Explosive nucleosynthesis of heavy elements:

an astrophysical and nuclear physics challenge

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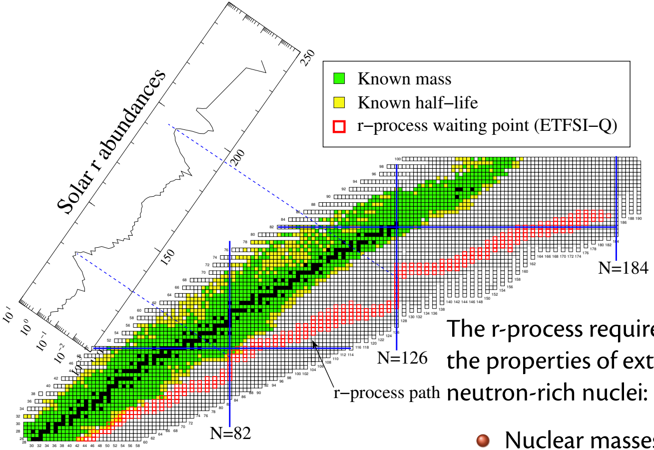
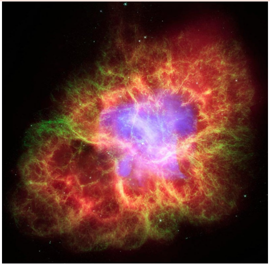
Making Gold in Nature: r-process nucleosynthesis



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

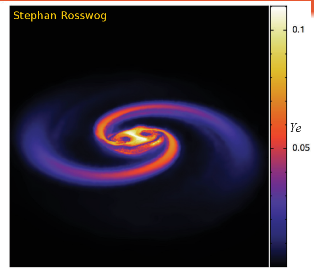
- Nuclear masses.
- Beta-decay half-lives.
- Neutron capture rates.
- Fission rates and yields.

r-process astrophysical sites



Core-collapse supernova

- Explosion of massive stars ($M \gtrsim 9$ M$_\odot$)
- Neutrino-winds from protoneutron stars. Strong sensitivity to neutrino interactions at subnuclear densities [GMP+, PRL 109, 251104 (2012)]
- Only intermediate mass elements are produced ($A \lesssim 100$) [GMP+, JPG 41, 044008 (2014)]

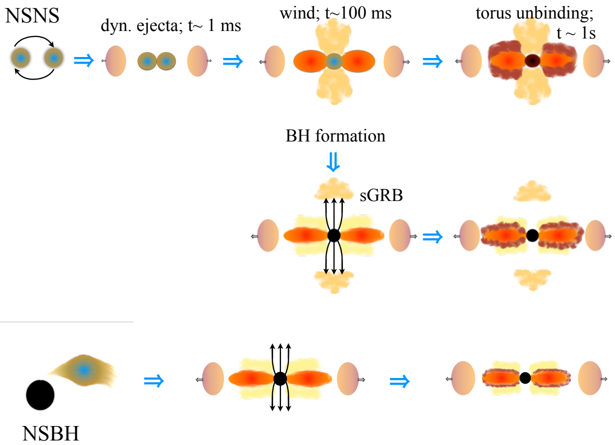


Neutron star mergers

- Mergers eject around 0.01 M$_\odot$ of very neutron rich-material ($Y_e \sim 0.01$). Similar amount of less neutron-rich matter ($Y_e \gtrsim 0.2$) ejected from accretion disk.
- Low frequency, high yield: consistent with astronomical observations.
- Observational signature: electromagnetic transient from radioactive decay of r-process nuclei

Merger channels and ejection mechanism

In mergers we deal with a variety of initial configurations (netron-star neutron-star vs neutron-star black-hole) with additional variations in the mass-ratio. The evolution after the merger also allows for further variations.

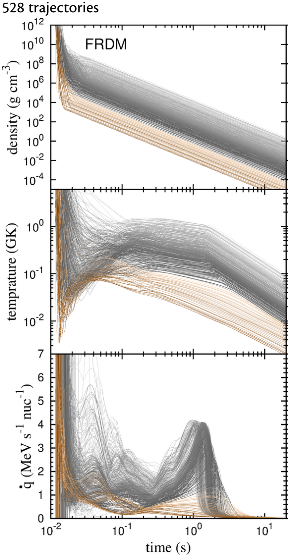


Rosswog, *et al*, Class. Quantum Gravity **34**, 104001 (2017)

Evolution nucleosynthesis in mergers

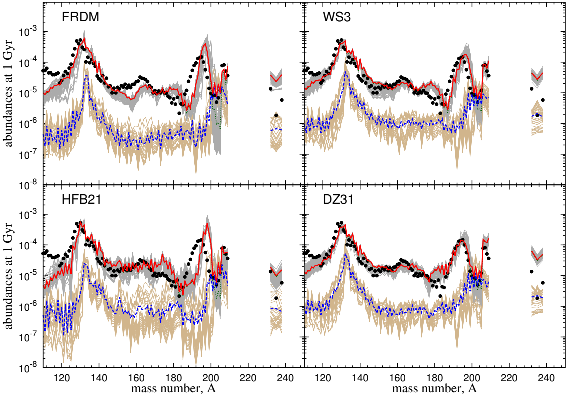
- r-process stars once electron fermi energy drops below ~ 10 MeV to allow for beta-decays ($\rho \sim 10^{11}$ g cm^{-3}).
- Important role of nuclear energy production (mainly beta decay).
- Energy production increases temperature to values that allow for an $(n,\gamma) \rightleftarrows (\gamma,n)$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

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



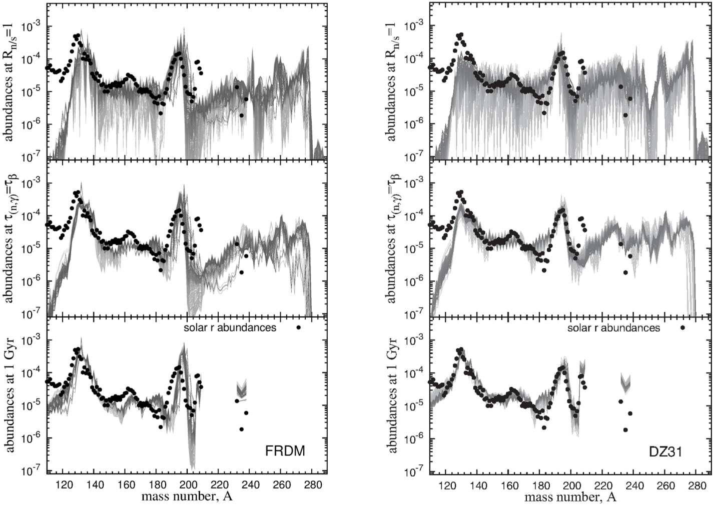
Final abundances different mass models

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



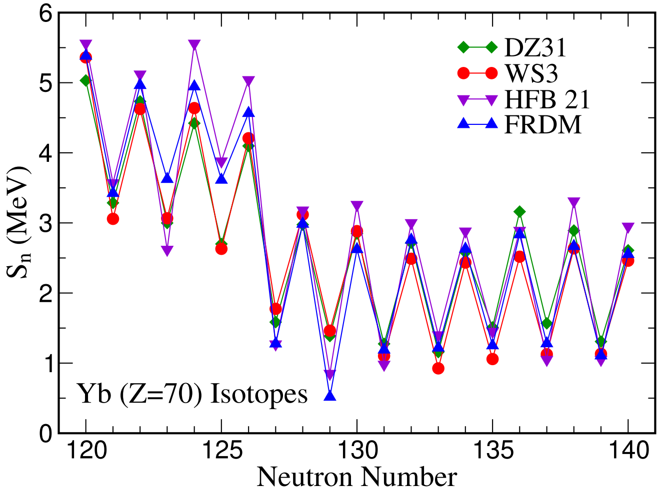
- Robustness astrophysical conditions, strong sensitivity to nuclear physics
- Second peak ($A \sim 130$) sensitive to fission yields.
- Third peak ($A \sim 195$) sensitive to masses (neutron captures) and beta-decay half-lives.
- Elements lighter than ($A \sim 120$) are not produced. Possible contribution of the ejecta from accretion disks.

Temporal evolution (selected phases)



Fission is fundamental to determine the final r-process abundances.

The role of $N \sim 130$

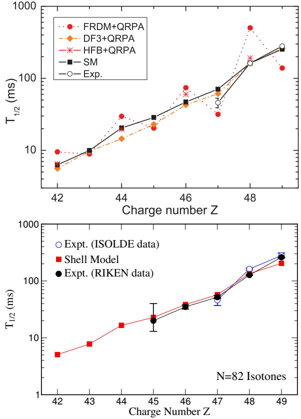


Both FRDM and HFB models predict a sudden drop in neutron separation energies approaching $N \sim 130$ for $Z \sim 70$ (shape coexistence region).

Global beta-decay calculations

- Beta-decay rates determine the speed of matter flow from light to heavy nuclei.
- r-process path determined by neutron separation energies
- nuclei with largest impact are those with larger instantaneous half-lives.
- Despite tremendous progress at RIB facilities (RIBF at RIKEN) most of the half-lives are based on theoretical calculations.

Zhi et al, PRC **87**, 024803 (2013)



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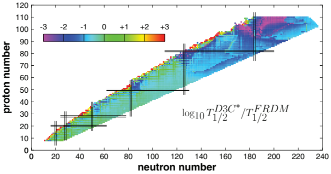
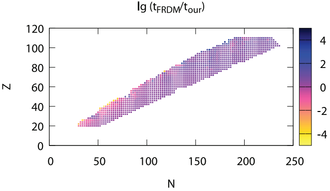
- Two microscopic calculations (GT+FF) have become available:
    - Covariant density functional theory + QRPA (Marketin+ 2016)
    - Skyrme finite-amplitude method (Mustonen & Engel 2016)

Marketin, Huther, GMP, PRC **93**, 025805 (2016)

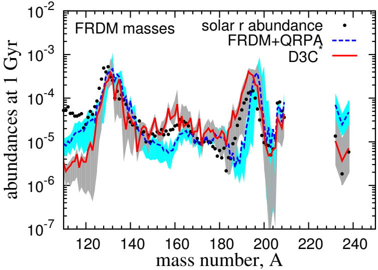


Mustonen & Engel, PRC **93**, 014304 (2016)



Impact on r-process abundances

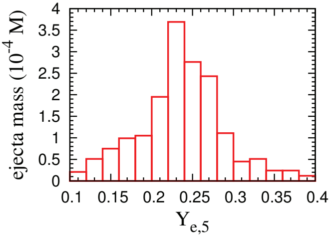
Shorter half-lives for $Z \gtrsim 80$ have a strong impact on the position of $A \sim 195$ (Eichler+ 2015).

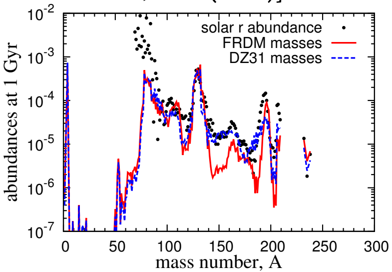


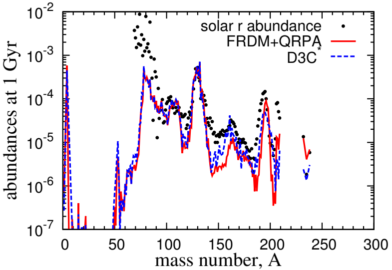
They also affect the robustness of the distribution, the shape of the 2nd peak and the amount of actinides
(Wu+, in preparation)

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)]

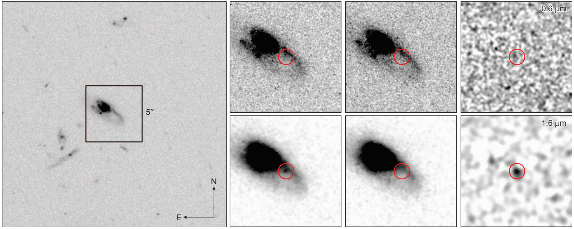


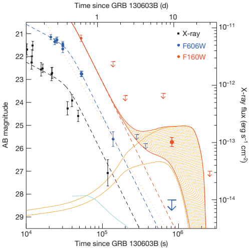




Kilonova/Macronova electromagnetic transient

- Electromagnetic transitent from radioactive decay r-process ejecta [Li & Paczyński 1998]
- Luminosities ~ 1000 times those of a nova [Metzger *et al*, 2010]
- Large optical opacities of Lanthanides delay the peak to timescales of a week in the red/infrared [Kasen *et al*, 2013]
- Probably observed associated to GRB 130603B

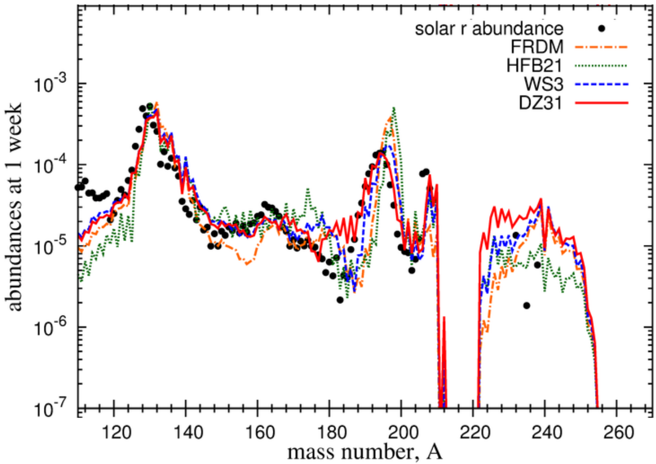




First direct observation of an r-process event?

Tanvir+, Nature **500**, 457 (2013)

Actinides affect opacities and energy production

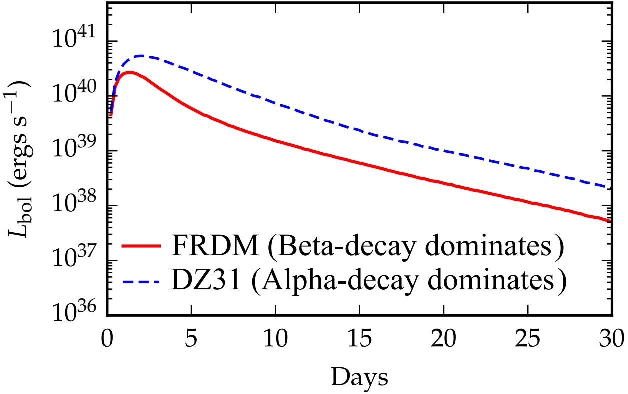


- Actinides can be an important opacity source at timescales of weeks.
- They can substantially contribute to energy production via alpha decay.

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

Impact on the light curve

Light curve contains nuclear physics signatures that impact the luminosity up to a factor 10.



Fundamental to determine the amount of material ejected in a merger.

Barnes, Kasen, Wu, GMP, ApJ **829**, 110 (2016); Rosswog et al, CQG **34**, 104001 (2017)

Summary

- Neutron star mergers most likely constitute the main r process site.
- The combination of dynamical ejecta and disk outflow ejecta can account for the solar system r-process abundances.
- Dynamical ejecta of neutron star mergers produce a robust r-process abundance pattern mainly determined by the fission yields of superheavy nuclei. Role of weak interaction on Y_e needs to be clarified.
- Ejecta from black hole accretion disks produce all r-process nuclides in all models considered.
- Nuclear physics is fundamental for abundance predictions and electromagnetic transient modeling.
- Transient detection provides a direct confirmation that r process occurs in mergers. Likely observed in GRB 130603B.