Nuclear Astrophysics
and
Related Nuclear Data Needs

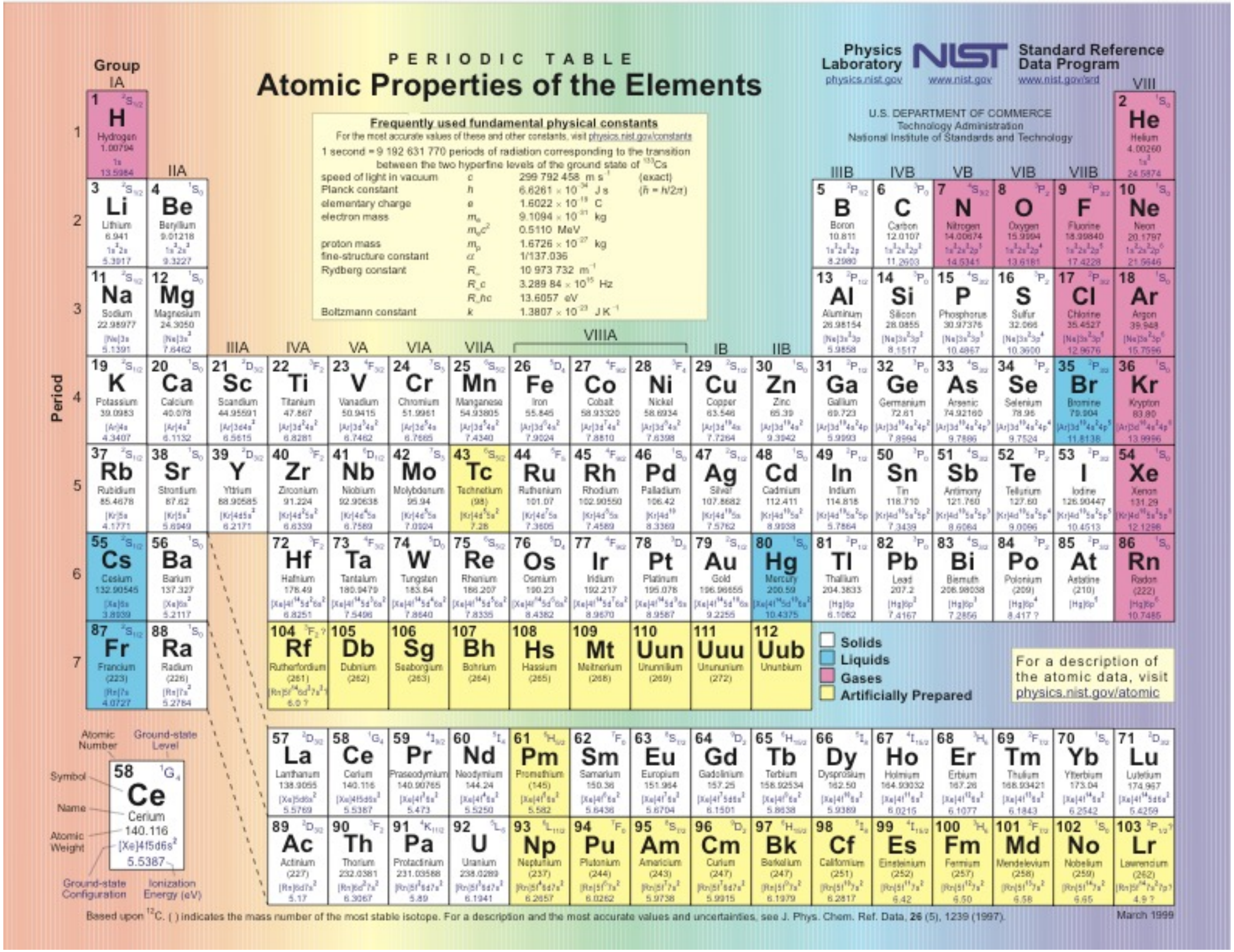
Lecture 2-3

Everything you always wanted to know about nucleosynthesis

1. The origin of the elements in the Universe (Lecture 2)
    - Production of light elements ($A \leq 56$)
    - s-, r-, i- and p-processes of nucleosynthesis
    - Some open astrophysical questions for the s- r-, i- and p-processes

2. Nuclear reactions of astrophysical interest (Lecture 3)
    - β-decay rates in a stellar plasma
    - Reaction rates in a stellar plasma
    - Extrapolation towards experimentally unknown nuclei
    - Some open nuclear physics questions for nucleosynthesis applications

Origin of the elements in the Universe ?



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

PERIODIC TABLE

Atomic Properties of the Elements

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	6.6261×10^{-34} J s	($\hbar = h/2\pi$)
elementary charge	e	1.6022×10^{-19} C	
electron mass	m_e	9.1094×10^{-31} kg	
	m_ec^2	0.5110 MeV	
proton mass	m_p	1.6726×10^{-27} kg	
fine-structure constant	α	1/137.036	
Rydberg constant	R_∞	10 973 732 m^{-1}	
	$R_\infty c$	$3.289\,84 \times 10^{15}$ Hz	
	$R_\infty hc$	13.6057 eV	
Boltzmann constant	k	1.3807×10^{-23} J K^{-1}	

Period	IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA	VIIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIII
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		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		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub						

57 La	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
89 Ac	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

☐ Solids
🟦 Liquids
🟪 Gases
🟨 Artificially Prepared

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

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

Chemical composition of the Sun

Chemical composition at the stellar surface is determined by the analysis of spectral lines (absorption wave length specific to each element): *Stellar spectroscopy*

The solar system plays a pivotal role in nucleosynthesis. It remains the main source (high quality, high quantity, coherence) of information for the *element* abundances:

- Detailed spectroscopy
- Meteorites: Carboneous chondrites representative of the protosolar nebula

Elemental solar composition 4.6 billion years ago

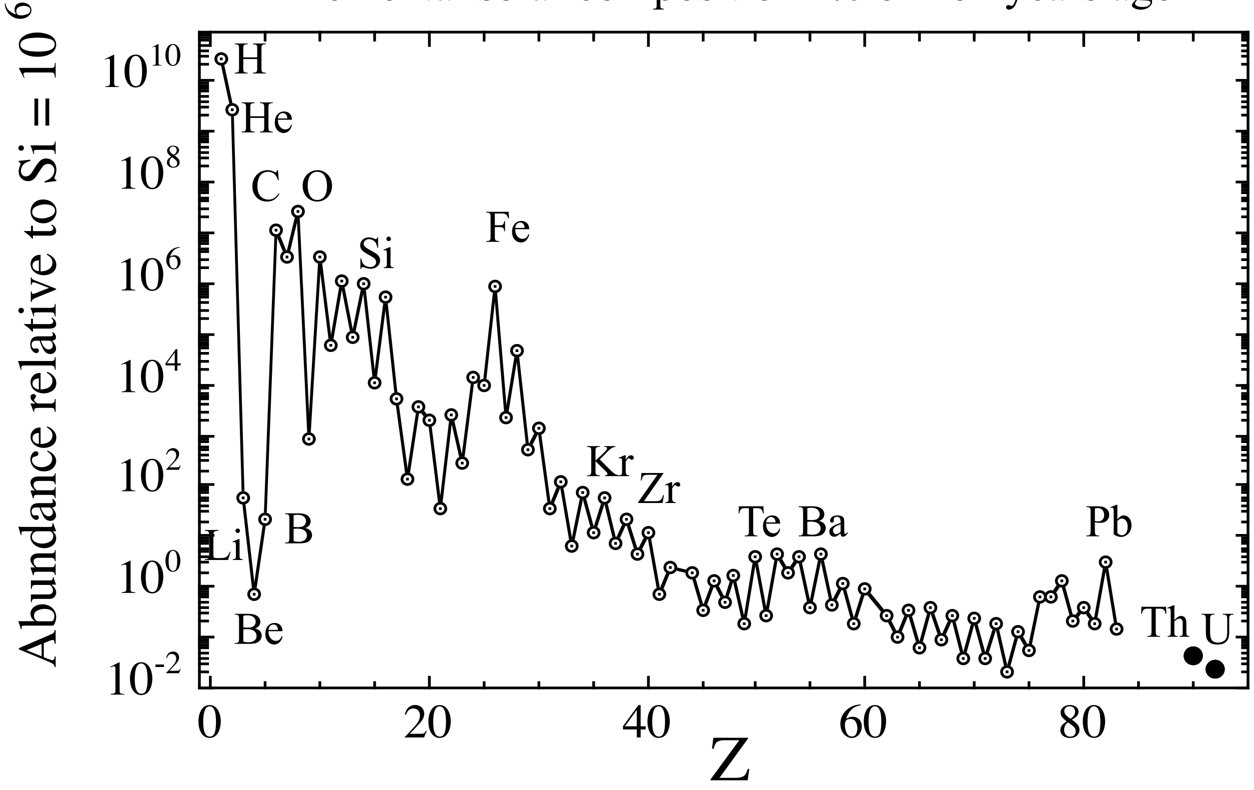
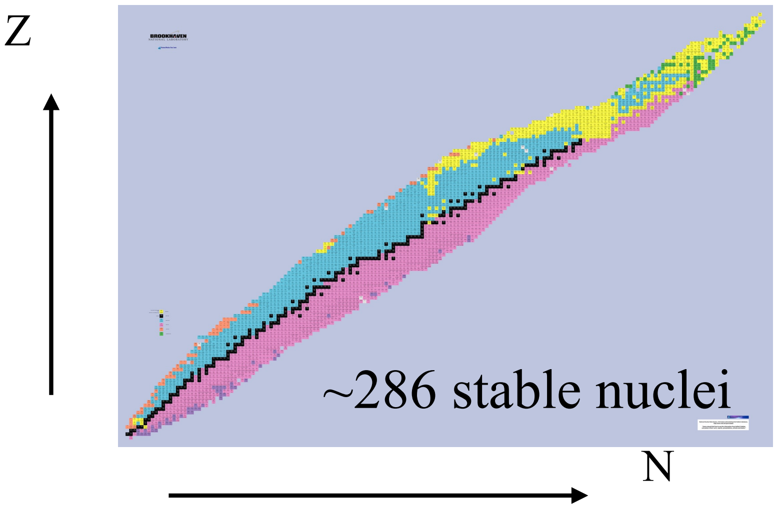
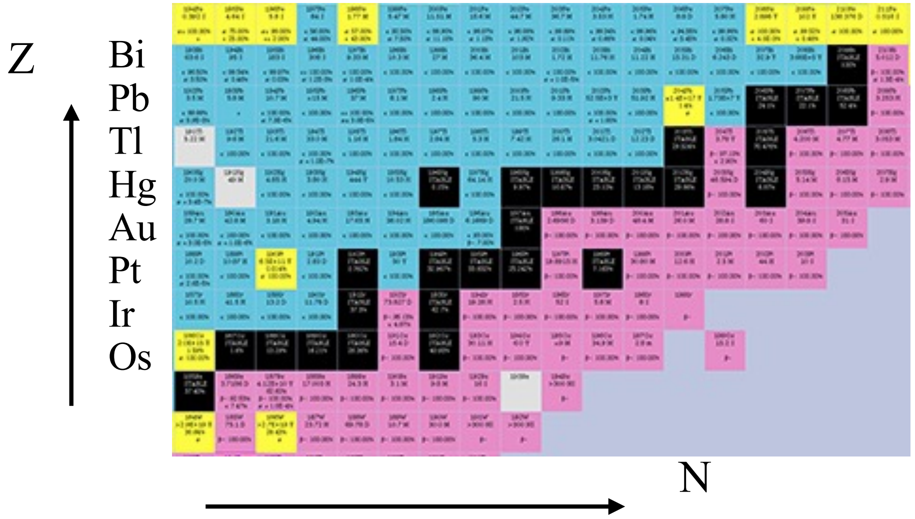


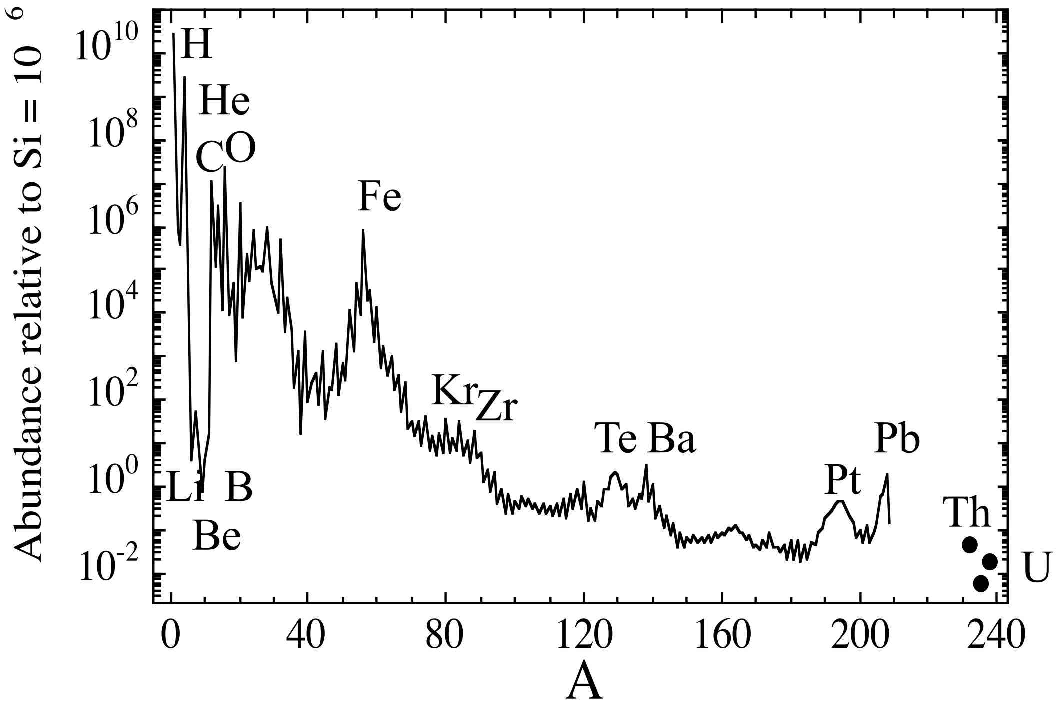

Photo by : Tim Heitz

Isotopic composition of the solar system





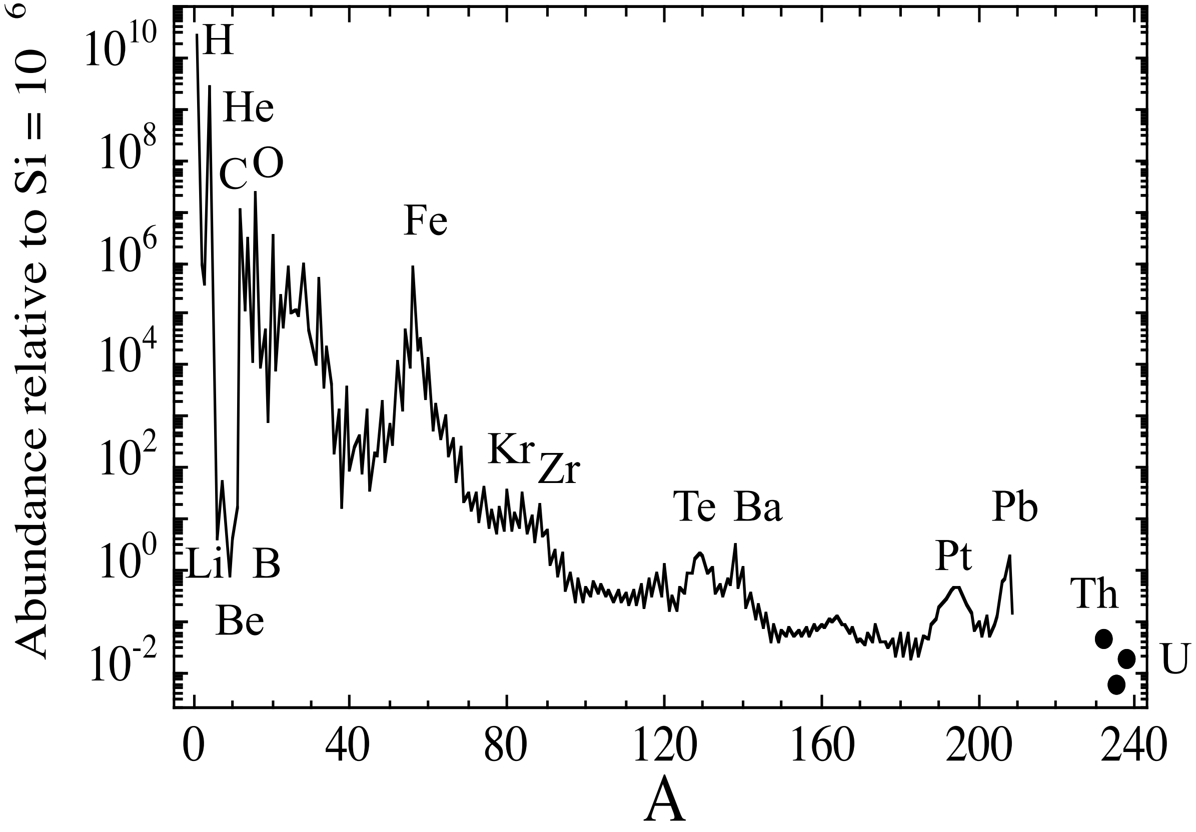
Isotopic composition obtained on the basis of the terrestrial isotopic composition

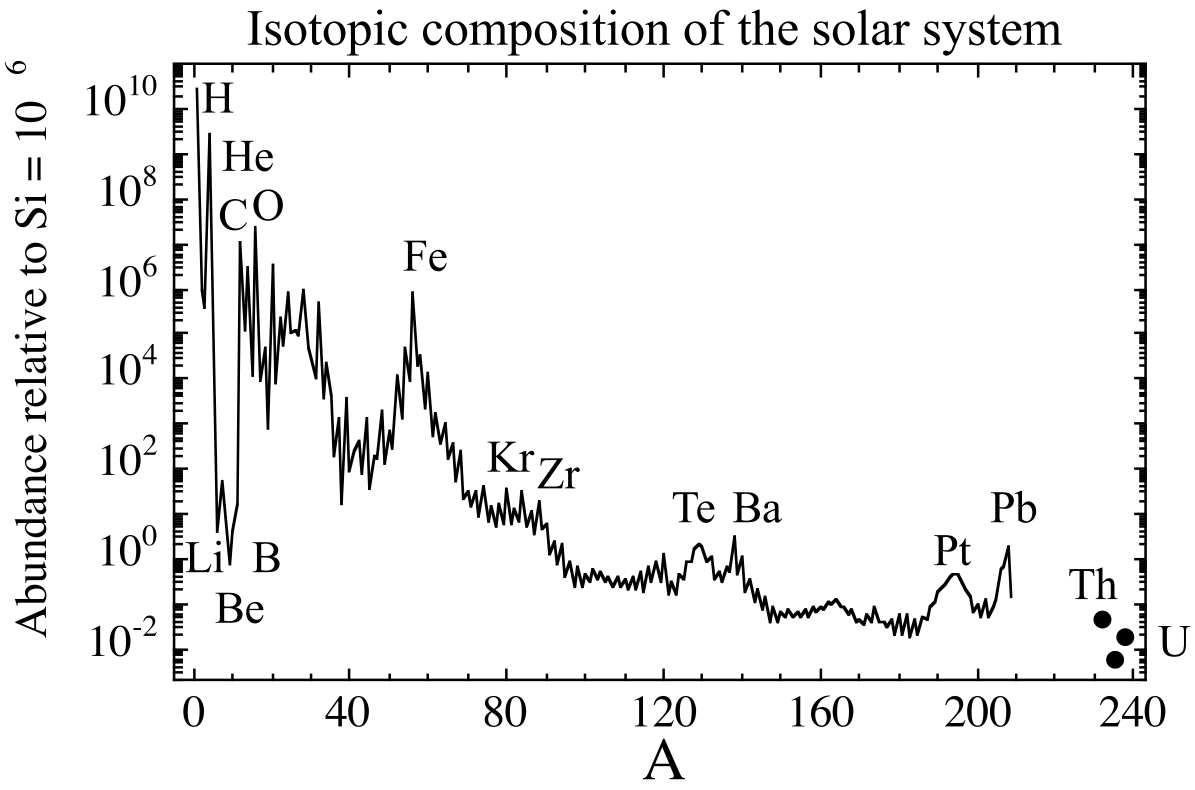


Nucleosynthesis

One of the major issues in modern astrophysics concerns the analysis of the present composition of the Universe and its various constituting objects.

Nucleosynthesis **models aim at explaining the origin of the different** ***nuclei*** **observed in nature by identifying the possible processes and nuclear mechanisms able to synthesize them.**





Isotopic composition of the solar system

Isotopic composition obtained on the basis of the terrestrial isotopic composition (the isotopic composition of the solar system material is not affected by chemico-physical processes and therefore shows a strong homogeneity in its isotopic composition)

→ **Strong correlations between nuclear properties and the solar system abundances**

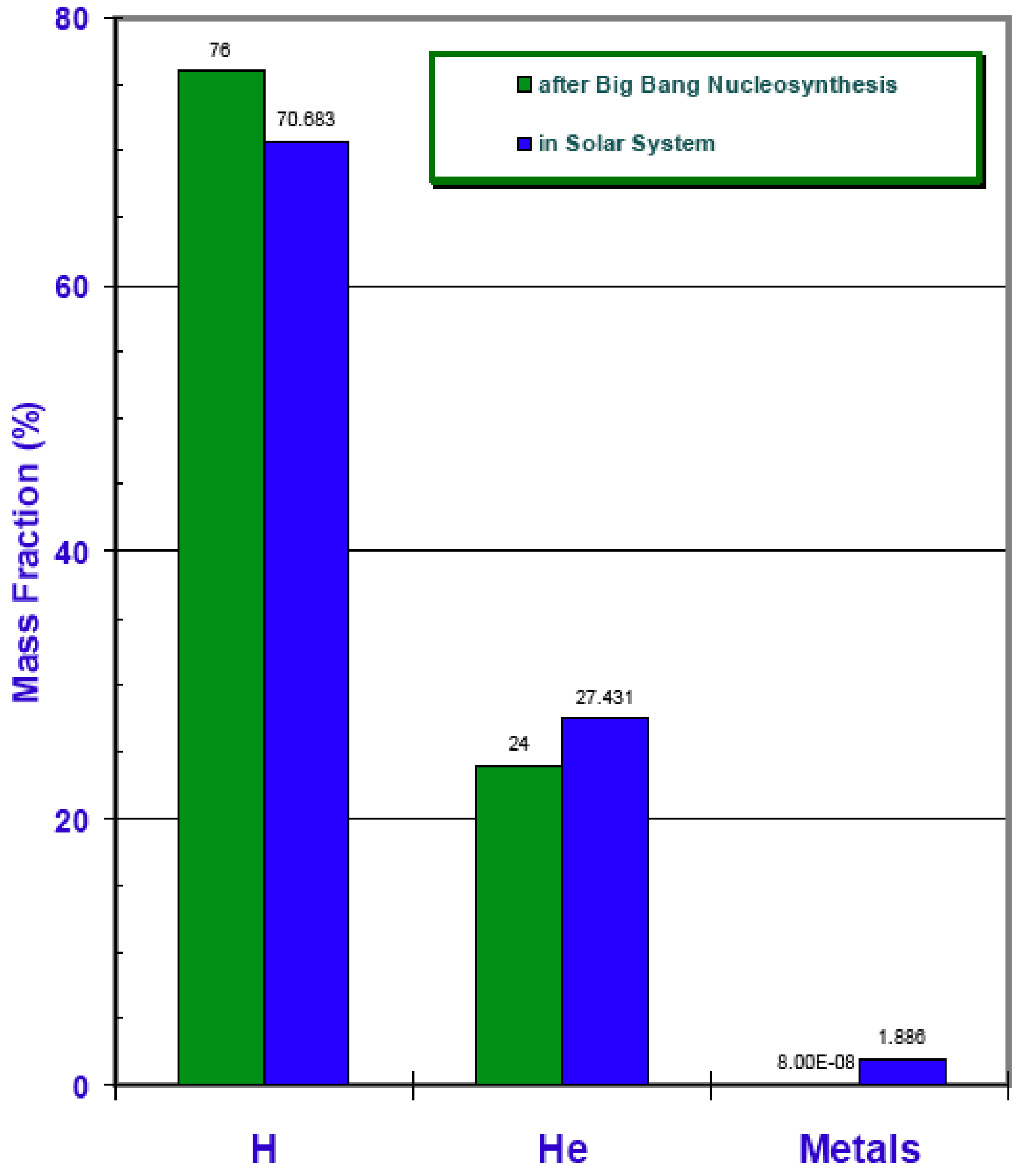
Nucleosynthesis theory aims at explaining the origin of the elements **and their isotopes** in the Universe

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

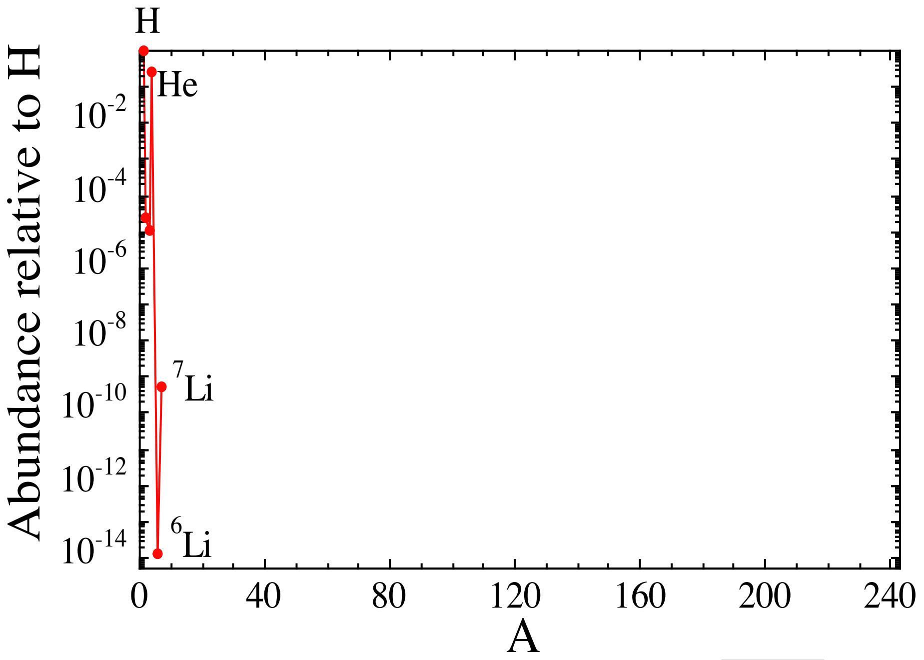
Direct proofs of some nucleosynthesis events in stars:

- spectroscopic observations of radioelements at the surface of some stars: Tc ($t_{1/2}$=0.21Myr)
- gamma-ray astronomy observations: ^{26}Al ($t_{1/2}$=0.7Myr)

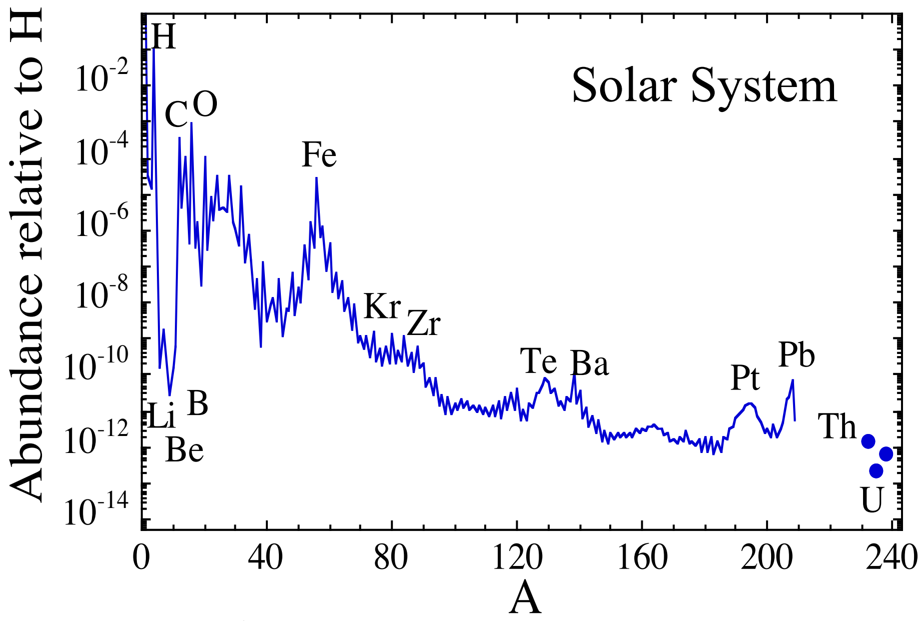
Matter composition

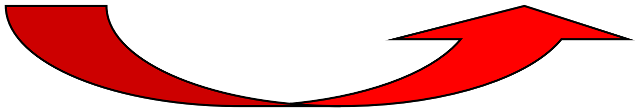


Big Bang nucleosynthesis



Stellar nucleosynthesis

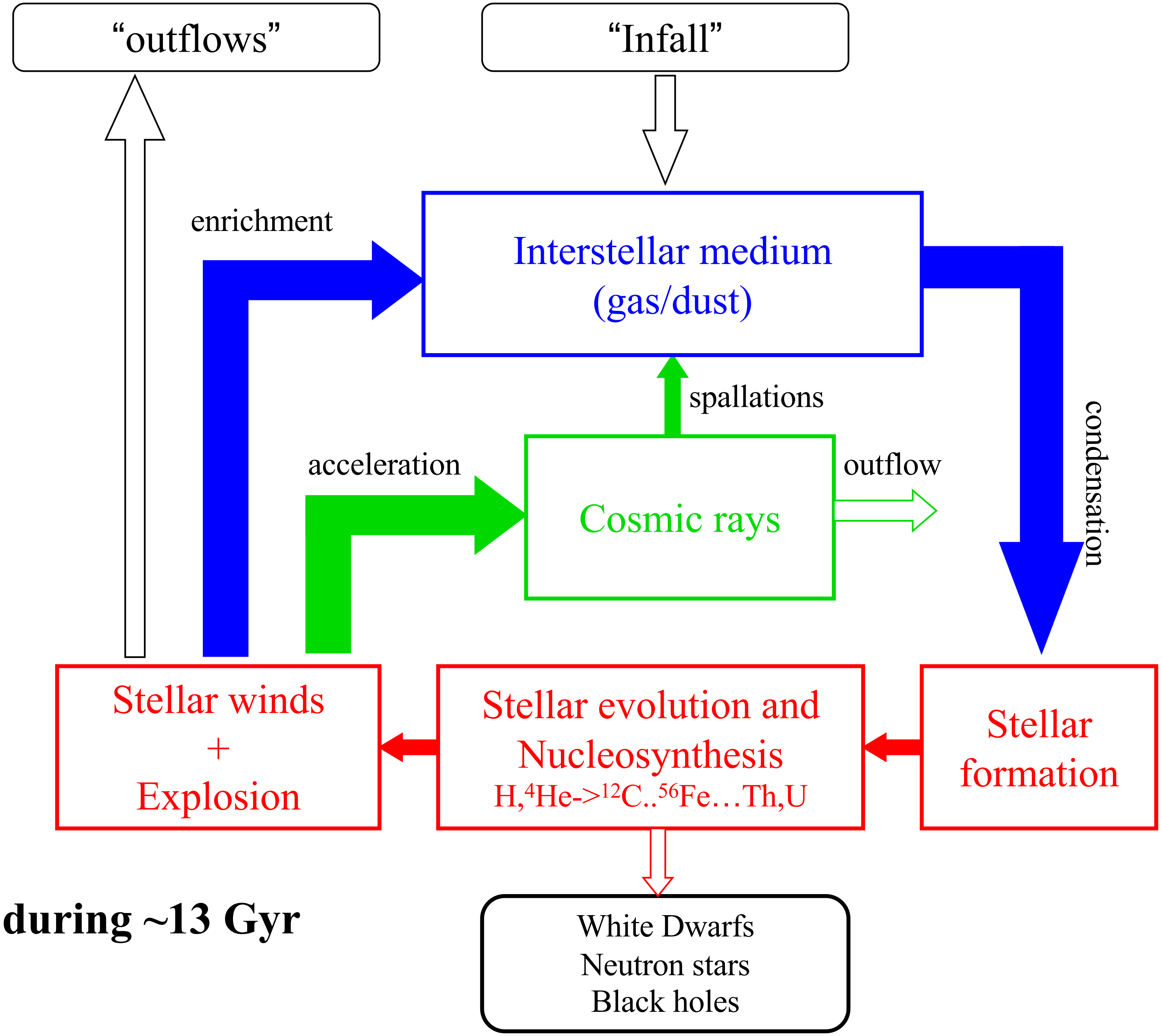




some 13 Gy after BB

Stars are the cosmos cauldrons

Chemical evolution of the Galaxy



"outflows"

"Infall"

enrichment

Interstellar medium
(gas/dust)

spallations

acceleration

Cosmic rays

outflow

condensation

Stellar winds
+
Explosion

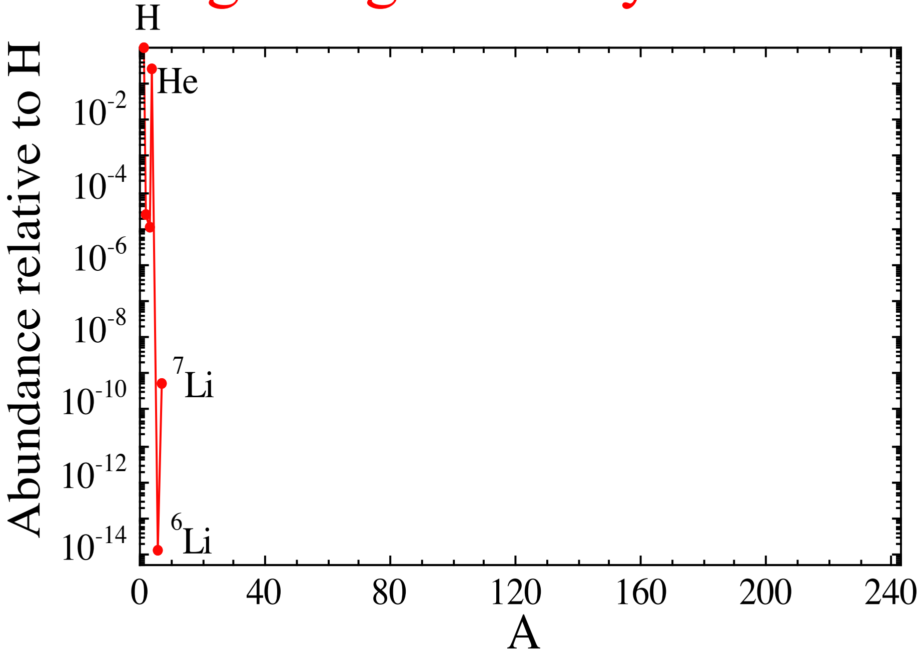
Stellar evolution and
Nucleosynthesis
H,^{4}He->^{12}C..^{56}Fe…Th,U

Stellar
formation

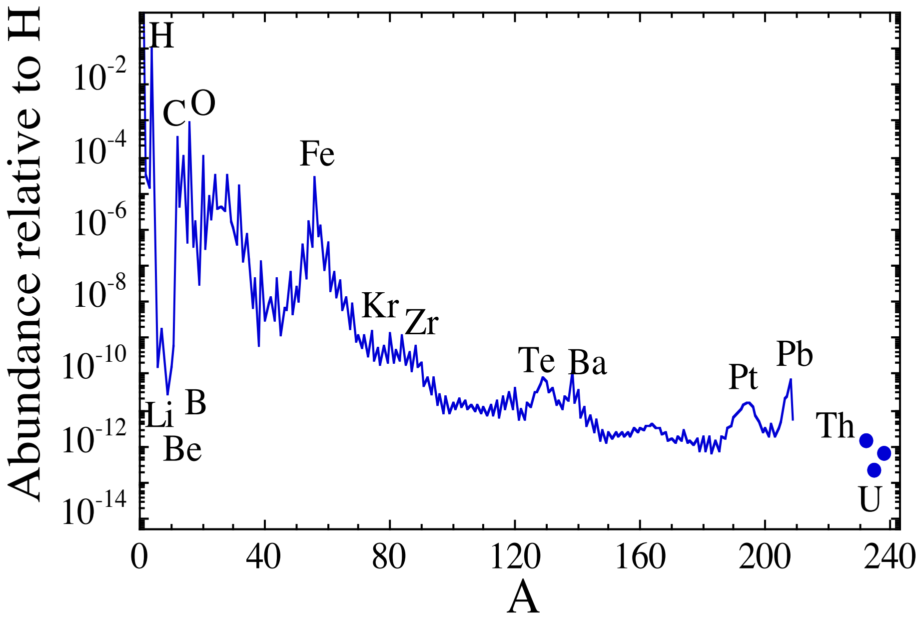
White Dwarfs
Neutron stars
Black holes

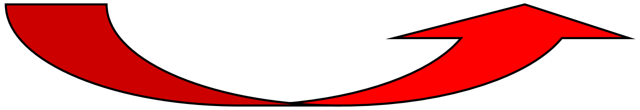
… and this during ~13 Gyr

Big Bang nucleosynthesis



Stellar nucleosynthesis



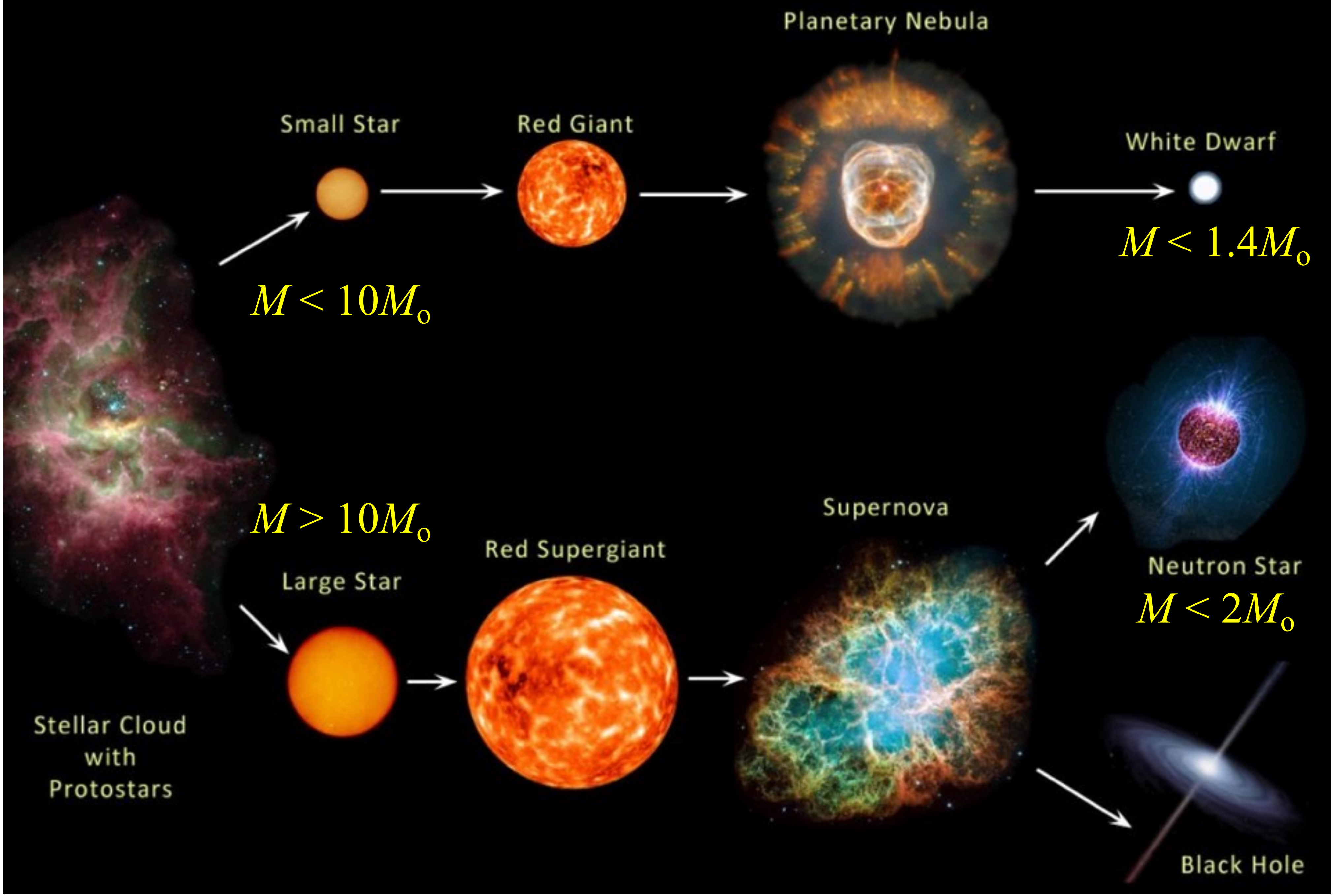


some 10 Gy after BB

Stars are the cosmos cauldrons: need to understand

- **stellar structure and stellar evolution (birth, life and death)**
- **various classes of stars (M, Z, binarity, accretion, …)**
- **interaction with cosmic rays**
- **nuclear physics properties of interacting nuclei**

Stars as gravitationally controlled nuclear reactors



$M < 10M_o$

$M < 1.4M_o$

$M > 10M_o$

$M < 2M_o$

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

Gravitationally controlled fusion in stars

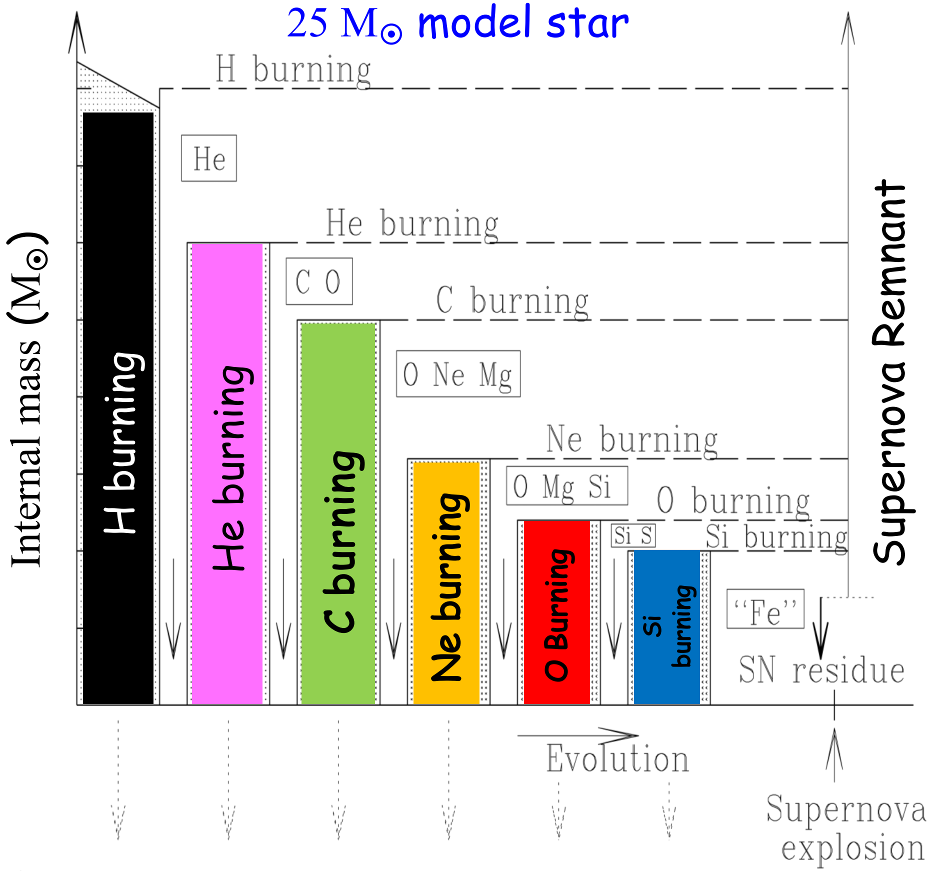
$M < 10M_o$

	T (K)
$4\ {}^{1}H \rightarrow {}^{4}He$	**H burning phase** > 10 10^6
$3\ {}^{4}He \rightarrow {}^{12}C$ ${}^{12}C + {}^{4}He \rightarrow {}^{16}O$	**He burning phase** >100 10^6

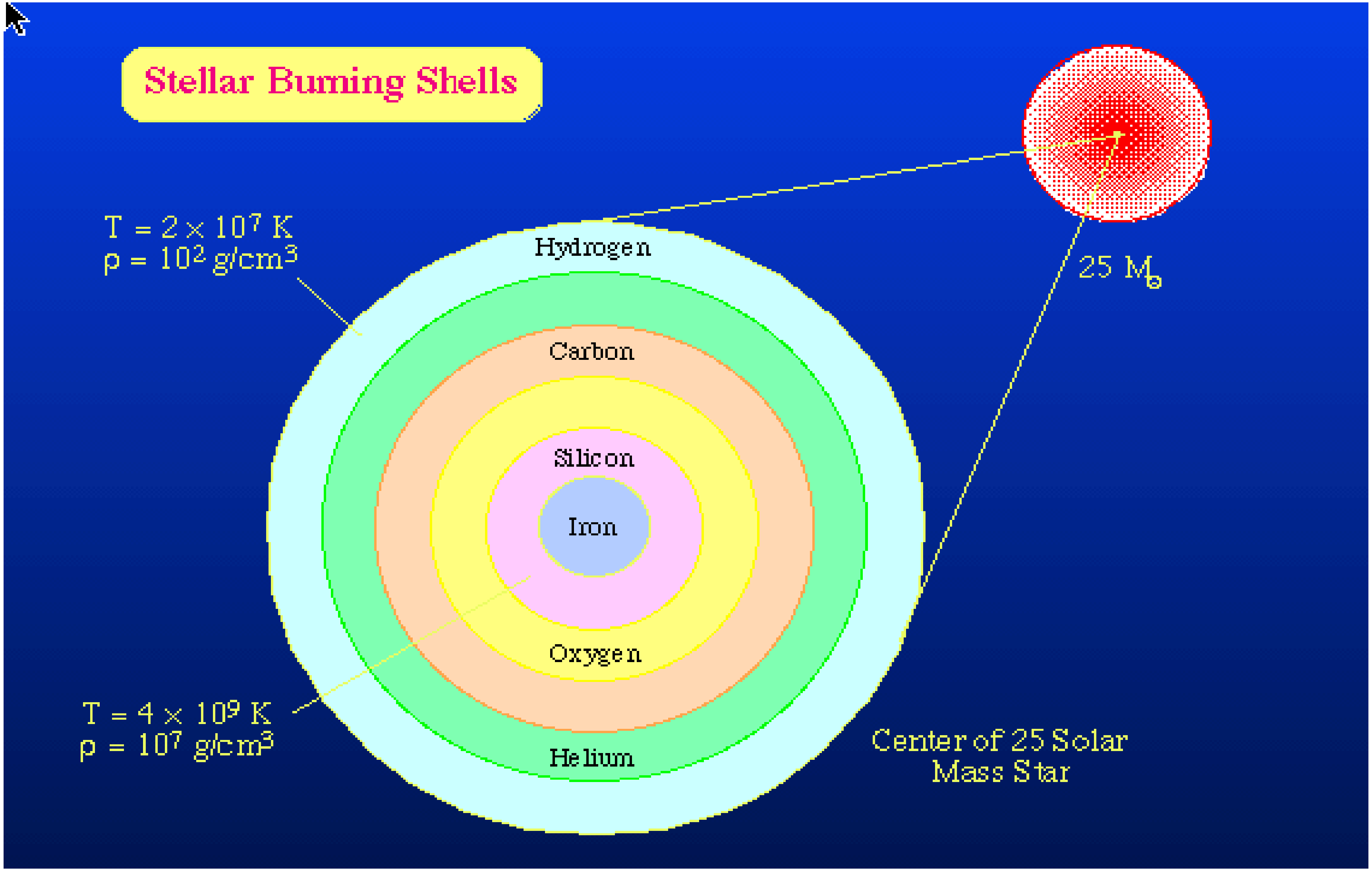
$M > 10M_o$

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

25 M$_\odot$ model star

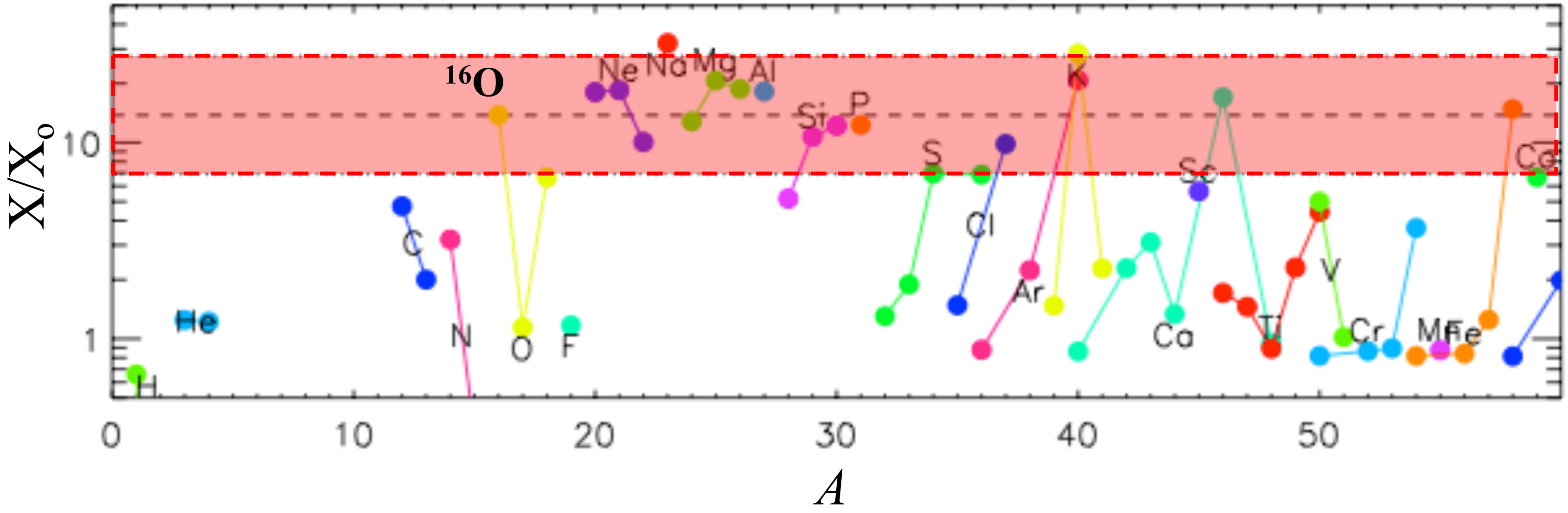


T_c(K)	6×10^7	2×10^8	9×10^8	1.7×10^9	2.3×10^9	4×10^9
ρ_c(g/cm^3)	5	700	2×10^5	4×10^6	10^7	3×10^7
Time-scale	7 ×10^6 y	5 ×10^5 y	600 y	0.5 y	6 d	1 d



The explosion of heavy-mass ($M>10M_\odot$) stars (SNII) enrich the interstellar medium in heavy elements

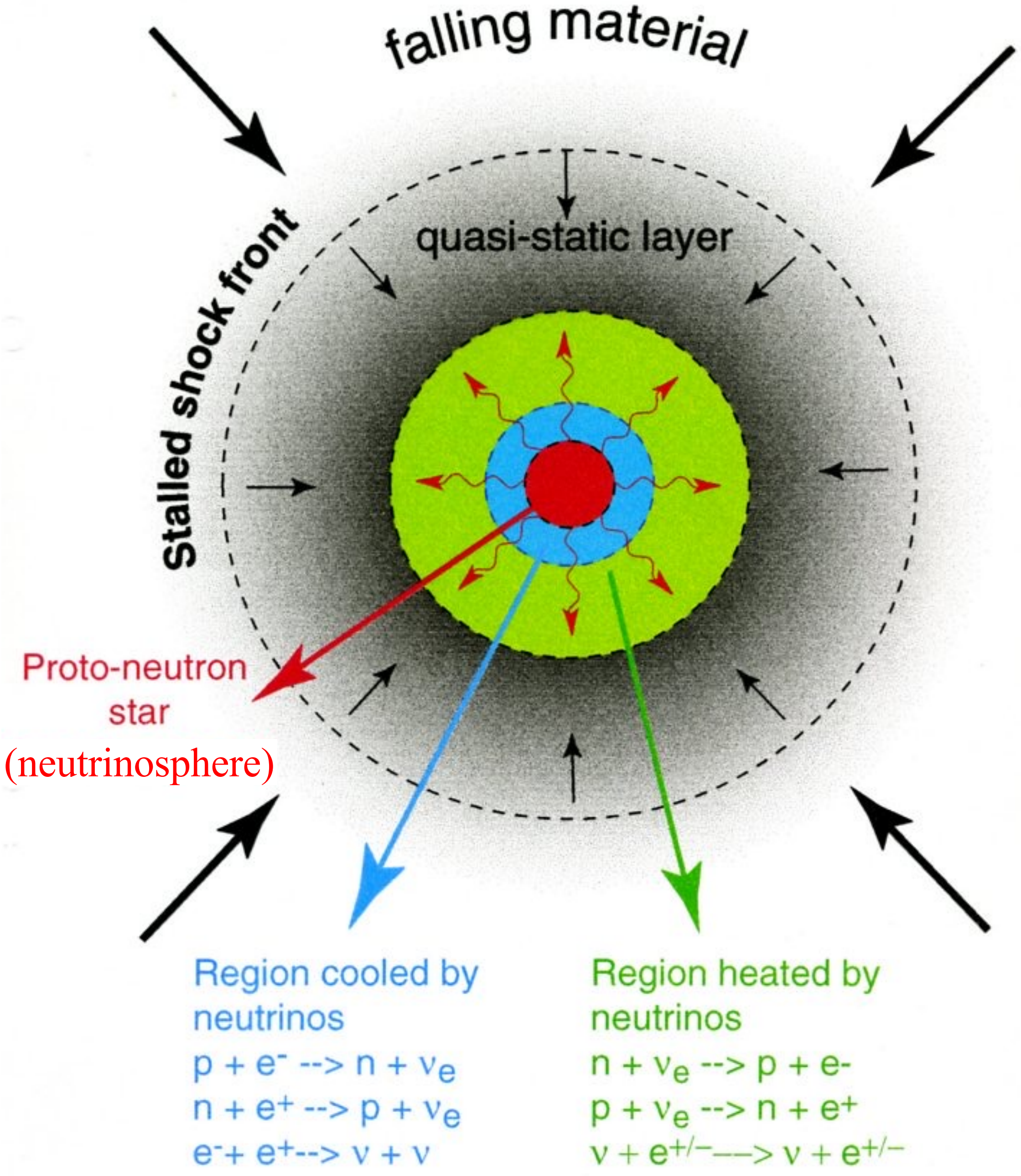
Pre-explosive production factors for a 21$M_\odot$ star



Elements with $20 \leq A \leq 40$ are more or less similarly overproduced

(by almost a factor of 10, as the O overproduction factor)

The $A > 40$ nuclei are on average only modestly enhanced.



Status of SN simulations:

No successful 1D SN simulation for stars developing an Fe iron ($M>10M_o$), in spite of neutrino energy and momentum transfer (shock wave remains not energetic enough)

Need multi-D simulations !

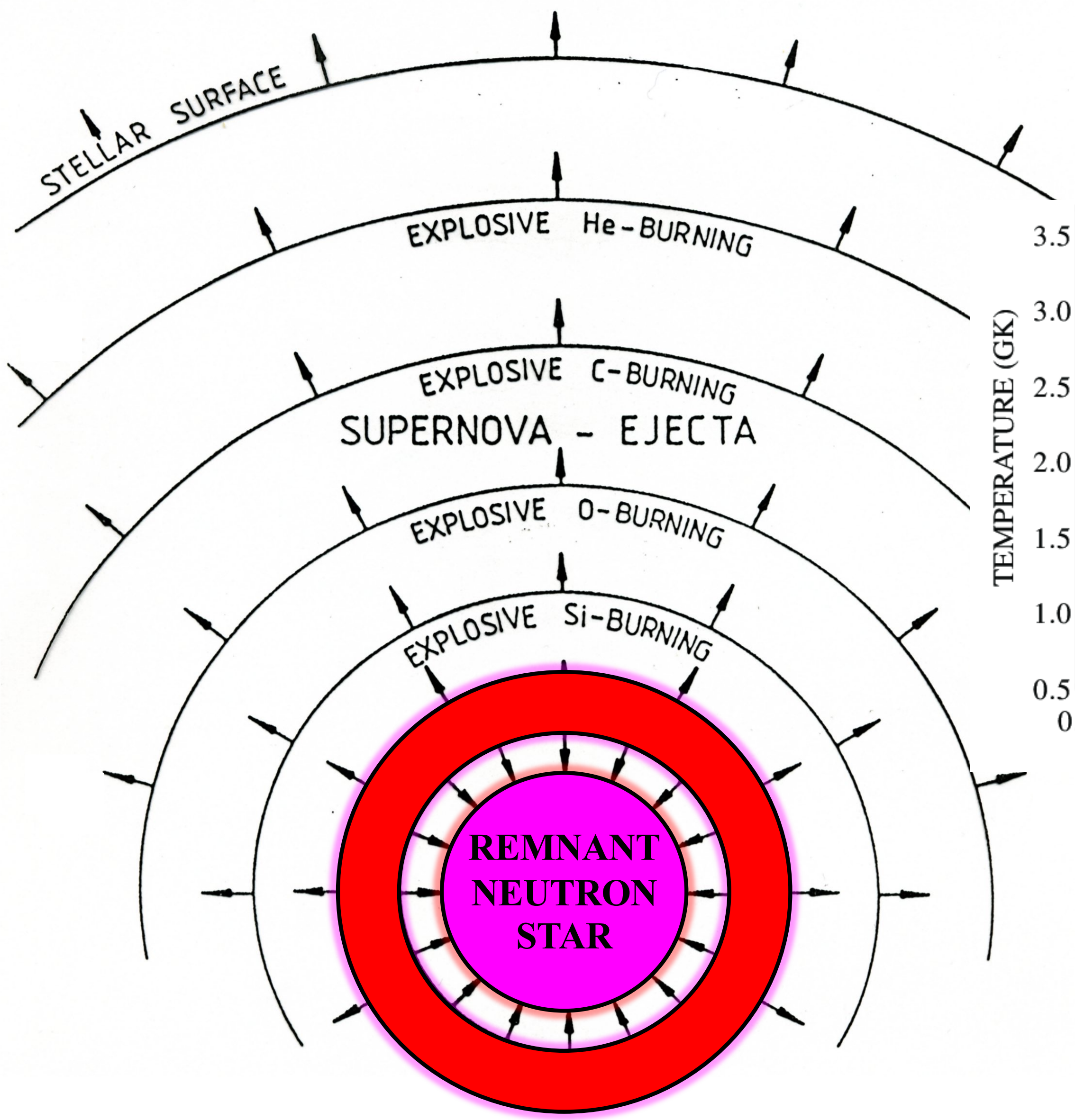
Possible energizing agents

- neutrinos
- rotation
- magnetic fields
- acoustic waves
- progenitor model
- muonic contribution

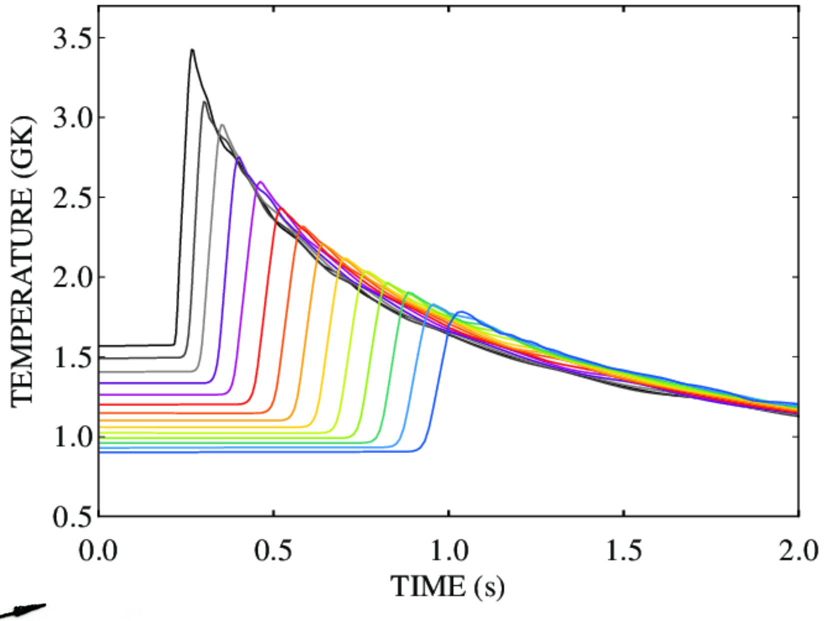
Now successful also for $M>15M_o$!!

Explosive nucleosynthesis

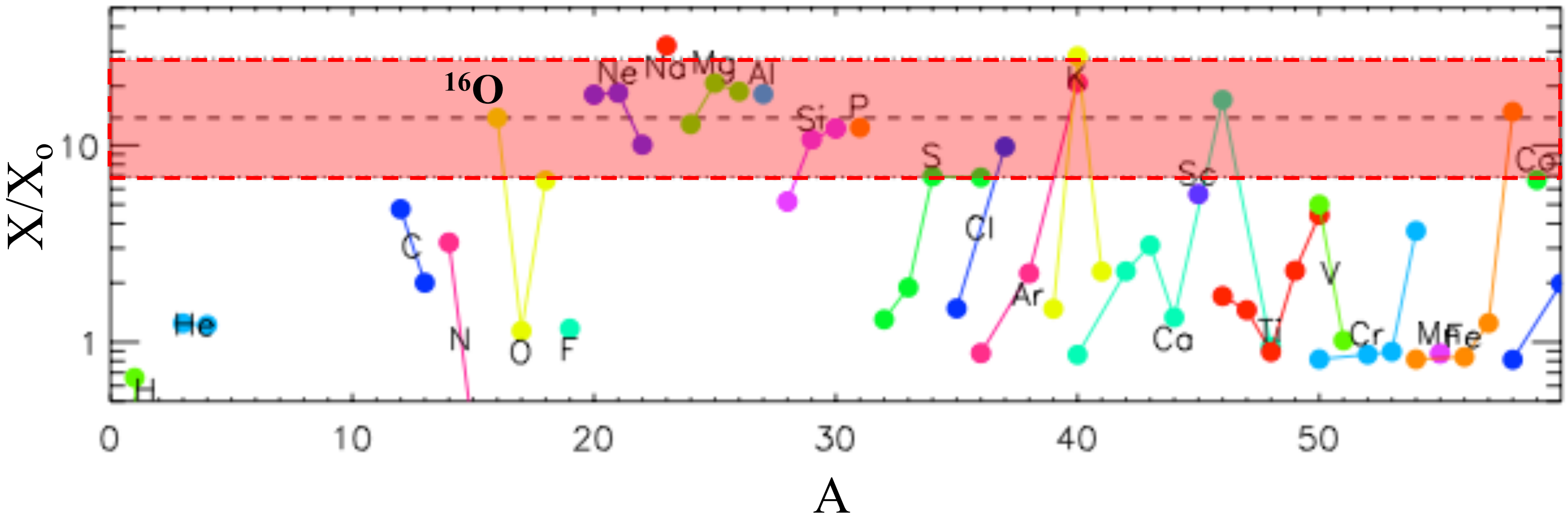
- a limited modification of the presupernova abundance of major species
- a possible drastic change of abundances of rarer species



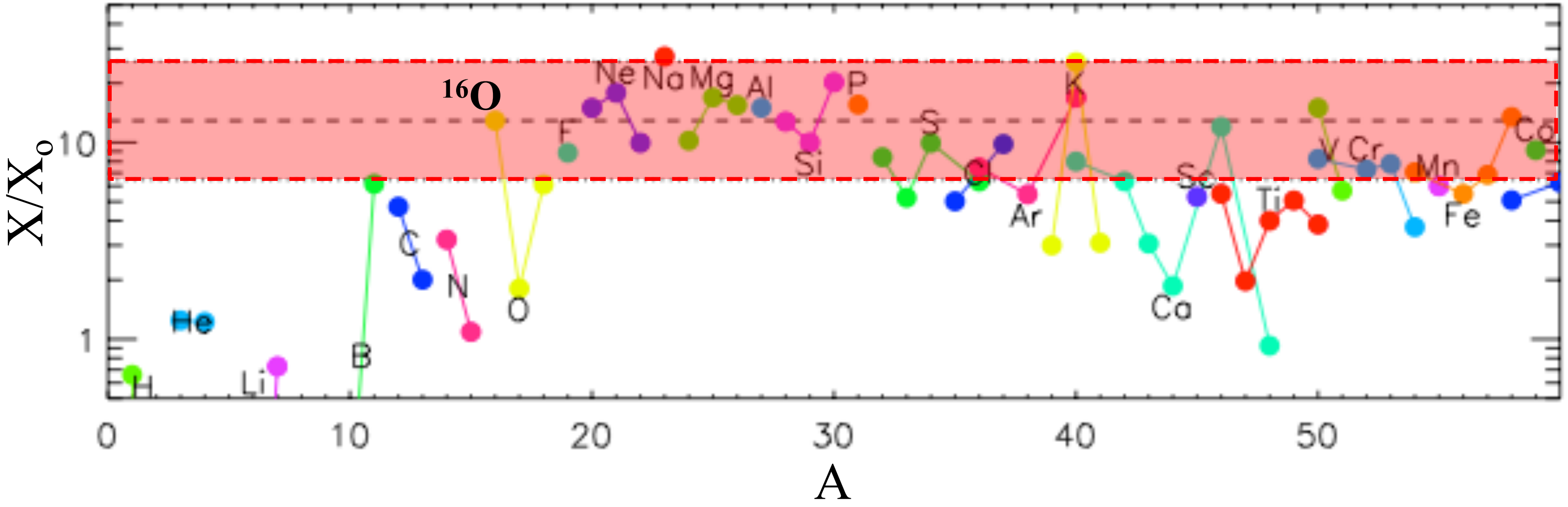
Temperature evolution during SN shock wave propagation



Pre-explosive production factors for a 21$M_\odot$ star

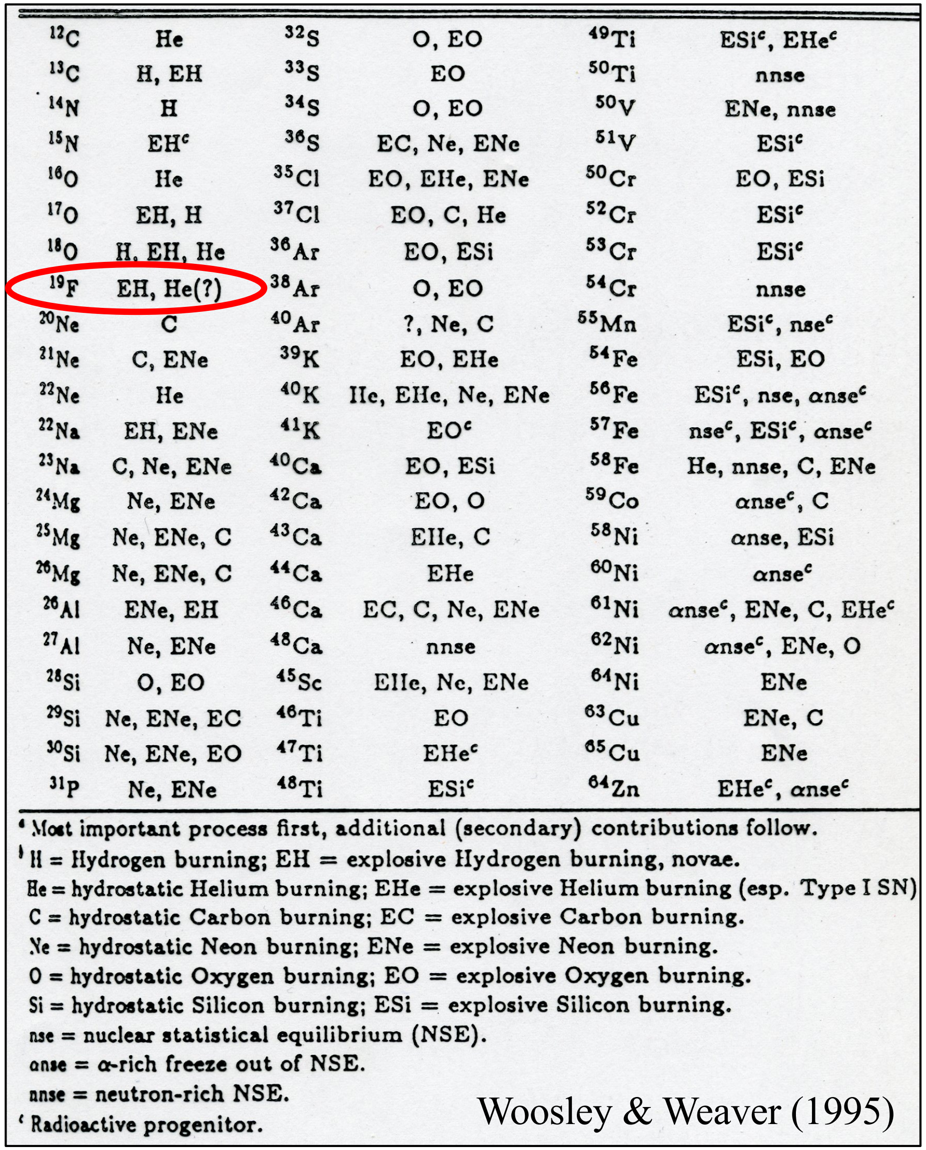


Post-explosive production factors for a 21$M_\odot$ star



The different burning phases responsible for the nucleosynthesis of light elements

from ^{12}C to Fe-group nuclei (66 nuclides)



^{12}C	He	^{32}S	O, EO	^{49}Ti	ESi^c, EHe^c
^{13}C	H, EH	^{33}S	EO	^{50}Ti	nnse
^{14}N	H	^{34}S	O, EO	^{50}V	ENe, nnse
^{15}N	EH^c	^{36}S	EC, Ne, ENe	^{51}V	ESi^c
^{16}O	He	^{35}Cl	EO, EHe, ENe	^{50}Cr	EO, ESi
^{17}O	EH, H	^{37}Cl	EO, C, He	^{52}Cr	ESi^c
^{18}O	H, EH, He	^{36}Ar	EO, ESi	^{53}Cr	ESi^c
^{19}F	EH, He(?)	^{38}Ar	O, EO	^{54}Cr	nnse
^{20}Ne	C	^{40}Ar	?, Ne, C	^{55}Mn	ESi^c, nse^c
^{21}Ne	C, ENe	^{39}K	EO, EHe	^{54}Fe	ESi, EO
^{22}Ne	He	^{40}K	He, EHe, Ne, ENe	^{56}Fe	ESi^c, nse, αnse^c
^{22}Na	EH, ENe	^{41}K	EO^c	^{57}Fe	nse^c, ESi^c, αnse^c
^{23}Na	C, Ne, ENe	^{40}Ca	EO, ESi	^{58}Fe	He, nnse, C, ENe
^{24}Mg	Ne, ENe	^{42}Ca	EO, O	^{59}Co	αnse^c, C
^{25}Mg	Ne, ENe, C	^{43}Ca	EHe, C	^{58}Ni	αnse, ESi
^{26}Mg	Ne, ENe, C	^{44}Ca	EHe	^{60}Ni	αnse^c
^{26}Al	ENe, EH	^{46}Ca	EC, C, Ne, ENe	^{61}Ni	αnse^c, ENe, C, EHe^c
^{27}Al	Ne, ENe	^{48}Ca	nnse	^{62}Ni	αnse^c, ENe, O
^{28}Si	O, EO	^{45}Sc	EHe, Ne, ENe	^{64}Ni	ENe
^{29}Si	Ne, ENe, EC	^{46}Ti	EO	^{63}Cu	ENe, C
^{30}Si	Ne, ENe, EO	^{47}Ti	EHe^c	^{65}Cu	ENe
^{31}P	Ne, ENe	^{48}Ti	ESi^c	^{64}Zn	EHe^c, αnse^c

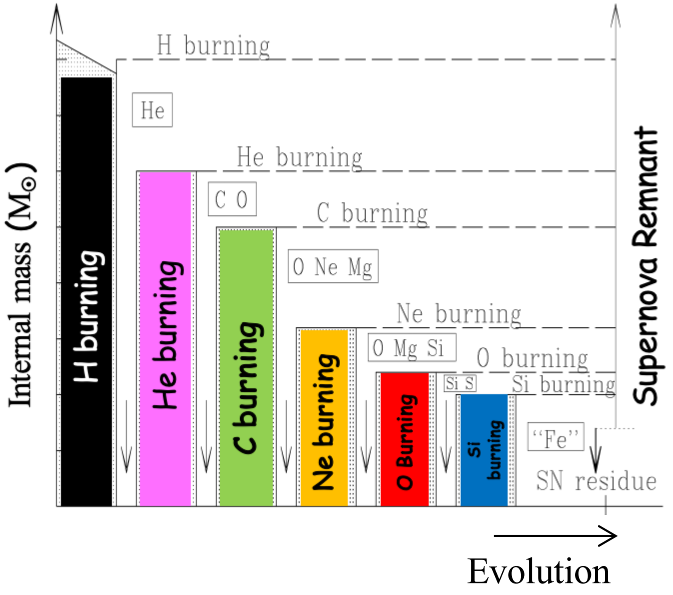
[a] Most important process first, additional (secondary) contributions follow.

[b] H = Hydrogen burning; EH = explosive Hydrogen burning, novae.
He = hydrostatic Helium burning; EHe = explosive Helium burning (esp. Type I SN)
C = hydrostatic Carbon burning; EC = explosive Carbon burning.
Ne = hydrostatic Neon burning; ENe = explosive Neon burning.
O = hydrostatic Oxygen burning; EO = explosive Oxygen burning.
Si = hydrostatic Silicon burning; ESi = explosive Silicon burning.
nse = nuclear statistical equilibrium (NSE).
αnse = α-rich freeze out of NSE.
nnse = neutron-rich NSE.

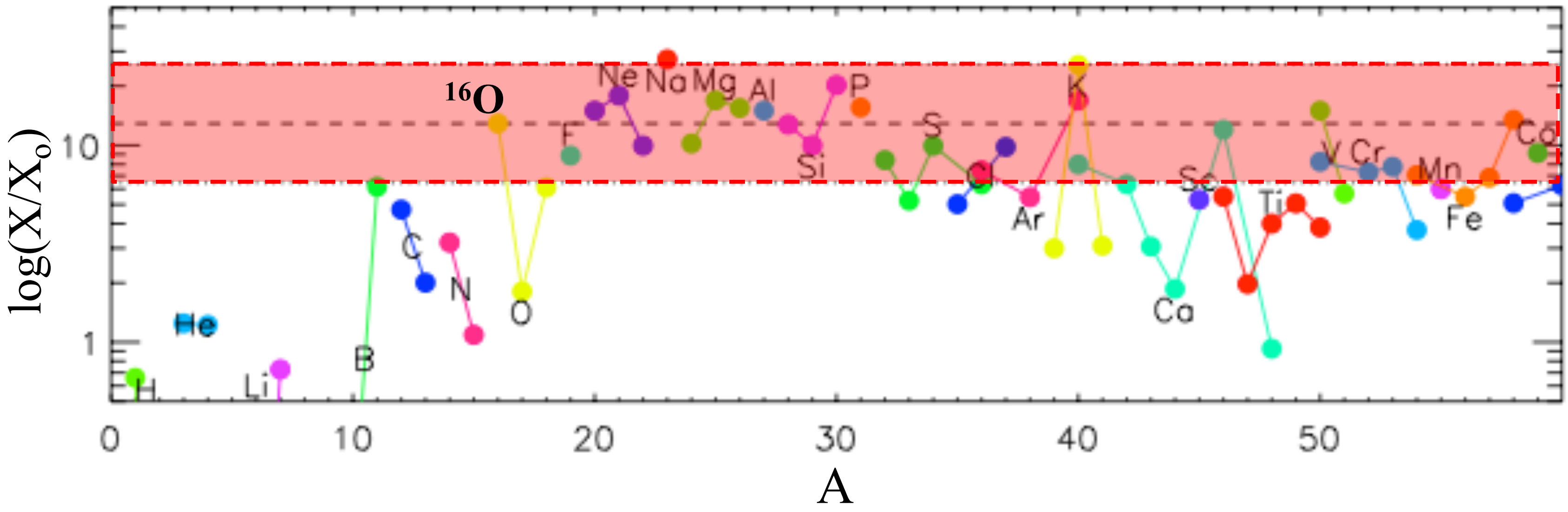
[c] Radioactive progenitor.

Woosley & Weaver (1995)

H = Hydrostatic H-burning
EH = Explosive H-burning
He = Hydrostatic He-burning
EHe = Explosive He-burning
C = Hydrostatic C-burning
EC = Explosive C-burning
Ne = Hydrostatic Ne-burning
ENe = Explosive Ne-burning
O = Hydrostatic O-burning
EO = Explosive O-burning
Si = Hydrostatic Si-burning
ESi = Explosive Si-burning
NSE = Nuclear Statistical Equilibrium



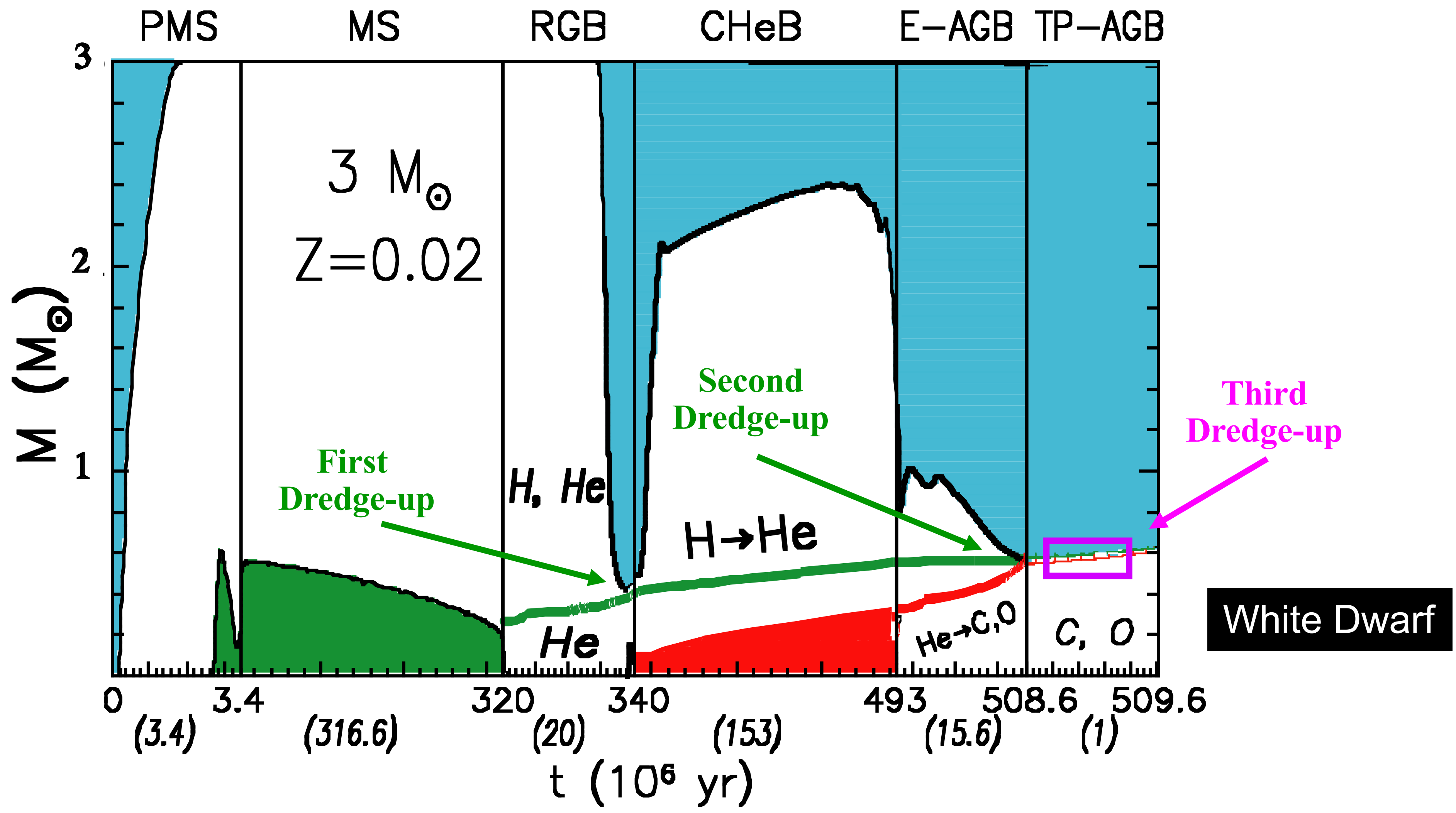
Post-explosive production factors for a 21$M_\odot$ star



What about

- Li-Be-B ? → GCR interaction with ISM
- $^{12\text{-}13}$C ? → AGB stars & Novae
- $^{14\text{-}15}$N ? → AGB stars & Novae
- ^{17}O ? → Novae
- ^{19}F ? → AGB stars ?
- Iron-group nuclei, and in particular ^{56}Fe ? → SNIa

The evolution of low- and intermediate-mass stars ($1\ M_o \leq M \leq 9\ M_o$)



During the Red Giant Branch (RGB) and the Early Asymptotic Giant Branch (E-AGB) phases, the convective envelope penetrates in the deep layers where the material has been processed by the H-burning, imprinting a detectable signature on the surface abundances. The second Dredge-up only takes place in stars with M>2.5M_o (for Z~Z_o).

The production of elements heavier than iron

The concept of synthesis by neutron captures

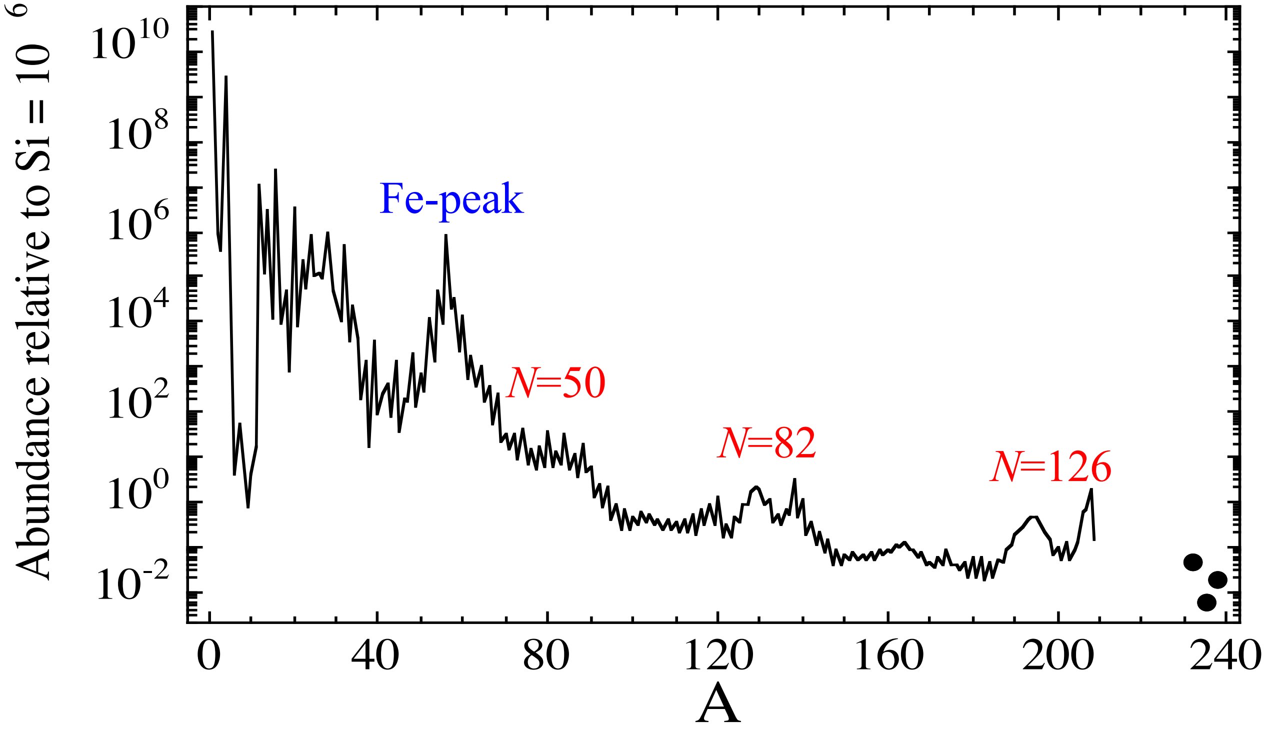
$\tau_p(A>56)$ & $\tau_\alpha(A>56)$ >>> typical evolution lifetime of a star

→ Charged-particle captures are inefficient to produce the bulk galactic $A > 56$ nuclei

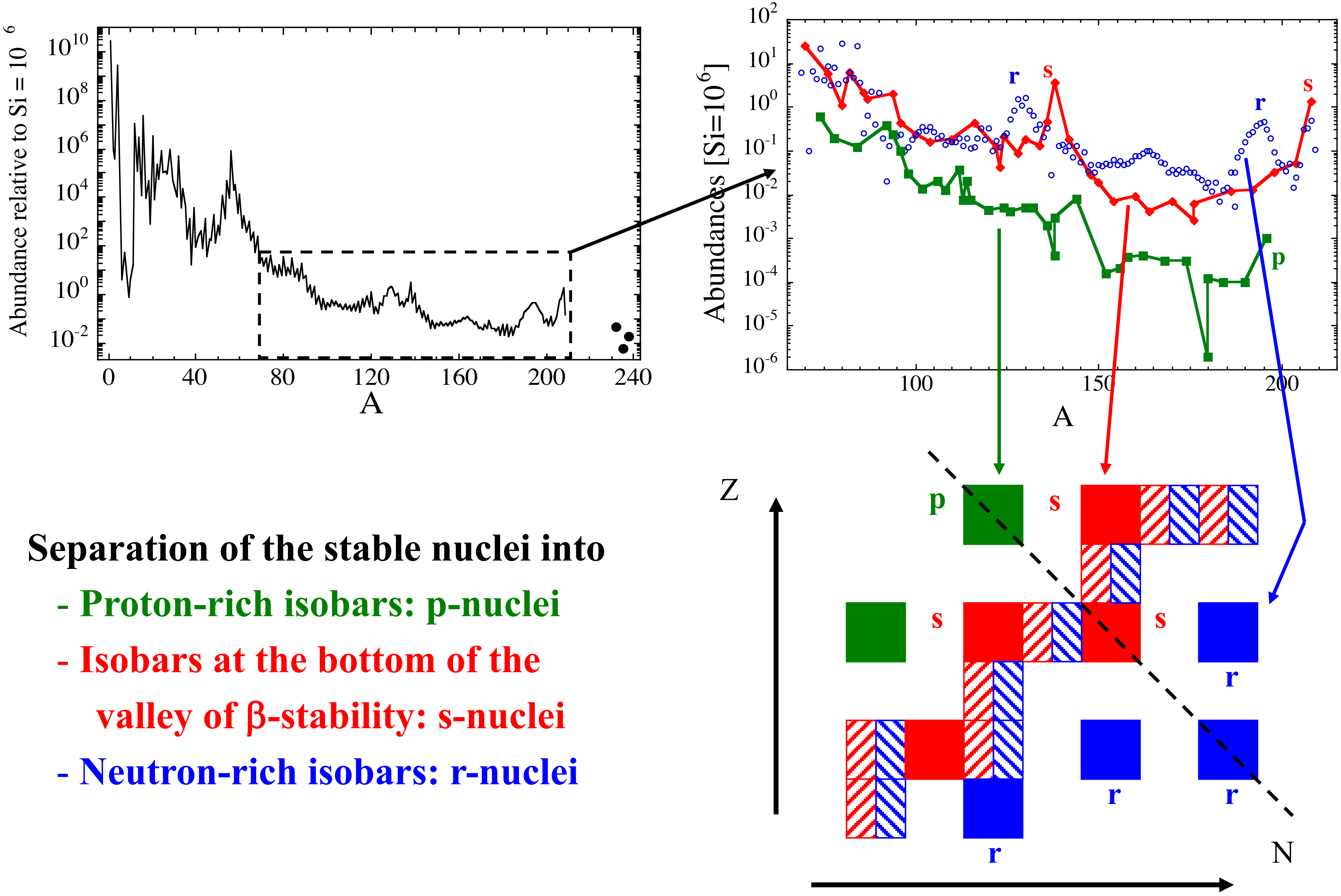
→ **Consider NEUTRONS instead !**

- **No coulomb barrier**
- **Natural explanation for the peaks observed in the solar system abundances at neutron magic numbers *N*=50, 82 and 126**

Solar System isotopic abundances



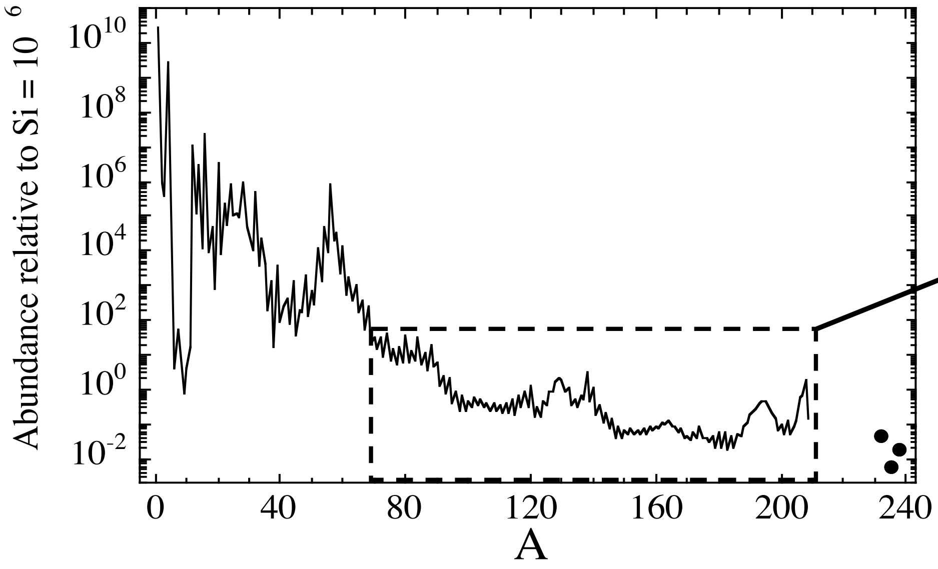
Decomposition of the solar abundances

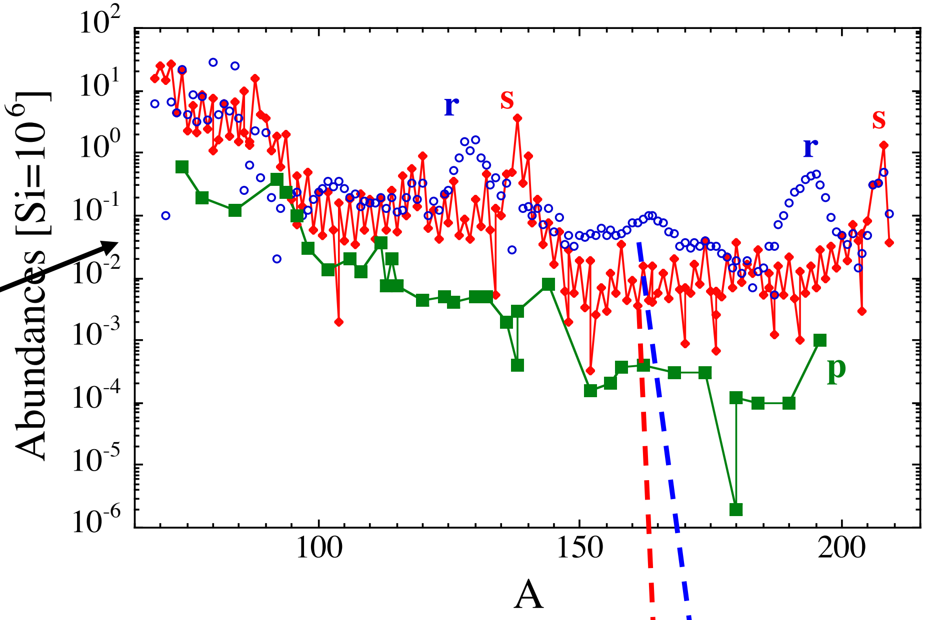


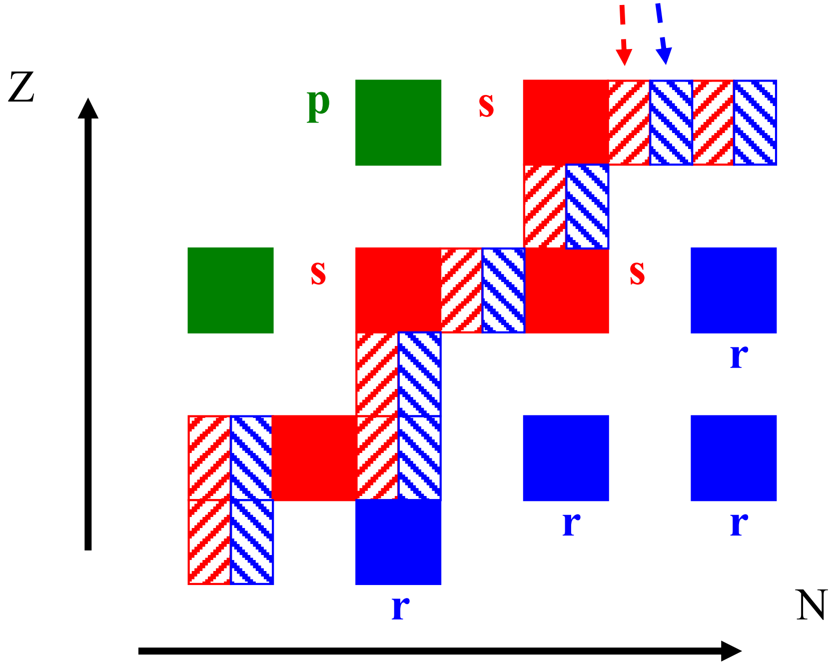
Separation of the stable nuclei into

- **Proton-rich isobars: p-nuclei**
- **Isobars at the bottom of the valley of β-stability: s-nuclei**
- **Neutron-rich isobars: r-nuclei**

Decomposition of the solar abundances







Separation of the stable nuclei into

- **Proton-rich isobars: p-nuclei**
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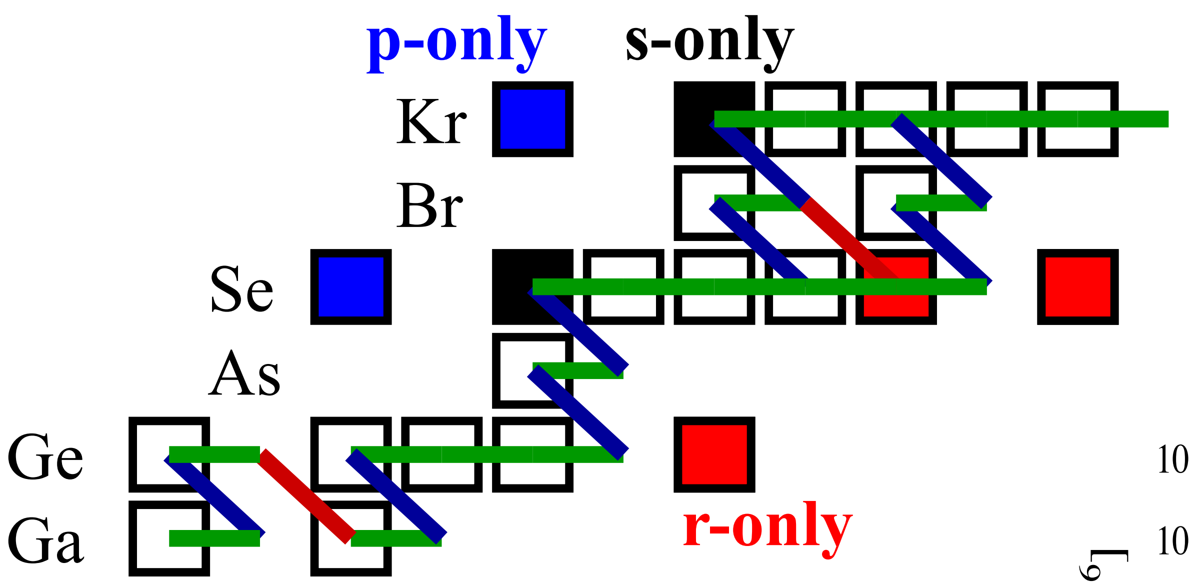
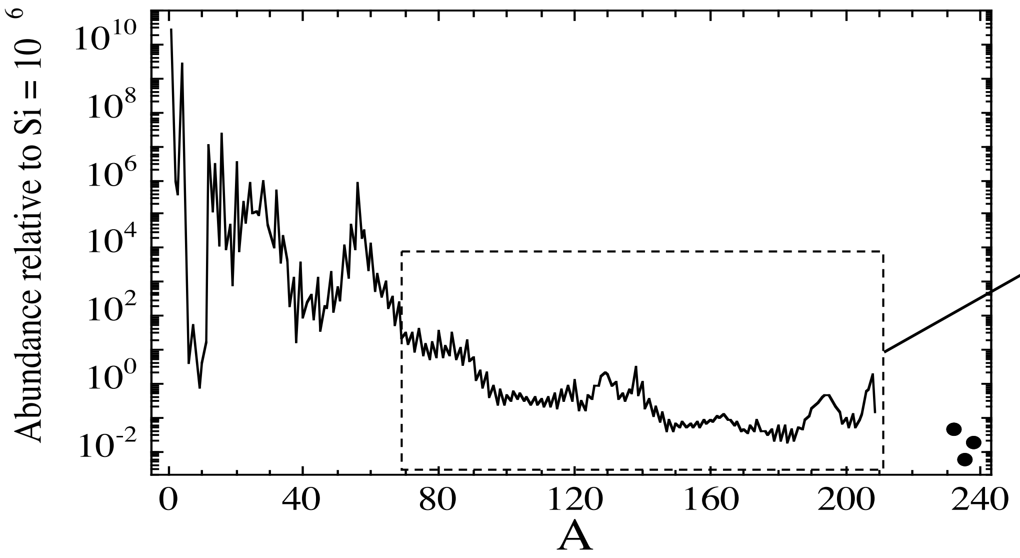
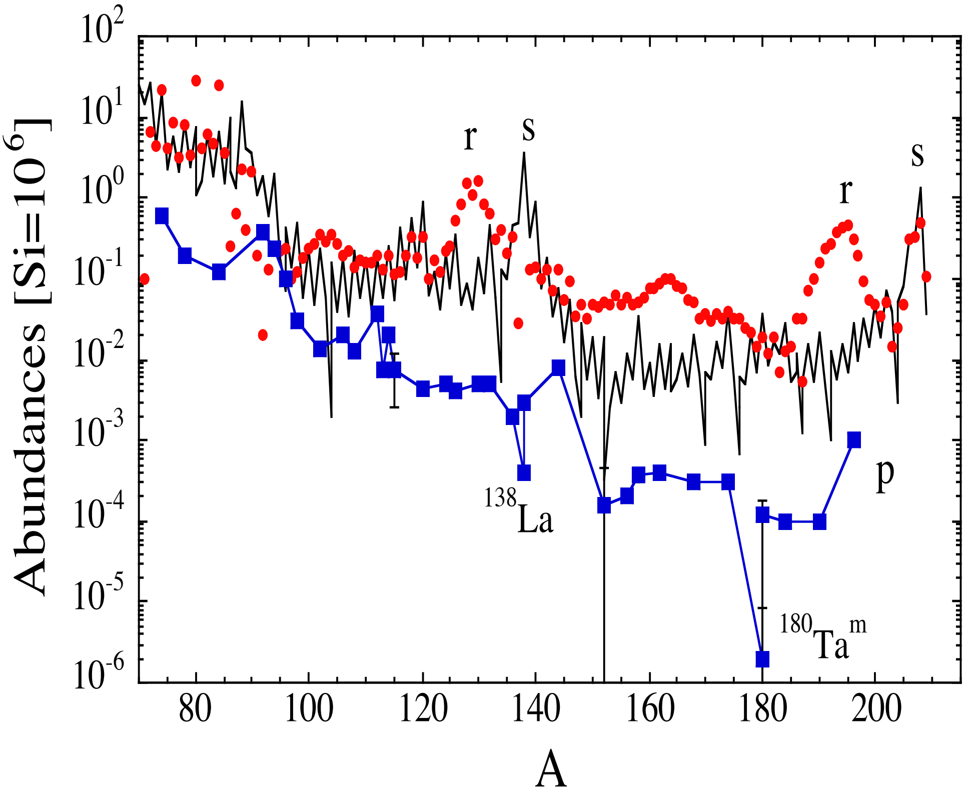
The production of elements heavier than iron



Separation of the stable nuclei into
- Proton-rich isobars: p-nuclei
- Neutron-rich isobars: r-nuclei
- Isobars at the bottom of the valley of β-stability: s-nuclei





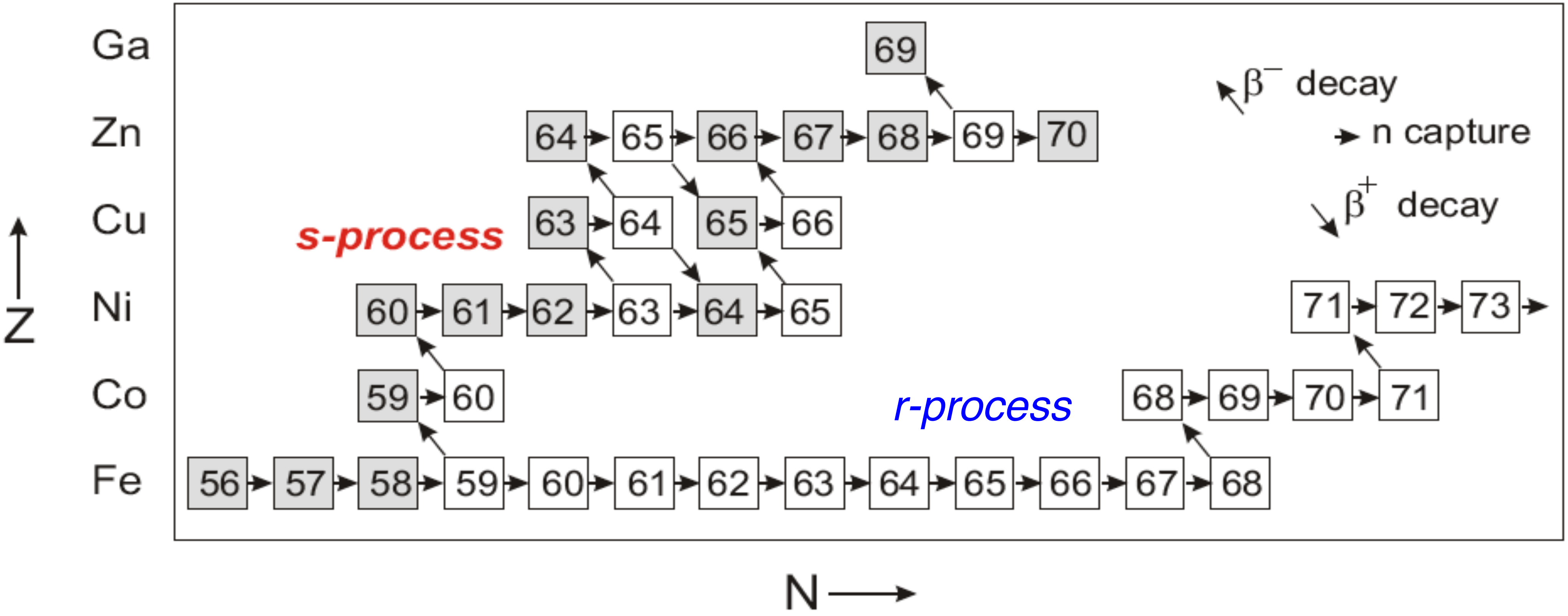
A schematic representation of the s- and r-processes

Slow neutron-capture process: $\tau_\beta \ll \tau_n$

Rapid neutron-capture process: $\tau_\beta \gg \tau_n$

τ_n = lifetime against neutron capture

τ_β = lifetime against β⁻ decay



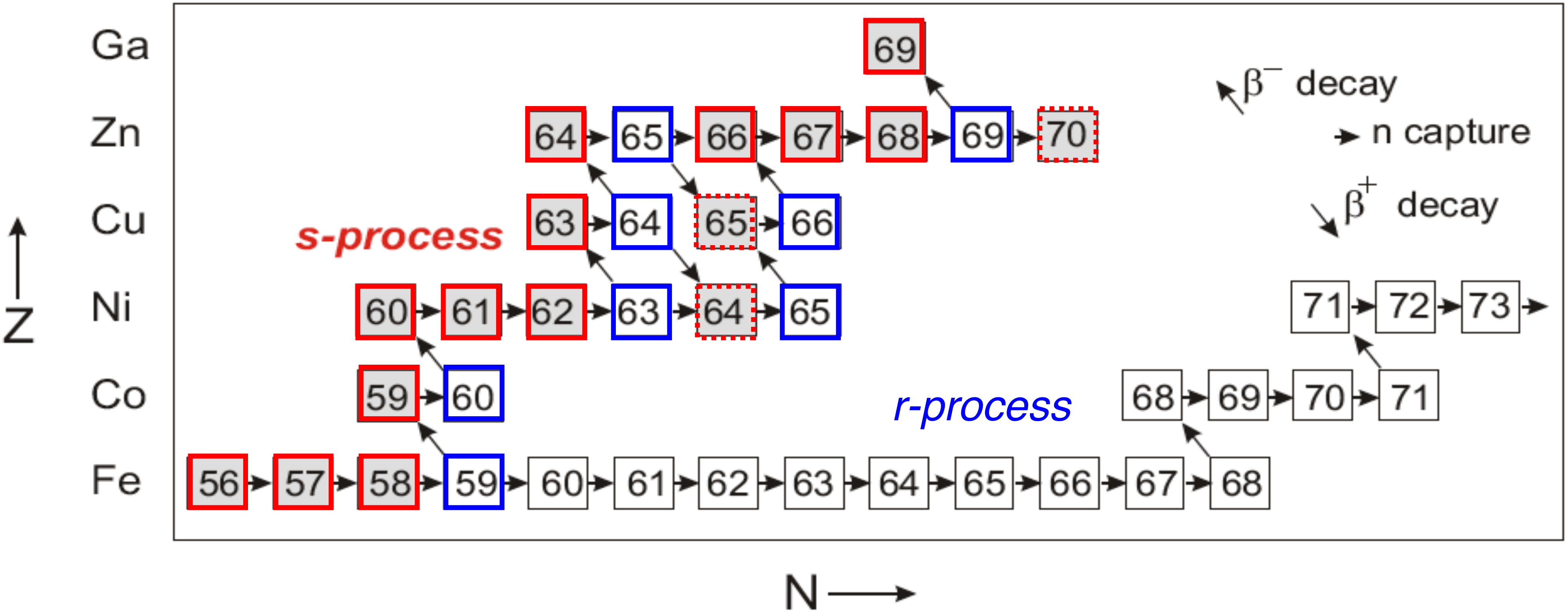
A schematic representation of the s- and r-processes

Slow neutron-capture process: $\tau_\beta << \tau_n$

N_n~10^7-10^{11} cm^{-3} T~1-3 10^8K t_{irr}~ 10-10^4yr

τ_n = lifetime against neutron capture

τ_β = lifetime against β⁻ decay



A schematic representation of the s- and r-processes

Slow neutron-capture process: $\tau_\beta \ll \tau_n$

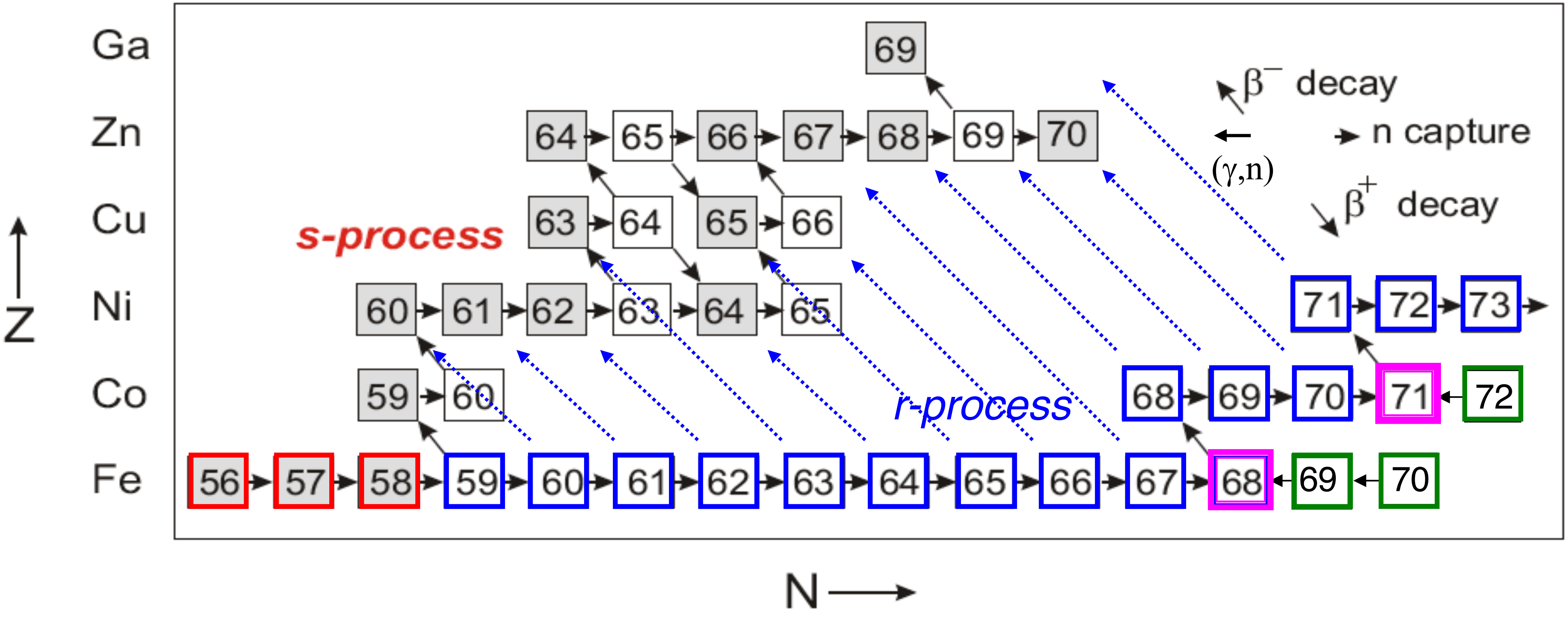
N_n~10^7-10^{11} cm^{-3} T~1-3 10^8K t_{irr}~ 10-10^4yr

Rapid neutron-capture process: $\tau_\beta \gg \tau_n$

N_n>>10^{20} cm^{-3} T~1-2 10^9K t_{irr}~ 1s

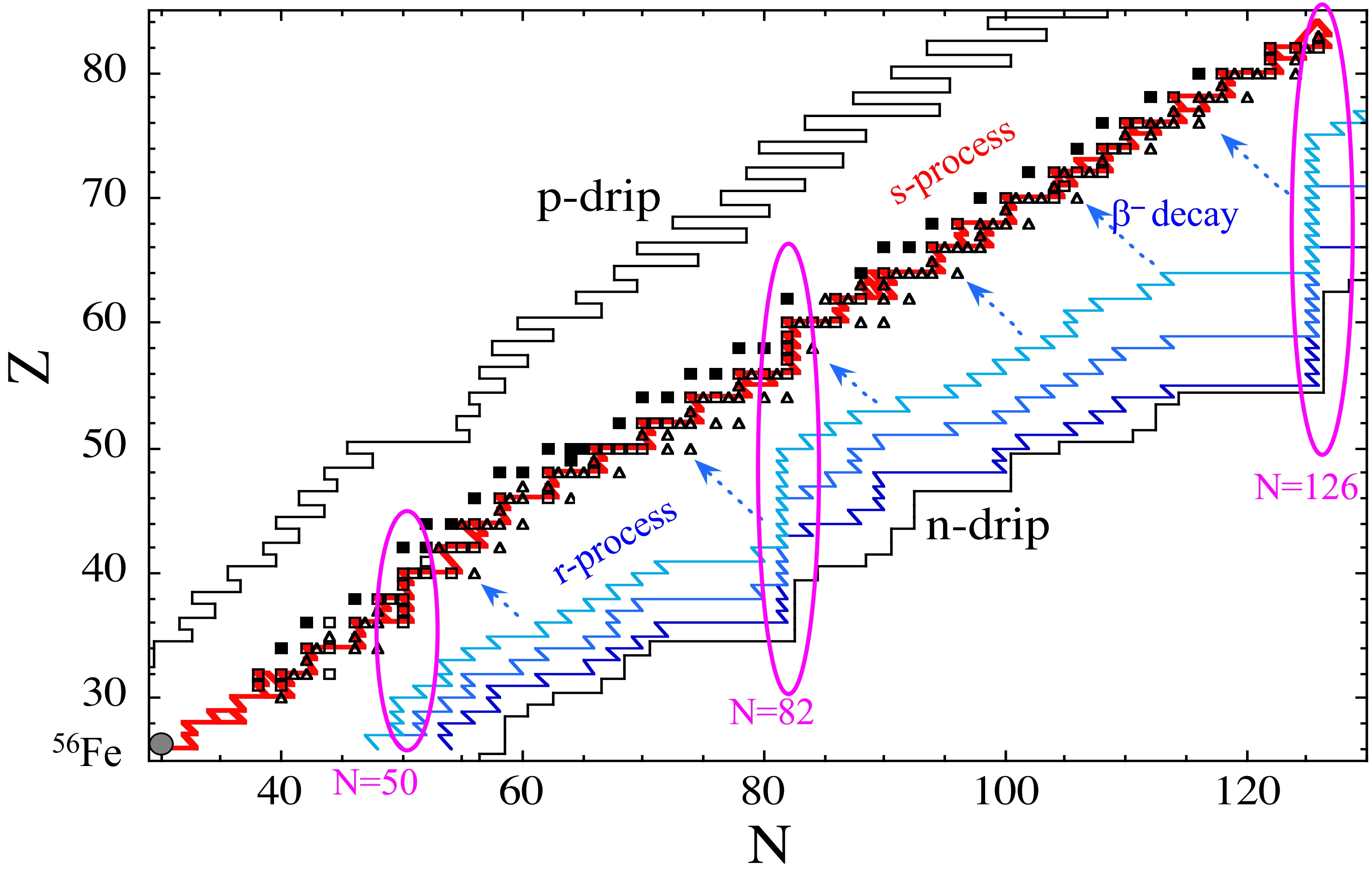
τ_n = lifetime against neutron capture

τ_β = lifetime against β⁻ decay

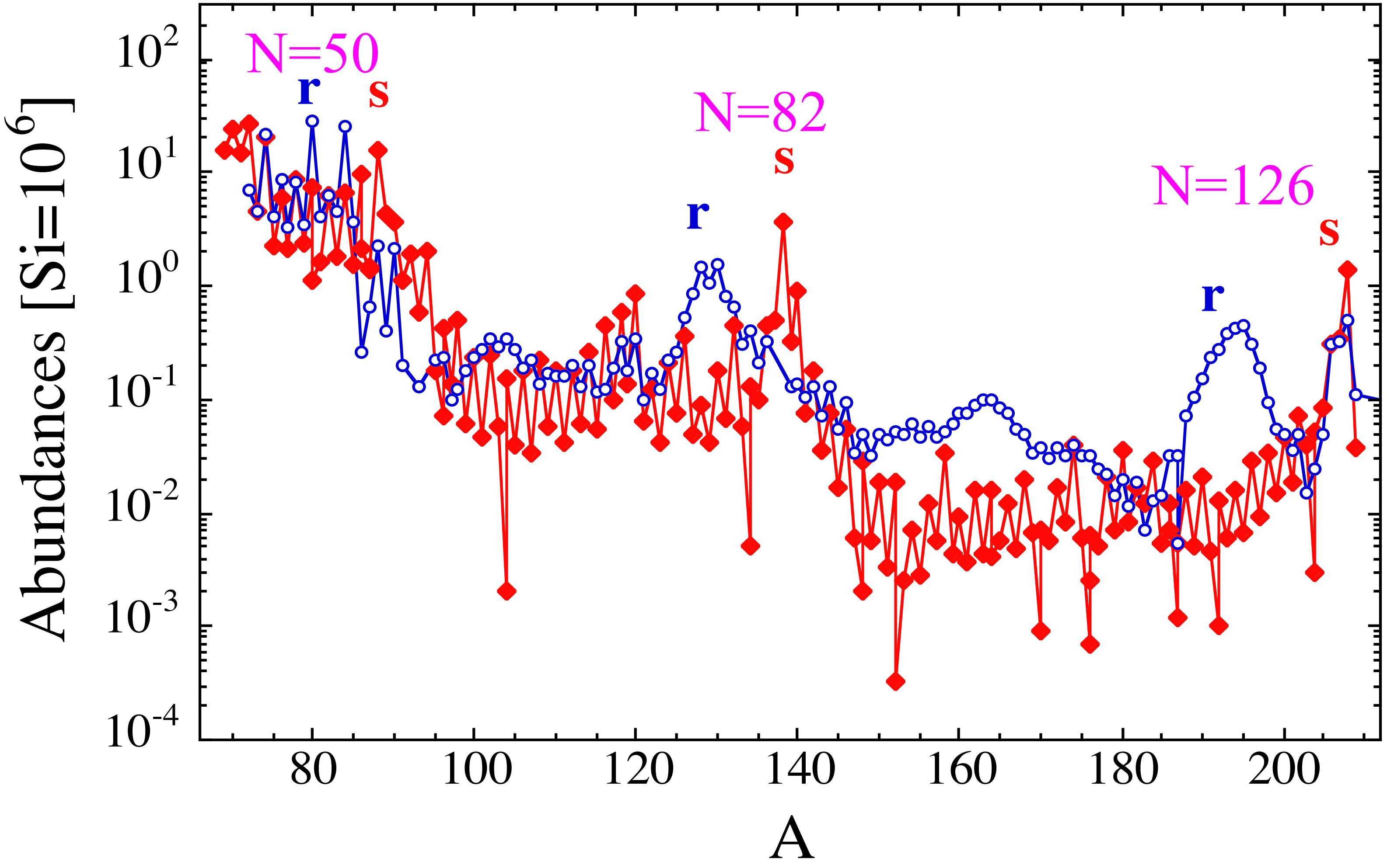


A schematic representation of the s- and r-processes

Closed shells at magic numbers N=50, 82, 126 --> slow n-capture



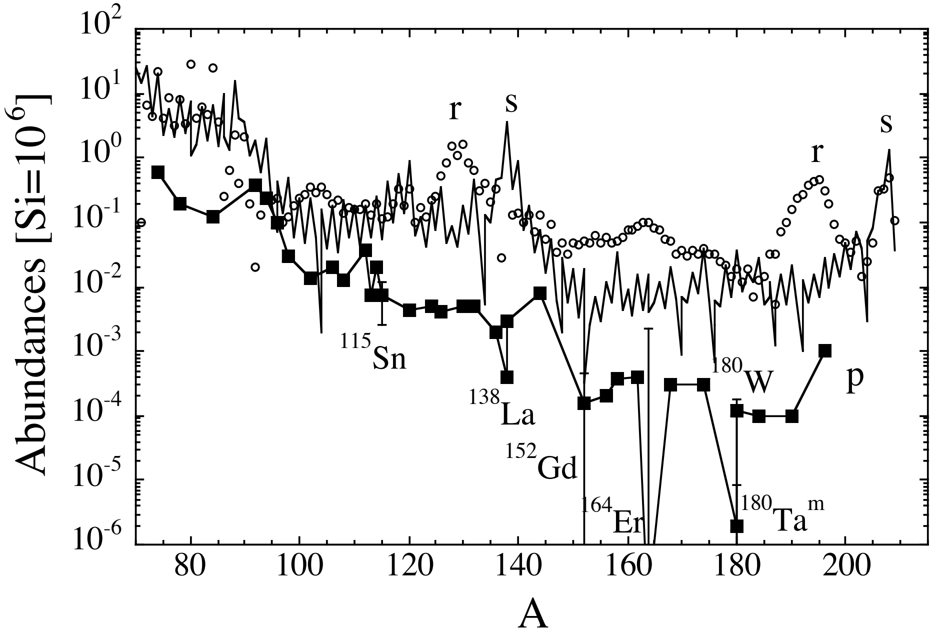
The signature of nuclear properties in the double-peak pattern of the solar abundance distribution

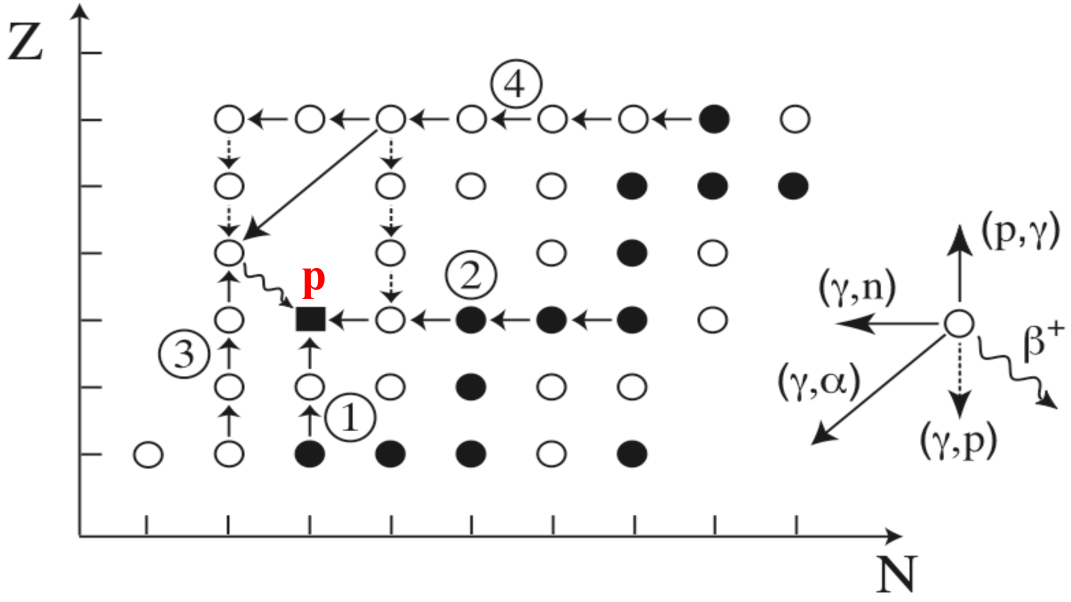


The nature of the p-process nucleosynthesis

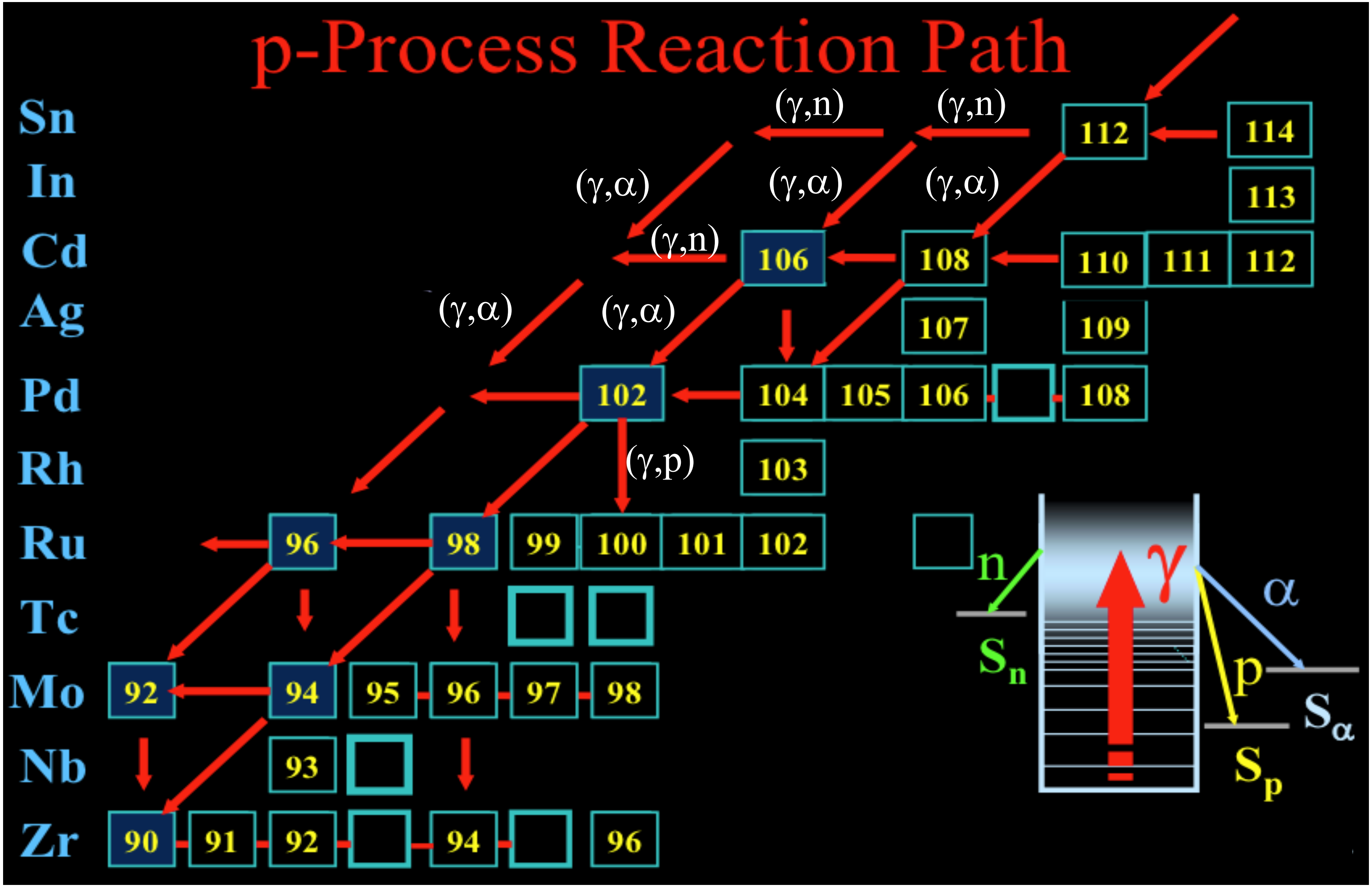
1. *Production of heavy seed nuclei* (s- and r-processes) in previous star generations. In particular the s-process during core He-burning leading to an increase of $70 \leq A \leq 90$ s-elements.
2. *Heating of the s-enriched and r-seeds* at a temperature of T=2-3 10^9 K for a few seconds leading to the photodissociation of the s- and r-nuclei into p-nuclei by (γ,n), (γ,p) and (γ,α) reactions. In some proton-rich environments, proton captures can be envisioned as contributing to the production of p-nuclei (but generally proton are absent in these environments).

p-nuclei are about 10 to 100 times less abundant than s and r-nuclei in the solar system

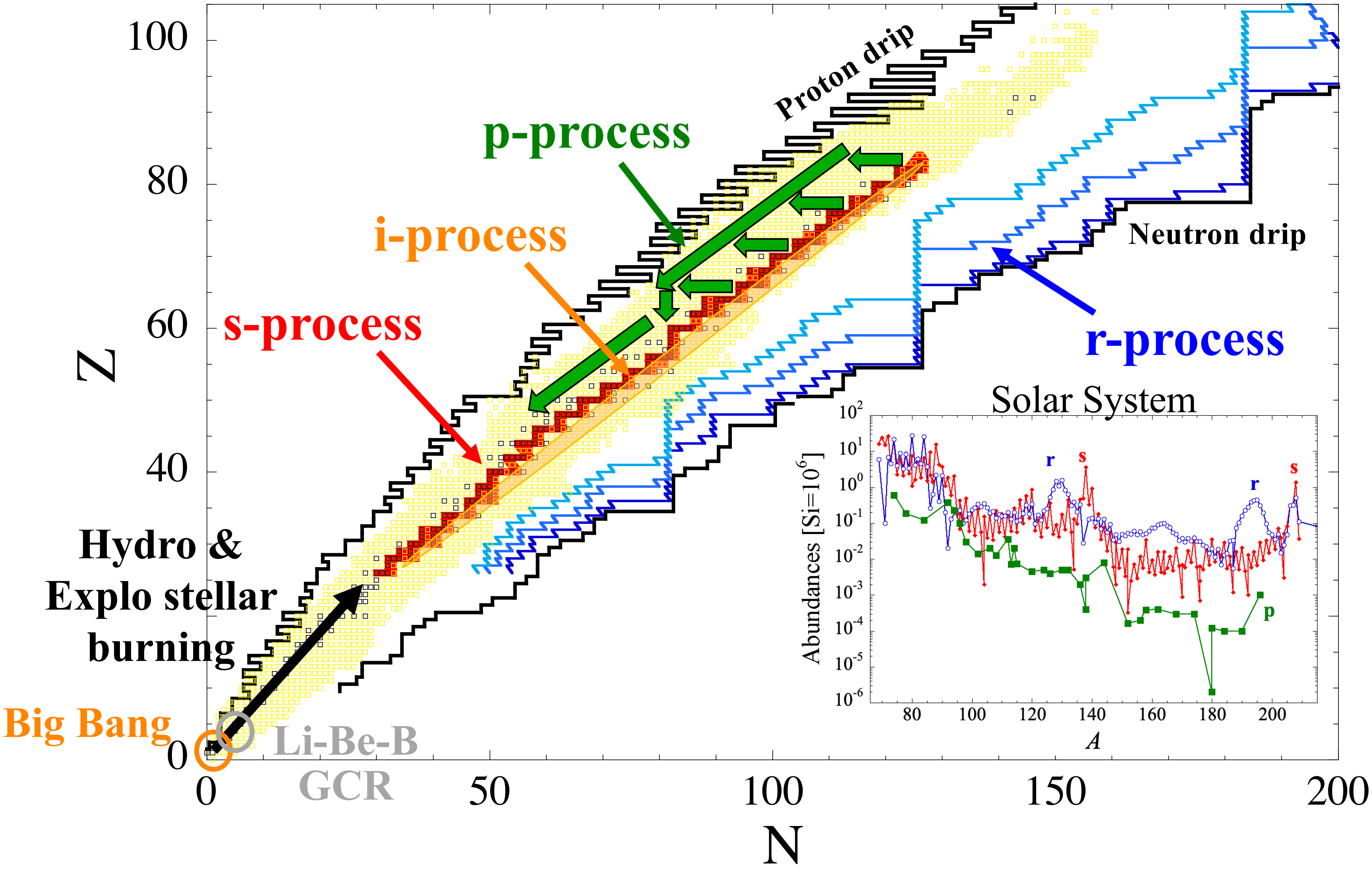




A schematic representation of the p-processes



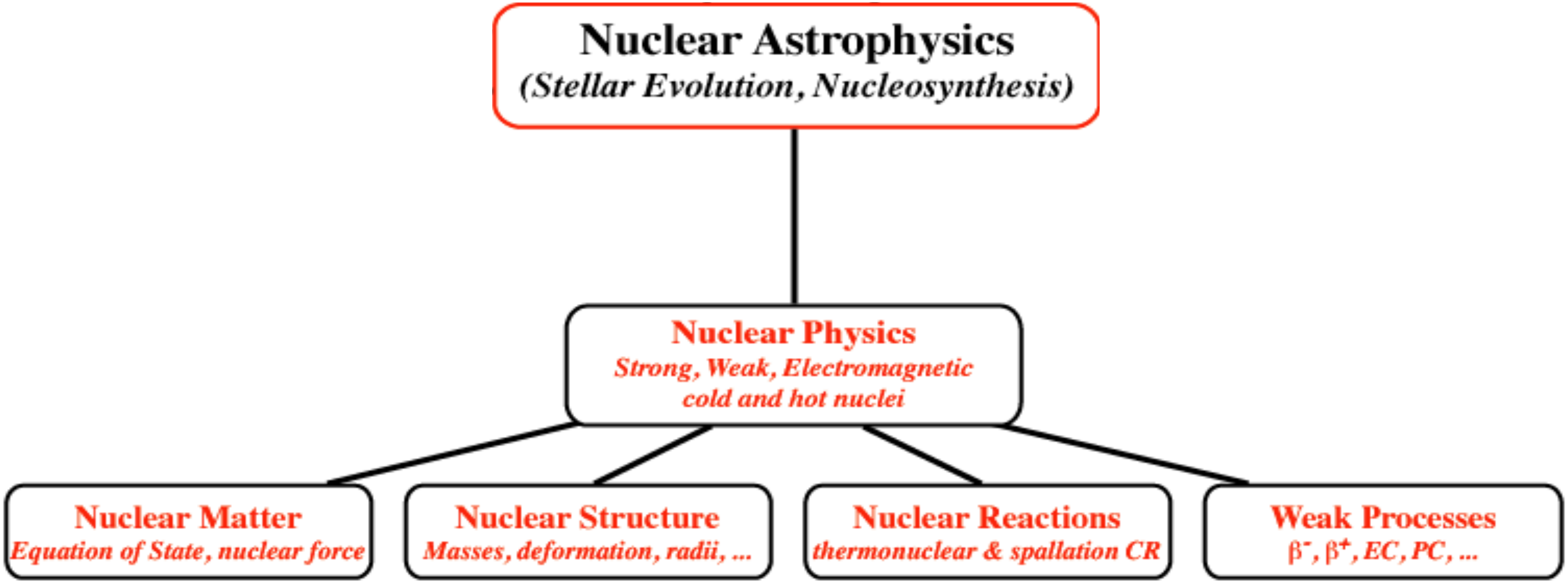
The various nucleosynthesis processes



All these processes are "thermal" except the LiBeB GCR nucleosynthesis

Nuclear Physics is a necessary condition for Nuclear Astrophysics

Strong correlations between stellar abundances and nuclear properties



Nuclear Astrophysics
(Stellar Evolution, Nucleosynthesis)

Nuclear Physics
Strong, Weak, Electromagnetic
cold and hot nuclei

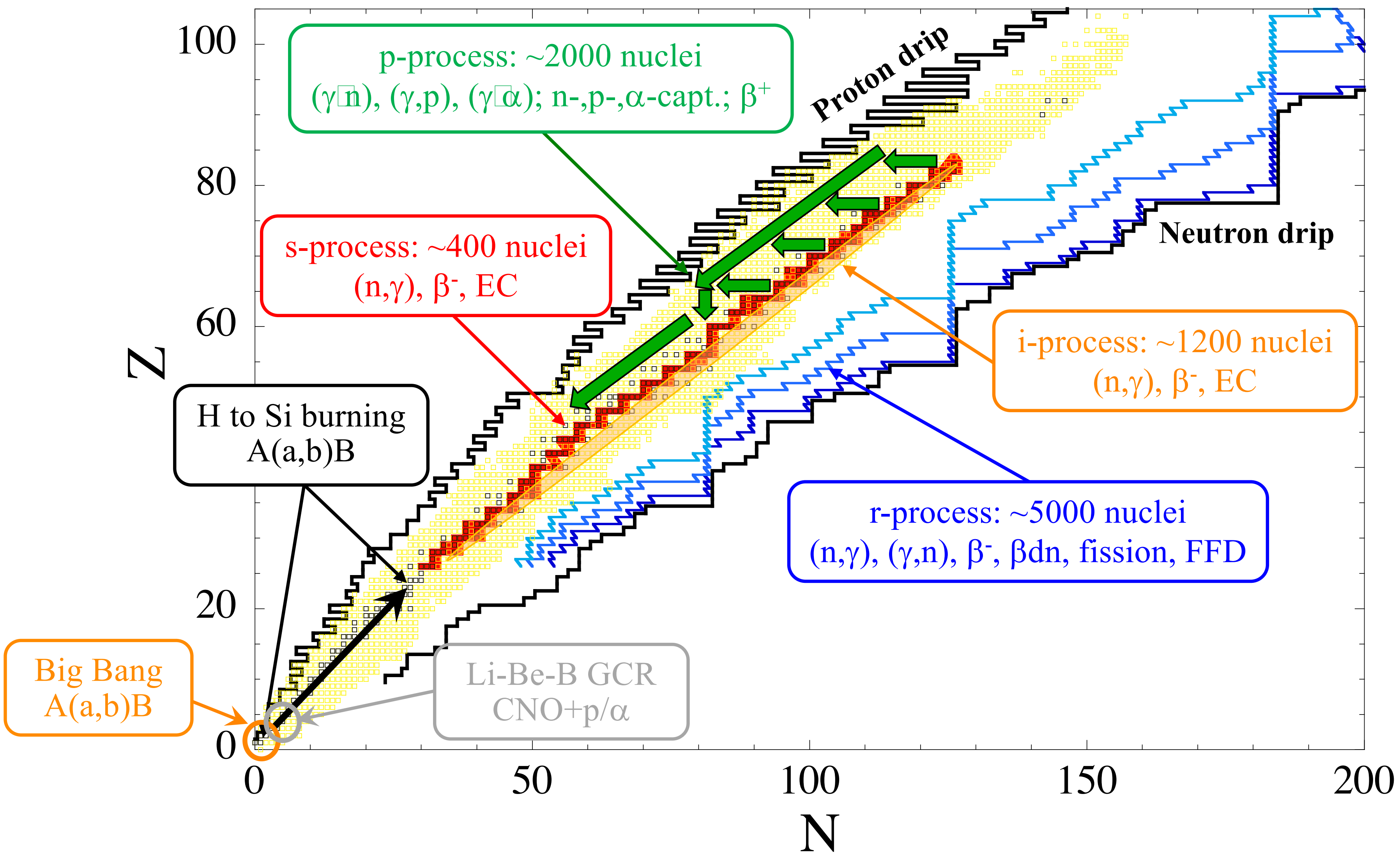
Nuclear Matter
Equation of State, nuclear force

Nuclear Structure
Masses, deformation, radii, ...

Nuclear Reactions
thermonuclear & spallation CR

Weak Processes
β^-, β^+, *EC, PC, ...*

Many different nuclear needs for the various nucleosynthesis processes



p-process: ~2000 nuclei
(γ□n), (γ,p), (γ□α); n-,p-,α-capt.; β^+

s-process: ~400 nuclei
(n,γ), β^-, EC

H to Si burning
A(a,b)B

i-process: ~1200 nuclei
(n,γ), β^-, EC

r-process: ~5000 nuclei
(n,γ), (γ,n), β^-, βdn, fission, FFD

Big Bang
A(a,b)B

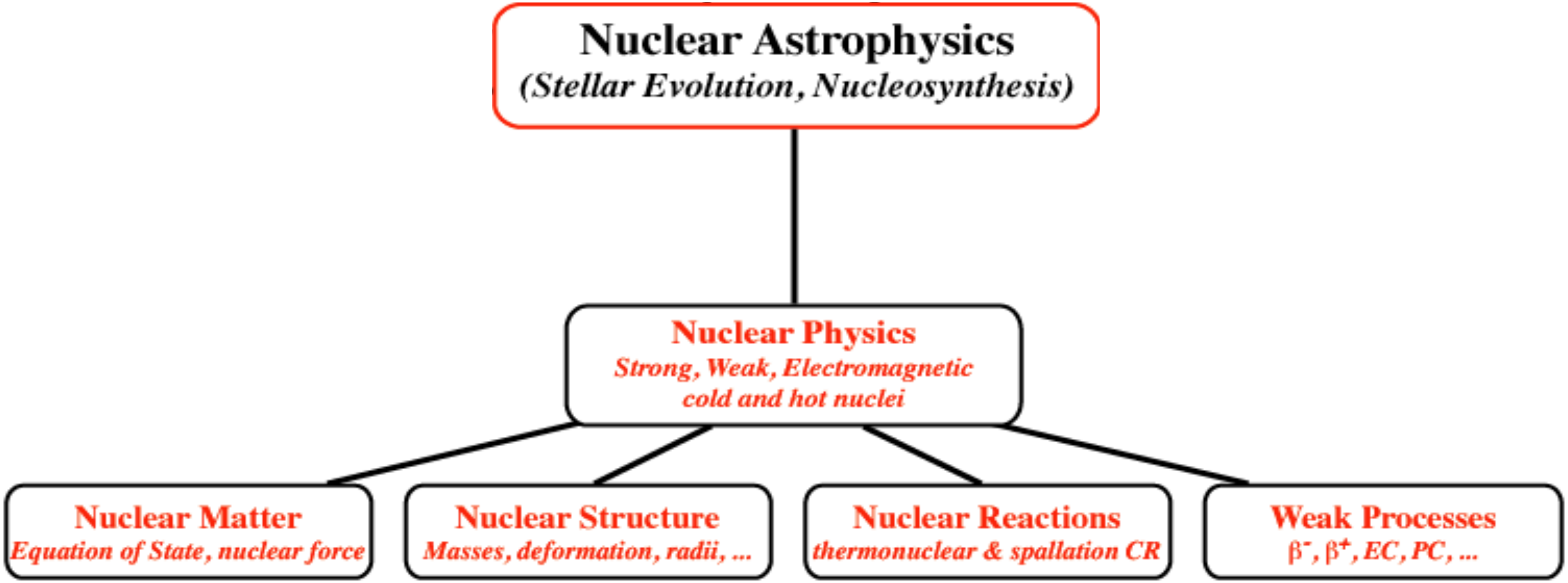
Li-Be-B GCR
CNO+p/α

Still a lot of questions regarding the associated nuclear physics input

BUT

Astrophysics needs for nuclear data are defined by the sensitivity of the astrophysics predictions to the nuclear inputs

Nuclear Physics is a necessary condition for Nuclear Astrophysics



Nuclear Astrophysics

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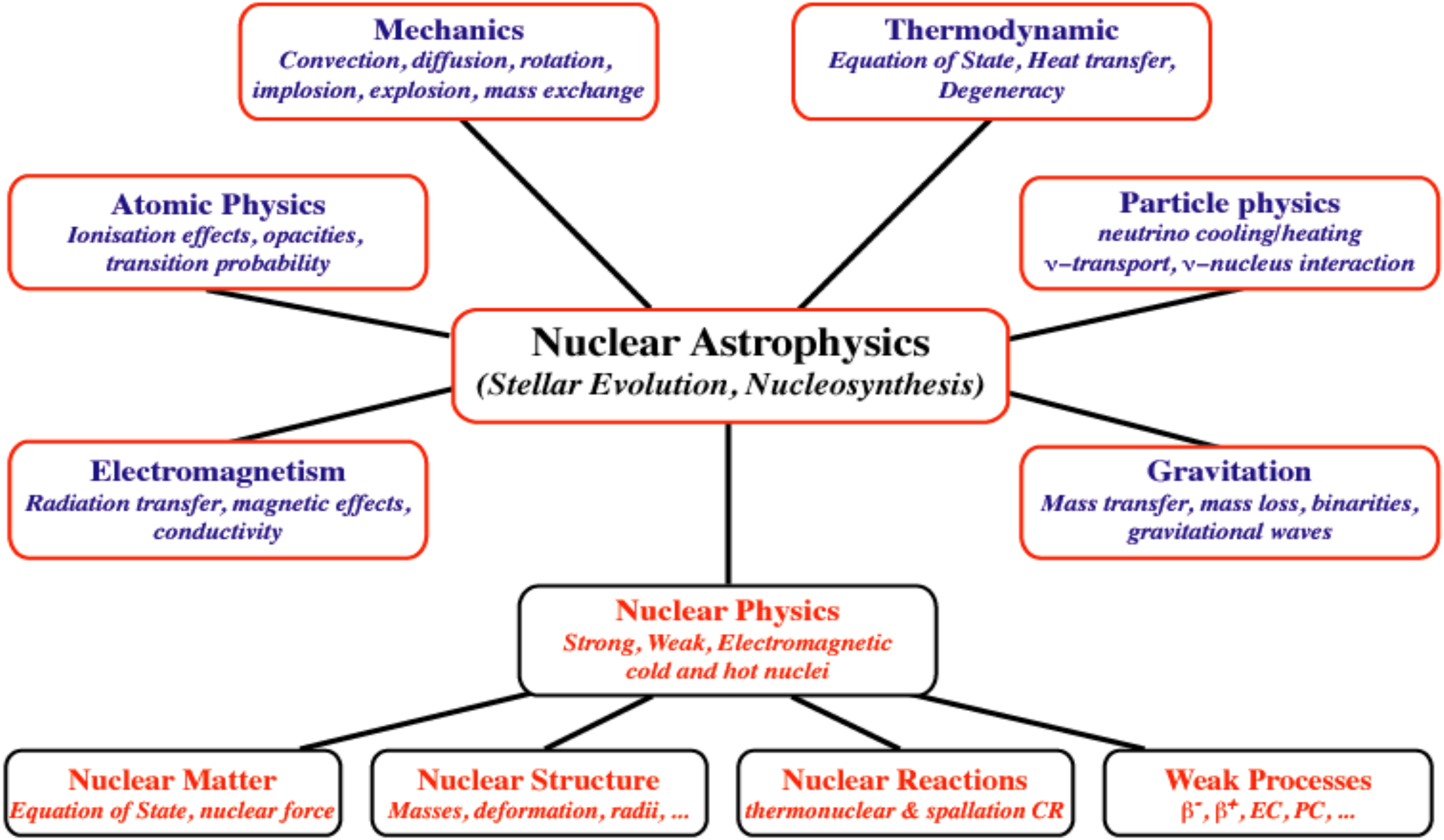
β^-, β^+, *EC, PC, ...*

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



Mechanics
Convection, diffusion, rotation, implosion, explosion, mass exchange

Thermodynamic
Equation of State, Heat transfer, Degeneracy

Atomic Physics
Ionisation effects, opacities, transition probability

Particle physics
neutrino cooling/heating
ν–transport, ν–nucleus interaction

Nuclear Astrophysics
(Stellar Evolution, Nucleosynthesis)

Electromagnetism
Radiation transfer, magnetic effects, conductivity

Gravitation
Mass transfer, mass loss, binarities, gravitational waves

Nuclear Physics
Strong, Weak, Electromagnetic
cold and hot nuclei

Nuclear Matter
Equation of State, nuclear force

Nuclear Structure
Masses, deformation, radii, ...

Nuclear Reactions
thermonuclear & spallation CR

Weak Processes
β^-, β^+, *EC, PC, ...*

Different types of astrophysics models

+ + – State of the art: 3D (~ self-consistent) models

p-process in SNIa explosions, r-process in NSM

+ – Realistic 1D (~ self-consistent) models

s-process in Massive Stars

– Parametrized (semi-realistic) 1D models

s-process in AGB Stars

– – Parametrized (unrealistic) 1D models

r-process in ν-driven wind

– – – Phenomenological parametrized site independent models

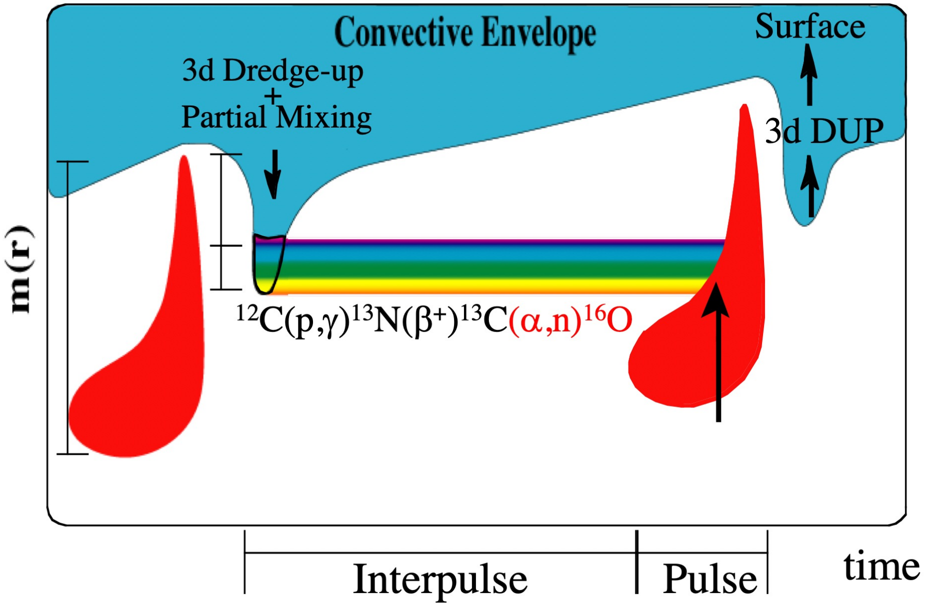
Canonical s- and r-processes

Remain critical about the astrophysics models

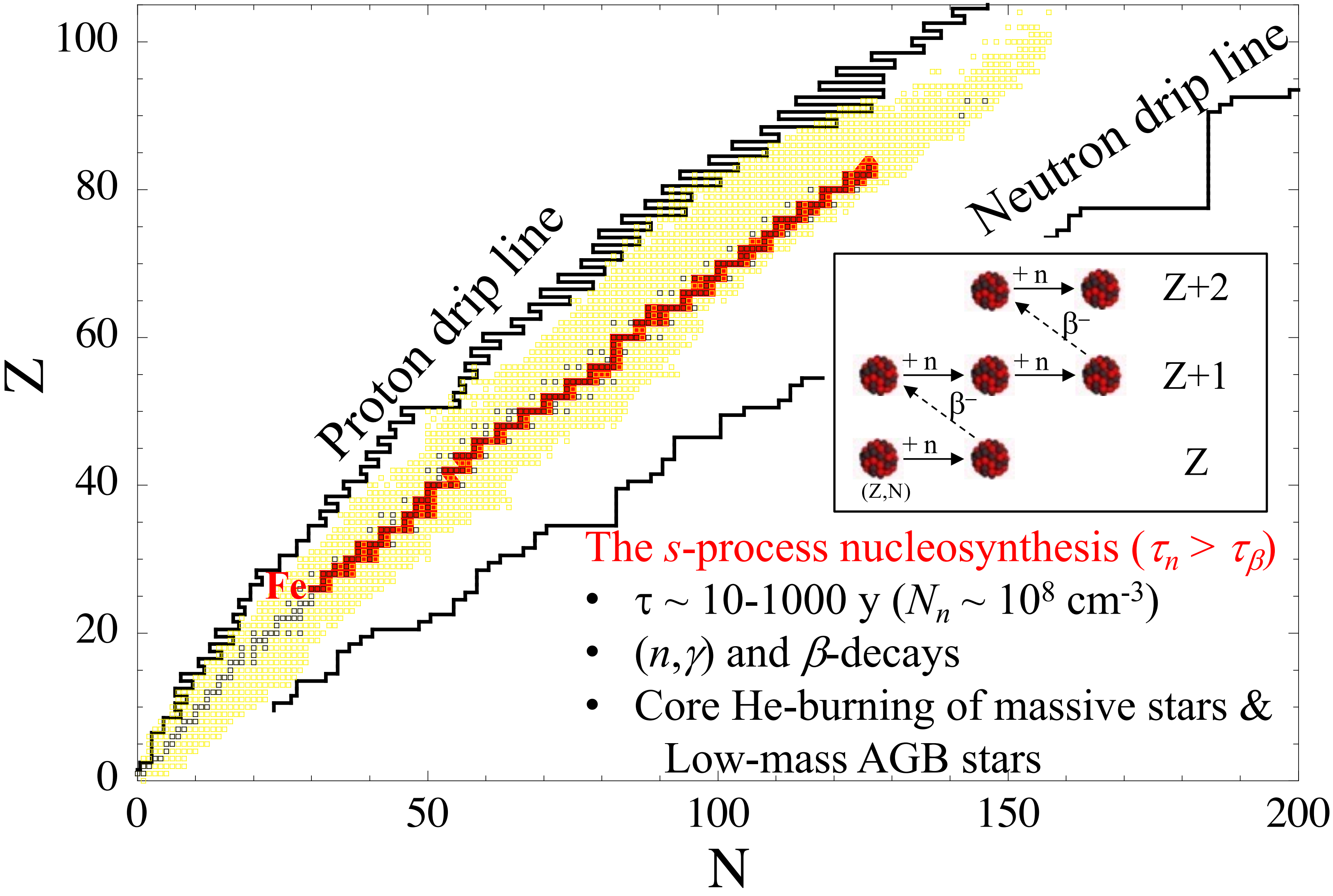
(even the 3D simulations are far from being free from astrophysical uncertainties!)

Obvious need for accurate and reliable nuclear data, … but
the uncertainties in the astrophysics models most of the time prevail

The s-process nucleosynthesis



The *s*-process nucleosynthesis

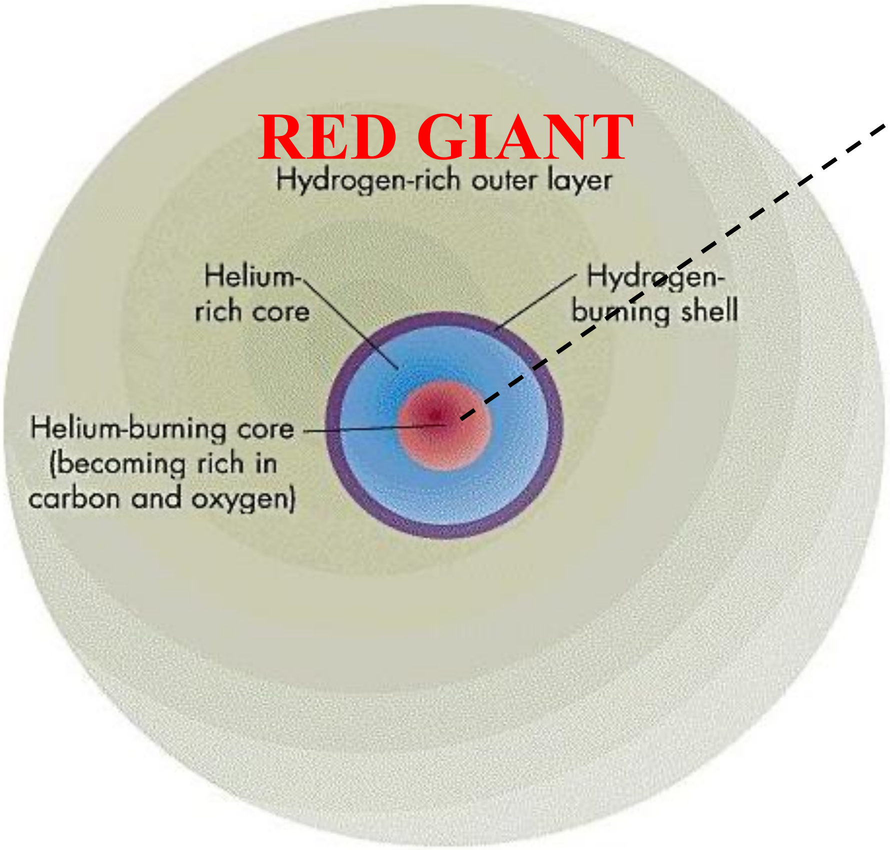


The *s*-process nucleosynthesis ($\tau_n > \tau_\beta$)

- τ ~ 10-1000 y ($N_n \sim 10^8$ cm^{-3})
- (n,γ) and β-decays
- Core He-burning of massive stars & Low-mass AGB stars

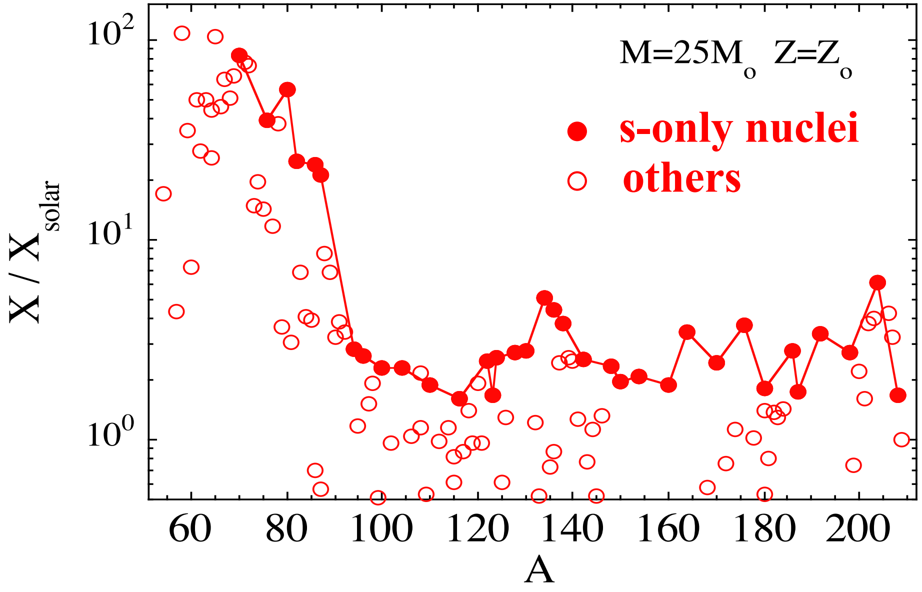
The s-process in massive stars: the weak component

^{14}N seed nuclei is transformed into ^{22}Ne by $^{14}N(\alpha\square\gamma)^{18}F(\beta^{+})^{18}O(\alpha\square\gamma)^{22}Ne$



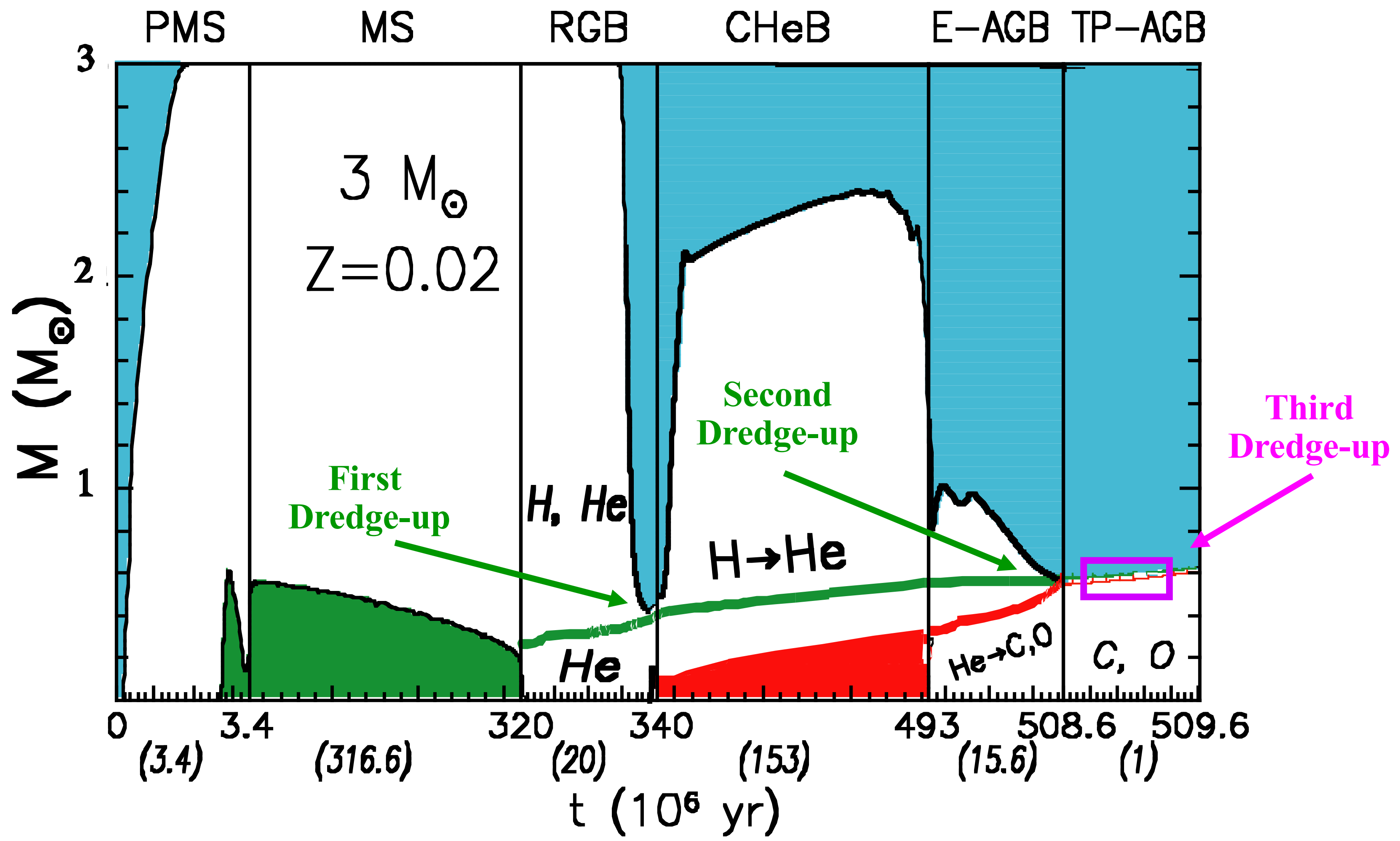
s-process during core He-burning
by $^{22}Ne(\alpha,n)^{25}Mg$

→ enrichment in $70 \leq A \leq 90$



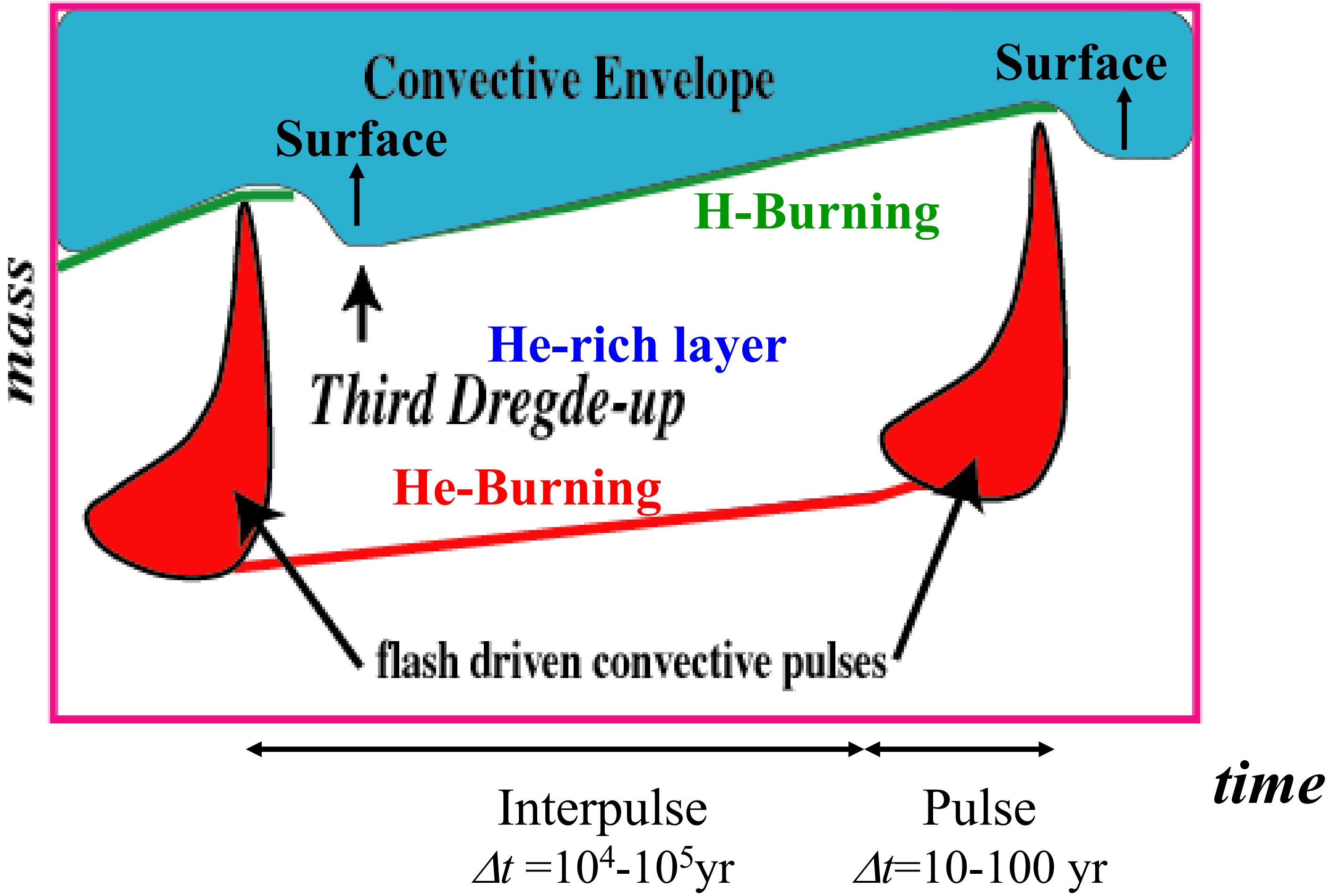
Pre-existing Fe (and other nuclei) serve as seed for a secondary s-process: the lower the metallicity, the lower the Fe content, the less heavy nuclei are produced (in absolute terms)

The AGB phase of low- and intermediate-mass stars ($1\ M_o \leq M \leq 9\ M_o$)



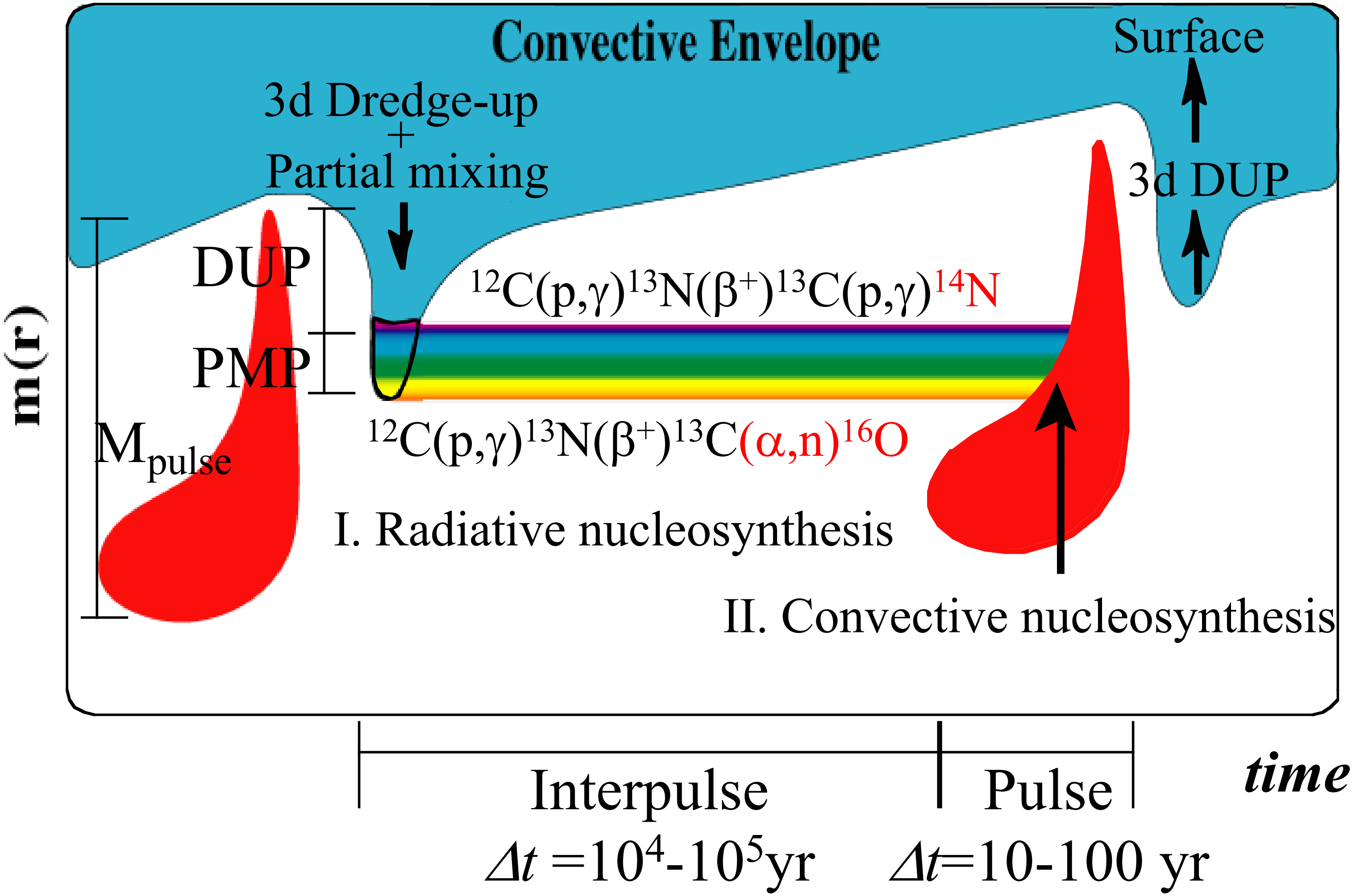
During the Red Giant Branch (RGB) and the Early Asymptotic Giant Branch (E-AGB) phases, the convective envelope penetrates in the deep layers where the material has been processed by the H-burning, imprinting a detectable signature on the surface abundances. The second Dredge-up only takes place in stars with $M > 2.5M_o$ (for $Z \sim Z_o$).

In AGB stars, a third Dredge-up is expected to occur periodically as a result of structural readjustments which follow the development of thermal instabilities in the He-burning shell. The deep convective envelope penetrates into the C-rich layers (resulting from the He-burning having taken place during the preceding flash-driven convective pulse). The abundances determined at the surface of AGB stars attest of a rich nucleosynthesis occuring in those stars which range from H-burning to He-burning to the slow neutron-capture process and the fluorine or sodium nucleosynthesis.



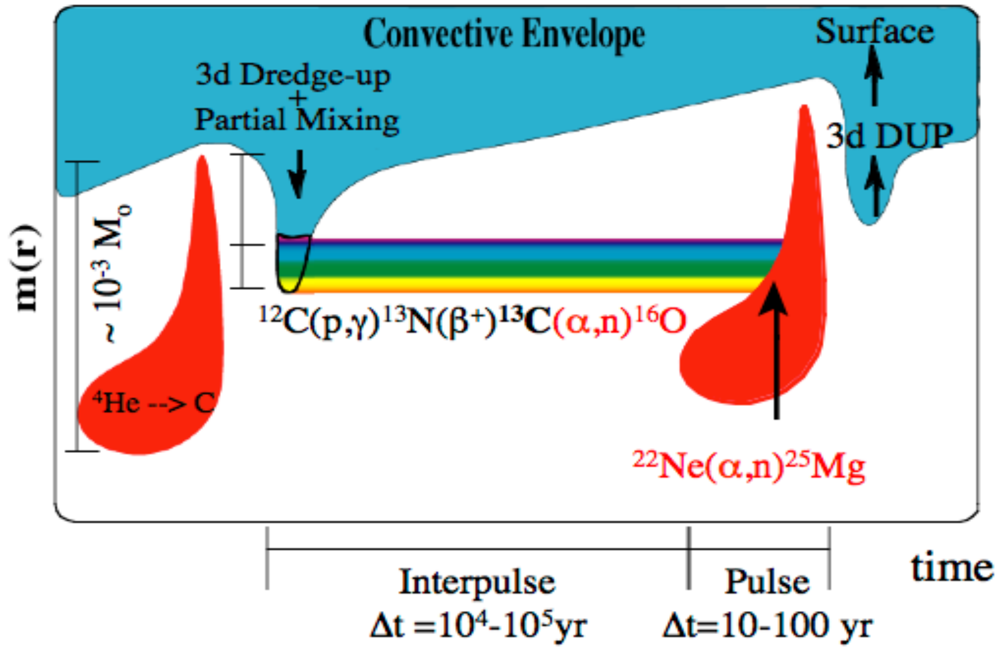
The partial mixing of protons (PMP) at the time of the 3d DUP

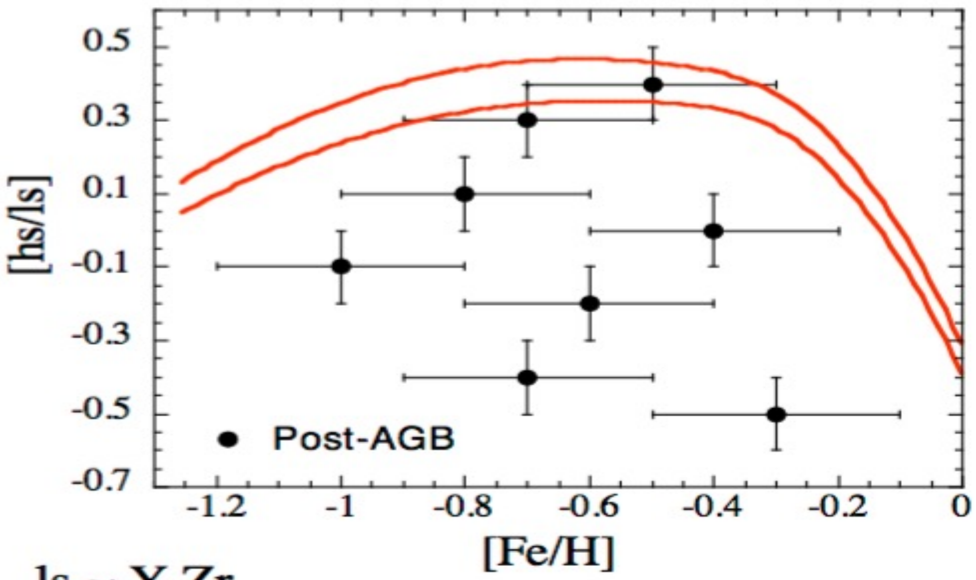
The third Dredge-up can also be accompanied by a partial mixing of protons into the C-rich layer



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

- How are the neutrons produced in AGB stars ?
- What is the contributions stemming from intermediate mass AGB stars ?
- How to explain specific observations ?
- (n,γ) and *T*-dependent β-decay rates of branching points ?





ls ~ Y,Zr
hs ~ Ba,La,Nd

The s-process nucleosynthesis

Slow neutron capture process characterized by

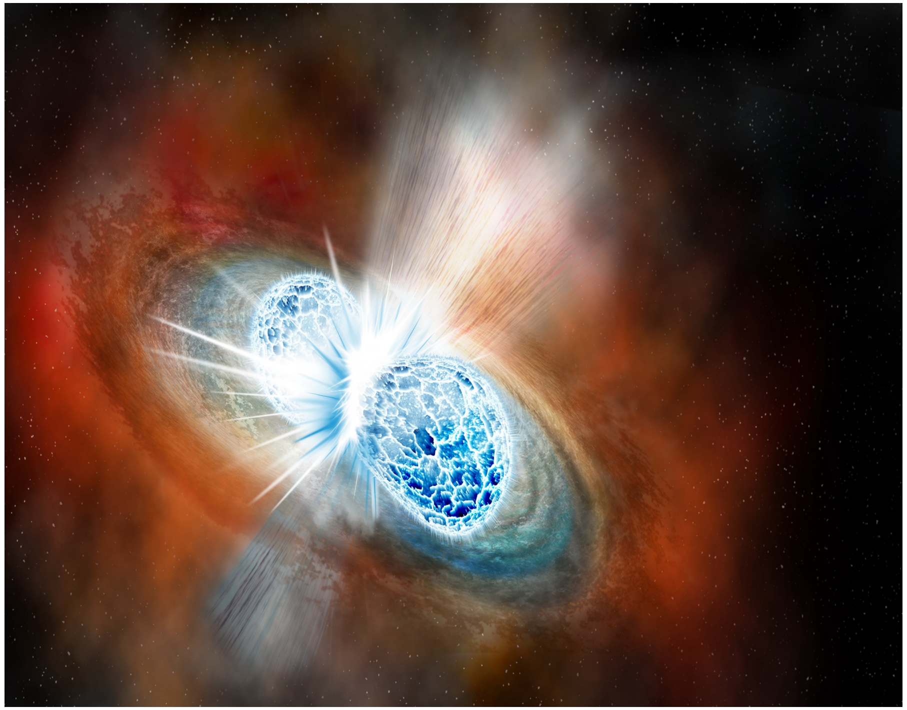
- $N_n \sim 10^7 - 10^{11}$ cm^{-3}
- $T \sim 1 - 3\ 10^8$ K
- $t \sim 1 - 10^5$ yr depending on the T, N_n conditions

The conditions are such that the $\tau_\beta < \tau_{(n,\gamma)}$ so that the s-process flow follows the valley of β-stability

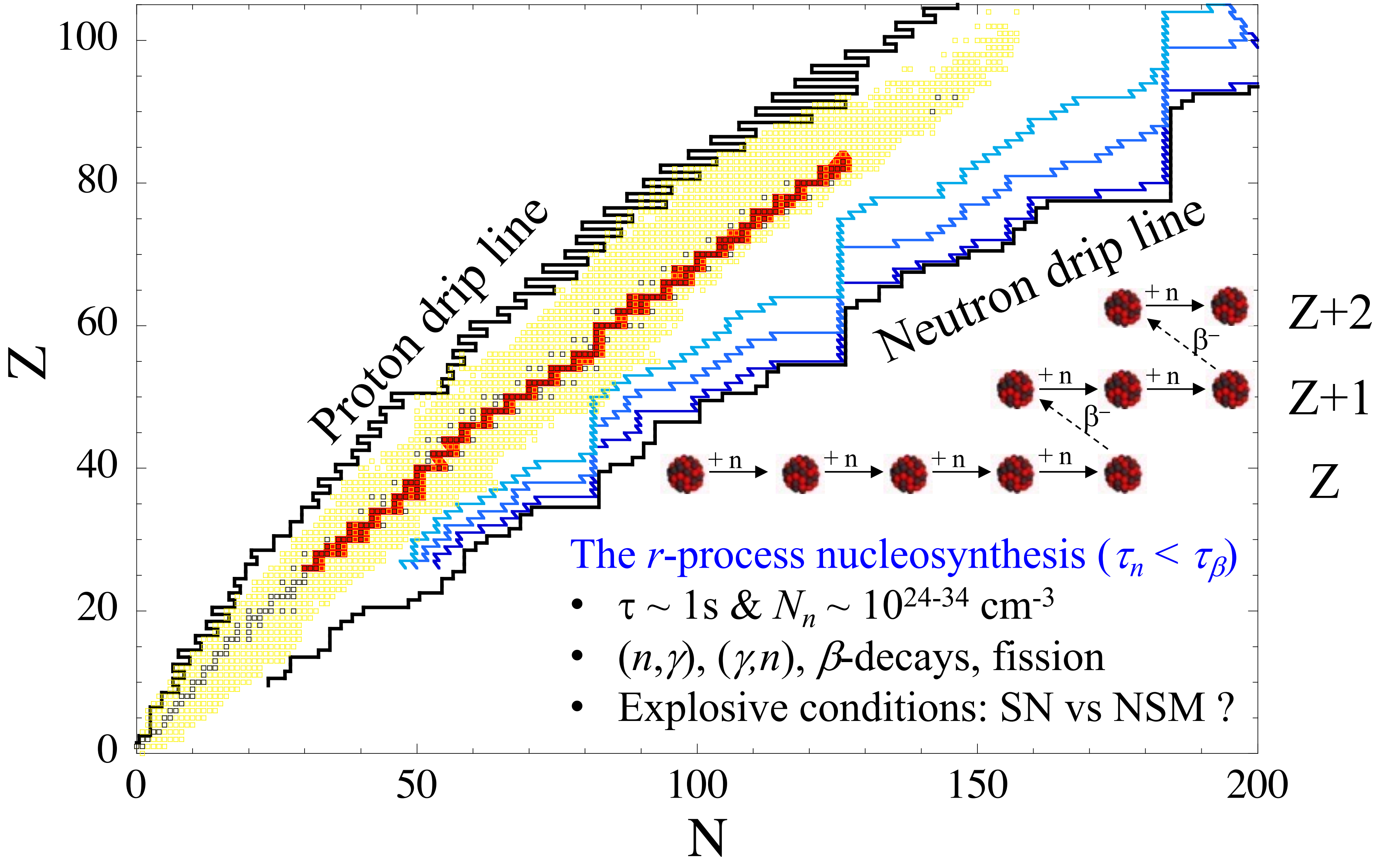
1. **Astrophysics aspects**
   - "Realistic" models: Core He-burning of massive stars ($70 \leq A \leq 90$)
   - "Semi-realistic" model: AGB phase of low & intermediate mass stars ($90 \leq A \leq 208$)

2. **Nuclear Physics aspects**
   - Neutron producing reactions: ^{13}C(α,n)^{16}O & ^{22}Ne(α,n)^{25}Mg
   - Neutron captures: 80% known experimentally (MACS)
     20% to be determined theoretically (unstable nuclei)
     thermalisation effects
     non-thermalisation of given isomers
   - Beta-decays: T- and ρ-dependence of the rate in a stellar plasma

The r-process nucleosynthesis



The *r*-process nucleosynthesis



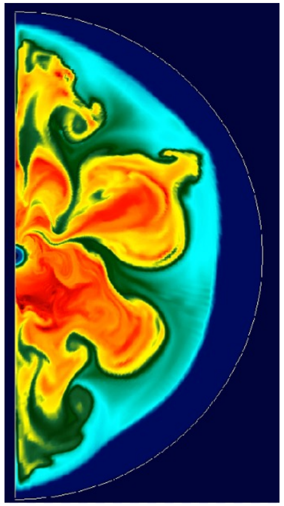
The *r*-process nucleosynthesis ($\tau_n < \tau_\beta$)

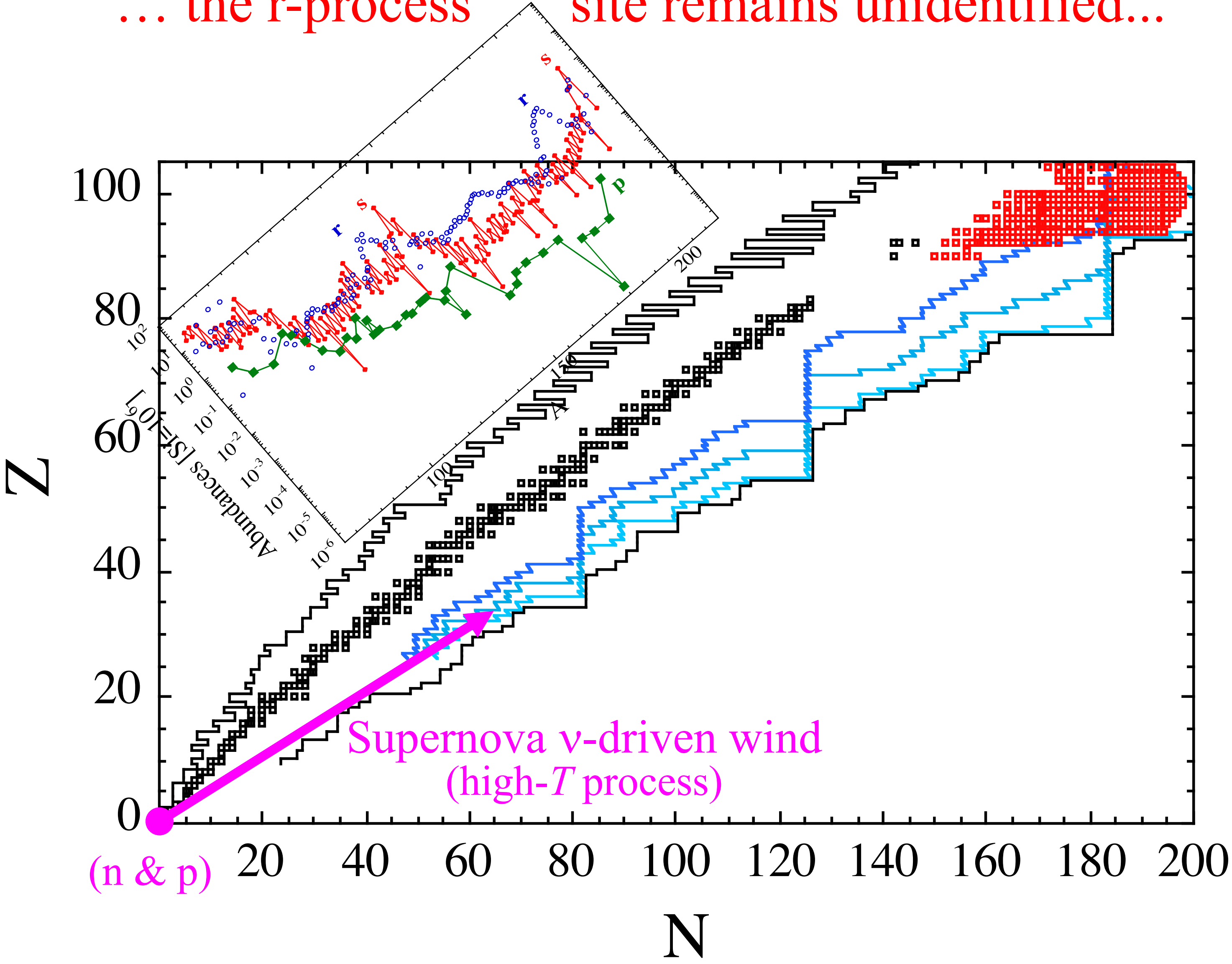
- τ ~ 1s & N_n ~ $10^{24\text{-}34}$ cm^{-3}
- (n,γ), (γ,n), β-decays, fission
- Explosive conditions: SN vs NSM ?

The r-process nucleosynthesis responsible for half the elements heavier than iron in the Universe

one of the still unsolved puzzles in nuclear astrophysics

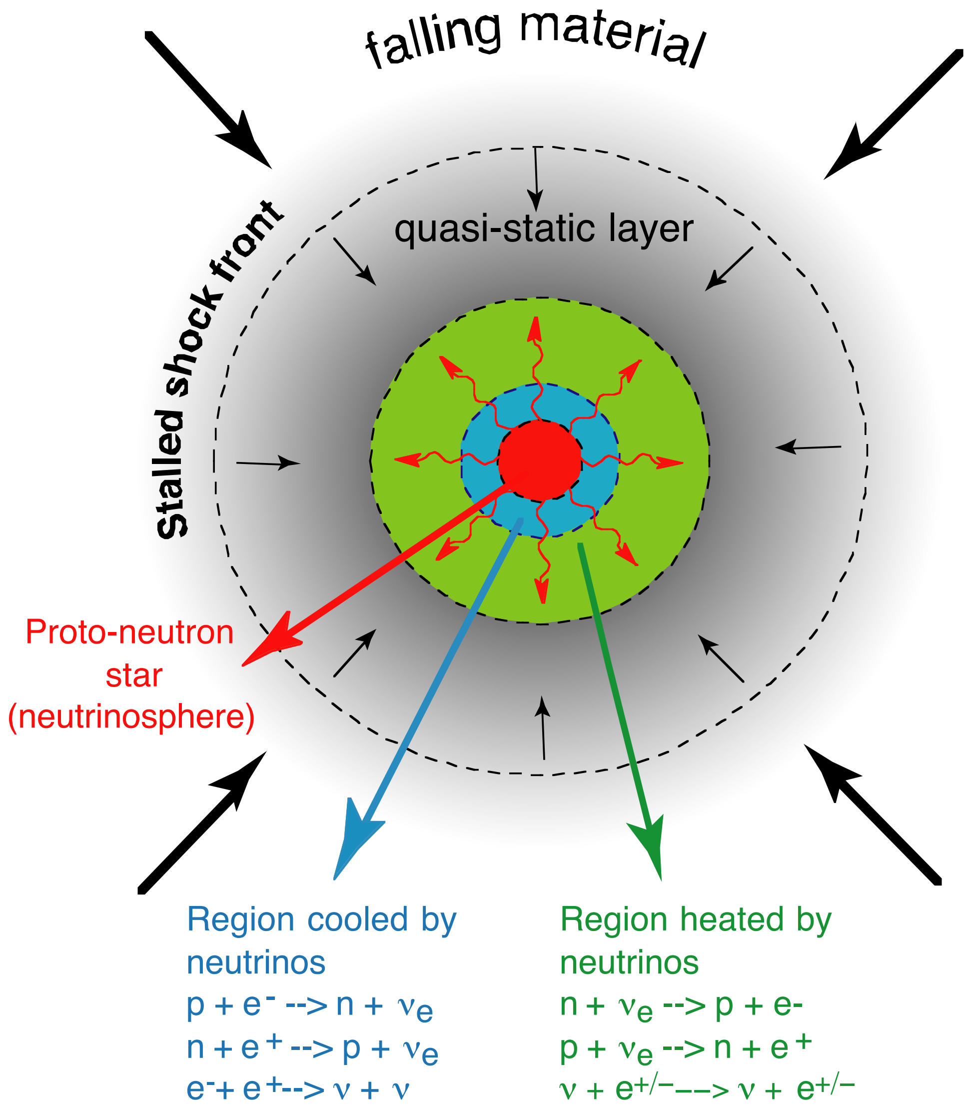
… the r-process site remains unidentified...





Supernova ν-driven wind
(high-T process)

Nucleosynthesis in the ν-driven wind



Decompression of hot material

n,p at $T_9 \approx 10$ $\rho \sim 10^6$g/cm^3

↓ NSE

^{4}He recombination

↓ $\alpha\alpha n$-^{9}Be(α,n)

^{12}C bottleneck

↓ (α,γ) & (α,n)

60≤A≤100 seed

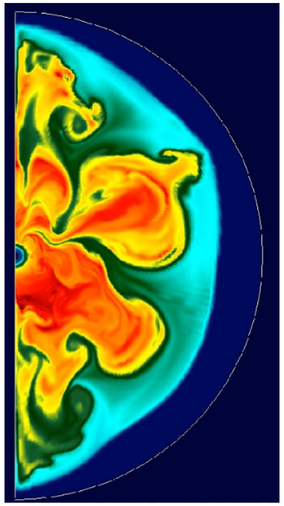
↓ (n,γ) & (γ,n) + β-decays

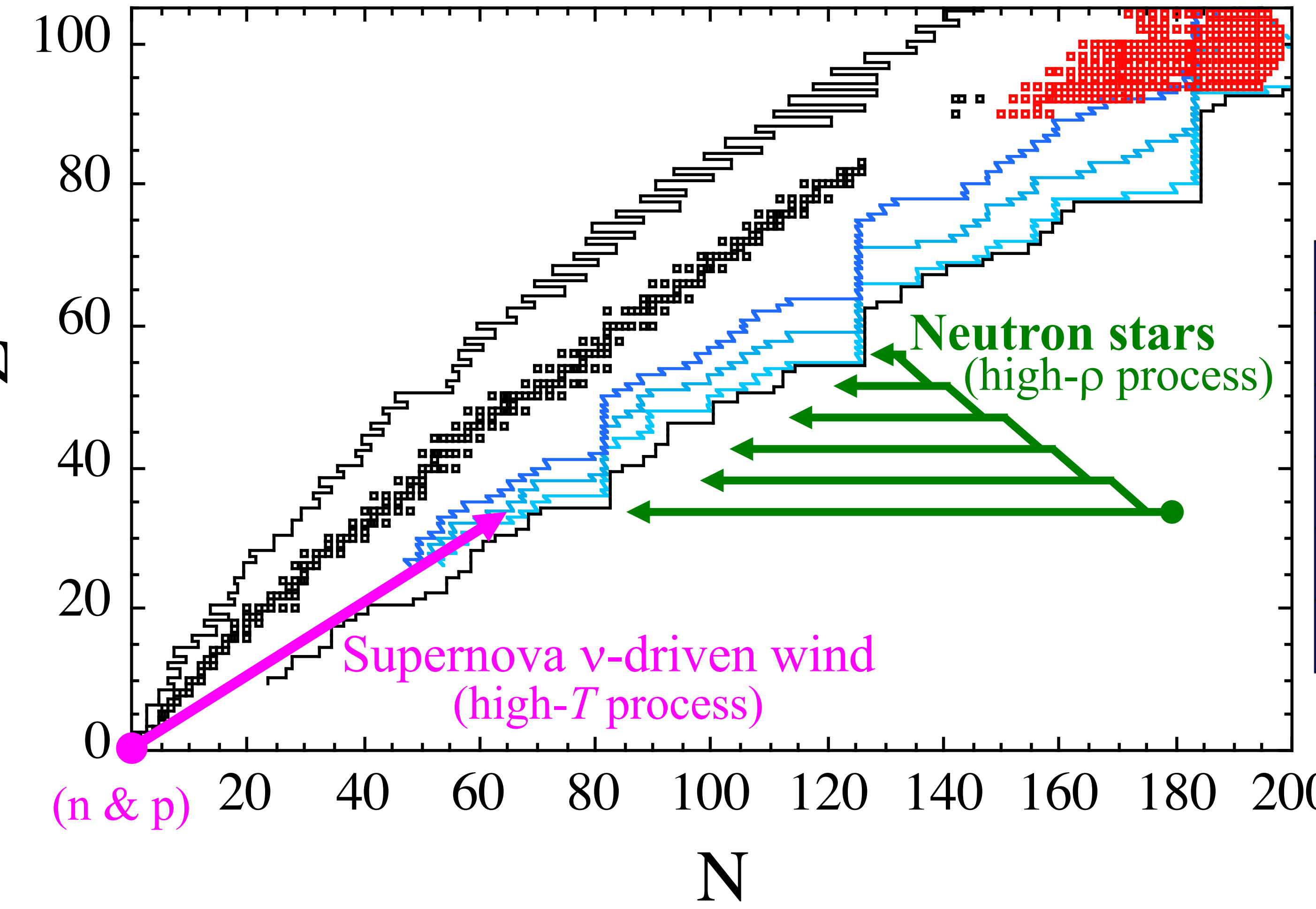
r-process

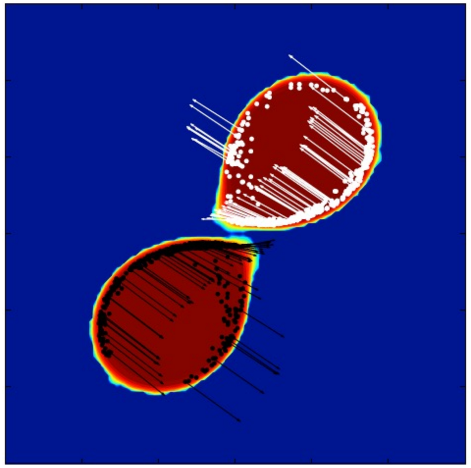
No r-process in realistic hydrodynamical simulations

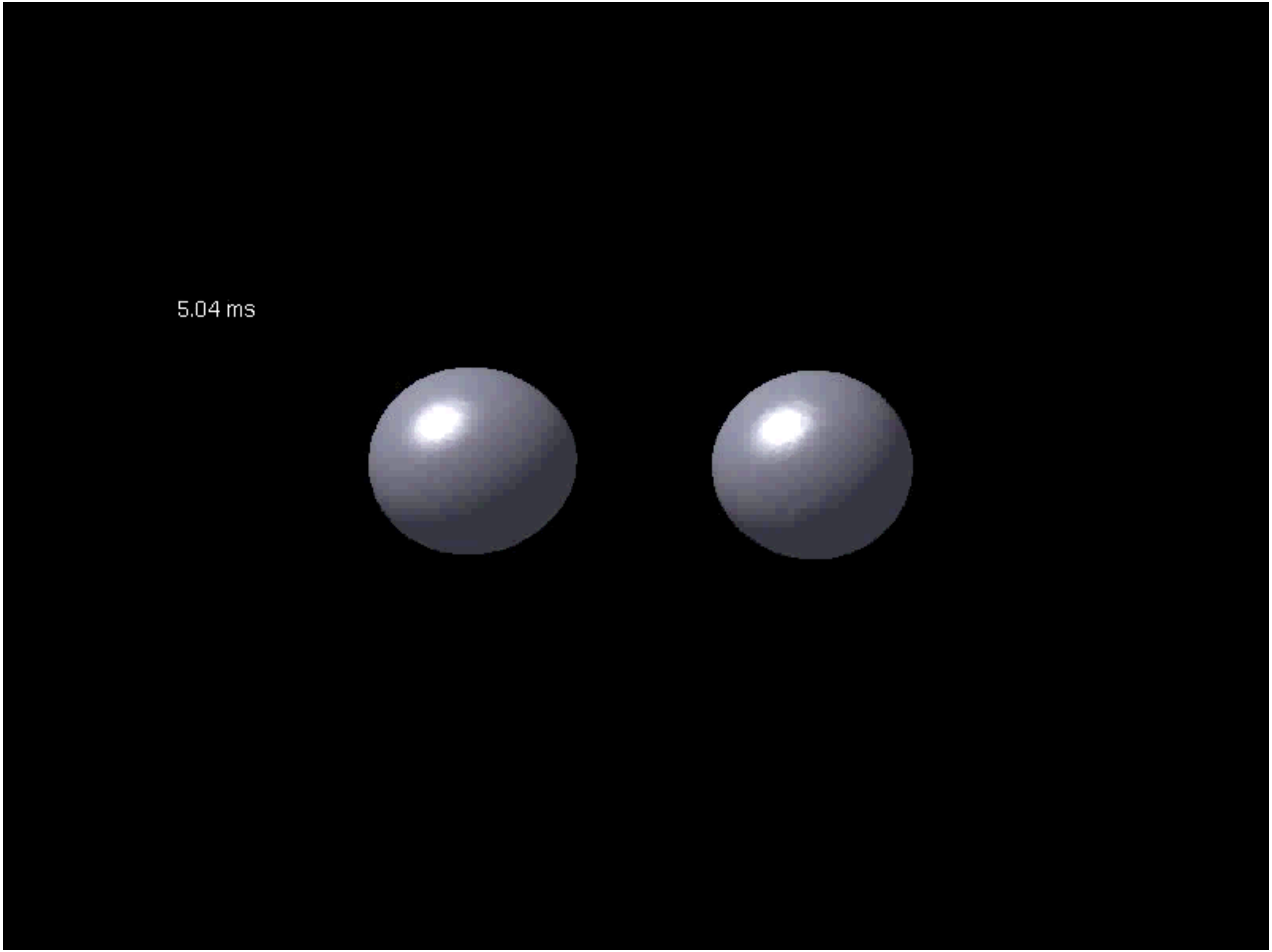
An alternative r-process scenario: the decompression of NS matter

(initial conditions: high-density matter)

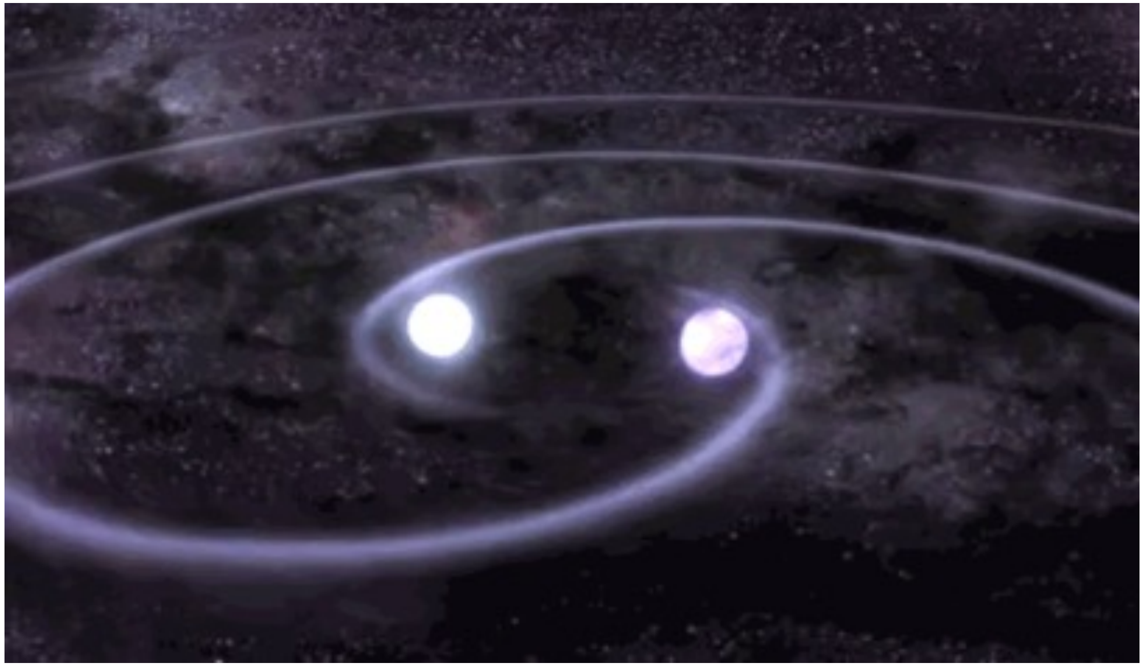






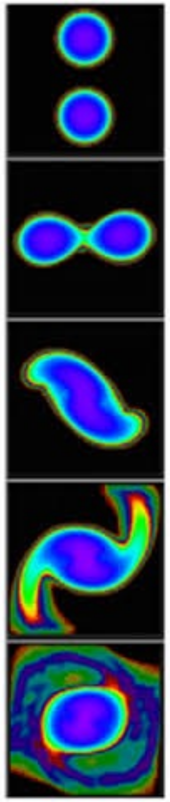

5.04 ms

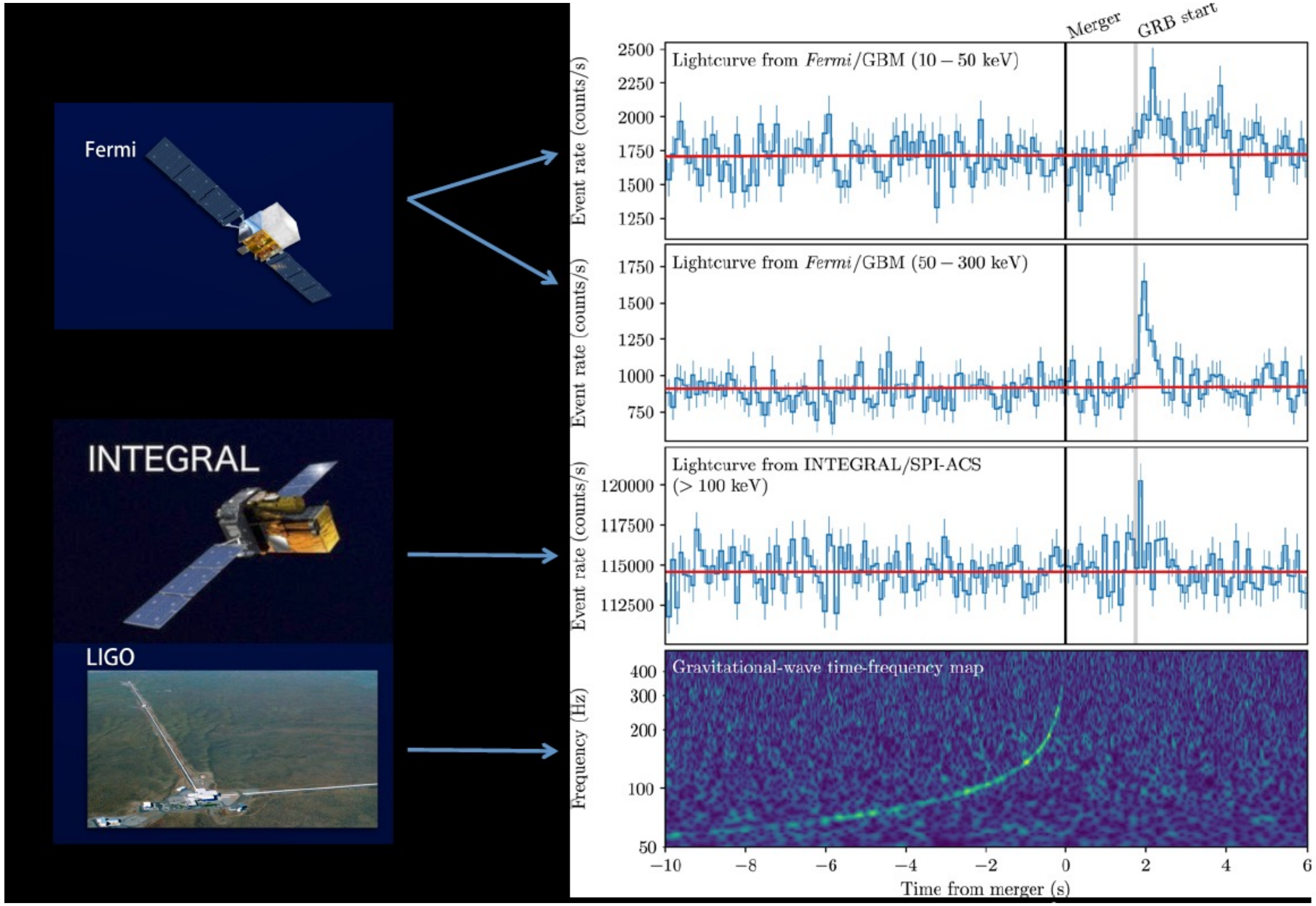
New observational insight thanks to the observation of GW170817 binary NS merger and its optical counterpart AT2017gfo



On August 17, 2017

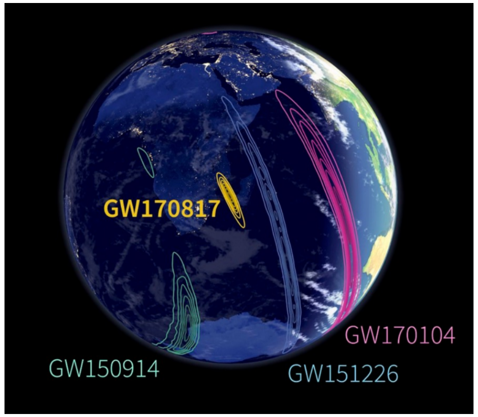
First detection of binary NS merger

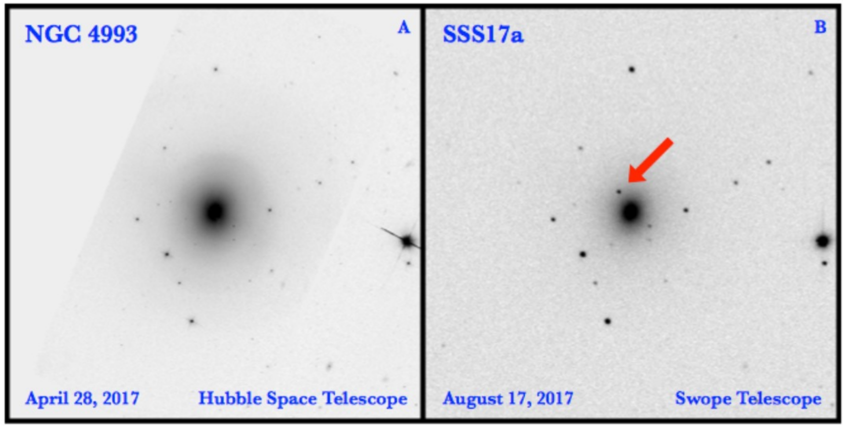




11h after

OPTICAL



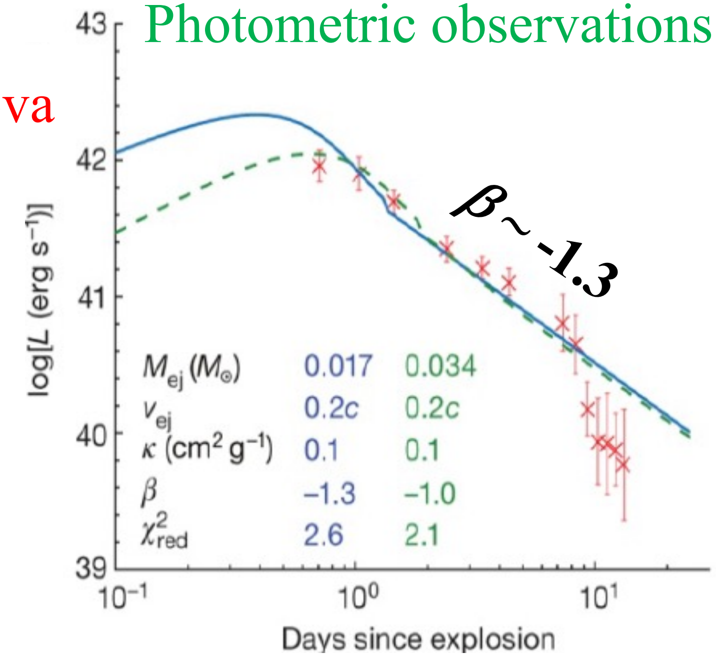


The analysis of the GW170817 light curve

- The kilonova light curve is compatible with an ejecta mass ($M_{ej} \approx 0.03$-$0.06\ M_\odot$)
  - "Blue" $A<140$ component with $M_{ej} \approx 0.01$-$0.02\ M_\odot$ and $v_{ej} \approx 0.26c$
  - "Red" $A>140$ component with $M_{ej} \approx 0.02$-$0.05\ M_\odot$ and $v_{ej} \approx 0.15c$

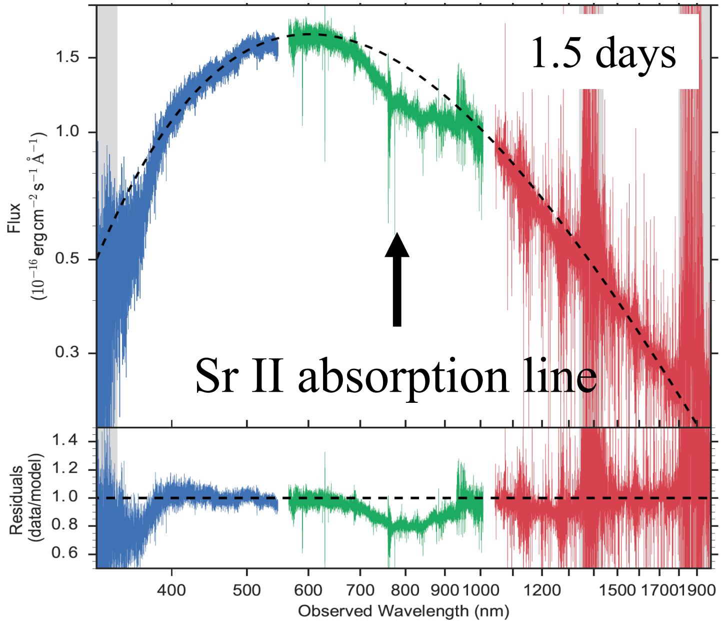
Kilonova

Photometric observations



$\beta \sim -1.3$

Spectroscopic observations

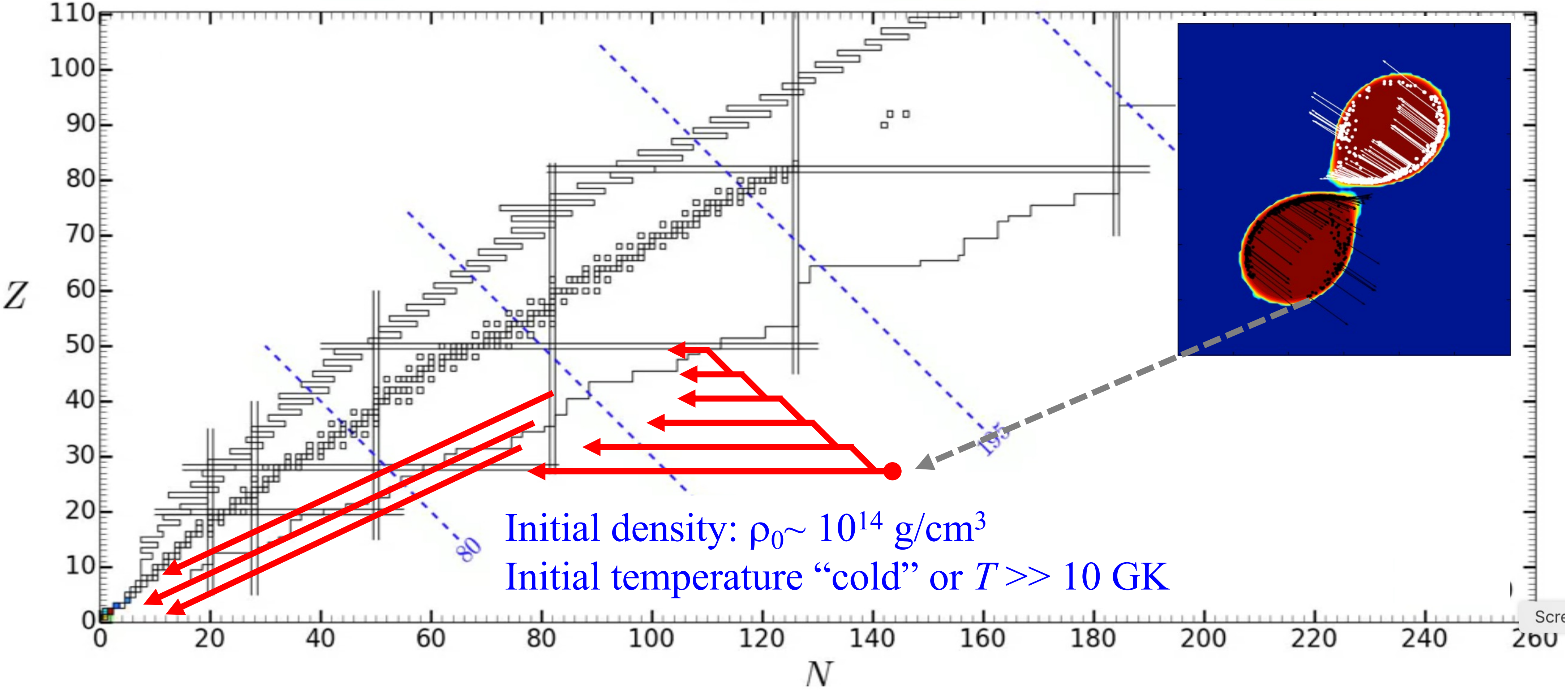


1.5 days

Sr II absorption line

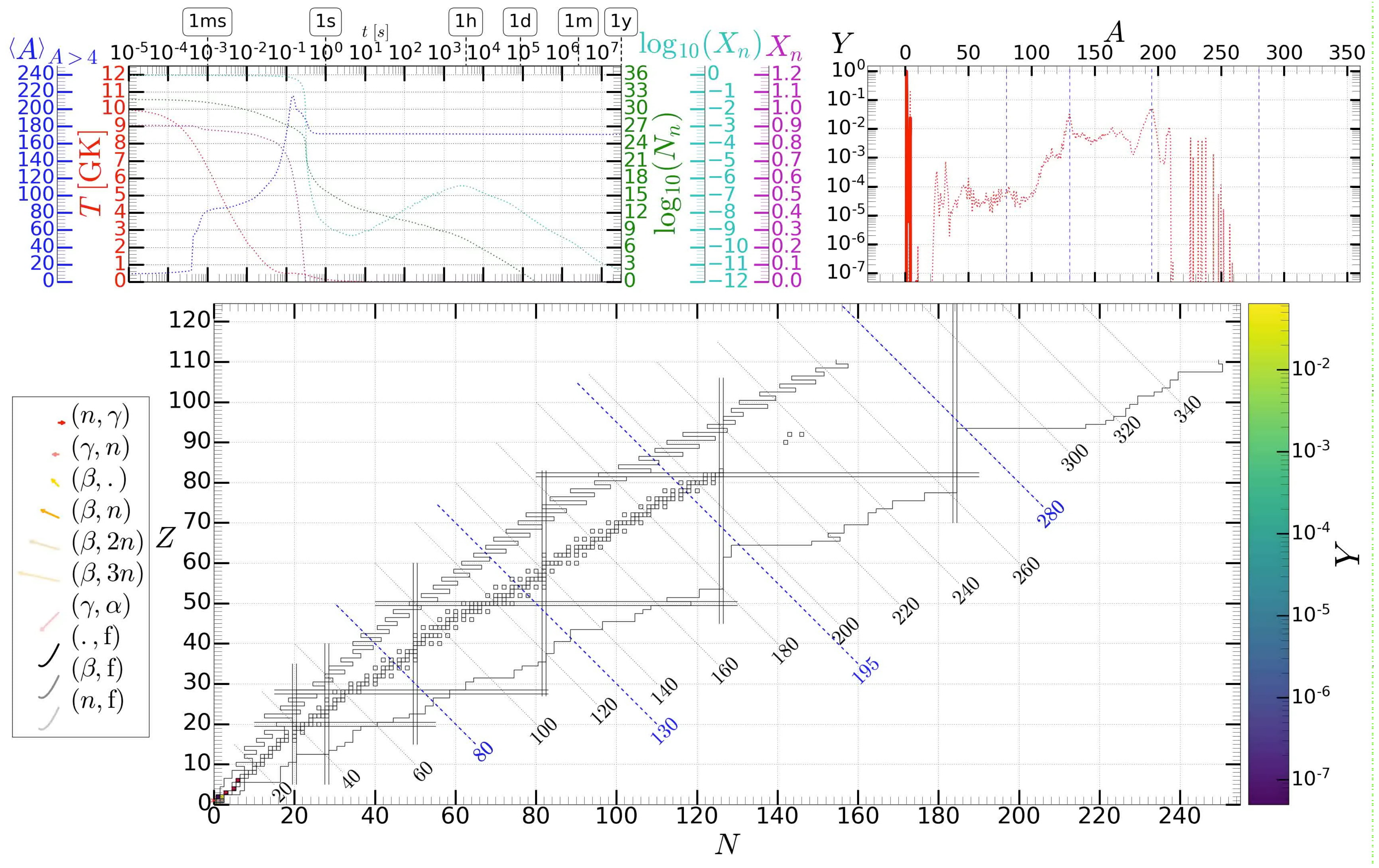
Watson et al. (2019)

- The ejected mass and new merger rate inferred from GW170817 imply that NSM can be a dominant source of *r*-process production in the Universe.



Initial density: $\rho_0 \sim 10^{14}$ g/cm^3

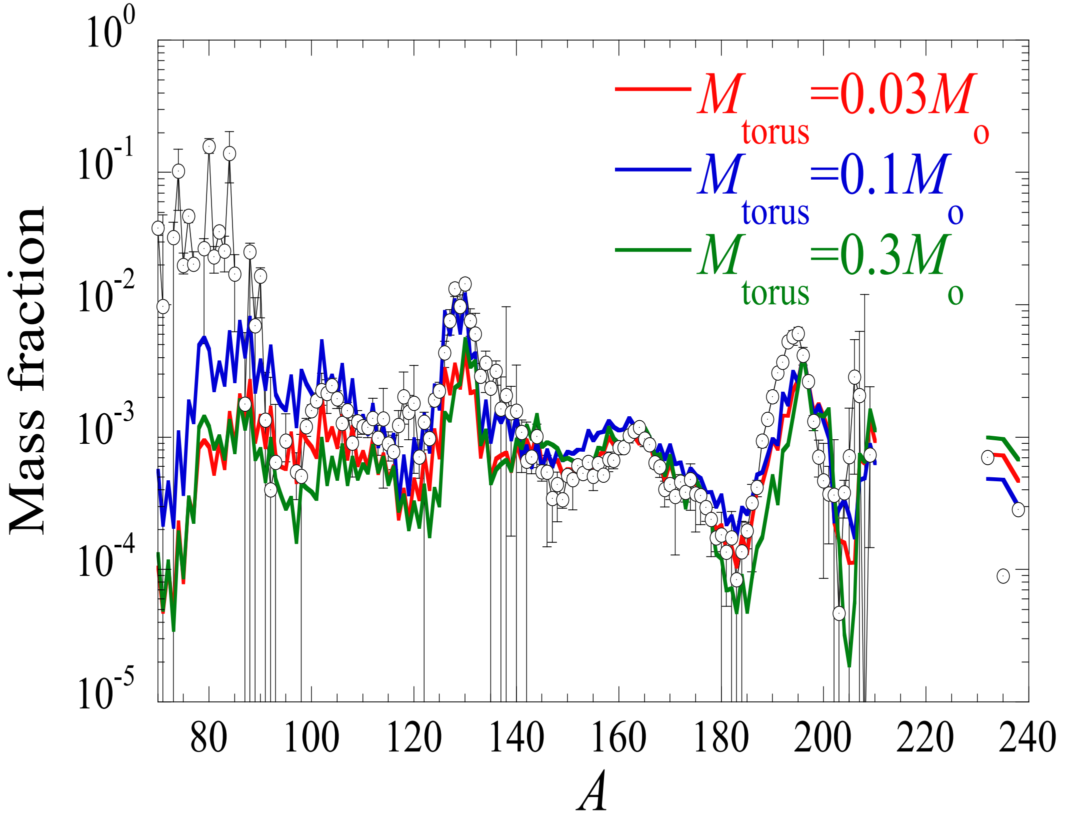
Initial temperature “cold” or $T >> 10$ GK


1ms
1s
1h
1d
1m
1y
$t\,[s]$
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
$\langle A\rangle_{A>4}$
240 220 200 180 160 140 120 100 80 60 40 20 0
$T\,[\mathrm{GK}]$
12 11 10 9 8 7 6 5 4 3 2 1 0
$\log_{10}(N_n)$
36 33 30 27 24 21 18 15 12 9 6 3 0
$\log_{10}(X_n)$
0 −1 −2 −3 −4 −5 −6 −7 −8 −9 −10 −11 −12
X_n
1.2 1.1 1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Y
A
0 50 100 150 200 250 300 350
10^{0} 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7}
(n,γ)
(γ,n)
$(\beta,.)$
(β,n)
$(\beta,2n)$
$(\beta,3n)$
(γ,α)
$(.,\mathrm{f})$
(β,f)
(n,f)
Z
0 10 20 30 40 50 60 70 80 90 100 110 120
N
0 20 40 60 80 100 120 140 160 180 200 220 240
20 40 60 80 100 120 130 140 160 180 195 200 220 240 260 280 300 320 340
Y
10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7}

Final abundance distributions from Binary Neutron Star Mergers

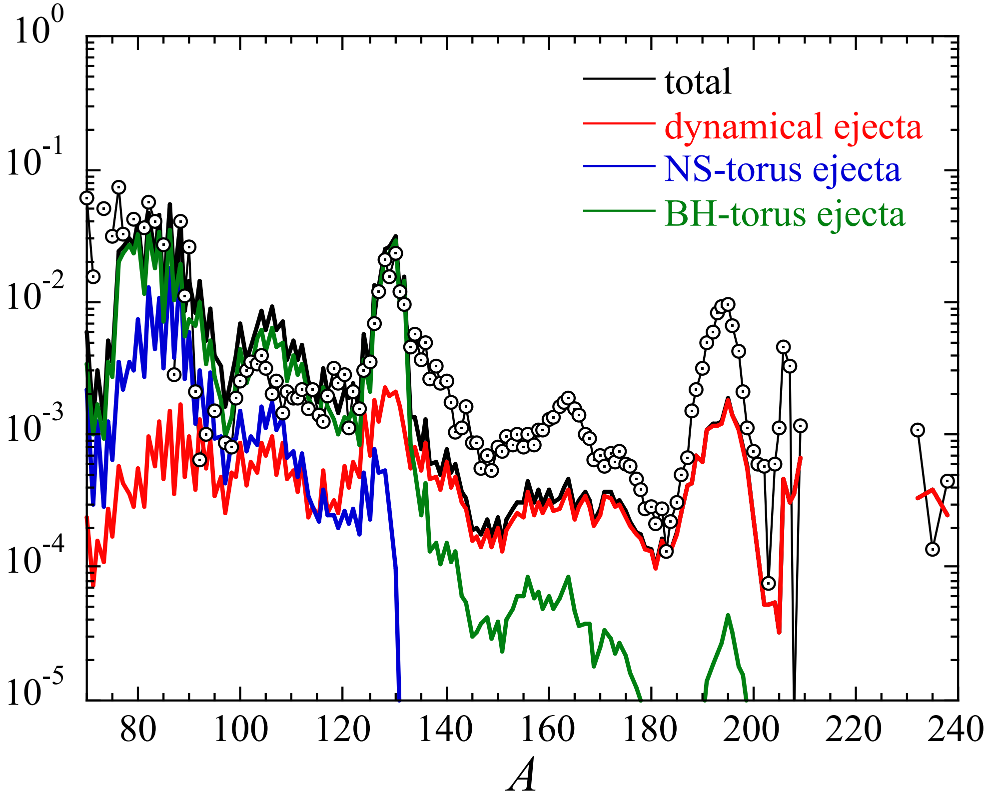
Dynamical + BH-Torus system

Just et al. (2015)



Dyn + HMNS +BH Torus system

Just et al. (2023)



Robust production of all $A \geq 90$ r-nuclei with a rather solar distribution

Our understanding of the r-process nucleosynthesis, i.e. the origin of about half of the nuclei heavier than Fe in the Universe is considered as
one of the top 11 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)

Still many open questions

- Site of the r-process ?
- Galactic chemical evolution ?
- Agreement with observation (spectroscopic, GCR, isotopic anomalies, marine sediments, …) ?
- Nuclear needs (site-dependent) ?
- Nuclear inputs (many properties on thousands of exotic n-rich nuclei) ?

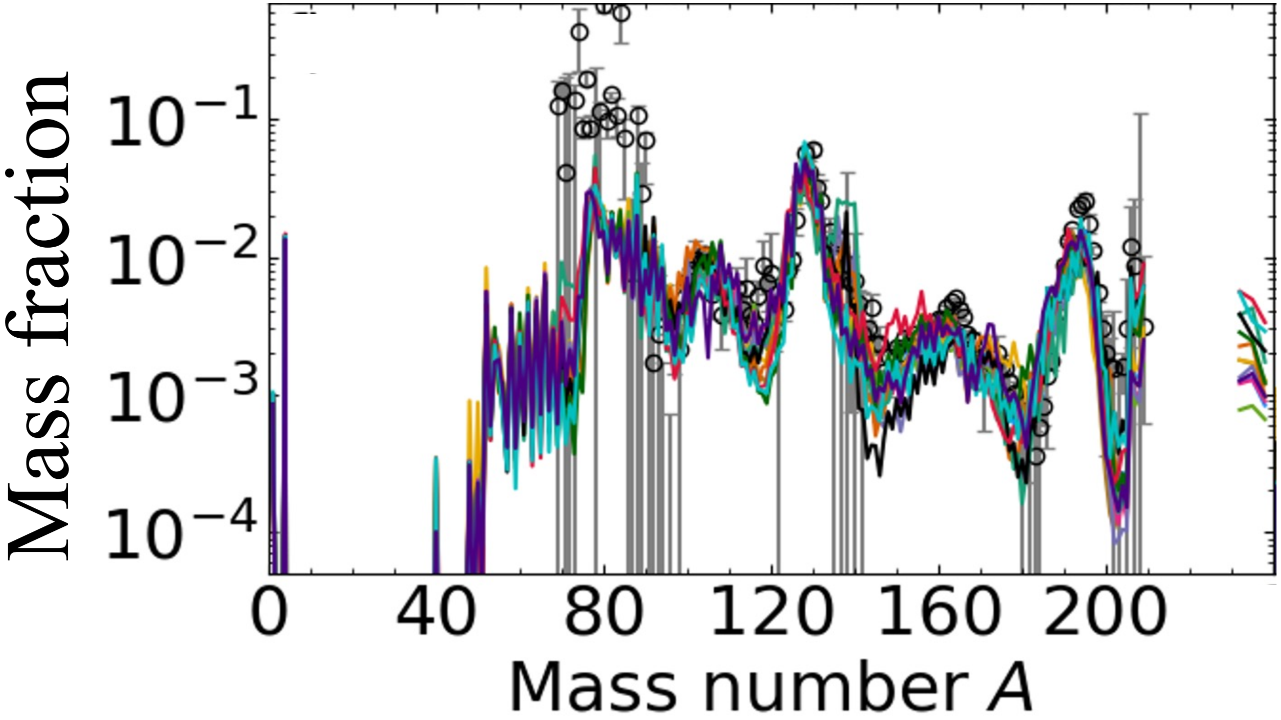
Nuclear physics input

(n,γ) – (γ,n) – β competition & Fission

- β-decay rates
- (n,γ) and (γ,n) rates (hence masses)
- Fission (nif, sf, βdf) rates
- Fission Fragments Distributions

Still many open questions

for some 5000 nuclei with $Z \leq 110$ on the n-rich side – essentially no exp. data

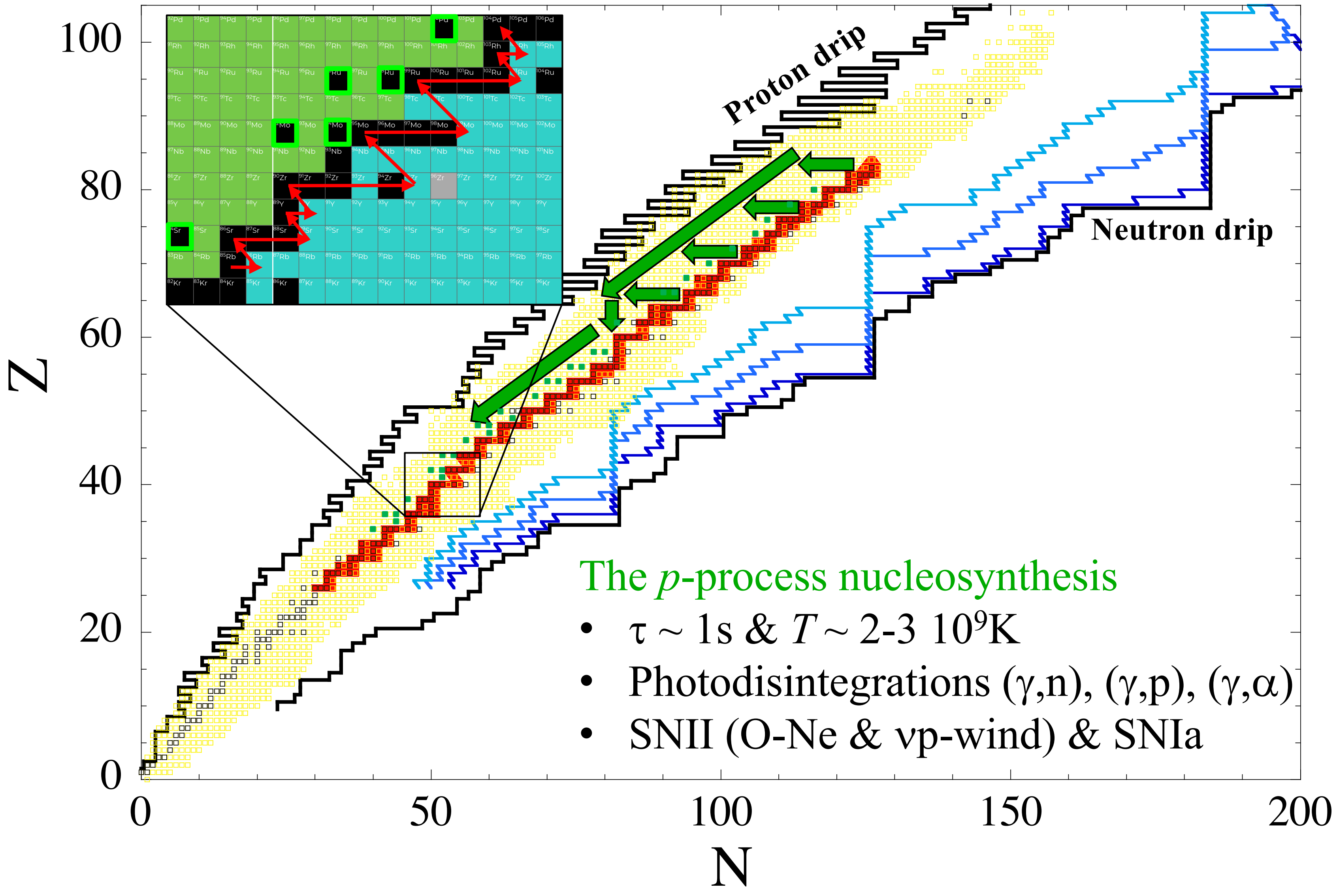


The p-process nucleosynthesis

The p-process nucleosynthesis

Neutron capture processes cannot synthesize neutron-deficient isotopes

35 p-nuclei, no p-element: need for a fundamentally different nucleosynthesis process !

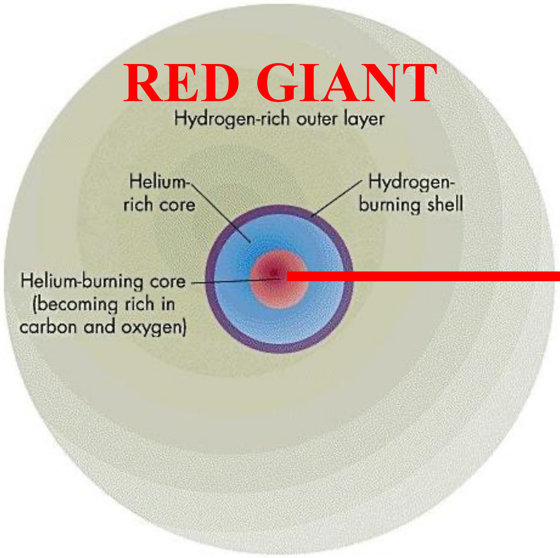


The *p*-process nucleosynthesis

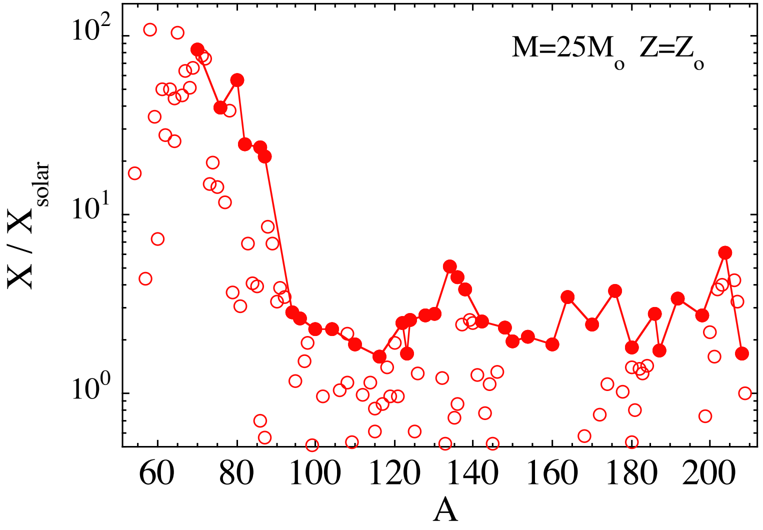
- $\tau \sim 1\text{s}$ & $T \sim 2\text{-}3\ 10^9\text{K}$
- Photodisintegrations (γ,n), (γ,p), (γ,α)
- SNII (O-Ne & νp-wind) & SNIa

The p-process: Ne/O-rich layers during SNII explosion of massive stars

1. **s-process during core He-burning by $^{22}Ne(\alpha,n)^{25}Mg$**

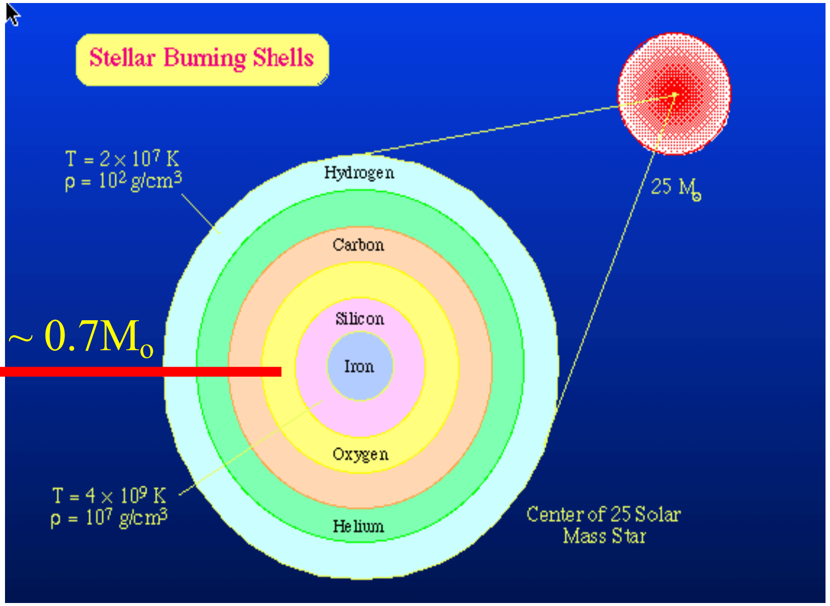


enrichment
in
s-elements
$70 \leq A \leq 90$



2. **p-process in O/Ne layers**
(hydrostatic pre-supernova as well as explosive supernova phases)

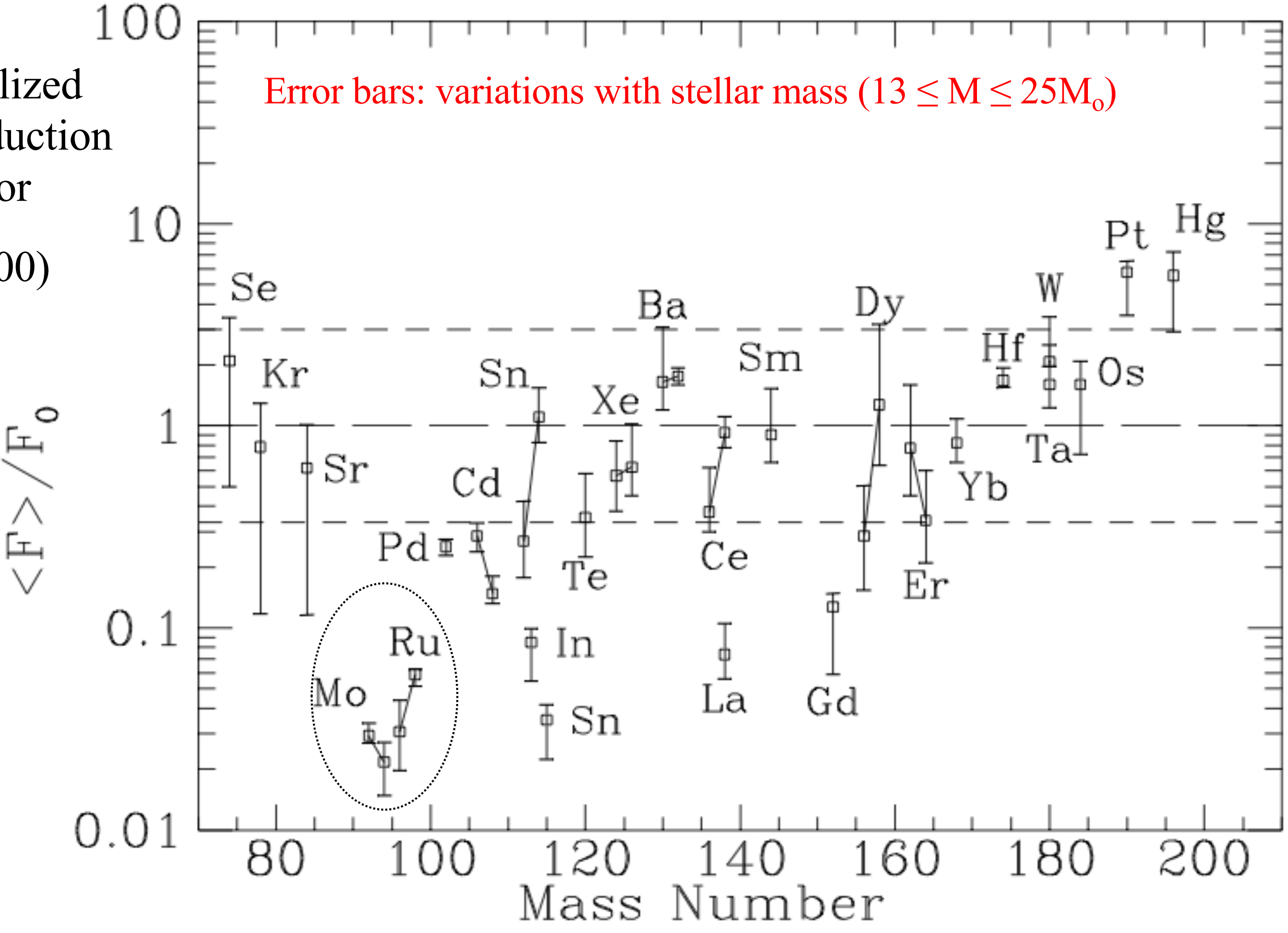
heating at T=2-3 10^9 K
of the s-enriched & r-seeds



P-nuclides yields obtained by convolution over a spectrum of stellar masses (assuming an Initital Mass Function)

Normalized overproduction factor

(F_0=100)



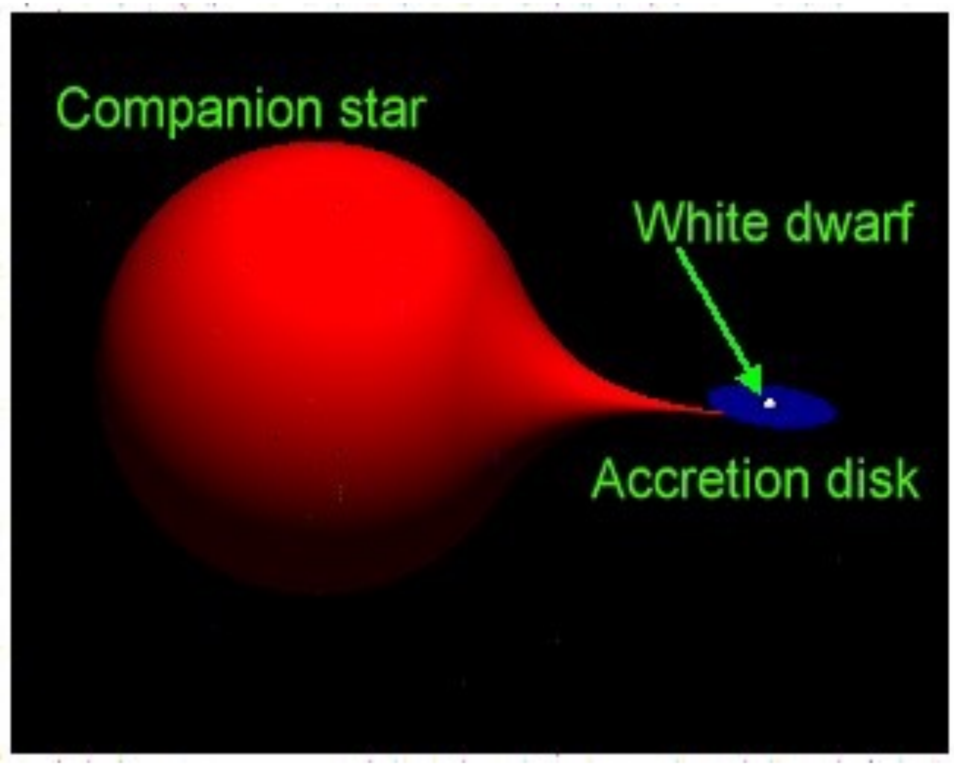
Error bars: variations with stellar mass ($13 \leq M \leq 25M_o$)

Within a factor of 3

Some major discrepancies remain: Mo and Ru p-isotopes, ^{113}In, ^{115}Sn and ^{138}La.

Accreting White Dwarf models for type Ia Supernovae

Matter accreted onto the surface of a white dwarf from its binary companion causes regions in its interior to become unstable to thermonuclear runaway → Carbon deflagration



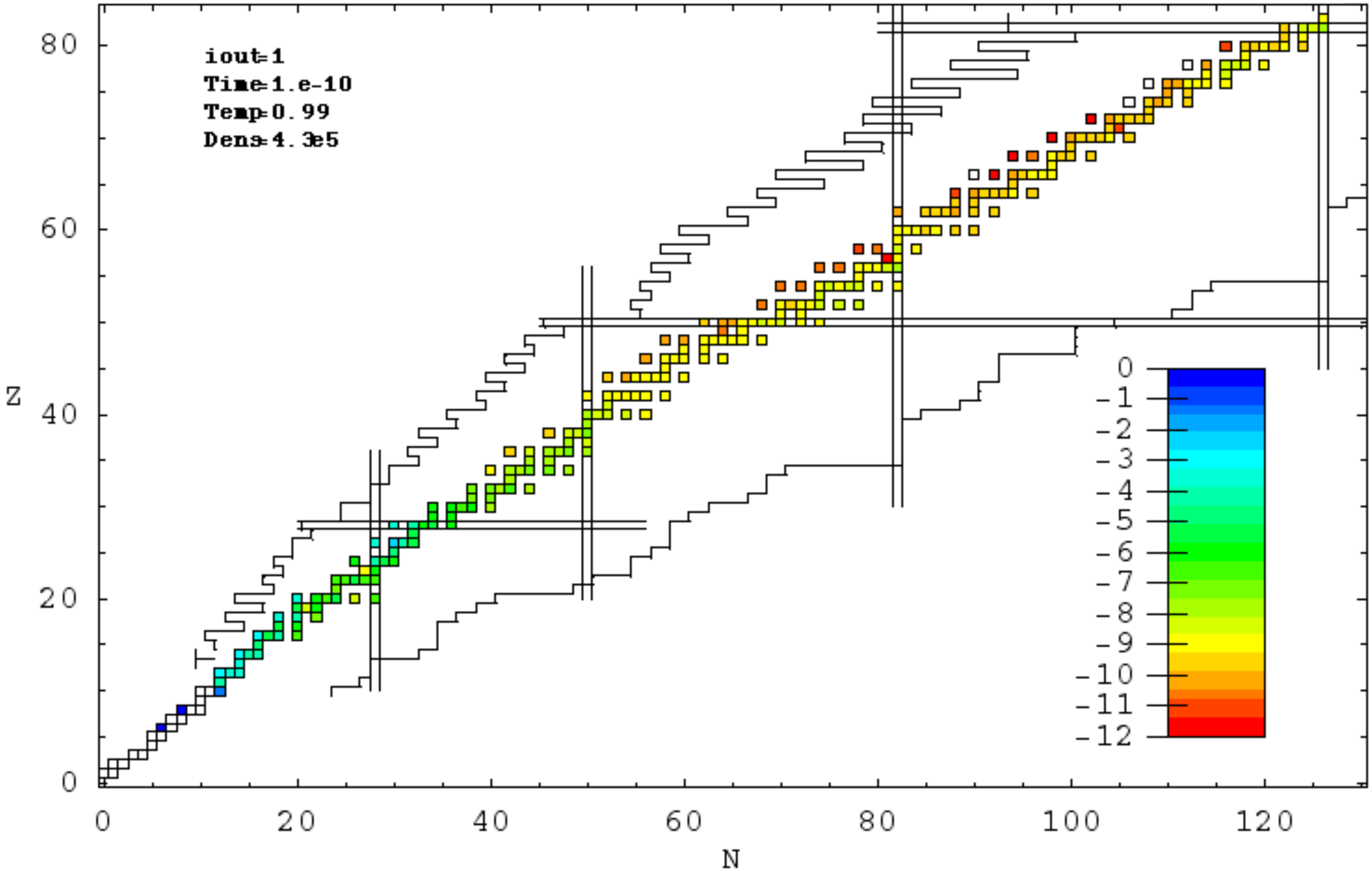
↓

p-process nucleosynthesis in layers heated at *T*=2-3 10^9 K (initial composition C+O+Ne)

Initial composition of the heavy seeds

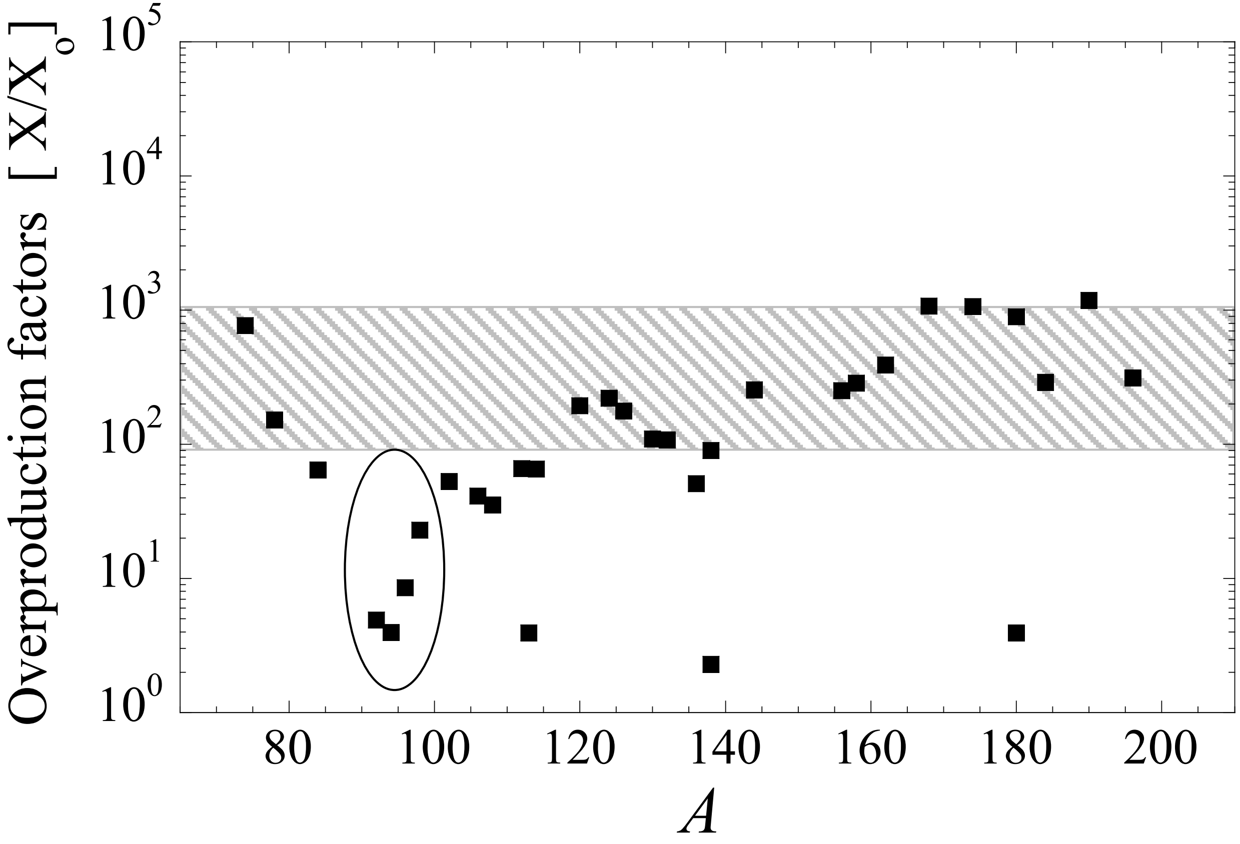
- solar composition ?
- s-process elements in WD ?
- s-process elements from AGB companion?
- s-process nucleosynthesis during accretion phase ?

SNIa model (W7): Layer heated at T_9=3.2



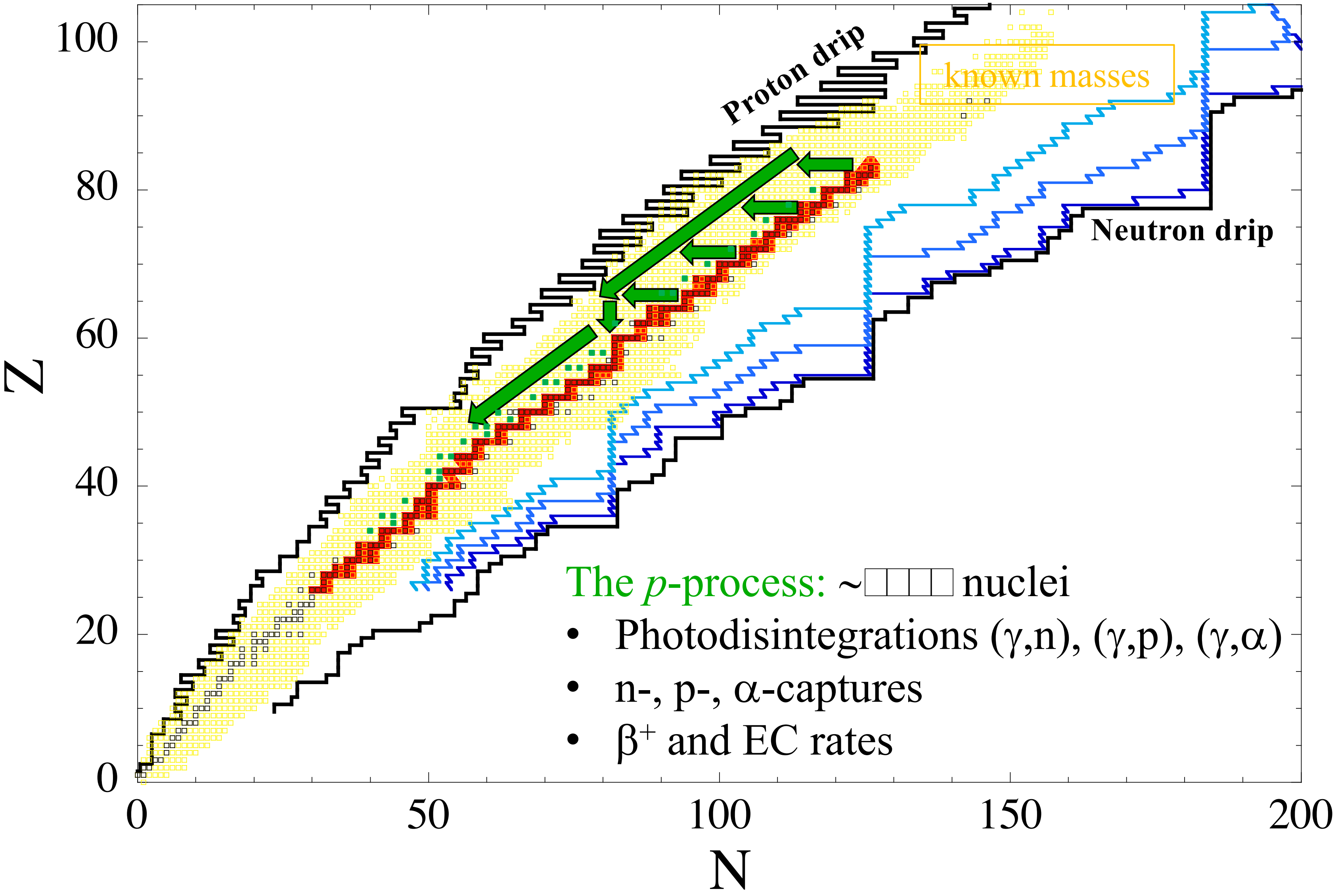
p-nuclide overproduction factor in type Ia supernovae

Heavy seed abundances: solar system distribution



Some discrepancies remain: Mo and Ru p-isotopes, ^{113}In, ^{138}La, and ^{180}Ta.

Nuclear needs for p-process calculations



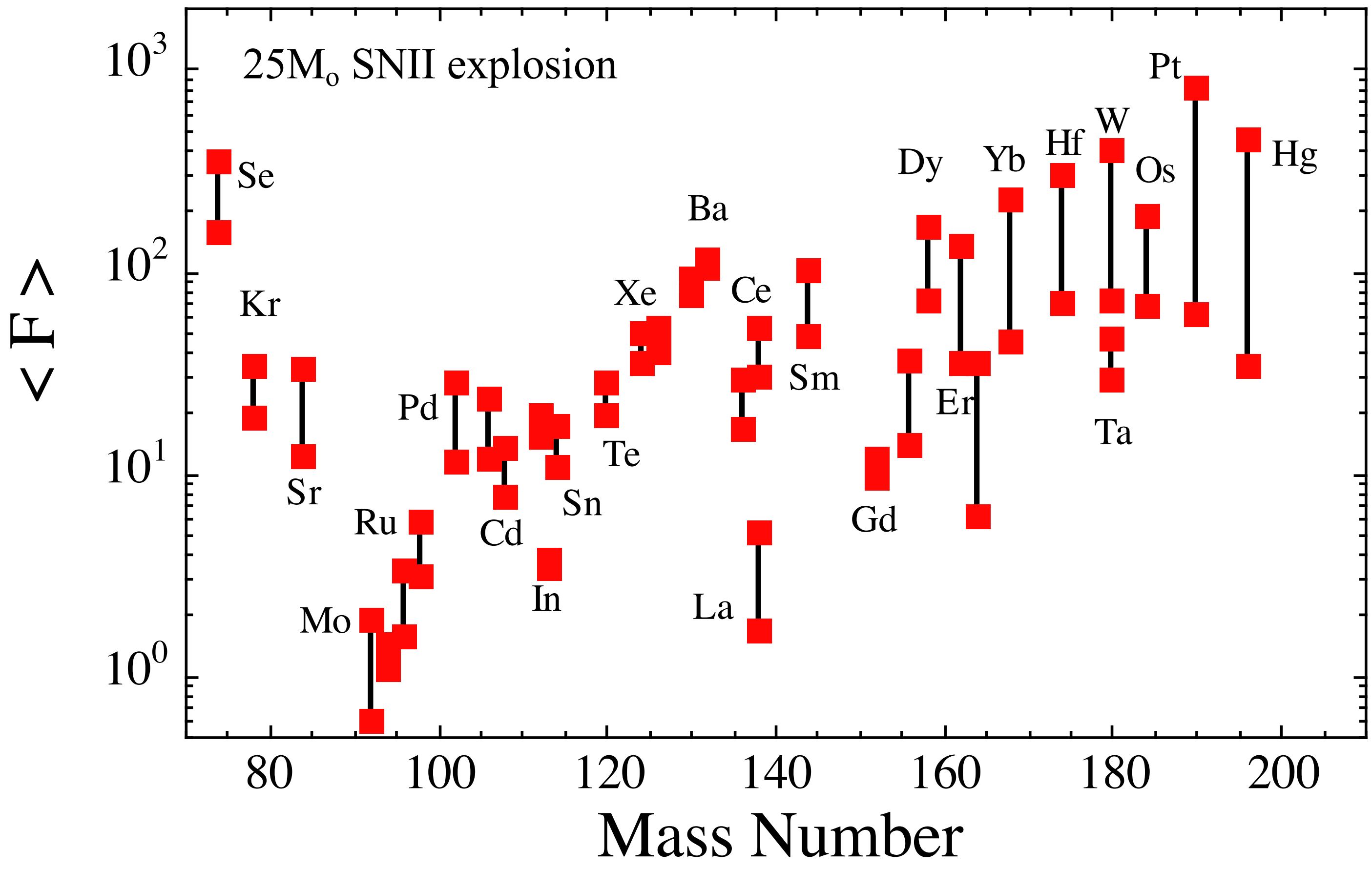
The *p*-process: ~□□□□ nuclei

- Photodisintegrations (γ,n), (γ,p), (γ,α)
- n-, p-, α-captures
- β^+ and EC rates

☺ Many nuclear masses and β^+-decay rates known experimentally

☹ Almost no n-, p- and α-capture rates and reverse rates known experimentally

Impact of the nuclear uncertainties on the p-nuclide overproduction factor <*F*>



The large variations in the abundances of the heaviest p-nuclides result almost entirely from the use of different alpha-nucleus optical potentials (essentially due to the lack of experimental data in the heavy mass range). The abundances of the lighter species are mainly affected by uncertainties in the predicted nuclear level densities and the nucleon-nucleus potential.

The ^{92,94}Mo, ^{96,98}Ru, ^{113}In, ^{115}Sn and ^{138}La discrepancies remain.

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

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