Ay 21

The Early Universe

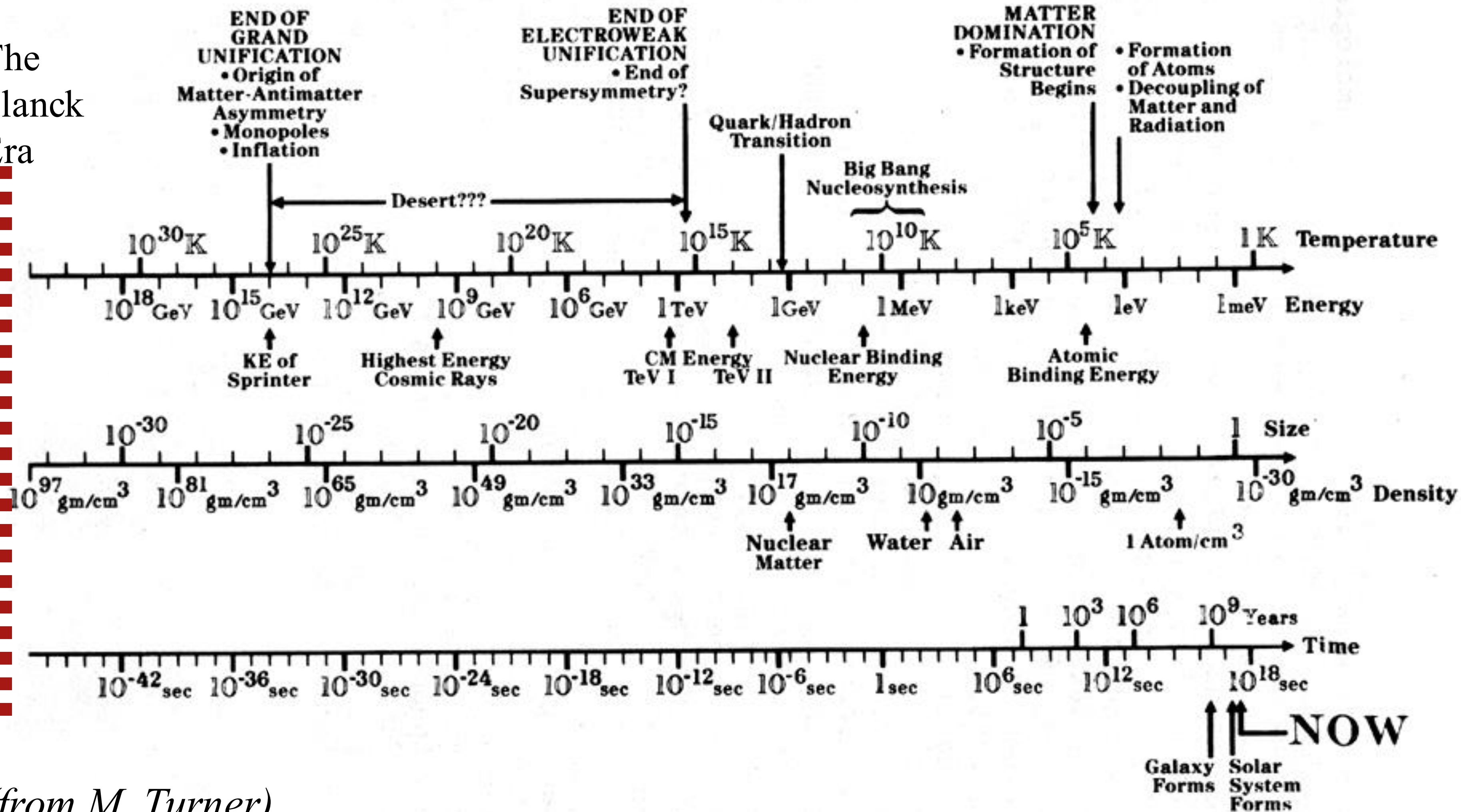
The Key Ideas

- Pushing backward in time towards the Big Bang, the universe was hotter and denser in a fairly predictable manner (aside from surprising "glitches" such as inflation…)
- At any given time, *the temperature translates into a characteristic mass of particles* ($kT \sim mc^2$), which dominates that epoch: the Universe as the ultimate accelerator?
- 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 $\sim 10^{-43}$ sec $\sim$ Planck time, where the quantum gravity must be important

The Cosmic Thermal History

… on a logarithmic time axis - a theorist's delight!

The Planck Era



(from M. Turner)

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

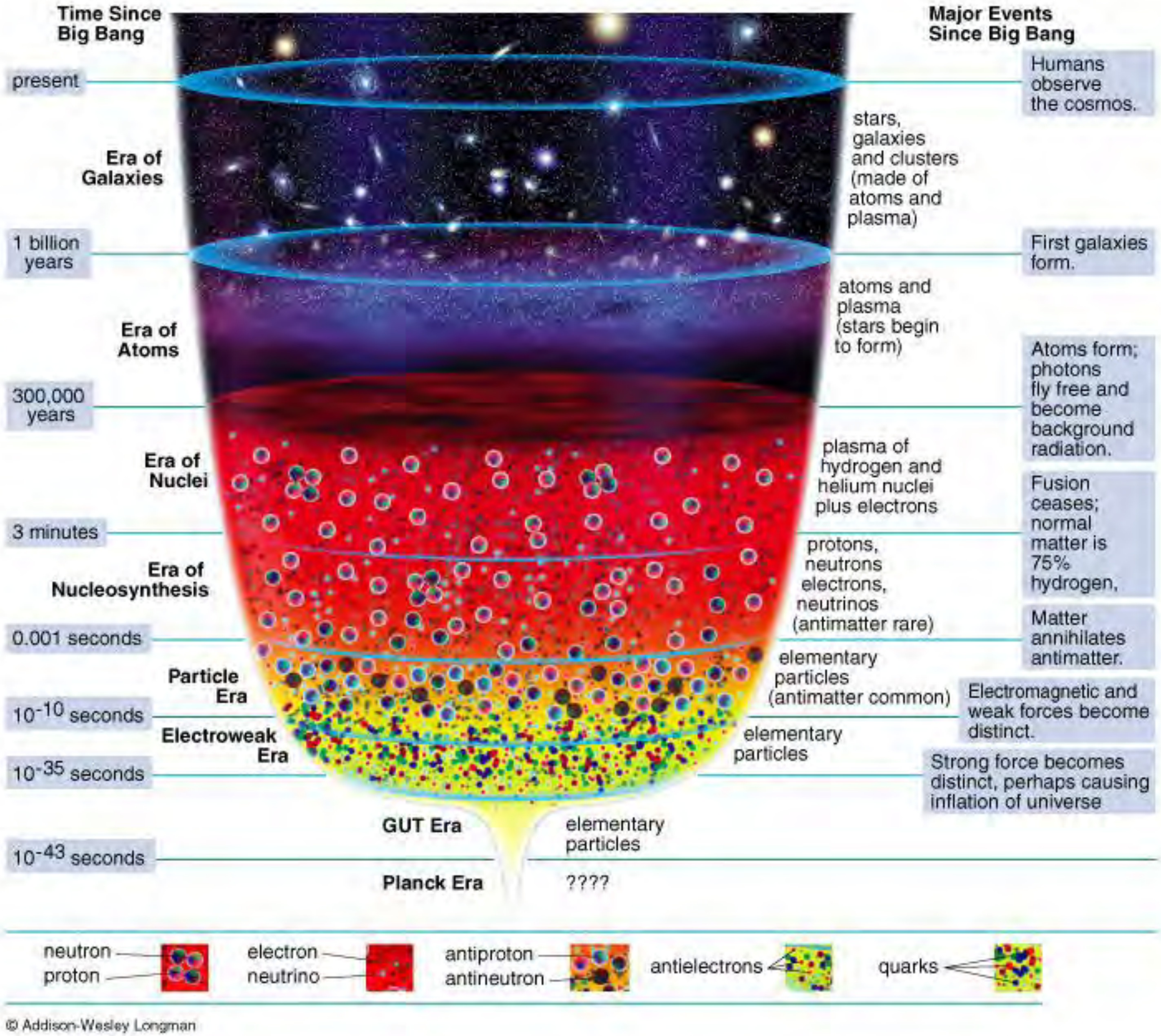
Some Key Moments in the Thermal History of the Universe:

- **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

Speculative physics →

← Known physics

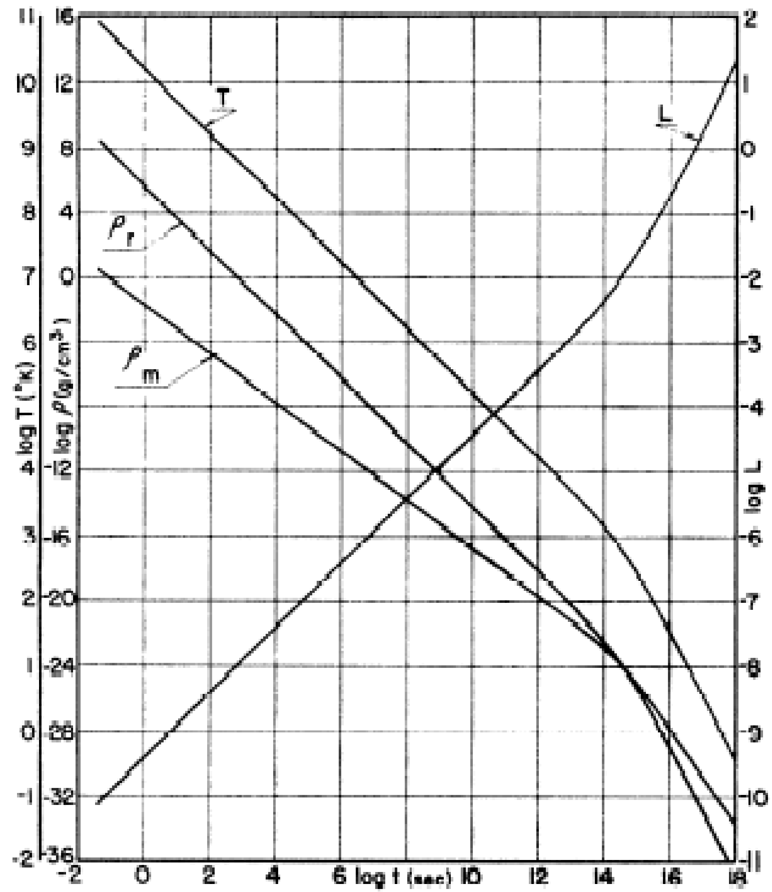
Another Schematic Outline:



CMBR and the Recombination Era

Prediction of CMB is trivial in Hot Big Bang model:

- Hot, ionised initial state should produce thermal radiation
- Photons decouple when universe stops being ionised (last scattering)
- Expansion by factor *a* cools a blackbody spectrum from *T* to *T/a*
- Therefore, we should now see a cool blackbody background
  - Alpher and Herman, 1949, "A temperature now of the order of 5 K"
  - Dicke et al., 1965, "<40 K"

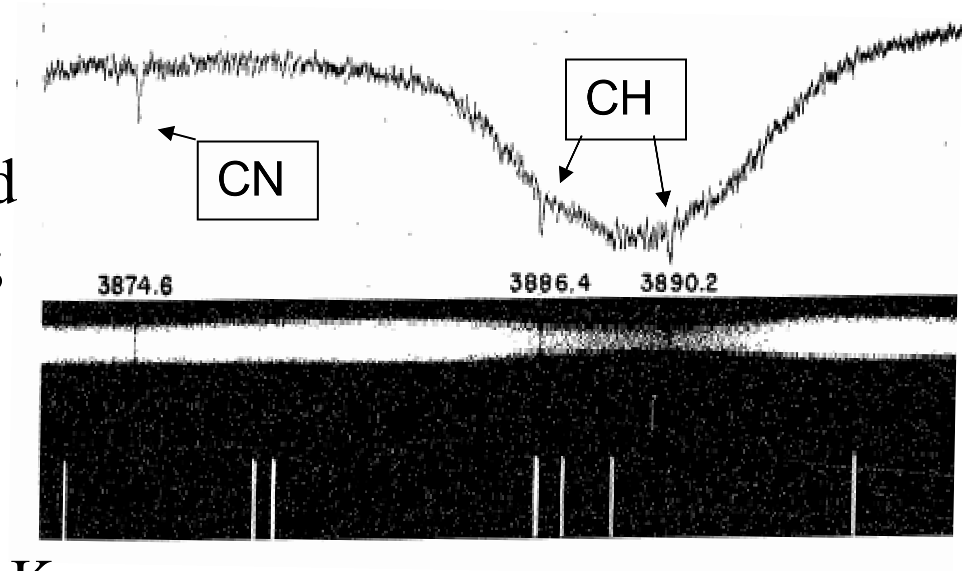


Note that the Gamow, Alpher & Herman prediction had been nearly forgotten at this time!

The CMBR Disoveries

First seen in 1941 (yes, 1941!)

- Lines seen in stellar spectra identified as interstellar CH and CN (Andrew McKellar, theory; Walter Adams, spectroscopy)
- Comparison of lines from different rotational states gave "rotational temperature" of 2-3 K



- Unfortunately, Gamow *et al*. did not have known about this
- Hoyle made the connection in 1950:

  "[the Big Bang model] would lead to a temperature of the radiation at present maintained throughout the whole of space much greater than McKellar's determination for some regions within the Galaxy."
- So, Penzias & Wilson made the recognized discovery in 1964

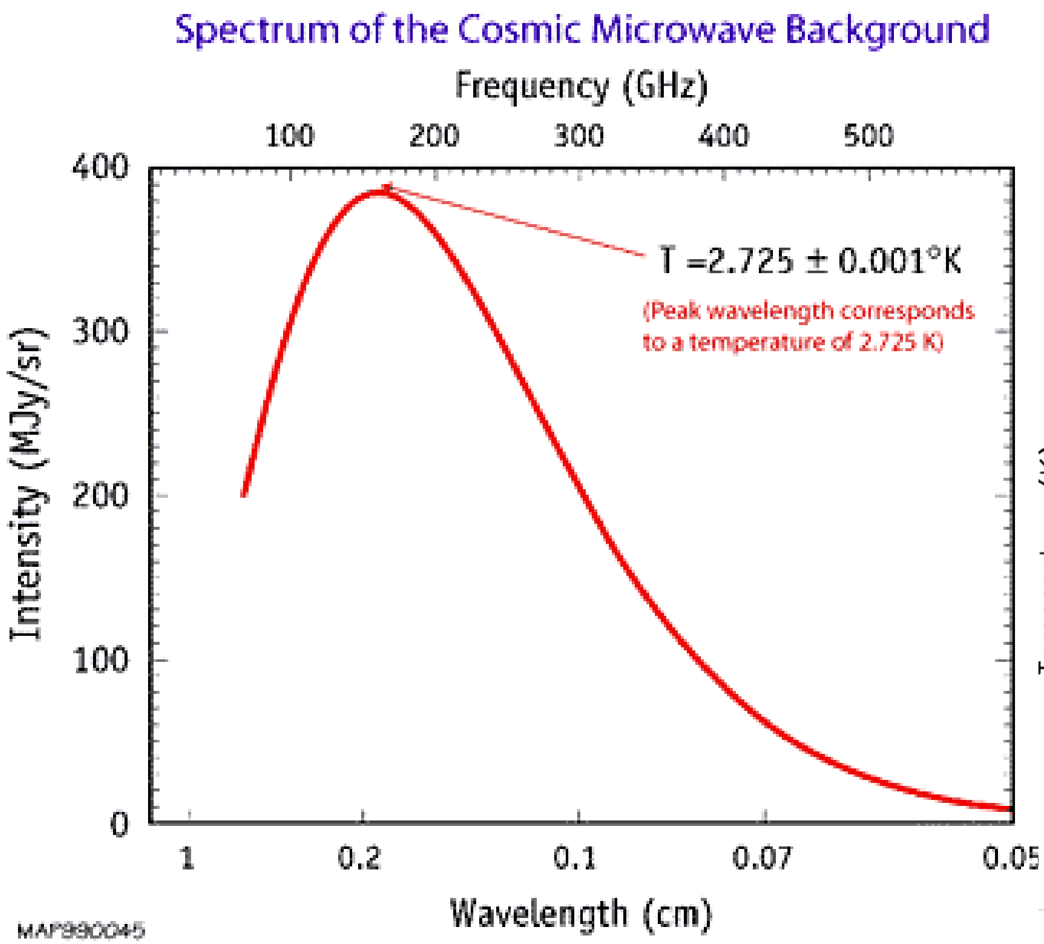
Discovery of the Cosmic Microwave Background (CMBR): A Direct Evidence for the Big Bang

Arno Penzias &
Robert Wilson (1965)

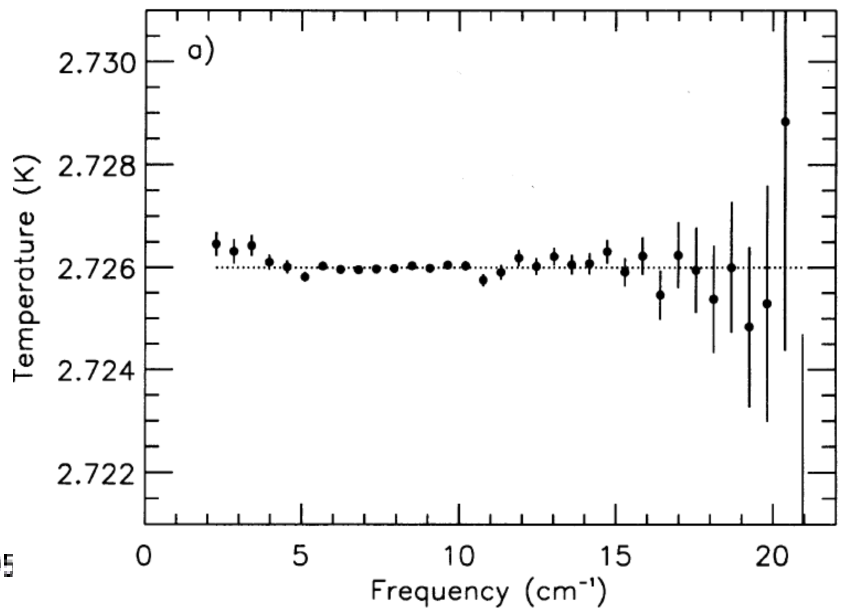
Nobel Prize, 1978

The CMBR Spectrum:
A Nearly Perfect Blackbody

Residuals from the BB strongly limit possible energy injection (e.g., from hypothetical decaying DM particles) during and after the recombination - no new physics here…



Residuals from the BB fit



Temperature of Recombination

Mean photon energy: $\langle E \rangle \sim 3k_B T$

Ionisation energy of H: $E = 13.6\,\mathrm{eV}$

Photoionisation Temperature: $T = \dfrac{13.6\,\mathrm{eV}}{3k_B} = 50000\mathrm{K}$

But there are many more photons than H ions: $n_g \approx 10^9 n_p$

Thus, the T can be lower and have enough photons with high enough energies to ionize H!

Boltzmann distribution: $n_g(>E) \propto \exp\left(E \big/ k_B T \right)$

So the actual T of recombination is:

$$T = \frac{13.6\,\mathrm{eV}}{3k_B 9 \ln(10)} = 2500\mathrm{K}$$

And thus, $z_{rec} \sim 1100$

The Extent of Recombination

This phase transition (ionized to neutral gas) has a finite duration: most of the plasma recombines before the last scattering, which is the CMBR photosphere we see

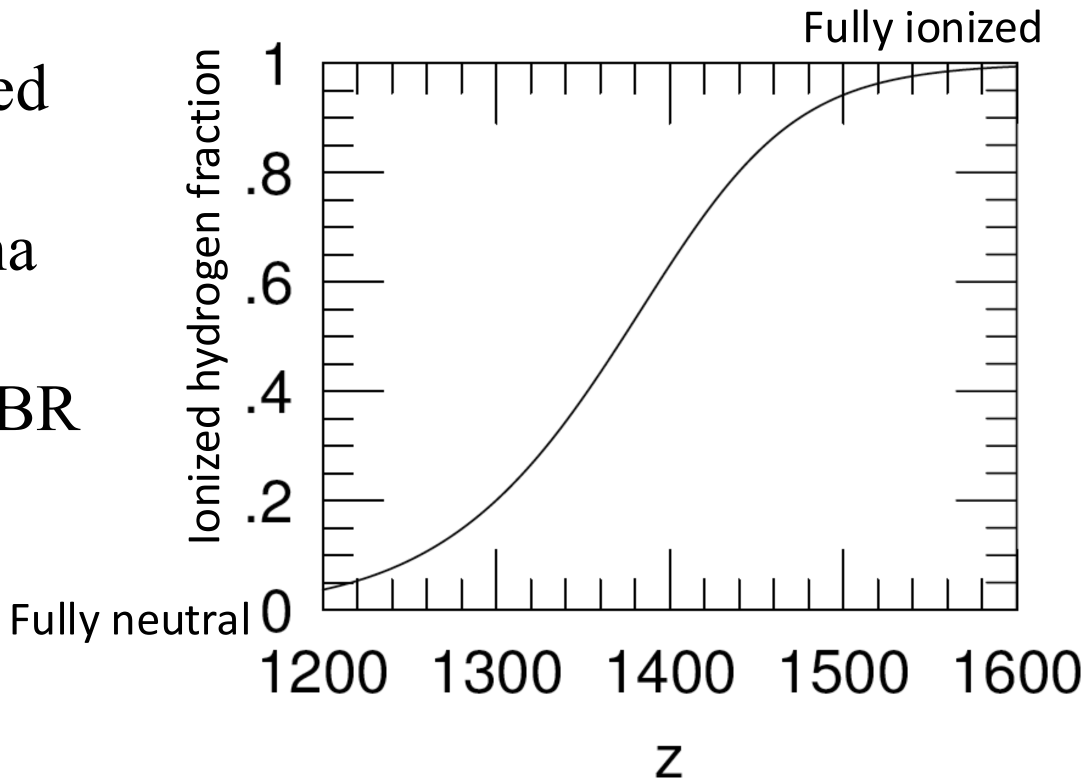
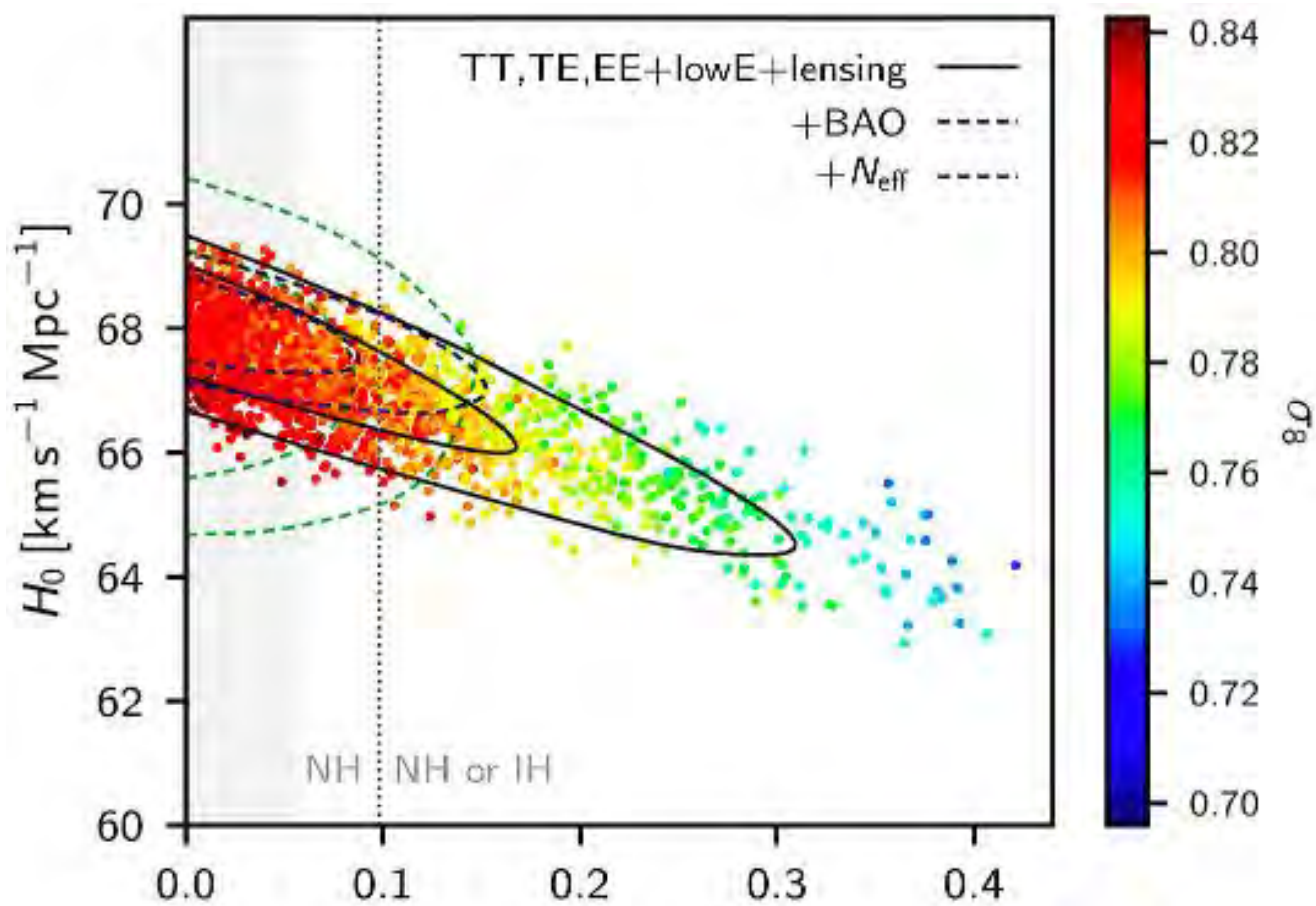


Table 9.1: Events in the early universe

event	redshift	temperature (K)	time (megayears)
radiation-matter equality	3570	9730	0.047
recombination	1370	3740	0.24
photon decoupling	1100	3000	0.35
last scattering	1100	3000	0.35

CMB and Particle Physics

In addition to the CMB, there is also a **cosmic neutrino background** from the nucleosynthesis. We know that neutrinos have mass, but we don't know much. CMB analysis provides some constraints:



Sum over all 3 neutrino species: Σm_ν [eV]

(Planck collab. 2018)

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* …

Asymmetry in Neutron / Proton Ratio

Mass difference between *n* and *p* causes an asymmetry via reactions:

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

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

It is slightly easier (requires less energy) to produce *p* than *n*:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$p \not\rightarrow n + e^+ + \nu_e$$

Thus, once $e^+ e^-$ annihilation occurs only neutrons can decay

We can calculate the equilibrium ratio of *n* to *p* via the Boltzmann equation,

$$X_n = \frac{N_n}{N_n + N_p} \sim 0.16 \exp\left(-\frac{t}{879\ \mathrm{s}}\right)$$

at T~ 10^{12} K, $n/p = 0.985$

The n/p ratio is "frozen" at the value it had at when T= 10^{10} K , $n/p = 0.223$, i.e., for every 1000 protons, there are 223 neutrons

Big Bang Nucleosynthesis (BBNS)

Free neutrons are unstable to beta decay, with *mean lifetime* = 879 sec, $n \rightarrow p + e^- + \nu_e$. This destroys ~ 25% of them, before they can combine with the protons

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

$$n + p \leftrightarrow {}^2H + g$$

$${}^2H + {}^2H « \ {}^3He + n$$

$${}^3He + n « \ {}^3H + p$$

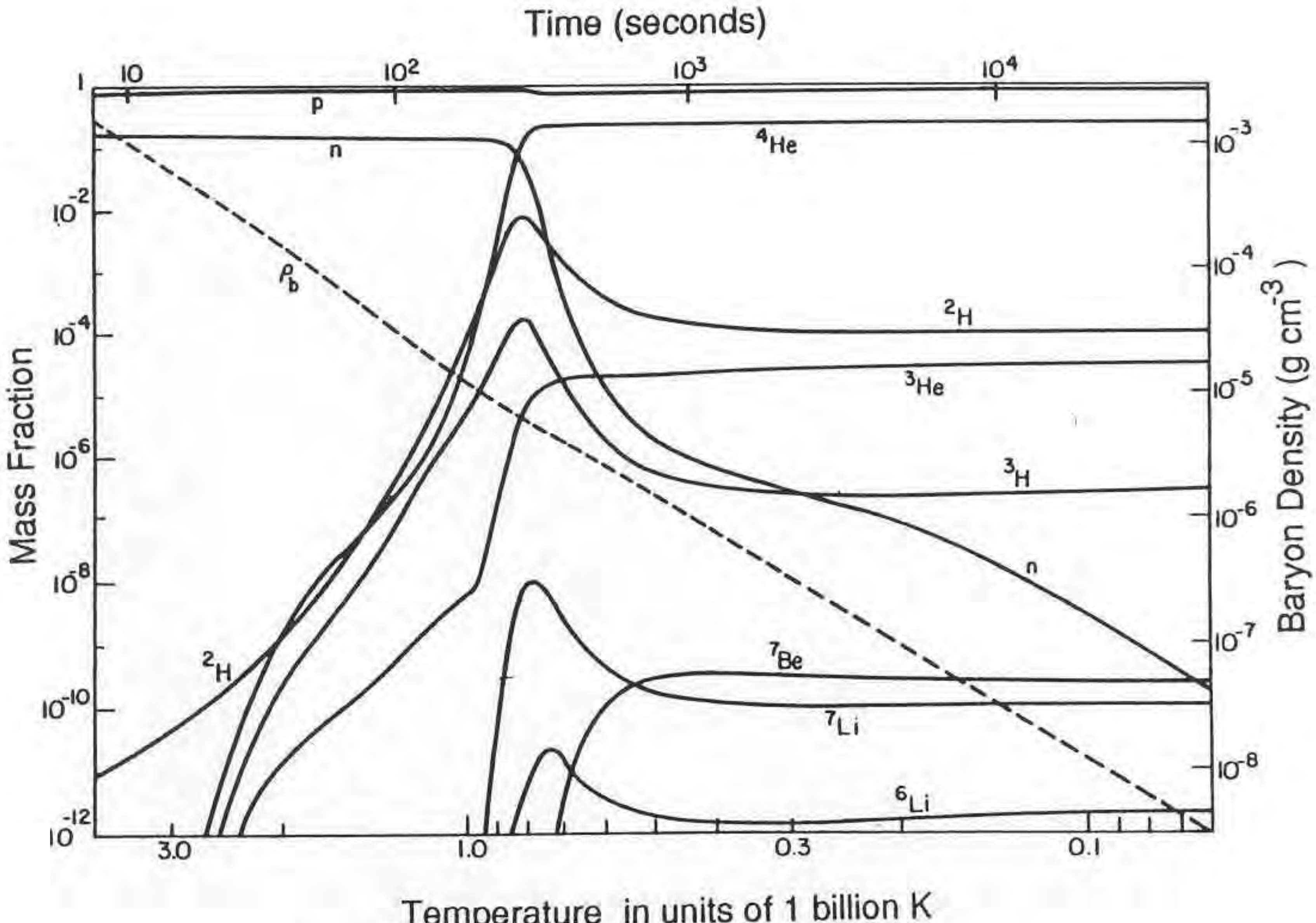
$${}^3H + {}^2H « \ {}^4He + n$$

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 being created and none are destroyed

The Evolution of Abundances in BBNS



Big Bang Nucleosynthesis End

At this point *n/p* ratio has dropped to ~ 0.14. The excess protons account for about 75% of the total mass, and since essentially all neutrons are incorporated into the He nuclei, *the predicted primordial He abundance is ~ 25% - about as measured*

Thus *neutron/proton asymmetry* caused by their mass difference and the *beta decay of neutrons* determines the primordial abundance of He and other light elements

Because all the neutrons are tied up in He, its abundance is not sensitive to the matter density. In contrast, the abundances of other elements produces in the early universe, D, ^{3}He, and ^{7}Li are dependent on the amount of baryonic matter in the universe

The universe expanded to rapidly to build up heavier elements!

BBNS Predictions

- The BBNS makes detailed predictions of the abundances of light elements: ^2D, ^3He, ^4He, ^7Li, ^8Be
- 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 spectacularly good agreement with the value from the CMB fluctuations:

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

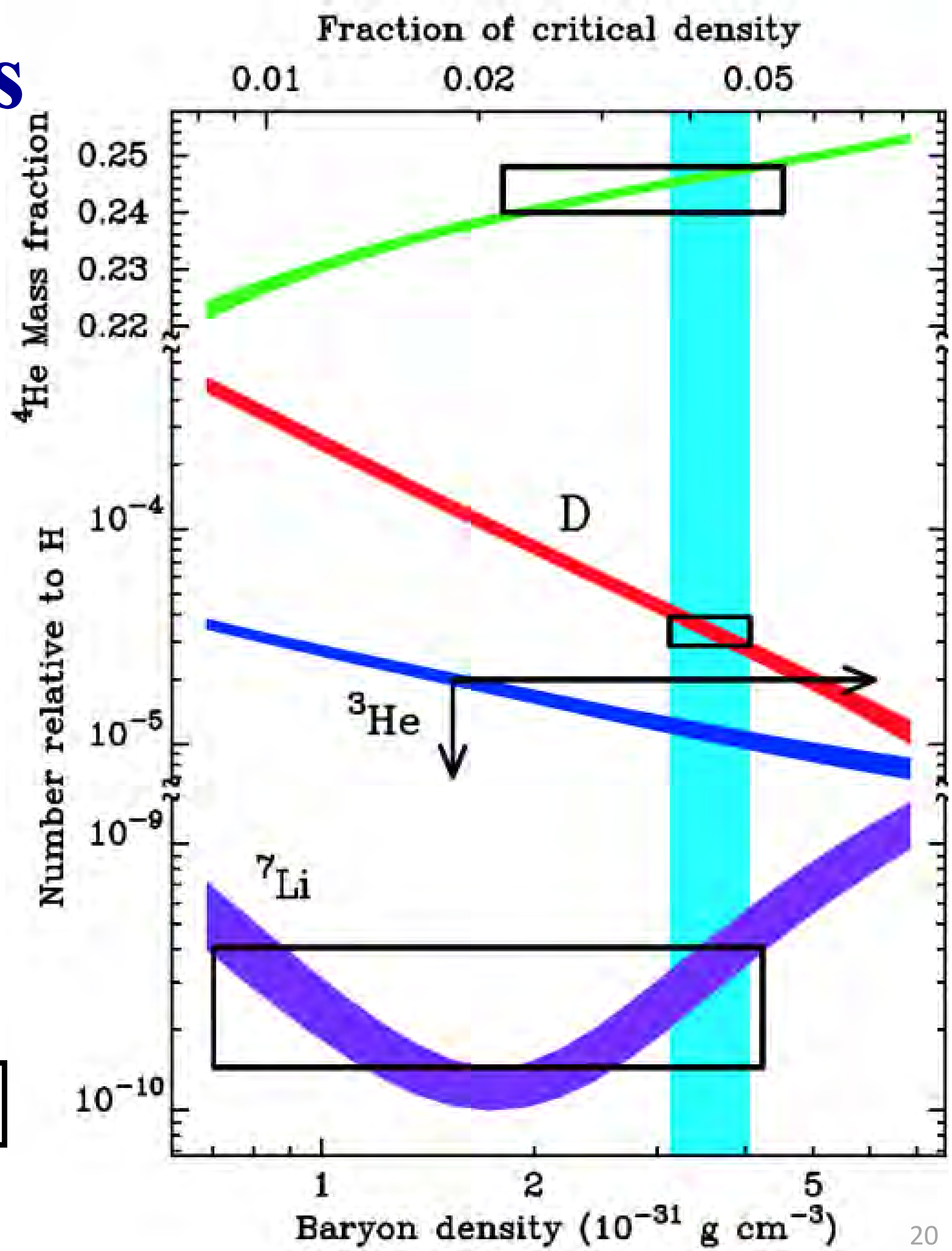
BBNS Predictions

^{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

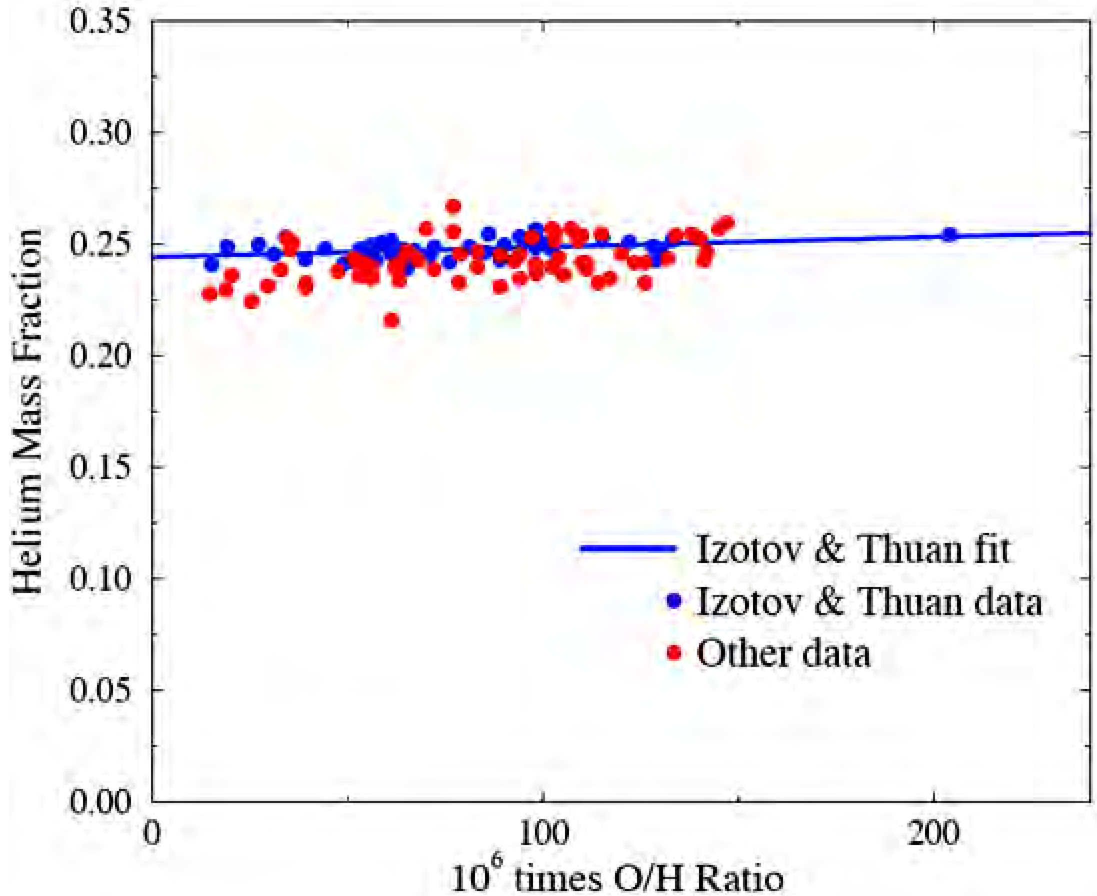
Boxes indicate observed values



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

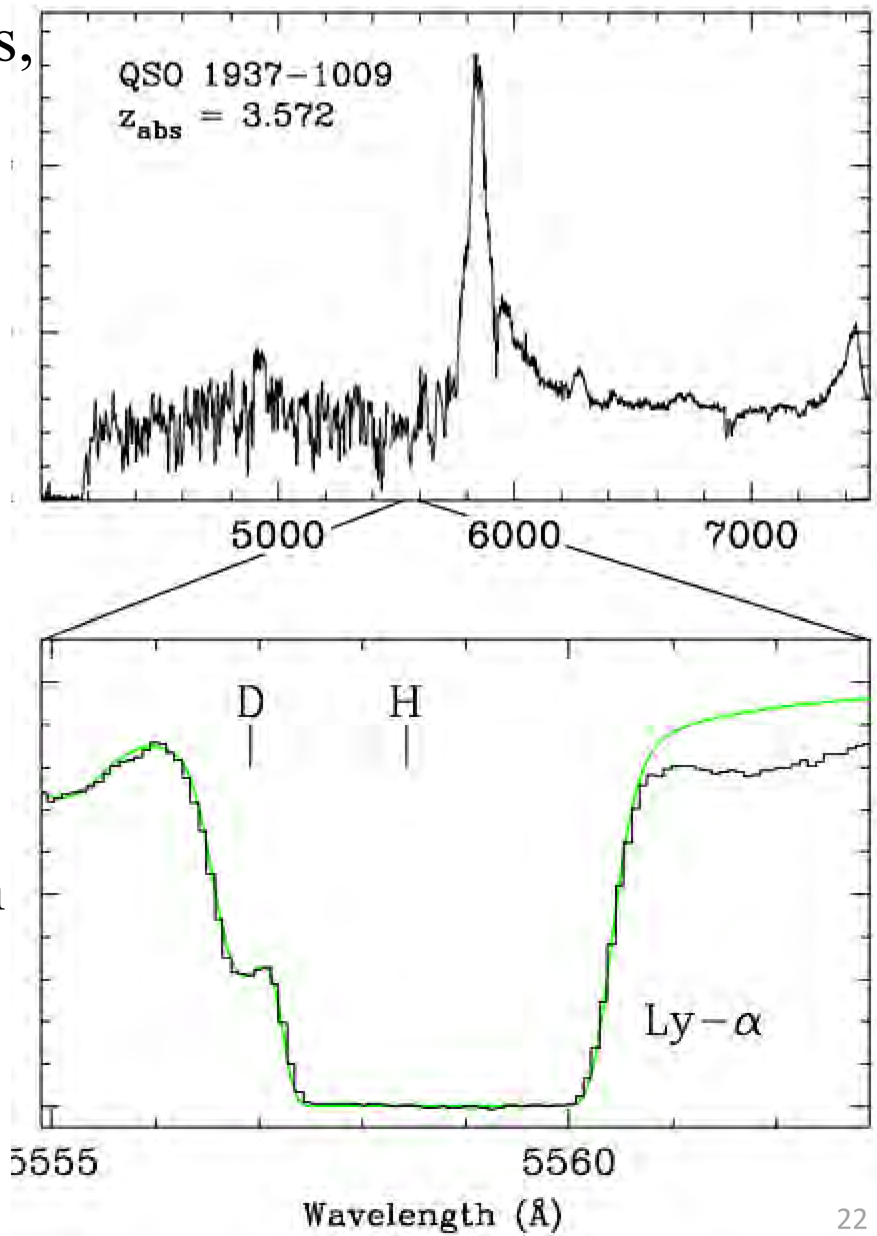
Deuterium is *easily destroyed* in stars, and there is *no known process* where it can be created in large amounts after the BBNS

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

D is heavier, so the absorption lines are shifted by –82 km/s

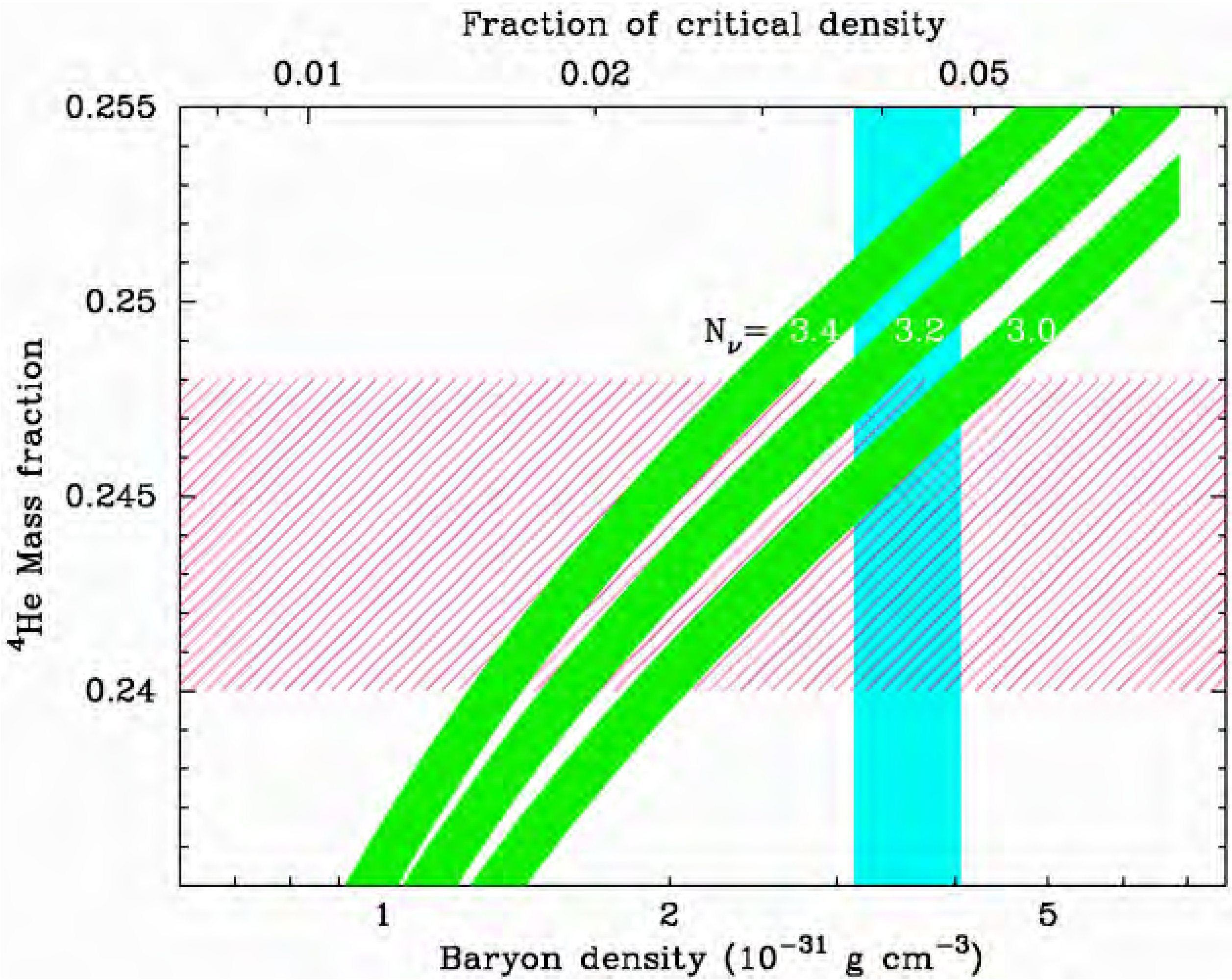
It is a tricky measurement, and it requires high resolution spectra from 8-10 m class telescopes

The result is: $$\frac{D}{H} = 2.74 \times 10^{-5}$$



BBNS and Particle Physics

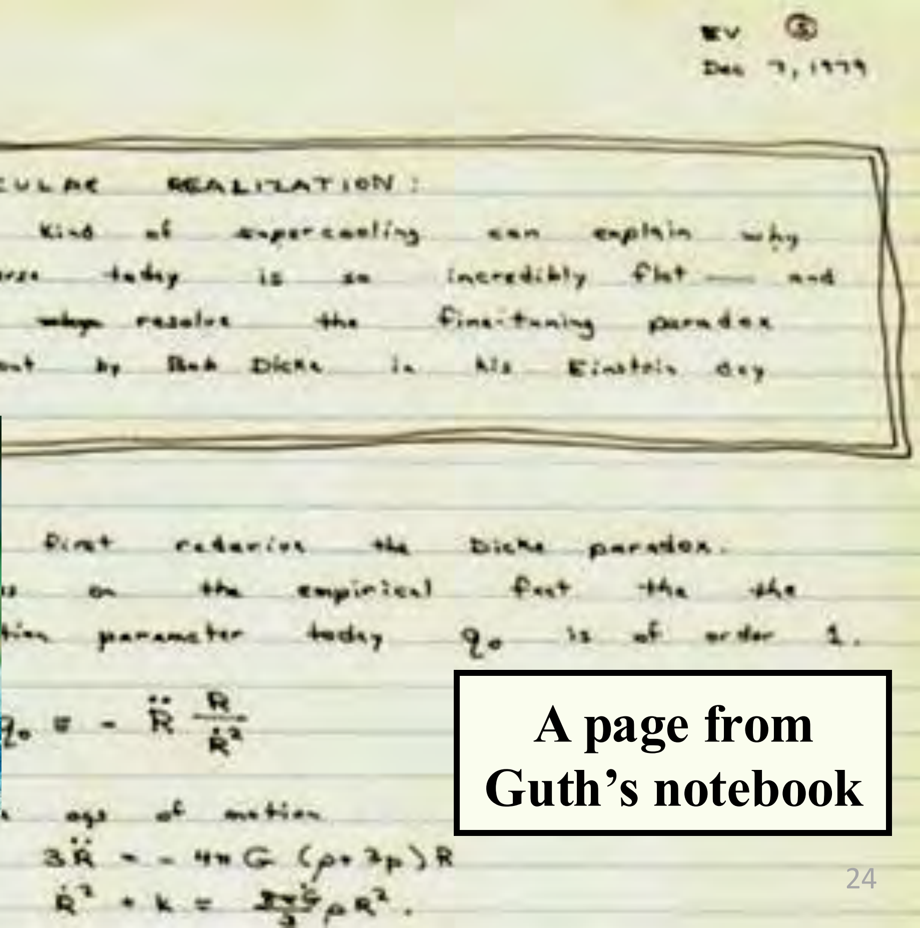
BBNS predictions also depend on the *number of lepton (neutrino) families*. Indeed, only 3 are allowed:



This is also confirmed by the CMB measurements

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 topological defects…
- Developed further by P. Steinhardt, A. Albrecht, A. Linde, and many others



A page from Guth's notebook

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

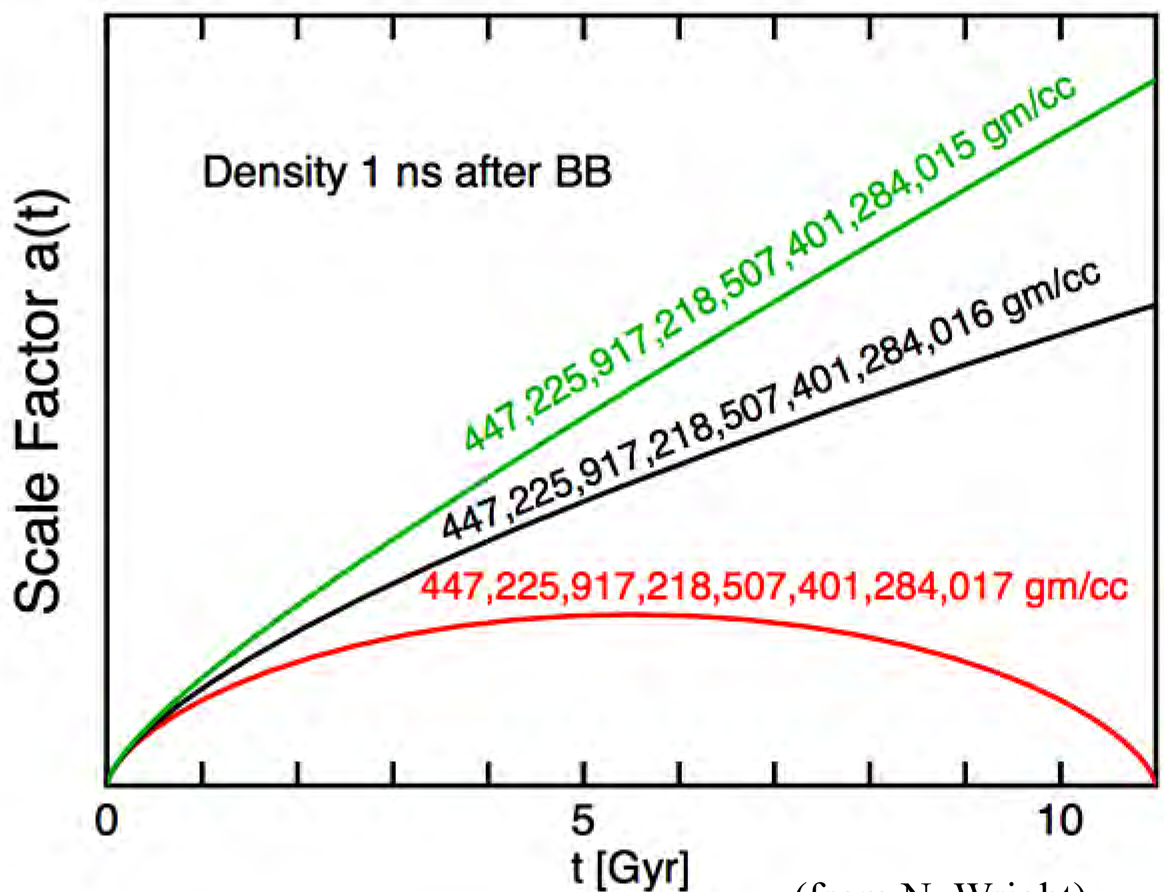
The Flatness Problem

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

$$1 - \Omega(t) = -\frac{kc^2}{H(t)^2 a(t)^2 R_0^2} = \frac{H_0^2(1-\Omega_0)}{H(t)^2 a(t)^2}$$

$$\left(\frac{H(t)}{H_0}\right)^2 = \frac{\Omega_{r0}}{a^4} + \frac{\Omega_{m0}}{a^3}$$

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)

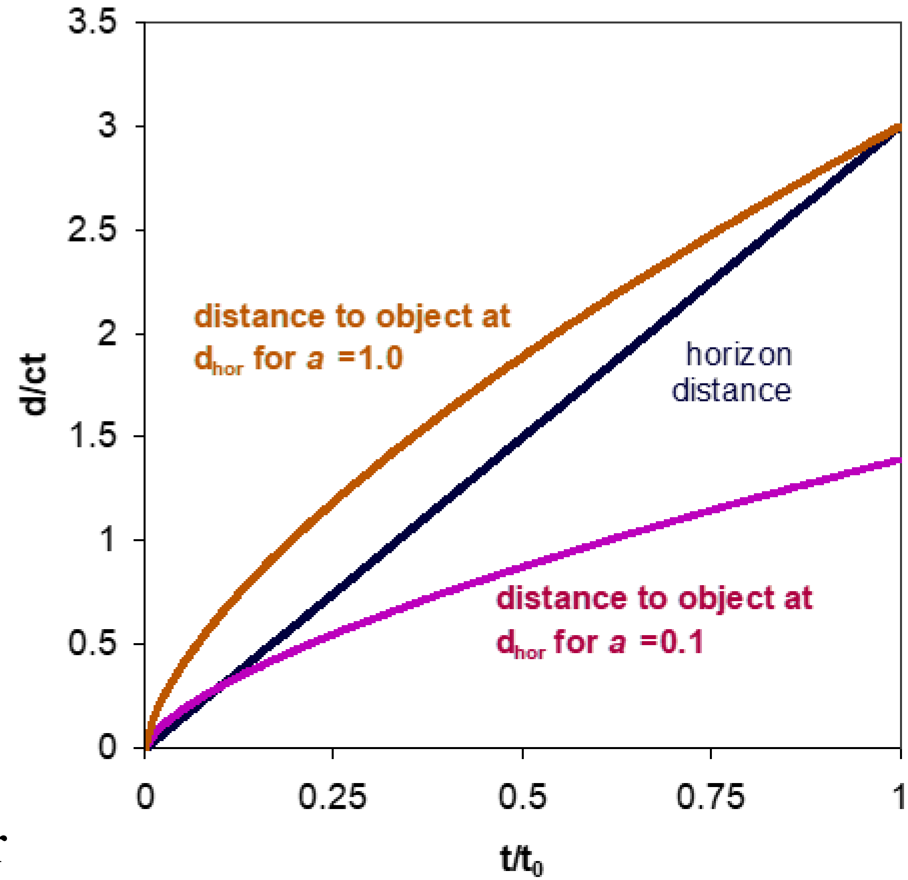
The Horizon Problem

Consider matter-only universe:

- Horizon distance $d_H(t) = 3ct$
- Scale factor $a(t) = (t/t_0)^{2/3}$
- Therefore horizon expands faster than the universe, so new" objects are constantly coming into view

Consider CMBR:

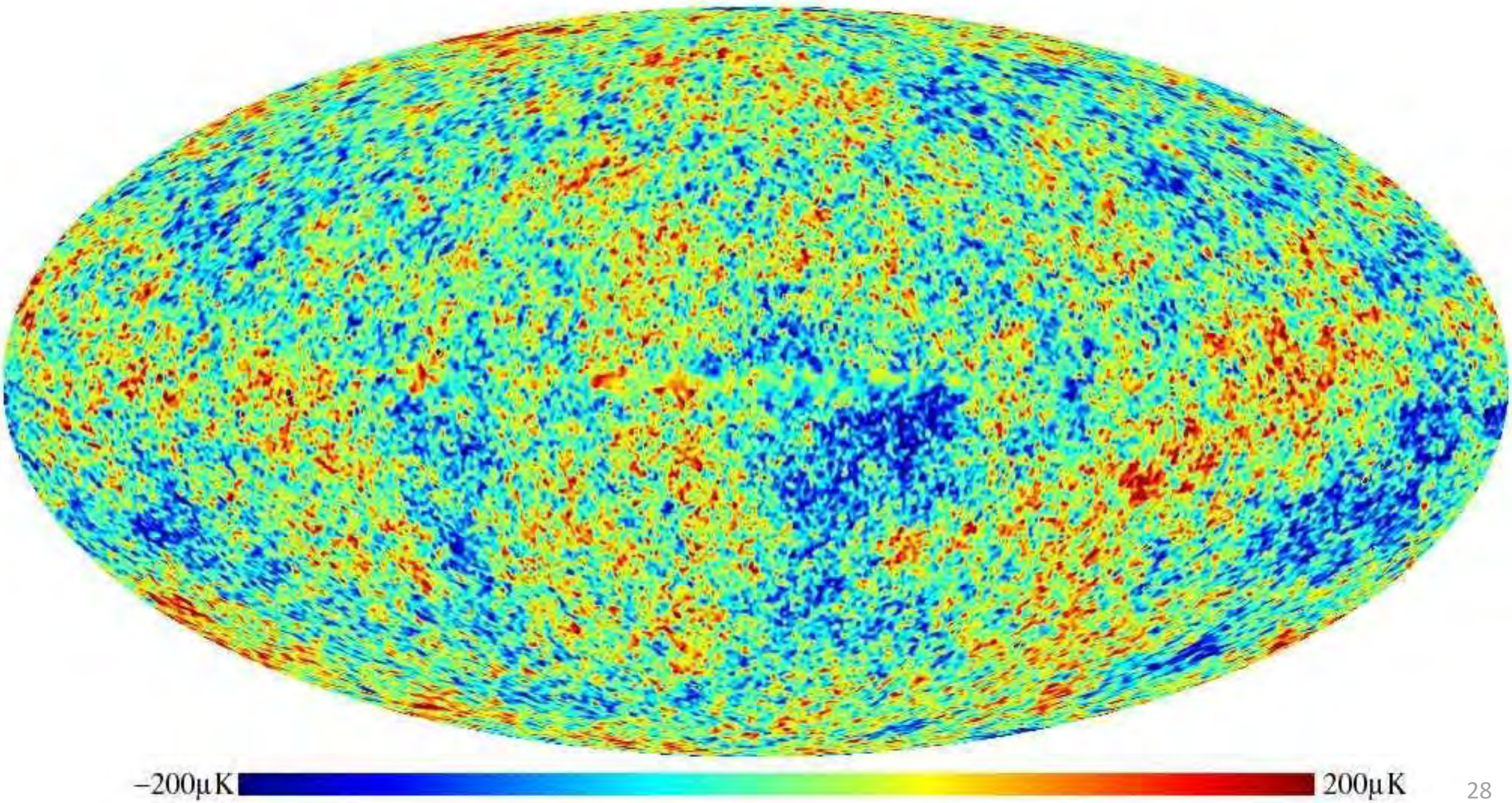
- It decouples at $1+z \sim 1100$
- i.e., $t_{CMB} = t_0/10^{4.5}$
- Then $d_H(t_{CMB}) = 3ct_0/10^{4.5}$
- Now this has expanded by a factor of 1000 to $3ct_0/10^{1.5}$
- But horizon distance now is $3ct_0$
- So angle subtended on sky by one CMB horizon distance is only ~ 2°



 Patches of CMB sky > 2° apart should not be causally connected!

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?

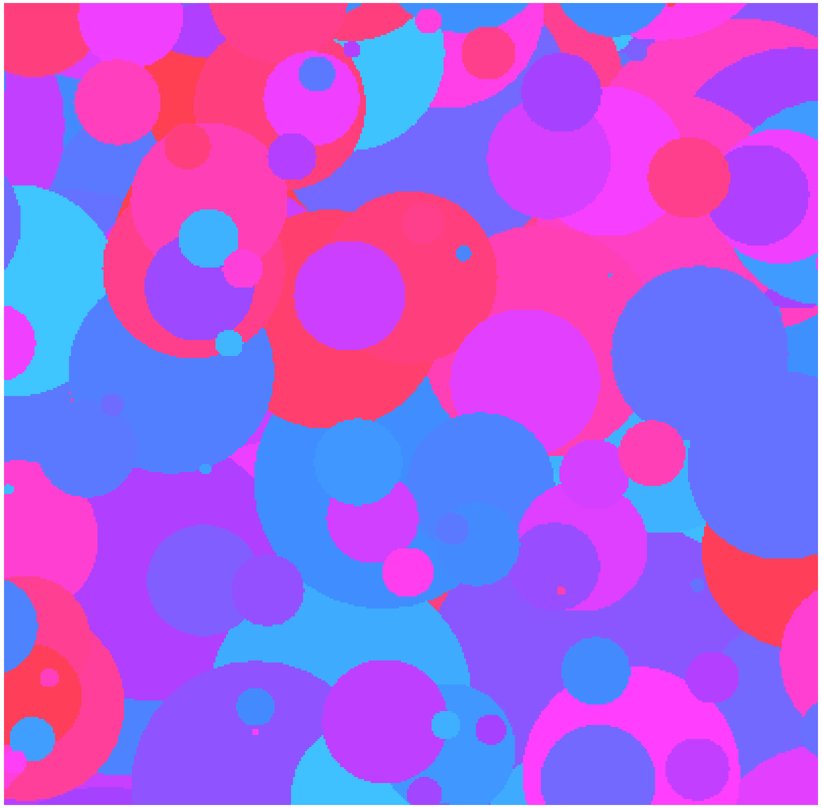


Inflationary Universe Scenario

- If there is a Theory of Everything (TOE) that unifies all four forces it will break spontaneously at the Planck time ($t \sim 10^{-43}$ sec) into the gravitation and a unified version of the magnetic, electroweak, and strong forces – a Grand Unified Theory (GUT)
- The GUT will hold until $T \sim 10^{28}$ K, or $t \sim 10^{-34}$ sec. At this point the universe entered a period of ***"false vacuum":*** the energy level higher than the lowest, "ground" state
- Symmetry breaking in GUT theories is associated with massive Higgs bosons, which are quanta of a scalar field that has an associated potential which describes the energy of the field
- The false vacuum is a metastable state, with its vacuum energy acting as a "negative pressure" causing the universe to expand exponentially as it "rolls down the scalar field"

Inflation as a Phase Transition

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



Regions of non-inflating universe are created through the nucleation of bubbles of true vacuum. When two such bubbles collide, the vast energy of the bubble walls is converted into the particles. This process is called reheating

Cosmic Inflation: Exponential Expansion

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:

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

Thus: $da/a = const. \times dt$

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:

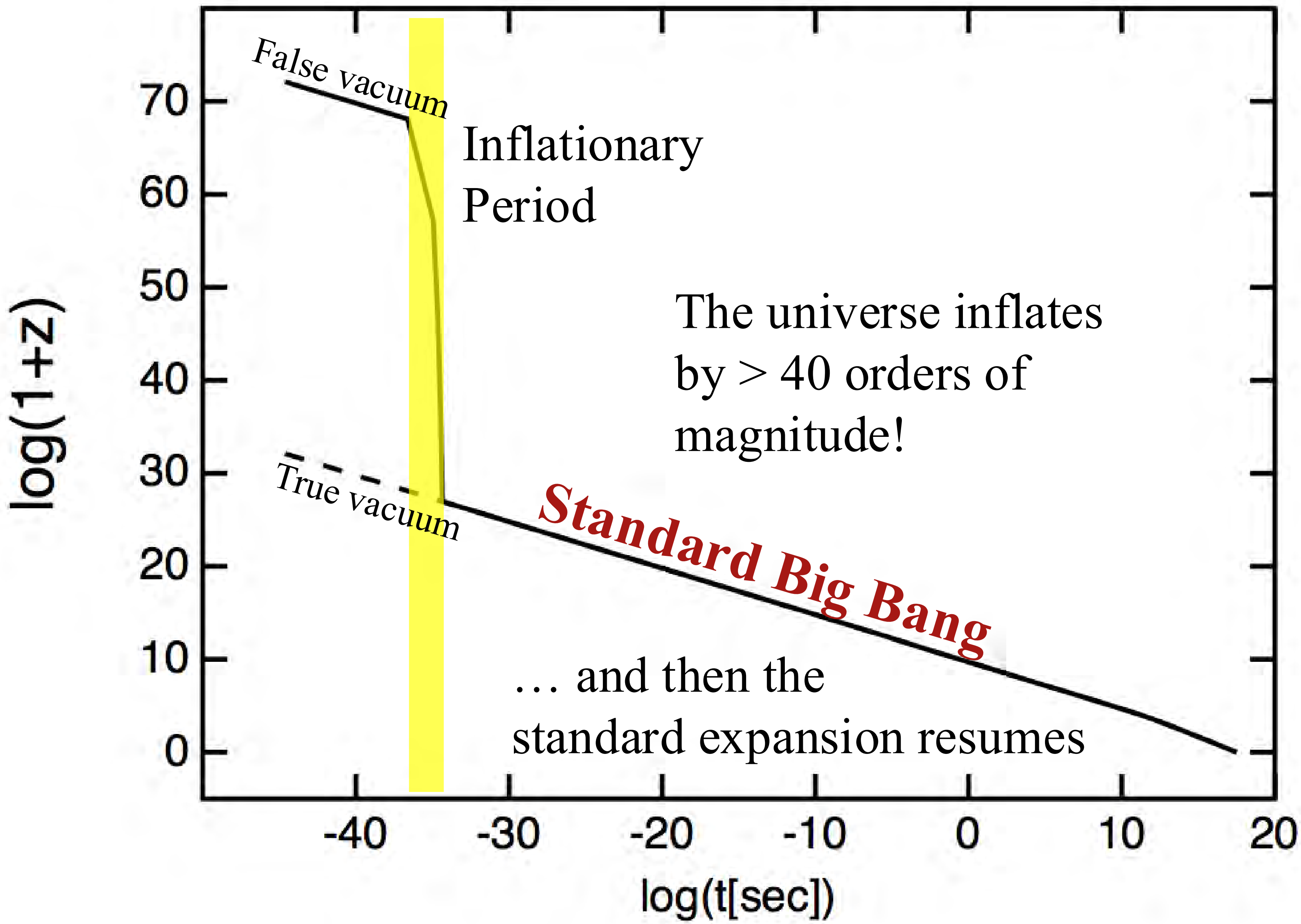
$$\frac{a(t_f)}{a(t_i)} \sim e^{100} \sim 10^{43}$$

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

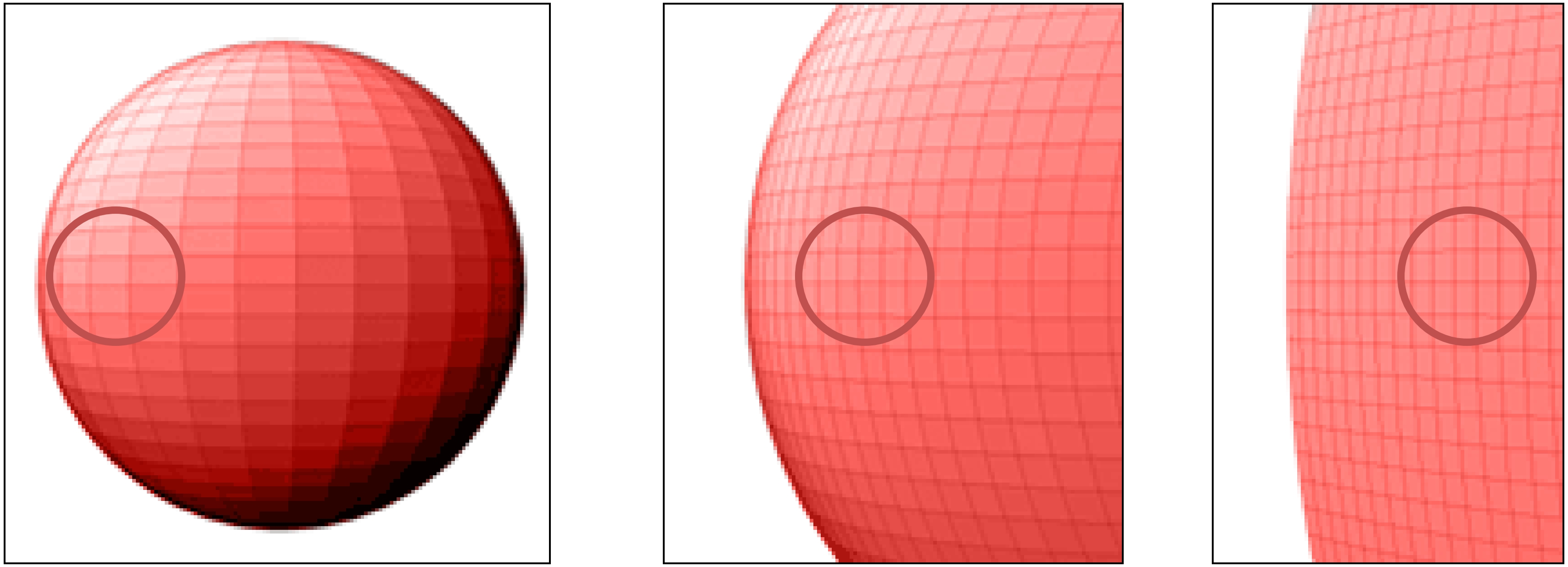
Thus:

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

The Inflationary Scenario



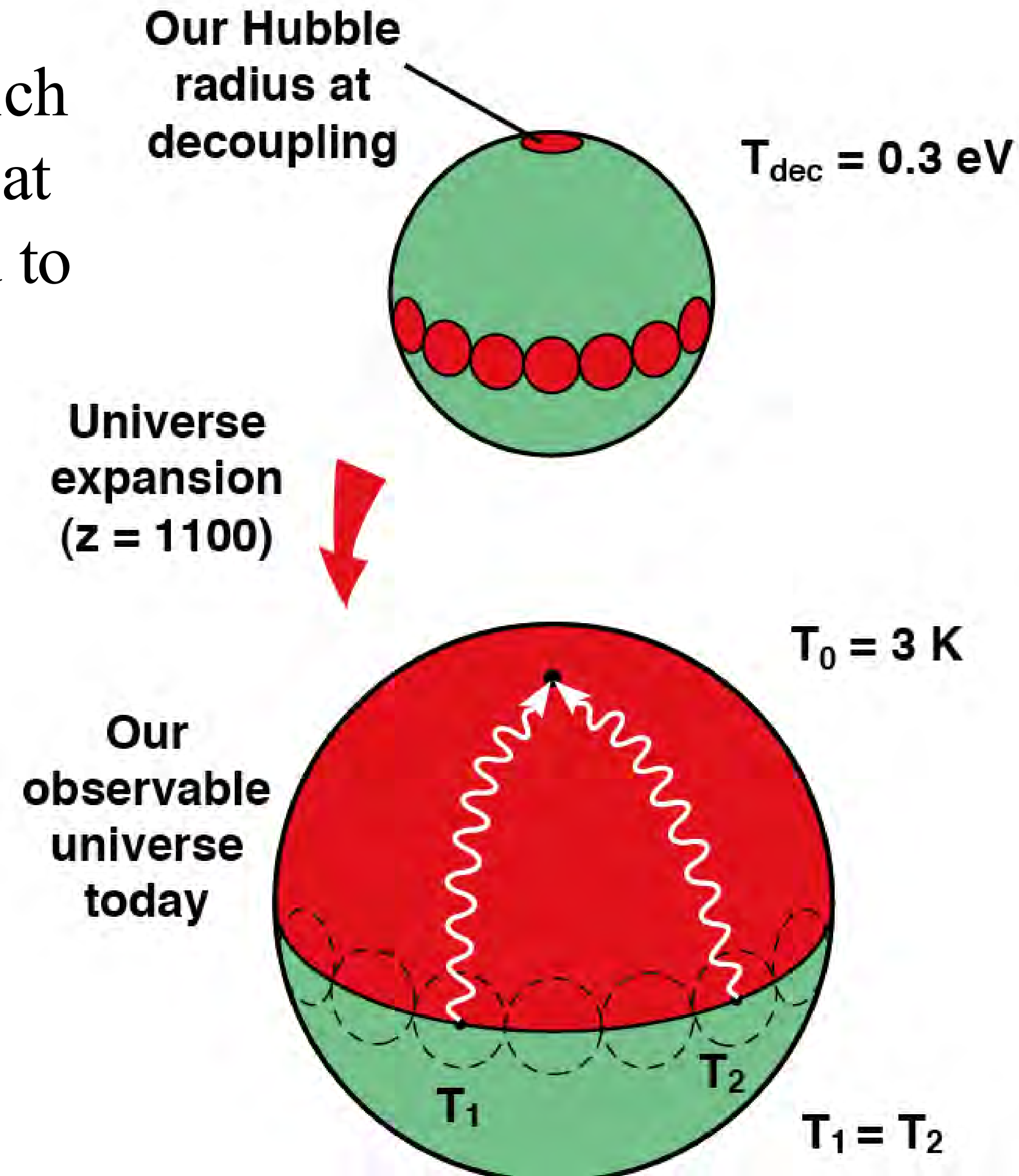
Inflation Solves the Flatness Problem



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

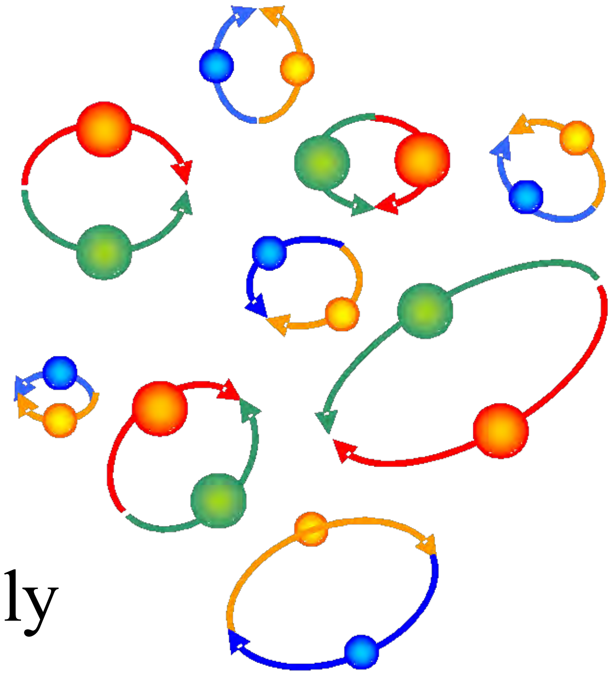
Regions of the universe which were causally disconnected at the end of the inflation used to be connected before the inflation - and thus in a thermal equilibrium



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

Inflation and Structure Formation

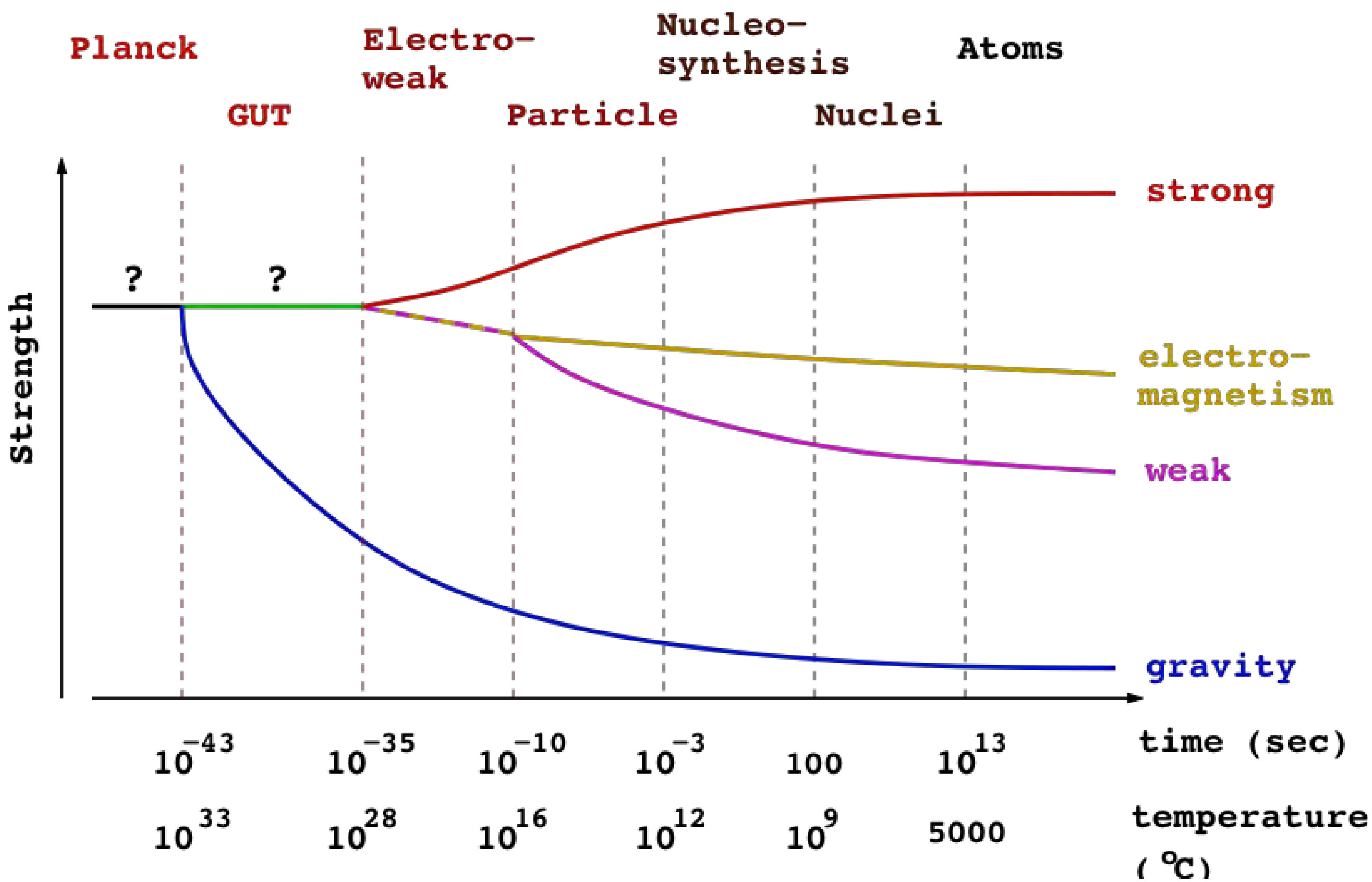
- Uncertainty Principle means that in quantum mechanics vacuum constantly produces temporary particle-antiparticle pairs
  - This creates minute *density fluctuations*
  - Inflation blows these up to macroscopic size
  - They become *the seeds for structure formation*



- Expect the mass 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

Physical Interactions in the Early Universe

As we get closer to *t* ⍰ 0 and *T* ⍰ ∞, 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 hypothetical 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

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

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 …

Where does it come from?

The Cosmic Baryogenesis

- The conditions required for the creation of more matter than anti-matter were first derived by A. Sakharov in 1967:
  1. **Baryon number violation**
     - Otherwise have same no. of particles and antiparticles
     - Never been observed
     - Predicted to occur in several GUT theories
  2. **C and CP violation**
     - Parity of antiparticles is opposite to that of particles
     - CP violation discovered in 1964 (Cronin and Fitch)
  3. **Departure from non-thermal equilibrium**
     - Otherwise all reactions go both ways
     - Provided by the expansion of the universe
- Now believed to be the mechanism responsible for the matter - antimatter asymmetry

Planck Units

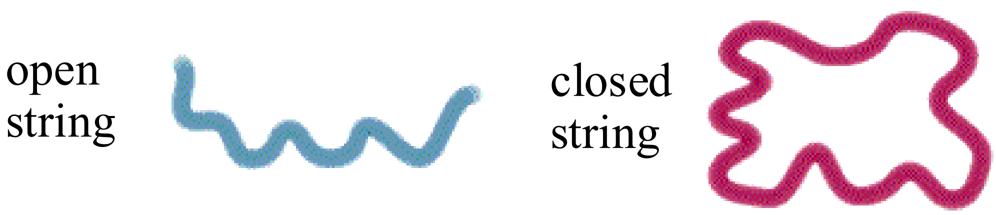
Proposed in 1899 by M. Planck, as the "natural" system of units based on the physical constants:

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

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



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

Summary of the Key Concepts

- As we look back in time towards the Big Bang, the universe was hotter and denser. At any given time, the temperature translates into a *characteristic mass or energies of particles* ($kT \sim mc^2$), which dominate that epoch
- As the energies increase, *different physical regimes* and different fundamental interactions come into play
  - Recombination at $z \sim 1100$ (atomic physics)
  - Nucleosynthesis at $z \sim 10^9$ (nuclear physics)
- The closer we get to the Big Bang (i.e., further away from the experimentally probed regime), the less certain the physics
- *Inflation* at $t \sim 10^{-33}$ sec solves important problems (flatness, horizon), but it is based on an *as-yet-unknown physics*
- Our extrapolations must break down by the epoch of $\sim 10^{-43}$ sec $\sim$ Planck time (?), where the quantum gravity must be important