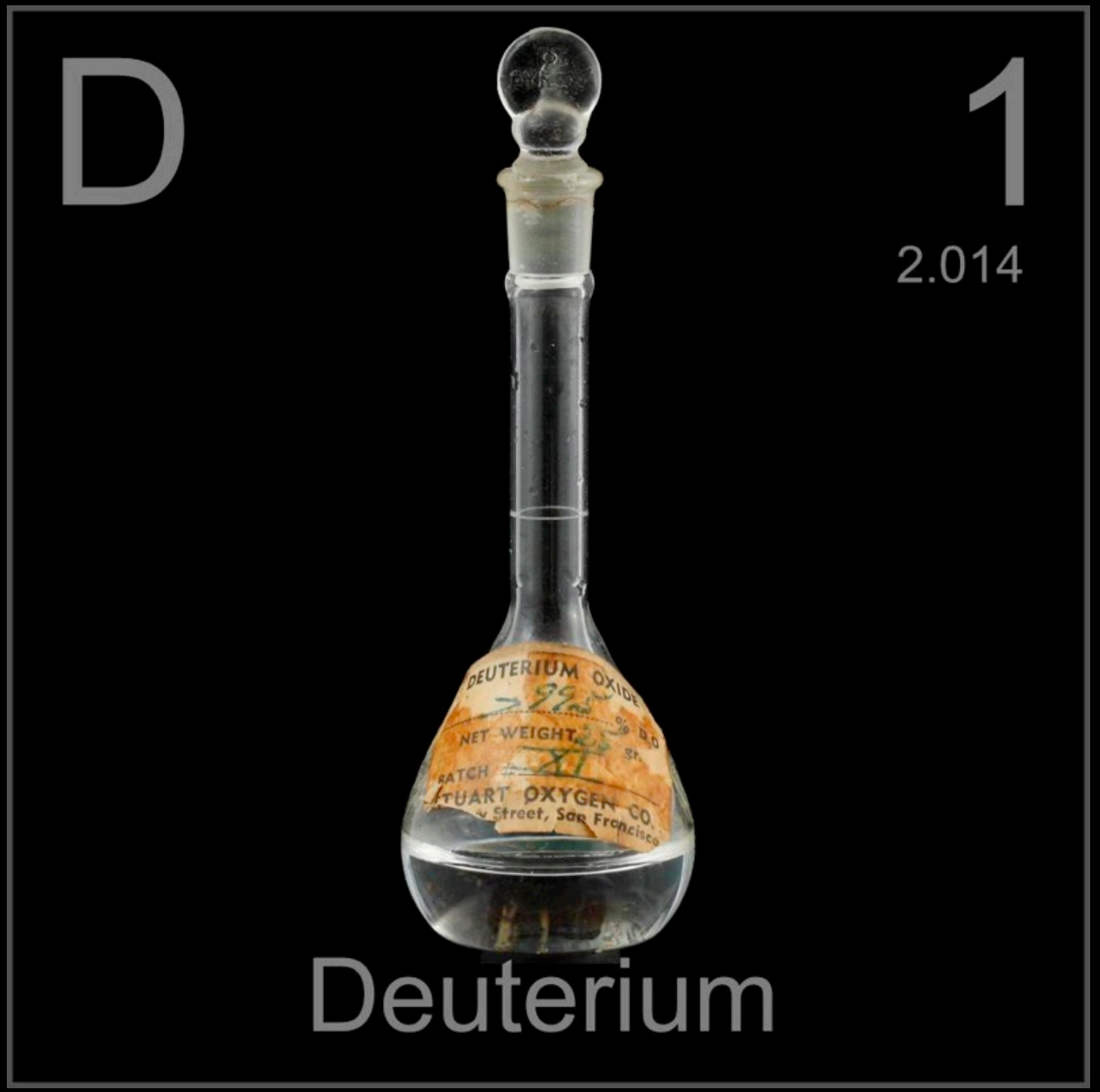
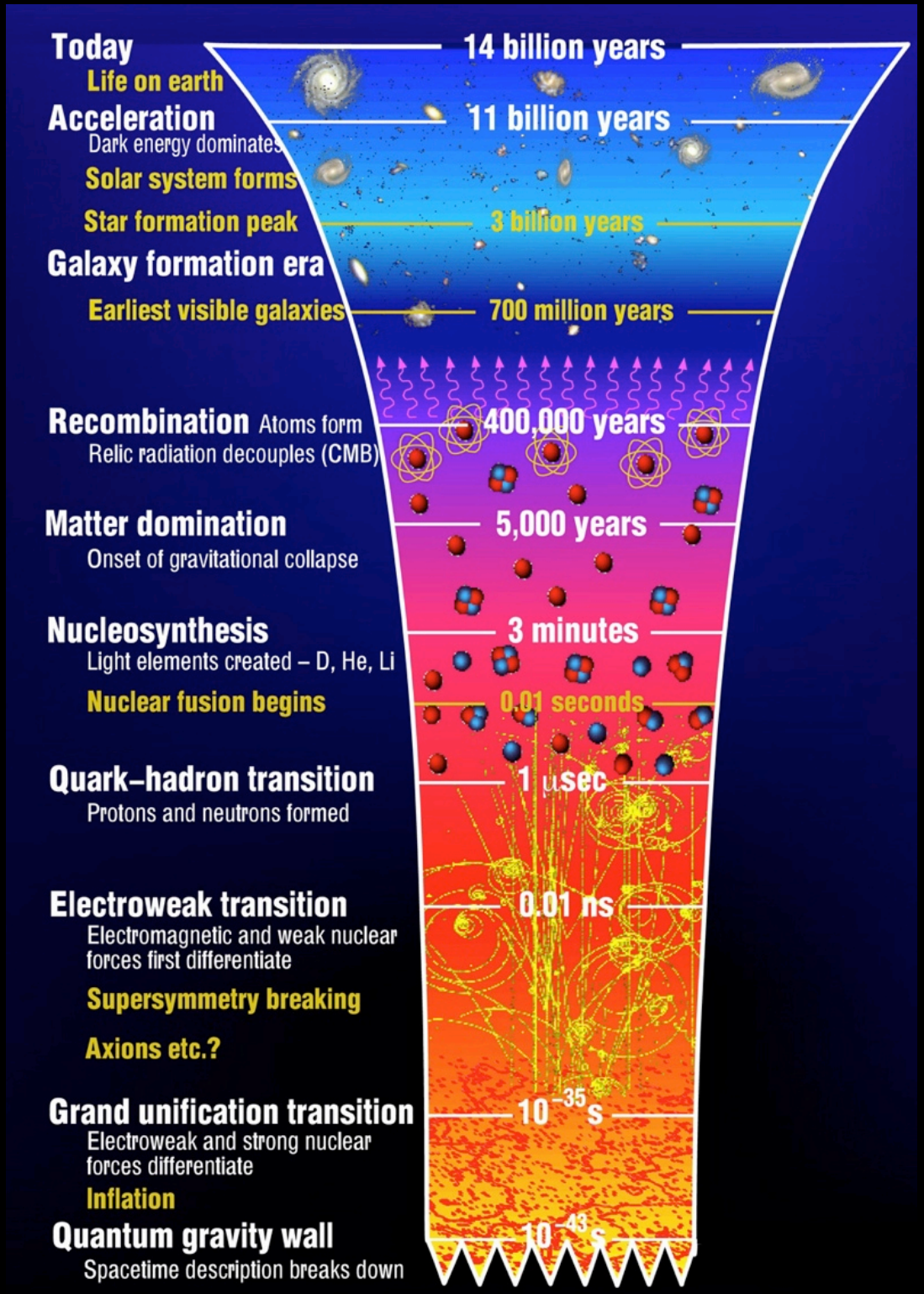
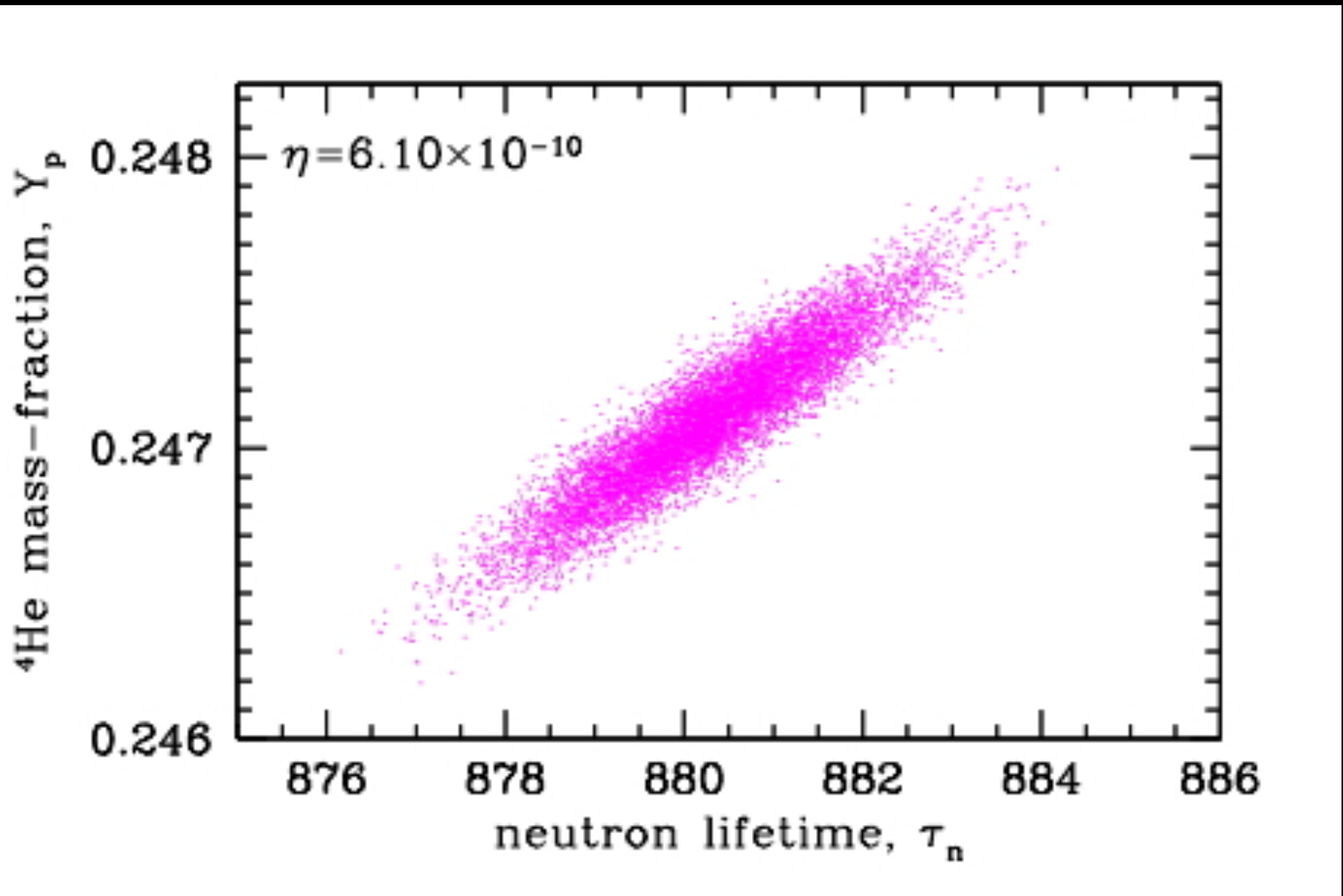
Introduction to Cosmology

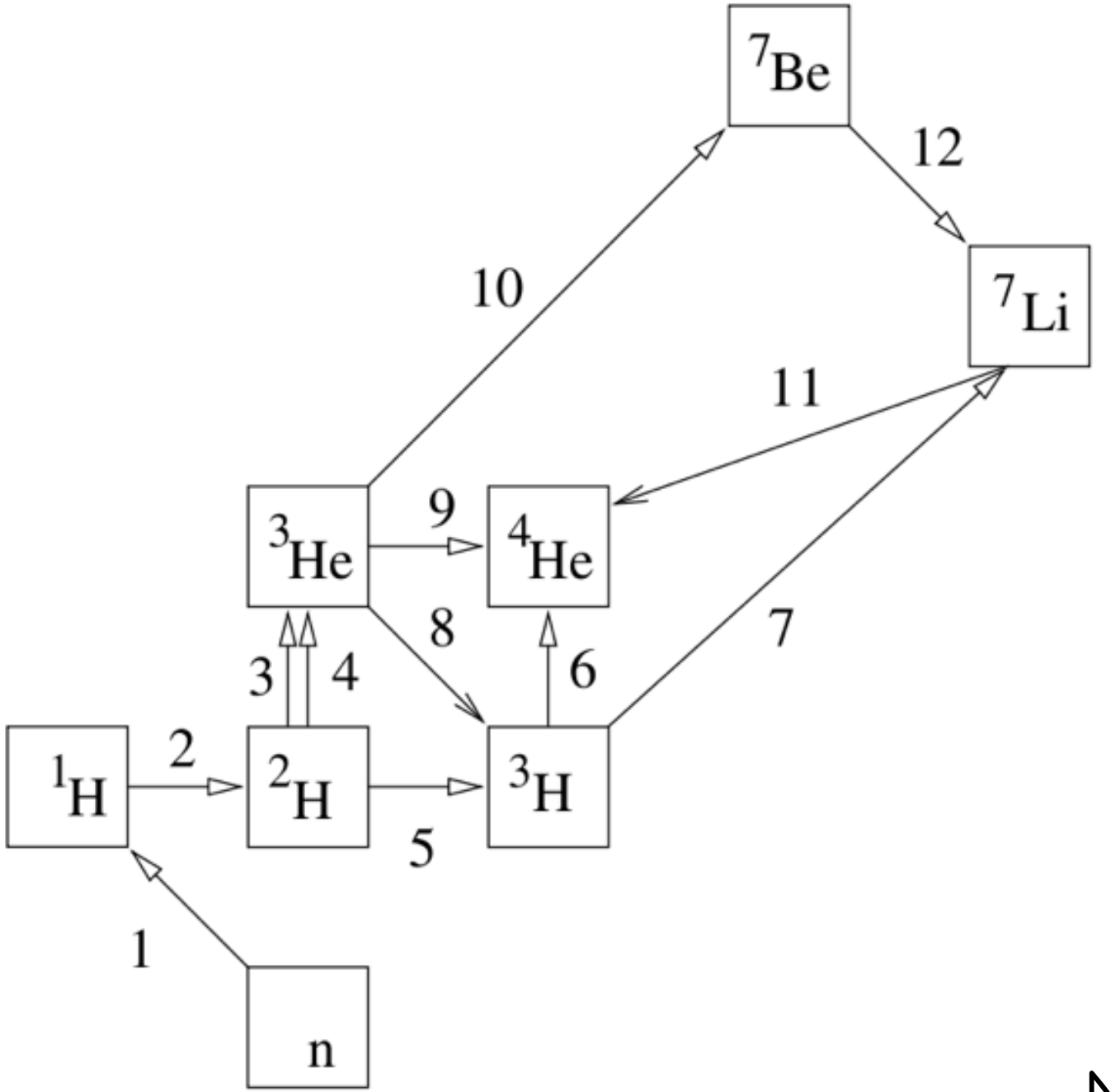
Lecture 8




Today
14 billion years
Life on earth
Acceleration
11 billion years
Dark energy dominates
Solar system forms
Star formation peak
3 billion years
Galaxy formation era
Earliest visible galaxies
700 million years
Recombination Atoms form
Relic radiation decouples (CMB)
400,000 years
Matter domination
Onset of gravitational collapse
5,000 years
Nucleosynthesis
Light elements created – D, He, Li
3 minutes
Nuclear fusion begins
0.01 seconds
Quark–hadron transition
Protons and neutrons formed
1 μsec
Electroweak transition
Electromagnetic and weak nuclear forces first differentiate
0.01 ns
Supersymmetry breaking
Axions etc.?
Grand unification transition
Electroweak and strong nuclear forces differentiate
10 −35 s
Inflation
Quantum gravity wall
Spacetime description breaks down
10 −43 s


η=6.10×10^{-10}
^{4}He mass−fraction, Y_p
0.248
0.247
0.246
876
878
880
882
884
886
neutron lifetime, τ_n

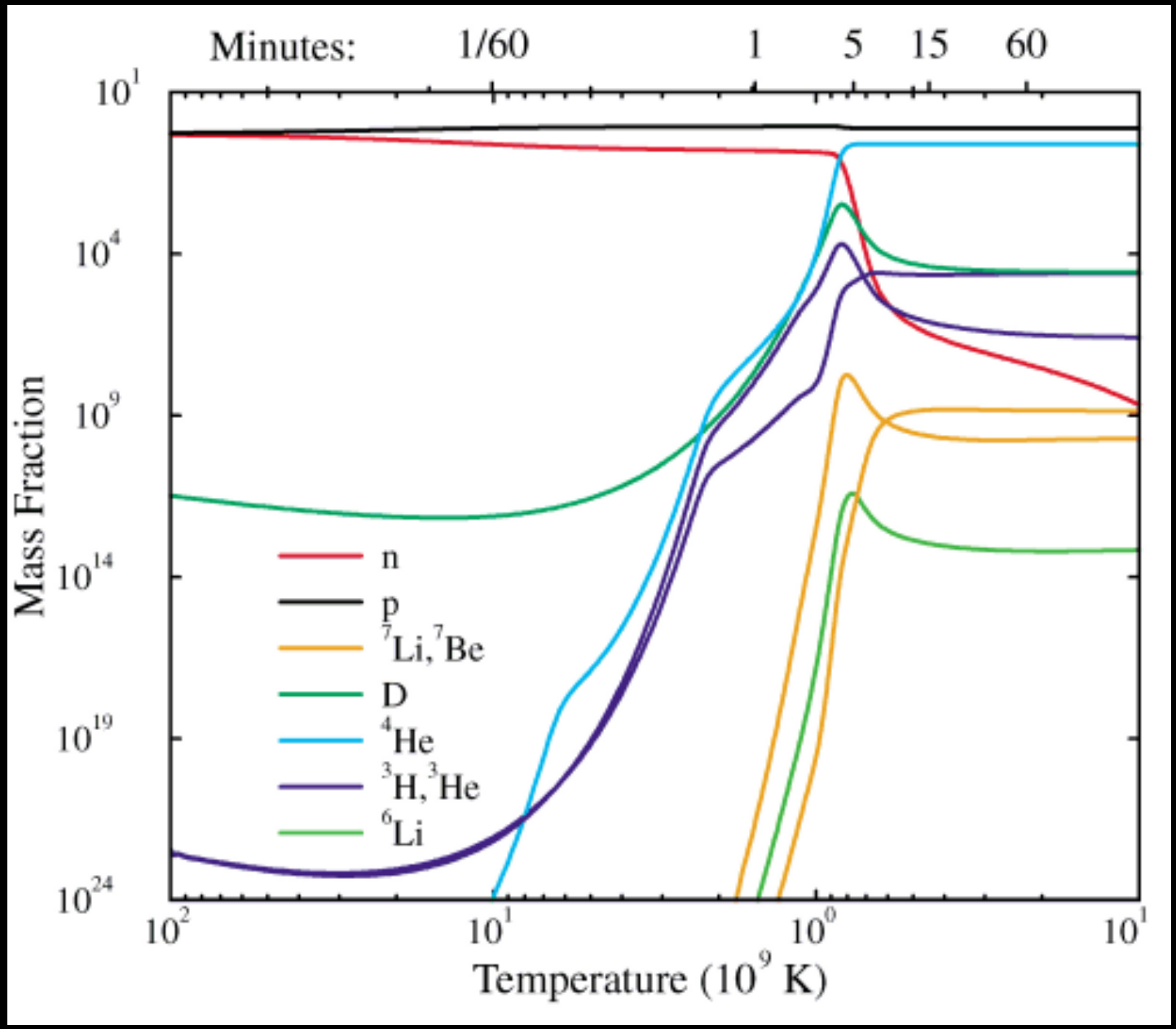
Cyburt+ 2015

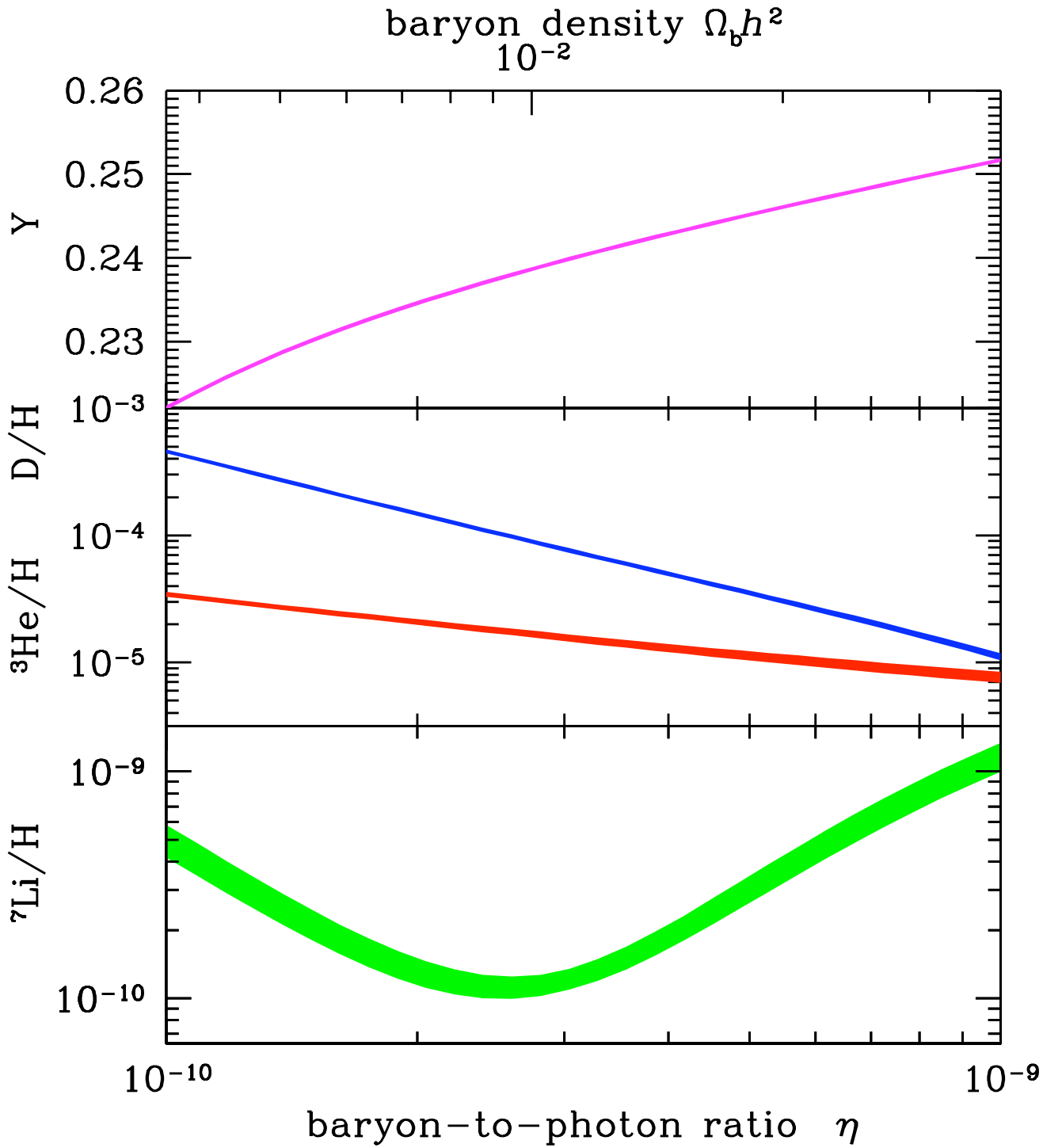


1. $p \longleftrightarrow n$
2. $p(n,\gamma)d$
3. $d(p,\gamma)^3\mathrm{He}$
4. $d(d,n)^3\mathrm{He}$
5. $d(d,p)t$
6. $t(d,n)^4\mathrm{He}$
7. $t(\alpha,\gamma)^7\mathrm{Li}$
8. $^3\mathrm{He}(n,p)t$
9. $^3\mathrm{He}(d,p)^4\mathrm{He}$
10. $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
11. $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$
12. $^7\mathrm{Be}(n,p)^7\mathrm{Li}$

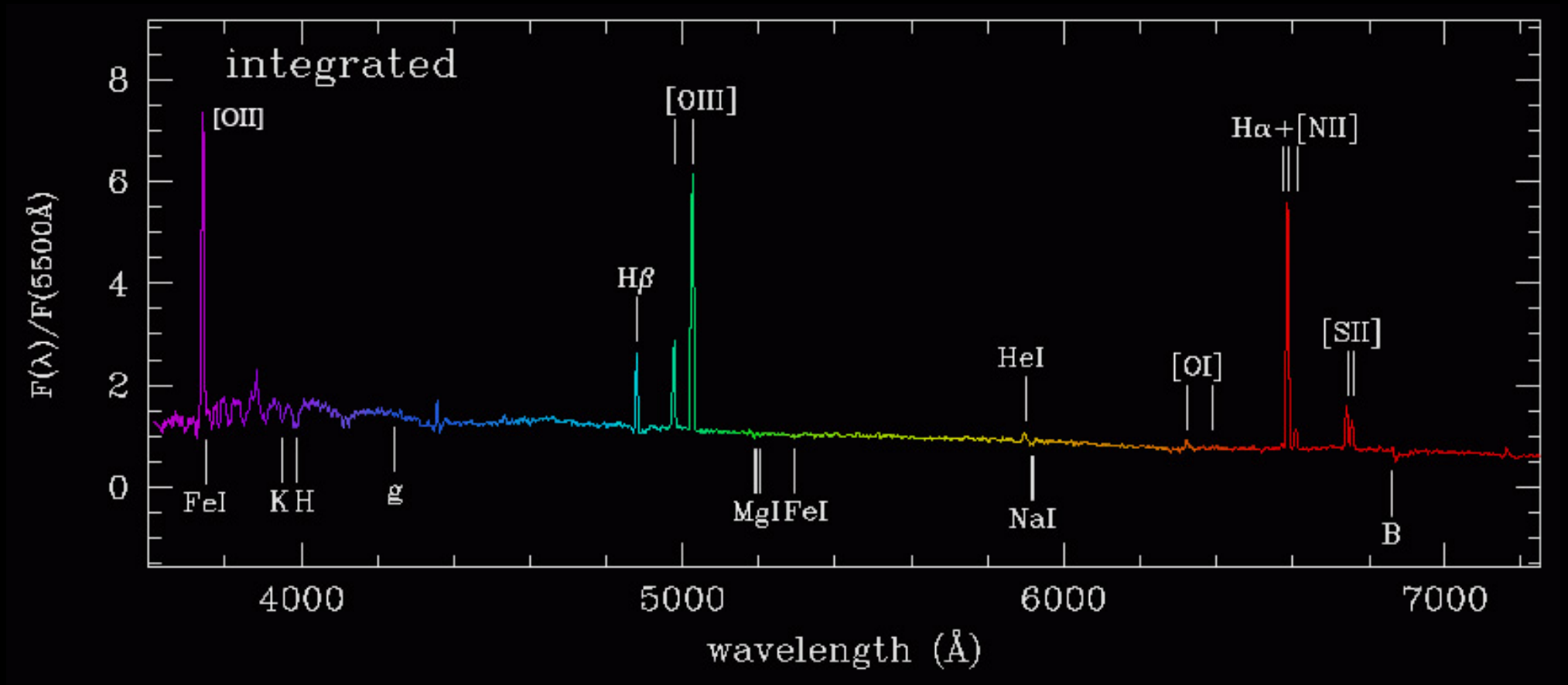
Nollett & Burles 2000

The lightest elements are created




baryon density $\Omega_b h^2$
10^{-2}
0.26
0.25
0.24
0.23
Y
10^{-3}
D/H
10^{-4}
10^{-5}
^{3}He/H
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon−to−photon ratio η

Cyburt+ 2015


integrated
[OII]
[OIII]
Hα+[NII]
Hβ
HeI
[OI]
[SII]
FeI
K H
g
MgI FeI
NaI
B
F(λ)/F(5500Å)
wavelength (Å)
0
2
4
6
8
4000
5000
6000
7000

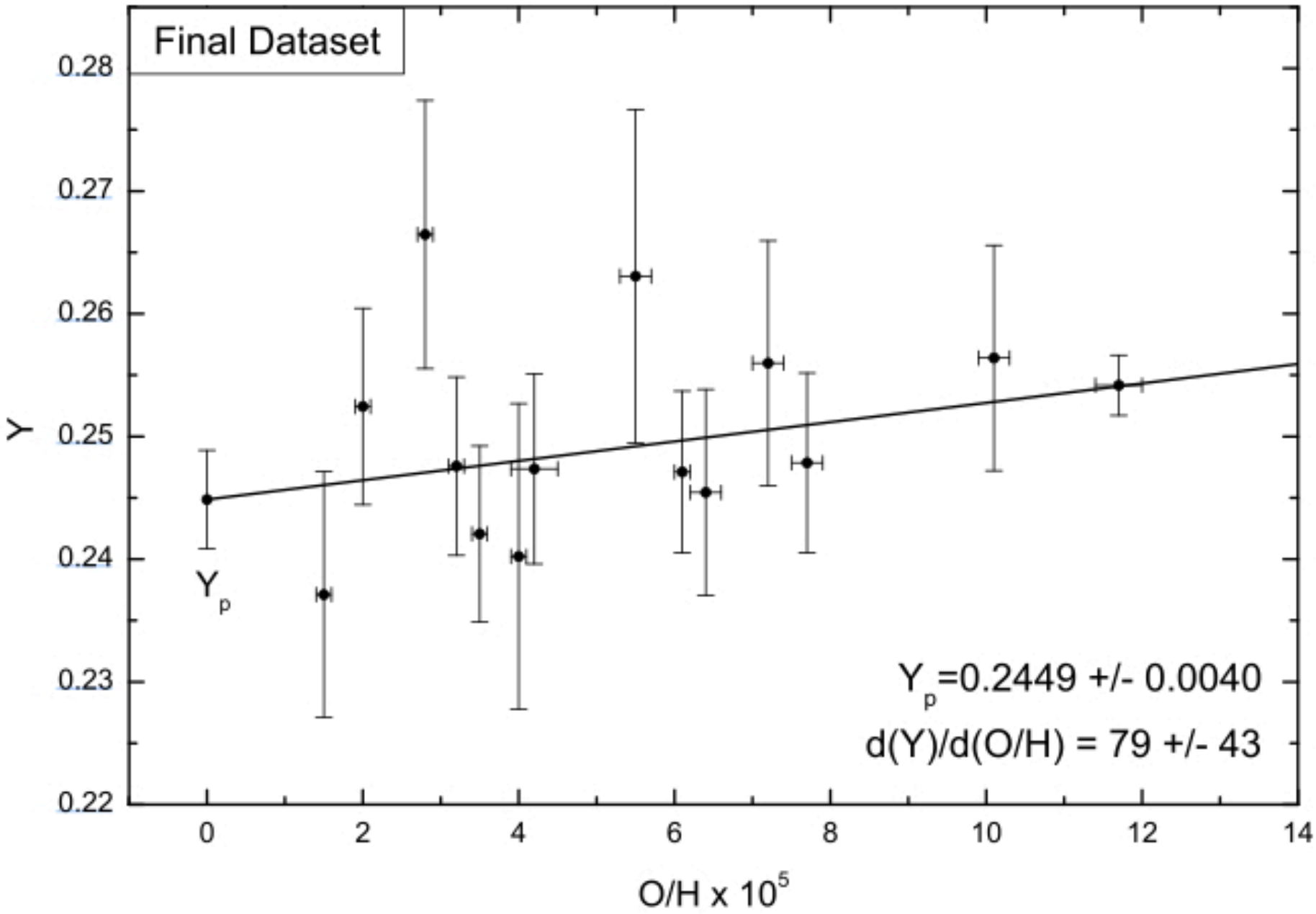
L Kewley

Galaxy I Zwicky 18

Hubble Space Telescope • ACS/WFC

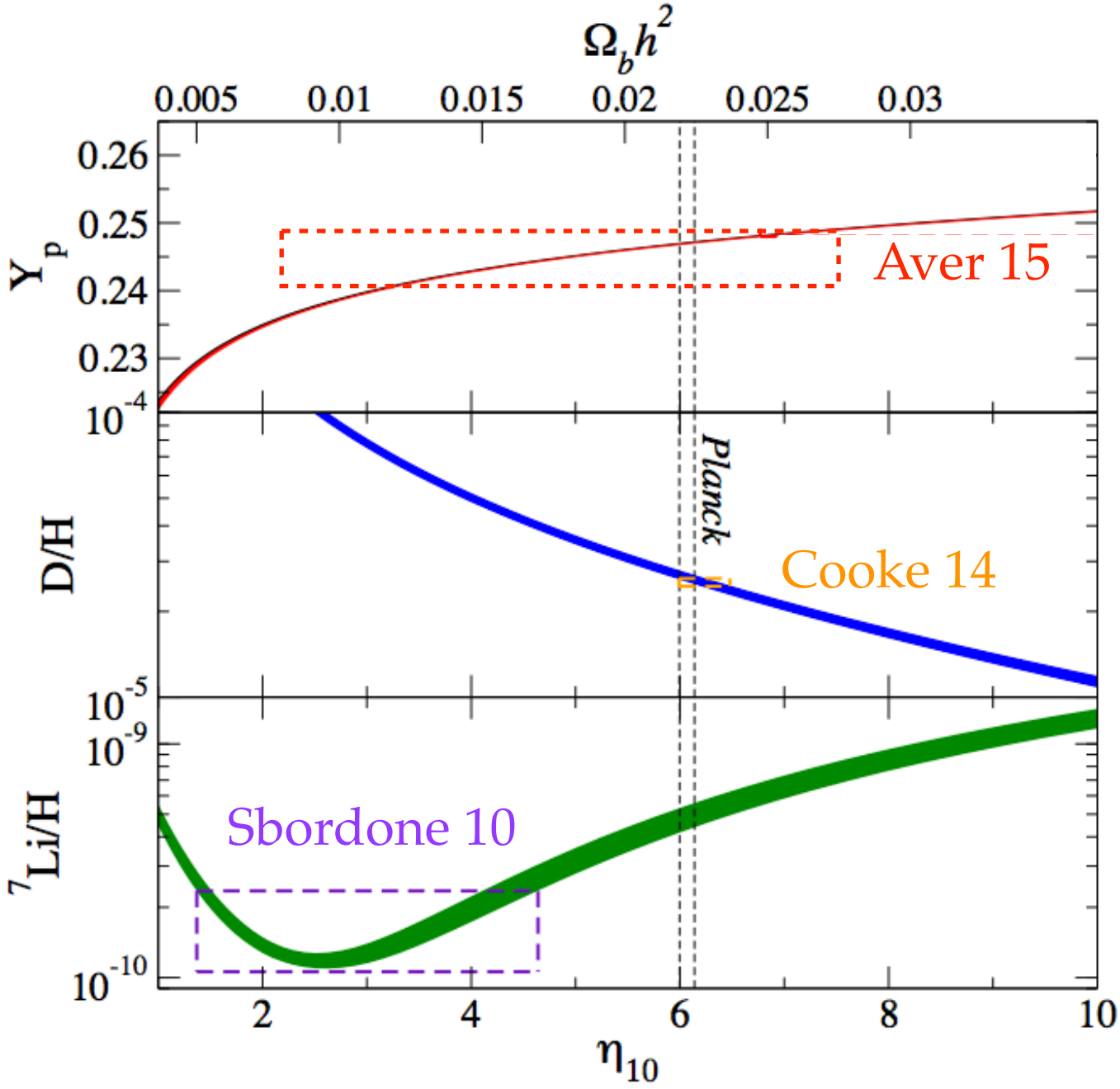
NASA, ESA, and A. Aloisi (STScI/ESA)

STScI-PRC07-35a

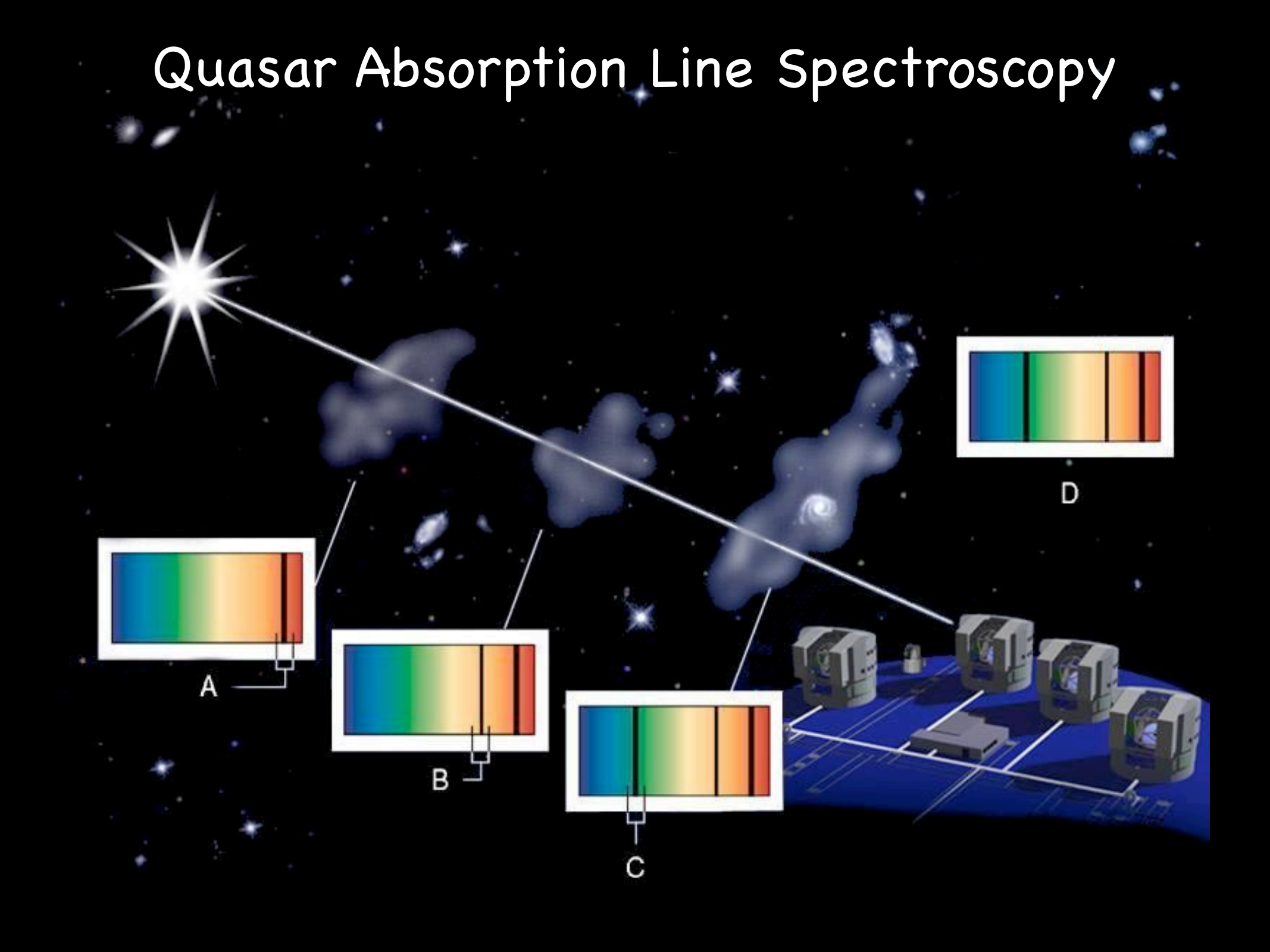

Final Dataset
0.28
0.27
0.26
0.25
0.24
0.23
0.22
Y
Y_p
Y_p=0.2449 +/- 0.0040
d(Y)/d(O/H) = 79 +/- 43
0
2
4
6
8
10
12
14
O/H x 10^5

Aver+ 2015

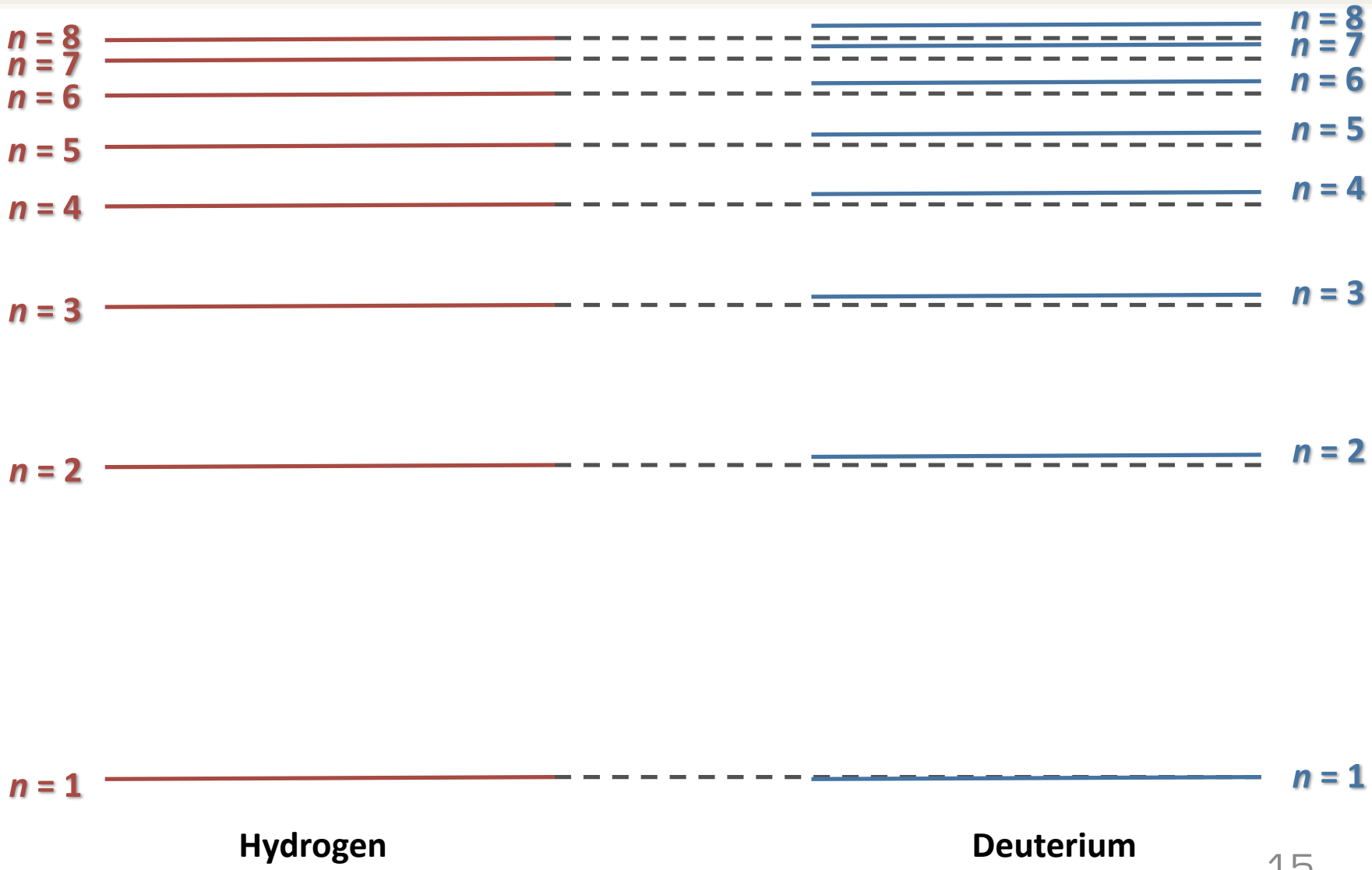
BBN theory confronts observations 2015



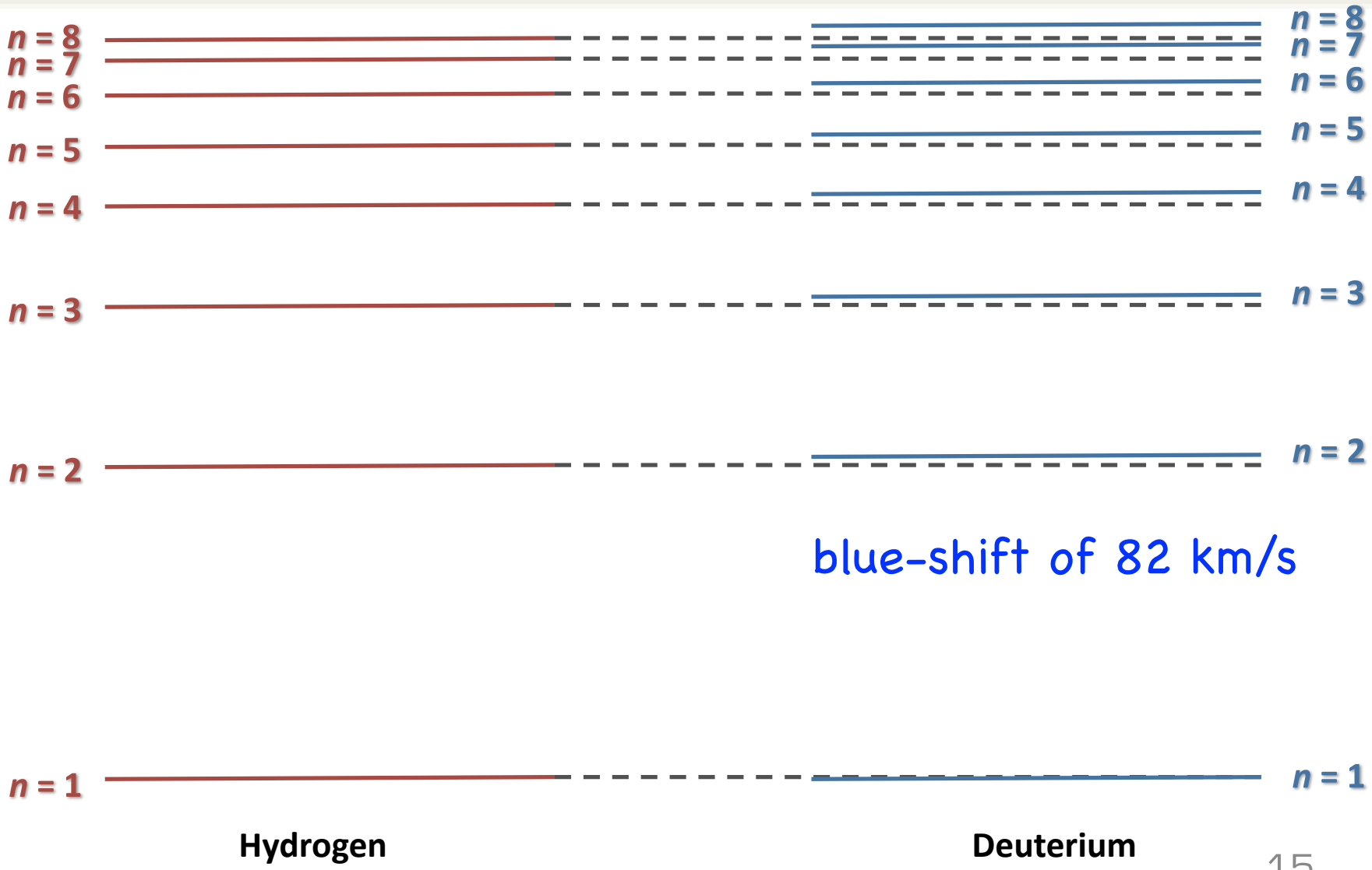
Quasar Absorption Line Spectroscopy

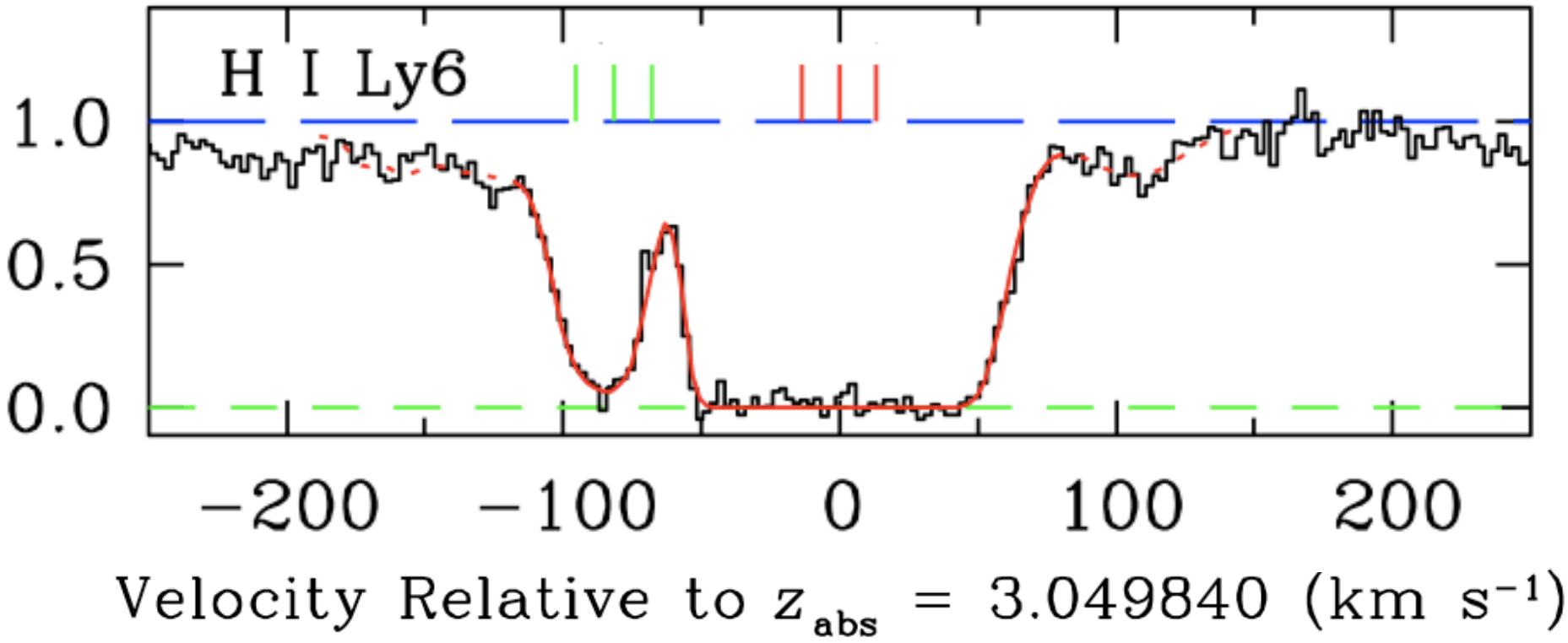


Energy Levels



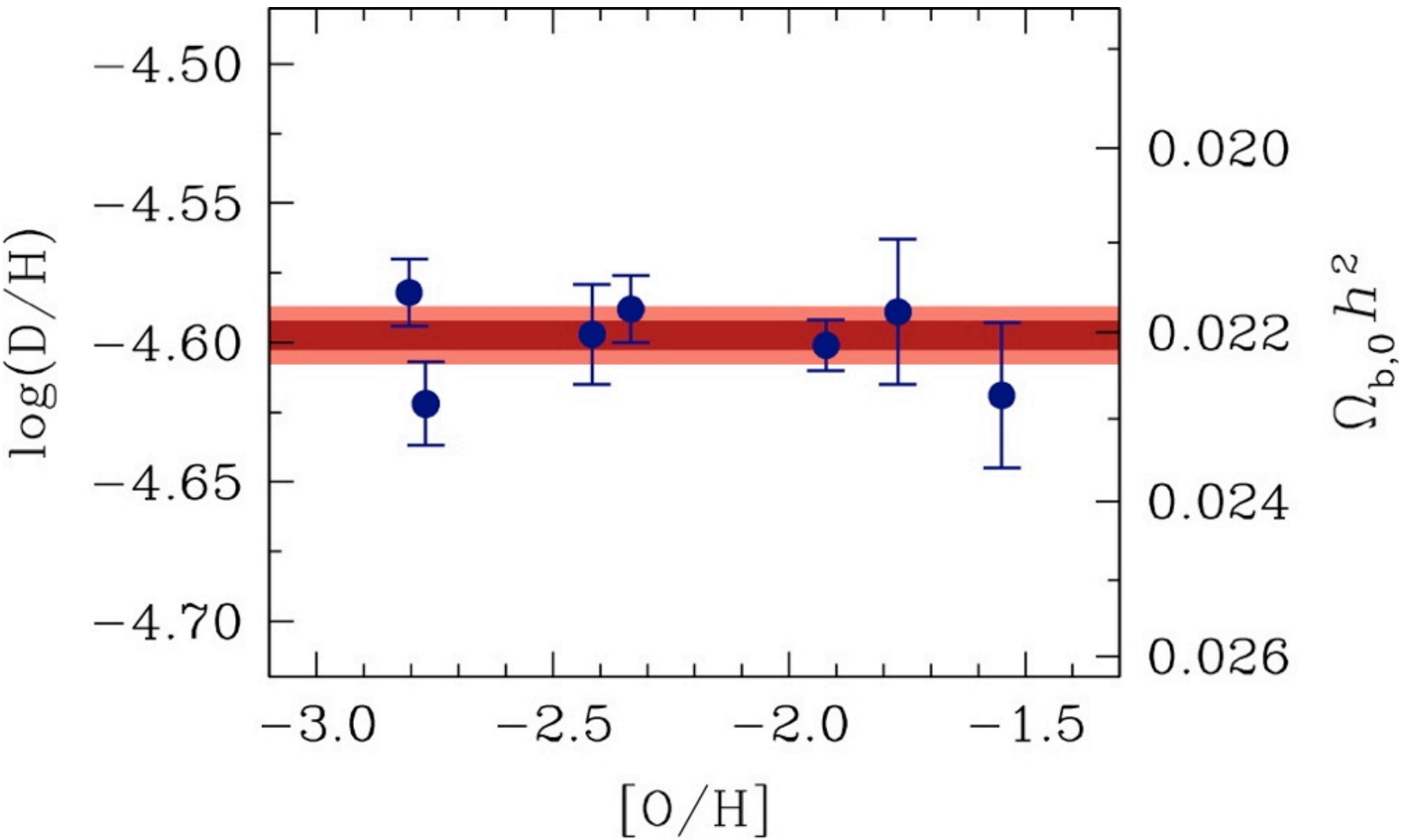
Energy Levels




H I Ly6
1.0
0.5
0.0
−200
−100
0
100
200
Velocity Relative to z_{abs} = 3.049840 (km s^{-1})

Precision Measures of (D/H) [Cooke et al. 2017]

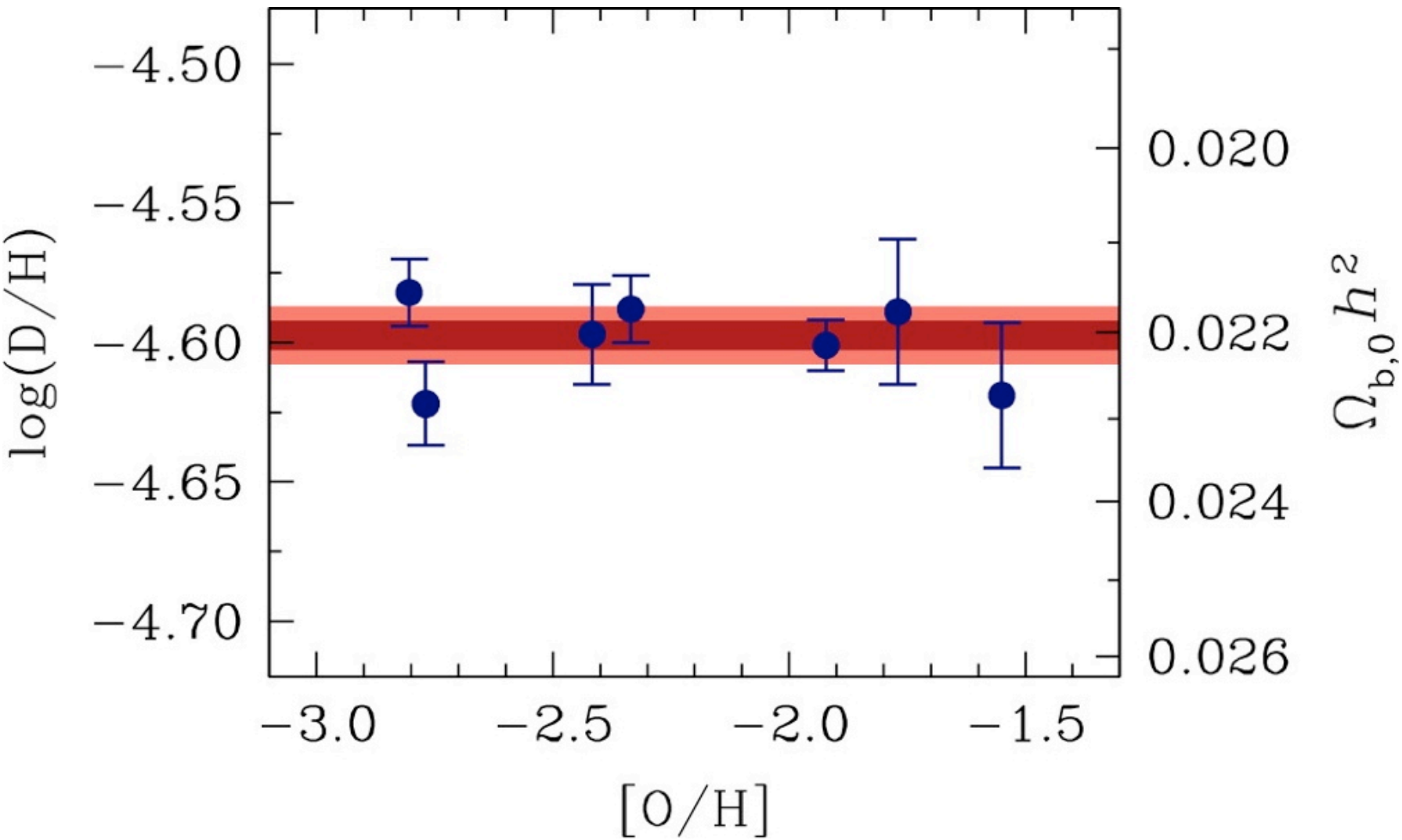
$$(\mathrm{D/H})_{\mathrm{DLA}} = (2.53 \pm 0.03) \times 10^{-5}$$



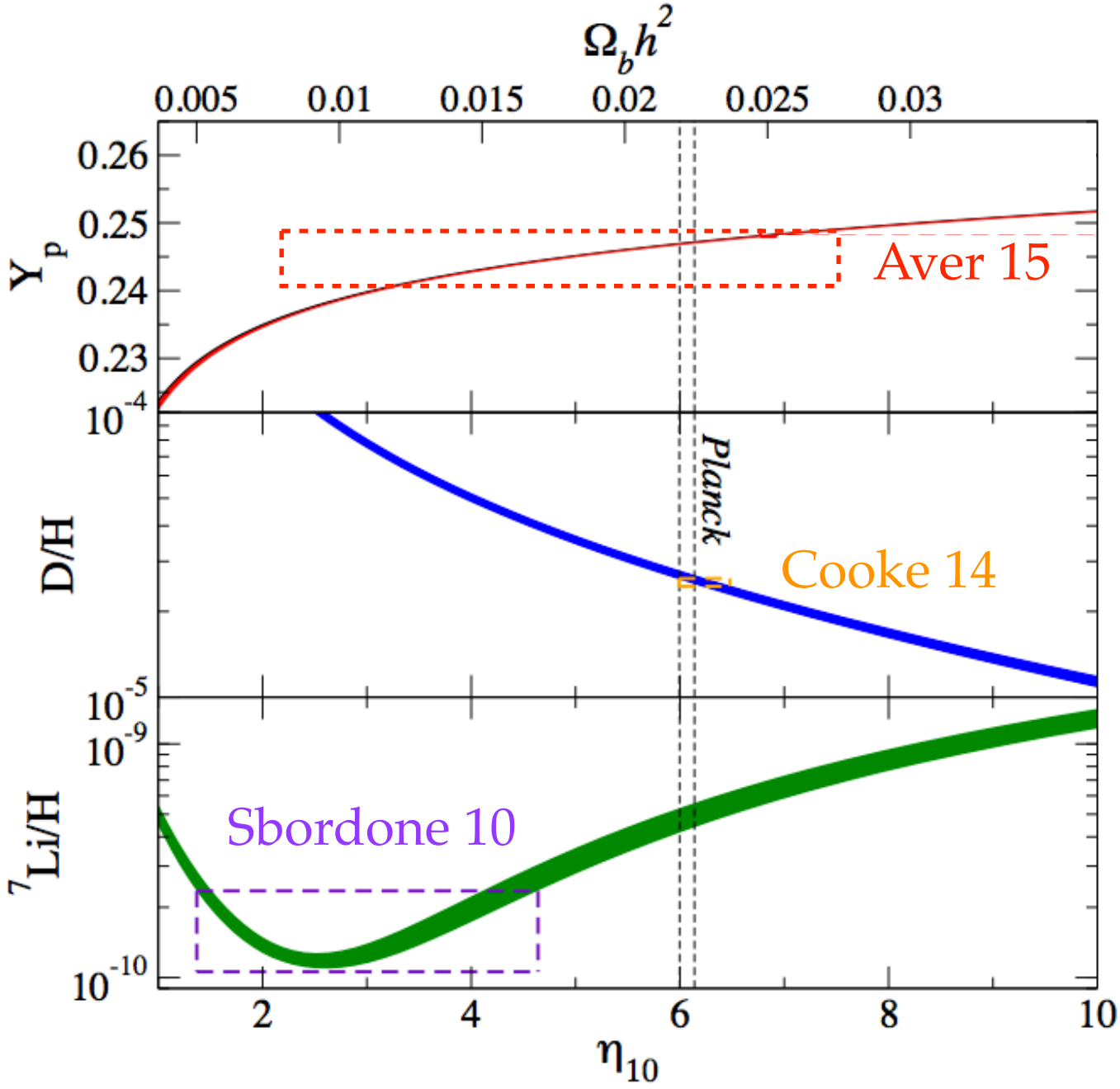
Precision Measures of (D/H) [Cooke et al. 2017]

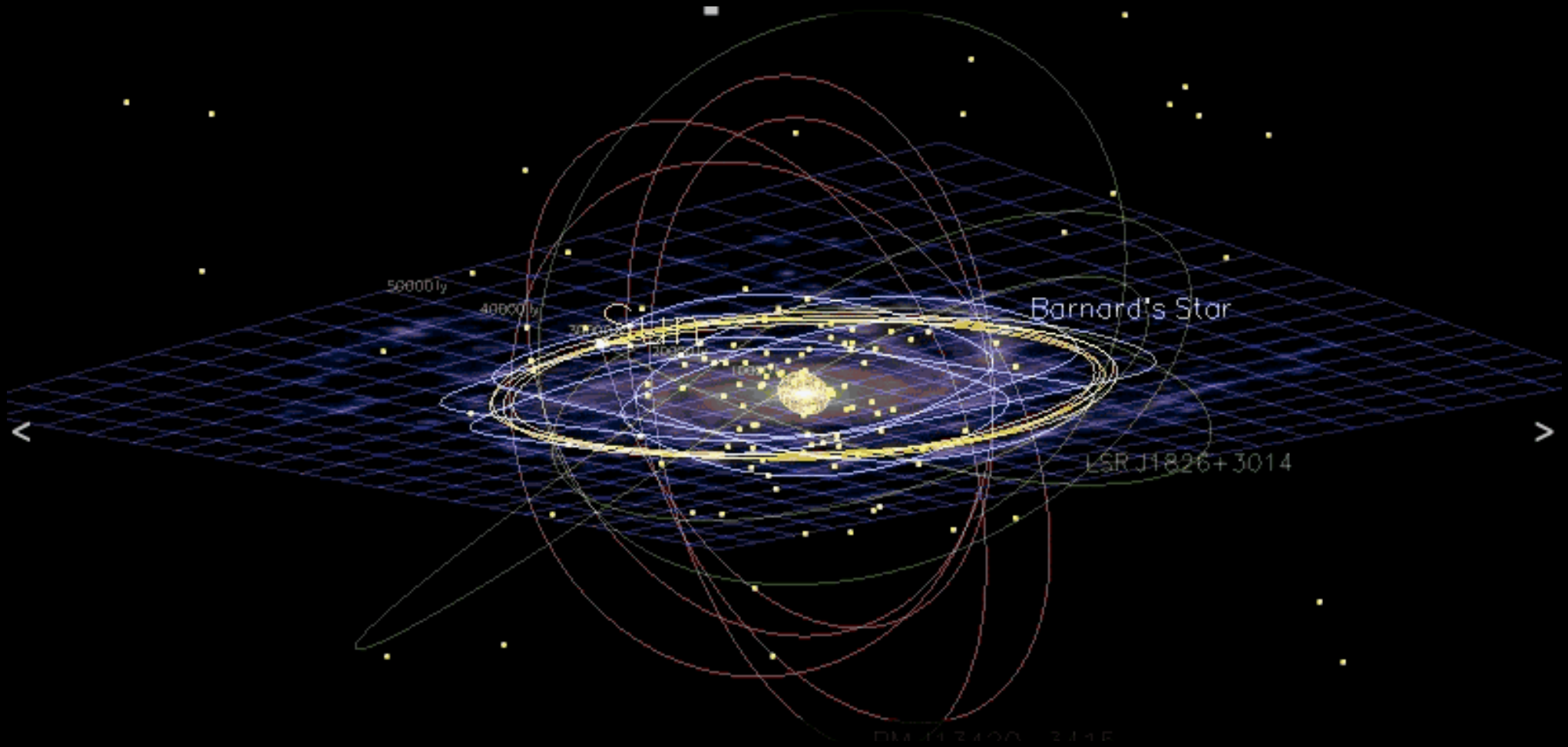
$$100\Omega_{\mathrm{b},0}h^2(\mathrm{BBN}) = 2.235 \pm 0.05$$

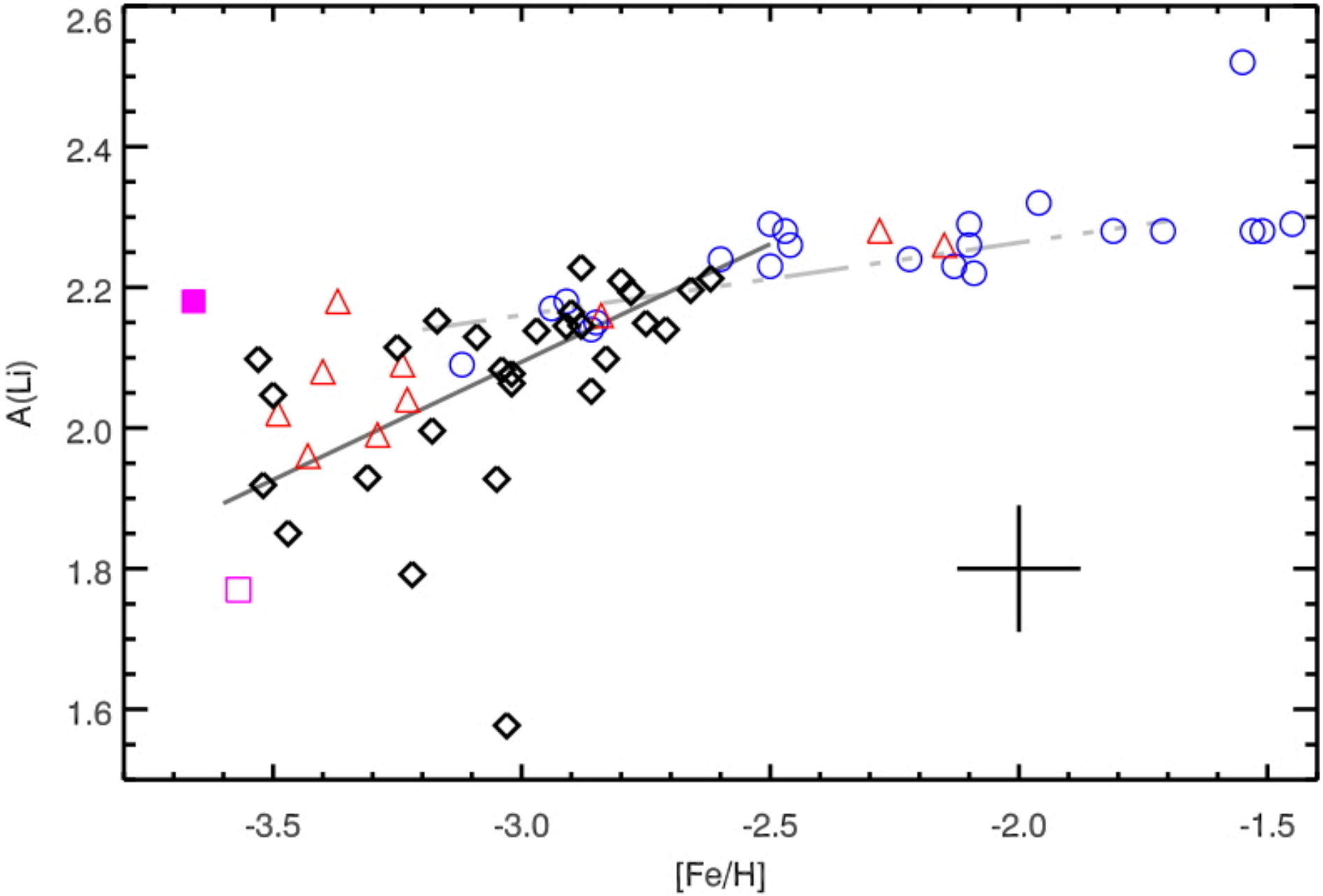
(Random + Systematic Error)



BBN theory confronts observations 2015

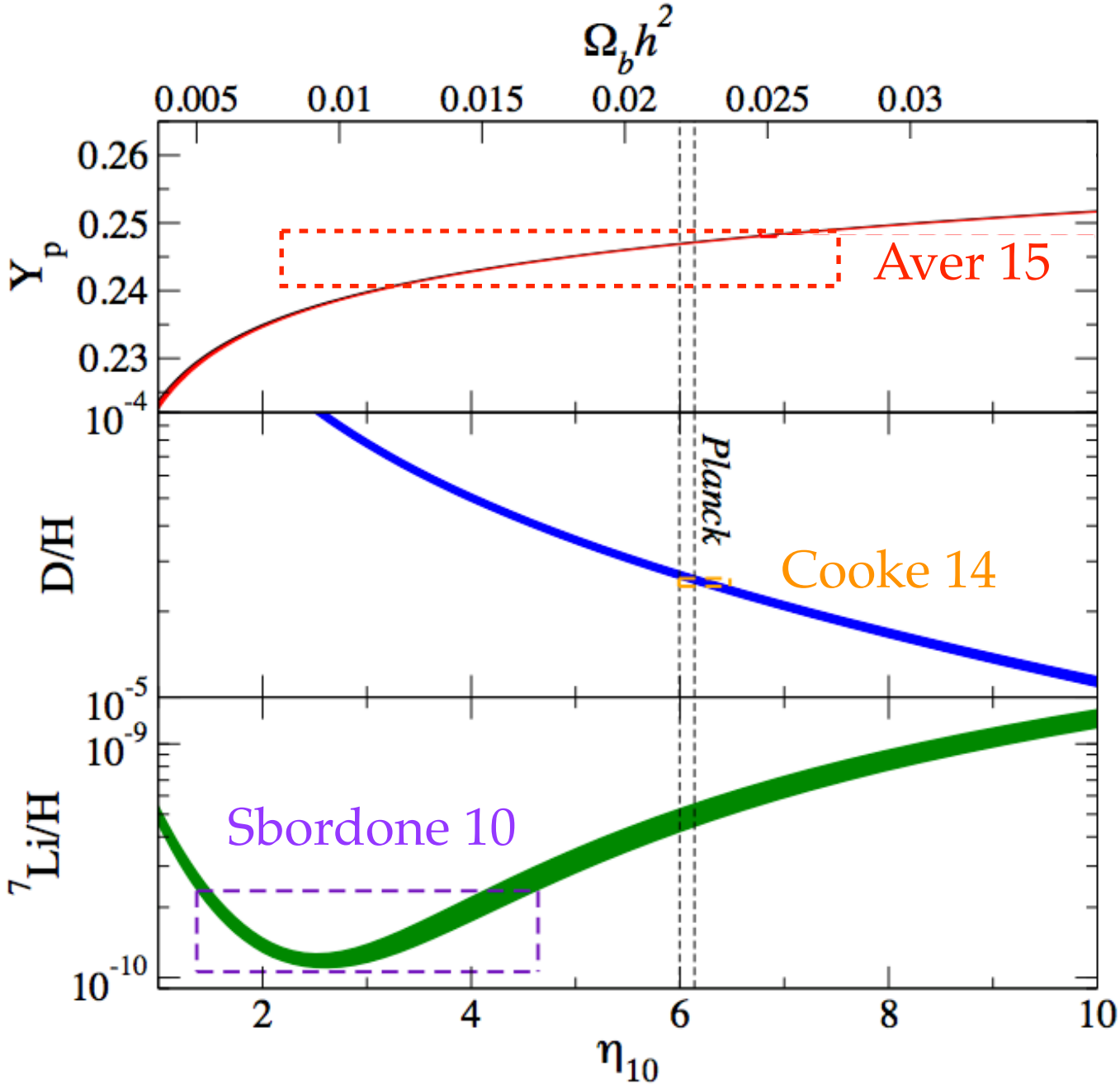



50000ly
40000ly
Barnard's Star
LSR J1826+3014
<
>



Sbordone+ 2010

BBN theory confronts observations 2015



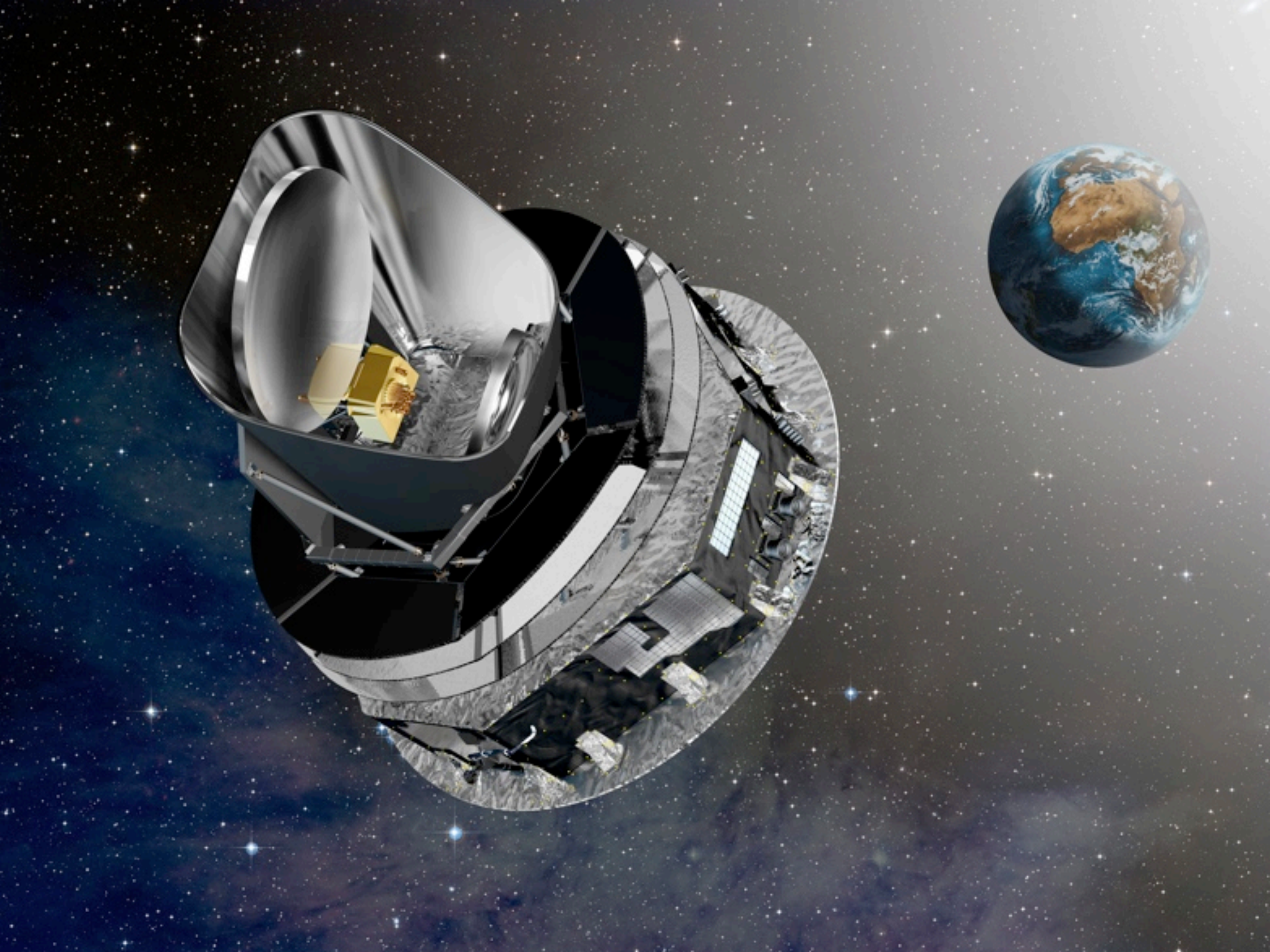
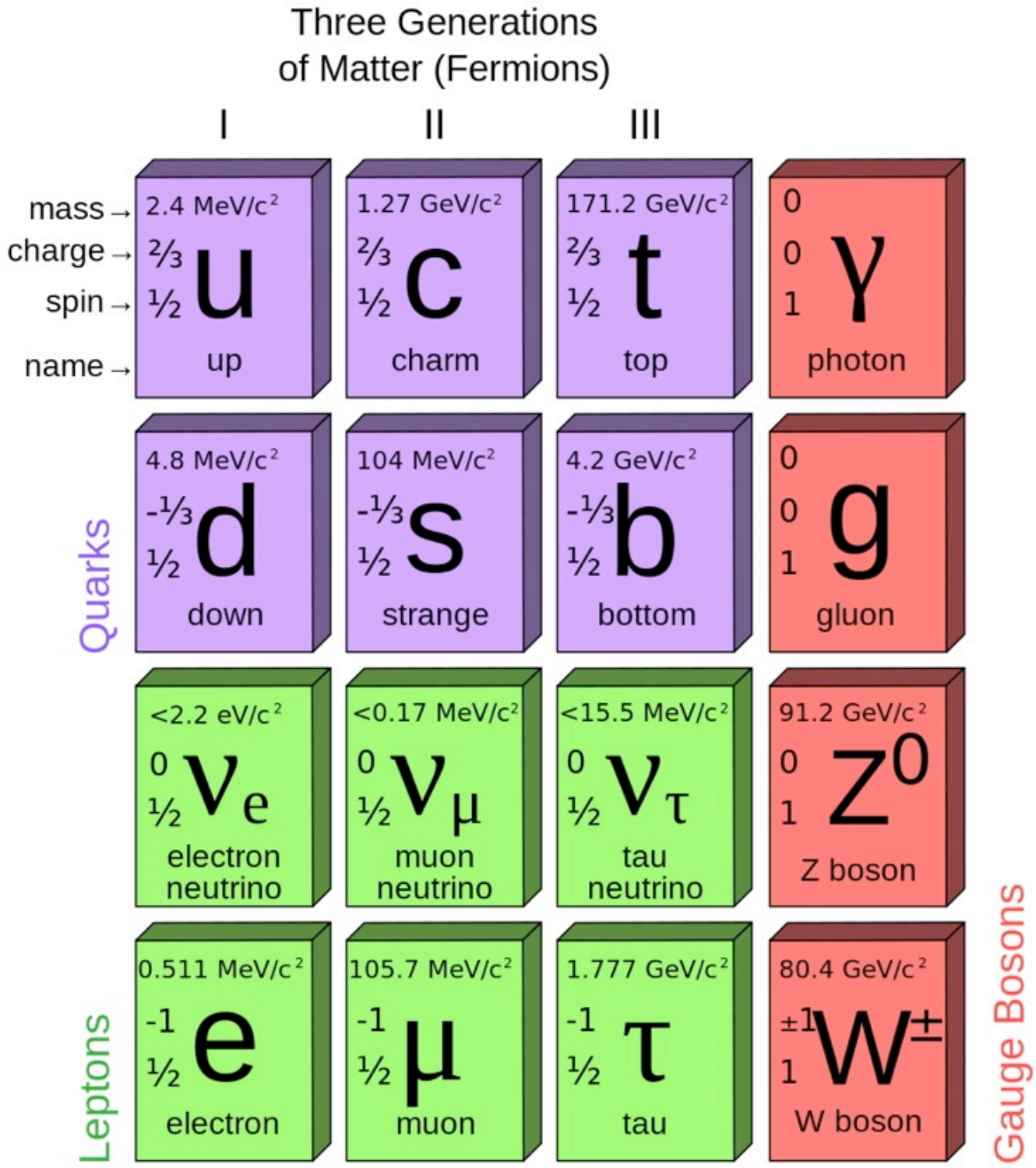
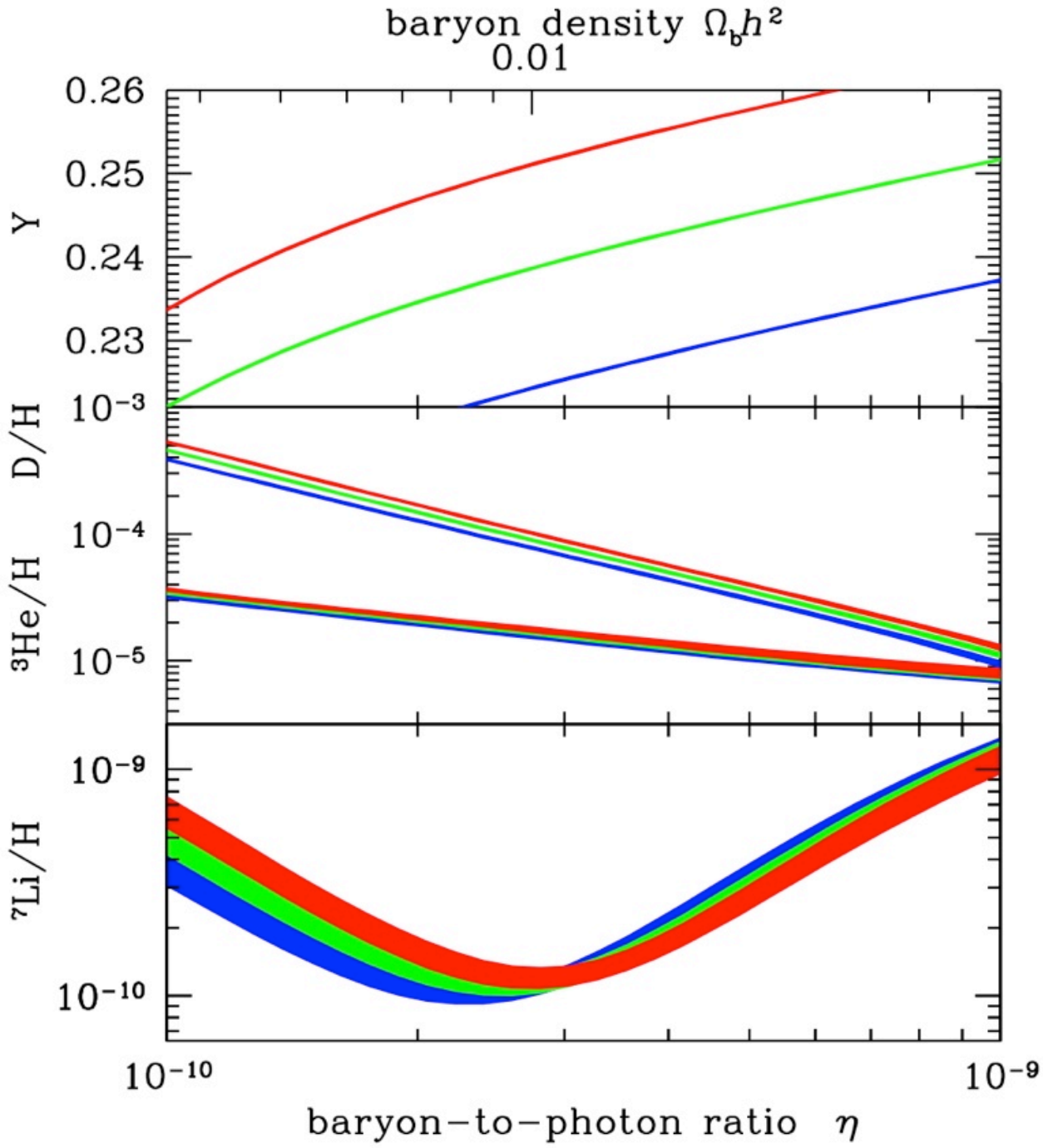


Table 1.1: Cosmic Inventory

Component	$\boldsymbol{\Omega}$ (ρ/ρ_c)
Dark Energy	$\mathbf{0.691 \pm 0.006}$
Matter (baryonic and non-baryonic)	$\mathbf{0.312 \pm 0.009}$
Baryons (Total)	$\mathbf{0.0488 \pm 0.0004}$
Baryons in stars and stellar remnants	$\mathbf{\sim 0.003}$
Neutrinos	$\mathbf{\sim 0.001}$
Photons (CMB)	$\mathbf{5 \times 10^{-5}}$


Three Generations
of Matter (Fermions)
I
II
III
mass →
charge →
spin →
name →
2.4 MeV/c²
⅔
½
u
up
1.27 GeV/c²
⅔
½
c
charm
171.2 GeV/c²
⅔
½
t
top
0
0
1
γ
photon
Quarks
4.8 MeV/c²
-⅓
½
d
down
104 MeV/c²
-⅓
½
s
strange
4.2 GeV/c²
-⅓
½
b
bottom
0
0
1
g
gluon
<2.2 eV/c²
0
½
νe
electron
neutrino
<0.17 MeV/c²
0
½
νμ
muon
neutrino
<15.5 MeV/c²
0
½
ντ
tau
neutrino
91.2 GeV/c²
0
1
Z⁰
Z boson
Leptons
0.511 MeV/c²
-1
½
e
electron
105.7 MeV/c²
-1
½
μ
muon
1.777 GeV/c²
-1
½
τ
tau
80.4 GeV/c²
±1
1
W±
W boson
Gauge Bosons

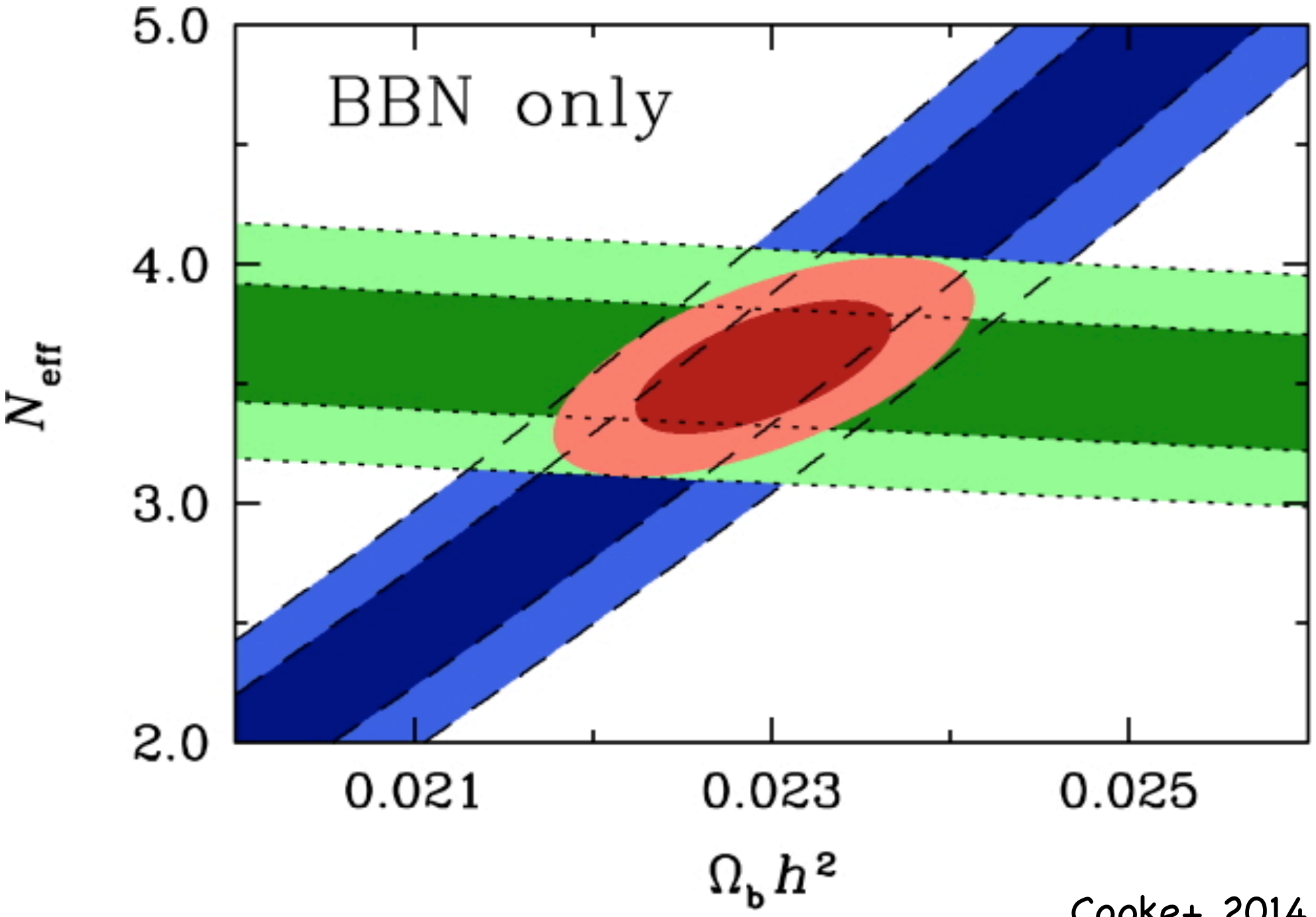


$\mathcal{N}_\nu = 4$

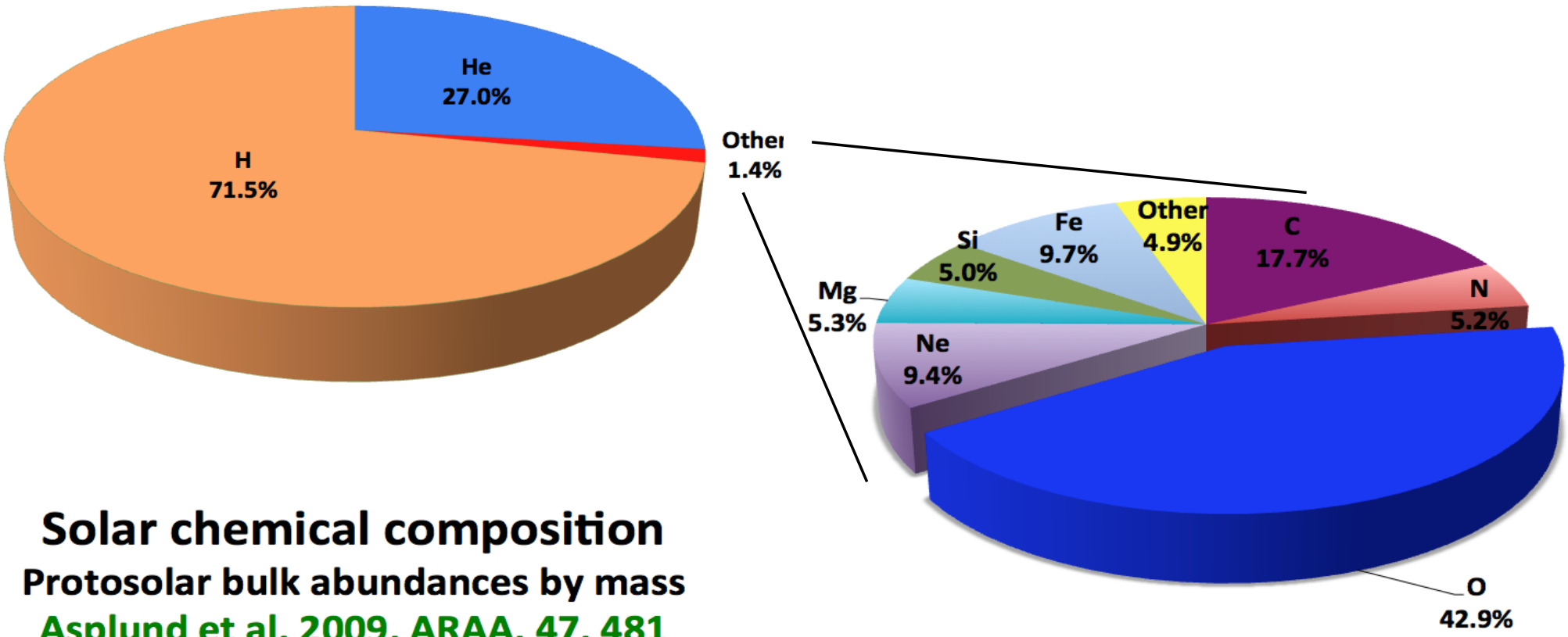
$\mathcal{N}_\nu = 3$

$\mathcal{N}_\nu = 2$

Cyburt+ 2015



Cooke+ 2014



Solar chemical composition

Protosolar bulk abundances by mass

Asplund et al. 2009, ARAA, 47, 481