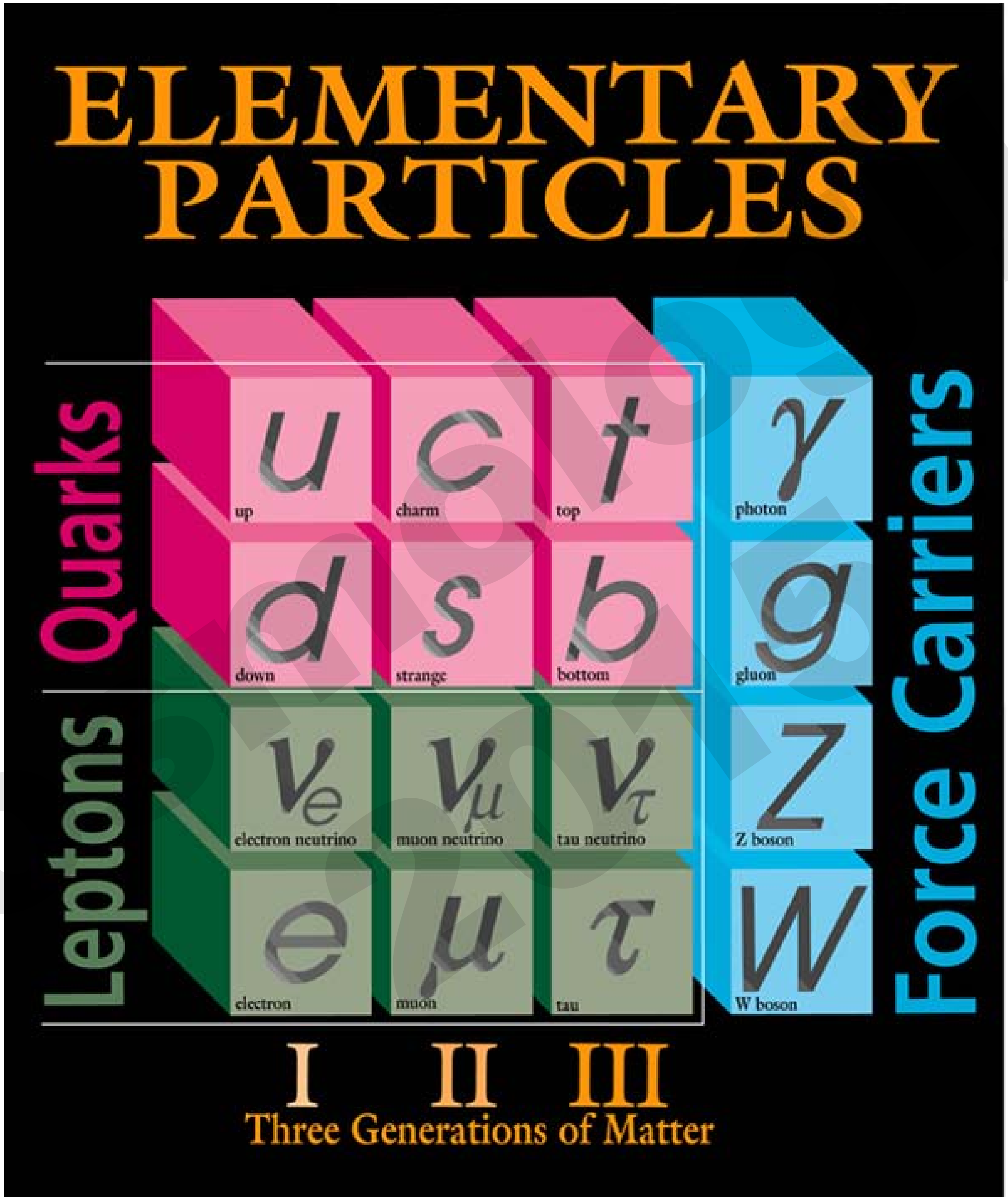
PRIMORDIJALNA NUKLEOSINTEZA: UVOD

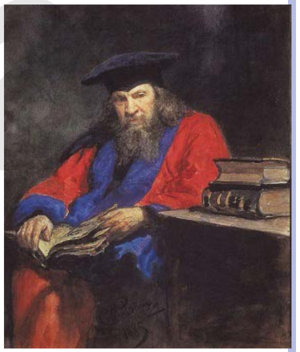
03. 07. 2015.

"I'LL BE WORKING ON THE LARGEST AND SMALLEST OBJECTS IN THE UNIVERSE—SUPERCLUSTERS AND NEUTRINOS. I'D LIKE YOU TO HANDLE EVERYTHING IN BETWEEN."



Fermilab 95-759

Periodni sistem



Dmitrij Mendeljejev 1869 – najveće otkriće u istoriji hemije

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII	VII	VII	IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

Naming conventions of new elements

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

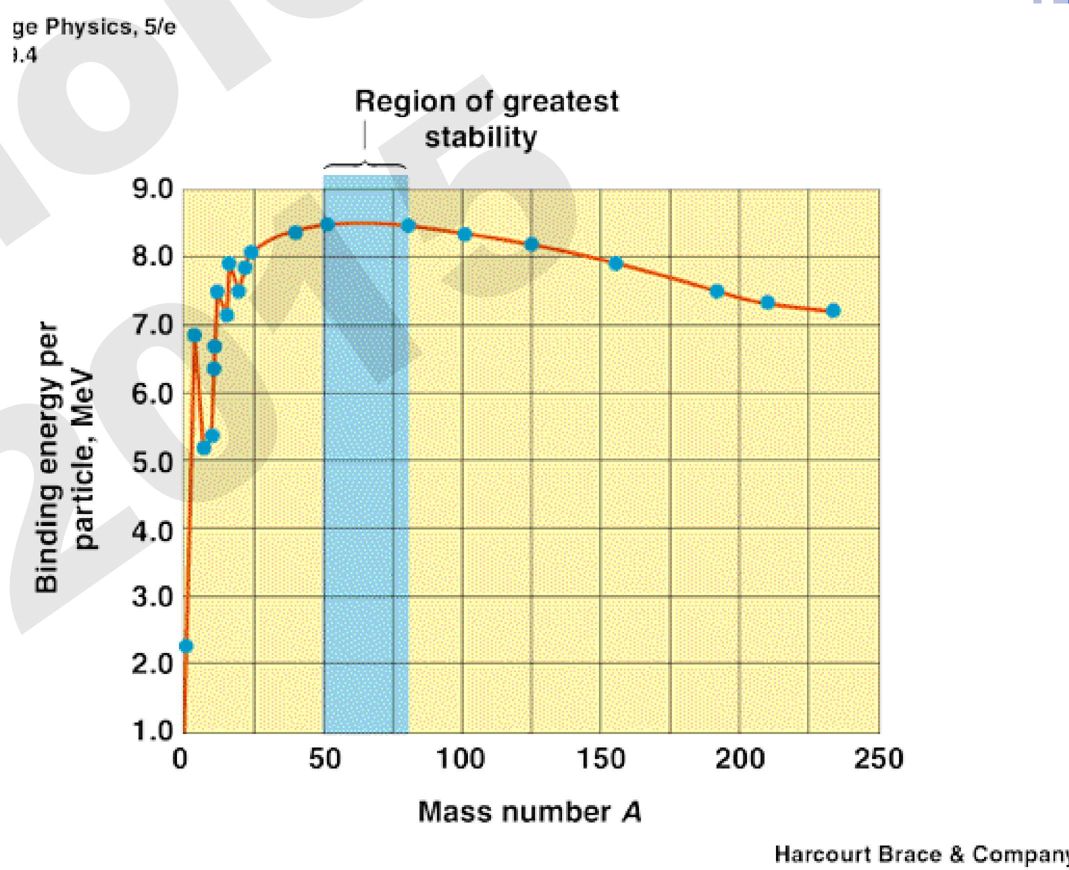
Z = atomski broj (broj protona)

A = maseni broj (broj protona + neutrona)

Kako su nastala atomska jezgra?

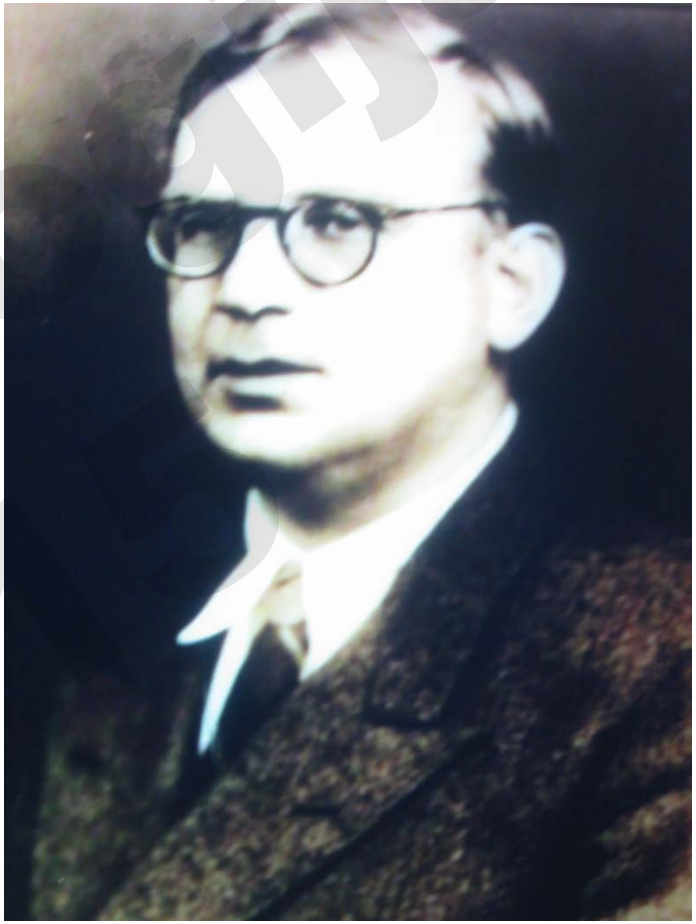
- Stvaranje jezgara = **nukleosinteza**!

- Podrazumeva se da je nastanak jezgara istovremeno i nastanak atoma!
- Ključ = **nuklearna stabilnost**
- Laki elementi teže da se **spajaju**, teški da se **cepaju**
- **Gde mogu postojati takvi uslovi?**

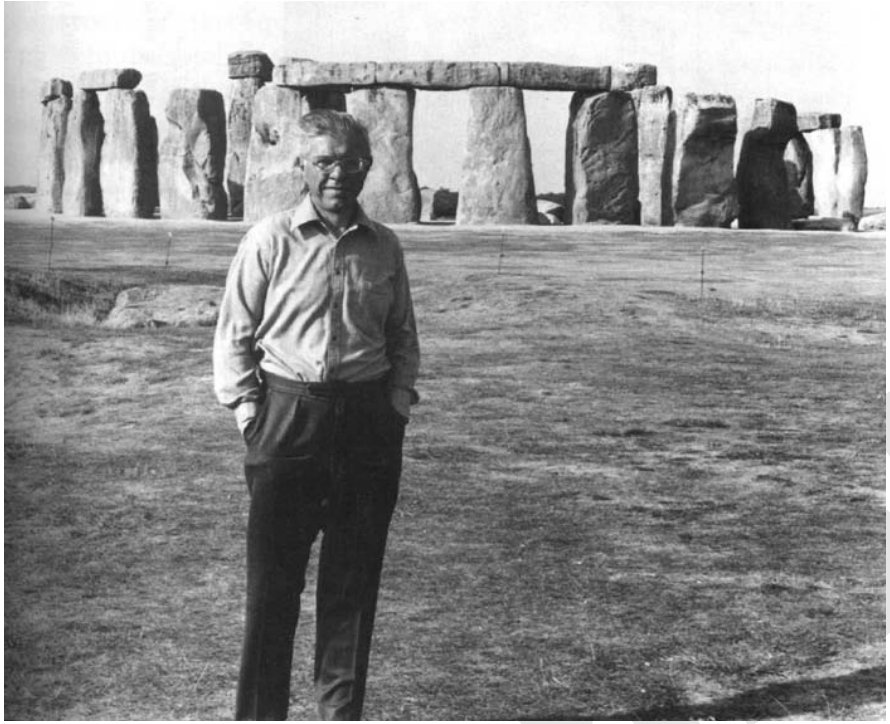


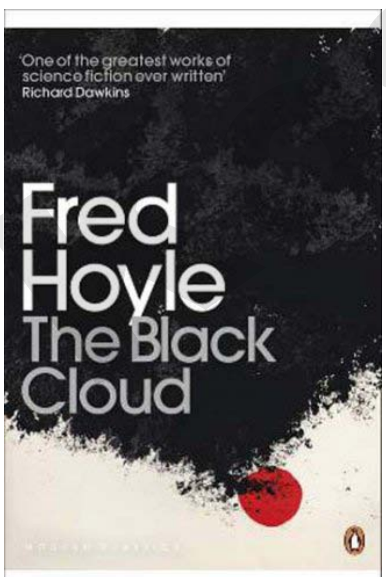
DVA GENIJA REŠAVAJU STVAR...

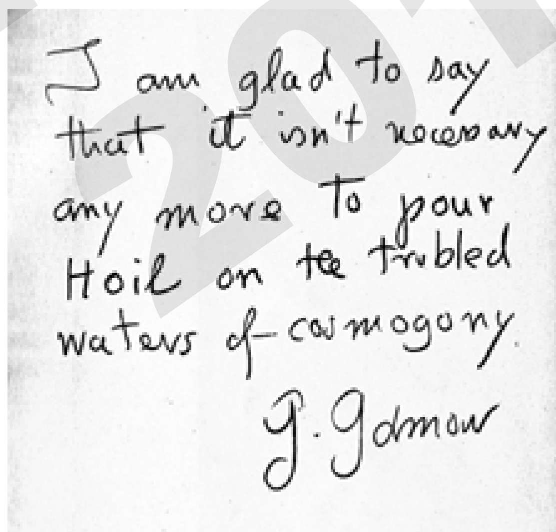
Ser Fred Hojl (1915-2001)

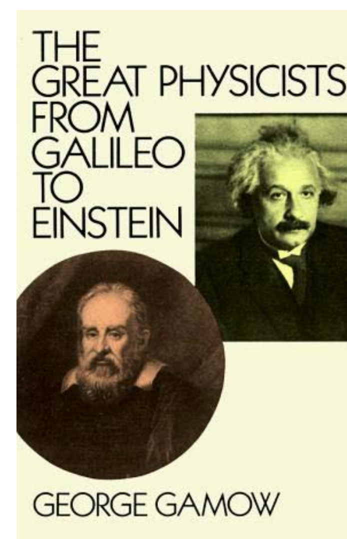


Georgij (Džordž) Antonovič Gamov (1904-1968)

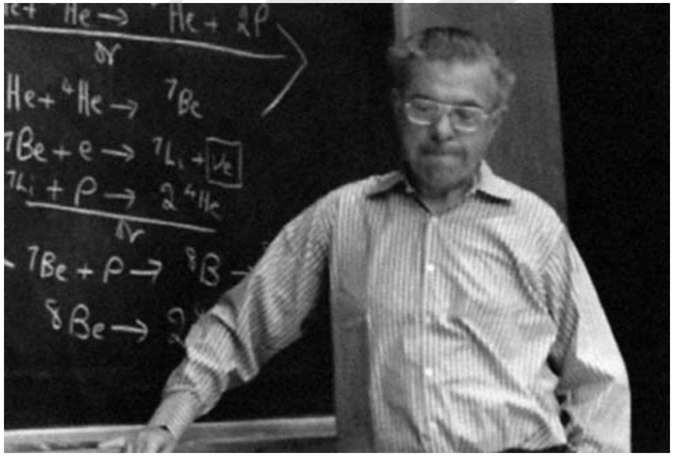


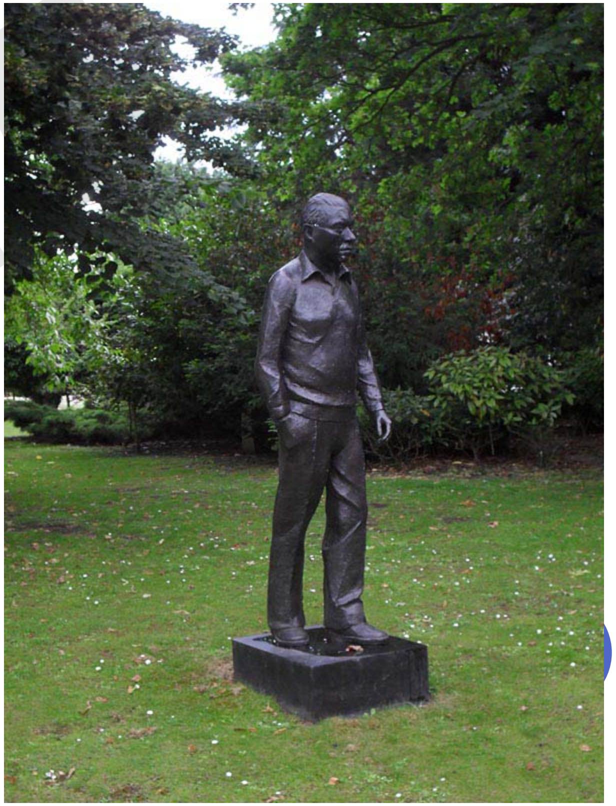

'One of the greatest works of science fiction ever written'
Richard Dawkins
Fred Hoyle
The Black Cloud


I am glad to say that it isn't necessary any more to pour Hoil on the trubled waters of cosmogony
G. Gamow


THE GREAT PHYSICISTS FROM GALILEO TO EINSTEIN
GEORGE GAMOW


Institute of Astronomy
Hoyle Building
Main Entrance


7Be + e → 7Li + νe
7Li + P → 2 4He
7Be + P → 8B



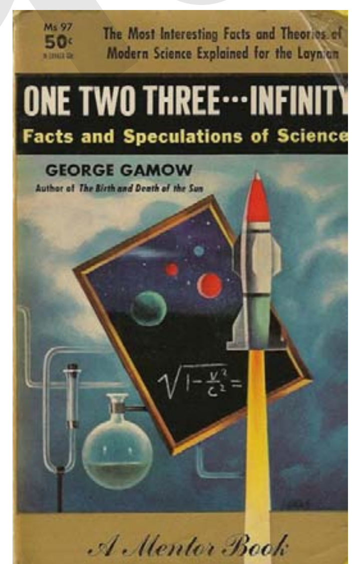

THINGS ARE THE
WAY THEY ARE
BECAUSE THEY
WERE THE WAY
THEY WERE
FRED HOYLE

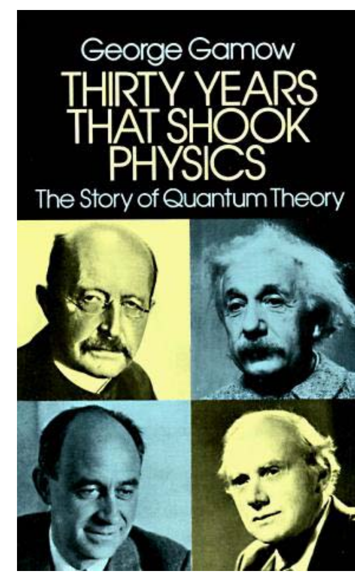
Genije iz Odese

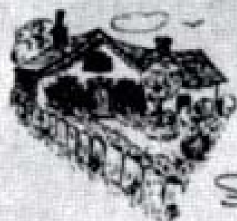
- Studirao kod Fridmana do 1925, potom kod Bora i Raderforda
- „Tri musketara“: Gamov i
  - Lav Landau
  - Dmitrij Ivanjenko
  - Matvej Bronštajn
- 1931. postao najmlađi član Sovjetske akademije u istoriji – i zabranjeno mu da putuje (!)
- Dvaput pokušao da pobegne **kajakom**...
- 1933. prvi Solvejev kongres, dobija pomoć od Marije Kiri
- Od 1934. živi u SAD, najpre GWU (Sent Luis), a poslednjih godina UC (Boulder)
- Poslednjih godina težak alkoholičar, iznenada umire u Boulderu 1968.

VELIKO DELO...

- Rešenje problema kvantnog tuneliranja
- Gamovljev faktor u alfa-raspadu
- Nuklearni model kapi
- Nastanak Sunčevog sistema
- Prvi sugerisao triplete u DNK/RNK kao „reči“
- Primordijalna nukleosinteza
- Veliki popularizator nauke!







Sept 29th 1963
The Gamow Dacha
785 - 6th Street
Boulder, Colorado

Dear Dr. Penzias,

~~Send~~ Thank you for sending me your paper on 3 °K radiation. It is very nicely written except that "early history" is not "quite complete". The theory of, what is now knows as "primeval fireball" was first developed by me in 1946 (Phys. Rev. 70, 572, 1946; 74, 505, 1948; Nature 162, 680, 1948). The prediction of the numerical value of the present (residual) temperature could ~~can~~ be found in Alpher & Hermann's paper (Phys. Rev. 75, 1093, 1949) who estimate it as 5 °K, and in my paper (Kong Dansk. Ved. Sels. 27 no 10, 1953) with the estimate of 7 °K. Even in my popular book "Creation of Universe" (Viking 1952) you can find (on p. 42) the formula $T = 1.5 \cdot 10^{10}/t^{1/2}$ °K, and the upper limit of 50 °K. Thus, you see the world did not start with almighty Dicke.

Sincerely G. Gamow?

αβγ TEORIJA

- Alferova doktorska dizertacija
- Gamovljeva šala sa Beteom
- Zahvat neutrona kao osnovni proces
- „Svi hemijski elementi nastali su za kraće vreme nego što je domaćici potrebno da skuva ručak.“
- Hojl sreću kvari: nema A = 5 (i drugih **masenih procepa**)!
- Bete → Zaharijus ☺

PHYSICAL REVIEW VOLUME 73, NUMBER 7 APRIL 1, 1948

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

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./cm³.

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./cm³. 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 2.5×10^5 g sec./cm³ which can possibly be understood if we

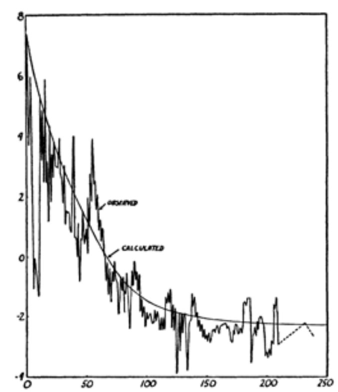
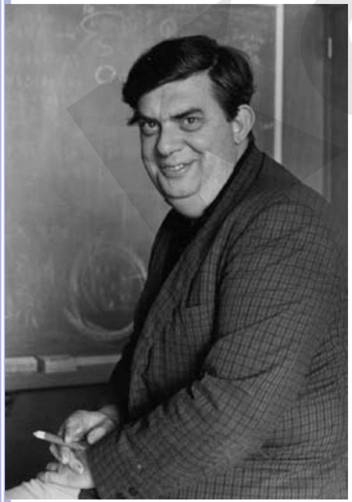
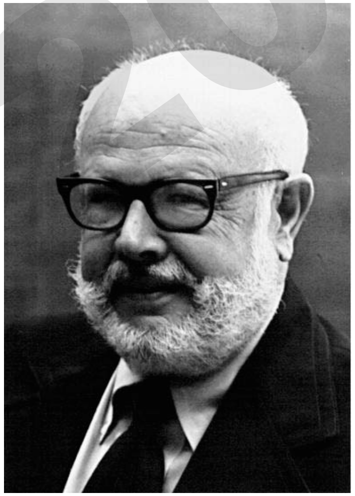


FIG. 1.
Log of relative abundance
Atomic weight

HOJLOV ODGOVOR: ZVEZDANA NUKLEOSINTEZA!

- B^2FH članak
- Jezgra nastaju u unutrašnjostima zvezda **termonuklearnom fuzijom**
- Ovaj proces se odvija u svim vrstama zvezda, različitim intenzitetom





REVIEWS OF MODERN PHYSICS

VOLUME 29, NUMBER 4 — OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

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* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

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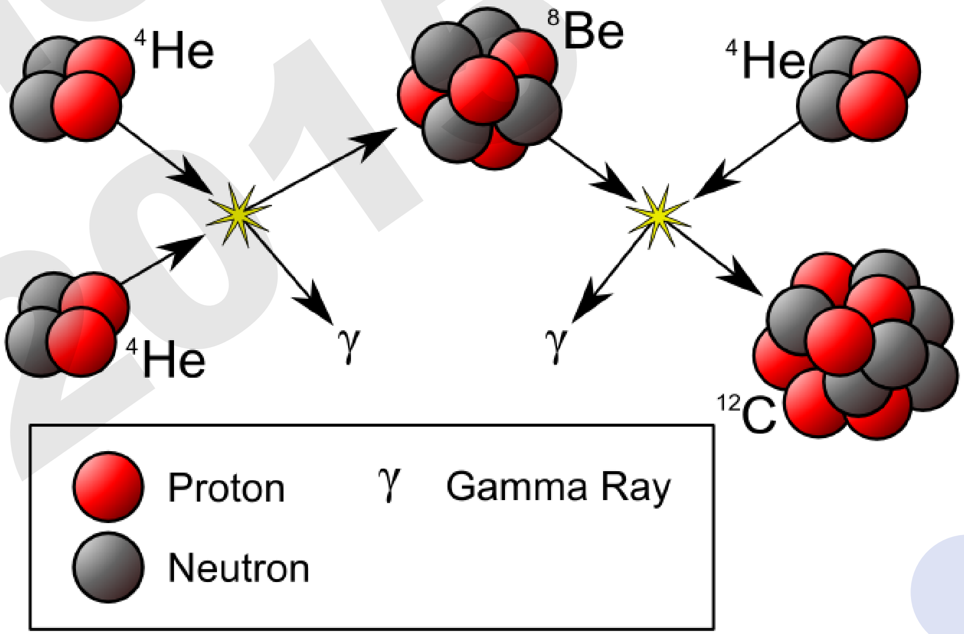
OSNOVA PERIODNOG SISTEMA: "TROSTRUKA ALFA"

- Hojl (1952): reakcija koja se **mora** odigrati

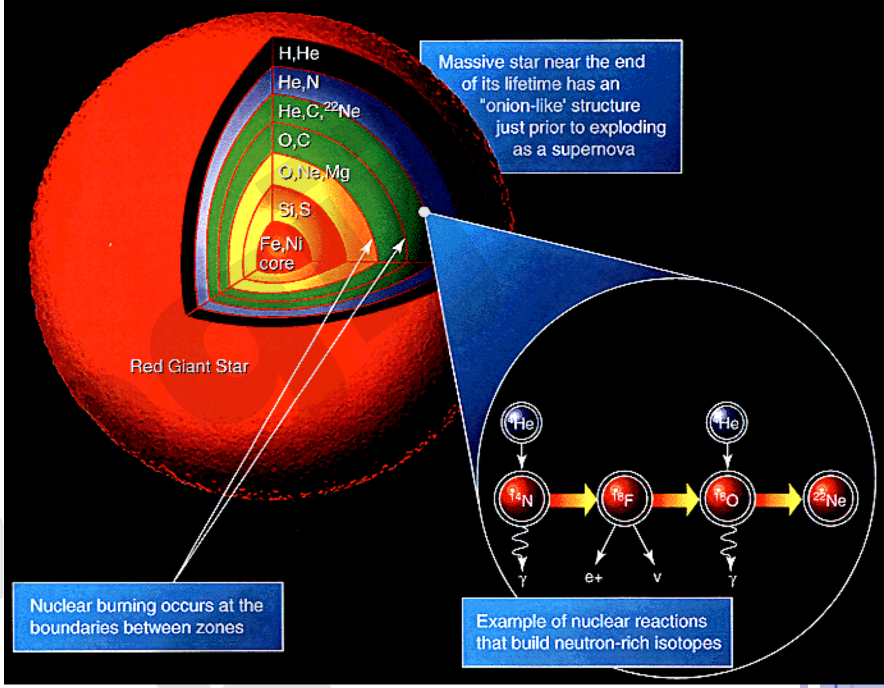
$$^{4}\mathrm{He} + {}^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} + 2\gamma$$

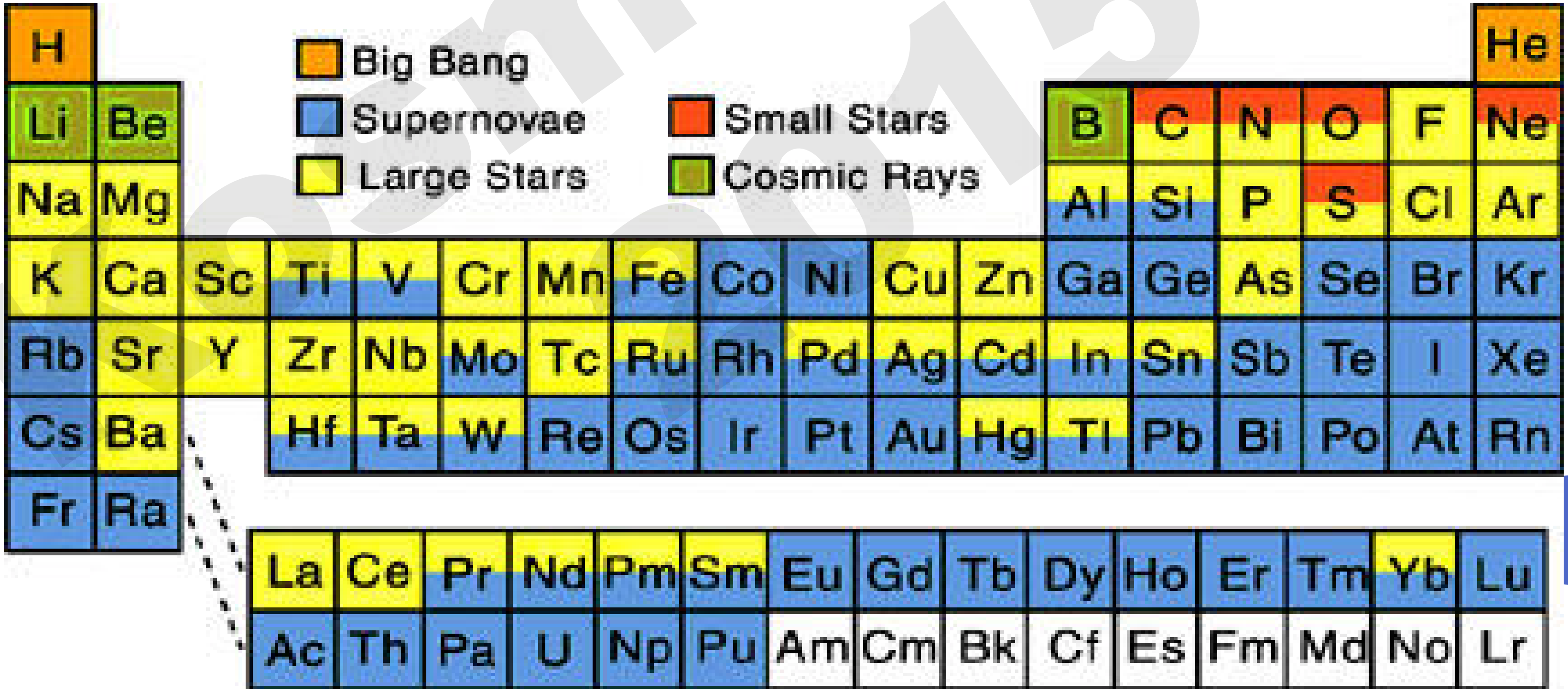
- Stopa reakcije $\propto T^{30}$ (!!!)

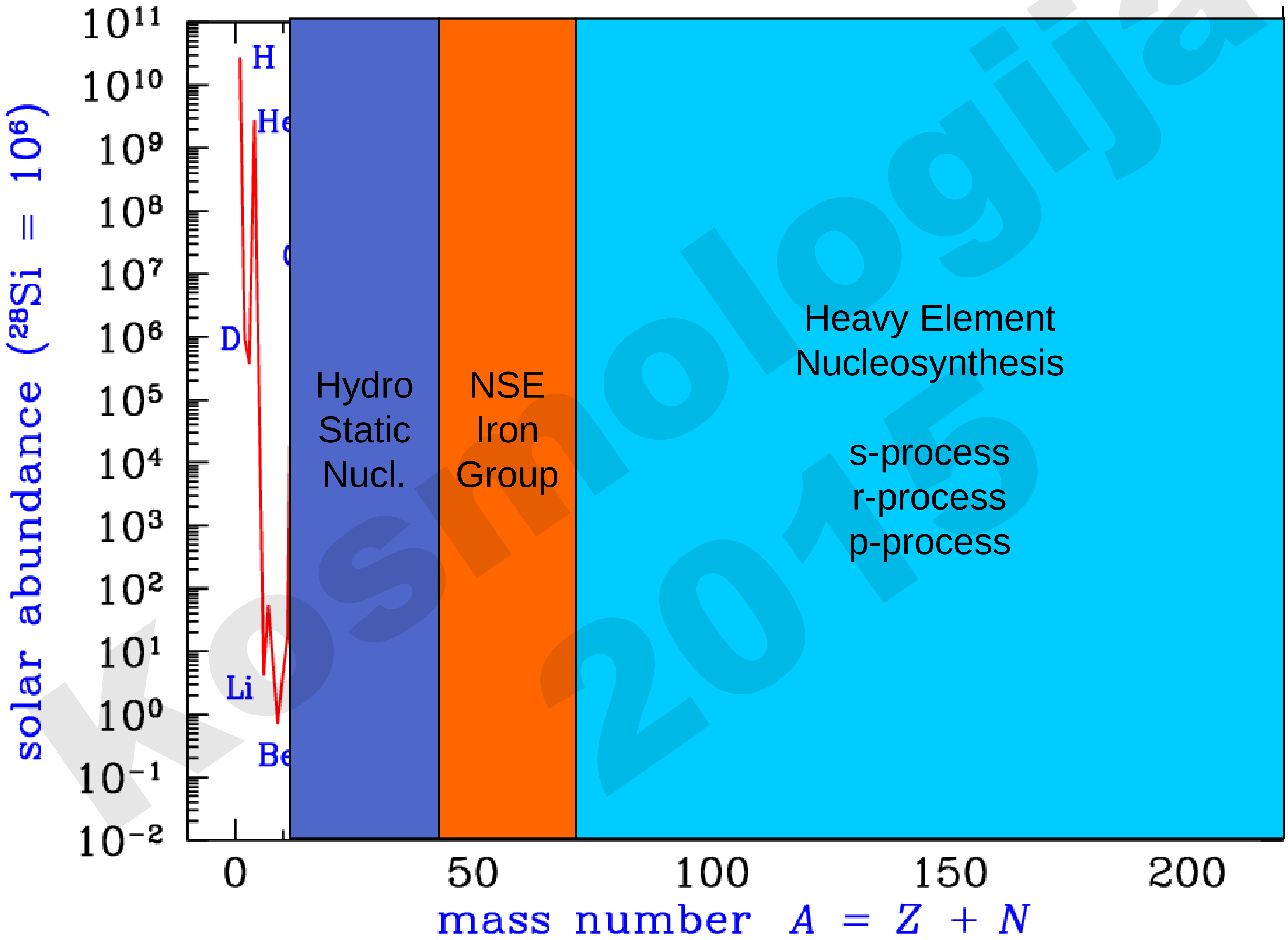


Raznoliko poreklo...

- ...različitih elemenata!

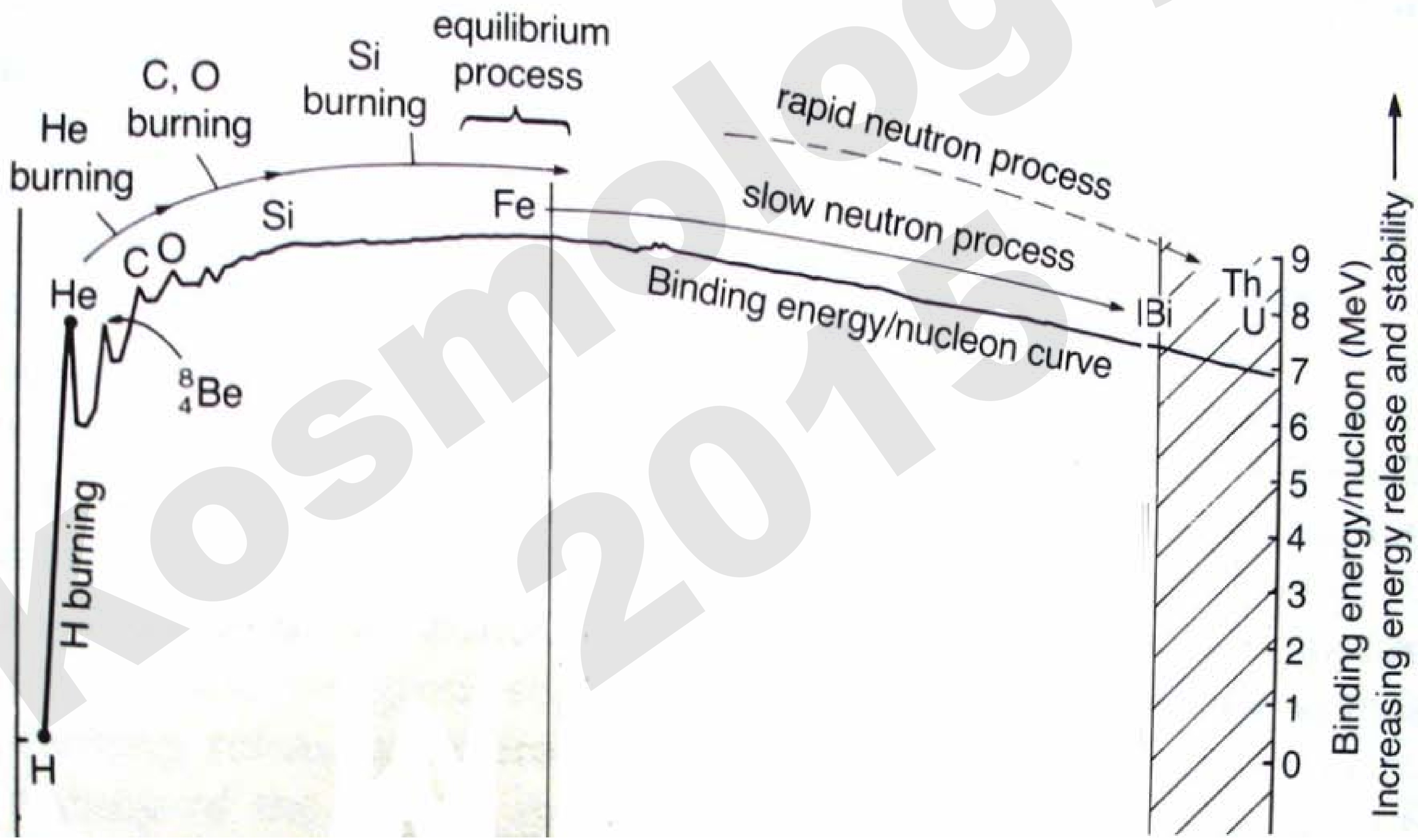






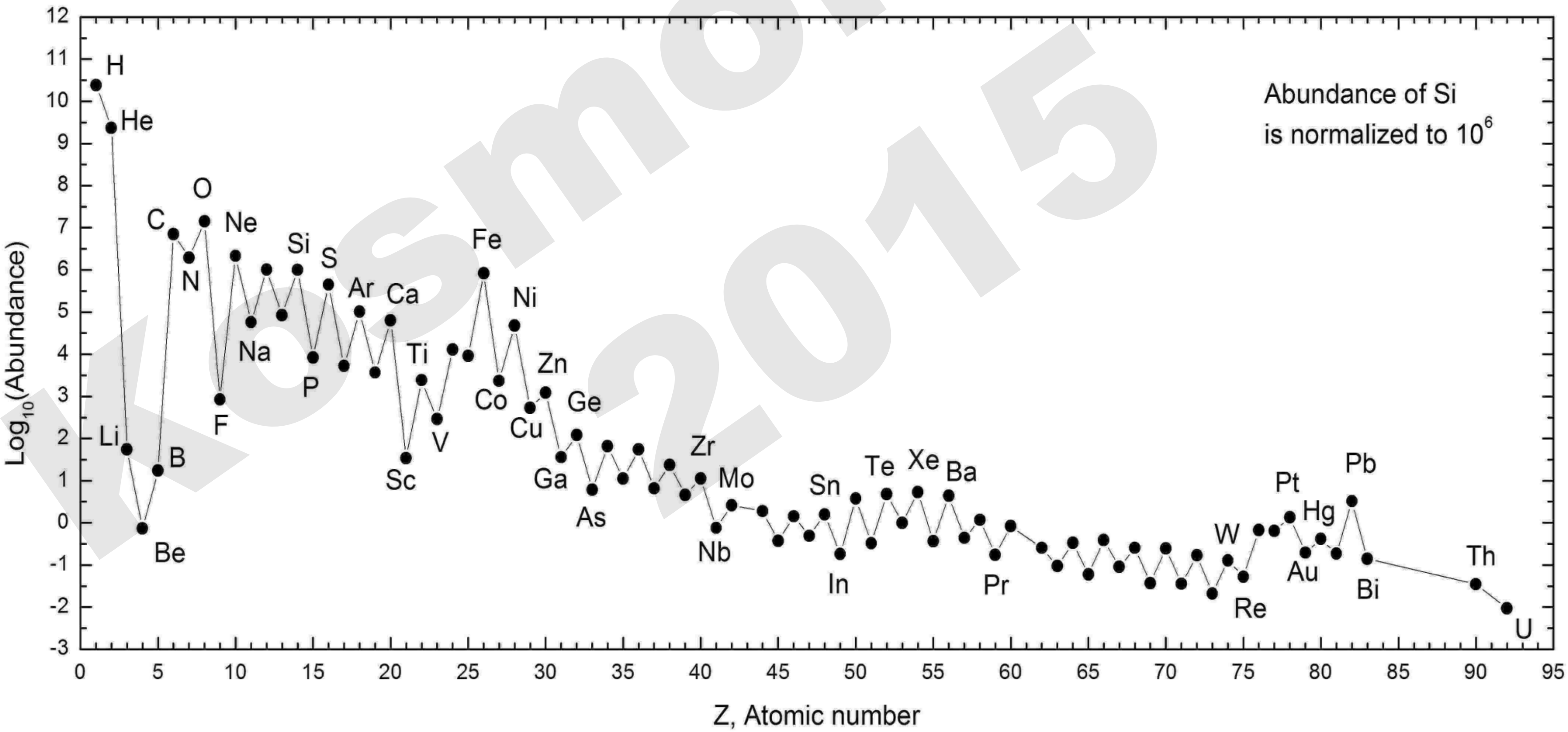
solar abundance (^{28}Si = 10^6)
mass number $A = Z + N$
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
50
100
150
200
H
He
D
Li
Be
Hydro Static Nucl.
NSE Iron Group
Heavy Element Nucleosynthesis
s-process
r-process
p-process

DETALJI STABILNOSTI



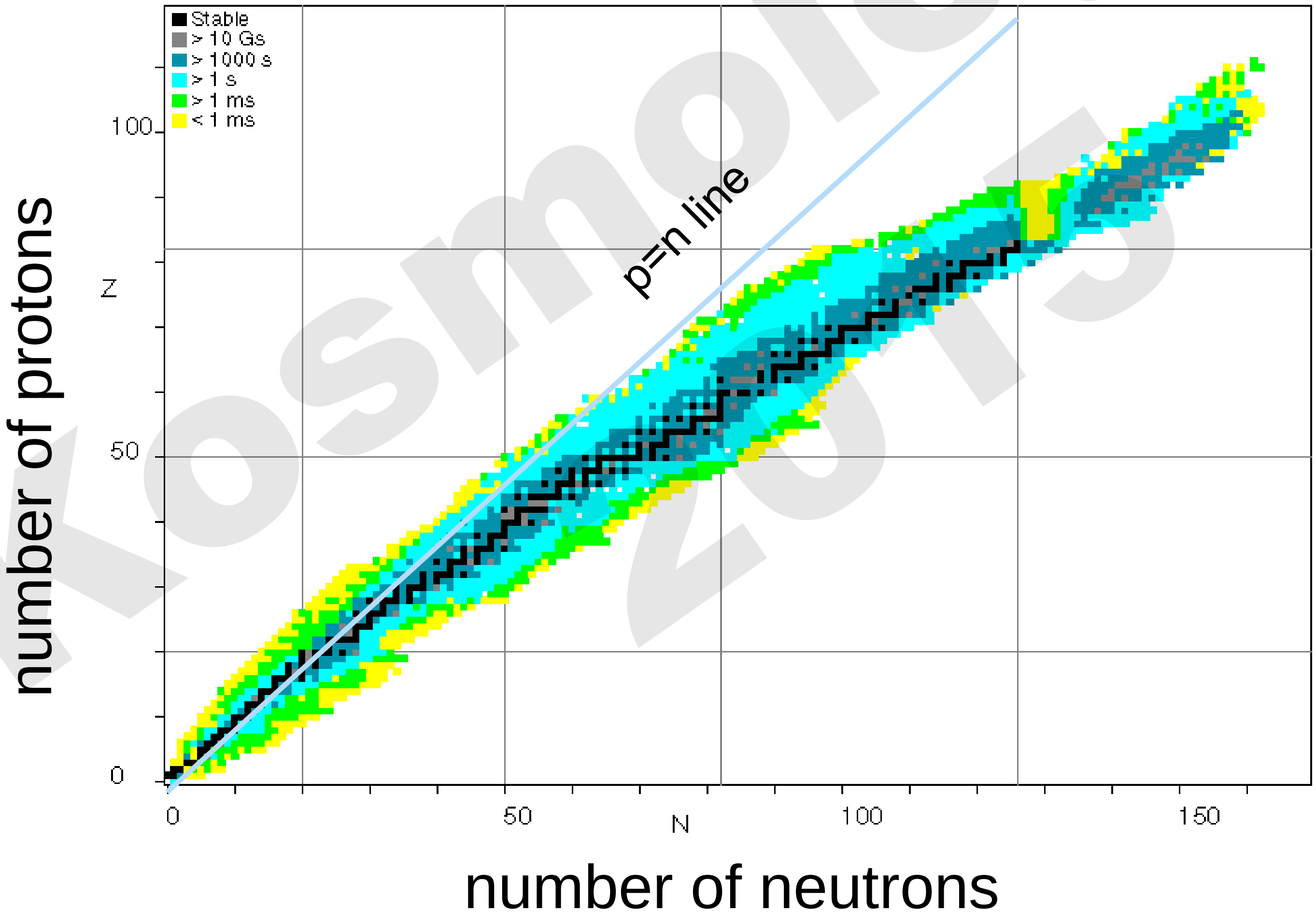
STANDARDNI SUNČEV HEMIJSKI SASTAV

1) Ignorišemo **tamnu stranu** (Λ, CDM) svemira!
2) Generalno opadanje sa atomskim brojem (H najčešći, U najređi)
3) Velike negativne anomalije za Be, B, Li – umerena pozitivna anomalija oko Fe („gvozdeni vrh“), testerasta raspodela od parno-neparnog efekta

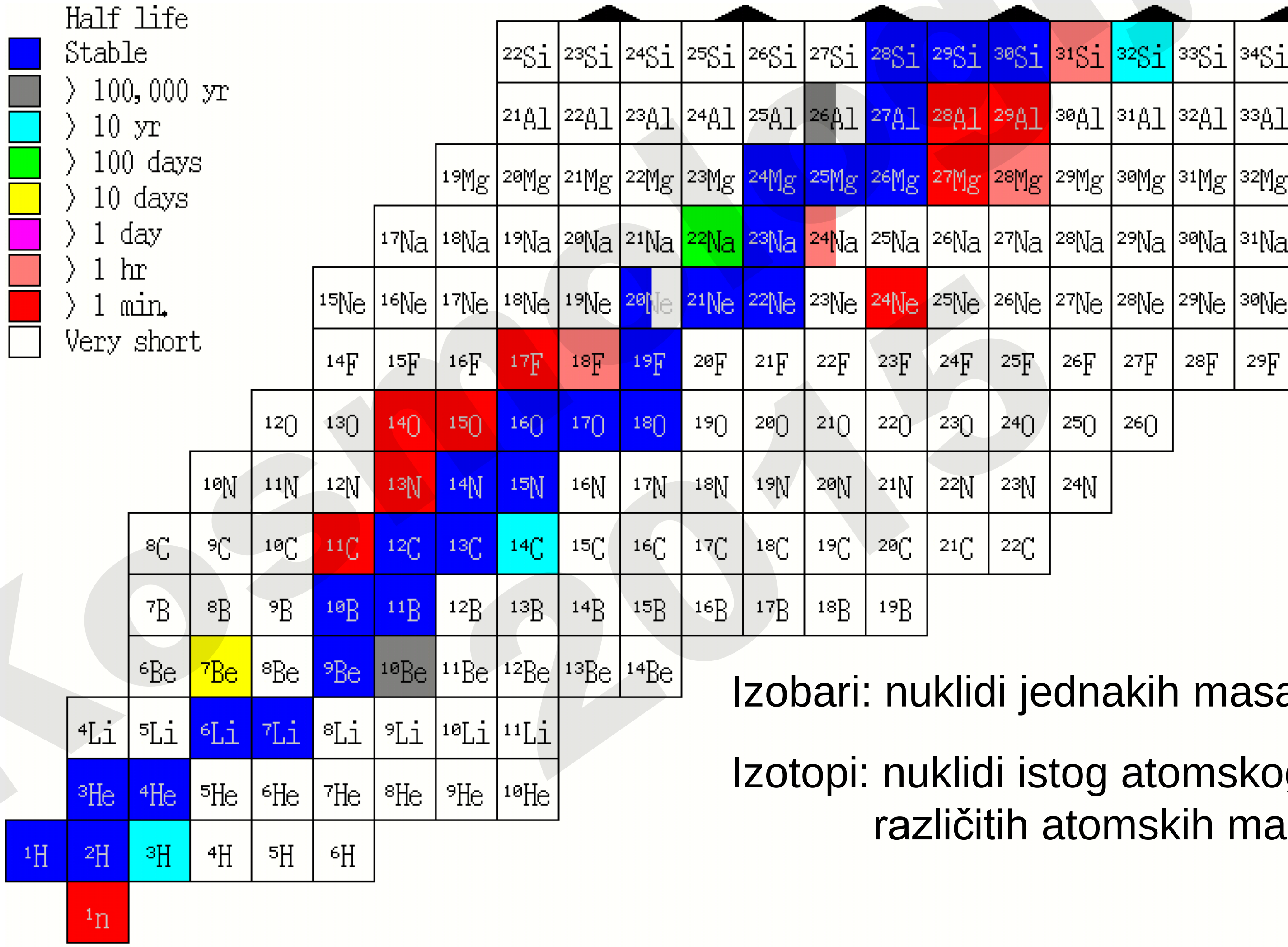


NUKLIDSKA MAPA

Prirodni nuklidi definišu putanju maksimalne stabilnosti: za male mase ($N = Z$), ali sa porastom A stabilni n/p odnos se povećava do $N/Z = 1.5$.



U DETALJIMA…



Broj protona

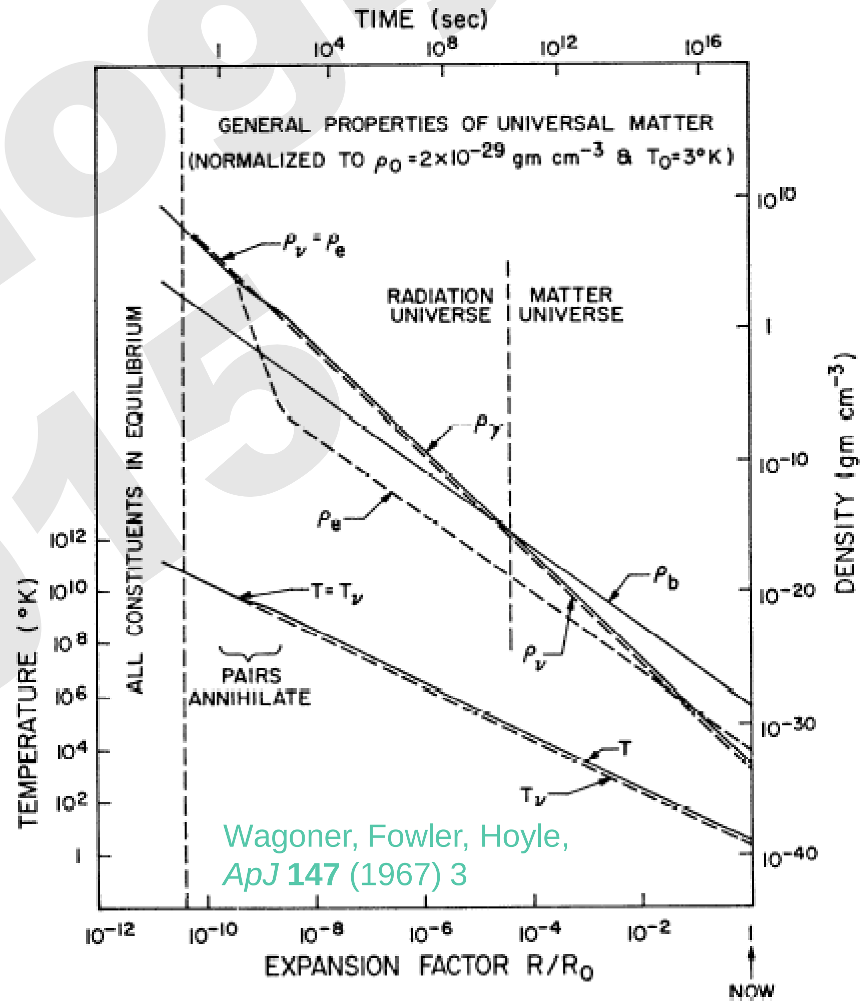
Broj neutrona

Izobari: nuklidi jednakih masa

Izotopi: nuklidi istog atomskog broja, različitih atomskih masa

PRIMORDIJALNA NUKLEOSINTEZA

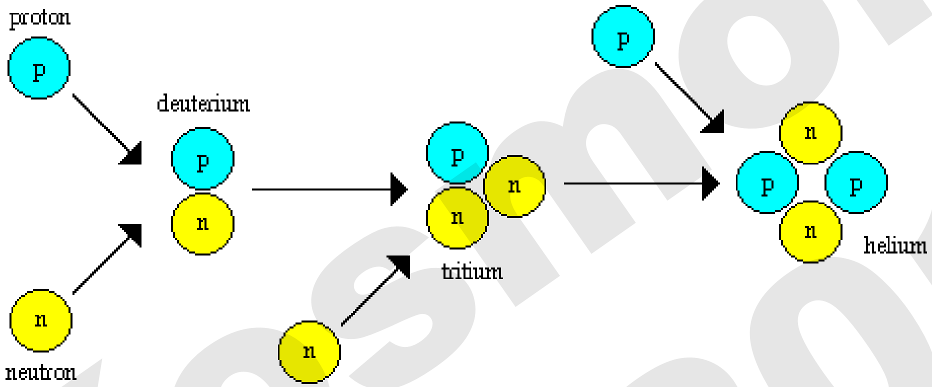
- Prvi detaljni proračuni Wagoner, Fowler and Hoyle
- Osnovni principi
  - Na veoma visokim T, neutroni i protoni su u ravnoteži: $p + e^- \leftrightarrow n + \nu$
  - Odnos neutron:proton dat je sa $\exp(-\Delta mc^2/kT)$ gde je Δm razlika u masi, a T temperatura na kojoj se neutrini „zamrzavaju" (*freeze- out*, $\sim 10^{10}$ K)
  - To je u praksi ~1:5



Wagoner, Fowler, Hoyle, *ApJ* **147** (1967) 3

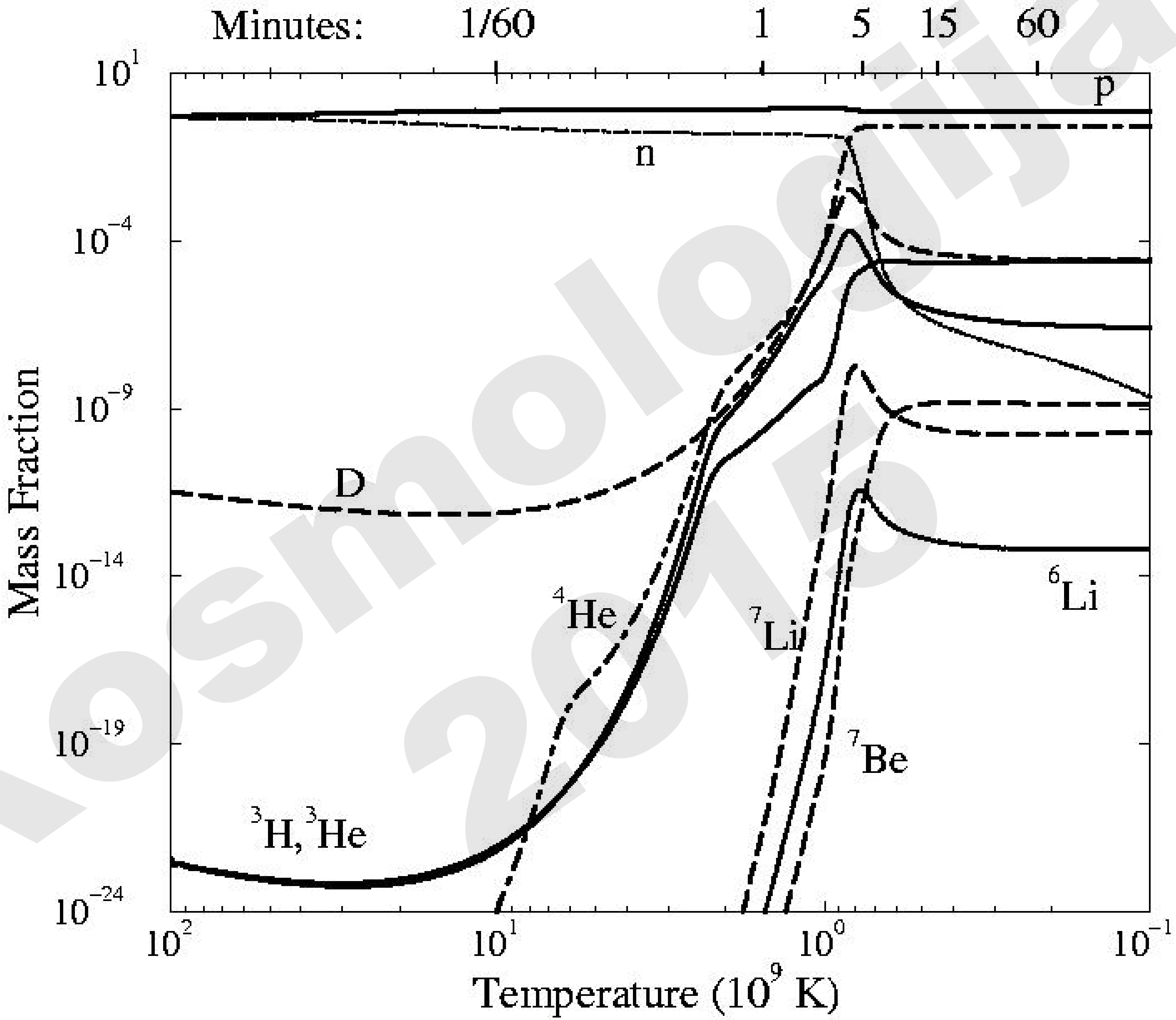
Deuterijumsko „usko grlo“

- Kada jednom nastanu veće količine deuterijuma, teža jezgra nastaju veoma brzo
- Post-deuterijumske reakcije se odvijaju kroz jake kanale, sa velikim presecima i visokim stopama reakcije
- Reakcije koje vode do helijuma su brze



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

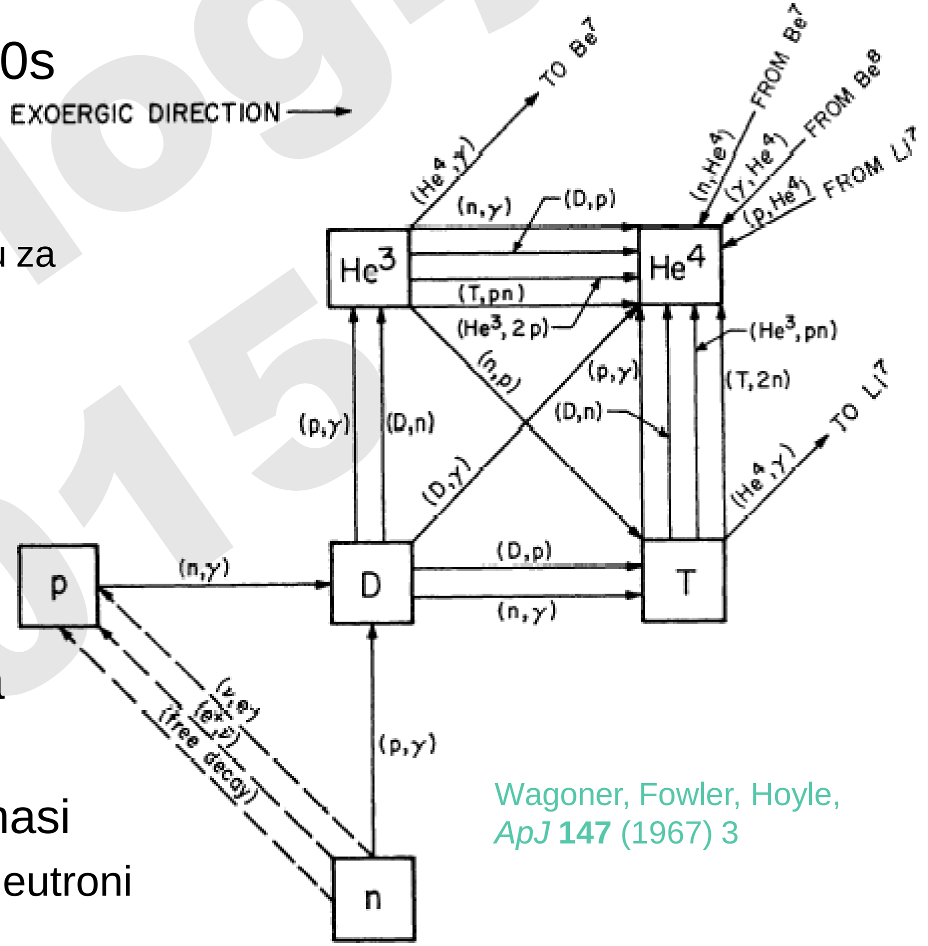
$${}^3H + p \to {}^4He + \gamma$$
$${}^3He + n \to {}^4He + \gamma$$
$${}^3H + D \to {}^4He + n$$
$${}^3He + D \to {}^4He + p$$



Minutes: 1/60 1 5 15 60
p
n
D
^{4}He
^{7}Li
^{7}Be
^{6}Li
^{3}H, ^{3}He
Mass Fraction
10^1
10^{-4}
10^{-9}
10^{-14}
10^{-19}
10^{-24}
10^2 10^1 10^0 10^{-1}
Temperature (10^9 K)
Kosmologija 2015

Deuterijum: ključ svega

- Kako se univerzum hladi, na t = 200s
  - $p + n \leftrightarrow d + \gamma$
    - Deuteroni se grade ispod $T \sim 10^9$ K
      - Pozadinski fotoni više nemaju energiju za povratnu reakciju
  - $d + p \rightarrow {}^3He + \gamma$
    $d + n \rightarrow {}^3H + \gamma$
    $d + d \rightarrow {}^3H + p$ or ${}^3He + n$
  - Brze reakcije tada vode do ${}^4He$
    (i pomalo ${}^7Li$)
- Ultimativno svaki neutron završava kao ${}^4He$!
  - ${}^4He$ frakcija ~1:8 po broju, 1:2 po masi
    - Zapravo malo manje pošto se neki neutroni raspadaju!



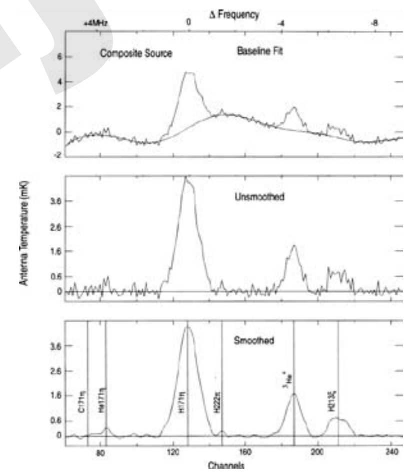
Wagoner, Fowler, Hoyle, *ApJ* **147** (1967) 3

Šta dobijamo?

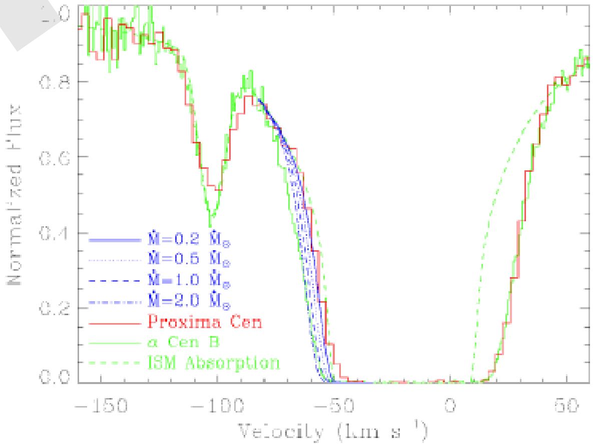
- Konačne količine ^2H, ^3He, ^4He i ^7Li zavise od
  - neutronskog vremena života (mereno u laboratoriji)
    - 885.7±0.8 s (PDG, 2004)
  - broja vrsta neutrina (isto kao i CMB)
    - pošto u because eri dominacije zračenja $H^2 \propto \rho_{rel} = \rho_\gamma + N_\nu \rho_\nu$
    - 2.984±0.008 (kombinovani LEP eksperimenti)
  - *H* (mereno astronomski: HST, WMAP)
    - 72±8 km/s/Mpc (HST), 70.1±1.3 km/s/Mpc (WMAP)
  - Gustine bariona (tj. koncentracije protona+neutrona)

POSMATRANJA LAKIH ELEMENATA

- Helijum 4
  - spektri zvezda Pop. II
  - veliki faktor korekcije za zvezdanu nukleosintezu
- Helijum 3
  - Meren u radio domenu (spinska linija $^3He^+$ at 3.46 cm)
- Deuterijum
  - linije se mogu razdvojiti od ^1H
  - „astracija“ ga potpuno uništava
  - trenutno najbolje izmereni izotop
- Litijum 7
  - meren u spektrima hladnih zvezda
  - proizvode ga i kosmički zraci („spalacija“), a uništavaju zvezde
  - rezultati nisu baš saglasni („litijumska anomalija“)



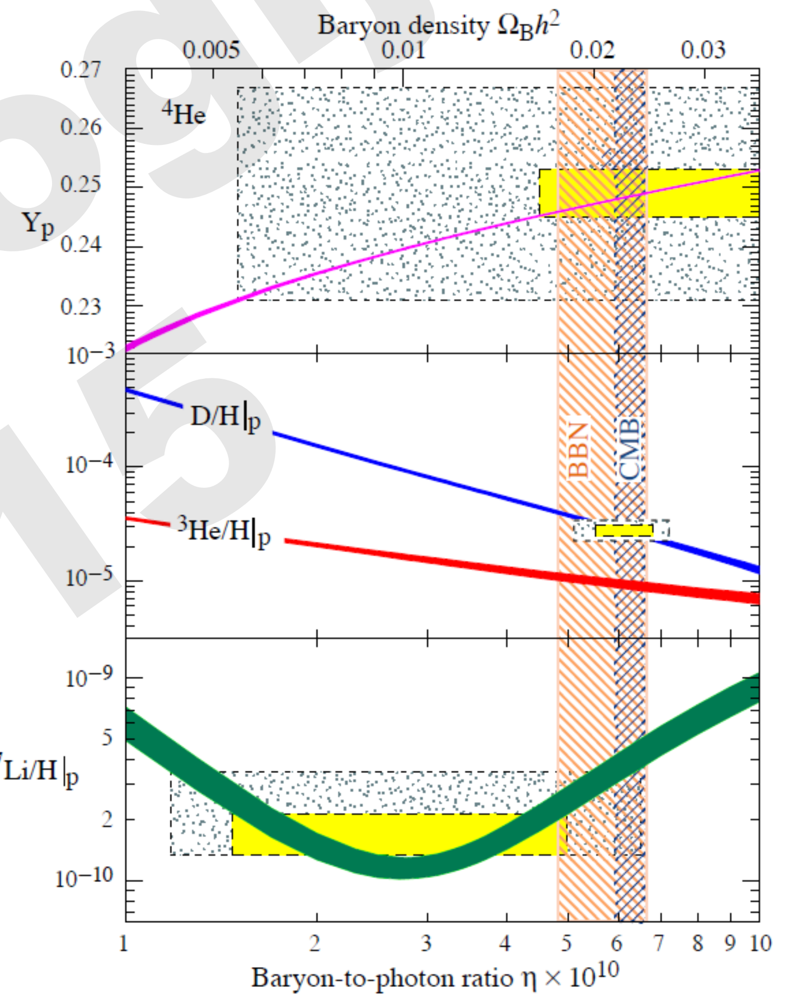
Bania et al., *ApJSS* **113** (1997) 353

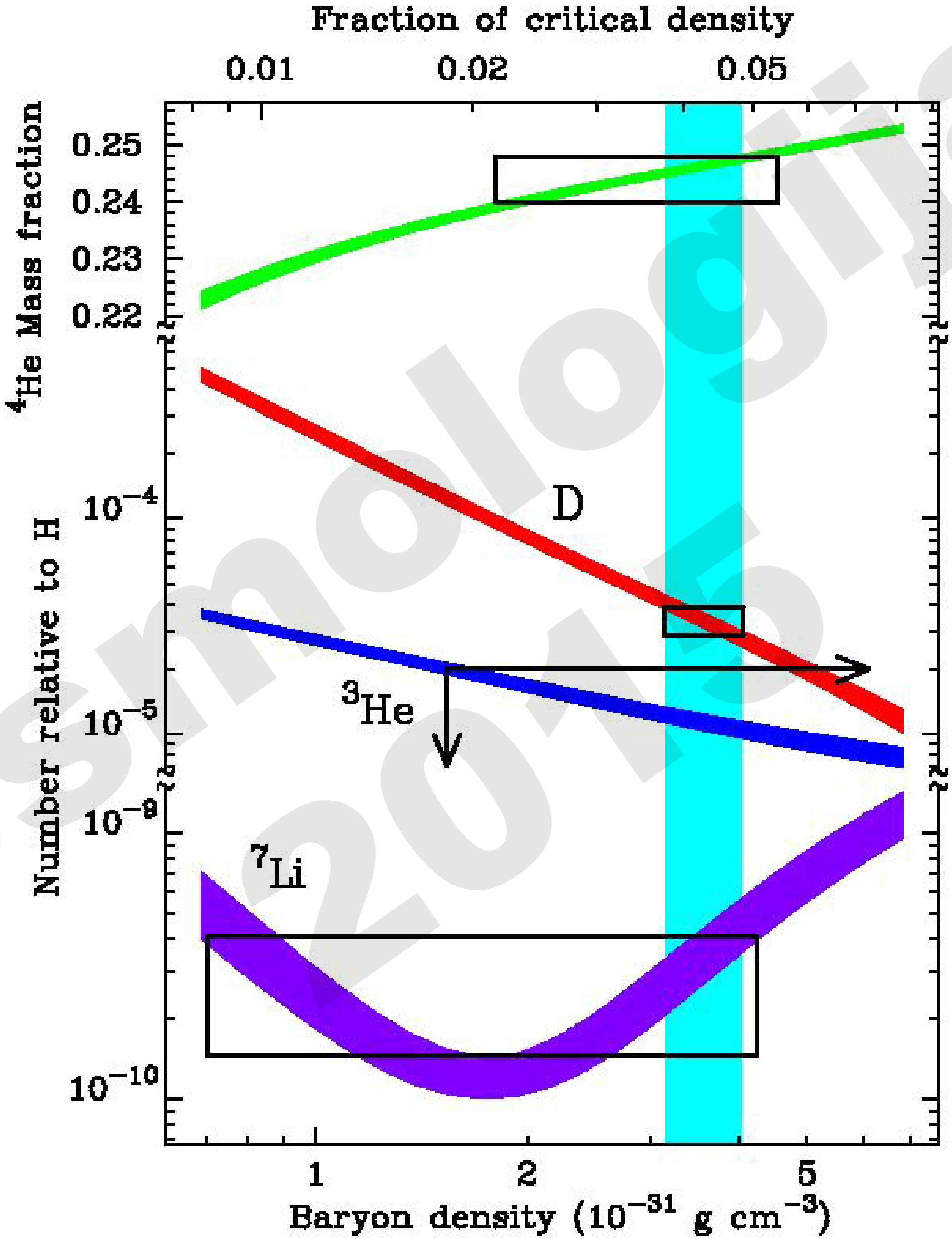


Linsky, Sp. Sci. Rev. **106** (2003) 49

VISOKOPRECIZNA KOSMOLOGIJA

- Trenutni rezultati
  Fields and Sarkar, PDG 2008
  - D/H = (2.84±0.26) × 10^{-5}
  - ^{7}Li/H = (1.23±0.06) × 10^{-10}
    - Ali moglo bi biti i za faktor 2 više
  - Y = 0.249±0.009
  - ^{3}He je izmeren samo u Mlečnom pu – sistematske greške suviše velike da bi bio koristan
- ^{7}Li je donekle nesaglasan
  - Ali možda je uništen u ranom svem u zvezdama Pop III
  - D/H je saglasan sa WMAP Ω_b
  - $0.018 \leq \Omega_b\, h^2 \leq 0.022$




Fraction of critical density
0.01
0.02
0.05
^{4}He Mass fraction
0.25
0.24
0.23
0.22
D
10^{-4}
Number relative to H
^{3}He
10^{-5}
10^{-9}
^{7}Li
10^{-10}
1
2
5
Baryon density (10^{-31} g cm^{-3})

Neutrinske generacije i BBN