Heavy element nucleosynthesis: the r-process and the νr-process

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FRIB-TA Topical Program: Theoretical Justifications and Motivations for Early High-Profile FRIB Experiments

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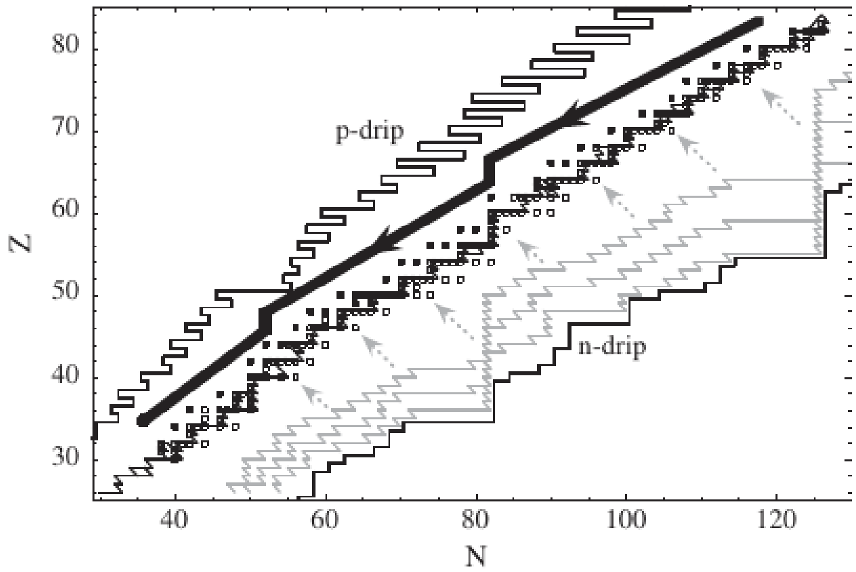
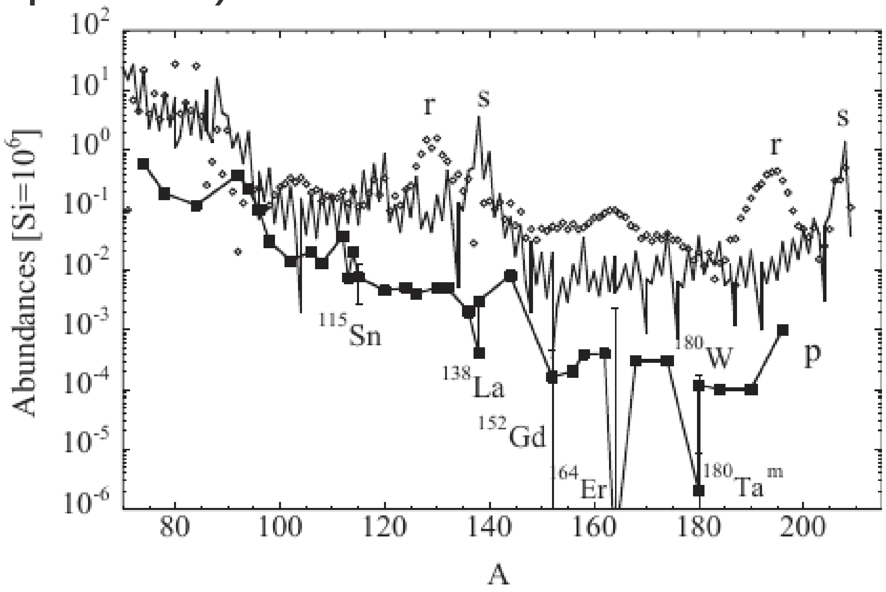
ERC AdG KILONOVA

Nucleosynthesis beyond iron

Two main processes contribute to the nucleosynthesis beyond Iron: s-process, r-process and p-process (γ-process)





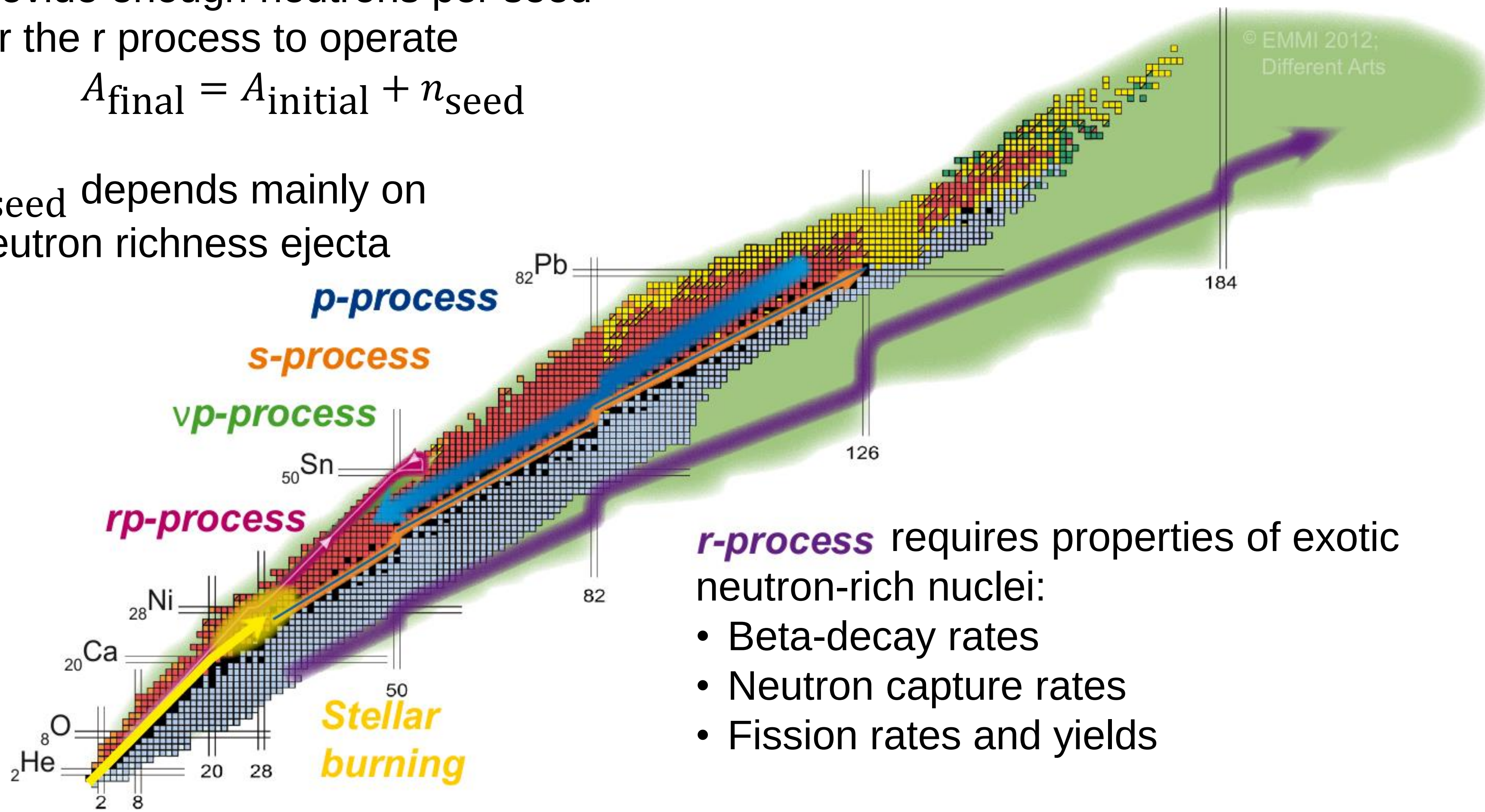
- s process: low neutron densities, $n_n = 10^{10-12}$ cm^{-3}, $\tau_n > \tau_\beta$ (site: intermediate mass stars)
- r process: large neutron densities, $n_n > 10^{20}$ cm^{-3}, $\tau_n \ll \tau_\beta$ (site: binary neutron star mergers?)
- Additional process(es) required to produce neutron-deficient p-nuclei
  - γ-process: photodissociation material enriched by s-process
  - νp-process: (p,γ) and (n,p) reactions catalysed by $\bar{\nu}_e + p \rightarrow n + e^+$

R process needs

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

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

n_{seed} depends mainly on neutron richness ejecta



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

- Beta-decay rates
- Neutron capture rates
- Fission rates and yields

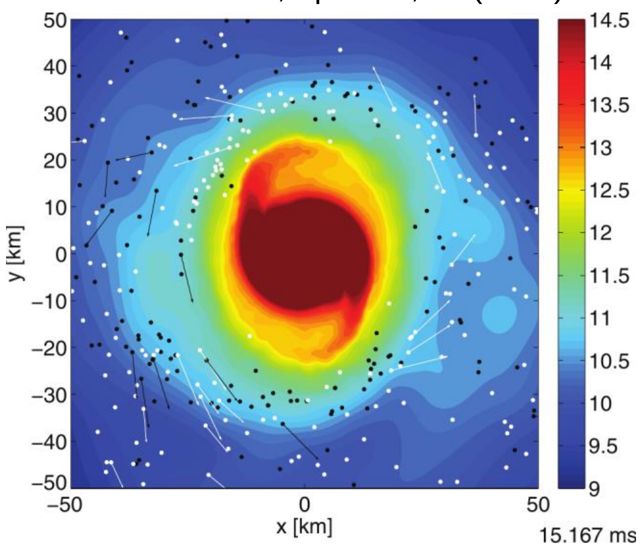
Benchmark against observations:

- Indirect: Solar and stellar abundances (contribution many events, chemical evol.)
- Direct: Kilonova electromagnetic emission (single event, sensitive Atomic and Nuclear Physics)

Pipeline for r-process in mergers

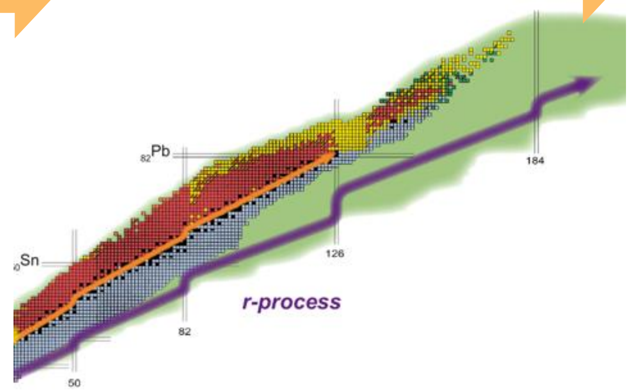
Simulations

Bauswein et al, ApJ 773, 78 (2013)



- Properties ejecta: proton-to-nucleon ratio (Y_e)
- Role of equation of state
- Role of neutrinos

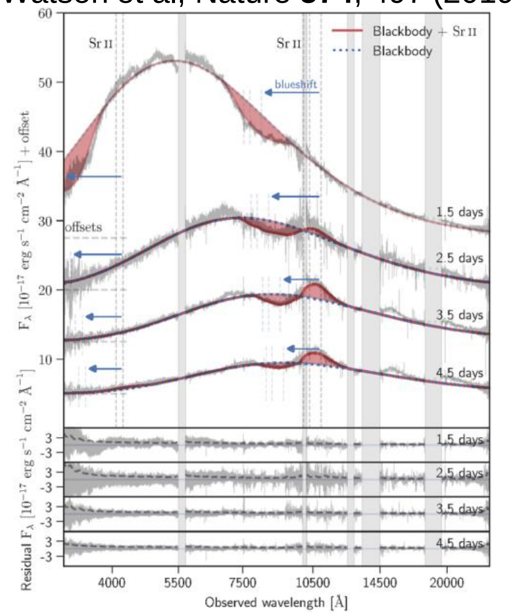
Nucleosynthesis



- Physics of neutron-rich and heavy nuclei

Light curve and spectra modelling

Watson et al, Nature **574**, 497 (2019)



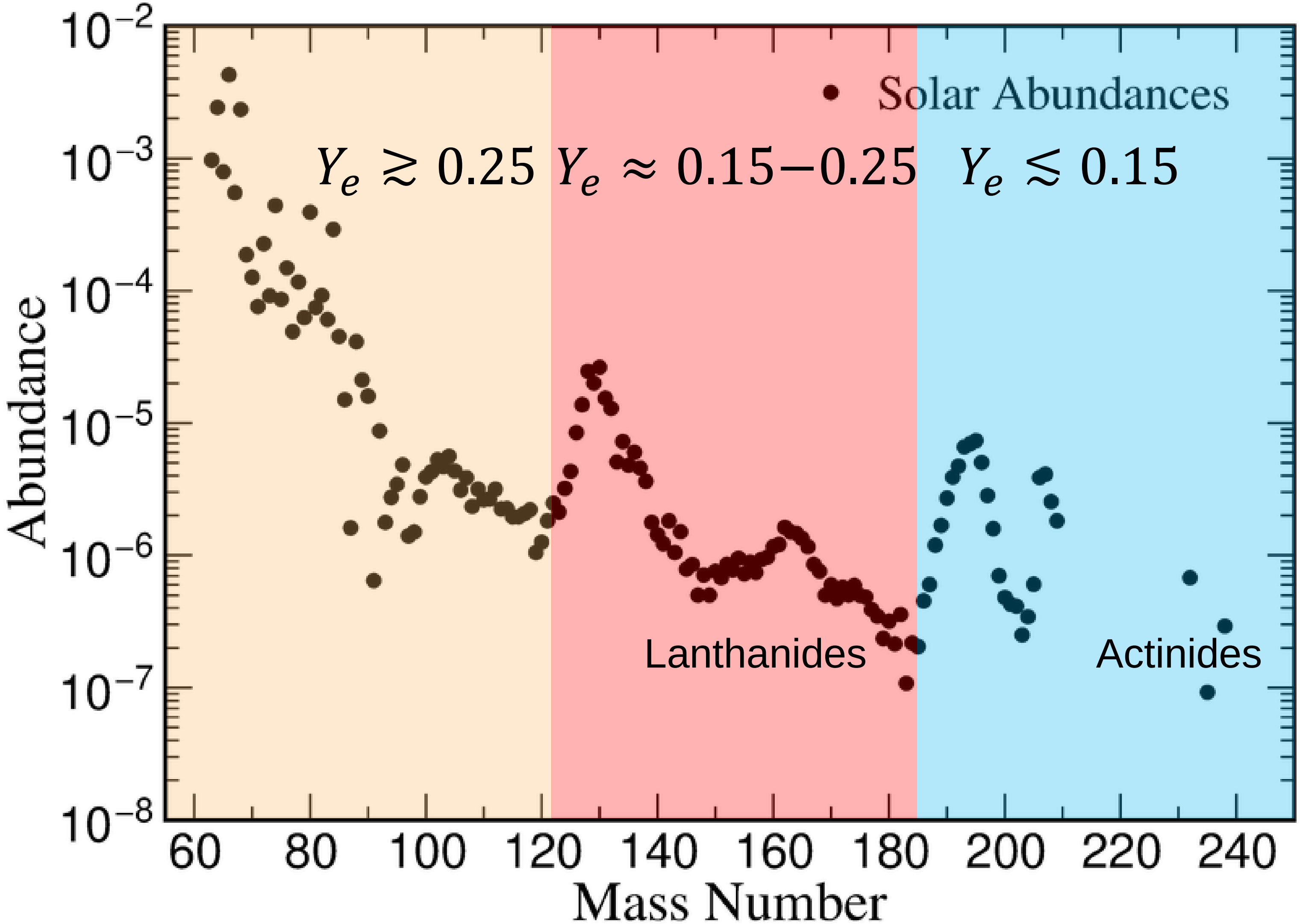
- Radioactive energy deposition
- Thermalization decay products (Barnes+ 2016, Kasen+ 2019)
- Spectra formation: atomic data depends on ejecta evolution (LTE vs NLTE)

- Which r-process elements are produced in mergers?
- Are mergers the (main) r-process site?

Nucleosynthesis dependence on Y_e

Nucleosynthesis mainly sensitive to proton-to-nucleon ratio, $Y_e = n_p/(n_n + n_p)$

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

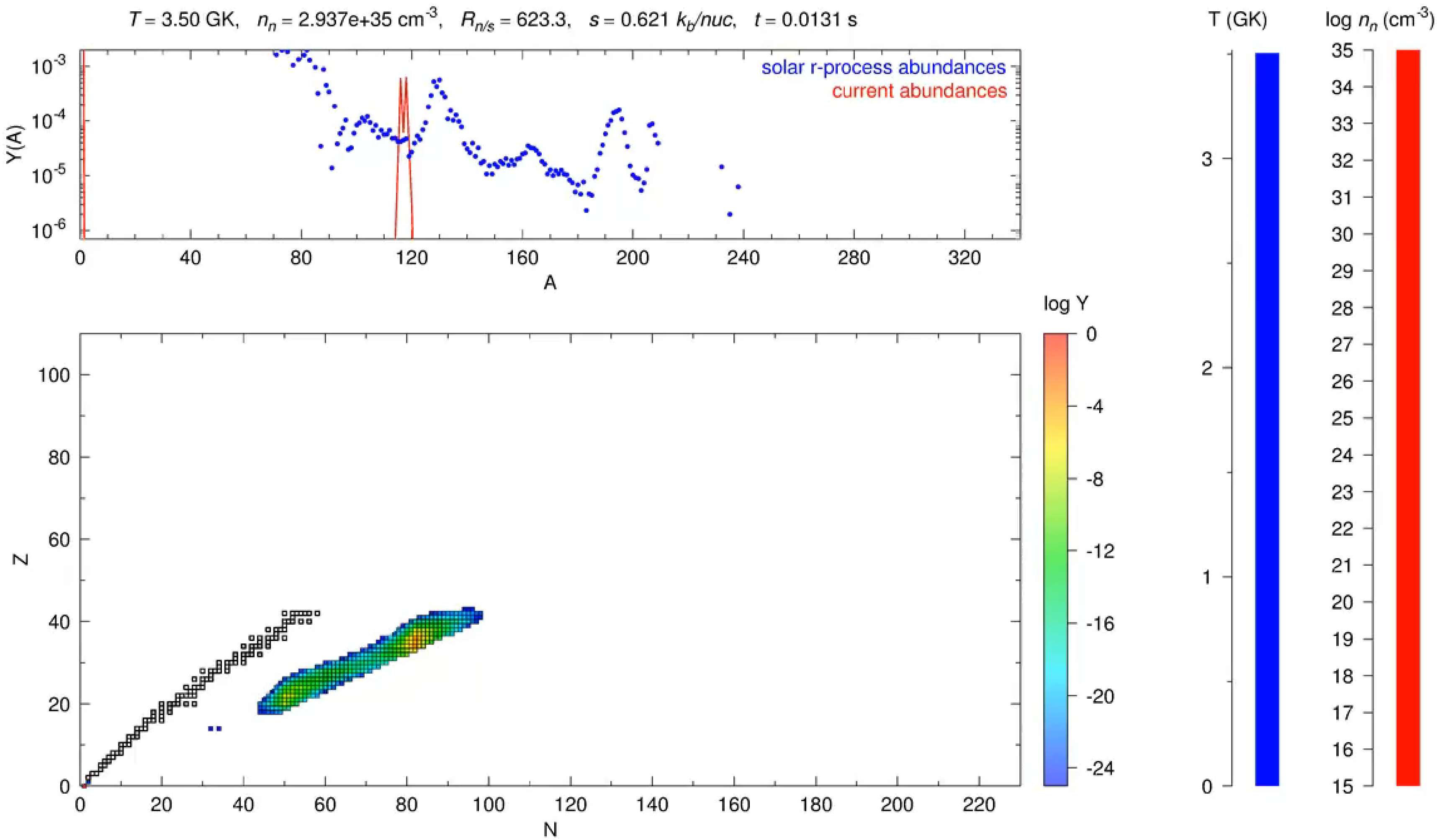


Phases during the operation of the r-process

- **Weak freeze-out:** proton-to-nucleon ratio determined by (anti)neutrino absorption and their inverses
- **Seed production**: Charged particle reactions operating for $T \gtrsim 2\ GK$ produce the seed nuclei and neutrons
- **Neutron-capture phase:** neutrons are captured on the available seed nuclei on a typical times of $\sim 1\ s$. Different equilibria are achieved:
  - $(n,\gamma) \rightleftarrows (\gamma,n)$ equilibrium defines the r-process path that is mainly sensitive to the nuclear masses
  - Beta-flow equilibrium: abundance given element is proportional to the beta-decay half-lives. R-process peaks associated to nuclei with longest half-lives.
- **Freeze-out and decay to stability:** fully dynamical phase in which competition between neutron-captures, beta-decay (and fission) determines the final abundance pattern. Most sensitive phase to the nuclear input

R-process operation

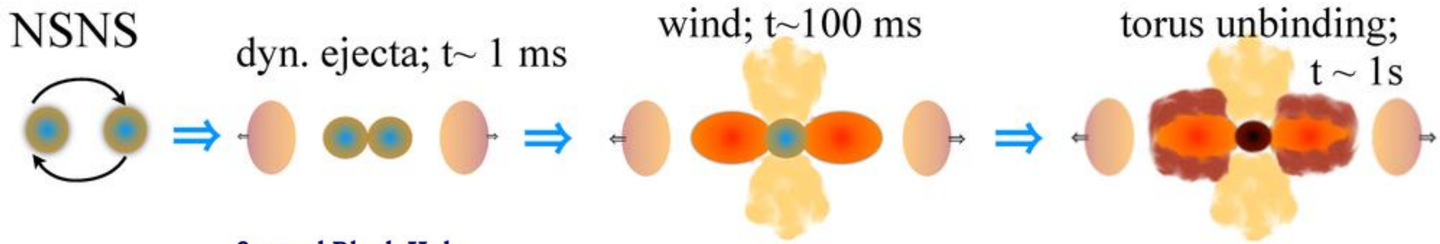
Heavy elements produced by the r-process. Radioactive decay liberates energy

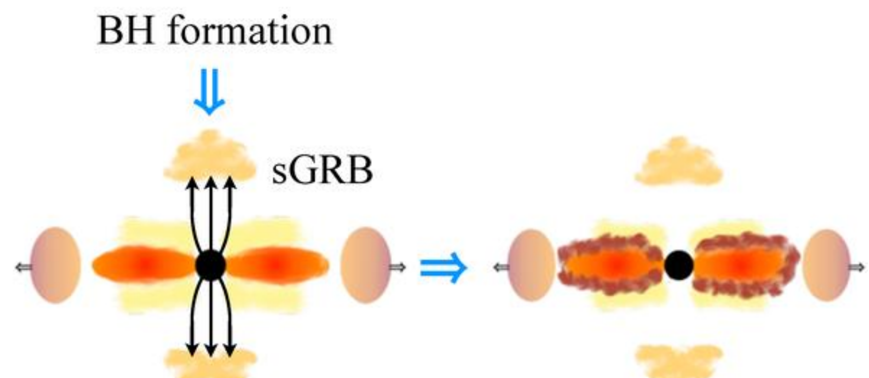


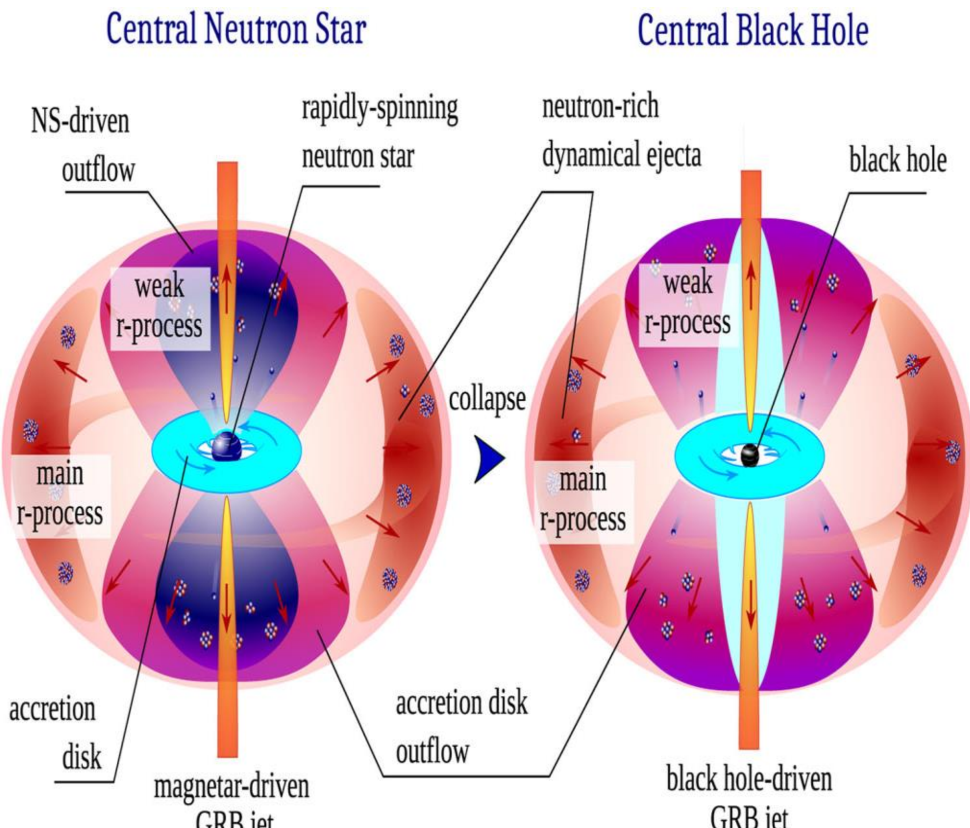
Neutron star mergers:
Different ejection mechanisms

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

Gravitational wave emission







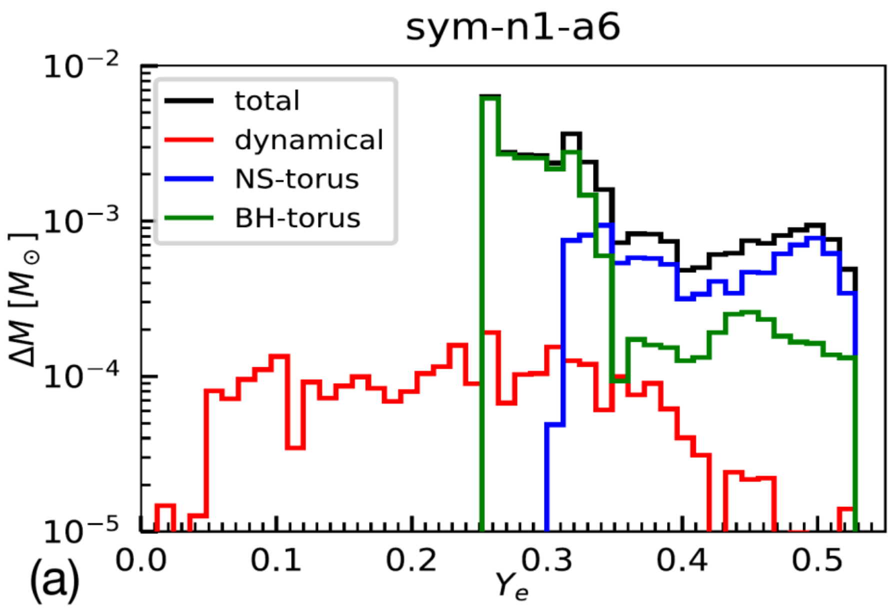
S. Rosswog and O. Korobkin, Annalen Der Physik **2022**, 2200306 (2022).

Two sources of ejecta:

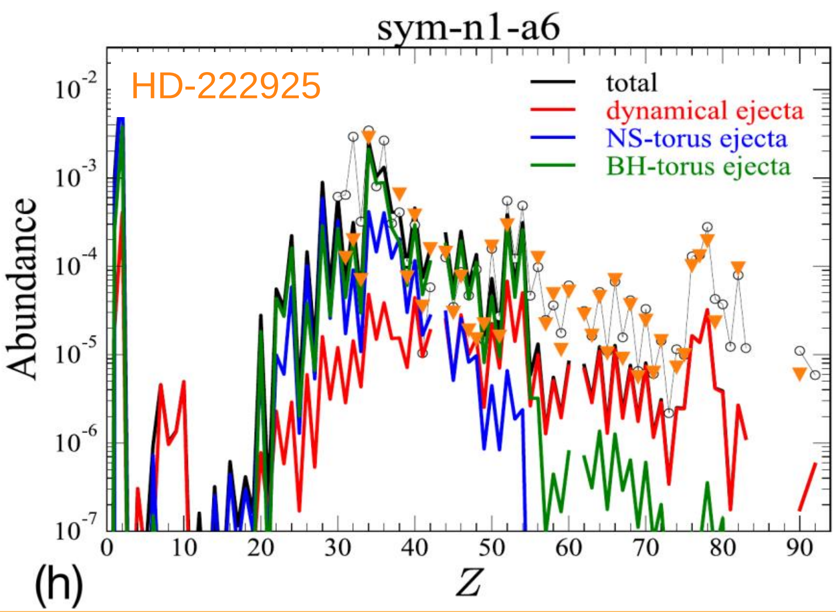
- Dynamical during the early phases of the merger ($M \lesssim 0.01\ M_\odot$)
- Accretion disc on longer timescales ($M \lesssim 0.05\ M_\odot$)
- Liftetime neutron-star determines impact neutrinos

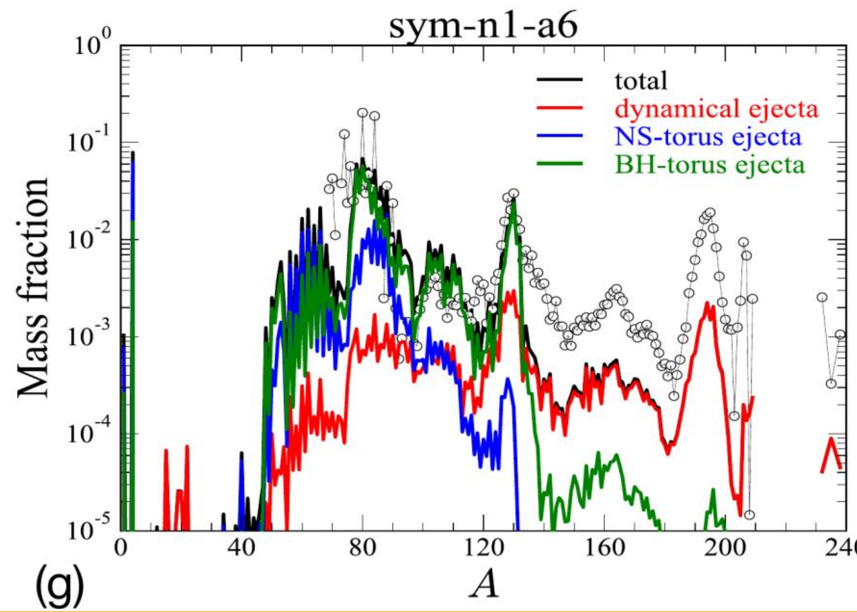
Long term merger simulations

First long-term simulations with neutron star lifetimes 0.1-1 s and describe all components of the ejecta: dynamical, NS-remnant ejecta, and final viscous ejecta from BH torus.

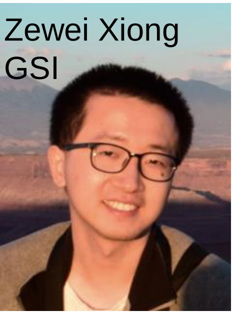


Just et al, arXiv:2302.10928





The νr-process



arXiv:2305.11050v1 [astro-ph.HE] 18 May 2023

Production of p-nuclei from r-process seeds: the νr-process

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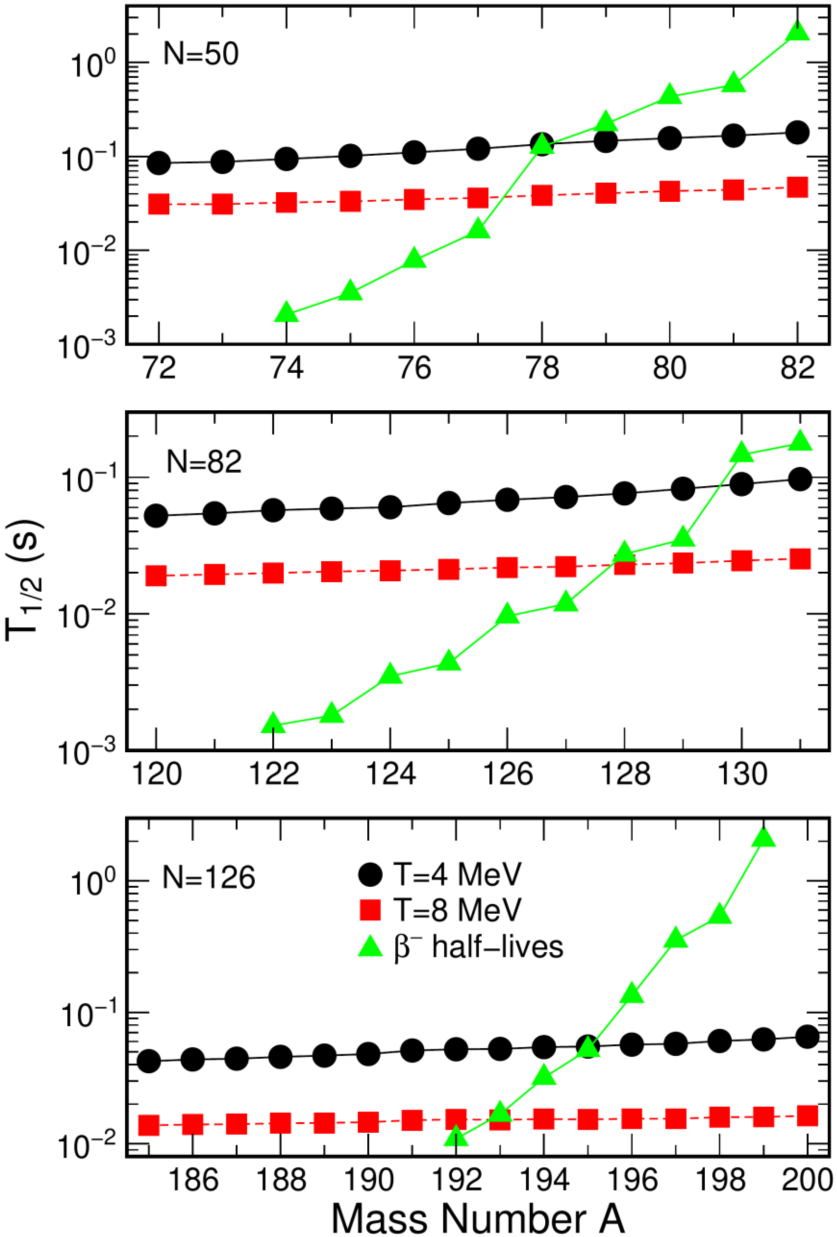
We present a *new* nucleosynthesis process that may take place on neutron-rich ejecta experiencing an intensive neutrino flux. The nucleosynthesis proceeds similarly to the standard r-process, a sequence of neutron-captures and beta-decays, however with charged-current neutrino absorption reactions on nuclei operating much faster than beta-decays. Once neutron capture reactions freeze-out the produced r-process neutron-rich nuclei undergo a fast conversion of neutrons into protons and are pushed even beyond the β-stability line producing the neutron-deficient p-nuclei. This scenario, which we denote as the νr-process, provides an alternative channel for the production of p-nuclei and the short-lived nucleus ^{92}Nb. We discuss the necessary conditions posed on the astrophysical site for the νr-process to be realized in nature. While these conditions are not fulfilled by current neutrino-hydrodynamic models of r-process sites, future models, including more complex physics and a larger variety of outflow conditions, may achieve the necessary conditions in some regions of the ejecta.

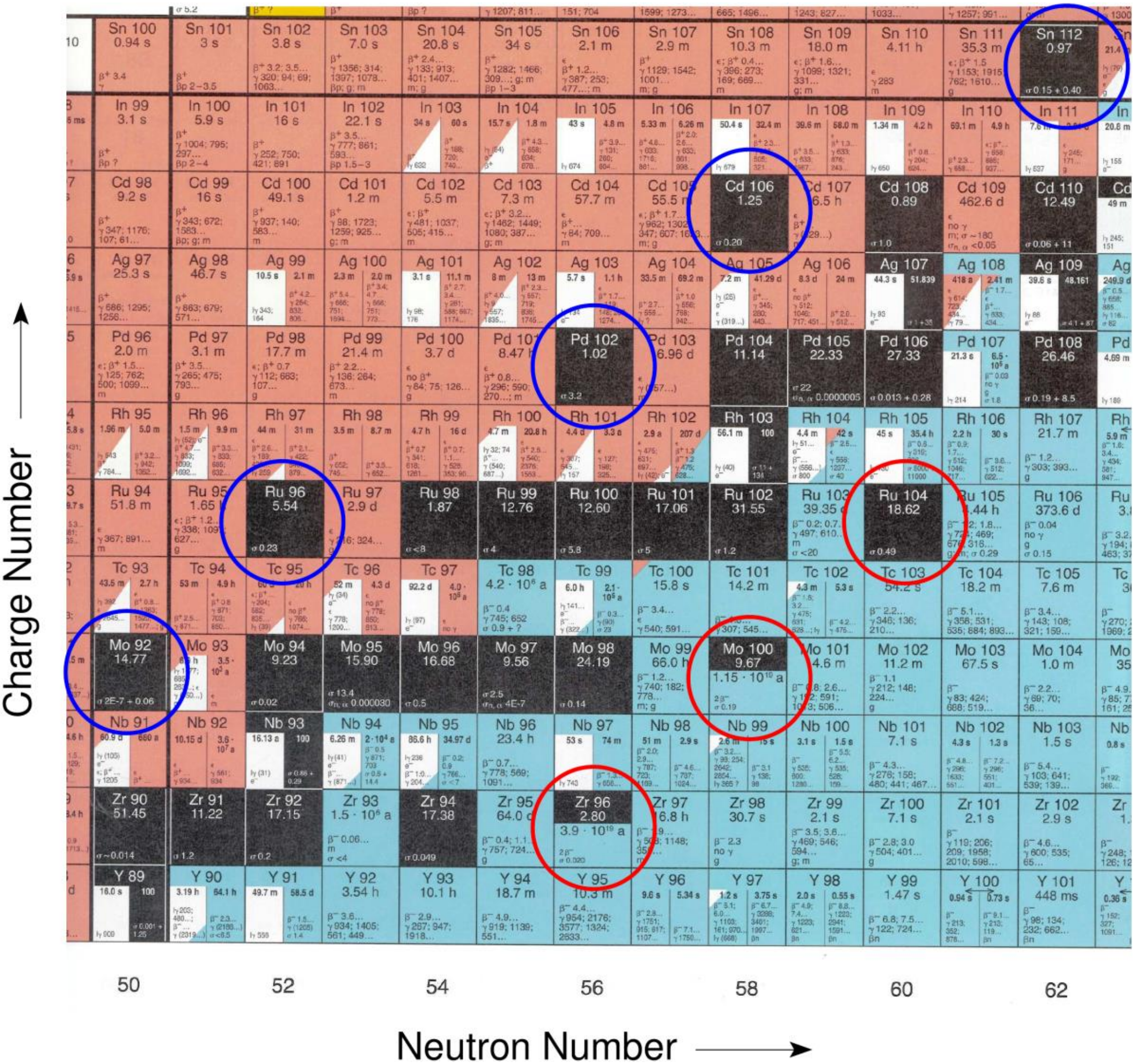
- A new nucleosynthesis process that may operate in binary neutron star mergers under strong neutrino fluxes when nuclei are present: charged-current neutrino-nucleus reactions faster than β^- decays.
- Novel mechanism for production of p-nuclei from neutron-rich nuclei.

Role of neutrinos in r-process

- Large (anti)neutrino fluxes drive composition to $Y_e \sim 0.5$ during alpha-particle formation (Meyer et al, 1995)
- large neutrino fluxes during the phase of neutron captures erode r-process peaks related to long beta-decays (Langanke, GMP, 2003)
- ν_e absorption cross sections $\sim (N - Z)$
- What will be the resulting nucleosynthesis?



Possible source of light p-nuclei and ^{92}Nb



γ-process fails to produce light p-nuclei ^{92,94}Mo and ^{96,98}Ru in solar proportions

Supernova neutrino winds:

- Ejecta with $Y_e \sim 0.48$ produce ^{92}Mo
- νp-process ($Y_e \gtrsim 0.55$) produces ^{94}Mo, ^{96,98}Ru.

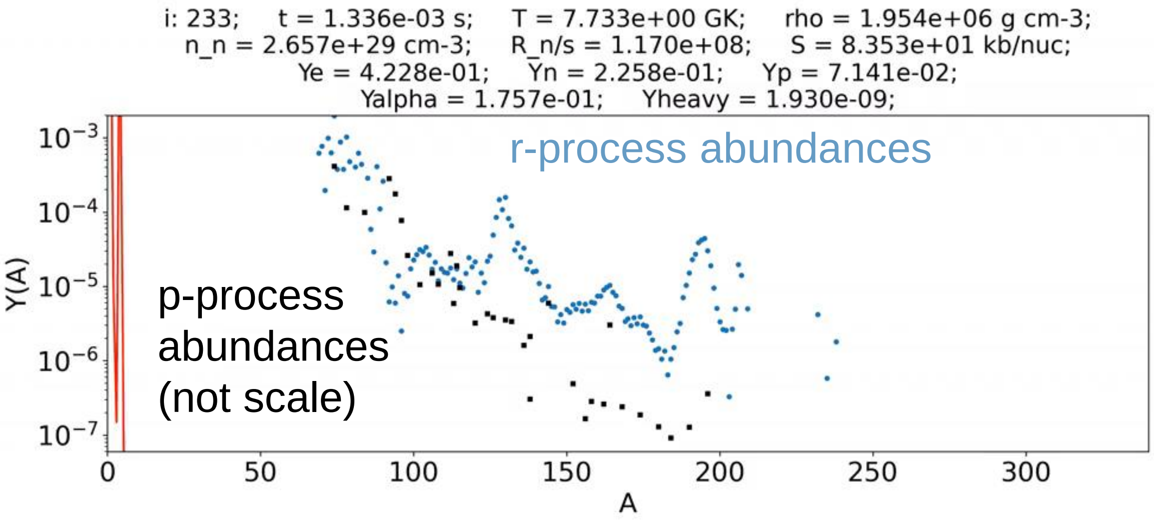
Long-lived ^{92}Nb present in early solar system. Cannot be produced by the νp-process

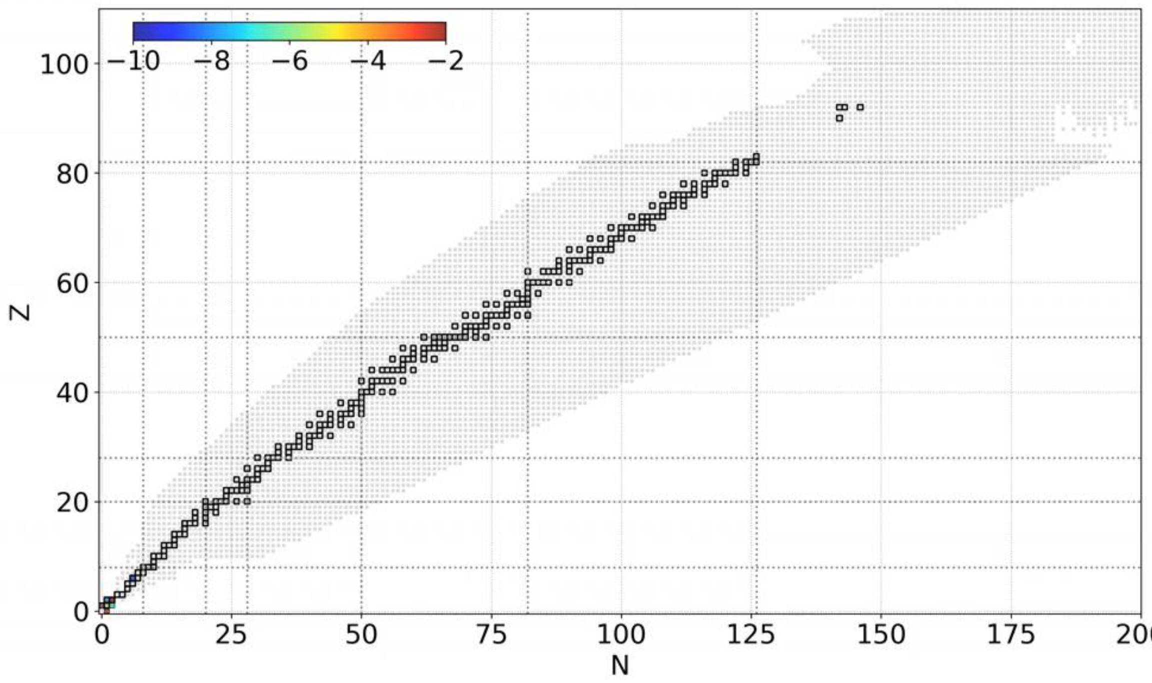
Can we produce all those nuclei in the same environment including heavier p-nuclei?

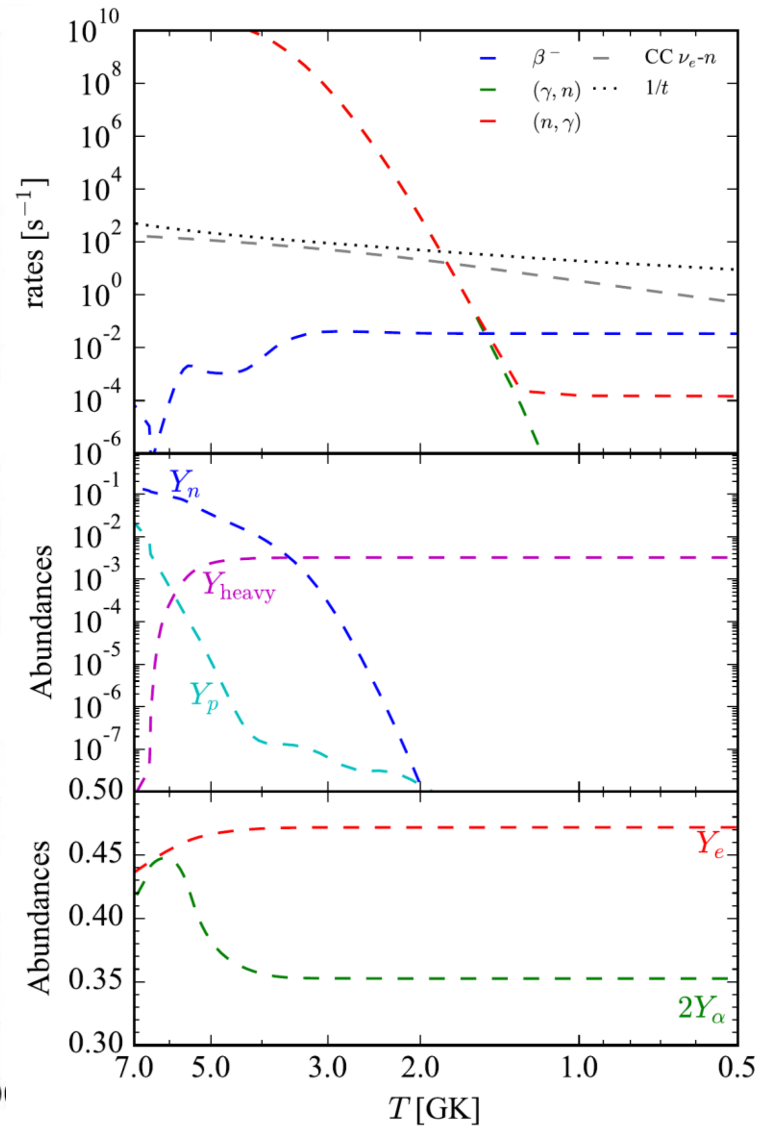
Phases during the operation of the νr-process

- **Seed production:** Strong neutrino fluxes drive material to $Y_e \sim 0.5$
- **Neutron-capture phase:** neutrons are used relatively fast by two competing mechanisms:
  - $n(\nu_e, e^-)p$ converts neutrons into protons that are captures in medium mass nuclei
  - $A(\nu_e, e^- X)\ X = n, p, \alpha$ speeds up the decay of nuclei and the build up of heavy nuclei
- **Fast "decay" to stability and beyond:** $A(\nu_e, e^- X)$ reactions drive material to beta-stability and beyond
  - Neutrons, protons and alphas produced by both charged-current and neutral current spallation reactions.
  - Protons and alphas captured mainly in light nuclei
  - Equilibrium between $A(\nu_e, e^- X)$ and $A(n, \gamma)$ determines final abundance

Nucleosynthesis (no neutrino-nucleus)

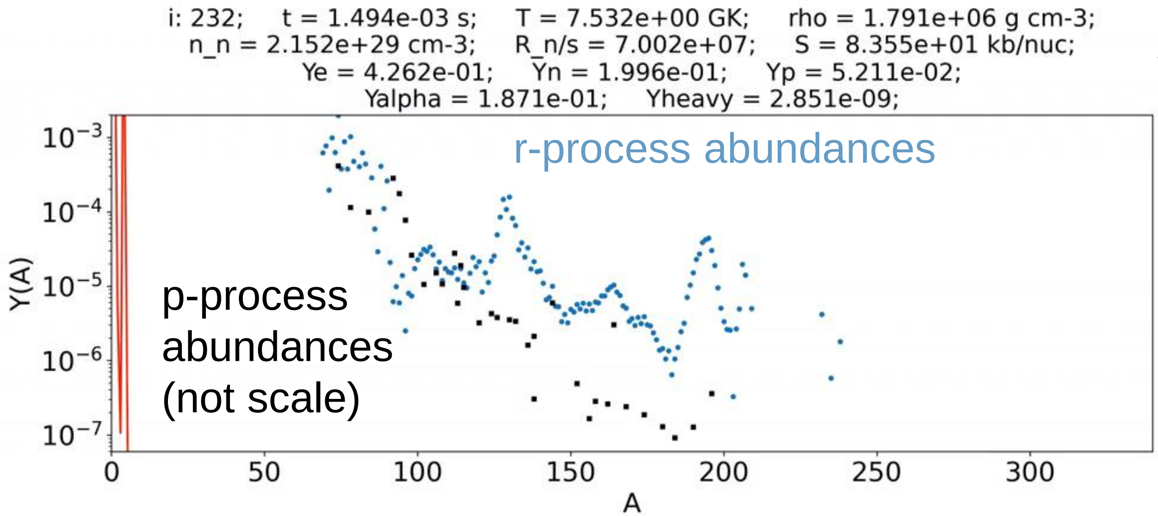


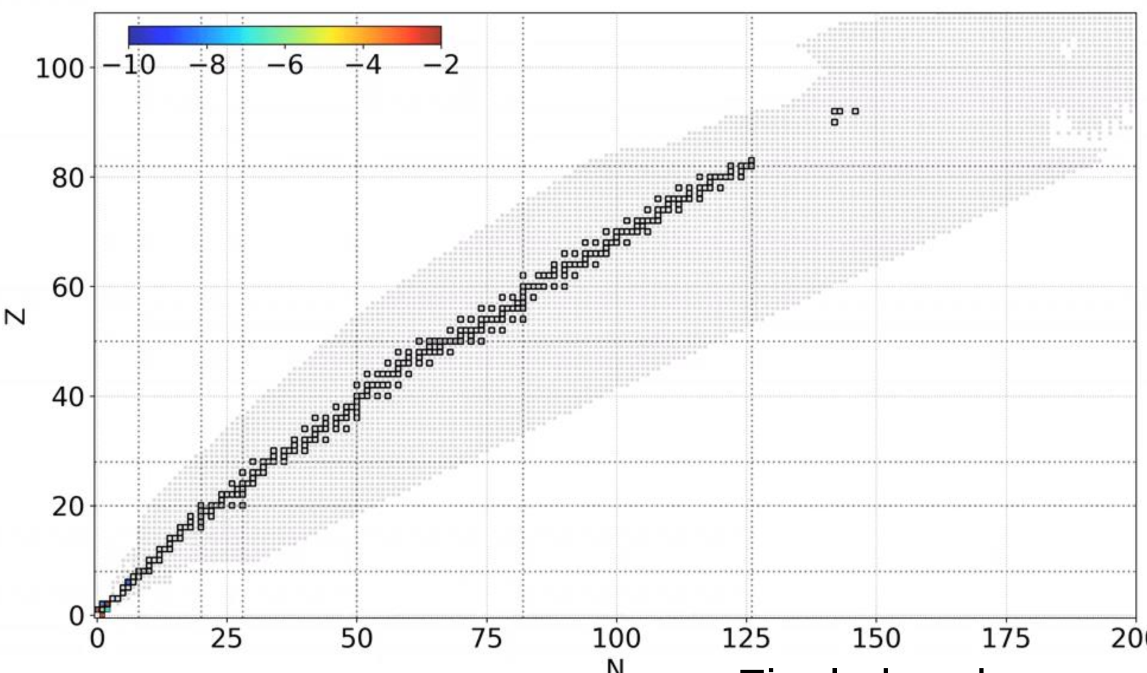


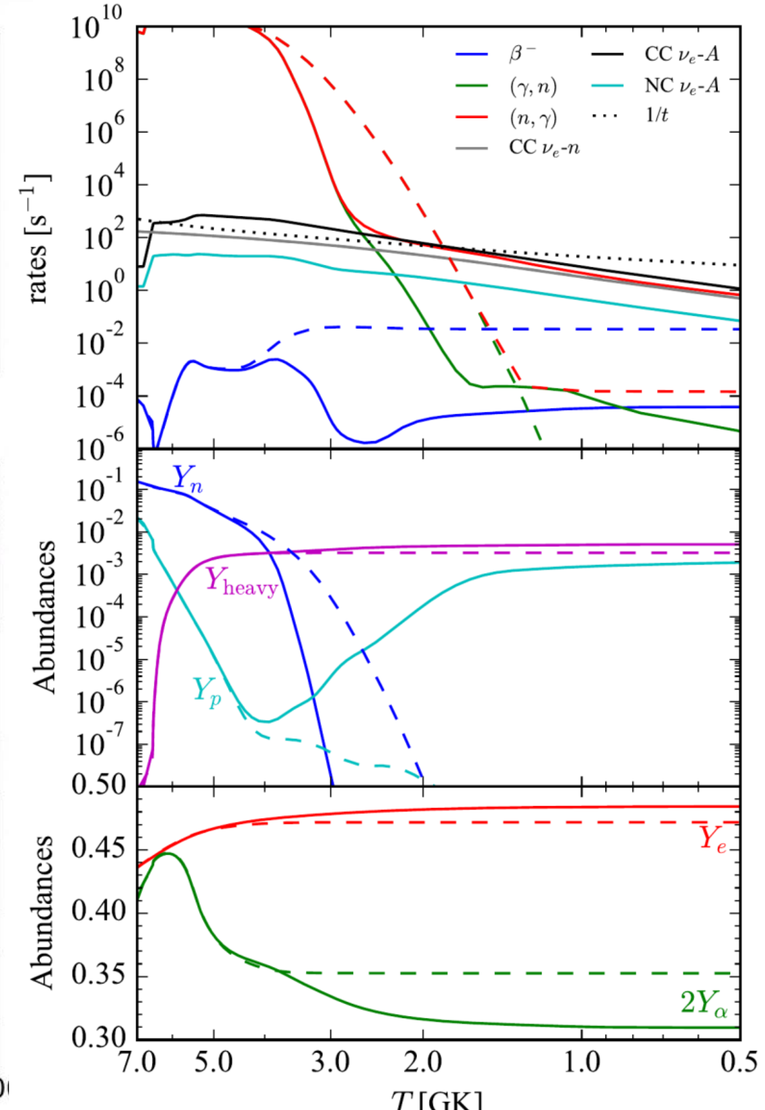


Nucleosynthesis (with neutrino-nucleus)

$\nu - A$ cross sections from Sieverding, et al, ApJ 865, 143 (2018).





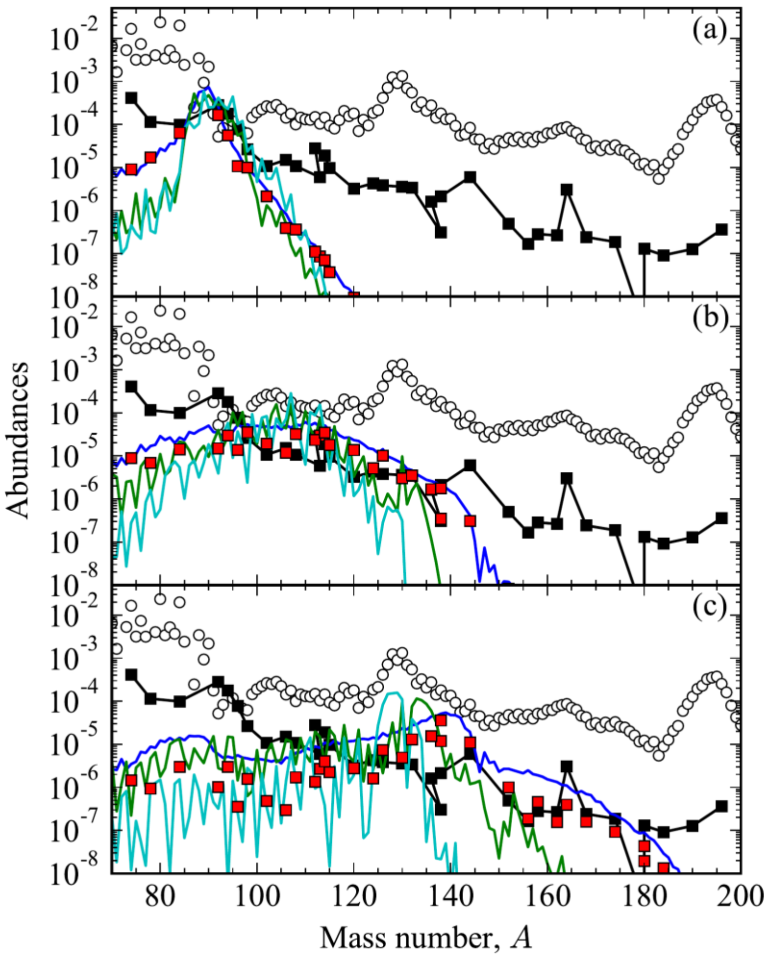


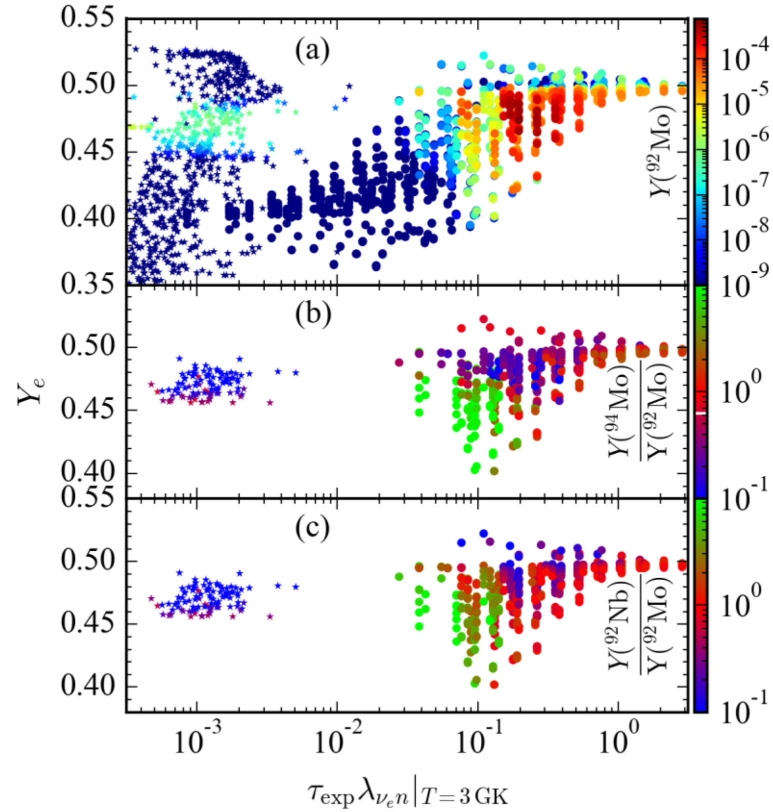
Final abundance quilibrium between (ν_e, e^-) and (n, γ)

Dependence on neutrino fluence

Increasing neutrino fluence allows to produce heavier p-nuclei

Dependence Y_e and neutrino fluence

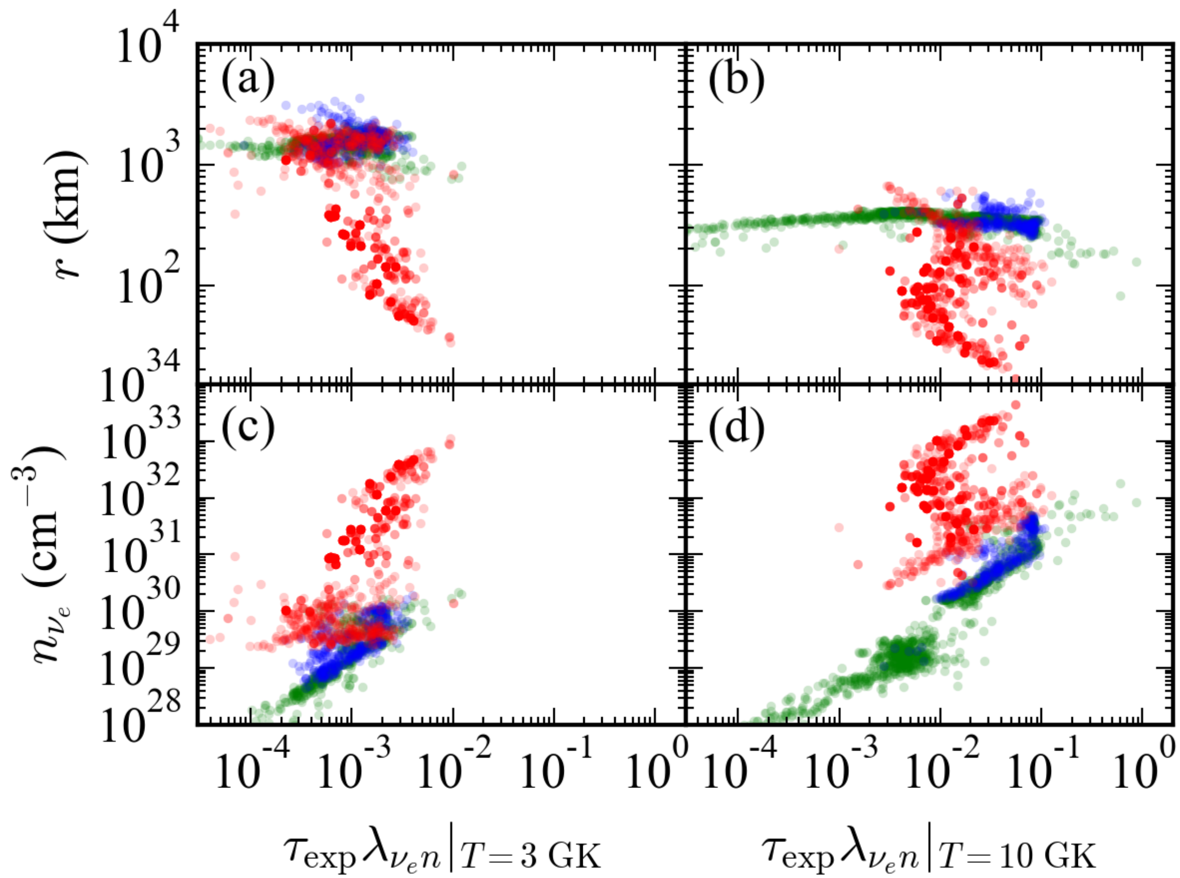




Current neutrino-hydrodynamical models far from the necessary conditions

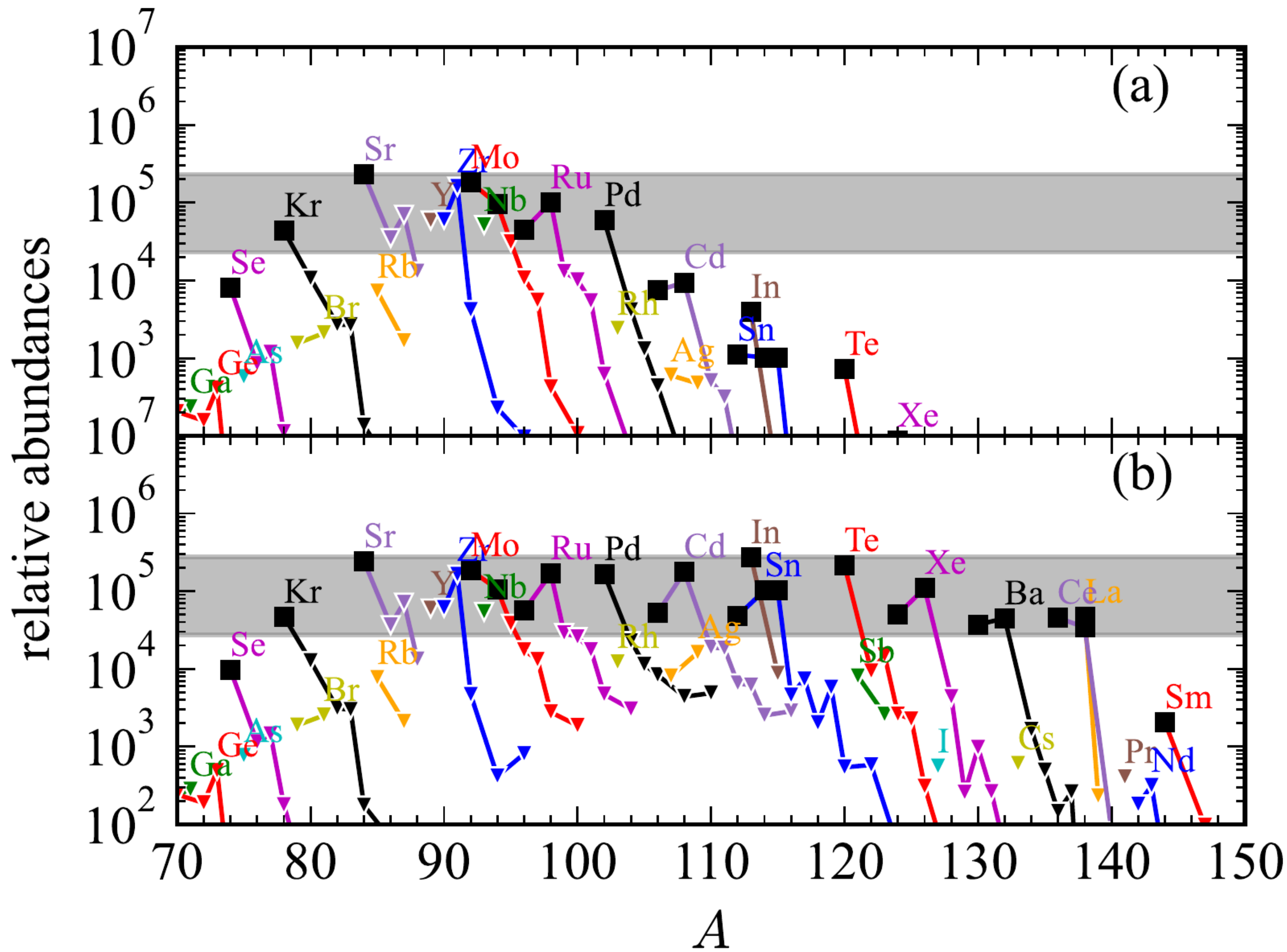
Conditions current merger models

Dynamical, neutron-star torus, black-hole torus



- Material reaches the necessary fluence conditions but it is too hot form nuclei
- A non-thermal ejection mechanism is necessary (magnetic fields?)

Coproduction of all p-nuclei



- All p-nuclei can be consistently produced
- Assuming the same astrophysical site produces both r-process and p-nuclei around 1% of the ejecta should reach νr-process conditions

Summary

- Multi-messenger observations (Gravitational and Electromagnetic waves) from binary neutron star mergers provide unique opportunities to study the production of heavy elements:
  - Neutron star mergers identified as one astrophysical site where the r-process operates
  - Kilonova observations provide direct evidence of the "in situ operation of the r-process"
- Strong synergies with FRIB and FAIR experiments
- νr-process: new mechanism production p-nuclei:
  - Gamow-Teller and (spin-)dipole resonances near stability determine neutrino cross sections.
  - Important role of (n,γ) cross sections near stability.