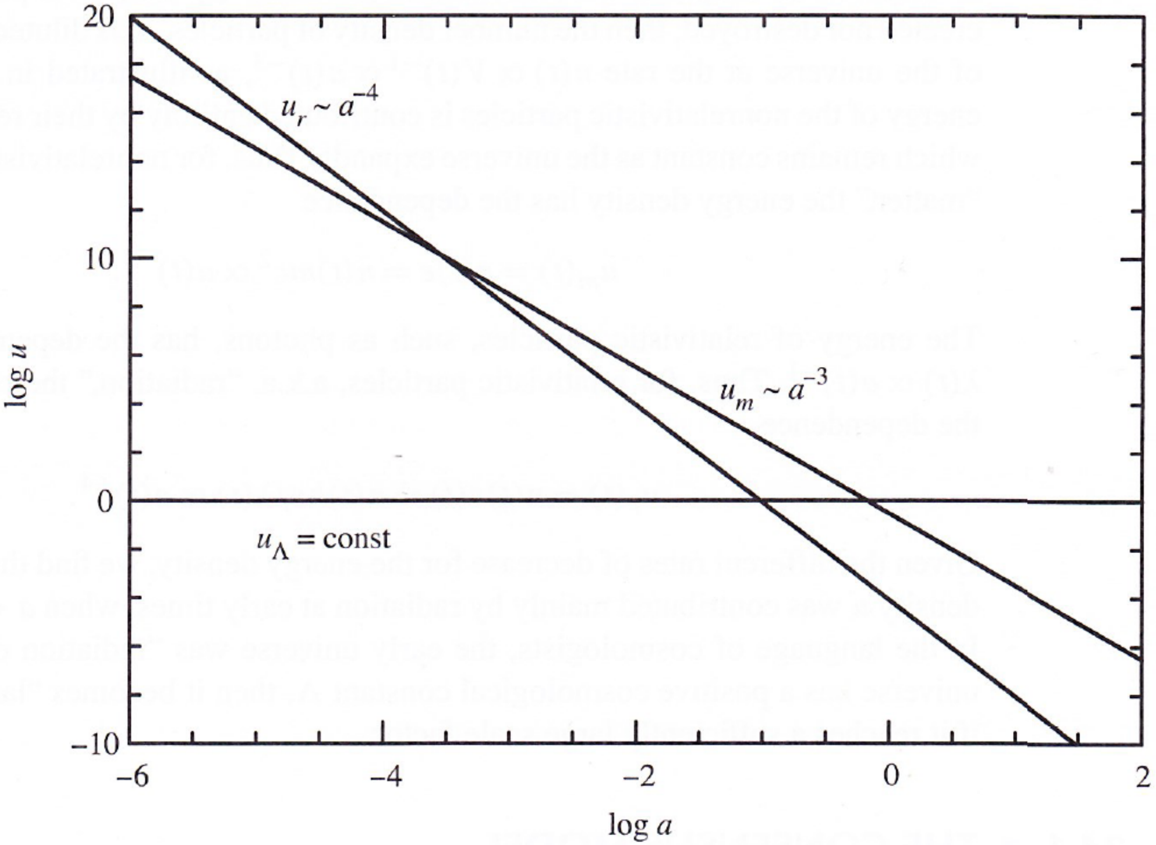
Cosmology

- Thermal history of the universe
- Primordial nucleosynthesis
- WIMPs as dark matter
- Recombination
- Horizon problem
- Flatness problem
- Inflation

Energy density versus scale factor



$z=1/a-1$

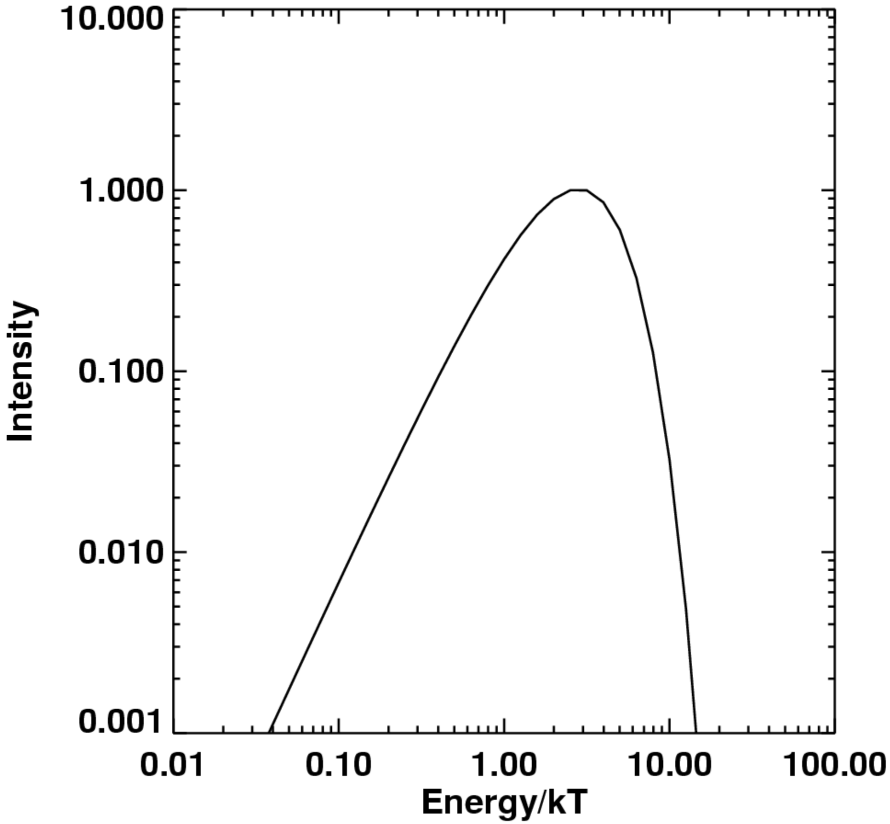
- Early times, $z > 3600$ or age < 47 kyr, were radiation dominated
- Energy density $u = 4\sigma T^4/c$.
- Temperature was higher at smaller scale factors = earlier times.

Thermal Radiation

Average photon energy is proportional to temperature.

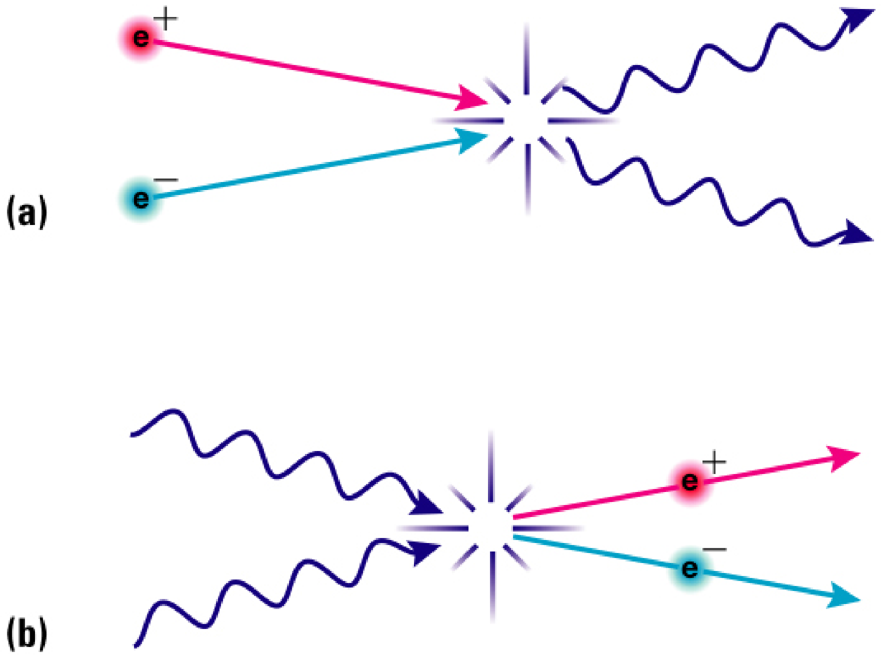
Describe temperature either in degrees or in energy units.

k = Boltzmann constant = 8.62×10^{-5} eV/K



Thermal spectrum peaks at 2.8 kT, falls off exponentially at higher energies.

Particle creation



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- At sufficiently high temperatures, pairs of photons will have enough energy to create particle-antiparticle pairs.
- For $kT >> mc^2$ will have equal numbers of photons and particles.
- Will have equal numbers of particles and antiparticles.

Decoupling

- What happens as universe cools?
- When $kT < mc^2$ can no longer have $\gamma + \gamma \rightarrow x + \bar{x}$ but can have $x + \bar{x} \rightarrow \gamma + \gamma$.
- Rest mass energy of particles will be transferred into thermal energy of photons, increasing the photon temperature.
- Since equal numbers of particles and antiparticles are present when in equilibrium, should expect all particles to annihilate.
- Net presence of particles (e^-, p) indicates some asymmetry in the laws of physics. Figuring out exactly where is a major question in particle physics.
- Can make predictions about what happened in the early universe for temperatures lower than energies where we well understand the elementary particle physics, < 1 GeV.

Decoupling

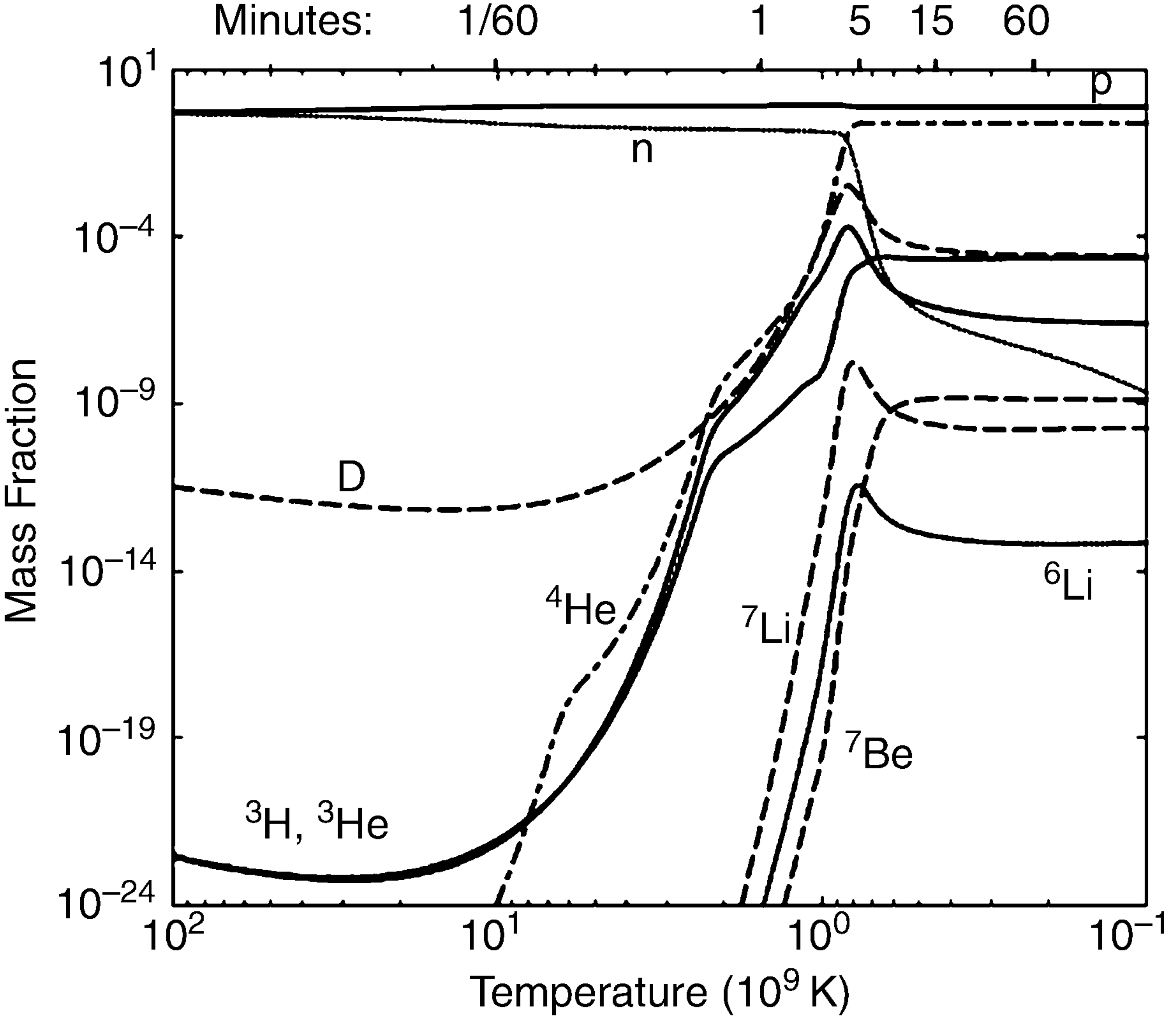
- Particles can also decouple if reaction rate is too low.
- Reaction rate ~ (number density) × (cross section)
- Number density ~ a^{-3}
- Cross section ~ energy^2 ~ T^2 ~ a^{-2}
- Time available for reaction ~ $1/H$
- When (reaction rate) × (time for reaction) < 1, few reactions will occur and the particle will no longer maintain equilibrium.

- This is important for neutrinos and happens at T ~ 10^{10} K or energy ~ 10^6 eV = 1 MeV.

Primordial nucleosynthesis

- Neutrons and protons stay in equilibrium as long as neutrinos are in equilibrium via reactions like $p + \bar{\nu} \leftrightarrow n + e^+$.
- In equilibrium $n_n/n_p = \exp(-\Delta mc^2/kT)$ where $\Delta m = m_n - m_p = 1.293$ MeV/c^2.
- When neutrinos freeze out, $n_n/n_p \sim 1/3$, neutrons start to decay via $n \rightarrow p + e^- + \bar{\nu}$ with a lifetime of 882 seconds and n_n/n_p decreases.
- Simplest stable nucleus with a neutron is deuterium, $n + p \rightarrow D + \gamma$, binding energy of D is only 2.225 MeV and there are still photons of this energy around that photo-dissociate the D.
- Need to wait for universe to cool, during which time neutrons decay, $n_n/n_p \sim 1/7$.
- As soon as density of D builds up, ^{4}He start to form. Binding energy of ^{4}He is 28 MeV, well above photon energies.

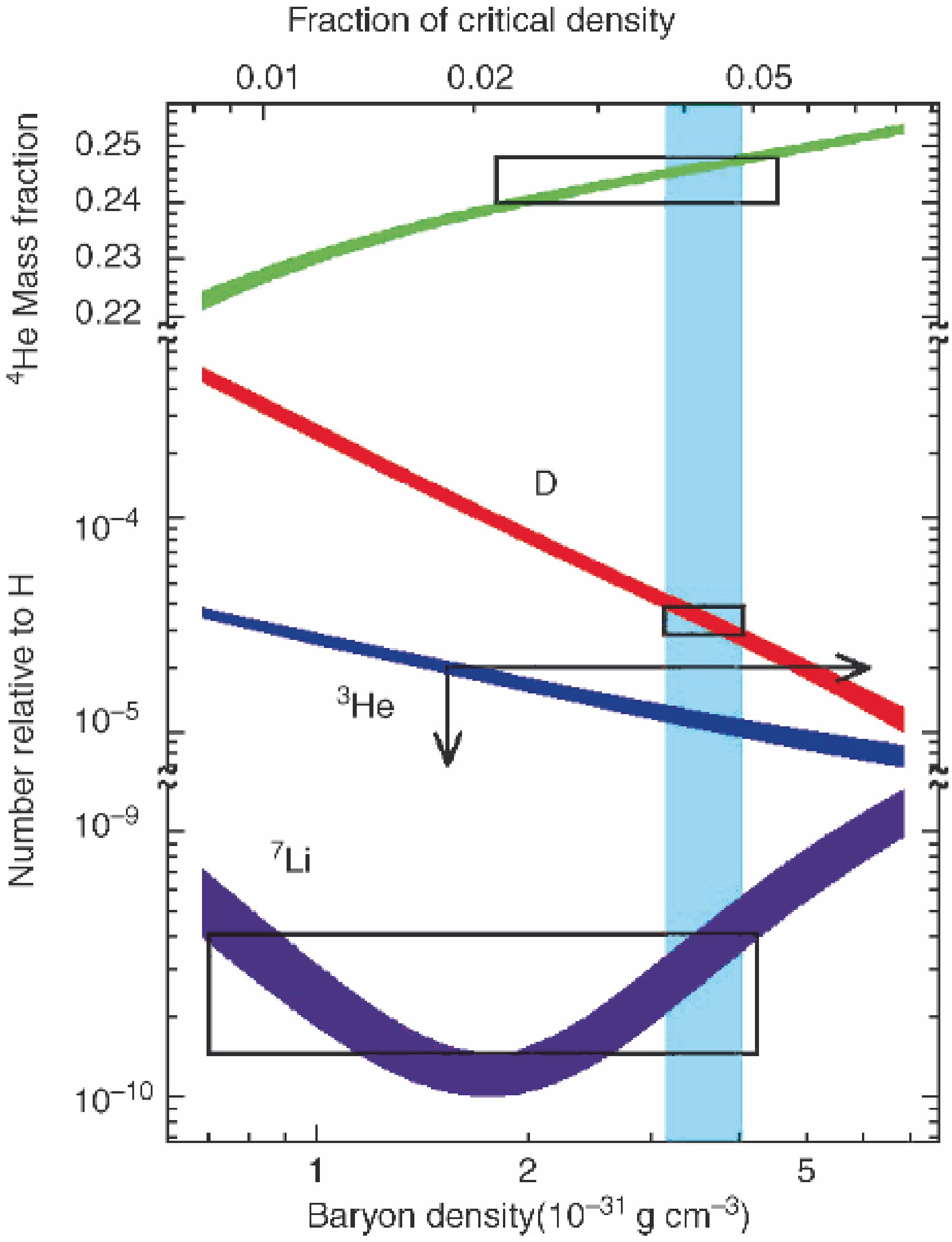
Primordial nucleosynthesis



Primordial nucleosynthesis

Production of light elements is sensitive to baryon density, really to the baryon to photon ratio.

Implies $\Omega_b = 0.04$



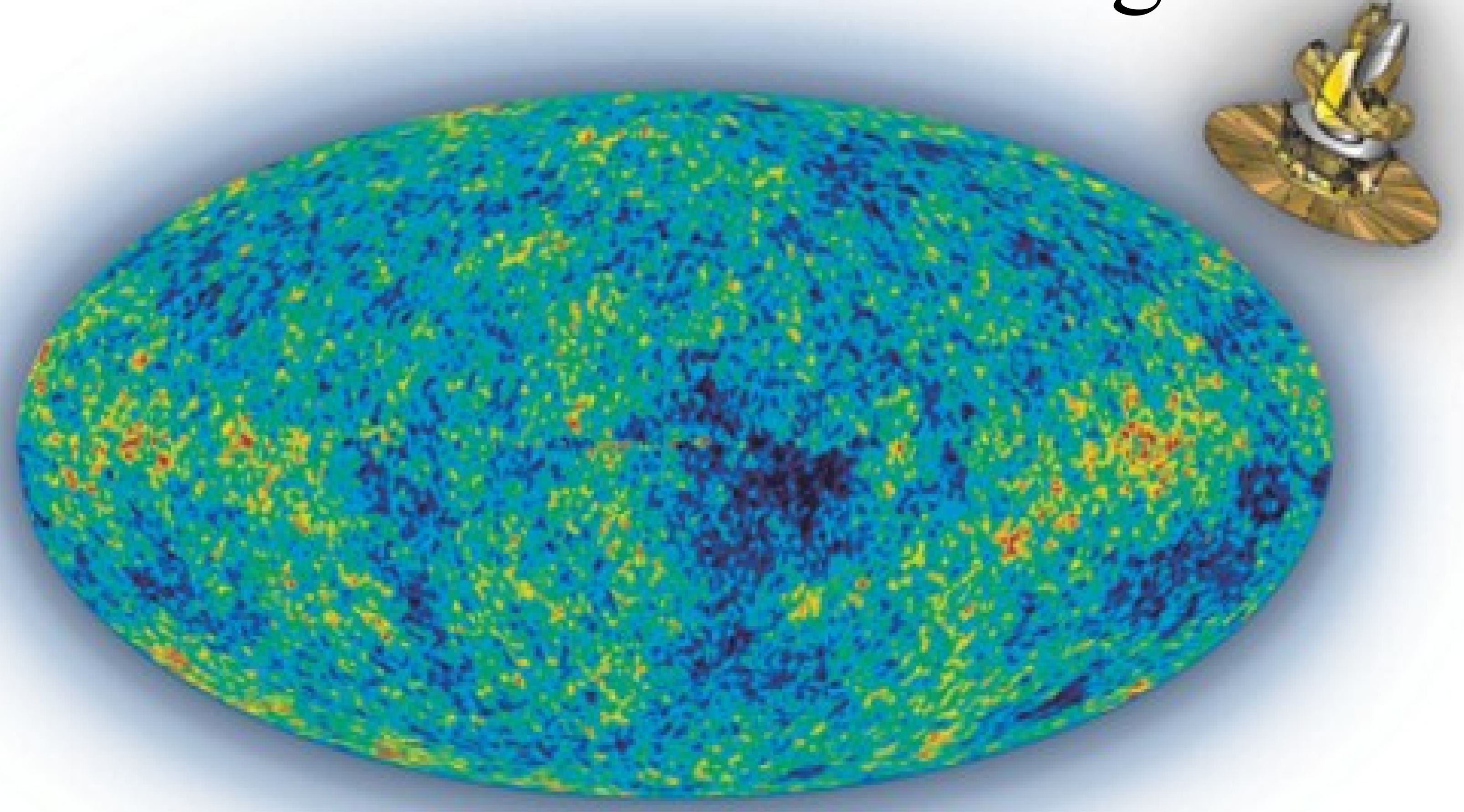
WIMPs as dark matter

- If dark matter interacts via the weak force (i.e Weakly Interacting Massive Particles), then it will decouple in the same way as neutrinos.
- If $m_{\mathrm{WIMP}} < 1$ MeV, then WIMPs were relativistic at freeze-out and will behave in the same manner as neutrinos and the number density will be the same (currently 113 cm^{-3}).
- We can calculate the density in any weakly interacting particle with mass < 1 MeV:

$$\Omega_{\mathrm{w}} h^2 = m_{\mathrm{w}}/91.5\ \mathrm{eV}$$

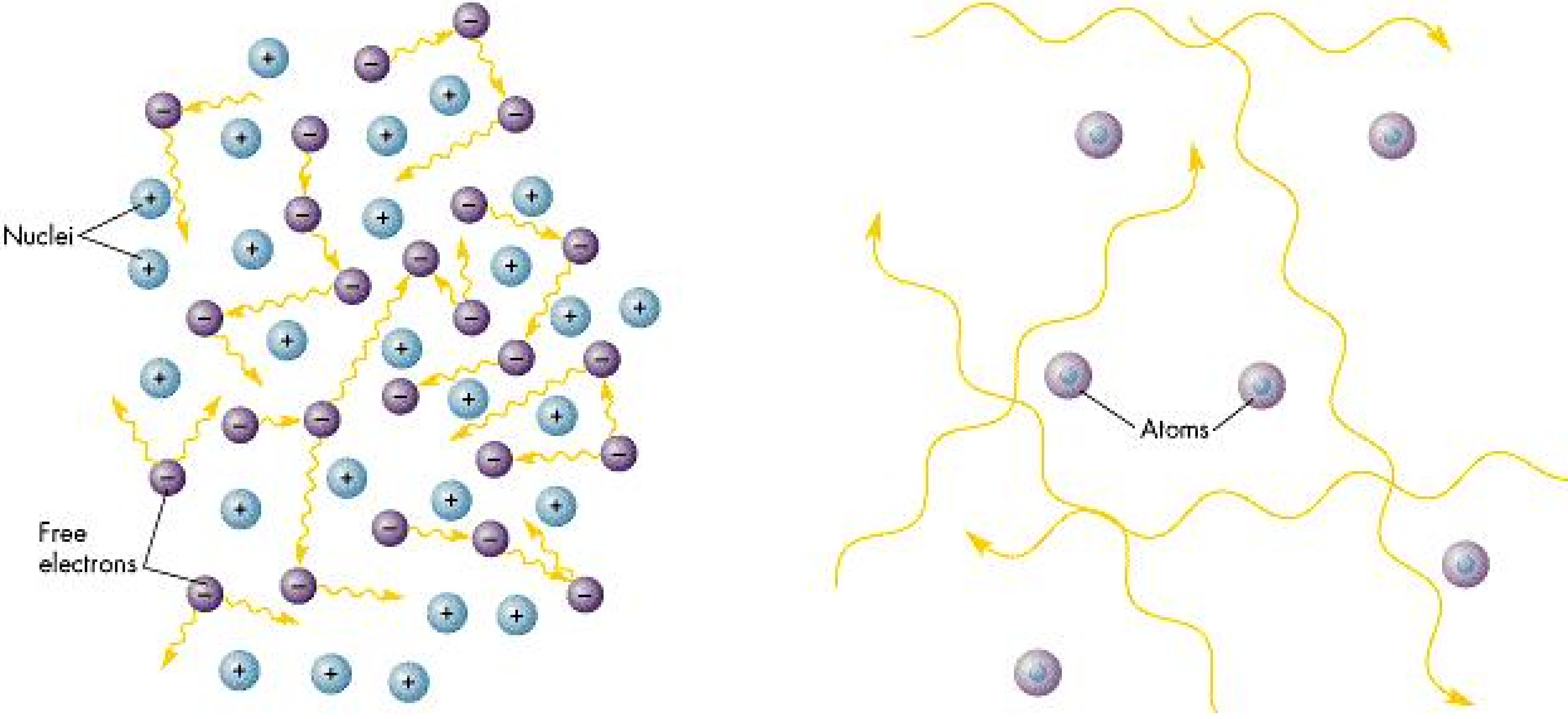
- Can rule out existence of any weakly interacting particle with mass in the range 100 eV to 1 MeV, including neutrinos and WIMPs.
- Search for dark matter particle is a major current effort in particle and astroparticle physics. Search methods include: direct production at LHC, direct detection in laboratory experiments, indirect search for decay in astrophysical settings.

Cosmic Microwave Background



The Universe glows at 2.7 K in every direction.

Where did this light come from?



A Before recombination: The universe was opaque

B After recombination: The universe was transparent

Recombination

- Electromagnetic interaction is much stronger than weak, so recombination occurs instead of decoupling (as for neutrinos), mean free path = $1/n_e\sigma_T$ << horizon at recombination.
- Ionization energy of H is 13.6 eV. If radiation were monoenergetic, recombination would occur when $E_\gamma < 13.6$ eV.
- Radiation has blackbody spectrum with peak at 2.82 kT, thus $E_\gamma \sim 2.8\ kT < 13.6$ eV leads to T ~ 50,000 K.
- High energy tail can still ionize H even when $3kT < 13.6$ eV. High ratio of photons to baryons ~ 2×10^9 enhances the tail.

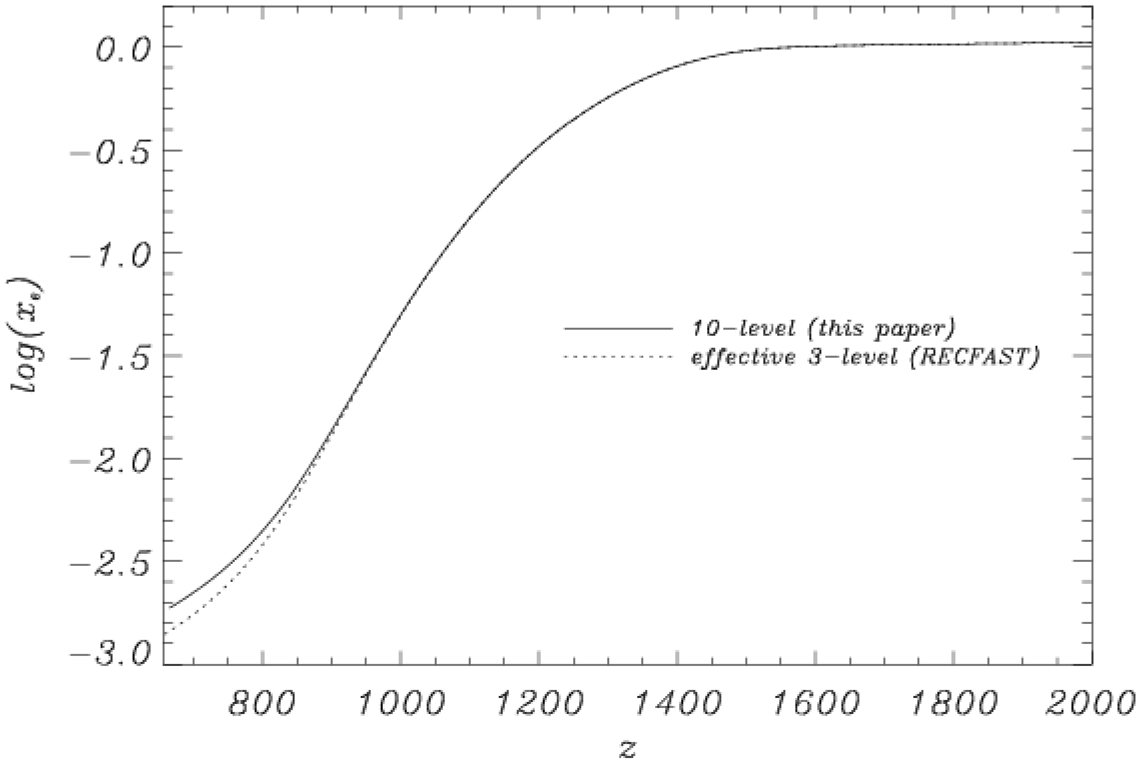
Recombination

- Saha equation describes equilibrium between two different ionization levels:

$$\frac{1-x}{x^2} \approx 3.84\,\eta\left(\frac{kT}{m_e c^2}\right)^{3/2}\exp\left(\frac{\chi}{kT}\right)$$

- $x = n_{\text{e-free}}/n_{\text{p}}$, χ = energy difference, $\eta = n_{\text{b}}/n_{\gamma} \sim 6\times10^{-10}$.
- For $x = 0.1$, find $T \sim 3600$ K.
- Note that recombination directly to the ground state produces a photon that ionizes another atom → zero net recombination.
- Stepwise recombination also zero net recombination.
- Recombination proceeds via two-photon decay.

Recombination

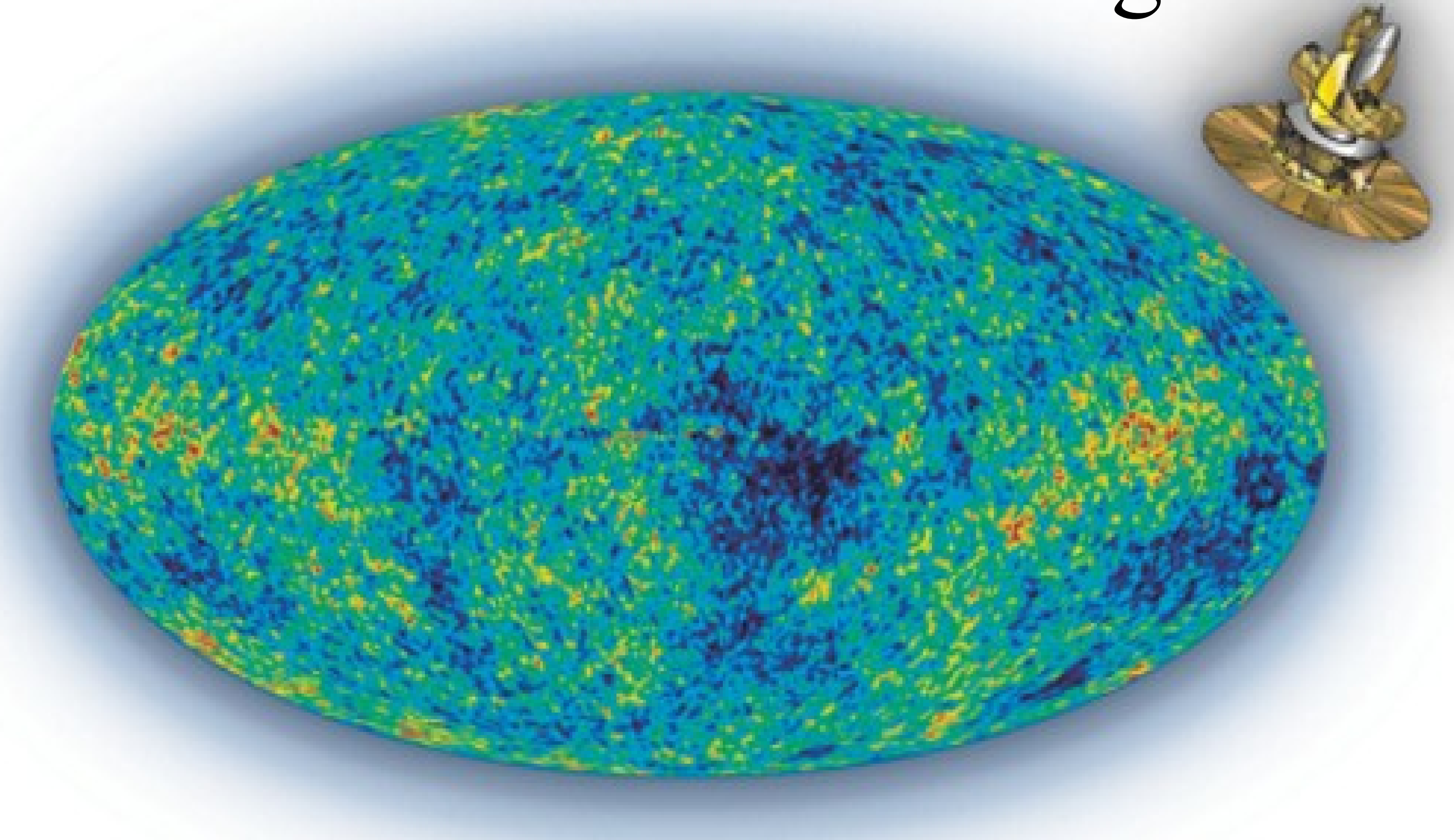


- Full calculation must take account of decay rates and expansion of universe.
- Recombination took place over a range of redshifts.
- Age of universe ~ 200-600 kyr.

Problems with the Big Bang

- The horizon problem
- The flatness problem
- How to fix the problems: inflation

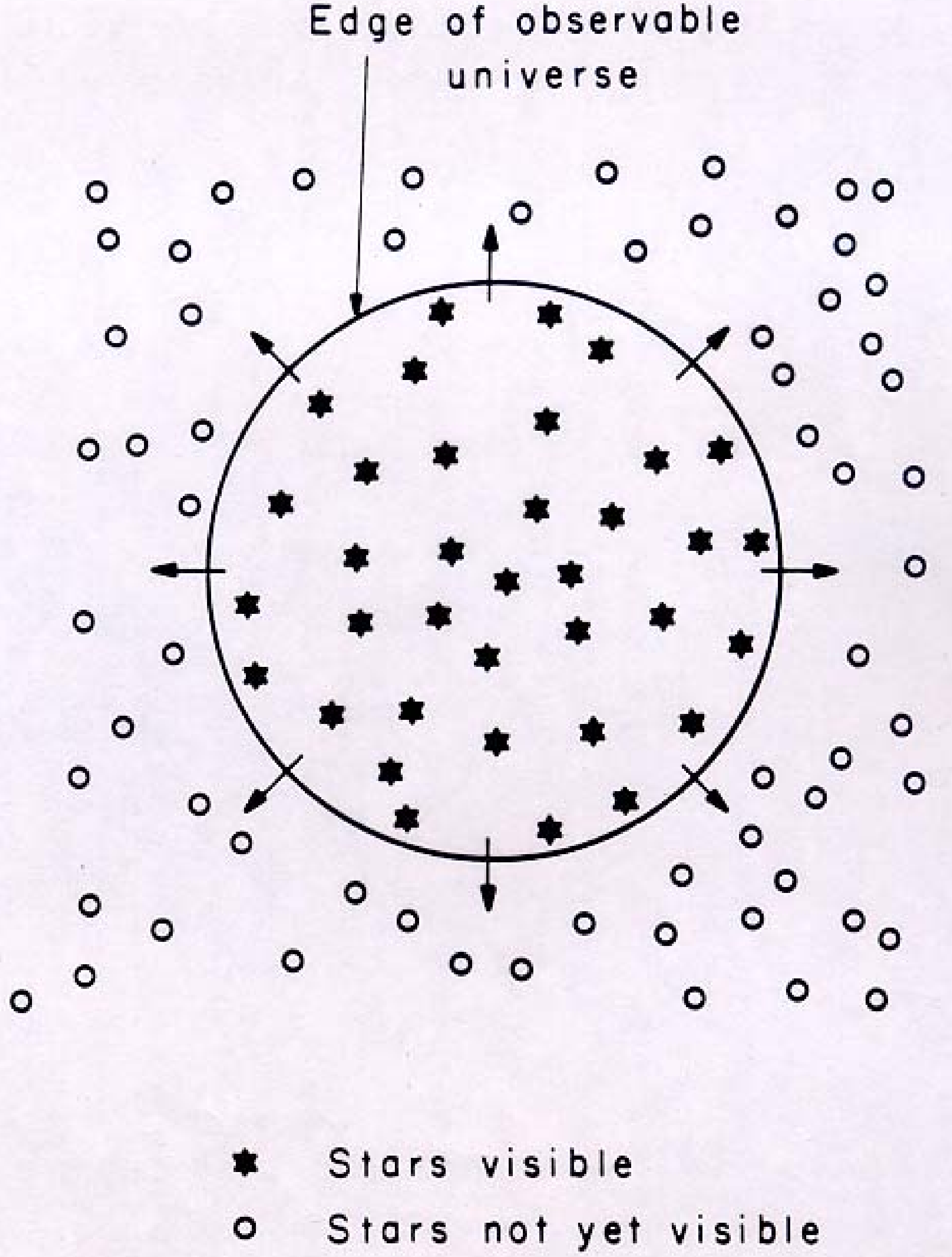
Cosmic Microwave Background



The Universe glows at 2.7 K in every direction.

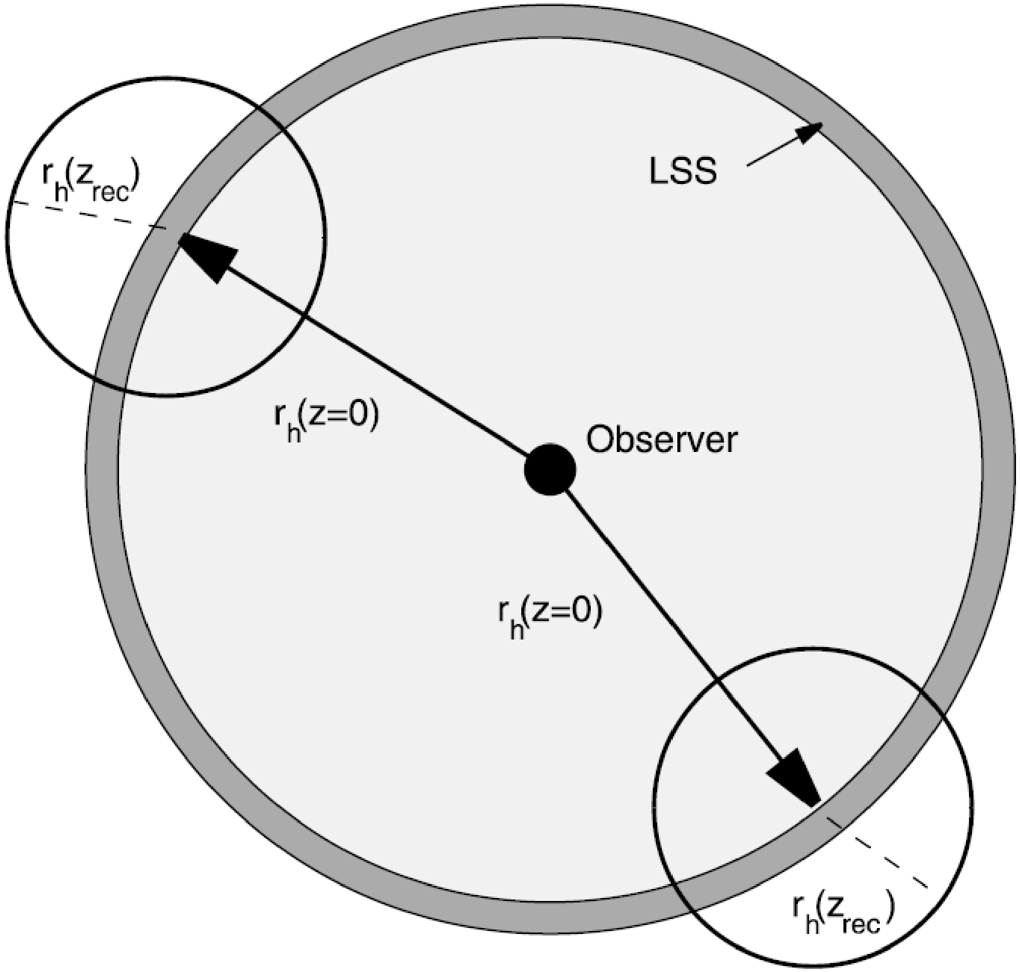
The temperature is the same to < 0.1%.

Observable Universe



We can only see the parts of the Universe from which light has had time to travel to us - horizon.

Horizon problem



- Current angular size of horizon length at recombination ~ 2° $\Omega_m^{1/2}$ ~ 1°.
- Yet CMB regions separated by 180° have the same temperature to within $\Delta T/T \sim 10^{-5}$.

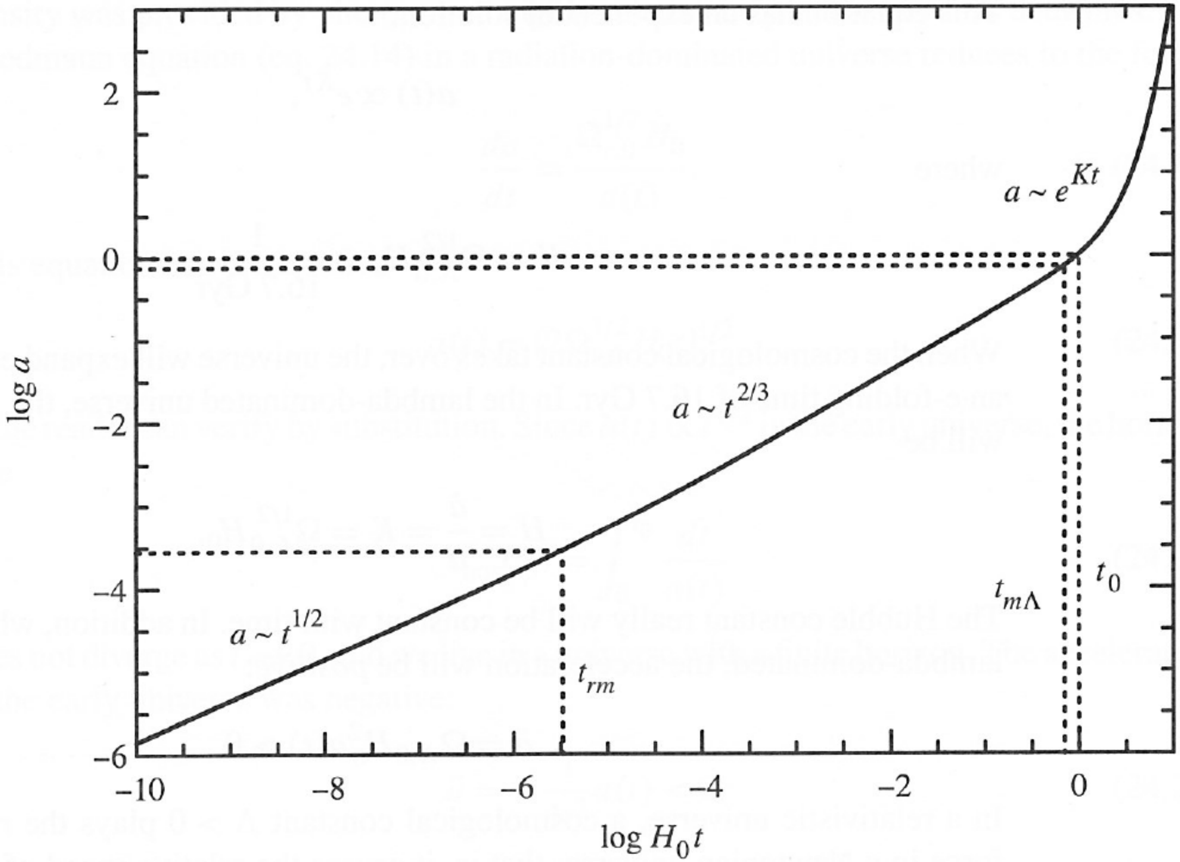
Flatness Problem

- In matter and radiation dominated eras, any deviation of Ω from 1 grows with time.
- Can rewrite expansion equation as

$$1-\Omega_0(z)=\left(\frac{H_0}{a\,H(a)}\right)^2\left[1-\Omega_0(0)\right]$$

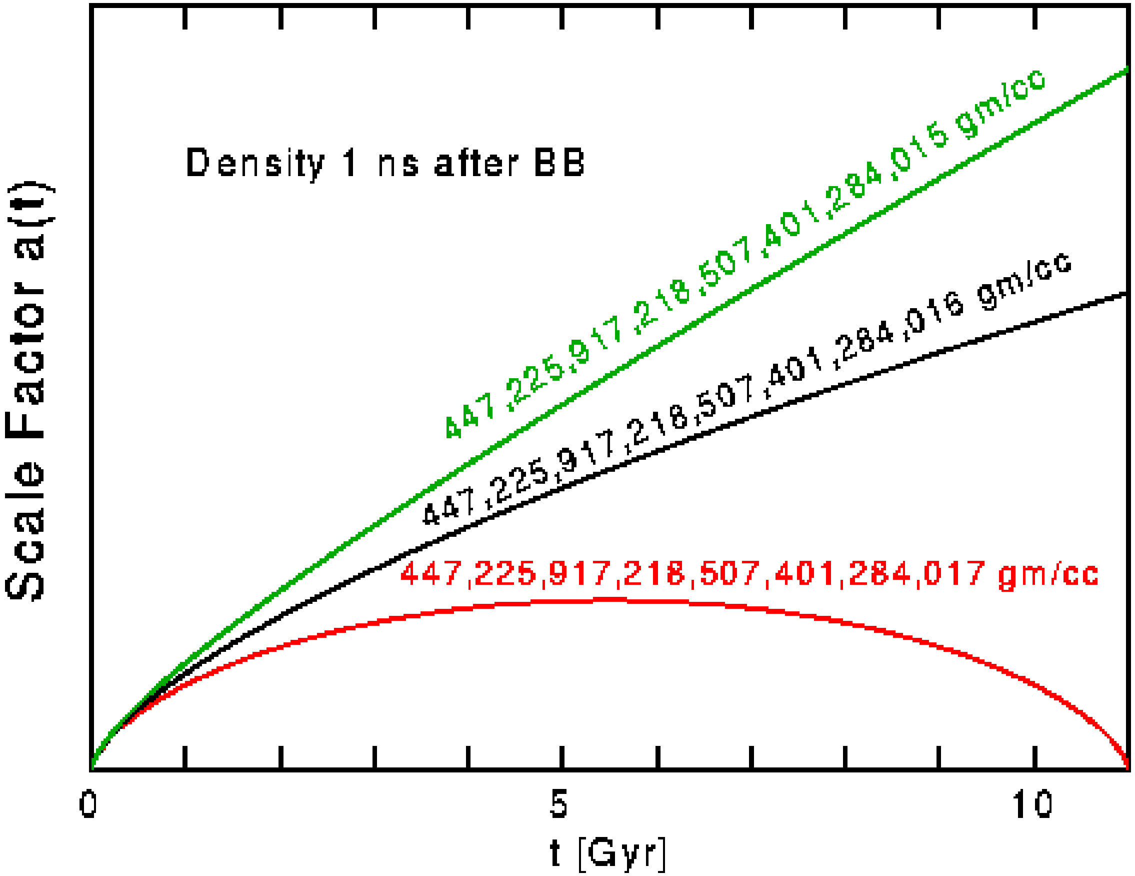
- At neutrino freeze-out, $z \sim 10^{10}$, $1-\Omega(z) \sim 10^{-15}[1-\Omega(0)]$.
- Universe must have been flat within 10^{-15}, extremely fine tuned.

Scale factor versus time



- Nuclei form at 3 minutes, radiation era ends at 47 kyr, flatness grows by 8×10^9.
- Matter dominated from 47 kyr to 9.8 Gyr. Deviation from flatness grows by $(9.8\times10^9/47{,}000)^{2/3} = 3500$.
- Now universe is flat to 0.02, at 3 minutes must have been flat to $0.02/(8\times10^9\times3500) = 7\times10^{-16}$

Flatness problem

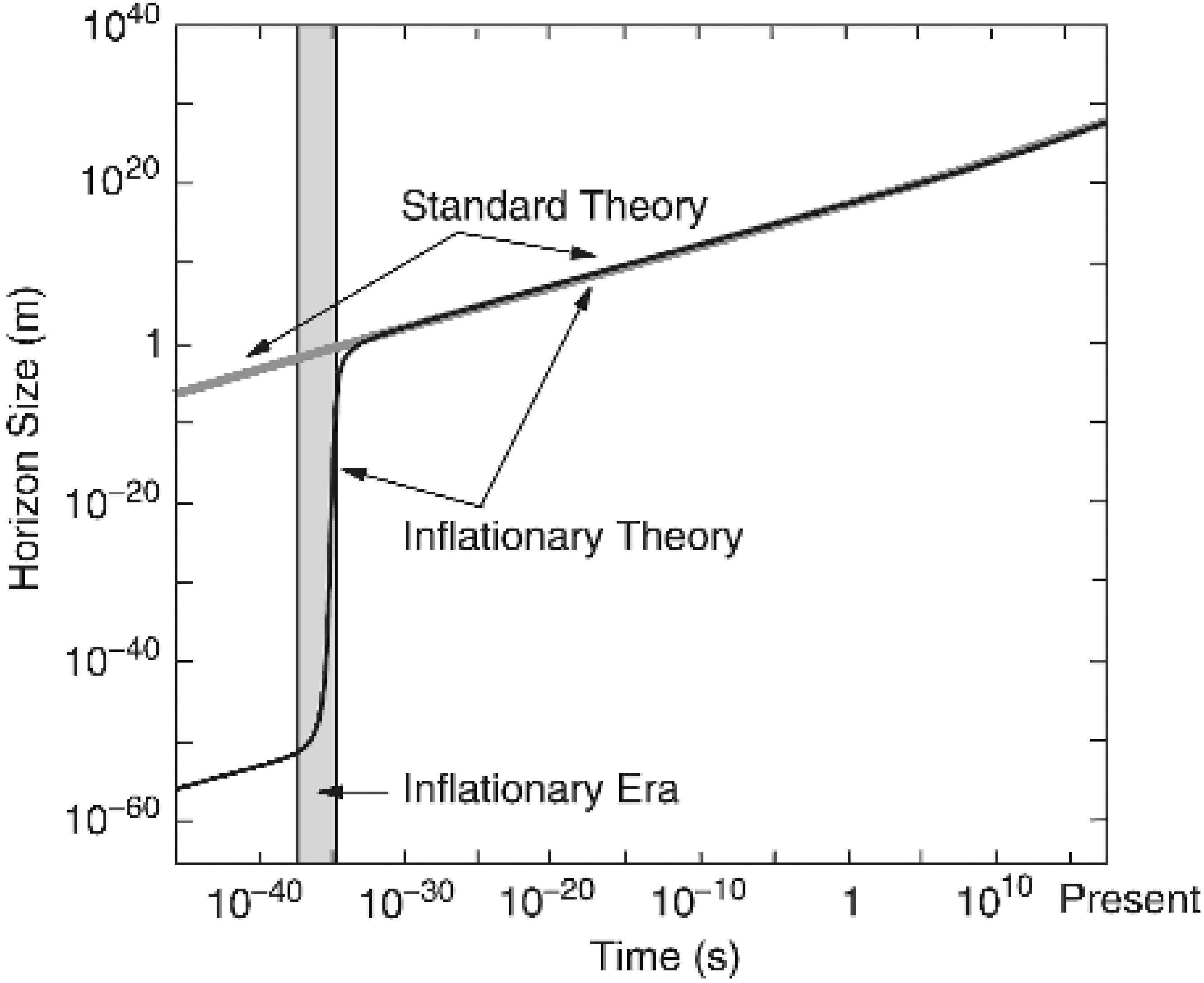


Any tiny deviation from the critical density is amplified over time.

Expansion due to cosmological constant

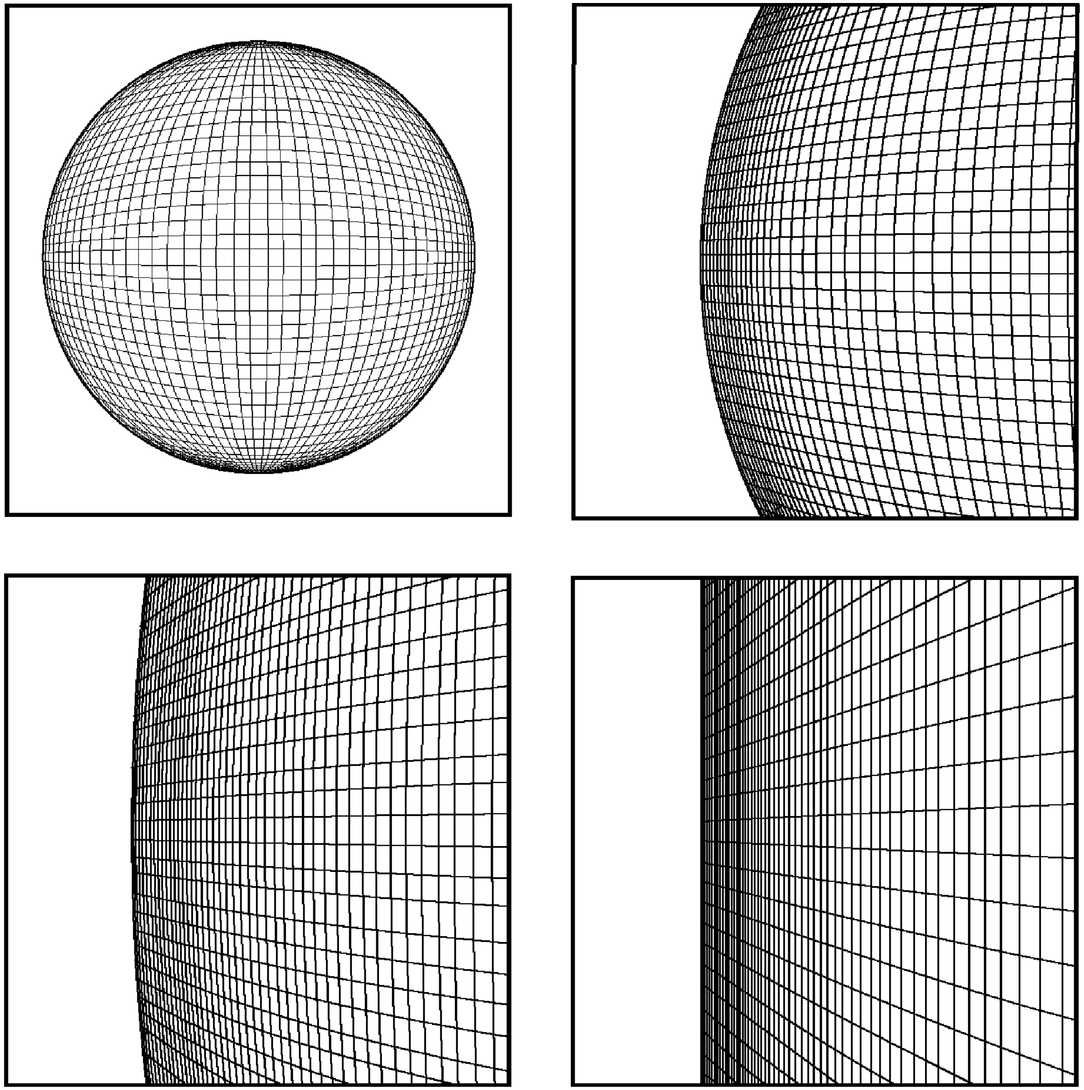
- Expansion equation: $\frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}\rho - \frac{Kc^2}{a^2} + \frac{\Lambda}{3}$
- When Λ dominates: $\frac{da}{dt} = a\sqrt{\frac{\Lambda}{3}}$
- Solution: $a(t) = C\exp\left(t\sqrt{\frac{\Lambda}{3}}\right), \qquad H(a) = \sqrt{\frac{\Lambda}{3}}$
- Recall: $1 - \Omega_0(z_f) = \left(\frac{H_i}{a_f H(a_f)}\right)^2 [1 - \Omega_0(z_i)]$
- Thus expansion drives universe exponentially close to flat.

Inflation



Whole observable universe came from a tiny region.

Inflation



Whole observable universe came from a tiny region.

Inflation in GUT

- In some Grand Unified Theories (GUT) there is a quantum mechanical field with an energy scale ~ 10^{25} eV that causes inflation at 10^{-35} s and lasts for ~100 e-foldings.
- Starting with a strongly curved universe, this would drive the flatness to $e^{-2\times100} \sim 10^{-87}$.
- If inflation ended at 10^{-33} s, then the sphere that we see as the current CMB surface had a radius of 4 meters.
- At start of inflation, this sphere had a radius ~ 10^{-43} m. The horizon at the start of inflation was ~ 10^{-27} m.

For next class

- Read 5.1-5.3.
- Choose project and e-mail choice to Kaaret.
- Read project paper.