Weak Interaction Data for Presupernova Evolution of Massive Stars

Jameel-Un Nabi
GIK Institute for Engineering Sciences & Technology
Pakistan

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Acknowledgement

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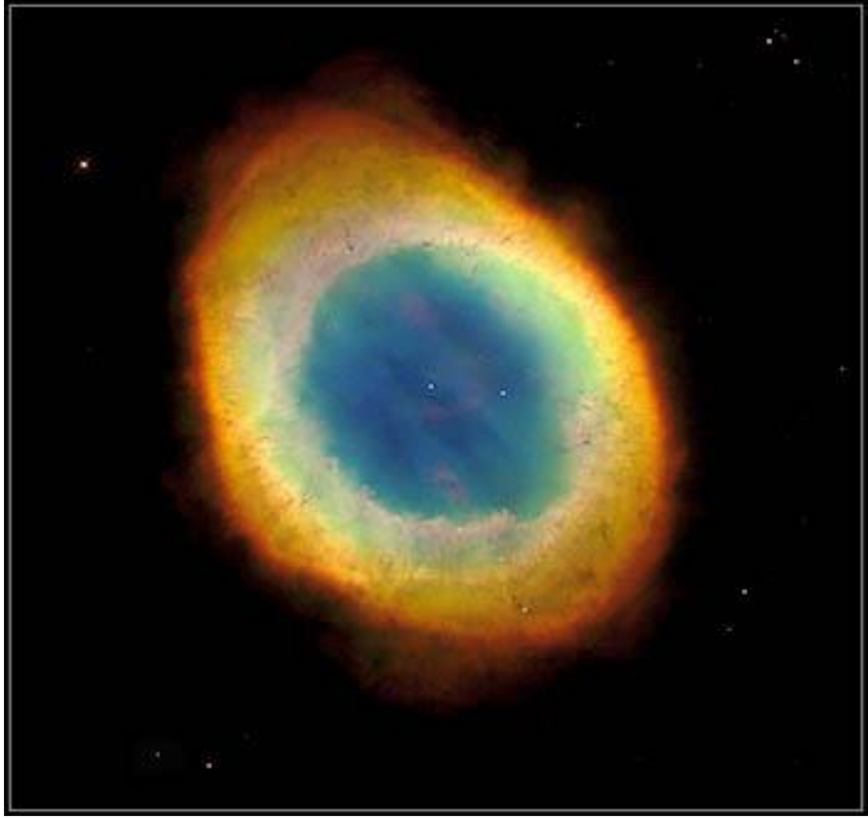
The Orion Nebula (www.nasa.gov)

Orion Nebula (www.nasa.gov)

Boomerang Nebula



The Ring Nebula (M57)

(www.nasa.gov)

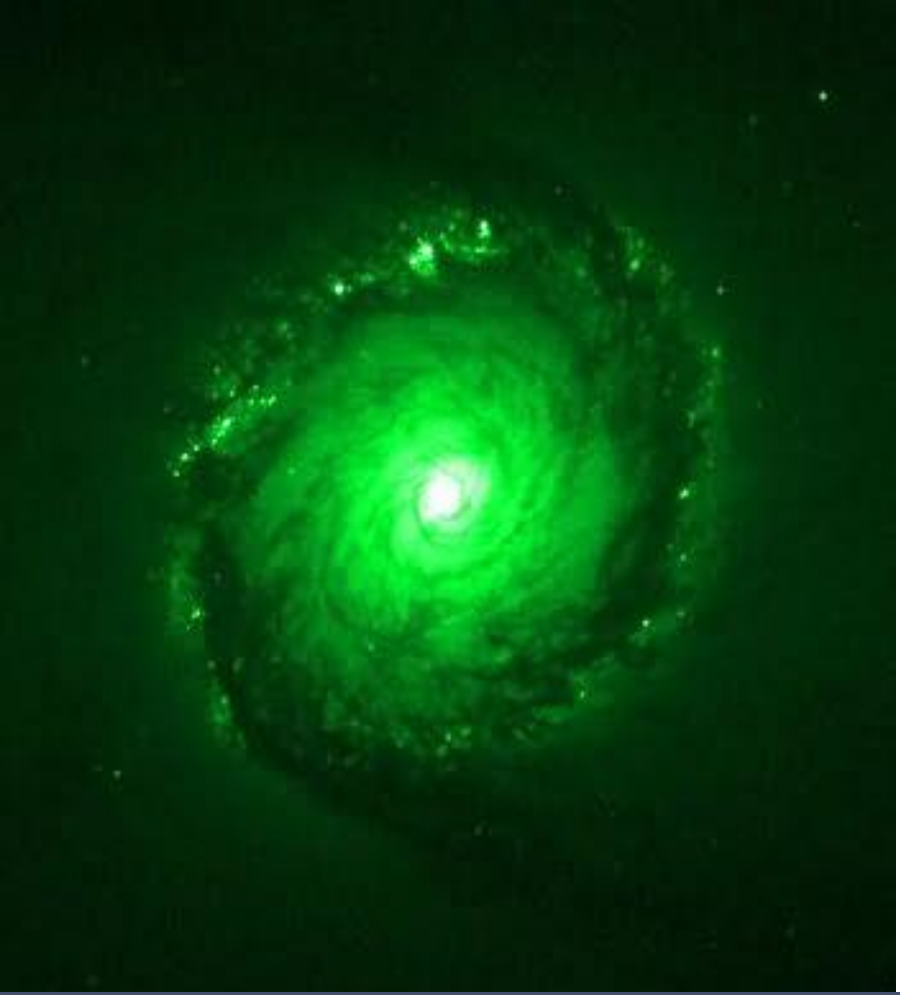
The Cat's Eye Nebula: Dying Star Creates Fantasy-like Sculpture of Gas and Dust

The Nebula NGC 2392 also known as "Eskimo"

(www.nasa.gov)

The Sombrero Galaxy - 28 million light years from Earth

(www.nasa.gov)



Galaxy NGC 1512 in Visible Light

The Starbust Galaxy Messier 82

(www.nasa.gov)

Star-Forming Region in the Carina Nebula

(www.nasa.gov)

Crab Nebula: a Dead Star Creates Celestial Havoc

The Colorful Demise of a Sun-like Star

(www.nasa.gov)

Layout of Presentation

- Introduction to weak force and evolution of massive stars
- Role of weak interactions in stellar core collapse
- Introduction of a microscopic theory to calculate stellar weak interaction rates
- Summary and possibilities for future collaboration

Interaction	Gravitational	Electromagnetic	Strong	Weak
Relative magnitude	10^{-39}	10^{-3}	1	10^{-13}_10^{-11}
Range	Infinite	Infinite	10^{-15}	10^{-18}
Mediating particles	Graviton	Photon	Gluons, pions	$W^{\pm}$, Z , bosons
Particles acted upon	Particles having mass	Charged particles	Hadrons	Hadrons, Leptons
Examples	Astronomical forces	Atomic forces	Nuclear forces	Forces involved in β-decay
Role in Universe	Assembles matter into planets stars and galaxies	Determines structure of atoms, molecules, solids and liquids	(i)Gluons holds quarks together to form nucleons (ii)Pions holds nucleons together to form atomic nuclei	Mediates transformation of quarks and leptons; Helps determine composition of atomic nuclei
Spin	2	1	1	1
Mass	0	0	0	90 GeV

Weak Forces & Nuclear Decay

- Marie and Pierre Curie discovered polonium and radium in 1898.
  - The simplest decay form is that of a gamma ray, which represents the nucleus changing from an excited state to lower energy state.
  - Other modes of decay include emission of α particles, β particles, protons, neutrons, and fission.

- The disintegrations or decays per unit time (activity).

$$\text{Activity} = -\frac{dN}{dt} = R$$

where dN / dt is negative because total number N decreases with time.

Radioactive decay

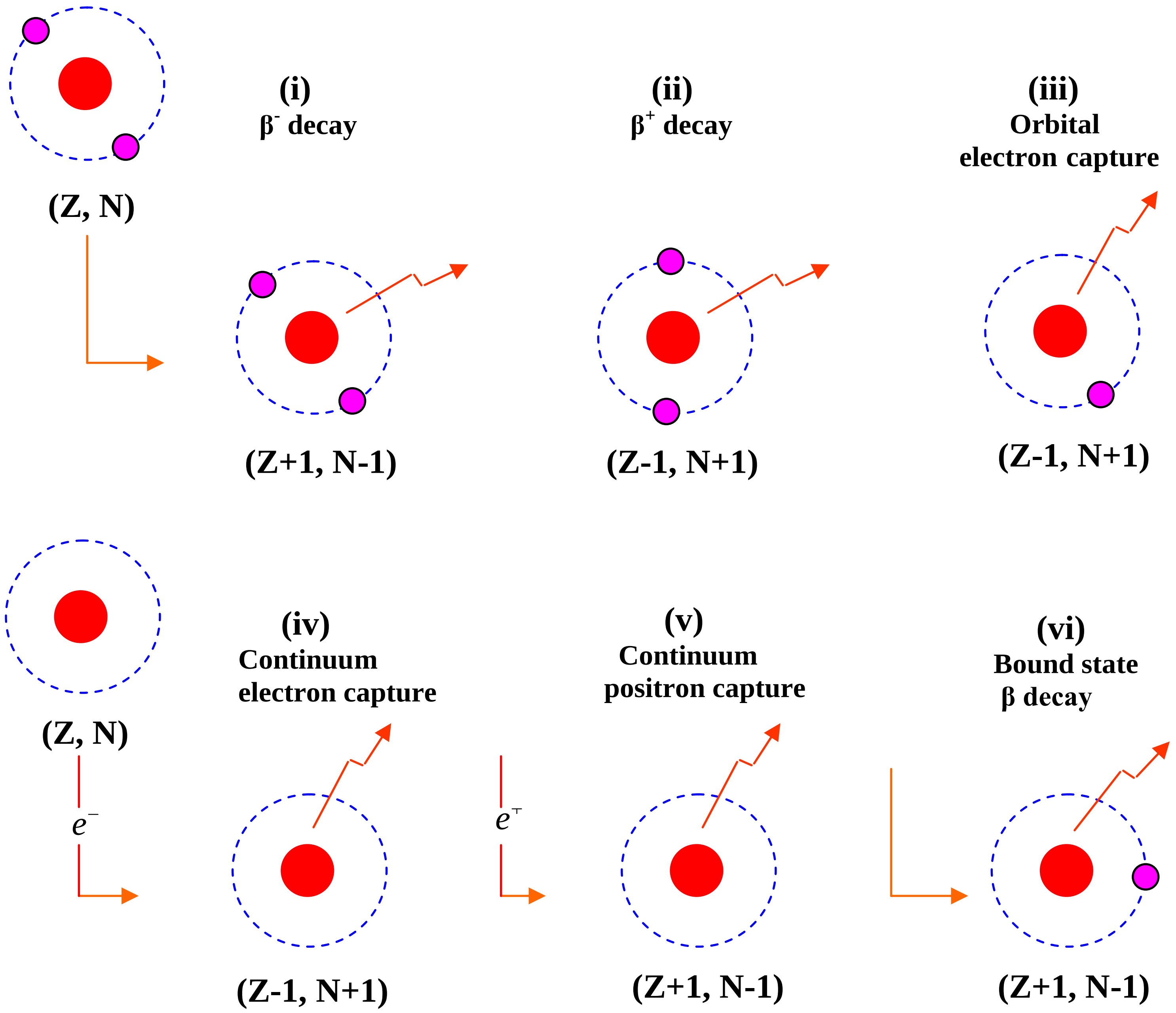
Basically there are three types of decay

- Alpha decay
- Beta decay
- Gamma decay

Weak Forces

- Weak forces play a conclusive role in the evolution of massive stars at the presupernova stage and supernova explosions:

- They initiate the gravitational collapse of the core of stars
- They affect the formation of heavy elements above iron via the r- and s-processes
- Play a key role in neutronisation of the core material via electron capture by free protons and by nuclei.


(Z, N)
(i)
β⁻ decay
(Z+1, N-1)
(ii)
β⁺ decay
(Z-1, N+1)
(iii)
Orbital
electron capture
(Z-1, N+1)
(Z, N)
e⁻
(iv)
Continuum
electron capture
(Z-1, N+1)
e⁺
(v)
Continuum
positron capture
(Z+1, N-1)
(vi)
Bound state
β decay
(Z+1, N-1)

Effect of Weak Forces at Galactic Level

- In domains of high temperature and density scales, weak forces are of decisive importance in studies of the stellar evolution.
- Beta decay and electron capture lead to:

- a change in the electron-to-proton ratio Ye [Y_e =1 (hydrogen burning) → 0.5 (carbon burning) → ~ 0.42 (before collapse)]
- cool the core to a lower entropy state
- determine the initial dynamics of the collapse
- determine the size of the collapsing-core
- determine the fate of shock wave released later

Weak interaction rates play a vital role in many astrophysical processes

Range of nuclei	Astrophysical importance
$12 \leq A \leq 25$	B-decay rates are used in hot CNO-Ne cycle hydrogen burning. (Audouze et al. Ap. J. 184, (1976) 493)
$24 \leq A \leq 44$	Hydrostatic oxygen burning in stars. (Woosley et al. Ap. J. 175, (1972) 731)
$21 \leq A \leq 60$	Determine the neutronization and neutrino energy loss rates during stellar evolution and collapse. (Fuller et al. Ap. J. 252, (1982) 715)

Range of nuclei	Astrophysical importance
$60 \leq A \leq 75$	For r- and s-processes and Supernova problem. (Fuller et al. Ap. J. 252, (1982) 715)
$A \leq 196$	For p-processes. (Arnould, Astron. Astro. 46, (1976) 117)

Supernovae

- Probably the most brilliant events that we observe (brightness increases by 10^{21} !).
- Basically of two types: Type I (no Balmer Hydrogen lines present in its spectra) and Type II (hydrogen present).
- These two SNe are the two major contributors to the element production in the universe.

Supernova type criteria					
No Balmer Lines Type I				Balmer Lines Type II	
Si II 6150	No Si			Plateau	Linear
	He I 5876	Weak He		then linear	
Ia	**Ib**	**Ic**		**IIP**	**IIL**

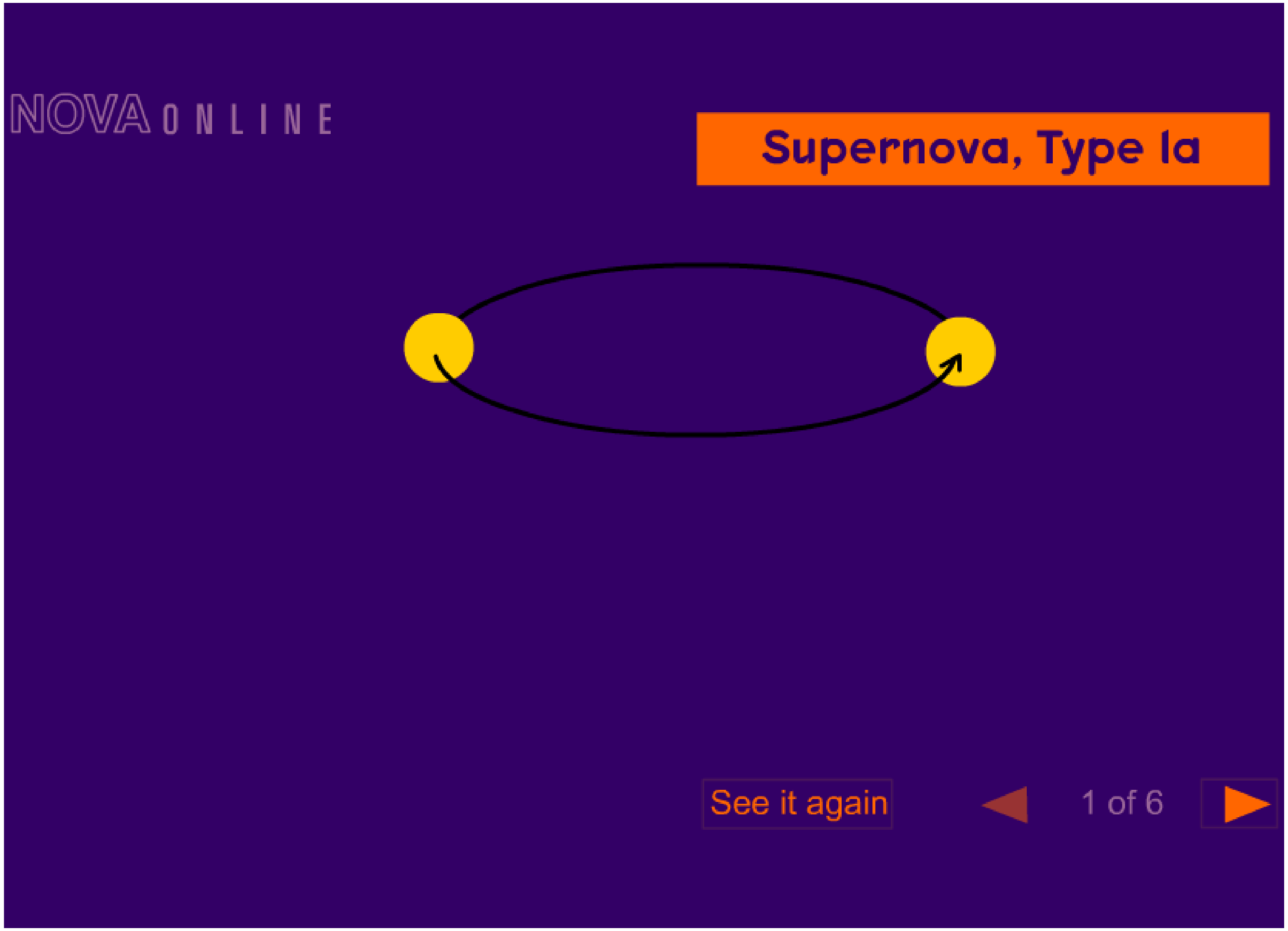
Supernova Bonanza in Nearby Galaxy NGC 1569

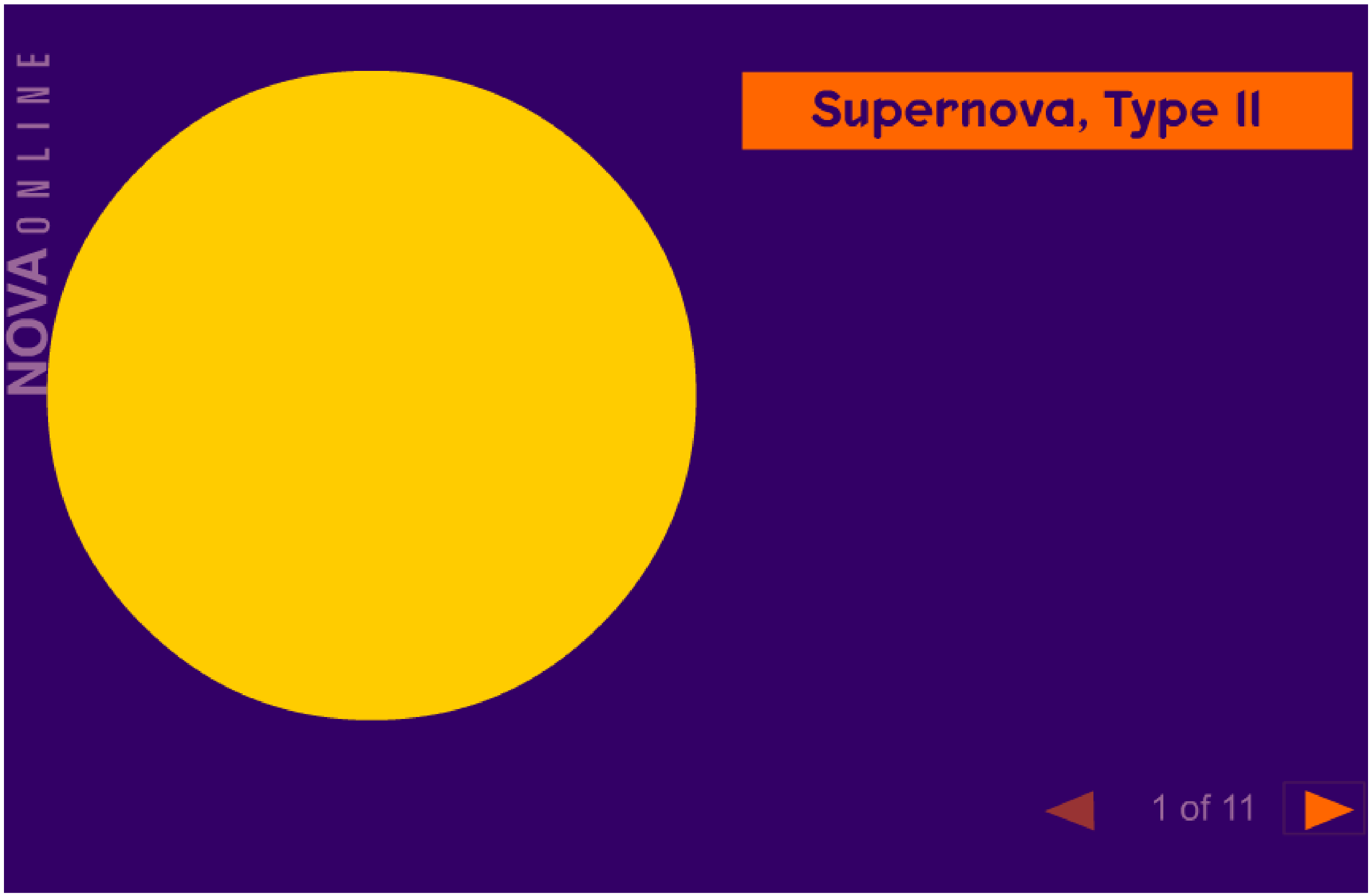
Supernova 1994D in Galaxy NGC 4526

(www.nasa.gov)

Type II supernova in the Large Magellanic Cloud in Feb. 1987

(www.nasa.gov)


NOVA ONLINE
Supernova, Type Ia
See it again
1 of 6


NOVA ONLINE
Supernova, Type II
1 of 11

Classical Papers

- Baade and Zwicky, PNAS 20 (1934) 254; 20 (1934) 259

(i) The total energy released in the event is $3 \times 10^{51} - 10^{55}$ erg

(ii) SNe are transitions of ordinary stars into neutron stars

(iii) SNe expel ionized gas shells at great speeds (containing nuclei of heavy elements)

- H.A. Bethe, Phys. Rev. 55 (1939) 434

  Energy production in stars belonging to carbon-nitrogen group; mass-luminosity relation and stellar evolution.

Classical Papers (contd.)

- E. M. Burbidge, G. R. Burbidge, W. A. Fowler and F. Hoyle, Rev. Mod. Phys. 29 (1957) 547

  A seminal work on nucleosynthesis in stars (r-, s- and p-processes)

- S. A. Colgate and H. J. Johnson, PRL 5 (1960) 235

  Pioneering calculation of supernova simulations.

- S. A. Colgate and R. White, ApJ 143 (1966) 626
- W. D. Arnett, Cand. J. Phys. 45 (1967) 1621

  Classical work on energy transport by neutrinos and antineutrinos in non-rotating massive stars.

Few Review Papers

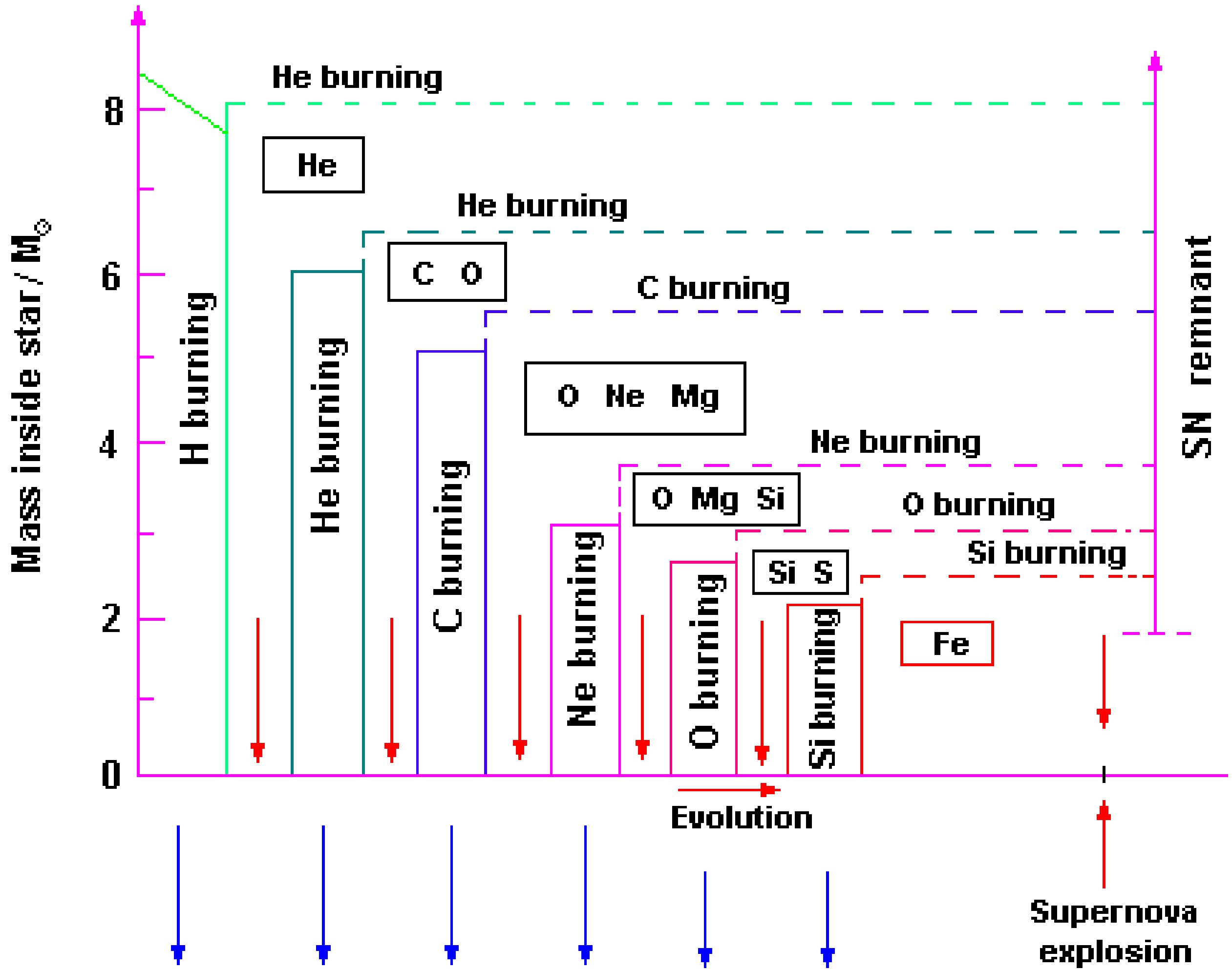
- For evolution and explosion of massive stars (e.g. S. E. Woosley, A. Heger and T. A. Weaver, Rev. Mod. Phys. 74 (2002) 1015)

- For a recent review of explosion mechanism, neutrino burst and gravitational wave, see K. Kotake, K. Sato and K. Takahashi, Rep. Prog. Phys. 69 (2006) 971

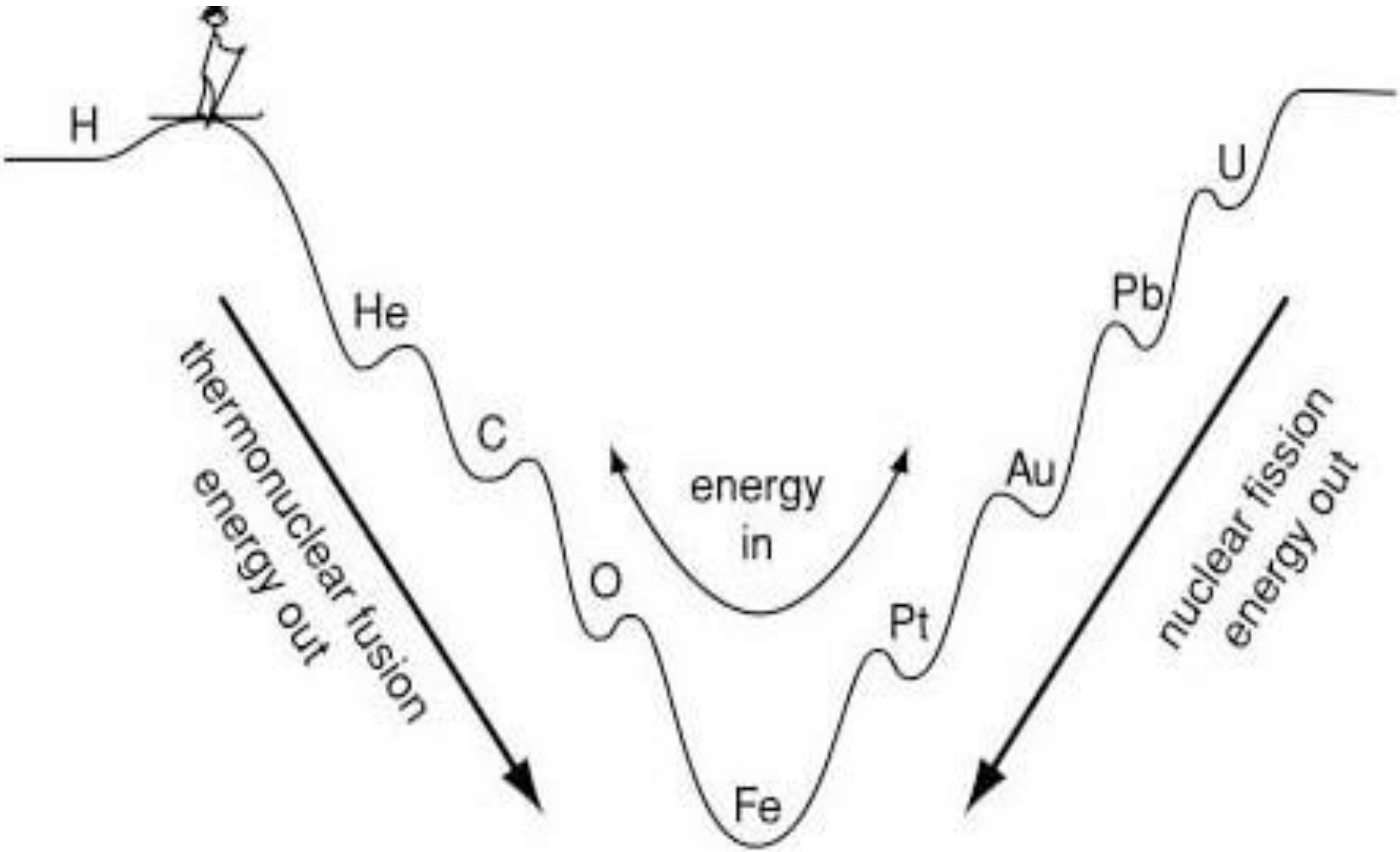
- For a quick check-up of basic supernova physics see E. Müller, J. Phys. G 16 (1990) 1571.

- For a comprehensive review of nuclear weak interaction processes in stars see K. Langanke and G. Marinez-Pinedo, Rev. Mod. Phys. 75 (2003) 819.

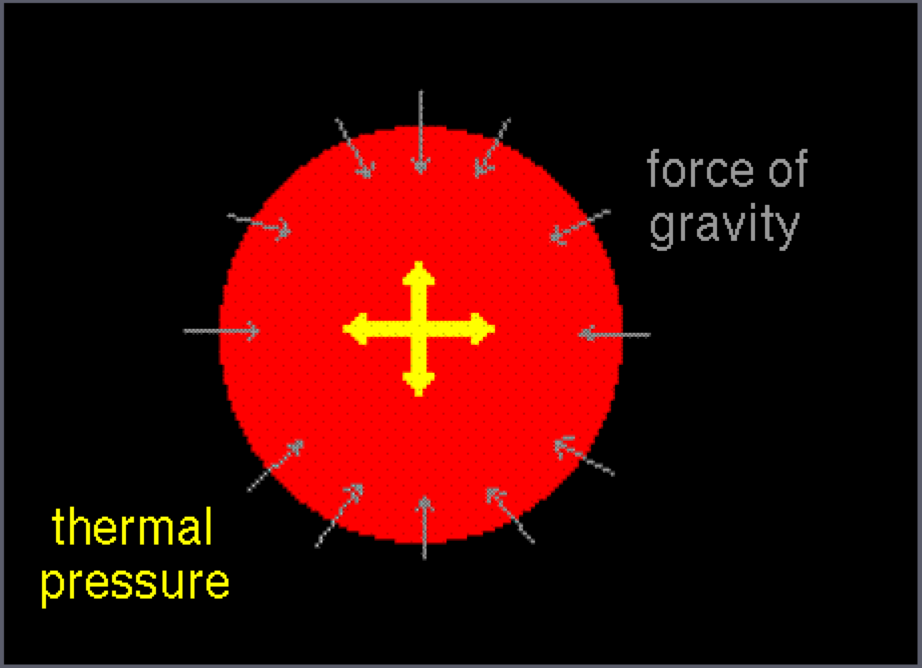
Stellar Evolution



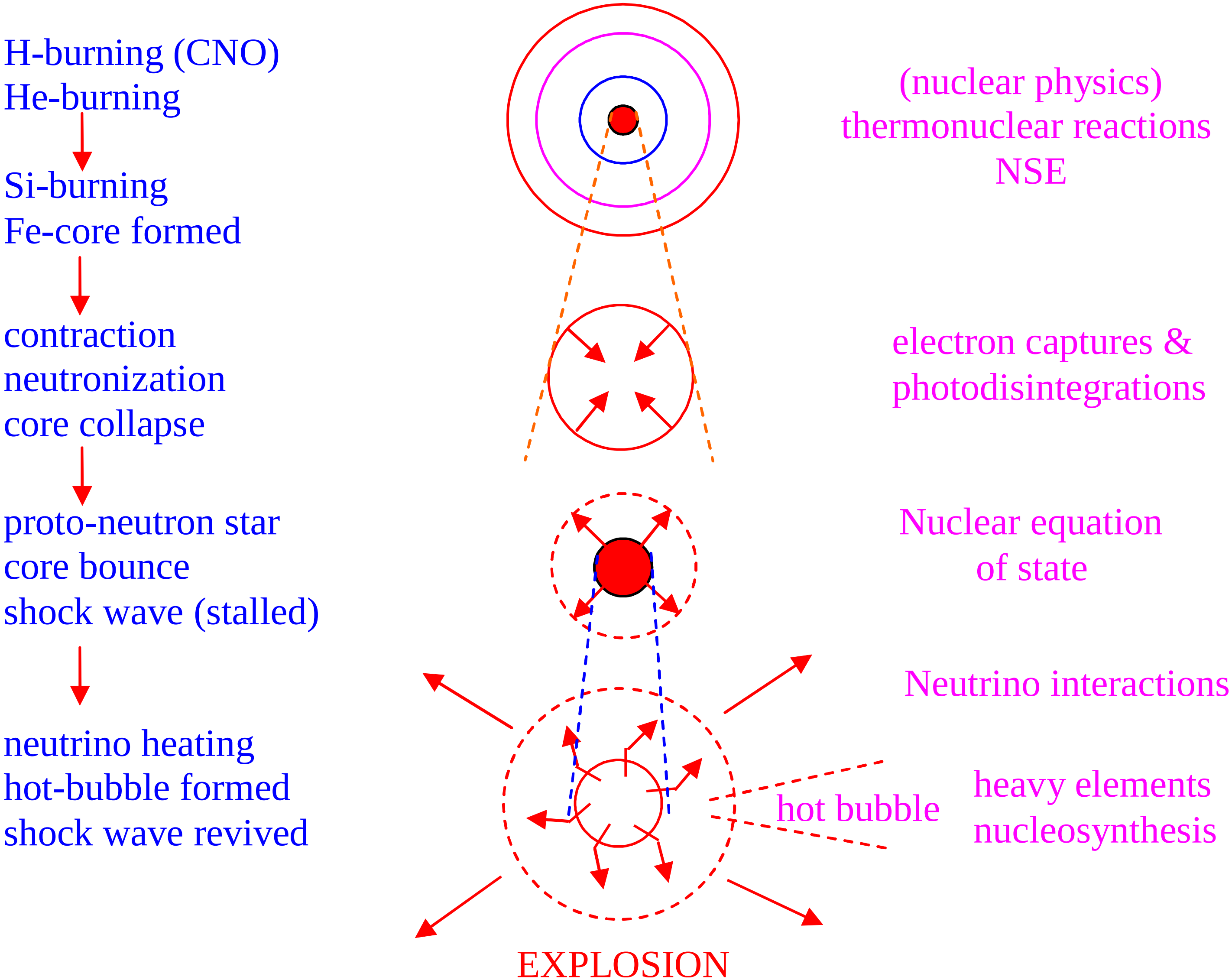
Temp. (K)	6×10^7	2×10^8	9×10^8	1.7×10^9	2.3×10^9	4×10^9
Density (g-cm^{-3})	5	700	2×10^5	4×10^6	1×10^7	3×10^7
Time (s)	2.2×10^{14}	1.6×10^{13}	1.9×10^{10}	1.6×10^7	5.2×10^5	8.6×10^4


H
He
C
O
Fe
Pt
Au
Pb
U
thermonuclear fusion
energy out
energy
in
nuclear fission
energy out

Pressure balance in a star

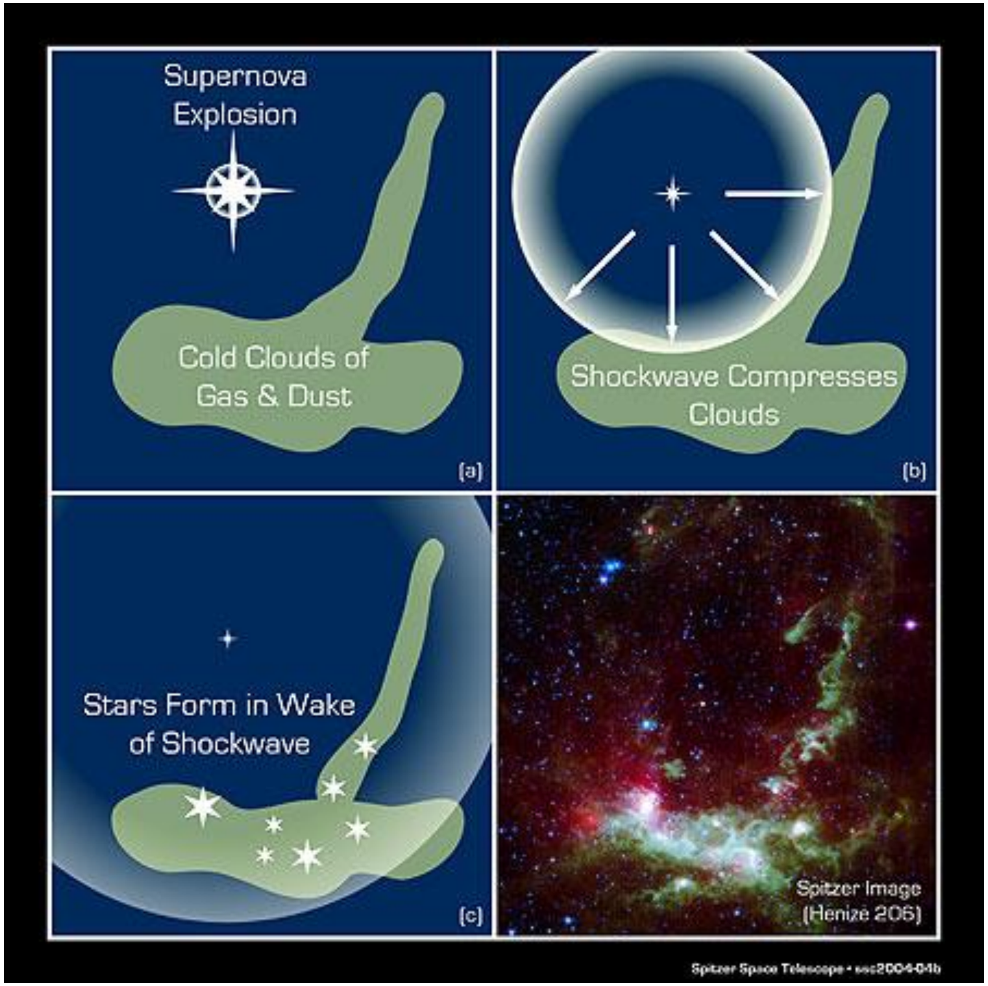


thermal pressure = force of gravity


H-burning (CNO)
He-burning
Si-burning
Fe-core formed
contraction
neutronization
core collapse
proto-neutron star
core bounce
shock wave (stalled)
neutrino heating
hot-bubble formed
shock wave revived
(nuclear physics)
thermonuclear reactions
NSE
electron captures &
photodisintegrations
Nuclear equation
of state
Neutrino interactions
hot bubble
heavy elements
nucleosynthesis
EXPLOSION

Nature's recycling factory

This three-panel diagram shows the process of triggered star formation. In the first panel, a massive, dying star explodes or "goes supernova." In the second panel, the shock wave from this explosion passes through clouds of gas and dust (green). In the third panel, a new wave of stars is born within the cloud, induced by the shock from the supernova blast.



The whole progression, from the death of one star to the birth of others, takes millions-billions of years to complete.

The initial mass of a star determines how it will age.

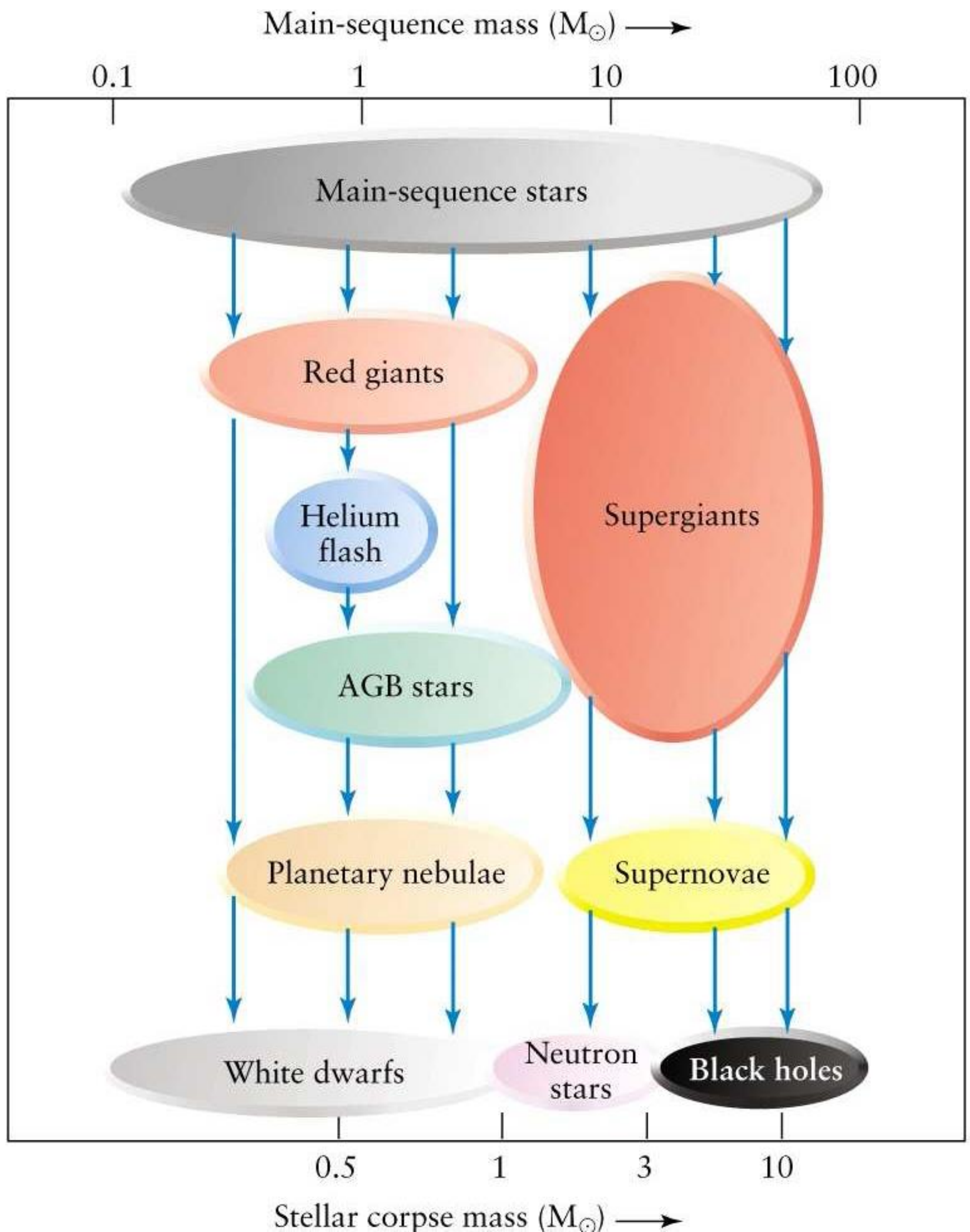


TABLE 1

$\int$ RATE / TOTAL RATE dY_e, MOST IMPORTANT CONTRIBUTORS TO ΔY_e, LMP 25$M_\odot$

Ion	Total	EC	β^-	β^+
10 Ions That Decrease Y_e				
^{55}Fe ……………..	6.27×10^{-3}	6.25×10^{-3}	5.36×10^{-7}	1.93×10^{-5}
^{54}Fe ……………	5.00×10^{-3}	4.97×10^{-3}	2.54×10^{-11}	2.53×10^{-5}
^{56}Fe …………..	4.45×10^{-3}	4.45×10^{-3}	2.22×10^{-6}	6.32×10^{-7}
^{55}Co ……………	4.36×10^{-3}	4.26×10^{-3}	7.73×10^{-15}	1.03×10^{-4}
^{53}Fe ……………	4.23×10^{-3}	3.87×10^{-3}	6.05×10^{-16}	3.57×10^{-4}
^{56}Ni ……………	3.69×10^{-3}	3.68×10^{-3}	…….	1.27×10^{-5}
^{57}Fe ……………	3.44×10^{-3}	3.52×10^{-3}	8.11×10^{-5}	1.89×10^{-7}
^{61}Ni ……………	2.90×10^{-3}	2.90×10^{-3}	6.16×10^{-7}	2.73×10^{-7}
^{54}Mn ……………	2.28×10^{-3}	2.30×10^{-3}	2.95×10^{-5}	8.45×10^{-6}
^{57}Ni ……………	1.90×10^{-3}	1.86×10^{-3}	3.13×10^{-14}	4.26×10^{-5}
10 Ions That Increase Y_e				
^{56}Mn ……………..	-3.27×10^{-3}	4.42×10^{-4}	3.71×10^{-3}	1.65×10^{-8}
^{52}V ……………..	-1.01×10^{-3}	2.69×10^{-4}	1.28×10^{-3}	7.34×10^{-9}
^{58}Mn ……………..	-9.74×10^{-4}	4.57×10^{-7}	9.74×10^{-4}	2.28×10^{-11}
^{55}Cr ……………..	-9.38×10^{-4}	1.42×10^{-6}	9.39×10^{-4}	1.91×10^{-10}
^{57}Mn ……………..	-9.22×10^{-4}	9.05×10^{-7}	9.23×10^{-4}	2.35×10^{-10}
^{62}Co ……………..	-6.59×10^{-4}	8.46×10^{-6}	6.68×10^{-4}	2.31×10^{-10}
^{60}Co ……………..	-2.78×10^{-4}	3.76×10^{-4}	6.55×10^{-4}	1.67×10^{-7}
^{53}V ……………..	-6.05×10^{-4}	2.65×10^{-6}	6.08×10^{-4}	1.32×10^{-10}
^{59}Fe ……………..	-4.07×10^{-4}	2.36×10^{-5}	4.30×10^{-4}	9.14×10^{-10}
^{61}Co ……………..	-2.78×10^{-4}	3.50×10^{-5}	3.13×10^{-4}	3.03×10^{-9}

TABLE 2

$\int$ RATE / TOTAL RATE d Y_e, MOST IMPORTANT CONTRIBUTORS TO ΔY_e, LMP 40 $M_\odot$

Ion	Total	EC	β^-	β^+
10 Ions That Decrease Y_e				
^{55}Fe ……………..	5.93×10^{-3}	5.91×10^{-3}	6.91×10^{-7}	2.27×10^{-5}
^{54}Fe ……………	5.21×10^{-3}	5.19×10^{-3}	4.40×10^{-11}	2.77×10^{-5}
^{1}H …………..	5.01×10^{-3}	5.01×10^{-3}	…………	…………
^{55}Co ……………	4.38×10^{-3}	4.27×10^{-3}	1.35×10^{-14}	1.15×10^{-4}
^{53}Fe ……………	4.28×10^{-3}	3.90×10^{-3}	1.03×10^{-15}	3.79×10^{-4}
^{56}Ni ……………	3.74×10^{-3}	3.72×10^{-3}	…….	1.57×10^{-5}
^{56}Fe ……………	3.04×10^{-3}	3.04×10^{-3}	3.90×10^{-6}	1.26×10^{-6}
^{57}Ni ……………	1.95×10^{-3}	1.90×10^{-3}	5.62×10^{-14}	4.77×10^{-5}
^{54}Mn ……………	1.80×10^{-3}	1.82×10^{-3}	3.12×10^{-5}	1.04×10^{-5}
^{53}Mn ……………	1.80×10^{-3}	1.78×10^{-3}	8.13×10^{-8}	1.17×10^{-5}
10 Ions That Increase Y_e				
^{56}Mn ……………..	-1.93×10^{-3}	2.10×10^{-4}	2.14×10^{-3}	3.21×10^{-8}
^{52}V ……………..	-6.49×10^{-4}	1.32×10^{-4}	7.80×10^{-4}	1.66×10^{-8}
^{55}Cr ……………..	-5.32×10^{-4}	8.86×10^{-7}	5.33×10^{-4}	5.00×10^{-10}
^{57}Mn ……………..	-5.03×10^{-4}	5.89×10^{-7}	5.03×10^{-4}	5.84×10^{-10}
^{58}Mn ……………..	-4.70×10^{-4}	2.39×10^{-7}	4.70×10^{-4}	4.78×10^{-11}
^{60}Co ……………..	-2.01×10^{-4}	2.06×10^{-4}	4.07×10^{-4}	2.39×10^{-7}
^{53}V ……………..	-3.30×10^{-4}	1.58×10^{-6}	3.32×10^{-4}	3.31×10^{-10}
^{59}Fe ……………..	-2.93×10^{-4}	1.11×10^{-5}	3.05×10^{-4}	2.09×10^{-9}
^{62}Co ……………..	-2.96×10^{-4}	3.42×10^{-6}	2.99×10^{-4}	3.89×10^{-10}
^{54}Cr ……………..	-2.44×10^{-4}	2.73×10^{-5}	2.71×10^{-4}	7.43×10^{-9}

In order to understand the complex dynamics of supernova explosion

- We need to know more about weak interaction rates – more precisely the electron capture and β-decay rates.
- Thousands of species of nuclei are present in the stellar core and many of them are unstable.
- We need a reliable microscopic model to calculate these rates.
- One such available choice is the pn-QRPA model.

pn-QRPA

pn-QRPA stands for:

proton-neutron ↔ charge-changing transitions

quasiparticle ↔ quasiparticle basis instead of usual particle basis

Random Phase Approximation ↔ accounts for proton-neutron ground state correlations

pn-QRPA as a 3 step model

Determination of single particle energies	$\rightarrow$	Wood-Saxon, Nilsson potential
Pairing calculation	$\rightarrow$	BCS approximation
pn-residual interaction	$\rightarrow$	RPA calculation

How reliable is the pn-QRPA model

The accuracy of the pn-QRPA model compared to experimental data (β^+/EC decay)

Conditions	$T_{1/2}^{exp}(s) \leq$	N	n	n(%)	$\bar{x}$
$\forall x_i \leq 10$	10^6	894	706	79.0	2.057
	60	327	304	93.0	1.718
	1	81	78	96.3	1.848
$\forall x_i \leq 2$	10^6	894	489	54.7	1.363
	60	327	245	74.9	1.308
	1	81	59	72.8	1.230

N denotes the number of experimentally known half-lives shorter than the limit in the second column,
n is the number (and percentage) of isotopes reproduced under the condition given in the first column,
x bar is the average deviation.

The accuracy of the pn-QRPA model compared to experimental data (β^- decay)

Conditions	$T_{1/2}^{exp}(s) \leq$	N	n	n(%)	$\bar{x}$
$\forall x_i \leq 10$	10^6	654	472	72.2	1.85 ± 1.21
	60	325	313	96.3	1.67 ± 1.02
	1	106	105	99.1	1.44 ± 0.40
$\forall x_i \leq 5$	10^6	654	456	69.7	1.68 ± 0.76
	60	325	307	94.5	1.56 ± 0.66
	1	106	105	99.1	1.44 ± 0.40
$\forall x_i \leq 3$	10^6	654	420	64.2	1.50 ± 0.46
	60	325	295	90.8	1.46 ± 0.43
	1	106	105	99.1	1.44 ± 0.40
$\forall x_i \leq 2$	10^6	654	369	56.4	1.37 ± 0.29
	60	325	267	82.2	1.36 ± 0.29
	1	106	96	90.6	1.35 ± 0.27

Weak Rate Formalism

The capture (decay) rates of a transition from the *i*th state of a parent nucleus to the j^{th} state of the daughter nucleus is given by

$$\lambda_{ij} = \left[\frac{\ln 2}{D}\right]\left[f_{ij}(T,\rho,E_f)\right]\left[B(F)_{ij} + \left(g_A/g_V\right)^2 B(GT)_{ij}\right]$$

$$\lambda = \sum_{ij} P_i \lambda_{ij}$$

History of pn-QRPA calculation in stellar matter

- Report on calculation of stellar weak rates (Nabi & Klapdor, Eur. Phys. J. A 5 (1999) 337)
- Calculation of stellar rates for sd-shell nuclei (Nabi & Klapdor, ADNDT 71 (1999) 149)
- Calculation of stellar rates for fp/fpg-shell nuclei (Nabi & Klapdor, ADNDT 88 (2004) 237). **A total of roughly 1 million weak rates were calculated in this project.**

Weak Rate Calculations

- The calculations essentially consist of 12 different weak-interaction mediated rates for each parent nucleus. This include:

  β^-–decay , β^+–decay, electron capture, positron capture, neutrino & antineutrino energy loss rates, gamma ray heating rates, energies of beta delayed protons and neutrons and the probabilities of these β–delayed particle emission processes.

- The calculations were performed as a function of stellar temperature, density and Fermi energy of the leptons.

- Apart from calculations of around 1 million weak rates mentioned earlier, detailed calculations and analysis of stellar weak rates have so far been performed for Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, Kr and Zr isotopes in the fp-shell domain and beyond.

Weak Rate Calculations

- The role of pairing correlations in calculation of β-decay half-lives is recently being investigated using the pn-QRPA model.

- A new recipe for calculation of phase space factors for calculation of β-decay half-lives was introduced. (Stoica et. al. Advances in High Energy Physics **2016,** Article ID 8729893 (2016).)

- Study of the effect of newly calculated phase space factor on β-decay half-lives was investigated (Nabi et al. Advances in High Energy Physics 2019, Article ID 5783618 (2019).)

- Role of forbidden transitions were investigated to accelerate r-process nucleosynthesis.

Summary

- The "artistic" pictures shown in the beginning put up a challenging task for collapse simulators working on world's fastest supercomputers.
- Self-consistent supernova calculations with presently known neutrino physics have not yet produced successful explosions.
- New and improved physics of universe can lead to success.
- Powerful space-based telescopes and rare-isotopes accelerator facilities (e.g. US, Germany, Japan) can help gather more useful observational/experimental data.
- A lot of input parameters are required by the simulation codes (mega-codes), nuclear physics input parameters being one of the key inputs.

Summary (contd.)

- Microscopic and reliable weak interaction rates are required for 100's of nuclei (most unstable) at different stellar temperatures and densities.
- More than a million rates were calculated for around 800 nuclei in stellar matter using the pn-QRPA theory.
- Others are being currently calculated. (Future projects)

❖ **Need more collaborators to go into the applied side of these calculated rates and related projects. I look forward to collaboration with groups working on presupernova evolution of massive stars in this respect.**

Thank You