

Set 5:

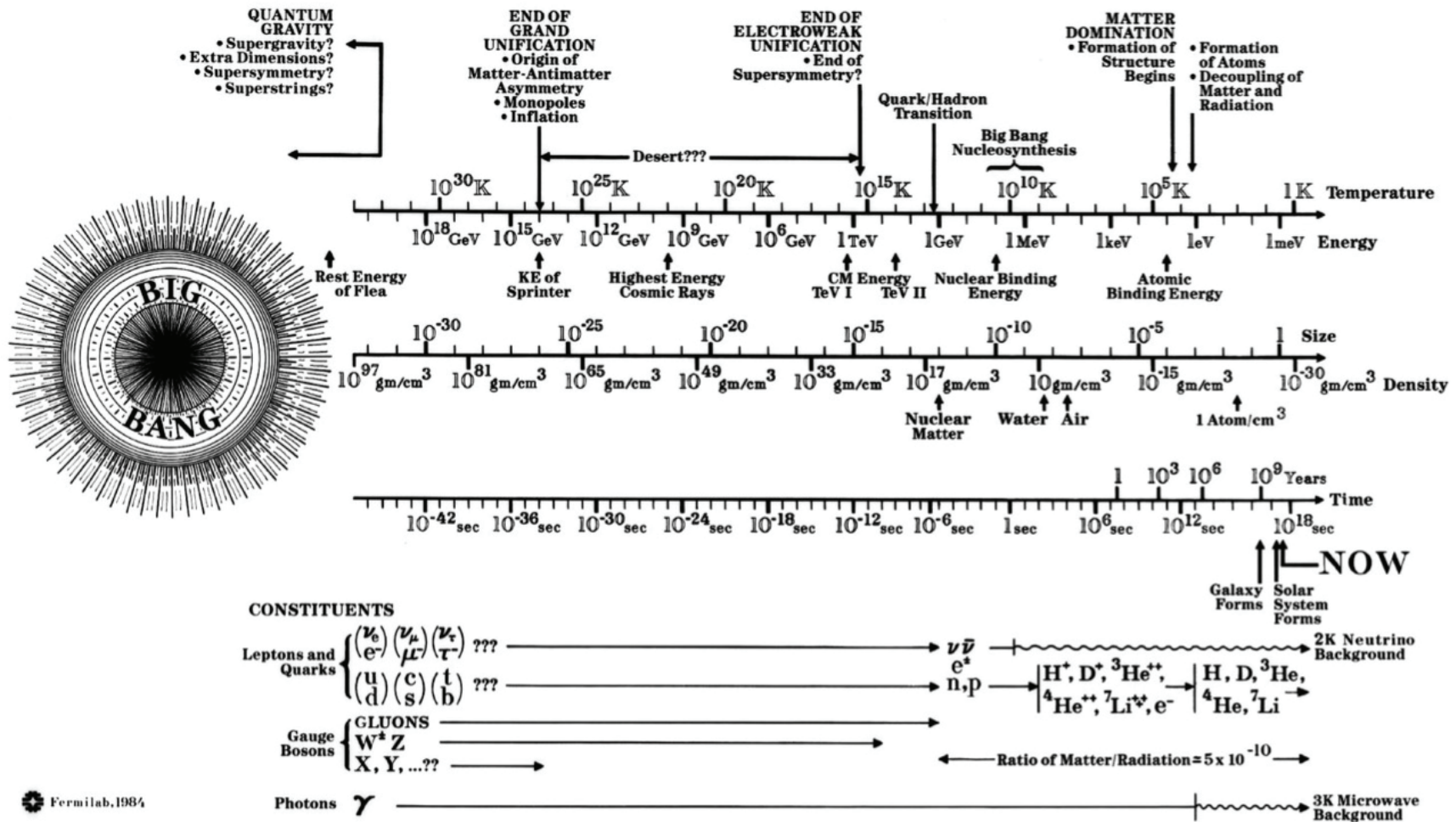
Hot Big Bang and Origin of Species

# Hot Big Bang

- CMB blackbody at 2.7K and the redshifting of the energy and hence temperature, implies that the Universe began in a hot dense state
- Rapid interactions in the hot dense plasma kept particle species in equilibrium
- When reaction rates become too low compared with the expansion rate, various particle species freeze out
- “Origin of species” as relics of the hot big bang
- For those of you who haven’t had statistical physics and want a crash course or those of you who have but want a review, see supplemental notes

# Brief Thermal History

- From Kolb and Turner



# Brief Thermal History

- Study the original while you have coffee in 4th floor ERC!



# Origin Examples

- Neutrino background (weak freezeout)
- CDM freezeout (annihilation freezeout)
- Light elements (nuclear statistical equilibrium freezeout)
- Baryogenesis (freezeout of baryon number changing processes)
- Blackbody freezeout (thermalization)
- Atomic hydrogen (recombination; free electron freezeout)
- Next lecture set: origin of structure from inflation - freezeout of quantum fluctuations

# Particle Distributions

- Phase space distribution of particles  $f$  gives the occupancy of quantum states of a given allowed momentum  $\mathbf{q}$  and position  $\mathbf{x}$
- Number density is the integral over momentum states

$$n = \int \frac{g}{(2\pi)^3} f d^3q$$

where  $g$  is quantum degeneracy of state (e.g. spin)

- Energy density is the integral weighted by energy

$$\rho = \int \frac{g}{(2\pi)^3} E(q) f d^3q, \quad E(q) = (q^2 + m^2)^{1/2}$$

- Pressure from change in momentum reflection of a wall

$$p(\mathbf{x}, t) = g \int \frac{d^3q}{(2\pi)^3} \frac{|q|^2}{3E(q)} f$$

# Vacuum Energy

- Aside for advanced students: we've excluded the energy density associated with the state of no particles or “vacuum”
- In QFT, like the simple harmonic oscillator in ordinary quantum mechanics, there is a zero point energy to the ground state
- For bosons,  $\hbar\omega/2 = E(q)/2$ , so the most naive version of the cosmological constant problem is that  $\rho \propto M^4$  where  $M = M_{\text{Pl}} = 1/\sqrt{8\pi G}$  if the theory applies out to the Planck scale
- The critical energy density  $\rho_c = 3H_0^2/8\pi G \approx 8 \times 10^{-47} h^2 \text{GeV}^4$  is more than  $10^{120}$  off  $M_{\text{Pl}}^4 \approx 2 \times 10^{76} \text{GeV}^4$ .
- This is the cosmological constant problem in its basic form - a more sophisticated QFT version is even given renormalization we expect  $\rho_{\text{vac}} \sim m^4$  for each particle of mass  $m$



# Freezeout Rule of Thumb

- Non expanding medium - given  $\Gamma$ , rate of thermalizing interactions

$$\frac{\partial f}{\partial t} = \Gamma (f - f_{\text{eq}})$$

- Add in expansion in a homogeneous medium - de Broglie wavelength  $\lambda \propto q^{-1} \propto a$  stretches with the expansion

$$\frac{\partial f}{\partial t} + \frac{dq}{dt} \frac{\partial f}{\partial q} = \Gamma (f - f_{\text{eq}})$$

$$(q \propto a^{-1} \rightarrow \frac{1}{q} \frac{dq}{dt} = -\frac{1}{a} \frac{da}{dt} = H)$$

$$\frac{\partial f}{\partial t} - H \frac{\partial f}{\partial \ln q} = \Gamma (f - f_{\text{eq}})$$

- So equilibrium will be maintained if collision rate exceeds expansion rate  $\Gamma = n \langle \sigma v \rangle > H$



# Thermal Physics

- In thermal physics there are two quantities of interest that become equal on the two sides of an interaction
  - Temperature  $T$  - from energy exchange
  - Chemical potential  $\mu$  - from particle exchange
- These quantities maximize the entropy or number of accessible states between systems that can exchange energy and particles
- The latter is associated with the law of mass action - for a change in number of species  $i$ ,  $\sum_i \mu_i dN_i = 0$  - e.g.  $e^- + p \leftrightarrow H + \gamma$  sets  $\mu_e + \mu_p = \mu_H + \mu_\gamma$
- If a particle can be created freely then its chemical potential is driven to zero aka chemical equilibrium, e.g. bremsstrahlung  $e^- + p \leftrightarrow e^- + p + \gamma$  implies  $\mu_e + \mu_p = \mu_e + \mu_p + \mu_\gamma$  or  $\mu_\gamma = 0$

# Statistical Mechanics

- All allowed quantum states are equally likely to be occupied - so the average number of particles in thermal equilibrium can just be found by maximizing the total number of allowed states between a system and a larger reservoir
- In the supplement we derive the probability of system being in state of energy  $E_i$  and number  $N_i$  (Gibbs Factor)

$$P(E_i, N_i) \propto \exp[-(E_i - \mu N_i)/T]$$

- Mean occupation of the state in thermal equilibrium

$$f \equiv \frac{\sum N_i P(E_i, N_i)}{\sum P(E_i, N_i)}$$

where the total energy is related to the particle energy as

$$E_i = N_i E \text{ (ignoring zero pt)}$$

# Fermi-Dirac Distribution

- For fermions, the occupancy can only be  $N_i = 0, 1$

$$\begin{aligned} f &= \frac{P(E, 1)}{P(0, 0) + P(E, 1)} \\ &= \frac{e^{-(E-\mu)/T}}{1 + e^{-(E-\mu)/T}} \\ &= \frac{1}{e^{(E-\mu)/T} + 1} \end{aligned}$$

- In the non-relativistic, non-degenerate limit

$$E = (q^2 + m^2)^{1/2} \approx m + \frac{1}{2} \frac{q^2}{m}$$

and  $m \gg T$  so the distribution is Maxwell-Boltzmann

$$f = e^{-(m-\mu)/T} e^{-q^2/2mT} = e^{-(m-\mu)/T} e^{-mv^2/2T}$$

# Bose-Einstein Distribution

- For bosons each state can have multiple occupation,

$$f = \frac{\frac{d}{d\mu/T} \sum_{N=0}^{\infty} (e^{-(E-\mu)/T})^N}{\sum_{N=0}^{\infty} (e^{-(E-\mu)/T})^N} \quad \text{with} \quad \sum_{N=0}^{\infty} x^N = \frac{1}{1-x}$$
$$= \frac{1}{e^{(E-\mu)/T} - 1}$$

- Again, non relativistic distribution is Maxwell-Boltzmann

$$f = e^{-(m-\mu)/T} e^{-q^2/2mT} = e^{-(m-\mu)/T} e^{-mv^2/2T}$$

with a spatial number density

$$n = g e^{-(m-\mu)/T} \int \frac{d^3q}{(2\pi)^3} e^{-q^2/2mT}$$
$$= g e^{-(m-\mu)/T} \left( \frac{mT}{2\pi} \right)^{3/2}$$

# Ultra-Relativistic Bulk Properties

- Chemical potential  $\mu = 0$ ,  $\zeta(3) \approx 1.202$
- Number density

$$n_{\text{boson}} = gT^3 \frac{\zeta(3)}{\pi^2} \quad \zeta(n+1) \equiv \frac{1}{n!} \int_0^\infty dx \frac{x^n}{e^x - 1}$$
$$n_{\text{fermion}} = \frac{3}{4} gT^3 \frac{\zeta(3)}{\pi^2}$$

- Energy density

$$\rho_{\text{boson}} = gT^4 \frac{3}{\pi^2} \zeta(4) = gT^4 \frac{\pi^2}{30}$$
$$\rho_{\text{fermion}} = \frac{7}{8} gT^4 \frac{3}{\pi^2} \zeta(4) = \frac{7}{8} gT^4 \frac{\pi^2}{30}$$

- Pressure  $q^2/3E = E/3 \rightarrow p = \rho/3$ ,  $w_r = 1/3$

# Entropy Density

- First law of thermodynamics

$$dS = \frac{1}{T}(d\rho(T)V + p(T)dV)$$

so that

$$\left.\frac{\partial S}{\partial V}\right|_T = \frac{1}{T}[\rho(T) + p(T)], \quad \left.\frac{\partial S}{\partial T}\right|_V = \frac{V}{T} \frac{d\rho}{dT}$$

- Since  $S(V, T) \propto V$  is extensive

$$S = \frac{V}{T}[\rho(T) + p(T)] \quad s = \frac{S}{V} = \frac{1}{T}[\rho(T) + p(T)]$$

So

$$\frac{\partial S}{\partial V} = s, \quad \frac{\partial}{\partial V} \left( \frac{\partial S}{\partial T} \right) = \frac{1}{T} \frac{d\rho}{dT}$$

# Entropy Density

- Integrability condition  $\partial^2 S / \partial V \partial T = \partial^2 S / \partial T \partial V$  relates the evolution of entropy density

$$\begin{aligned}\frac{ds}{dT} &= \frac{1}{T} \frac{d\rho}{dT} \\ \frac{ds}{dt} &= \frac{1}{T} \frac{d\rho}{dt} = \frac{1}{T} [-3(\rho + p)] \frac{d \ln a}{dt} = -3s \frac{d \ln a}{dt} \\ \rightarrow \frac{d \ln s}{dt} &= -3 \frac{d \ln a}{dt} \rightarrow s \propto a^{-3}\end{aligned}$$

comoving entropy density is conserved in thermal equilibrium

- Ultra relativistic bosons  $s_{\text{boson}} = 3.602 n_{\text{boson}}$ ; for fermions  $\times 7/8$  given scaling of  $\rho$

$$g_* = \sum_{\text{bosons}} g_b + \frac{7}{8} \sum g_f$$



# Evolution of Temperature

- We will use this to derive the evolution of  $T$  as different particle species annihilate in thermal equilibrium
- Setting the entropy density before and after is equivalent to setting

$$g_* T^3 \Big|_{\text{initial}} = g_* T^3 \Big|_{\text{final}}$$

- When particle species disappear through annihilation, they dump their entropy into the remaining species and hence raise the temperature

# Neutrino Freezeout

- Neutrino equilibrium maintained by weak interactions, e.g.  
 $e^+ + e^- \leftrightarrow \nu + \bar{\nu}$
- Weak interaction cross section  $T_{10} = T/10^{10} K \sim T/1\text{MeV}$

$$\sigma_w \sim G_F^2 E_\nu^2 \approx 4 \times 10^{-44} T_{10}^2 \text{cm}^2$$

- Rate  $\Gamma = n_\nu \sigma_w = H$  at  $T_{10} \sim 3$  or  $t \sim 0.2\text{s}$
- After neutrino freezeout, electrons and positrons annihilate dumping their entropy into the photons
- Before  $g_*$ :  $\gamma, e^+, e^- = 2 + \frac{7}{8}(2 + 2) = \frac{11}{2}$
- After  $g_*$ :  $\gamma = 2$ ; so conservation of entropy gives

$$g_* T^3 \Big|_{\text{initial}} = g_* T^3 \Big|_{\text{final}} \quad T_\nu = \left( \frac{4}{11} \right)^{1/3} T_\gamma$$

# Relic Neutrinos

- Relic number density (zero chemical potential; now required by oscillations & BBN)

$$n_\nu = n_\gamma \frac{3}{4} \frac{4}{11} = 112 \text{cm}^{-3}$$

- Relic energy density assuming one species with finite  $m_\nu$ :

$$\rho_\nu = m_\nu n_\nu$$

$$\rho_\nu = 112 \frac{m_\nu}{\text{eV}} \text{ eV cm}^{-3} \quad \rho_c = 1.05 \times 10^4 h^2 \text{ eV cm}^{-3}$$

$$\Omega_\nu h^2 = \frac{m_\nu}{93.7 \text{ eV}}$$

- Candidate for dark matter? an eV mass neutrino goes non relativistic around  $z \sim 1000$  and retains a substantial velocity dispersion  $\sigma_\nu$ .

# Hot Dark Matter

- Momenta for a nonrelativistic species redshifts like temperature for a relativistic one, so average momentum is still given by

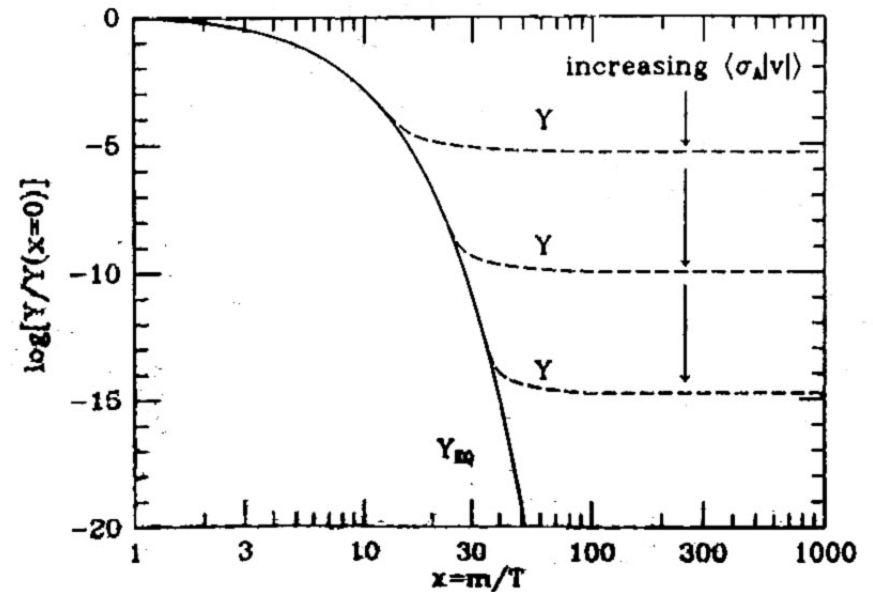
$$\langle q \rangle = 3T_\nu = m_\nu \sigma_\nu$$

$$\begin{aligned}\sigma_\nu &= 3 \left( \frac{m_\nu}{1\text{eV}} \right)^{-1} \left( \frac{T_\nu}{1\text{eV}} \right) = 3 \left( \frac{m_\nu}{1\text{eV}} \right)^{-1} \left( \frac{T_\nu}{10^4\text{K}} \right) \\ &= 6 \times 10^{-4} \left( \frac{m_\nu}{1\text{eV}} \right)^{-1} = 200\text{km/s} \left( \frac{m_\nu}{1\text{eV}} \right)^{-1}\end{aligned}$$

- Of order the rotation velocity of galactic halos and higher at higher redshift - small objects can't form: top down structure formation – not observed – must not constitute the bulk of the dark matter

# Cold Dark Matter

- Problem with neutrinos is they decouple while relativistic and hence have a comparable number density to photons - for a reasonable energy density, the mass must be small



- The equilibrium distribution for a non-relativistic species declines exponentially beyond the mass threshold

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$

- Exponential will eventually win soon after  $T < m$ , suppressing annihilation rates, so the freezeout temperature will be  $T \approx m$

# WIMP relic abundance

- Define the number density of cold dark matter  $n$  relative to the entropy density  $s$ , so that  $Y = \text{const}$  if both  $\propto a^{-3}$

$$Y \equiv n/s$$

- Freezeout curve is solution to the Boltzmann equation

$$\frac{dY}{d \ln a} = \frac{s \langle \sigma_A v \rangle}{H} (Y_{\text{eq}}^2 - Y^2)$$

where the abundance is at the equilibrium value  $Y_{\text{eq}} = n_{\text{eq}}/s$  if  $n \langle \sigma_A v \rangle \gg H$ , i.e. annihilation rate is large compared with  $H$

- Notice this takes the general Boltzmann form  $Y \propto \int d^3q f$

$$(Y_{\text{eq}}^2 - Y^2)s = (n_{\text{eq}} + n)(Y_{\text{eq}} - Y)$$

but with the square coming from the two particles involved in annihilation - can understand the solution with our rule of thumb

# WIMP Miracle

- Freezeout when annihilation rate equal expansion rate  $\Gamma \propto \sigma_A$ , increasing annihilation cross section decreases abundance

$$\Gamma = n\langle\sigma_A v\rangle = H, \quad H^2 \propto T^4 \sim m^4$$

$$\rho_{\text{freeze}} = mn \propto \frac{T^3}{\langle\sigma_A v\rangle}$$

$$\rho_c = \rho_{\text{freeze}} a^{-3} \approx \rho_{\text{freeze}} \left( \frac{T_{\text{CMB}}}{T} \right)^3 \propto \frac{1}{\langle\sigma_A v\rangle}$$

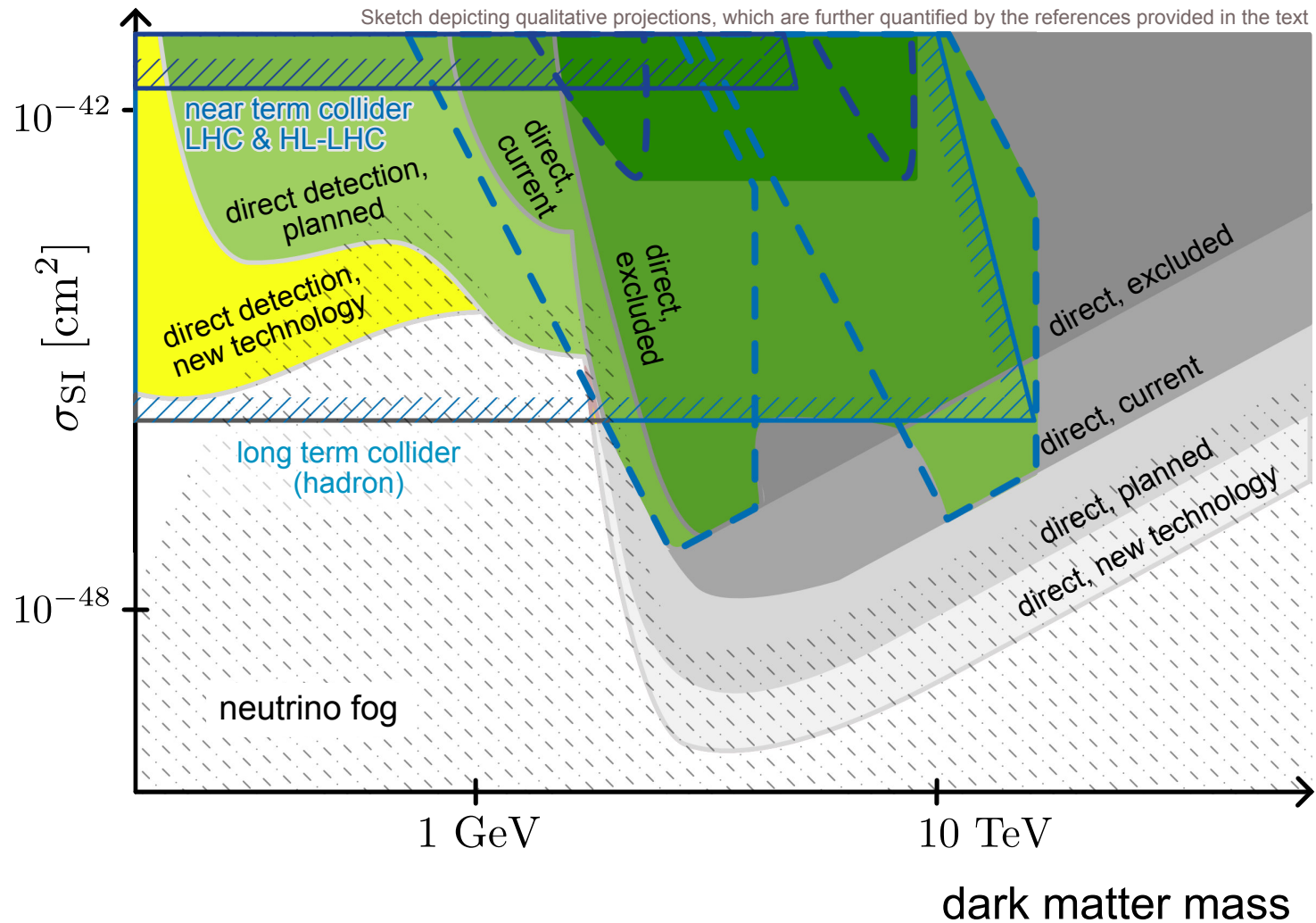
independently of the mass of the CDM particle and the temperature at freezeout

- Plug in some typical numbers for a particle with weak interaction scale cross sections or WIMPs (weakly interacting massive particles) of  $\langle\sigma_A v\rangle \approx 10^{-36} \text{ cm}^2$  and restore the proportionality constant  $\Omega_c h^2$  is of the right order of magnitude ( $\sim 0.1$ )!



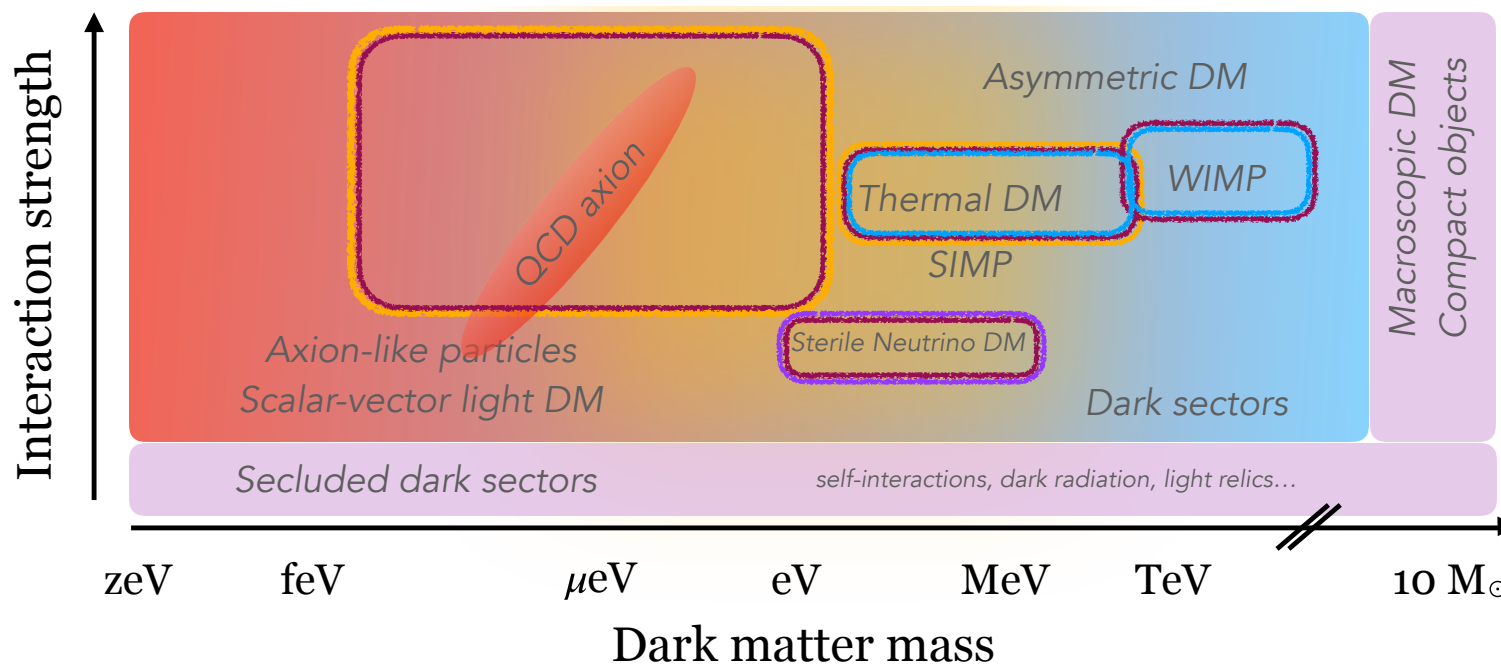
# WIMP Constraints

- Direct and indirect constraints increasingly stringent...



# Alternate DM Candidates

- Leading to a wide range of possible alternate candidates to the classical WIMP

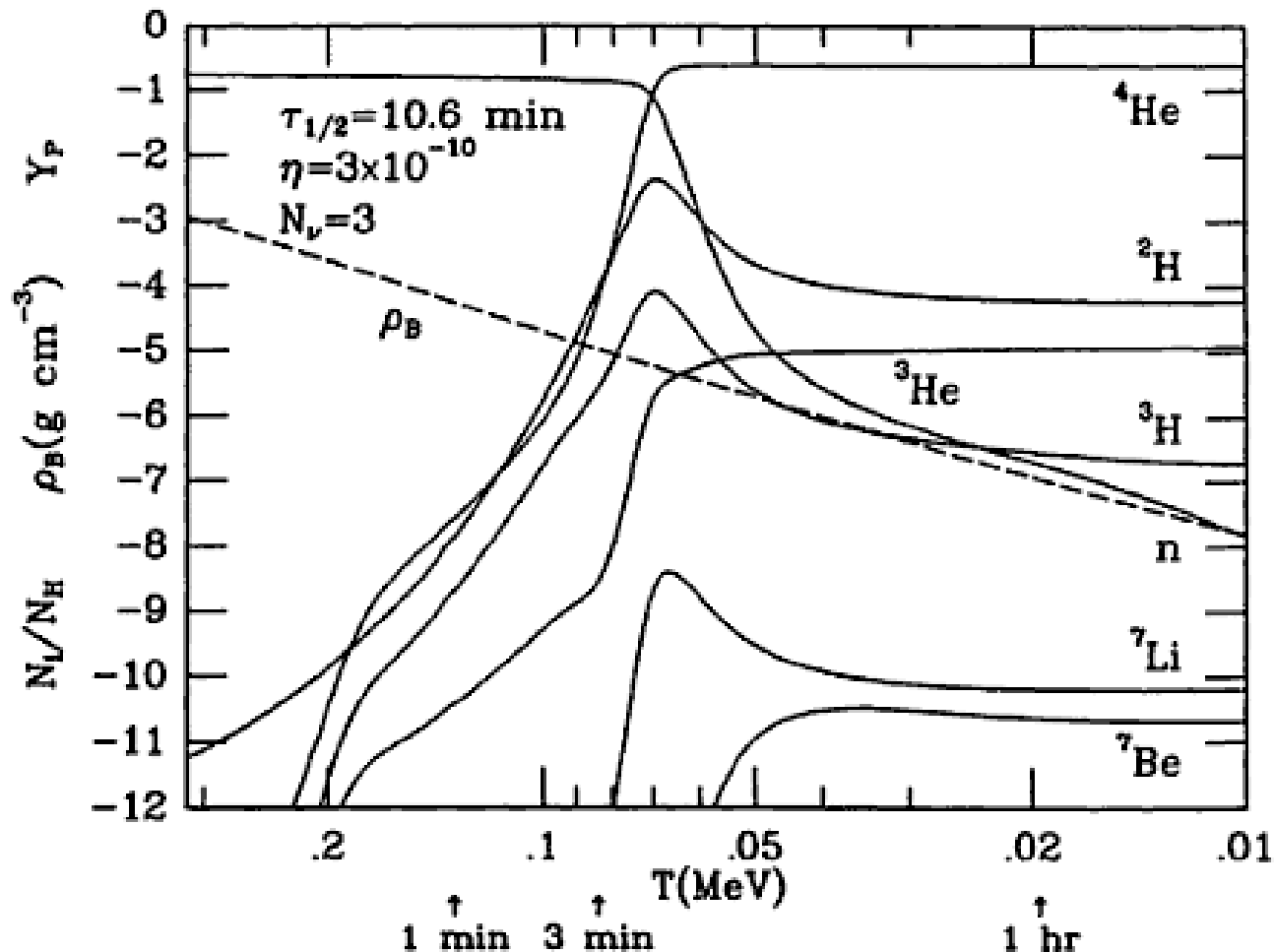


# Axions

- Alternate solution: keep light particle but not created in thermal equilibrium
- Example: axion dark matter - particle that solves the strong CP problem (smallness of neutron electron dipole moment)
- Either causality during symmetry breaking or inflation sets initial conditions, fluctuation from potential minimum
- Once Hubble scale smaller than the mass scale, field unfreezes
- Coherent oscillations of the axion field - condensate state. Can be very light  $m \ll 1\text{eV}$  and yet remain cold.
- Same reason a quintessence dark energy candidate must be lighter than the Hubble scale today

# Big Bang Nucleosynthesis

- Integrating the Boltzmann equation for nuclear processes during first few minutes leads to synthesis and freezeout of light elements



# Big Bang Nucleosynthesis

- Most of light element synthesis can be understood through nuclear statistical equilibrium and reaction rates
- Equilibrium abundance of species with mass number  $A$  and charge  $Z$  ( $Z$  protons and  $A - Z$  neutrons)

$$n_A = g_A \left( \frac{m_A T}{2\pi} \right)^{3/2} e^{(\mu_A - m_A)/T}$$

- In chemical equilibrium with protons and neutrons

$$\mu_A = Z\mu_p + (A - Z)\mu_n$$

$$n_A = g_A \left( \frac{m_A T}{2\pi} \right)^{3/2} e^{-m_A/T} e^{(Z\mu_p + (A - Z)\mu_n)/T}$$

# Big Bang Nucleosynthesis

- Eliminate chemical potentials with  $n_p, n_n$

$$e^{\mu_p/T} = \frac{n_p}{g_p} \left( \frac{2\pi}{m_p T} \right)^{3/2} e^{m_p/T}$$

$$e^{\mu_n/T} = \frac{n_n}{g_n} \left( \frac{2\pi}{m_n T} \right)^{3/2} e^{m_n/T}$$

$$n_A = g_A g_p^{-Z} g_n^{Z-A} \left( \frac{m_A T}{2\pi} \right)^{3/2} \left( \frac{2\pi}{m_p T} \right)^{3Z/2} \left( \frac{2\pi}{m_n T} \right)^{3(A-Z)/2} \\ \times e^{-m_A/T} e^{(Z\mu_p + (A-Z)\mu_n)/T} n_p^Z n_n^{A-Z}$$

$$(g_p = g_n = 2; m_p \approx m_n = m_b = m_A/A)$$

$$(B_A = Zm_p + (A-Z)m_n - m_A)$$

$$= g_A 2^{-A} \left( \frac{2\pi}{m_b T} \right)^{3(A-1)/2} A^{3/2} n_p^Z n_n^{A-Z} e^{B_A/T}$$

# Big Bang Nucleosynthesis

- Convenient to define abundance fraction

$$\begin{aligned}
 X_A &\equiv A \frac{n_A}{n_b} = A g_A 2^{-A} \left( \frac{2\pi}{m_b T} \right)^{3(A-1)/2} A^{3/2} n_p^Z n_n^{A-Z} n_b^{-1} e^{B_A/T} \\
 &= A g_A 2^{-A} \left( \frac{2\pi n_b^{2/3}}{m_b T} \right)^{3(A-1)/2} A^{3/2} e^{B_A/T} X_p^Z X_n^{A-Z} \\
 &\quad \left( n_\gamma = \frac{2}{\pi^2} T^3 \zeta(3) \quad \eta_{b\gamma} \equiv n_b / n_\gamma \right) \\
 &= A^{5/2} g_A 2^{-A} \left[ \left( \frac{2\pi T}{m_b} \right)^{3/2} \frac{2\zeta(3)\eta_{b\gamma}}{\pi^2} \right]^{A-1} e^{B_A/T} X_p^Z X_n^{A-Z}
 \end{aligned}$$

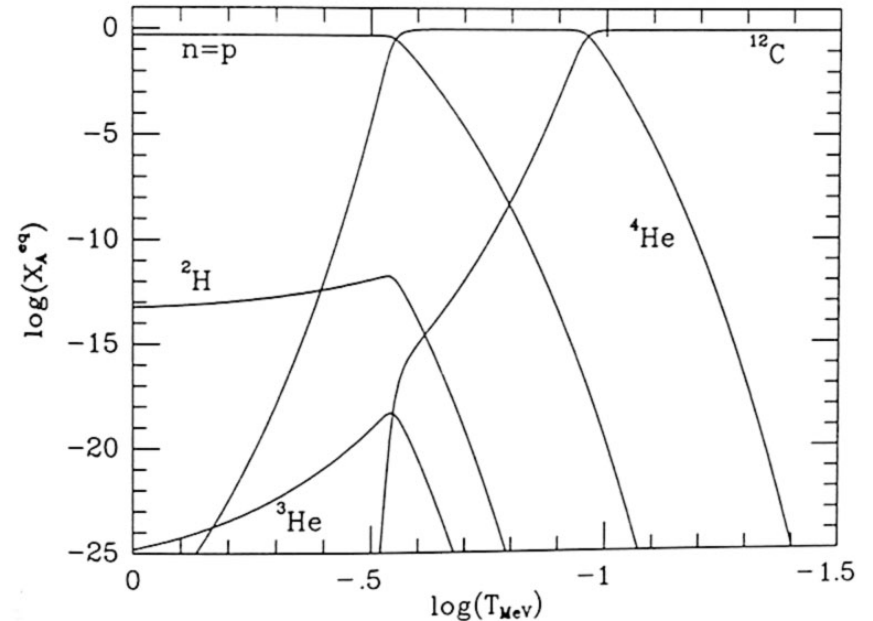


# Deuterium

- Deuterium  $A = 2$ ,  $Z = 1$ ,  $g_2 = 3$ ,  $B_2 = 2.225$  MeV

$$X_2 = \frac{3}{\pi^2} \left( \frac{4\pi T}{m_b} \right)^{3/2} \eta_{b\gamma} \zeta(3) e^{B_2/T} X_p X_n$$

- Deuterium  
“bottleneck” is mainly  
due to the low baryon-photon  
number of the universe  
 $\eta_{b\gamma} \sim 10^{-9}$ , secondarily due  
to the low binding energy  $B_2$



# Deuterium

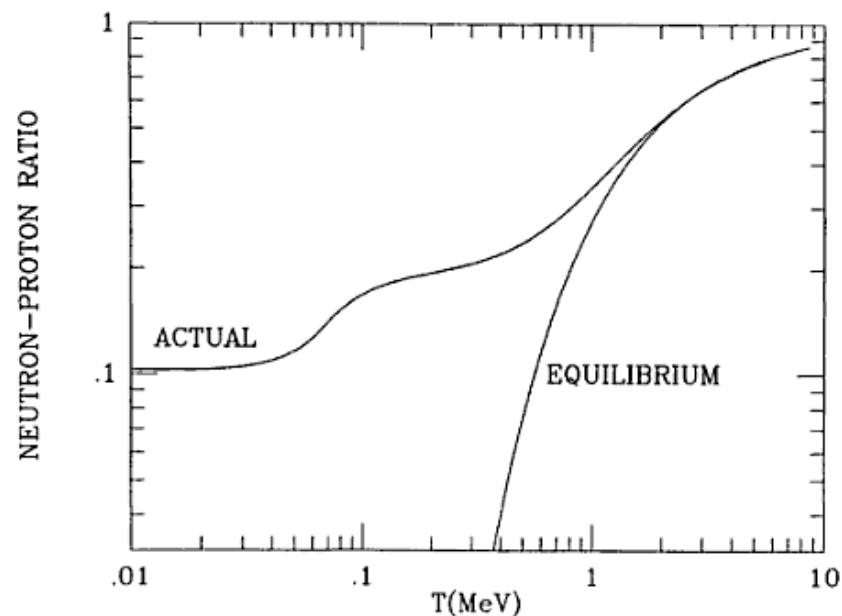
- $X_2/X_p X_n \approx \mathcal{O}(1)$  at  $T \approx 100\text{keV}$  or  $10^9$  K, much lower than the binding energy  $B_2$
- Most of the deuterium formed then goes through to helium via  
 $\text{D} + \text{D} \rightarrow {}^3\text{He} + p, {}^3\text{He} + \text{D} \rightarrow {}^4\text{He} + n$
- Deuterium freezes out as number abundance becomes too small to maintain reactions  $n_D = \text{const.}$  independent of  $n_b$
- The deuterium freezeout fraction  $n_D/n_b \propto \eta_{b\gamma}^{-1} \propto (\Omega_b h^2)^{-1}$  and so is fairly sensitive to the baryon density.
- Observations of the ratio in quasar absorption systems give  
 $\Omega_b h^2 \approx 0.02$

# Helium

- Essentially all neutrons around during nucleosynthesis end up in Helium
- In equilibrium, the neutron-to-proton ratio is determined by the mass difference

$$Q = m_n - m_p = 1.293 \text{ MeV}$$

$$\frac{n_n}{n_p} = \exp[-Q/T]$$



# Helium

- Equilibrium is maintained through weak interactions, e.g.  
 $n \leftrightarrow p + e^- + \bar{\nu}, \nu + n \leftrightarrow p + e^-, e^+ + n \leftrightarrow p + \bar{\nu}$  with rate

$$\frac{\Gamma}{H} \approx \frac{T}{0.8\text{MeV}}$$

- Freezeout fraction

$$\frac{n_n}{n_p} = \exp[-1.293/0.8] \approx 0.2$$

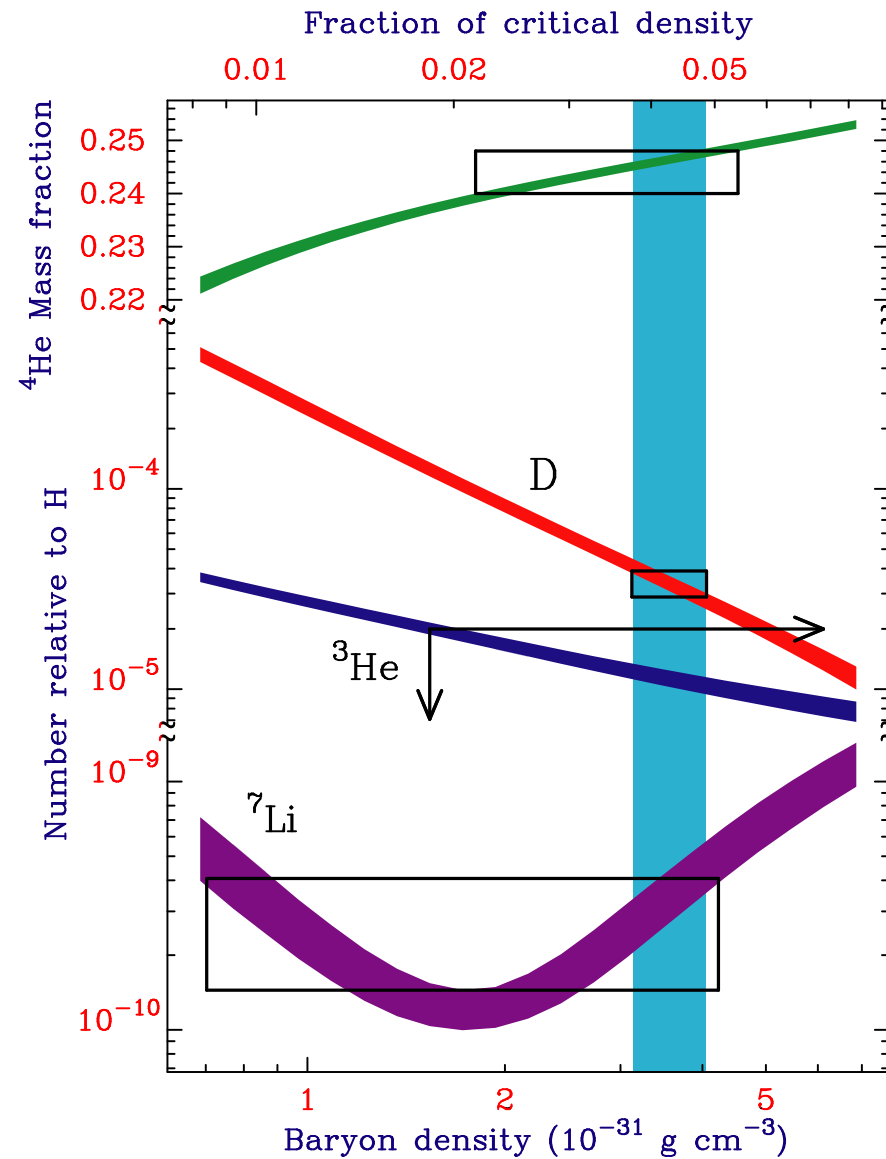
- Finite lifetime of neutrons brings this to  $\sim 1/7$  by  $10^9\text{K}$
- Helium mass fraction

$$\begin{aligned} Y_{\text{He}} &= \frac{4n_{\text{He}}}{n_b} = \frac{4(n_n/2)}{n_n + n_p} \\ &= \frac{2n_n/n_p}{1 + n_n/n_p} \approx \frac{2/7}{8/7} \approx \frac{1}{4} \end{aligned}$$

# Helium

- Depends mainly on the expansion rate during BBN - measure number of relativistic species
- Traces of  ${}^7\text{Li}$  as well. Measured abundances in reasonable agreement with deuterium measure  $\Omega_b h^2 = 0.02$  but the detailed interpretation is still up for debate

# Light Elements



Burles, Nollett, Turner (1999)

# Baryogenesis

- What explains the small, but non-zero, baryon-to-photon ratio?

$$\eta_{b\gamma} = n_b/n_\gamma \approx 3 \times 10^{-8} \Omega_b h^2 \approx 6 \times 10^{-10}$$

- Must be a slight excess of baryons  $b$  to anti-baryons  $\bar{b}$  that remains after annihilation
- Sakharov conditions
  - Baryon number violation: some process must change the net baryon number
  - CP violation: process which produces  $b$  and  $\bar{b}$  must differ in rate
  - Out of equilibrium: else equilibrium distribution with vanishing chemical potential (processes exist which change baryon number) gives equal numbers for  $b$  and  $\bar{b}$
- Expanding universe provides 3; physics must provide 1,2



# Baryogenesis

- Example: out of equilibrium decay of some heavy boson  $X, \bar{X}$
- Suppose  $X$  decays through 2 channels with baryon number  $b_1$  and  $b_2$  with branching ratio  $r$  and  $1 - r$  leading to a change in the baryon number per decay of

$$rb_1 + (1 - r)b_2$$

- And  $\bar{X}$  to  $-b_1$  and  $-b_2$  with ratio  $\bar{r}$  and  $1 - \bar{r}$

$$-\bar{r}b_1 - (1 - \bar{r})b_2$$

- Net production

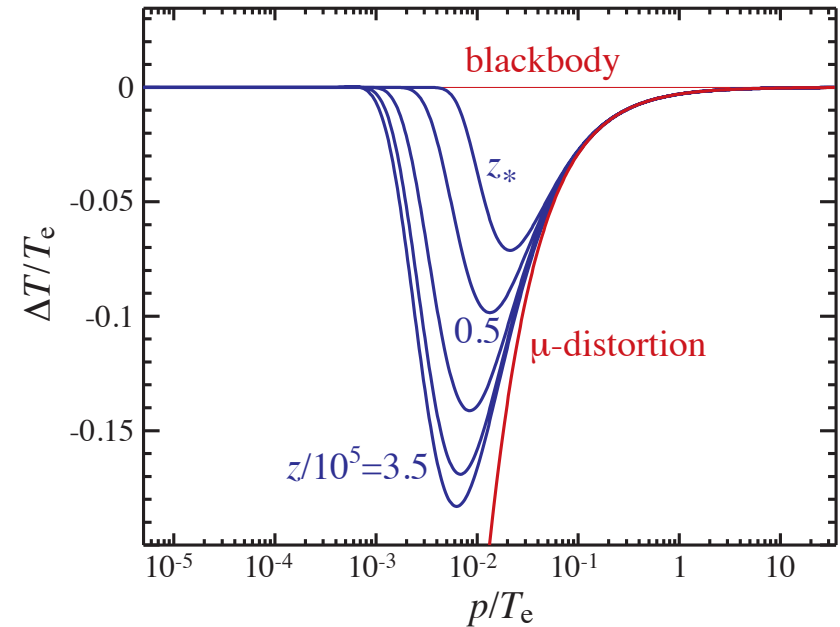
$$\Delta b = (r - \bar{r})(b_1 - b_2)$$

# Baryogenesis

- Condition 1:  $b_1 \neq 0, b_2 \neq 0$
- Condition 2:  $\bar{r} \neq r$
- Condition 3: out of equilibrium decay
- GUT and electroweak (instanton) baryogenesis mechanisms exist
- Active subject of research

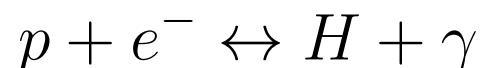
# Black Body Formation

- After  $z \sim 10^6$ , photon creating processes  $\gamma + e^- \leftrightarrow 2\gamma + e^-$  and bremsstrahlung  $e^- + p \leftrightarrow e^- + p + \gamma$  drop out of equilibrium for photon energies  $E \sim T$ .
- Compton scattering remains effective in redistributing energy via exchange with electrons
- Out of equilibrium processes like decays leave residual photon chemical potential imprint
- Observed black body spectrum places tight constraints on any that might dump energy into the CMB



# Recombination

- Maxwell-Boltzmann distribution determines the equilibrium distribution for reactions, e.g. big-bang nucleosynthesis, recombination:



$$\frac{n_p n_e}{n_H} \approx e^{-B/T} \left( \frac{m_e T}{2\pi} \right)^{3/2} e^{(\mu_p + \mu_e - \mu_H)/T}$$

where  $B = m_p + m_e - m_H = 13.6\text{eV}$  is the binding energy,  $g_p = g_e = \frac{1}{2}g_H = 2$ , and  $\mu_p + \mu_e = \mu_H$  in equilibrium

- Define ionization fraction

$$n_p = n_e = x_e n_b$$

$$n_H = n_b - n_e = (1 - x_e) n_b$$

# Recombination

- Saha Equation

$$\begin{aligned}\frac{n_e n_p}{n_H n_b} &= \frac{x_e^2}{1 - x_e} \\ &= \frac{1}{n_b} \left( \frac{m_e T}{2\pi} \right)^{3/2} e^{-B/T}\end{aligned}$$

- Naive guess of  $T_* = B$  wrong due to the low baryon-photon ratio  
–  $T_* \approx 0.3\text{eV}$  so recombination at  $z_* \approx 1000$
- But the photon-baryon ratio is very low

$$\eta_{b\gamma} \equiv n_b/n_\gamma \approx 3 \times 10^{-8} \Omega_b h^2$$

# Recombination

- Eliminate in favor of  $\eta_{b\gamma}$  and  $B/T$  through

$$n_\gamma = 0.244T^3, \quad \frac{m_e}{B} = 3.76 \times 10^4$$

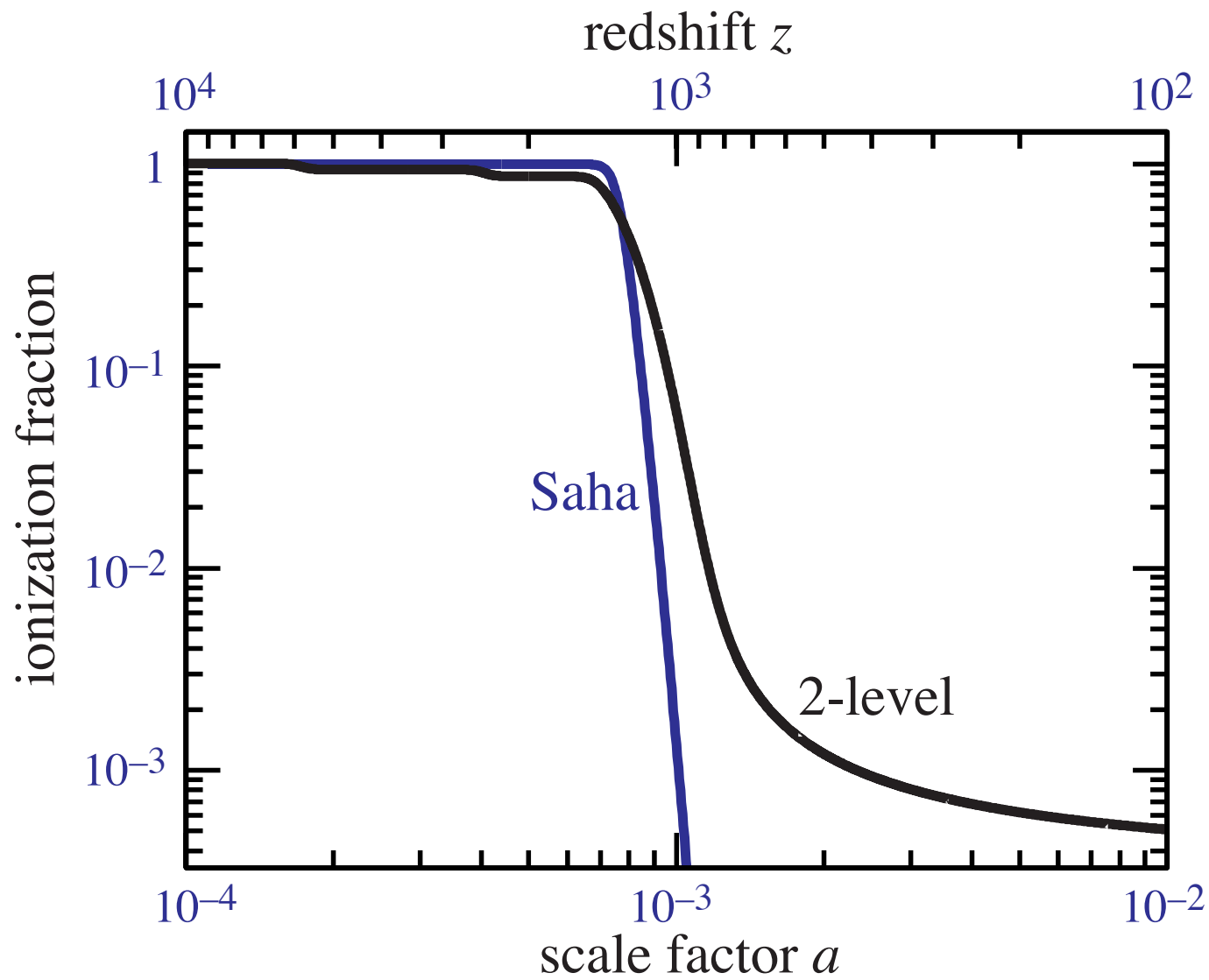
- Big coefficient

$$\frac{x_e^2}{1 - x_e} = 3.16 \times 10^{15} \left( \frac{B}{T} \right)^{3/2} e^{-B/T}$$

$$T = 1/3\text{eV} \rightarrow x_e = 0.7, T = 0.3\text{eV} \rightarrow x_e = 0.2$$

- Further delayed by inability to maintain equilibrium since net is through  $2\gamma$  process and redshifting out of line

# Recombination



# CMB Anisotropy

- Recombination can be viewed as the epoch where (most) of the CMB fluctuations freeze out
- Once neutral hydrogen forms, photons largely propagate unimpeded to the observer today
- CMB fluctuations thus provide an image of the universe at  $z \sim 1000$
- This leads to the famous horizon problem whose resolution is the subject of the next set of lectures...



