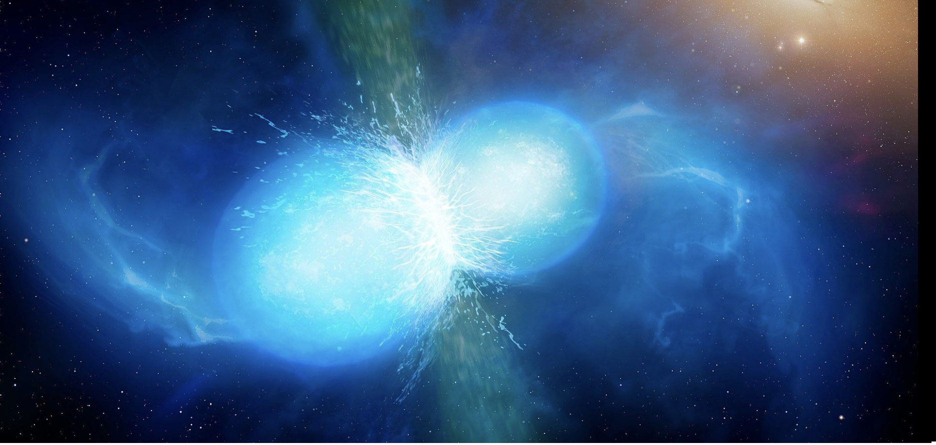
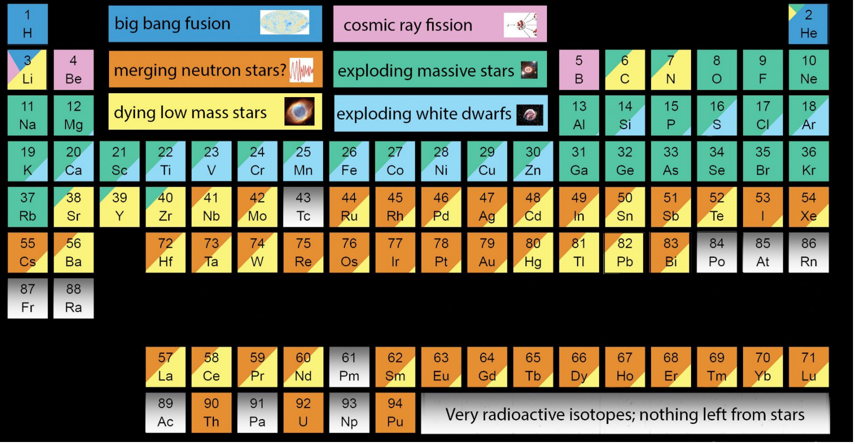
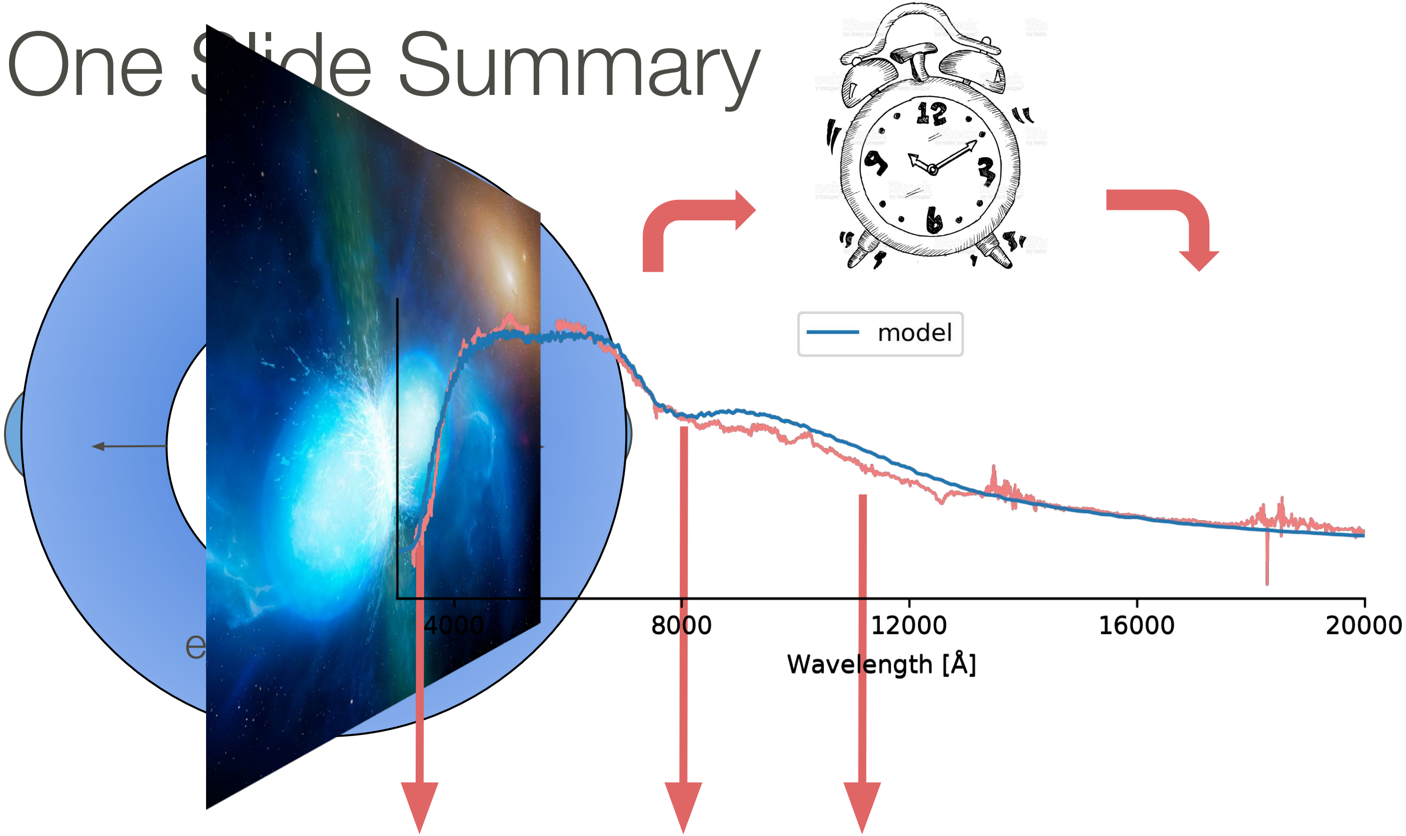




Electromagnetic Counterparts of Neutron Star Mergers: Signatures of Heavy r-Process Nucleosynthesis

Andreas Flörs (GSI)
Luke Shingles (GSI, QUB), Gerrit Leck (GSI), Gabriel Martínez-Pinedo (GSI)
Ricardo Ferreira da Silva (LIP)

One Slide Summary



ESO/VLT

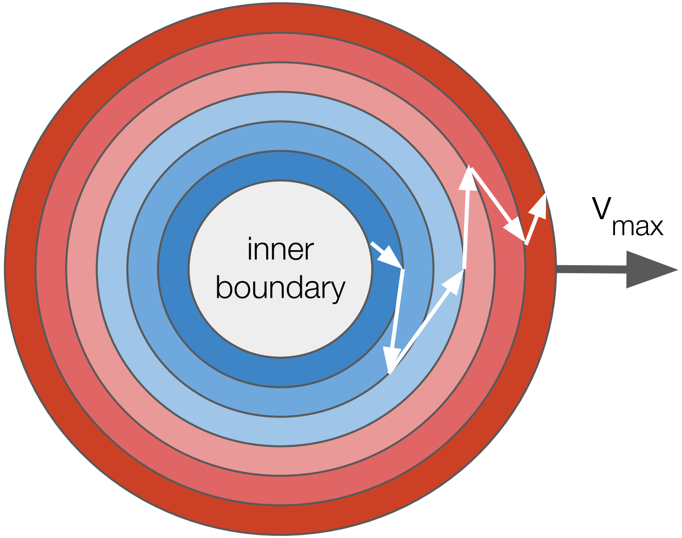
spectral signatures of r-process material?

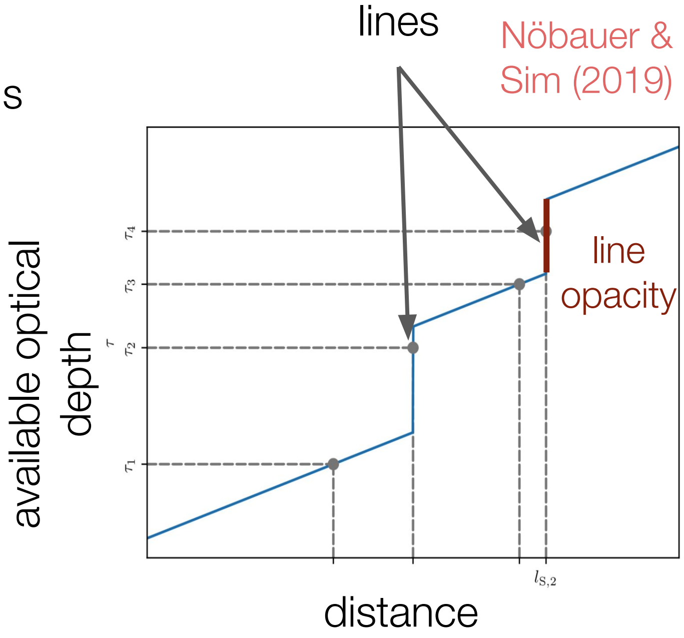
TARDIS

TARDIS!
Exploring supernovae made easy

TARDIS is a 1D open-source Monte-Carlo radiative transfer spectral synthesis code

→ Inner boundary: only early spectra possible
→ Sobolev approximation: requires energy levels + transitions





Nöbauer & Sim (2019)

Atomic Opacities (LTE)

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

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

Lower level number density

Oscillator strength

Transition wavelength

Partition function

Saha ionisation:

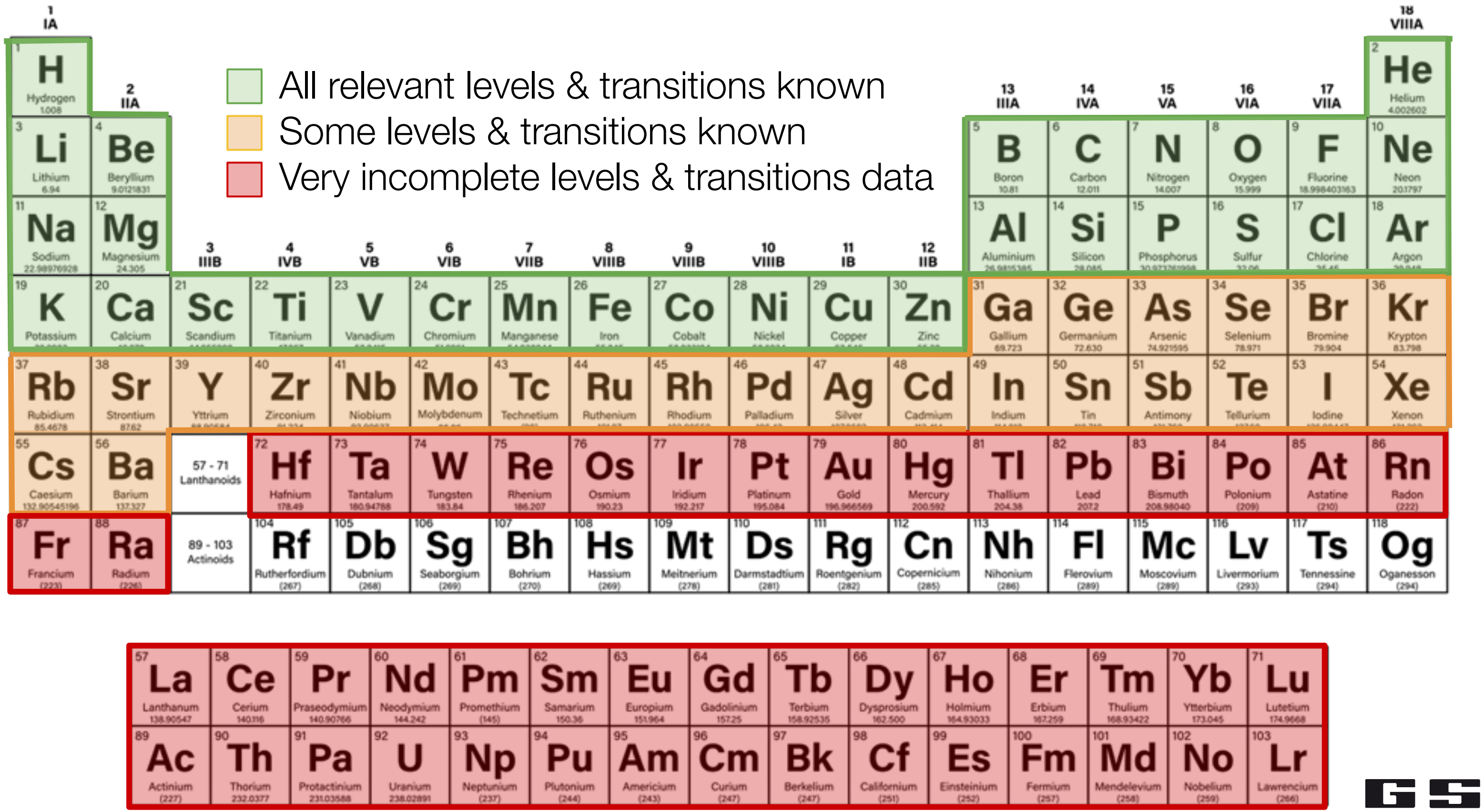
$$\frac{n^i}{n^{i-1}} = \frac{Z^i(T) g_e}{Z^{i-1}(T) n_e} e^{-(E_i - E_{i-1})/k_B T}$$

Ionisation energy

Boltzmann excitation:

$$n_l = \frac{g_l}{g_0} e^{-E_l/k_B T} n_0$$

Energy Levels - Opacity



🟩 All relevant levels & transitions known

🟧 Some levels & transitions known

🟥 Very incomplete levels & transitions data

Atomic Opacities: Level Energies

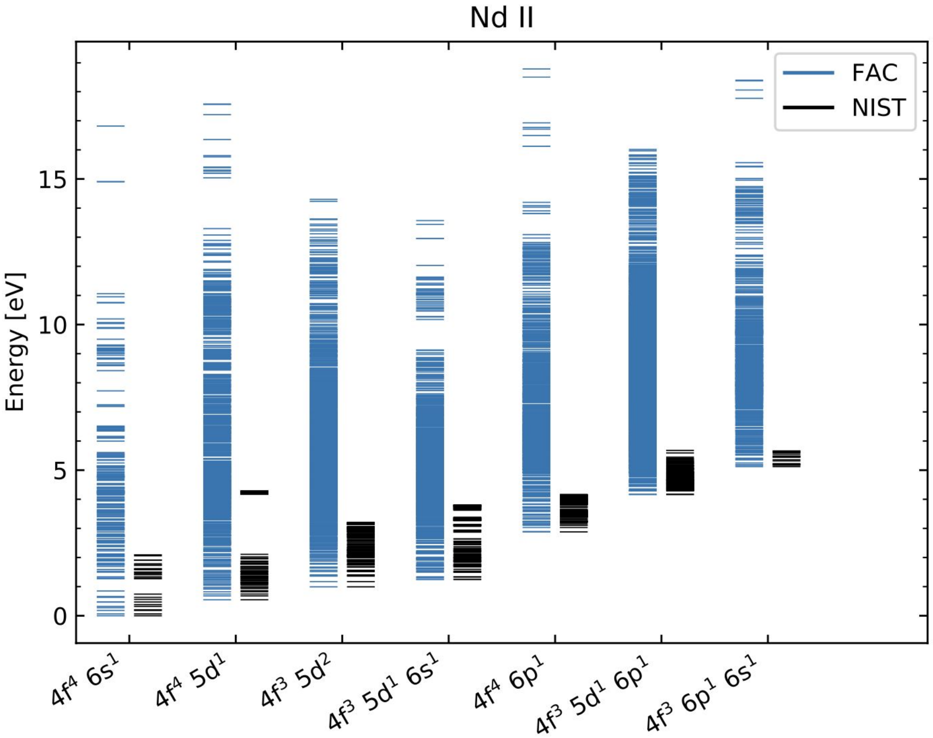
Energy corrections for each P-J and for each configuration

→ exact matching difficult due to mixing

→ shift to lowest measured level

Convergence of atomic data:

→ see presentation by Gerrit Leck (GSI)



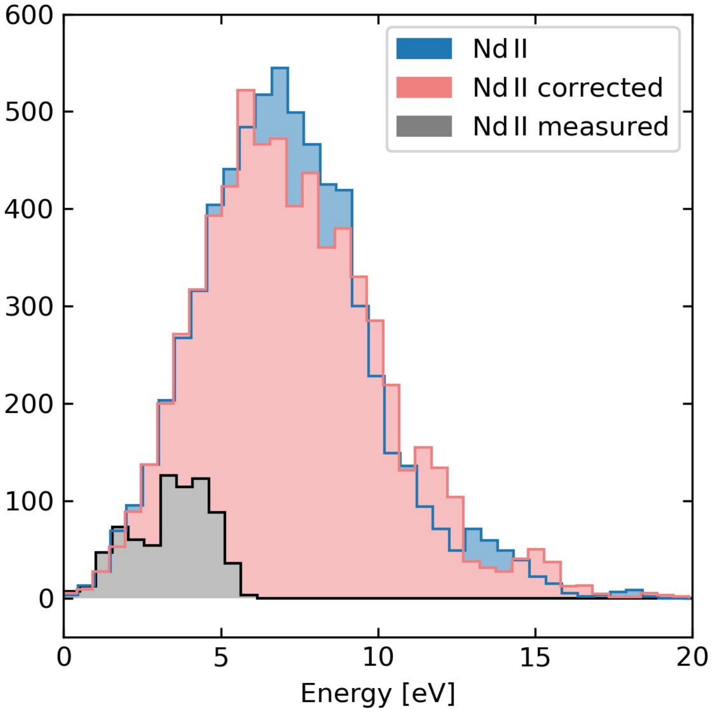
Atomic Opacities: Level Energies

Energy corrections for each P-J and for each configuration

→ exact matching difficult due to mixing

→ shift to lowest measured level

Density of low lying levels in agreement with measurements



Atomic Opacities: Ionisation Balance

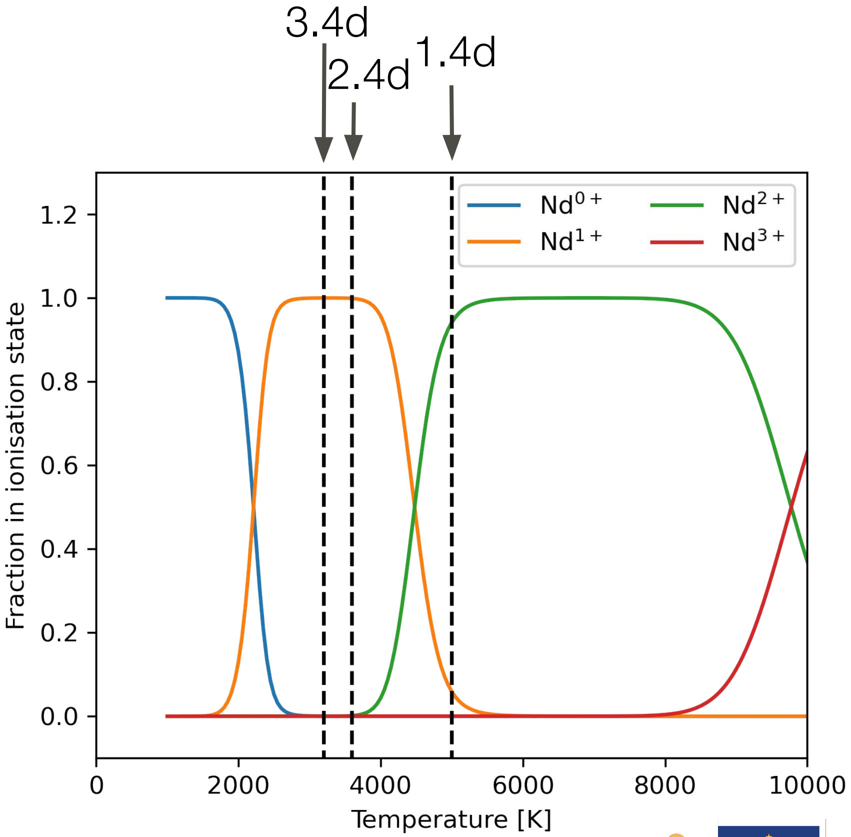
Lanthanides and actinides more highly ionised compared to the iron-group

→ early phases doubly ionised

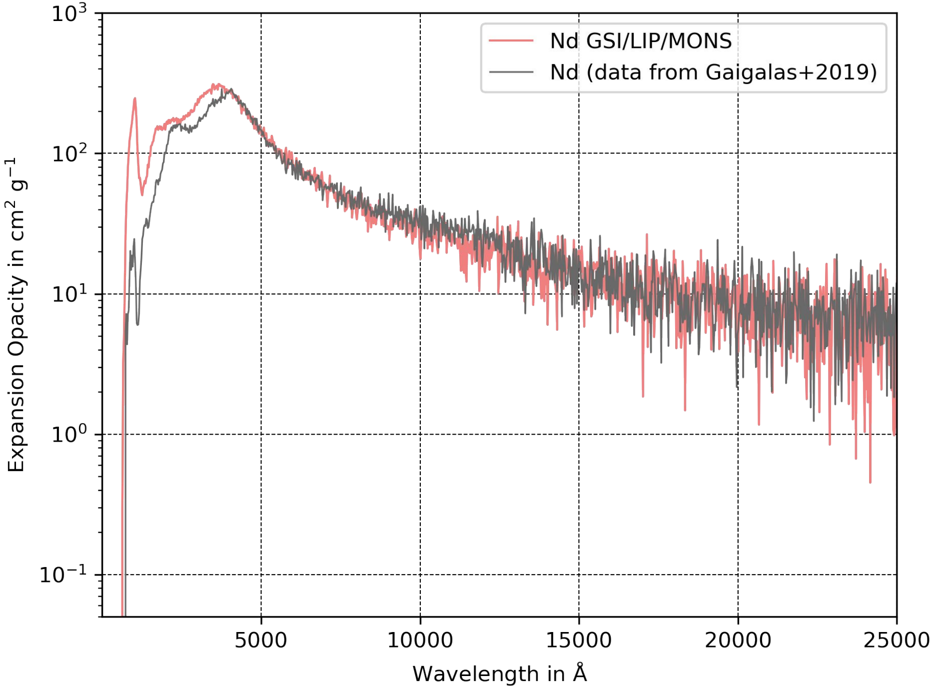
→ after ~2 days singly ionised

Singly ionised material has higher bound-bound opacity than doubly ionised material

→ ionisation transition showing up in the spectrum?



Atomic Opacities: Expansion Opacity



$\rho = 10^{-13}$ g/cm^3 T = 5000 K

very good agreement with published data from Gaigalas+2019

$$\kappa_{\exp}(\lambda) = \frac{1}{ct\rho}\sum_{l}\frac{\lambda_l}{\Delta\lambda}(1 - e^{-\tau_l})$$

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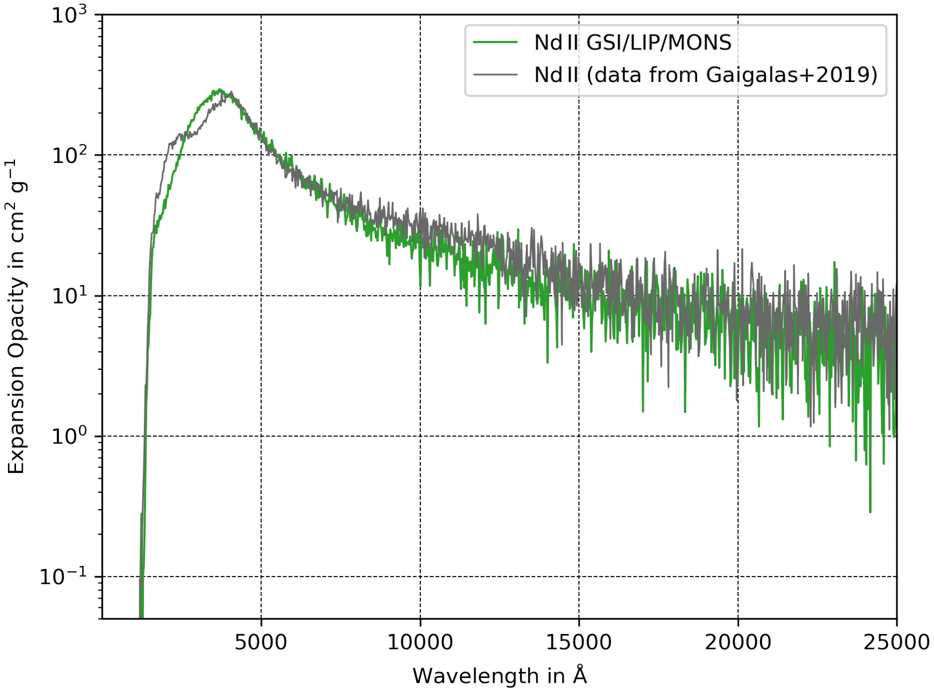
Atomic Opacities: Expansion Opacity



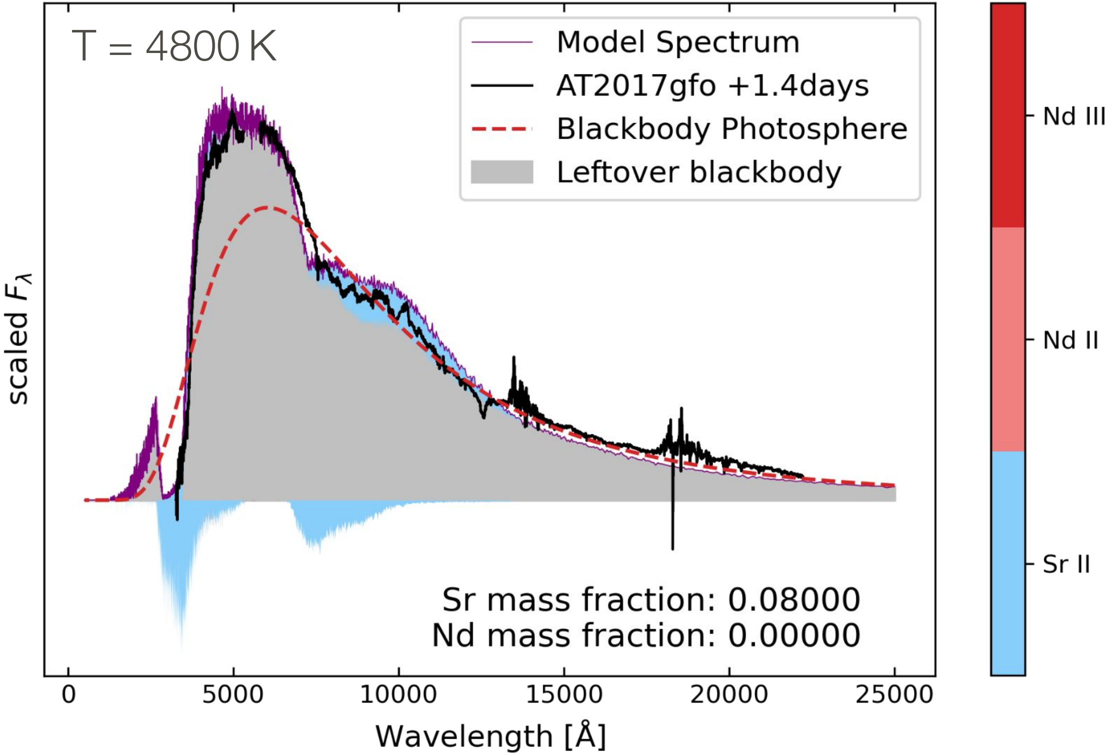
$\rho = 10^{-13}$ g/cm^3 T = 5000 K

very good agreement with published data from Gaigalas+2019

differences likely due to different atomic structure codes (FAC vs Hullac) and included configurations

$$\kappa_{\text{exp}}(\lambda) = \frac{1}{ct\rho} \sum_l \frac{\lambda_l}{\Delta\lambda}(1 - e^{-\tau_l})$$

Modelling a Nd Kilonova

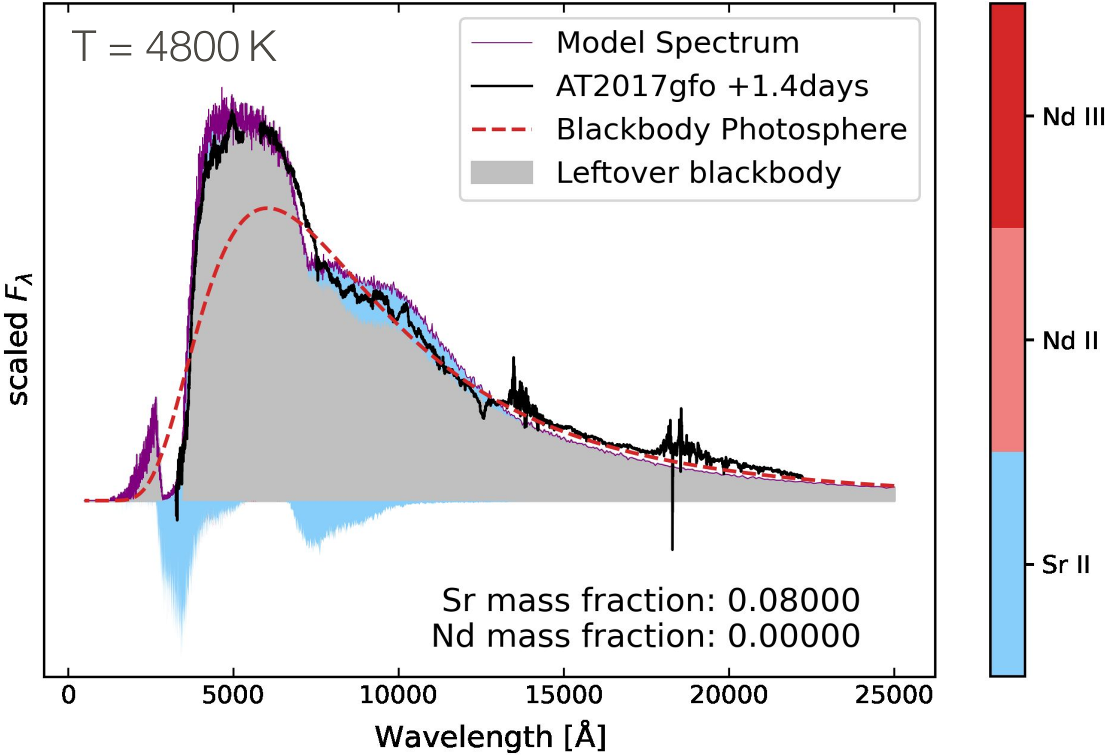


Exponential density profile

$$\rho(v, t_{\mathrm{exp}}) = \rho_0 \left(\frac{t_0}{t_{\mathrm{exp}}}\right)^3 \left(\frac{v}{v_0}\right)^{-\Gamma}$$

with power-law index Γ=3

Modelling a Nd Kilonova



Exponential density profile

$$\rho(v, t_{\text{exp}}) = \rho_0 \left(\frac{t_0}{t_{\text{exp}}}\right)^3 \left(\frac{v}{v_0}\right)^{-\Gamma}$$

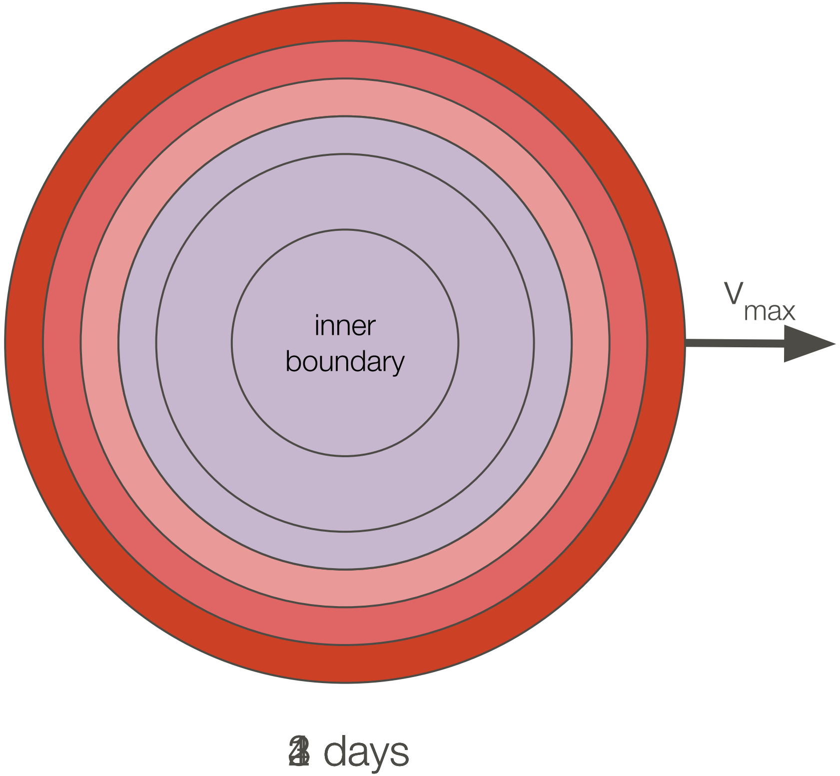
with power-law index $\Gamma=3$

Increase the Nd mass fraction from 10^{-5} to 10^{-1}

Low abundance:
only line blanketing

High abundance:
line blanketing in addition to spectral features in the NIR

Kilonova Tomography



Ejecta become transparent over time
→ photosphere moves inwards (in velocity space)

But composition of outer layers remains the same!

Fix properties of outermost layer (density, composition) by modelling the first observed spectrum

Find best solution for inner layers by modelling a later spectrum and keeping outer layers fixed

→ This can tell us how much heavy r-process material can be in the kilonova

Atomic Opacities (NLTE)

Late phases (> 1-2 weeks): electron–ion collisional excitation rates << radiative decay rates
→ LTE no longer valid → non-LTE
→ need to solve statistical equilibrium equations

$$
\begin{aligned}
\frac{dn_{m,i}}{dt} = & \overset{\text{ionisation into}}{\sum_j n_{m-1,j}\Gamma_{m-1,j\to m,i}} + \overset{\text{recombination into}}{\sum_j n_{m+1,j}\alpha_{m+1,j\to m,i}n_e} + \overset{\text{transitions into}}{\sum_{j\neq i} n_{m,j}T_{j,i}} \\
& \overset{\text{out}}{-\, n_{m,i}} \left(\overset{\text{transitions}}{\sum_{j\neq i} T_{i,j}} + \overset{\text{ionisation}}{\sum_j \Gamma_{m,i\to m+1,j}} + \overset{\text{recombination}}{\sum_j \alpha_{m,i\to m-1,j}} \right) .
\end{aligned}
$$

with $T_{i,j}$ including

$$
\begin{aligned}
T_{u,l} &= \overset{\substack{\text{thermal electron-ion}\\ \text{collisions}\\ \downarrow}}{C_{u,l}^{\text{thermal}}} + C_{u,l}^{\text{non-thermal}} + \overset{\substack{\text{spontaneous photon}\\ \text{emission}\\ \swarrow}}{T_{u,l}^{\text{spont}}} + T_{u,l}^{\text{stim}} \xleftarrow{\substack{\text{stimulated photon}\\ \text{emission}}} \\
T_{l,u} &= C_{l,u}^{\text{thermal}} + \underset{\substack{\nearrow\\ \text{non-thermal electron-ion}\\ \text{collisions}}}{C_{l,u}^{\text{non-thermal}}} + T_{l,u}^{\text{abs}} \xleftarrow{\text{photon absorption}}
\end{aligned}
$$

Summary

Spectral modelling of AT2017gfo (and future events) allows us to learn about r-process production sites

LTE modelling requires knowledge about energy levels and radiative transitions
→ very limited data available so far, no data for actinides

Calibration of computed atomic data essential - not possible for actinides

We computed atomic data for all elements from Zr to U → currently calibrating the data

Late-phase modelling requires even more atomic data
→ experimental input extremely important

We have evidence for r-process material in AT2017gfo
→ abundance tomography can tell us how much

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