Primordial Helium

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Tensions between the Early and the Late Universe

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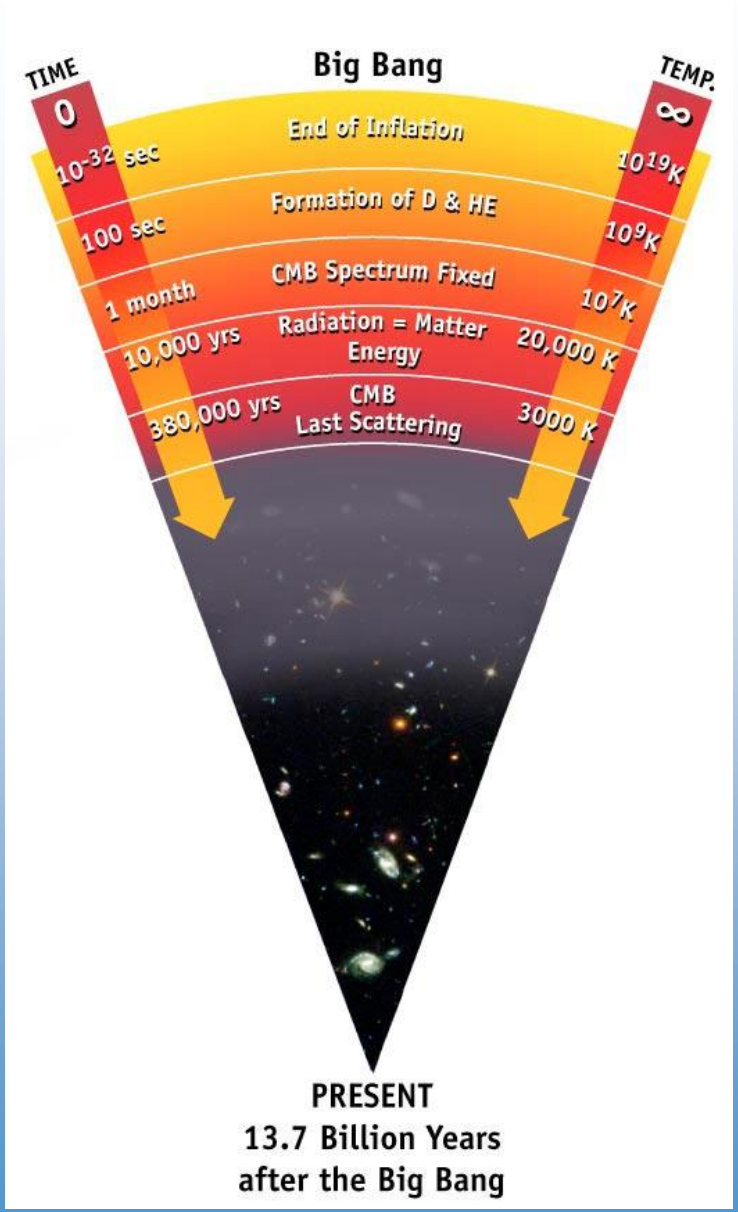
Outline

- BBN
- ^{4}He
- BCD's
- Model
- Y_p
- N_ν



The Early Universe, ~1s

- Initially Equilibrium:

$$n + e^{+} \leftrightarrow p + \overline{\nu_e}$$
$$n + \nu_e \leftrightarrow p + e^{-}$$
$$n \leftrightarrow p + e^{-} + \overline{\nu_e}$$

- Freeze-out: Weak Interaction rate vs. Expansion rate

$$\Gamma \sim T^5 / M_W^4 \qquad H \sim T^2 / M_p$$

$$\Rightarrow T_f \approx 0.8\,\mathrm{MeV}$$

- $$\frac{n_n}{n_p} \approx e^{\frac{-\Delta m}{T}} \approx \frac{1}{6}$$

Big Bang Nucleosynthesis Delayed

- Deuterium Bottleneck:

$$p + n \rightarrow D + \gamma \qquad \Gamma_p \sim n_B \sigma$$

$$p + n \leftarrow D + \gamma \qquad \Gamma_d \sim n_\gamma \sigma e^{-E_B/T}$$

$$\Gamma_p \sim \Gamma_d \;\Rightarrow\; \frac{n_B}{n_\gamma} \sim e^{-E_B/T}$$

$$\Rightarrow \; \mathrm{T} \approx 0.1\ \mathrm{MeV}$$

$$\eta = \frac{n_B}{n_\gamma} \sim 10^{-10}$$

- Neutron Decay:

$$\frac{n_n}{n_p} \longrightarrow \frac{1}{7}$$

- Nucleosynthesis finally Begins:

$$D + D \rightarrow p + T \qquad D + D \rightarrow n + {}^3He$$

$$D + D \rightarrow \gamma + {}^4He \qquad {}^3He + {}^3He \rightarrow 2p + {}^4He$$

$$D + T \rightarrow n + {}^4He \qquad {}^3He + D \rightarrow p + {}^4He$$

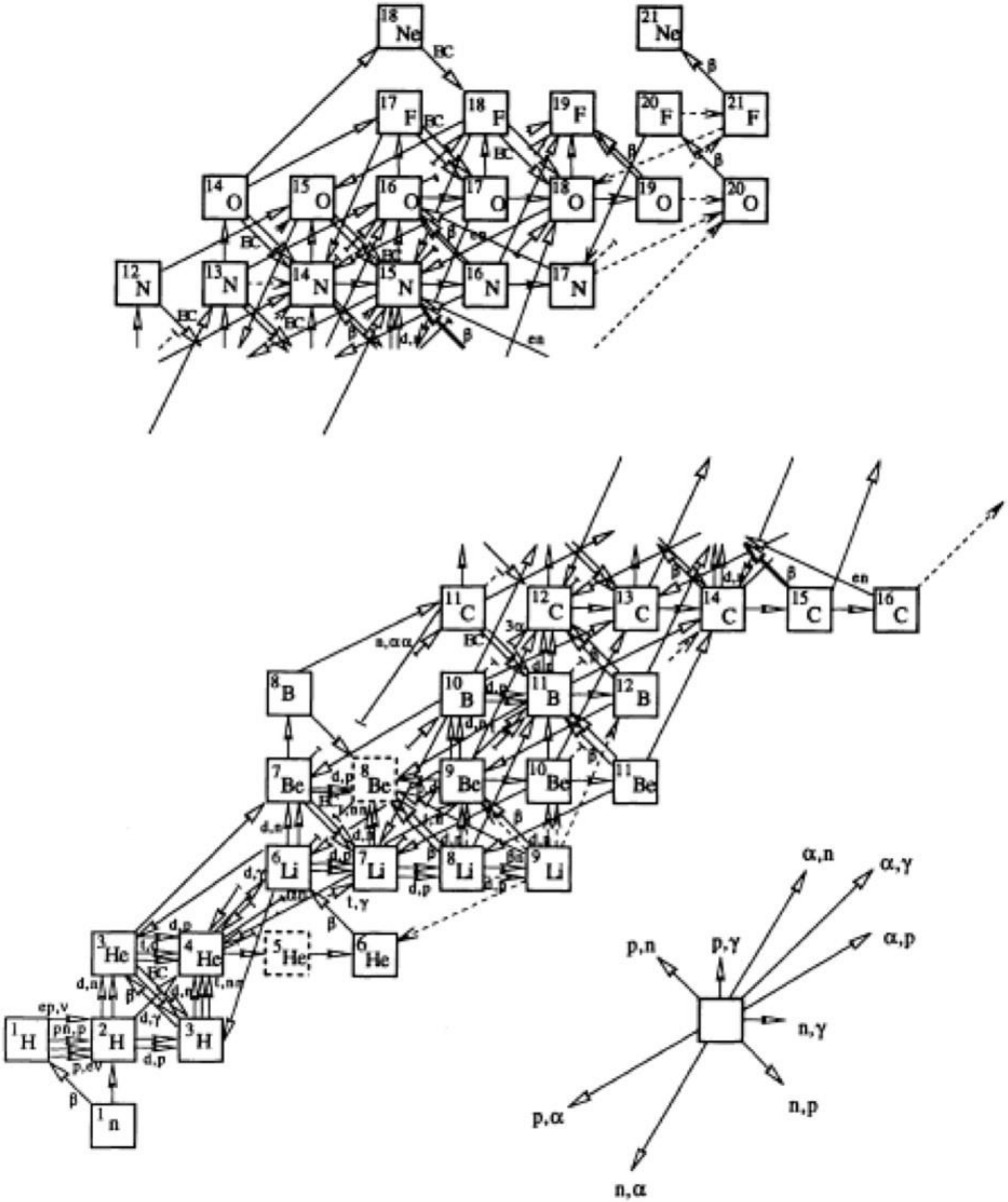


FIG. 1.—Reaction network used in the code. Estimated reactions are shown with dashed lines.

^{4}He

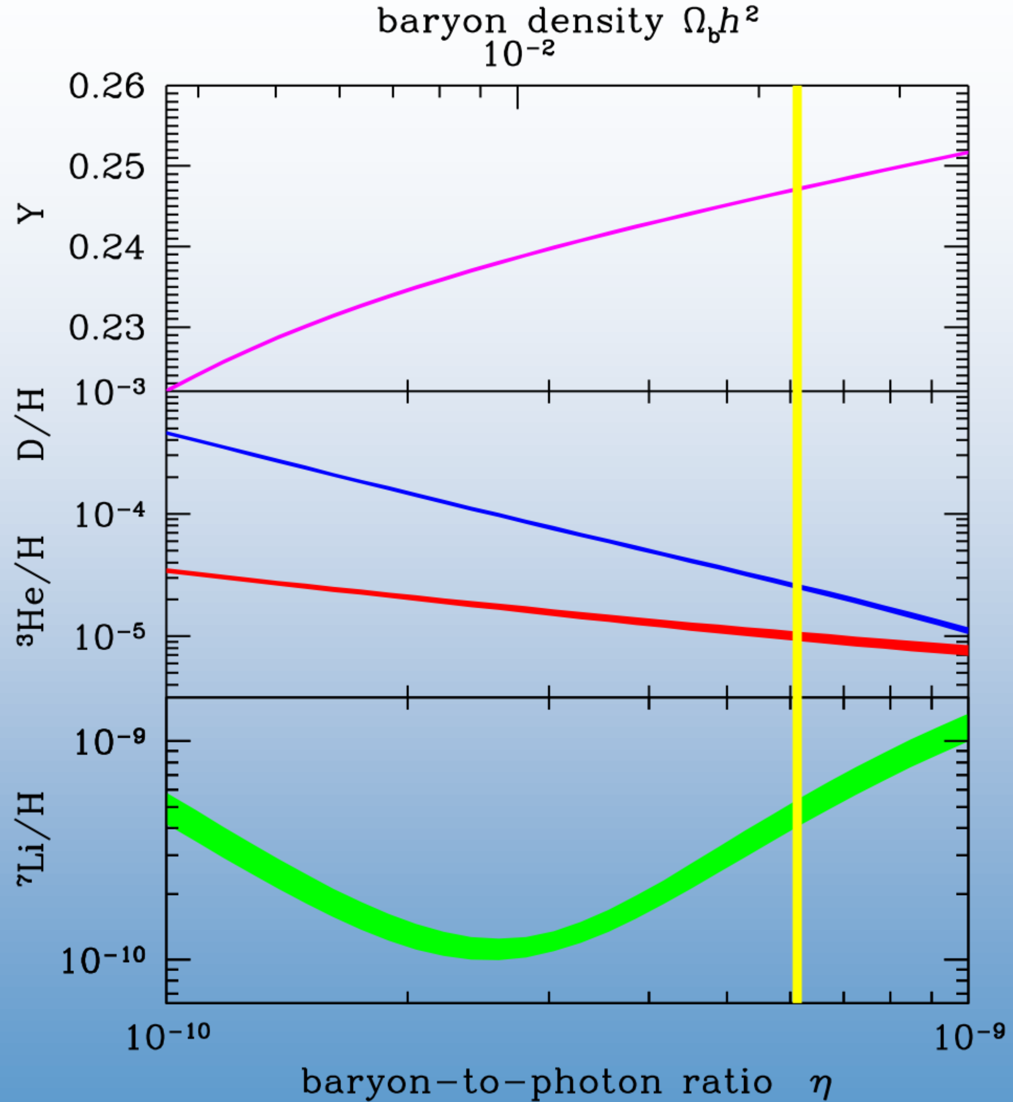
- Absence of stable A=5
- 99% efficient n $\rightarrow$ ^{4}He

$$Y_p = \frac{4n_{He}}{n_H + 4n_{He}} = \frac{4\left(\frac{1}{2}n_n\right)}{\left(n_p - n_n\right) + 4\left(\frac{1}{2}n_n\right)} = \frac{2n_n}{n_p + n_n} = \frac{2\frac{n_n}{n_p}}{1 + \frac{n_n}{n_p}} = \frac{\frac{2}{7}}{\frac{8}{7}} = 0.25$$

- D, ^{3}He, ^{4}He, ^{7}Li
- Depend on η
- Sensitive to N_ν

CMB + BBN

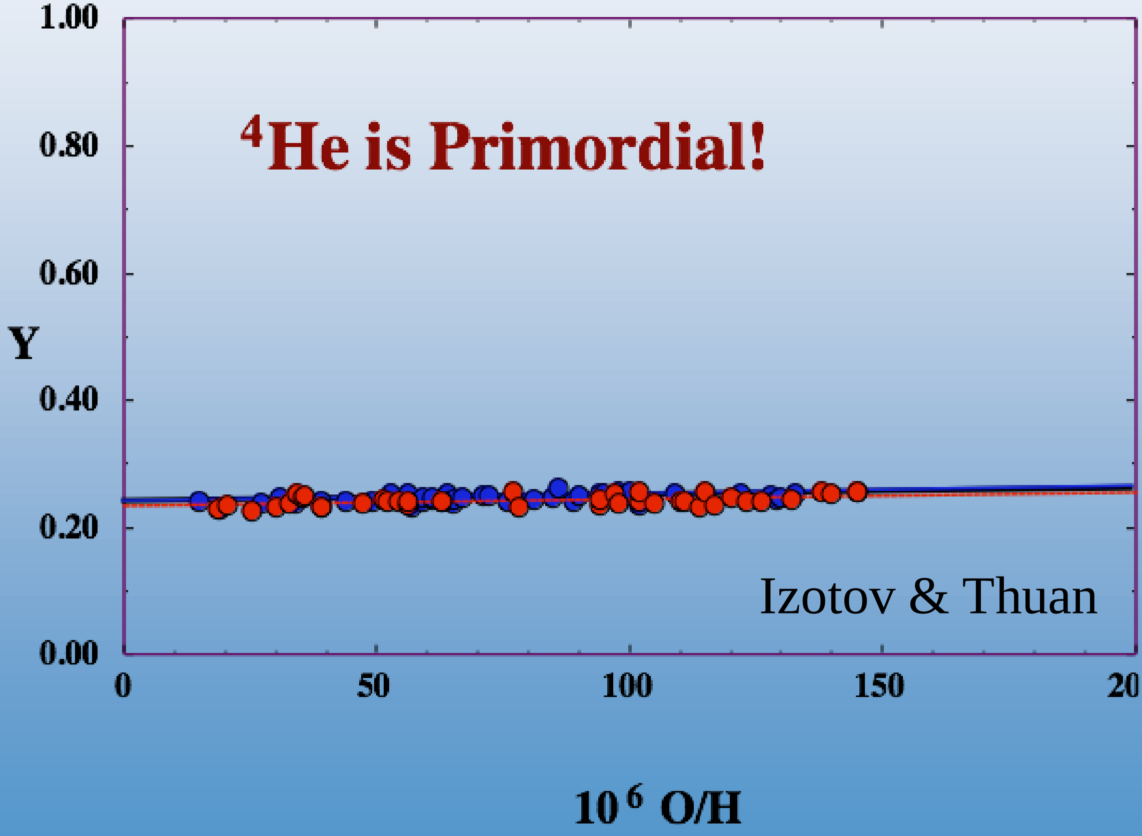
- CMB Power Spectrum highly sensitive to Ω_B
- CMB+BBN
  => very high precision primordial abundances
- $\Omega_B h^2 = 0.02237 \pm 0.00015$
- $\eta = (6.12 \pm 0.04) \times 10^{-10}$
- $Y_p = 0.2447 \pm 0.0002$

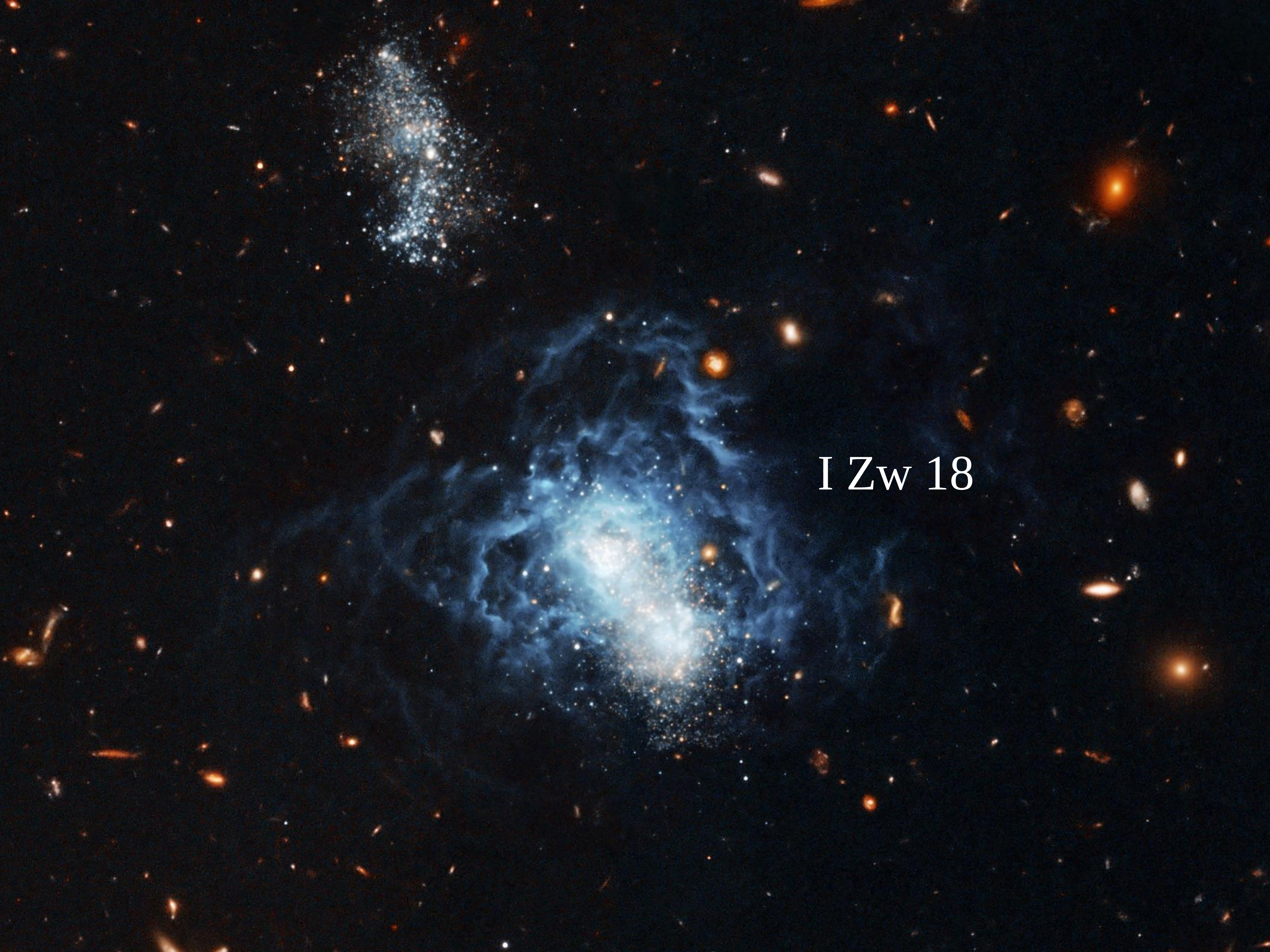


Cyburt, Fields, Olive, Yeh (2015)

^{4}He

- Low Metallicity Extragalactic HII Regions

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It's Simple, Right?

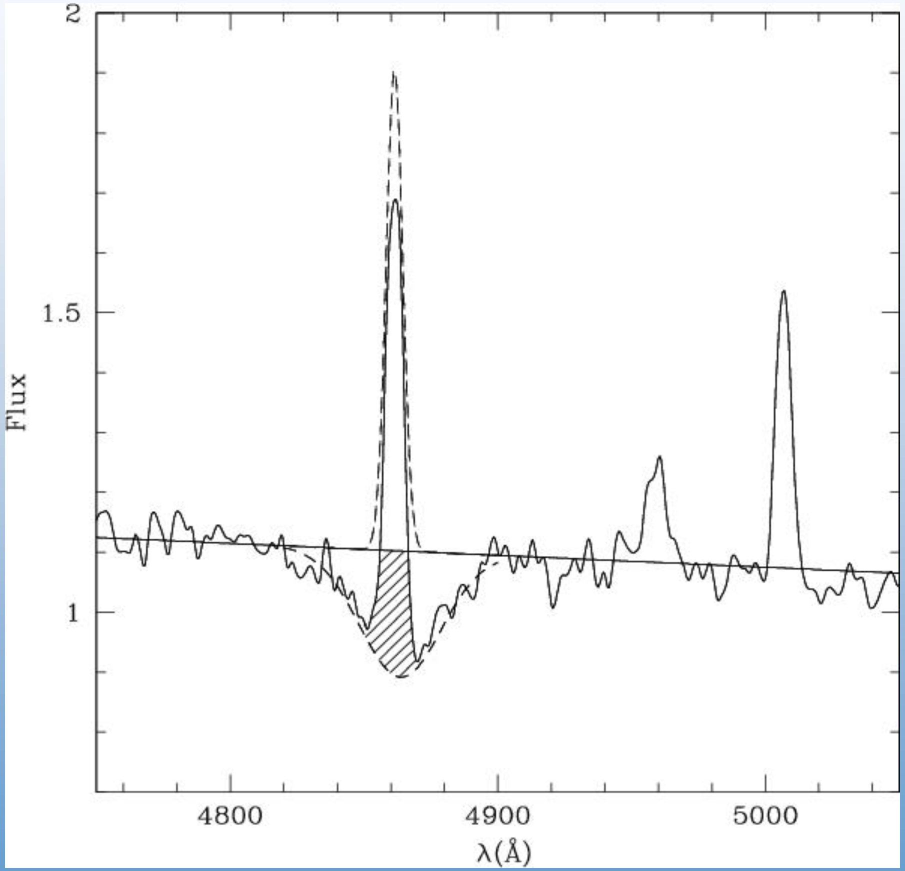
- Measure an Emission Line Spectrum
- Measure the Electron Temperature and Density
- Calculate the Emissivity
- Convert relative Fluxes into Abundances

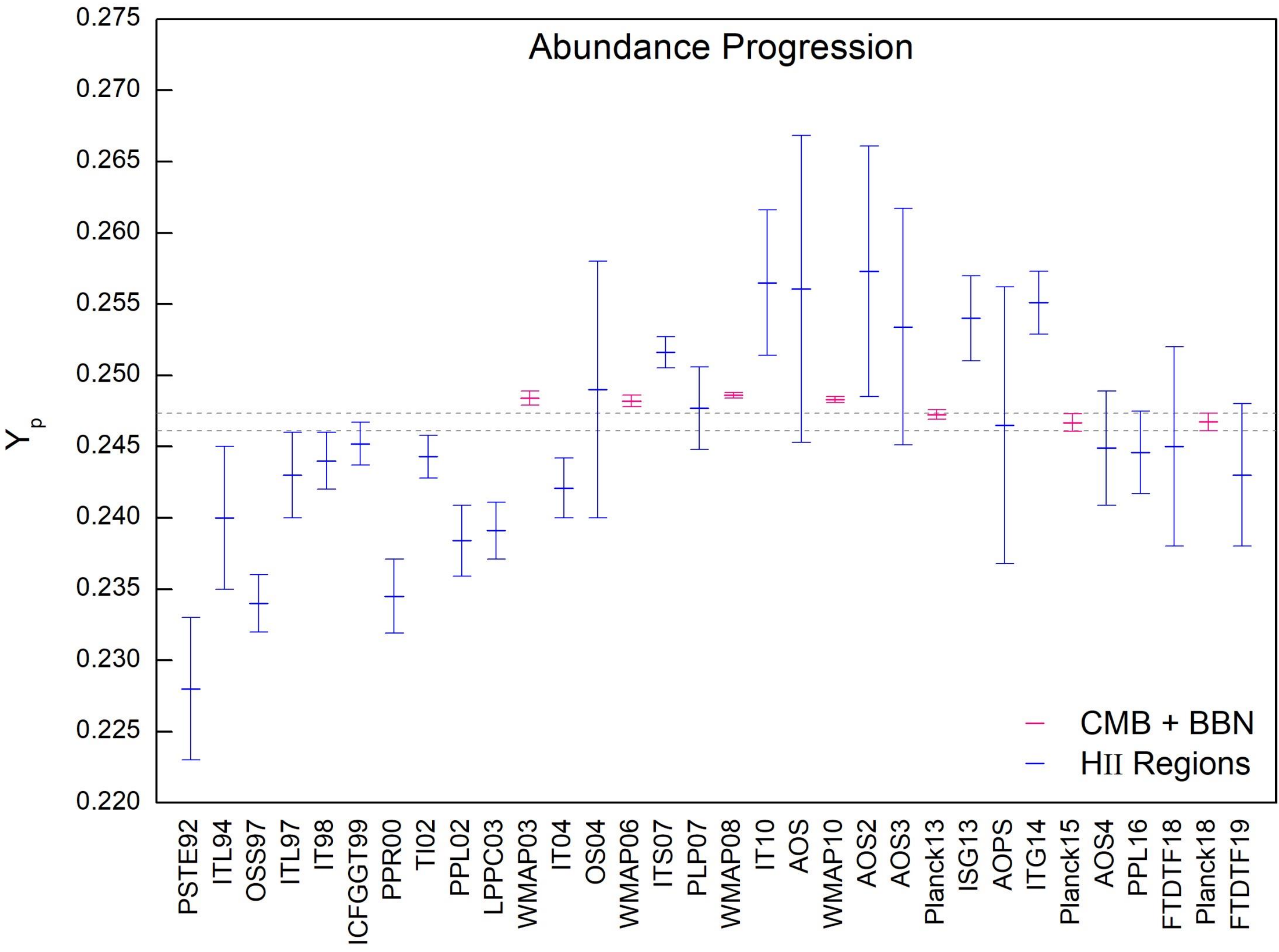
$$\frac{n(He)}{n(H)} = \frac{F(He)}{F(H)} \frac{E(H)}{E(He)}$$

- Plot He/H vs. O/H, and Regress back to O/H=0

Complications

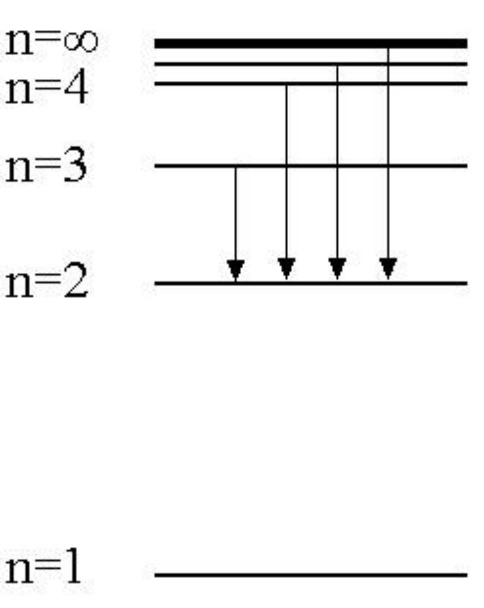
- Emission Lines:
  - Reddening
  - Underlying Absorption
- Temperature & Density
  - Which Ion?
  - Fluctuations
- Collisional Excitation
- Self-Absorption of He I (Optical Depth)





Abundance Progression
Y_p
0.275
0.270
0.265
0.260
0.255
0.250
0.245
0.240
0.235
0.230
0.225
0.220
CMB + BBN
HII Regions
PSTE92
ITL94
OSS97
ITL97
IT98
ICFGGT99
PPR00
TI02
PPL02
LPPC03
WMAP03
IT04
OS04
WMAP06
ITS07
PLP07
WMAP08
IT10
AOS
WMAP10
AOS2
AOS3
Planck13
ISG13
AOPS
ITG14
Planck15
AOS4
PPL16
FTDTF18
Planck18
FTDTF19

Determine ^{4}He & Corrections Simultaneously

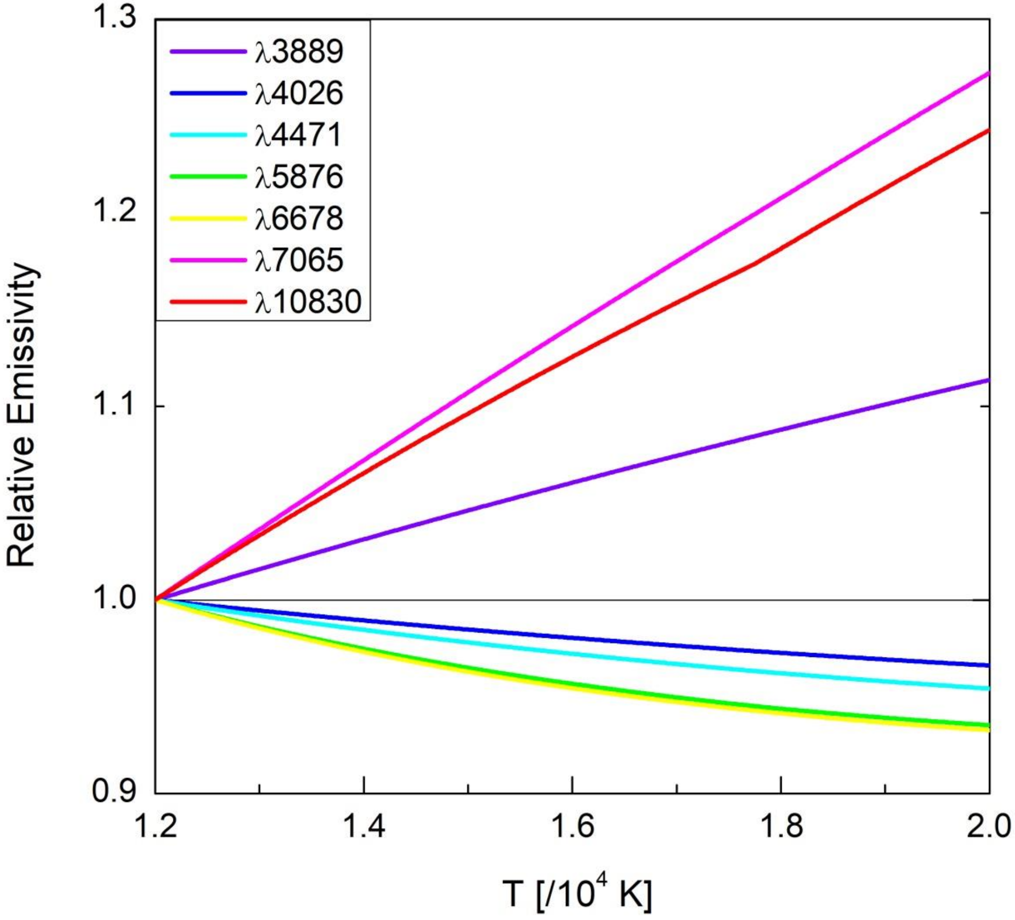


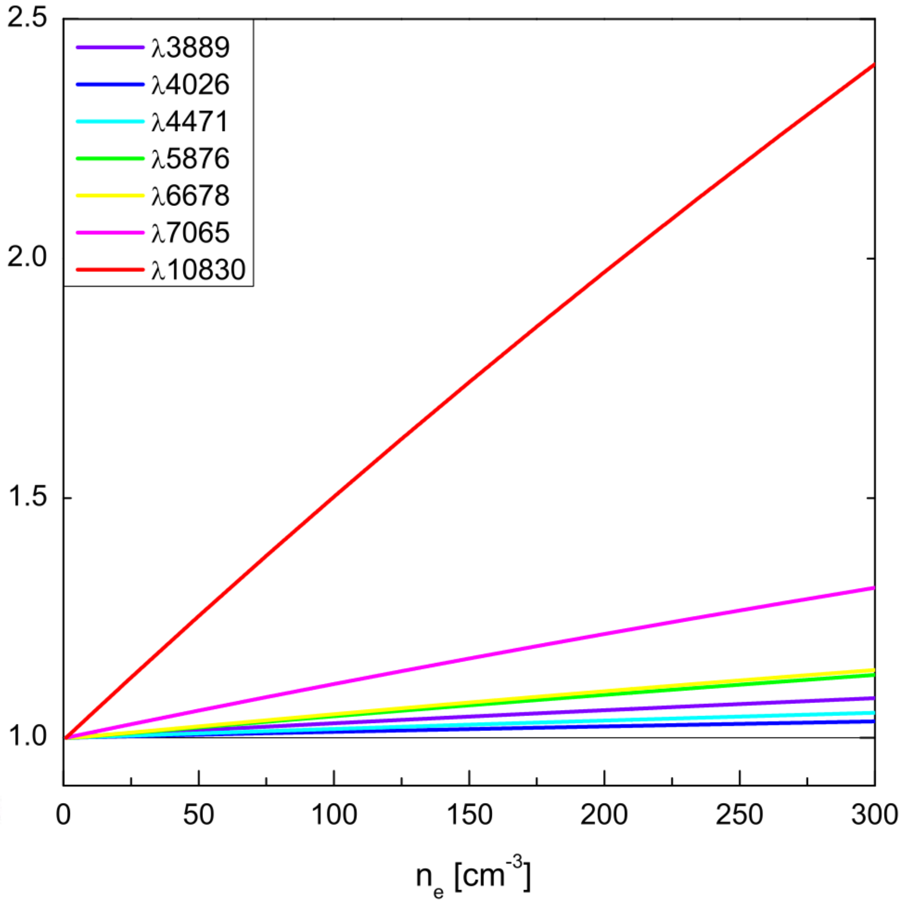
- He λ3889, 4026, 4471, 5876
  6678, 7065, 10830 (IR)
  Hα, Hβ, Hγ, Hδ
- Model for observed fluxes
- y^+, n_e, a_{He}, **τ,** T, $C_{H\beta}$, a_H, ξ
- Minimize

$$\chi^2 = \sum \frac{\left(F(\lambda)_{meas} - F(\lambda)_{calc}\right)^2}{\sigma(\lambda)^2}$$

- $$\frac{F(\lambda)}{F(H\beta)} = y^+ \frac{E(\lambda)}{E(H\beta)} \frac{\frac{W(H\beta)+a_H(H\beta)}{W(H\beta)}}{\frac{W(\lambda)+a_{He}(\lambda)}{W(\lambda)}} f_\tau(\lambda) \frac{1+\frac{C}{R}(\lambda)}{1+\frac{C}{R}(H\beta)} 10^{-f(\lambda)C(H\beta)}$$

Parameter Dependence

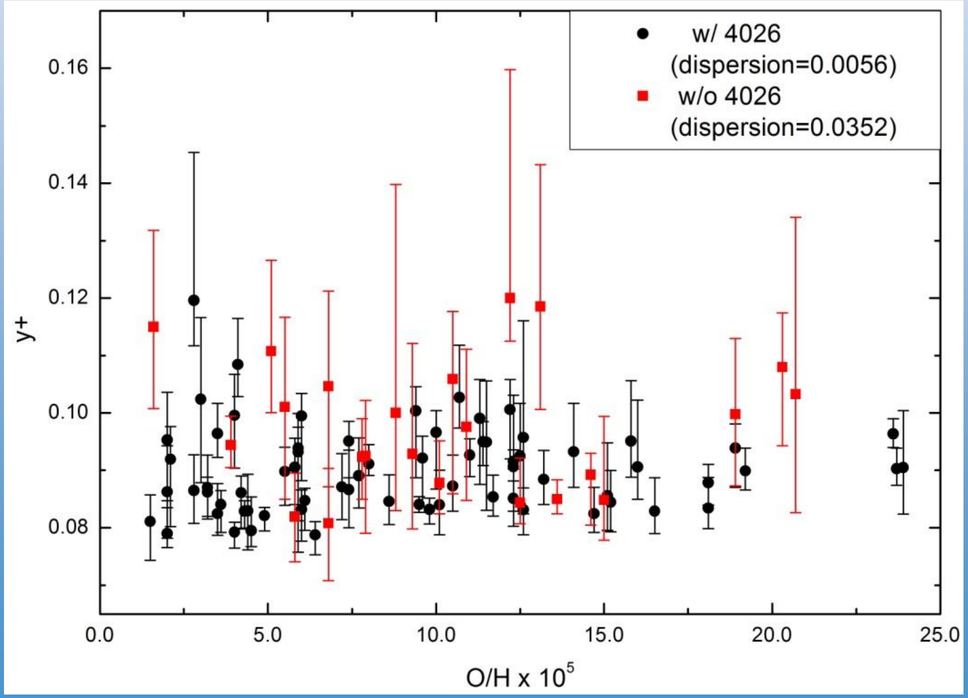




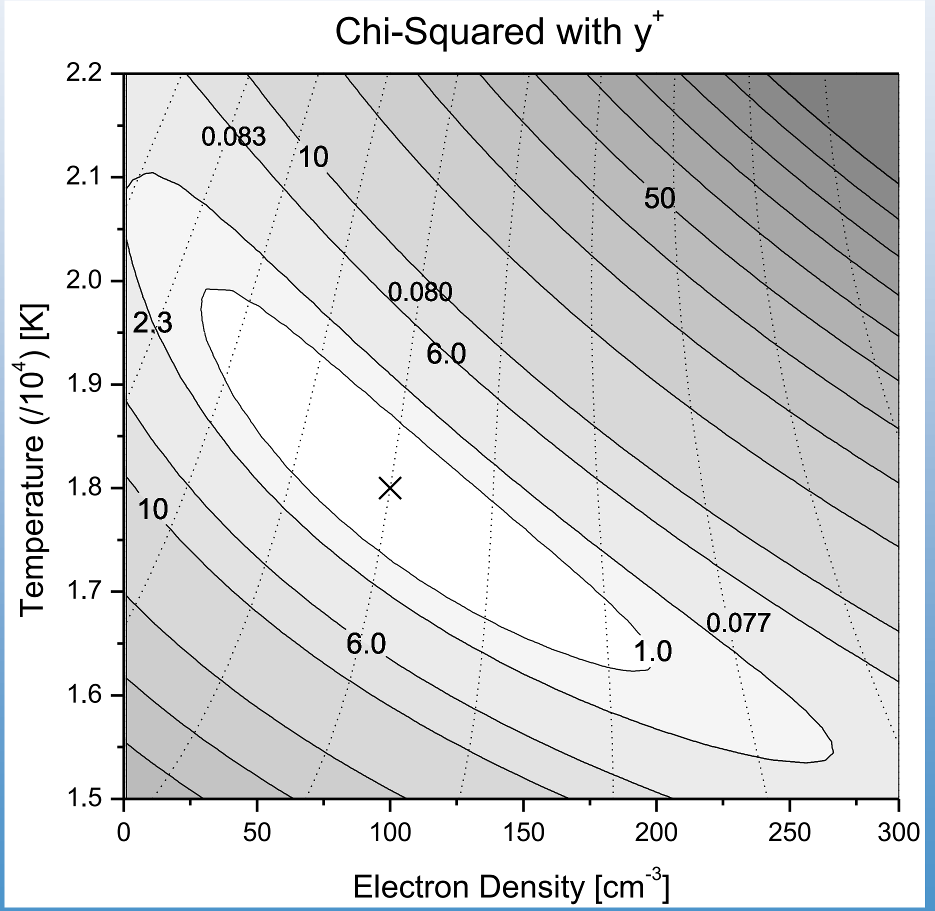
Aver, Olive, Skillman (2015)

Quality Screening

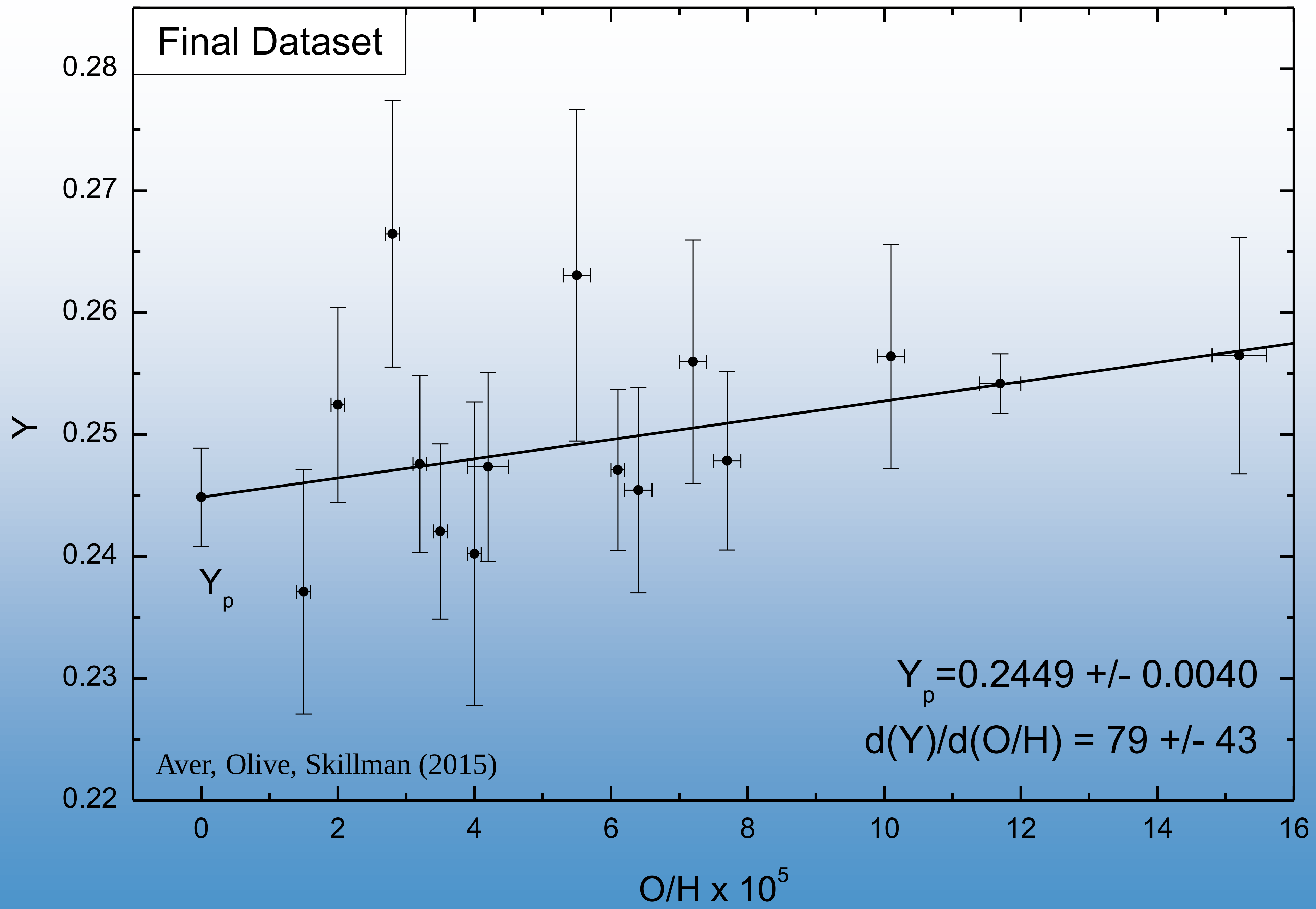
- MCMC
- Frequentist
- $\chi^2 < 4$
- He I λ4026, T(OIII) Prior



Aver, Olive, Skillman (2012)



Aver, Olive, Skillman (2011)



Final Dataset
0.28
0.27
0.26
0.25
0.24
0.23
0.22
Y
Yp
0
2
4
6
8
10
12
14
16
O/H x 10^5
Yp=0.2449 +/- 0.0040
d(Y)/d(O/H) = 79 +/- 43
Aver, Olive, Skillman (2015)

N_ν

$$\Gamma_{\rm wk}(T_f) = H(T_f)$$

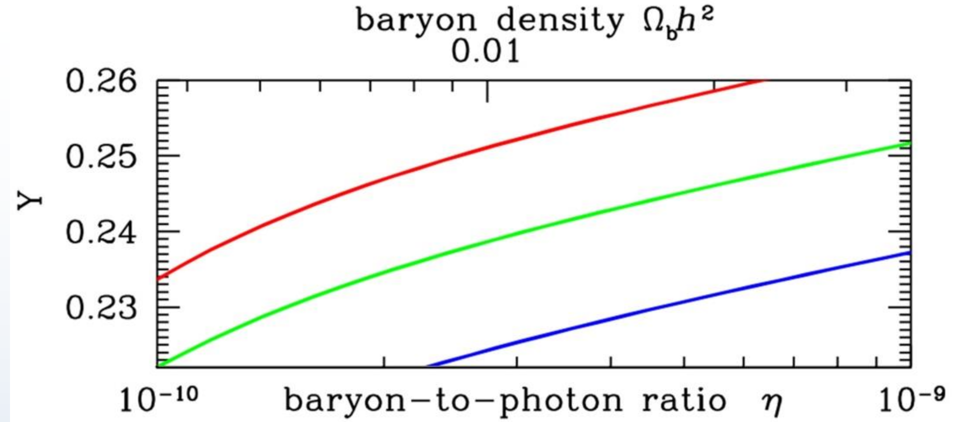
$$H(T_f) \sim G_N^{1/2} T^2$$

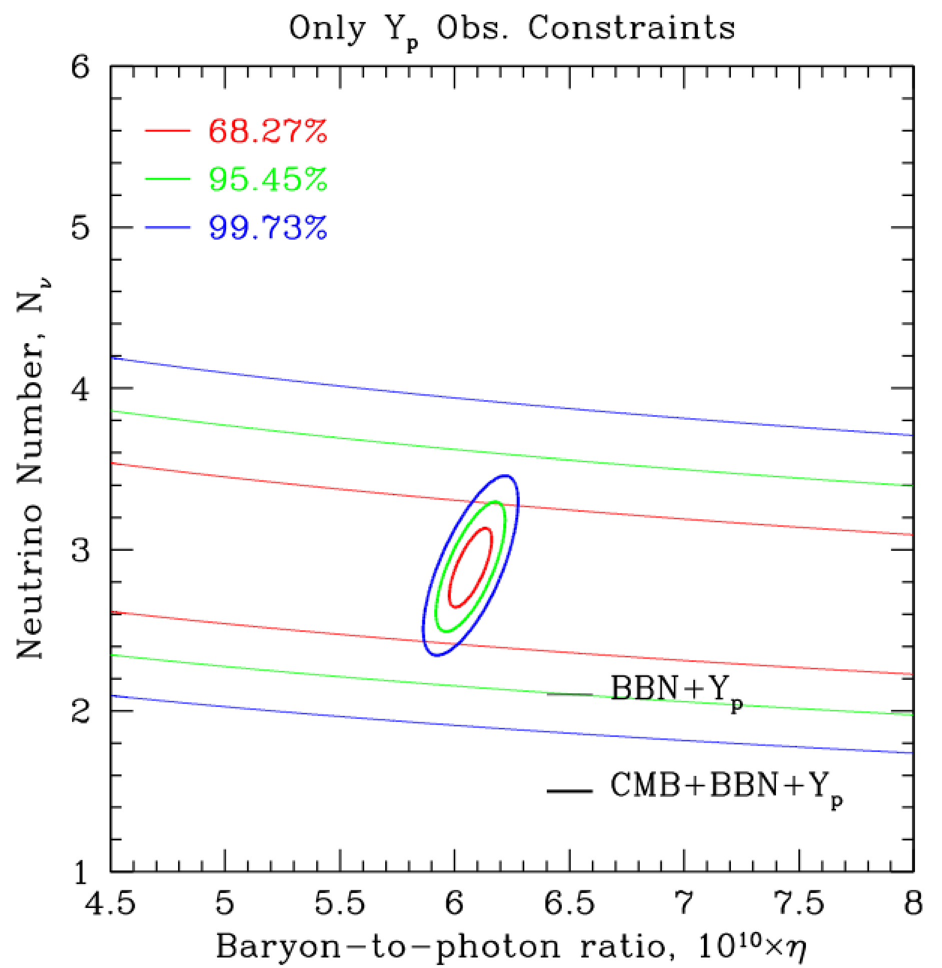
$$\Gamma_{\rm wk}(T_f) \sim G_F^2 T^5$$

$$H^2 = \frac{8\pi}{3} G_N \rho$$

$$\rho = \frac{\pi^2}{30}\left(2 + \frac{7}{2} + \frac{7}{4} N_\nu\right) T^4$$

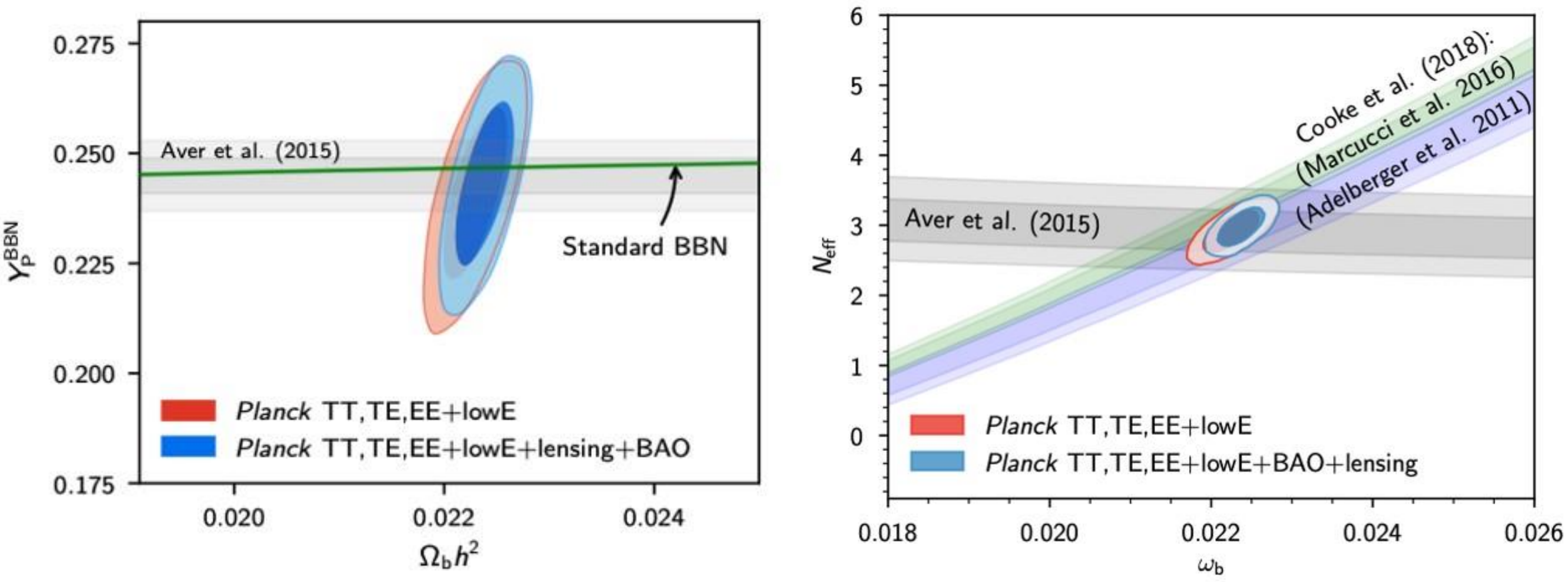
$$\frac{n}{p} \sim e^{-\Delta m/T} \qquad Y \sim \frac{2(n/p)}{1 + (n/p)}$$





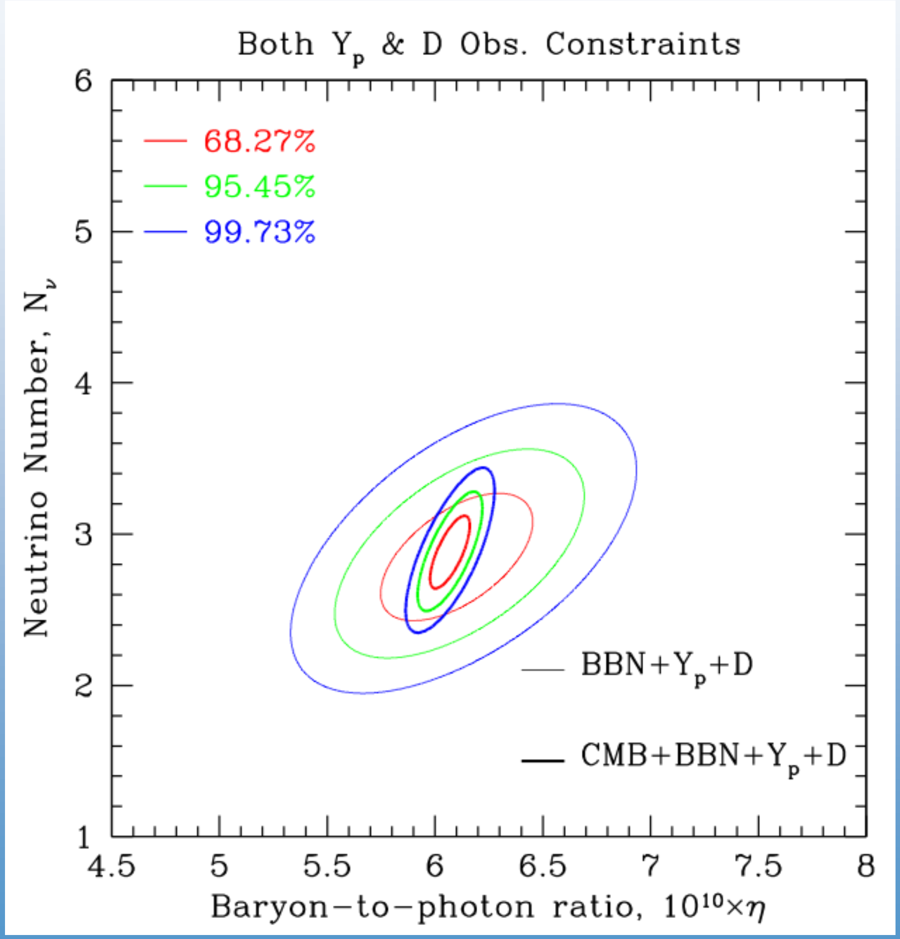
Cyburt, Fields, Olive, Yeh (2015)

Y_p, BBN, & the CMB



Planck (2018)

Y_p & BBN



Cyburt, Fields, Olive, Yeh (2015)

- $Y_p = 0.2449 \pm 0.0040$
  $\frac{D}{H} = (2.53 \pm 0.04) \times 10^{-5}$
  $\Rightarrow \ \Omega_B h^2 = 0.02228 \pm 0.00084$
  $N_\upsilon = 2.85 \pm 0.28$
- w/ CMB
  $\Rightarrow \ \Omega_B h^2 = 0.02217 \pm 0.00022$
  $N_\upsilon = 2.88 \pm 0.16$
- Izotov, Thuan, Guseva (2014)
  $Y_p = 0.2551 \pm 0.0022 \ \left(w/ \ \frac{D}{H}\right)$
  $\Rightarrow \ \Omega_B h^2 = 0.0240 \pm 0.0017$
  $N_\upsilon = 3.53 \pm 0.25$

State of ^{4}He

- Most Recent Result: $Y_p = 0.2449 \pm 0.0040$
  Planck BBN Result: $Y_p = 0.2470 \pm 0.0002$
  - Agree well
  - Realistic Uncertainty
  - Reduce Uncertainty
- Higher Quality & Higher Resolution Spectra
  - LBT
  - IR
  - Additional H Lines

Summary

- BBN's ability to predict the light element abundances with high precision is a great accomplishment of the Big Bang model.
- Our determination of the Primordial Helium Abundance agrees well with the CMB result.
- Self-consistent analysis of ^{4}He using MCMC has proved insightful and effective.
- Systematic uncertainties pose challenges, and higher quality spectra are needed (and coming!).