Chemical Evolution

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UC Irvine Center for Galaxy Evolution
(until Thursday)

Caltech
(starting Friday)

Schedule

- Monday, 11:30 am – 12:30 pm
  - *Sources of Nucleosynthesis and Timescales*
- Monday, 2:30 pm – 5:00 pm
  - Workshop with Carla Fröhlich
- Tuesday, 11:30 am – 12:30 pm
  - *Analytic Models of Chemical Evolution*
  - lots of equations
- Wednesday, 11:30 am – 12:30 pm
  - *Measurements in the Galaxy and Beyond*

Useful links

http://mahler.ps.uci.edu/issac/

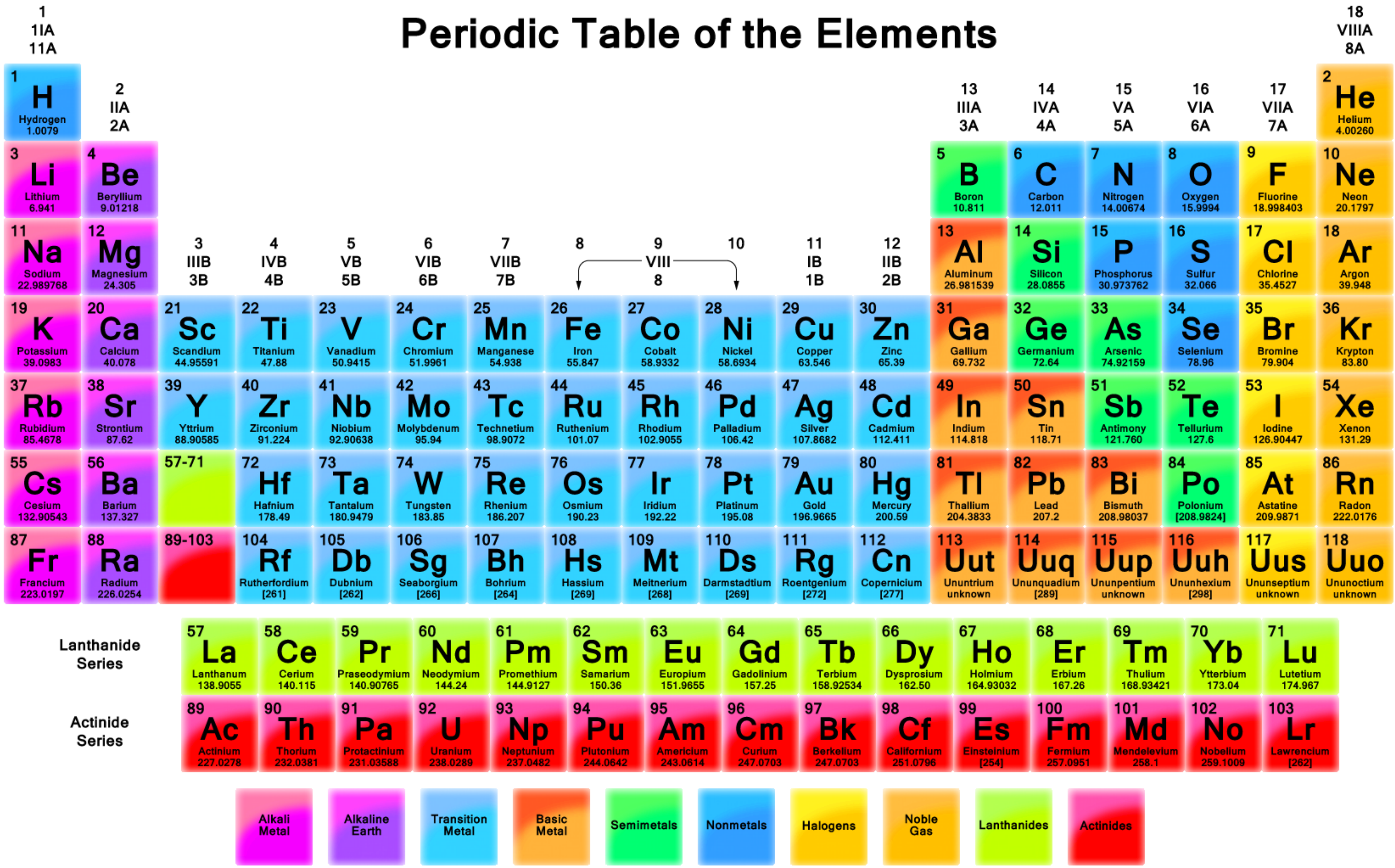
gordon.sdsc.edu:/home/train90/

UCSD_Summer_School_Workshop.pdf

Sources of Nucleosynthesis and Timescales

- Quick orientation to the elements
- Nucleosynthetic sources
    - Type II supernovae
    - Type Ia supernovae
    - AGB stars

Periodic Table of the Elements



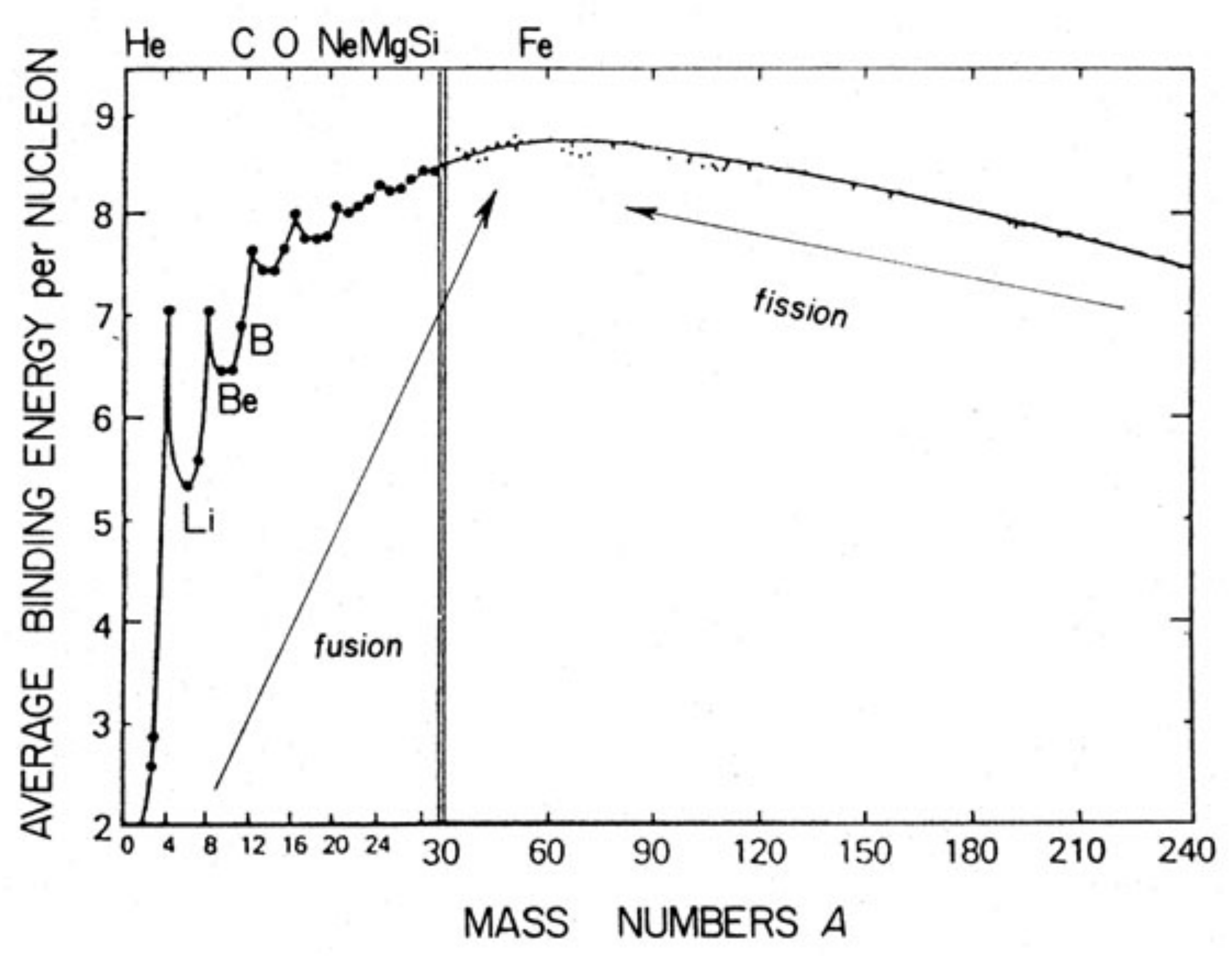
1 1IA 11A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.0079																	2 He Helium 4.00260
3 Li Lithium 6.941	4 Be Beryllium 9.01218											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.998403	10 Ne Neon 20.1797
11 Na Sodium 22.989768	12 Mg Magnesium 24.305											13 Al Aluminum 26.981539	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.95591	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.64	33 As Arsenic 74.92159	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98.9072	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90543	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.9665	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium [208.9824]	85 At Astatine 209.9871	86 Rn Radon 222.0176
87 Fr Francium 223.0197	88 Ra Radium 226.0254	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Uuq Ununquadium [289]	115 Uup Ununpentium unknown	116 Uuh Ununhexium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

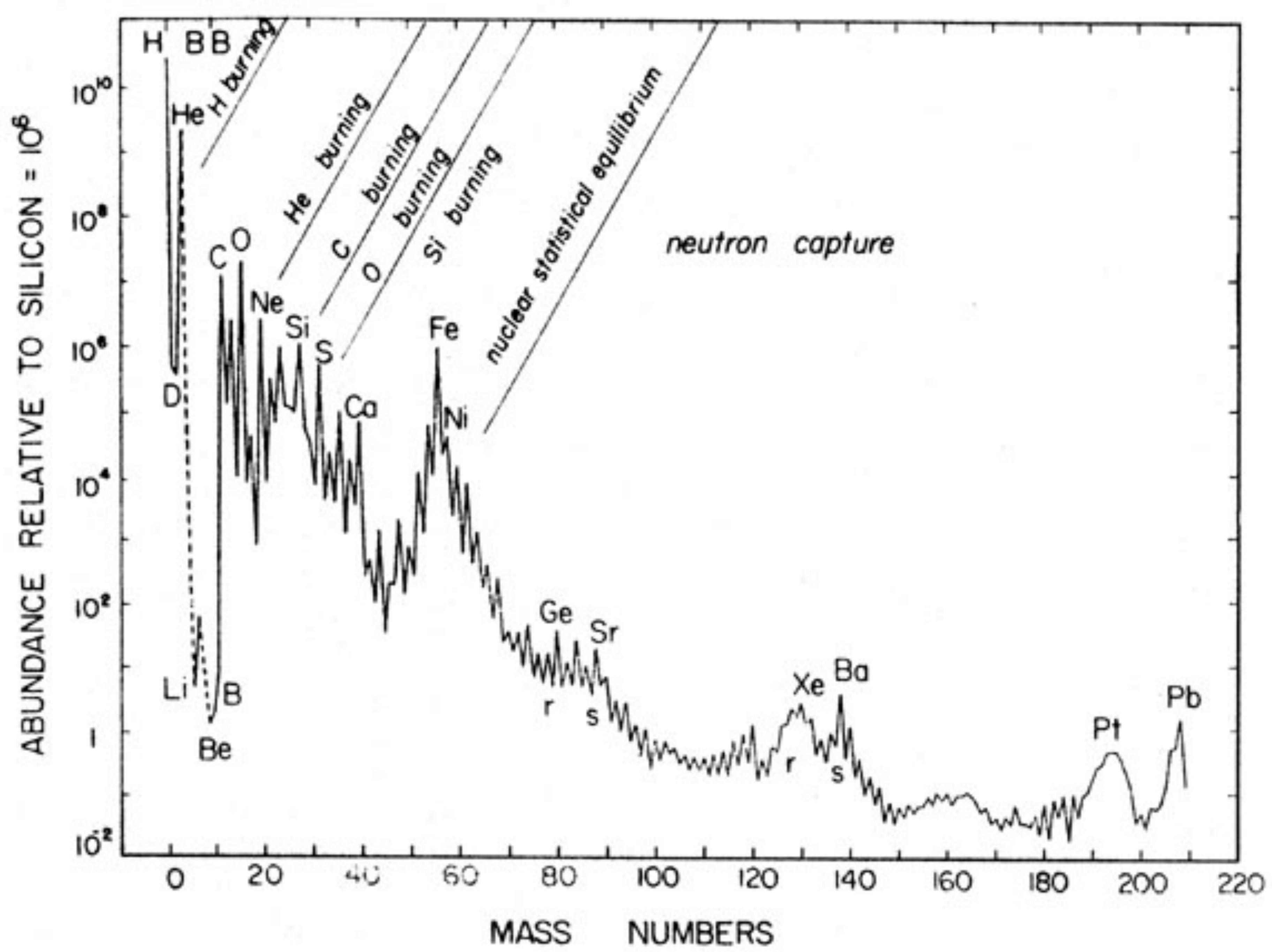
Lanthanide Series	57 La Lanthanum 138.9055	58 Ce Cerium 140.115	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium 144.9127	62 Sm Samarium 150.36	63 Eu Europium 151.9655	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.0278	90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.0289	93 Np Neptunium 237.0482	94 Pu Plutonium 244.0642	95 Am Americium 243.0614	96 Cm Curium 247.0703	97 Bk Berkelium 247.0703	98 Cf Californium 251.0796	99 Es Einsteinium [254]	100 Fm Fermium 257.0951	101 Md Mendelevium 258.1	102 No Nobelium 259.1009	103 Lr Lawrencium [262]

Alkali Metal · Alkaline Earth · Transition Metal · Basic Metal · Semimetals · Nonmetals · Halogens · Noble Gas · Lanthanides · Actinides

Nucleosynthesis cheat sheet

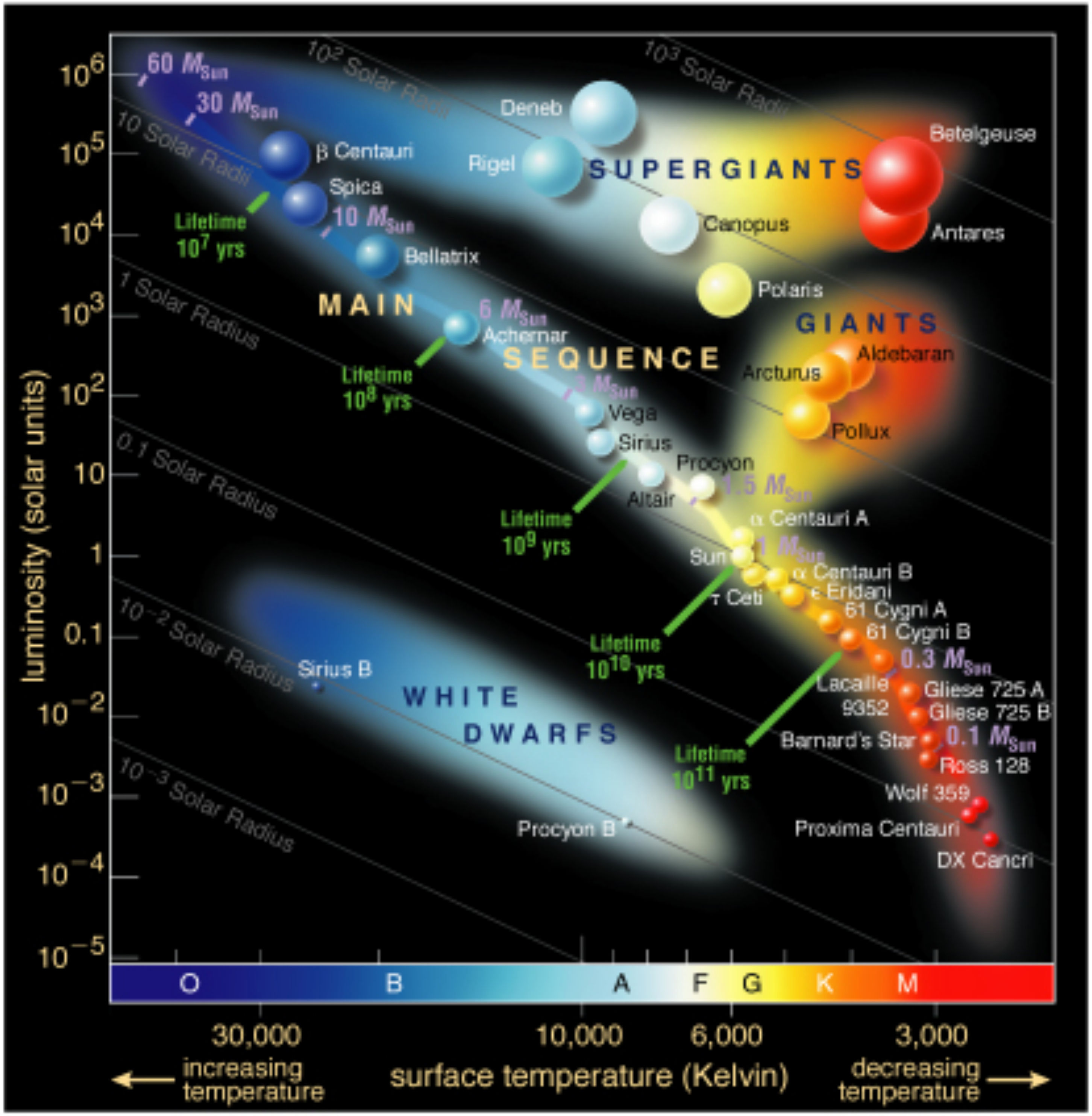
- Type II SNe: low-mass elements (He, C, N, O), α elements (O, Ne, Mg, Si, S, Ar, Ca), some Fe peak, *r*-process?
- Type Ia SNe: mostly Fe peak (Sc-Zn)
- AGB stars: He, C, N, *s*-process


He
C
O
Ne
Mg
Si
Fe
AVERAGE BINDING ENERGY per NUCLEON
2
3
4
5
6
7
8
9
Li
Be
B
fusion
fission
0
4
8
12
16
20
24
30
60
90
120
150
180
210
240
MASS NUMBERS *A*


H
BB
H burning
He
He burning
C burning
O burning
Si burning
nuclear statistical equilibrium
neutron capture
D
Li
B
Be
C
O
Ne
Si
S
Ca
Fe
Ni
Ge
Sr
r
s
Xe
Ba
r
s
Pt
Pb
ABUNDANCE RELATIVE TO SILICON = 10⁶
10¹⁰
10⁸
10⁶
10⁴
10²
1
10⁻²
0
20
40
60
80
100
120
140
160
180
200
220
MASS NUMBERS

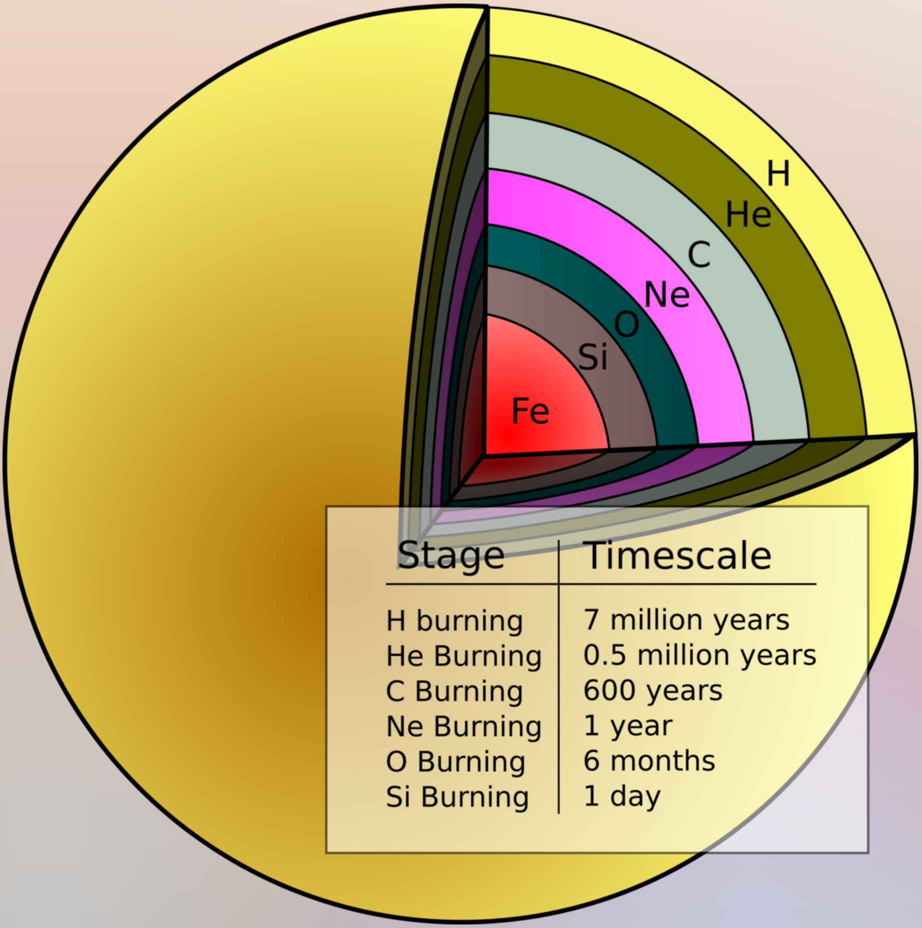
Nucleosynthetic sources

- Major
  - Core collapse (Type II) supernovae 4-25 Myr
  - Asymptotic giant branch (AGB) stars 50+ Myr
  - Thermonuclear (Type Ia) supernovae 0.1?-14 Gyr
- Minor
  - Winds from low-mass stars $\gtrsim 1$ Gyr
  - Neutron star mergers ≈ 1 Gyr
  - Cosmic ray spallation


10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
luminosity (solar units)
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
3 M_{Sun}
1.5 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
β Centauri
Spica
Bellatrix
MAIN
SEQUENCE
Achernar
Vega
Sirius
Altair
Procyon
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Deneb
Rigel
SUPERGIANTS
Betelgeuse
Canopus
Antares
Polaris
GIANTS
Aldebaran
Arcturus
Pollux
Sirius B
WHITE DWARFS
Procyon B
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

Core collapse (Type II) supernova

- 10-50 $M_{\odot}$
- 17% of stars by mass
- 0.8% by number



Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

Core collapse nucleosynthesis
(Woosley & Weaver 1995)

- pre-explosion
  - hydrostatic: He, C, N, O, Ne, Na, Mg, Al, (Si-Sc)
  - *s*-process

explosion

neutrinos: F

explosive burning: (Si-Sc), Ti-Zn

r-process

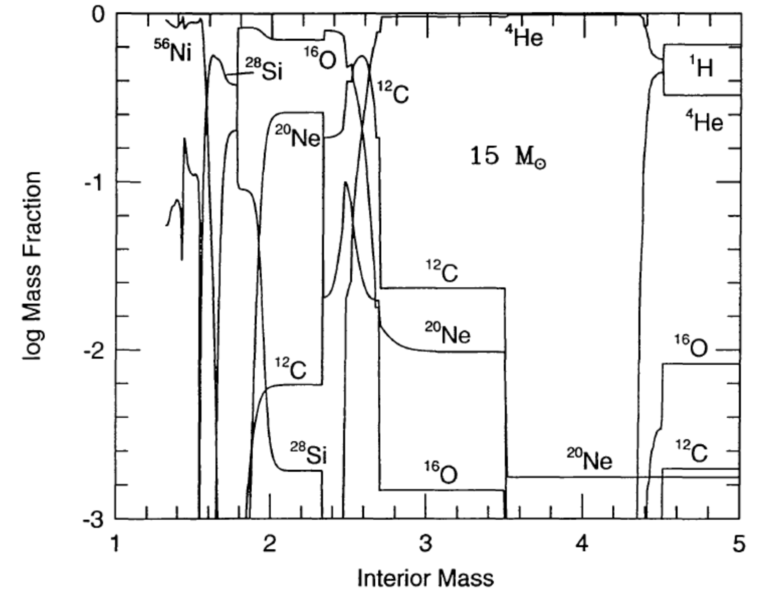


FIG. 10*a*

Core collapse nucleosynthesis (Woosley & Weaver 1995)

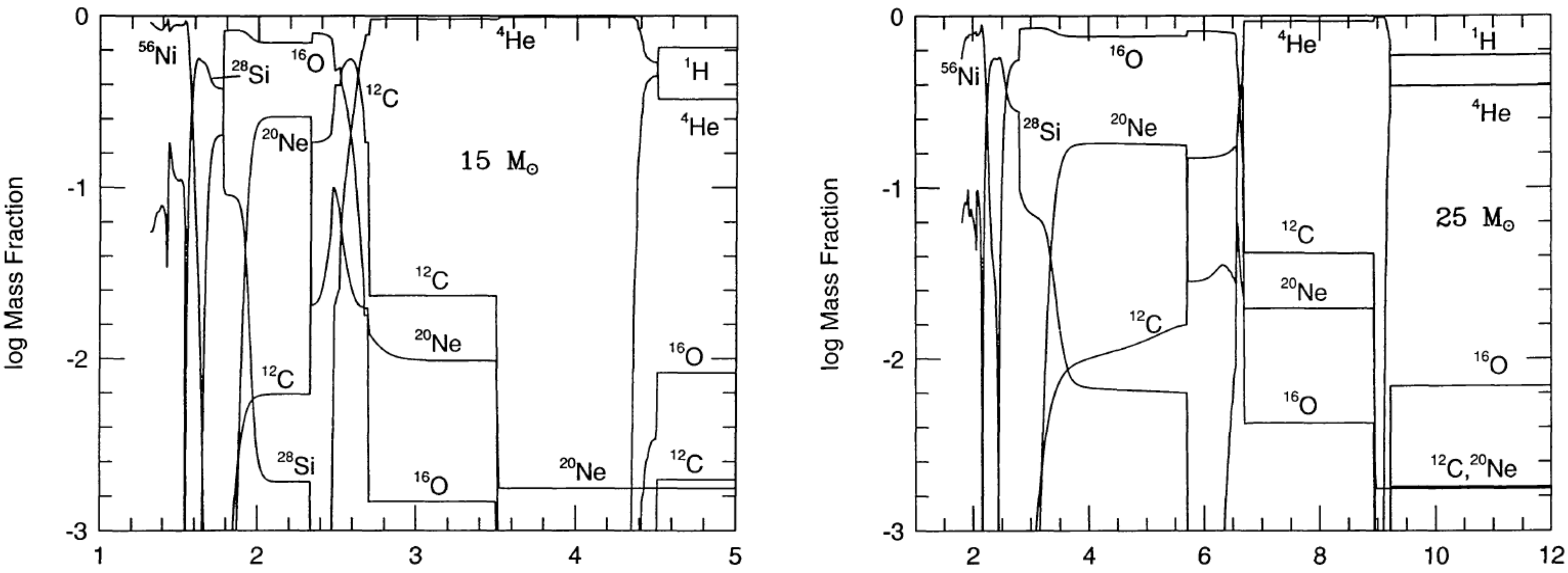


FIG. 10*a*

FIG. 10*b*

FIG. 10.—Final mass fractions of the major abundances — ^{1}H, ^{4}He, ^{12}C, ^{16}O, ^{20}Ne, ^{28}Si, and ^{56}Ni—(*a*) the inner 5 $M_\odot$ of a 15 $M_\odot$ solar metallicity supernova (model S15A); (*b*) the inner 12 $M_\odot$ of the ejecta of a 25 $M_\odot$ solar metallicity supernova (model S25A). Each had an explosion energy of 1.2×10^{51} ergs (Table 3).

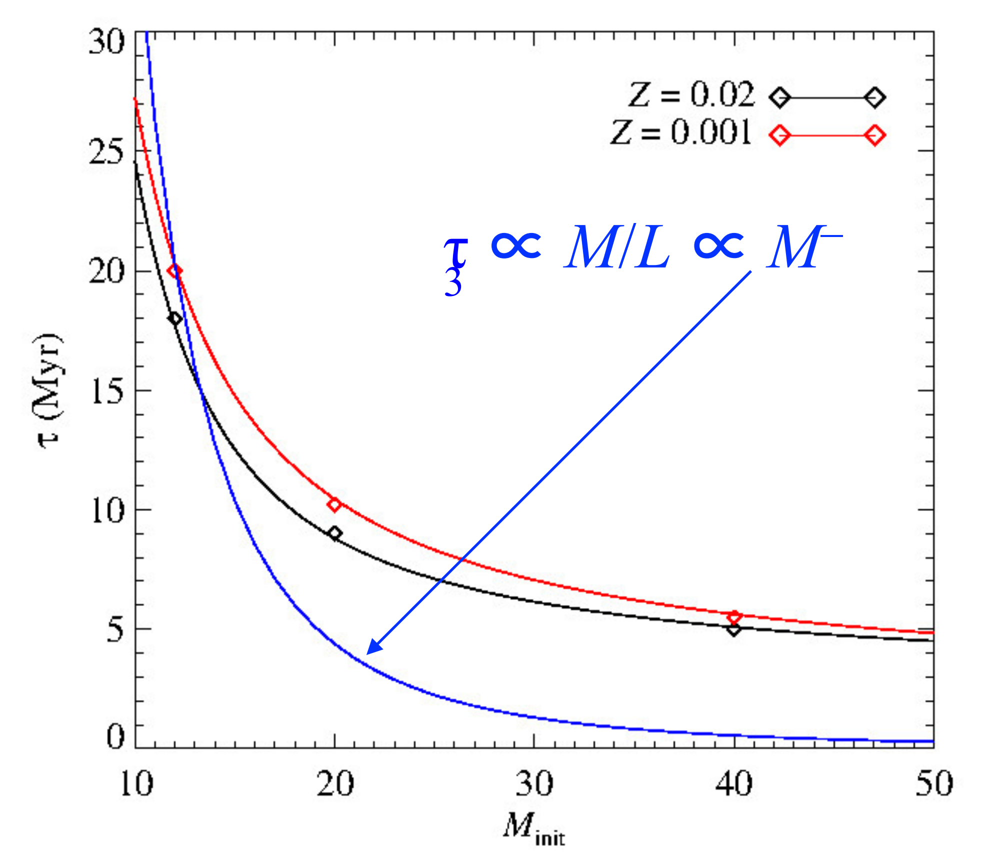
Woosley & Weaver 1995, ApJS, 101, 181 (2300+ citations)

TABLE 19

THE ORIGIN OF THE LIGHT AND INTERMEDIATE-MASS ELEMENTS

Species	Origin	Species	Origin	Species	Origin
^{1}H	BB	^{29}Si	Ne,xNe	^{50}Ti	nse-Ia-MCh
^{2}H	BB	^{30}Si	Ne,xNe	^{50}V	Ne,xNe,xO
^{3}He	BB,L*	^{31}P	Ne,xNe	^{51}V	α,Ia-det,xSi,xO,ν
^{4}He	BB,L*,H	^{32}S	xO,O	^{50}Cr	xSi,xO,α,Ia-det
^{6}Li	CR	^{33}S	xO,xNe	^{52}Cr	xSi,α,Ia-det
^{7}Li	BB,ν,L*,CR	^{34}S	xO,O	^{53}Cr	xO,xSi
^{9}Be	CR	^{36}S	Ne,xNe	^{54}Cr	nse-Ia-MCh
^{10}B	CR	^{35}Cl	xO,xNe,ν	^{55}Mn	Ia, xSi, ν
^{11}B	ν	^{37}Cl	xO,xNe	^{54}Fe	Ia,xSi
^{12}C	L*,He	^{36}Ar	xO,O	^{56}Fe	xSi,Ia
^{13}C	L*,H	^{38}Ar	xO,O	^{57}Fe	xSi,Ia
^{14}N	L*,H	^{40}Ar	C,Ne	^{58}Fe	He(s),nse-Ia-MCh
^{15}N	Nova,ν	^{39}K	xO,O.ν	^{59}Co	He(s),α,Ia,ν
^{16}O	He	^{40}K	C,Ne	^{58}Ni	α,Ia
^{17}O	H	^{41}K	xO	^{60}Ni	α, He(s)
^{18}O	He	^{40}Ca	xO,O	^{61}Ni	α,Ia-det,He(s)
^{19}F	ν,He	^{42}Ca	xO	^{62}Ni	α,He(s)
^{20}Ne	C	^{43}Ca	C,Ne	^{64}Ni	He(s)
^{21}Ne	C,He(s)	^{44}Ca	α,Ia-det	^{63}Cu	He(s), α
^{22}Ne	He	^{46}Ca	C,Ne	^{65}Cu	He(s)
^{23}Na	C,He(s),H	^{48}Ca	nse-Ia-MCh	^{64}Zn	He(s),α
^{24}Mg	C,Ne	^{45}Sc	α,C,Ne,ν	^{66}Zn	He(s),α,nse-Ia-MCh
^{25}Mg	C,Ne,He(s)	^{46}Ti	xO, Ia-det	^{67}Zn	He(s)
^{26}Mg	C,Ne,He(s)	^{47}Ti	xO, xSi, Ia-det	^{68}Zn	He(s)
^{27}Al	C,Ne	^{48}Ti	xSi,Ia-det		
^{28}Si	xO,O	^{49}Ti	xSi,He(s)		

Type II delay time distribution



$\tau \propto M/L \propto M^{-3}$

$Z = 0.02$: $\tau = (9.5 \times 10^9)\, M_{\rm init}^{-2.8} + (3.6 \times 10^7)\, M_{\rm init}^{-0.65} + 1.5 \times 10^6$

$Z = 0.001$: $\tau = (6.5 \times 10^9)\, M_{\rm init}^{-2.7} + (1.0 \times 10^8)\, M_{\rm init}^{-0.90} + 1.7 \times 10^6$

$dN \propto M_{\rm init}^{-2.35}\, dM$ (Salpeter IMF)

Type Ia nucleosynthesis

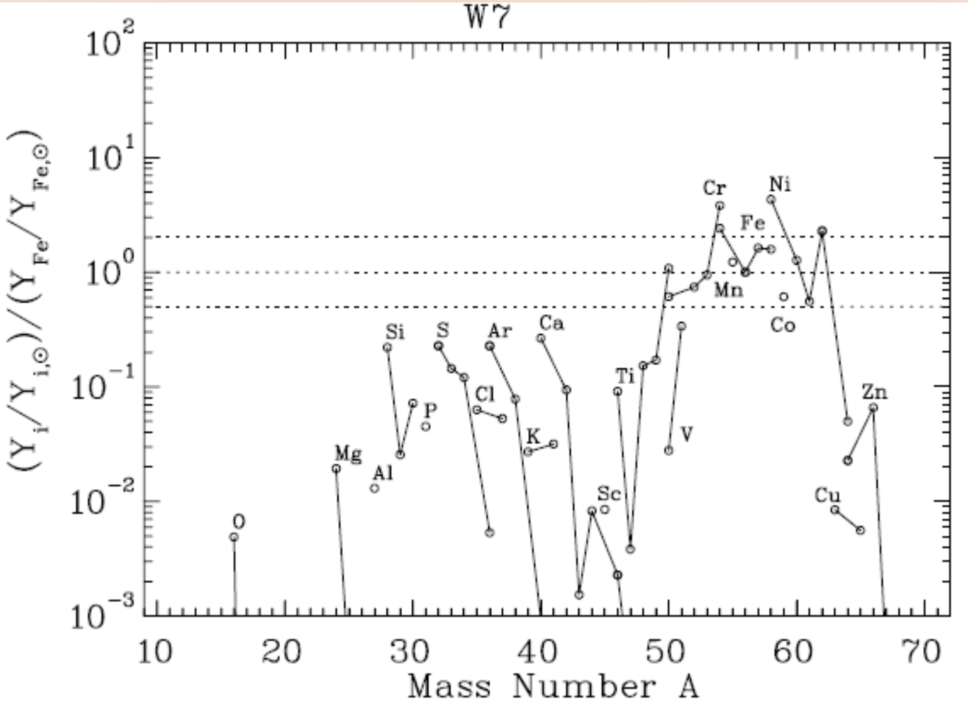
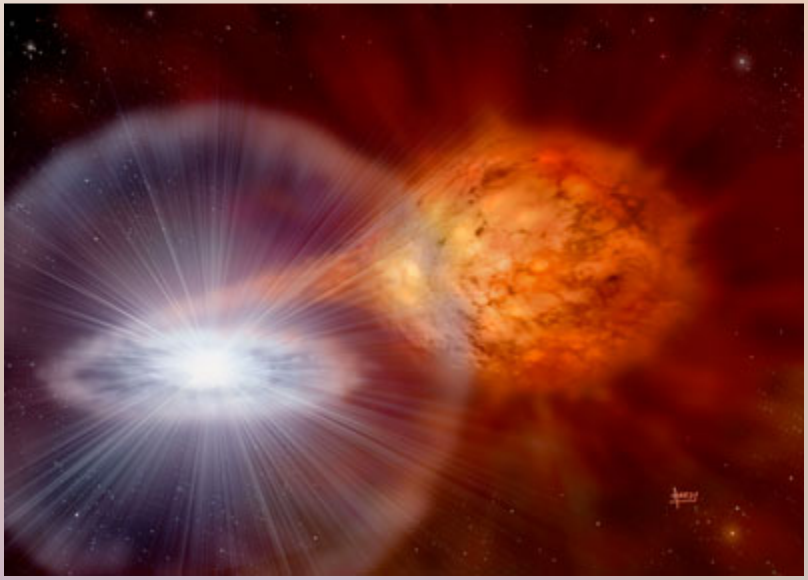


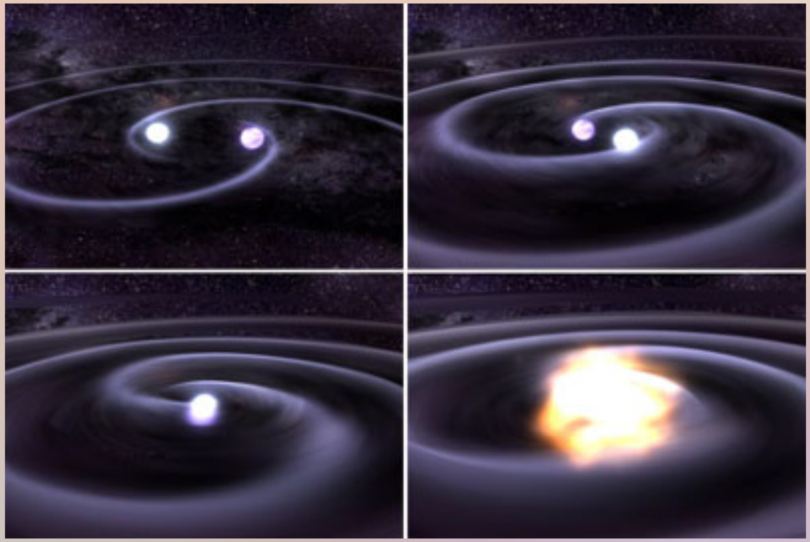
FIG. 12.—Ratio of abundances to solar predicted in model W7 (this is a recalculation of the 1986 model [Thielemann et al. 1986] with presently available updated reaction rates and a screened NSE treatment for temperatures beyond 6×10^9 K, as described in Hix & Thielemann 1996). Isotopes of one element are connected by lines. The ordinate is normalized to ^{56}Fe. Intermediate mass elements exist but are underproduced by a factor of 2–3 in comparison to Fe-group elements. Among the Fe-group, ^{54}Cr and ^{58}Ni are overproduced by a factor of 4, which exceeds the permitted factor of ∼3.

Iwamoto et al. 1999, ApJS, 125, 439 (500+ citations)

Type Ia models: SD vs. DD



single degenerate



double degenerate

Type Ia DTD

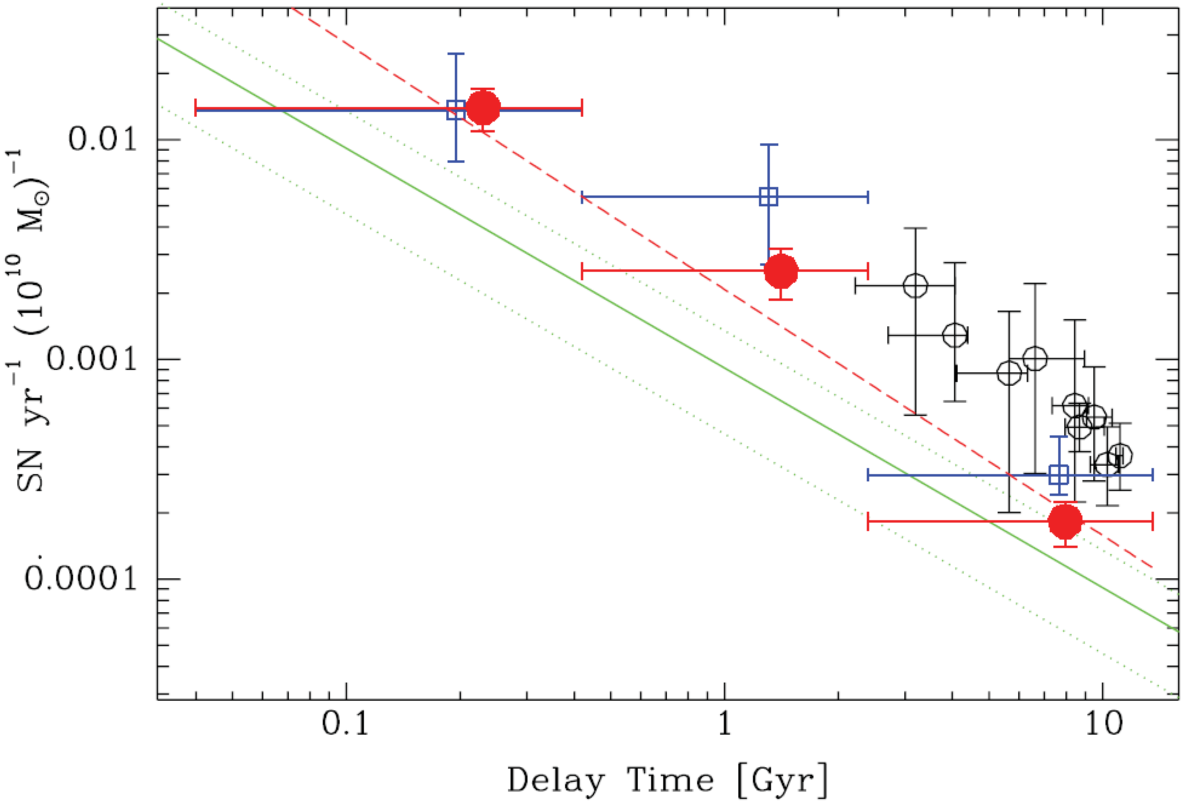


Figure 1. Recovered SN Ia DTD for the SDSS2 SN sample. Filled red circles mark the best-fitting DTD values for each time bin, whose time range is indicated by the horizontal error bars. Vertical error bars show the Gaussian 1σ uncertainties. Red dashed line is the best power-law fit, with index -1.12, to the recovered DTD. Previous DTD measurements also shown are as follows: M11 analysis of the nearby LOSS sample (empty blue squares, with central values slightly shifted to the left, for clarity); Maoz et al. (2010) analysis based on SN Ia rates in galaxy clusters (empty black circles); and t^{-1} power-law DTD found by Graur et al. (2011), based on comparison of volumetric SN Ia rates and cosmic SFH (solid green line, with dotted lines marking the 1σ range).

Maoz, Mannucci, & Brandt 2012, MNRAS, 426, 3282

Type Ia delay time distribution

$$\Psi_{\mathrm{Ia}} \approx 10^{-3}\,\tau^{-1.1}\ \mathrm{SN\ Gyr^{-1}}\ M_\odot^{-1} \qquad \tau \gtrsim 0.11\ \mathrm{Gyr}$$

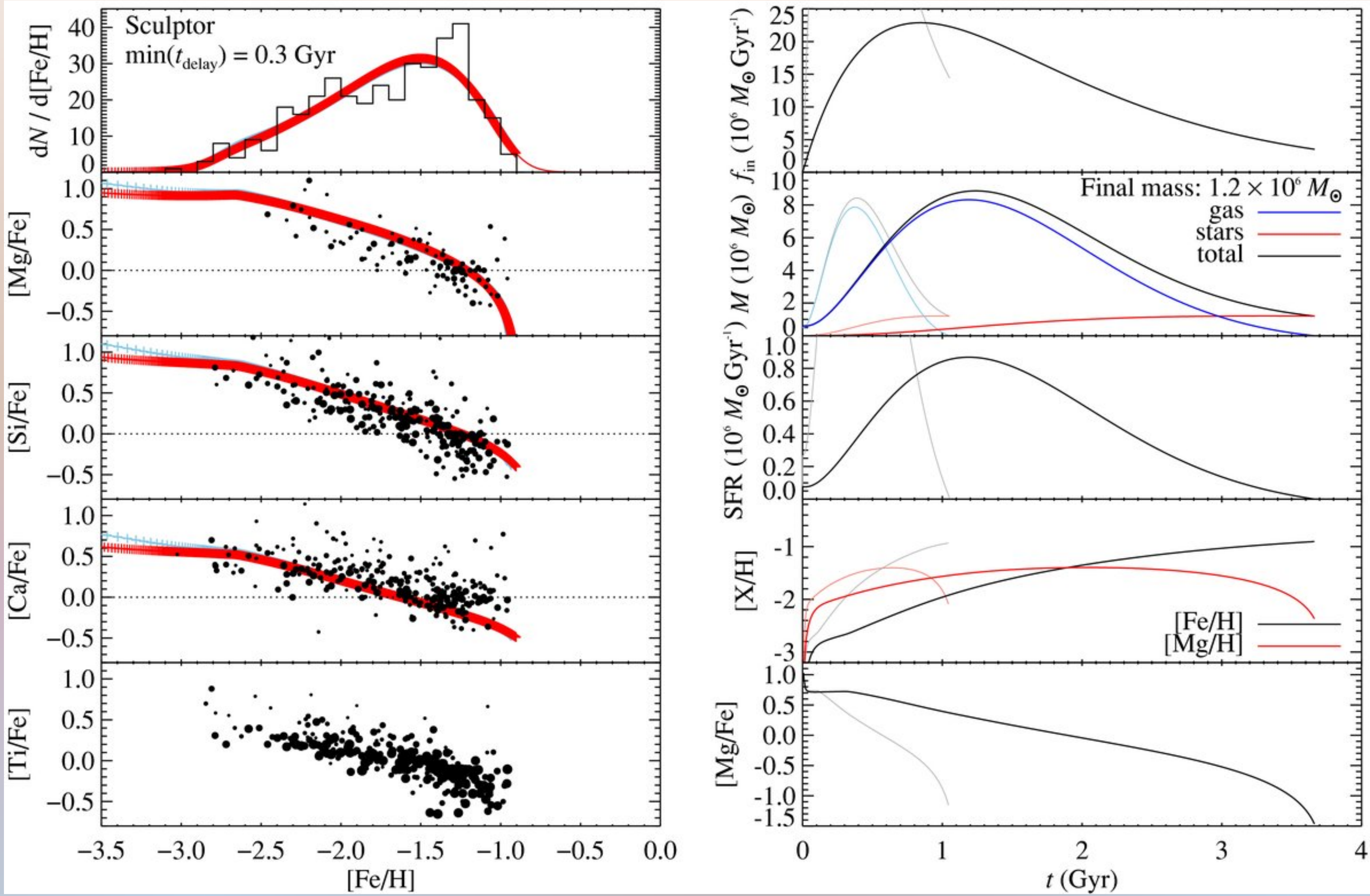
$$\Psi_{\mathrm{Ia}} = ??? \qquad \tau < 0.11\ \mathrm{Gyr}$$

$$\int_{0.11\ \mathrm{Gyr}}^{13.6\ \mathrm{Gyr}} \Psi_{\mathrm{Ia}}\,d\tau = 4.8 \times 10^{-3}\ \mathrm{SN}\ M_\odot^{-1}$$

$$\int_{0.11\ \mathrm{Gyr}}^{\infty} \Psi_{\mathrm{Ia}}\,d\tau = 1.2 \times 10^{-2}\ \mathrm{SN}\ M_\odot^{-1}$$

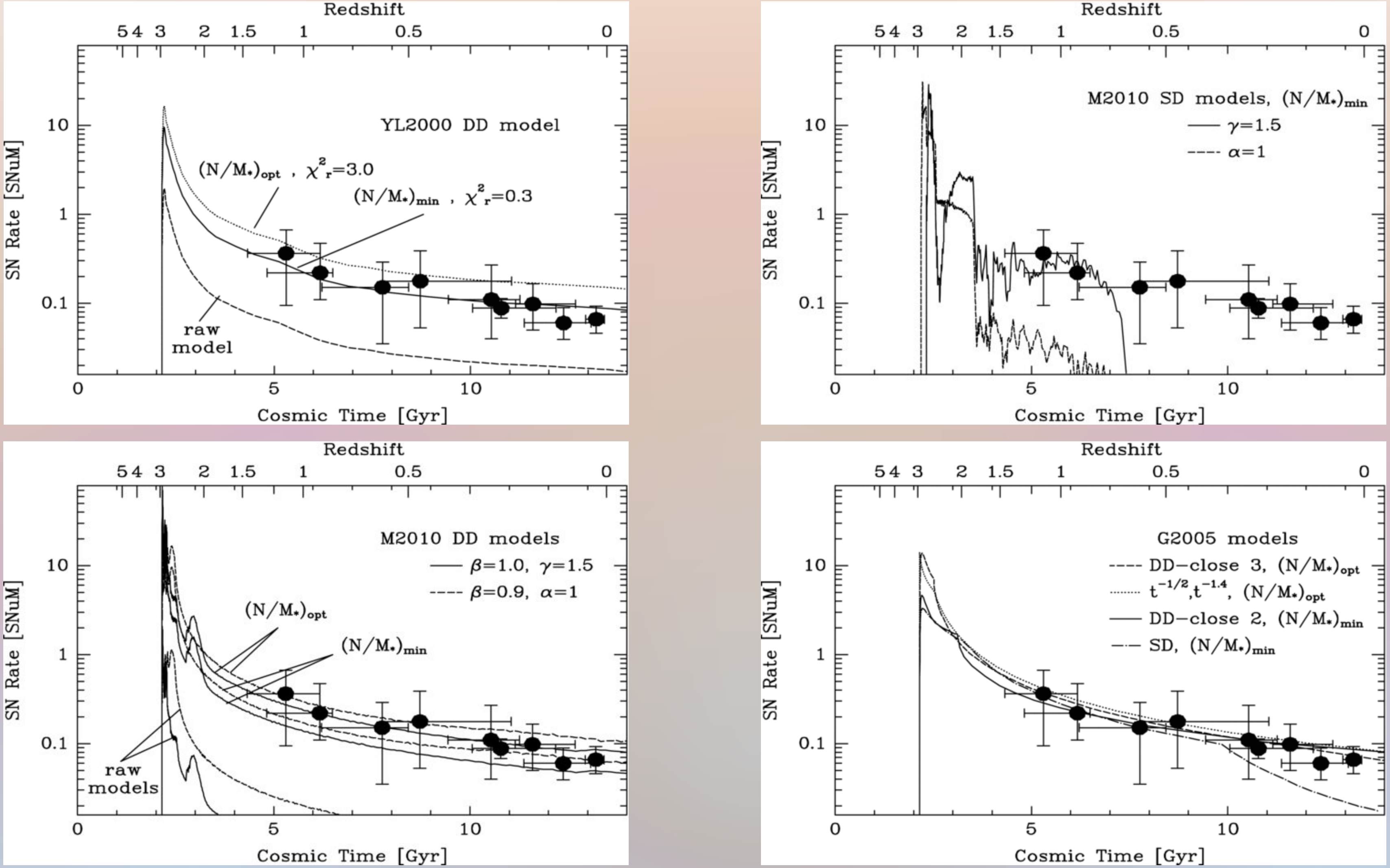
$$\int_{0.01\ \mathrm{Gyr}}^{13.6\ \mathrm{Gyr}} \Psi_{\mathrm{Ia}}\,d\tau = 8.1 \times 10^{-3}\ \mathrm{SN}\ M_\odot^{-1}$$

Effect of uncertainty in Type Ia DTD on chemical evolution models



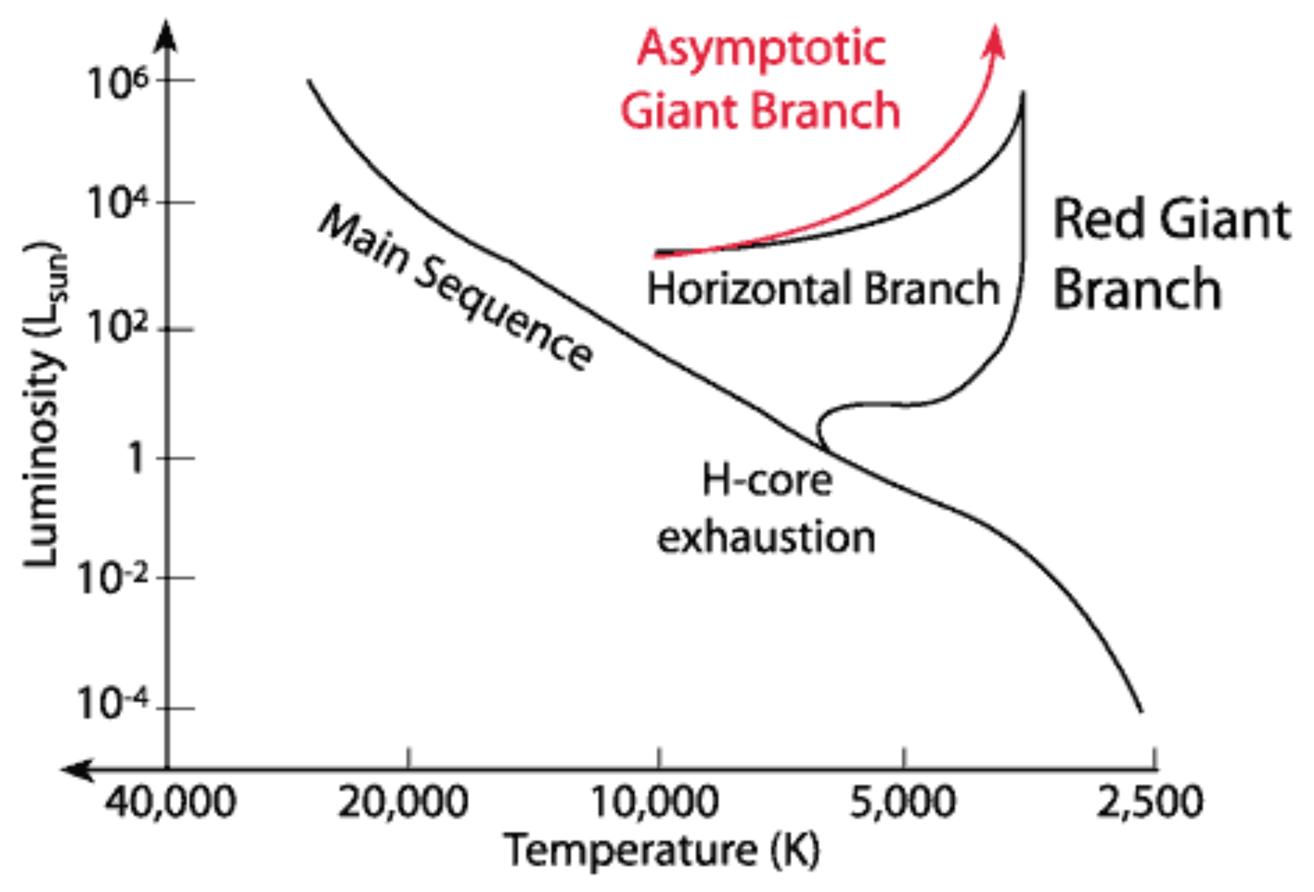
Kirby et al. 2011, ApJ, 727, 79

Type Ia models: SD vs. DD



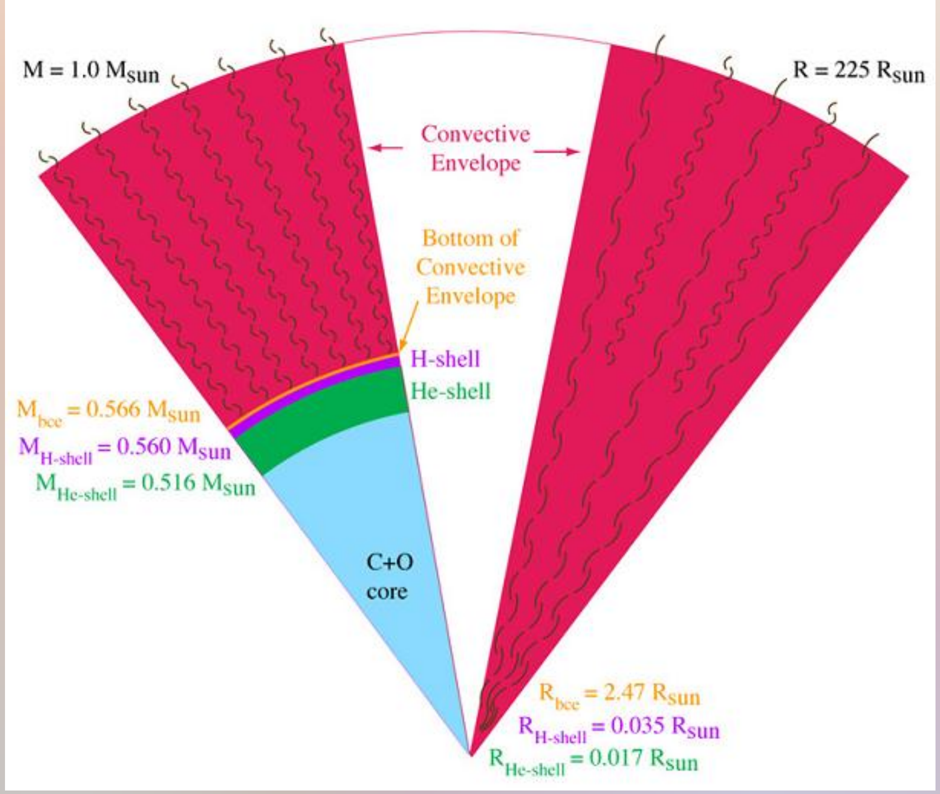
Maoz, Sharon, & Gal-Yam 2010, ApJ, 722, 1879

Asymptotic giant branch (AGB) stars



AGB nucleosynthesis

- Major elements: C, N, O, F, Ne, Na *s*-process
- Mass loss up to 70% of initial mass during thermal pulses



AGB thermal pulses

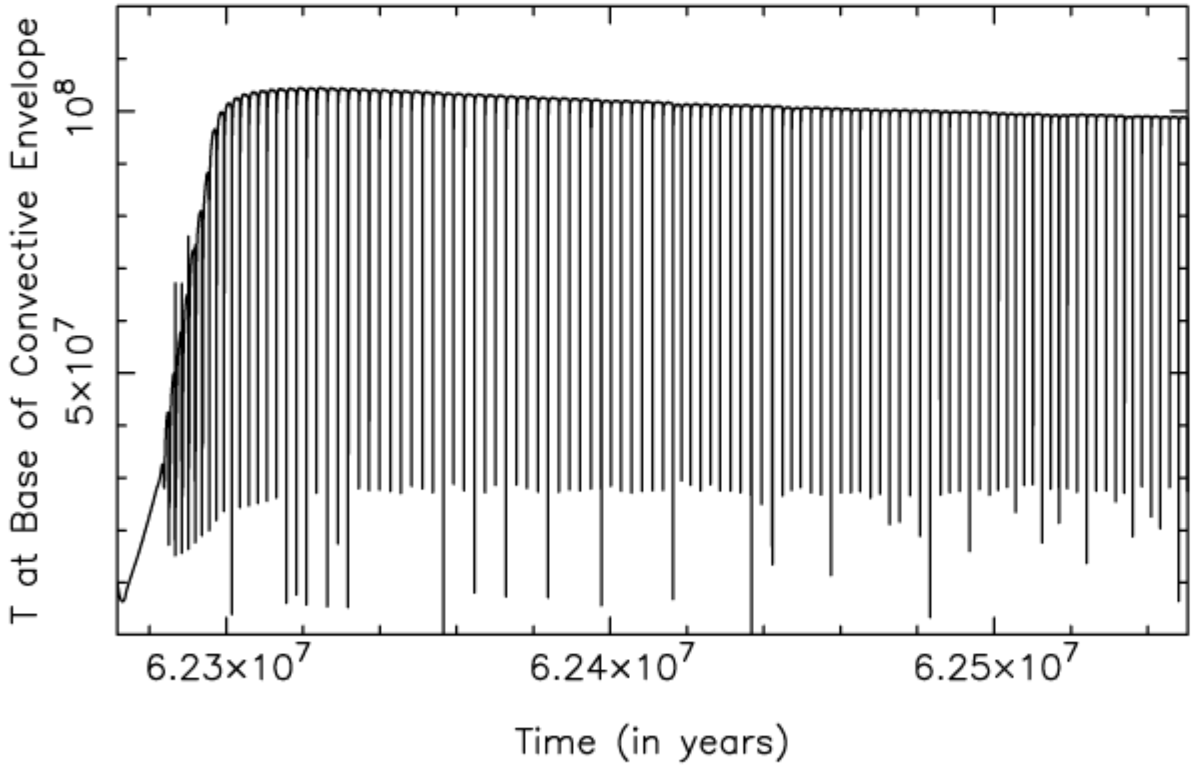
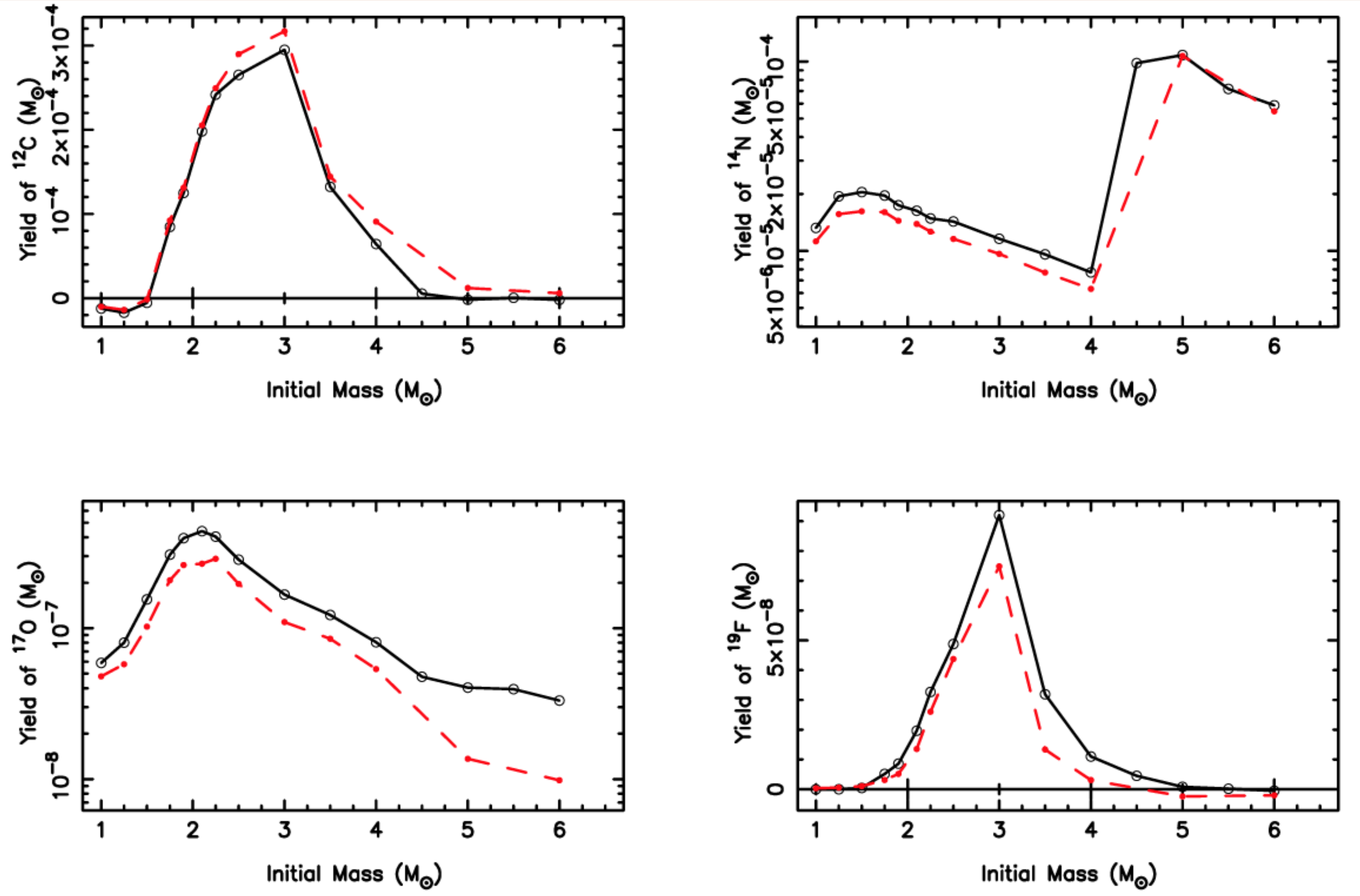


Figure 1. The temporal evolution during the TP–AGB of the temperature at the base of the convective envelope for $6\,M_\odot$ $Z = 0.0001$ models with R75 (top panel) and VW93 (lower panel) mass loss.

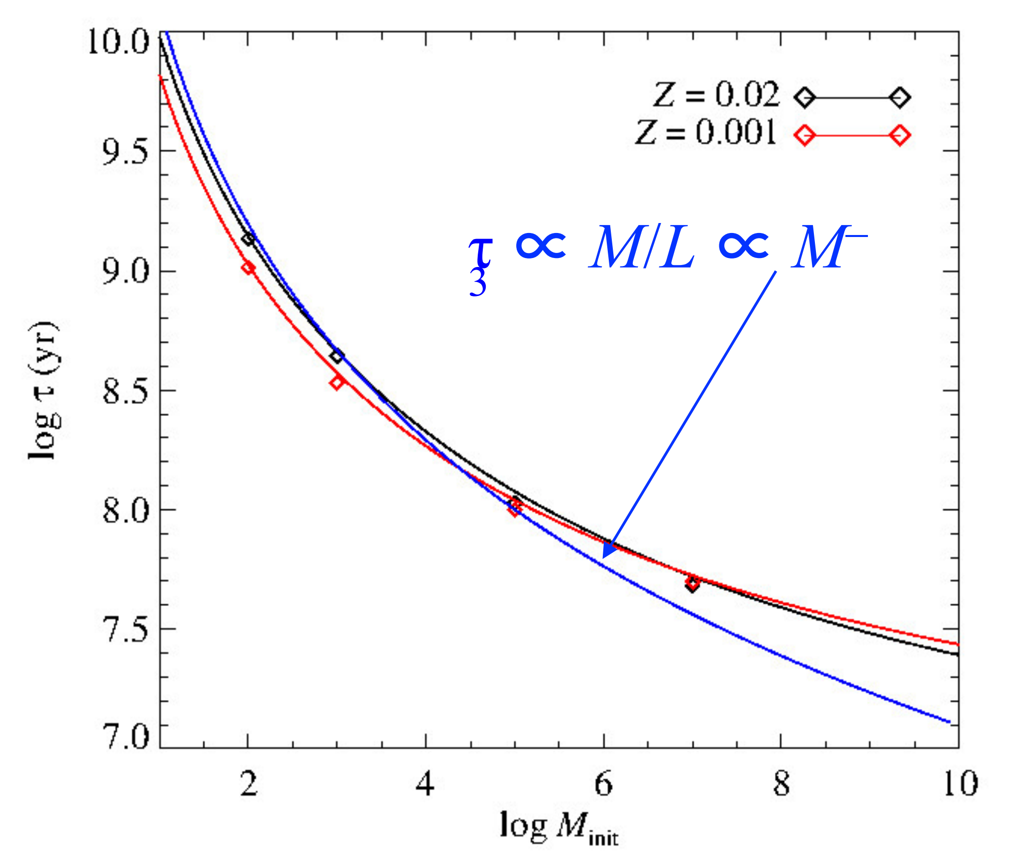
Karakas 2010, MNRAS, 403, 1413

AGB nucleosynthesis



Karakas 2010, MNRAS, 403, 1413

AGB delay time distribution



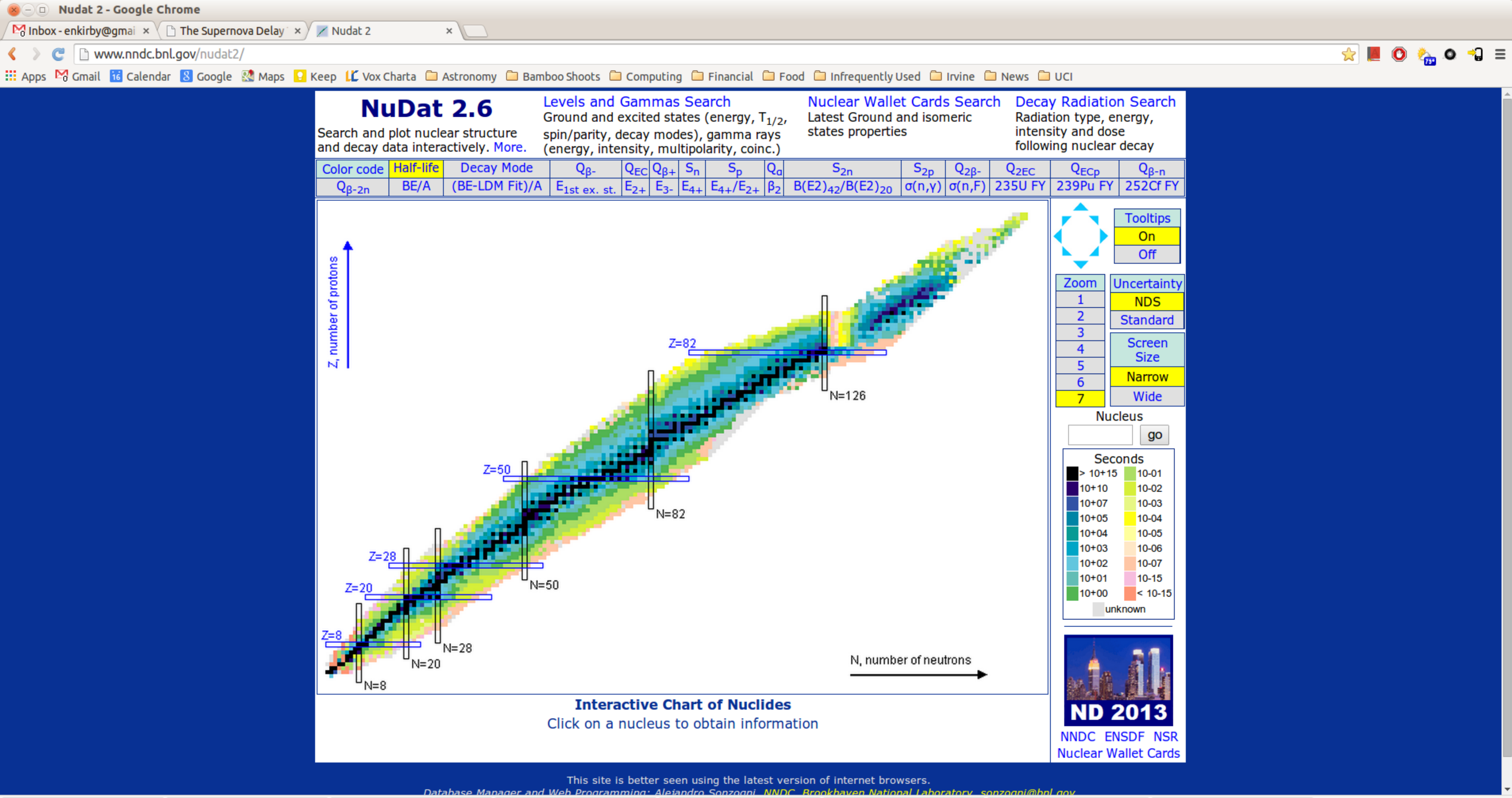
$Z = 0.02$: $\tau = (9.5 \times 10^9)\, M_{init}^{-2.8} + (3.6 \times 10^7)\, M_{init}^{-0.65} + 1.5 \times 10^6$

$Z = 0.001$: $\tau = (6.5 \times 10^9)\, M_{init}^{-2.7} + (1.0 \times 10^8)\, M_{init}^{-0.90} + 1.7 \times 10^6$

$dN \propto M_{init}^{-2.35}\, dM$ (Salpeter IMF)

Neutron-capture nucleosynthesis

http://www.nndc.bnl.gov/nudat2/



NuDat 2.6

Search and plot nuclear structure and decay data interactively. More.

Levels and Gammas Search
Ground and excited states (energy, $T_{1/2}$, spin/parity, decay modes), gamma rays (energy, intensity, multipolarity, coinc.)

Nuclear Wallet Cards Search
Latest Ground and isomeric states properties

Decay Radiation Search
Radiation type, energy, intensity and dose following nuclear decay

Color code	Half-life	Decay Mode	$Q_{\beta-}$	Q_{EC}	$Q_{\beta+}$	S_n	S_p	Q_α	S_{2n}	S_{2p}	$Q_{2\beta-}$	Q_{2EC}	Q_{ECp}	$Q_{\beta\text{-}n}$
$Q_{\beta\text{-}2n}$	BE/A	(BE-LDM Fit)/A	$E_{1st\ ex.\ st.}$	E_{2+}	E_{3-}	E_{4+}	E_{4+}/E_{2+}	β_2	$B(E2)_{42}/B(E2)_{20}$	σ(n,γ)	σ(n,F)	235U FY	239Pu FY	252Cf FY

Seconds

■	> 10+15	■	10-01
■	10+10	■	10-02
■	10+07	■	10-03
■	10+05	■	10-04
■	10+04	■	10-05
■	10+03	■	10-06
■	10+02	■	10-07
■	10+01	■	10-15
■	10+00	■	< 10-15
■	unknown		

Interactive Chart of Nuclides

Click on a nucleus to obtain information

This site is better seen using the latest version of internet browsers.

Database Manager and Web Programming: Alejandro Sonzogni, NNDC, Brookhaven National Laboratory, sonzogni@bnl.gov

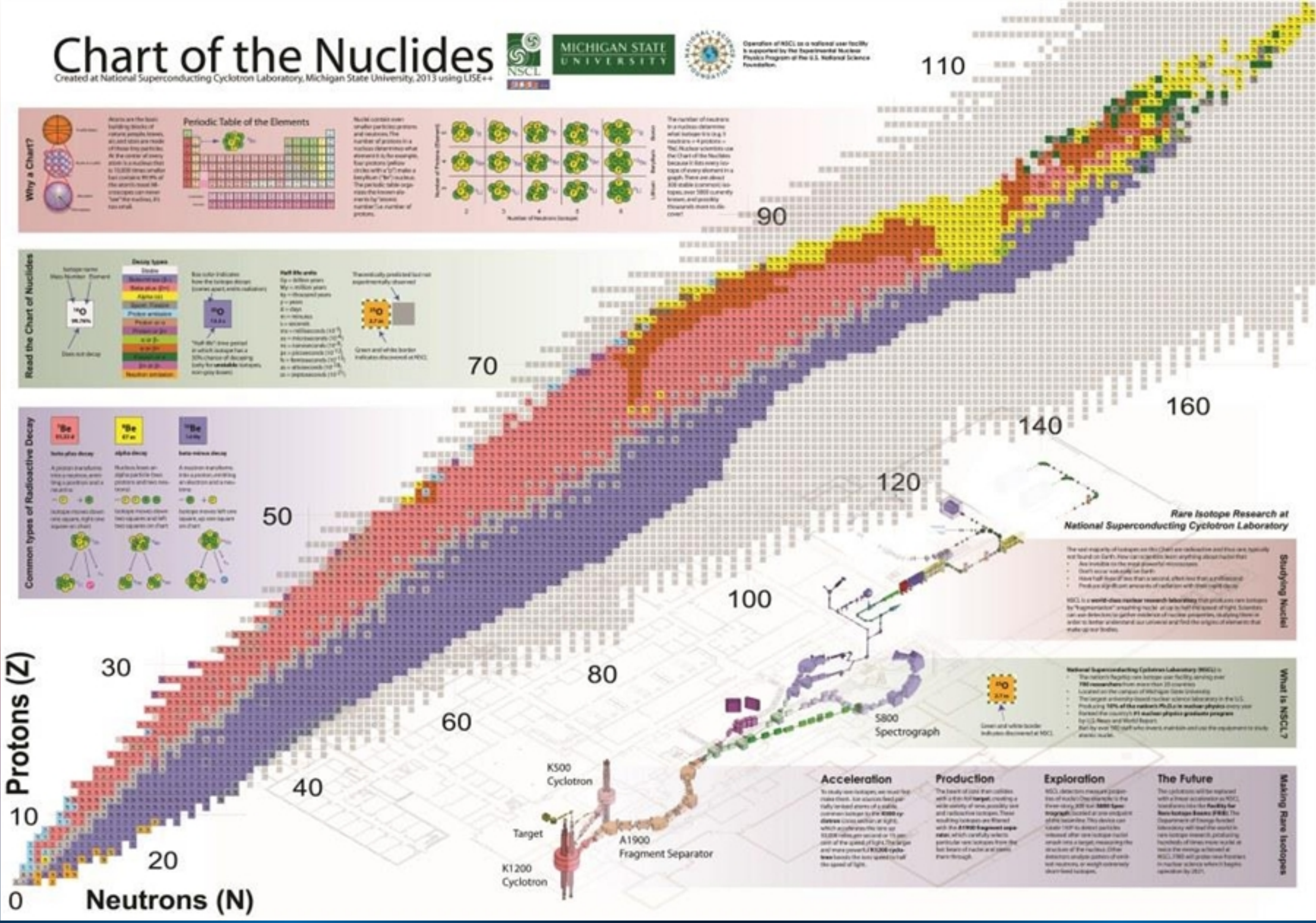


Chart of the Nuclides

Created at National Superconducting Cyclotron Laboratory, Michigan State University, 2013 using LISE++

Why a Chart?

Periodic Table of the Elements

Read the Chart of Nuclides

Common types of Radioactive Decay

Rare Isotope Research at National Superconducting Cyclotron Laboratory

Studying Nuclei

What is NSCL?

Making Rare Isotopes

Acceleration

Production

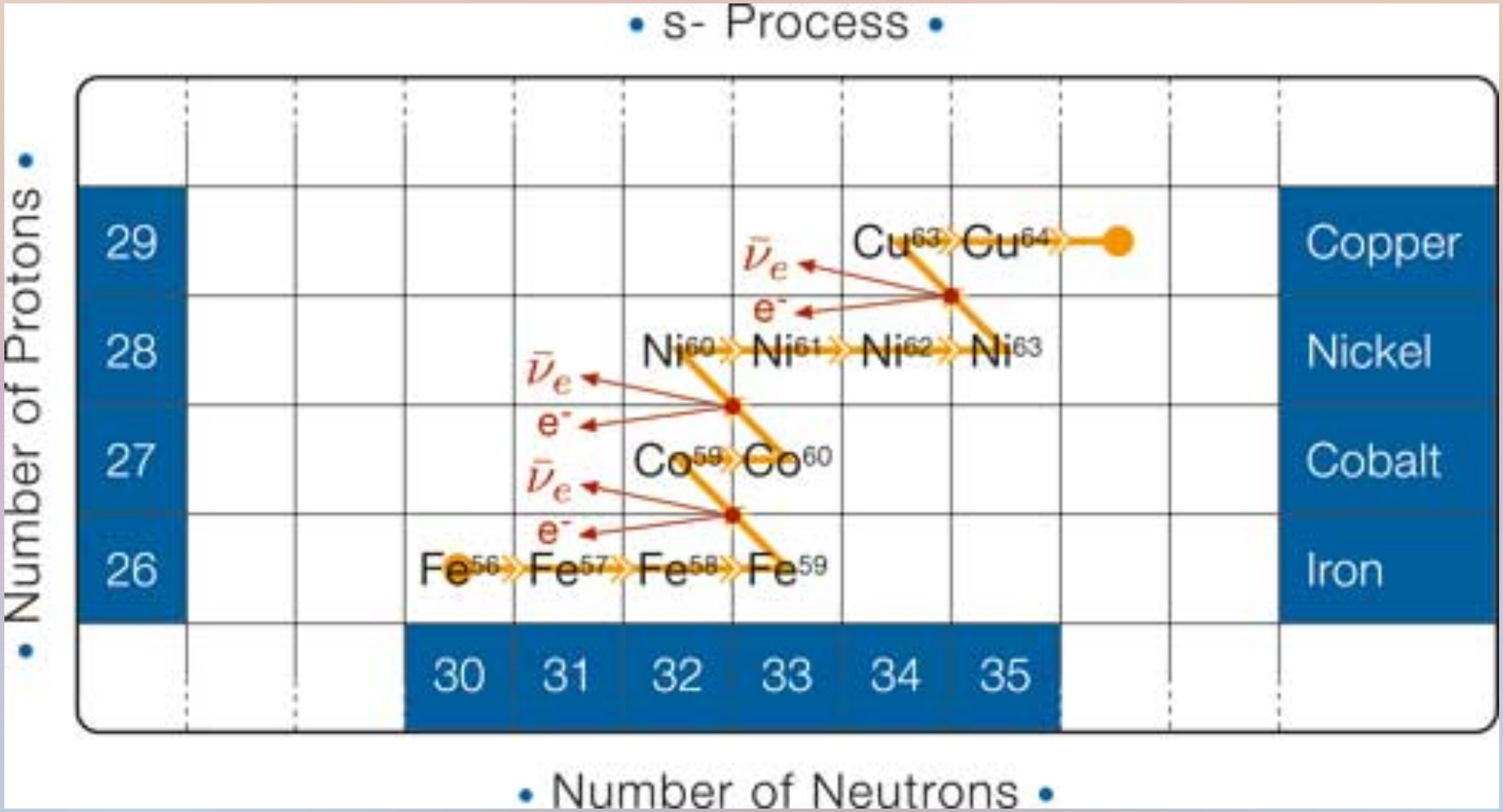
Exploration

The Future

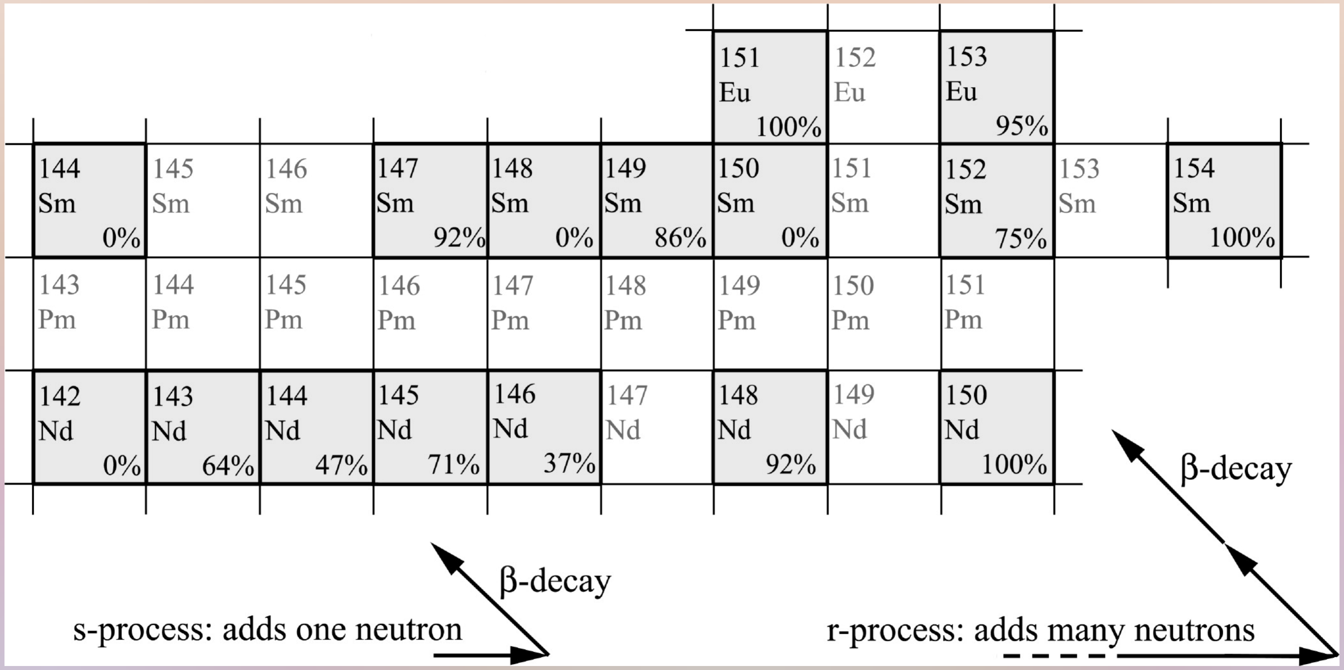
AGB neutrons

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

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



r-process



Roederer et al. 2008, ApJ, 675, 723

r-process