BIG BANG NUCLEOSYNTHESIS

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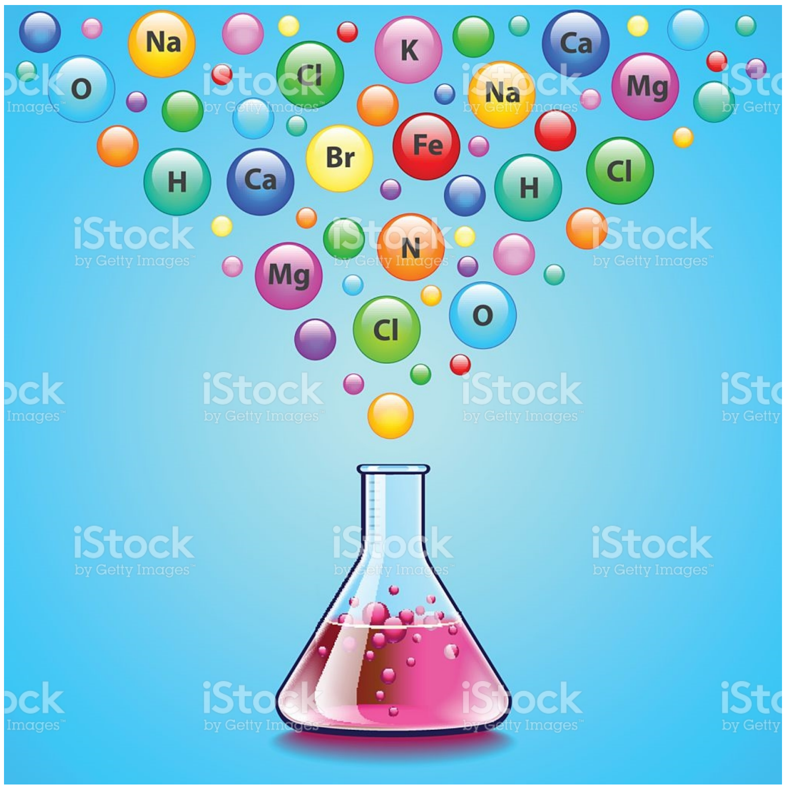
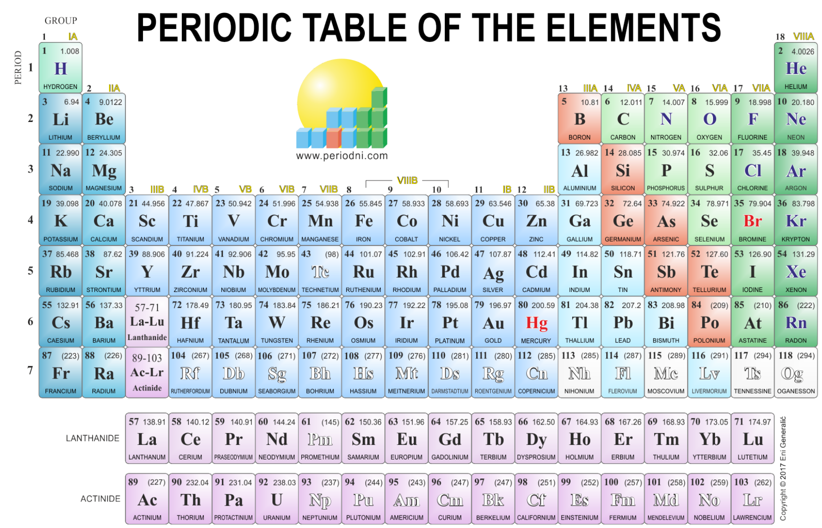
Galaxies Étoiles Physique et Instrumentation

Chemical elements?

?





Primordial Nucleosynthesis

- **Production of nuclei other than H in a period $1\mathrm{s} \leq t \leq 300\mathrm{s}$ after Big Bang**
- **The prediction of the Standard Model on the production of D, ^{3}He, ^{4}He, ^{7}Li is overall in good agreement with the observations**
- **BBN started with the work of Gamow, Alpher and Herman in the 1940s who predicted connection between the elements formation and the 3 K background radiation**

  they predicted the production of all elements, not only the light ones; with the discovery of the instability of the Z=5 element it revealed clear that this is not possible

Primordial Nucleosynthesis

- Standard Model of the very early Universe simple and determined by three milestones:
  - expansion governed by General Relativity;
  - particle interactions governed by Standard Model;
  - particle distribution governed by statistical physics.
- SBBN depends on only ONE parameter:
  - **baryon-to-photon ratio** $\eta = \frac{n_b}{n_\gamma}$ (baryons: protons, neutrons and nuclei) or
  - **baryon density** Ω_b (dimensionless quantity)
  - the ^{4}He abundance depends also on expansion rate

Baryon to photon ratio

- η
  - baryon-to-photon ratio $\eta = \frac{n_b}{n_\gamma}$
  - baryon-to-photon ratio $\eta_{10} = \frac{\eta}{10^{-10}}$
  - The predicted abundance of light elements depends only on η
- Number of photon n_γ
  - in the present Universe known from the cosmic background temperature (411 ± 2 photons per cm^3)
  - the number of photons has not changed in time (emission from stars is negligible)

Baryon to photon ratio

- Present: $\Omega_{b,0}$
  - $\Omega_{b,0}h^2 = 3.65 \times 10^{-3}\eta_{10}$
  - h present expansion rate:
    $h = \frac{H_0}{100\mathrm{kms}^{-1}\mathrm{Mpc}^{-1}}$ with
    - $H_0 = \frac{\dot{R}_0}{R_0}$, H_0 present Hubble constant.
    - $R(t)$ cosmic scale factor, evolving in time and describing expansion of the Universe; with t the cosmic time
    - $\left(\frac{\dot{R}_0}{R_0}\right)^2 = H^2(t) = \frac{1}{8t^2} = \frac{8\pi G}{3}\rho(t)$ with $\rho(t)$ the energy of the Universe, G Newton constant.

Cosmic

- $\frac{n_b}{n_\gamma}$ at the BBN time is the same as at the recombination time ($\sim 40000\,$yr after BB)

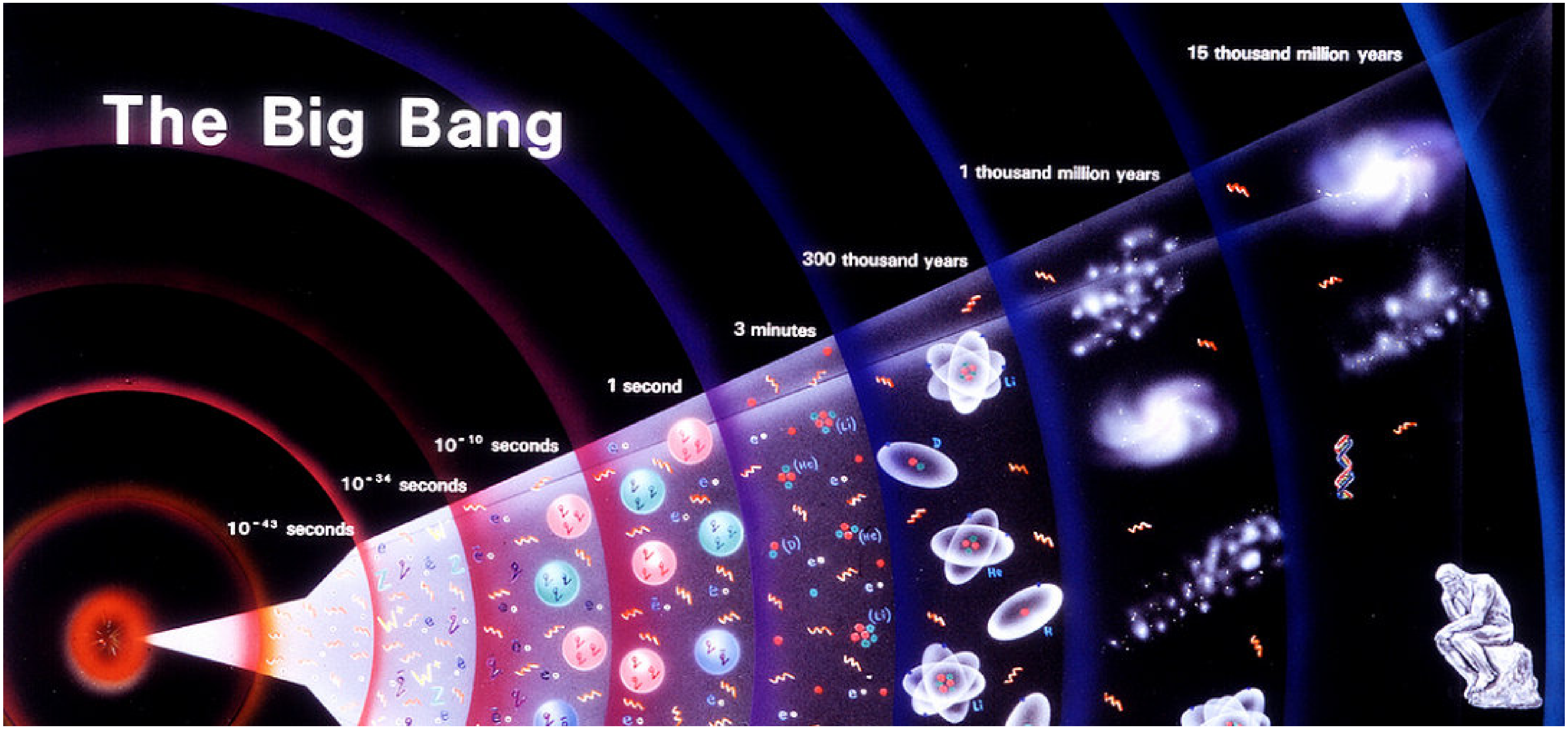
- Abundances of primordial elements, in the Standard Model context, can be derived by using the Cosmic Microwave Background (CMB) radiation derived by Planck

- By using for the CMB the Planck observations $\Omega_{b,0}h^2 = 0.02226 \pm 0.00023$, the primordial elements are (68% confidence):
  - primordial fraction of baryons consisting of ^{4}He: $\mathrm{Y_p} = 0.2471 \pm 0.0005$
  - primordial abundance ratio of D with respect to H: $\mathrm{D/H} = (2.414 \pm 0.047)/10^5$
  - primordial abundance ratio of ^{3}He with respect to H: $^3\mathrm{He/H} = (1.110 \pm 0.022)/10^5$
  - primordial abundance ratio of ^{7}Li: $\mathrm{A}(^7\mathrm{Li/H}) = 2.745 \pm 0.021$ (with $\mathrm{A}(^7\mathrm{Li/H}) = \log_{10}(^7\mathrm{Li/H}) + 12$)

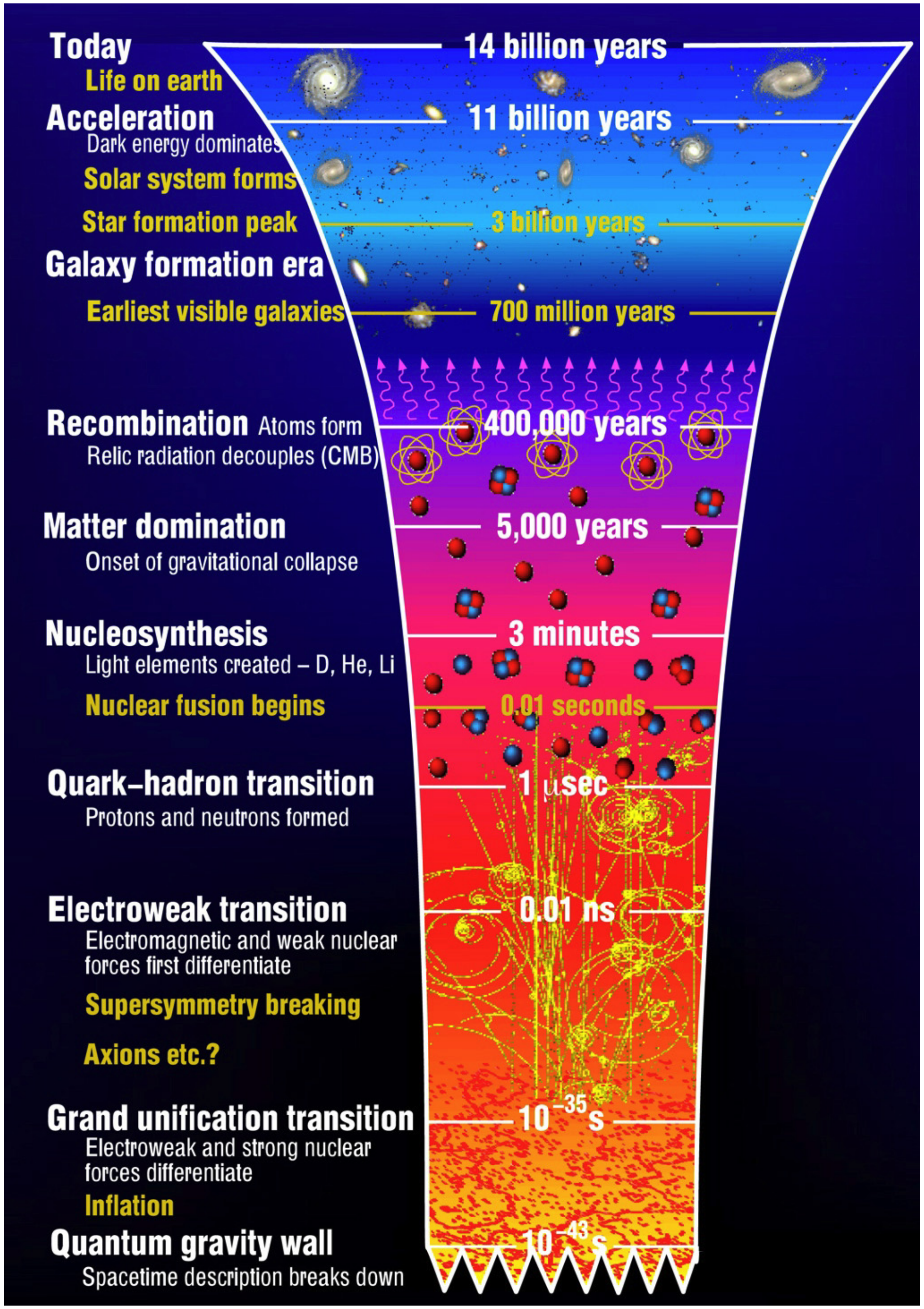
Big Bang first modelled time

- According to Standard Model at $t = 0\,\text{s}$, the instant of the Big Bang, matter and radiation of the Universe were condensed in a point

- First time that can be modelled at $t = 10^{-43}\,\text{s}$
  - gravitational, strong, weak, electromagnetic forces were undistinguished
  - there are particle of matter and antimatter in equal proportion
  - particles create radiation and are created from radiation



At $t \sim 10^{-34}$ s tiny excess of matter over antimatter (one matter particle surviving over 10^9 particles to annihilate with antimatter)



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

Big Bang first times

- At $t \sim 10^{-5}$ s
  - Protons and neutrons builded
  - Remaining antimatter (in form of positrons e^+) disappeared significantly when energy below level to create couples $e^+ + e^-$

Early Universe

- **Early times: $T \sim 10^{12}$ K, $t \sim 10^{-4}$ s**
  - Universe filled by gas extremely hot and dense
  - matter completely dissociated
  - matter in equilibrium with radiation
- As Universe evolve:
  - $T(t)$ changes due to expansion in timescale-order $H(t)$:
    - $H^{-1}(t) = \left(\frac{\dot{R}_0}{R_0}\right)^{-1}$
  - Particles couple directly or indirectly with with photons, rate of interaction:
    - $\Gamma = n\langle\sigma v\rangle$
      with n number density of target particles
      v relative velocity
      σ interaction cross section
    - for $\Gamma(t) > H(t)$ interactions can maintain equilibrium

Early Universe $t < 1$ s

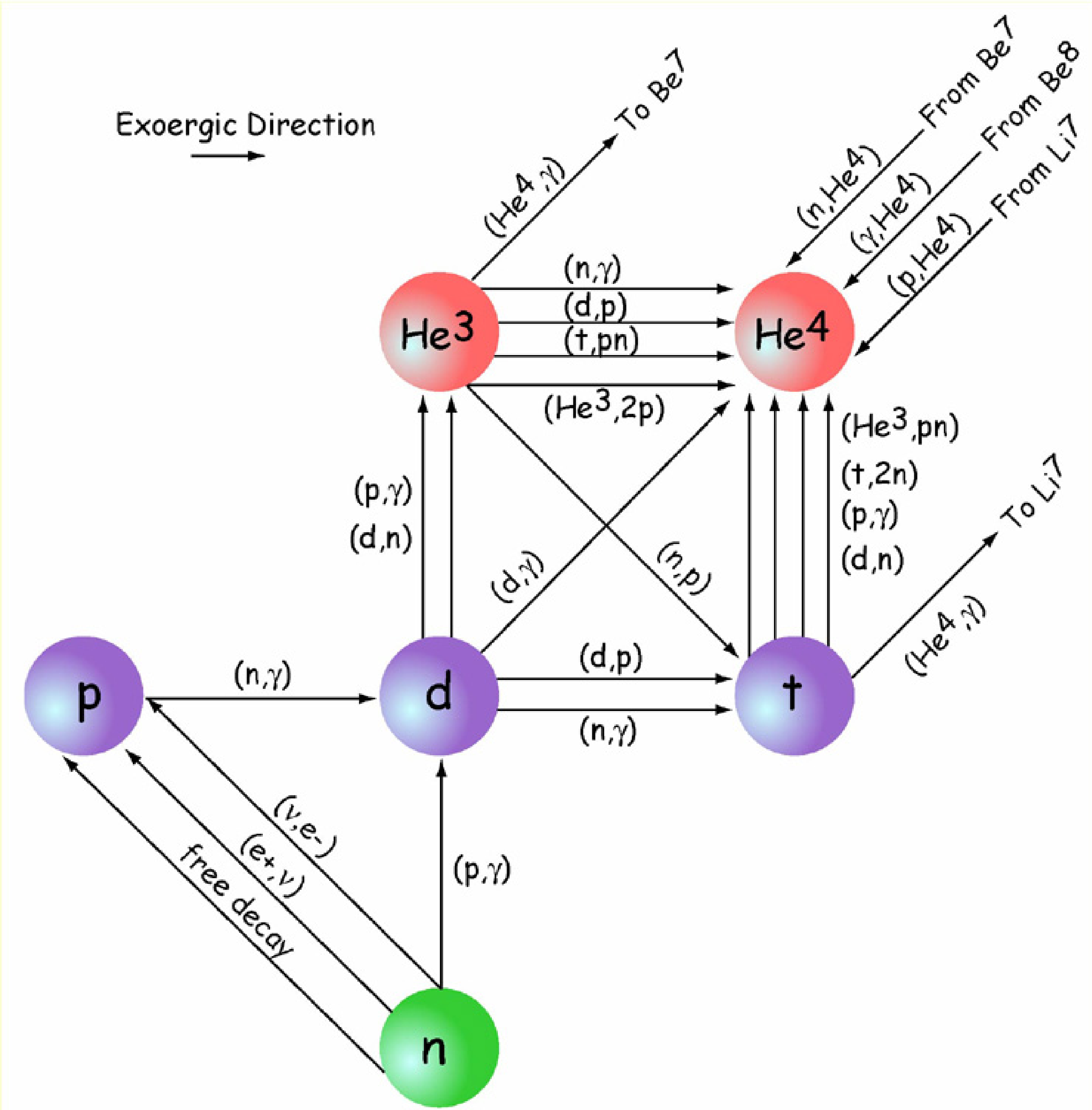
- At $T > 10^{10}$ K and $t < 1$ s there is statistical and thermal equilibrium
- inter-conversion between neutron and proton:
  - $n + \nu \longleftrightarrow p + e^-$
  - $n + e^+ \longleftrightarrow p + \nu$
  - $n \longleftrightarrow p + e^- + \bar{\nu}$
- $\frac{n}{p} = \exp\left(-\frac{Q}{T}\right)$ will be maintained as long as $n - p$ reactions are rapid enough ($Q = 1.293$ MeV)
- as the temperature is such that $\Gamma(T) < H(T)$
  - **n/p ratio get frozen**
  - only the β-decay, $n \longrightarrow p + e^- + \bar{\nu}$, continues
  - **this happens for $T \sim 0.8$ MeV at $t \sim 1$ s**, and $\frac{n}{p} \sim \frac{1}{6}$
  - $\frac{n}{p}$ slowly decreases (occasional weak interactions, dominated by n decay)
  - $\frac{n}{p} \sim \frac{1}{7}$ **at the time nucleosynthesis begins**

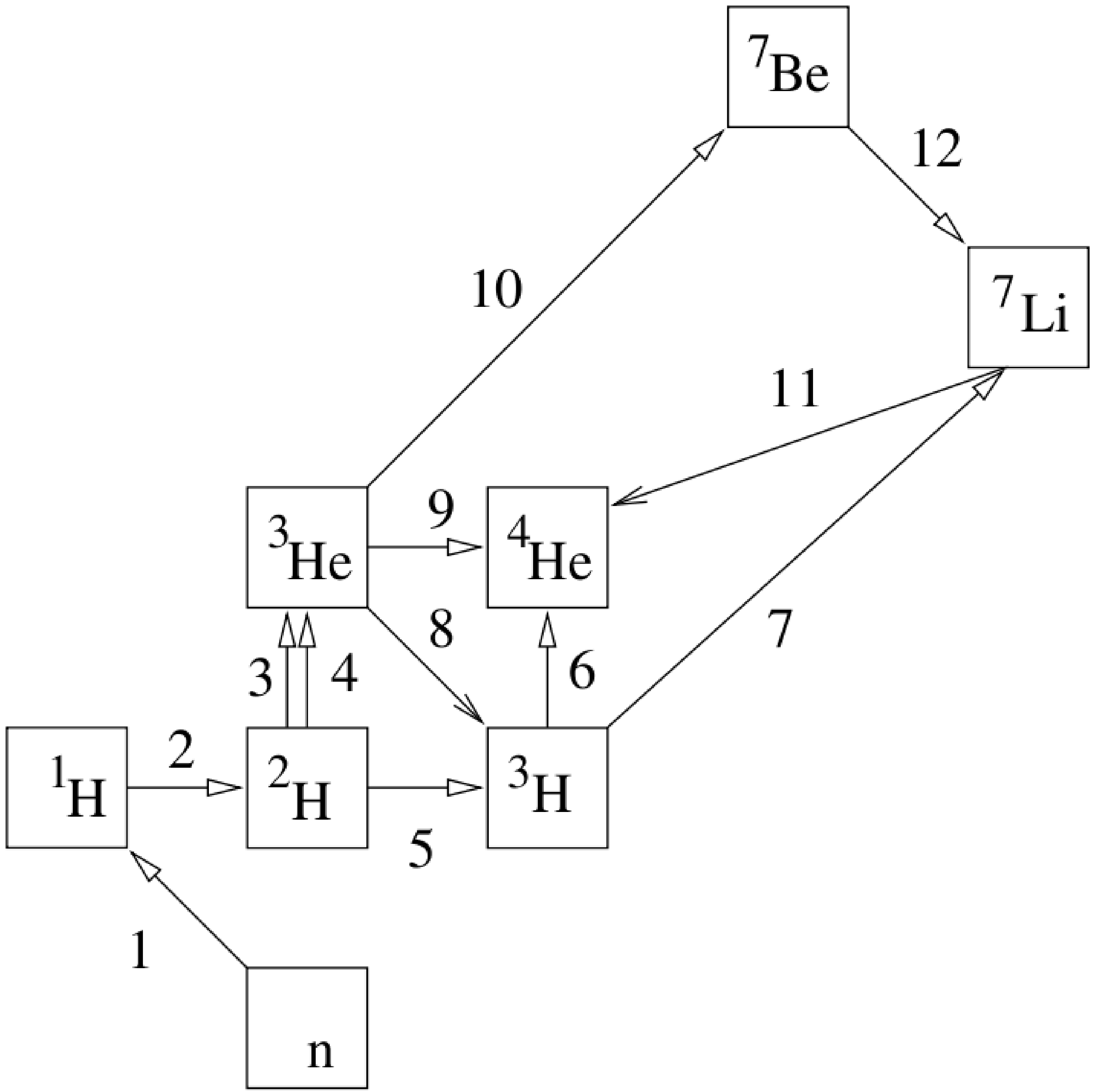
D formation

- When $n - p$ no more in equilibrium
  - $\frac{n}{p} \sim \frac{1}{6}$
  - it starts $n + p \longrightarrow D + \gamma$
  - but for $T \geq 10^9$ K (at $t \leq 100$ s)
    - γ enough energetic for
    - $\mathrm{D} + \gamma \longrightarrow n + p$ faster than
    - $n + \mathrm{D} \longrightarrow^3 \mathrm{H} + \gamma$ and $p + \mathrm{D} \longrightarrow^3 \mathrm{He} + \gamma$
    - tiny abundances of D, $^3\mathrm{He}$ and $^4\mathrm{He}$

D and He formation

- For $T \sim 10^9$ K (~ 0.1 MeV), at $t \sim 100$ s)
- nuclei are built
  - $n + \mathrm{D} \longrightarrow^3 \mathrm{H}$
  - $p + \mathrm{D} \longrightarrow^3 \mathrm{He}$
  - $n + \mathrm{He} \longrightarrow^4 \mathrm{He}$
  - $\mathrm{D} + \mathrm{D} \longrightarrow^4 \mathrm{He}$
- **D is the bottleneck, the first stepping stone to build heavier elements**


Exoergic Direction
To Be7
From Be7
From Be8
From Li7
(He4,γ)
(n,He4)
(γ,He4)
(p,He4)
(n,γ)
(d,p)
(t,pn)
(He3,2p)
He3
He4
(p,γ)
(d,n)
(d,γ)
(n,p)
(He3,pn)
(t,2n)
(p,γ)
(d,n)
To Li7
(He4,γ)
p
(n,γ)
d
(d,p)
(n,γ)
t
(ν,e-)
(e+,ν)
free decay
(p,γ)
n



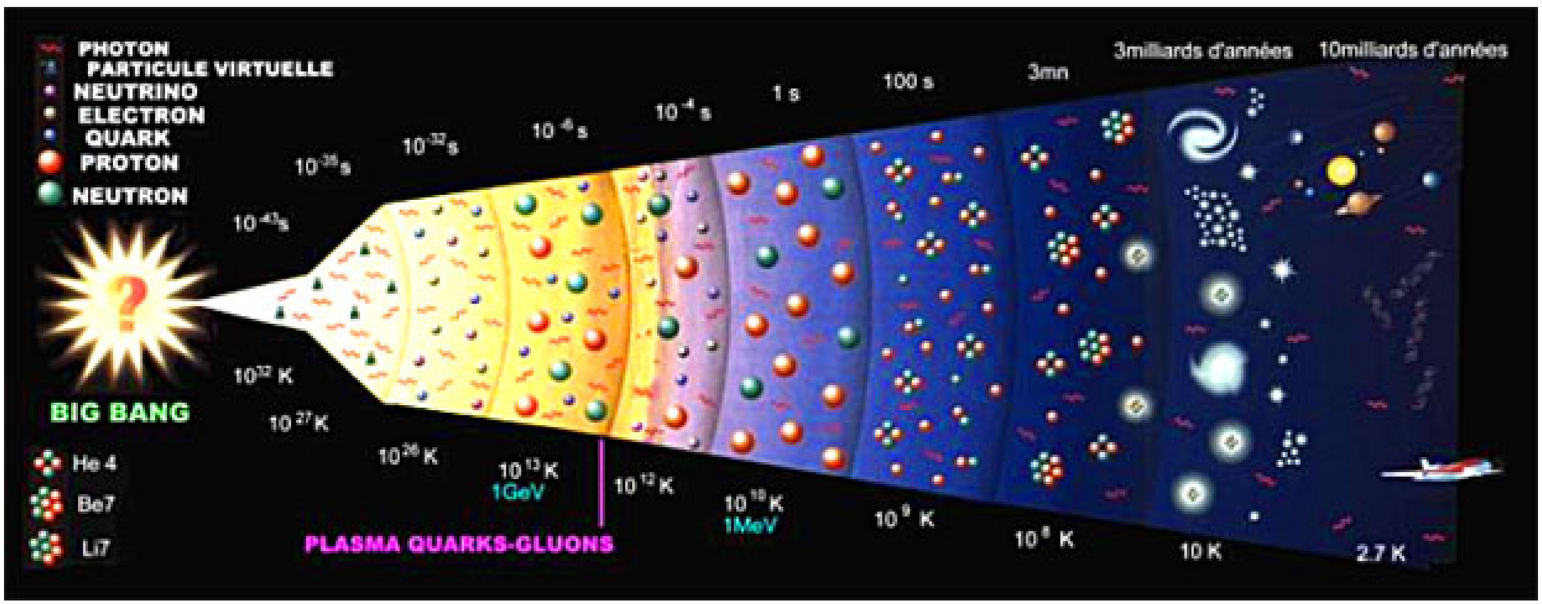
1. $p \longleftrightarrow n$
2. $p(n, \gamma)d$
3. $d(p, \gamma)^3\mathrm{He}$
4. $d(d, n)^3\mathrm{He}$
5. $d(d, p)t$
6. $t(d, n)^4\mathrm{He}$
7. $t(\alpha, \gamma)^7\mathrm{Li}$
8. $^3\mathrm{He}(n, p)t$
9. $^3\mathrm{He}(d, p)^4\mathrm{He}$
10. $^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}$
11. $^7\mathrm{Li}(p,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

- At $t \sim 100\,\mathrm{s}$
  - $\frac{n}{p} \sim \frac{1}{7}$
  - Assuming all available n end bond in ${}^4\mathrm{He}$
  - Mass fraction of ${}^4\mathrm{He}$:
    $\mathrm{Y} = \frac{4n_n/2}{n_n+n_p} = \frac{2n/p}{1+n/p} \sim 0.25$
  - if the n number density is n_n, $n_n/2$ ${}^4\mathrm{He}$ can be formed.

- be T_* temperature for $\Gamma(T_*) = H(T_*)$
- but $\Gamma(T) \sim T^5 t$
- and $H(T) \sim \frac{1}{2t} \sim g^{1/2}(T) T^2 \sqrt{\frac{8\pi G}{3}}$
- so T_* depends on $g(T)$, the number of degree of freedom of the radiation at $T = T_*$
- $g(T_*) = 2 \left[1_\gamma + (7/8 + 7/8)_{e^+ + e^-} + (7/8 N_\nu)_{N_{\nu\bar{\nu}}} \right]$
  - $N_\nu = 3$, $g(T) = 43/4$, but changes if number light neutrino is different
  - $N_\nu = 2, 3, 4$ give $Y \sim 0.227, 0.242, 0.254$

- There is no stable element for atomic mass of 5
- To build elements heavier than $^{4}\mathrm{He}$:
  - collisions of rare D, $^{3}\mathrm{H}$ or $^{3}\mathrm{He}$ with $^{4}\mathrm{He}$ required
  - majority D, $^{3}\mathrm{H}$ or $^{3}\mathrm{He}$ are burnt into $^{4}\mathrm{He}$
- $\Longrightarrow$ **there is very little of heavier elements**

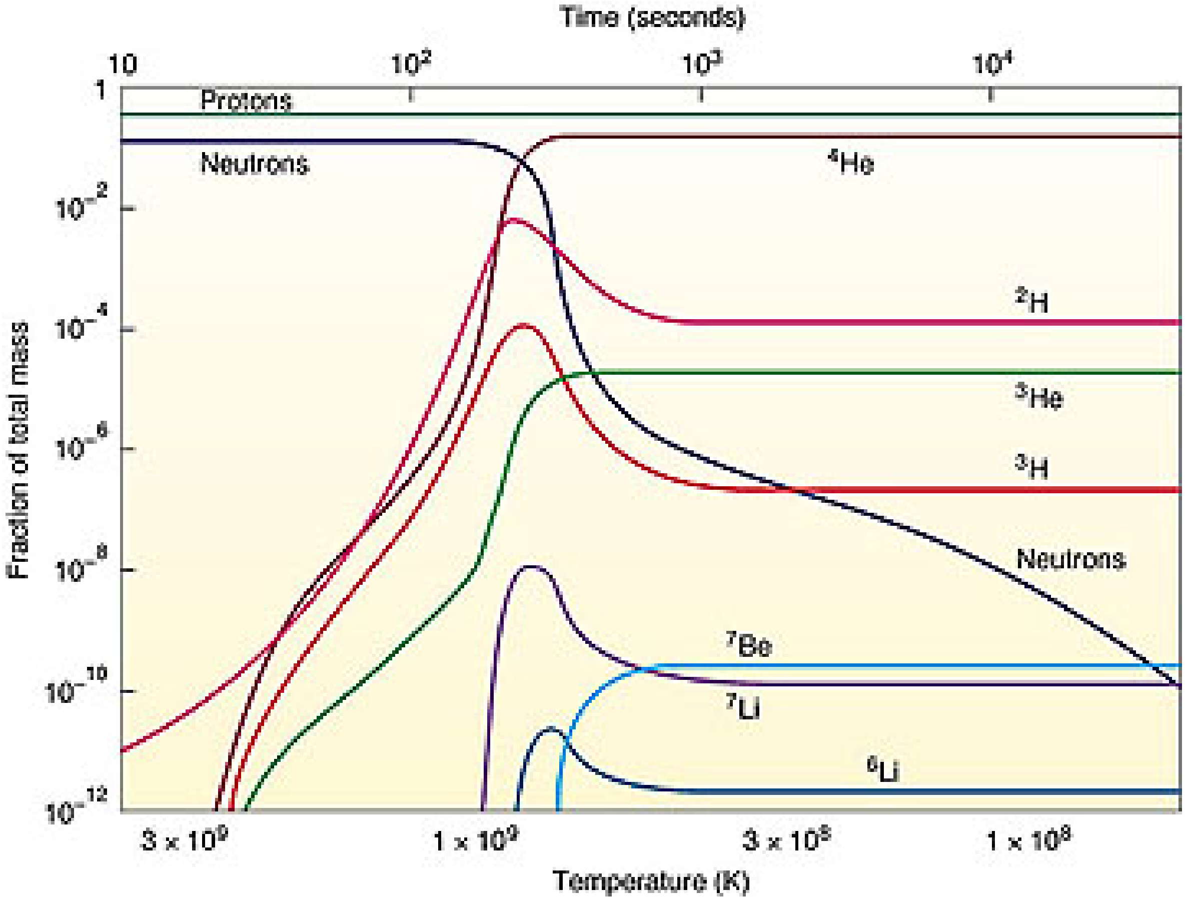
- Universe continue to expand and cool
  - temperature and density decrease
  - nuclear reactions more and more rare
- At $t \sim 10^3\,$s nucleosynthesis is over

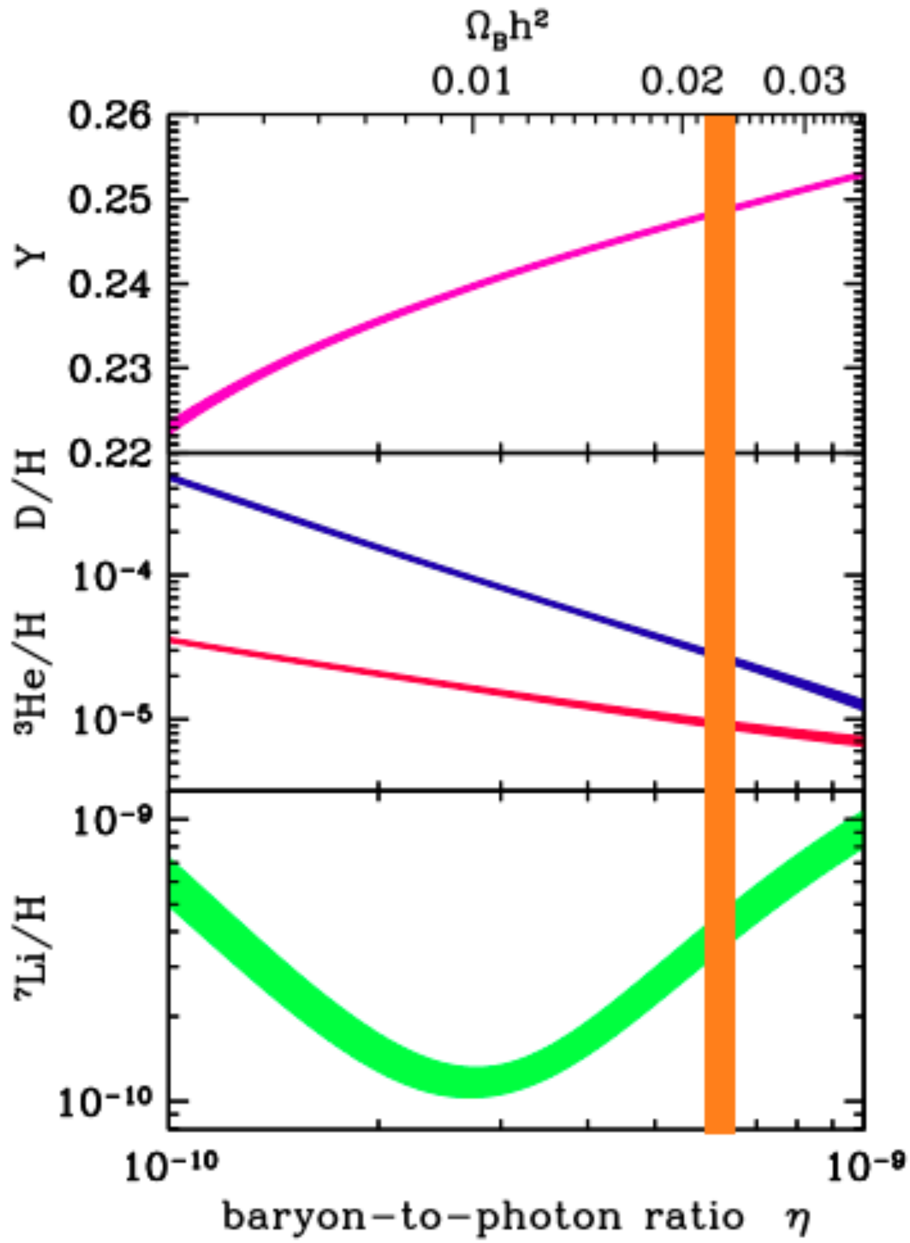


Models

- Two main cosmological parameters on which predictions depend
  - number of degree of freedom g (at $T \sim 1\,\mathrm{MeV}$)
  - baryon to photon ratio
- An increase in g increases $H(T) \sim \sqrt{g}T^2$ leading to higher freeze out temperature ($T_* \sim g^{1/6}$) and higher He abundance.
- Dependence on η is more complicate $\Longrightarrow$ nucleosynthesis can be followed with large number of equations (code).
- Wagoner (1973, ApJ 179, 343) wrote first code, improved by Kawano (1992, preprint FERMILAB Pub 92/04A).

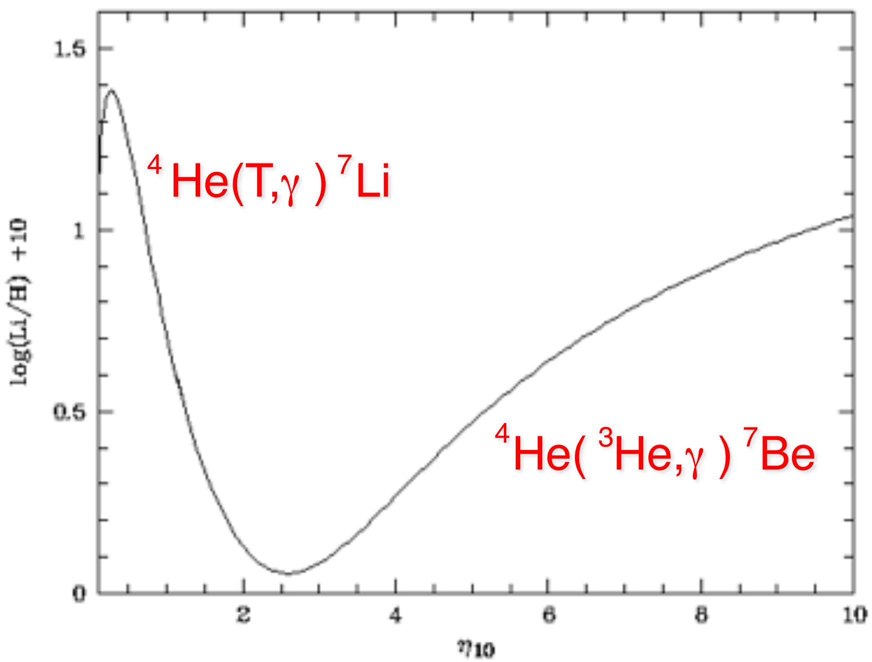
Primordial abundances



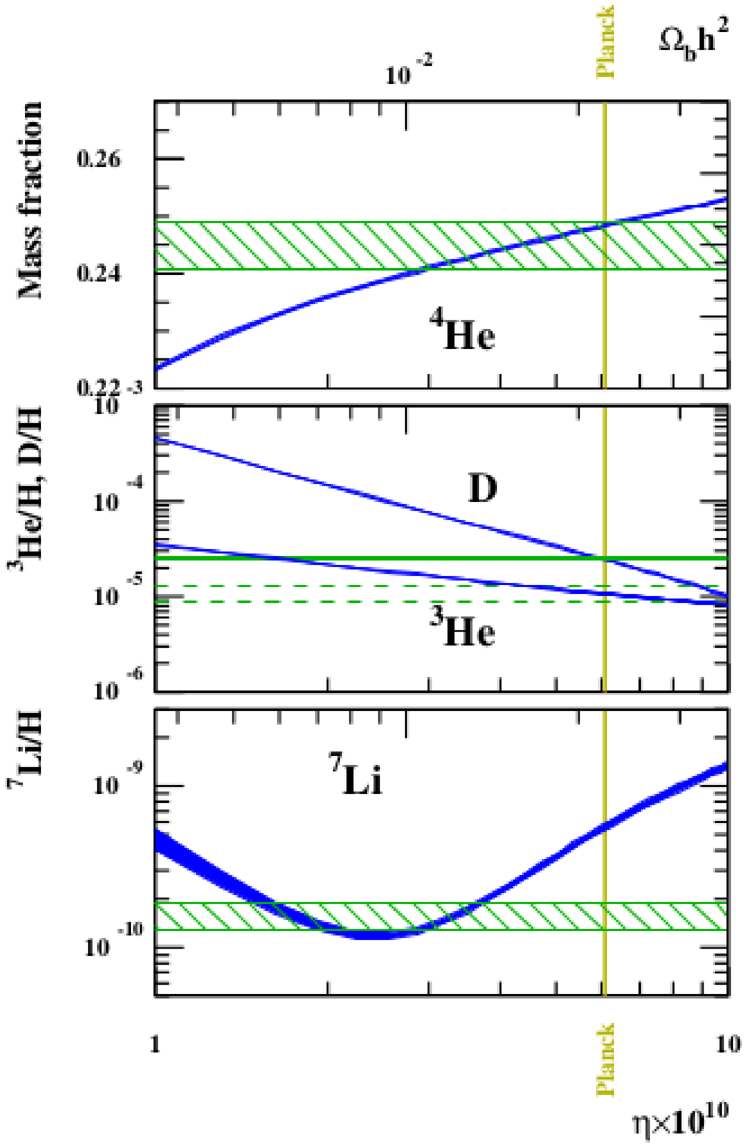


$\Omega_B h^2$
0.01
0.02
0.03
0.26
0.25
0.24
0.23
0.22
Y
D/H
10^{-4}
^{3}He/H
10^{-5}
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon−to−photon ratio η

The lithium valley



SBBN predicts an ABSOLUTE minimum for the Li abundance

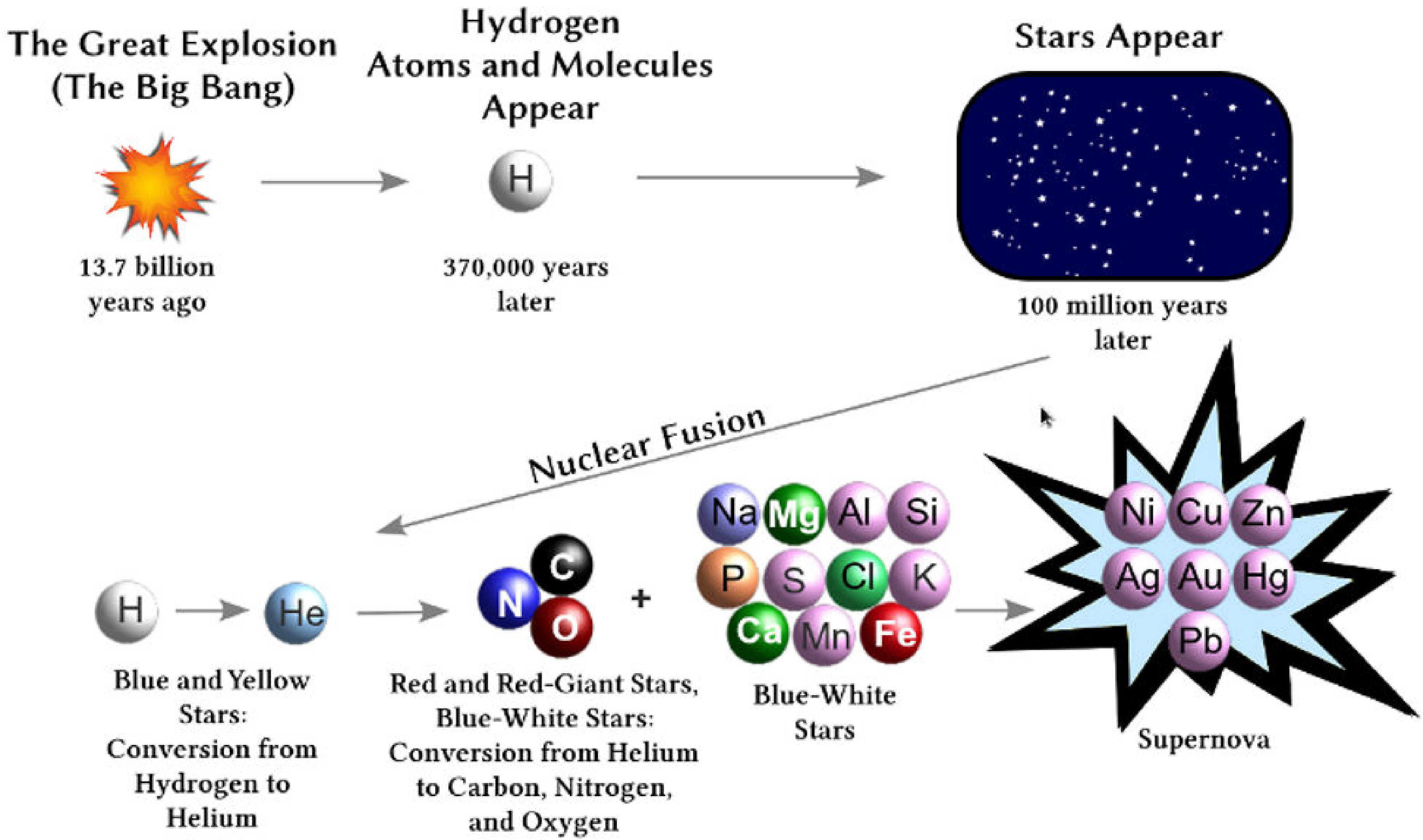


From Coc & Vangioni 2017
Vertical strip the CMB baryonic; horizontal green areas represent the primordial abundances.

Observations

- **Goal would be to derive the primordial abundance of D, ^{3}He, ^{4}He, ^{7}Li**
  - **A good precision needed (at the limit or beyond of current capabilities)**
  - **A theoretical understanding for each element of all mechanisms of**
    - **production**
    - **destruction**
  - **Observe in the right place.**

- **As stars are formed, metals are synthesised in (massive) stars**
- **As massive stars explode as supernovae, ISM is enriched by metals**
- $\Longrightarrow$ **metal content is an indication of age**
  - **Old stars are poor in metals (metal-poor stars)**
  - **Young ones are rich (Sun)**
- **Stars "produce" elements**
  - **up to iron in their interior**
  - **heavier in cataclysmic events**
  - **no production of D, Li, Be, B**
- **D is synthesised only in BBN**
- **Li, Be and B can be produced by cosmic rays spallation**
- **Li is produced by novae and AGB stars**
- **Only ^{10}B and ^{11}B stable**



The Great Explosion (The Big Bang)
13.7 billion years ago
Hydrogen Atoms and Molecules Appear
H
370,000 years later
Stars Appear
100 million years later
Nuclear Fusion
H
He
Blue and Yellow Stars: Conversion from Hydrogen to Helium
C
N
O
Red and Red-Giant Stars, Blue-White Stars: Conversion from Helium to Carbon, Nitrogen, and Oxygen
+
Na Mg Al Si
P S Cl K
Ca Mn Fe
Blue-White Stars
Ni Cu Zn
Ag Au Hg
Pb
Supernova

Deuterium

- **Never produced in stars**
- **Low binding energy: 2.2 MeV**
- **Destroyed by stellar evolution processes, via**

$$D + p \longrightarrow ^3 He + \gamma + 5.49\mathrm{MeV}$$

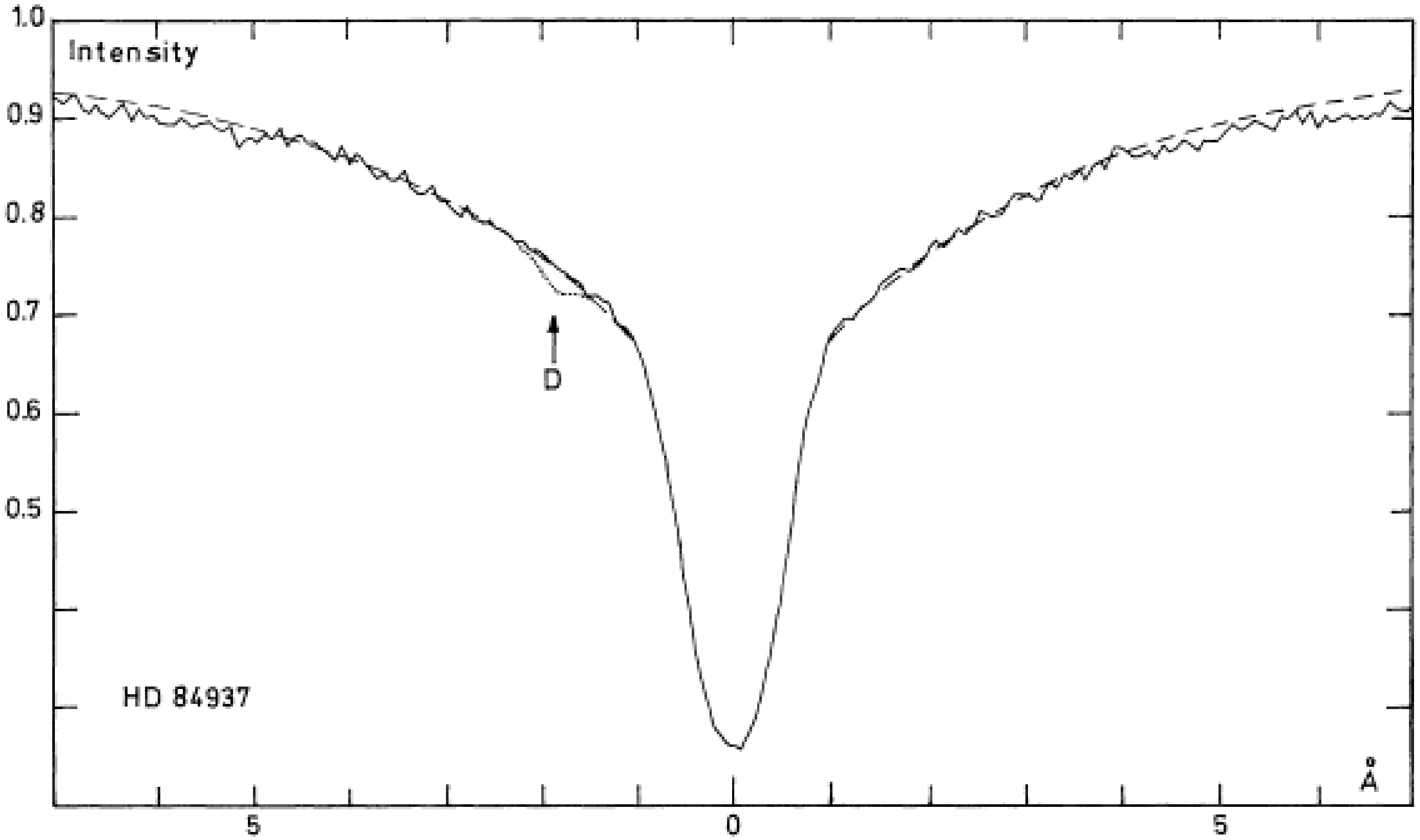
- **Its abundance decreases with time**
- **Observations provide lower limit of its primordial value**
- **Its abundance in low-metallicity environment has to be close to BBN value**
- **Its primordial abundance very sensitive to Ω_b (monotonic behaviour, $\frac{\mathrm{D}}{\mathrm{H}} \propto \eta^{-1.6}$)**

Deuterium

- Historically the first determinations from Lyman limit systems
  - D information detectable only on Lyman-α line
- D can be safely measured only in high red-shift, low-metallicity damped Lyman α where observations challenging

Difficult to derive D in old stars' atmospheres

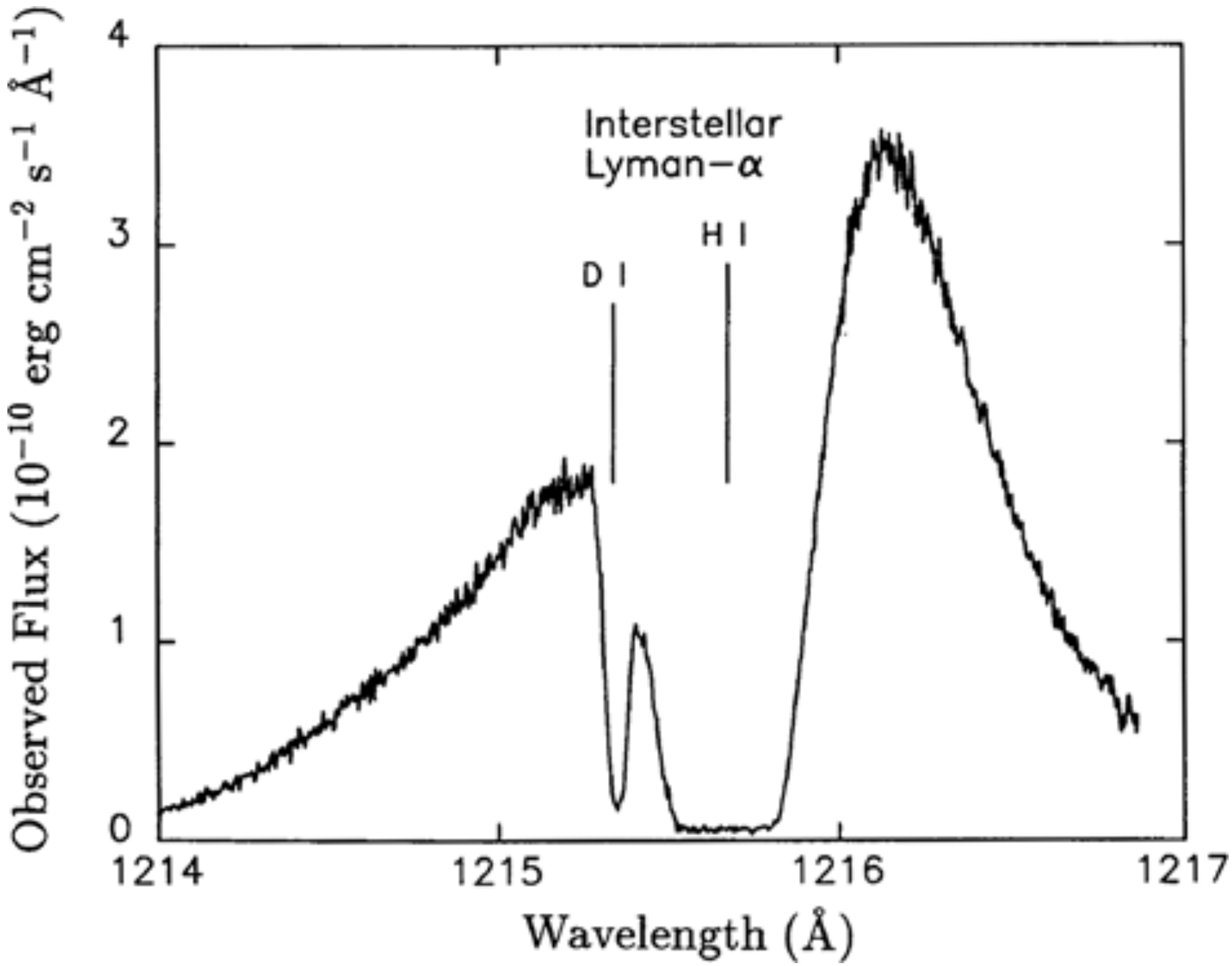
Hα in HD 84937 (6250 K/4.0/–2.1)

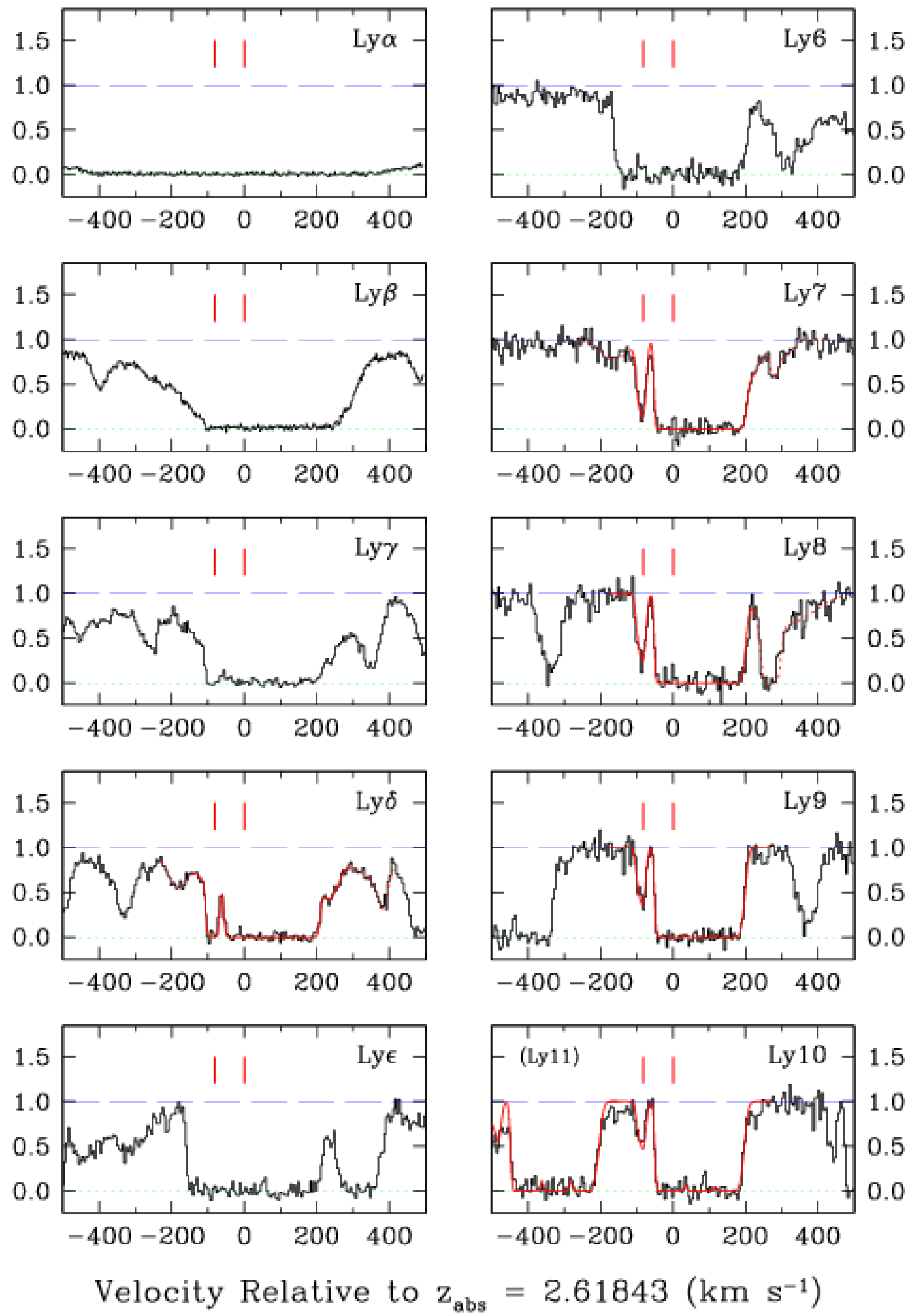


$N_D/N_H = 4 \times 10^{-5}$ (dotted line) $N_D/N_H = 0$ (dashed line)

from Spite, Maillard, & Spite (1983) A&A 128,252

Lyman limit system





Pettini et al. 2008

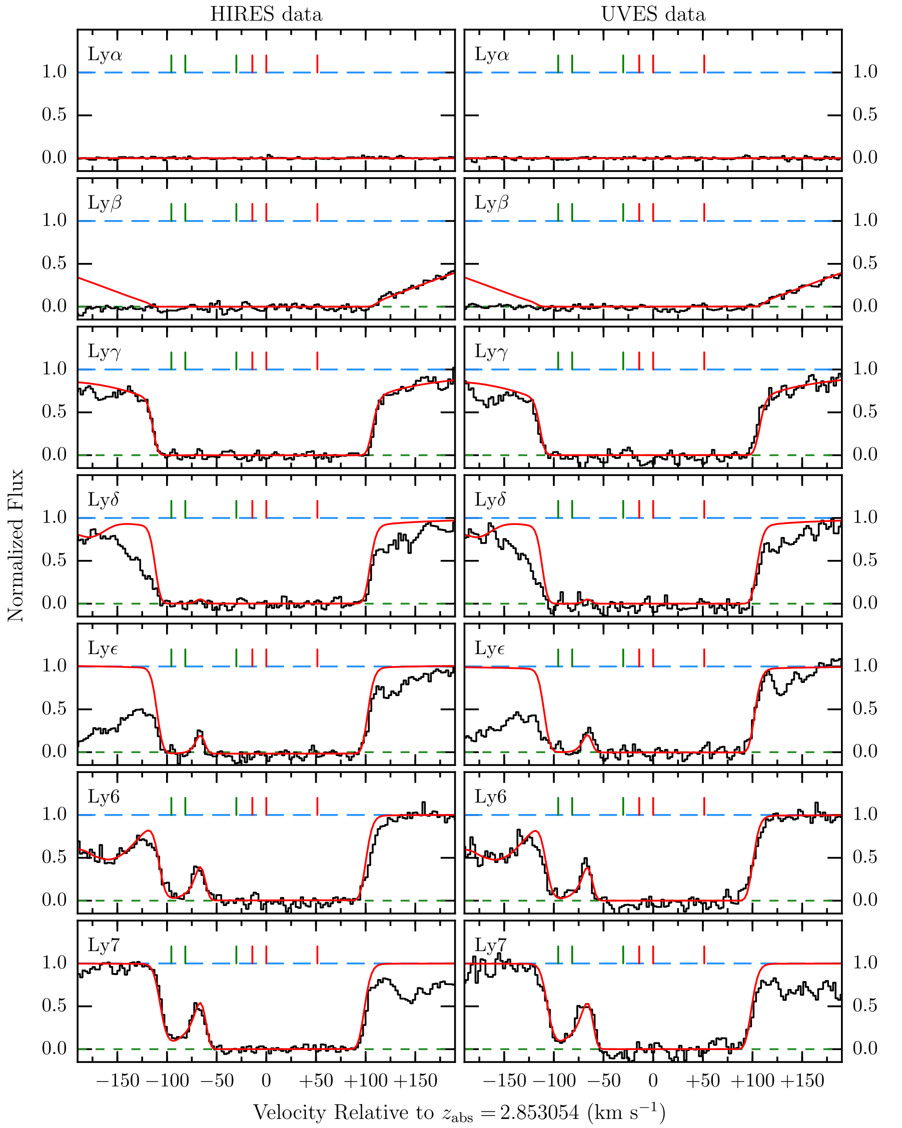
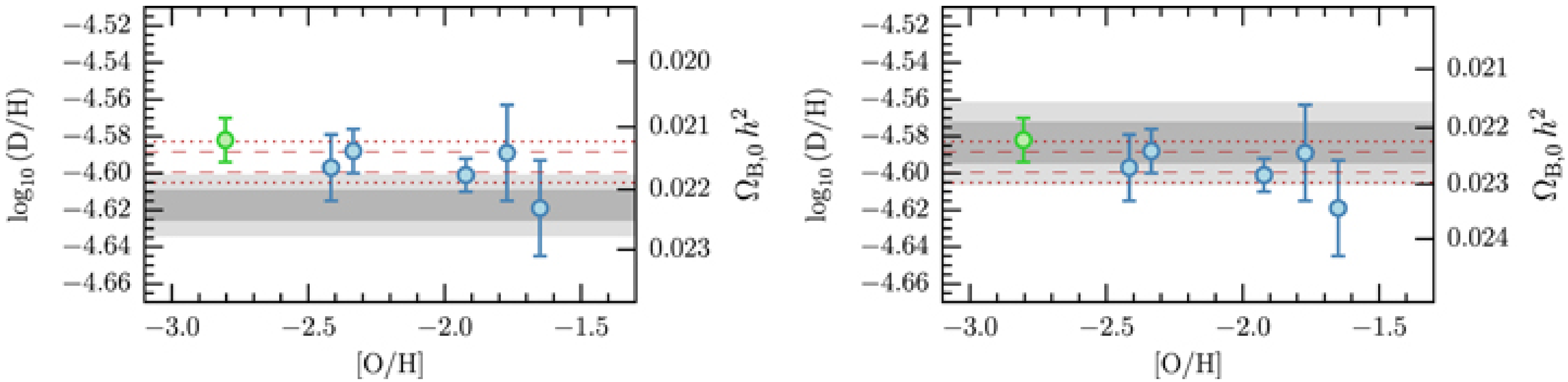


Figure 3. The black histogram shows our HIRES data (left panels) and UVES data (right panels), covering the H I and D I Lyman series absorption lines from Lyα–Ly7 (top to bottom panels, respectively). Our best-fitting model is overlaid with the solid red line. The plotted data have been corrected for the best-fitting zero-level (short green dashed line), and are normalized by the best-fitting continuum model (long blue dashed line). Tick marks above the spectrum indicate the absorption components for H I (red ticks) and D I (green ticks).

High red-shift, low-metallicity damped Lyman α systems, Cooke et al. 2016, ApJ 830, 148

Deuterium



Grees symbols: from Cooke et al. 2016; blue symbols: from Cooke et al. 2014;
dashed and dotted red lines: 68% and 95% confidence interval;
gray area: standard model D/H from authors' calculations;
from Cooke et al. 2016, ApJ 830, 148
Right scale in the two panels uses different of $\mathrm{D} + \mathrm{p} \longrightarrow {}^3\mathrm{He} + \gamma$

Deuterium

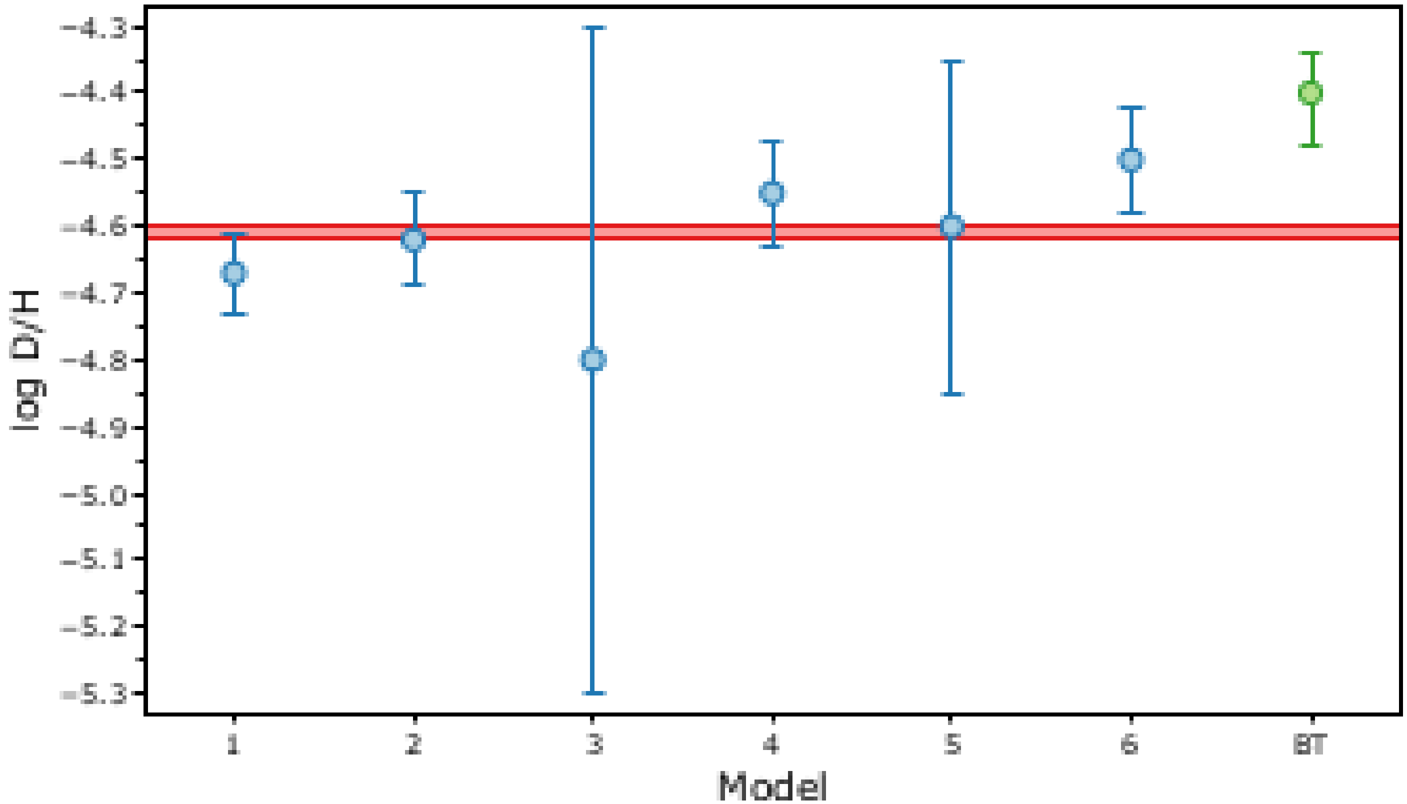
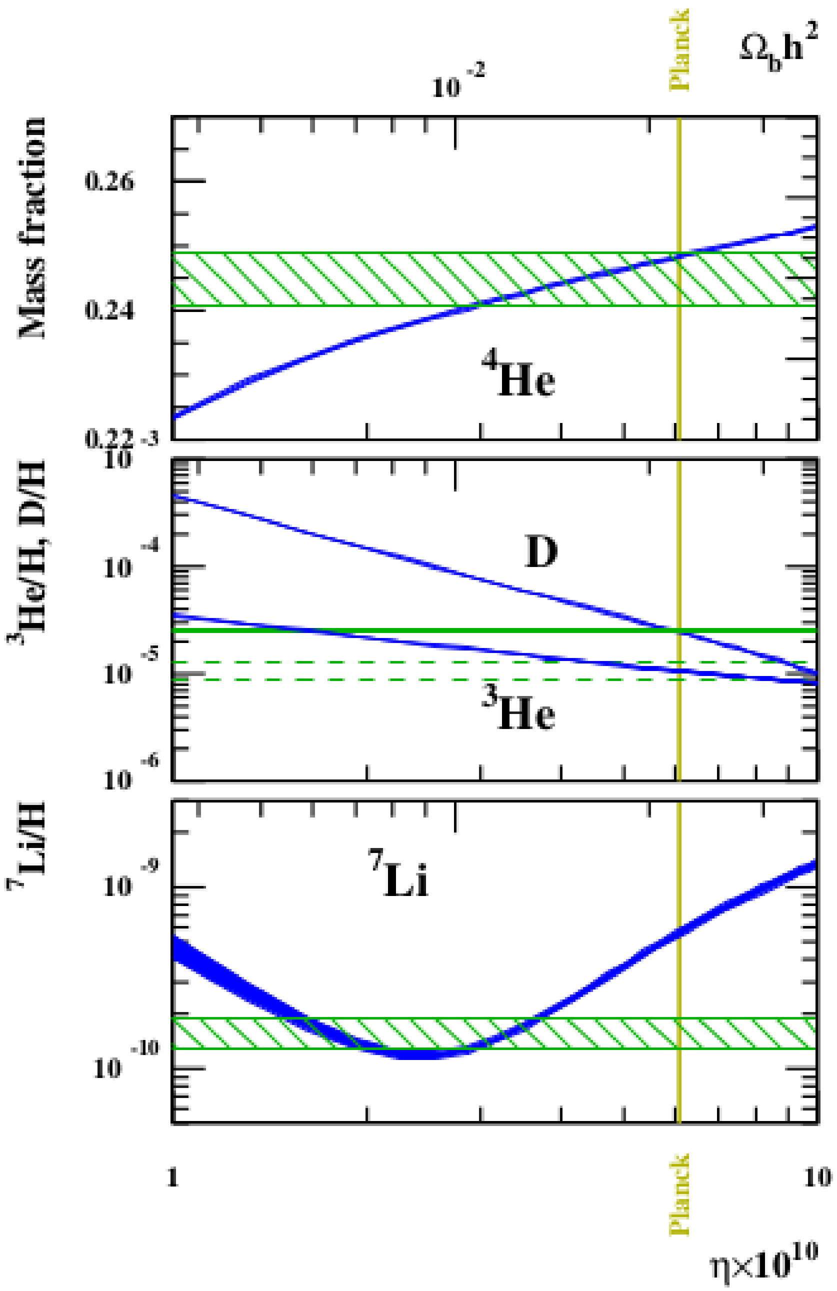


Figure 5. D/H values with 1σ confidence intervals (y-axis) for each of the six models considered (indicated on the x-axis). The BT measurement is shown at the far right. The horizontal band indicates the 1σ confidence interval for the CMB prediction by Coc et al. (2015).

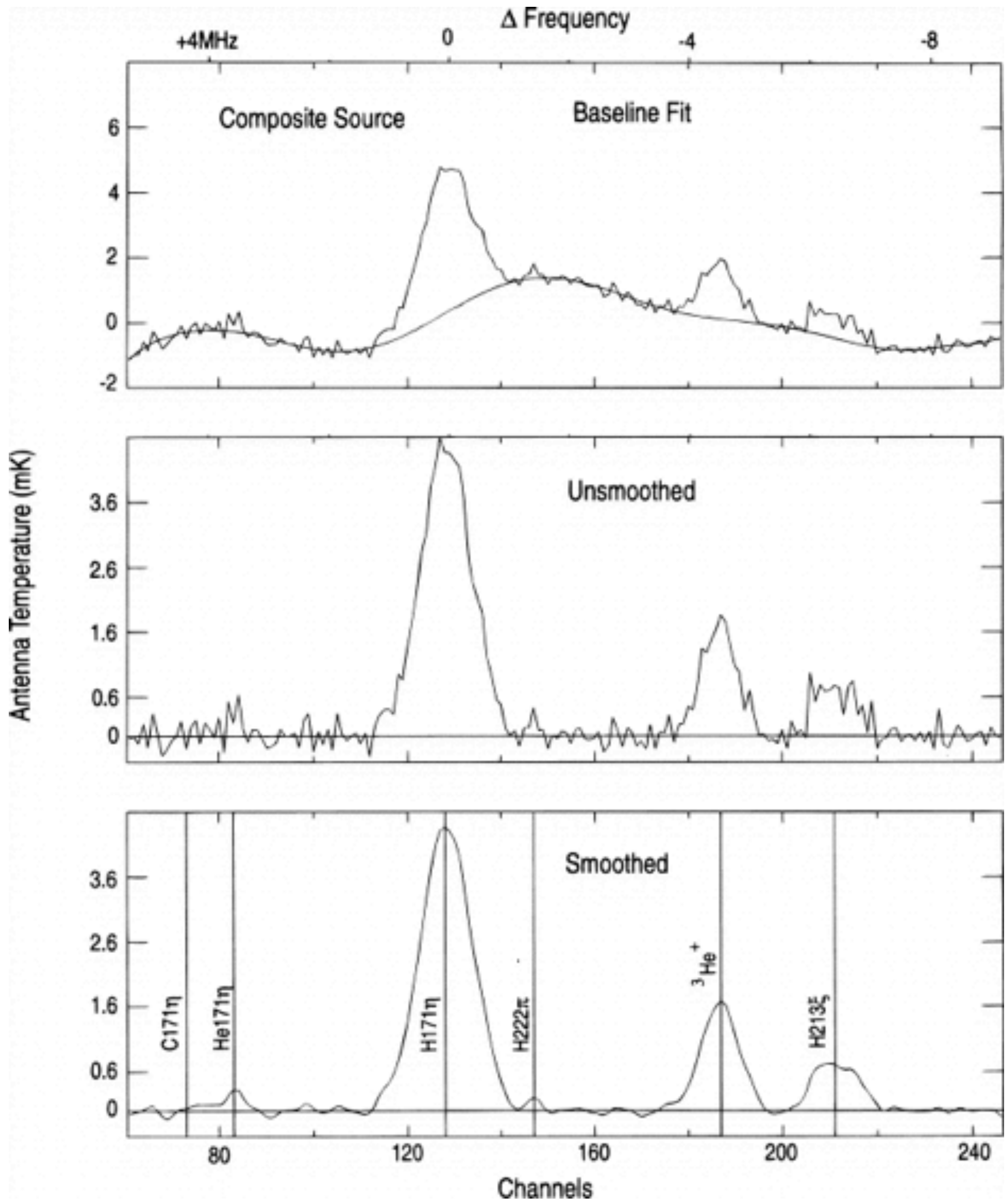
from Zavarygin et al. 2017


Planck
$\Omega_b h^2$
10 -2
Mass fraction
0.26
0.24
0.22
^{4}He
^{3}He/H, D/H
10 -3
10 -4
10 -5
10 -6
D
^{3}He
^{7}Li/H
10 -9
10 -10
^{7}Li
1
10
Planck
$\eta \times 10^{10}$

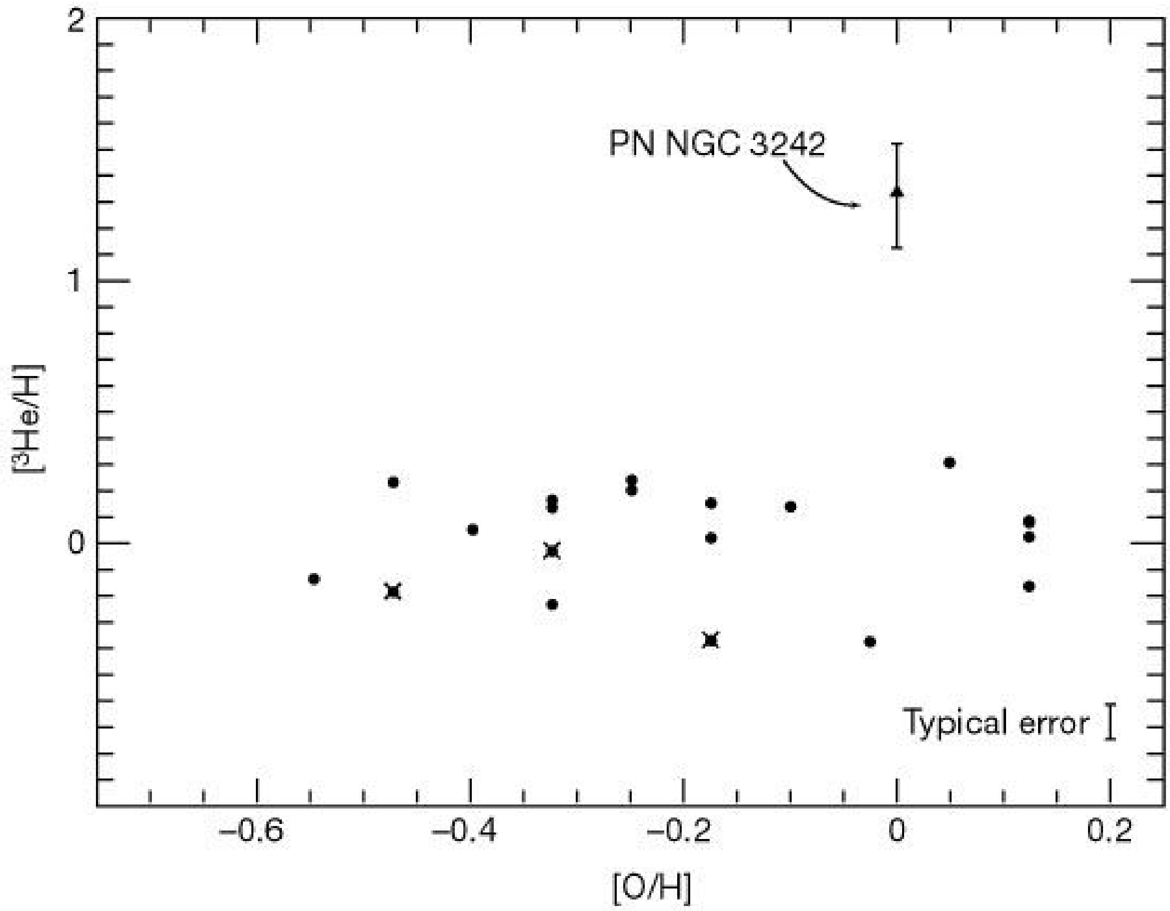
^{3}Helium

- Its primordial abundance very sensitive to Ω_b
- It can be produced/destroyed in stellar interiors $\Longrightarrow$ stellar and galactic evolution models necessary to track back primordial ^{3}He
- Detectable via its hyperfine emission line, but detectable only in Milky Way gas clouds that are not formed by pristine material
- Observations
  - Terrestrial determination ($\frac{^3\mathrm{He}}{^4\mathrm{He}} \sim 10^{-6}, 10^{-8}$ from balloon and continental rock measurements) but terrestrial ^{4}He also product of α decays
  - Solar system: Solar wind, Jupiter atmosphere
  - Local inter-stellar medium
  - Stars

Again the best place to look is HII regions (and also PNe). where the spin-flip transition of $^3He^+$ at 3.46 cm is observed



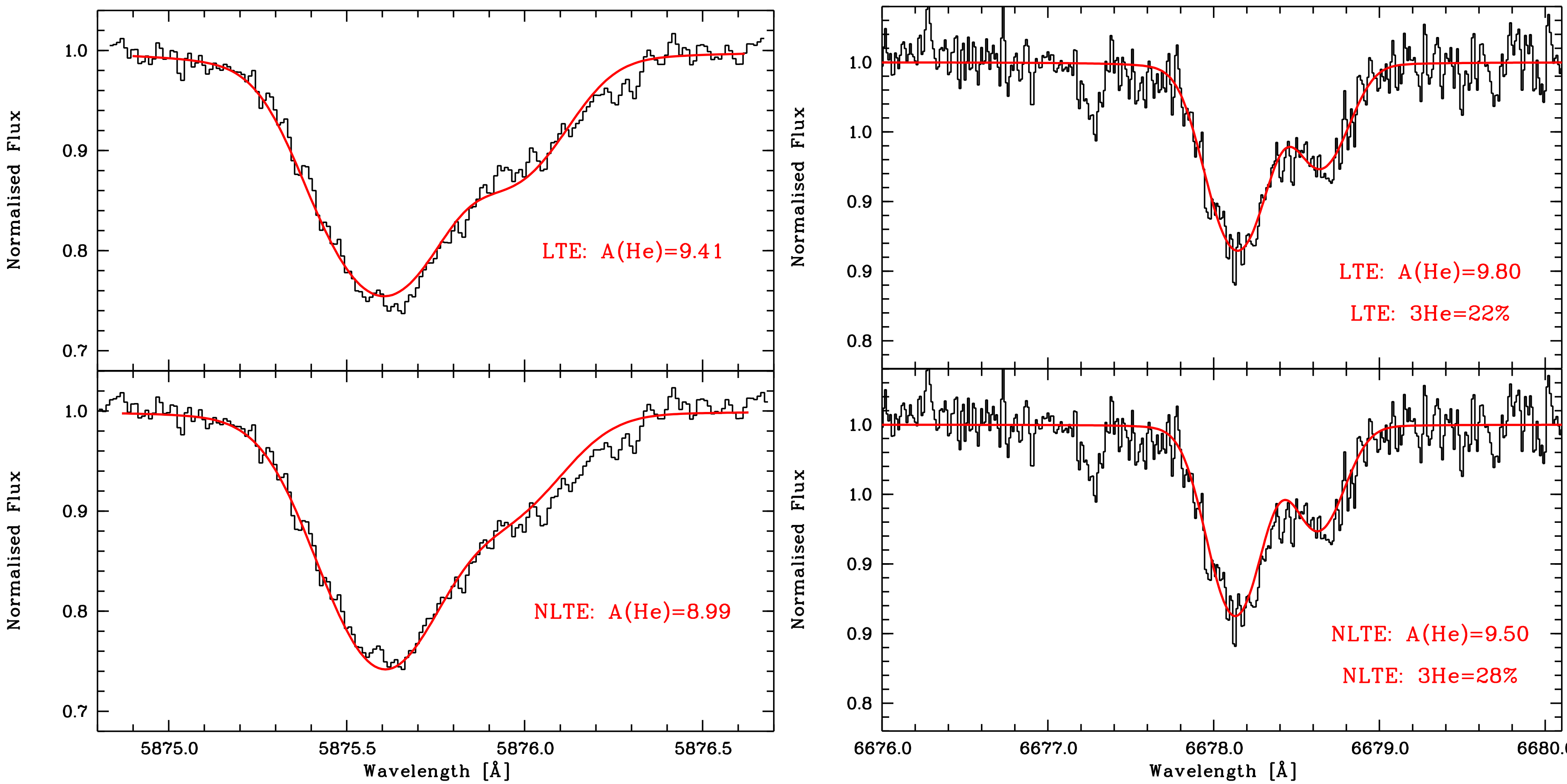
^{3}Helium



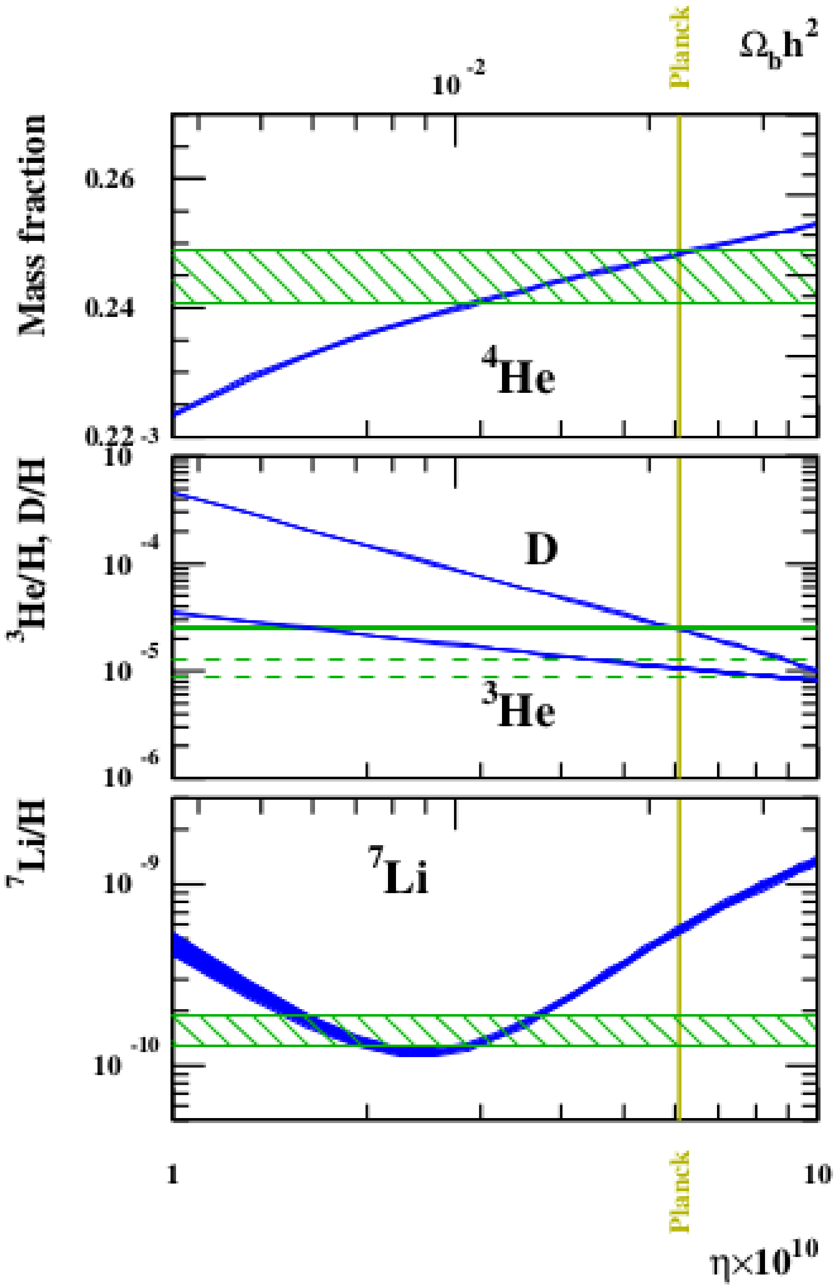
Bania et al. 2002 derived ^{3}He in a sample of H II regions (radio observations)

^{3}Helium

Feige 86 (16430 K/4.2/0.0)



HARPS (R=110 000), Caffau et al. 2014, AN 335, 29


Planck
$\Omega_b h^2$
10^{-2}
Mass fraction
0.26
0.24
0.22
^{4}He
^{3}He/H, D/H
10^{-3}
10^{-4}
10^{-5}
10^{-6}
D
^{3}He
^{7}Li/H
10^{-9}
10^{-10}
^{7}Li
1
10
Planck
$\eta \times 10^{10}$

^{4}Helium

- **Its primordial abundance almost completely controlled by free n number, so related to freeze-out temperature of weak $n \leftrightarrow p$ rate**
- **mass fraction ^{4}Helium** $\mathrm{Y_p} = \frac{2n/p}{1+n/p} \approx 0.25$
- $\mathrm{Y_p}$ **depends:**
  - **logarithmically on baryon density**
  - **sensitive to freeze-out temperature**
- **Synthesised in stellar interiors**
- **Usually measured in old, very little evolved system**

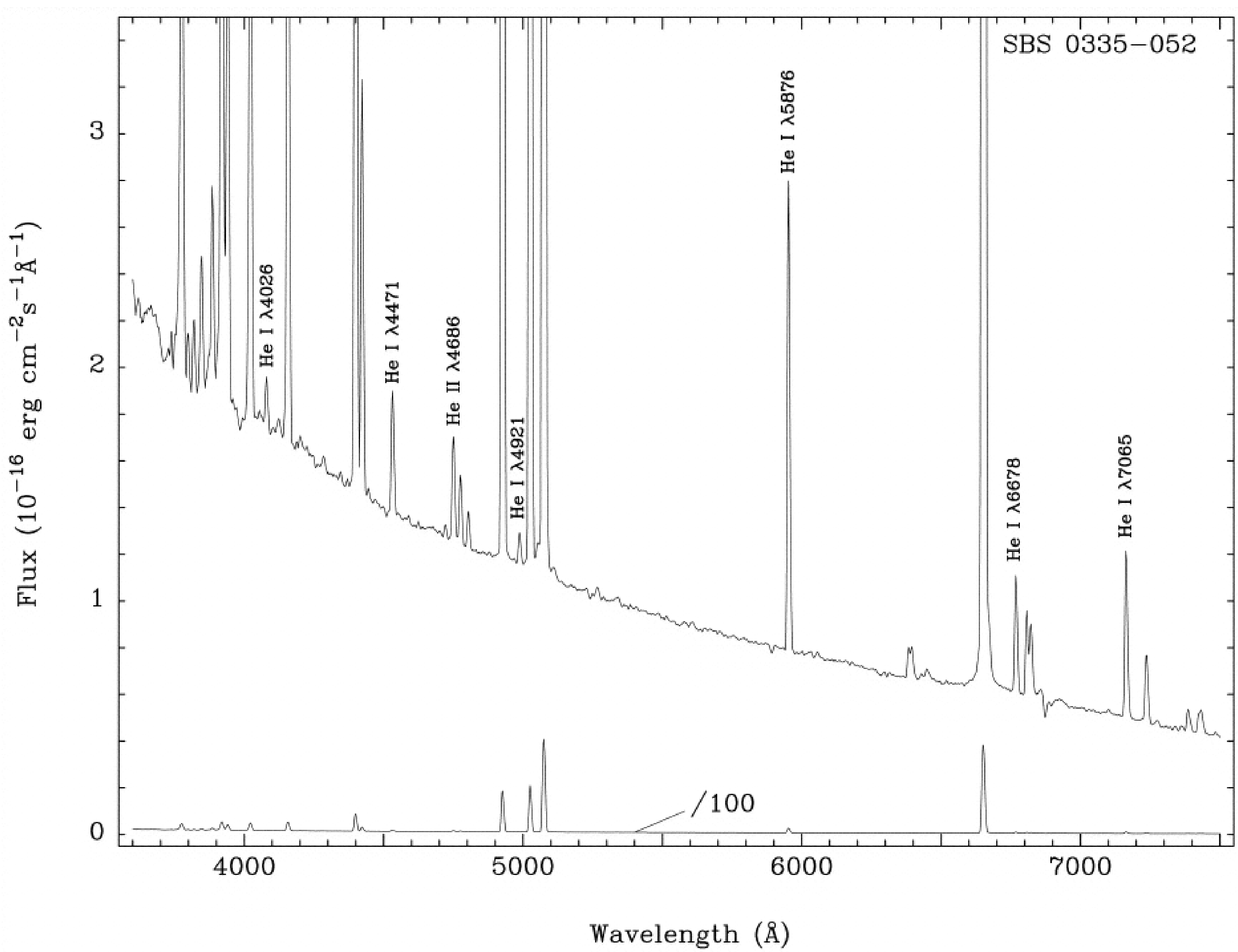
^{4}Helium

- Its abundance determined by He emission lines in extra-galactic H II regions

- He synthesised also in stars $\Longrightarrow$ primordial value derived with regression of He abundances versus metallicity

- Theoretical model used to extract He abundance depends on 8 physical parameters (electron density, optical depth, temperature, equivalent width of underlying absorption of H and He, reddening correction, H fraction, He abundance) to predict flux of nine emission lines ratios

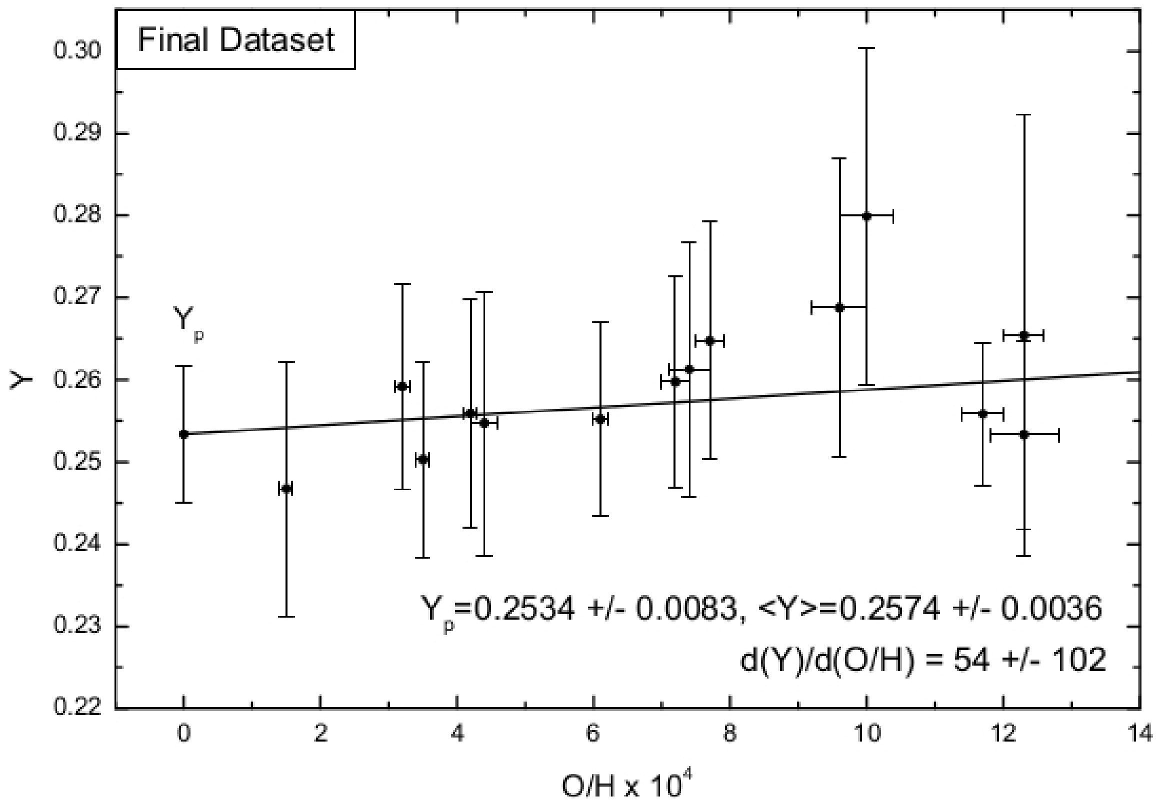
^{4}Helium



Izotov et al. 1999

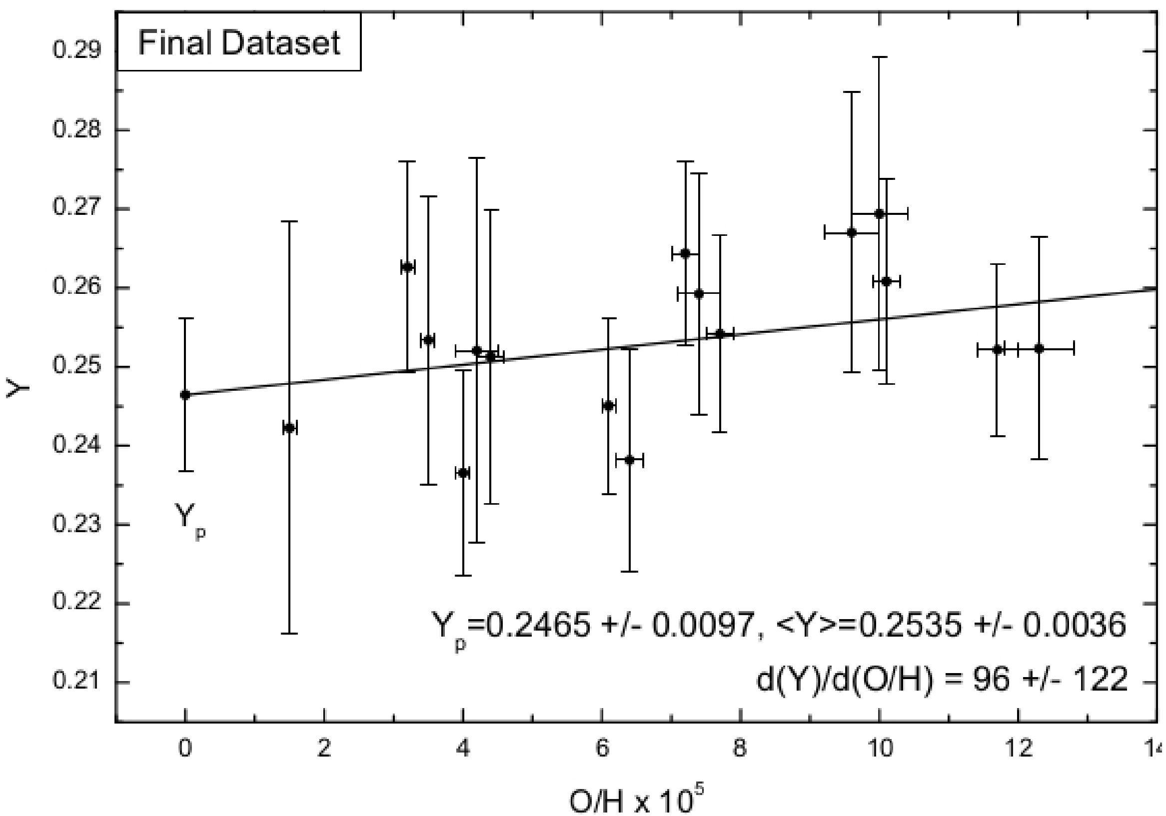
^{4}Helium

- Of the several H II region analysed, 25 best objects provided (Aver et al. 2012, JCAP 4, 04)
  - $Y_p = 0.2534 \pm 0.0083$ based on linear regression
  - $Y_p = 0.2574 \pm 0.0036$ based on weighted mean of the data



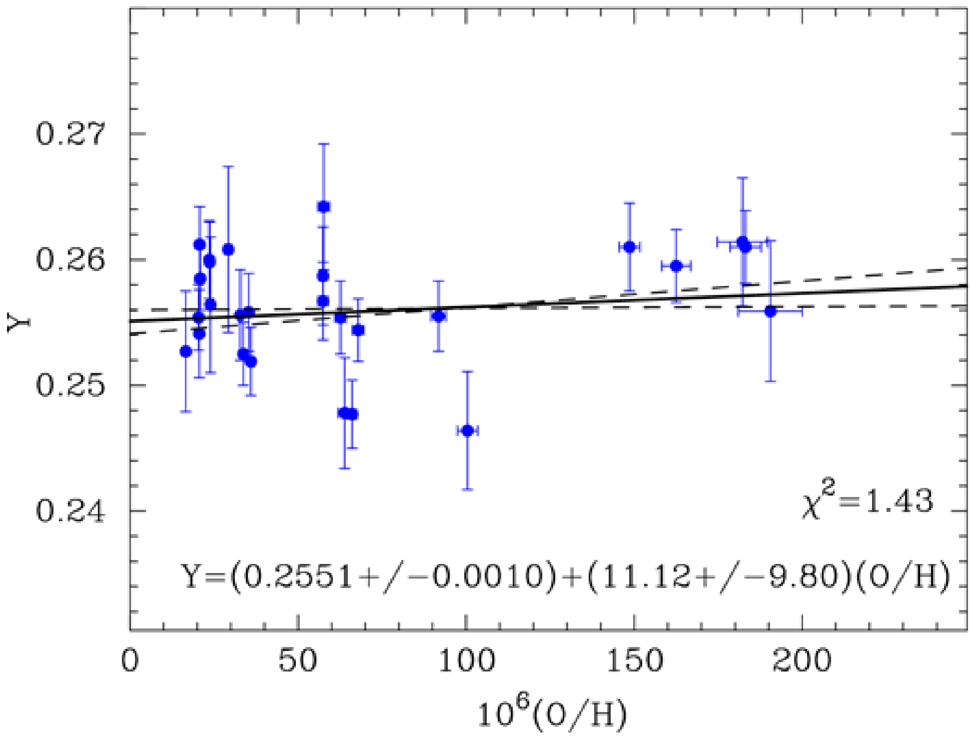
^{4}Helium

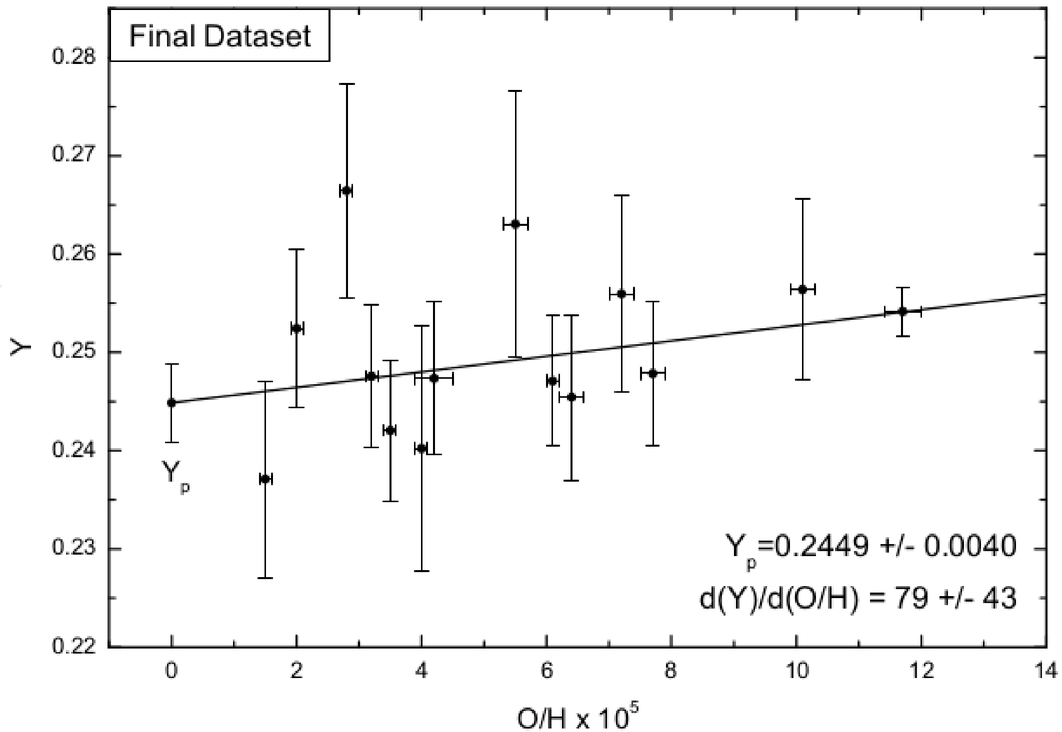
- With a new analysis of theoretical emissivities of Potter et al. 2012, 2013
- Aver et al. 2013, JCAP 11, 01)
  - $Y_p = 0.2465 \pm 0.0097$ based on linear regression
  - $Y_p = 0.2535 \pm 0.0036$ based on weighted mean of the data



^{4}He

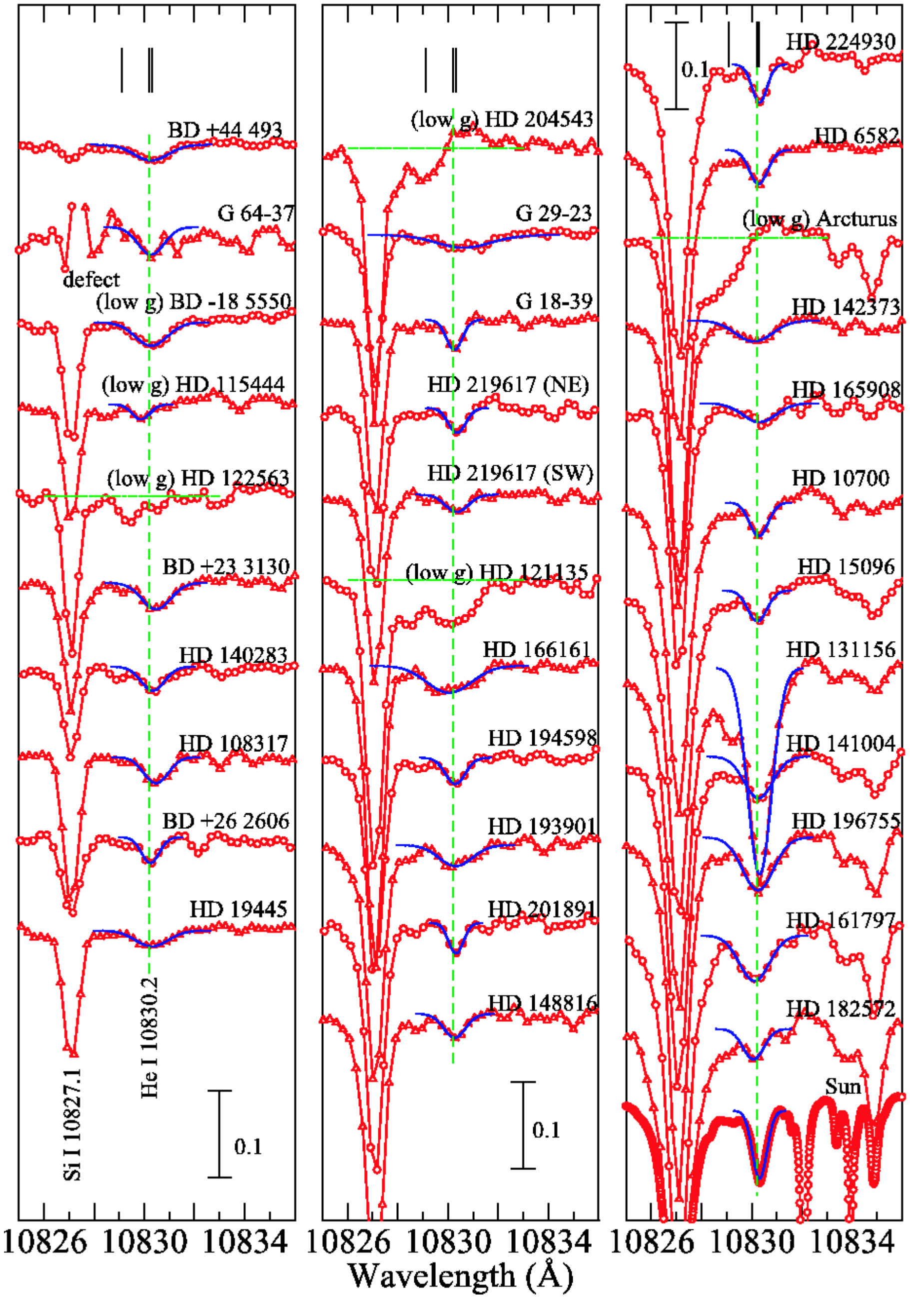
Introduction of IR line:
Izotov et al. 2014, MNRAS 445, 778 and Aver at al. JCAP 07, 011



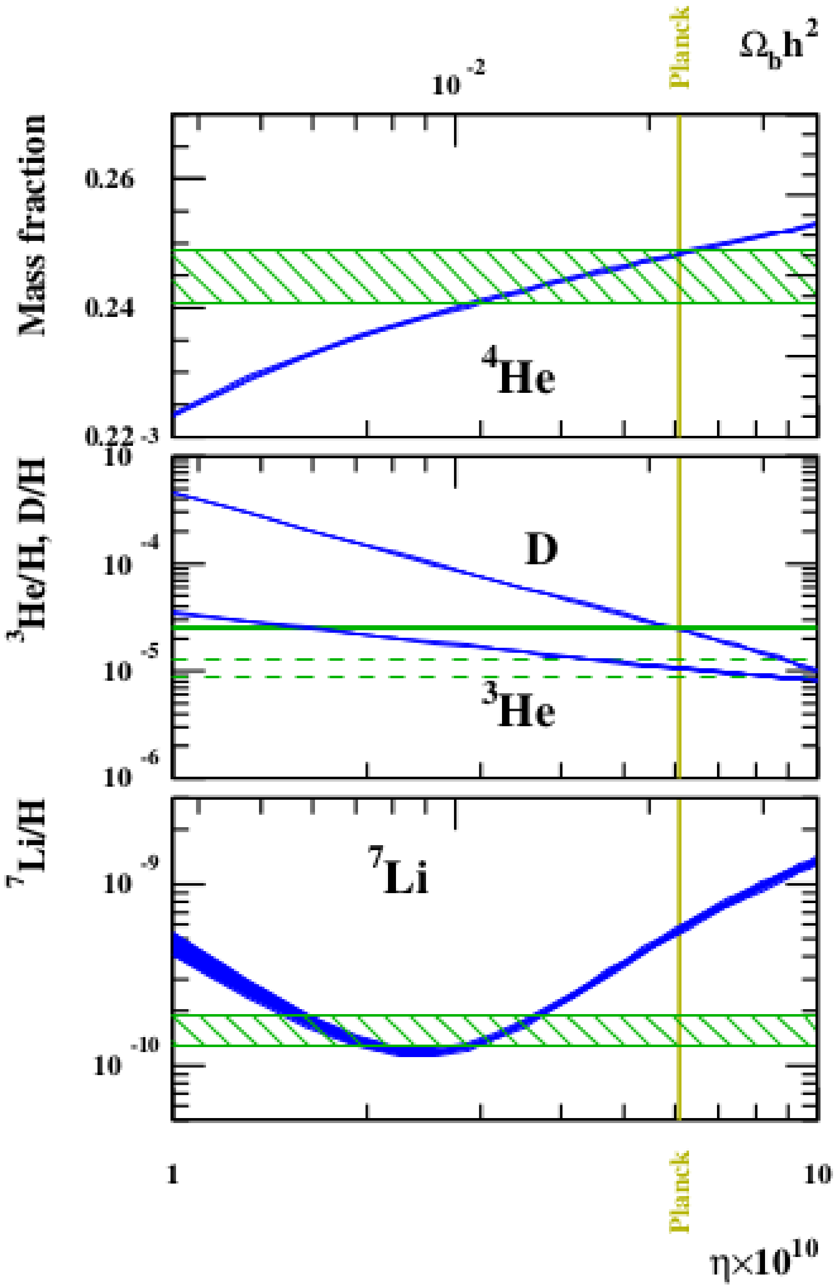


^{4}He

Peimbert et al. 2017 from observations in H II regions derived
$Y_p = 0.2446 \pm 0.0029$



Takeda et al. 2011, PASJ 63, S547


Planck
$\Omega_b h^2$
10^{-2}
Mass fraction
0.26
0.24
0.22
^{4}He
10^{-3}
10^{-4}
10^{-5}
10^{-6}
^{3}He/H, D/H
D
^{3}He
^{7}Li/H
10^{-9}
10^{-10}
^{7}Li
1
10
Planck
$\eta\times10^{10}$

Lithium

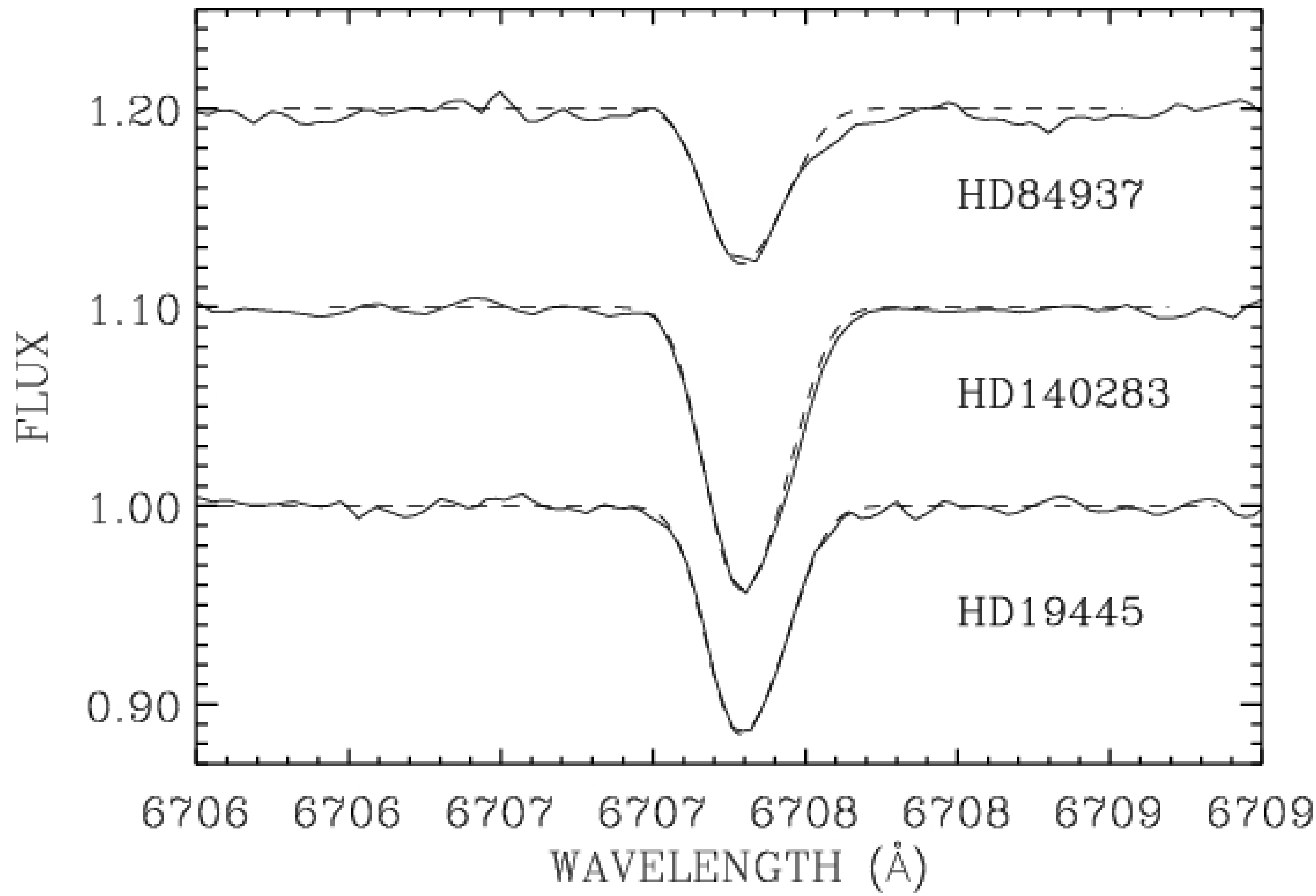
- **Li fragile element, destroyed in stellar interiors**
  - ^{7}**Li destroyed at** $\mathrm{T} \leq 2.5 \times 10^6$ **K**
  - ^{6}**Li destroyed at lower Temperatures**

- **Li also produced (spallation, AGB stars, novae) but you need time**

- **To derive A(Li) in stars**
  - **670.7 nm doublet, clear range in metal-poor stars (EW of some pm)**
  - **subordinate line at 610.4 nm, much weaker**
  - **model-atmosphere knowledge able to reproduce the line-profile**

- **From Spite & Spite (1982)**
  - **metal-poor** $(-2.4 \leq [\mathrm{Fe/H}] \leq -1.4)$ **dwarf stars show constant Li abundance;**
  - **this "Spite plateau" should represents the primordial Li**
  - **Metal-poor stars with** $\mathrm{T_{eff}} > 5800$ **K have shallow convective zone, they do not destroy Li**
  - **Cooler metal-poor stars have deep convective zone, they destroy Li**

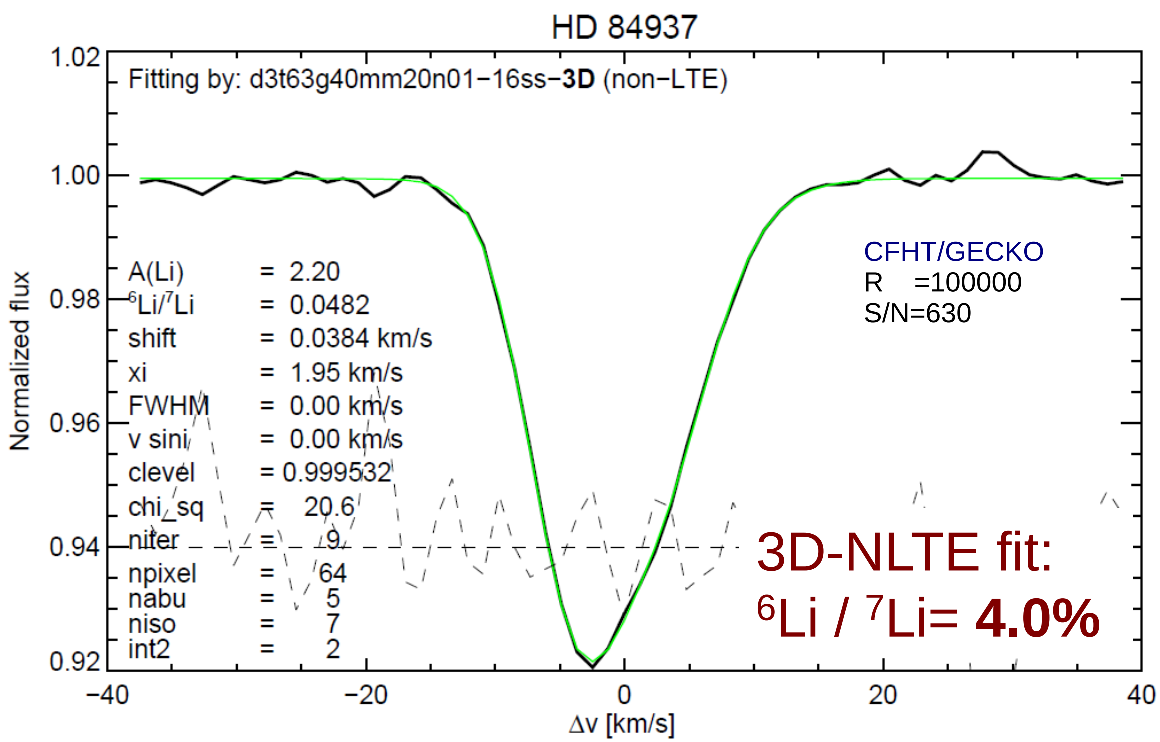
Lithium: features



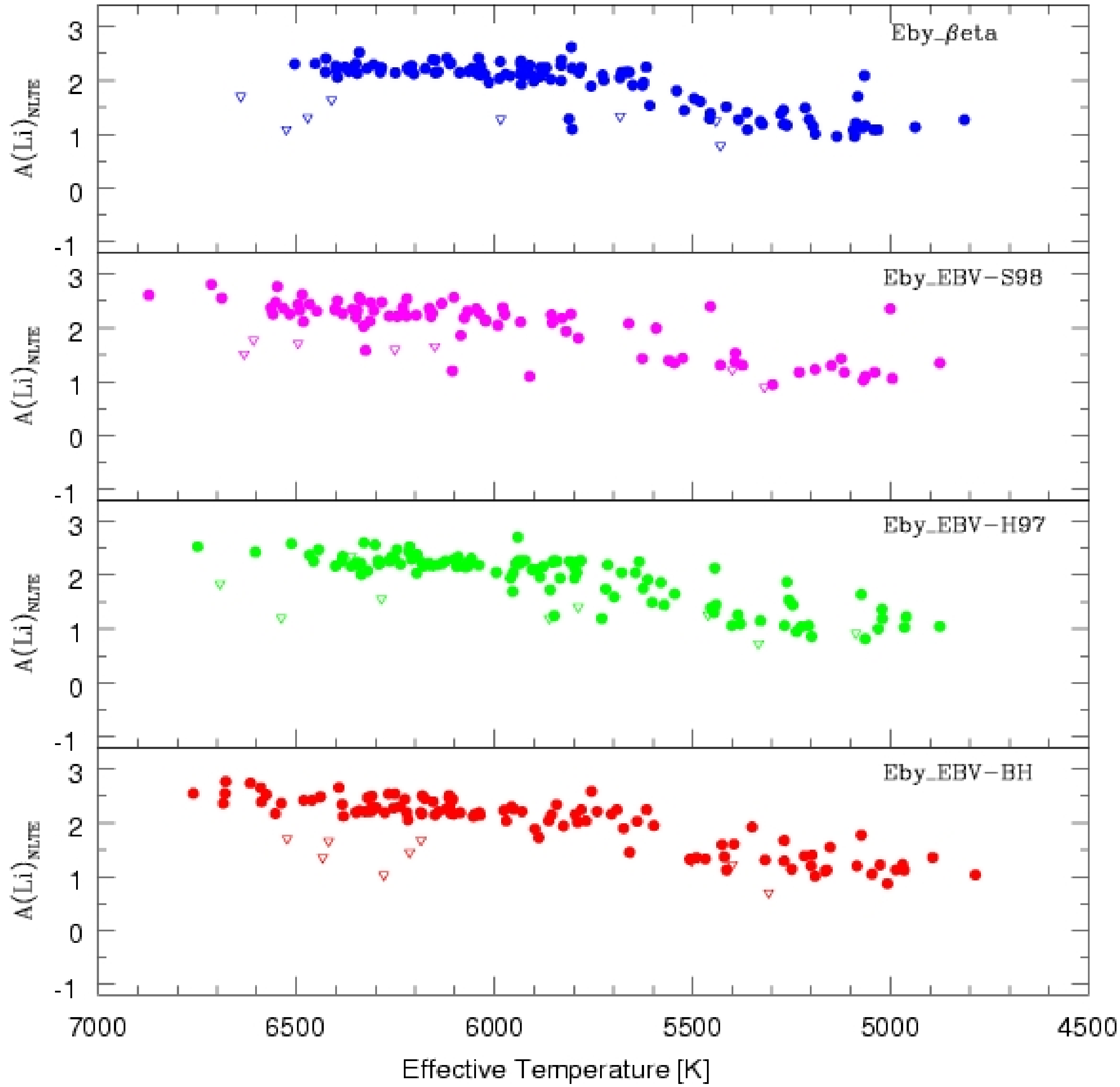
Shi et al. 2007

Lithium: features

^{6}Li detection in HD 84937

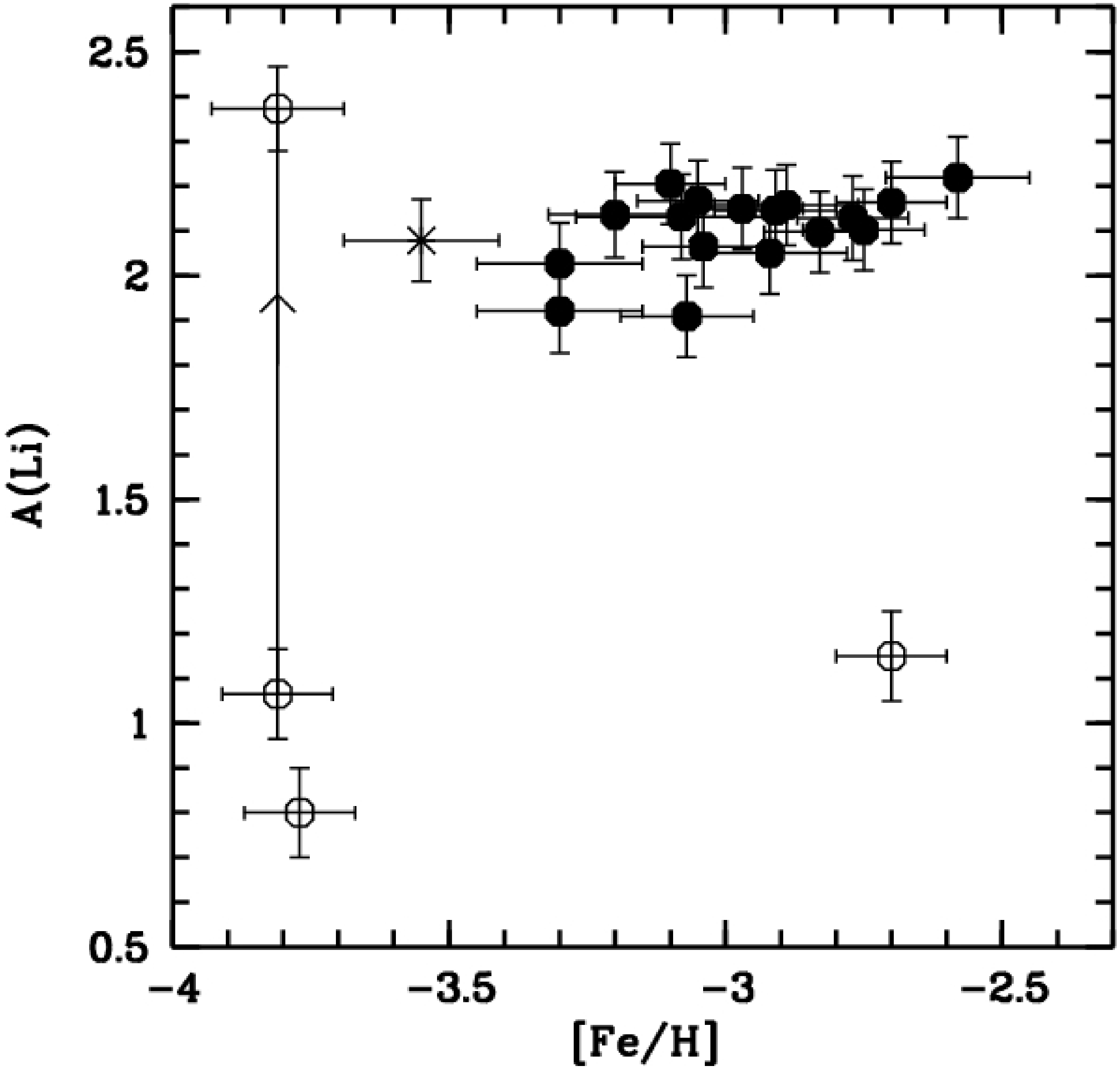


Lithium: Spite plateau



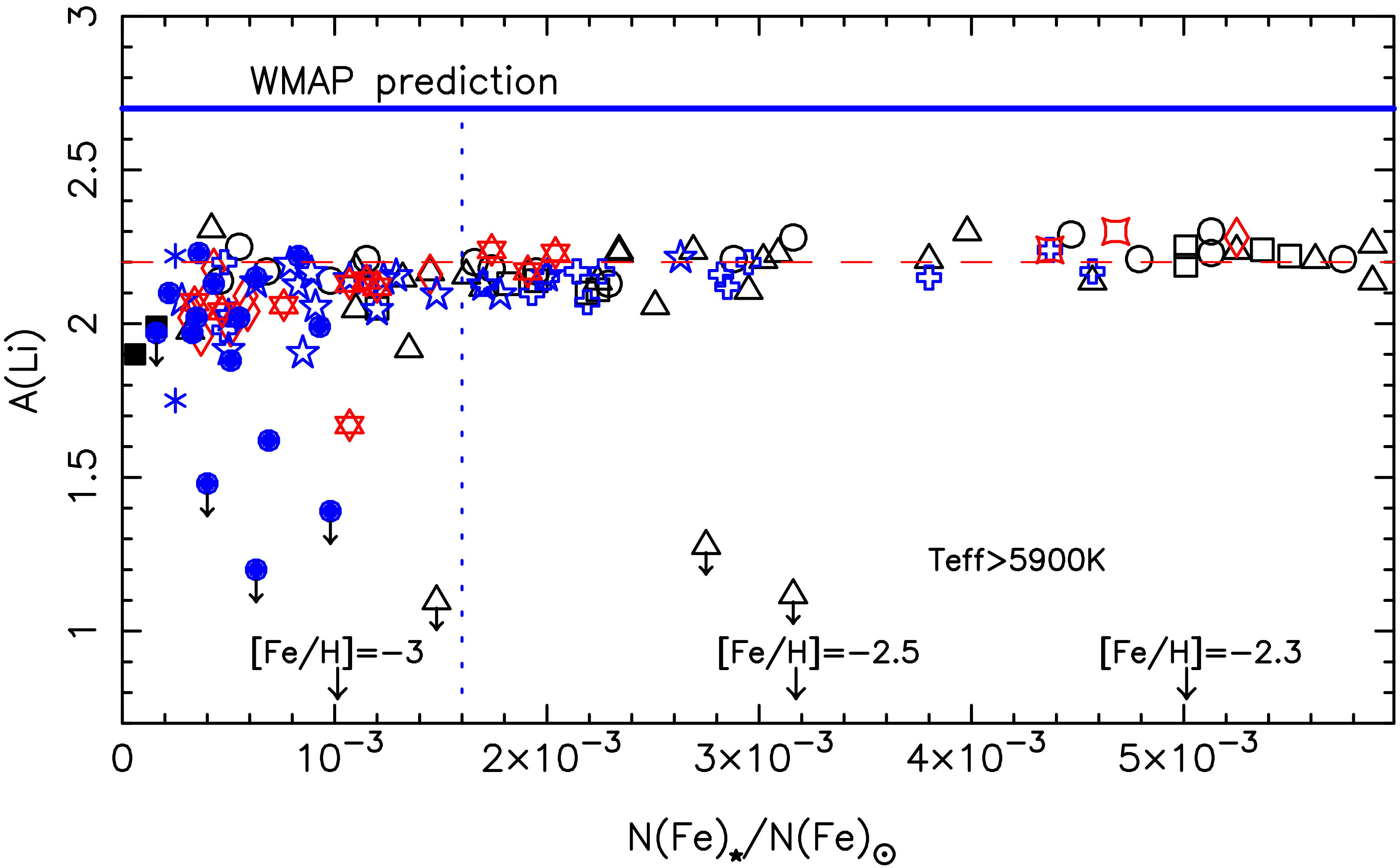
Charbonnel & Primas 2005, A&A 442, 961

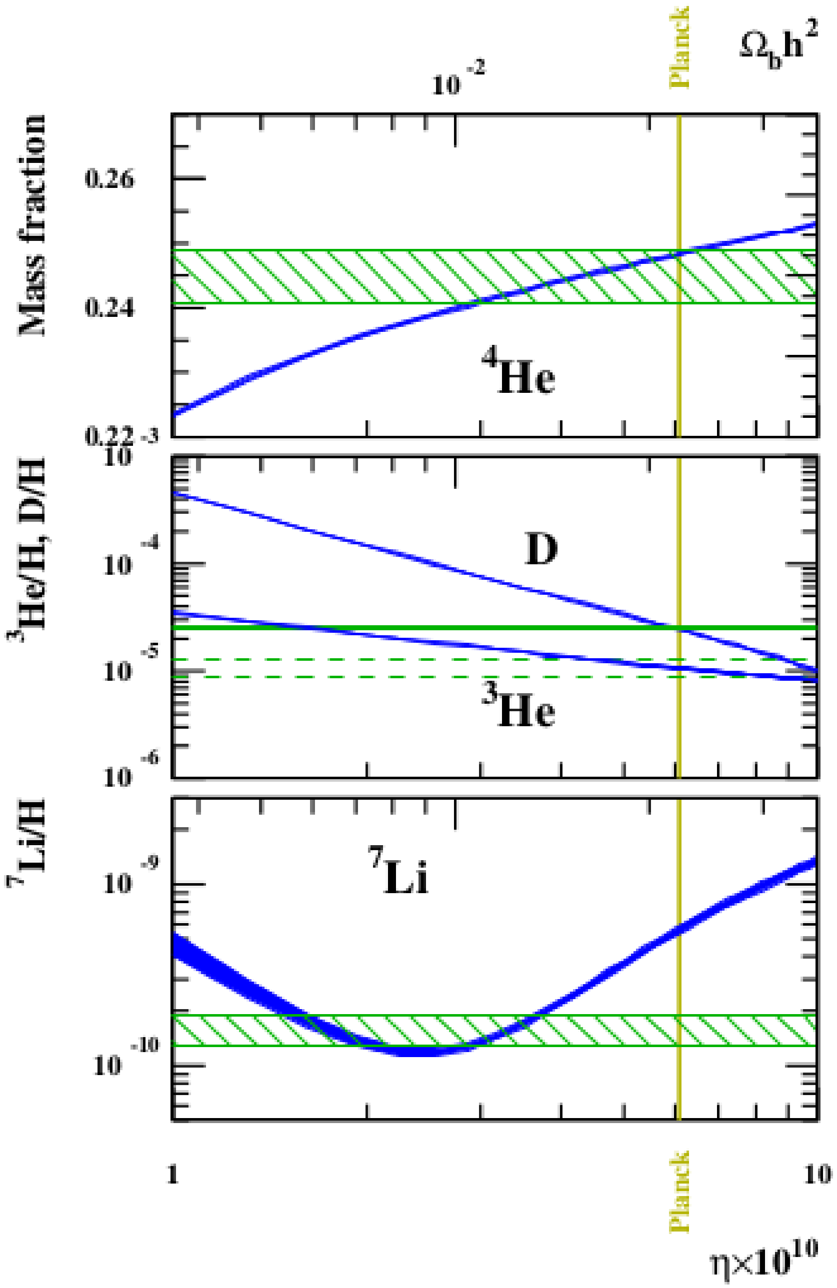
Lithium: Spite plateau



Bonifacio et al. 2007, A&A 462, 851

Lithium meltdown




Planck
$\Omega_b h^2$
10^{-2}
Mass fraction
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0.24
0.22
^{4}He
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10^{-6}
^{3}He/H, D/H
D
^{3}He
^{7}Li/H
10^{-9}
10^{-10}
^{7}Li
1
10
Planck
$\eta\times10^{10}$

Lithium

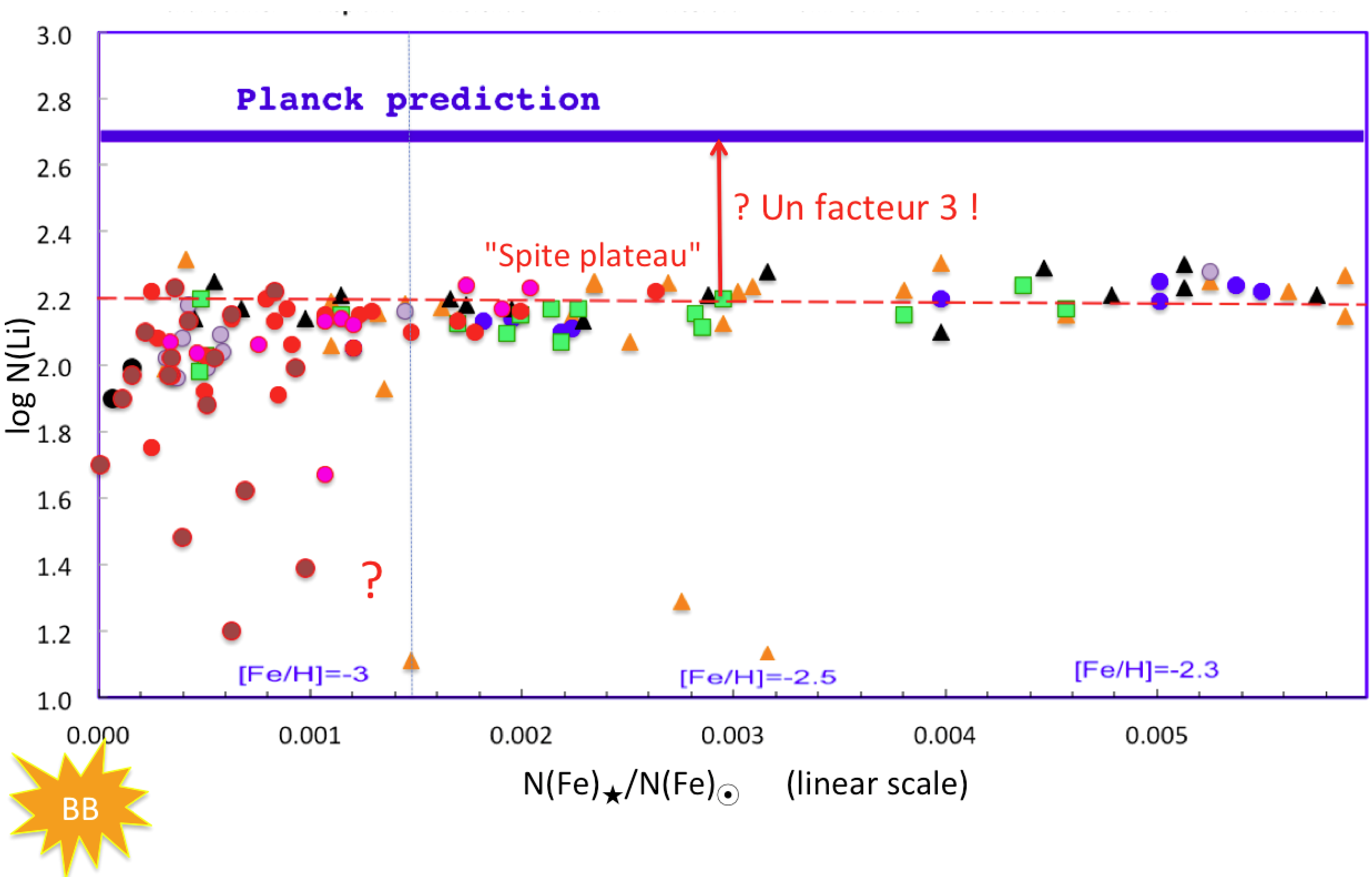
- **Lithium destroyed from the primordial value inside stars:**
  - **Li is depleted by diffusion in the stellar atmosphere (Richard et al. 2002, ApJ 580, 1100), difficult to reconcile with the constant Li content in Pop. II stars, whatever $T_{\rm eff}$, gravity and [Fe/H]**
  - **EMP low mass stars were all formed by fragmentation of higher mass clouds; they remain fast rotators through pre-MS; rotational mixing leads to Li destruction**
  - **Pre-MS stars always depletes all Li, late accretion of unprocessed material restores Li to some extent (Fu et al. 2016); EMP stars lack or have an inefficient late accretion phase**
  - **Within the dark matter (DM) mini-halo a significant fraction of the mass (%50 ?) is rapidly processed through massive stars, this leads to Li depletion; low-mass stars only form from this pre-processed material**

Lithium

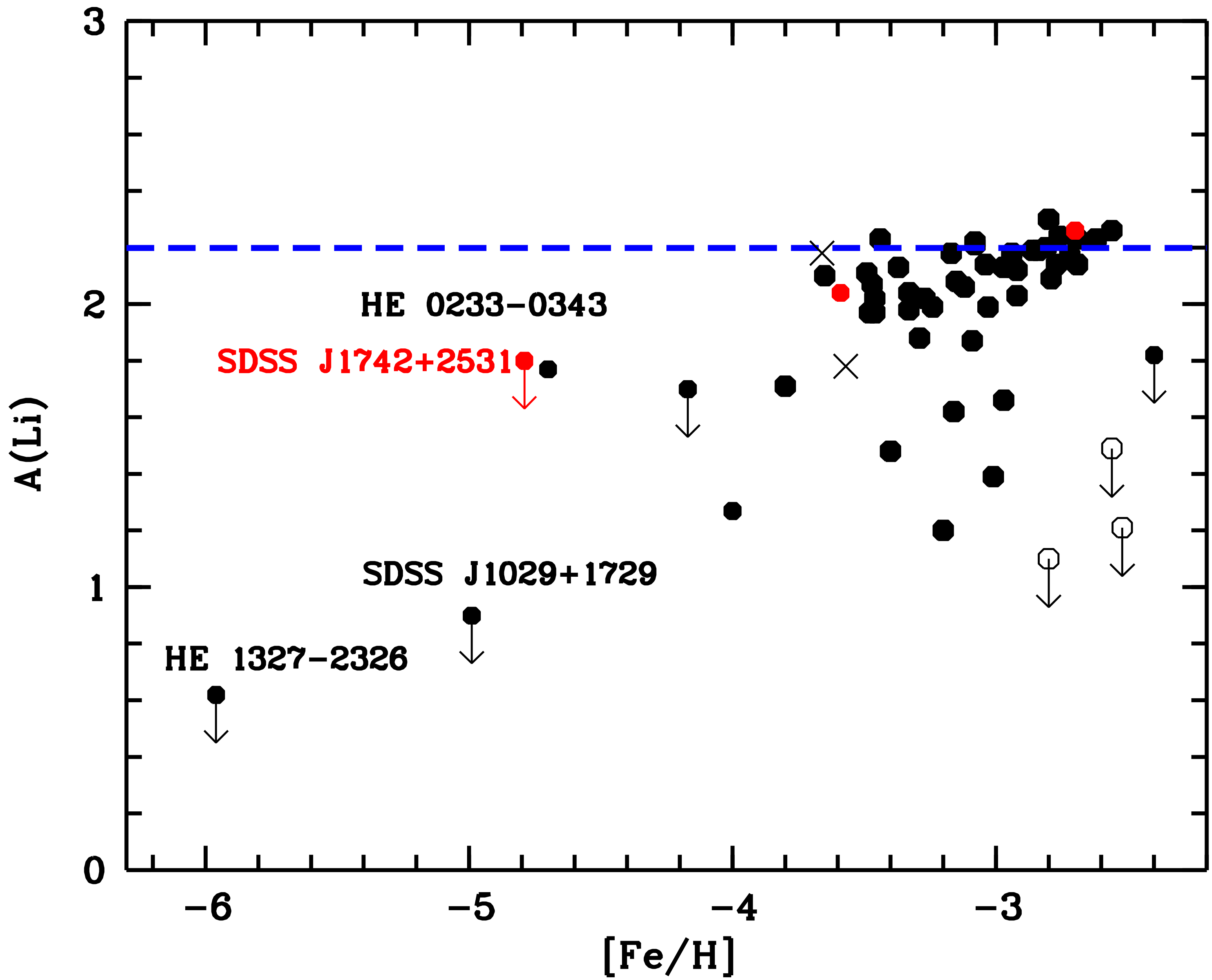
- **Lithium produced in BBN can be smaller than at present established, e.g.**
  - **Jedamzik et al. 2006 investigated the possibility of late decaying relic particles in the constrained minimal supersymmetric standard model coupled to gravity**
  - **Scherrer & Scherrer 2017 suggest a stability of ^{8}Be**
  - **Goudelis, Pospelov, Pradler (2016) suggest presence of light neutral particle X having substantial interactions with nucleons, having $1.6 \leq \mathrm{m_X} \leq 20$ MeV and $100 \leq \tau_{\mathrm{X}} \leq 10^4$ s**
  - **Hou et al. 2017 suggest a generalised distribution (characterised by a parameter q) to describe the velocity to describe nucleus; for $1.069 \leq q \leq 1.082$ the agreement observations/predictions is good**

Some curiosities

Lithium meltdown

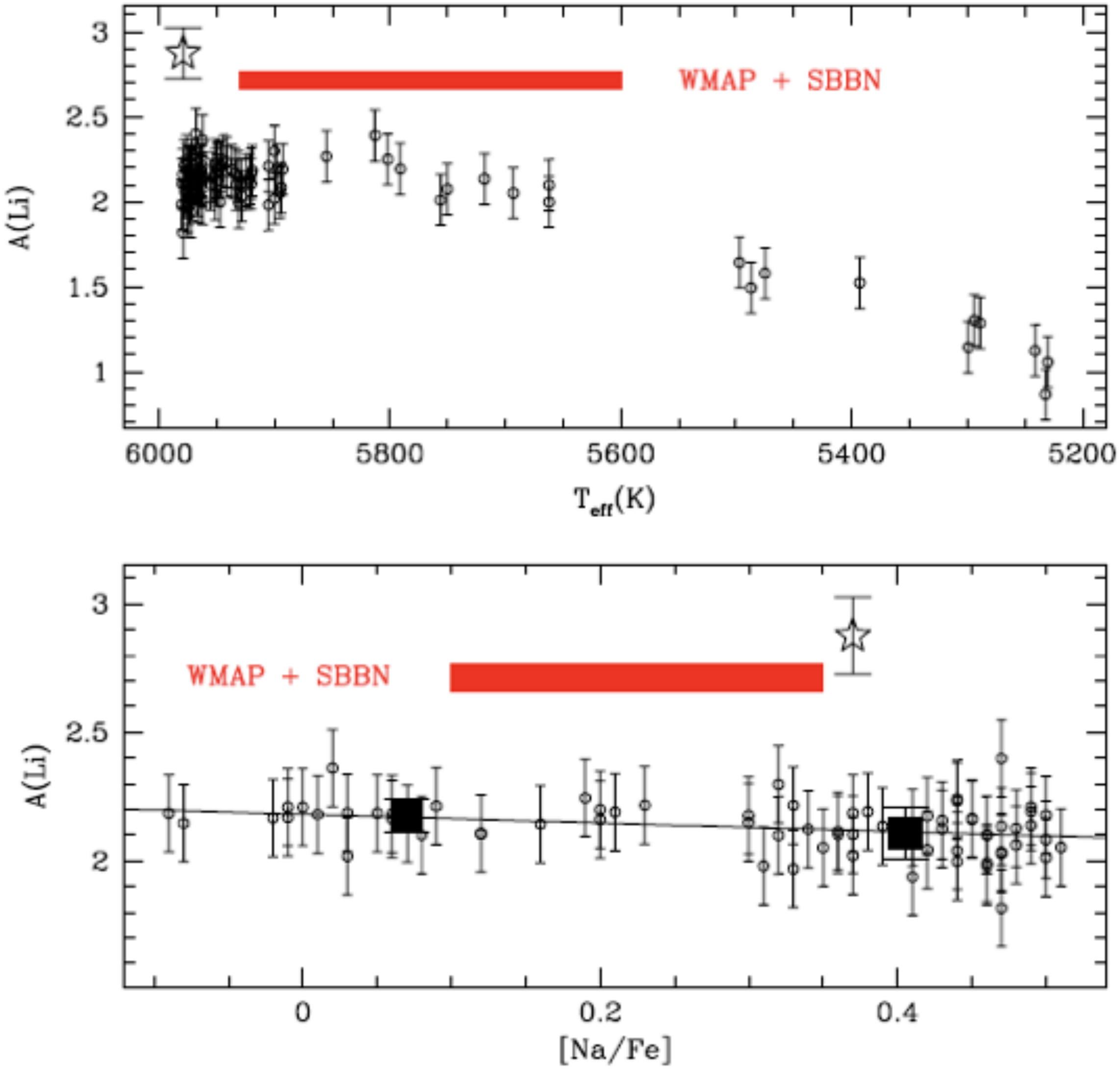


Lithium meltdown

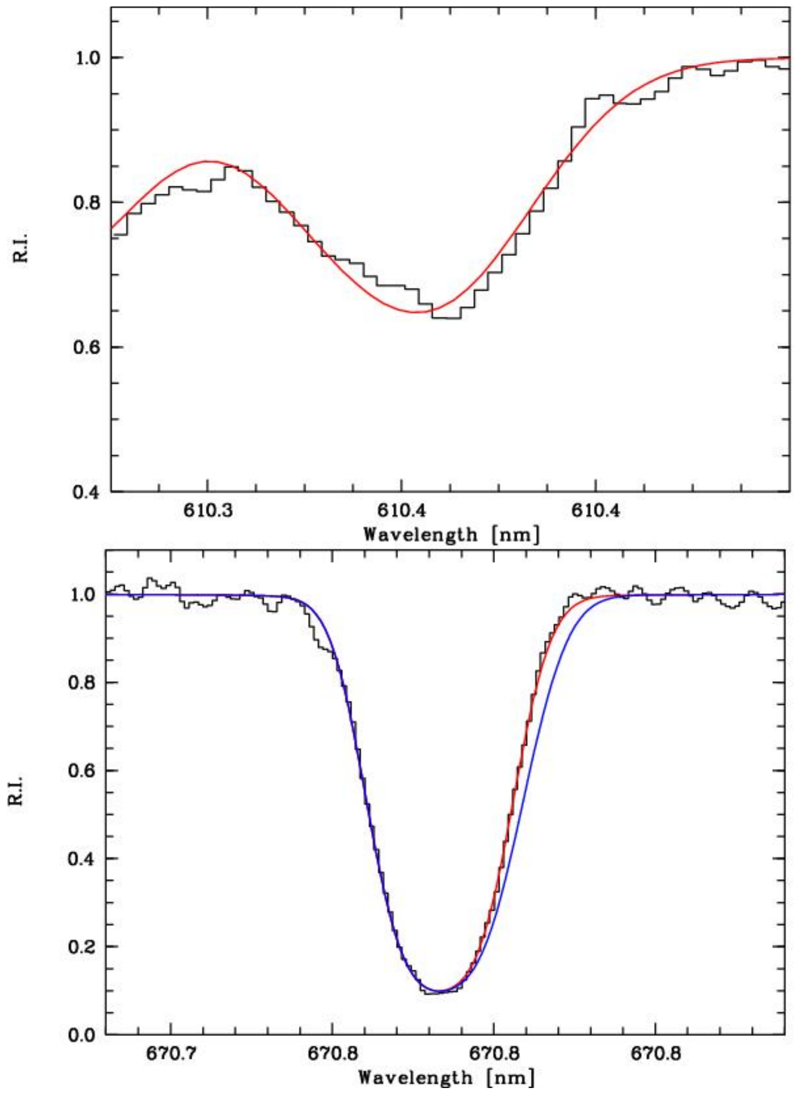


M4 - Monaco et al. 2012

Nature or nurture ?

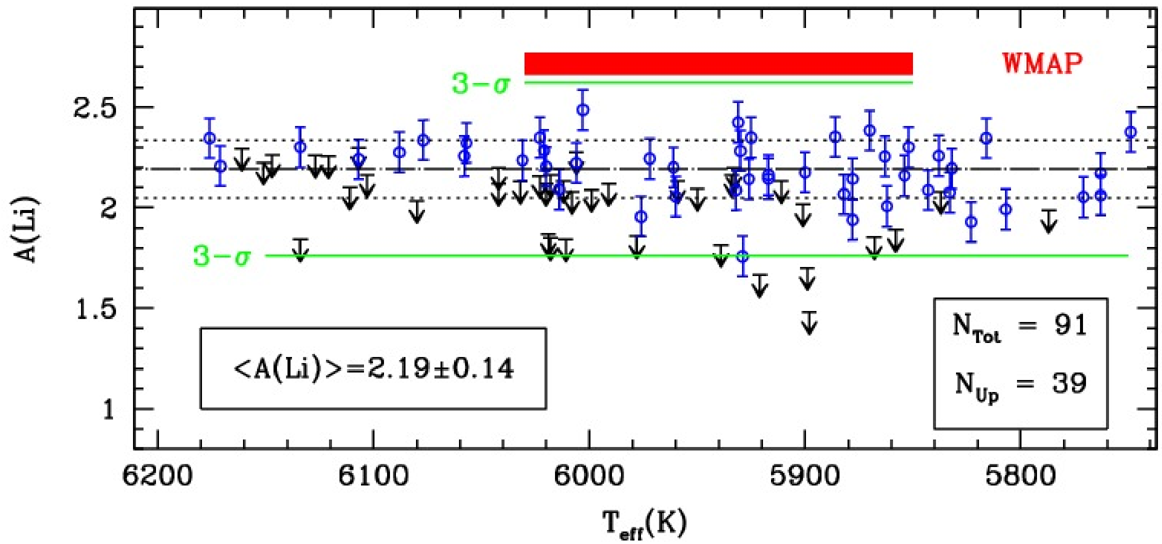


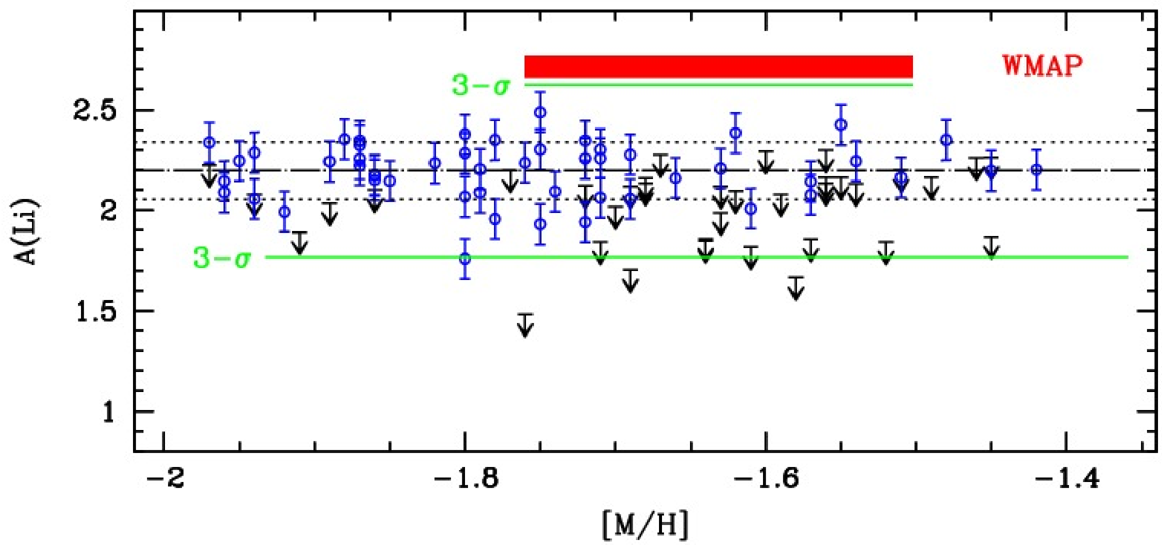
High Lithium star



Solid black: observed spectrum; solid red 3D-NLTE synthesis; 3D-NLTE synthesis with 2% ^{6}Li.
Monaco et al. 2014, A&A 564, L6 - Tr 5

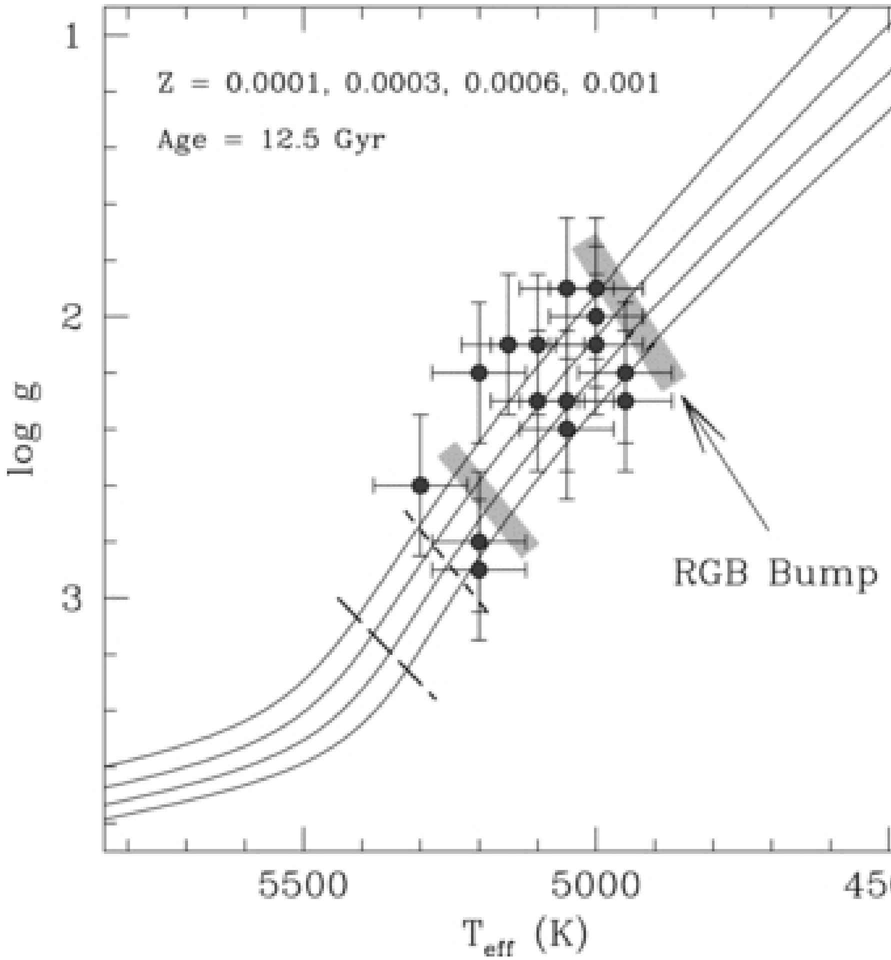
Lithium: Spite plateau in ω Centauri

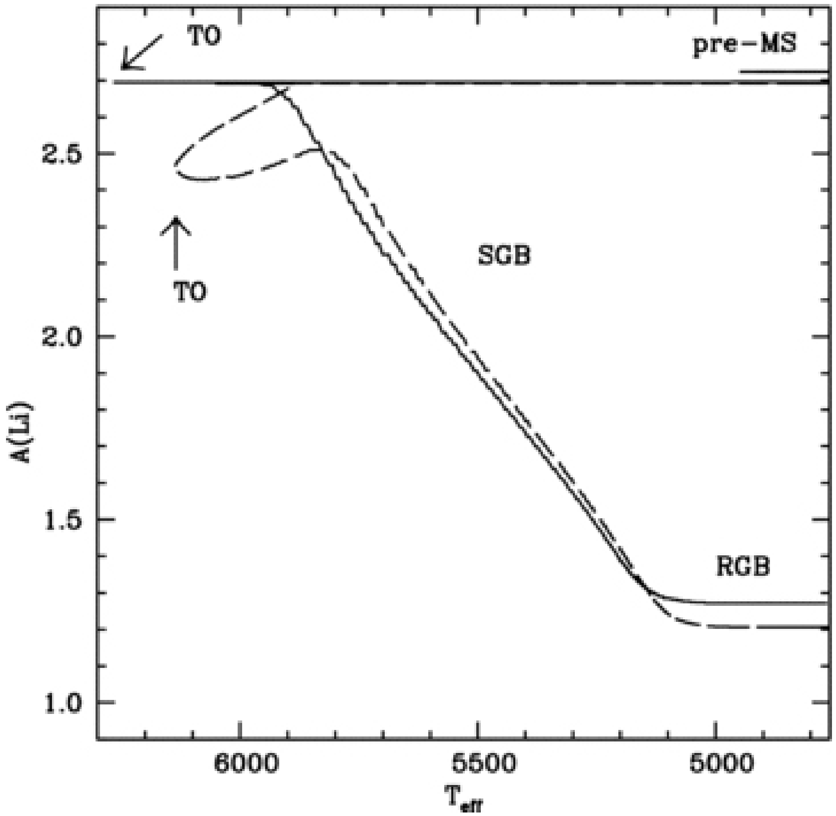




Monaco et al. 2010, A&A 519, L3

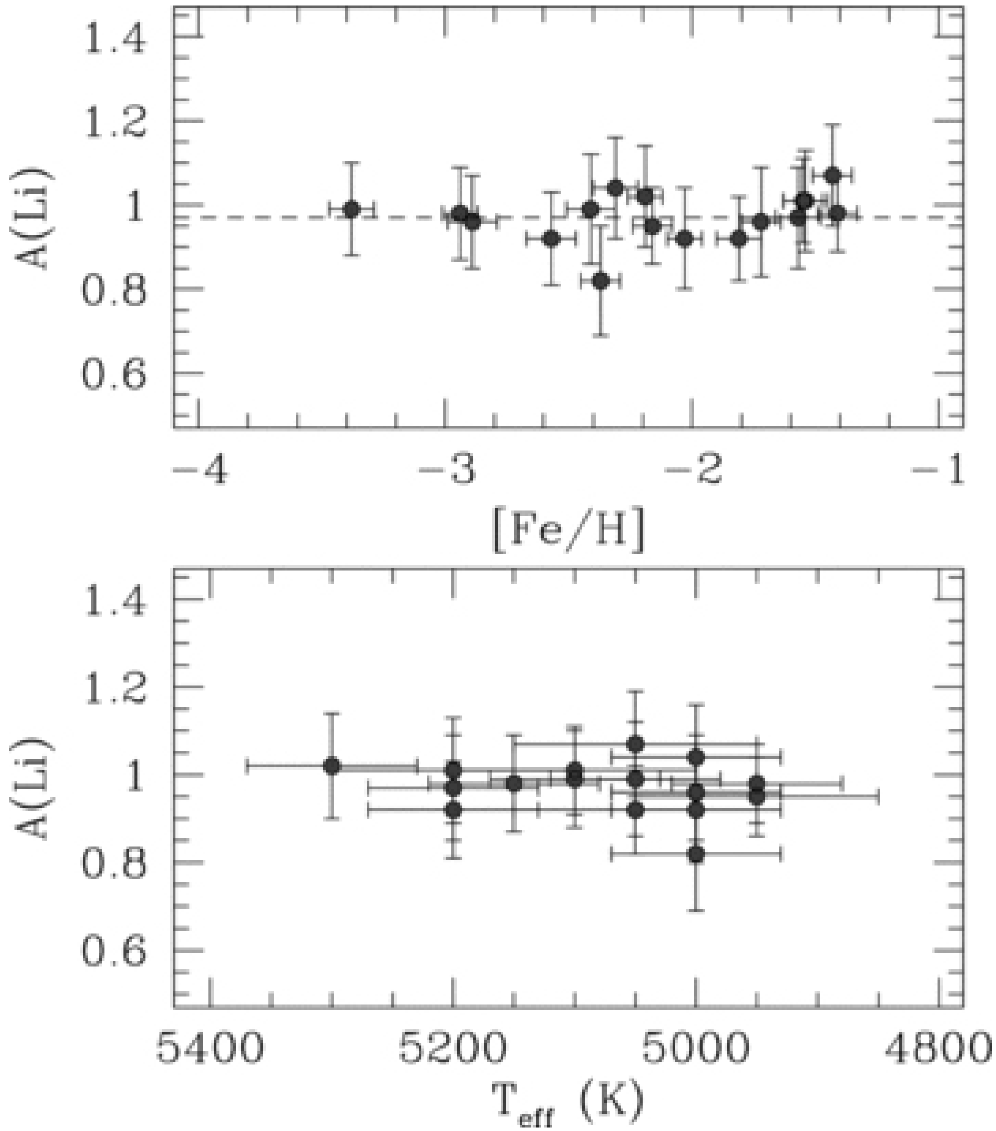
Lithium: Mucciarelli's plateau





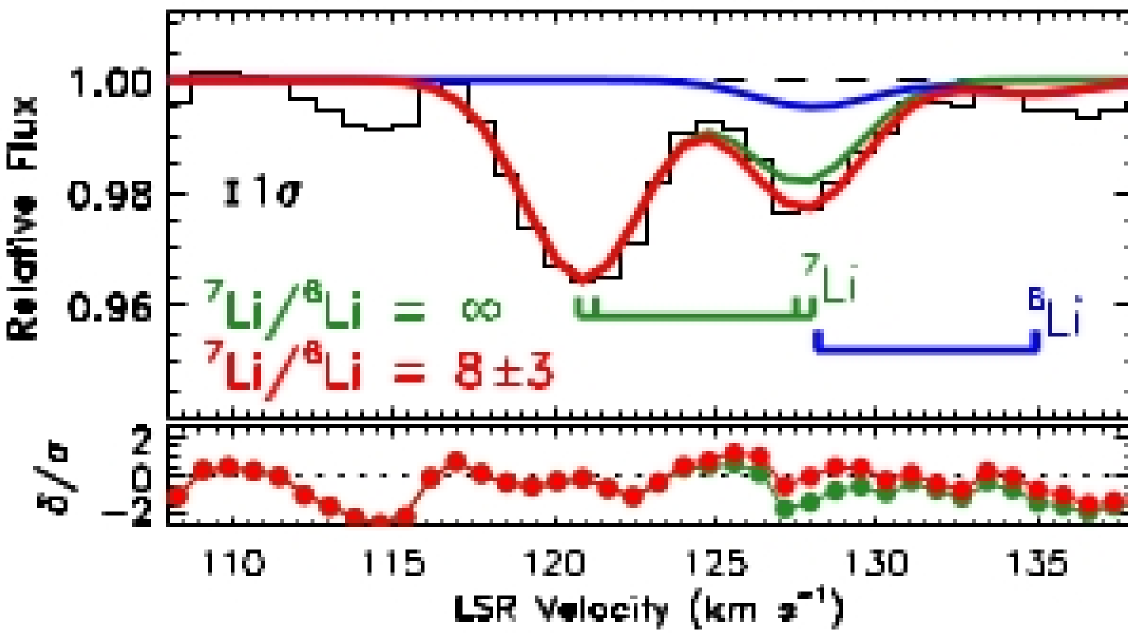
Mucciarelli et al. 2012, MRAS 419, 2195

Lithium: Mucciarelli's plateau



Mucciarelli et al. 2012, MRAS 419, 2195

Lithium in IS medium in Small Magellanic Cloud



$\mathrm{A(Li)} = 2.79 \pm 0.11$
Howk et al. 2013, Nature 489, 121

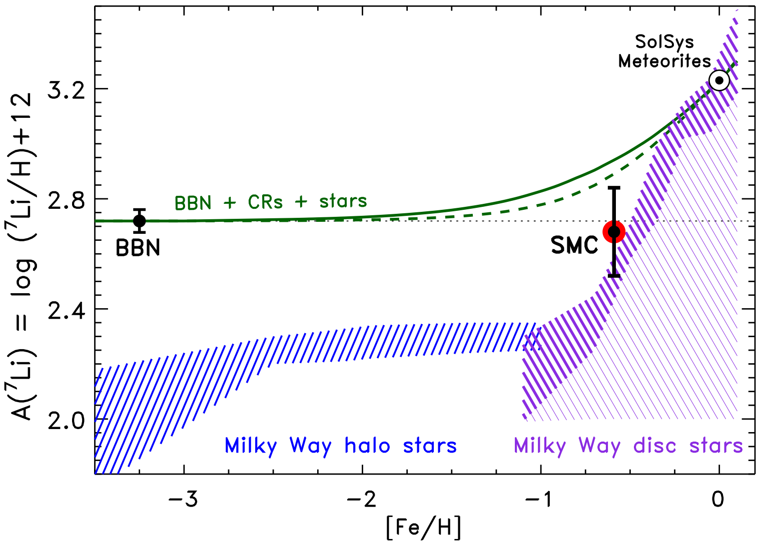
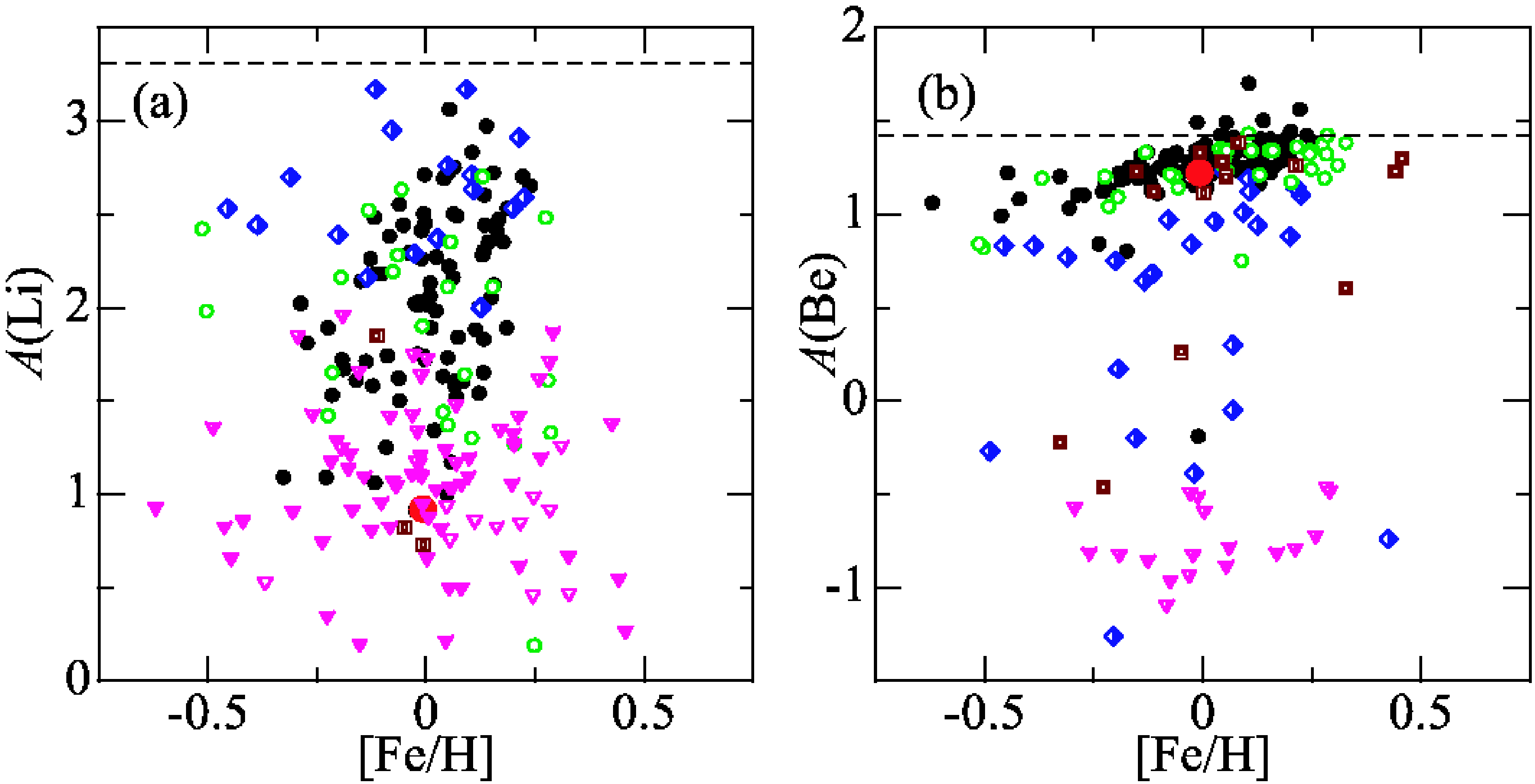


Figure 2: **Estimates of the lithium abundance in the SMC interstellar medium and in several different environments.** Our best estimate for interstellar gas+dust phase abundance of $A(^7\mathrm{Li})$ in the SMC is shown as the red circle with black core derived from the ^{7}Li I/K I ratio. The present day metallicity of the SMC from early-type stars is $[\mathrm{Fe/H}] = -0.59 \pm 0.06$. (All uncertainties are 1σ.) The point marked BBN and dotted horizontal line show the primordial abundance predicted by standard BBN.[3] The green curves show recent models[25] for post-BBN ^{7}Li nucleosynthesis due to cosmic rays (CRs) and stars. By adjusting the yields from low-mass stars, the models are forced to match the solar system meteoritic abundance[23] (see Supplementary Information). The solid and dashed lines correspond to models A and B[25] which respectively include or not a presumed contribution to ^{7}Li from core-collapse supernovae. The blue hatched area shows the range of abundances derived for Population II stars in the Galactic halo,[6] with the "Spite plateau" in this sample at $A(^7\mathrm{Li})_{\mathrm{PopII}} \approx 2.10 \pm 0.10$.[6] The violet hatched region shows the range of measurements seen in Galactic thin disk stars, where the thicker lines denote the six most Li-rich stars in a series of eight metallicity bins.[16] The selection of thin disk stars includes objects over a range of masses and temperatures, including stars that are expected to have destroyed a fair fraction of their Li. Thus, the upper envelope of the distribution represents the best estimate of the intrinsic ISM Li abundance at the epoch of formation for those stars, and the thicker dashed lines for the thin disk sample are most appropriate for comparison with the SMC value. The most Li-rich stars in the Milky Way thin disc[16] within 0.1 dex of the SMC metallicity give $A(^7\mathrm{Li})_{\mathrm{MW}} = 2.54 \pm 0.05$, consistent with our estimate $A(^7\mathrm{Li})_{SMC} = 2.68 \pm 0.16$.

Lithium

- **Li can also be produced**
  - **Cameron-Fowler mechanism in AGB and RGB stars (needed deep convection envelope to transport fresh H and CNO)**
  - **Energetic flares in magnetic active stars**
  - **Planet engulfment**
- **Mechanisms not interesting for unevolved old stars**

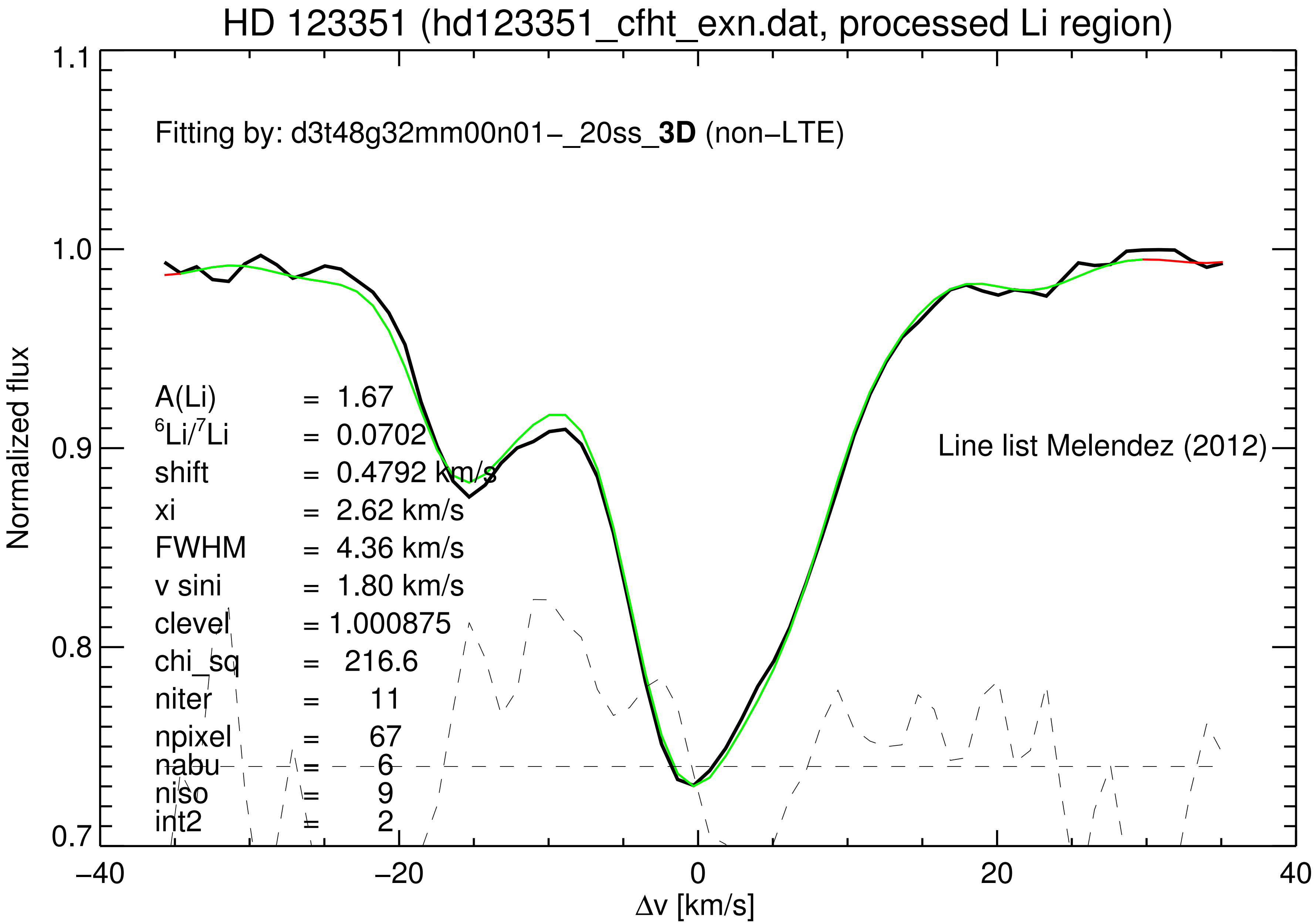
Lithium in solar-metallicity stars



Filled black circles: 118 solar analog; half-filled blue diamonds: 39 F-type stars; open green circles: 34 early G-type stars; outlined brown squares: 14 standard late G- early K-type stars; large red circle: Sun; pink downward tingles: upper limits; horizontal dashed lines: meteoritic value: A(Li)=3.31 and A(Be)=1.42.

Takeda et al. 2011 PASJ 63, 697

Lithium in solar-metellicity stars



Lithium

- **Remaining problems**
  - **A(Li)=2.2 three times smaller than primordial Li, possible explanations:**
    - **EMP low mass stars were all formed by fragmentation of higher mass clouds; they remain fast rotators through pre-MS; rotational mixing leads to Li destruction**
    - **Pre-MS stars always depletes all Li, late accretion of unprocessed material restores Li to some extent (Fu et al. 2016); EMP stars lack or have an inefficient late accretion phase**
    - **Within the DM mini-halo a significant fraction of the mass (%50 ?) is rapidly processed through massive stars, this leads to Li depletion; low-mass stars only form from this pre-processed material**
  - **Li meltdown**