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Explosive nucleosynthesis, nucleosynthesis beyond Fe

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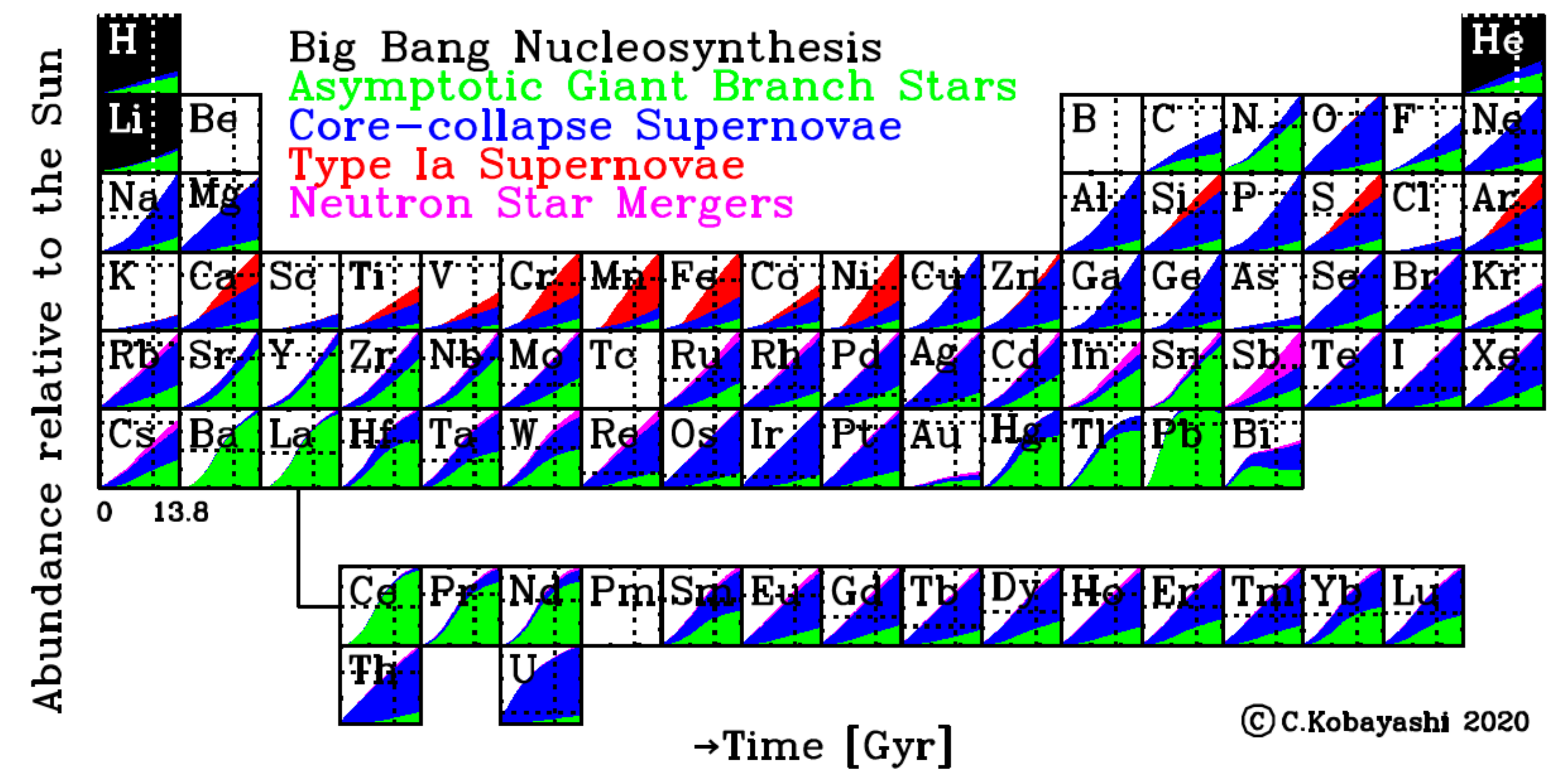
NuGriD collaboration

Nucleosynthesis of the elements



The core-collapse supernova scenario

- Massive stars ($M>9\ M_{\odot}$) go through all the nuclear burning stages in a non degenerate environment, form a Fe core, and eventually explode as core-collapse supernova (CCSN).

- The Fe core becomes unstable, collapses to nuclear density, rebounces, and through a sequence of events a shock wave is launched, driving the explosion of the star.

- The propagation of the shock wave through the mantle of the star induces compression and heating → some modification of the chemical composition produced during the hydrostatic burning stages is expected → **Explosive nucleosynthesis**.

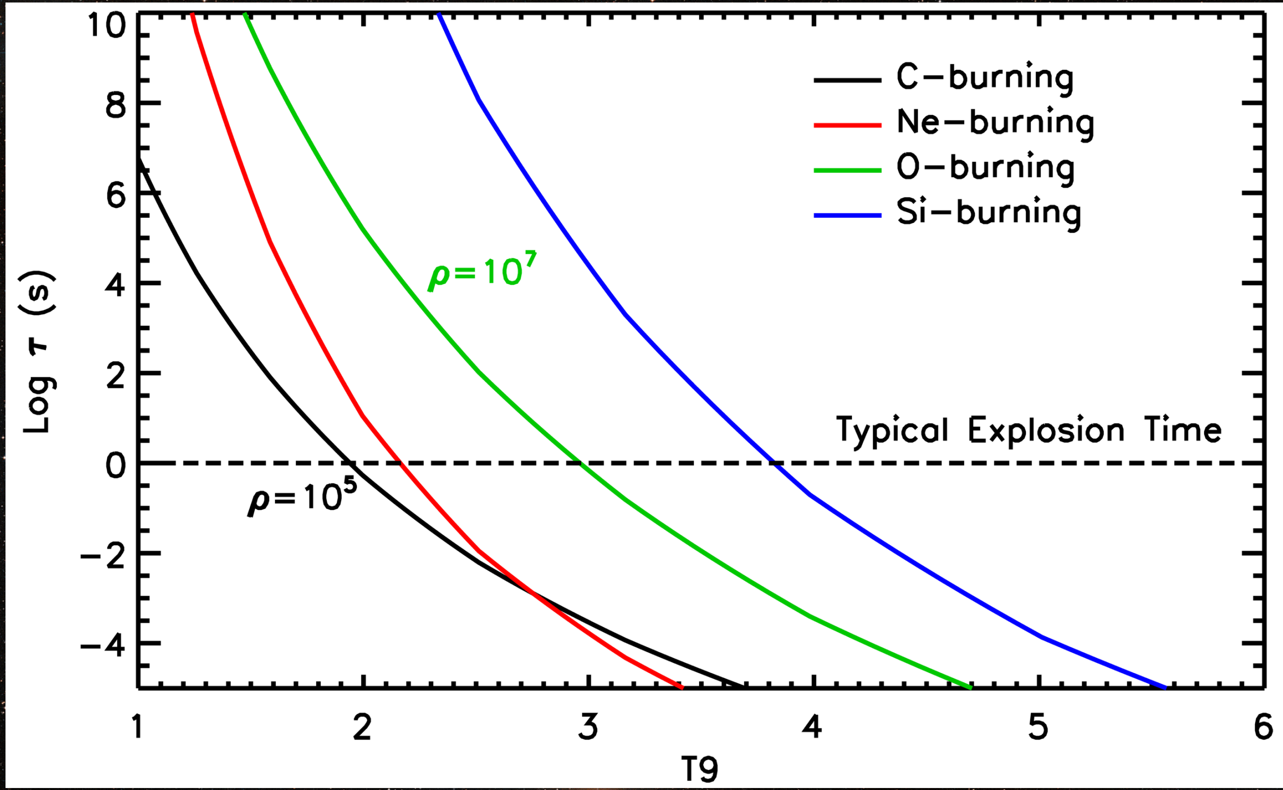
The core-collapse supernova scenario

Explosive nucleosynthesis occurs on a much shorter timescale than that of the hydrostatic nucleosynthesis.

Therefore, higher temperatures are required to exhaust a certain nuclear fuel.

For the typical explosion timescale (~1 s), the typical burning temperature for any given nuclear burning to occur is:

Explosive Burning	Temperature
Si burning	$T \gtrsim 4 \cdot 10^9$ K
O burning	$T \gtrsim 3.3 \cdot 10^9$ K
Ne burning	$T \gtrsim 2.1 \cdot 10^9$ K
C burning	$T \gtrsim 1.9 \cdot 10^9$ K



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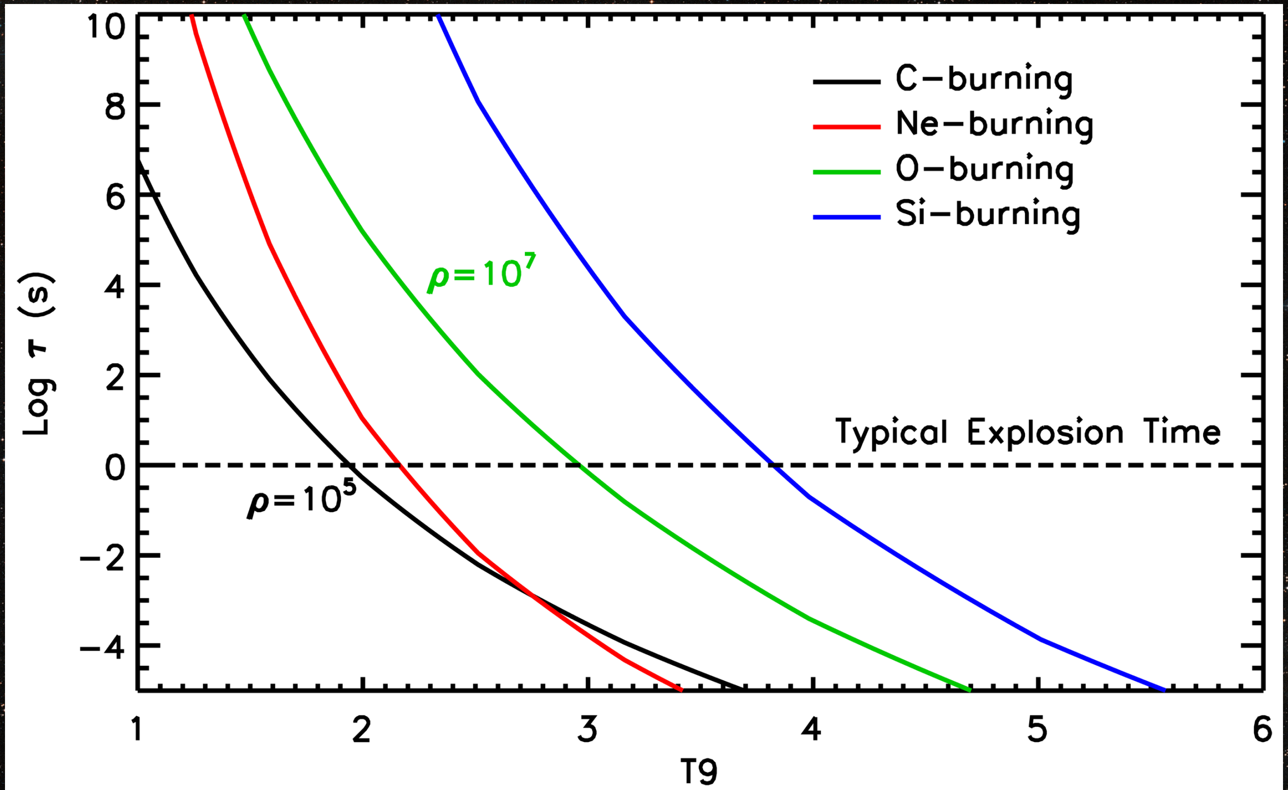
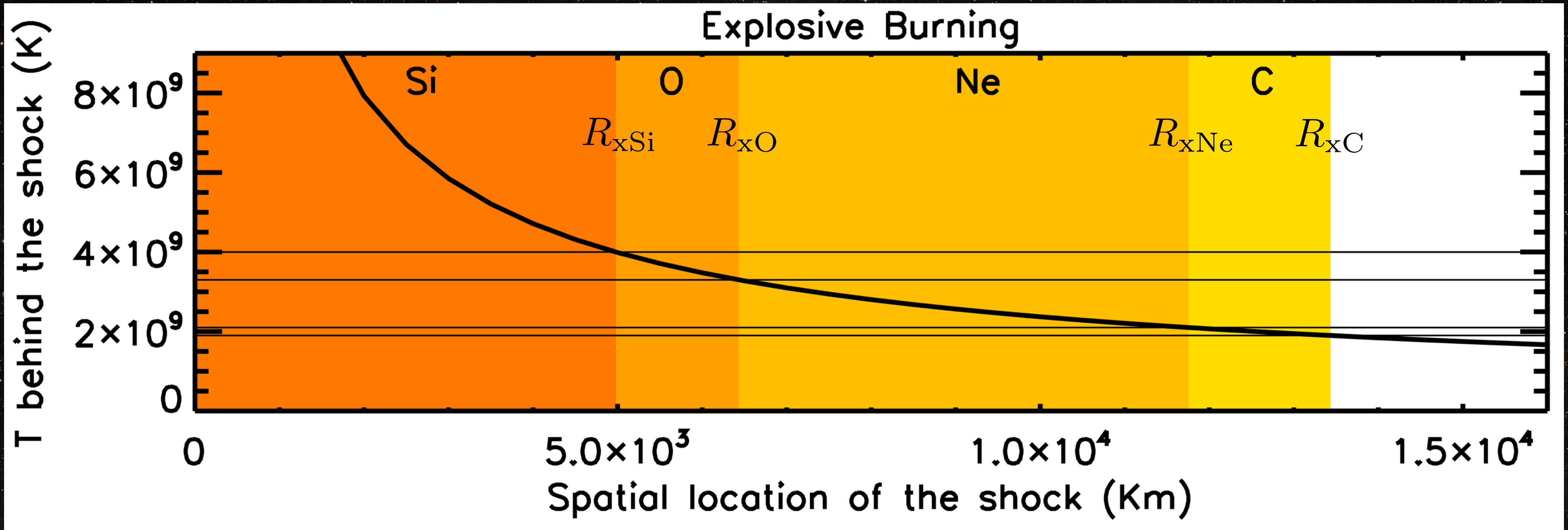


No major nuclear burning occurs over the typical explosion timescale at $T < 1.9 \cdot 10^9$ K. Explosive He-H burning? n-process?

The core-collapse supernova scenario



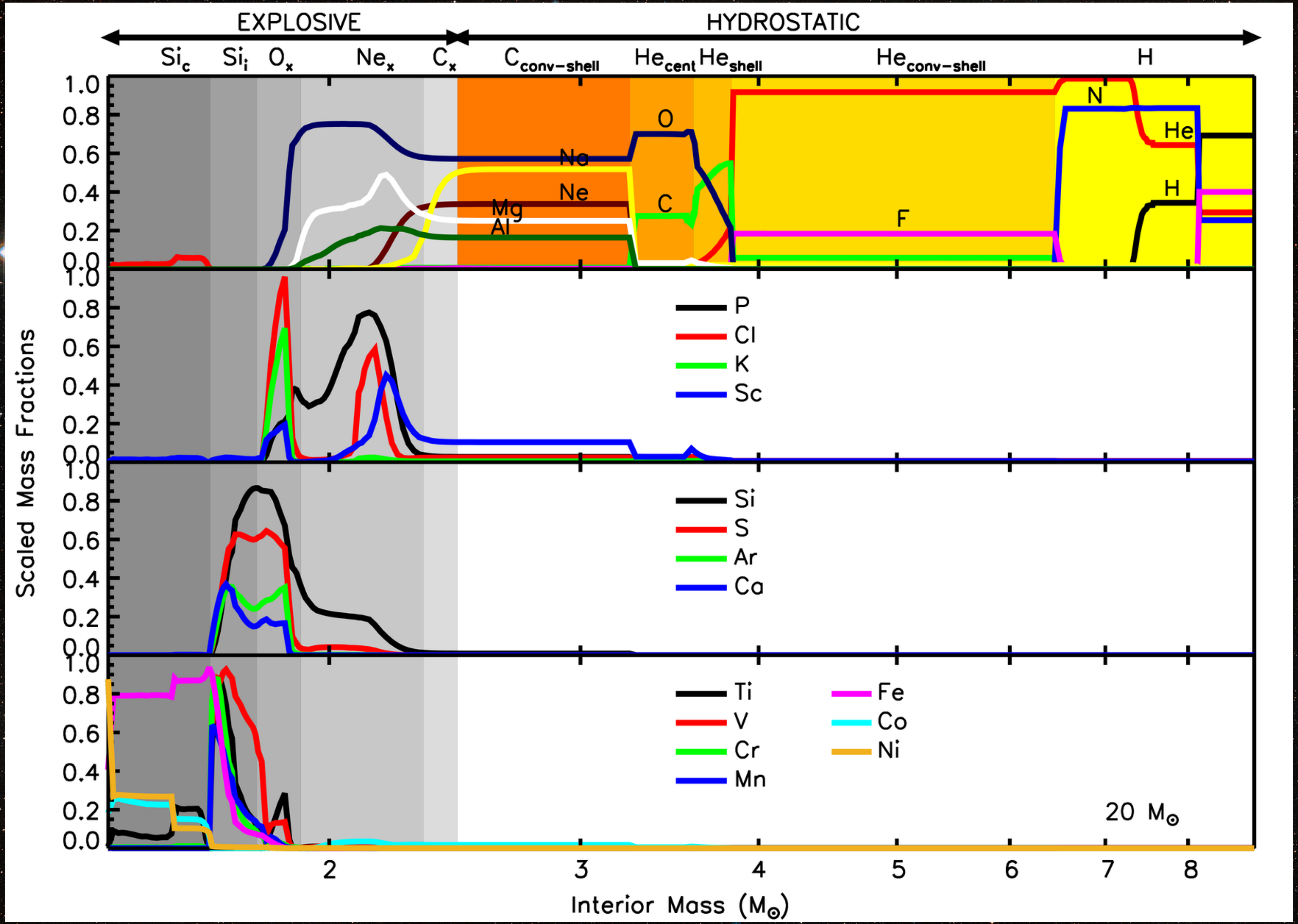
The explosion is radiation dominated: we can identify "volumes" in the star within which the various explosive burning can occur →This is (almost) independent from the properties of the pre-supernova star!

$$E_{expl} \simeq 1\ \text{foe}\ (1\ \text{foe} = 10^{51}\text{erg})$$

$$T_{shock} = \left(\frac{3E_{expl}}{4\pi a R_{shock}^3}\right)^{1/4}$$

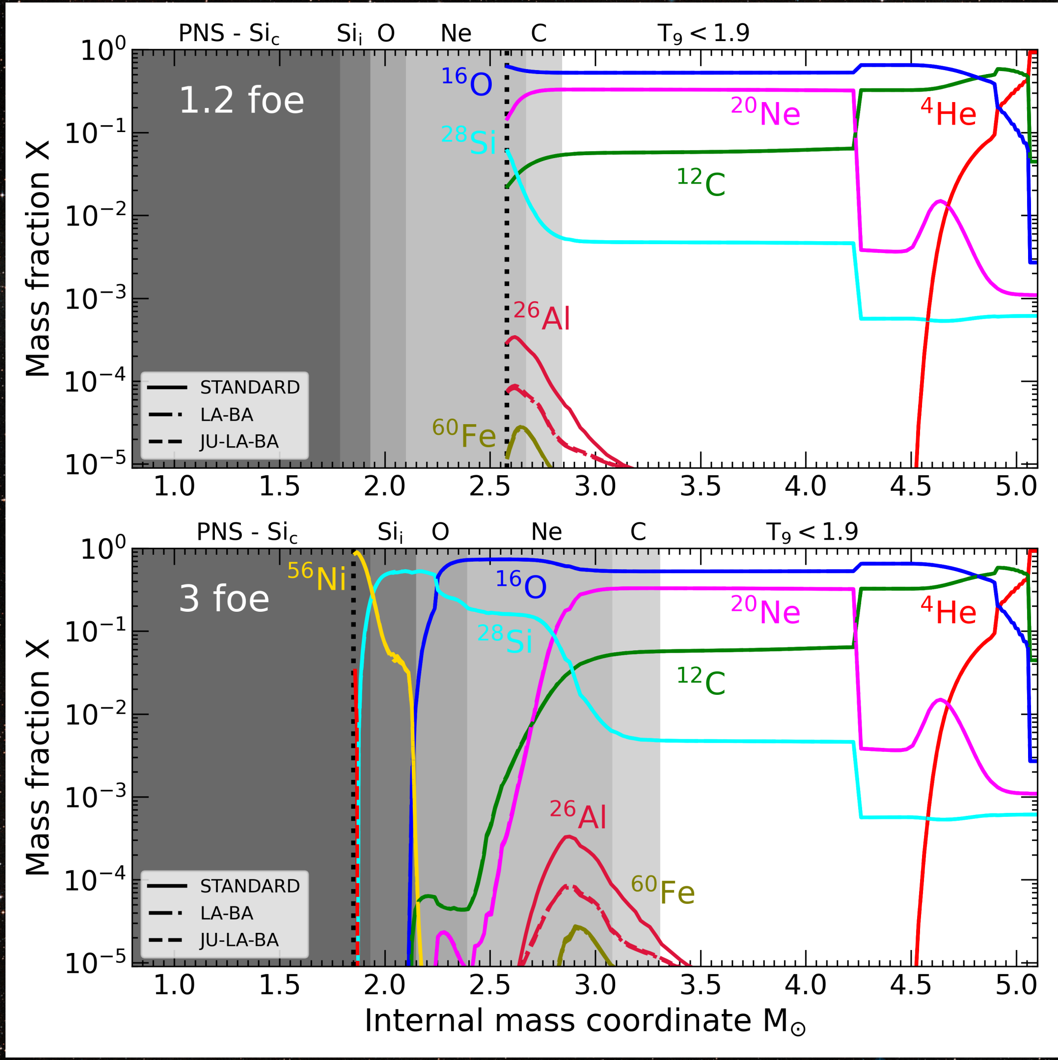
$T_9 \geq 4 \rightarrow R_{xSi} \leq 5000$ km
$T_9 \geq 3.3 \rightarrow R_{xO} \leq 6400$ km
$T_9 \geq 2.1 \rightarrow R_{xNe} \leq 11750$ km
$T_9 \geq 1.9 \rightarrow R_{xC} \leq 13400$ km

Explosive nucleosynthesis in CCSNe



Element	Production Site
N (^{14}N)	Hydrostatic H burning
F (^{19}F)	Hydrostatic He convective shell
C (^{12}C) O (^{16}O)	Hydrostatic core He burning (^{16}O partially modified by Cshell and Ne_x)
Ne (^{20}Ne) Na (^{23}Na) Mg (^{24}Mg) Al (^{27}Al)	Hydrostatic C convective shell Partially destroyed by C_x (^{23}Na) and Ne_x (^{20}Ne) Partially produced by Ne_x (^{24}Mg,^{27}Al)
P (^{31}P)	Ne_x
Cl (^{35}Cl, ^{37}Cl)	Ne_x+O_x
K (^{39}K)	O_x
Sc (^{45}Sc)	Hydrostatic C convective shell Ne_x+O_x
Si (^{28}Si) S (^{32}S) Ar (^{36}Ar) Ca (^{40}Ca)	O_x+Si_i
V (^{51}Cr) Cr (^{52}Cr,^{52}Fe) Mn (^{55}Mn,^{55}Co)	Si_i
Ti (^{48}Cr)	O_x+Si_i+Si_c
Fe (^{56}Ni) Co (^{59}Co,^{59}Ni) Ni (^{58}Ni,^{60}Ni)	Si_c

Radioactive nuclei

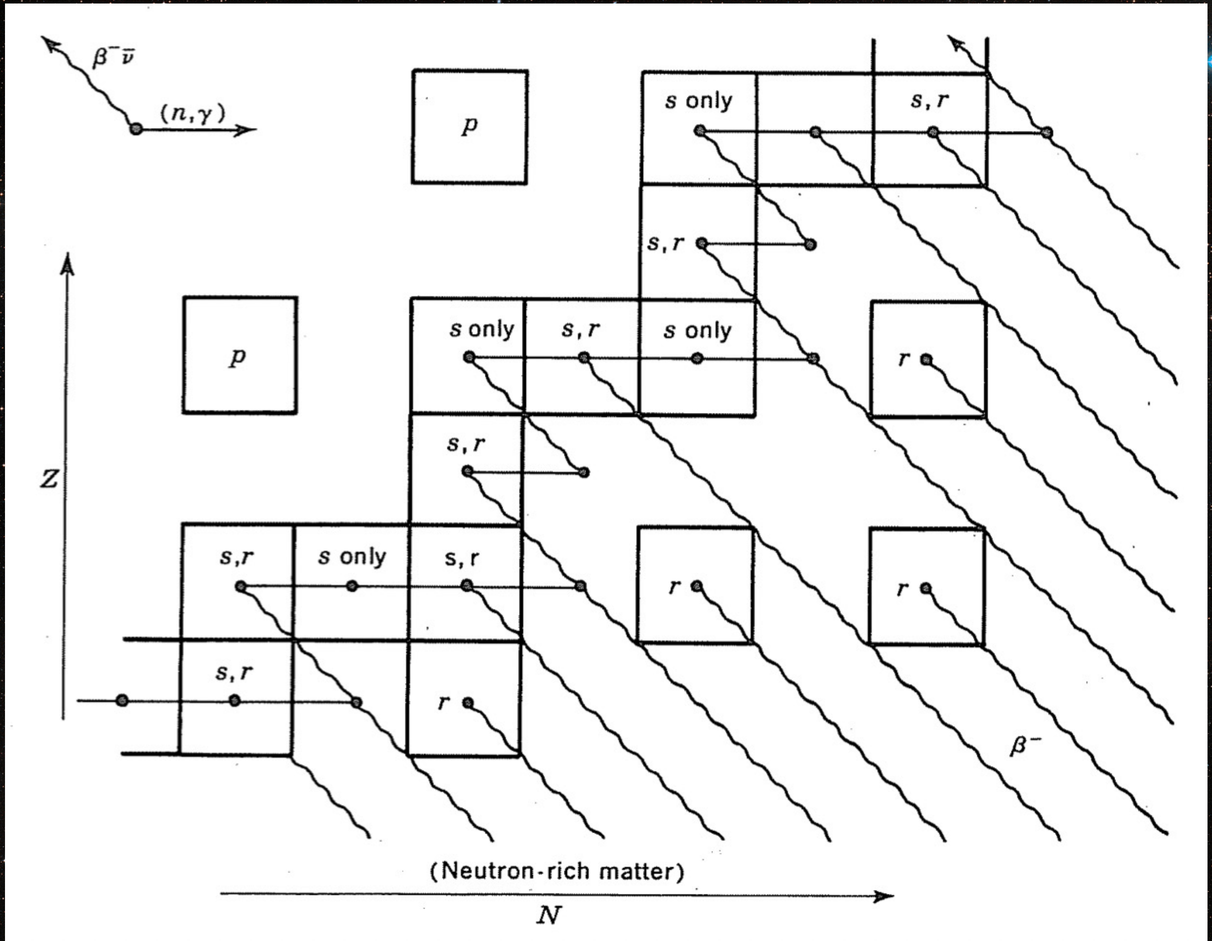


Battino, Roberti et al., 2024, Universe, 10, 204

Production of Short-Lived Radioactive (SLR) nuclei:

- ^{26}Al and ^{60}Fe produced in Ne$_x$ burning;
- ^{36}Cl produced via n-captures in C$_x$ burning;
- ^{41}Ca and ^{53}Mn produced in Si$_x$ and O$_x$ burning;
- ^{92}Nb, ^{97,98}Tc, ^{146}Sm via the γ−process in Ne$_x$ burning.

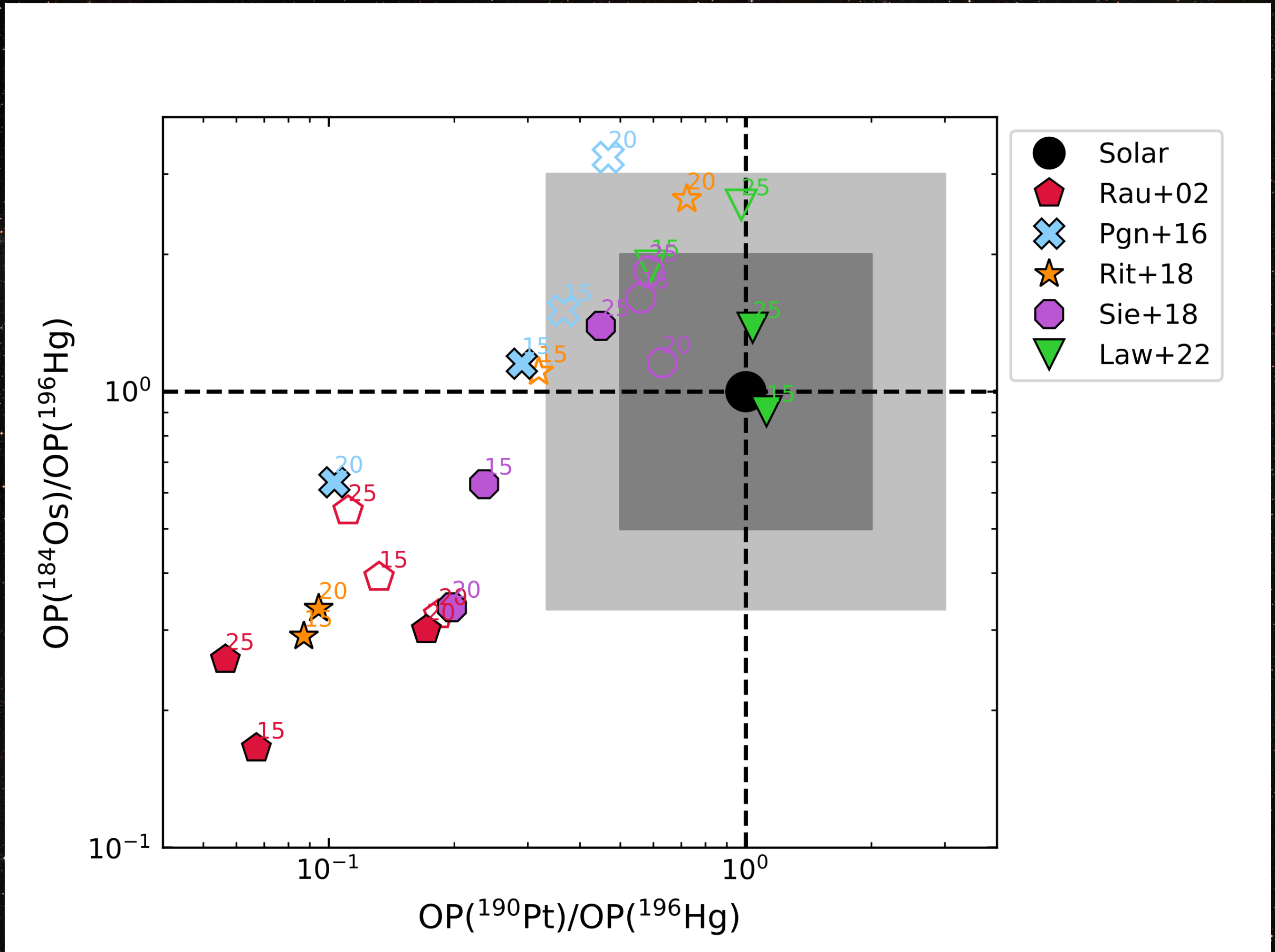
The γ −process nucleosynthesis



Clayton, D.D. (1968) Principles of Stellar Evolution and Nucleosynthesis. University of Chicago Press, Chicago.

- The **γ-process:** a sequence of photodisintegrations (γ,n), (γ,p), and (γ,α) in O/Ne rich layers in CCSN explosions from massive star progenitors (e.g., Woosley & Howard, 1978; Rayet et al., 1995);
- Production of **p-nuclei**: 35 neutron-deficient isotopes of elements heavier than Fe;
- **Underproduction** of typical γ-process yields from massive stars (factor of ~2-4) compared to the solar system abundances. **Larger underproduction** of ^{92,94}Mo and ^{96,98}Ru yields (~1 order of magnitude).

The γ −process nucleosynthesis



Roberti et al., 2023, A&A, 677, A22

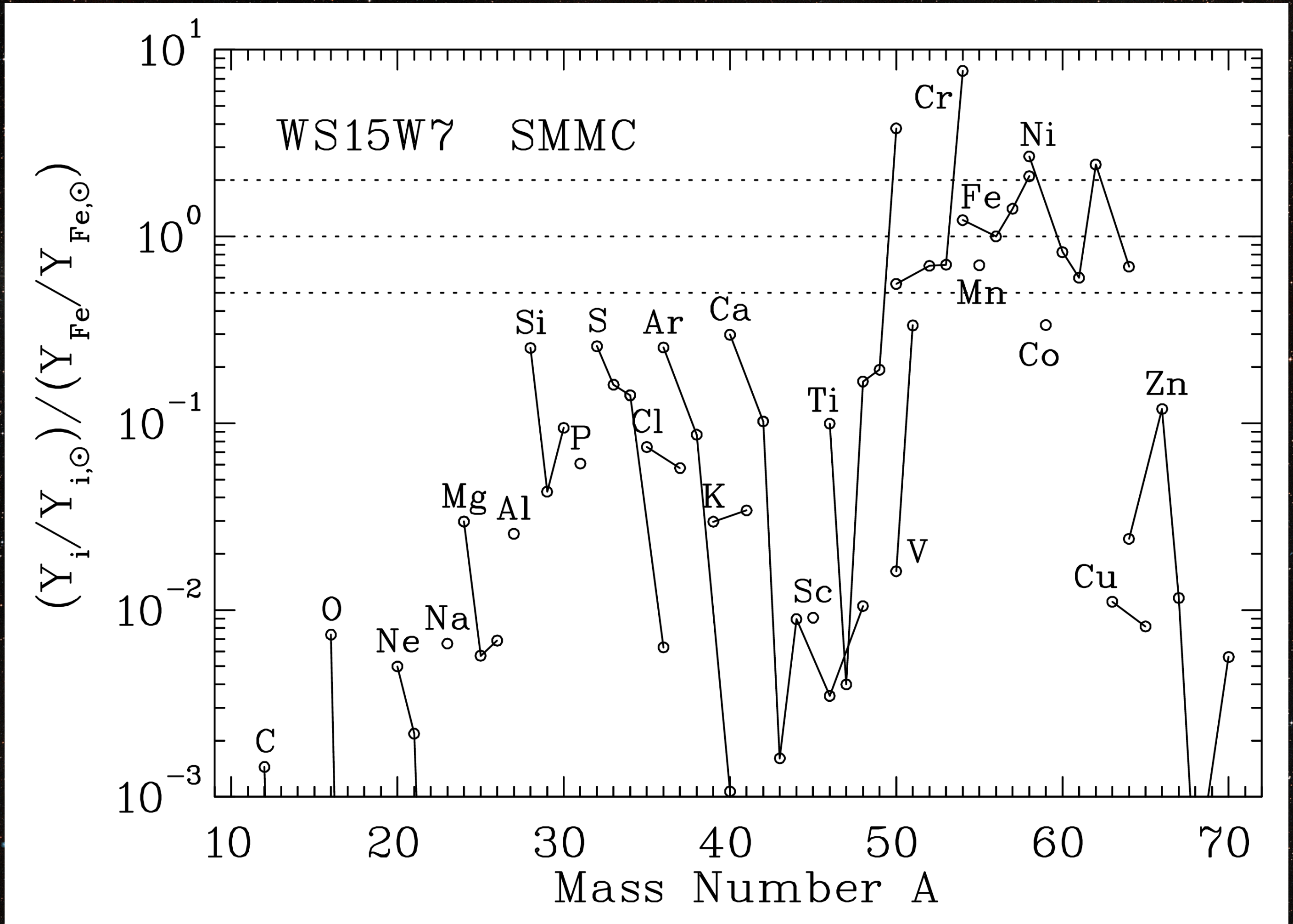
- Temperature: between 2 and 3.5 GK → explosive O and Ne burning;
- It is a chain of photodisintegrations: the nuclear uncertainties propagate from heavier to lighter nuclei;
- Difficulty to explain even the heaviest p-nuclei isotopic ratios.

The γ −process nucleosynthesis

35 stable proton-rich nuclei: ^{74}Se, ^{78}Kr, ^{84}Sr, $^{92,94}Mo$, $^{96,98}Ru$, ^{102}Pd, $^{106,108}Cd$, $^{112,114,115}Sn$, ^{113}In, ^{120}Te, $^{124,126}Xe$, $^{130,132}Ba$, $^{136,138}Ce$, ^{138}La, ^{144}Sm, ^{152}Gd, $^{156,158}Dy$, $^{162,164}Er$, ^{168}Yb, ^{174}Hf, ^{180}Ta, ^{180}W, ^{184}Os, ^{190}Pt and ^{196}Hg.

- Different explosive contributions (e.g., α- & νp-process, Woosley & Hoffman 1992, Froehlich et al. 2006, Arcones & Montes 2011);
- r-process contribution (Dillmann et al. 2008);
- neutrino capture (Goriely et al. 2001);
- s-process contribution (Bisterzo et al. 2011);
- s-process and neutrino capture (Bisterzo et al. 2011, Arnould & Goriely 2003);
- cold γ-process in pre-SN for A<110 (Roberti et al. 2023).

The Type IA supernova scenario



Brachwitz et al., 2000, ApJ, 536, 934

- **Type Ia Supernovae:** explosion of an electron degenerate structure (COWD or ONeWD) due to accretion of H-/ He-/ C/O-rich matter from a companion.
- Thermonuclear runaway in a degenerate environment: the incineration of the matter up to an NSE chemical composition.
- Main products are **Fe-peak nuclei**. Possible contribution to **p-nuclei** from s-process seeds.
- Single or Double degenerate scenarios, deflagration or detonation?

Other explosive scenarios

- **Novae:** stellar explosions that occur in close binary systems. Hydrogen-rich matter is transferred via Roche lobe overflow from a low-mass main-sequence star to the surface of a compact white dwarf (CO or ONe).
- **X-Ray Bursts:** thermonuclear explosions that take place on the surface of accreting neutron stars in binary systems.
- **Common envelope with NS:** similar to XRB, accretion on a neutron star in a common envelope system.

Summary and conclusions

- Explosive nucleosynthesis made a large fraction of the element of the periodic table;
- Massive stars end their lives as CCSNe, ejecting newly formed elements;
- The shock-driven explosive burning reshapes the chemical composition of stellar layers, producing intermediate elements, radioactive and p-nuclei;
- Type Ia SNe, novae, and X-ray bursts (possibly) complement CCSNe in Galactic enrichment.