

Exotic nuclei and explosive nucleosynthesis

Gabriel Martínez Pinedo



TECHNISCHE
UNIVERSITÄT
DARMSTADT



ISOLDE workshop & users meeting

November 25-27, 2013, Cern



Nuclear Astrophysics Virtual Institute

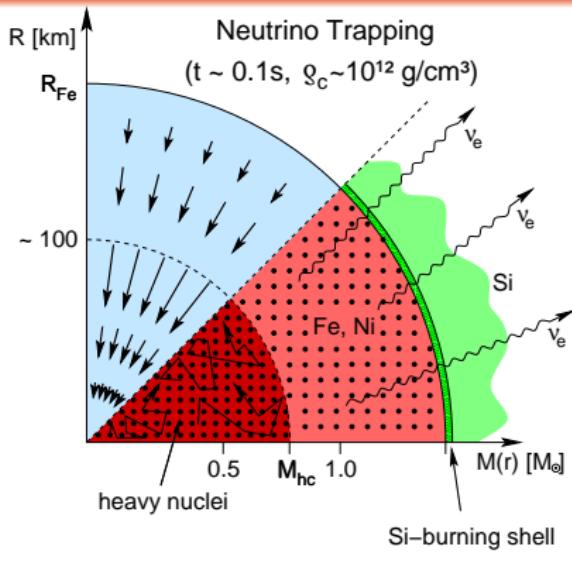


DFG

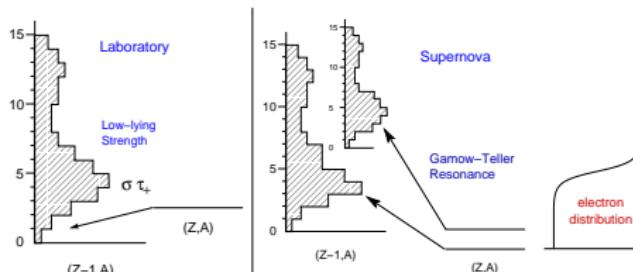
Outline

- 1 Electron capture in Core-collapse supernova
- 2 Heavy-element nucleosynthesis: The r-process
- 3 Summary

Weak interactions during collapse

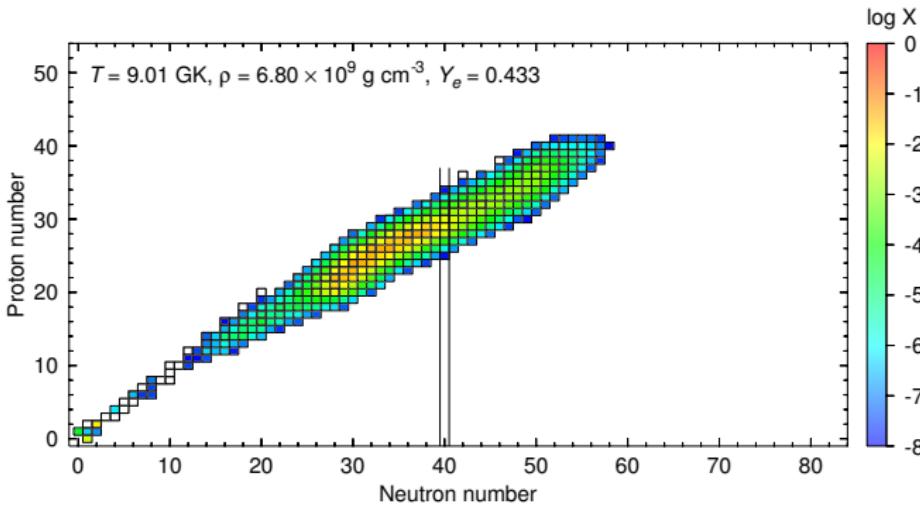


- Composition of Iron group and heavier nuclei
 - Dominant process, electron capture on nuclei:
$$e^- + A(Z, N) \rightleftharpoons A(Z-1, N+1) + \nu_e$$
 - Dominated by Gamow-Teller transitions.
 - Evolution decreases the number of electrons (Y_e) and Chandrasekhar mass ($M_{ch} = 1.4(2Y_e)^2 M_\odot$)



Early composition

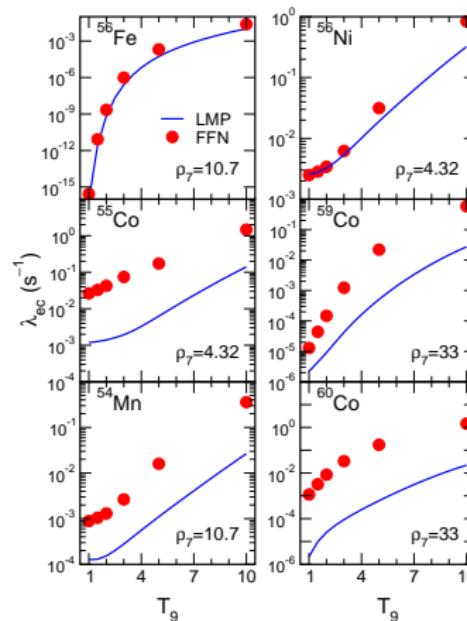
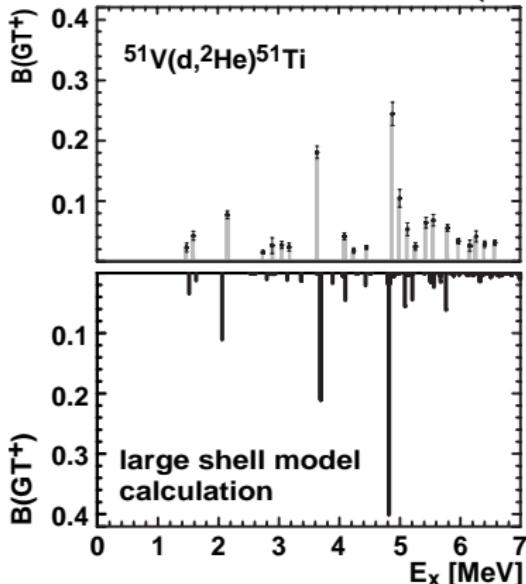
Initially the composition is mainly given by Iron group nuclei.



GMP, M. Liebendörfer, D. Frekers, NPA 777, 395 (2006).

Shell-model based electron capture rates

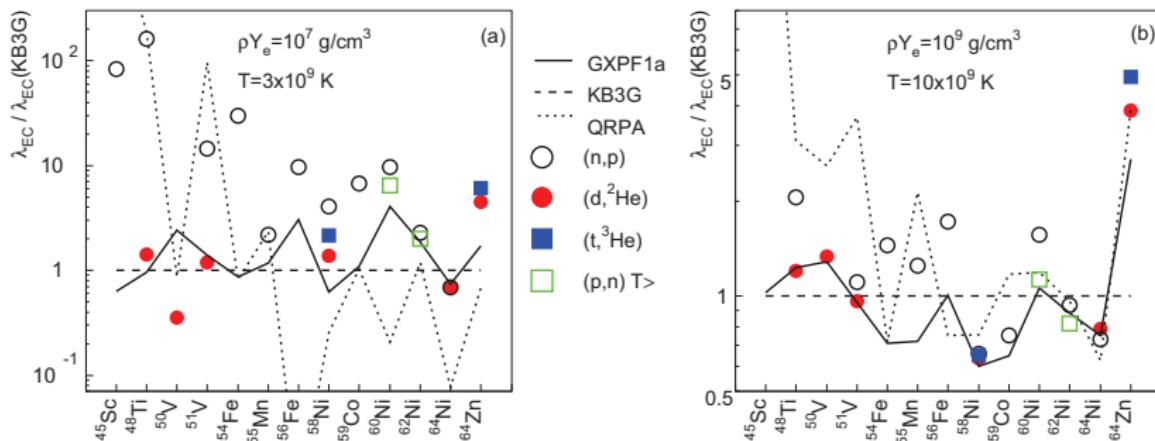
C. Bäumer *et al.* PRC **68**, 031303 (2003)



- Capture rates on iron group nuclei calculated by large scale shell-model (Langanke & GMP, 2000)
 - Capture rates are noticeable smaller than assumed before

Systematic study measured GT strengths

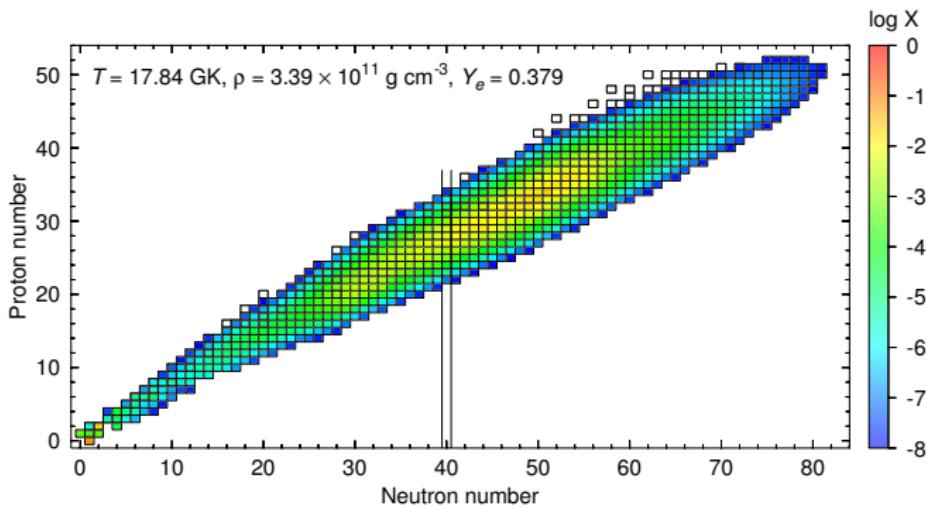
A. L. Cole *et al.*, PRC 86, 015809 (2012)



- Rates for iron-group nuclei are under control
 - With increasing density, less sophisticated models like QRPA may suffice.

Late time composition

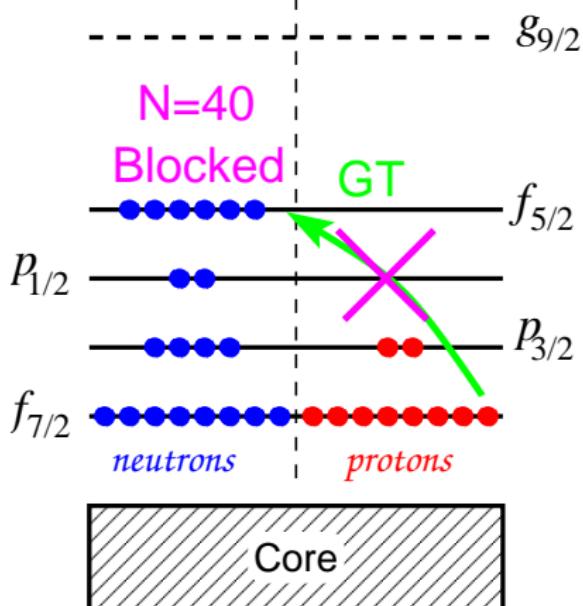
With decreasing Y_e the composition moves to more neutron rich nuclei.



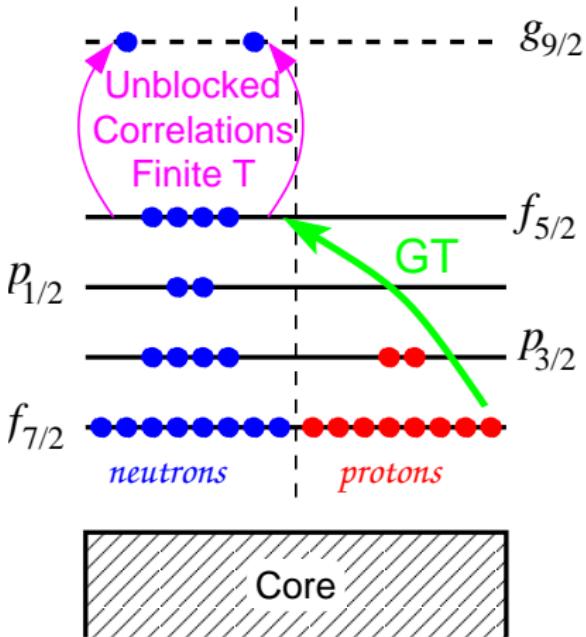
GMP, M. Liebendörfer, D. Frekers, NPA 777, 395 (2006).

Challenge: electron capture around N=40

Independent particle treatment



Fuller, ApJ 252, 741 (1982)



Langanke & GMP, RMP 75, 819 (2003)

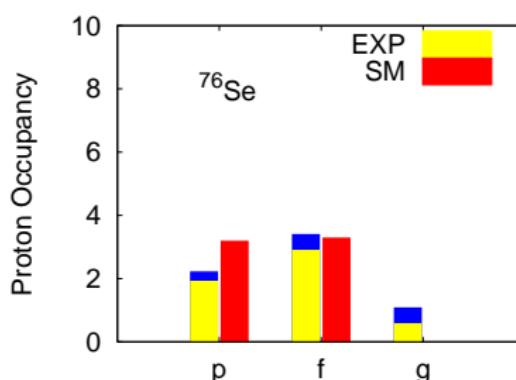
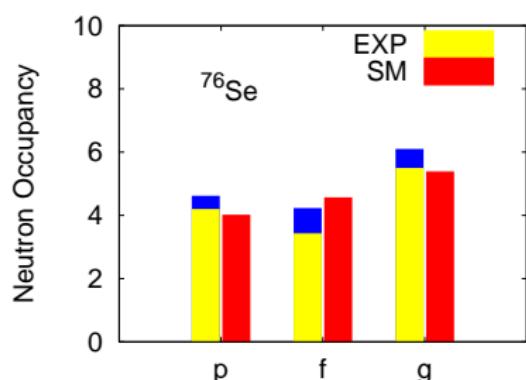
Correlations around N=40: GT+ strength for ^{76}Se

The structure of ^{76}Se ($Z = 34, N = 42$) has been the subject of several recent studies due to its important for the double beta decay of ^{76}Ge

Measured occupation numbers in transfer reactions

Schiffer *et al*, PRL **100**, 112501 (2008)

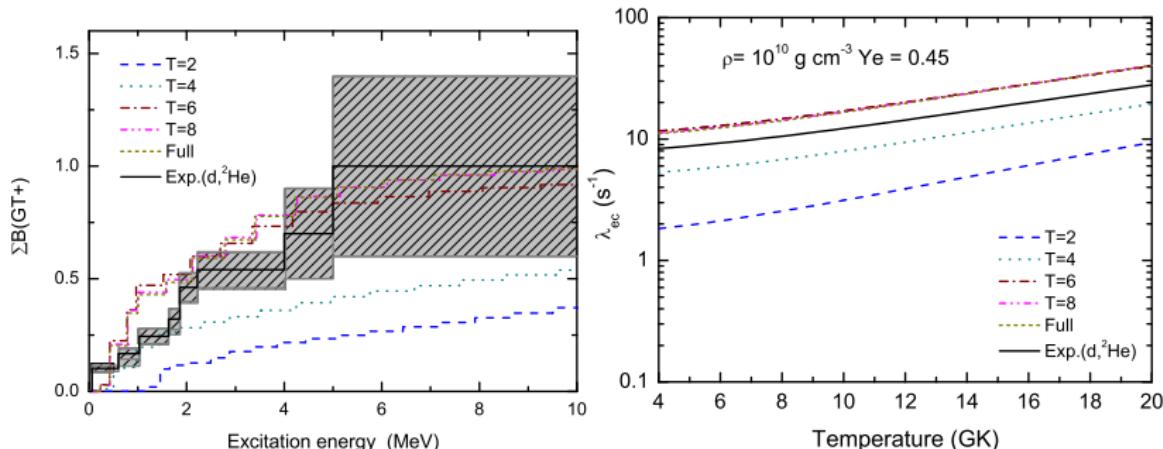
Kay *et al*, PRC **79**, 021301(R) (2009)



Occupation of $g_{9/2}$ orbital is larger than naive IPM estimates.

Correlations around N=40: GT+ strength for ^{76}Se

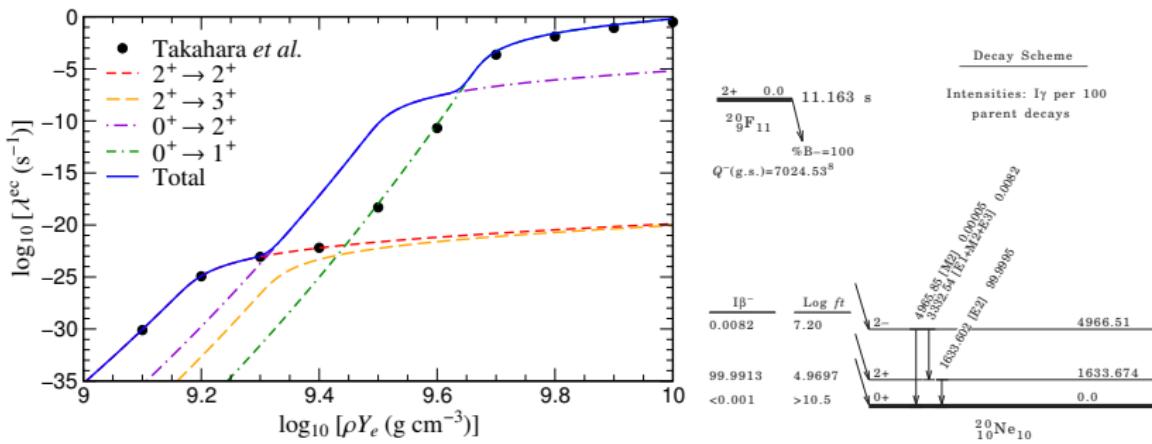
Gamow-Teller strength measured in charge-exchange reactions:
 $(d, {}^2\text{He})$: Grewe *et al.*, PRC **78**, 044301 (2008)



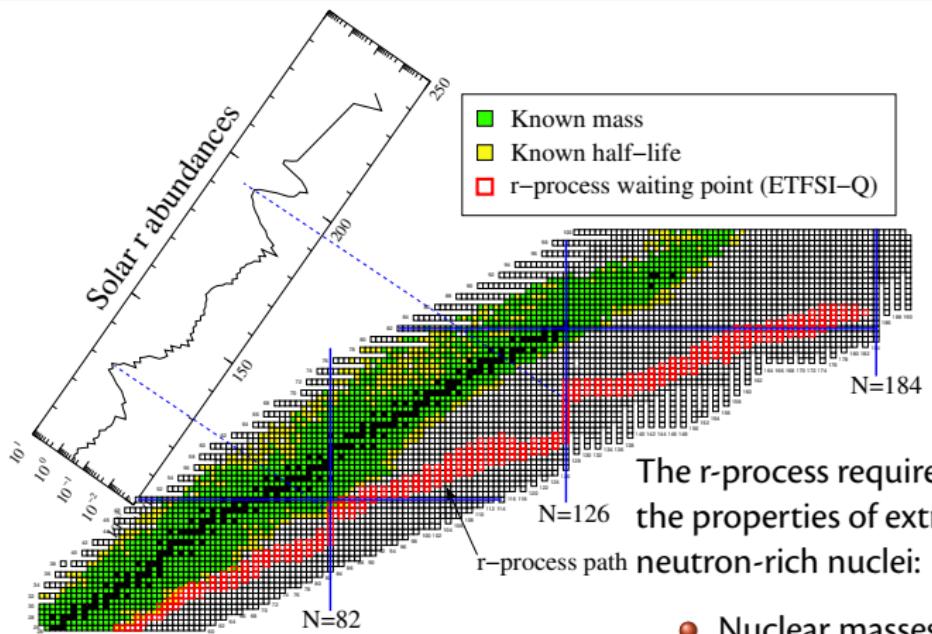
- Slow convergence of cross-shell correlations.
- Thermofield dynamics or finite temperature QRPA models, which consider only 2p-2h ($T=2$) correlations, do not suffice.
- What is the role of the $N = 40$ ($Z \lesssim 26$) island of inversion on electron capture rates?

Electron capture supernova

- Low mass stars ($\sim 9 M_{\odot}$) develop an ONeMg core during the evolution that becomes unstable due to electron captures.
- Particularly important is electron capture on ^{20}Ne . The rate is basically known experimentally except for an unknown second-forbidden ground-state ground-state transition.



Making Gold in Nature: r-process nucleosynthesis

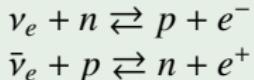


The r-process requires the knowledge of the properties of extremely neutron-rich nuclei:

- Nuclear masses.
- Beta-decay half-lives.
- Neutron capture rates.
- Fission rates and yields.

Neutrino-driven winds

Main processes:

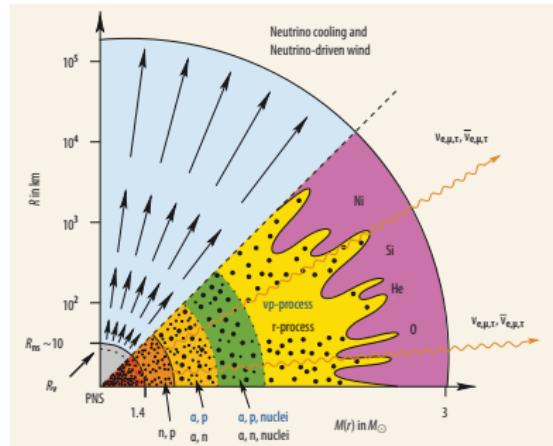


Neutrino interactions determine the proton to neutron ratio.

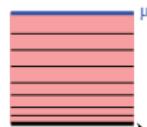
Neutron-rich ejecta:

$$\langle E_{\bar{\nu}_e} \rangle - \langle E_{\nu_e} \rangle > 4\Delta_{np} - \left[\frac{L_{\bar{\nu}_e}}{L_{\nu_e}} - 1 \right] \left[\langle E_{\bar{\nu}_e} \rangle - 2\Delta_{np} \right]$$

- Neutron-richness related to nuclear symmetry energy [GMP, Fischer, Lohs, Huther 2012; Roberts, Reddy, Shen 2012]

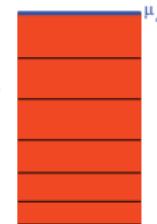
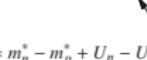


$$E_n = \frac{p_n^2}{2m_n^*} + m_n^* + U_n$$



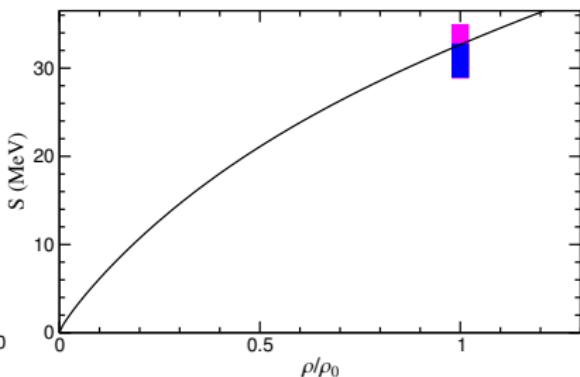
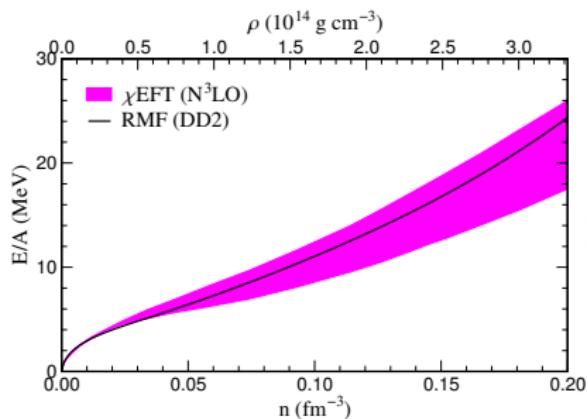
$$E_p = \frac{p_p^2}{2m_p^*} + m_p^* + U_p$$

$$Q = m_n^* - m_p^* + U_n - U_p$$



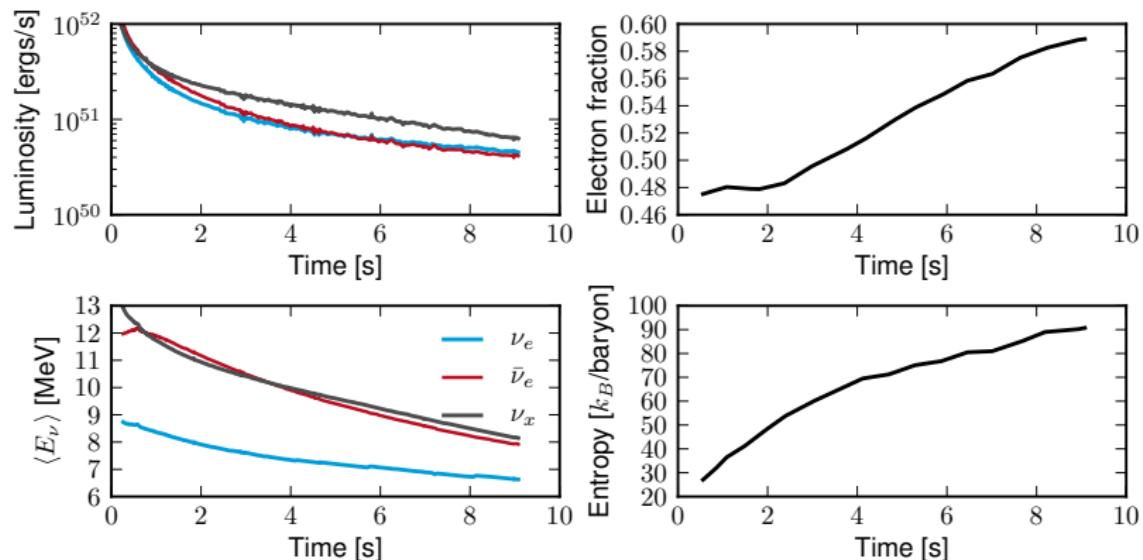
Constrains in the symmetry energy

- Energy per nucleon for neutron matter determined by χ EFT at $N^3\text{LO}$ order (Tews *et al* 2013, Krüger *et al* 2013).
- Symmetry energy constrained by χ EFT and nuclear physics experiments and astronomical observations (Lattimer & Lim 2013)



Impact on neutrino luminosities and Y_e evolution

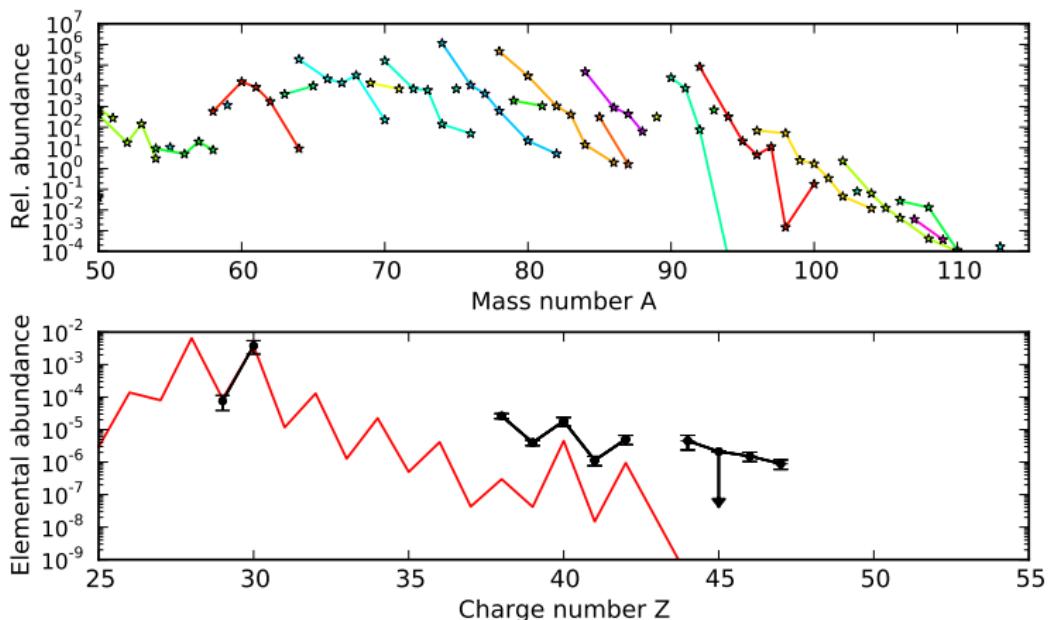
Boltzmann transport radiation simulations based on a $11.2 M_{\odot}$ progenitor.



Y_e is moderately neutron-rich at early times and later becomes proton-rich.

GMP, Fischer, Huther, arXiv:1309.5477

Nucleosynthesis



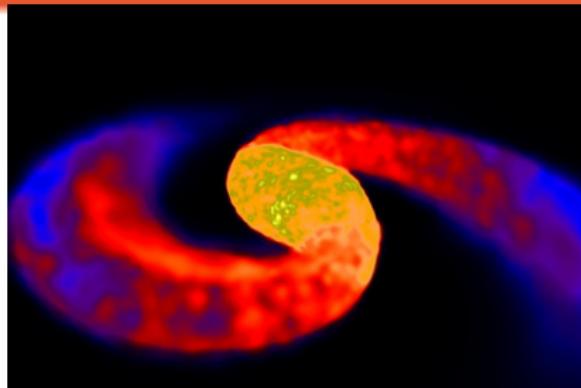
- Elements between Zn and Mo, including ^{92}Mo , are produced
- Mainly neutron-deficient isotopes are produced.
- No elements heavier than Mo ($Z = 42$) are produced.

r-process Astrophysical sites



Core-collapse supernova

- Neutrino-winds from protoneutron stars.
- Aspherical explosions, Jets, Magnetorotational Supernova, ...
[Winteler *et al*, ApJ **750**, L22 (2012)]



Neutron star mergers

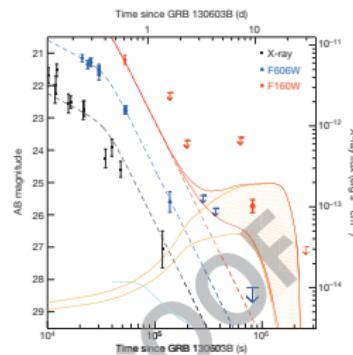
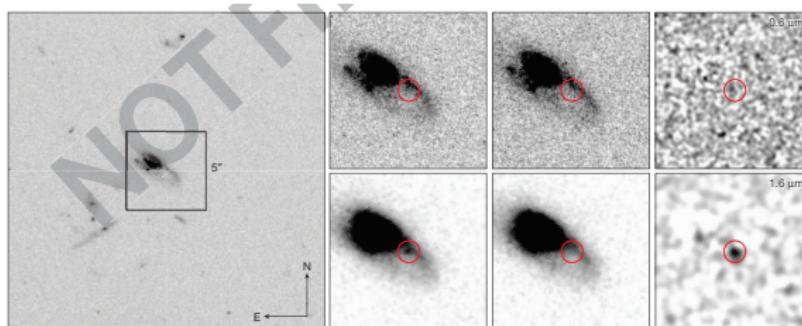
- Matter ejected ($\sim 0.01 M_{\odot}$) dynamically during merger.
- Electromagnetic emission from radioactive decay of r-process nuclei [KiloNova, Metzger, *et al*, MNRAS **406**, 2650 (2010)]
- Recent observational claim of an r-process kilonova associated with GRB 130603B

Kilonova Observation

LETTER

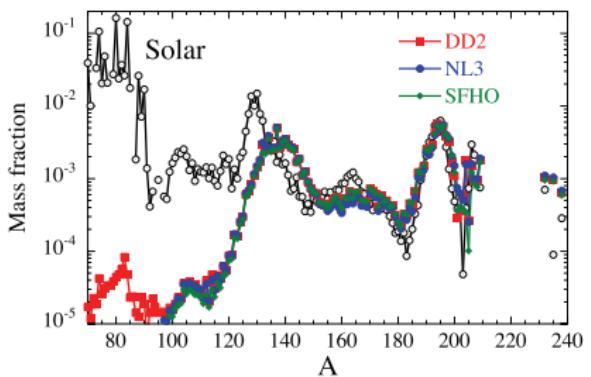
doi:10.1038/nature12505

A ‘kilonova’ associated with the short-duration γ-ray burst GRB 130603B

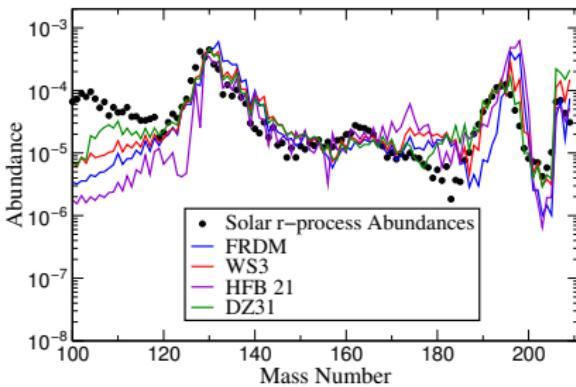
N. R. Tanvir¹, A. J. Levan², A. S. Fruchter³, J. Hjorth⁴, R. A. Hounsell³, K. Wiersema¹ & R. L. Tunnicliffe²

Direct observation of an r-process nucleosynthesis event?

Sensitive to nuclear physics input



Bauswein, Goriely, Janka, ApJ 773, 78 (2013)

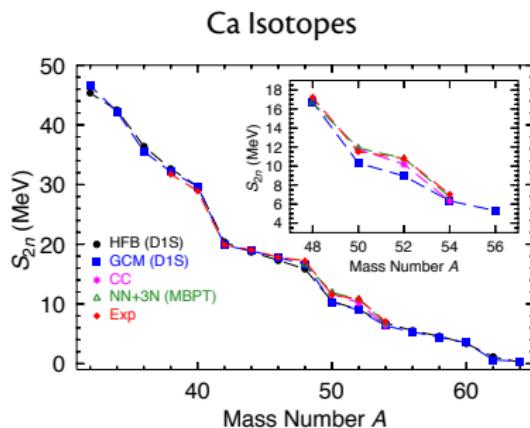


Joel Mendoza-Temis (PhD)

Strong sensitivity nuclear physics input: particularly masses and fission yields.

Beyond mean field calculations of nuclear masses

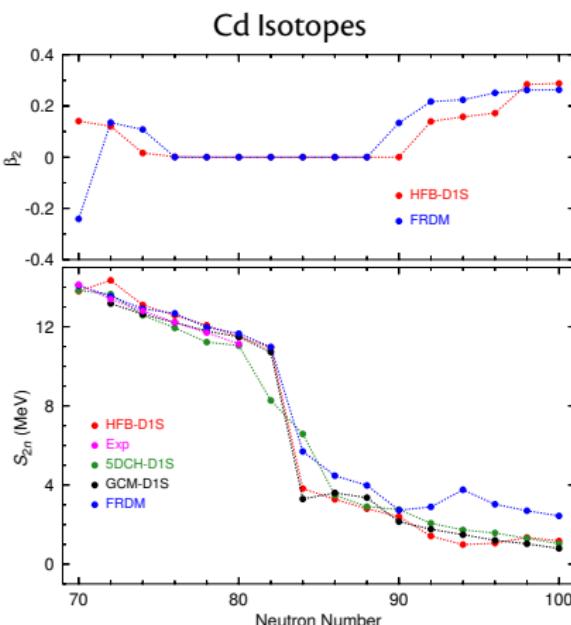
- All global mass models assume a static nuclear shape. Moreover, the HFB wave functions break particle number and angular momentum symmetries.
- These effects can be accounted using beyond mean field methods including particle and angular momentum projection and configuration mixing using the Generator Coordinate Method.
- Additionally these methods allow for a complete description of all low energy spectroscopic properties.

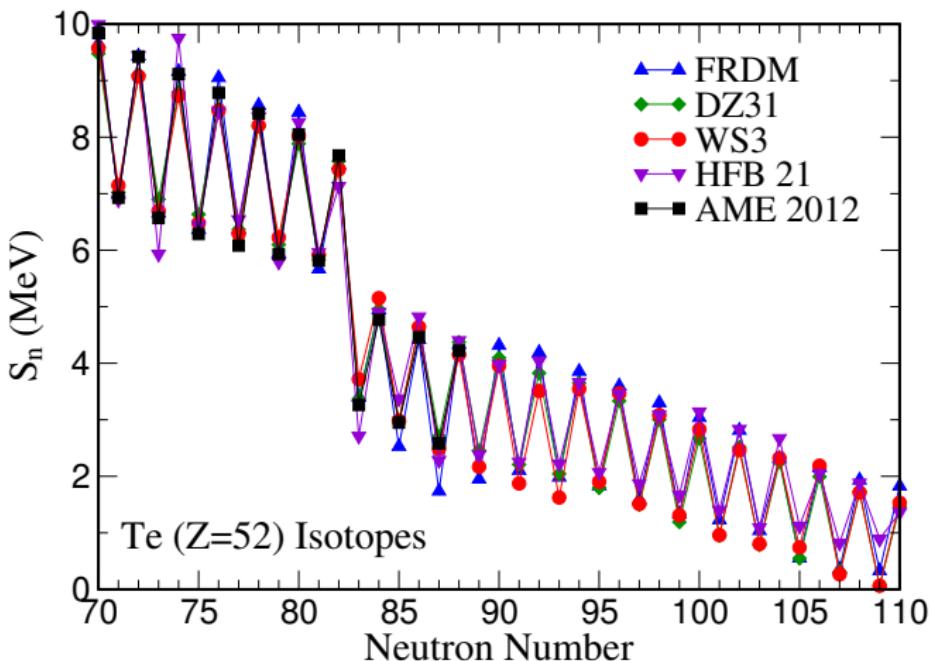


A. Akzhanov, T. Rodriguez, GMP, in preparation

Beyond mean field calculations of nuclear masses

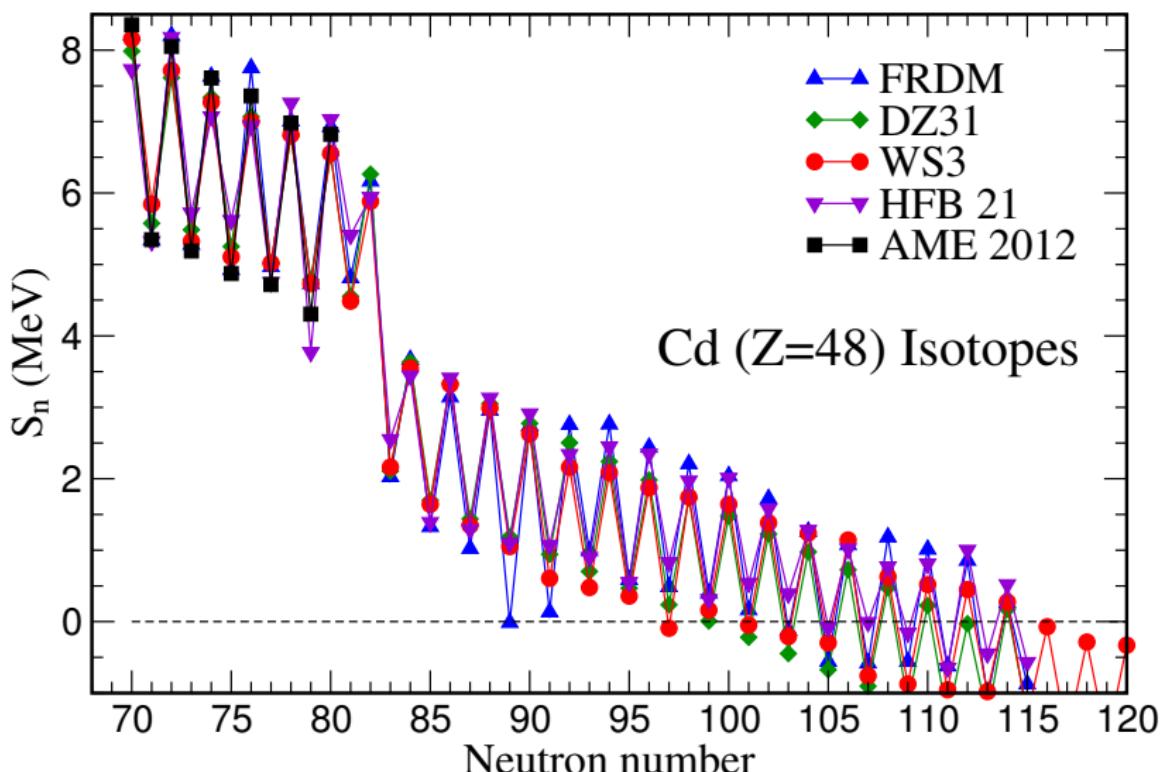
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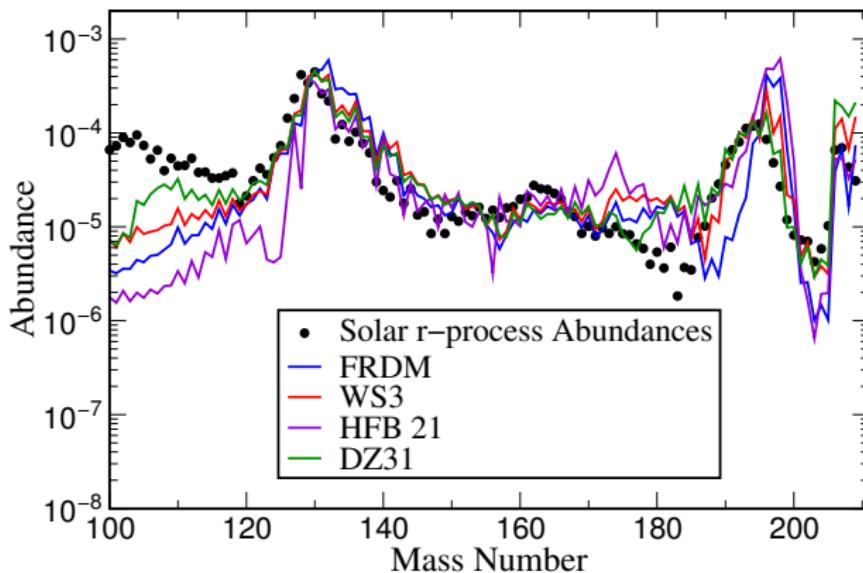
Role $N \sim 90$ nuclei (Te isotopes)

Experimental masses:

Hakala *et al*, PRL 109, 032501 (2012) (JYFLTRAP)Van Schelt, *et al*, PRC 85, 045805 (2012) (Canadian penning trap)

Role $N \sim 90$ nuclei (Cd isotopes)

Impact r-process abundances (NS Mergers)



- Masses around $N = 90$ determine the mass flow from second to third r-process peaks.

Summary

- Shell-model calculations of iron-group electron capture rates have been validated by charge-exchange data.
- New experimental evidence of collectivity around $N \sim 40$ can potentially influence electron capture rates.
- Neutrino-winds simulations based on an EoS that is consistent with constraints on the symmetry energy produce elements between Zn and Mo, including ^{92}Mo . No heavier elements are produced.
- Heavier r-process elements can be produced in neutron-star mergers.
- Beyond mean field models can provide an accurate description of nuclear masses for r-process nucleosynthesis.
- The collectivity of nuclei with $Z \lesssim 50$ and $N \sim 90$ has a strong impact in r-process nucleosynthesis.