Nuclear properties and the astrophysical *r* process

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University of Jyväskylä

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Nuclear properties and the astrophysical *r* process

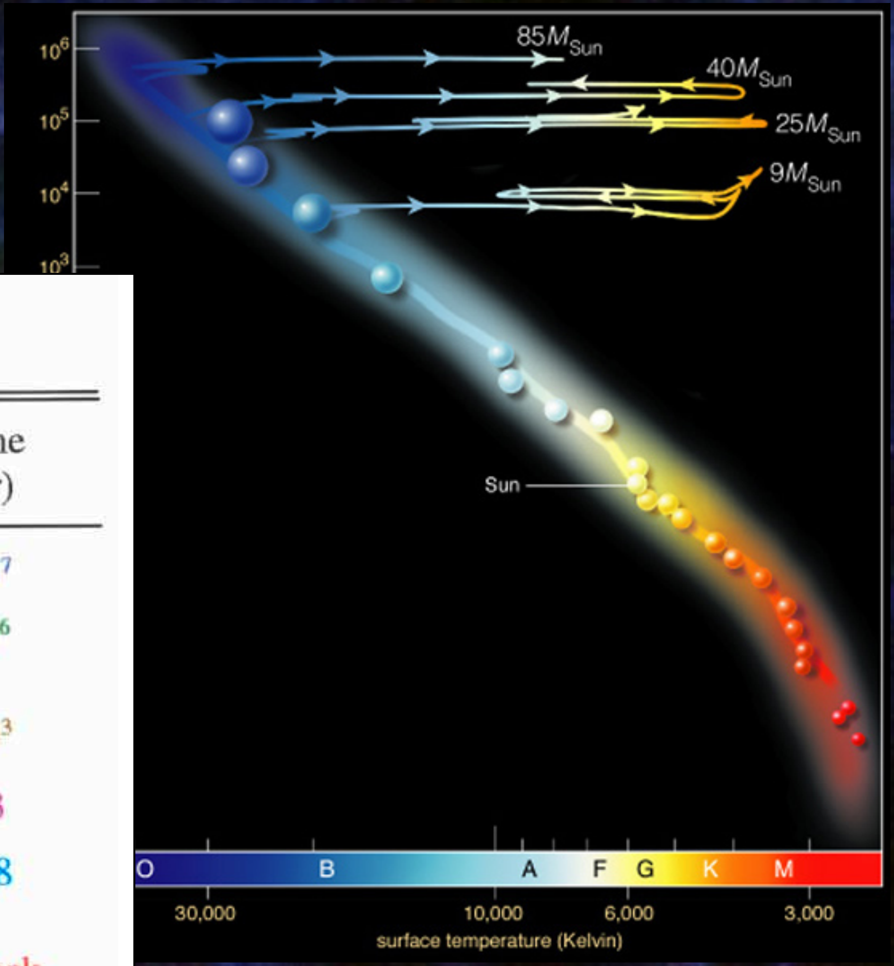
What is the astrophysical origin of the heaviest elements??

Class #	Subject
1	Introduction, chemical abundances
2	Origins of the elements up to helium
3	Origins of the elements up to iron, *r*-process dynamics
4	Astrophysical sites of the *r* process
5	Nuclear data for the *r* process

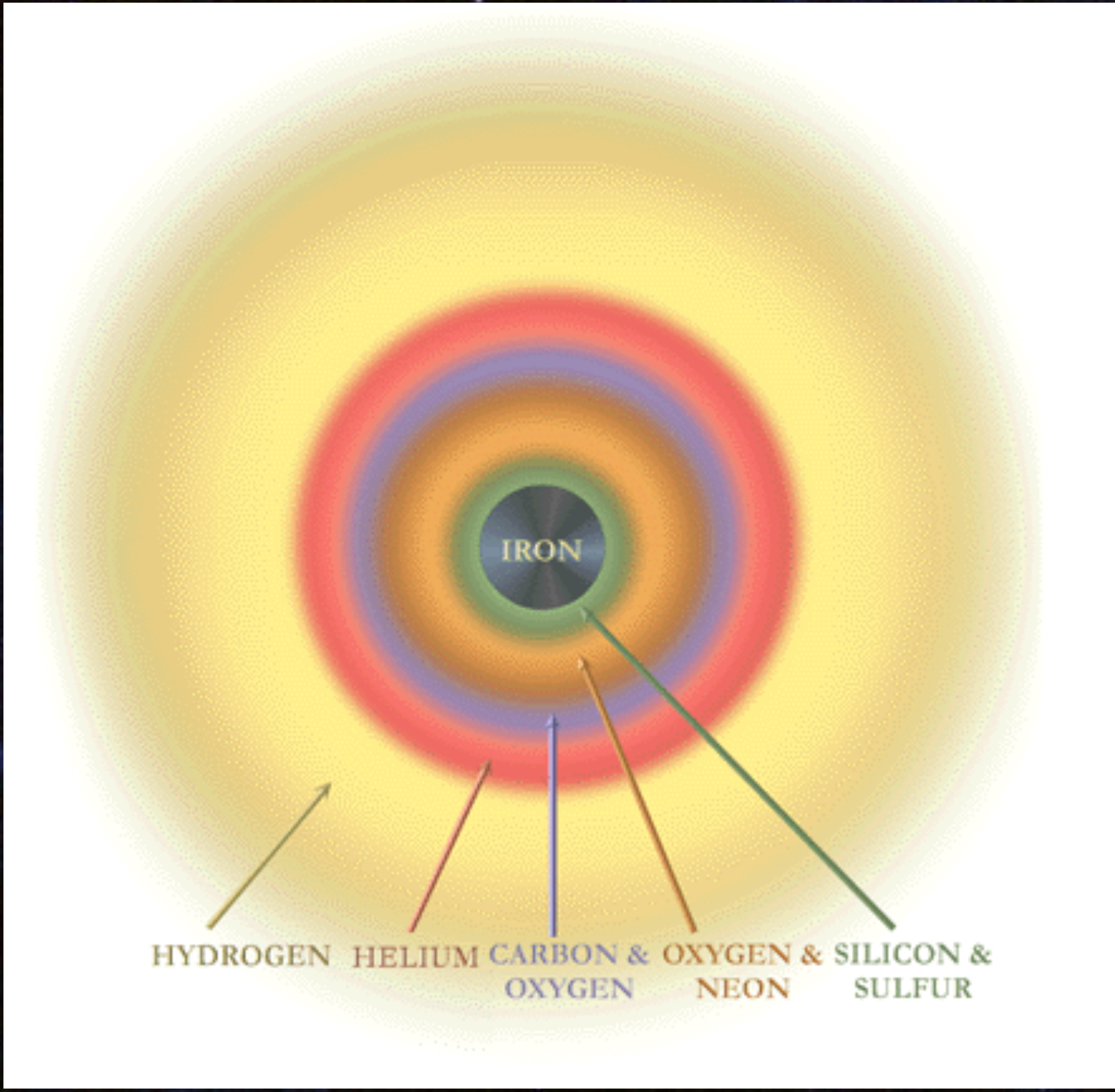
advanced burning stages: overview

Advanced Nuclear Burning Stages
(e.g., 20 solar masses)

Fuel	Main Product	Secondary Products	Temp (10^9 K)	Time (yr)
H	He	^{14}N	0.02	10^7
He	C,O	^{18}O, ^{22}Ne s- process	0.2	10^6
C	Ne, Mg	Na	0.8	10^3
Ne	O, Mg	Al, P	1.5	3
O	Si, S	Cl, Ar K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week



end-stage massive star



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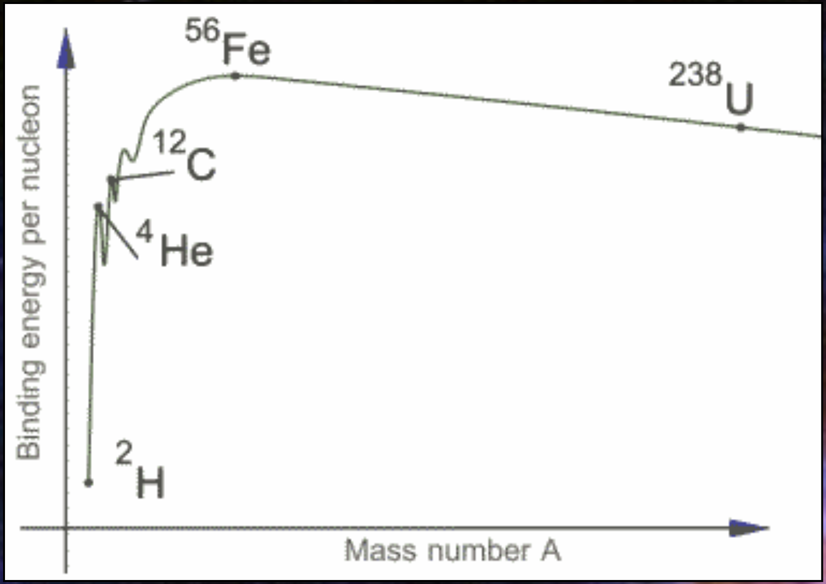
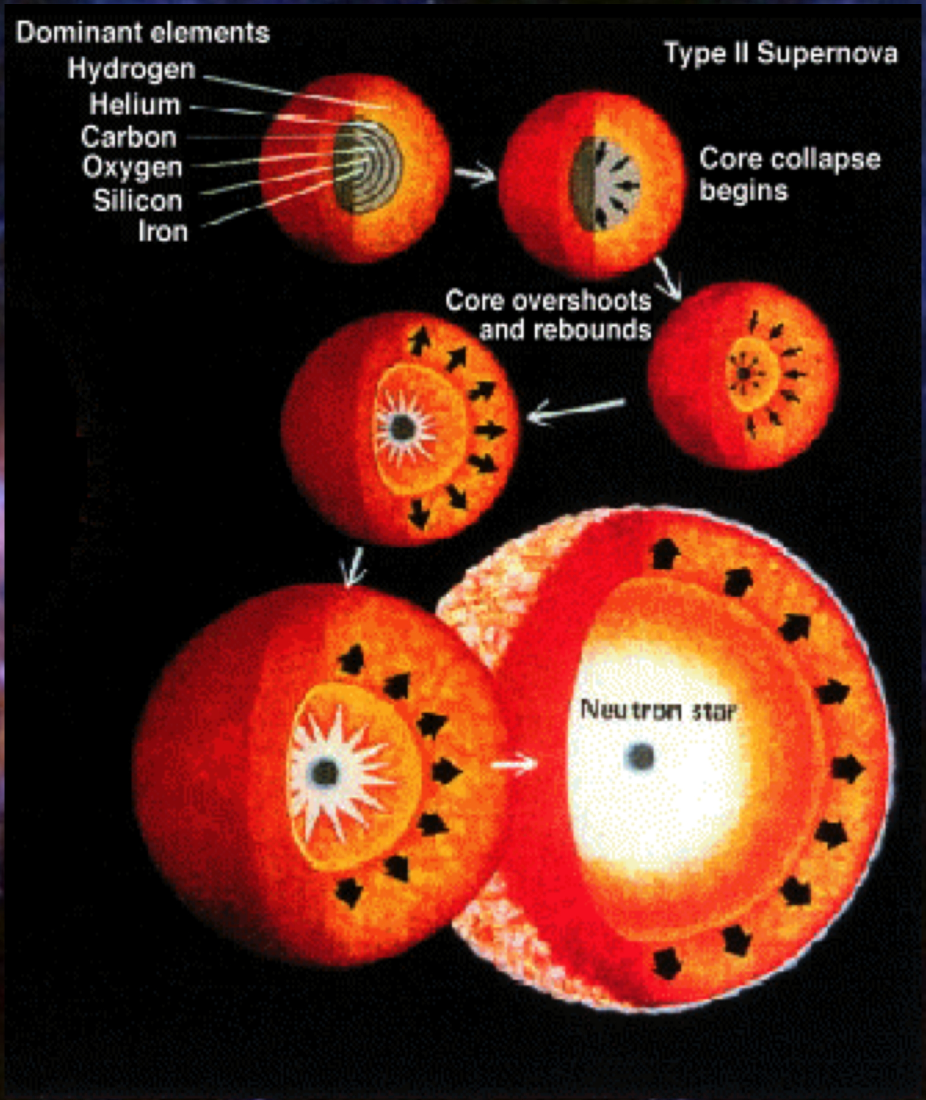
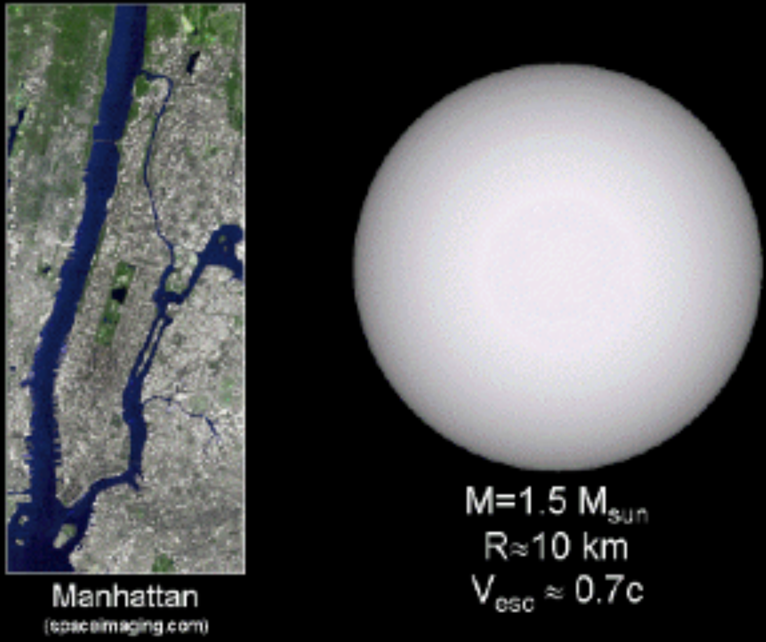
iron core collapse

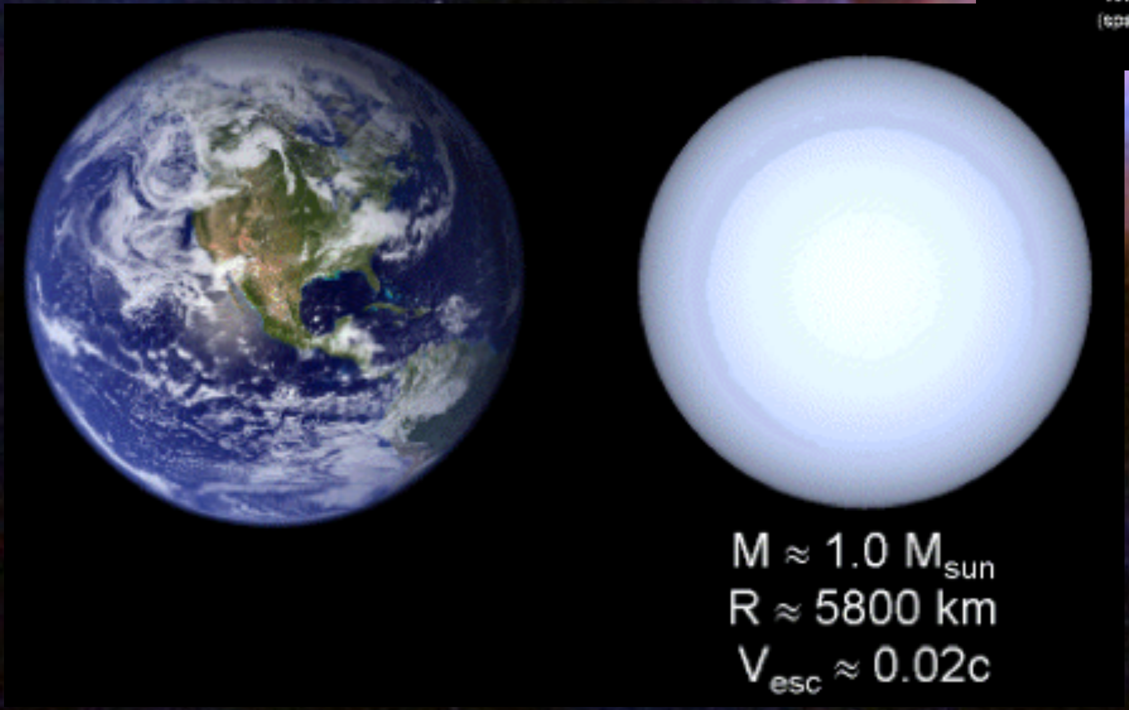




neutron stars and white dwarfs



white dwarfs: Earth-sized



neutron stars: town-sized

A teaspoon of neutron star material weighs about as much as…

A – the Giza pyramids

B – 400 Airbus A380 airplanes

C – the mass of the entire human population

D – the amount of CO_2 put by humans into the atmosphere annually

A teaspoon of neutron star material weighs about as much as…

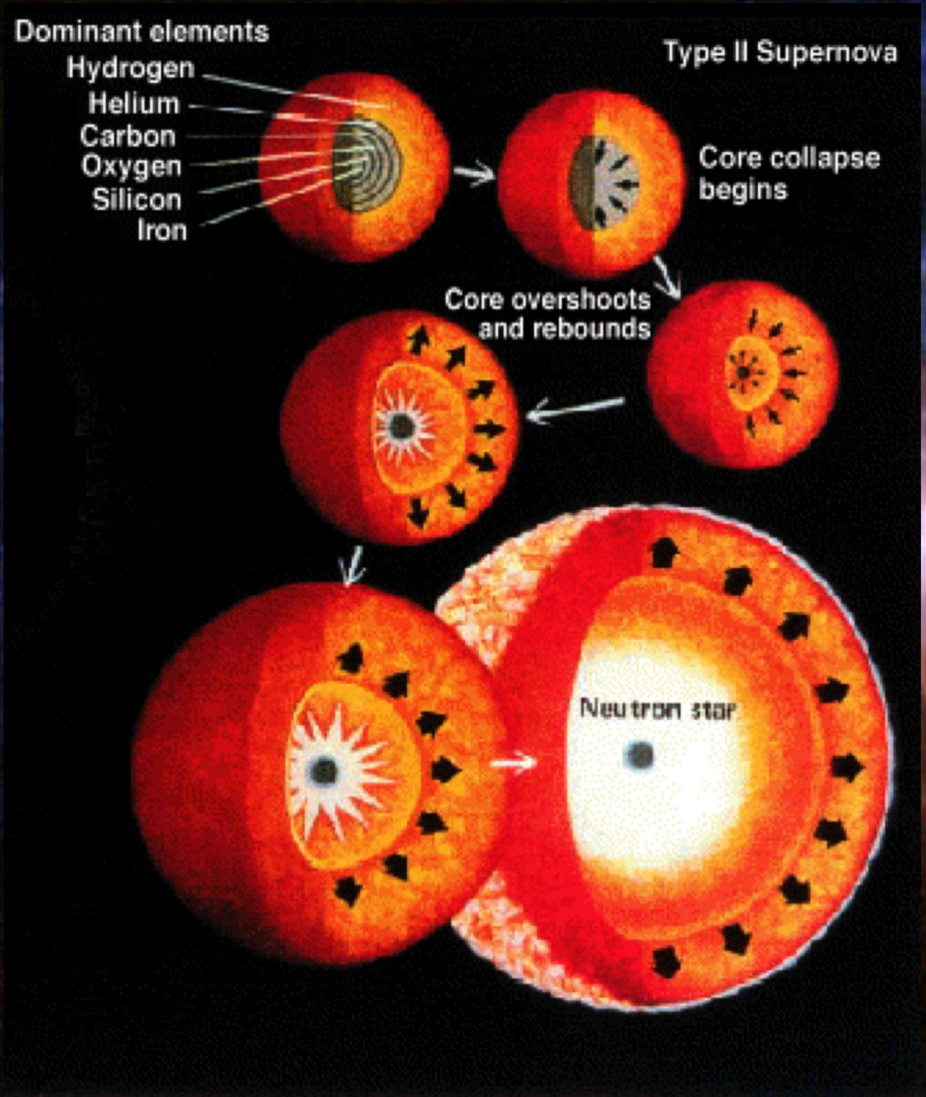
A – the Giza pyramids: 6.3 billion tons

B – 400 Airbus A380 airplanes: 400 million tons

C – the mass of the entire human population: 4 billion tons

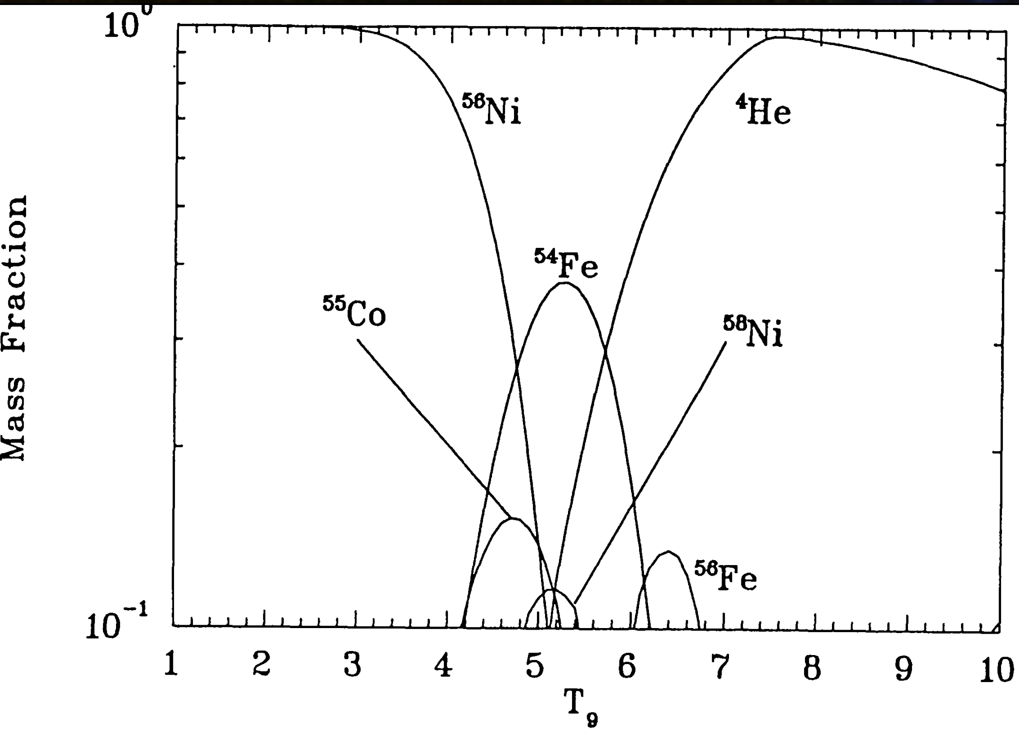
D – the amount of CO_2 put by humans into the atmosphere annually: 40 billion tons

explosive burning in core-collapse supernovae

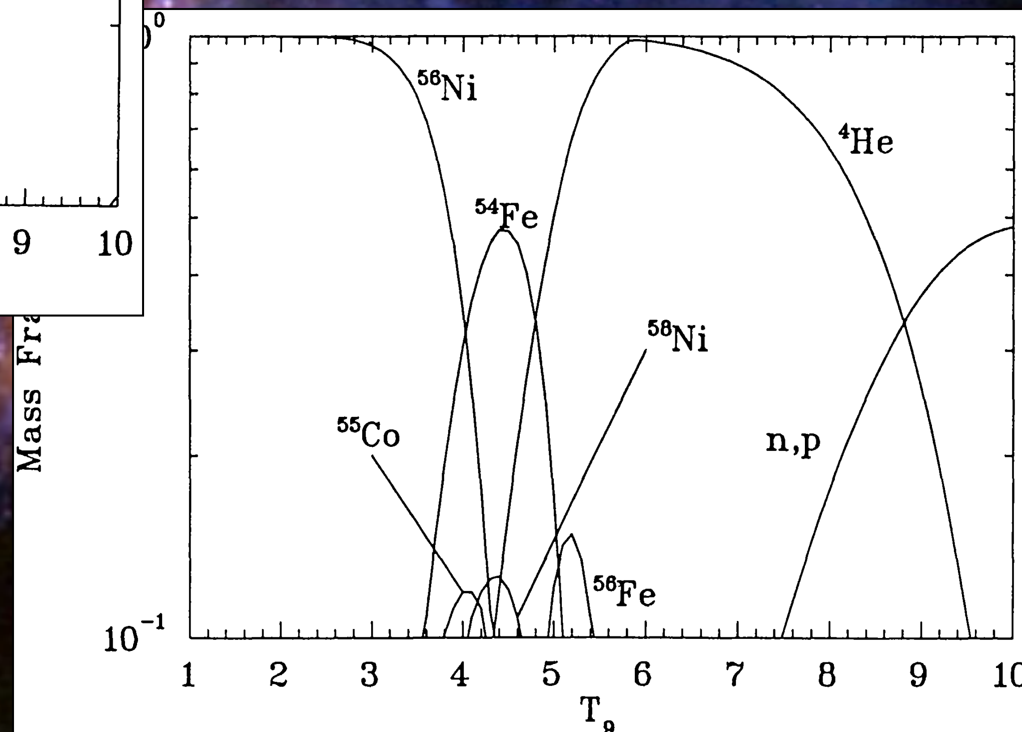


Outgoing shock wave heats inner Si and O layers – nuclear statistical equilibrium (NSE) is achieved and rapidly freezes out as shock passes

sample NSE distributions



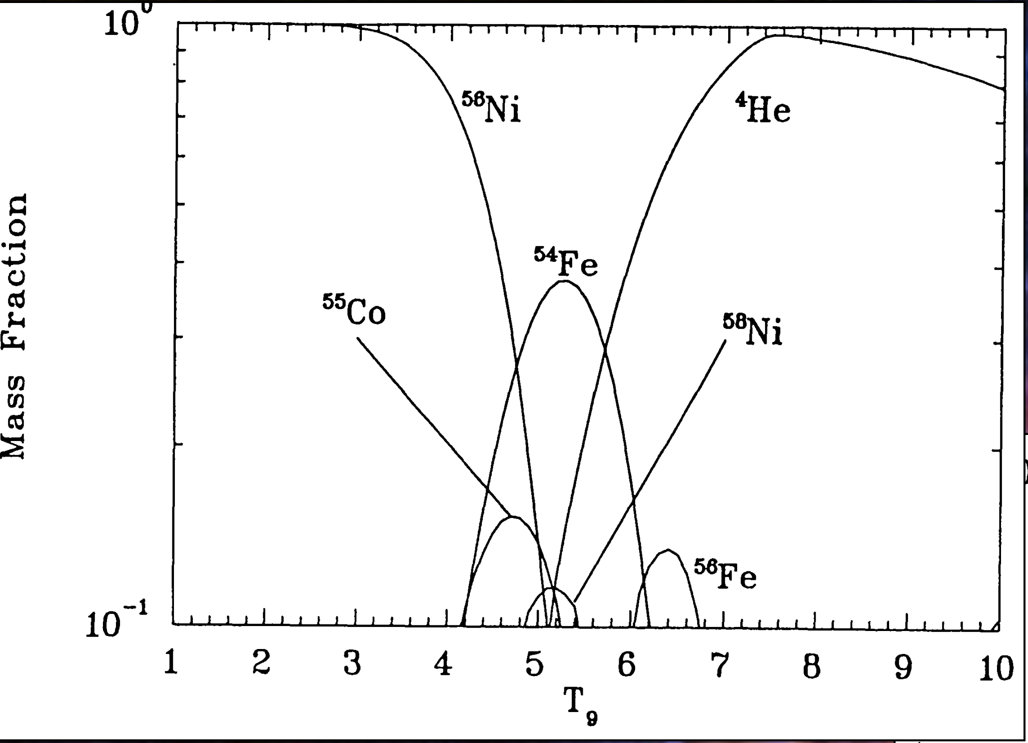
entropy $s/k = 10$, $Y_e = 0.5$



from Meyer (1994)

entropy $s/k = 100$, $Y_e = 0.5$

sample NSE distributions



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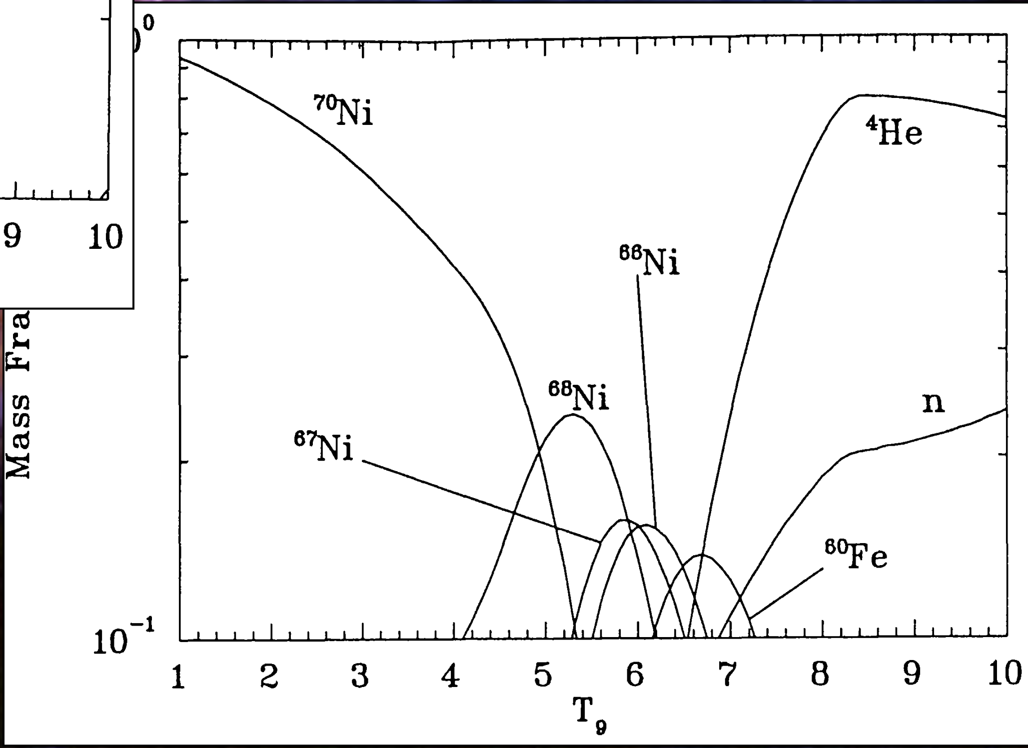
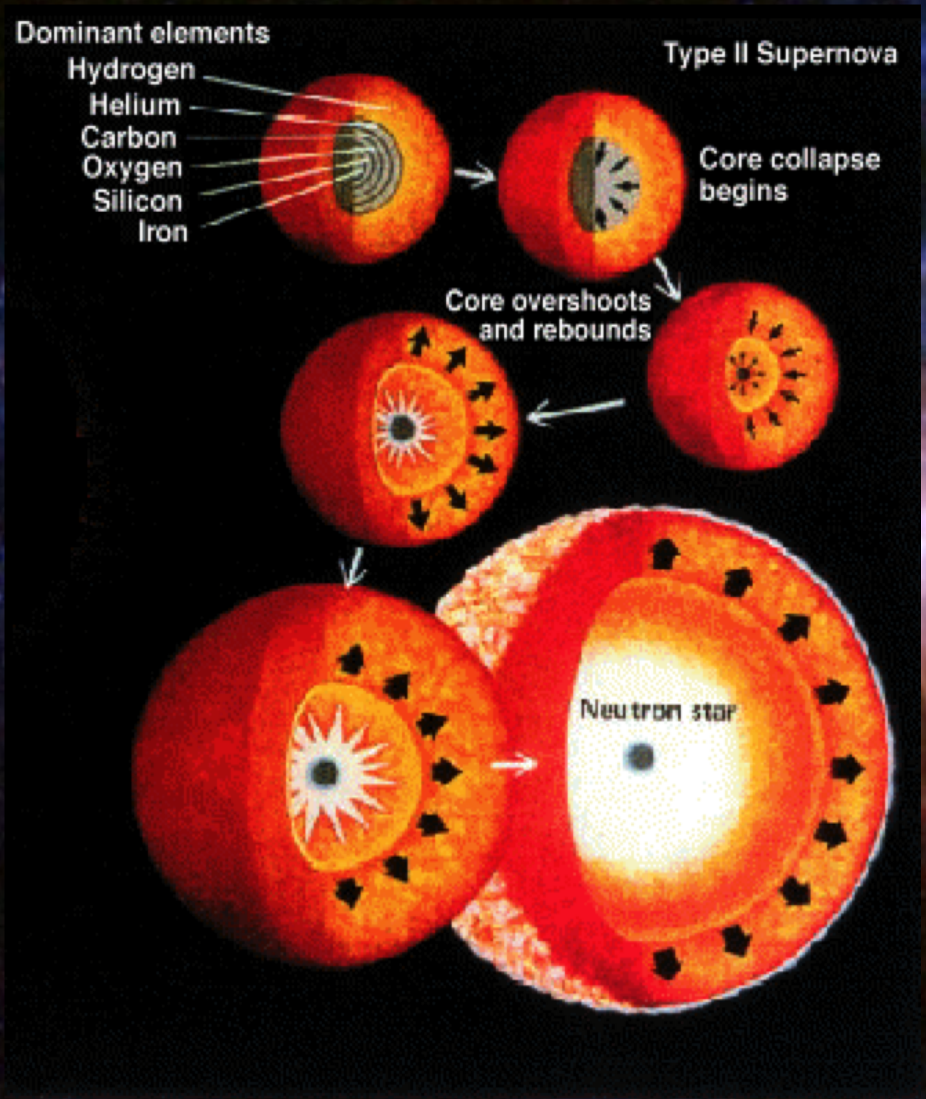


from Meyer (1994)

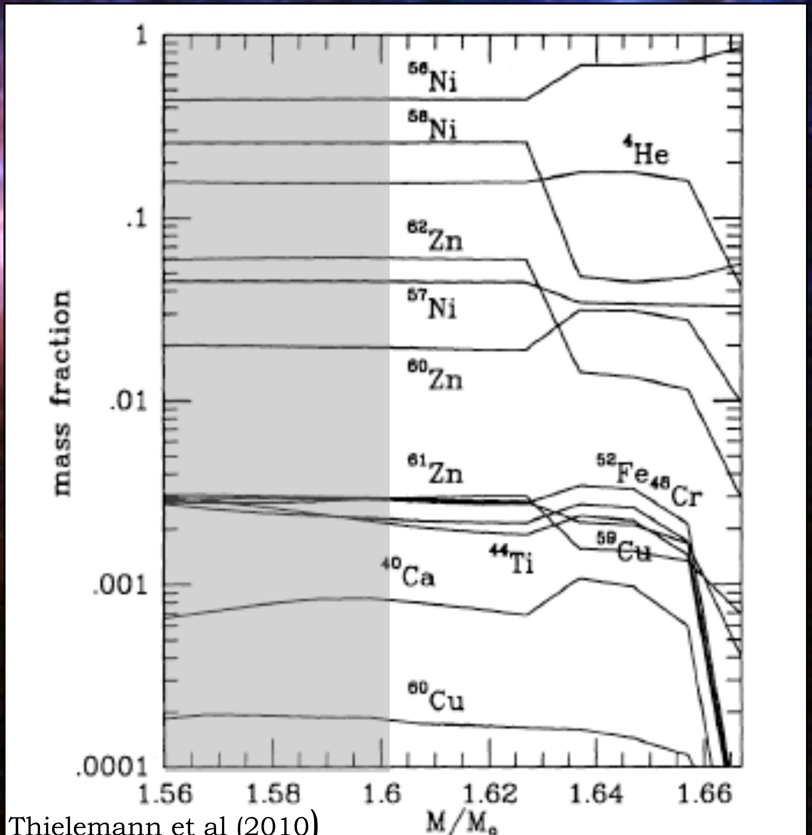
(Can do your own NSE calculations at: http://nucleo.ces.clemson.edu/pages/nse/0.1)

entropy $s/k = 10$, $Y_e = 0.4$

explosive burning in core-collapse supernovae

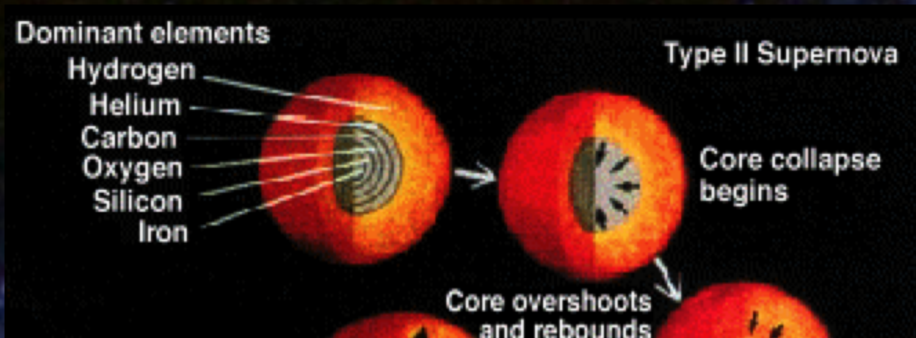


Outgoing shock wave heats inner Si and O layers – NSE is achieved and rapidly freezes out as shock passes

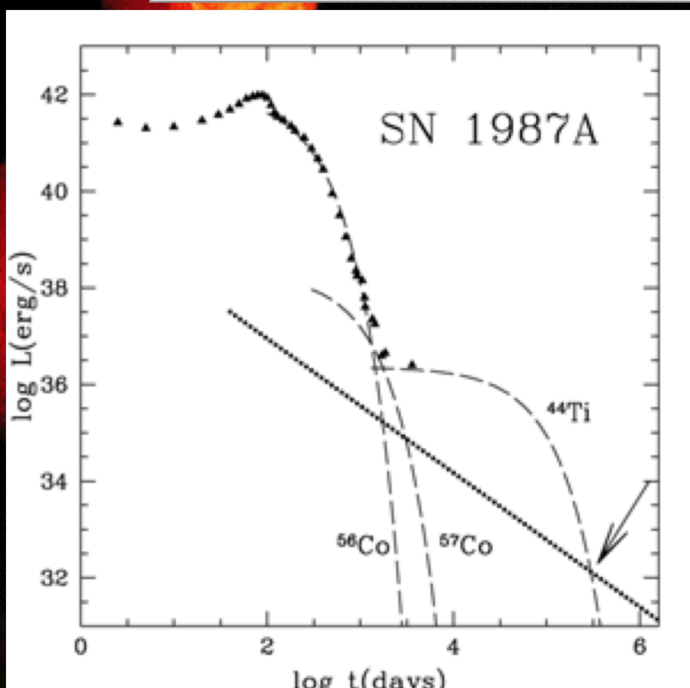


Thielemann et al (2010)

explosive burning in core-collapse supernovae



$^{56}Ni \longrightarrow$ $^{56}Co \longrightarrow$ ^{56}Fe
(6 days) (77 days)



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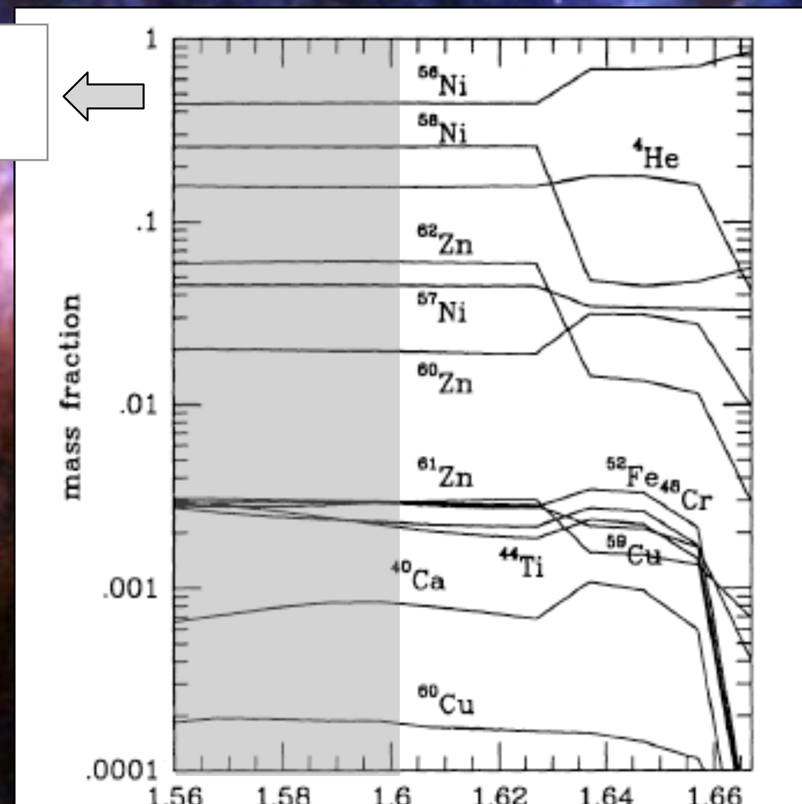
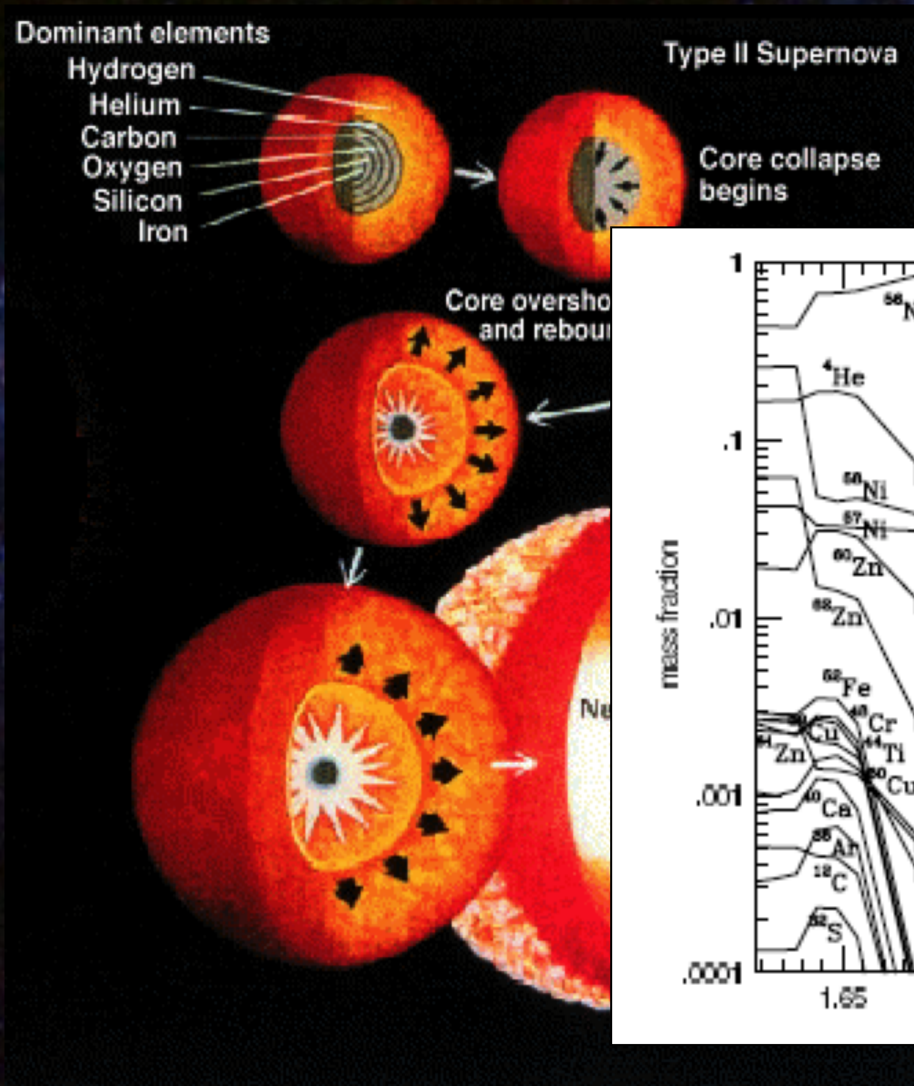
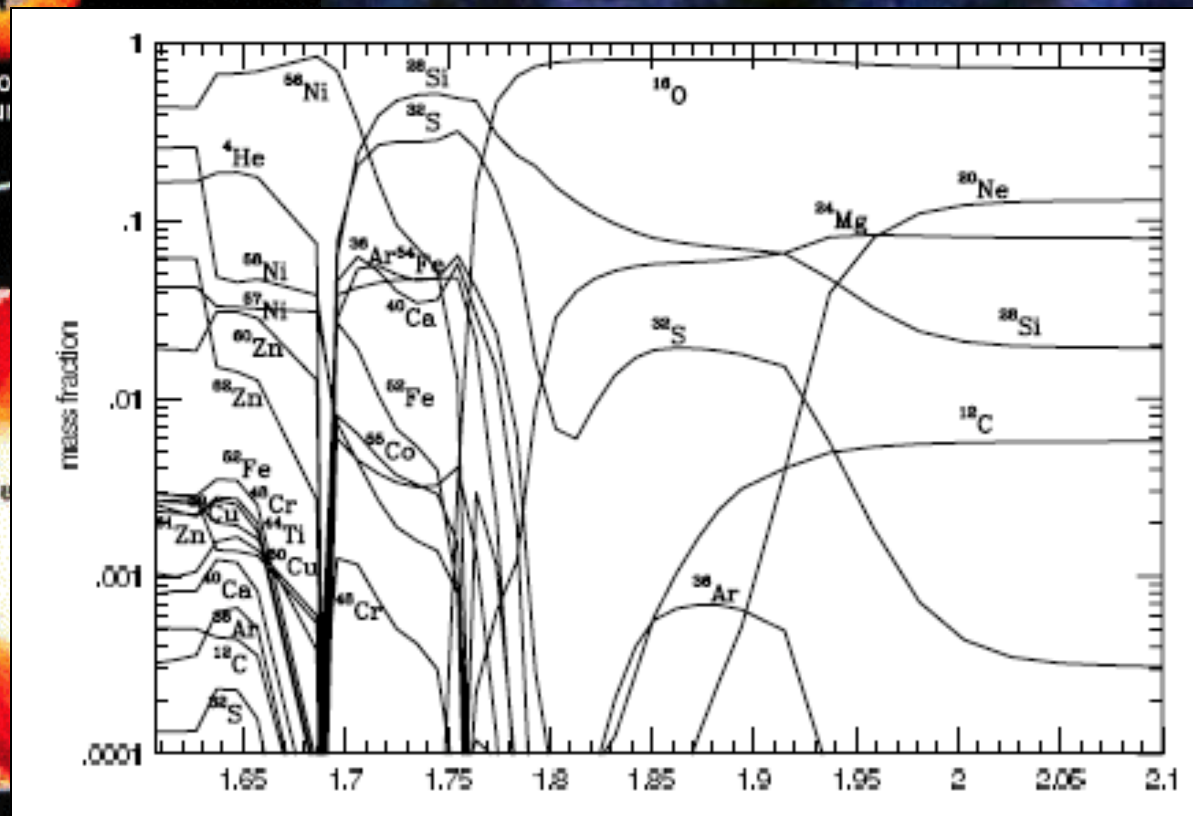


Thielemann et al (2010)

explosive burning in core-collapse supernovae

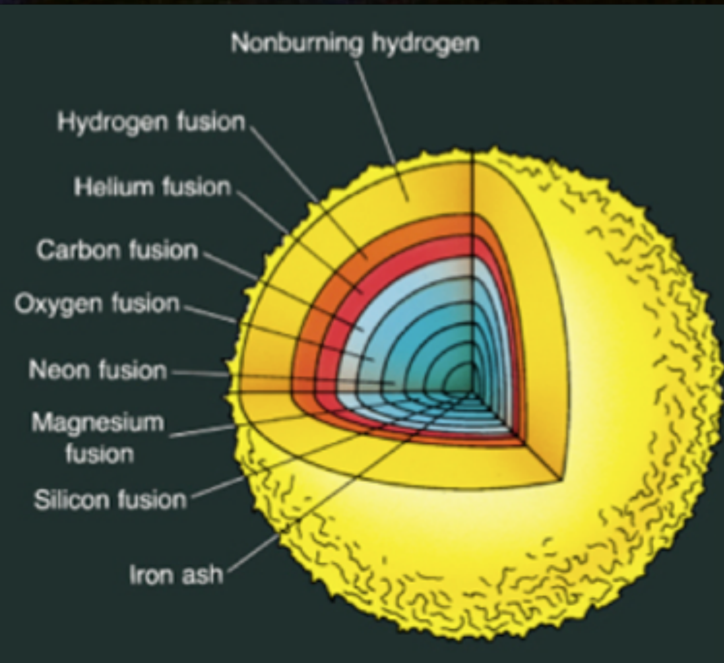


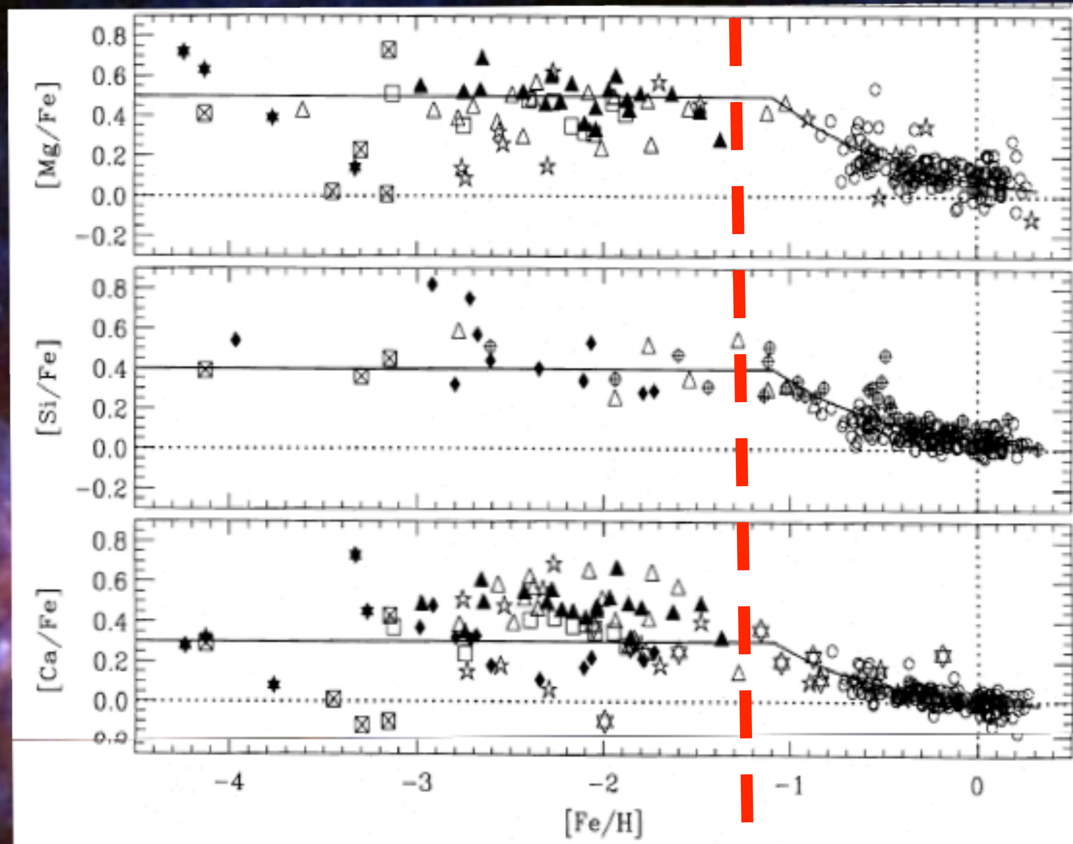
explosive Si, O, Ne, and C burning follow as the shock moves outward



Thielemann et al (2010)

abundance trends: alpha elements





Ne, Mg, Si, S, Ar, Ca, Ti

Synthesis during stellar evolution and α-capture in supernovae of massive stars (> 8x mass of Sun)

α elements produced in explosions of massive stars

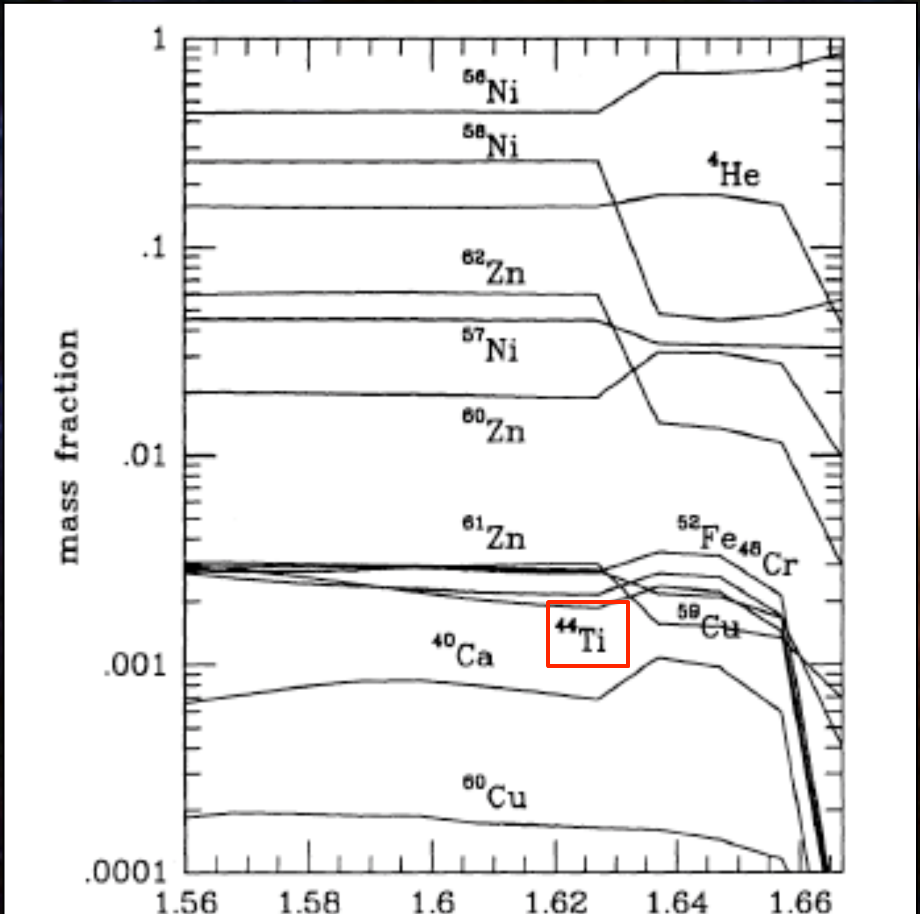
SNe nucleosynthesis: long-lived radionuclides

^{44}Ti

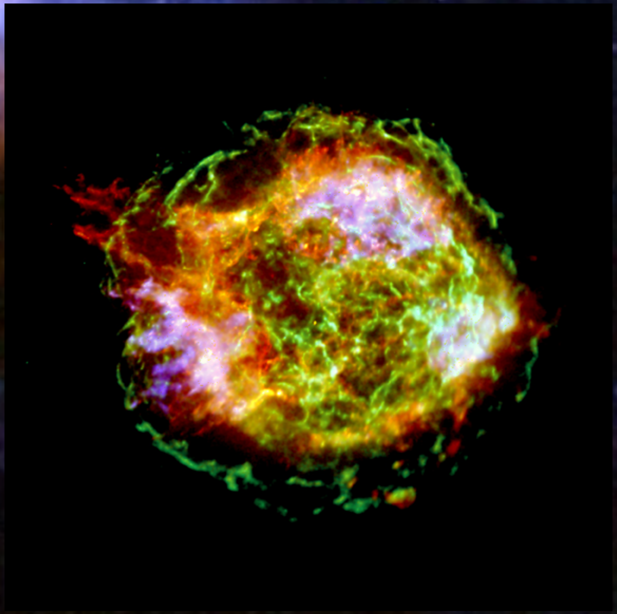
created in alpha-rich freezeout from NSE, close to the mass cut

$T_{1/2} \sim 60$ years

x-rays from the decay chain observed in SNe remnants Cas-A and RX J0852.0-4622



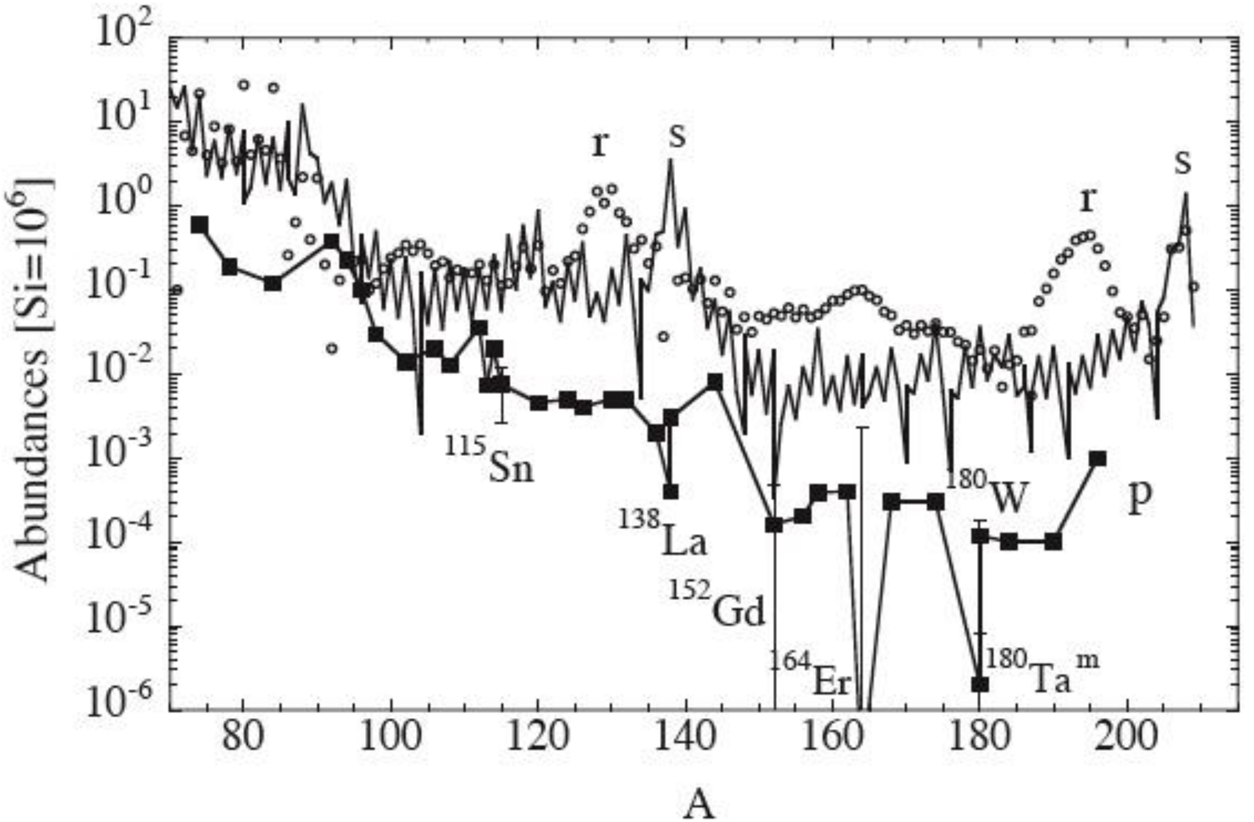
Thielemann et al (2010)



SNe nucleosynthesis: proton-rich heavy elements

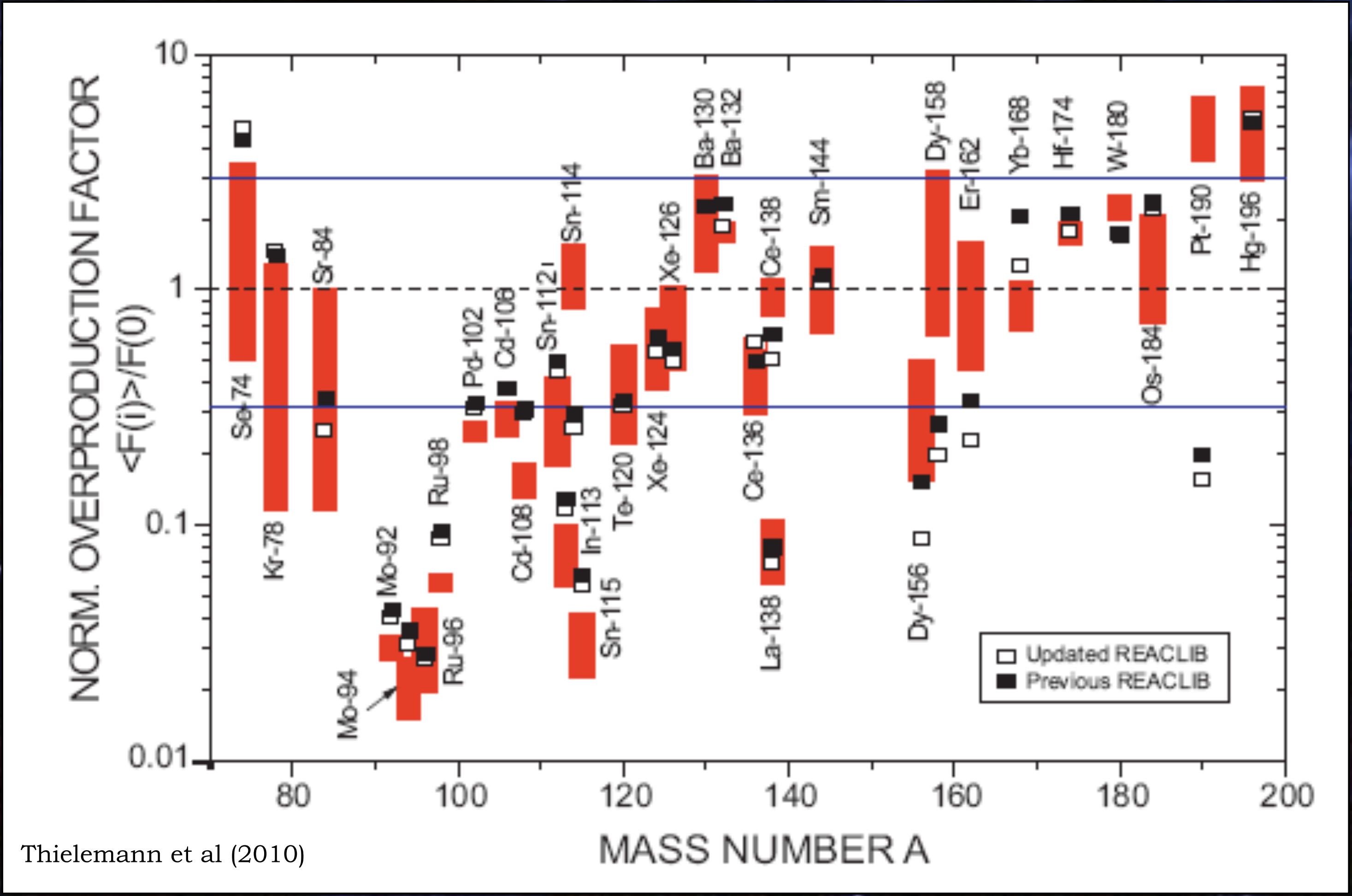
heavy *p*-process nuclei are made by (γ,*n*) photodissociations of pre-existing *r*- and *s*- process nuclei

M. Arnould, S. Goriely / Physics Reports 384 (2003) 1–84



SNe nucleosynthesis: proton-rich heavy elements

but particularly the light *p*-process nuclei are insufficiently produced – need another contribution



Thielemann et al (2010)

In a core-collapse supernova, the gravitational binding energy of the star is converted primarily into:

A – radiation

B – kinetic energy of the ejecta

C – the synthesis of heavy nuclei

D – neutrinos

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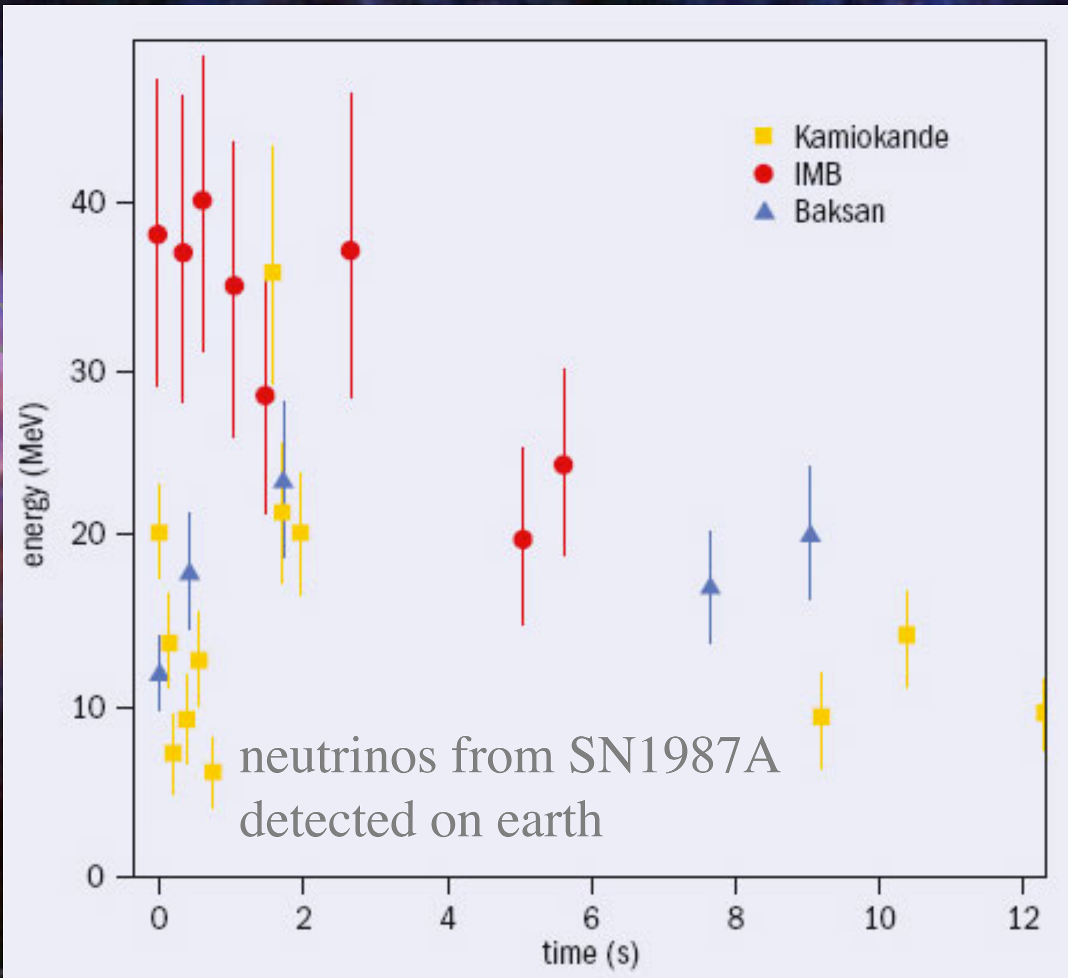
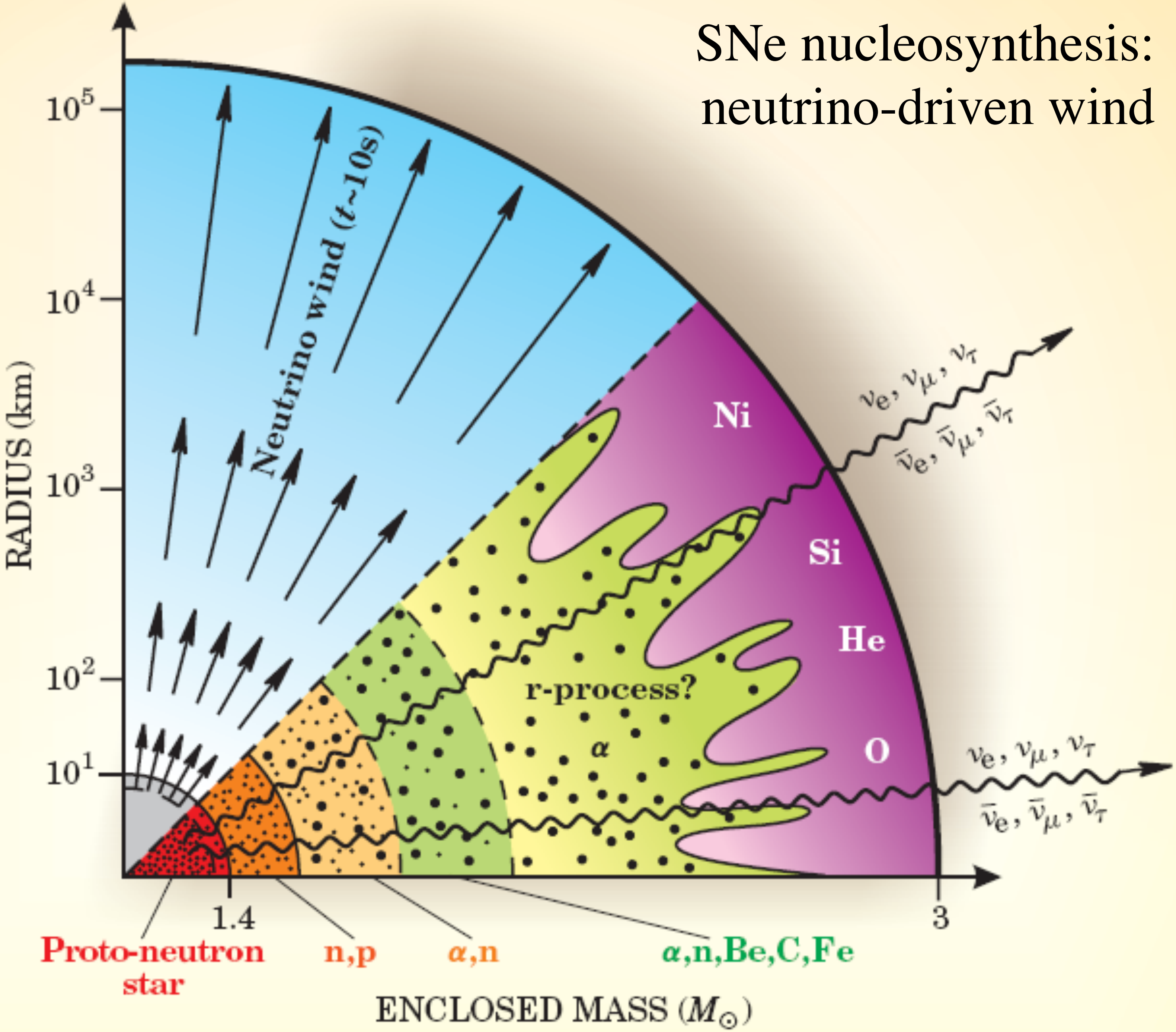


neutrinos from SN1987A detected on earth

SNe nucleosynthesis: neutrino-driven wind

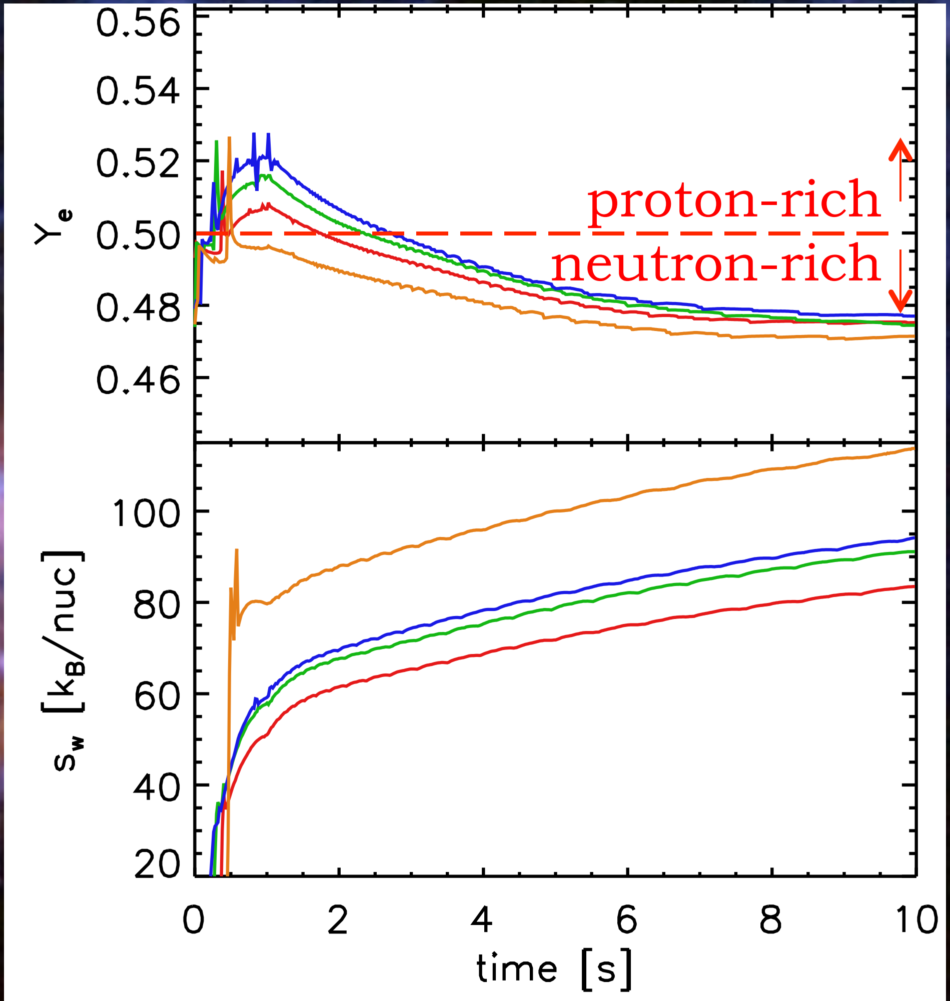


SNe nucleosynthesis: neutrino-driven wind

$$p + \bar{\nu}_e \leftrightarrow n + e^+$$
$$n + \nu_e \leftrightarrow p + e^-$$

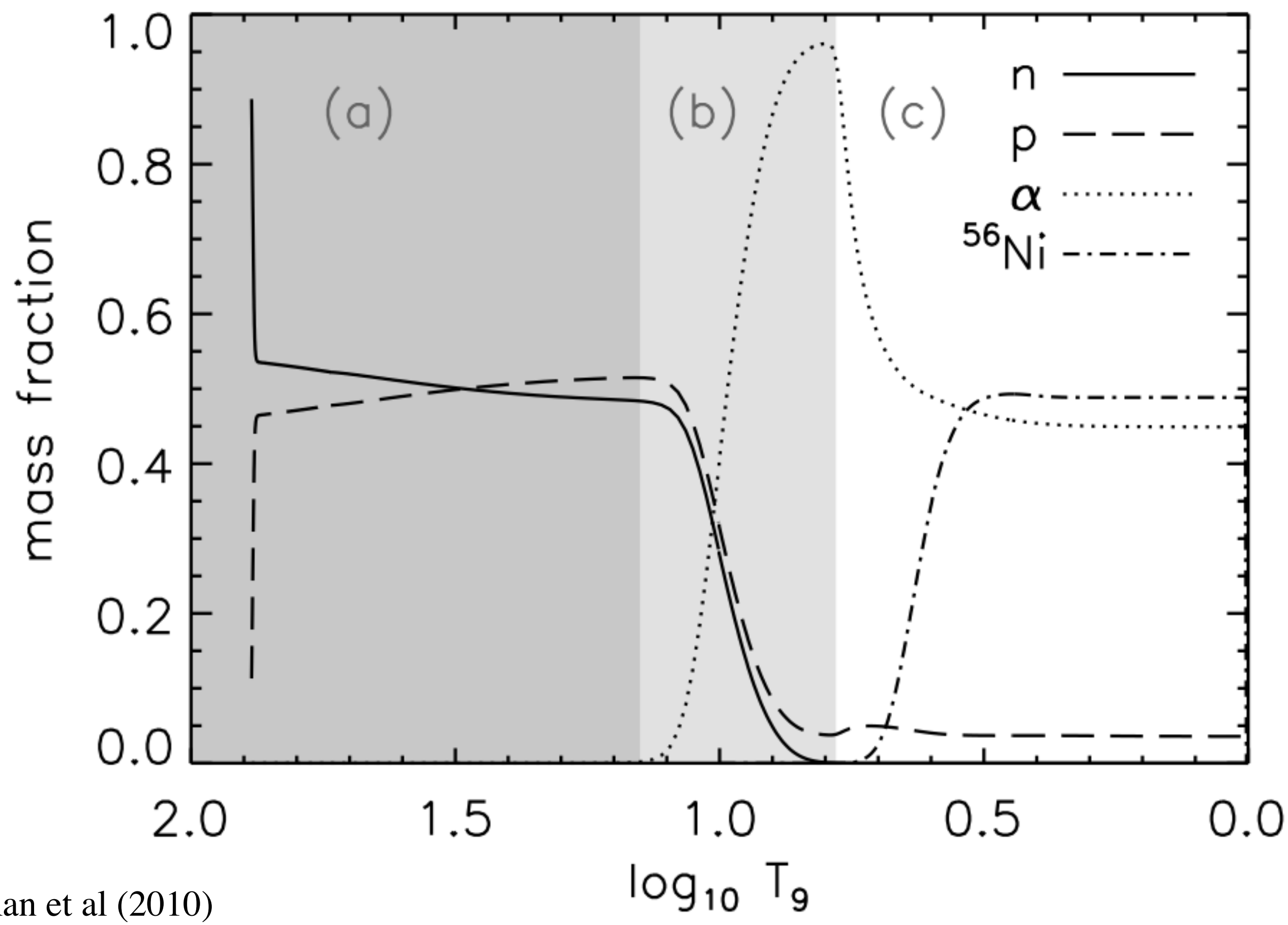
conditions are proton-rich if:

$$\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} < 4(m_n c^2 - m_p c^2)$$



Arcones and Janka (2007)

SNe nucleosynthesis: neutrino-driven wind



Surman et al (2010)

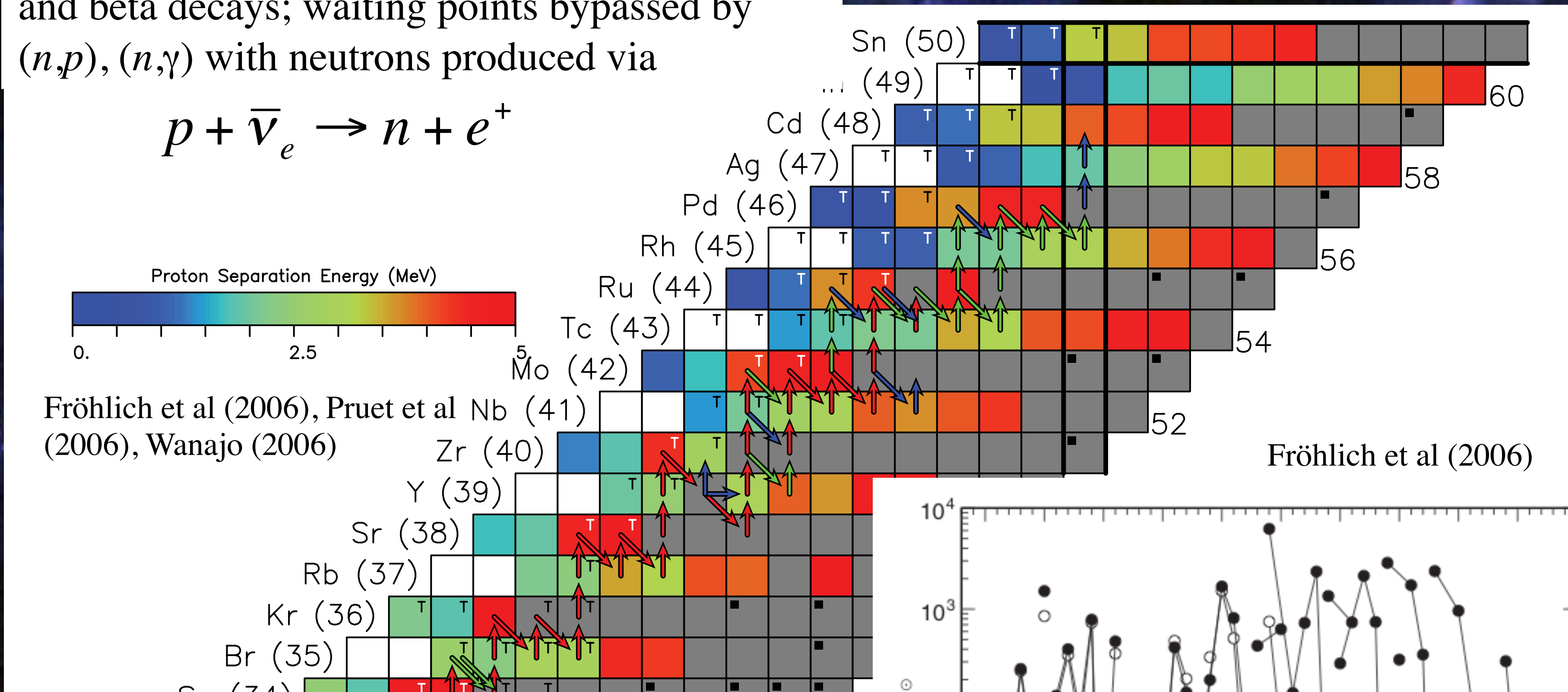
Disclaimer: this figure is not from a traditional supernova simulation, but it is an example of a proton-rich, α-rich freezeout from NSE

SNe nucleosynthesis: *νp* process

heavy elements built up by proton captures (p,γ) and beta decays; waiting points bypassed by (n,p), (n,γ) with neutrons produced via

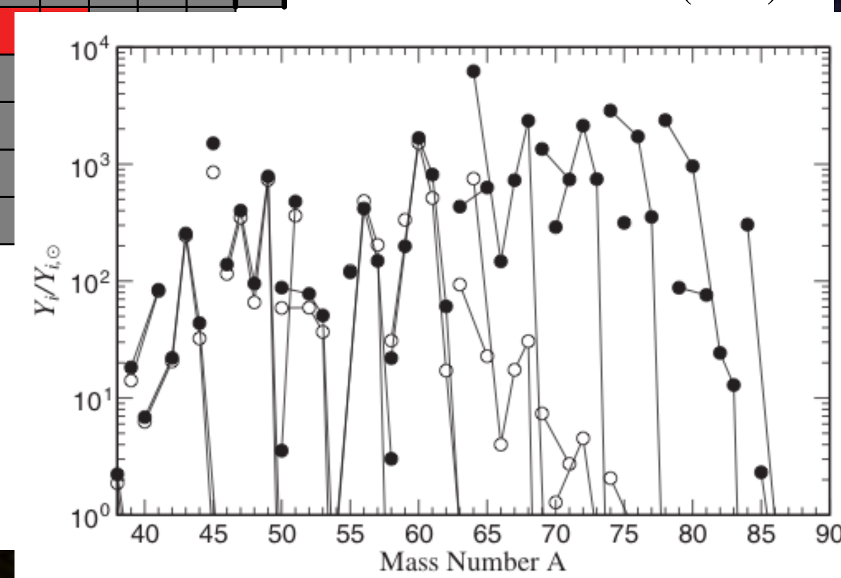
$$p + \bar{\nu}_e \rightarrow n + e^+$$

Pruet et al (2006)



Fröhlich et al (2006), Pruet et al (2006), Wanajo (2006)

Fröhlich et al (2006)



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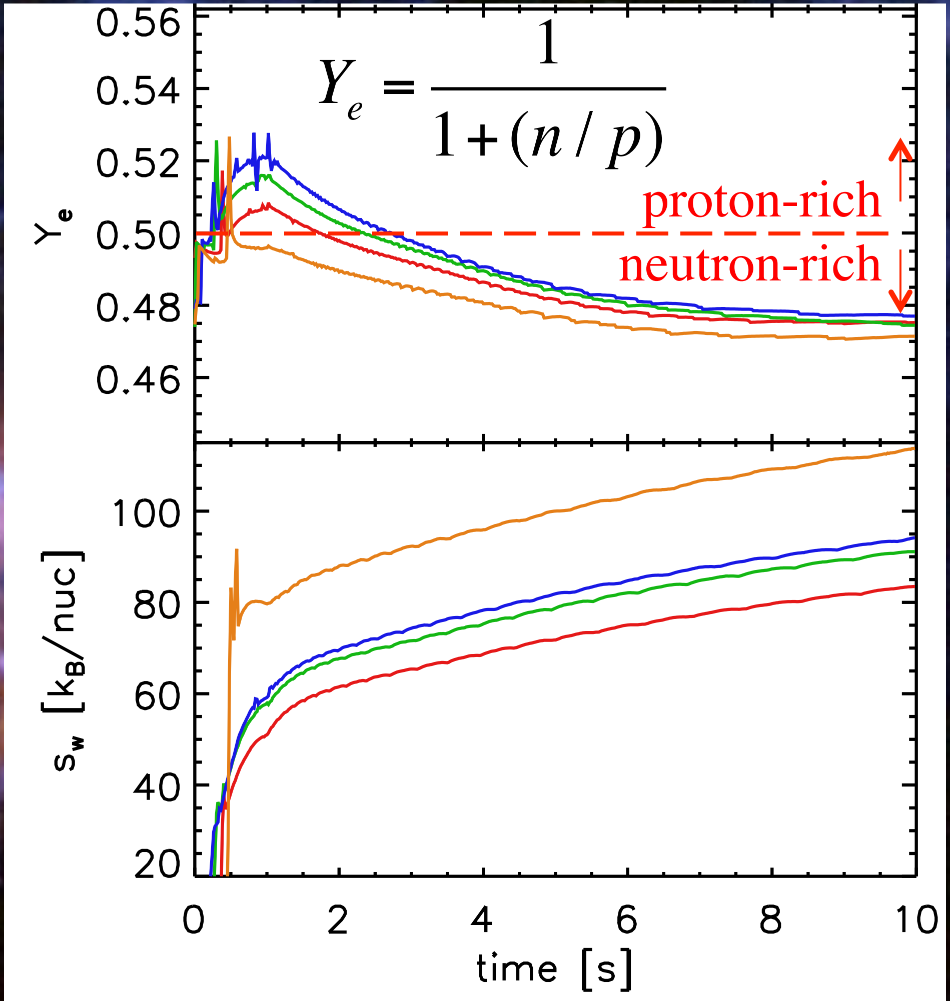

Arcones and Janka (2007)

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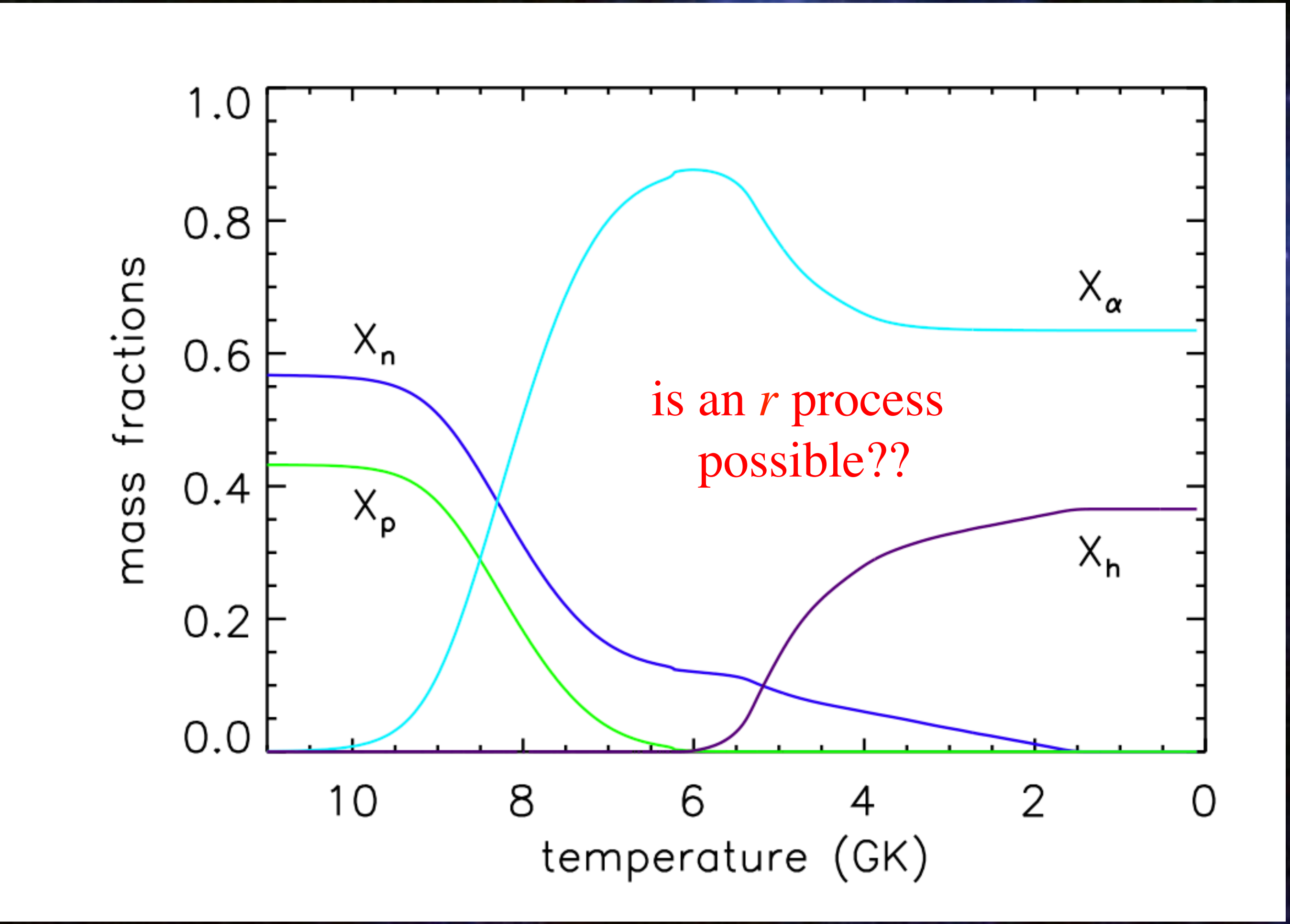
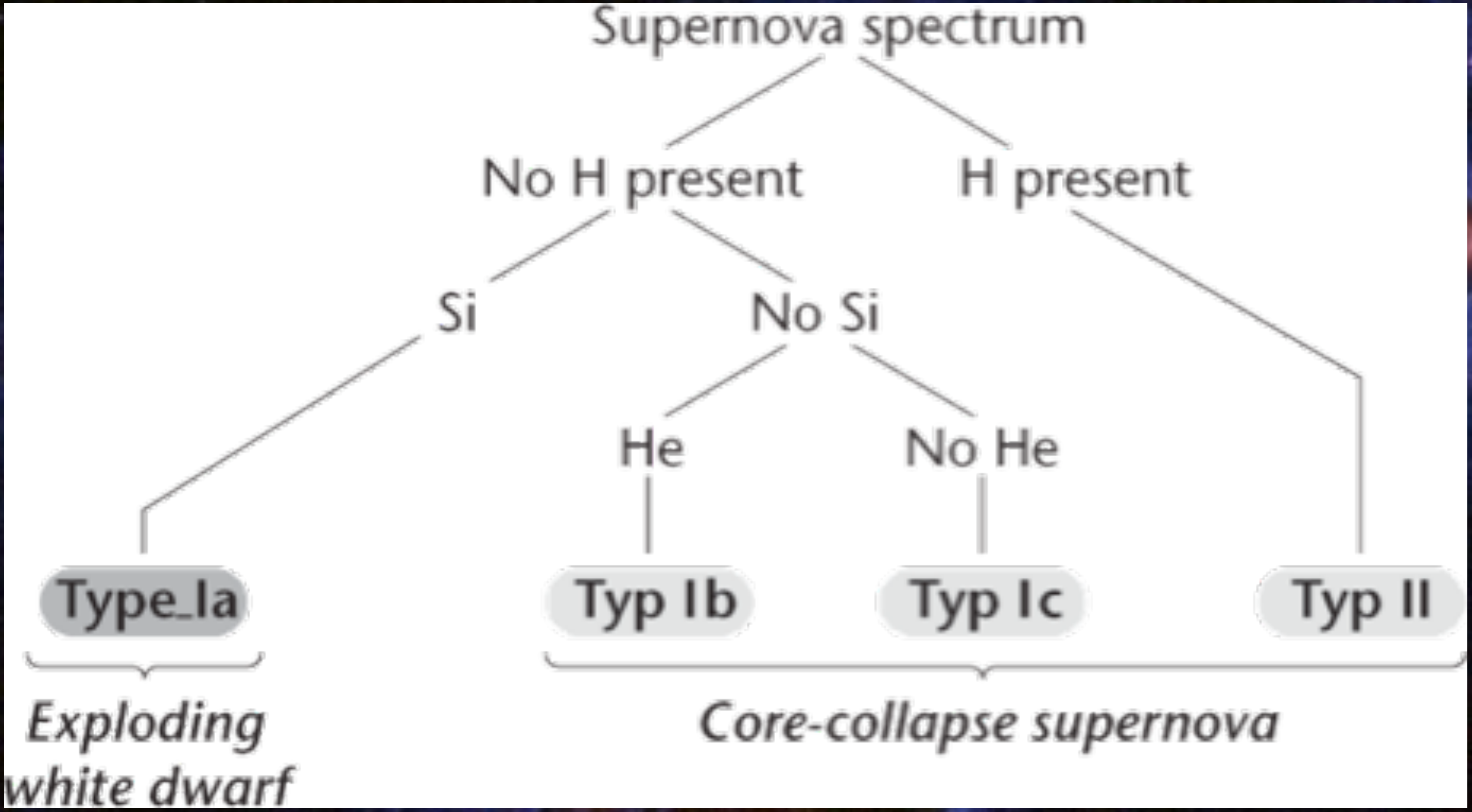
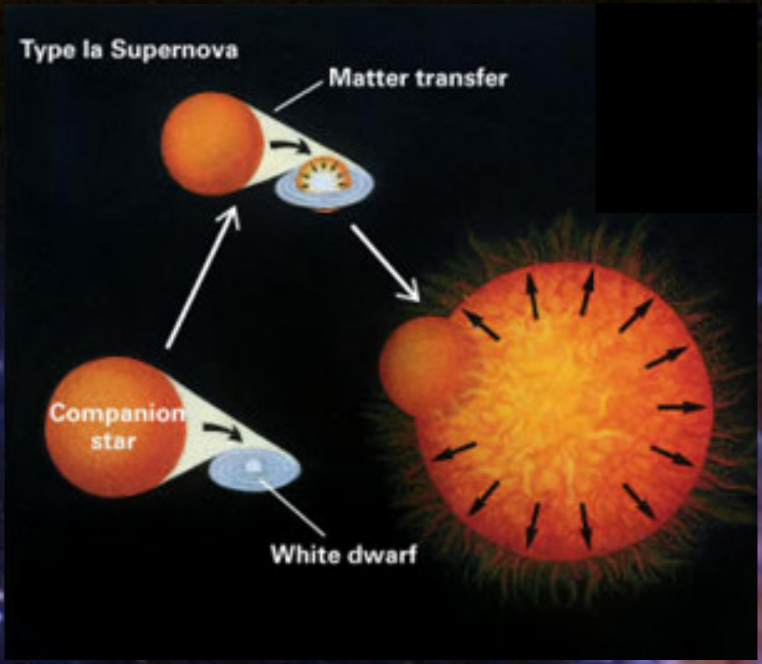


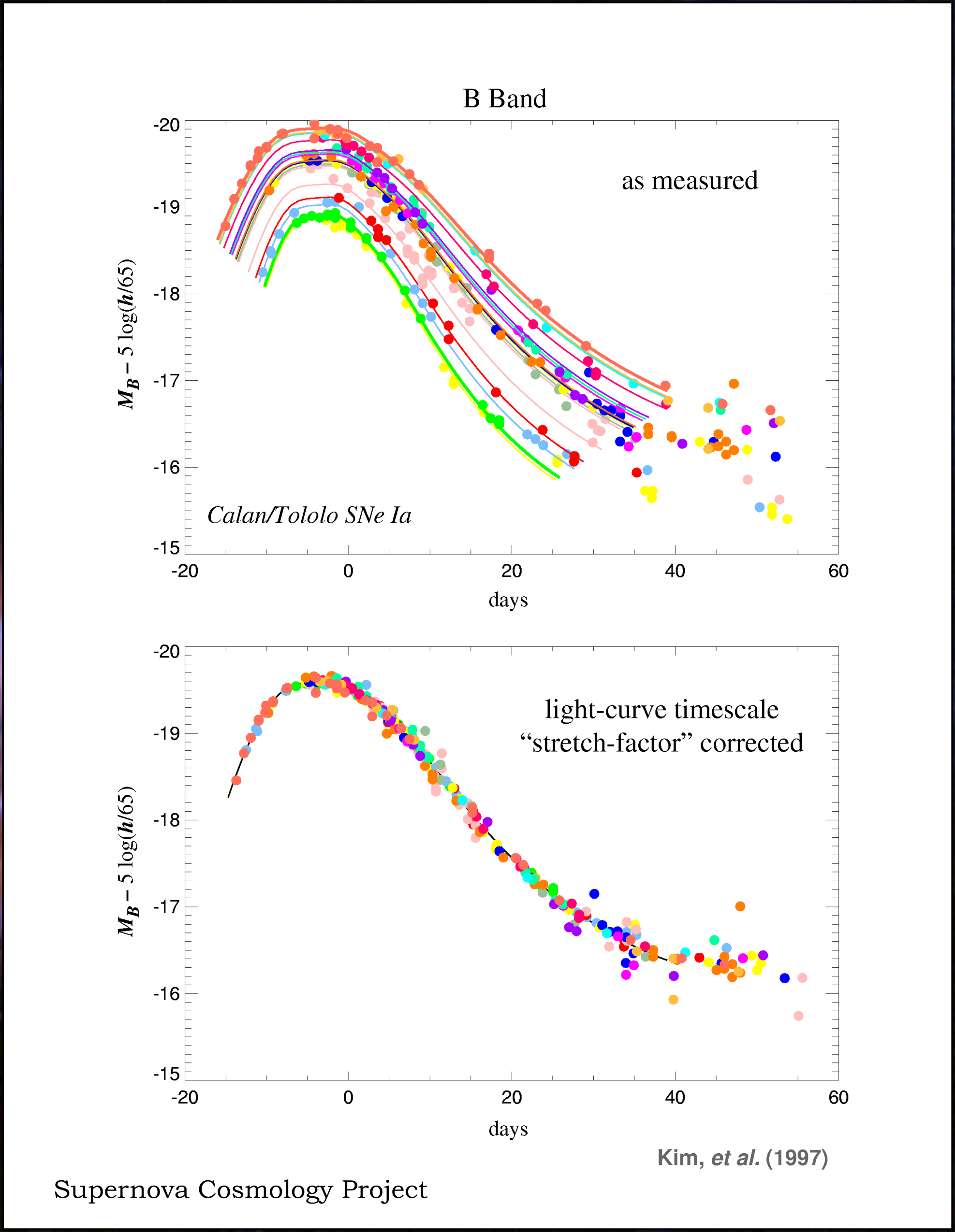
supernova classification



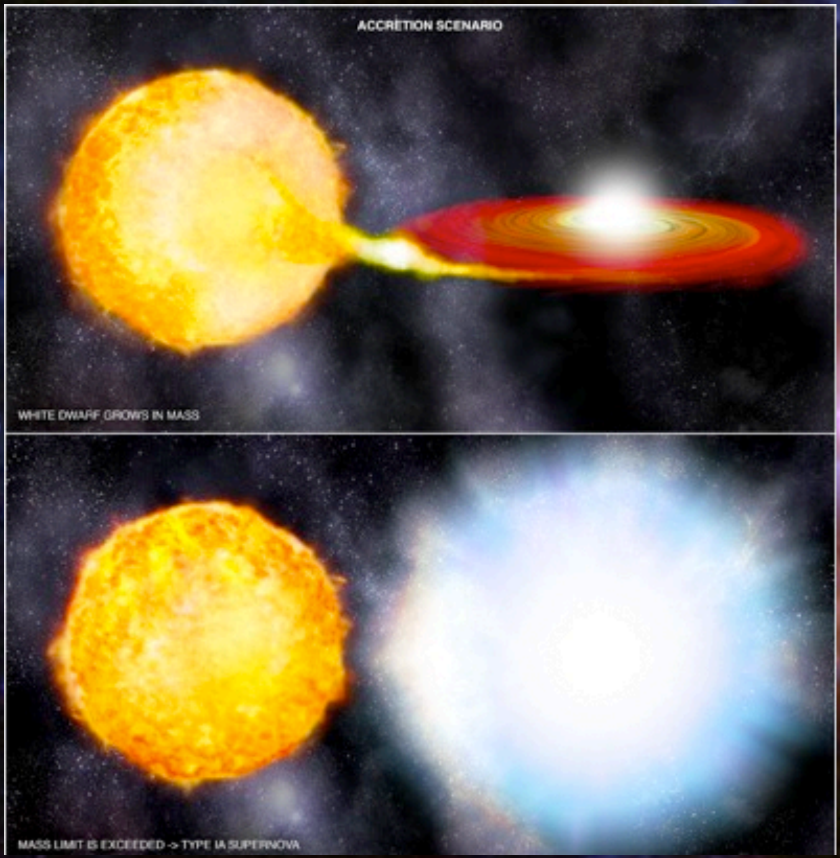
SNe Ia

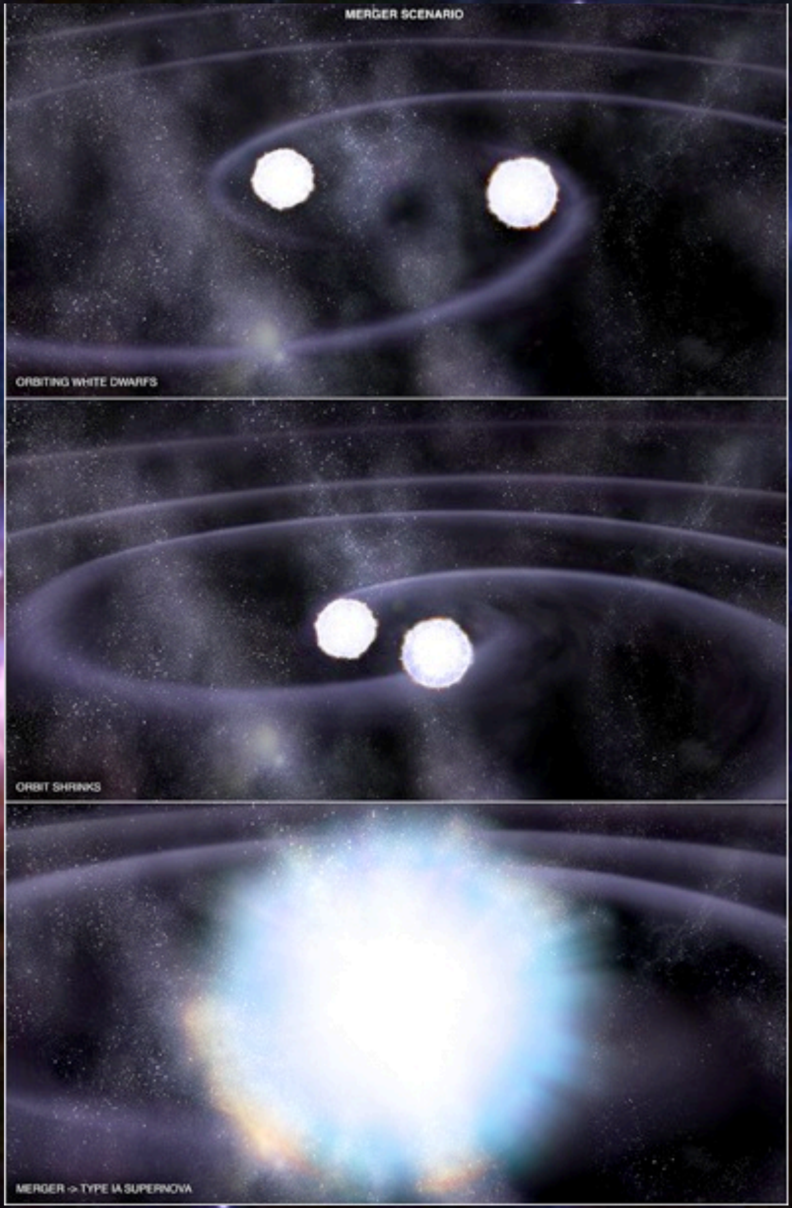


NSE at low neutron excess – produces primarily ^{28}Si, ^{56}Ni



SNe Ia

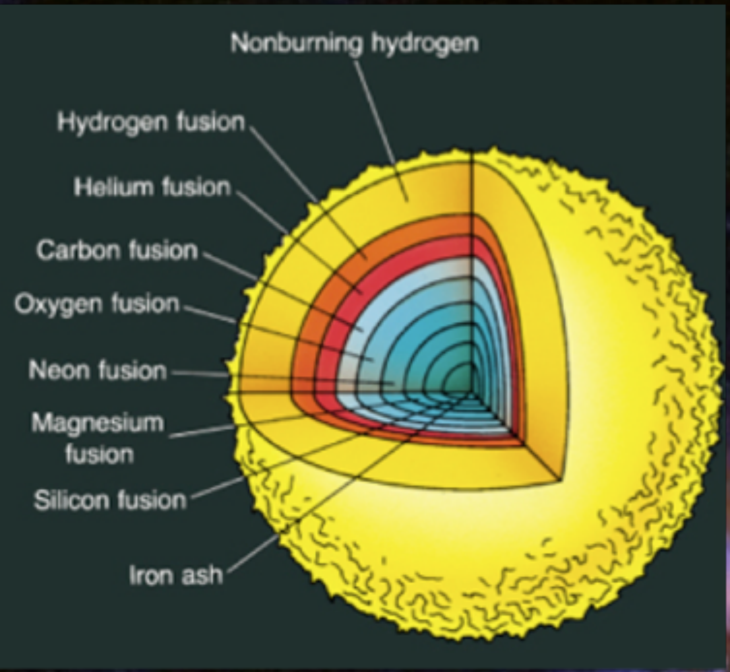


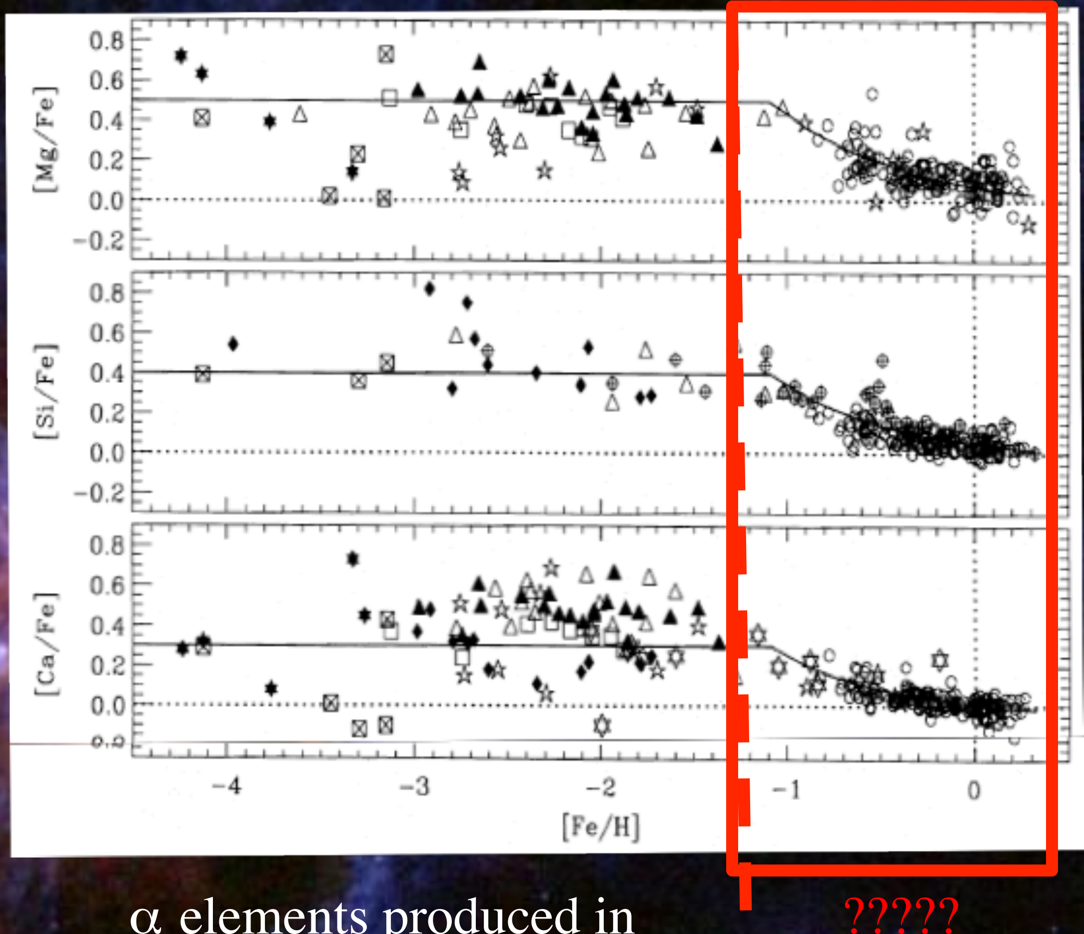


single degenerate…

…or double degenerate?

abundance trends: alpha elements





Ne, Mg, Si, S, Ar, Ca, Ti

Synthesis during stellar evolution and α-capture in supernovae of massive stars (> 8x mass of Sun)

α elements produced in explosions of massive stars

Type Ia and core-collapse supernovae *both* make iron. What is the reason for the change in slope of the α element [X/Fe] ratios in the previous plot?

A – Massive stars evolve quickly and so core collapse supernovae no longer occur.

B – There were no Type Ia supernovae early in galactic history.

C – Core-collapse supernovae make much more iron than Type Ia supernovae.

D – There is an additional major source of iron in the galaxy besides supernovae.

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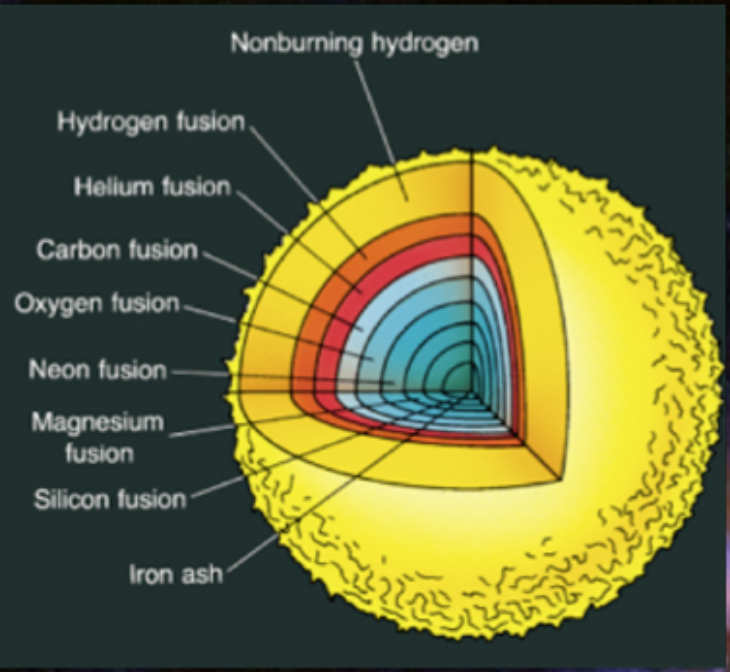
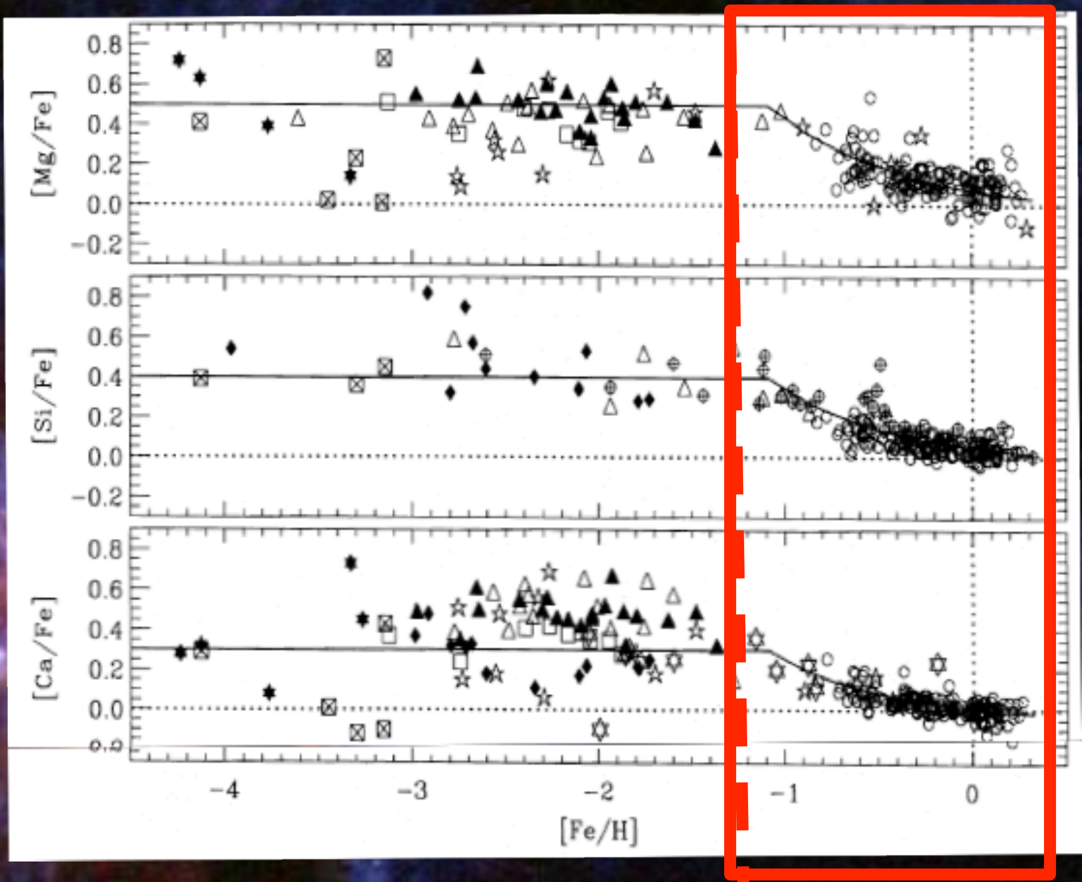
abundance trends: alpha elements





Ne, Mg, Si, S, Ar, Ca, Ti

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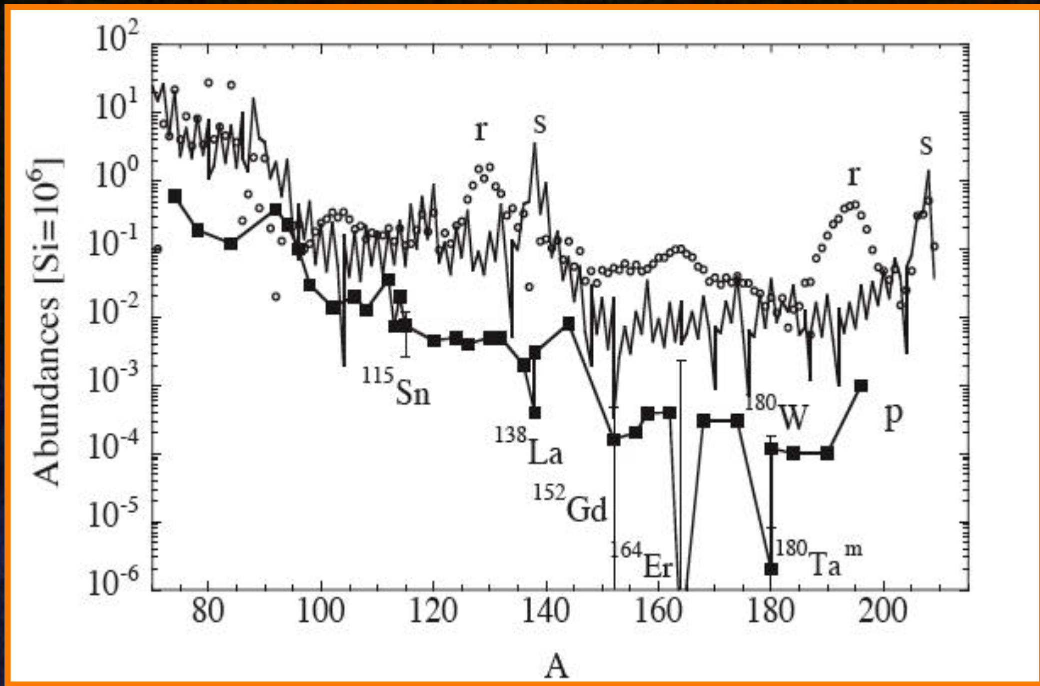
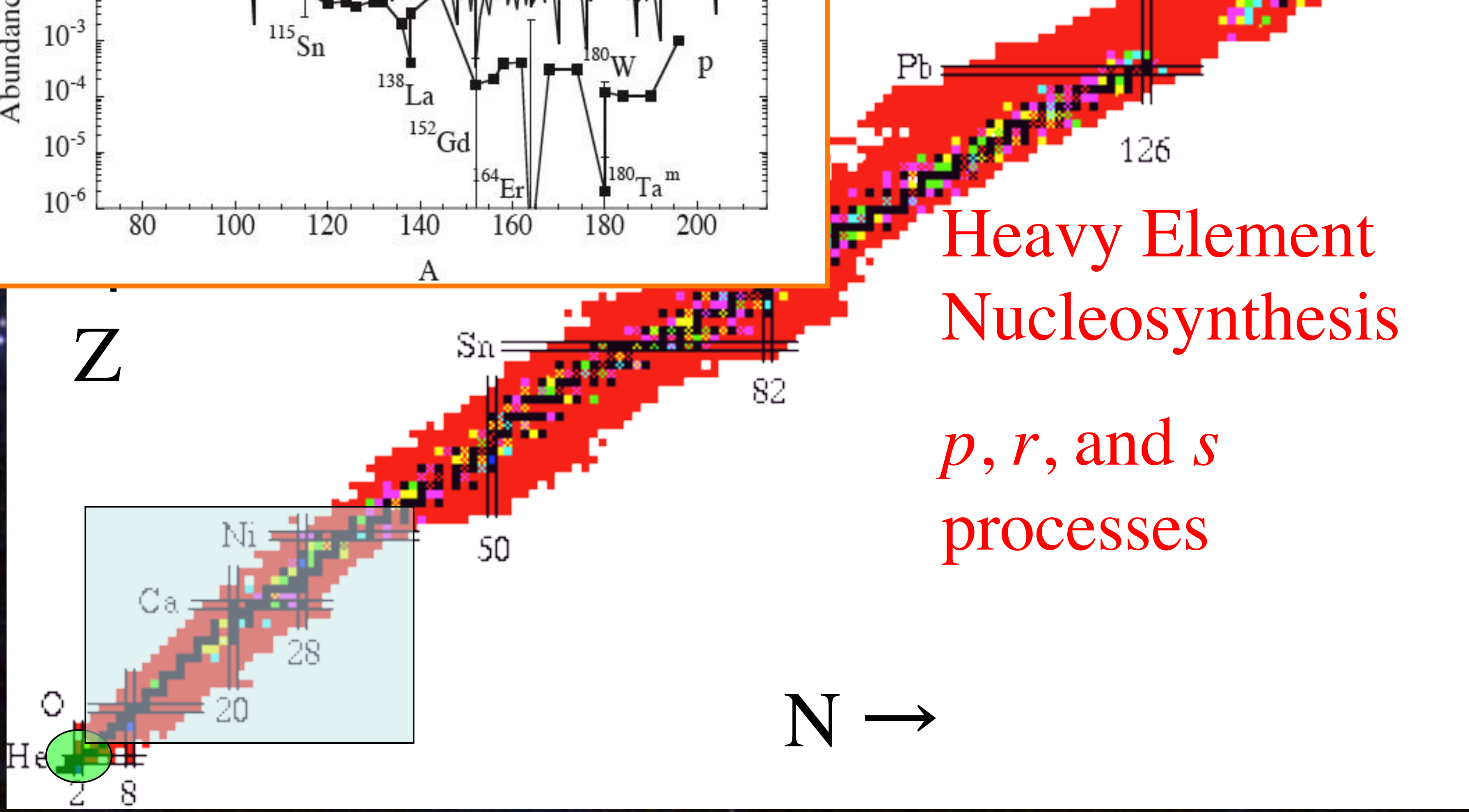
add'l Fe comes from Type Ia SN

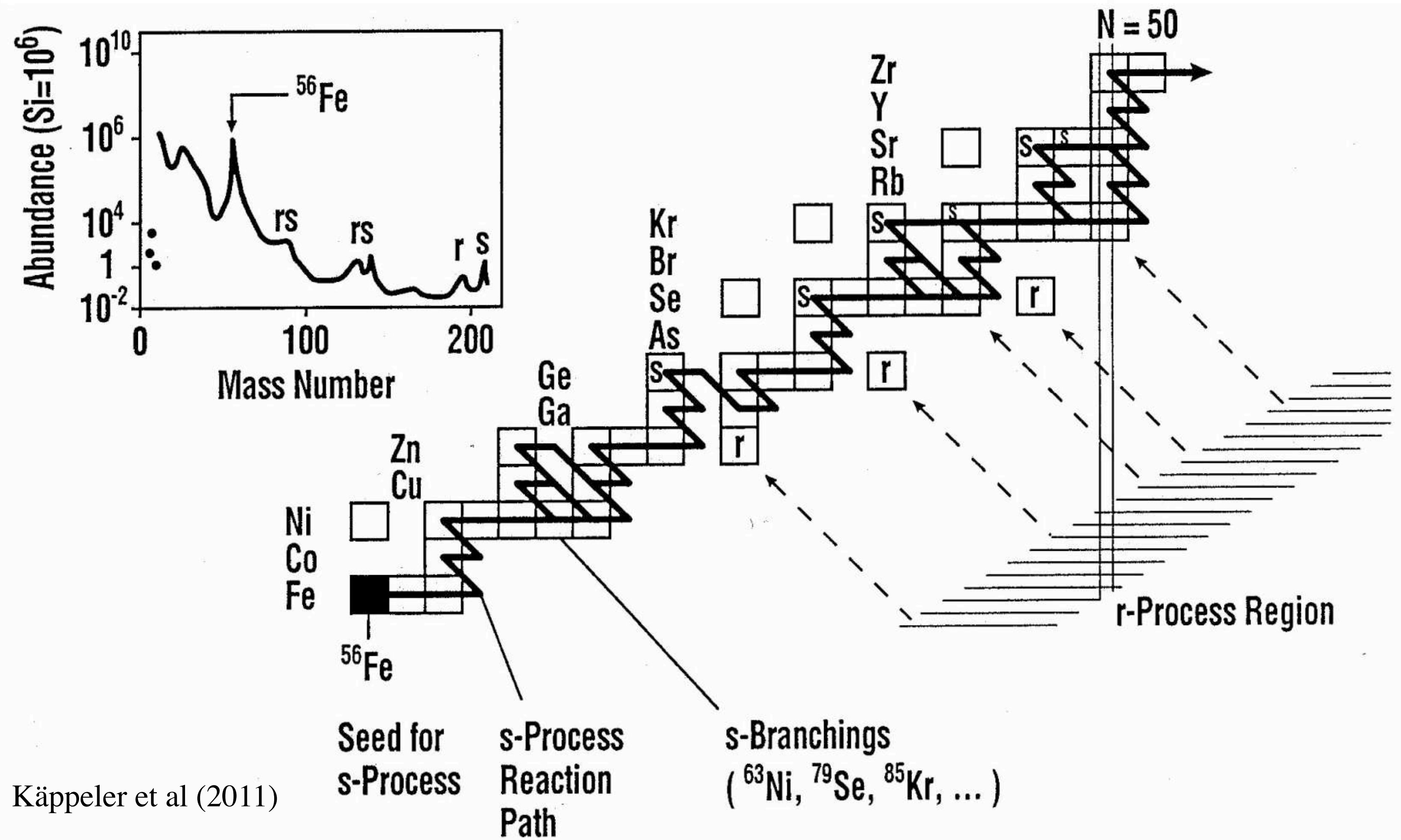




Heavy Element Nucleosynthesis

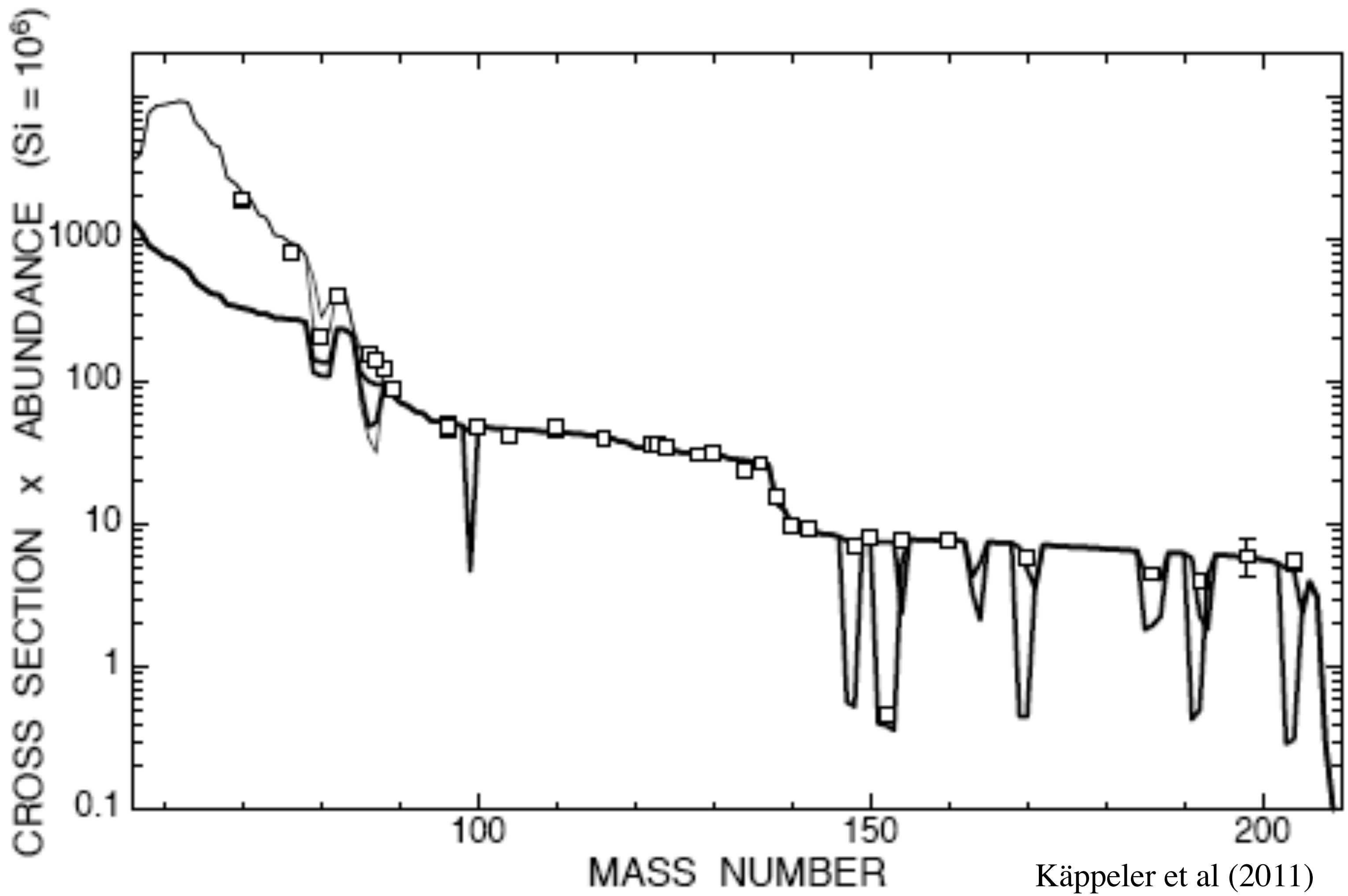
p, *r*, and *s* processes

s-process nucleosynthesis



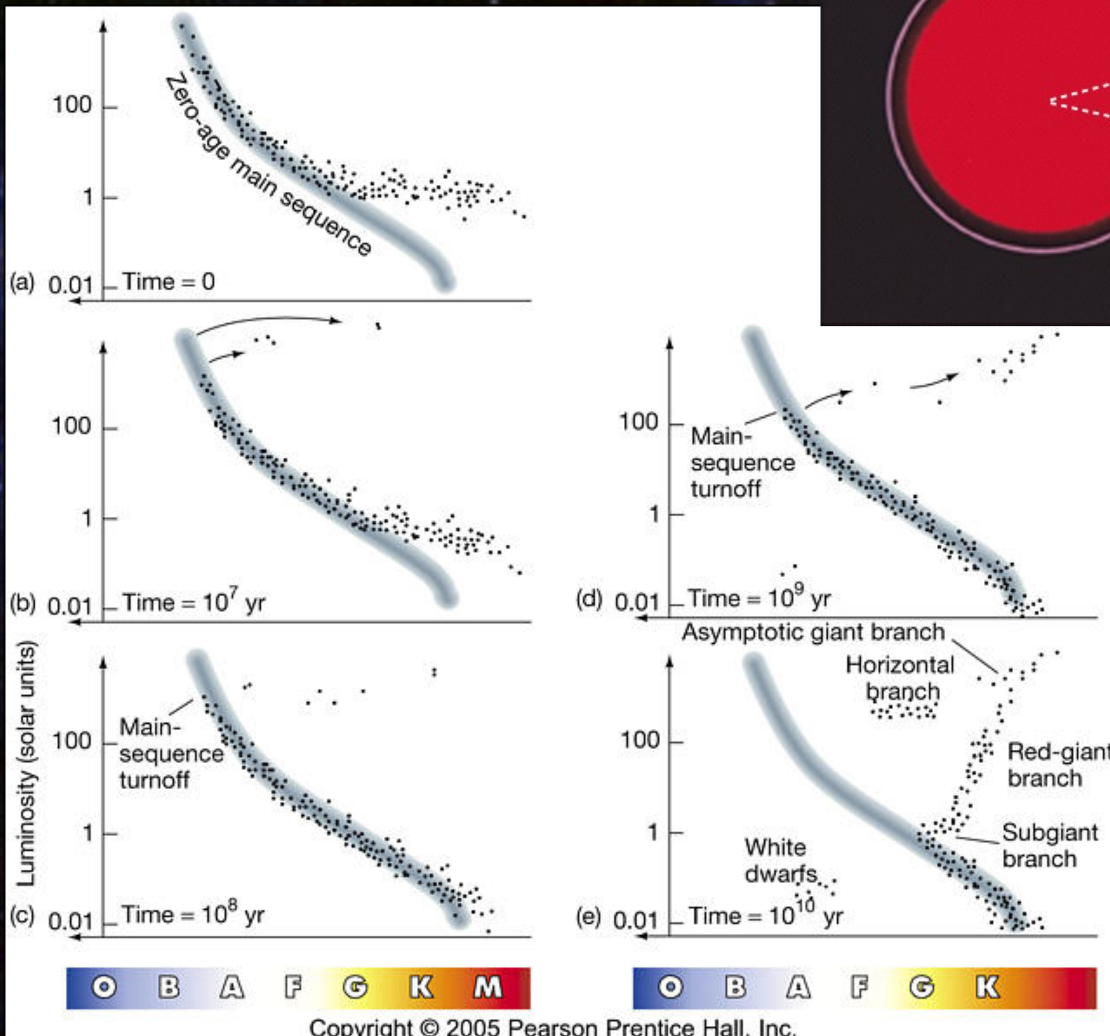
Käppeler et al (2011)

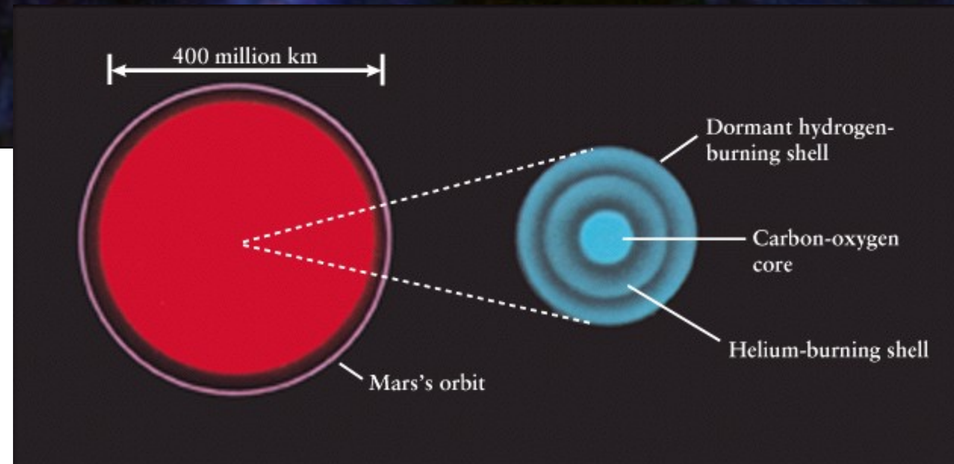
modeling *s*-process nucleosynthesis



Käppeler et al (2011)

main *s*-process component

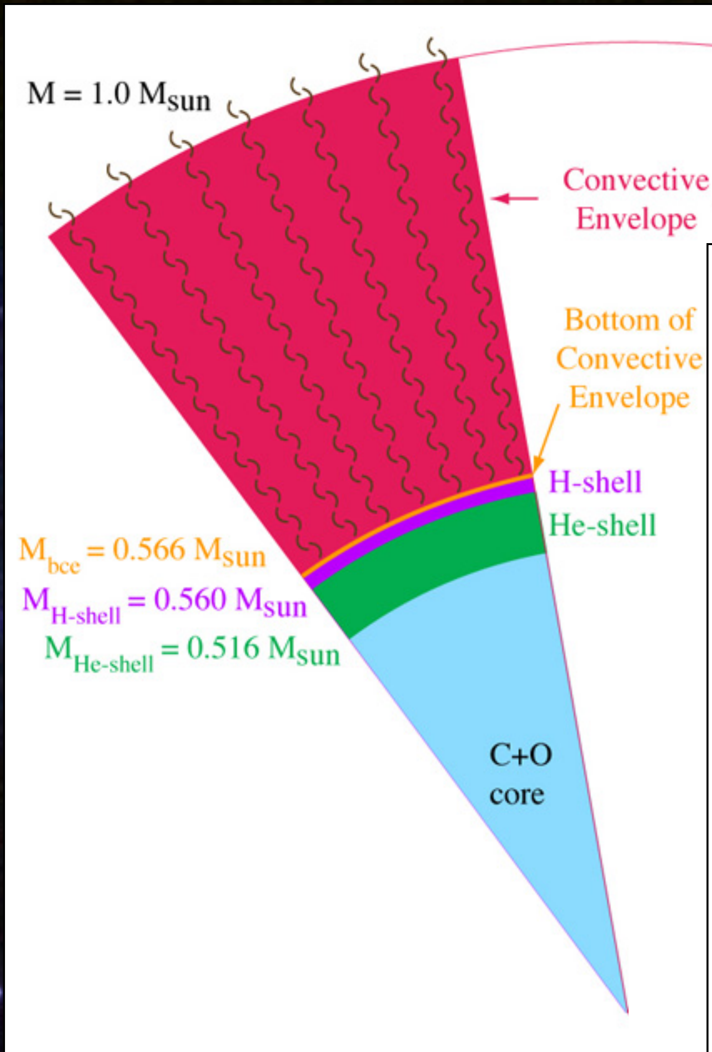




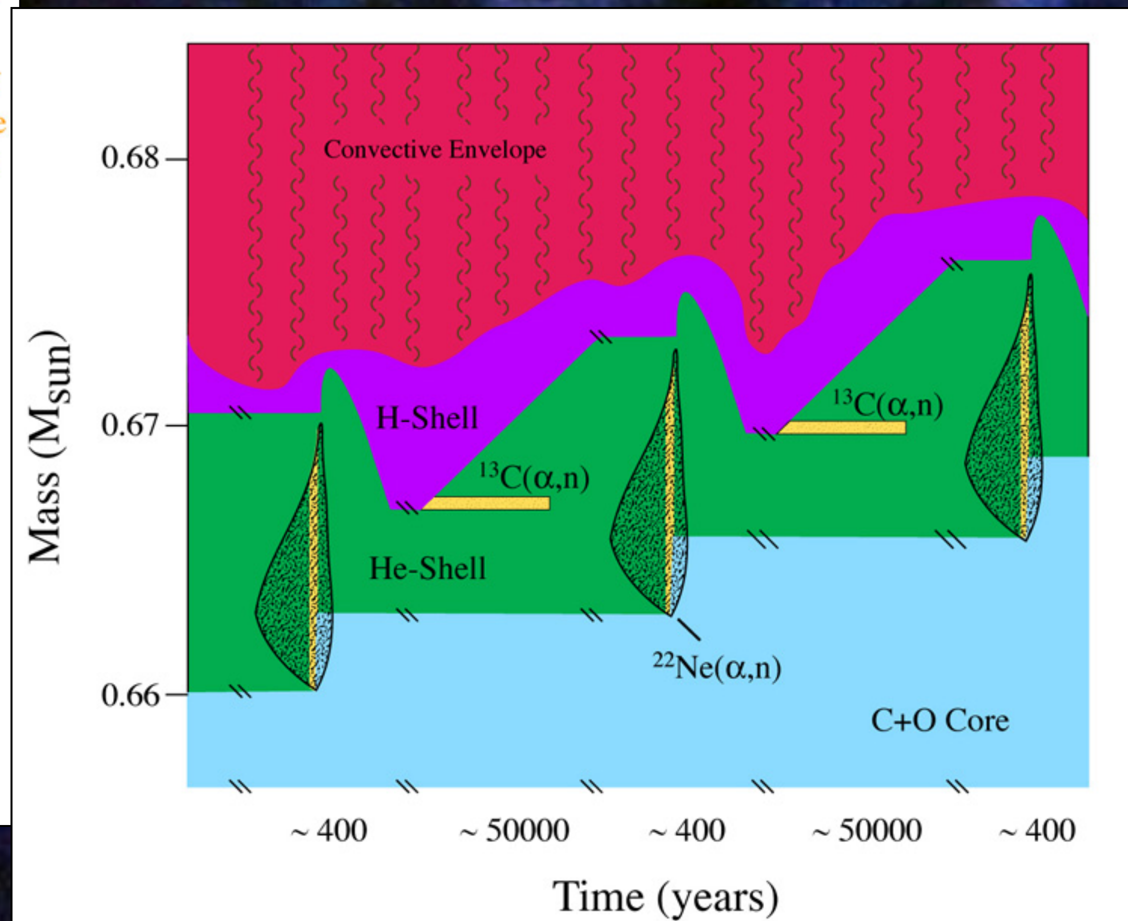
main component –
low mass AGB stars

Käppeler et al (2011)

main *s*-process component



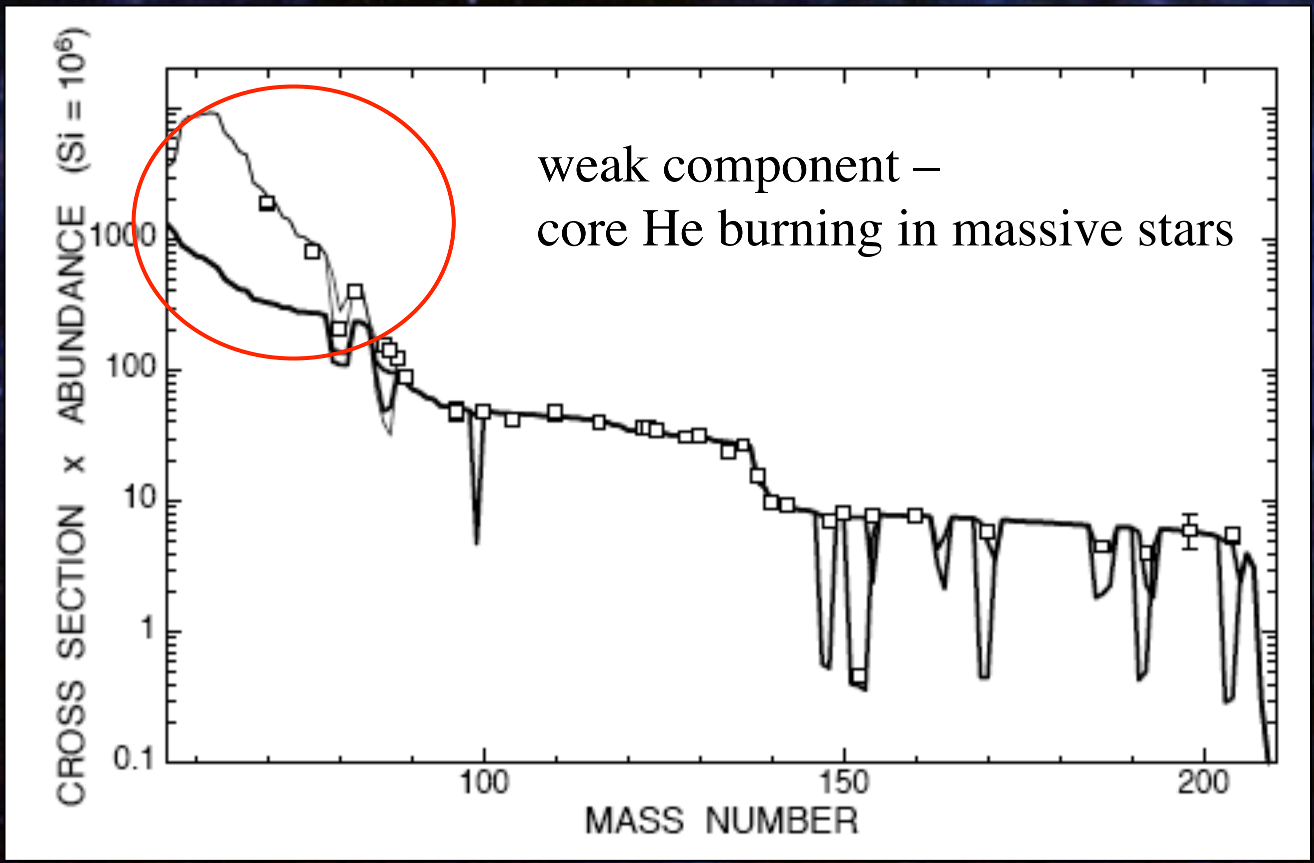
$^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C \rightarrow {}^{13}C(\alpha,n)$



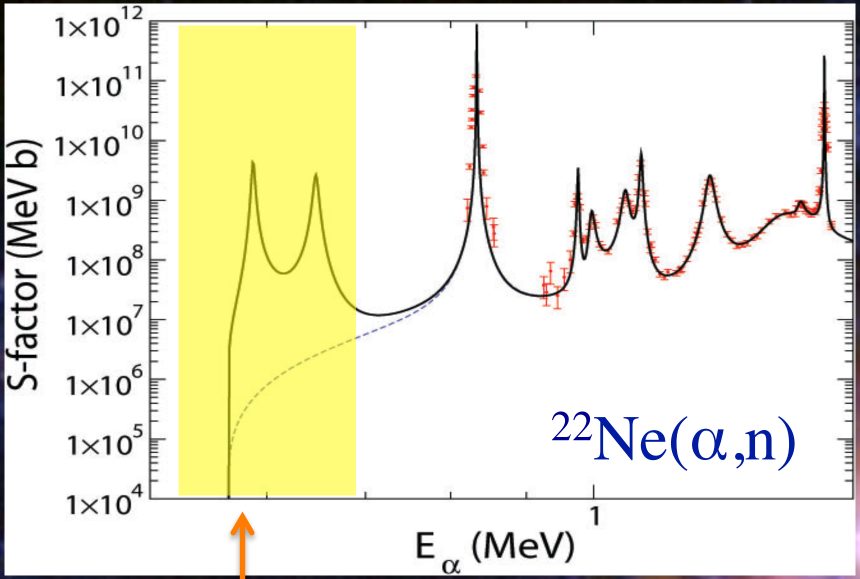
weak s-process component

$^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne \rightarrow$

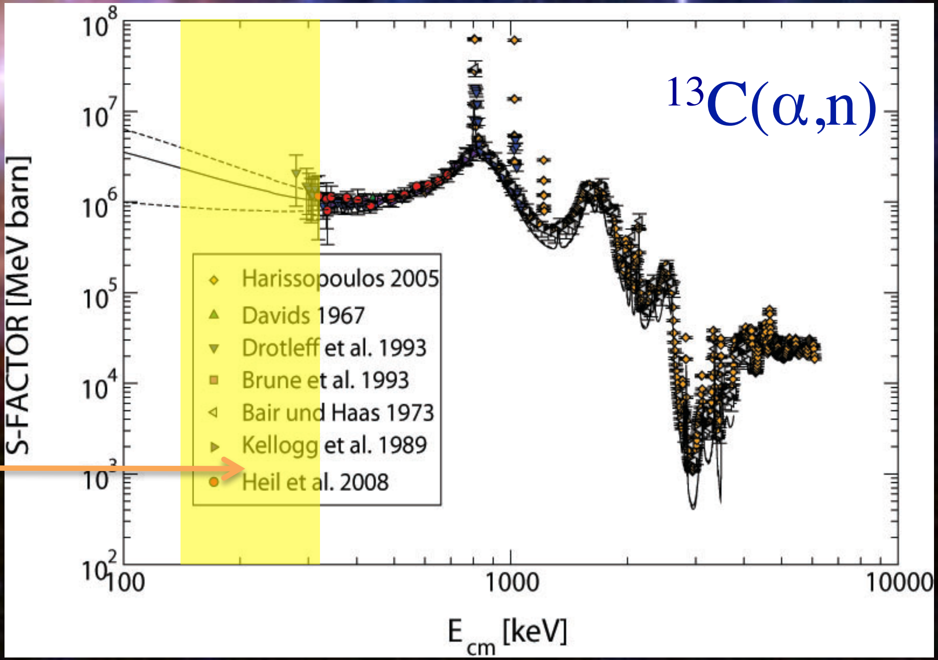
$^{22}Ne(\alpha,n)^{25}Mg$



s-process neutron source reactions

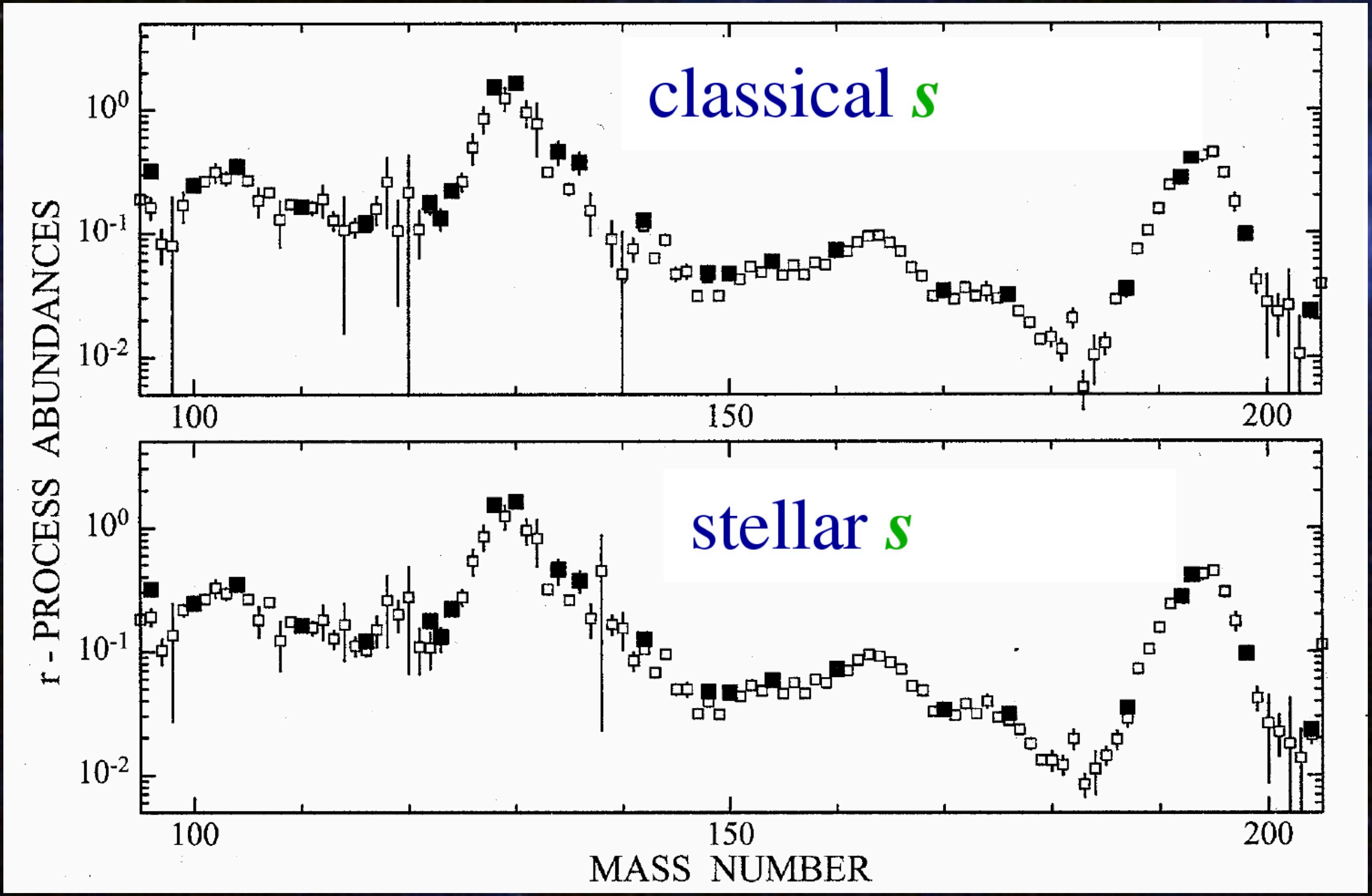


plots from M.Couder

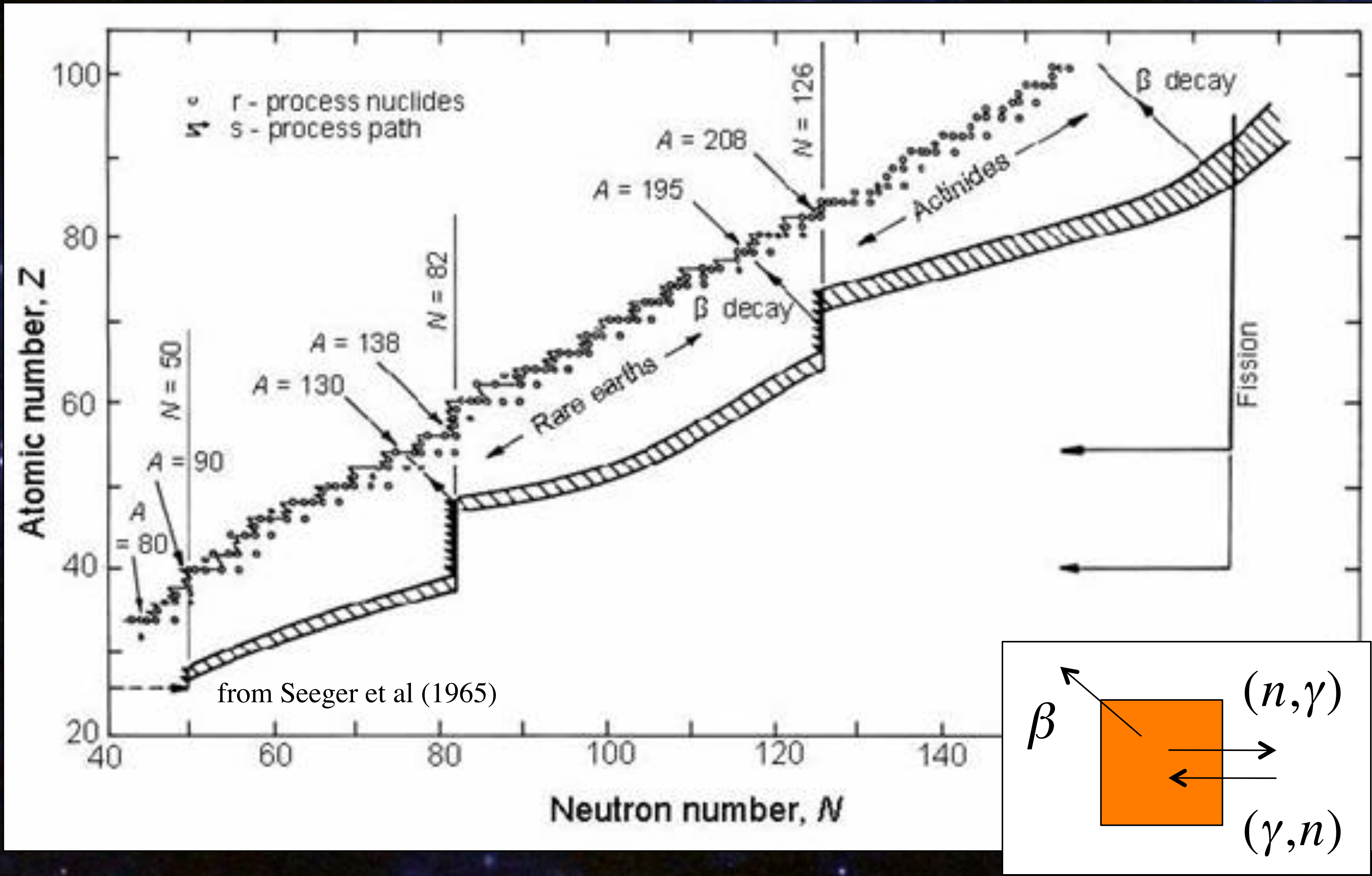


regions of interest for *s*-process conditions

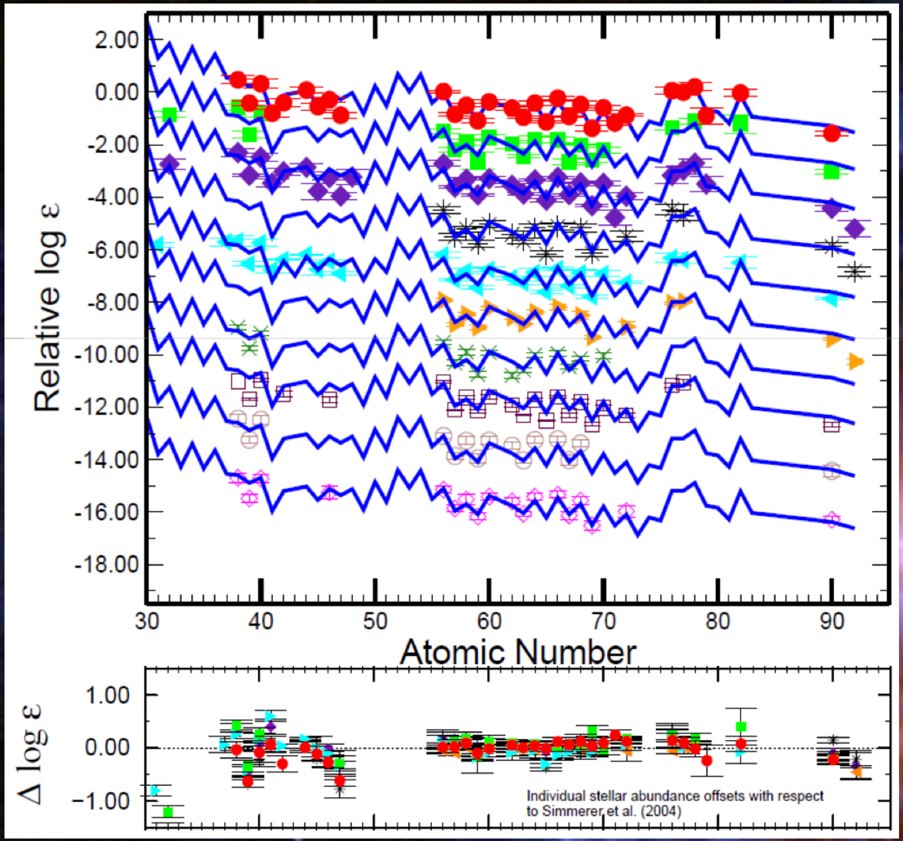
r-process residuals



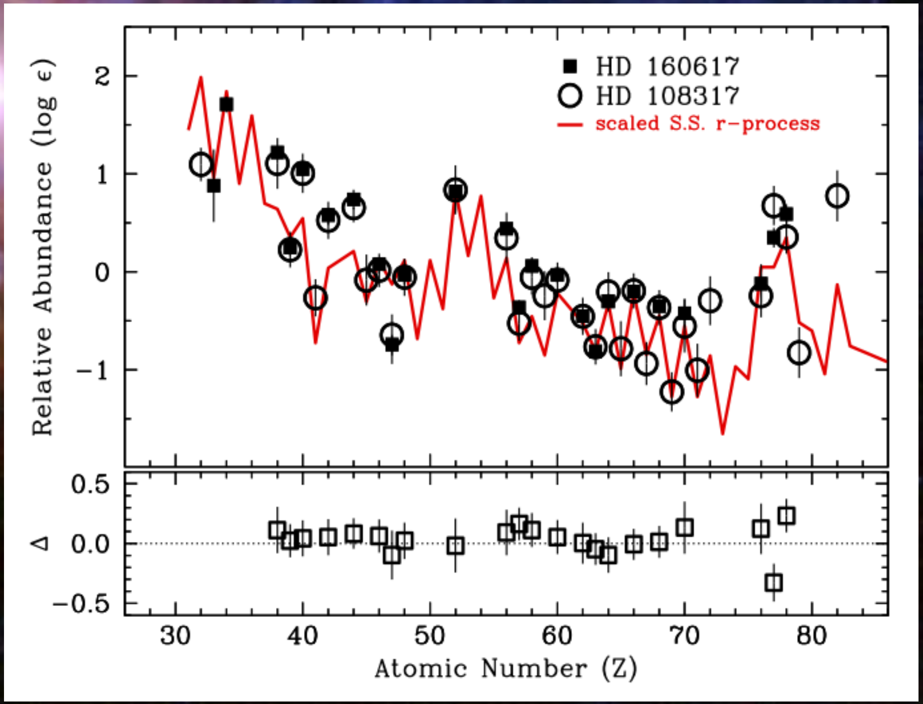
r-process basics



r-process elements in metal-poor stars



Cowan et al (2011)



Roederer & Lawler (2012)

where do the neutrons come from? neutrinos?

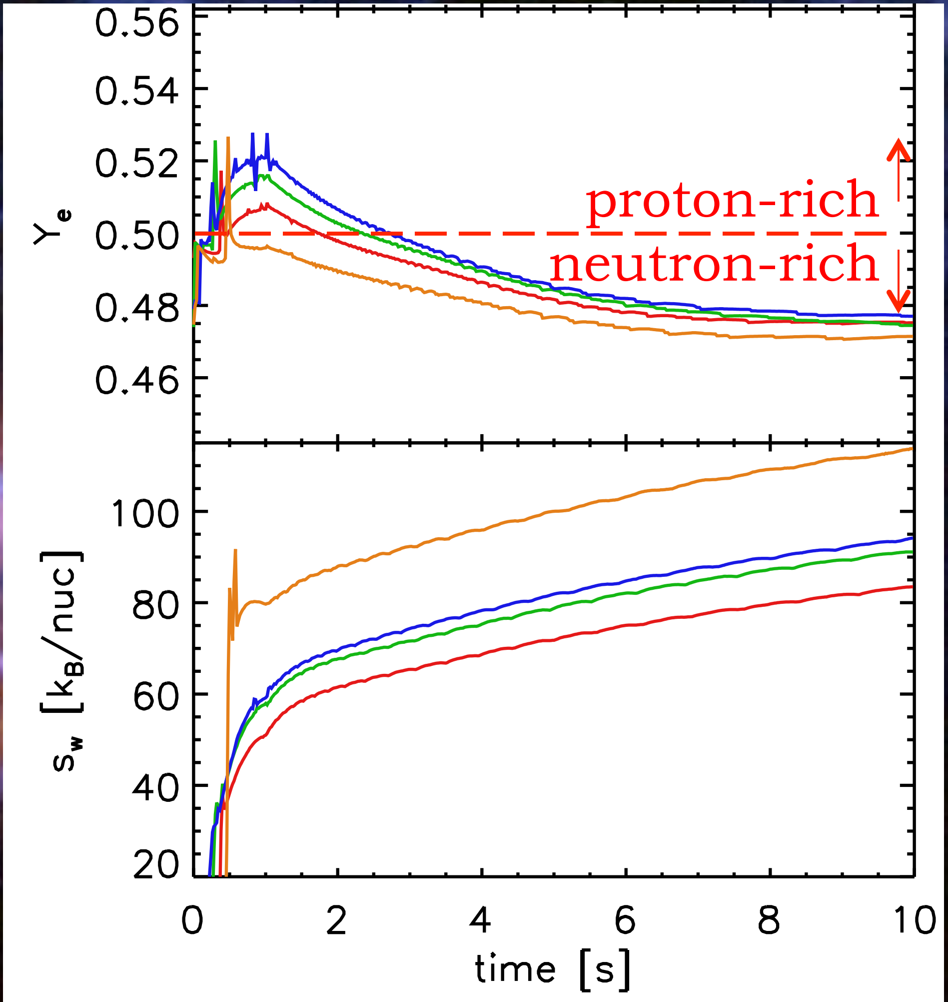
neutrino-driven wind from a core-collapse supernova

$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

$$n + \nu_e \leftrightarrow p + e^-$$

conditions are proton-rich if:

$$\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} < 4(m_n c^2 - m_p c^2)$$



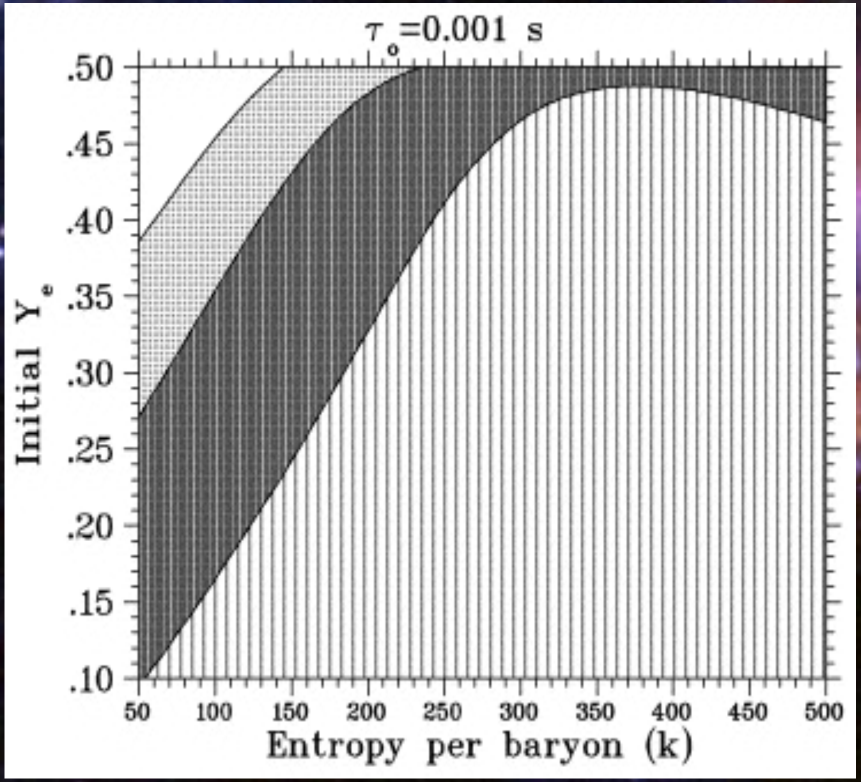
Arcones and Janka (2007)

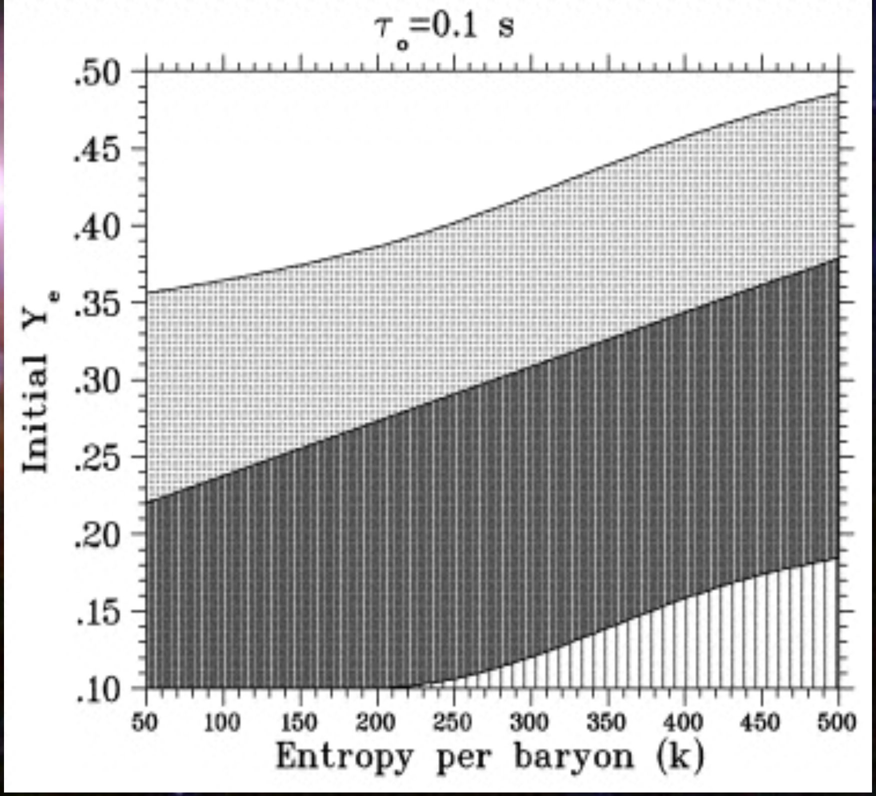
neutrino-driven wind conditions

Key quantities:

- electron fraction Y_e
- entropy s/k
- dynamic timescale t

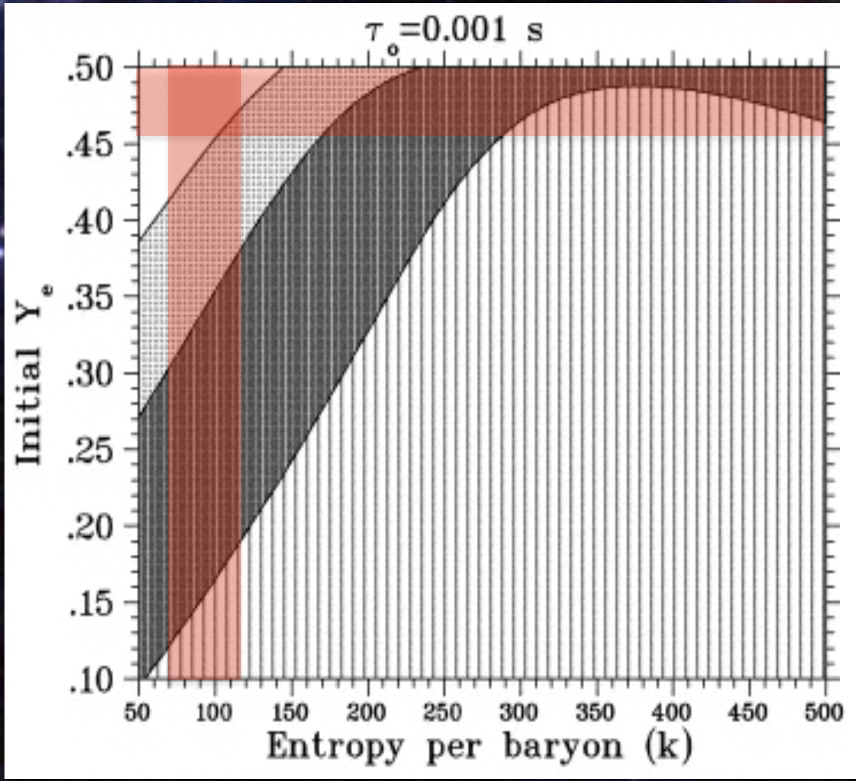
} neutron to seed ratio R

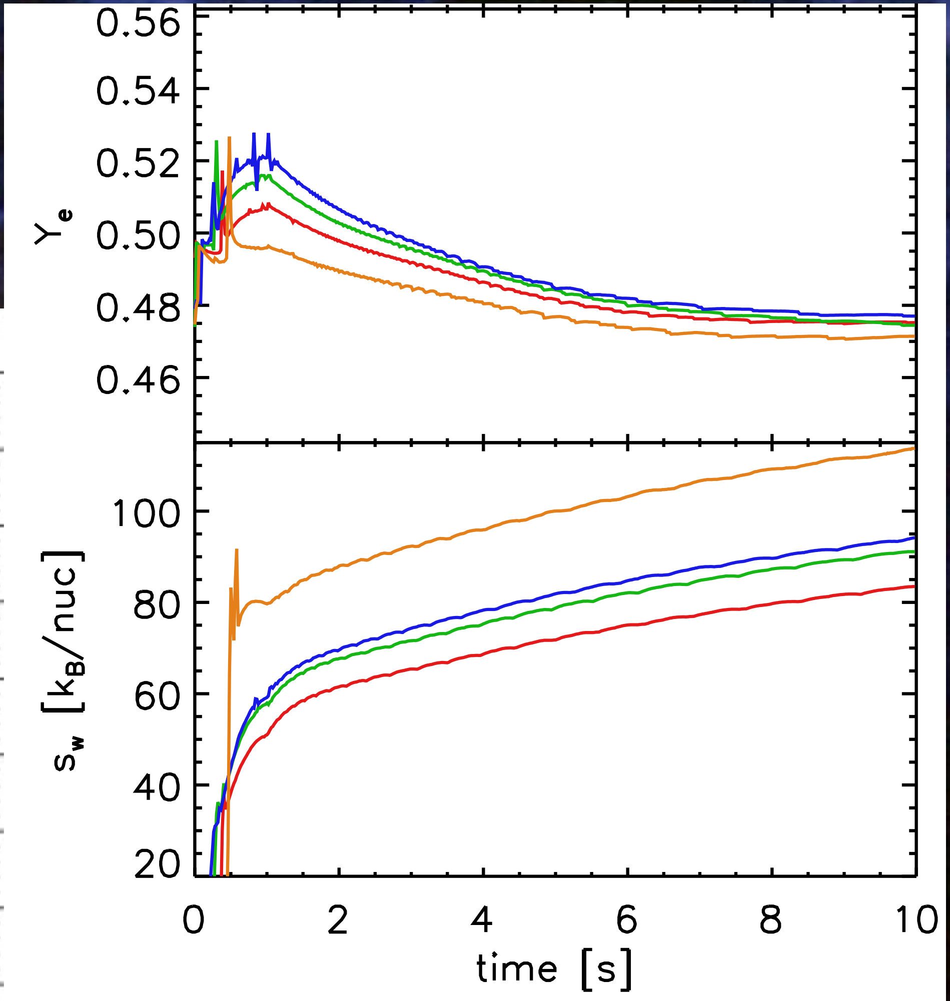




Meyer and Brown (1997)

neutrino-driven wind conditions

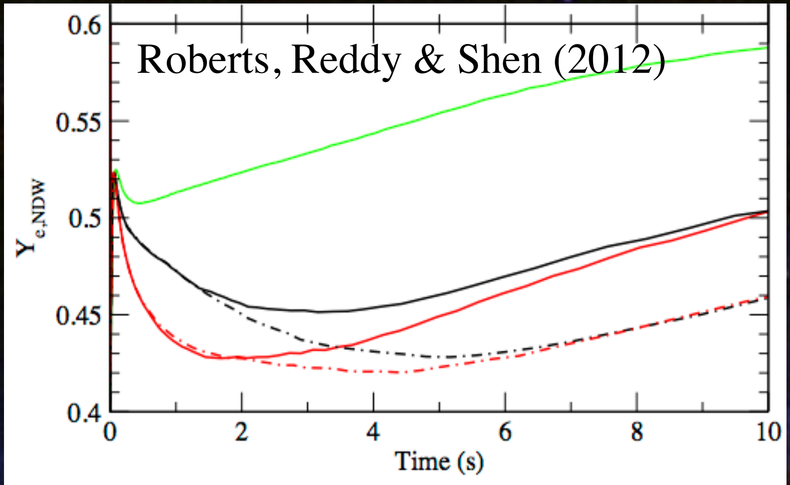


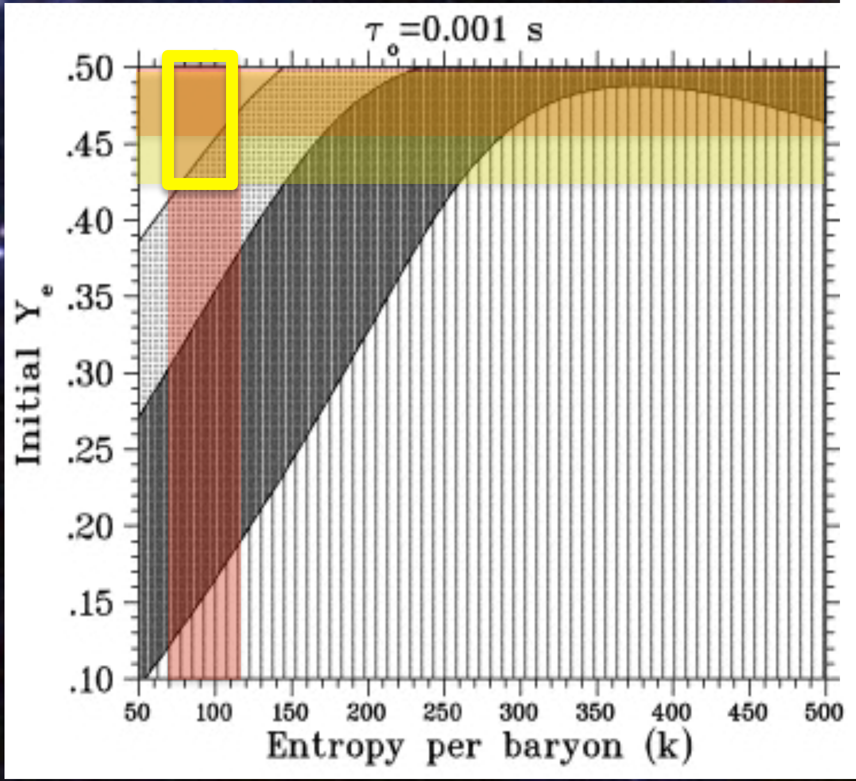


Arcones and Janka (2007)

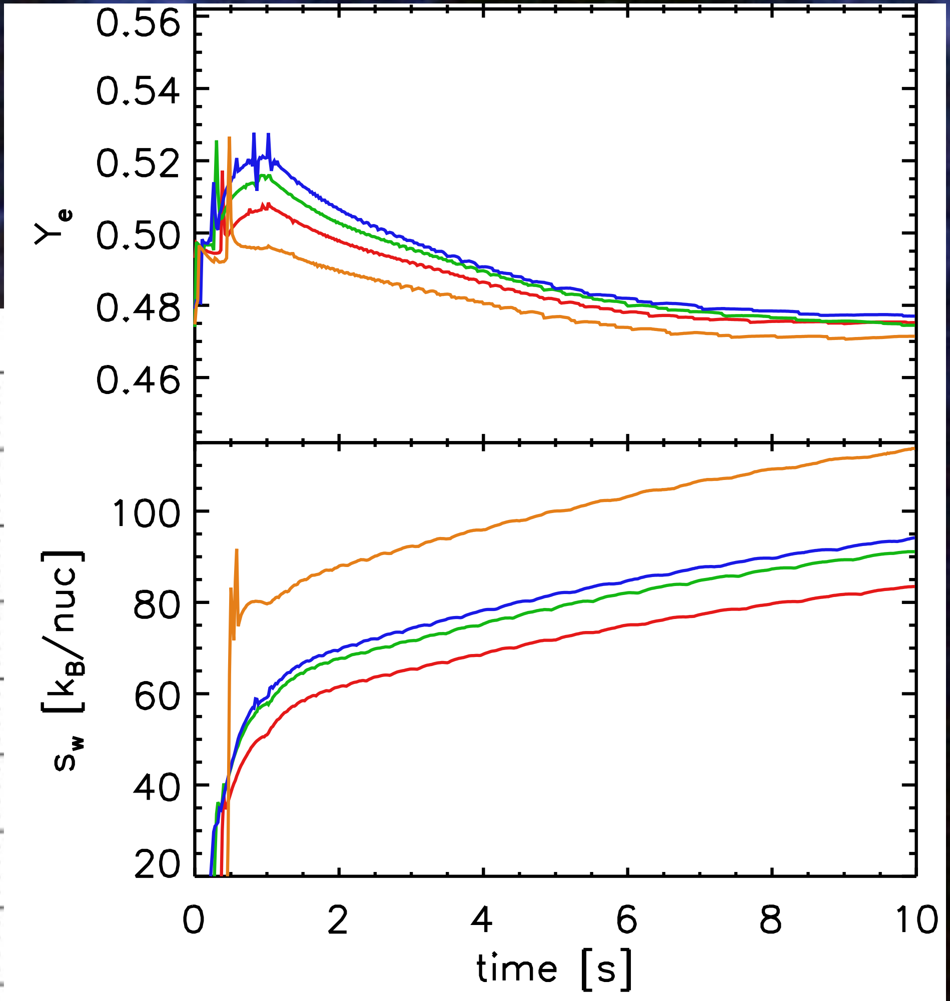
Meyer and Brown (1997)

neutrino-driven wind conditions



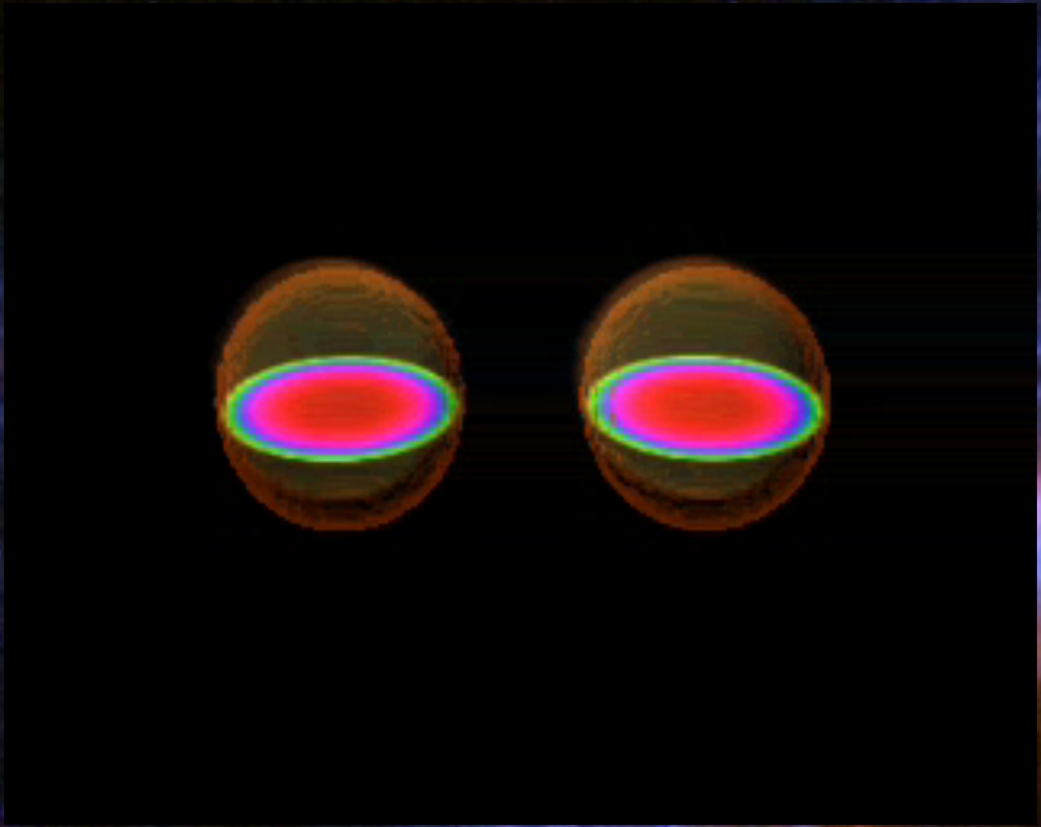


Meyer and Brown (1997)



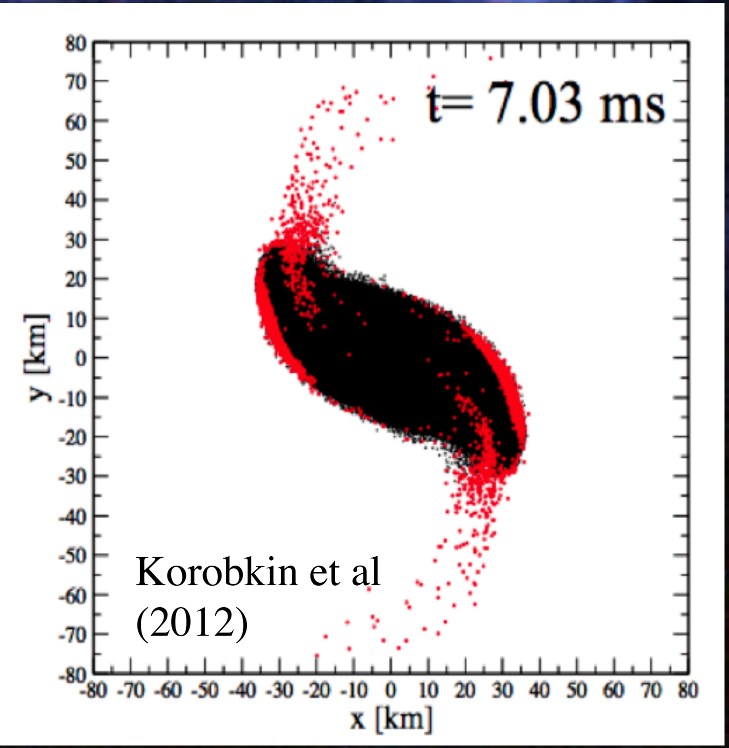
Arcones and Janka (2007)

where do the neutrons come from? gravity?

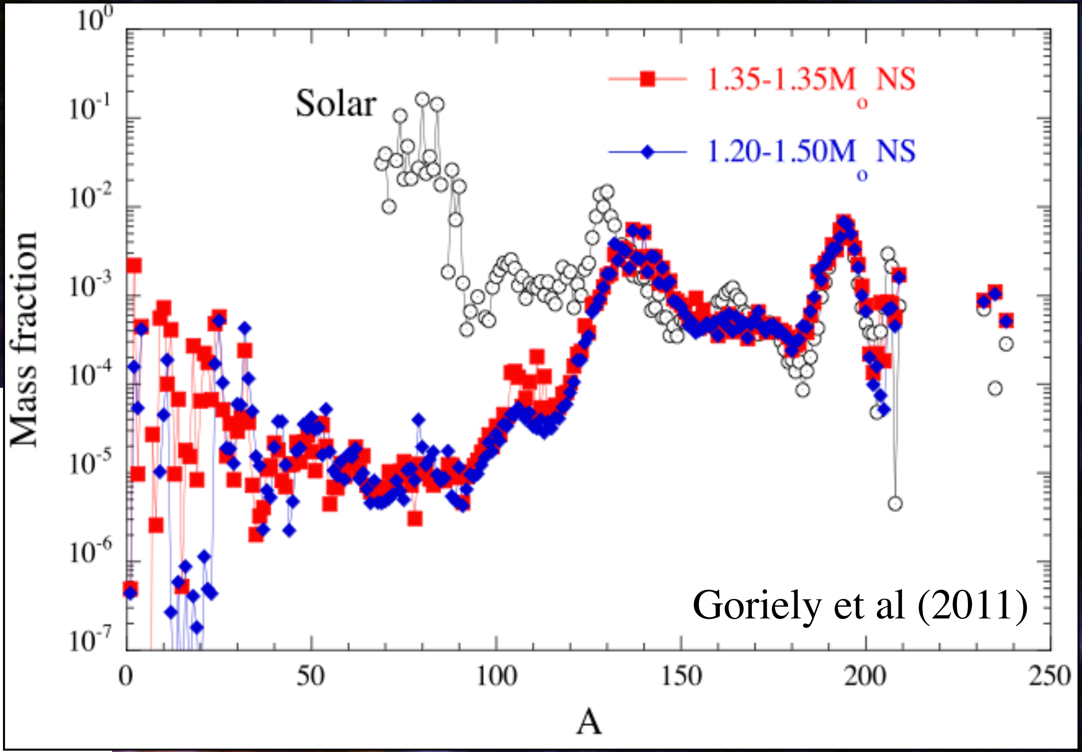


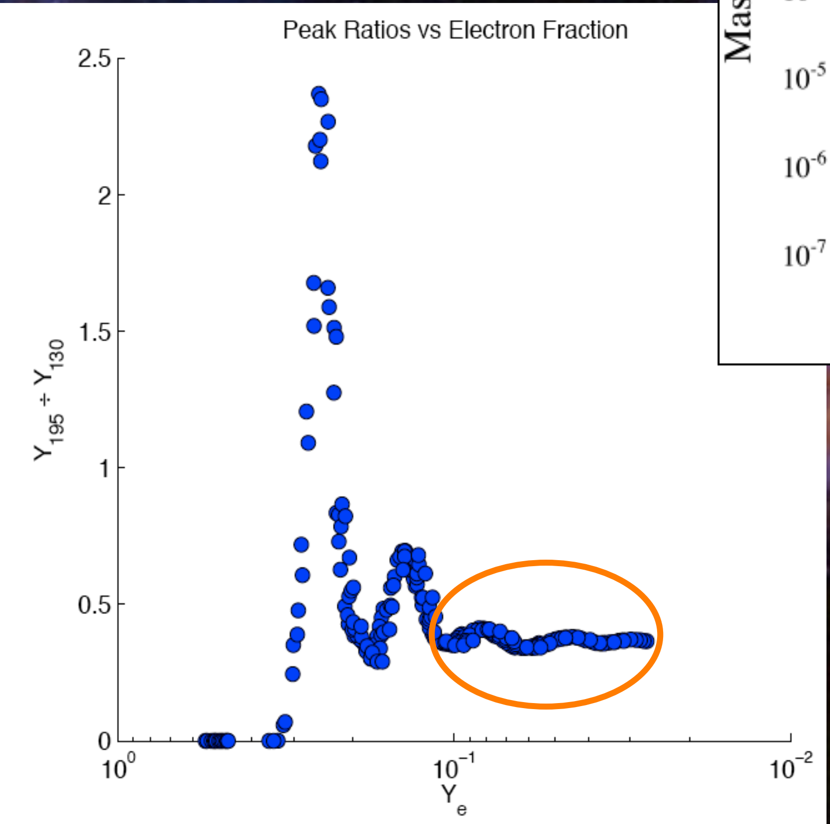
animation: NASA/SkyWorks

neutron star-neutron star or black hole-neutron star mergers



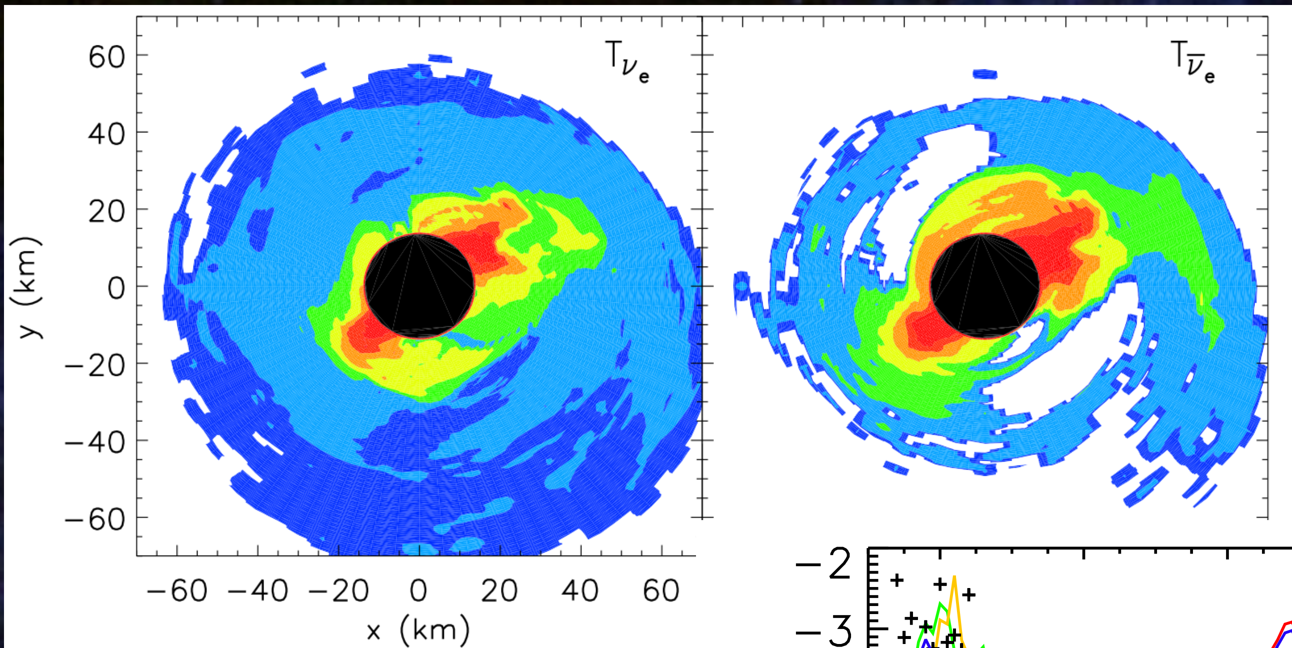
r process in prompt merger ejecta





Beun, McLaughlin, Surman, Hix (2008)

r process in accretion disk ejecta



Surman, McLaughlin, Ruffert, Janka, Hix (2008)

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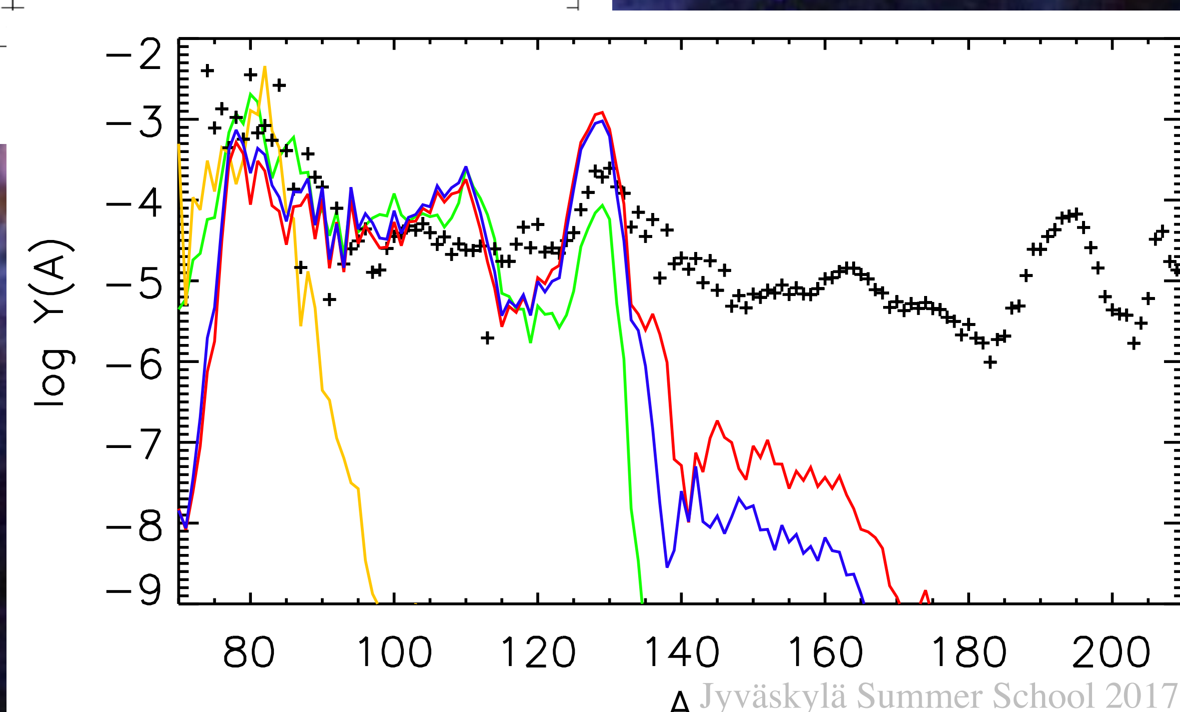


no GR

redshift, bending

+ rotation

+ Kerr metric for redshift

Caballero, McLaughlin, Surman (2011)

kilonova: an *r*-process transient

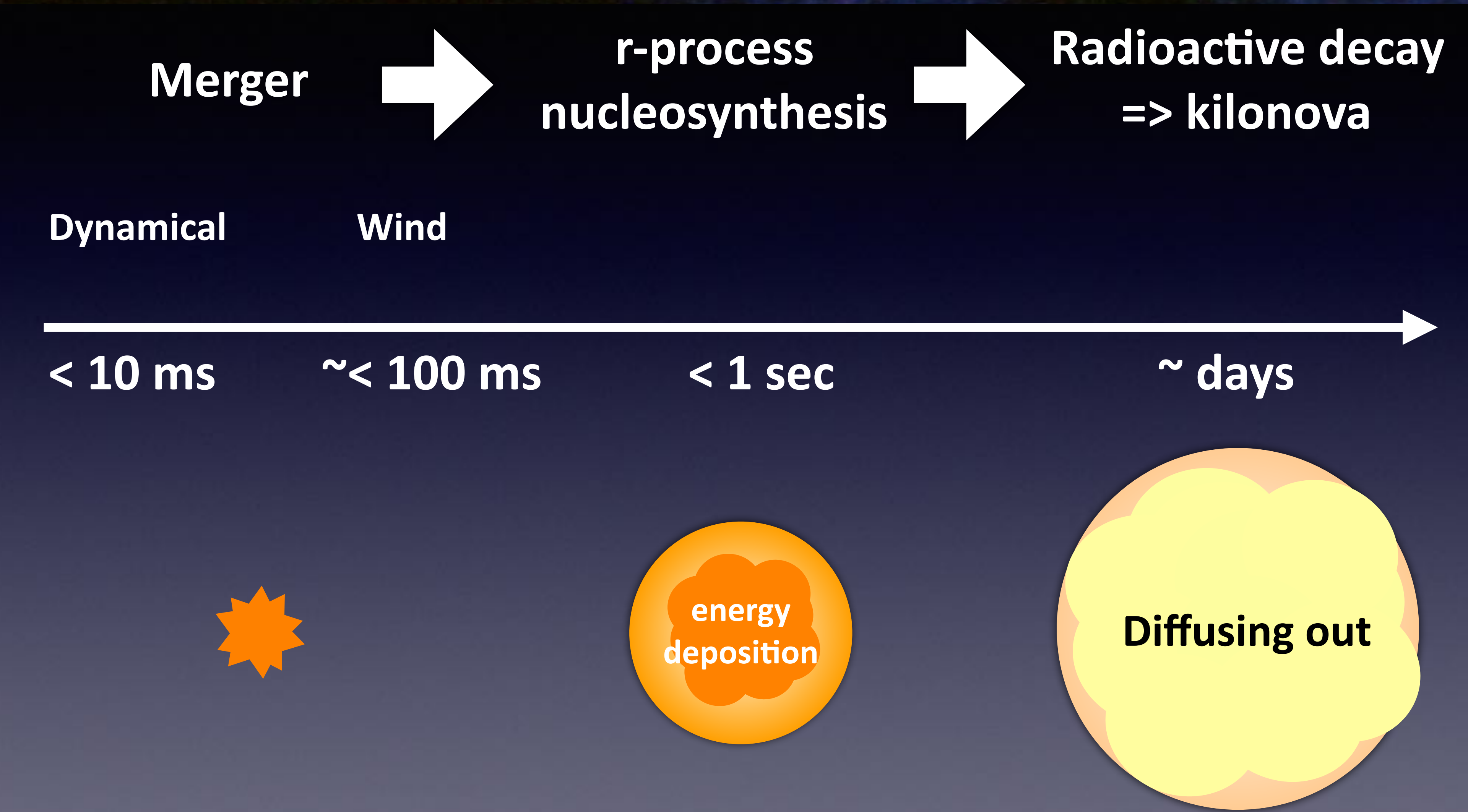
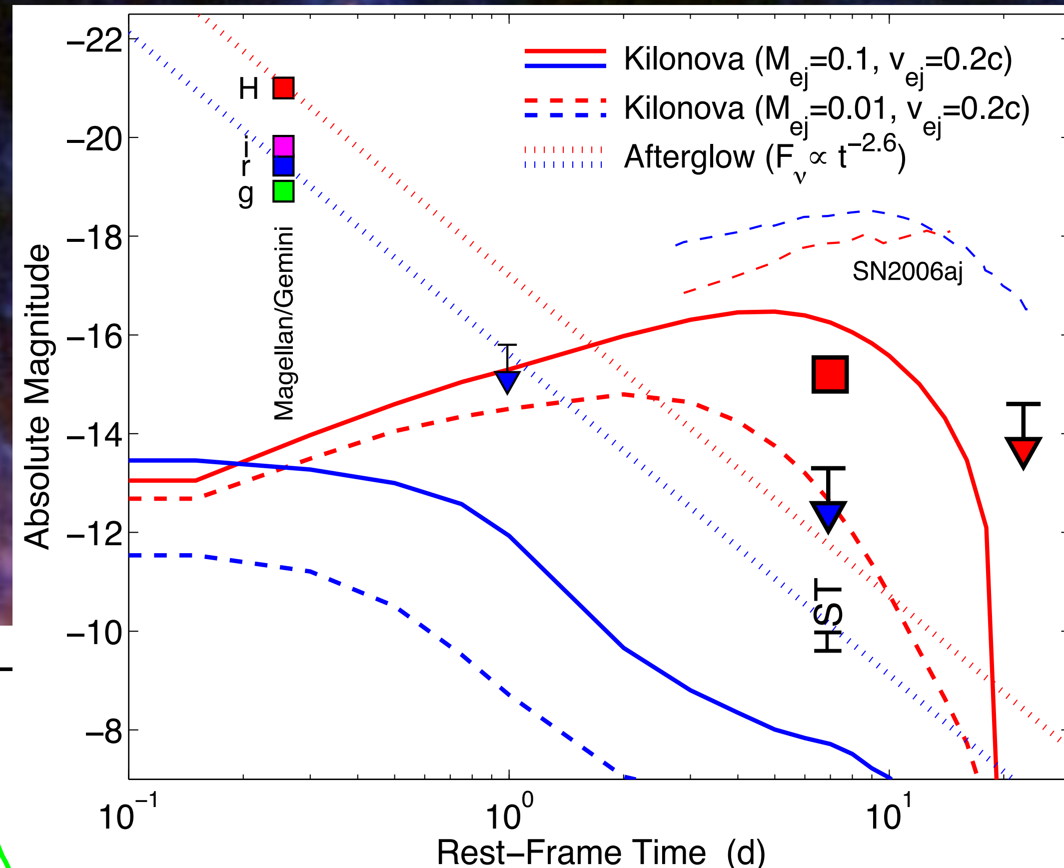
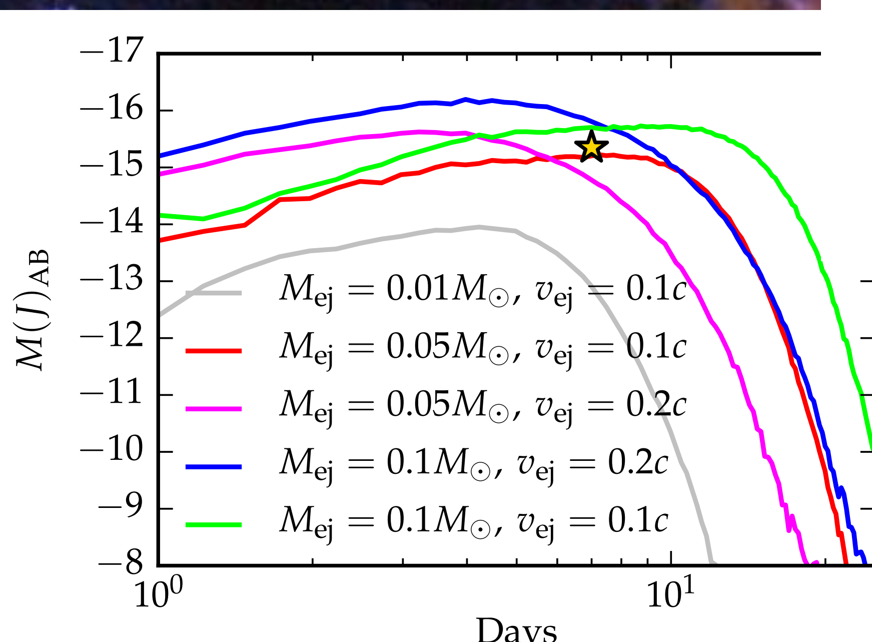


figure from M. Tanaka

kilonova: an *r*-process transient

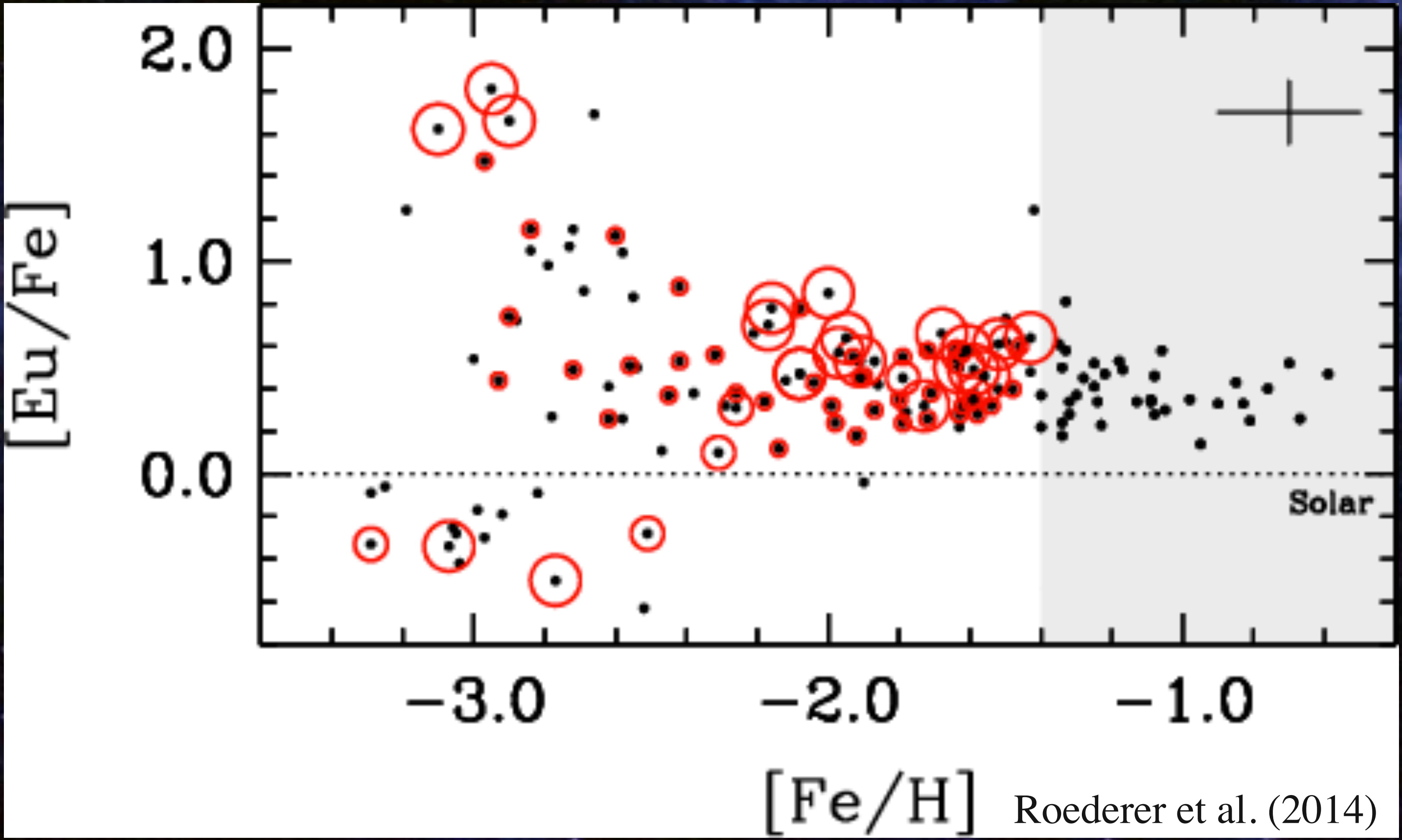
Tanvir+2013, Berger 2013: observations of a kilonova candidate sGRB 130603B





Barnes et al (2016)

metal-poor stars and the *r* process



Roederer et al. (2014)

Observations of Europium in metal-poor stars have been used to argue *against* NS-NS/NS-BH mergers as the main source of galactic *r*-process elements because…

A – these types of mergers are too rare.

B – most merger ejecta ends up falling back into the central black hole.

C –mergers do not occur sufficiently early in galactic history.

D – most binary stellar systems are kicked out of the galactic plane when one star goes supernova, so mergers cannot enrich the galactic disk gas.

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