Anti-neutrino energy loss rates due to isotopes of titanium for presupernova evolution

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Supernova Bonanza in Nearby Galaxy NGC 1569

Supernova 1994D in Galaxy NGC 4526

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.

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.

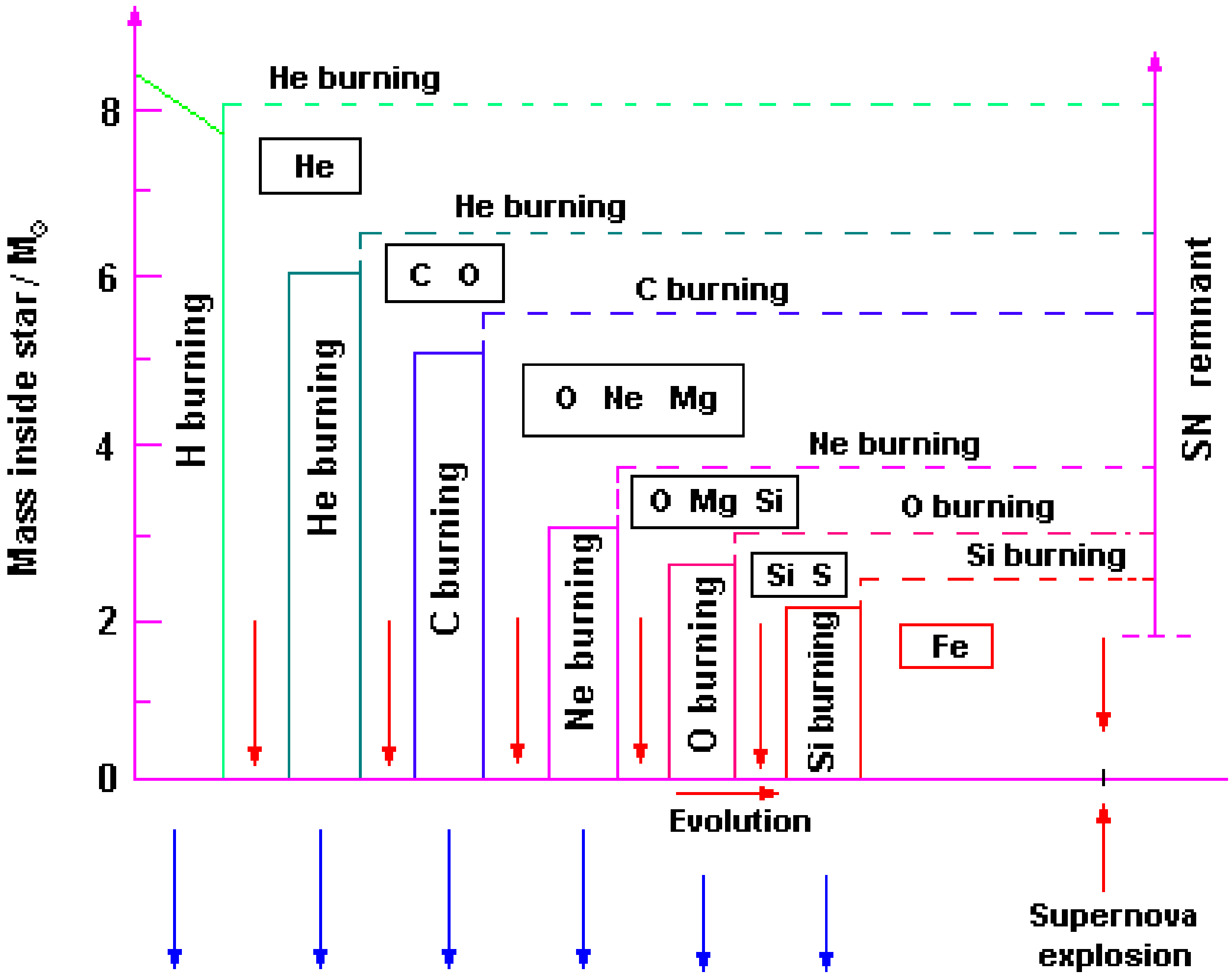
Few Review Papers

- 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.

Layout of Presentation

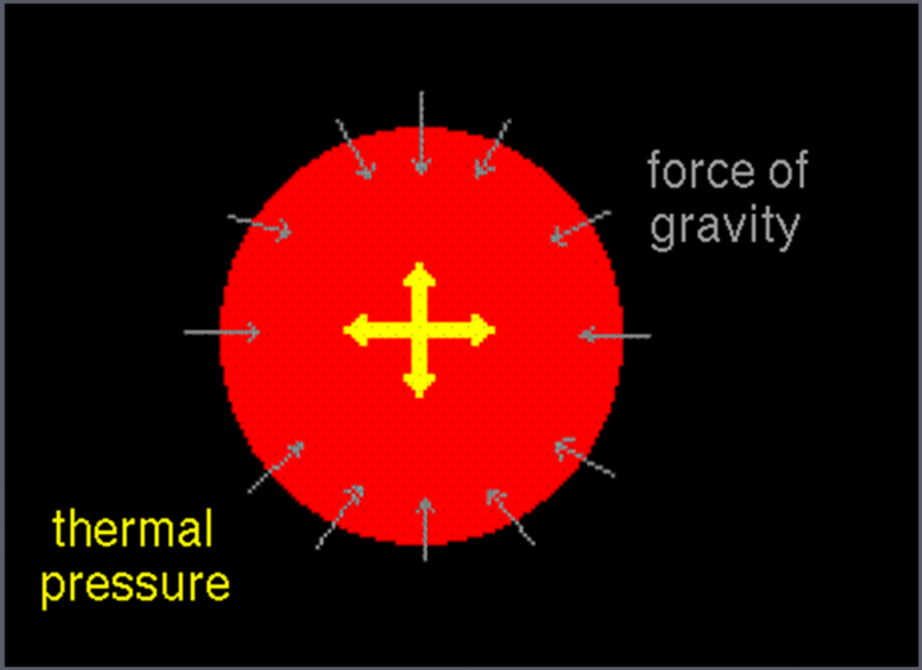
- Introduction to evolution of massive stars
- Role of titanium isotopes during presupernova evolution
- Calculation and comparison
- Astrophysical implications

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 ($g\text{-}cm^{-3}$)	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

Pressure balance in a star



thermal pressure = force of gravity

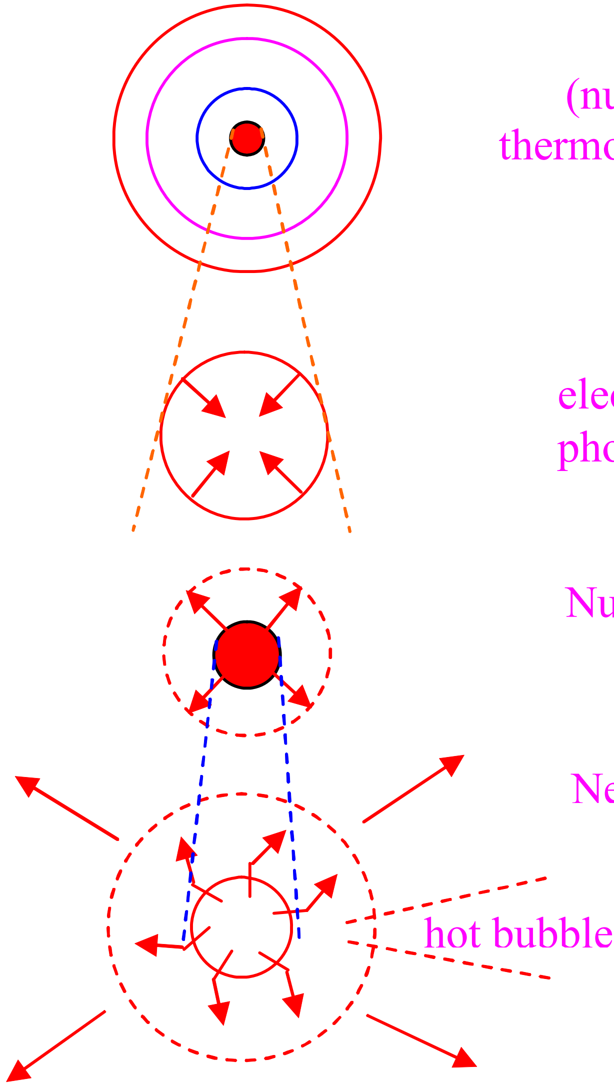
H-burning (CNO)
He-burning

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

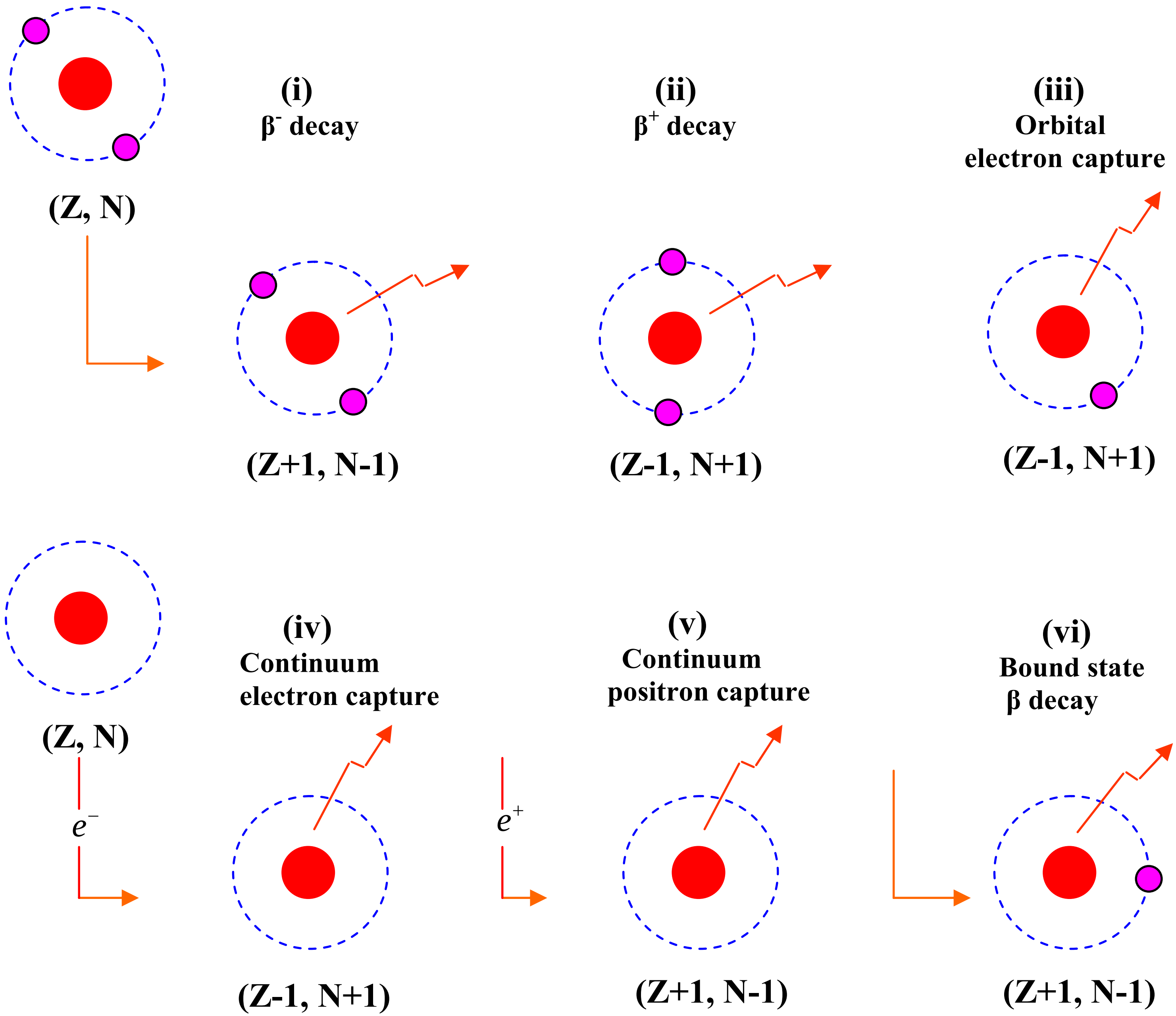
Neutrino interactions

heavy elements
nucleosynthesis

Weak Processes

- Weak interactions 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-process
- 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)

Stellar Weak Interactions

- In domains of high temperature and density scales, weak rates 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 [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

Motivation for calculation

- Astrophysical importance of titanium isotopes were heavily discussed and assigned differing nucleosynthetic origins by Clayton (Nucleosynthesis, Origin of the Elements, 1972)

- Aufderheide and collaborators (ApJS, **91** (1994) 389) included $^{51-56}$**Ti** in the list of very important beta decay nuclei in prespernova evolution of stars.

- Heger et al. (ApJ, **560** (2001) 307) recently included isotopes of titanium in compilation of a list consisting of key nuclei whose weak interaction rates are of vital importance for the presupernova evolutionary phases of massive stars.

Titanium isotopes calculation

- I calculated the following weak-interaction mediated rates for key titanium isotopes in stellar matter

  - Electron and positron capture rates
  - Beta and positron decay rates
  - Neutrino and anti-neutrino energy loss rates

- The calculation was performed microscopically using the pn-QRPA model.

Key References (pn-QRPA)

- Development of model (Halbleib & Sorenson, Nucl. Phys. A 98 (1967) 542)
- Inclusion of pp interaction in the model (Cha, PRC 27 (1983) 2269)
- Extension of model to deformed nuclei (Krumlinde and Möller, Nucl. Phys. A 417 (1984) 419)
- First extensive calculation of β^{-}decay calculations (Staudt et al. ADNDT 44 (1990) 79)
- Extension of model to include treatment of odd-odd nuclei and transitions from nuclear excited states (Muto et al. Zeit. Phys. A 341 (1992) 407)
- First extensive calculation of β^{+}/EC calculations (Hirsch et al. ADNDT 53 (1993) 165)
- Application of calculated rates in astrophysics, nuclear physics and cosmology (Klapdor, Prog. Part. Nucl. Phys. 10 (1983) 131, 17 (1986) 419)

Key References (pn-QRPA) (contd.)

- 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.

Antineutrino Energy Losses

$${}_{Z}^{A}Ti + e^{+} \rightarrow {}_{Z+1}^{A}Ti + \bar{\nu}$$ (Positron capture)

$${}_{Z}^{A}Ti \rightarrow {}_{Z+1}^{A}Ti + e^{-} + \bar{\nu}$$ (Beta decay)

Weak Rate Formalism

The neutrino (antineutrino) energy loss 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

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

$$\lambda^{\bar{\nu}} = \sum_{ij} P_i \lambda_{ij}^{\bar{\nu}},$$

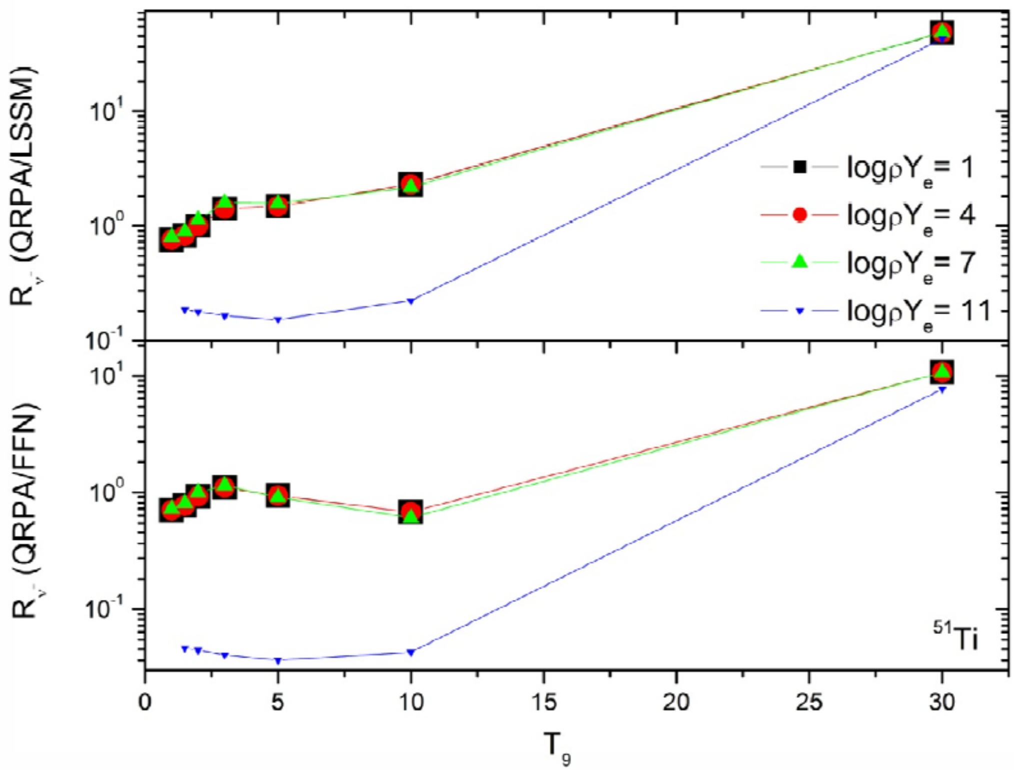
where $\lambda_{ij}^{\bar{\nu}}$ is the sum of positron capture and beta decay rates for the transition $i \to j$.

$log\rho Y_e$	T_9	^{49}Ti		^{51}Ti		^{52}Ti		^{53}Ti	
		λ_ν	$\lambda_{\bar{\nu}}$	λ_ν	$\lambda_{\bar{\nu}}$	λ_ν	$\lambda_{\bar{\nu}}$	λ_ν	$\lambda_{\bar{\nu}}$
1.0	0.01	-100	-100	-100	-2.607	-100	-3.449	-100	-1.804
1.0	0.10	-100	-59.070	-100	-2.637	-100	-3.449	-100	-1.804
1.0	0.20	-61.794	-32.015	-100	-2.677	-100	-3.449	-100	-1.802
1.0	0.40	-35.769	-17.468	-91.759	-2.708	-100	-3.449	-100	-1.763
1.0	0.70	-23.720	-10.992	-55.415	-2.723	-73.852	-3.449	-71.037	-1.691
1.0	1.00	-17.711	-9.082	-39.656	-2.724	-52.450	-3.448	-50.164	-1.645
1.0	1.50	-12.765	-7.354	-27.028	-2.686	-35.482	-3.431	-33.669	-1.604
1.0	2.00	-10.130	-6.295	-20.455	-2.596	-26.795	-3.337	-25.268	-1.575
1.0	3.00	-7.258	-4.942	-13.560	-2.356	-17.768	-2.791	-16.639	-1.336
1.0	5.00	-4.550	-3.355	-7.634	-1.667	-9.957	-1.597	-9.321	-0.320
1.0	10.00	-1.609	-1.099	-2.483	-0.095	-3.249	0.239	-2.939	0.904
1.0	30.00	2.887	2.888	3.065	3.660	2.699	3.560	3.149	4.068
4.0	0.01	-100	-100	-100	-2.608	-100	-3.452	-100	-1.805
4.0	0.10	-100	-62.245	-100	-2.638	-100	-3.451	-100	-1.805
4.0	0.20	-58.738	-35.071	-100	-2.678	-100	-3.451	-100	-1.802
4.0	0.40	-32.754	-20.483	-88.744	-2.708	-100	-3.450	-100	-1.764
4.0	0.70	-21.352	-13.359	-53.047	-2.723	-71.484	-3.450	-68.669	-1.691
4.0	1.00	-16.661	-10.131	-38.606	-2.725	-51.400	-3.450	-49.114	-1.645
4.0	1.50	-12.607	-7.511	-26.870	-2.687	-35.324	-3.437	-33.511	-1.605
4.0	2.00	-10.094	-6.329	-20.420	-2.597	-26.759	-3.345	-25.232	-1.575
4.0	3.00	-7.251	-4.947	-13.554	-2.356	-17.762	-2.795	-16.633	-1.336
4.0	5.00	-4.548	-3.355	-7.632	-1.668	-9.956	-1.598	-9.319	-0.320
4.0	10.00	-1.608	-1.098	-2.482	-0.094	-3.247	0.239	-2.938	0.904
4.0	30.00	2.889	2.890	3.067	3.662	2.700	3.562	3.151	4.070
7.0	0.01	-100	-100	-100	-2.939	-100	-3.907	-100	-1.895
7.0	0.10	-74.334	-87.805	-100	-2.960	-100	-3.906	-100	-1.895
7.0	0.20	-40.507	-46.899	-100	-2.990	-100	-3.905	-100	-1.893
7.0	0.40	-22.993	-26.402	-78.982	-3.011	-100	-3.900	-100	-1.850
7.0	0.70	-15.052	-17.539	-46.746	-3.016	-65.184	-3.888	-62.368	-1.770
7.0	1.00	-11.663	-13.895	-33.608	-3.006	-46.402	-3.871	-44.116	-1.719

$log\rho Y_e$	T_9	^{49}Ti		^{51}Ti		^{52}Ti		^{53}Ti	
		λ_{ν}	$\lambda_{\bar{\nu}}$	λ_{ν}	$\lambda_{\bar{\nu}}$	λ_{ν}	$\lambda_{\bar{\nu}}$	λ_{ν}	$\lambda_{\bar{\nu}}$
7.0	1.50	-8.825	-10.799	-23.089	-2.936	-31.543	-3.833	-29.729	-1.673
7.0	2.00	-7.273	-8.936	-17.598	-2.805	-23.939	-3.792	-22.411	-1.640
7.0	3.00	-5.541	-6.528	-11.844	-2.504	-16.052	-3.665	-14.923	-1.391
7.0	5.00	-3.846	-3.945	-6.929	-1.764	-9.253	-2.224	-8.616	-0.360
7.0	10.00	-1.510	-1.189	-2.383	-0.161	-3.149	0.167	-2.839	0.867
7.0	30.00	2.892	2.887	3.070	3.659	2.704	3.559	3.155	4.067
10.0	0.01	2.448	-100	0.705	-100	-2.099	-100	-2.444	-100
10.0	0.10	2.451	-100	0.646	-100	-2.093	-100	-2.440	-100
10.0	0.20	2.452	-100	0.569	-100	-2.092	-100	-2.439	-100
10.0	0.40	2.459	-100	0.503	-100	-2.087	-100	-2.431	-75.486
10.0	0.70	2.481	-85.387	0.474	-63.156	-2.074	-66.149	-2.412	-44.389
10.0	1.00	2.504	-60.612	0.540	-44.980	-2.051	-46.814	-2.393	-31.731
10.0	1.50	2.540	-41.152	0.910	-30.618	-1.973	-31.527	-2.359	-21.662
10.0	2.00	2.573	-31.298	1.281	-23.292	-1.827	-23.724	-2.284	-16.478
10.0	3.00	2.626	-21.274	1.733	-15.781	-1.364	-15.715	-1.280	-11.090
10.0	5.00	2.709	-13.005	2.144	-9.521	-0.132	-9.017	0.447	-6.483
10.0	10.00	2.981	-6.274	2.679	-4.460	1.876	-3.579	2.224	-2.607
10.0	30.00	4.388	1.354	4.582	2.129	4.213	2.038	4.666	2.544
11.0	0.01	5.525	-100	4.591	-100	4.801	-100	4.328	-100
11.0	0.10	5.522	-100	4.578	-100	4.799	-100	4.328	-100
11.0	0.20	5.524	-100	4.558	-100	4.801	-100	4.328	-100
11.0	0.40	5.525	-100	4.547	-100	4.801	-100	4.328	-100
11.0	0.70	5.529	-100	4.542	-100	4.801	-100	4.328	-100
11.0	1.00	5.532	-100	4.547	-100	4.801	-100	4.328	-96.327
11.0	1.50	5.538	-84.221	4.601	-73.687	4.801	-74.596	4.328	-64.731
11.0	2.00	5.543	-63.605	4.705	-55.599	4.801	-56.031	4.329	-48.785
11.0	3.00	5.551	-42.822	4.921	-37.329	4.797	-37.263	4.334	-32.638
11.0	5.00	5.562	-25.953	5.172	-22.468	4.774	-21.964	4.391	-19.431
11.0	10.00	5.630	-12.792	5.455	-10.979	4.928	-10.095	5.057	-9.125
11.0	30.00	6.228	-0.973	6.478	-0.198	6.093	-0.287	6.556	0.219

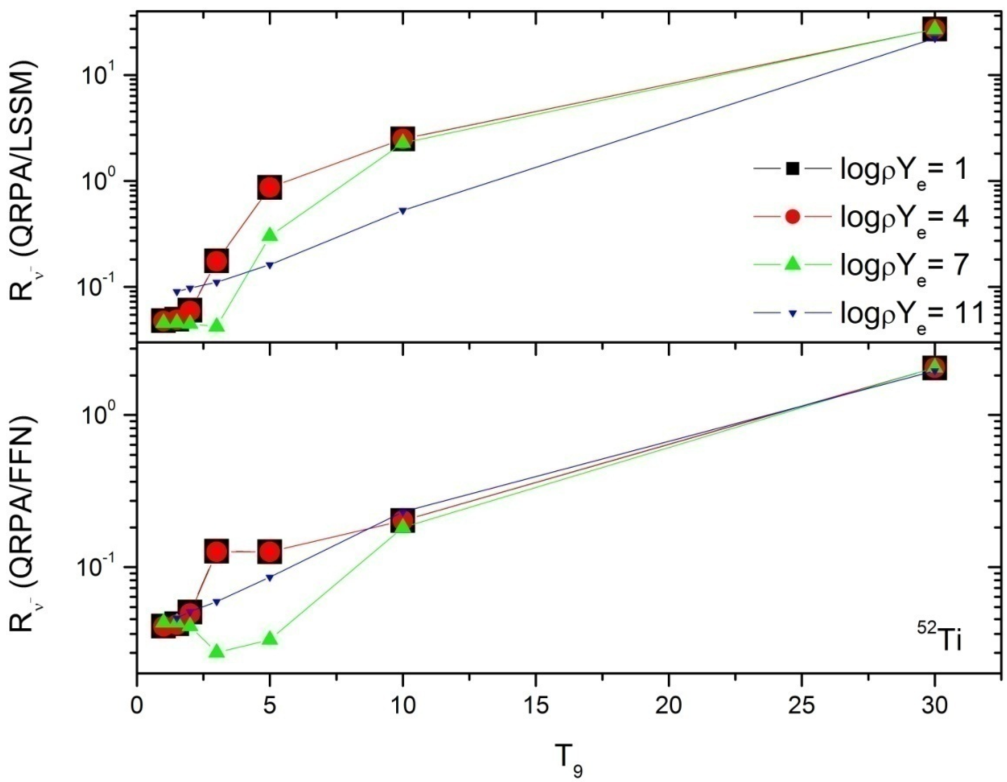
$log\rho Y_e$	T_9	^{54}Ti		^{55}Ti		^{56}Ti	
		λ_ν	$\lambda_{\bar{\nu}}$	λ_ν	$\lambda_{\bar{\nu}}$	λ_ν	$\lambda_{\bar{\nu}}$
1.0	0.01	-100	-0.174	-100	0.296	-100	1.531
1.0	0.10	-100	-0.174	-100	0.296	-100	1.531
1.0	0.20	-100	-0.174	-100	0.296	-100	1.531
1.0	0.40	-100	-0.174	-100	0.298	-100	1.531
1.0	0.70	-89.296	-0.174	-89.048	0.351	-100	1.531
1.0	1.00	-62.883	-0.174	-62.506	0.488	-74.004	1.531
1.0	1.50	-41.968	-0.174	-41.587	0.710	-49.274	1.531
1.0	2.00	-31.322	-0.174	-30.966	0.854	-36.724	1.531
1.0	3.00	-20.418	-0.169	-20.108	1.017	-23.904	1.531
1.0	5.00	-11.255	-0.081	-11.019	1.196	-13.197	1.542
1.0	10.00	-3.584	1.051	-3.470	1.542	-4.418	2.002
1.0	30.00	2.850	4.052	3.061	4.239	2.552	4.387
4.0	0.01	-100	-0.175	-100	0.296	-100	1.531
4.0	0.10	-100	-0.175	-100	0.296	-100	1.531
4.0	0.20	-100	-0.175	-100	0.296	-100	1.531
4.0	0.40	-100	-0.175	-100	0.298	-100	1.531
4.0	0.70	-86.929	-0.175	-86.680	0.351	-100	1.531
4.0	1.00	-61.833	-0.175	-61.456	0.488	-72.954	1.531
4.0	1.50	-41.810	-0.175	-41.429	0.710	-49.116	1.531
4.0	2.00	-31.286	-0.174	-30.930	0.854	-36.689	1.531
4.0	3.00	-20.411	-0.169	-20.102	1.017	-23.898	1.531
4.0	5.00	-11.254	-0.081	-11.017	1.196	-13.195	1.542
4.0	10.00	-3.583	1.051	-3.469	1.542	-4.417	2.002
4.0	30.00	2.852	4.054	3.062	4.240	2.553	4.389
7.0	0.01	-100	-0.289	-100	0.240	-100	1.498
7.0	0.10	-100	-0.289	-100	0.240	-100	1.499
7.0	0.20	-100	-0.289	-100	0.240	-100	1.499
7.0	0.40	-100	-0.288	-100	0.242	-100	1.499
7.0	0.70	-80.628	-0.287	-80.379	0.301	-96.738	1.499
7.0	1.00	-56.835	-0.285	-56.458	0.448	-67.956	1.500
7.0	1.50	-38.028	-0.280	-37.648	0.680	-45.334	1.500

$log\rho Y_e$	T_9	^{54}Ti		^{55}Ti		^{56}Ti	
		λ_ν	$\lambda_{\bar{\nu}}$	λ_ν	$\lambda_{\bar{\nu}}$	λ_ν	$\lambda_{\bar{\nu}}$
7.0	1.50	-38.028	-0.280	-37.648	0.680	-45.334	1.500
7.0	2.00	-28.465	-0.274	-28.109	0.828	-33.868	1.502
7.0	3.00	-18.701	-0.261	-18.392	0.996	-22.188	1.504
7.0	5.00	-10.551	-0.201	-10.314	1.179	-12.492	1.516
7.0	10.00	-3.484	0.999	-3.370	1.517	-4.318	1.978
7.0	30.00	2.855	4.050	3.066	4.237	2.557	4.386
10.0	0.01	-100	-100	-100	-100	-100	-100
10.0	0.10	-48.507	-100	-51.341	-100	-100	-100
10.0	0.20	-27.864	-100	-28.499	-88.596	-85.726	-94.766
10.0	0.40	-16.932	-86.965	-16.466	-46.252	-45.055	-49.332
10.0	0.70	-11.544	-50.916	-10.838	-27.654	-27.000	-29.408
10.0	1.00	-8.808	-36.237	-8.361	-19.996	-19.407	-21.185
10.0	1.50	-6.314	-24.554	-6.228	-13.836	-13.225	-14.510
10.0	2.00	-4.890	-18.528	-5.028	-10.624	-9.953	-10.979
10.0	3.00	-3.214	-12.247	-3.614	-7.232	-6.418	-7.185
10.0	5.00	-1.171	-6.834	-1.259	-4.244	-3.020	-3.740
10.0	10.00	1.589	-2.215	1.679	-1.564	0.758	-0.549
10.0	30.00	4.367	2.541	4.577	2.727	4.068	2.917
11.0	0.01	4.577	-100	3.963	-100	3.961	-100
11.0	0.10	4.580	-100	3.963	-100	3.959	-100
11.0	0.20	4.574	-100	3.963	-100	3.958	-100
11.0	0.40	4.577	-100	3.963	-100	3.959	-100
11.0	0.70	4.578	-100	3.962	-100	3.960	-100
11.0	1.00	4.578	-100	3.961	-84.583	3.960	-85.621
11.0	1.50	4.579	-67.600	3.957	-56.898	3.961	-57.458
11.0	2.00	4.580	-50.818	3.955	-42.926	3.963	-43.194
11.0	3.00	4.583	-33.783	3.955	-28.776	3.967	-28.667
11.0	5.00	4.593	-19.774	3.972	-17.189	3.982	-16.635
11.0	10.00	4.815	-8.724	4.556	-8.076	4.261	-7.014
11.0	30.00	6.252	0.219	6.453	0.404	5.964	0.611



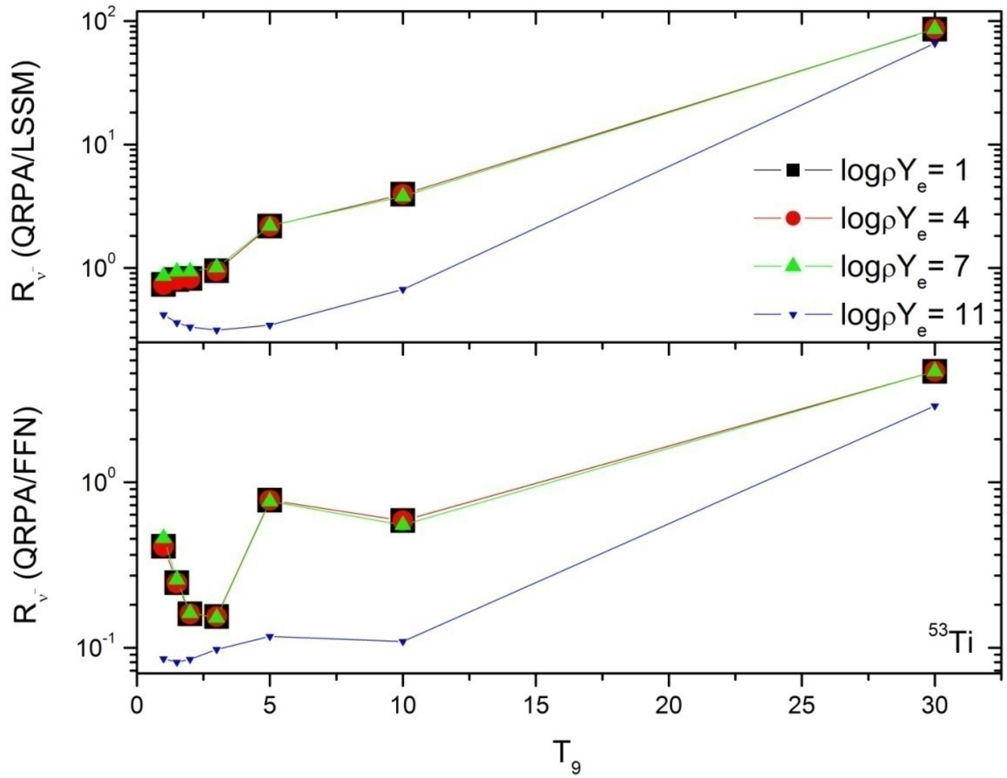
Anti-neutrino energy loss rate comparison due to Titanium-51

QRPA: This work (IJMPE 2010)
LSSM: NPA, 673 (2000) 481
FFN: ApJS, 48 (1982) 279



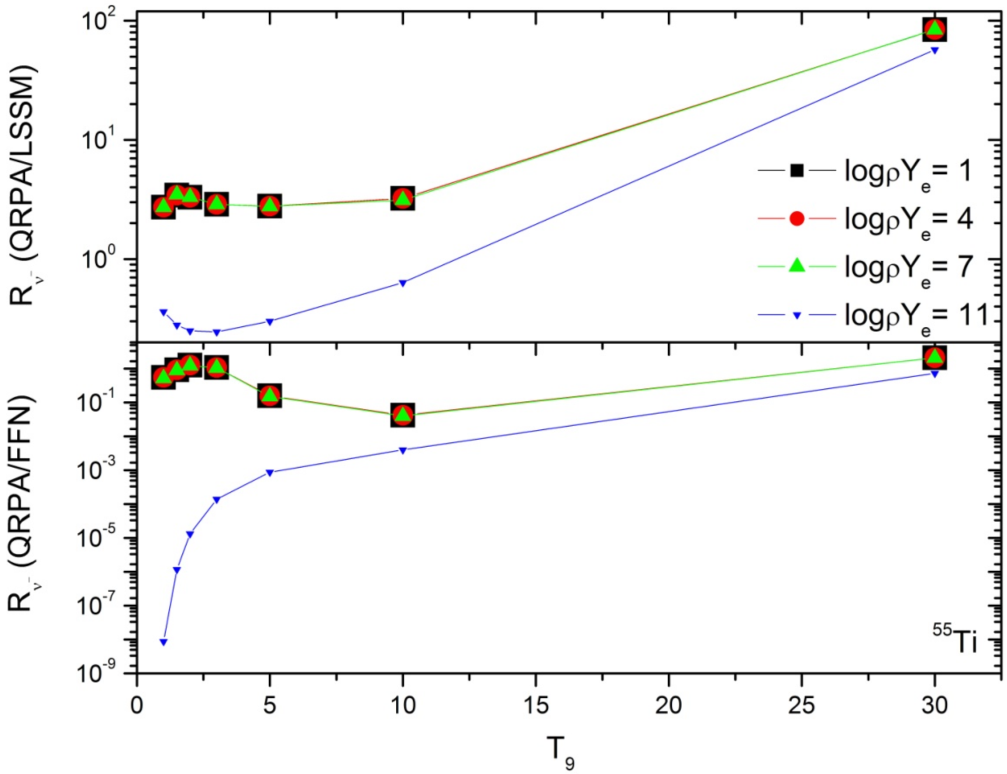
Anti-neutrino energy loss rate comparison due to Titanium-52

QRPA: This work (IJMPE 2010)
LSSM: NPA, 673 (2000) 481
FFN: ApJS, 48 (1982) 279



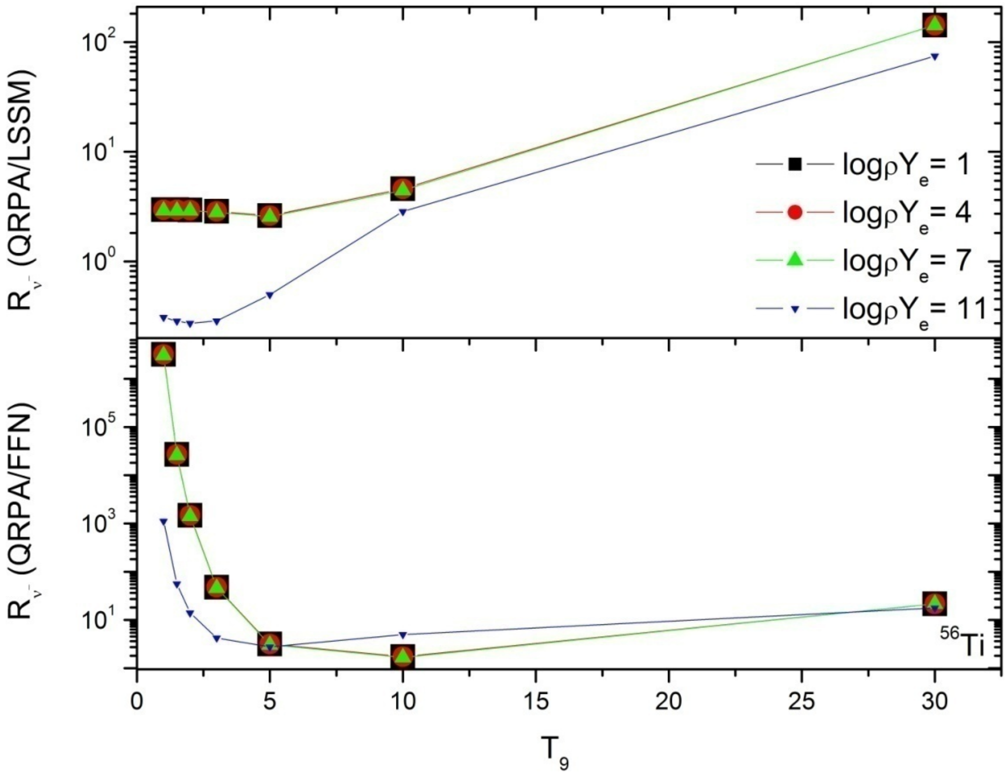
Anti-neutrino energy loss rate comparison due to Titanium-53

QRPA: This work (IJMPE 2010)
LSSM: NPA, 673 (2000) 481
FFN: ApJS, 48 (1982) 279



Anti-neutrino energy loss rate comparison due to Titanium-55

QRPA: This work (IJMPE 2010)
LSSM: NPA, 673 (2000) 481
FFN: ApJS, 48 (1982) 279



Anti-neutrino energy loss rate comparison due to Titanium-56

QRPA: This work (IJMPE 2010)
LSSM: NPA, 673 (2000) 481
FFN: ApJS, 48 (1982) 279

Comparison of LSSM and pn-QRPA calculations

Density (g-cm^3)	Temperature (10^9 K)	QRPA/SM ^{51}Ti	QRPA/SM ^{52}Ti	QRPA/SM ^{53}Ti
10^7	1	0.805	0.0458	0.863
10^7	1.5	0.897	0.0459	0.935
10^7	2	1.130	0.0449	0.938
10^7	3	1.600	0.0421	1.010
10^7	5	1.570	0.3020	2.200
10^7	10	2.170	2.2900	3.810

Comparison of LSSM and pn-QRPA calculations

Density ($g\text{-}cm^3$)	Temperature (10^9 K)	QRPA/SM ^{54}Ti	QRPA/SM ^{55}Ti	QRPA/SM ^{56}Ti
10^7	1	11.9	2.73	2.92
10^7	1.5	11.8	3.48	2.91
10^7	2	11.6	3.32	2.90
10^7	3	10.2	2.88	2.81
10^7	5	3.3	2.77	2.55
10^7	10	2.7	3.13	4.45

Conclusions

- The calculated antineutrino energy loss rates due to ^{51,53}**Ti** are in good comparison with LSSM rates. At high temperatures pn-QRPA rates are bigger by a factor of **2-4**.

- For ^{52}**Ti** the calculated rates are smaller by a factor of **25**. As temperature increases the pn-QRPA rate comparison improves till at $T_9 = 10$, the pn-QRPA rate is almost doubled.

- For ^{54,55,56}**Ti**, the pn-QRPA rates are bigger at all temperatures by as much as factor of **12 (^{54}Ti)**.

Astrophysical Implications

- Isotopes of titanium are amongst the key iron-regime nuclei that play a consequential role in the late phases of stellar evolution of massive stars.
- The weak-interaction mediated reactions on these nuclei change the Y_e during the late phases of stellar evolution.
- The temporal variation of Y_e within the core of a massive star has a pivotal role to play in the stellar evolution and a fine-tuning of this parameter at various stages of presupernova evolution is the key to generate an explosion.
- The neutrinos and antineutrinos produced as a result of these weak interaction reactions are transparent to the stellar matter at presupernova densities and therefore assist in cooling the core to a lower entropy state.

Astrophysical Implications (Contd.)

- A lower entropy environment can assist to achieve higher densities for the ensuing collapse generating a stronger bounce and in turn forming a more energetic shock wave.
- The pn-QRPA theory was employed to microscopically calculate the antineutrino energy loss rates due to titanium isotopes.
- The antineutrino energy loss rates were calculated on a detailed density-temperature grid point and the ASCII files of the rates are available.
- Except for the case of **^{52}Ti**, the calculated rates are bigger as compared to LSSM rates.

Astrophysical Implications (Contd.)

- The enhanced pn-QRPA energy loss rates favor cooler cores with lower entropies. This may affect the temperature, entropy and the Y_e ratio during the hydrostatic phases of stellar evolution which becomes very important going into stellar collapse.
- The core-collapse simulators are urged to test run the reported stellar antineutrino energy loss rates in core-collapse simulation codes to check for some interesting outcome.
- Details of this work may be seen from Nabi (IJMPE, 2010).


Thank You