LECTURE #3: EXPLOSIVE BURNING

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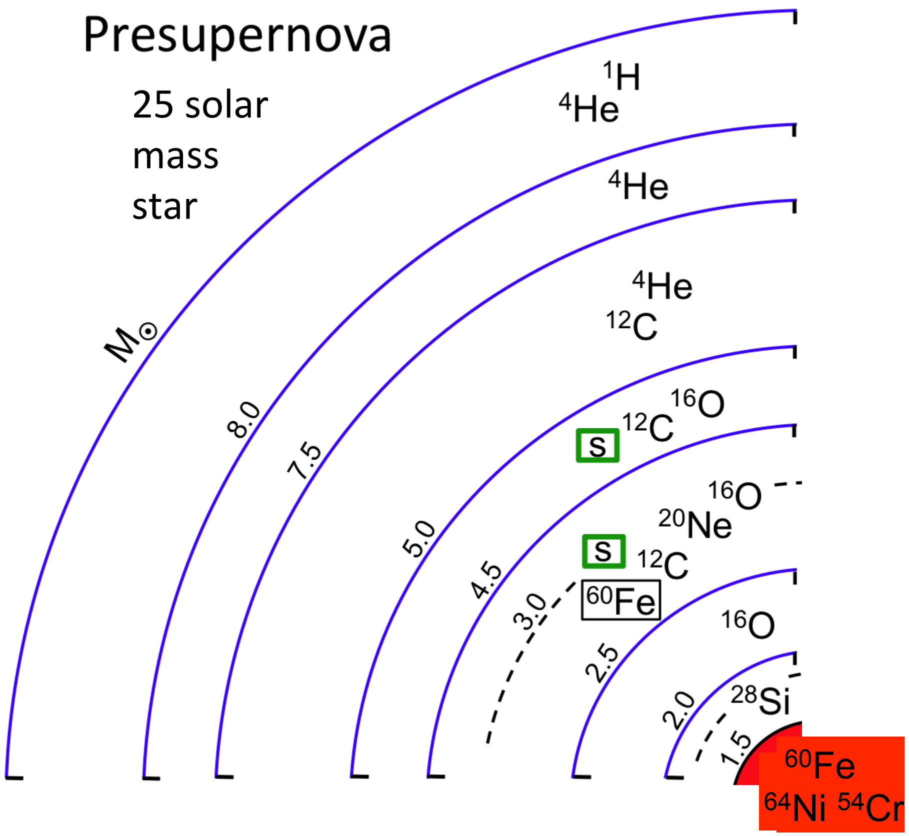
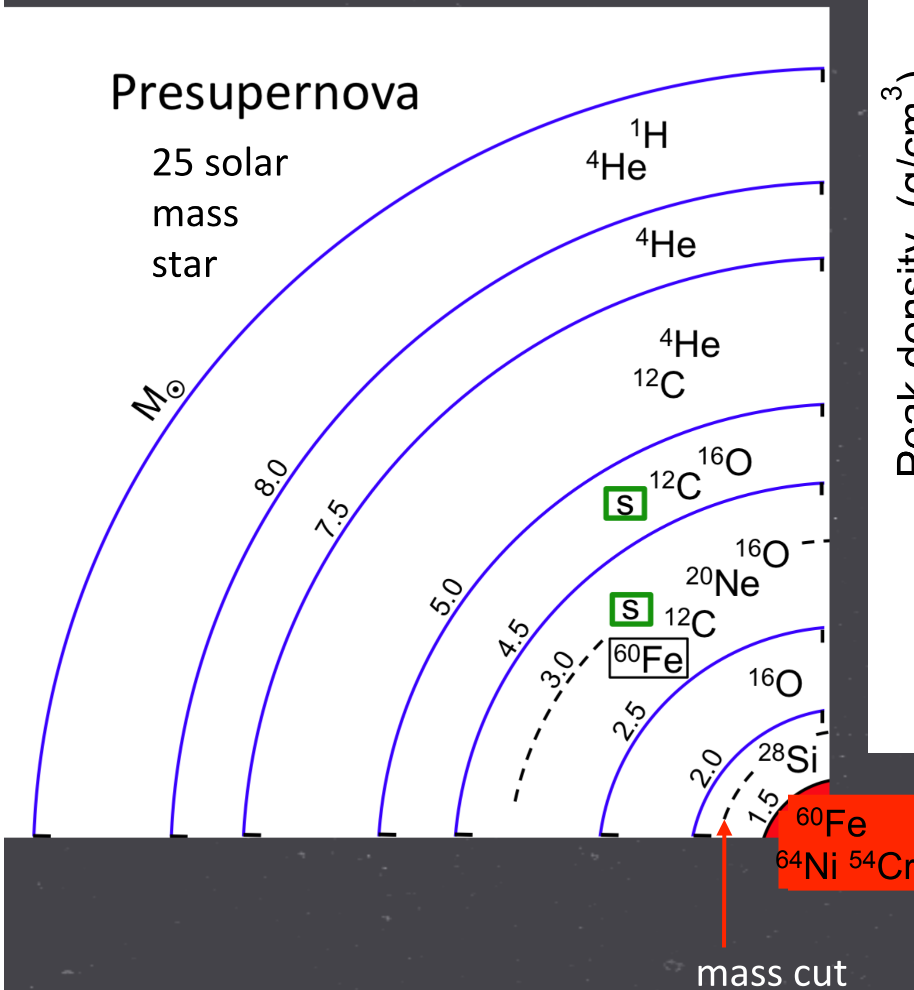
TUNL

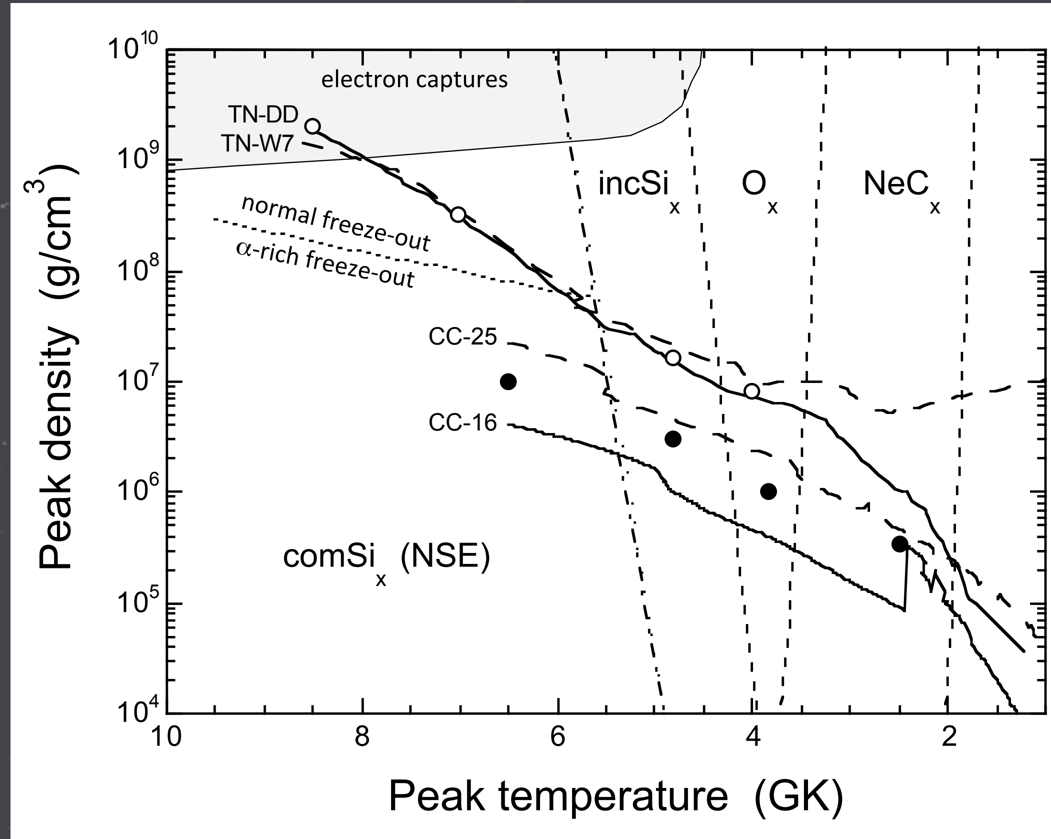
"Onion Shell" Structure of Massive Star: Instant Before Core Collapse



- no other nuclear energy source is available to core
- core is in NSE, with $T=10^{10}$ K and $\rho=10^{10}$ g/cm^3
- grows in mass; when it reaches 1.4 times solar mass, electron degeneracy pressure is unable to counteract gravity…
- core collapses in free fall…
- when $\rho=10^{14}$ g/cm^3: nuclei and nucleons feel short-range nuclear force [repulsive at very short distance]
- inner part of core rebounds, producing an outward moving shock wave…

EXPLOSIVE BURNING: SHOCK MOVING THROUGH "ONION" LAYERS





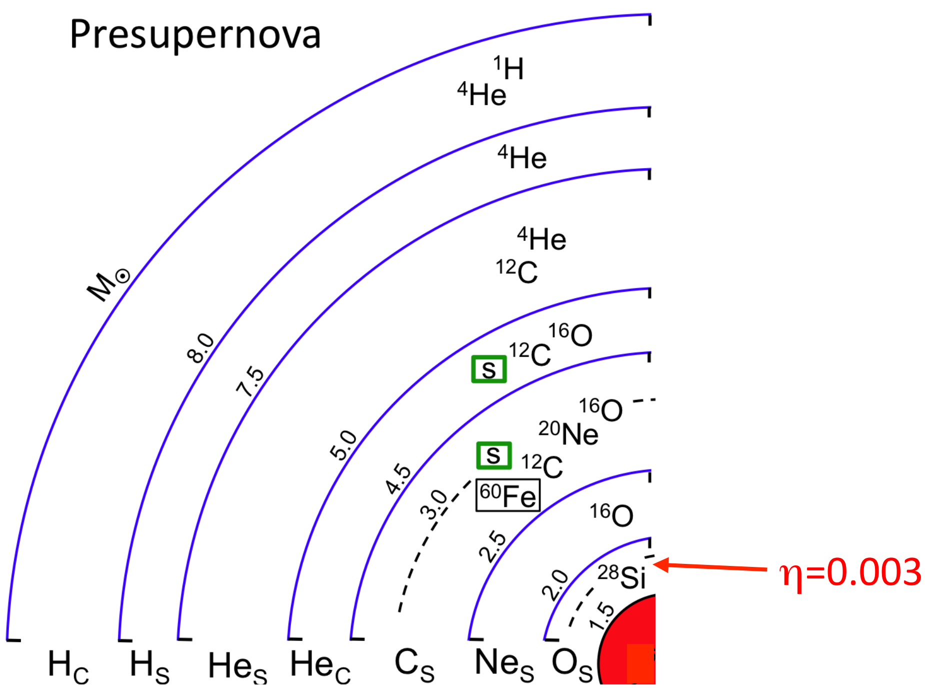
CC-16: Young et al., ApJ 640, 891 (2006)

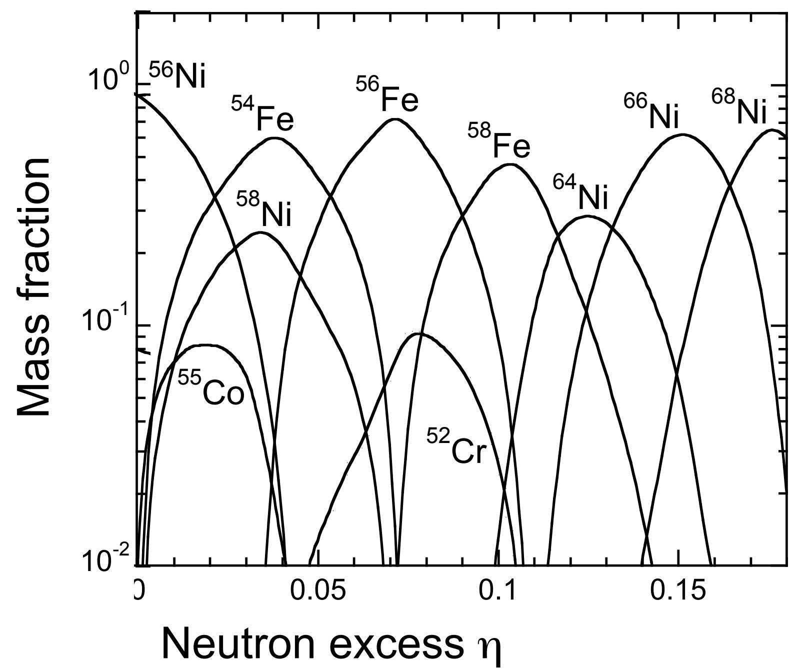
CC-25: Limongi & Chieffi, ApJ 592, 404 (2003)

COMPLETE EXPLOSIVE Si BURNING

T=6.5 GK

outgoing shock wave heats inner ^{28}Si layer of star to high T and ρ; matter approaches NSE: composition entirely determined by values of T, ρ, and neutron excess η

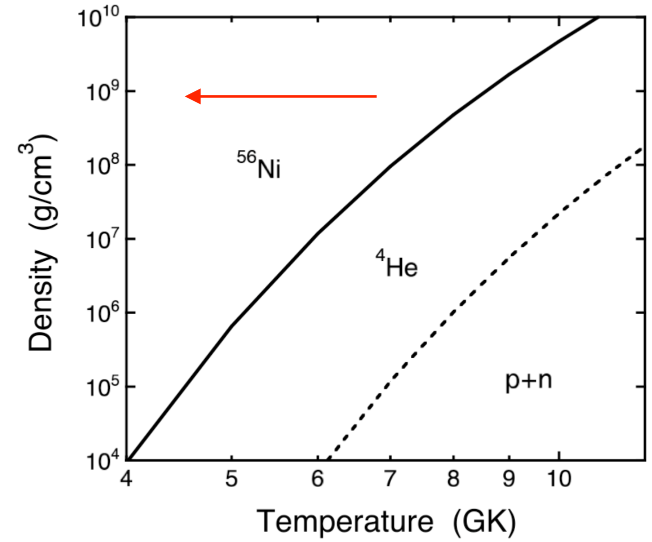




- at T=6 GK, NSE is quickly established
- since neutron excess is small, NSE favors ^{56}Ni as main constituent
- complete conversion of ^{28}Si to ^{56}Ni ["complete explosive silicon burning"]

COMPLETE EXPLOSIVE Si BURNING

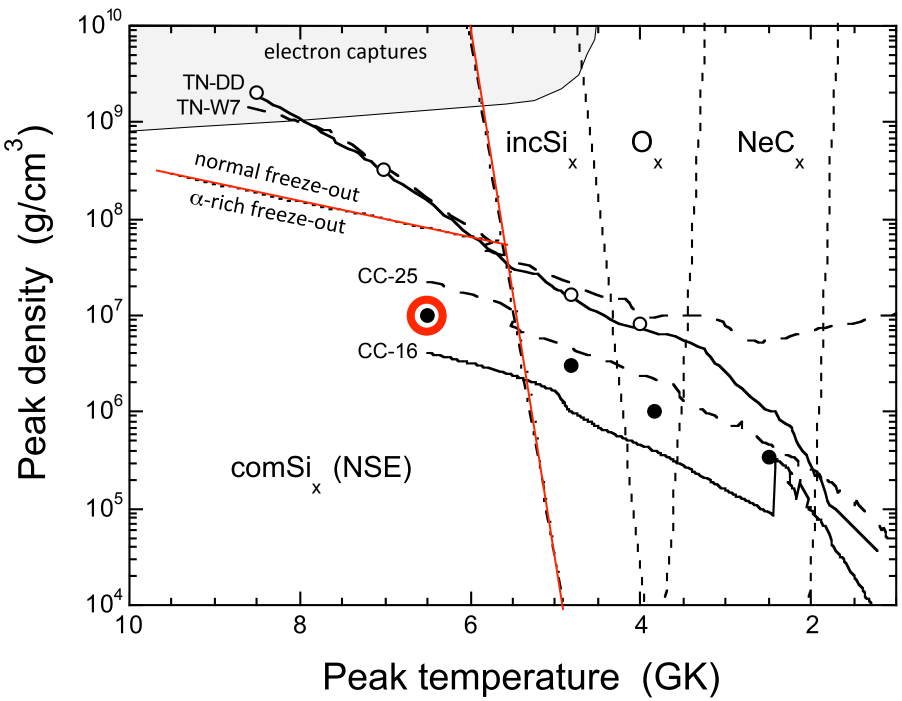
T=6.5 GK



fate of matter after shock wave passes through layer depends on expansion time scale τ, and density of n, p, α abundances when reactions start to fall out of equilibrium at a the "freeze-out" temperature

if ρ large and τ slow: NSE is terminated by lack of light particles ("normal freeze-out"): ejected abundances are close to those derived from NSE [mainly ^{56}Ni since $\eta \approx 0.003$]

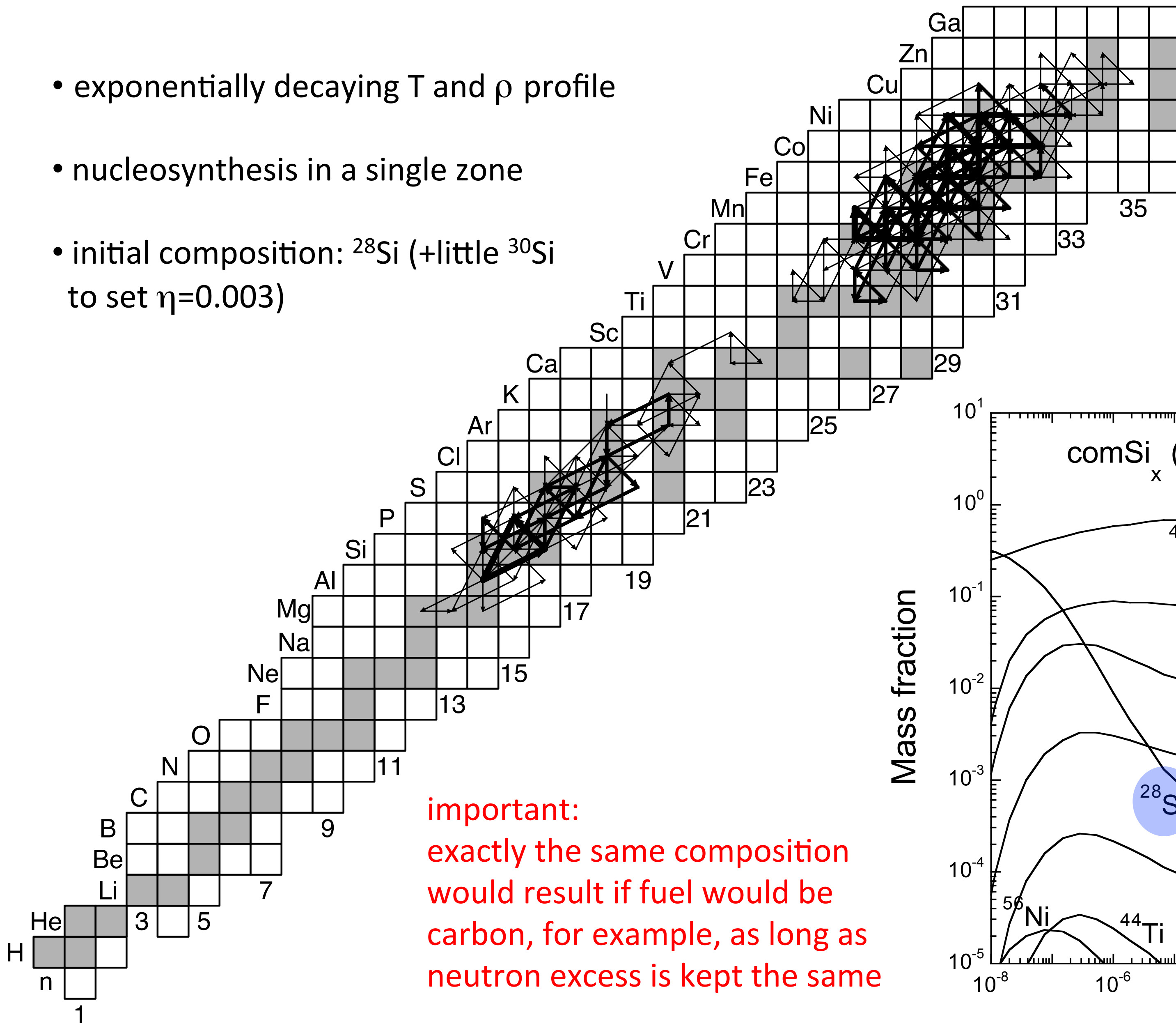
if ρ small and τ fast: NSE is terminated by excess of α-particles ("α-rich freeze-out"): ejected abundances change somewhat from NSE [still mainly ^{56}Ni for $\eta \approx 0.003$; also ^{44}Ti]



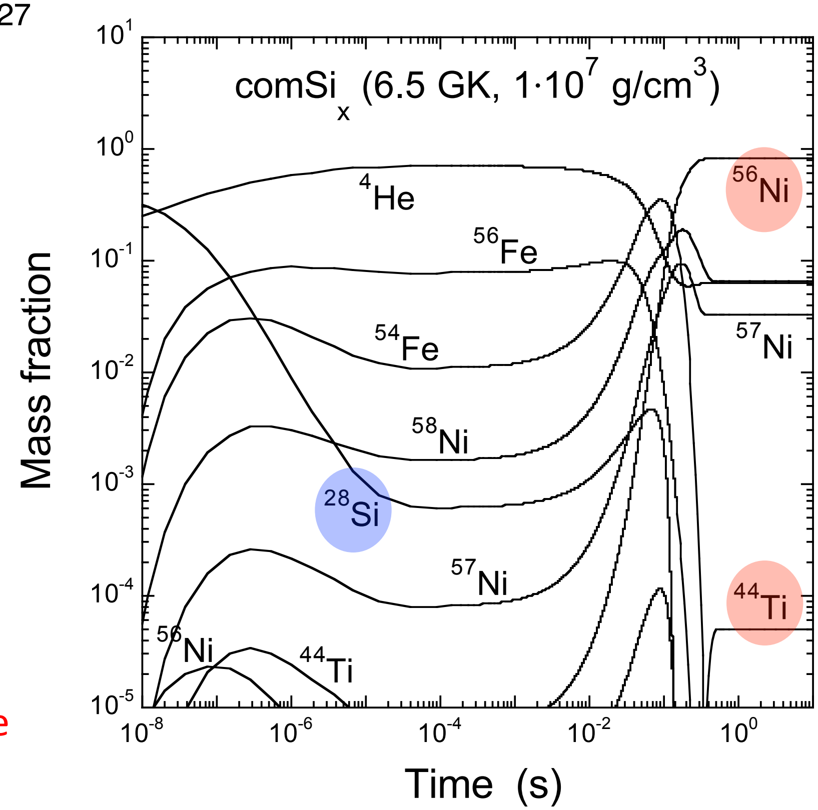
COMPLETE EXPLOSIVE Si BURNING

T=6.5 GK

- exponentially decaying T and ρ profile
- nucleosynthesis in a single zone
- initial composition: ^{28}Si (+little ^{30}Si to set η=0.003)

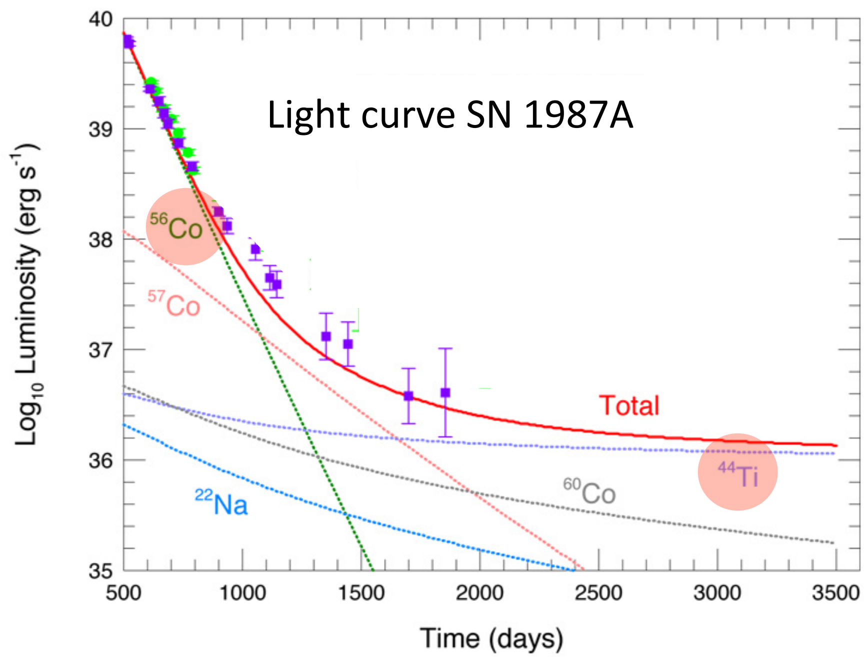


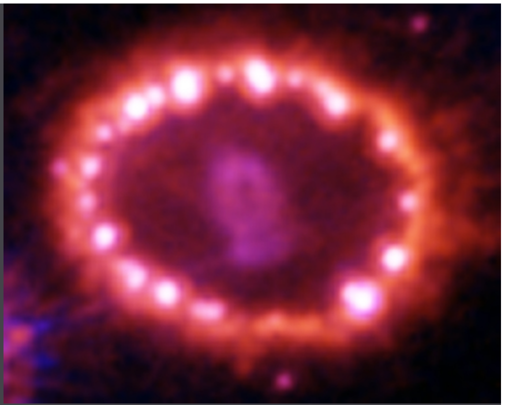
important:
exactly the same composition would result if fuel would be carbon, for example, as long as neutron excess is kept the same



CORE COLLAPSE SUPERNOVA OBSERVATIONS

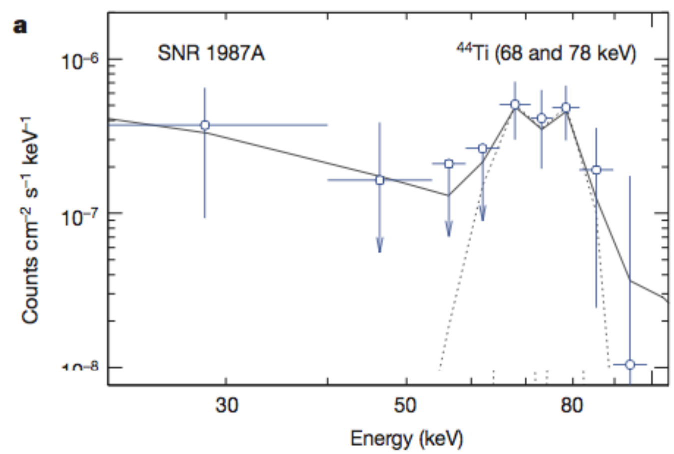
http://cococubed.asu.edu/images/ti44_co60





Supernova 1987A

$m(^{44}Ti)=(3.1\pm0.8)\times10^{-4}\ M_{sol}$



$T_{1/2}=6.1$ d $\qquad T_{1/2}=77.3$ d

$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$ (stable)

SN1987A: $m(^{56}Ni)=0.07\pm0.01\ M_{sol}$

Hard-X-ray emission lines from the decay of ^{44}Ti in the remnant of supernova 1987A

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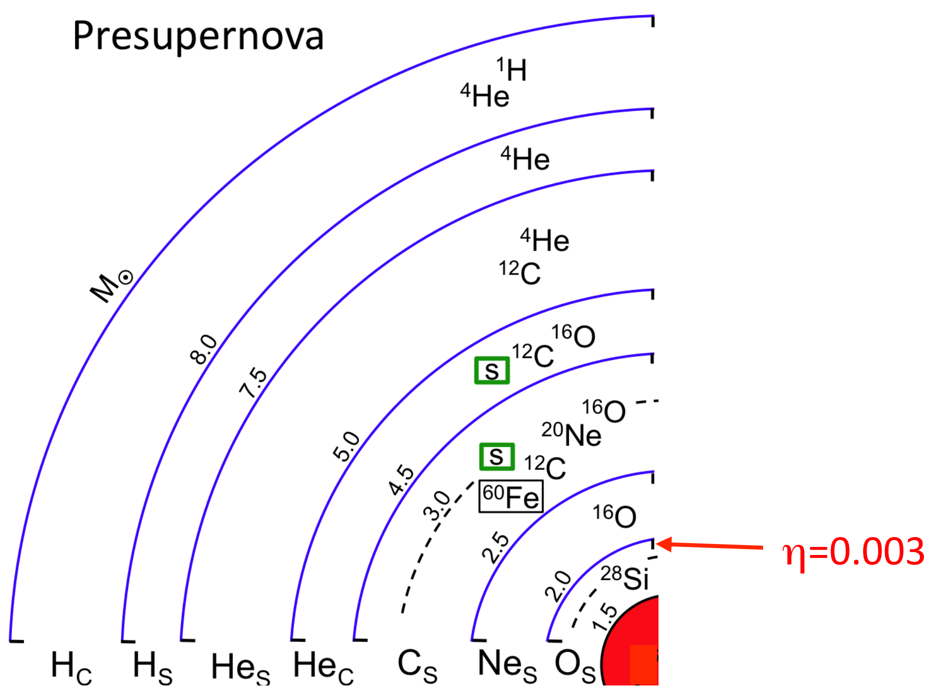
Nature **490**, 373–375 (18 October 2012) | doi:10.1038/nature11473

Received 23 November 2011 | Accepted 13 August 2012 | Published online 17 October 2012

INCOMPLETE EXPLOSIVE Si BURNING

T=4.8 GK

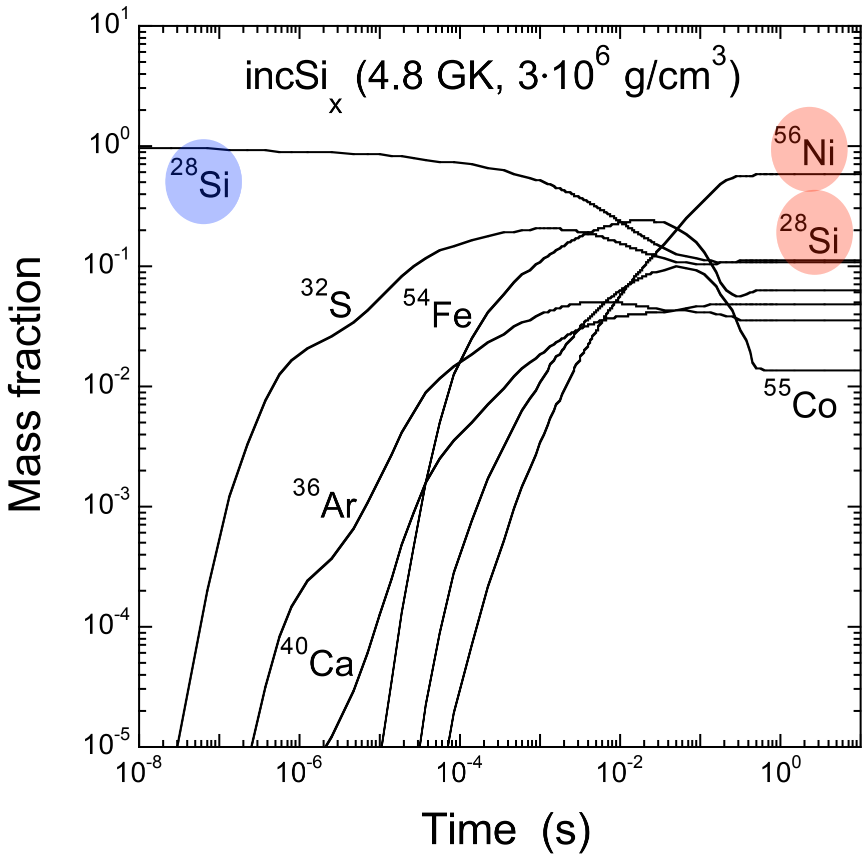
outgoing shock wave heats outer ^{28}Si layer of star to high T and ρ; matter approaches QSE [since temperature is smaller]

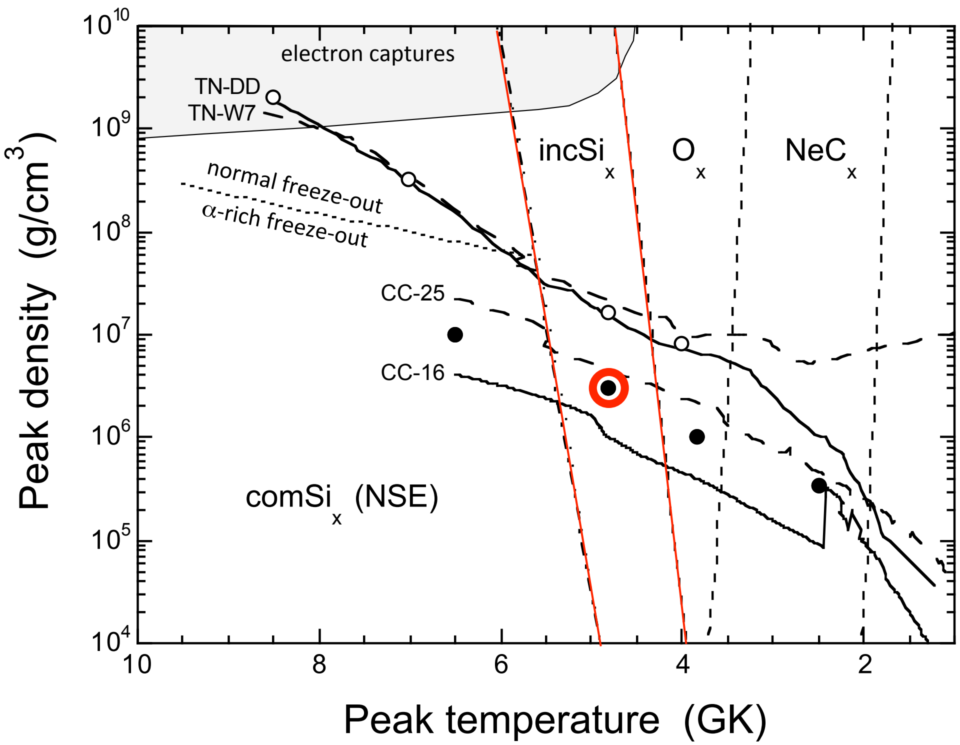


- two quasi-equilibrium clusters form: one built around ^{28}Si [highest B/A in this mass region], the other one built around iron peak [even higher B/A]
- situation resembles hydrostatic silicon burning
- if enough time would be available, all silicon would be destroyed and matter would reach NSE
- however, expansion causes freeze-out before this can happen
- since a significant fraction of ^{28}Si remains: "incomplete explosive silicon burning"

INCOMPLETE EXPLOSIVE Si BURNING

T=4.8 GK

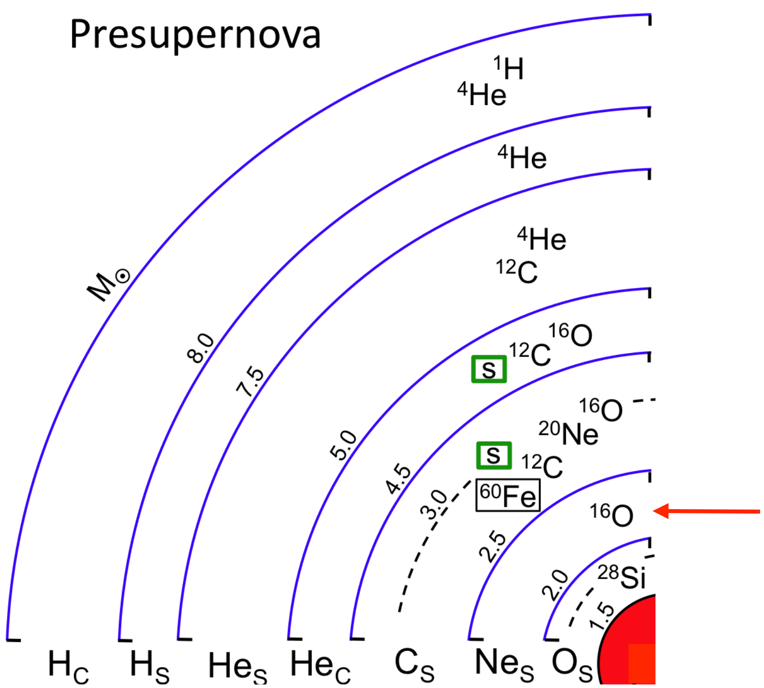




main nucleosynthesis products: ^{56}Ni, ^{28}Si, intermediate-mass elements

EXPLOSIVE O BURNING

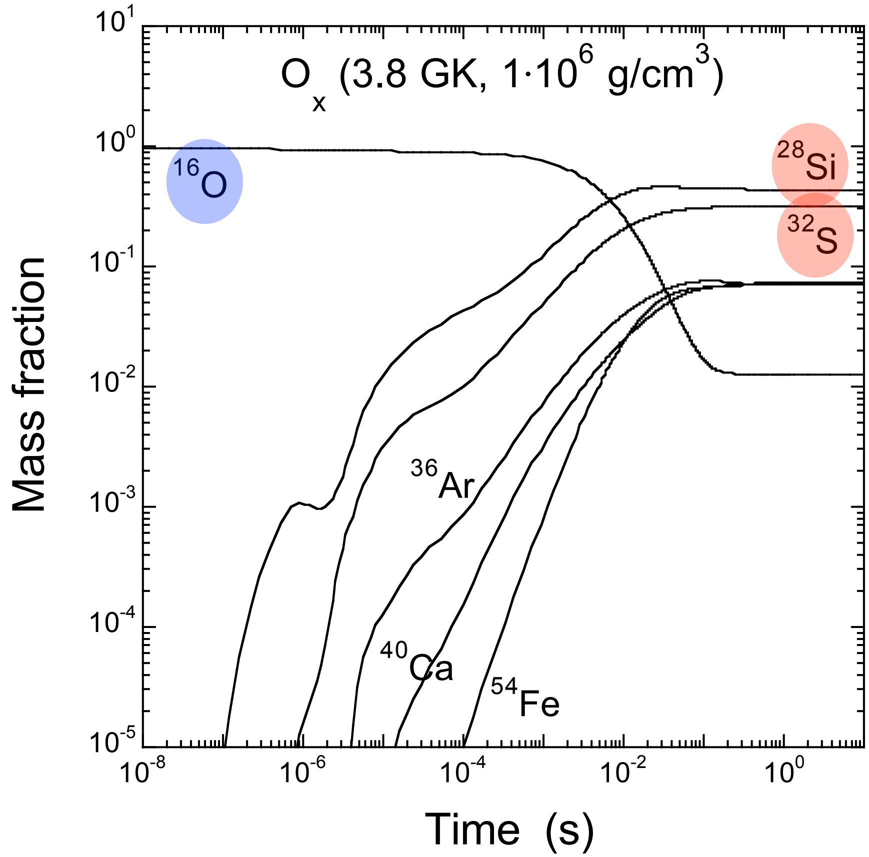
T=3.8 GK

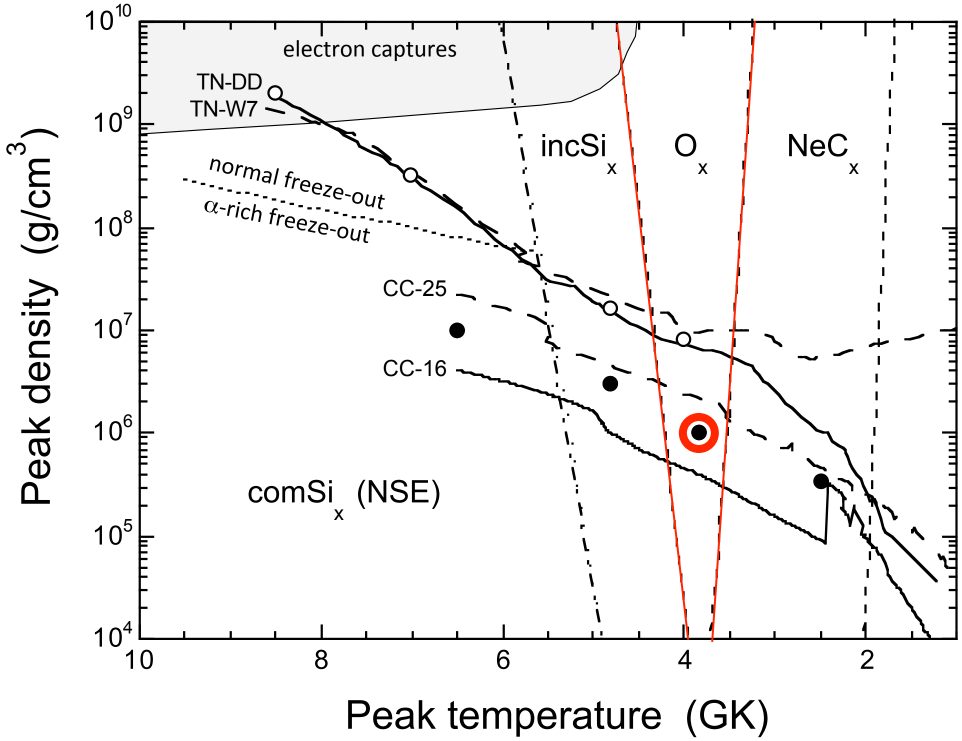


- next layer reached by shock is composed of ^{16}O
- process similar to incomplete silicon burning: ^{16}O fuel is depleted via ^{16}O+^{16}O, ^{16}O(γ,α)^{12}C, etc., giving rise to two QSE clusters in the mass regions of Si and Fe
- however, temperature is lower and thus less matter is converted to the Fe peak and much more material remains locked in the silicon region

EXPLOSIVE O BURNING

T=3.8 GK

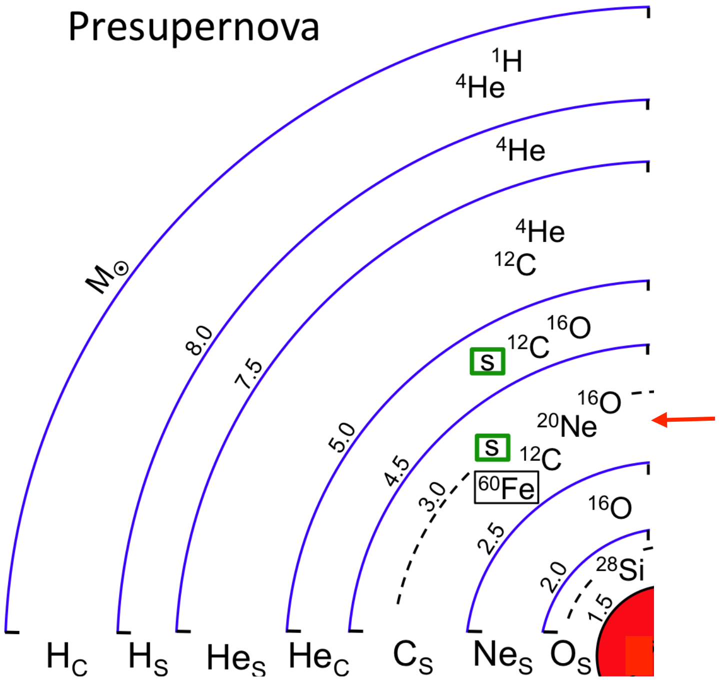




most abundant nuclides after freeze-out: ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca ("α-elements") and some iron peak species

EXPLOSIVE NeC BURNING

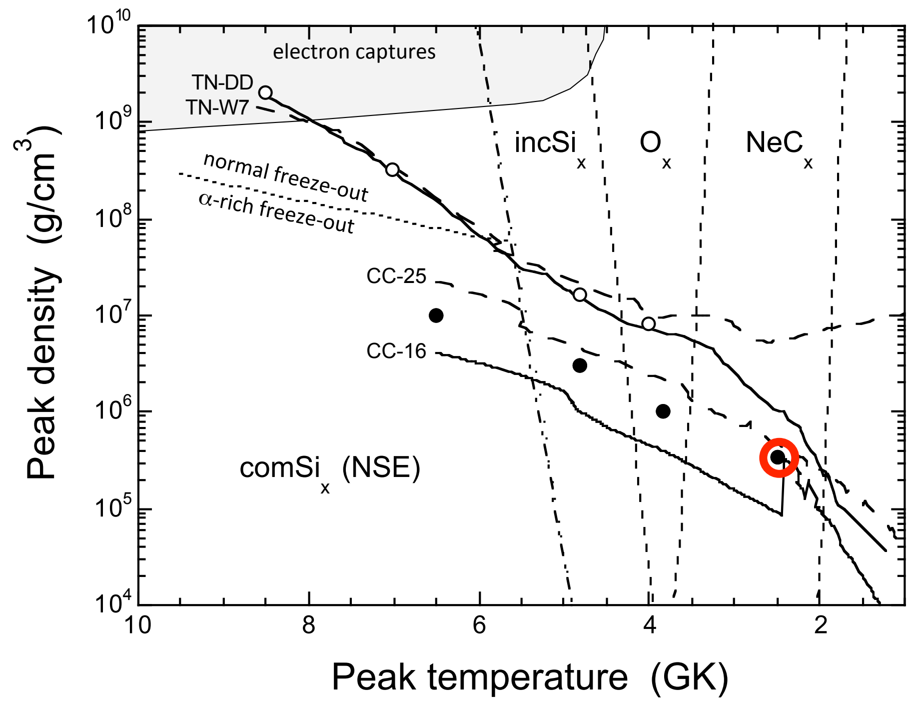
T=2.5 GK



• next layer reached by shock is composed of ^{16}O, ^{20}Ne, ^{12}C

• thus ^{20}Ne, and to a lesser extent ^{12}C, will burn explosively

• but T is too small for establishing QSE and the forward and reverse nuclear reactions operate far from equilibrium



• abundance of a given species depends on initial composition and detailed reaction rates

EXPLOSIVE NeC BURNING

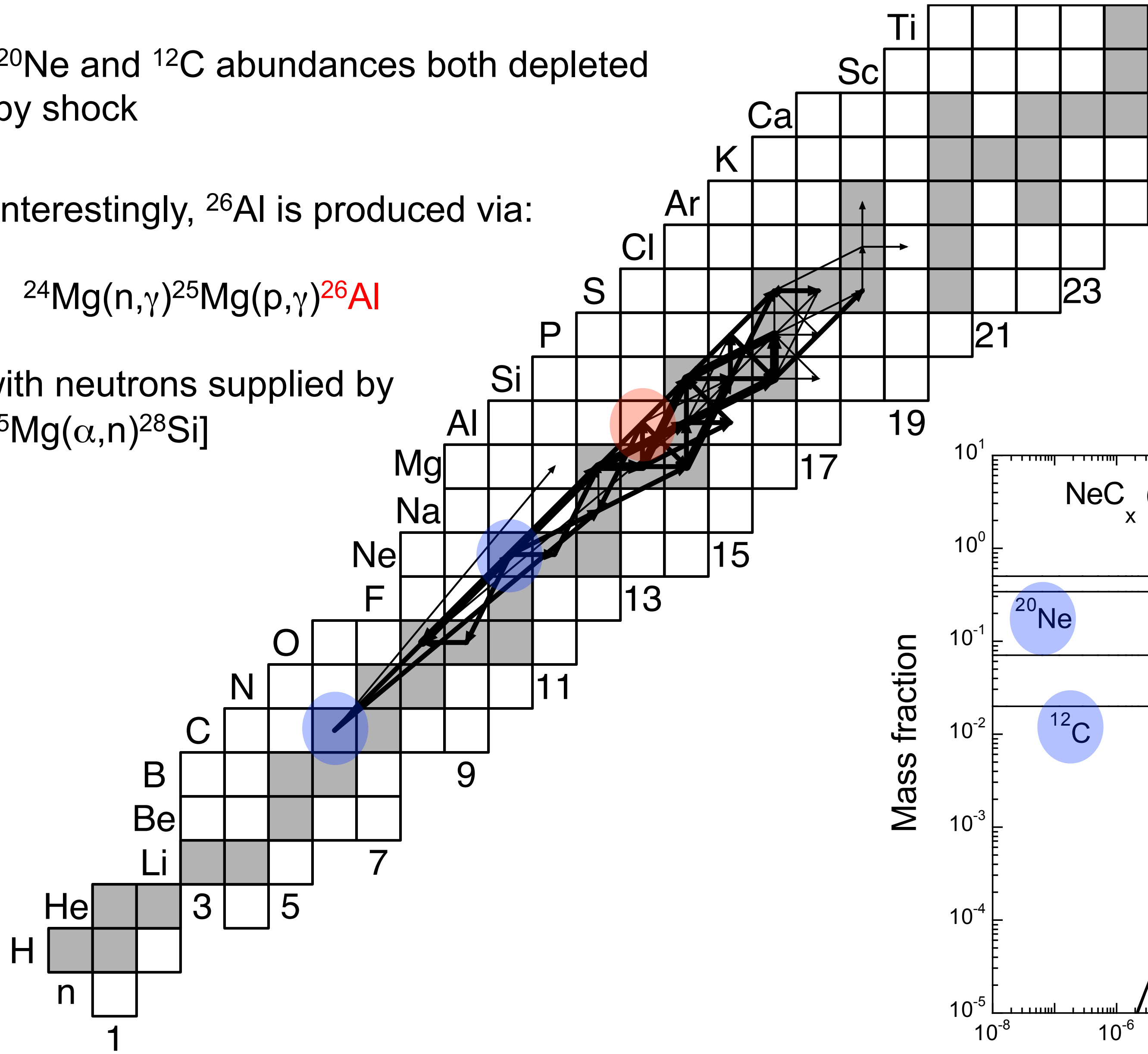
T=2.5 GK

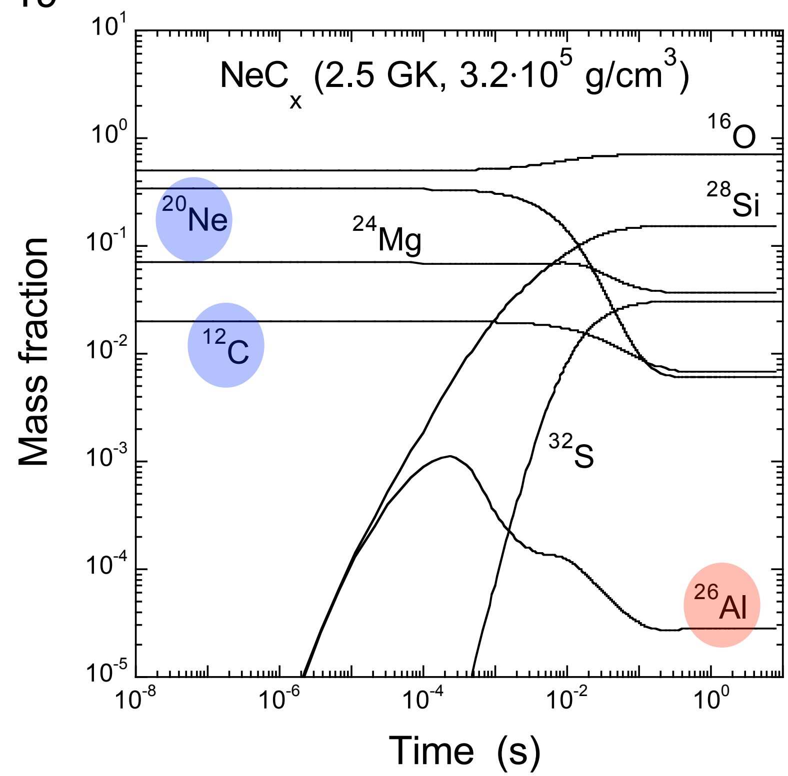
- ^{20}Ne and ^{12}C abundances both depleted by shock

- interestingly, ^{26}Al is produced via:

^{24}Mg(n,γ)^{25}Mg(p,γ)^{26}Al

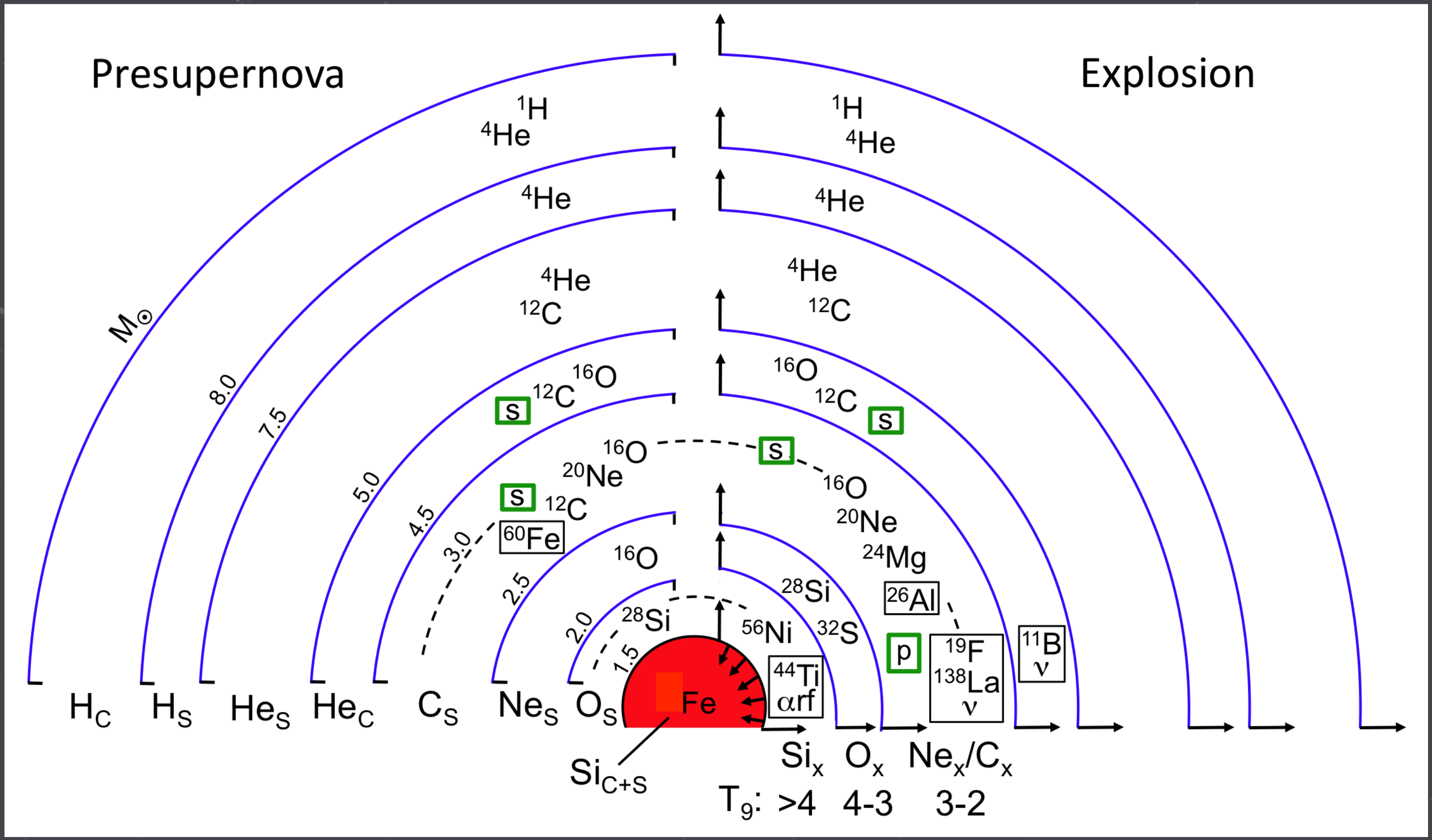
[with neutrons supplied by ^{25}Mg(α,n)^{28}Si]





EXPLOSIVE BURNING: SHOCK MOVING THROUGH "ONION" LAYERS

about 1 hour after core collapse, the shock reaches stellar surface



J. Jose & C. Iliadis, "The Unfinished Quest for the Origin of the Elements",
Rep. Prog. Phys. 74, 096901 (2011)