Probing heavy element nucleosynthesis through electromagnetic observations

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Nuclei in the Cosmos (NIC XVII),
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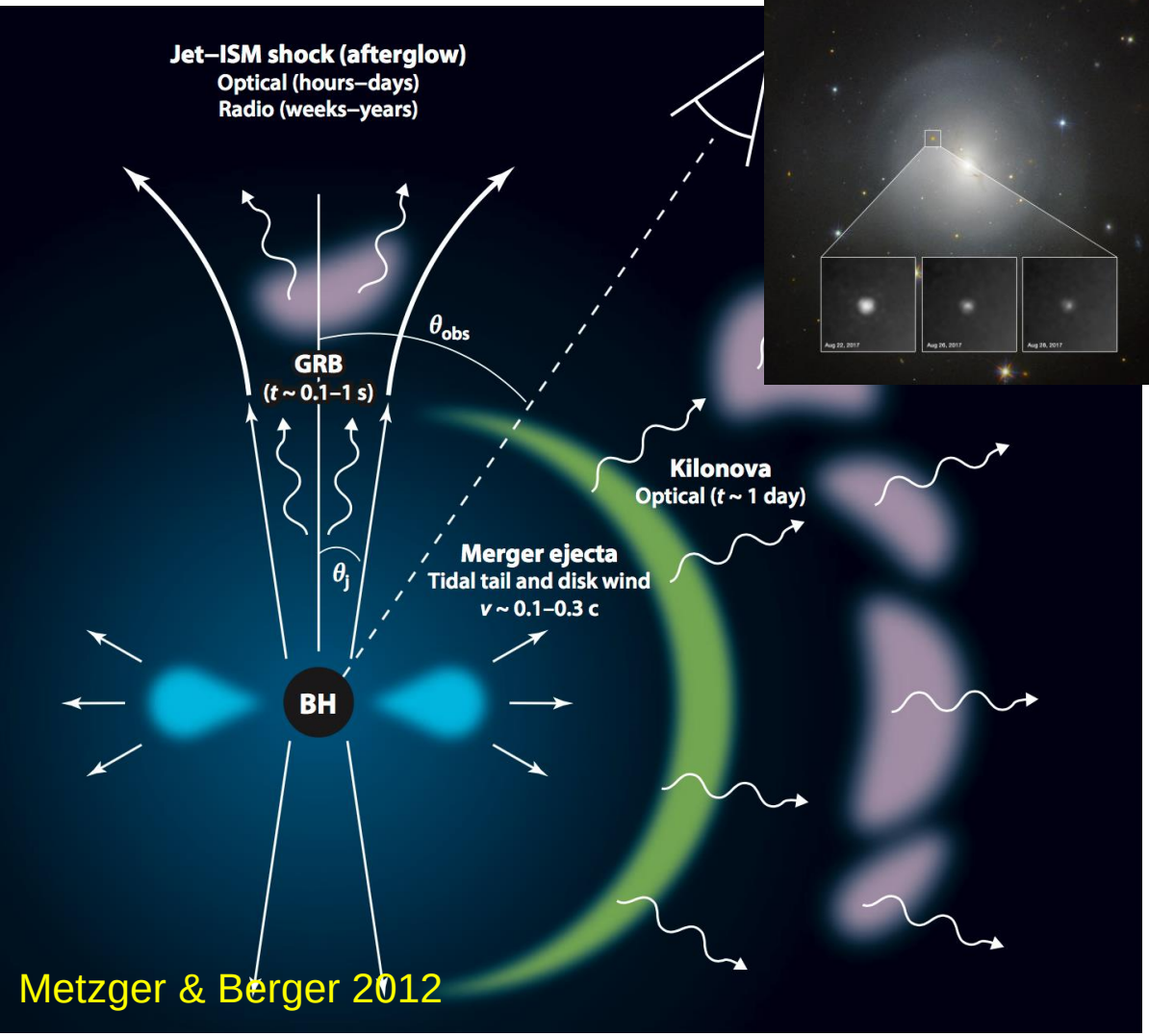
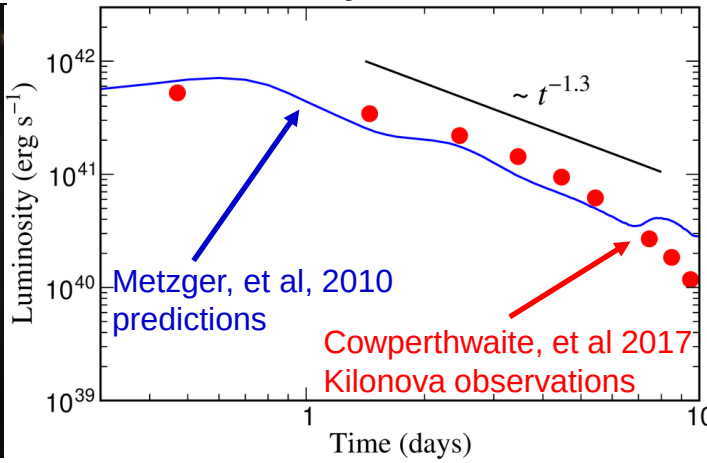
ERC AdG KILONOVA

Kilonova: signature of the r-process

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





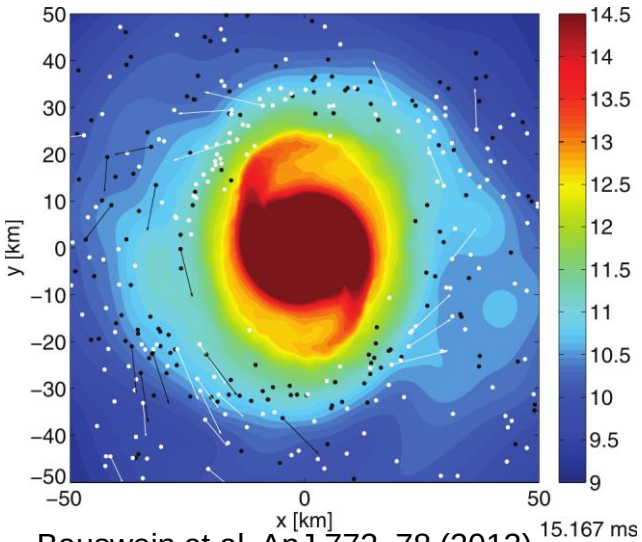
- Electromagnetic counterpart to Gravitational Waves
- Diagnostics physical processes at work during merger
- Direct probe of the formation r-process nuclei
- Information elements produced single event

Pipeline for r-process in mergers

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

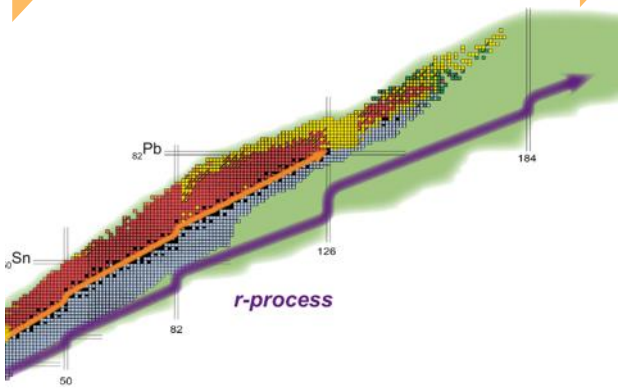
- Physics of neutron-rich and heavy nuclei

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



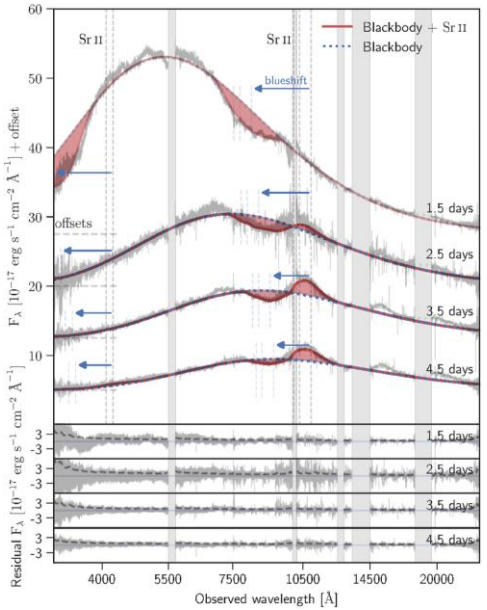
Bauswein et al, ApJ 773, 78 (2013)

forward modelling



backward modelling

Infer components ejecta (Y_e)

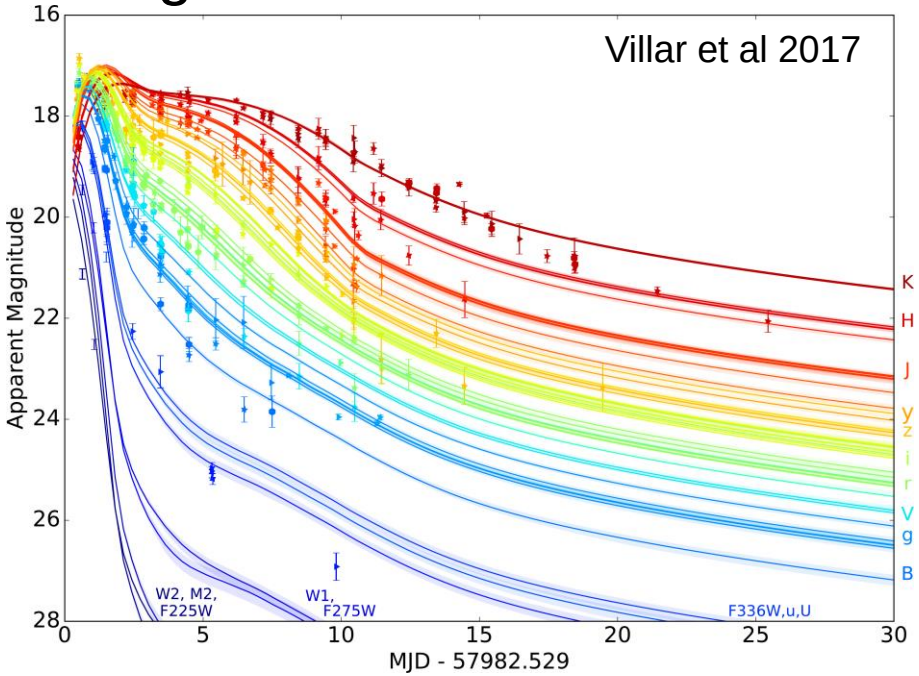


Watson et al, Nature **574**, 497 (2019)

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

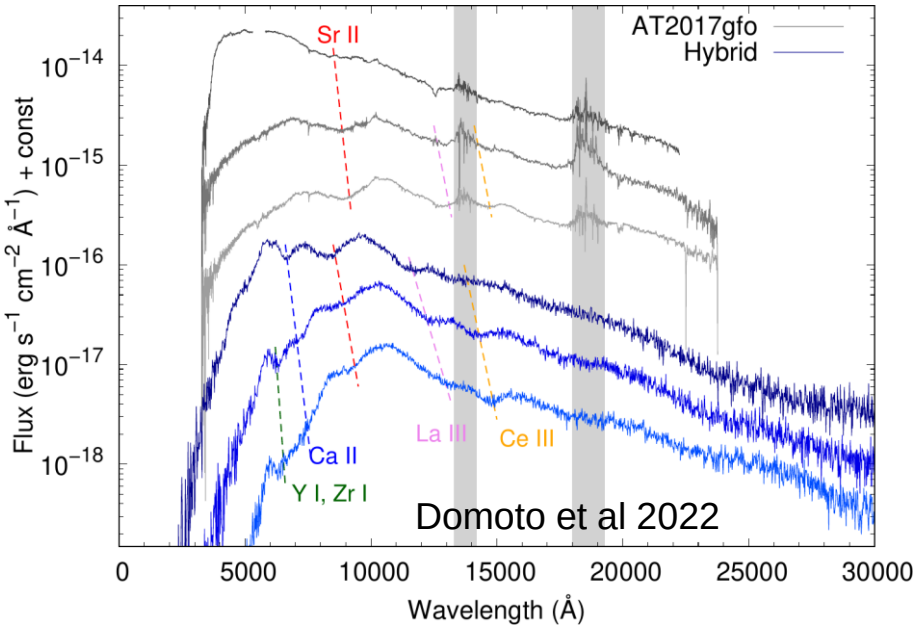
Kilonova modelling

Light curve



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

Spectral modelling

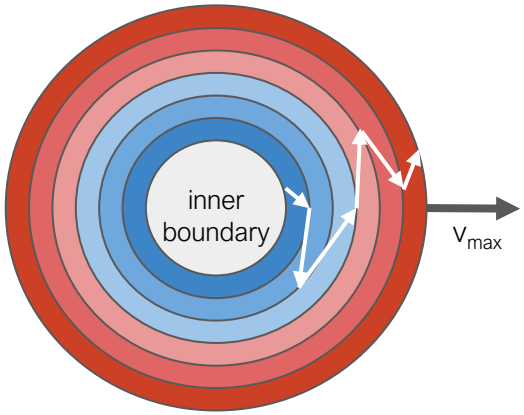


- Accurate data
  - LTE: line list bound-bound transitions
  - NLTE: + electron ion and photoionization cross sections, recombination coef
- Several elements observed

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

Atomic Opacities (LTE)

- Sobolev optical depth (for a line l)



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

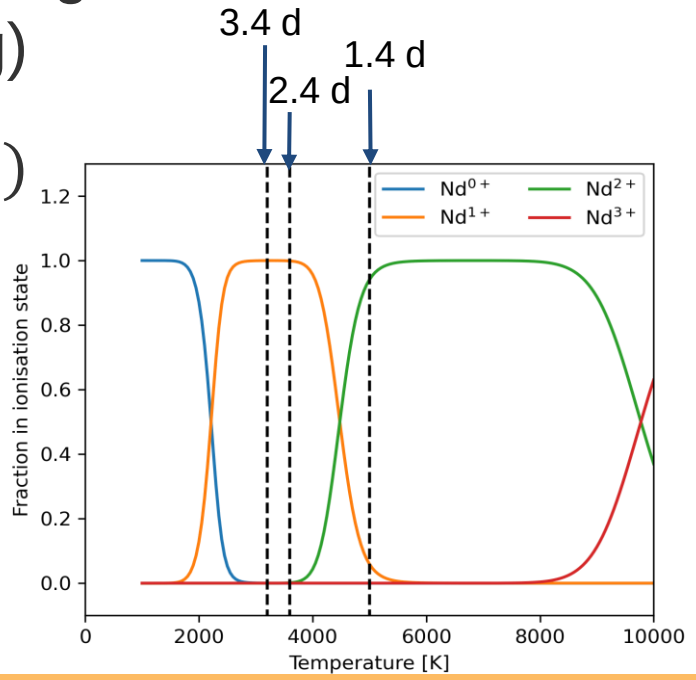
Transition wavelength

Oscillator strength

Population lower level (Saha eq. and partition functions)

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

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



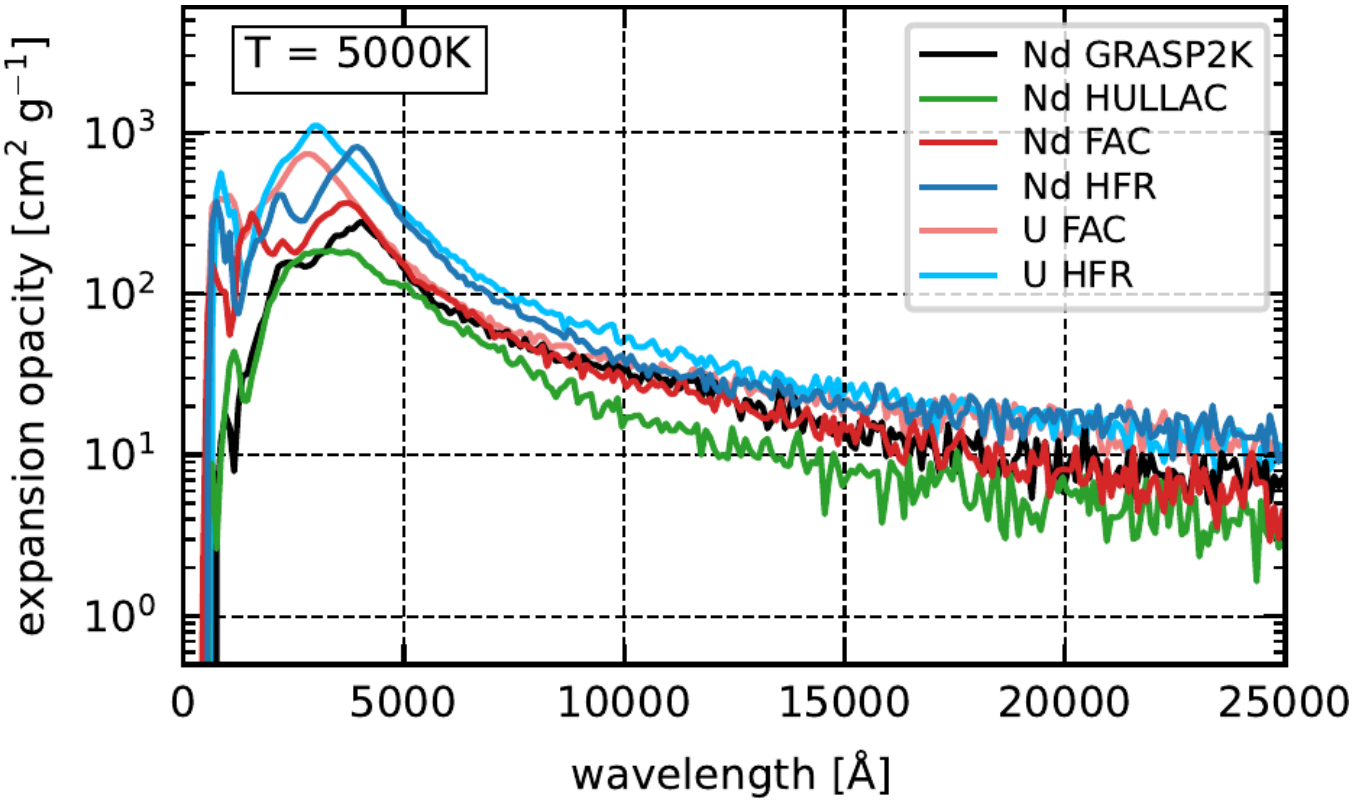
A. Flörs G. Leck R. Silva



Goal: Develop database well calibrated atomic opacities

Neodymion and Uranium opacities

- U has larger opacity than Nd (similar behaviour expected for other Actinides)
- Confirmed by independent calculations HFR code (U. Mons) and Los Alamos suite (Fontes+2023)



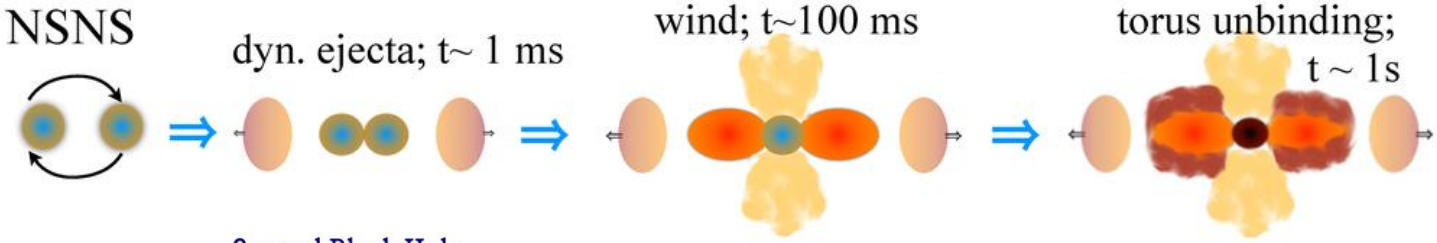
Silva et al, Atoms 10, 18 (2022); Flörs, Silva, et al, MNRAS 524, 3083 (2023)

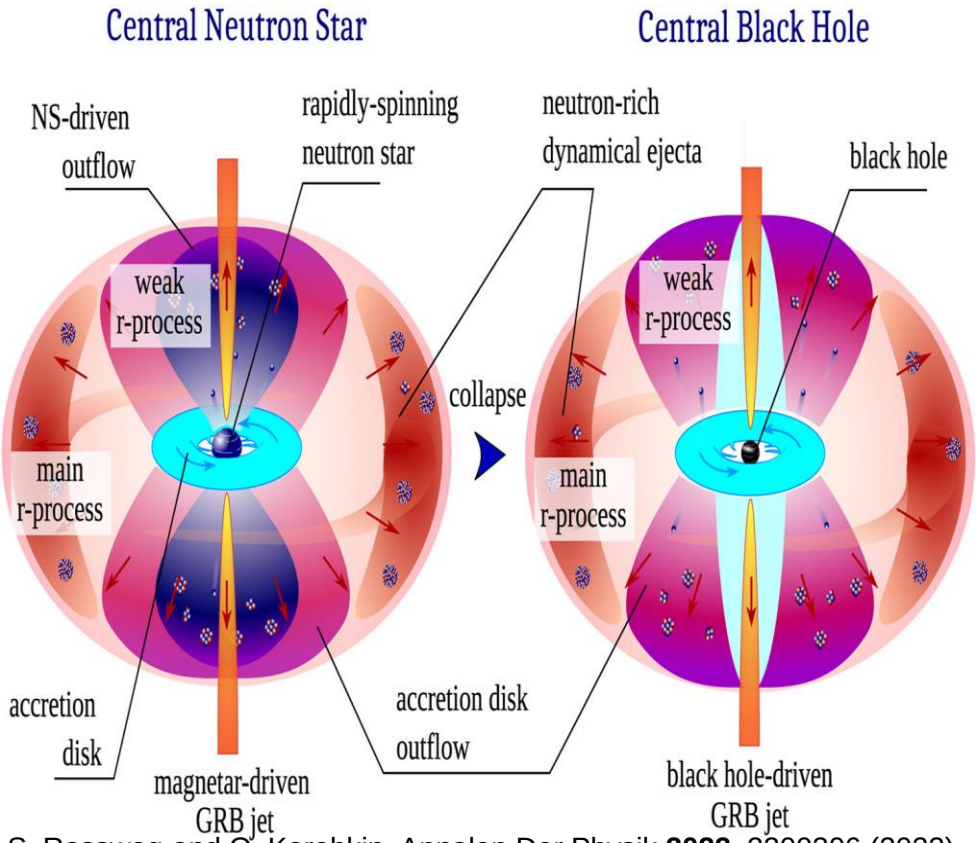
Offers a method to identify presence of Actinides in spectra.

Neutron star mergers: Different ejection mechanisms

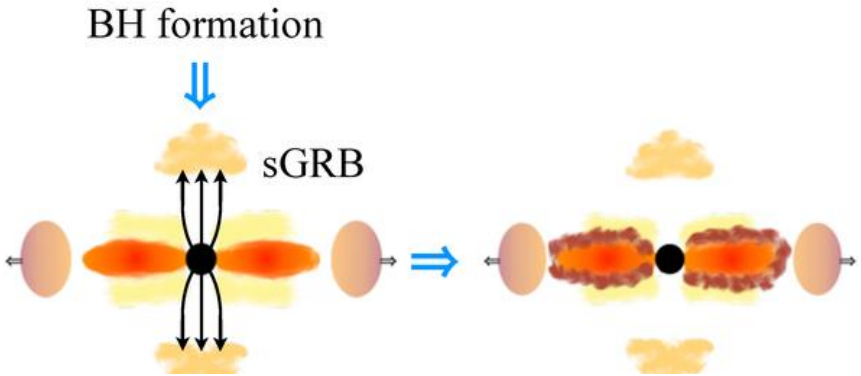
S. Rosswog, et al, Class. Quantum Gravity 34, 104001 (2017).

Gravitational wave emission





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



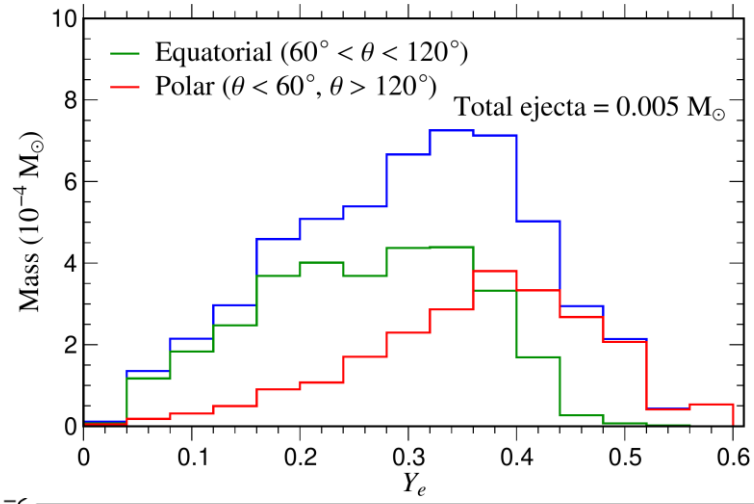
Two sources of ejecta:

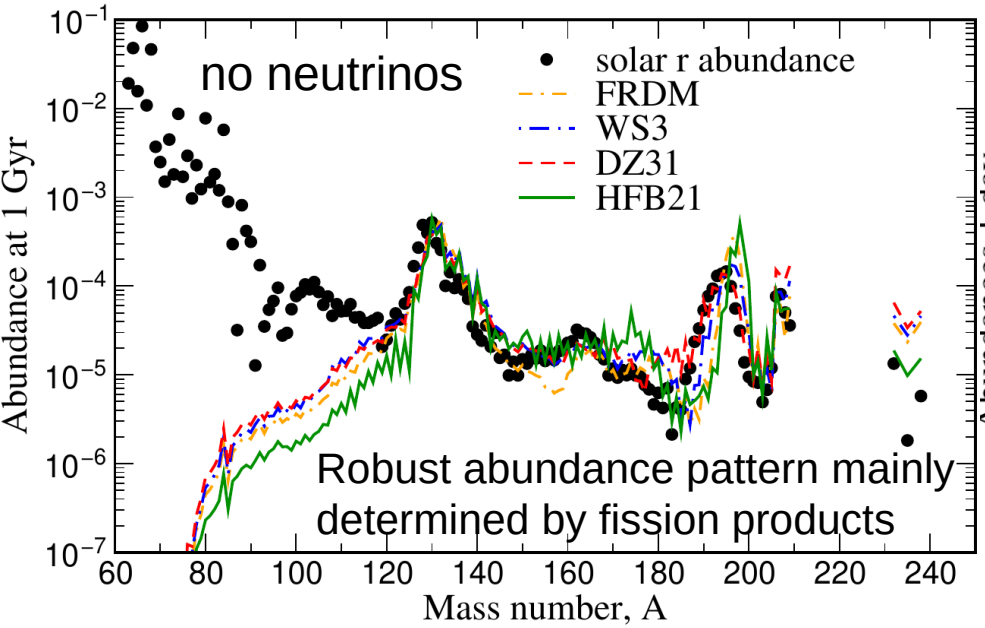
- Dynamical during the early phases of the merger ($M \lesssim 0.01\ M_\odot$)
- Accretion disc on longer timescales ($M \lesssim 0.05\ M_\odot$)
- Liftetime neutron-star determines impact neutrinos

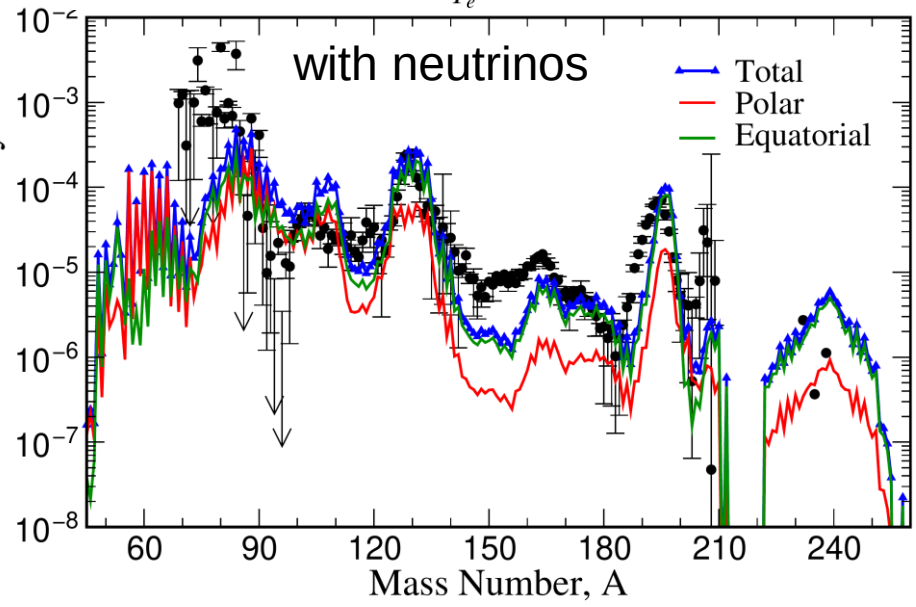
Dynamical ejecta (simulations)

- 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



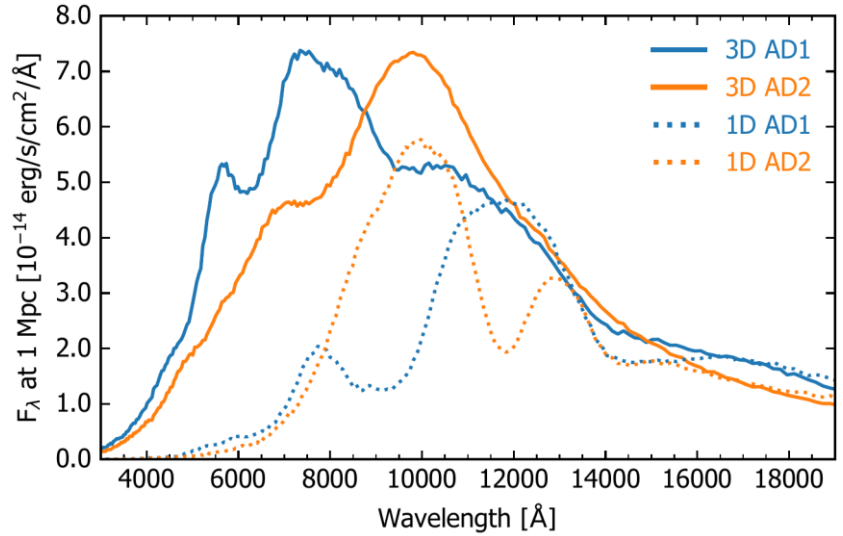


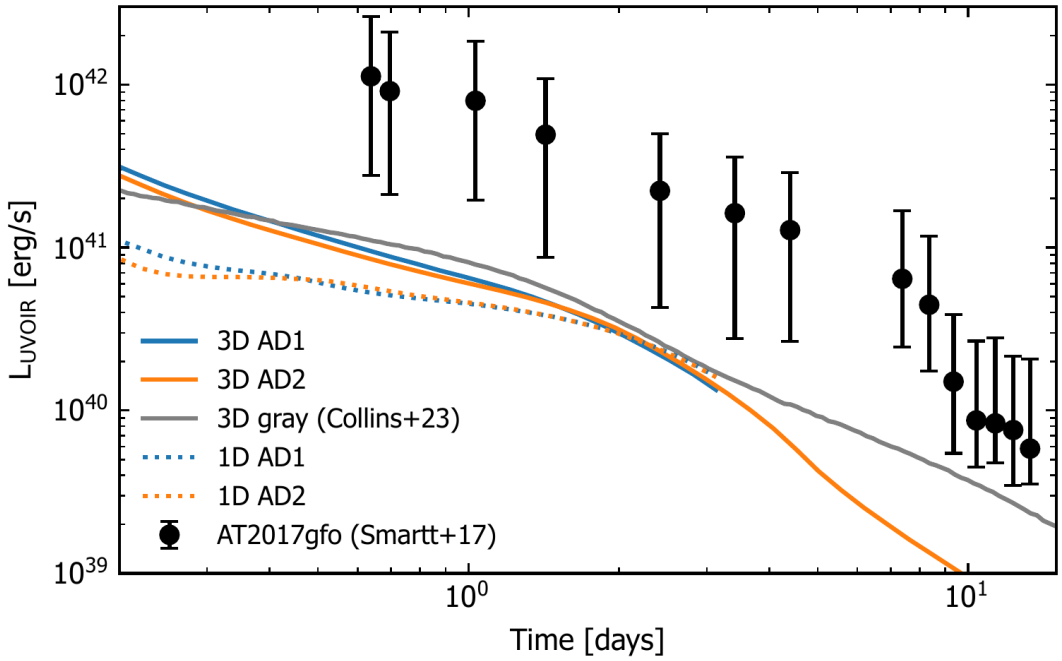


Mendoza-Temis, et al, PRC 92, 055805 (2015)

Self-consistent 3D radiative transfer

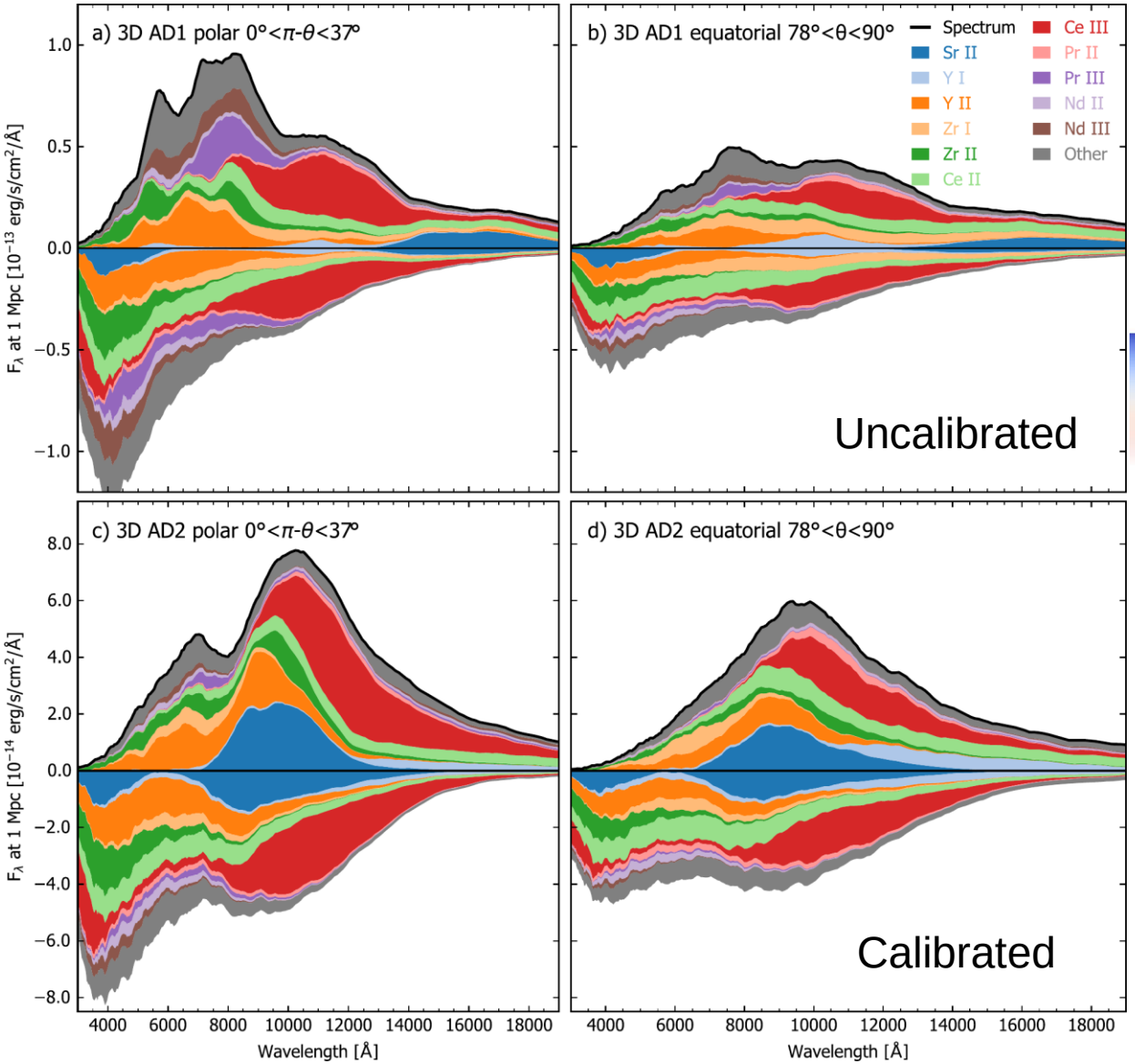
- Monte Carlo 3D radiative transfer using the ARTIS code. https://github.com/artis-mcrt/artis
- Matter distribution based on SPH Dynamical ejecta (0.005 $M_{\odot}$)
- LTE simulation: follows 2591 nuclei (283 ions with gamma-ray transport and electron thermalization, 44 millions atomic transitions lines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

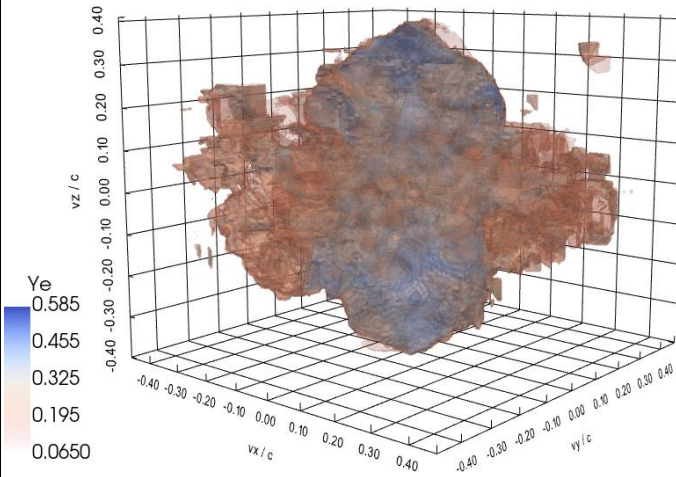




Shingles et al, ApJ 954, L41 (2023)

Angular dependence spectra

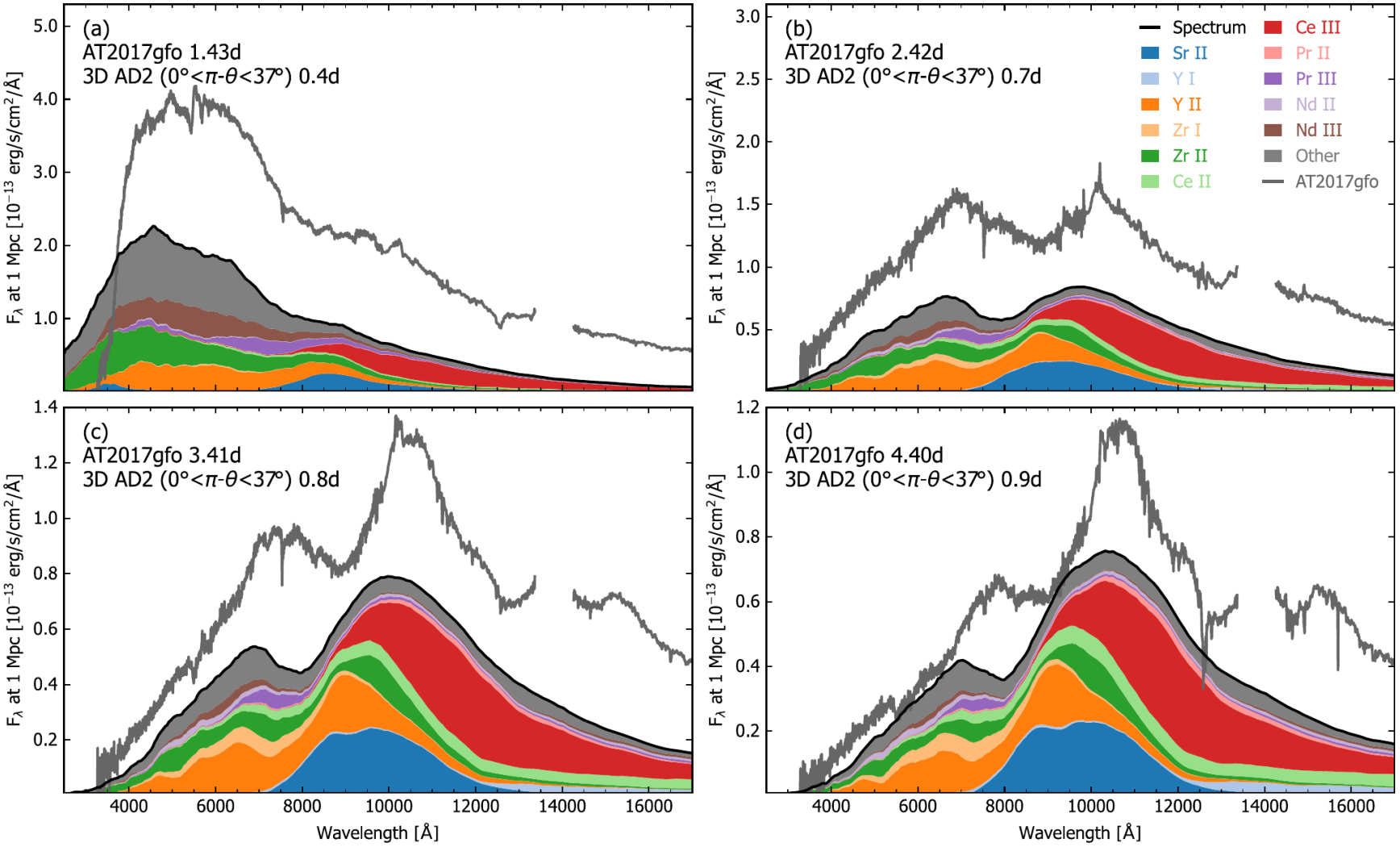




Differences reflect directional dependence of nucleosynthesis yields

Shingles et al, ApJ 954, L41 (2023)

Comparison AT2017gfo

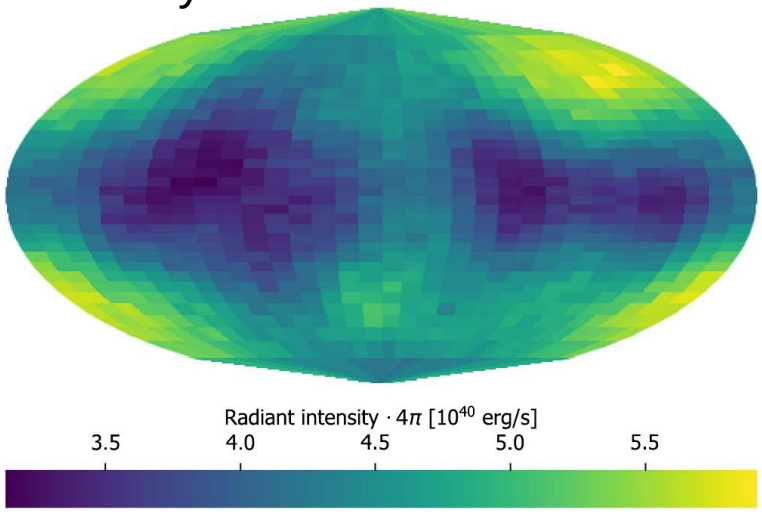


Similar spectral evolution that AT2017gfo once differences in brightness are accounted

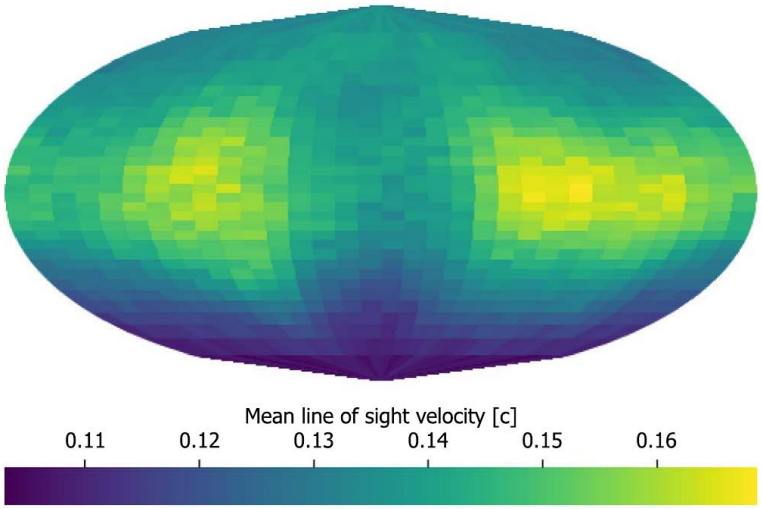
Shingles et al, ApJ 954, L41 (2023)

Asymmetry observables

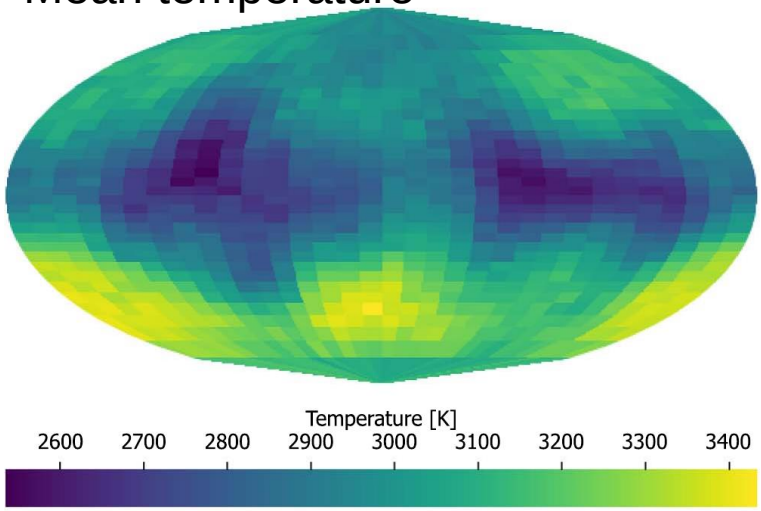
Intensity



Line-of-sight velocity



Mean temperature

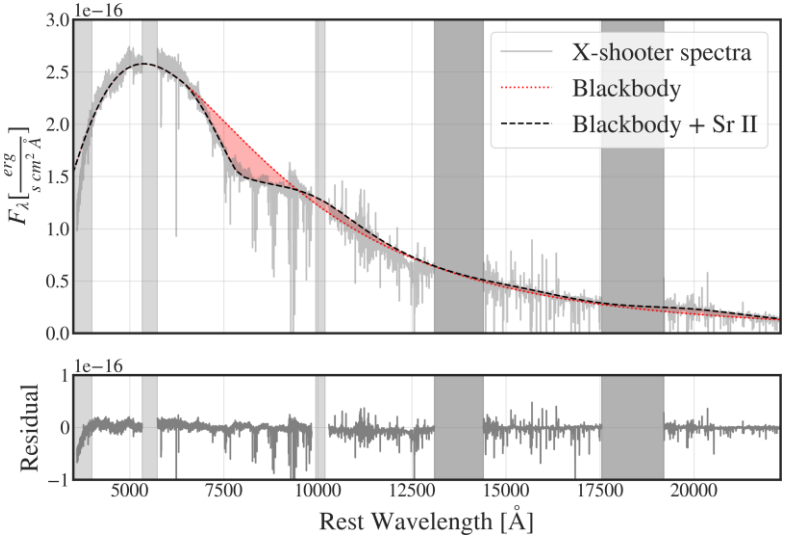


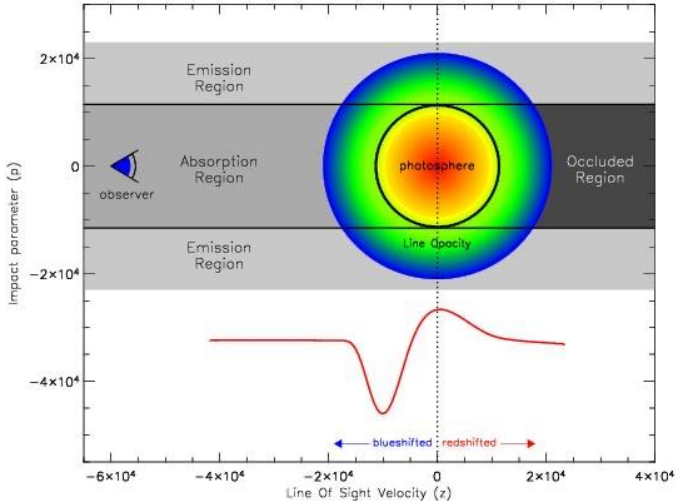
- Strong asymmetry observables
- Is this consistent with observations?

Shingles et al, ApJ 954, L41 (2023)

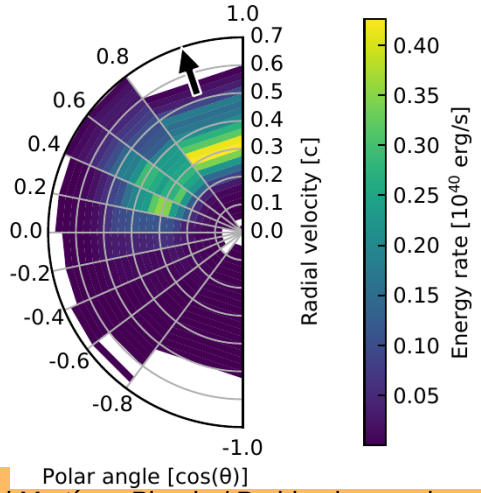
Benchmark against AT2017gfo

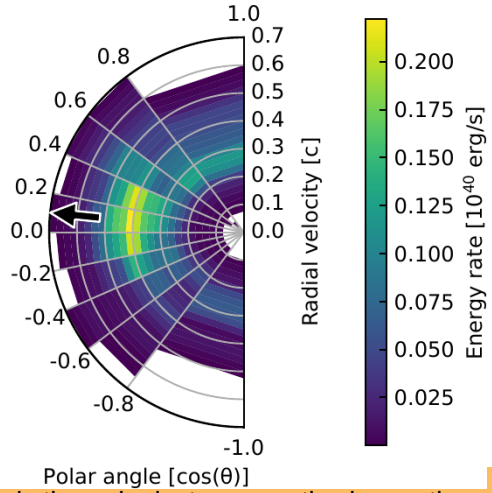
Analysis of AT2017gfo Sr II P-Cygni feature shows kilonova is highly spherical at early epochs [Sneppen et al, Nature 614, 436 (2023)]





Similar analysis based on 3D radiative transfer simulations suggest sphericity depends on observer line of sight [Collins et al, arXiv:2309.05579]

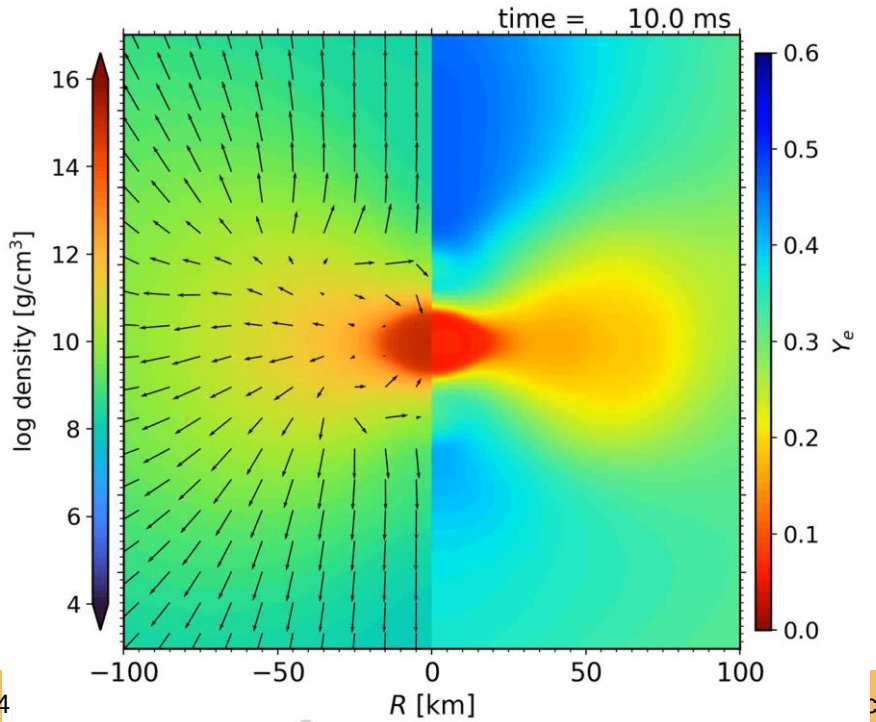


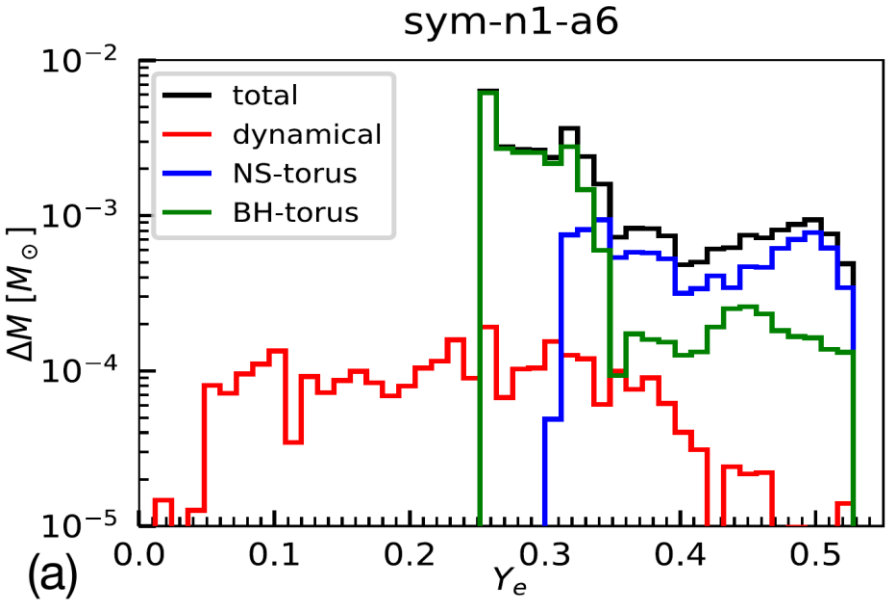


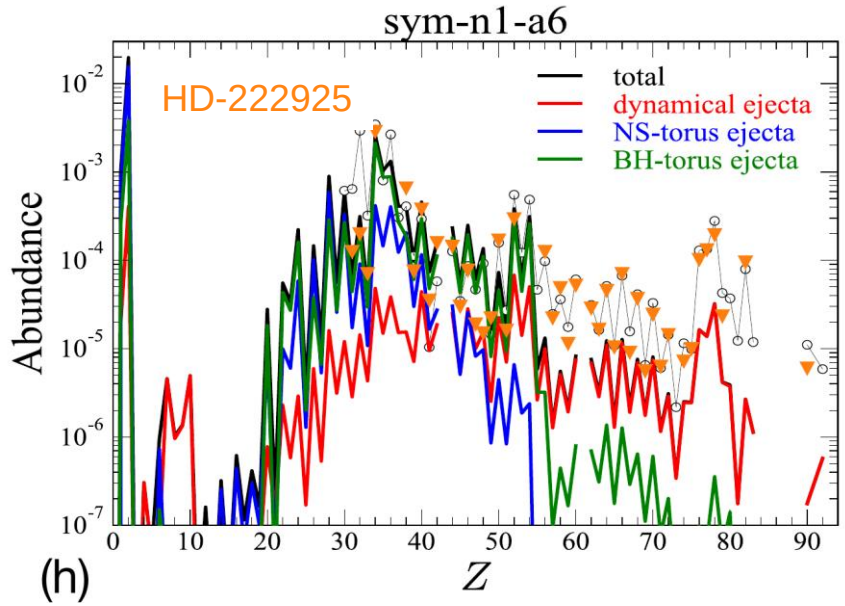
Long term merger simulations

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)

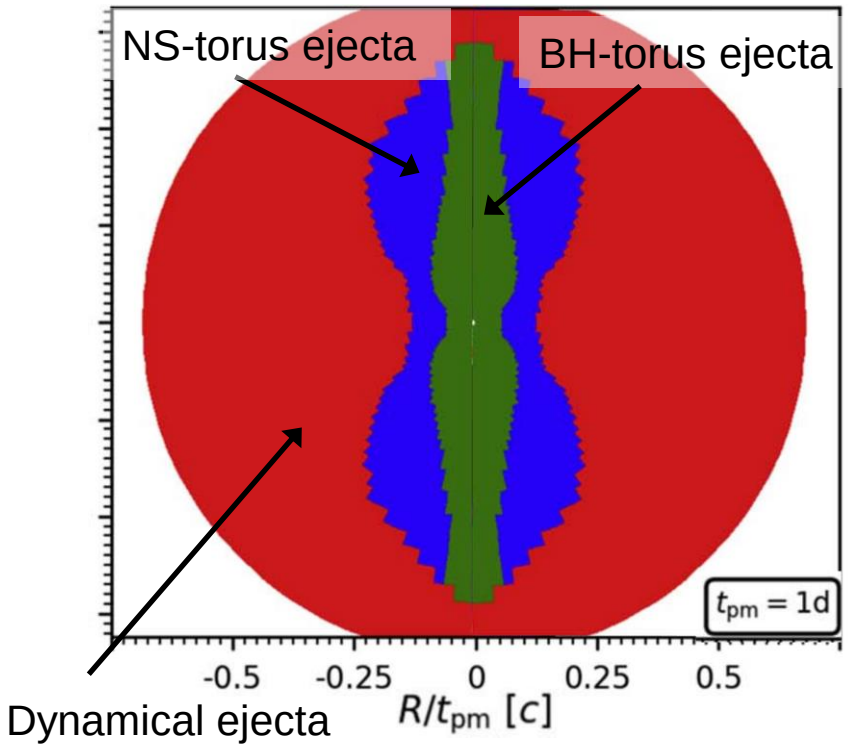


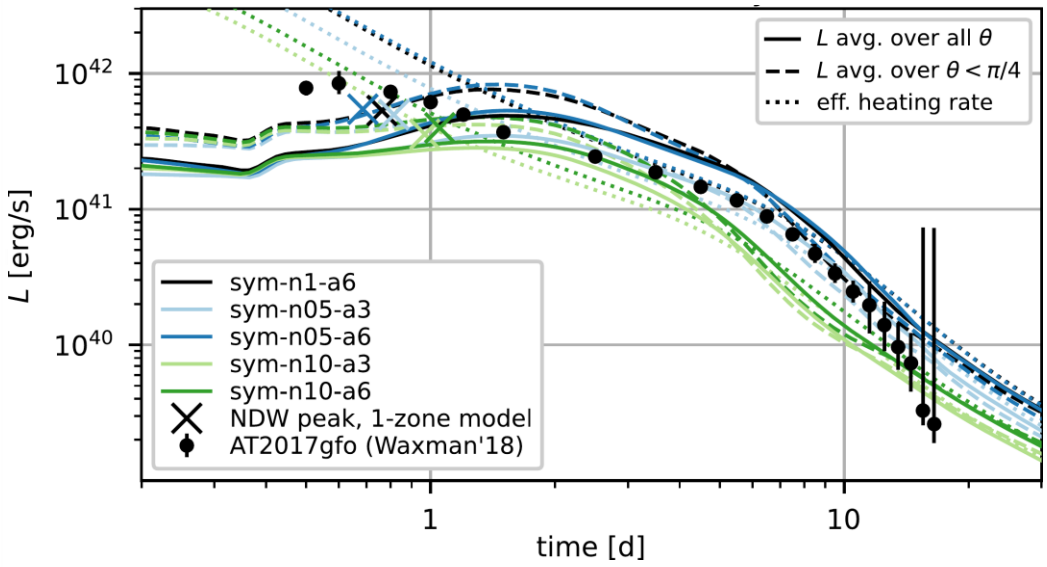




End to end kilonova models

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

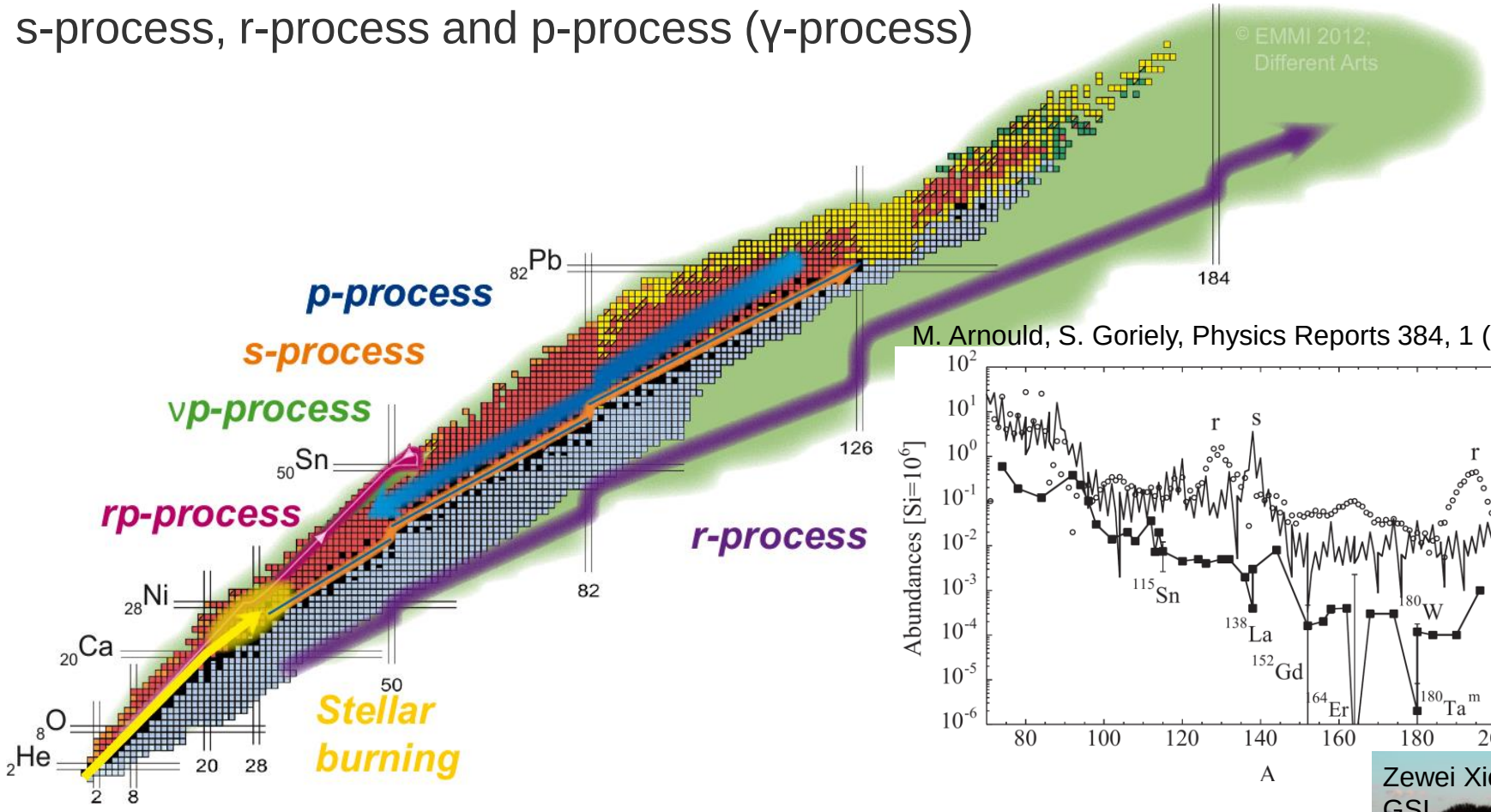




Just et al, ApJL, L12 (2023)

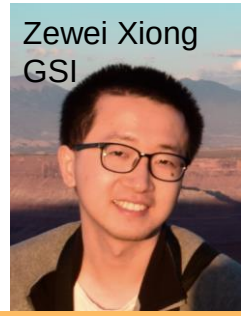
Nucleosynthesis beyond iron

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

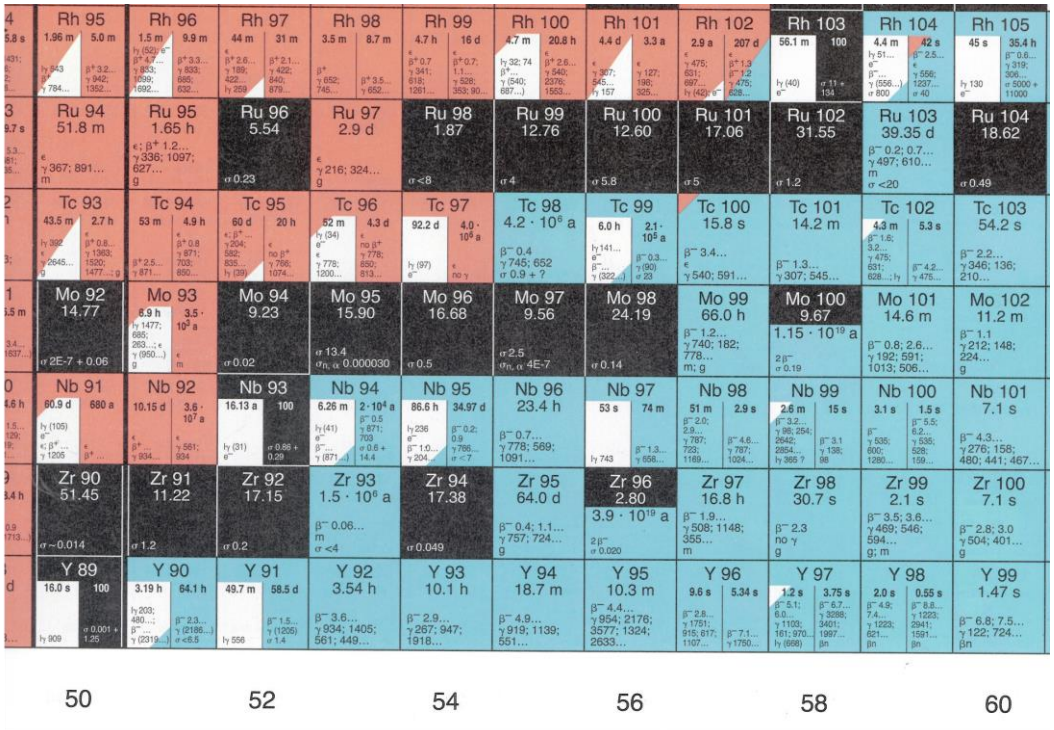


M. Arnould, S. Goriely, Physics Reports 384, 1 (2003)

- The ***νr*-process** (arXiv:2305.11050): a new nucleosynthesis process that operates 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.



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 (Raucher+2013)

Supernova neutrino winds:

- Ejecta with $Y_e \sim 0.48$ produce ^{92}Mo (Hofmann+1992)
- νp-process ($Y_e \gtrsim 0.55$) produces ^{94}Mo, ^{96,98}Ru (Fröhlich+2006)

Long-lived ^{92}Nb present in early solar system (Harper+1996).

Cannot be produced by the νp-process nor ν-process (Hayakawa+2013, Sieverding+2018)

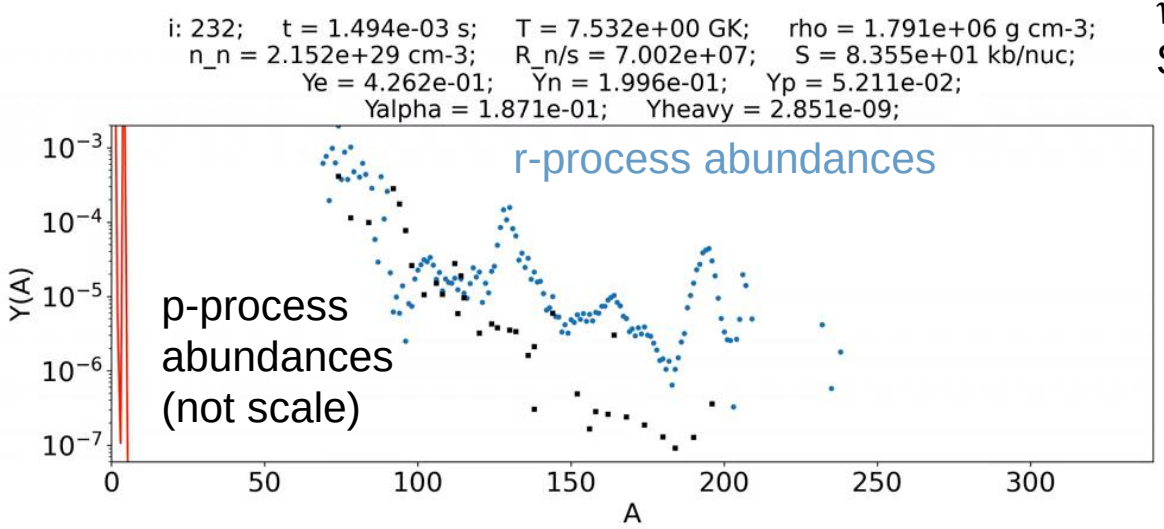
Can we produce all these nuclei in the same environment including heavier p-nuclei?

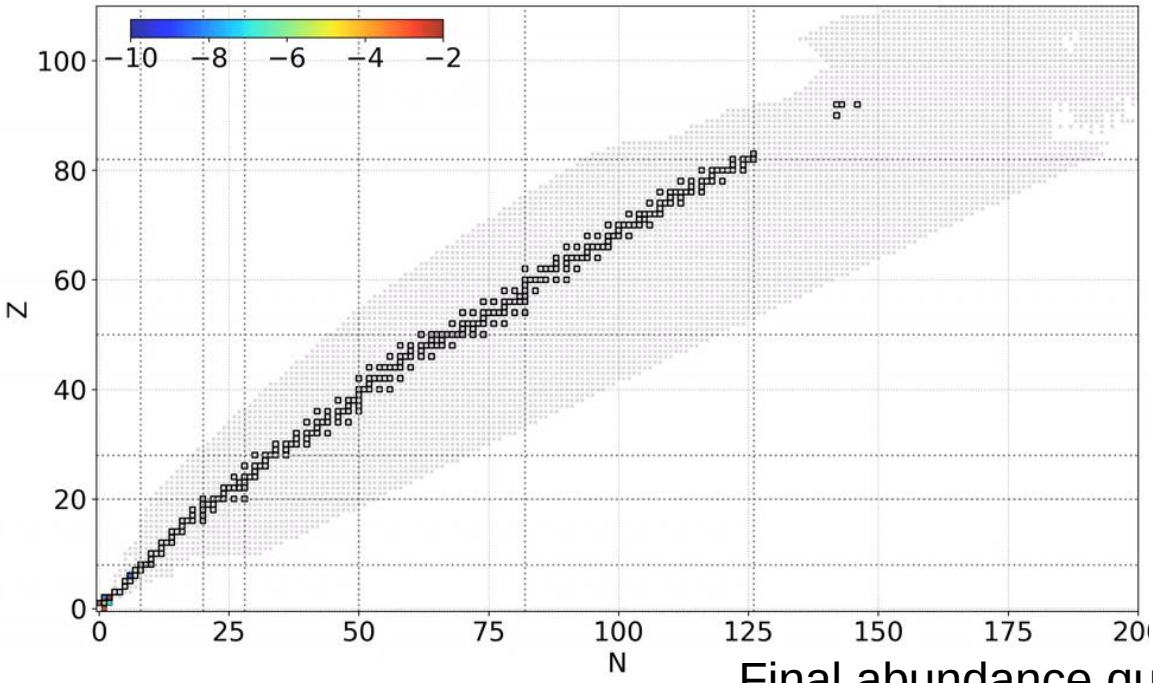
Phases during the operation of the vr-process

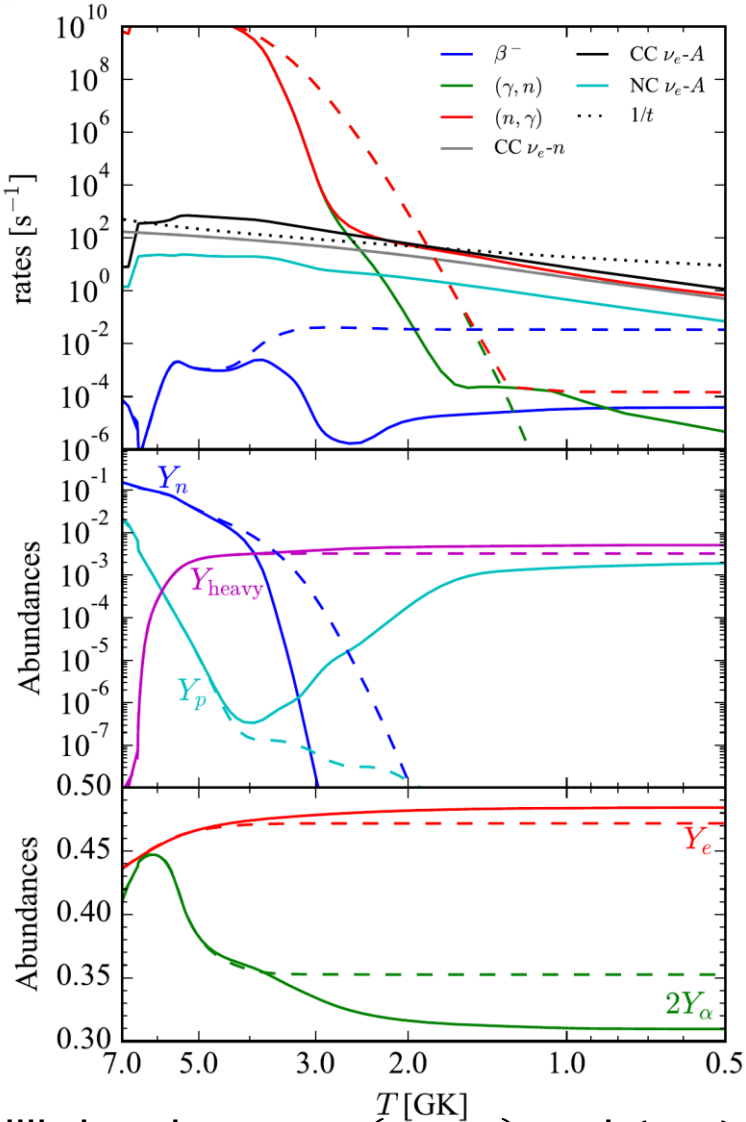
- **Seed production:** Strong neutrino fluxes drive material to $Y_e \sim 0.5$
- **Neutron-capture phase:** neutrons are used relatively fast by two competing mechanisms:
  - $n(\nu_e, e^-)p$ converts neutrons into protons that are captures in medium mass nuclei
  - $A(\nu_e, e^- X)\ X = n, p, \alpha$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

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



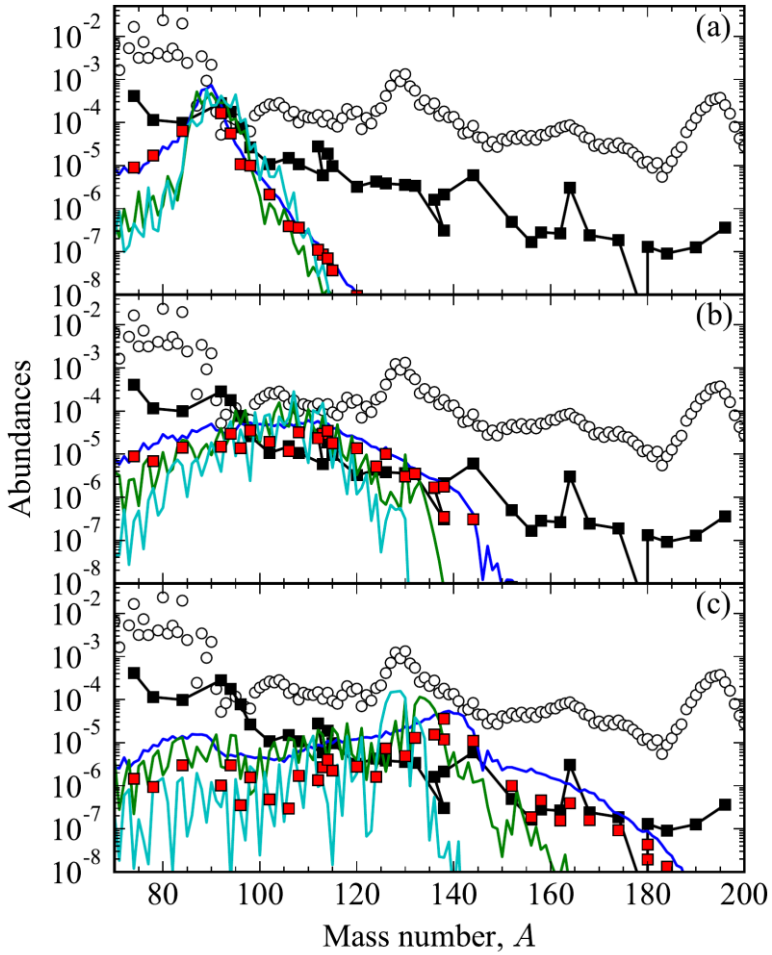




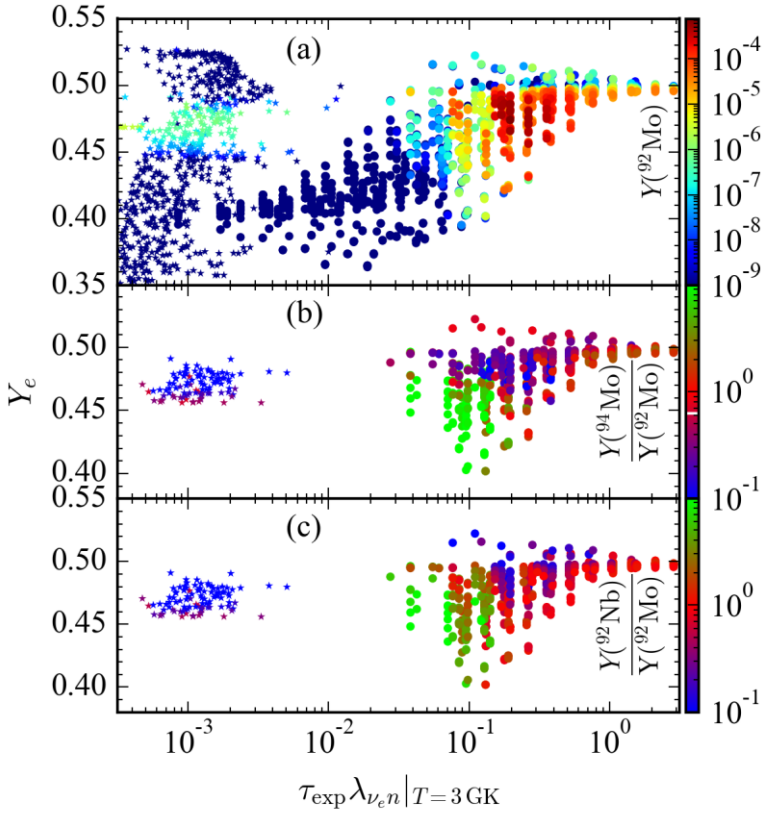
Final abundance quilibrium between (ν_e, e^-) and (n, γ)

Dependence on neutrino fluence

Increasing neutrino fluence allows to produce heavier p-nuclei

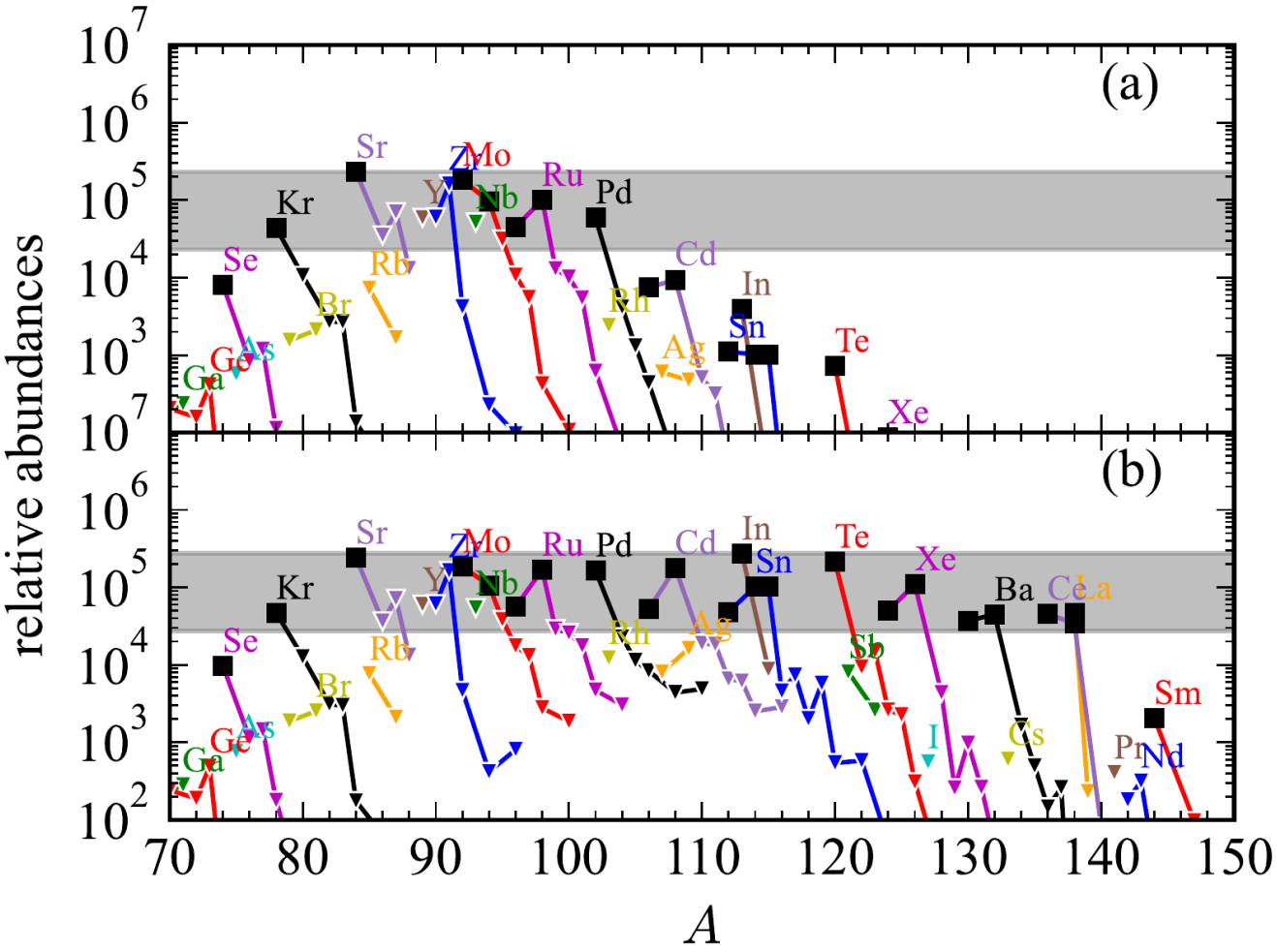


Dependence Y_e and neutrino fluence



Current neutrino-hydrodynamical models are 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 vr-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”
  - 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
- vr-process: new mechanism production p-nuclei

Collaborators

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