Nuclear Astrophysics:
The origin of heavy elements
Lecture 3: The r process

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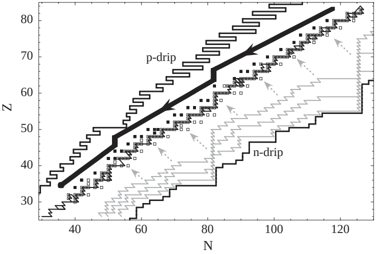
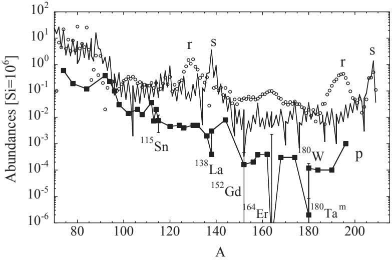
Outline

1. Signatures of heavy element nucleosynthesis
2. Nucleosynthesis in core-collapse supernovae
3. Nucleosynthesis in neutron star mergers
    - Dynamical ejecta
    - Accretion disk ejecta
4. Summary

Nucleosynthesis beyond iron

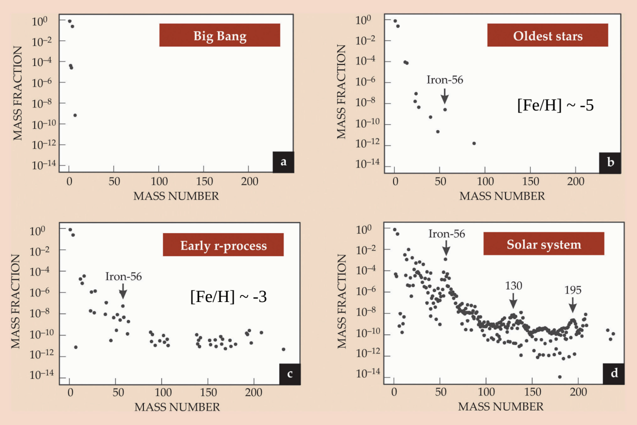
Three processes contribute to the nucleosynthesis beyond iron: s process, r process and p process (γ-process).





- s process: low neutron densities, $n_n = 10^{10-12}\ \mathrm{cm}^{-3}$, $\tau_n > \tau_\beta$ (site: intermediate mass stars)
- r process: large neutron densities, $n_n > 10^{20}\ \mathrm{cm}^{-3}$, $\tau_n \ll \tau_\beta$ (unknown astrophysical site)
- p process: photodissociation of s-process material.

Time evolution: metalicity



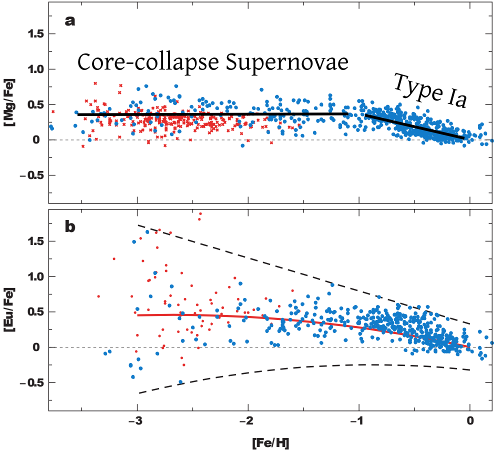
Astronomers use the metalicity:

$$[\mathrm{Fe/H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{*} - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\odot}$$

as a proxy for age.

Evolution metalicity

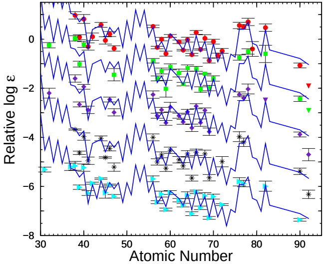
Sneden, Cowan & Gallino 2008



- r process occurs already at early galactic history
- Large scatter at low metalicities: r process is related to rare events not correlated with iron.

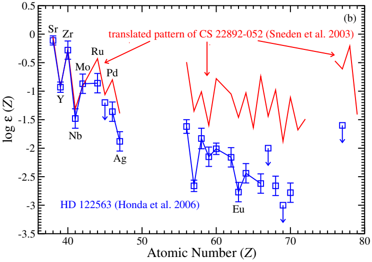
Heavy elements and metal-poor stars

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



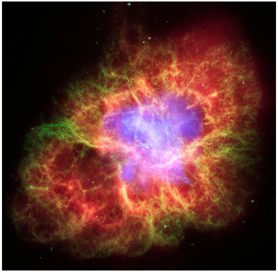
- Stars rich in heavy r-process elements ($Z > 50$) and poor in iron (r-II stars, $[\mathrm{Eu}/\mathrm{Fe}] > 1.0$).
- Robust abundance patter for $Z > 50$, consistent with solar r-process abundance.
- Abundances are the result of events that do not produce iron. [Qian & Wasserburg, Phys. Rept. **442**,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

- 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.



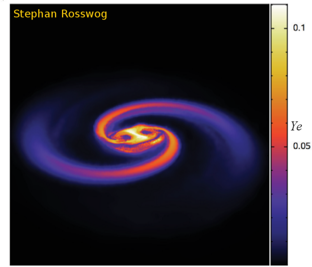
Honda *et al*, ApJ **643**, 1180 (2006)

r-process astrophysical sites



Core-collapse supernovae

- Explosion of massive stars ($M \gtrsim 9\,\mathrm{M}_\odot$)
- Site: neutrino-winds from cooling of hot protoneutron star.
- High frequency ($\sim 0.3\ \mathrm{yr}^{-1}$), low yield ejecta ($10^{-4}$–$10^{-5}\ \mathrm{M}_\odot$)
- Observations: not every supernovae produces r process

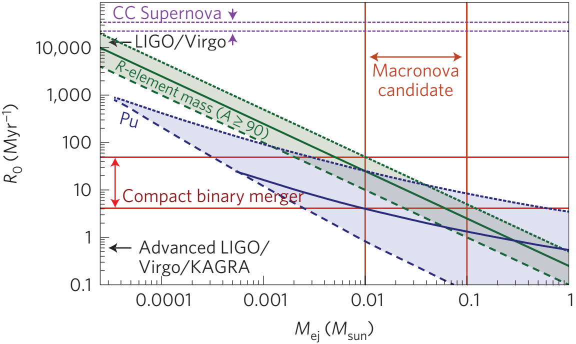


Neutron star mergers

- Mergers eject around $0.01\ \mathrm{M}_\odot$ 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
- Observational signature: electromagnetic transient from radioactive decay of r-process nuclei [Kilonova/Macronova, Metzger *et al* (2010)]

Measurements long-lived radioactive nuclei

Both the $^{244}\mathrm{Pu}$ ($\tau = 81$ Myr) accreted via interstellar particles in the Earth deepsea floor and the Early Solar System abundanced are naturally explained with the low-rate/high-yield astrophysical scenario. [Hotokezaka et al, Nature Physics 11, 1042 (2015)]

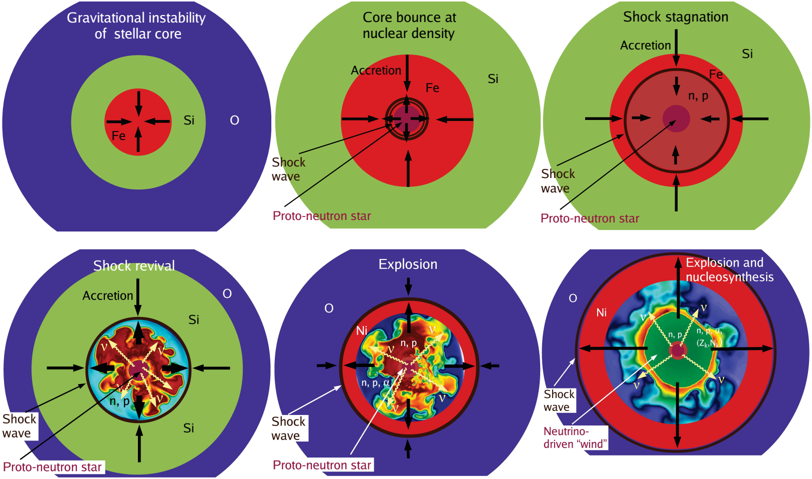


Any astrophysical site should fulfill:

$$\mathcal{R}\mathcal{M}_{\mathrm{ej}} = M(A > 90)$$

Core-collapse supernovae

H.-Th. Janka, *et al*, PTEP 01A309 (2012)



The movie of the supernova simulation is available here

Neutrino-driven winds

Main processes:

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

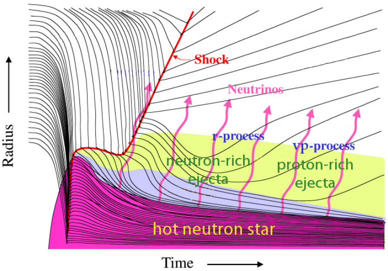
Neutrino interactions determine the proton to neutron ratio.

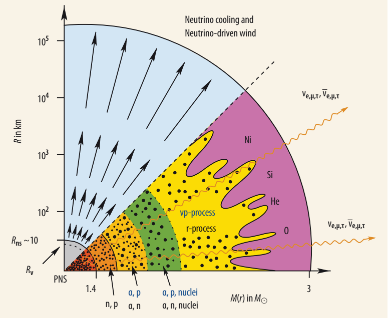
Condition neutron-rich ejecta:

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

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

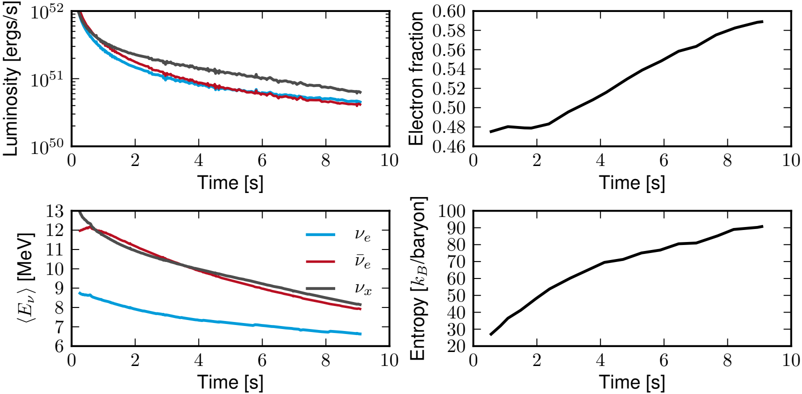
Nucleosynthesis sensitive to spectral differences between ν_e and $\bar{\nu}_e$





Evolution luminosities and Y_e

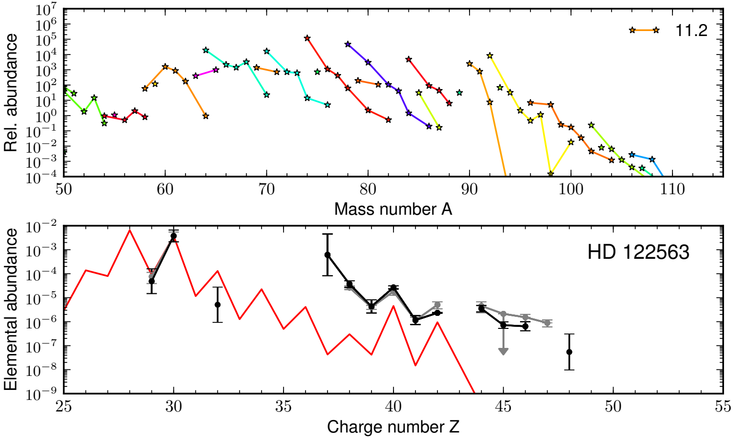
1D Boltzmann transport radiation simulations (artificially induced explosion) for a 11.2 $M_\odot$ progenitor based on the DD2 EoS (Stefan Typel and Matthias Hempel).



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

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

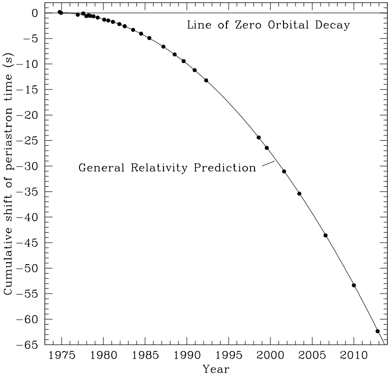
Nucleosynthesis



- Elements between Zn and Mo ($A \sim 90$) are produced
- Mainly neutron-deficient isotopes are produced

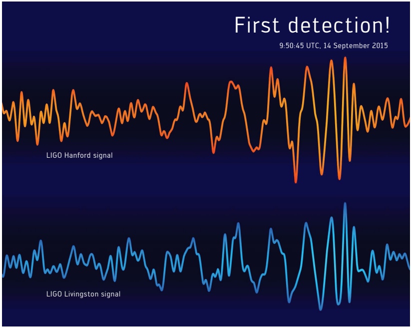
Compact binary systems: gravitational waves

Orbital decay Hulse & Taylor binary pulsar



Weisberg & Huang, ApJ **829**, 55 (2016)

Gravitational waves binary black holes merger

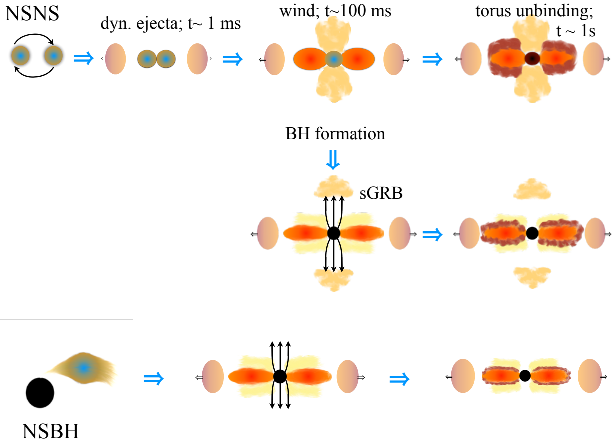


Abbott *et al*, PRL **116**, 061102 (2016)

Compact binary systems exist and eventually merge

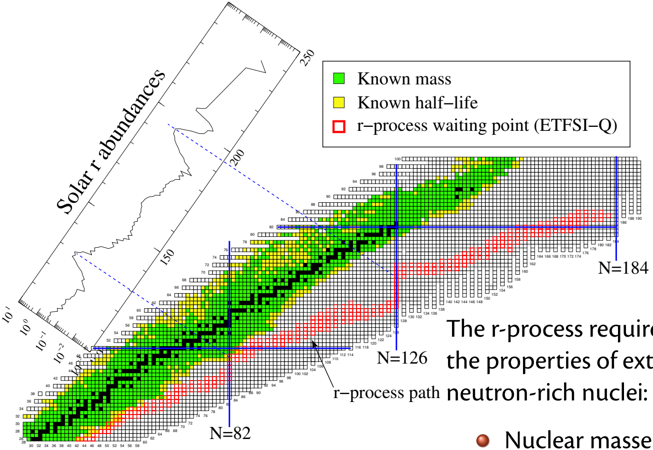
Merger channels and ejection mechanism

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*, arXiv:1611.09822

Making Gold in Nature: r-process nucleosynthesis

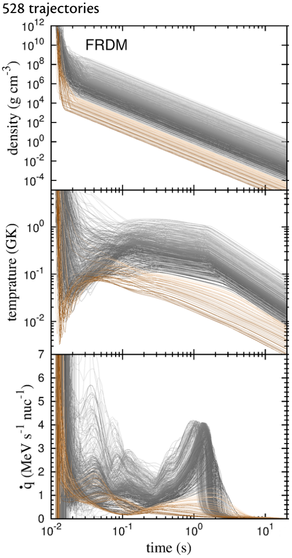


The r-process requires the knowledge of the properties of extremely neutron-rich nuclei:

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

Evolution nucleosynthesis in mergers

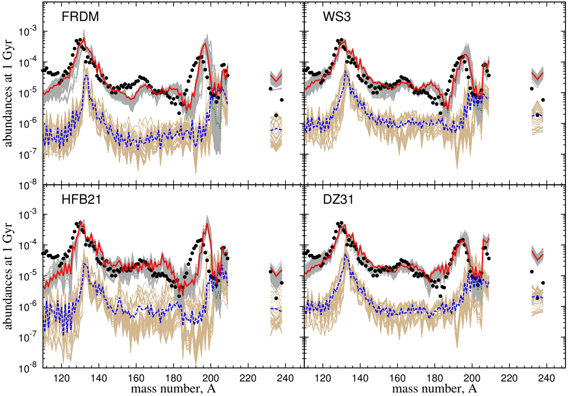
- r-process stars once electron fermi energy drops below $\sim 10\,\mathrm{MeV}$ to allow for beta-decays ($\rho \sim 10^{11}$ g cm^{-3}).
- Important role of nuclear energy production (mainly beta decay).
- Energy production increases temperature to values that allow for an $(n,\gamma) \rightleftarrows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

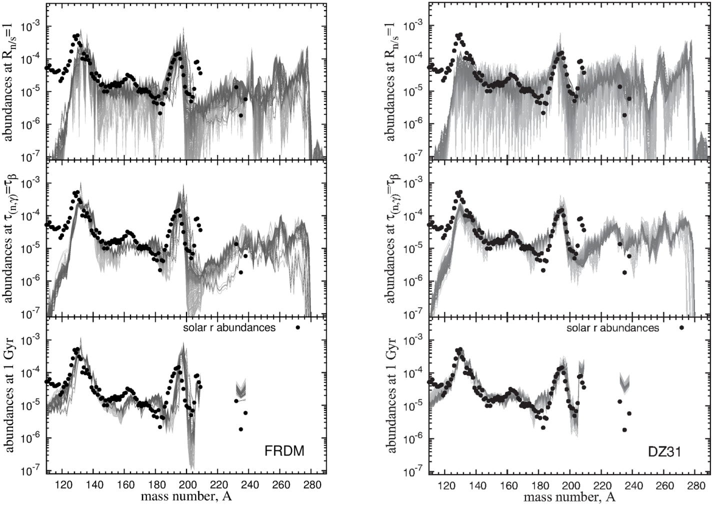
Final abundances different mass models

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.

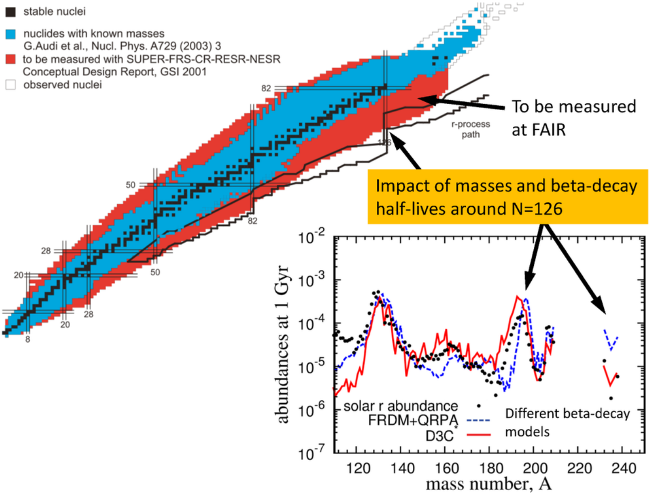
Temporal evolution (selected phases)



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

Nuclear physics uncertainties: beta decays

Masses around $N \sim 126$ and half-lives for $Z \gtrsim 80$ have a strong impact on the position of $A \sim 195$ [Eichler *et al.*, ApJ **808**, 30 (2015)]

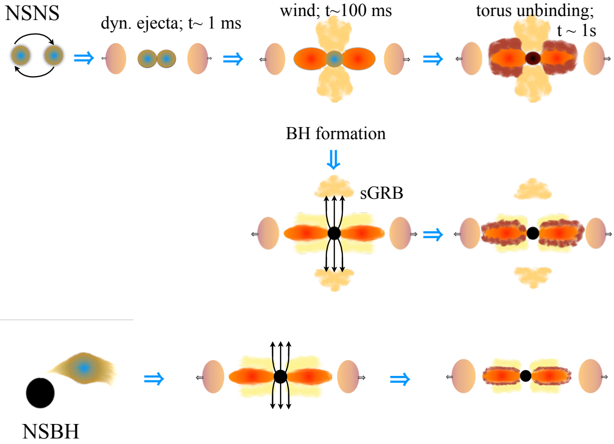


To be measured at FAIR

Impact of masses and beta-decay half-lives around N=126

Merger channels and ejection mechanism

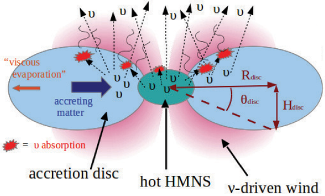
In mergers we deal with a variety of initial configurations (netron-star neutron-star vs neutron-star black-hole) with additional variations in the mass-ratio. The evolution after the merger also allows for further variations.

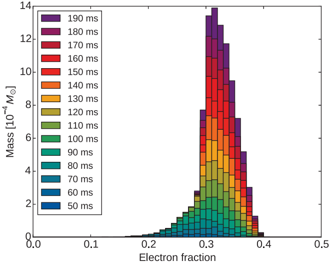


Rosswog, *et al*, arXiv:1611.09822

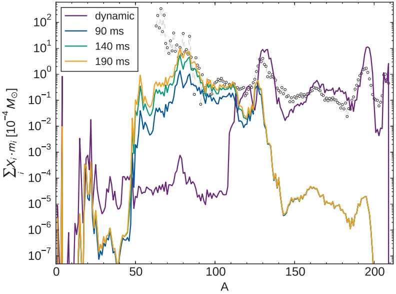
Ejecta from neutron star accretion disks

Perego, *et al*, MNRAS 443, 3134 (2014)





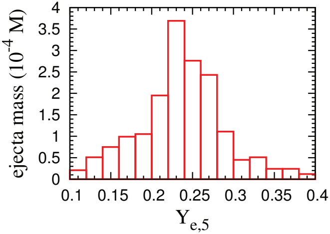
Martin, *et al*, ApJ 813, 2 (2015)

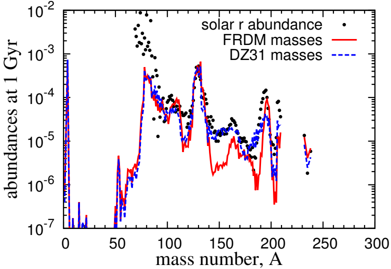


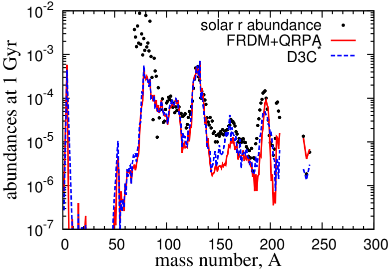
Contributes mainly to the production of nuclei with $A < 120$.

Nucleosynthesis in black-hole accretion disk ejecta

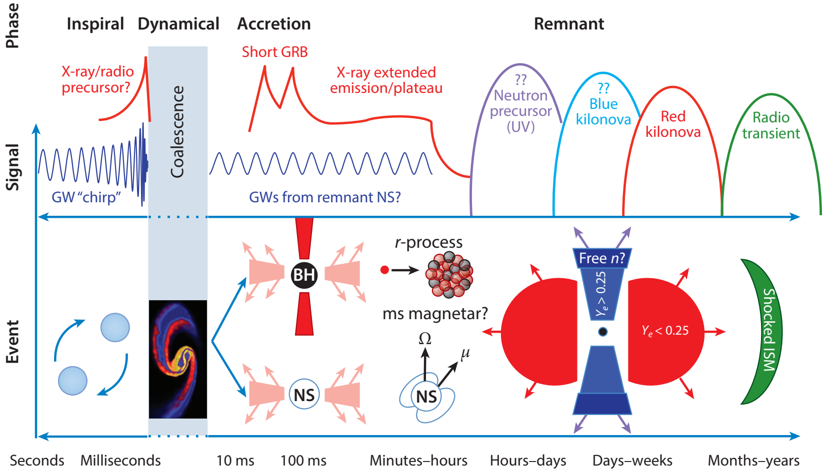
- Accretion disk around compact object is expected to eject material with broad Y_e distribution [Fernández, Metzger, MNRAS 435, 502 (2013)]
- This material is expected to contribute to the production of all r-process nuclides [Wu *et al*, MNRAS 463, 2323 (2016)]







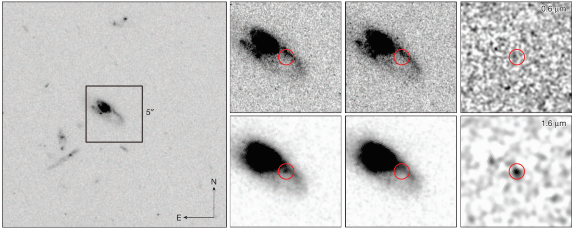
Observational signatures

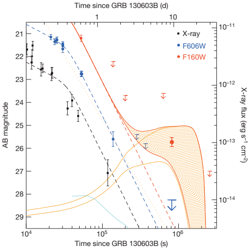


Fernández and Metzger, Annu. Rev. Nucl. Part. Sci. 66, 23 (2016)
Metzger, arXiv:1610.09381 [astro-ph.HE]

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]
- Proably observed associated to GRB 130603B

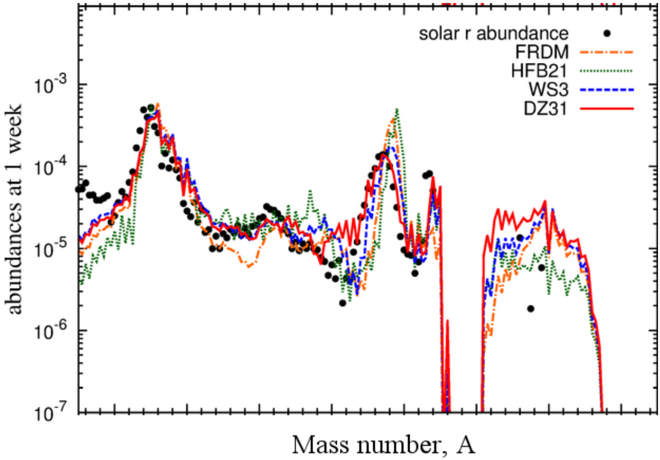




First direct observation of an r-process event?

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

Actinides affect opacities and energy production

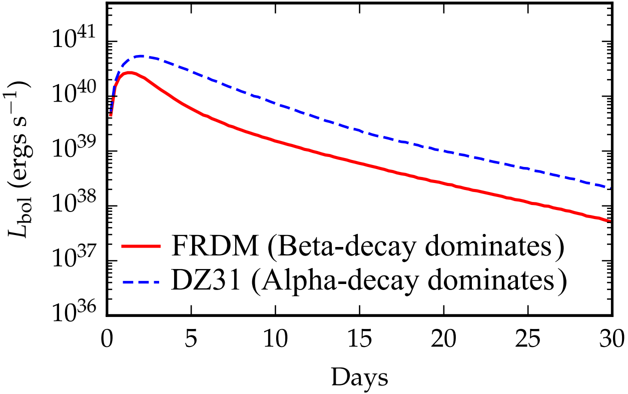


- Actinides can be an important opacity source at timescales of weeks.
- They can substantially contribute to energy production via alpha decay.

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

Impact on the light curve

Light curve contains nuclear physics signatures.



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, ApJ 829, 110 (2016)

Summary

- Heavy element nucleosynthesis in core-collapse supernovae is limited to elements between Zn and Mo ($A \sim 90$).
- Neutron star mergers are likely the site where the “main r process” takes place.
- The combination of dynamical ejecta and disk outflow ejecta can account for the solar system r-process abundances.
- Radioactive decay of r-process ejecta produces an electromagnetic transient.
- Likely observed in GRB 130603B. Further detections necessary to confirm that the r process occurs in mergers.

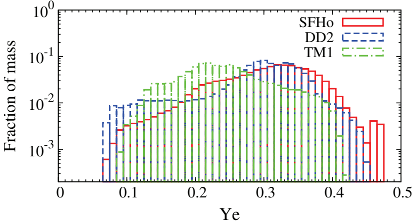
Modeling uncertainties

- Dynamical ejecta originates from shock heated regions during the merger.
- Weak processes at high temperature can affect the neutron richness of ejecta:

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

- There is no consensus on the impact
- Not important for neutron star - black hole mergers.

Sekiguchi, *et al*, PRD **91**, 064059 (2015)



Radice, *et al*, MNRAS **460** 3255 (2016)