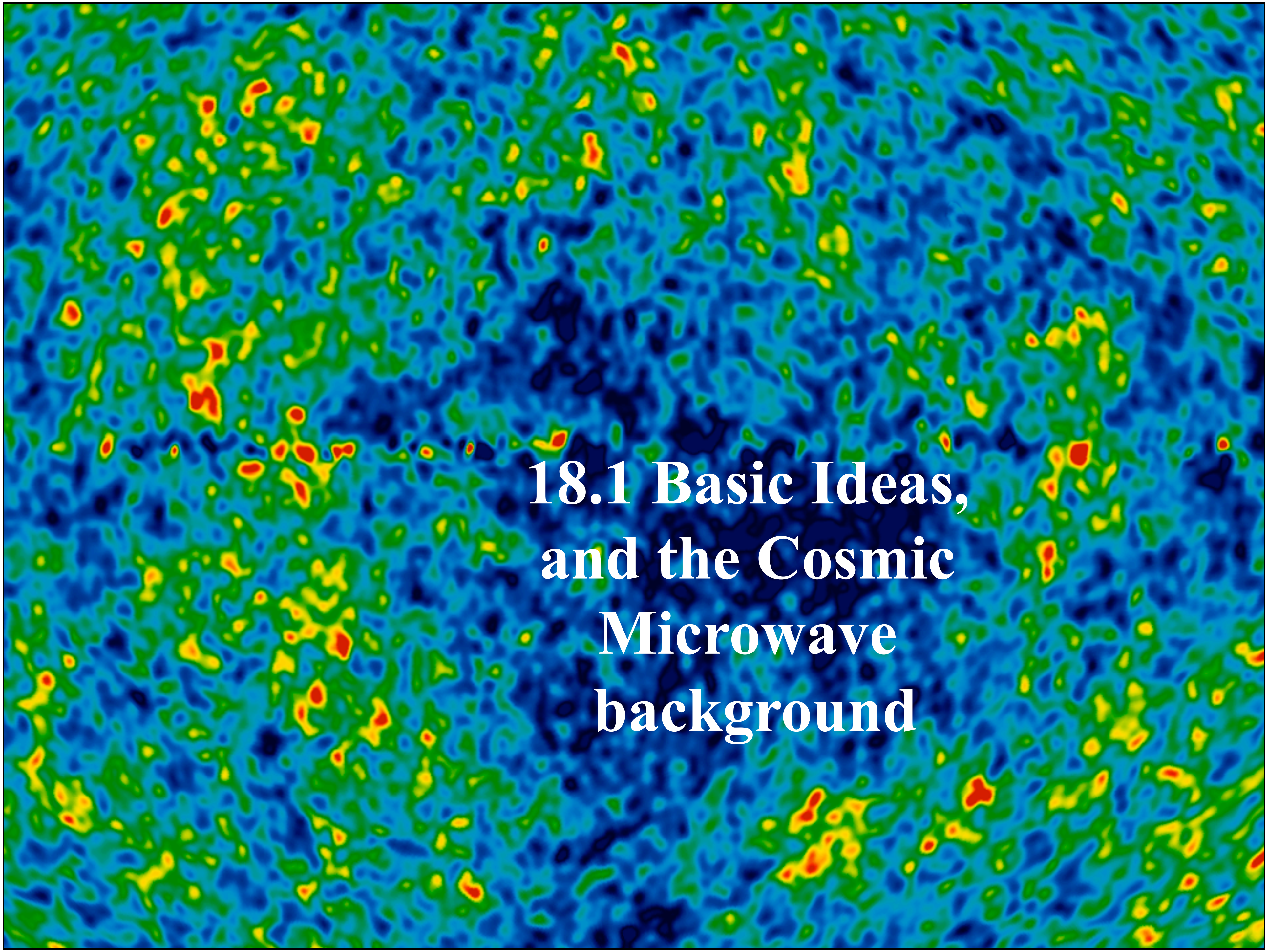
Ay1 – Lecture 18

The Early Universe

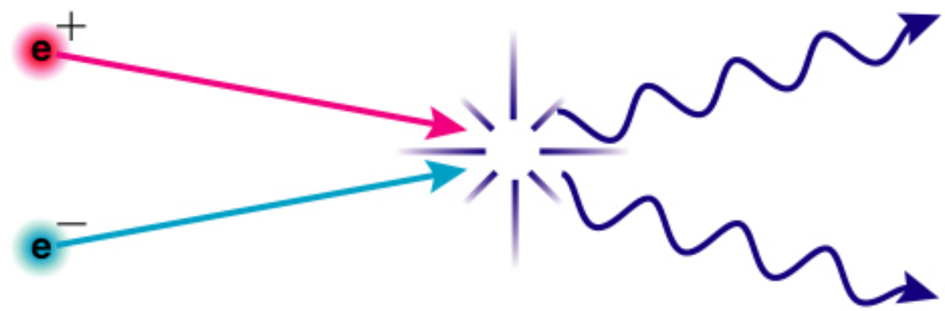
and the Cosmic Microwave Background



18.1 Basic Ideas, and the Cosmic Microwave background

The Key Ideas

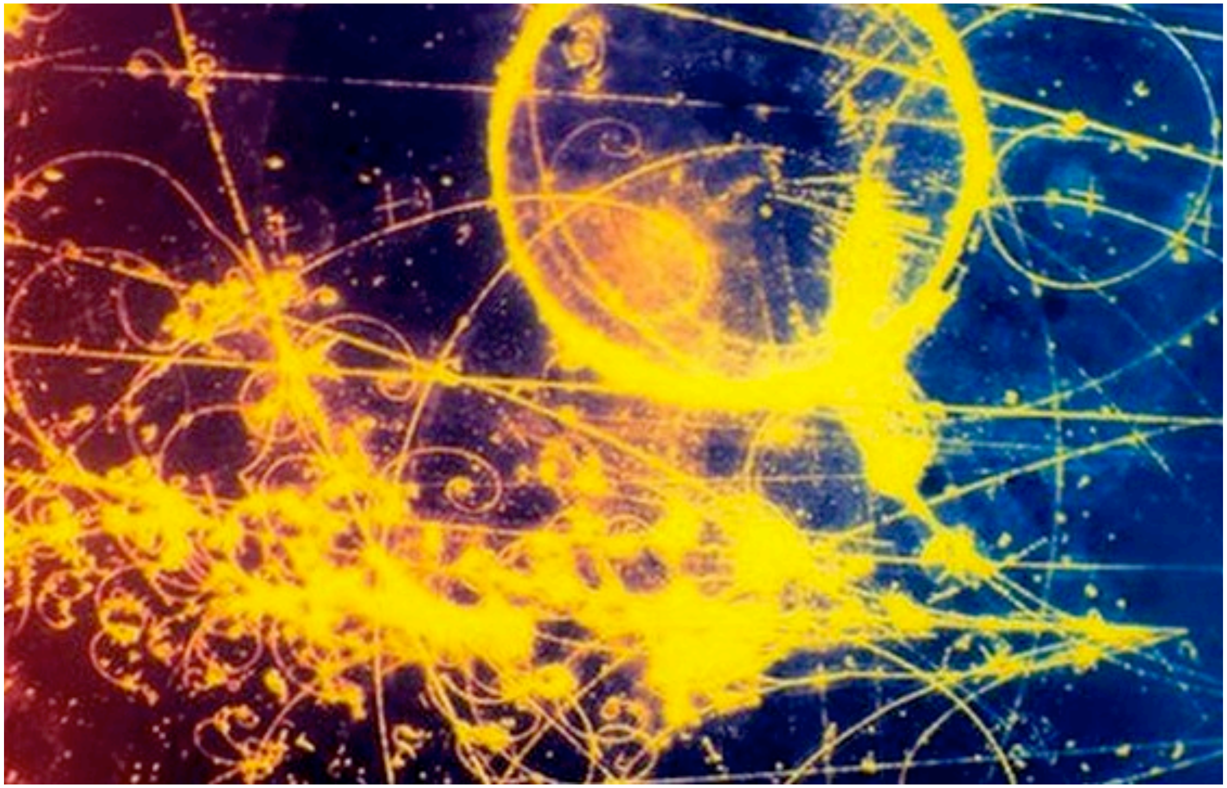
- Pushing backward in time towards the Big Bang, the universe was hotter and denser in a fairly predictable manner (aside from he surprising “glitches” such as the inflation…)
- At any given time, the radiation temperature translates into characteristic masses of particles, with the particle-antiparticle pairs created, which then annihilate and dominate that epoch: the universe as the ultimate accelerator?



$$mc^2 \sim kT$$

The Key Ideas

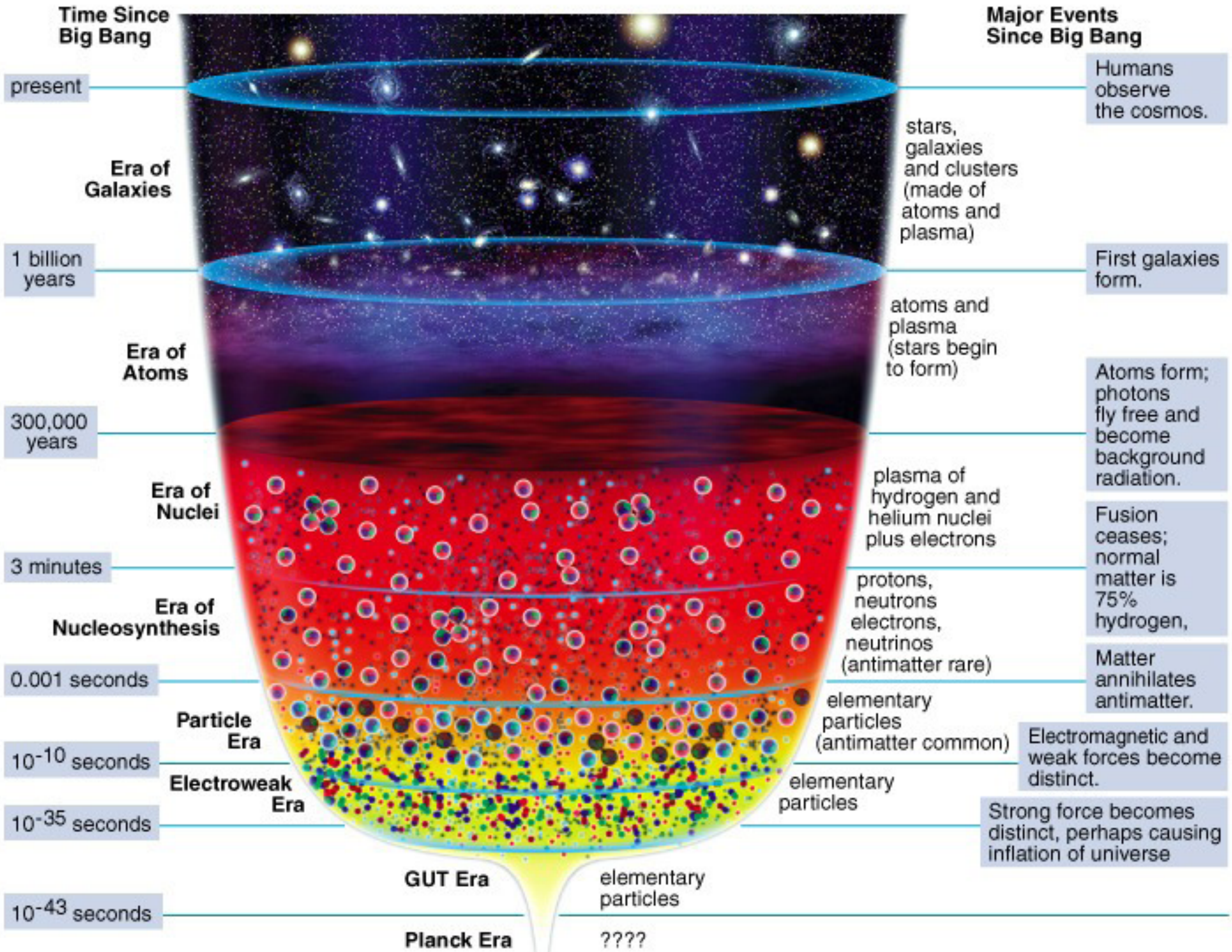
- As the energies increase, different physical regimes and different fundamental interactions come into play
- The closer we get to the Big Bang (i.e., further away from the experimentally probed regime), the less certain the physics: the early universe as the laboratory of physics beyond the standard model?



- Our extrapolations must break down by the epoch of ~ 10^{-43} sec ~ Plack time, where quantum gravity must be important

Some Key Moments in the Thermal History of the Universe:

- **Planck era, t ~ 10^{-43} sec**: quantum gravity, … ??? …
- **Inflation, t ~ 10^{-33} sec**: vacuum phase transition, exponential expansion
- **Grand Unification, t ~ 10^{-32} sec**: strong and electroweak interactions split
- **Baryogenesis , t ~ 10^{-6} sec**: quark-hadron transition
- **Nucleosynthesis , t ~ 1 ms to 3 min**: D, He, Li, Be form
- **Radiation to matter dominance transition, t ~ 10^{5} yr**: structure begins to form
- **Recombination, t ~ 380,000 yr**: hydrogen becomes neutral, CMBR released, dark ages begin
- **Reionization, t ~ 0.3 - 1 Gyr**: first galaxies and QSOs reionize the universe, the cosmic renaissance



Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
Era of Galaxies
stars, galaxies and clusters (made of atoms and plasma)
1 billion years
First galaxies form.
Era of Atoms
atoms and plasma (stars begin to form)
300,000 years
Atoms form; photons fly free and become background radiation.
Era of Nuclei
plasma of hydrogen and helium nuclei plus electrons
3 minutes
Fusion ceases; normal matter is 75% hydrogen,
Era of Nucleosynthesis
protons, neutrons electrons, neutrinos (antimatter rare)
0.001 seconds
Matter annihilates antimatter.
Particle Era
elementary particles (antimatter common)
10^{-10} seconds
Electromagnetic and weak forces become distinct.
Electroweak Era
elementary particles
10^{-35} seconds
Strong force becomes distinct, perhaps causing inflation of universe
GUT Era
elementary particles
10^{-43} seconds
Planck Era
????

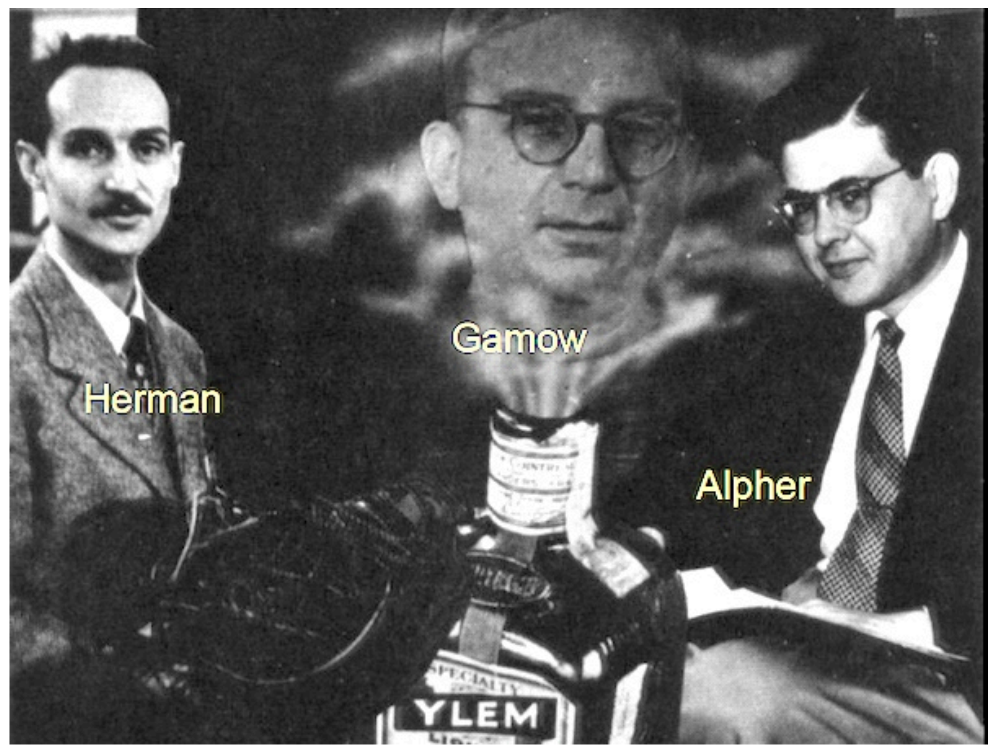
Empirical Evidence

- **The CMBR:** probes the recombination era, $t \sim 10^5$ yr, $z \sim 1100$, based on a well understood atomic and macroscopic physics
- **Nucleosynthesis:** probes the $t \sim 10^{-3}$ - 10^2 sec era, $z \sim 10^9$, compare the model predictions with observed abundances of the lightest elements, based on a well understood nuclear physics
- **Matter-antimatter asymmetry:** probes the baryogenesis era, $t \sim 10^{-6}$ sec, $z \sim 10^{12}$, but only in suggesting that some symmetry breaking did occur
- **Predictions of the inflationary scenario:** flatness, uniformity of CMBR, absence of monopoles, the right type of density fluctuation spectrum - it all supports the idea that inflation did happen, but does not say a lot about its detailed physics
- Cosmological observations can indicate or constrain physics well outside the reach of laboratory experiments

CMB and the Recombination Era

Prediction of the Cosmic Microwave Background (CMB) is trivial in Hot Big Bang model:

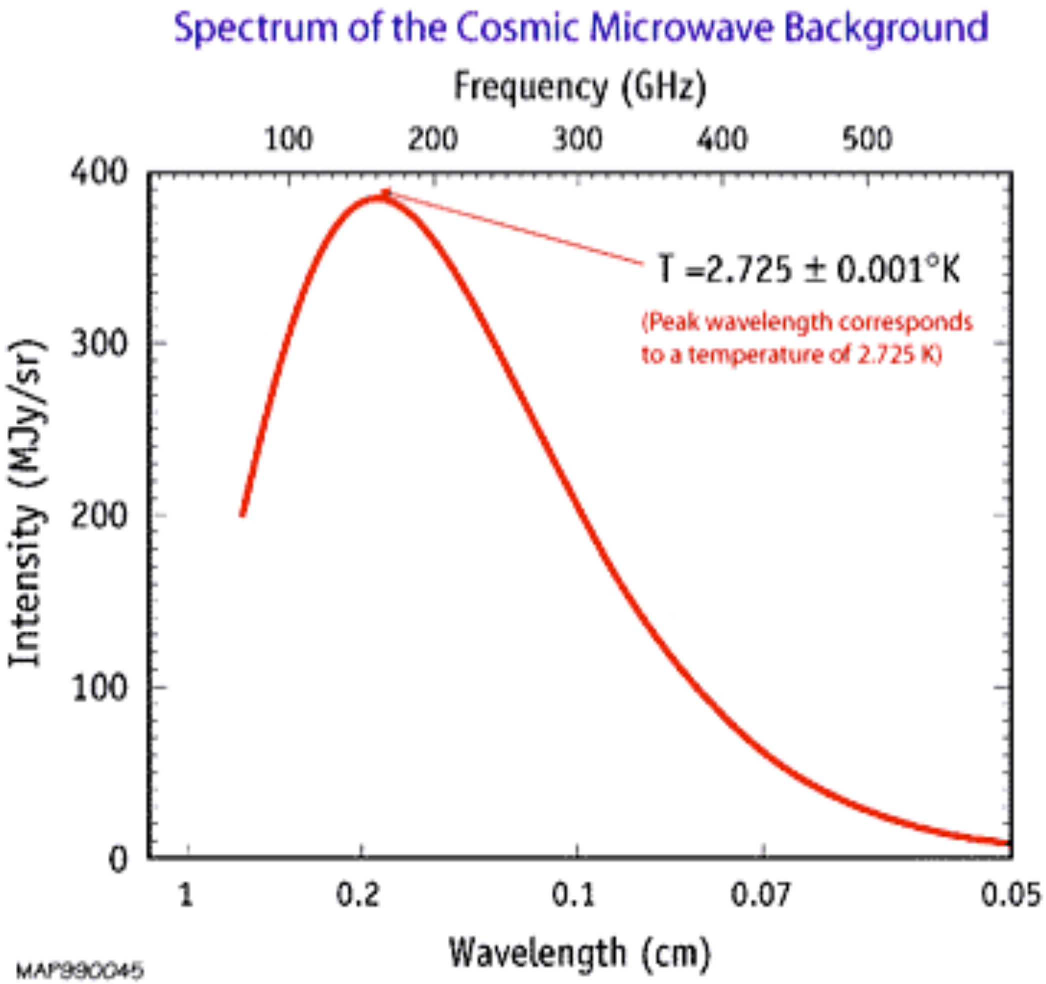
- Hot, ionised initial state should produce thermal radiation
- Photons decouple when universe recombines (last scattering)
- Expansion by factor *R* cools a blackbody spectrum $T \Rightarrow T/R$
- Early prediction by Gamow, Alpher, and Herman in 1949, estimated T ~ 5 K



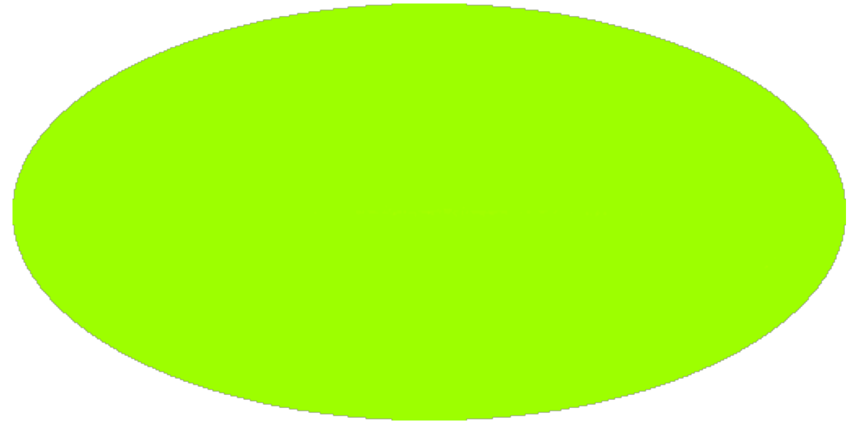
Discovery of the Cosmic Microwave Background (CMB):
A Direct Evidence for the hot Big Bang

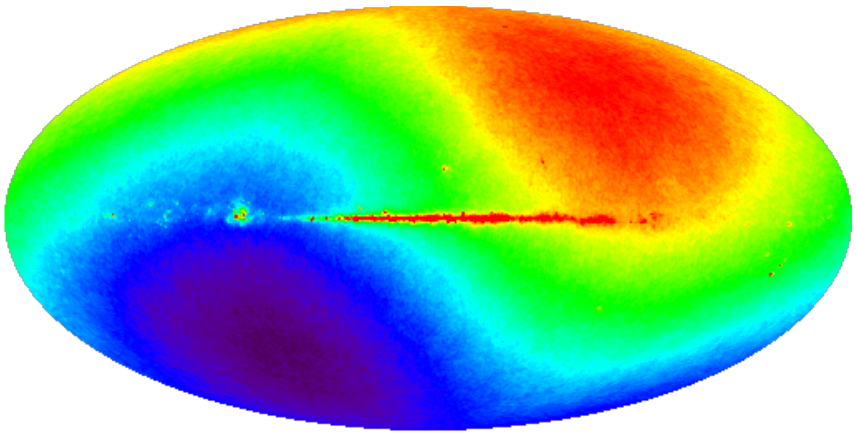
A. Penzias & R. Wilson (1965)

Nobel Prize, 1978



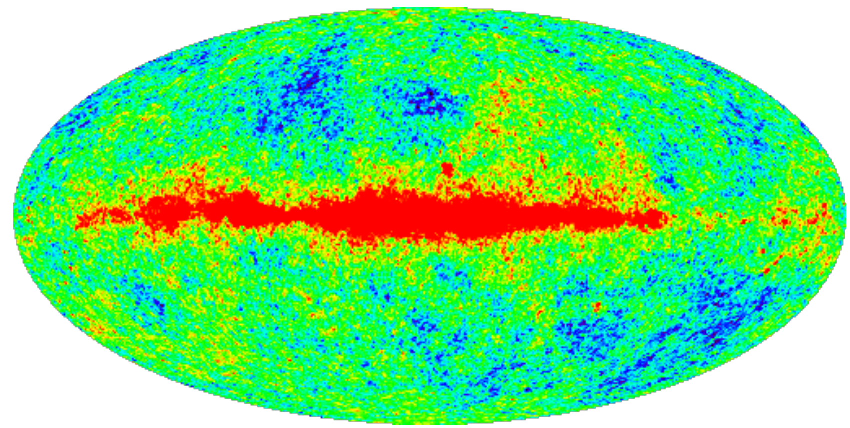
The CMBR sky from WMAP ➡

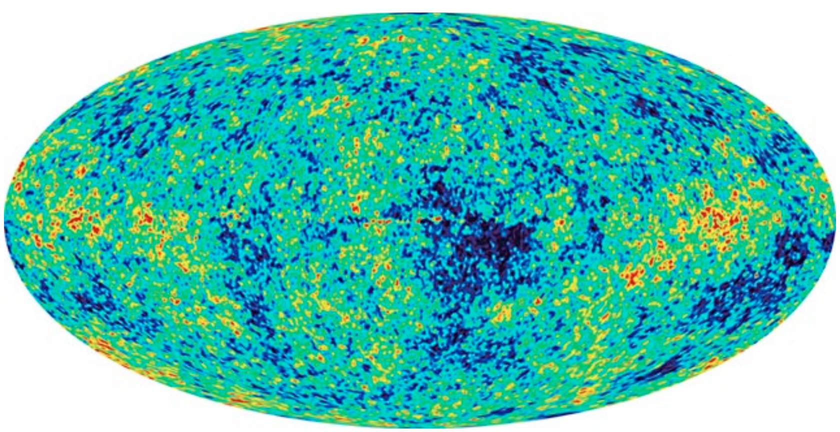




⬅ Enhance the conttrast by 10^3

Remove the dipole and
enhance the contrast to 10^5 ➡

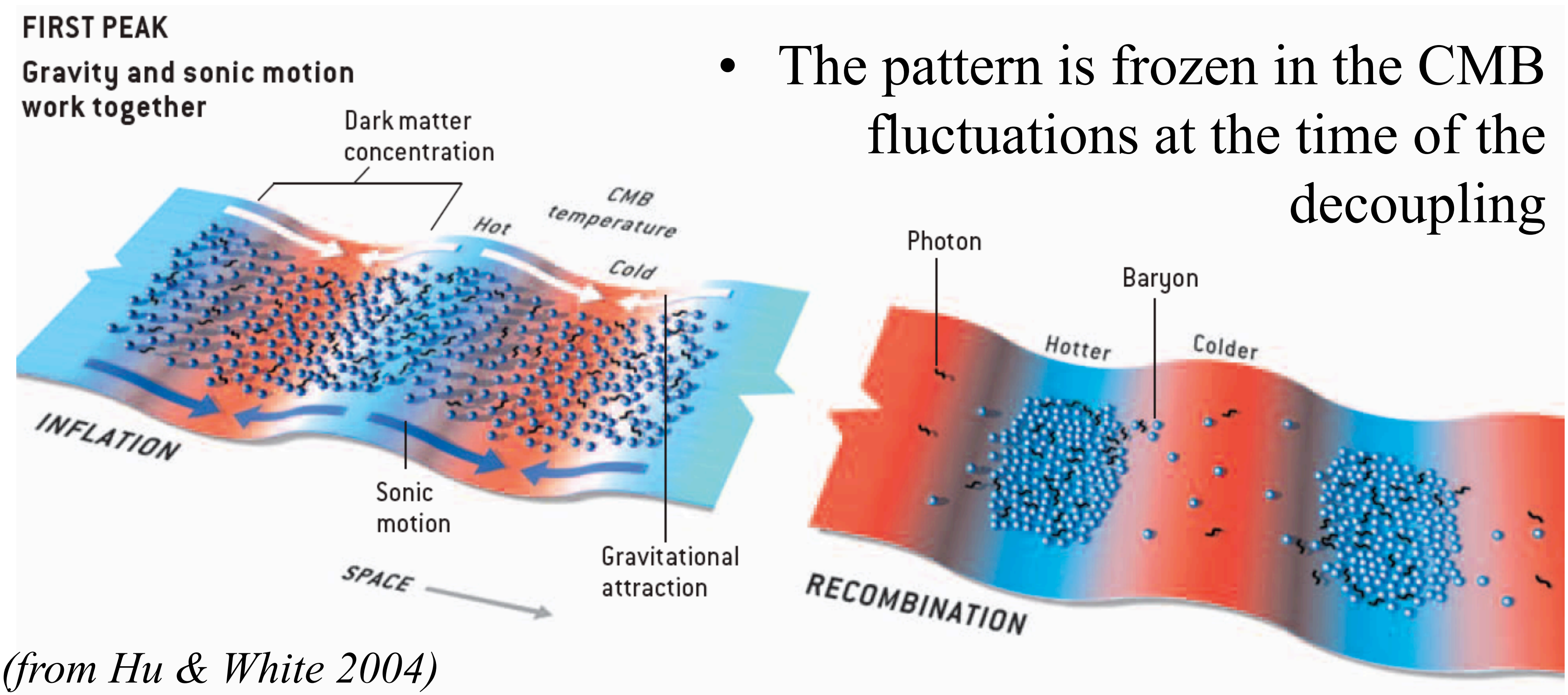




⬅ Remove the Galaxy, the
contrast is 10^5 and see the
primordial density fluctuations

The Cosmic Sound

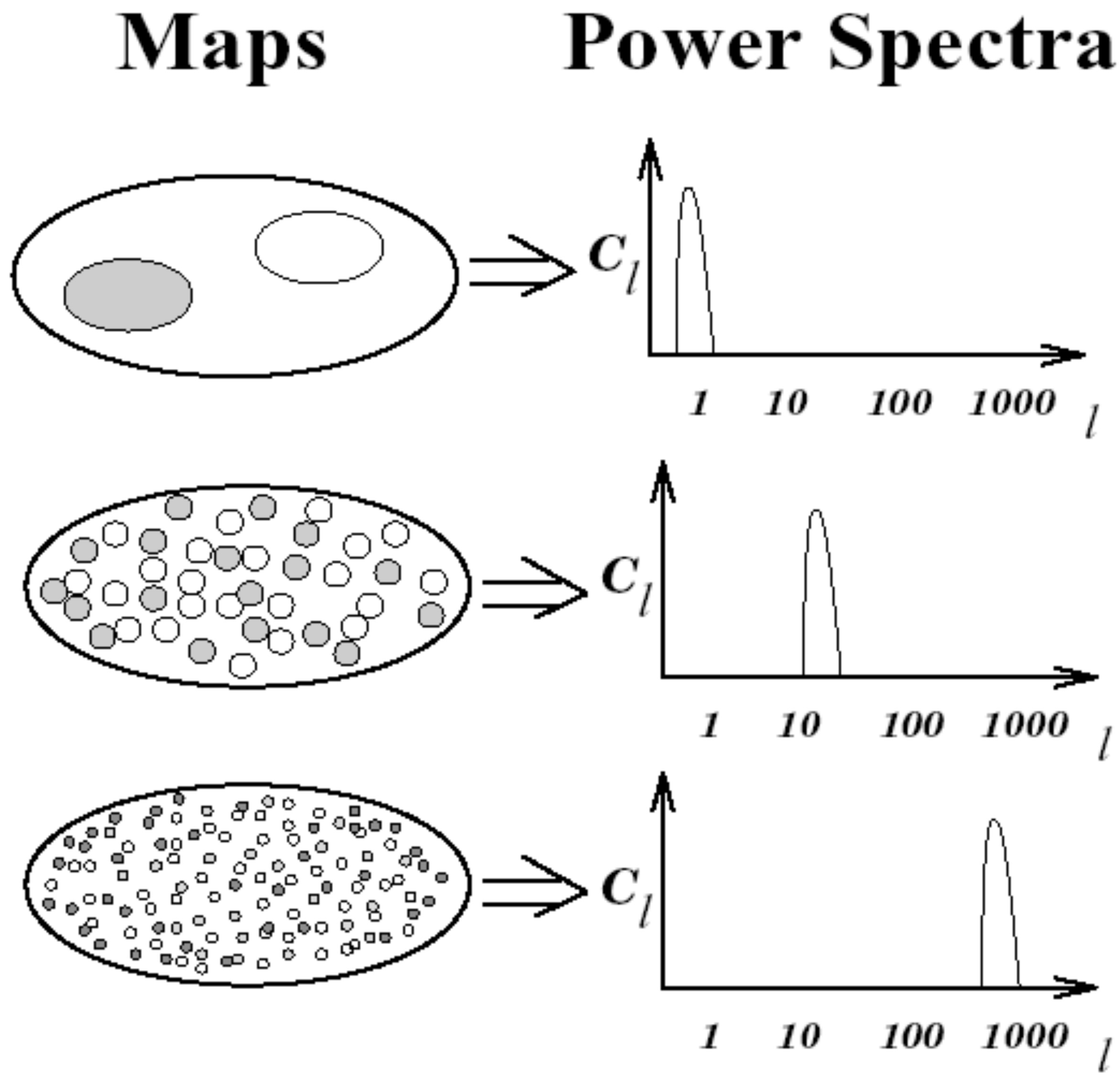
- Large-scale density fluctuations in the early universe attract baryons and photons. Their streaming motion, compression, generate sound waves.
  - The largest wavelength corresponds to the size of the particle horizon at the time
  - The pattern is frozen in the CMB fluctuations at the time of the decoupling



(from Hu & White 2004)

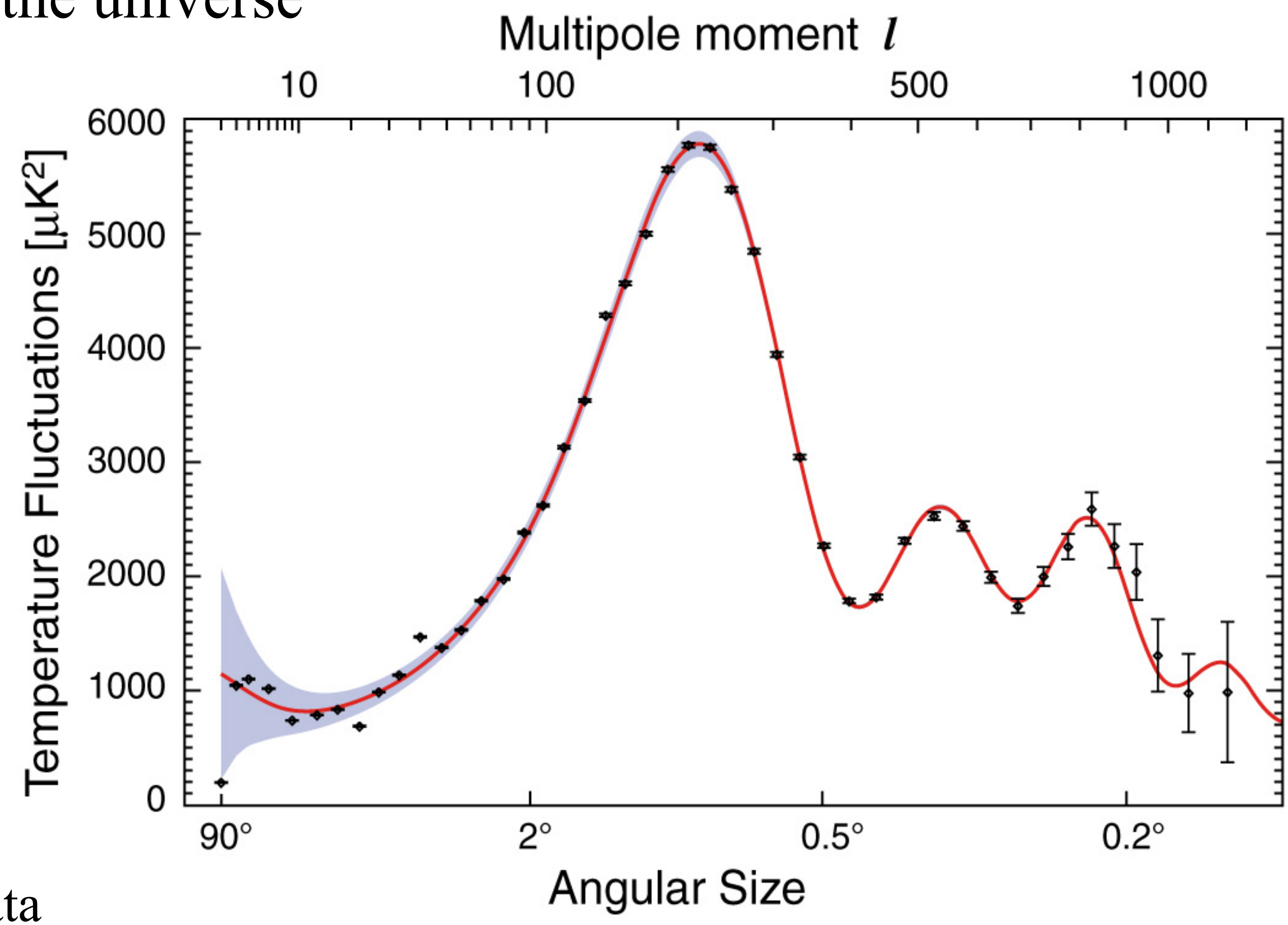
The Angular Power Spectrum

To quantify this, we evaluate the angular (spherical harmonic) power spectra



Observed CMB Angular Power Spectrum

Doppler peaks define a physical scale of the particle horizon at recombination. The corresponding angular size depends on the geometry of the universe



WMAP 7 yr data

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18.2 The Big Bang Nucleosynthesis (BBNS)

Into the Nucleosynthesis Era

- In the pre-nucleosynthesis universe, the radiation produces pairs of electrons and positrons, as well as protons and antiprotons, neutrons and antineutrons, and they can annihilate; *e*+ *e*- reactions produce electron neutrinos (ν_e) and antineutrinos:

$$e^- + e^+ \longleftrightarrow \nu_e + \nu_e$$

$$e^- + p \longleftrightarrow n + \nu_e\,,\ \nu_e + p \longleftrightarrow n + e^+$$

$$n \longleftrightarrow p + e^- + \nu_e$$

$$e^- + e^+ \longleftrightarrow \gamma + \gamma$$

- This occurs until the temperature drops to T~10^{10} K, t ~ 1 sec
- In equilibrium there will slightly more protons than neutrons since the neutron mass is slightly (1.293 MeV) larger
- This leads to an asymmetry between protons and neutrons …

Big Bang Nucleosynthesis (BBNS)

Free neutrons are unstable to beta decay, with *mean lifetime* = 886 sec, $n \rightarrow p + e^{-} + \nu_e$. This destroys ~ 25% of them, before they can combine with the protons

$$n + p \leftrightarrow {}^{2}H + \gamma$$
$${}^{2}H + {}^{2}H \leftrightarrow {}^{3}He + n$$
$${}^{3}He + n \leftrightarrow {}^{3}H + p$$
$${}^{3}H + {}^{2}H \leftrightarrow {}^{4}He + n$$

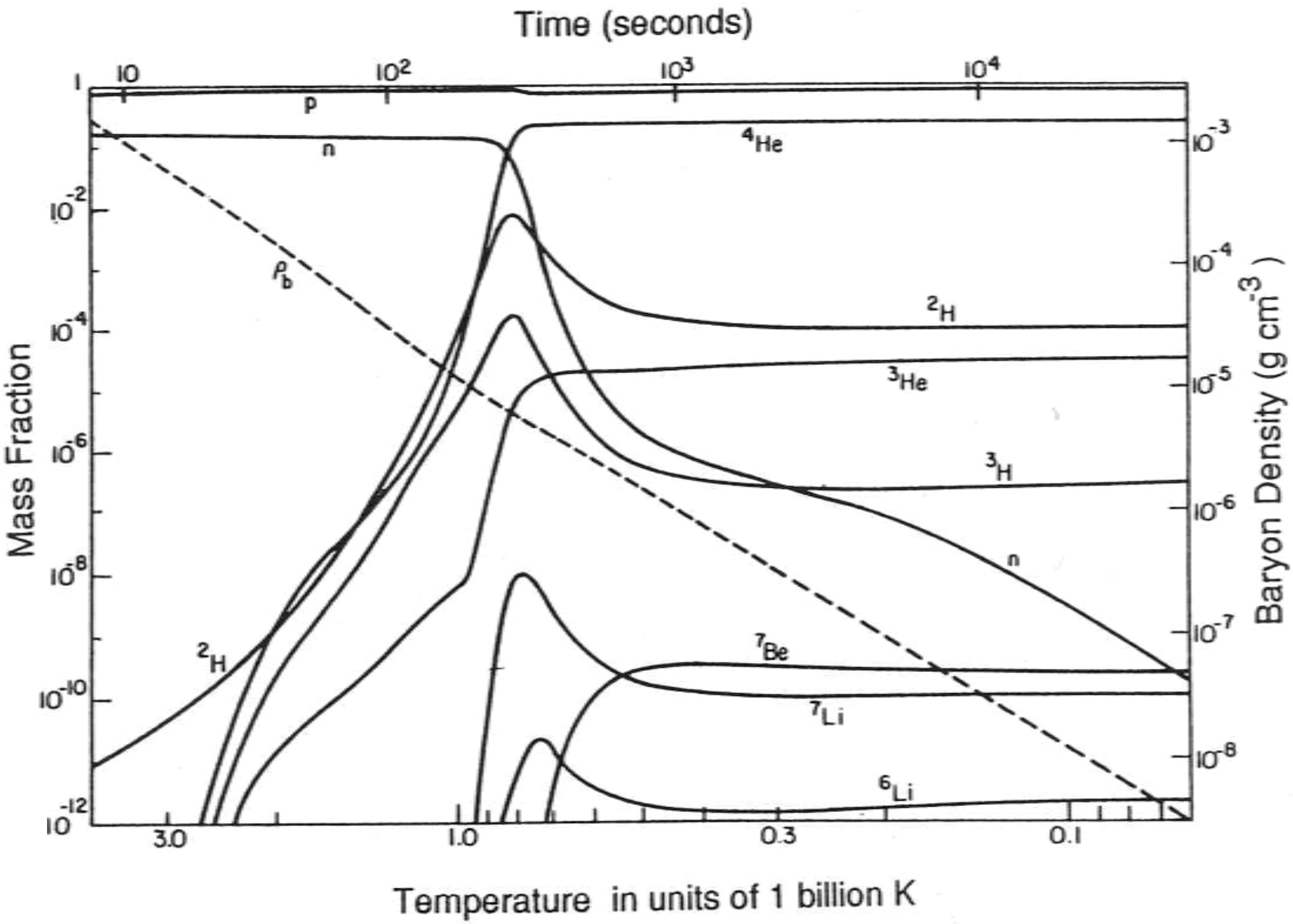
When the temperature drops to ~ 10^9 K (t=230s), neutrons and protons combine to form deuterium, and then helium:

Note that these are not the same reactions as in stars (the *pp* chain)!

Photons break the newly created nuclei, but as the temperature drops, the photodissociation stops

At $t \sim 10^3$ sec and T < 3×10^8 K, the density also becomes too low for fusion, and BBN ends. This is another "freeze-out", as no new nuclei are created and none are destroyed

The Evolution of Abundances in BBNS



BBNS Predictions

- The BBNS makes detailed predictions of the abundances of light elements: ^{2}D, ^{3}He, ^{4}He, ^{7}Li, ^{8}Be
- These are generally given as a function of the baryon to photon ratio $\eta = n_n/n_\gamma$, usually defined in units of 10^{10}, and directly related to the baryon density Ω_b: $\eta_{10} = 10^{10}(n_n/n_\gamma) = 274\ \Omega_b h^2$
- As the universe evolves η is preserved, so that what we observe today should reflect the conditions in the early universe
- Comparison with observations (consistent among the different elements) gives:

$$\Omega_{baryons} h^2 = 0.021 \rightarrow 0.025$$

- This is in a spectacularly good agreement with the value from the CMB fluctuations:

$$\Omega_{baryons} h^2 = 0.024 \pm 0.001$$

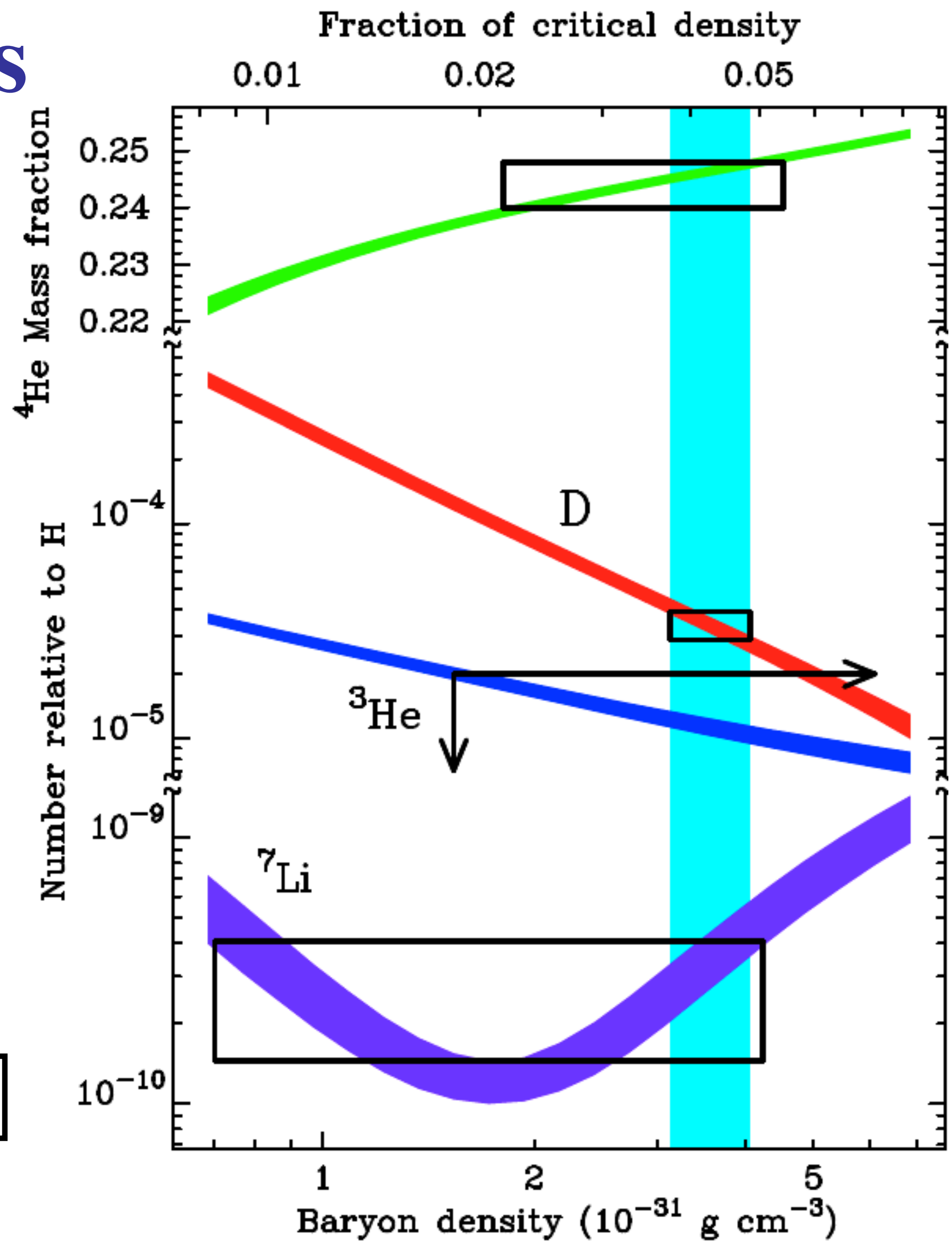
BBNS Predictions

^{4}He: the higher the density, the more of it is made ➔

^{2}D, ^{3}He: easily burned into ^{4}He, so abundances are lower at higher densities ➔

^{7}Li: … complicated ➔

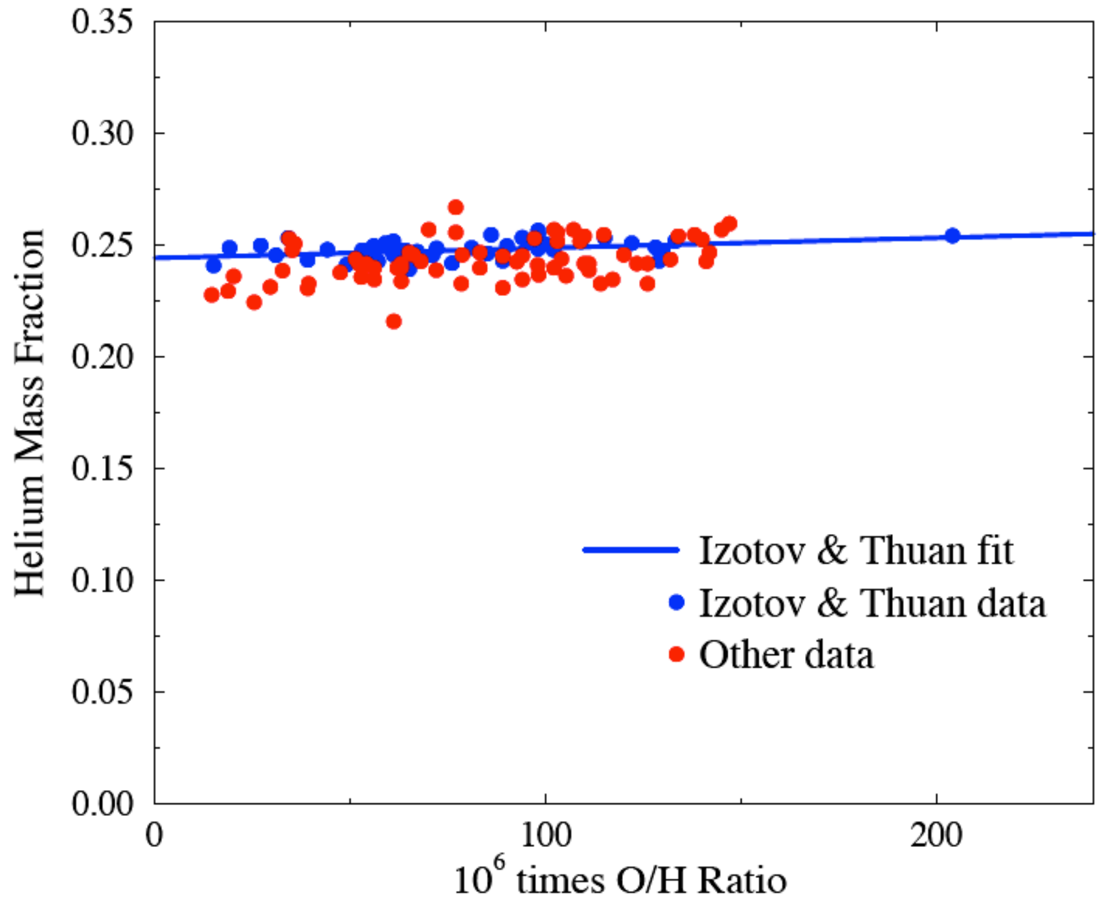
Boxes indicate observed values



Helium-4 Measurements

- He is also produced in stars, but this "secondary" abundance is expected to correlate with abundances of other nucleosynthetic products, e.g., oxygen

- Observe ^{4}He from recombination lines in extragalactic HII regions in low-metallicity starforming galaxies



- The intercept at the zero oxygen abundance should represent the primordial (BBNS) value
- The result is: $\mathbf{Y_{BBNS} = 0.238 +/- 0.005}$

Deuterium Measurements

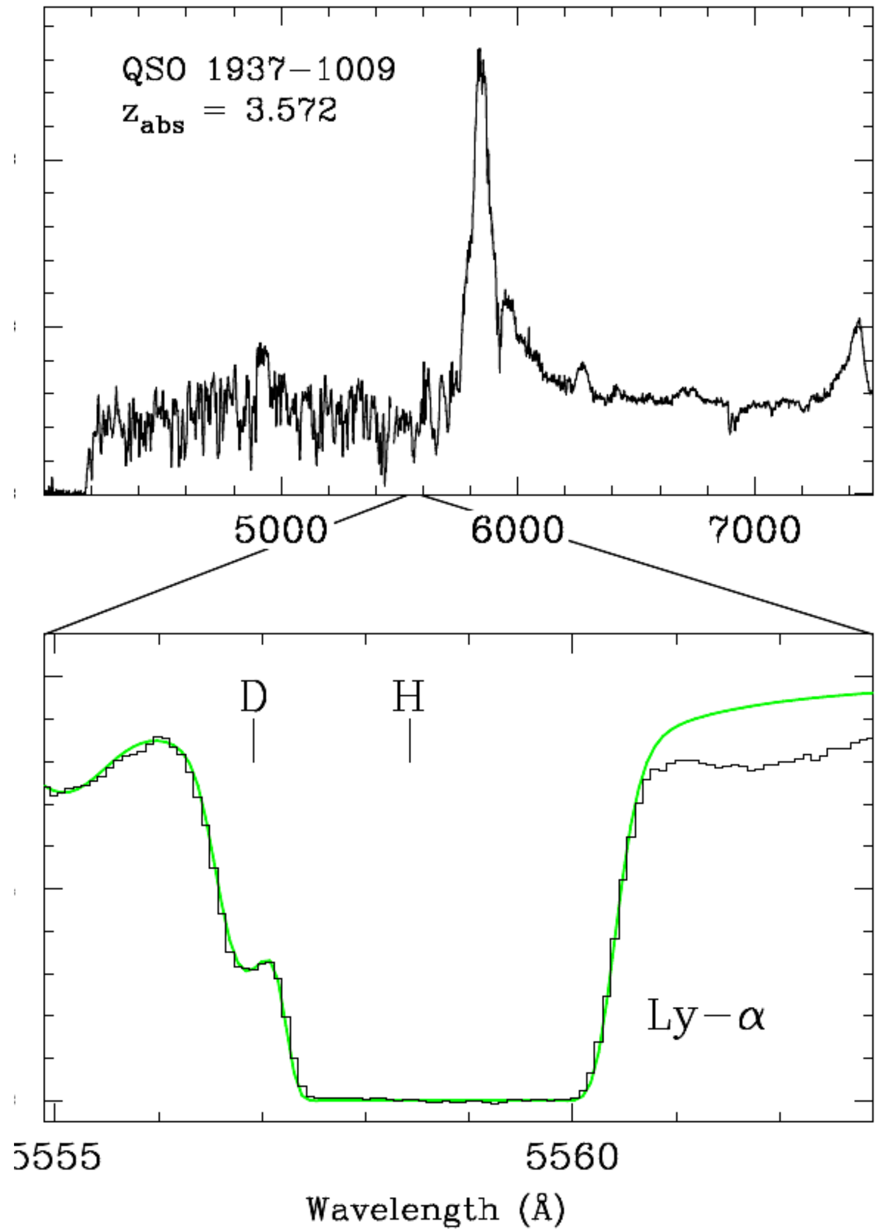
Deuterium is easily destroyed in stars, and there is no known astrophysical process where it can be created in large amounts after the BBNS

Thus, we need to measure it in a "pristine" environment, e.g., in QSO absorption line systems

It is a tricky measurement and it requires high resolution spectra from 8-10 m class telescopes

The result is:

$$\frac{D}{H} = 2.74 \times 10^{-5}$$



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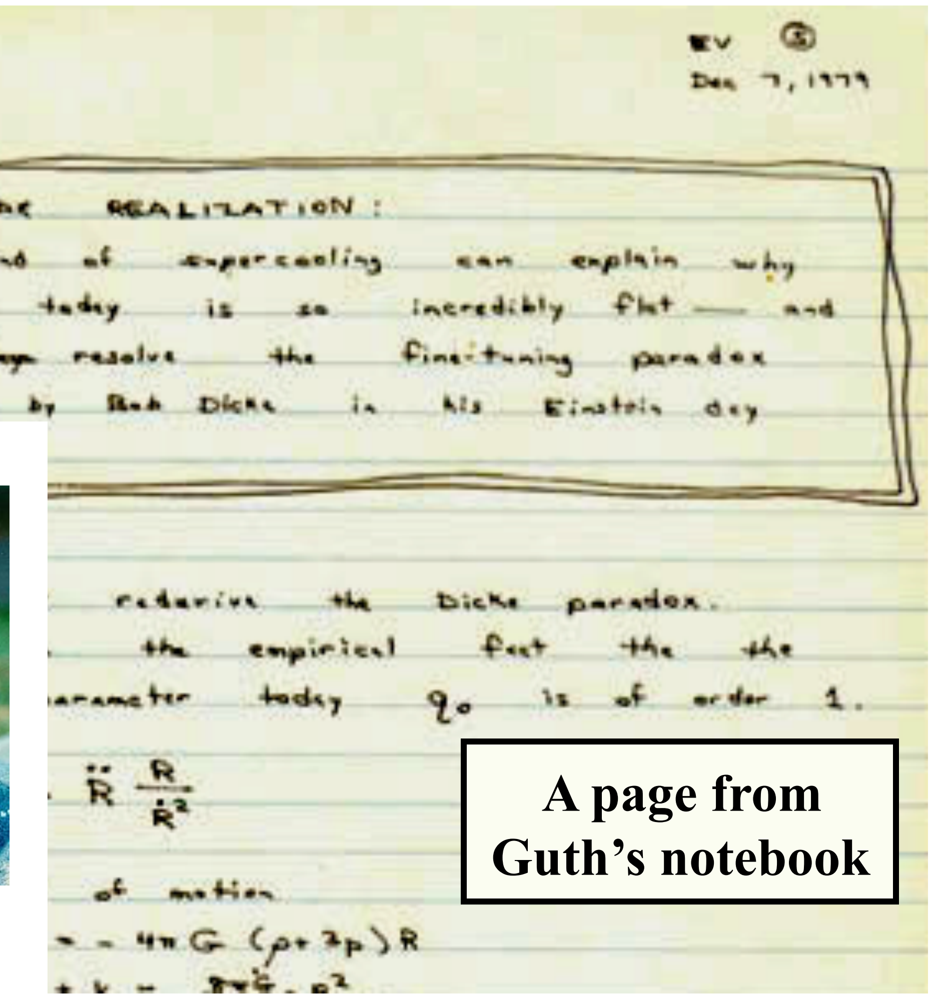
18.3 The Cosmic Inflation

The Idea of Inflation

- Alan Guth (1980); precursors: D. Kazanas, A. Starobinsky
- Explains a number of fundamental cosmological problems: flatness, horizon, origin of structure, absence of monopoles…
- Develped further by P. Steinhardt, A. Albrecht, A. Linde, and many others



A page from Guth's notebook

Kavli Prize 2014!

A. Guth

A. Starobinsky

A. Linde

The Inflationary Scenario

It solves ***3 key problems*** of the Big Bang cosmology:

1. **The flatness problem**: why is the universe so close to being flat today?
2. **The horizon problem**: how comes the CMBR is so uniform?
3. **The monopole problem**: where are the copious amounts of magnetic monopoles predicted to exist in the BB cosmology?

… It also *accounts naturally for the observed power spectrum of the initial density perturbations*

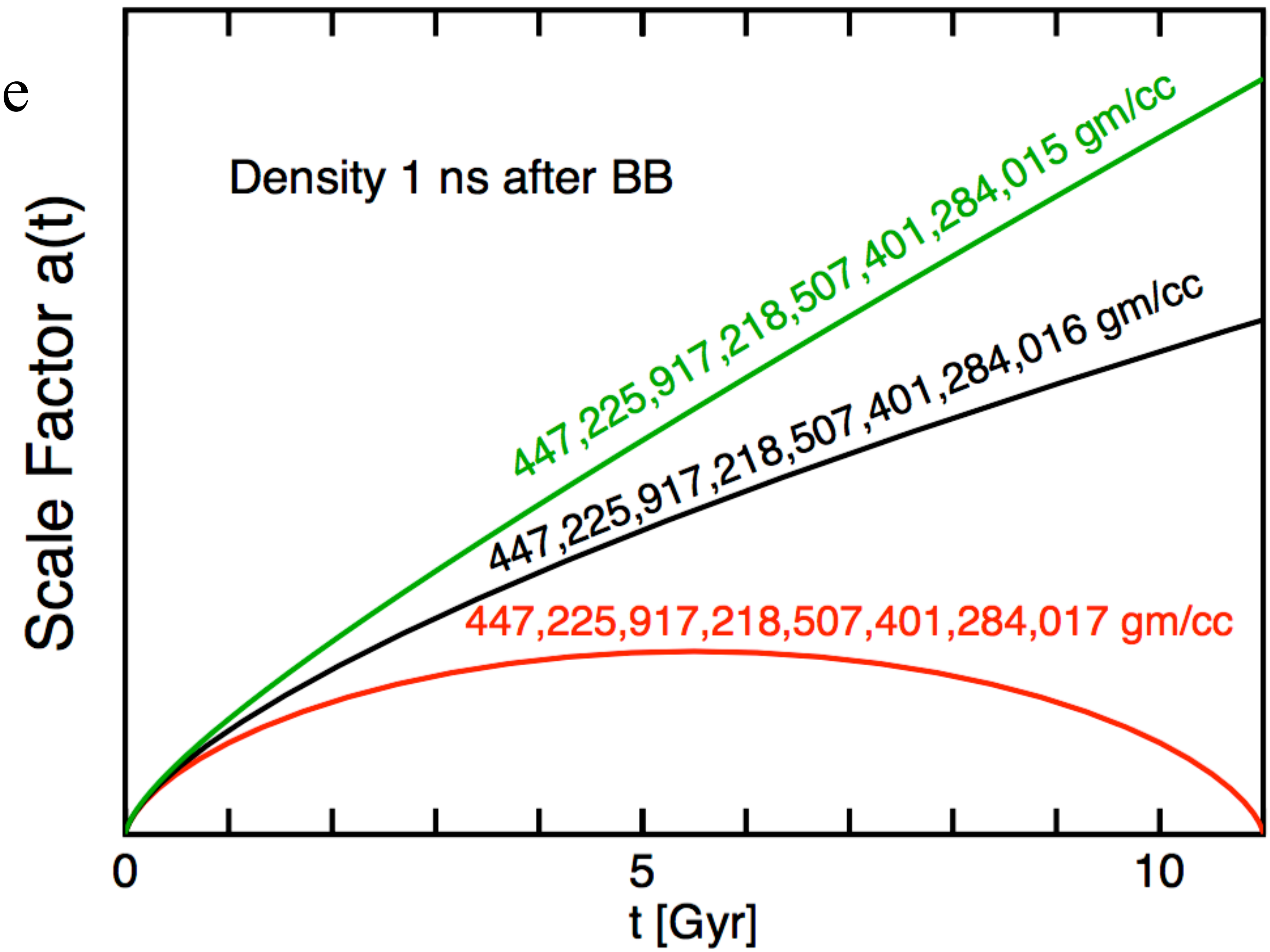
… *It predicts* a similar, scale-invariant spectrum for the cosmic gravitational wave background

… And it implies a much, much(!) bigger universe than the observable one

The Flatness Problem

The expanding universe always *evolves away* from $\Omega_{tot} = 1$

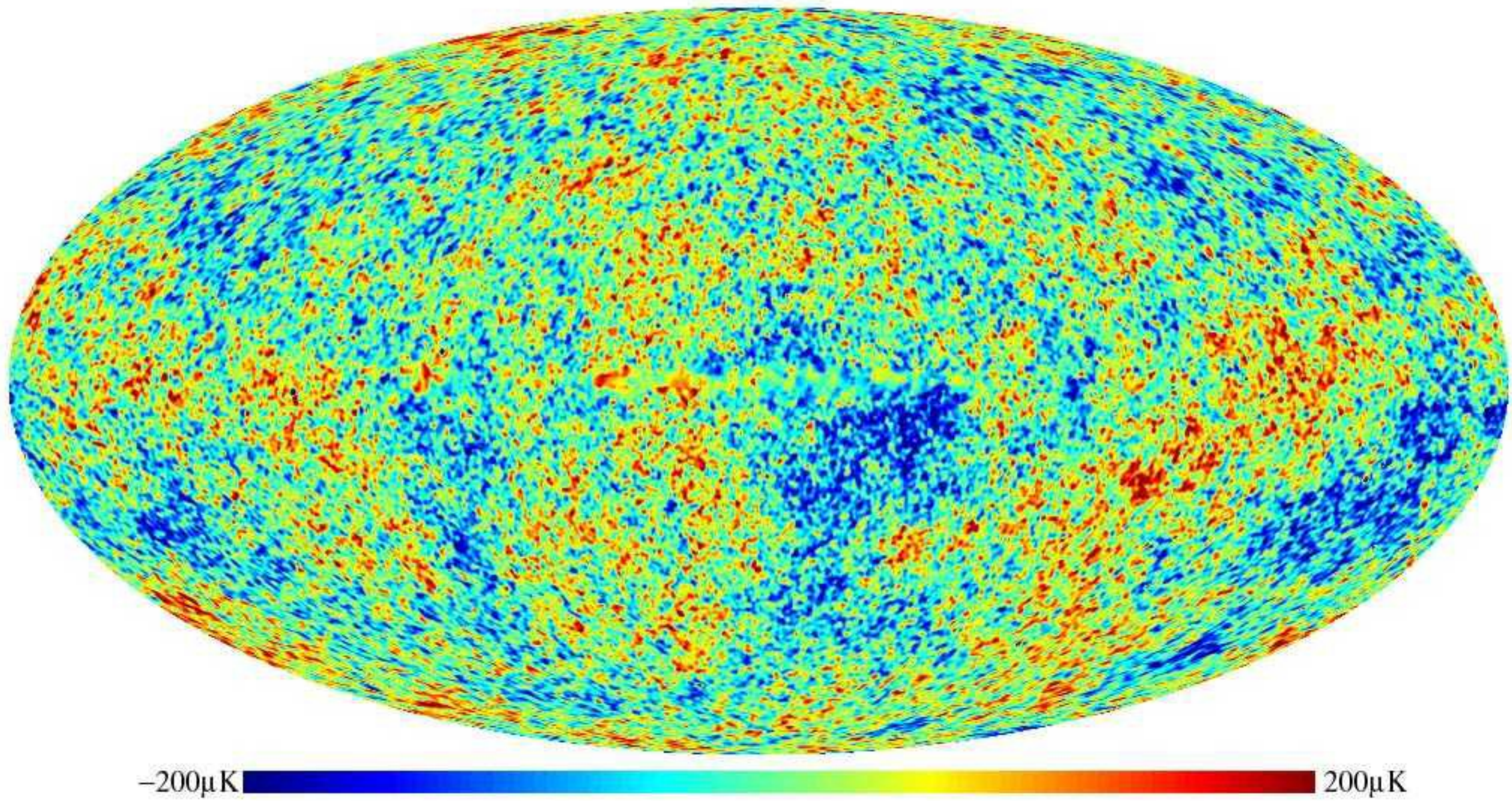
This creates an *enormous fine-tuning problem*: the early universe must have been remarkably close to $\Omega_{tot} = 1$ in order to have $\Omega_{tot} \sim 1$ today !



(from N. Wright)

CMBR is Uniform to $\Delta T/T \sim 10^{-6}$

Yet the projected size of the particle horizon at the decoupling was ~ 2° - these regions were causally disconnected - so how come?



Inflationary Universe Scenario

- At $t \sim 10^{-34}$ sec after the Big Bang, the universe was in a ***"false vacuum":*** the energy level higher than the lowest, ground state
- The false vacuum is a metastable state, and the universe undergoes a ***phase transition*** from a state of a false vacuum, to a ground state; this releases enormous amounts of energy ("latent heat") which drives an exponential expansion
- This also generates all of the energy content of the universe
- There may be many such inflating "bubbles" of the physical vacuum, each corresponding to a separate universe in a larger multiverse (this is *highly speculative*!)
- This theory is called the ***chaotic inflation***

The Cosmic Inflation

Recall that the energy density of the physical vacuum is described as the ***cosmological constant***. If this is the dominant density term, the Friedmann Eqn. is:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda_i}{3}$$

(a = scaling factor, Λ = cosmological constant)

The solution is obviously: $a(t) \propto e^{H_i t}$

In the model where the GUT phase transition drives the inflation, the net expansion factor is:

$$\frac{a(t_f)}{a(t_i)} \sim e^{100} \sim 10^{43}$$

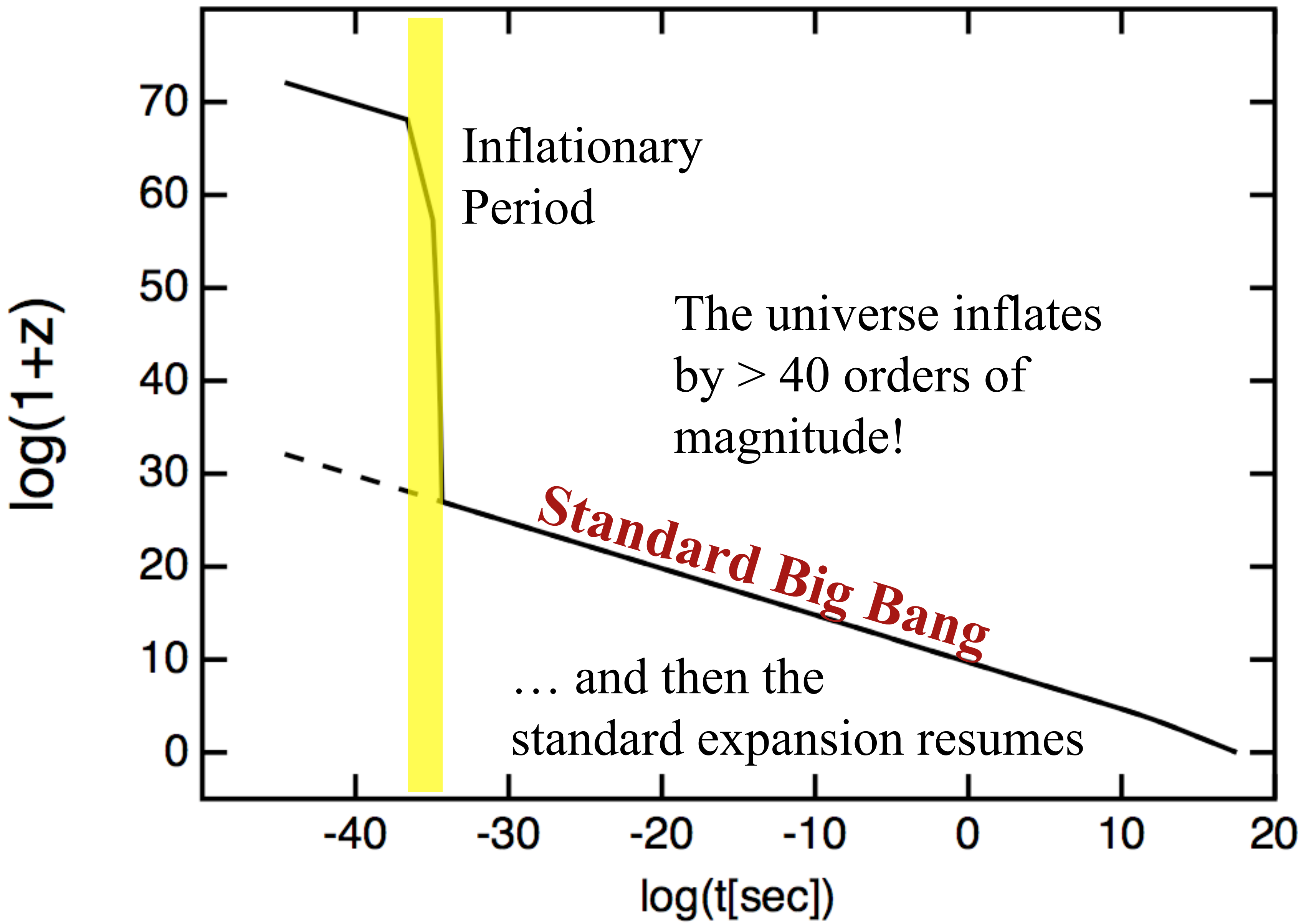
The density parameter evolves as: $|1 - \Omega(t)| \propto e^{-2H_i t}$

Thus:

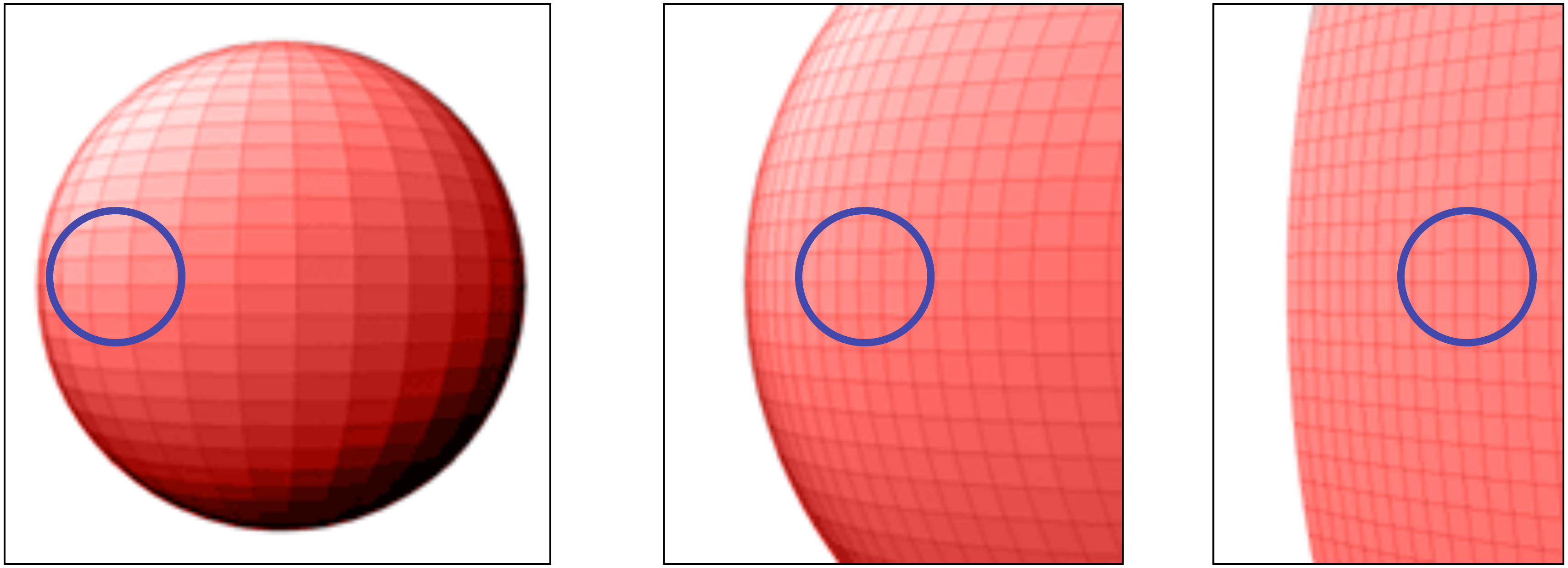
$$|1 - \Omega(t_f)| \sim e^{-2N} \sim e^{-200} \sim 10^{-87}$$

The universe becomes ***asymptotically flat***

The Inflationary Scenario



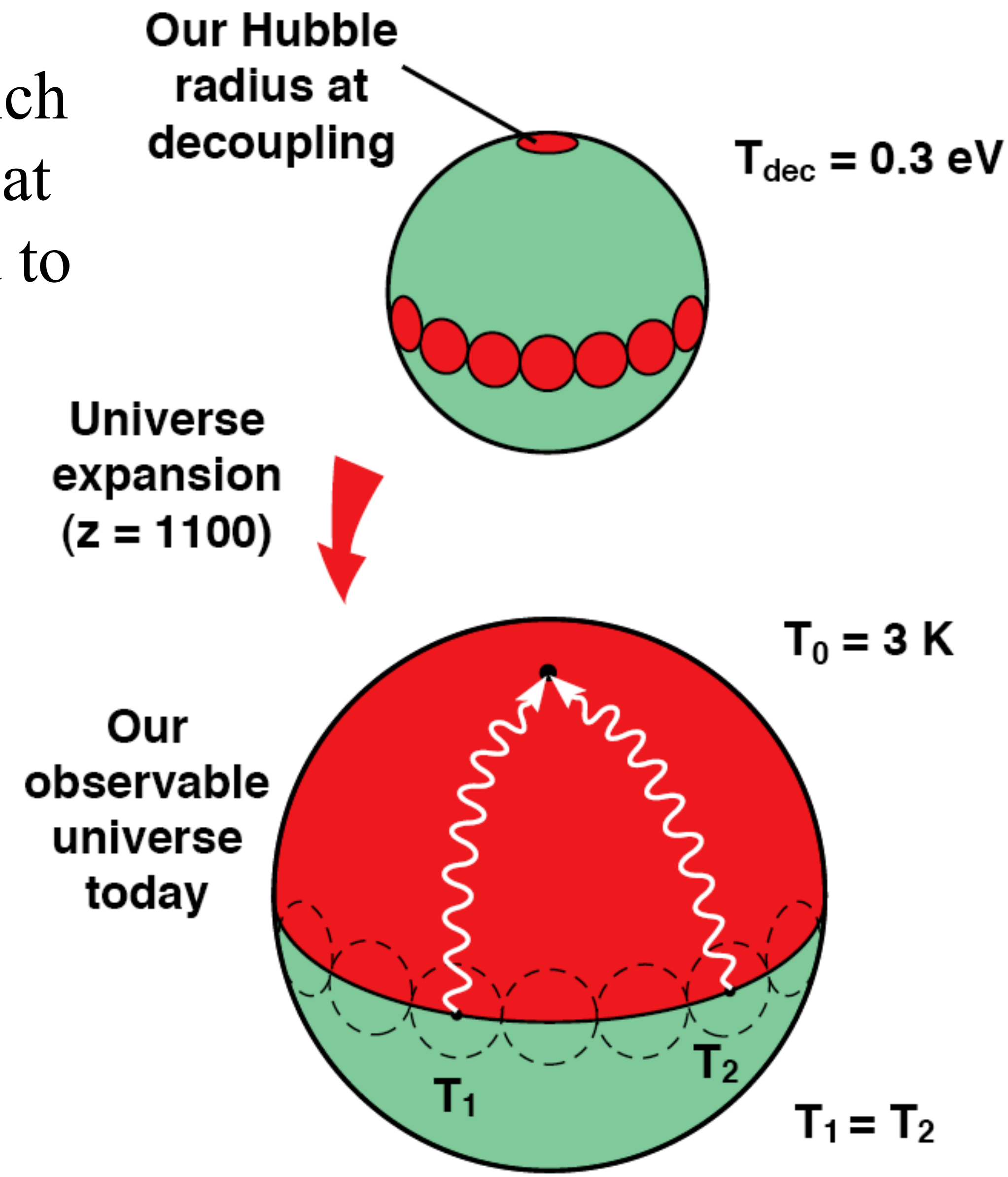
Inflation Solves the Flatness Problem



As the universe inflates, the local curvature effects become negligible in comparison to the vastly increased "global" radius of curvature: the universe becomes extremely close to flat locally (which is the observable region now). Thus, at the end of the inflation, $\Omega = 1 \pm \varepsilon$

Inflation Solves the Horizon Problem

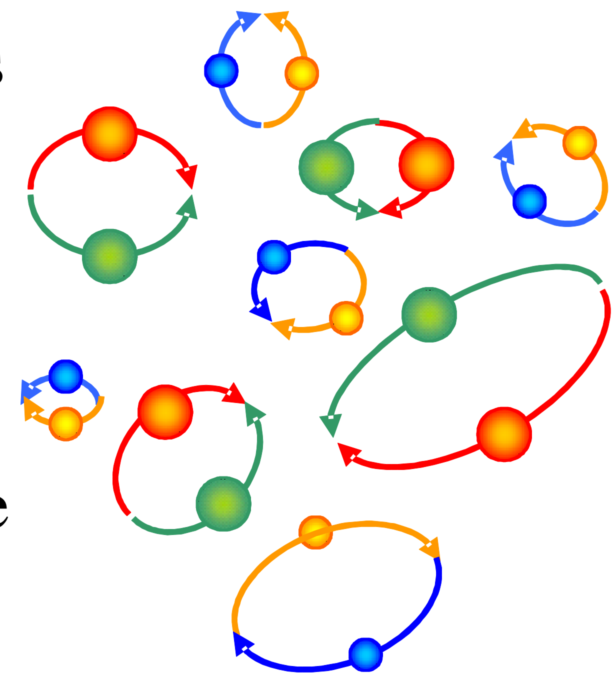
Regions of the universe which were causally disconnected at the end of the inflation used to be connected before the inflation - and thus in a thermal equilibrium



Note that the *inflationary expansion is superluminal*: the space can expand much faster than ***c***

Inflation and Structure Formation

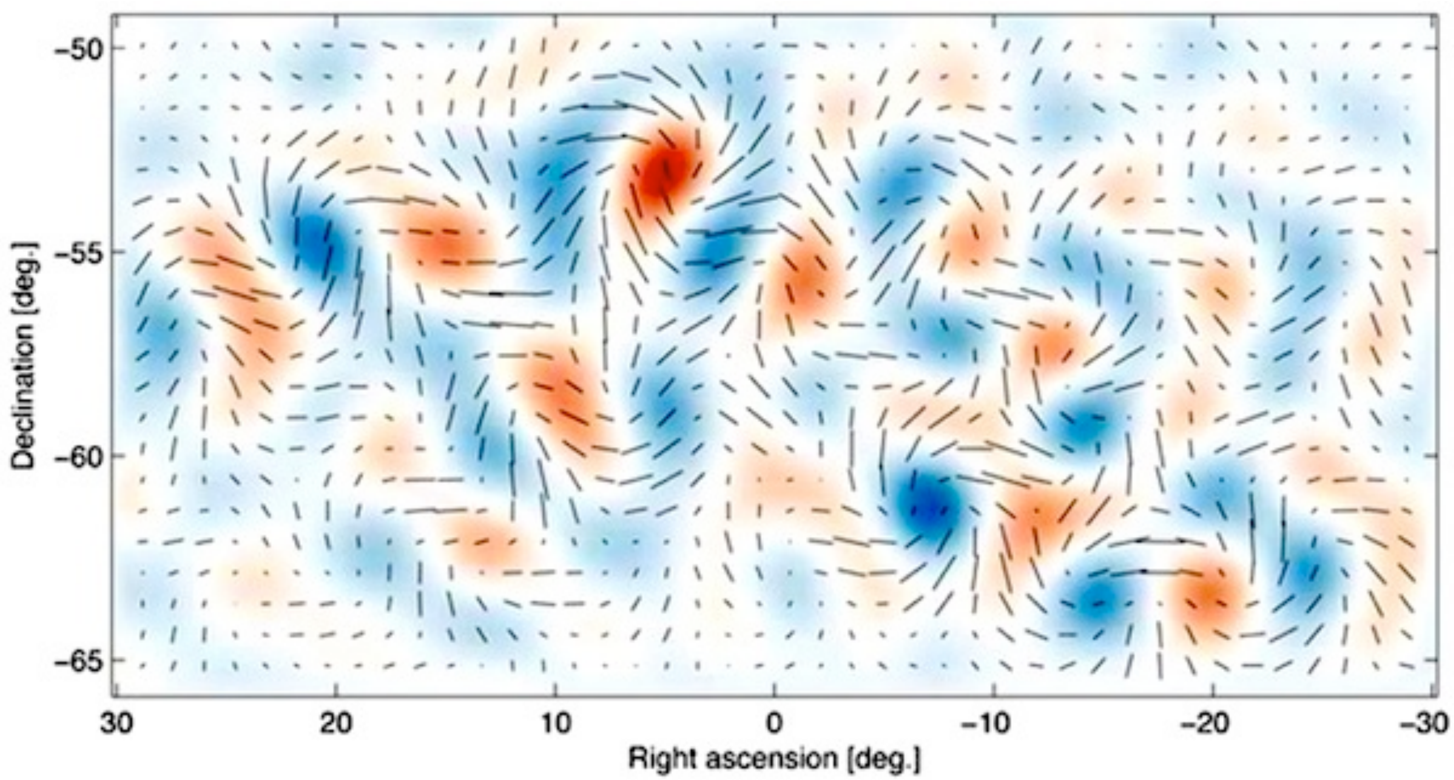
- Uncertainty Principle means that in quantum mechanics vacuum constantly produces temporary particle-antiparticle pairs
  - This creates minute density fluctuations
  - Inflation blows these up to macroscopic size
  - They become the seeds for structure formation



- Expect the mass power spectrum of these density fluctuations to be approximately scale invariant
  - This is indeed as observed!
  - Not a “proof” of inflation, but a welcome consistency test

Primordial Gravitational Wave Background

- Inflation also predicts the existence of a primordial gravitational wave background, ~ a gravitational equivalent of the CMB
- Far too weak to be detected directly today, however, expected to leave a circular polarization signature in the CMB fluctuations
- Probably observed by the BICEP2 team:



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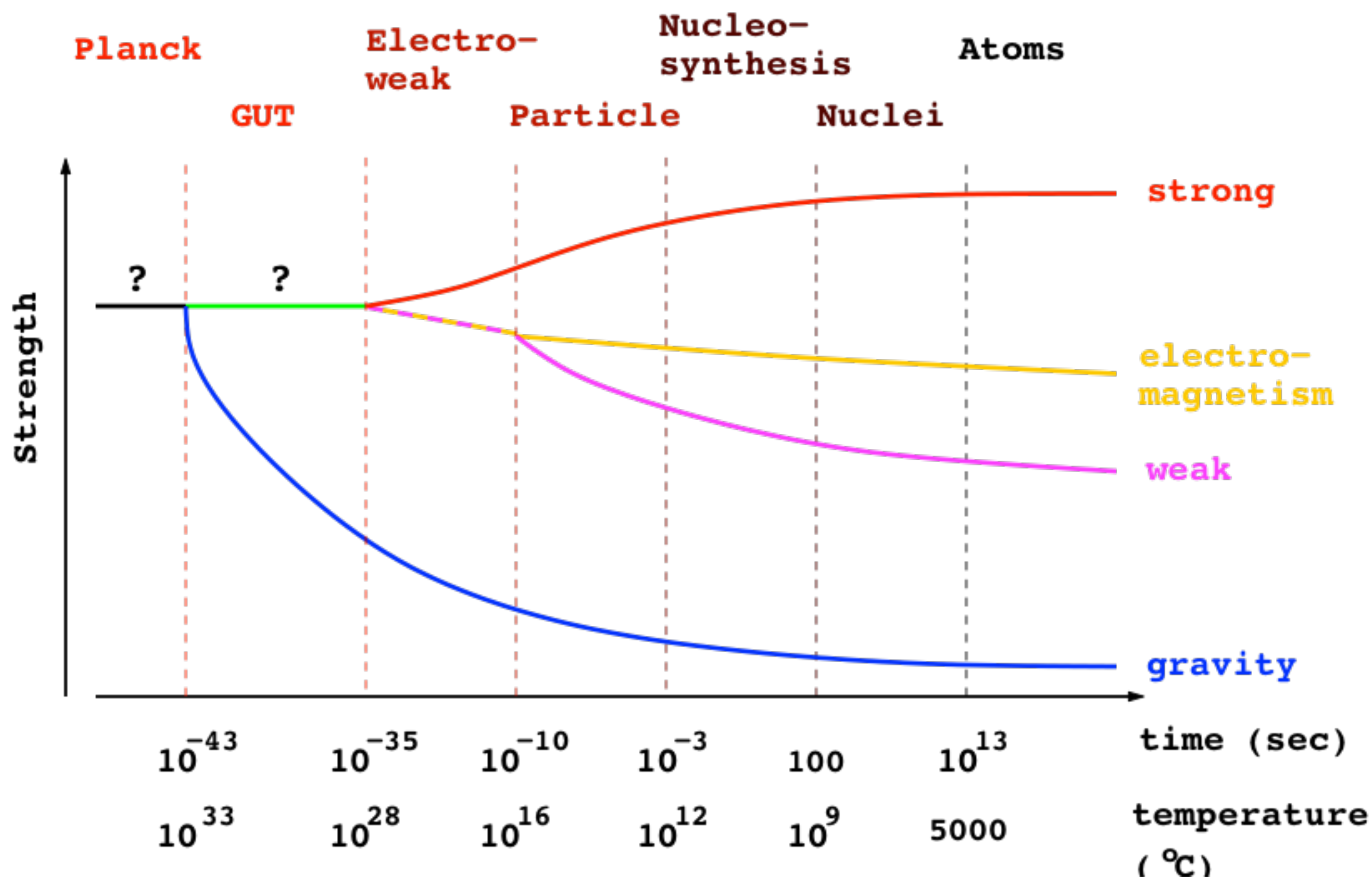
18.4 The Very Early Universe

Physical Interactions in the Early Universe

As we get closer to $t \to 0$ and $T \to \infty$, we probe physical regimes in which different fundamental interactions dominate. Their strength is a function of energy, and at sufficiently high energies they become unified



The Electroweak Era: up to 10^{-10} sec

- At $T \sim 10^{28}$ K, three distinct forces in the universe: Gravity, Strong, and **Electroweak:** unified Electromagnetism and Weak nuclear force
- At $T < 10^{15}$ K, Electromagnetism and Weak nuclear force split; this is the **Electroweak phase transition**
- Limit of what we can test in particle accelerators

The GUT Era: up to 10^{-35} sec

- At $T > 10^{29}$ K, electroweak force and strong nuclear force join to form the GUT (grand unified theory) interaction
- Relatively solid theoretical framework (but may be wrong), but not directly testable in experiments
- This **GUT phase transition** may be driving the Inflation (but there are other candidates)

Matter - Antimatter Asymmetry

The universe today contains negligible amounts of the antimatter

Matter Particles	Antimatter Particles
10,000,000,001	10,000,000,000

In the early universe, there must have been a slight excess of the matter over the antimatter particles. They basically have all annihilated away except a tiny difference between them

This process leads to the preponderance of photons over the leftover baryons today by the same factor

A mechanism to generate this asymmetry was proposed by A. Sakharov in 1967. It requires a non-conservation of the baryon number, a violation of the C and CP symmetries in particle physics, and a departure from the equilibrium

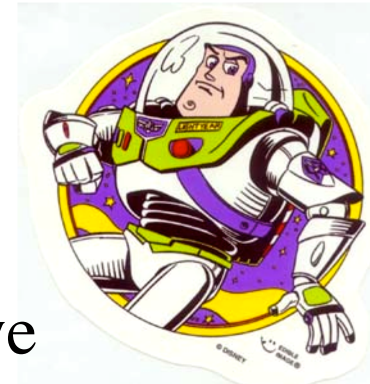
Planck Units

Proposed in 1899 by M. Planck, as the "natural" system of units based on the physical constants:

Name	Dimension	Expression	Approx. SI equivalent measure
Planck time	Time (T)	$t_P = \frac{l_P}{c} = \sqrt{\frac{\hbar G}{c^5}}$	5.39121×10^{-44} s
Planck length	Length (L)	$l_P = \sqrt{\frac{\hbar G}{c^3}}$	1.61624×10^{-35} m
Planck mass	Mass (M)	$m_P = \sqrt{\frac{\hbar c}{G}}$	2.17645×10^{-8} kg
Planck charge	Electric charge (Q)	$q_P = \sqrt{\hbar c 4\pi\epsilon_0}$	$1.8755459 \times 10^{-18}$ C
Planck temperature	Temperature (Θ)	$T_P = \frac{m_P c^2}{k} = \sqrt{\frac{\hbar c^5}{G k^2}}$	1.41679×10^{32} K

They may be indicative of the physical parameters and conditions at the era when gravity is unified with other forces … assuming that ***G*, *c***, and ***h*** do not change … and that there are no other equally fundamental constants

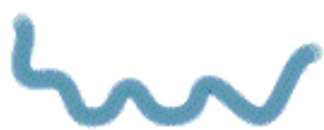
Towards the Planck Era



"To Infinity, and Beyond…"

- Probably gravity unified with the other forces - so we need a theory of Quantum Gravity
  - Characteristic time ~ Planck Time ~ 10^{-43} sec after the Big Bang
  - Size of the universe then ~ Planck Length
- *Highly Speculative* theories include
  - **M-theory:** particles are excitations on high dimensional membranes (D-branes). This includes…
  - **String Theory**, where particles are different vibrations of one type of strings

open string



closed string

  - **Ekpyrotic cosmology, String Landscape, …**
- The future of fundamental physics?

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