

Francois chair Professor 2020-2021

Professor Stéphane Goriely

Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles

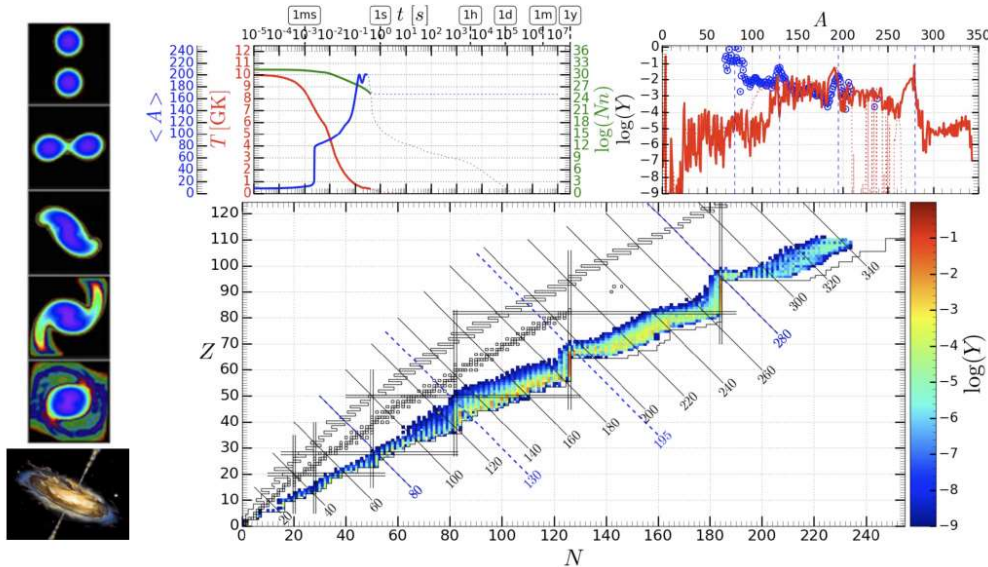
"About the creation of elements in the Universe"

The inaugural lecture will take place **online** on **Monday, May 3rd, 2021 at 17:00**

Programme

17:00 Welcome and introduction by Prof. Piet Van Duppen, Department Chair

17:10 Inaugural lecture by Prof. S. Goriely



Lecture series:

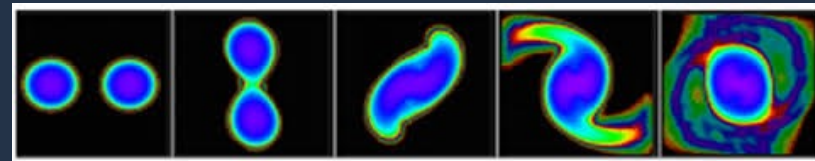
Monday May 10th 2021, 14:00 - 16:00

Monday May 17th 2021, 14:00 - 16:00

Tuesday May 25th 2021, 16:00 - 18:00

Monday May 31st 2021, 14:00 - 16:00

About the creation of elements in the Universe



PERIODIC TABLE

Atomic Properties of the Elements

Physics
Laboratory
physics.nist.gov

NIST
www.nist.gov

Standard Reference
Data Program
www.nist.gov/srd

VIII

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum c 299 792 458 m s $^{-1}$ (exact)
Planck constant h 6.626 069 3 $\times 10^{-34}$ J s (exact)
($\hbar = h/2\pi$)

elementary charge e 1.602 176 634 $\times 10^{-19}$ C

electron mass m_e 9.109 383 56 $\times 10^{-31}$ kg

proton mass m_p 1.672 621 63 $\times 10^{-27}$ kg

fine-structure constant α 1/137.035 999 074

Rydberg constant R_∞ 10 973 731.568 16 m $^{-1}$

R_H 10 973 731.568 16 m $^{-1}$

R_∞ 10 973 731.568 16 m $^{-1}$

Boltzmann constant k 1.380 658 $\times 10^{-23}$ J K $^{-1}$

U.S. DEPARTMENT OF COMMERCE

Technology Administration

National Institute of Standards and Technology

IIIB

IVB

VB

VIB

VIIB

VIII

5 B

6 C

7 N

8 O

9 F

10 Ne

Boron

Carbon

Nitrogen

Oxygen

Fluorine

Neon

10.811

12.0107

14.00643

15.9994

18.9984

20.1797

1s 2 2s 2 2p 1

1s 2 2s 2 2p 2

1s 2 2s 2 2p 3

1s 2 2s 2 2p 4

1s 2 2s 2 2p 5

1s 2 2s 2 2p 6

2.2995

11.2603

14.5344

13.6181

17.4223

21.9444

13 Al

14 Si

15 P

16 S

17 Cl

18 Ar

Aluminum

Silicon

Phosphorus

Sulfur

Chlorine

Argon

26.98154

28.0855

30.97376

32.065

35.4527

39.948

[Ne]3s 2 3p 1

[Ne]3s 2 3p 2

[Ne]3s 2 3p 3

[Ne]3s 2 3p 4

[Ne]3s 2 3p 5

[Ne]3s 2 3p 6

3.5958

4.1517

10.4857

10.3650

12.9676

15.7595

Period

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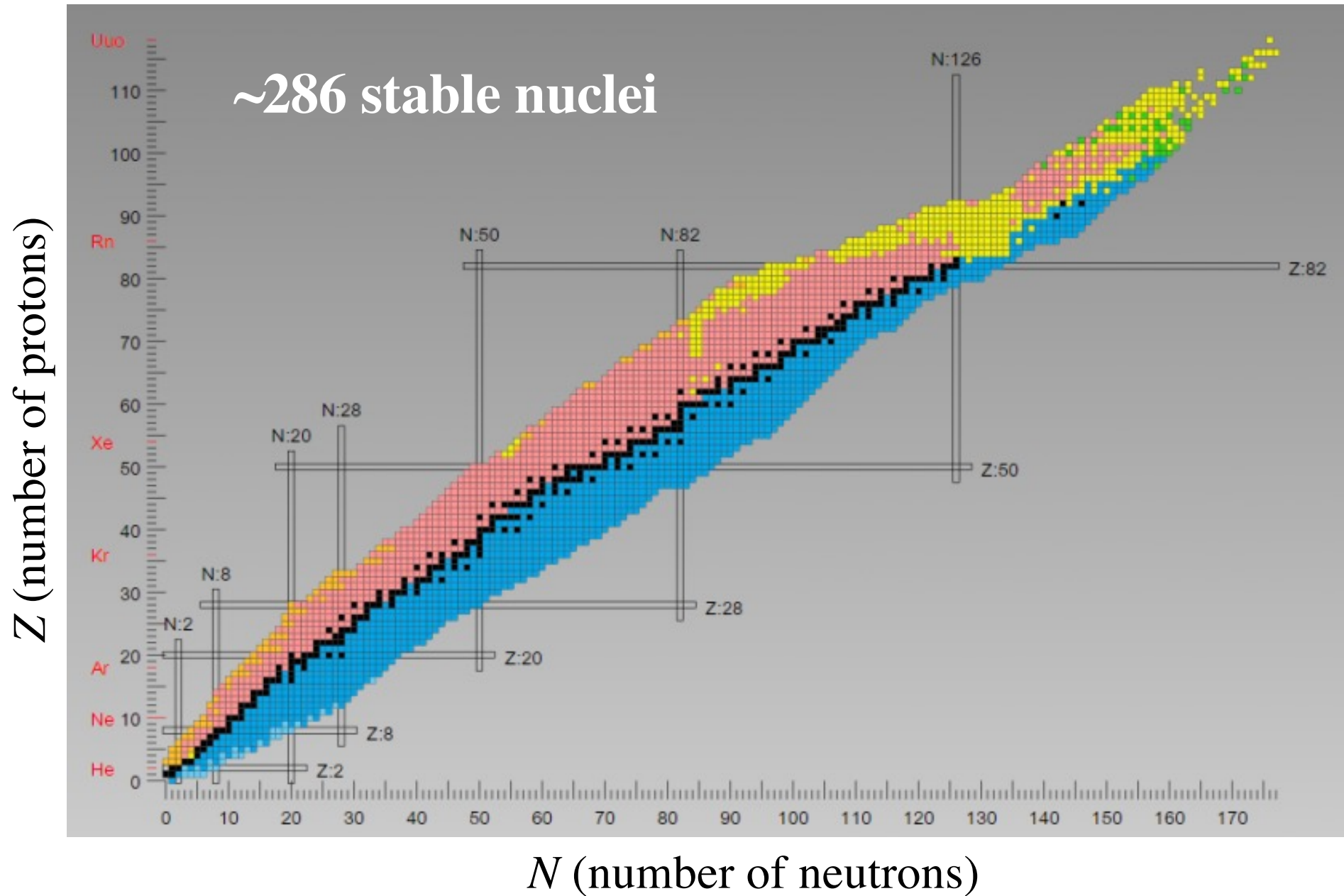
269

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Origin of the elements in the Universe ?

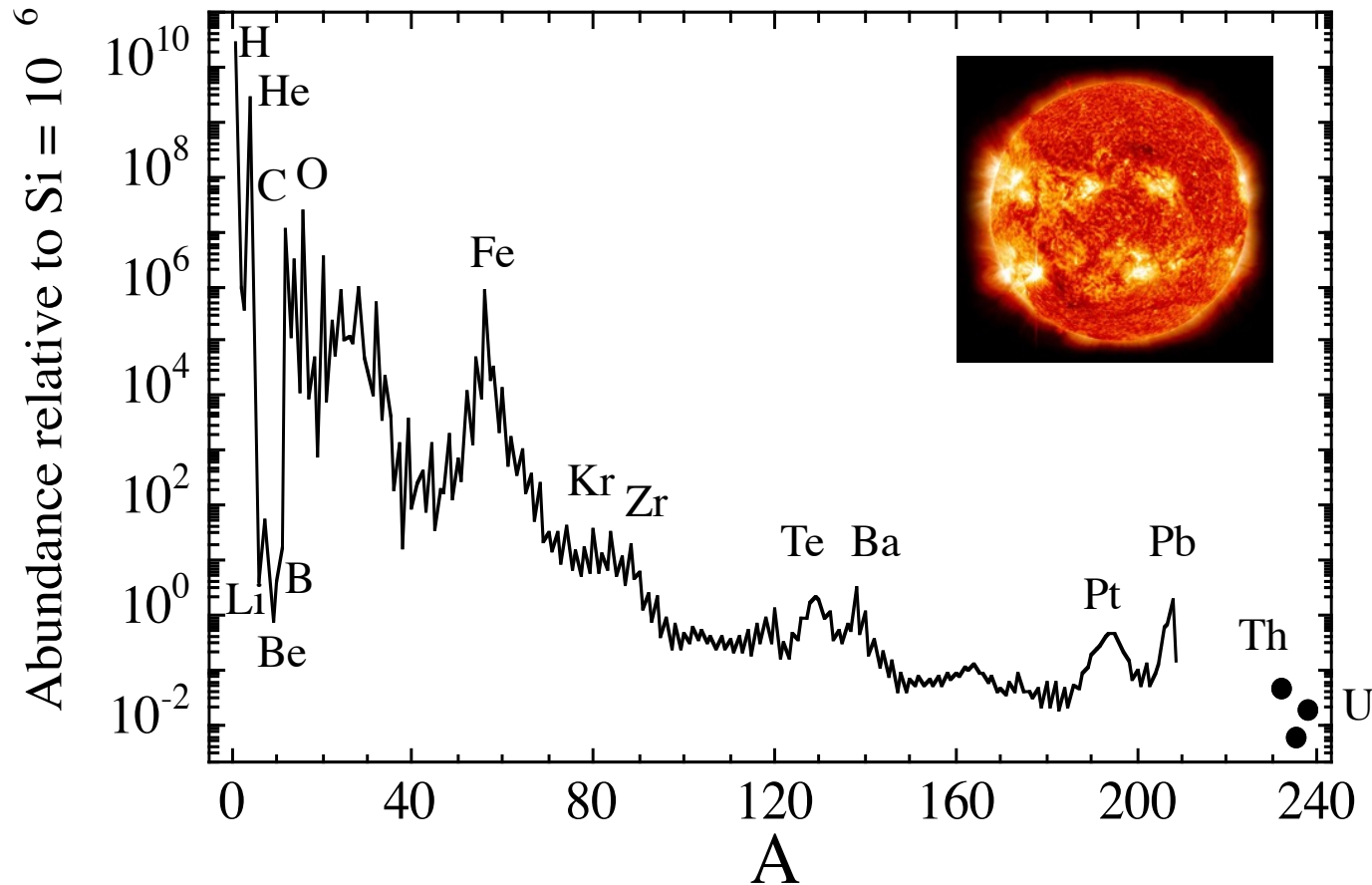
~ 83 naturally occurring elements on Earth

Chart of Nuclides



Isotopic composition of the Solar System

based essentially on the analysis of meteorites,
solar spectroscopy, and the earth isotopic composition



Prime fingerprint of astrophysical nuclear processes

Clear correlation between the Solar System abundances and nuclear properties

Some important dates in the history of nucleosynthesis

1938: Gamow, von Weizsacker et Bethe identify the energy source in stars:

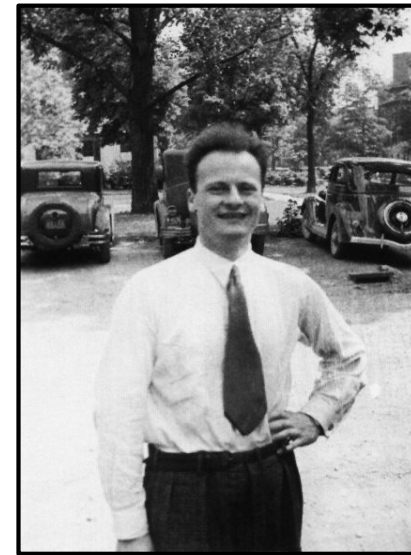
➔ p-p chains and CNO cycle



Gamow



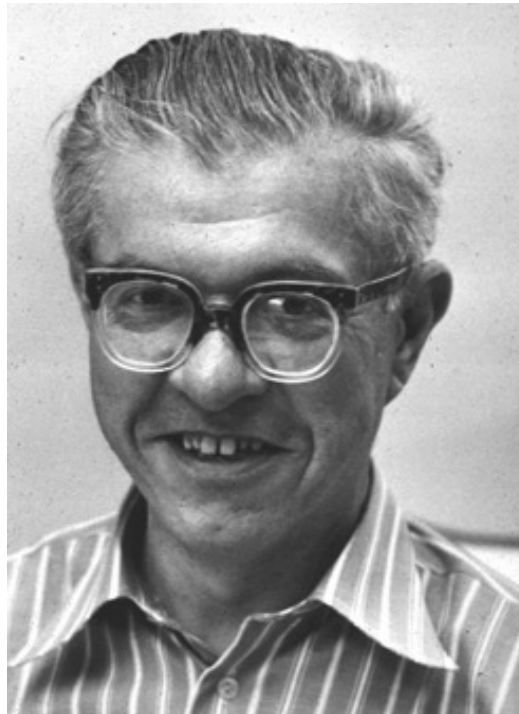
Von Weizsacker



Bethe

Net result: $4p \rightarrow {}^4\text{He} + 2e^+ + 2\nu + Q_{\text{eff}}$

1946: Hoyle predicts most of the elements and their isotopes are made by stars



Hoyle

1952: P.W. Merrill discovers Tc at the surface of stars

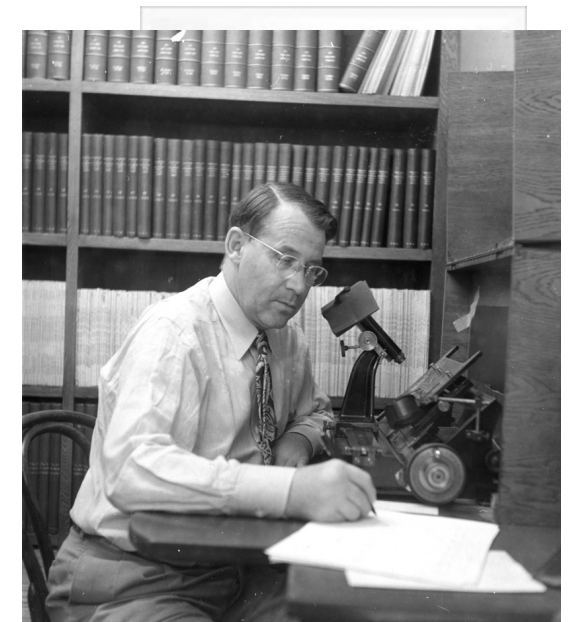
➔ rich and present nucleosynthesis in stars

Tc ➔

Pd 96 2.0 m	Pd 97 3.1 m	Pd 98 17.7 m	Pd 99 21.4 m	Pd 100 3.7 d	Pd 101 8.47 h	Pd 102 1.02	Pd 103 16.96 d	Pd 104 11.14	Pd 105 22.33	Pd 106 27.33
Rh 95 1.96 m	Rh 96 1.5 m	Rh 97 44 m	Rh 98 3.8 m	Rh 99 4.7 h	Rh 100 4.7 m	Rh 101 4.4 h	Rh 102 25 s	Rh 103 4.8 m	Rh 104 42 s	Rh 105 45 s
Ru 94 51.8 m	Ru 95 1.65 h	Ru 96 5.52	Ru 97 2.9 d	Ru 98 1.88	Ru 99 12.7	Ru 100 12.6	Ru 101 17.0	Ru 102 31.6	Ru 103 39.35 d	Ru 104 18.7
Tc 93 45.5 m	Tc 94 32 m	Tc 95 60 d	Tc 96 4.3 d	Tc 97 93.2 d	Tc 98 4.2 · 10 ⁵ a	Tc 99 6.8 h	Tc 100 15.8 s	Tc 101 14.2 m	Tc 102 45 m	Tc 103 54.2 s
Mo 92 14.6 d	Mo 93 4.4 h	Mo 94 9.25	Mo 95 15.92	Mo 96 16.68	Mo 97 9.55	Mo 98 24.13	Mo 99 66.0 h	Mo 100 9.63	Mo 101 14.6 m	Mo 102 11.2 m
Nb 91 67.8 d	Nb 92 10.5 d	Nb 93 16.13 a	Nb 94 2.10 ⁴ a	Nb 95 96.8 h	Nb 96 23.4 h	Nb 97 63 s	Nb 98 3.9 s	Nb 99 3.4 m	Nb 100 3.1 s	Nb 101 7.1 s
Zr 90 51.45	Zr 91 11.22	Zr 92 17.15	Zr 93 1.5 · 10 ⁶ a	Zr 94 17.38	Zr 95 64.0 d	Zr 96 2.80	Zr 97 16.8 h	Zr 98 30.7 s	Zr 99 2.1 s	Zr 100 7.1 s

Z=43

$$T_{1/2}(\text{Tc}) < 4\text{Myr}$$

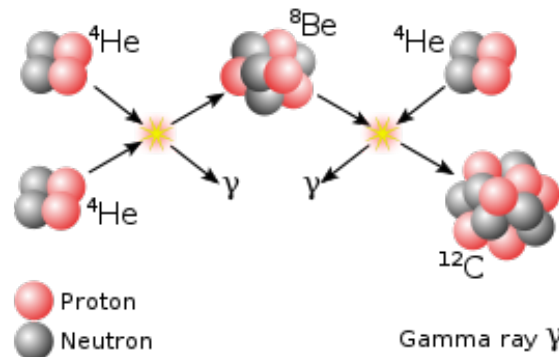


P.W. Merrill

1951-1952: Identification of the 3α reaction to cross the $A=8$ gap thanks to the theoretical predictions and experimental confirmation of the 0^+ resonance state at 7.7 MeV in ^{12}C

➔ Nucleosynthesis beyond He: $3\alpha \rightarrow ^{12}\text{C}$

		A=8					
Z	6	7B	8B	9B	10B	11B	
	1.4 MeV	770 MS	0.54 KeV	STABLE	STABLE		
	2P	P	α : 100.00% ϵ : 100.00%	2 α : 100.00% P: 100.00%	19.8%	80.2%	
	5Be	6Be	7Be	8Be	9Be	10Be	
	92 KeV	53.22 D	1.57 eV	STABLE	1.51E+6 Y		
	P	α : 100.00% P: 100.00%	ϵ : 100.00%	α : 100.00%	100%	β^- : 100.00%	
3	3Li	4Li	5Li	6Li	7Li	8Li	
	6.03 MeV	≈ 1.5 MeV	STABLE	STABLE	839.9 MS	178.3 MS	
2	P	P: 100.00%	α : 100.00% P: 100.00%	7.59%	92.41%	178.3 MS	
1	1H	2H	3H	4H	5H	6H	
	STABLE	STABLE	STABLE	STABLE	STABLE	STABLE	
	99.985%	0.015%	100.00%	100.00%	100.00%	100.00%	
	0	1	2	3	4	5	
		N					



Hoyle

1954-1957: Nucleosynthesis theories are forged

1946, 1954: Hoyle & 1957: B²FH, Cameron

REVIEWS OF MODERN PHYSICS

VOLUME 29, NUMBER 4

OCTOBER, 1957

Synthesis of the Elements in Stars*

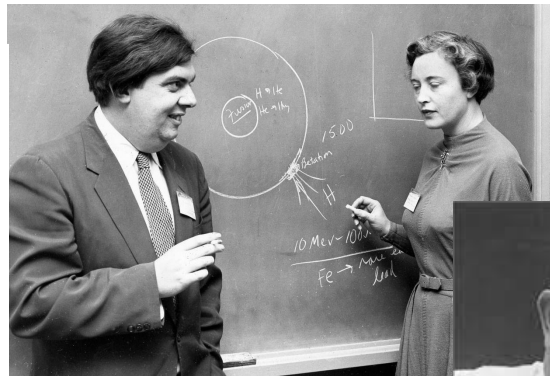
E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

*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)



Burbidge



Fowler

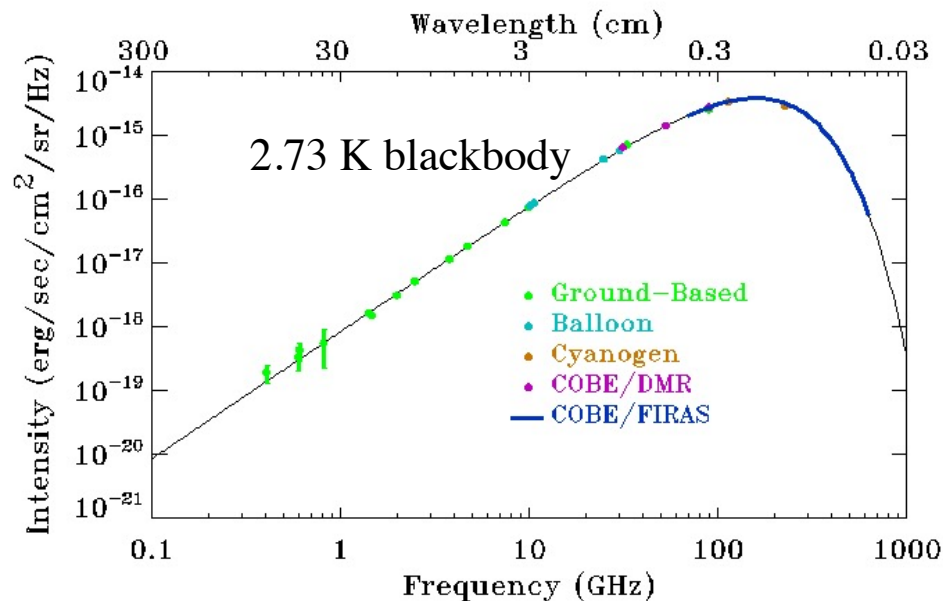
Hoyle



Cameron

1964: Cosmic micro-wave background at 2.7K is
accidentally discovered by A. Penzias and R. Wilson

➡ Primordial nucleosynthesis (Big Bang)



Penzias & Wilson

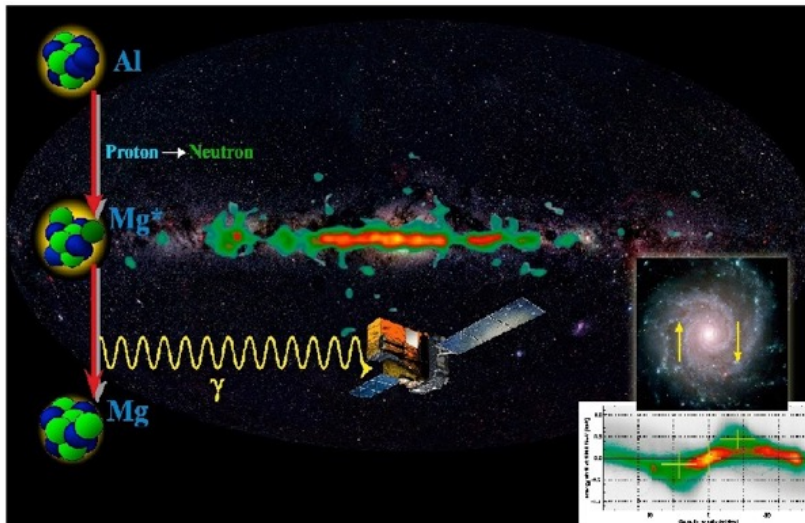
1970s: Nuclear Astrophysics as a “real” multi-disciplinary field with a European leadership

M. Arnould (ULB) & W. Hillebrandt (MPA) & K. Takahashi (GSI)



1982: Discovery of the γ -ray emitted during the decay of ^{26}Mg produced by ^{26}Al β -decay ($T_{1/2}=7.4 \cdot 10^5\text{y}$)

➡ development of a new astronomy: the γ -astronomy



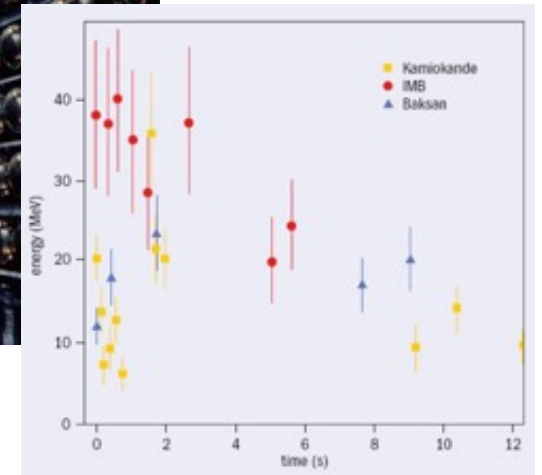
1.8 MeV γ -ray line observed in the Galactic plane



Compton γ -ray observatory

1987: Explosion of SN1987A in the LMC: non-solar neutrinos detected

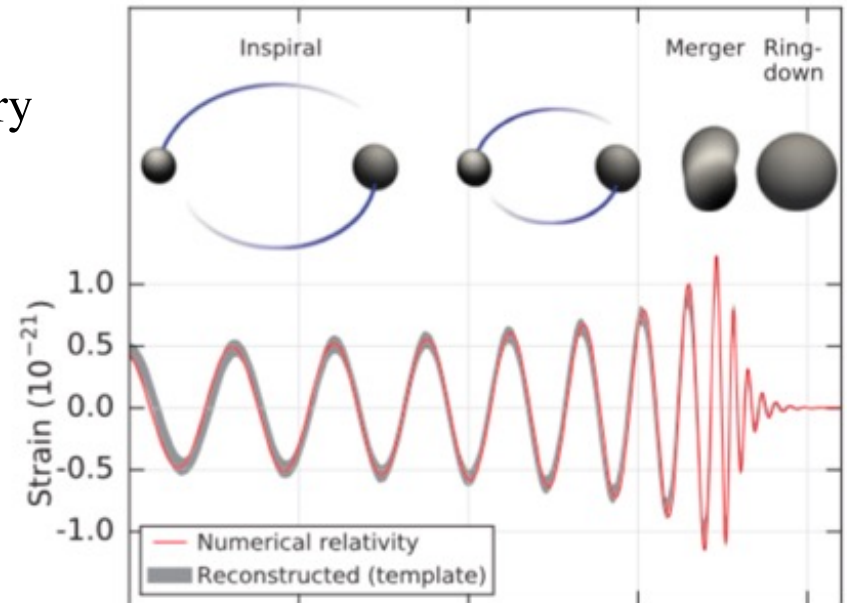
➡ neutrino astronomy & link to explosive nucleosynthesis



2017: first direct detection of gravitational waves from a binary NS-NS system merger and its electromagnetic counterpart (kilonova)

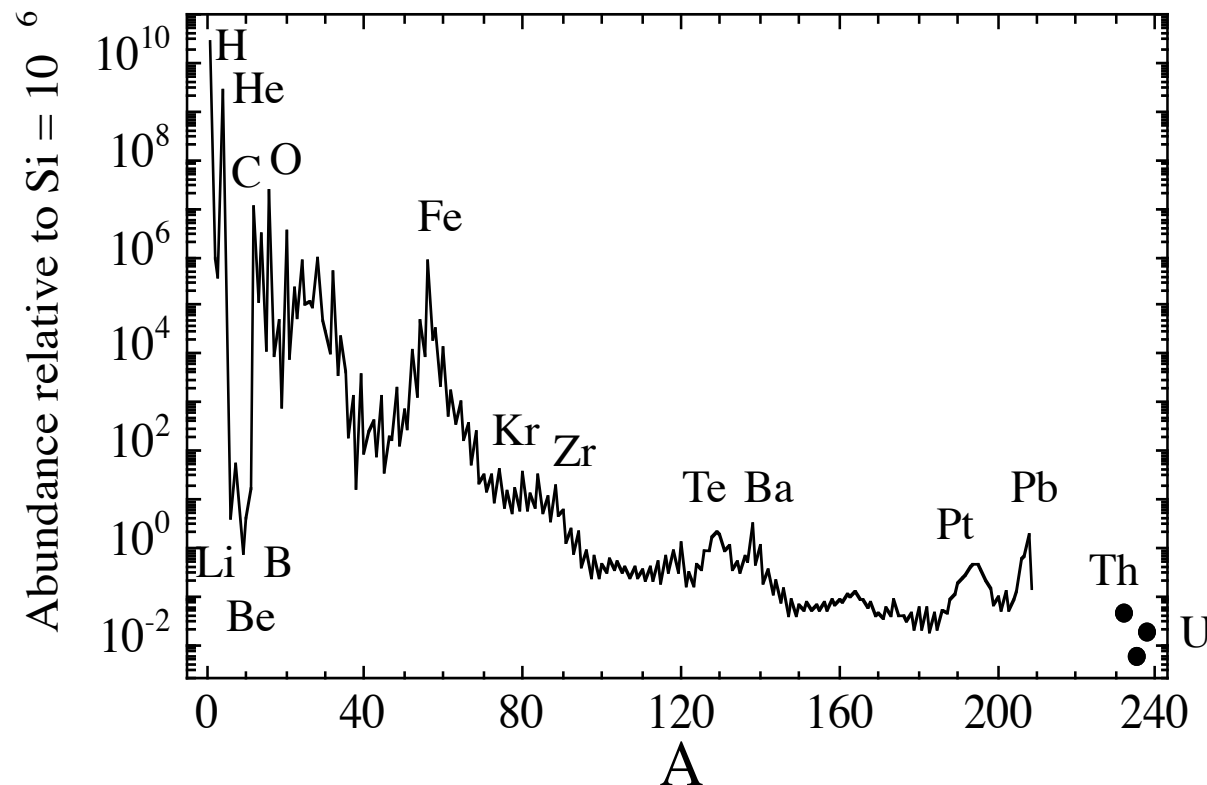
- ➡ Multi-messenger Astronomy
- ➡ breakthrough for the rapid neutron-capture process (or r-process) nucleosynthesis

Laser Interferometer Gravitational-Wave Observatory



Origin of the elements in the Universe

- Primordial (Big-Bang) nucleosynthesis: H, He, and some Li
- Cosmic rays: Li-Be-B at the stellar surface or in the ISM
- Stars: stars evolve and transform light H-He elements into heavier species

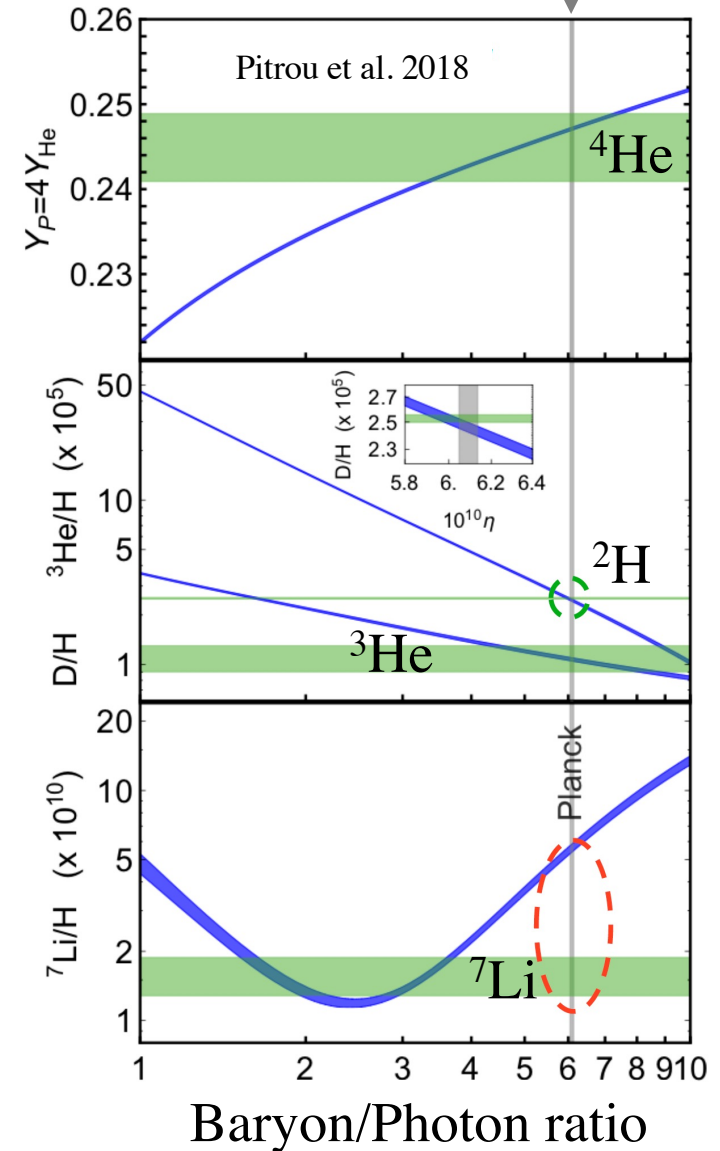
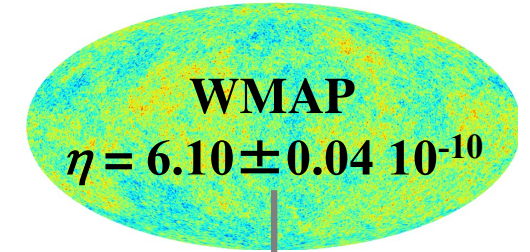
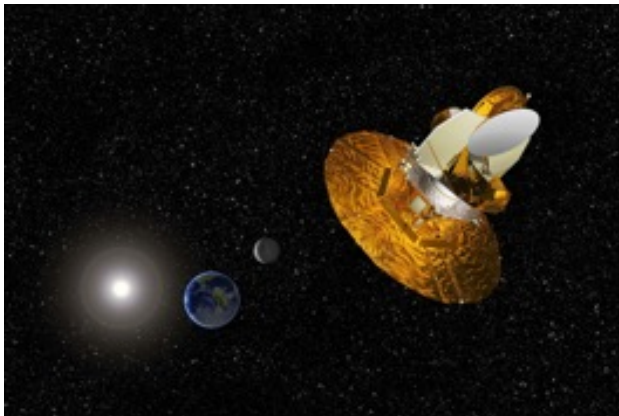




Primordial nucleosynthesis

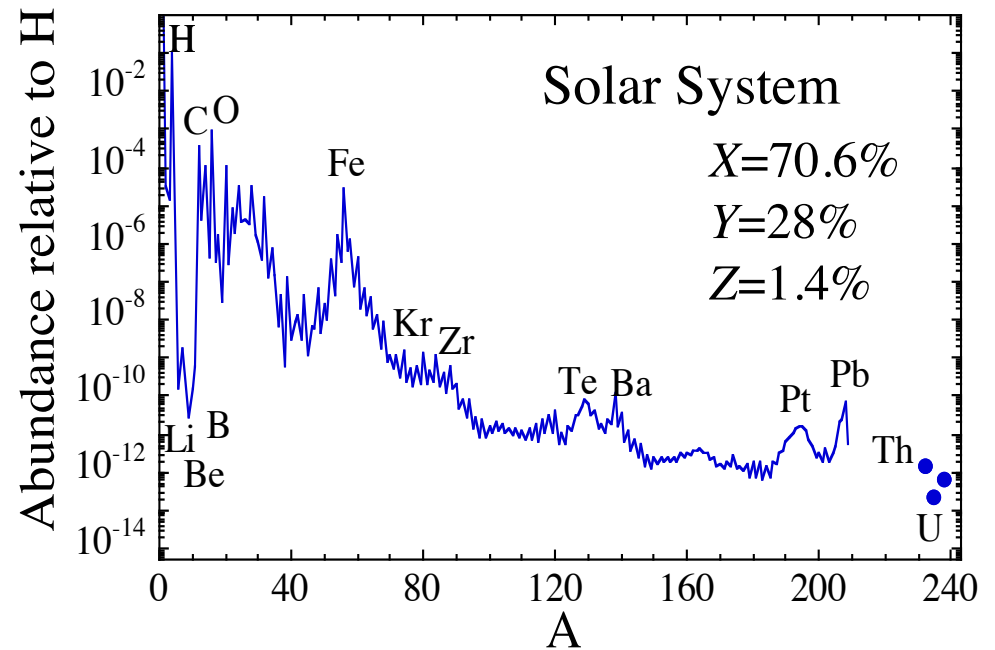
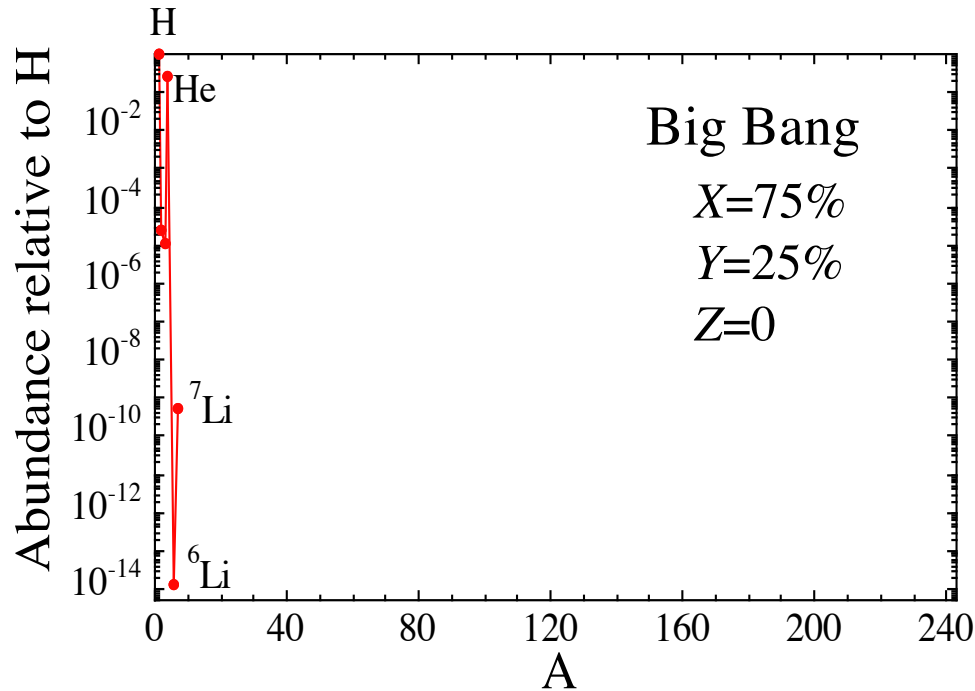
One of the major pillars of the Big Bang theory:
Reproduce observed primordial abundances of H, He, Li over 9 orders of magnitude

(Li underestimated by a factor of ~ 3)



Abundances resulting from the BB

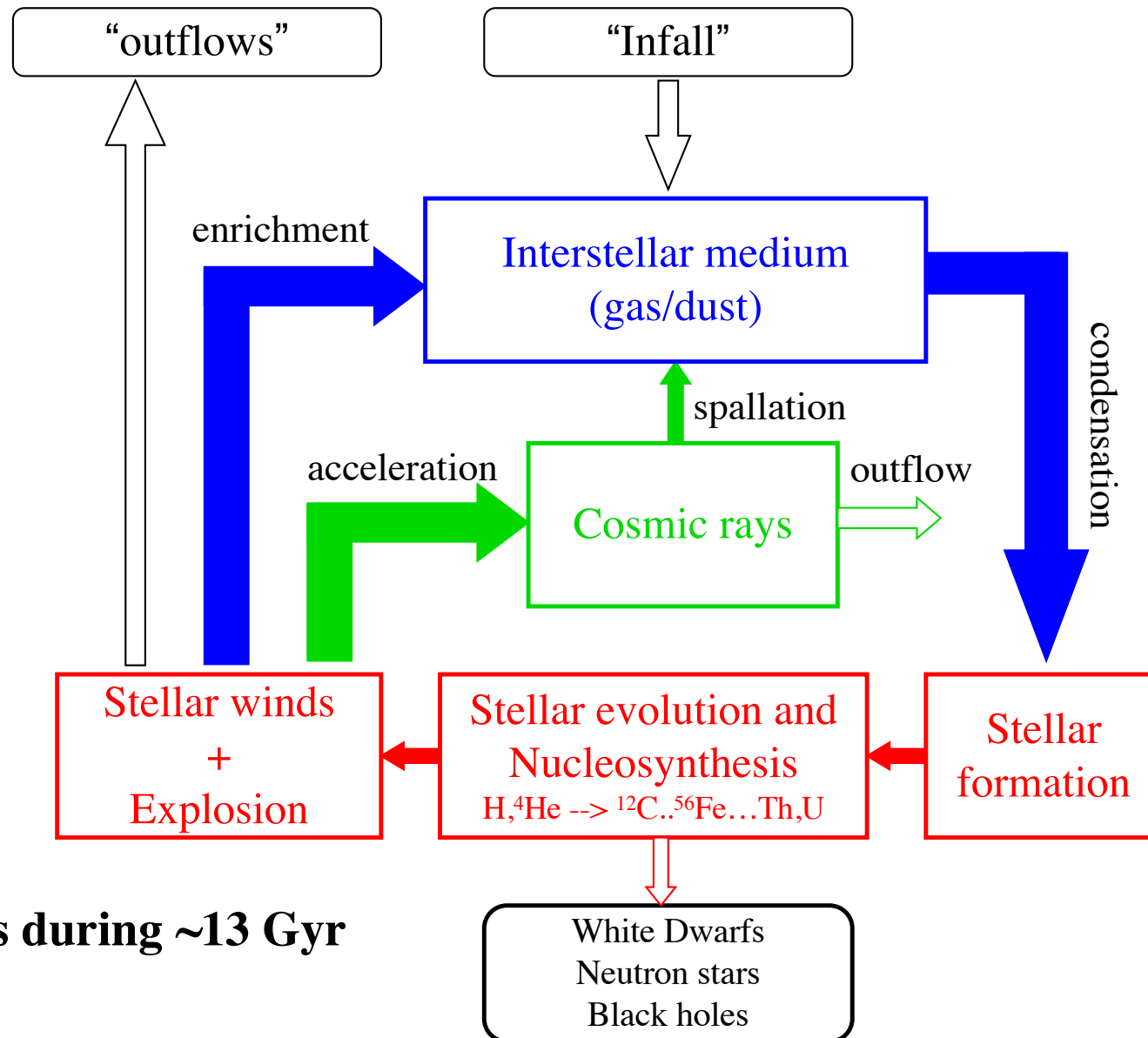
Abundances in SoS today



Some 13 Gy after the BB

Stars are the cosmic chauldrons

Chemical evolution of the Galaxy



Primordial nucleosynthesis

PERIODIC TABLE

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U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

Frequently used fundamental physical constants

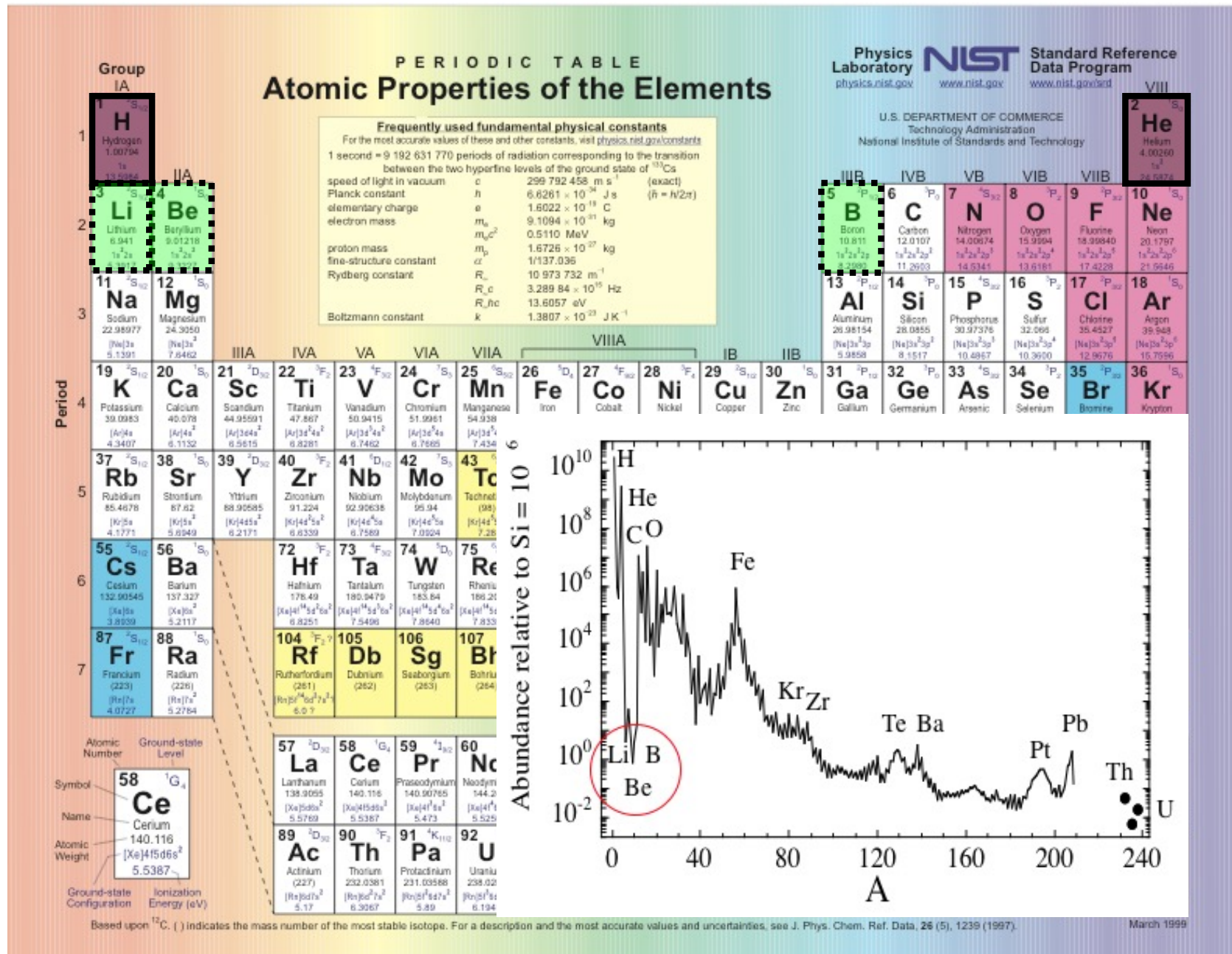
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	$m_e c^2$	0.511 0 MeV
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fine-structure constant	α	1/137.035 999 084
Rydberg constant	R_∞	10 973 731.568 160 m ⁻¹
	R_H	10 973 731.568 160 m ⁻¹
	$R_\infty hc$	13.605 698 eV
Boltzmann constant	k	1.380 658 × 10 ⁻²³ J K ⁻¹

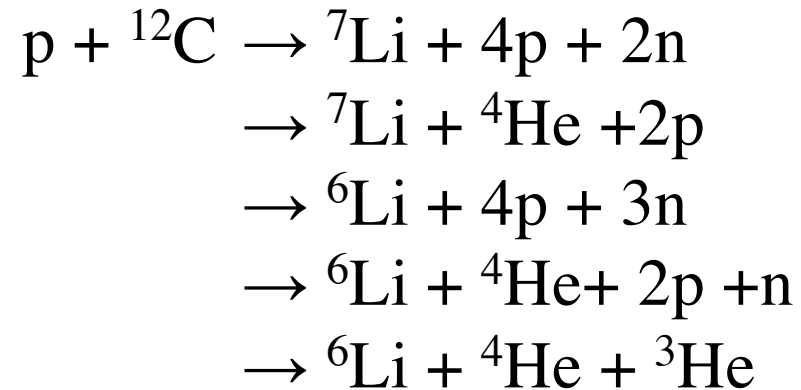
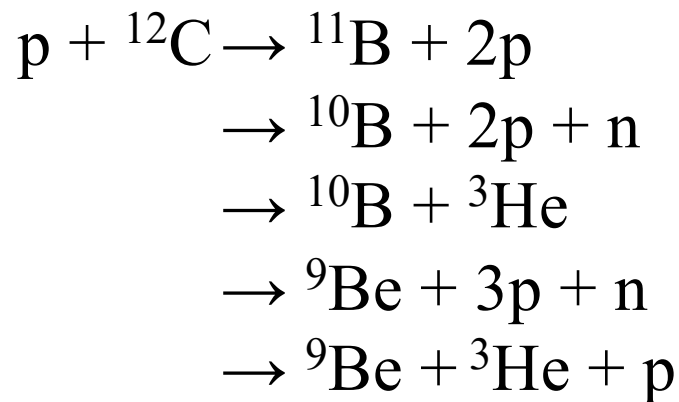
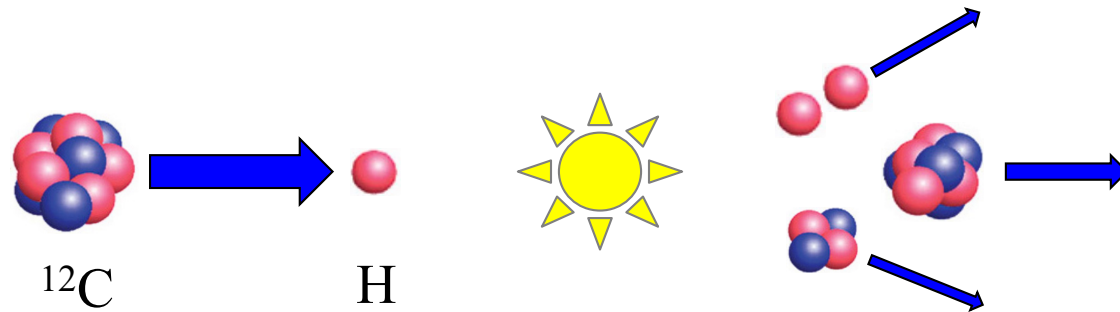
Group	IA	IIA	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIA	VIIIA	IB	IIB
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The Li-Be-B nucleosynthesis



Non-thermal nucleosynthesis by spallation reactions

C-N-O elements accelerated at high energies in GCR and bombarding H from the interstellar medium



Li – Be – B production

Could spallation reactions contribute to the production of other elements ??

Nucleosynthesis of elements lighter than Fe

PERIODIC TABLE

Atomic Properties of the Elements

Physics
Laboratory
physics.nist.gov

NIST
www.nist.gov

Standard Reference
Data Program
www.nist.gov/srd

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum c 299 792 458 m s $^{-1}$ (exact)

Planck constant h 6.626 069 3 $\times 10^{-34}$ J s ($h = h/2\pi$)

elementary charge e 1.602 176 634 $\times 10^{-19}$ C

electron mass m_e 9.109 383 56 $\times 10^{-31}$ kg

proton mass m_p 1.672 621 63 $\times 10^{-27}$ kg

fine-structure constant α 1/137.035 999 074

Rydberg constant R_∞ 10 973 731.568 160 m $^{-1}$

Boltzmann constant k 1.380 658 $\times 10^{-23}$ J K $^{-1}$

5 B Boron 10.811 $1s^2 2s^2 2p^1$ 8.0085	6 C Carbon 12.0107 $1s^2 2s^2 2p^2$ 11.4920	7 N Nitrogen 14.00644 $1s^2 2s^2 2p^3$ 14.00307	8 O Oxygen 15.9994 $1s^2 2s^2 2p^4$ 14.8186	9 F Fluorine 18.99840 $1s^2 2s^2 2p^5$ 16.8109	10 Ne Neon 20.1797 $1s^2 2s^2 2p^6$ 16.8109
13 Al Aluminum 26.98154 $(\text{Ne})3s^2 3p^1$ 8.9894	14 Si Silicon 28.0855 $(\text{Ne})3s^2 3p^2$ 8.5517	15 P Phosphorus 30.97376 $(\text{Ne})3s^2 3p^3$ 10.4867	16 S Sulfur 32.065 $(\text{Ne})3s^2 3p^4$ 10.3600	17 Cl Chlorine 35.4527 $(\text{Ne})3s^2 3p^5$ 10.9670	18 Ar Argon 39.948 $(\text{Ne})3s^2 3p^6$ 10.7555

Group IA	2 He Helium 4.00260 $1s^1$ 24.8687	3 Li Lithium 6.941 $1s^2 2s^1$ 5.3912	4 Be Beryllium 9.01218 $1s^2 2s^2$ 5.2913	5 B Boron 10.811 $1s^2 2s^2 2p^1$ 8.0085	6 C Carbon 12.0107 $1s^2 2s^2 2p^2$ 11.4920	7 N Nitrogen 14.00644 $1s^2 2s^2 2p^3$ 14.00307	8 O Oxygen 15.9994 $1s^2 2s^2 2p^4$ 14.8186	9 F Fluorine 18.99840 $1s^2 2s^2 2p^5$ 16.8109	10 Ne Neon 20.1797 $1s^2 2s^2 2p^6$ 16.8109	11 Na Sodium 22.98977 $(\text{Ne})3s^1$ 5.1390	12 Mg Magnesium 24.3050 $(\text{Ne})3s^2$ 7.3802	13 Al Aluminum 26.98154 $(\text{Ne})3s^2 3p^1$ 8.9894	14 Si Silicon 28.0855 $(\text{Ne})3s^2 3p^2$ 8.5517	15 P Phosphorus 30.97376 $(\text{Ne})3s^2 3p^3$ 10.4867	16 S Sulfur 32.065 $(\text{Ne})3s^2 3p^4$ 10.3600	17 Cl Chlorine 35.4527 $(\text{Ne})3s^2 3p^5$ 10.9670	18 Ar Argon 39.948 $(\text{Ne})3s^2 3p^6$ 10.7555	19 K Potassium 39.0983 $(\text{Ar})4s^1$ 4.3407	20 Ca Calcium 40.078 $(\text{Ar})4s^2$ 6.1132	21 Sc Scandium 44.95591 $(\text{Ar})3d^1 4s^2$ 6.8221	22 Ti Titanium 47.867 $(\text{Ar})3d^2 4s^2$ 6.8221	23 V Vanadium 50.9415 $(\text{Ar})3d^3 4s^2$ 6.8221	24 Cr Chromium 51.9961 $(\text{Ar})3d^5 4s^1$ 6.8221	25 Mn Manganese 54.93805 $(\text{Ar})3d^5 4s^2$ 6.8221	26 Fe Iron 55.845 $(\text{Ar})3d^6 4s^2$ 7.0504	27 Co Cobalt 58.93320 $(\text{Ar})3d^7 4s^2$ 7.0504	28 Ni Nickel 58.6934 $(\text{Ar})3d^8 4s^2$ 7.0504	29 Cu Copper 63.546 $(\text{Ar})3d^{10} 4s^1$ 7.2264	30 Zn Zinc 65.39 $(\text{Ar})3d^{10} 4s^2$ 9.3952	31 Ga Gallium 69.723 $(\text{Ar})3d^{10} 4s^2 4p^1$ 9.3952	32 Ge Germanium 72.61 $(\text{Ar})3d^{10} 4s^2 4p^2$ 9.3952	33 As Arsenic 74.92160 $(\text{Ar})3d^{10} 4s^2 4p^3$ 9.3952	34 Se Selenium 78.96 $(\text{Ar})3d^{10} 4s^2 4p^4$ 9.3952	35 Br Bromine 79.904 $(\text{Ar})3d^{10} 4s^2 4p^5$ 11.8136	36 Kr Krypton 83.80 $(\text{Ar})3d^{10} 4s^2 4p^6$ 13.9996	37 Rb Rubidium 85.4678 $(\text{Kr})5s^1$ 4.1771	38 Sr Strontium 87.62 $(\text{Kr})5s^2$ 5.8949	39 Y Yttrium 88.90585 $(\text{Kr})4d^1 5s^2$ 6.2171	40 Zr Zirconium 91.224 $(\text{Kr})4d^2 5s^2$ 6.8339	41 Nb Niobium 92.90638 $(\text{Kr})4d^4 5s^1$ 6.7589	42 Mo Molybdenum 95.94 $(\text{Kr})4d^5 5s^1$ 7.0924	43 Tc Technetium (98) $(\text{Kr})4d^5 5s^2$ 7.28	44 Ru Ruthenium 101.07 $(\text{Kr})4d^7 5s^1$ 7.3605	45 Rh Rhodium 102.90550 $(\text{Kr})4d^8 5s^1$ 7.4589	46 Pd Palladium 106.42 $(\text{Kr})4d^{10}$ 7.3605	47 Ag Silver 107.8682 $(\text{Kr})4d^{10} 5s^1$ 7.5762	48 Cd Cadmium 112.411 $(\text{Kr})4d^{10} 5s^2$ 8.9938	49 In Indium 114.818 $(\text{Kr})4d^{10} 5s^2 5p^1$ 5.7864	50 Sn Tin 118.710 $(\text{Kr})4d^{10} 5s^2 5p^2$ 7.3439	51 Sb Antimony 121.760 $(\text{Kr})4d^{10} 5s^2 5p^3$ 8.6564	52 Te Tellurium 127.60 $(\text{Kr})4d^{10} 5s^2 5p^4$ 9.0596	53 I Iodine 126.90447 $(\text{Kr})4d^{10} 5s^2 5p^5$ 10.4513	54 Xe Xenon 131.29 $(\text{Kr})4d^{10} 5s^2 5p^6$ 12.1286	55 Cs Cesium 132.90545 $(\text{Xe})6s^1$ 3.8939	56 Ba Barium 137.327 $(\text{Xe})6s^2$ 5.2117	57 La Lanthanum 138.9055 $(\text{Xe})4f^1 5d^1 6s^2$ 6.8251	58 Ce Cerium 140.116 $(\text{Xe})4f^1 5d^1 6s^2$ 7.5496	59 Pr Praseodymium 140.90765 $(\text{Xe})4f^3 6s^2$ 7.8640	60 Nd Neodymium 144.24 $(\text{Xe})4f^4 6s^2$ 7.8335	61 Pm Promethium (145) $(\text{Xe})4f^5 6s^2$ 7.8335	62 Sm Samarium 150.36 $(\text{Xe})4f^6 6s^2$ 8.9570	63 Eu Europium 151.964 $(\text{Xe})4f^7 6s^2$ 9.2255	64 Gd Gadolinium 157.25 $(\text{Xe})4f^7 5d^1 6s^2$ 10.4375	65 Tb Terbium 158.92534 $(\text{Xe})4f^9 6s^2$ 9.2255	66 Dy Dysprosium 162.50 $(\text{Xe})4f^{10} 6s^2$ 10.4375	67 Ho Holmium 164.93032 $(\text{Xe})4f^{11} 6s^2$ 10.4375	68 Er Erbium 167.26 $(\text{Xe})4f^{12} 6s^2$ 10.4375	69 Tm Thulium 168.93421 $(\text{Xe})4f^{13} 6s^2$ 10.4375	70 Yb Ytterbium 173.04 $(\text{Xe})4f^{14} 6s^2$ 10.4375	71 Lu Lutetium 174.967 $(\text{Xe})4f^{14} 5d^1 6s^2$ 10.4375	72 Hf Hafnium 178.49 $(\text{Xe})4f^{14} 5d^2 6s^2$ 6.8251	73 Ta Tantalum 180.9479 $(\text{Xe})4f^{14} 5d^3 6s^2$ 7.5496	74 W Tungsten 183.84 $(\text{Xe})4f^{14} 5d^4 6s^2$ 7.8640	75 Re Rhenium 186.207 $(\text{Xe})4f^{14} 5d^5 6s^2$ 7.8335	76 Os Osmium 190.23 $(\text{Xe})4f^{14} 5d^6 6s^2$ 8.4382	77 Ir Iridium 192.222 $(\text{Xe})4f^{14} 5d^7 6s^2$ 8.9570	78 Pt Platinum 195.078 $(\text{Xe})4f^{14} 5d^9 6s^1$ 8.9570	79 Au Gold 196.96655 $(\text{Xe})4f^{14} 5d^{10} 6s^1$ 9.2255	80 Hg Mercury 200.59 $(\text{Xe})4f^{14} 5d^{10} 6s^2$ 10.4375	81 Tl Thallium 204.3833 $(\text{Hg})6p^1$ 6.1062	82 Pb Lead 207.2 $(\text{Hg})6p^2$ 7.4167	83 Bi Bismuth 208.98038 $(\text{Hg})6p^3$ 7.2856	84 Po Polonium (209) $(\text{Hg})6p^4$ 8.417 ?	85 At Astatine (210) $(\text{Hg})6p^5$ 8.417 ?	86 Rn Radon (222) $(\text{Hg})6p^6$ 10.7485	87 Fr Francium (223) $(\text{Rn})7s^1$ 4.0727	88 Ra Radium (226) $(\text{Rn})7s^2$ 5.2784	89 Ac Actinium (227) $(\text{Rn})5f^1 7s^2$ 5.17	90 Th Thorium 232.0381 $(\text{Rn})6d^2 7s^2$ 6.3067	91 Pa Protactinium 231.03688 $(\text{Rn})5f^2 7s^2$ 5.89	92 U Uranium 238.02891 $(\text{Rn})5f^3 7s^2$ 6.1941	93 Np Neptunium 237 $(\text{Rn})5f^4 7s^2$ 6.2657	94 Pu Plutonium 244 $(\text{Rn})5f^6 7s^2$ 6.0262	95 Am Americium (243) $(\text{Rn})5f^7 7s^2$ 5.9738	96 Cm Curium (247) $(\text{Rn})5f^7 7s^2 7p^1$ 5.9915	97 Bk Berkelium (247) $(\text{Rn})5f^7 7s^2 7p^2$ 6.1979	98 Cf Californium (251) $(\text{Rn})5f^7 7s^2 7p^3$ 6.2817	99 Es Einsteinium (252) $(\text{Rn})5f^7 7s^2 7p^4$ 6.42	100 Fm Fermium (257) $(\text{Rn})5f^7 7s^2 7p^5$ 6.50	101 Md Mendelevium (258) $(\text{Rn})5f^7 7s^2 7p^6$ 6.58	102 No Nobelium (259) $(\text{Rn})5f^7 7s^2 7p^7$ 6.65	103 Lr Lawrencium (262) $(\text{Rn})5f^7 7s^2 7p^7$ 4.9 ?
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□ Solids
□ Liquids
□ Gases
□ Artificially Prepared

For a description of
the atomic data, visit
physics.nist.gov/atomic

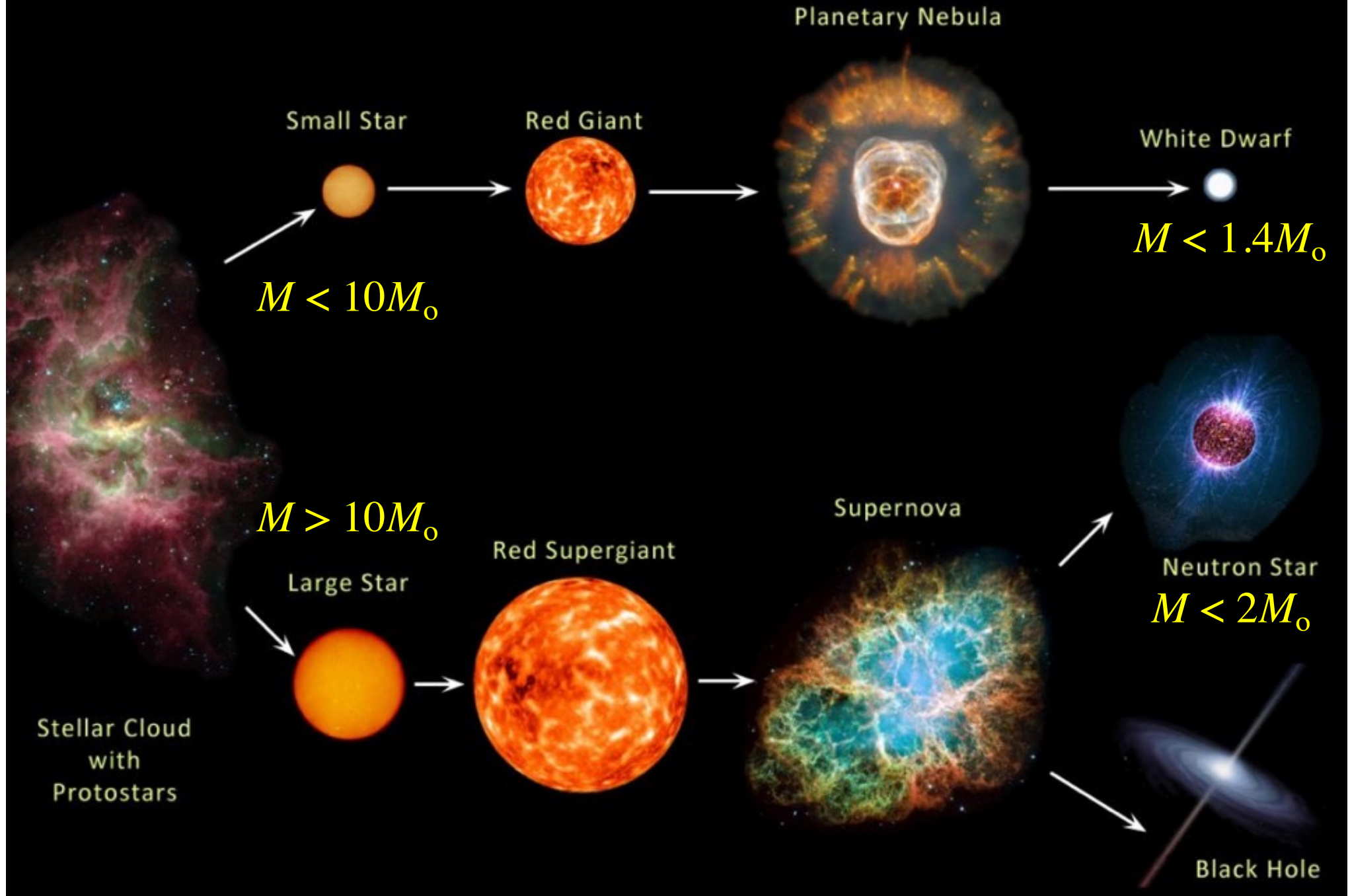
Atomic Number
Ground-state Level
Symbol
Name
Atomic Weight
Ground-state Configuration
Ionization Energy (eV)

58 1G_4
Ce
Cerium
140.116
 $(\text{Xe})4f^1 5d^1 6s^2$
5.5387

Based upon ^{12}C . () indicates the mass number of the most stable isotope. For a description and the most accurate values and uncertainties, see J. Phys. Chem. Ref. Data, 26 (5), 1239 (1997).

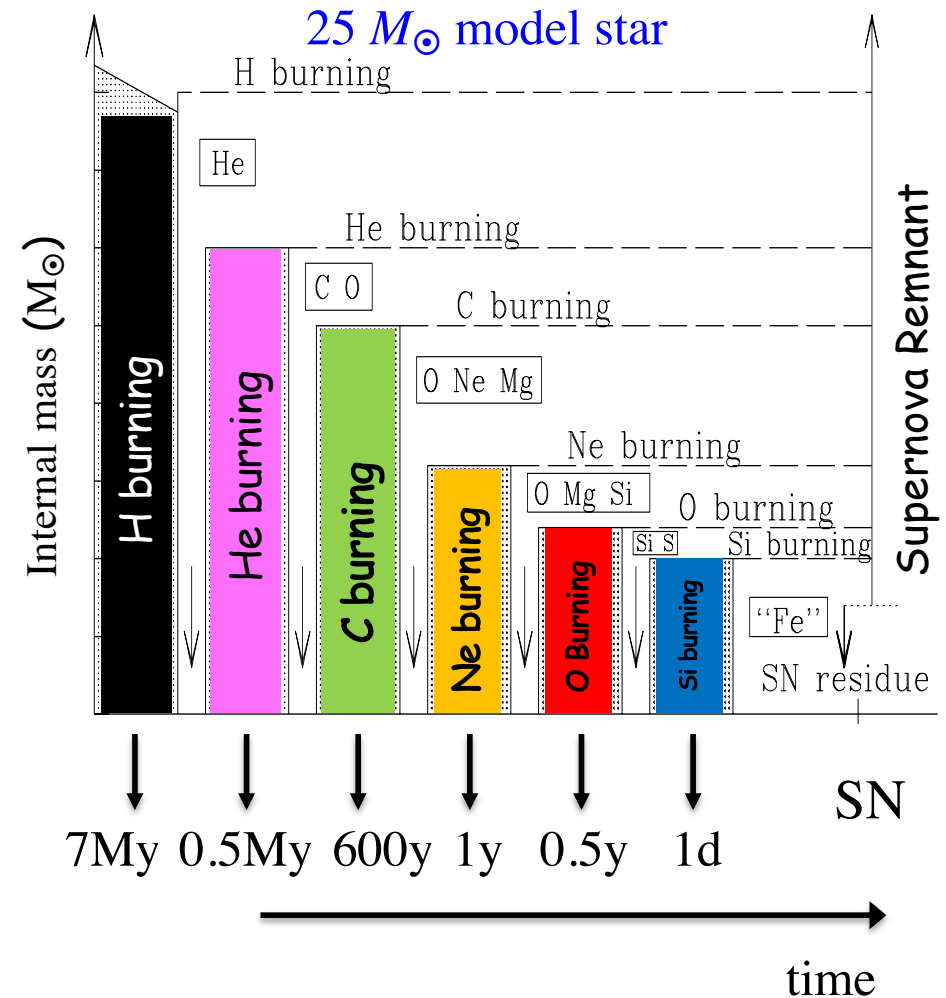
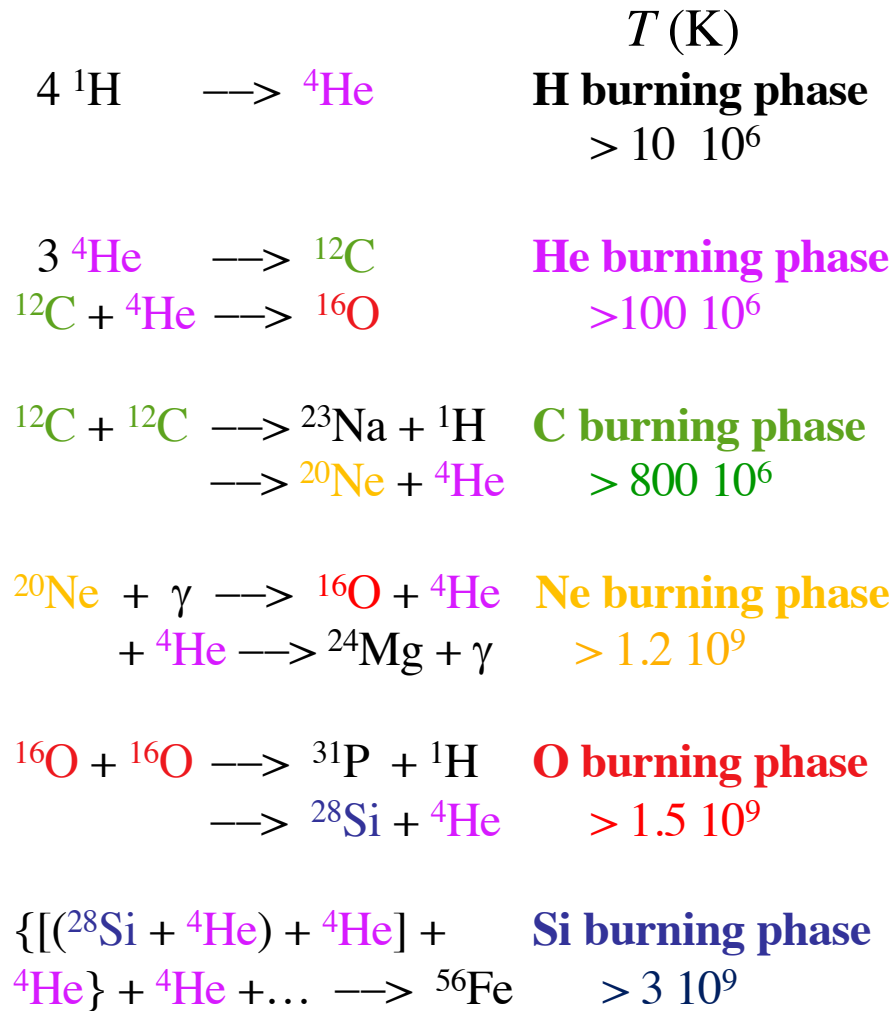
March 1999

Stars: gravitationnally controlled nuclear reactors

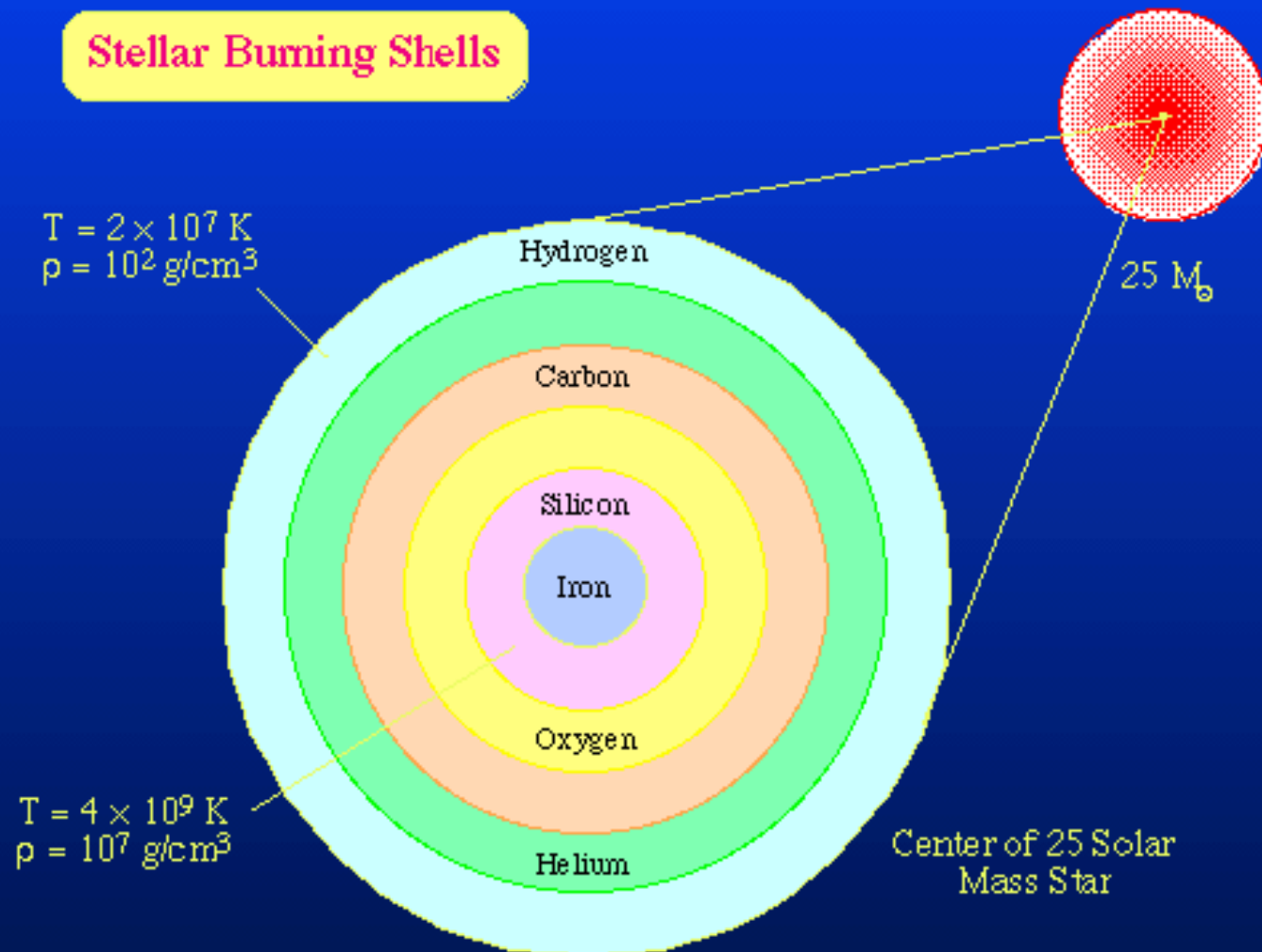


The evolution and nucleosynthesis of massive stars ($M \geq 10 M_{\odot}$)

Gravitationally controlled fusion in stars



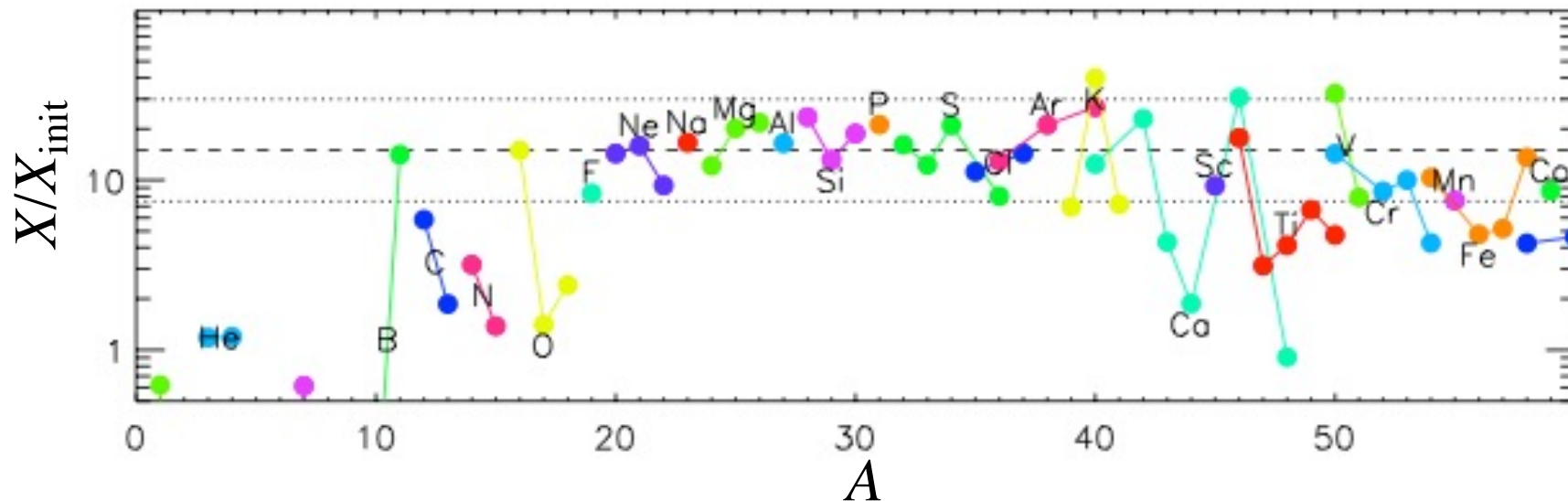
Stellar Burning Shells



Supernova explosions of massive stars enrich the interstellar medium in heavy elements up to the Fe group



Overproduction factors of isotopes from H to Fe in a $25 M_{\odot}$ star



Origin of the 52 elements heavier than Fe

PERIODIC TABLE
Atomic Properties of the Elements

Physics Laboratory **NIST** Standard Reference Data Program
physics.nist.gov www.nist.gov www.nist.gov/srd

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum c 299 792 458 m s⁻¹ (exact)
Planck constant h 6.626 069 3 × 10⁻³⁴ J s ($\hbar = h/2\pi$)
elementary charge e 1.602 176 634 × 10⁻¹⁹ C
electron mass m_e 9.109 383 56 × 10⁻³¹ kg
 $m_e c^2$ 0.5110 MeV
proton mass m_p 1.672 621 63 × 10⁻²⁷ kg
fine-structure constant α 1/137.035 999 074
Rydberg constant R_∞ 10 973 731 568 160 m⁻¹
 R_H 10 973 731 568 160 m⁻¹
 $R_\infty h c$ 13.605 698 eV
Boltzmann constant k 1.380 658 × 10⁻²³ J K⁻¹

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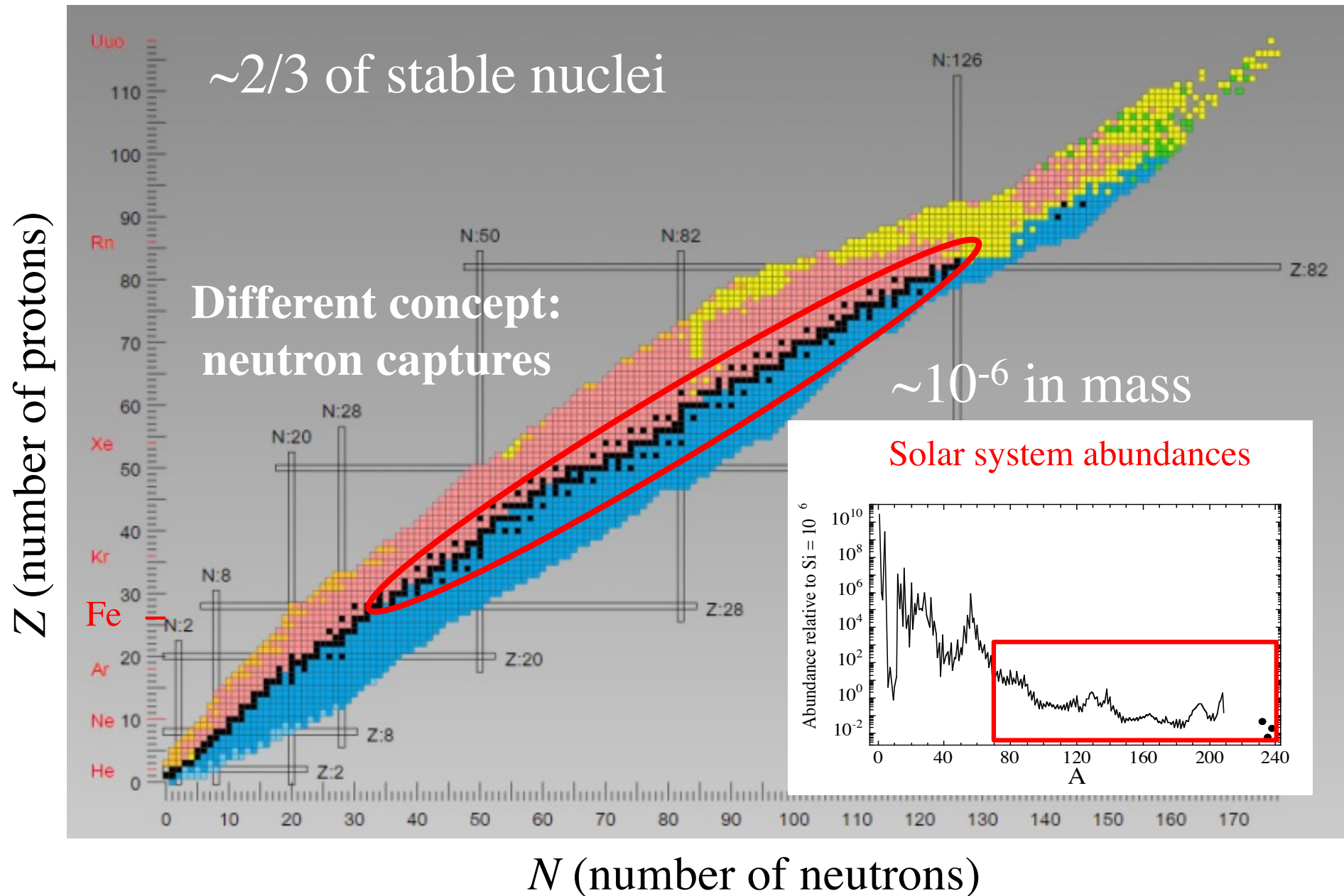
Period

Group

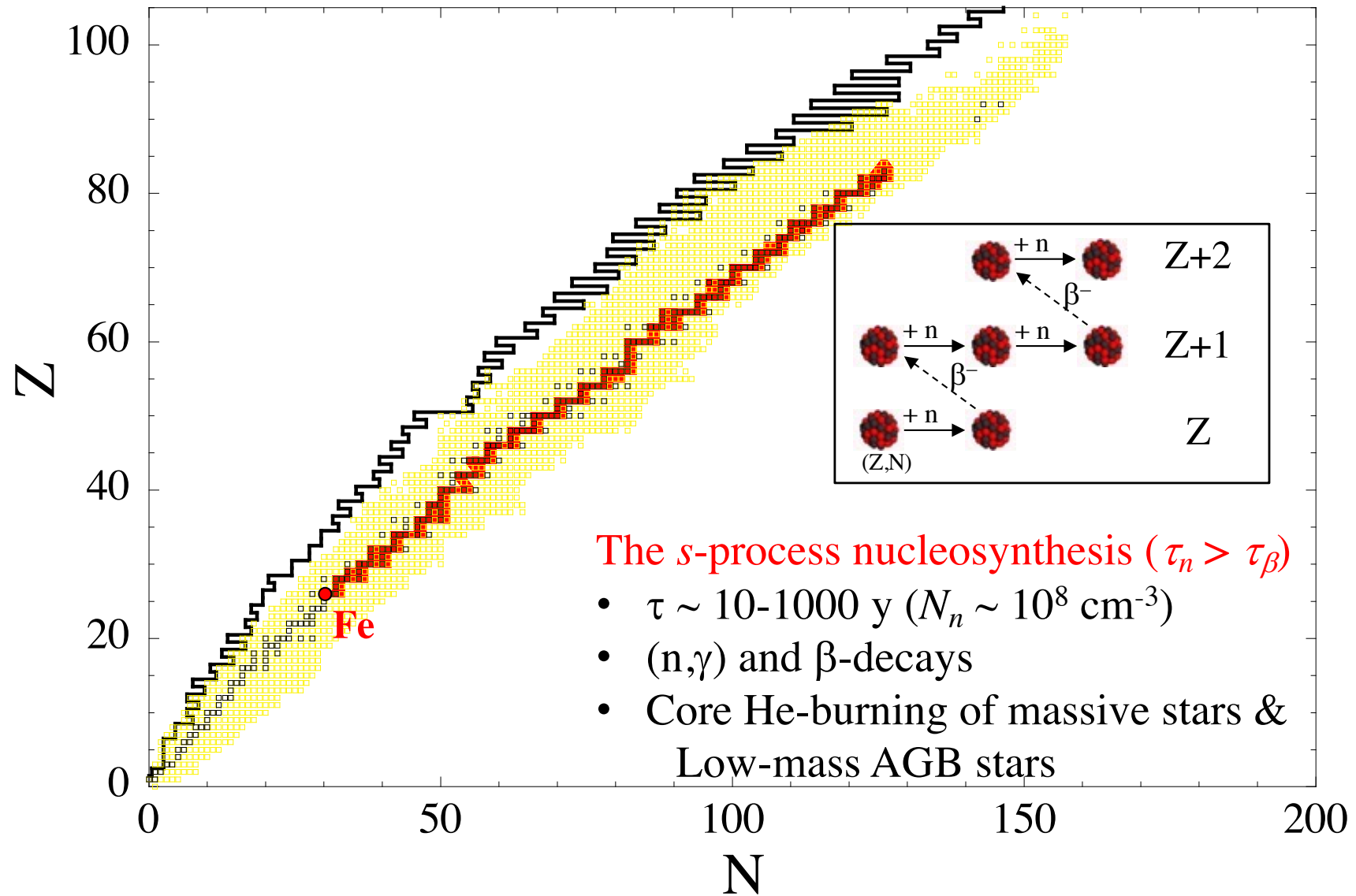
IA IIA IIIA IVA VA VIA VIIA VIIIA IB IIB

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Nucleosynthesis of the elements heavier than iron



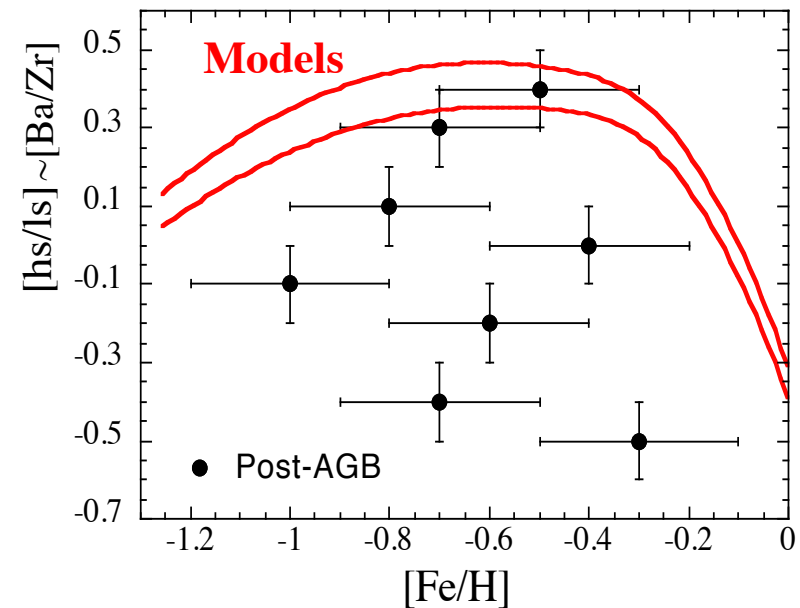
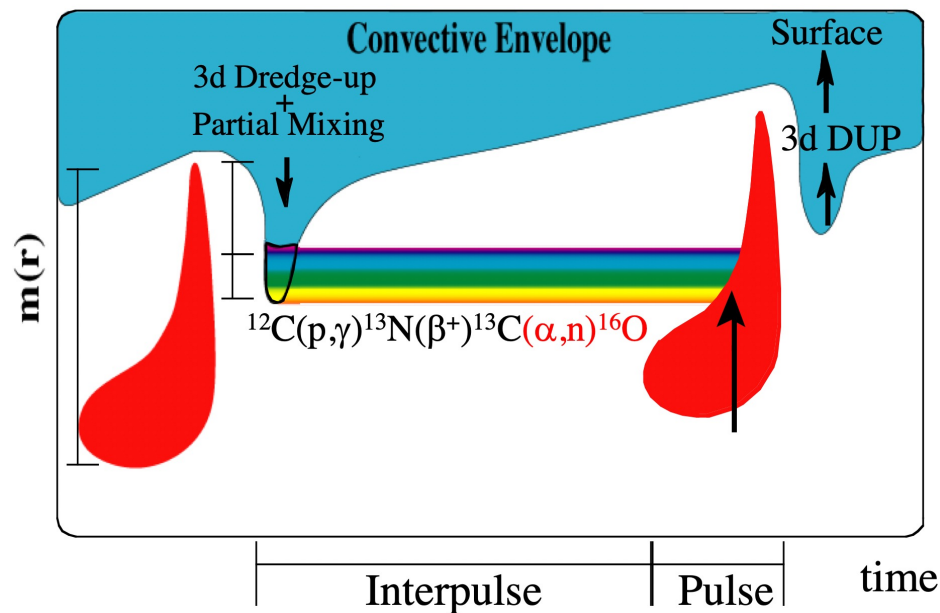
The slow neutron-capture process (or s-process)



The s-process is responsible for about half of the elements heavier than iron in the Universe

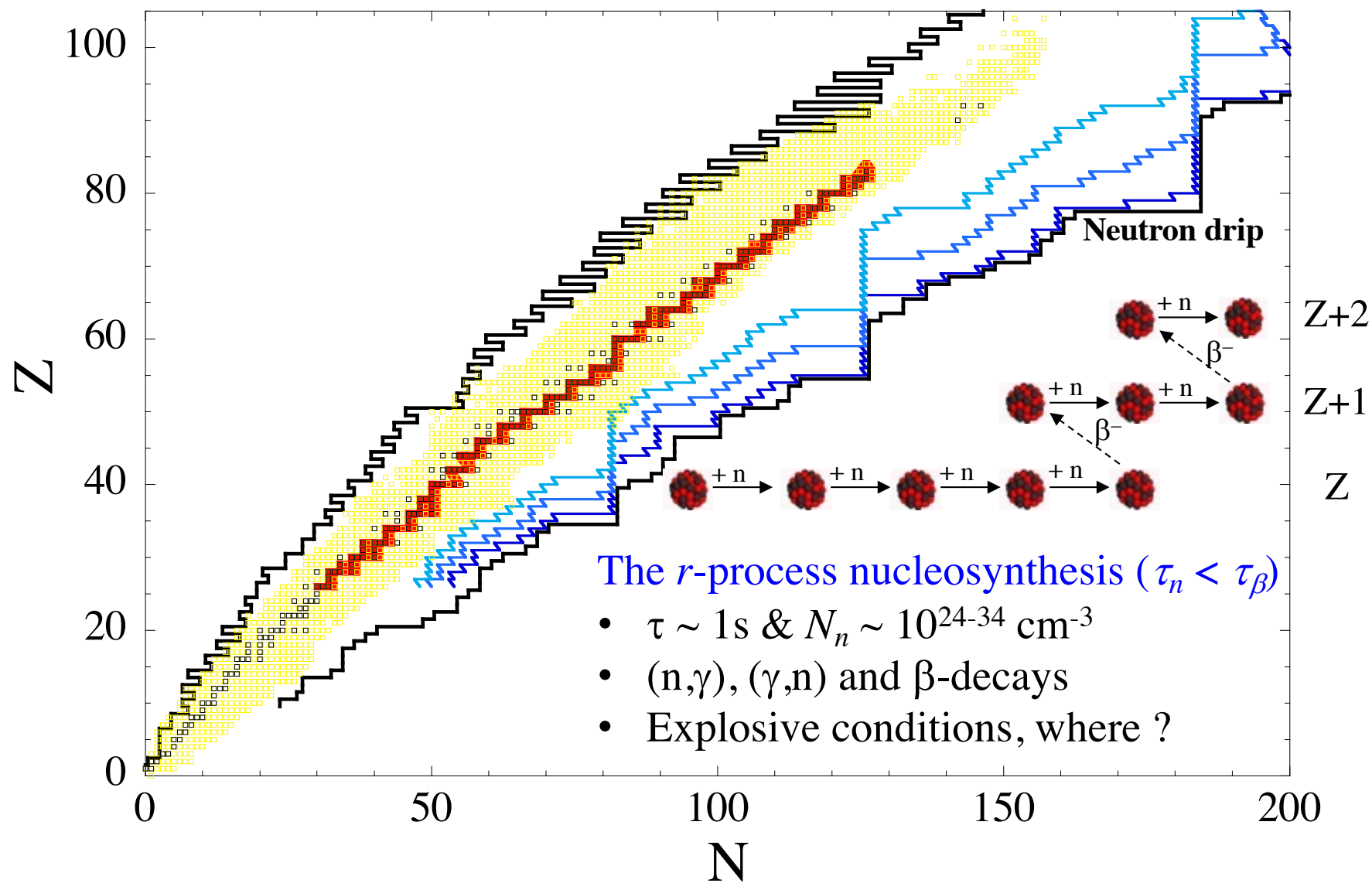
The s-process nucleosynthesis is responsible for half of the elements heavier than iron in the Universe

- How are the neutrons produced in AGB stars ?
- What is the role of the various mixing mechanisms ?
- What is the contributions from intermediate- M AGB stars ?
- How to explain specific observations ?
- (n,γ) and T -dependent β -decay rates of unstable nuclei ?

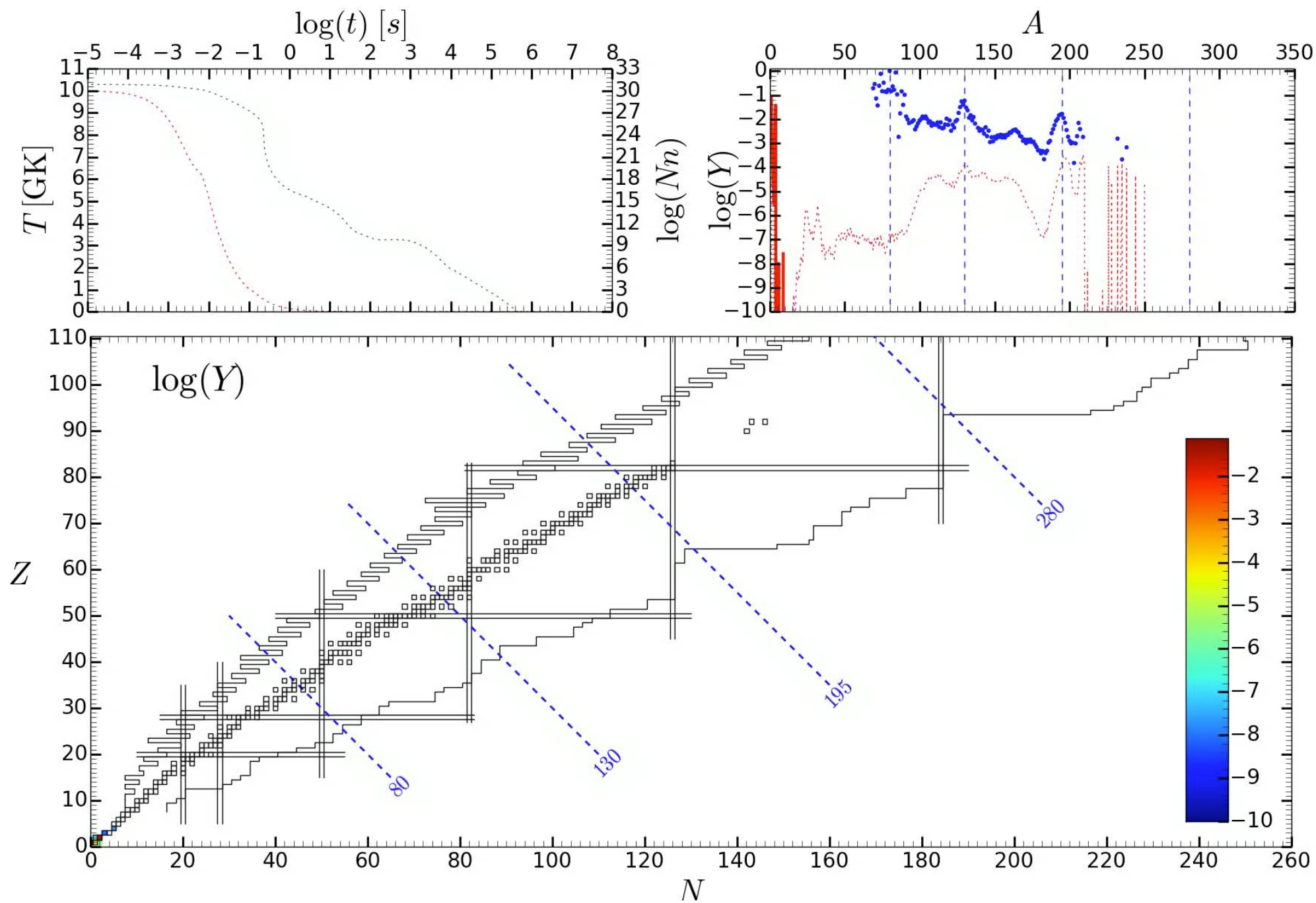


Van Winckel (2003, AARA)

The rapid neutron-capture process (or r-process)



The r-process is responsible for the other half of the elements heavier than iron in the Universe



**Our understanding of the r-process nucleosynthesis,
i.e. the origin of about half of the elements heavier than Fe in the
Universe, has been considered as one of the 11 top fundamental
questions in Physics and Astronomy**

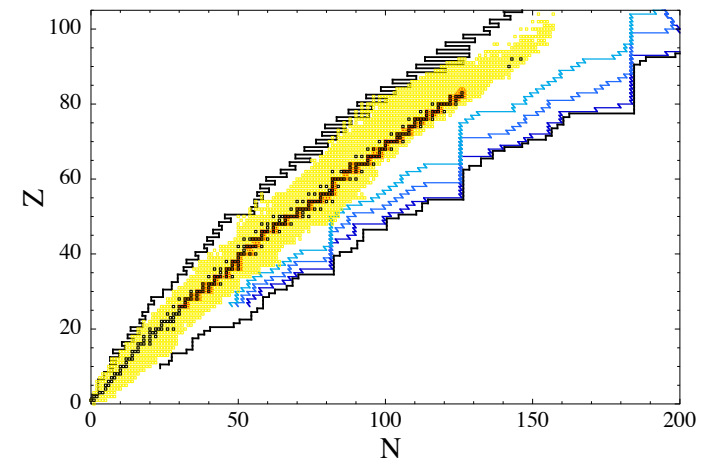
(“Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century”: 2003,
National research council of the national academies, USA)

Some clear signatures

- Rapid neutron-capture process: $N_n \sim 10^{24-34} \text{ cm}^{-3}$
- Explosive environment: $\tau \sim 1\text{s}$, $T \sim 10^9\text{K}$
- Early enrichment of the Galaxy

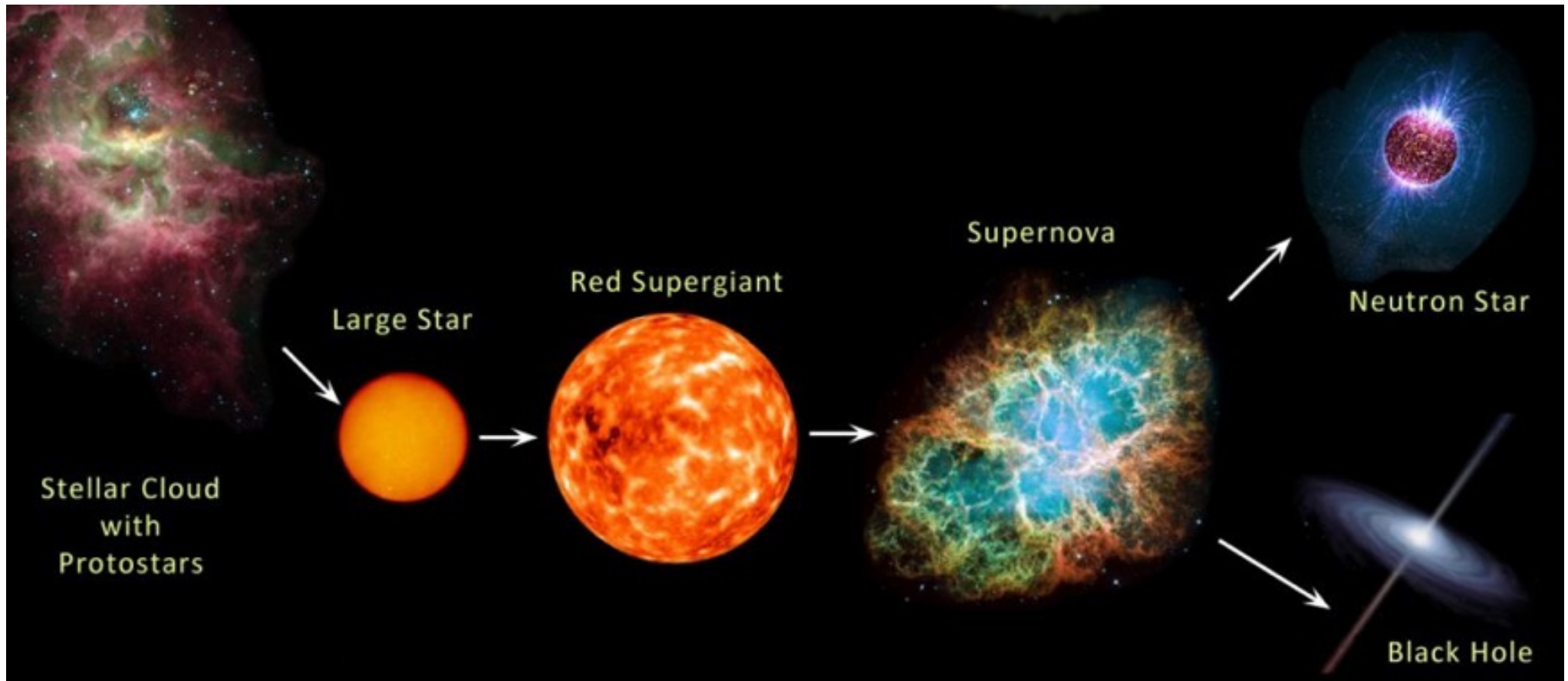
Still many open questions:

- **Astrophysical Site ?**
Where ? When ? How ?
- **Associated Nuclear Physics (no exp)?**
- **Chemical Evolution of the Galaxy ?**



R-process site favoured for a long time: Supernova explosion of massive stars

Explosive environment – enrichment of the interstellar medium



But up to now ... without success ...

An alternative scenario: the decompression of neutron star matter

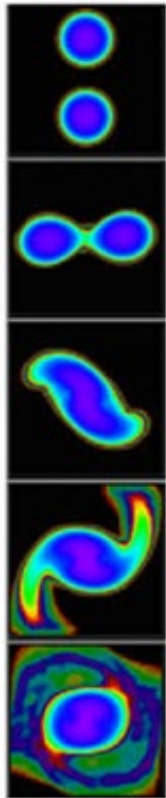
An alternative scenario: binary neutron star mergers

5.04 ms



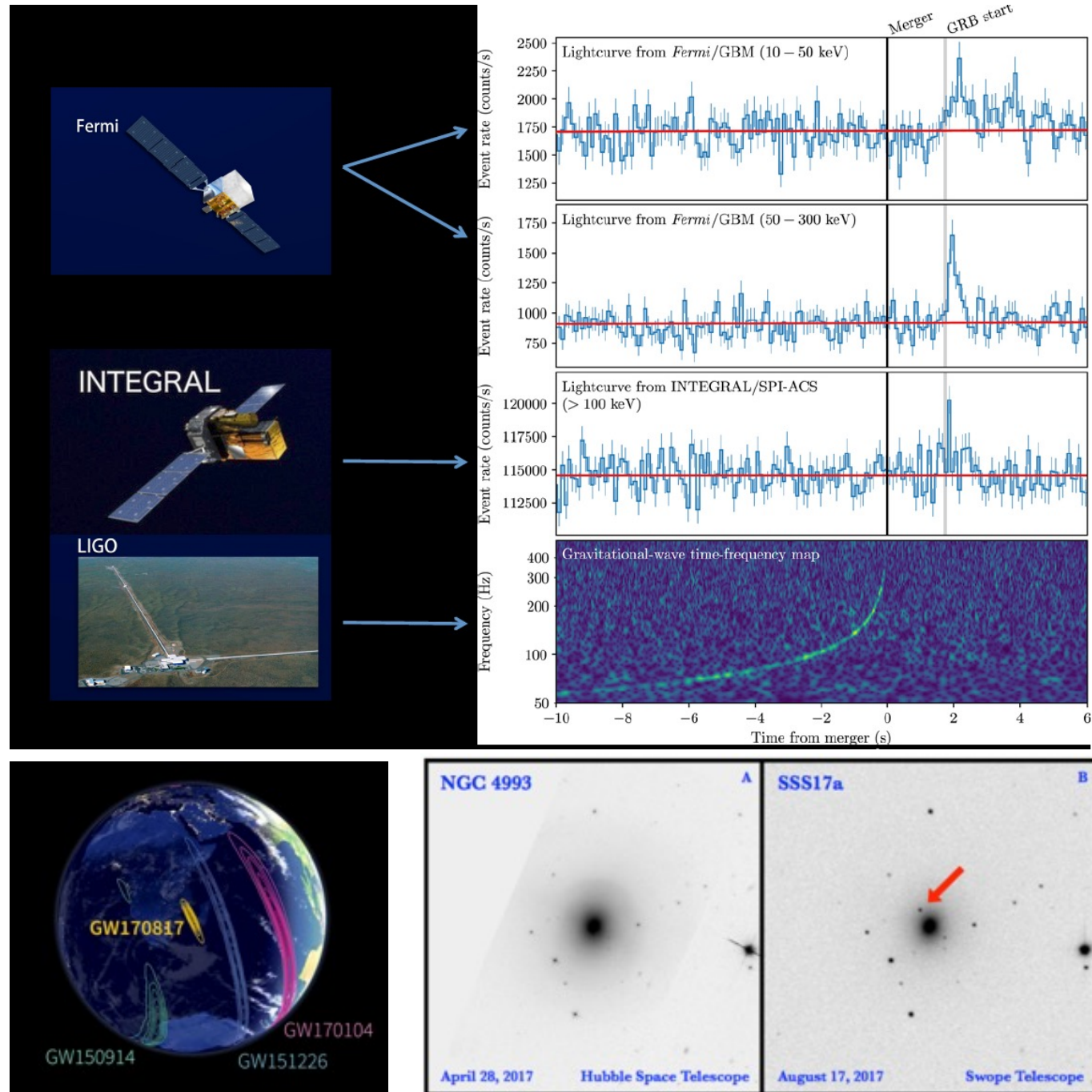
17 August 2017

1st detection of a
neutron star
merger



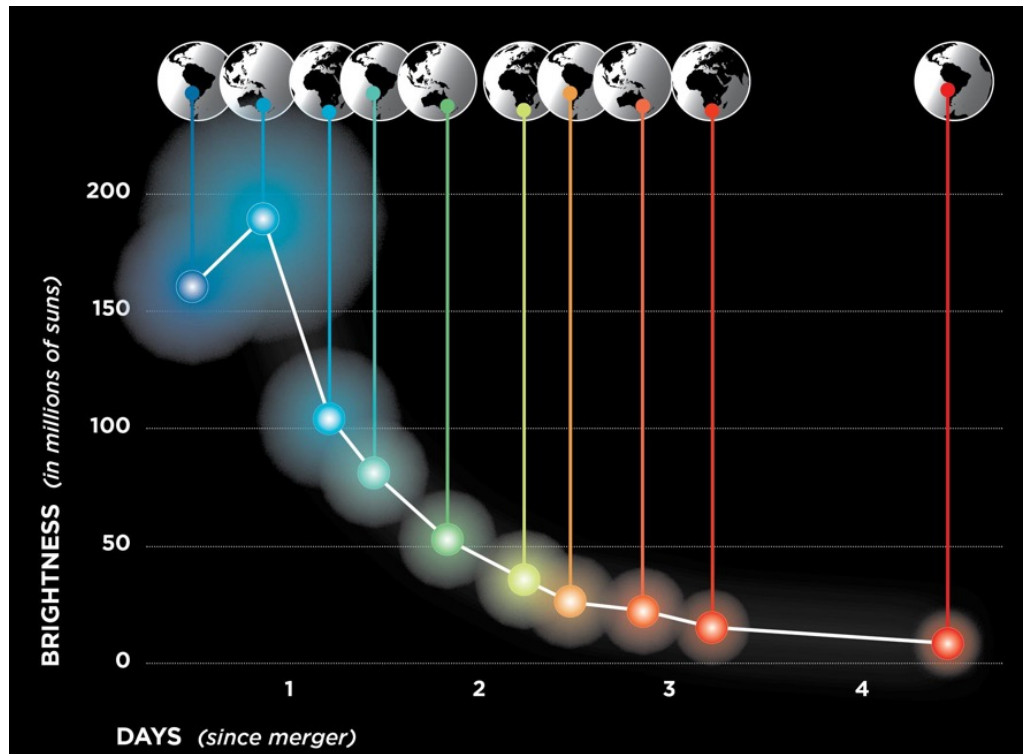
11h later

Optical
multi-messenger
observations



First observation of a “Kilonova”

Light curve ($\sim t^{-1.3}$) compatible with the one from the coalescence of 2 NSs caused by the radioactive decay of heavy elements

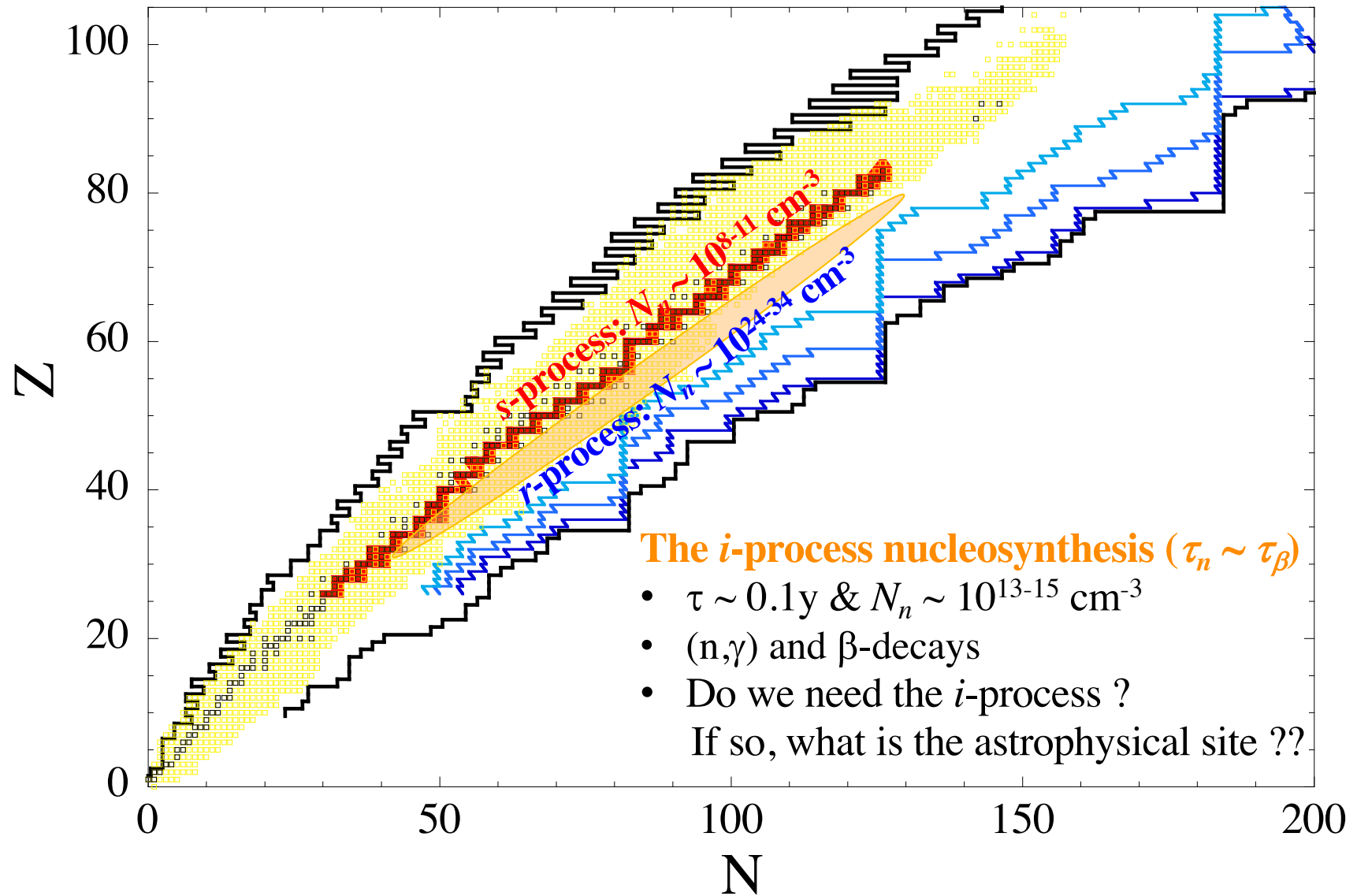


Observations confirm

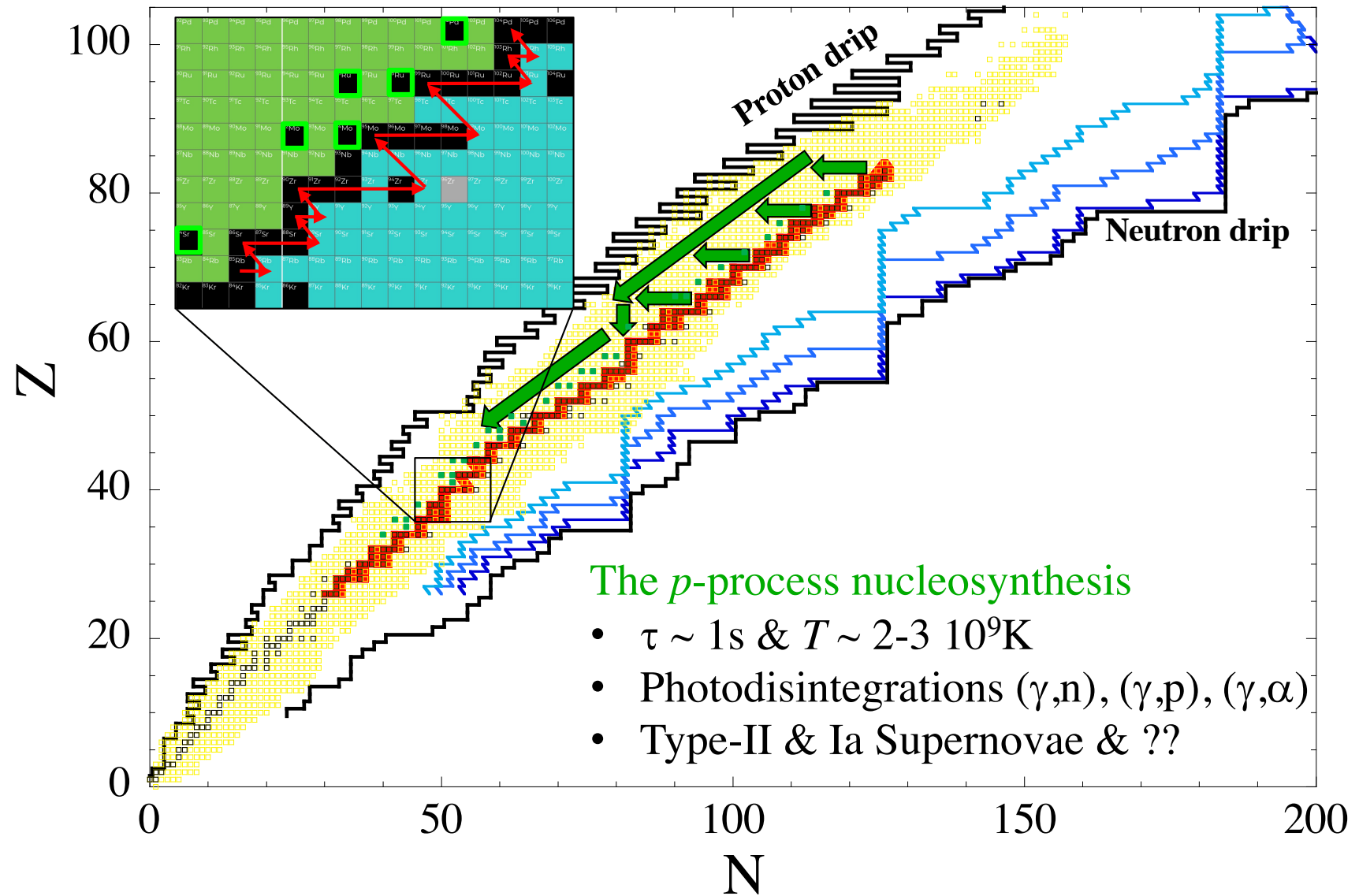
- Ejecta rich in heavy elements ($A > 140$)
- Presence of Sr (produced by the r-process)

The ejected mass and the merger rate derived from GW170817 suggested that neutron star mergers could dominate the *r*-element production in the Universe

What about an intermediate neutron-capture process ?

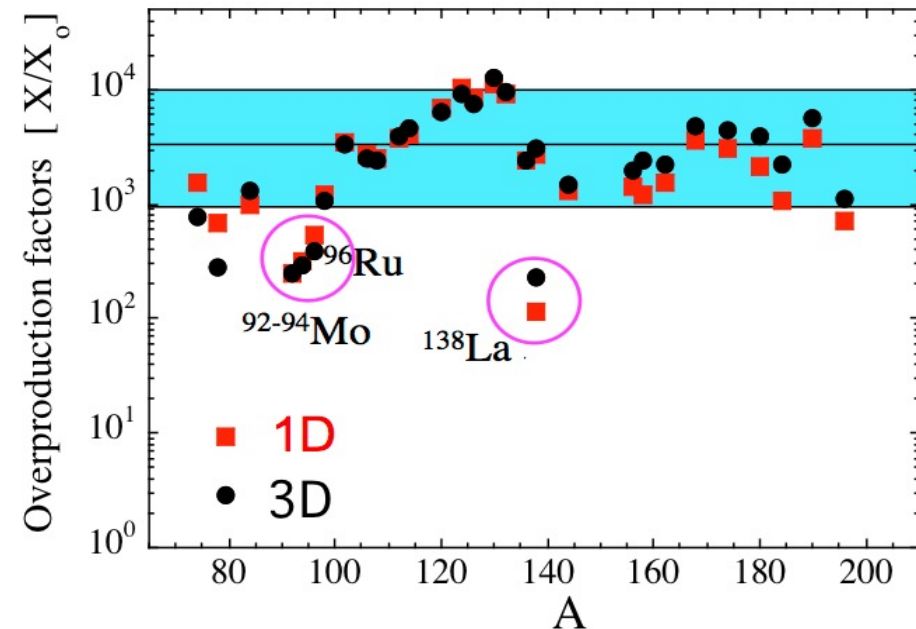
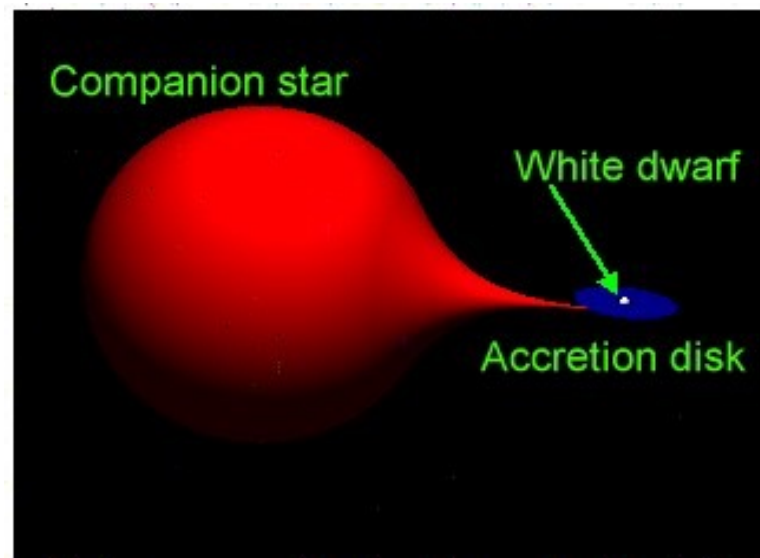


The p-process nucleosynthesis

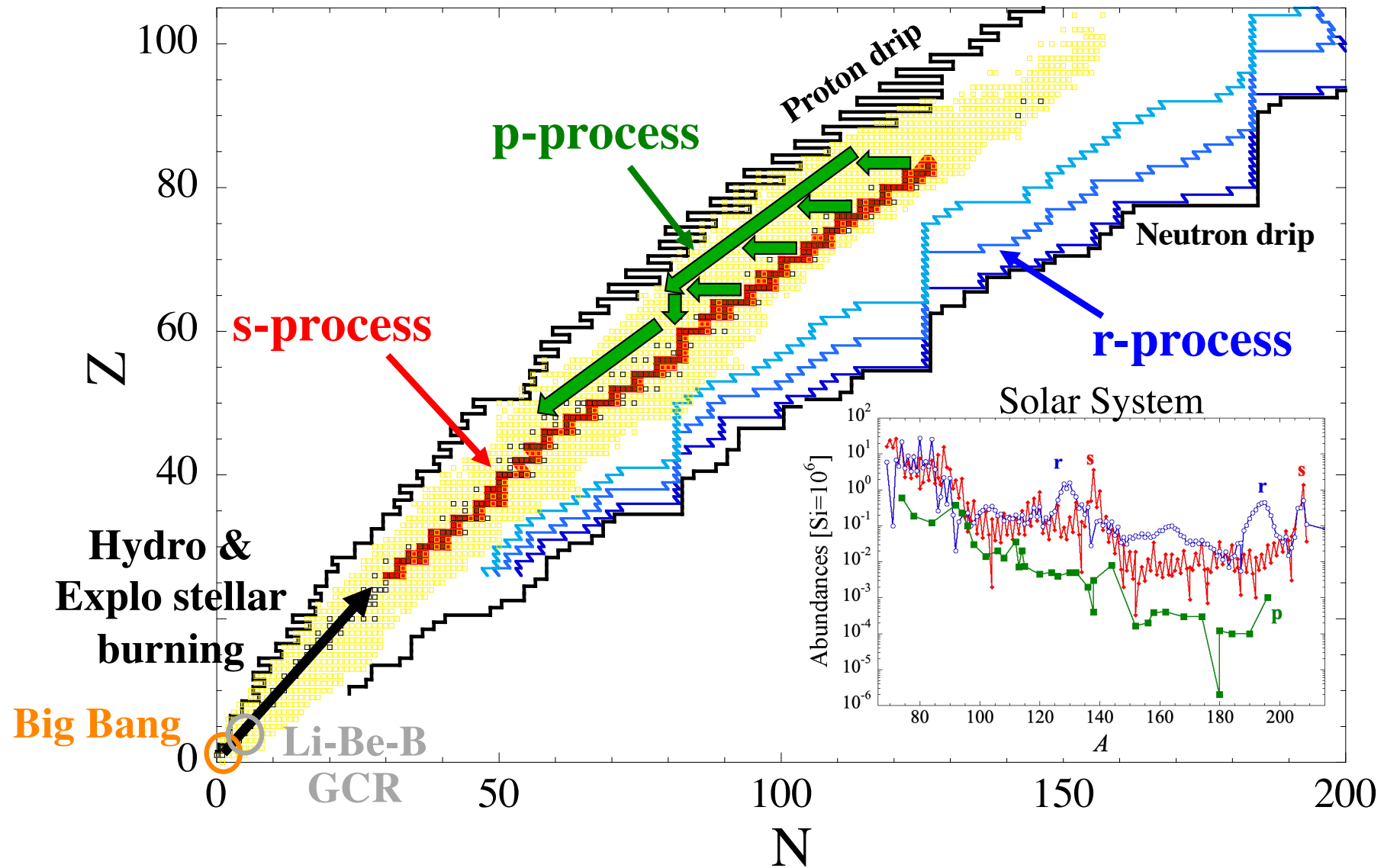


The p-process nucleosynthesis is responsible for n-deficient elements heavier than iron in the Universe

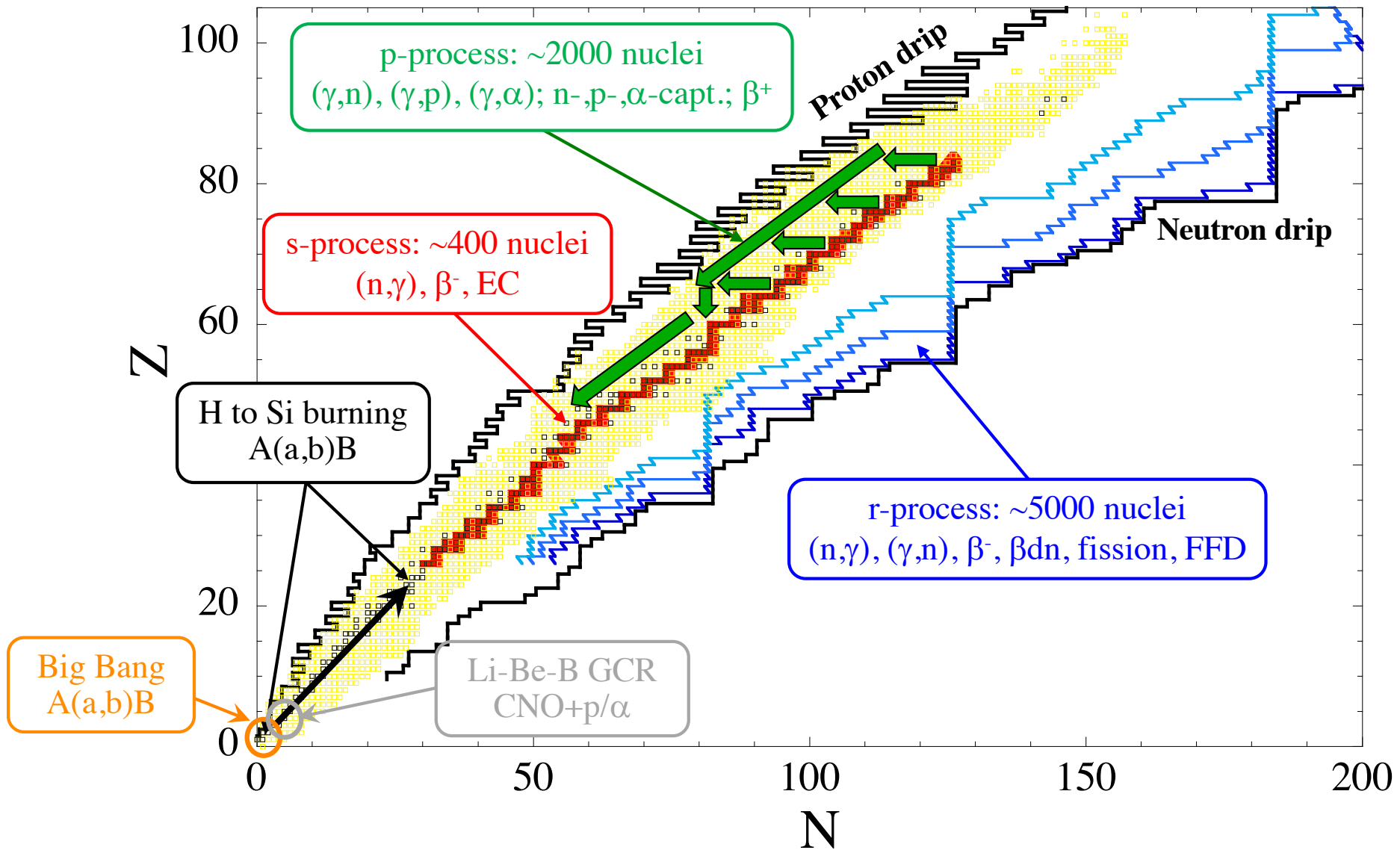
- What is the contribution of SN Ia or p-rich v-wind, if any ?
- What are the seed nuclei feeding the p-process ?
- How to explain the origin of $^{92,94}\text{Mo}$, ^{96}Ru , ^{138}La ?
- What is the role of neutrinos for rare species ?
- What is the photodissociation rates of nuclei involved ?



The various nucleosynthesis processes

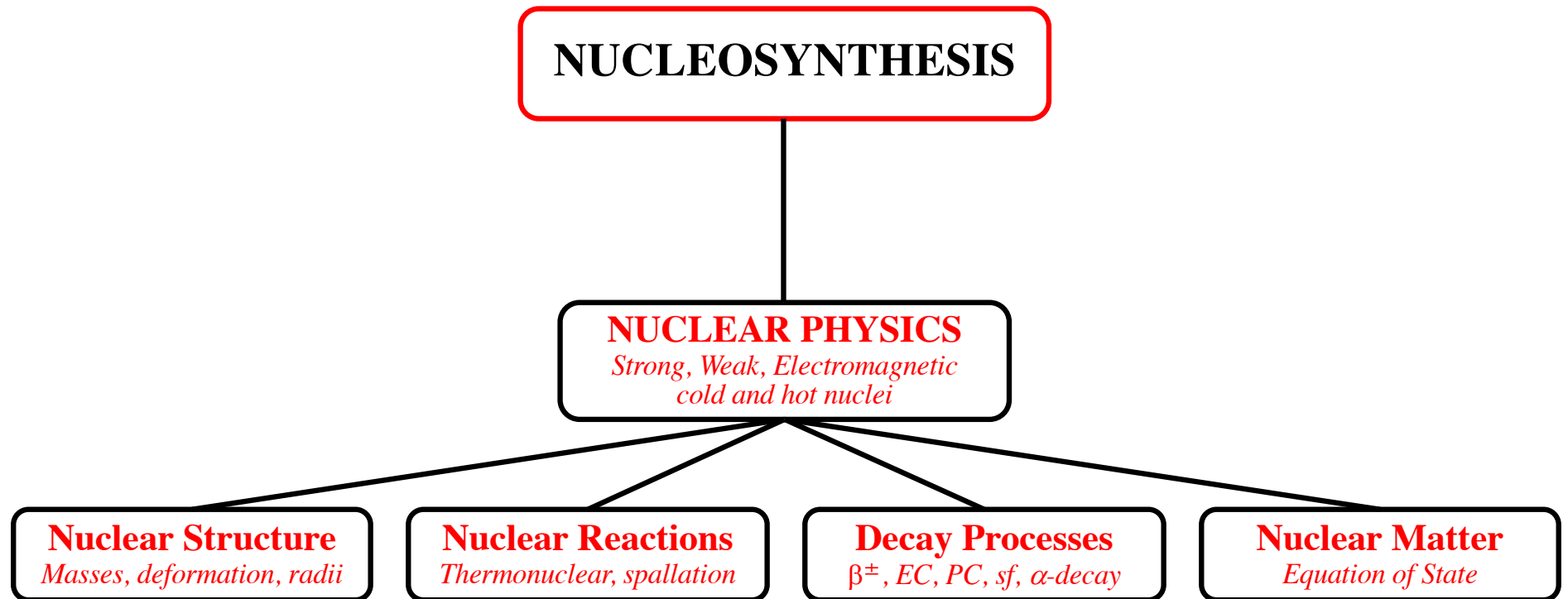


Many different nuclear needs for the various nucleosynthesis processes

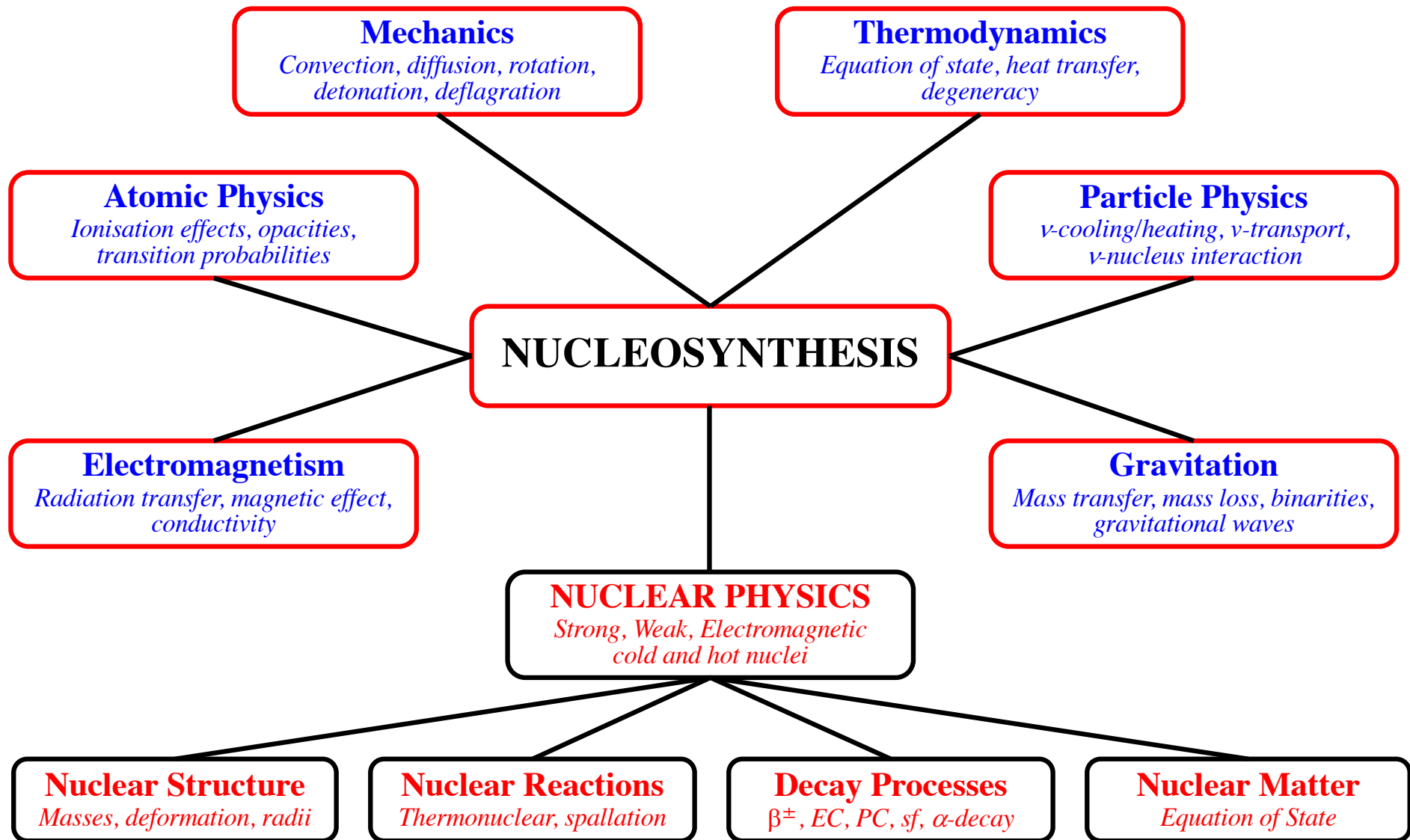


Essentially - Charged-particle-induced reactions: proton & alpha
 - Neutron-induced reactions
 - Photon-induced reactions

Nuclear Physics is a necessary condition for Nucleosynthesis



Nuclear physics is a necessary but not a sufficient condition for Nucleosynthesis



SUMMARY

	ASTRO	NUCLEAR	OBS	
BIG-BANG	+	+	+	LECTURE 1
Li-Be-B	+	+	+	LECTURE 1
SYNTHESIS < FE	+	+	+	LECTURE 1
SPALLATION (?)	--	--	--	LECTURE 1
S-PROCESS	-/+	+/-	+/-	LECTURE 2
I-PROCESS	-/+	+/-	+/-	LECTURE 2
R-PROCESS	-/+	--	-/+	LECTURE 3-4
P-PROCESS	-/+	-	-	LECTURE 4

Still many observations remain unexplained, astrophysical sites
unexplored, nuclear reactions undetermined.

**THANK YOU
FOR
YOUR ATTENTION**