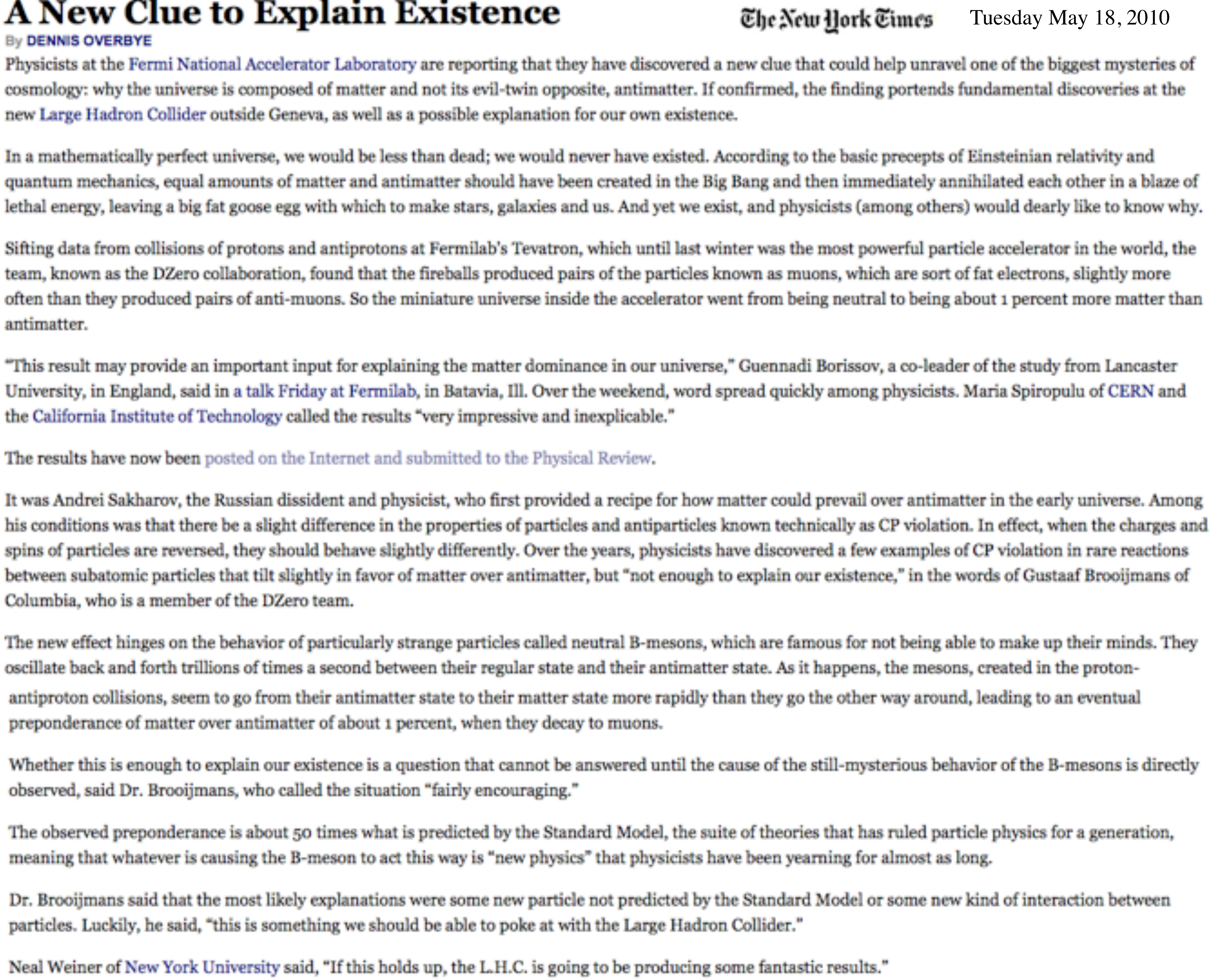
Several mechanisms have been proposed to understand the baryon asymmetry:

1. **GUT Baryogenesis**. Grand Unified Theories unify the gauge interactions of the strong, weak and electromagnetic interactions in a single gauge group. They inevitably violate baryon number, and they have heavy particles, with mass of order $M_{GUT} \approx 10^{16}$ GeV, whose decays can provide a departure from equilibrium. The main objections to this possibility come from issues associated with inflation. While there does not exist a compelling microphysical model for inflation, in most models, the temperature of the universe after reheating is well below M_{GUT}. But even if it were very large, there would be another problem. Successful unification requires supersymmetry, which implies that the graviton has a spin-3/2 partner, called the gravitino. In most models for supersymmetry breaking, these particles have masses of order TeV, and are very long lived. Even though these particles are weakly interacting, too many gravitinos are produced unless the reheating temperature is well below the unification scale -- too low for GUT baryogenesis to occur.

2. **Electroweak baryogenesis**. The Standard Model satisfies all of the conditions for baryogenesis, but any baryon asymmetry produced is far too small to account for observations. In certain extensions of the Standard Model, it is possible to obtain an adequate asymmetry, but in most cases the allowed region of parameter space is very small.

3. **Leptogenesis**. The possibility that the weak interactions will convert some lepton number to baryon number means that if one produces a large lepton number at some stage, this will be processed into a net baryon and lepton number at the electroweak phase transition. The observation of neutrino masses makes this idea highly plausible. Many but not all of the relevant parameters can be directly measured.

4. **Production by coherent motion of scalar fields (the Affleck-Dine mechanism)**, which can be highly efficient, might well be operative if nature is supersymmetric.



A New Clue to Explain Existence

The New York Times

Tuesday May 18, 2010

By **DENNIS OVERBYE**

Physicists at the Fermi National Accelerator Laboratory are reporting that they have discovered a new clue that could help unravel one of the biggest mysteries of cosmology: why the universe is composed of matter and not its evil-twin opposite, antimatter. If confirmed, the finding portends fundamental discoveries at the new Large Hadron Collider outside Geneva, as well as a possible explanation for our own existence.

In a mathematically perfect universe, we would be less than dead; we would never have existed. According to the basic precepts of Einsteinian relativity and quantum mechanics, equal amounts of matter and antimatter should have been created in the Big Bang and then immediately annihilated each other in a blaze of lethal energy, leaving a big fat goose egg with which to make stars, galaxies and us. And yet we exist, and physicists (among others) would dearly like to know why.

Sifting data from collisions of protons and antiprotons at Fermilab's Tevatron, which until last winter was the most powerful particle accelerator in the world, the team, known as the DZero collaboration, found that the fireballs produced pairs of the particles known as muons, which are sort of fat electrons, slightly more often than they produced pairs of anti-muons. So the miniature universe inside the accelerator went from being neutral to being about 1 percent more matter than antimatter.

"This result may provide an important input for explaining the matter dominance in our universe," Guennadi Borissov, a co-leader of the study from Lancaster University, in England, said in a talk Friday at Fermilab, in Batavia, Ill. Over the weekend, word spread quickly among physicists. Maria Spiropulu of CERN and the California Institute of Technology called the results "very impressive and inexplicable."

The results have now been posted on the Internet and submitted to the Physical Review.

It was Andrei Sakharov, the Russian dissident and physicist, who first provided a recipe for how matter could prevail over antimatter in the early universe. Among his conditions was that there be a slight difference in the properties of particles and antiparticles known technically as CP violation. In effect, when the charges and spins of particles are reversed, they should behave slightly differently. Over the years, physicists have discovered a few examples of CP violation in rare reactions between subatomic particles that tilt slightly in favor of matter over antimatter, but "not enough to explain our existence," in the words of Gustaaf Brooijmans of Columbia, who is a member of the DZero team.

The new effect hinges on the behavior of particularly strange particles called neutral B-mesons, which are famous for not being able to make up their minds. They oscillate back and forth trillions of times a second between their regular state and their antimatter state. As it happens, the mesons, created in the proton-antiproton collisions, seem to go from their antimatter state to their matter state more rapidly than they go the other way around, leading to an eventual preponderance of matter over antimatter of about 1 percent, when they decay to muons.

Whether this is enough to explain our existence is a question that cannot be answered until the cause of the still-mysterious behavior of the B-mesons is directly observed, said Dr. Brooijmans, who called the situation "fairly encouraging."

The observed preponderance is about 50 times what is predicted by the Standard Model, the suite of theories that has ruled particle physics for a generation, meaning that whatever is causing the B-meson to act this way is "new physics" that physicists have been yearning for almost as long.

Dr. Brooijmans said that the most likely explanations were some new particle not predicted by the Standard Model or some new kind of interaction between particles. Luckily, he said, "this is something we should be able to poke at with the Large Hadron Collider."

Neal Weiner of New York University said, "If this holds up, the L.H.C. is going to be producing some fantastic results."

arXiv:1005.2757

Fermilab-Pub-10/114-E

Evidence for an anomalous like-sign dimuon charge asymmetry

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(Dated: May 16, 2010)

We measure the charge asymmetry A of like-sign dimuon events in 6.1 fb^{-1} of $p\bar{p}$ collisions recorded with the D0 detector at a center-of-mass energy $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider. From A, we extract the like-sign dimuon charge asymmetry in semileptonic b-hadron decays: $A^b_{\rm sl} = -0.00957 \pm 0.00251$ (stat) ± 0.00146 (syst). This result differs by 3.2 standard deviations from the standard model prediction $A^b_{\rm sl}(SM) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$ and provides first evidence of anomalous CP-violation in the mixing of neutral B mesons.

PACS numbers: 13.25.Hw; 14.40.Nd

I. INTRODUCTION

Studies of particle production and decay under the reversal of discrete symmetries (charge, parity and time reversal) have yielded considerable insight on the structure of the theories that describe high energy phenomena. Of particular interest is the observation of CP violation, a phenomenon well established in the K^0 and B^0_d systems, but not yet observed for the B^0_s system, where all CP violation effects are expected to be small in the standard model (SM) [1] (See [2] and references therein for a review of the experimental results and of the theoretical framework for describing CP violation in neutral mesons decays). The violation of CP symmetry is a necessary condition for baryogenesis, the process thought to be responsible for the matter-antimatter asymmetry of the universe [3]. However, the observed CP violation in the K^0 and B^0_d systems, consistent with the standard model expectation, is not sufficient to explain this asymmetry, suggesting the presence of additional sources of CP violation, beyond the standard model.

The D0 experiment at the Fermilab Tevatron proton-antiproton ($p\bar{p}$) collider, operating at a center-of-mass

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energy $\sqrt{s} = 1.96$ TeV, is in a unique position to study possible effects of CP violation, in particular through the study of charge asymmetries in generic final states, given that the initial state is CP-symmetric. The high center-of-mass energy provides access to mass states beyond the reach of the B-factories. The periodic reversal of the D0 solenoid and toroid polarities results in a cancellation at the first order of most detector-related asymmetries. In this paper we present a measurement of the like-sign dimuon charge asymmetry A, defined as

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}, \tag{1}$$

where N^{++} and N^{--} represent, respectively, the number of events in which the two muons of highest transverse momentum satisfying the kinematic selections have the same positive or negative charge. After removing the contributions from backgrounds and from residual detector effects, we observe a net asymmetry that is significantly different from zero.

We interpret this result assuming that the only source of this asymmetry is the mixing of neutral B mesons that decay semileptonically, and obtain a measurement of the asymmetry $A^b_{\rm sl}$ defined as

$$A^b_{\rm sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}, \tag{2}$$

where N_b^{++} and N_b^{--} represent the number of events containing two b hadrons decaying semileptonically and producing two positive or two negative muons, respectively. As shown in Appendix A each neutral B^0_q meson ($q = d, s$) contributes a term to this asymmetry given by:

$$a^q_{\rm sl} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q, \tag{3}$$

where ϕ_q is the CP-violating phase, and ΔM_q and $\Delta\Gamma_q$ are the mass and width differences between the eigen-

provide larger values of ϕ_q [6–9]. Measurements of $A^b_{\rm sl}$ or ϕ_q that differ significantly from the SM expectations would indicate the presence of new physics.

The asymmetry $A^b_{\rm sl}$ is also equal to the charge asymmetry $a^b_{\rm sl}$ of semileptonic decays of b hadrons to muons of "wrong charge" (i.e. a muon charge opposite to the charge of the original b quark) induced through $B^0_q\bar{B}^0_q$ oscillations [10]:

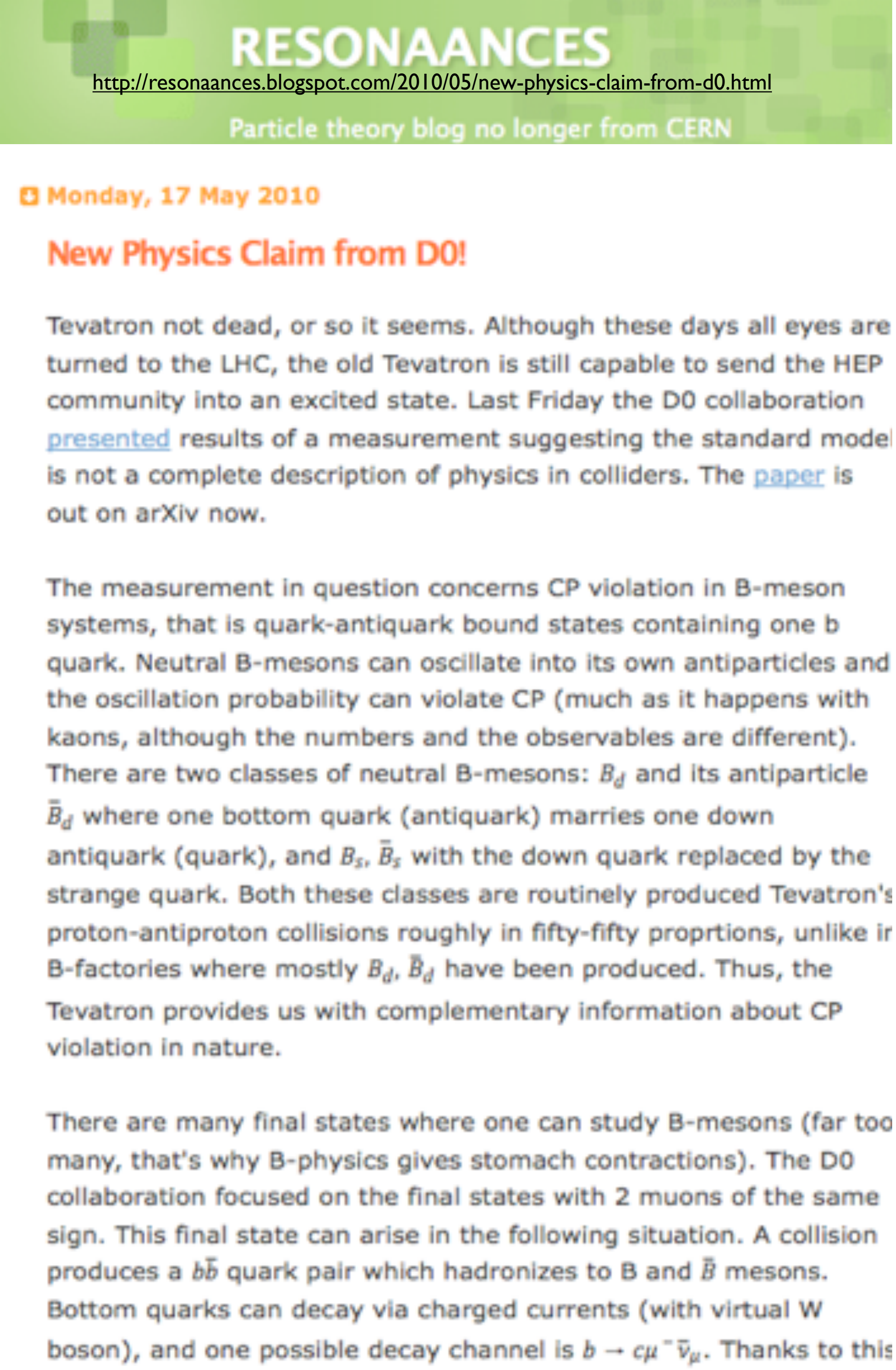
$$a^b_{\rm sl} \equiv \frac{\Gamma(\bar{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(\bar{B} \to \mu^+ X) + \Gamma(B \to \mu^- X)} = A^b_{\rm sl}. \tag{5}$$

We extract $A^b_{\rm sl}$ from two observables. The first is the like-sign dimuon charge asymmetry A of Eq. (1), and the second observable is the inclusive muon charge asymmetry a defined as

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-}, \tag{6}$$

where n^+ and n^- correspond to the number of detected positive and negative muons, respectively.

At the Fermilab Tevatron collider, b quarks are produced mainly in $b\bar{b}$ pairs. The signal for the asymmetry A is composed of like-sign dimuon events, with one muon arising from direct semileptonic b-hadron decay $b \to \mu^- X$ [11], and the other muon resulting from $B^0_q\bar{B}^0_q$ oscillation, followed by the direct semileptonic $\bar{B}^0_q$ meson decay $B^0_q \to \bar{B}^0_q \to \mu^- X$. Consequently the second muon has the "wrong sign" due to $B^0_q\bar{B}^0_q$ mixing. For the asymmetry a, the signal comes from mixing, followed by the semileptonic decay $B^0_q \to \bar{B}^0_q \to \mu^- X$. The main backgrounds for these measurements arise from events with at least one muon from kaon or pion decay, or from the sequential decay of b quarks $b \to c \to \mu^+ X$. For the asymmetry a, there is an additional background from direct production of c-quarks followed by their semileptonic decays.



http://resonaances.blogspot.com/2010/05/new-physics-claim-from-d0.html

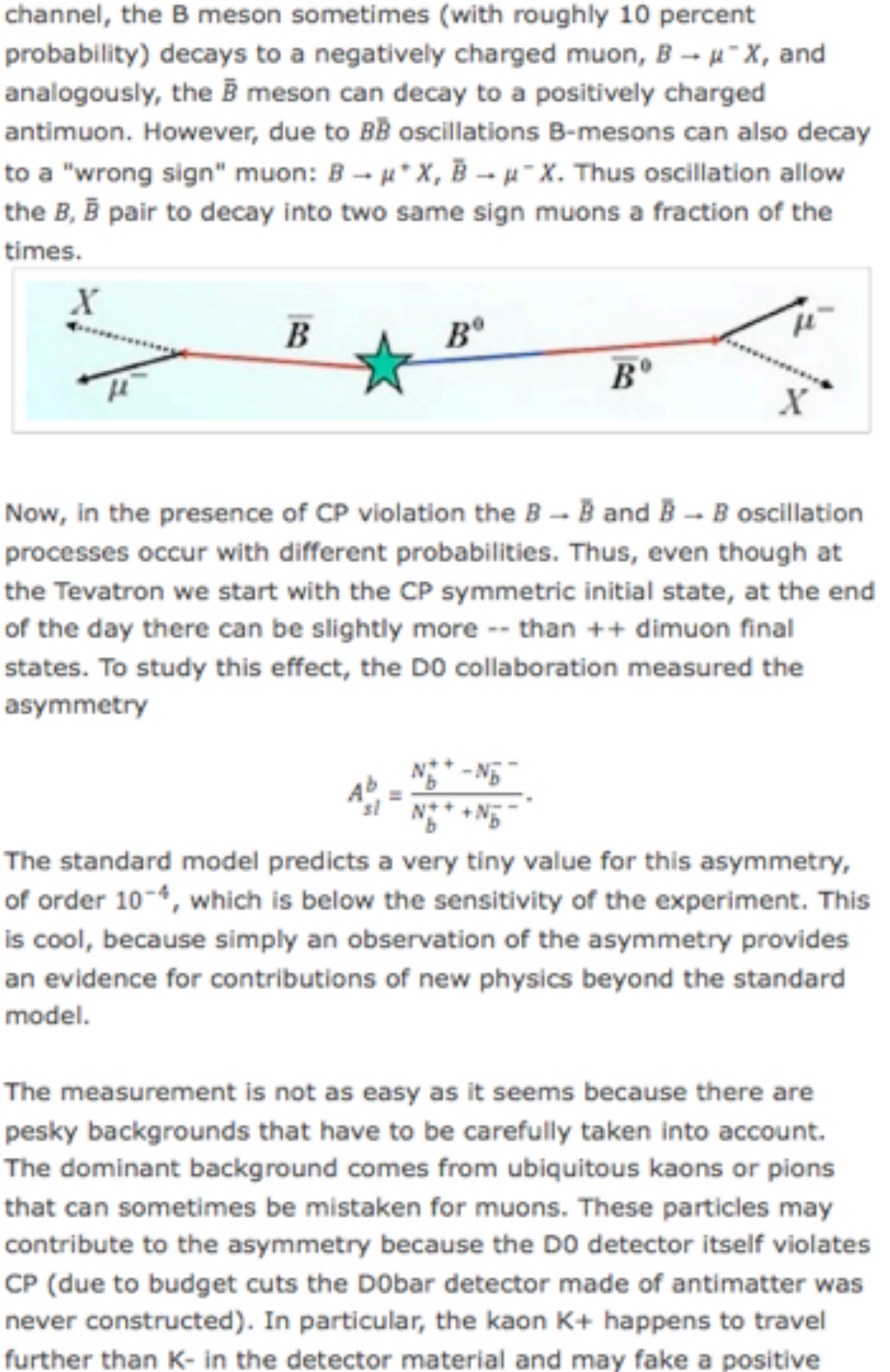
Monday, 17 May 2010

New Physics Claim from D0!

Tevatron not dead, or so it seems. Although these days all eyes are turned to the LHC, the old Tevatron is still capable to send the HEP community into an excited state. Last Friday the D0 collaboration presented results of a measurement suggesting the standard model is not a complete description of physics in colliders. The paper is out on arXiv now.

The measurement in question concerns CP violation in B-meson systems, that is quark-antiquark bound states containing one b quark. Neutral B-mesons can oscillate into its own antiparticles and the oscillation probability can violate CP (much as it happens with kaons, although the numbers and the observables are different). There are two classes of neutral B-mesons: B_d and its antiparticle $\bar{B}_d$ where one bottom quark (antiquark) marries one down antiquark (quark), and B_s, $\bar{B}_s$ with the down quark replaced by the strange quark. Both these classes are routinely produced Tevatron's proton-antiproton collisions roughly in fifty-fifty proprtions, unlike in B-factories where mostly B_d, $\bar{B}_d$ have been produced. Thus, the Tevatron provides us with complementary information about CP violation in nature.

There are many final states where one can study B-mesons (far too many, that's why B-physics gives stomach contractions). The D0 collaboration focused on the final states with 2 muons of the same sign. This final state can arise in the following situation. A collision produces a $b\bar{b}$ quark pair which hadronizes to B and $\bar{B}$ mesons. Bottom quarks can decay via charged currents (with virtual W boson), and one possible decay channel is $b \to c\mu^-\bar{\nu}_\mu$. Thanks to this channel, the B meson sometimes (with roughly 10 percent probability) decays to a negatively charged muon, $B \to \mu^- X$, and analogously, the $\bar{B}$ meson can decay to a positively charged antimuon. However, due to $B\bar{B}$ oscillations B-mesons can also decay to a "wrong sign" muon: $B \to \mu^+ X$, $\bar{B} \to \mu^- X$. Thus oscillation allow the B, $\bar{B}$ pair to decay into two same sign muons a fraction of the times.



Now, in the presence of CP violation the $B \to \bar{B}$ and $\bar{B} \to B$ oscillation processes occur with different probabilities. Thus, even though at the Tevatron we start with the CP symmetric initial state, at the end of the day there can be slightly more -- than ++ dimuon final states. To study this effect, the D0 collaboration measured the asymmetry

$$A_{sl}^b = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}.$$

The standard model predicts a very tiny value for this asymmetry, of order 10^{-4}, which is below the sensitivity of the experiment. This is cool, because simply an observation of the asymmetry provides an evidence for contributions of new physics beyond the standard model.

The measurement is not as easy as it seems because there are pesky backgrounds that have to be carefully taken into account. The dominant background comes from ubiquitous kaons or pions that can sometimes be mistaken for muons. These particles may contribute to the asymmetry because the D0 detector itself violates CP (due to budget cuts the D0bar detector made of antimatter was never constructed). In particular, the kaon K+ happens to travel further than K- in the detector material and may fake a positive these effects right and carefully subtracted them away. At the end of the day D0 quotes the measured asymmetry to be

$$A^b_{sl} = -0.00957 \pm 0.00251(stat) \pm 0.00146(syst),$$

that is the number of produced muons is larger than the number of produced antimuons with the statistical significance estimated to be 3.2 sigma. The asymmetry is some 100 times larger than the value predicted by the standard model!

Of course, it's too early to start dancing and celebrating the downfall of the standard model, as in the past the bastard have recovered from similar blows. Yet there are reasons to get excited. The most important one is that the latest D0 result goes well in hand with the anomaly in the B_s system reported by the Tevatron 2 years ago. The asymmetry measured by D0 receives contributions from both B_s and B_d mesons. The B_d mesons are much better studied because they were produced by tons in BaBar and Belle, and to everyone's disappointment they were shown to behave according to the standard model predictions. However BaBar and Belle didn't produce too many B_s mesons (their beams were tuned to the Upsilon(4s) resonance which is a tad too light to decay into B_s mesons), and so the B_s sector can still hold surprises. Two years ago CDF and D0 measured CP violation in B_s decays into $J/\psi\varphi$, and they both saw a small, 2-sigma level discrepancy from the standard model. When these 2 results are combined with all other flavor physics data it was argued that the discrepancy becomes more than 3 sigma. The latest D0 results is another strong hint that something fishy is going on in the B_s sector.

Both the old and the new anomaly prompts introducing to the fundamental lagrangian a new effective four-fermion operator that contributes to the amplitude of $B_s\bar{B}_s$ oscillations:

$$L_{newphysics} \sim \frac{c}{\Lambda^2}(\bar{b}s)^2 + \text{h.c.},$$

with a complex coefficient c and the scale in the denominator on the order of 100 TeV. At this point there are no hints from experiment what could be the source of this new operator, and the answer may even lie beyond the reach of the LHC. In any case, in the coming weeks theorists will derive this operator using extra dimensions, little Higgs, fat Higgs, unhiggs, supersymmetry, bricks, golf balls, and old tires. Yet the most important question is whether the asymmetry is real, and we're dying to hear from CDF and Belle. There will be more soon, I hope...

7 comments:

↪ Lumo said...

Thanks, Jester, interesting!

My comments about it are under the clickable link. Cheers, LM

17 May 2010 17:04

3. Leptogenesis.

There is now compelling experimental evidence that neutrinos have mass, both from solar and atmospheric neutrino experiments and accelerator and reactor experiments. The masses are tiny, fractions of an eV. The “see-saw mechanism” is a natural way to generate such masses. One supposes that in addition to the neutrinos of the Standard Model, there are some SU(2)xU(1)-singlet neutrinos, N. Nothing forbids these from obtaining a large mass. This could be of order M_{GUT}, for example, or a bit smaller. These neutrinos could also couple to the left handed doublets ν_L, just like right handed charged leptons. Assuming that these couplings are not particularly small, one would obtain a mass matrix, in the {N, ν_L} basis, of the form

$$M_\nu = \begin{pmatrix} M & M_W \\ M_W^T & 0 \end{pmatrix}$$

This matrix has an eigenvalue $\frac{M_W^2}{M}$.

The latter number is of the order needed to explain the neutrino anomaly for M ~ 10^{13} or so, i.e. not wildly different than the GUT scale and other scales which have been proposed for new physics. For **leptogenesis** (Fukugita and Yanagida, 1986), what is important in this model is that the couplings of N break lepton number. N is a heavy particle; it can decay both to h + ν and h + ν-bar, for example. The partial widths to each of these final states need not be the same. CP violation can enter through phases in the Yukawa couplings and mass matrices of the N’s.

As the universe cools through temperatures of order the of masses of the N's, they drop out of equilibrium, and their decays can lead to an excess of neutrinos over antineutrinos. Detailed predictions can be obtained by integrating a suitable set of Boltzmann equations. These decays produce a net lepton number, but not baryon number (and hence a net B − L). The resulting lepton number will be further processed by sphaleron interactions, yielding a net lepton and baryon number (recall that sphaleron interactions preserve B − L, but violate B and L separately). Reasonable values of the neutrino parameters give asymmetries of the order we seek to explain.

It is interesting to ask: assuming that these processes are the source of the observed asymmetry, how many parameters which enter into the computation can be measured, i.e. can we relate the observed number to microphysics. It is likely that, over time, many of the parameters of the light neutrino mass matrices, including possible CP-violating effects, will be measured. But while these measurements determine some of the couplings and masses, they are not, in general, enough. In order to give a precise calculation, analogous to the calculations of nucleosynthesis, of the baryon number density, one needs additional information about the masses of the fields N. One either requires some other (currently unforseen) experimental access to this higher scale physics, or a compelling theory of neutrino mass in which symmetries, perhaps, reduce the number of parameters.

4. Production by coherent motion of scalar fields (the Affleck-Dine mechanism)

The formation of an AD condensate can occur quite generically in cosmological models. Also, the AD scenario potentially can give rise simultaneously to the ordinary matter and the dark matter in the universe. This can explain why the amounts of luminous and dark matter are surprisingly close to each other, within one order of magnitude. If the two entities formed in completely unrelated processes (for example, the baryon asymmetry from leptogenesis, while the dark matter from freeze-out of neutralinos), the observed relation $\Omega_{DARK} \sim \Omega_{baryon}$ is fortuitous.

In supersymmetric theories, the ordinary quarks and leptons are accompanied by scalar fields. These scalar fields carry baryon and lepton number. A coherent field, i.e., a large classical value of such a field, can in principle carry a large amount of baryon number. As we will see, it is quite plausible that such fields were excited in the early universe. To understand the basics of the mechanism, consider first a model with a single complex scalar field. Take the Lagrangian to be

$$\mathcal{L} = |\partial_\mu \phi|^2 - m^2 |\phi|^2$$

This Lagrangian has a symmetry, $\varphi \rightarrow e^{i\alpha}\varphi$, and a corresponding conserved current, which we will refer to as baryon current:

$$j^\mu_B = i(\phi^* \partial^\mu \phi - \phi \partial^\mu \phi^*).$$

It also possesses a "CP" symmetry: $\varphi \leftrightarrow \varphi^*$. With supersymmetry in mind, we will think of m as of order M_W.

Let us add interactions in the following way, which will closely parallel what happens in the supersymmetric case. Include a set of quartic couplings:

$$\mathcal{L}_I = \lambda|\phi|^4 + \epsilon\phi^3\phi^* + \delta\phi^4 + c.c.$$

These interactions clearly violate B. For general complex ε and δ, they also violate CP. In supersymmetric theories, as we will shortly see, the couplings will be extremely small. In order that these tiny couplings lead to an appreciable baryon number, it is necessary that the fields, at some stage, were very large.

To see how the cosmic evolution of this system can lead to a non-zero baryon number, first note that at very early times, when the Hubble constant, $H \gg m$, the mass of the field is irrelevant. It is thus reasonable to suppose that at this early time $\varphi = \varphi_o \gg 0$. How does the field then evolve? First ignore the quartic interactions. In the expanding universe, the equation of motion for the field is as usual

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0.$$

At very early times, $H \gg m$, and so the system is highly overdamped and essentially frozen at φo. At this point, $B = 0$.

Once the universe has aged enough that $H \ll m$, φ begins to oscillate. Substituting $H = 1/2t$ or $H = 2/3t$ for the radiation and matter dominated eras, respectively, one finds that

$$\phi = \begin{cases} \frac{\phi_o}{(mt)^{3/2}} \sin(mt) & \text{(radiation)} \\ \frac{\phi_o}{(mt)} \sin(mt) & \text{(matter).} \end{cases}$$

In either case, the energy behaves, in terms of the scale factor, $R(t)$, as

$$E \approx m^2 \phi_o^2 (\frac{R_o}{R})^3$$

Now let's consider the effects of the quartic couplings. Since the field amplitude damps with time, their significance will decrease with time. Suppose, initially, that $\varphi = \varphi_o$ is real. Then the imaginary part of φ satisfies, in the approximation that ε and δ are small,

$$\ddot{\phi}_i + 3H\dot{\phi}_i + m^2\phi_i \approx \mathrm{Im}(\epsilon + \delta)\phi_r^3.$$

For large times, the right hand falls as $t^{-9/2}$, whereas the left hand side falls off only as $t^{-3/2}$. As a result, baryon number violation becomes negligible. The equation goes over to the free equation, with a solution of the form

$$\phi_i = a_r \frac{\mathrm{Im}(\epsilon + \delta)\phi_o^3}{m^2 (mt)^{3/4}} \sin(mt + \delta_r) \ \ \text{(radiation)}, \qquad \phi_i = a_m \frac{\mathrm{Im}(\epsilon + \delta)\phi_o^3}{m^3 t} \sin(mt + \delta_m) \ \ \text{(matter)},$$

The constants can be obtained numerically, and are of order unity

$$a_r = 0.85 \qquad a_m = 0.85 \qquad \delta_r = -0.91 \qquad \delta_m = 1.54.$$

But now we have a non-zero baryon number; substituting in the expression for the current,

$$n_B = 2a_r \mathrm{Im}(\epsilon+\delta)\frac{\phi_o^2}{m(mt)^2}\sin(\delta_r+\pi/8) \quad \text{(radiation)}$$

$$n_B = 2a_m \mathrm{Im}(\epsilon+\delta)\frac{\phi_o^2}{m(mt)^2}\sin(\delta_m) \quad \text{(matter)}.$$

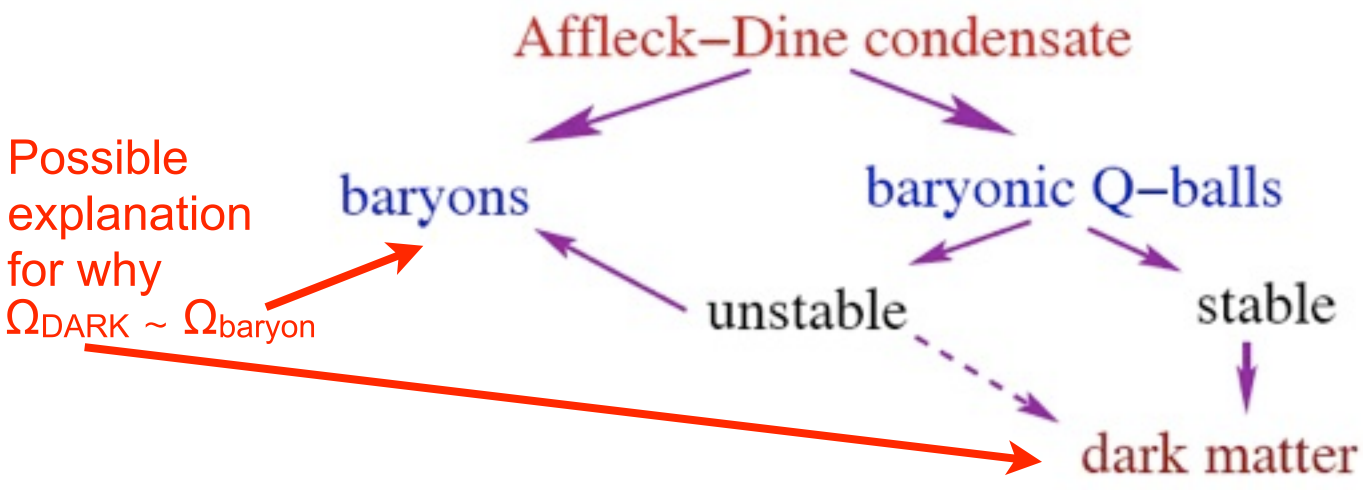
Two features of these results should be noted. First, if ε and δ vanish, n_B vanishes. If they are real, and φ_o is real, n_B vanishes. It is remarkable that the Lagrangian parameters can be real, and yet φ_o can be complex, still giving rise to a net baryon number. Supersymmetry breaking in the early universe can naturally lead to a very large value for a scalar field carrying B or L. Finally, as expected, n_B is conserved at late times.

This mechanism for generating baryon number could be considered without supersymmetry. In that case, several questions arise:

- What are the scalar fields carrying baryon number?
- Why are the φ^4 terms so small?
- How are the scalars in the condensate converted to more familiar particles?

In the context of supersymmetry, there is a natural answer to each of these questions. First, there are scalar fields (squarks and sleptons) carrying baryon and lepton number. Second, in the limit that supersymmetry is unbroken, there are typically directions in the field space in which the quartic terms in the potential vanish. Finally, the scalar quarks and leptons will be able to decay (in a baryon and lepton number conserving fashion) to ordinary quarks.

In addition to topologically stable solutions to the field equations such as strings or monopoles, it is sometimes also possible to find non-topological solutions, called Q-balls, which can form as part of the Affleck-Dine condensate. These are usually unstable and could decay to the dark matter, but in some theories they are stable and could be the dark matter. The various possibilities are summarized as follows:



Possible explanation for why $\Omega_{DARK} \sim \Omega_{baryon}$

The parameter space of the MSSM consistent with LSP dark matter is very different, depending on whether the LSPs froze out of equilibrium or were produced from the evaporation of AD baryonic Q-balls. If supersymmetry is discovered, one will be able to determine the properties of the LSP experimentally. This will, in turn, provide some information on the how the dark-matter SUSY particles could be produced. The discovery of a Higgsino-like LSP would be a evidence in favor of Affleck–Dine baryogenesis. This is a way in which we might be able to establish the origin of matter-antimatter asymmetry.

Review of mechanisms that have been proposed to generate the baryon asymmetry:

1. **GUT Baryogenesis**. Grand Unified Theories unify the gauge interactions of the strong, weak and electromagnetic interactions in a single gauge group. They inevitably violate baryon number, and they have heavy particles, with mass of order $M_{GUT} \approx 10^{16}$ GeV, whose decays can provide a departure from equilibrium. The main objections to this possibility come from issues associated with inflation. While there does not exist a compelling microphysical model for inflation, in most models, the temperature of the universe after reheating is well below M_{GUT}. But even if it were very large, there would be another problem. Successful unification requires supersymmetry, which implies that the graviton has a spin-3/2 partner, called the gravitino. In most models for supersymmetry breaking, these particles have masses of order TeV, and are very long lived. Even though these particles are weakly interacting, too many gravitinos are produced unless the reheating temperature is well below the unification scale -- too low for GUT baryogenesis to occur.

2. **Electroweak baryogenesis**. The Standard Model satisfies all of the conditions for baryogenesis, but any baryon asymmetry produced is far too small to account for observations. In certain extensions of the Standard Model, it is possible to obtain an adequate asymmetry, but in most cases the allowed region of parameter space is very small.

3. **Leptogenesis**. The possibility that the weak interactions will convert some lepton number to baryon number means that if one produces a large lepton number at some stage, this will be processed into a net baryon and lepton number at the electroweak phase transition. The observation of neutrino masses makes this idea highly plausible. Many but not all of the relevant parameters can be directly measured.

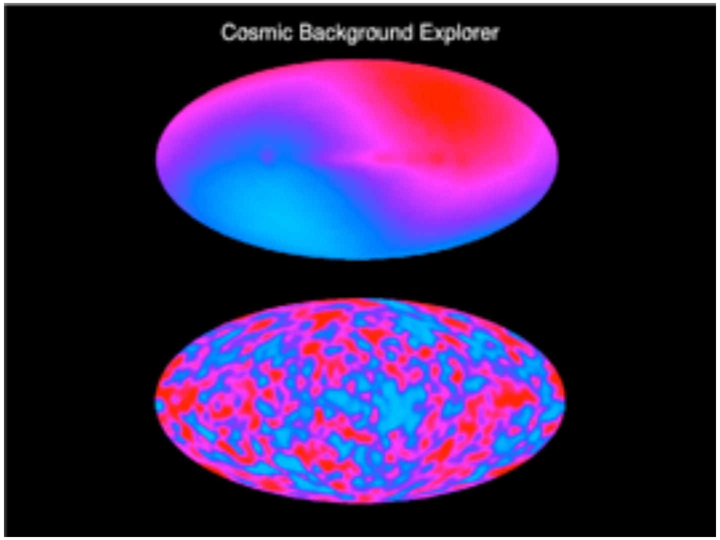
4. **Production by coherent motion of scalar fields (the Affleck-Dine mechanism)**, which can be highly efficient, might well be operative if nature is supersymmetric.

Cosmic Microwave Background

Early History

Although Penzias and Wilson discovered the CMB in 1965, Weinberg (p. 104) points out that Adams and McKellar had shown that the rotational spectra of cyanogen (CN) molecules observed in 1941 suggested that the background temperature is about 3K.

The COBE FIRAS measurements showed that the spectrum is that of thermal radiation with T = 2.73K.

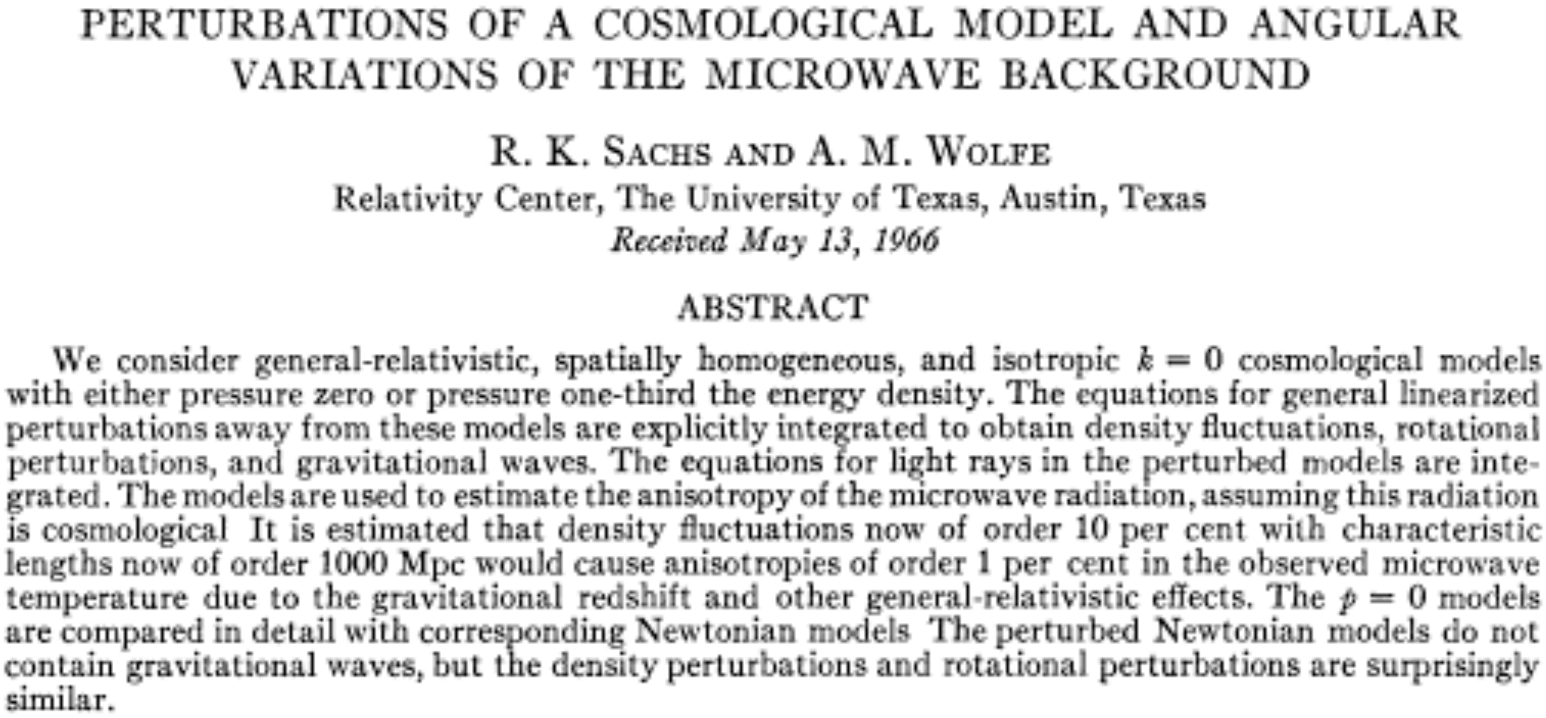


The CMB dipole anisotropy was discovered by Paul Henry (1971) and Edward Conklin (1972), and confirmed by Conklin and Wilkinson (1977) and Smoot, Gorenstein, and Muller (1977) -- see http://www.astro.ucla.edu/~wright/CMB-dipole-history.html

The upper panel of the figure shows the CMB dipole anisotropy in the COBE data. It is usually subtracted when the temperature anisotropy map is displayed (lower panel).

CMB Temperature Anisotropy

Sachs & Wolfe (1967, ApJ, 147, 73) showed that on large angular scales the temperature anisotropy is $\Delta T/T = \varphi/3c^2$. White & Hu give a pedagogical derivation in http://background.uchicago.edu/~whu/Papers/sw.pdf



PERTURBATIONS OF A COSMOLOGICAL MODEL AND ANGULAR VARIATIONS OF THE MICROWAVE BACKGROUND

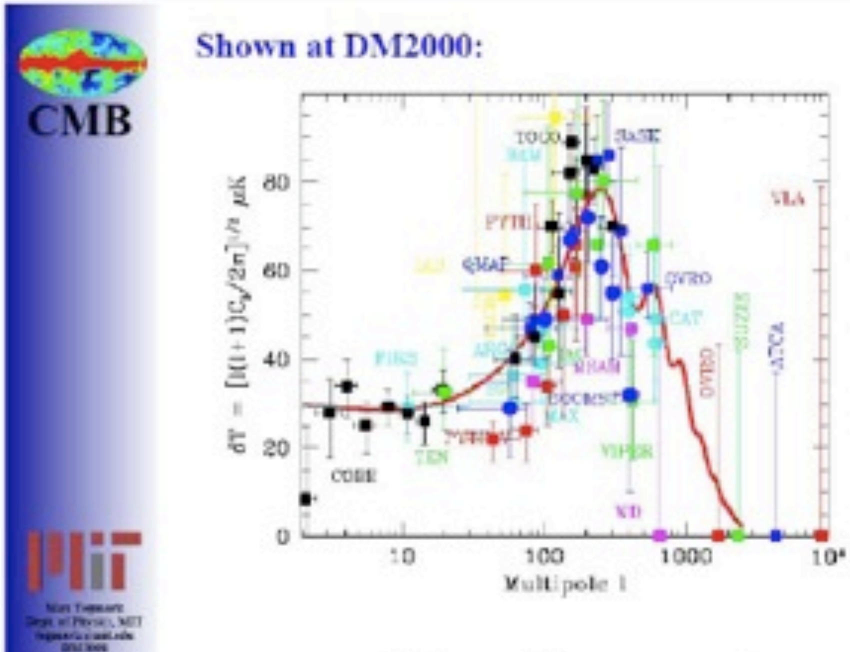
R. K. SACHS AND A. M. WOLFE
Relativity Center, The University of Texas, Austin, Texas

Received May 13, 1966

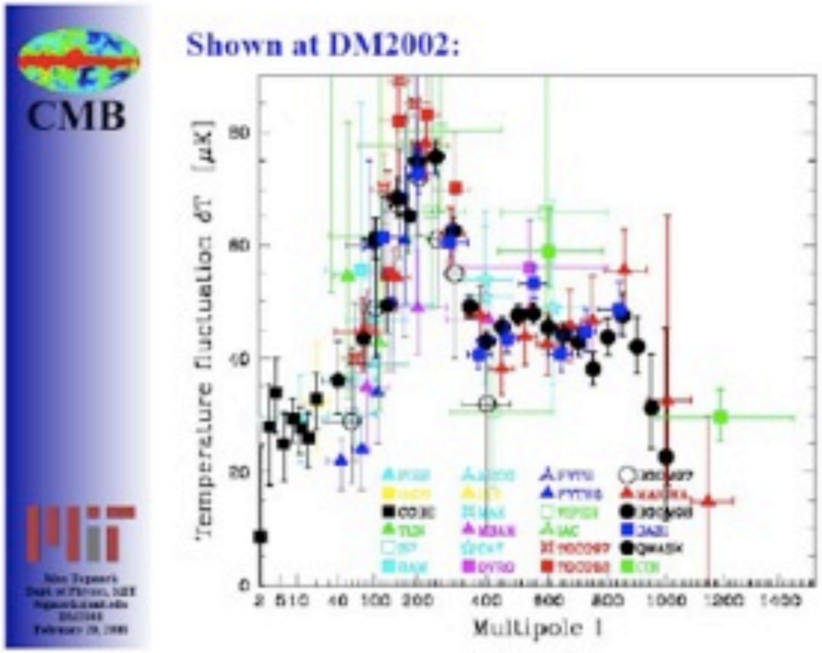
ABSTRACT

We consider general-relativistic, spatially homogeneous, and isotropic $k = 0$ cosmological models with either pressure zero or pressure one-third the energy density. The equations for general linearized perturbations away from these models are explicitly integrated to obtain density fluctuations, rotational perturbations, and gravitational waves. The equations for light rays in the perturbed models are integrated. The models are used to estimate the anisotropy of the microwave radiation, assuming this radiation is cosmological It is estimated that density fluctuations now of order 10 per cent with characteristic lengths now of order 1000 Mpc would cause anisotropies of order 1 per cent in the observed microwave temperature due to the gravitational redshift and other general-relativistic effects. The $p = 0$ models are compared in detail with corresponding Newtonian models The perturbed Newtonian models do not contain gravitational waves, but the density perturbations and rotational perturbations are surprisingly similar.

This was first convincingly seen by the COBE DMR experiment, reported by George Smoot on April 27, 1992. Their result $\Delta T/T = 10^{-5}$ had been predicted by the CDM model (Blumenthal, Faber, Primack, & Rees 1984). The search then began for smaller-angular-scale CMB anisotropies.

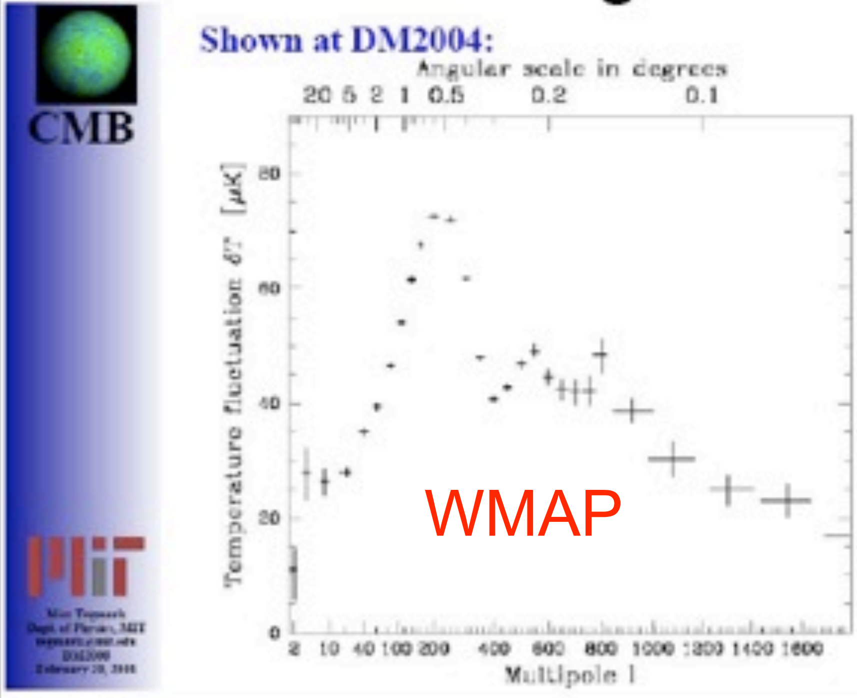


Shown at DM2000:



Shown at DM2002:

Max Tegmark



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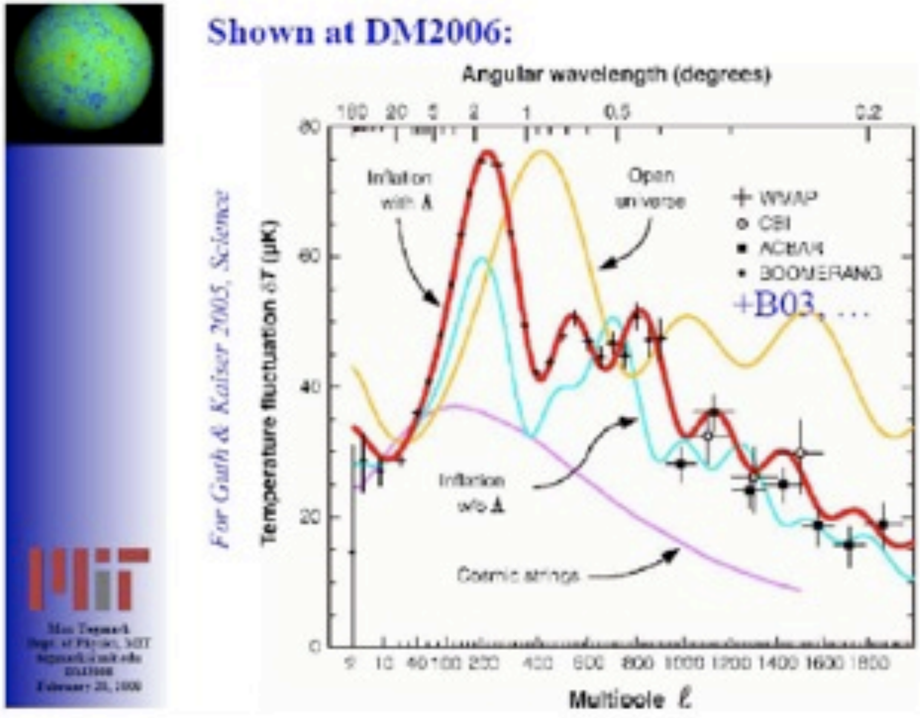
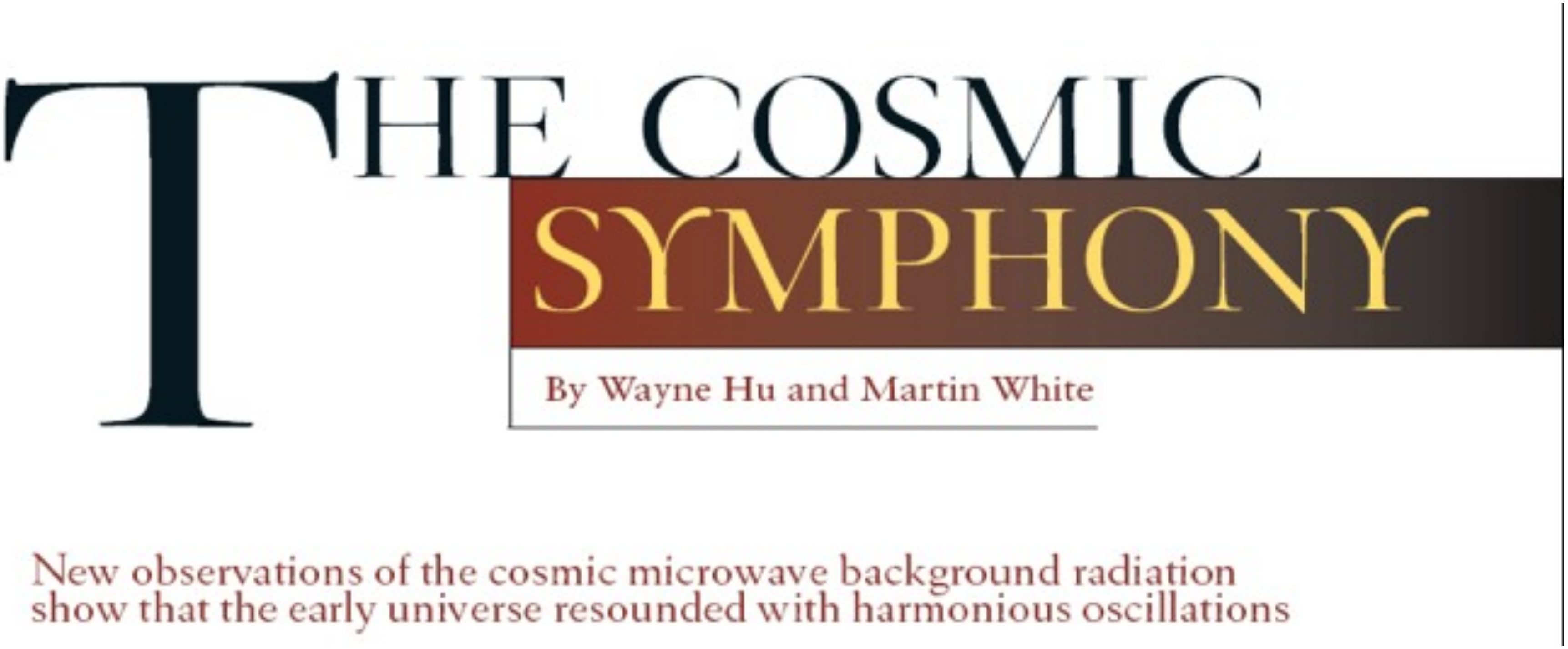


Shown at DM2006:



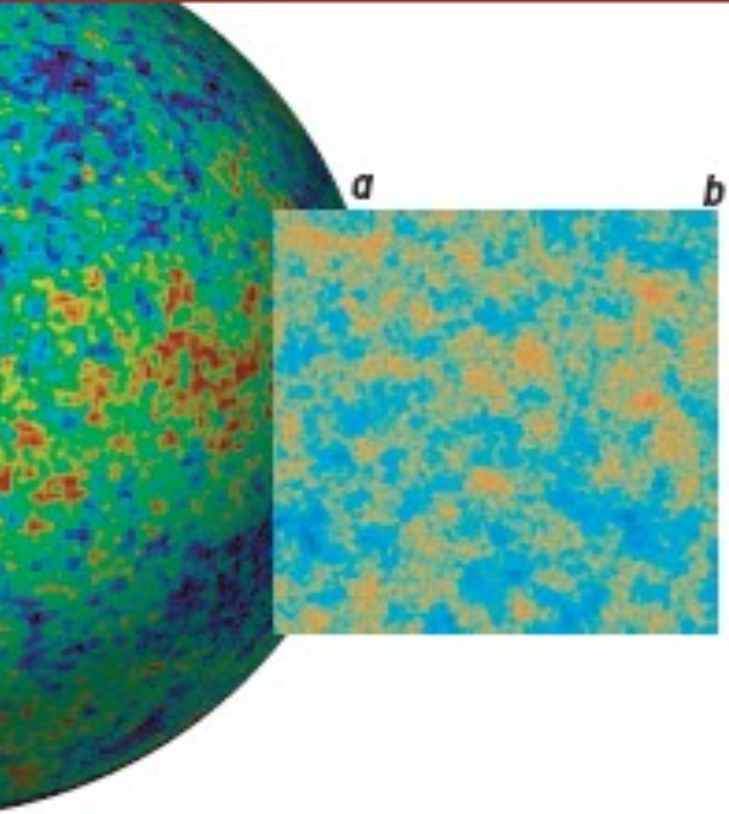
THE COSMIC SYMPHONY

By Wayne Hu and Martin White

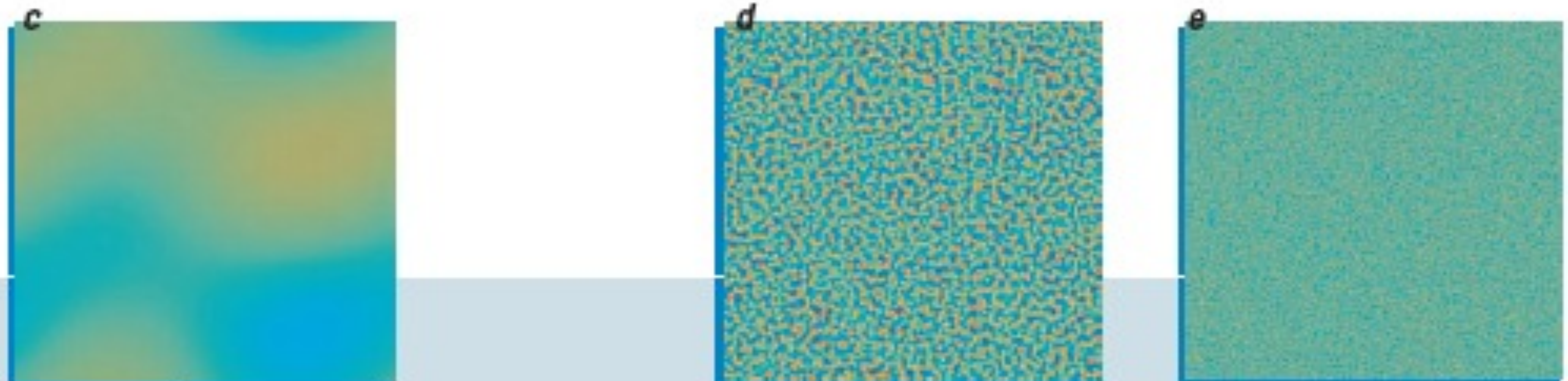
New observations of the cosmic microwave background radiation show that the early universe resounded with harmonious oscillations

Scientific American February 2004

THE POWER SPECTRUM



OBSERVATIONS OF THE CMB provide a map of temperature variations across the whole sky (*a*). When researchers analyze portions of that map (*b*), they use band filters to show how the temperature of the radiation varies at different scales. The variations are barely noticeable at large scales corresponding to regions that stretch about 30 degrees across the sky (*c*) and at small scales corresponding to regions about a tenth of a degree across (*e*). But the temperature differences are quite distinct for regions about one degree across (*d*). This first peak in the power spectrum (*graph at bottom*) reveals the compressions and rarefactions caused by the fundamental wave of the early universe; the subsequent peaks show the effects of the overtones.

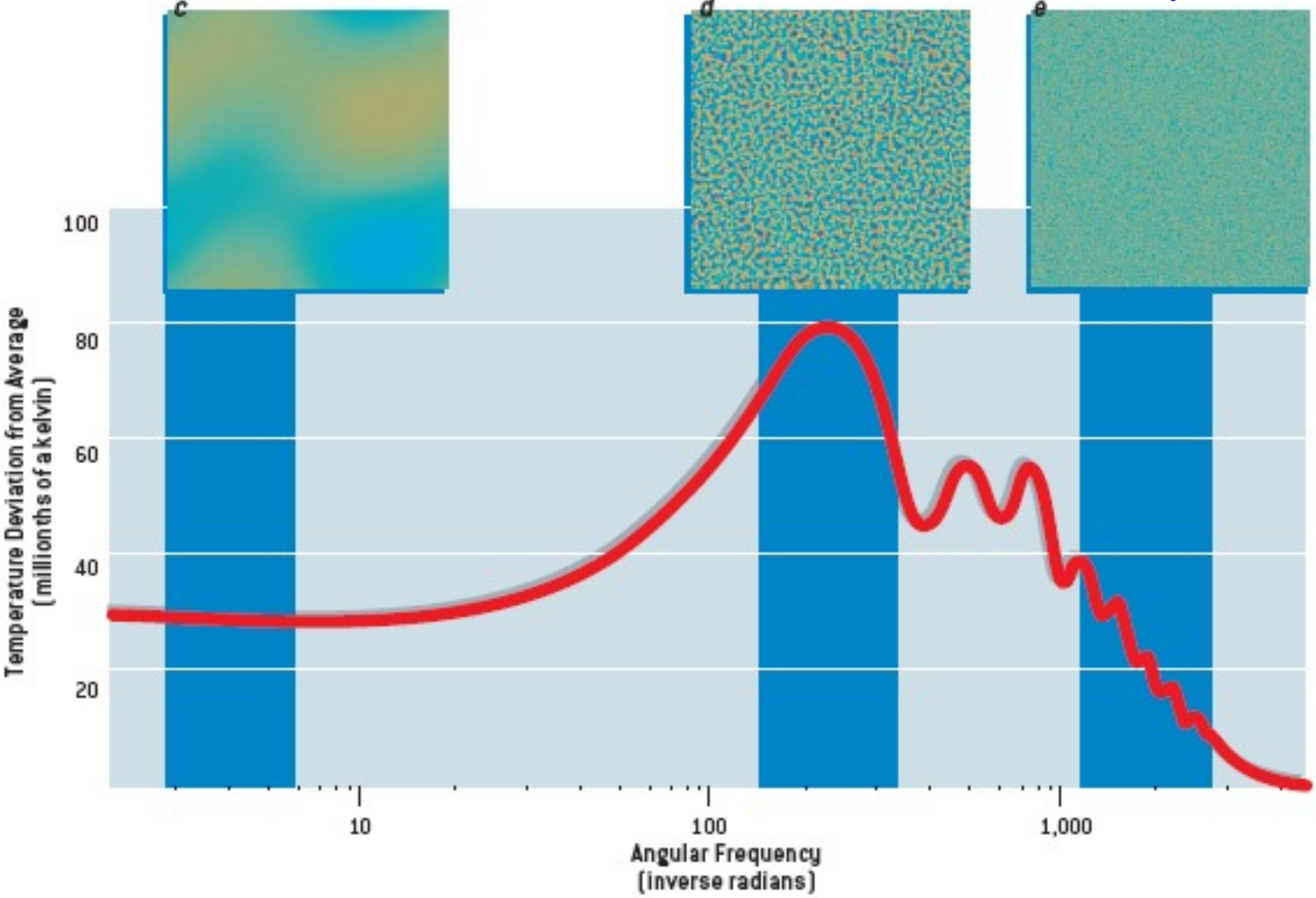


Angular Thermal Variations

30° barely visible

1° prominent

0.1° barely visible

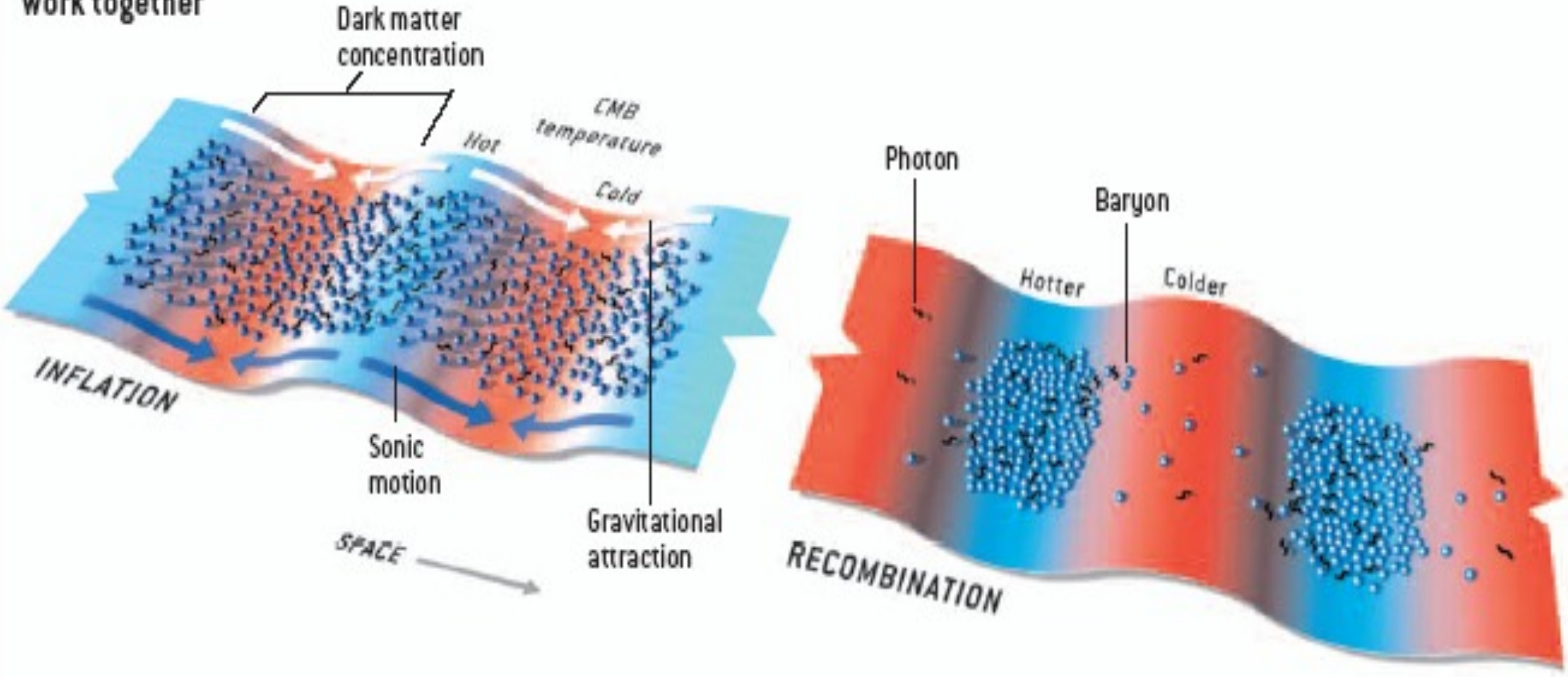


GRAVITATIONAL MODULATION

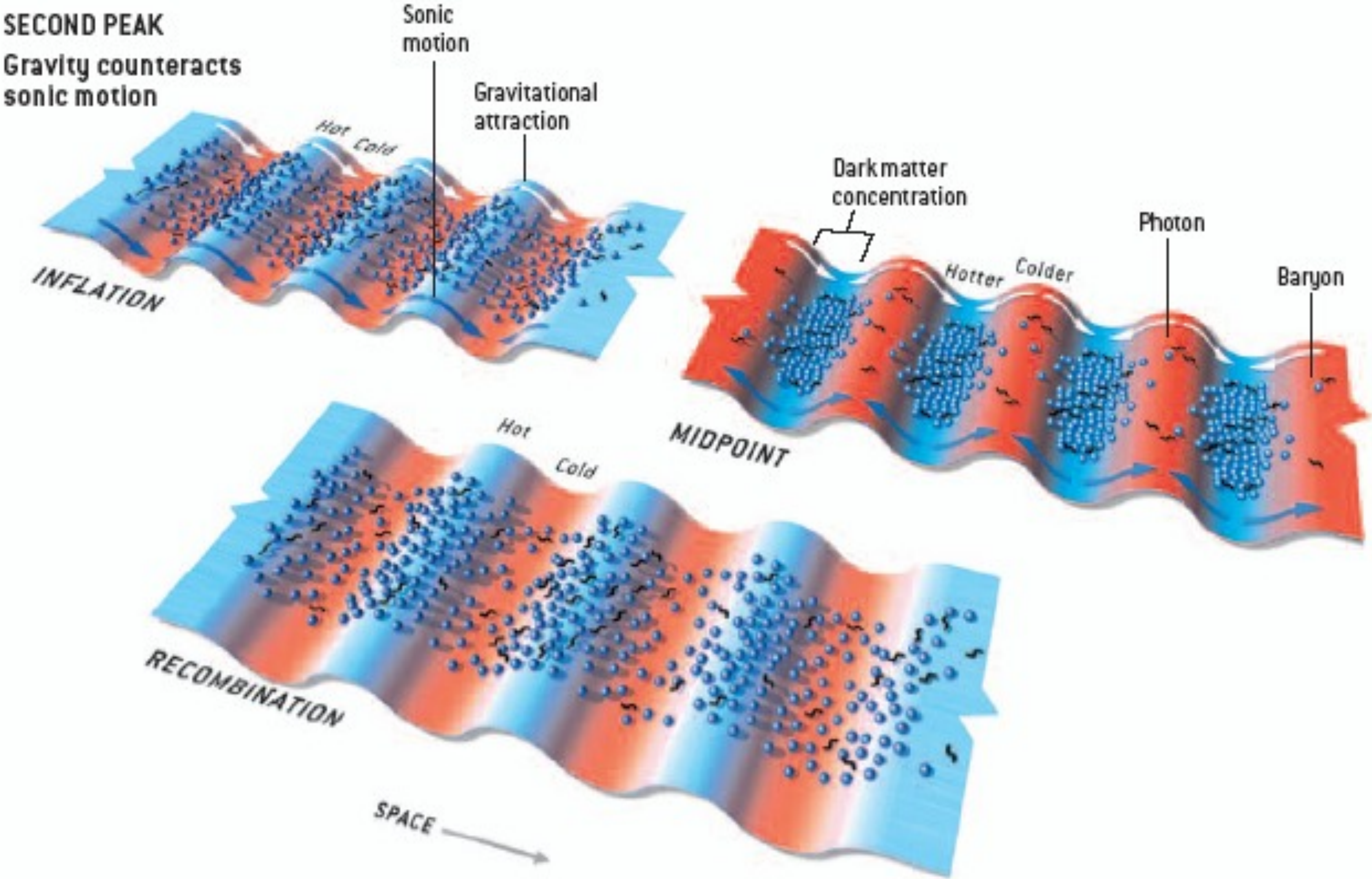
INFLUENCE OF DARK MATTER modulates the acoustic signals in the CMB. After inflation, denser regions of dark matter that have the same scale as the fundamental wave (*represented as troughs in this potential-energy diagram*) pull in baryons and photons by gravitational attraction. (The troughs are shown in red because gravity also reduces the temperature of any escaping photons.) By the time of recombination, about 380,000 years later, gravity and sonic motion have worked together to raise the radiation temperature in the troughs (*blue*) and lower the temperature at the peaks (*red*).

FIRST PEAK

Gravity and sonic motion work together



AT SMALLER SCALES, gravity and acoustic pressure sometimes end up at odds. Dark matter clumps corresponding to a second-peak wave maximize radiation temperature in the troughs long before recombination. After this midpoint, gas pressure pushes baryons and photons out of the troughs (*blue arrows*) while gravity tries to pull them back in (*white arrows*). This tug-of-war decreases the temperature differences, which explains why the second peak in the power spectrum is lower than the first.

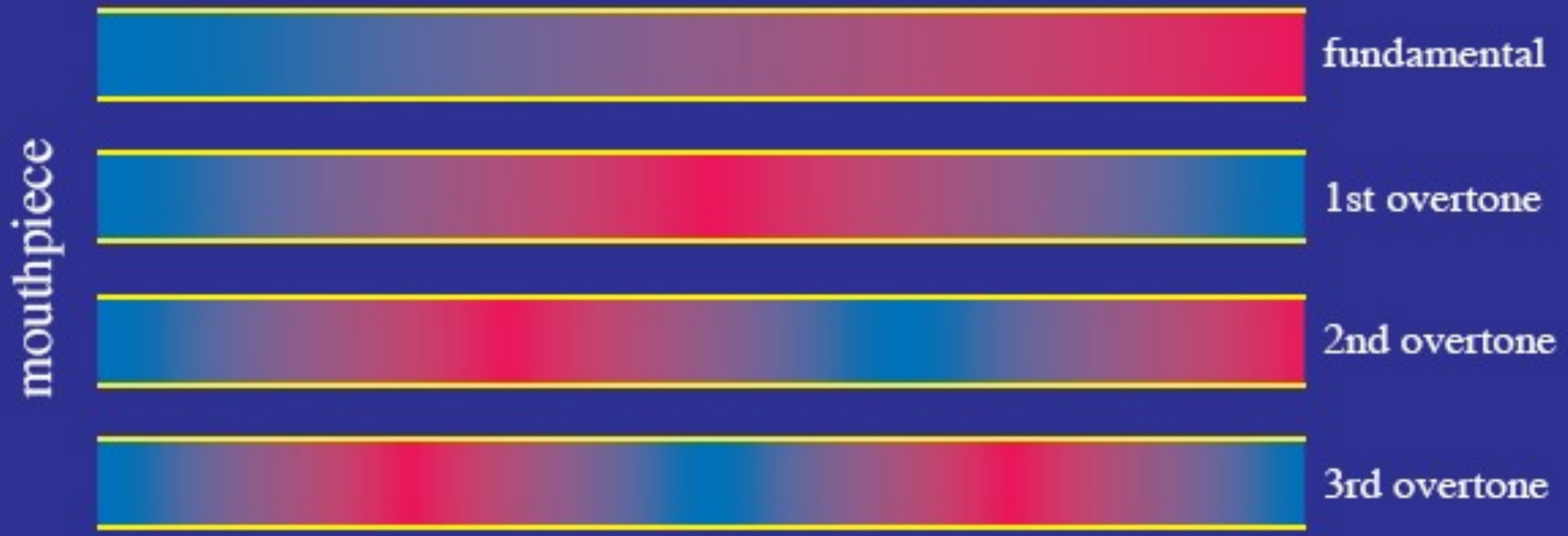


SECOND PEAK

Gravity counteracts sonic motion

Piper at the Gates of Dawn

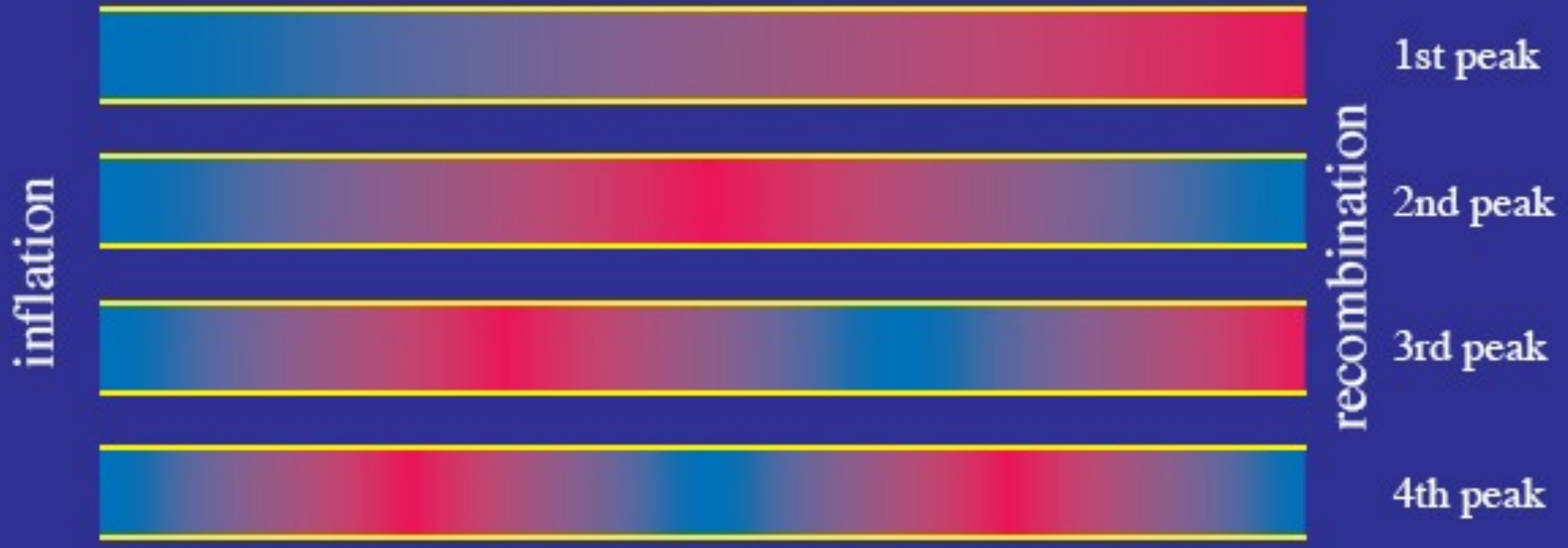
- Blow into a flute or an open pipe
- Spectrum of sound contains a fundamental frequency and harmonic overtones



This and the next several slides are from a talk by Wayne Hu; see http://background.uchicago.edu/~whu/beginners/introduction.html

Piper at the Gates of Dawn

- **Inflation** is the source of sound waves at the **beginning of time**
- Sound waves are frozen at **recombination**, yielding a **harmonic spectrum** of frequencies that reach **maximum displacement**



See also Annual Rev. Astron. and Astrophys. 2002

Cosmic Microwave Background Anisotropies

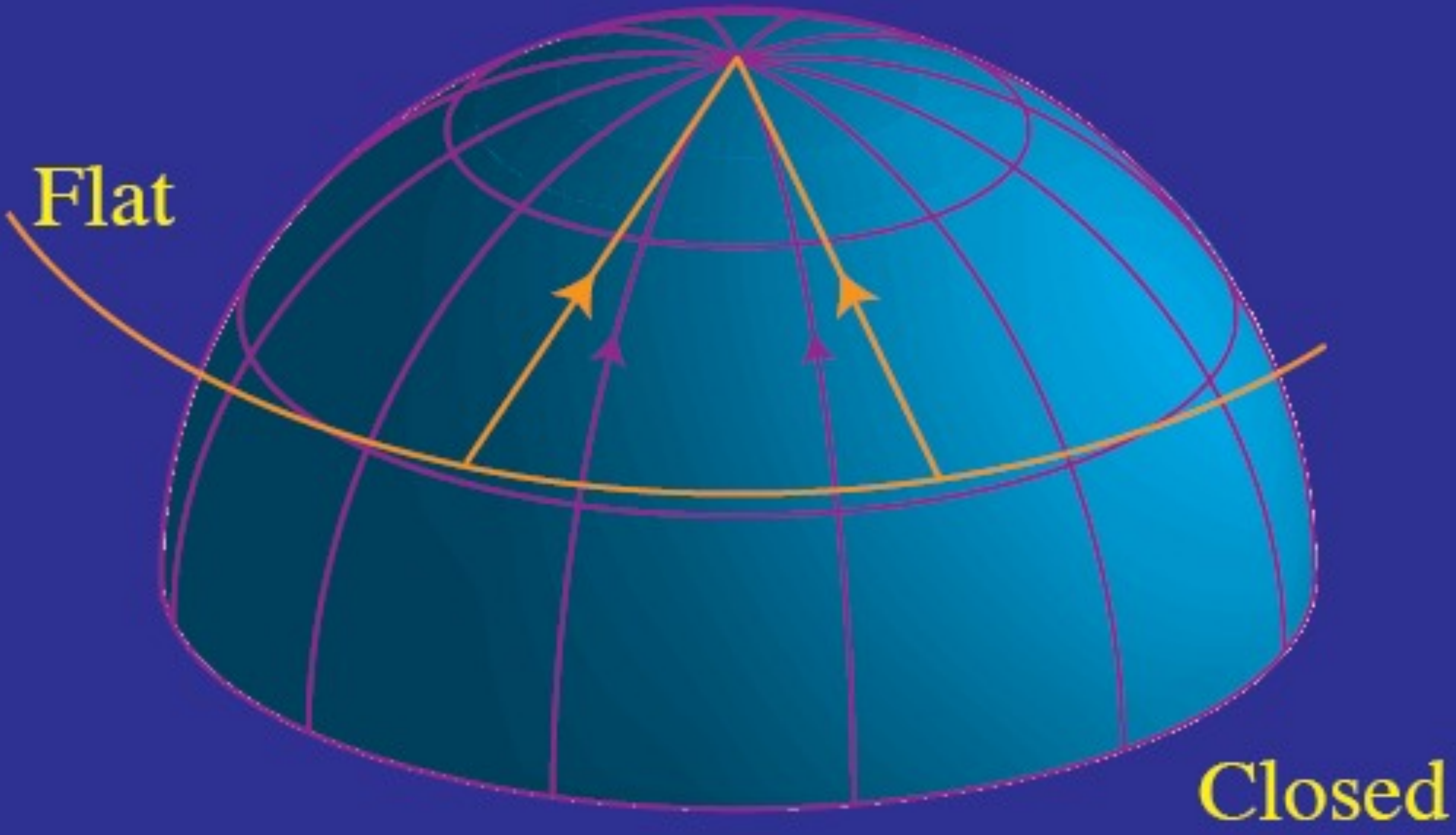
by Wayne Hu and Scott Dodelson

Harmonic Signature

- Much like a musical instrument, identify construction through the pattern of overtones on the fundamental frequency
- Without inflation, fluctuations must be generated at intermediate times
- Like drilling holes in the pipe and blowing in random places, harmonic structure of peaks destroyed
- Observed frequency spectrum consistent with inflationary origin
- Detailed examination of the overtones, reveals the composition of the universe
- But first...

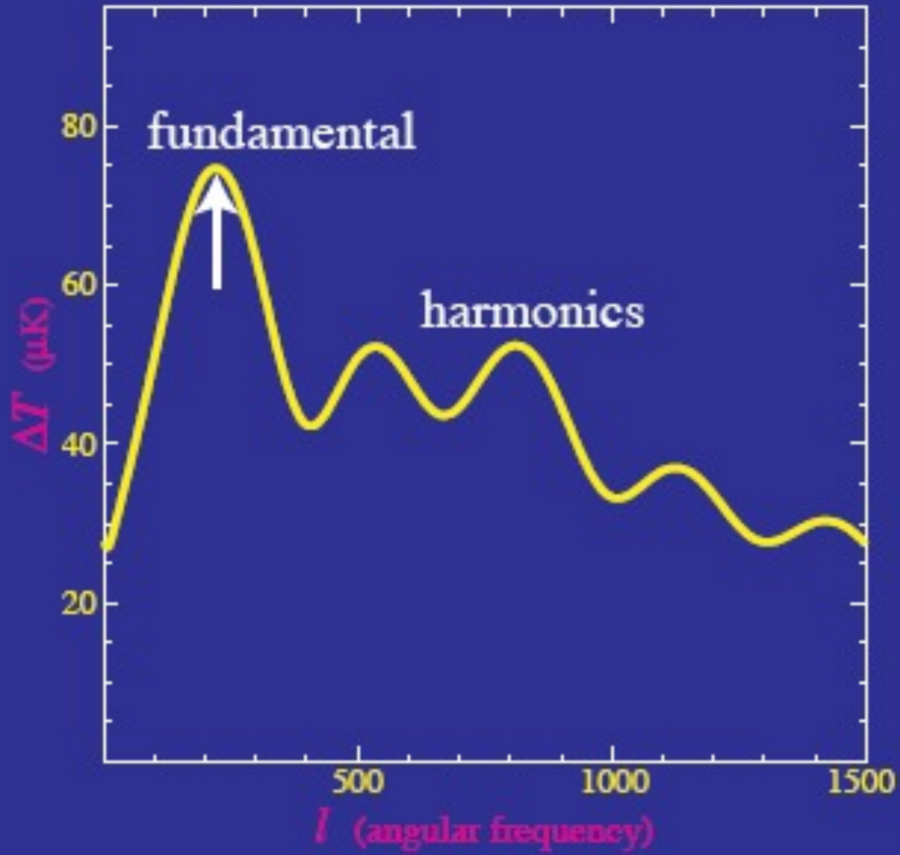
Fundamental: Weighing the Universe

- Measuring the angular extent of the fundamental wavelength (spot size) yields the curvature - universe is spatially flat
- Einstein says matter-energy density curves space: universe is at the critical density



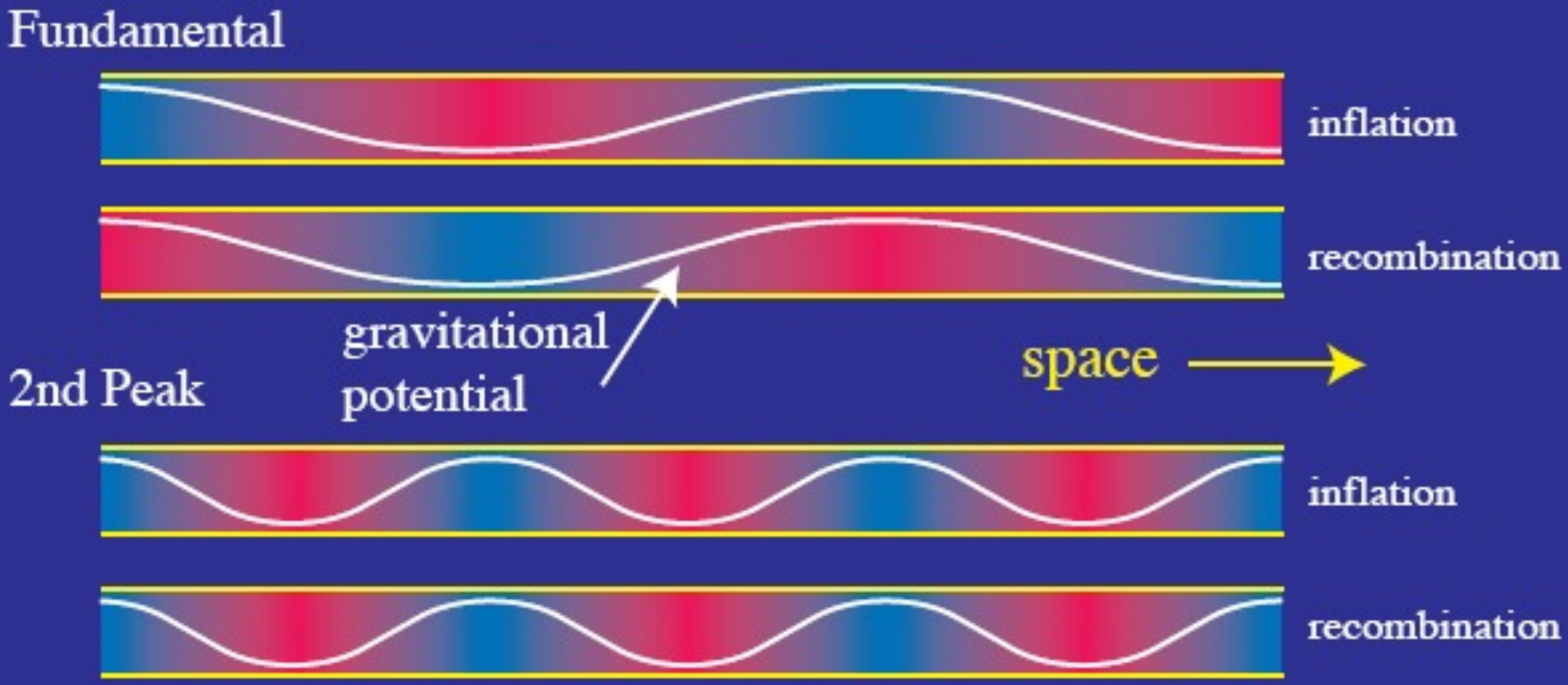
Sound Spectrum

- Spectrum of sound shows harmonics at integer ratios of the fundamental
- Other models that generate structure causally at intermediate times would not have these harmonics



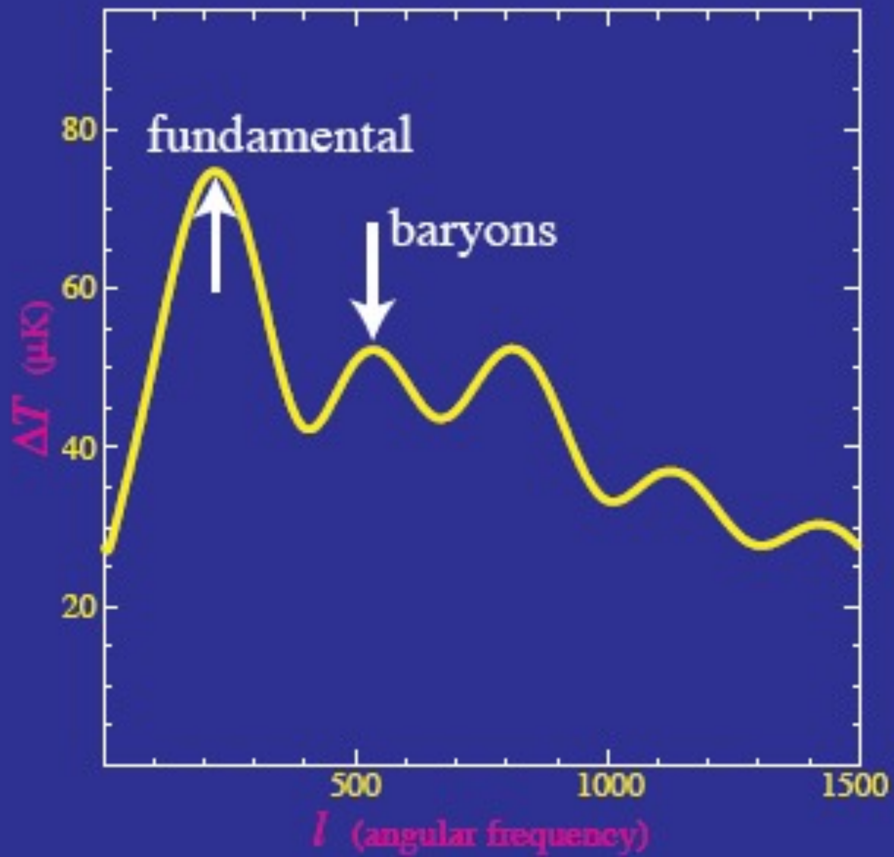
Harmonics: Ordinary Matter

- Competition between gravity and pressure depends on phase of oscillation
- At the fundamental (and odd frequency multiples) gravity assists sonic motion; at second peak (and even multiples) gravity fights sonic motion



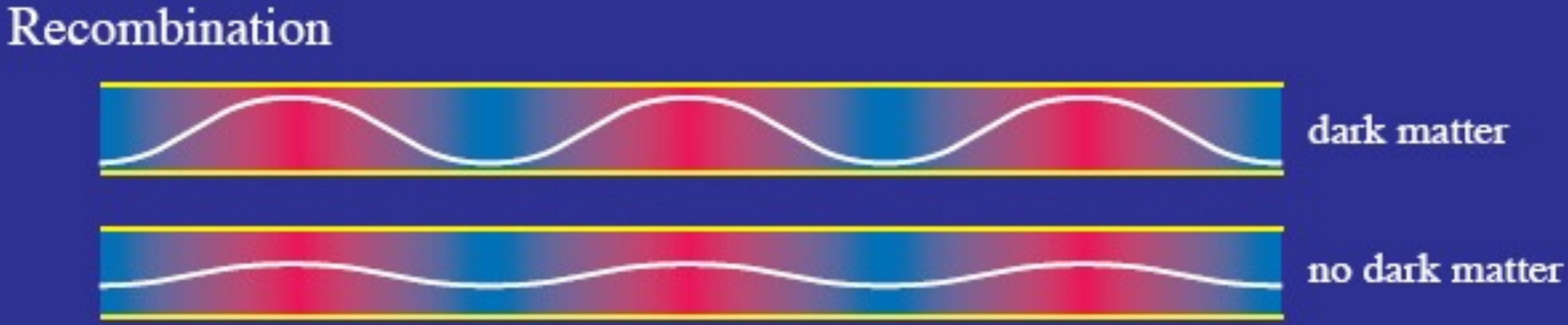
Ordinary Matter

- A low second peak indicates baryon or ordinary matter density comparable to photon density
- Ordinary matter consists of ~5% of the critical density today



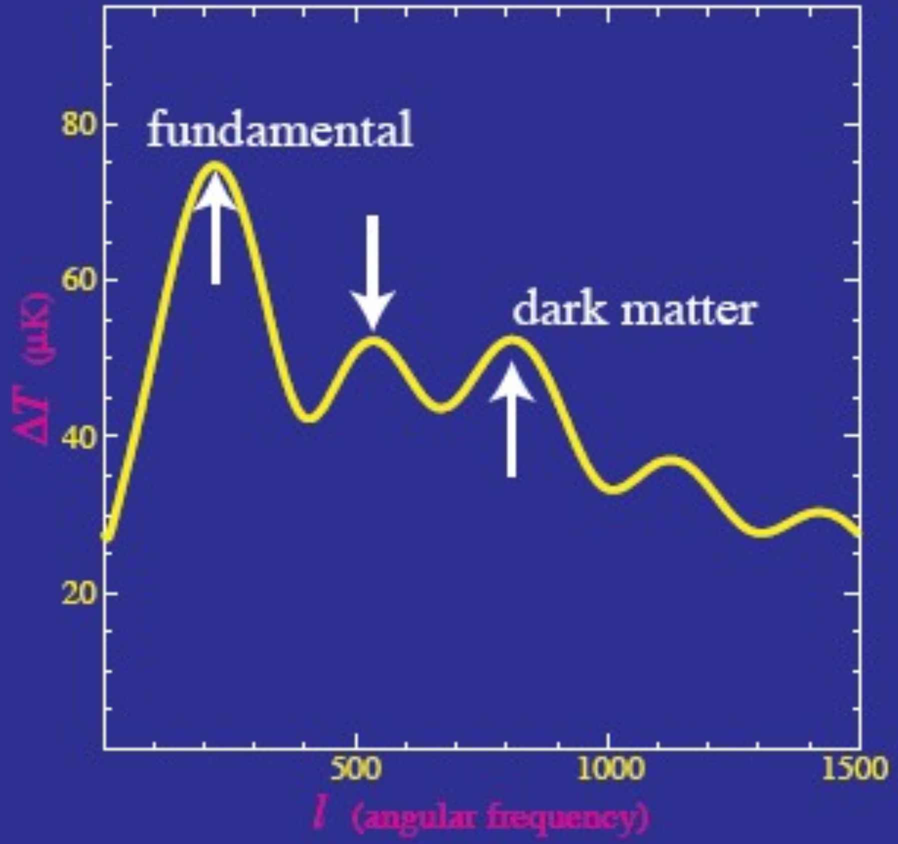
Harmonics: Dark Matter

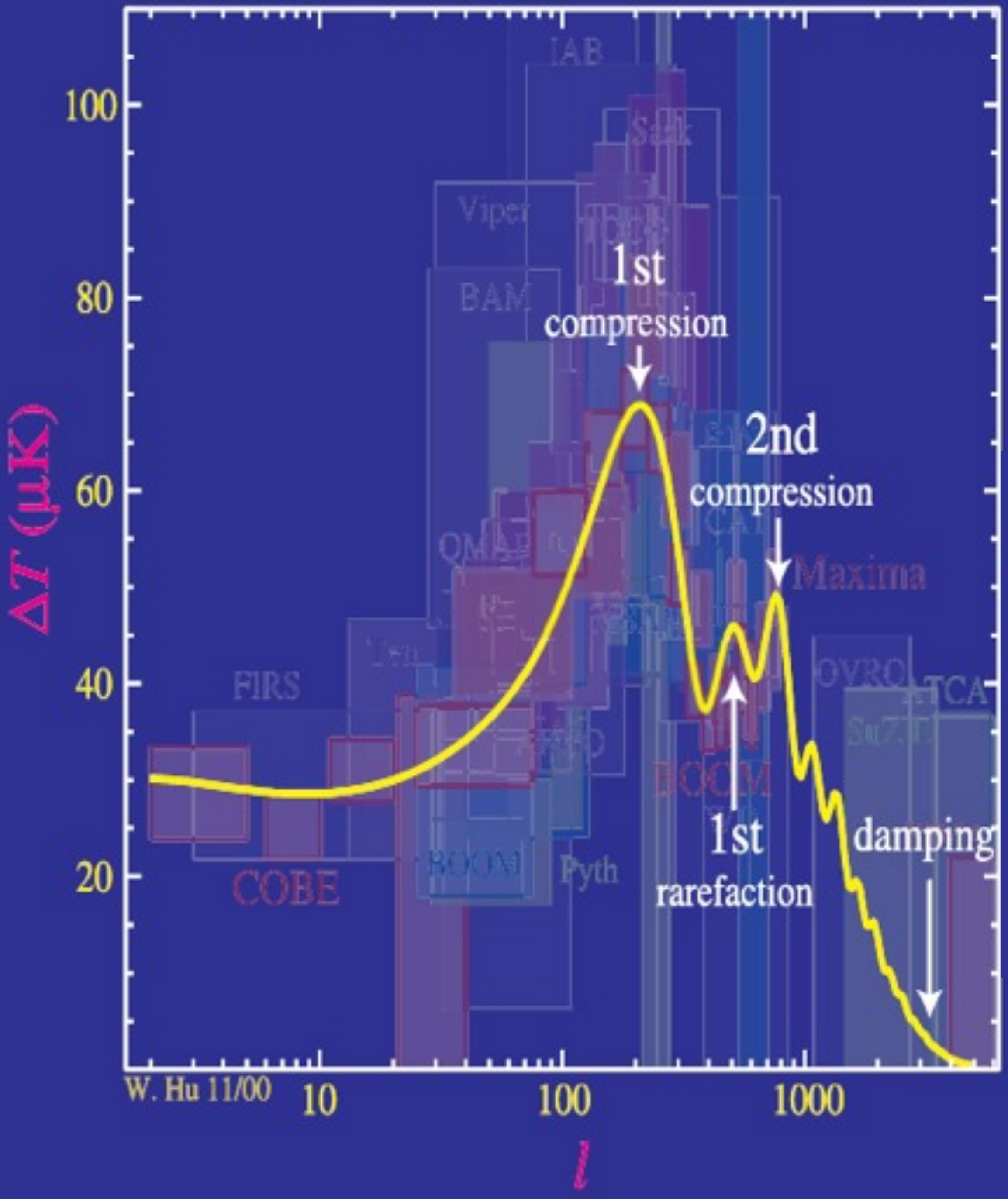
- What maintains the gravitational potential if the ordinary matter oscillates as a stable sound wave?
- Without matter that does not interact with photons/light or dark matter, gravitational potentials decay once ordinary matter enters into oscillation
- Gravitational enhancement destroyed soon after 1st peak



Dark Matter

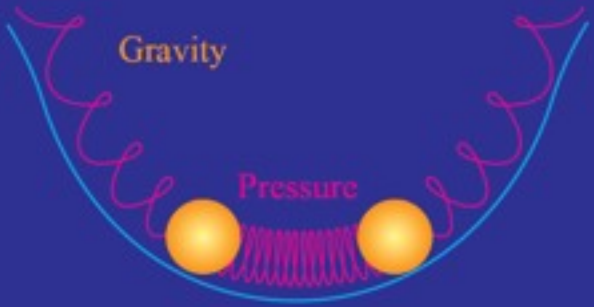
- A third peak comparable to second peak indicates a dark matter density ~5x that of ordinary matter
- Dark matter ~25% of the critical density





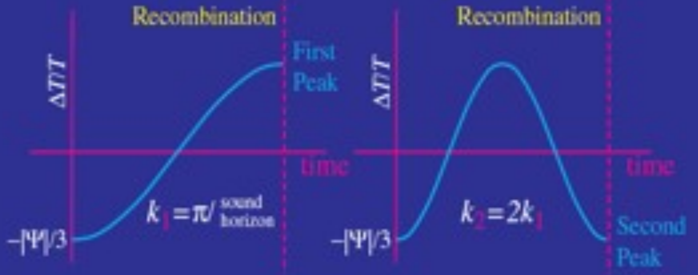
Gravitational Ringing

- Potential wells = inflationary seeds of structure
- Fluid falls into wells, pressure resists: acoustic oscillations



Extrema=Peaks

- First peak = mode that just compresses
- Second peak = mode that compresses then rarefies: twice the wavenumber
- Harmonic peaks: 1:2:3 in wavenumber

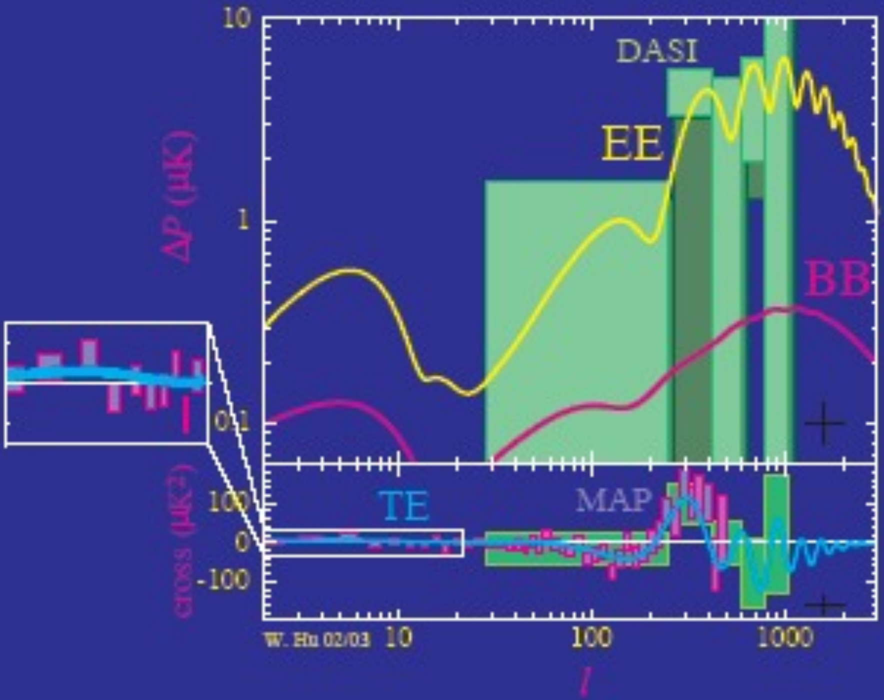


From Wayne Hu's Warner Prize Lecture, AAS meeting Jan 2001

http://background.uchicago.edu/~whu/Presentations/warnerprint.pdf

Predictive Power

- Model predicts the precise form of the damping of sound waves: observed ✔
- Model predicts that associated with the damping, the CMB becomes polarized: observed ✔
- Model predicts that temperature fluctuations correlated with local structure due to the dark energy: observed ✔



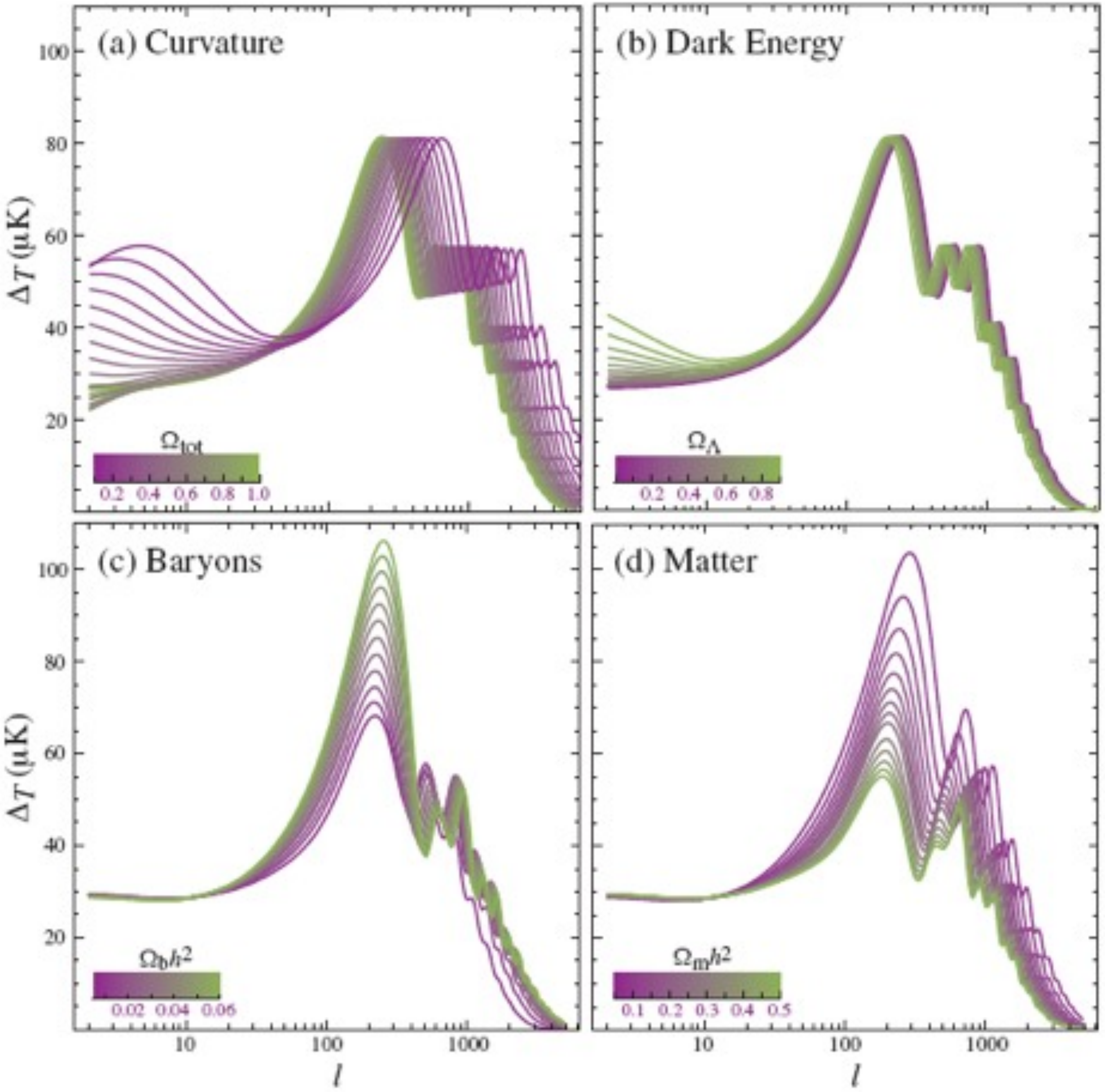


Plate 4: Sensitivity of the acoustic temperature spectrum to four fundamental cosmological parameters (a) the curvature as quantified by Ω_{tot} (b) the dark energy as quantified by the cosmological constant Ω_Λ ($w_\Lambda = -1$) (c) the physical baryon density $\Omega_b h^2$ (d) the physical matter density $\Omega_m h^2$, all varied around a fiducial model of $\Omega_{tot} = 1$, $\Omega_\Lambda = 0.65$, $\Omega_b h^2 = 0.02$, $\Omega_m h^2 = 0.147$, $n = 1$, $z_{ri} = 0$, $E_i = 0$.

Annu. Rev. Astron. and Astrophys. 2002
Cosmic Microwave Background Anisotropies by **Wayne Hu** and **Scott Dodelson**

For animation of the effects of changes in cosmological parameters on the CMB angular power spectrum and the matter power spectrum, plus links to many CMB websites, see Max Tegmark's and Wayne Hu's websites:

http://space.mit.edu/home/tegmark/

http://background.uchicago.edu/~whu/physics/physics.html

WMAP 5-year data and papers are at http://lambda.gsfc.nasa.gov/

G. Hinshaw et al. ApJS, 180, 225 (2009)

Five-Year Wilkinson Microwave Anisotropy Probe (WMAP[1]) Observations: Data Processing, Sky Maps, & Basic Results

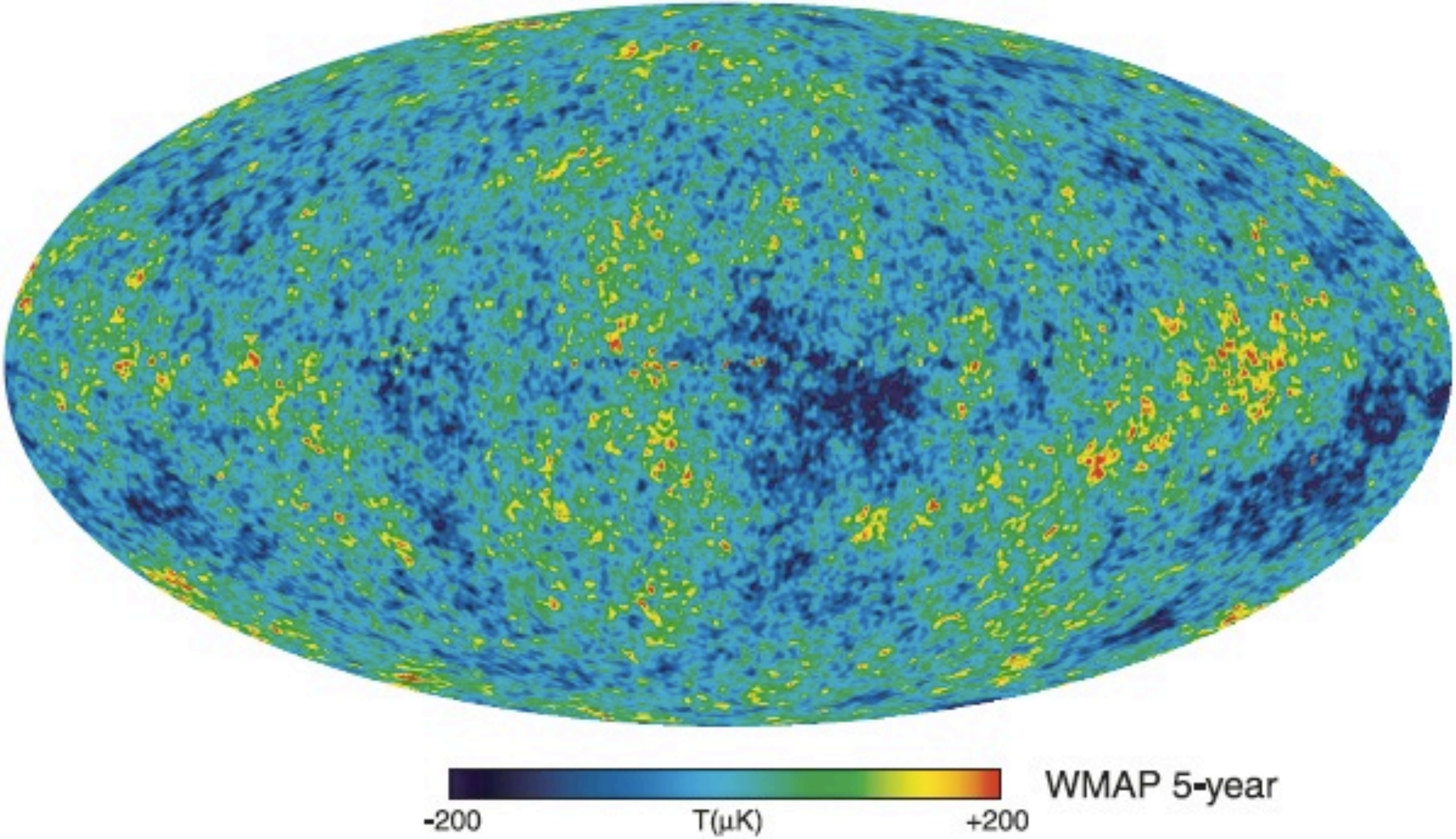


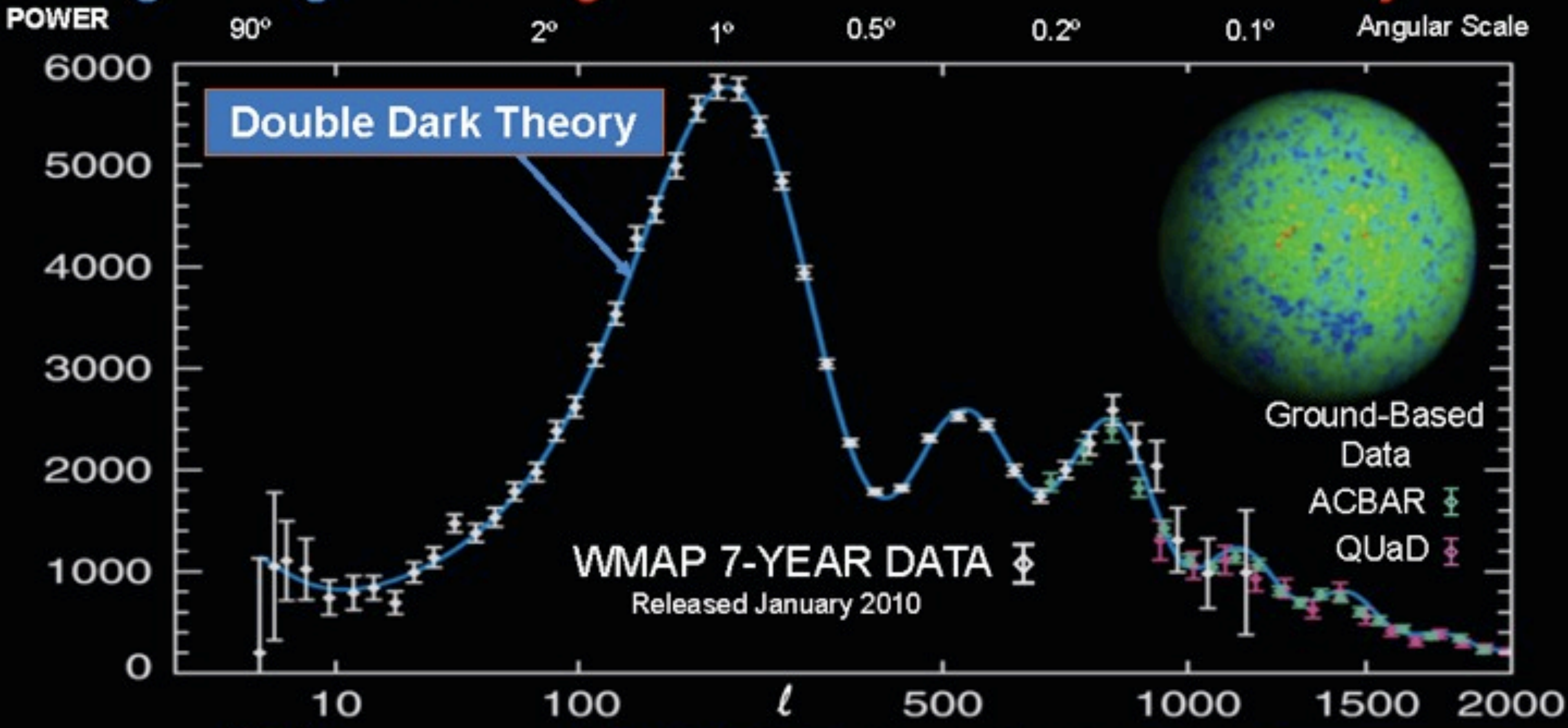
Fig. 12. The foreground-reduced Internal Linear Combination (ILC) map.

J. Dunkley, et.al. Five-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Likelihoods and Parameters from WMAP Data

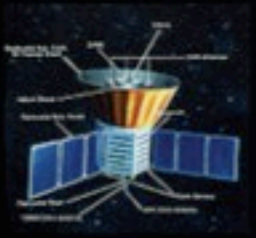
Final paragraph of Conclusions:

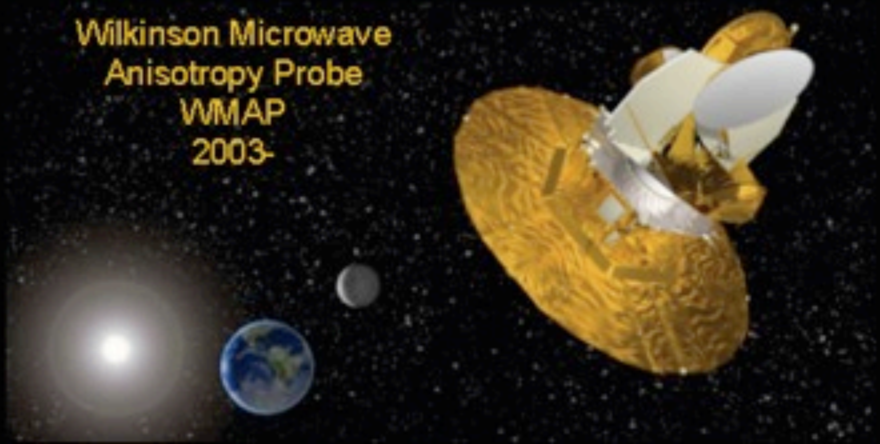
Considering a range of extended models, we continue to find that **the standard ΛCDM model is consistently preferred by the data**. The improved measurement of the third peak now requires the existence of light relativistic species, assumed to be neutrinos, at high confidence. The standard scenario has three neutrino species, but the three-year WMAP data could not rule out models with none. **The CDM model also continues to succeed in fitting a substantial array of other observations.** Certain tensions between other observations and those of WMAP, such as the amplitude of matter fluctuations measured by weak lensing surveys and using the Ly-α forest, and the primordial lithium abundance, have either been resolved with improved understanding of systematics, or show promise of being explained by recent observations. With further WMAP observations we will better probe both the universe at a range of epochs, measuring fluctuation characteristics to probe the initial inflationary process, or other non-inflationary scenario, improving measurements of the composition of the universe at the recombination era, and characterizing the reionization process in the universe.

Big Bang Data Agrees with Double Dark Theory!



Cosmic
Background
Explorer
COBE
1992



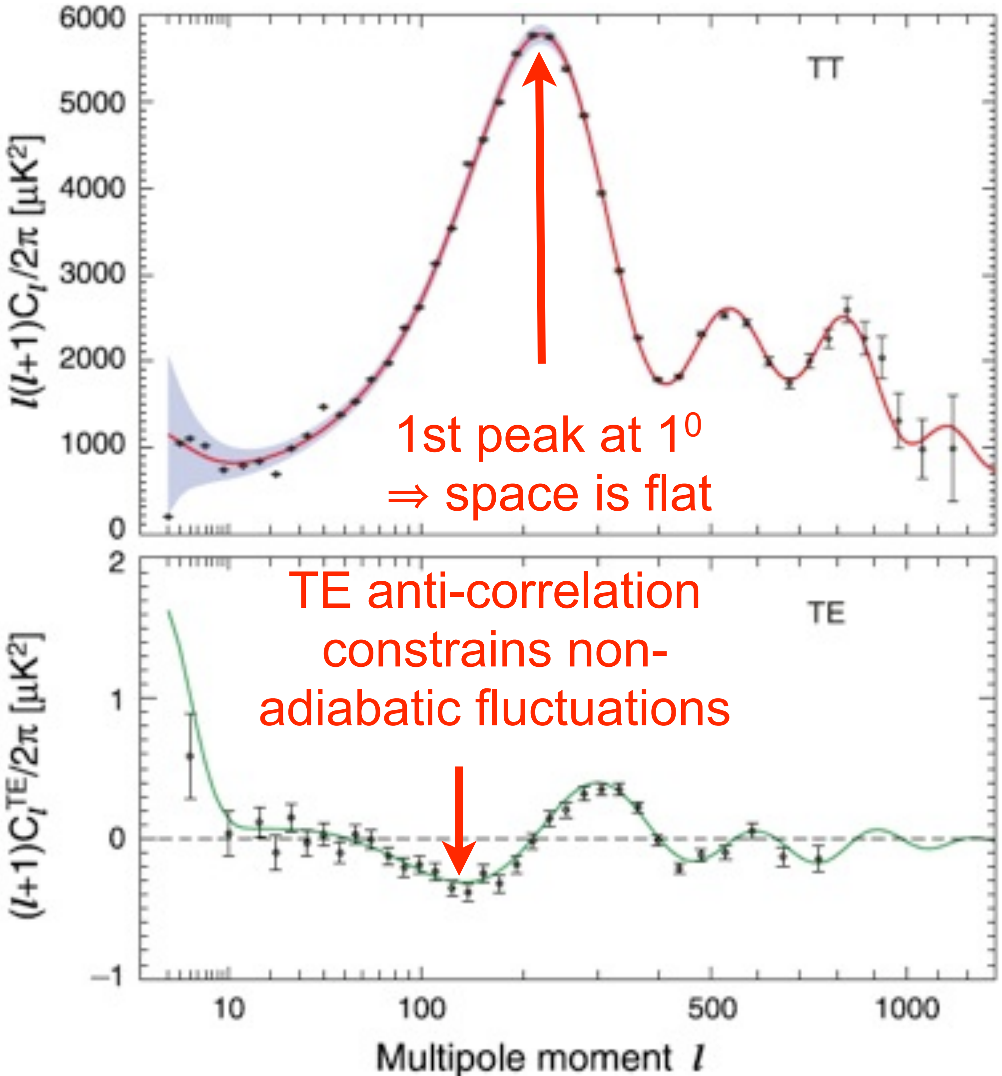


Wilkinson Microwave
Anisotropy Probe
WMAP
2003-

LEGACY ARCHIVE FOR MICROWAVE BACKGROUND DATA ANALYSIS

http://lambda.gsfc.nasa.gov/product/space/

Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations:
Sky Maps, Systematic Errors, and Basic Results - N. Jarosik et al. - January 2010



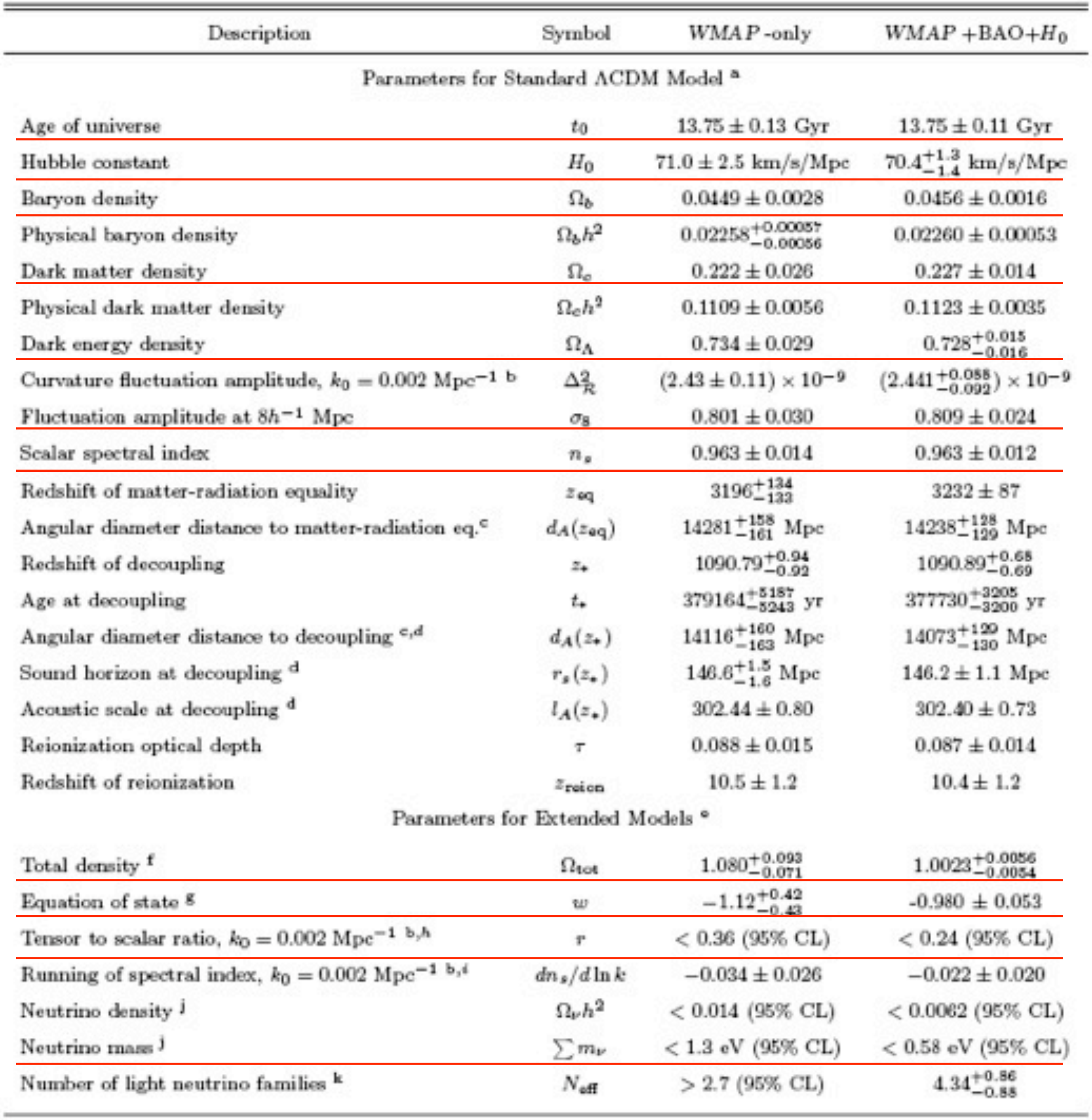
1st peak at 1^0
⇒ space is flat

TE anti-correlation constrains non-adiabatic fluctuations

Fig. 9.— The temperature (TT) and temperature-polarization (TE) power spectra for the seven-year WMAP data set. The solid lines show the predicted spectrum for the best-fit flat ΛCDM model. The error bars on the data points represent measurement errors while the shaded region indicates the uncertainty in the model spectrum arising from cosmic variance.

N. Jarosik et al. - January 2010

Table 8. WMAP Seven-year Cosmological Parameter Summary



Description	Symbol	*WMAP*-only	*WMAP*+BAO+H_0
Parameters for Standard ΛCDM Model [a]			
Age of universe	t_0	13.75 ± 0.13 Gyr	13.75 ± 0.11 Gyr
Hubble constant	H_0	71.0 ± 2.5 km/s/Mpc	$70.4^{+1.3}_{-1.4}$ km/s/Mpc
Baryon density	Ω_b	0.0449 ± 0.0028	0.0456 ± 0.0016
Physical baryon density	$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$	0.02260 ± 0.00053
Dark matter density	Ω_c	0.222 ± 0.026	0.227 ± 0.014
Physical dark matter density	$\Omega_c h^2$	0.1109 ± 0.0056	0.1123 ± 0.0035
Dark energy density	Ω_Λ	0.734 ± 0.029	$0.728^{+0.015}_{-0.016}$
Curvature fluctuation amplitude, $k_0 = 0.002$ Mpc^{-1} [b]	$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.441^{+0.088}_{-0.092}) \times 10^{-9}$
Fluctuation amplitude at $8h^{-1}$ Mpc	σ_8	0.801 ± 0.030	0.809 ± 0.024
Scalar spectral index	n_s	0.963 ± 0.014	0.963 ± 0.012
Redshift of matter-radiation equality	z_{eq}	3196^{+134}_{-133}	3232 ± 87
Angular diameter distance to matter-radiation eq.[c]	$d_A(z_{eq})$	14281^{+158}_{-161} Mpc	14238^{+128}_{-129} Mpc
Redshift of decoupling	z_*	$1090.79^{+0.94}_{-0.92}$	$1090.89^{+0.68}_{-0.69}$
Age at decoupling	t_*	379164^{+5187}_{-5243} yr	377730^{+3205}_{-3200} yr
Angular diameter distance to decoupling [c,d]	$d_A(z_*)$	14116^{+160}_{-163} Mpc	14073^{+129}_{-130} Mpc
Sound horizon at decoupling [d]	$r_s(z_*)$	$146.6^{+1.5}_{-1.6}$ Mpc	146.2 ± 1.1 Mpc
Acoustic scale at decoupling [d]	$l_A(z_*)$	302.44 ± 0.80	302.40 ± 0.73
Reionization optical depth	τ	0.088 ± 0.015	0.087 ± 0.014
Redshift of reionization	z_{reion}	10.5 ± 1.2	10.4 ± 1.2
Parameters for Extended Models [e]			
Total density [f]	Ω_{tot}	$1.080^{+0.093}_{-0.071}$	$1.0023^{+0.0056}_{-0.0054}$
Equation of state [g]	w	$-1.12^{+0.42}_{-0.43}$	-0.980 ± 0.053
Tensor to scalar ratio, $k_0 = 0.002$ Mpc^{-1} [b,h]	r	< 0.36 (95% CL)	< 0.24 (95% CL)
Running of spectral index, $k_0 = 0.002$ Mpc^{-1} [b,i]	$dn_s/d\ln k$	-0.034 ± 0.026	-0.022 ± 0.020
Neutrino density [j]	$\Omega_\nu h^2$	< 0.014 (95% CL)	< 0.0062 (95% CL)
Neutrino mass [j]	$\sum m_\nu$	< 1.3 eV (95% CL)	< 0.58 eV (95% CL)
Number of light neutrino families [k]	N_{eff}	> 2.7 (95% CL)	$4.34^{+0.86}_{-0.88}$

The parameters reported in the first section assume the 6 parameter flat CDM model, first using WMAP data only (Larson et al. 2010), **then using WMAP +BAO+H_0 data** (Komatsu et al. 2010). The H_0 data consists of a Gaussian prior on the present-day value of the Hubble constant, H_0 = 74.2 Å} 3.6 km s^{-1} Mpc^{-1}(Riess et al. 2009), while the BAO priors on the distance ratio $r_s(z_d)/D_V(z)$ at $z = 0.2, 0.3$ are obtained from the Sloan Digital Sky Survey Data Release 7 (Percival et al. 2009). **Uncertainties are 68% CL unless otherwise noted.**

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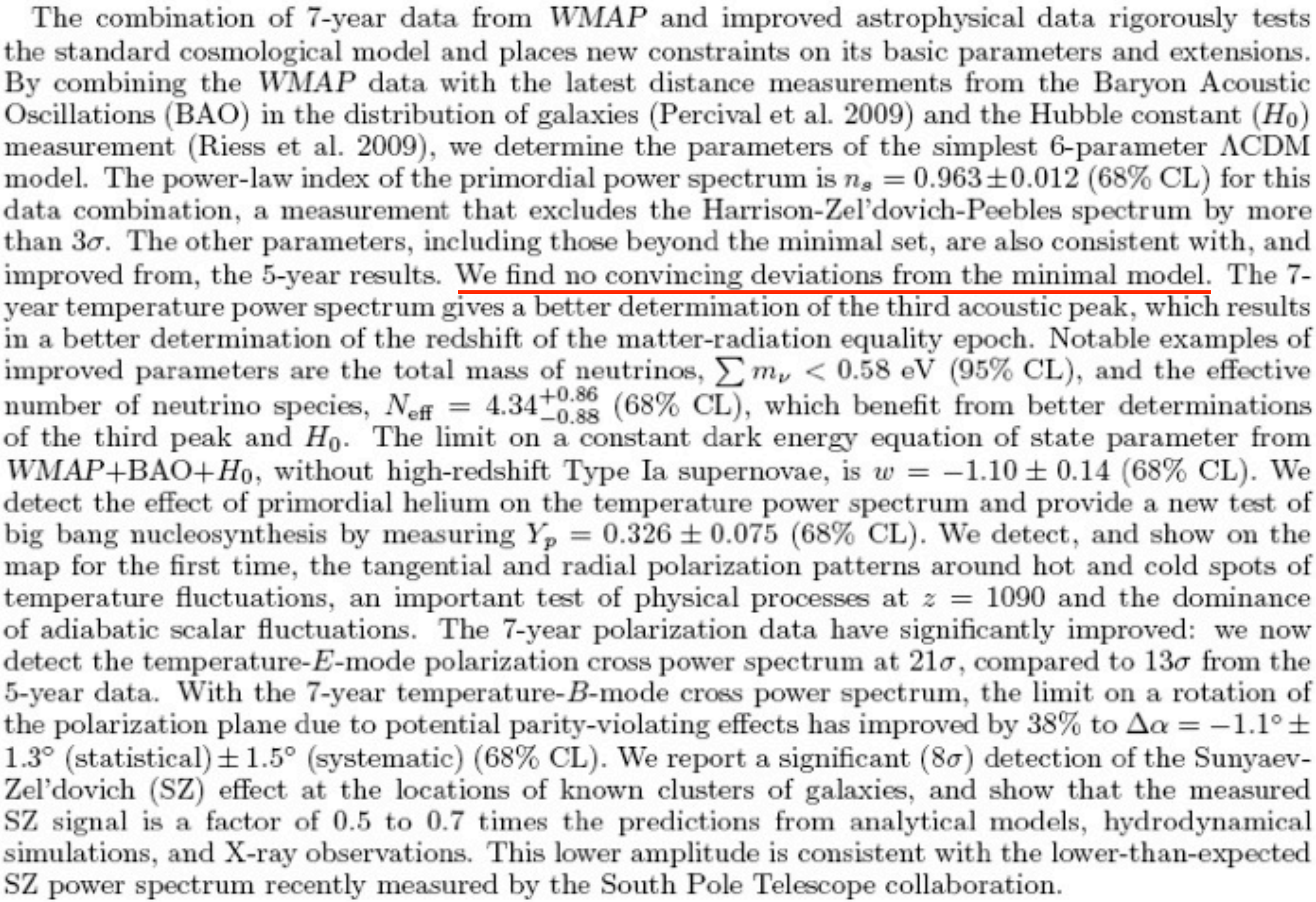

The combination of 7-year data from *WMAP* and improved astrophysical data rigorously tests the standard cosmological model and places new constraints on its basic parameters and extensions. By combining the *WMAP* data with the latest distance measurements from the Baryon Acoustic Oscillations (BAO) in the distribution of galaxies (Percival et al. 2009) and the Hubble constant (H_0) measurement (Riess et al. 2009), we determine the parameters of the simplest 6-parameter ΛCDM model. The power-law index of the primordial power spectrum is $n_s = 0.963 \pm 0.012$ (68% CL) for this data combination, a measurement that excludes the Harrison-Zel'dovich-Peebles spectrum by more than 3σ. The other parameters, including those beyond the minimal set, are also consistent with, and improved from, the 5-year results. We find no convincing deviations from the minimal model. The 7-year temperature power spectrum gives a better determination of the third acoustic peak, which results in a better determination of the redshift of the matter-radiation equality epoch. Notable examples of improved parameters are the total mass of neutrinos, $\sum m_\nu < 0.58$ eV (95% CL), and the effective number of neutrino species, $N_{\rm eff} = 4.34^{+0.86}_{-0.88}$ (68% CL), which benefit from better determinations of the third peak and H_0. The limit on a constant dark energy equation of state parameter from *WMAP*+BAO+H_0, without high-redshift Type Ia supernovae, is $w = -1.10 \pm 0.14$ (68% CL). We detect the effect of primordial helium on the temperature power spectrum and provide a new test of big bang nucleosynthesis by measuring $Y_p = 0.326 \pm 0.075$ (68% CL). We detect, and show on the map for the first time, the tangential and radial polarization patterns around hot and cold spots of temperature fluctuations, an important test of physical processes at $z = 1090$ and the dominance of adiabatic scalar fluctuations. The 7-year polarization data have significantly improved: we now detect the temperature-E-mode polarization cross power spectrum at 21σ, compared to 13σ from the 5-year data. With the 7-year temperature-B-mode cross power spectrum, the limit on a rotation of the polarization plane due to potential parity-violating effects has improved by 38% to $\Delta\alpha = -1.1^\circ \pm 1.3^\circ$ (statistical) $\pm 1.5^\circ$ (systematic) (68% CL). We report a significant (8σ) detection of the Sunyaev-Zel'dovich (SZ) effect at the locations of known clusters of galaxies, and show that the measured SZ signal is a factor of 0.5 to 0.7 times the predictions from analytical models, hydrodynamical simulations, and X-ray observations. This lower amplitude is consistent with the lower-than-expected SZ power spectrum recently measured by the South Pole Telescope collaboration.

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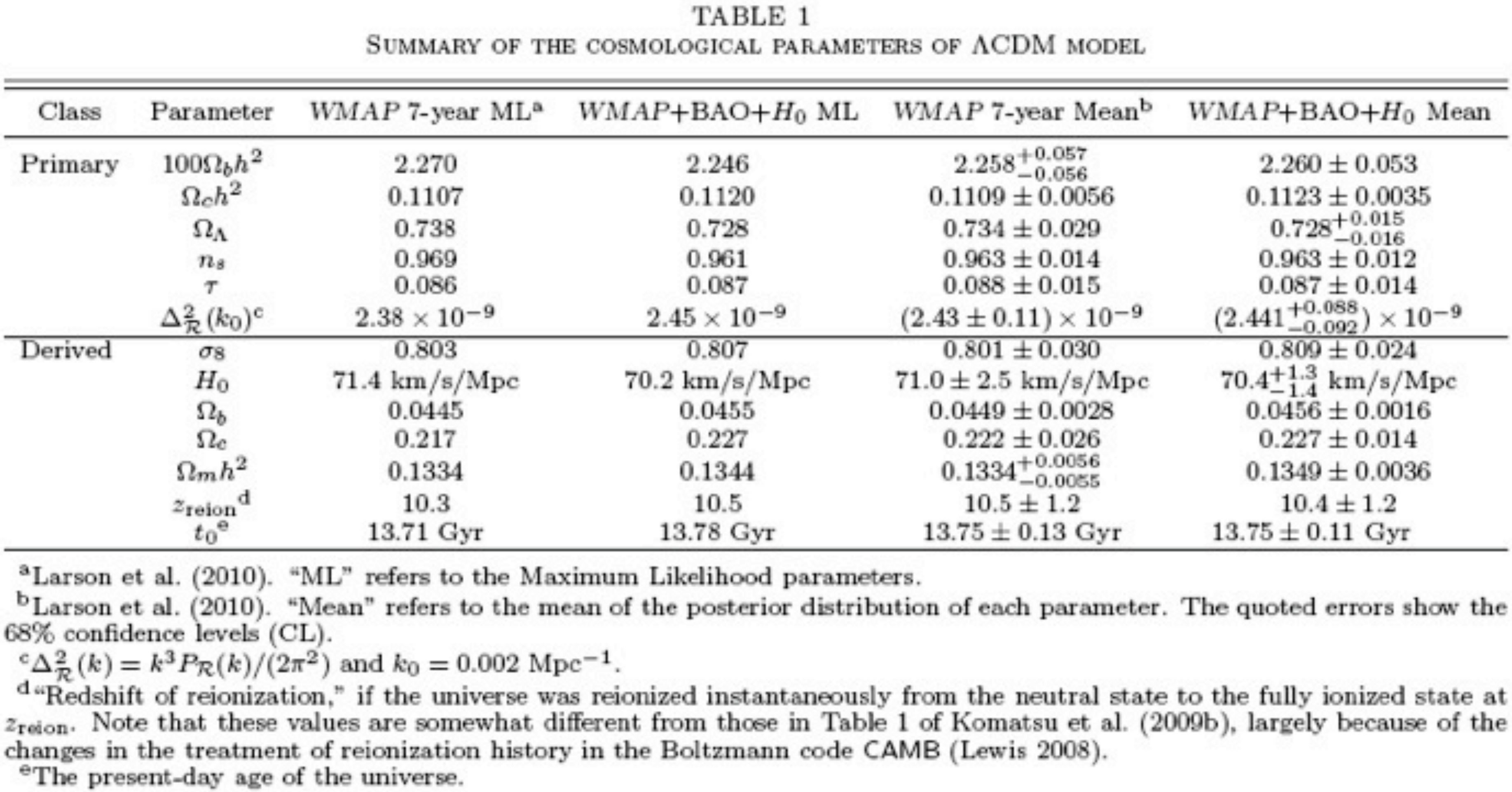


TABLE 1
SUMMARY OF THE COSMOLOGICAL PARAMETERS OF ΛCDM MODEL

Class	Parameter	*WMAP* 7-year ML[a]	*WMAP*+BAO+H_0 ML	*WMAP* 7-year Mean[b]	*WMAP*+BAO+H_0 Mean
Primary	$100\Omega_b h^2$	2.270	2.246	$2.258^{+0.057}_{-0.056}$	2.260 ± 0.053
	$\Omega_c h^2$	0.1107	0.1120	0.1109 ± 0.0056	0.1123 ± 0.0035
	Ω_Λ	0.738	0.728	0.734 ± 0.029	$0.728^{+0.015}_{-0.016}$
	n_s	0.969	0.961	0.963 ± 0.014	0.963 ± 0.012
	τ	0.086	0.087	0.088 ± 0.015	0.087 ± 0.014
	$\Delta^2_{\mathcal{R}}(k_0)$[c]	2.38×10^{-9}	2.45×10^{-9}	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.441^{+0.088}_{-0.092}) \times 10^{-9}$
Derived	σ_8	0.803	0.807	0.801 ± 0.030	0.809 ± 0.024
	H_0	71.4 km/s/Mpc	70.2 km/s/Mpc	71.0 ± 2.5 km/s/Mpc	$70.4^{+1.3}_{-1.4}$ km/s/Mpc
	Ω_b	0.0445	0.0455	0.0449 ± 0.0028	0.0456 ± 0.0016
	Ω_c	0.217	0.227	0.222 ± 0.026	0.227 ± 0.014
	$\Omega_m h^2$	0.1334	0.1344	$0.1334^{+0.0056}_{-0.0055}$	0.1349 ± 0.0036
	$z_{\rm reion}$[d]	10.3	10.5	10.5 ± 1.2	10.4 ± 1.2
	t_0[e]	13.71 Gyr	13.78 Gyr	13.75 ± 0.13 Gyr	13.75 ± 0.11 Gyr

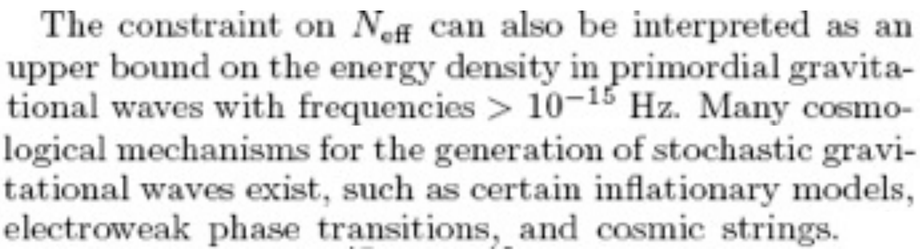
[a] Larson et al. (2010). "ML" refers to the Maximum Likelihood parameters.

[b] Larson et al. (2010). "Mean" refers to the mean of the posterior distribution of each parameter. The quoted errors show the 68% confidence levels (CL).

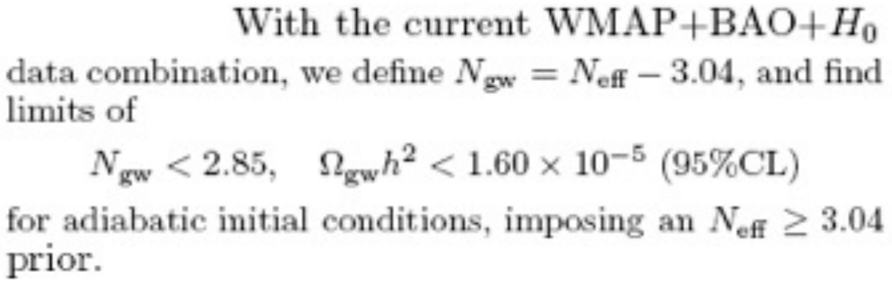
[c] $\Delta^2_{\mathcal{R}}(k) = k^3 P_{\mathcal{R}}(k)/(2\pi^2)$ and $k_0 = 0.002$ Mpc^{-1}.

[d] "Redshift of reionization," if the universe was reionized instantaneously from the neutral state to the fully ionized state at $z_{\rm reion}$. Note that these values are somewhat different from those in Table 1 of Komatsu et al. (2009b), largely because of the changes in the treatment of reionization history in the Boltzmann code CAMB (Lewis 2008).

[e] The present-day age of the universe.



The constraint on $N_{\rm eff}$ can also be interpreted as an upper bound on the energy density in primordial gravitational waves with frequencies $> 10^{-15}$ Hz. Many cosmological mechanisms for the generation of stochastic gravitational waves exist, such as certain inflationary models, electroweak phase transitions, and cosmic strings.



With the current WMAP+BAO+H_0 data combination, we define $N_{\rm gw} = N_{\rm eff} - 3.04$, and find limits of

$$N_{\rm gw} < 2.85, \quad \Omega_{\rm gw} h^2 < 1.60 \times 10^{-5} \ (95\%\text{CL})$$

for adiabatic initial conditions, imposing an $N_{\rm eff} \geq 3.04$ prior.