# Probing heavy element nucleosynthesis through electromagnetic observations

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ERC EXOTIC workshop – Frontiers in Nuclear Physics
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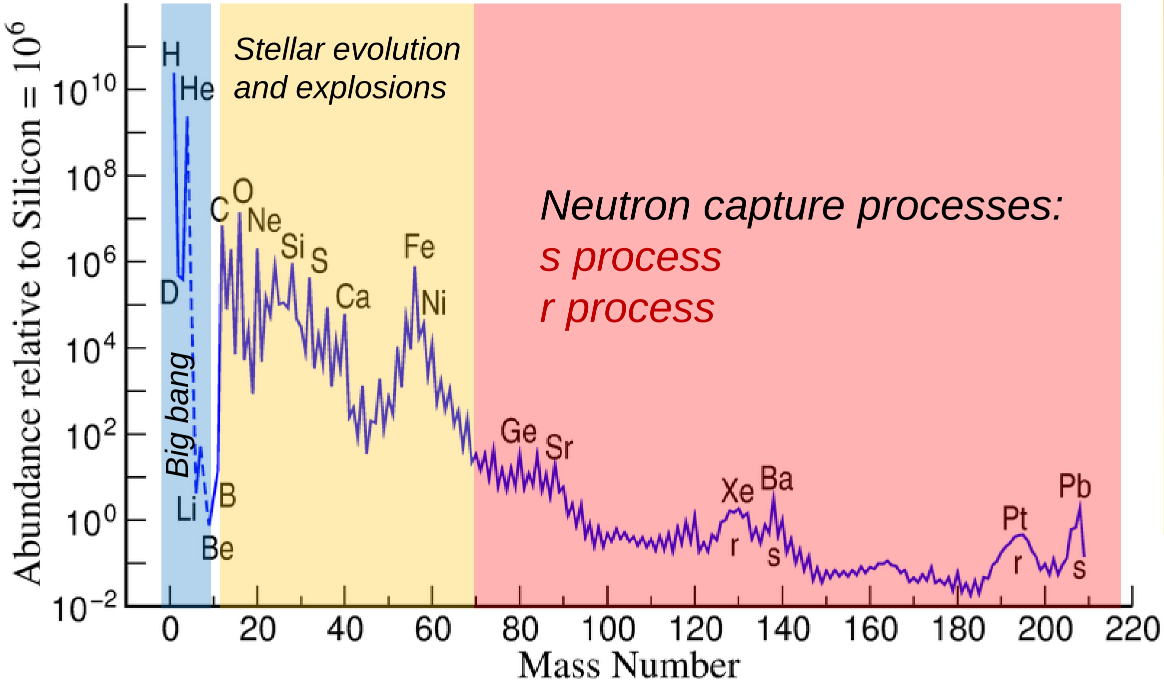
ERC AdG KILONOVA

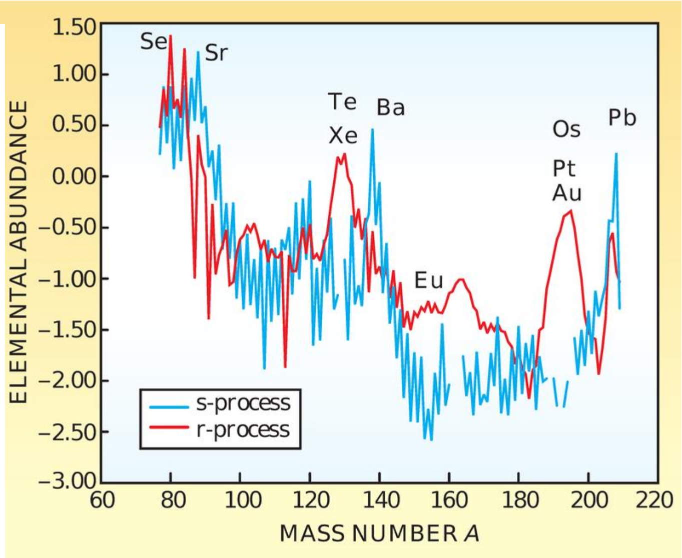
# Signatures of nucleosynthesis

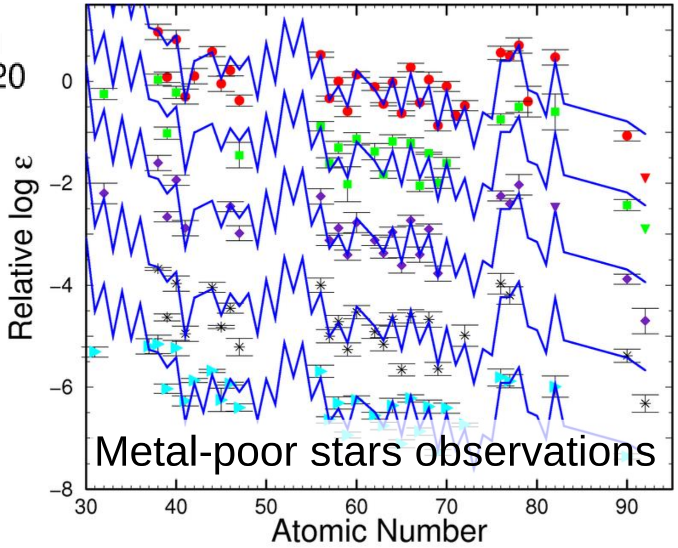


*Neutron capture processes:*

*s process*

*r process*





Metal-poor stars observations

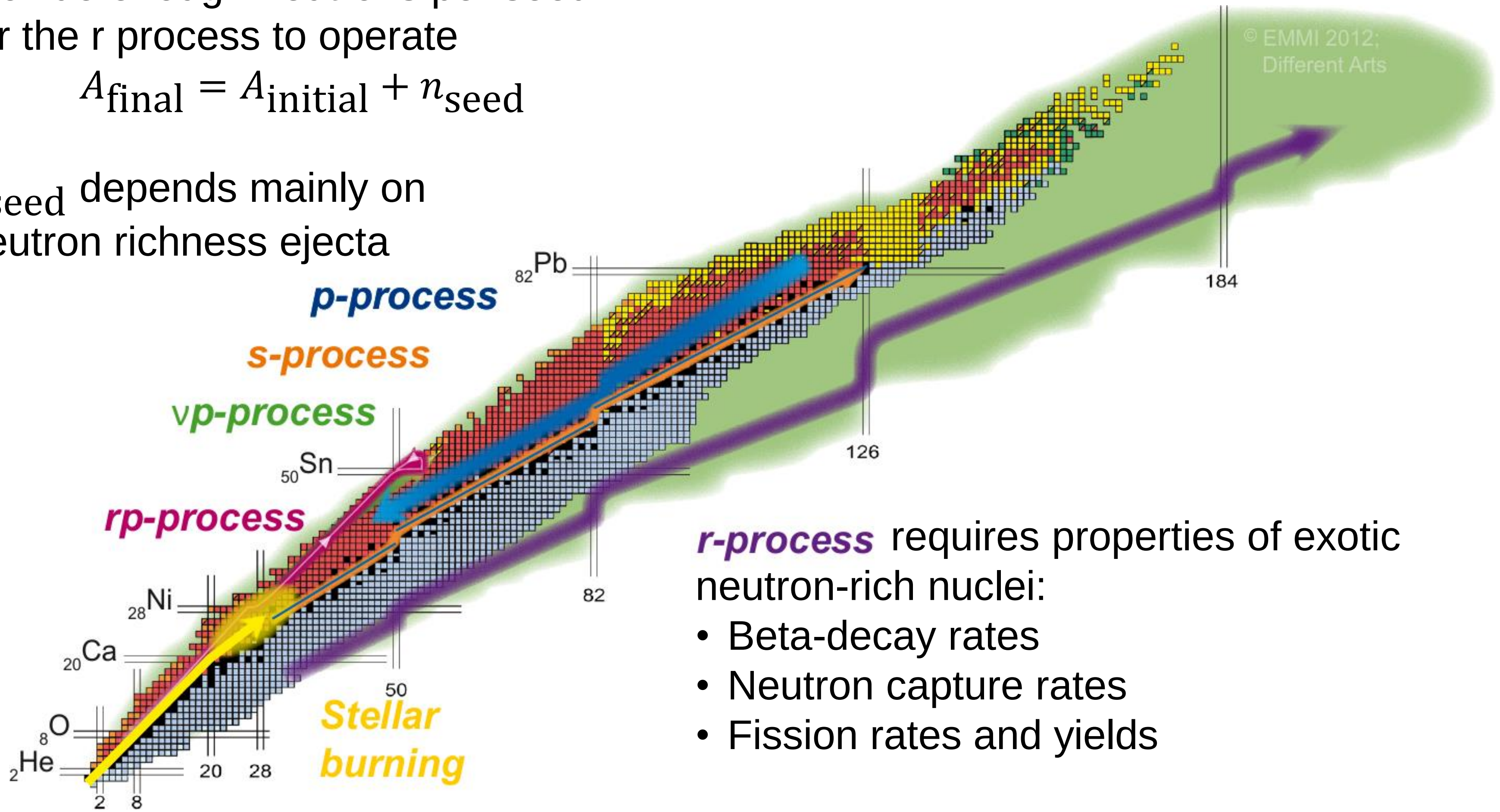
- Heavy elements produced in neutron capture processes
- Observations indicate that r process operates from early Galactic history in rare (high yield) events

# R process needs

Astrophysical environment should provide enough neutrons per seed for the r process to operate

$$A_{\text{final}} = A_{\text{initial}} + n_{\text{seed}}$$

$\mathrm{n}_{\text{seed}}$ depends mainly on neutron richness ejecta



***r-process*** requires properties of exotic neutron-rich nuclei:

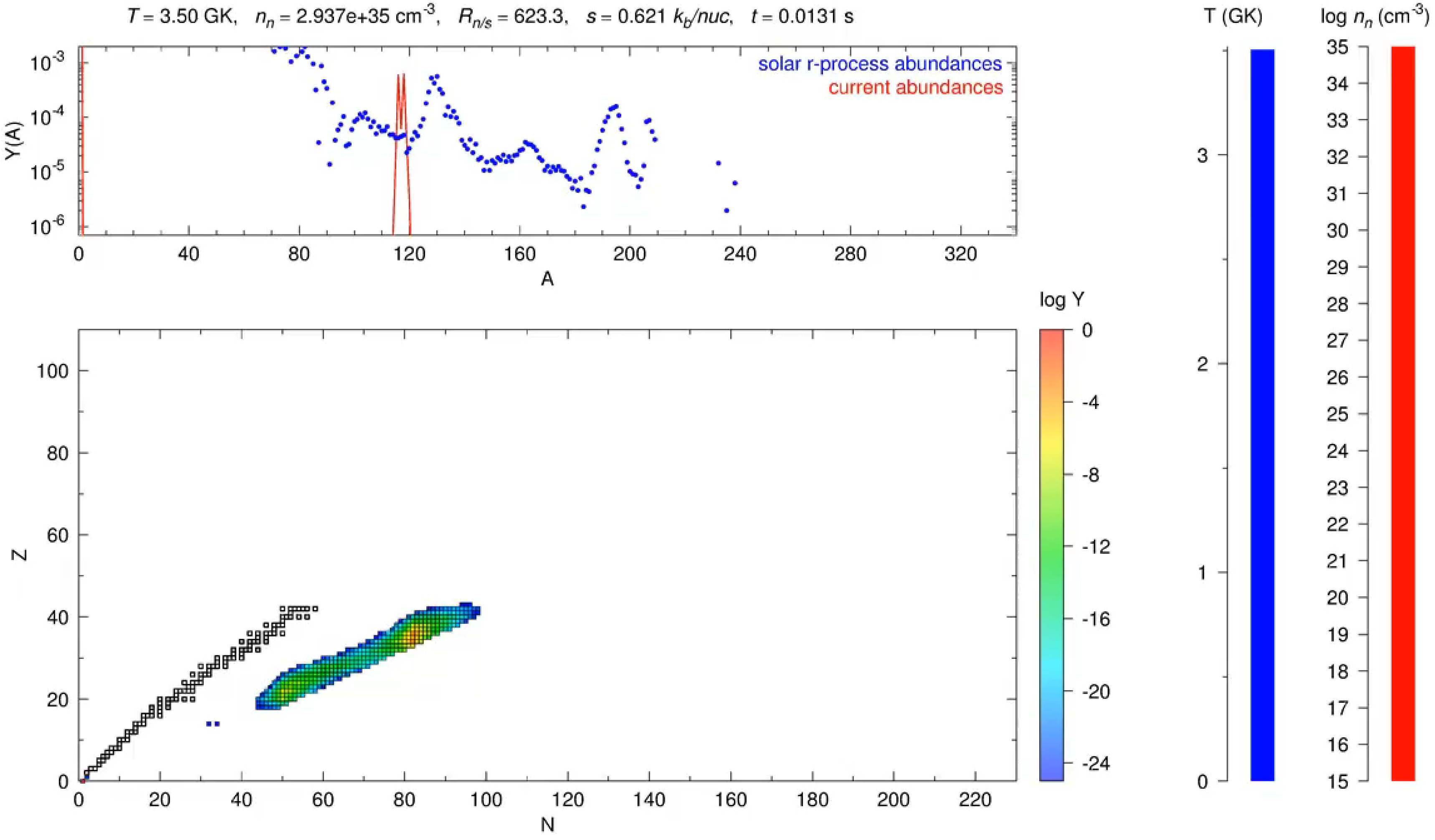
- Beta-decay rates
- Neutron capture rates
- Fission rates and yields

Benchmark against observations:

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

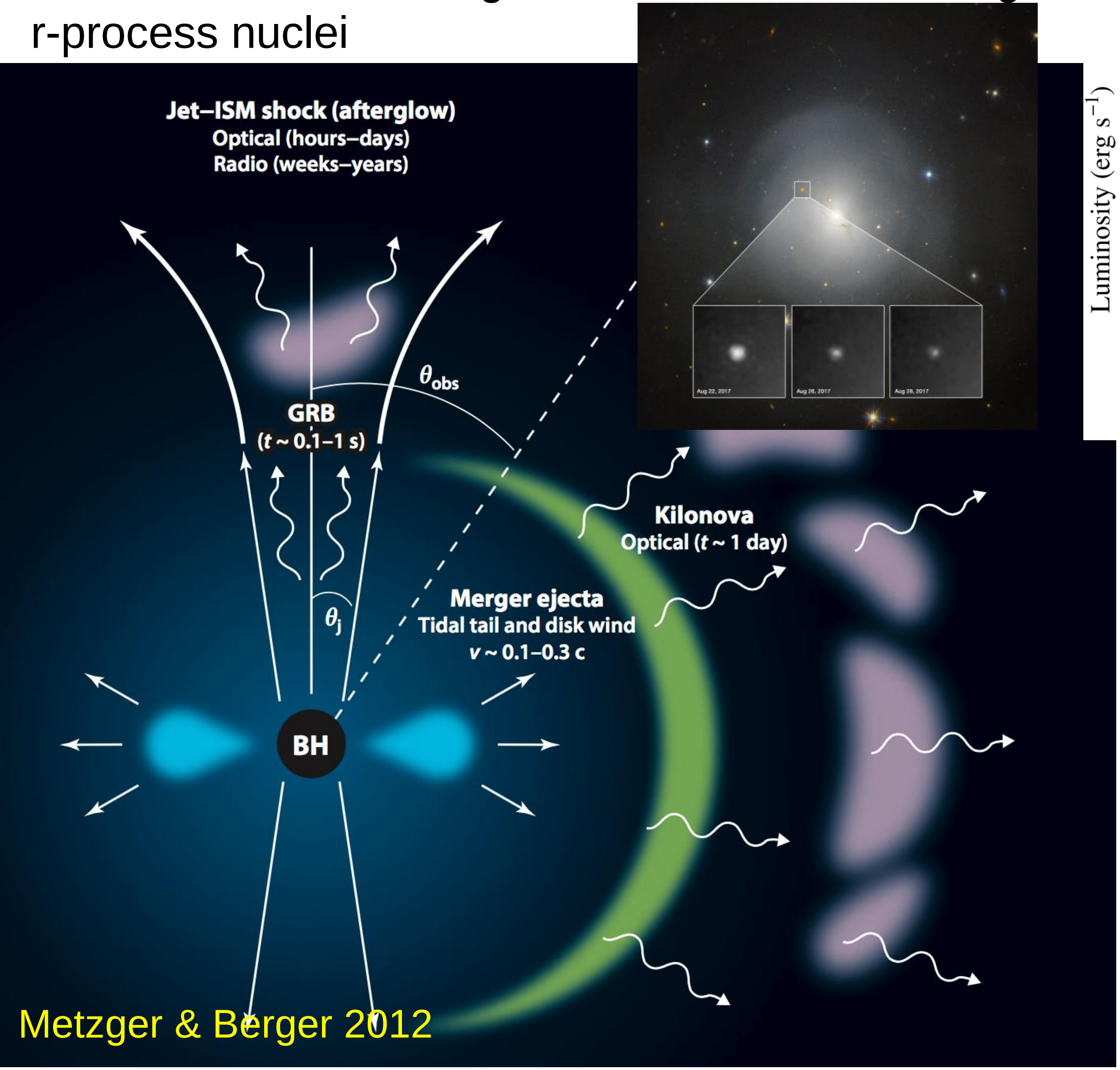
# R-process operation

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

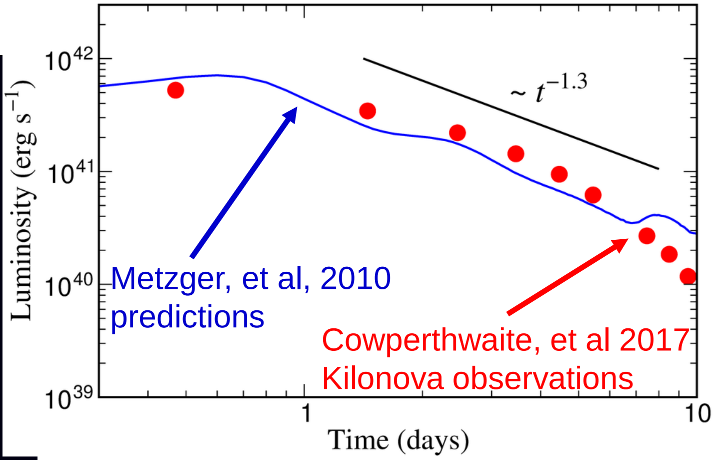


# Kilonova: signature of the r-process

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



Metzger & Berger 2012



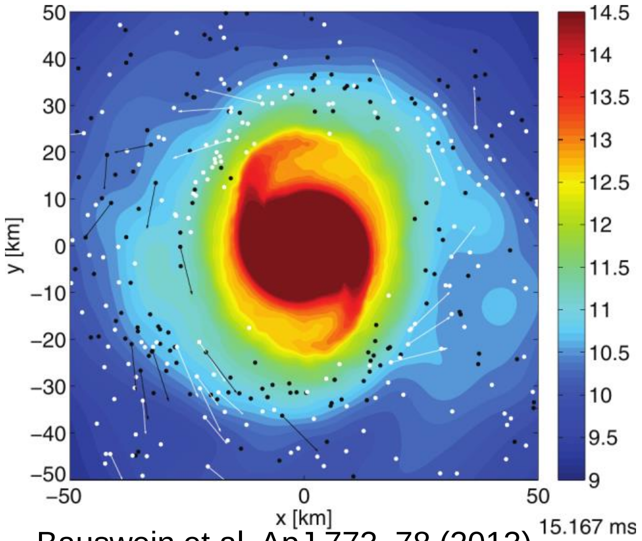
- Electromagnetic counterpart to Gravitational Waves
- Diagnostics physical processes at work during merger
- Direct probe of the formation r-process nuclei
- Information elements produced single event

# Pipeline for r-process in mergers

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

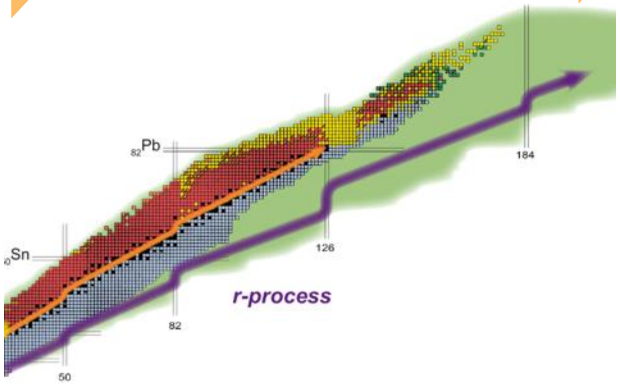
- Physics of neutron-rich and heavy nuclei

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



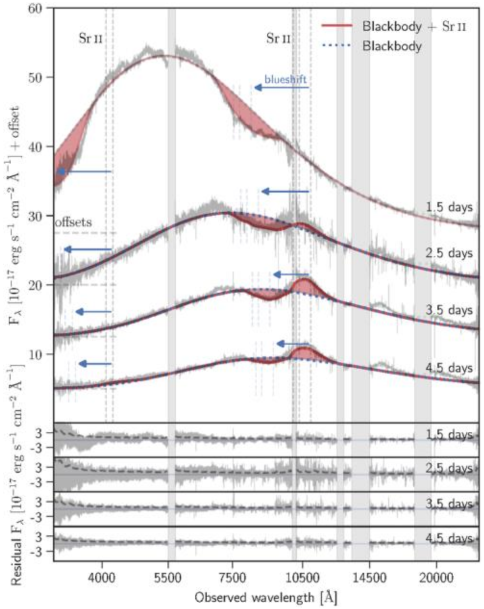
Bauswein et al, ApJ 773, 78 (2013)

forward modelling



backward modelling

Infer components ejecta ($Y_e$)

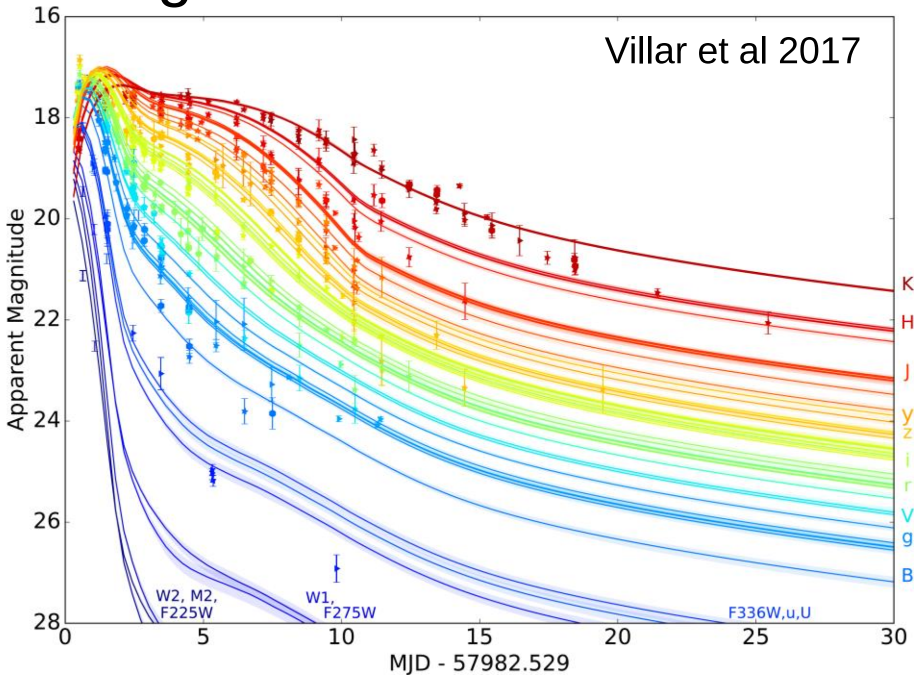


Watson et al, Nature **574**, 497 (2019)

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

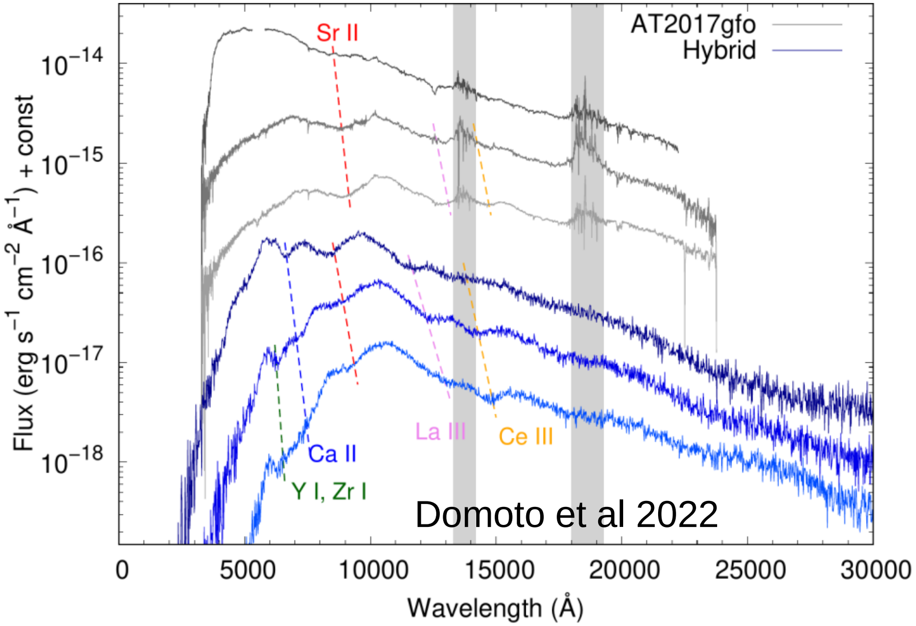
# Kilonova modelling

## Light curve



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

## Spectral modelling

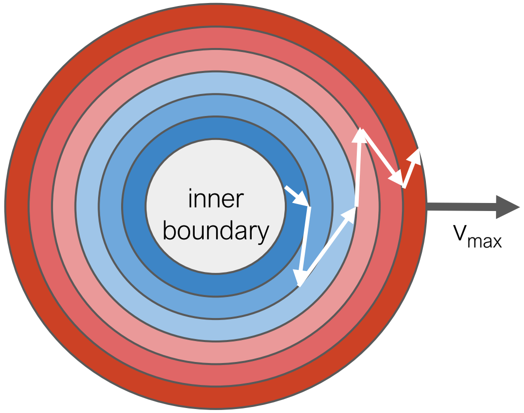


- Accurate data
  - LTE: line list bound-bound transitions
  - NLTE: + electron ion and photoionization cross sections, recombination coef
- Several elements observed

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

# Atomic Opacities (LTE)

- Sobolev optical depth (for a line $l$)



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

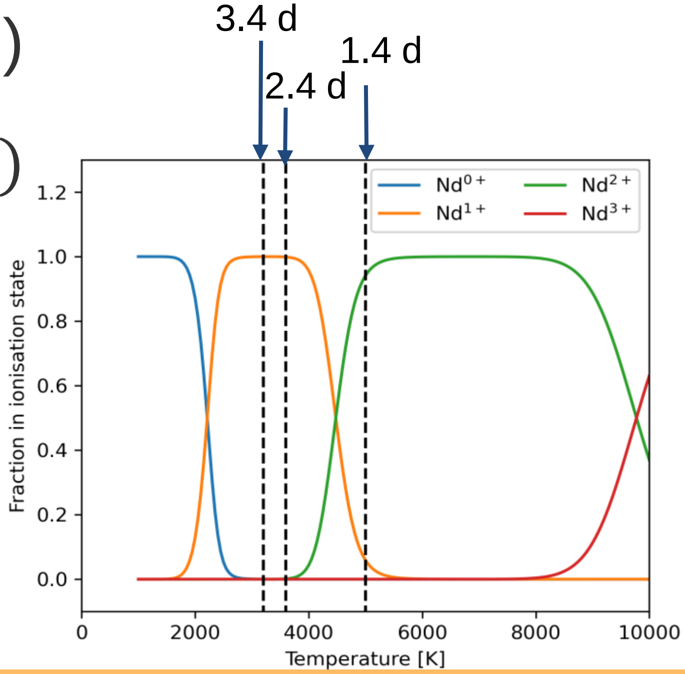
Transition wavelength

Oscillator strength

Population lower level
(Saha eq. and partition functions)

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

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



A. Flörs

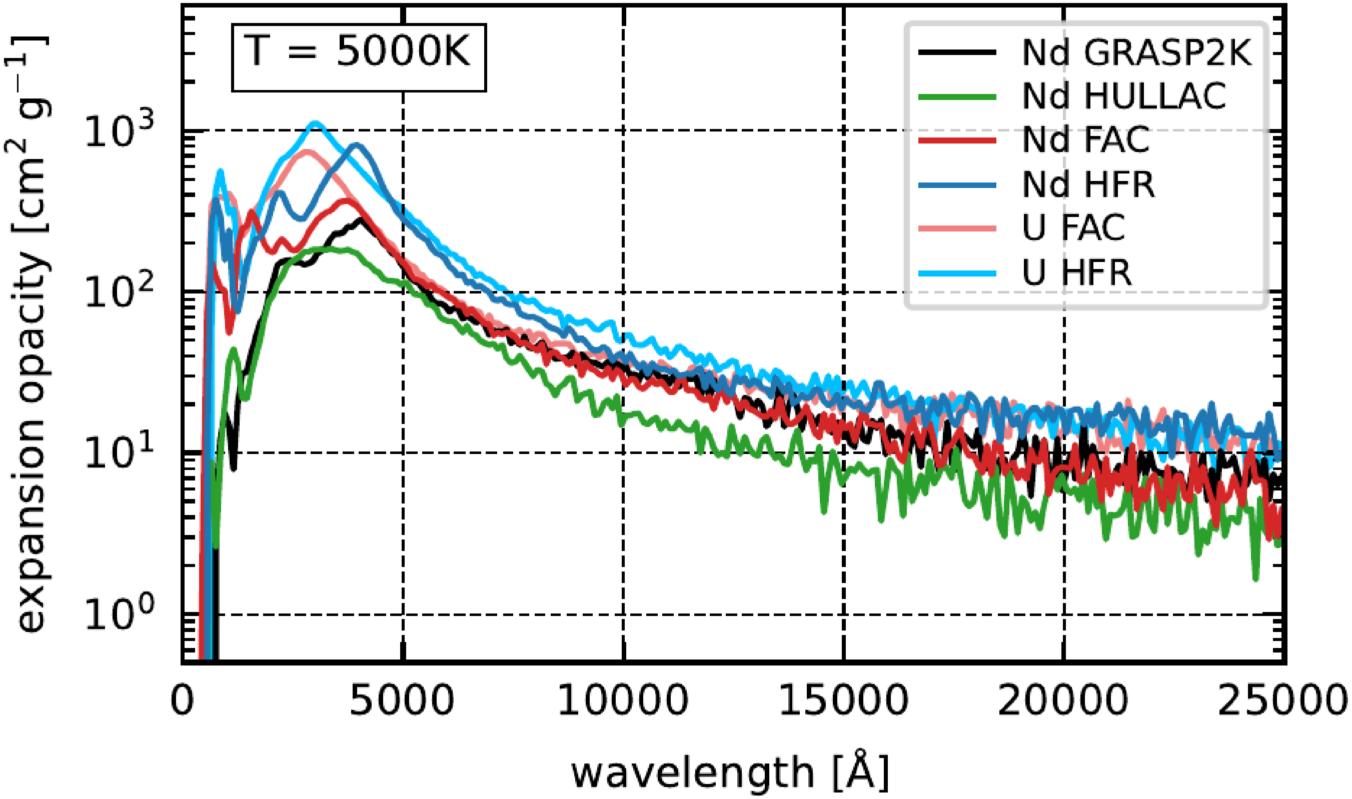
G. Leck

R. Silva

Goal: Develop database well calibrated atomic opacities

# 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)



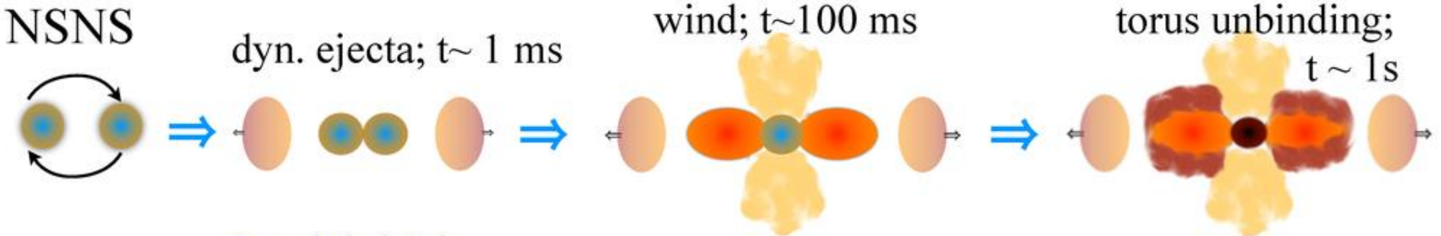
Silva et al, Atoms 10, 18 (2022); Flörs, Silva, et al, MNRAS 524, 3083 (2023)

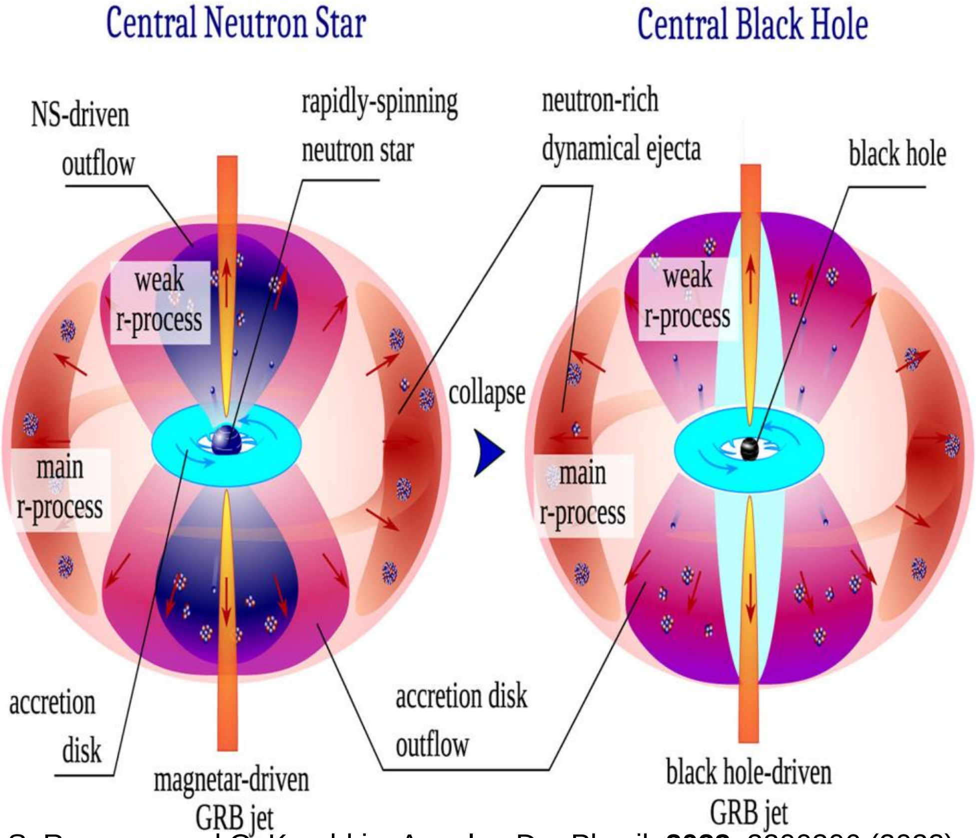
Offers a method to identify presence of Actinides in spectra.

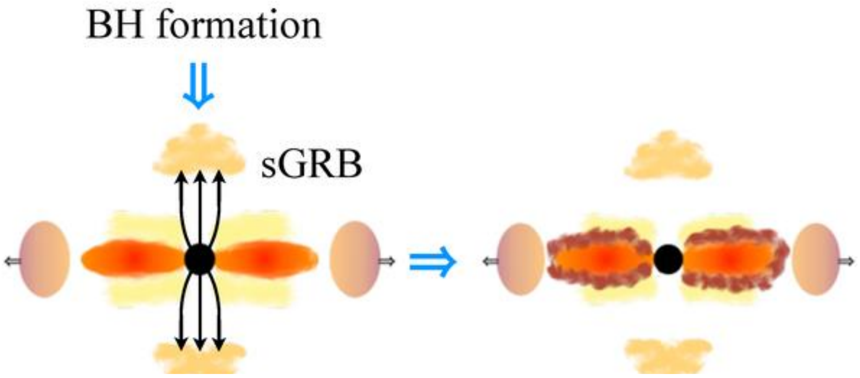
# Neutron star mergers: Different ejection mechanisms

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

Gravitational wave emission







Two sources of ejecta:

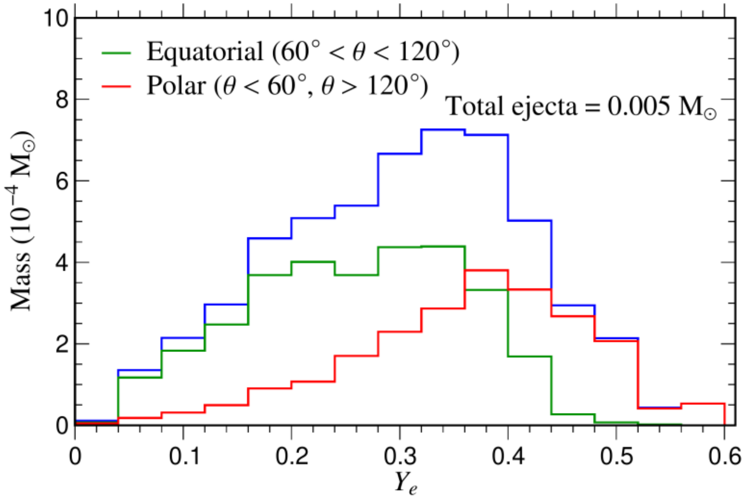
- Dynamical during the early phases of the merger ($M \lesssim 0.01\ M_\odot$)
- Accretion disc on longer timescales ($M \lesssim 0.05\ M_\odot$)
- Liftetime neutron-star determines impact neutrinos

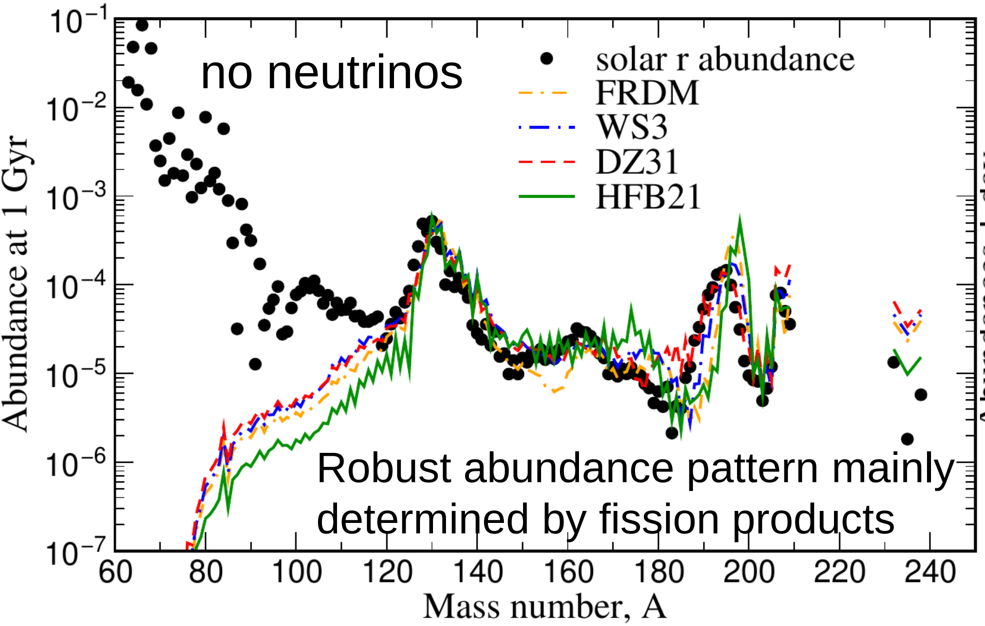
S. Rosswog and O. Korobkin, Annalen Der Physik **2022**, 2200306 (2022).

# Dynamical ejecta (simulations)

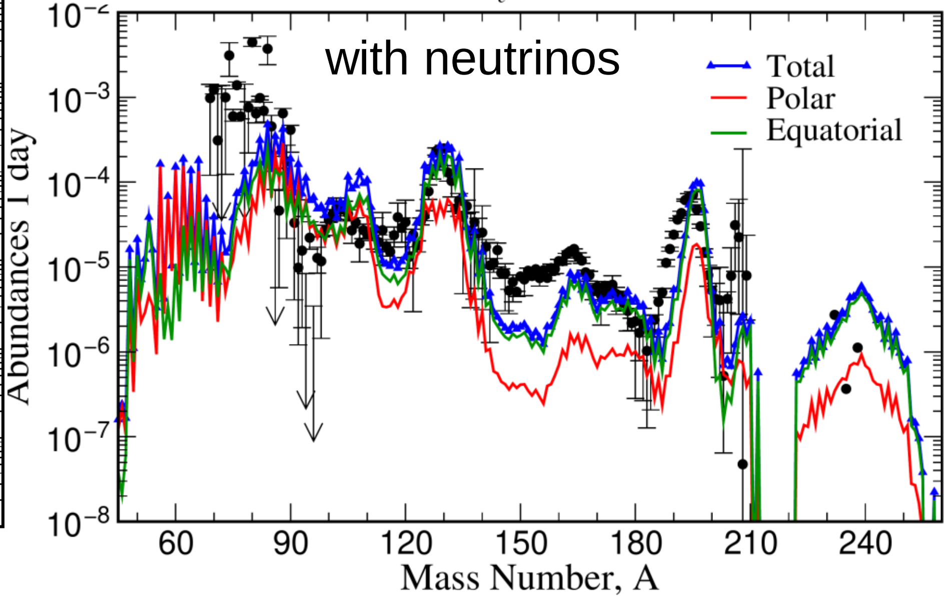
SPH Simulation **Vimal Vijayan**
Neutrino transport: ILEAS
1.35 – 1.35 $M_\odot$, SFHo EoS

- 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





Robust abundance pattern mainly determined by fission products

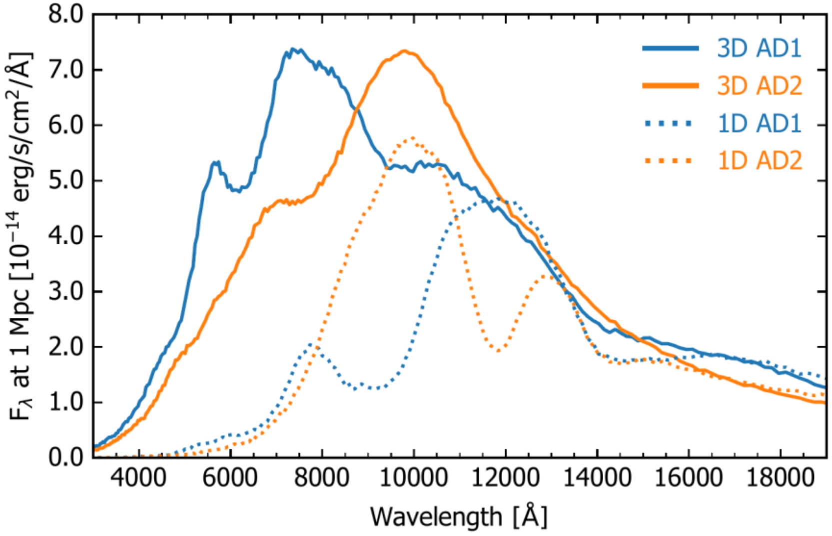


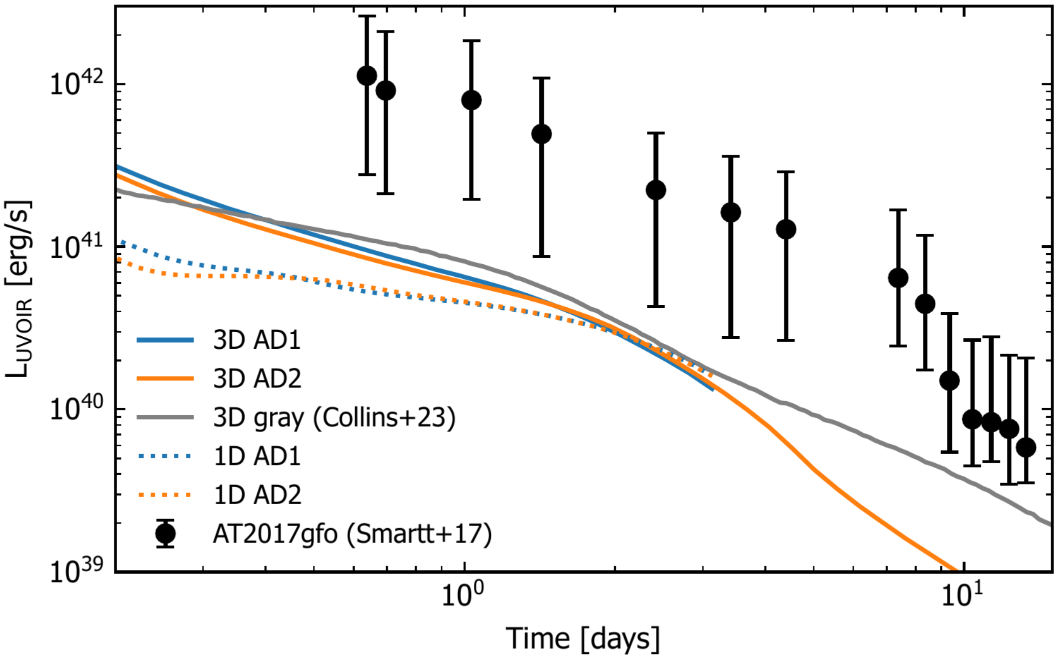
Mendoza-Temis, et al, PRC 92, 055805 (2015)

# Self-consistent 3D radiative transfer


L. Shingles

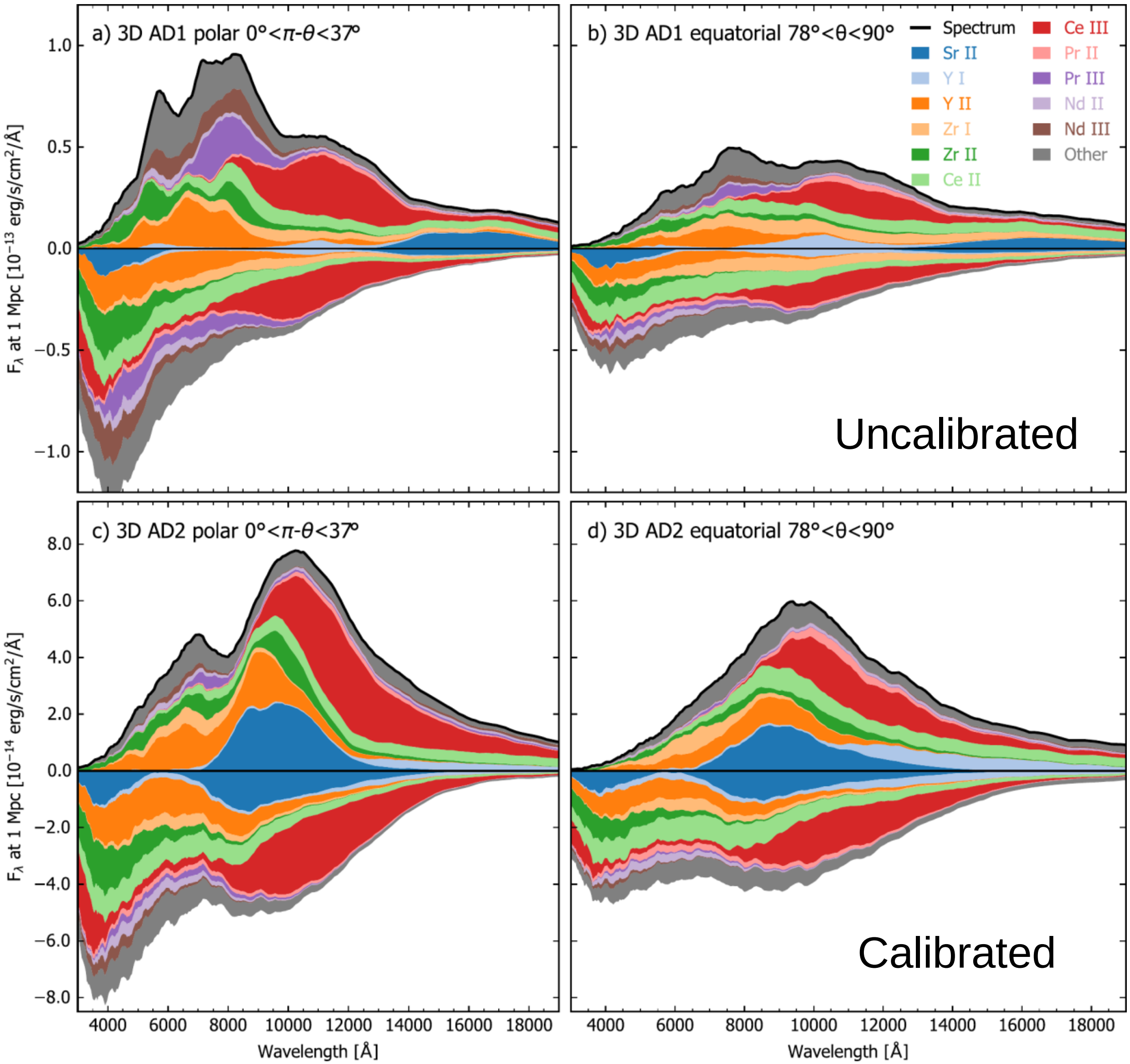
- Monte Carlo 3D radiative transfer using the ARTIS code. https://github.com/artis-mcrt/artis
- Matter distribution based on SPH Dynamical ejecta (0.005 $M_{\odot}$)
- LTE simulation: follows 2591 nuclei (283 ions with gamma-ray transport and electron thermalization, 44 millions atomic transitions lines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

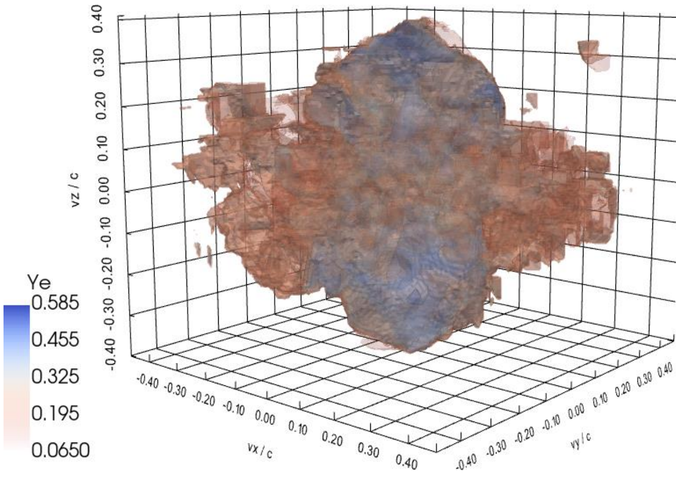




Shingles et al, ApJ 954, L41 (2023)

# Angular dependence spectra

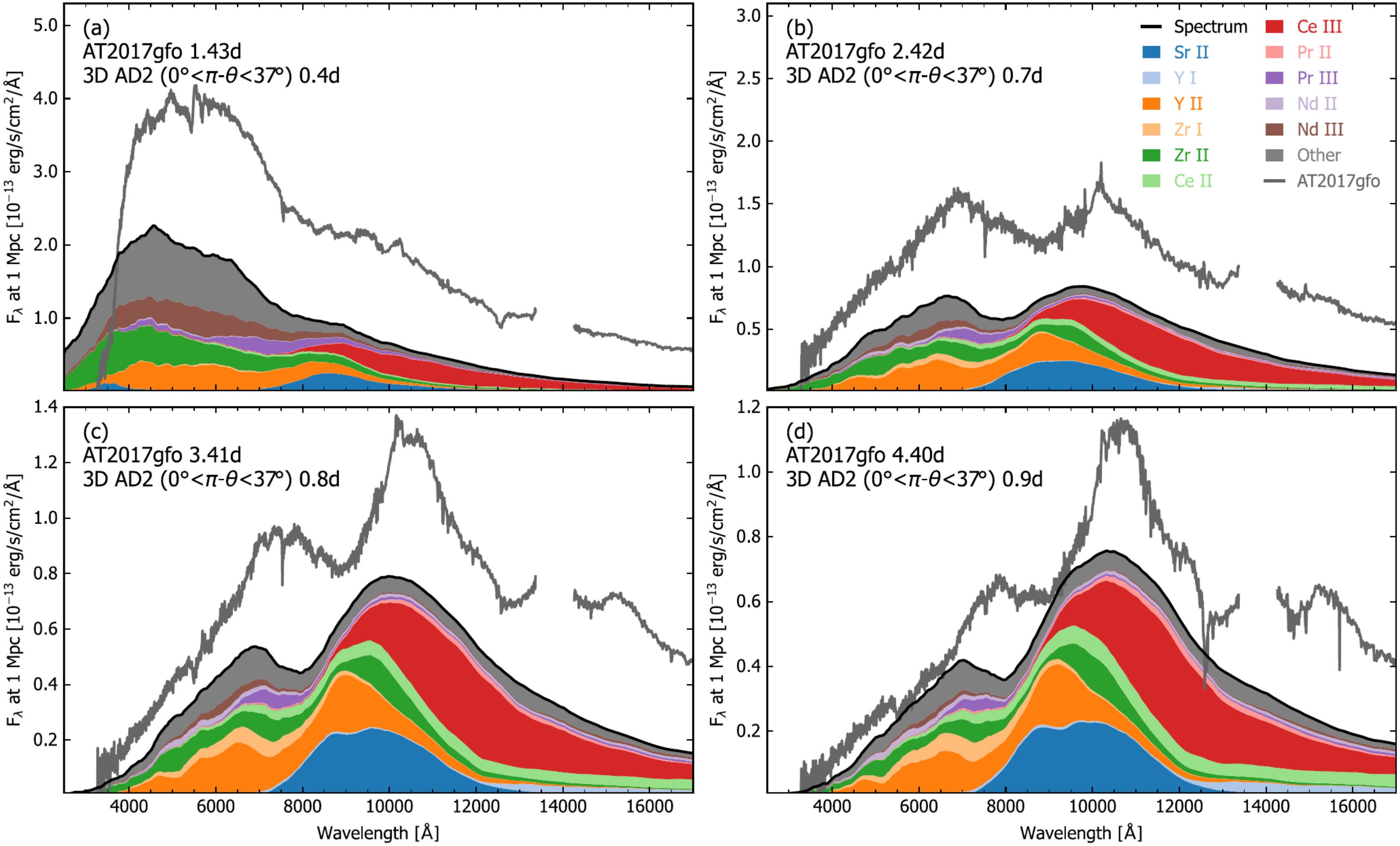




Differences reflect directional dependence of nucleosynthesis yields

Shingles et al, ApJ 954, L41 (2023)

# Comparison AT2017gfo

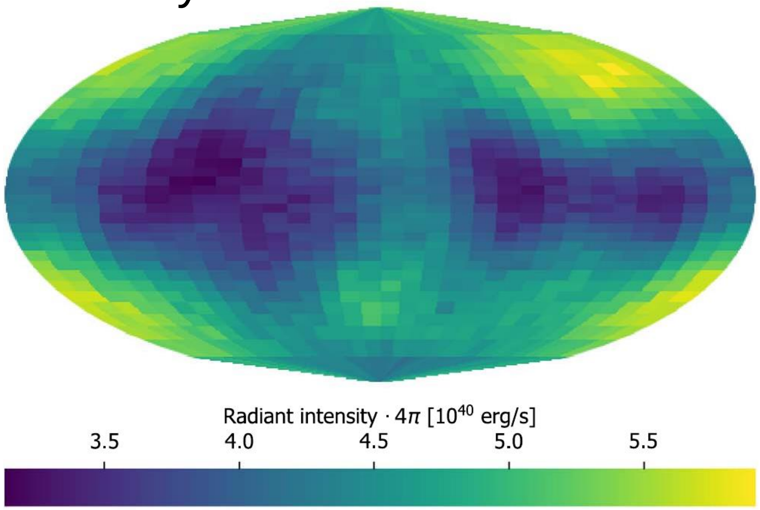


Similar spectral evolution that AT2017gfo once differences in brightness are accounted

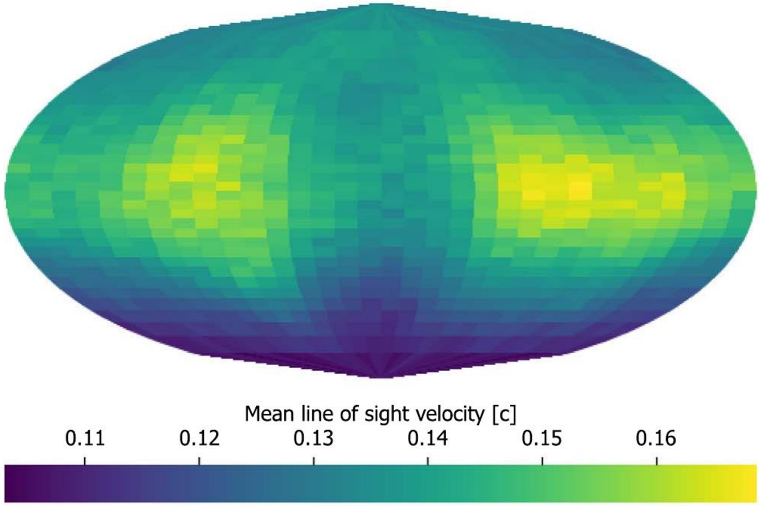
Shingles et al, ApJ 954, L41 (2023)

# Asymmetry observables

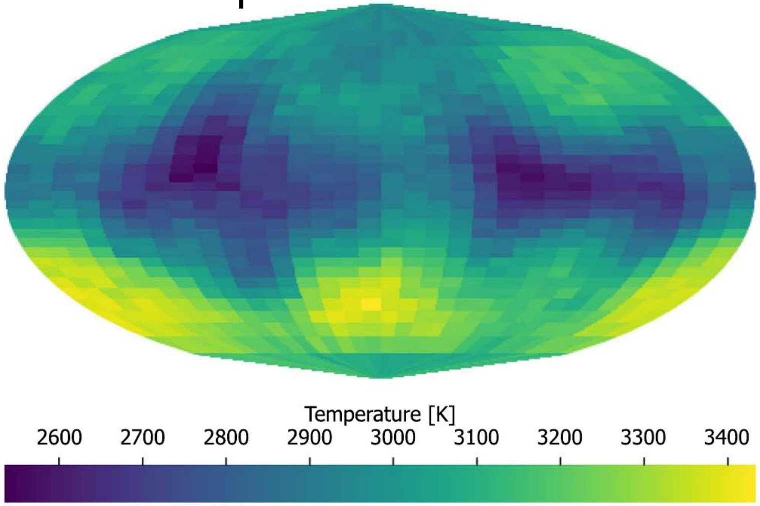
Intensity



Line-of-sight velocity



Mean temperature

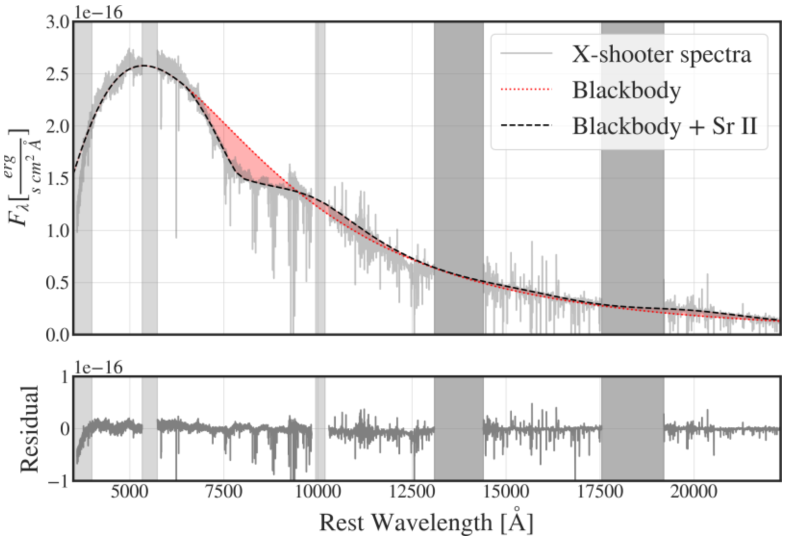


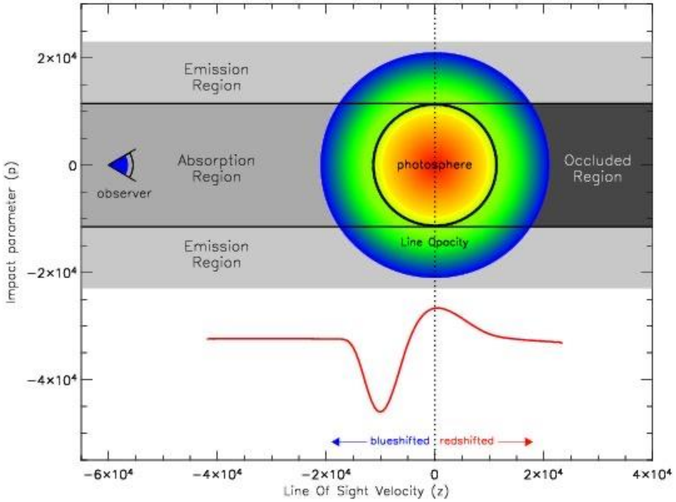
- Strong asymmetry observables
- Is this consistent with observations?

Shingles et al, ApJ 954, L41 (2023)

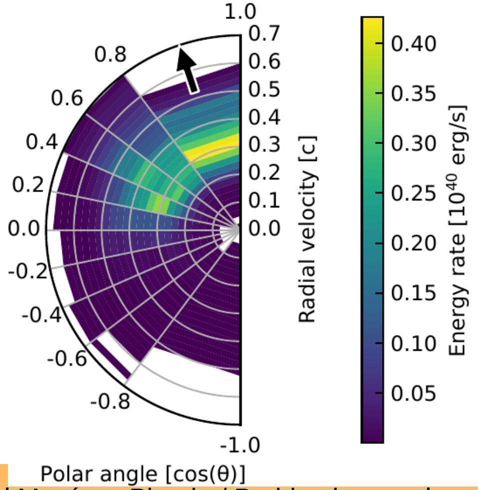
# Benchmark against AT2017gfo

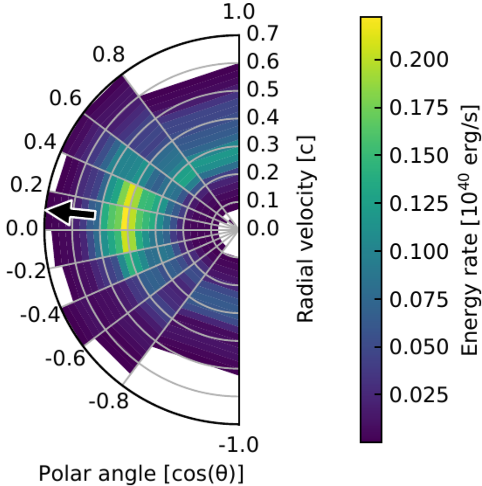
Analysis of AT2017gfo Sr II P-Cygni feature shows kilonova is highly spherical at early epochs [Sneppen et al, Nature 614, 436 (2023)]





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

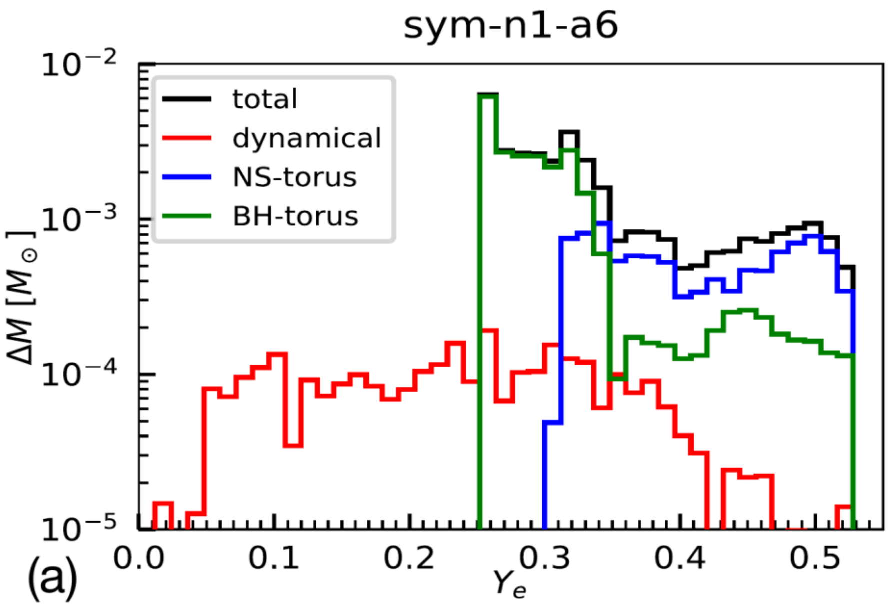


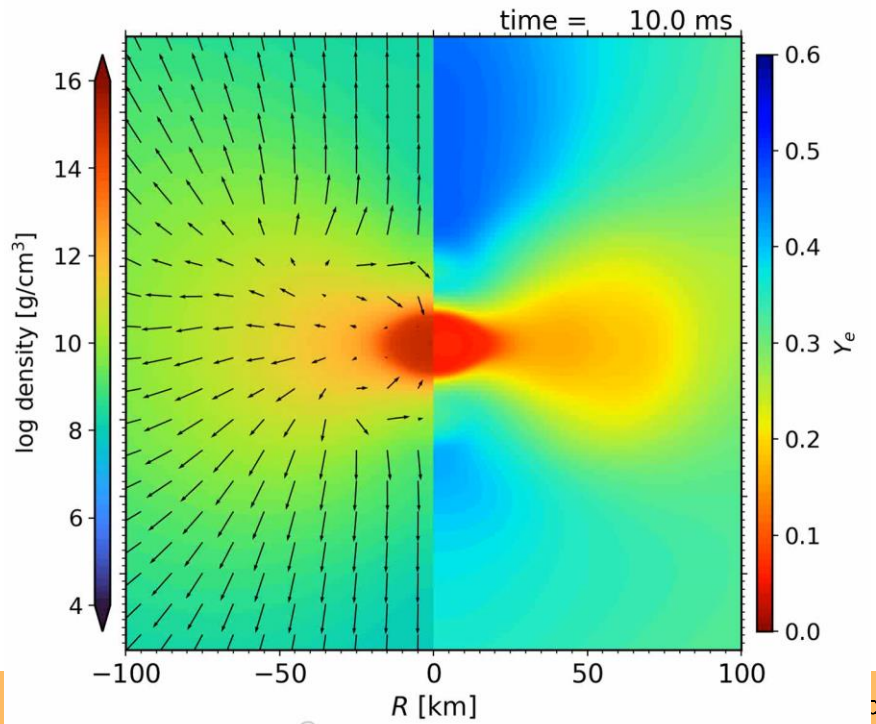


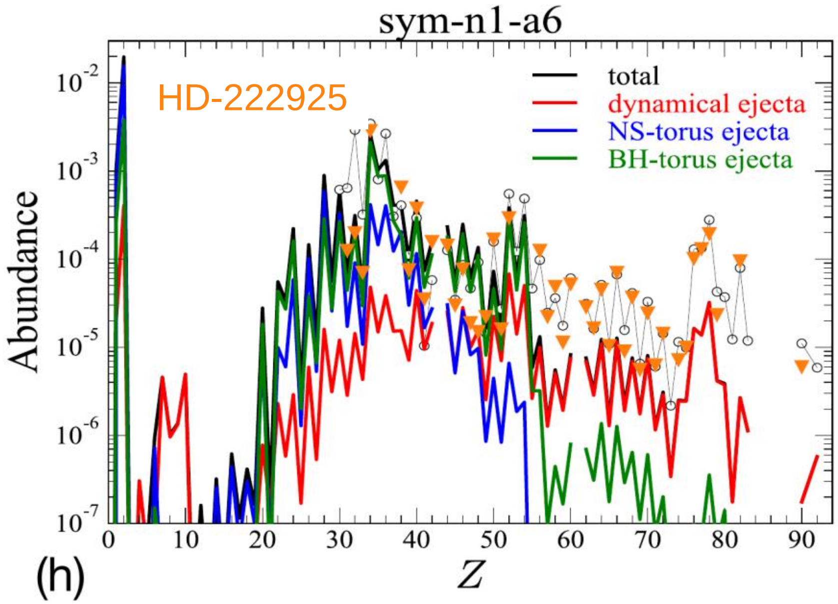
# Long term merger simulations

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

Just et al, ApJL, L12 (2023)

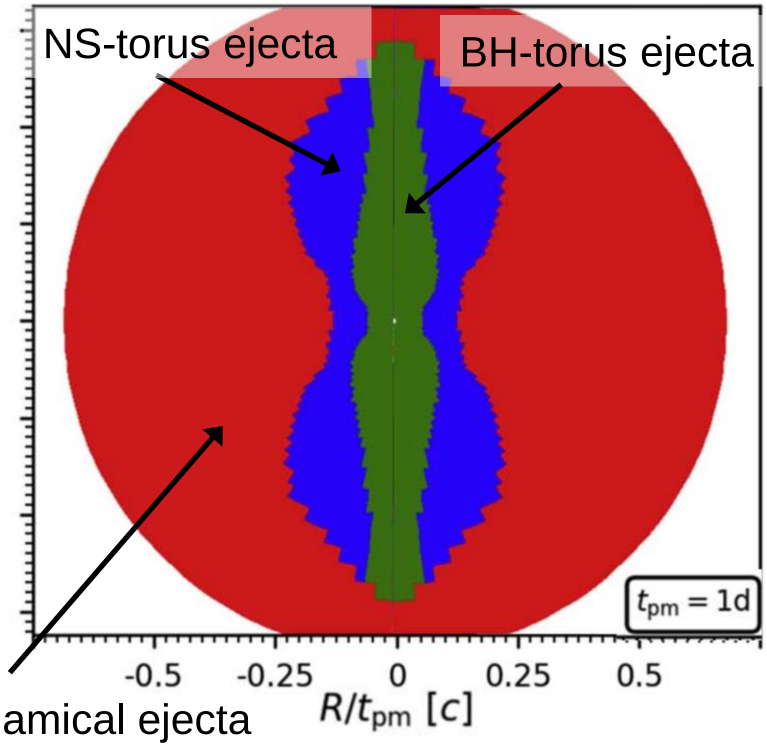




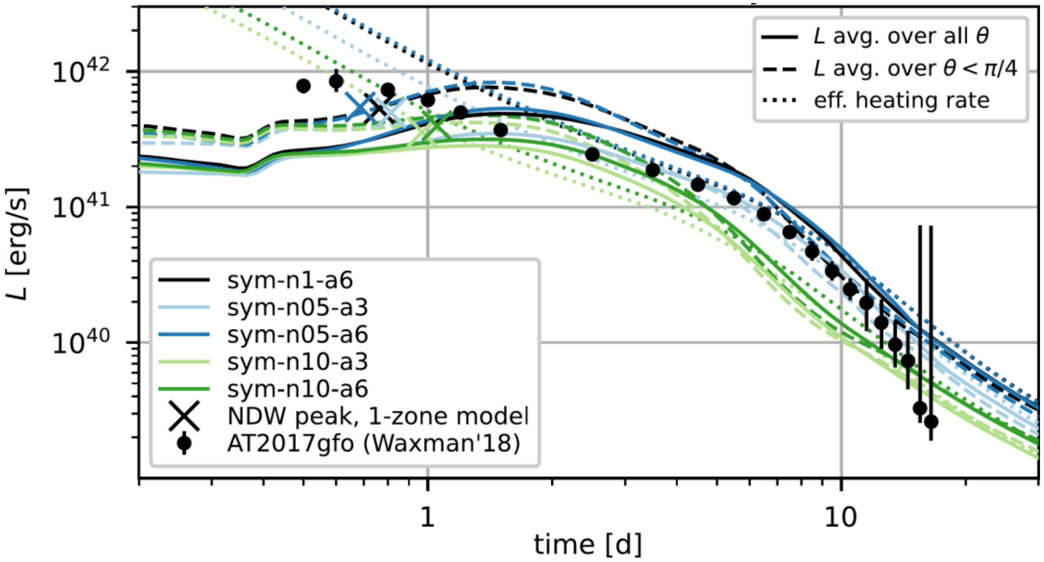


# End to end kilonova models

- 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



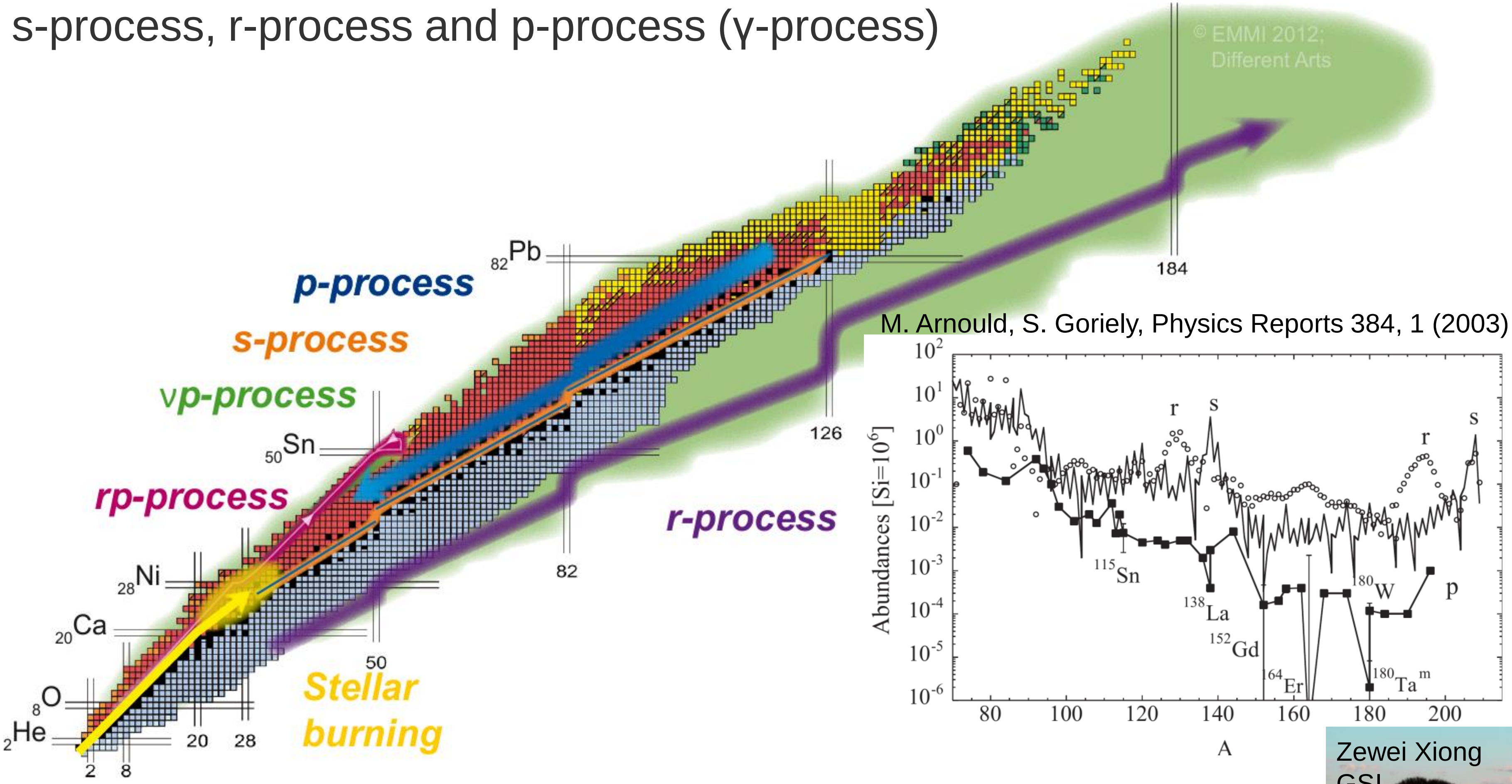
Dynamical ejecta



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)

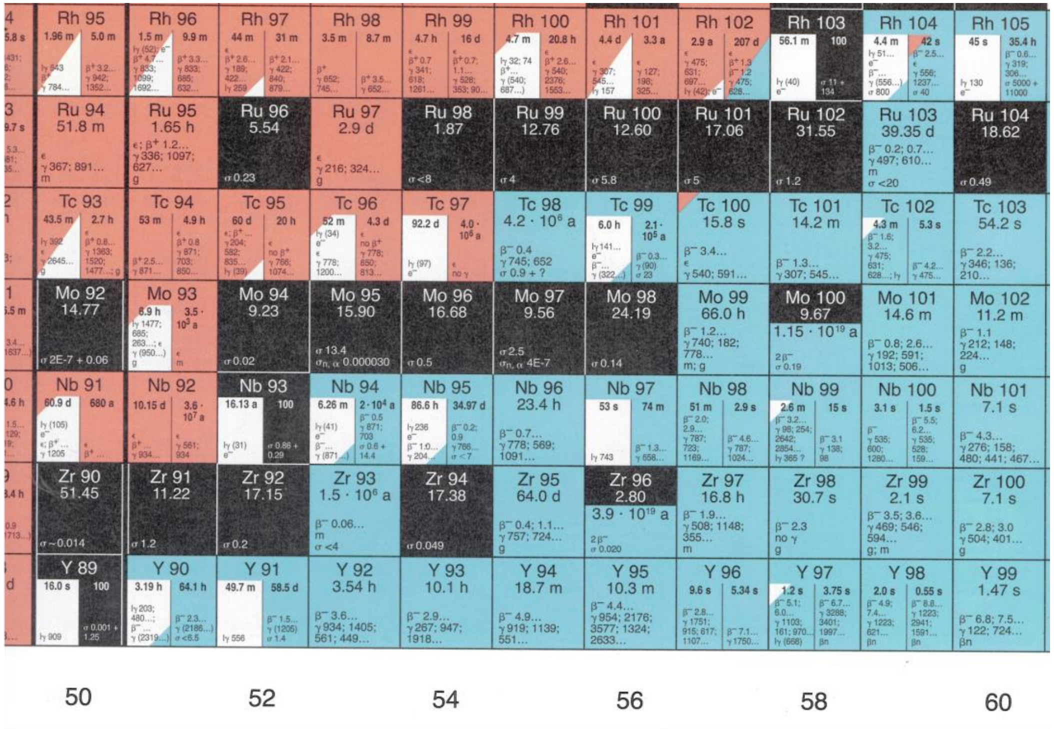


M. Arnould, S. Goriely, Physics Reports 384, 1 (2003)


Zewei Xiong
GSI

- The **$\nu r$-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 $\beta^-$ 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)
- $\nu p$-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 $\nu p$-process nor $\nu$-process (Hayakawa+2013, Sieverding+2018)

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

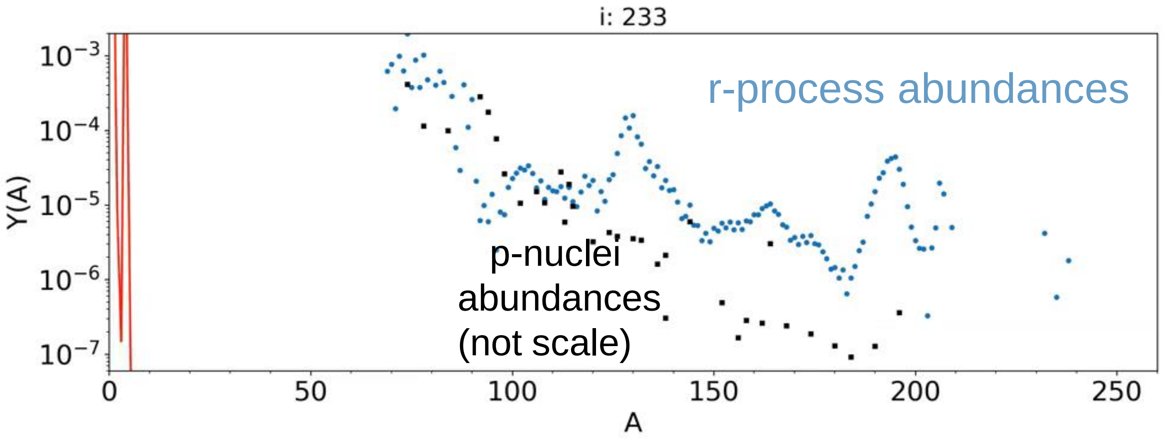
# r-process vs νr-process

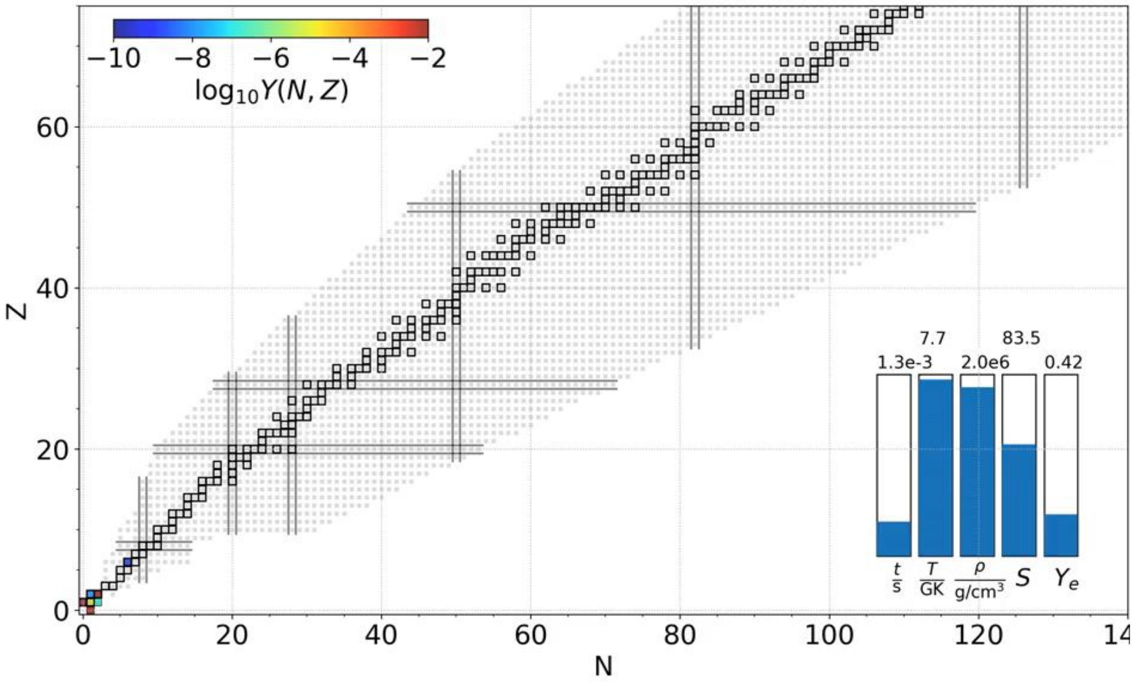
**Weak freeze-out**: proton-to-nucleon ratio determined by (anti)neutrino absorption and their inverses

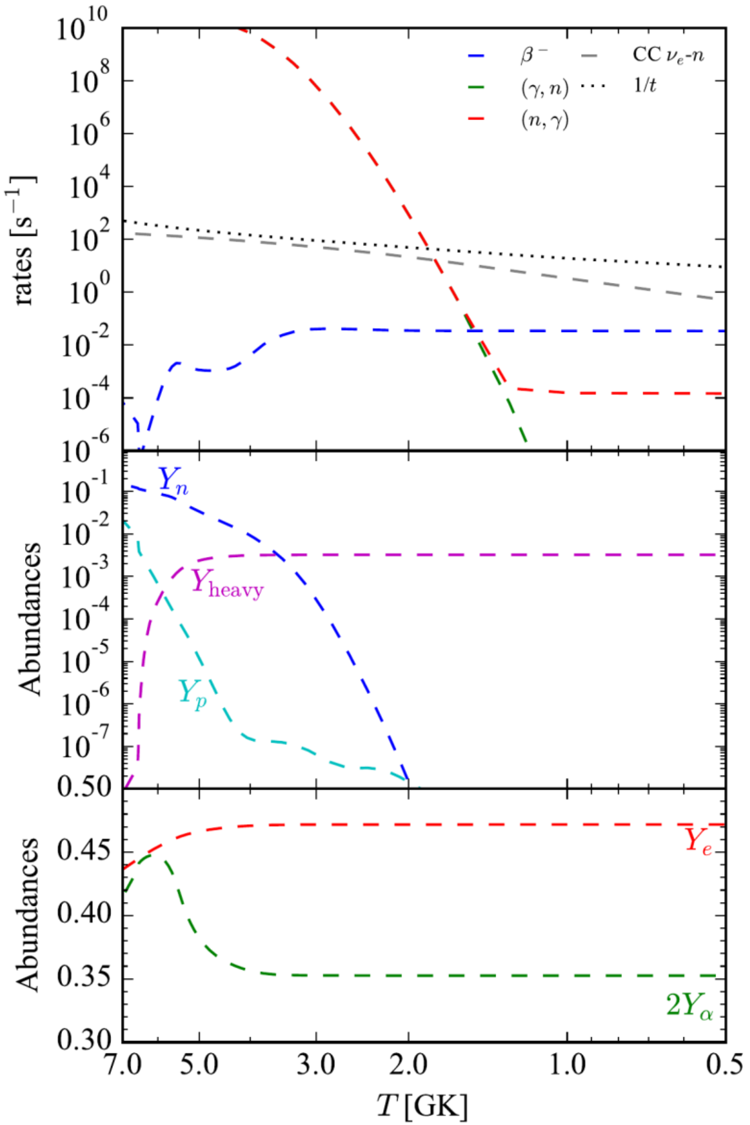
- **Seed production**: Charged particle reactions operating for $T \gtrsim 2\ GK$ to produce the seed nuclei and neutrons
- **Neutron-capture phase:** neutrons are captured on the available seed nuclei on a typical times of $\sim 1\ s$. Different equilibria are achieved:
  - $(n,\gamma) \rightleftarrows (\gamma,n)$ 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

- **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
  - $A(\nu_e, e^- X)\ X = n, p, \alpha$ speeds up 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.
  - Equilibrium between $A(\nu_e, e^- X)$ and $A(n,\gamma)$ determines final abundance

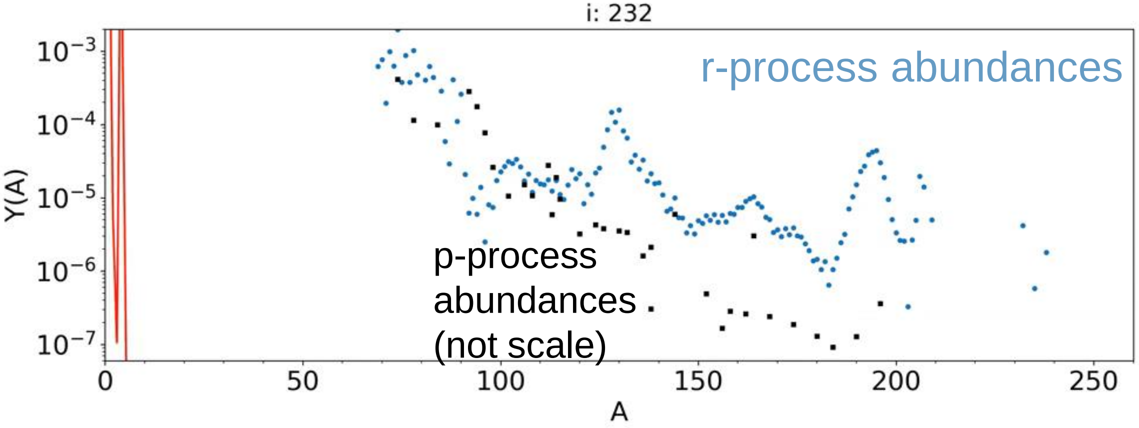
# Nucleosynthesis (no neutrino-nucleus)





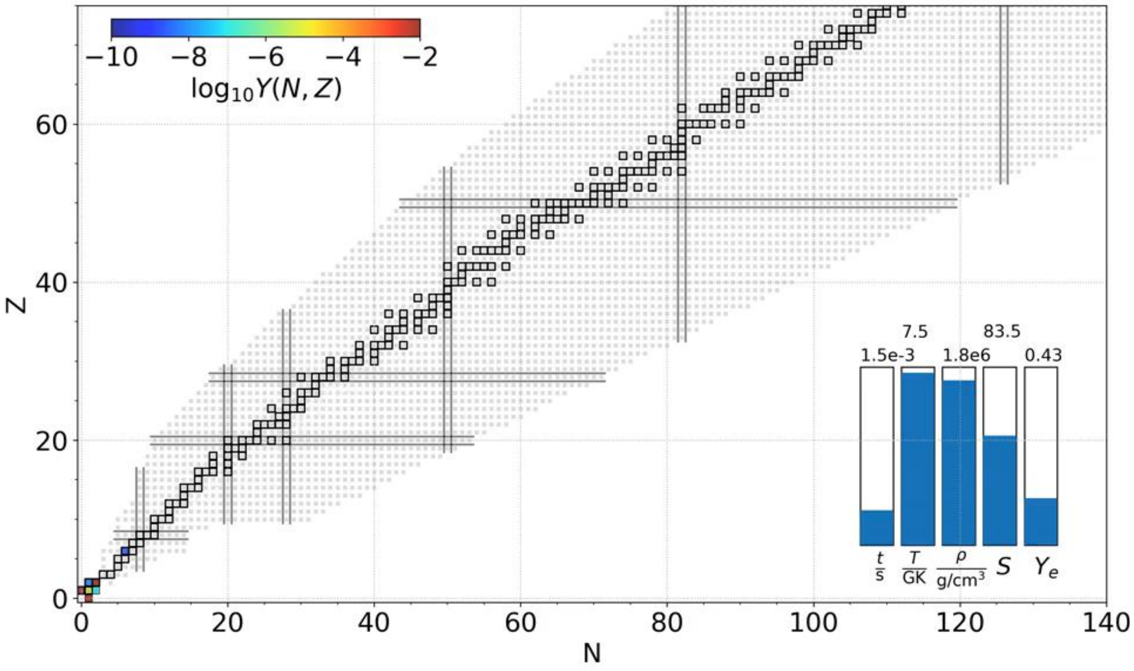


# Nucleosynthesis (with neutrino-nucleus)

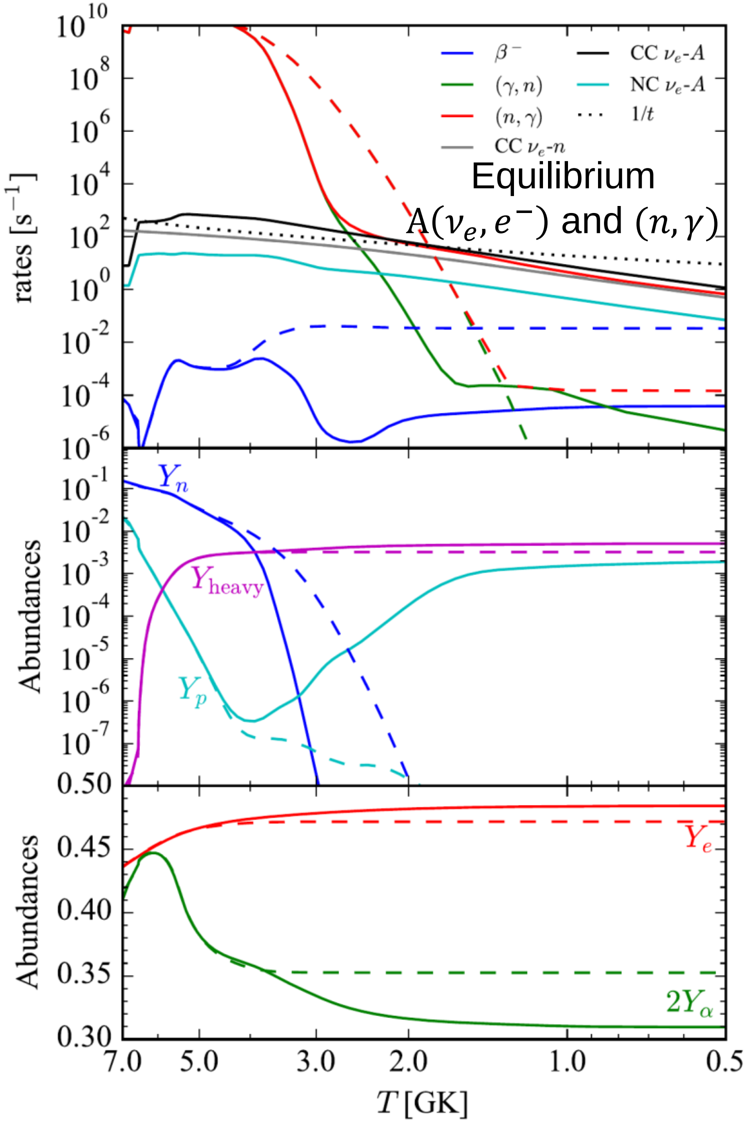


r-process abundances

p-process abundances (not scale)



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



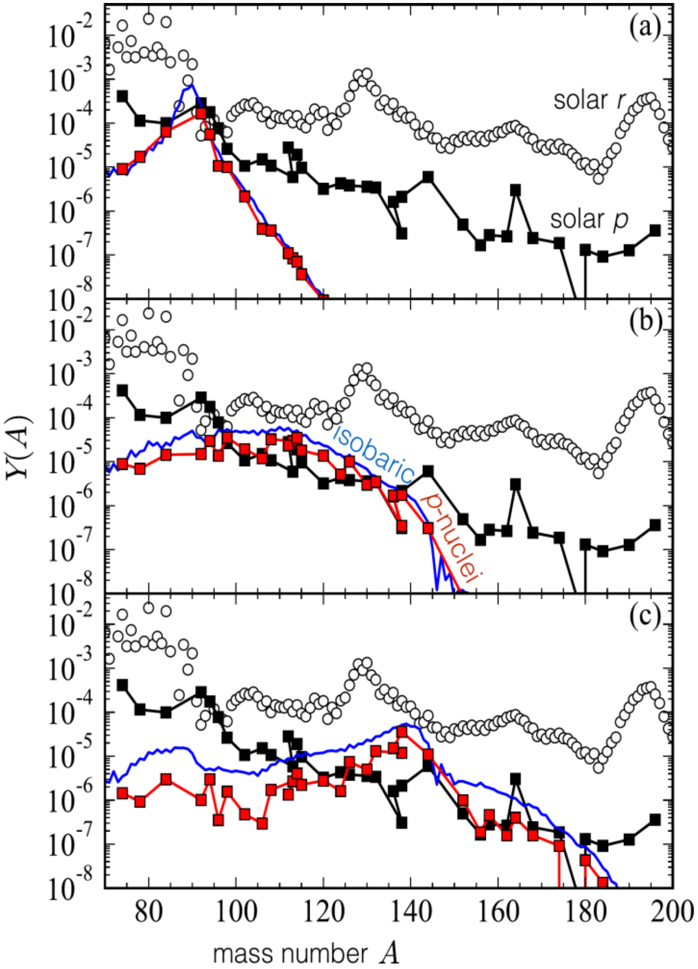
Equilibrium $A(\nu_e, e^-)$ and $(n, \gamma)$

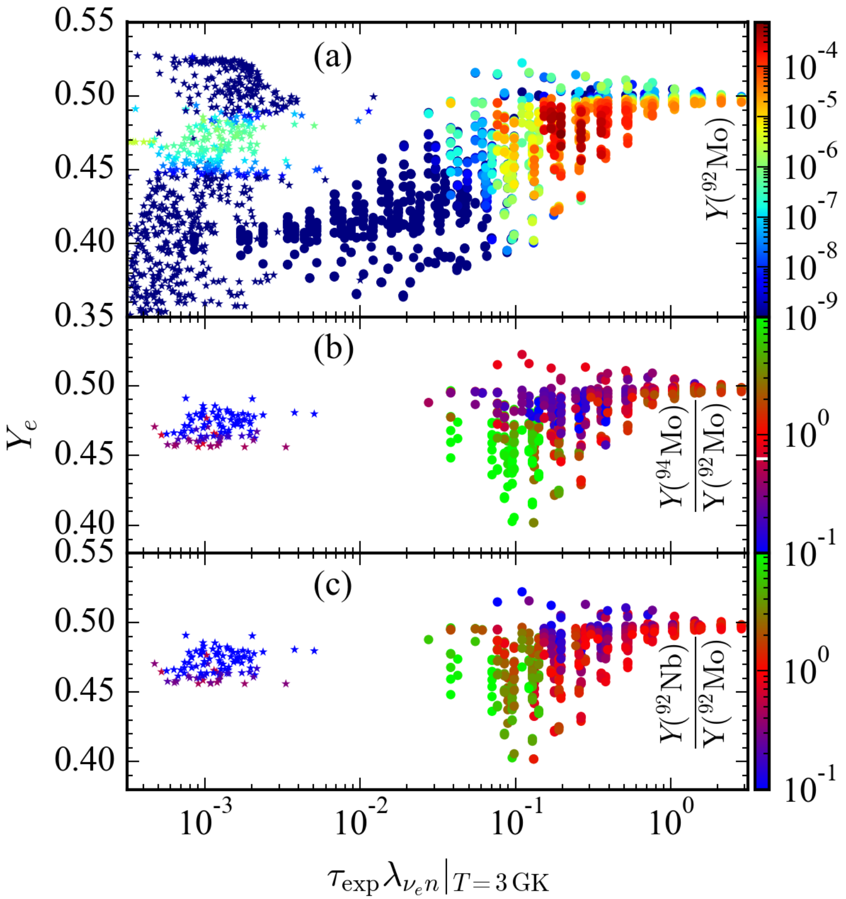
# Dependence on neutrino fluence

Increasing neutrino fluence allows to produce heavier p-nuclei

Dependence $Y_e$ and neutrino fluence

Stronger neutrino flux

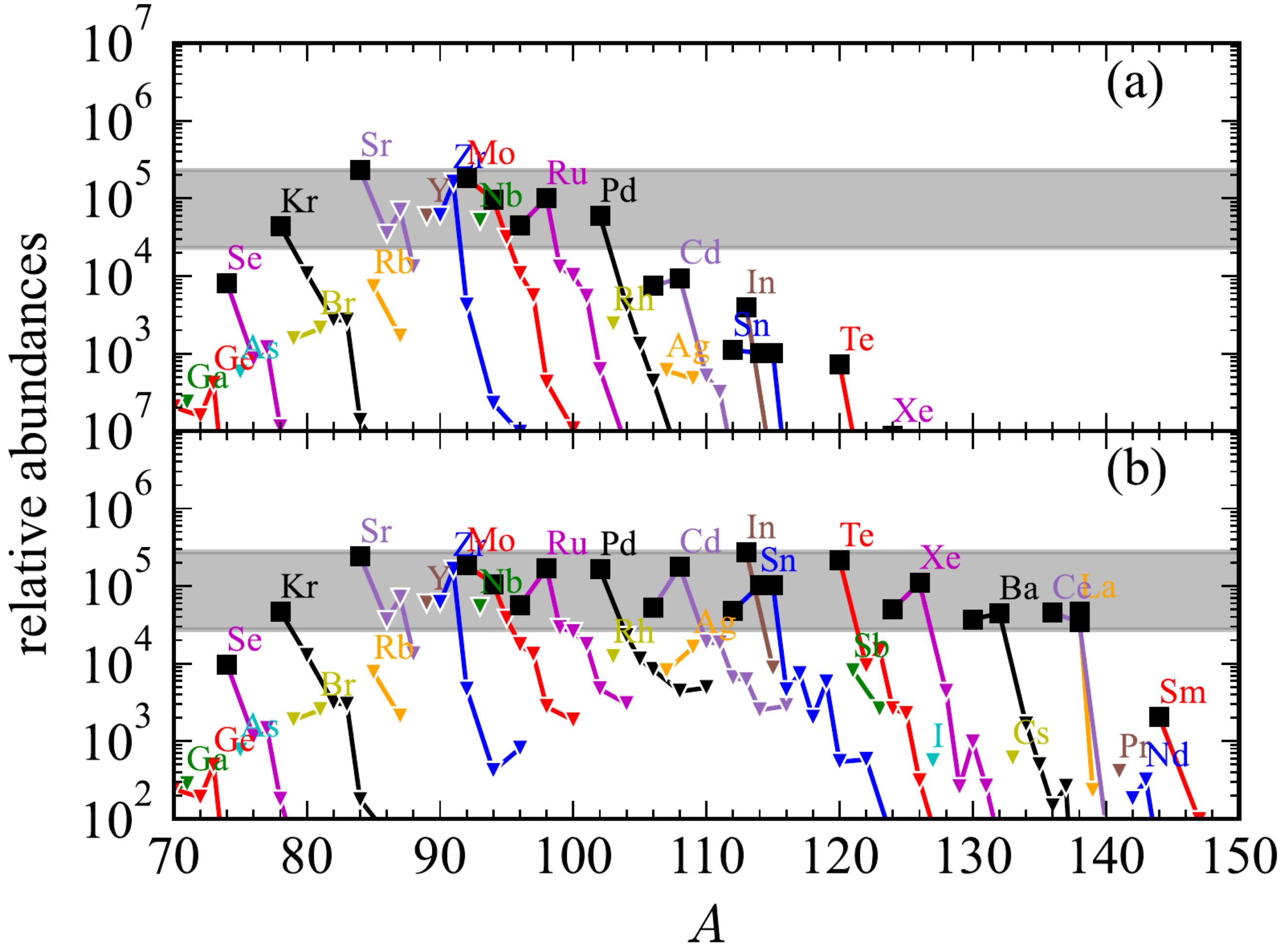




Current neutrino-hydrodynamical models are far from the necessary conditions

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 $\nu r$-process conditions

# Pions in neutron-star mergers

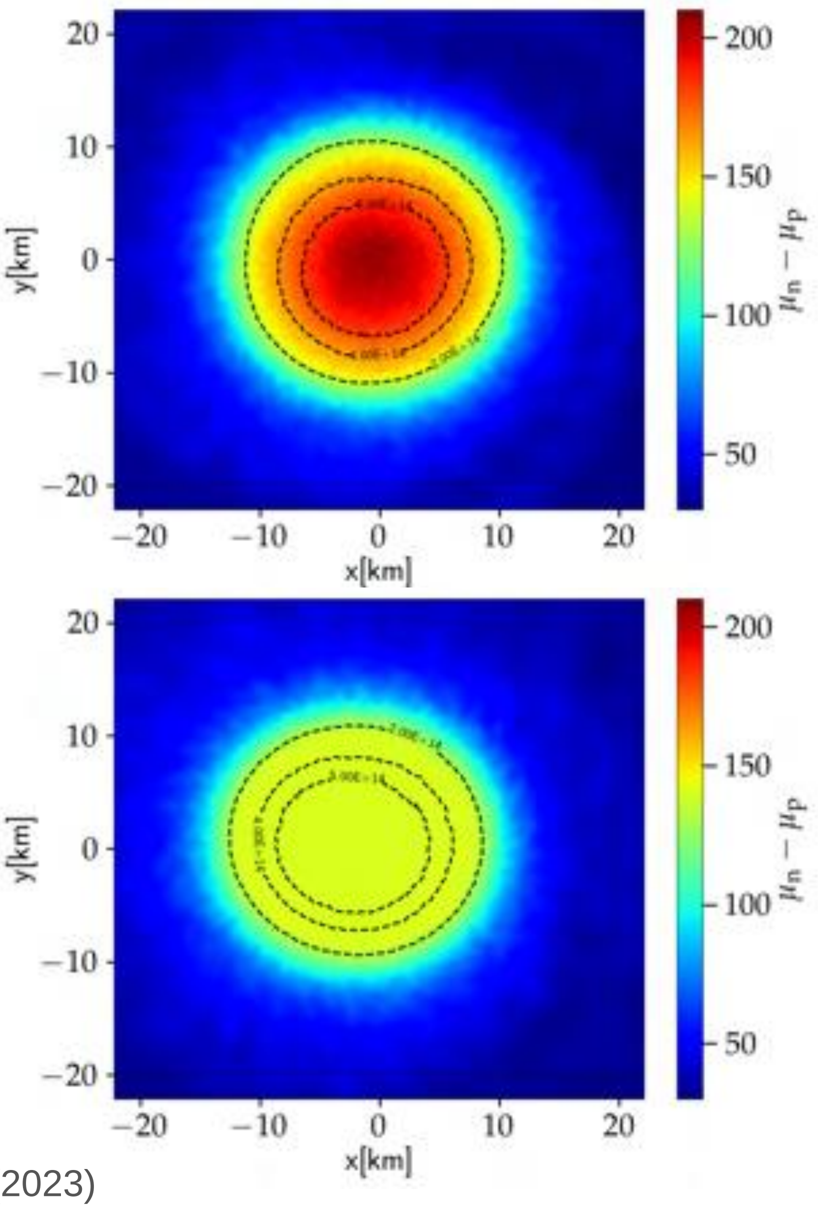
- Remnant has large temperatures and is very neutron-rich

$$\mu_n - \mu_p > m_\pi$$

- Pions included in EoS assuming non-interacting boson-gas in thermal and chemical equilibrium

$$\mu_{\pi^\pm} = \mp(\mu_n - \mu_p)$$

- Pions can form a condensate



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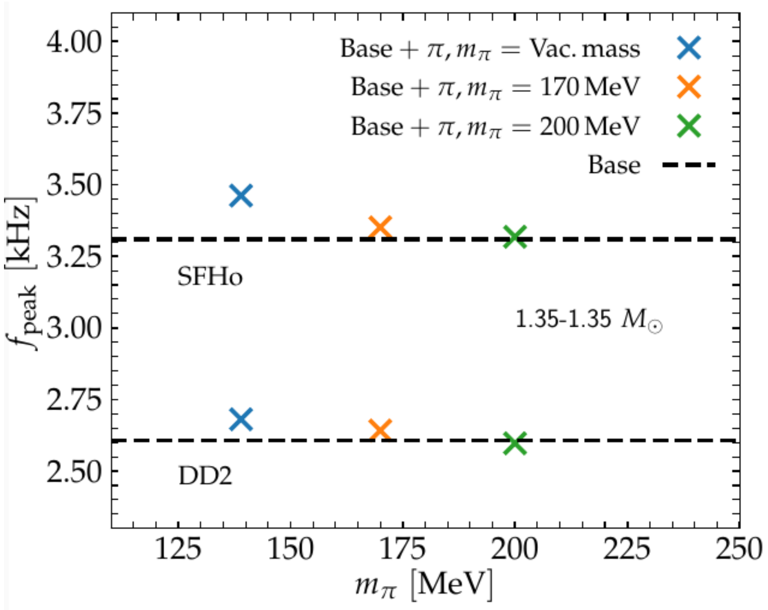
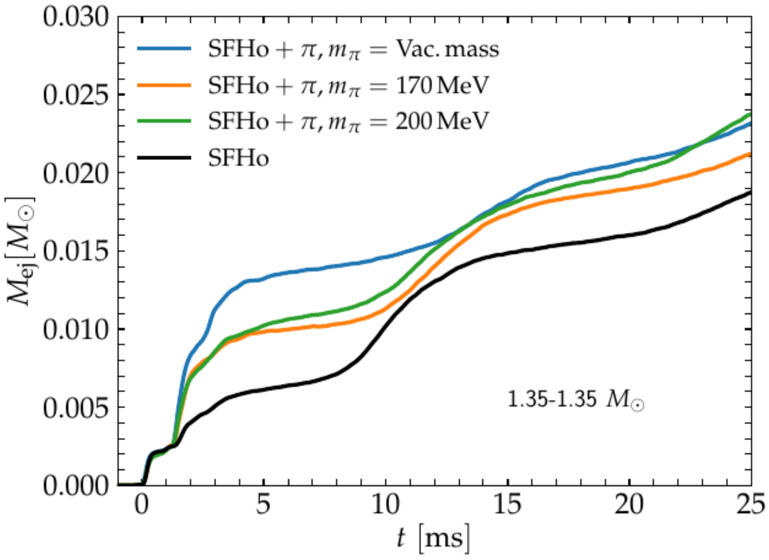
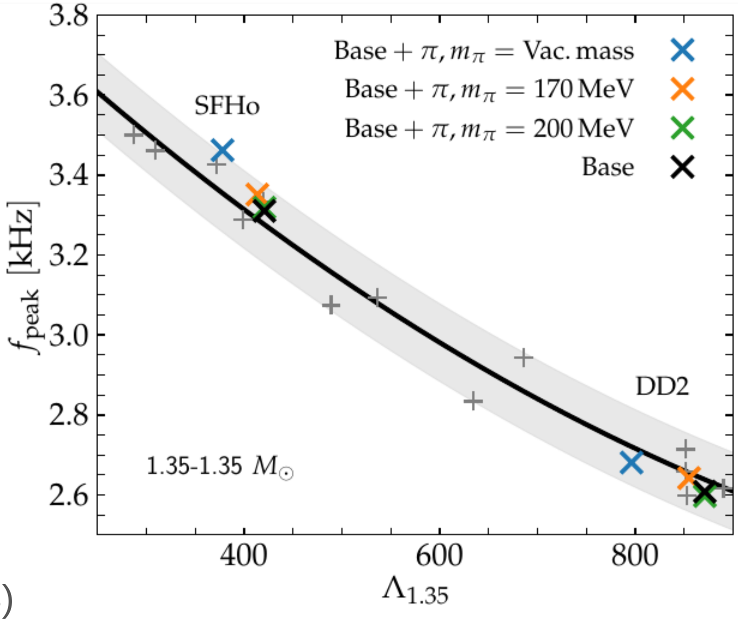
# Results

- Increase post-merger gravitational wave frequency by up to 150 Hz.
- Pronounced increase ejected mass







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# 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
- $\nu r$-process: new mechanism production p-nuclei

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GSI theory

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