Tema 7

Nucleosíntesis de elementos pesados A>60

Asignatura de Física Nuclear

Curso académico 2008/2009

Universidad de Santiago de Compostela

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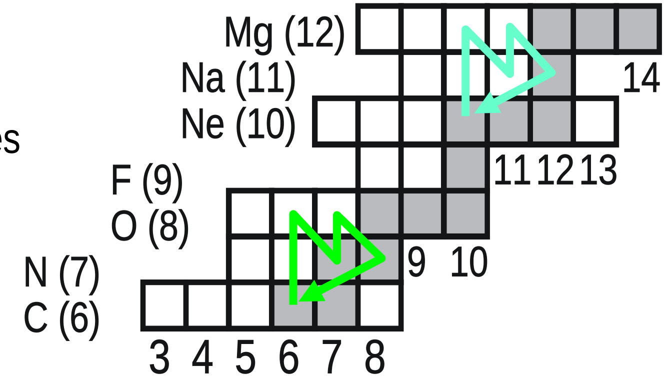
Explosive hydrogen-helium burning

1.1 Stellar scenario

For stellar temperatures T<0.4 GK, very little material is lost from the operation of either the cold or the hot CNO cycles. This is explained by the fact that the heaviest nuclei synthesized in the CNO and HCNO cycles are ^{19}F and ^{18}F, respectively. Since the branching ratios $B_{p\alpha}/B_{p\gamma}$ of these two nuclei are 10^3-10^4 in the temperature range of these cycles, both nuclei are predominantly converted into lighter nuclei via (p,α) reactions closing both cycles. At higher temperatures (T>0.5 GK) the situation changes because in this case α-particle induce reactions on ^{14}O or ^{15}O breakout the HCNO cycle producing heavier nuclei.



The breakout of the CNO cycles requires stellear scenarios having hydrogen and helium fuel at temperatures above T=0.5 GK. Such conditions can only be met in binary system where a massive old star absorves Hydrogen/helium from a companion star. These are the typical conditions of X-ray bursters or X-ray pulsars

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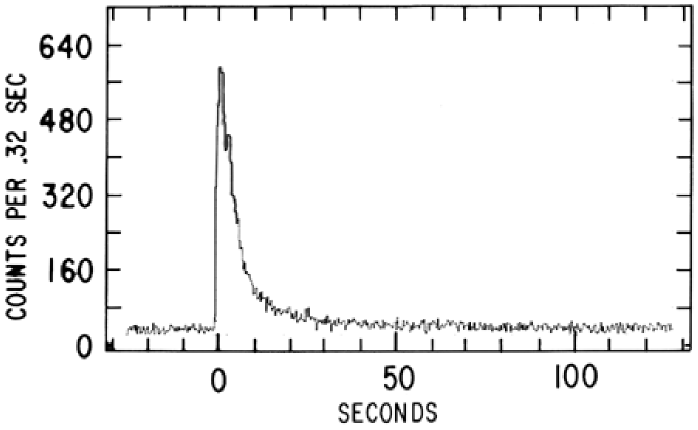
1.1 Stellar scenario

X-ray bursts:

- ✓ binary system: neutron star + less evolved star
- ✓ regular accreation of matter
- ✓ sudden increase of surface temperature and density
  $T \sim 10^9$ K, $\rho \sim 10^6$ g cm^{-3}
- ✓ explosive ignition of H and/or He (via $3\alpha \rightarrow {}^{12}C$)
- ✓ emission of strong X-rays (X-ray burst)
- ✓ cooling down of surface after explosion
- ✓ typical burst duration 10-100 s



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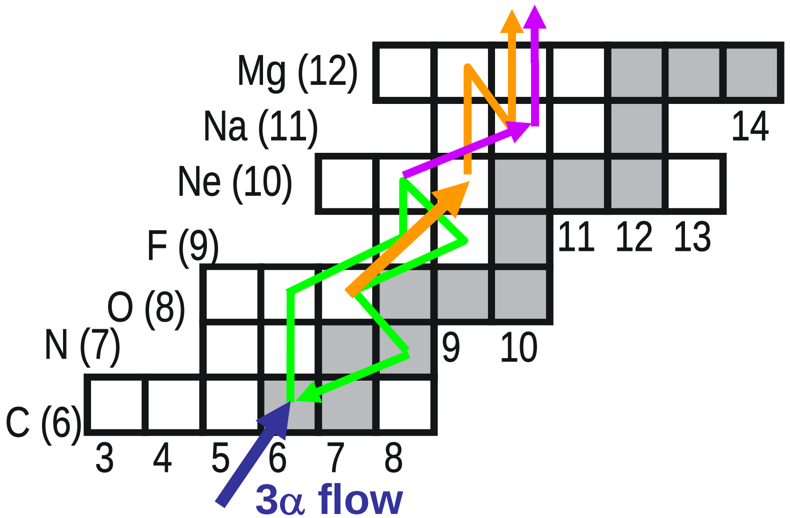
1.2 Breakout from the HCNO cycles

At temperatures above T>0.5 GK, a-particle induced reactions convert 14O and 15O to nuclei in the mass A=20-21. The main breakout reactions are:

$^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na$

$^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne(\alpha,p)^{21}Na$

$^{14}O(\alpha,p)^{17}F(\gamma,p)^{16}O(\alpha,\gamma)^{20}Ne$



T_9 >~ 0.3 $^{15}O(\alpha,\gamma)^{19}Ne$

T_9 >~ 0.6 $^{18}Ne(\alpha,p)^{21}Na$

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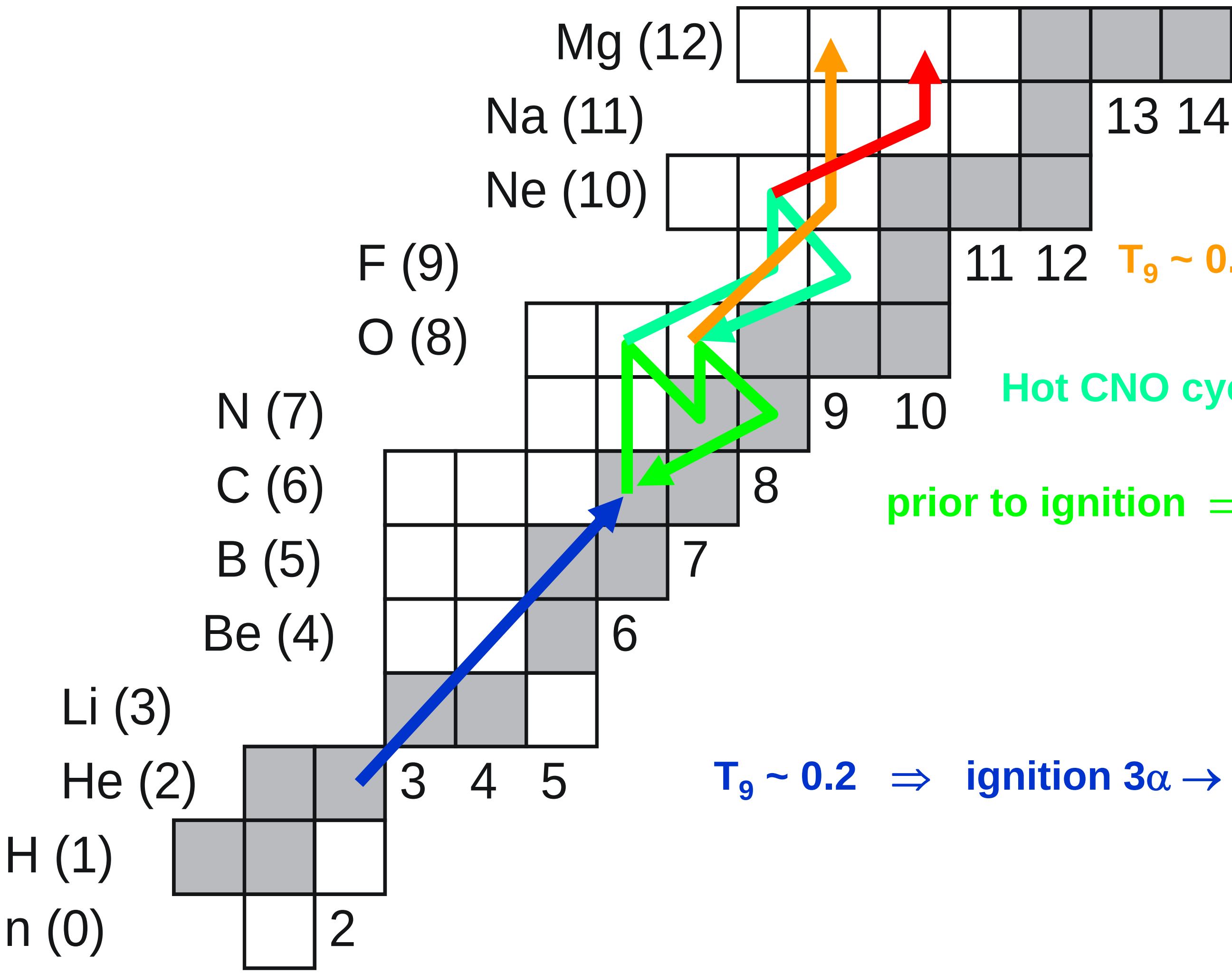
1.2 Breakout from the HCNO cycles



T_9 ~ 0.8 ⇒ **breakout 2: ^{18}Ne(α,p)**

(~50 ms after breakout 1) leads to rp process and main energy production

T_9 ~ 0.7 ⇒ breakout 1: ^{15}O(α,γ)

Hot CNO cycle II

prior to ignition ⇒ hot CNO cycle

T_9 ~ 0.2 ⇒ ignition 3α → ^{12}C

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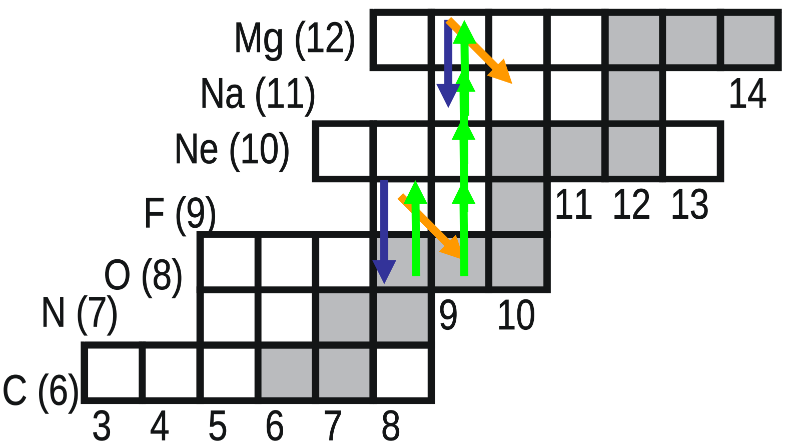
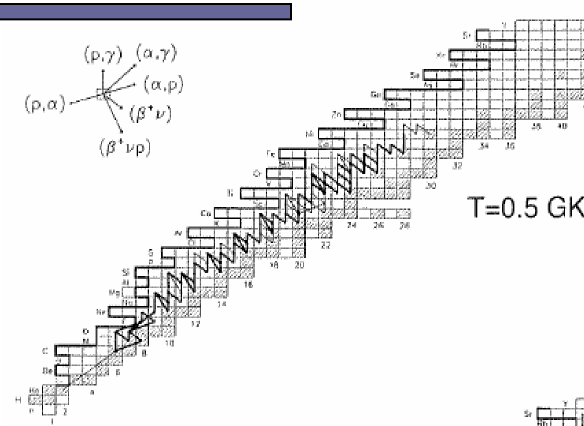
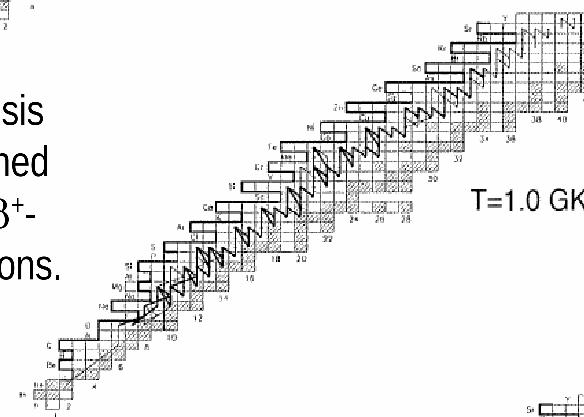
1.3 The rp process

After the initiation of the CHNO breakout, sequences of (p,γ) reactions and β⁺-decays transform CNO nuclei within ~100 s to the Fe-Co region. The resulting reaction network is known as *rapid proton capture* or rp-process.

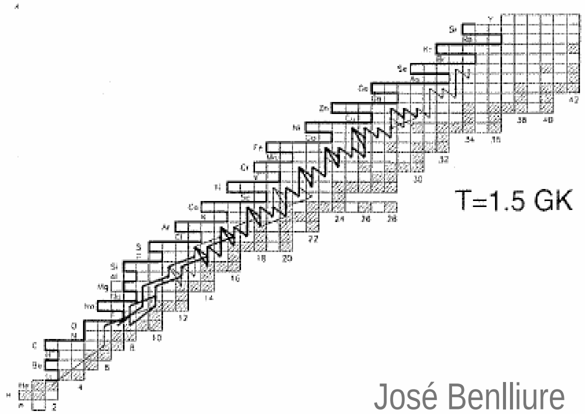


The most likely nucleosynthesis path in the rp-process is defined by the competition between β⁺-decays, (p,γ) and (γ,p) reactions.





The proton capture rate increases with temperature producing heavier and more neutron-deficient nuclei. Indeed, at temperatures above T>1 GK, the nucleosynthesis path is located close to the proton drip-line.



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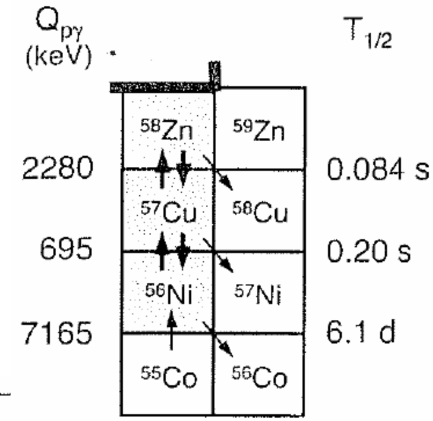
1.5 Bottleneck nuclei and the end of the rp-process

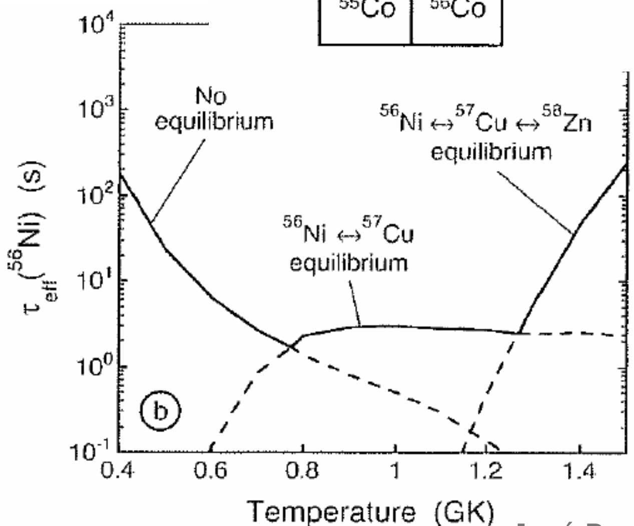
The time scale of the rp-process nucleosynthesis is mainly determined by nuclei having long β^+-decay half-lives and small $Q_{p\gamma}$-values known as waiting points: ^{22}Mg, ^{26}Si, ^{30}S, ^{34}Ar, ^{56}Ni, ^{60}Zn, ^{64}Ge, ^{68}Se and ^{72}Kr..



^{56}Ni is a particular case because of its relatively long half-live and the small $Q_{p\gamma}$-value. Its effective mean lifetime can be obtained as:

$$\lambda_{eff}(^{56}Ni) = \frac{\lambda_{^{57}Cu(p,\gamma)}}{\lambda_{^{57}Cu(\gamma,p)}}\left(\frac{\lambda_{^{57}Cu(p,\gamma)}}{\lambda_{^{58}Zn(\gamma,p)}}\lambda_{^{58}Zn(\beta^+\nu)} + \lambda_{^{57}Cu(\beta^+\nu)}\right)$$

The temperature dependence of the effective lifetime defines a window at intermediate temperatures where ^{56}Ni does not represent a major waiting point. At lower and higher temperatures, the Coulomb barrier of ^{56}Ni(p,γ)^{57}Cu and two sequential photodisintegration reactions are responsible for the substantial increase of the effective lifetime.



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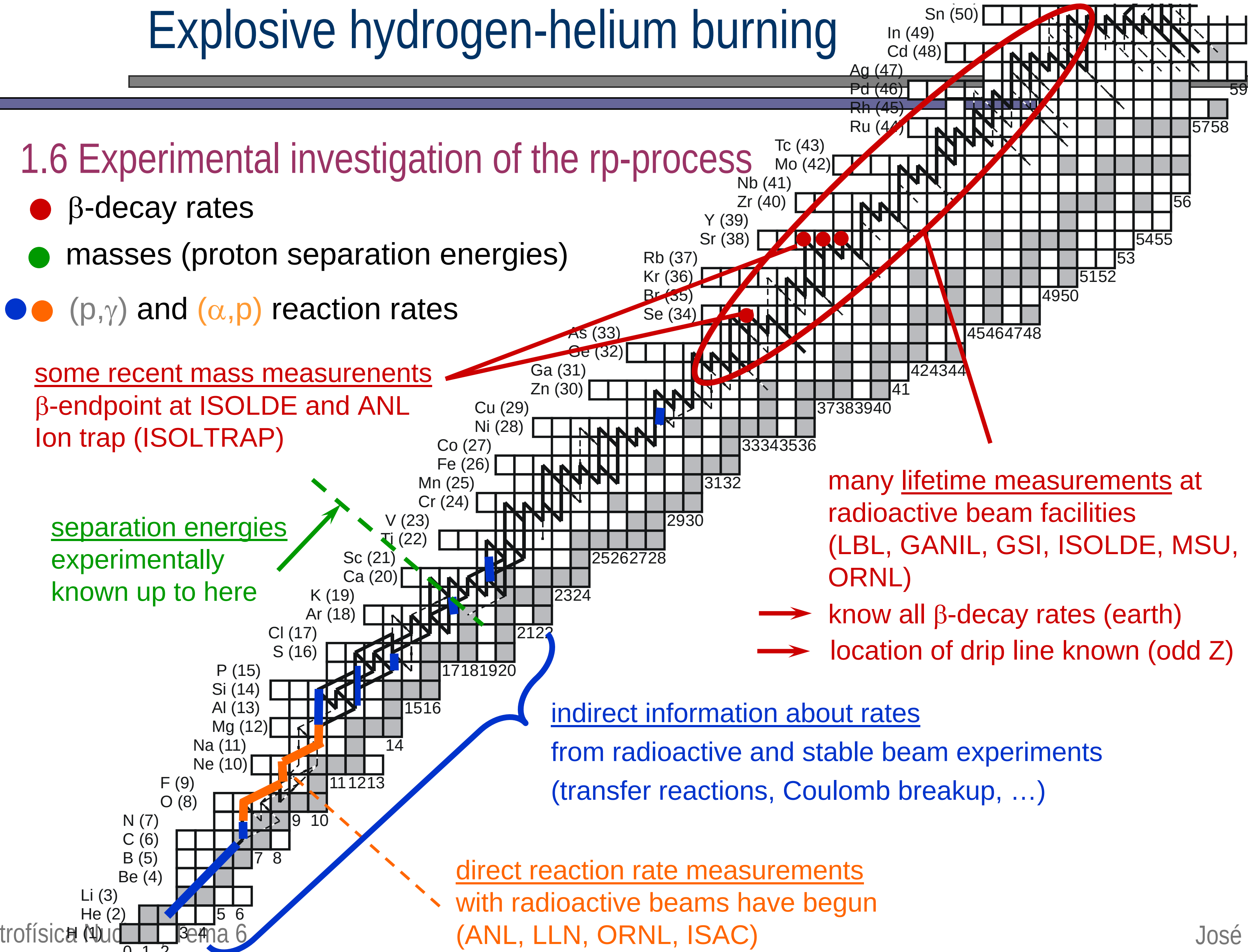
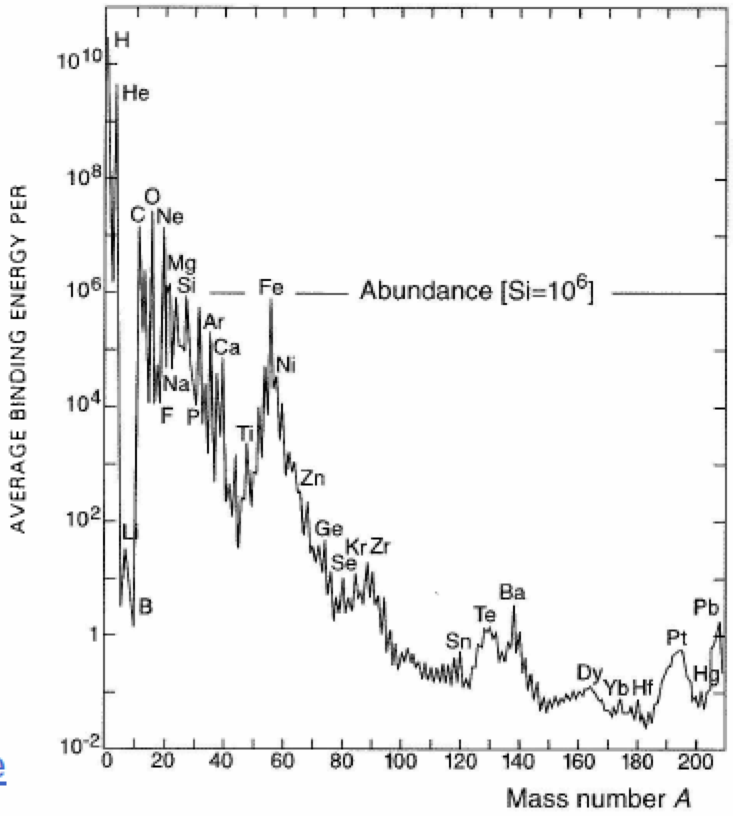
1.6 Experimental investigation of the rp-process

- β-decay rates
- masses (proton separation energies)
- (p,γ) and (α,p) reaction rates

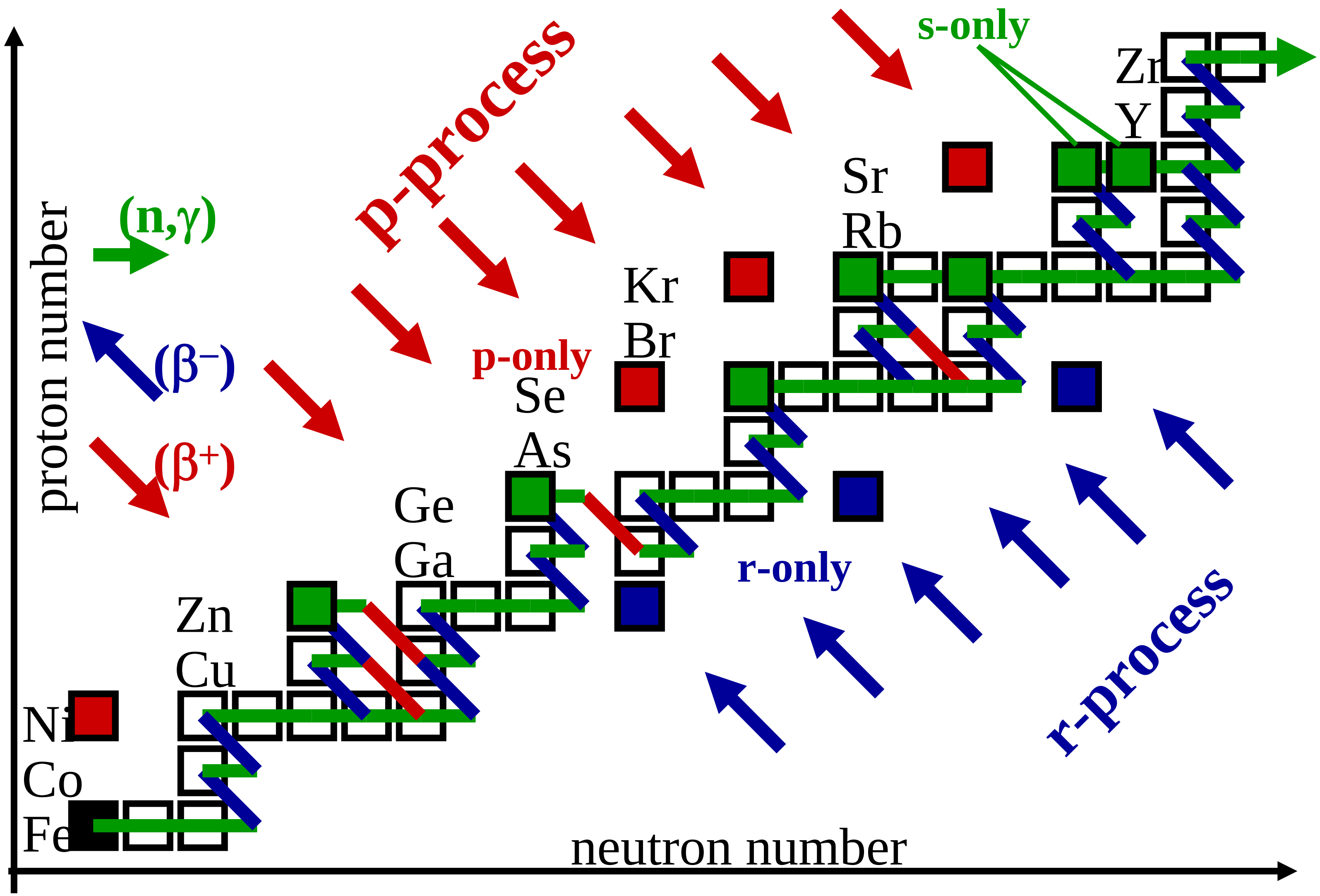


The neutron capture processes

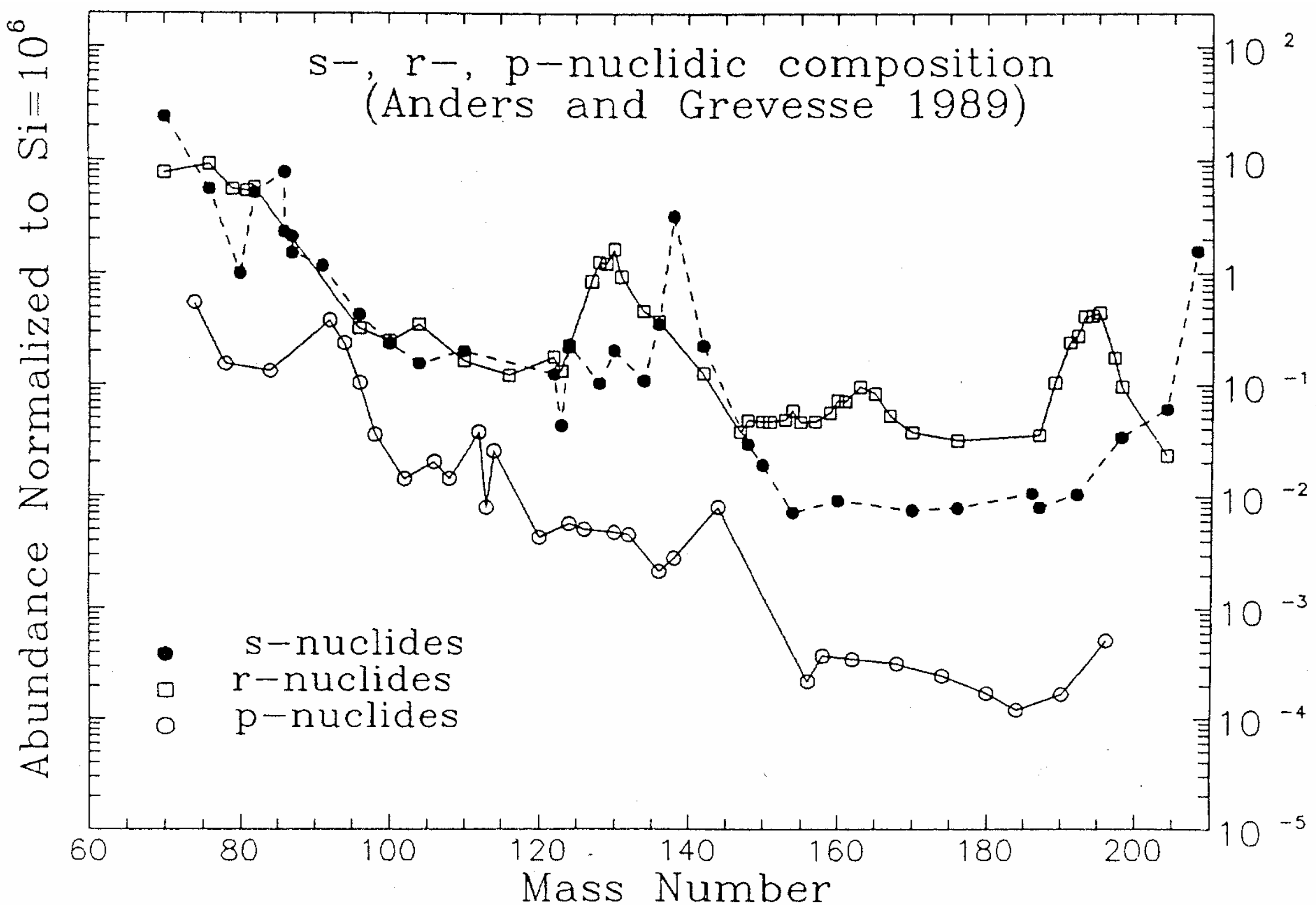
- exponential abundance decrease up to Fe
  ⇔ exponential decrease in tunnelling probability for charged-particle reactions
- almost constant abundances beyond Fe
  ⇔ non-charged-particle reactions
- binding energy curve ⇔ fusion reactions beyond iron are endothermic
- characteristic abundance peaks at magic neutron numbers
- neutron capture cross sections for heavy elements increasingly larger
- large neutron fluxes can be made available during certain stellar stages



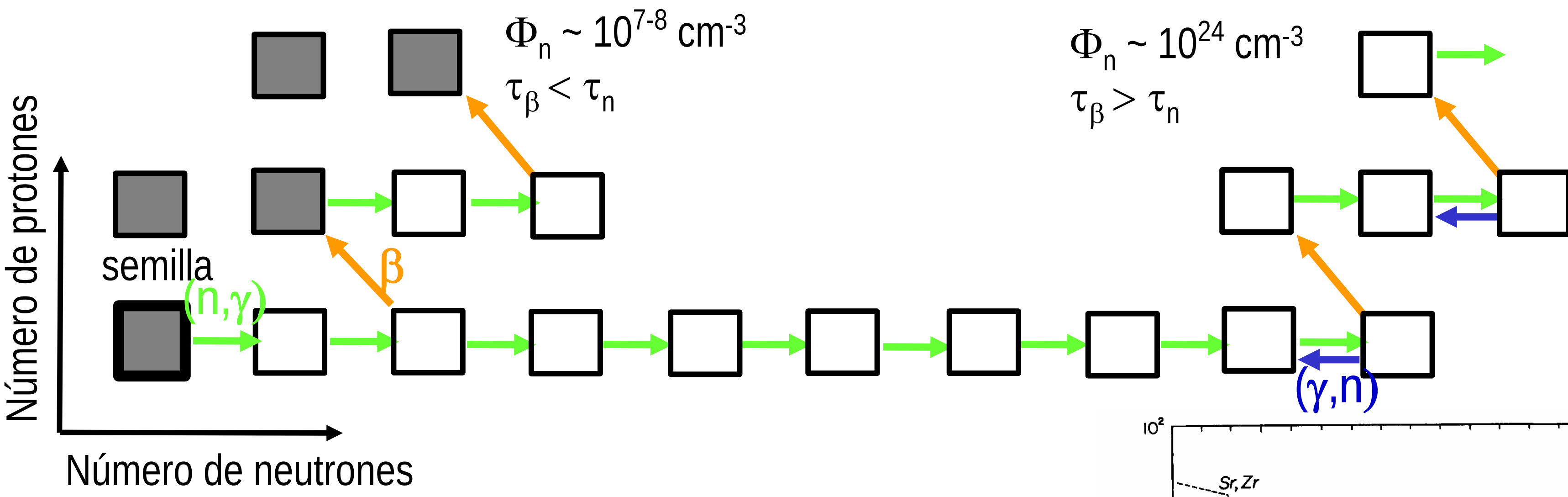
The neutron capture processes



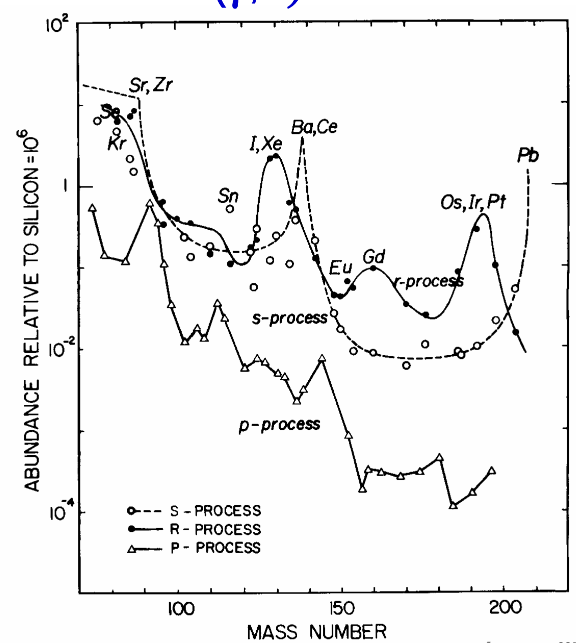
The neutron capture processes



The neutron capture processes



proceso	condiciones	escala	escenario
proceso s captura de n	T ~ 0.1 GK τ_n~ 1-10^3 a, Φ_n~$10^{7\text{-}8}$cm^{-3}	~ 1-$10^{5\text{-}6}$ a	estrellas AGB
proceso r captura de n	T ~ 1-2 GK τ_n~ μs, Φ_n~$10^{24\text{-}26}$cm^{-3}	< 1 s	supernovas II estre. neutrones
proceso p captura de p	T ~ 2-3 GK	~ 1 s	supernovas II



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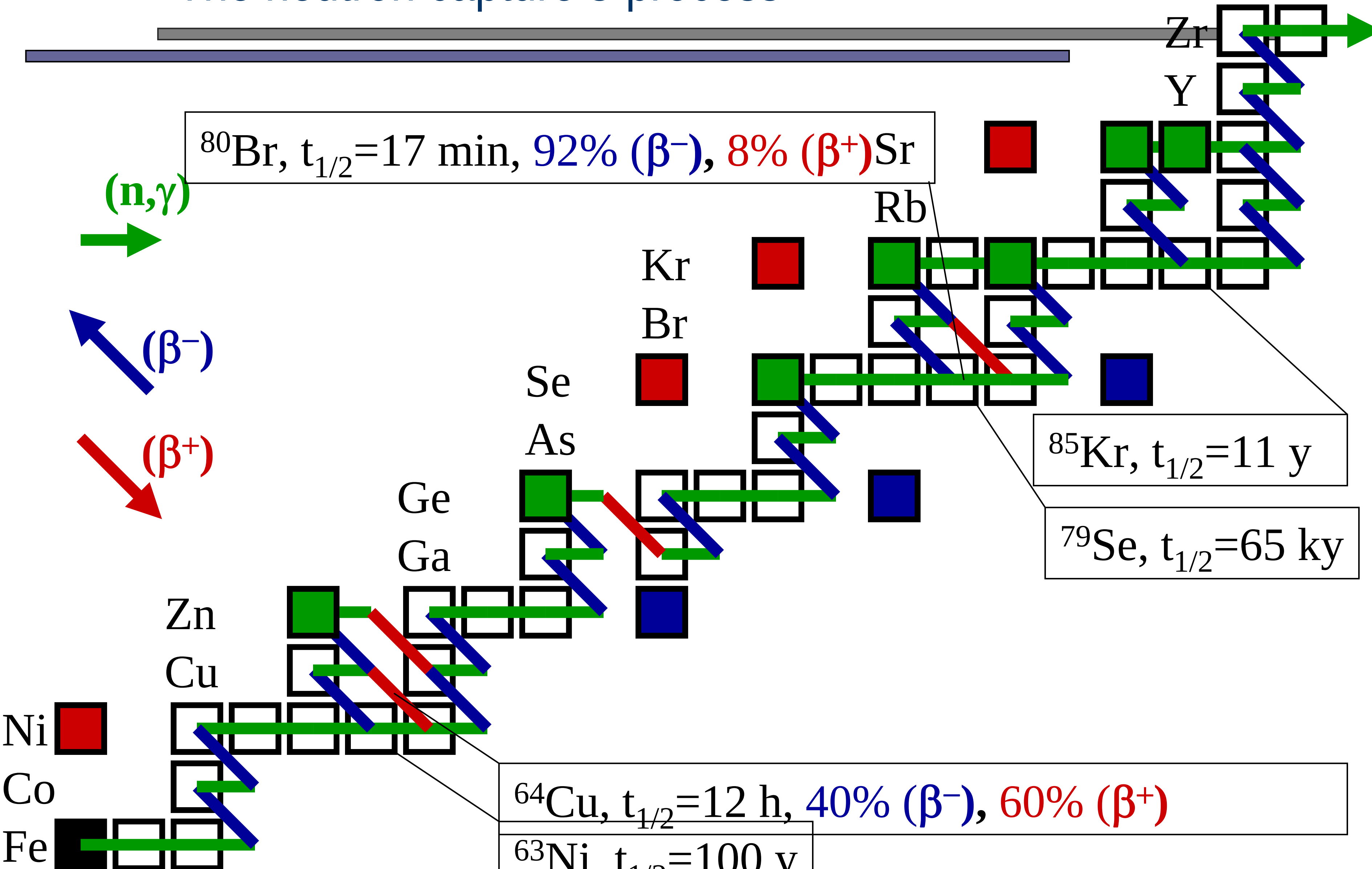
The neutron capture s-process

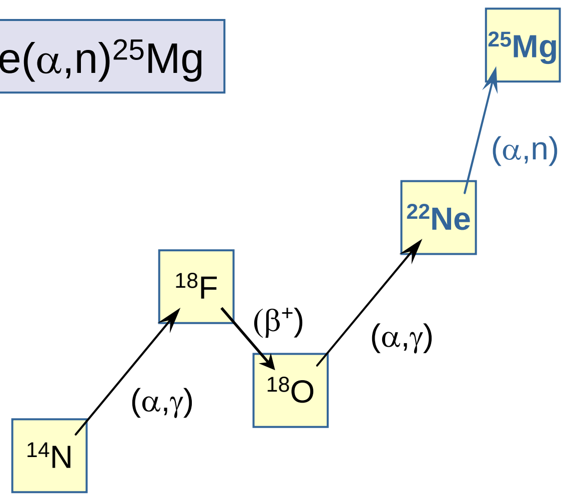


The neutron capture s-process

free neutrons are unstable $\Rightarrow$ they must be produced in situ

most likely candidates as neutron source are:

$^{22}Ne(\alpha,n)^{25}Mg$

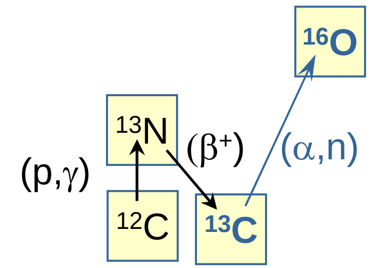


astrophysical site:

core He burning (and shell C-burning) in massive stars (e.g. 25 solar masses)
$T_8 \sim 2.2 - 3.5$

contribution to weak s-process

$^{13}C(\alpha,n)^{16}O$



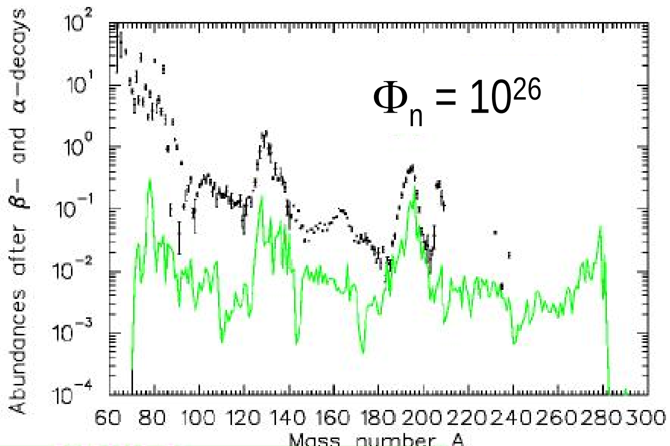
astrophysical site:

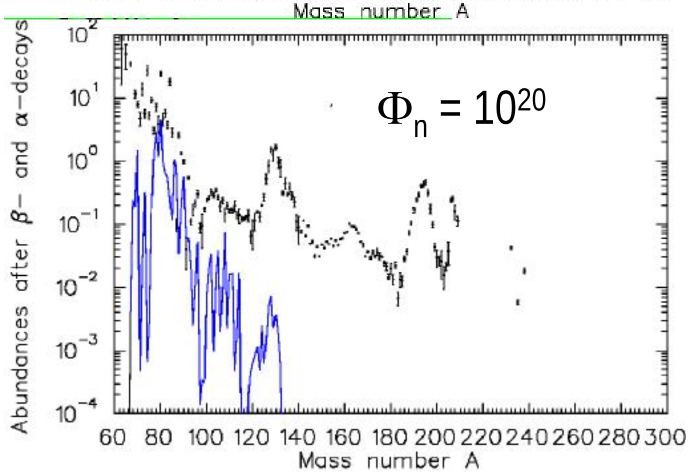
He-flashes followed by H mixing into ^{12}C enriched zones
low-mass (1.5 - 3 M_{sun}) TP-AGB stars
$T_8 \sim 0.9 - 2.7$

contribution to main s-process

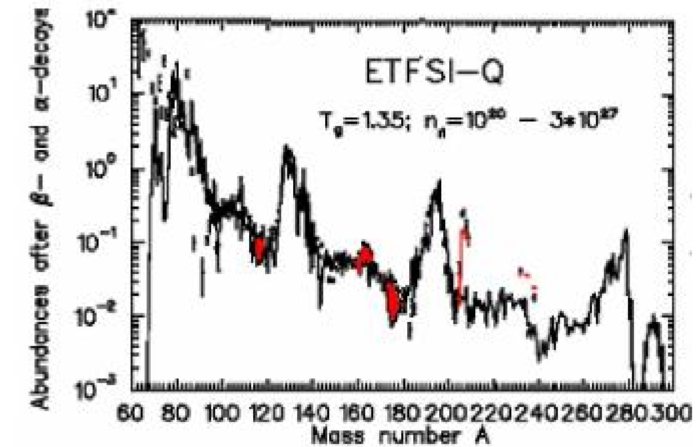
Modelos del proceso r

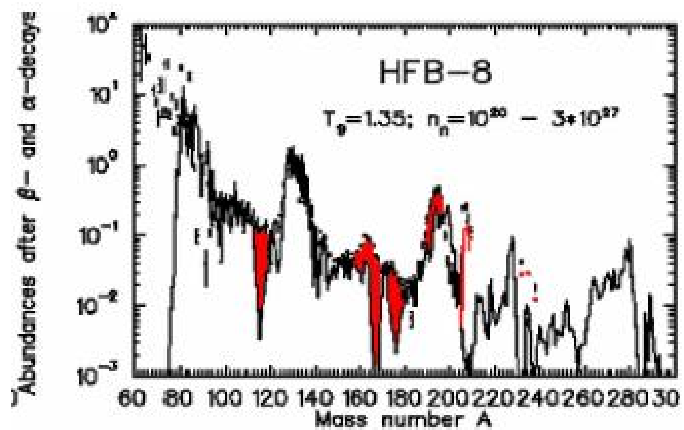
Modelos independientes del escenario: estáticos o dinámicos





- ✓ $\Phi_n > 10^{23}$ cm^{-3}
- ✓ T~10^9 K
- ✓ Tiempo de irradiación
- ✓ Semilla inicial
- ✓ Entropía
- ✓ Tiempo de expansión
- ✓ Física nuclear





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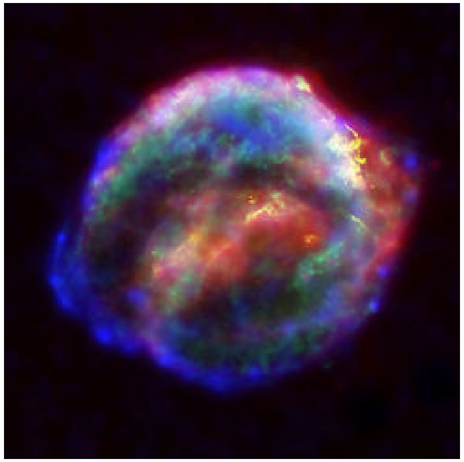
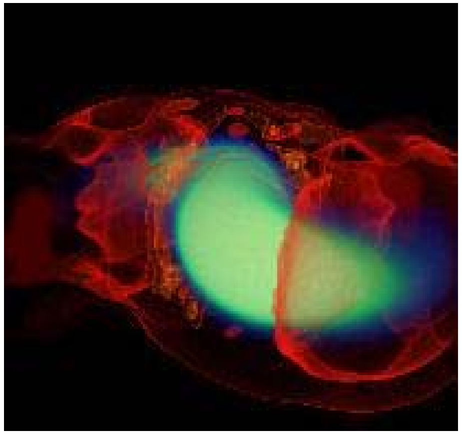
Escenarios astrofísicos del proceso r

Modelos hidrodinámicos de evolución estelar

Supernova tipo II

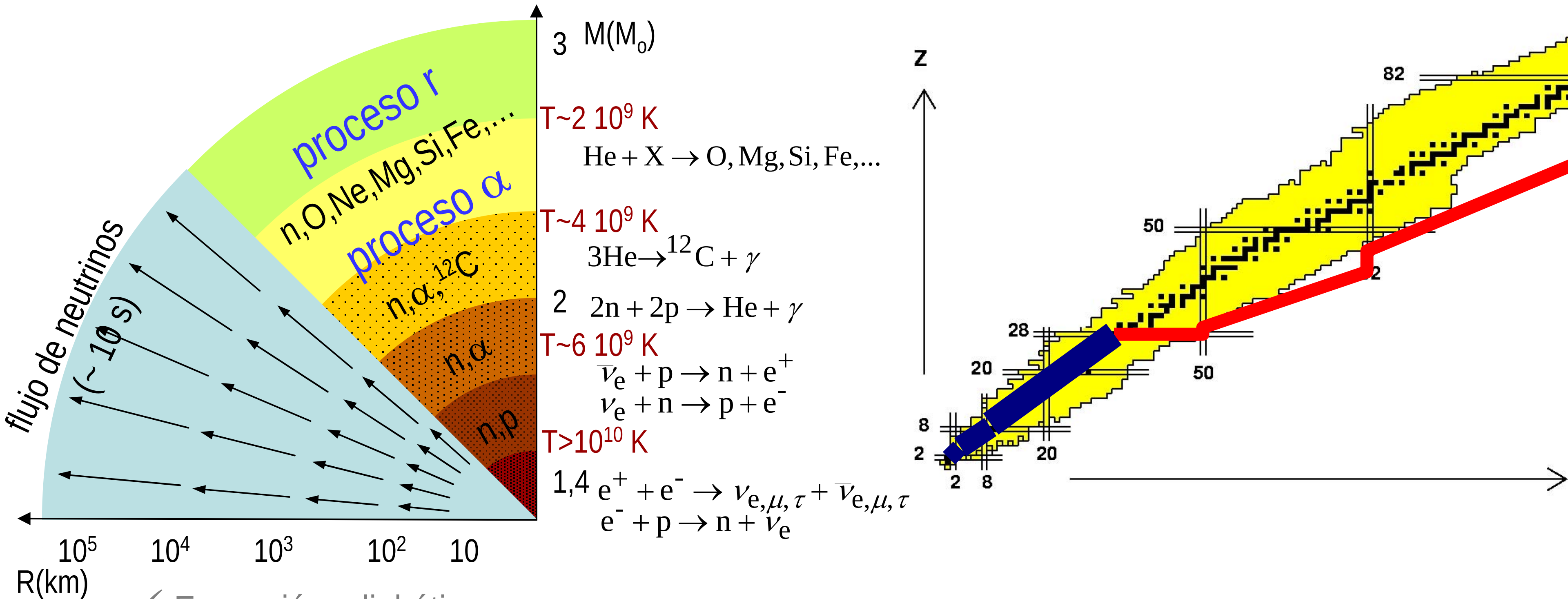


Colapso de un sistema binario de estrellas de neutrones



	Colapso de E.N:	Supernovas II
Frecuen./año y galaxia	$10^{-5} – 10^{-4}$	$2.2\ 10^{-2}$
Masa ejectada (M_o)	$4\ 10^{-3} – 4\ 10^{-2}$	$10^{-6} – 10^{-5}$

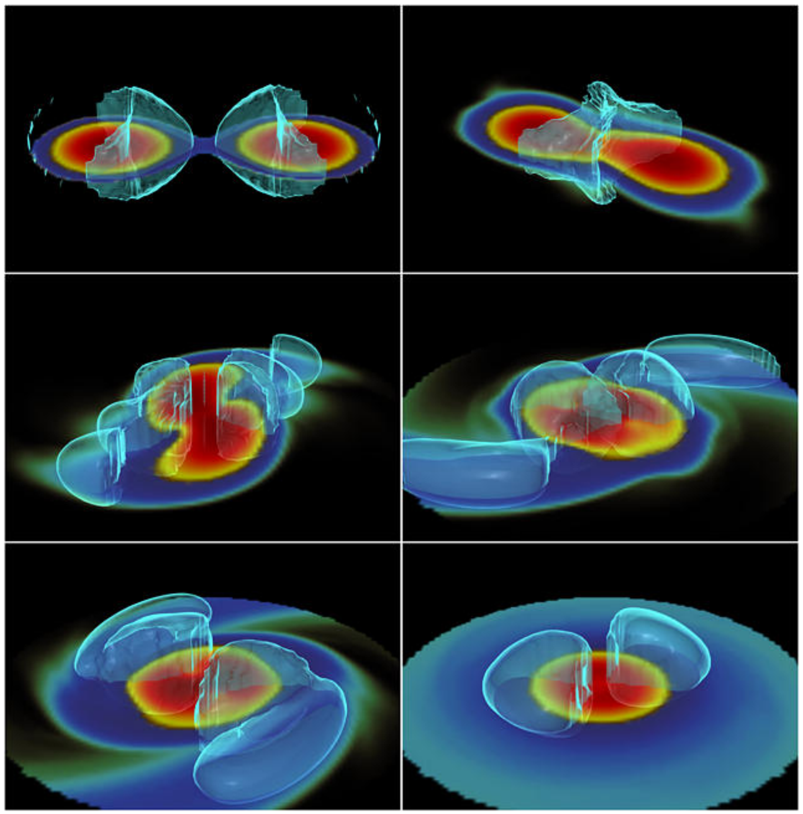
El proceso r en explosiones de supernovas

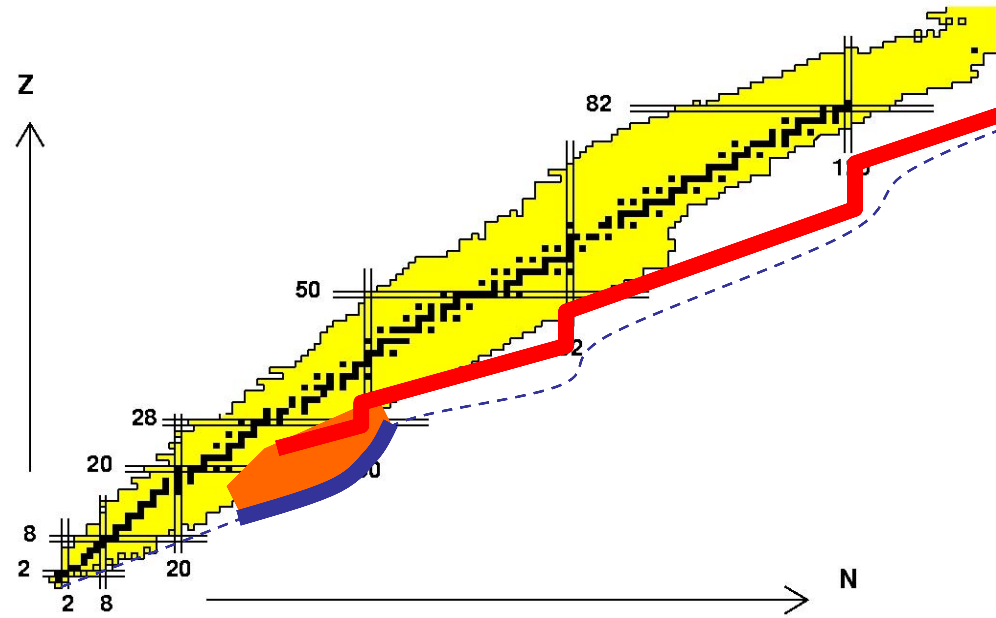


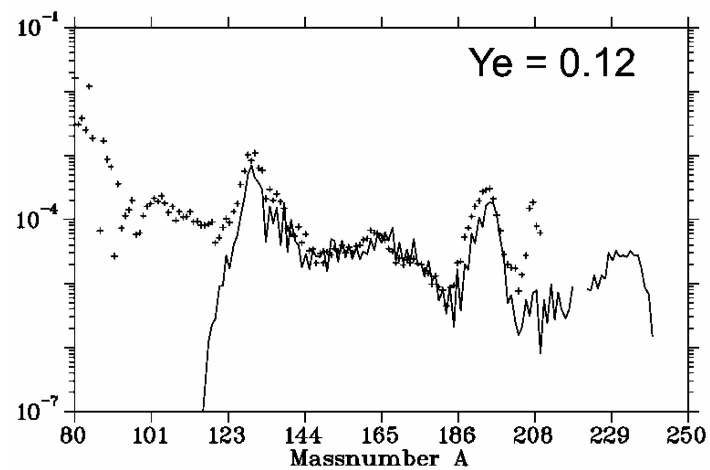
- ✓ Expansión adiabática
- ✓ Alta entropía
- ✓ Equilibrio nuclear
- ✓ Abundancia de neutrones

El proceso r en estrellas de neutrones

Colapso de un sistema binario de estrellas de neutrones

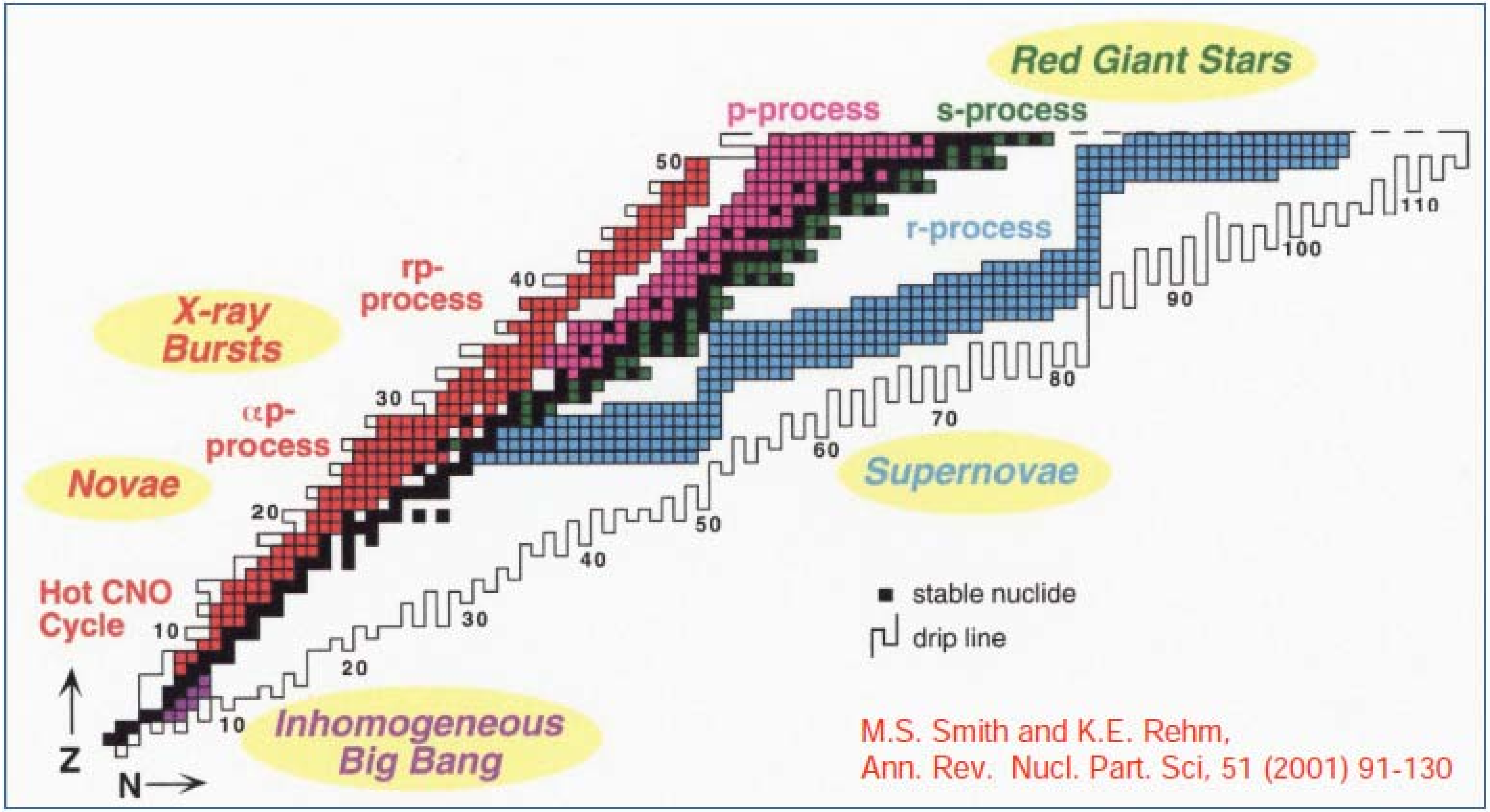






- ✓ Baja entropía
- ✓ Abundancia de neutrones

Overview on the nucleosynthesis process



Overview on the nucleosynthesis process