Neutrino-nucleus reactions in supernovae

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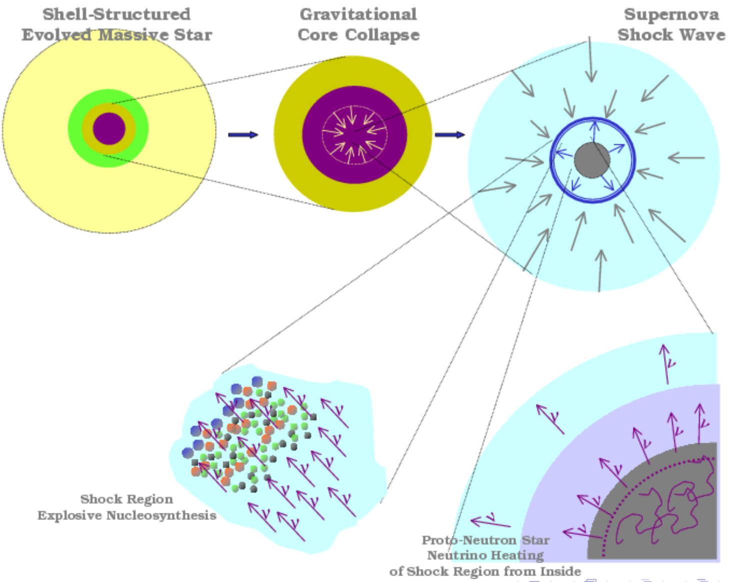
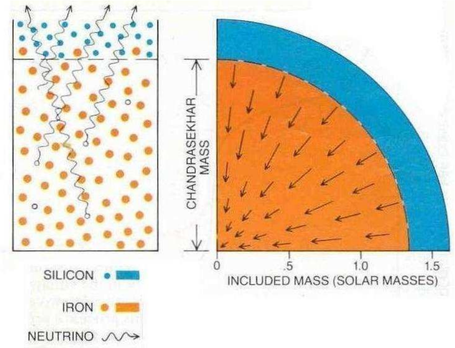
Core-collapse supernova.



Electron captures in core collapse.

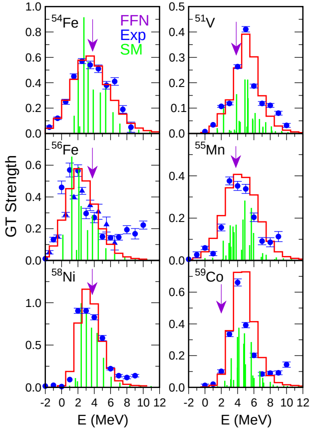


- $T = 0.5$–2.0 MeV, $\rho = 10^8$–10^{13} g cm^{-3}.
- The dynamical time scale set by electron captures: $e^- + (N, Z) \rightarrow (N+1, Z-1) + \nu_e$
- Evolution decreases number of electrons (Y_e) and Chandrasekhar mass ($M_{Ch} \approx 1.4(2Y_e)^2$ M$_\odot$)

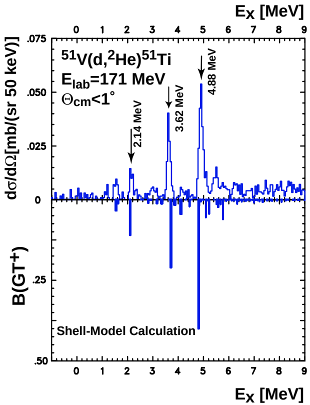
- Capture rates on individual nuclei computed by:
  - Shell Model ($A < 65$)
  - Shell Model Monte Carlo ($A > 65$)

Gamow-Teller strength distributions in pf-shell nuclei.

(n,p) experiments, TRIUMF



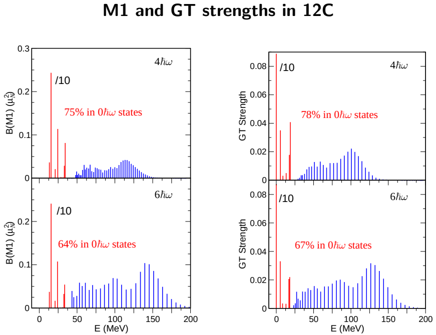
(d,^{2}He) experiments, KVI Groningen



shell model results agree after overall quenching by $(0.77)^2$

GT strength in multi-shell calculations

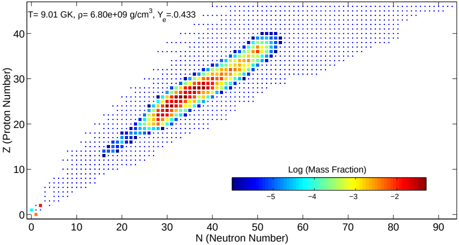
- No-core shell model calculation of ^{12}C
- Gamow-Teller strength shifted to higher excitation energies



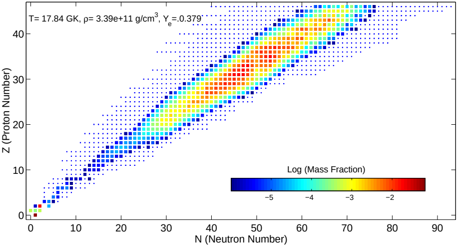
E. Caurier, G. Martinez-Pinedo, F. Nowacki

Collapse abundances

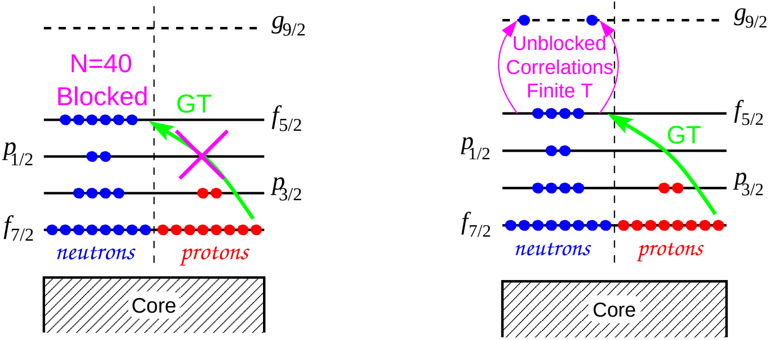
Presupernova stage



Neutrino trapping



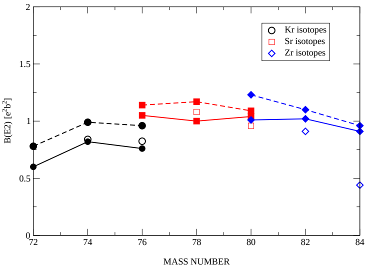
Pauli blocking of Gamow-Teller transition



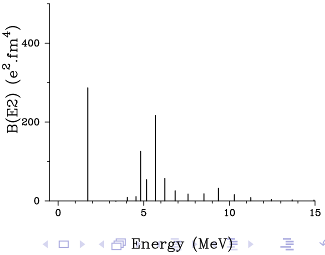
- Unblocking mechanism: correlations and finite temperature
- calculation of rate in SMMC + RPA model

Correlations across $N = 40$ shell gap

- strong deformation in $N \sim Z \sim 40$ nuclei
- SMMC ((fp gds) model space)
- deformation due to $g_{9/2}$ orbital
- with W. Nazarewicz, D. Dean

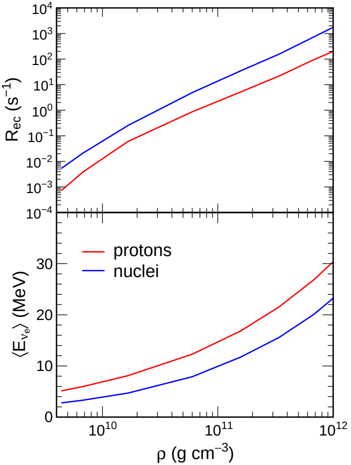


- B(E2) strength in ^{68}Ni
- most strength in excited states
- neutron pair excitation across shell gap
- shell model (F. Nowacki)

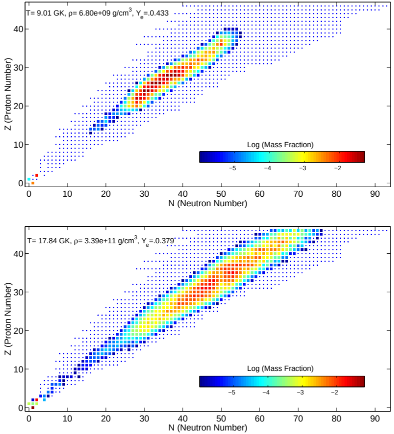


Electron capture: nuclei vs protons

Capture rate and average energy

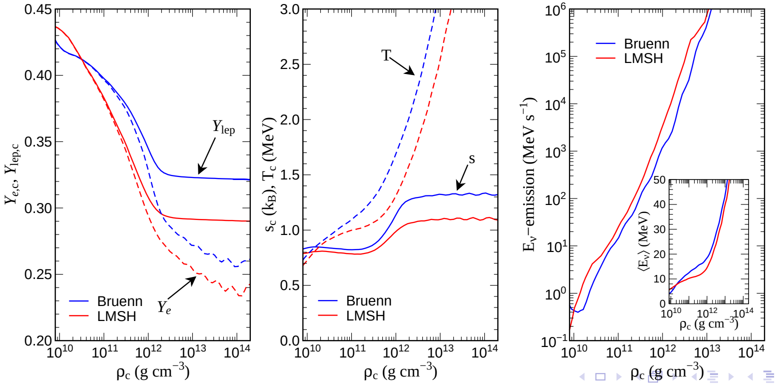


Mass abundances

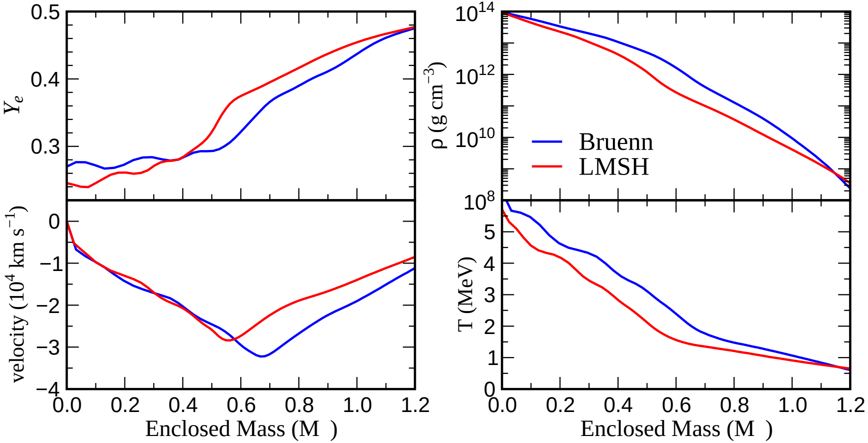


Consequences

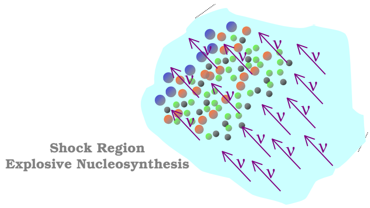
With Rampp & Janka (General Relativistic model)
15 $M_\odot$ presupernova model from A. Heger & S. Woosley



Consequences



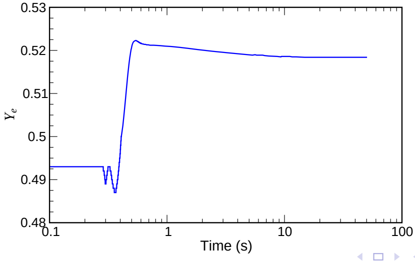
Explosive nucleosynthesis in supernova



- Consistent treatment of supernova dynamics coupled with a nuclear network.
- Essential neutrino reactions in the shock heated region

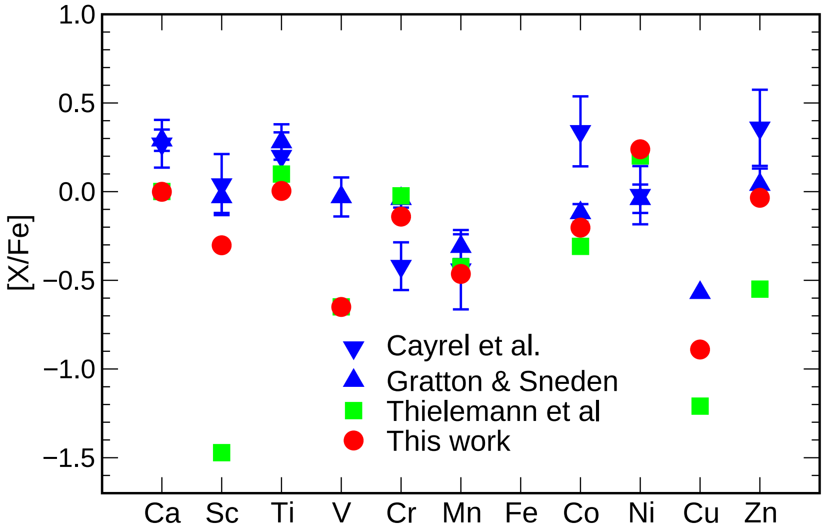
$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

Y_e evolution of a mass element



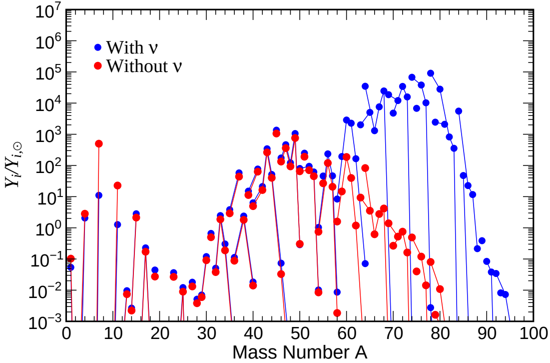
Comparison with observations.

Carla Fröhlich *et al.*, Ap.J., in press (astro-ph/0410208)



Effect of neutrinos on nucleosynthesis.

G. Martínez-Pinedo, C. Fröhlich

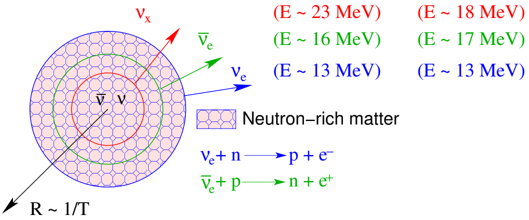


- Without neutrinos flow stops at ^{64}Ge ($t_{1/2} = 64$ s)
- With neutrinos:

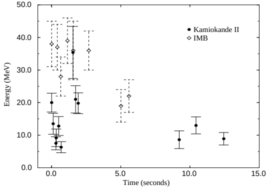
$\bar{\nu}_e + p \rightarrow e^+ + n$; $\quad n + {}^{64}\text{Ge} \rightarrow {}^{64}\text{Ga} + p$; $\quad {}^{64}\text{Ga} + p \rightarrow {}^{65}\text{Ge}; \ldots$

Neutrinos from supernovae

Raffelt *et al.*, astro-ph/0303226

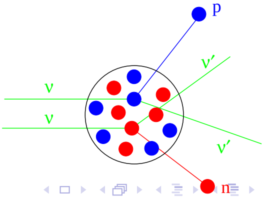


neutrino detection (SN1987A)



Neutrino nucleosynthesis

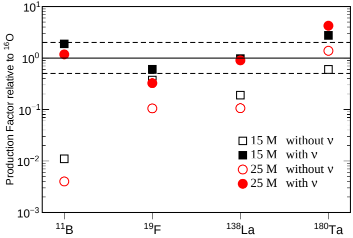
$^{12}\mathrm{C}(\nu,\nu' p)^{11}\mathrm{B}$ $^{12}\mathrm{C}(\nu,\nu' n)^{11}\mathrm{C}$

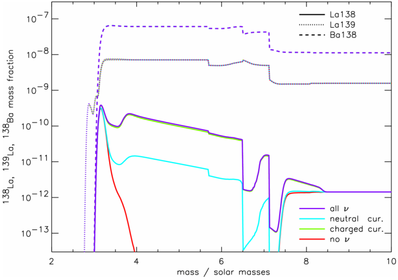


Neutrino nucleosynthesis

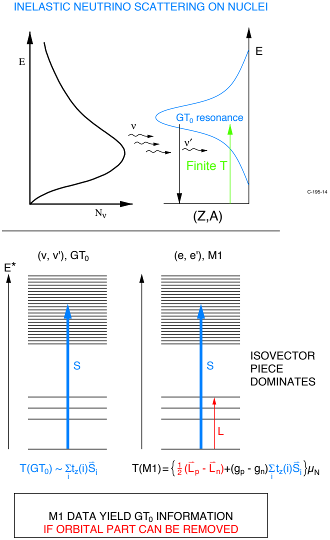
A. Heger *et al*, PLB 606 (2005) 258

Product	Parent	Reaction
^{11}B	^{12}C	$(\nu,\nu' n), (\nu,\nu' p)$
^{19}F	^{20}Ne	$(\nu,\nu' n), (\nu,\nu' p)$
^{138}La	^{138}Ba	(ν_e, e^-)
	^{139}La	$(\nu,\nu' n)$
^{180}Ta	^{180}Hf	(ν_e, e^-)
	^{181}Ta	$(\nu,\nu' n)$

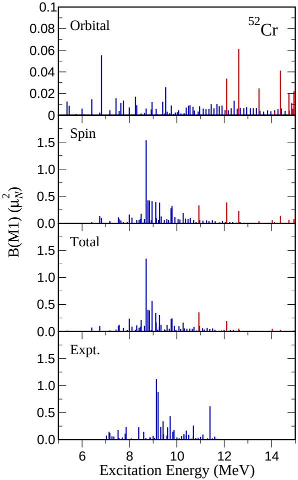


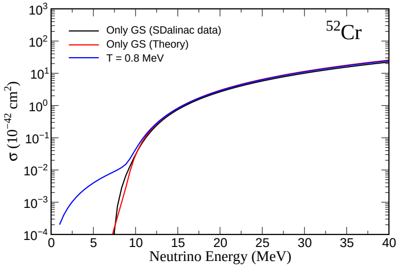


Determining inelastic neutrino-nucleus cross sections



Neutrino cross sections from electron scattering

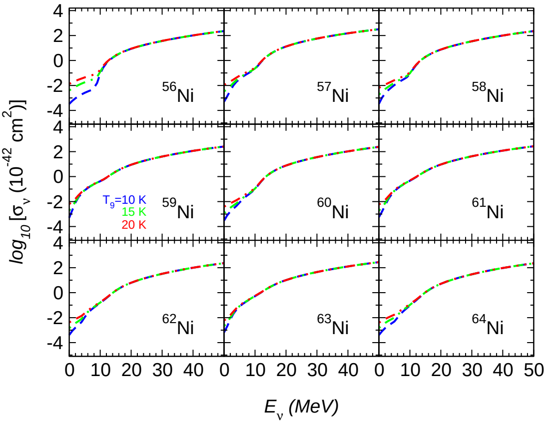




- high-precision SDalinac data
- large-scale shell model

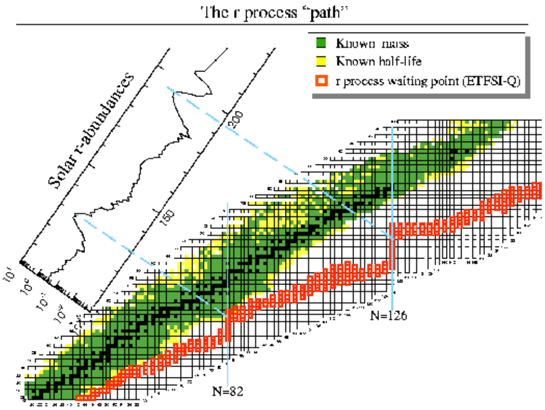
- neutrino cross sections from (e, e') data
- validation of shell model
- G.Martinez-Pinedo, P. v. Neumann-Cosel, A. Richter

Inelastic neutrino-nucleus cross sections



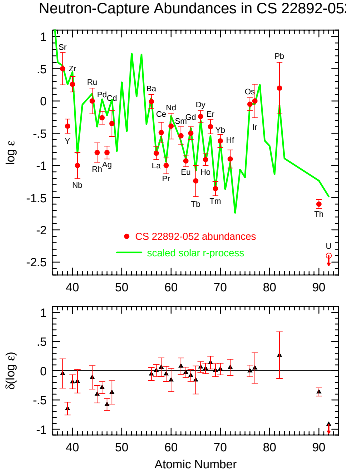
- large-scale shell model (allowed transitions), finite-T effects
- random phase approximation (forbidden transitions)
- A. Juodagalvis, G. Martinez-Pinedo, J.M. Sampaio

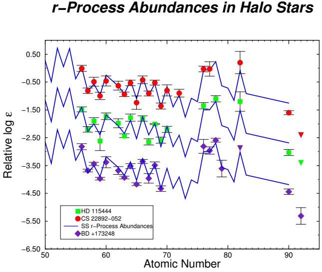
r-process



$T \approx 100$ keV $\quad n \gtrsim 10^{20}$ cm^{-3} implies $\tau_n \ll \tau_\beta$
$(n,\gamma) \rightleftarrows (\gamma,n)$ implies $S_n \approx 2$ MeV

Abundances observed in metal-poor stars





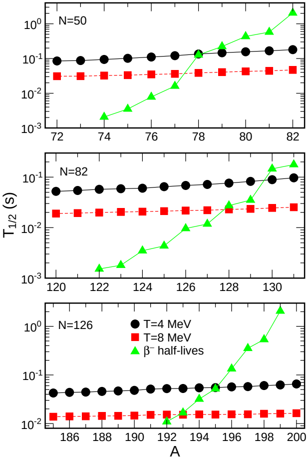
- Abundances for nuclei $Z \geq 56$ consistent with normalized solar distribution.
- U/Th ratio can be used to estimate age of the galaxy.
  (CS 22892-052, 15.6 $\pm$ 4.6 Gyr)

Role of neutrinos during r-process

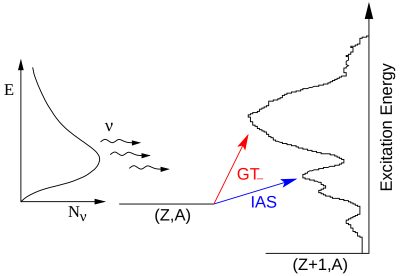
- ν_e+n, $\bar{\nu}_e$+p sets neutron/proton ratio
- α effect hinders r-process (Meyer)
- ν_e+A $\rightarrow A' + e^- + \text{free neutrons}$
  ν+A $\rightarrow A' + \nu + \text{free neutrons}$ (post-processing)
  changes r-process abundance distribution after freeze-out
  (Haxton, Qian, Vogel)
- neutrino-induced fission responsible for $A \sim 90$ and 132 peaks in metal-poor stars? (Qian, Fuller, Kolbe)
- charged-current reactions can speed up matter flow

The role of neutrinos during the r-process

ν_e charge-current interactions can accelerate the flow of matter ($\lambda = \lambda_\beta + \lambda_{\nu_e}$)



Neutrino rates are not sensitive to shell-effects



- $E_{\rm iso} = \Delta E_c - (m_n - m_H)$, $B(F) = (N - Z)$.
- $E_{\rm GT} - E_{\rm iso} = a + b(N-Z)/A$, $B(GT) \approx 3(N - Z)$

Summary

Improved nuclear ingredients for supernova simulations

- Electron capture rates on nuclei
- Neutrino-nucleus cross sections
- level densities; partition functions
- Equation of state; matter composition

The future of nuclear astrophysics is FAIR