Evolution of Galaxies:
Nucleosynthesis

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Nuclear Reactions

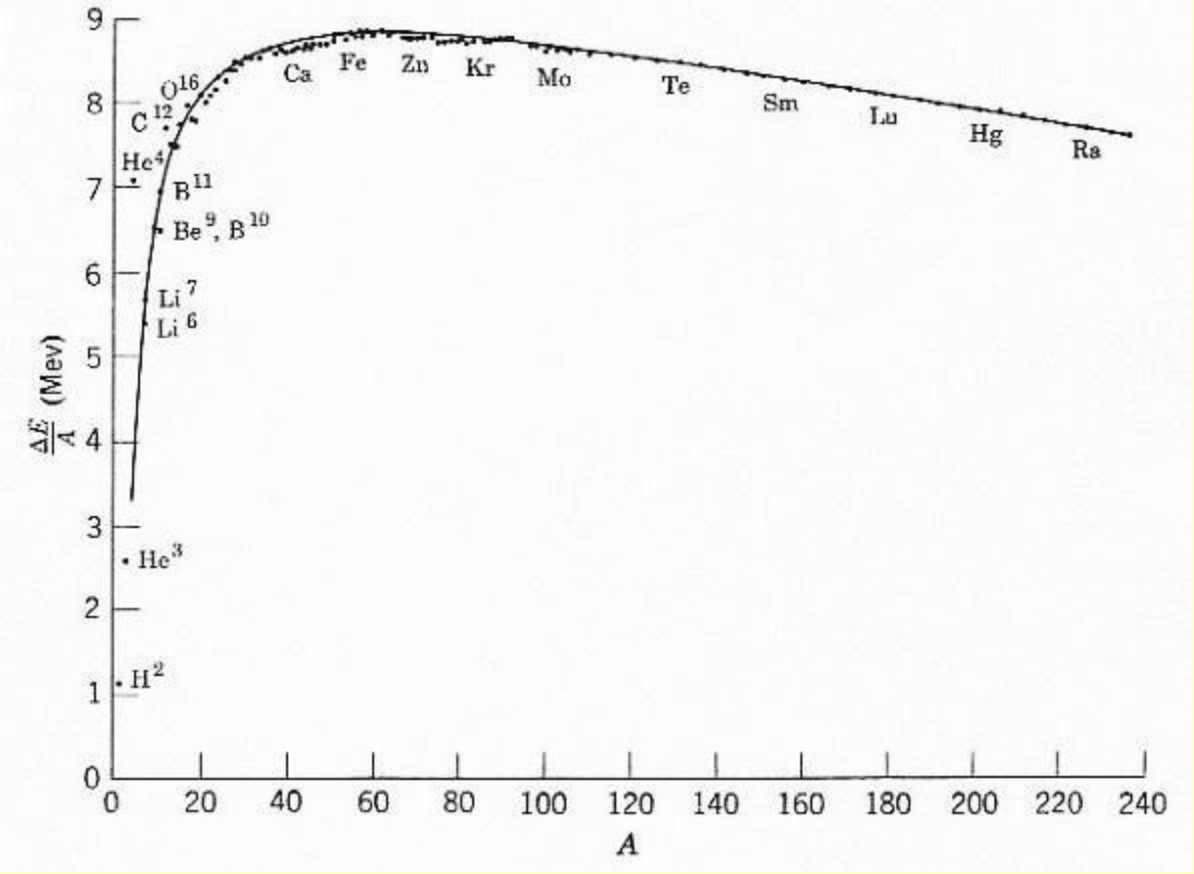
- Notation: A(b,c)D: $A + b \rightarrow c + D + Q$
- Thermal equilibrium: Big Bang
- Exothermic reactions: Q >0
  - Fusion: stellar energy source + element synthesis … works up to ^{56}Fe
  - Example: H –burning

$$4\,m_H = 4.03000 \text{ amu}$$

$$m_{He} = 4.00130$$

$$0.0280 \xrightarrow{mc^2} 26.7 \text{ MeV}$$

Binding Energy per Nucleon



Nuclear Reactions

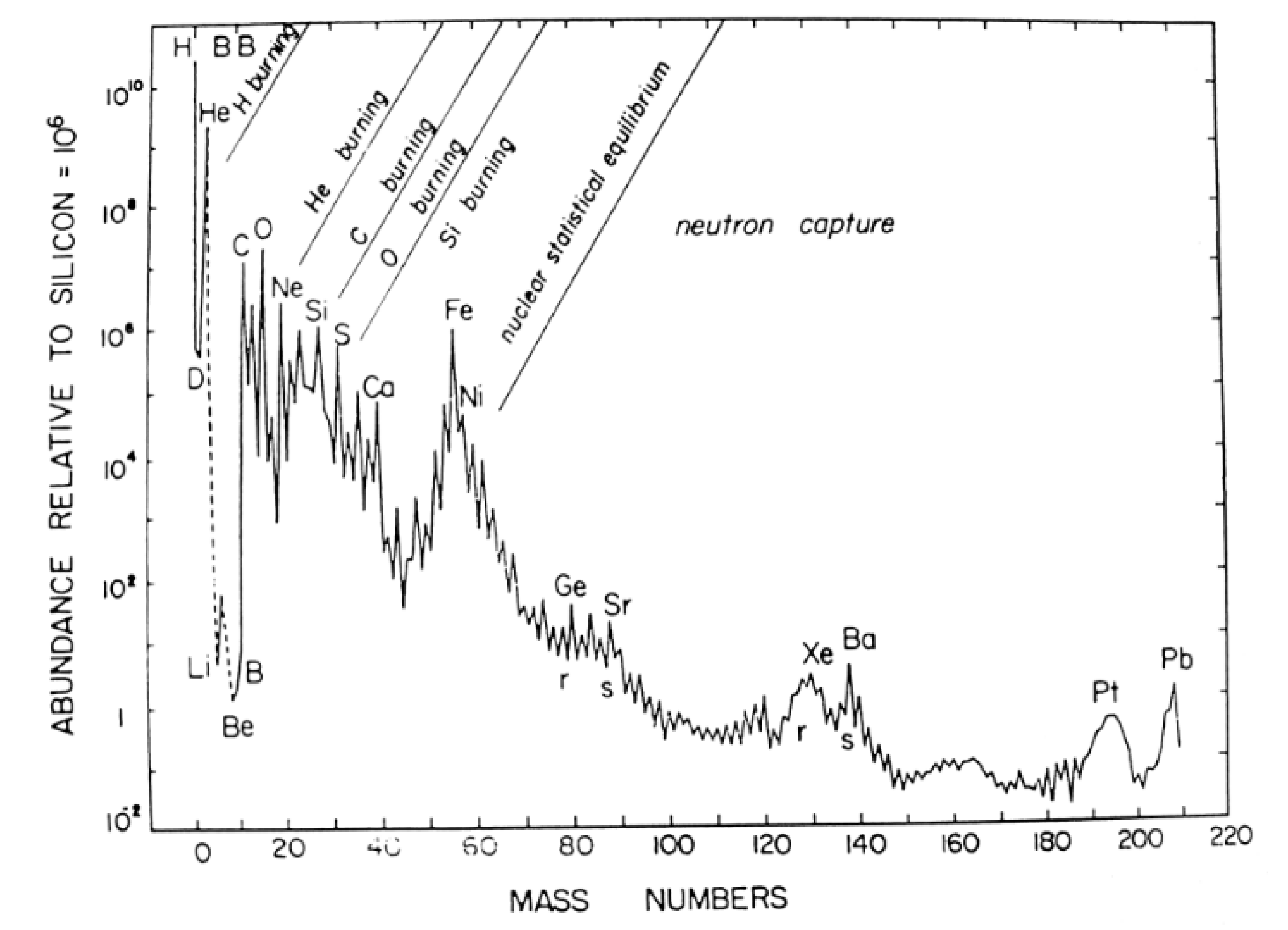
- Endothermic: $Q < 0$
  - Neutron capture
    - rapid
    - slow

    } process: make anything beyond ^{56}Fe; when? where?
  - Spallation: collision of cosmic rays (>150 MeV/particle) with ISM

    $p,\alpha + C,N,O \rightarrow {}^{6}Li, {}^{7}Li, {}^{8}Be, {}^{9}B$ - 30 MeV

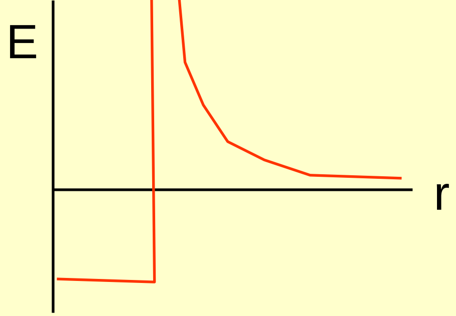
All these make the Cosmic abundance pattern

Cosmic abundance pattern



Burbidge^2 Fowler Hoyle

fusion in stars produces the abundance pattern (1958)



Fusion

<u>Problem</u>: p and nuclei positively charged: repelling energy

$$V = Z_1 Z_2 e^2/r^2 = 1.44 \text{ MeV } Z_1 Z_2/r^2 \text{ [fm]}$$

much larger than thermal energy

$$kT = 8.6\ 10^{-8} \text{ keV} * T \quad [K]$$

<u>Solution</u>: Tunnel effect = finite probability to penetrate potential wall (Gamov 1940)

$$\propto \exp(-2\pi Z_1 Z_2/\hbar v_{rel})$$

Fusion

Reaction rate: A(b,c)D in $cm^{-3}s^{-1}$

$n_A\, n_b \, < \sigma_{AbcD}\, v_{rel} > = n_A\, n_b\, \lambda_{AbcD}$

Average over Maxwell distribution (thermal plasma with temperature T):

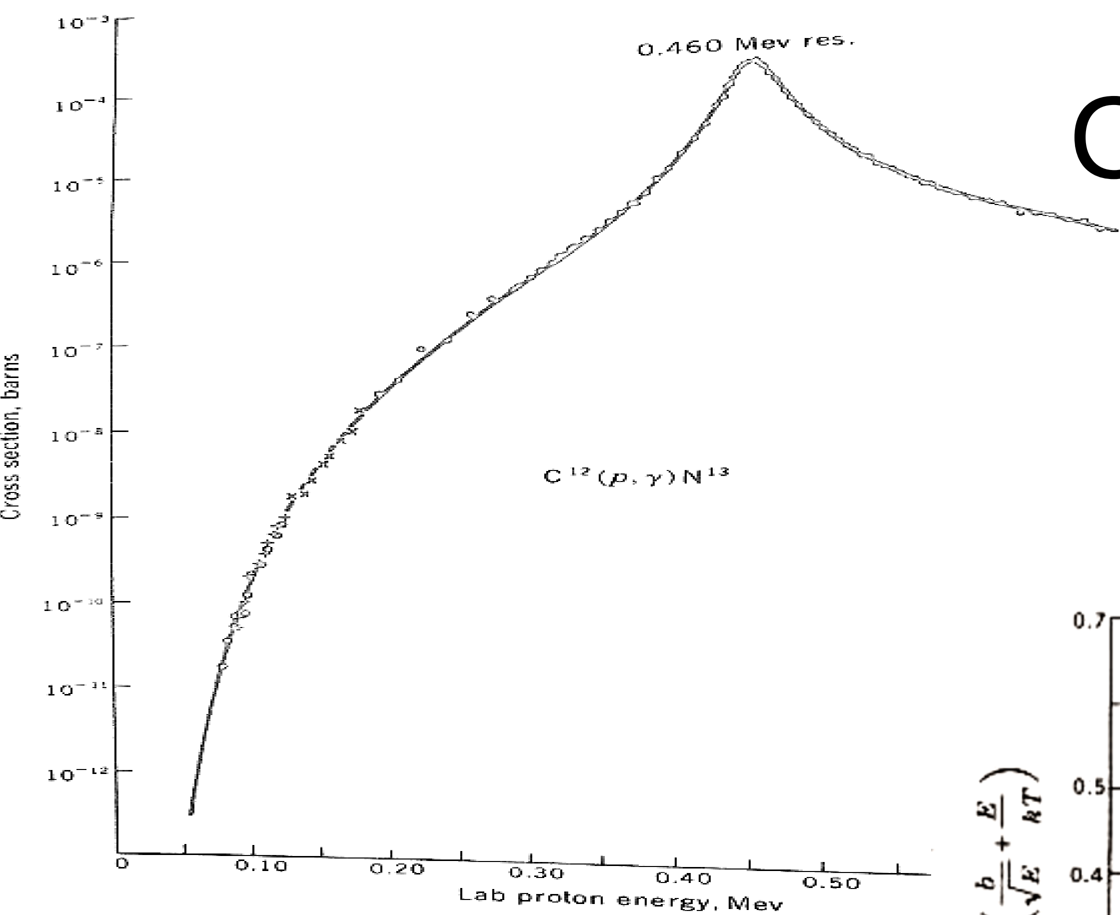
$$\lambda = \frac{2}{\sqrt{\pi}} \int_0^\infty \sigma(E) \frac{E}{kT} \exp\left(-\frac{E}{kT}\right) dE/\sqrt{kTE}$$

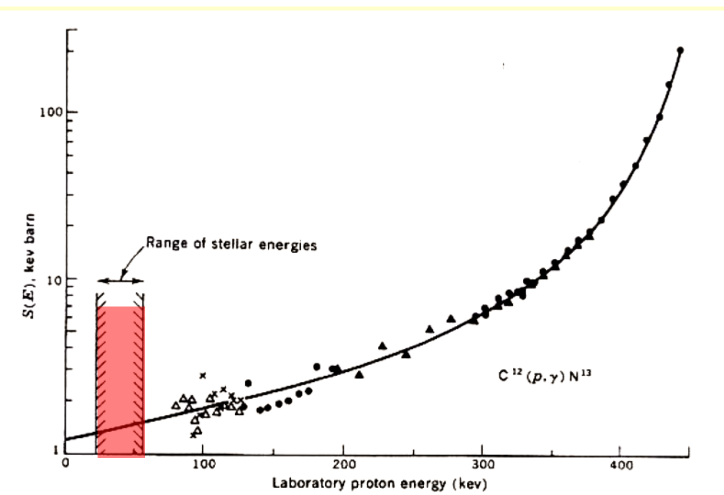
For nonresonant reactions

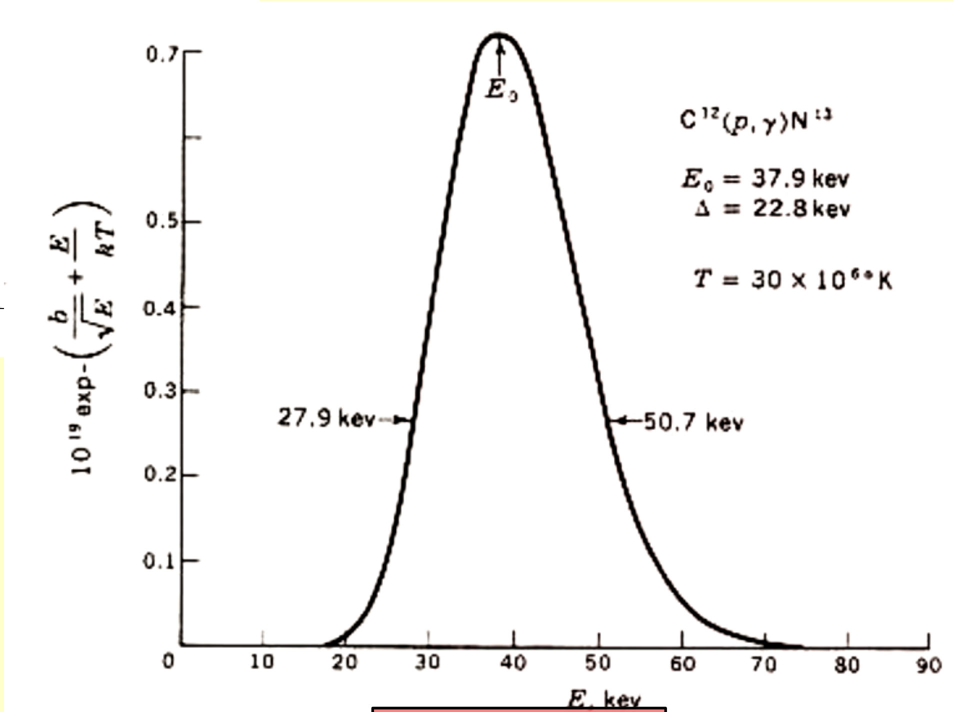
$$\sigma(E) = \frac{S(E)}{E} \exp\left(-\frac{Z_1 Z_2 e^2}{\hbar v_{rel}}\right)$$

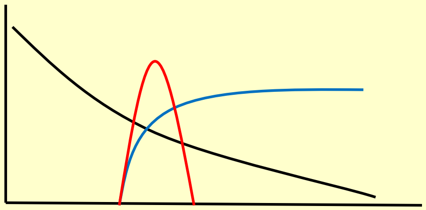
quantum mech. geometry factor ($\pi\lambda^2 \sim 1/E$; $\lambda_{Broglie} = h/p$)

Cross section









Evaluate integral .....

Maxwell | Tunnel

$$\lambda = \int_0^\infty \ldots \exp\left(-\frac{E}{kT}\right) \exp\left(-\frac{b}{\sqrt{E}}\right) dE$$

$$\approx \int_0^\infty \ldots e^{-\tau} \exp\left(-\frac{(E-E_0)^2}{\Delta^2/2}\right) dE$$

Gauss-function! mean $E_0 = (bkT/2)^{3/2}$

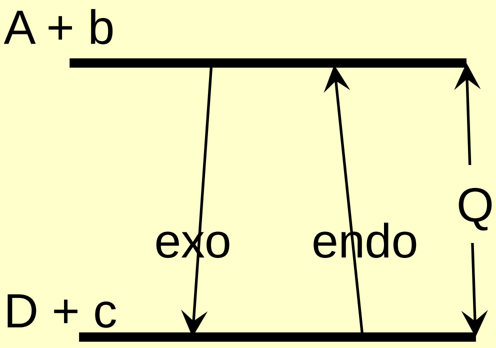
width $\Delta = 4\sqrt{E_0 kT/3}$

$\tau = 2\, E_0/kT \propto T^{-1/3}$

$$\Rightarrow \lambda = \exp\left(-\frac{3E_0}{kT}\right) \int_0^\infty S(E) \exp\left(-\frac{(E-E_0)^2}{\Delta^2/2}\right) dE$$

S(0) and dS/dE are sufficient

Inverse reactions: always exist



- thermal equilibrium

$$\frac{n_A}{n_D} \propto \exp\left(-\frac{Q}{kT}\right)$$

- stars (kT << Q): reactions go mainly exothermic (‘downward’)

- kT ~ Q: Big bang, SN explosion: inverse reactions take place!!

$$\sigma_{AbcD} / \sigma_{DcbA} = \text{const}$$

H-burning: pp-chains

$p + p \rightarrow {}^2D + e^+ + \nu + 0.42$ MeV

$e^+ + e^- \rightarrow 2\gamma \qquad = + 1.022$ MeV

overall energy release 1.442 MeV

$S(0) = 3.78\ 10^{-22}$ keV barn

$dS/dE = 4.2\ 10^{-24}$ barn

$\lambda = 3.09\ 10^{-37}\ t^{-2/3} \exp(-33.81/t^{-1/3})\ (1 + 0.0123\ t^{1/3} + 0.0109\ t^{2/3} + 0.00095\ t)$ with $t = T/10^6$ K

Energy prod.rate = $n^2 * \lambda * 1.442$ MeV

H-burning: pp-chains

$$\xrightarrow[\text{Q [Mev]}]{\lambda^{-1}\text{ (sun, yrs)}}$$

PPI

$$p + p \xrightarrow[1.44]{7.9\ 10^{9}} {}^{2}D + e^{+} + \nu \longrightarrow \ldots$$

$$p + {}^{2}D \xrightarrow[5.5]{0.4} {}^{3}He + \gamma$$

$$2\ {}^{3}He \xrightarrow[12.9]{2.4\ 10^{5}} {}^{4}He + 2p$$

PPII

$${}^{4}He + {}^{3}He \xrightarrow[1.6]{10^{6}} {}^{7}Be + \gamma$$

$${}^{7}Be + e^{-} \xrightarrow[0.86]{0.4} {}^{7}Li + \nu$$

$${}^{7}Li + p \xrightarrow[17]{10^{-5}} 2\ {}^{4}He$$

PPIII

$$p + {}^{7}Be \xrightarrow[0.13]{60} {}^{8}B + \gamma$$

$${}^{8}B \longrightarrow {}^{8}Be + e^{+} + \nu$$

$${}^{8}Be \xrightarrow[18.1]{3\ 10^{-8}} 2\ {}^{4}He$$

NB: D, Li, Be, B are destroyed (consumption faster than creation)

Rate equations

$$\frac{dn_p}{dt} = -\lambda_{pp} n_p^2 - \lambda_{pD} n_p n_D + 2\lambda_{He3}\, n_{He3} - \lambda_{pLi}\, n_p n_{Li} - \lambda_{pBe}\, n_p n_{Be}$$

$$\frac{dn_D}{dt} = \ ...$$

for long times (t >> max(1/λ)) system tends towards equilibrium. Setting dn/dt = 0 results in a system of non-linear equations …

Solar neutrinos

- Former problem of solar neutrinos: fewer are measured than are produced

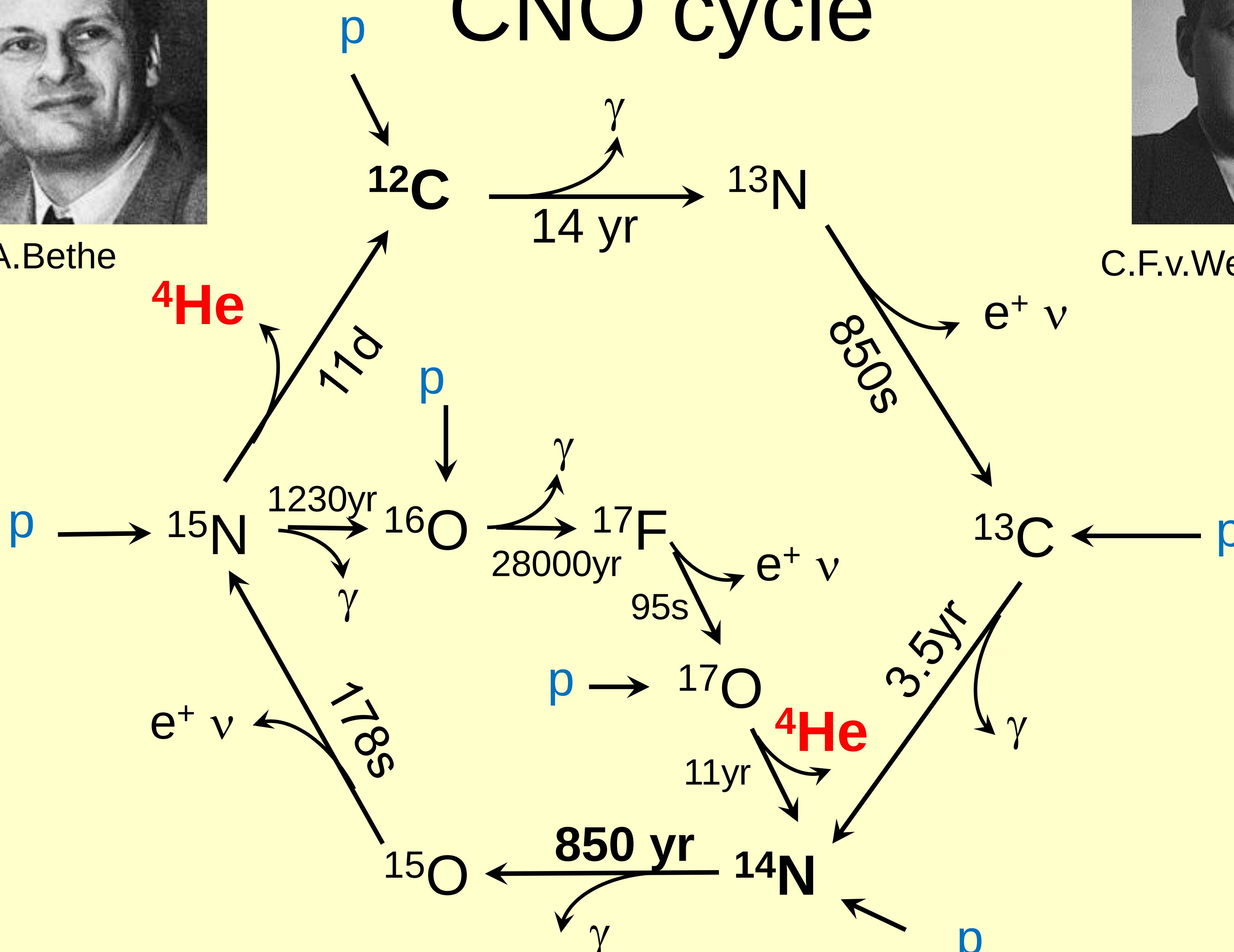
detector	**Homestack mine** **$^{37}Cl + \nu \rightarrow {}^{37}Ar + e$**	**Kamiokande**	**Gallex, SAGE**
source	Be, B	B	pp, Be, B
expected (SNU)	7.2 ± 1	5.1 ± 1	127 ± 5
observed	2.2 ± 0.3	2.7 ± 0.3	87 ± 16 ± 8

- Solution: Kamiokande proved that neutrinos change flavour (‘oscillation’); indicates non-zero rest mass

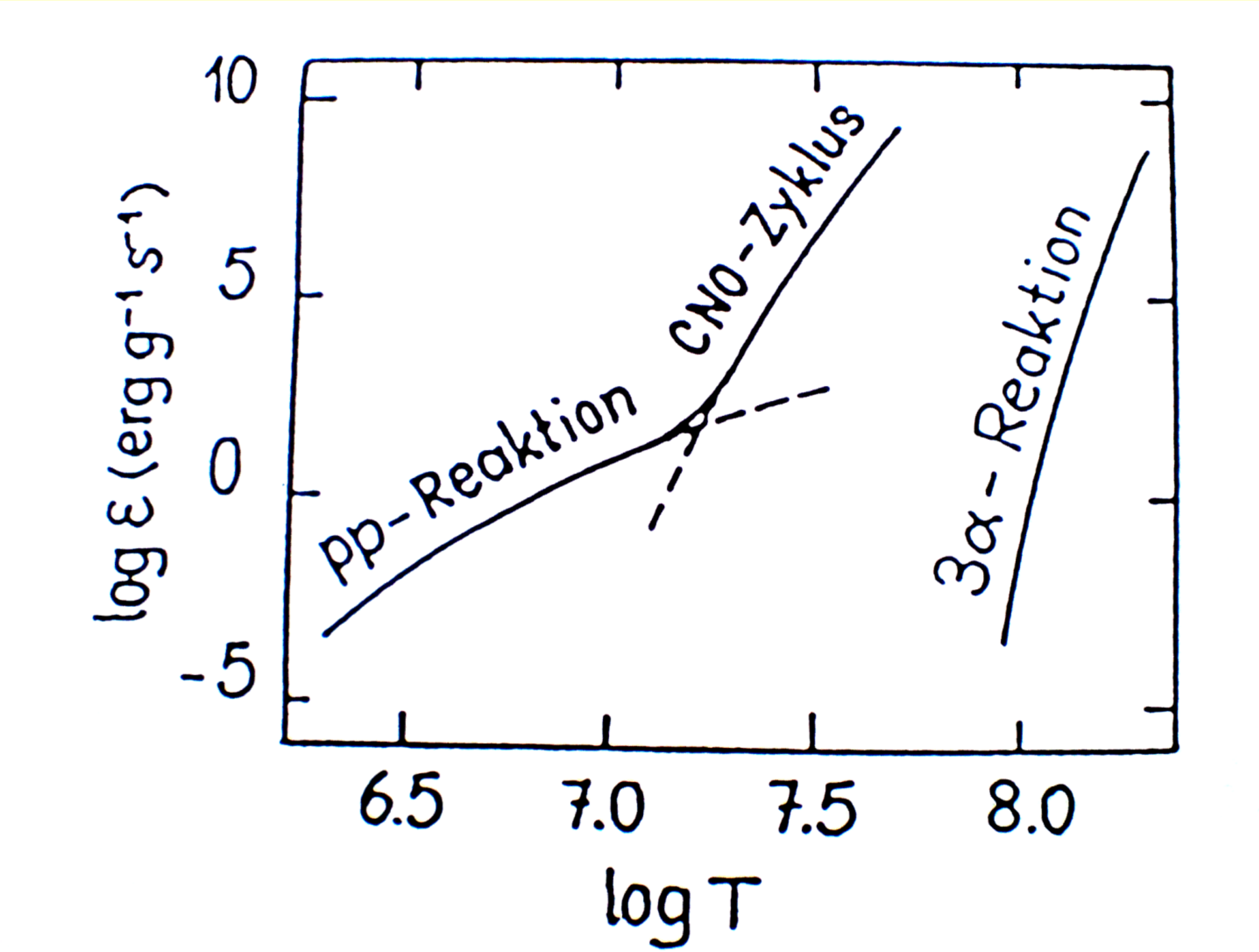
CNO cycle

H.A.Bethe

C.F.v.Weizsäcker



T-sensitivity of H-burning



He-burning: Triple α process

$2\,{}^{4}He \rightarrow {}^{8}Be$

$${}^{8}Be + {}^{4}He \rightarrow {}^{12}C^{*} \rightarrow {}^{12}C + \gamma$$

$Q = +\,7.87$ MeV

$\lambda \propto \exp(-43 / t^{1/3})$ $\quad$ $t = T/10^{8}$ K

He-burning: α processes

$^{12}C + {}^{4}He \rightarrow {}^{16}O + \gamma \quad + 7.16$ MeV

Explosive synthesis at >10^9 K:

$^{16}O + {}^{4}He \rightarrow {}^{20}Ne + \gamma \quad + 4.73$ MeV

………… $\rightarrow {}^{24}Mg + \gamma \quad + 9.31$ MeV

………… $\rightarrow {}^{28}Si$

………… $\rightarrow {}^{32}S$ …… $\rightarrow {}^{40}Ar$

………… $\rightarrow {}^{44}Ca$ …… $\rightarrow {}^{48}Ti$

………… $\rightarrow {}^{52}Cr$ …… $\rightarrow {}^{56}Fe$

Higher stages

$^{12}C + {}^{12}C \rightarrow {}^{24}Mg + \gamma \quad + 13.9$ MeV

$\rightarrow {}^{20}Ne + \alpha \quad + 4.6$ MeV

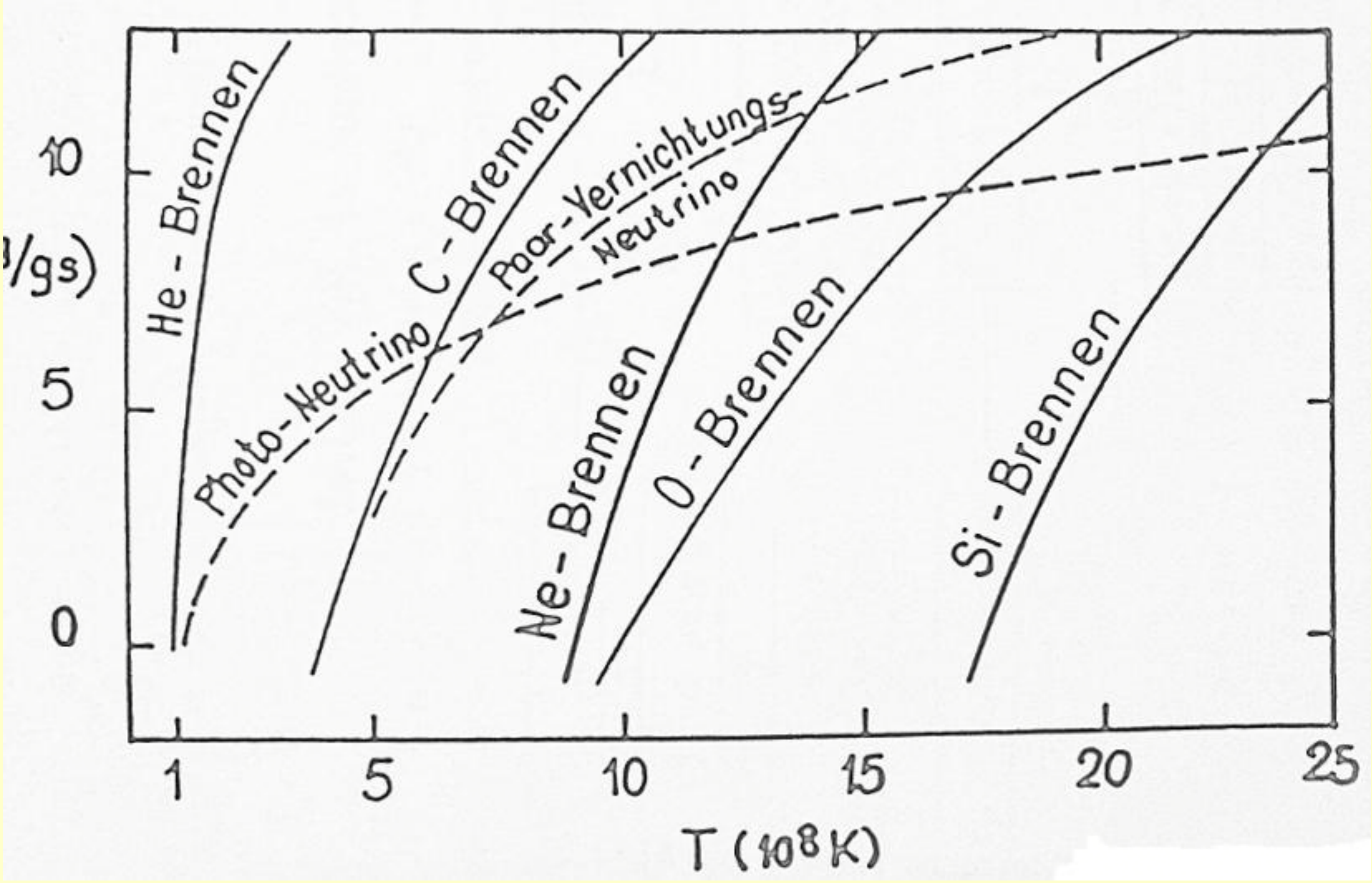
$\rightarrow {}^{16}Ne + 2\alpha \quad - 0.11$ MeV

$^{16}O + {}^{16}O \rightarrow$

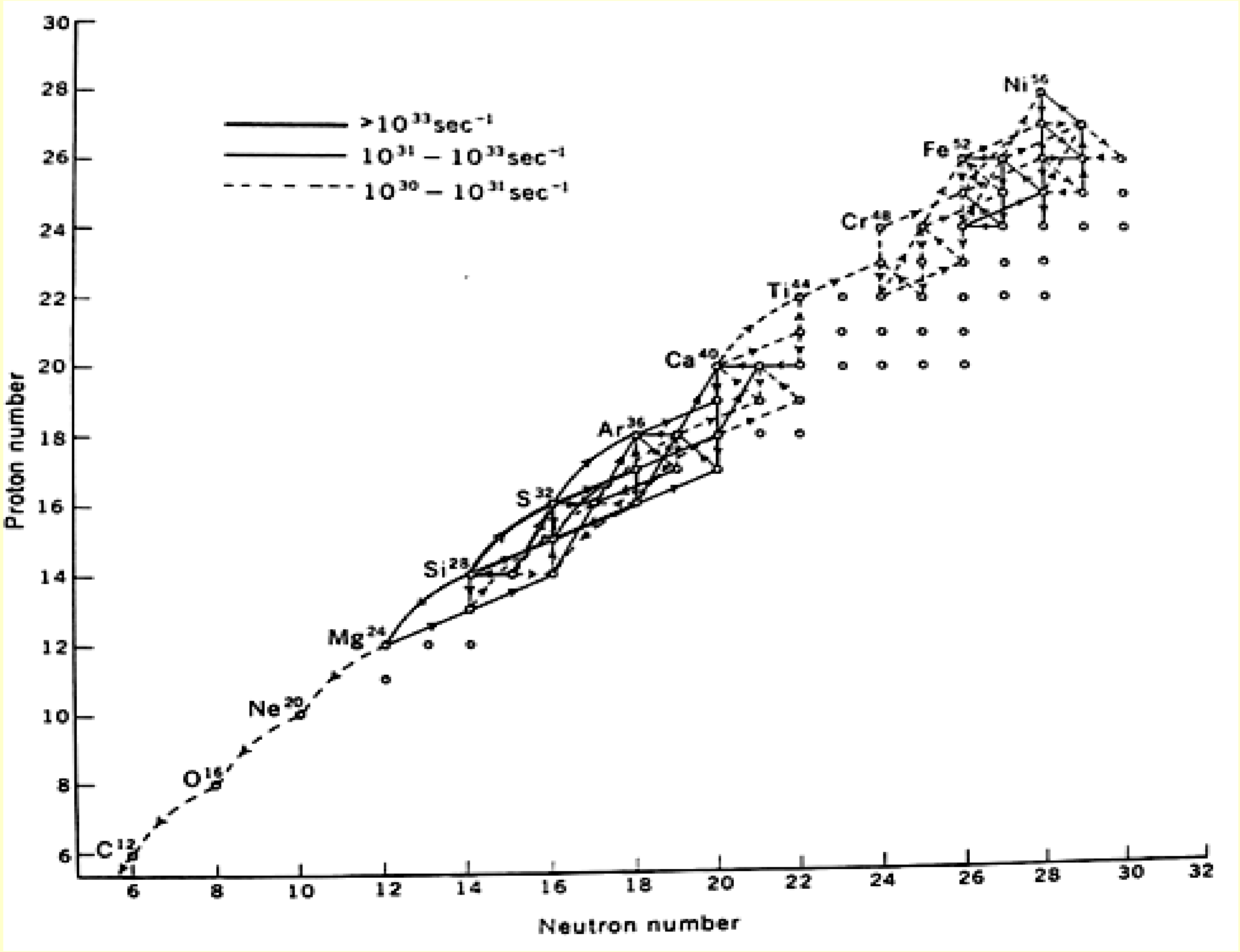
$^{28}Si + {}^{28}Si \rightarrow$

at increasingly higher temperatures …

Higher stages



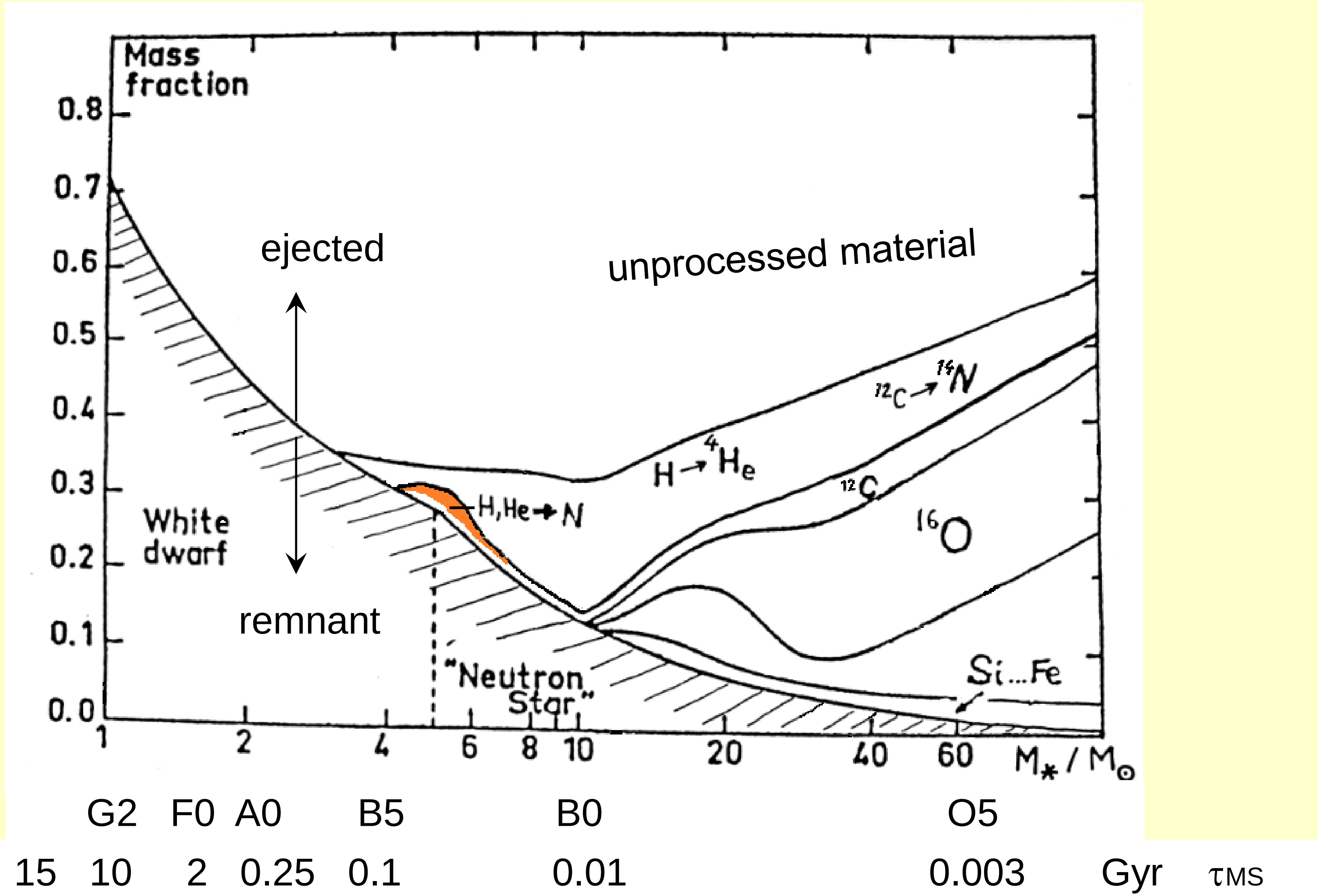
Reaction network Si-burning



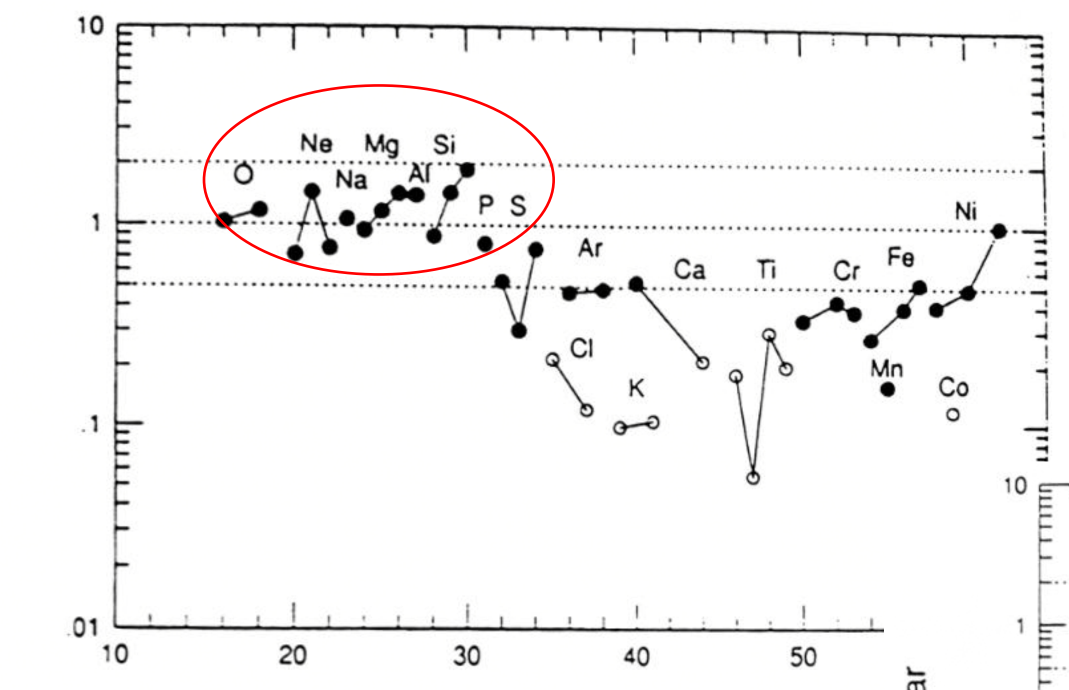
Nuclear burnings from H to Fe

burn	main reactions	main products	temperature	energy release
H	H → He	He4	1…4 E7	60 E17 erg/g
He	3He→C,C(α,γ)O	C12, O16	1…3 E8	6…9
C	2C→Ne+α, Na+p	O16, Ne20, Mg24	6…7 E8	~4
Ne	Ne(γ,α)O, Ne(a,g)Mg	O16, Mg24	1.1 E9	~2
O	2O→Si+α, P+p	Mg24, Si28, S32	1.3 E9	~4
S	S(γ,α)Si, Mg (α,γ)Si	Mg24, Si28	1.6 E9	
Mg	Mg(γ,α)Ne ….	Si28	1.8 E9	~3
Si	Si(γ,α)Mg ….	Fe56	2.0 E9	

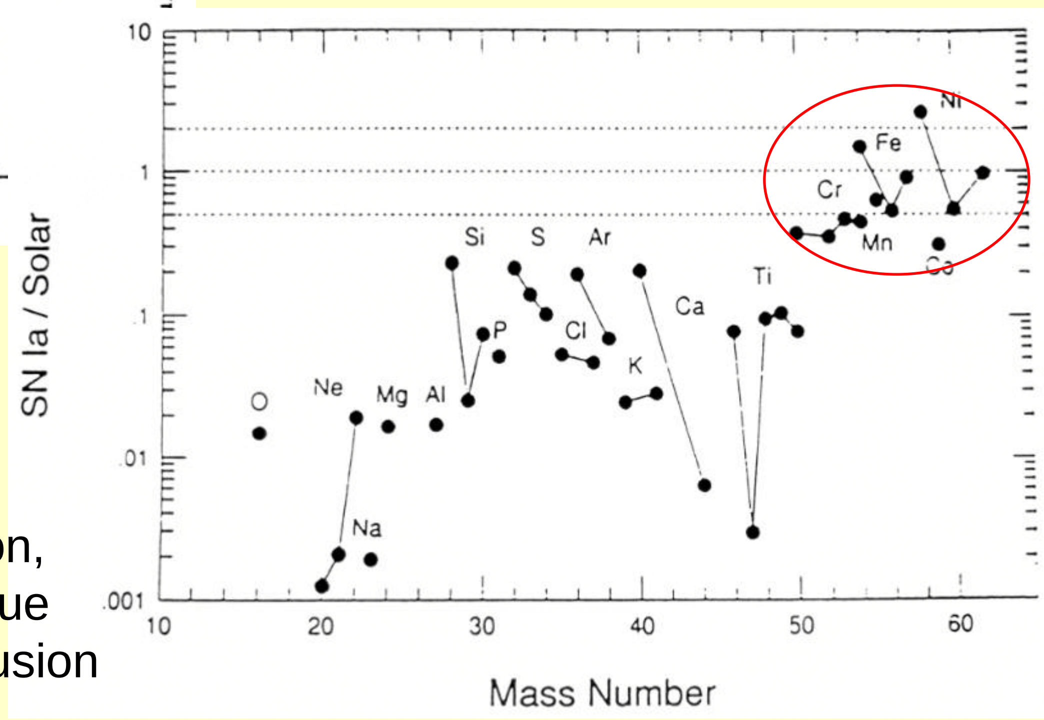
What we shall only need …



SNII and SNIa



SNII = core-collapse SN
= end of normal massive stars



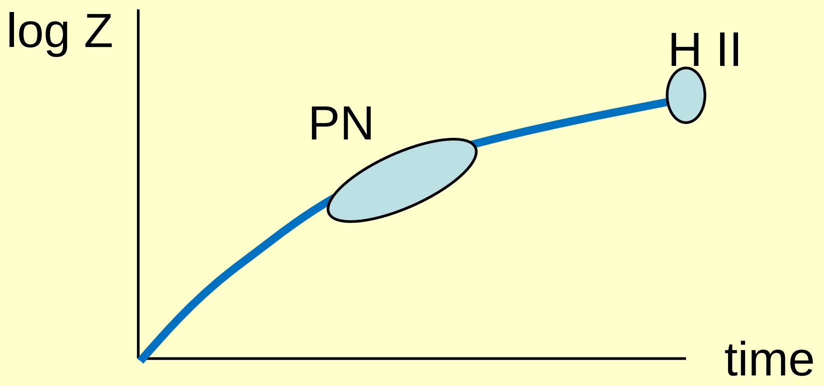
SNIa = WD accretes gas from companion, ignition of fusion, thermal runaway due to degenerate WD, explosive C+O fusion

Abundance ratios from PN-HII

	MWG	LMC	SMC	
He	**0.00**	**+0.07**	**+0.09**	**production**
C	**+0.28**	**+0.87**	**1.58**	**production**
N	**+0.39**	**+0.71**	**1.05**	**production**
O	-0.02	-0.01	0.22*	
Ne	0.08	-0.03	0.19*	chem.evolution
S	-0.18	-0.36**	-0.04	gives neg.values
Ar	-0.11	-0.34**	-0.17	

*   ????

** ICF problems?



Light elements

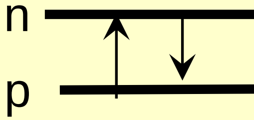
- Fragile nuclei, destroyed in stellar interiors

$^{2}D(p,\gamma)^{3}He$	for	$T > 0.5\ 10^{6}$ K
$^{6}Li(p,\alpha)^{3}He$		2
$^{7}Li(p,\alpha)^{4}He$		2.5
$^{9}Be(p,\alpha)^{6}Li$; $(p,D)^{8}Be \rightarrow 2\alpha$		3.5
$^{10}B(p,\alpha)^{7}Be(EC)\ ^{7}Li$		5.3
$^{11}B(p,\alpha)^{8}Be \rightarrow 2\alpha$		5
$^{3}He(^{3}He,\ \alpha)^{4}He+2p$		10

- Origin
  - D and some Li: Big Bang
  - Li,Be,B: overabundant in cosmic rays (100x ..1000x) spallation, α-α fusion (Q = -30 .. -40 MeV)

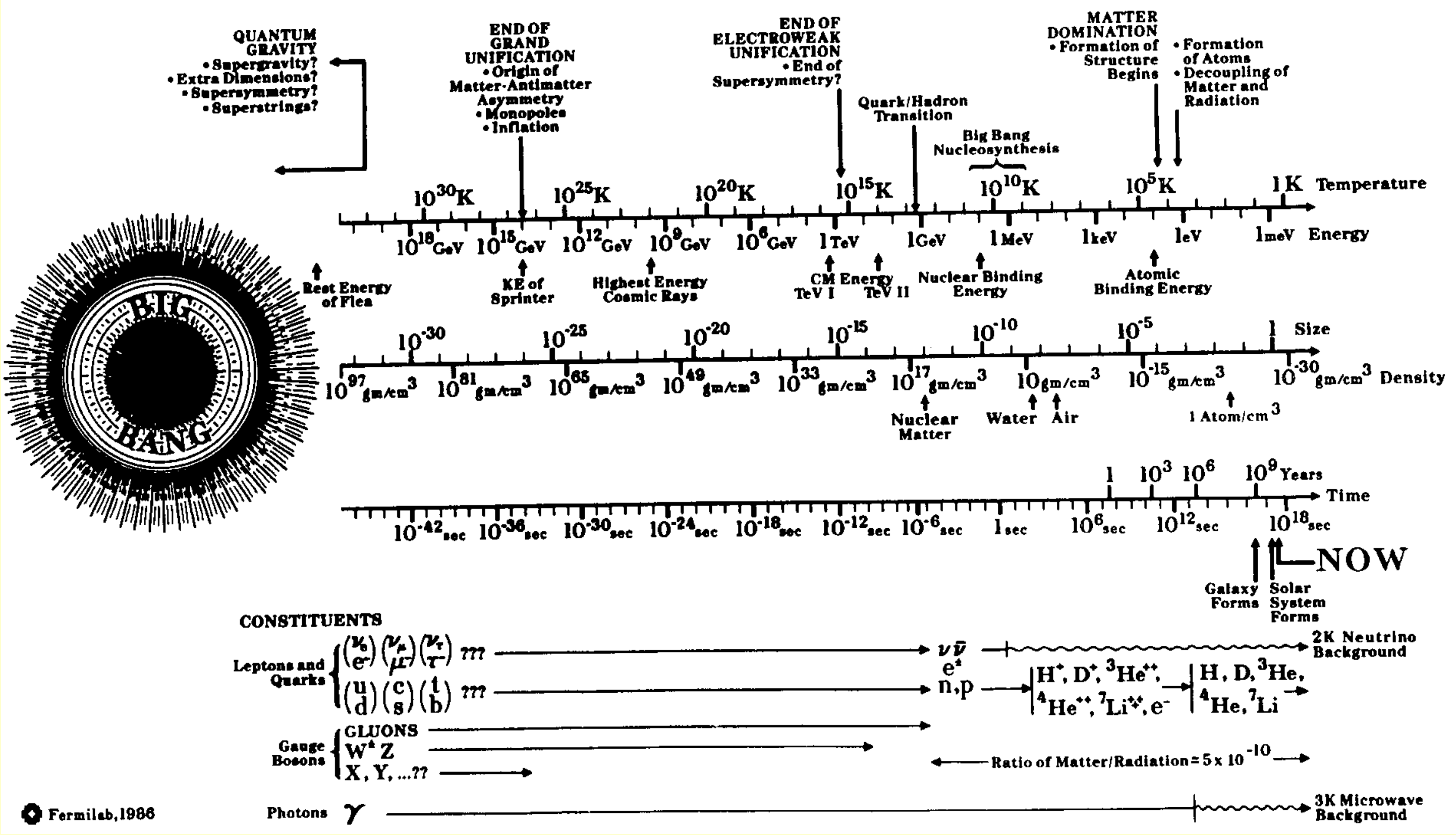
Nucleosynthesis in the Big Bang

- Expansion of matter and photons in thermal equilibrium: $\rho(t) = 3/(32\pi G\, t^2) \propto T^4$

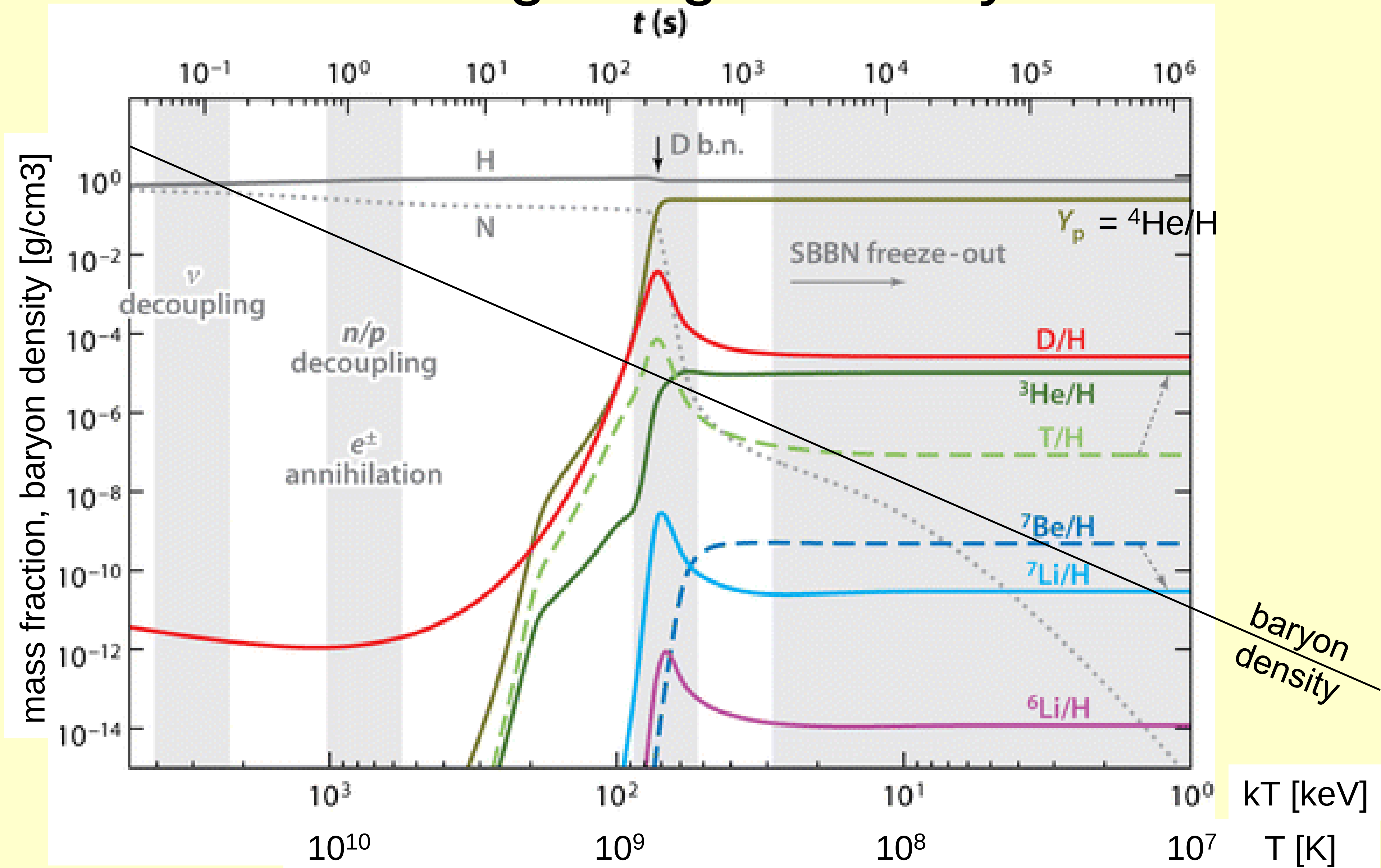


- $t > 1s$ ($kT < 1$ MeV):
  - $(n/p)_{Equil} = \exp(-(m_n - m_p)c^2/kT) = \exp(-1.29 \text{ MeV}/kT)$
  - At kT = 0.8 MeV (~10^{10} K): n, p 'freeze-out' (density becomes too low to support $n + \nu \Leftrightarrow p^+ + e^-$ etc … reactions to go in both ways) ➔ n/p = 0.223 ➔ no further generation of neutrons
  - β-decay continues: $n \rightarrow p^+ + e^- + \underline{\nu}$ (10 min half-life)
- t = 100…1000 s ($T=10^9$... $3\ 10^8$ K) : build-up of ^2D, ^3T, ^3He, ^4He, ^7Li, …
- Light elements freeze out before destruction can be finished

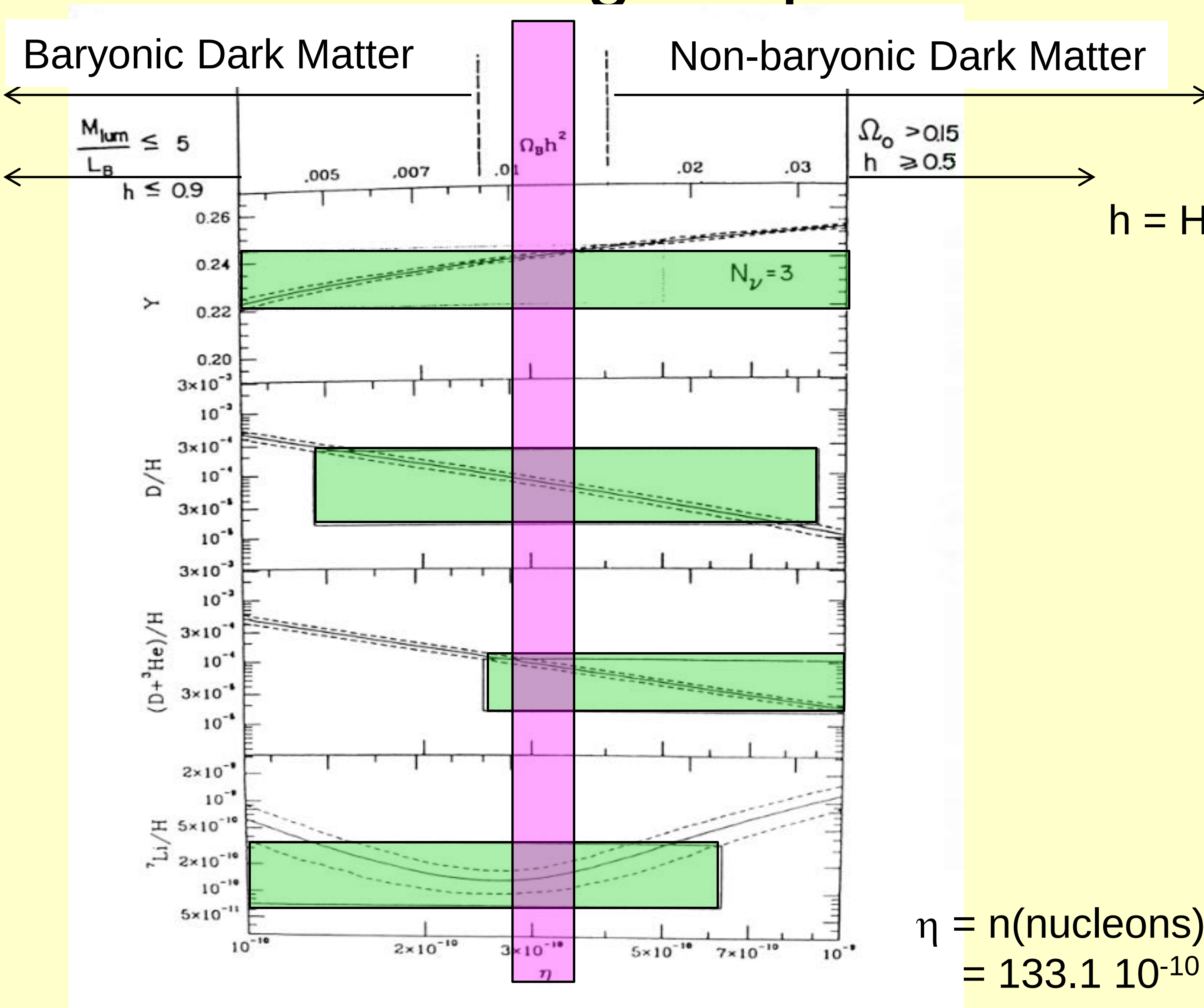
Complete history of Universe



Standard BigBangNucleosynthesis



Light element abundances depend on cosmological parameter

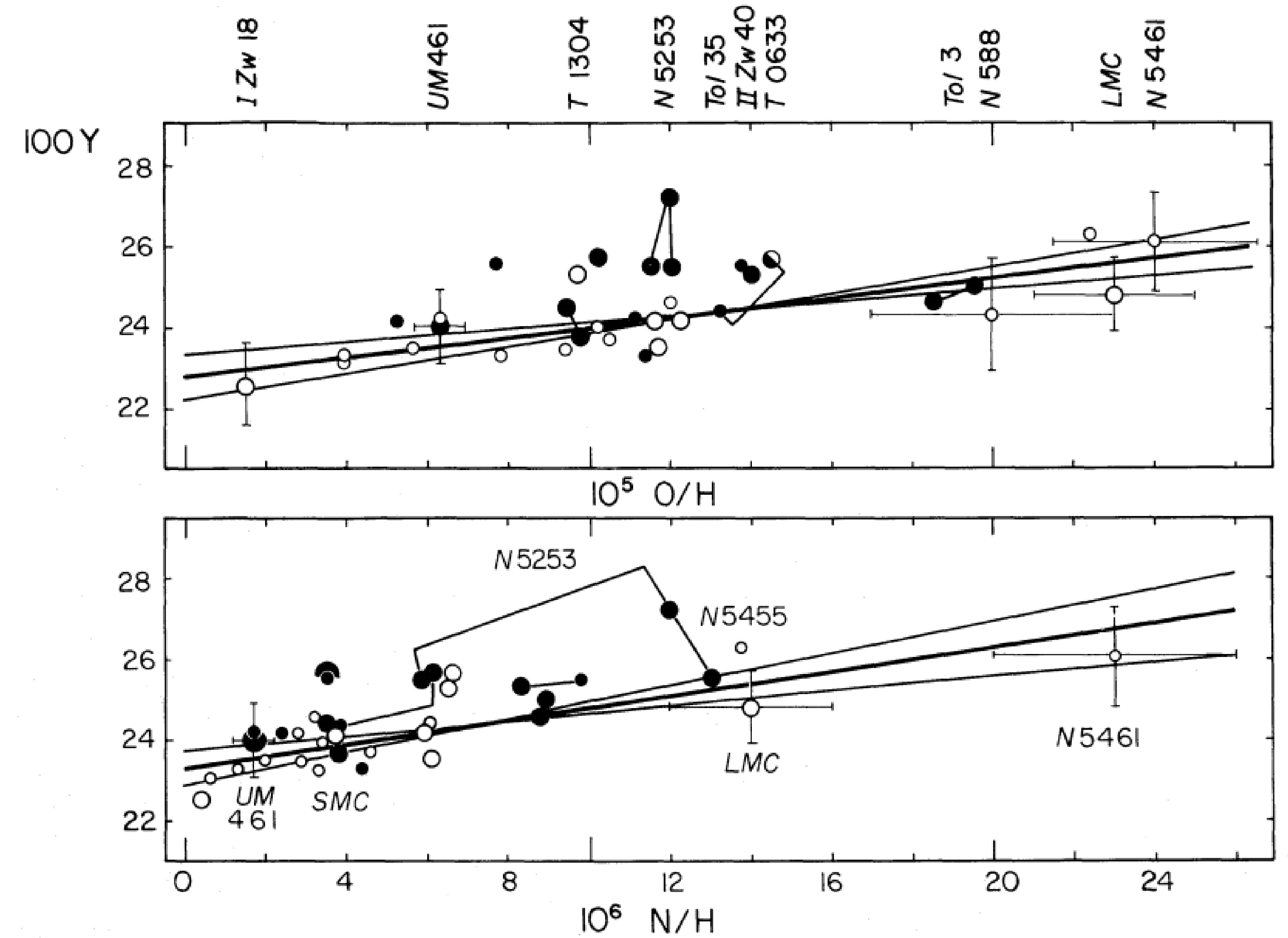


h = H0 / 100 km/s/Mpc

Pagel 1997

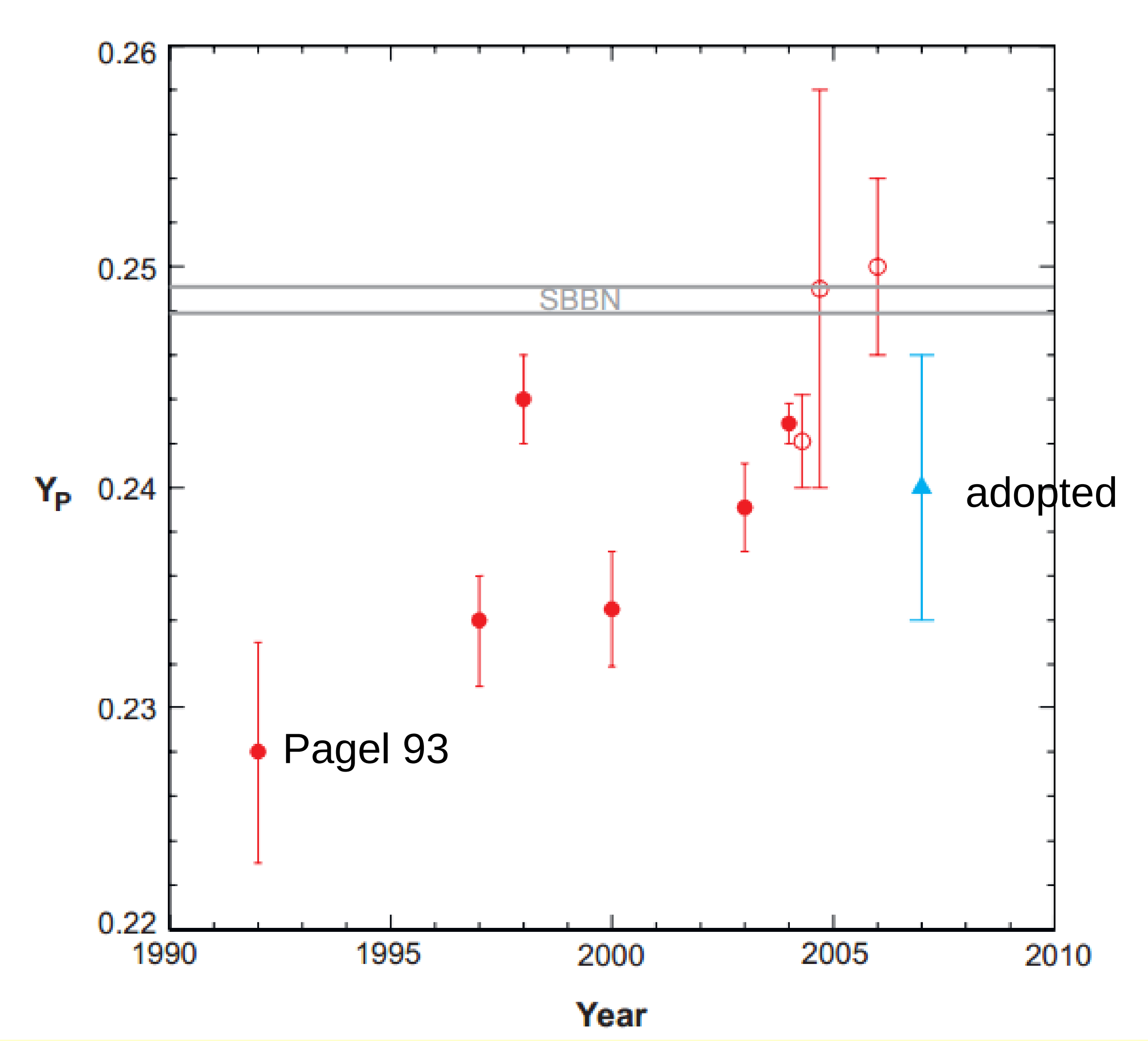
η = n(nucleons)/n(photons)
= 133.1 10^{-10} Ω_{b0}

Primordial He abundance

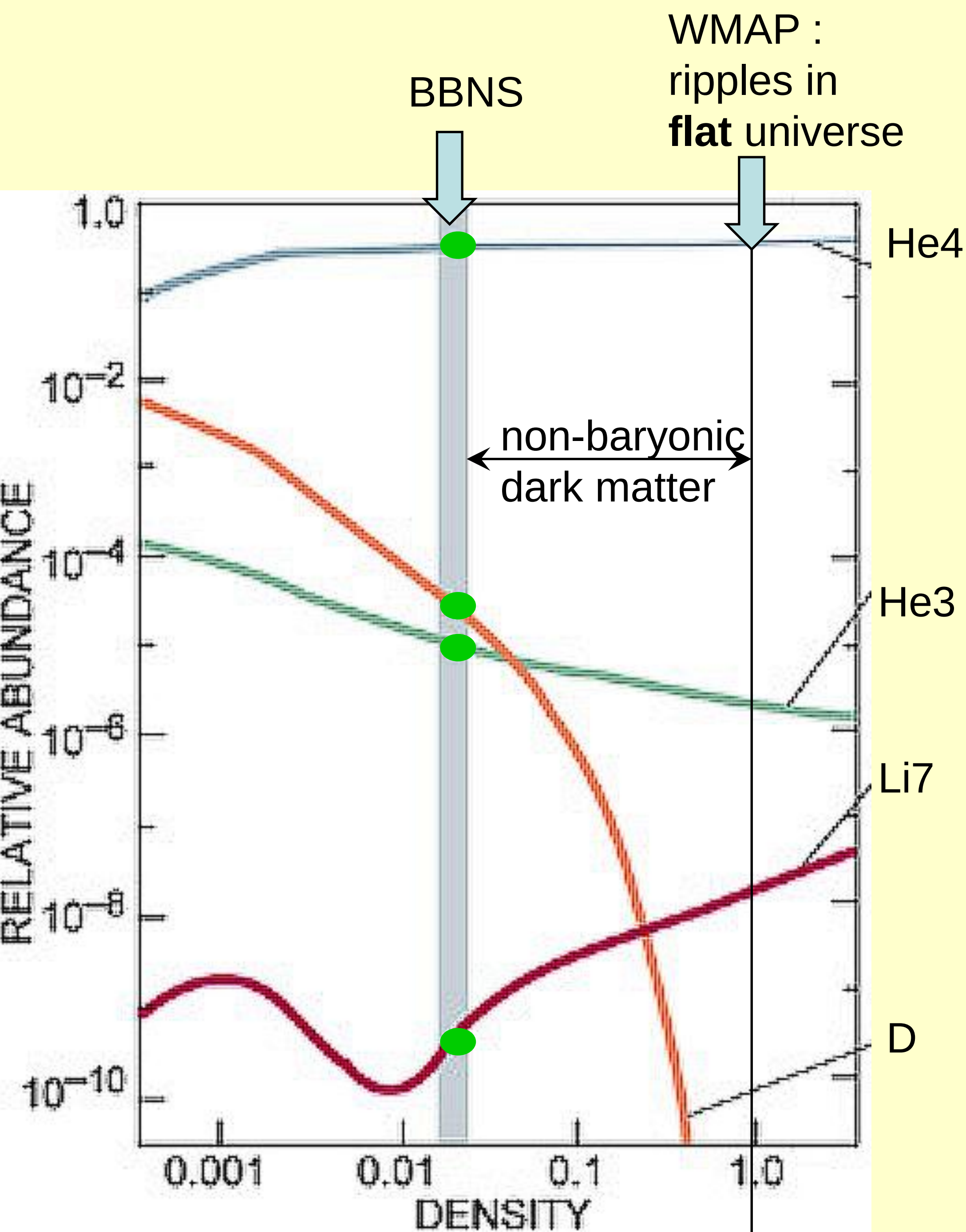


Pagel 1993

Primordial He abundances …



Steigman 2007



Unfortunately, there is a wide gap between the density required to match the observed abundances and the density inferred from the ripples in the microwave background …

Big Bang Theory

These **two** worked it out (1948)

R.A.Alpher H.A.Bethe G.A.Gamov

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

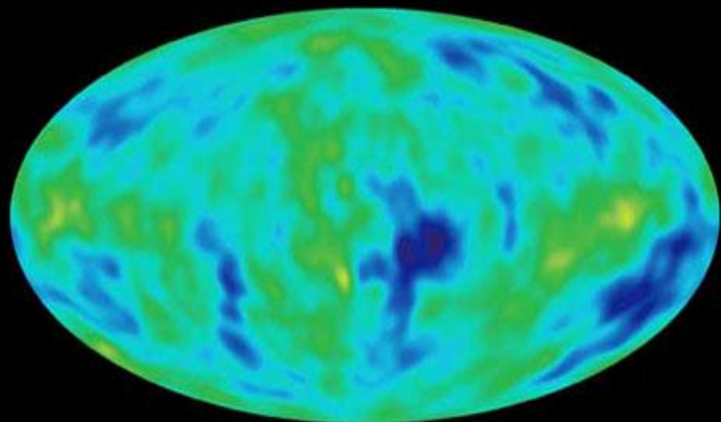
G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

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,

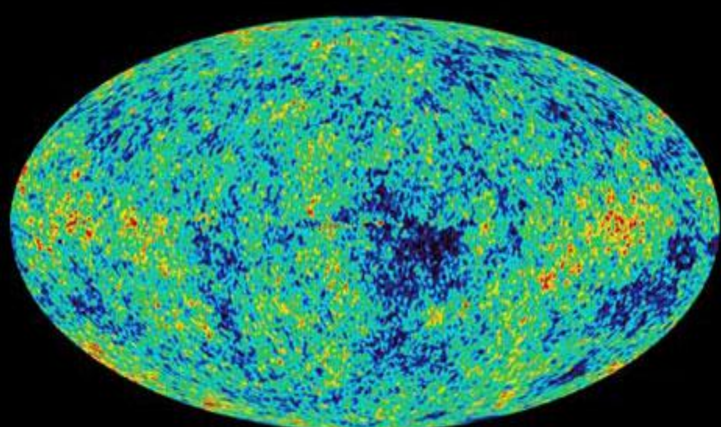
He didn't like it at all …
… he ridiculed it …
and so gave it its name!

Fred Hoyle

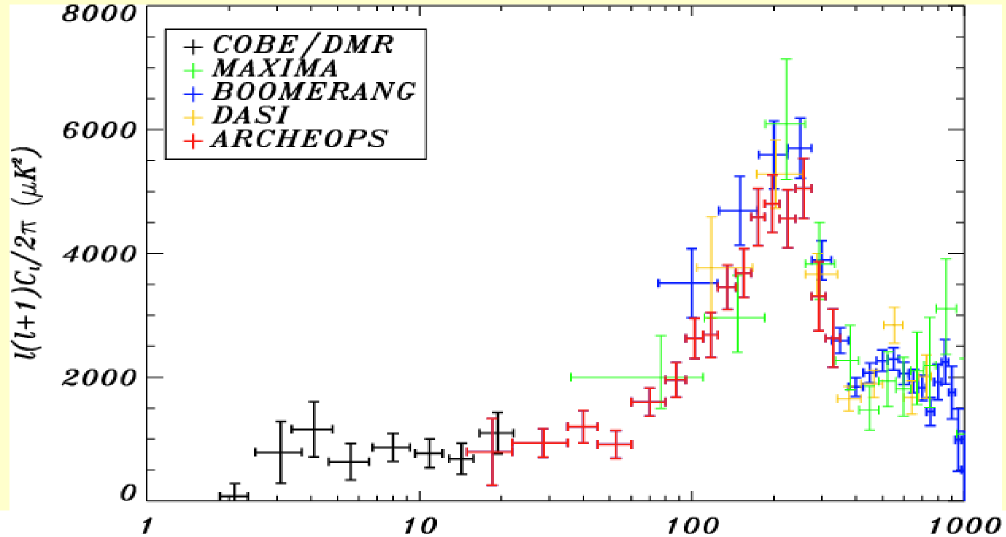
Cosmic ripples

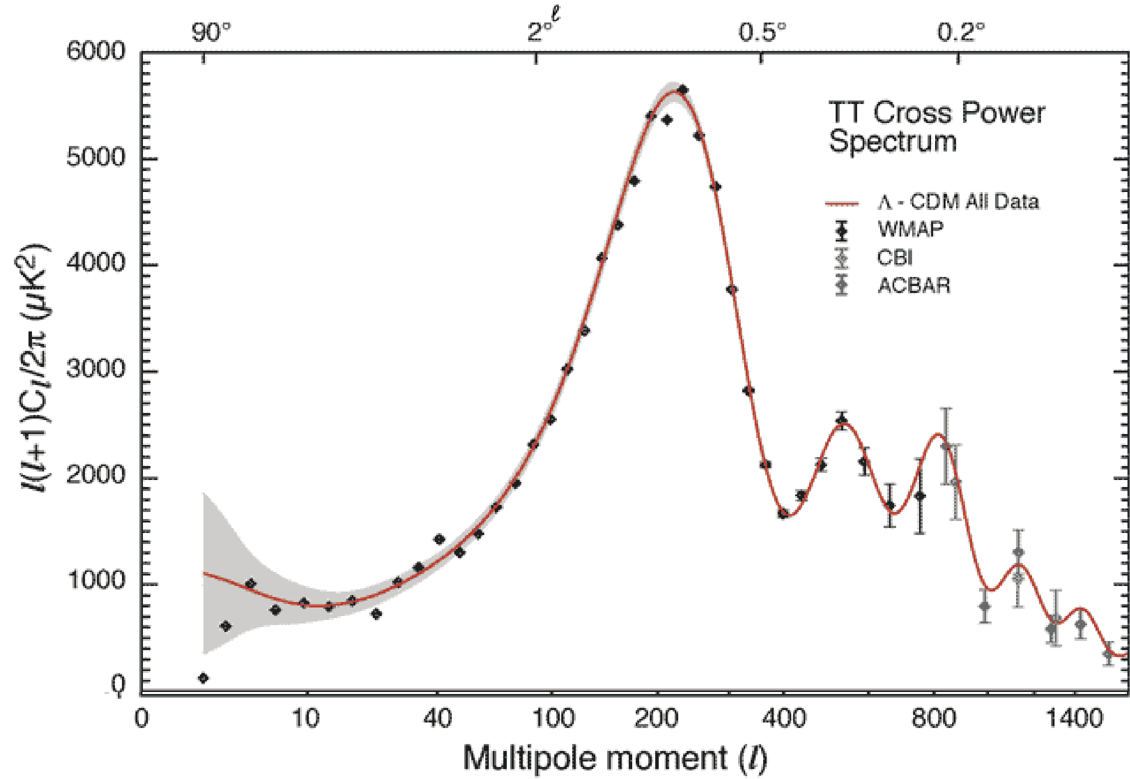


COBE



WMAP





Our best model of the universe

- Age 13.7 ± 0.1 Gyr
- Flat universe (done by Inflation)
- Normal matter: 4%
- (cold) Dark matter: 23%
- Dark energy: 73%

… is also the worst: with unknown stuff

Haven’t we had that before?

Crystal spheres	abt. 0 … 1610	Galilei: Jupiter’s moons	Newton: gravity and dynamics
Phlogiston	1400 … 1780	Lavoisier: ‘Rien se perd’	Conservation of mass, energy, …
Nebulium	1853 … 1927	Bowen: metastable doubly ionized O	Quantum mechanics
Ether	1870 … 1910	Michelson/Morley: Speed of light	Einstein: relativity
Dark Matter	1960 …	?	
Inflation	1980 …	?	
Dark Energy	2000 …	?	

The discovery of the Higgs (July 2012) was a disappointment: …
it merely confirmed the
‘standard model’,
thus it did not open the door to a New Physics ☹