Astr 323: Extragalactic Astronomy and Cosmology

Spring Quarter 2014, University of Washington, Željko Ivezić

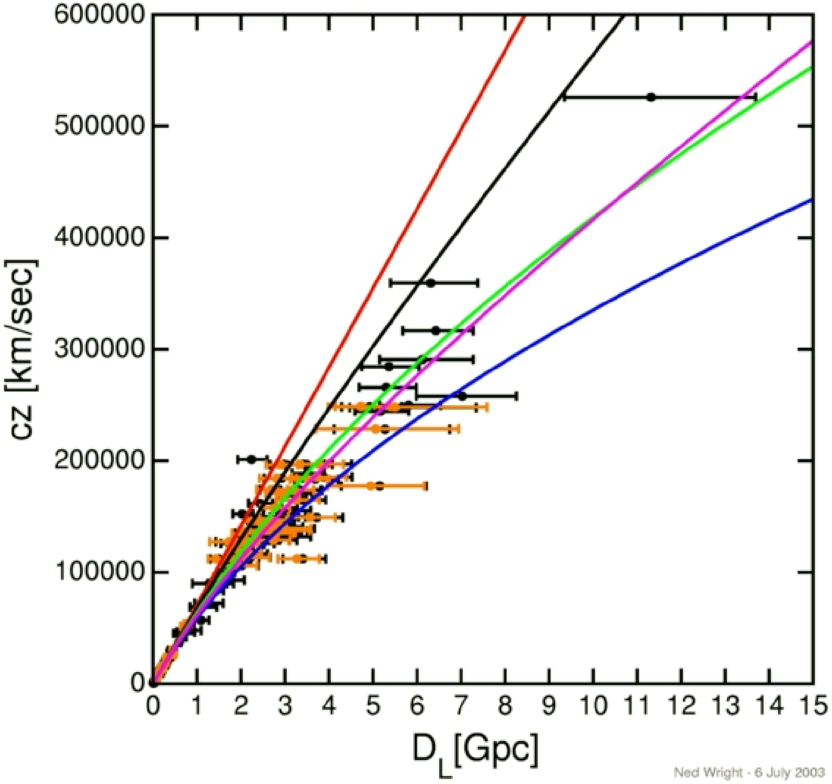
Lecture 8:

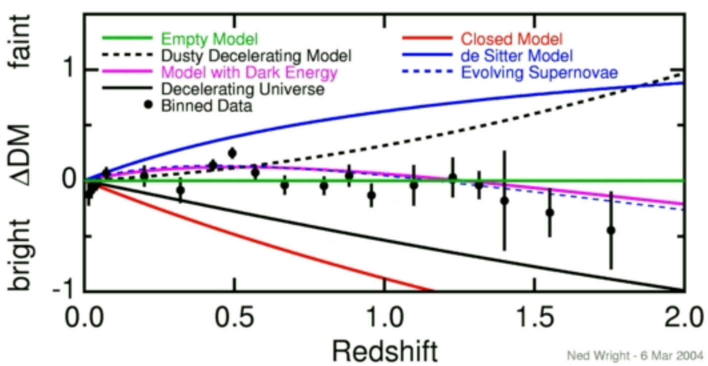
The Big Bang and Early Universe

Observational Cosmology

Key observations that support the Big Bang Theory

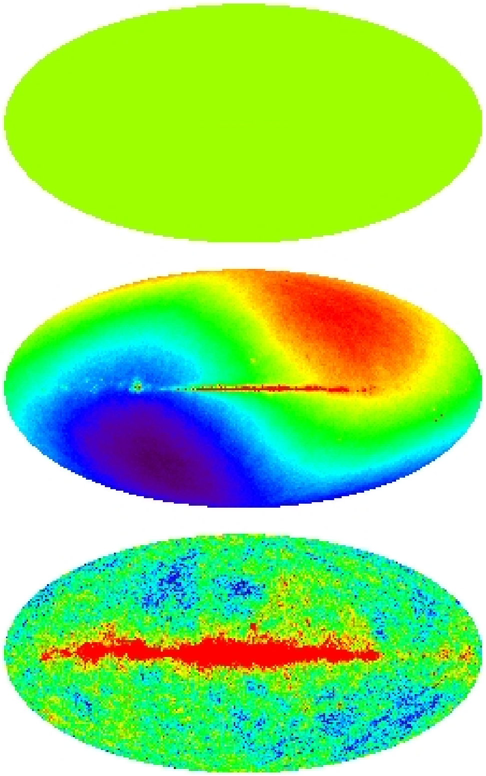
- Expansion: the Hubble law
- Cosmic Microwave Background
- The light element abundance
- Recent advances: baryon oscillations, integrated Sachs-Wolfe effect, etc.

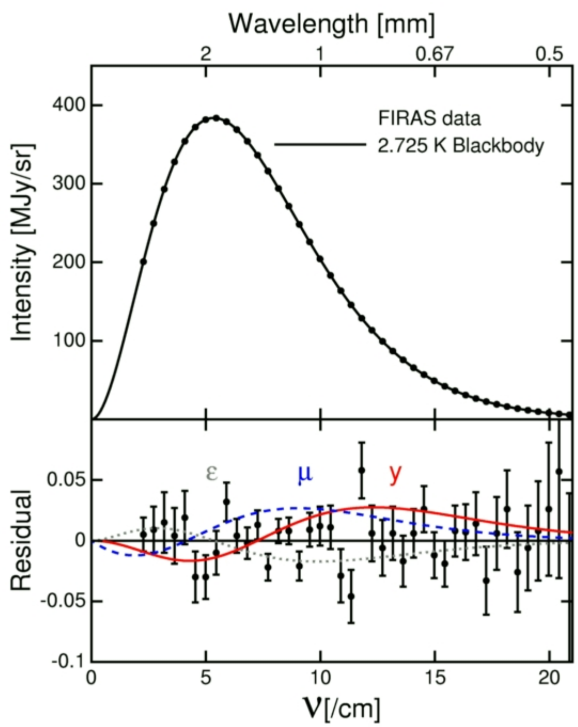




Expansion of the Universe

- Discovered as a linear law ($v = H\,D$) by Hubble in 1929.
- With distant SNe, today we can measure the deviations from linearity in the Hubble law due to cosmological effects
- The curves in the top panel show a closed Universe ($\Omega = 2$) in red, the critical density Universe ($\Omega = 1$) in black, the empty Universe ($\Omega = 0$) in green, the steady state model in blue, and the WMAP based concordance model with $\Omega_m = 0.27$ and $\Omega_\Lambda = 0.73$ in purple.
- The data imply an accelerating Universe at low to moderate redshifts but a decelerating Universe at higher redshifts, consistent with a model having both a cosmological constant and a significant amount of dark matter.



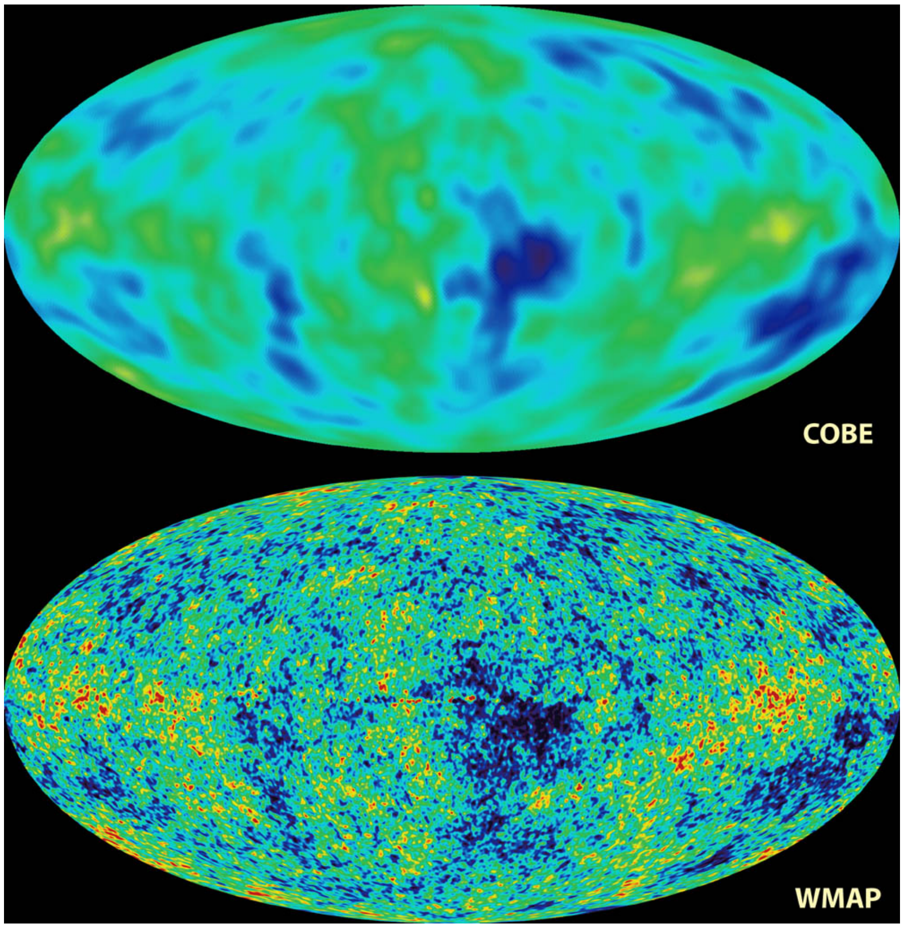


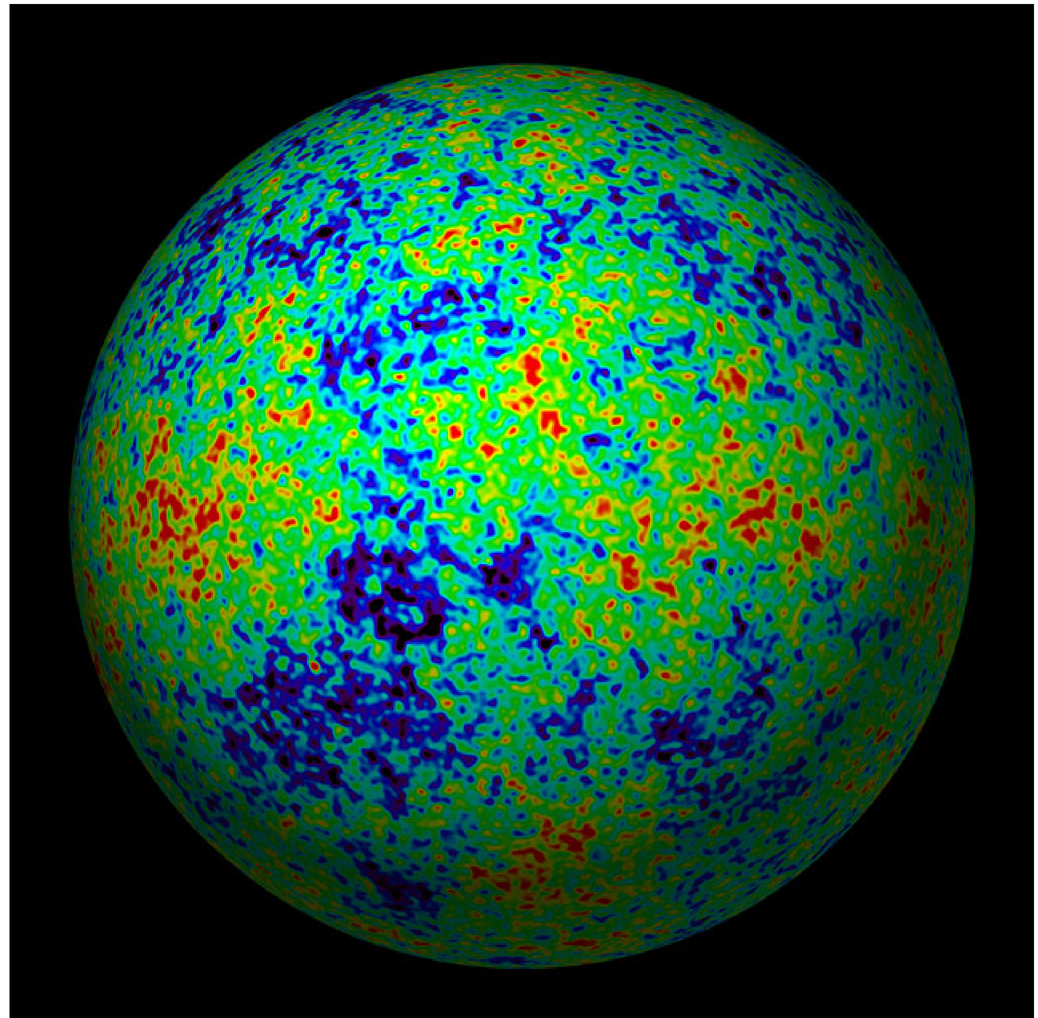
Cosmic Microwave Background (CMB)

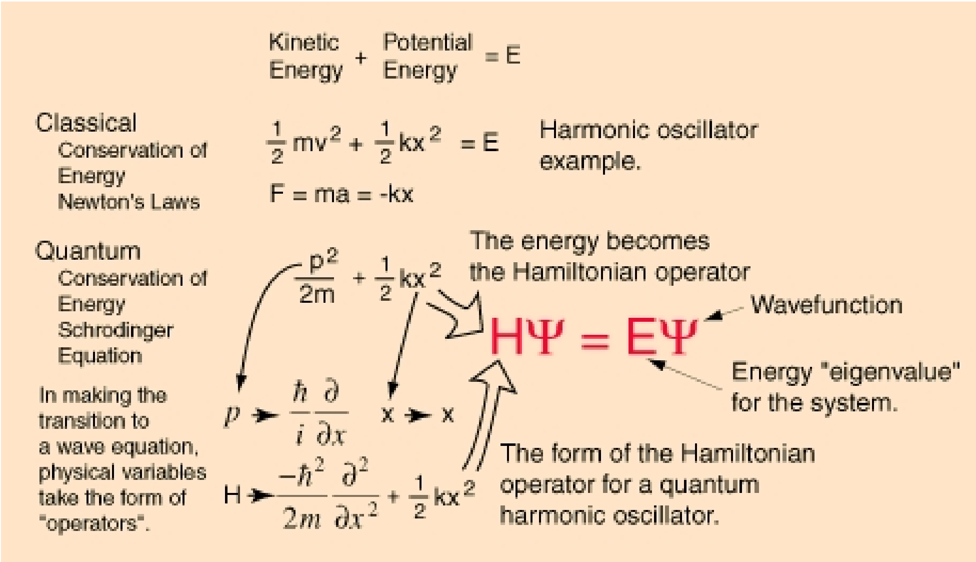
- The CMB was discovered by Penzias & Wilson in 1965 (although there was an older measurement of the "sky" temperature by McKellar using interstellar molecules in 1940, whose significance was not recognized)
- This is the best black-body spectrum ever measured, with $T = 2.73$ K. It is also remarkably uniform accross the sky (to one part in $\sim 10^{-5}$), after dipole induced by the solar motion is corrected for.
- The existance of CMB was predicted by Gamow in 1946.
- Fluctuations in the CMB at the level of $\sim 10^{-5}$ were first detected by the COBE satellite.
- The WMAP satellite has recently measured these fluctuations at a much higher angular resolution.

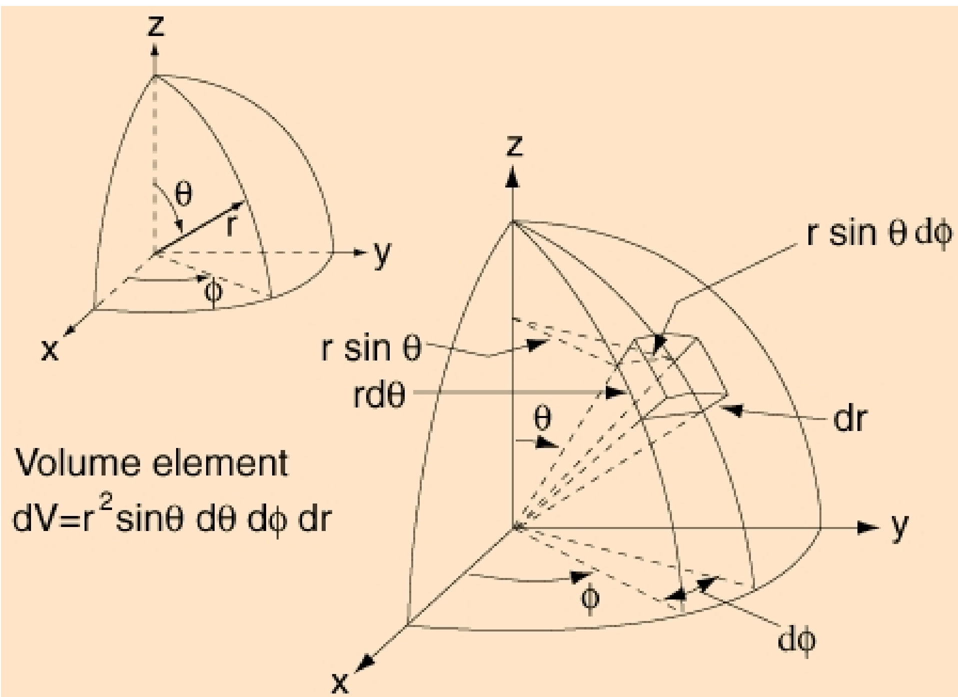
Cosmic Microwave Background (CMB)

- The CMB fluctuations, recently observed by WMAP at a high angular resolution, show a characteristic size of $\sim 1^\circ$
- A statistical description of the anisotropies is given by the power spectrum. The power spectrum encodes constraints on cosmological parameters.





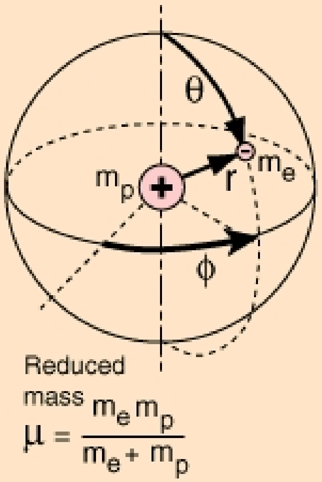




Spherical Harmonics

- Recall: a one-dimensional periodic function can be expanded into a Fourier series; the (squared) amplitudes vs. frequency plot shows the contribution of each mode: the power spectrum
- Similarly, a two-dimensional function defined on a sphere can be expanded in spherical harmonics; the power spectrum shows the constribution of each characteristic size
- Spherical harmonics are extensively used in quantum mechanics: the Schrödinger equation in spherical coordinates

Hydrogen Schrodinger Equation



The electron in the hydrogen atom sees a spherically symmetric potential, so it is logical to use spherical polar coordinates to develop the Schrodinger equation. The potential energy is simply that of a point charge:

$$U(r) = \frac{-e^2}{4\pi\varepsilon_0 r}$$

The expanded form of the Schrodinger equation is shown below. Solving it involves separating the variables into the form

$$\Psi(r,\theta,\phi) = R(r)P(\theta)F(\phi)$$

The starting point is the form of the Schrodinger equation:

$$\frac{-\hbar^2}{2\mu}\frac{1}{r^2\sin\theta}\left[\sin\theta\frac{\partial}{\partial r}\left(r^2\frac{\partial\Psi}{\partial r}\right)+\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\Psi}{\partial\theta}\right)+\frac{1}{\sin\theta}\frac{\partial^2\Psi}{\partial\phi^2}\right]$$
$$-U(r)\Psi(r,\theta,\phi) = E\,\Psi(r,\theta,\phi)$$

$$\frac{d^2\Phi}{d\phi^2}+m_\ell^2\Phi = 0 \quad \textit{with solution} \quad \Phi_{m_\ell}(\phi) = \frac{1}{\sqrt{2\pi}}e^{i m_\ell \phi}$$

$$\frac{1}{\sin\theta}\frac{d}{d\theta}\left(\sin\theta\frac{d\Theta}{d\theta}\right)+\left[\ell(\ell+1)-\frac{m_\ell^2}{\sin^2\theta}\right]\Theta = 0$$

$$\ell = 0,1,2,3\ldots \qquad m_\ell = 0,\pm1,\pm2,\ldots,\pm\ell$$

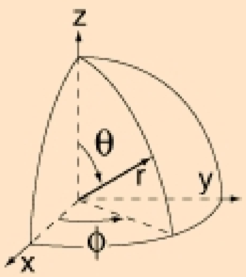
$$\Theta_{\ell,m_\ell}(\theta)\Phi_{m_\ell}(\phi) = Y_{\ell,m_\ell}(\theta,\phi)$$

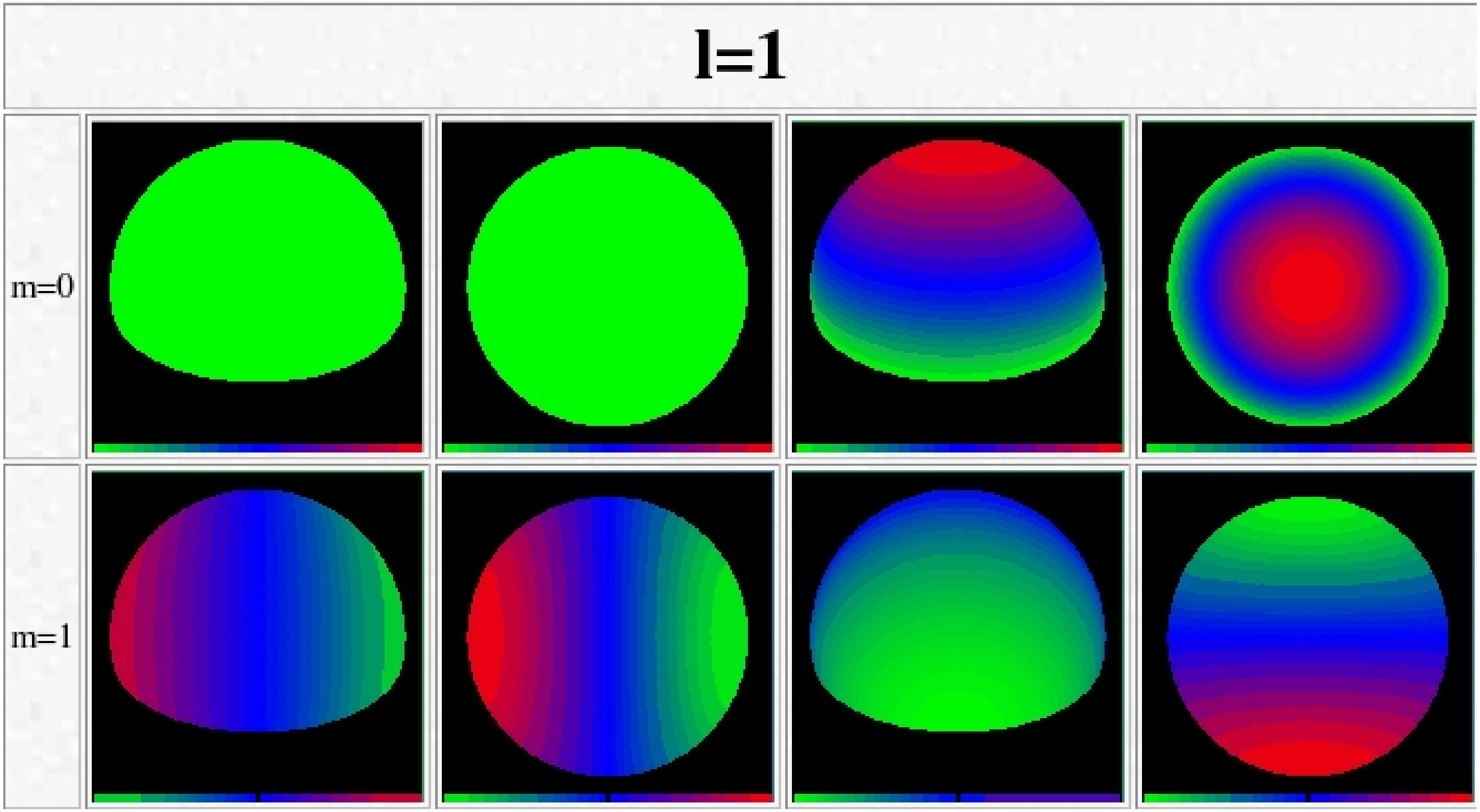
ℓ	m_ℓ	$Y_{\ell m_l}(\theta,\phi) = \Theta_{\ell m_l}(\theta)\Phi_{m_l}(\phi)$
0	0	$(1/4\pi)^{1/2}$
1	0	$(3/4\pi)^{1/2}\cos\theta$
1	±1	$\mp(3/8\pi)^{1/2}\sin\theta e^{\pm i\phi}$
2	0	$(5/16\pi)^{1/2}(3\cos^2\theta-1)$
2	±1	$\mp(15/8\pi)^{1/2}\sin\theta\cos\theta e^{\pm i\phi}$
2	±2	$(15/32\pi)^{1/2}\sin^2\theta e^{\pm 2i\phi}$

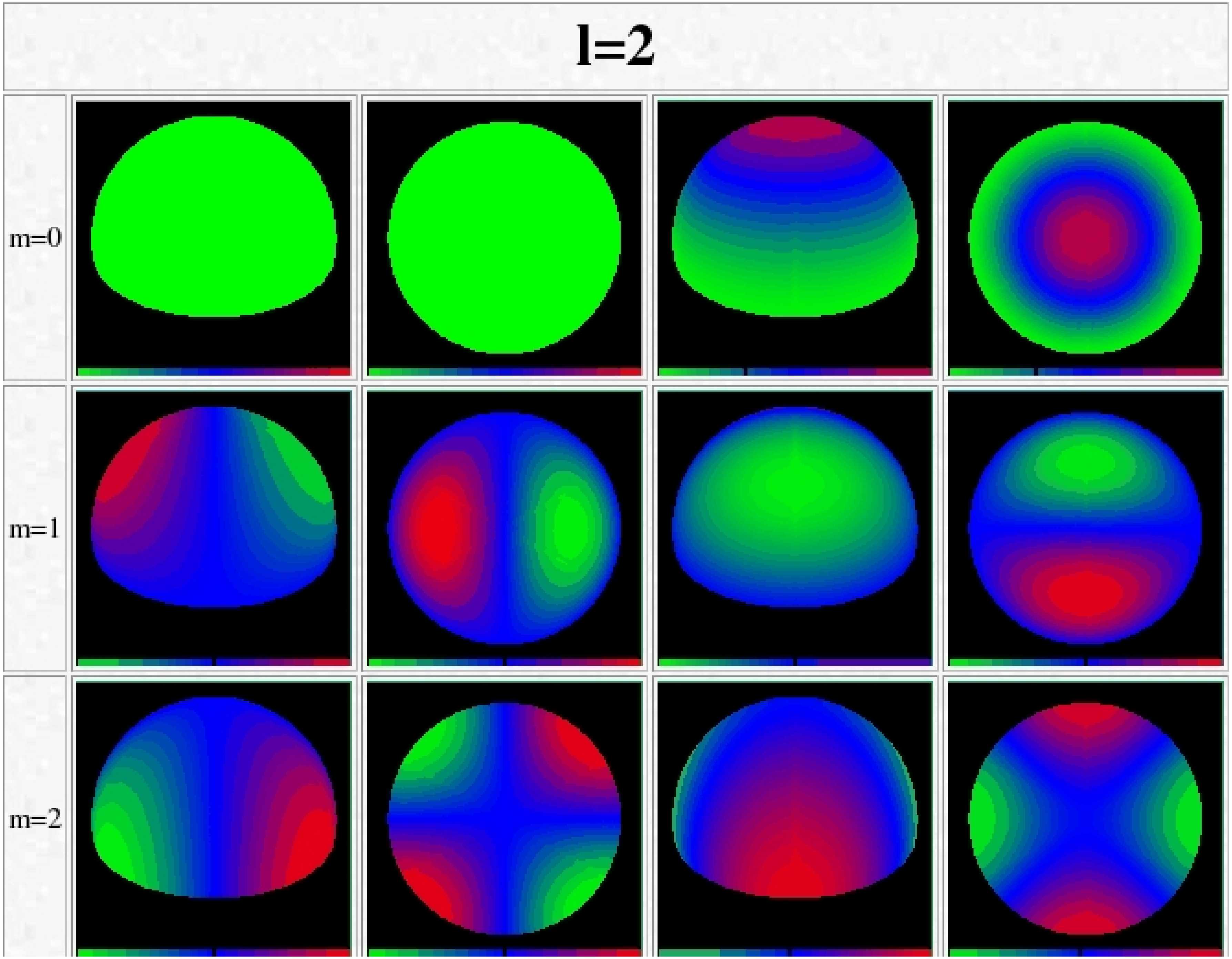
$$\Phi_{m_\ell}(\phi) = \frac{1}{\sqrt{2\pi}}e^{i m_\ell \phi}$$

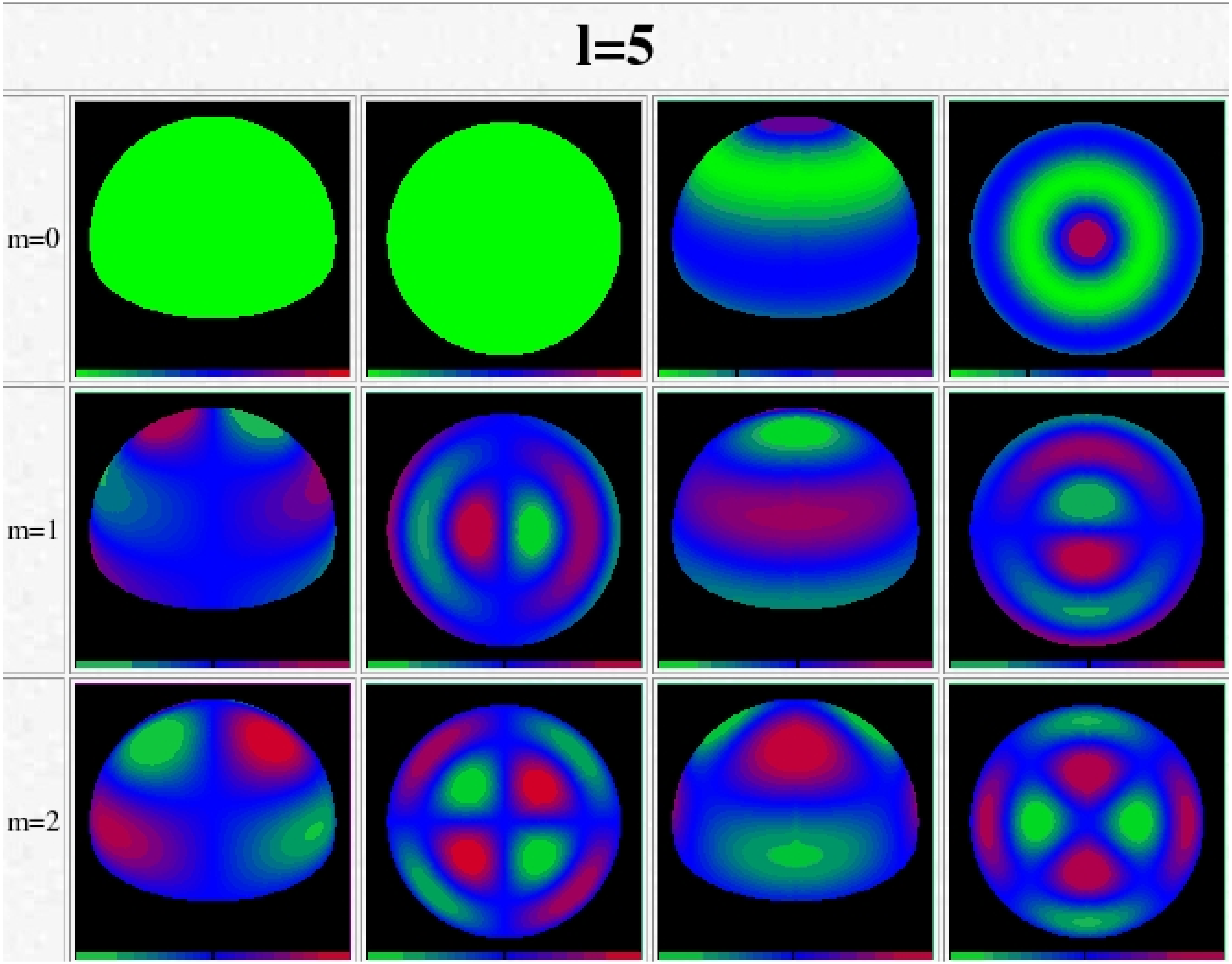
$$\Theta_{\ell m_\ell}(\theta) = \left[\frac{2\ell+1}{2}\frac{(\ell-m_\ell)!}{(\ell+m_\ell)!}\right]^{1/2} P_\ell^{m_\ell}(\theta)$$

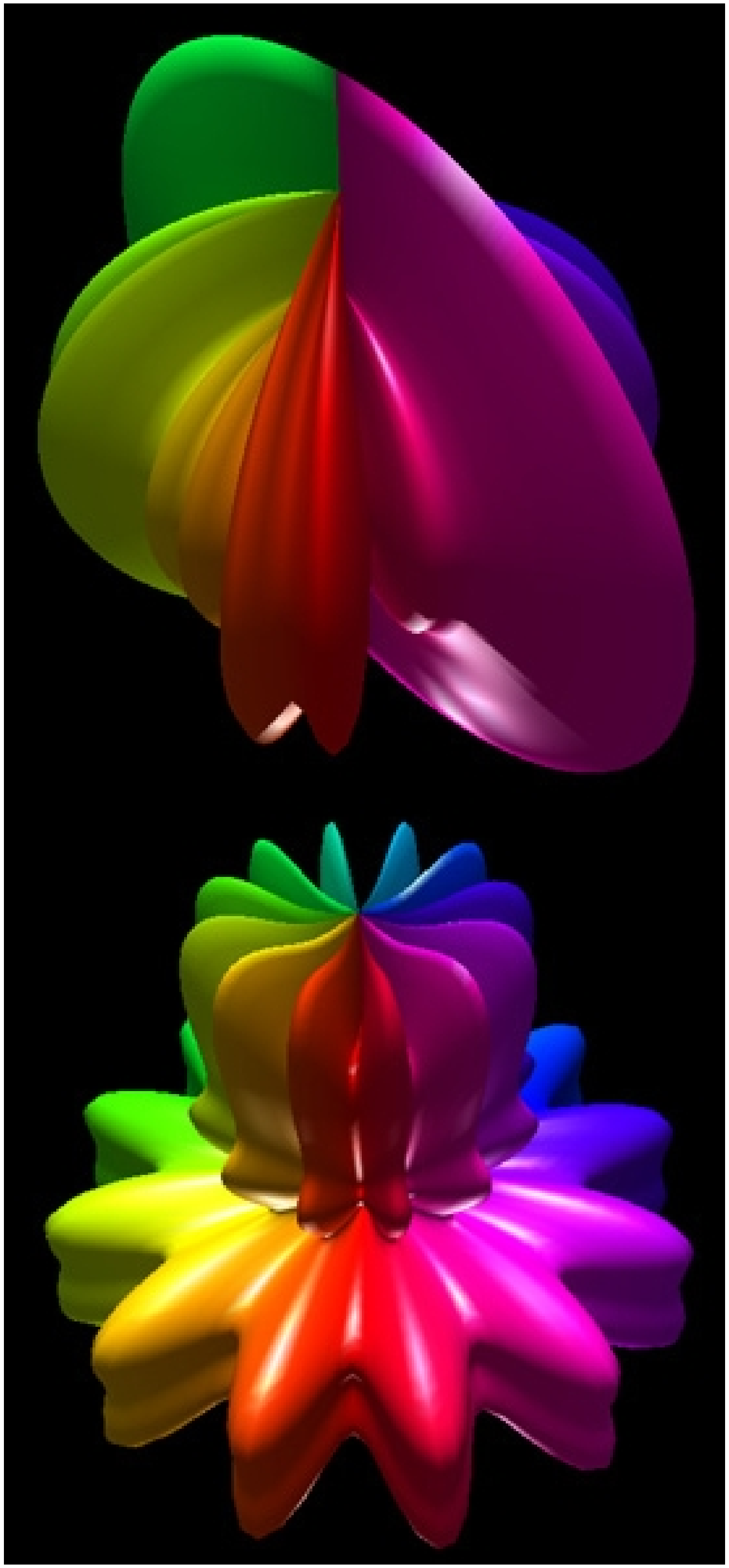
$$P_\ell^{m_\ell}(\theta) = \textit{associated Legendre polynomial}$$

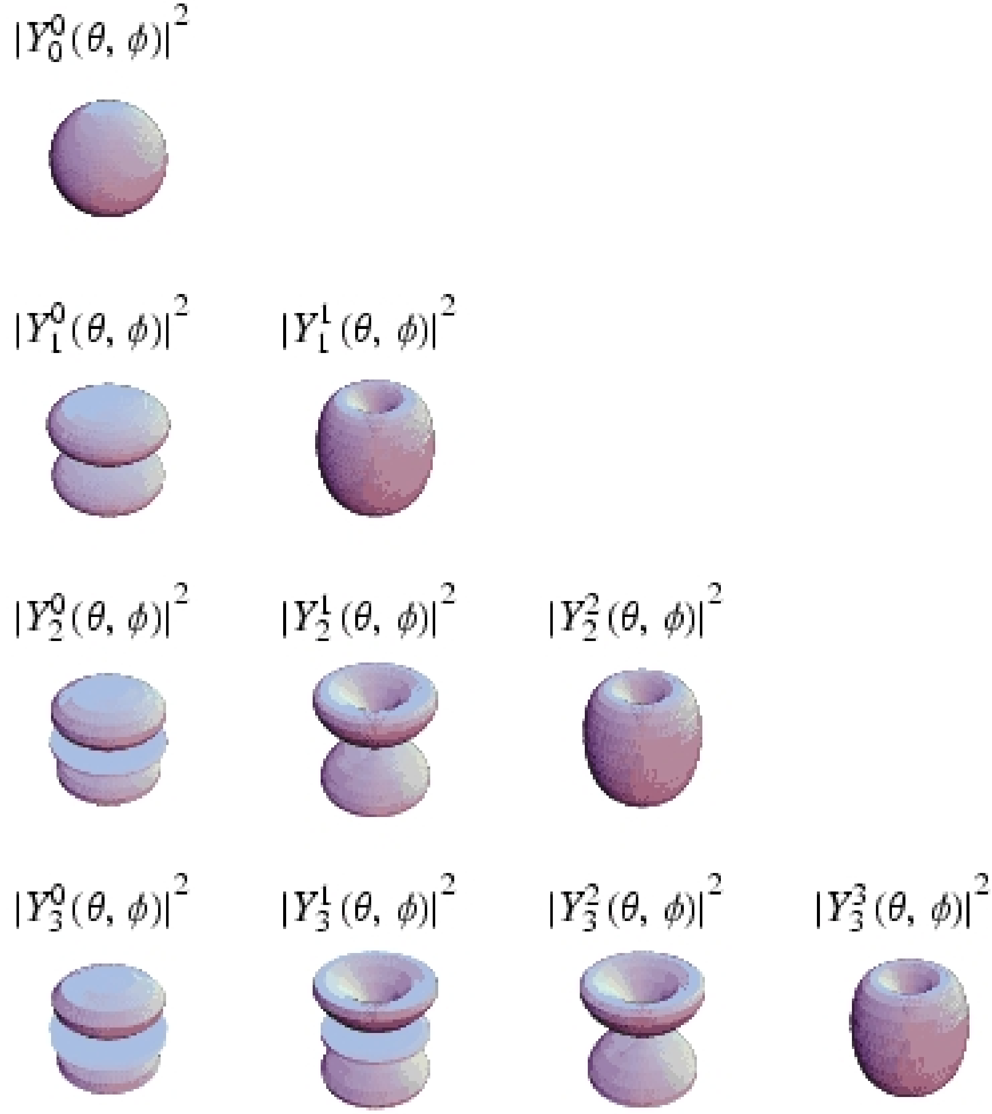



l=1
m=0
m=1


l=2
m=0
m=1
m=2


l=5
m=0
m=1
m=2

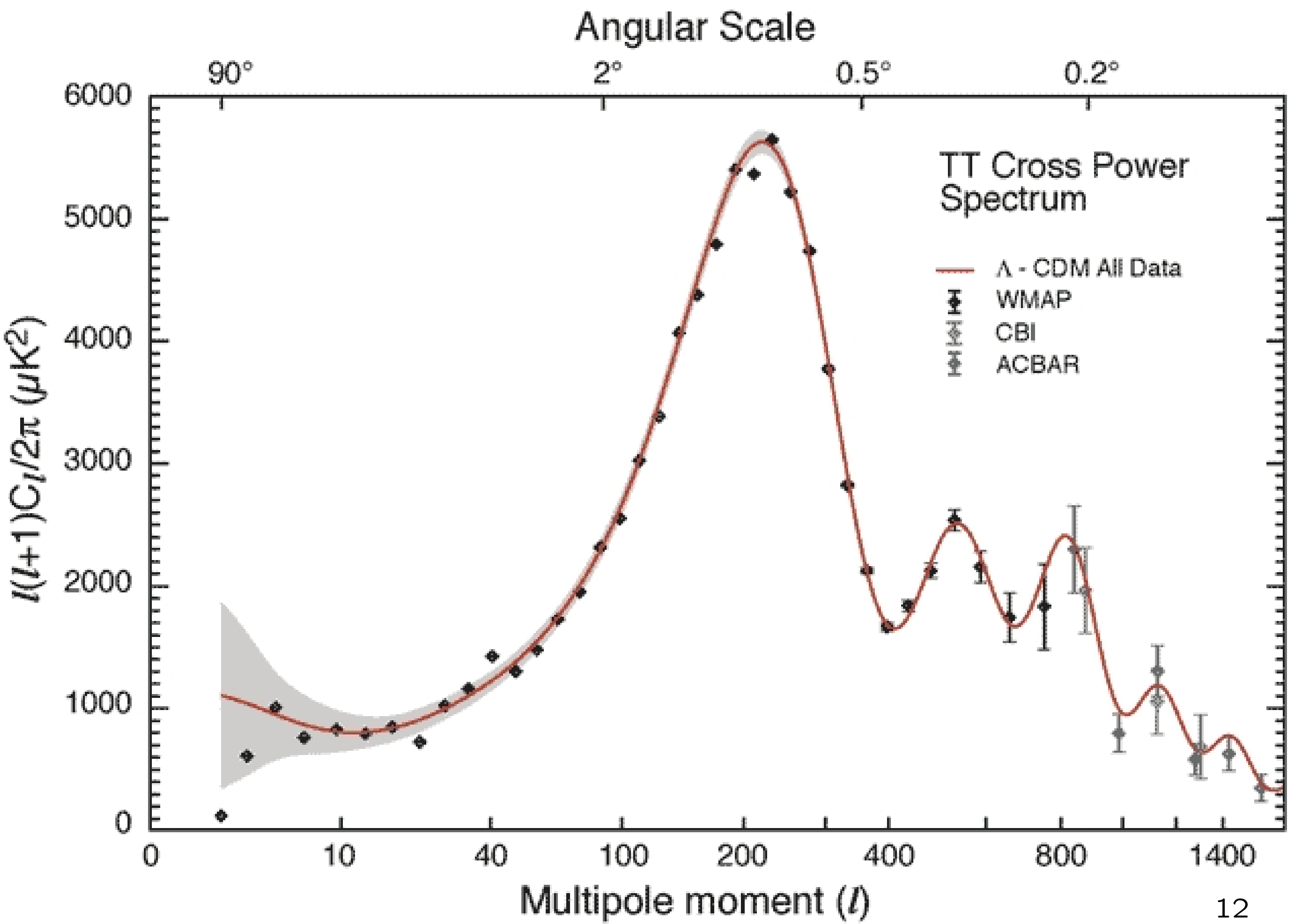


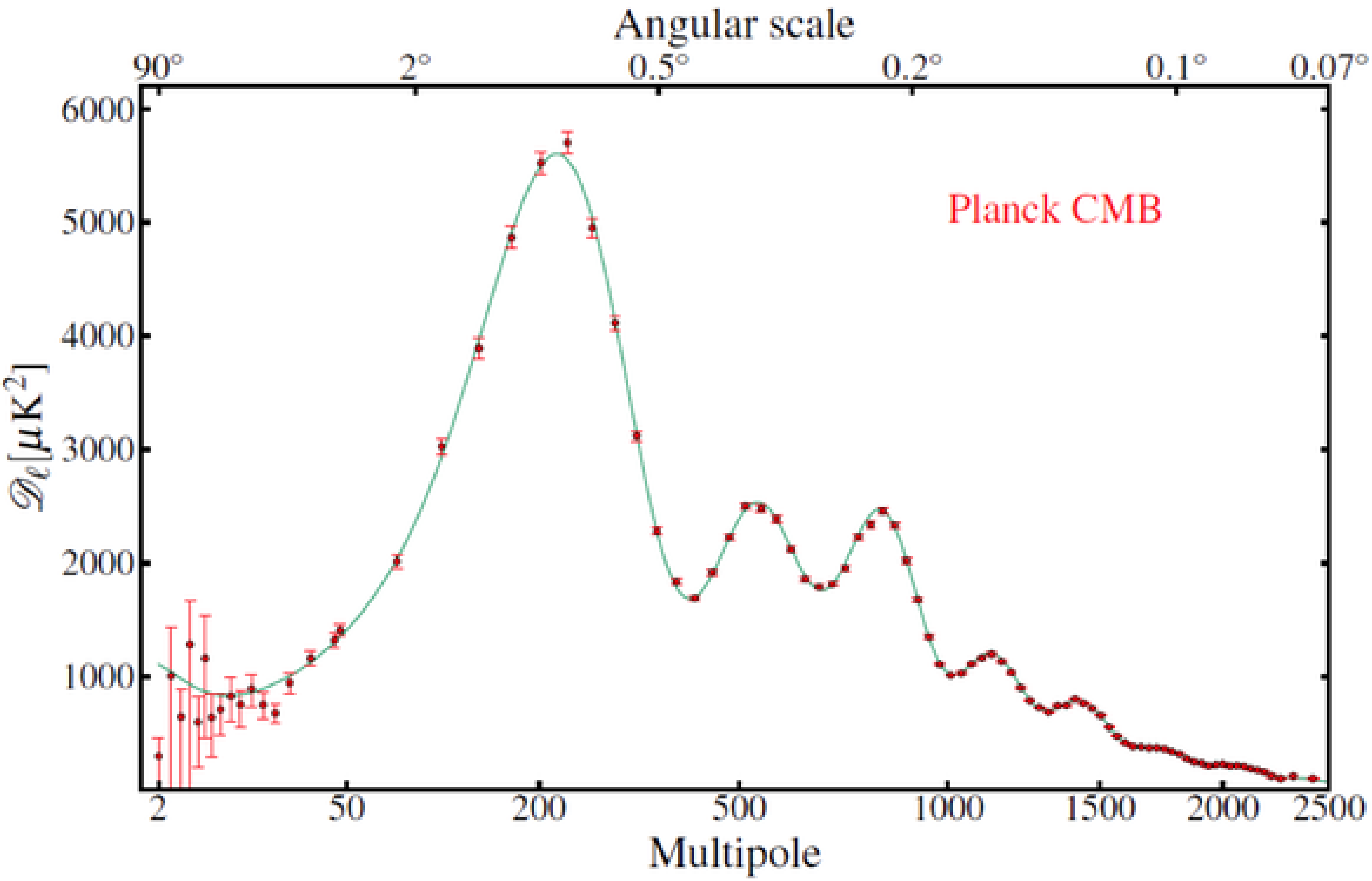

$|Y_0^0(\theta, \phi)|^2$
$|Y_1^0(\theta, \phi)|^2$
$|Y_1^1(\theta, \phi)|^2$
$|Y_2^0(\theta, \phi)|^2$
$|Y_2^1(\theta, \phi)|^2$
$|Y_2^2(\theta, \phi)|^2$
$|Y_3^0(\theta, \phi)|^2$
$|Y_3^1(\theta, \phi)|^2$
$|Y_3^2(\theta, \phi)|^2$
$|Y_3^3(\theta, \phi)|^2$

WMAP Power Spectrum

Basic flat WMAP parameters: $W_L = 0.71$, $W_m = 0.29$ ($W_c = 0.24$, $W_b = 0.047$), $n = 0.93$, $h = 0.71$.

WMAP + other: $W_L = 0.71$, $W_m = 0.27$ ($W_c = 0.23$, $W_b = 0.044$), $n = 0.93$, $h = 0.71$.




Angular scale
90°
2°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
$\mathcal{D}_\ell\,[\mu K^2]$
Planck CMB
2
50
200
500
1000
1500
2000
2500
Multipole

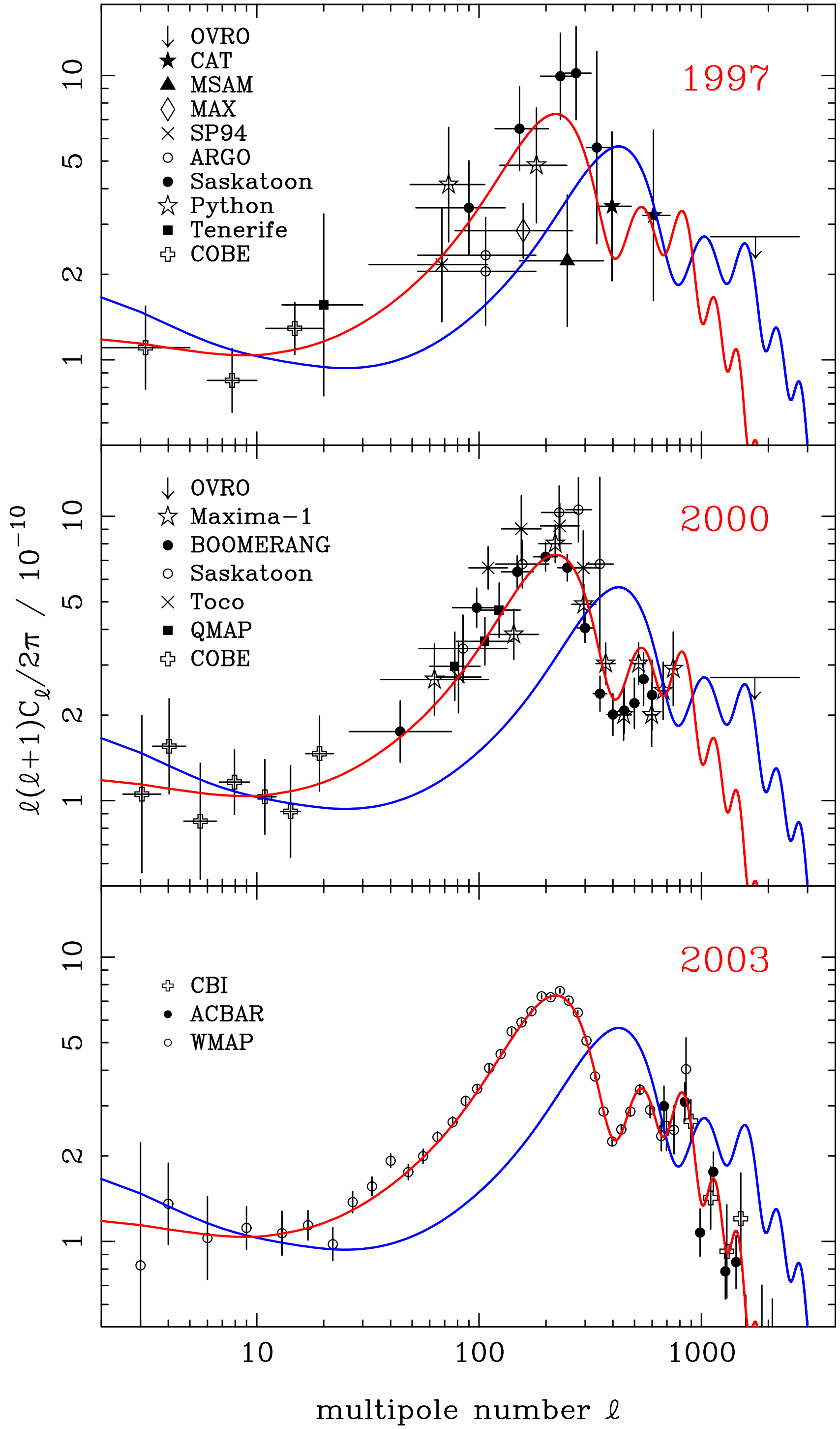


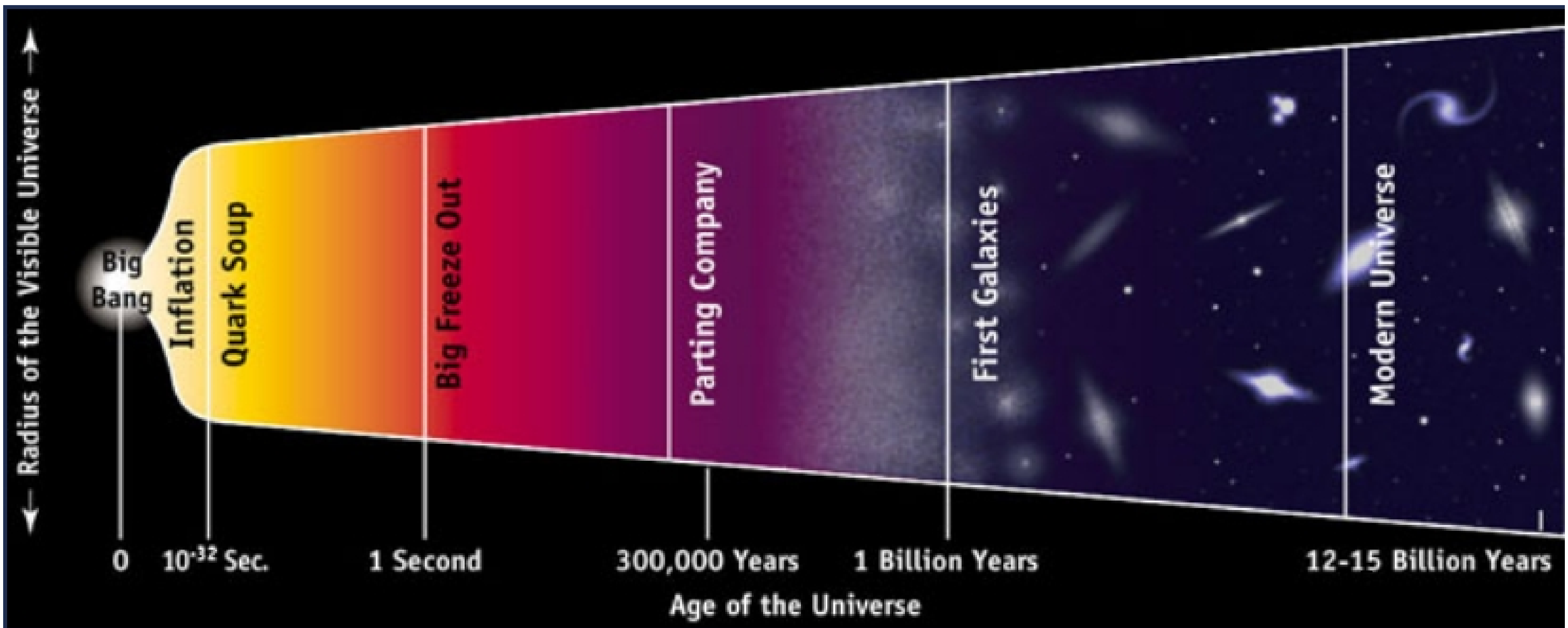
FIGURE 18. Dramatic change took place in CMB power spectrum measurements around the turn of the 21st century. Although some rise from the COBE level was arguably known even by 1997, a clear peak around $\ell \simeq 200$ only became established in 2000, whereas by 2003 definitive measurements of the spectrum at $\ell \lesssim 800$, limited mainly by cosmic variance, had been made

The origin of CMB

- A historical note: the accuracy of CMB measurements is improving fast – the accuracy delivered by WMAP is truly spectacular! (Note: Facebook was founded in 2004)
- Why do we have CMB? It is a remnant of hot radiation field from the beginning of the Universe – at some time in the past radiation and matter were in equilibrium! How do we know this?

The origin of CMB

- As the universe expands, the energy density of radiation $\propto R^{-4}$ (because the total energy, which is proportional to T^4, is also proportional to the product of volume and characteristic wavelength) and that of matter $\propto R^{-3}$. Therefore, at some time in the past radiation and matter must have been in equilibrium.
- From the photon-to-nucleon number ratio ($\sim 10^9$), one can estimate that the radiation temperature at that time was $\sim$ 3000. Since $T \propto 1/R \propto (1+z)$, the corresponding redshift is $z \sim 1000$), or about 380,000 years after the Big Bang.



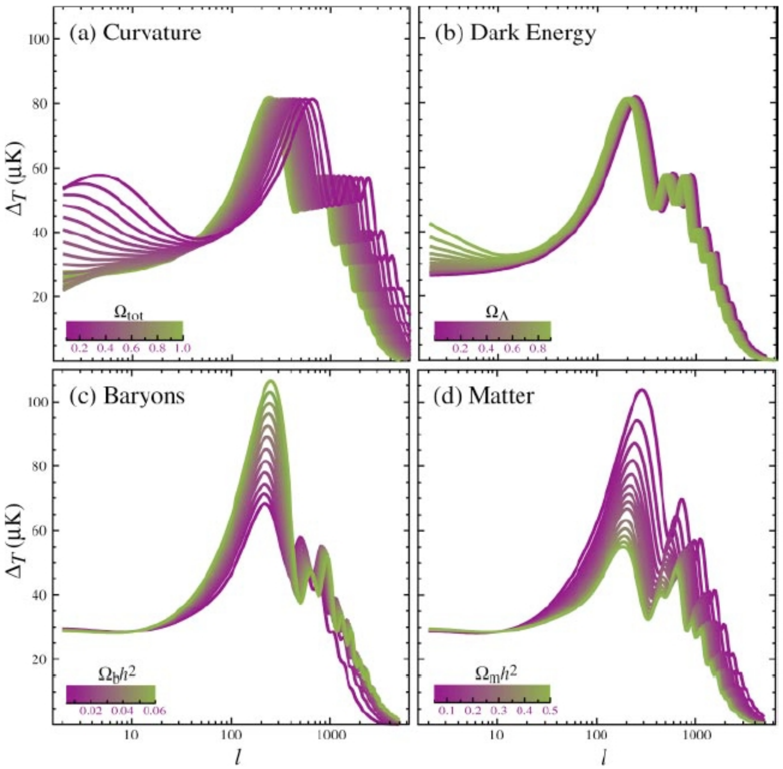


Figure 4 Sensitivity of the acoustic temperature spectrum to four fundamental cosmological parameters. (*a*) The curvature as quantified by Ω_{tot}. (*b*) The dark energy as quantified by the cosmological constant Ω_Λ ($w_\Lambda = -1$). (*c*) The physical baryon density $\Omega_b h^2$. (*d*) The physical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

What do we learn from P(k)?

- The position of the first peak is **very** sensitive to Ω_{tot} and not very sensitive to other parameters. Roughly, $l_1 = 220/\Omega_{tot}$. Thus, the measurement of the angular size of the "spots" in the CMB fluctuation map is essentially a **direct** measurement of Ω_{tot}!
- WMAP measured the peak position to be $l_1 \sim 216 \pm 4$ (implying an angular size of $180/l_1 \sim 0.83$ degree, which is just slightly larger than full Moon), and thus $\Omega_{tot} = 1.02 \pm 0.02$. The Universe is flat!
- Detailed modeling of the whole power spectrum also constrains H_o, Ω_b, Ω_m, and a few other parameters (six in total).

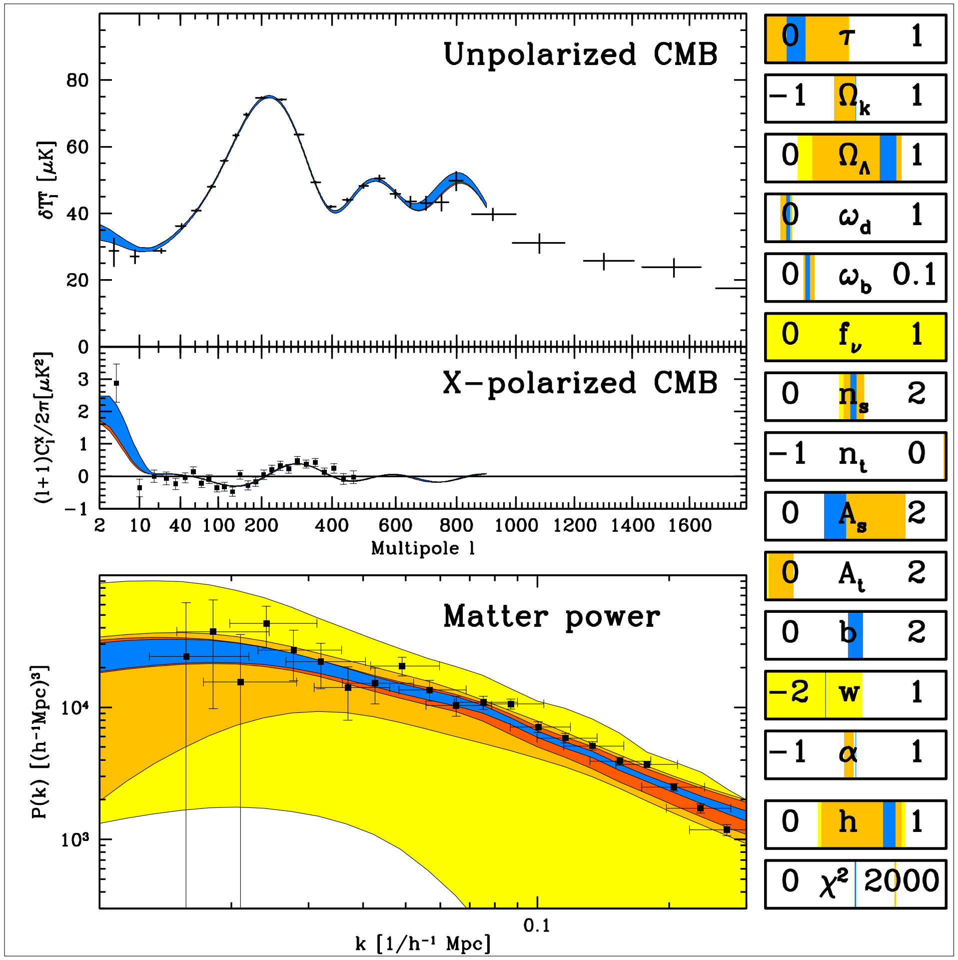


FIG. 1: Summary of observations and cosmological models. Data points are for unpolarized CMB experiments combined (top; Appendix A.3 details data used) cross-polarized CMB from WMAP (middle) and Galaxy power from SDSS (bottom). Shaded bands show the 1-sigma range of theoretical models from the Monte-Carlo Markov chains, both for cosmological parameters (right) and for the corresponding power spectra (left). From outside in, these bands correspond to WMAP with no priors, adding the prior $f_\nu = 0$, $w = -1$, further adding the priors $\Omega_k = r = \alpha = 0$, and further adding the SDSS information, respectively. These four bands essentially coincide in the top two panels, since the CMB constraints were included in the fits. Note that the ℓ-axis in the upper two panels goes from logarithmic on the left to linear on the right, to show important features at both ends, whereas the k-axis of the bottom panel is simply logarithmic.

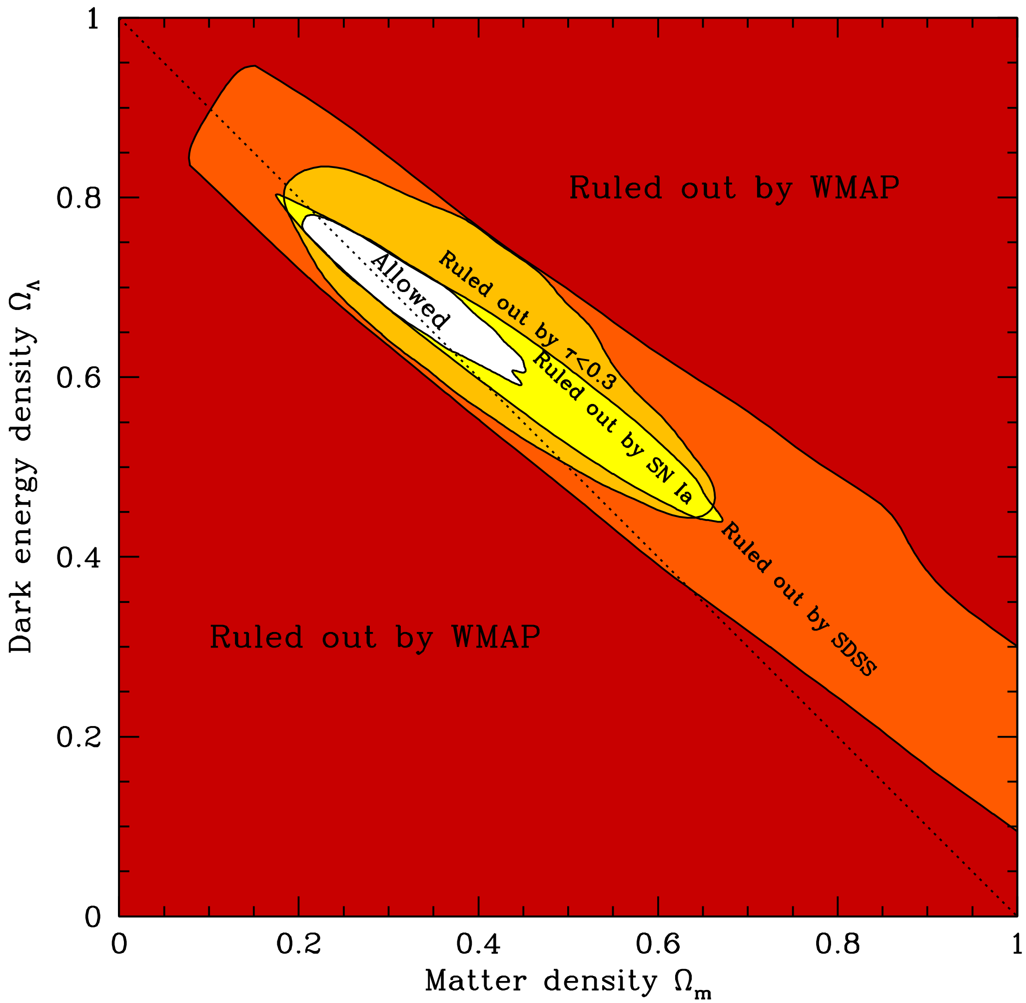
Cosmological Parameters with SDSS

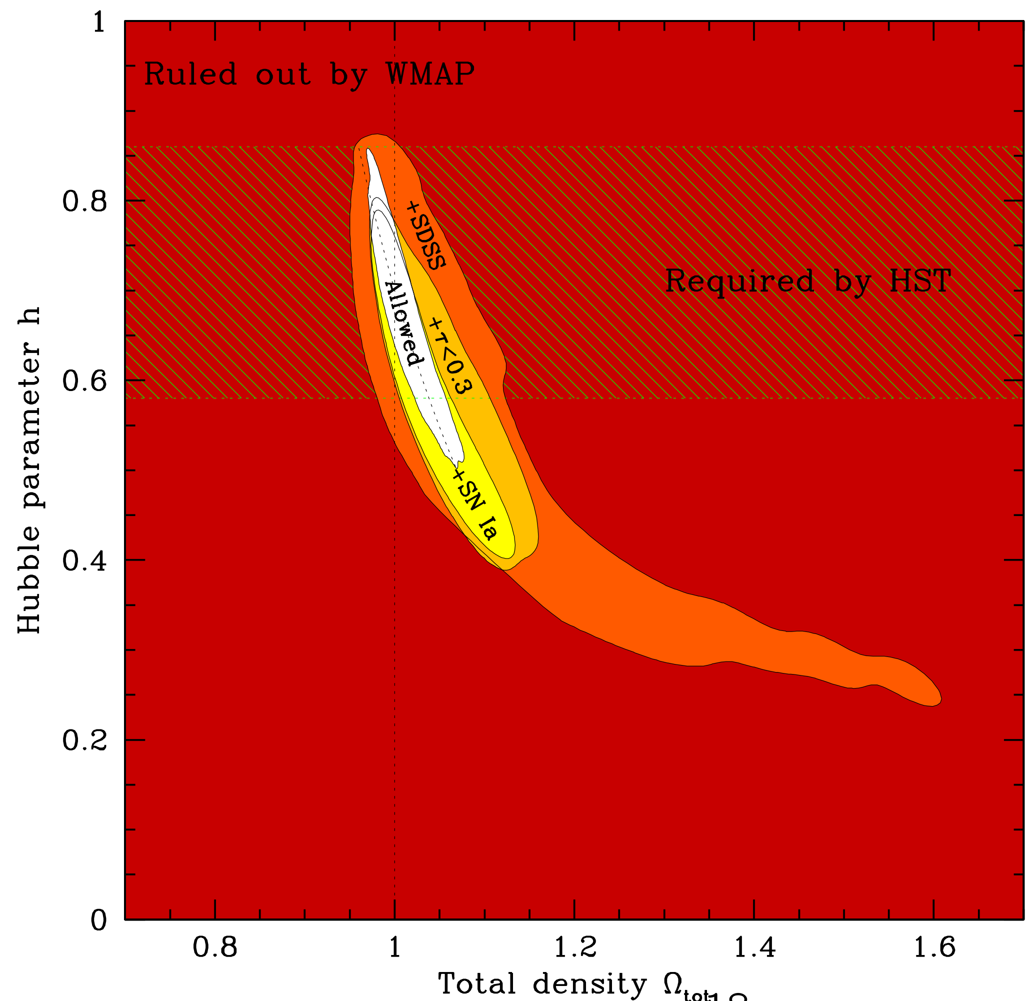
- CMB alone cannot break some degeneracies of cosmological parameters – need non-CMB data.
- Non-CMB measurements are "the weakest link in the quest for precision cosmology"

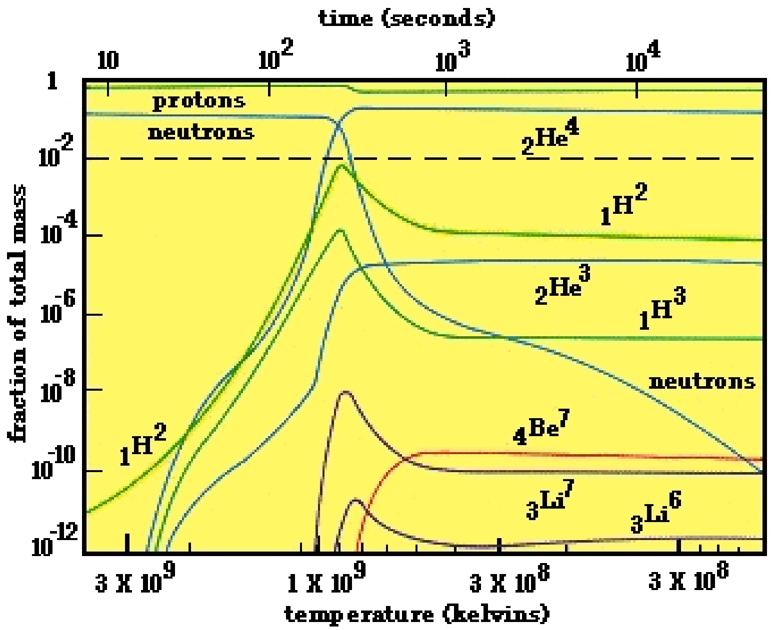
Cosmological Parameters with SDSS

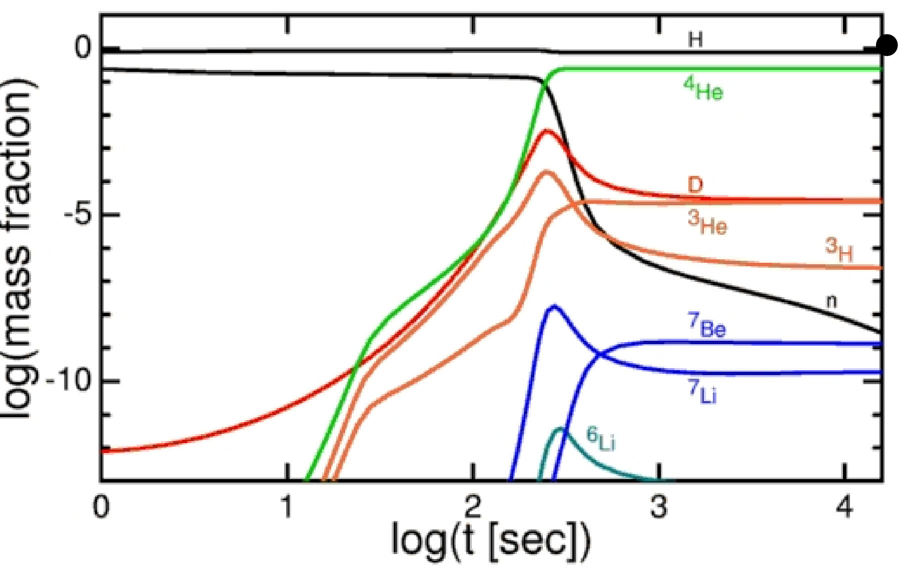
Tegmark et al. 2004

- SDSS helps to constrain the allowed range of cosmological parameters!





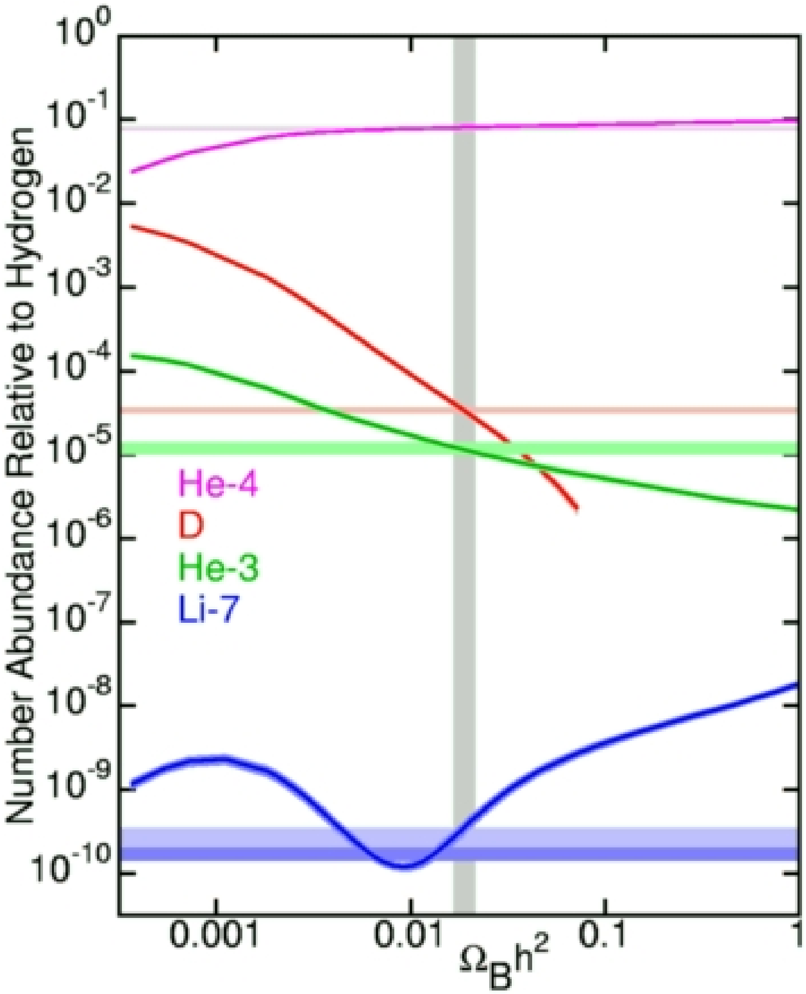




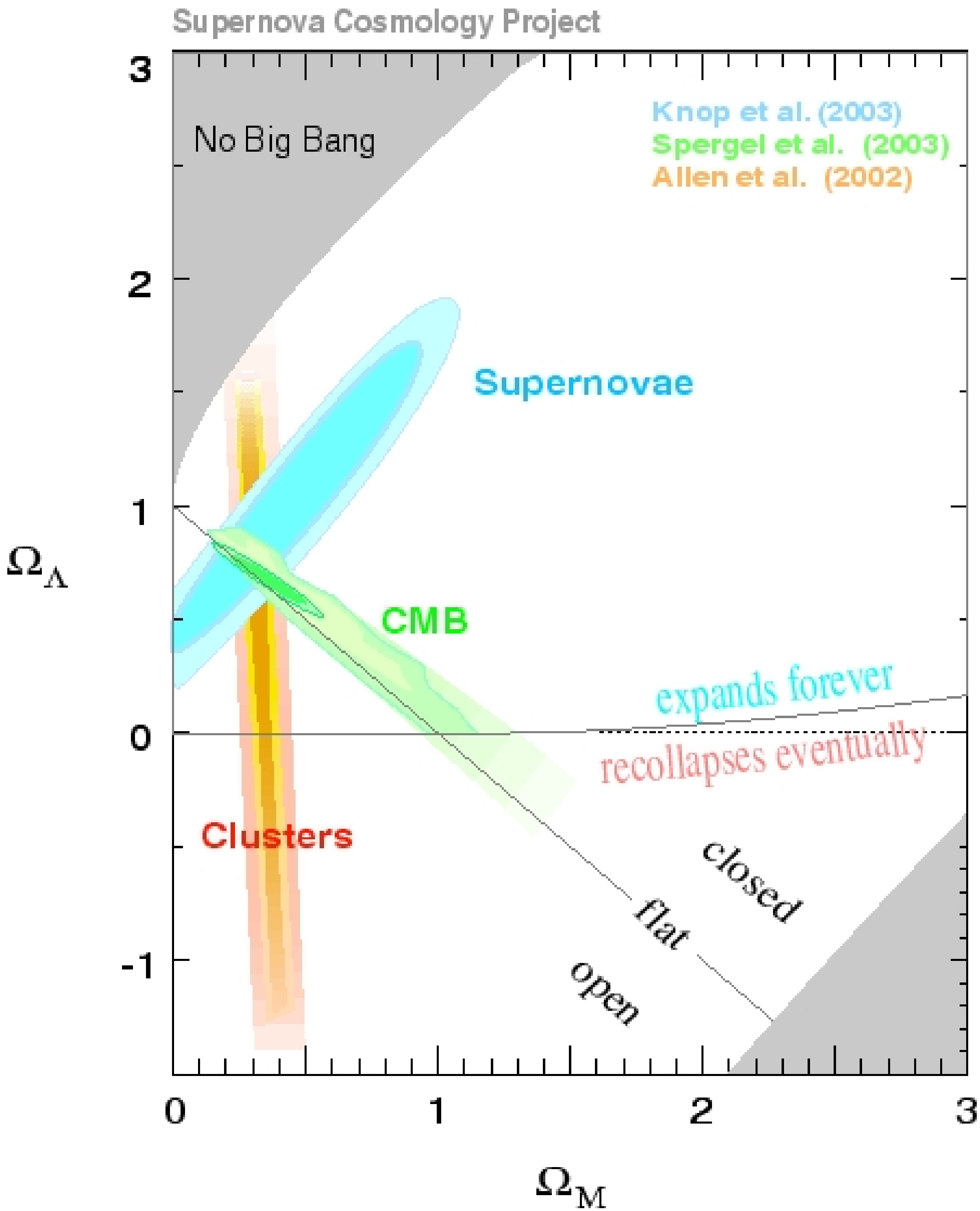
The Formation of Light Elements

- At high temperatures only neutrons (13%) and protons (87%) exist. When nucleosynthesis began, all the neutrons were incorporated into He nuclei, while the leftover protons remained as hydrogen nuclei. After this first wave of nucleosynthesis was completed, the universe consisted of roughly 25% He and 75% H (by weight).
- The deuterium (H^2), He^3, He^4 and Li^7 abundances depend on the single parameter of the current density of ordinary matter made out of protons and neutrons: baryonic matter, or Ω_b.

The Light Element Abundance as a Cosmological Constraint



- The graph shows the predicted abundance vs. baryon density for these light isotopes as curves, the observed abundances as horizontal stripes, and the derived baryon density as the vertical stripe.
- A single value of the baryon density Ω_b fits 4 abundances simultaneously.
- This value ($\sim$ 0.04) is much smaller than $\Omega_m \sim 0.24$ measured by other means (CMB, SNe, dynamical methods). Hence, most of matter is in non-baryonic form. Candidates are massive neutrinos, WIMPS (weakly interacting massive particles), axions, etc.

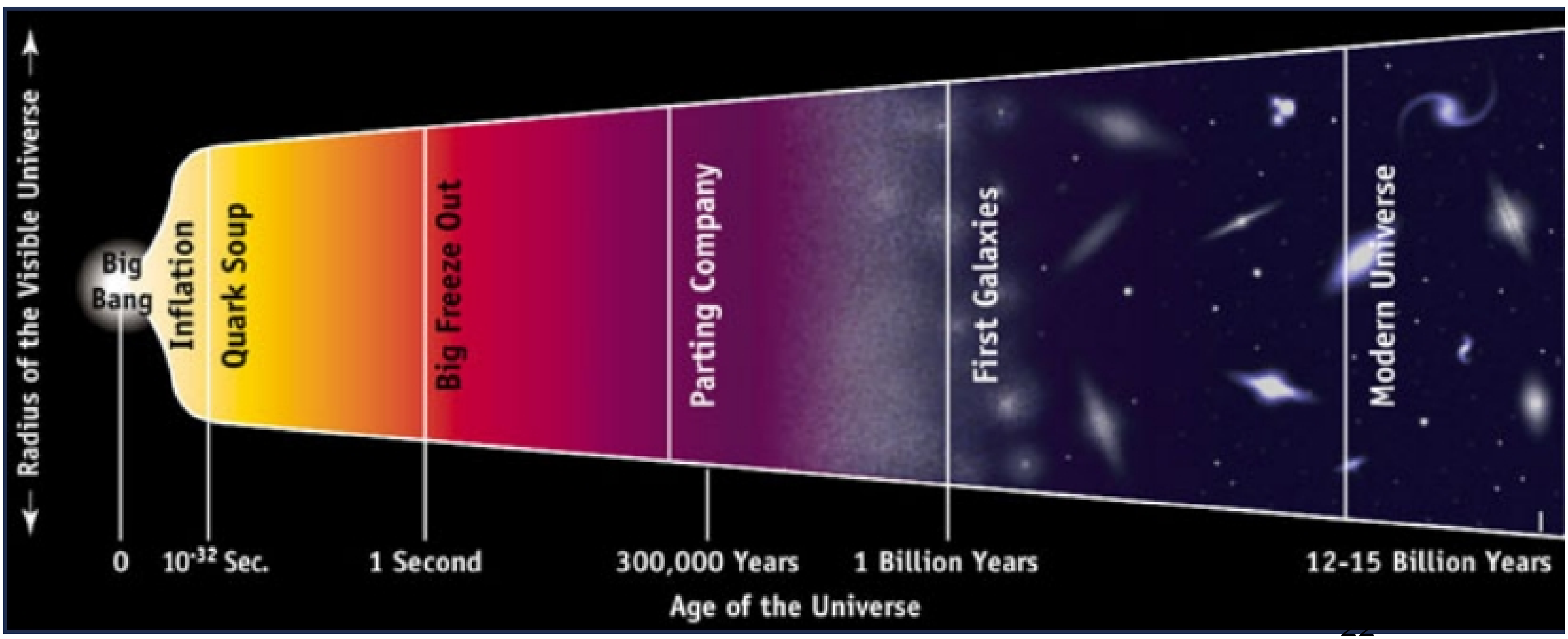


The Concordance Model

- A large number of fundamentally different observations are explained with the same model
- There is no other theory except the Big Bang that can explain all these observations
- Nevertheless, there are some unresolved "issues" with the Big Bang theory...

Early Universe and Inflation

- A brief review of elementary particle physics
- The density and temperature in the early universe were much higher than today – some major phases when the matter was in significantly different forms than today
- Unresolved problems with the Big Bang theory
- Inflation



A brief review of elementary particle physics

- Baryonic (*barys* means heavy in Greek) matter: particles made of three quarks (quarks are fundamental spin 1/2 particles, their names are *up, down, strange, charm, bottom and top*), e.g. protons (uud) and neutrons (udd) are baryons with the largest contributions to Ω_b (NB *nucleosynthesis* is the generation of atomic nuclei from neutrons and protons).
- Baryons other than protons and neutrons do exist (e.g. lambda particle), but are not stable and do not contribute to baryonic Ω (they are called *hyperons*).
- Electrons are leptons (rather than baryons), but they **are** considered as contributors (though minor, *lepton* means light in Greek) to baryonic (aka *normal*) matter. Leptons also include muons and tau particles. Each lepton has a corresponding neutrino (and each lepton has an antilepton, which also has a corresponding antineutrino).

A brief review of elementary particle physics

- There are about 10^9–10^{10} photons per each baryon in the Universe (NB the most common particles in the universe are neutrinos, or perhaps axions). Neutrinos are **very** lightweight. For example, the current upper limit on the mass of electron neutrino is 1/1,000,000 of the electron mass (and the latter is only 1/2000 of the nucleon's mass).
- When particles turn into each other, in addition to dynamical quantities such as energy and momentum, quantities such as charge, baryon number and lepton numbers also need to be **conserved**. For example, this is allowed

$$n \to p + e^- + \overline{\nu}_e \tag{1}$$

but this is not (lepton number is not conserved)

$$n \to p + e^- + \nu_e \tag{2}$$

Non-baryonic matter

- The contribution to the mass of the Universe from these particles is **not** sufficient to account for all the gravitational forces observed in the Universe.
- This suggests that other matter, known as dark matter, also exists that must be in some other form which we call non-baryonic matter. Examples are neutralinos, axions, massive neutrinos, etc.

Elementary particles in the early Universe:

Particle	Symbol	Mass (MeV)	Spin (h)	Charge (e)	Interaction
Quarks	u		1/2	2/3	G,W,E,S
	d			-1/3	
	c			2/3	
	s			-1/3	
	t			2/3	
	b			-1/3	
Leptons	ν_e	$< 3 \times 10^{-6}$	1/2	0	G,W
	e	0.511		-1	G,W,E
	ν_μ	< 0.19		0	G,W
	μ^-	105.66		-1	G,W,E
	ν_τ	< 18.2		0	G,W
	τ^-	1777		-1	G,W,E
Bosons	graviton	$< 10^{-36}$	2	0	G
	γ	$< 2 \times 10^{-22}$	1	0	G,E
	gluons		1	0	G,S
	$W^\pm$	8.04×10^4	1	-1	G,W,E
	Z^0	9.12×10^4	1	0	G,W

Early Universe: temperature vs. time

- As we run the cosmic time **backwards**, the density and temperature increase. The matter density (today $\Omega_m = 0.3$) increases as $(1+z)^3$, and the radiation density (today $\Omega_r = 5 \times 10^{-5}$) increases as $(1+z)^4$ (NB the lookback time connects time and redshift z). Therefore, despite being feeble today, the radiation used to be the dominant component in the universe.
- During the radiation-dominated era, the temperature T is equal to time t by

$$T \approx \sqrt{\frac{1\,\mathrm{sec}}{t}}\, 10^{10}\ \mathrm{K} \tag{3}$$

- This expression can be trusted for times after the Planck time

$$t_P = \sqrt{\frac{\hbar G}{c^5}} = 5.39 \times 10^{-44}\,\mathrm{s} \tag{4}$$

- For times earlier than that we cannot trust the physics we know, because we can't test it at implied extremely high energies/temperatures. But that's only one part in $\sim 10^{61}$ of the age of the universe, so we are not that bad...

Early Universe: radiation–matter equality

- Given Ω_r and Ω_m today, one would naively expect that the epoch of radiation–matter equality happens around $z \sim \Omega_m/\Omega_r \approx 10,000$. Recall that $R = 1/(1+z)$ and $T(t)R(t)$=const. Therefore, the radiation temperature is

$$T_r \approx 3\,(1+z)\,\mathrm{K} \tag{5}$$

  and thus for $z = 10,000$, we get $T_r = 30,000$ K.
- However, this is not the correct temperature for the radiation–matter equality. One needs to take into account that there are 10^9–10^{10} photons per each baryon, and hence even much lower temperature will have enough high energy photons ($E > 13.1$ eV) to ionize hydrogen. Using Planck function, we can find that already for $T = 3,000$ K, there are a fraction of $\sim 10^{-9}$ photons with $E > 13.1$ eV. Matter and radiation decouple when $T \sim 3,000$ K.
- This temperature corresponds to $z \sim 1000$, and represents the epoch observed today as the CMB.

Early Universe: the freezing of the N_n/N_p ratio

- After matter and radiation decouple, radiation evolves in an uneventful fashion, while matter collapses to make galaxies, stars, you and me.
- What was the state of matter at the time of decoupling?
- Let's start from the cosmic time equal to 10^{-4} sec. This corresponds to $z \approx 10^{12}$, and the temperature at that time was $T \approx 10^{12}$ K.
- The decay times of exotic particles are much shorter than 10^{-4} sec, and thus at that time all baryonic matter is in form of protons and neutrons. The universe also contains a mixture of photons and leptons (electrons, positrons, neutrinos, etc).
- At this temperature, the characteristic thermal energy of particles is

$$E_{kT} = \left(\frac{T}{10^{12}\,\mathrm{K}}\right) 86\,\mathrm{MeV} \tag{6}$$

- This is much higher energy than the proton-to-neutron mass difference of 1.3 MeV, and thus their numbers are practically equal (no nuclei exist!).

Early Universe: the freezing of the N_n/N_p ratio

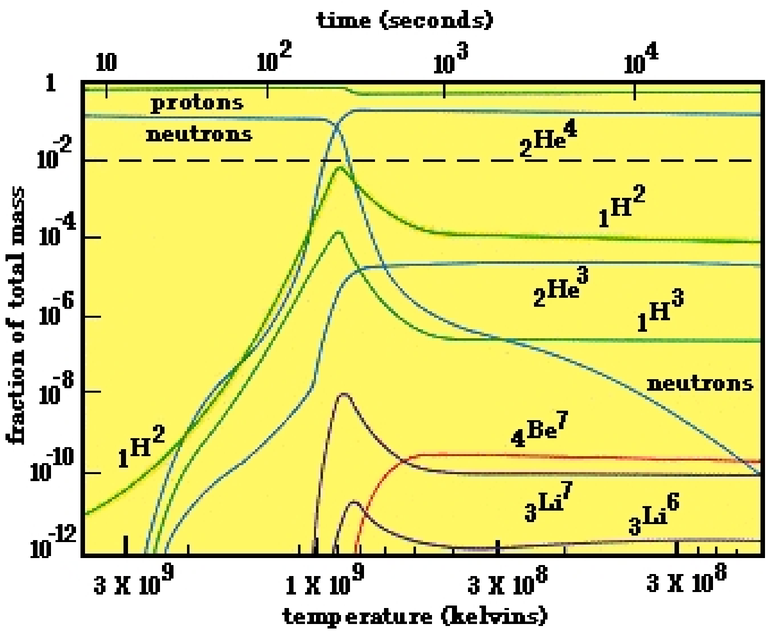
- The equilibrium number ratio of neutrons and protons is given by the Boltzmann equation

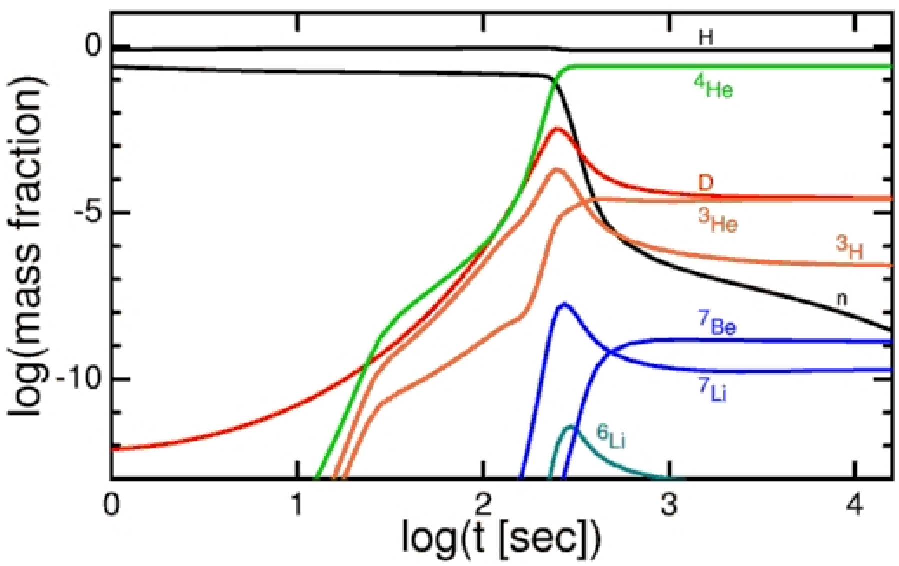
$$\frac{N_n}{N_p} = \mathrm{e}^{-\frac{(m_p - m_c)c^2}{kT}} \tag{7}$$

- The characteristic timescale for nuclear reactions that maintain this equilibrium is a strong function of temperature

$$\tau_{n \rightleftharpoons p} = \left(\frac{10^{10}\,\mathrm{K}}{T}\right)^5, 10\,\mathrm{sec} \tag{8}$$

- For $T >> 10^{10}$ K, these reactions are much faster than the age of the universe (which is proportional to T^{-2}), but for $T << 10^{10}$ K they become very slow (with timescale much longer than the age of the universe)
- The result is that, as the temperature falls below $\sim 10^{10}$ K, the neutron to proton number ratio becomes "frozen" at $N_n/N_p \sim 0.15$. What's next?





The Formation of Light Elements

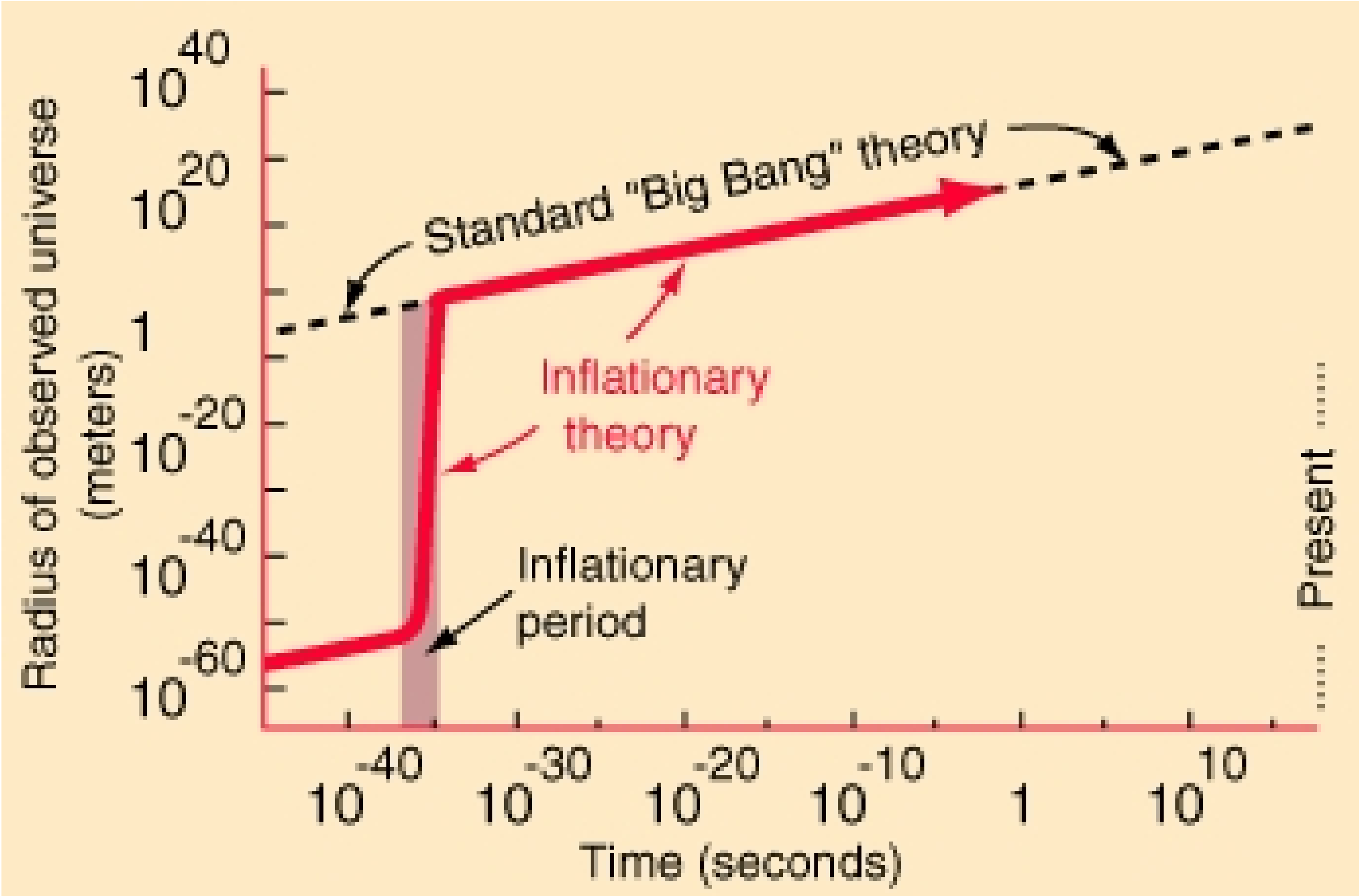
- At high temperatures only neutrons (13%) and protons (87%) exist.
- When nucleosynthesis began, roughly 10 sec after the Big Bang, all the neutrons were incorporated into He nuclei, while the leftover protons remained as hydrogen nuclei.
- After this first wave of nucleosynthesis was completed in about 3 minutes, the universe consisted of roughly 25% He and 75% H (by weight).
- The deuterium (H^2), He^3, He^4 and Li^7 abundances depend on a single parameter: the current density of ordinary matter made out of protons and neutrons: baryonic matter, or Ω_b.

The Problems with the Big Bang Theory

- The Big Bang is a scientific theory and thus it is constantly subjected to critical re-examination in the context of new observations and theoretical results. **No scientist** thinks that the Big Bang theory **must** be correct! Indeed, there are some problems with the picture that we discussed so far:
- Why is the CMB so smooth (fluctuations are only one part in $\sim 10^{-5}$)? How did causaly disconnected photons know what should be their temperature? The horizon problem.
- Why is the universe (so nearly) flat? Unless it is **exactly flat**, we have a fine-tuning problem. The flatness problem.
- Why is the universe made of matter, rather than of antimatter? What caused this asymmetry? The matter-antimatter asymmetry problem.
- Why are there so many photons in the universe?
- What physical process produced the initial fluctuations in the density of matter?
- How can we begin to understand these problems?

The Inflation Theory

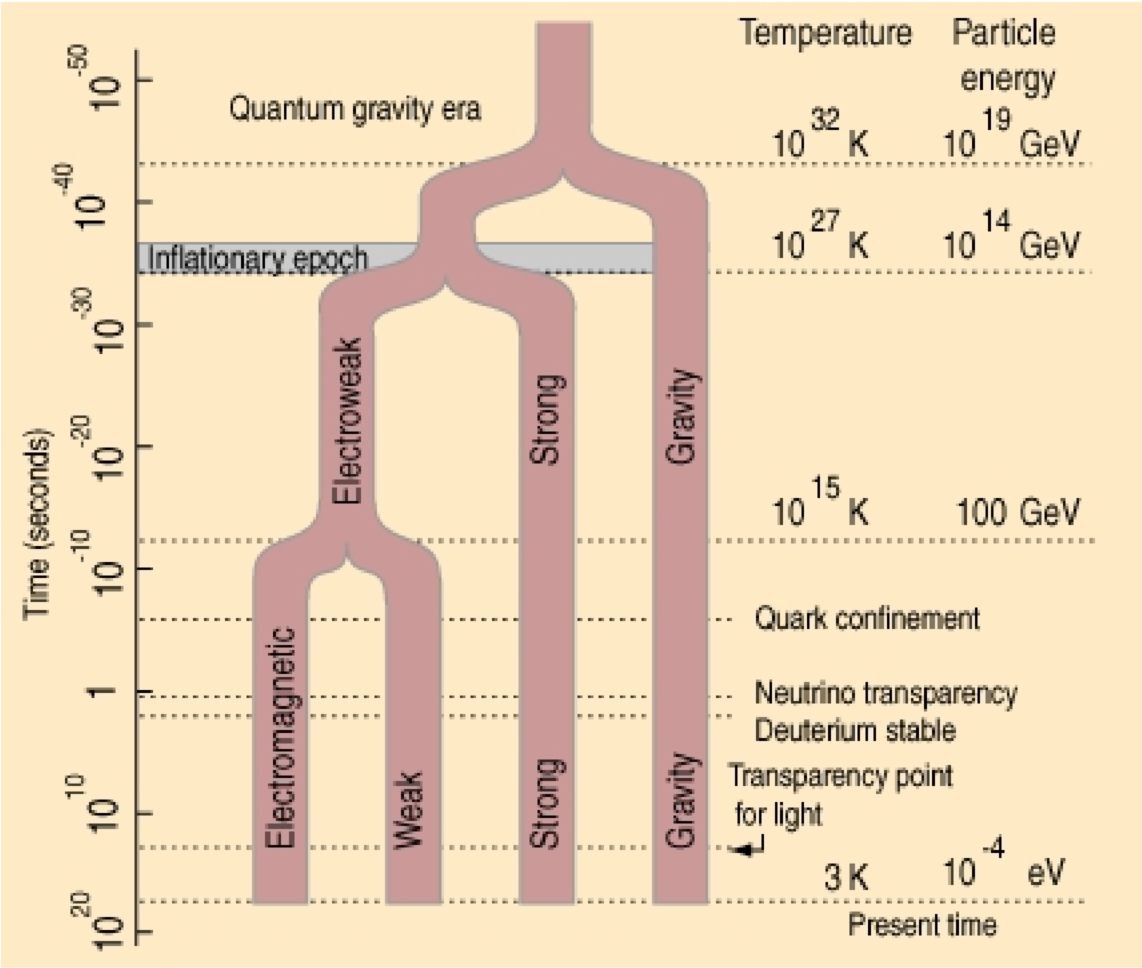
- The inflation theory links important ideas in modern physics, such as symmetry breaking and phase transitions, to cosmology.
- Inflation theory is based on the presence of vacuum energy: particles and antiparticles forming out of nothing and then re-combining (Alan Guth, the proposer of this theory, called this "the ultimate free lunch").
- The theory **assumes** a period of extremely rapid (exponential) expansion of the universe about 10^{-35} seconds after the Big Bang, during which time the energy density of the universe was dominated by a cosmological constant term. This caused very strong acceleration lasting for about 10^{-32} seconds, during which the universe increased its size scale by about a factor of 10^{50}!
- Then the universe settled down into the big bang evolution that we have discussed prior to this point.



Radius of observed universe (meters)
10^{40}
10^{20}
1
10^{-20}
10^{-40}
10^{-60}
Standard "Big Bang" theory
Inflationary theory
Inflationary period
Present
10^{-40}
10^{-30}
10^{-20}
10^{-10}
1
10^{10}
Time (seconds)

The Inflation Theory

- This fast "inflationary" expansion, much faster than assumed in the standard big bang models, is a consequence of the nuclear force breaking away from the weak and electromagnetic forces, that it was unified with at higher temperatures, in what is called a phase transition.

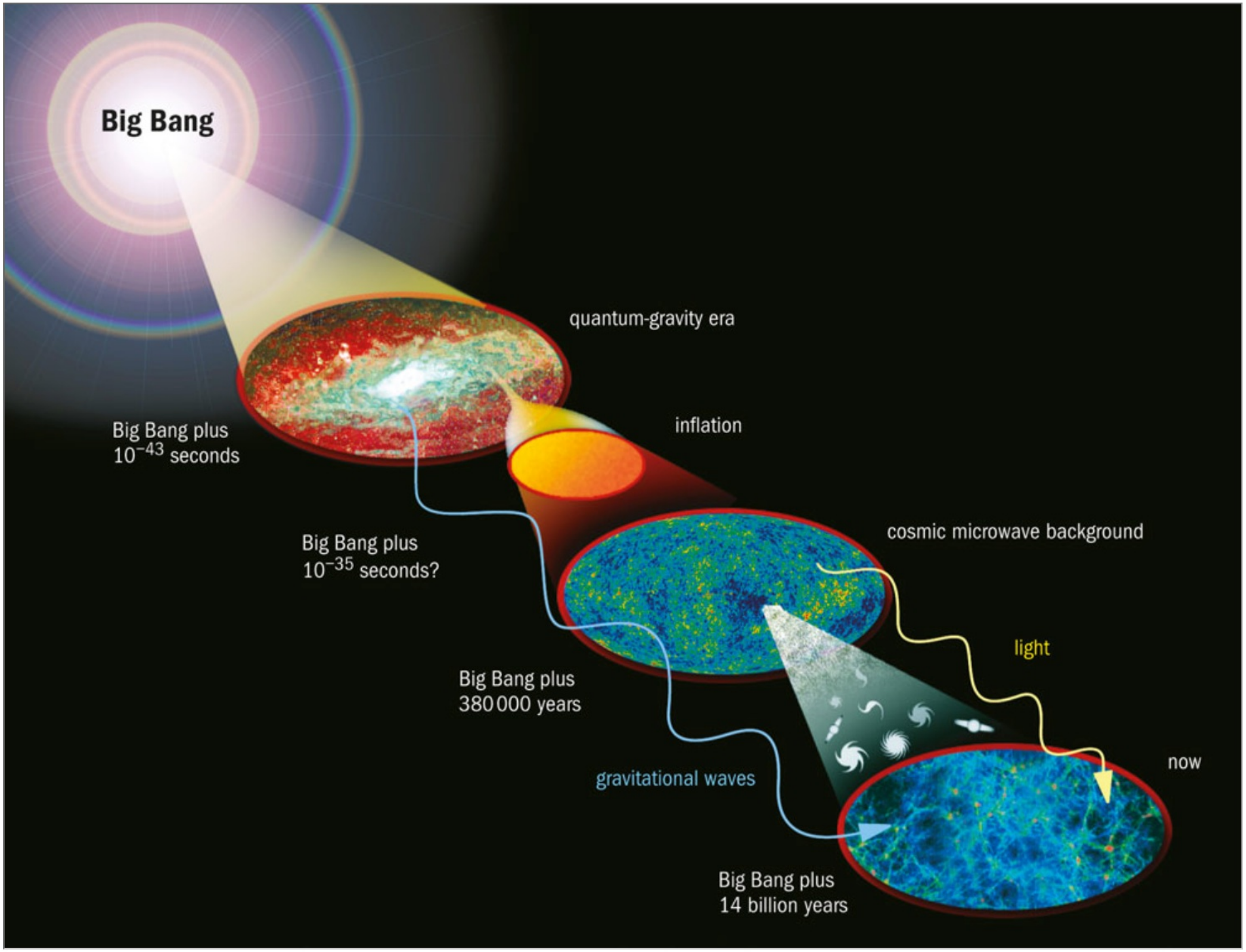


The Inflation Theory

- This fast "inflationary" expansion, much faster than assumed in the standard big bang models, is a consequence of the nuclear force breaking away from the weak and electromagnetic forces, that it was unified with at higher temperatures, in what is called a phase transition.
- The fast expansion simultaneously solves the horizon and flatness problems. The tremendous expansion means that regions that we see widely separated in the sky now at the horizon were much closer together before inflation and thus could have been in causal contact.
- This cosmological constant term, due to vacuum energy, later decayed to produce the matter and radiation that fill the universe today.
- Bonus: the inflation is capable of producing small density fluctuations that can later in the history of the Universe provide the seeds to cause matter to begin to clump together to form the galaxies and other observed structure.

Predictions of the inflation theory

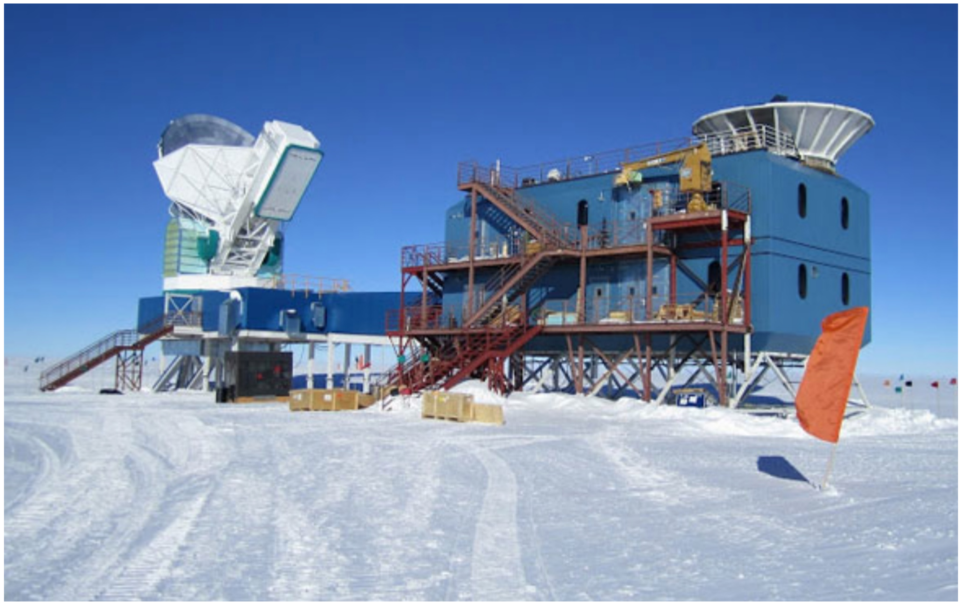
- One of the basic tenants of science is that theories must have predictions that can be tested:
- The density of the universe is close to the critical density, and thus the geometry of the universe is flat.
- The fluctuations in the primordial density in the early universe had the same amplitude on all physical scales.
- There should be, on average, equal numbers of hot and cold spots in the fluctuations of the cosmic microwave background temperature.
- WMAP has recently tested these predictions and they seem to hold up.
- Nevertheless, there are unsolved theoretical problems within the inflation theory, and this is an active area of research. Most cosmologists today believe inflation to be correct at least in its outlines, but further investigation is definitely required to establish whether this is indeed so.

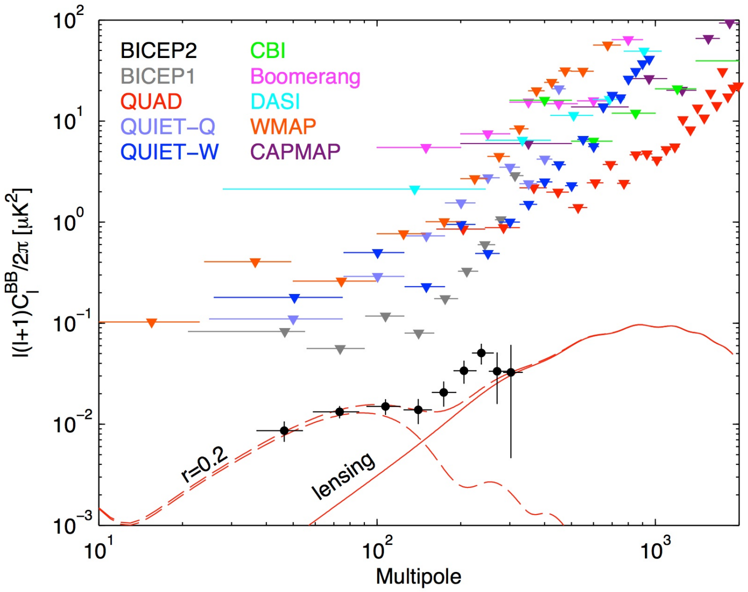


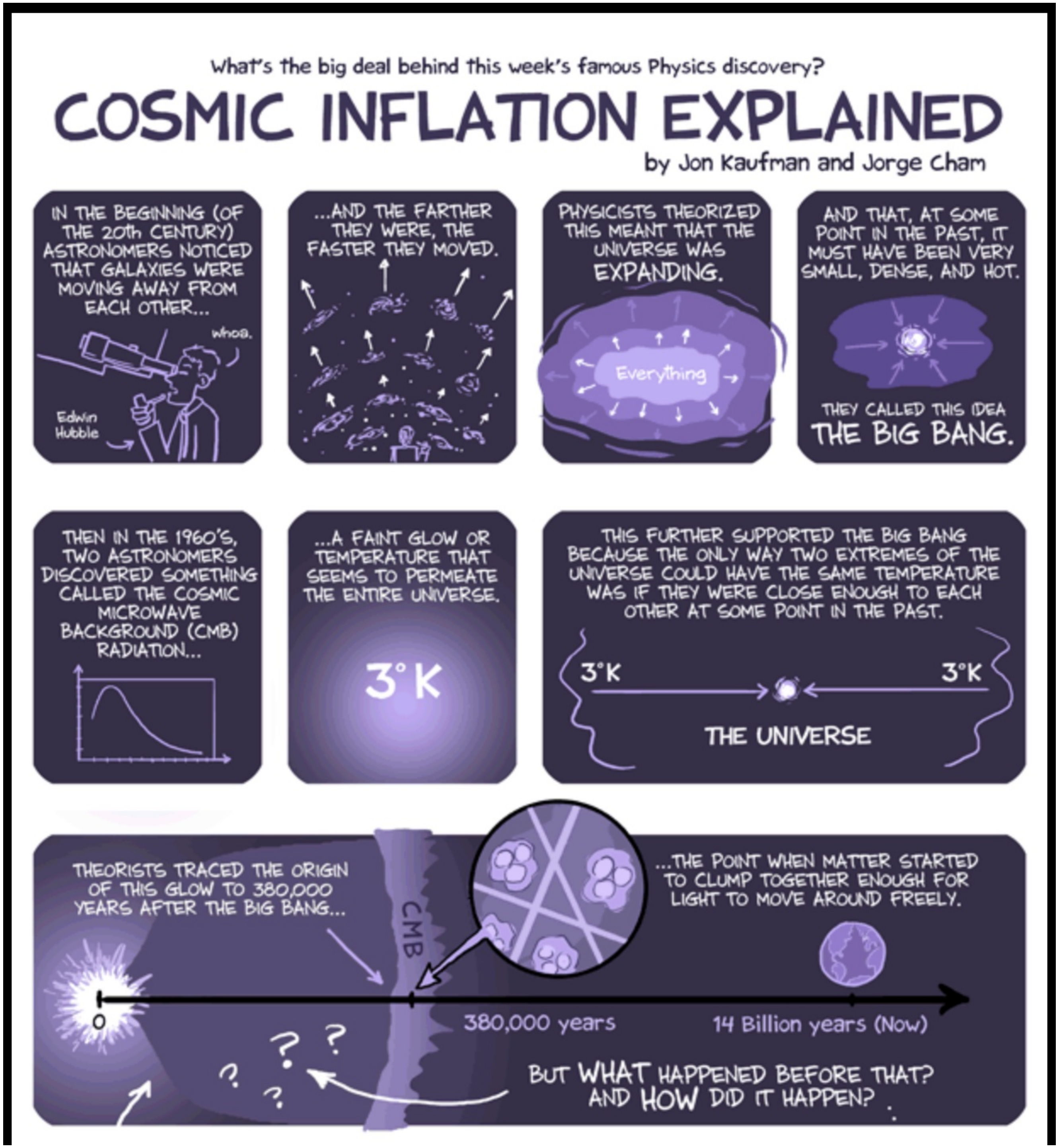
The universe has undergone several dramatic changes in its 13.7 billion-year history, although our knowledge of the early universe contains some gaps. The cosmic microwave background reveals the intensity and polarization of primordial light as it was 380,000 years after the Big Bang, when the universe became transparent to light. We therefore cannot use electromagnetic radiation to directly study the universe before this time, although fluctuations in the temperature and polarization of the microwave background on very large scales do preserve much earlier events that took place during cosmic inflation. (Courtesy: NASA)

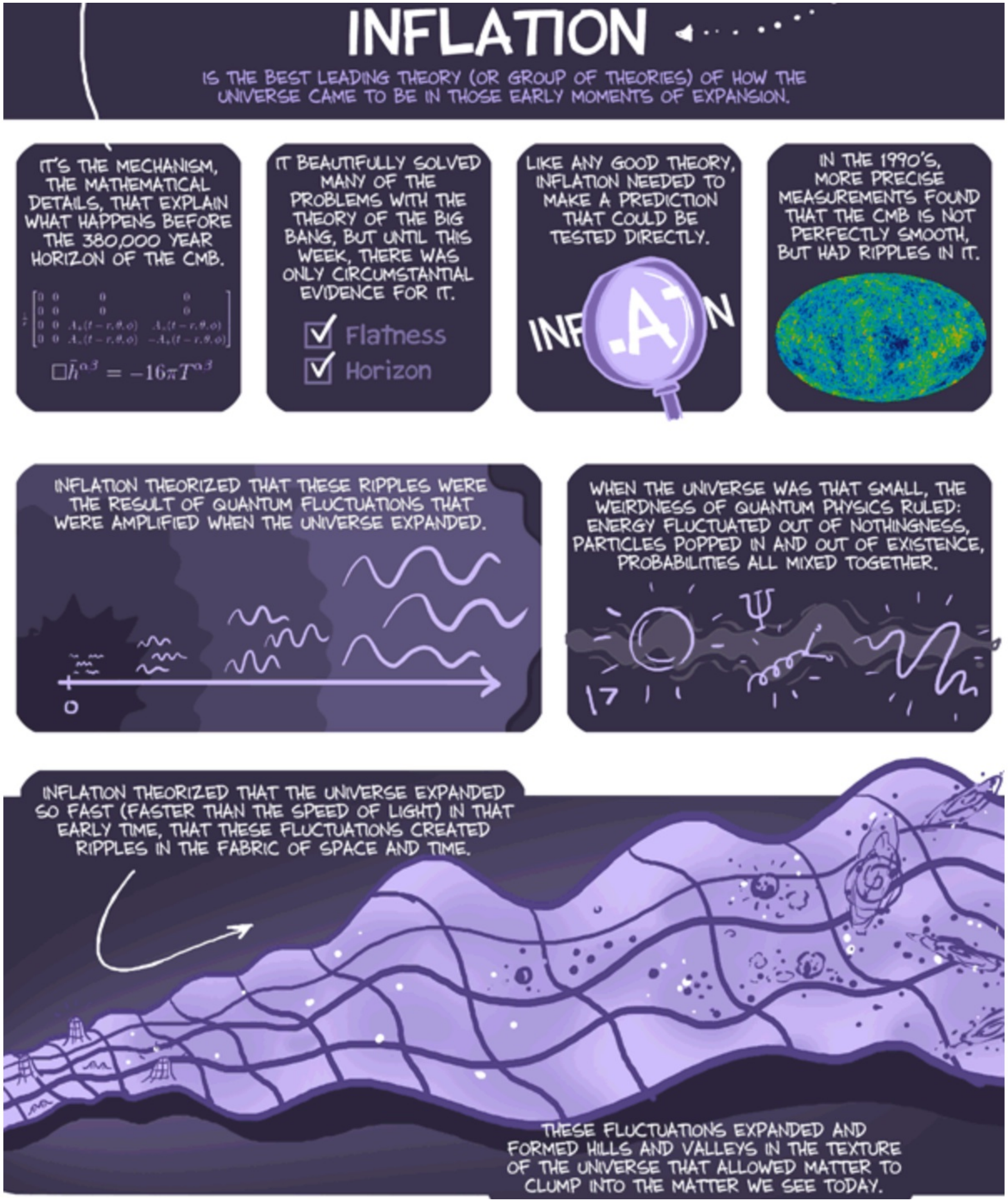
Latest news on inflation!

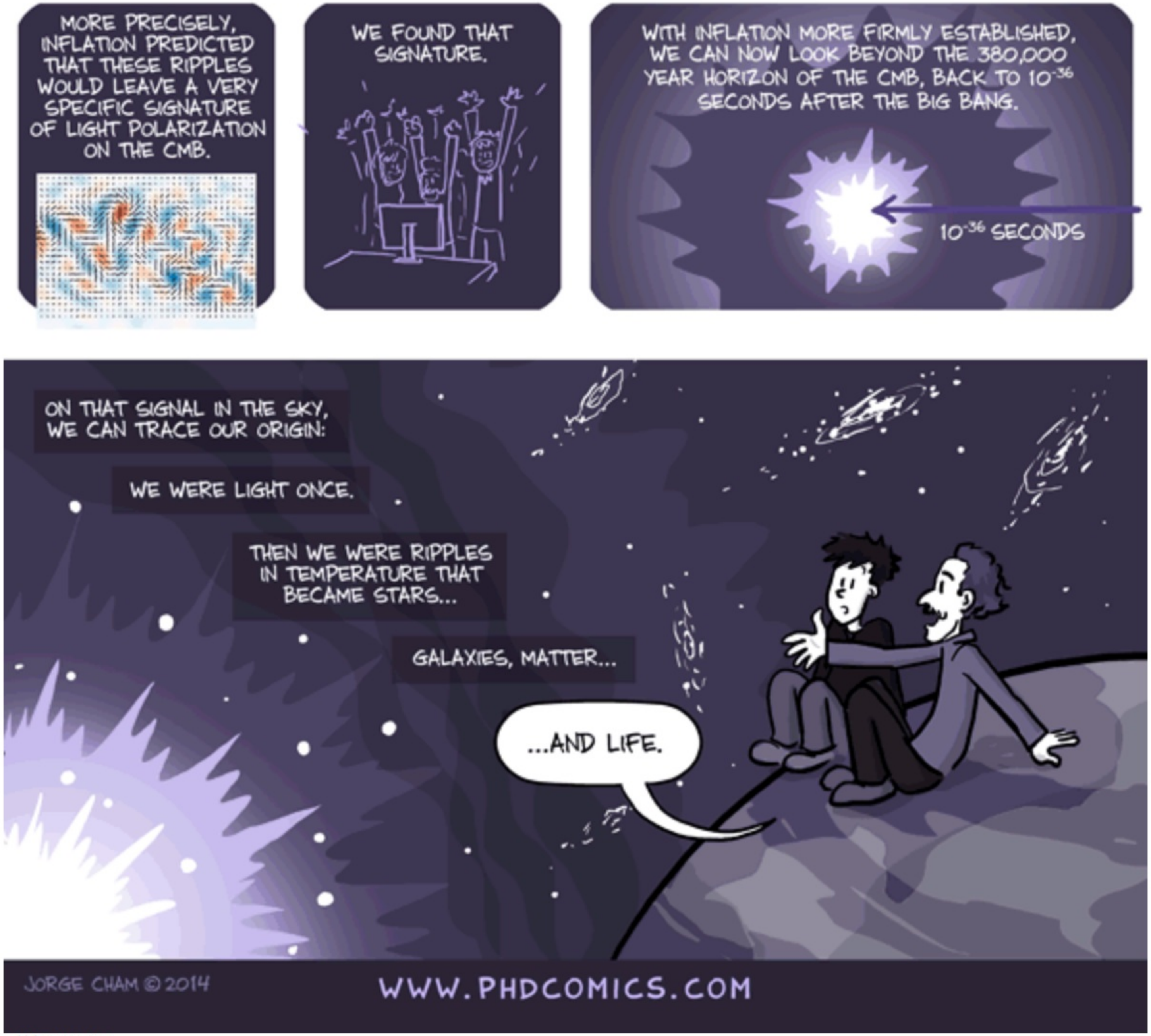
- BICEP2 collaboration reported "Detection Of B-mode Polarization at Degree Angular Scales" (arXiv:1403.3985)
- What does that mean? The primordial B-mode polarization signal, which is related to primordial gravitational waves that flowed through the early universe, is the first direct evidence for cosmic inflation.
- If true, of course... This is a brand new result and more experimental verification is needed...






What's the big deal behind this week's famous Physics discovery?
COSMIC INFLATION EXPLAINED
by Jon Kaufman and Jorge Cham
IN THE BEGINNING (OF THE 20th CENTURY) ASTRONOMERS NOTICED THAT GALAXIES WERE MOVING AWAY FROM EACH OTHER...
whoa.
Edwin Hubble
...AND THE FARTHER THEY WERE, THE FASTER THEY MOVED.
PHYSICISTS THEORIZED THIS MEANT THAT THE UNIVERSE WAS EXPANDING.
Everything
AND THAT, AT SOME POINT IN THE PAST, IT MUST HAVE BEEN VERY SMALL, DENSE, AND HOT.
THEY CALLED THIS IDEA THE BIG BANG.
THEN IN THE 1960'S, TWO ASTRONOMERS DISCOVERED SOMETHING CALLED THE COSMIC MICROWAVE BACKGROUND (CMB) RADIATION...
...A FAINT GLOW OR TEMPERATURE THAT SEEMS TO PERMEATE THE ENTIRE UNIVERSE.
3°K
THIS FURTHER SUPPORTED THE BIG BANG BECAUSE THE ONLY WAY TWO EXTREMES OF THE UNIVERSE COULD HAVE THE SAME TEMPERATURE WAS IF THEY WERE CLOSE ENOUGH TO EACH OTHER AT SOME POINT IN THE PAST.
3°K
3°K
THE UNIVERSE
THEORISTS TRACED THE ORIGIN OF THIS GLOW TO 380,000 YEARS AFTER THE BIG BANG...
CMB
...THE POINT WHEN MATTER STARTED TO CLUMP TOGETHER ENOUGH FOR LIGHT TO MOVE AROUND FREELY.
0
380,000 years
14 Billion years (Now)
BUT WHAT HAPPENED BEFORE THAT? AND HOW DID IT HAPPEN?


INFLATION
IS THE BEST LEADING THEORY (OR GROUP OF THEORIES) OF HOW THE UNIVERSE CAME TO BE IN THOSE EARLY MOMENTS OF EXPANSION.
IT'S THE MECHANISM, THE MATHEMATICAL DETAILS, THAT EXPLAIN WHAT HAPPENS BEFORE THE 380,000 YEAR HORIZON OF THE CMB.
$\Box\bar{h}^{\alpha\beta} = -16\pi T^{\alpha\beta}$
IT BEAUTIFULLY SOLVED MANY OF THE PROBLEMS WITH THE THEORY OF THE BIG BANG, BUT UNTIL THIS WEEK, THERE WAS ONLY CIRCUMSTANTIAL EVIDENCE FOR IT.
Flatness
Horizon
LIKE ANY GOOD THEORY, INFLATION NEEDED TO MAKE A PREDICTION THAT COULD BE TESTED DIRECTLY.
INFLATION
IN THE 1990'S, MORE PRECISE MEASUREMENTS FOUND THAT THE CMB IS NOT PERFECTLY SMOOTH, BUT HAD RIPPLES IN IT.
INFLATION THEORIZED THAT THESE RIPPLES WERE THE RESULT OF QUANTUM FLUCTUATIONS THAT WERE AMPLIFIED WHEN THE UNIVERSE EXPANDED.
0
WHEN THE UNIVERSE WAS THAT SMALL, THE WEIRDNESS OF QUANTUM PHYSICS RULED: ENERGY FLUCTUATED OUT OF NOTHINGNESS, PARTICLES POPPED IN AND OUT OF EXISTENCE, PROBABILITIES ALL MIXED TOGETHER.
INFLATION THEORIZED THAT THE UNIVERSE EXPANDED SO FAST (FASTER THAN THE SPEED OF LIGHT) IN THAT EARLY TIME, THAT THESE FLUCTUATIONS CREATED RIPPLES IN THE FABRIC OF SPACE AND TIME.
THESE FLUCTUATIONS EXPANDED AND FORMED HILLS AND VALLEYS IN THE TEXTURE OF THE UNIVERSE THAT ALLOWED MATTER TO CLUMP INTO THE MATTER WE SEE TODAY.



****footnote:***

Jon Kaufman (soon to be Dr. Jon Kaufman) is a member of the BICEP2 team that made the discovery described above. As one of the Ph.D. students in the project, Jon spent many months in the South Pole (there is an actual pole), recharging the liquid Helium on the telescope, for which he received a medal. It was his idea to draw this comic.