Exotic Nuclei in supernova evolution and r-process nucleosynthesis

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TECHNISCHE
UNIVERSITÄT
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für Bildung
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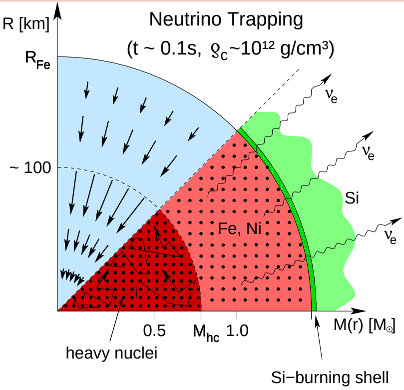
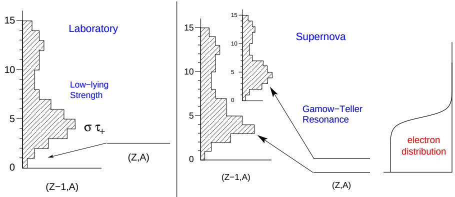
Outline

Weak interactions during collapse

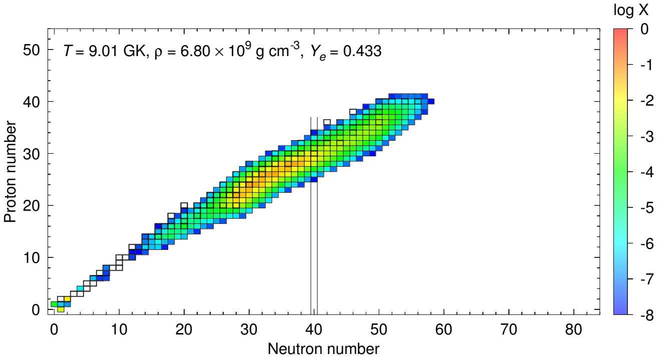


- Composition of Iron group and heavier nuclei
- Dominanting process, electron capture on nuclei: $e^- + A(Z,N) \rightleftarrows A(Z-1,N+1) + \nu_e$
- Dominated by Gamow-Teller transitions.
- Evolution decreases the number of electrons (Y_e) and Chandrashekhar mass ($M_{\mathrm{ch}} = 1.4(2Y_e)^2\ M_\odot$)



Early composition

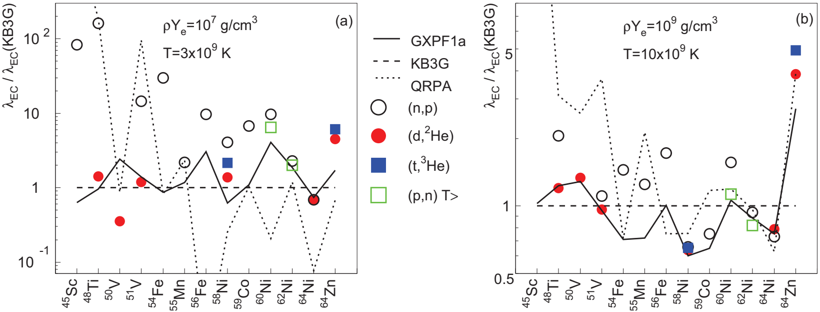
Initially the composition is mainly given by Iron group nuclei.



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

Systematic study measured GT strengths

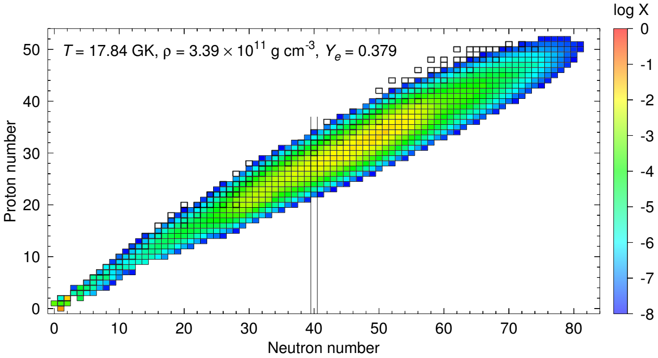
A. L. Cole *et al.*, PRC **86**, 015809 (2012)



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

Late time composition

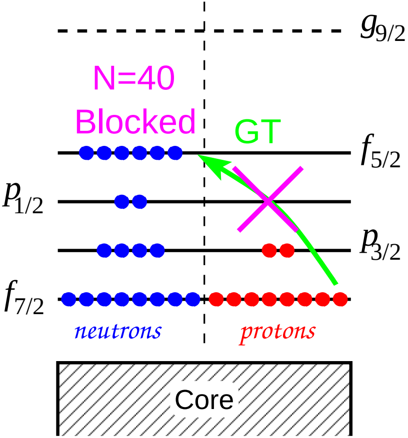
With decreasing Y_e the composition moves to more neutron rich nuclei.



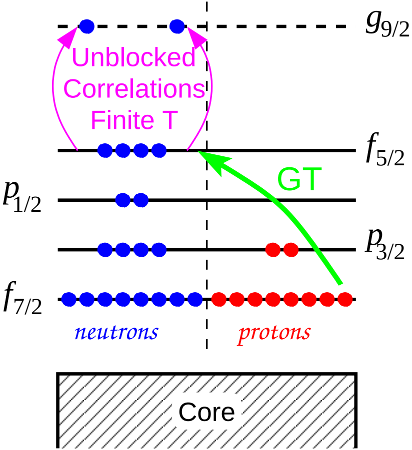
GMP, M. Liebendörfer, D. Frekers, NPA **777**, 395 (2006).

Challenge: electron capture beyond N=40

Independent particle treatment



Fuller, ApJ **252**, 741 (1982)



Langanke & GMP, RMP **75**, 819 (2003)

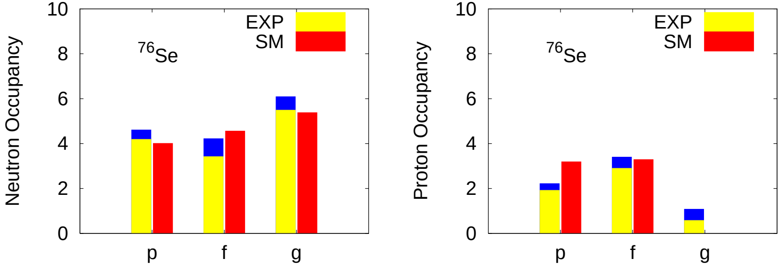
Correlations around N=40: GT+ strength for ^{76}Se

The structure of ^{76}Se ($Z = 34, N = 42$) has been the subject of several 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)

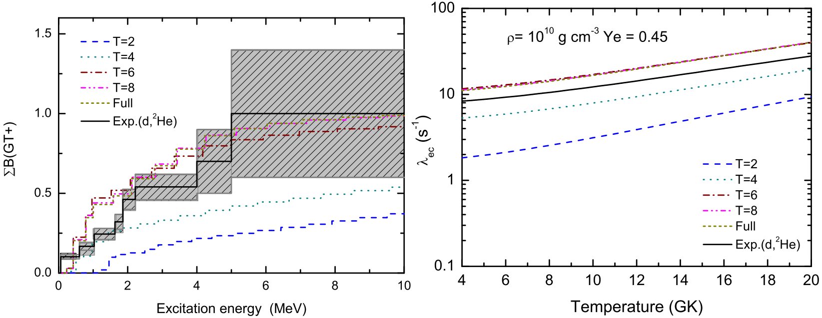
Kay *et al*, PRC **79**, 021301(R) (2009)



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:
$(d, {}^2\mathrm{He})$: Grewe *et al.*, PRC **78**, 044301 (2008)

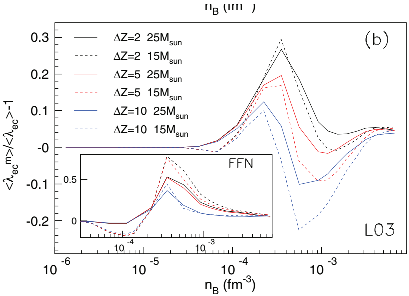


- Slow convergence of cross-shell correlations.
- Thermofield dynamics or finite temperature QRPA models, which consider only 2p-2h (T=2) correlations, do not suffice.
- What is the role of the $N = 40$ ($Z \lesssim 26$) island of inversion on electron capture rates?

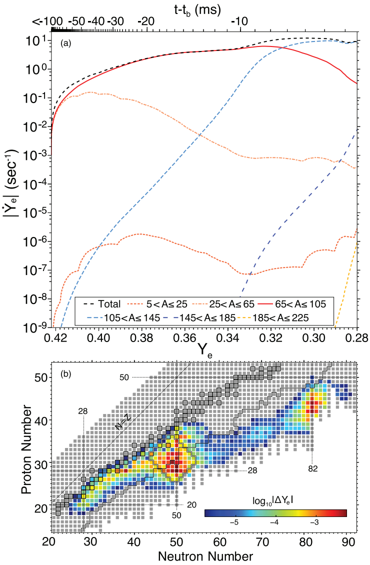
Zhi, Langanke, GMP, Nowacki, Sieja, NPA **859**, 172 (2011)

Most important nuclei

- Most relevant nuclei are those around $N = 50$.
- Shell closure enhances the abundances.
- Results are sensitive to assumptions about shell closure far from stability.

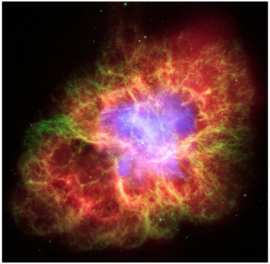


Raduta, *et al*, PRC **93**, 025803 (2016)



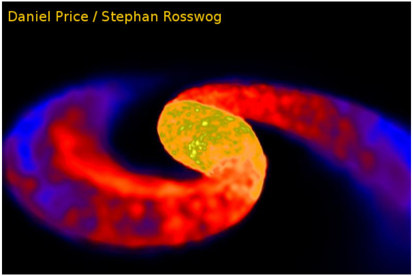
Sullivan *et al*, ApJ **816**, 44 (2015).

r-process astrophysical sites



Core-collapse supernova

- Neutrino-winds from protoneutron stars.
- Aspherical explosions, Jets, Magnetorotational Supernova, … [Winteler *et al*, ApJ **750**, L22 (2012); Mösta *et al*, arXiv:1403.1230]

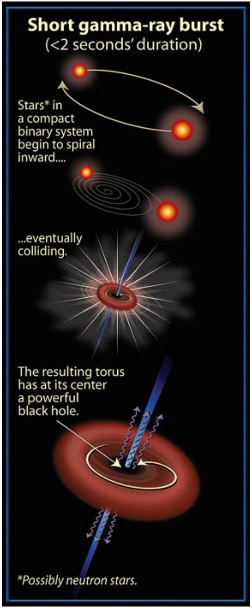


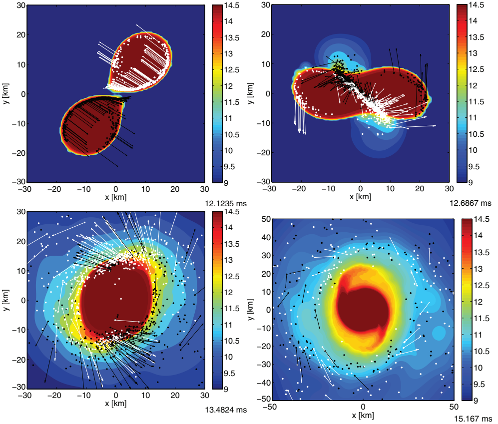
Daniel Price / Stephan Rosswog

Neutron star mergers

- Mergers are expected to eject around $0.01\ M_\odot$ of neutron rich-material. Similar amount ejected from accretion disk.
- Observational signature: electromagnetic transient from radioactive decay of r-process nuclei [KiloNova, Metzger *et al* (2010), Roberts *et al* (2011), Bauswein *et al* (2013)]

Neutron star mergers: Short gamma-ray bursts and r-process

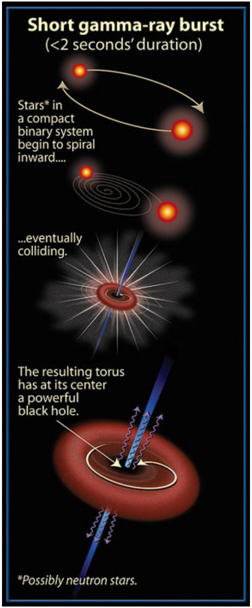


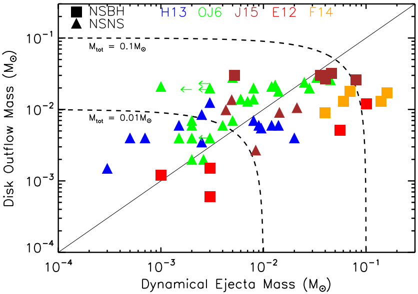


Bauswein, Goriely, Janka, ApJ 773, 78 (2013)

- Mergers are expected to eject dynamically around 0.001-0.01 $M_\odot$ of neutron rich-material. Impact of weak interactions remains to be understood.

Neutron star mergers: Short gamma-ray bursts and r-process





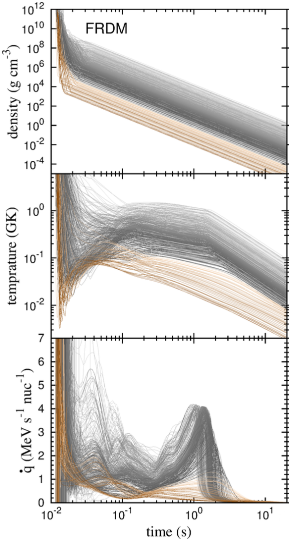
Fernández & Metzger, 2016

- A similar amount of material less neutron rich $Y_e \gtrsim 0.2$ is expected to be ejected from the disk. Conditions and ejection mechanism depend on central object (neutron star or black hole).
- Both dynamical and disk ejecta contribute to nucleosynthesis and radioactive electromagnetic transient (kilonova).

Evolution nucleosynthesis in mergers

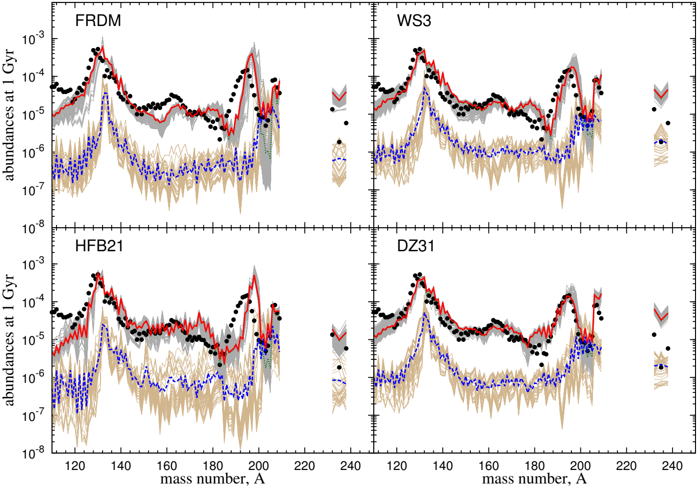
- r-process stars once electron fermi energy drops below $\sim 10\ \mathrm{MeV}$ to allow for beta-decays ($\rho \sim 10^{11}\ \mathrm{g\ cm}^{-3}$).
- Important role of nuclear energy production (mainly beta decay).
- Energy production increases temperature to values that allow for an $(n,\gamma) \rightleftarrows (\gamma,n)$ equilibrium for most of the trajectories.
- Systematic uncertainties due to variations of astrophysical conditions and nuclear input

528 trajectories



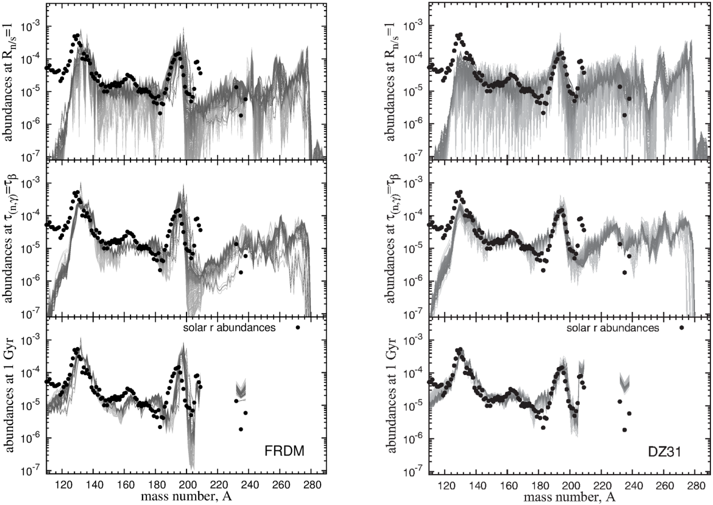
Mendoza-Temis, Wu, Langanke, GMP, Bauswein, Janka, PRC **92**, 055805 (2015)

Final abundances different mass models



Mendoza-Temis, Wu, Langanke, GMP, Bauswein, Janka,
PRC **92**, 055805 (2015)

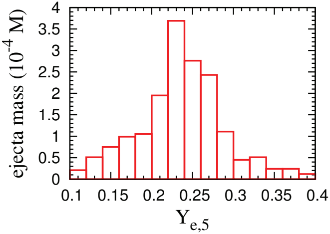
Temporal evolution (selected phases)

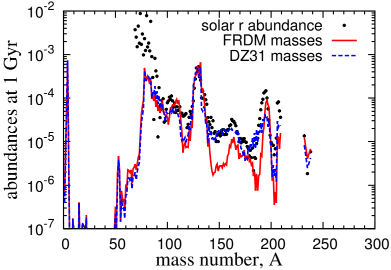


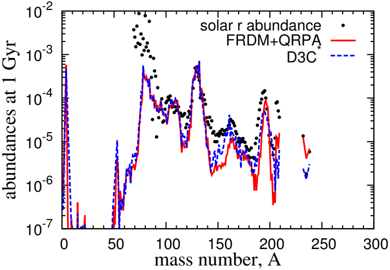
- Abundances around 130 mainly determined by fission from material accumulated in superheavy region.
- Third peak ($A \sim 195$) sensitive to masses and beta-decay half-lives.

Nucleosynthesis in black-hole accretion disk ejecta

- Accretion disk around compact object is expected to eject material with broad Y_e distribution [Fernández, Metzger, MNRAS 435, 502 (2013)]
- This material is expected to contribute to the production of all r-process nuclides [Wu *et al*, MNRAS 463, 2323 (2016)]

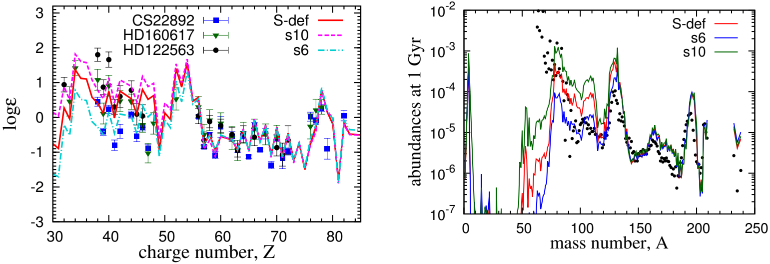






Comparison with metal poor stars

Except for elements around $Z \sim 40$ ($A \sim 90$) disk ejecta produce all r-process nuclides.

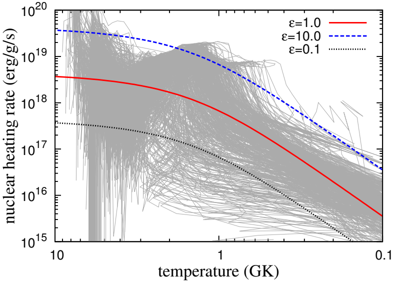


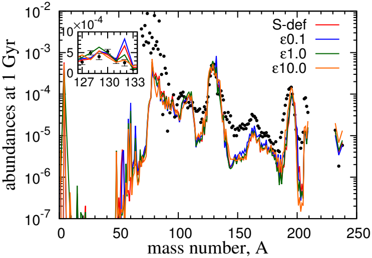
Heavy r-process shows robust abundance pattern

Wu *et al*, MNRAS 463, 2323 (2016)

Effect r-process heating

- Some of the models shows anomalous abundance peak at ^{132}Sn due to convection in the disk. Material is partly reheated after neutron exhaustion.
- Nuclear energy production by the r process suppresses the last reheating phase.

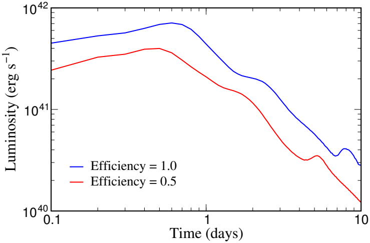


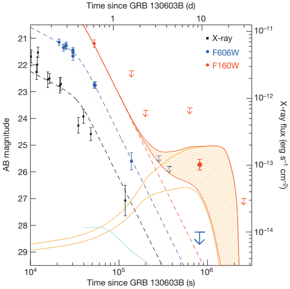


Observing the r process in mergers

- Large amount of ejected radioactive r-process material can produce an electromagnetic transient [Li & Paczyński 1998]
- “Kilonova” transient: Typical luminosities 1000 times those of a Nova.
- Large opacities of Lanthanides delay the peak to timescales of a week (Kasen *et al*, 2013).
- Probably observed in GRB 130603B.

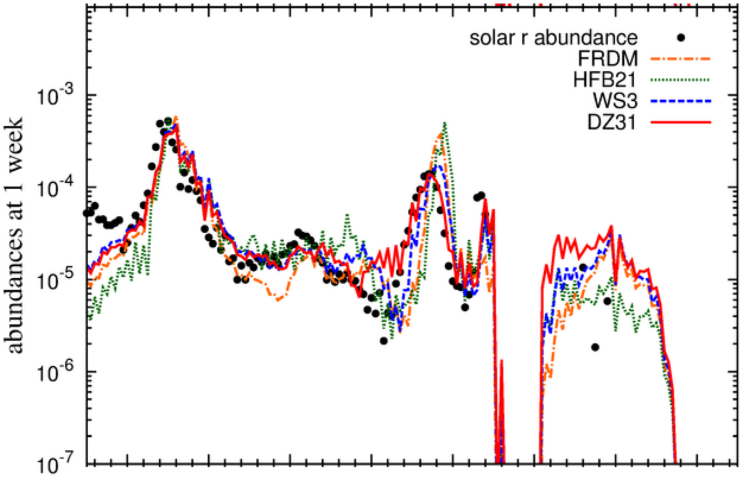
Metzger, GMP, Darbha, Quataert, Arcones *et al*, MNRAS **406**, 2650 (2010)





Tanvir et al, Nature **500**, 457 (2013)

Actinides affect opacities and energy production



Actinides can be an important opacity source at timescales of weeks.

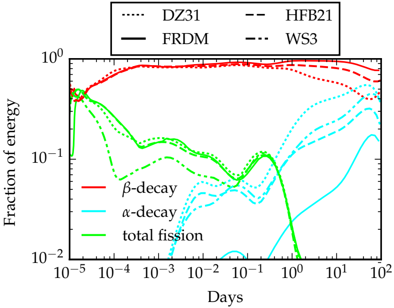
Mendoza-Temis, Wu, Langanke, GMP, Bauswein, Janka, PRC **92**, 055805 (2015)

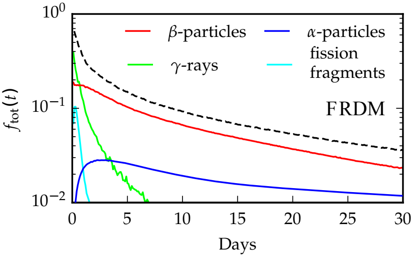
Electromagnetic transient (Kilonova)

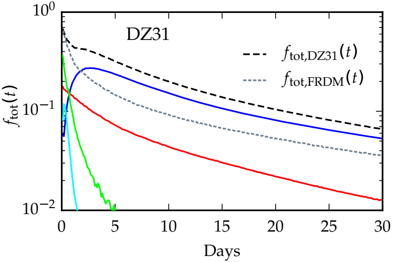
Kinolova models must address:

- Total amount of radioactive energy released ($\dot{q} \sim t^{-\alpha}$, $\alpha = 1.1$–1.4)
- Dominating decay channels at different phases
- Efficiency of decay products thermalization

Important differences abudances α-decaying nuclei between Pb and U.



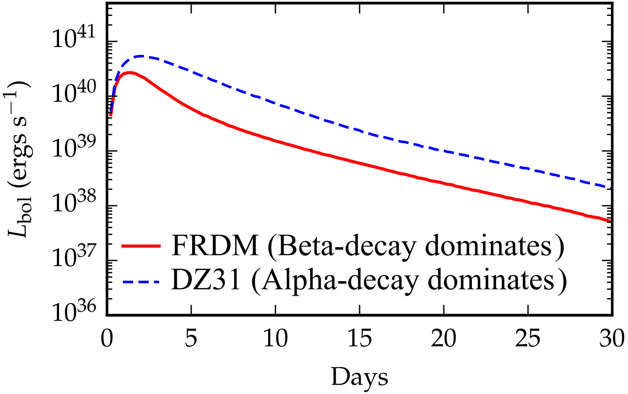




Barnes, Kasen, Wu, GMP, arXiv:1605.07218, ApJ in press

Kilonova light curve

Light curve contains nuclear physics signatures.



Ratio of luminosities at peak value and at late times can be used to constrain the produced amount of nuclei between Pb and U.

Barnes, Kasen, Wu, GMP, arXiv:1605.07218, ApJ in press

Summary

- Experimental evidence of collectivity beyond $N \sim 40$ can potentially influence electron capture rates.
- Heavier r-process elements can be produced in neutron-star mergers.
- Fission plays a fundamental role in determining the final abundance pattern in dynamical ejecta.
- Ejecta from black-hole accretion produce all r process elements independently of the contribution from dynamical ejecta. Role of nuclear physics remains to be explored.
- Kilonova observations will provide a direct proof that the r process occurs in mergers.

Hirschegg 2017

Neutron star mergers:
From gravitational waves to nucleosynthesis

International Workshop XLV on
Gross Properties of Nuclei and Nuclear Excitations
Darmstädter Haus, Hirschegg, Kleinwalsertal, Austria

January 15-21, 2017

Topics:

- ★ Observations of gravitational waves and electromagnetic signals
- ★ Simulations of compact object mergers and their neutrino-driven winds
- ★ Chemical evolution and nucleosynthesis
- ★ Nuclear physics of the r-process: masses, lifetimes, fission
- ★ Neutron stars from crust to core and equation of state
- ★ Neutrino-matter interactions and oscillation phenomena

Organizers:
A. Arcones, H. Feldmeier, G. Martínez-Pinedo,
T. Neff (coordinator), R. Roth, A. Schwenk

Program advisors:
A. Frebel (Cambridge), K. Langanke (Darmstadt), G. McLaughlin (Raleigh),
C. Pethick (Copenhagen), L. Rezzolla (Frankfurt), H. Sakurai (Tokyo),
F.-K. Thielemann (Basel), J. Wambach (Trento)

Invited speakers:
T. Aumann (Darmstadt), J. Barnes (Berkeley), K. Blaum (Heidelberg), N. Chamel (Brussels), J. Engel* (Chapel Hill), A. Frebel* (Cambridge), P. Freire (Bonn), C. Hansen (Copenhagen), K. Hebeler (Darmstadt), T. Janka* (Garching), J. Lattimer (Stony Brook), F. Matteucci* (Trieste), G. McLaughlin (Raleigh), S. Nishimura (Wako), T. Piran (Jerusalem), B. Sathyaprakash (Cardiff), S. Reddy (Seattle), L. Rezzolla (Frankfurt), S. Rosswog (Stockholm), R. Surman (South Bend), S. Typel (Darmstadt), M.-R. Wu (Darmstadt)

* to be confirmed

Further information:
http://theory.gsi.de/hirschegg/2017/
Registration deadline: November 30, 2016