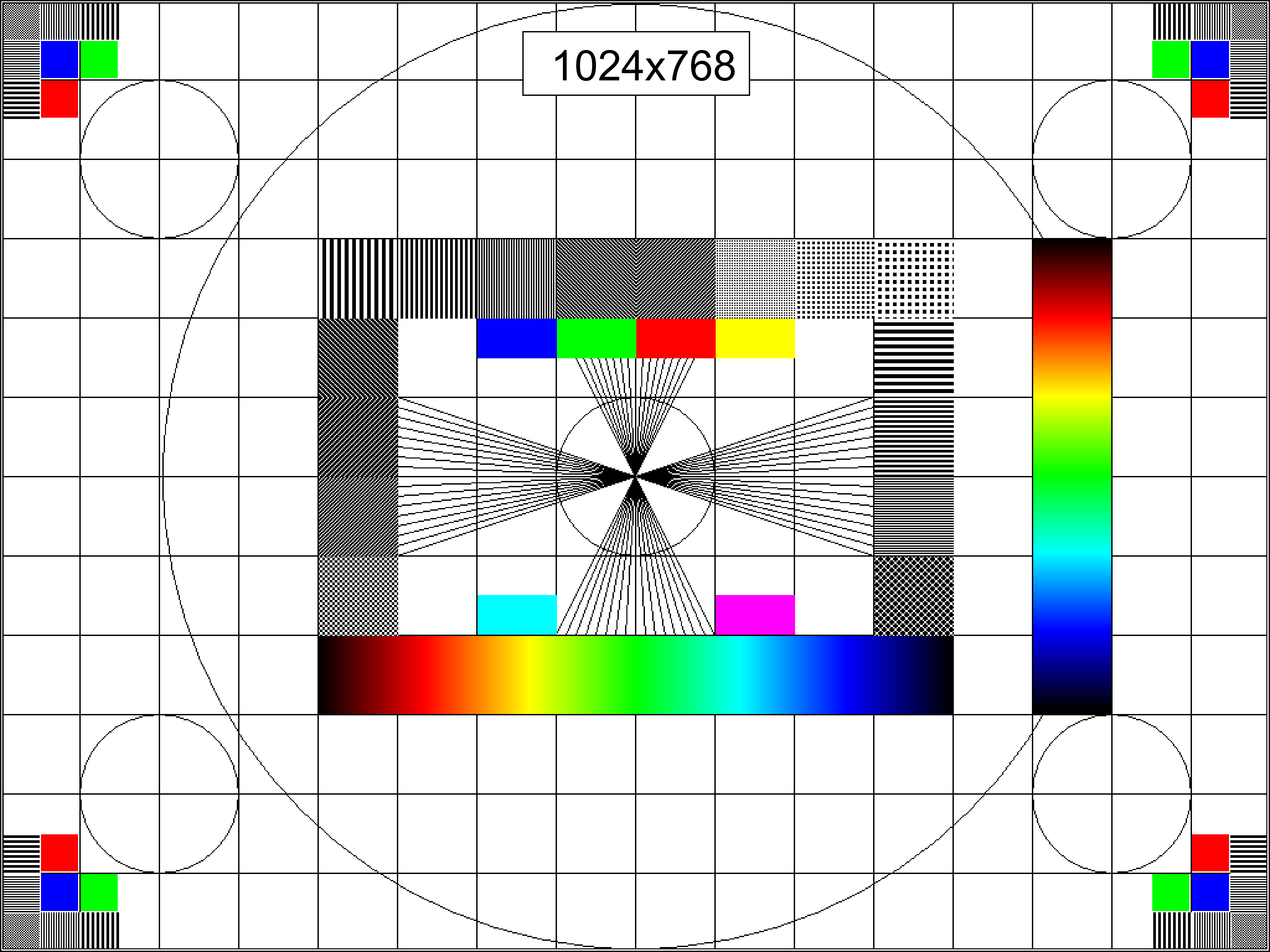
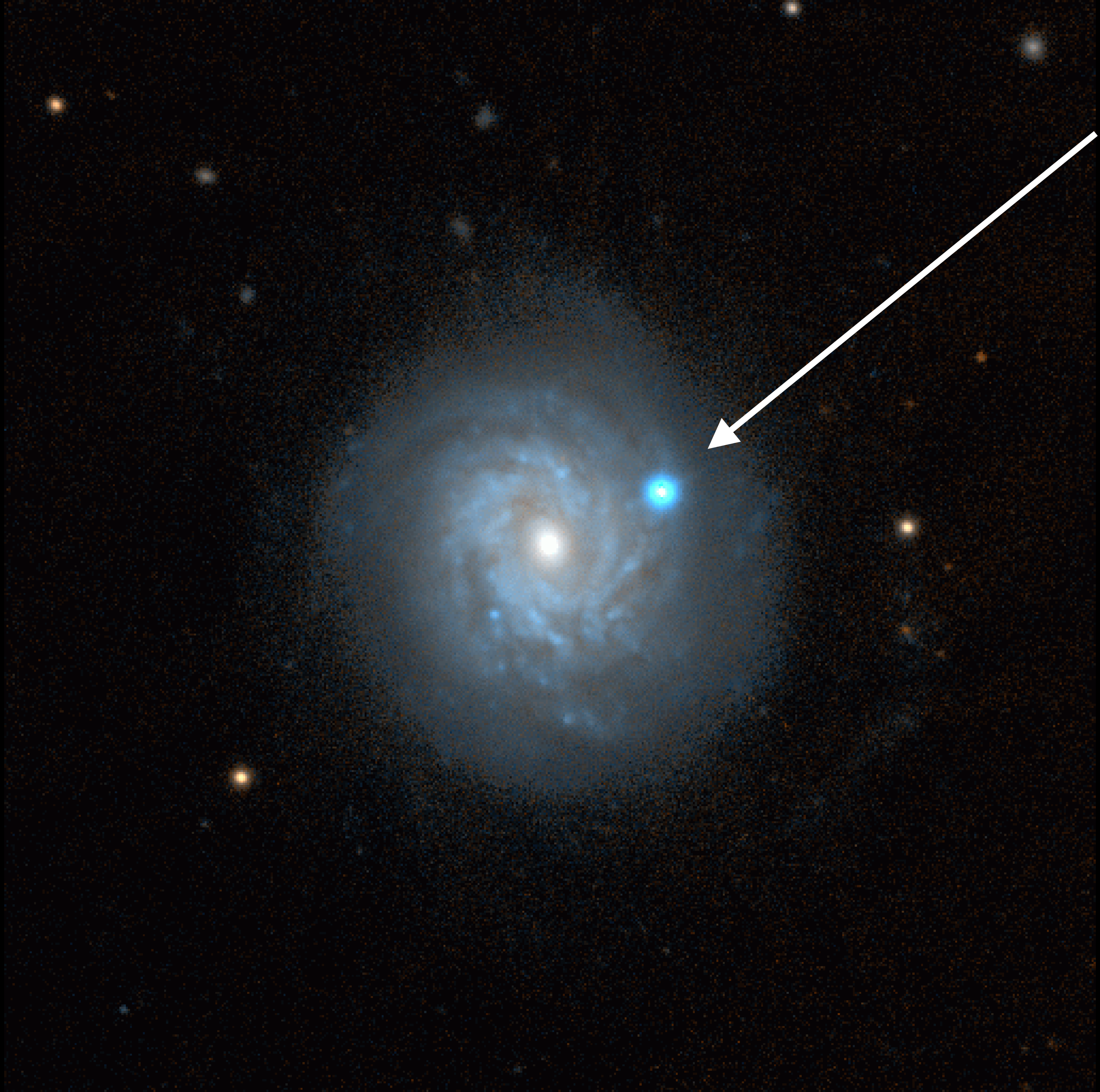
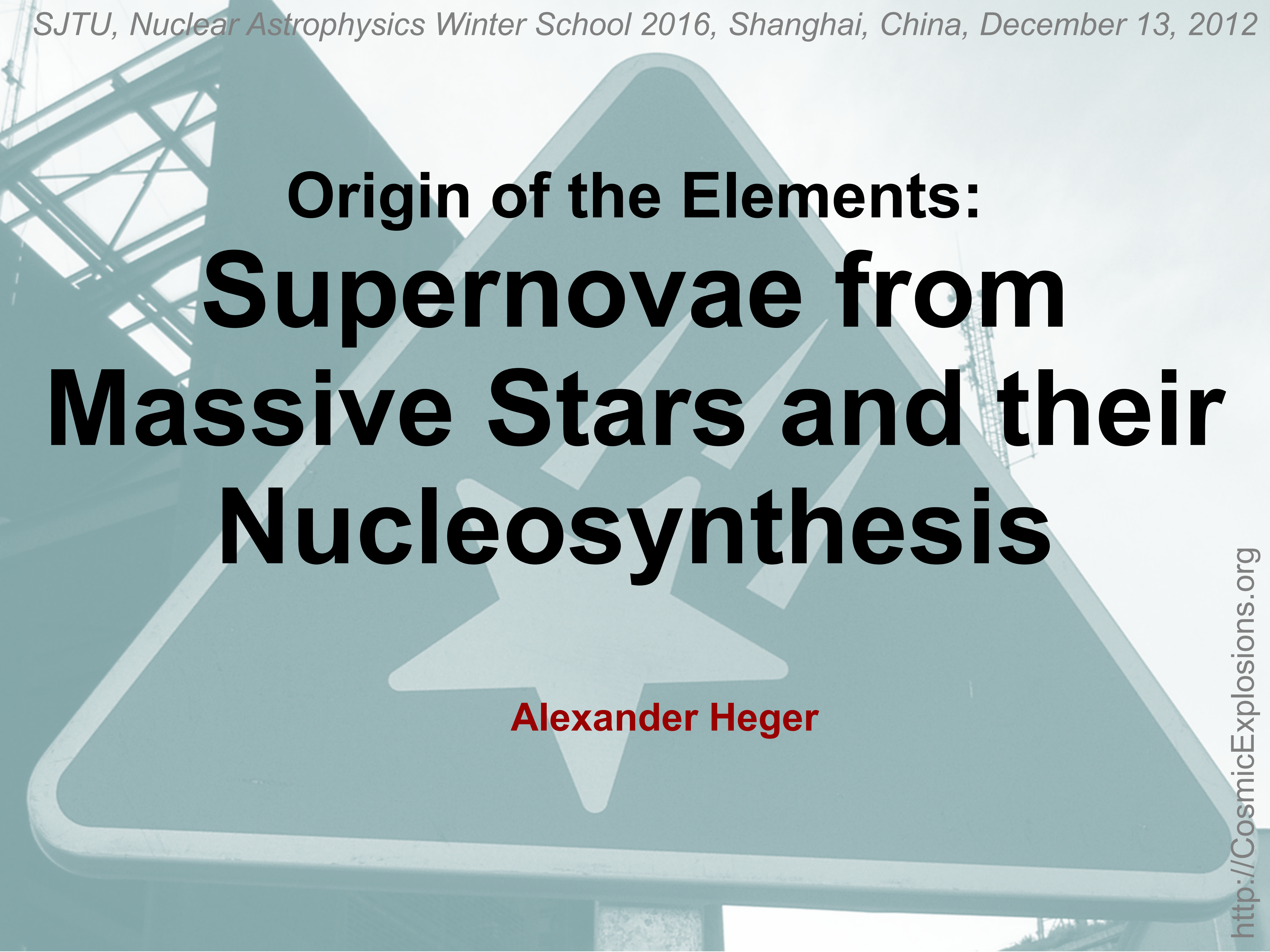

1024x768



NGC3982



Origin of the Elements:

Supernovae from Massive Stars and their Nucleosynthesis

Alexander Heger

http://CosmicExplosions.org

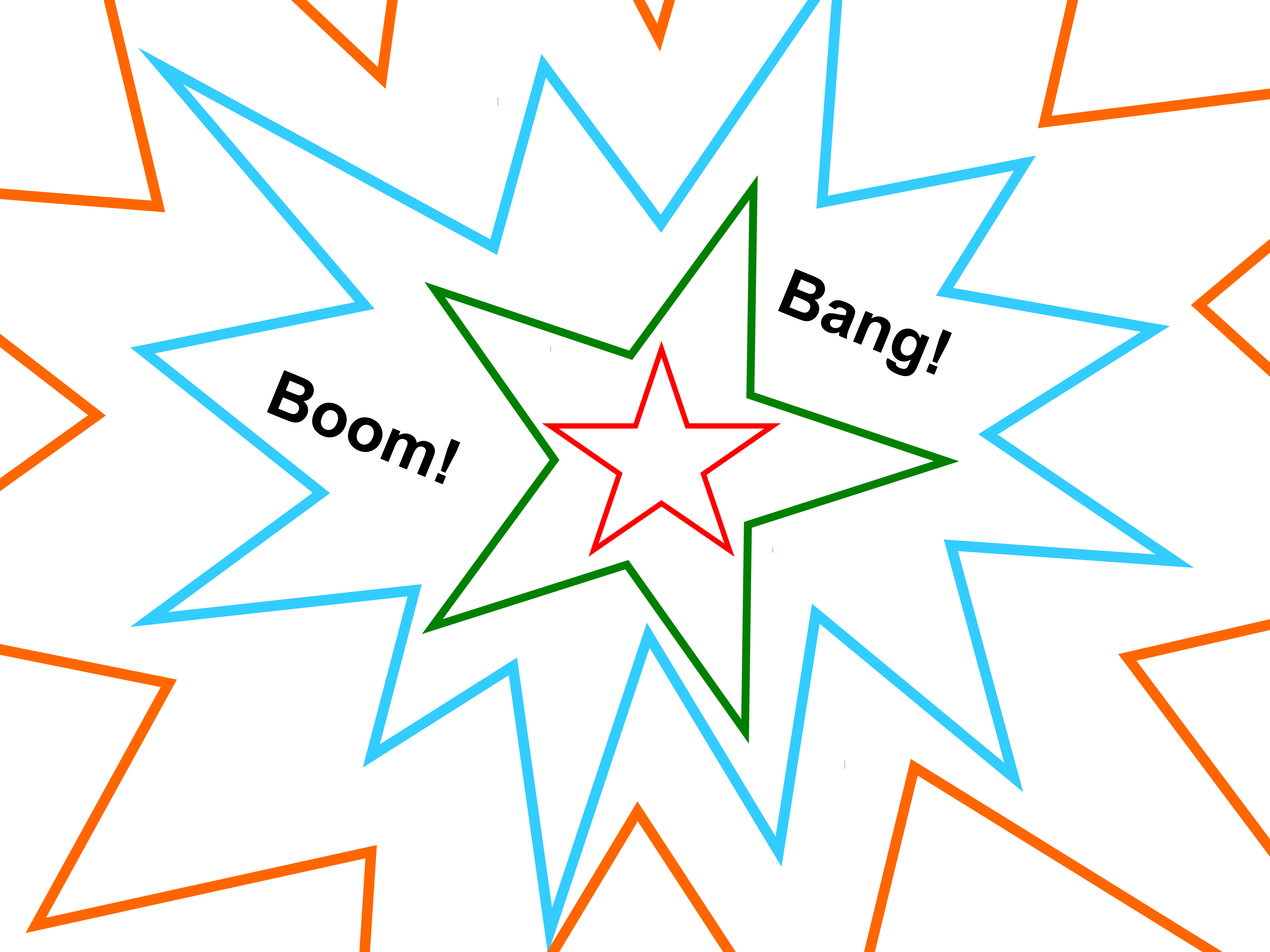
Overview

- Nucleosynthesis in Supernova
- Varieties of Stellar Deaths

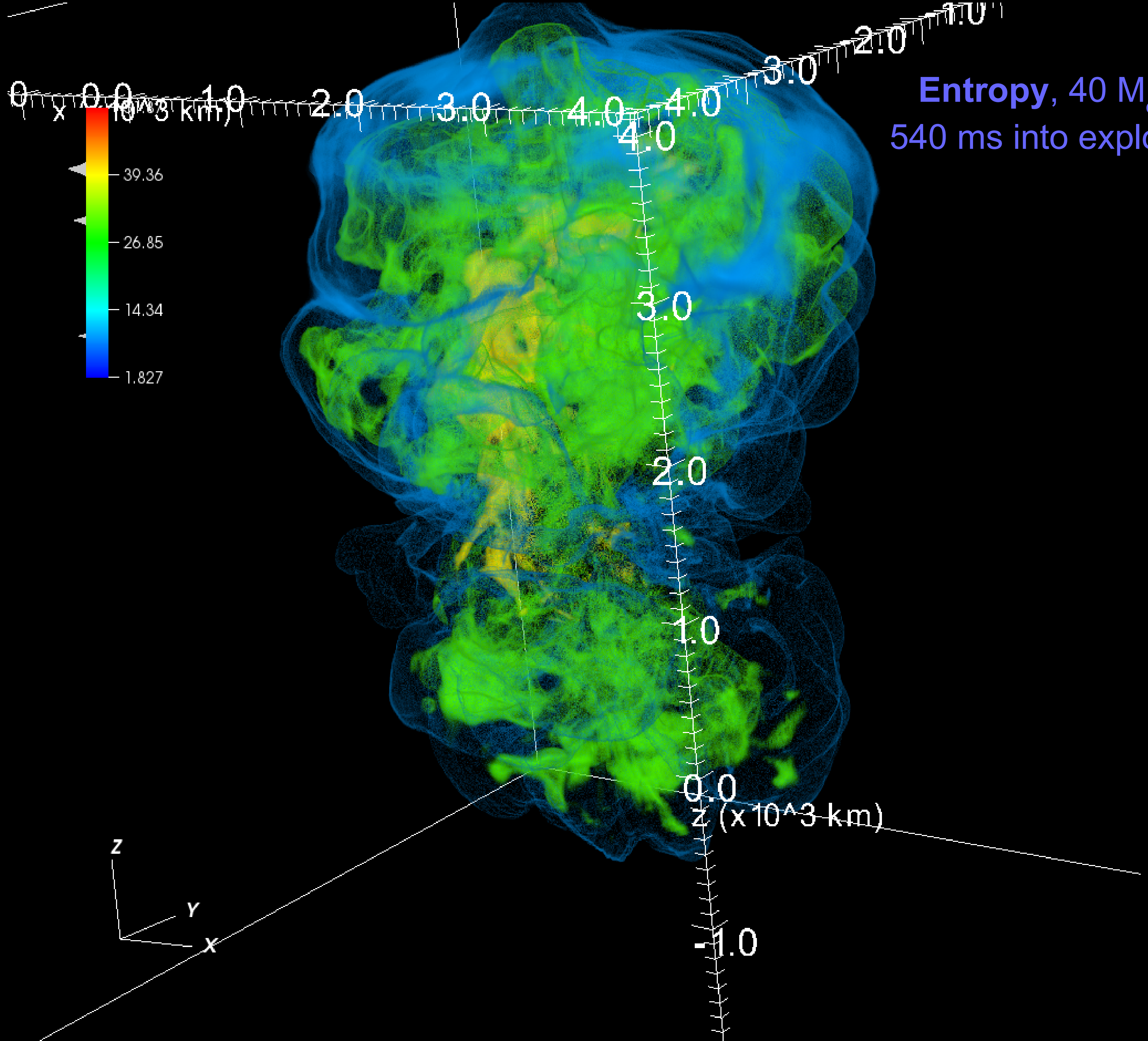
A First Look

Core Collapse Supernovae

(Massive Stars, Pop I)

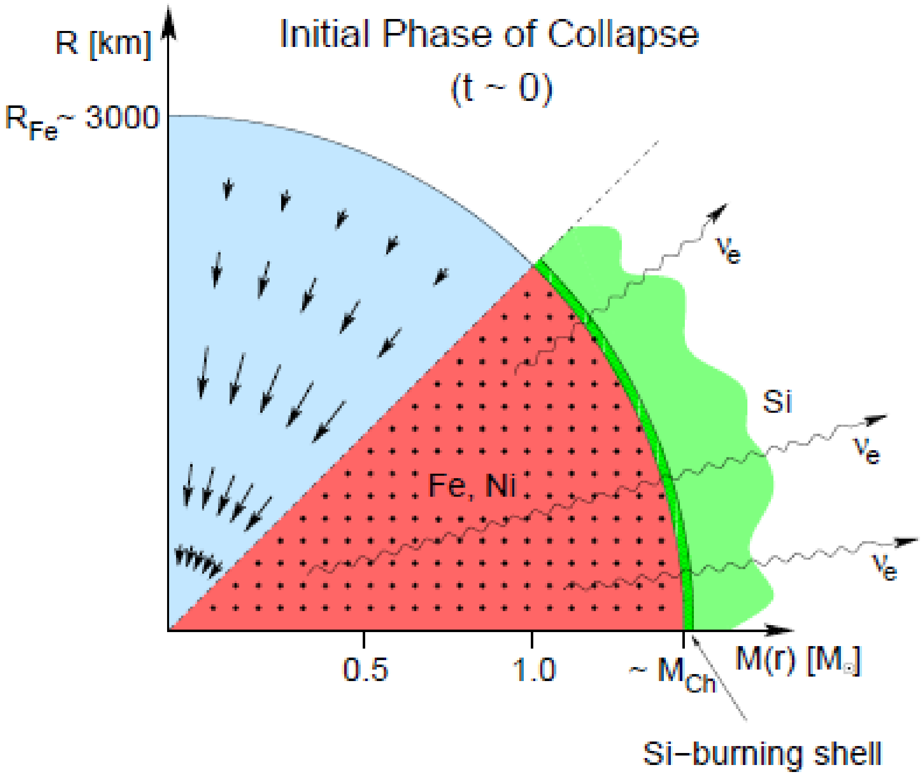

Boom!
Bang!

Entropy, 40 M_o star
540 ms into explosion



Mueller, Chan, Heger 2016 in prep.

Iron Core Collapse



- Iron core supported by degeneracy pressure of relativistic electrons:

$$P = K(\rho Y_e)^{4/3}$$

$$Y_e : \text{electrons per nucleon}$$

- Polytrope! → Lecture 5
- Maximum mass:

$$M_{Ch} \approx 5.84\, M_\odot\, Y_e^2$$

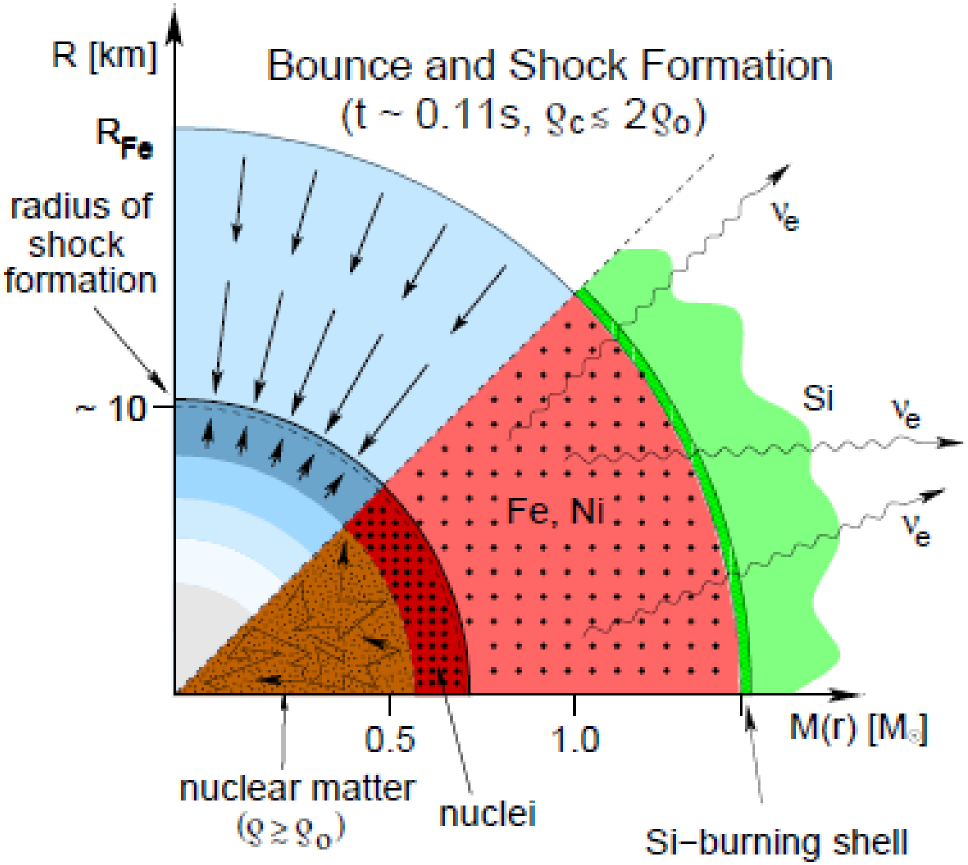
- Core must contract, density and temperature go up, then:

$$e^- + \underbrace{A}_{nucleus} \rightarrow A' + \nu_e$$

$$\gamma + A \rightarrow x\alpha \rightarrow y\,n + z\,p$$

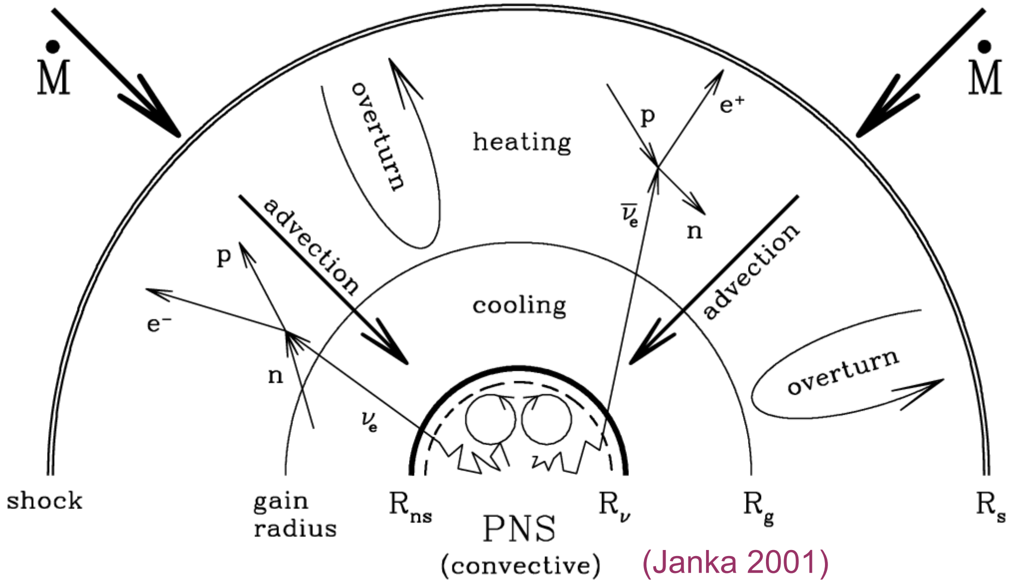
Pressure drain → collapse!

From Collapse to Explosion

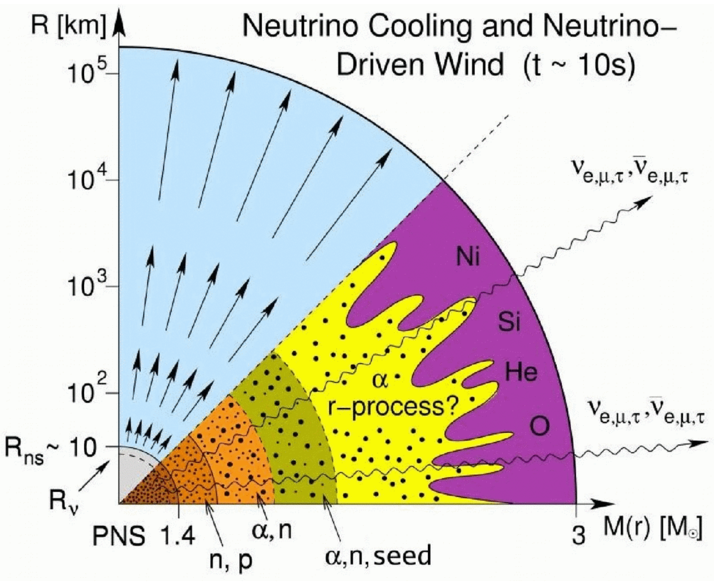


- Nuclear forces become repulsive above $\sim 1.7\times10^{14}$g/cm^3.
- Collapse of inner core is stopped → neutron star born.
- Rebounding neutron star crashes into outer shells, launches shock wave.
- Does the shock wave expel the envelope?
- No. Shock dies. Other mechanism have to do!

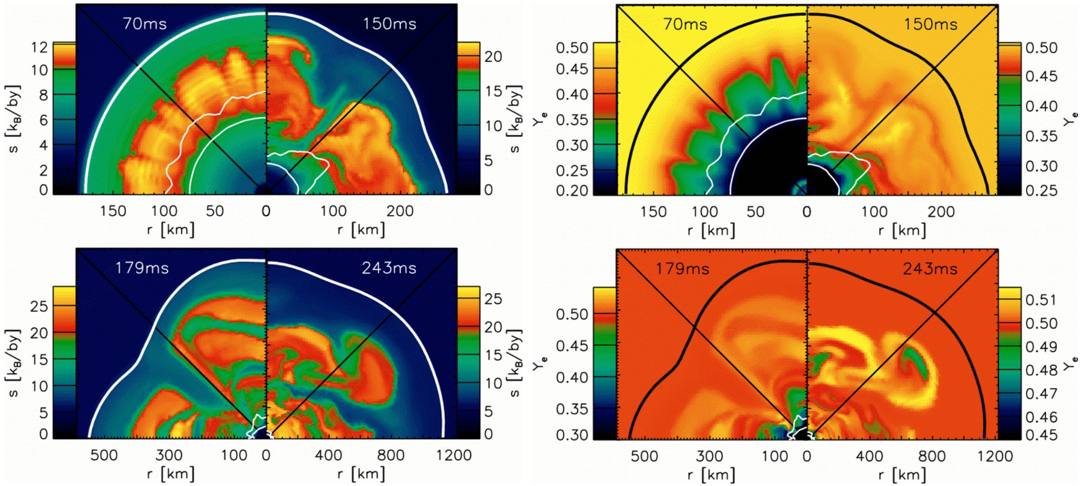
Core Collapse Supernovae



(Janka 2001)



(Woosley & Janka 2006)



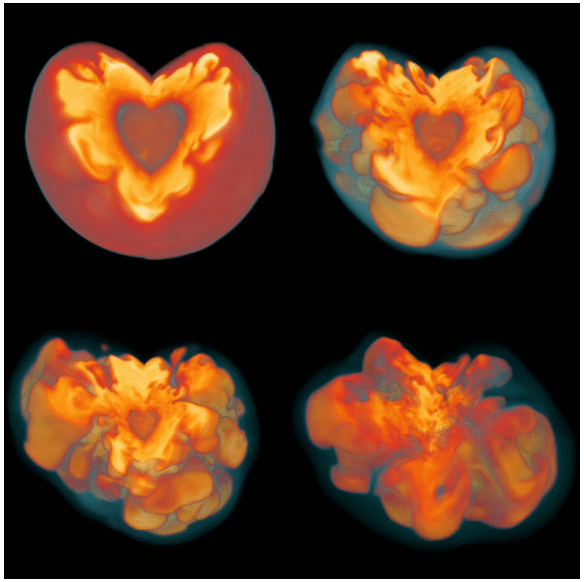
(Buras *et al.* 2006)

←Entropy and electron per baryon (Y_e) at different time snapshots in a core collapse supernova

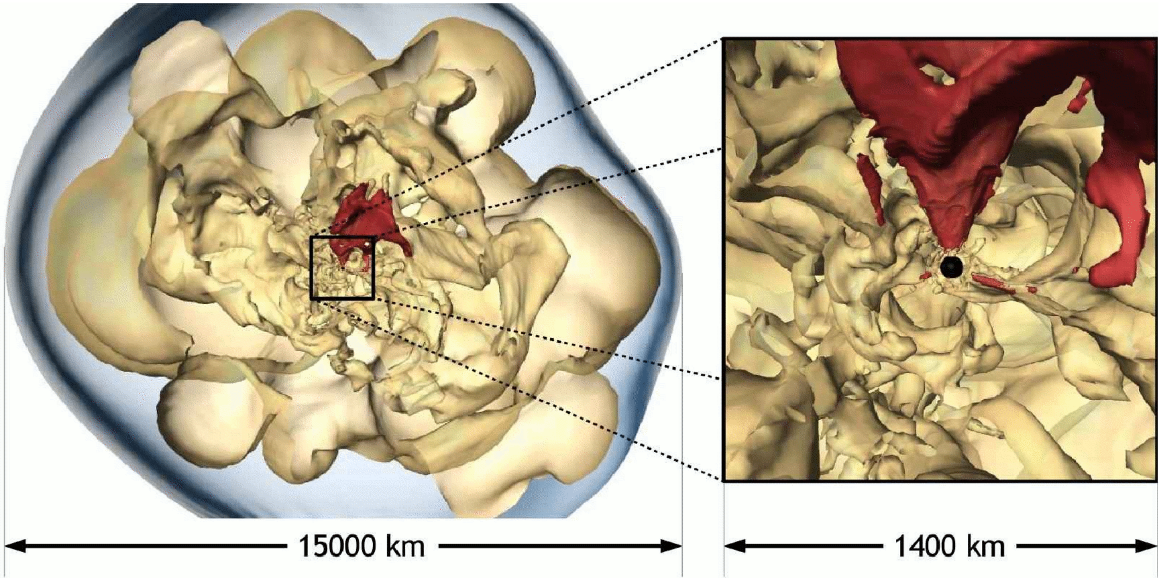
(simulation: equatorial band)

Core Collapse Supernovae – 3D

Cold inflow and **hot outflow** in 3D simulations ➔ similar to dipolar flow pattern observed in 2D rotationally symmetric simulations



(Scheck, Janka, *et al.* 2006)

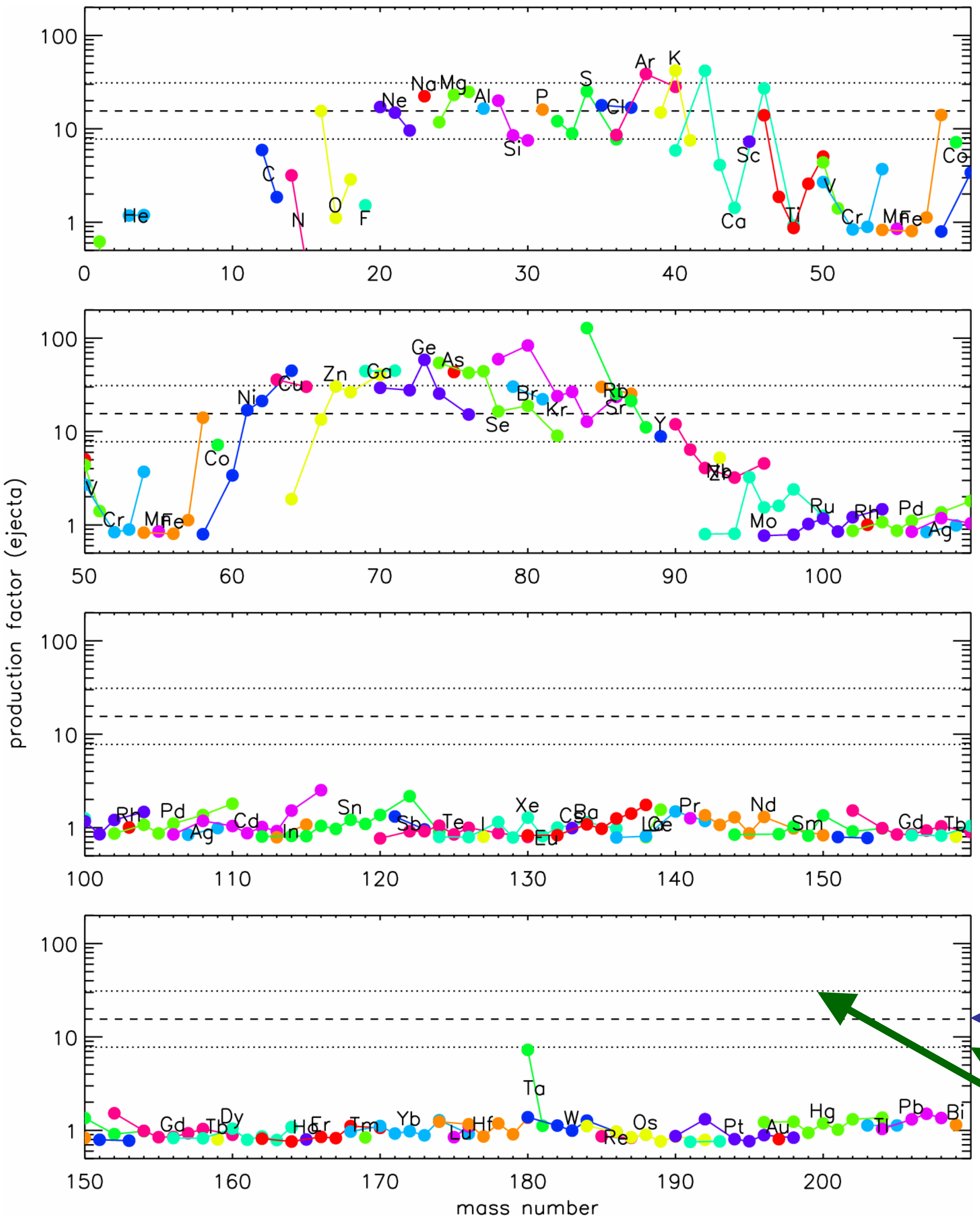


(Janka *et al.* 2005)

A First Look

Supernovae & Nucleosynthesis

(Massive Stars, Pop I)



25 $M_\odot$ star

Presupernova production factors relative to solar composition

“band of acceptable co-production” defined by

^{16}O production

(± a factor 2)

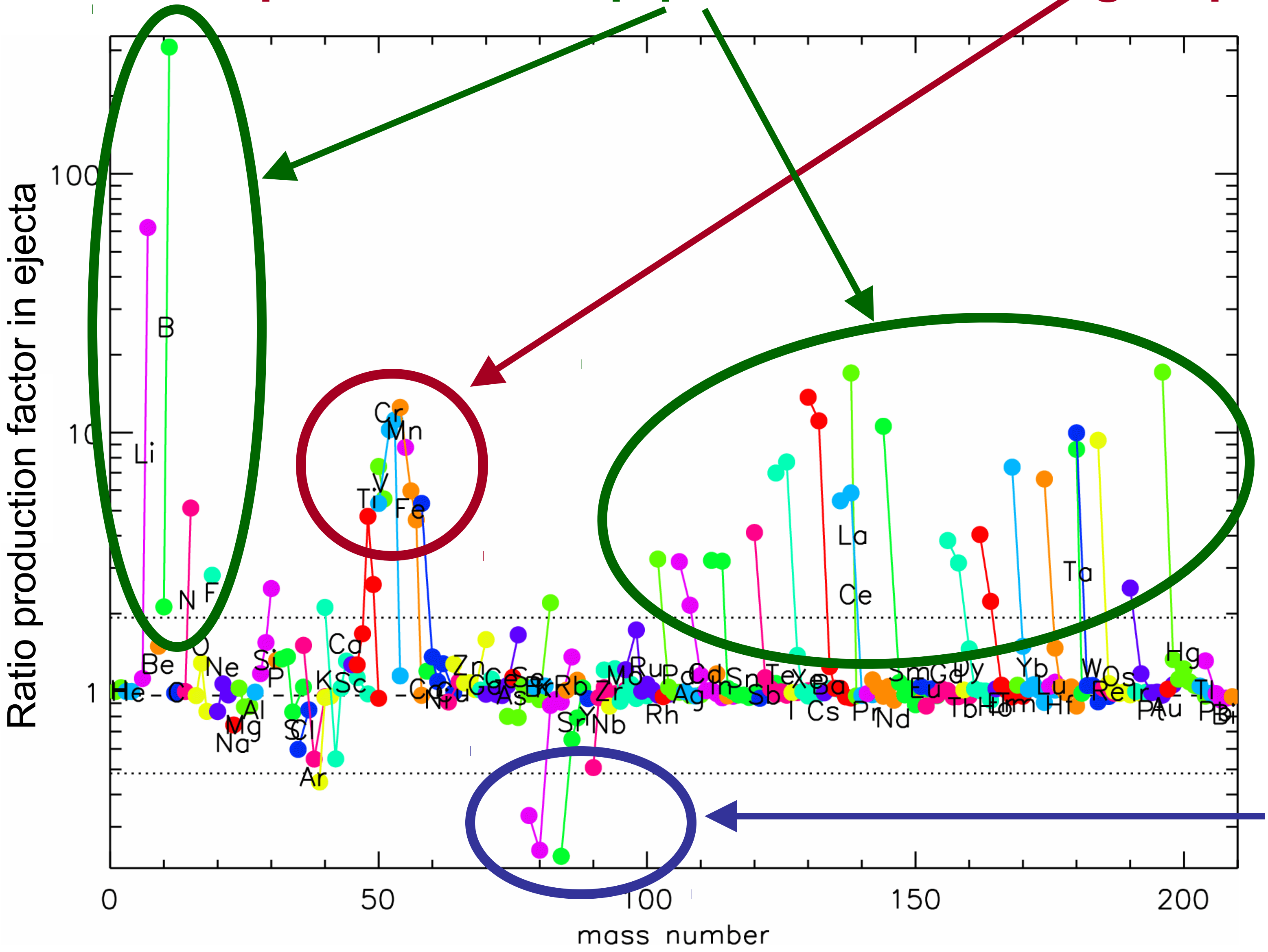
Explosive Nucleosynthesis

in supernovae from massive stars

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (s)	Main Reaction
Innermost ejecta	*r*-process ν*p*-process	-	>10?	1	(n,γ), β^-
Si, O	^{56}Ni	iron group	>4	0.1	(α,γ)
O	Si, S	Cl, Ar, K, Ca	3 - 4	1	$^{16}O + ^{16}O$
O, Ne	O, Mg, Ne	Na, Al, P	2 - 3	5	(γ,α)
		p-process ^{11}B, ^{19}F, ^{138}La, ^{180}Ta	2 - 3	5	(γ,n)
		ν-process		5	(ν, ν'), (ν, e^-)

Explosive Nucleosynthesis contribution

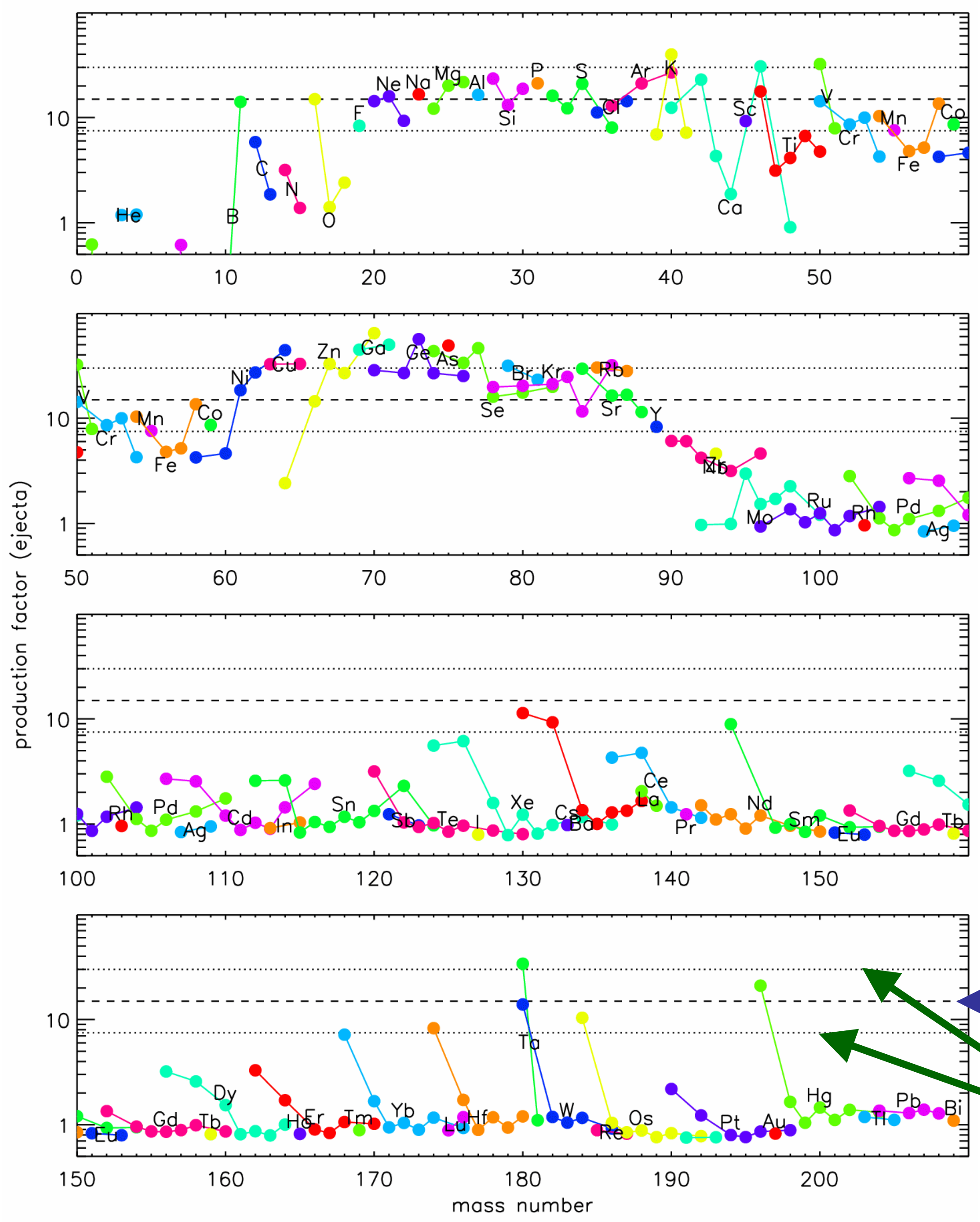
➔production of p-process and iron group



25 M_{o} star

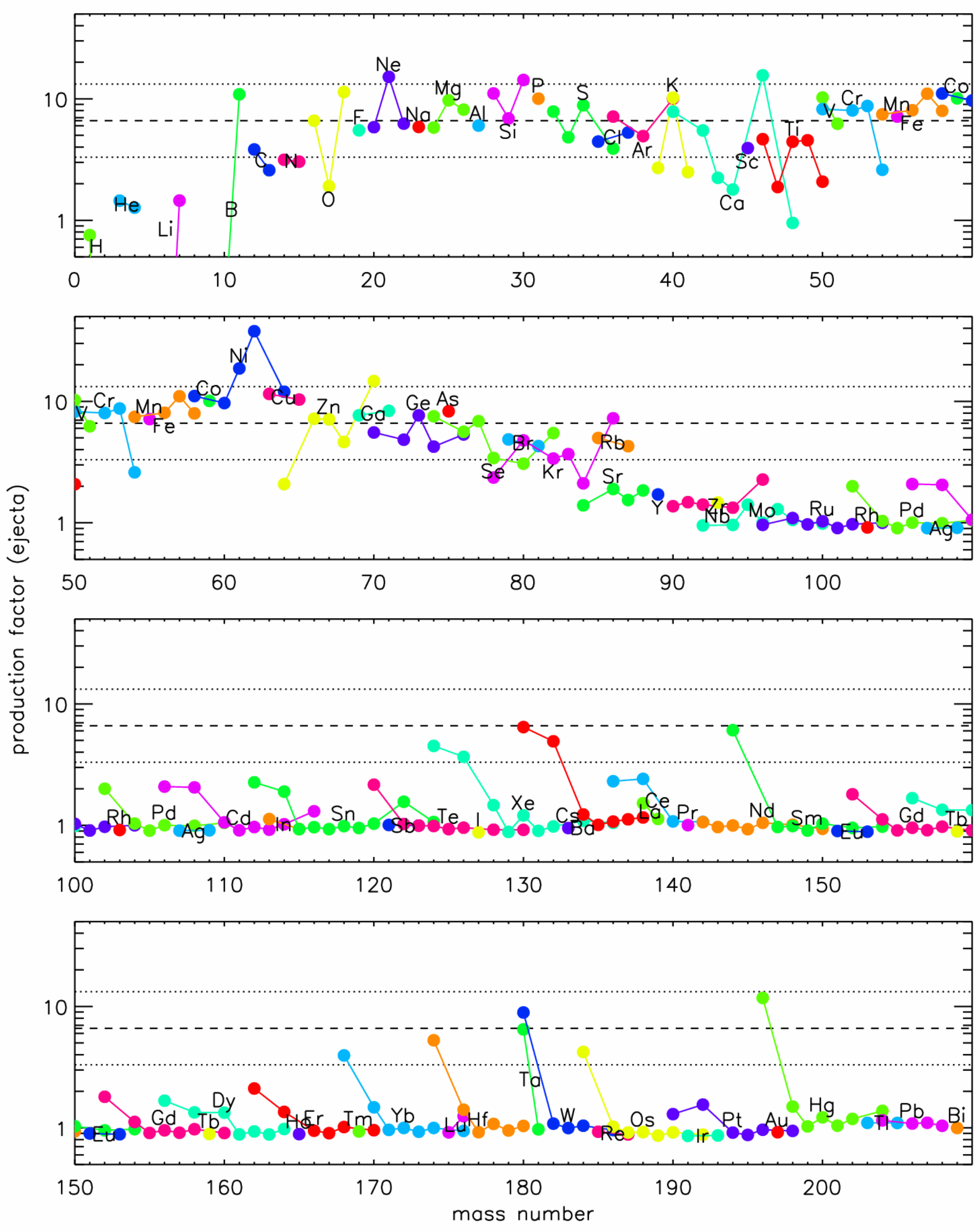
some destruction

25 $M_{\odot}$ star



Production factors relative to solar composition

“band of acceptable co-production” defined by ^{16}O production (± a factor 2)

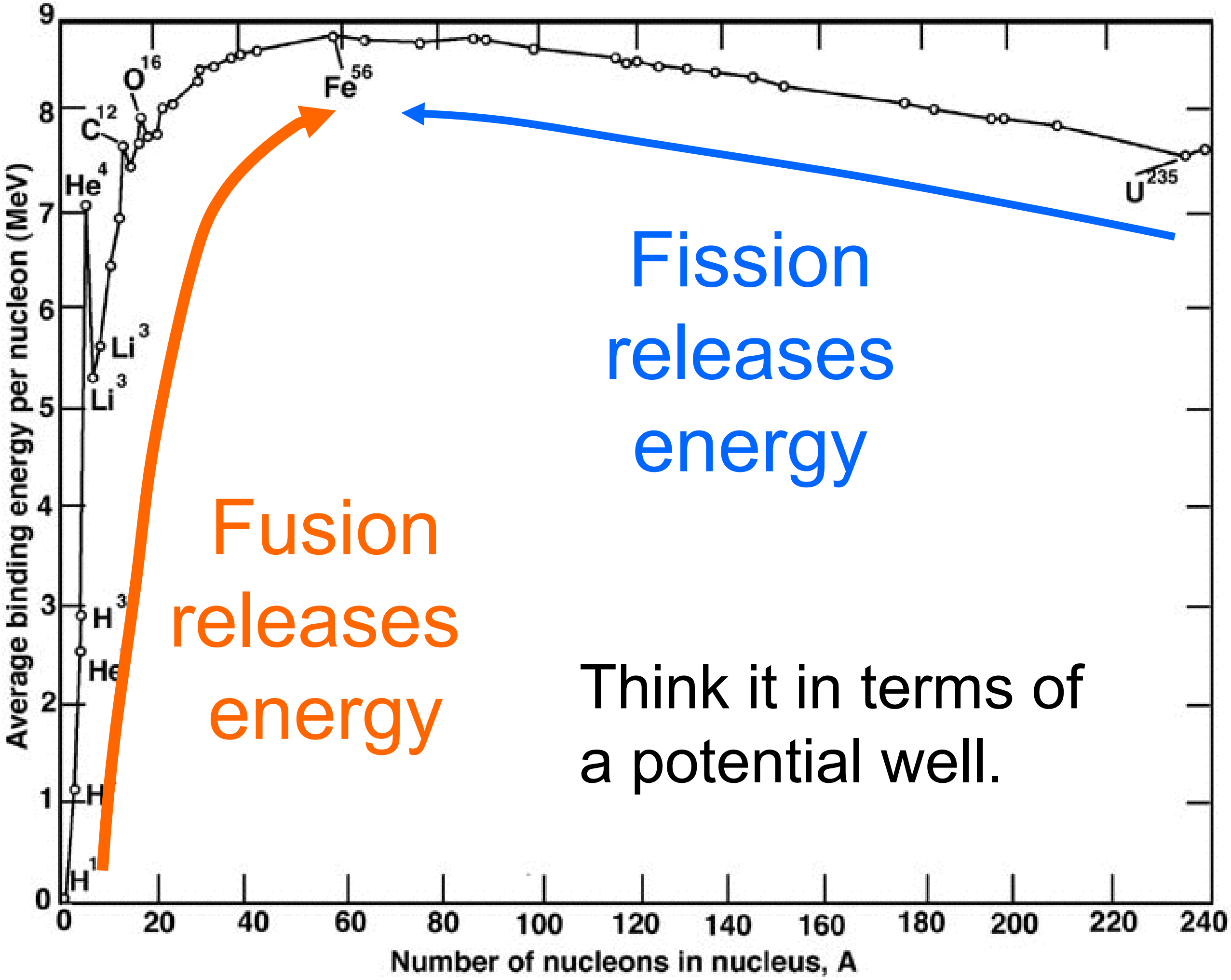


15 $M_\odot$ star

Production factors relative to solar composition

“band of acceptable co-production” defined by ^{16}O production (± a factor 2)

Binding Energy Curve



Fission releases energy

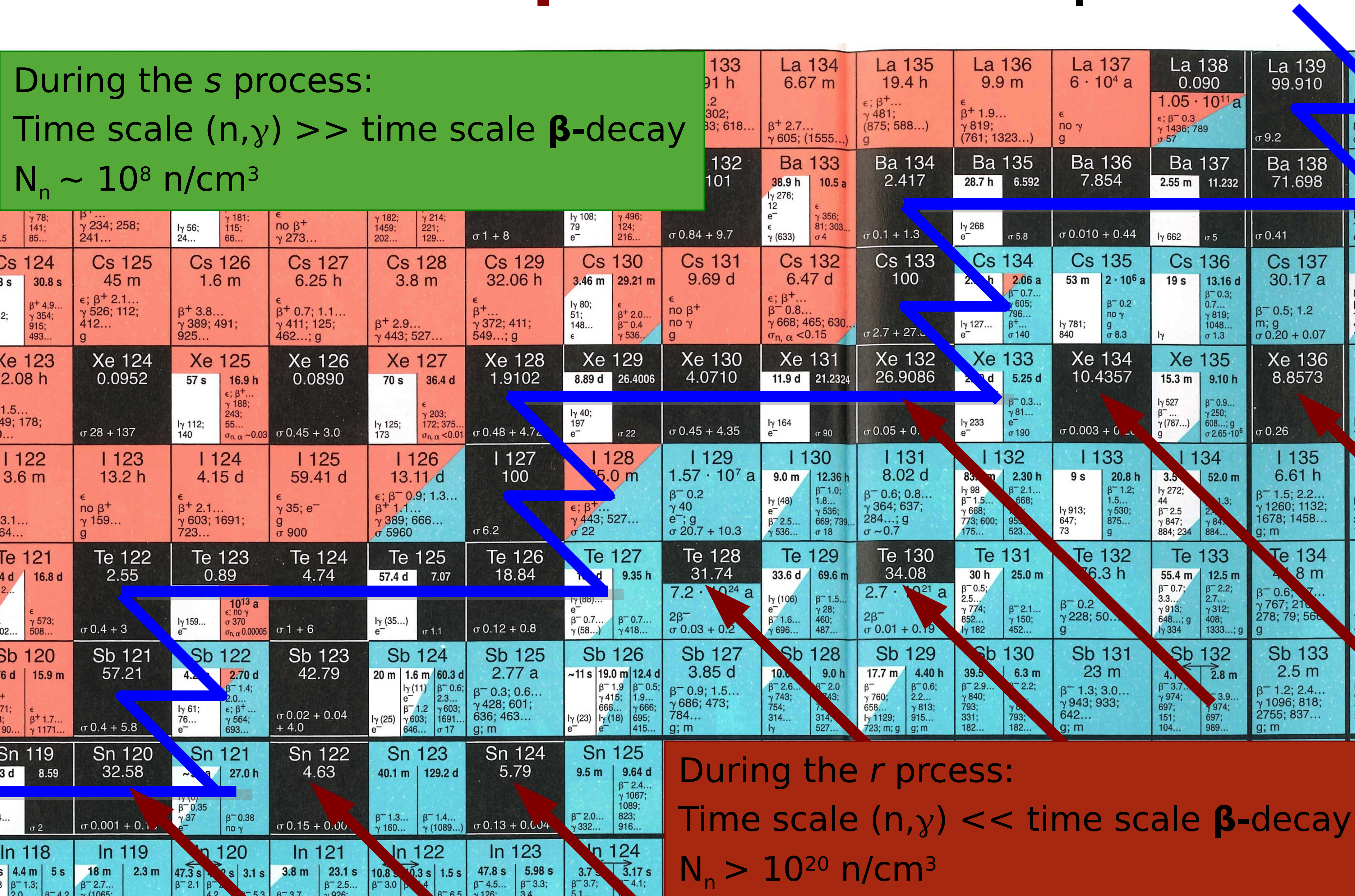
Fusion releases energy

Think it in terms of a potential well.

Beyond Fe

- Need to add energy to do fusion
- Nuclear reactions do not contribute anymore to the energy of a star
- High coulomb barrier prevents proton or alpha captures, because they are charged
- Have to add neutrons to make heavier elements!

Slow and **Rapid** neutron captures



During the *s* process:

Time scale (n,γ) >> time scale **β-**decay

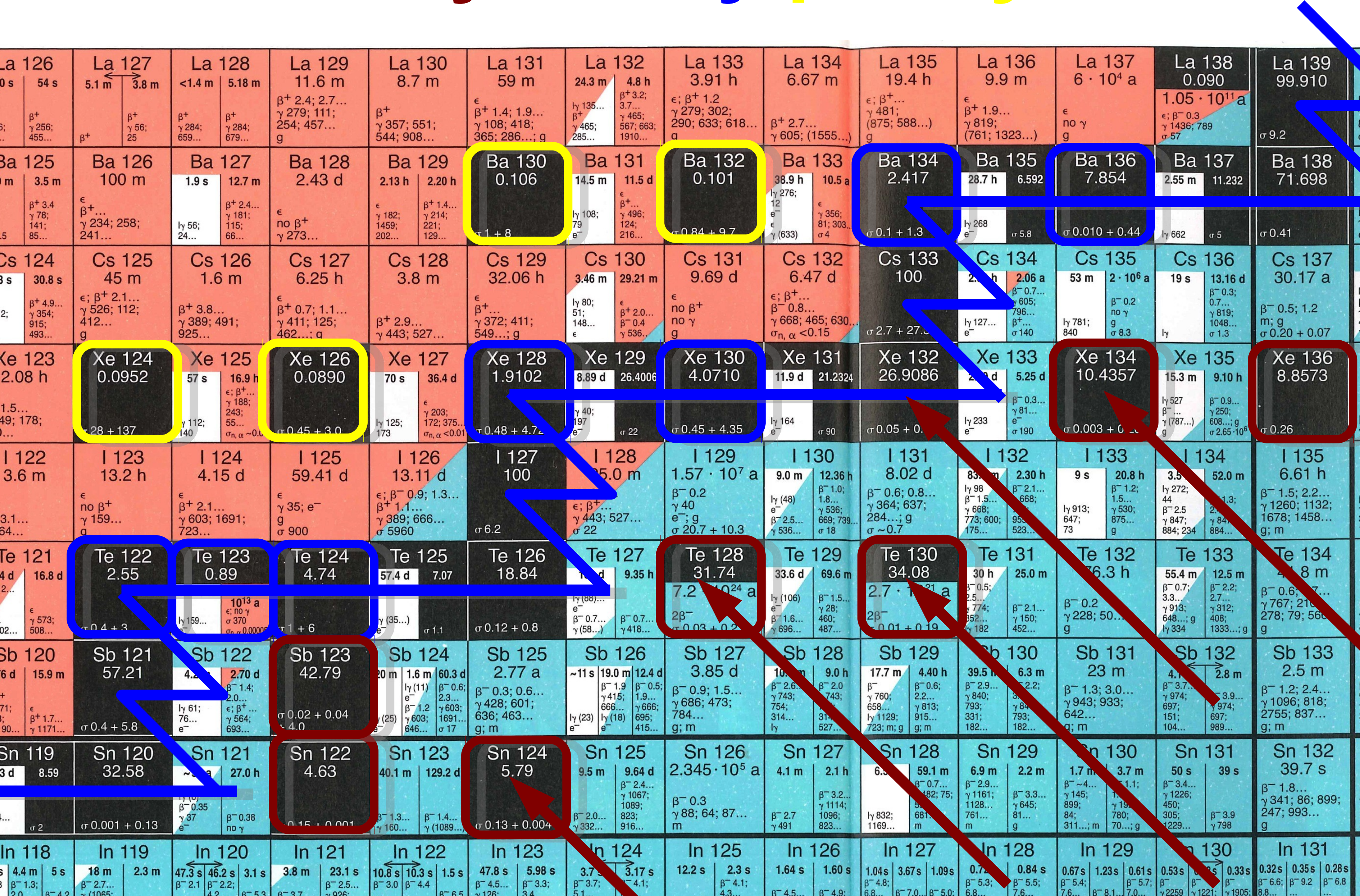
$N_n \sim 10^8$ n/cm³

During the *r* prcess:

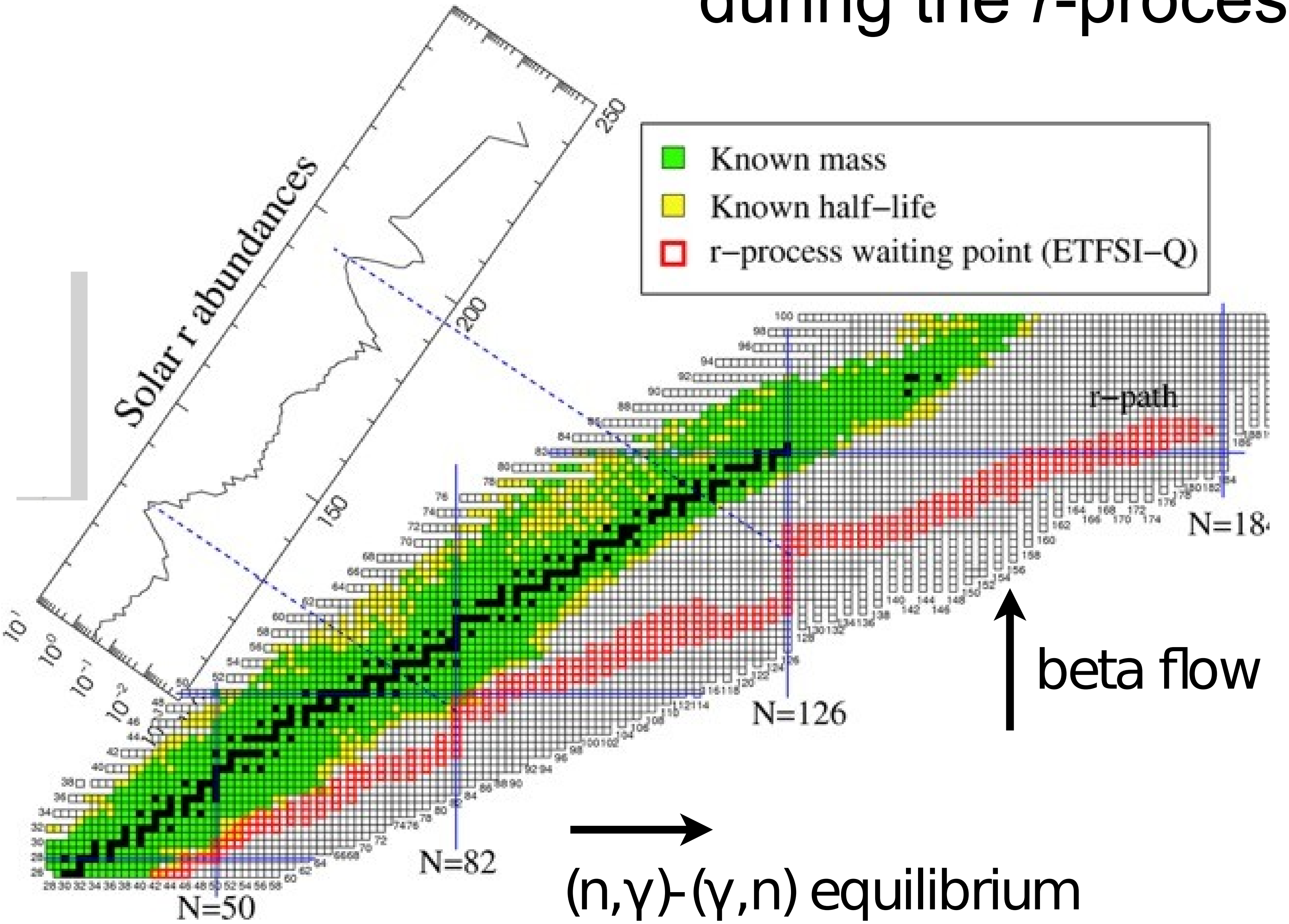
Time scale (n,γ) << time scale **β-**decay

$N_n > 10^{20}$ n/cm³

r-only s-only p-only



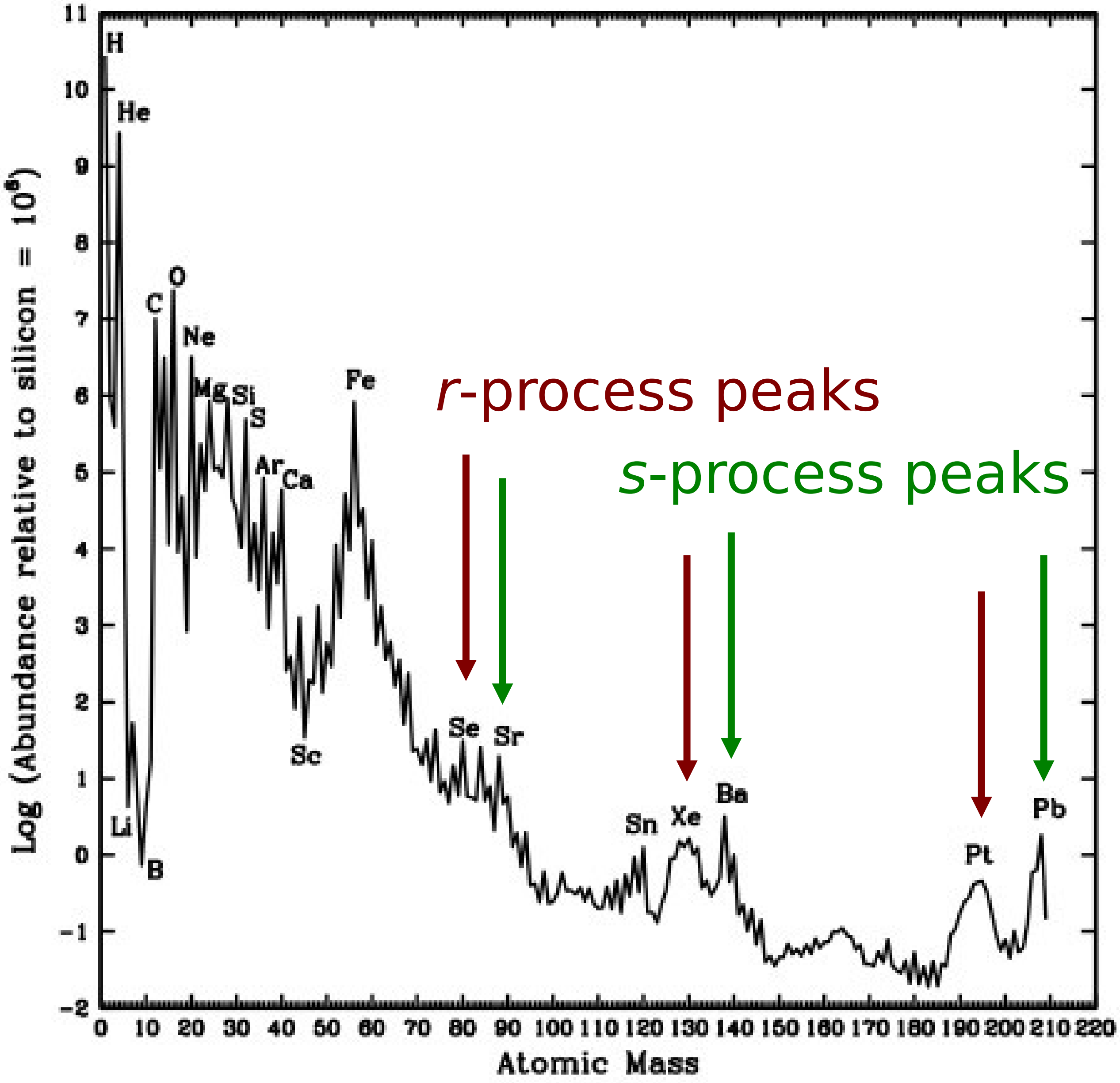
Unstable magic nuclei act as “waiting points” during the *r*-process



beta flow

(n,γ)-(γ,n) equilibrium

The Solar System abundances

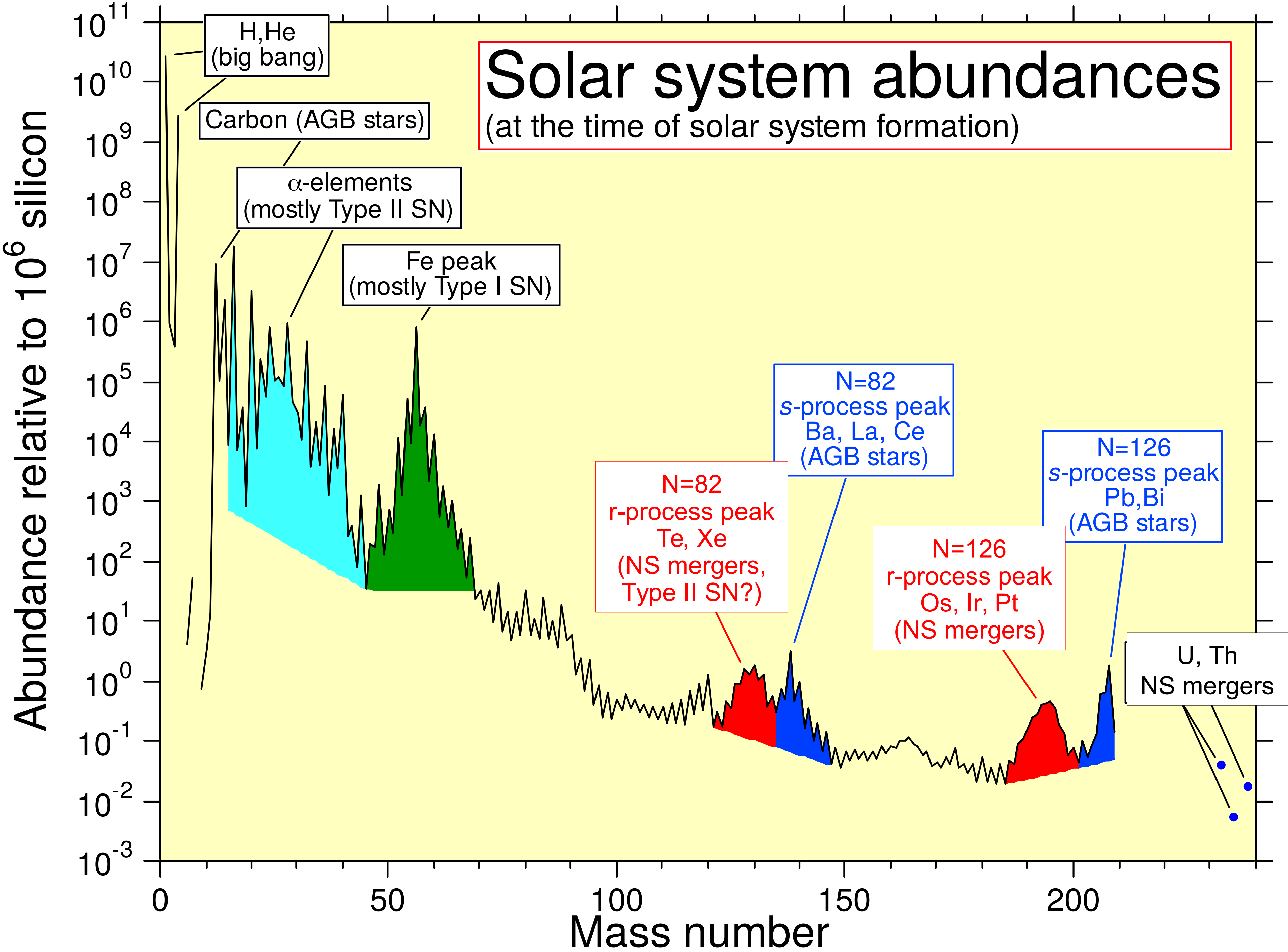


r-process peaks

s-process peaks

The *r*-process peaks correspond to *unstable nuclei* with *N*=50,82,126

The *s*-process peaks correspond to *stable nuclei* with ***Neutron Magic Numbers*** *N*=50,82,126


Solar system abundances
(at the time of solar system formation)
H,He
(big bang)
Carbon (AGB stars)
α-elements
(mostly Type II SN)
Fe peak
(mostly Type I SN)
N=82
r-process peak
Te, Xe
(NS mergers,
Type II SN?)
N=82
s-process peak
Ba, La, Ce
(AGB stars)
N=126
r-process peak
Os, Ir, Pt
(NS mergers)
N=126
s-process peak
Pb,Bi
(AGB stars)
U, Th
NS mergers
Abundance relative to 10^6 silicon
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
0
50
100
150
200
Mass number