Elements formation in radiation-hydrodynamics simulations of kilonovae

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Binary Neutron Star Mergers

- Detection:
  - Gravitational Waves: **GW170817**
  - Kilonovae, short γ-ray bursts
- Simulation:
  - Ab-initio Numerical Relativity simulations (`WhiskyTHC`[1])
  - Dynamical, spiral-wave and disk ejecta

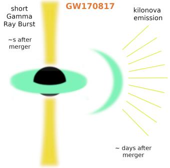
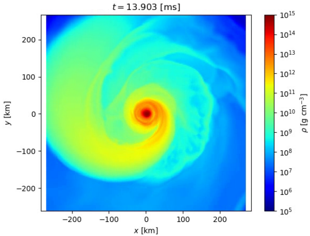


Figure: F. Zappa



[1] D. Radice et al. 2018, 2021

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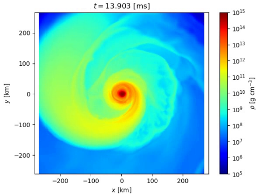
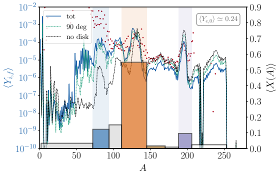
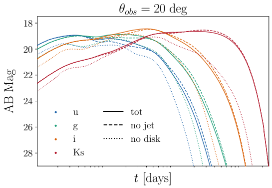
Simulations of Kilonovae

Test kilonovae physics with targeted simulations

- Constraints from GW (or not)
- Targeted numerical relativity simulations
- Radiation-hydrodynamic simulations to predict
  - Matter composition evolution
  - Kilonovae light curves







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Kilonovae Nuclear Engine

- **Thermal** emission from expanding ejecta
- Powered by nuclear decays
  - Production of heavy elements

$$\tau_n \sim \tau_\beta \longrightarrow$$ neutron captures

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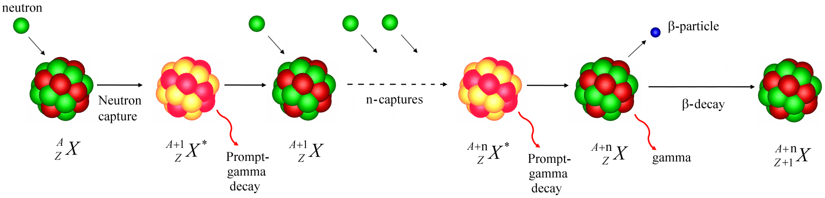
Kilonovae Nuclear Engine

- **Thermal** emission from expanding ejecta
- Powered by nuclear decays
  - Production of r-process peaks elements

    $Y_e \lesssim 0.22 \longrightarrow \tau_n \ll \tau_\beta \longrightarrow$ **rapid** neutron captures
  - **Nuclear heating** from heavy, neutron-rich nuclei



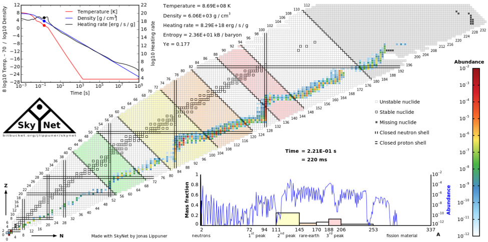
Nuclear Network

Numerical solution of the **detailed balance** equation

$$\frac{dY_i}{dt} = \sum_{\alpha} \lambda_\alpha \left(-R_i^\alpha + P_i^\alpha\right) N_i^\alpha \prod_{m \in \mathcal{R}_\alpha} Y_m^{N_m^\alpha}$$

`SkyNet`[2] Nuclear Network (NN)

- ~ 7800 isotopes
- strong, weak, EM reactions



[2] J. Lippuner & L. Roberts 2018

Standard approaches

- Pre-process for heating rates:
  - analytical fits for radiation-hydrodynamics[3-4]
- Post-process with homologous expansion ($\rho \propto t^{-3}$)
  - from extracted profiles[4-5]
  - following tracers[3,6-7]
- Isolated fluid elements
  decoupling nuclear reactions and dynamics

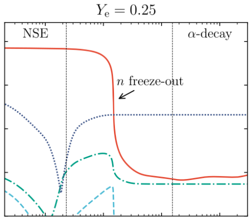


Figure: Abundances evolution (from [5])

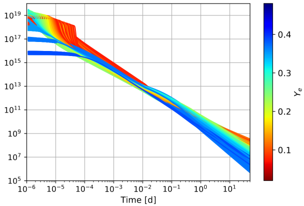


Figure: Heating rate fits (from [4])

[3] S. Rosswog et al. 2014
[4] Z. Wu et al. 2022
[5] A. Perego et al. 2022
[6] L. Combi and D. Siegel 2023a
[7] C. Collins et al. 2023

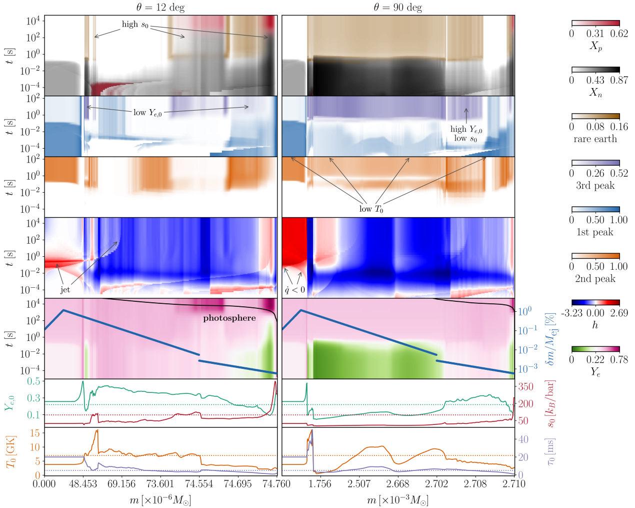
Ejecta Evolution

2D Radiation-Hydrodynamics with *online* nuclear network

- Initial profiles from numerical relativity
  - Results for LS220 $q \simeq 1.43$
- Ray-by-ray Lagrangian radiation-hydrodynamics
  - Effects of a polar jet
- *Online* nuclear network coupling (`SkyNet`[2])
  - Self-consistent composition tracking
  - Dynamics affected on the fly

[2] J. Lippuner & L. Roberts 2018

Detailed ejecta evolution



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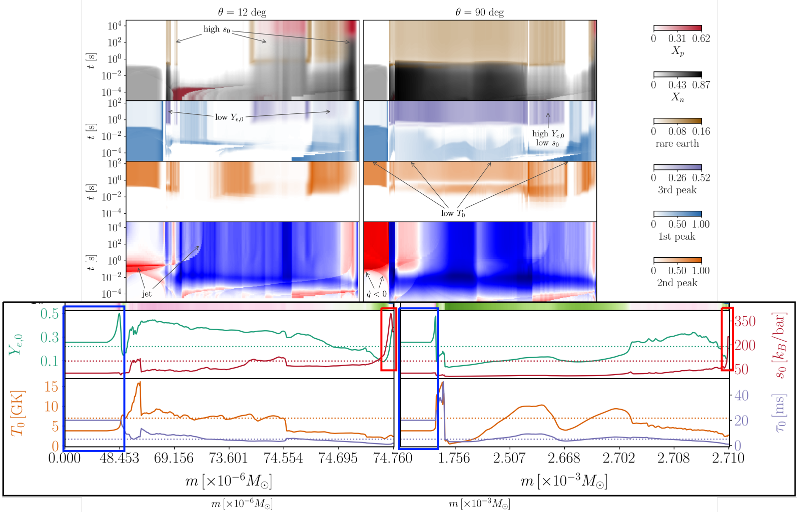
arXiv:2403.13883
Fabio Magistrelli

Detailed ejecta evolution



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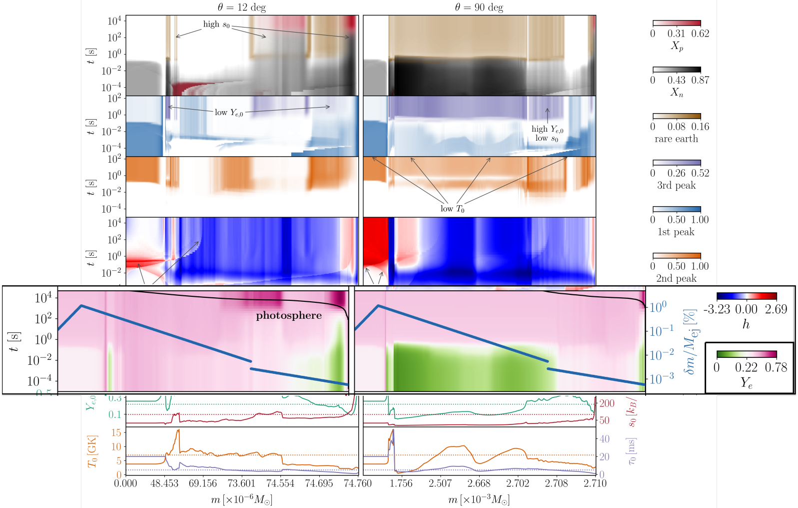
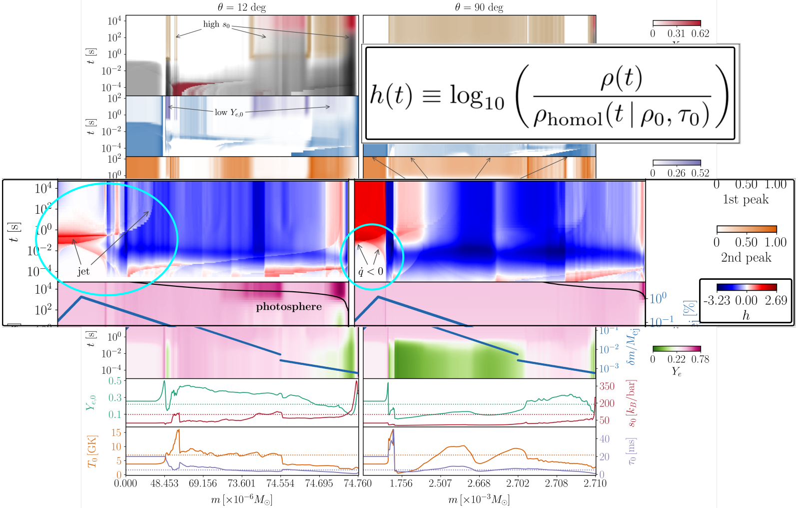
Detailed ejecta evolution



Detailed ejecta evolution



$$h(t) \equiv \log_{10}\left(\frac{\rho(t)}{\rho_{\mathrm{homol}}(t\,|\,\rho_0,\tau_0)}\right)$$

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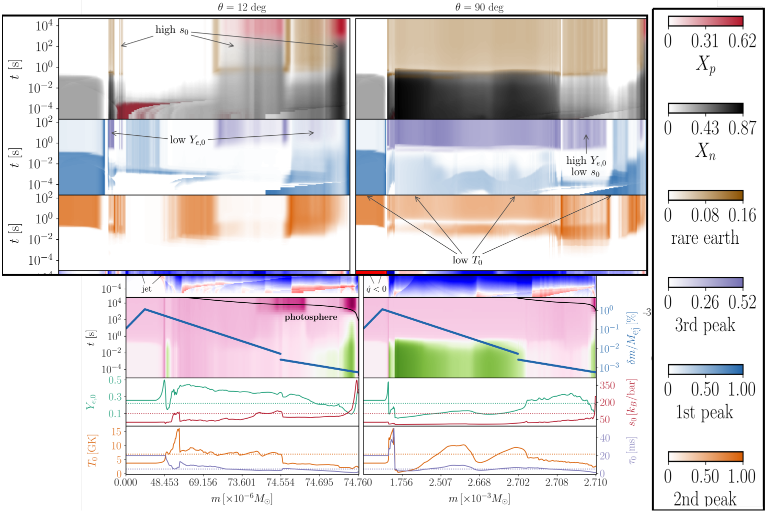
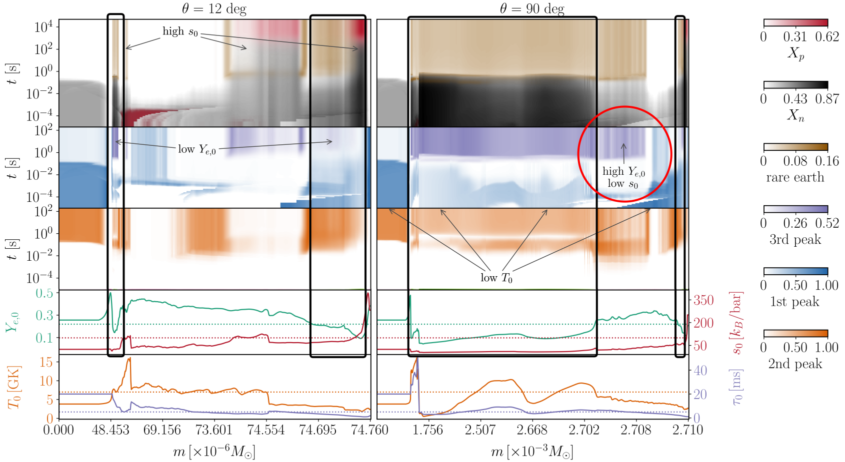
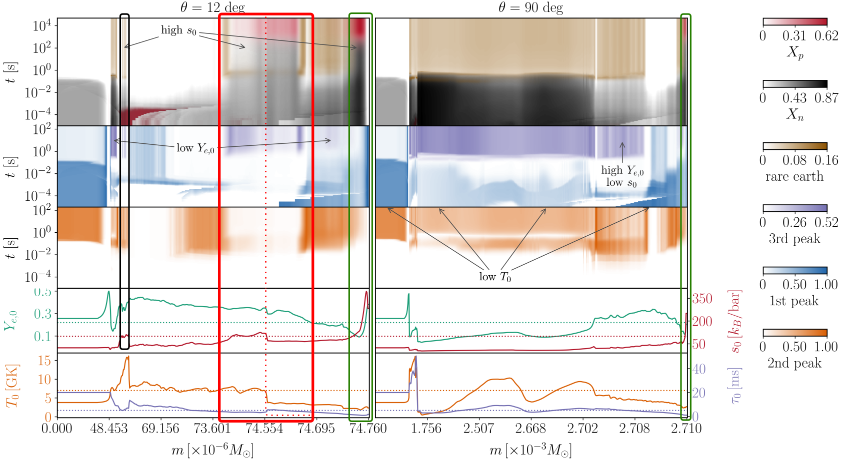
Detailed ejecta evolution



Detailed ejecta evolution



Detailed ejecta evolution



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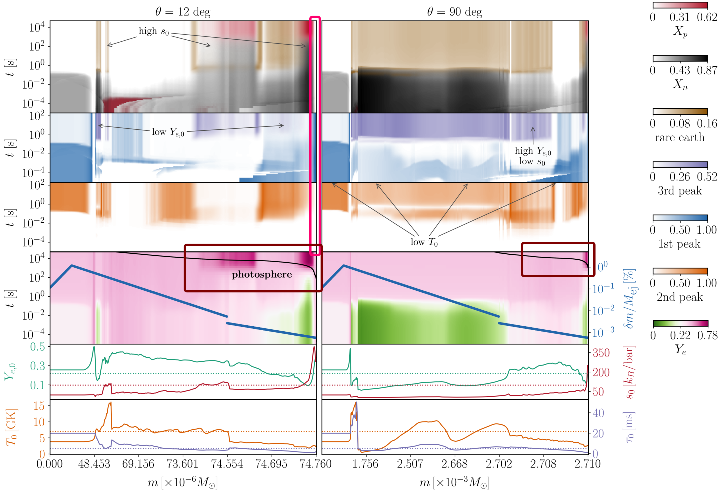
Detailed ejecta evolution



r-process nucleosynthesis yields

- r-peaks and rare-earths
- Mostly from equatorial plane
- Light elements from disk
- No significant global effects from jet
- discrepancies $\gtrsim 10\%$ with post-process of [5]

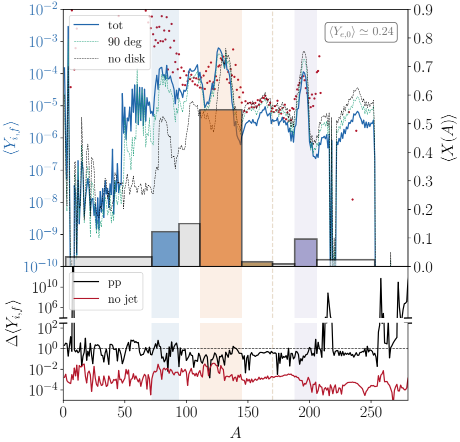
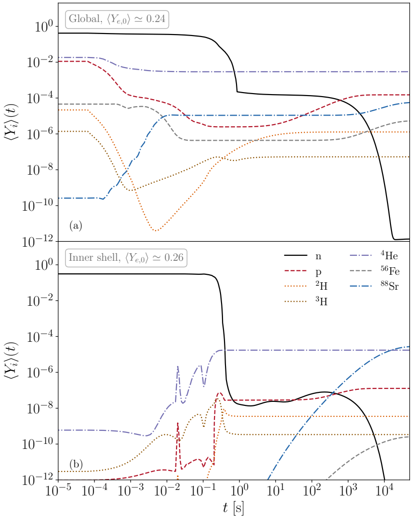


Figure: Final abundances and cumulative mass fractions

[5] A. Perego et al. 2022

Selected elements abundances

- n freeze-out at $t \sim 1$ s, then β-decay
- Signs of incomplete burning and α-rich freeze-out



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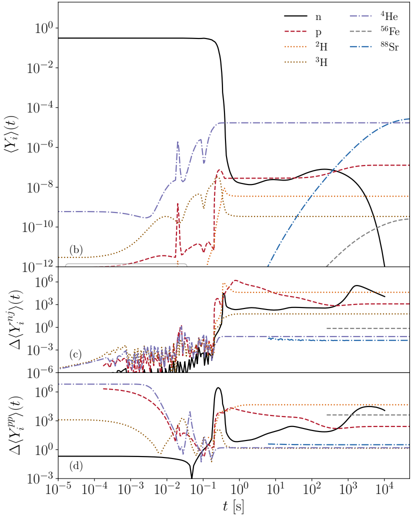
Selected elements abundances

- n freeze-out at $t \sim 1$ s, then β-decay
- Signs of incomplete burning and α-rich freeze-out
- polar jet (inner shells):
  - p and n boost
  - inhibition of light element burning
- significant **deviations from post-process** nuclear networks (e.g. [5])



[5] A. Perego et al. 2022

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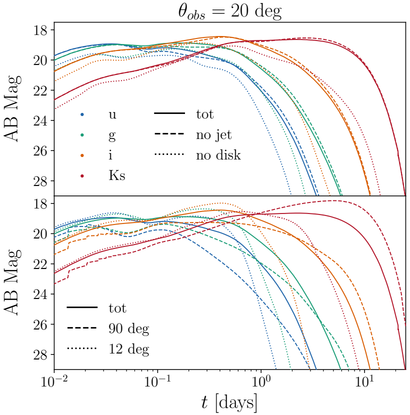
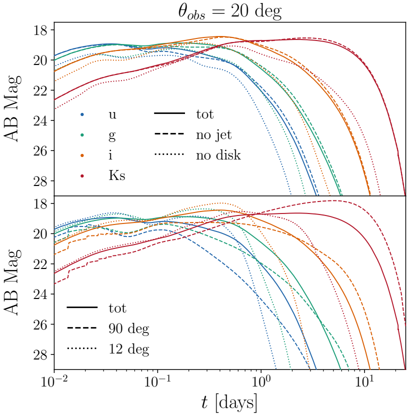
Kilonova Light Curves

- UV/blue precursor at $t \sim$ hours
- Disk emission screened by lanthanide curtain
- Red and blue from equatorial and disk-edge ejecta



Kilonova Light Curves

- UV/blue precursor at $t \sim$ hours
- Disk emission screened by lanthanide curtain
- Red and blue from equatorial and disk-edge ejecta
- Jet raises early temperature:
  - Slightly bluer and brighter early emission
  - Faster matter cooling: redder and dimmer late emission



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Summary and Outlook

- Ray-by-ray radiation-hydrodynamic with online nuclear network[8]
- **Nucleosynthesis** strongly connected to **dynamics**:
  - Final yields **not** determined by initial thermodynamic properties solely
  - Abundance evolution **strongly differs** from post-process
  - Dynamics affected by nuclear events
- Further investigations
  - Systematic investigation of kilonovae
  - Explore dependencies on EoS and mass ratios

[8] **FM**, S. Bernuzzi, A. Perego and D. Radice, (2024)