Francqui chair Professor 2020-2021

Professor Stéphane Goriely

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

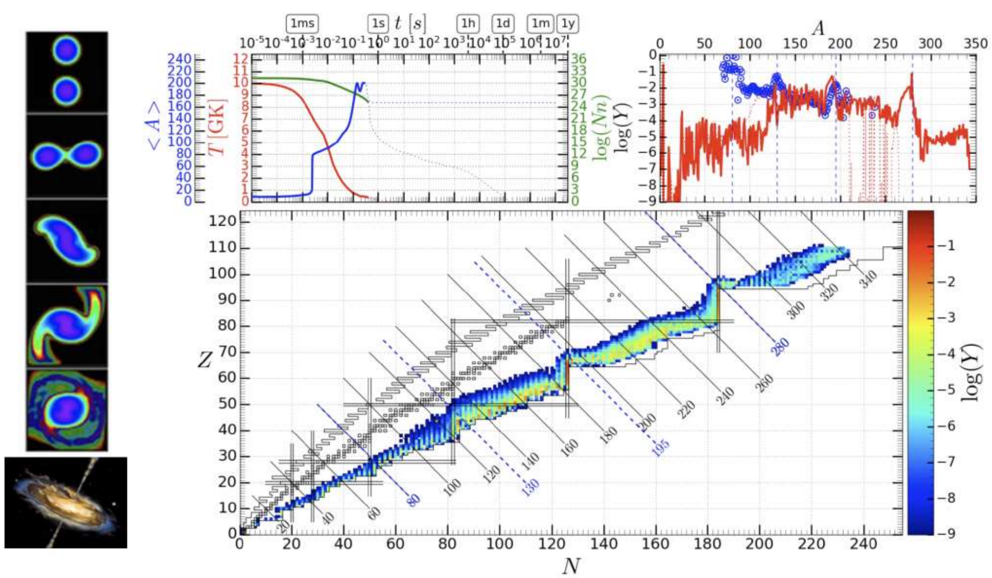
" About the creation of elements in the Universe"

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

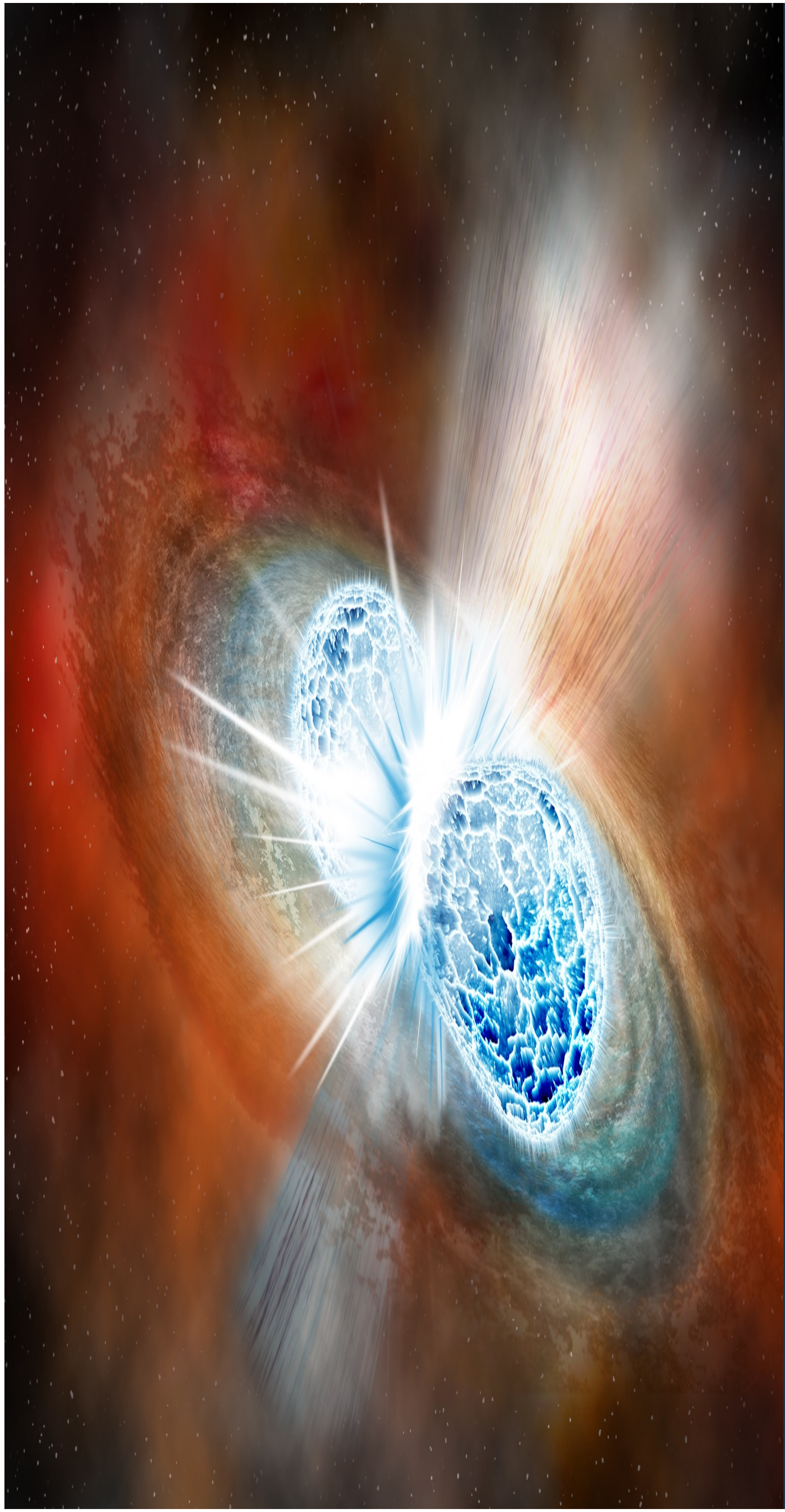
Programme

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

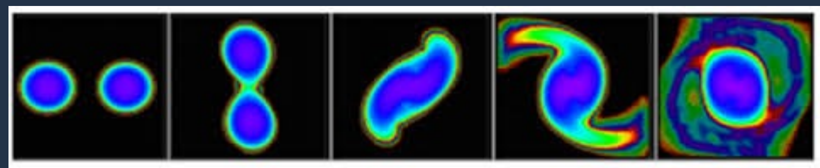
17:10 Inaugural lecture by Prof. S. Goriely



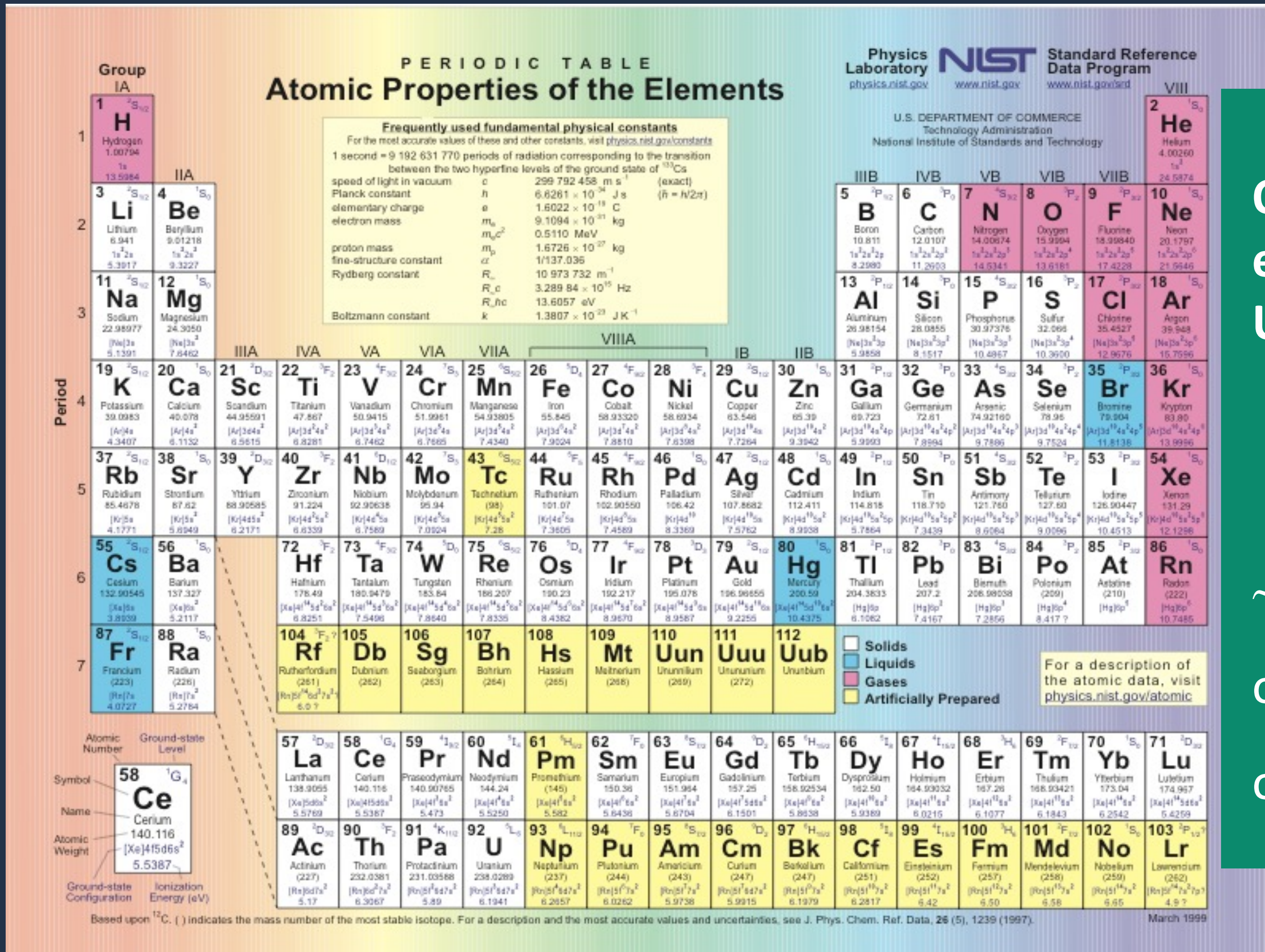
Lecture series:
Monday May 10th 2021, 14:00 - 16:00
Monday May 17th 2021, 14:00 - 16:00
Tuesday May 25th 2021, 16:00 - 18:00
Monday May 31st 2021, 14:00 - 16:00



About the creation of elements in the Universe



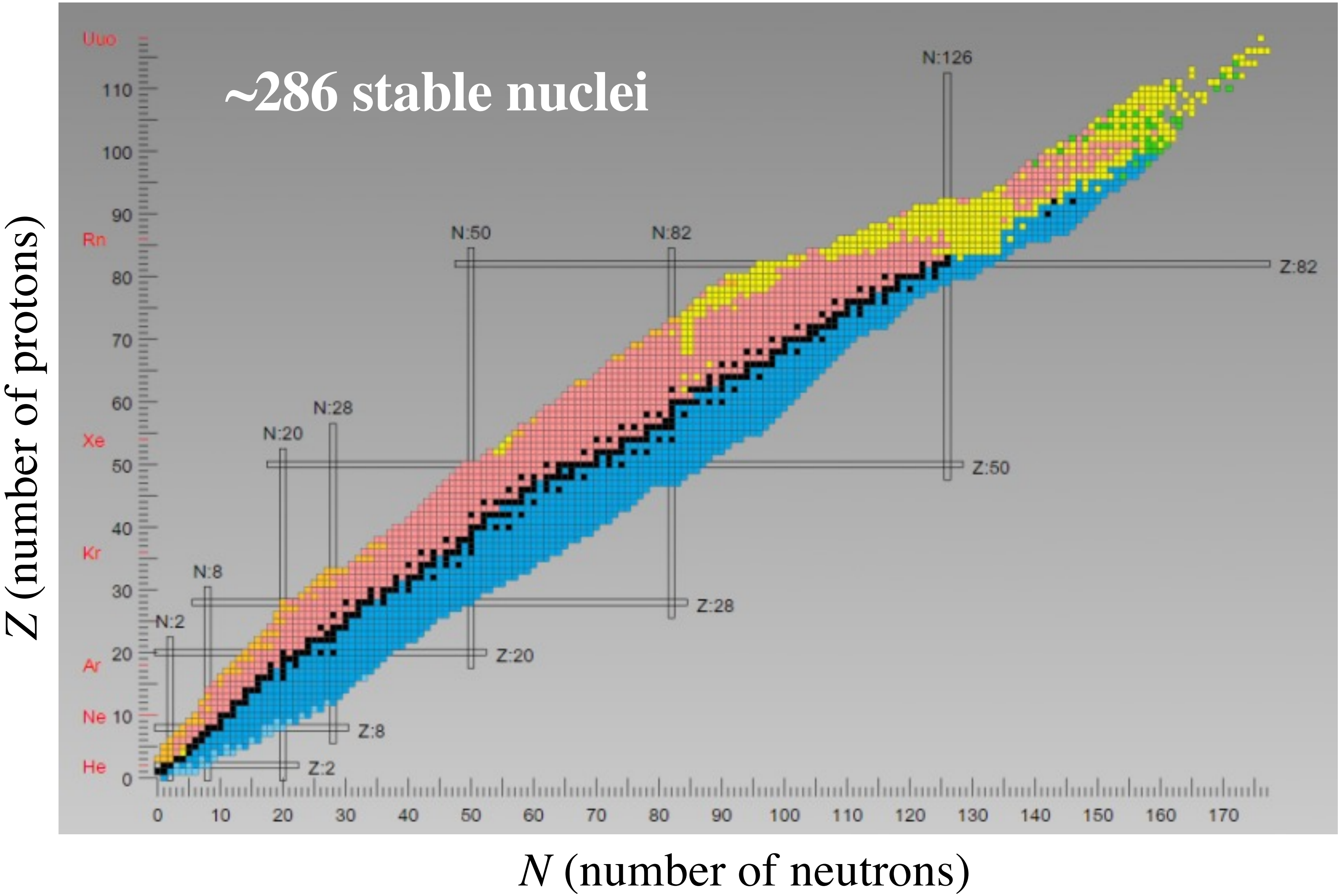
S. Goriely (IAA-ULB)



Origin of the elements in the Universe ?

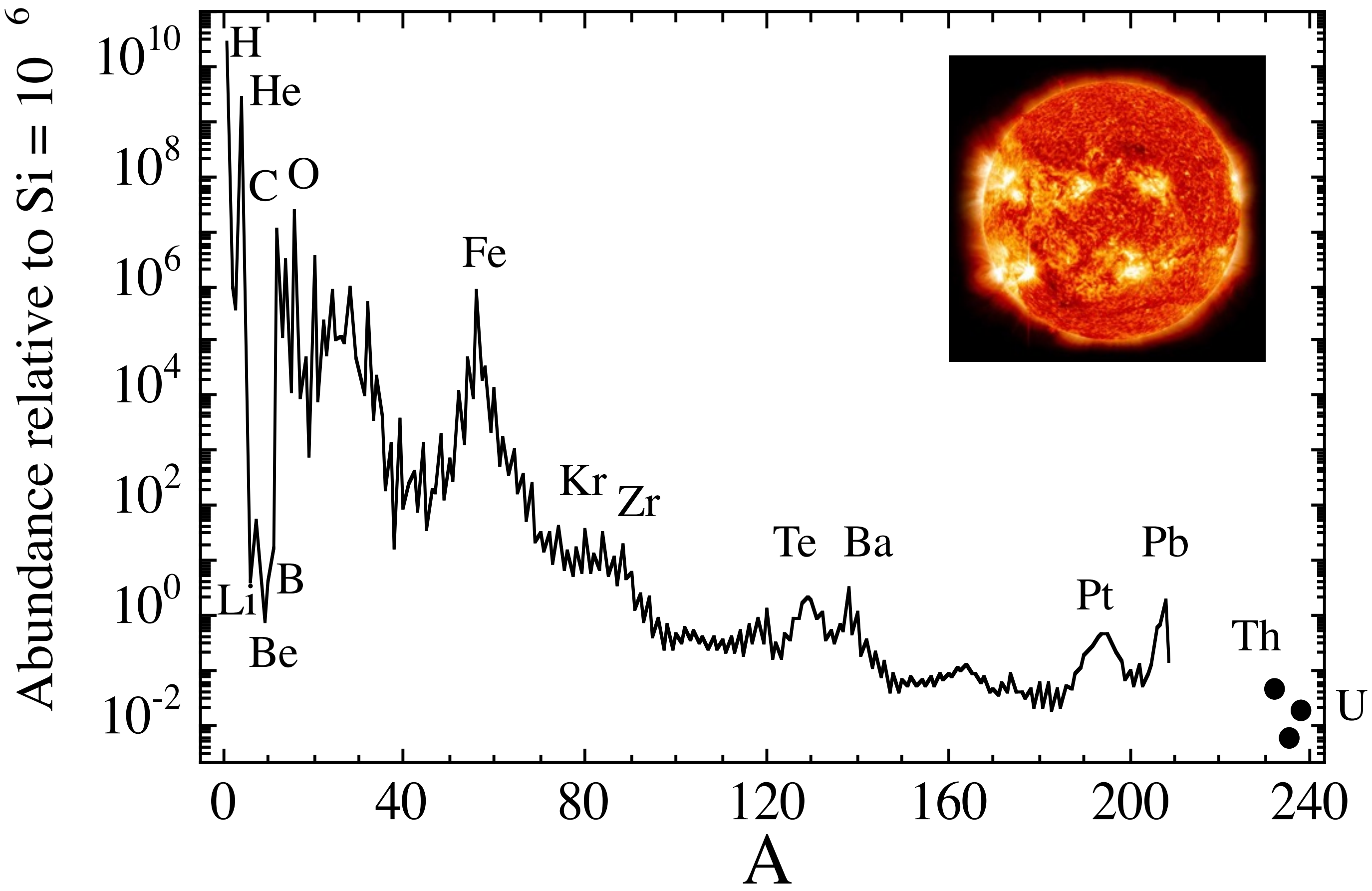
~ 83 naturally occuring elements on Earth

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

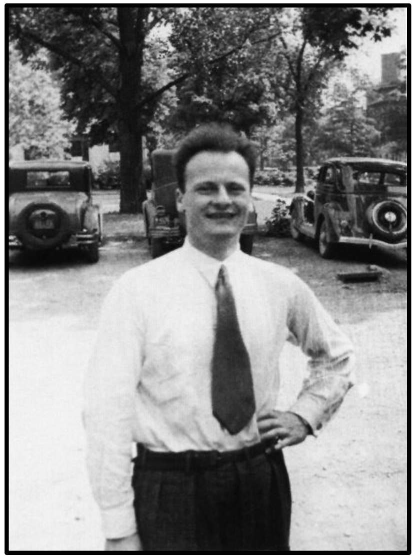
Some important dates in the history of nucleosynthesis

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

$\longrightarrow$ p-p chains and CNO cycle

Gamow

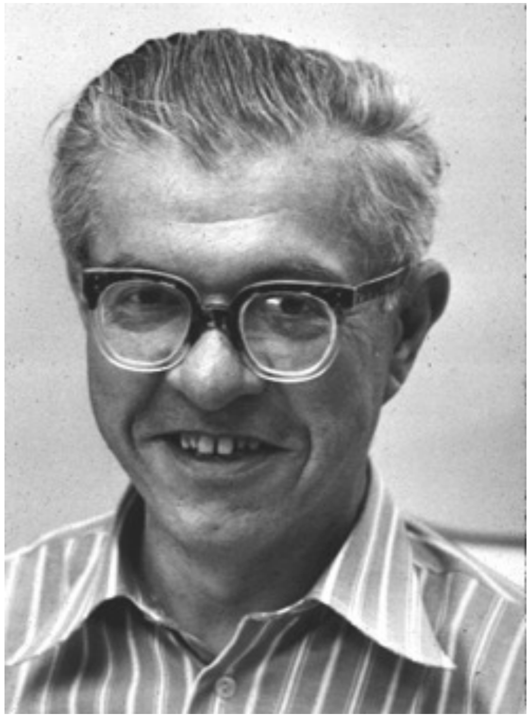
Von Weizsacker



Bethe

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

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



Hoyle

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

→ rich and present nucleosynthesis in stars

Tc →

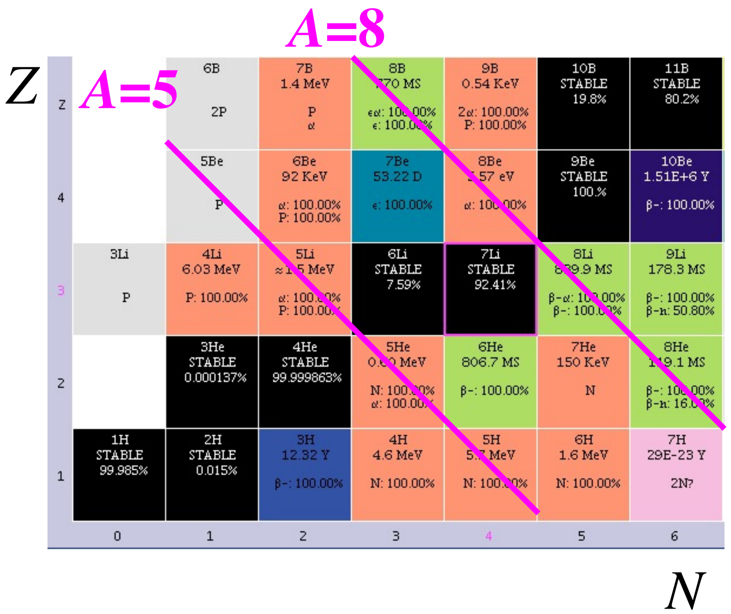
Z=43

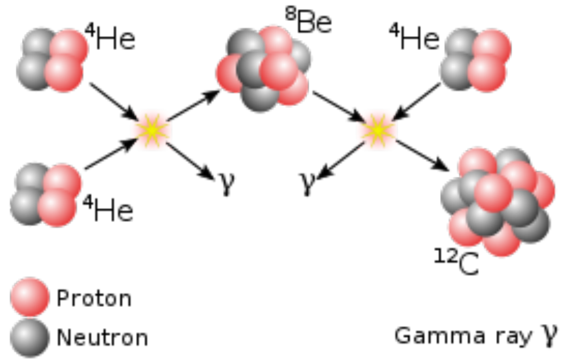
$T_{1/2}$(Tc) < 4Myr

P.W. Merill

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: $3\alpha \longrightarrow {}^{12}C$





Hoyle

1954-1957: Nucleosynthesis theories are forged

1946, 1954: Hoyle & 1957: B^{2}FH, Cameron

REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

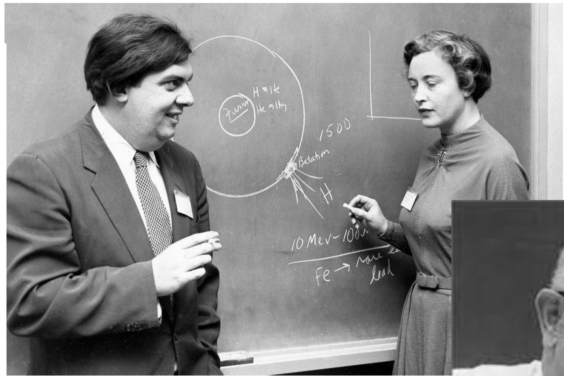
E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

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

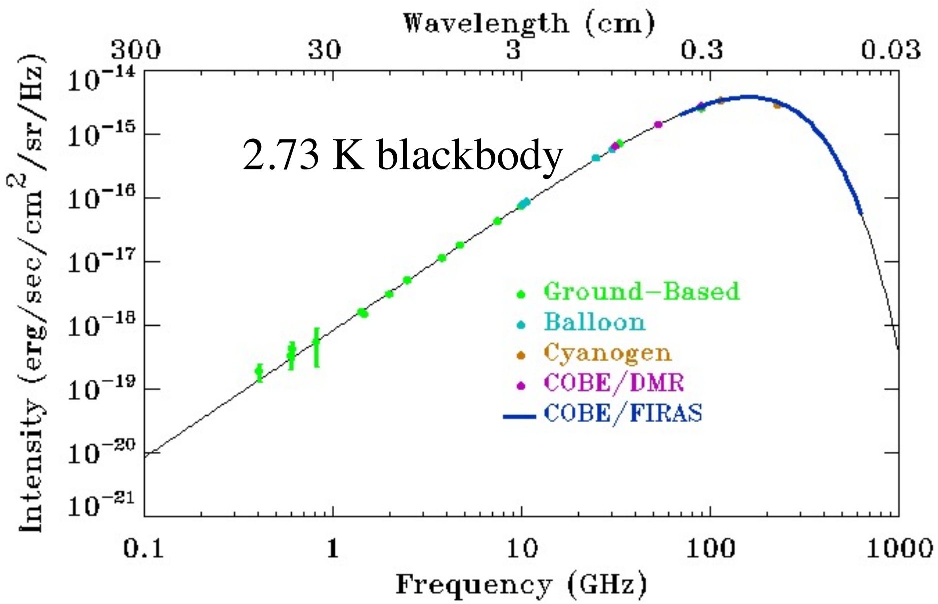
Fowler

Hoyle

Cameron

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

→ Primordial nucleosynthesis (Big Bang)



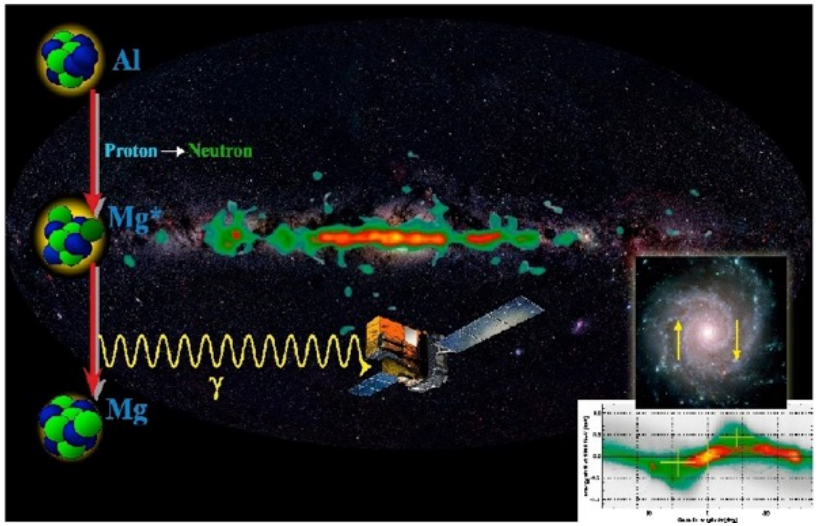
Penzias & Wilson

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 10^5y)

⟶ development of a new astronomy: the γ-astronomy

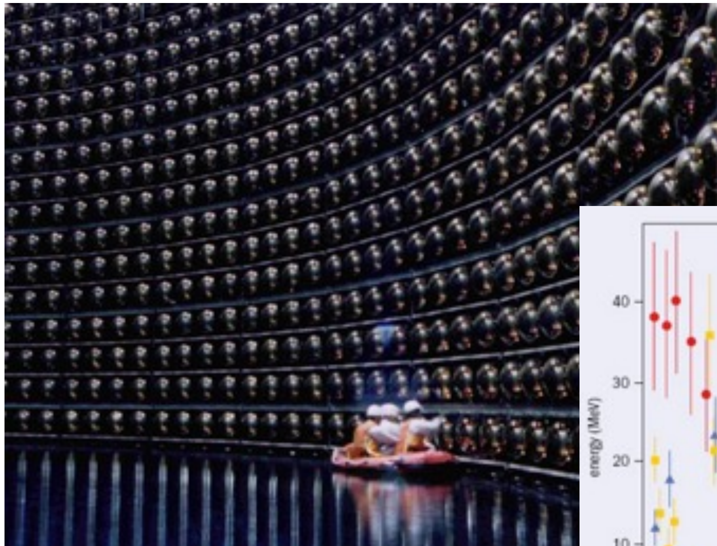


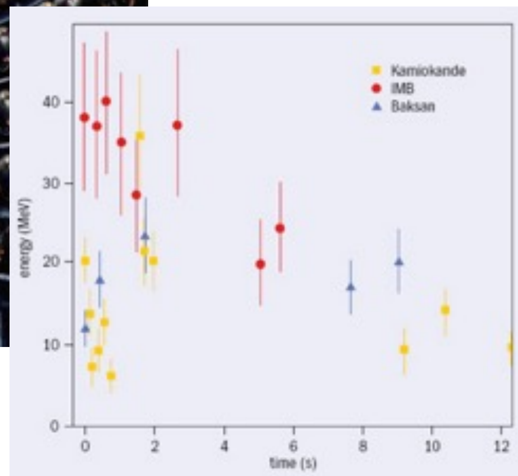
1.8 MeV γ-ray line observed in the Galactic plane


Compton γ-ray observatory

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

→ neutrino astronomy & link to explosive nucleosynthesis

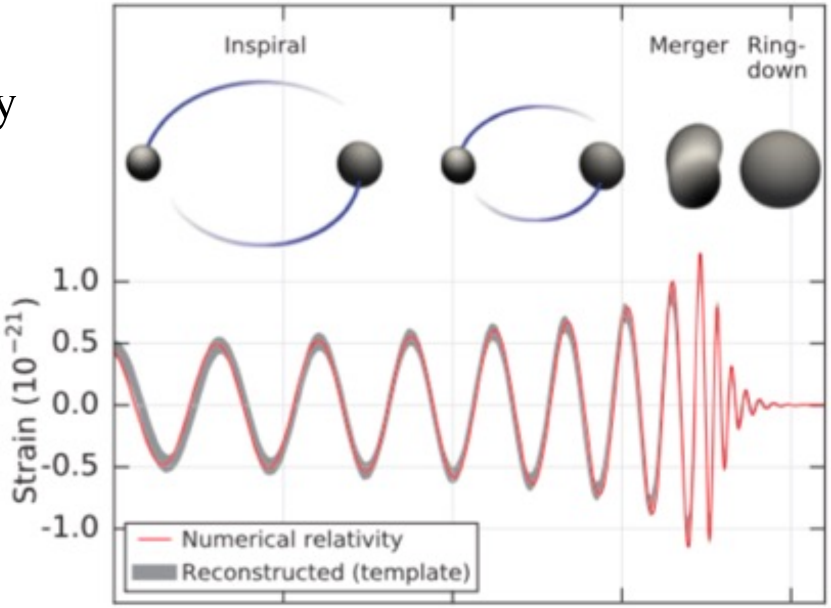




2017: first direct detection of gravitational waves from a binary NS-NS system merger and its electromagnetic counterpart (kilonova)

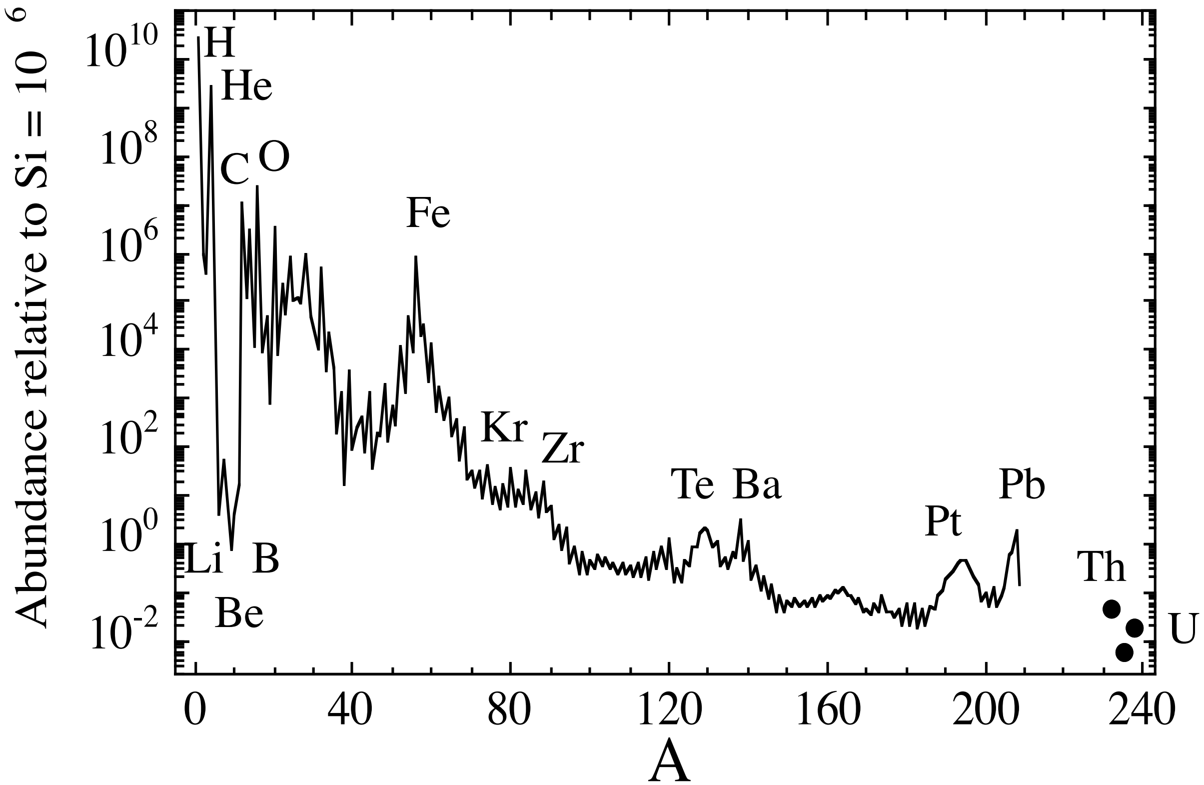
- ➡ Multi-messenger Astronomy
- ➡ breakthrough for the rapid neutron-capture process (or r-process) nucleosynthesis

Laser Interferometer Gravitational-Wave Observatory

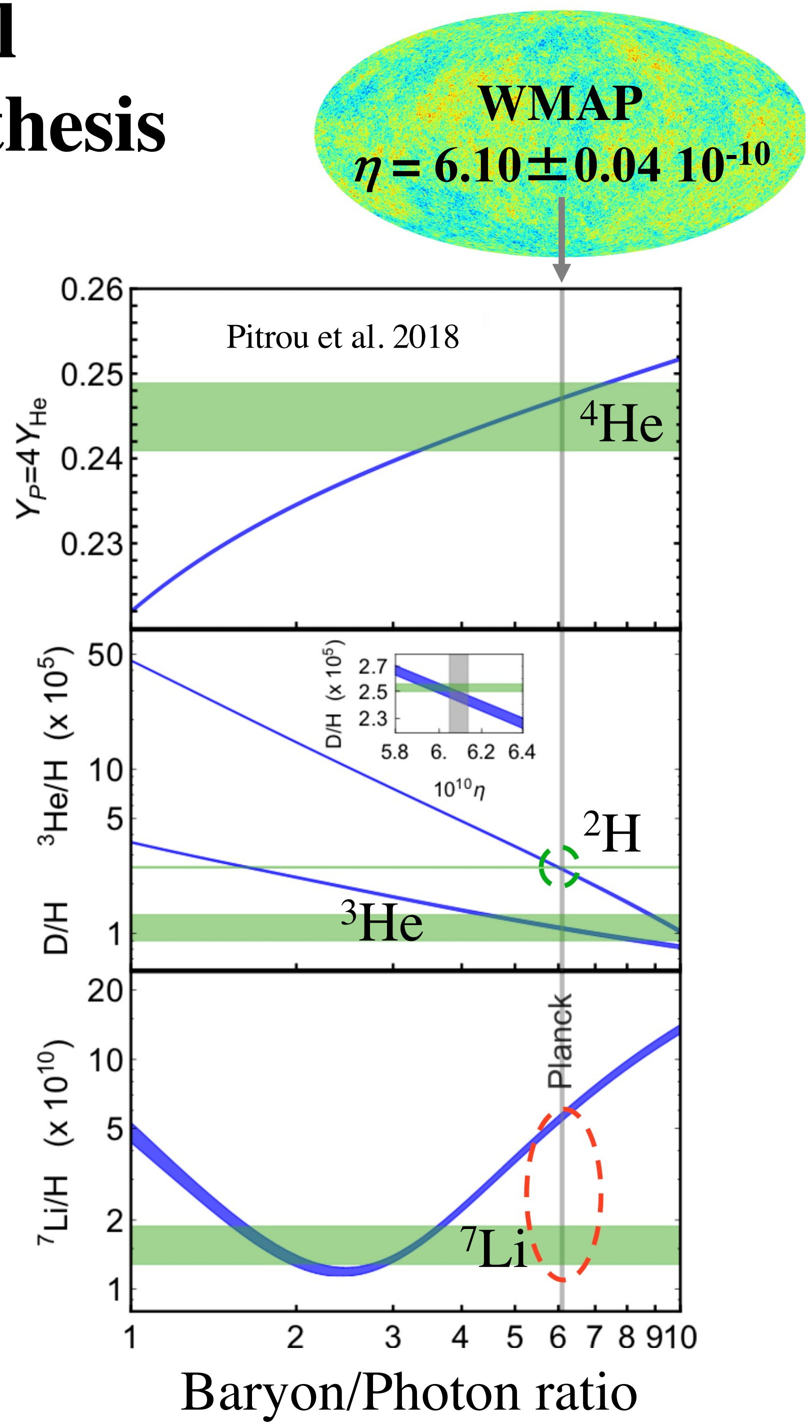


Origin of the elements in the Universe

- 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

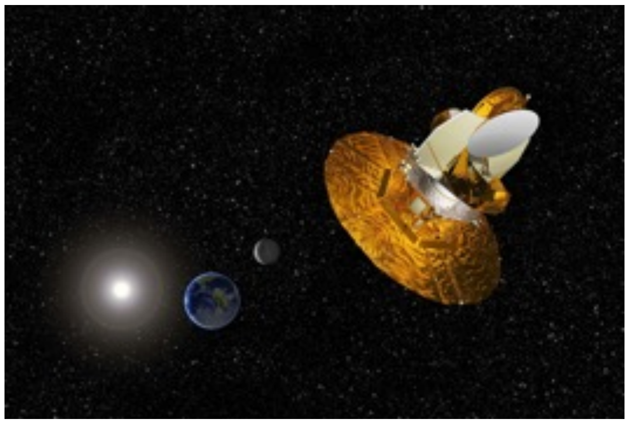


Primordial nucleosynthesis



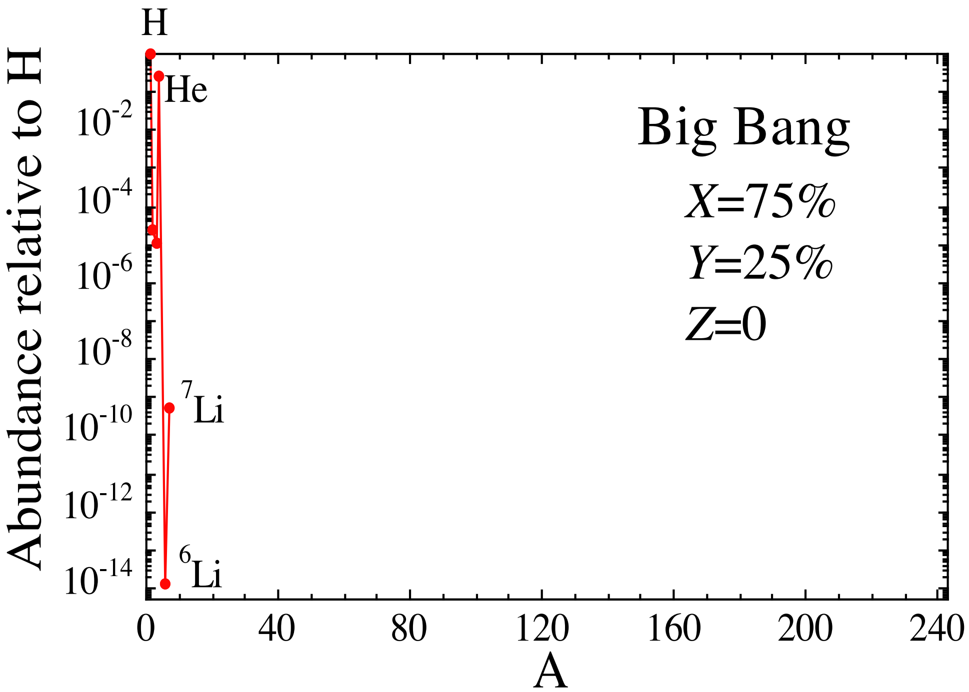
One of the major pillars of the Big Bang theory:
Reproduce observed primordial abundances of H, He, Li over 9 orders of magnitude

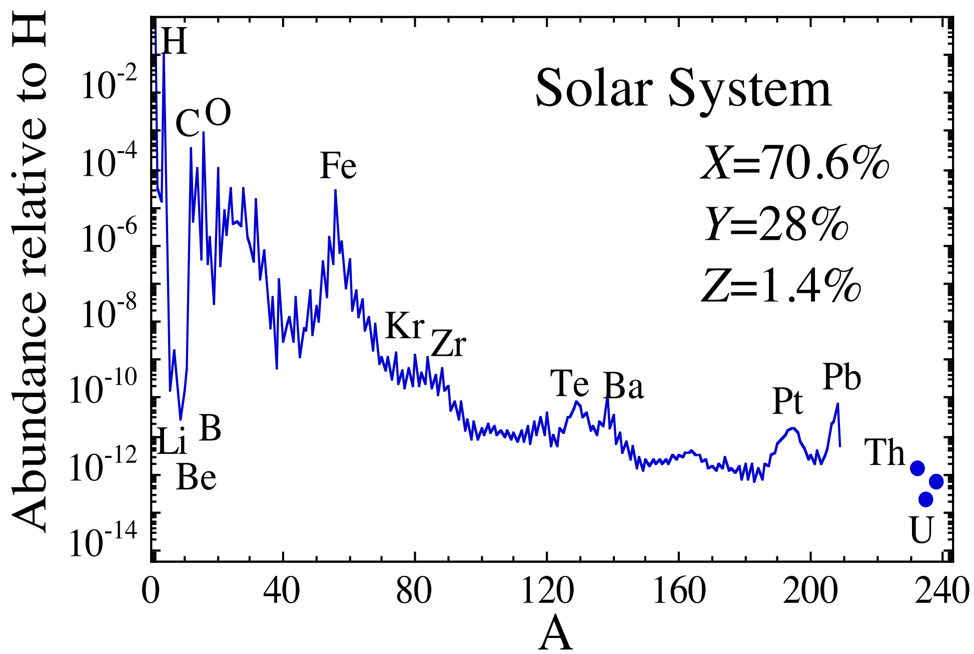
(Li underestimated by a factor of ~3)



Abundances resulting from the BB

Abundances in SoS today

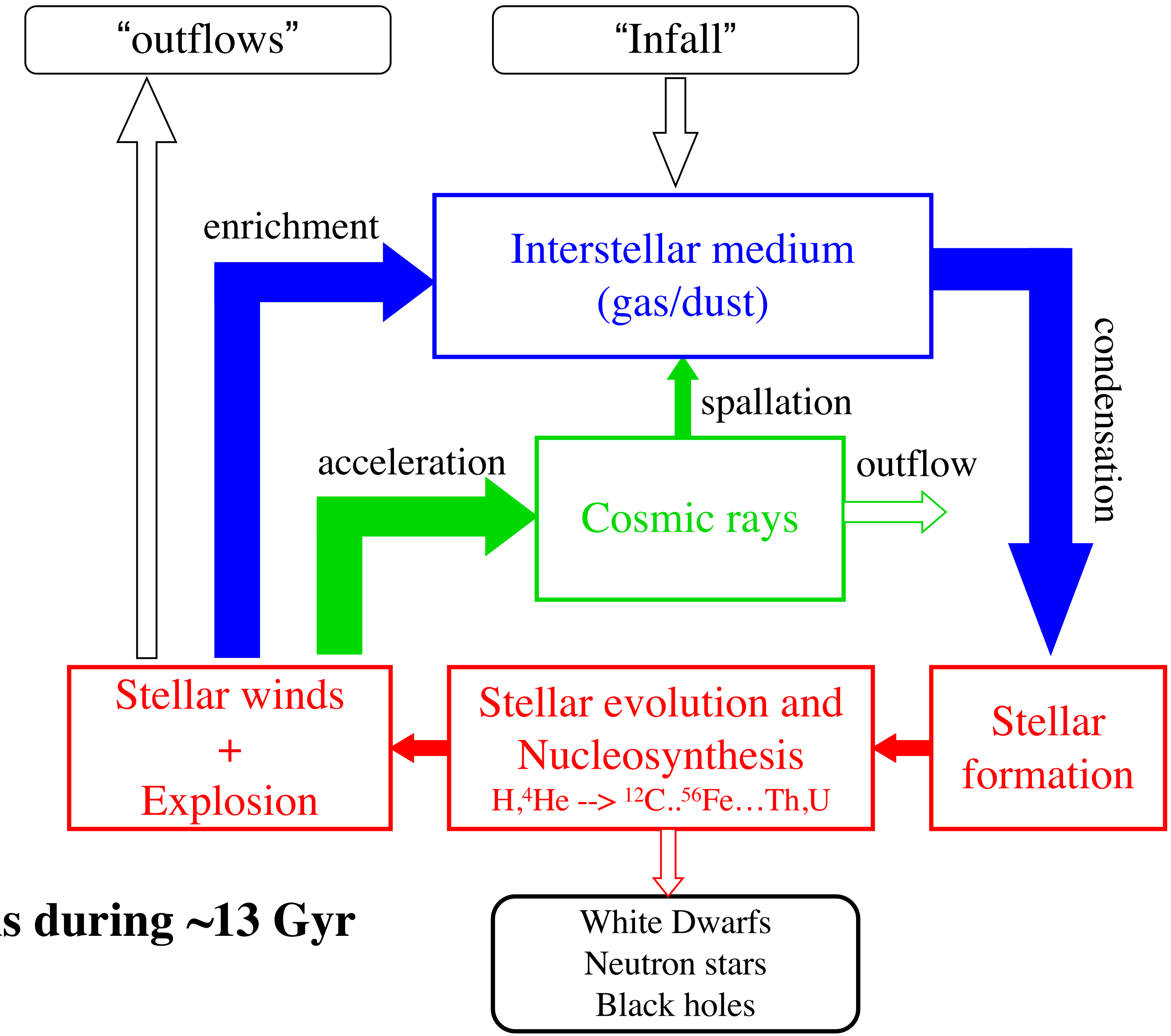




Some 13 Gy after the BB

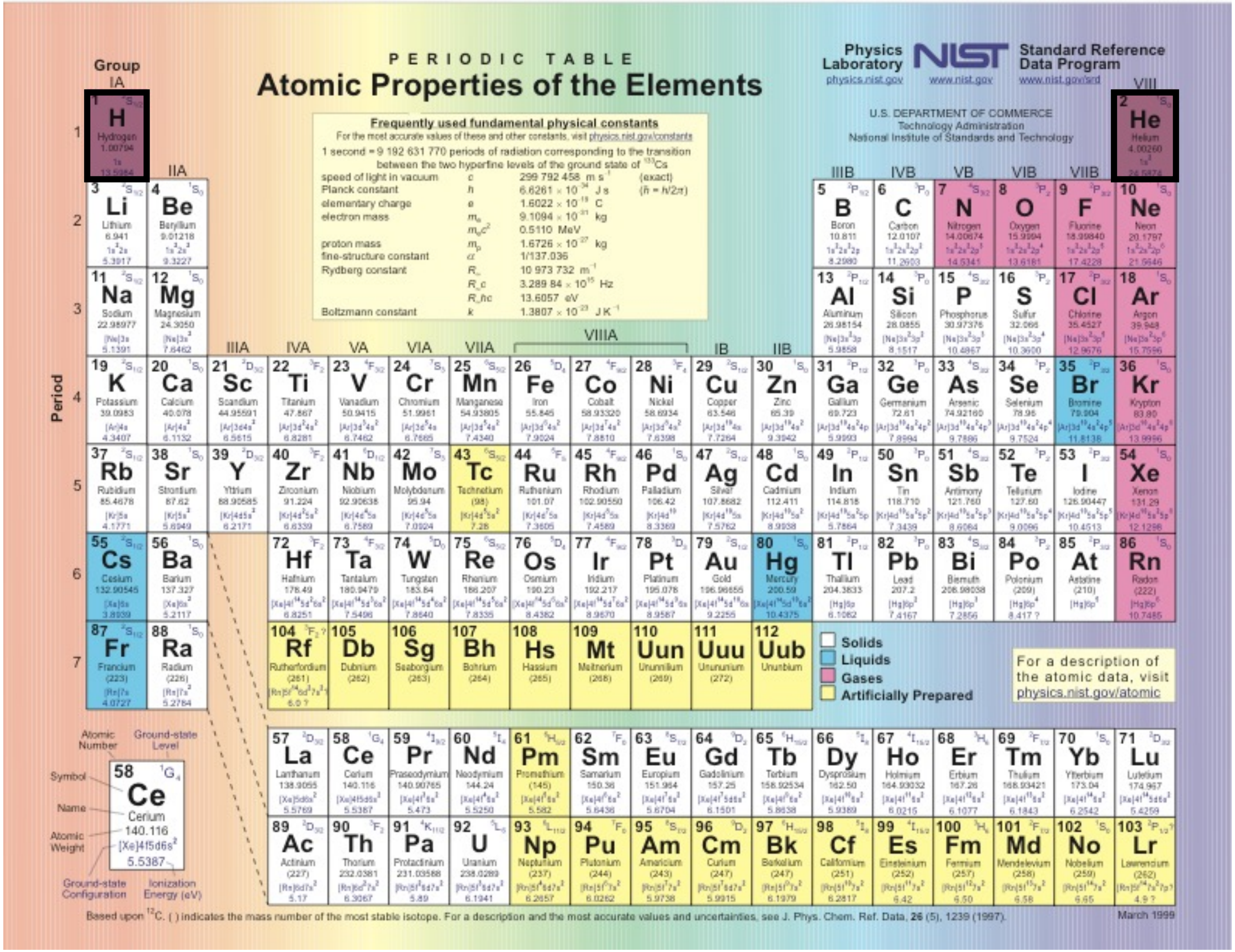
Stars are the cosmic chauldrons

Chemical evolution of the Galaxy

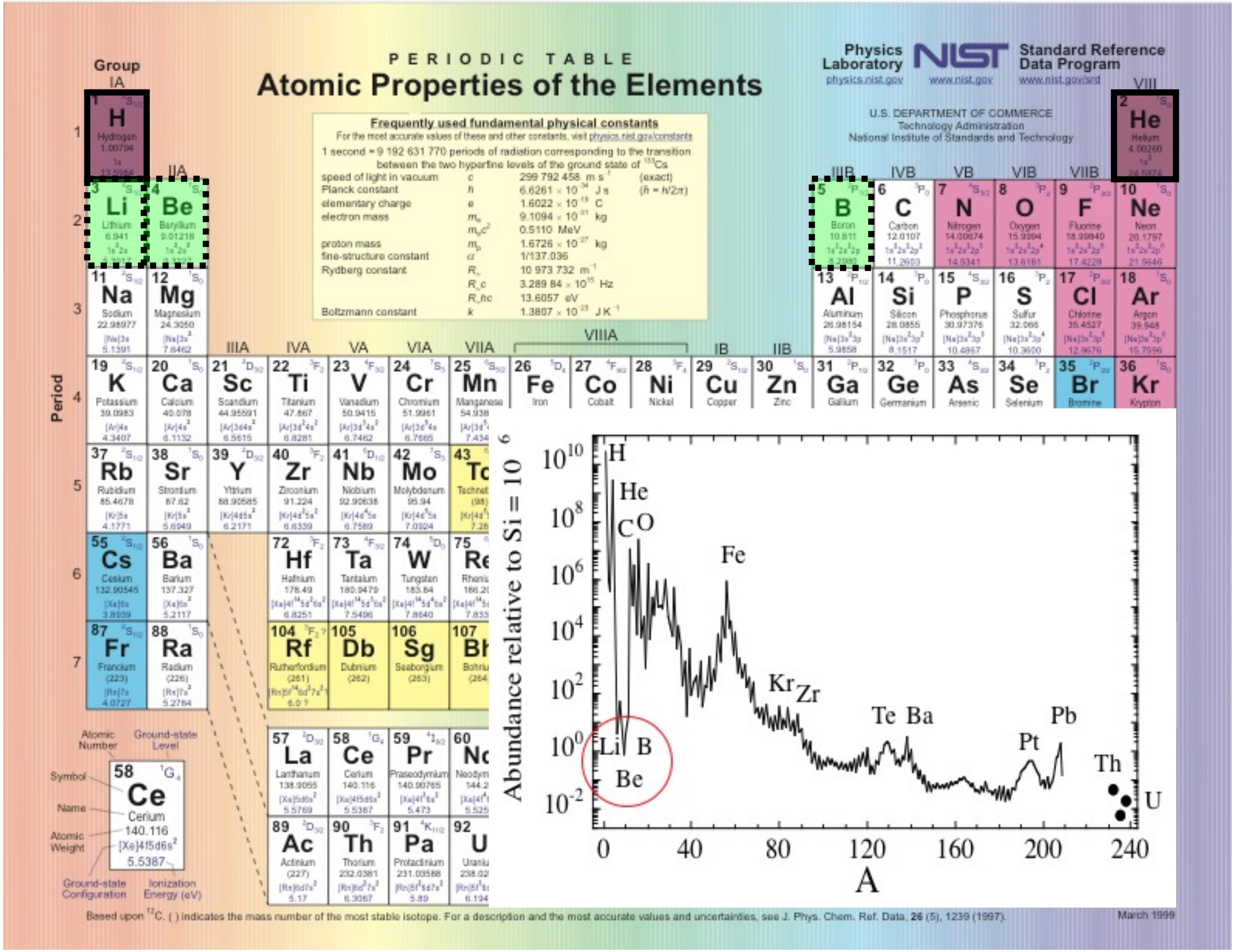


… and this during ~13 Gyr

Primordial nucleosynthesis

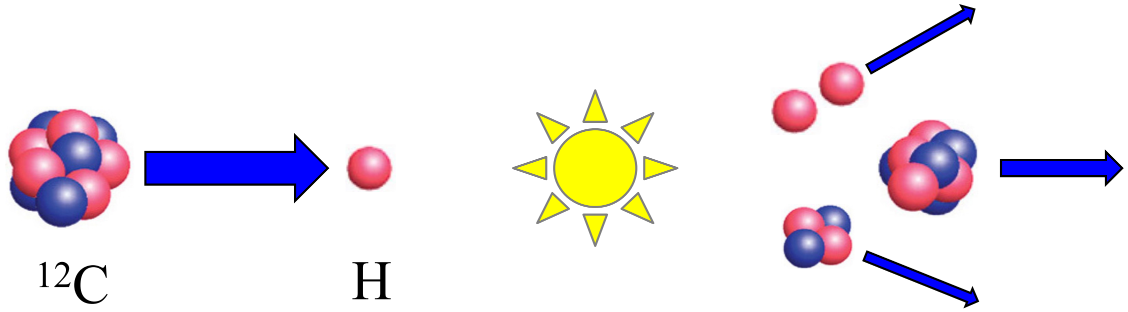


The Li-Be-B nucleosynthesis



Non-thermal nucleosynthesis by spallation reactions

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



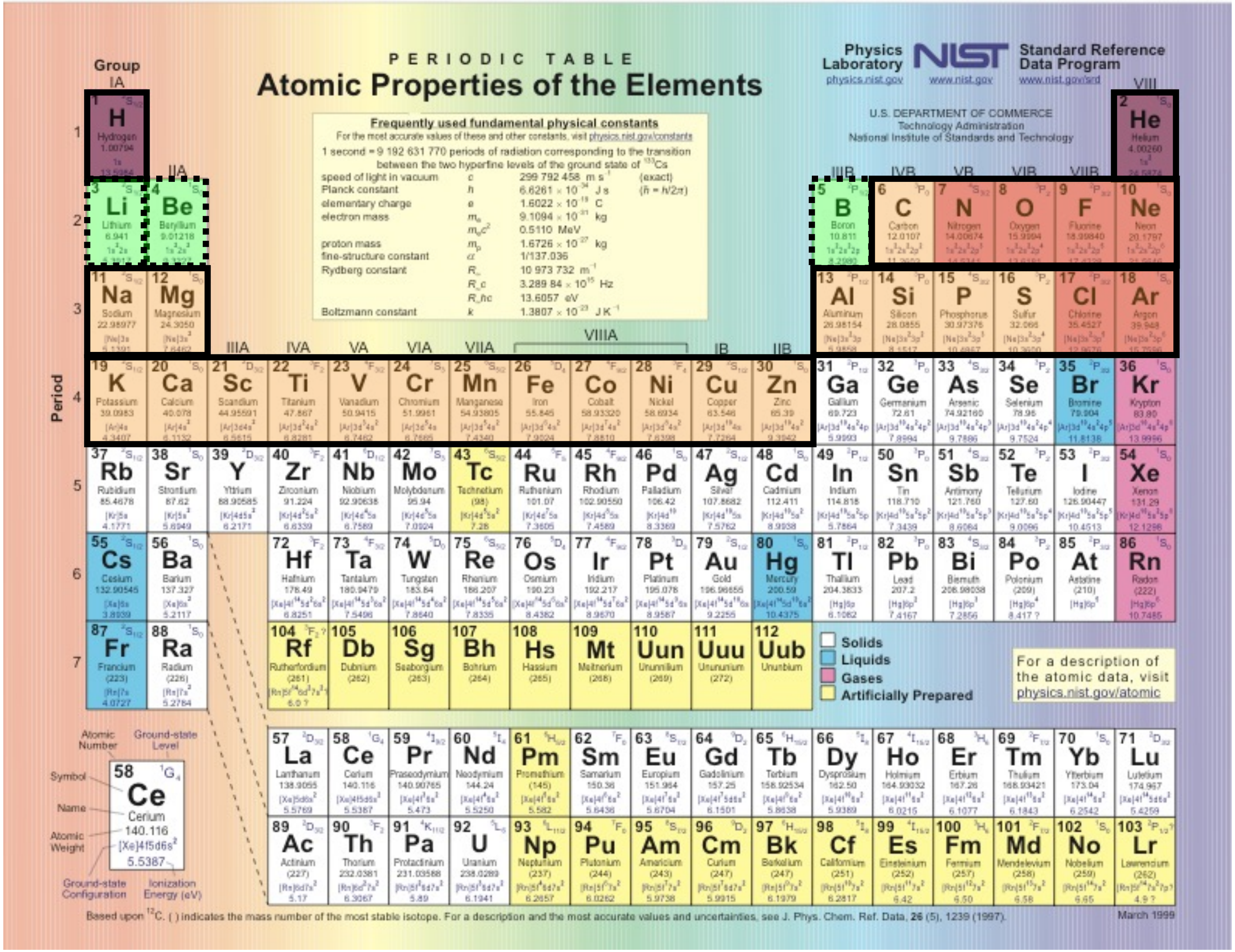
$$
\begin{aligned}
p + {}^{12}C &\rightarrow {}^{11}B + 2p \\
&\rightarrow {}^{10}B + 2p + n \\
&\rightarrow {}^{10}B + {}^{3}He \\
&\rightarrow {}^{9}Be + 3p + n \\
&\rightarrow {}^{9}Be + {}^{3}He + p
\end{aligned}
$$

$$
\begin{aligned}
p + {}^{12}C &\rightarrow {}^{7}Li + 4p + 2n \\
&\rightarrow {}^{7}Li + {}^{4}He + 2p \\
&\rightarrow {}^{6}Li + 4p + 3n \\
&\rightarrow {}^{6}Li + {}^{4}He + 2p + n \\
&\rightarrow {}^{6}Li + {}^{4}He + {}^{3}He
\end{aligned}
$$

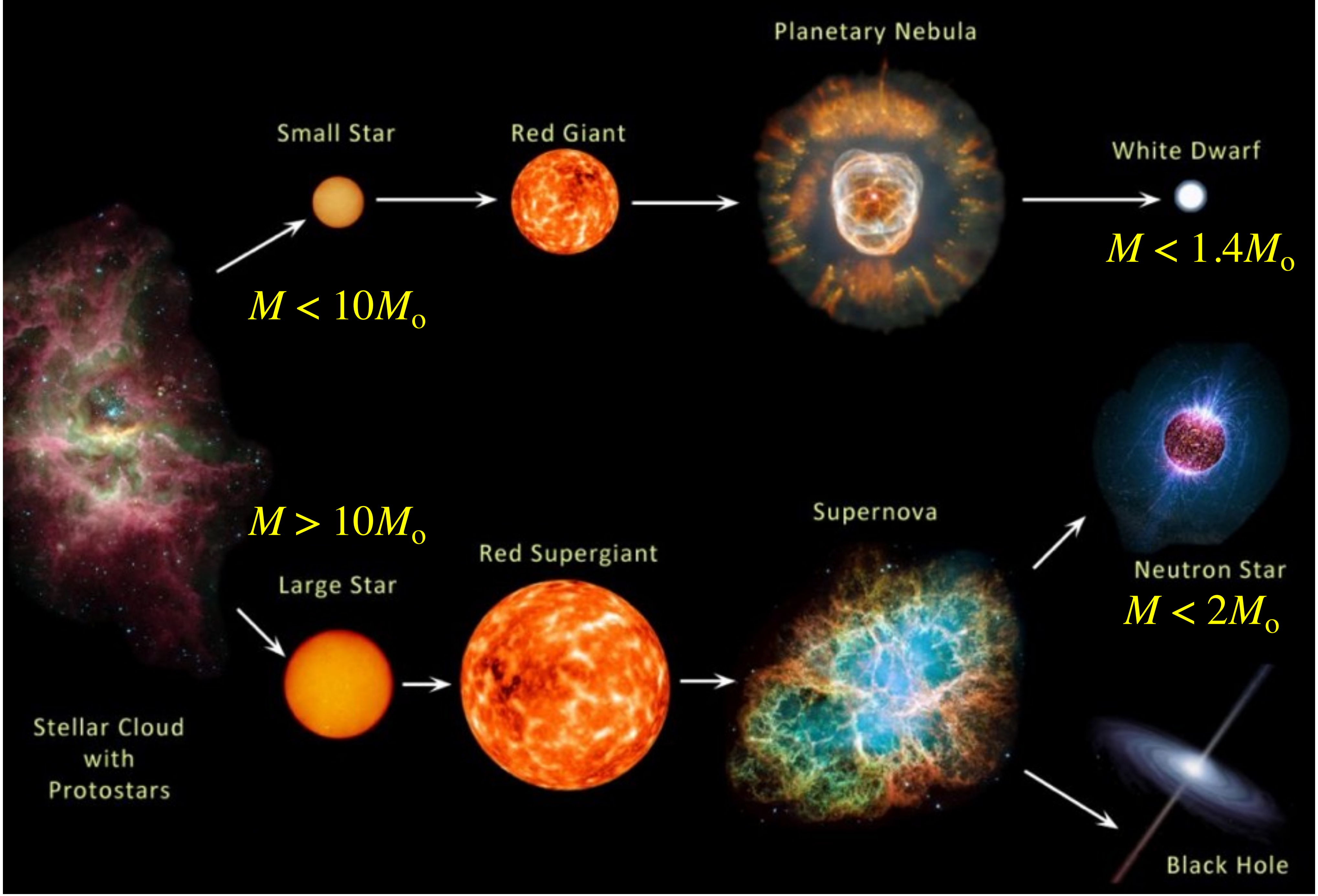
Li – Be – B production

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

Nucleosynthesis of elements lighter than Fe



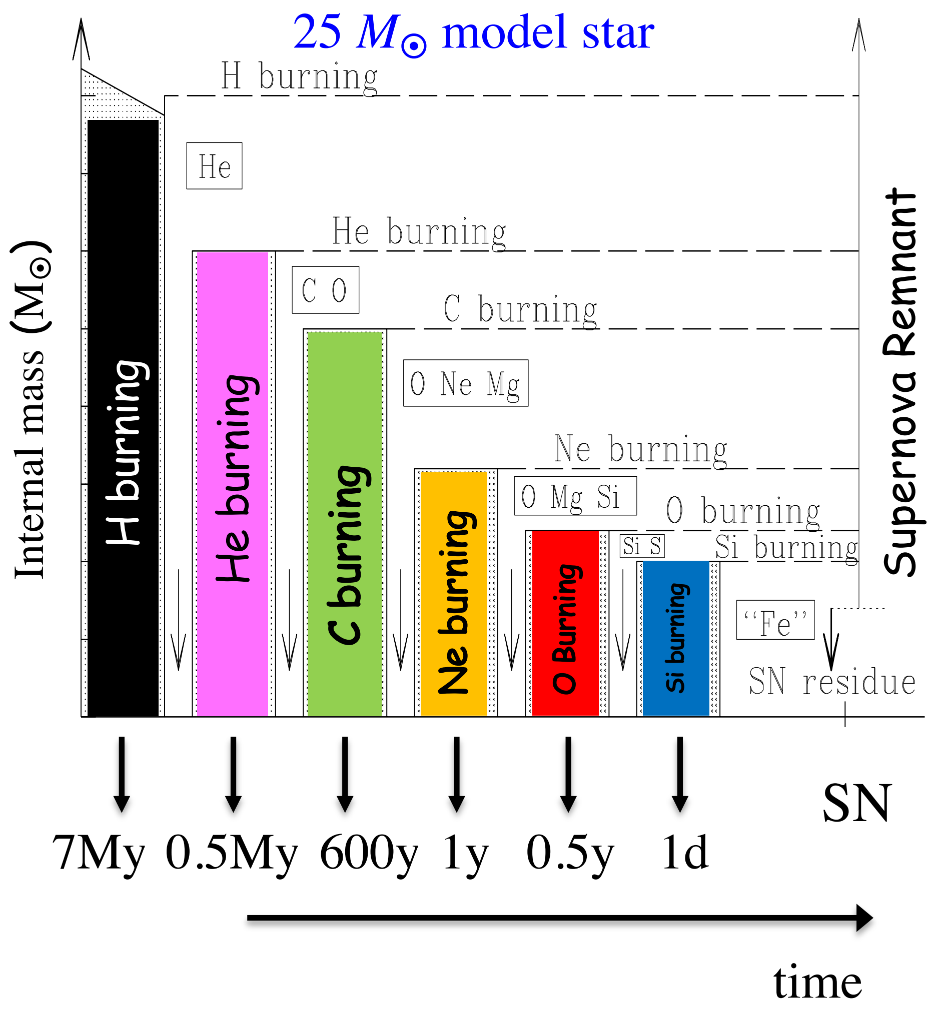
Stars: gravitationnally controlled nuclear reactors

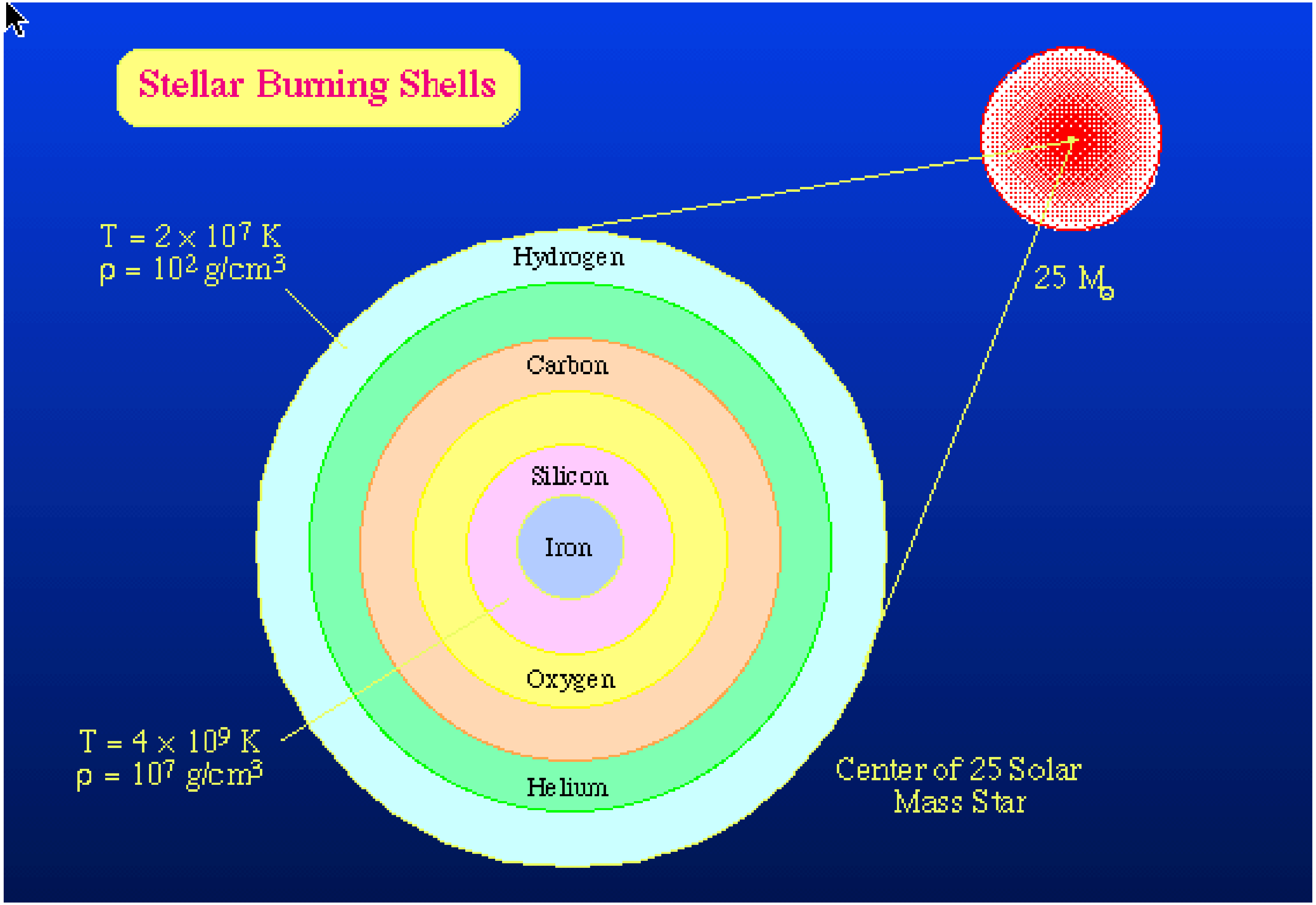


The evolution and nucleosynthesis of massive stars ($M \geq 10\ M_\odot$)

Gravitationally controlled fusion in stars

		T (K)
$4\ {}^{1}H \longrightarrow {}^{4}He$		**H burning phase**
		$> 10\ 10^{6}$
$3\ {}^{4}He \longrightarrow {}^{12}C$		**He burning phase**
${}^{12}C + {}^{4}He \longrightarrow {}^{16}O$		$> 100\ 10^{6}$
${}^{12}C + {}^{12}C \longrightarrow {}^{23}Na + {}^{1}H$		**C burning phase**
$\longrightarrow {}^{20}Ne + {}^{4}He$		$> 800\ 10^{6}$
${}^{20}Ne + \gamma \longrightarrow {}^{16}O + {}^{4}He$		**Ne burning phase**
$+ {}^{4}He \longrightarrow {}^{24}Mg + \gamma$		$> 1.2\ 10^{9}$
${}^{16}O + {}^{16}O \longrightarrow {}^{31}P + {}^{1}H$		**O burning phase**
$\longrightarrow {}^{28}Si + {}^{4}He$		$> 1.5\ 10^{9}$
$\{[({}^{28}Si + {}^{4}He) + {}^{4}He] +$		**Si burning phase**
${}^{4}He\} + {}^{4}He + \ldots \longrightarrow {}^{56}Fe$		$> 3\ 10^{9}$

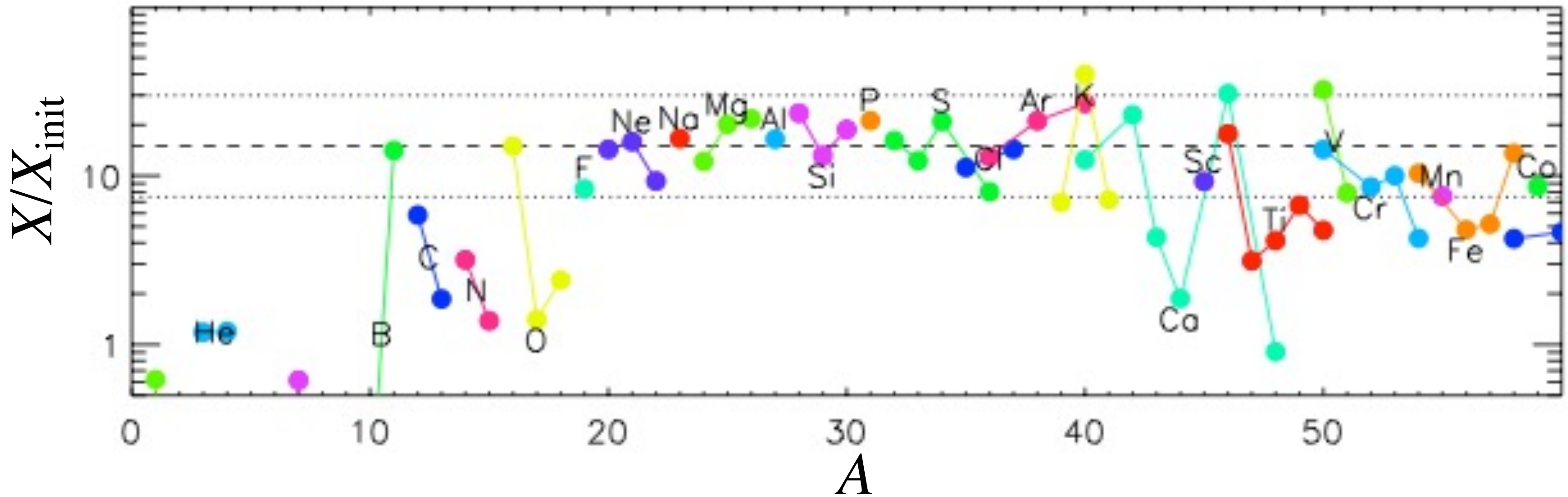




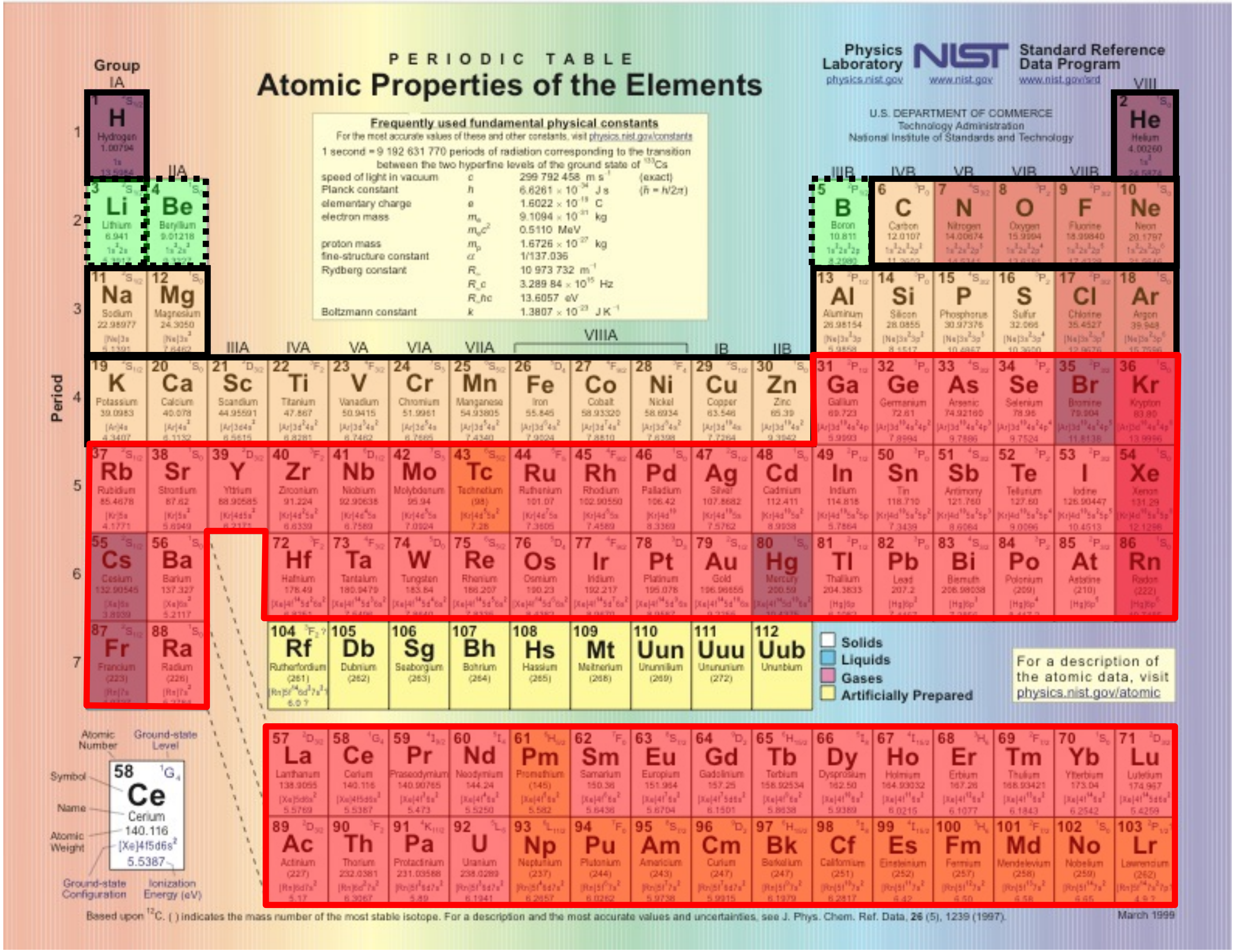
Stellar Burning Shells
T = 2 × 10^7 K
ρ = 10^2 g/cm^3
Hydrogen
Helium
Carbon
Oxygen
Silicon
Iron
T = 4 × 10^9 K
ρ = 10^7 g/cm^3
25 M☉
Center of 25 Solar Mass Star

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

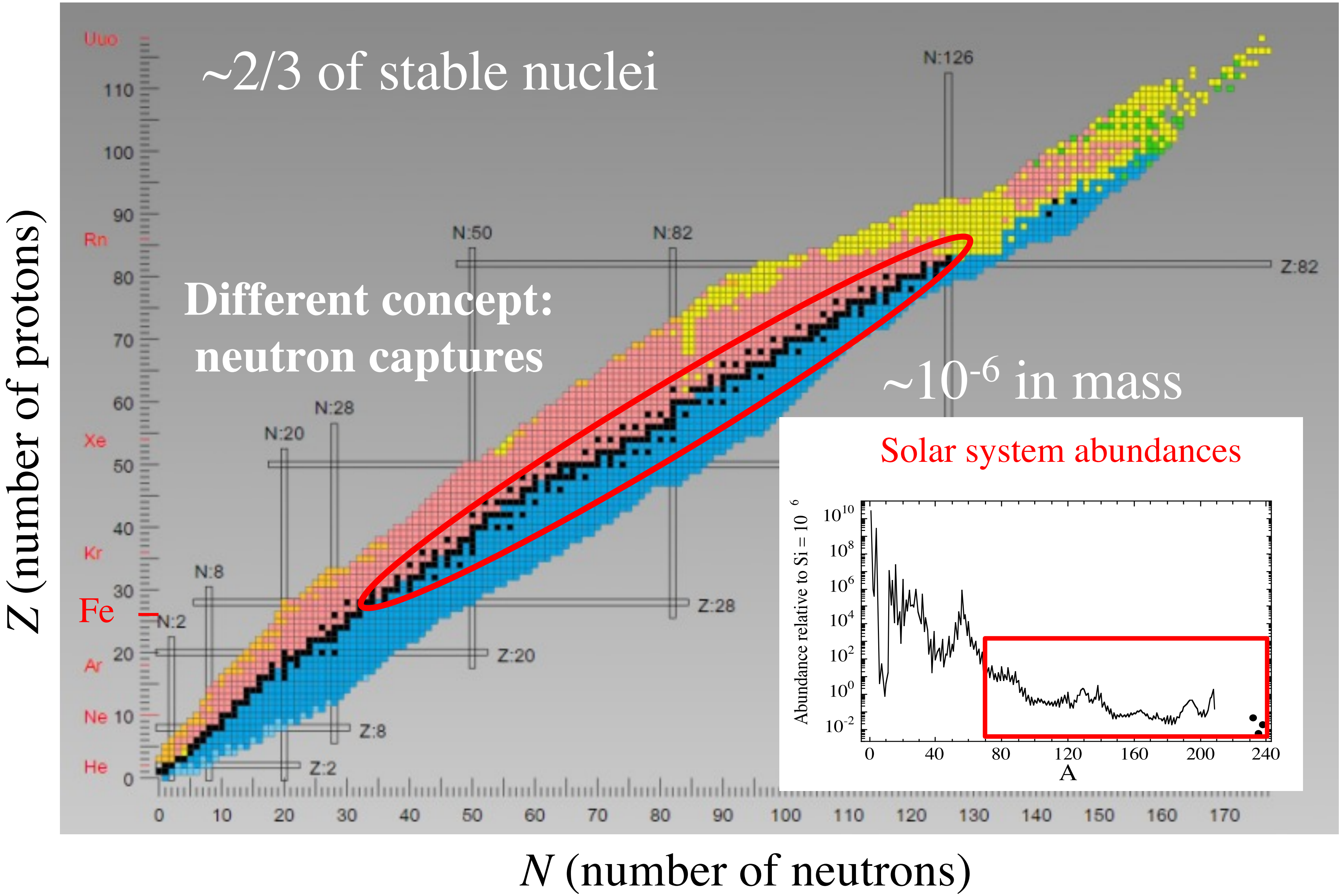
Overproduction factors of isotopes from H to Fe in a 25 $M_{\odot}$ star



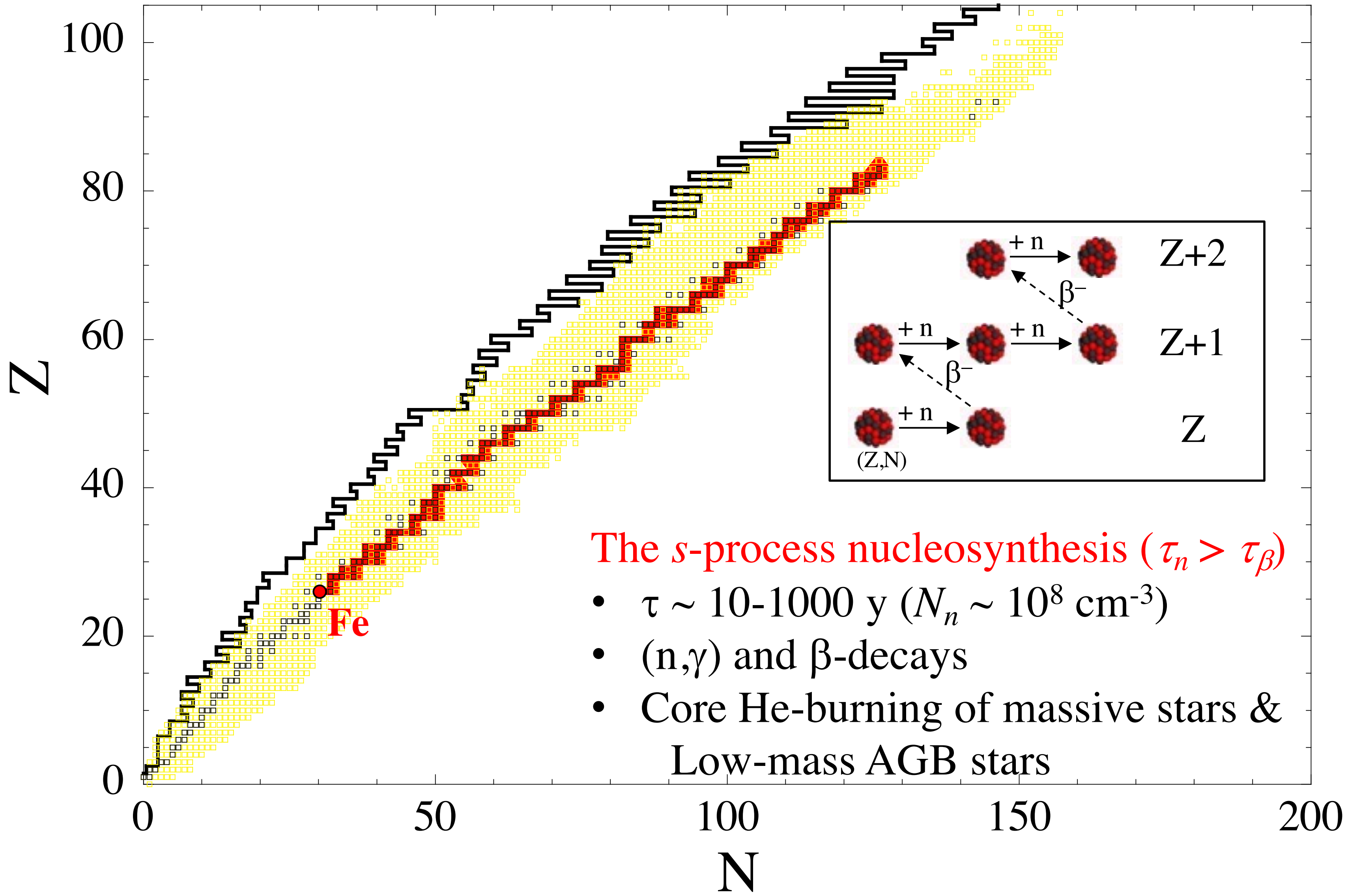
Origin of the 52 elements heavier than Fe



Nucleosynthesis of the elements heavier than iron



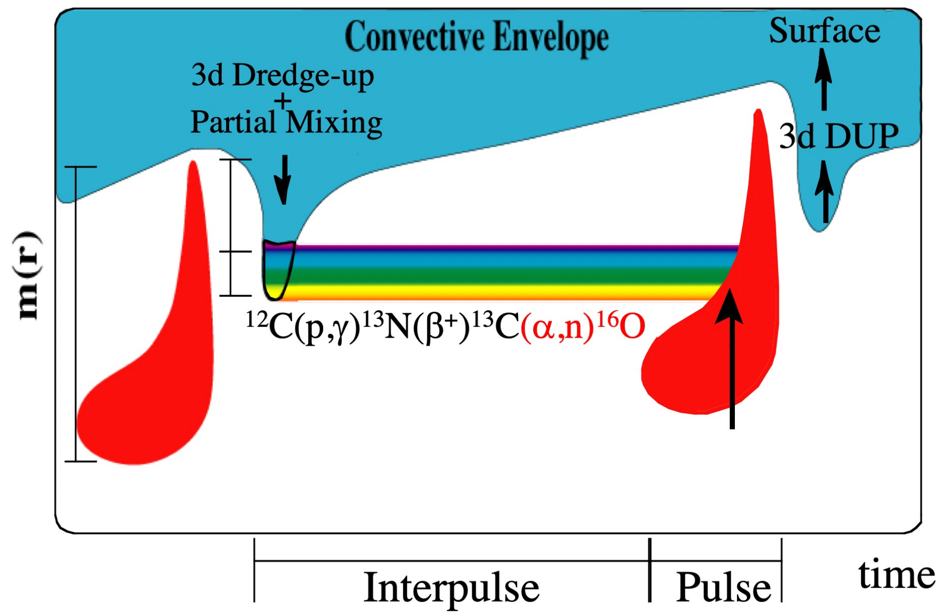
The slow neutron-capture process (or s-process)

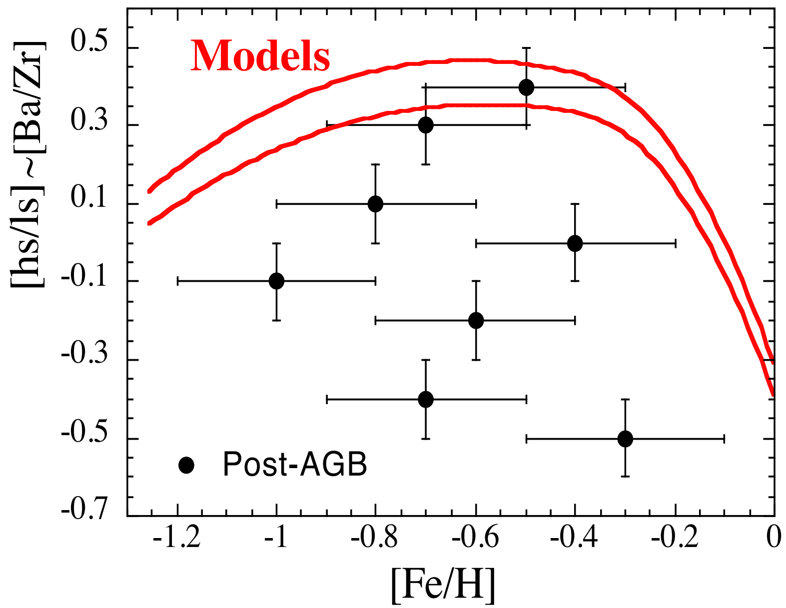


The s-process is responsible for about half of the elements heavier than iron in the Universe

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

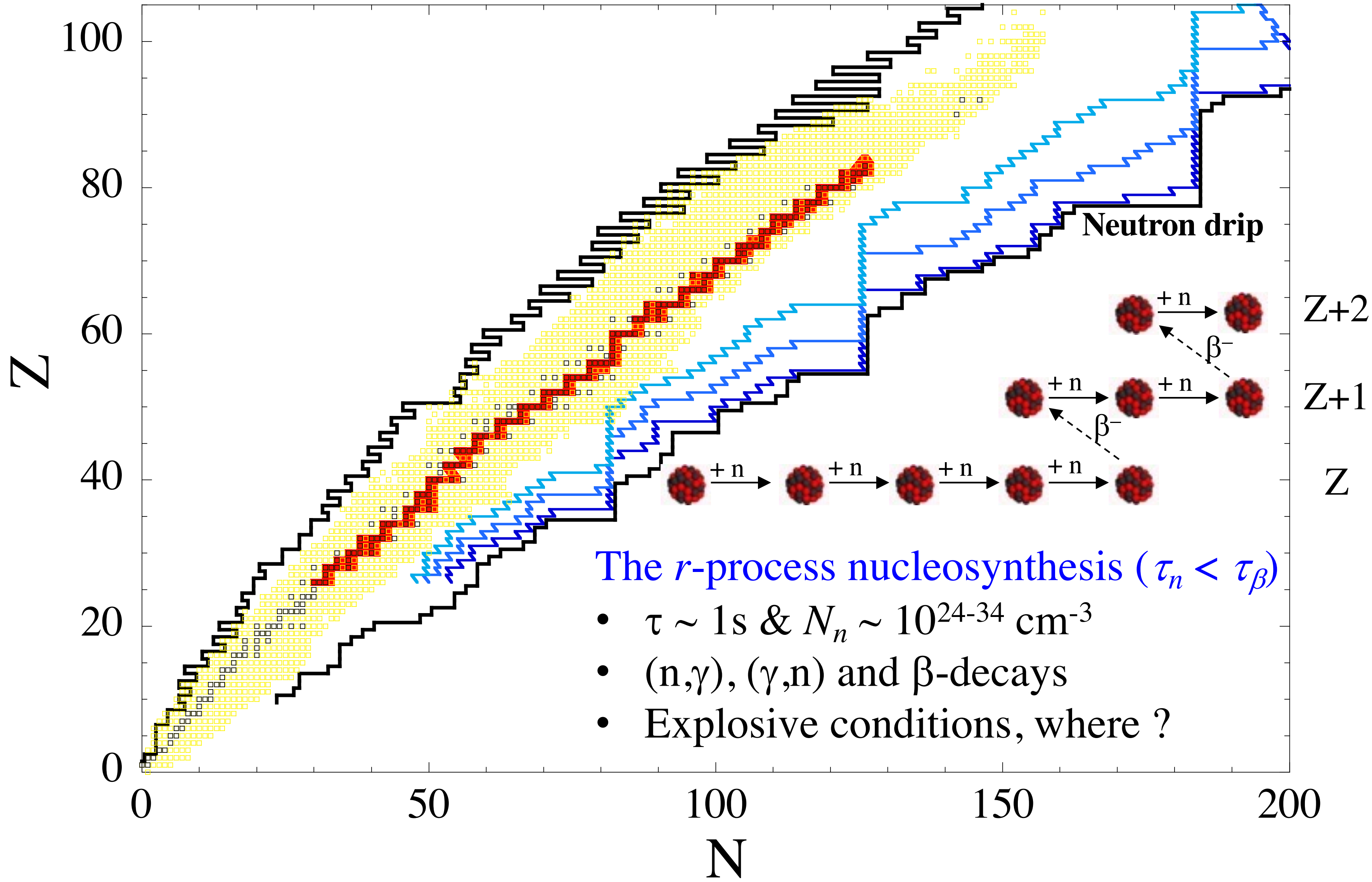
- How are the neutrons produced in AGB stars ?
- What is the role of the various mixing mechanisms ?
- What is the contributions from intermediate-*M* AGB stars ?
- How to explain specific observations ?
- (n,γ) and *T*-dependent β-decay rates of unstable nuclei ?



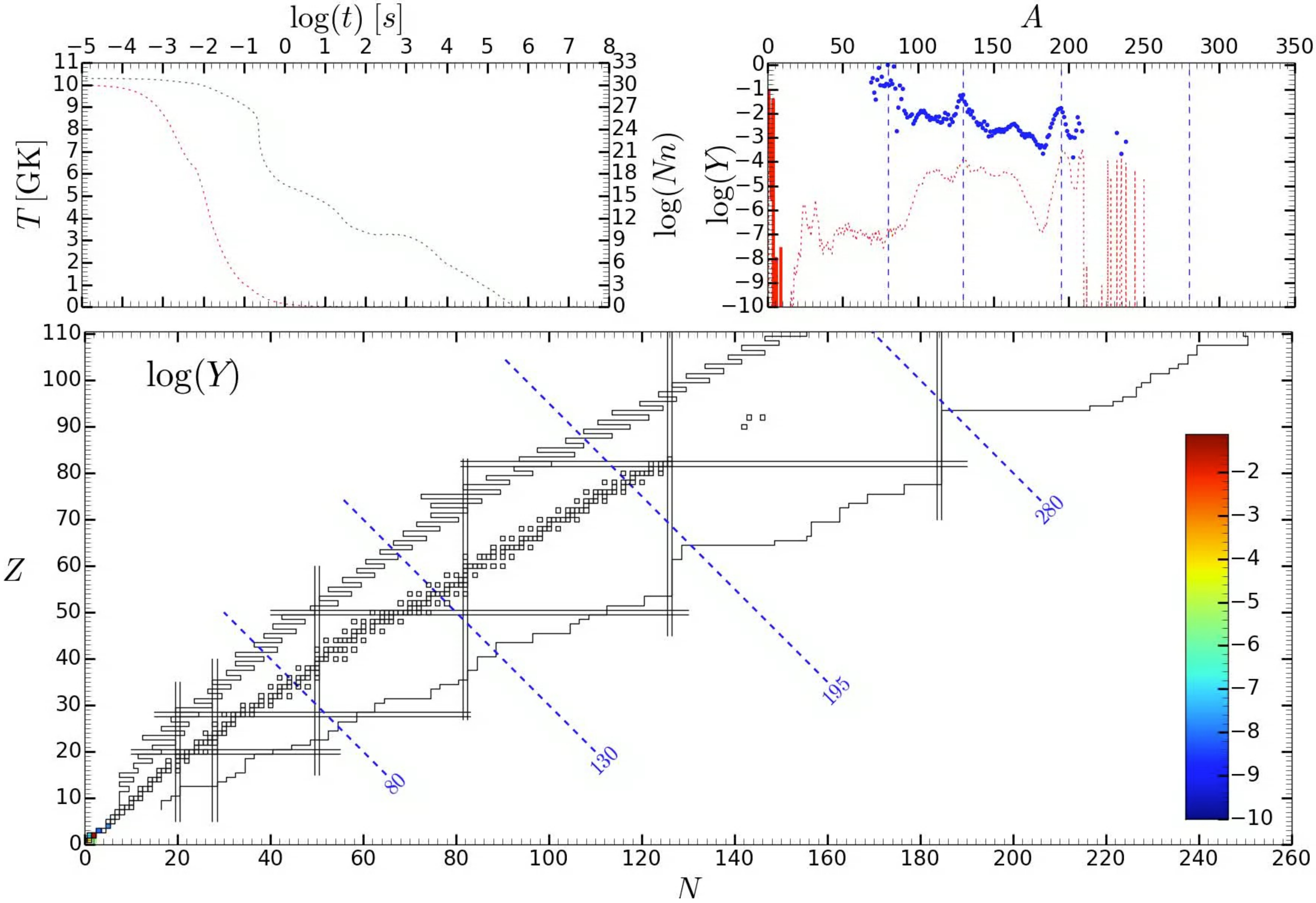


Van Winckel (2003, AARA)

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



log(t) [s]
T [GK]
log(Nn)
A
log(Y)
log(Y)
Z
N
80
130
195
280

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)

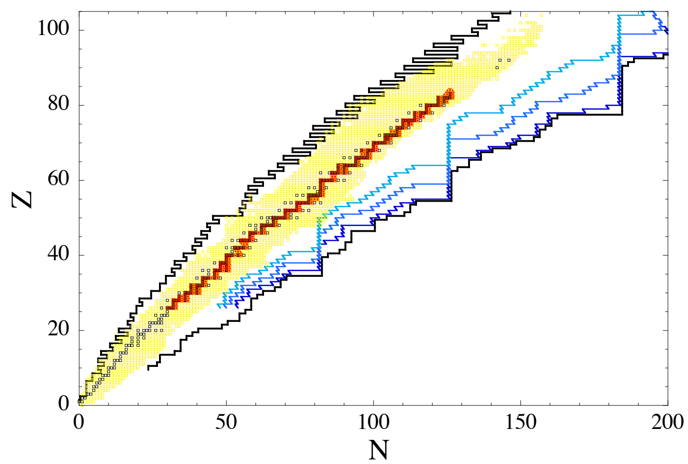
Some clear signatures

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

Still many open questions:

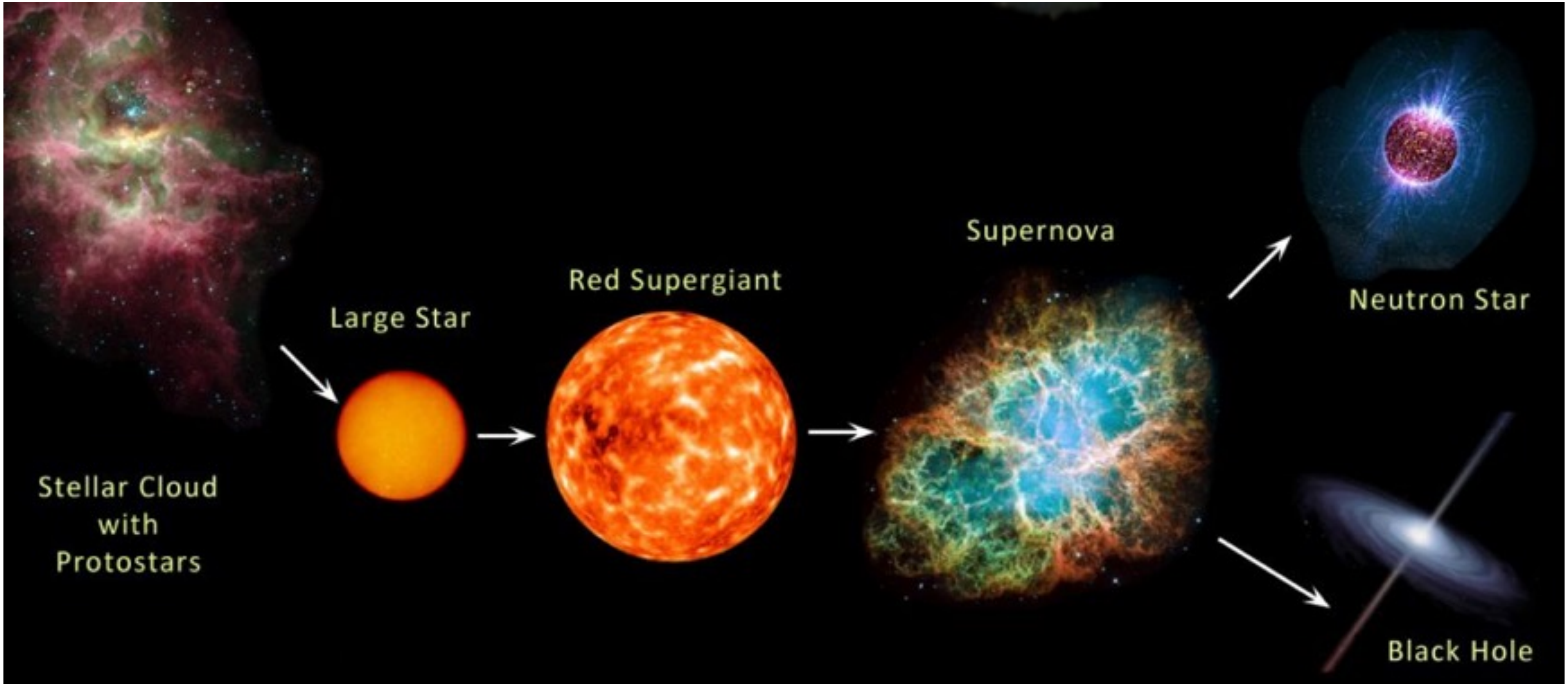
- Astrophysical Site ?

  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



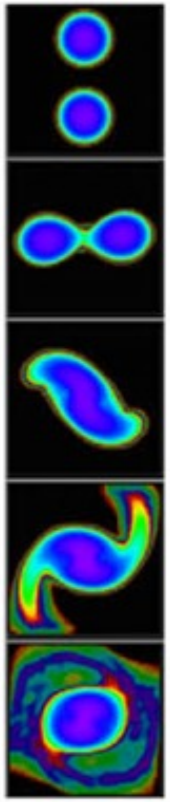
But up to now ... without success ...

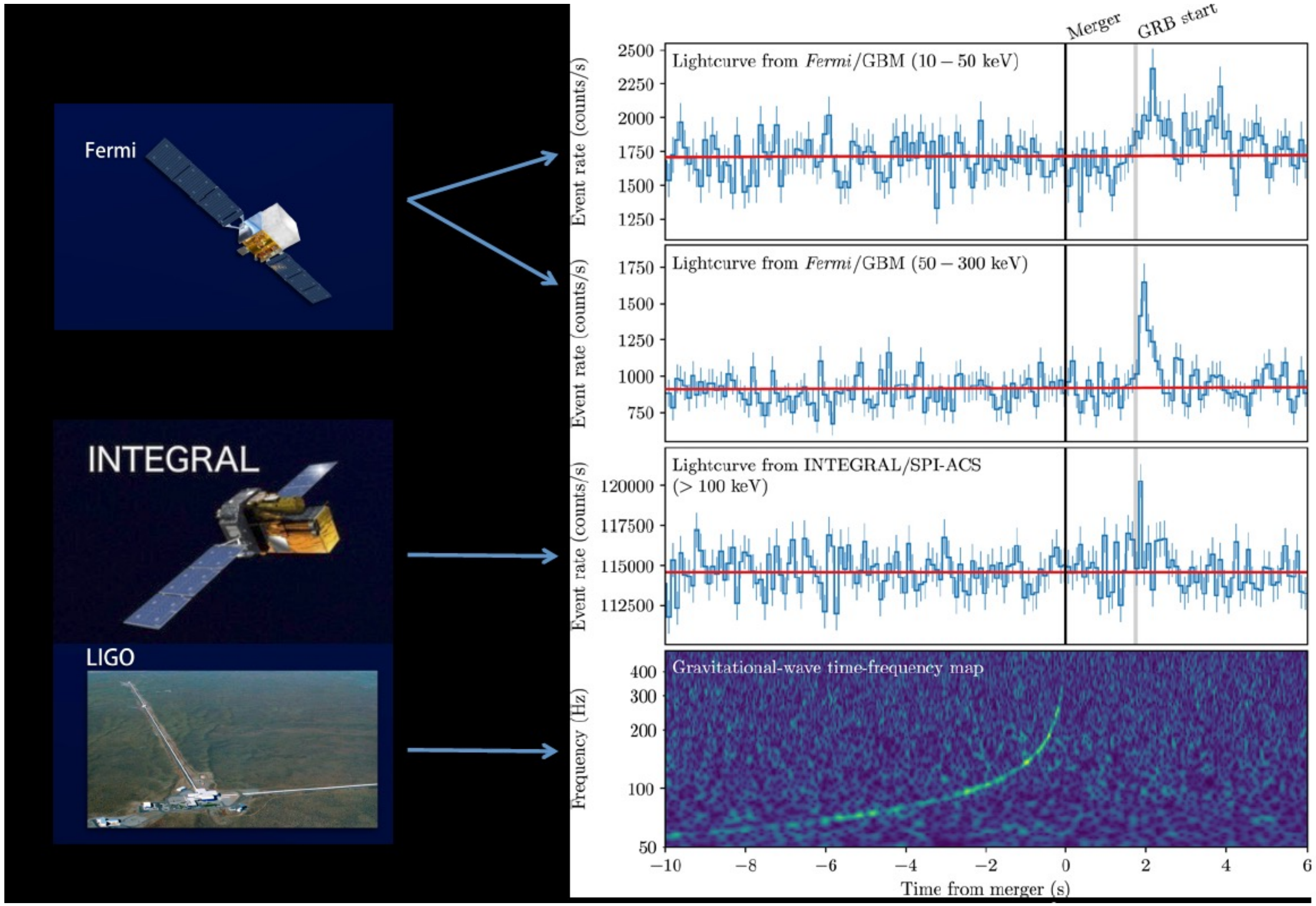
An alternative scenario: the decompression of neutron star matter

An alternative scenario: binary neutron star mergers

17 August 2017

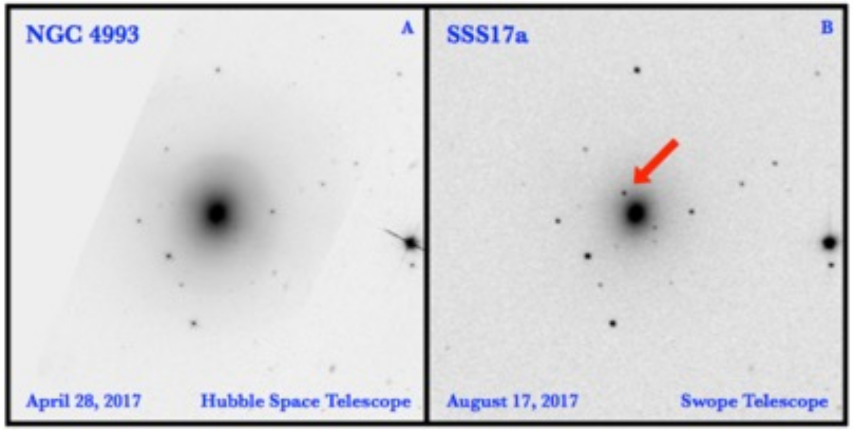
1st detection of a neutron star merger





11h later

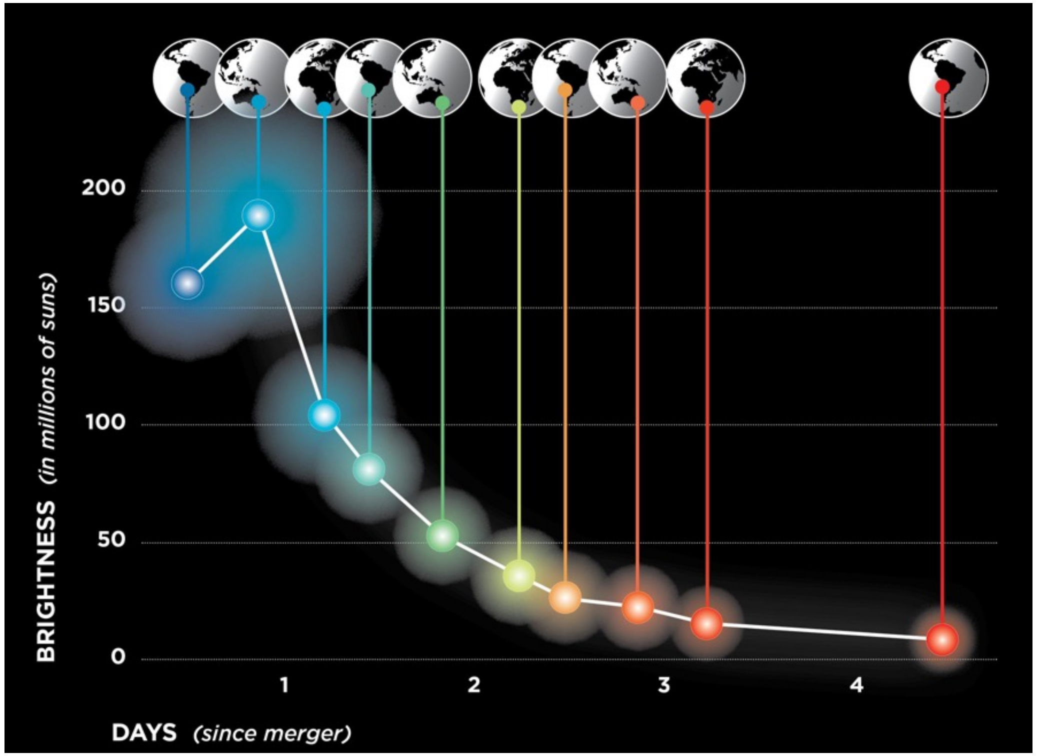
Optical



multi-messenger observations

First observation of a "Kilonova"

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

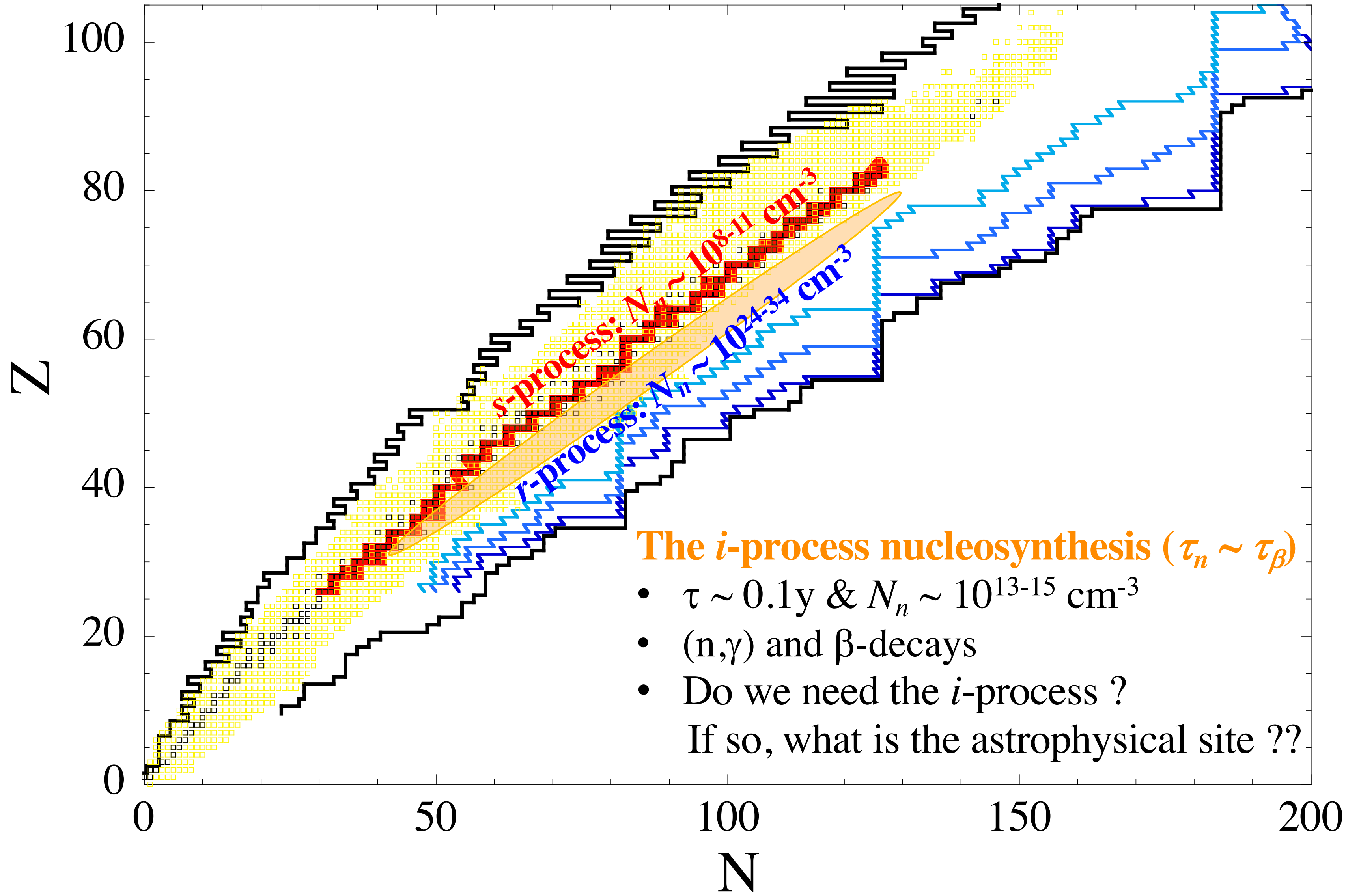


Observations confirm

- 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

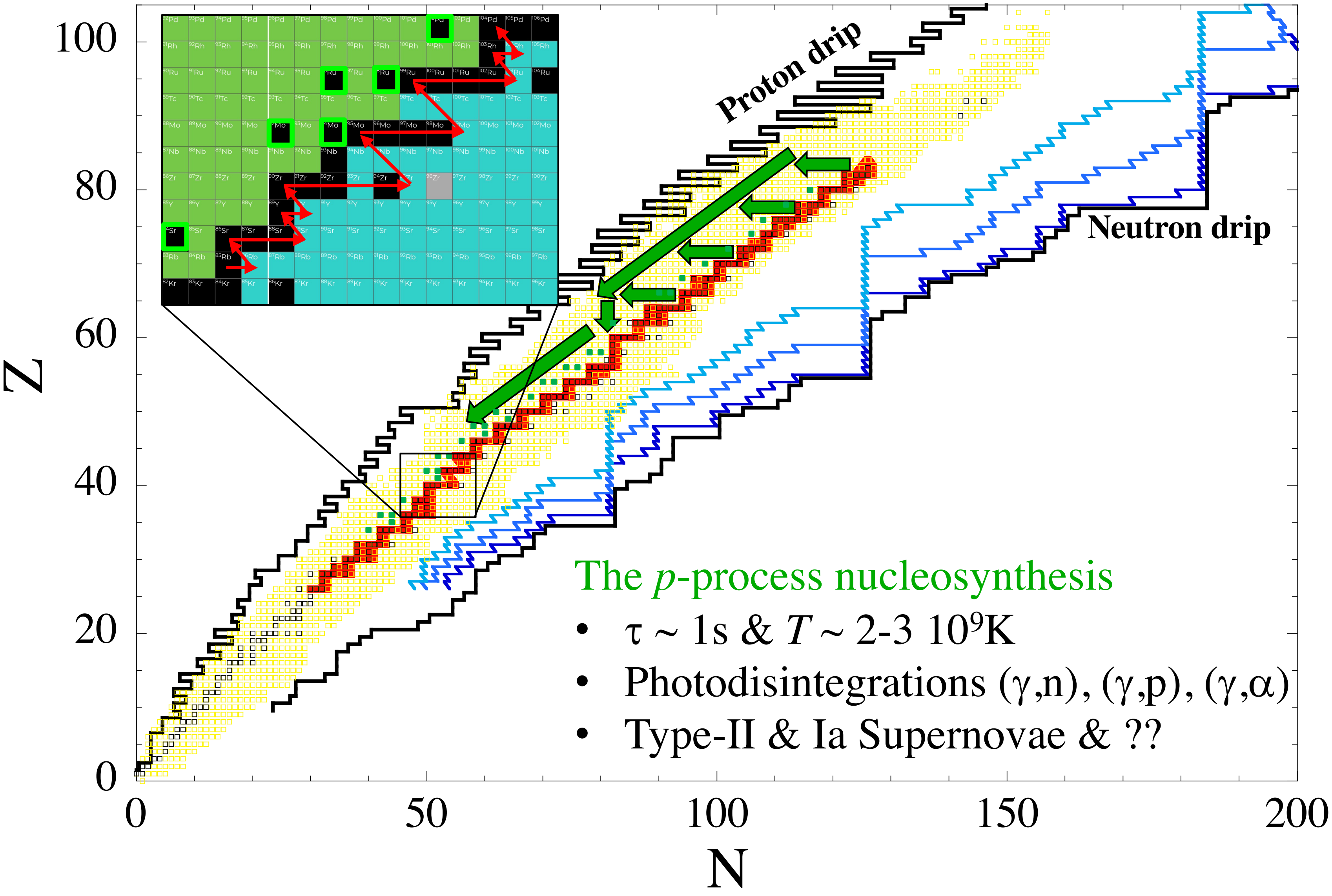
What about an intermediate neutron-capture process ?



The *i*-process nucleosynthesis ($\tau_n \sim \tau_\beta$)

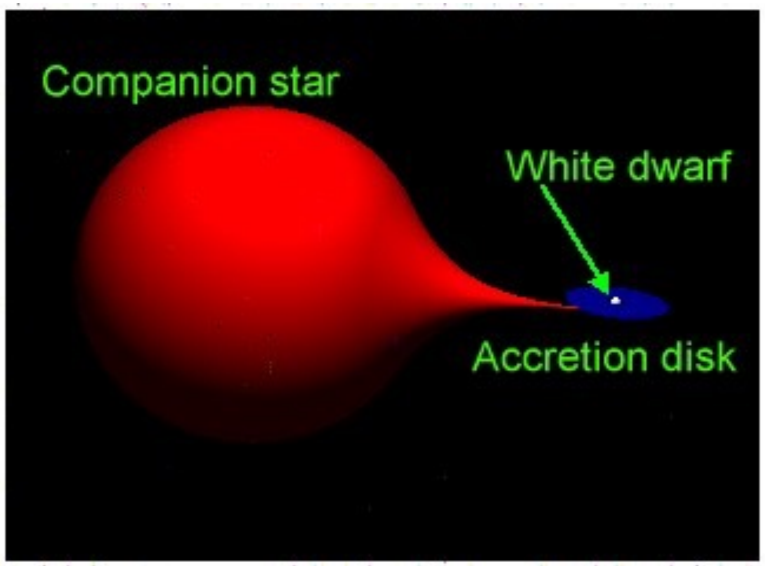
- $\tau \sim 0.1$y & $N_n \sim 10^{13\text{-}15}$ cm^{-3}
- (n,γ) and β-decays
- Do we need the *i*-process ?
  If so, what is the astrophysical site ??

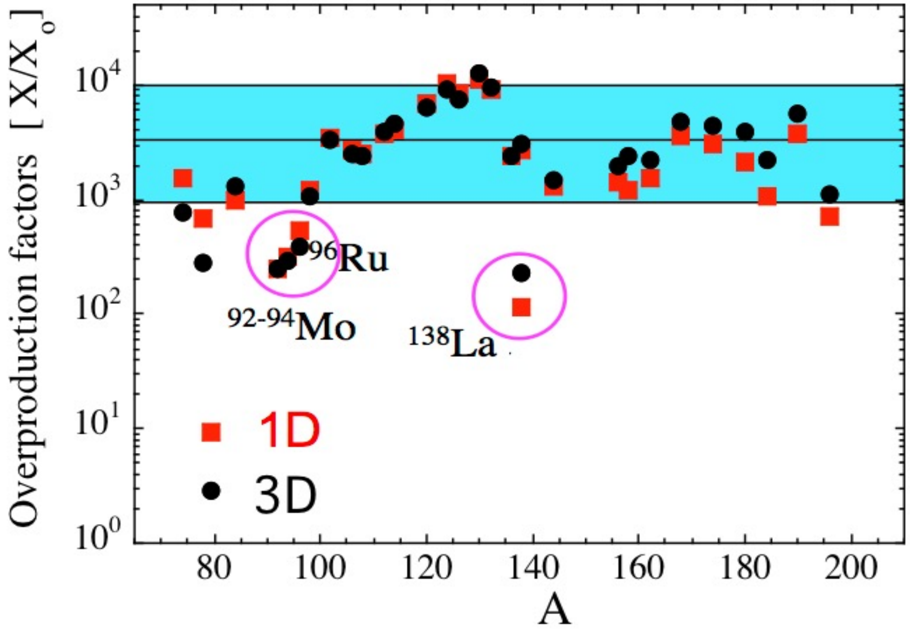
The p-process nucleosynthesis



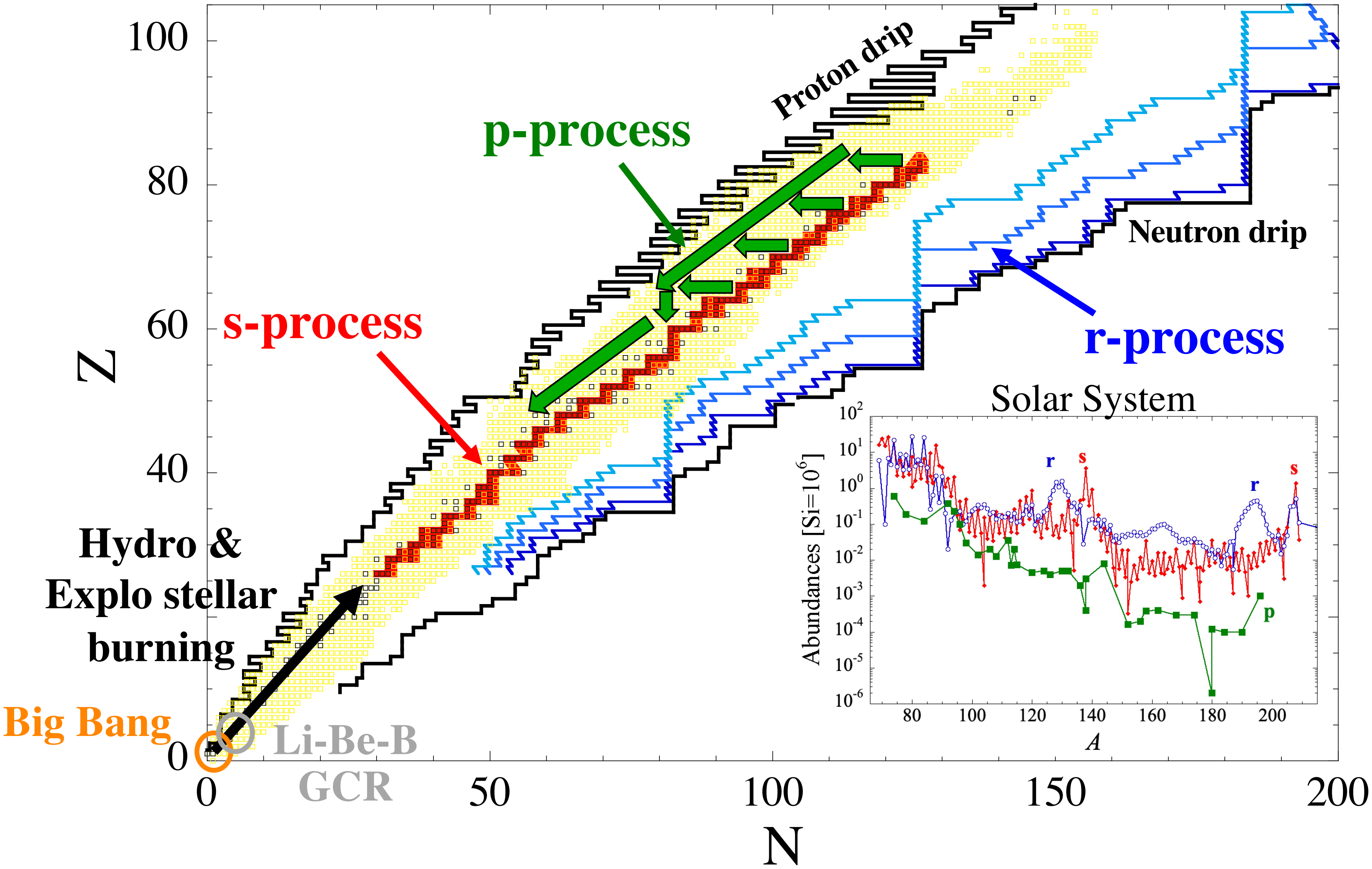
The p-process nucleosynthesis is responsible for n-deficient elements heavier than iron in the Universe

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

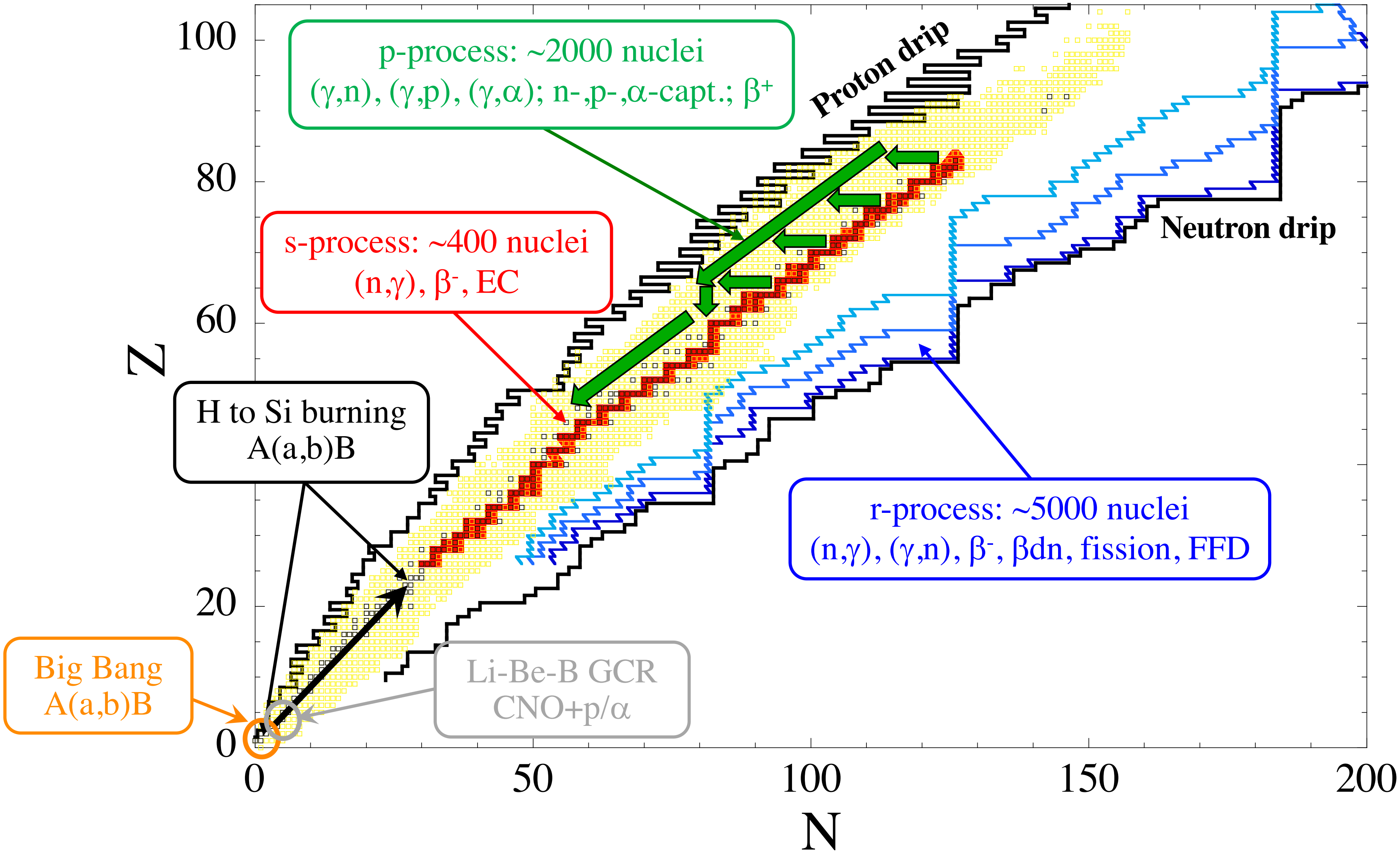




The various nucleosynthesis processes

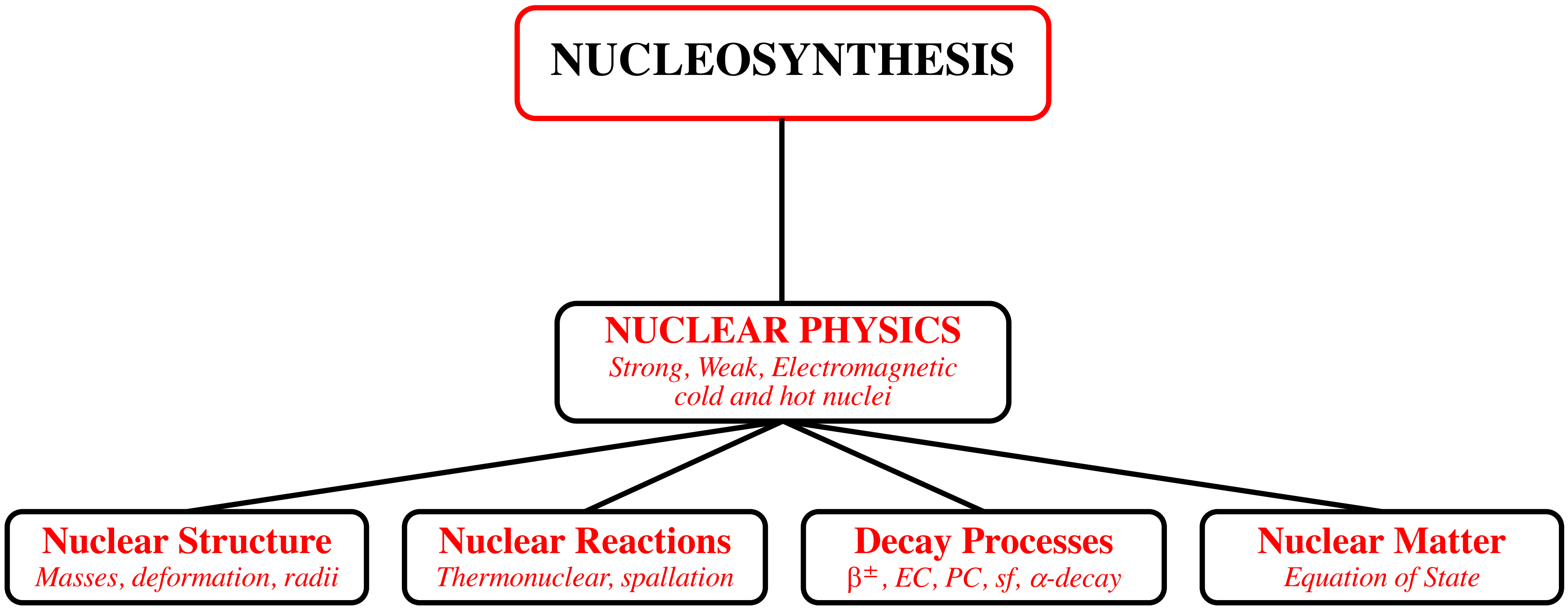


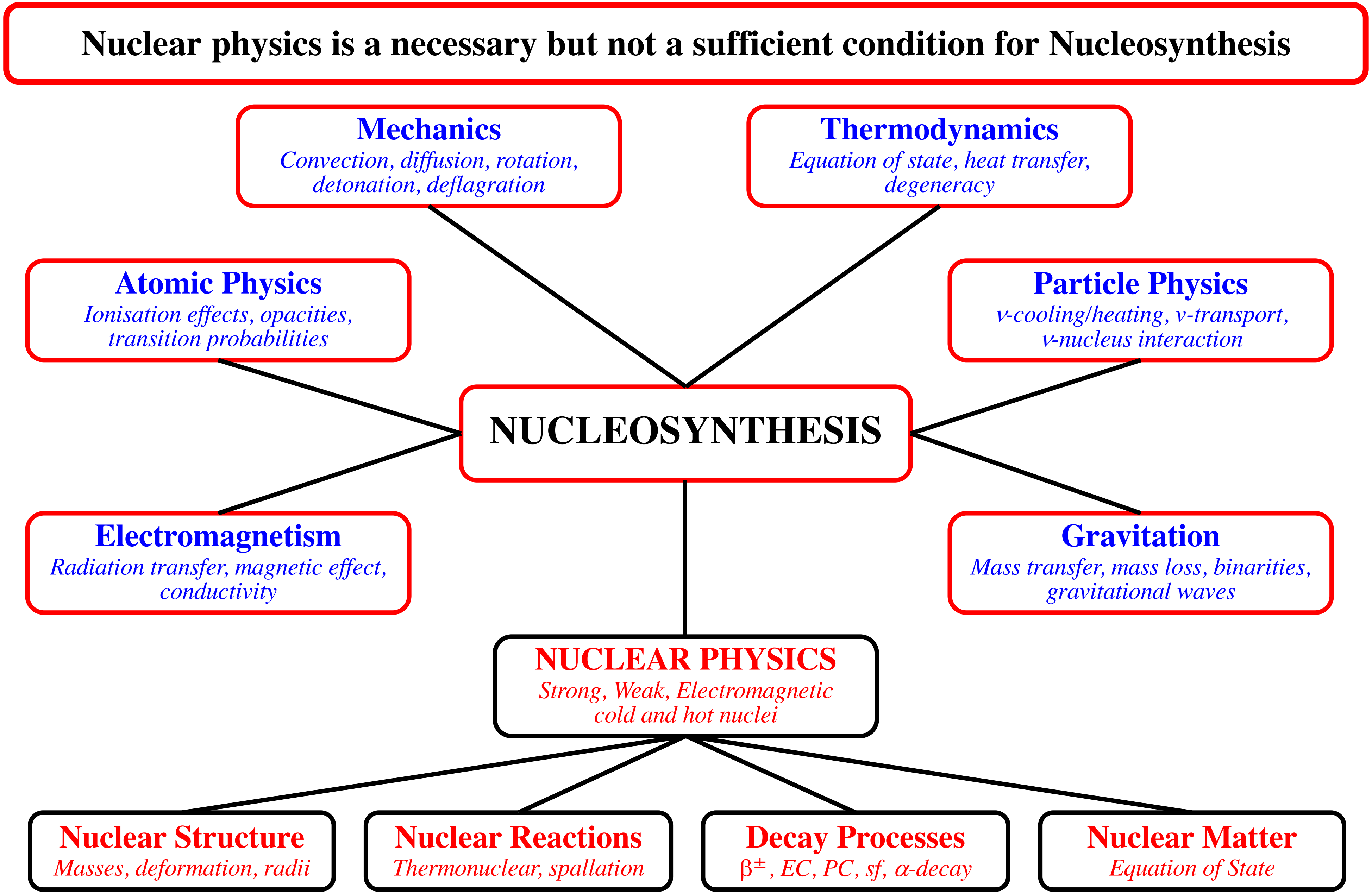
Many different nuclear needs for the various nucleosynthesis processes



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
Mechanics
Convection, diffusion, rotation, detonation, deflagration
Thermodynamics
Equation of state, heat transfer, degeneracy
Atomic Physics
Ionisation effects, opacities, transition probabilities
Particle Physics
ν-cooling/heating, ν-transport, ν-nucleus interaction
NUCLEOSYNTHESIS
Electromagnetism
Radiation transfer, magnetic effect, conductivity
Gravitation
Mass transfer, mass loss, binarities, gravitational waves
NUCLEAR PHYSICS
Strong, Weak, Electromagnetic cold and hot nuclei
Nuclear Structure
Masses, deformation, radii
Nuclear Reactions
Thermonuclear, spallation
Decay Processes
β±, EC, PC, sf, α-decay
Nuclear Matter
Equation of State

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