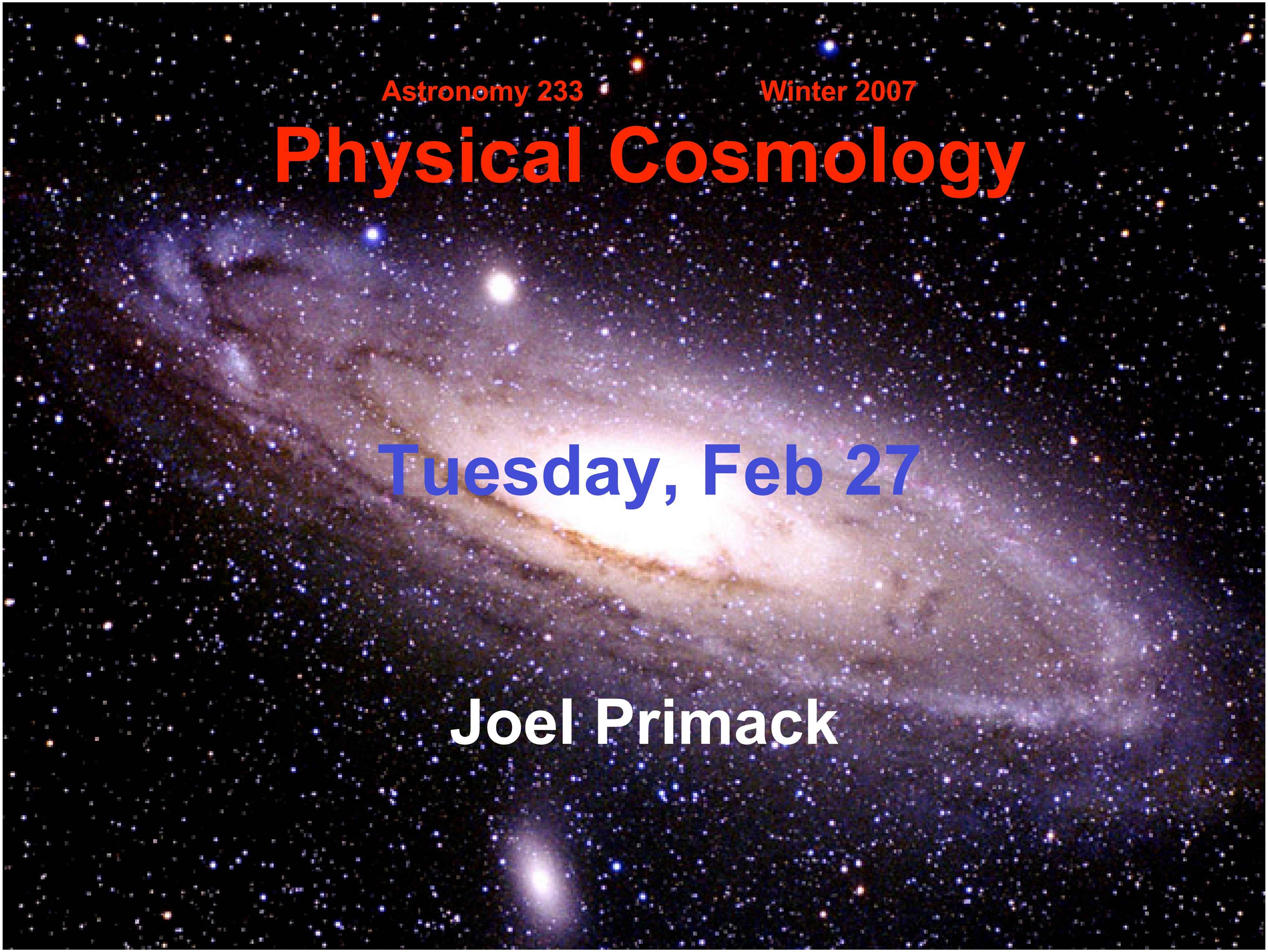


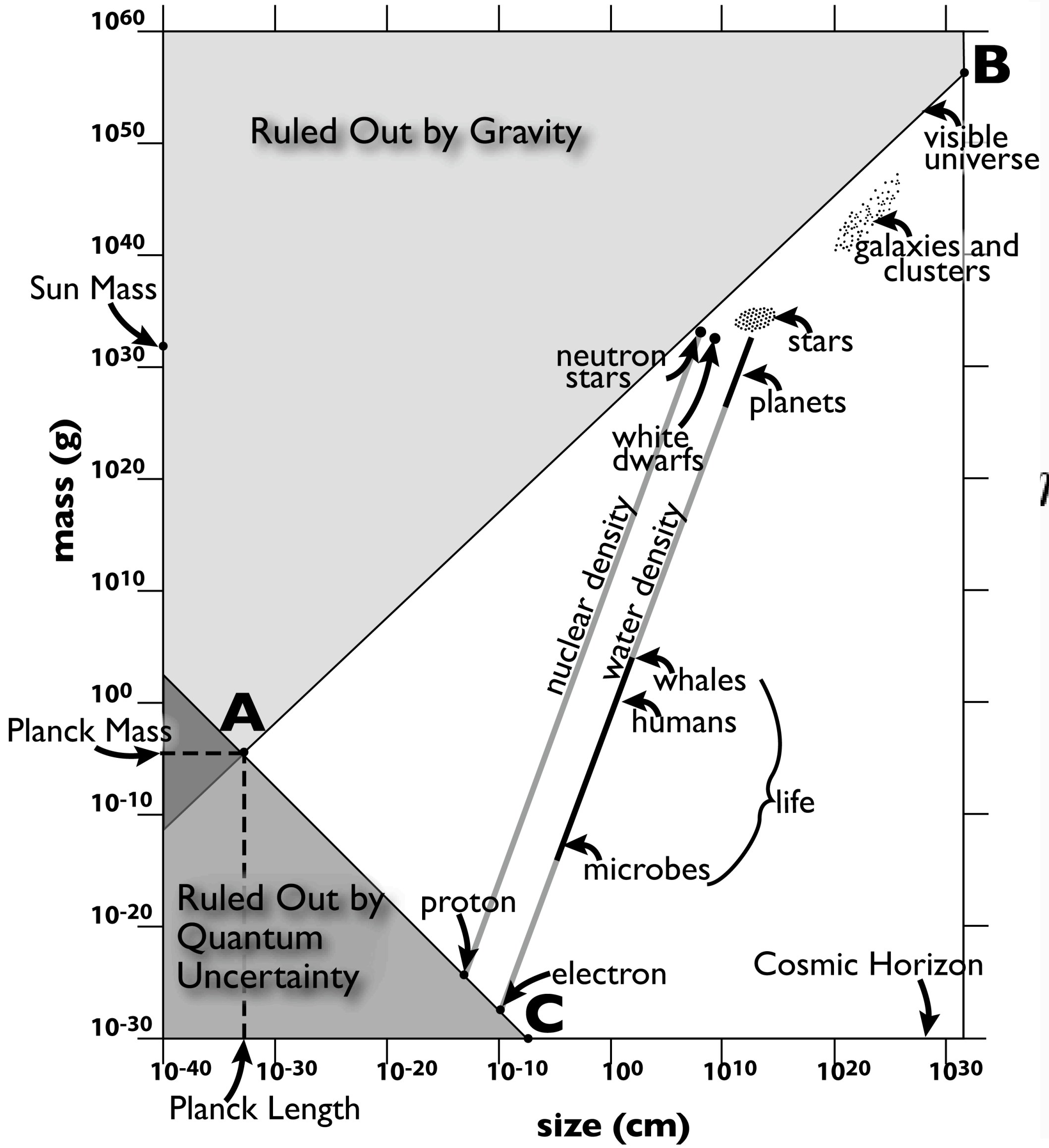
Astronomy 233 Winter 2007

Physical Cosmology

Tuesday, Feb 27

Joel Primack

The Wedge of Material Reality



From *The View from the Center of the Universe* © 2006

The **Planck Length**

$$l_{Pl} = \sqrt{\frac{hG}{2\pi c^3}} = 1.6 \times 10^{-33}\ \text{cm}$$

is the smallest possible length.
Here h is Planck's constant

$$h = 6.626068 \times 10^{-34}\ \text{m}^2\ \text{kg} / \text{s}$$

The Planck Mass is

$$m_{Pl} = \sqrt{\frac{hc}{2\pi G}} = 2.2 \times 10^{-5}\ \text{g}$$

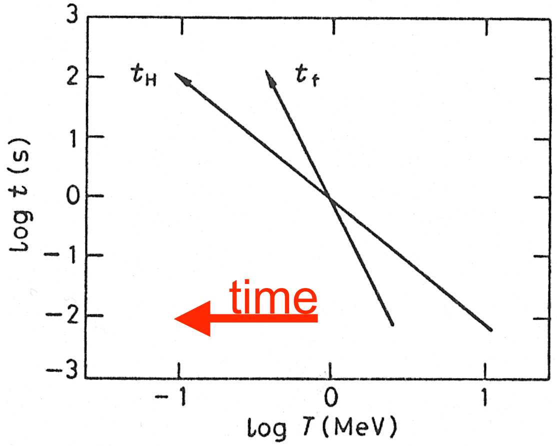
The Compton (i.e. quantum) wavelength $l_C = \frac{h}{2\pi mc}$

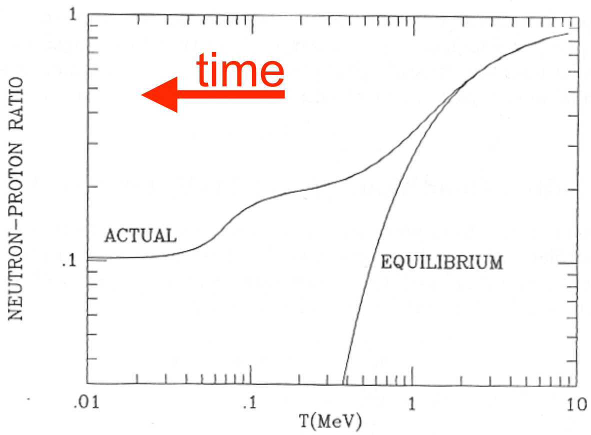
equals the Schwarzschild radius $l_S \approx \frac{Gm}{c^2}$

when $m = m_{Pl}$

Big Bang Nucleosynthesis

BBN was conceived by Gamow in 1946 as an explanation for the formation of all the elements, but the absence of any stable nuclei with A=5,8 makes it impossible for BBN to proceed past Li. The formation of carbon and heavier elements occurs instead through the triple-α process in the centers of red giants (Burbage^2, Fowler, & Hoyle). At the BBN baryon density of $2\times10^{-29}\,\Omega_b\, h^2\, (T/T_0)^3$ g cm^{-3} $\approx$ 2×10^{-5} g cm^{-3}, the probability of the triple-α process is negligible even though $T \approx 10^9$K.





Kolb & Turner

Thermal equilibrium between n and p is maintained by weak interactions, which keeps $n/p = \exp(-Q/T)$ (where $Q = m_n - m_p = 1.293$ MeV) until about $t \approx 1$ s. But because the neutrino mean free time $t_\nu^{-1} \approx \sigma_\nu\, n_{e\pm} \approx (G_F T)^2 (T^3)$ is increasing as $t_\nu \propto T^{-5}$ (here the Fermi constant $G_F \approx 10^{-5}$ GeV^{-2}), while the horizon size is increasing only as $t_H \approx (G\rho)^{-1/2} \approx M_{Pl}\, T^{-2}$, these interactions freeze out when T drops below about 0.8 MeV. This leaves $n/(p+n) \approx 0.14$. The neutrons then decay with a mean lifetime 887 ± 2 s until they are mostly fused into D and then ^{4}He. The higher the baryon density, the higher the final abundance of ^{4}He and the lower the abundance of D that survives this fusion process. Since D/H is so sensitive to baryon density, David Schramm called deuterium the “baryometer.” He and his colleagues also pointed out that since the horizon size increases more slowly with T^{-1} the larger the number of light neutrino species N_ν contributing to the energy density ρ, BBN predicted that $N_\nu \approx 3$ before N_ν was measured at accelerators by measuring the width of the Z^0. Latest (Cyburt et al. 2005): $2.67 < N_\nu < 3.85$.

Boltzmann Equation

$$a^{-3}\frac{d\left(n_1a^3\right)}{dt} = \int\frac{d^3p_1}{(2\pi)^3 2E_1}\int\frac{d^3p_2}{(2\pi)^3 2E_2}\int\frac{d^3p_3}{(2\pi)^3 2E_3}\int\frac{d^3p_4}{(2\pi)^3 2E_4}$$

$$\times (2\pi)^4\delta^3(p_1+p_2-p_3-p_4)\delta(E_1+E_2-E_3-E_4)\left|\mathcal{M}\right|^2$$

$$\times \left\{f_3f_4[1\pm f_1][1\pm f_2] - f_1f_2[1\pm f_3][1\pm f_4]\right\}.$$

Dodelson (3.1)

In the absence of interactions (rhs=0) n_1 falls as a^{-3}

+ bosons
- fermions

We will typically be interested in T>> E-μ (where μ is the chemical potential). In this limit, the exponential in the Fermi-Dirac or Bose-Einstein distributions is much larger than the ±1 in the denominator, so that

$$f(E) \to e^{\mu/T}e^{-E/T}$$

and the last line of the Boltzmann equation above simplifies to

$$f_3f_4[1\pm f_1][1\pm f_2] - f_1f_2[1\pm f_3][1\pm f_4]$$

$$\to \quad e^{-(E_1+E_2)/T}\left\{e^{(\mu_3+\mu_4)/T} - e^{(\mu_1+\mu_2)/T}\right\}.$$

The number densities are given by $n_i = g_i e^{\mu_i/T}\int\frac{d^3p}{(2\pi)^3}e^{-E_i/T}$. For our applications, i's are

Table 3.1. Reactions in This Chapter: $1+2 \leftrightarrow 3+4$

	1	2	3	4
Neutron-Proton Ratio	n	ν_e or e^+	p	e^- or $\bar{\nu}_e$
Recombination	e	p	H	γ
Dark Matter Production	X	X	l	l

$$n_i^{(0)} \equiv g_i \int \frac{d^3p}{(2\pi)^3} e^{-E_i/T} = \begin{cases} g_i \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T} & m_i \gg T \\ g_i \frac{T^3}{\pi^2} & m_i \ll T \end{cases} . \tag{3.6}$$

With this defintion, $e^{\mu_i/T}$ can be rewritten as $n_i/n_i^{(0)}$, so the last line of Eq. (3.1) is equal to

$$e^{-(E_1+E_2)/T} \left\{ \frac{n_3 n_4}{n_3^{(0)} n_4^{(0)}} - \frac{n_1 n_2}{n_1^{(0)} n_2^{(0)}} \right\} . \tag{3.7}$$

With these approximations the Boltzmann equation now simplifies enormously. Define the thermally averaged cross section as

$$\langle \sigma v \rangle \equiv \frac{1}{n_1^{(0)} n_2^{(0)}} \int \frac{d^3p_1}{(2\pi)^3 2E_1} \int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} e^{-(E_1+E_2)/T}$$
$$\times (2\pi)^4 \delta^3(p_1 + p_2 - p_3 - p_4) \delta(E_1 + E_2 - E_3 - E_4) \left|\mathcal{M}\right|^2 . \tag{3.8}$$

Then, the Boltzmann equation becomes

$$a^{-3} \frac{d\left(n_1 a^3\right)}{dt} = n_1^{(0)} n_2^{(0)} \langle \sigma v \rangle \left\{ \frac{n_3 n_4}{n_3^{(0)} n_4^{(0)}} - \frac{n_1 n_2}{n_1^{(0)} n_2^{(0)}} \right\} . \tag{3.9}$$

If the reaction rate $n_2\langle \sigma v \rangle$ is much larger than the expansion rate (~ H), then the {} on the rhs must vanish. This is called *chemical equilibrium* in the context of the early universe, *nuclear statistical equilibrium* (NSE) in the context of Big Bang nucleosynthesis, and the *Saha equation* when discussing recombination of electrons and protons to form neutral hydrogen.

As the temperature of the universe cools to 1 MeV, the cosmic plasma consists of:

- **Relativistic particles in equilibrium: photons, electrons and positrons.** These are kept in close contact with each other by electromagnetic interactions such as $e^+e^- \leftrightarrow \gamma\gamma$. Besides a small difference due to fermion/boson statistics, these all have the same abundances.
- **Decoupled relativistic particles: neutrinos.** At temperatures a little above 1 MeV, the rate for processes such as $\nu e \leftrightarrow \nu e$ which keep neutrinos coupled to the rest of the plasma drops beneath the expansion rate. Neutrinos therefore share the same temperature as the other relativistic particles, and hence are roughly as abundant, but they do not couple to them.
- **Nonrelativistic particles: baryons.** If there had been no asymmetry in the initial number of baryons and anti-baryons, then both would be completely depleted by 1 MeV. However, such an asymmetry did exist: $(n_b - n_{\bar{b}})/s \sim 10^{-10}$ initially,[1] and this ratio remains constant throughout the expansion. By the time the temperature is of order 1 MeV, all anti-baryons have annihilated away (Exercise 12) so

$$\eta_b \equiv \frac{n_b}{n_\gamma} = 5.5 \times 10^{-10} \left(\frac{\Omega_b h^2}{0.020}\right). \tag{3.11}$$

There are thus many fewer baryons than relativistic particles when $T \sim$ MeV.

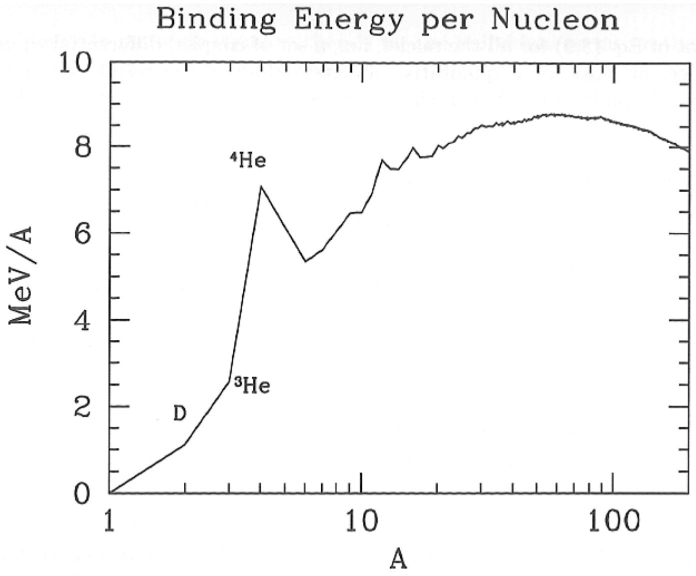


Figure 3.1. Binding energy of nuclei as a function of mass number. Iron has the highest binding energy, but among the light elements, ^{4}He is a crucial local maximum. Nucleosynthesis in the early universe essentially stops at ^{4}He because of the lack of tightly bound isotopes at $A = 5 - 8$. In the high-density environment of stars, three ^{4}He nuclei fuse to form ^{12}C, but the low baryon number precludes this process in the early universe.

Lightning Introduction to Nuclear Physics

A single proton is a hydrogen nucleus, referred to as ^{1}H or simply p; a proton and a neutron make up deuterium, ^{2}H or D; one proton and two neutrons make tritium, ^{3}H or T. Nuclei with two protons are helium; these can have one neutron (^{3}He) or two (^{4}He). Thus unique elements have a fixed number of protons, and isotopes of a given element have differing numbers of neutrons. The total number of neutrons and protons in the nucleus, the *atomic number*, is a superscript before the name of the element.

The total mass of a nucleus with Z protons and $A - Z$ neutrons differs slightly from the mass of the individual protons and neutrons alone. This difference is called the binding energy, defined as

$$B \equiv Z m_p + (A - Z) m_n - m \tag{3.12}$$

where m is the mass of the nucleus. For example, the mass of deuterium is 1875.62 MeV while the sum of the neutron and proton masses is 1877.84 MeV, so the binding energy of deuterium is 2.22 MeV. Nuclear binding energies are typically in the MeV range, which explains why Big Bang nucleosynthesis occurs at temperatures a bit less than 1 MeV even though nuclear masses are in the GeV range.

Neutrons and protons can interconvert via weak interactions:

$$p + \bar{\nu} \leftrightarrow n + e^+ \quad ; \quad p + e^- \leftrightarrow n + \nu \quad ; \quad n \leftrightarrow p + e^- + \bar{\nu} \tag{3.13}$$

where all the reactions can proceed in either direction. The light elements are built up via electromagnetic interactions. For example, deuterium forms from $p + n \to \text{D} + \gamma$. Then, $\text{D} + \text{D} \to n + {}^3\text{He}$, after which ${}^3\text{He} + \text{D} \to p + {}^4\text{He}$ produces ^{4}He.

$$\frac{n_D}{n_n n_p} = \frac{n_D^{(0)}}{n_n^{(0)} n_p^{(0)}}. \tag{3.14}$$

The integrals on the right, as given in Eq. (3.6), lead to

$$\frac{n_D}{n_n n_p} = \frac{3}{4} \left(\frac{2\pi m_D}{m_n m_p T}\right)^{3/2} e^{[m_n + m_p - m_D]/T}, \tag{3.15}$$

the factor of 3/4 being due to the number of spin states (3 for D and 2 each for p and n). In the prefactor, m_D can be set to $2m_n = 2m_p$, but in the exponential the small difference between $m_n + m_p$ and m_D is important: indeed the argument of the exponential is by defintion equal to the binding energy of deuterium, $B_D = 2.22$ MeV. Therefore, as long as equilibrium holds,

$$\frac{n_D}{n_n n_p} = \frac{3}{4} \left(\frac{4\pi}{m_p T}\right)^{3/2} e^{B_D/T}. \tag{3.16}$$

Both the neutron and proton density are proportional to the baryon density, so roughly,

$$\frac{n_D}{n_b} \sim \eta_b \left(\frac{T}{m_p}\right)^{3/2} e^{B_D/T}. \tag{3.17}$$

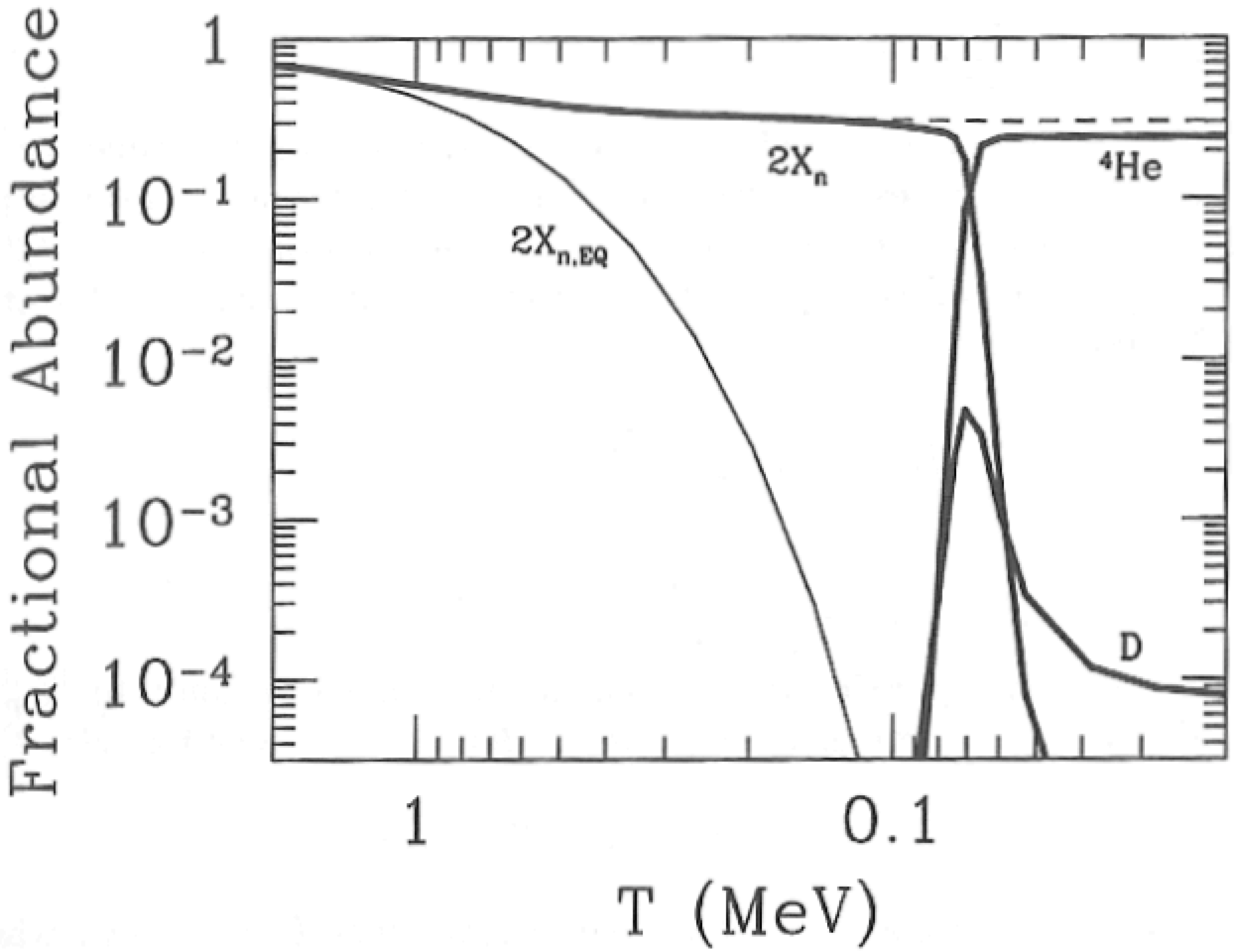
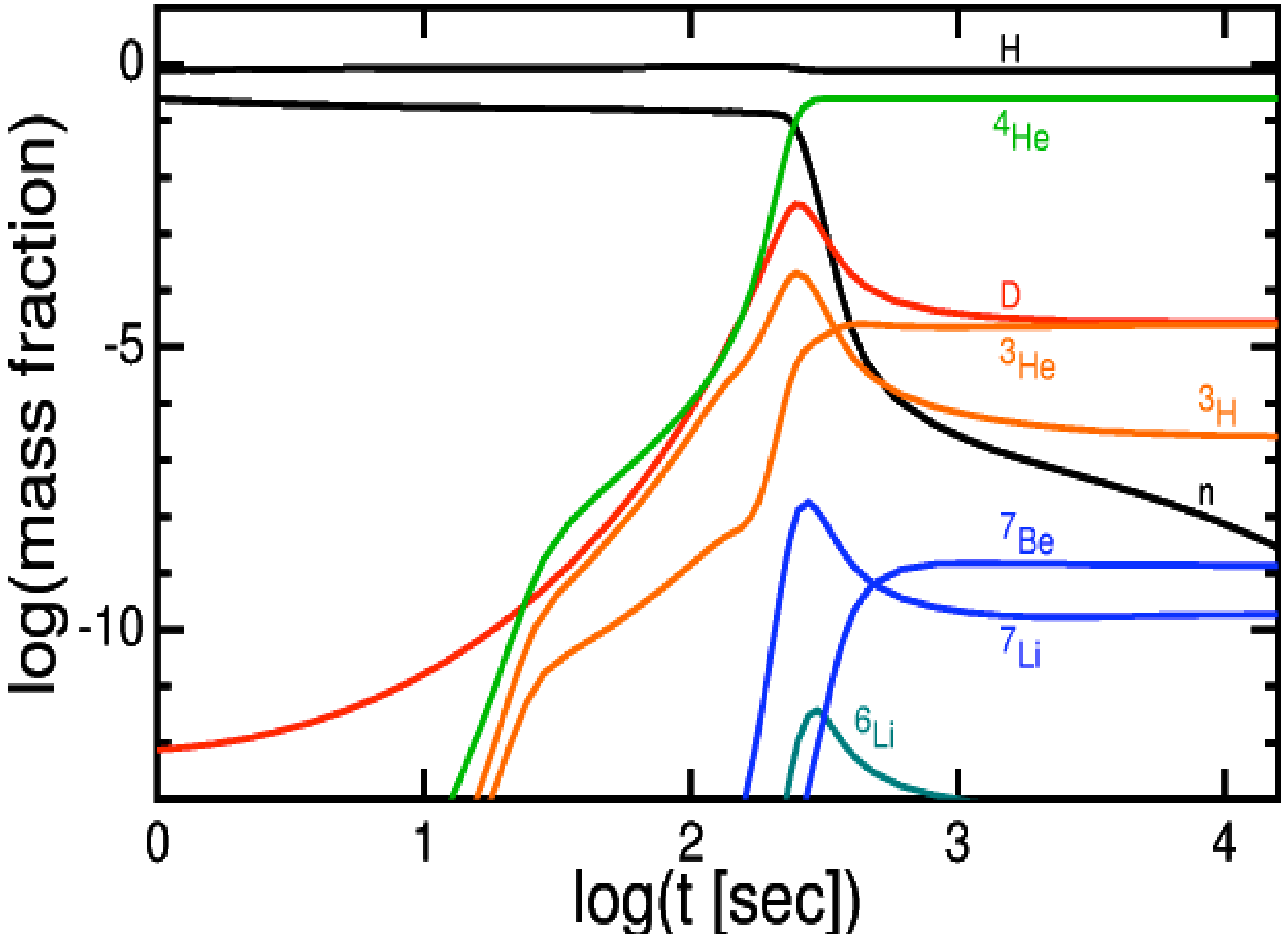


Figure 3.2. Evolution of light element abundances in the early universe. Heavy solid curves are results from Wagoner (1973) code; dashed curve is from integration of Eq. (3.27); light solid curve is twice the neutron equilibrium abundance. Note the good agreement of Eq. (3.27) and the exact result until the onset of neutron decay. Also note that the neutron abundance falls out of equilibrium at T ~MeV.

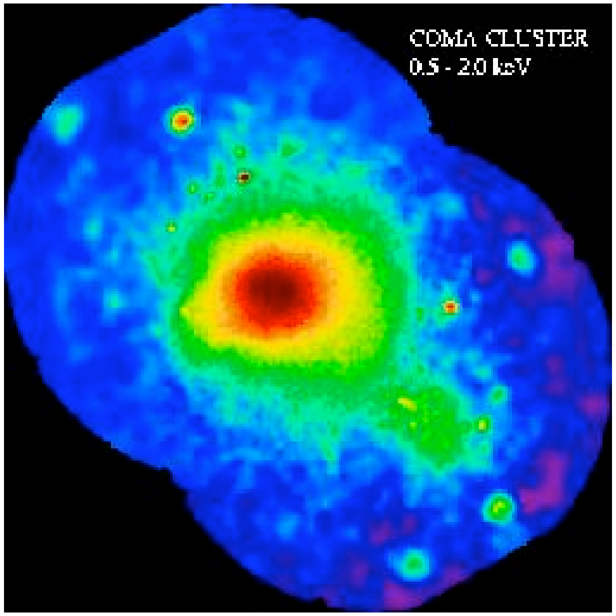


The detailed production of the lightest elements out of protons and neutrons during the first three minutes of the universe's history. The nuclear reactions occur rapidly when the temperature falls below a billion degrees Kelvin. Subsequently, the reactions are shut down, because of the rapidly falling temperature and density of matter in the expanding universe.

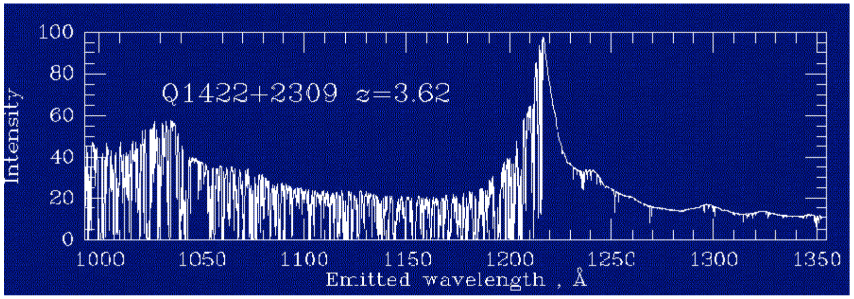
Ken Kawano's (1992) BBN code is available at
http://www-thphys.physics.ox.ac.uk/users/SubirSarkar/bbn.html

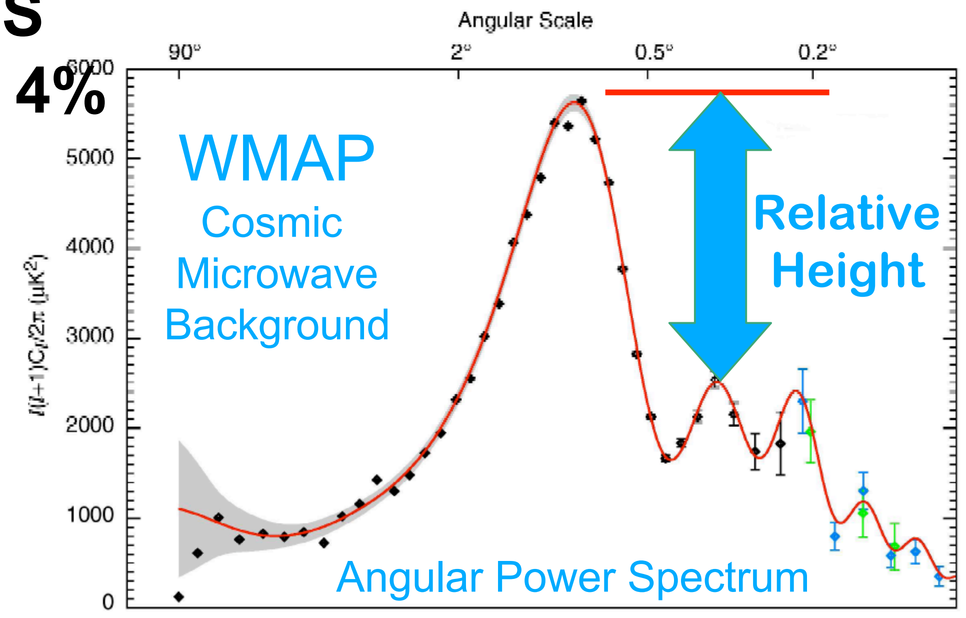
5 INDEPENDENT MEASURES AGREE: ATOMS ARE ONLY 4% OF THE COSMIC DENSITY

Galaxy Cluster in X-rays



Absorption of Quasar Light





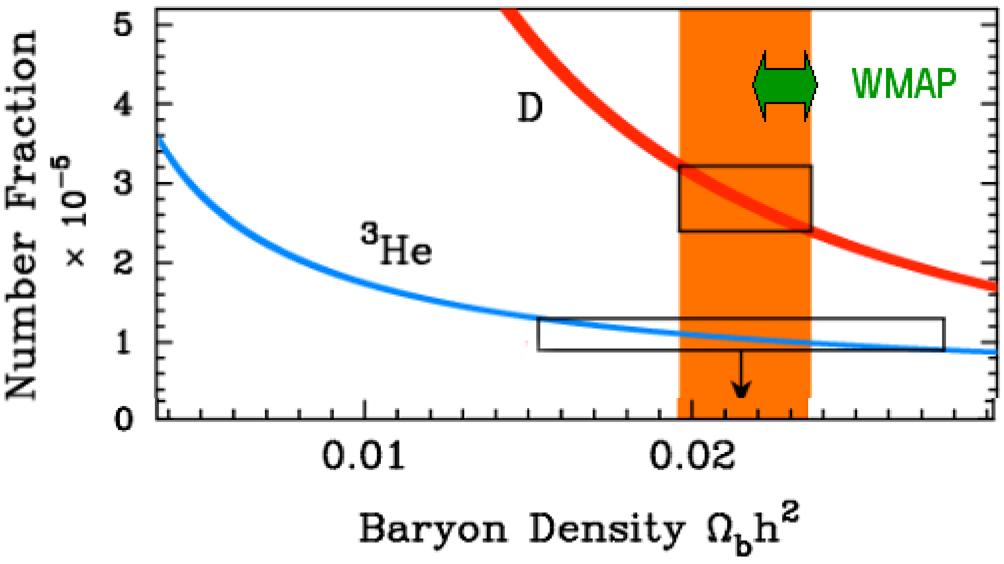
WMAP

Cosmic Microwave Background

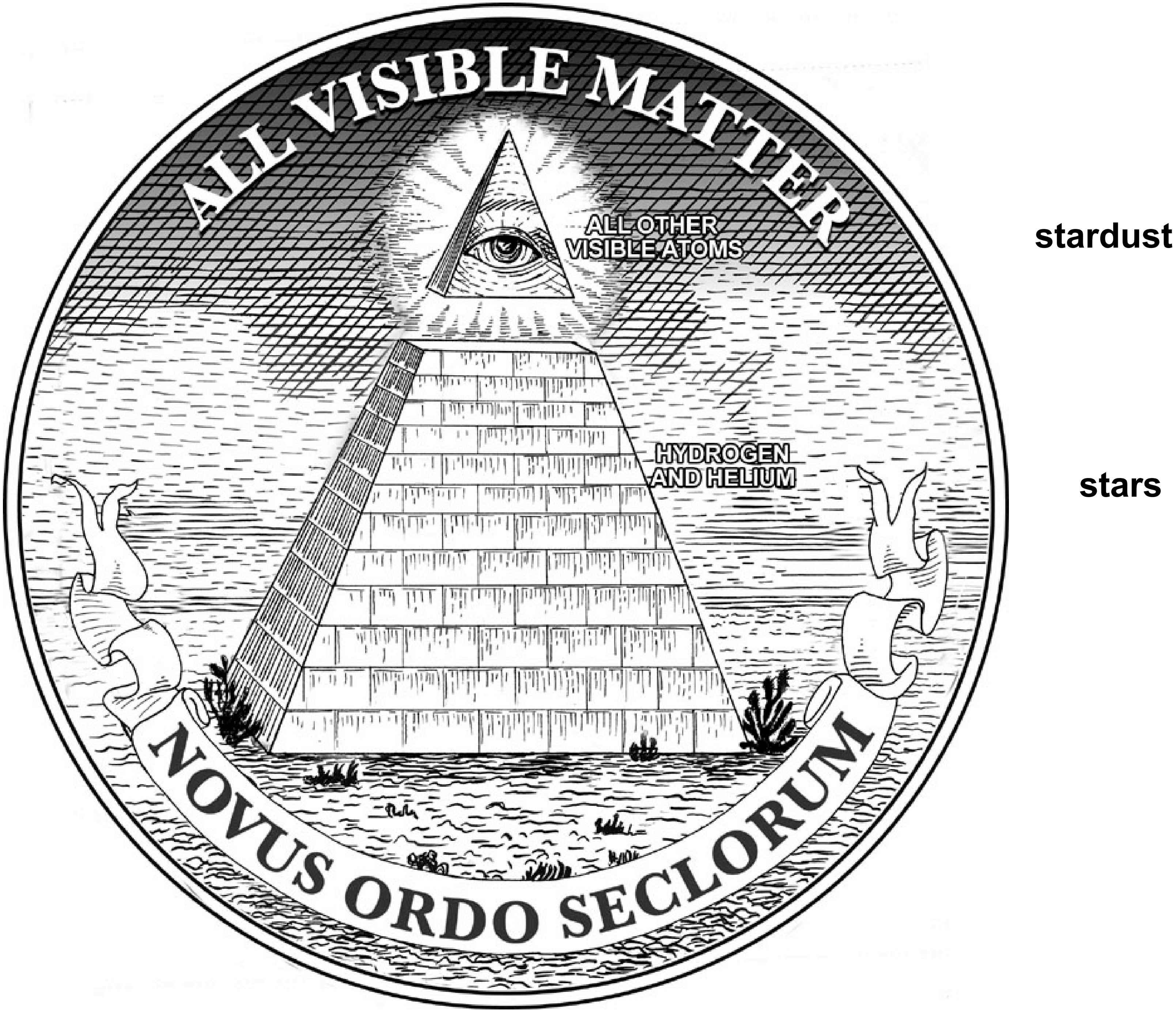
Relative Height

Angular Power Spectrum

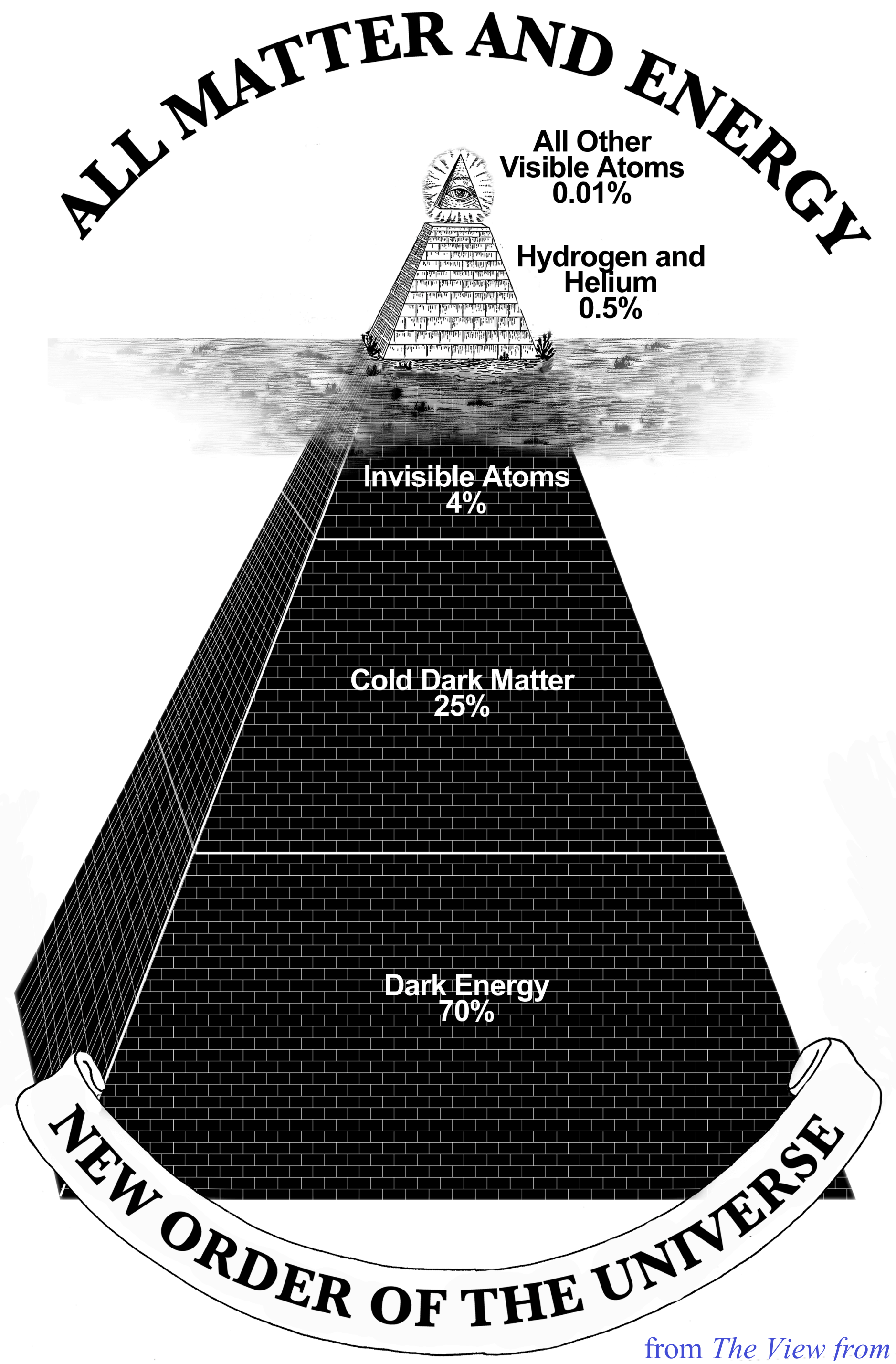
Deuterium Abundance
+ Big Bang Nucleosynthesis



& WIGGLES IN GALAXY P(k)



From *The View from the Center of the Universe* © 2006



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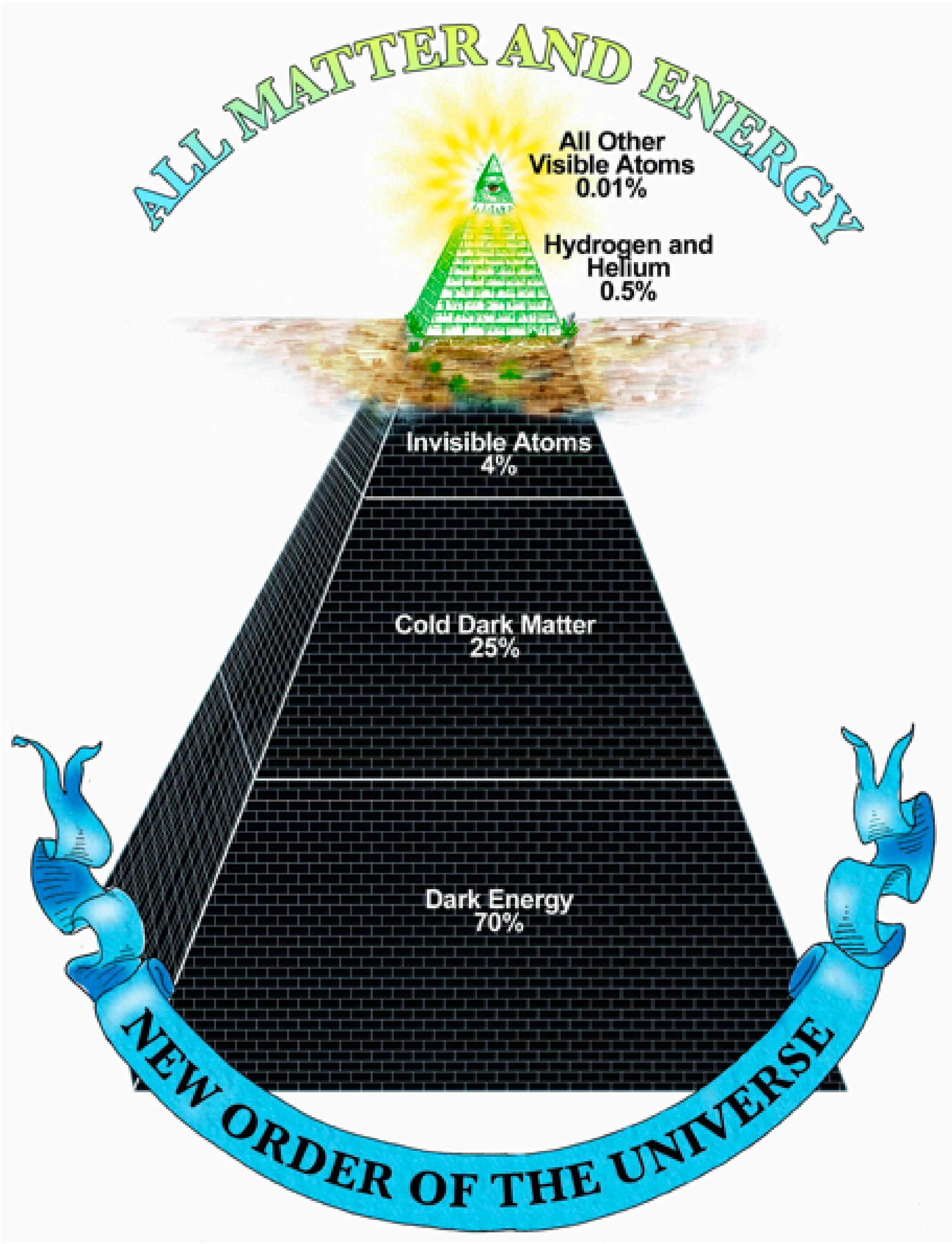
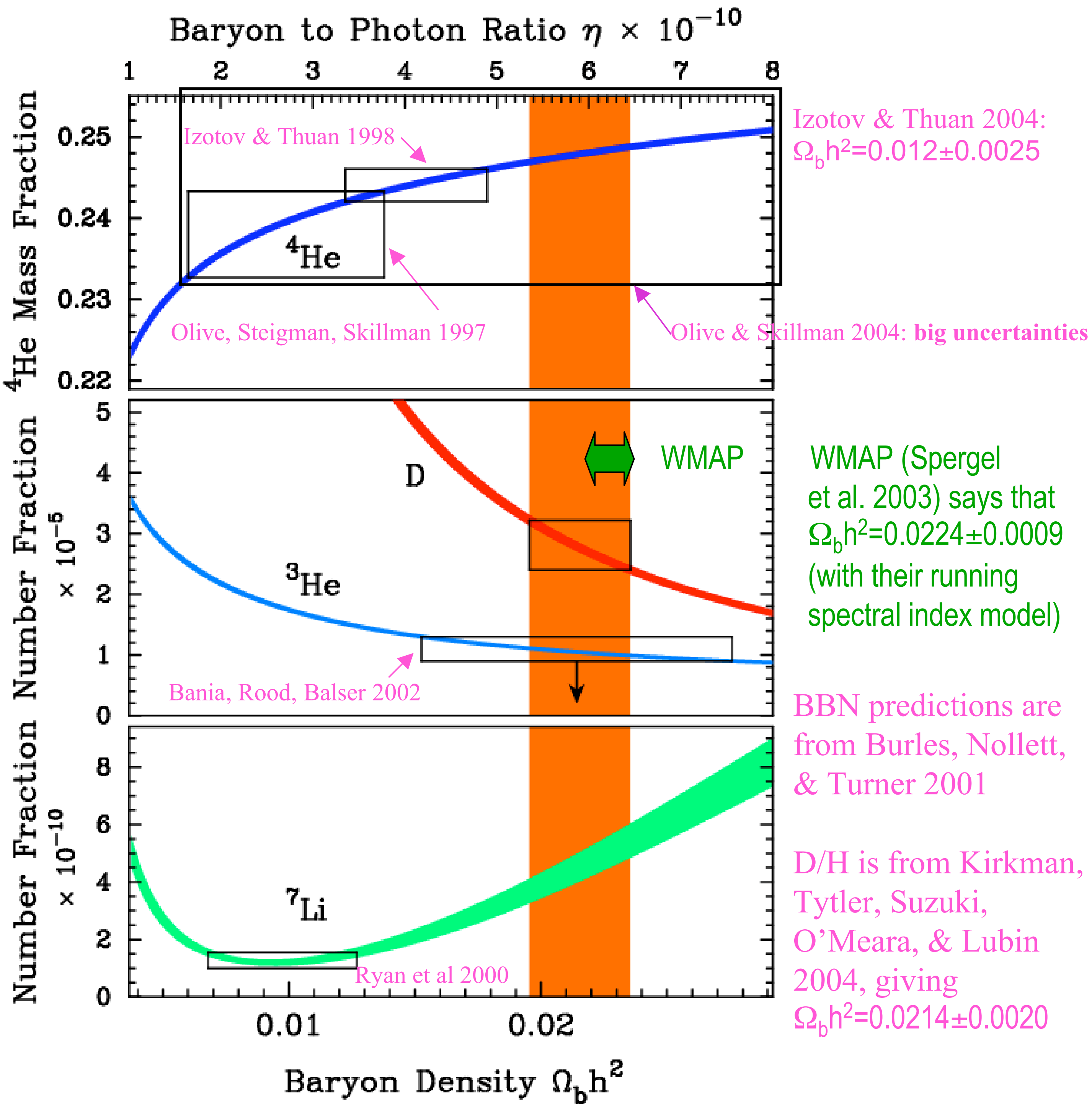

ALL MATTER AND ENERGY
All Other Visible Atoms 0.01%
Hydrogen and Helium 0.5%
Invisible Atoms 4%
Cold Dark Matter 25%
Dark Energy 70%
NEW ORDER OF THE UNIVERSE

BBN Predicted vs. Measured Abundances of D, ^{3}He, ^{4}He, and ^{7}Li

^{7}Li IS NOW DISCORDANT



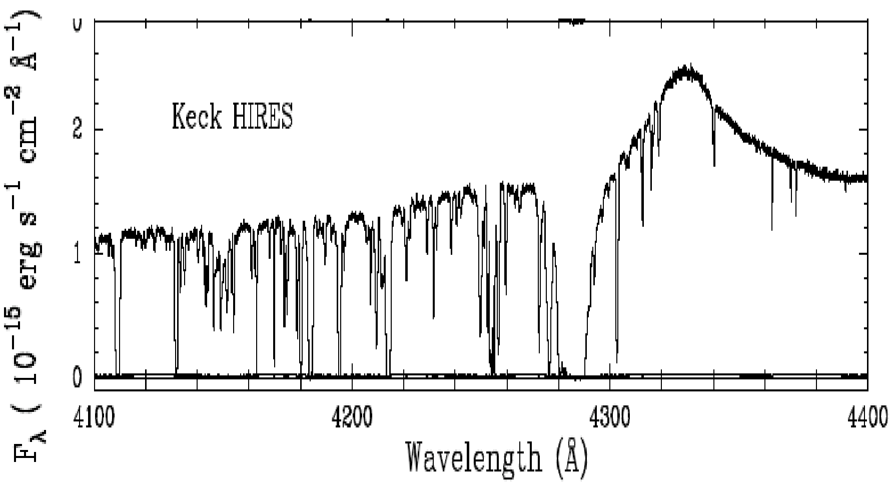
Izotov & Thuan 2004: $\Omega_b h^2 = 0.012 \pm 0.0025$

WMAP (Spergel et al. 2003) says that $\Omega_b h^2 = 0.0224 \pm 0.0009$ (with their running spectral index model)

BBN predictions are from Burles, Nollett, & Turner 2001

D/H is from Kirkman, Tytler, Suzuki, O'Meara, & Lubin 2004, giving $\Omega_b h^2 = 0.0214 \pm 0.0020$

Deuterium absorption at redshift 2.525659 towards Q1243+3047



The Lyα absorption near 4285 Å is from the system in which we measure D/H.

The detection of Deuterium and the modeling of this system seem convincing. This is just a portion of the evidence that the Tytler group presented in this paper. They have similarly convincing evidence for several other Lyman alpha clouds in quasar spectra.

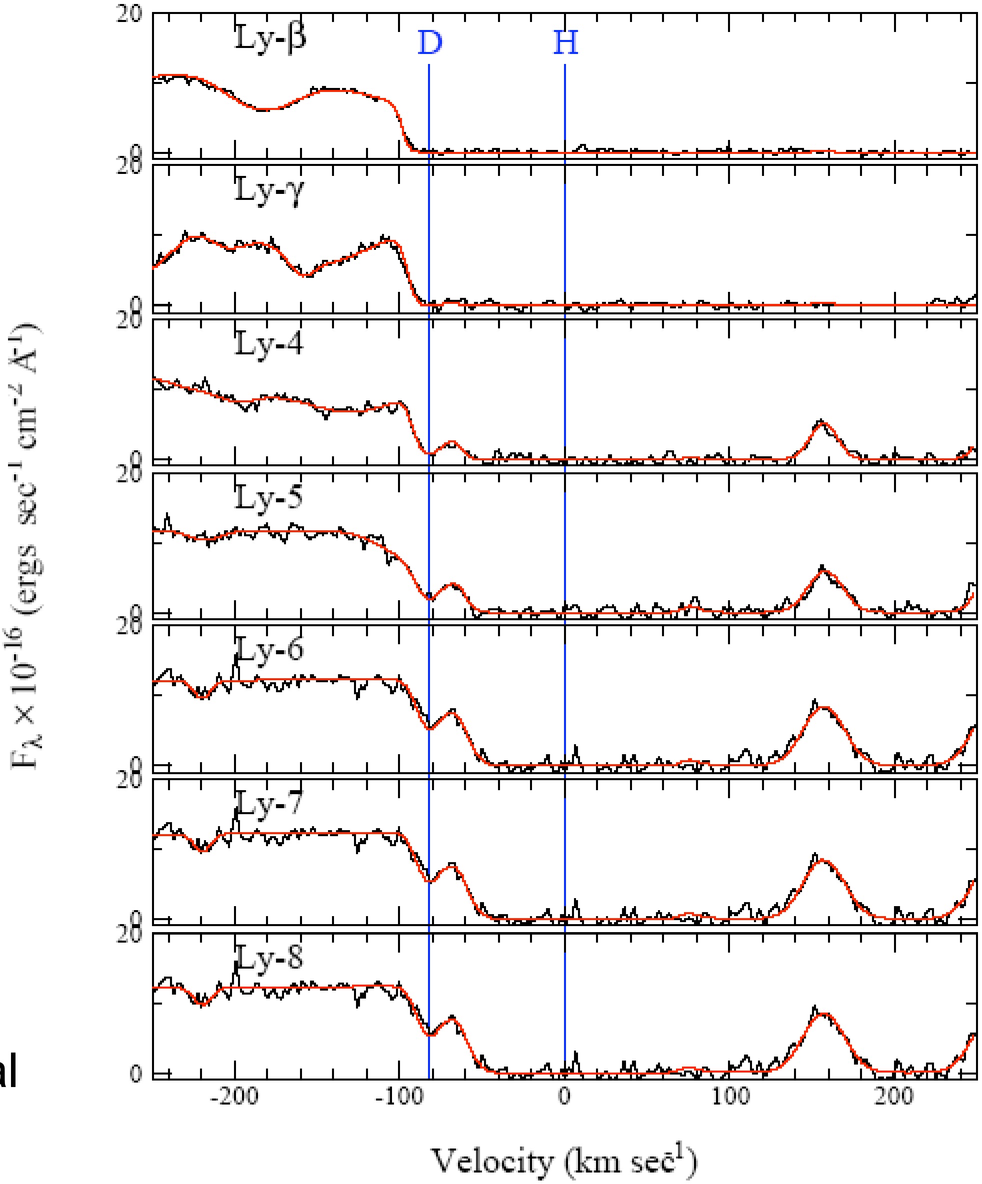
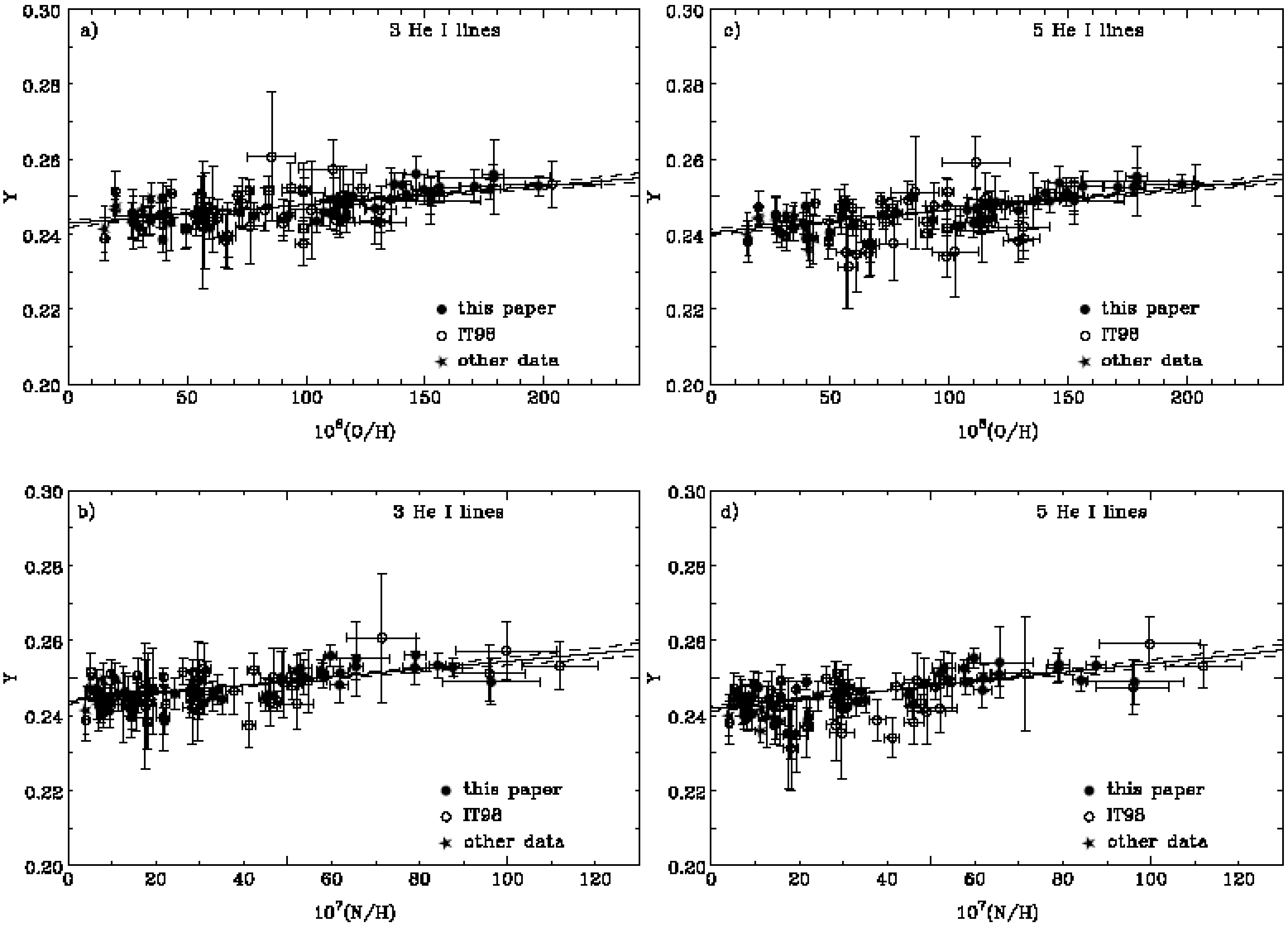


Fig. 7.— The HIRES spectrum of Ly-2 to 8, together with our model of the system, as given in Table 3.

Kirkman, Tytler, Suzuki, O'Meara, & Lubin 2004

Determination of primordial He^4 abundance Y$_p$ by linear regression

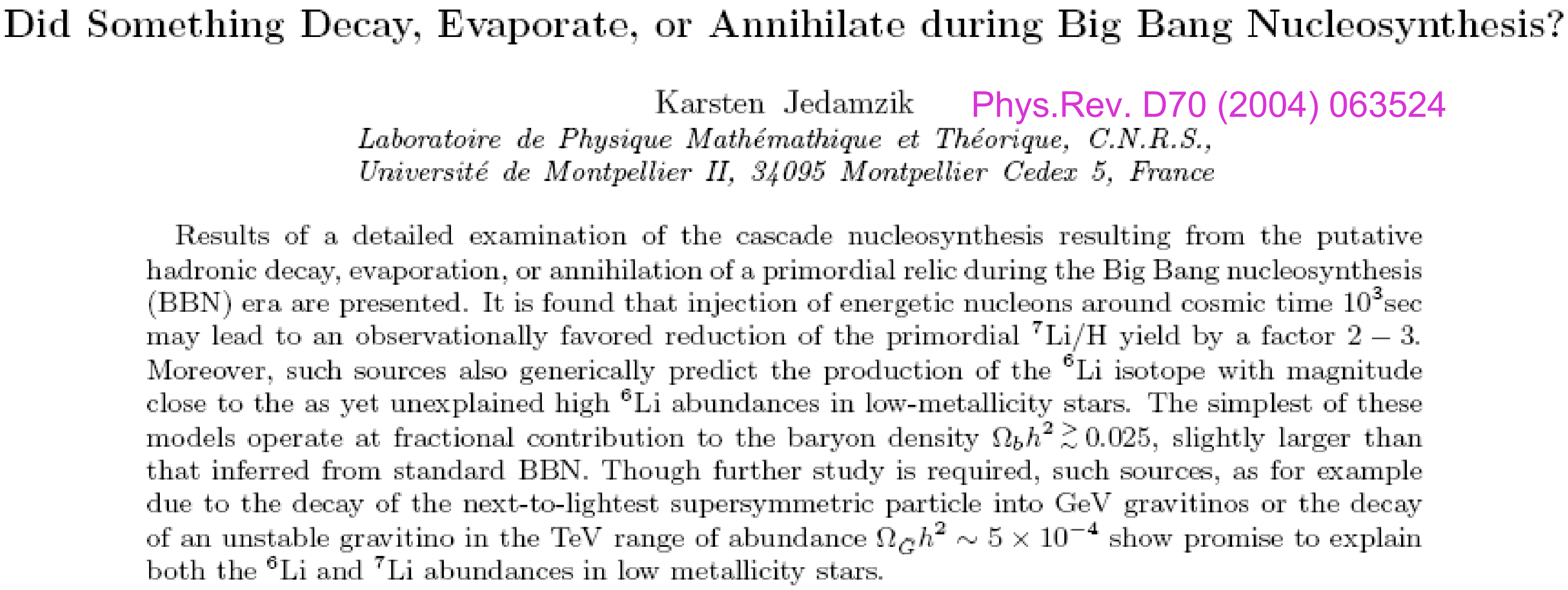


Y = M(^{4}He)/M(baryons), Primordial Y ≡ Yp = zero intercept

Note: BBN plus D/H ⇒ Yp = 0.247± 0.001

Izotov & Thuan 2004

The Li abundance disagreement with BBN may indicate new physics



Did Something Decay, Evaporate, or Annihilate during Big Bang Nucleosynthesis?

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Phys.Rev. D70 (2004) 063524

Results of a detailed examination of the cascade nucleosynthesis resulting from the putative hadronic decay, evaporation, or annihilation of a primordial relic during the Big Bang nucleosynthesis (BBN) era are presented. It is found that injection of energetic nucleons around cosmic time 10^3sec may lead to an observationally favored reduction of the primordial ^{7}Li/H yield by a factor $2-3$. Moreover, such sources also generically predict the production of the ^{6}Li isotope with magnitude close to the as yet unexplained high ^{6}Li abundances in low-metallicity stars. The simplest of these models operate at fractional contribution to the baryon density $\Omega_b h^2 \gtrsim 0.025$, slightly larger than that inferred from standard BBN. Though further study is required, such sources, as for example due to the decay of the next-to-lightest supersymmetric particle into GeV gravitinos or the decay of an unstable gravitino in the TeV range of abundance $\Omega_G h^2 \sim 5 \times 10^{-4}$ show promise to explain both the ^{6}Li and ^{7}Li abundances in low metallicity stars.

See also “Supergravity with a Gravitino LSP”
Jonathan L. Feng, Shufang Su, Fumihiro Takayama
Phys.Rev. D70 (2004) 075019

(Re)combination: $e^- + p \rightarrow H$

As long as e- + p ⇔ H remains in equilibrium, the condition

$$\left\{\frac{n_3 n_4}{n_3^{(0)} n_4^{(0)}} - \frac{n_1 n_2}{n_1^{(0)} n_2^{(0)}}\right\} = 0$$

with 1 = e^-, 2 = p, 3 = H, ensures that

$$\frac{n_e n_p}{n_H} = \frac{n_e^{(0)} n_p^{(0)}}{n_H^{(0)}}.$$

Neutrality ensures $n_p = n_e$. Defining the free electron fraction

$$X_e \equiv \frac{n_e}{n_e + n_H} = \frac{n_p}{n_p + n_H},$$

the equation above becomes

$$\frac{X_e^2}{1 - X_e} = \frac{1}{n_e + n_H}\left[\left(\frac{m_e T}{2\pi}\right)^{3/2} e^{-\underline{[m_e + m_p - m_H]/T}}\right]$$

, which

ε = 13.6 eV

is known as the *Saha equation*. When T ~ ε, the rhs ~ 10^{15}, so X_e is very close to 1 and very little recombination has yet occurred. As T drops, the free electron fraction also drops, and as it approaches 0 equilibrium cannot be maintained. To follow the freezeout of the electron fraction, it is necessary to use the Boltzmann equation

$$a^{-3}\frac{d\left(n_e a^3\right)}{dt} = n_e^{(0)} n_p^{(0)} \langle \sigma v \rangle \left\{\frac{n_H}{n_H^{(0)}} - \frac{n_e^2}{n_e^{(0)} n_p^{(0)}}\right\}$$

$$= n_b \langle \sigma v \rangle \left\{(1 - X_e)\left(\frac{m_e T}{2\pi}\right)^{3/2} e^{-\epsilon_0/T} - X_e^2 n_b\right\}$$

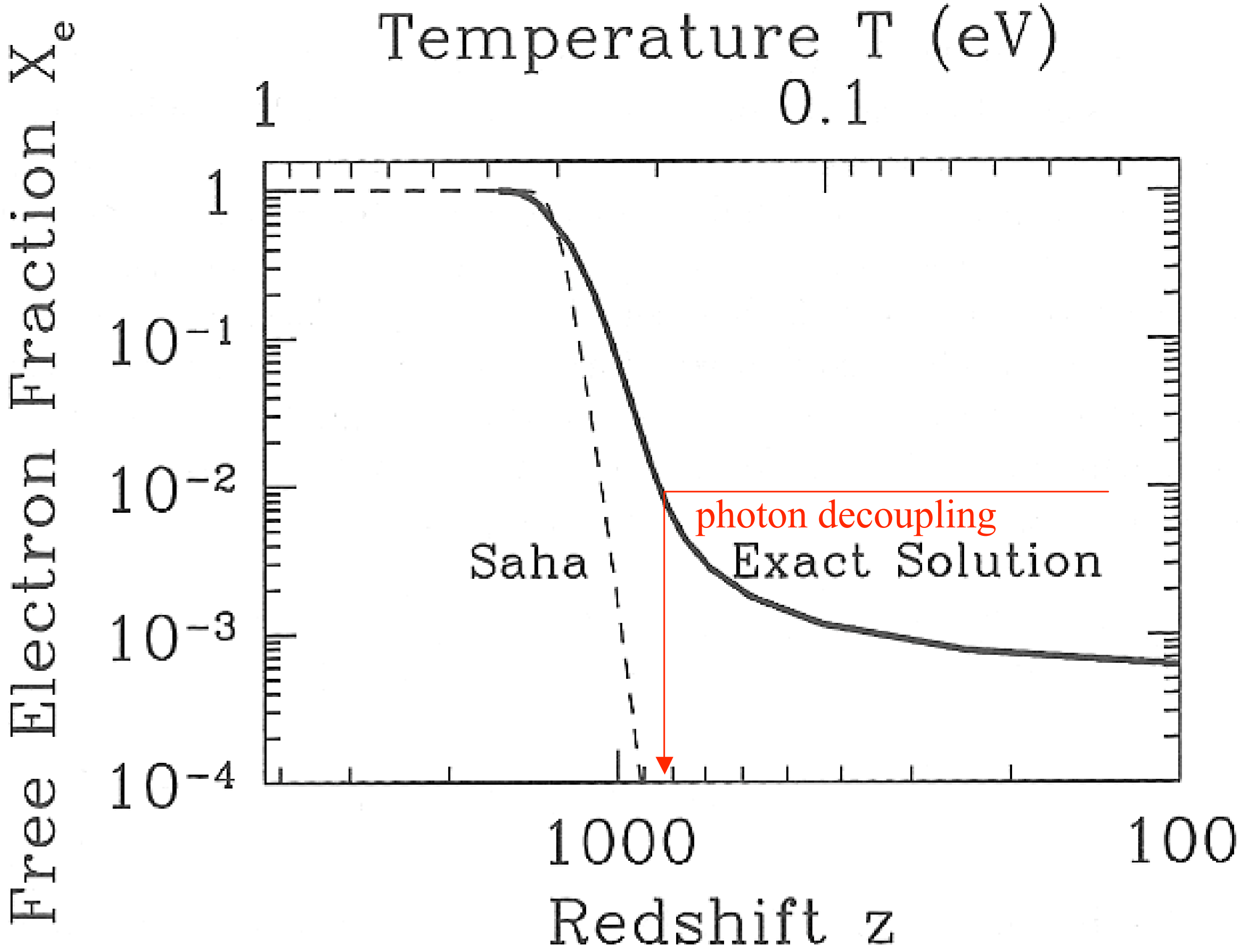


Figure 3.4. Free electron fraction as a function of redshift. Recombination takes place suddenly at $z \sim 1000$ corresponding to $T \sim 1/4$ eV. The Saha approximation, Eq. (3.37), holds in equilibrium and correctly identifies the redshift of recombination, but not the detailed evolution of X_e. Here $\Omega_b = 0.06, \Omega_m = 1, h = 0.5$.

Dodelson, *Modern Cosmology*, p. 72

Dark Matter Annihilation

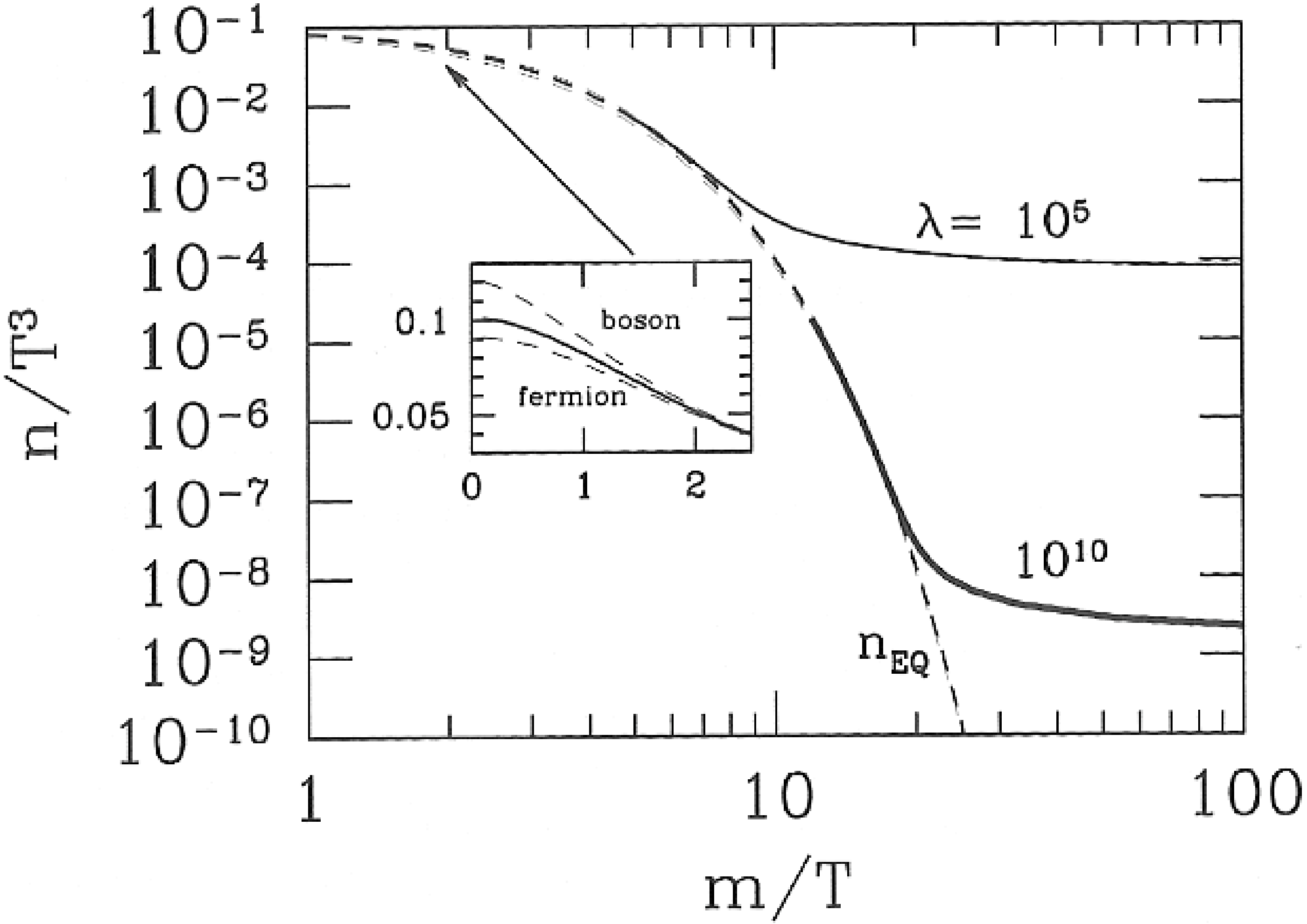


Figure 3.5. Abundance of heavy stable particle as the temperature drops beneath its mass. Dashed line is equilibrium abundance. Two different solid curves show heavy particle abundance for two different values of λ, the ratio of the annihilation rate to the Hubble rate. Inset shows that the difference between quantum statistics and Boltzmann statistics is important only at temperatures larger than the mass.

Dodelson, *Modern Cosmology*, p. 76

Dark Matter Annihilation

The abundance today of dark matter particles X of the WIMP variety is determined by their survival of annihilation in the early universe. Supersymmetric neutralinos can annihilate with each other (and sometimes with other particles: “co-annihilation”). Dark matter annihilation follows the same pattern as the previous discussions: initially the abundance of dark matter particles X is given by the equilibrium Boltzmann exponential exp(-m_X/T), but as they start to disappear they have trouble finding each other and eventually their number density freezes out. The freezeout process can be followed using the Boltzmann equation, as discussed in Kolb and Turner, Dodelson, and other textbooks. For a detailed discussion of Susy WIMPs, see the review article by Jungman, Kamionkowski, and Griest (1996). The result is that the abundance today of WIMPs X is given in most cases by (Dodelson’s Eqs. 3.59-60)

$$\Omega_X = \left[\frac{4\pi^3 G g_*(m)}{45}\right]^{1/2} \frac{x_f T_0^3}{30\langle\sigma v\rangle\rho_{\rm cr}} = 0.3h^{-2}\left(\frac{x_f}{10}\right)\left(\frac{g_*(m)}{100}\right)^{1/2}\frac{10^{-39}\,{\rm cm}^2}{\langle\sigma v\rangle}.$$

Here $x_f \approx 10$ is the ratio of m_X to the freezeout temperature T_f, and $g_*(m_X) \approx 100$ is the density of states factor in the expression for the energy density of the universe when the temperature equals m_X

$$\rho = \frac{\pi^2}{30}T^4\left[\sum_{i={\rm bosons}} g_i + \frac{7}{8}\sum_{i={\rm fermions}} g_i\right] \equiv g_*\frac{\pi^2}{30}T^4.$$

The sum is over relativistic species *i* (see the graph of *g*(*T*) on the next slide). Note that more X’s survive, the weaker the cross section σ. For Susy WIMPs the natural values are $\sigma \sim 10^{-39}$ cm^2, so $\Omega_X \approx 1$ naturally.

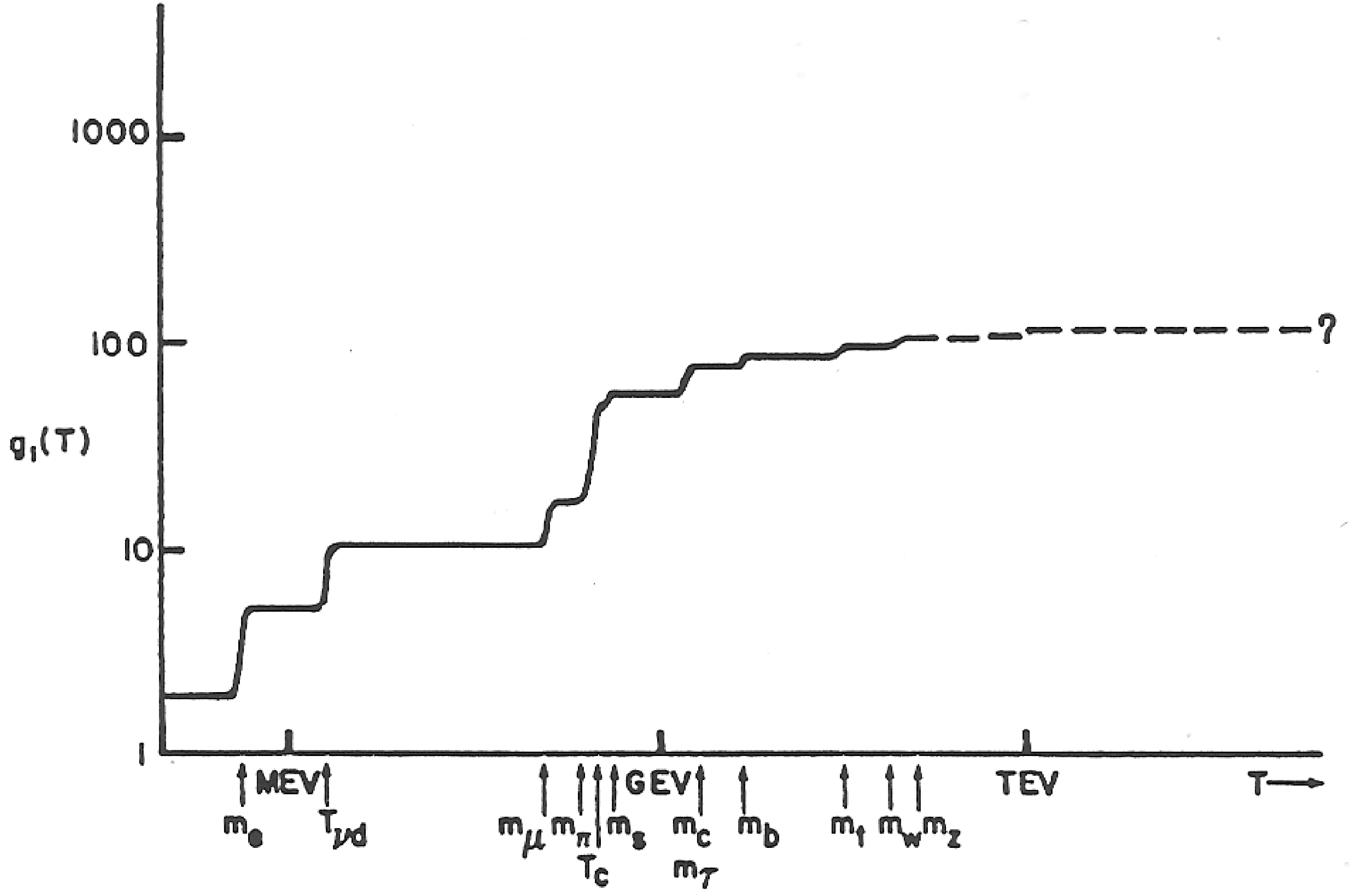


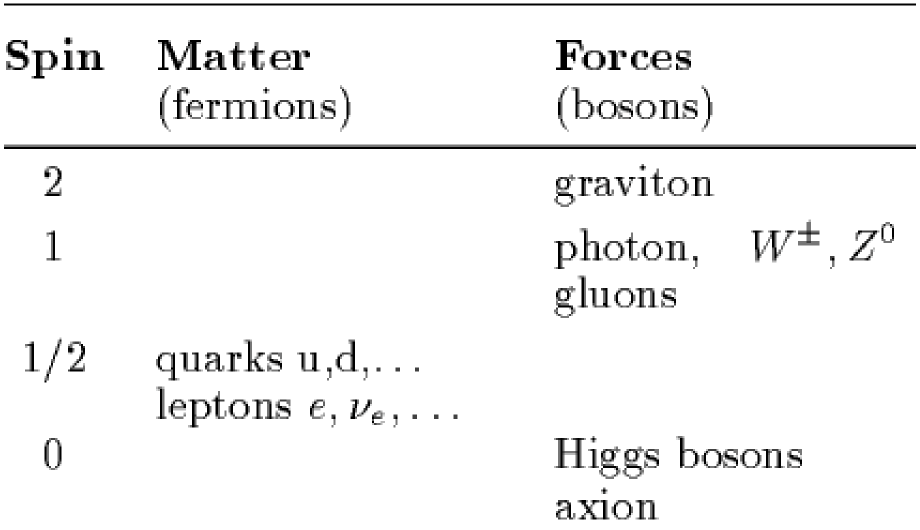
Fig. 1 The effective number of degrees of freedom of thermally interacting relativistic particles as a function of temperature.

Supersymmetry is the basis of most attempts, such as superstring theory, to go beyond the current “Standard Model” of particle physics. Heinz Pagels and Joel Primack pointed out in a 1982 paper that the lightest supersymmetric partner particle is stable because of R-parity, and is thus a good candidate for the dark matter particles – weakly interacting massive particles (**WIMP**s).

Michael Dine and others pointed out that the **axion**, a particle needed to save the strong interactions from violating CP symmetry, could also be the dark matter particle. Searches for both are underway.

Supersymmetric WIMPs

When the British physicist Paul Dirac first combined Special Relativity with quantum mechanics, he found that this predicted that for every ordinary particle like the electron, there must be another particle with the opposite electric charge – the anti-electron (positron). Similarly, corresponding to the proton there must be an anti-proton. Supersymmetry appears to be required to combine General Relativity (our modern theory of space, time, and gravity) with the other forces of nature (the electromagnetic, weak, and strong interactions). The consequence is another doubling of the number of particles, since supersymmetry predicts that for every particle that we now know, including the antiparticles, there must be another, thus far undiscovered particle with the same electric charge but with *spin* differing by half a unit.



Spin	**Matter** (fermions)	**Forces** (bosons)
2		graviton
1		photon, $W^\pm$, Z^0 gluons
1/2	quarks u,d,. . . leptons e, ν_e, . . .	
0		Higgs bosons axion

Supersymmetric WIMPs

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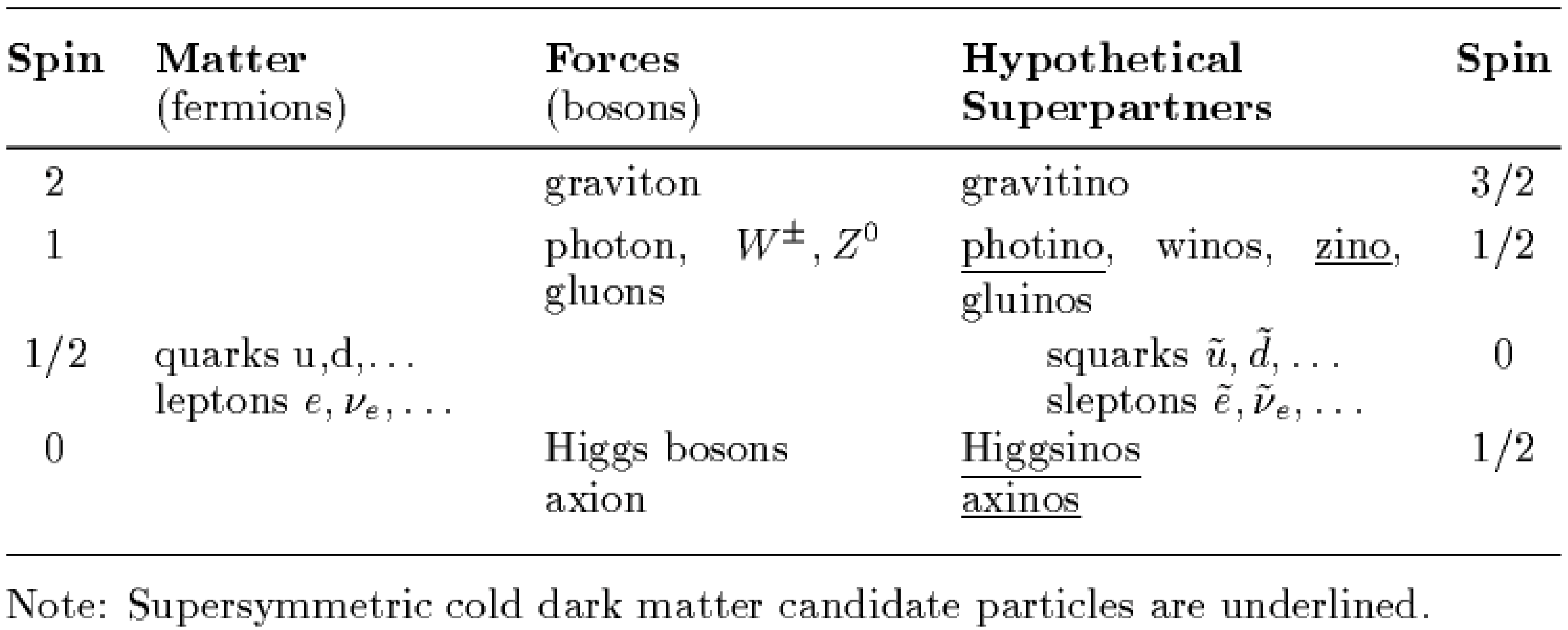
after doubling



Spin	**Matter** (fermions)	**Forces** (bosons)	**Hypothetical Superpartners**	**Spin**
2		graviton	gravitino	3/2
1		photon, $W^{\pm}$, Z^0 gluons	photino, winos, zino, gluinos	1/2
1/2	quarks u,d,... leptons e, ν_e, ...		squarks $\tilde{u}$, $\tilde{d}$, ... sleptons $\tilde{e}$, $\tilde{\nu}_e$, ...	0
0		Higgs bosons axion	Higgsinos axinos	1/2

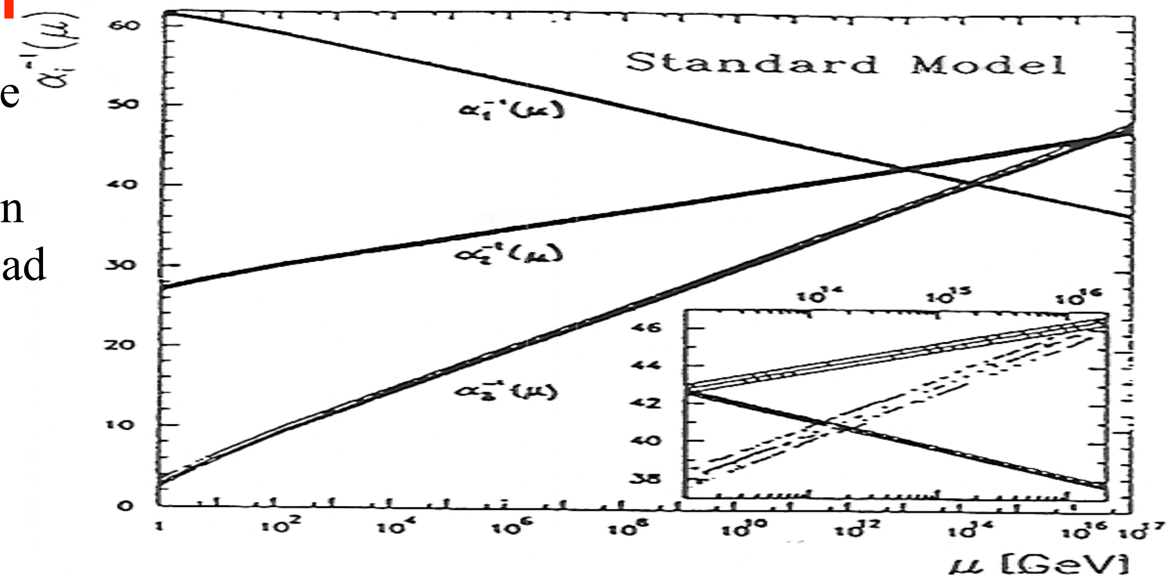
Note: Supersymmetric cold dark matter candidate particles are underlined.

Supersymmetric WIMPs, continued

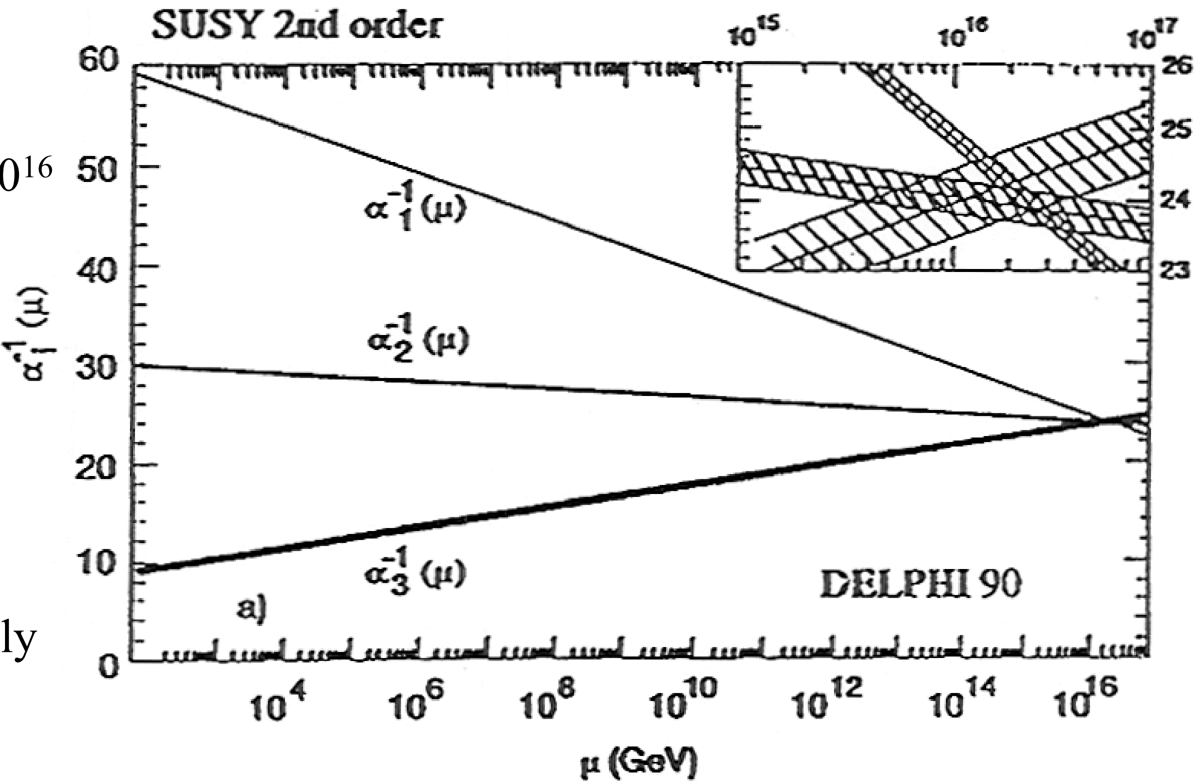
Spin is a fundamental property of elementary particles. Matter particles like electrons and quarks (protons and neutrons are each made up of three quarks) have spin _, while force particles like photons, W,Z, and gluons have spin 1. The supersymmetric partners of electrons and quarks are called selectrons and squarks, and they have spin 0. The supersymmetric partners of the force particles are called the photino, Winos, Zino, and gluinos, and they have spin _, so they might be matter particles. The lightest of these particles might be the photino. Whichever is lightest should be stable, so it is a natural candidate to be the dark matter WIMP. Supersymmetry does not predict its mass, but it must be more than 50 times as massive as the proton since it has not yet been produced at accelerators. But it will be soon, if it exists!

SUPERSYMMETRY

The only experimental evidence for supersymmetry is that running of coupling constants in the Standard Model does not lead to Grand Unification (of the weak, electromagnetic, and strong interactions)



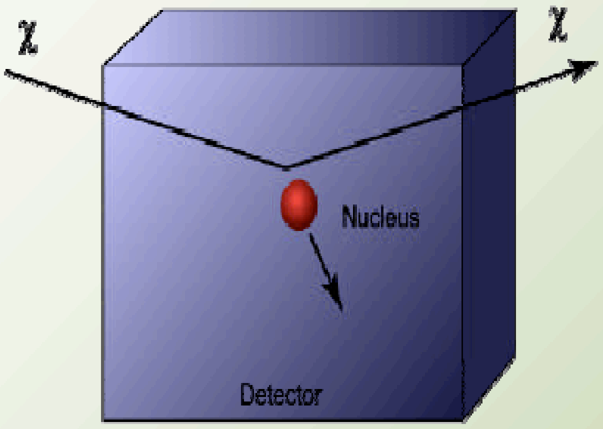
while with supersymmetry the three couplings all do come together at a scale just above 10^{16} GeV.



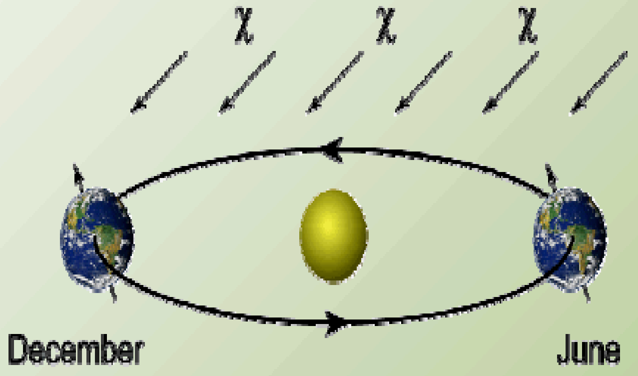
Other arguments for SUSY include: helps unification of gravity since it controls the vacuum energy and moderates loop divergences, solves the hierarchy problem, and naturally leads to DM with $\Omega \approx 1$.

Experiments are Underway for Detection of WIMPs

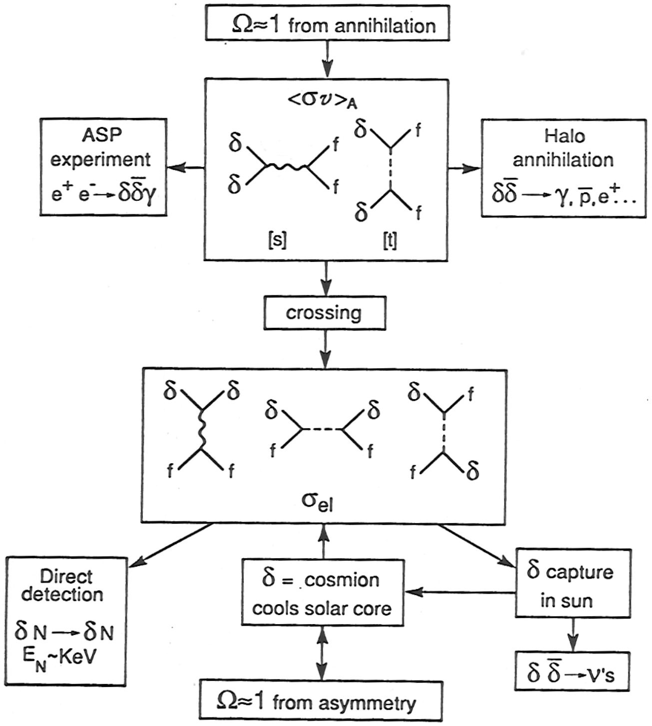
Direct detection - general principles

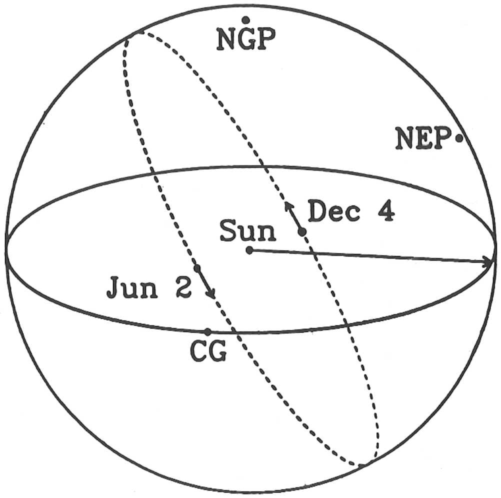


- WIMP + nucleus → WIMP + nucleus
- Measure the nuclear recoil energy
- Suppress backgrounds enough to be sensitive to a signal, or...



- Search for an annual modulation due to the Earth's motion around the Sun

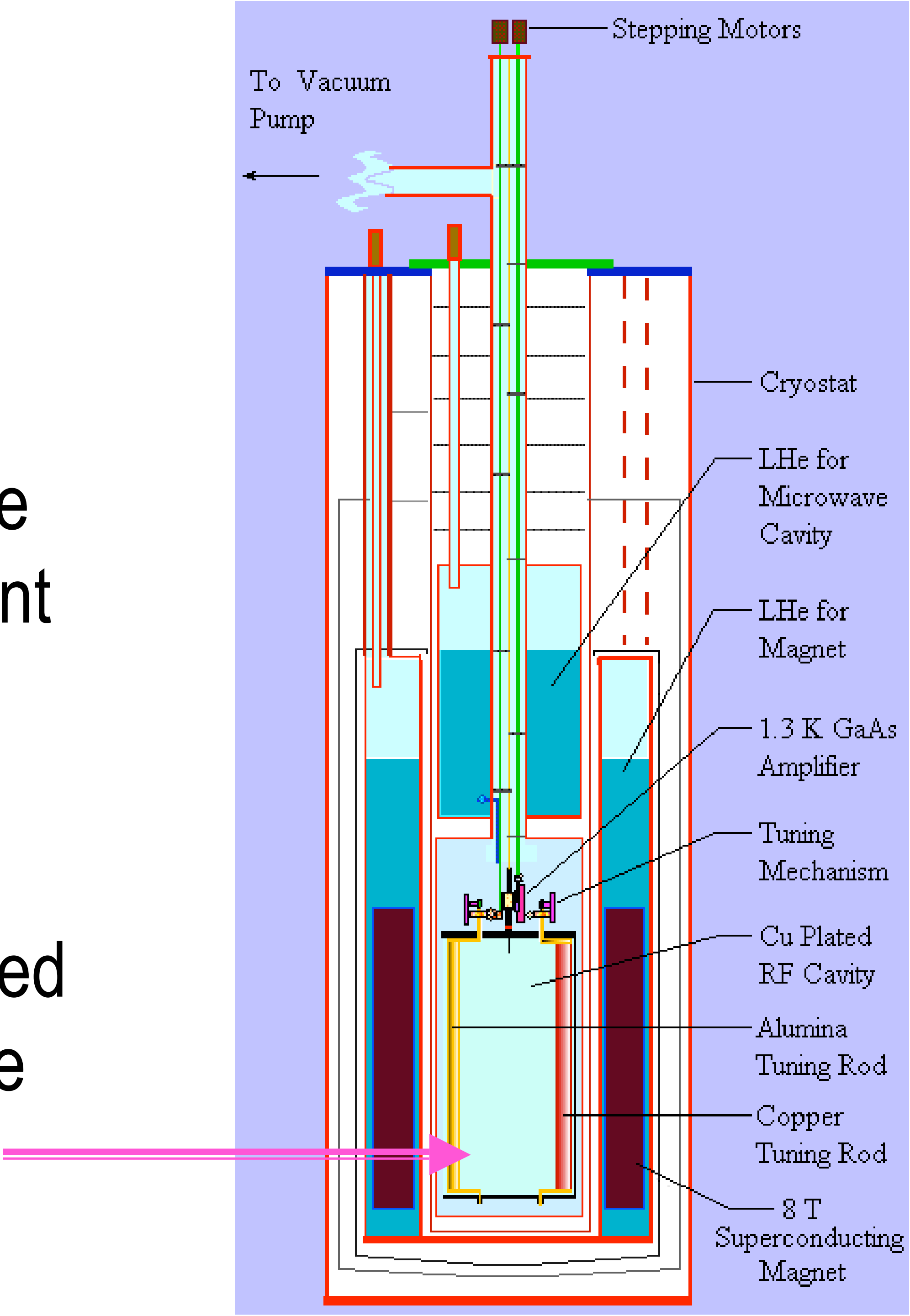




Primack, Seckel, & Sadoulet (1987)

and also AXIONs

The diagram at right shows the layout of the axion search experiment now underway at the Lawrence Livermore National Laboratory. Axions would be detected as extra photons in the Microwave Cavity.



Types of Dark Matter

Ω_i represents the fraction of the critical density $\rho_c = 10.54\ h^2$ keV/cm^3 needed to close the Universe, where h is the Hubble constant H_0 divided by 100 km/s/*Mpc*.

Dark Matter Type	Fraction of Critical Density	Comment
Baryonic	$\Omega_b \sim 0.04$	about 10 times the visible matter
Hot	$\Omega_\nu \sim 0.001\text{–}0.1$	light neutrinos
Cold	$\Omega_c \sim 0.3$	most of the dark matter in galaxy halos

Dark Matter and Associated Cosmological Models

Ω_m represents the fraction of the critical density in all types of matter.
Ω_Λ is the fraction contributed by some form of "dark energy."

Acronym	Cosmological Model	Flourished
HDM	hot dark matter with $\Omega_m = 1$	1978–1984
SCDM	standard cold dark matter with $\Omega_m = 1$	1982–1992
CHDM	cold + hot dark matter with $\Omega_c \sim 0.7$ and $\Omega_\nu = 0.2\text{–}0.3$	1994–1998
ΛCDM	cold dark matter $\Omega_c \sim 1/3$ and $\Omega_\Lambda \sim 2/3$	1996–today

Joel Primack, *Beam Line*, Fall 2001

Neutrinos

See the notes in the Neutrino Particle Listings for discussions of neutrino masses, flavor changes, and the status of experimental searches.

ν_e

$J = \frac{1}{2}$

The following results are obtained using neutrinos associated with e^+ or e^-. See the Note on "Electron, muon, and tau neutrinos" in the Particle Listings.

Mass $m < 3$ eV   Interpretation of tritium beta decay experiments is complicated by anomalies near the endpoint, and the limits are not without ambiguity.
Mean life/mass, $\tau/m_\nu > 7 \times 10^9$ s/eV [i]   (solar)
Mean life/mass, $\tau/m_\nu > 300$ s/eV, CL = 90% [i]   (reactor)
Magnetic moment $\mu < 1.5 \times 10^{-10}$ μ_B, CL = 90%

ν_μ

$J = \frac{1}{2}$

The following results are obtained using neutrinos associated with μ^+ or μ^-. See the Note on "Electron, muon, and tau neutrinos" in the Particle Listings.

Mass $m < 0.19$ MeV, CL = 90%
Mean life/mass, $\tau/m_\nu > 15.4$ s/eV, CL = 90%
Magnetic moment $\mu < 6.8 \times 10^{-10}$ μ_B, CL = 90%

ν_τ

$J = \frac{1}{2}$

The following results are obtained using neutrinos associated with τ^+ or τ^-. See the Note on "Electron, muon, and tau neutrinos in the Particle Listings.

Mass $m < 18.2$ MeV, CL = 95%
Magnetic moment $\mu < 3.9 \times 10^{-7}$ μ_B, CL = 90%
Electric dipole moment $d < 5.2 \times 10^{-17}$ $e\,$cm, CL = 95%

Number of Neutrino Types and Sum of Neutrino Masses

Number $N = 2.994 \pm 0.012$ (Standard Model fits to LEP data)
Number $N = 2.92 \pm 0.07$ (Direct measurement of invisible Z width)

Neutrino Mixing

There is now compelling evidence that neutrinos have nonzero mass from the observation of neutrino flavor change, both from the study of atmospheric neutrino fluxes by SuperKamiokande, and from the combined study of solar neutrino cross sections by SNO (charged and neutral currents) and SuperKamiokande (elastic scattering).

Solar Neutrinos

Detectors using gallium ($E_\nu \gtrsim 0.2$ MeV), chlorine ($E_\nu \gtrsim 0.8$ MeV), and Čerenkov effect in water ($E_\nu \gtrsim 5$ MeV) measure significantly lower neutrino rates than are predicted from solar models. From the determination of the ^{8}B solar neutrino flux via elastic scattering (SuperKamiokande and SNO), via the charged-current process (SNO) and via the neutral-current process (SNO), one can determine the flux of non-ν_e active neutrinos to be $\phi(\nu_{\mu\tau}) = (3.45^{+0.65}_{-0.62}) \times 10^6$ cm^{-2} s^{-1}, providing a 5.5 σ evidence for neutrino flavor change. A global analysis of the solar neutrino data favors large mixing angles and values for $\Delta(m^2)$ ranging from 10^{-3} to 10^{-5} eV^2. See the Notes "Neutrino Physics as Explored by Flavor Change" and "Solar Neutrinos" in the Listings.

Atmospheric Neutrinos

Underground detectors observing neutrinos produced by cosmic rays in the atmosphere have measured a ν_μ/ν_e ratio much less than expected and also a deficiency of upward going ν_μ compared to downward. This can be explained by oscillations leading to the disappearance of ν_μ with $\Delta m^2 \approx (2\text{–}4) \times 10^{-3}$ eV^2 and almost full mixing between ν_μ and ν_τ. See the Note "Neutrino Physics as Explored by Flavor Change" in the Listings.

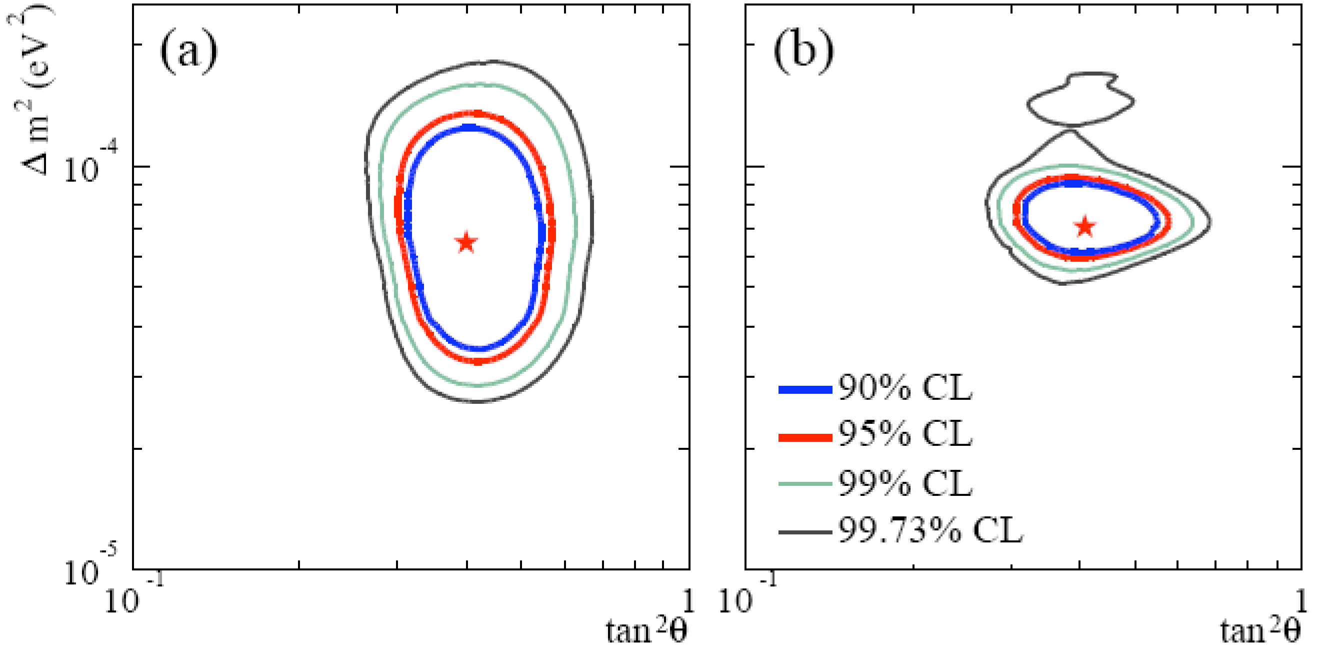
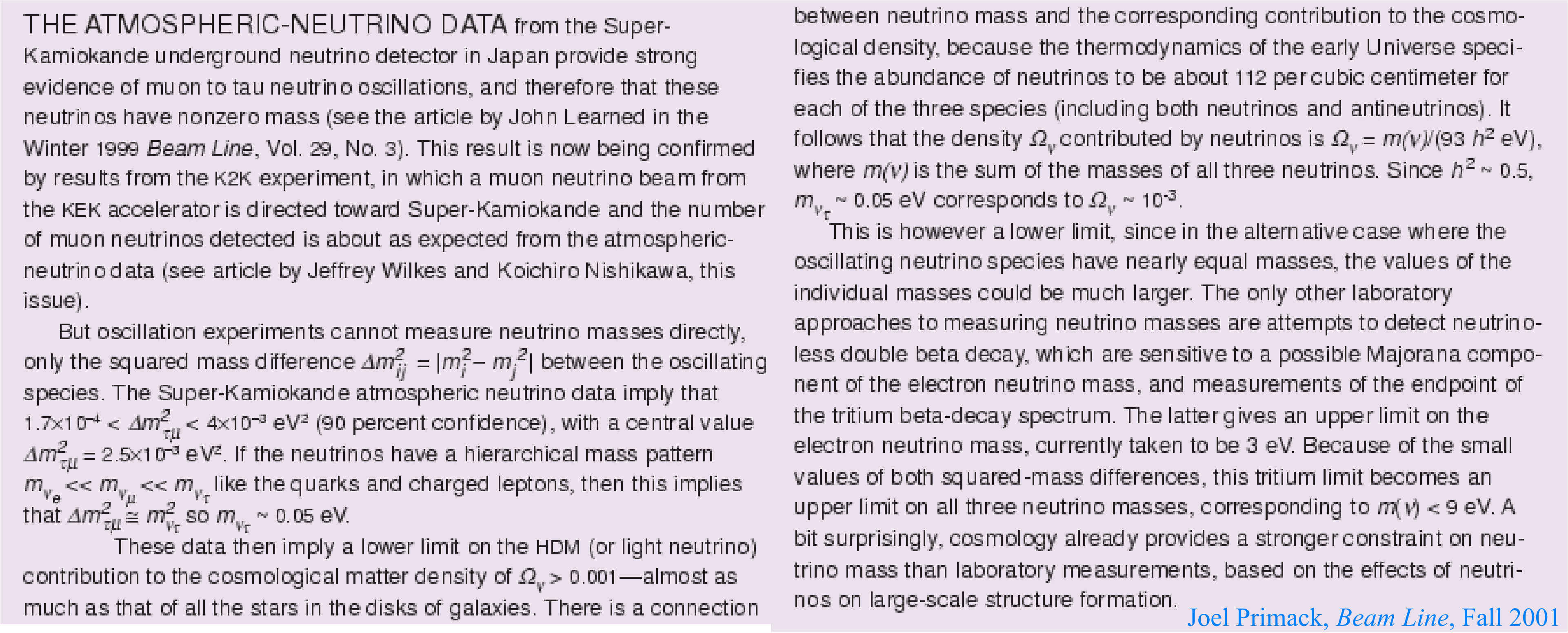


FIG. 5: Global neutrino oscillation contours. (a) Solar global: D_2O day and night spectra, salt CC, NC, ES fluxes, SK, Cl, Ga. The best-fit point is $\Delta m^2 = 6.5 \times 10^{-5}$, $\tan^2\theta = 0.40$, $f_B = 1.04$, with χ^2/d.o.f.=70.2/81. (b) Solar global + KamLAND. The best-fit point is $\Delta m^2 = 7.1 \times 10^{-5}$, $\tan^2\theta = 0.41$, $f_B = 1.02$. In both (a) and (b) the ^{8}B flux is free and the *hep* flux is fixed.

Ahmed et al. (Sudbury Neutrino Observatory) 2003, nucl-ex/0309004

$$\Delta m_{12}{}^2 = 7\text{x}10^{-5}\ \text{eV}^2 \Rightarrow m_2 \geq 8\text{x}10^{-3}\ \text{eV}$$



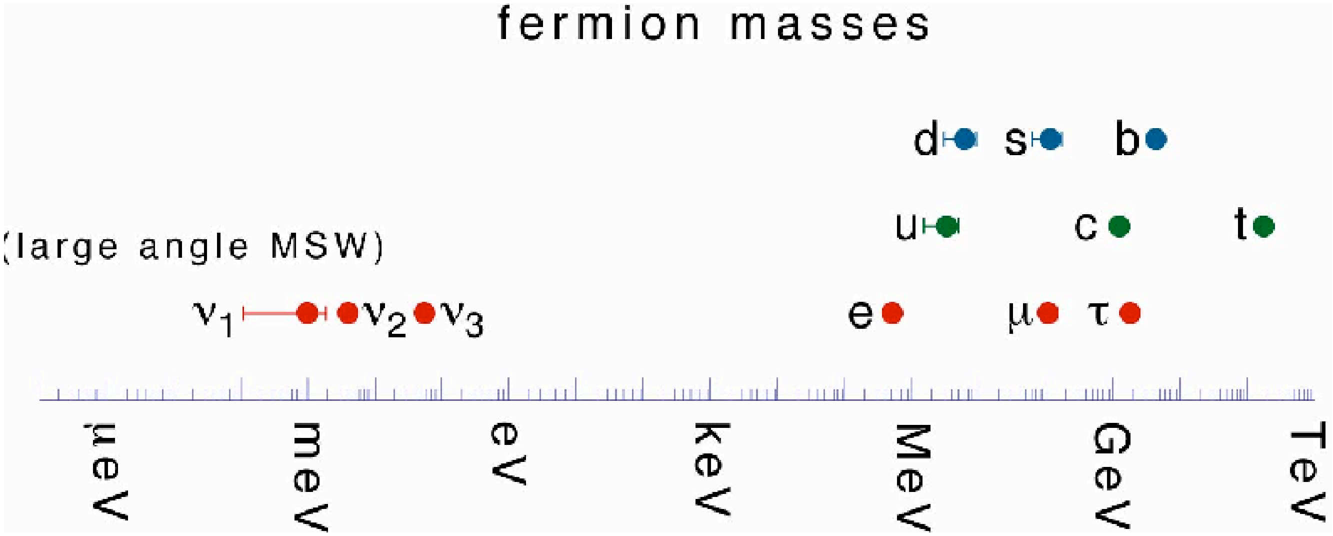
THE ATMOSPHERIC-NEUTRINO DATA from the Super-Kamiokande underground neutrino detector in Japan provide strong evidence of muon to tau neutrino oscillations, and therefore that these neutrinos have nonzero mass (see the article by John Learned in the Winter 1999 *Beam Line*, Vol. 29, No. 3). This result is now being confirmed by results from the K2K experiment, in which a muon neutrino beam from the KEK accelerator is directed toward Super-Kamiokande and the number of muon neutrinos detected is about as expected from the atmospheric-neutrino data (see article by Jeffrey Wilkes and Koichiro Nishikawa, this issue).

But oscillation experiments cannot measure neutrino masses directly, only the squared mass difference $\Delta m^2_{ij} = |m_i^2 - m_j^2|$ between the oscillating species. The Super-Kamiokande atmospheric neutrino data imply that $1.7\times10^{-4} < \Delta m^2_{\tau\mu} < 4\times10^{-3}$ eV² (90 percent confidence), with a central value $\Delta m^2_{\tau\mu} = 2.5\times10^{-3}$ eV². If the neutrinos have a hierarchical mass pattern $m_{\nu_e} << m_{\nu_\mu} << m_{\nu_\tau}$ like the quarks and charged leptons, then this implies that $\Delta m^2_{\tau\mu} \cong m^2_{\nu_\tau}$ so $m_{\nu_\tau} \sim 0.05$ eV.

These data then imply a lower limit on the HDM (or light neutrino) contribution to the cosmological matter density of $\Omega_\nu > 0.001$—almost as much as that of all the stars in the disks of galaxies. There is a connection between neutrino mass and the corresponding contribution to the cosmological density, because the thermodynamics of the early Universe specifies the abundance of neutrinos to be about 112 per cubic centimeter for each of the three species (including both neutrinos and antineutrinos). It follows that the density Ω_ν contributed by neutrinos is $\Omega_\nu = m(\nu)/(93\,h^2\text{ eV})$, where $m(\nu)$ is the sum of the masses of all three neutrinos. Since $h^2 \sim 0.5$, $m_{\nu_\tau} \sim 0.05$ eV corresponds to $\Omega_\nu \sim 10^{-3}$.

This is however a lower limit, since in the alternative case where the oscillating neutrino species have nearly equal masses, the values of the individual masses could be much larger. The only other laboratory approaches to measuring neutrino masses are attempts to detect neutrinoless double beta decay, which are sensitive to a possible Majorana component of the electron neutrino mass, and measurements of the endpoint of the tritium beta-decay spectrum. The latter gives an upper limit on the electron neutrino mass, currently taken to be 3 eV. Because of the small values of both squared-mass differences, this tritium limit becomes an upper limit on all three neutrino masses, corresponding to $m(\nu) < 9$ eV. A bit surprisingly, cosmology already provides a stronger constraint on neutrino mass than laboratory measurements, based on the effects of neutrinos on large-scale structure formation.

Joel Primack, *Beam Line*, Fall 2001

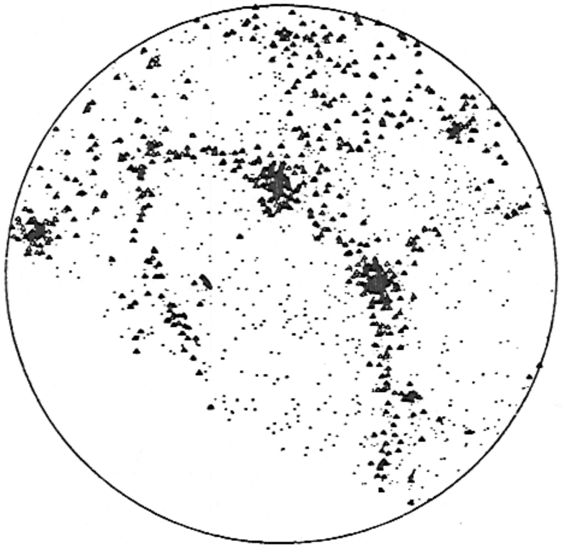


fermion masses

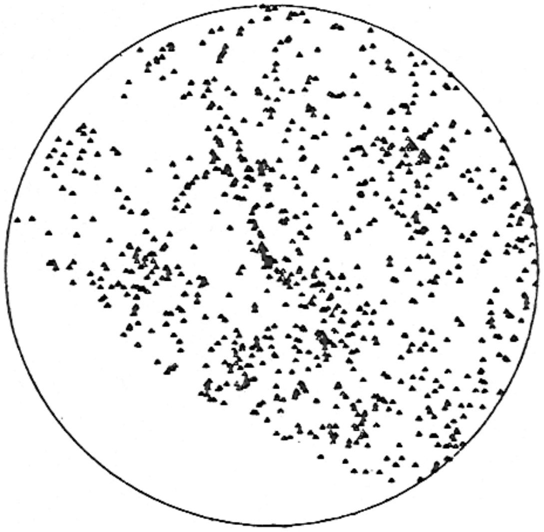
Hitoshi Murayama

Whatever Happened to Hot Dark Matter?

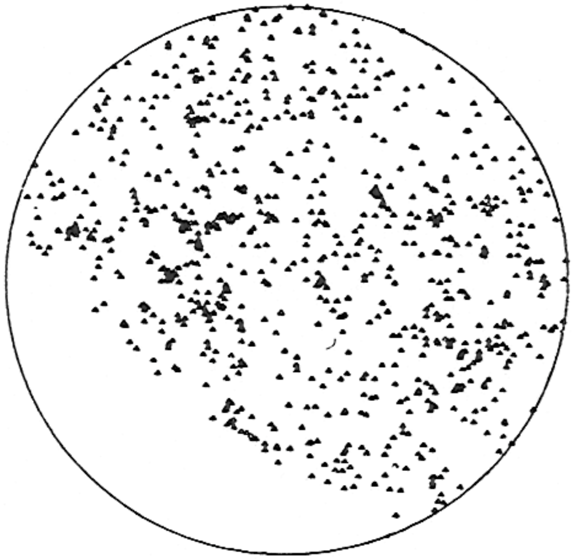
In ~1980, when purely baryonic adiabatic fluctuations were ruled out by the improving upper limits on CMB anisotropies, theorists led by Zel'dovich turned to what we now call the HDM scenario, with light neutrinos making up most of the dark matter. However, in this scheme the fluctuations on small scales are damped by relativistic motion ("free streaming") of the neutrinos until T becomes less than m_ν, which occurs when the mass entering the horizon is about 10^{15} solar masses, the supercluster mass scale. Thus superclusters would form first, and galaxies later by fragmentation. This predicted a galaxy distribution much more inhomogeneous than observed.



HDM



Observed Galaxy Distribution



CDM

Since 1984, the most successful structure formation scenarios have been those in which most of the matter is CDM. With the COBE CMB data in 1992, two CDM variants appeared to be viable: ΛCDM with $\Omega_m \approx 0.3$, and $\Omega_m = 1$Cold+Hot DM with $\Omega_\nu \approx 0.2$. A potential problem with CHDM was that, like all $\Omega_m = 1$ theories, it predicted rather late structure formation. A potential problem with ΛCDM was that the correlation function of the dark matter was higher around 1 Mpc than the power-law $\xi_{gg}(r) = (r/r_0)^{-1.8}$ observed for galaxies, so "scale-dependent anti-biasing" was required (Klypin, Primack, & Holtzman 1996, Jenkins et al. 1998). When better ΛCDM simulations could resolve halos that could host galaxies, they were found to have the same correlations as observed for galaxies.

By 1998, the evidence of early galaxy and cluster formation and the increasing evidence that $\Omega_m \approx 0.3$ had doomed CHDM. But now we also know from neutrino oscillations that neutrinos have mass. The upper limit from cosmology is $\Omega_\nu h^2 < 0.002$, corresponding to $m_\nu < 0.17$ eV (95% CL) for the most massive neutrino (Seljak et al. 2006).