Explosive nucleosynthesis of heavy elements

An astrophysical and nuclear physics challenge

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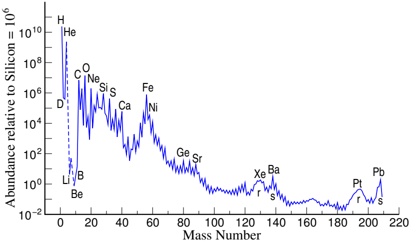
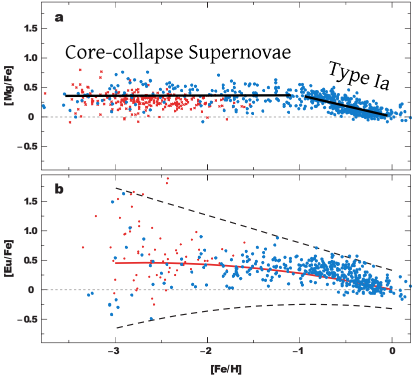
Outline

Signatures and nucleosynthesis processes

- Solar system abudances contain signatures of nuclear structure and nuclear stability.
- They are the result of different nucleosynthesis processes operating in different astrophysical environments and the chemical evolution of the galaxy.

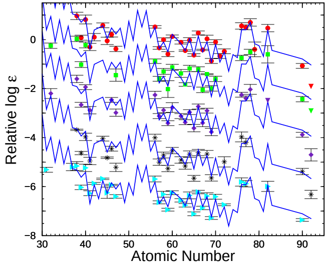


Sneden, Cowan & Gallino 2008



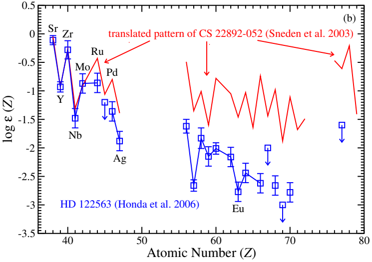
Heavy elements and metal-poor stars

Cowan & Sneden, Nature **440**, 1151 (2006)



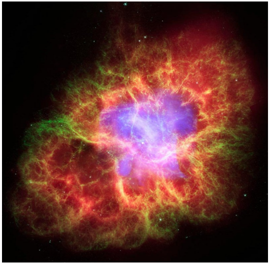
- Stars rich in heavy r-process elements ($Z > 50$) and poor in iron (r-II stars, $[\mathrm{Eu/Fe}] > 1.0$).
- Robust abundance patter for $Z > 50$, consistent with solar r-process abundance.
- These abundances seem the result of events that do not produce iron. [Qian & Wasserburg, Phys. Rept. **442**, 237 (2007)]
- Possible Astrophysical Scenario: Neutron star mergers.

- Stars poor in heavy r-process elements but with large abundances of light r-process elements (Sr, Y, Zr)
- Production of light and heavy r-process elements is decoupled.
- Astrophysical scenario: neutrino-driven winds from core-collapse supernova



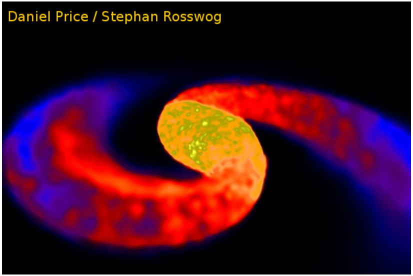
Honda *et al*, ApJ **643**, 1180 (2006)

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]



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)]

Role of weak interactions

Main processes:

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

Neutrino interactions determine the proton to neutron ratio.

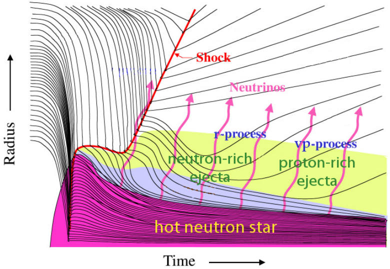
Neutron-rich ejecta:

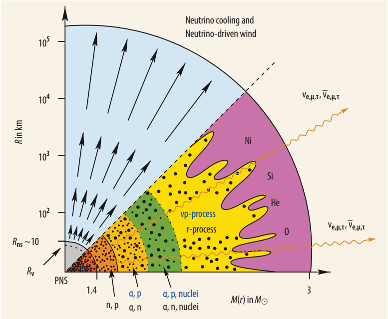
$$\langle E_{\bar{\nu}_e} \rangle - \langle E_{\nu_e} \rangle > 4\Delta_{np} - \left[\frac{L_{\bar{\nu}_e}}{L_{\nu_e}} - 1 \right] \left[\langle E_{\bar{\nu}_e} \rangle - 2\Delta_{np} \right]$$

- neutron-rich ejecta: r-process
- proton-rich ejecta: νp-process

We need accurate knowledge of ν_e and $\bar{\nu}_e$ spectra

Energy difference related to nuclear symmetry energy (GMP *et al* 2012, Roberts *et al* 2012)





Constraints in the symmetry energy

- Combination nuclear physics experiments and astronomical observations (Lattimer & Lim 2013)
- Isobaric Analog States (Danielewicz & Lee 2013)
- Chiral Effective Field Theory calculations (Drischler+ 2014)

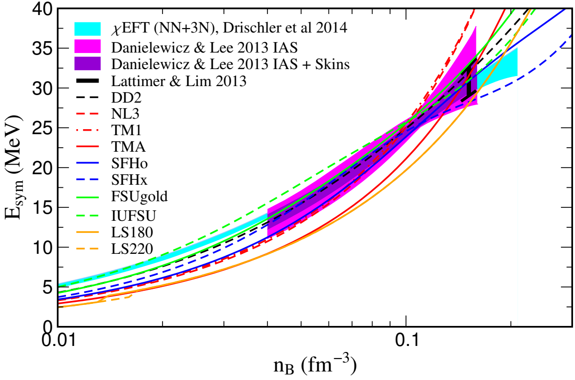
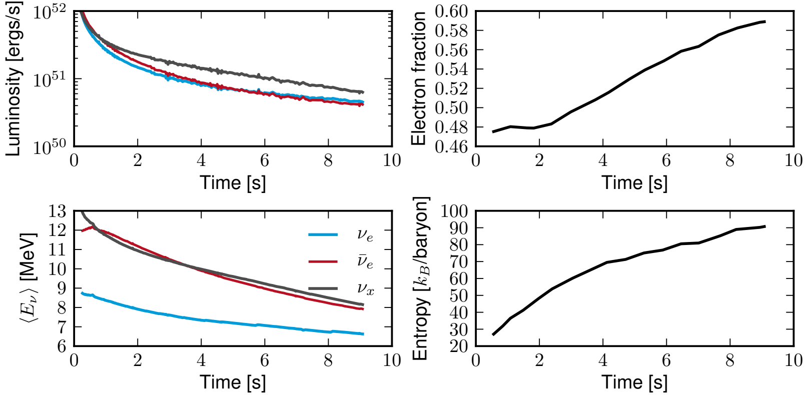


Figure data from Matthias Hempel (Basel)

Impact on neutrino luminosities and Y_e evolution

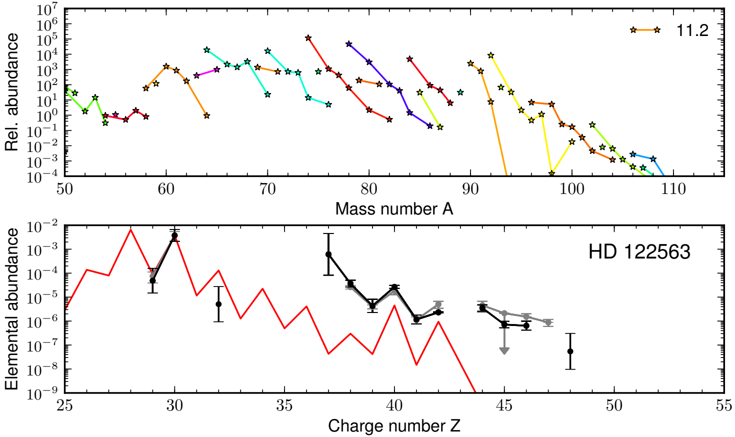
1D Boltzmann transport radiation simulations (artificially induced explosion) for a 11.2 $M_\odot$ progenitor based on the DD2 EoS (Stefan Typel and Matthias Hempel).



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

GMP, Fischer, Huther, J. Phys. G **41**, 044008 (2014).

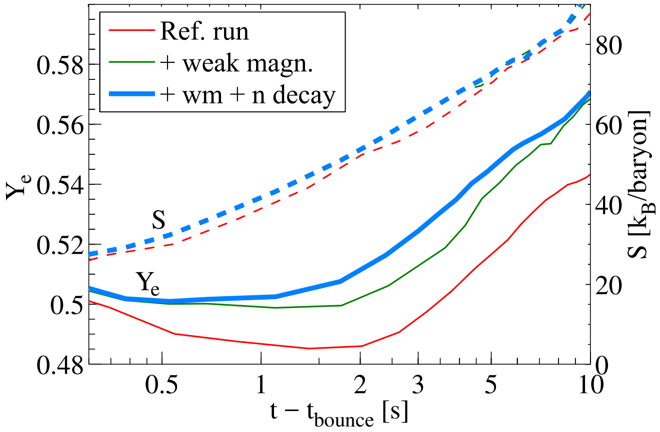
Nucleosynthesis



- Elements between Zn and Mo ($A \sim 90$) are produced
- Mainly neutron-deficient isotopes are produced
- Uncertainties: Equation of State, neutrino reactions (mainly $\bar{\nu}_e$), Neutrino oscillations(?).

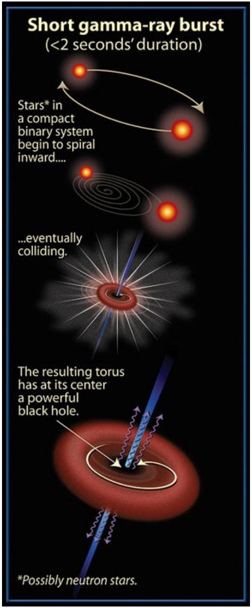
Impact opacities on Y_e

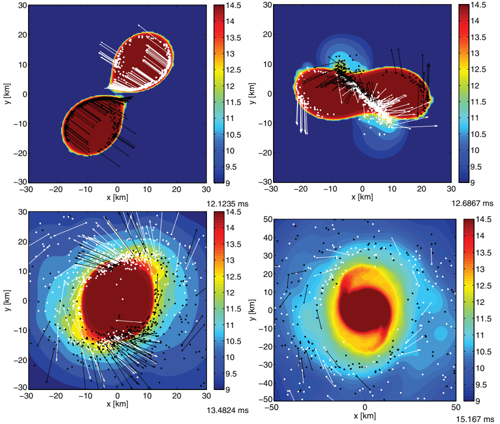
Weak magnetism and inverse neutron decay ($\bar{\nu}_e + e^- + p \rightarrow n$) have a strong impact on Y_e



Fischer, GMP, Wu, Lohs, Qian, in preparation

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

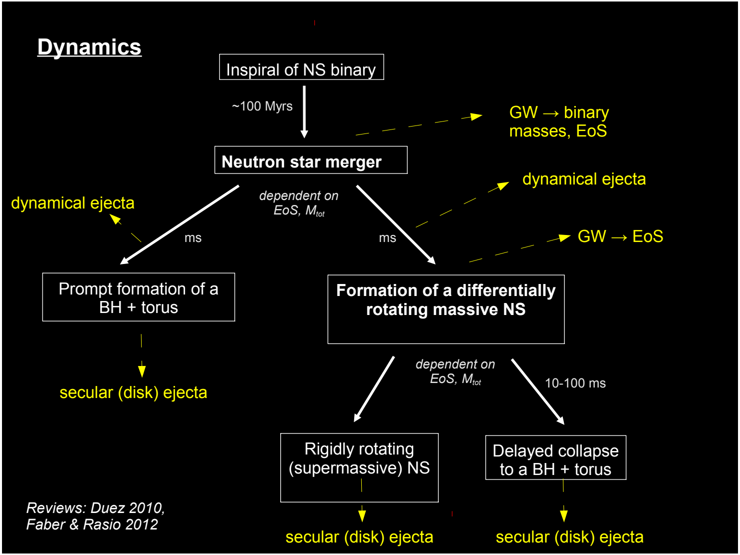




Bauswein, Goriely, Janka, ApJ 773, 78 (2013)

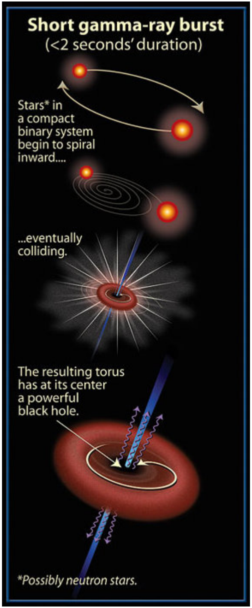
- Mergers are expected to eject dynamically around $0.001\text{-}0.01\ M_\odot$ of neutron rich-material. Impact of weak interactions remains to be understood.

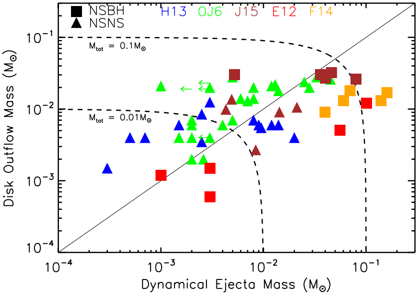
Dynamical evolution in mergers



From A. Bauswein.

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

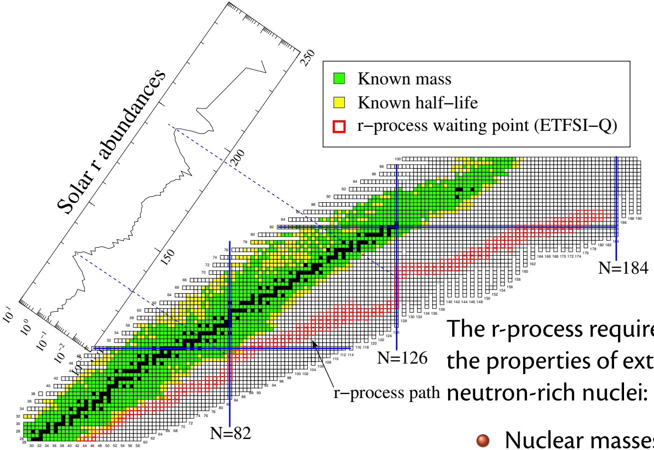




Fernández & Metzger, 2016

- 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 may contribute to radioactive electromagnetic transient (kilonova).

Making Gold in Nature: r-process nucleosynthesis

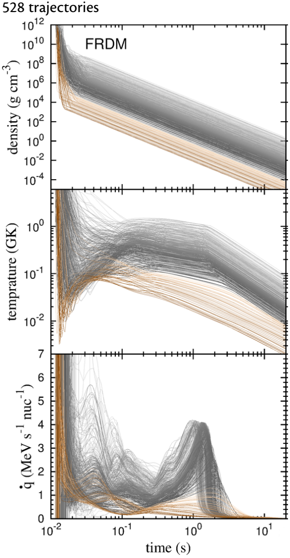


The r-process requires the knowledge of the properties of extremely neutron-rich nuclei:

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

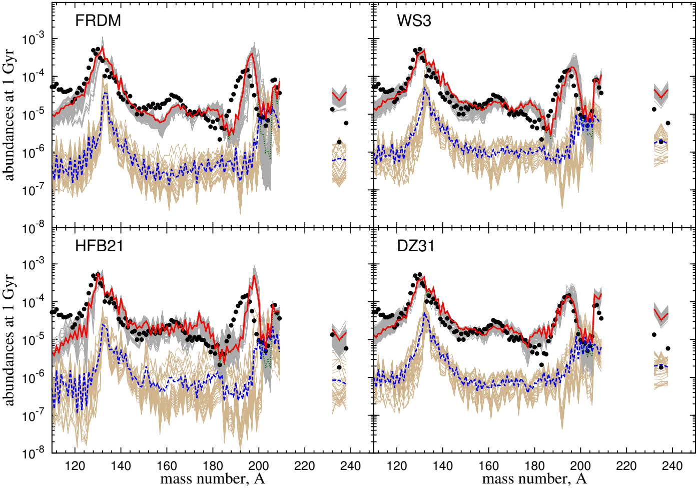
Evolution nucleosynthesis in mergers

- 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



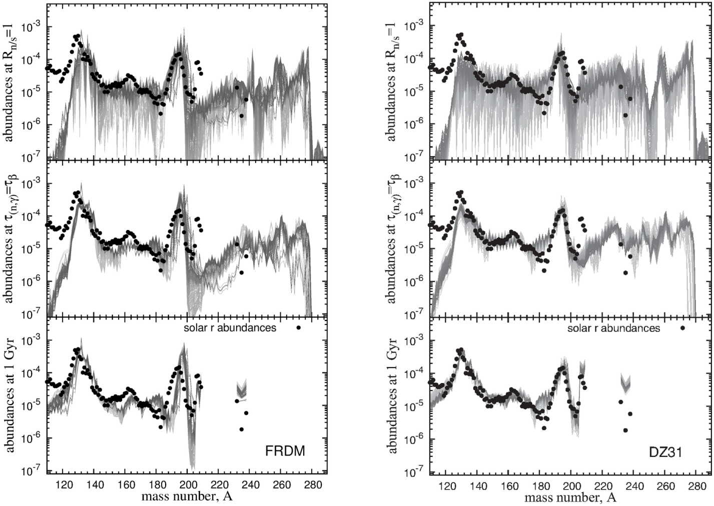
Mendoza-Temis, Wu, Langanke, GMP, Bauswein, Janka, PRC **92**, 055805 (2015)

Final abundances different mass models



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

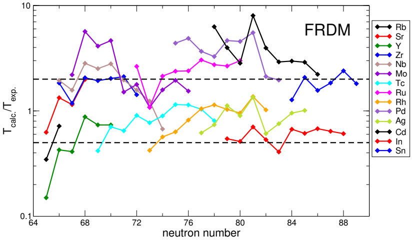
Temporal evolution (selected phases)



Abundance distribution mainly determined by fission from material accumulated in superheavy region.

Beta decays and r process

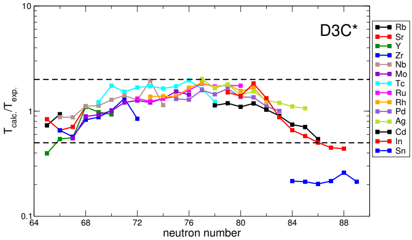
- Beta-decay half-lives the speed of matter flow from light to heavy nuclei.
- In the astrophysical environment competition between nuclear time scales (beta decays) and hydrodynamical time scales (expansion).
- Radioactive beam facilities (present RIKEN, future FRIB and FAIR) are reaching the r-process relevant regions.
- RIKEN has recently measured 110 half-lives around $N = 82$ [Lorusso et al, PRL **114**, 192501 (2015)]

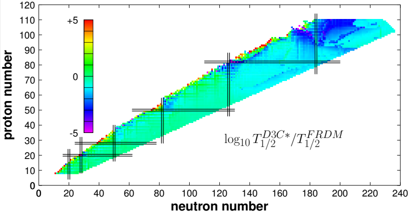


Data implies shorter half-lives than commonly used in r-process simulations [FRDM+QRPA: Möller *et al.*, PRC **67**, 055802 (2003)]

New global calculation of beta-decay half-lives

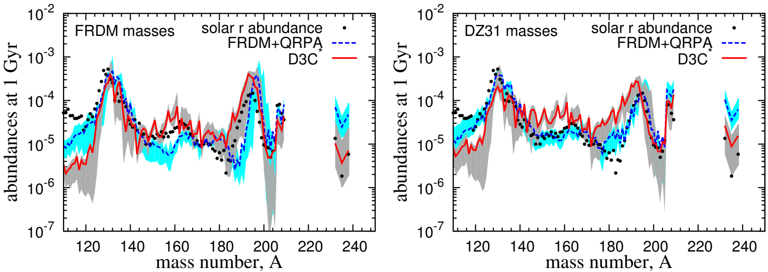
- New global calculation of beta-decay half-lives for r-process nuclei [T. Marketin, L. Huther, GMP, PRC **93**, 025805 (2016)]
- Good agreement with RIKEN data.
- Substantially shorter half lives for nuclei with ($Z \gtrsim 80$)





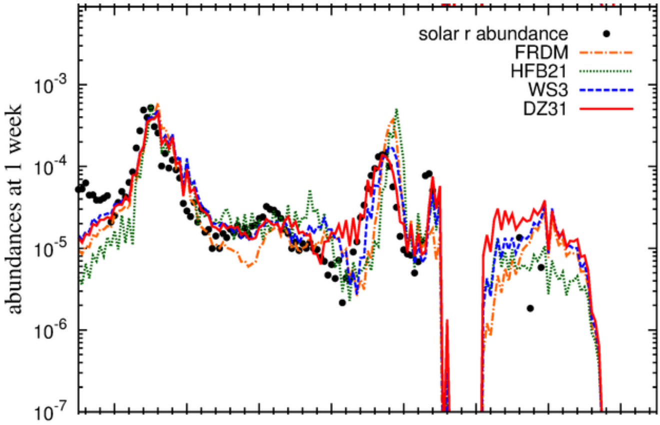
Impact on r-process abundances (dynamical ejecta)

Shorter half-lives for $Z \gtrsim 80$ have a strong impact on the position of $A \sim 195$ [Eichler *et al.*, ApJ **808**, 30 (2015)]



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

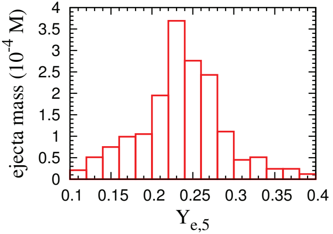
Actinides affect opacities and energy production

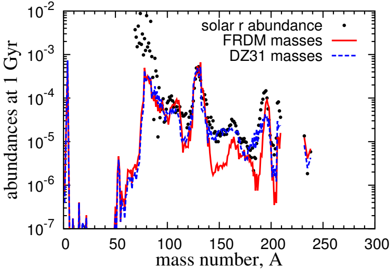


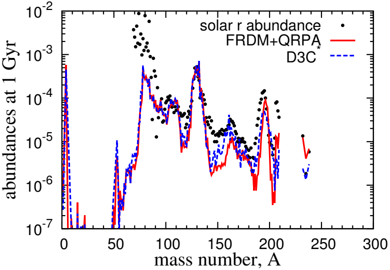
- Actinides can be an important opacity source at timescales of weeks (Mendoza-Temis *et al* 2015)
- Important contribution to energy production via alpha decay (Barnes *et al* 2016)

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)]

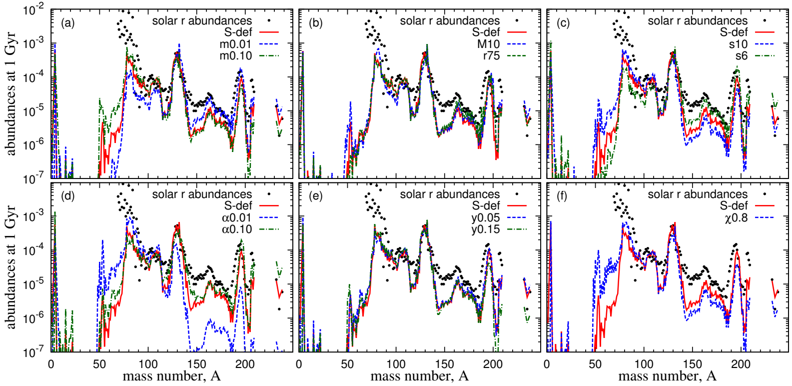






Broad range of disk models considered

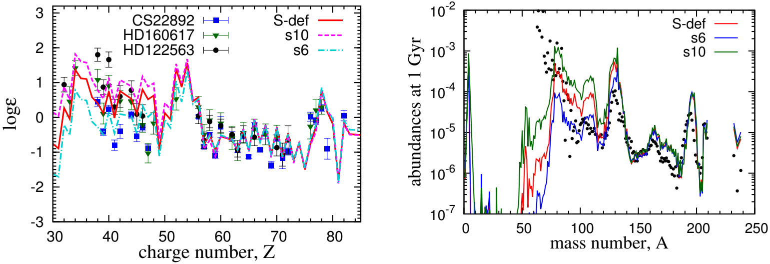
Despite variations in black-hole mass, spin, disk mass, viscosity, entropy and Y_e models produce all r-process nuclides



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.

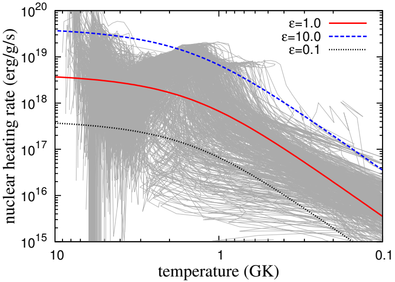


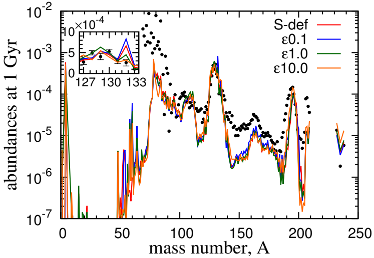
Heavy r-process shows robust abundance pattern

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.





Summary

- Neutrino-winds from core-collapse are expected to produce elements between Zn and Mo ($A \sim 90$).
- Within present uncertainties on equation of state and neutrino-matter interactions no substantial production of heavier elements is expected. Is the weak r-process excluded from typical supernova?
- 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.