Many-Body challenges in nuclear astrophysics

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Recent Progress in Many-Body Theories

July 16, 2007

HELMHOLTZ
GEMEINSCHAFT

Outline

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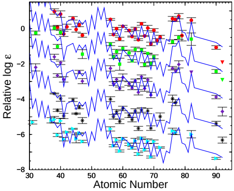
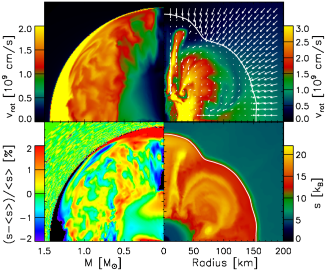
Nuclear Astrophysics

Improved observational capabilities

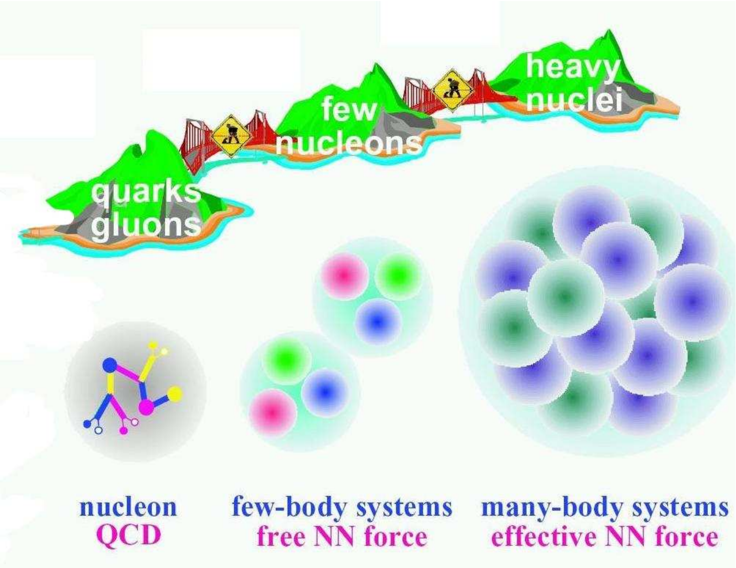


Improved supernovae models

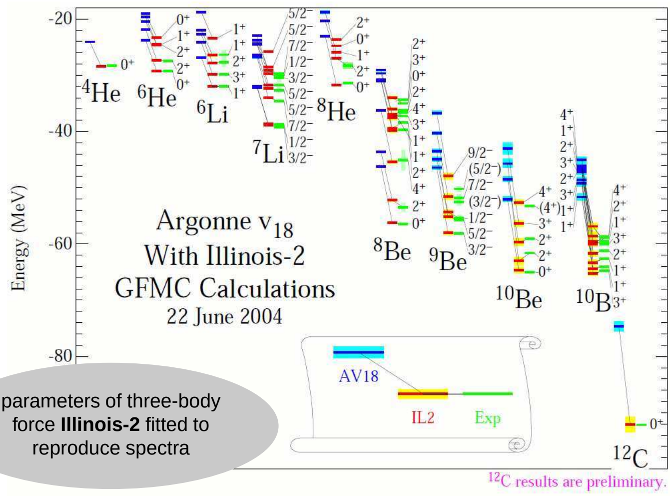


- New radioactive ion beam facilities (RIBF, SPIRAL 2, FAIR) are being built or developed that allow to explore many nuclei produced in explosive events.
- We need improved many body models to fully exploit the potential offered by these facilities.

Nuclear Interaction and Dregrees of Freedom



Green's Function Monte Carlo

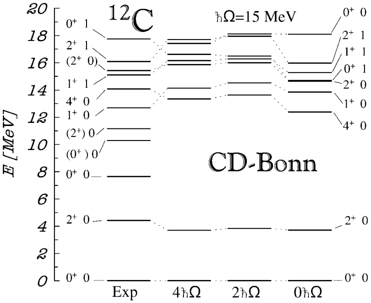


parameters of three-body force **Illinois-2** fitted to reproduce spectra

Wiringa, Pieper, PRL **89** (2002) 182501

No-Core Shell Model

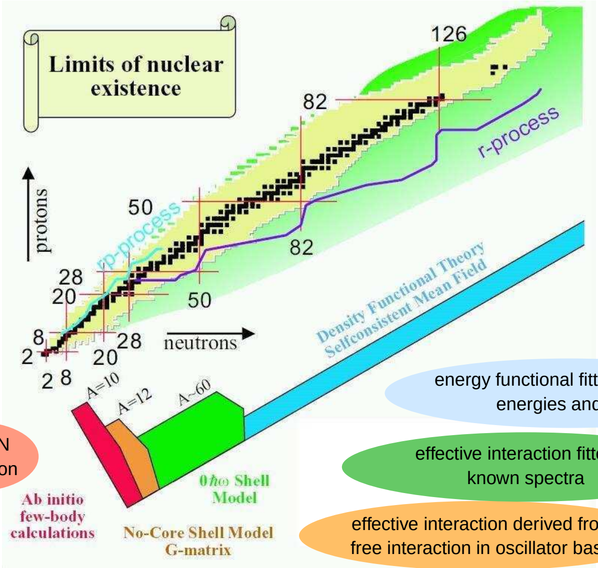
- Solves the nuclear many body problem for light nuclei using realistic NN forces.
- The calculations are done in a large but finite harmonic-oscillator basis using an effective interaction derived via an unitary Lee-Suzuki transformation.



P. Navrátil, *et al.* PRL **84** (2000) 5728.

Problems describing states with a clear cluster structure like the Hoyle state (0^+ at 7.654 MeV in ^{12}C)

Quest for a unified description of nuclei



Free NN interaction

energy functional fitted to binding energies and radii

effective interaction fitted to known spectra

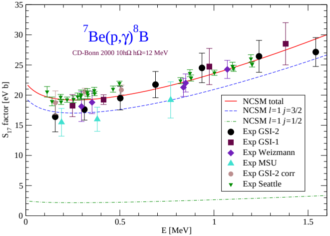
effective interaction derived from free interaction in oscillator basis

Ab initio approaches

Several attempts have been pursued to extend *ab initio* approaches to astrophysical reactions.

- Variational Monte Carlo calculations have been done for $^2\mathrm{H}(\alpha,\gamma)^6\mathrm{Li}$, $^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li}$, and $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ capture reactions (Nollet *et al*, PRC **63** (2001) 054002).
- $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ have been computed using the no-core shell model approach (Navrátil *et al* **73** (2006) 065801).
- They are not yet completely *ab initio* as the scattering states are computed using simple potential models.

$$S(E) = \sigma(E) E e^{2\pi\eta(E)}$$



We need a consistent description of bound, resonant and scattering states.

Fermion Molecular Dynamics

Feldmeier & Schnack, RMP **72** (2000) 655

Fermionic

$$| Q \rangle = \mathcal{A}\Big(| q_1 \rangle \otimes \cdots \otimes | q_A \rangle \Big)$$

- antisymmetrized A-body state

Molecular

single particle states

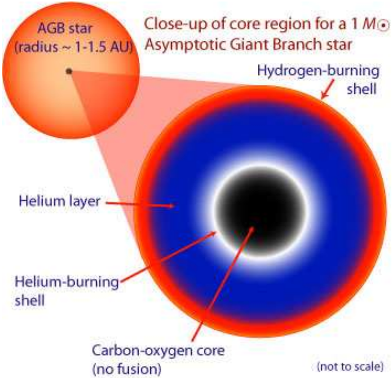
$$\langle \vec{x} | q \rangle = \sum_i c_i \exp\left\{ -\frac{(\vec{x} - \vec{b}_i)^2}{2a_i} \right\} \otimes | \chi^{\uparrow}_i, \chi^{\downarrow}_i \rangle \otimes | \xi \rangle$$

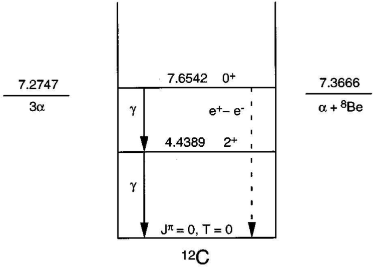
- Gaussian wave-packets in phase-space (complex parameter $\vec{b}_i$ encodes mean position and mean momentum), spin is free, isospin is fixed.
- width a_i (and $\vec{b}_i$) are independent variational parameters for each wave packet.

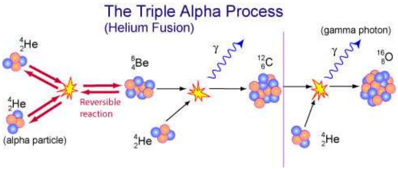
Dynamics

- Interaction derived from Argonne V18 interaction by explicit inclusion of short-range central and tensor correlations via the Unitary Correlation Operator Method (Neff & Feldmeier, NPA **713** (2003) 311)
- Projection on parity, linear and angular momentum (before or after variation).

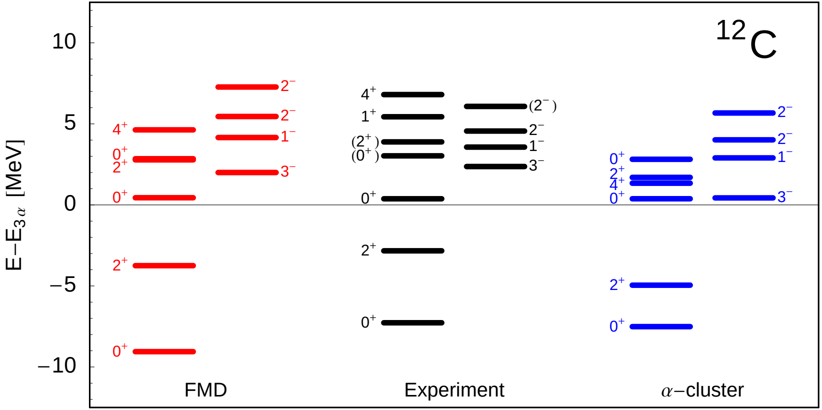
Hoyle State and tripple α reaction





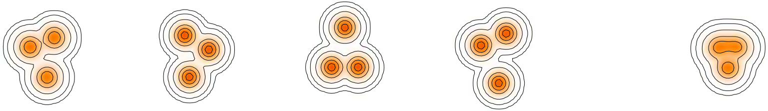


^{12}C description



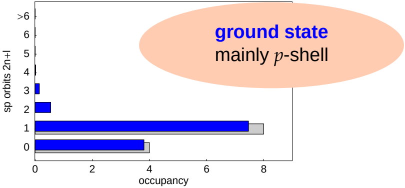
Important Configurations and Occupation numbers

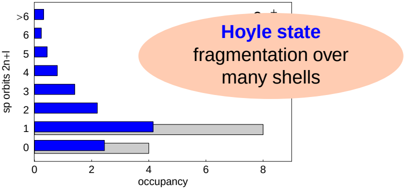
- Most important contributions to Hoyle state and ground state (FMD states not orthogonal)



$\left\| \langle \cdot \,\|\, 0_1^+ \rangle \right\| = 0.30$	$\left\| \langle \cdot \,\|\, 0_1^+ \rangle \right\| = 0.25$	$\left\| \langle \cdot \,\|\, 0_1^+ \rangle \right\| = 0.15$	$\left\| \langle \cdot \,\|\, 0_1^+ \rangle \right\| = 0.08$	$\left\| \langle \cdot \,\|\, 0_1^+ \rangle \right\| = 0.94$
$\left\| \langle \cdot \,\|\, 0_2^+ \rangle \right\| = 0.72$	$\left\| \langle \cdot \,\|\, 0_2^+ \rangle \right\| = 0.71$	$\left\| \langle \cdot \,\|\, 0_2^+ \rangle \right\| = 0.61$	$\left\| \langle \cdot \,\|\, 0_2^+ \rangle \right\| = 0.61$	$\left\| \langle \cdot \,\|\, 0_2^+ \rangle \right\| = 0.04$

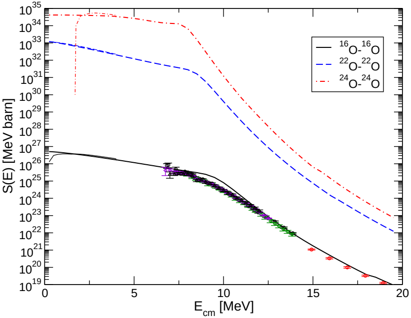
- Harmonic Oscillator Occupation Numbers.



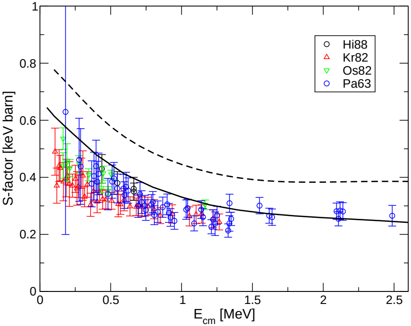


Astrophysical applications

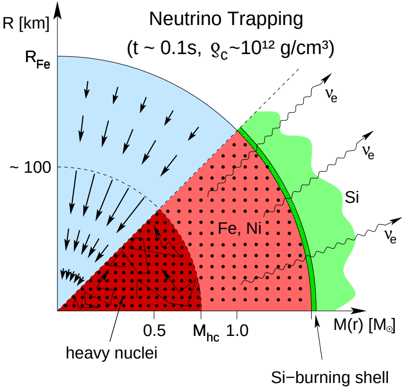
Fusion cross-sections for Oxygen isotopes:
(Neff *et al*, nucl-th/0703030)



Radiative alpha capture :
(Neff *et al*, preliminary)



Electron capture during the collapse



Important processes:

- Neutrino transport (Boltzmann equation):
  $\nu + A \rightleftarrows \nu + A$ (trapping)
  $\nu + e^- \rightleftarrows \nu + e^-$ (thermalization)

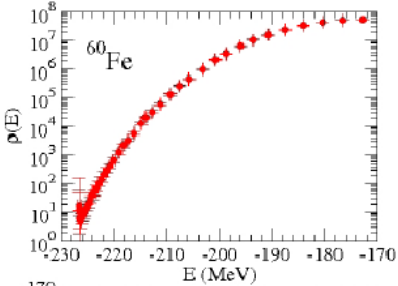
  cross sections $\sim E_\nu^2$
- electron capture on protons:
  $e^- + p \rightleftarrows n + \nu_e$
- electron capture on nuclei:
  $e^- + A(Z, N) \rightleftarrows A(Z-1, N+1) + \nu_e$
- Traditional treatment (Independent particle model) suppresses electron capture on nuclei for $N = 40$.

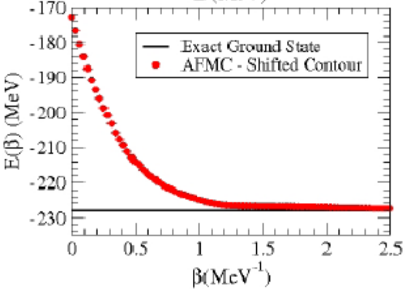
- Gamow-Teller strength can be determined by charge exchange reactions
- Theory is needed to account for finite temperature effects (excited states) (Shell-Model diagonalizations, Shell-Model (Auxiliary Field) Monte Carlo

Level densities with Auxiliary Field Monte Carlo

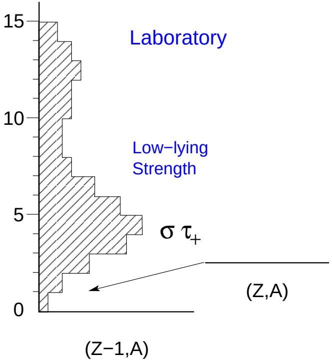
- Level densities are necessary for the calculation of cross sections in medium and heavy nuclei using the Hauser-Feshbach statistical model and for the calculation of partition functions.
- AFMC has been extensively been used for the calculation of level densities using schematical interactions (pairing plus quadrupole) due to sign problem (Alhassid, Langanke, ...).
- Very recently has been possible to avoid the sign problem shifting the MC integration to the Hartree minimum of the fields.
- This allows to use fully realistic interactions.

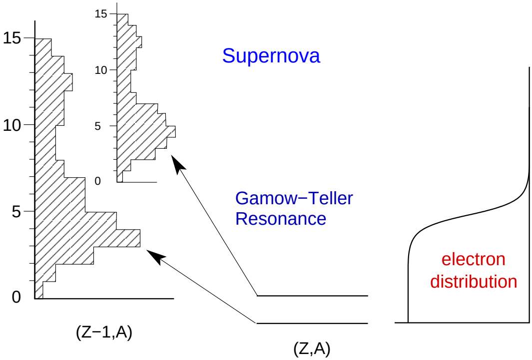
D. Dean, INPC 2007 talk





Laboratory vs. stellar electron capture



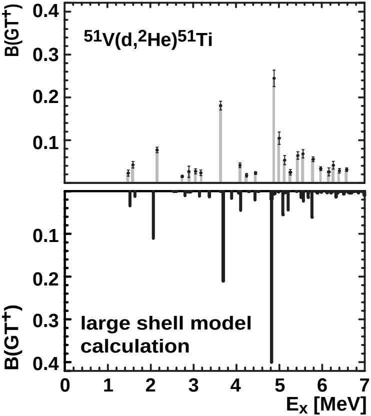


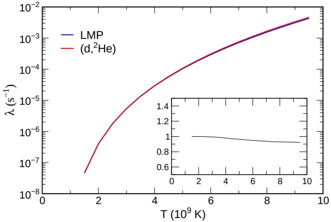
Capture of K-shell electrons to tail of GT strength distribution. Parent nucleus in the ground state

Capture of electrons from the high energy tail of the FD distribution. Capture to states with large GT matrix elements (GT resonance). Thermal ensemble of initial states.

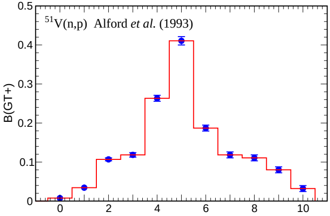
KVI results using $(d, {}^2\mathrm{He})$

C. Bäumer *et al.* PRC **68**, 031303 (2003)





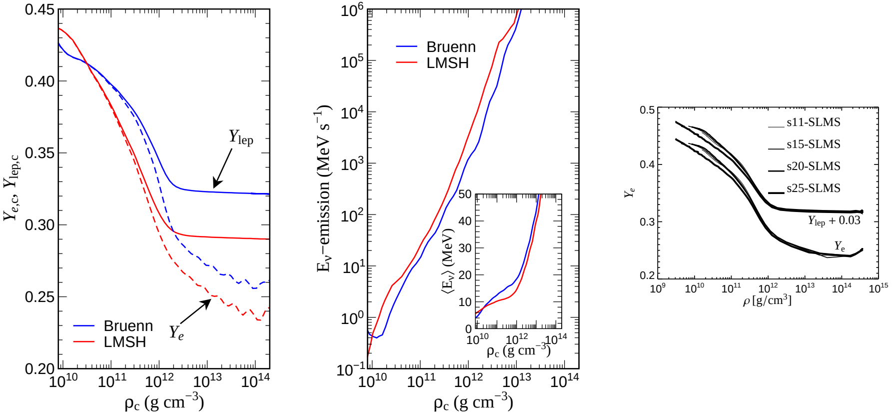
Old (n, p) data



GT strength in ^{48}Sc, ^{50}V, ^{58}Ni, ^{64}Ni also measured.

Effects Realistic calculation

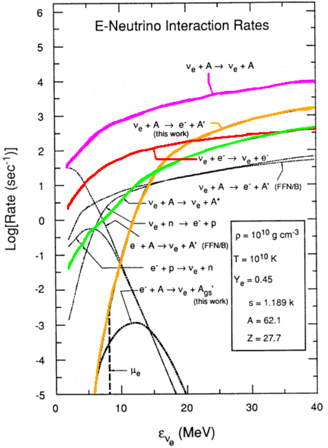
Marek et al, in preparation



- Electron capture on nuclei dominates over capture on protons
- All models converge to a “norm” stellar core at the moment of shock formation.

Neutrino interactions during the collapse

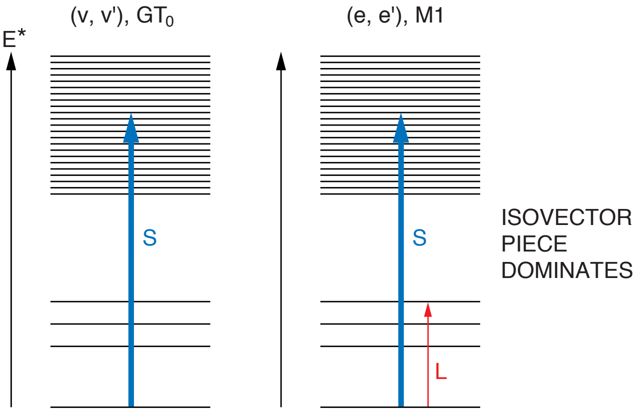
Bruenn and Haxton (1991)
Based on results for ^{56}Fe



- Elastic scattering:
  $\nu + A \rightleftarrows \nu + A$ (trapping)
- Absorption:
  $\nu_e + (N, Z) \rightleftarrows e^- + (N-1, Z+1)$
- ν-e scattering:
  $\nu + e^- \rightleftarrows \nu + e^-$ (thermalization)
- Inelastic ν-nuclei scattering:
  $\nu + A \rightleftarrows \nu + A^*$

Inelastic Neutrino-nucleus interactions had not been included in collapse simulations.

Neutrino scattering from (e, e')



$T(GT_0) \sim \sum_i t_z(i)\vec{S}_i$

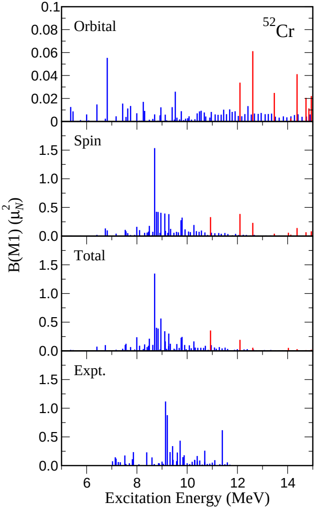
$T(M1) = \left\{ \frac{1}{2}(\vec{L}_p - \vec{L}_n) + (g_p - g_n)\sum_i t_z(i)\vec{S}_i \right\}\mu_N$

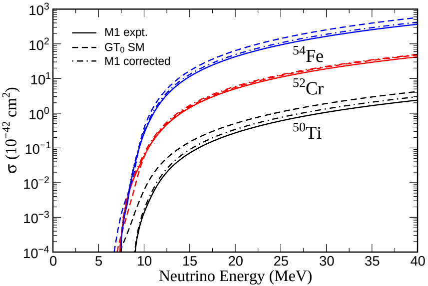
M1 data give GT_0 information

if Orbital contribution can be removed

Neutrino Scattering from (e, e')

K. Langanke *et al*, PRL **93**, 202501 (2004)

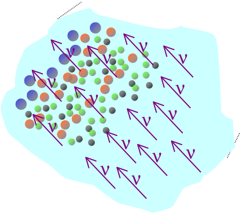




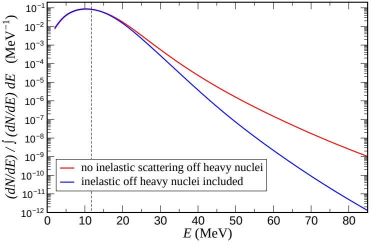
$M1$ data (S-Dalinac) can be used to constrain supernovae inelastic neutrino cross sections.

Influence on neutrino spectra

Langanke *et al* arXiv:0706.1687



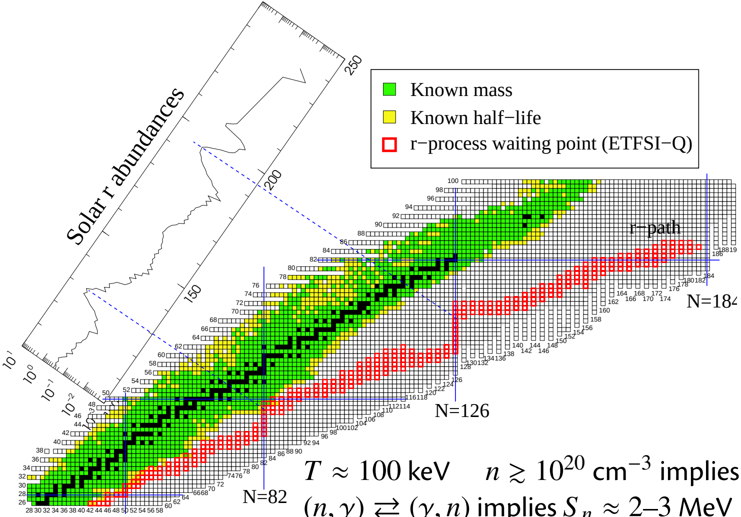
- A future detection of a close by supernova could bring information about supernova dynamics.
- We have done detailed simulations and shown that the spectrum of the initial ν_e burst is affected by the inclusion of inelastic neutrino scattering with nuclei (B. Müller *et al*).
- At later times (relevant for nucleosynthesis) spectra is unchanged as all nuclei are dissociated.



Material	$\langle\sigma\rangle$ (10^{-42} cm^2) With INNS	Without INNS	Change
e	0.106	0.110	3%
d	4.92	5.36	8%
^{12}C	0.050	0.080	37%
^{16}O	0.0053	0.0128	58%
^{40}Ar	13.4	15.1	11%
^{56}Fe	6.2	7.5	17%
^{208}Pb	103.3	124.5	17%

The r-process

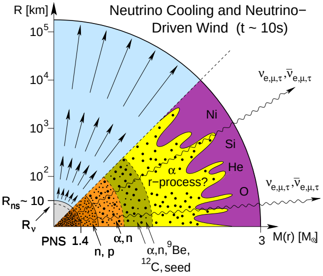
The r-process is responsible for the synthesis of half the nuclei with $A > 60$ including U, Th and maybe the super-heavies.



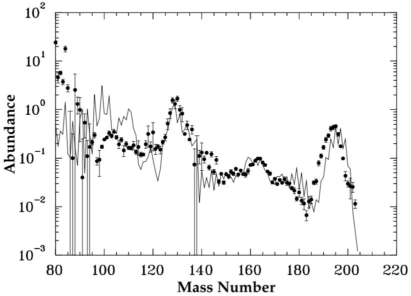
$T \approx 100$ keV $\quad n \gtrsim 10^{20}$ cm^{-3} implies $\tau_n \ll \tau_\beta$

$(n,\gamma) \rightleftarrows (\gamma,n)$ implies $S_n \approx 2$–3 MeV

Neutrino-driven wind scenario



(S. Woosley *et al*)



- Neutrino-wind from (cooling) NS

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

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

- α-process (formation seed nuclei)

  ^{4}He$(\alpha n,\gamma)^9$Be$(\alpha,n)^{12}$C

  ^{4}He$(t,\gamma)^7$Li$(n,\gamma)^8$Li$(\alpha,n)^{11}$Li

Main parameter determining the nucleosynthesis is the neutron to seed ratio (~ 100)

r-process needs

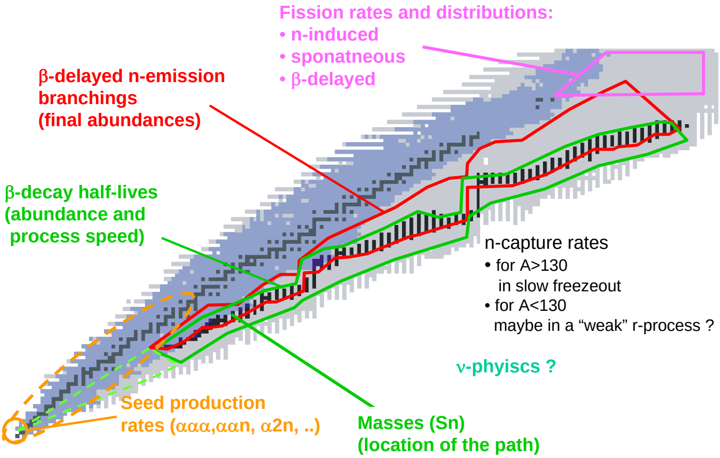
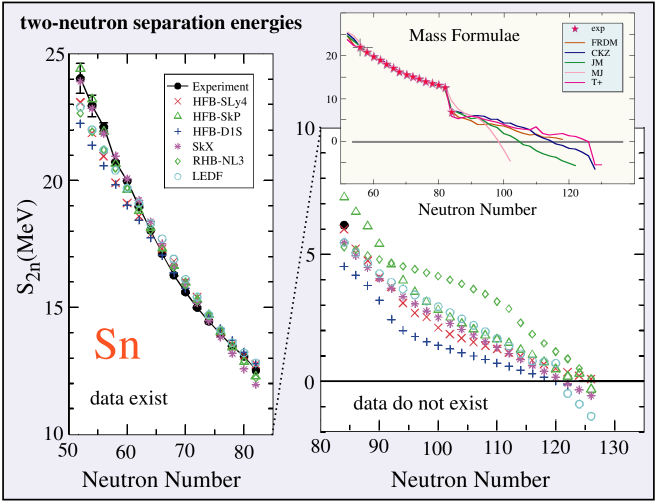


figure from H. Schatz

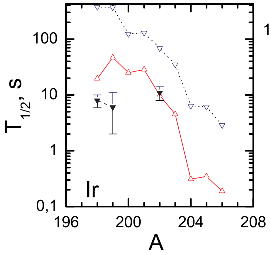
Masses for r-process nuclei

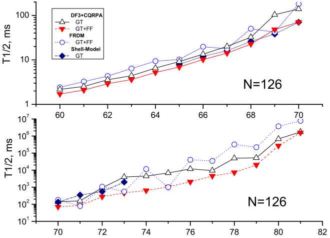
We need reliable models to determine masses for r-process nuclei (DFT with functional connected to QCD via EFT)



Beta-decay half-lives (N=126)

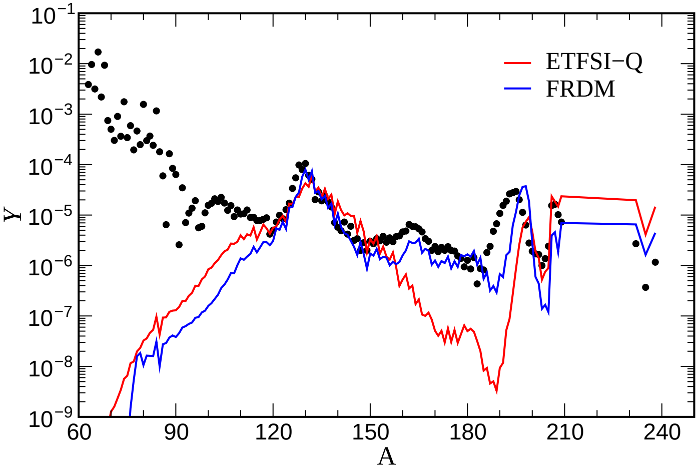
The N=126 nuclei are not yet accessible experimentally. However, in a recent experiment at the FRS (GSI) several nuclei were produced approaching the $N = 126$ (Kurtukian-Nieto *et al*, 2007)





Influence on the input data

Two different sets of neutron capture rates, half-lives, fission-barriers, ...



Conclusions

- Nuclear astrophysics requires the knowledge of the relevant nuclear physics input combined with state-of-the-art hydrodynamic modelling, which then leads to testable predictions with actual observations.
- Future challenges for nuclear structure theory are the extension of ab-initio calculations based on realistic nucleon-nucleon interactions to nuclei beyond $A = 12$, and extend ab-initio models to the description of nuclear reactions.
- The r-process requires large amounts of data. We need to develop models that are generally applicable and at the same time describe reliable the properties of the involved nuclei.