INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

SMR.626 - 29

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

15 June - 31 July 1992

LECTURES ON COSMOLOGY

A. STEBBINS
Fermi National Accelerator Lab.
Batavia
USA

Please note: These are preliminary notes intended for internal distribution only.

SMR.626 - 27

ICTP Lectures on Cosmology

July 27-31 1992
Albert Stebbins

TOPICS:

1) Objects in the Universe
   a) Galaxies and redshifts (slides?)
   b) Clusters and Superclusters of Galaxies (slides?)
   c) Quasars and AGN's (slides?)
   d) Cosmic Microwave Background Radiation (MBR)

2) Evidence for FRW Cosmology:
   a) Isotropy of Quasars and Radio Sources (figure?)
   b) MBR Isotropy
   c) Cosmic Nucleosynthesis

3) Cosmic Nucleosynthesis and element abundance
   a) High and low entropy limits (figures?)
   b) Simple estimate of He abundance
   c) Detailed predictions and observations (figures)

4) Large Scale Structure
   a) Galaxy identification surveys (figures?)
   b) Galaxy redshift surveys (video)
   c) Galaxy cluster surveys
   d) Shot noise and excess variance
   e) Power Spectra in number and mass density (figure)
   f) Small-Scale Peculiar velocities (figure)
   g) Large-Scale Peculiar velocities (figure)

(continued)

TOPICS (cont'd):

5) Evidence for Dark Matter
   a) Spiral galaxy rotation curves (figure)
   b) Mass to Light Ratios
   c) Velocity dispersion of clusters of galaxies
   d) Large scale dynamical estimates
   e) Non-baryonic dark matter(?)
   f) Most baryons are dark!

6) Luminous Matter and the "Invisible" Universe
   a) Adiabatic Gaussian random noise initial conditions
   b) Dissipative versus non-dissipative flow
   c) The peaks model and biasing (figure)
   d) N-body and Hydrodynamic Simulations (video)
   e) Cooperative galaxy formation
   f) Can velocities save the day?
   g) Gravitational lensing and image distortions (slides)
   h) MBR anisotropies

7) Topological defects and cosmology
   a) Symmetry breaking and defects (figure)
   b) Local and Global symmetries
   c) Monopoles, Strings, Walls, Textures
   d) Causality and defect formation

8) Matter Inhomogeneities from Defects.
   a) Cosmic string wakes
   b) Synchronous gauge and the flow of matter
   c) Attraction and repulsion
   d) Inhomogeneity yields inhomogeneity

(continued)

TOPICS (cont'd):

9) MBR anisotropies from defects
   - a) Temperature discontinuity from a cosmic string
   - b) The geodesic equation and the Sachs-Wolfe integral
   - c) A cosmological wall (figure)
   - d) A cosmological string (slides)

10) Topological Defects versus Observations
   - a) The "spectrum" of the universe (figure)
   - b) The Anisotropy/Inhomogeneity ratio
   - c) Hot versus Cold (figure)
   - d) How much bias is too much

1a) Galaxies and Redshifts:

1) Galaxies are large collections of stars and hot and cold gas.

2) They are generally widely serperated from nearby galaxies compared to their size.

3) We live inside of large galaxy called the Milky Way.

4) With the naked eye what one sees in the sky are almost completely nearby stars in the Milky Way. One can see a nearby large galaxy called Andromeda or M31. If one lives far enough south one can see 2 very nearby dwarf galaxies called the Large and Small Magellenic Clouds.

5) Through a telescope essentially all one sees outside of our own galaxy is other galaxies. These are essentially our only tracer of the universe around us. 1 T

6) Galaxies come in a few distinct varieties
   - a) Spirals - 3S (M51, NGC 1365, NGC 5236)
   - b) Ellipticals - 2S (M87 twice)
   - c) Irregulars - 4S (LMC, SMC, NGC 3109, Sculptor

7) We can determine how far away a galaxy is and hence how big and bright it is using the Hubble Law and taking redshifts,
   - a) measuring the spectra, identifying spectral lines of the atoms which are emitted from the stellar atmospheres of billions of the stars in the galaxy, and see how much the frequency is shifted.
   - b) The velocity can be written

$$v_{\rm recession} = H_o\, r + v_{\rm pec}$$

1a) Galaxies and Redshifts (cont'd):

where v_{pec} is the peculiar velocity. Typically v_{pec} is bounded to a few 1000 km/sec while the "Hubble velocity" grows with distance. Hence for distant enough galaxies we may ignore v_{pec}.

8) What is found is that the distribution of luminosities of galaxies is given by the Schechter Function

$$dn/(d\ln L\, dV) = \phi^* \,(L/L^*)^{(1-\alpha)} \exp(-L/L^*)$$

$$\phi^* = 1/(4.3\ \mathrm{Mpc}/h)^3 \quad \alpha = 1.1$$

$$L^* = 3.10^{10}\ L_\odot \quad L_\odot = \text{Solar Luminosity}$$

which means:

a) as one looks at fainter and fainter galaxies one sees an "unlimited" number of galaxies but the number only increases slowly.

b) most of the luminosity is in galaxies with luminosity L^*

c) there are very few galaxies with luminosity much greater than L^* but many with luminosity much less

d) the density of bright galaxy gives an "average" (no gal. may have n.n < ave) distance of 4Mpc between nearby bright galaxy, however since galaxies cluster, the distance between bright neighbors is often much less than this.

9) The typical size of the bright part of a bright galaxy is 10 kpc, 100's of times smaller than the distance to the nearest bright galaxy.

1b) Clusters and Superclusters of galaxies

1) Clusters of galaxies are very dense collections of galaxies containing perhaps 100's of bright galaxies within a few Mpc.

2) Small "clusters" are known as groups. 25 (Hercules Coma)

3) Galaxy clusters often contain large amounts of hot gas which can be detected by its X-ray emission. The amount of hot gas, $\sim 10^{14}\ M_\odot$, is comparable the mass in stars.

4) Groups and clusters are "virialized" objects, in that their members have orbited around each other many times.

5) Superclusters of galaxies are much less dense and much bigger collections of galaxies and galaxy clusters, ususally >10Mpc in size. They are not virialized (yet).

L15

(CfA Slice

1c) Quasars, AGN's, and Radio Sources

1) In addition to nearby galaxies one finds numerous objects of another kind of objects.
   a) QSO's (with radio = quasars) are unresolved objects with a spectra unlike stars (=galaxies). There redshift is typically 1 or higher.
   b) Extragalactic radio sources: some nearby galaxies show extensive radio emission. However most radio sources appear to be at redshift close to 1.

2) Taking the redshifts to indicate the cosmological distance one can estimate the comoving number density of QSO's and extragalactic radio sources. It appears that there were many more of the objects in the past than there are today.

3) It is believed that both high-redshift radio sources and quasars are galaxies in the past which are exhibiting extraordinary activity which for some reason is not very common among galaxies in the present epoch. This activity is believed to be associated with a large black hole in the center of the galaxy.

4) Many low redshift galaxies exhibit a similar type of activity in their central regions, but at a much lower level. These galaxies have Active Galactic Nulei (or AGN's).

25 (NGC 5128, M87)

1d) Cosmic Microwave Background Radiation

1) In addition to localized sources of radiation one finds "diffuse backgrounds" of radiation at all frequencies where one looks, from radio waves to γ-rays.

2) In many bands Galactic emission obscures the "extraGalactic backgrounds". Two backgrounds which are not strongly obscured are the
   a) "the X-ray background" (0.5-100 keV)
   b) "the Microwave Background" (0.1-100 cm) a.k.a. MBR, CMB, CMBR

   The source of the X-ray background is not understood.

3) The MBR is a perfect blackbody (as far as we can tell) with a temperature of 2.735 K. It is believed to be a remnant of the thermal radiation from the universe at early times.

2) Evidence for FRW Cosmology:

1) The FRW model of the universe requires that the universe be homogeneous and isotropic. We do not require this to be true exactly, only that it is true on average, over cosmologically large scales (1000's Mpc).

2) There are at least two ways to observationally test this:
   a) Measure the distribution of objects around as an determine whether they are distributed homogeneously and isotropically in a statistical sense. This requires measuring distances.
   b) If we use the Cosmological Principle to assert that we are not in a special place in the universe. Then if we find that the universe around is isotropic, then we can assert that other observers in the universe would also find an isotropic distribution. This implies that the universe is homogeneous.

3) Until recently redshift surveys of nearby galaxies found larger and larger inhomogeneities, giving no indication of a homogeneous distribution of galaxies.

2a) Isotropy of QSO's and radio sources

1) The distribution of Quasar's and other high redshift radio sources on the sky is extraordinarily uniform.

2) Since we are seeing the distribution in projection the small inhomogeneities we see in nearby galaxies is washed out. However careful analysis can detect deviations from a Poisson distribution and only on very small angular scales corresponding to 10 Mpc (Shafer and Iovino).

3) The lack of structure on larger scales combined with the fact that these objects are probably galaxies, indicates that the distribution of galaxies must get more uniform as one goes to larger and larger scales.

2b) MBR Isotropy

1S -(COBE DMR)

1) The MBR is also extraordinarily isotropic. It's intensity is uniform to 2 parts in 1000. At that level there is a deviation in the form of a dipole pattern which can be interpreted as our motion (peculiar velocity) with respect to the cosmic rest frame. After subtracting the dipole there is no deviation from isotropy to 1 part in 10^5. This combined with 2a) indicate that the universe is very homogeneous on the scale of 1000's of Mpc.

2c) Cosmic Nucleosynthesis

3) Cosmic Nucleosynthesis and elemental abundances:

1) One fundamental aspect of our universe is the abundance of the various chemical elements, e.g. He, C, Fe, etc. Some of these are probably produced in stars but is was realized that the abundance of He^4 was much higher than expected in stars. Many of the lighter elements were produced predominantly in the early universe. The processes which produced the light elements occured at a very early time in the universe (t<3 min.) so testing light element abundance gives us an important clue that our picture of the universe is correct.

3a) High and Low Entropy Limits

1) If the physical processes in the early universe are efficien enough then the universe should remain in equilibrium. For a weakly interacting gas of particles the number density is

$$n_a = \frac{g}{2\pi^2\hbar^3}\int_{m_a}^{\infty}\frac{E\sqrt{E^2-m_a^2}\,dE}{\exp[(E-\mu_a)/T]\pm 1}$$

where μ_a is the chemical potential. For a non-relativistic gas this becomes the Saha Equation

$$n_a = g_a\left(\frac{m_a T}{2\pi\hbar^3}\right)^{3/2}\exp[(\mu_a - m_a)/T]$$

If $(m_a-\mu_a)-(m_b-\mu_b)>>T$ then species a is much less abundant than species b.

3a) High and Low Entropy Limits

2) For each efficient reaction $a+b$ <--> $c+d$ the chemical potential potentials will obey $\mu_a+\mu_b=\mu_c+\mu_d$. Thus the number of independent μ's is just the number of conserved quantities.

3) Considering weak and strong interactions the only conserved quantities for atoms are the baryon number and the charge. The relative abundances of atoms with atomic number A and atomic number Z is

$$n_A = g_A\left(\frac{m_A T}{2\pi\hbar^3}\right)^{3/2}\exp[(A(\mu_b - m_p) + Z\mu_q)/T]\,\exp[AB_A/T]$$

in equilibrium for T << 1GeV, where $B_A=m_p-m_A/A$ is the binding energy per nucleon of the atom. Here μ_b and μ_q are determined implicitly by the requirement that they give zero net charge, and the correct baryon density.

4) Given that the typical difference in B_A between different nuclei is a few 100 keV, one would find in equilibrium at T<<100keV that all of the the baryon number of the universe would reside in the atom with the largest B_A, which is ^{56}Fe. There is plenty of non-iron elements around us so the universe is not in equilibrium. Nucleosynthesis in stars are bringing us somewhat closer to equilibrium, but slowly.

1T

3a) High and Low Entropy Limits

5) The universe may go out of equilibrium because of the decreasing density of particles can make it decreasingly likely that certain multi-body interactions will take place.

6) For example, for the neutron to proton ratio remain in equilibriur the reaction p+e <--> n+ν is important. The rate at which the inverse reaction happens is $\Gamma \sim n_\nu \sigma v \sim (T^3)(G_F{}^2 T^2)(1) \sim G_F{}^2 T^5$., comparing with the expansion rate T^2/M_{Pl} we find equilibrium (i.e. many neutrons will be converted to protons in this way) for $T > T_F \sim 1/(G_F{}^2 M_{Pl})^{1/3} \sim 1$ **MeV.** After this epoch, weak interactions are out-of-equilibrium except for 1-body processes such as weak spontaneous decays (e.g. neutron decay). The n/p ration at "freeze-out" $\sim \exp[-(m_n - m_p)/T_F] \sim 1/6$.

7) After weak interactions are out-of-equilibrium and ignoring weak decays, the neutron and proton number are fixed, leading to two new conserved quantities and henced two new chemical potentials μ_n and μ_p. Equilibrium with fixed n/p is known as **Nuclear Statistical Equilibrium** or **NSE.**

8) If the baryon/photon ratio were high enough then the remnant protons and neutrons would then proceed to make heavier elements in NSE like Fe. Stars would have nothing to burn!

9) If the baryon/photon ratio were too low then no 2-body nuclear reactions would proceed and all the neutrons would decay to protons. In this hydrogen universe stars would form and stellar nucleosynthesis could take place.

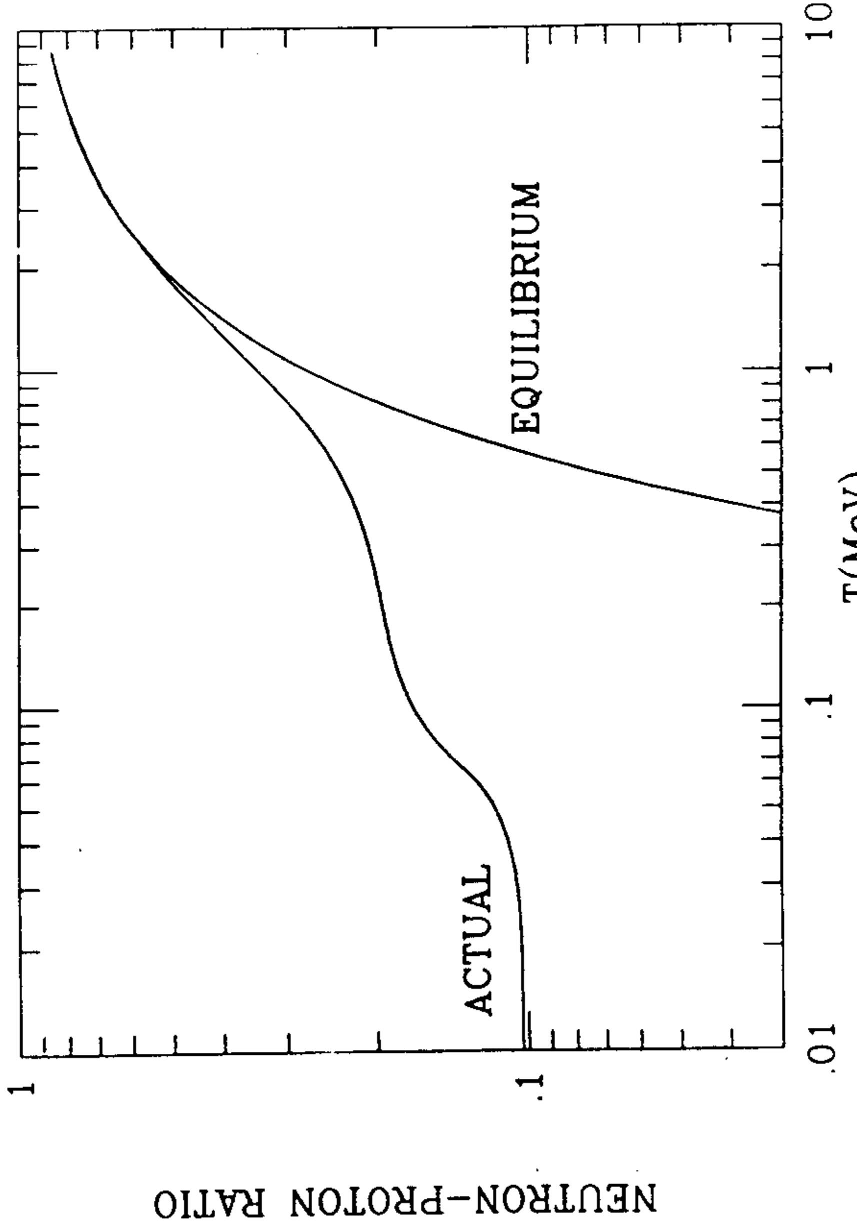


Fig. 4.1: The equilibrium and actual values of the neutron to proton ratio.

3b) Simple Estimate of Helium Abundance.

1) In NSE the dominant species should become ^{4}He as the temperature falls below 0.3MeV. However the only 2-body mechanism to form ^{4}He involves ^{2}H whose equilibrium abundance is very small. If $\Omega_b \sim 1$ then these reactions are out-of-equilibrium so the ^{4}He abundance is remains low for some time. This bottleneck delays the production of ^{4}He to T~0.08 MeV at which time almost all of the neutrons go into ^{4}He.

2) At low temperatures, nuclear reaction rates are suppressed by the Coulumb Barrier of the positively charged nuclei. Thus suppresses the cross-section by $\sim \exp[-2A^{1/2}(Z_1Z_2)^{2/3}/T^{1/3}]$. At the low temperatures when the ^{4}He is produced the cross-section becomes so small that other nuclear reaction rates to make heavier elements are out-of-equilibrium and essentially all the neutrons remain in ^{4}He. Note that the baryon density would have to be much higher for the increased density to make up for the Coulumb suppression for very heavy elements.

3) Thus to a good approximation all of the neutrons at freeze-out go into ^{4}He. If follows that $Y \sim 4n_{^4He}/n_b \sim 2(n/p)/(1+n/p) \sim 0.28$ for $n/p \sim 1/6$. Including neutron decay after freeze-out decreases this somewhat. The metallicity $Z \sim \Sigma_{Z>2} A n_A / n_b \ll 1$. Thus the heavier elements were essentially all produced in stars.

1T (go back 2)

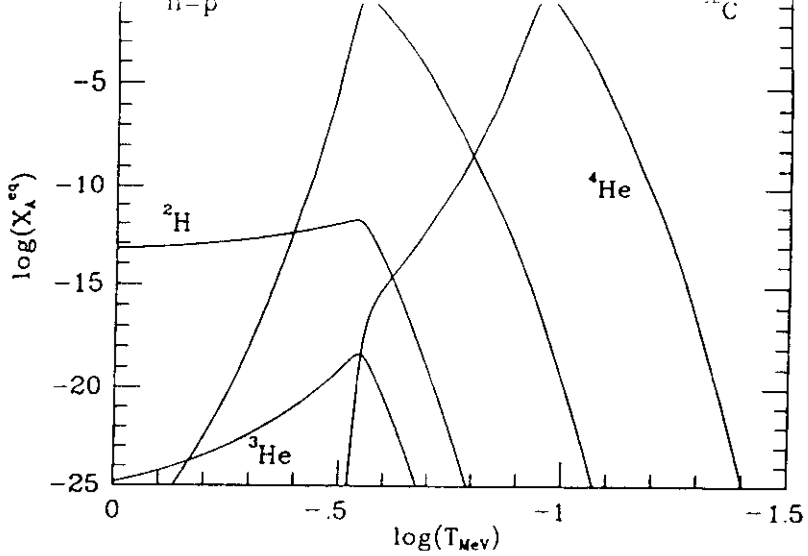


Fig. 4.2: The NSE mass fractions for the system of n, p, D, ^{3}He, ^{4}He, and ^{12}C as a function of temperature. For simplicity we have taken $X_n = X_p$.

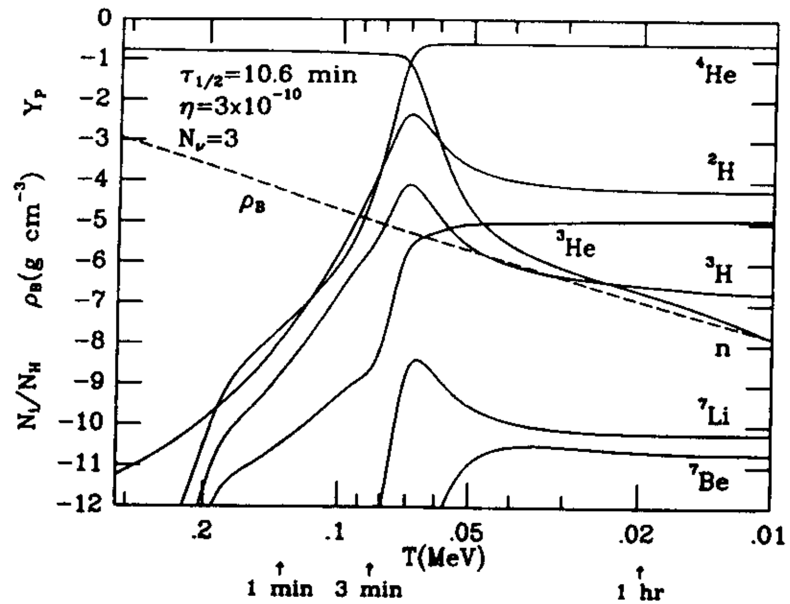


Fig. 4.3: The development of primordial nucleosynthesis. The dashed line is the baryon density, and the solid lines are the mass fraction of ^{4}He, and the number abundance (relative to H) for the other light elements.

3c) Detailed Predictions and Observations

1) Using nuclear cross-sections and the rate equation one may numerically evolve the abundance of each species. Significant uncertainties from the number of light neutrino species and the neutron lifetime have been decreases recently.

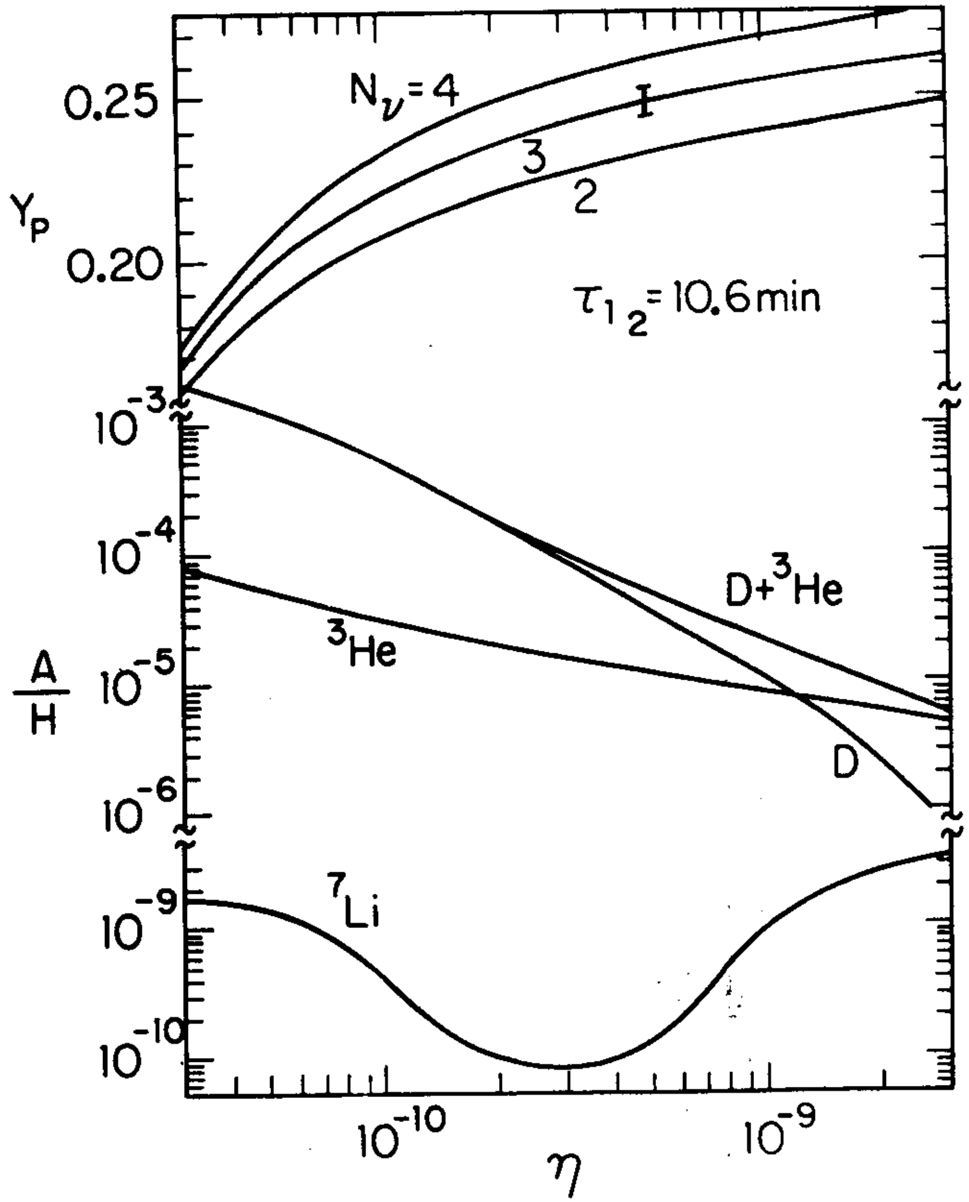
2) If we could measure the "primordial" abundances of the elements we could determine the photon to baryon ratio, and hence the baryon density, quite accurately. However comparison to observed abundances is complicated by the "contamination" from stellar nucleosynthesis as well as cosmic ray "spallation" and stellar "astration" (i.e. reduction of elemental abundances by stellar burning.)

3) ^{4}He should not be significantly astrated or spallated so the smallest observed ^{4}He abundance is presumably a good upper limit on the primordial amount, and hence places an upper limit on the baryon density. $Y<0.24$ has been observed in a few low-Z hot gas clouds.

4) More complicated arguments involving ^{2}H, ^{3}He, ^{7}Li lead to to more stringent bounds on the baryon density.

5) Olive, Schramm, Steigman, and Walker give the limits on the baryon density to be **$0.0095<\Omega_b h^2<0.016$.** Unless H_0 is very small baryons cannot close the universe. Unless Ω_0, is very small baryons are probably a small fraction of the matter in the universe.

2T



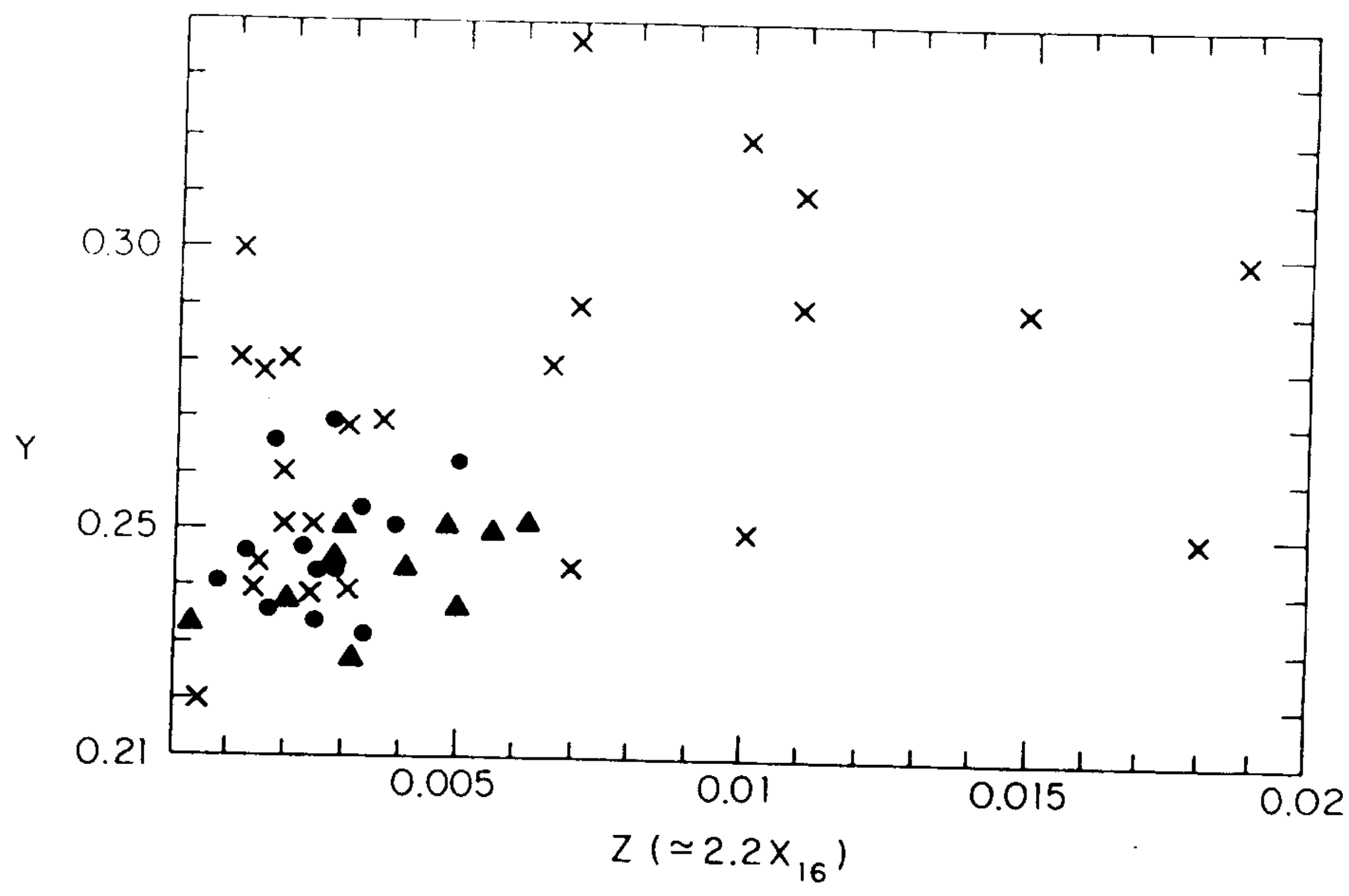


Fig. 4.5: Summary of ^{4}He determinations for galactic and extragalactic HII regions. The filled circles and triangles are two carefully studied sets of metal-poor extragalactic HII regions.