Probing heavy element nucleosynthesis through electromagnetic observations

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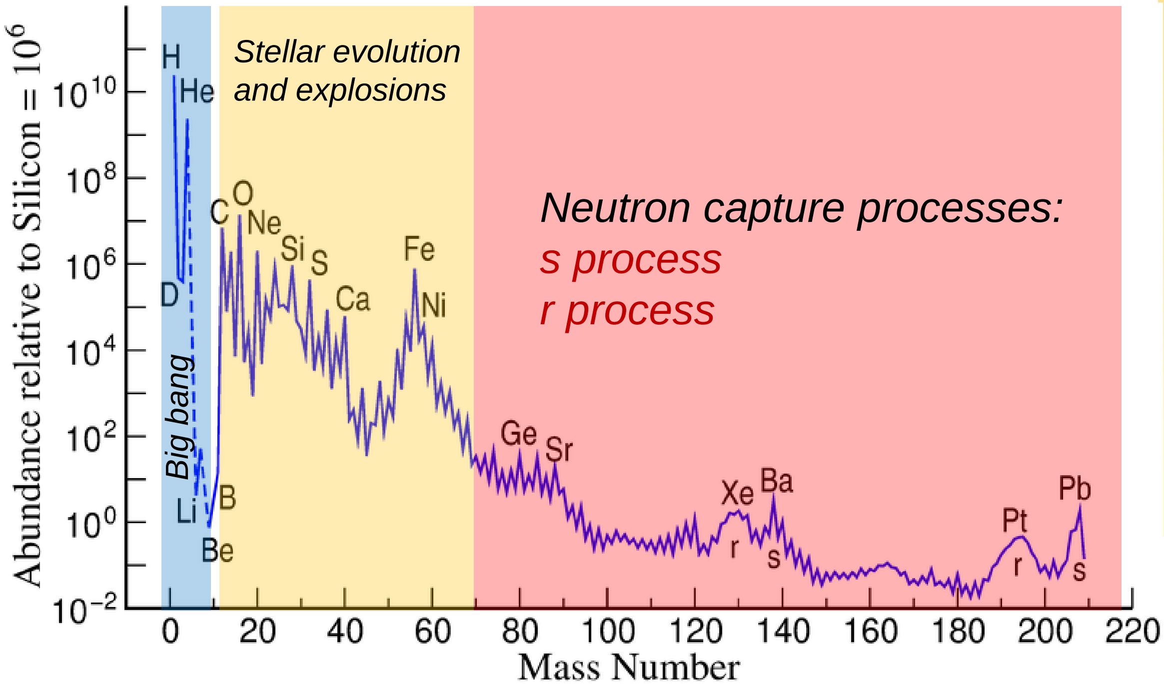
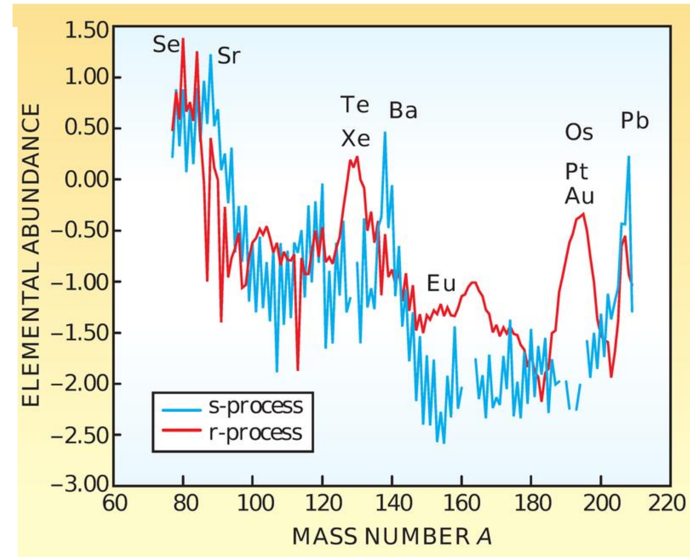
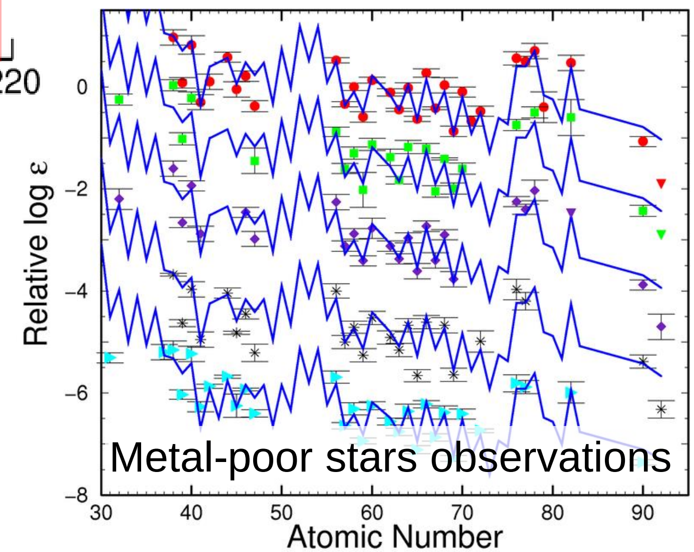
Signatures of nucleosynthesis







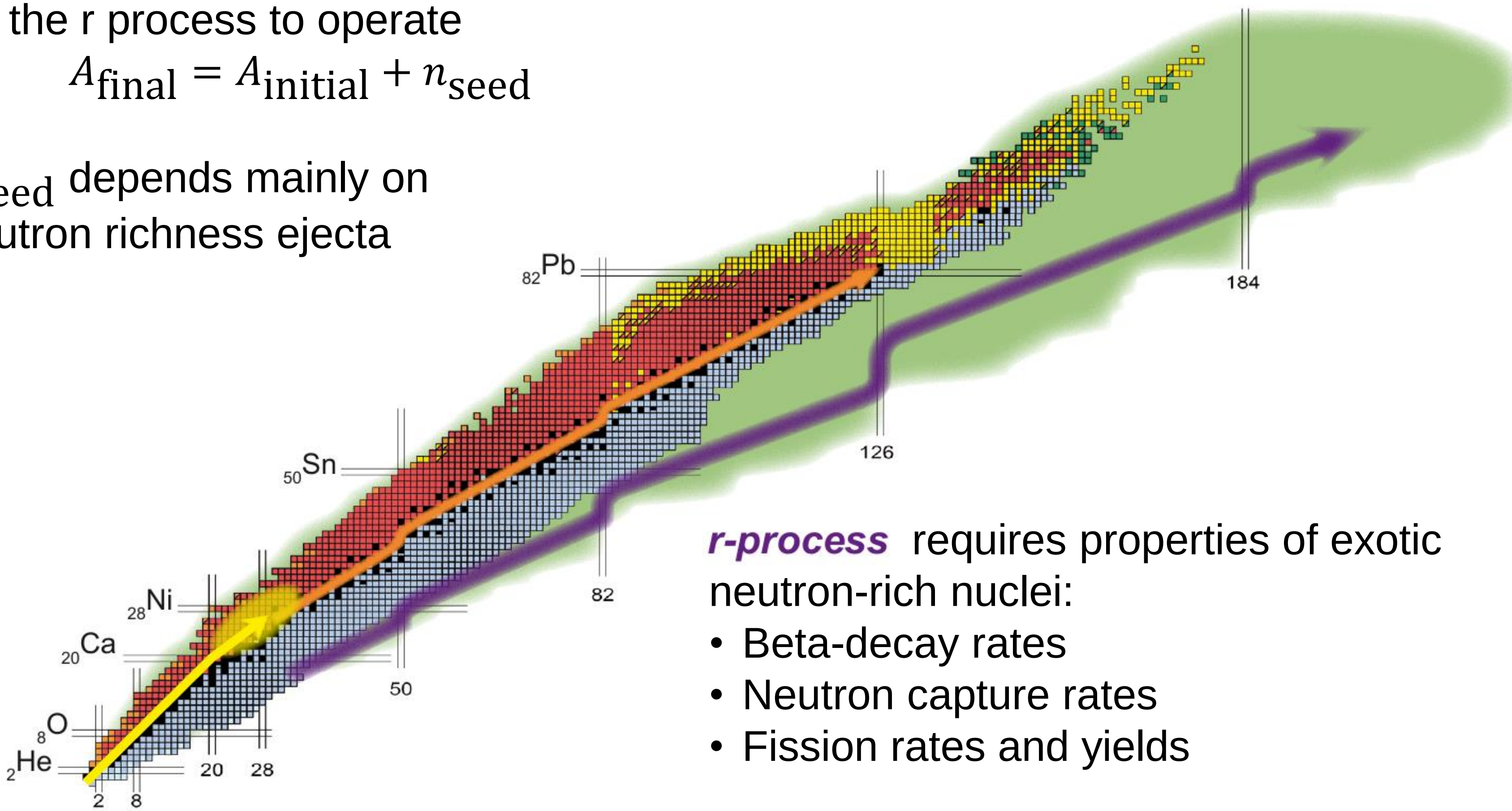
- Heavy elements produced in neutron capture processes
- Observations indicate that r process operates from early Galactic history in rare (high yield) events

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:

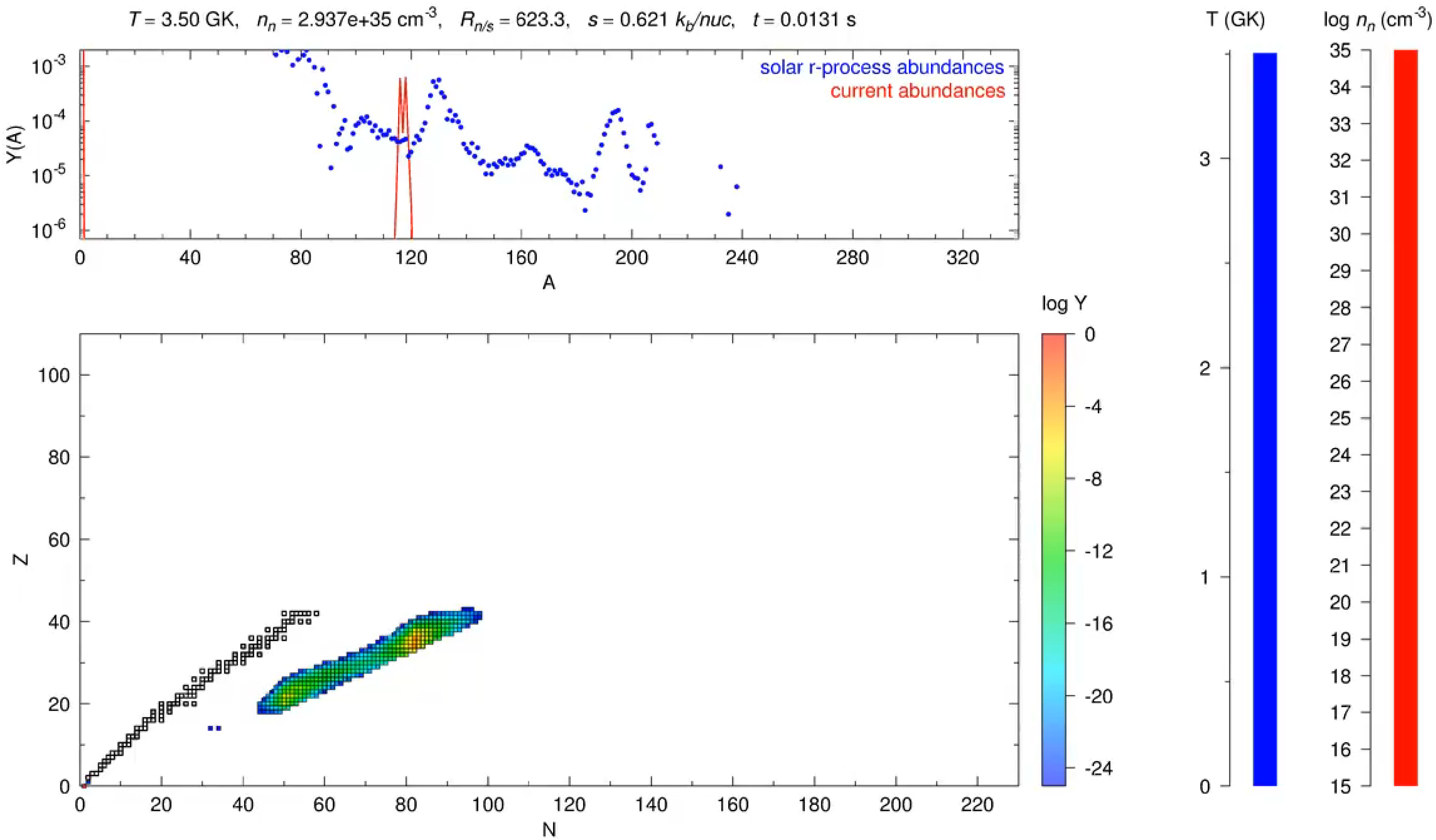
- Beta-decay rates
- Neutron capture rates
- Fission rates and yields

Benchmark against observations:

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

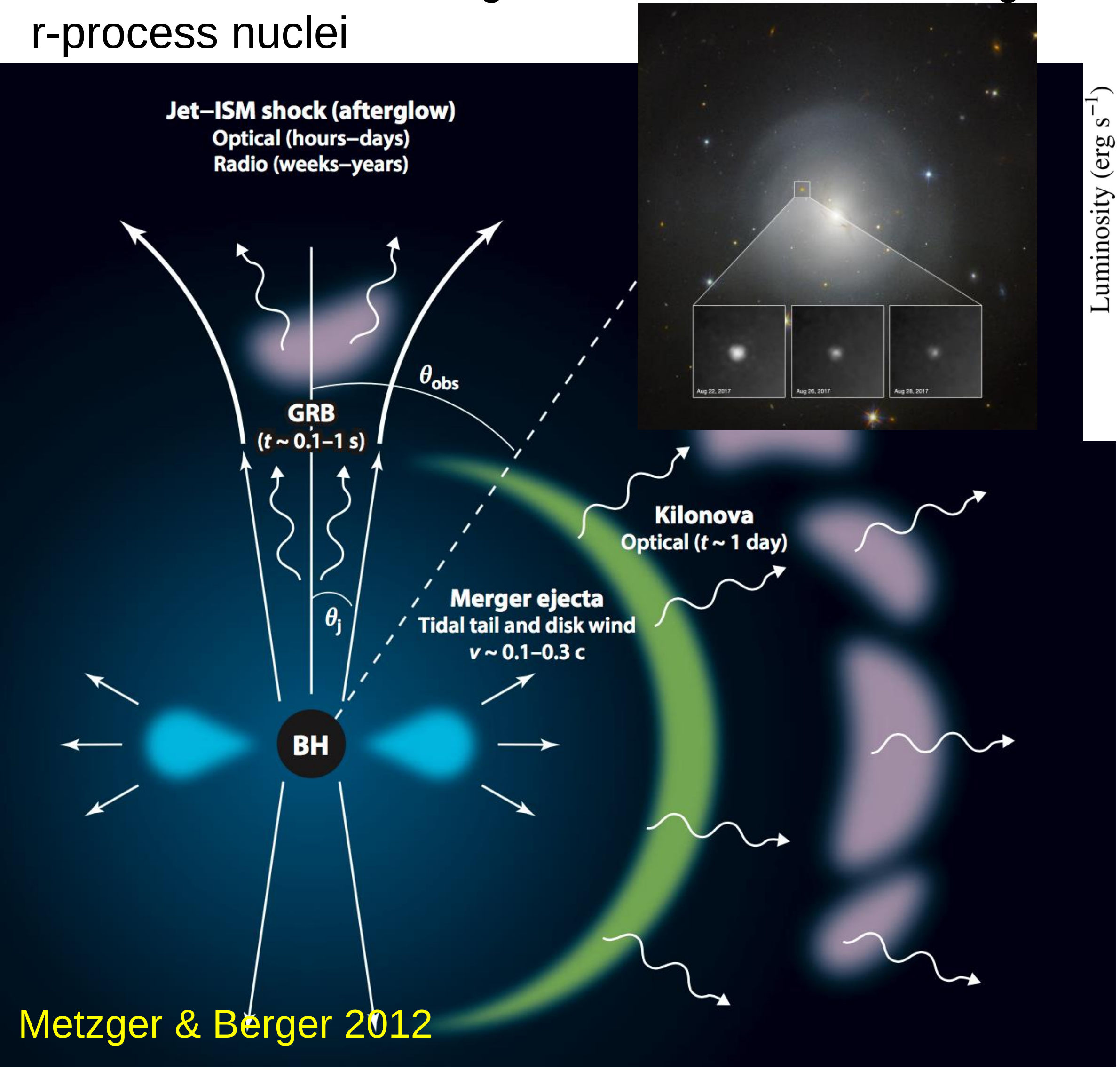
R-process operation

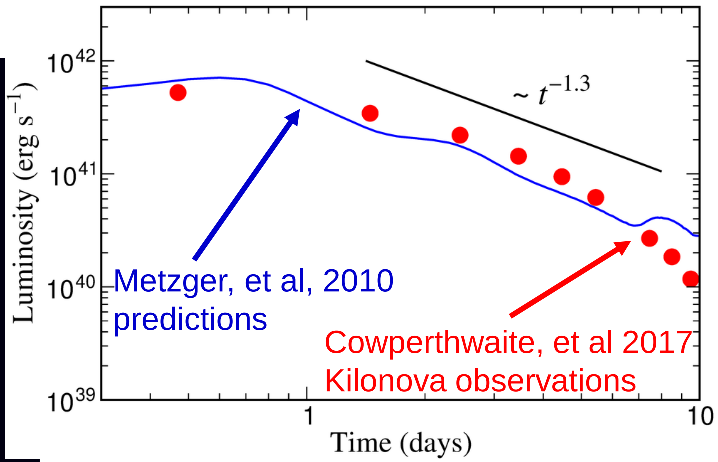
Heavy elements produced by the r-process. Radioactive decay liberates energy



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

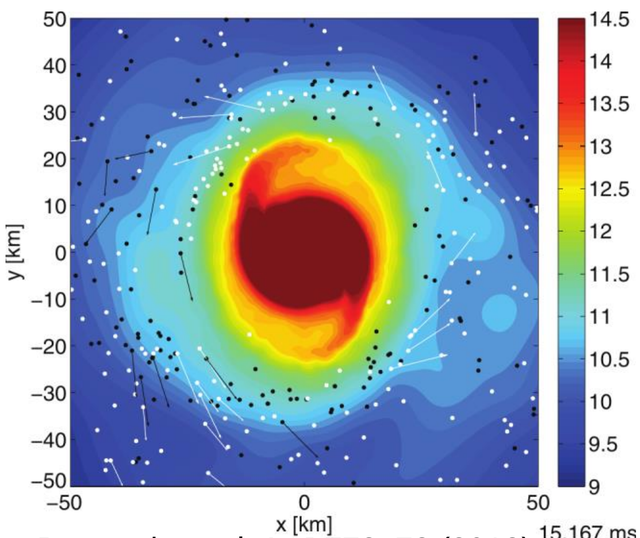
- Properties ejecta: proton-to-nucleon ratio (Y_e)
- Role of equation of state
- Role of neutrinos

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

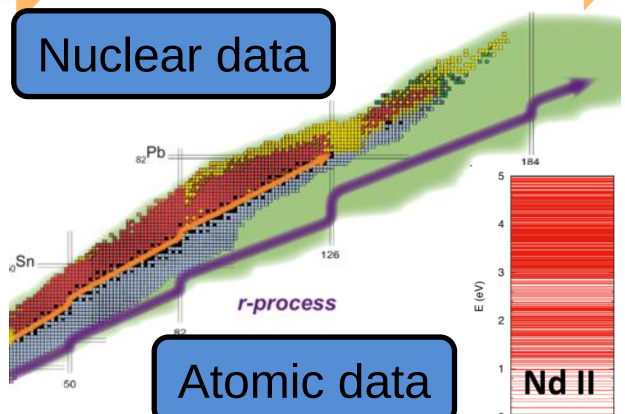
- Radioactive transfer modelling
- Thermalization decay products (Barnes+ 2016, Kasen+ 2019)
- Spectra formation: atomic data depends on ejecta evolution (LTE vs NLTE)

forward modelling

Nuclear data

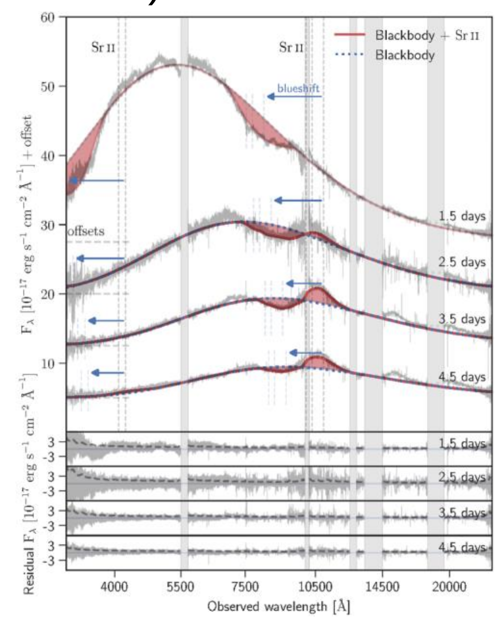


Bauswein et al, ApJ 773, 78 (2013)



Atomic data

backward modelling



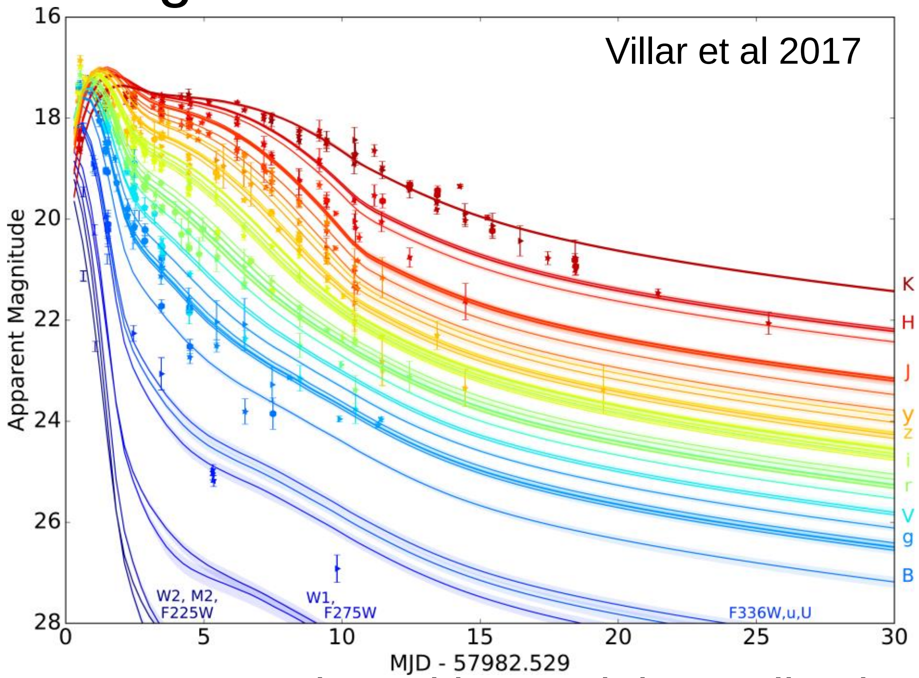
Watson et al, Nature **574**, 497 (2019)

Infer components ejecta (Y_e)

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

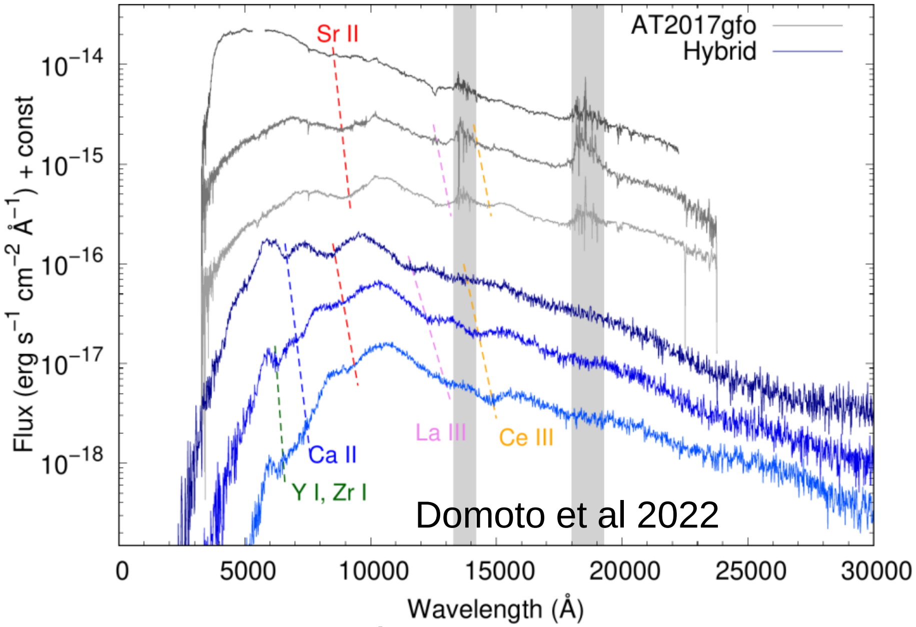
Kilonova modelling

Light curve



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

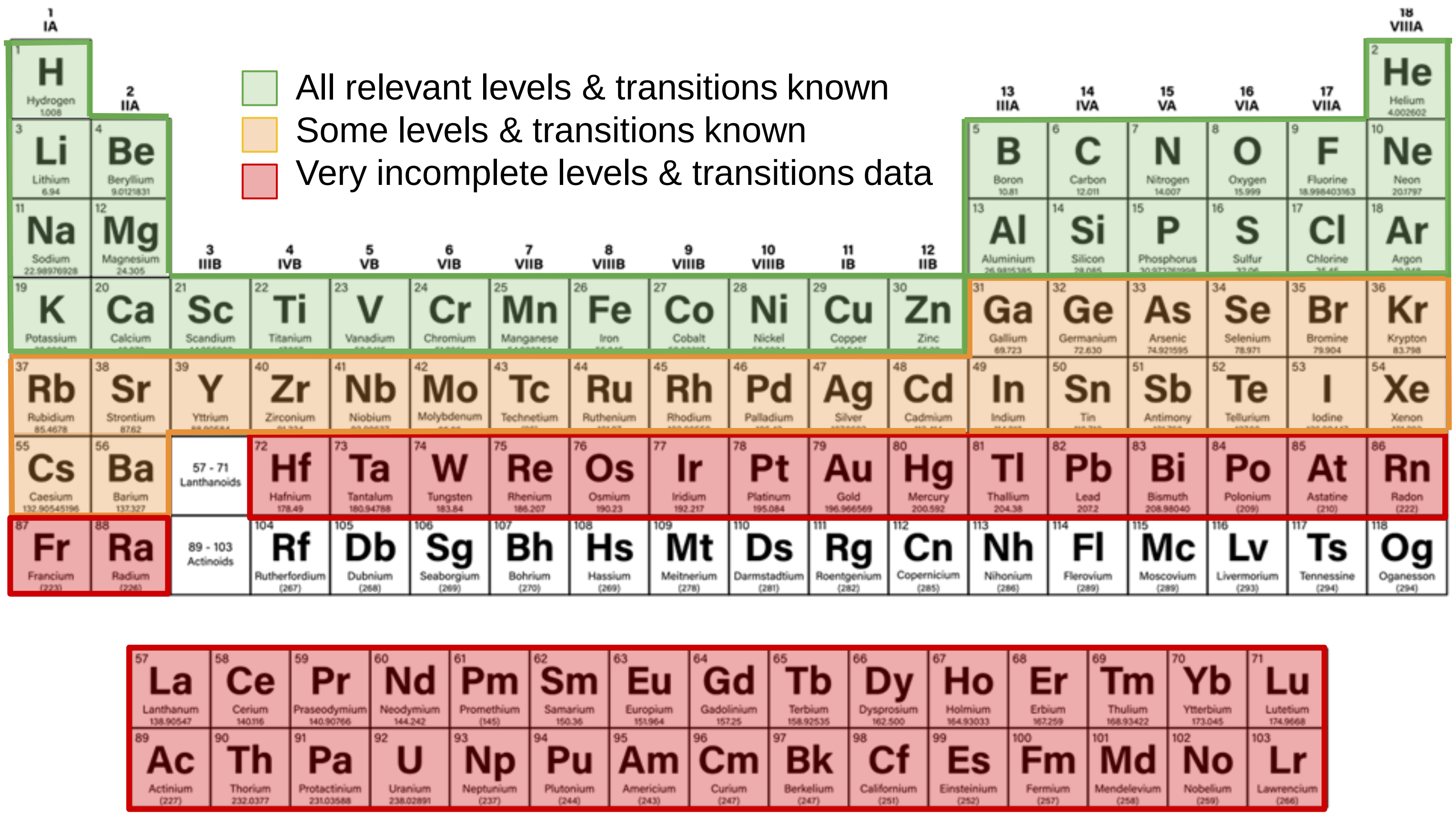
Spectral modelling



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

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

Available experimental data

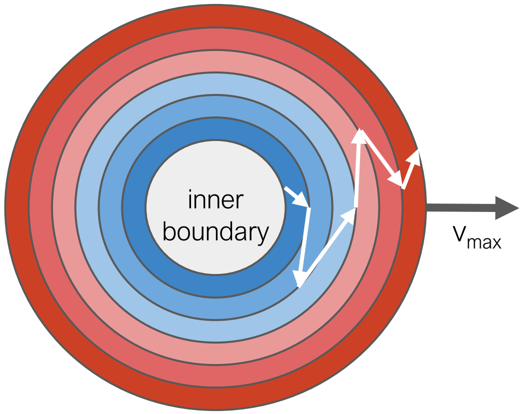


- **Energies and transition probabilities** between many levels required

- **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)



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

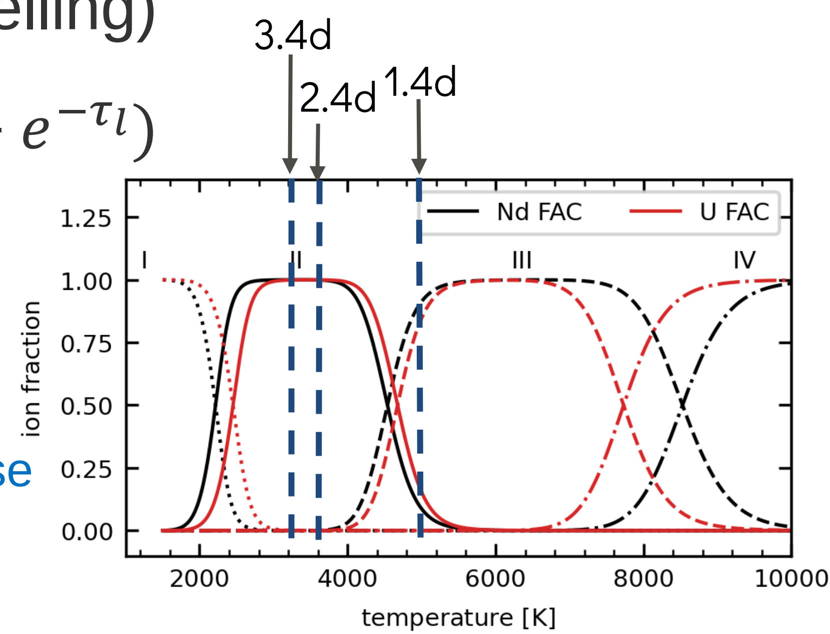
Transition wavelength

Oscillator strength

Population lower level (Saha eq. and partition functions)

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

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



A. Flörs

G. Leck

R. Silva

Goal: Develop database well calibrated atomic opacities

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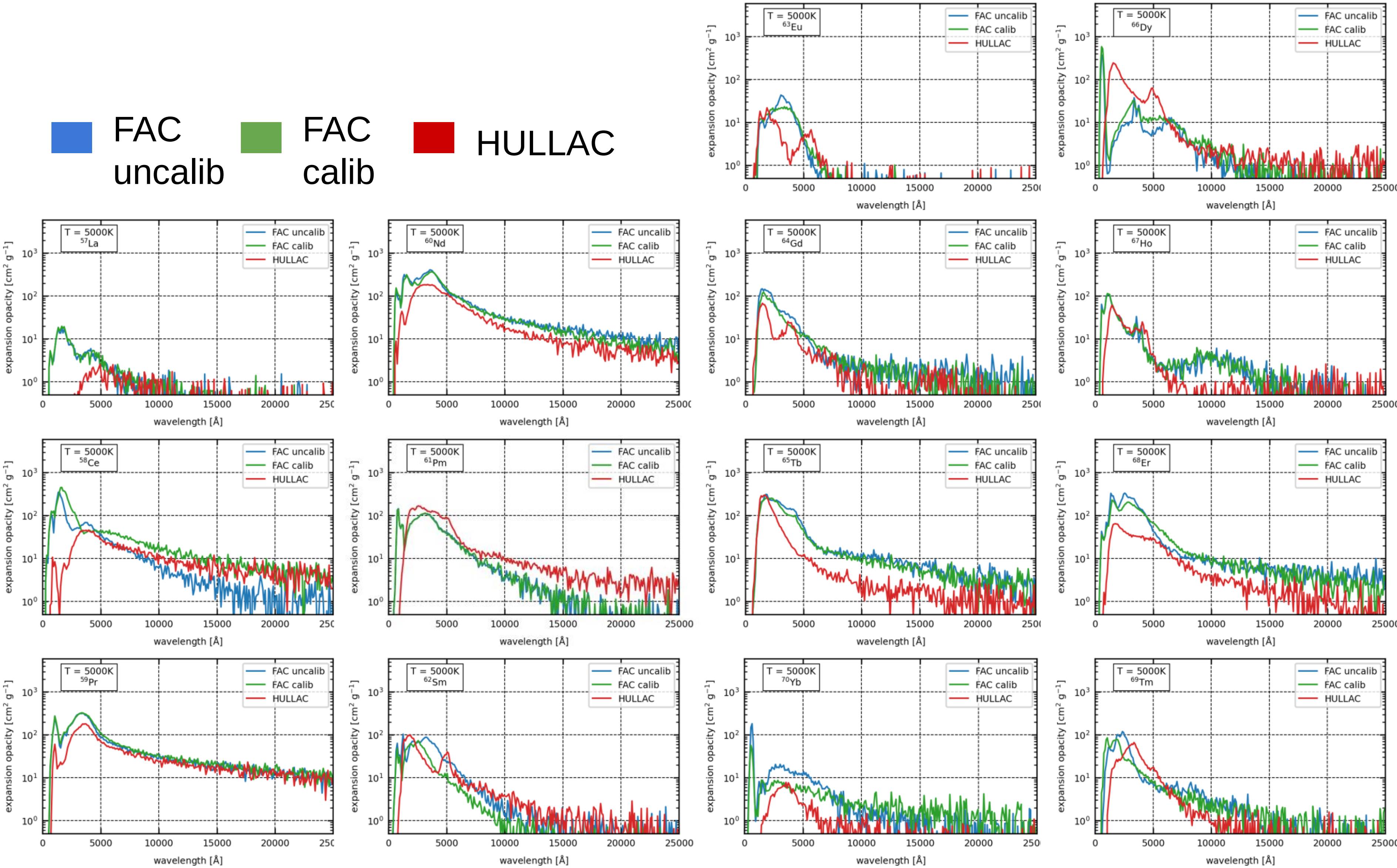
Lanthanide Opacities

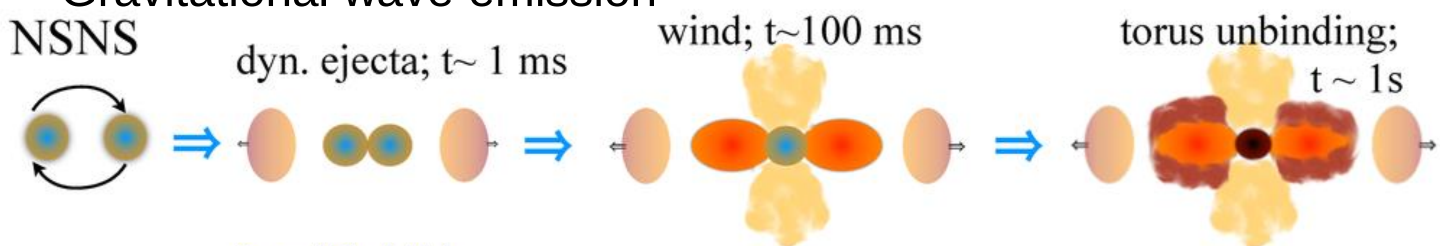


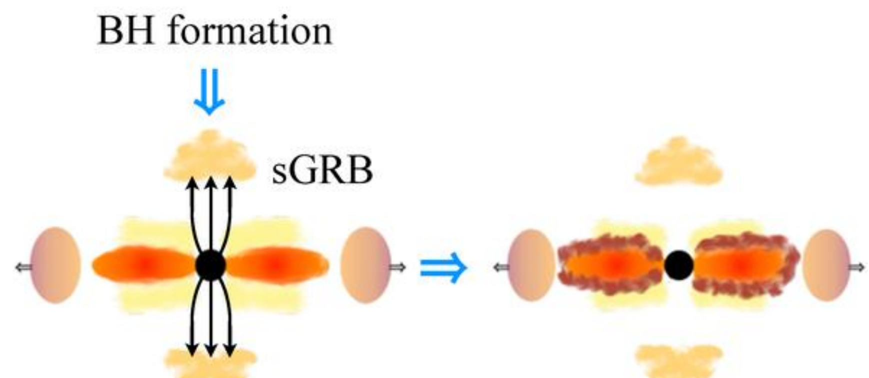
Flörs, Silva, et al, MNRAS **524**, 3083 (2023) A. Flörs, et al, in preparation

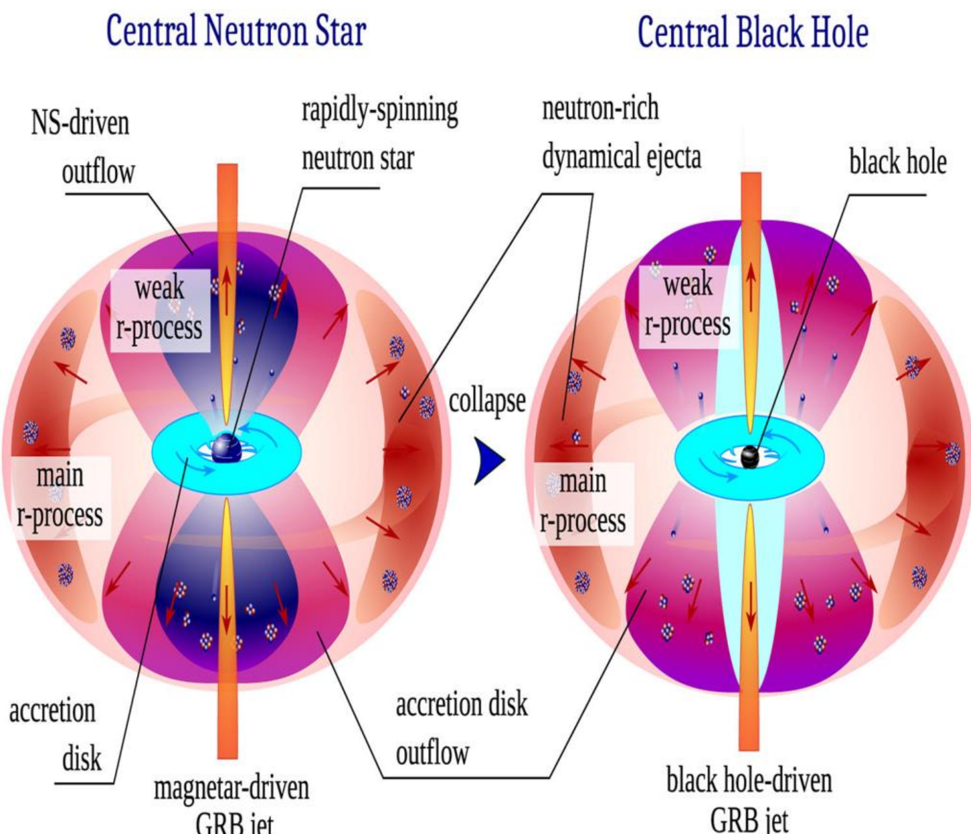
Neutron star mergers: Different ejection mechanisms

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

Gravitational wave emission







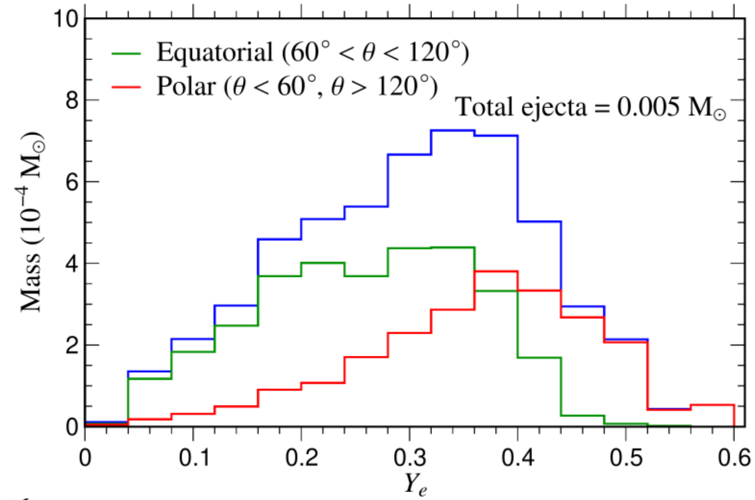
S. Rosswog and O. Korobkin, Annalen Der Physik **2022**, 2200306 (2022).

Two sources of ejecta:

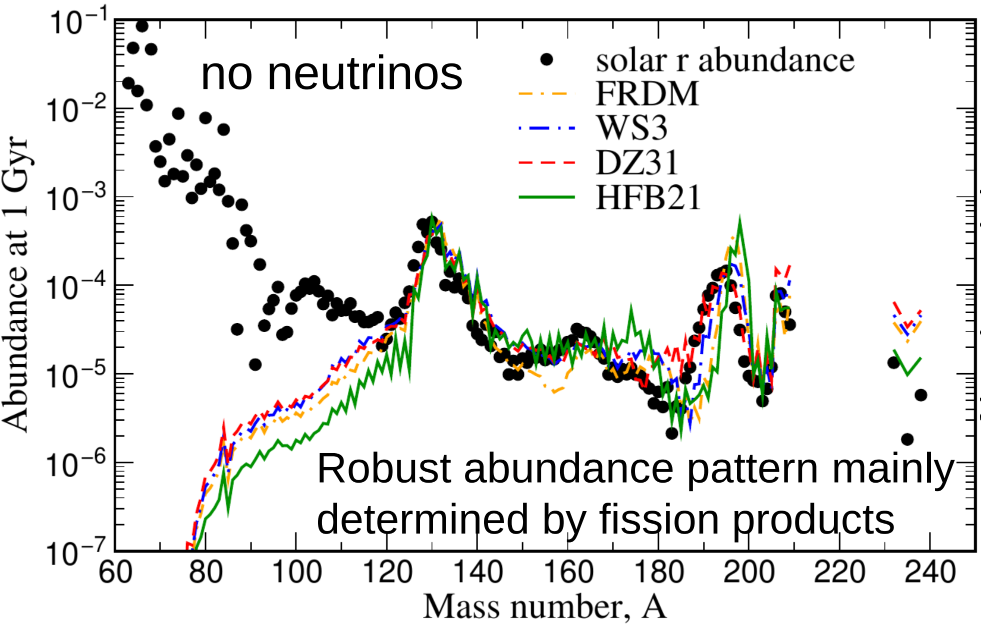
- Dynamical during the early phases of the merger ($M \lesssim 0.01\ M_\odot$)
- Accretion disc on longer timescales ($M \lesssim 0.05\ M_\odot$)
- Liftetime neutron-star determines impact neutrinos

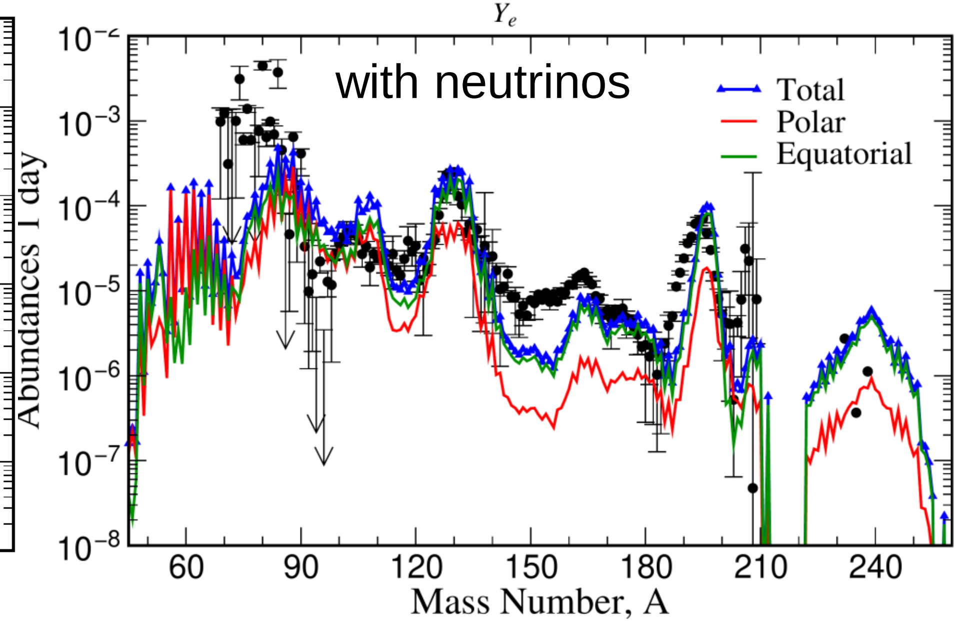
Dynamical ejecta (simulations)

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

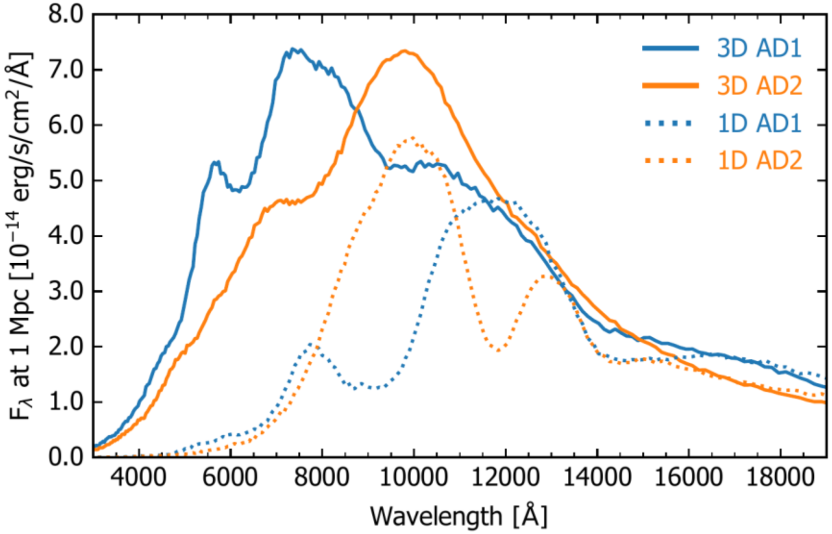


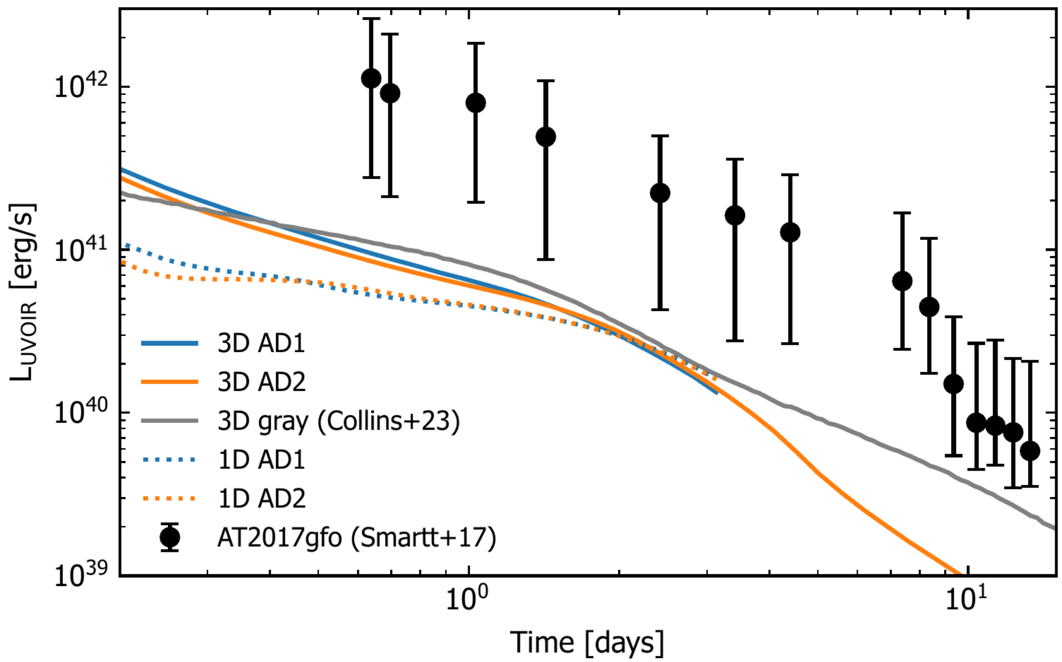


Mendoza-Temis, et al, PRC 92, 055805 (2015)

Self-consistent 3D radiative transfer

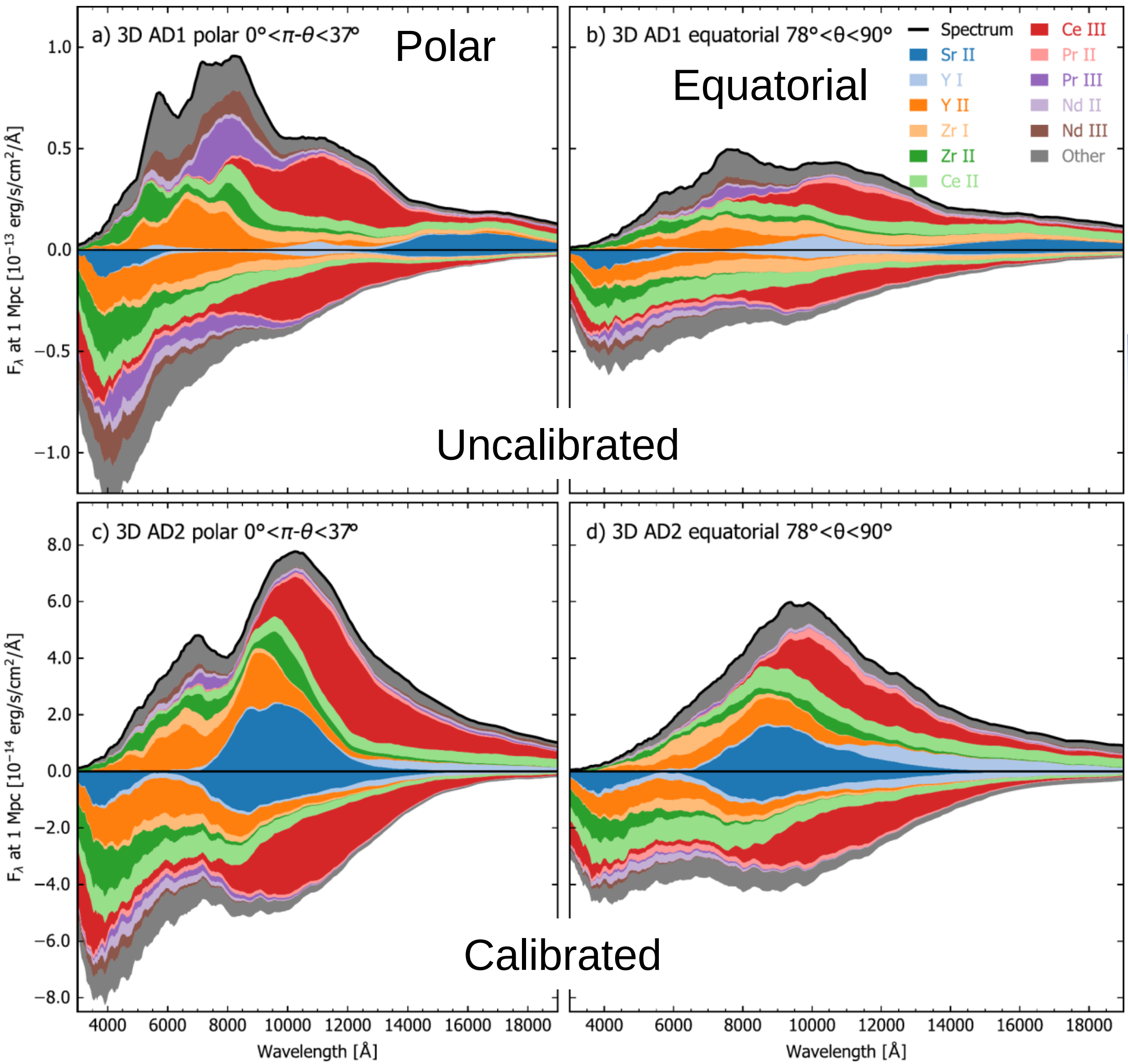
- Monte Carlo 3D radiative transfer using the ARTIS code.
  https://github.com/artis-mcrt/artis
- Matter distribution based on SPH Dynamical ejecta (0.005 $M_\odot$)
- LTE simulation: follows 2591 nuclei (283 ions with gamma-ray transport and electron thermalization, 44 millions atomic transitions lines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

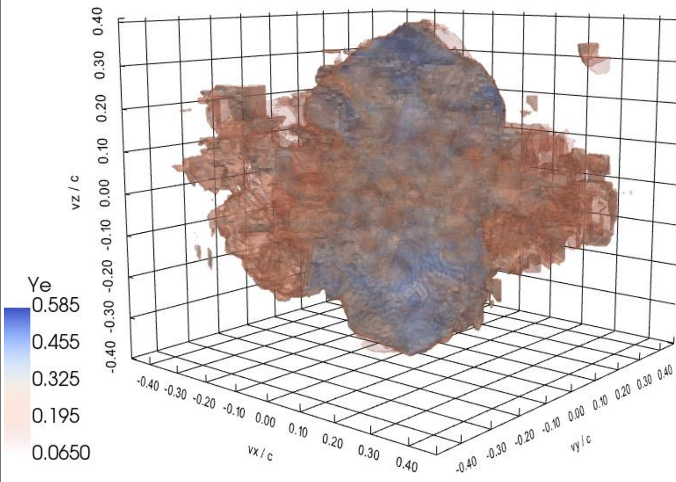




Shingles et al, ApJ **954**, L41 (2023)

Angular dependence spectra

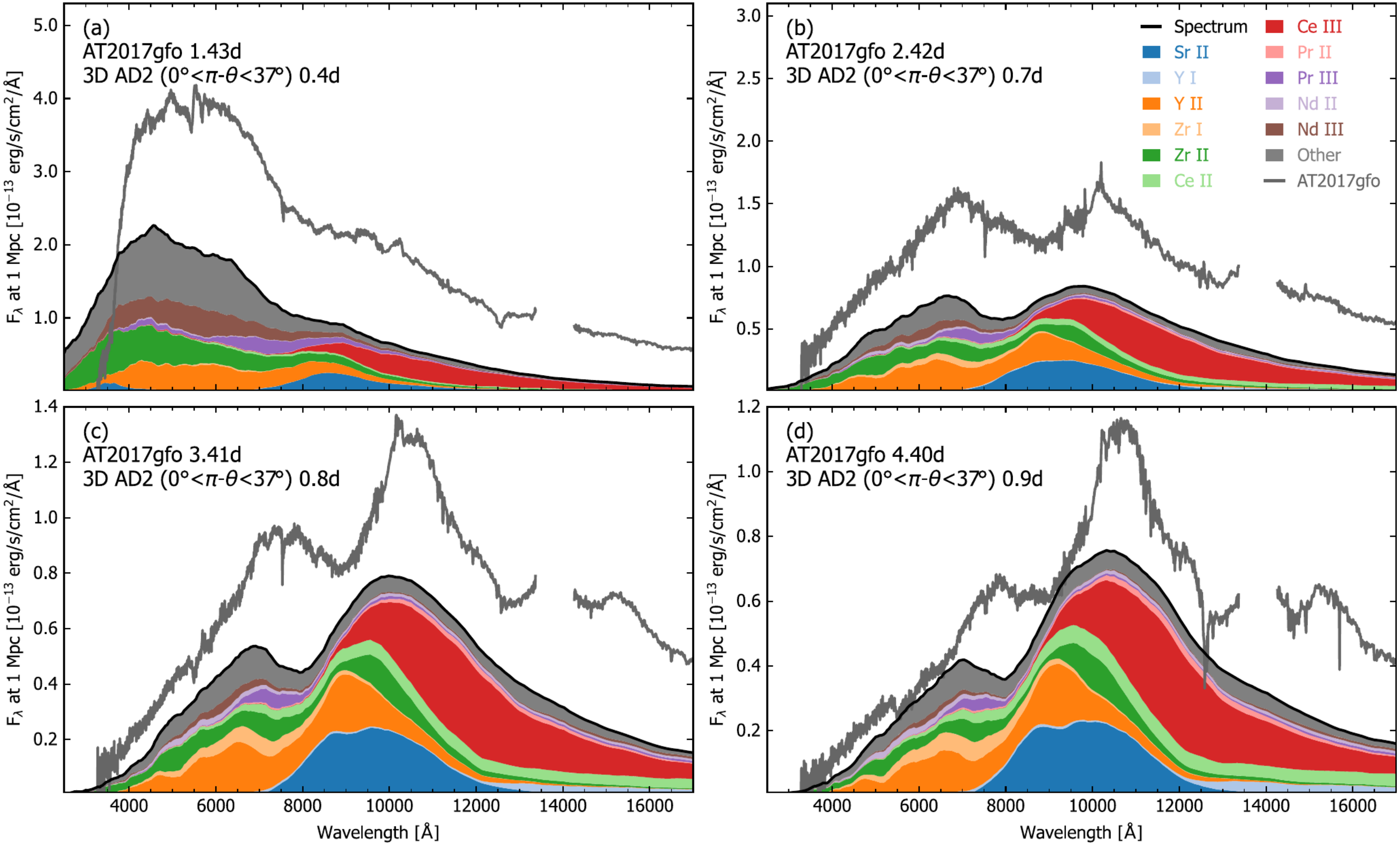




Differences reflect directional dependence of nucleosynthesis yields

Shingles et al, ApJ 954, L41 (2023)

Comparison AT2017gfo

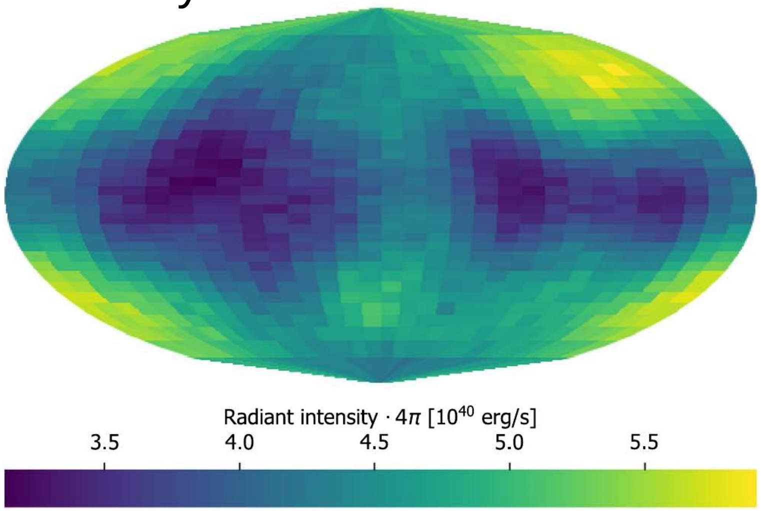


Similar spectral evolution that AT2017gfo once differences in brightness are accounted

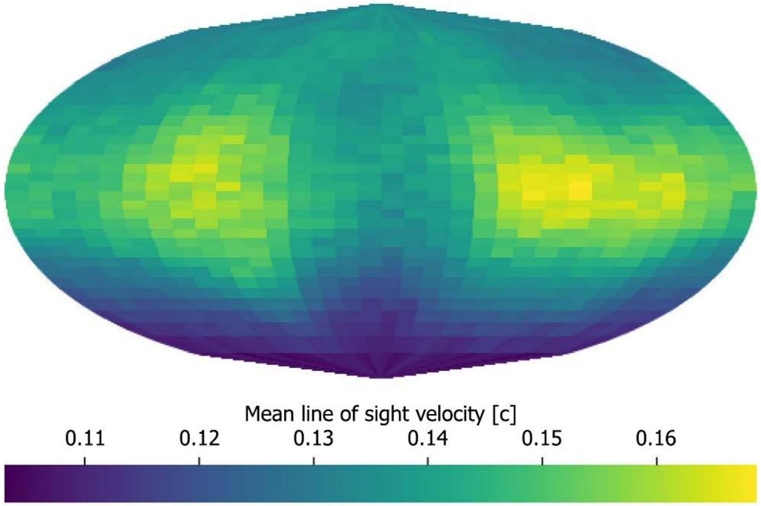
Shingles et al, ApJ 954, L41 (2023)

Asymmetry observables

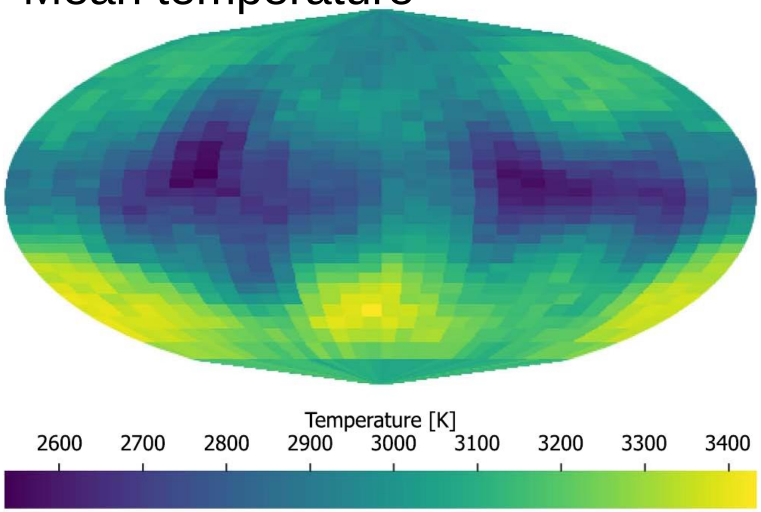
Intensity



Line-of-sight velocity



Mean temperature



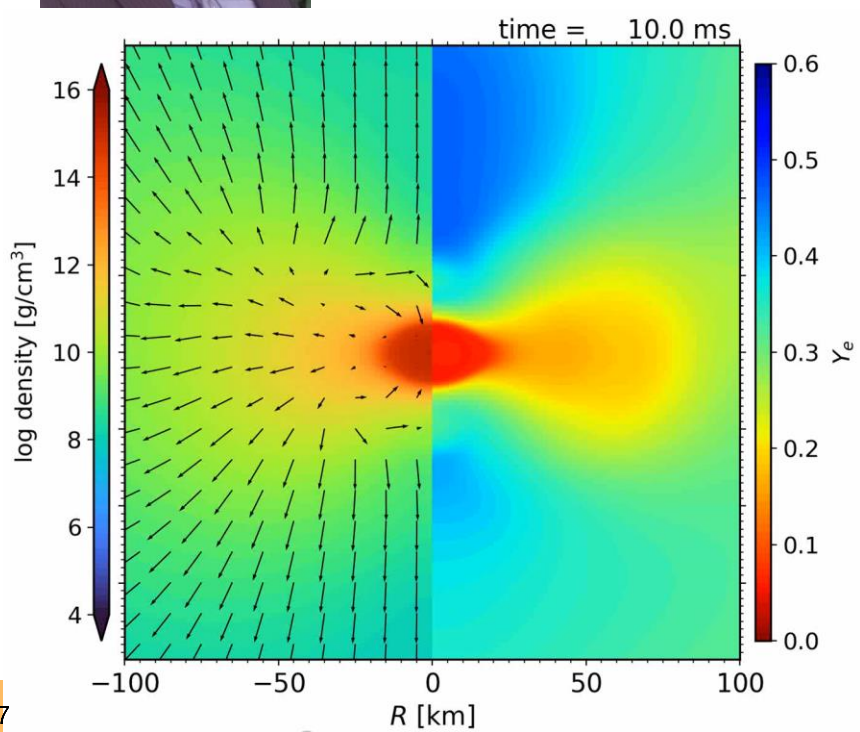
- Strong asymmetry observables
- Need of further observations

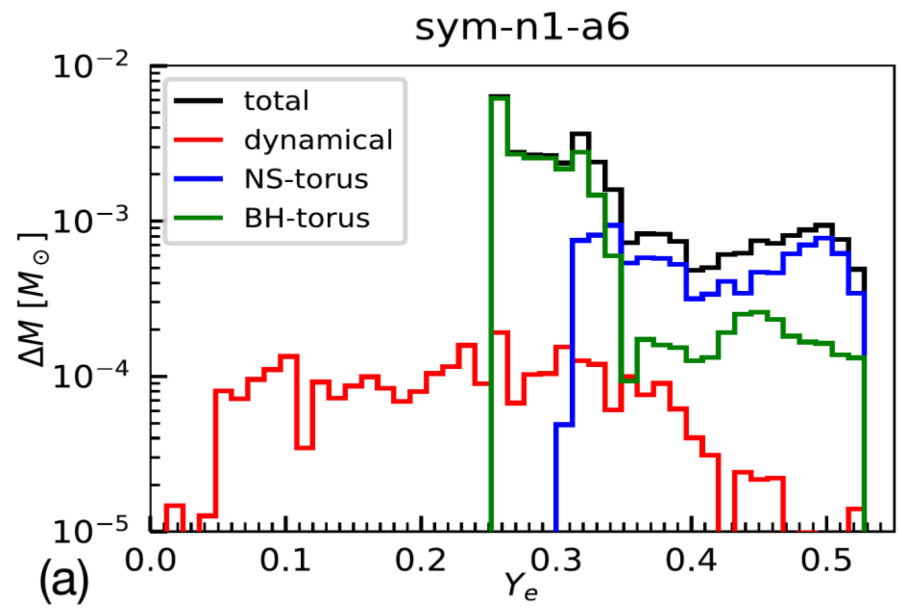
Shingles et al, ApJ 954, L41 (2023)

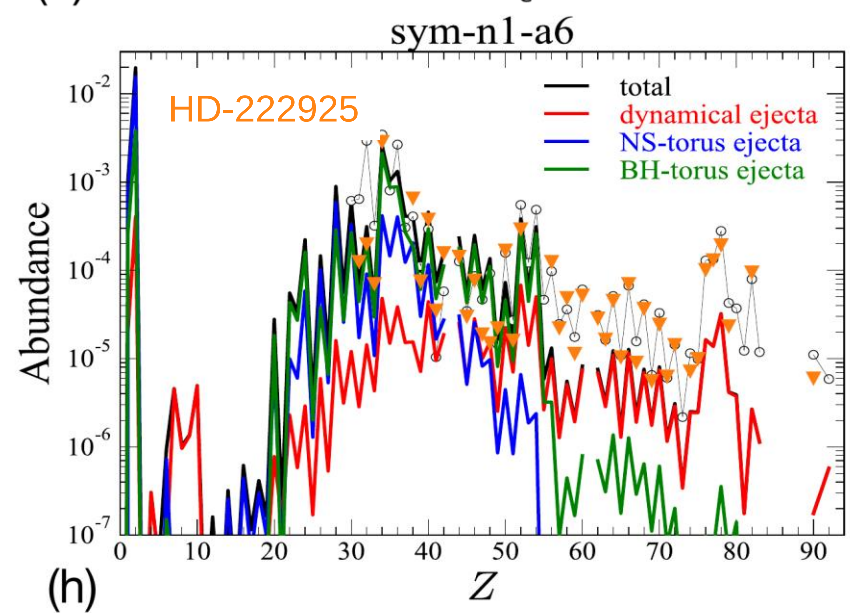
Long term merger simulations

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

Just et al, ApJL, L12 (2023)

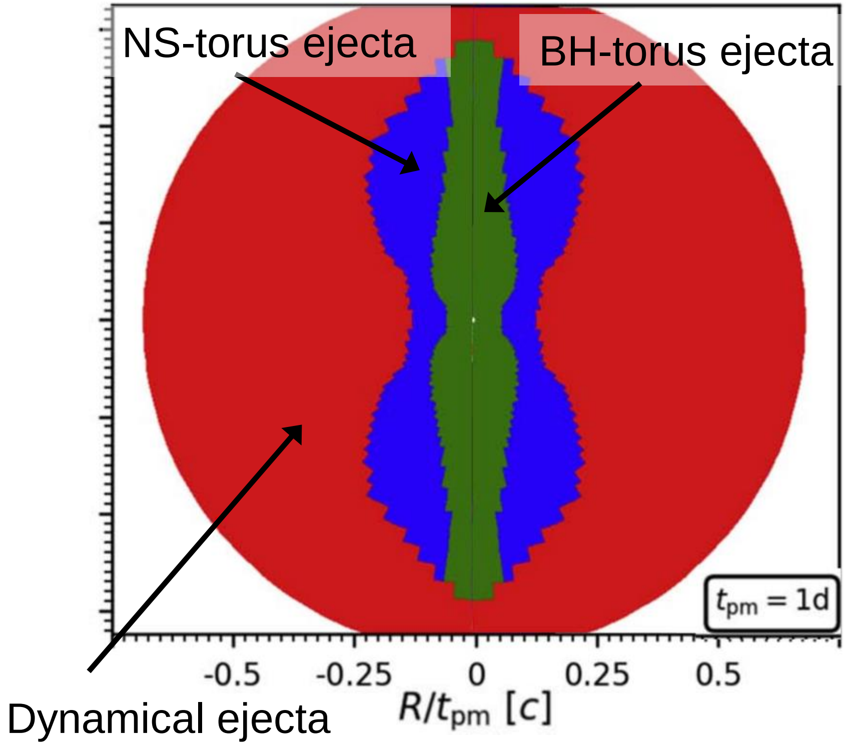


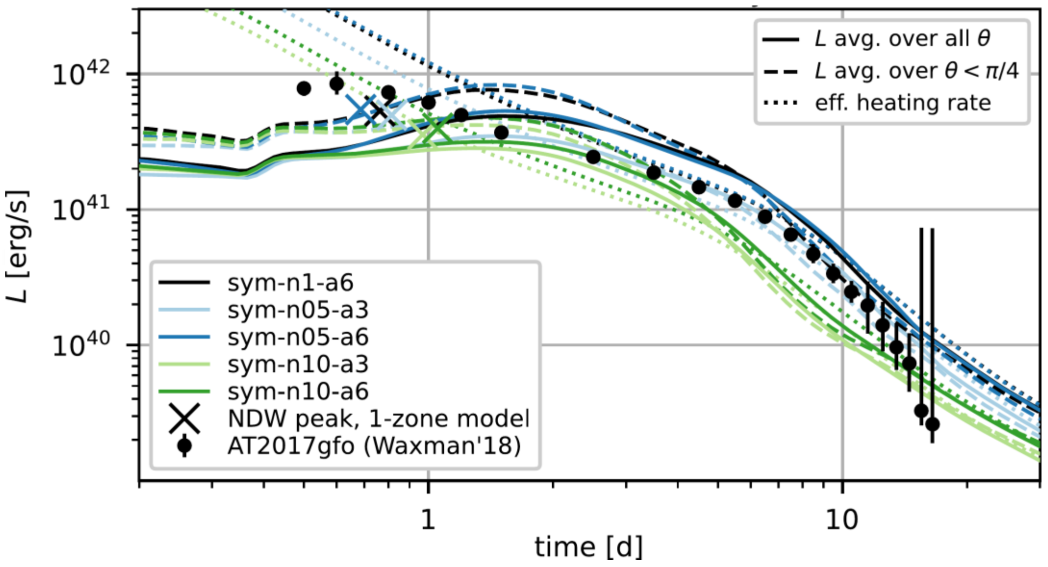




End to end kilonova models

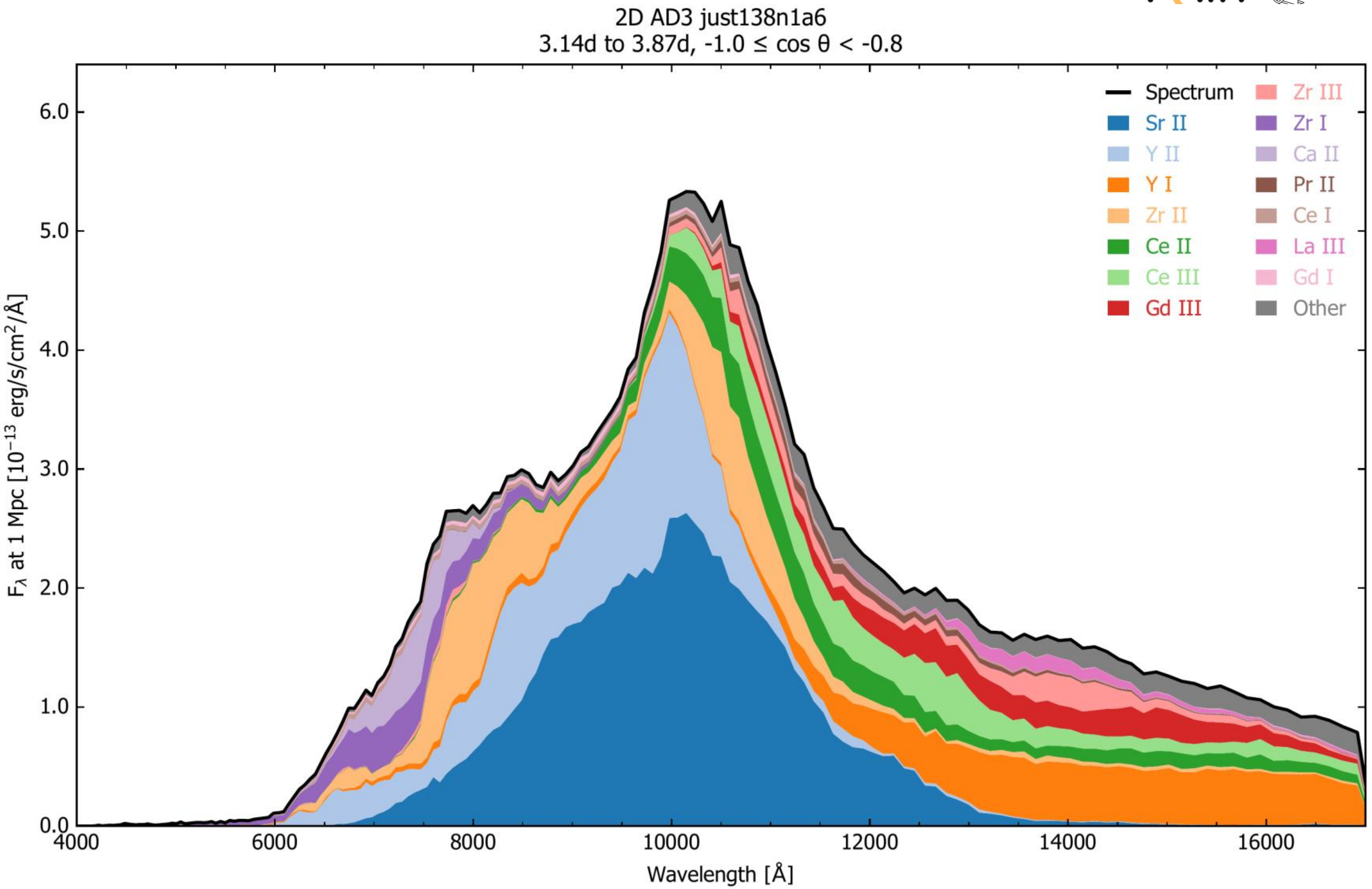
- Based on grey opacities using approximate radiative transfer model (generalization ALCAR neutrino module)
- Agreement with AT2017gfo after times of several days
- Accounting for all ejecta components fundamental to reproduce light curve





Just et al, ApJL, L12 (2023)

Spectra long term models



- Different spectral features than model considering dynamical ejecta
- Possible dependence on dimensionality simulation (here 2D)

Shingles et al, in preparation

Can we find a signature of actinides?

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Relevant α-decays

Wu, Barnes, GMP, Metzger, PRL **122**, 062701 (2019)

- If actinides are present alpha-decay chains may dominate the energy generation on days.
- Fission plays a secondary role except perhaps the presence of ^{254}Cf

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

Collaborators

GSI theory
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QUEEN'S UNIVERSITY BELFAST
UNIVERSITÉ LIBRE DE BRUXELLES
UMONS Université de Mons
UNIVERSITÄT BIELEFELD
UAM Universidad Autónoma de Madrid
Max-Planck-Institut für Astrophysik

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