An overview heavy element nucleosynthesis: the r-process and the νr-process

Gabriel Martínez-Pinedo

The Radiative Transfer and Atomic Physics of Kilonovae

Wenner-Gren Center, Stockholm,

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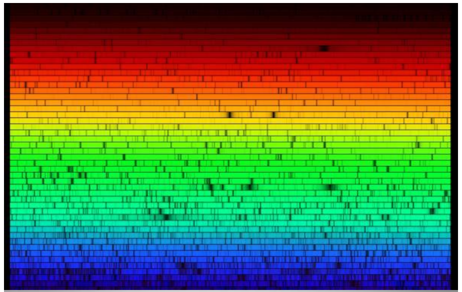
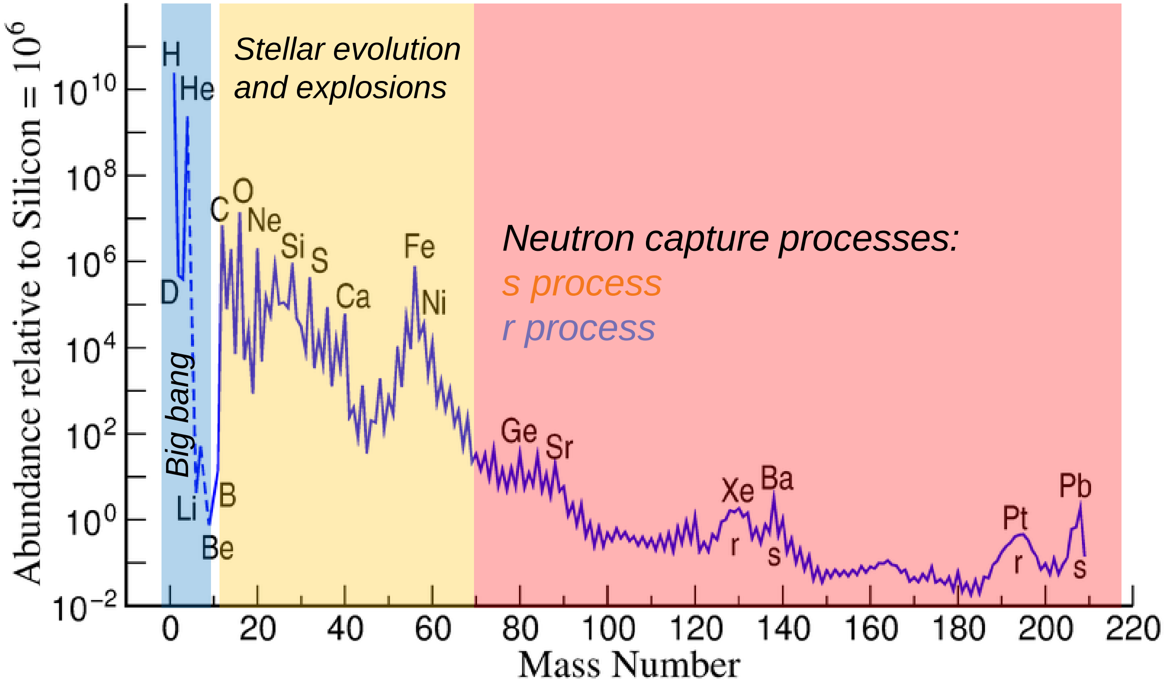
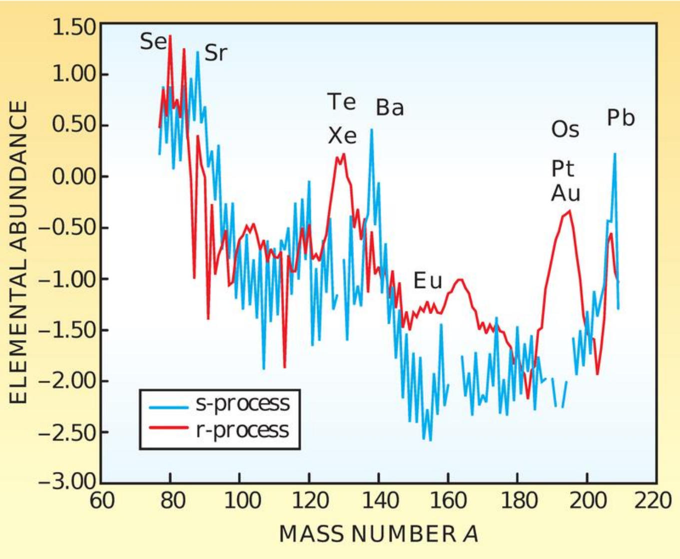
Solar system abundances

Solar photosphere and meteorites:
chemical signature of gas cloud where the Sun formed

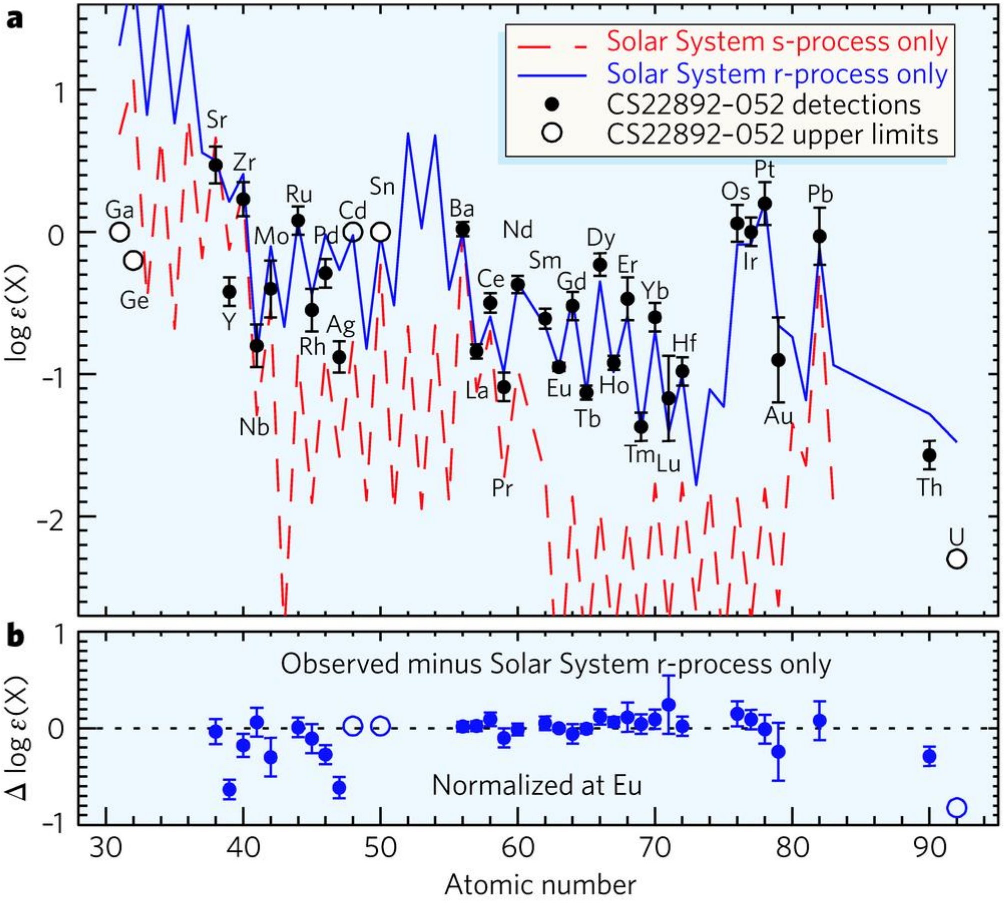


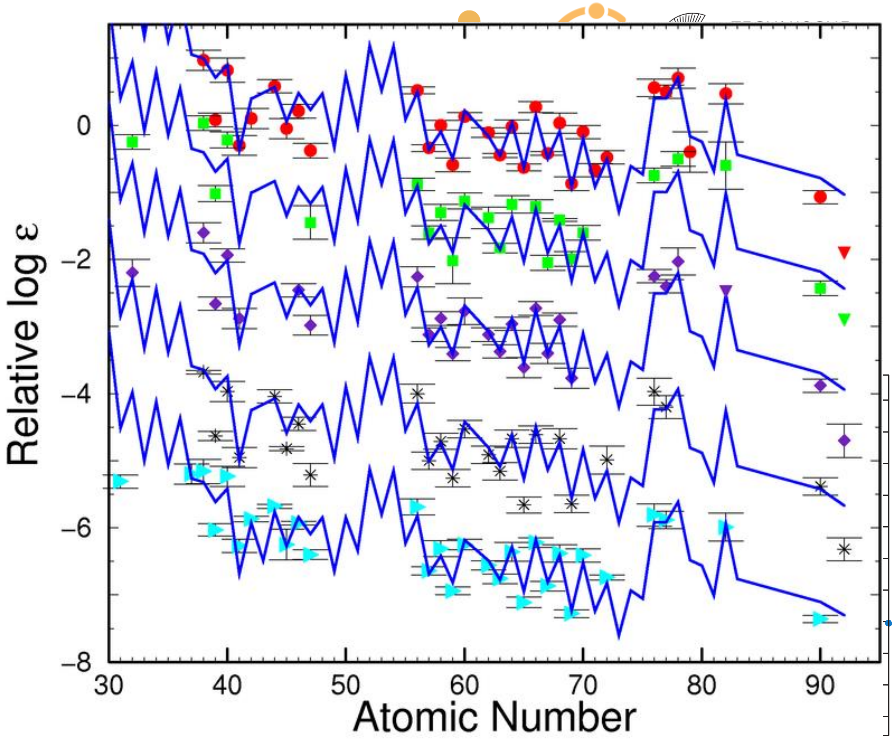


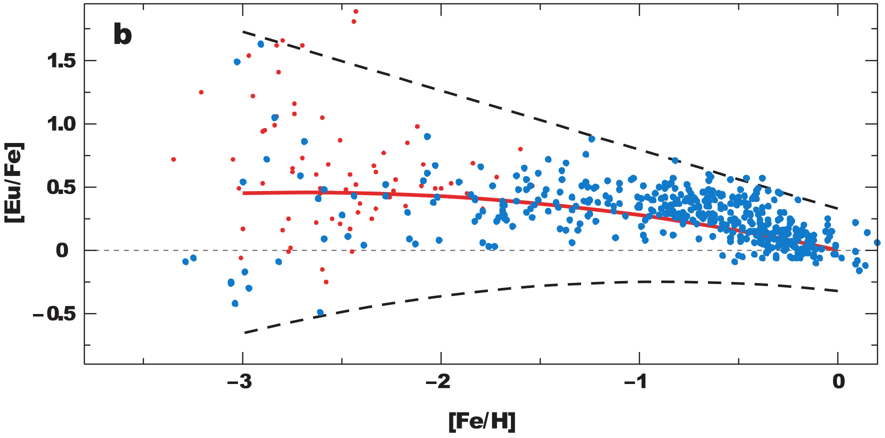
- Signatures of nuclear structure and nuclear stability
  Contributions of different nucleosynthesis processes
- Heavy elements produced by neutron capture processes



Metal-poor stars observations



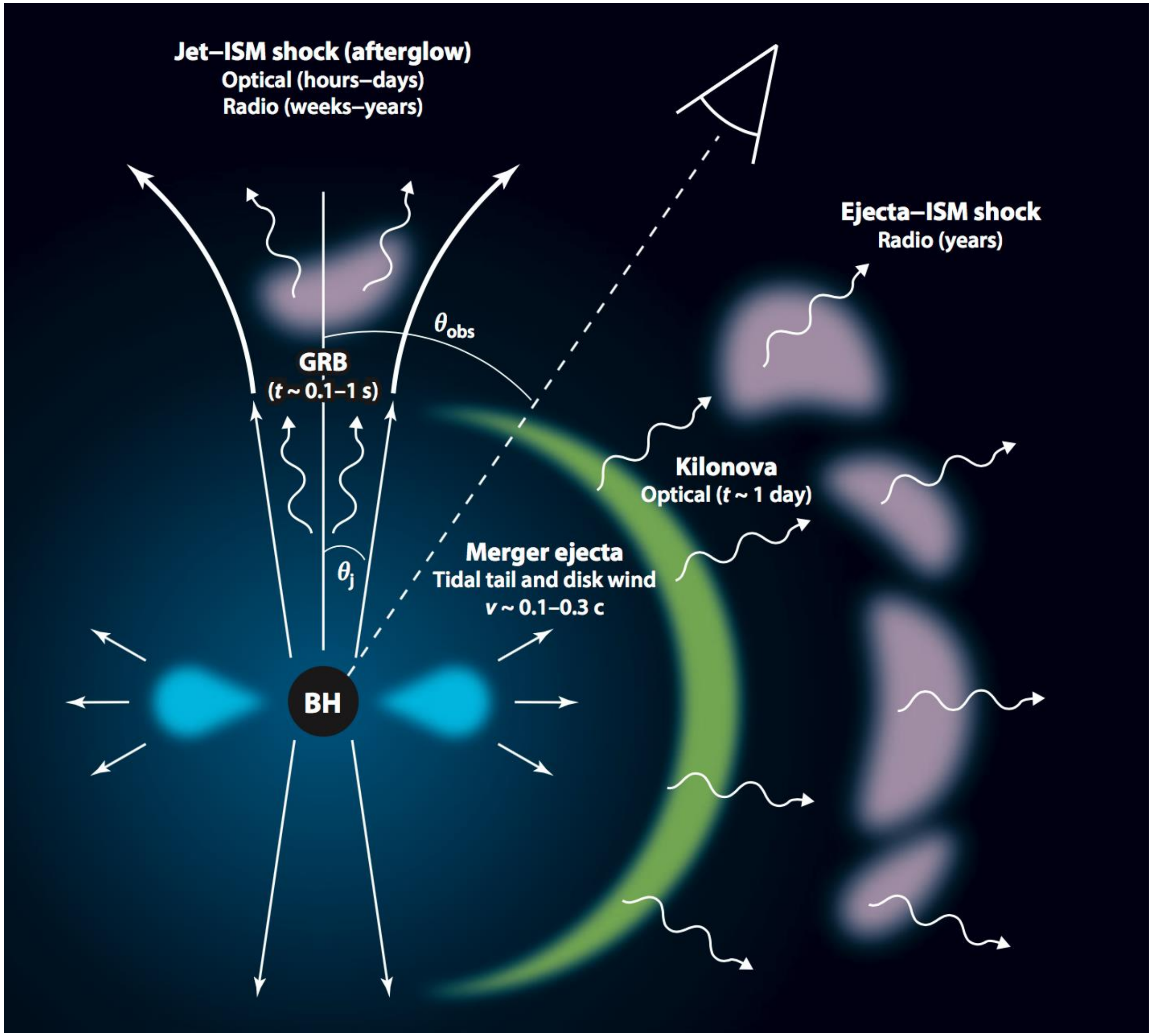




- Observations indicate that r process operates from early Galactic history in rare (high yield) events
- What are the nucleosynthesis yields from single events?

Kilonova: signature of the r-process

Line of view GW170817



Metzger & Berger 2012

Kilonova: An electromagnetic transient due to long term radioactive decay of r-process nuclei

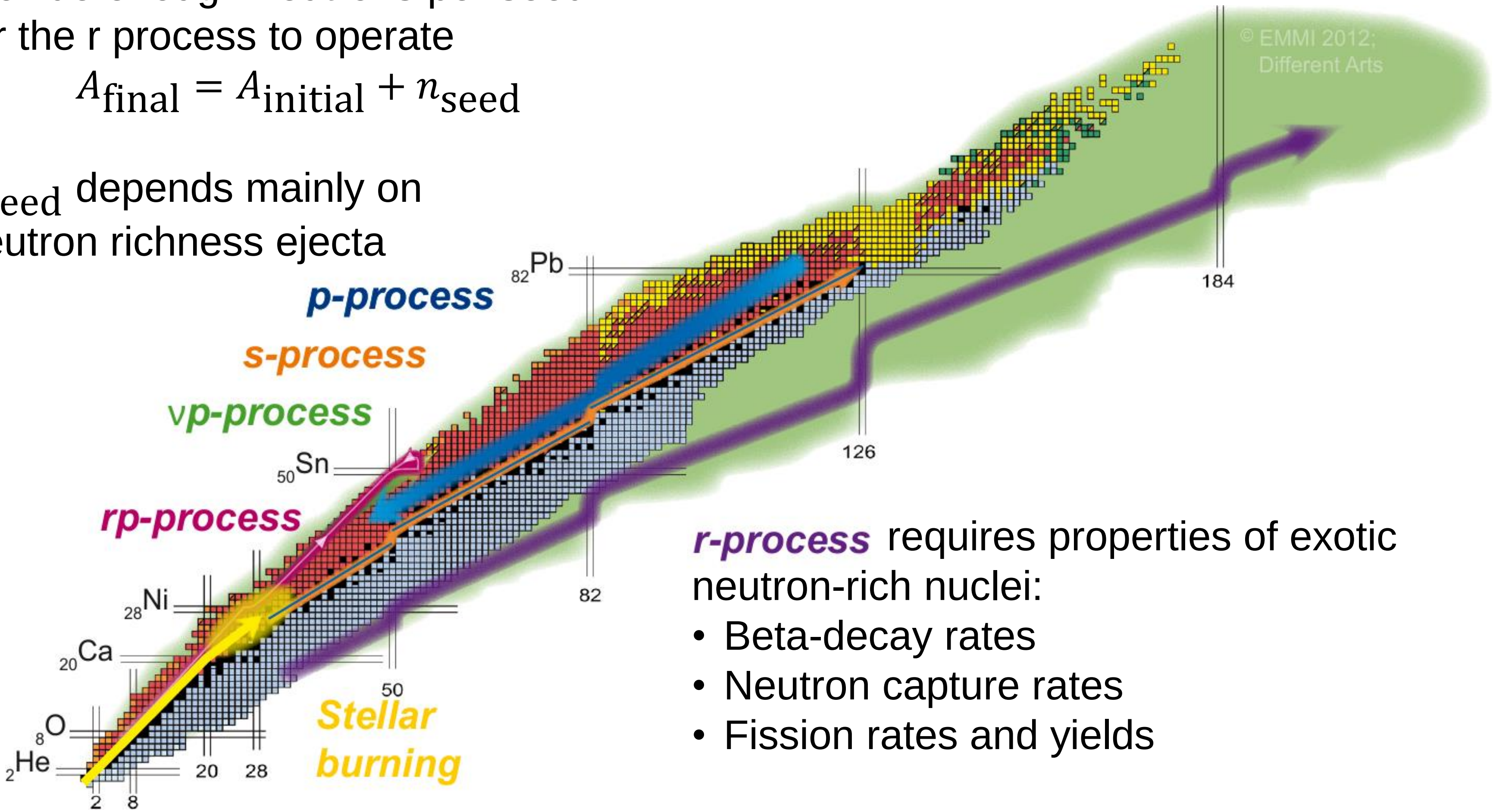
- Electromagnetic counterpart to Gravitational Waves
- Diagnostics physical processes at work during merger
- Direct probe of the formation r-process nuclei

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

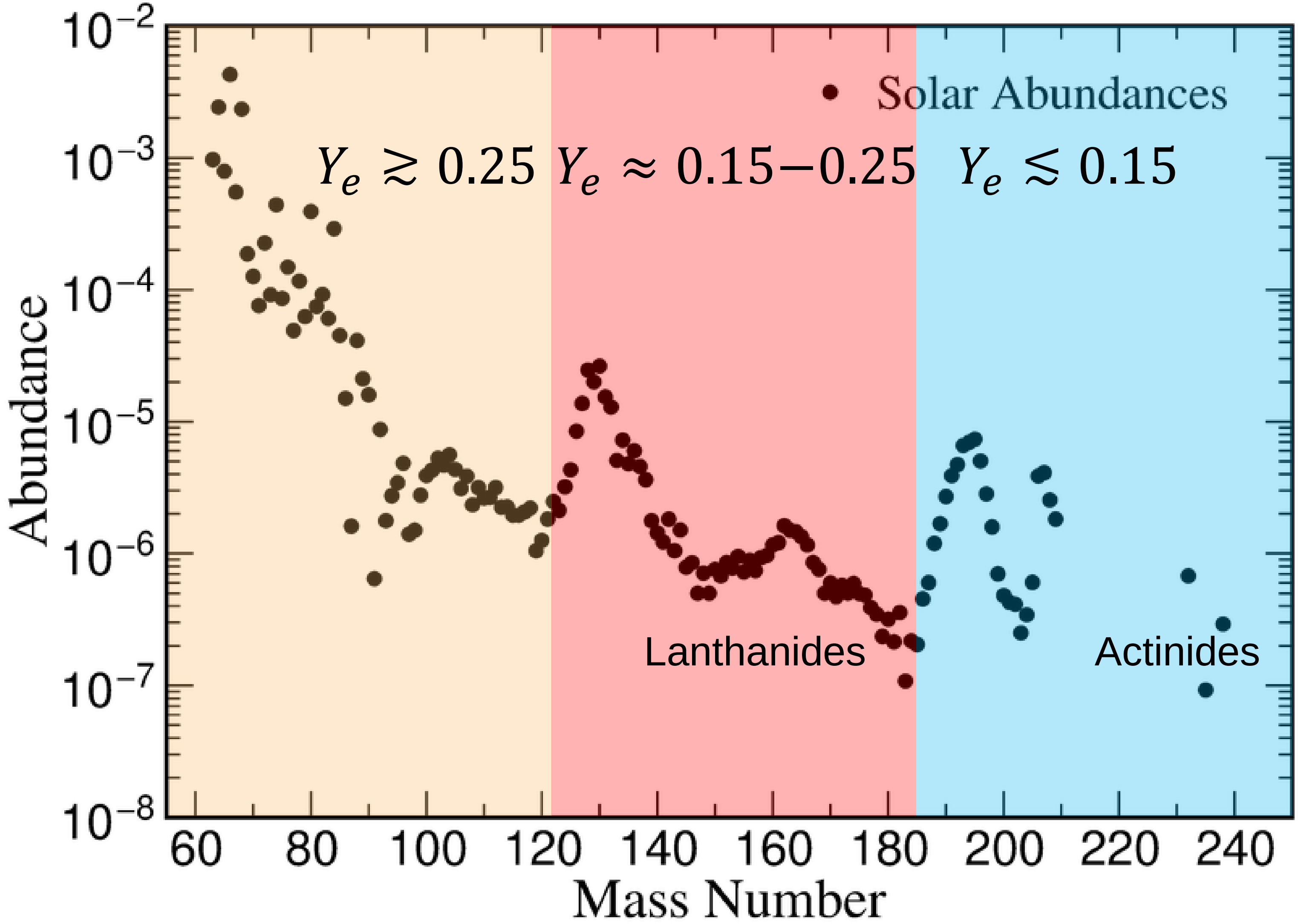
Benchmark against observations:

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

Nucleosynthesis dependence on Y_e

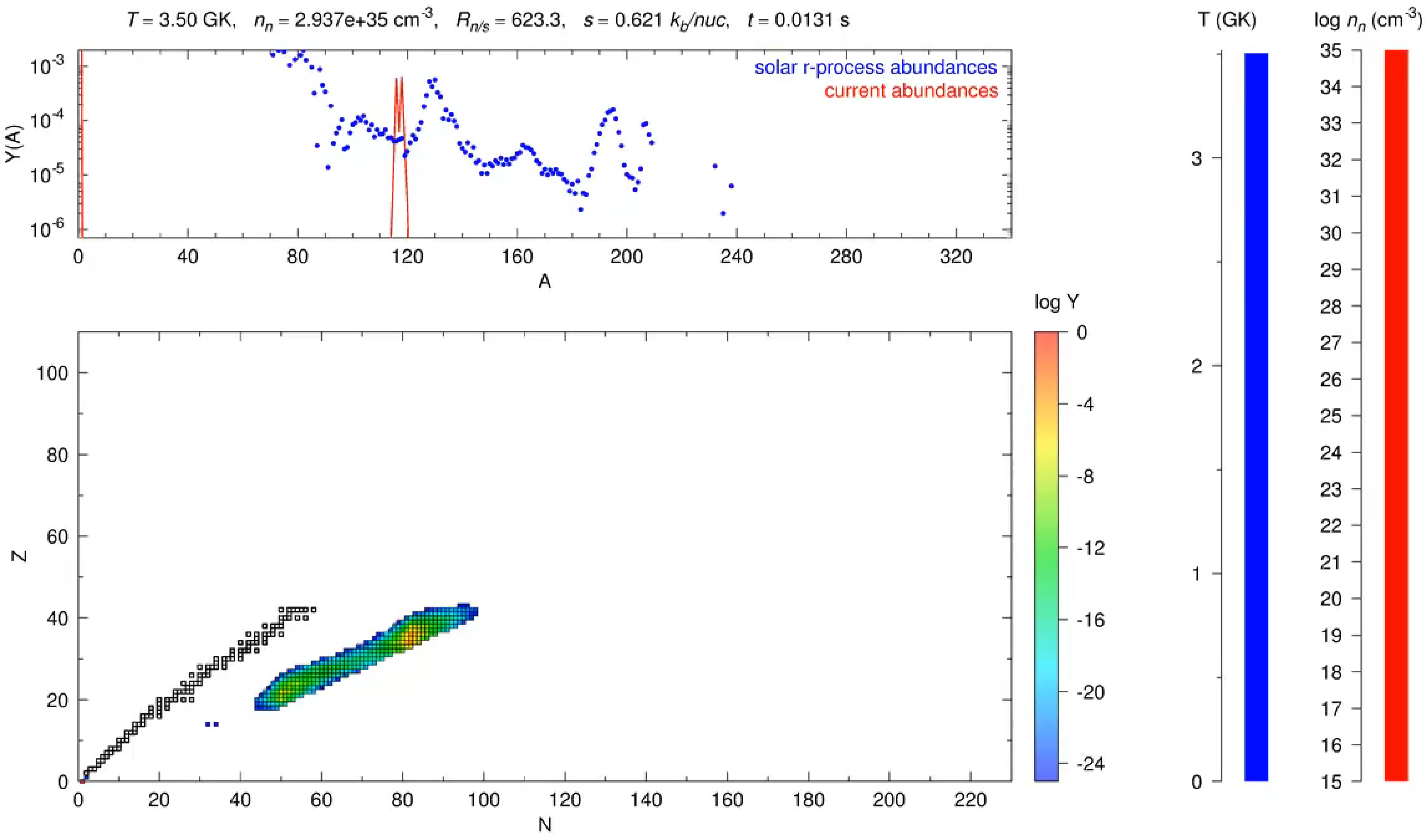
Nucleosynthesis mainly sensitive to proton-to-nucleon ratio, $Y_e = n_p/(n_n + n_p)$

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



R-process operation

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



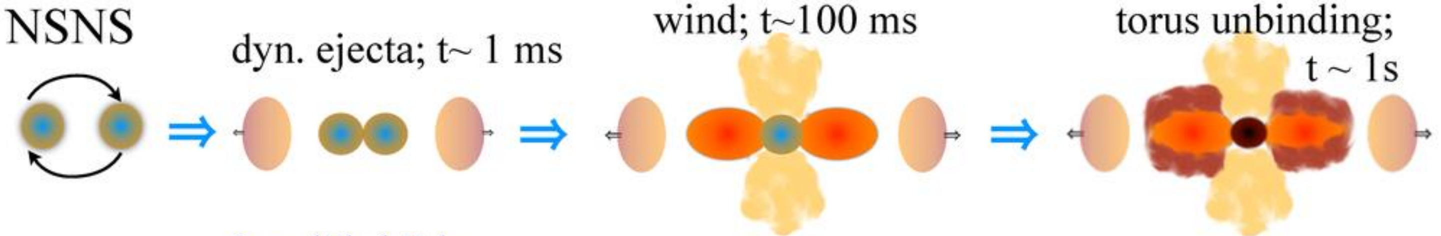
Phases during the operation of the r-process

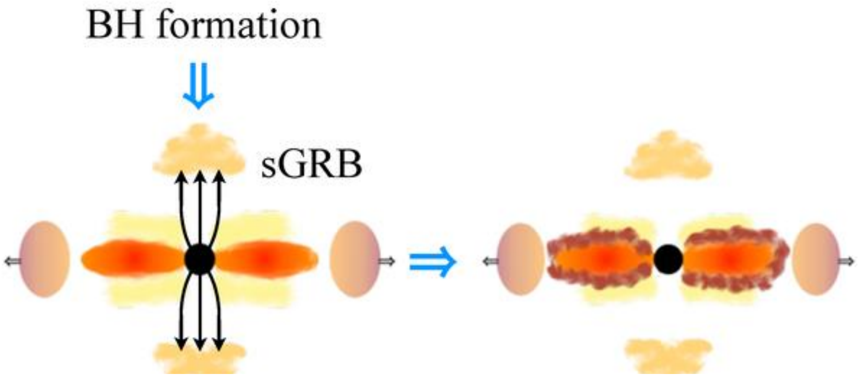
- **Weak freeze-out:** proton-to-nucleon ratio determined by (anti)neutrino absorption and their inverses
- **Seed production**: Charged particle reactions operating for $T \gtrsim 2\ GK$ produce the seed nuclei and neutrons
- **Neutron-capture phase:** neutrons are captured on the available seed nuclei 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

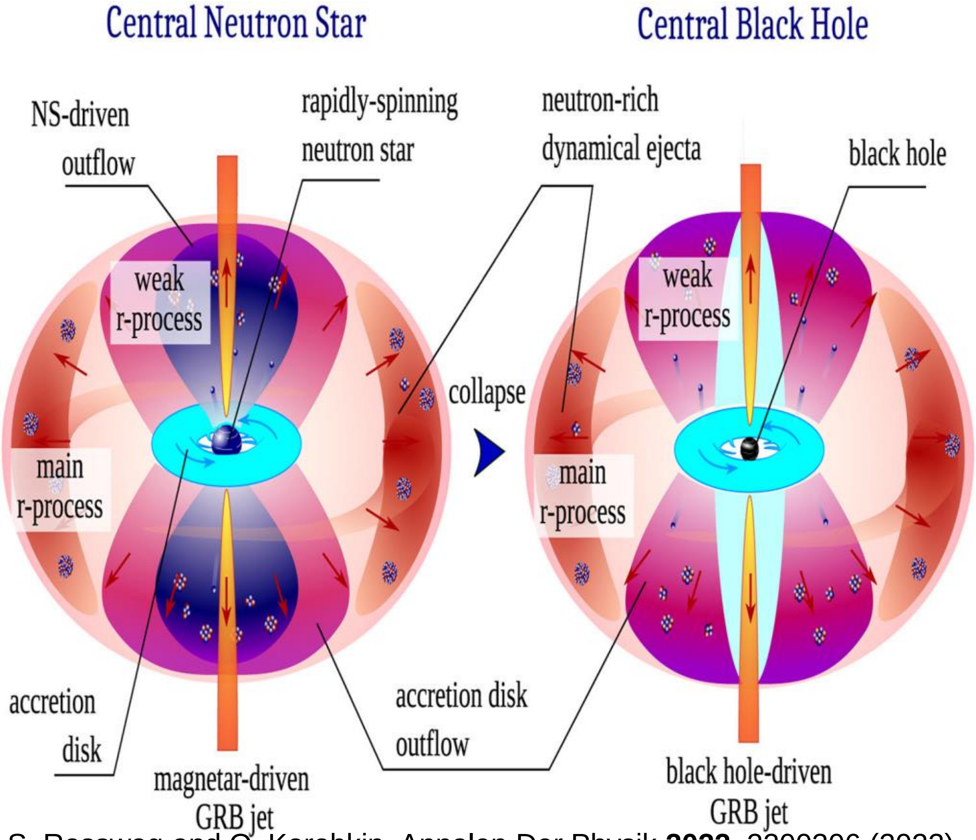
Neutron star mergers:
Different ejection mechanisms

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

Gravitational wave emission







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

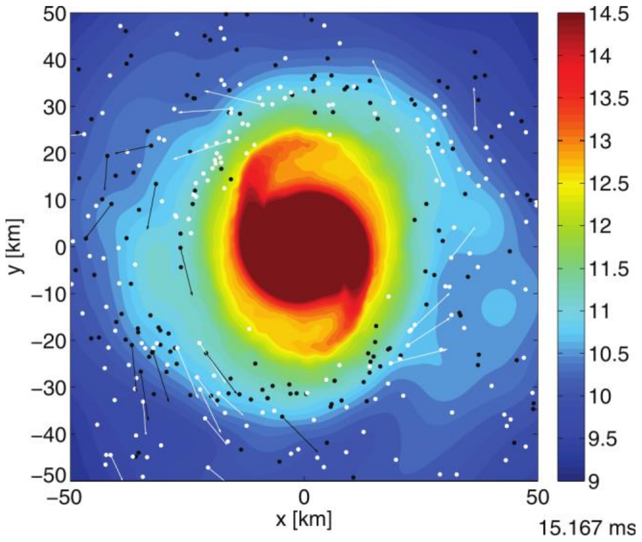
Two sources of ejecta:

- 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

Pipeline for r-process in mergers

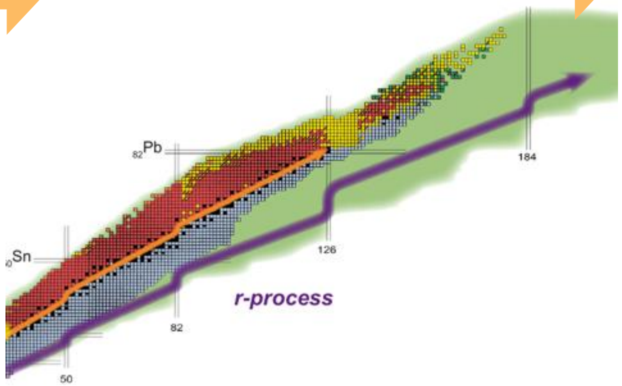
Simulations

Bauswein et al, ApJ 773, 78 (2013)



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

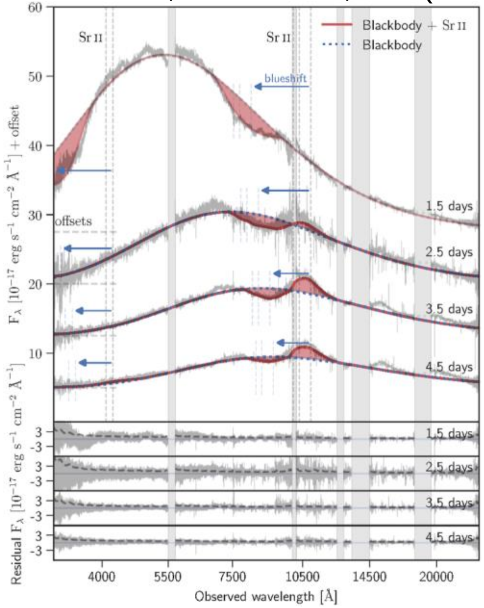
Nucleosynthesis



- Physics of neutron-rich and heavy nuclei

Light curve and spectra modelling

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



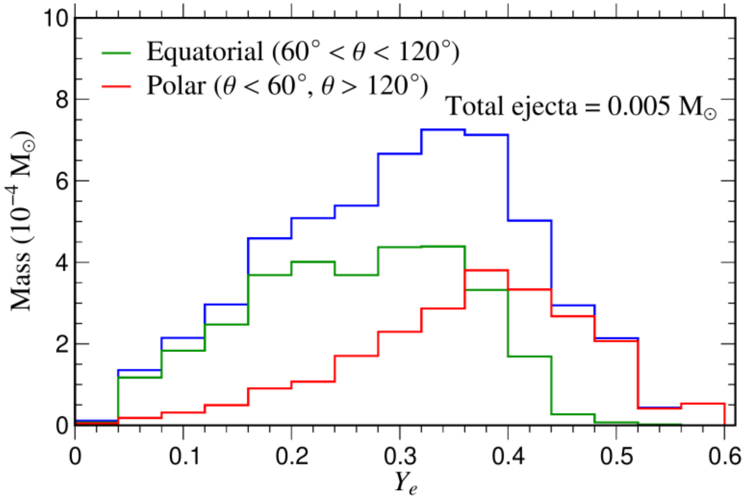
- Radioactive energy deposition
- Thermalization decay products (Barnes+ 2016, Kasen+ 2019)
- Spectra formation: atomic data depends on ejecta evolution (LTE vs NLTE)

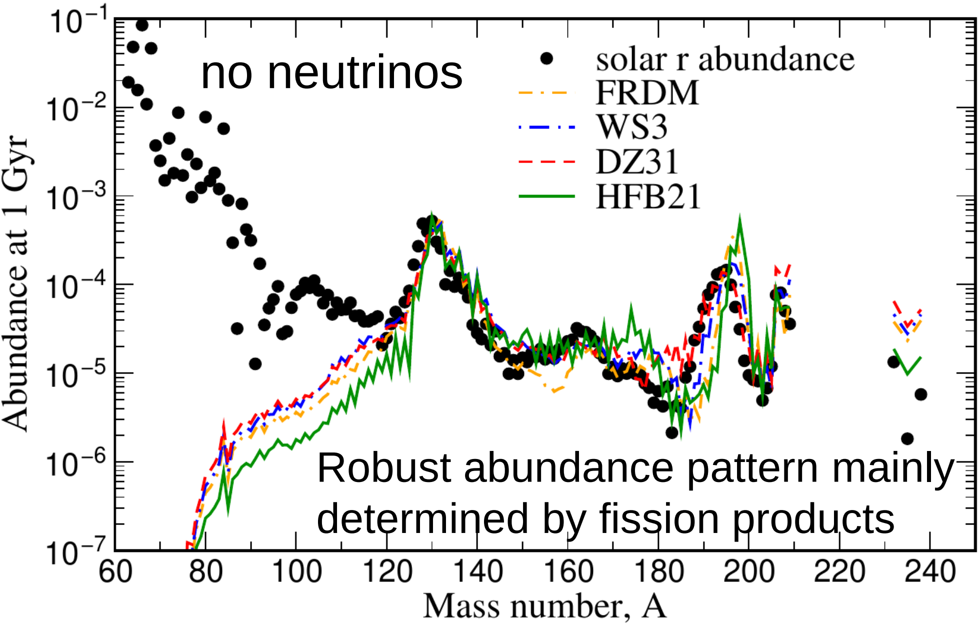
- Which r-process elements are produced in mergers?
- Are mergers the (main) r-process site?

Dynamical ejecta (simulations)

SPH Simulation **Vimal Vijayan**
Neutrino transport: ILEAS
1.35 – 1.35 $M_\odot$, SFHo EoS

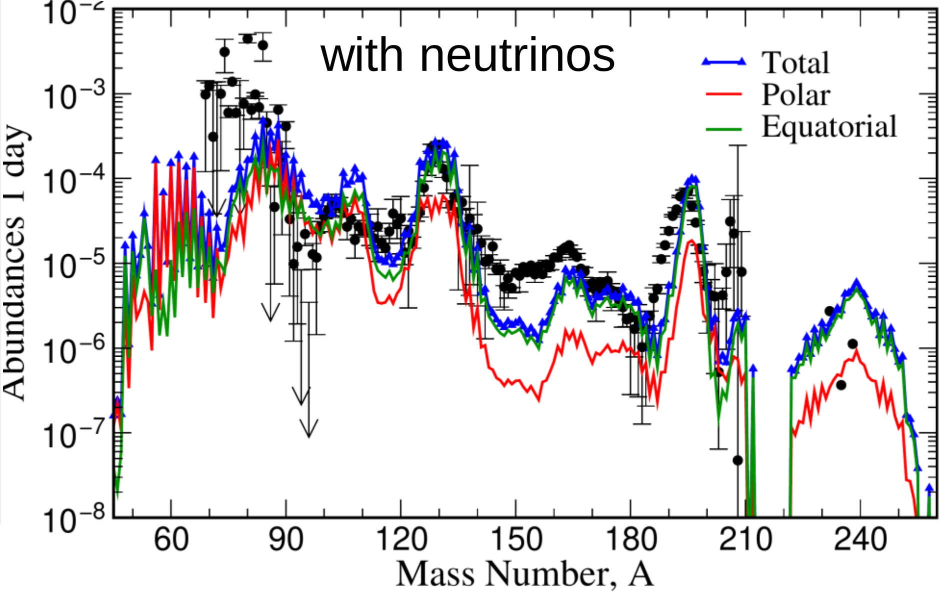
- Initially dynamical ejecta was assumed to be very neutron rich ($Y_e \lesssim 0.1$).
- Starting with the work of Wanajo et al 2014, several studies have shown that weak processes modify the neutron-to-proton ratio
- Largest impact in the polar regions




no neutrinos

Robust abundance pattern mainly determined by fission products

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

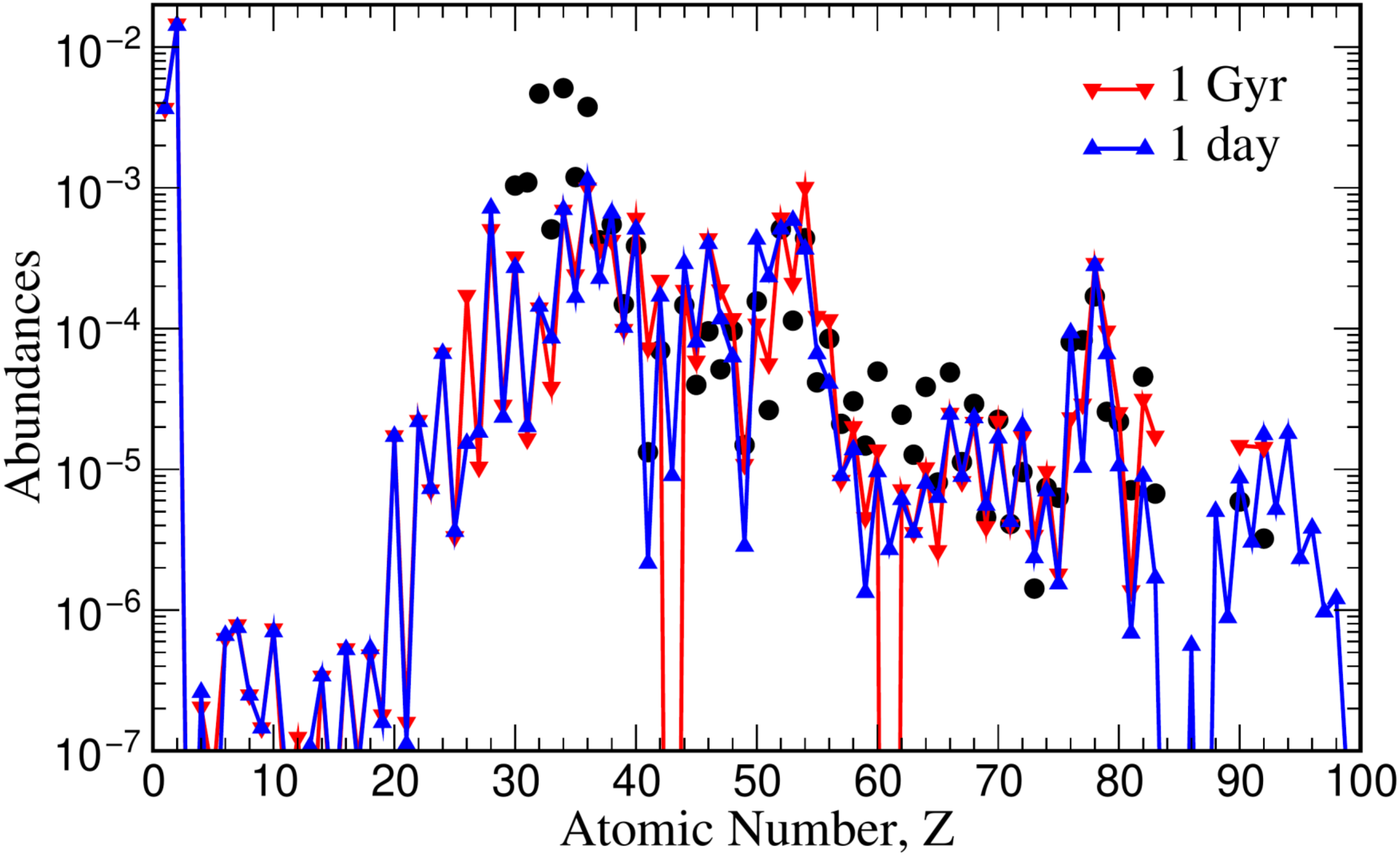

with neutrinos

Collins et al, MNRAS 521, 1858 (2023)

See also: Kullman+ 2022, Just+ 2022

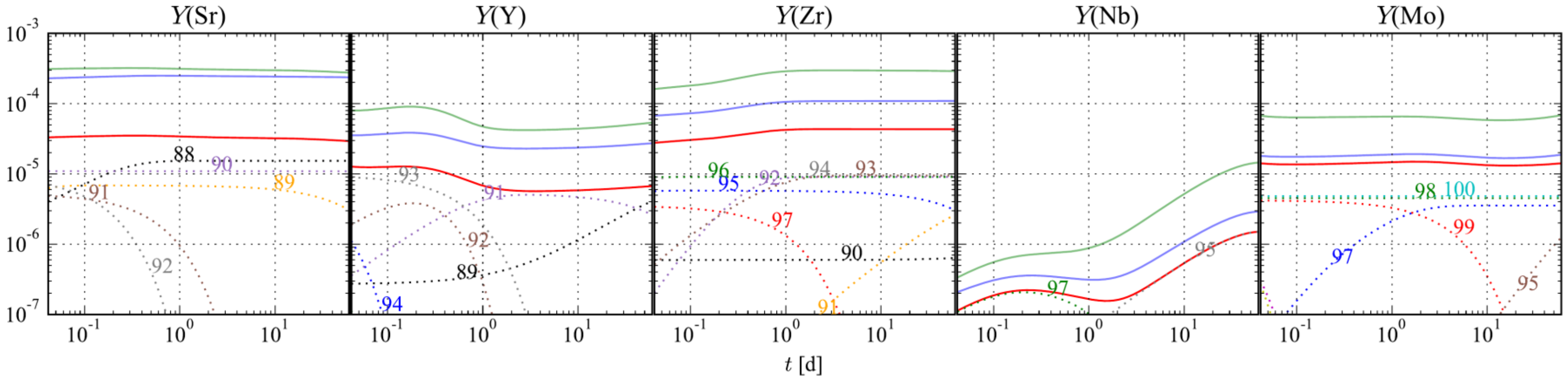
Elemental abundances

- At kilonova timescales (days) elemental abundances have not yet converged to final abundances



Evolution selected abundances

- Odd Z elements show larger variation
- Contributions single isotope
- Even Z, several isotopes contribute



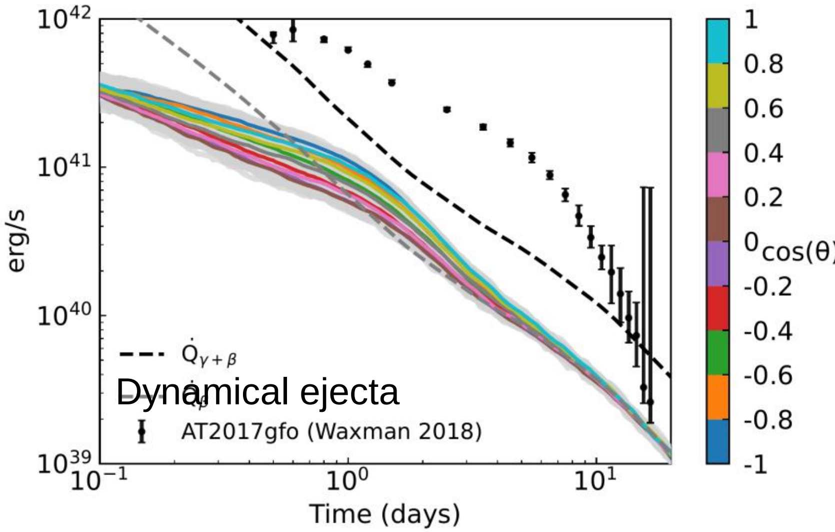
3D Kilonova light curves and spectra

3D modelling using radiation transport monte-carlo ARTIS code

Gray Ye dependent opacities
Christine Collins et al
MNRAS 521, 1858 (2023)

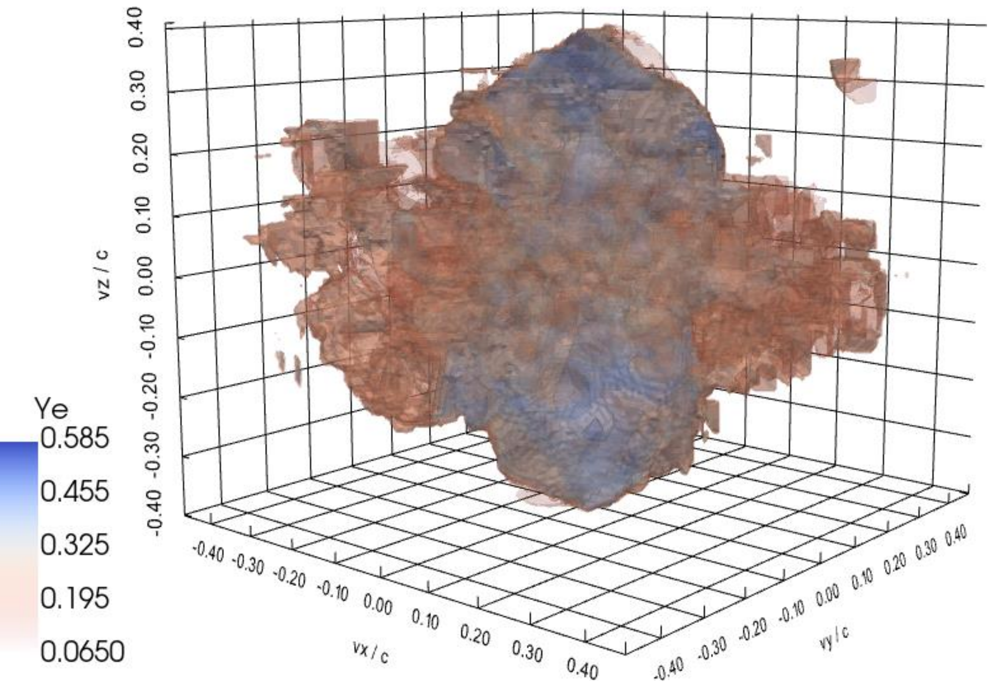
Tanaka+ 2020

Y_e	κ $\mathrm{cm^2\ g^{-1}}$
$Y_e \leq 0.1$	19.5*
$0.1 < Y_e \leq 0.15$	32.2
$0.15 < Y_e \leq 0.2$	22.3
$0.2 < Y_e \leq 0.25$	5.60
$0.25 < Y_e \leq 0.3$	5.36
$0.3 < Y_e \leq 0.35$	3.30
$Y_e > 0.35$	0.96

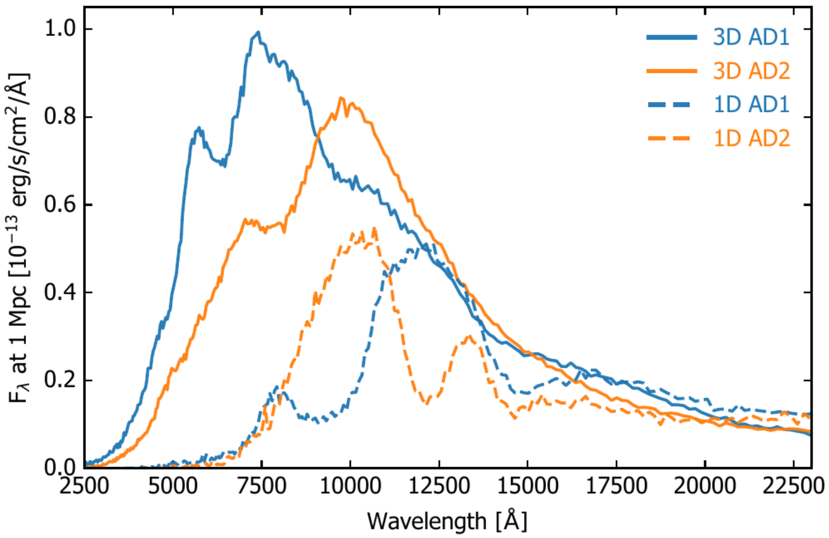


Angular dependence disappears once ejecta becomes transparent

Similar blue to red color evolution to AT2017gfo



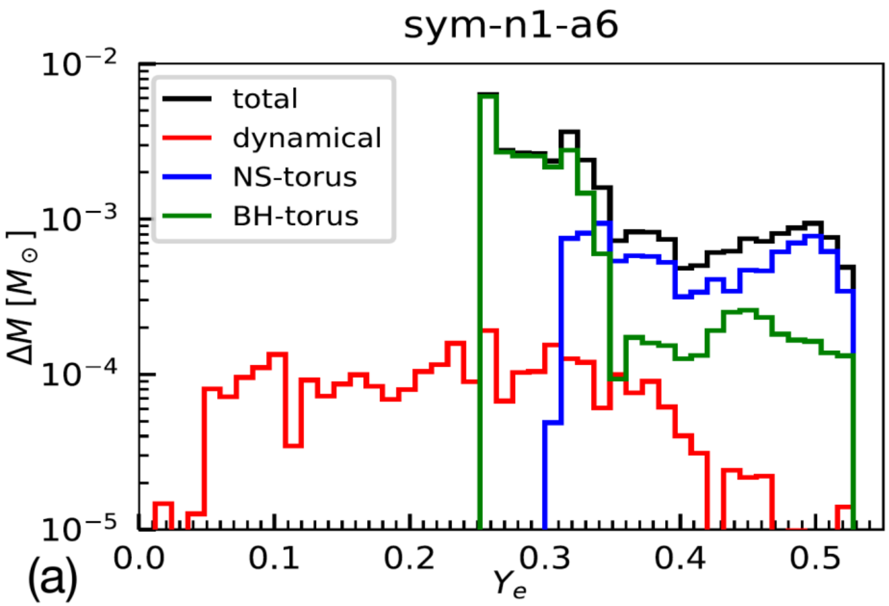
Extended to use line-by-line opacities
Luke Shingles et al arXiv:2306.17612

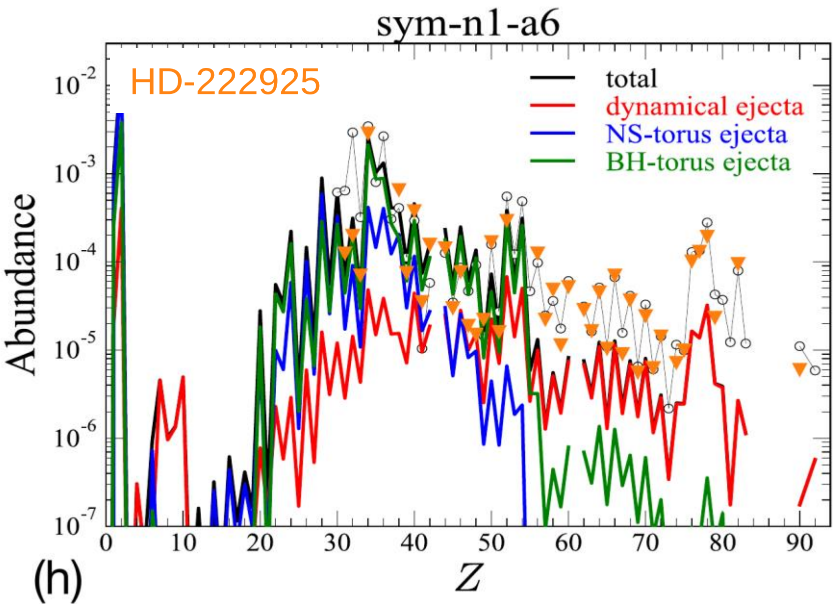


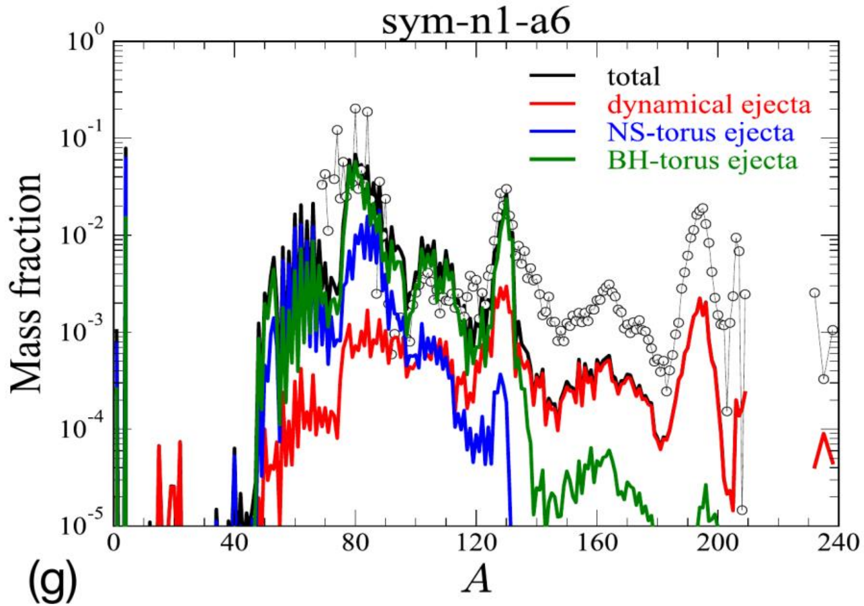
Long term merger simulations

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, ApJL, L12 (2023)

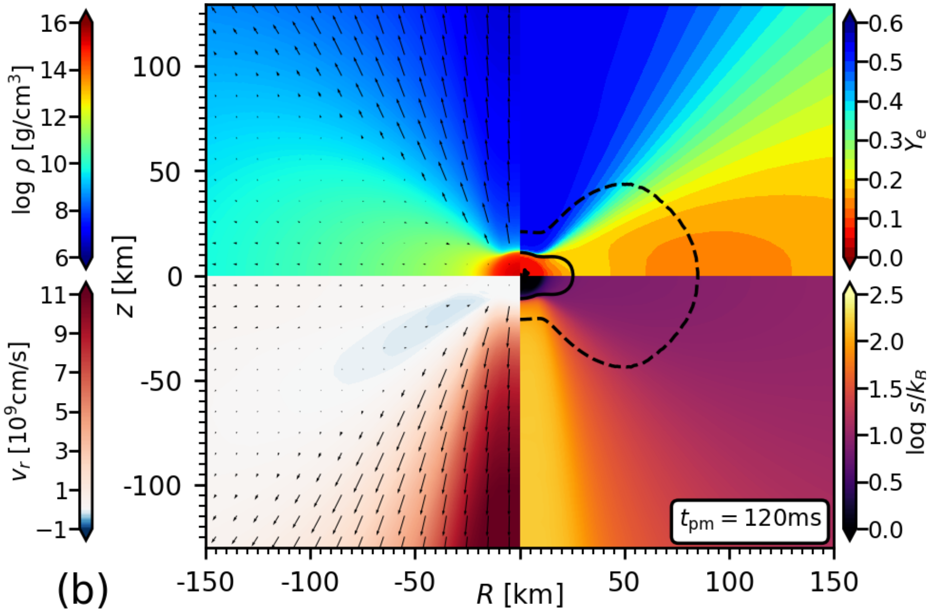


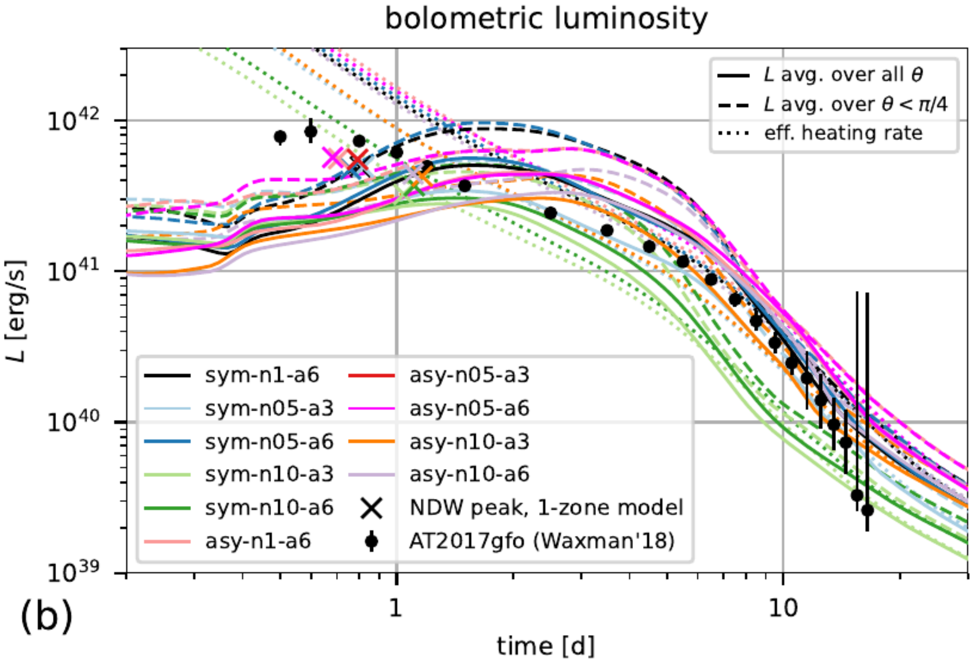




End to end kilonova models

- Based on grey opacities using approximate radiative transfer model (generalization ALCAR neutrino module)
- promising agreement with AT2017gfo after times of several days
- inconsistencies at early times suggests stronger neutrino-driven wind





Just et al, ApJL, L12 (2023)

Comparison viscous accretion disk models

Viscous hydrodynamic evolution of neutron star merger accretion disks: a code comparison

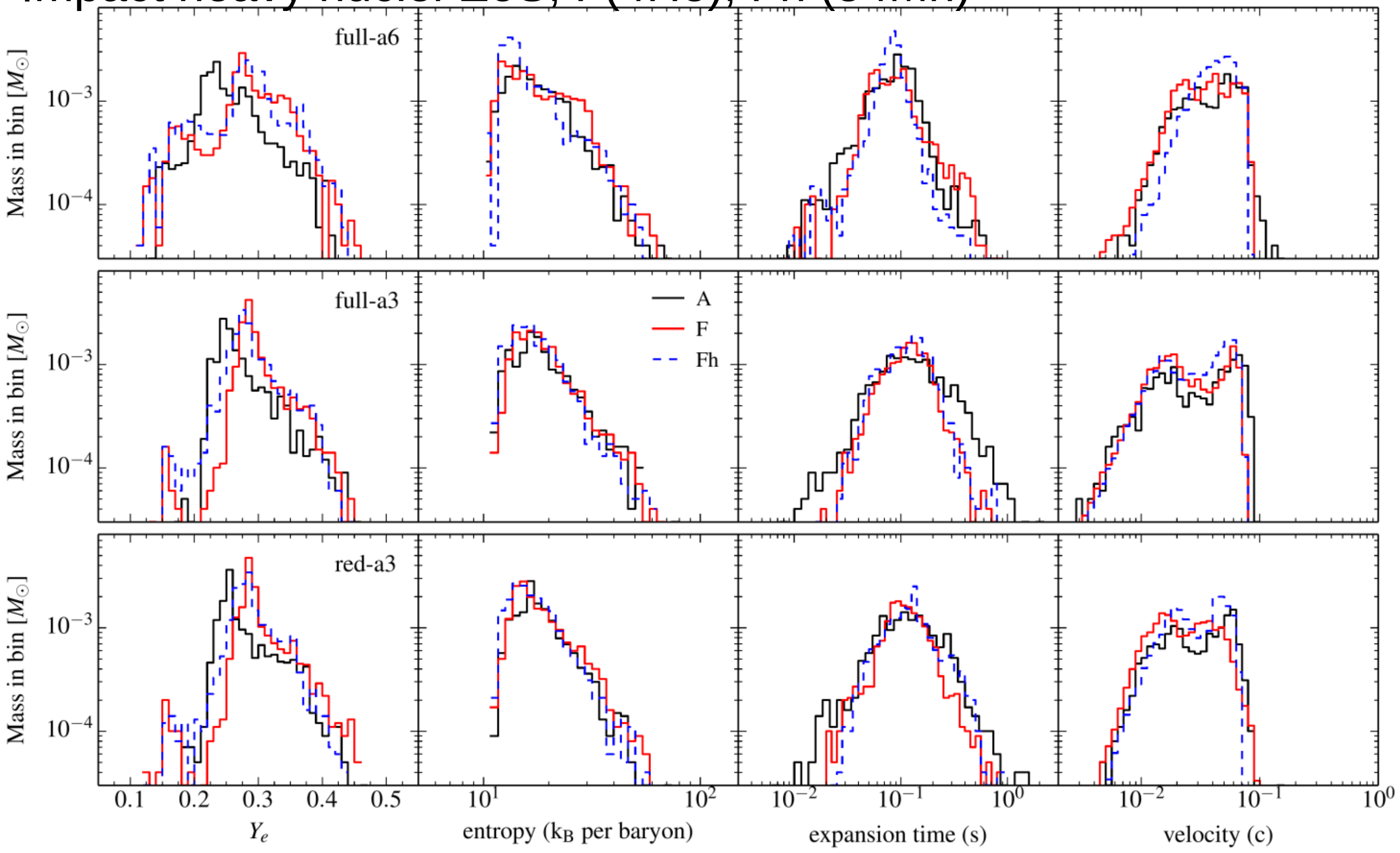
Rodrigo Fernández,[1,*] Oliver Just,[2,3] Zewei Xiong,[2] and Gabriel Martínez-Pinedo[2,4]

arXiv:2307.02554

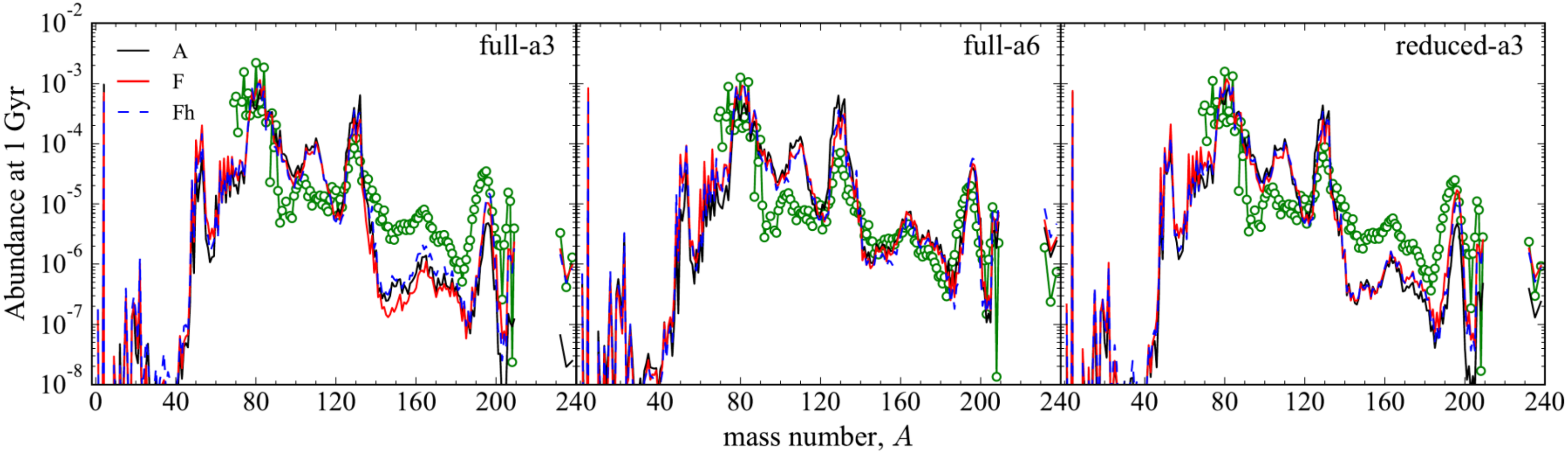
Variations viscous parameter (a3, a6), two codes: FLASH vs ALCAR

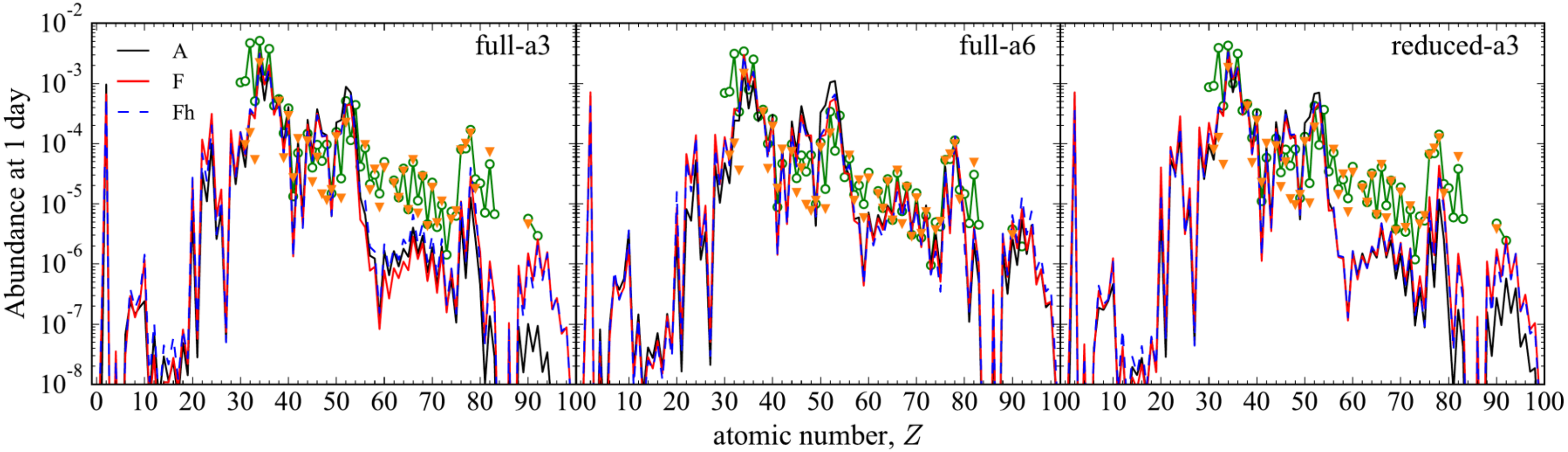
Treatment neutrino reactions (reduced, full)

Impact heavy nuclei EoS, F(4He), Fh (54Mn)



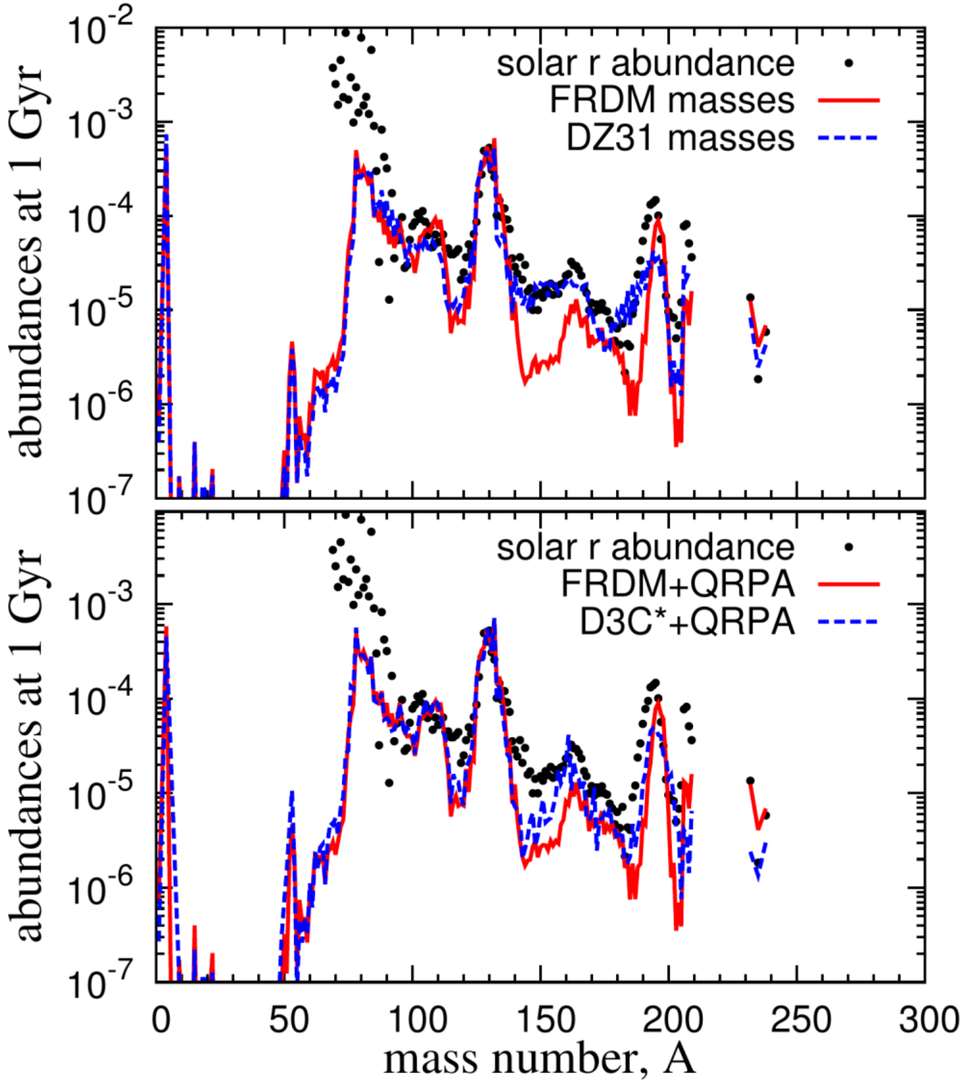
Impact nucleosynthesis





In addition to modelling uncertainties we also have nuclear physics uncertainties

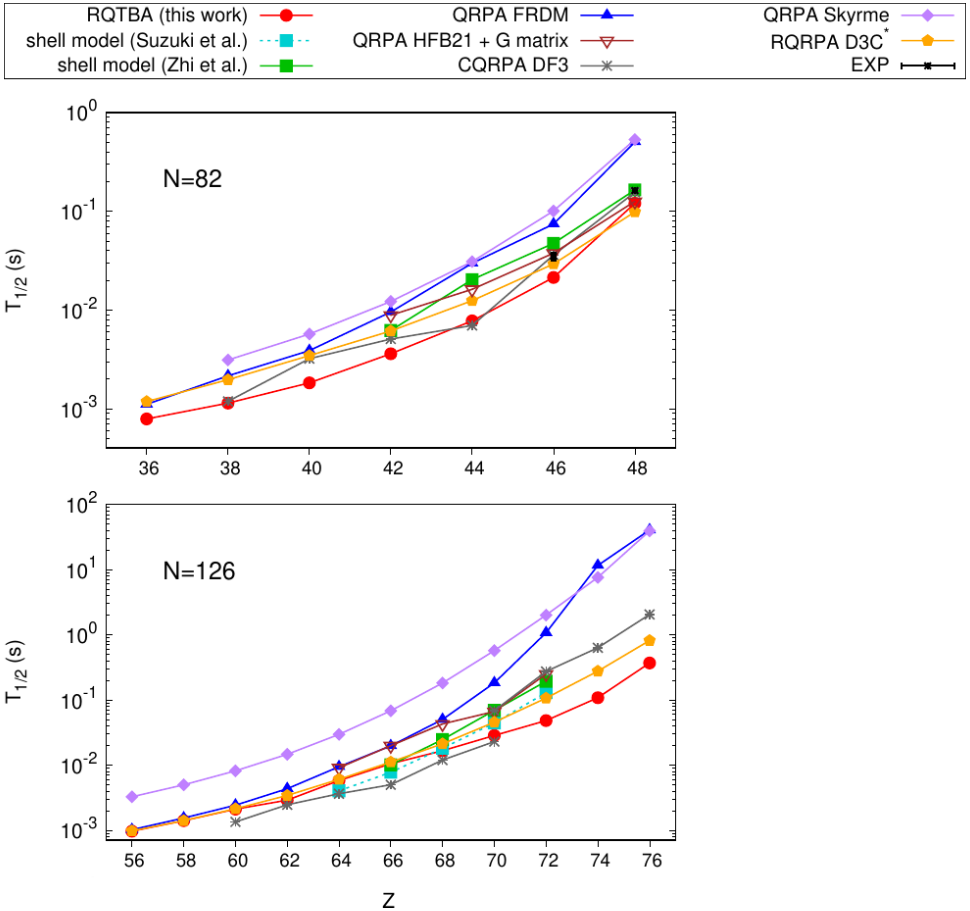
Impact nuclear physics



Wu et al, MNRAS 463, 2323 (2016)

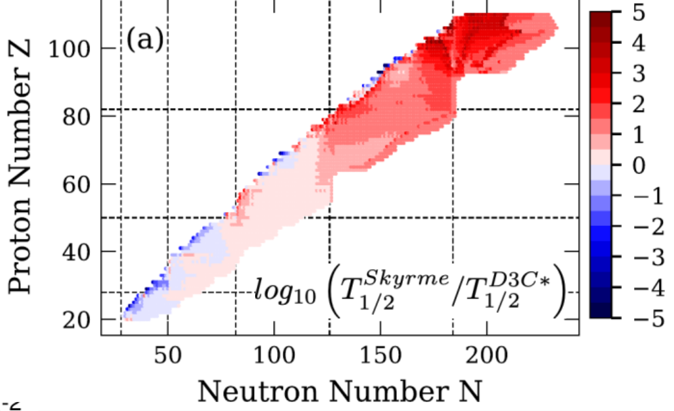
Nuclear physics input: beta-decay half-lives

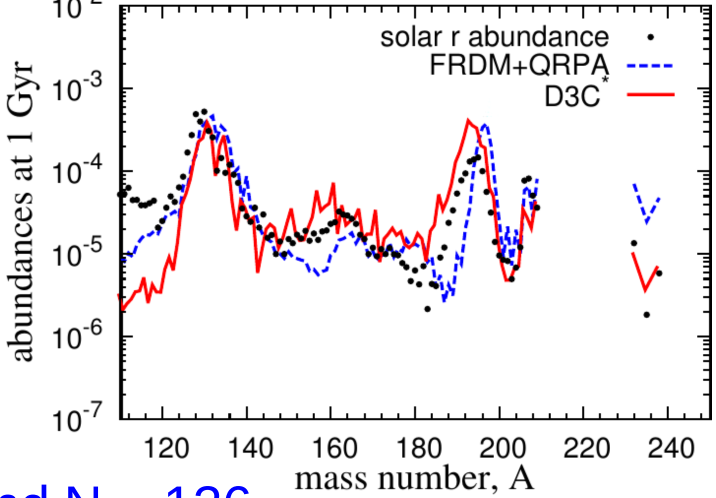
- Beta-decay half-lives determine the speed at which heavy elements are build starting from light ones
- N~126 Half-lives have a strong impact on the position of the A ~ 195 peak



C. Robin, GMP, in preparation

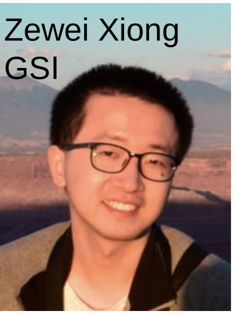
DC3*: Marketin+PRC 93, 025805 (2016)
Skyrme: Ney+ PRC102, 034326 (2020)

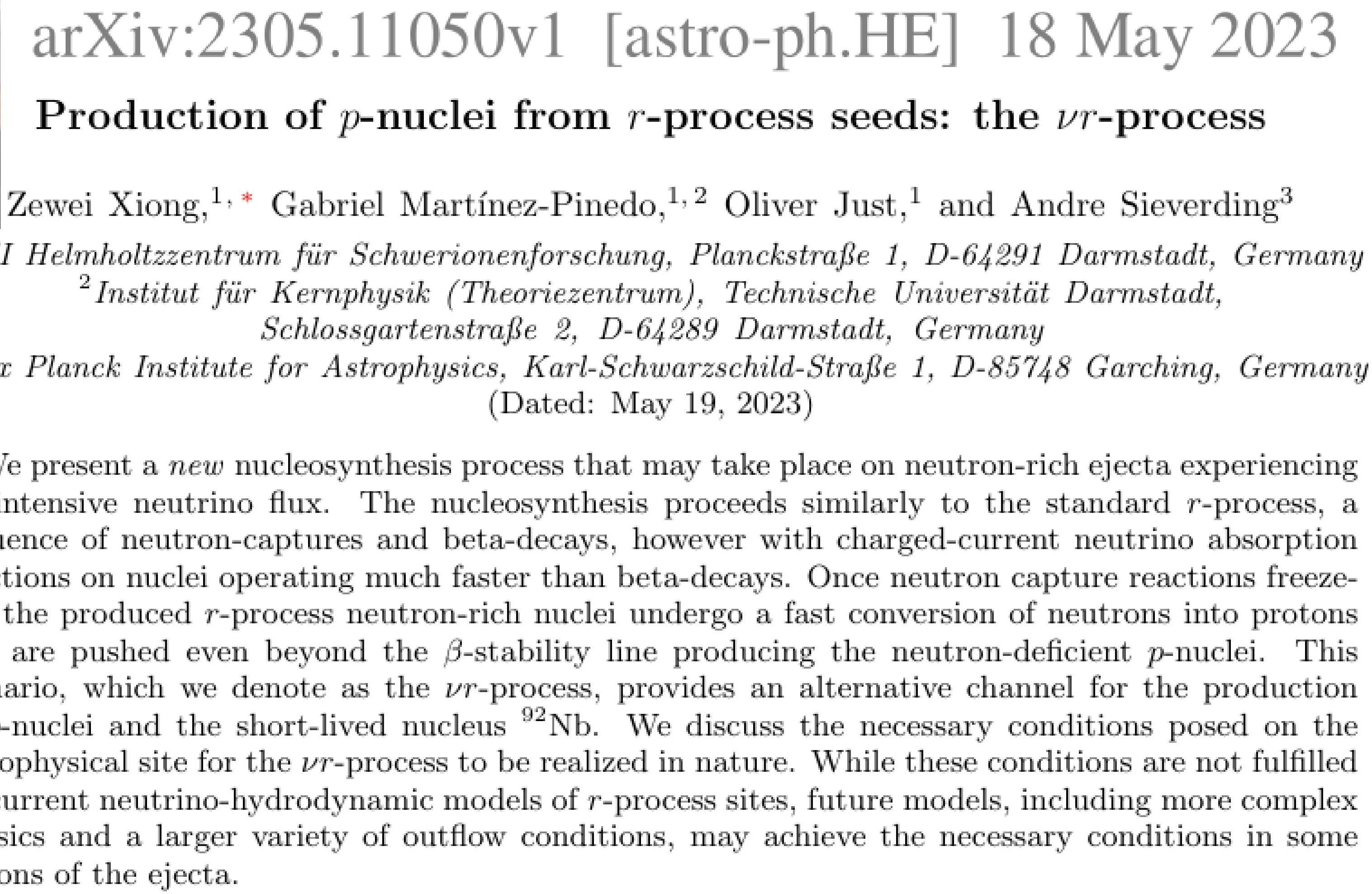




Need data for beta decay half-lives around N ~ 126

The νr-process


Zewei Xiong
GSI


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

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

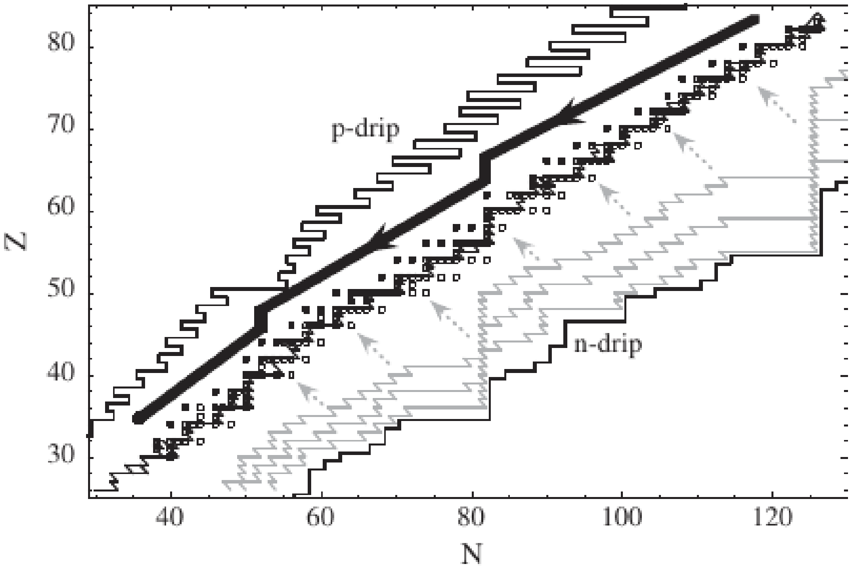
Zewei Xiong,[1,*] Gabriel Martínez-Pinedo,[1,2] Oliver Just,[1] and Andre Sieverding[3]
[1] *GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, D-64291 Darmstadt, Germany*
[2] *Institut für Kernphysik (Theoriezentrum), Technische Universität Darmstadt, Schlossgartenstraße 2, D-64289 Darmstadt, Germany*
[3] *Max Planck Institute for Astrophysics, Karl-Schwarzschild-Straße 1, D-85748 Garching, Germany*
(Dated: May 19, 2023)

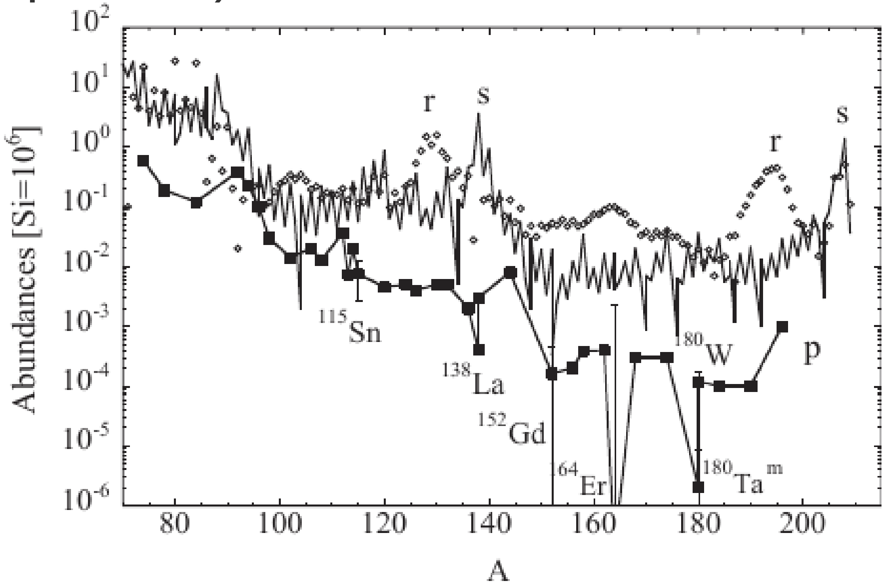
We present a *new* nucleosynthesis process that may take place on neutron-rich ejecta experiencing an intensive neutrino flux. The nucleosynthesis proceeds similarly to the standard r-process, a sequence of neutron-captures and beta-decays, however with charged-current neutrino absorption reactions on 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.

Nucleosynthesis beyond iron

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

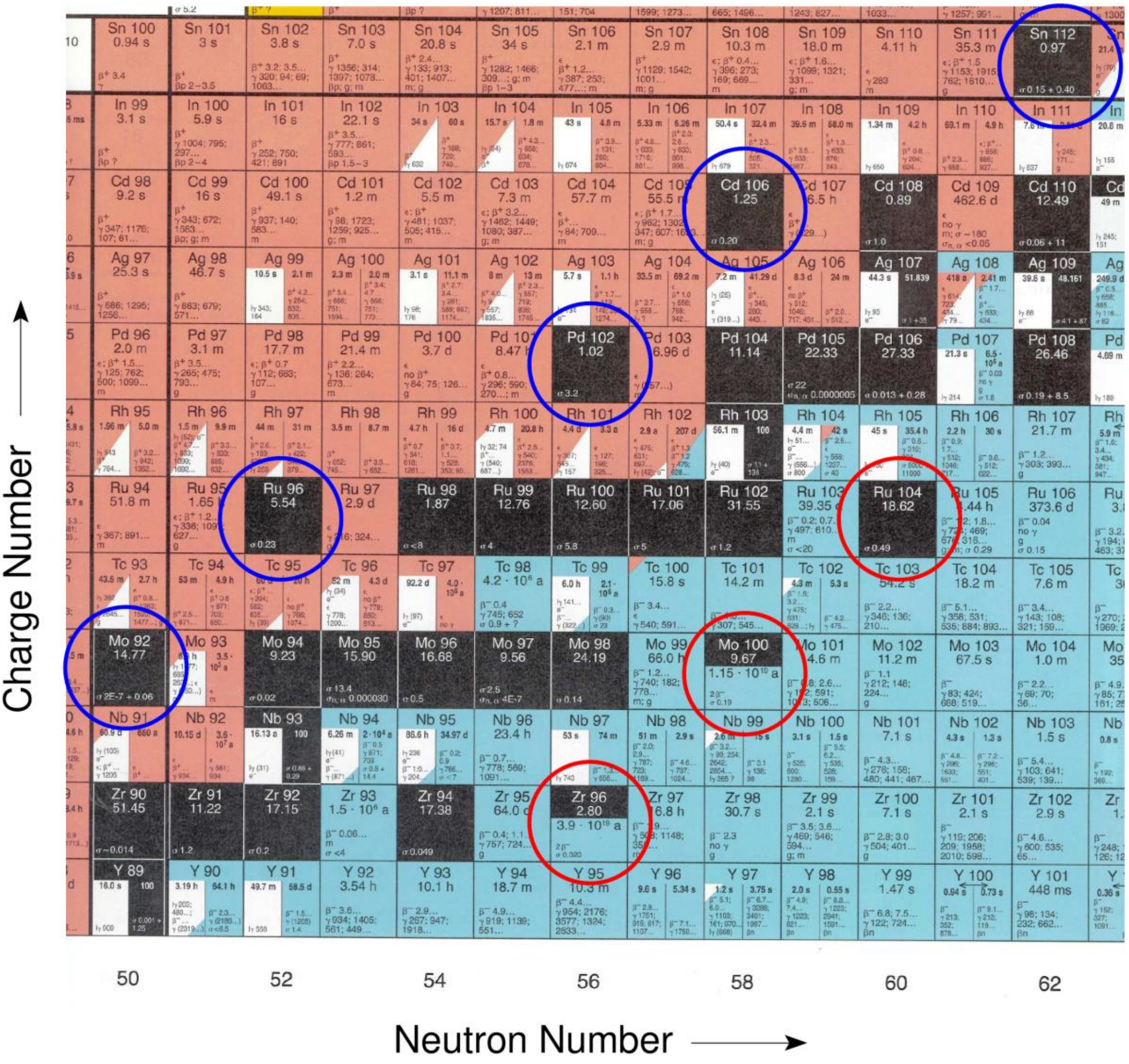




M. Arnould, S. Goriely / Physics Reports 384, 1 (2003)

- 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
  - **p-process or** γ-process: photodissociation material enriched by s-process
  - νp-process: (p,γ) and (n,p) reactions catalysed by $\bar{\nu}_e + p \rightarrow n + e^+$

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.

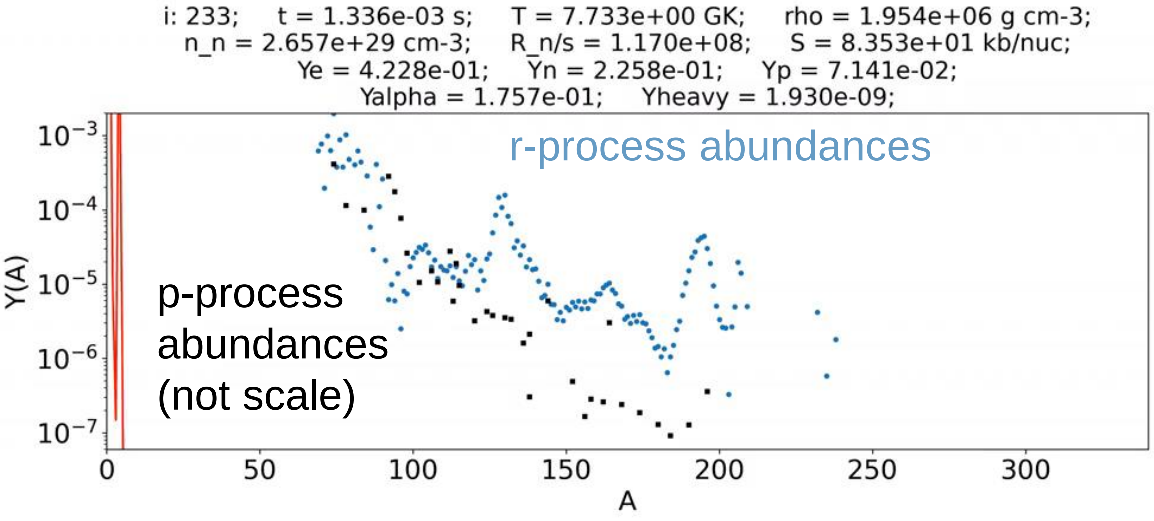
Long-lived ^{92}Nb present in early solar system. Cannot be produced by the νp-process

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

Phases during the operation of the νr-process

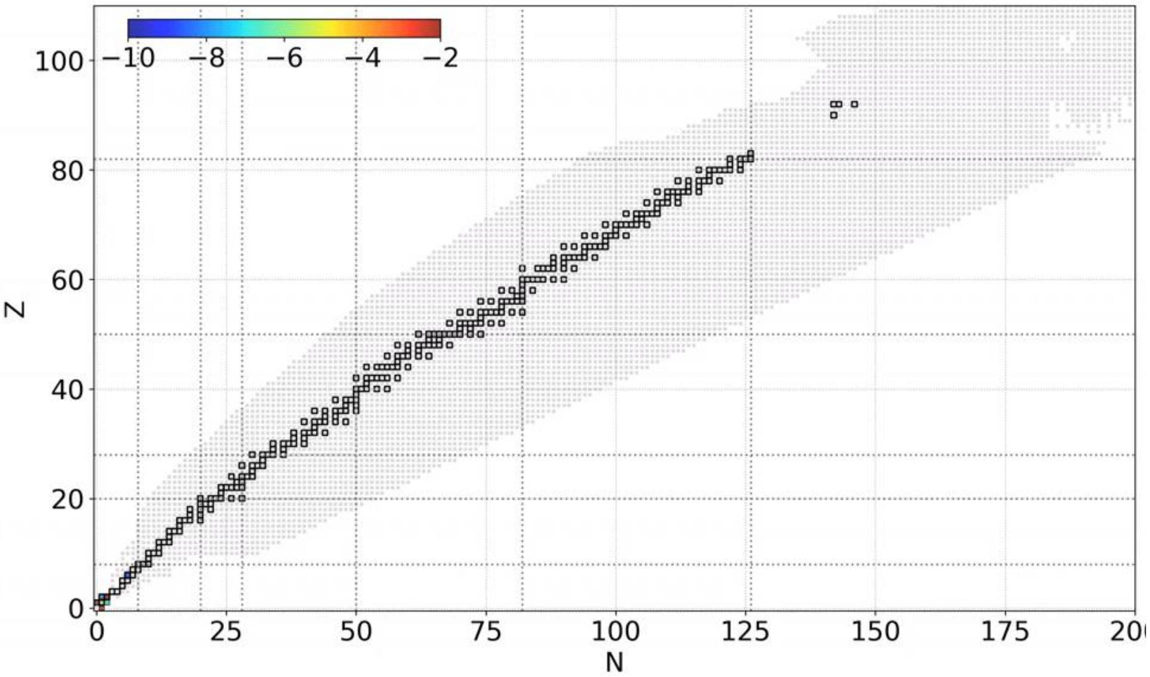
- **Seed production:** Strong neutrino fluxes drive material to $Y_e \sim 0.5$
- **Neutron-capture phase:** neutrons are used relatively fast by two competing mechanisms:
  - $n((\nu_e, e^-))p$ converts neutrons into protons that are captures in medium mass nuclei
  - $A\big((\nu_e, e^-)X\big)$ $X = n, p, \alpha$ 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

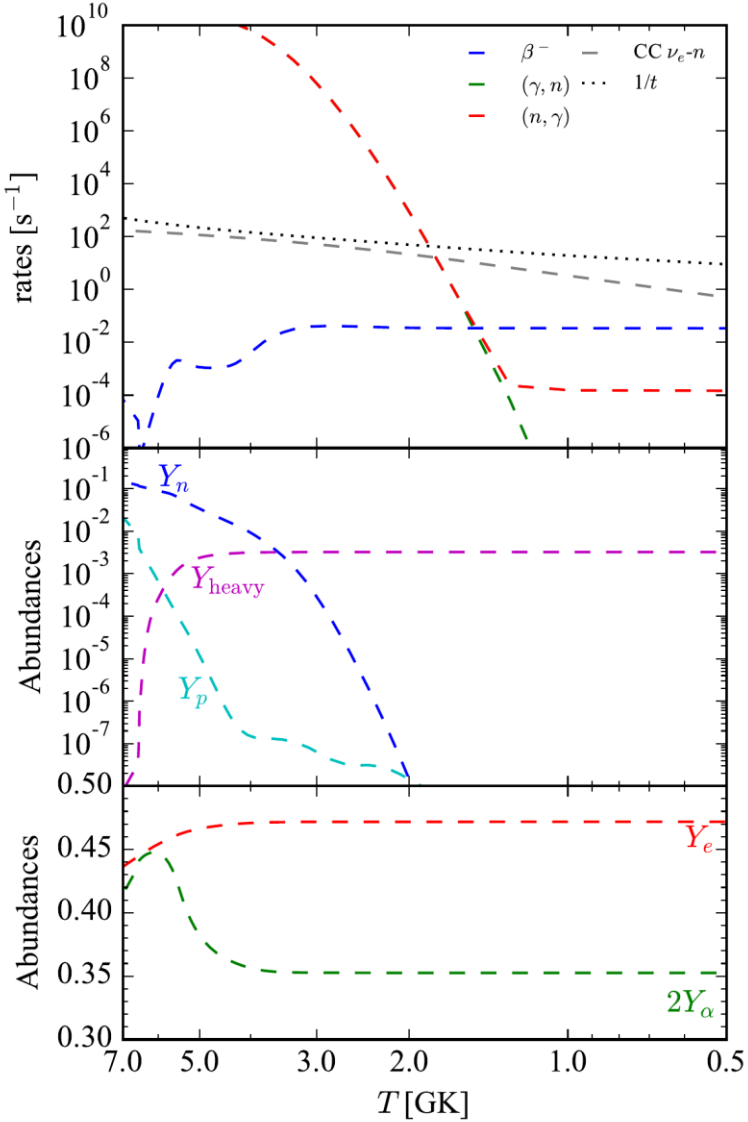
Nucleosynthesis (no neutrino-nucleus)


i: 233; t = 1.336e-03 s; T = 7.733e+00 GK; rho = 1.954e+06 g cm-3;
n_n = 2.657e+29 cm-3; R_n/s = 1.170e+08; S = 8.353e+01 kb/nuc;
Ye = 4.228e-01; Yn = 2.258e-01; Yp = 7.141e-02;
Yalpha = 1.757e-01; Yheavy = 1.930e-09;

r-process abundances

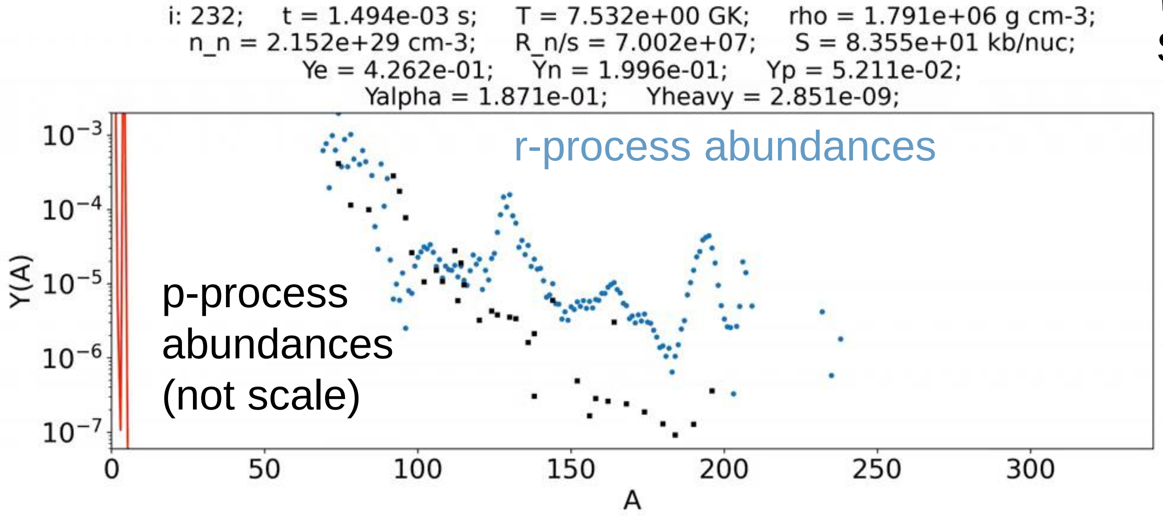
p-process abundances (not scale)





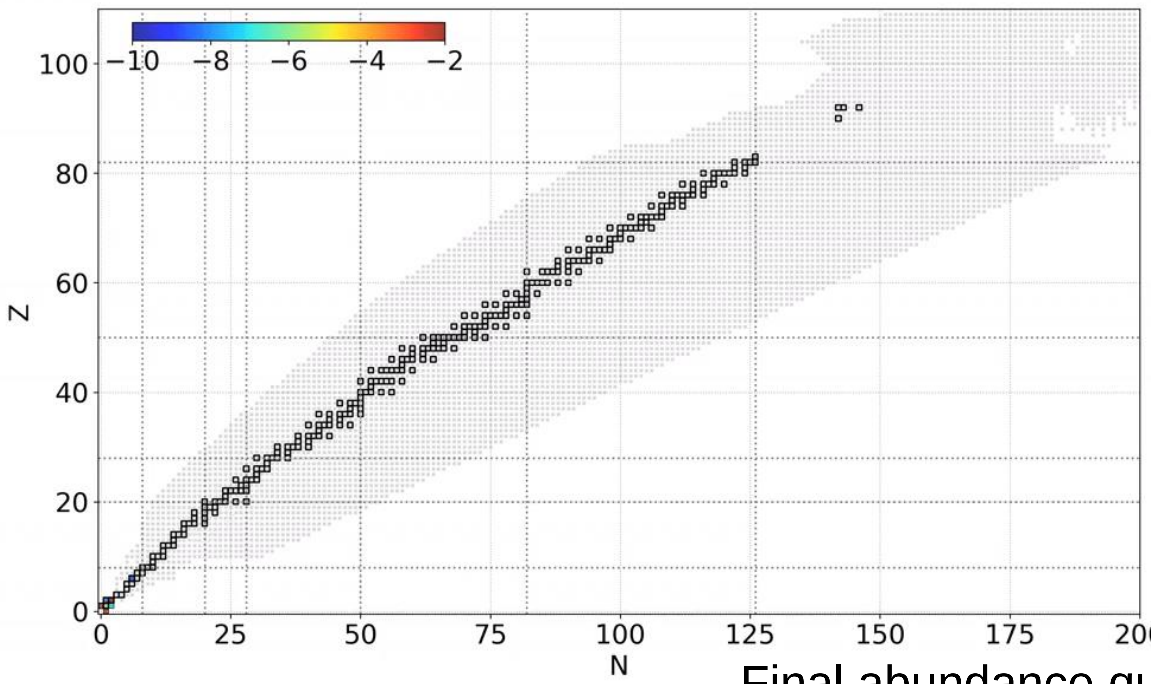
Nucleosynthesis (with neutrino-nucleus)

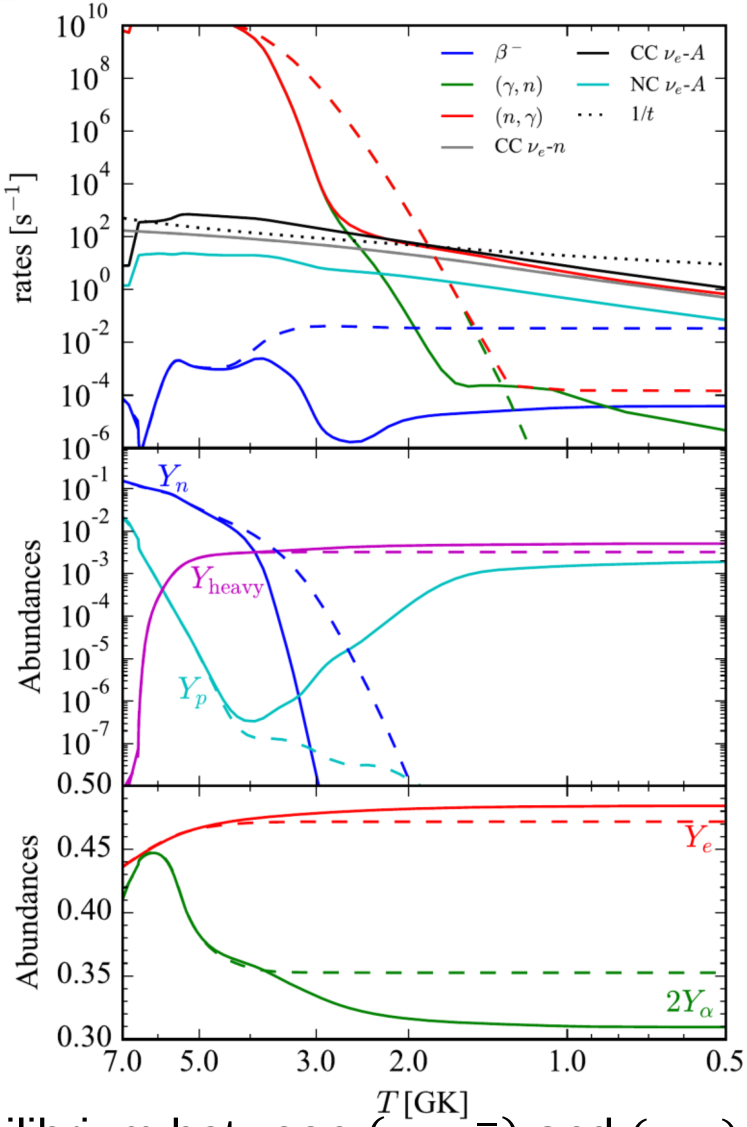
$\nu - A$ cross sections from Sieverding, et al, ApJ 865, 143 (2018).



r-process abundances

p-process abundances (not scale)

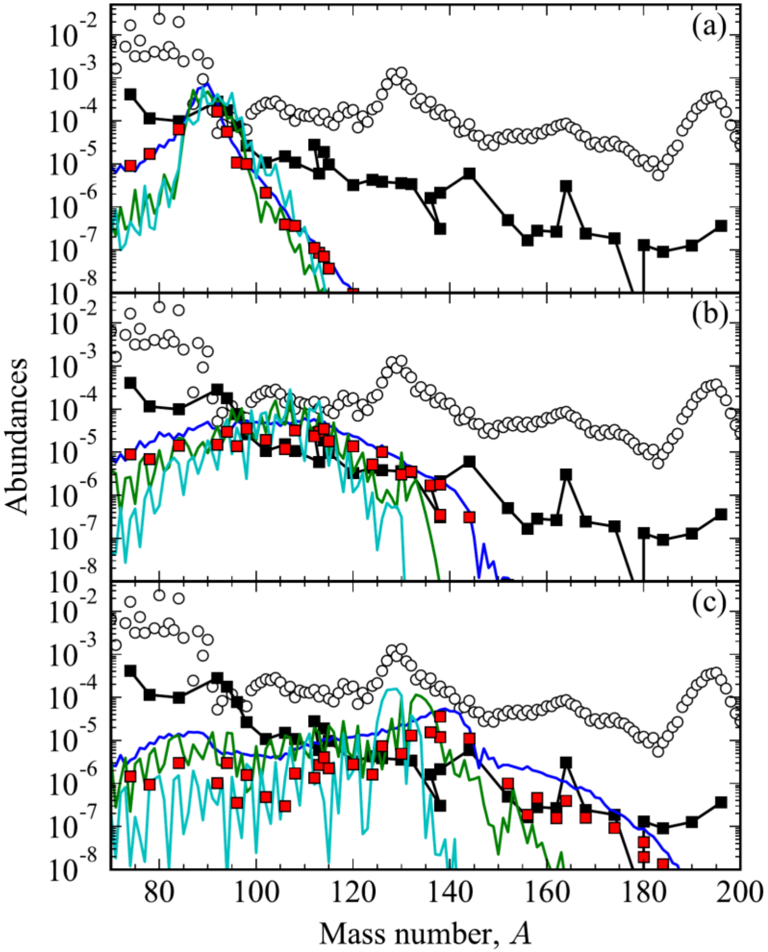




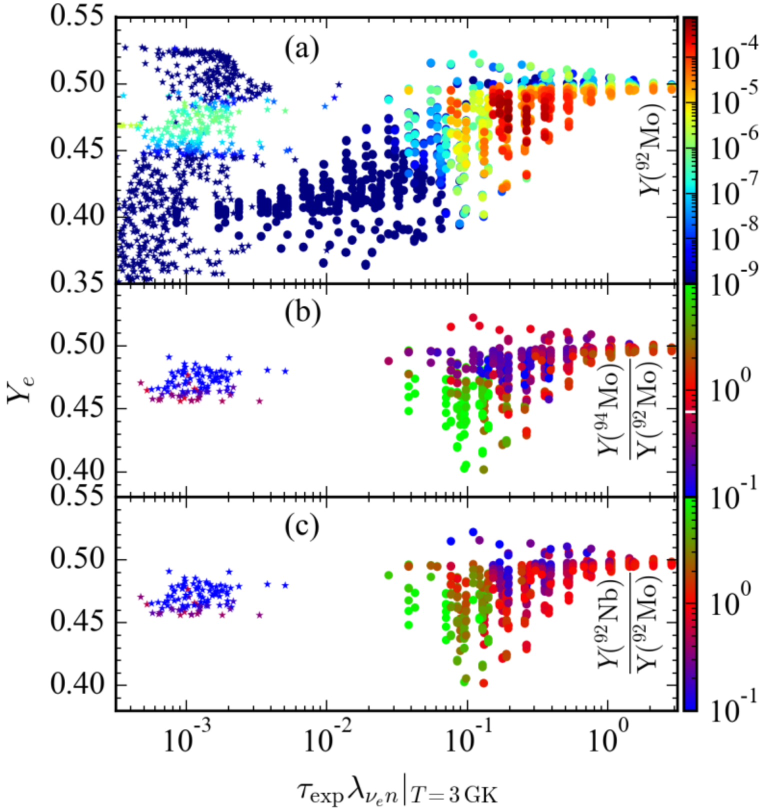
Final abundance quilibrium between (ν_e, e^-) and (n, γ)

Dependence on neutrino fluence

Increasing neutrino fluence allows to produce heavier p-nuclei

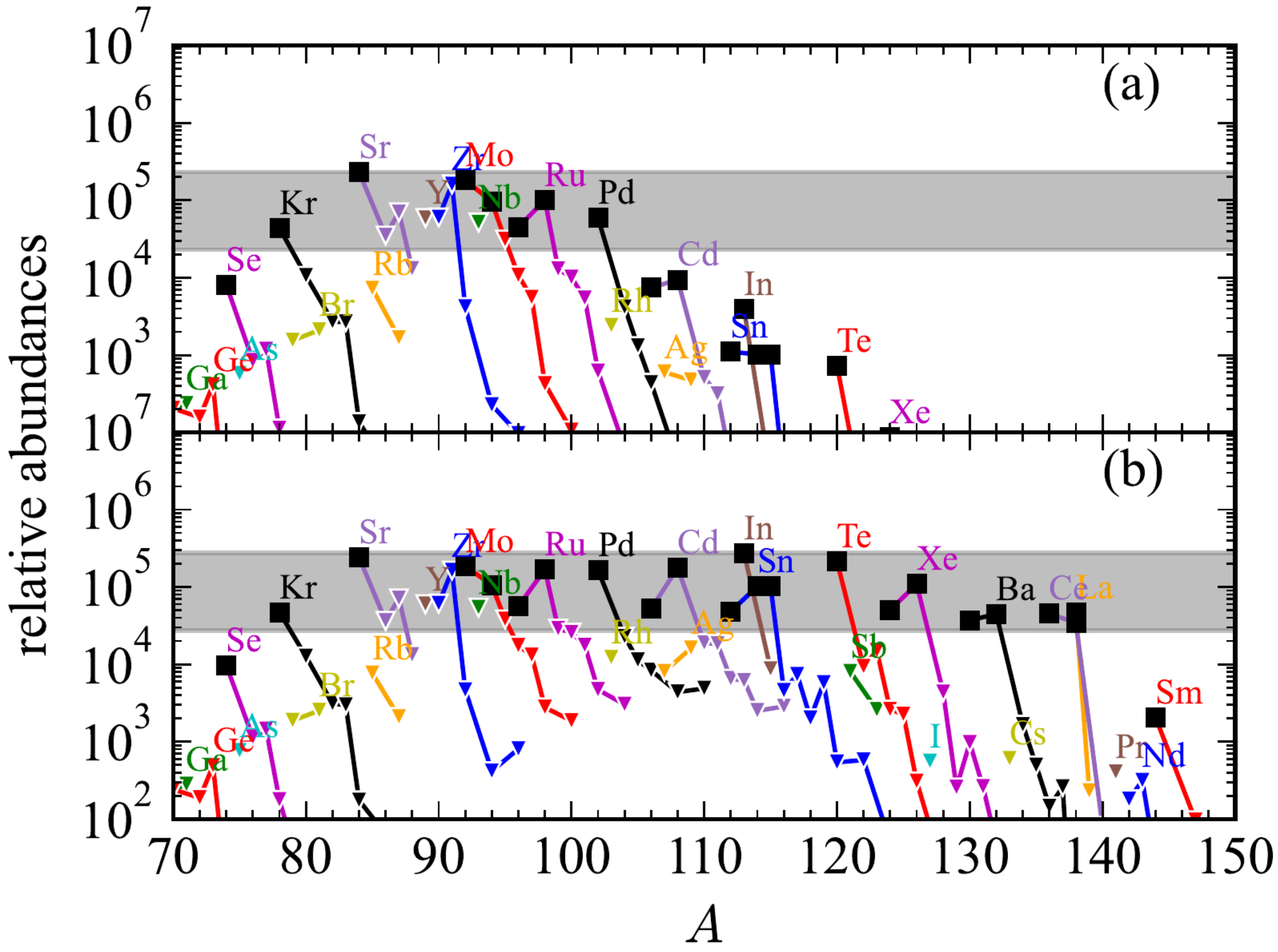


Dependence Y_e and neutrino fluence



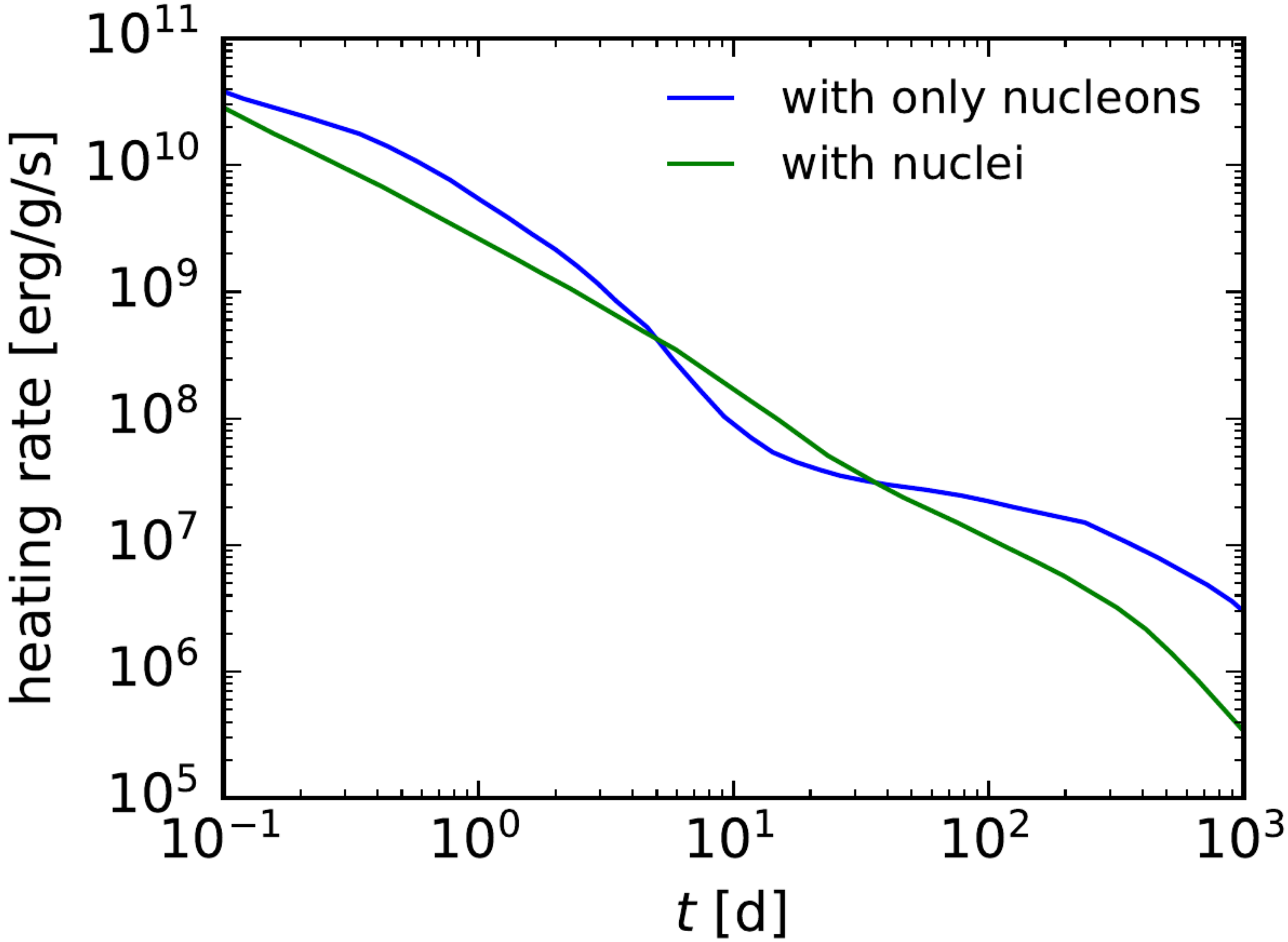
Current neutrino-hydrodynamical models far from the necessary conditions
A non-thermal ejection mechanism is necessary (magnetic fields?)

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

Heating rate



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 laboratory experiments
- νr-process: new mechanism production p-nuclei
- Challenges:
  - Impact of weak processes and EoS in the ejecta properties
  - Improved nuclear and atomic input
  - Kilonova spectral modelling

Collaborators

GSI theory

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