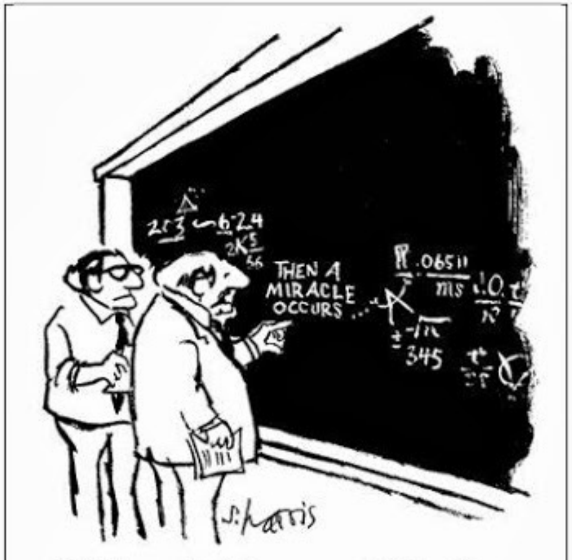
Big Bang Nucleosynthesis

Alexander Knebe (*Universidad Autonoma de Madrid*)



"I think you should be more explicit here in step two."

- introduction
- particle physics
- synthesis of elements
- big bang nucleosynthesis
- observations

- ***introduction***
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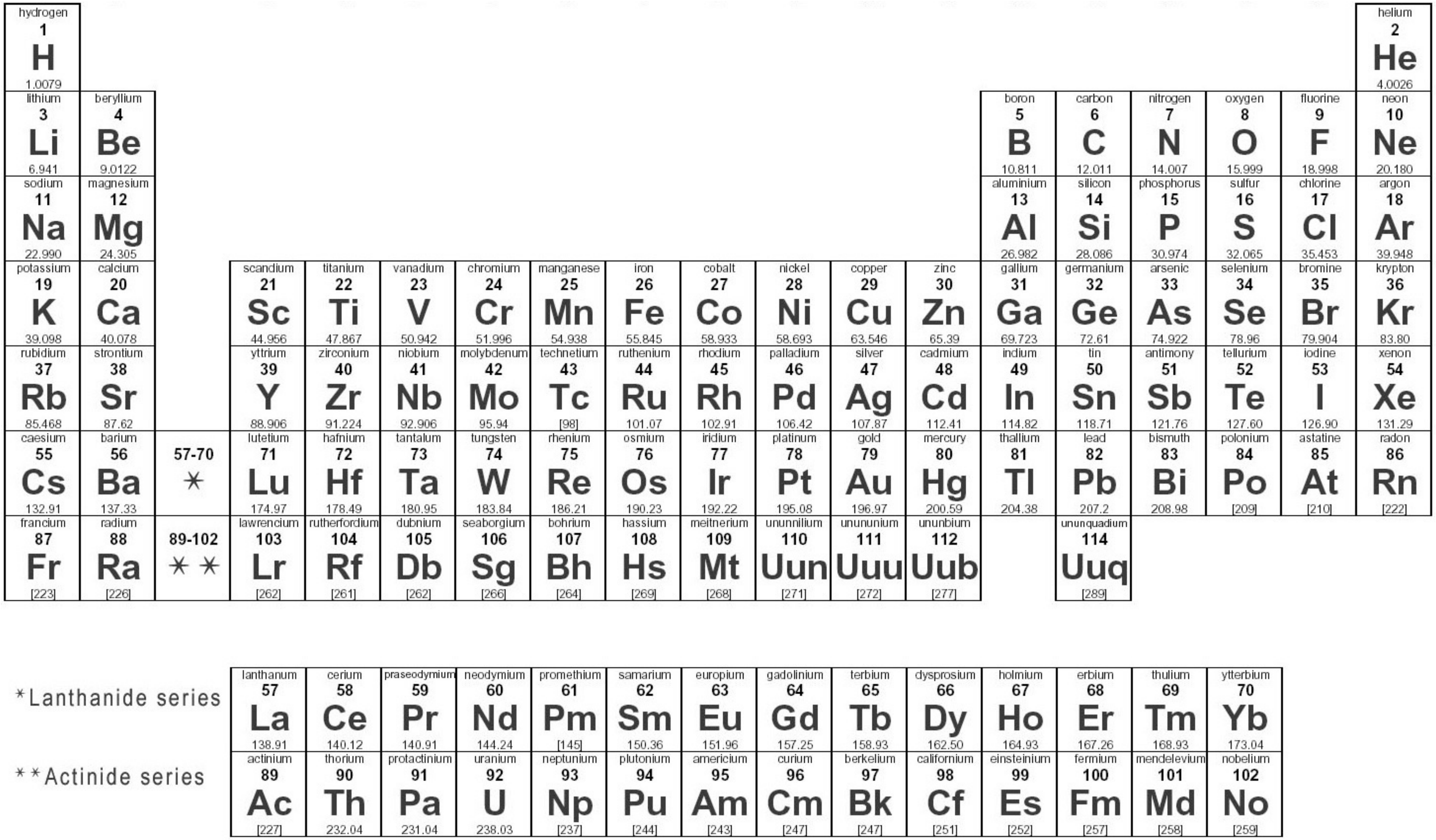
where do all the elements come from?



hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

*Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
* *Actinide series	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

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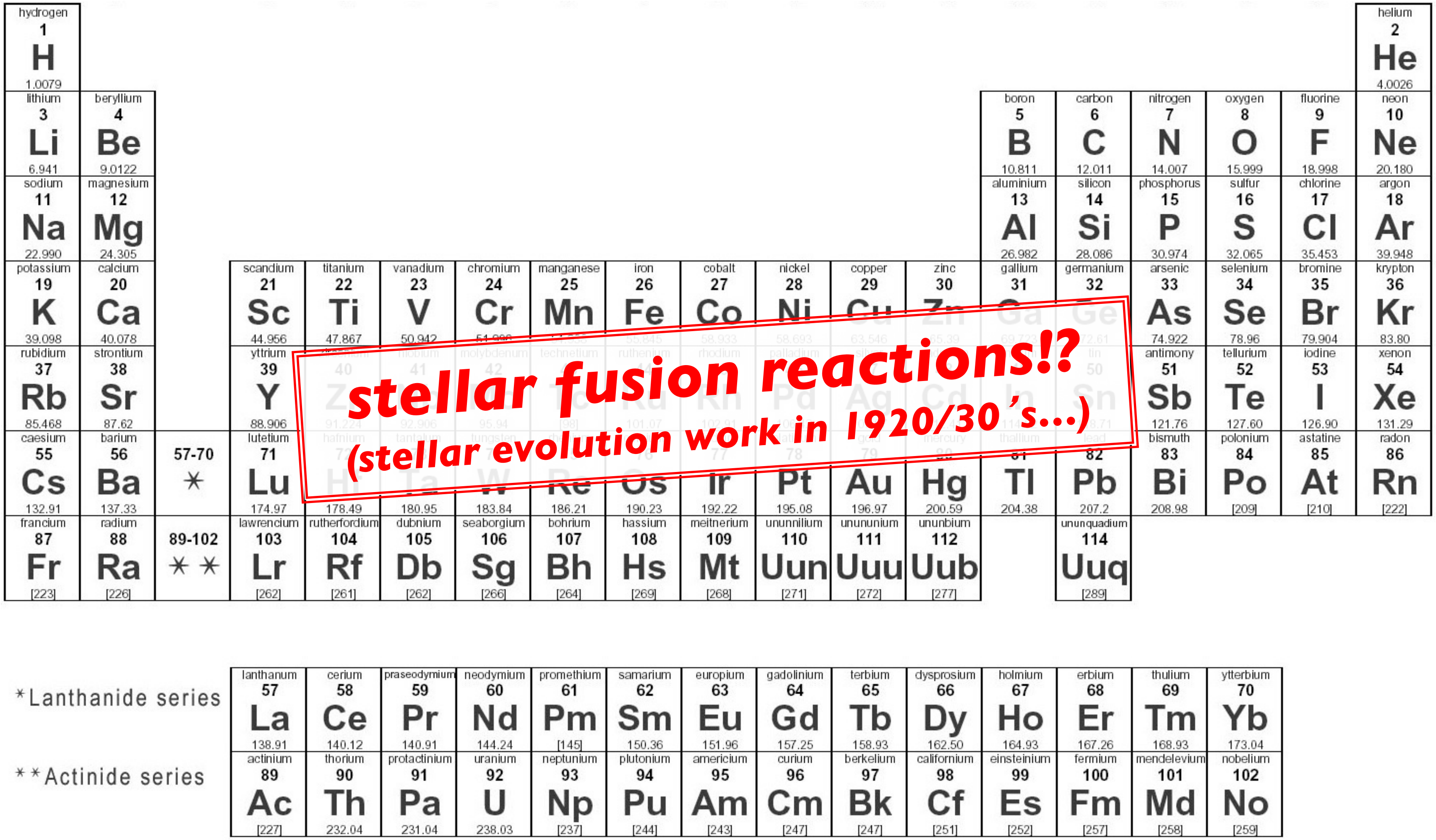

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stellar fusion reactions!?

(stellar evolution work in 1920/30's...)

- **stellar fusion…**
  - cannot account for observed ^{4}He abundance

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    → if MW were to "shine" for 10^{10} years, it would generate*

    4% ^{4}He

---

*(Burbidge, 1958, PASP, 70, 83)

- **stellar fusion…**

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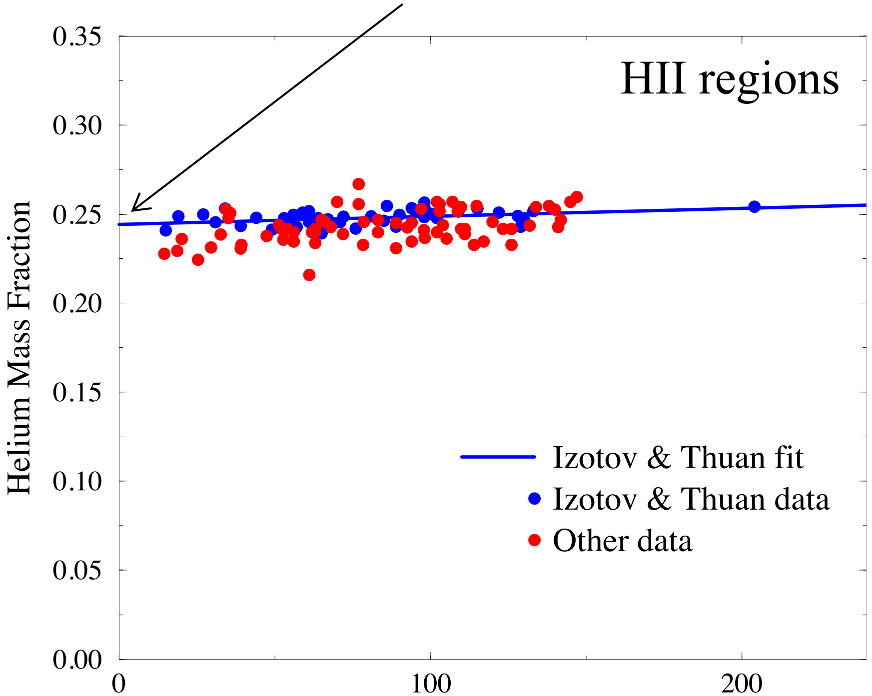
    → if MW were to "shine" for 10^{10} years, it would generate

    4% ^{4}He vs. 24% ^{4}He as observed!



(Burles, Nollett & Turner, arxiv:9903300, Fig.4)

("metalicity" = indicator of stellar processing)

- **stellar fusion…**
  - cannot account for observed ^{4}He abundance
  - cannot create D* but only burn it:

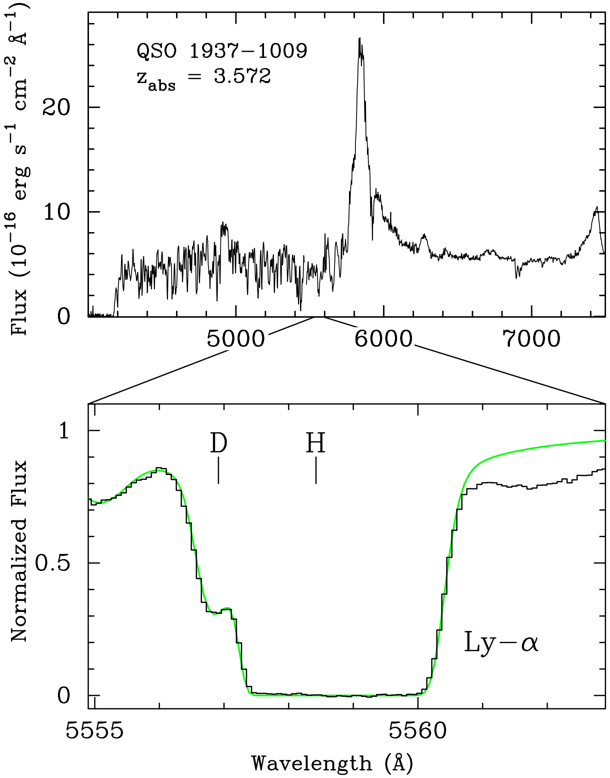
    fusion reactions in the sun are consuming D faster than generating it

*D=^{2}H=p+n

- **stellar fusion…**
  - cannot account for observed ^{4}He abundance
  - cannot create D but only burn it:

    fusion reactions in the sun are consuming D faster than generating it

…but we do observe D
in the interstellar medium:



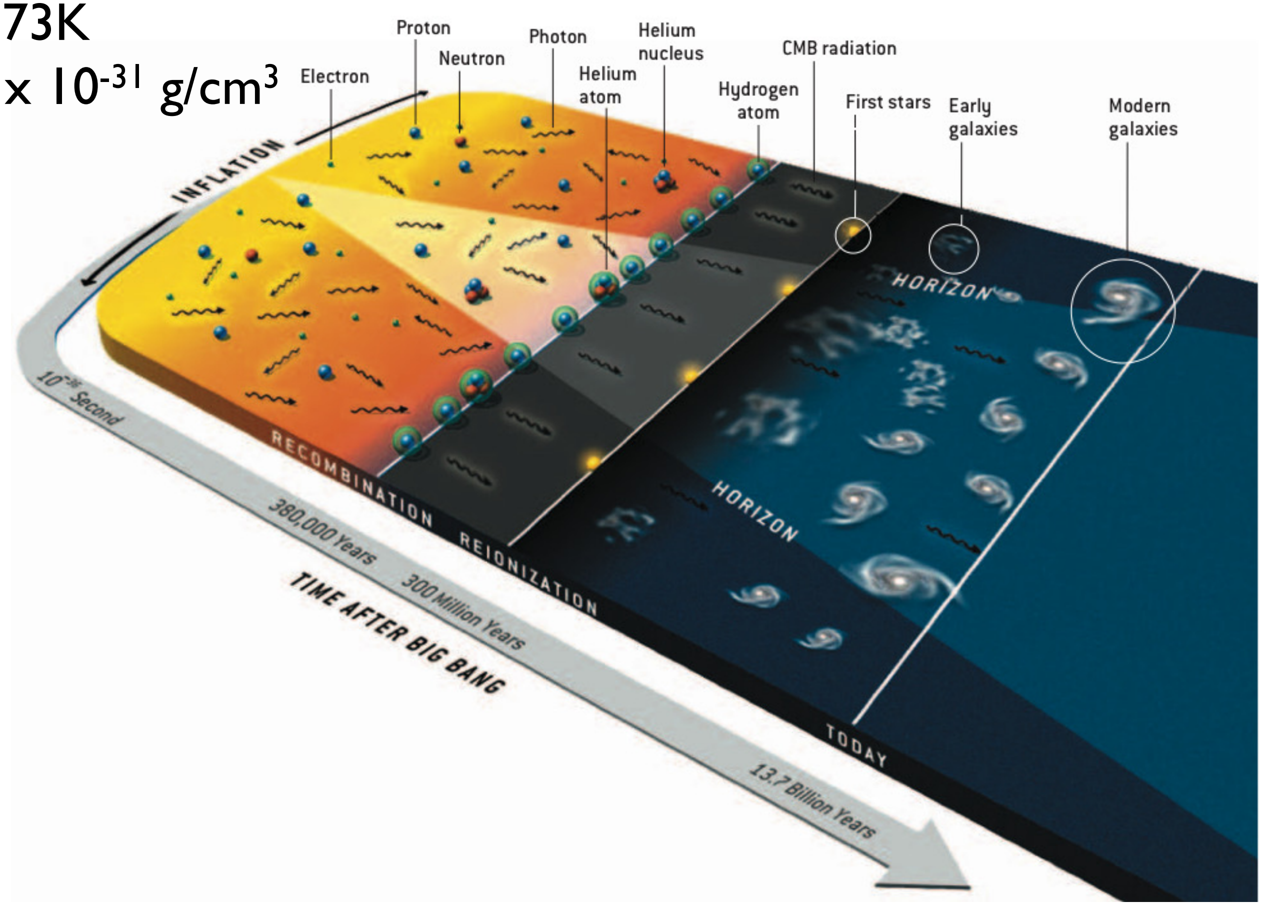
(Burles, Nollett & Turner, arxiv:9903300, Fig.2)

- **stellar fusion…**
  - cannot account for observed ^{4}He abundance
  - cannot create D but only burn it

fusion events other than stellar must have happened during the ca. 13.7 Gyrs of the Universe's existence…

- **cosmological considerations**
  - $z = 0$ (today):

T_{CMB} = 2.73K
ρ_b = 5 x 10^{-31} g/cm^3



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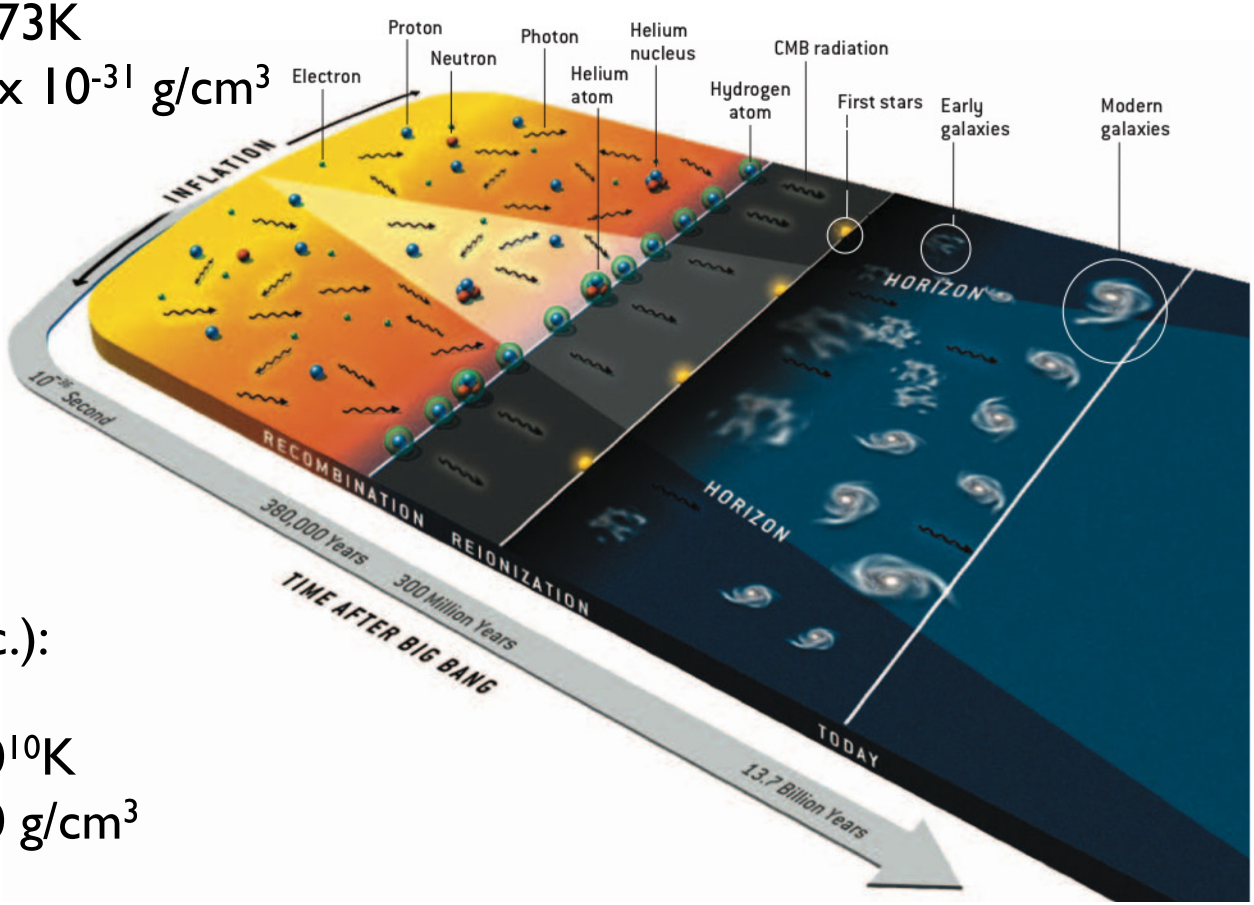

  - $z \approx 10^{10}$ (t≈1sec.):

    T_{CMB} ≈ 10^{10}K
    ρ_b ≈ 80 g/cm^3

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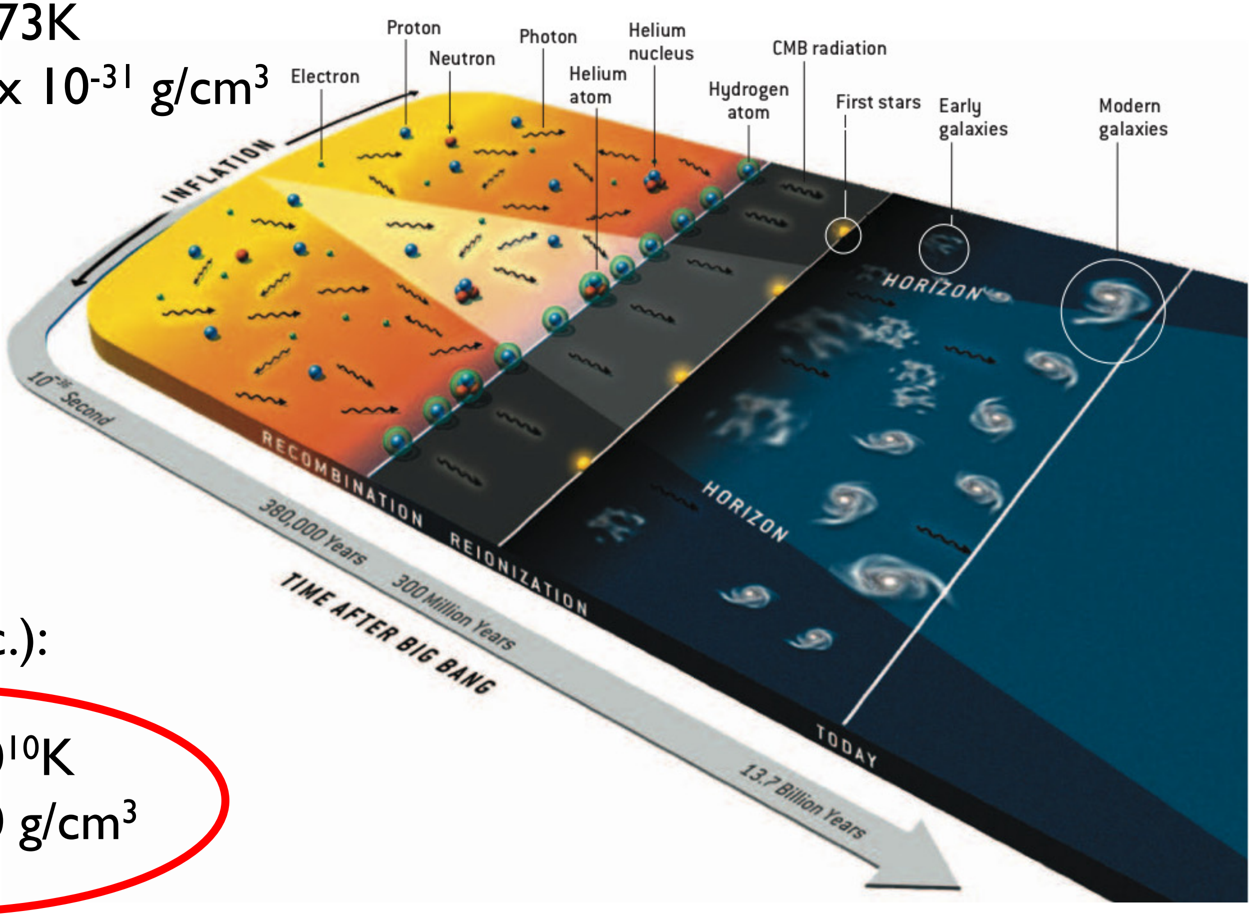

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sufficient for nuclear fusion!

▪ cosmological considerations

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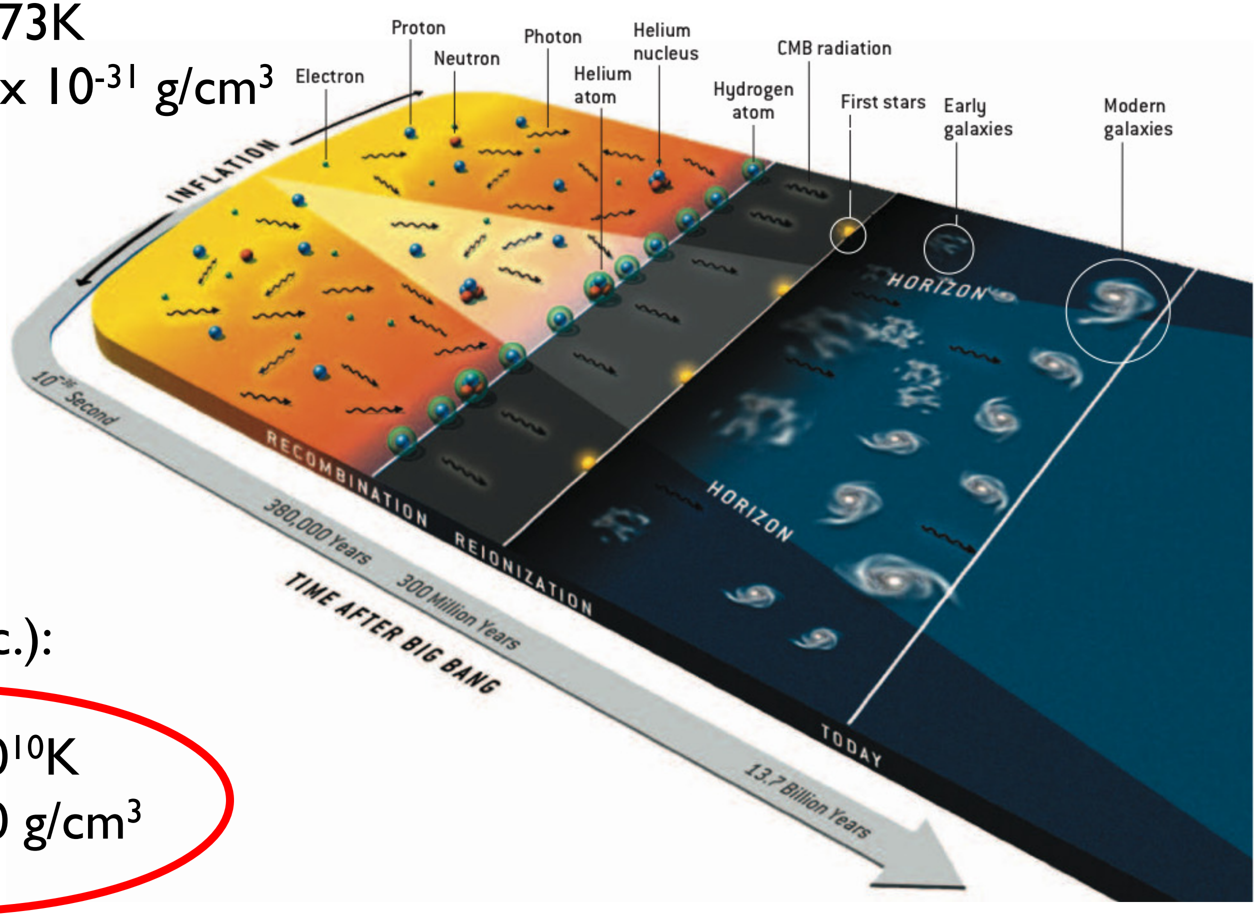

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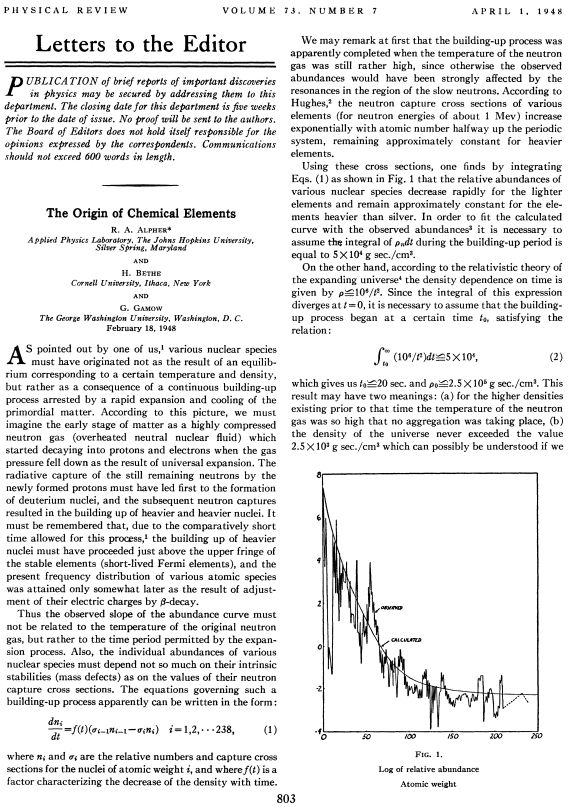
sufficient for nuclear fusion ➔ "Big Bang Nucleosynthesis" ⁉

- **BBN:**

Alpher, Bethe & Gamow (1948)
“The Origin of Chemical Elements”



PHYSICAL REVIEW VOLUME 73, NUMBER 7 APRIL 1, 1948

Letters to the Editor

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The Origin of Chemical Elements

R. A. Alpher*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
AND
H. Bethe
Cornell University, Ithaca, New York
AND
G. Gamow
The George Washington University, Washington, D. C.
February 18, 1948

As pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as the result of universal expansion. The radiative capture of the still remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei. It must be remembered that, due to the comparatively short time allowed for this process,[1] the building up of heavier nuclei must have proceeded just above the upper fringe of the stable elements (short-lived Fermi elements), and the present frequency distribution of various atomic species was attained only somewhat later as the result of adjustment of their electric charges by β-decay.

Thus the observed slope of the abundance curve must not be related to the temperature of the original neutron gas, but rather to the time period permitted by the expansion process. Also, the individual abundances of various nuclear species must depend not so much on their intrinsic stabilities (mass defects) as on the values of their neutron capture cross sections. The equations governing such a building-up process apparently can be written in the form:

$$\frac{dn_i}{dt}=f(t)(\sigma_{i-1}n_{i-1}-\sigma_i n_i) \quad i=1,2,\cdots 238, \qquad (1)$$

where n_i and σ_i are the relative numbers and capture cross sections for the nuclei of atomic weight i, and where $f(t)$ is a factor characterizing the decrease of the density with time.

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm^3.

On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho\cong10^6/t^2$. Since the integral of this expression diverges at $t=0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying the relation:

$$\int_{t_0}^{\infty}(10^6/t^2)dt\cong5\times10^4, \qquad (2)$$

which gives us $t_0\cong20$ sec. and $\rho_0\cong2.5\times10^5$ g sec./cm^3. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value 2.5×10^3 g sec./cm^3 which can possibly be understood if we

Fig. 1.

Log of relative abundance

Atomic weight

Big Bang Nucleosynthesis

- **BBN:**

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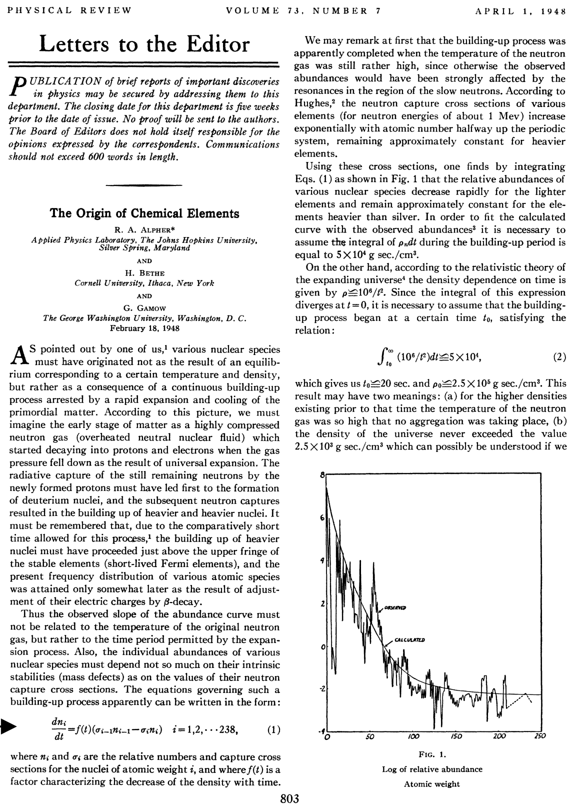

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Log of relative abundance

Atomic weight

803

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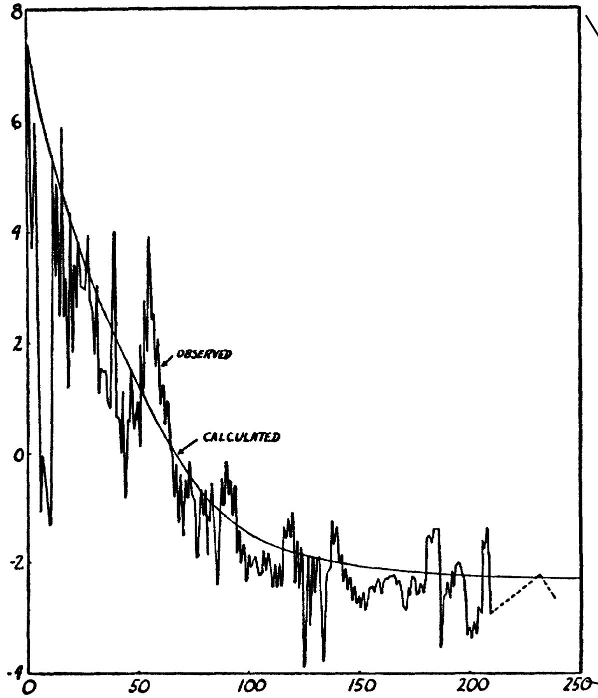

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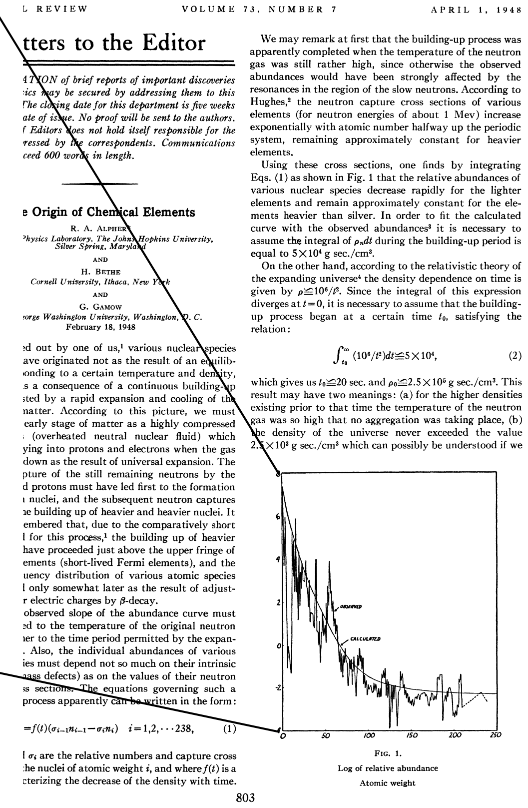

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all elements are produced in BBN !?

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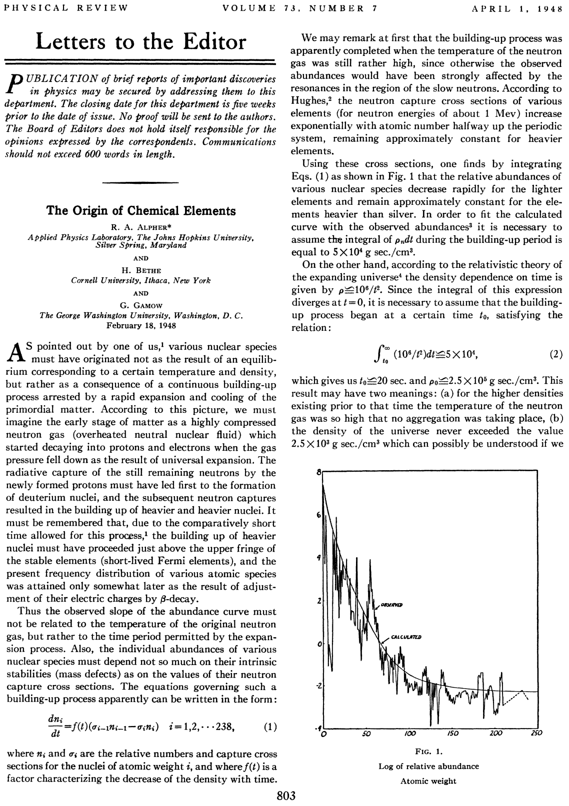

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$$\frac{dn_i}{dt}=f(t)(\sigma_{i-1}n_{i-1}-\sigma_i n_i) \quad i=1,2,\cdots 238, \qquad (1)$$

where n_i and σ_i are the relative numbers and capture cross sections for the nuclei of atomic weight i, and where $f(t)$ is a factor characterizing the decrease of the density with time.

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume ~~the~~ integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm^3.

On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho\cong10^6/t^2$. Since the integral of this expression diverges at $t=0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying the relation:

$$\int_{t_0}^{\infty}(10^6/t^2)dt\cong5\times10^4, \qquad (2)$$

which gives us $t_0\cong20$ sec. and $\rho_0\cong2.5\times10^5$ g sec./cm^3. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value 2.5×10^3 g sec./cm^3 which can possibly be understood if we

FIG. 1.

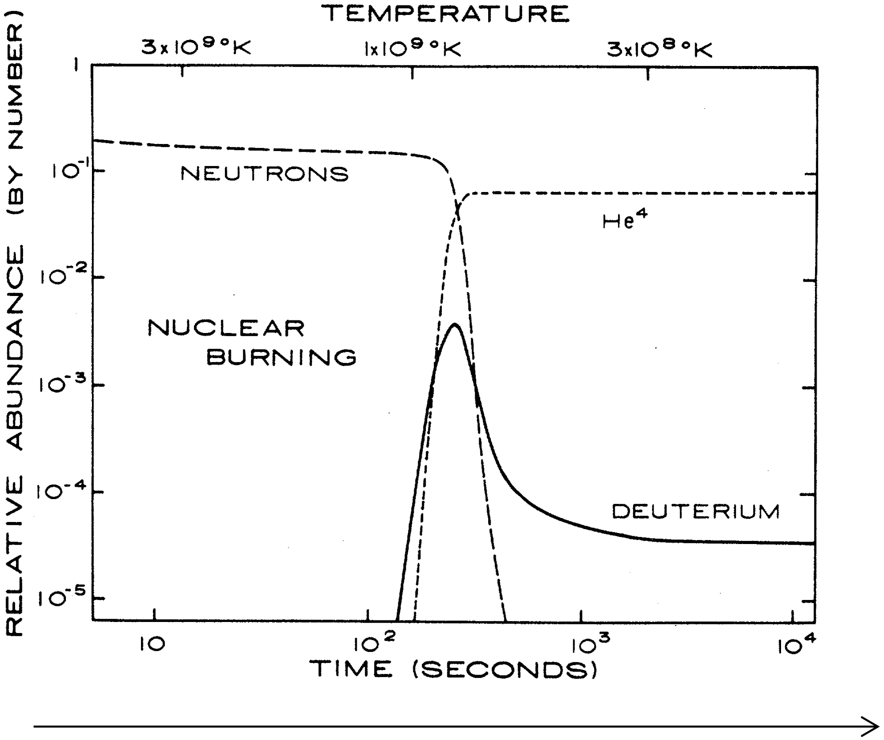
Log of relative abundance

Atomic weight

this is the whole publication!

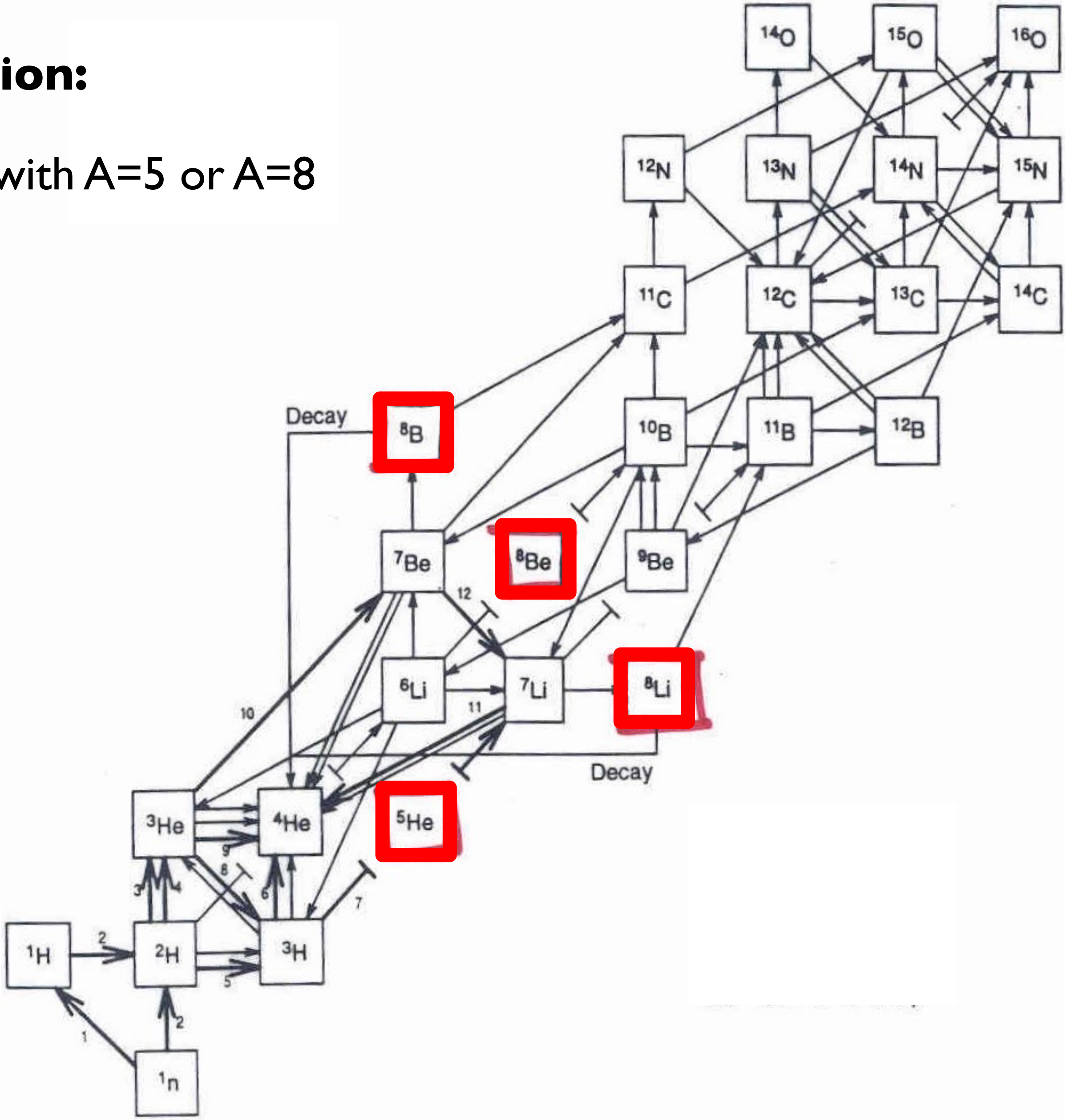
- **BBN:**

Peebles (1966)
“Primeval Helium abundance and the primeval Fireball”

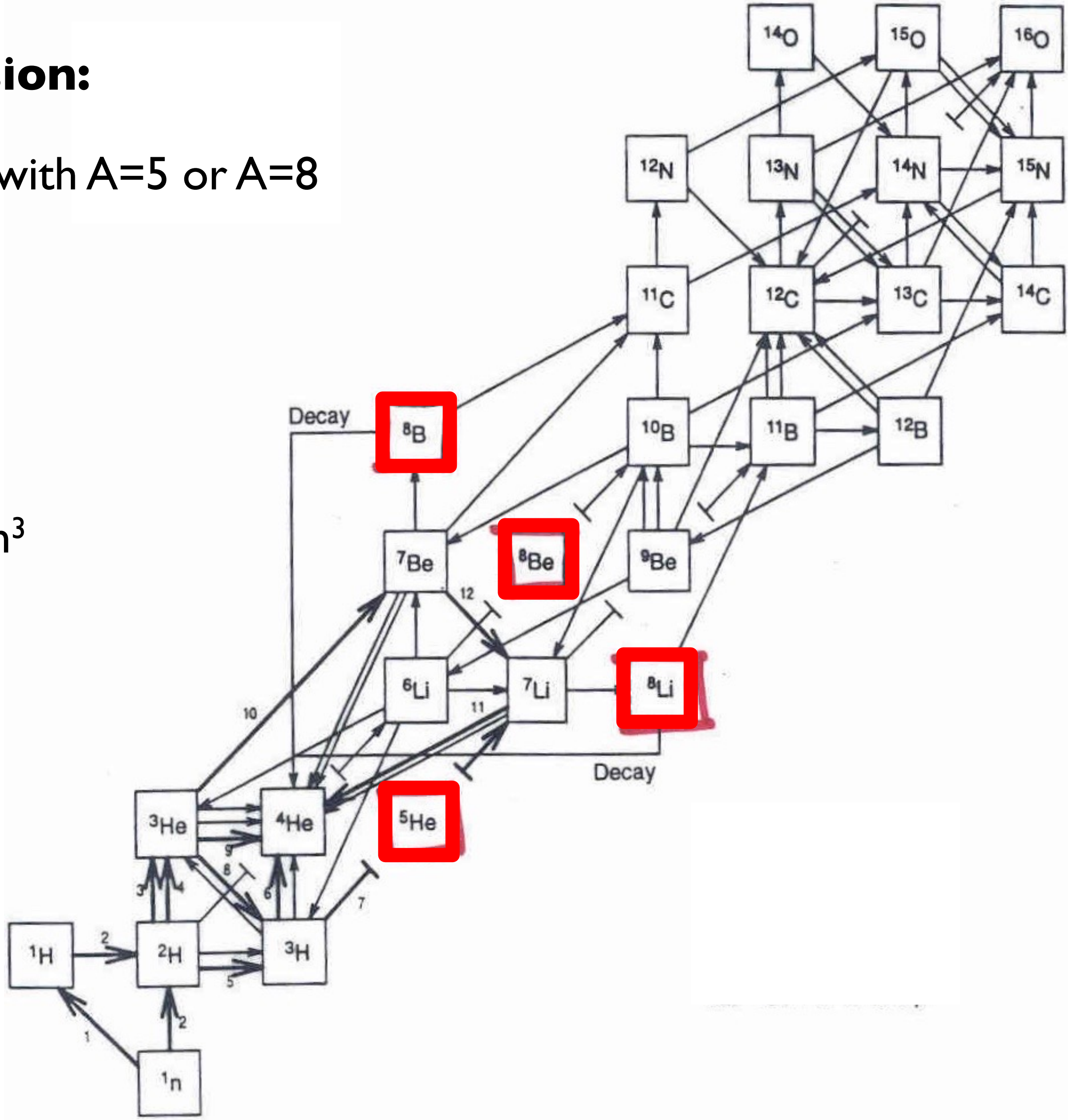


$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right)$: detailed calculation of the temporal evolution of element abundances…

- **BBN vs. stellar fusion:**
  - no stable elements with A=5 or A=8



- **BBN vs. stellar fusion:**
  - no stable elements with A=5 or A=8
  - BBN: $\rho_b \approx 80\ \mathrm{g/cm^3}$
  - sun: $\rho_b \approx 150\ \mathrm{g/cm^3}$



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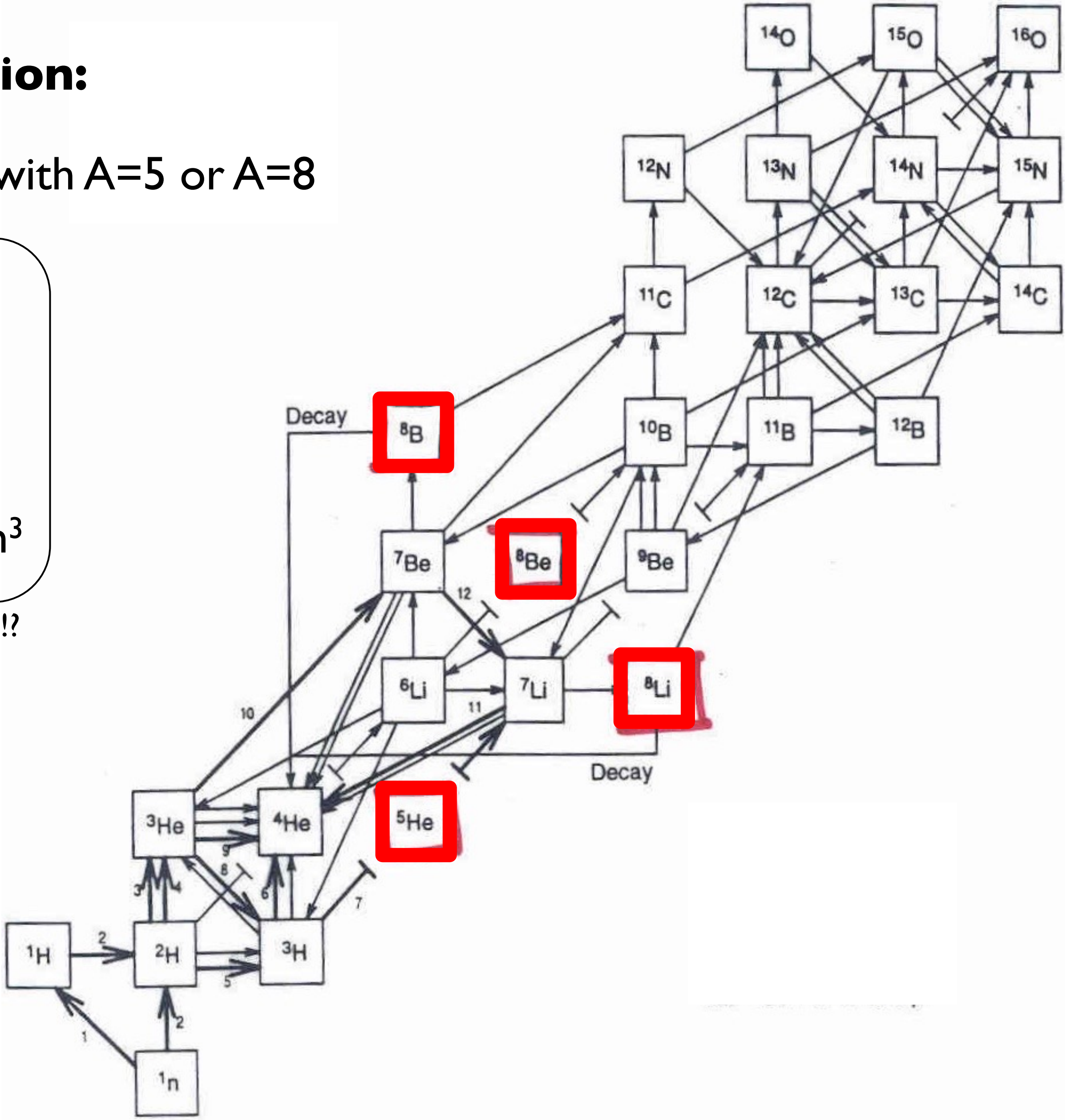
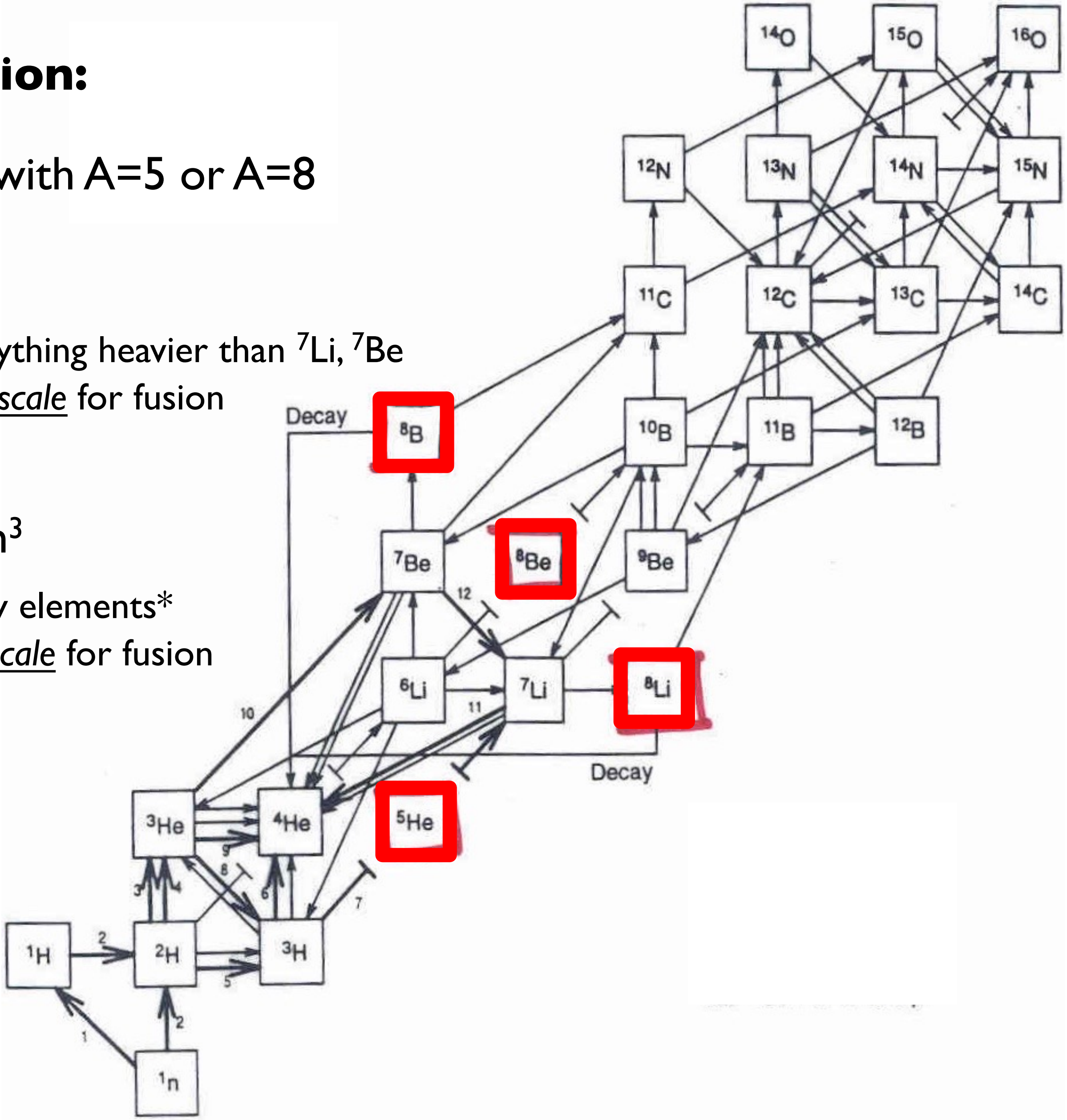
similar conditions!?



- **BBN vs. stellar fusion:**
  - no stable elements with A=5 or A=8
  - BBN: $\rho_b \approx 80\ \mathrm{g/cm^3}$

    → unable to process anything heavier than ^{7}Li, ^{7}Be due to *very short timescale* for fusion
  - sun: $\rho_b \approx 150\ \mathrm{g/cm^3}$

    → able to process heavy elements* due to *extended timescale* for fusion



*via unstable ^{8}Be ("triple-α process")

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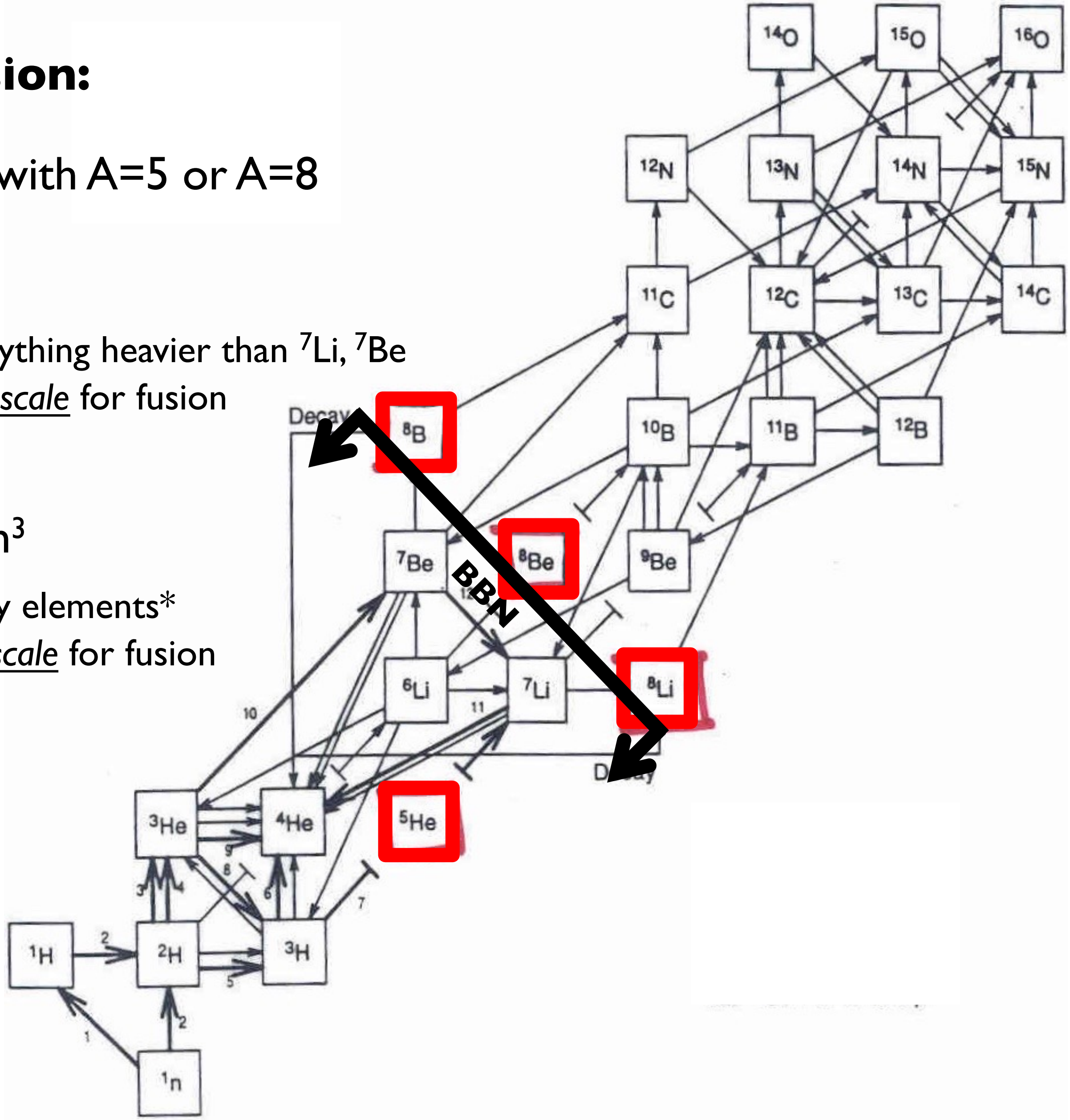
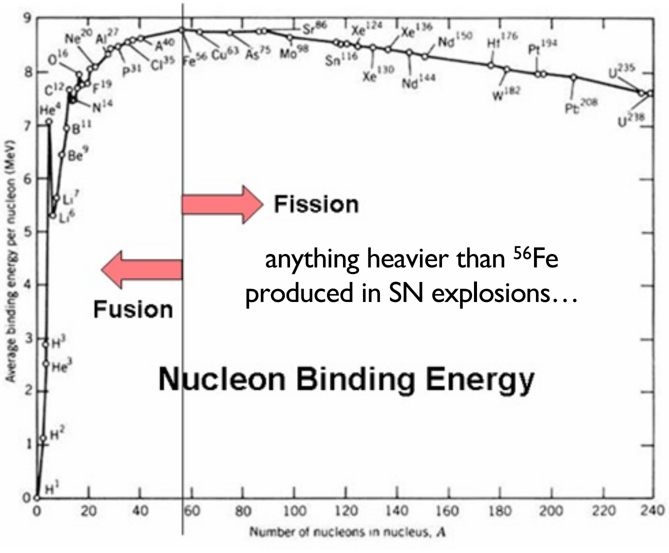


*via unstable ^{8}Be ("triple-α process")

- **BBN summary:**
  - production of H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Be, ^{7}Li

^{2}H: deuterium D
^{3}H: trillium T

- **all other elements are in fact produced in stars…**



anything heavier than ^{56}Fe produced in SN explosions…

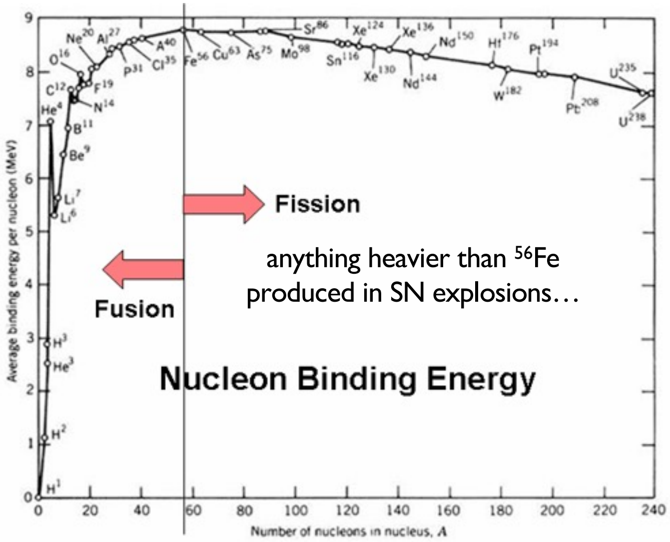
- **BBN summary:**
  - production of H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Be, ^{7}Li

^{2}H: deuterium D
^{3}H: trillium T

  - *prediction* for mass fractions:

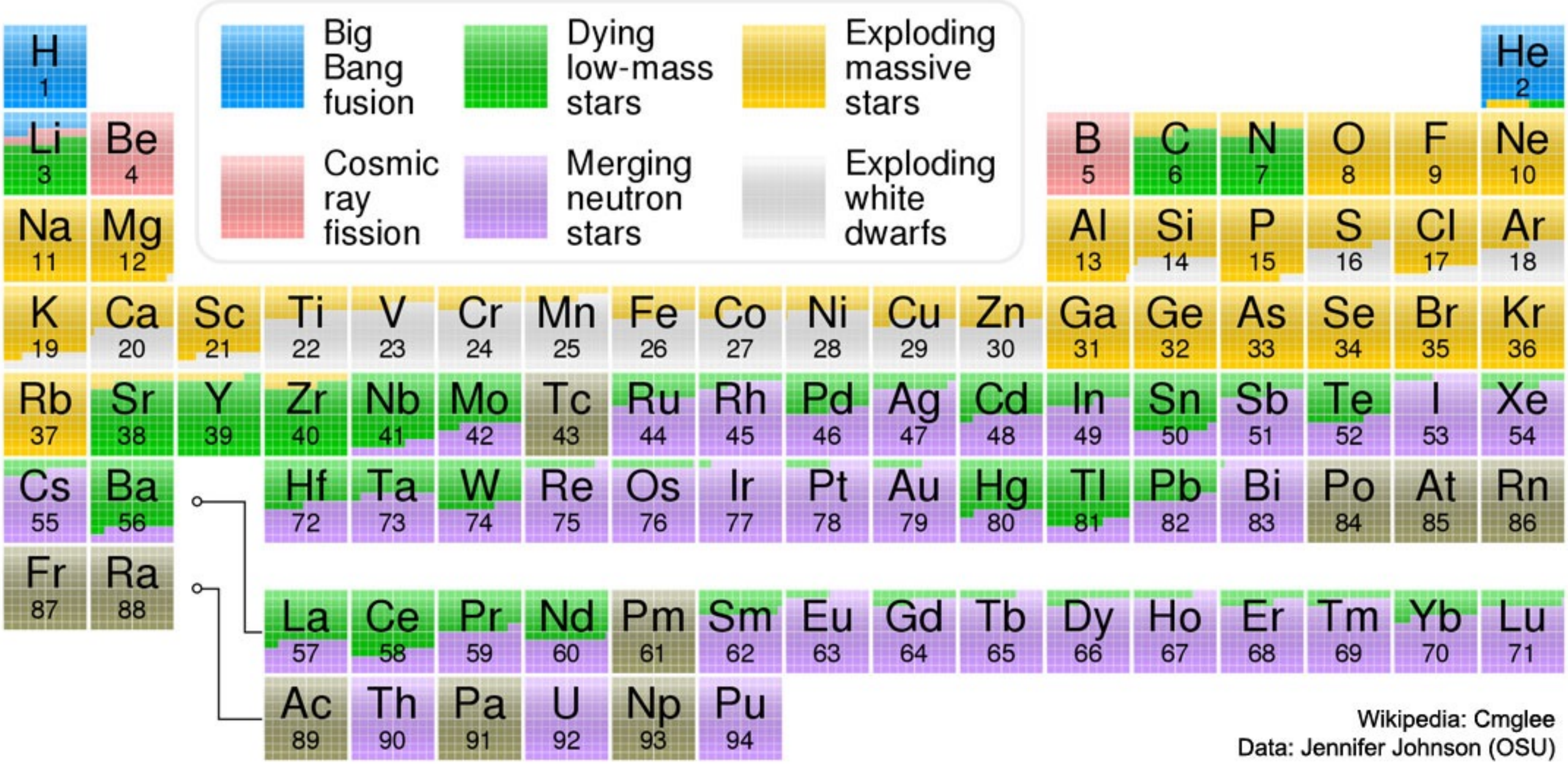
$$Y_{\mathrm{He}} \approx \mathbf{0.24}$$
$$Y_{\mathrm{H}} \approx \mathbf{0.73}$$

- **all other elements are in fact produced in stars…**



anything heavier than ^{56}Fe produced in SN explosions…

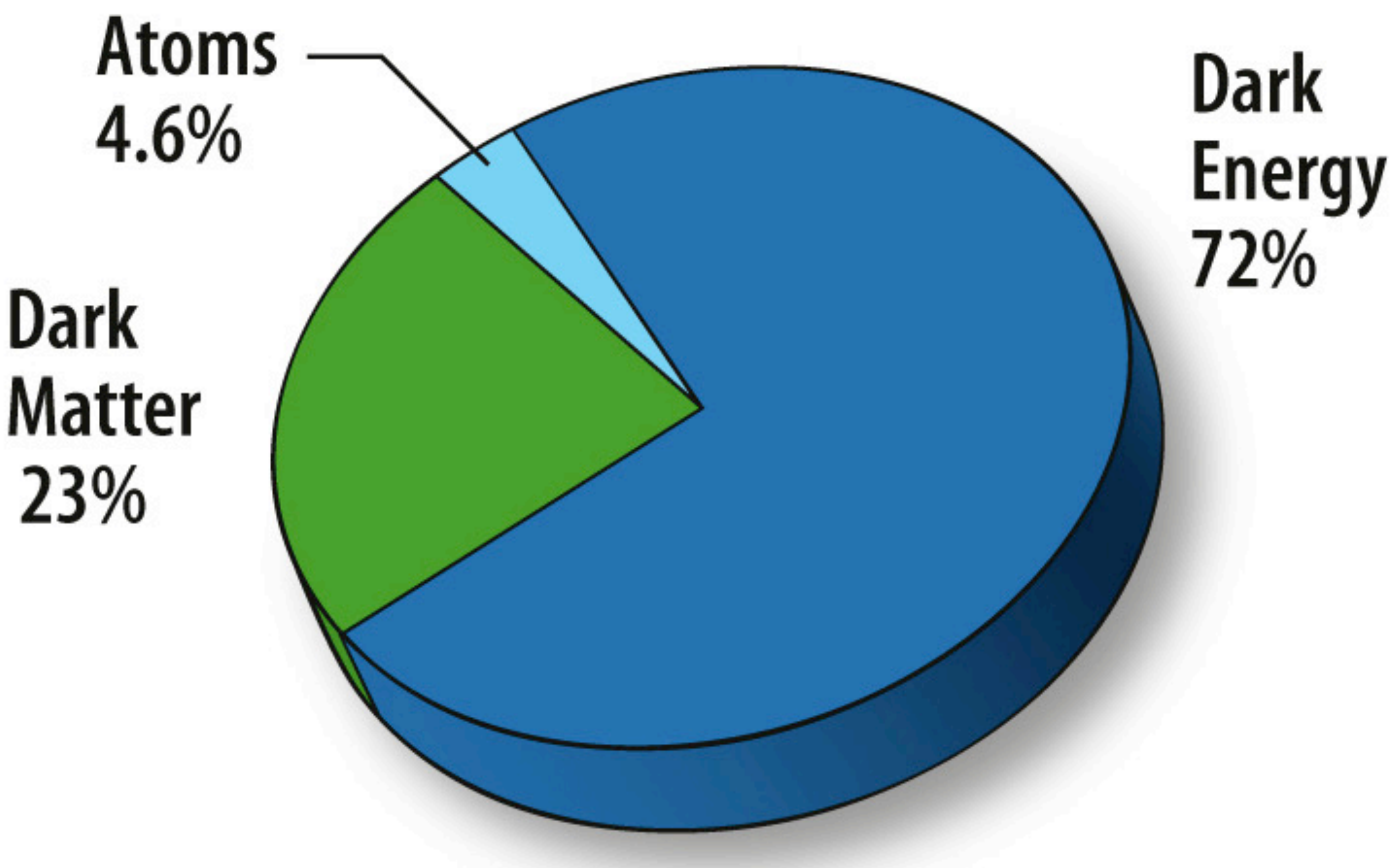
where do all the elements come from?



Wikipedia: Cmglee
Data: Jennifer Johnson (OSU)

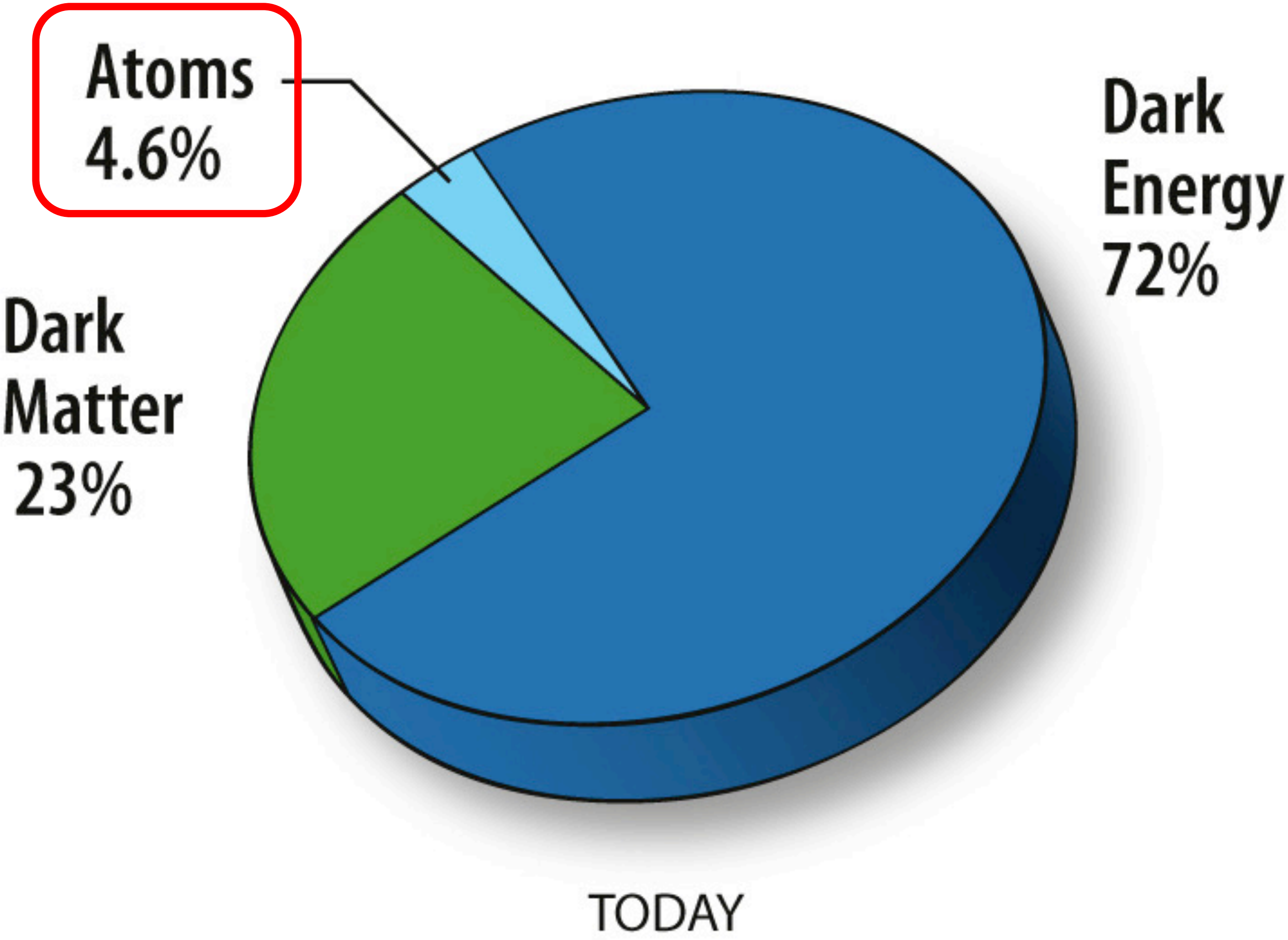
(APOD 24/10/2017)

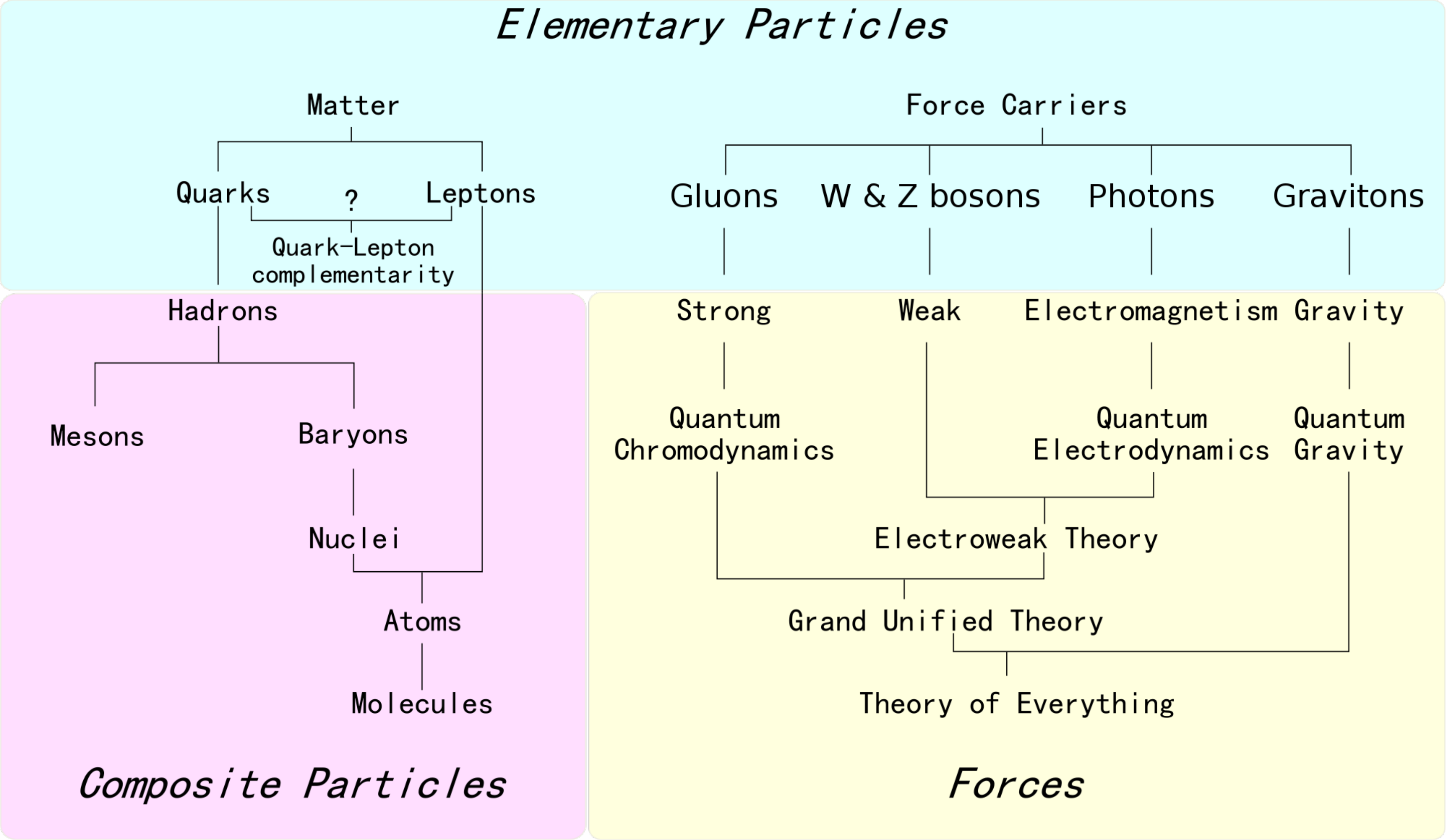
- introduction
- ***particle physics***
- synthesis of elements
- big bang nucleosynthesis
- observations



TODAY

we are only talking about their nuclei here...





Elementary Particles

Matter

Quarks

?

Leptons

Quark-Lepton complementarity

Force Carriers

Gluons

W & Z bosons

Photons

Gravitons

Hadrons

Mesons

Baryons

Nuclei

Atoms

Molecules

Composite Particles

Strong

Weak

Electromagnetism

Gravity

Quantum Chromodynamics

Quantum Electrodynamics

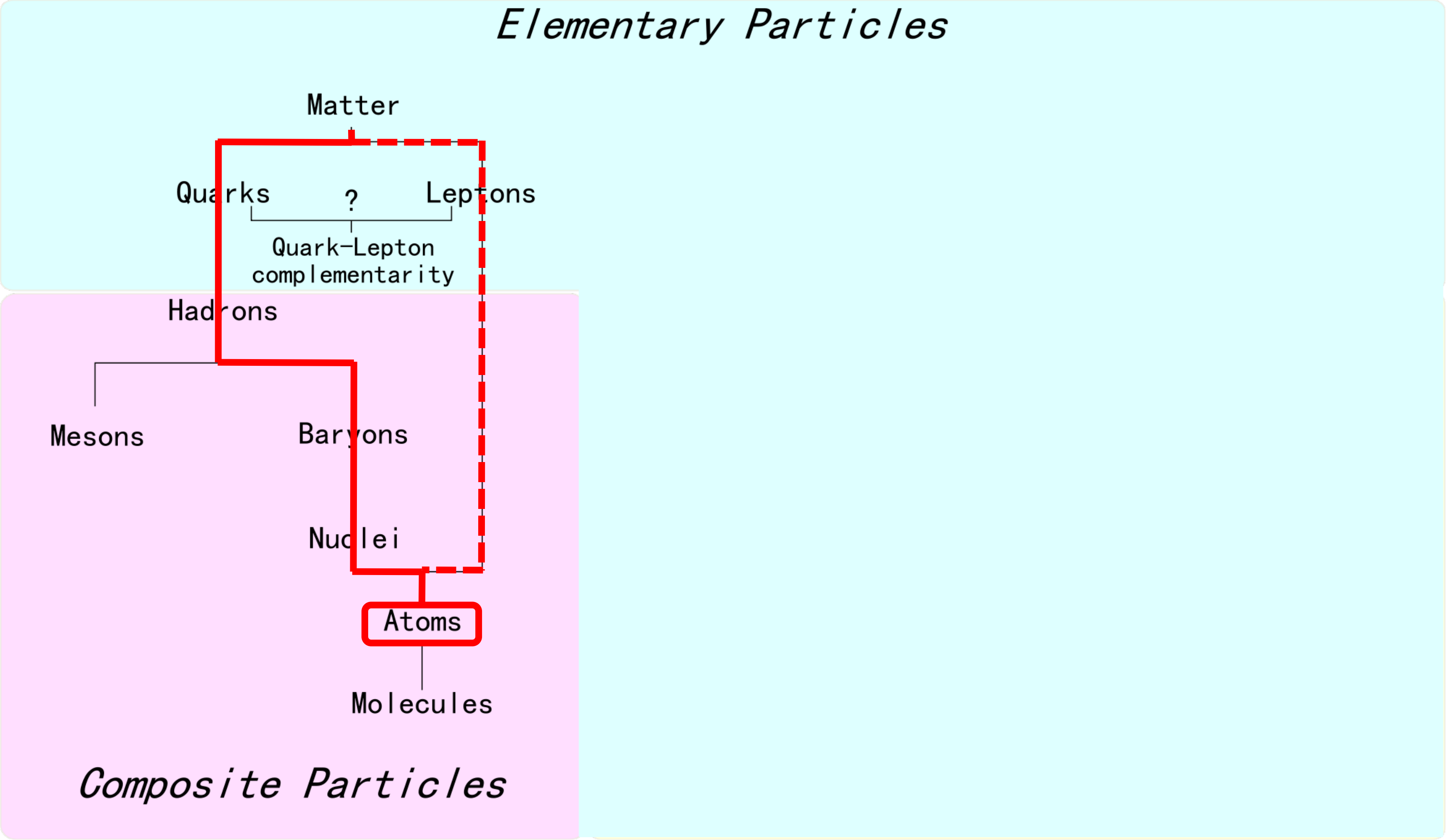
Quantum Gravity

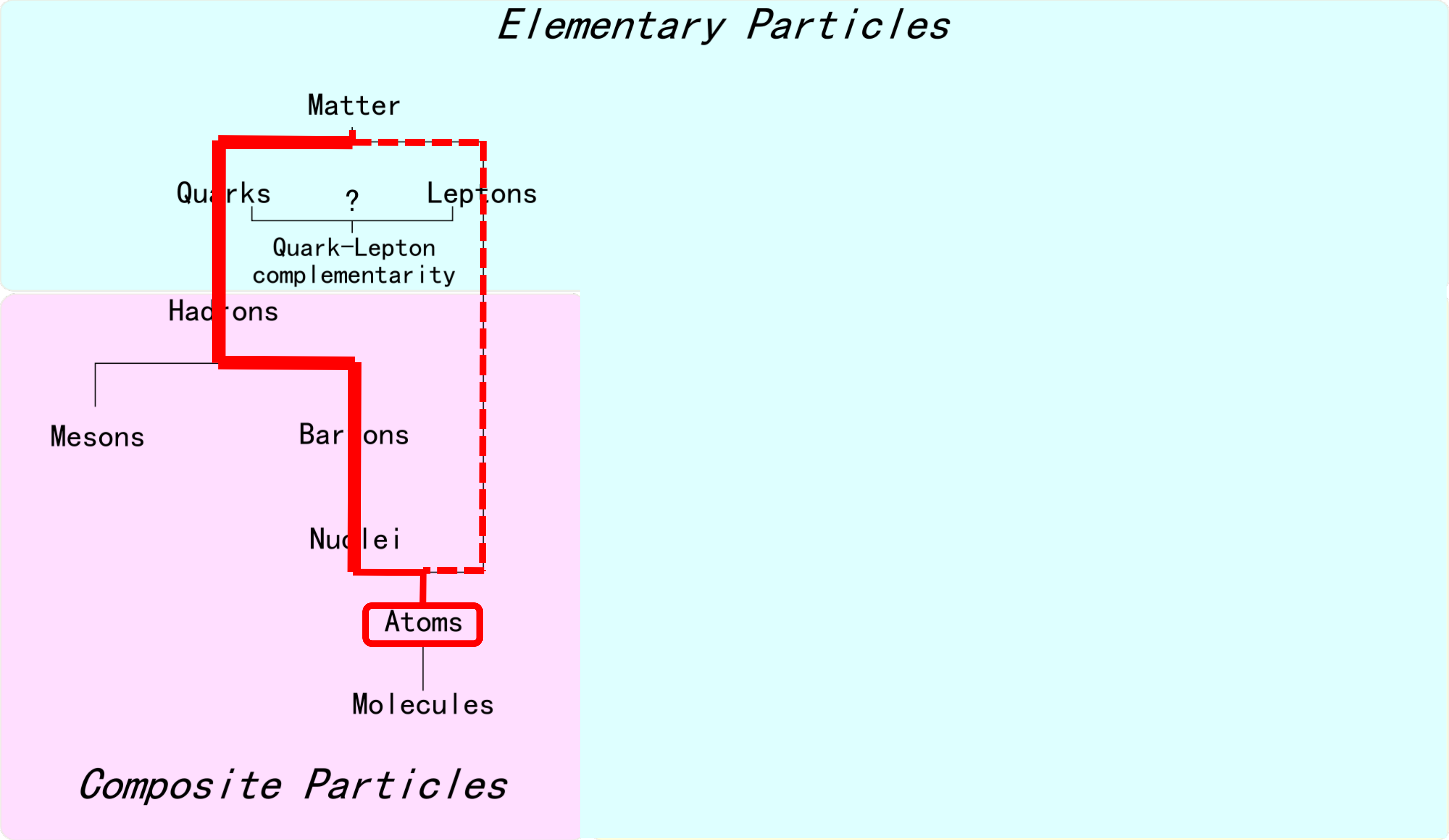
Electroweak Theory

Grand Unified Theory

Theory of Everything

Forces


Elementary Particles
Matter
Quarks
?
Leptons
Quark–Lepton complementarity
Hadrons
Mesons
Baryons
Nuclei
Atoms
Molecules
Composite Particles



Elementary Particles

Matter

Quarks

?

Leptons

Quark–Lepton complementarity

Hadrons

Mesons

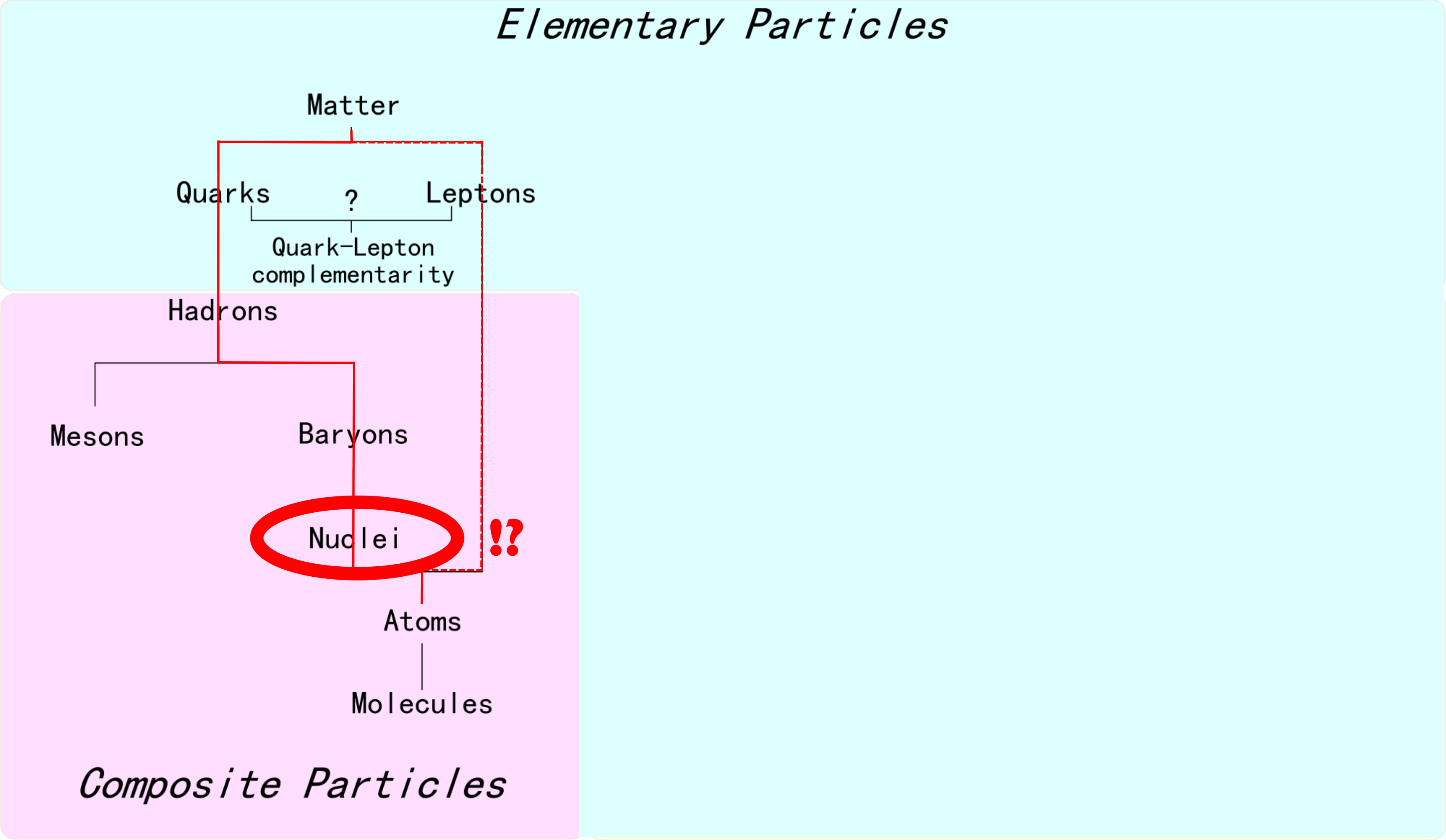
Baryons

Nuclei

Atoms

Molecules

Composite Particles



Elementary Particles

Matter

Quarks ? Leptons

Quark–Lepton complementarity

Hadrons

Mesons

Baryons

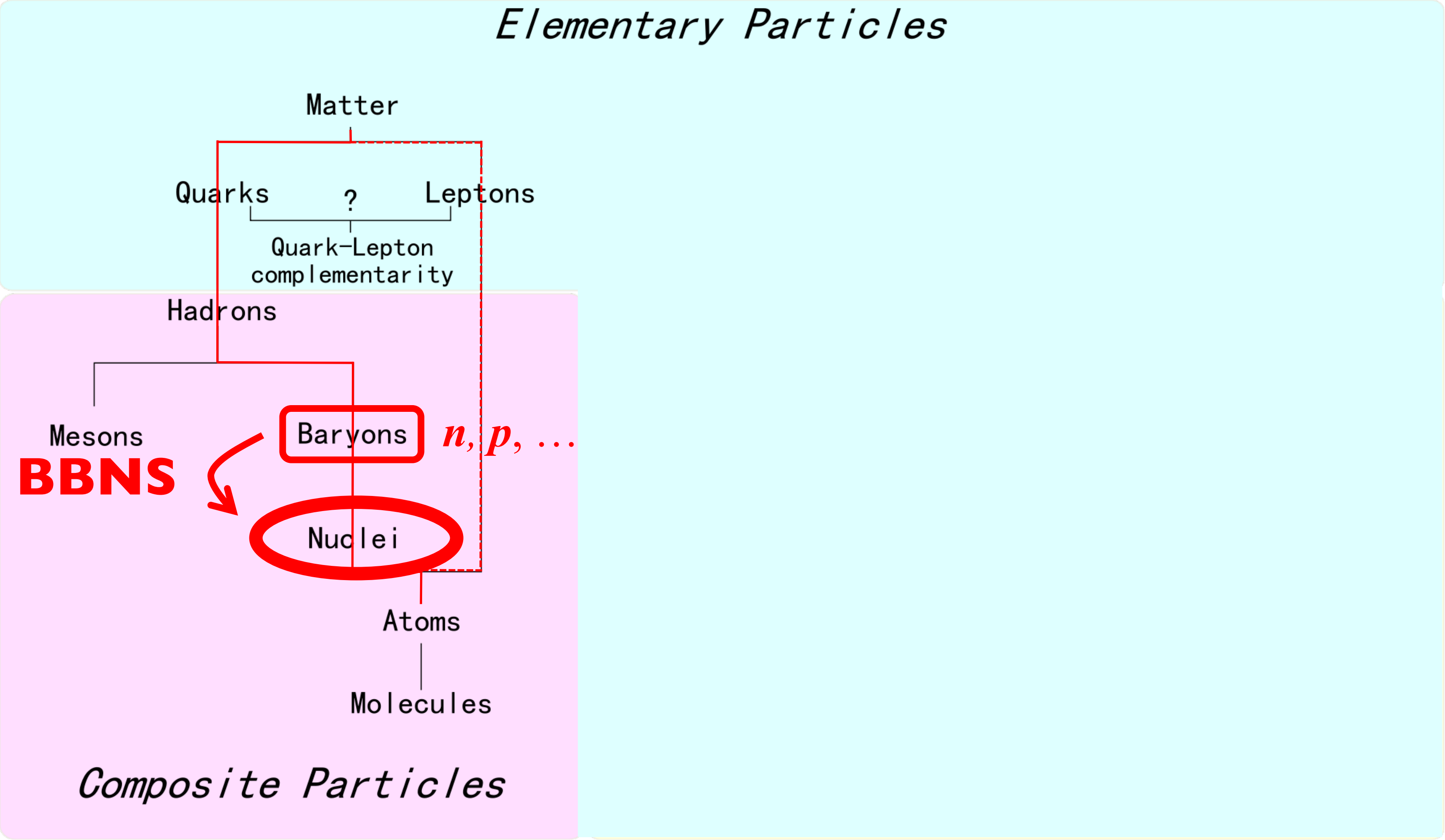
Nuclei

⁉

Atoms

Molecules

Composite Particles



Elementary Particles

Matter

Quarks ? Leptons

Quark–Lepton complementarity

Hadrons

Mesons

Baryons

$n, p, \ldots$

BBNS

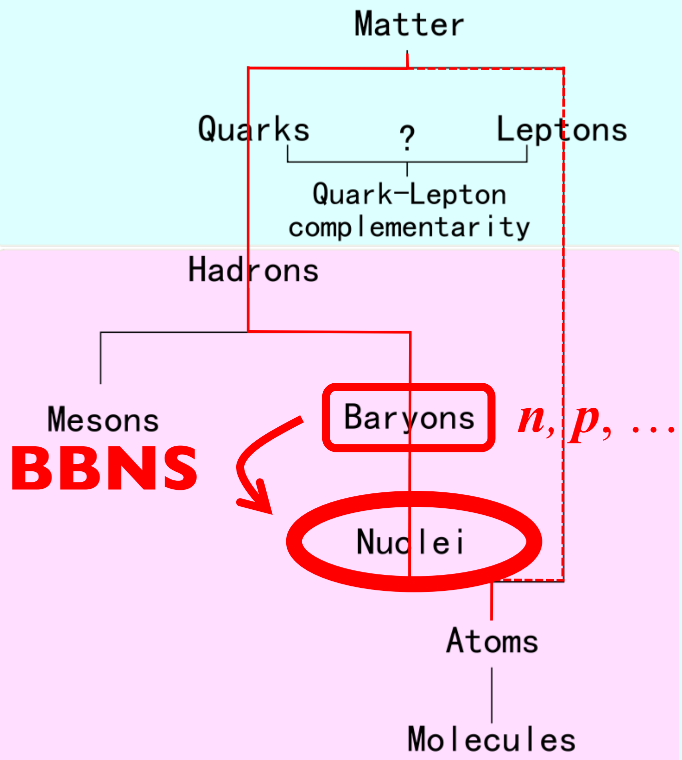
Nuclei

Atoms

Molecules

Composite Particles

Elementary Particles



Composite Particles

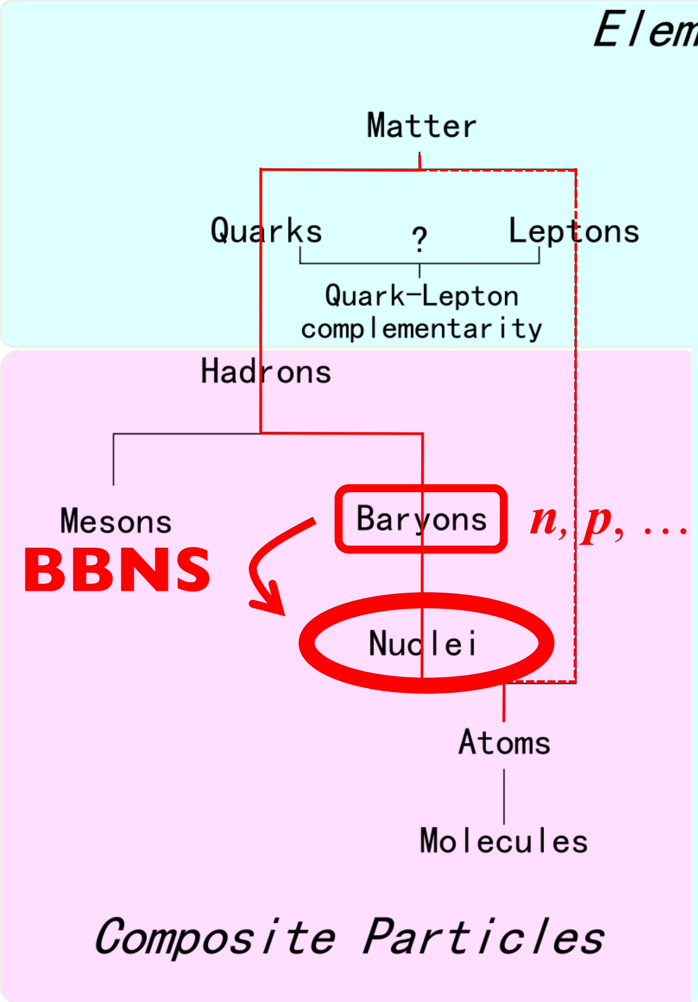
$$\nu_e + n \Leftrightarrow p + e^-$$

$$e^+ + n \Leftrightarrow p + \bar{\nu}_e$$

$$n \Leftrightarrow p + e^- + \bar{\nu}_e$$

p and n held in equilibrium via weak interaction

Big Bang Nucleosynthesis



Elementary Particles

Matter

Quarks ? Leptons

Quark–Lepton complementarity

Hadrons

Mesons

Baryons *n*, *p*, …

BBNS

Nuclei

Atoms

Molecules

Composite Particles

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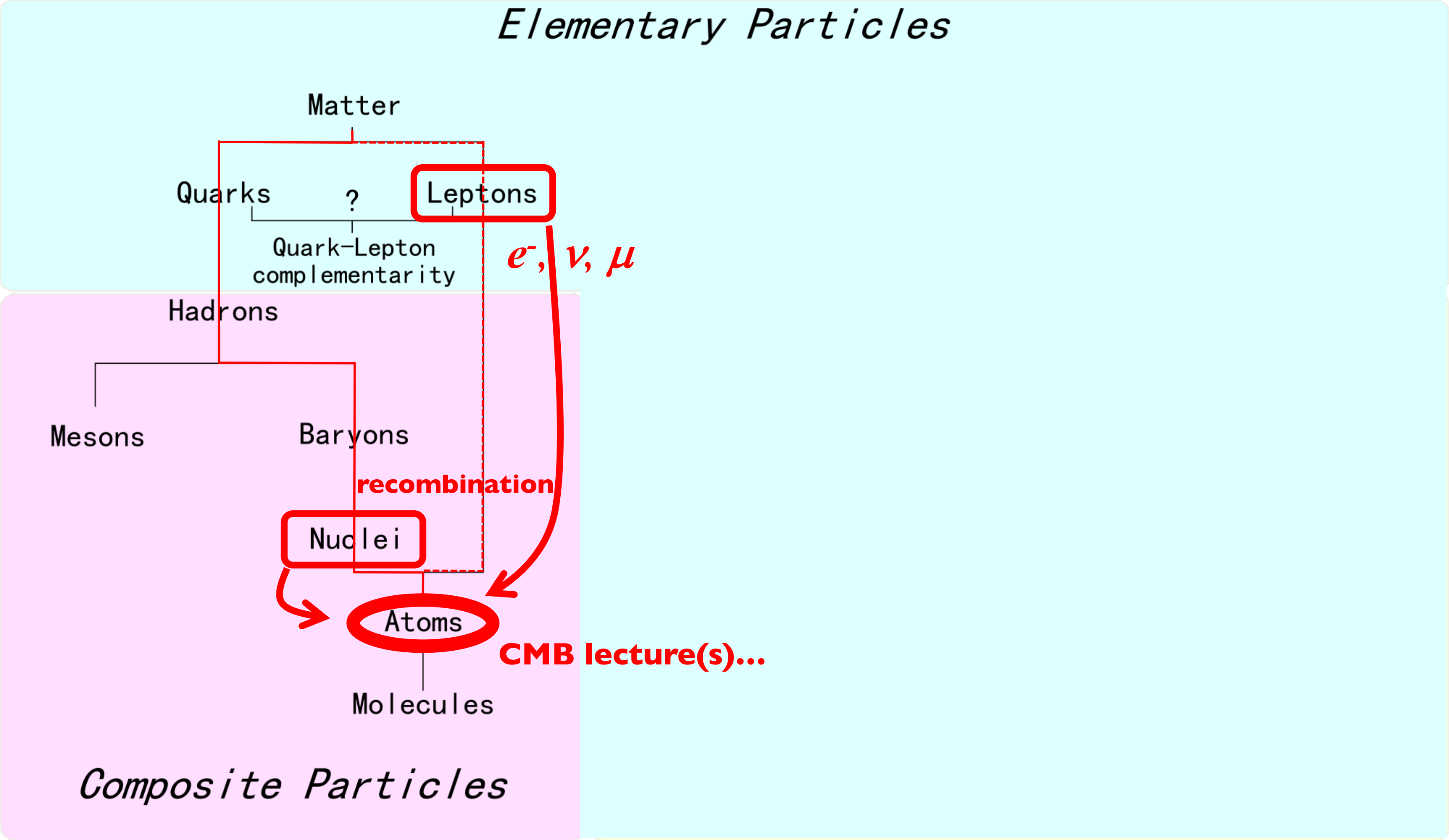
$$e^+ + n \Leftrightarrow p + \bar{\nu}_e$$

$$n \Leftrightarrow p + e^- + \bar{\nu}_e$$

p and n held in equilibrium via weak interaction

BBNS can only start after neutrino decoupling!


Elementary Particles
Matter
Quarks
?
Leptons
Quark–Lepton complementarity
e^-, ν, μ
Hadrons
Mesons
Baryons
recombination
Nuclei
Atoms
CMB lecture(s)...
Molecules
Composite Particles

Big Bang Nucleosynthesis

Event	time t	redshift z	temperature T
Inflation	10^{-34} s (?)	–	–
Baryogenesis	?	?	?
EW phase transition	20 ps	10^{15}	100 GeV
QCD phase transition	20 μs	10^{12}	150 MeV
Dark matter freeze-out	?	?	?
Neutrino decoupling	1 s	6×10^9	1 MeV
Electron-positron annihilation	6 s	2×10^9	500 keV
Big Bang nucleosynthesis	3 min	4×10^8	100 keV
Matter-radiation equality	60 kyr	3400	0.75 eV
Recombination	260–380 kyr	1100–1400	0.26–0.33 eV
Photon decoupling	380 kyr	1000–1200	0.23–0.28 eV
Reionization	100–400 Myr	11–30	2.6–7.0 meV
Dark energy-matter equality	9 Gyr	0.4	0.33 meV
Present	13.8 Gyr	0	0.24 meV

- introduction
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Big Bang Nucleosynthesis

synthesis of elements

H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Be, ^{7}Li

Big Bang Nucleosynthesis

synthesis of elements

H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Be, ^{7}Li

- Hydrogen: $p + e^- \rightarrow H + \gamma$

Big Bang Nucleosynthesis

H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Be, ^{7}Li

- Hydrogen: $p + e^- \rightarrow H + \gamma$

this requires free electrons,
but they are still coupled to the photons…

- Hydrogen: $(p + e^{-} \rightarrow H + \gamma)$

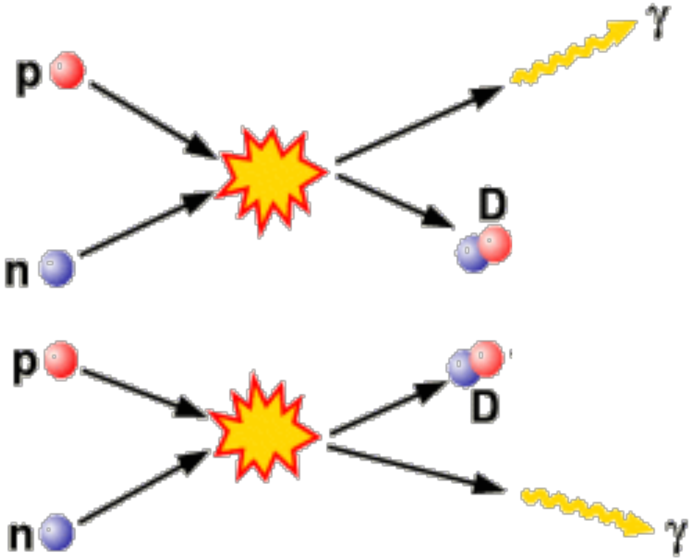
this requires free electrons,
but they are still coupled to the photons…

Note: in BBNS we are forming *nuclei* and not atoms!

Big Bang Nucleosynthesis

H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Be, ^{7}Li

- Hydrogen: $(p + e^- \rightarrow H + \gamma)$
- Deuterium: $p + n \rightarrow D + \gamma$



two-body processes only,
as probability for others too low
(‘bottom-up’ fusion of He^4)

Big Bang Nucleosynthesis

H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Be, ^{7}Li

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- all A>2 nuclei require D and n for synthesis

Big Bang Nucleosynthesis

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- Hydrogen: $(p + e^{-} \rightarrow H + \gamma)$
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$$E_b \approx 2 MeV$$

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Big Bang Nucleosynthesis

synthesis of elements

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but: D easily photo-dissociated by γ until $kT_D \cong 0.086MeV$ (ca. $t \approx 100s^{*}$)

$$* \quad \frac{T}{1MeV} \cong 1.5 g_{*S}^{-1/4} \left(\frac{1s}{t}\right)^{1/2}$$

Big Bang Nucleosynthesis

synthesis of elements

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---

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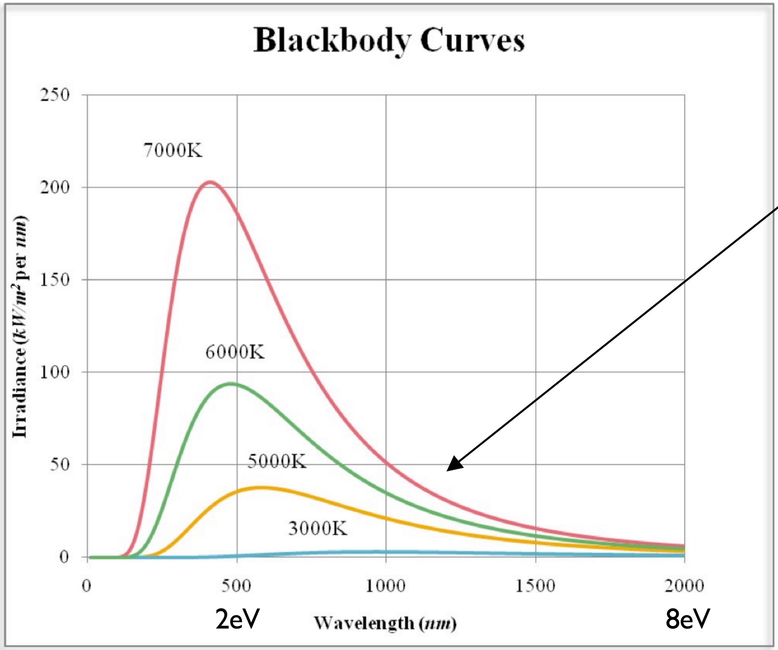

for temperatures $kT_D < E_b$

there will still be lots of higher energy photons in the Planck distribution

synthesis of elements

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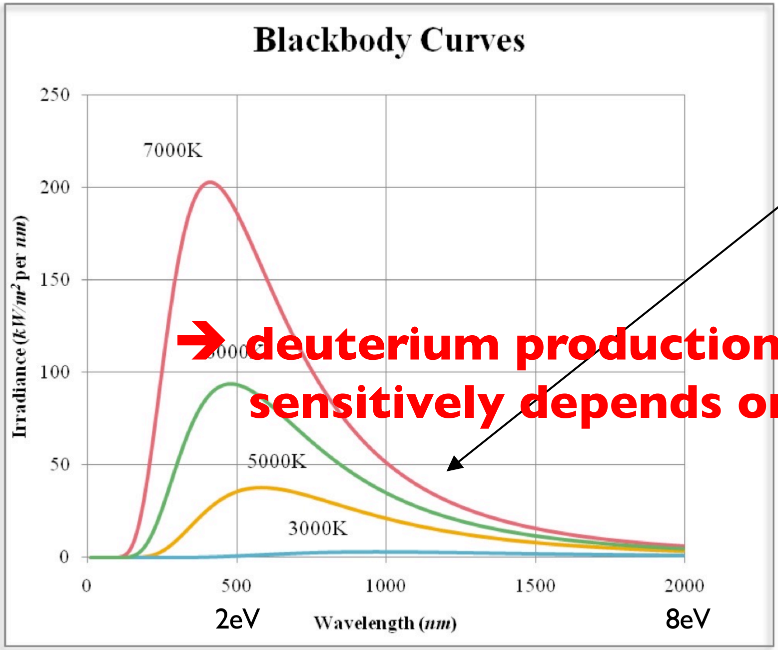

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there will still be lots of higher energy photons in the Planck distribution

➔ deuterium production (and all successive nuclei) sensitively depends on baryon-to-*photon* ratio!

Big Bang Nucleosynthesis

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→ 'Deuterium bottleneck':

- too few D → important fusion agent is missing
- too much D → locks up neutrons for further synthesis

➔ deuterium production (and all successive nuclei) sensitively depends on baryon-to-*photon* ratio!

Big Bang Nucleosynthesis

synthesis of elements

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➔ deuterium production (and all successive nuclei) sensitively depends on baryon-to-*photon* ratio!

- photon-to-baryon ratio* (frozen in at BBNS):

$$\eta = \frac{n_b}{n_\gamma} = 10^{-10}\,\eta_{10} = 10^{-10} \cdot 274\,\Omega_b h^2$$

*see Baryogenesis lecture

H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Be, ^{7}Li

- Hydrogen: $(p + e^{-} \rightarrow H + \gamma)$
- Deuterium: $p + n \rightarrow D + \gamma$

Big Bang Nucleosynthesis

synthesis of elements

H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Be, ^{7}Li

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- Deuterium: $p + n \rightarrow D + \gamma$
- lighter elements:

$$
\begin{aligned}
D + n &\rightarrow {}^3H + \gamma \\
D + D &\rightarrow {}^3H + p \\
D + p &\rightarrow {}^3He + \gamma \\
D + D &\rightarrow {}^3He + n \\
{}^3He + n &\rightarrow {}^3H + p
\end{aligned}
$$

H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Be, ^{7}Li

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  $D + p \rightarrow {}^{3}He + \gamma$
  $D + D \rightarrow {}^{3}He + n$
  ${}^{3}He + n \rightarrow {}^{3}H + p$
- ^{4}He:
  $D + D \rightarrow {}^{4}He + \gamma$
  $D + {}^{3}He \rightarrow {}^{4}He + p$
  $D + {}^{3}H \rightarrow {}^{4}He + n$
  ${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$
  ${}^{3}He + n \rightarrow {}^{4}He + \gamma$
  ${}^{3}H + p \rightarrow {}^{4}He + \gamma$

Big Bang Nucleosynthesis

synthesis of elements

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{}^3He + n &\rightarrow {}^3H + p
\end{aligned}
$$

- ^{4}He:

$$
\begin{aligned}
D + D &\rightarrow {}^4He + \gamma \\
D + {}^3He &\rightarrow {}^4He + p \\
D + {}^3H &\rightarrow {}^4He + n \\
{}^3He + {}^3He &\rightarrow {}^4He + 2p \\
{}^3He + n &\rightarrow {}^4He + \gamma \\
{}^3H + p &\rightarrow {}^4He + \gamma
\end{aligned}
$$

$$E_{^4He} \approx 28.3 MeV$$

$\Rightarrow$ **safe from photo-dissociation**

Big Bang Nucleosynthesis

synthesis of elements

H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Be, ^{7}Li

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$$D + p \rightarrow {}^3He + \gamma$$
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$${}^3He + n \rightarrow {}^3H + p$$

- ^{4}He:

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

- ^{7}Be, ^{7}Li:

$${}^3He + {}^4He \rightarrow {}^7Be + \gamma$$
$${}^7Be \rightarrow {}^7Li + e^+ + \nu_e$$
$${}^3H + {}^4He \rightarrow {}^7Li + e^+ + \nu_e$$

synthesis of elements

$\mathrm{H}, {}^2\mathrm{H}, {}^3\mathrm{H}, {}^3\mathrm{He}, {}^4\mathrm{He}, {}^7\mathrm{Be}, {}^7\mathrm{Li}$

- Hydrogen: $(\mathrm{p} + \mathrm{e}^- \rightarrow \mathrm{H} + \gamma)$
- Deuterium: $\mathrm{p} + \mathrm{n} \rightarrow \mathrm{D} + \gamma$
- lighter elements:

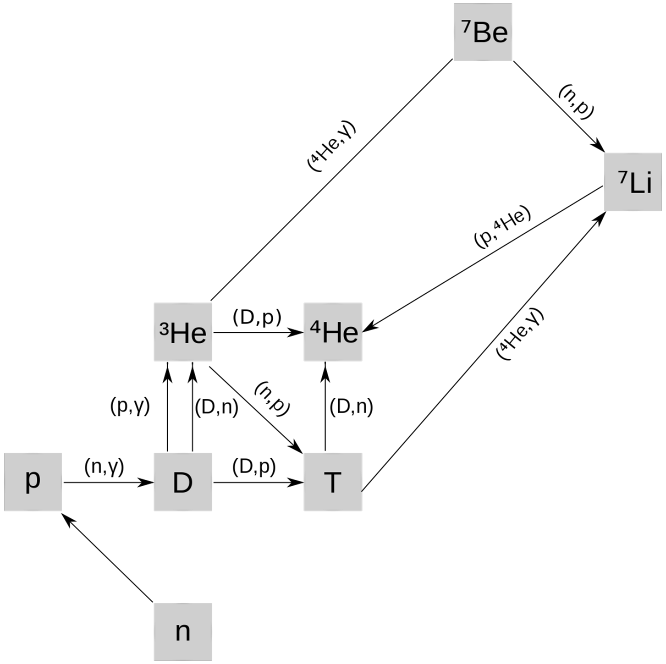
$$\begin{aligned}
\mathrm{D} + \mathrm{n} &\rightarrow {}^3\mathrm{H} + \gamma \\
\mathrm{D} + \mathrm{D} &\rightarrow {}^3\mathrm{H} + \mathrm{p} \\
\mathrm{D} + \mathrm{p} &\rightarrow {}^3\mathrm{He} + \gamma \\
\mathrm{D} + \mathrm{D} &\rightarrow {}^3\mathrm{He} + \mathrm{n} \\
{}^3\mathrm{He} + \mathrm{n} &\rightarrow {}^3\mathrm{H} + \mathrm{p}
\end{aligned}$$

- ${}^4\mathrm{He}$:

$$\begin{aligned}
\mathrm{D} + \mathrm{D} &\rightarrow {}^4\mathrm{He} + \gamma \\
\mathrm{D} + {}^3\mathrm{He} &\rightarrow {}^4\mathrm{He} + \mathrm{p} \\
\mathrm{D} + {}^3\mathrm{H} &\rightarrow {}^4\mathrm{He} + \mathrm{n} \\
{}^3\mathrm{He} + {}^3\mathrm{He} &\rightarrow {}^4\mathrm{He} + 2\mathrm{p} \\
{}^3\mathrm{He} + \mathrm{n} &\rightarrow {}^4\mathrm{He} + \gamma \\
{}^3\mathrm{H} + \mathrm{p} &\rightarrow {}^4\mathrm{He} + \gamma
\end{aligned}$$

- ${}^7\mathrm{Be}, {}^7\mathrm{Li}$:

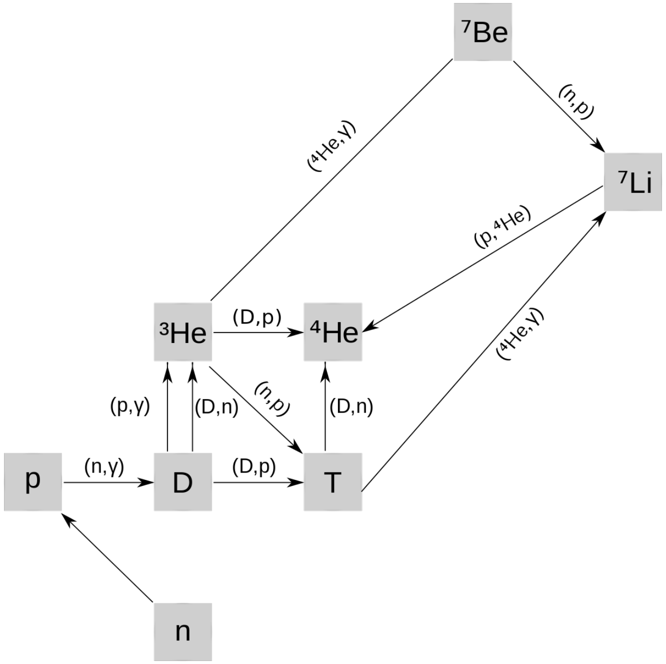
$$\begin{aligned}
{}^3\mathrm{He} + {}^4\mathrm{He} &\rightarrow {}^7\mathrm{Be} + \gamma \\
{}^7\mathrm{Be} &\rightarrow {}^7\mathrm{Li} + e^+ + \nu_\mathrm{e} \\
{}^3\mathrm{H} + {}^4\mathrm{He} &\rightarrow {}^7\mathrm{Li} + e^+ + \nu_\mathrm{e}
\end{aligned}$$



synthesis of elements

H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Be, ^{7}Li

- Hydrogen: $(p + e^{-} \rightarrow H + \gamma)$
- Deuterium: $p + n \rightarrow D + \gamma$
- lighter elements:
  $$D + n \rightarrow {}^{3}H + \gamma$$
  $$D + D \rightarrow {}^{3}H + p$$
  $$D + p \rightarrow {}^{3}He + \gamma$$
  $$D + D \rightarrow {}^{3}He + n$$
  $${}^{3}He + n \rightarrow {}^{3}H + p$$
- ^{4}He:
  $$D + D \rightarrow {}^{4}He + \gamma$$
  $$D + {}^{3}He \rightarrow {}^{4}He + p$$
  $$D + {}^{3}H \rightarrow {}^{4}He + n$$
  $${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$$
  $${}^{3}He + n \rightarrow {}^{4}He + \gamma$$
  $${}^{3}H + p \rightarrow {}^{4}He + \gamma$$
- ^{7}Be, ^{7}Li:
  $${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$$
  $${}^{7}Be \rightarrow {}^{7}Li + e^{+} + \nu_e$$
  $${}^{3}H + {}^{4}He \rightarrow {}^{7}Li + e^{+} + \nu_e$$



gap at A=8 prohibits production of heavier isotopes!

Big Bang Nucleosynthesis

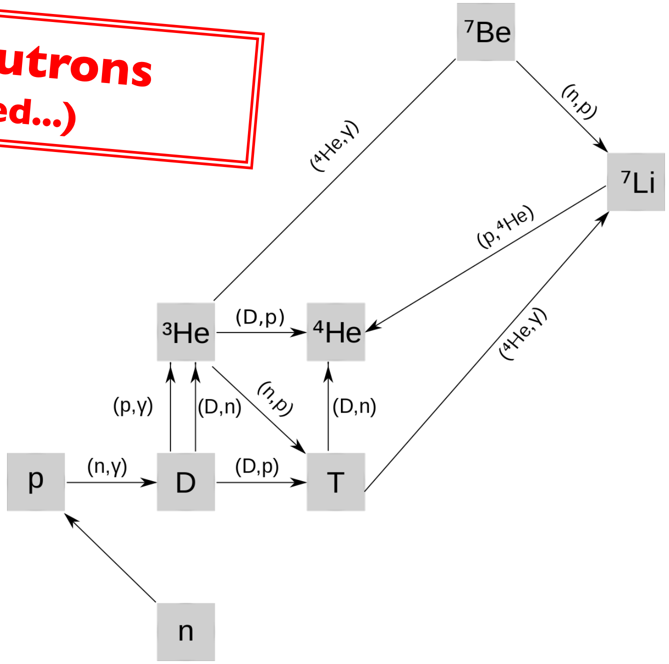
H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Be, ^{7}Li

- Hydrogen: $(p + e^- \rightarrow H + \gamma)$
- Deuterium: $p + n \rightarrow D + \gamma$
- lighter elements:
  $D + n \rightarrow {}^3H + \gamma$
  $D + D \rightarrow {}^3H + p$
  $D + p \rightarrow {}^3He + \gamma$
  $D + D \rightarrow {}^3He + n$
  ${}^3He + n \rightarrow {}^3H + p$

we require free protons and neutrons
(weak-interaction freeze-out revisited...)

- ^{4}He:
  $D + D \rightarrow {}^4He + \gamma$
  $D + {}^3He \rightarrow {}^4He + p$
  $D + {}^3H \rightarrow {}^4He + n$
  ${}^3He + {}^3He \rightarrow {}^4He + 2p$
  ${}^3He + n \rightarrow {}^4He + \gamma$
  ${}^3H + p \rightarrow {}^4He + \gamma$
- ^{7}Be, ^{7}Li:
  ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
  ${}^7Be \rightarrow {}^7Li + e^+ + \nu_e$
  ${}^3H + {}^4He \rightarrow {}^7Li + e^+ + \nu_e$

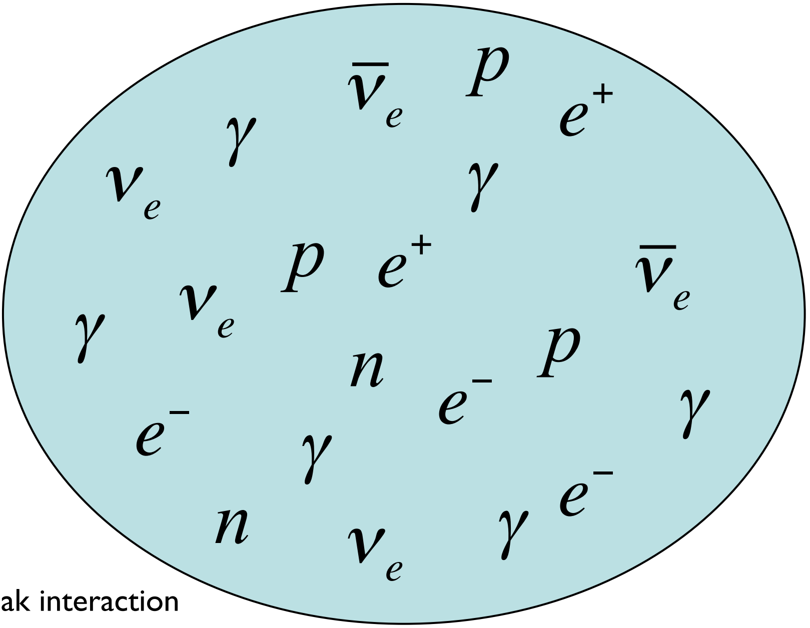
gap at A=8 prohibits production of heavier isotopes!



- introduction
- particle physics
- synthesis of elements
- ***big bang nucleosynthesis***
- observations

- thermal equilibrium of neutrons & protons:

$$\left.\begin{aligned} \nu_e + n &\Leftrightarrow p + e^- \\ e^+ + n &\Leftrightarrow p + \bar{\nu}_e \\ n &\Leftrightarrow p + e^- + \bar{\nu}_e \end{aligned}\right\} \text{weak interaction*}$$

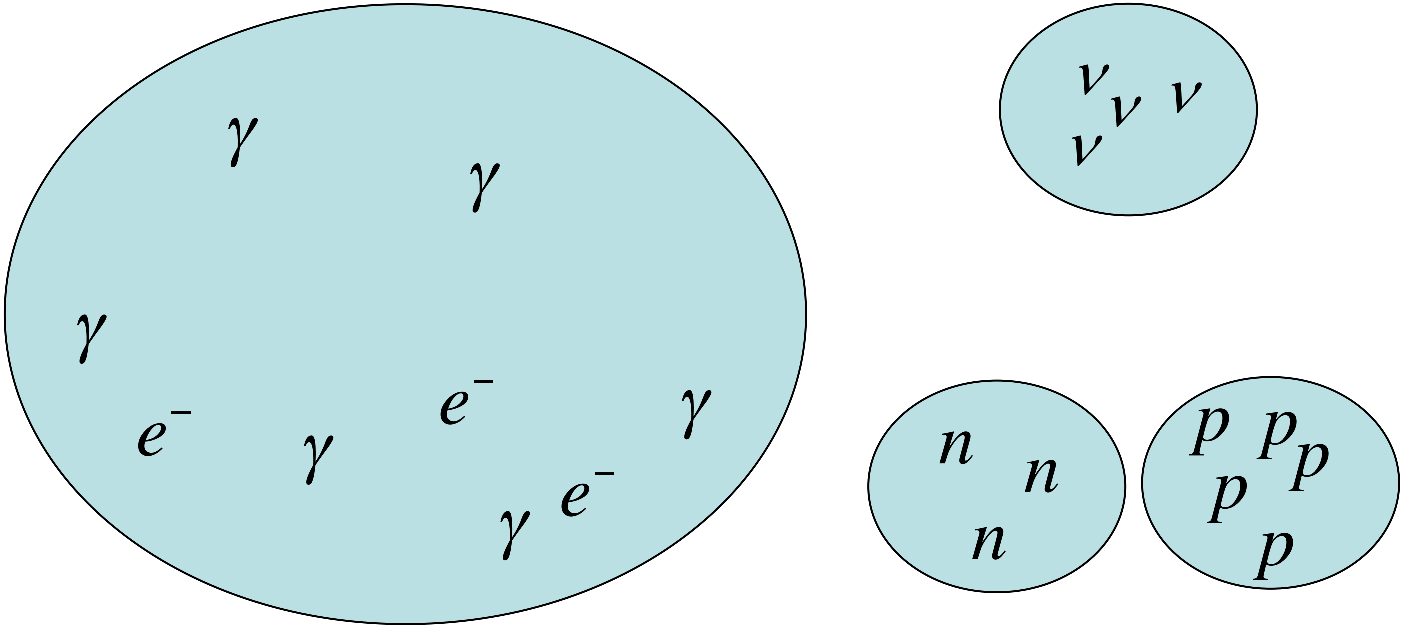


*only ν_e contributes to weak interaction

- thermal equilibrium of neutrons & protons:

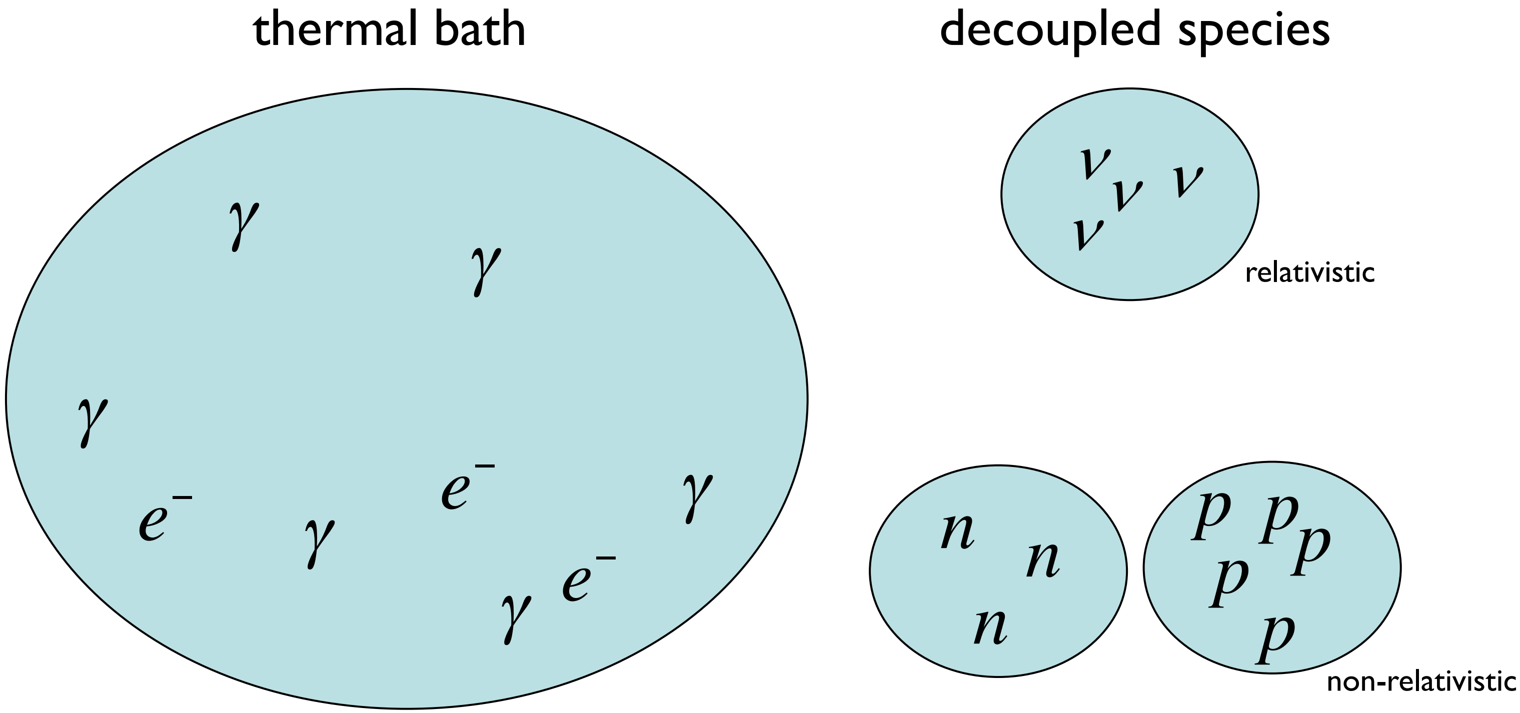
$$\left.\begin{aligned} \nu_e + n &\Leftrightarrow p + e^- \\ e^+ + n &\Leftrightarrow p + \bar{\nu}_e \\ n &\Leftrightarrow p + e^- + \bar{\nu}_e \end{aligned}\right\} \text{weak interaction}$$

- weak interaction freezes out at $T \approx 0.8\ \mathrm{MeV}$



weak interaction freeze-out, revisited

- inventory (T < 0.8MeV):
  - relativistic particles in equilibrium: e^-, e^+
  - decoupled relativistic particles: ν
  - decoupled non-relativistic particles: n, p

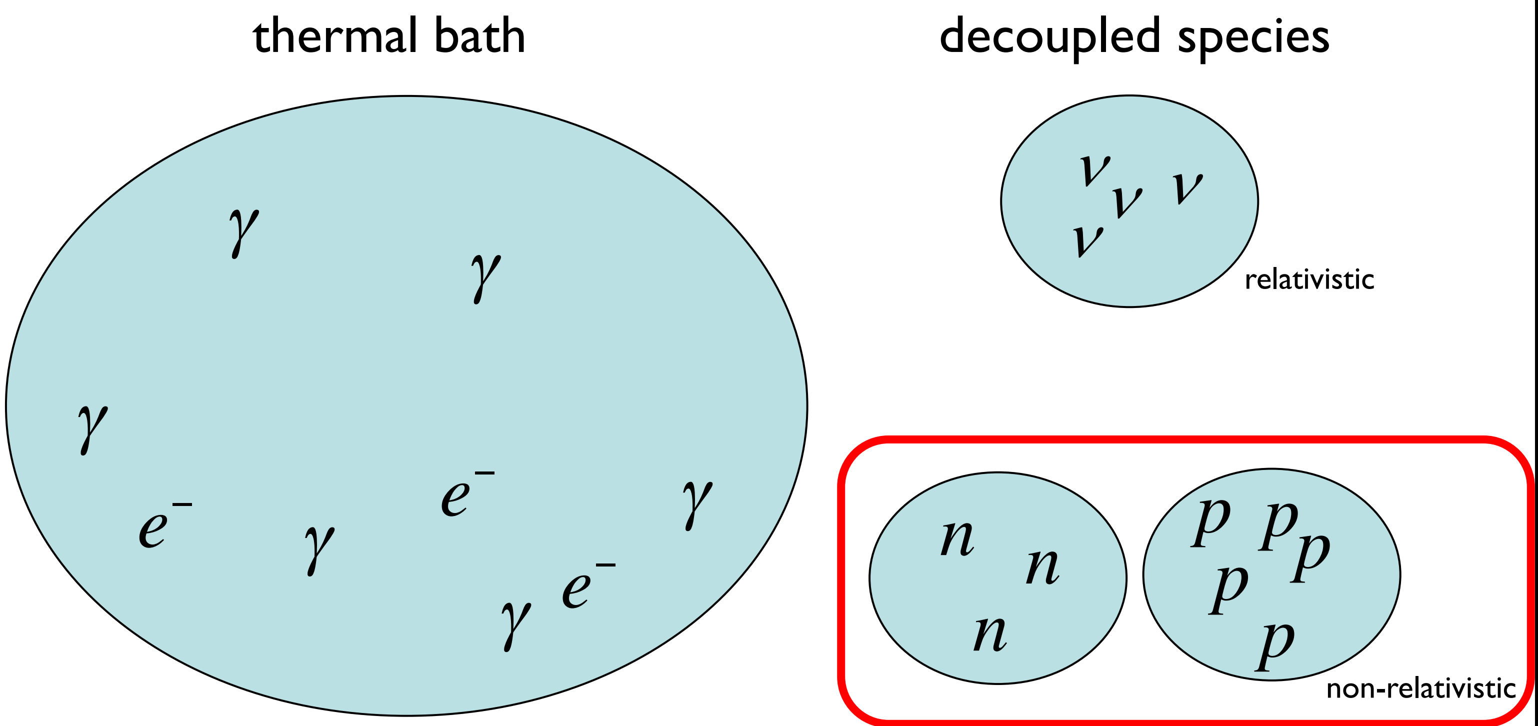


thermal bath

decoupled species

weak interaction freeze-out, revisited

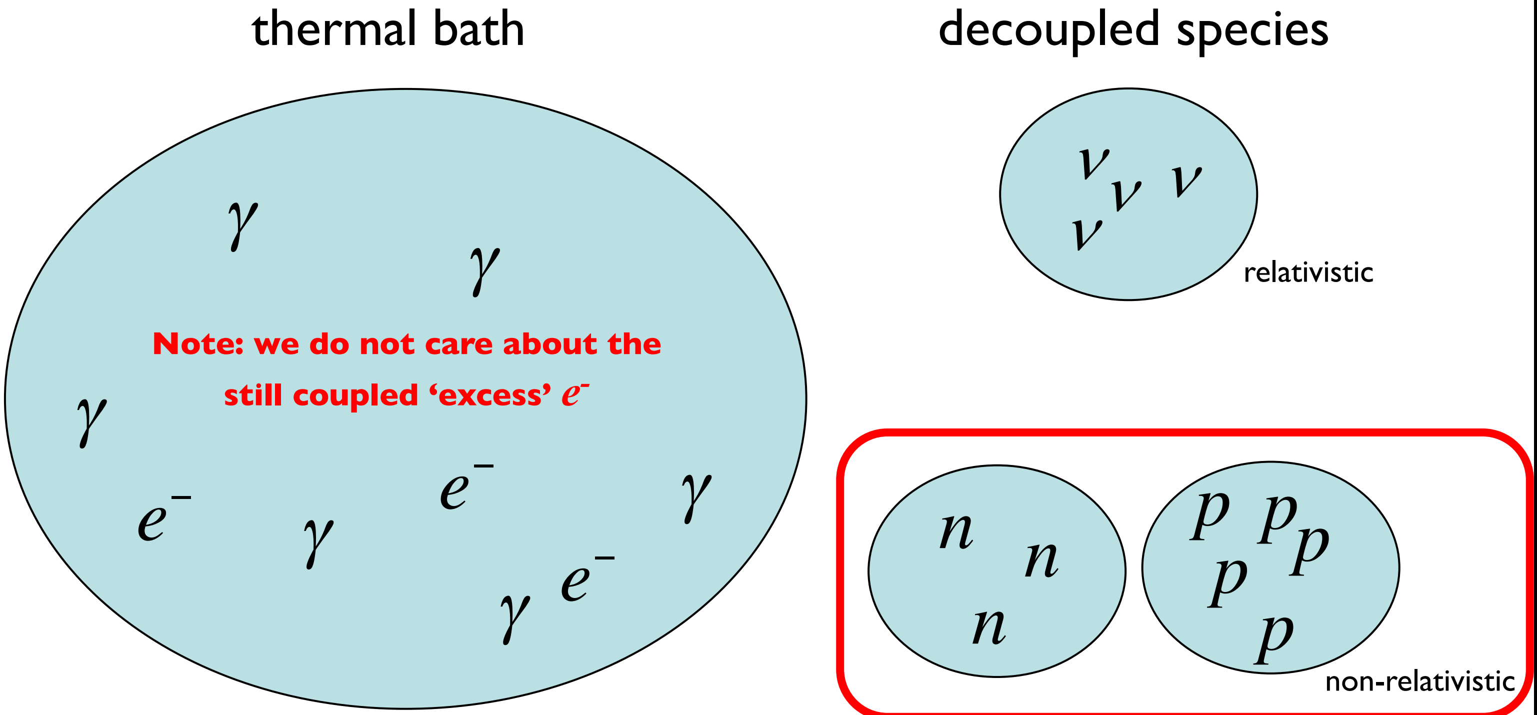
- inventory (T < 0.8MeV):
  - relativistic particles in equilibrium: e^-, e^+
  - decoupled relativistic particles: ν
  - decoupled non-relativistic particles: $\boxed{n, p}$ **building blocks for nuclei!**



thermal bath

decoupled species

- inventory (T < 0.8MeV):
  - relativistic particles in equilibrium: e^-, e^+
  - decoupled relativistic particles: ν
  - decoupled non-relativistic particles: $\boxed{n, p}$ **building blocks for nuclei!**

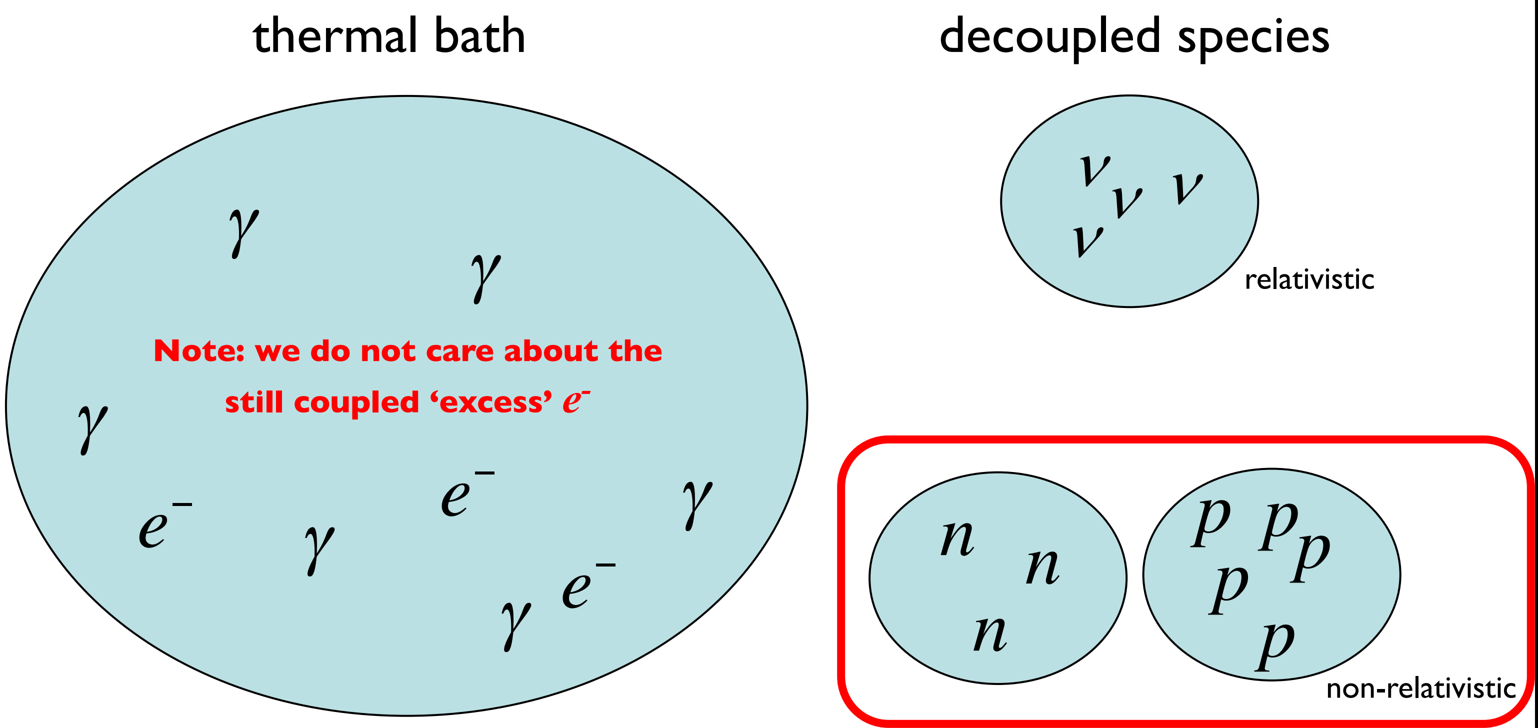


Note: we do not care about the still coupled 'excess' e^-

weak interaction freeze-out, revisited

- inventory ($T < 0.8$MeV):
  - relativistic particles in equilibrium: e^-, e^+
  - decoupled relativistic particles: ν
  - decoupled non-relativistic particles: $\boxed{n, p}$ **building blocks for nuclei!**

let's calculate the number densities of n and p...



Note: we do not care about the still coupled 'excess' e^-

- neutron-to-proton ratio:*

the abundance of neutrons determines

how many nuclei beyond (A=1) can be formed…

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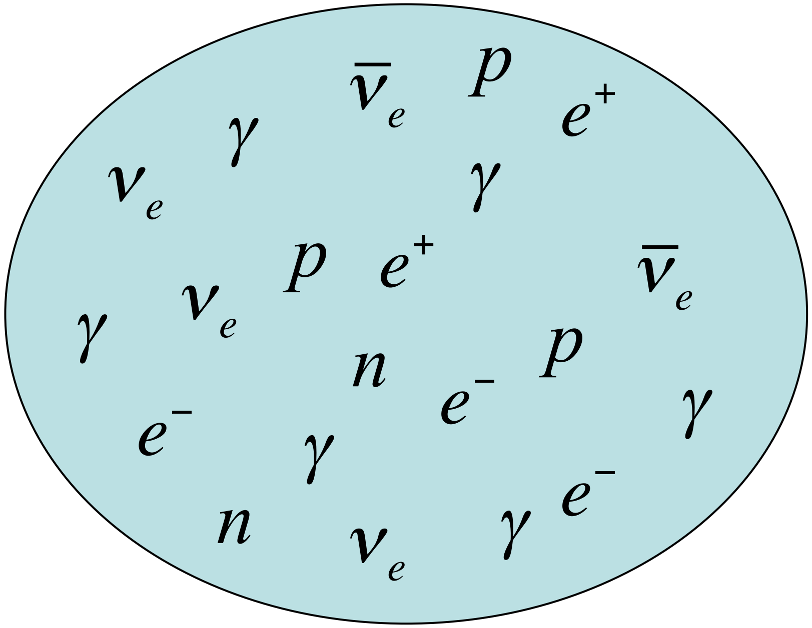
*we will measure neutron abundance relative to protons…

- neutron-to-proton ratio:



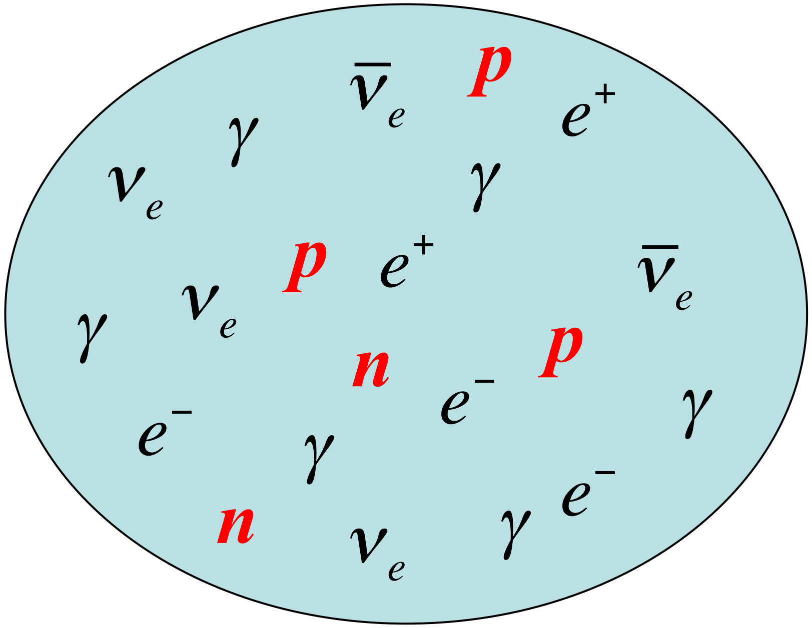
thermal bath

$$\begin{aligned} \nu_e + n &\Leftrightarrow p + e^- \\ e^+ + n &\Leftrightarrow p + \bar{\nu}_e \\ n &\Leftrightarrow p + e^- + \bar{\nu}_e \end{aligned}$$

$$e^- + \gamma \Leftrightarrow e^- + \gamma$$

- neutron-to-proton ratio:

$$n_A = \;?$$



thermal bath

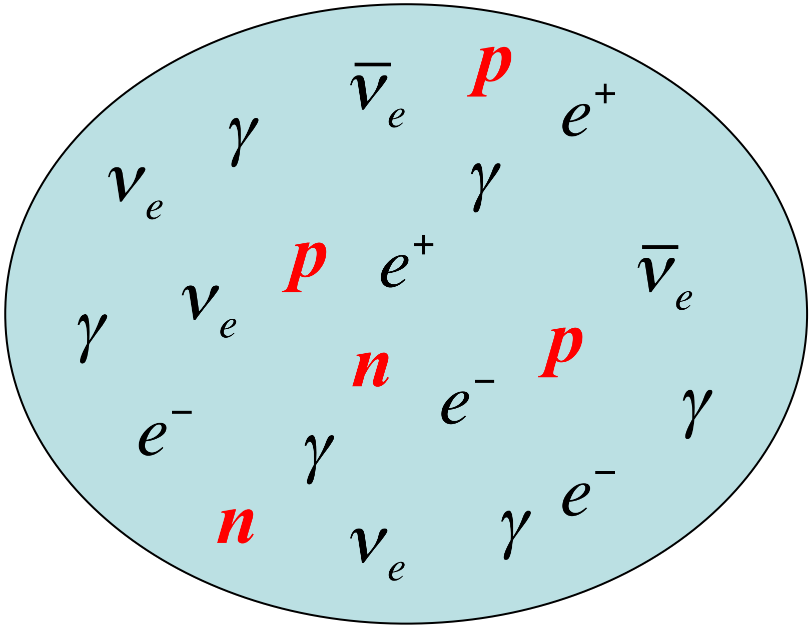
$$\nu_e + n \Leftrightarrow p + e^-$$
$$e^+ + n \Leftrightarrow p + \bar{\nu}_e$$
$$n \Leftrightarrow p + e^- + \bar{\nu}_e$$

$$e^- + \gamma \Leftrightarrow e^- + \gamma$$

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)



thermal bath

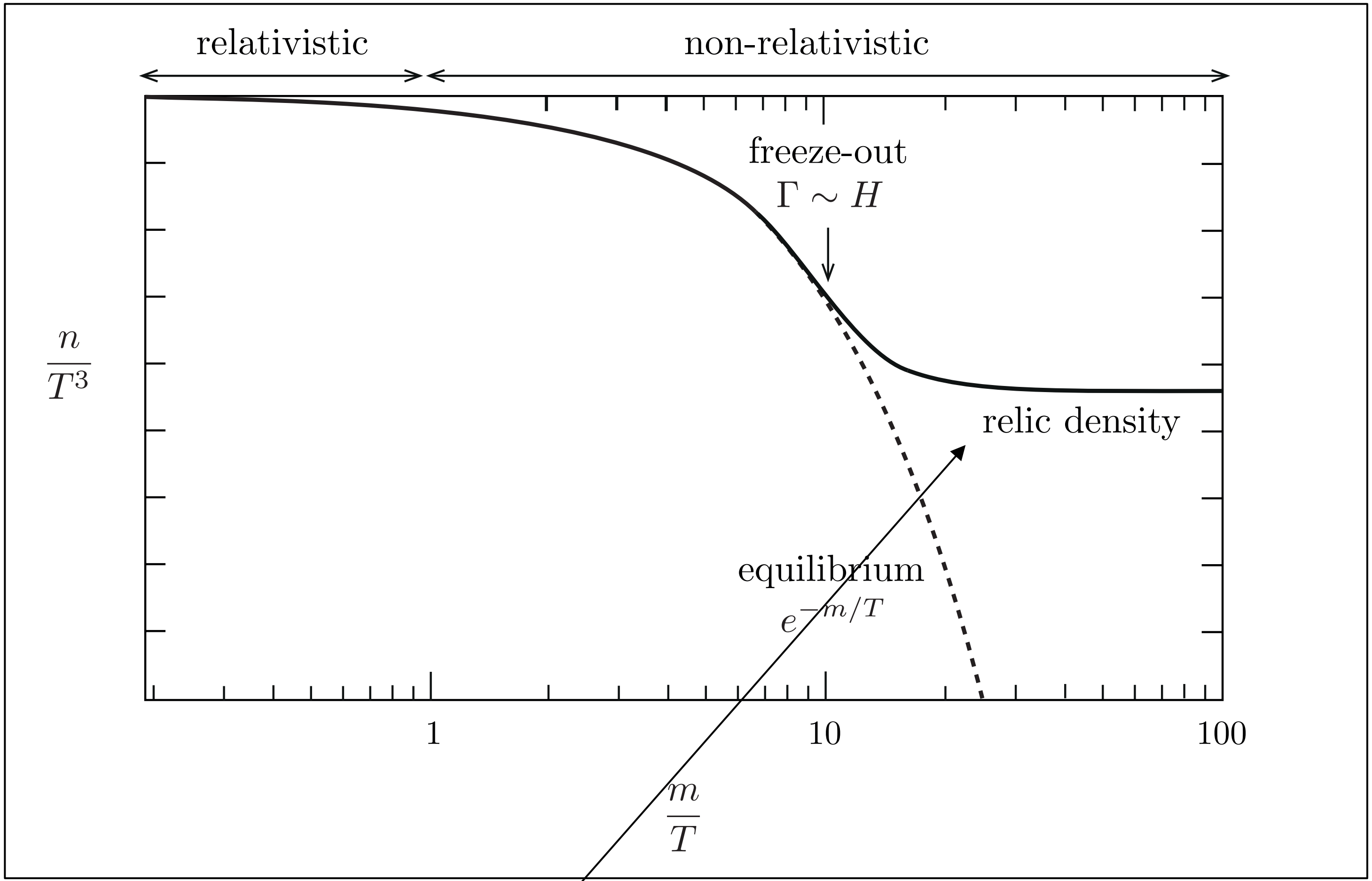
$$\nu_e + n \Leftrightarrow p + e^-$$

$$e^+ + n \Leftrightarrow p + \bar{\nu}_e$$

$$n \Leftrightarrow p + e^- + \bar{\nu}_e$$

$$e^- + \gamma \Leftrightarrow e^- + \gamma$$

- neutron-to-proton ratio:



we start before the freeze-out of weak interaction,
as the equilibrium distributions will be ‚frozen' in at freeze-out

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

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(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{(\mu_n - \mu_p)/kT}$$

(Q=1.293 MeV)

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{(\mu_n - \mu_p)/kT}$$

(Q=1.293 MeV)

what about μ_n and μ_p?

(for relativisitic species we could neglect μ, but not so for non-relativistic)

Big Bang Nucleosynthesis *neutron-to-proton ratio*

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{(\mu_n - \mu_p)/kT}$$

(Q=1.293 MeV)

what about μ_n and μ_p?

- chemical potential:
  - energy absorbed or released during chemical reaction
  - chemical equilibrium*: $A + B \leftrightarrow C + D \xrightarrow{\text{chemical equilibrium}} \mu_A + \mu_B = \mu_C + \mu_D$

---

*nuclear reactions are faster than cosmic expansion…

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{(\mu_n - \mu_p)/kT}$$

(Q=1.293 MeV)

what about μ_n and μ_p?

- chemical potential:
  - energy absorbed or released during chemical reaction
  - chemical equilibrium: $\boxed{A + B \leftrightarrow C + D} \xrightarrow{\text{chemical equilibrium}} \mu_A + \mu_B = \mu_C + \mu_D$

what reaction is going on?

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{(\mu_n - \mu_p)/kT}$$

(Q=1.293 MeV)

what about μ_n and μ_p?

- β-decay:

$$\nu_e + n \leftrightarrow p + e^- \quad \longrightarrow \mu_{\nu_e} + \mu_n = \mu_p + \mu_e$$

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$ (non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{(\mu_e - \mu_{\nu_e})/kT}$$ (Q=1.293 MeV)

what about $\mu_{\nu e}$ and μ_e?

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{(\mu_e - \mu_{\nu_e})/kT}$$

(Q=1.293 MeV)

what about $\mu_{\nu e}$ and $\boxed{\mu_e?}$

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{(\mu_e - \mu_{\nu_e})/kT}$$

(Q=1.293 MeV)

what about $\mu_{\nu e}$ and $\boxed{\mu_e?}$

the Universe is neutral => $n_{e^-} - n_{e^+} = n_p$

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$ (non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{(\mu_e - \mu_{\nu_e})/kT}$$ (Q=1.293 MeV)

what about $\mu_{\nu e}$ and $\boxed{\mu_e ?}$

the Universe is neutral => $n_{e^-} - n_{e^+} = n_p$

$$n_{e^-} - n_{e^+} = \frac{2T^3}{6\pi^2} \left(\pi^2 \left(\frac{\mu_e}{T} \right) + \left(\frac{\mu_e}{T} \right)^3 \right)$$

neutron-to-proton ratio

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{(\mu_e - \mu_{\nu_e})/kT}$$

(Q=1.293 MeV)

what about μ_{ve} and $\boxed{\mu_e?}$

the Universe is neutral => $n_{e^-} - n_{e^+} = n_p$

$$n_{e^-} - n_{e^+} = \frac{2T^3}{6\pi^2} \left(\pi^2 \left(\frac{\mu_e}{T} \right) + \left(\frac{\mu_e}{T} \right)^3 \right)$$

expression using

η = baryon-to-photon ratio

$$n_p \approx \eta n_\gamma = \eta \frac{2\zeta(3)}{\pi^2} T^3$$

neutron-to-proton ratio

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{(\mu_e - \mu_{\nu_e})/kT}$$

(Q=1.293 MeV)

what about $\mu_{\nu e}$ and $\boxed{\mu_e ?}$

the Universe is neutral => $n_{e^-} - n_{e^+} = n_p$

$$\frac{2T^3}{6\pi^2} \left(\pi^2 \left(\frac{\mu_e}{T} \right) + \left(\frac{\mu_e}{T} \right)^3 \right) = \eta \frac{2\zeta(3)}{\pi^2} T^3$$

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{(\mu_e - \mu_{\nu_e})/kT}$$

(Q=1.293 MeV)

what about $\mu_{\nu e}$ and $\boxed{\mu_e ?}$

the Universe is neutral => $n_{e^-} - n_{e^+} = n_p$

$$\frac{1}{6}\left(\pi^2 \left(\frac{\mu_e}{T} \right) + \left(\frac{\mu_e}{T} \right)^3 \right) = \eta \zeta(3)$$

neutron-to-proton ratio

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{(\mu_e - \mu_{\nu_e})/kT}$$

(Q=1.293 MeV)

what about $\mu_{\nu e}$ and $\boxed{\mu_e?}$

the Universe is neutral => $n_{e^-} - n_{e^+} = n_p$

$$\left(\frac{\mu_e}{T} \right) + \left(\frac{\mu_e}{T} \right)^3 = \frac{6\zeta(3)}{\pi^2} \eta$$

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{(\mu_e - \mu_{\nu_e})/kT}$$

(Q=1.293 MeV)

what about $\mu_{\nu e}$ and $\boxed{\mu_e?}$

the Universe is neutral => $n_{e^-} - n_{e^+} = n_p$

$$\Rightarrow \quad \frac{\mu_e}{T} \approx \frac{6}{\pi^2} \zeta(3)\, \eta$$

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{(\mu_e - \mu_{\nu_e})/kT}$$

(Q=1.293 MeV)

what about $\mu_{\nu e}$ and $\boxed{\mu_e ?}$

the Universe is neutral => $n_{e^-} - n_{e^+} = n_p$

$$\Rightarrow \quad \frac{\mu_e}{T} \approx \frac{6}{\pi^2} \zeta(3)\, \eta \quad \xrightarrow{\eta \approx 10^{-9}} \quad \mu_e << T$$

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{-\mu_{\nu_e}/kT}$$

(Q=1.293 MeV)

what about $\boxed{\mu_{\nu e}}$?

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{-\mu_{\nu_e}/kT}$$

(Q=1.293 MeV)

what about $\boxed{\mu_{\nu e}}$?

CMB measurements by WMAP/Planck

$$\Rightarrow \quad \frac{\mu_{\nu_e}}{T} < 0.2$$

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT} e^{-\mu_{\nu_e}/kT}$$

(Q=1.293 MeV)

what about $\boxed{\mu_{\nu e}}$?

CMB measurements by WMAP/Planck

$$\Rightarrow \quad \frac{\mu_{\nu_e}}{T} < 0.2 \quad \xrightarrow{BBN} \quad \frac{\mu_{\nu_e}}{T} < 10^{-10}$$

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT}$$

(Q=1.293 MeV)

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p} \right)^{3/2} e^{-Q/kT}$$

(Q=1.293 MeV)

$$kT > 1.3 MeV \quad \Rightarrow \quad n_n \approx n_p$$

$$kT < 1.3 MeV \quad \Rightarrow \quad n_n < n_p$$

- neutron-to-proton ratio:

$$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

(non-relativistic particles)

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⇒ **we therefore end up with less neutrons than protons!**

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$kT \approx 0.72$ MeV*
=> $$\frac{n_n}{n_p} \approx \frac{1}{6}$$ (ratio of free neutrons & protons!?)

---

*Note, the weak interaction will not instantaneously freeze-out at 0.8MeV

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BBN could now start ... or not?

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Deuterium bottleneck:

D easily photo-dissociated by γ until $kT_D \cong 0.086 MeV$

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<u>Deuterium bottleneck</u>:

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Big Bang Nucleosynthesis *neutron-to-proton ratio*

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something else happens in those 140s!

neutron-to-proton ratio

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<u>Deuterium bottleneck</u>:

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→ neutrons have a limited lifetime $\tau_n \approx 887\ s$

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- remaining free neutrons being incorporated into nuclei (e.g. D)

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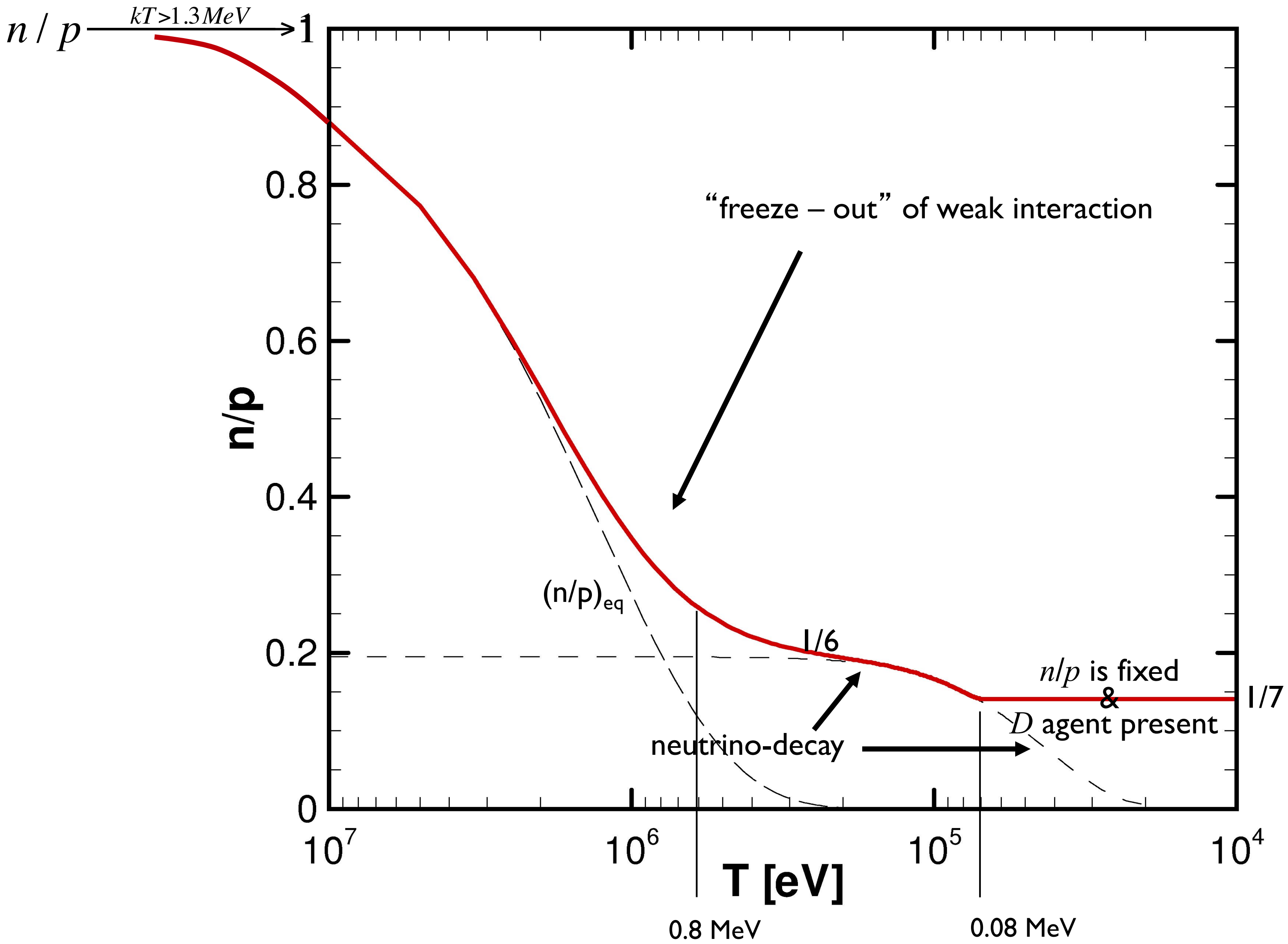
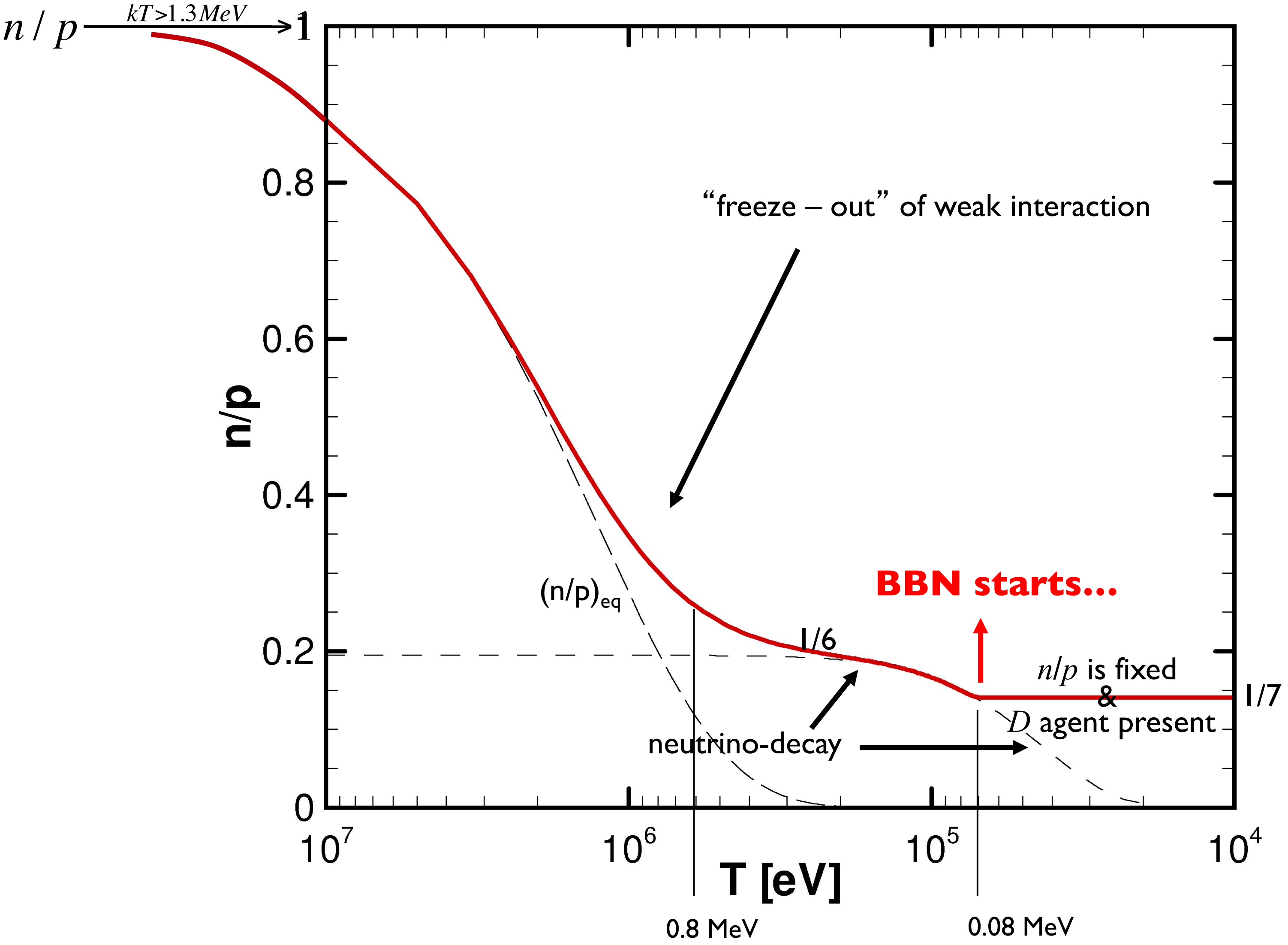
- remaining free neutrons decaying away
- remaining free neutrons being incorporated into nuclei (e.g. D)

$$\Rightarrow \quad \frac{n_n}{n_p} = \frac{1}{6} e^{-t/\tau_n} \approx \frac{1}{7}$$

- neutron-to-proton ratio:



- neutron-to-proton ratio:



$n / p \xrightarrow{kT>1.3MeV} 1$

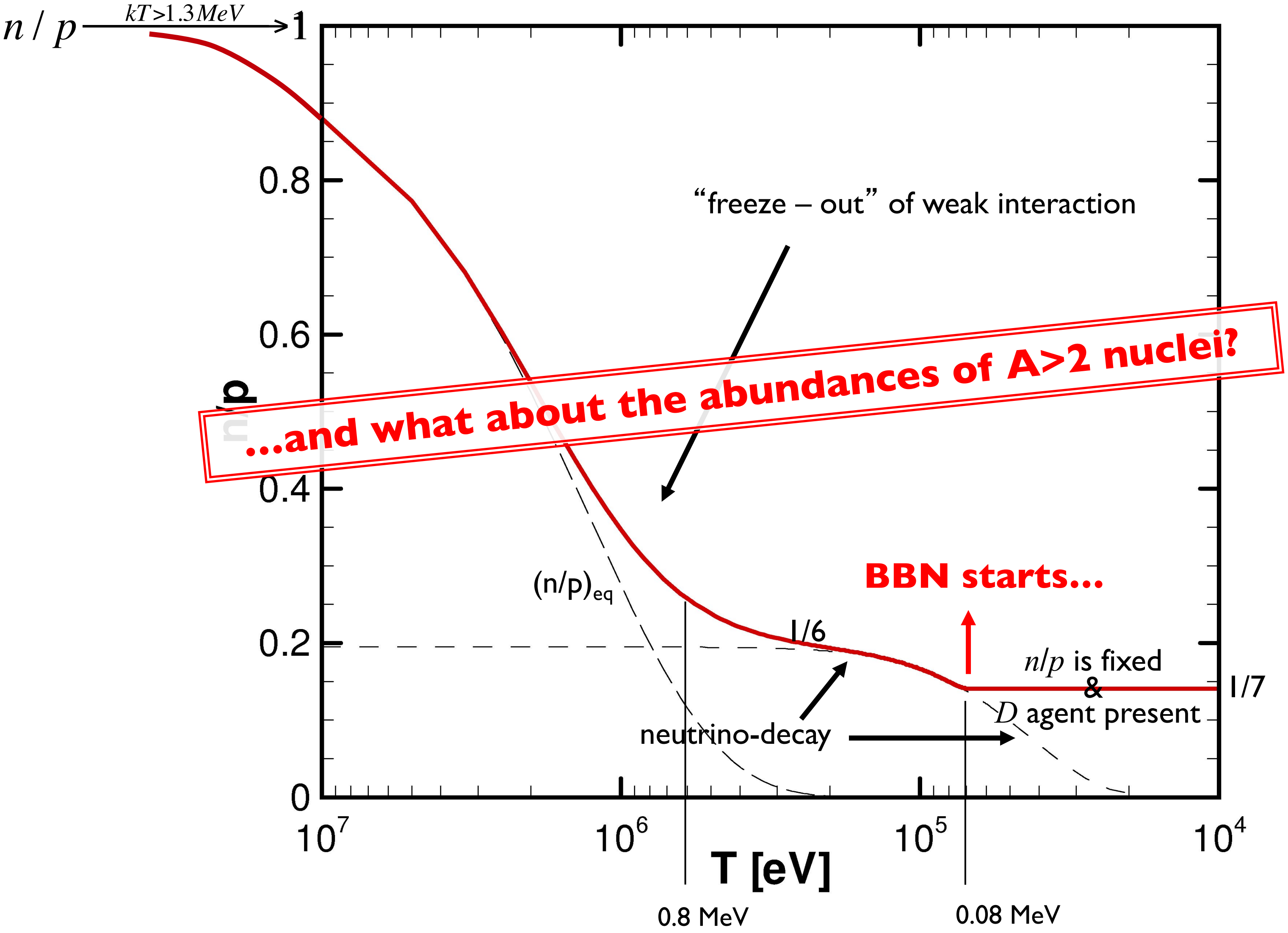
"freeze – out" of weak interaction

BBN starts…

n/p is fixed & D agent present

neutrino-decay

- neutron-to-proton ratio:



...and what about the abundances of A>2 nuclei?

BBN starts...

- neutron-to-proton ratio: primordial Helium abundance:

$$\Rightarrow \quad X_{He} = Y = \frac{m_{He}}{m_{He} + m_H} = ?$$

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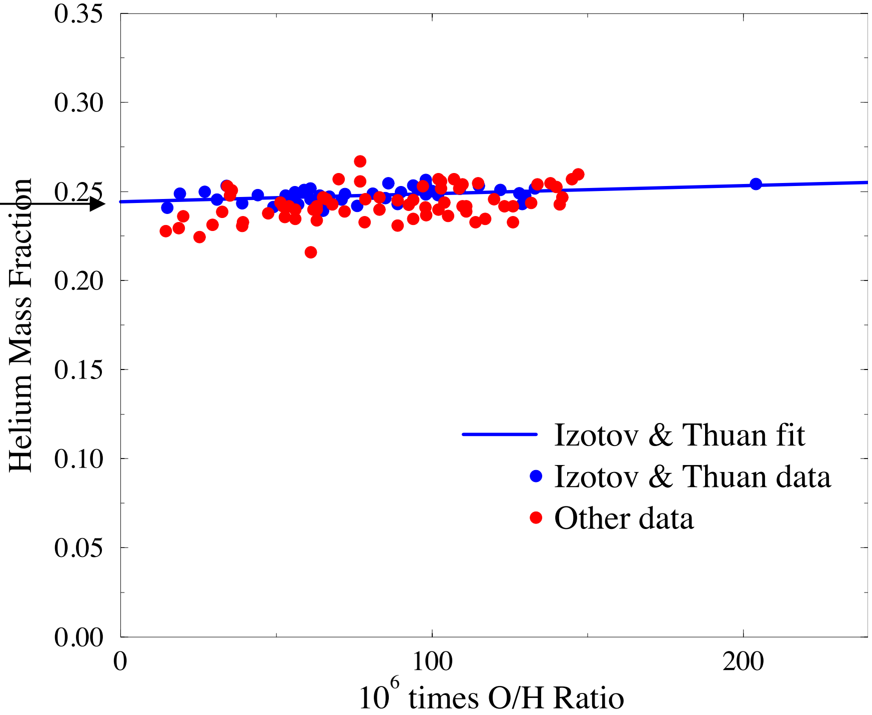

(“metalicity” = indicator of stellar processing)

(Burles, Nollett & Turner, arxiv:9903300, Fig.4)

- neutron-to-proton ratio: primordial Helium abundance:

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

$$n_{He} = \frac{n_n}{2}$$ (**all** neutrons end up in $^4He=2n+2p$)

$$m_p \approx m_n$$

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Big Bang Nucleosynthesis *primordial abundances*

- neutron-to-proton ratio: primordial Helium abundance:

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

$$n_{He} = \frac{n_n}{2}$$ (**all** neutrons end up in ${}^4He=2n+2p$, but not all protons)

$$m_p \approx m_n$$

$$\Rightarrow \quad X_{He} = Y = \frac{4n_{He}}{4n_{He}+n_H} = \frac{2n_n}{2n_n + \underbrace{(n_p - n_n)}_{\text{protons } \textbf{not} \text{ in } {}^4\text{He}}} = \frac{2n_n}{n_n+n_p} = \frac{2(n_n/n_p)}{1+(n_n/n_p)} = \frac{2\times 1/7}{1+1/7} = 0.25$$

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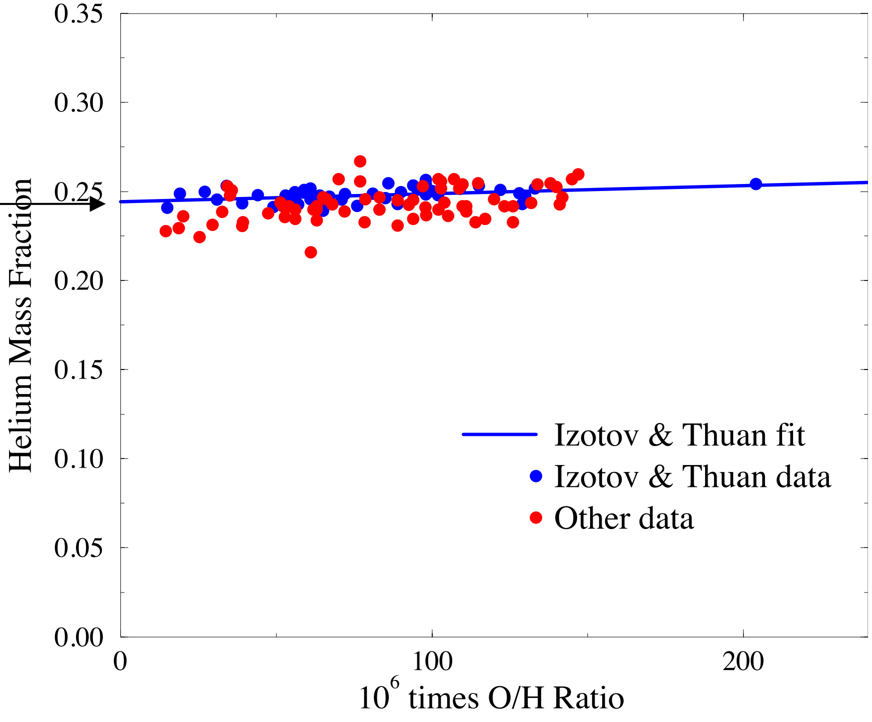

(“metalicity” = indicator of stellar processing)

(Burles, Nollett & Turner, 1999, Fig.4)

- neutron-to-proton ratio: primordial Helium abundance:

proper calculation leads to…

$$X_{He} = Y \approx 0.2454 + 0.0198(N_\nu - 3)$$

- nuclear statistical equilibrium: (non-relativistic nucleus $A = N_n + Z$ = #neutrons + #protons)
  - number density: $$n_A = g_A \left(\frac{m_A kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_A - \mu_A)c^2/kT}$$

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→ relate to...

- proton number density n_p
- neutron number density n_n
- baryon-to-photon ratio η

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- chemical reaction: $A \leftrightharpoons Z\, p + N_n\, n$

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- chemical equilibrium*: $$\mu_A = Z\mu_p + N_n\mu_n = Z\mu_p + (A - Z)\mu_n$$

---

*nuclear reactions are faster than cosmic expansion

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$$\downarrow \qquad \downarrow$$

eliminate μ_p and μ_n by…

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↓ ↓

…introducing n_p and n_n

$$n_p = 2\left(\frac{m_p kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_p - \mu_p)c^2/kT}$$

$$n_n = 2\left(\frac{m_n kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_n - \mu_n)c^2/kT}$$

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↓ ↓

…introducing n_p and n_n

$$e^{-\mu_p c^2/kT} = \frac{2}{n_p}\left(\frac{m_p kT}{2\pi\hbar^2}\right)^{3/2} e^{-m_p c^2/kT} \qquad \Leftarrow \qquad n_p = 2\left(\frac{m_p kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_p-\mu_p)c^2/kT}$$

$$e^{-\mu_n c^2/kT} = \frac{2}{n_n}\left(\frac{m_n kT}{2\pi\hbar^2}\right)^{3/2} e^{-m_n c^2/kT} \qquad\qquad n_n = 2\left(\frac{m_n kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_n-\mu_n)c^2/kT}$$

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…introducing n_p and n_n

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$$\Leftarrow$$

$$n_p = 2\left(\frac{m_p kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_p - \mu_p)c^2/kT}$$

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$$n_A = g_A \frac{A^{3/2}}{2^A} \left(\frac{m_A}{A} \frac{kT}{2\pi\hbar^2} \right)^{3(1-A)/2} n_p^Z n_n^{(A-Z)} e^{B_A/kT}$$

$$B_A = \left(Z m_p + (A-Z) m_n - m_A \right) c^2$$ (binding energy of nucleus)

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nucleus	^{2}H	^{3}H	^{3}He	^{4}He
B_A	2.2 MeV	8.48 MeV	7.72 MeV	28.3 MeV

(all above temperature of Universe at these times…)

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replace with baryon-to-photon ratio*…

*remember Deuterium bottleneck and relevance of photon density…

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$\eta = n_b/n_\gamma$: baryon-to-photon ratio

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$\eta = n_b/n_\gamma$: baryon-to-photon ratio

$$n_\gamma = \frac{2\zeta(3)}{\pi^2} \left(\frac{k_B}{\hbar c} \right)^3 T^3$$

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$$\propto g_A A^{5/2}\left(\frac{kT}{m_A}\right)^{3(A-1)/2} X_p^Z X_n^{(A-Z)} \ \eta^{A-1} e^{B_A/kT}$$

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mass fraction reduced to...

proton mass fraction	X_p
neutron mass fraction	X_n
baryon-to-photon ratio	η

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mass fraction reduced to...

- proton mass fraction X_p
- neutron mass fraction X_n
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$$\eta = \frac{n_b}{n_\gamma} = 10^{-10}\eta_{10} = 10^{-10} \cdot 274\Omega_b h^2$$

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primordial abundances

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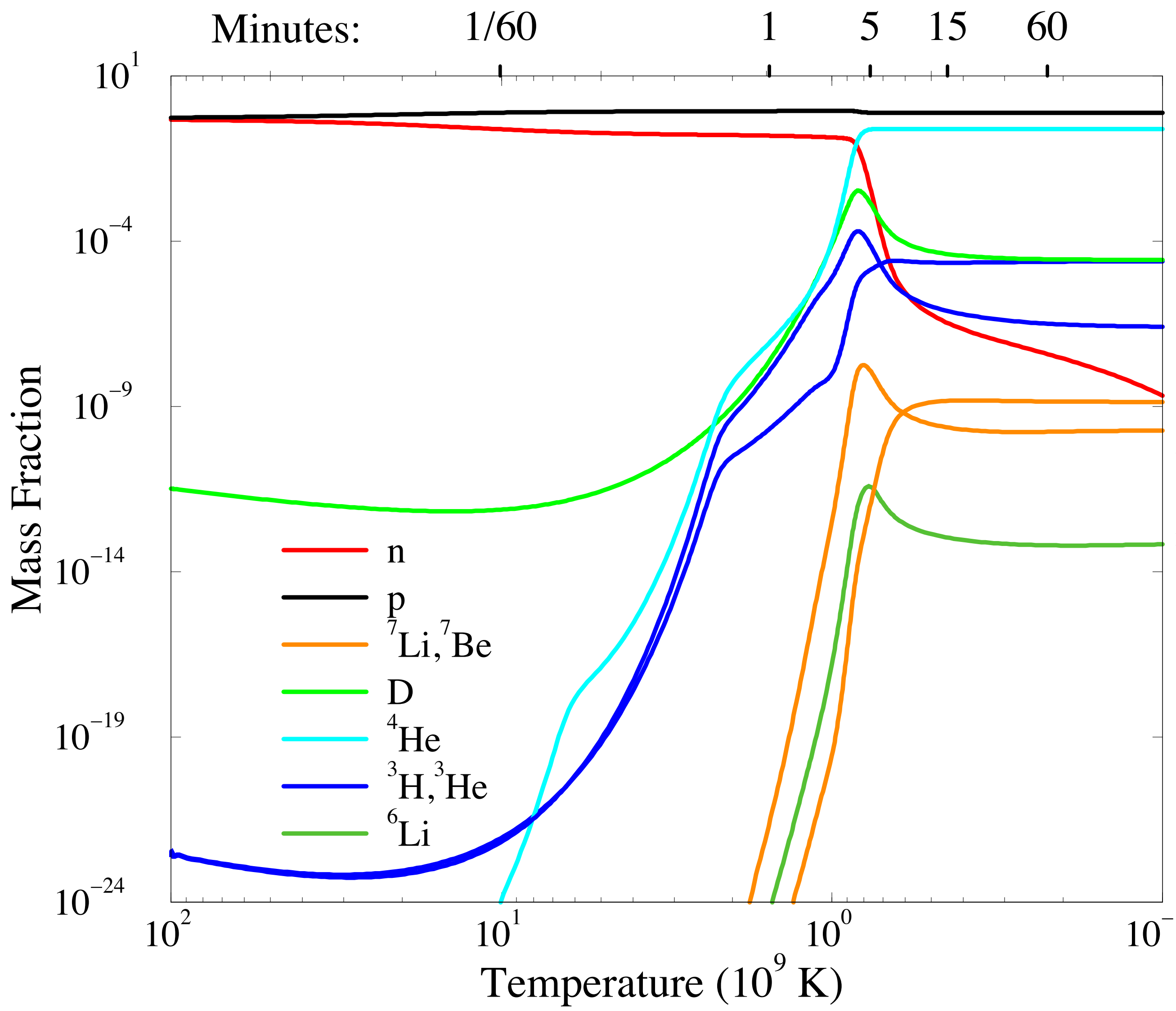
$$\frac{dX_A}{dt} = -\Gamma_A \left(X_A - (1 - X_A) e^{-B_A/kT} \right) \qquad \longrightarrow$$

- numerical calculations of cosmic evolution of mass fractions



(Burles, Nollett & Turner, arxiv:9903300, Fig.3)

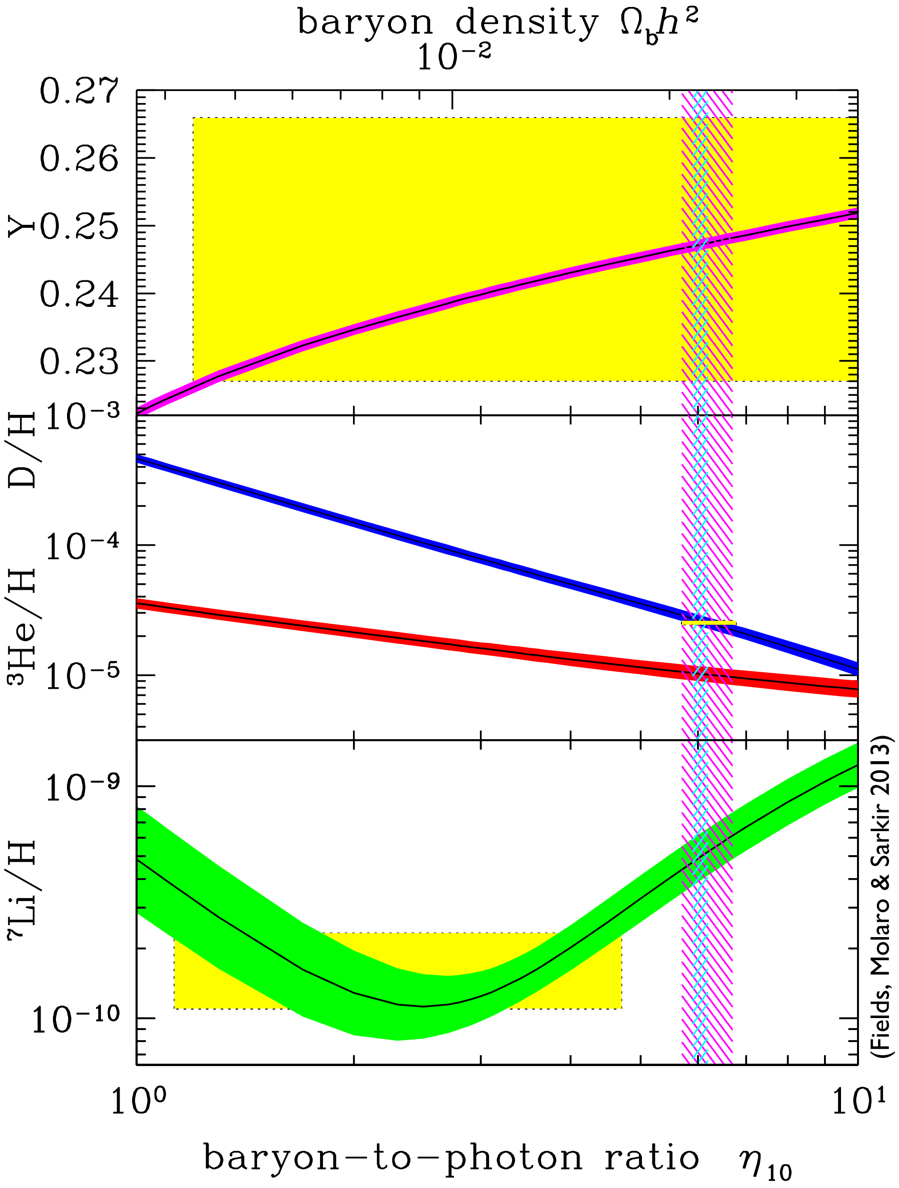
- dependence on baryon density:

- Ω_b ↗ → Y ↗ (as BBN starts earlier)

- D and ^{3}He are primarily consumed

- Ω_b ↗ → ^{7}Be ↗

- Ω_b ↗ → ^{7}Li ↘↗



(Fields, Molaro & Sarkir 2013)

Remember: $Y = X_{4He}$

- dependence on baryon density:

9 orders of magnitude!

- Ω_b ↗ → Y ↗ (as BBN starts earlier)
- D and ^{3}He are primarily consumed
- Ω_b ↗ → ^{7}Be ↗
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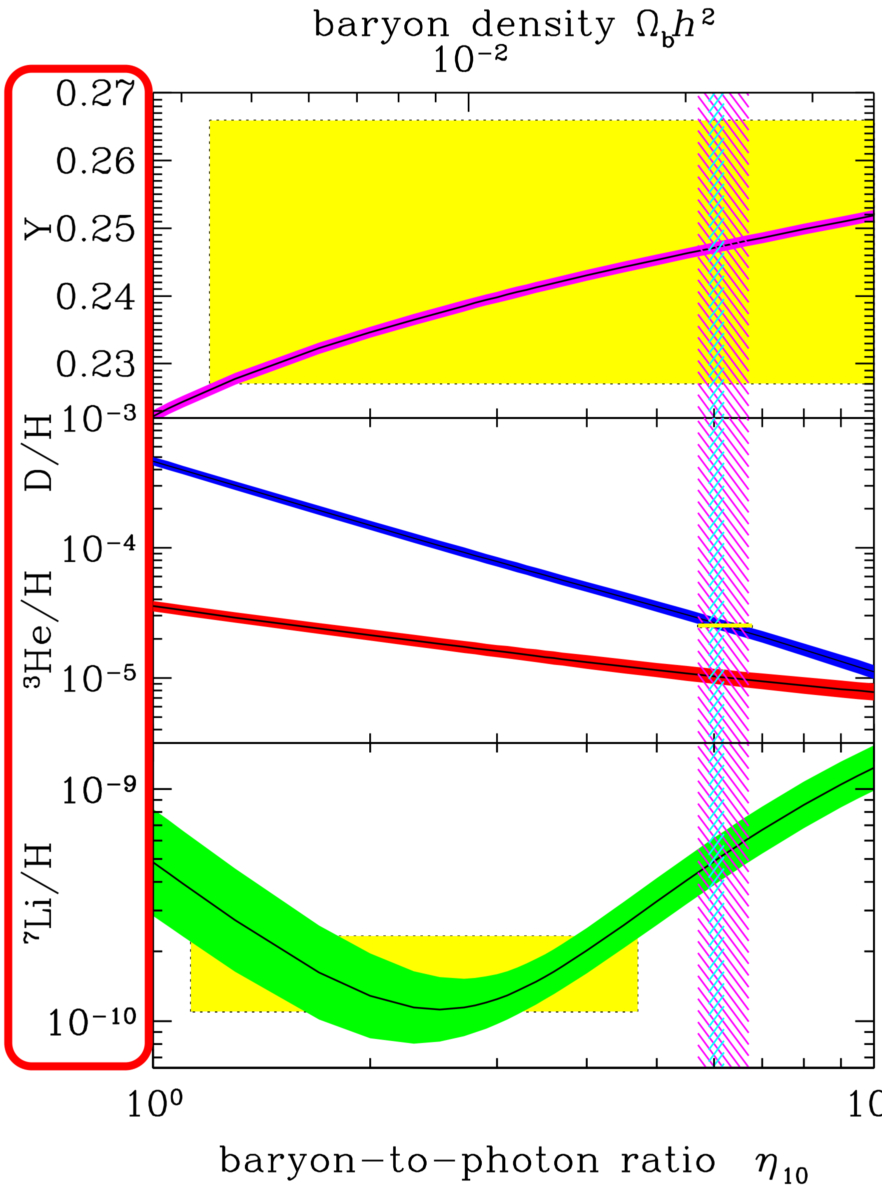

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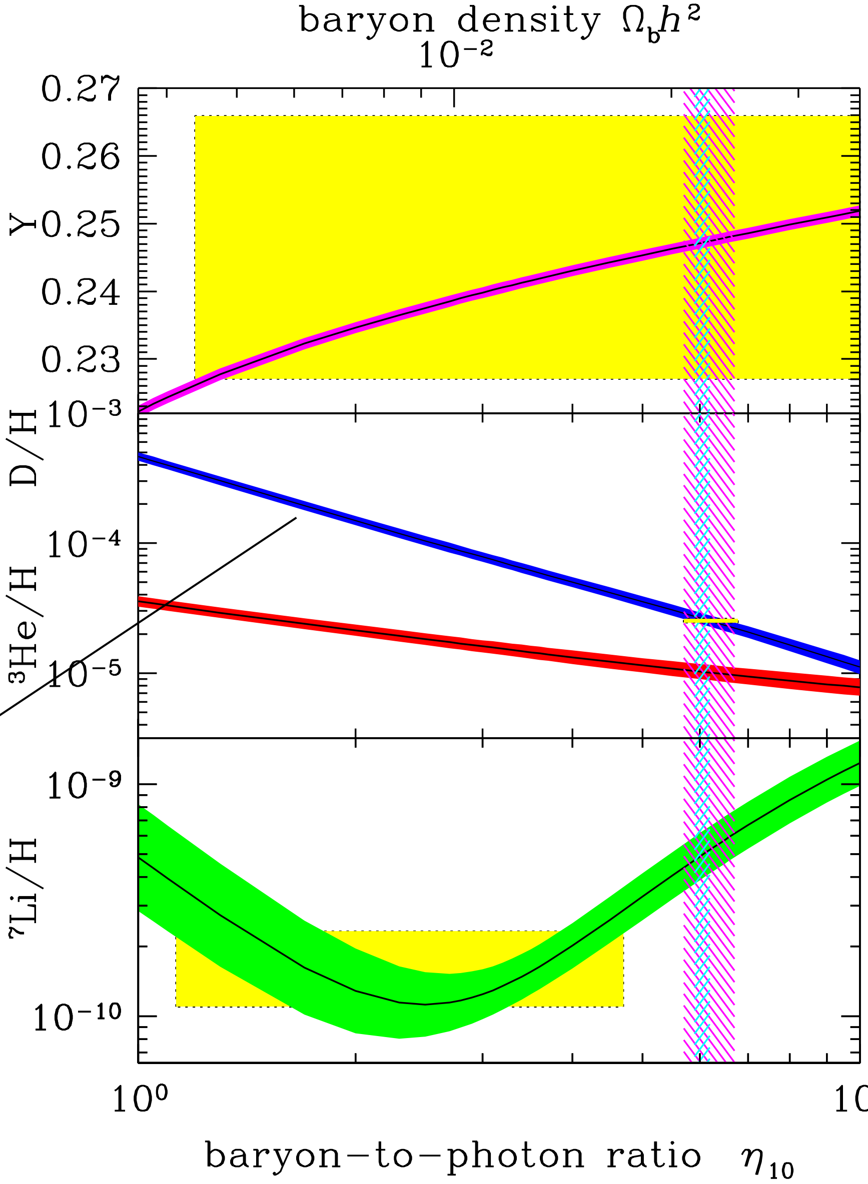
• Ω_b↗ → ^{7}Li↘↗

sensitive to baryon density!
(“Baryometer”)



(Fields, Molaro & Sarkir 2013)

Big Bang Nucleosynthesis

primordial abundances

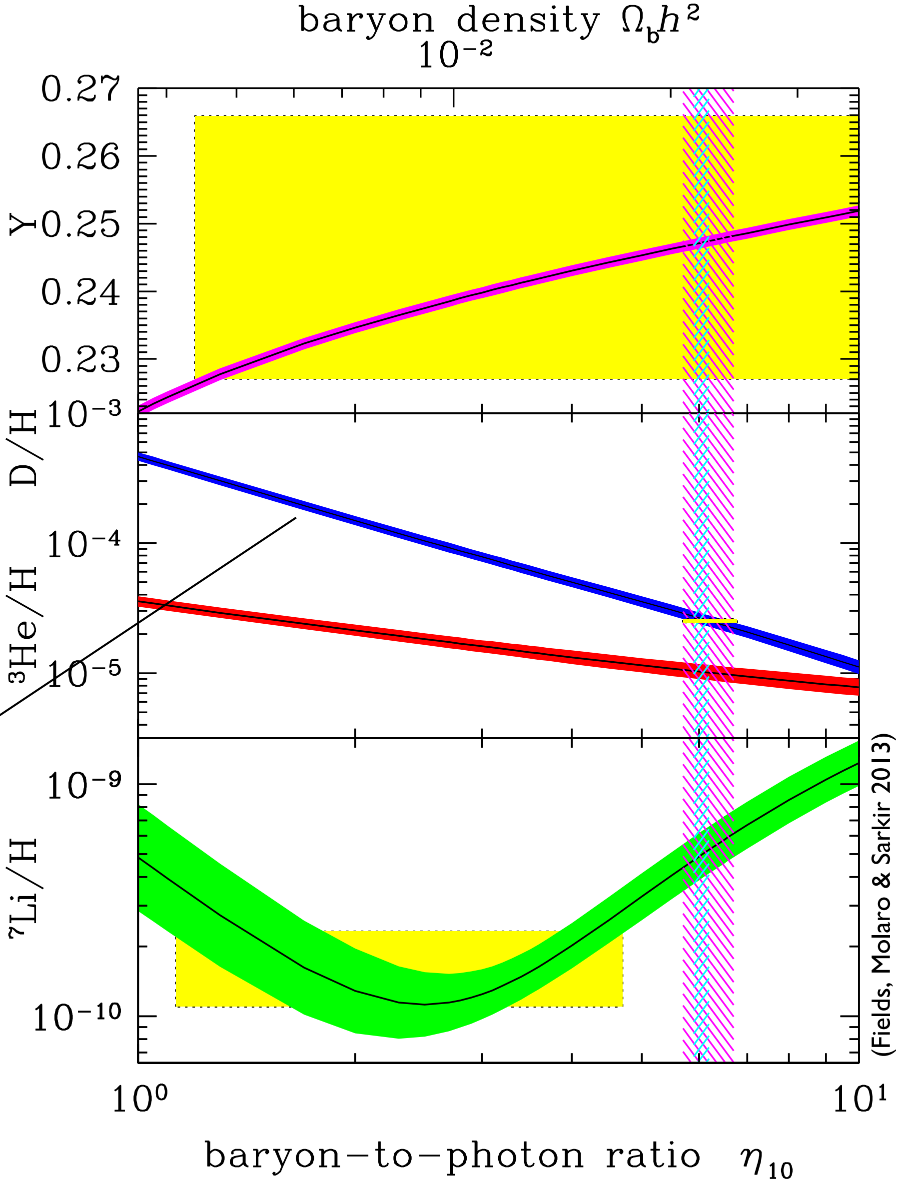
- dependence on baryon density:

- Ω_b ↗ → Y ↗ (as BBN starts earlier)
- D and ^{3}He are primarily consumed
- Ω_b ↗ → ^{7}Be ↗
- Ω_b ↗ → ^{7}Li ↘ ↗

sensitive to baryon density!
("Baryometer")

Note:
- D is only created during BBN
- D has highest sensitivity to Ω_b

=> best Baryometer!



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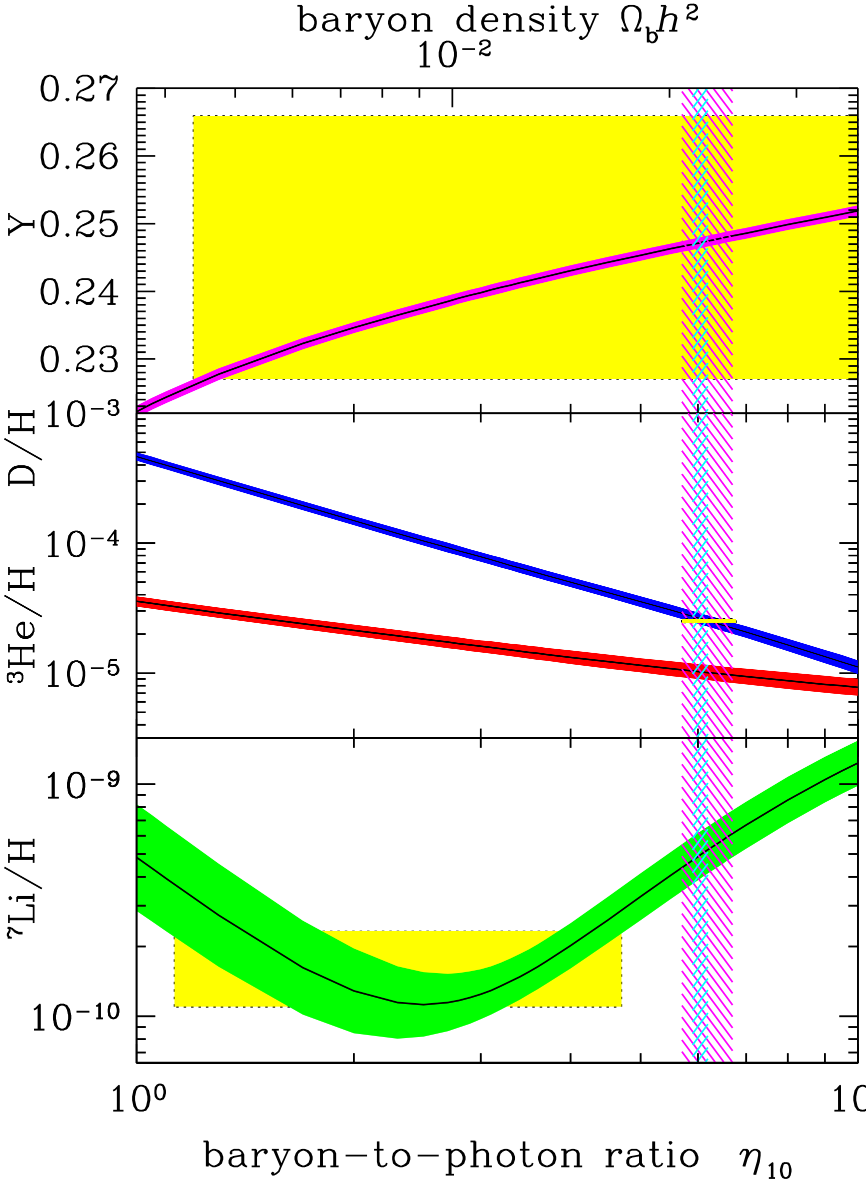
- Ω_b ↗ → ^{7}Li ↘↗

^{7}Li shape:

destruction:
p + ^{7}Li → ^{4}He + ^{4}He

formation:
^{3}H + ^{4}He → ^{7}Li + $e^+ + \nu_e$

^{3}He + ^{4}He → ^{7}Be + γ
^{7}Be → ^{7}Li + $e^+ + \nu_e$ } dominates for higher η



(Fields, Molaro & Sarkir 2013)

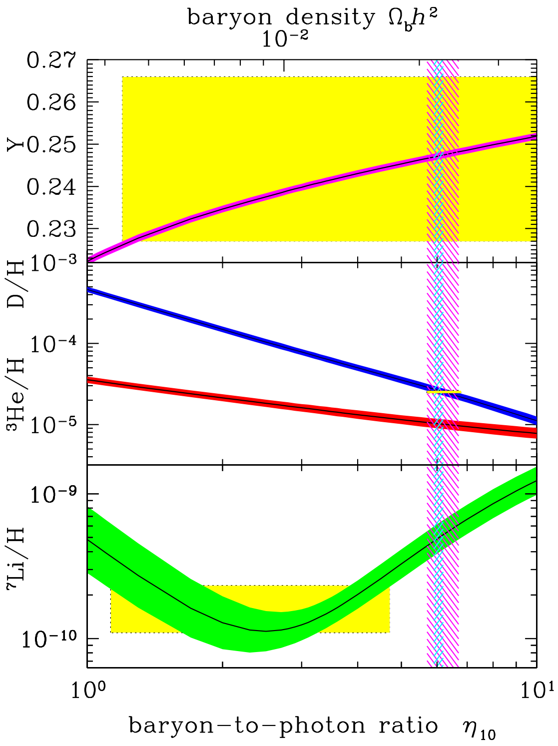
sensitivity to physics

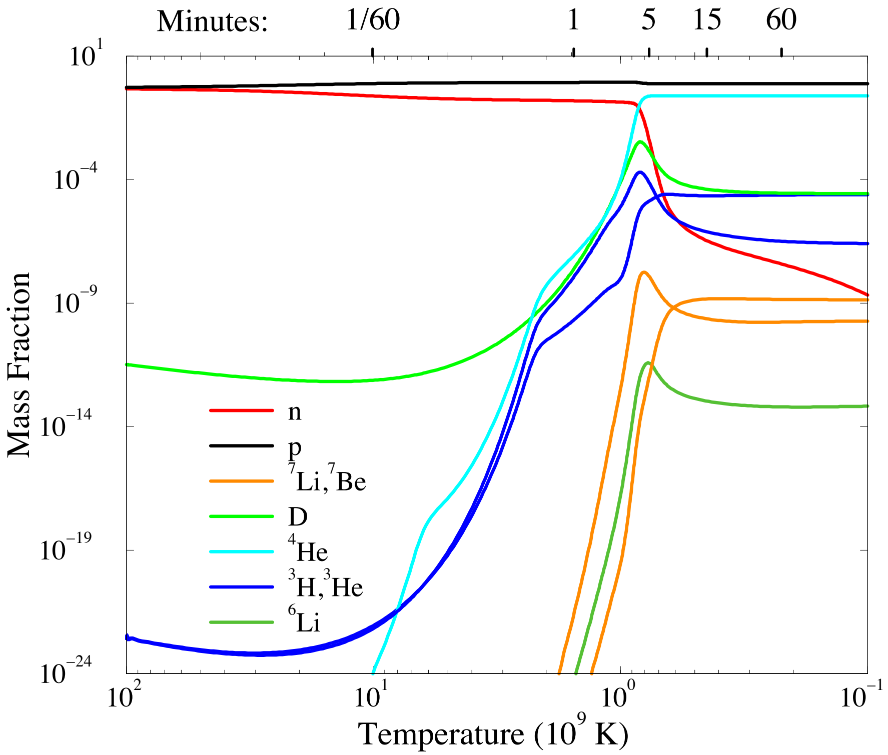
- BBN depends on various ‘parameters’:
  - g_*: $g_* \nearrow \quad \rightarrow \quad T_f \nearrow \quad \rightarrow \quad n/p \nearrow \quad \rightarrow \quad {}^4\mathrm{He} \nearrow$
  - τ_n: $\tau_n \nearrow \quad \rightarrow \quad T_f \nearrow \quad \rightarrow \quad n/p \nearrow \quad \rightarrow \quad {}^4\mathrm{He} \nearrow$
  - G_N: $G_N \nearrow \quad \rightarrow \quad T_f \nearrow \quad \rightarrow \quad n/p \nearrow \quad \rightarrow \quad {}^4\mathrm{He} \nearrow$
  - Q: $Q \nearrow \quad \rightarrow \quad n/p \searrow \quad \rightarrow \quad {}^4\mathrm{He} \searrow$
  - η: $\eta \nearrow \quad \rightarrow \quad X_A \nearrow \quad \rightarrow \quad {}^4\mathrm{He} \nearrow$ & D,T,^{3}He$\searrow$

→ BBN is a probe of fundamental physics!

- **BBN summary:**
  - production of H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Be, ^{7}Li
  - all other elements are in fact produced in stars
  - mass fractions:

^{2}H: deuterium D
^{3}H: trillium T





remember: we are forming *nuclei* and not atoms…

- **BBN summary:**
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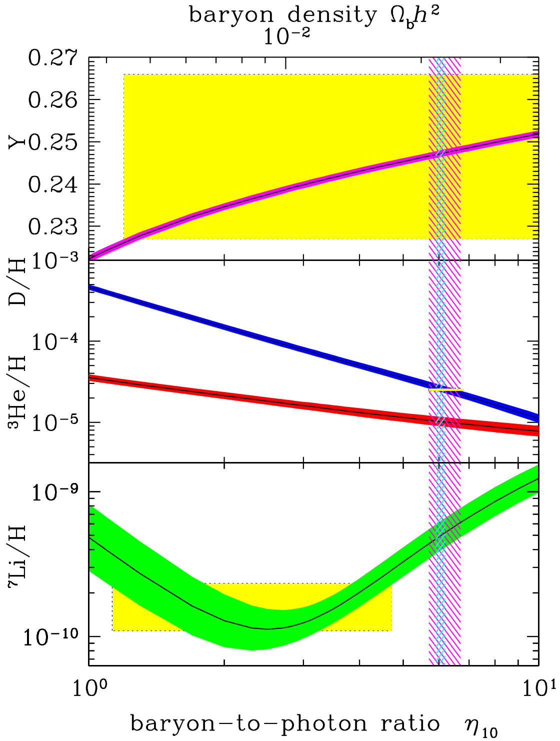

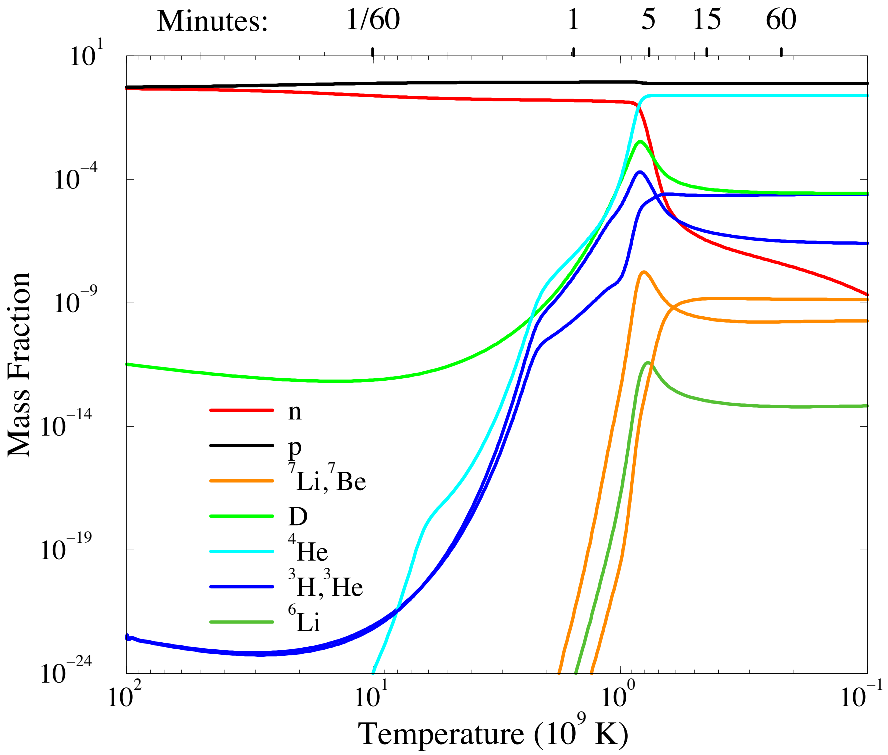

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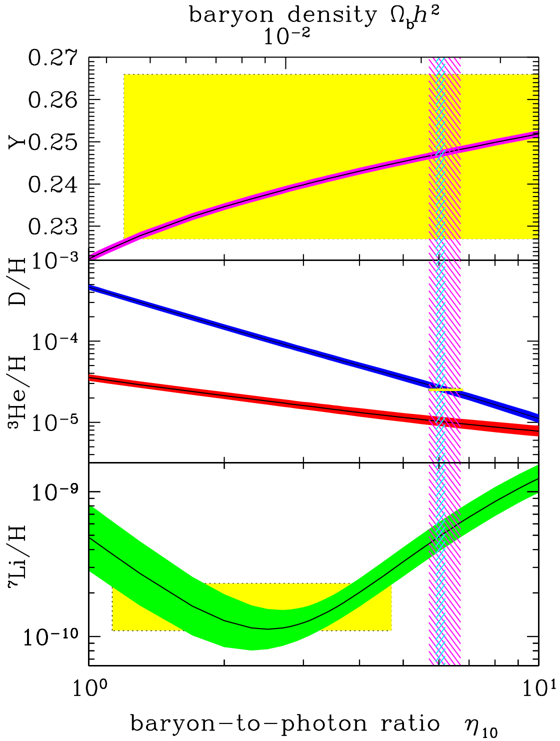
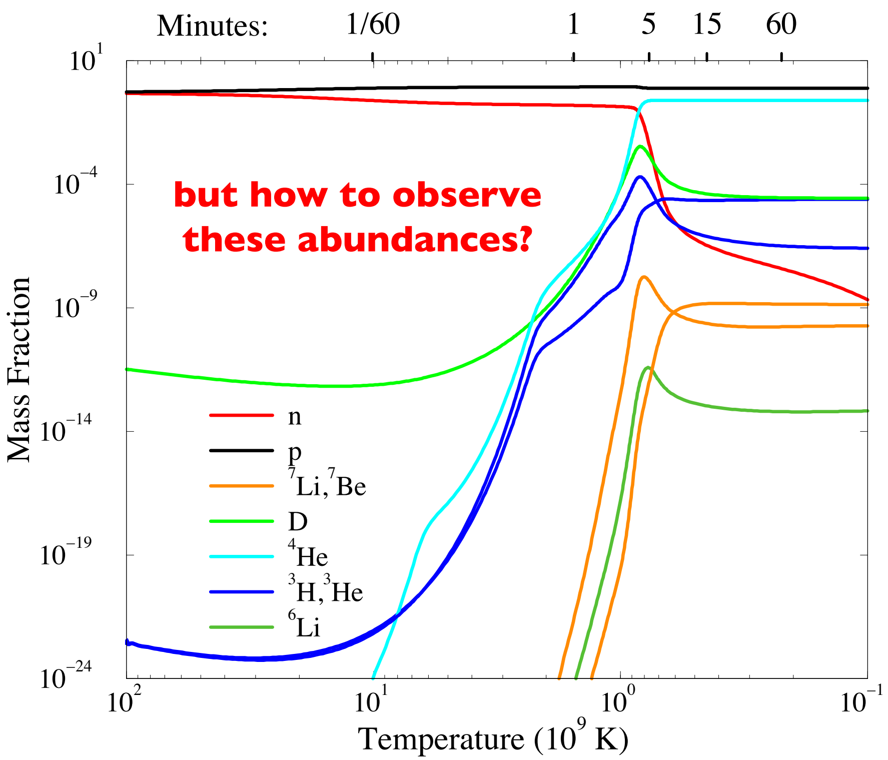
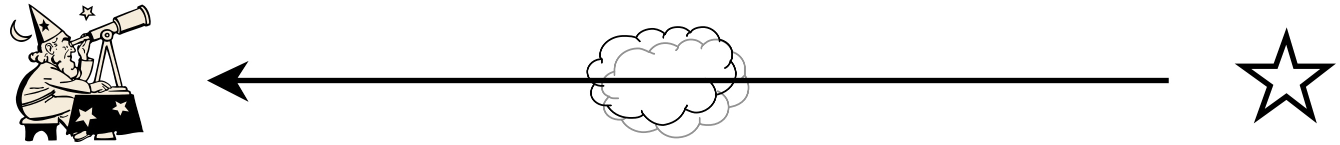


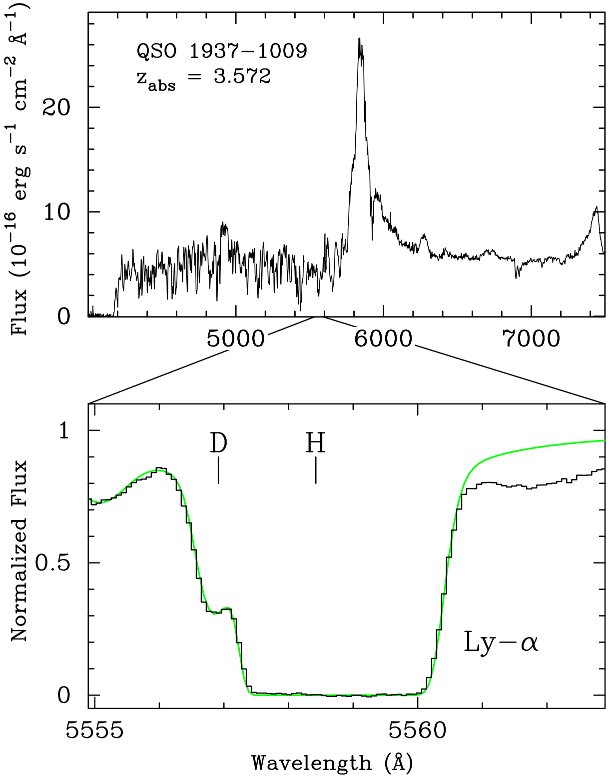


but how to observe these abundances?

- introduction
- particle physics
- synthesis of elements
- big bang nucleosynthesis
- ***observations***

- Ly-α clouds (not polluted by stars):
  - line strength in QSQ absorption spectra provide abundance measures





(Burles, Nollett & Turner, arxiv:9903300, Fig.2)

Big Bang Nucleosynthesis *observations*

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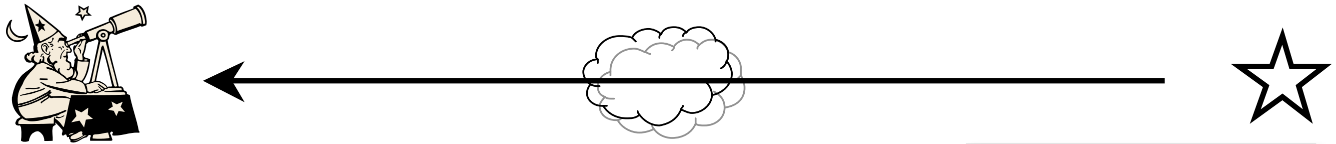

- nearby dwarf galaxies
  - high gas/star ratio and low metal/H in gas suggest that their interstellar medium is close to primordial

Big Bang Nucleosynthesis

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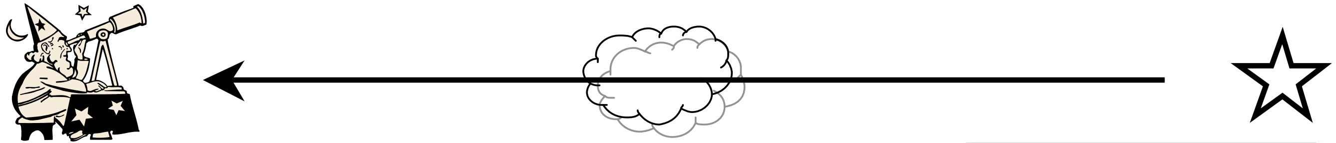

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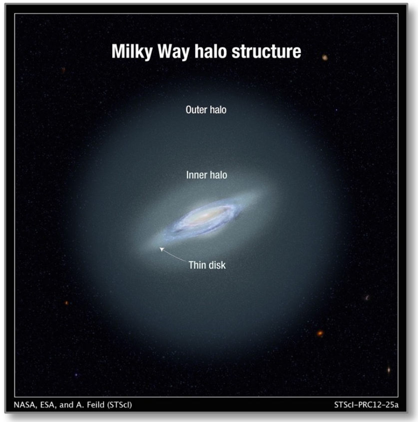

- Galactic halo
  - contains very old stellar population

Big Bang Nucleosynthesis *observations*

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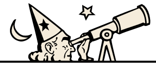

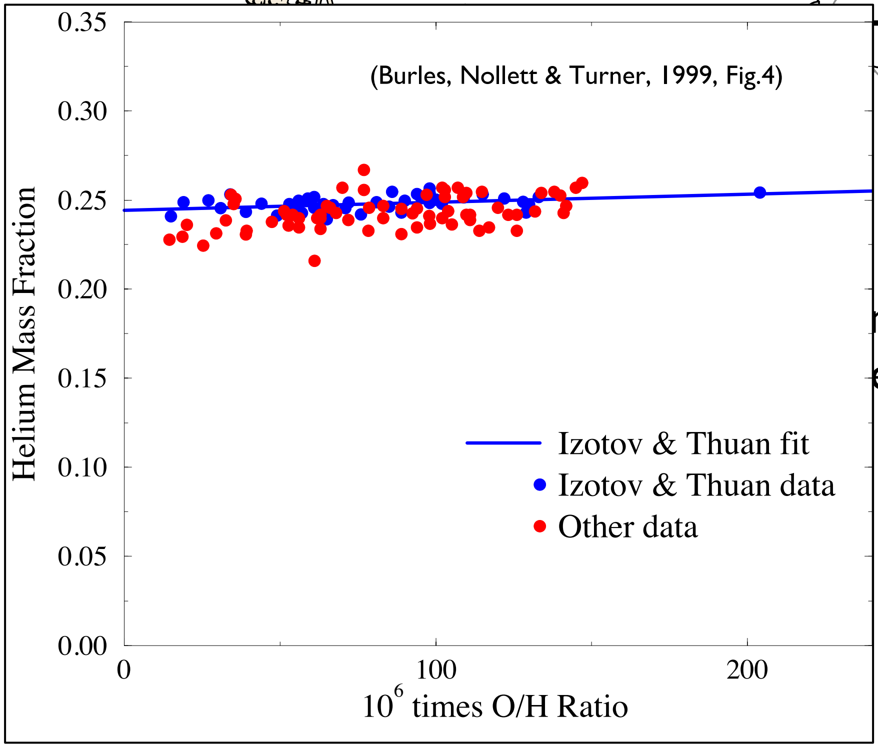
(Burles, Nollett & Turner, 1999, Fig.4)

n gas suggest
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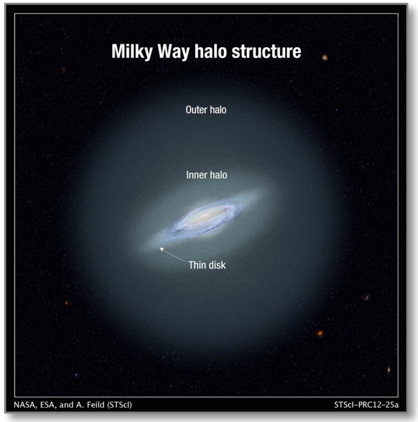
Barnard's galaxy (satellite of MW)

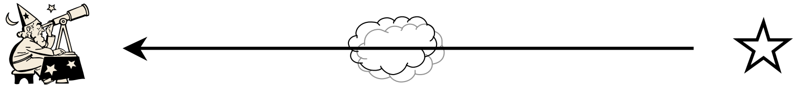


- HII regions
  - low-density cloud of partially ionized gas in which star formation took/takes place


HII region in Triangulum Galaxy

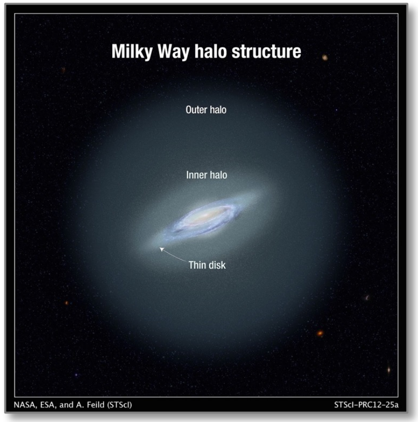
observations

- Ly-α clouds (not polluted by stars):
  - line strength in QSQ absorption spectra provide abundance measures
    - *IGM observations:* $\eta \simeq 2.5$ x 10^{-5}



Barnard's galaxy (satellite of MW)

- nearby dwarf galaxies
    - *ISM observations:* $\eta \simeq 1.6$ x 10^{-5}



Milky Way halo structure

NASA, ESA, and A. Feild (STScI)

STScI-PRC12-25a

- Galactic halo
  - *^{7}Li observed in spectra of cool low-mass starts in Galactic halo*

- HII regions
  - *^{4}He probed via emission from optical recombination lines in HII regions*

HII region in Triangulum Galaxy

Big Bang Nucleosynthesis

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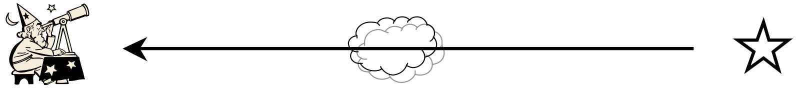

$$\eta = \frac{n_b}{n_\gamma} = 10^{-10}\eta_{10} = 10^{-10} \cdot 274\Omega_b h^2$$

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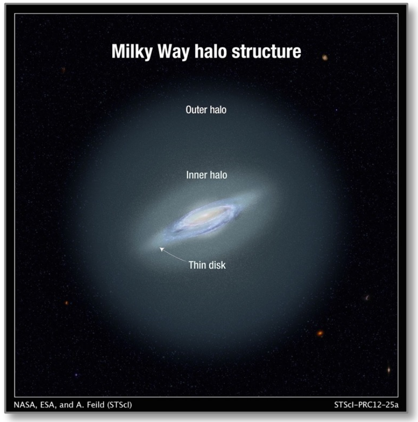

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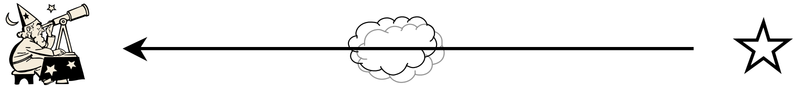

$$\downarrow$$

$$\Omega_b h^2 \approx 0.0214$$

$$\uparrow$$

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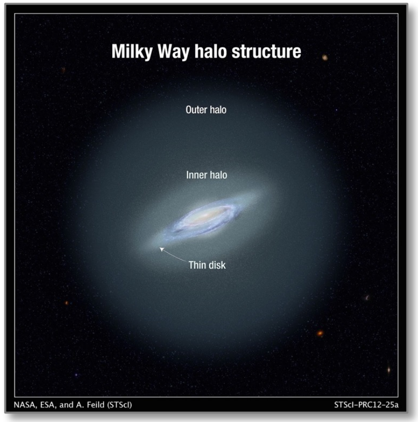

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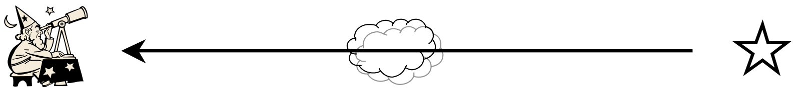

$\downarrow$

$$\Omega_b h^2 \approx 0.0214$$

even BBN claims for the existence of non-baryonic matter!

$\uparrow$

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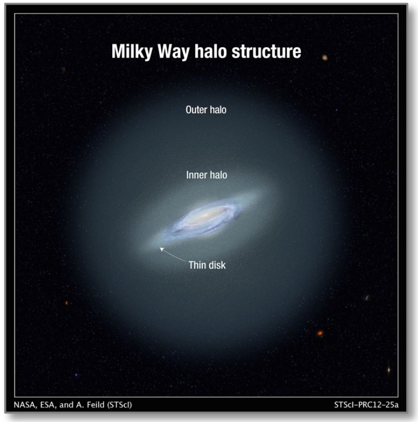

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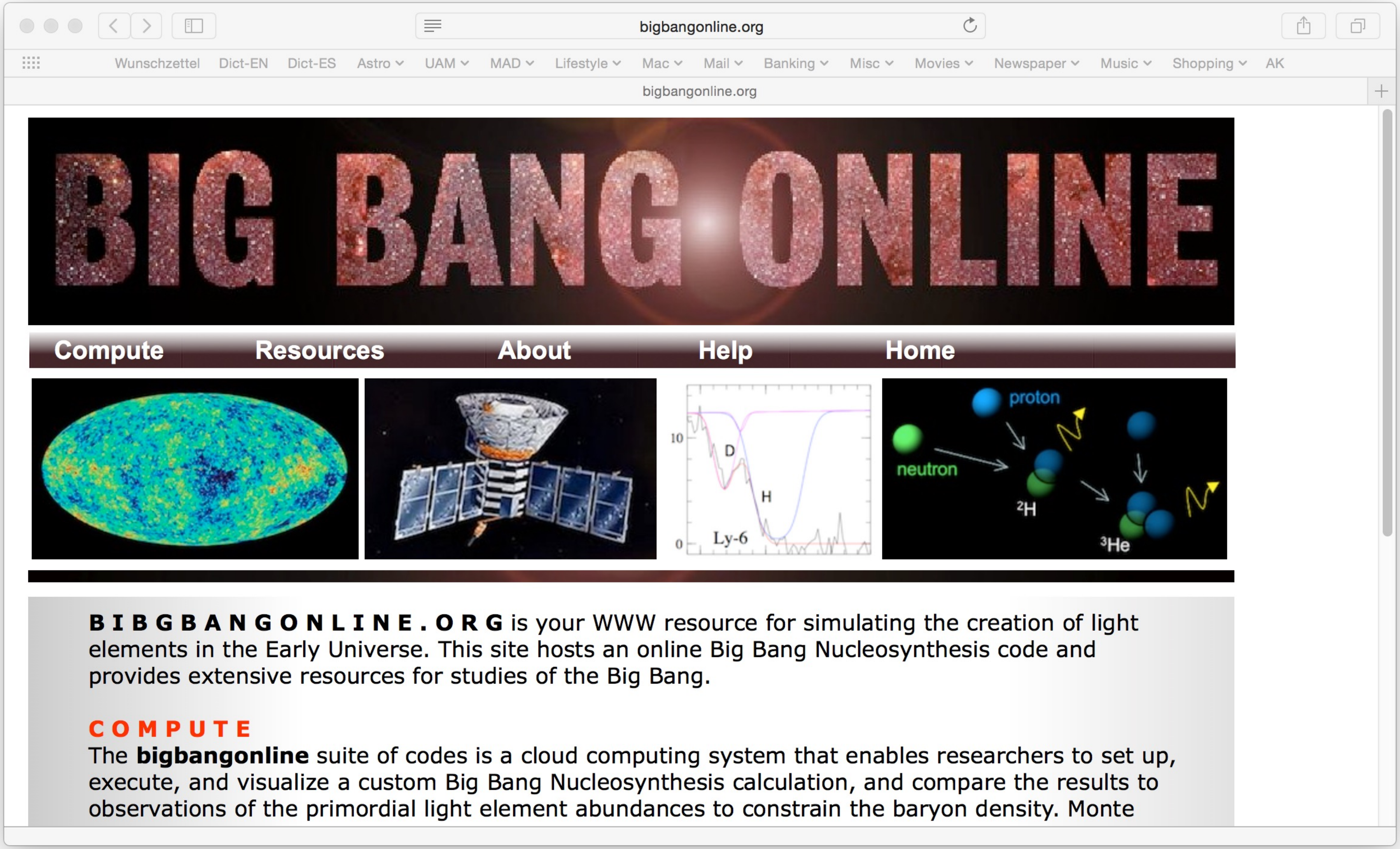
Big Bang Nucleosynthesis

summary



BIBGBANGONLINE.ORG is your WWW resource for simulating the creation of light elements in the Early Universe. This site hosts an online Big Bang Nucleosynthesis code and provides extensive resources for studies of the Big Bang.

COMPUTE

The **bigbangonline** suite of codes is a cloud computing system that enables researchers to set up, execute, and visualize a custom Big Bang Nucleosynthesis calculation, and compare the results to observations of the primordial light element abundances to constrain the baryon density. Monte