R-process nucleosynthesis in neutron star mergers

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EMMI Workshop: New avenues for low energy NuSTAR program at GSI-FAIR

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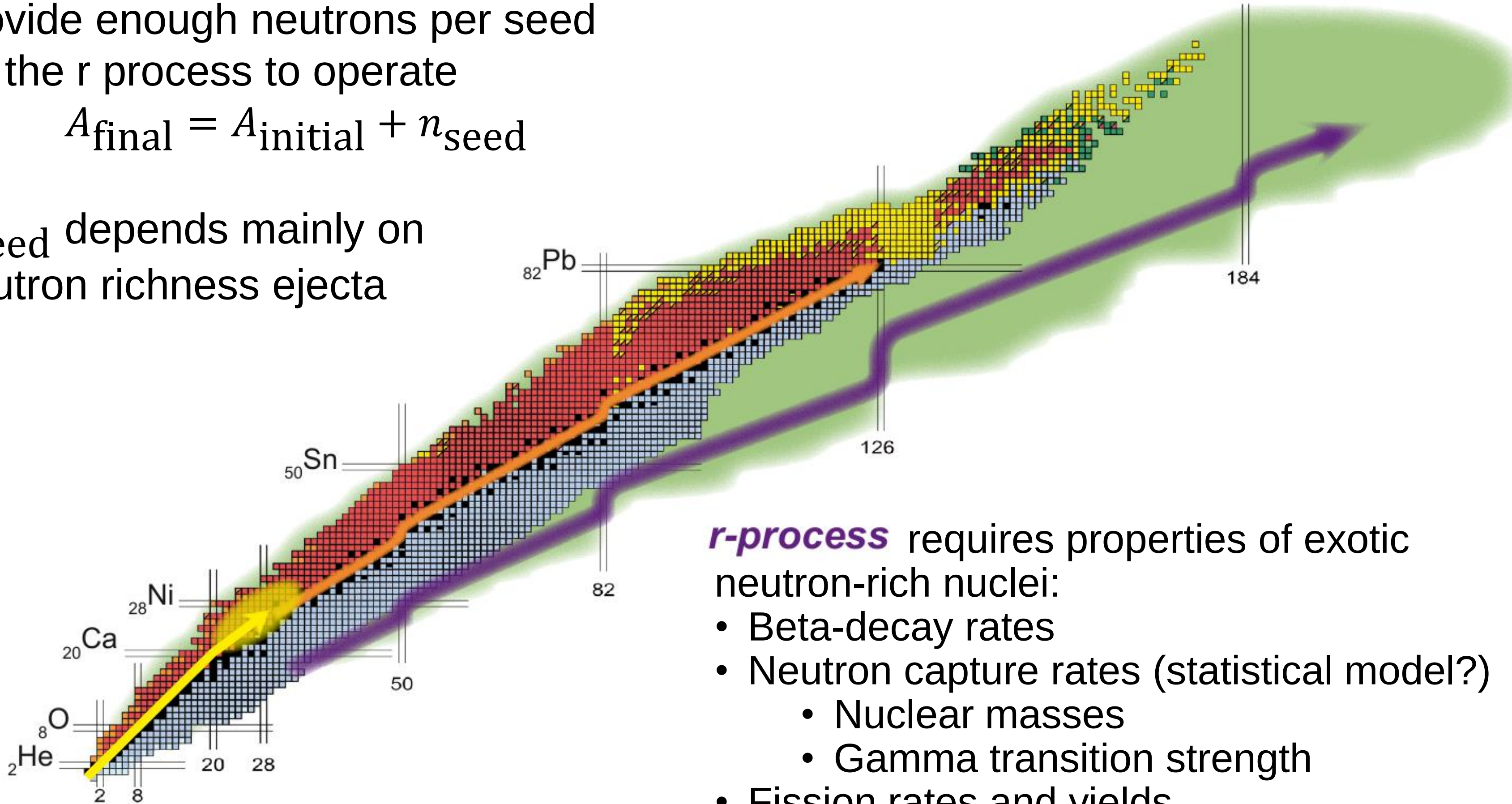
R process nuclear needs

Astrophysical environment should provide enough neutrons per seed for the r process to operate

$$A_{\mathrm{final}} = A_{\mathrm{initial}} + n_{\mathrm{seed}}$$

n_{seed} depends mainly on neutron richness ejecta



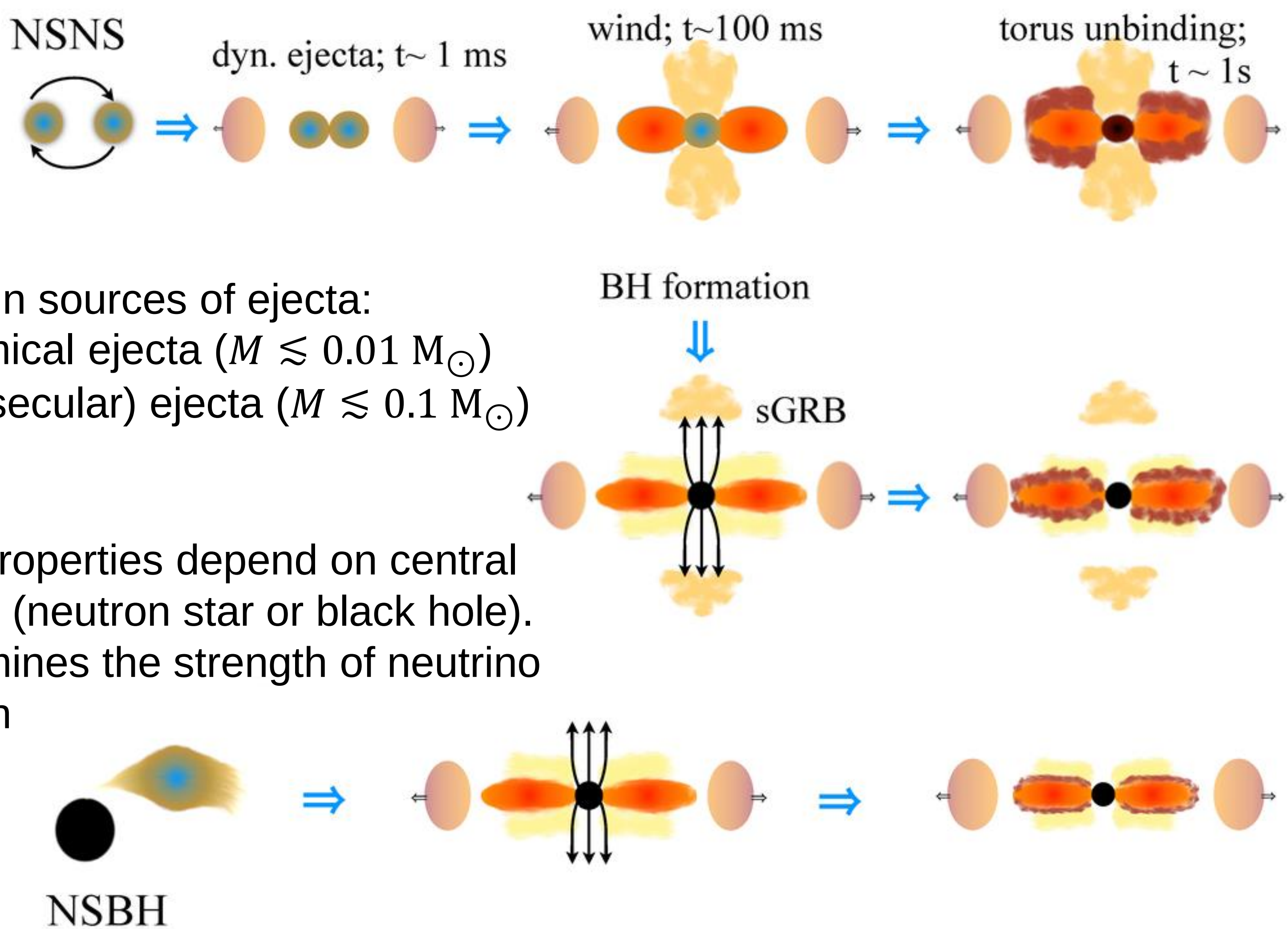
r-process requires properties of exotic neutron-rich nuclei:

- Beta-decay rates
- Neutron capture rates (statistical model?)
    - Nuclear masses
    - Gamma transition strength
- Fission rates and yields
    - Fission barriers

Benchmark against observations:

- Solar and stellar abundances (indirect)
- Electromagnetic emission, kilonova (direct), sensitive Atomic and Nuclear Physics

Ejecta in neutron star mergers



Two main sources of ejecta:

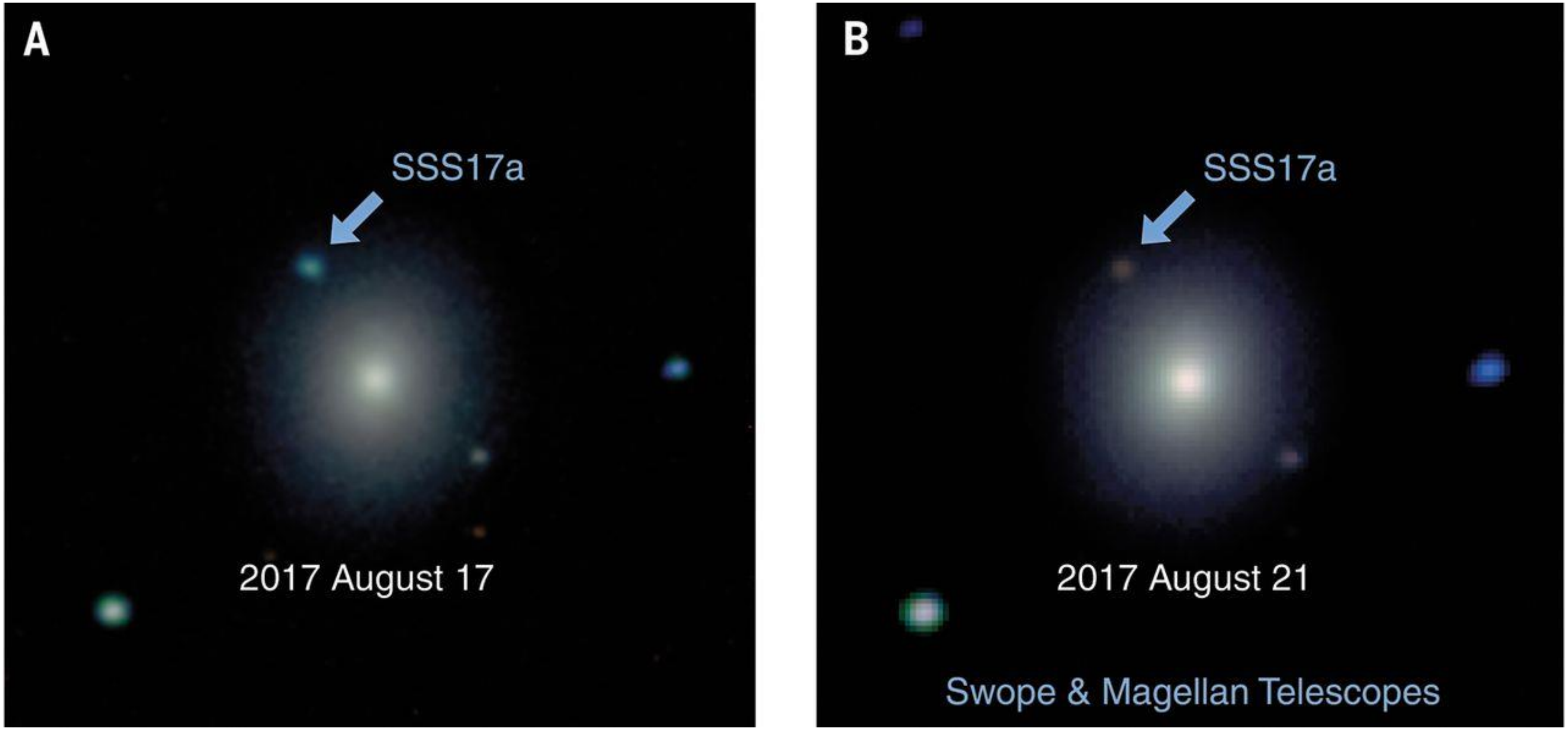
- Dynamical ejecta ($M \lesssim 0.01\ \mathrm{M}_\odot$)
- Disk (secular) ejecta ($M \lesssim 0.1\ \mathrm{M}_\odot$)

Ejecta properties depend on central remnant (neutron star or black hole). It determines the strength of neutrino emission

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

Kilonova:
Electromagnetic transient associated to GW170817

M. R. Drout et al. Science 2017;358:1570-1574

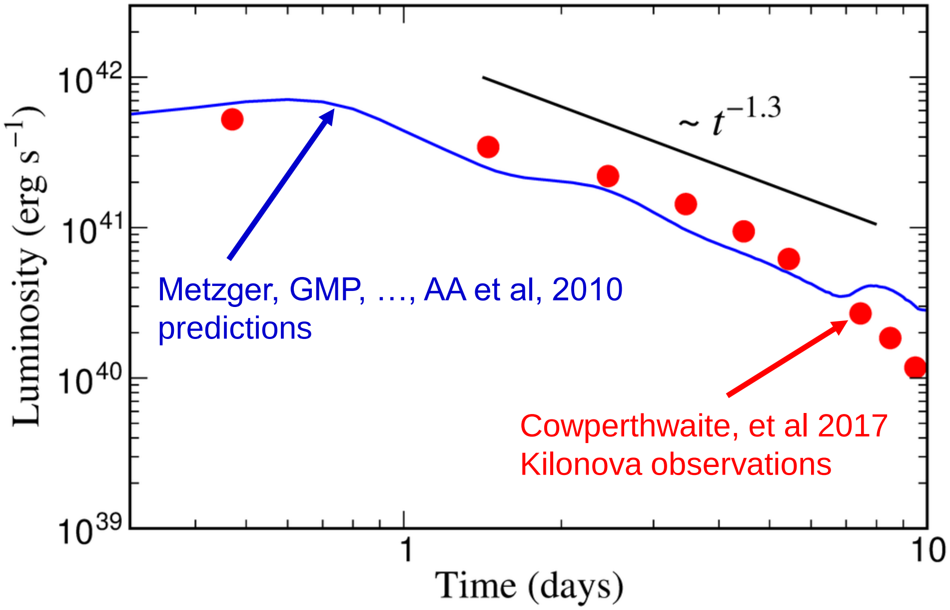


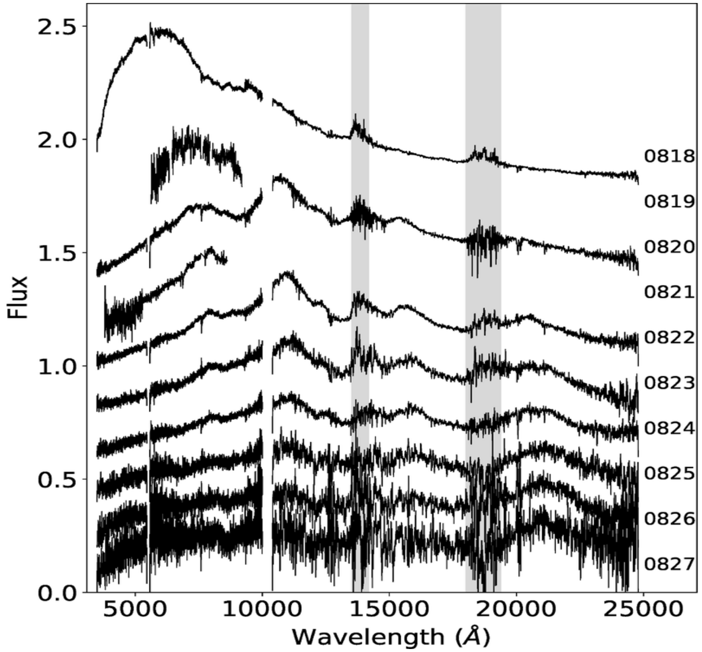
Novel fast evolving transient powered radioactive decay r-process material

Emission evolves from blue to red in a few days

Kilonova: Electromagnetic transient powered by decay of r-process nuclei

Pian et al., Nature 551, 67 (2017)



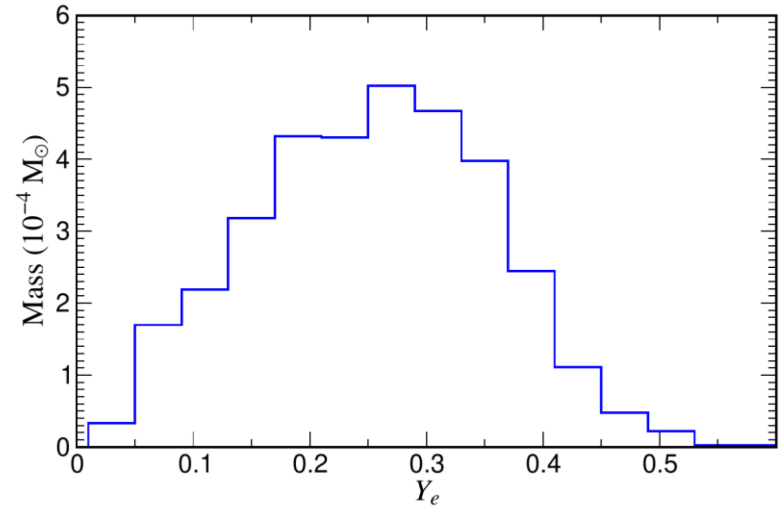


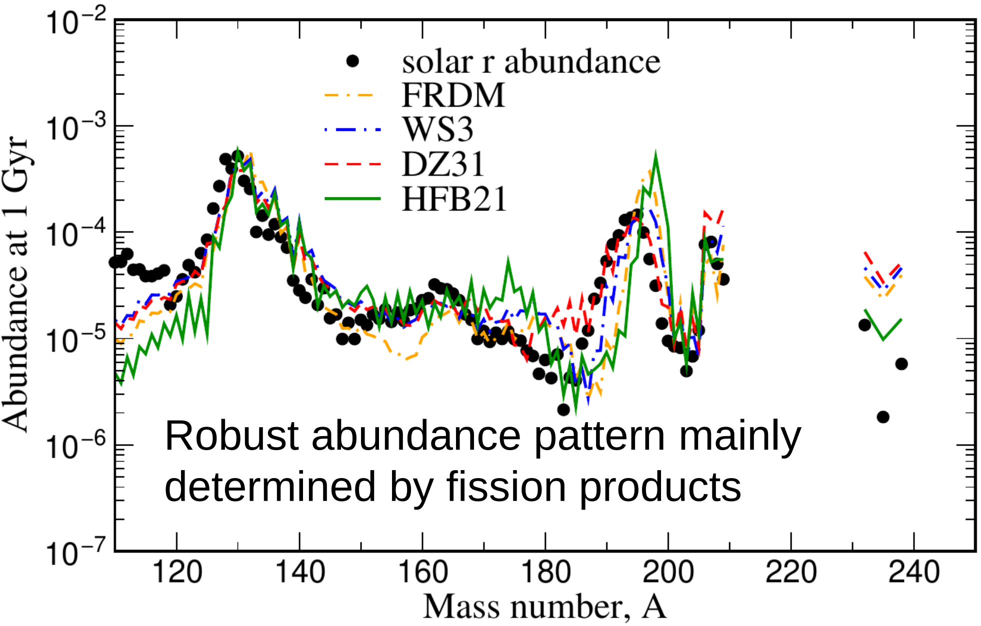
- Time evolution determined by the radioactive decay of r-process nuclei
- Two components, Kasen et al, Nature 551, 80 (2017)
  - Blue dominated by light elements (Z < 50) ($M = 0.025\ M_{\odot}, v = 0.3c, X_{\rm lan} = 10^{-4}$, dynamical ejecta?, signature neutrino interactions)
  - Red due to presence of Lanthanides ($M = 0.04\ M_{\odot}, v = 0.15c, X_{\rm lan} = 10^{-1.5}$, ejecta accretion disk?, points to the formation of a black hole)
- Spectroscopic identification of r-process element Sr (Watson et al, 2019)

Dynamical ejecta (simulations)

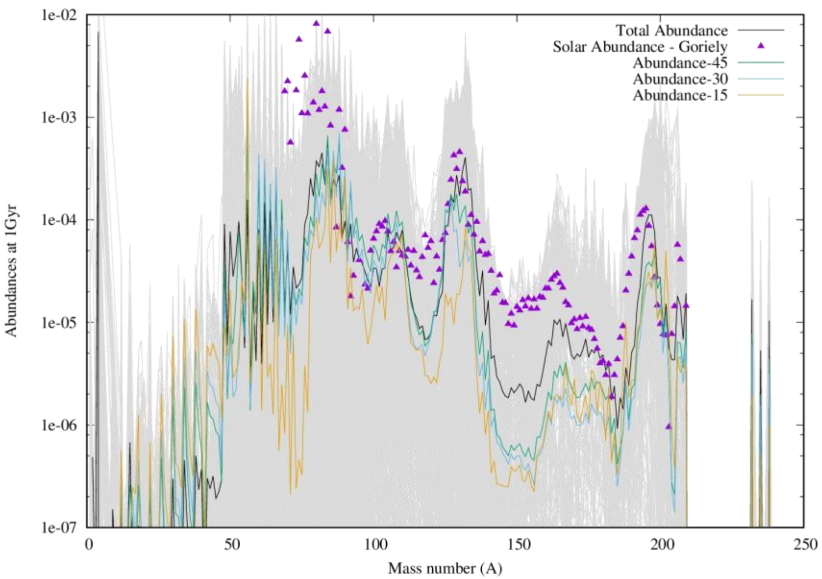
- Initially dynamical ejecta was assumed to be very neutron rich ($Y_e \lesssim 0.1$).
- Starting with the work of Wanajo et al 2014, several studies have shown that weak processes modify the neutron-to-proton ratio
- Largest impact in the polar regions

Systematic evaluation role of weak processes [Vimal Viajayan, PhD group A. Bauswein]





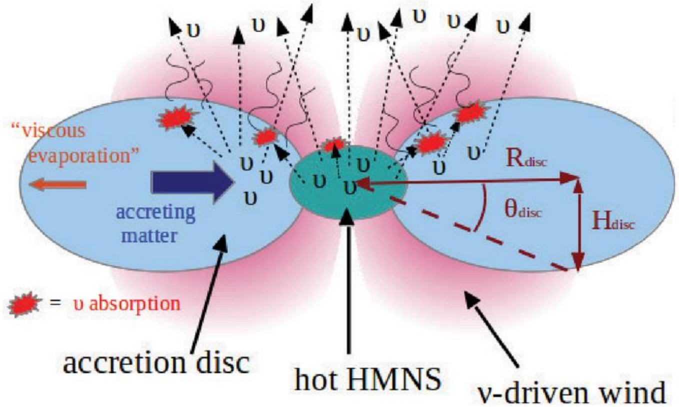
Robust abundance pattern mainly determined by fission products



Mendoza-Temis, et al, PRC 92, 055805 (2015)

Disk (secular) ejecta

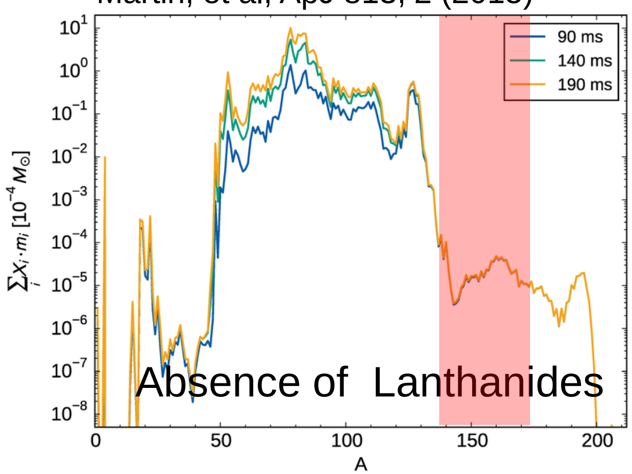
After the merger an hyper massive neutron star is formed that can be temporarily stable before collapsing to a black hole



Large neutrino fluxes mainly in polar region decrease neutron-to-proton ratio by reactions

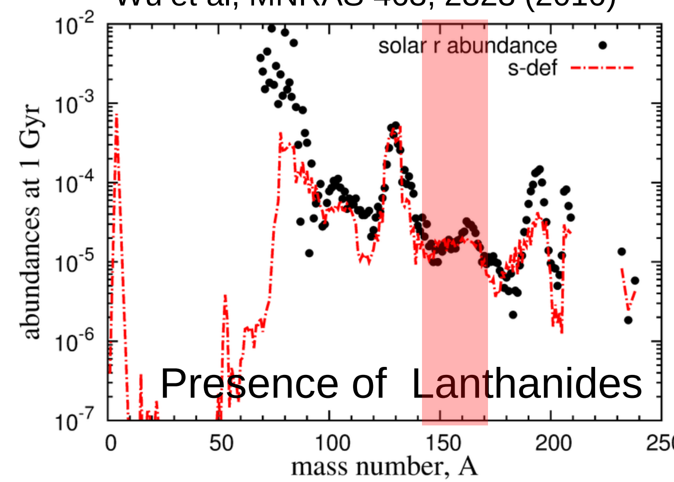
$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$

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



Once neutron star collapses to a black hole neutrinos emission ceases. Larger neutron-to-proton ratio

Wu et al, MNRAS 463, 2323 (2016)



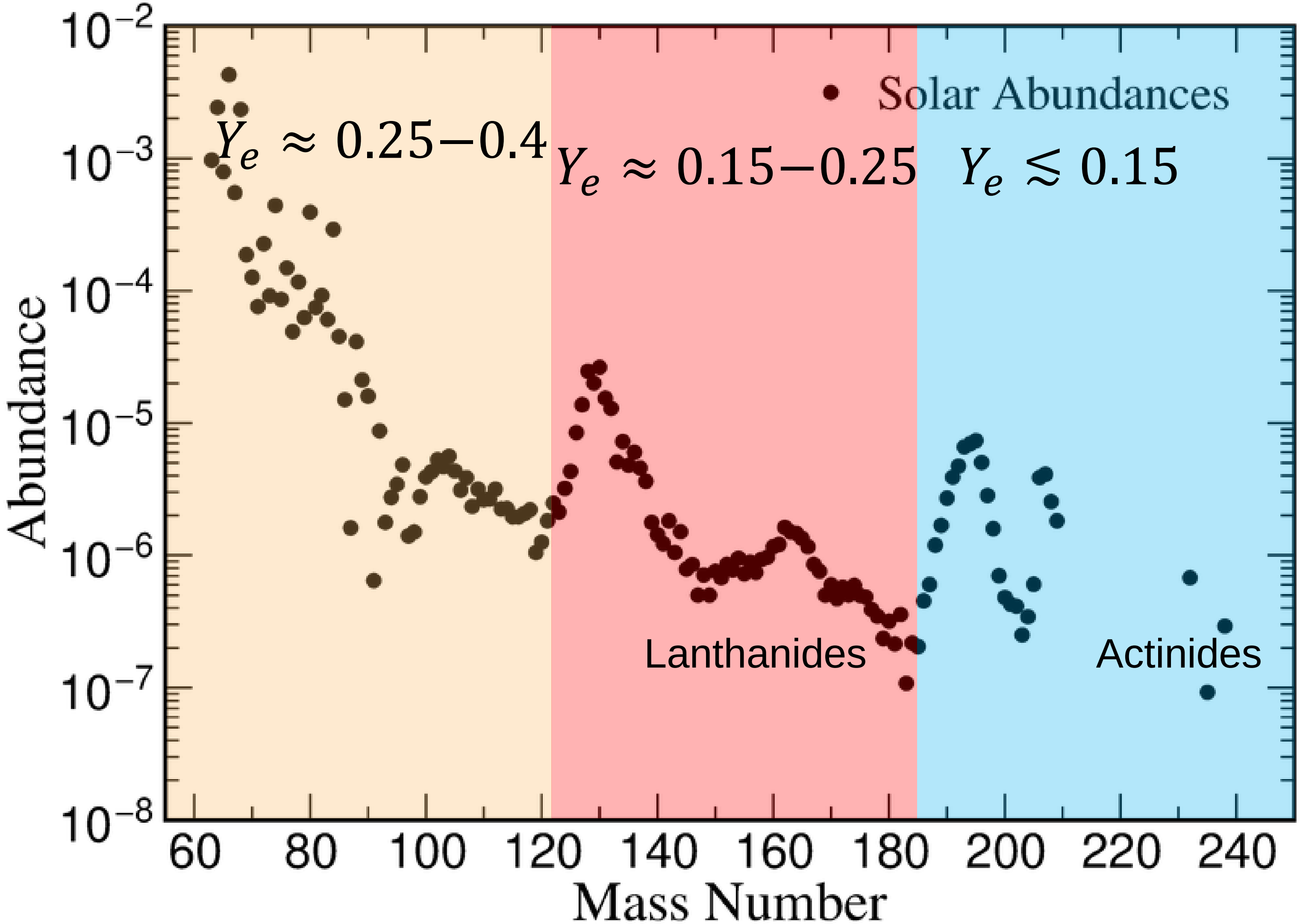
see also Lippuner et al, MNRAS 472 904 (2017)

See also Just et al, MNRAS **448**, 541 (2015), Siegel and Metzger PRL **119**, 231102 (2017).

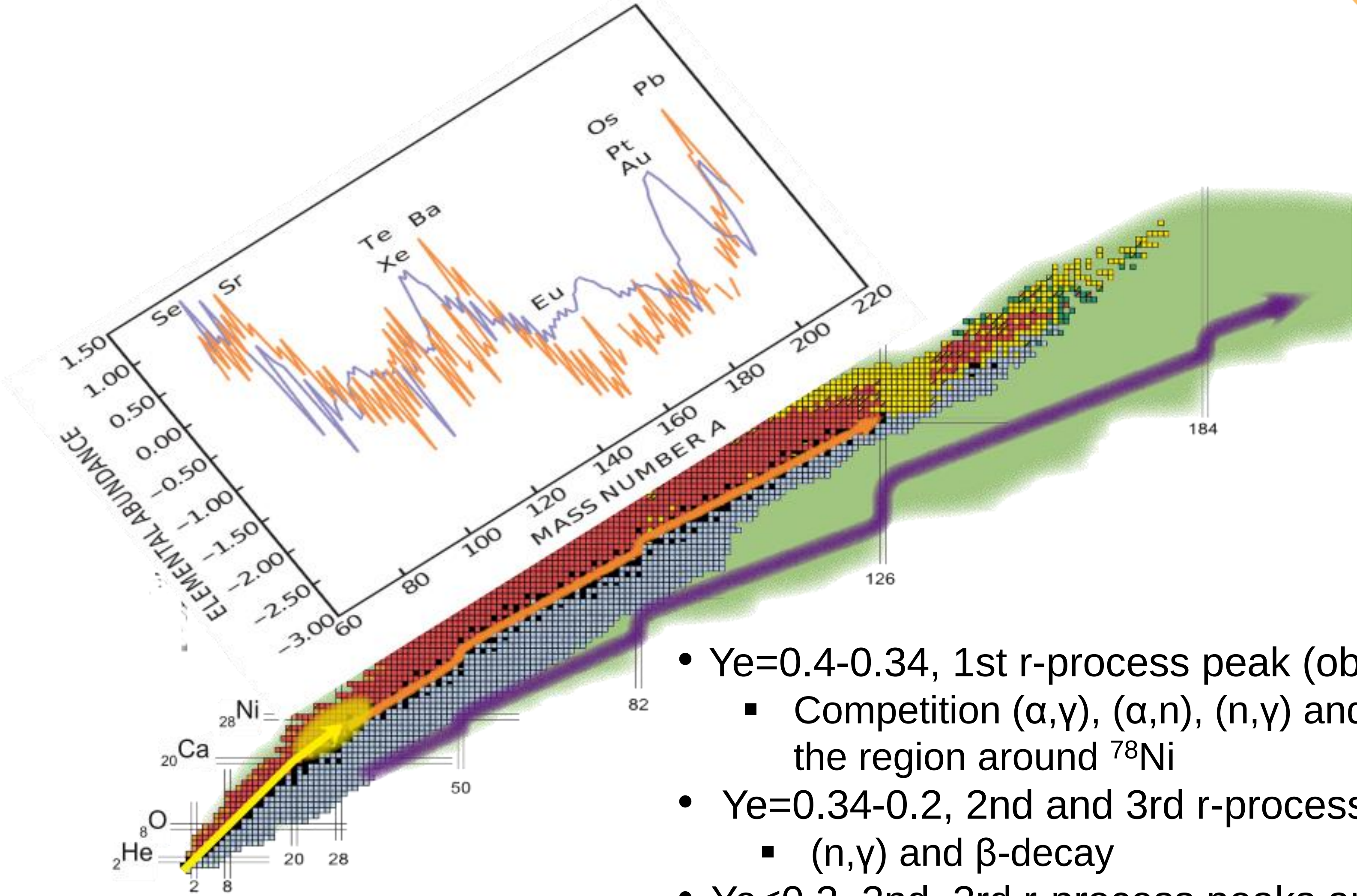
Nucleosynthesis dependence on Y_e

Mergers produce broad range of neutron rich ejecta, $Y_e = n_p/(n_n + n_p)$

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



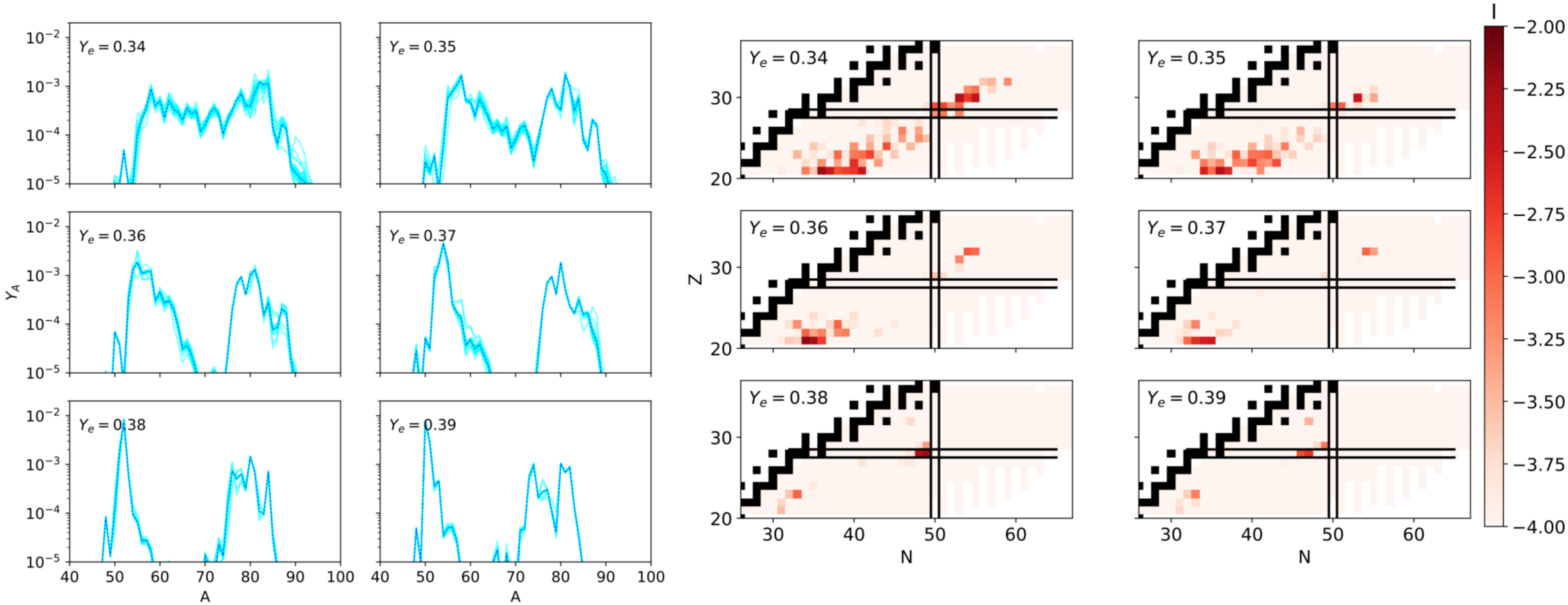
Nuclear needs depend on Ye



- Ye=0.4-0.34, 1st r-process peak (observed Sr)
  - Competition (α,γ), (α,n), (n,γ) and β-decay in the region around ^{78}Ni
- Ye=0.34-0.2, 2nd and 3rd r-process peak
  - (n,γ) and β-decay
- Ye<0.2, 2nd, 3rd r-process peaks and actinides
  - (n,γ) and β-decay and fission

Production 1st r-process peak

Sensitivity to individual variations of masses

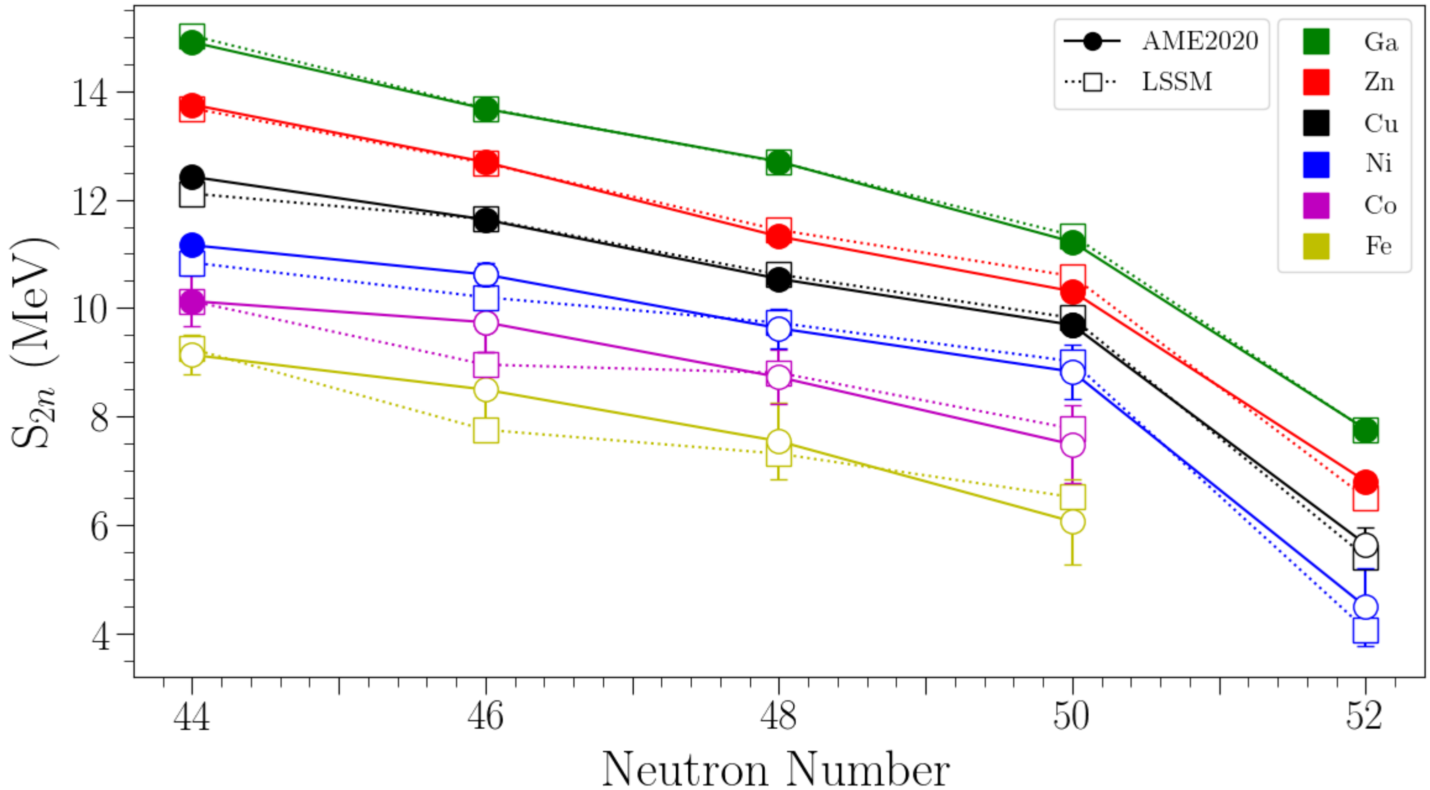


- α captures important for high Ye (two distinct peaks)
- Transition to n captures and beta-decays at high Ye

S. Nikas (PhD thesis, TU Darmstadt, 2021)

Large scale shell-model calculations

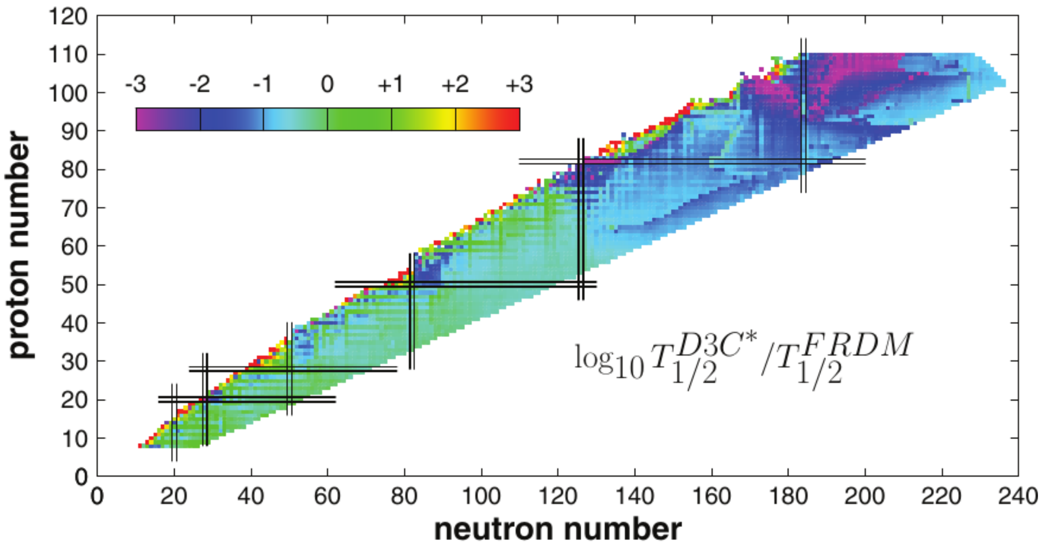
- Region around ^{78}Ni can be studied by large scale shell model calculations e.g. Nowacki, Obertelli, Poves, Prog. Part. Nucl. Phys. 120, 103866 (2021)

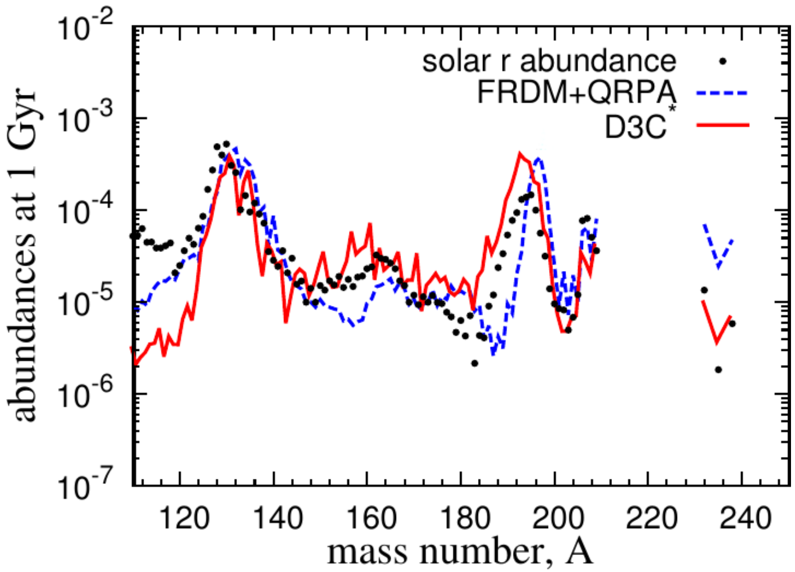


Estimation of nuclear masses based on LSSM calculations
Z. Iftikhar (PhD), R. Mancino (Postdoc)

beta-decay half-lives

- Beta-decay half-lives determine the speed at which heavy elements are build starting from light ones
- Theoretical advances allow for global microscopic calculations including Gamow-Teller and forbidden transitions, Marketin+, PRC 93, 25805 (2016)

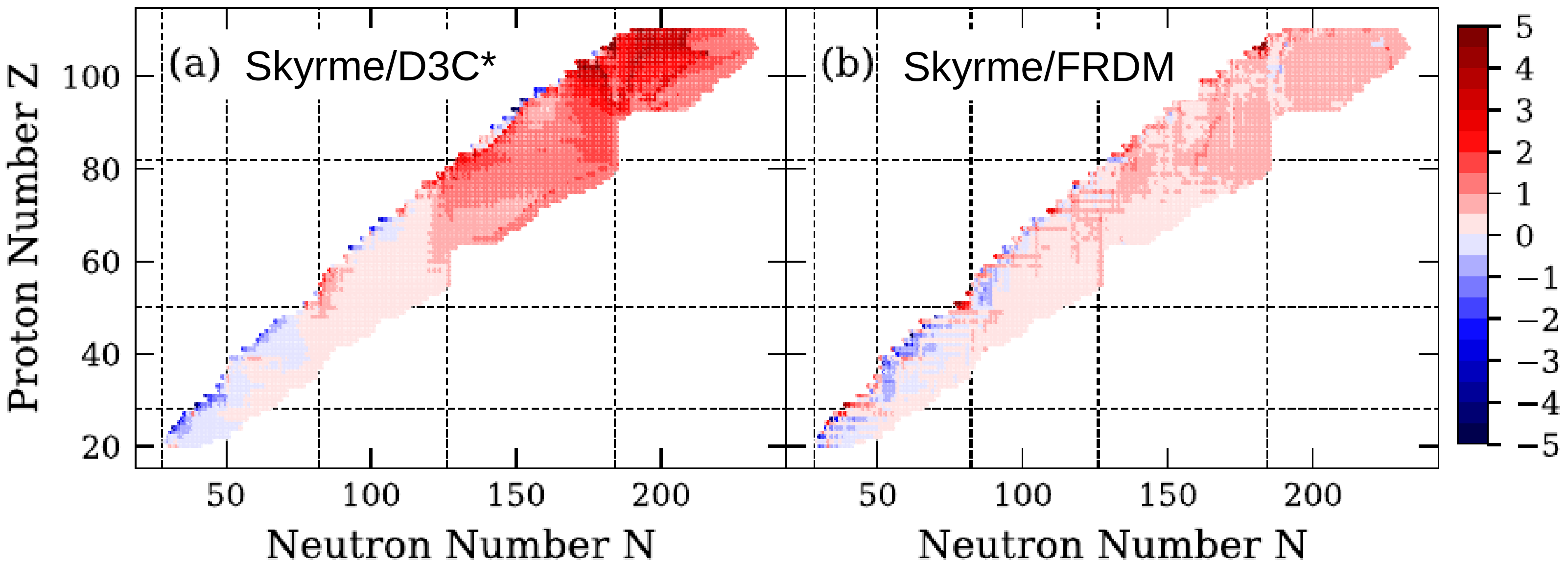




- Predict shorter half-lives for nuclei $Z > 70$ when compared with FRDM (Möller+ 2003) having a strong impact on the position of the A ~ 195 peak [Eichler et al, ApJ 808, 30 (2015)]

Further models

- More recently microscopic calculations have become available based on Skyrme functional, Ney et al, PRC 102, 034326 (2020), that do not show such reduction on lifetimes

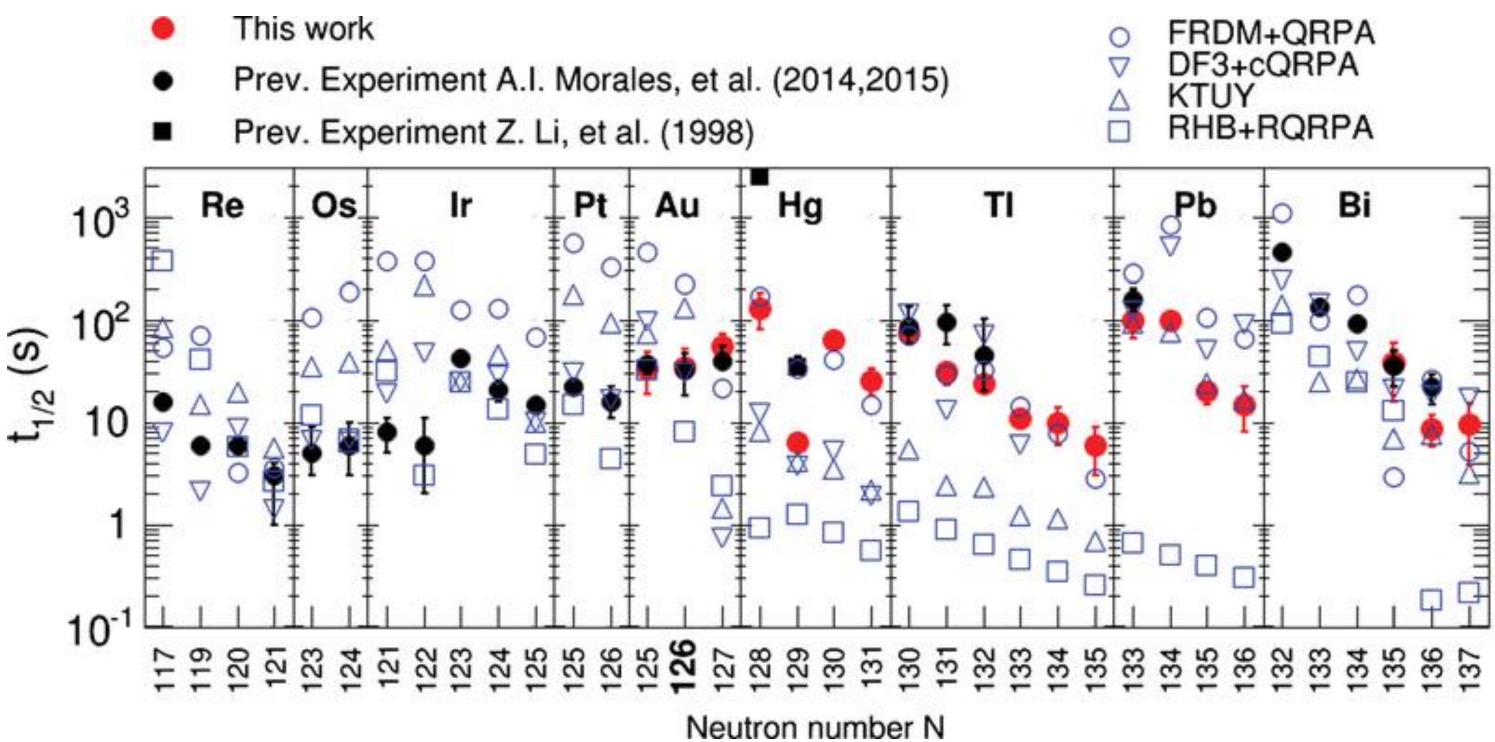


Experimental information

Caballero-Folch et al, experiment performed at GSI

PRL 117, 012501 (2016) PHYSICAL REVIEW LETTERS week ending 1 JULY 2016

First Measurement of Several β-Delayed Neutron Emitting Isotopes Beyond $N = 126$

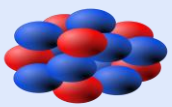


- Available data seems to favor shorter lifetimes. However, still far from r-process region.
- Nevertheless even long lifetimes (seconds) can affect energy production for kilonova modelling

Extension beyond QRPA
Particle-vibration coupling

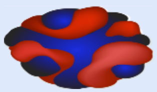
C. Robin and E. Litvinova
PRC 98, 051301 (2018); EPJA 52, 205 (2016);

Degrees of freedom in Relativistic Nuclear Field Theory



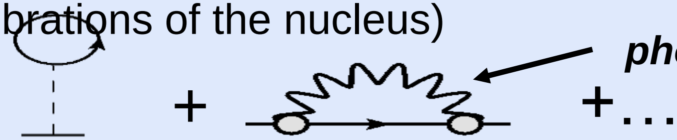
=

- relativistic nucleons p n
- relativistic mesons π σ ω ρ (+ photon)
- phonons (collective vibrations of the nucleus)

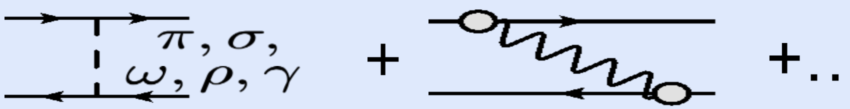


phonon

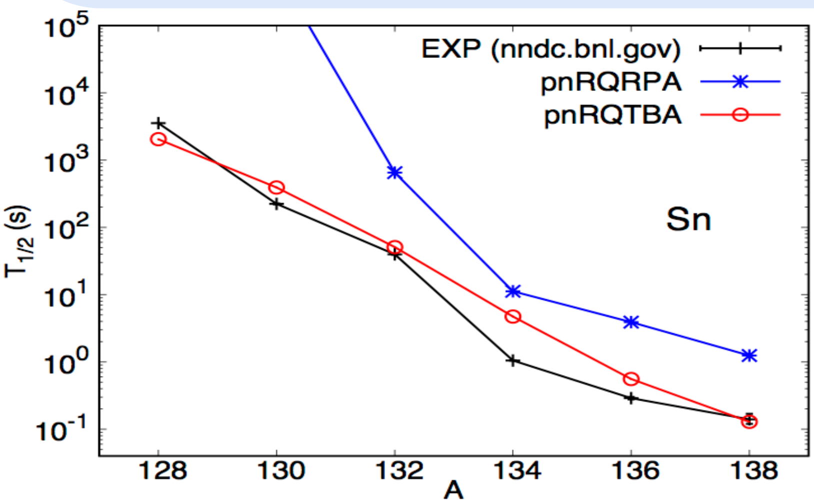
Nucleon self-energy =



Effective NN interaction =

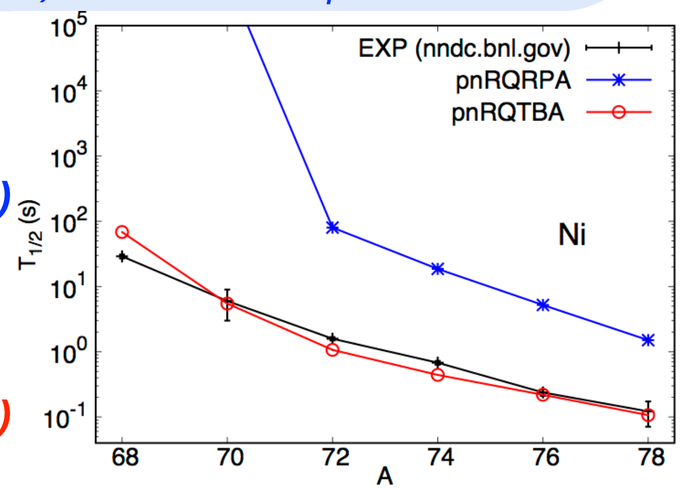


1p-1h (QRPA) *2p-2h*



without coupling to phonons (1p-1h)

with coupling to phonons (2p-2h)

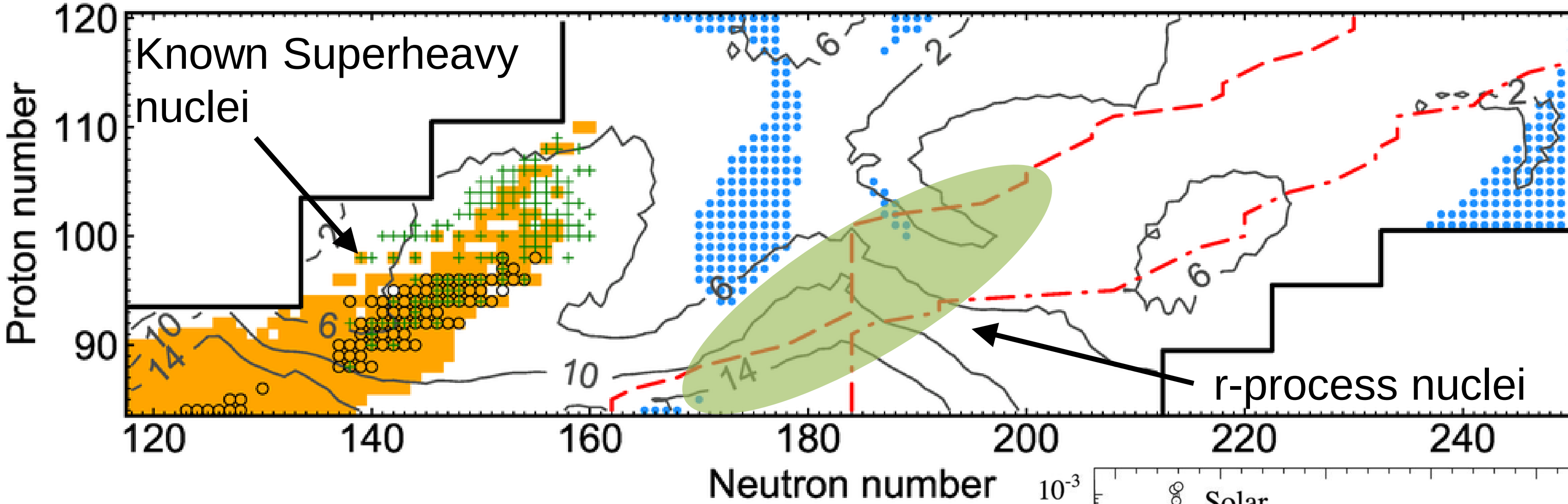


no adjustable proton-neutron pairing

Work lead by Caroline Robin

What is the role of fission in the r-process nucleosynthesis?

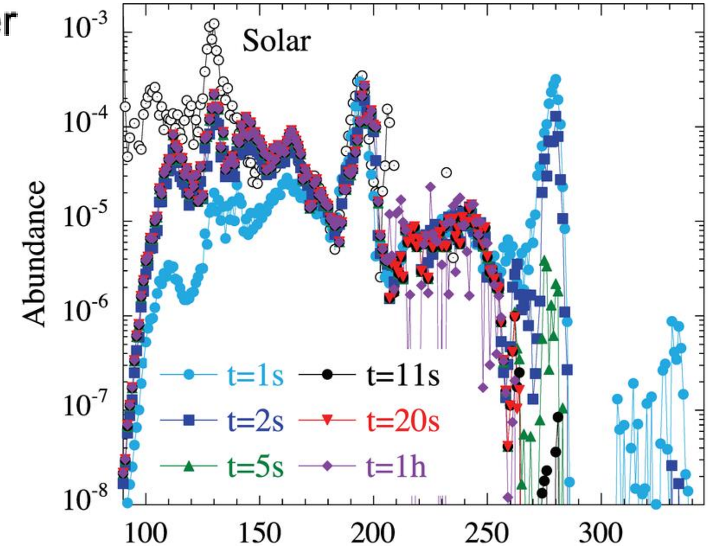
Giuliani et al 2018, 2020



Current r-process modes predict substantial production of nuclei around A~ 280 (Z ~ 96 N ~ 184)

However during their decay to beta stability they fission on timescales of seconds to hours.

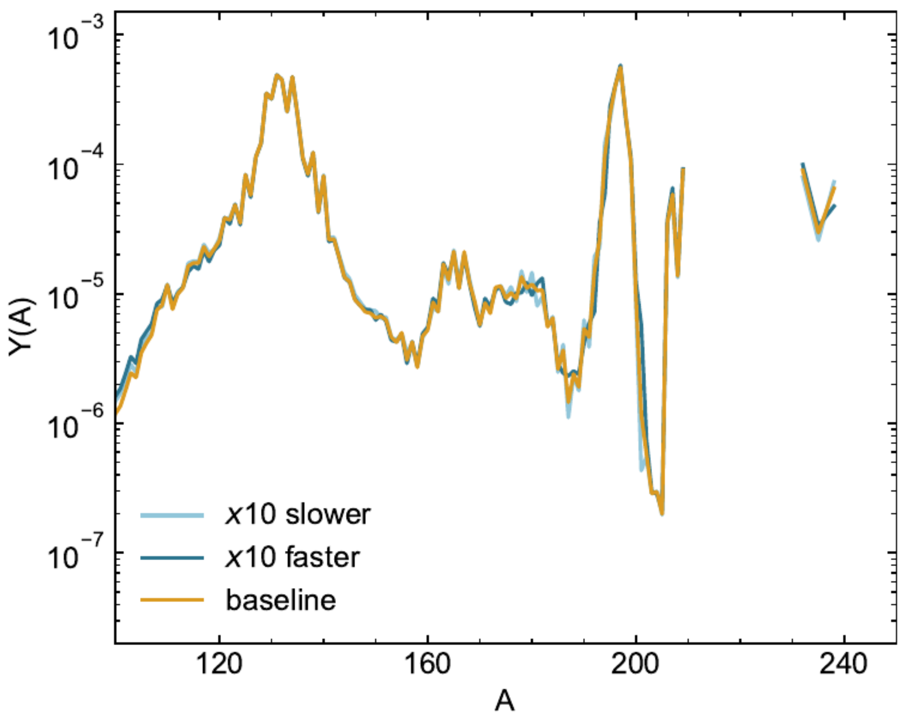
Can we find signatures of (super)heavy nuclei in kilonova light curves?
Light curves sensitive to ^{254}Cf (Wu et al 2019)

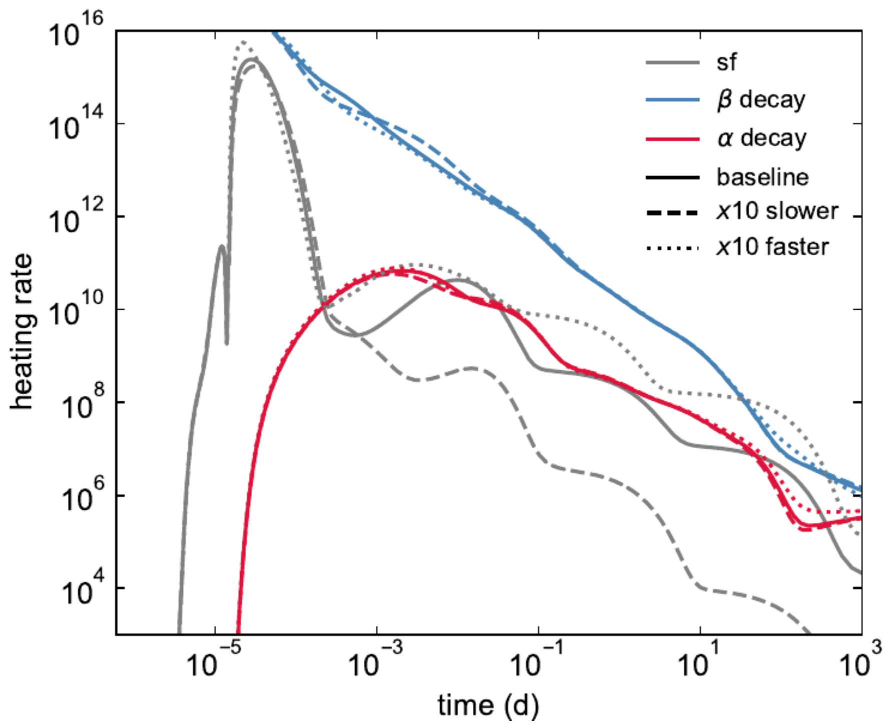


Goriely and GMP NPA **944**, 158 (2015).

Impact long beta half-lives

- 254Cf is produced by a competition between (n,fission) and beta-decay operating on timescales > 1 second
- No experimental information about the beta half-lives of he progenitors is known. Strong impact on radioactive heating





S. Giuliani et al, in preparation

Summary

- Kilonova from GW170817 originates from the statistical radioactive decay of heavy elements. Direct evidence of the “in situ” operation of the r-process. Sr is the only element directly identified

- Evidence of important role of weak processes (neutrino emission and absorption) in determining the neutron richness of the ejecta. Challenge for simulations.

- Ejecta with different neutron-to-proton ratio requiring very different nuclear inputs.