Probing heavy element nucleosynthesis through electromagnetic observations

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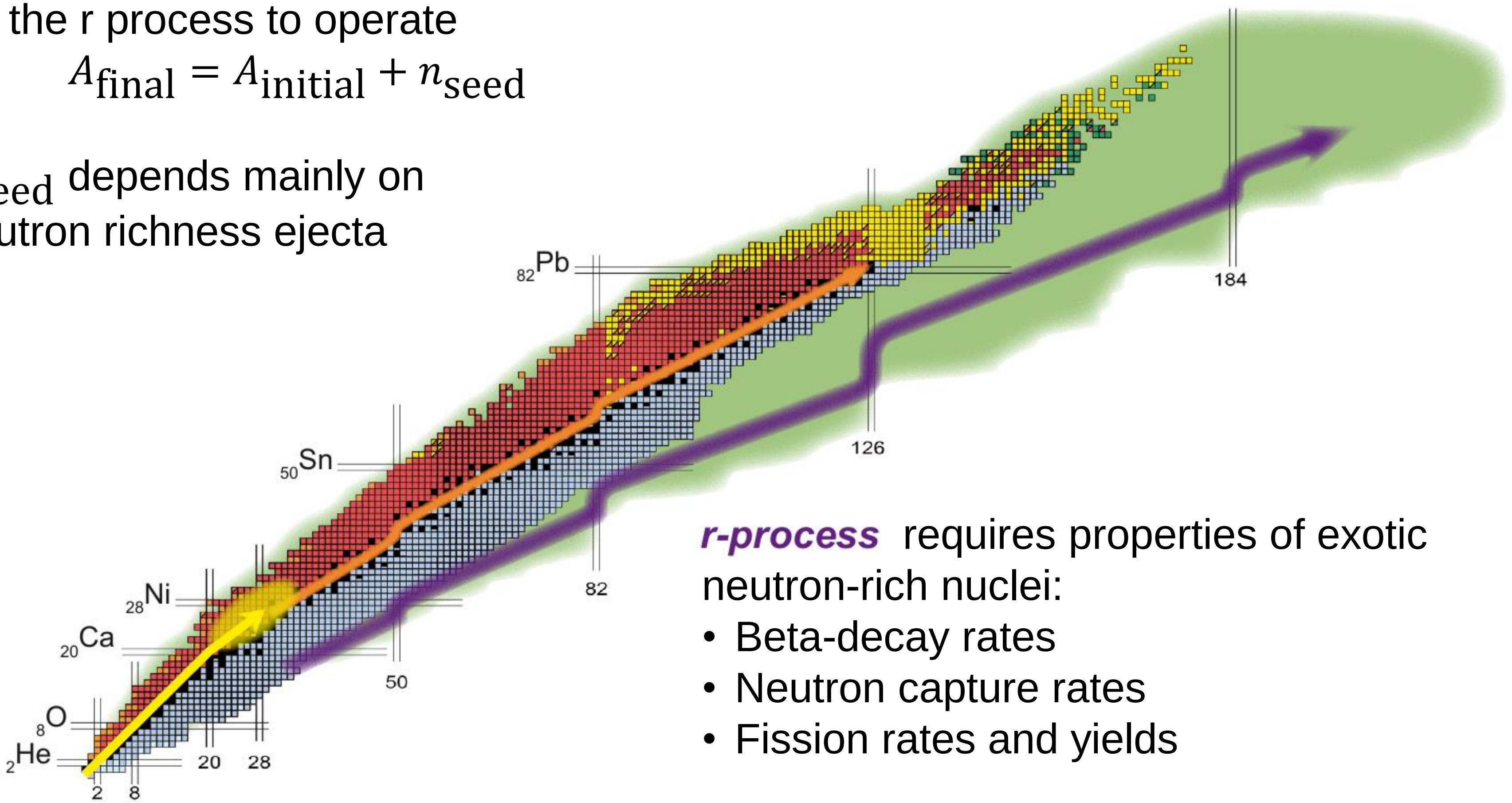
ERC AdG KILONOVA

R process modelling

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:

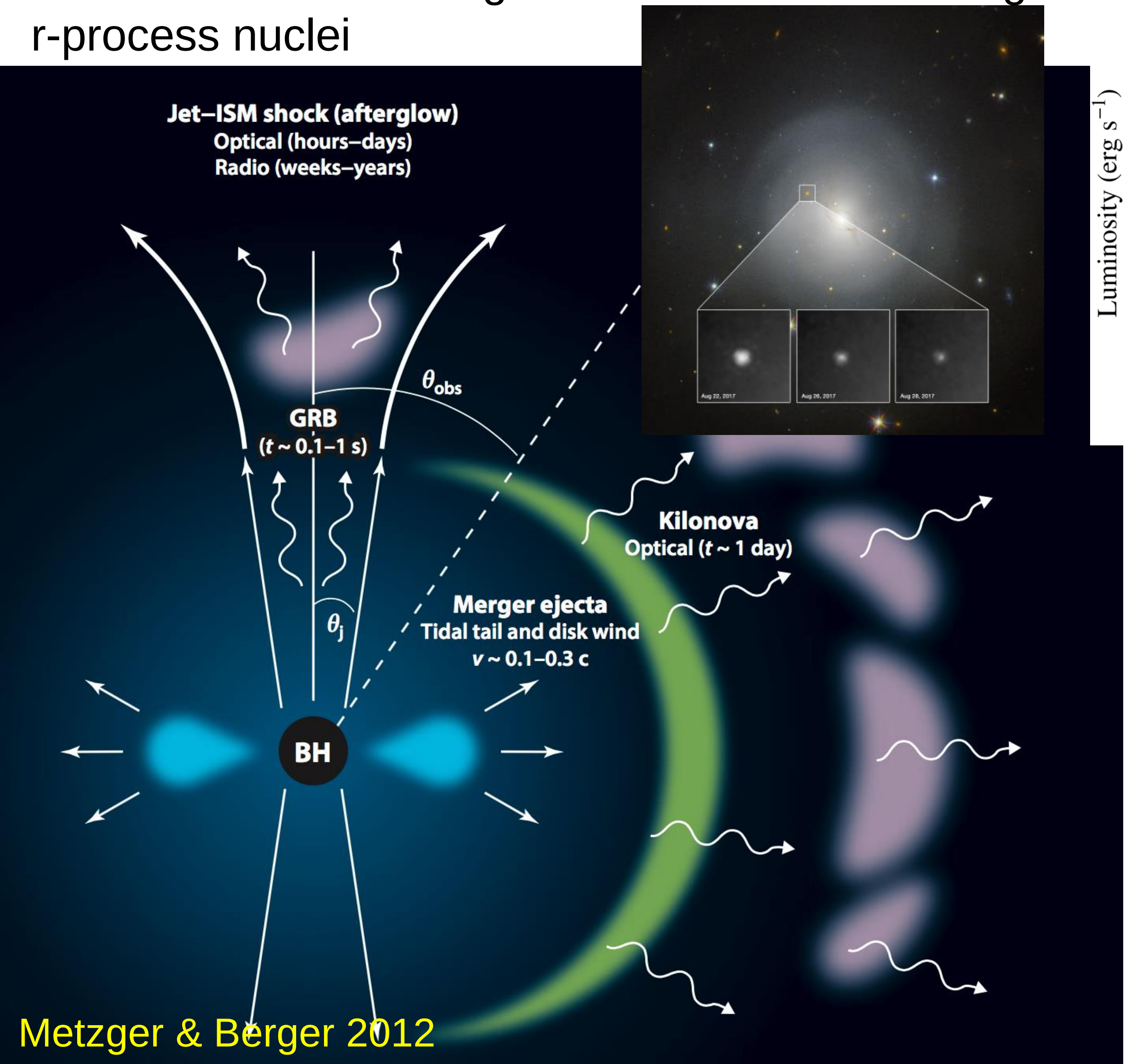
- Beta-decay rates
- Neutron capture rates
- Fission rates and yields

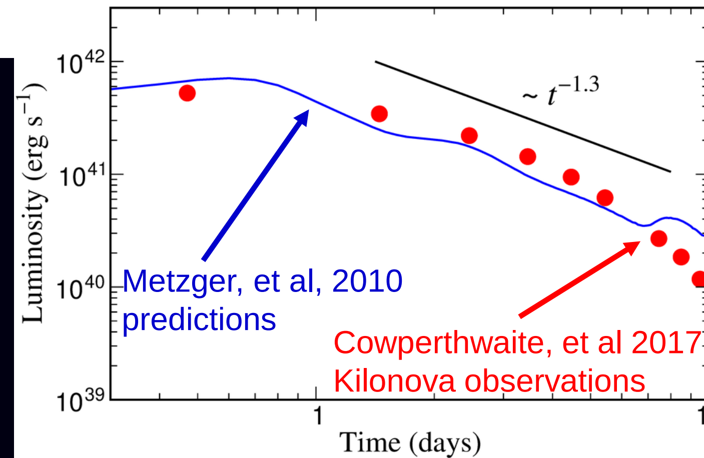
Benchmark against observations:

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

Kilonova: signature of the r-process

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





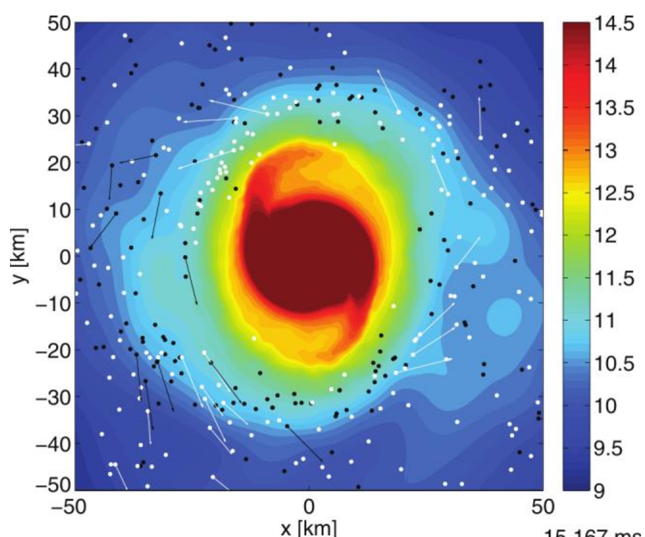
- Electromagnetic counterpart to Gravitational Waves
- Diagnostics physical processes at work during merger
- Direct probe of the formation r-process nuclei
- Information elements produced single event

Pipeline for r-process in mergers

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

- Physics of neutron-rich and heavy nuclei
- Atomic data

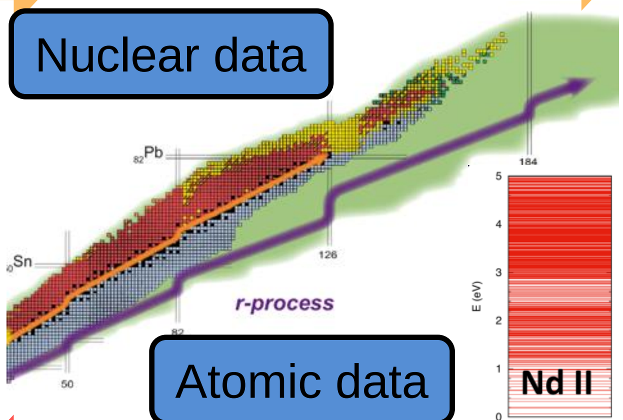
- Radioactive transfer modelling
- Thermalization decay products (Barnes+ 2016, Kasen+ 2019)
- Spectra formation: atomic data depends on ejecta evolution (LTE vs NLTE)



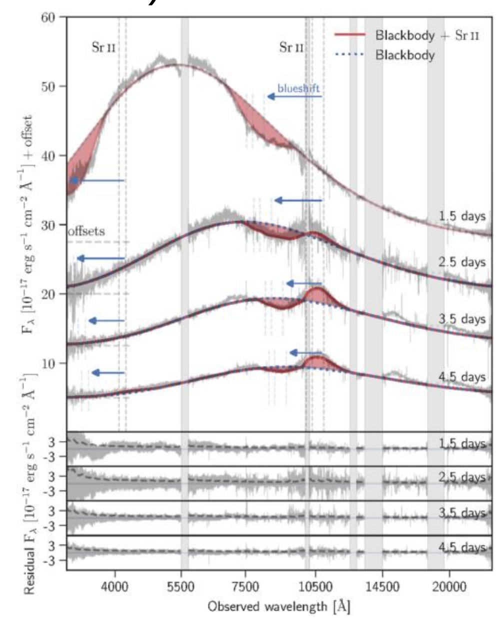
Bauswein et al, ApJ 773, 78 (2013)

Infer components ejecta (Y_e)

forward modelling



backward modelling

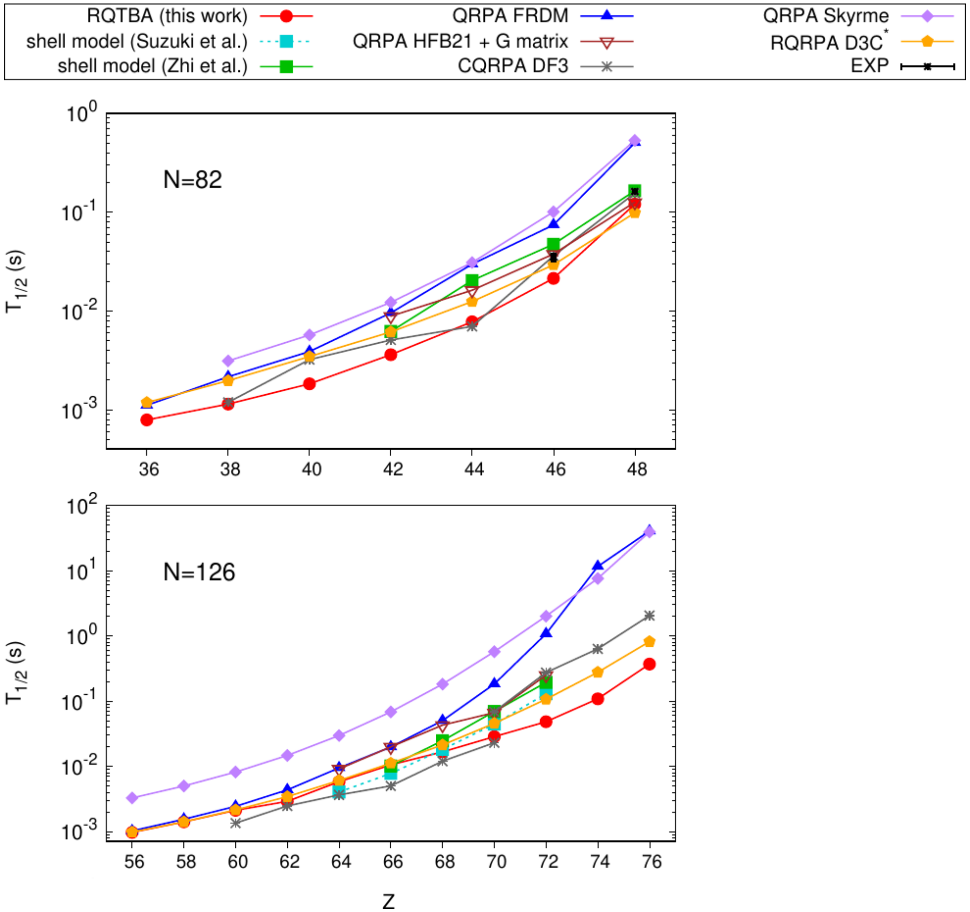


Watson et al, Nature **574**, 497 (2019)

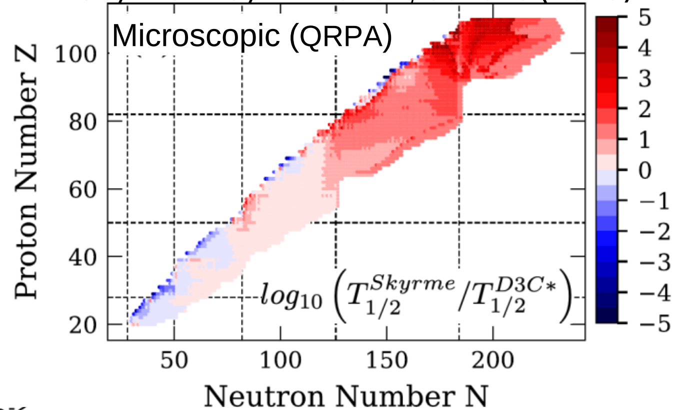
- Which r-process elements are produced in mergers?
- Are mergers the (main) r-process site?

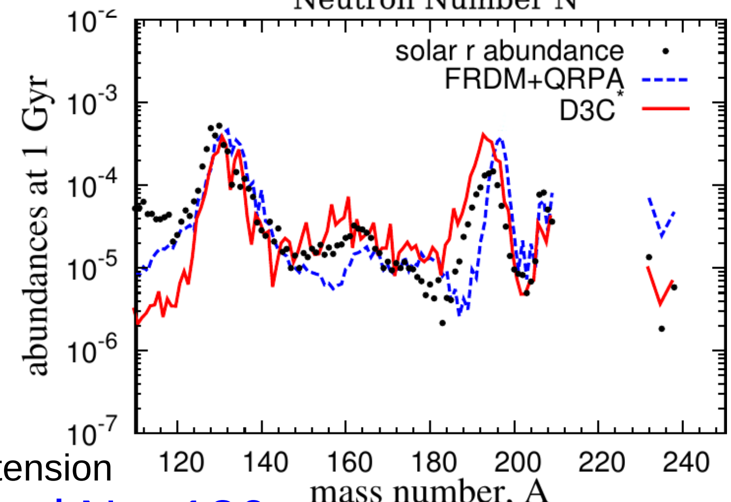
Nuclear physics input: beta-decay half-lives

- 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



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



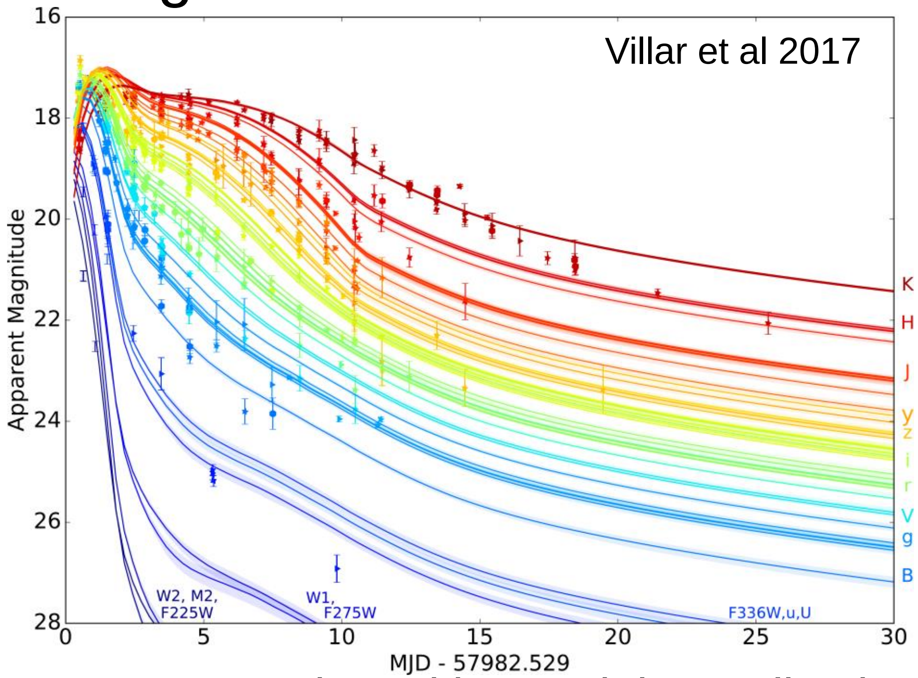


C. Robin, GMP, arXiv:2403.17115, beyond-mean field extension

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

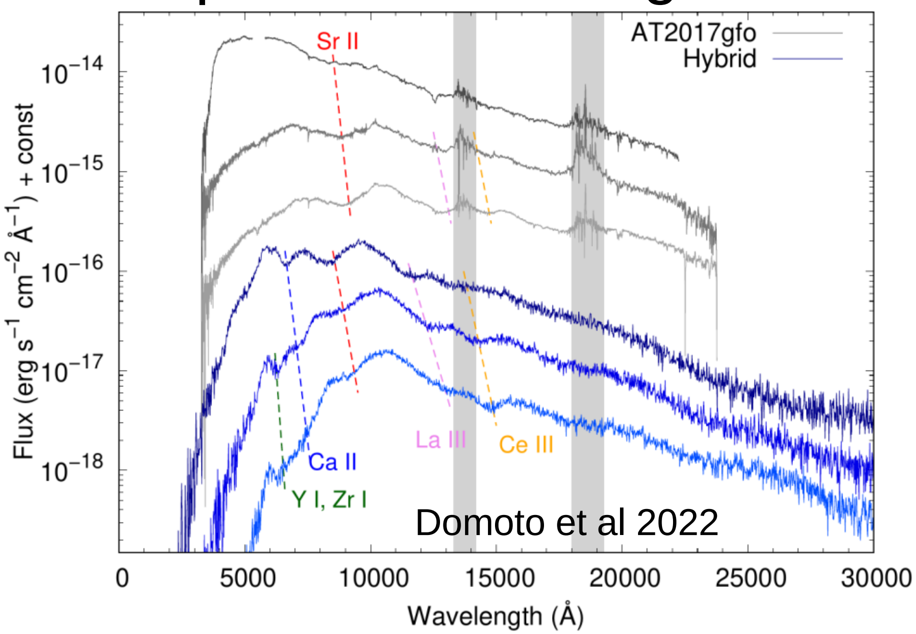
Kilonova modelling

Light curve



- Energy deposition and thermalization
- **Complete** transition data: total opacity
- Color evolution: High vs Low opacity material
- Presence of Lanthanides/Actinides (high opacity)

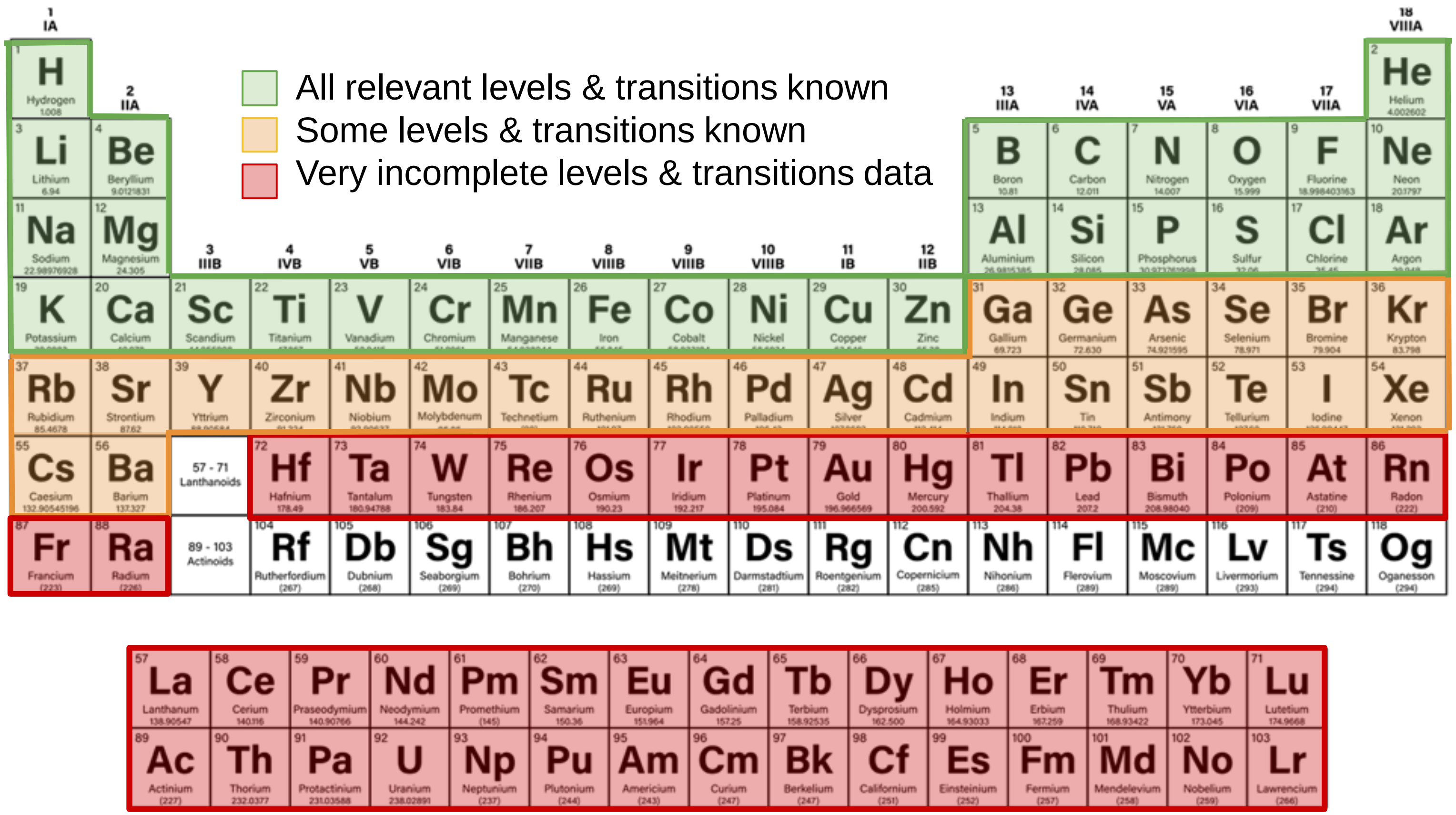
Spectral modelling



- Accurate data
  - LTE: line list bound-bound transitions
  - NLTE: + electron ion and photoionization cross sections, recombination coefficients
- Several elements observed

Sr (Watson+22), Y, Zr, La, Ce (Domoto+22, Gillanders+23, Sneppen+23)

Available experimental data

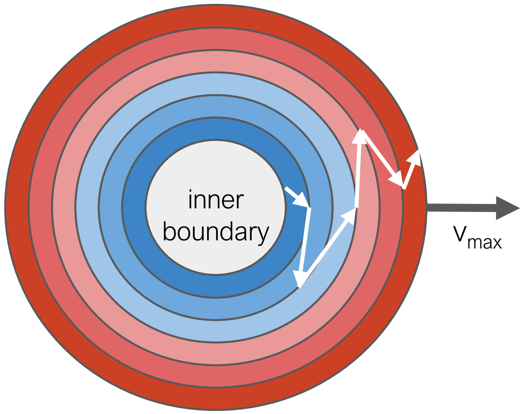


- **Energies and transition probabilities** between many levels required

- **Systematic improvement** of atomic data possible with the use of **experimental data** or *ab initio* calculations for few low lying levels

Atomic Opacities (LTE)

- Sobolev optical depth (for a line l)



$$\tau_l = \frac{\pi e^2}{m_e c} t \, f_l \, n_l \, \lambda_l$$

Transition wavelength

Oscillator strength

Population lower level (Saha eq. and partition functions)

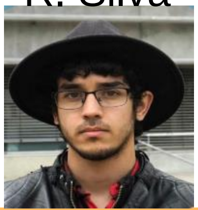
- Expansion opacity (homologous expanding material, not used in the radiation transport modelling)

$$\kappa_{\rm exp}^{\rm bb} = \frac{1}{\rho c t} \sum_l \frac{\lambda_l}{\Delta\lambda_{\rm bin}} \left(1 - e^{-\tau_l}\right)$$

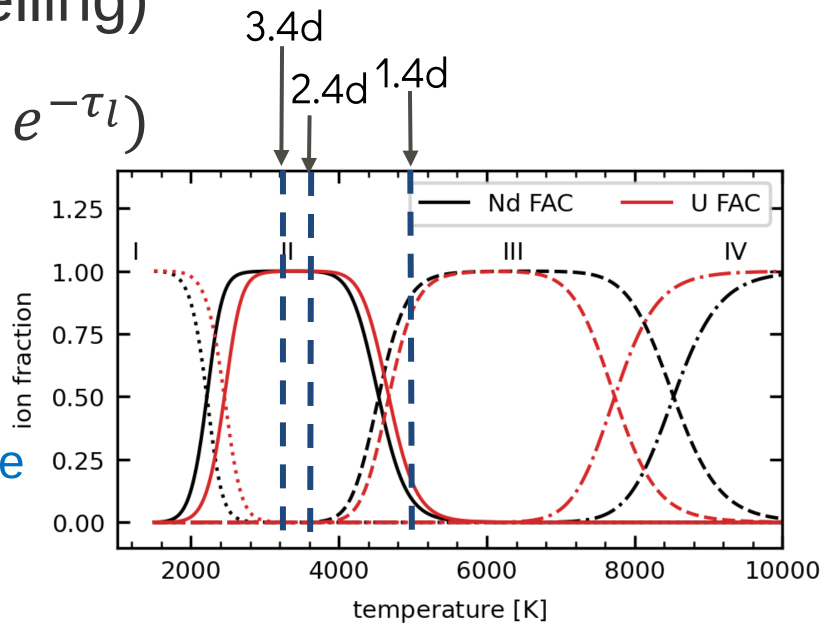
A. Flörs

G. Leck

R. Silva

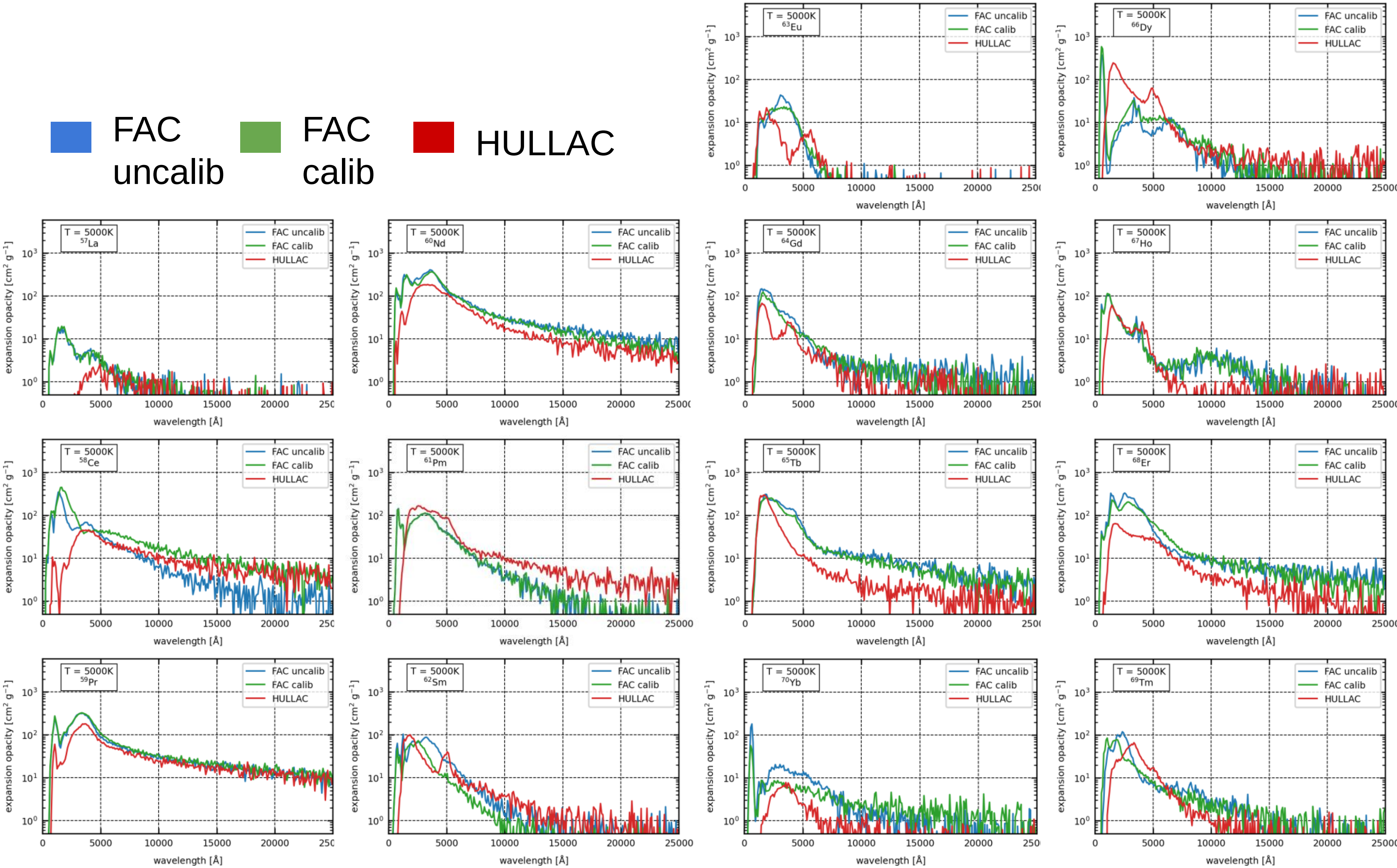


Goal: Develop database well calibrated atomic opacities



Lanthanide Opacities

FAC uncalib FAC calib HULLAC

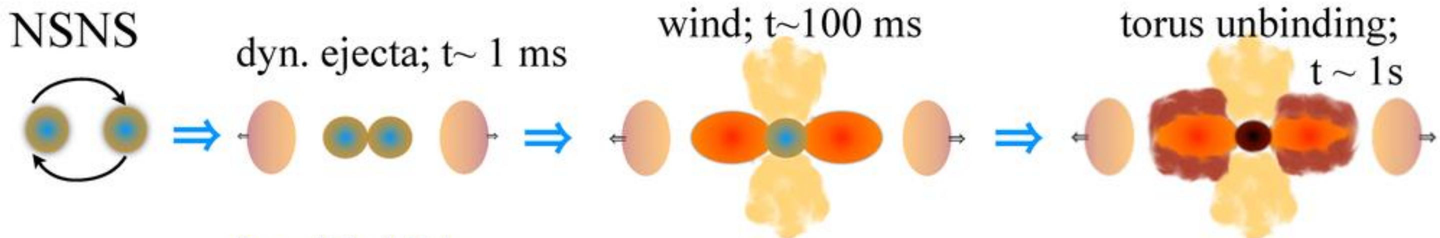


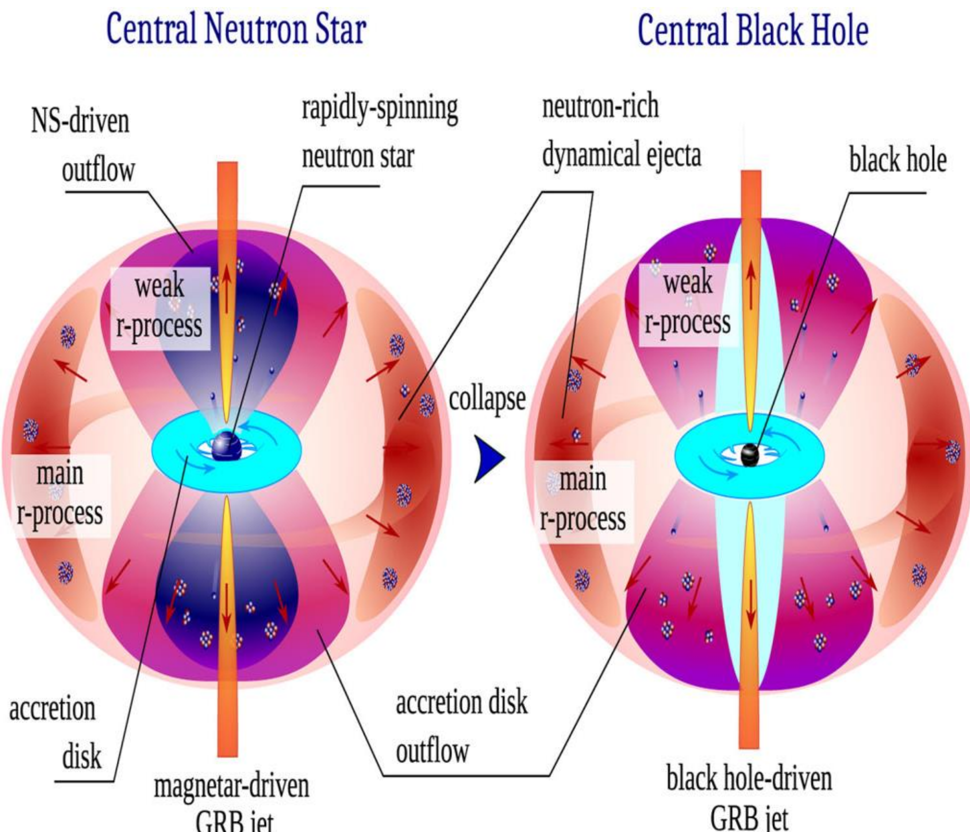
Flörs, Silva, et al, MNRAS 524, 3083 (2023) A. Flörs, et al, in preparation

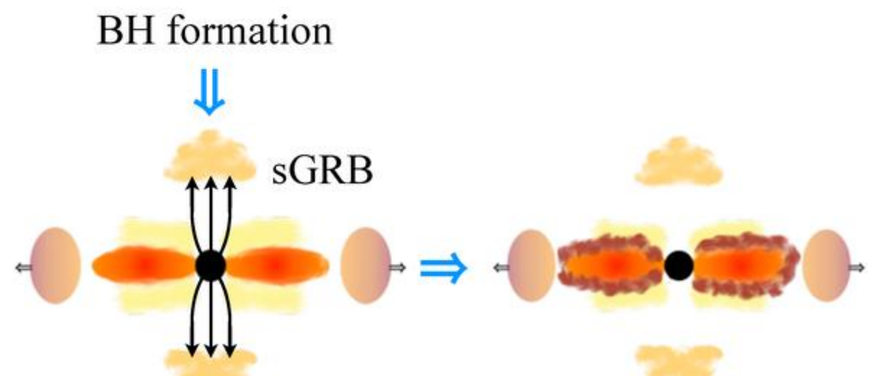
Neutron star mergers: Different ejection mechanisms

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

Gravitational wave emission







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

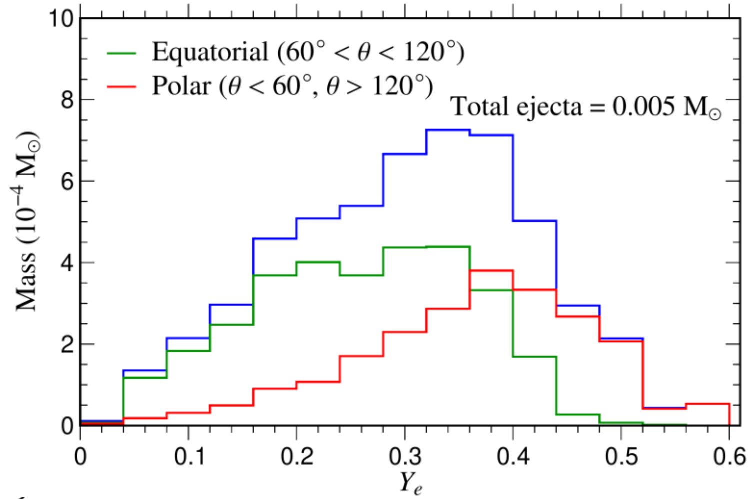
Two sources of ejecta:

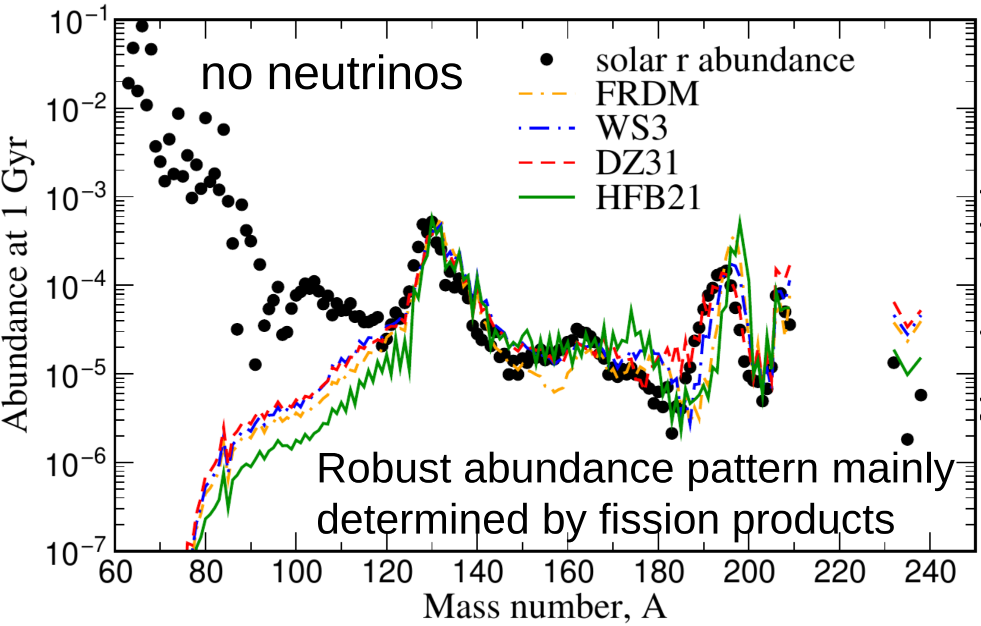
- Dynamical during the early phases of the merger ($M \lesssim 0.01\ M_\odot$)
- Accretion disc on longer timescales ($M \lesssim 0.05\ M_\odot$)
- Liftetime neutron-star determines impact neutrinos

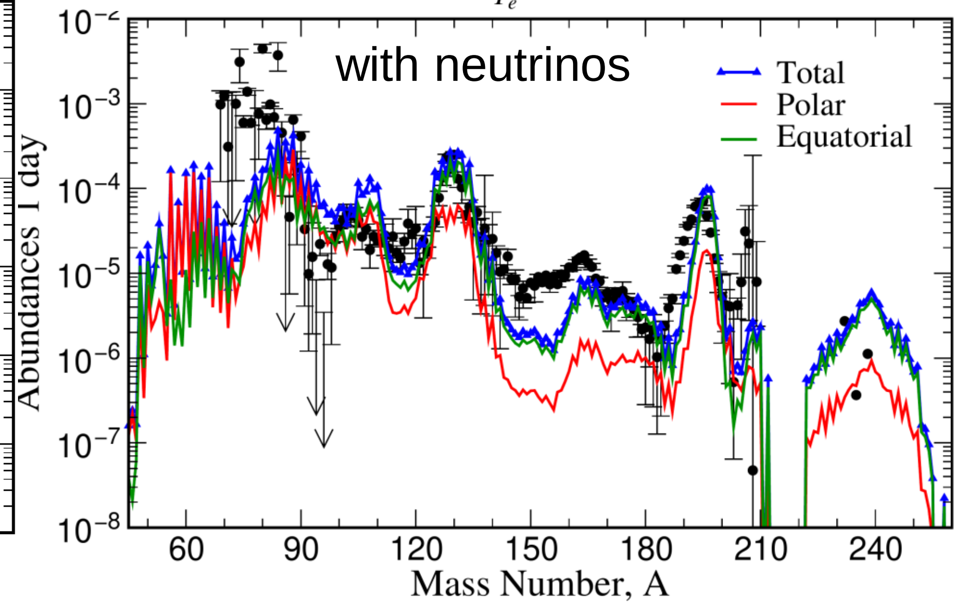
Dynamical ejecta (simulations)

- 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

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





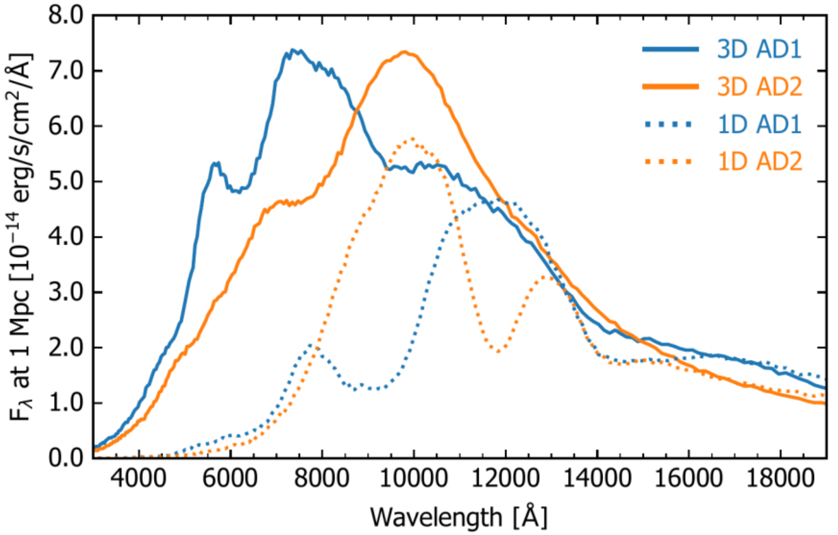


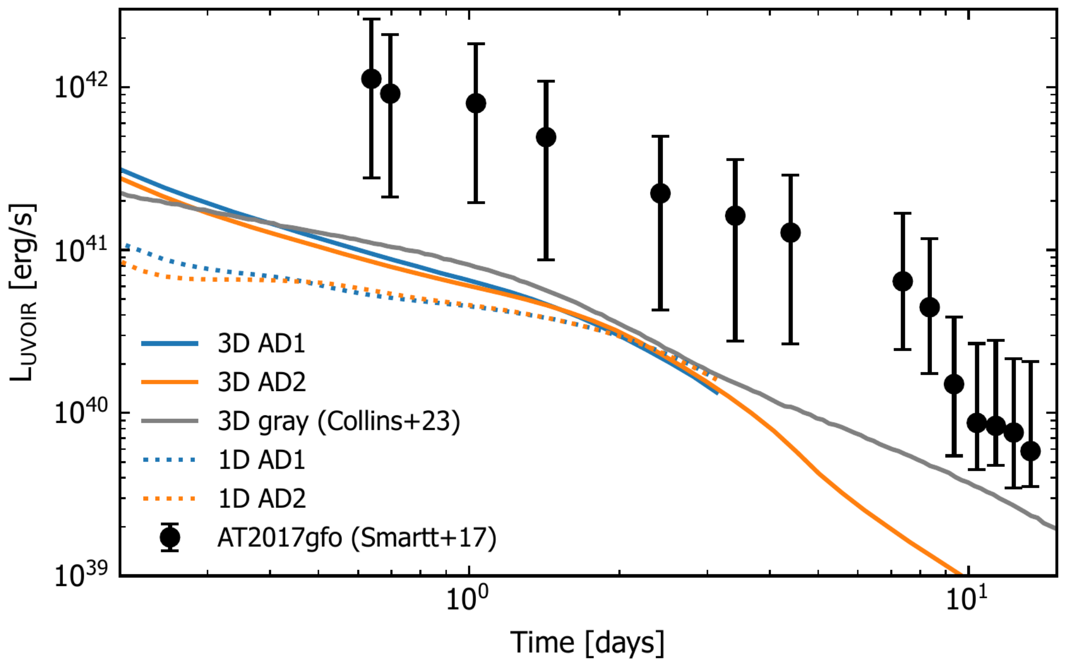
Mendoza-Temis, et al, PRC 92, 055805 (2015)

Self-consistent 3D radiative transfer

- Monte Carlo 3D radiative transfer using the ARTIS code. https://github.com/artis-mcrt/artis
- Matter distribution based on SPH Dynamical ejecta (0.005 $M_\odot$)
- LTE simulation: follows 2591 nuclei (283 ions with gamma-ray transport and electron thermalization, 44 millions atomic transitions lines)
  AD1: Japan-Lithuania database (HULLAC) Z=28-88, Tanaka+ 2020
  AD2: AD1 + calibrated lines for Sr, Y, and Zr, Kurucz 2018

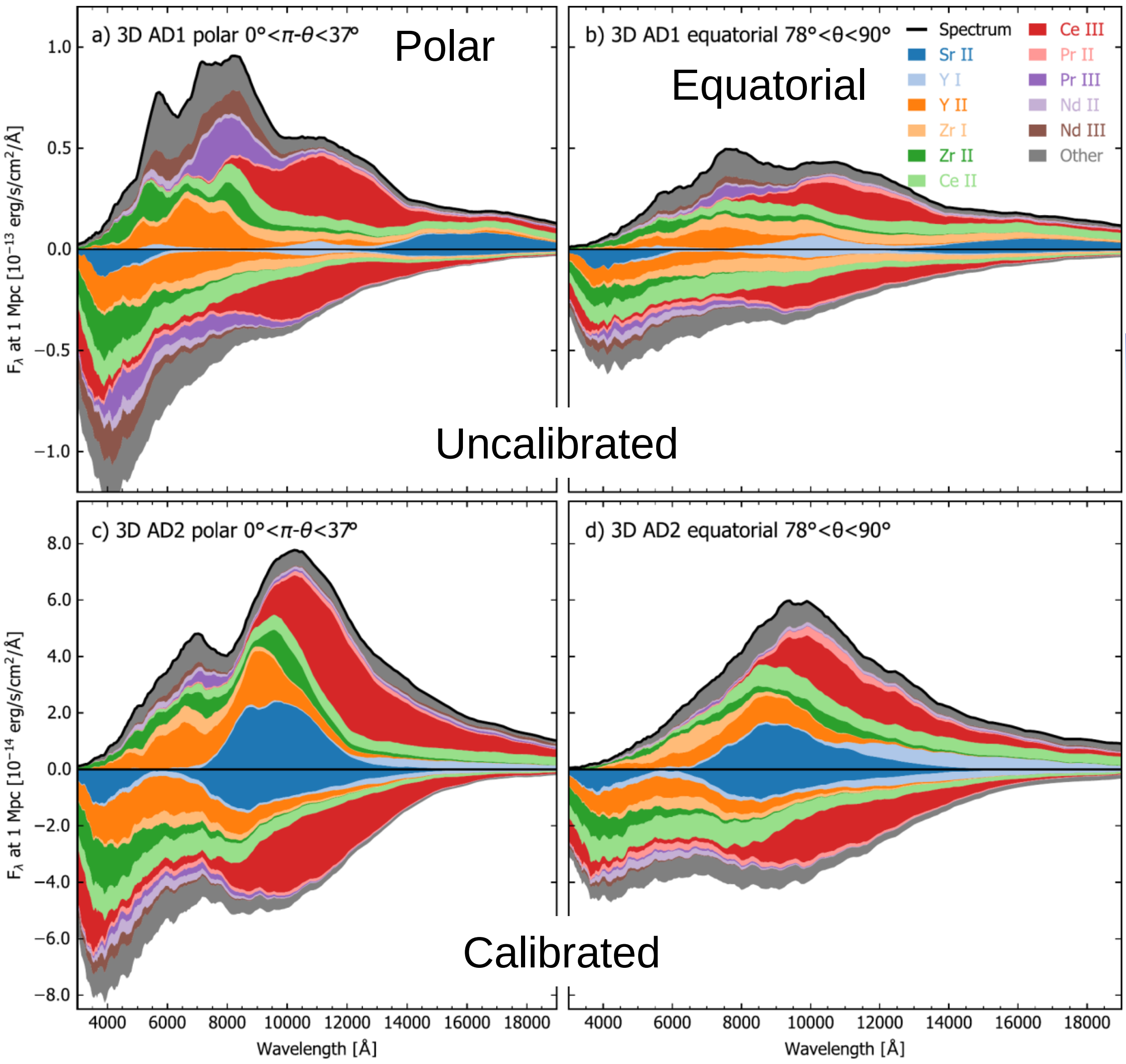
L. Shingles

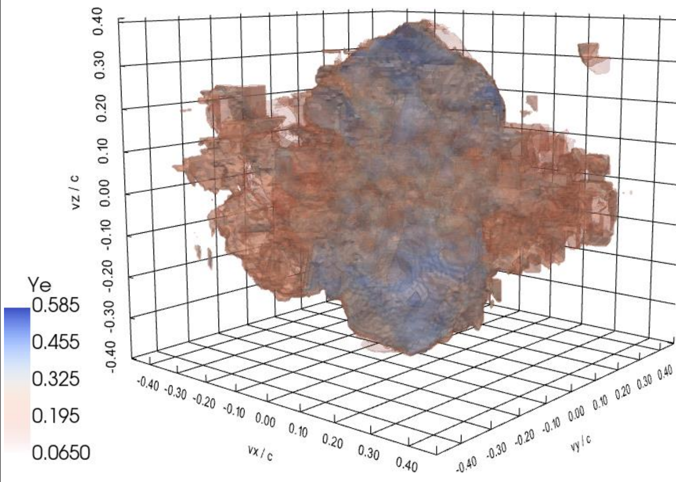




Shingles et al, ApJ 954, L41 (2023)

Angular dependence spectra

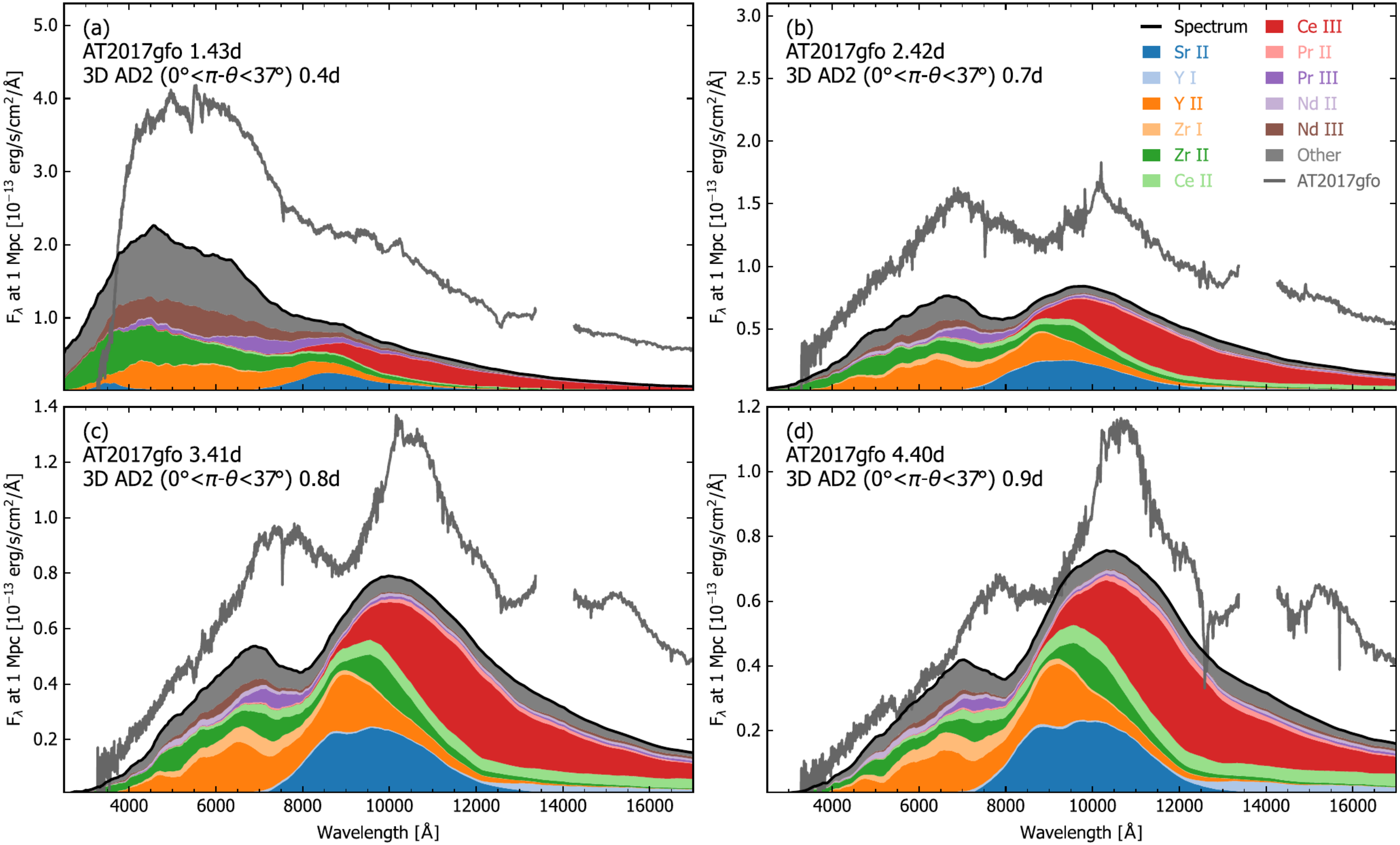




Differences reflect directional dependence of nucleosynthesis yields

Shingles et al, ApJ 954, L41 (2023)

Comparison AT2017gfo

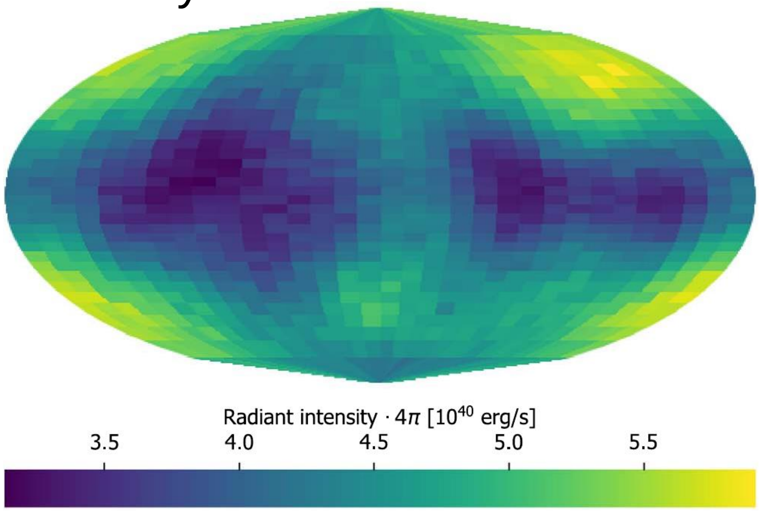


Similar spectral evolution that AT2017gfo once differences in brightness are accounted

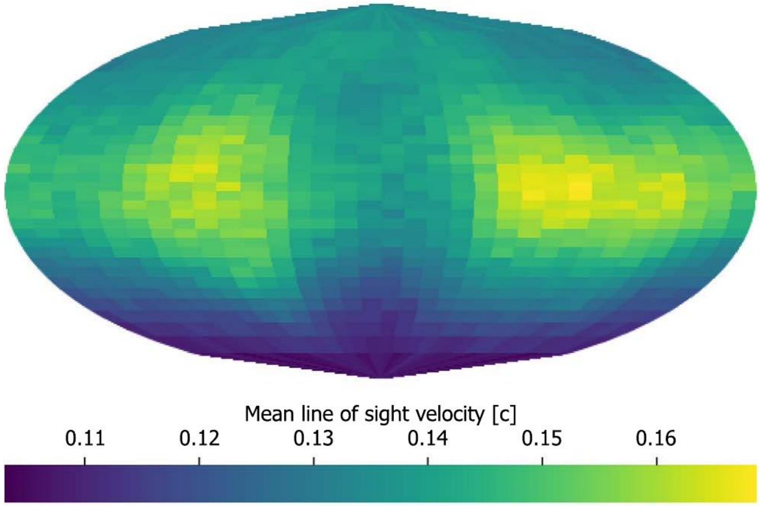
Shingles et al, ApJ 954, L41 (2023)

Asymmetry observables

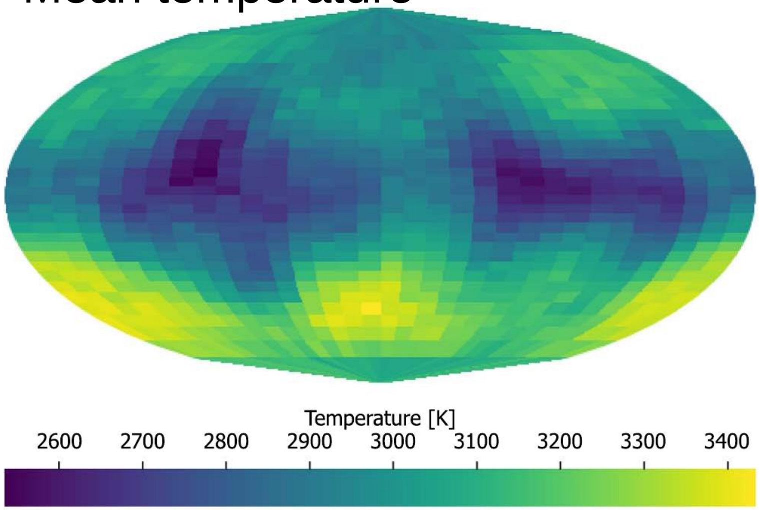
Intensity



Line-of-sight velocity



Mean temperature



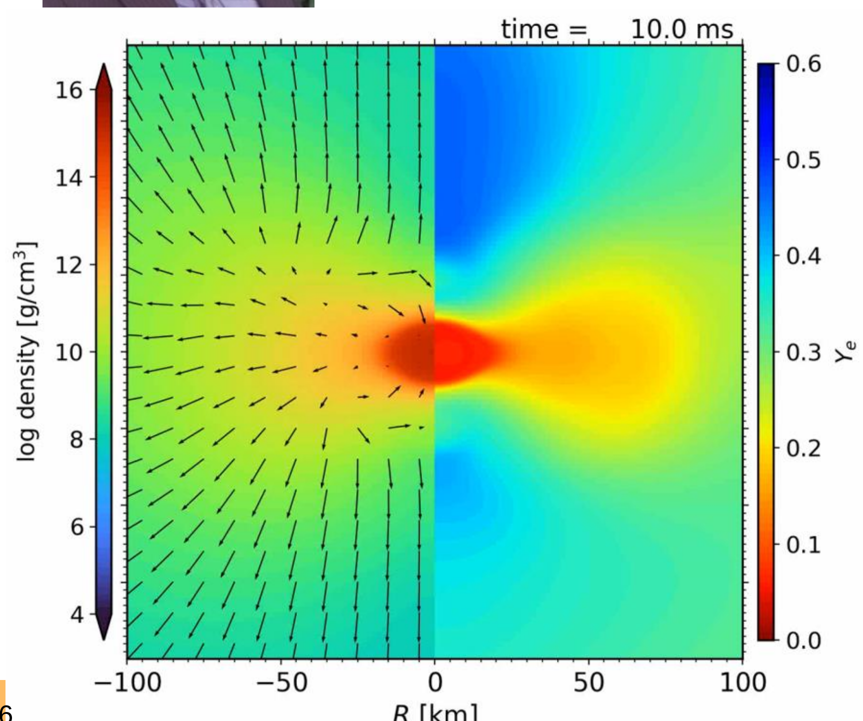
- Strong asymmetry observables
- Need of further observations

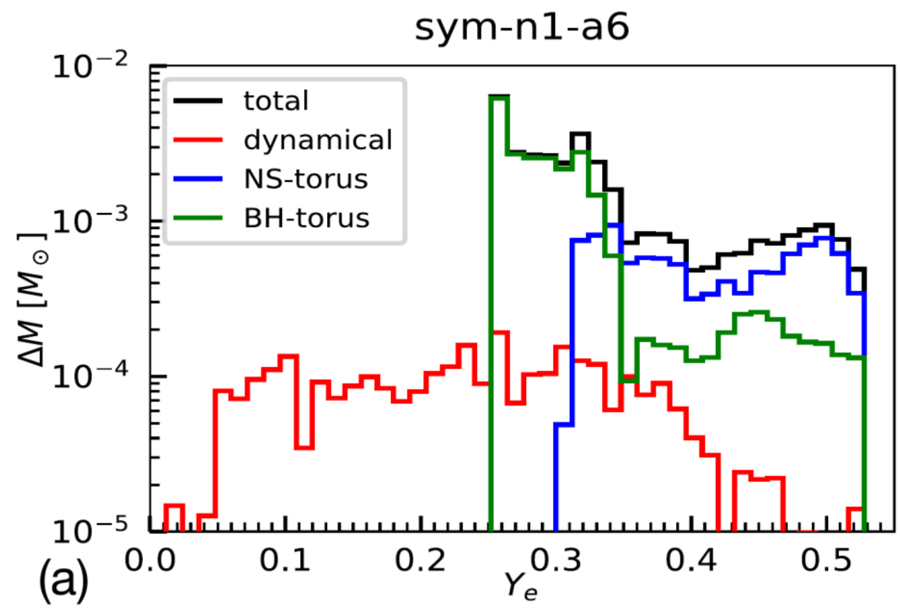
Shingles et al, ApJ 954, L41 (2023)

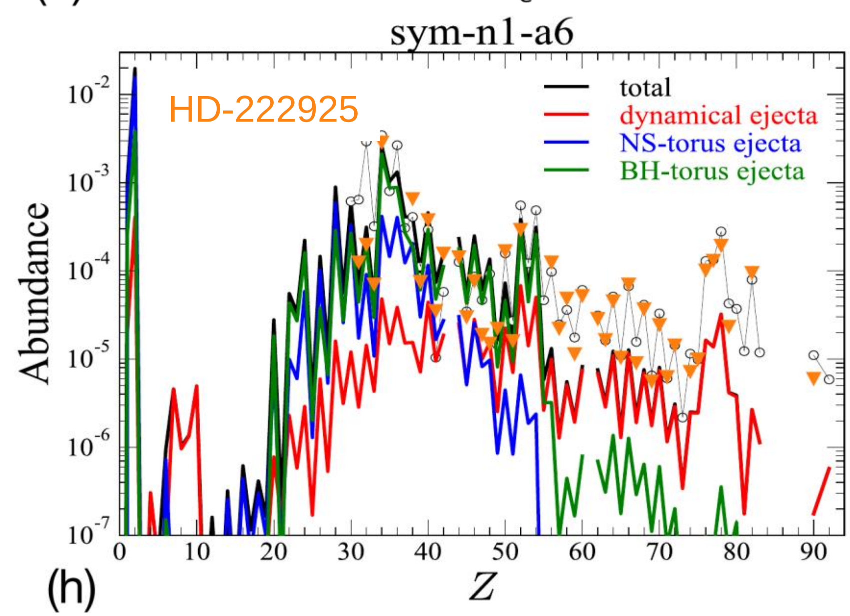
Long term merger simulations

Long-term simulations with neutron star lifetimes 0.1-1 s and describe all components of the eject*a: d*ynamical, NS-torus ejecta, and final viscous ejecta from BH torus.

Just et al, ApJL, L12 (2023)

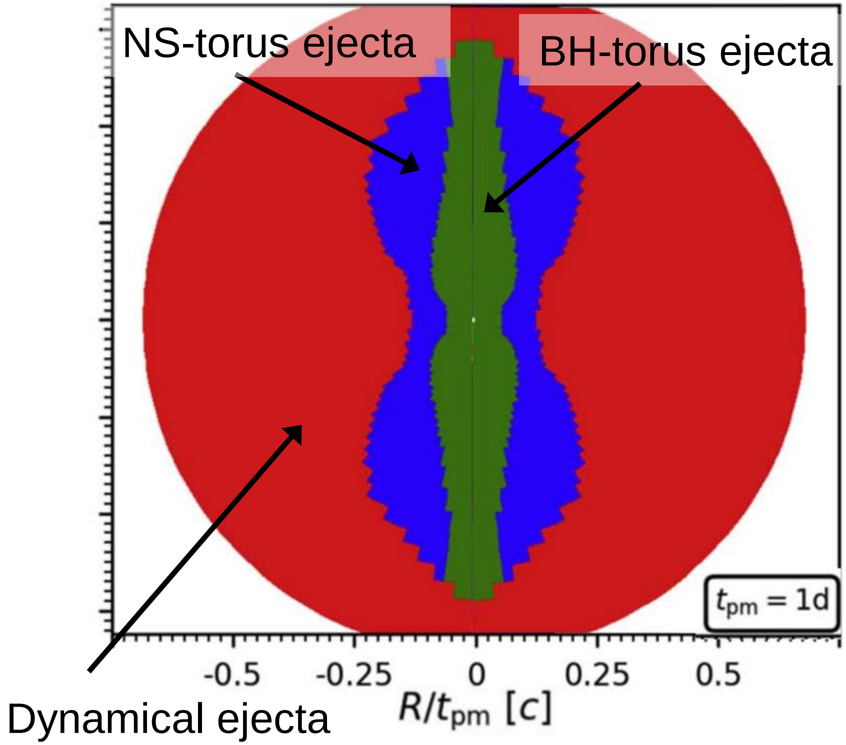


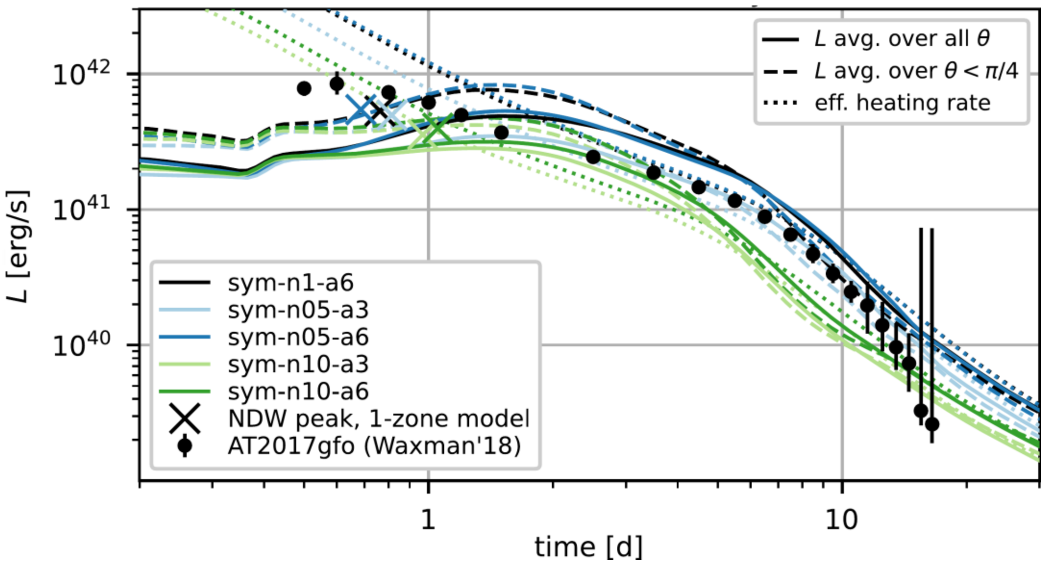




End to end kilonova models

- Based on grey opacities using approximate radiative transfer model (generalization ALCAR neutrino module)
- Promising agreement with AT2017gfo after times of several days
- Accounting for all ejecta components fundamental to reproduce light curve

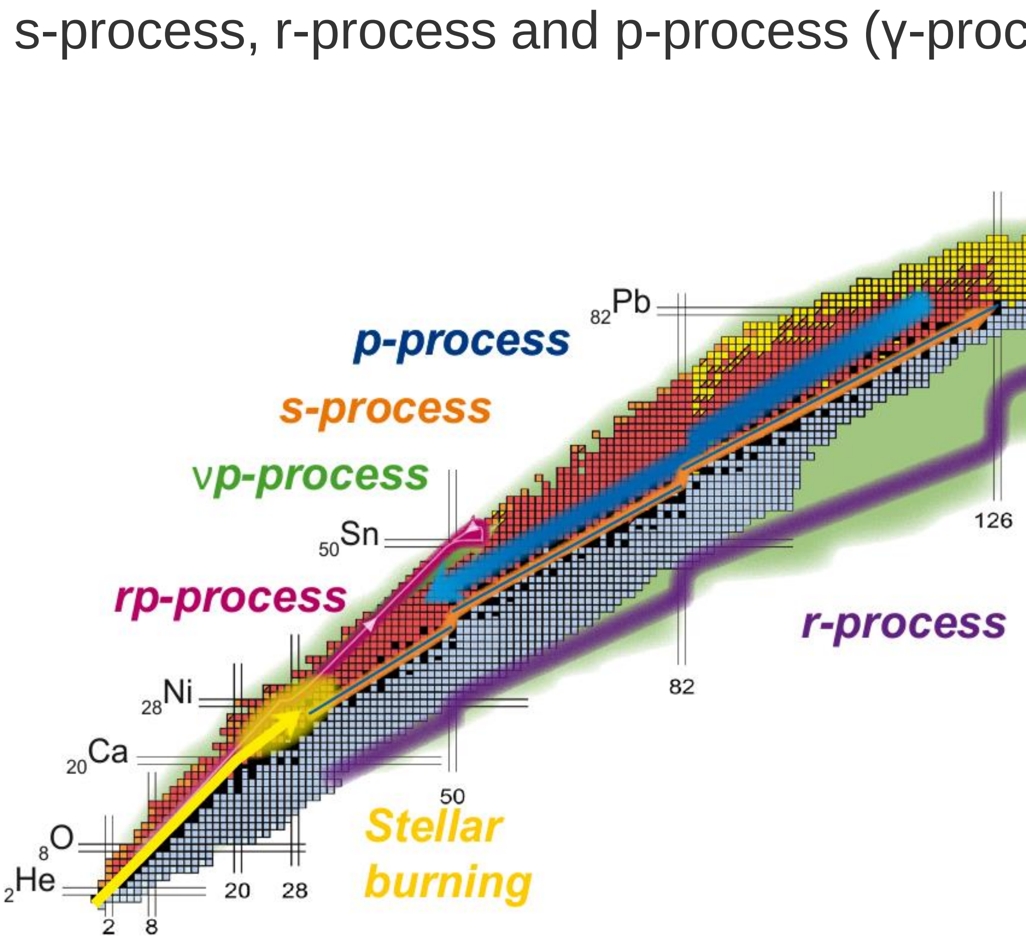




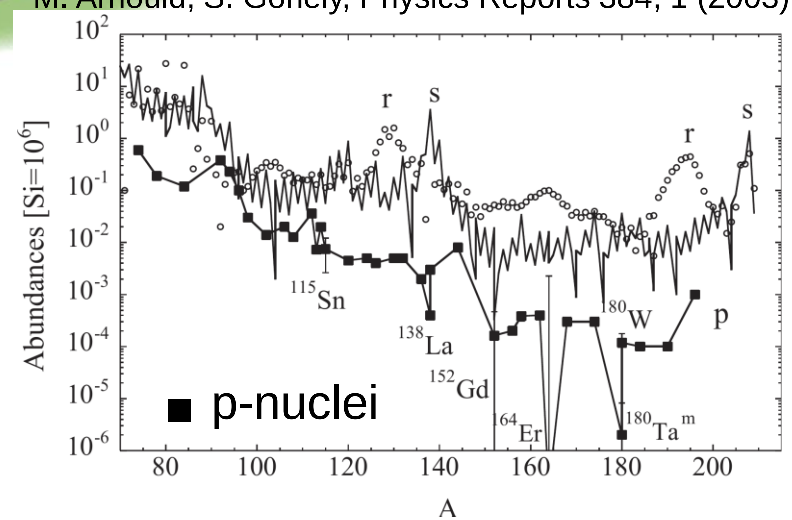
Just et al, ApJL, L12 (2023)

Nucleosynthesis beyond iron

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



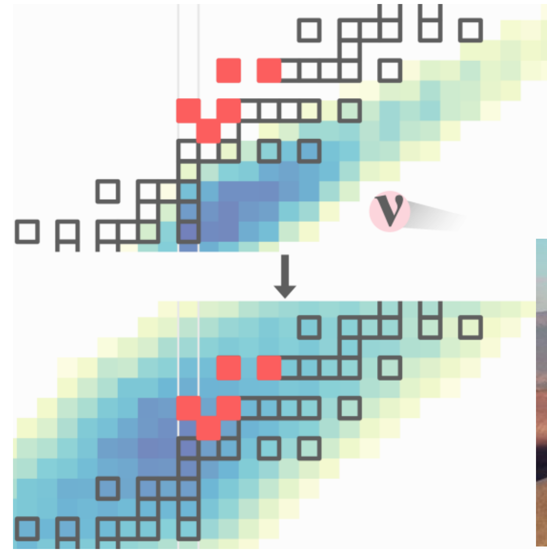
M. Arnould, S. Goriely, Physics Reports 384, 1 (2003)

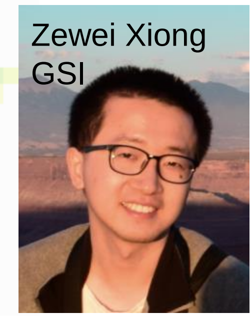


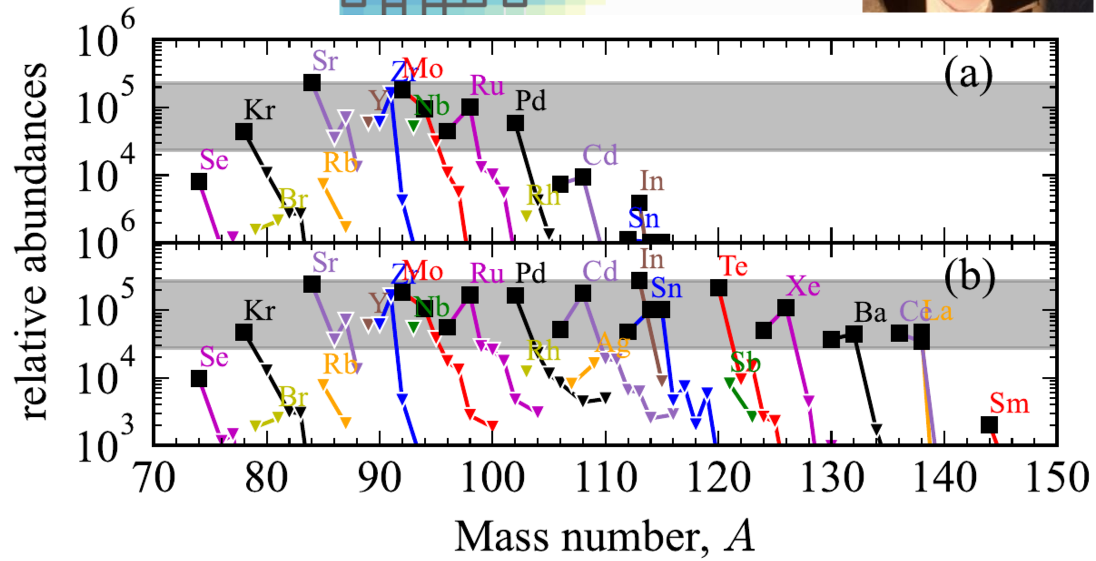
- Origin p-nuclei unclear
- Can neutrino-nucleus reactions help producing p-nuclei?

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

- Novel nucleosynthesis process that operates under strong neutrino fluxes
- Sequence of neutron captures and charged-current neutrino-nucleus reactions.
- Production of p-nuclei from neutron-rich nuclei.
- May require high magnetic fields as found in magnetars (see arXiv:2402.06003)
- Experimental constraints to neutrino-nucleus cross sections are necessary







Xiong, Just, GMP, Sieverding PRL132, 192701 (2024)

Editors' Suggestion **Featured in Physics**

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”
  - 3D radiative transfer allows to benchmark models with observations.
- Challenges:
  - Impact of weak processes and EoS in the ejecta properties
  - Improved nuclear and atomic input
  - Kilonova spectral modelling
- νr-process: new mechanism production p-nuclei

Collaborators

A. Bauswein, **C. Collins**, **A. Flörs**, **O. Just**, **G. Leck**, **L. Shingles**, N. Rahman, **V. Vijayan**, **Z. Xiong**
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