







1 H	big bang fusion 										cosmic ray fission 										2 He																			
3 Li	4 Be	merging neutron stars? 										exploding massive stars 										5 B	6 C	7 N	8 O	9 F	10 Ne													
11 Na	12 Mg	dying low mass stars 										exploding white dwarfs 										13 Al	14 Si	15 P	16 S	17 Cl	18 Ar													
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr																							
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe																							
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn																						
87 Fr	88 Ra																																							
																				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu						
																				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	Very radioactive isotopes; nothing left from stars														

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

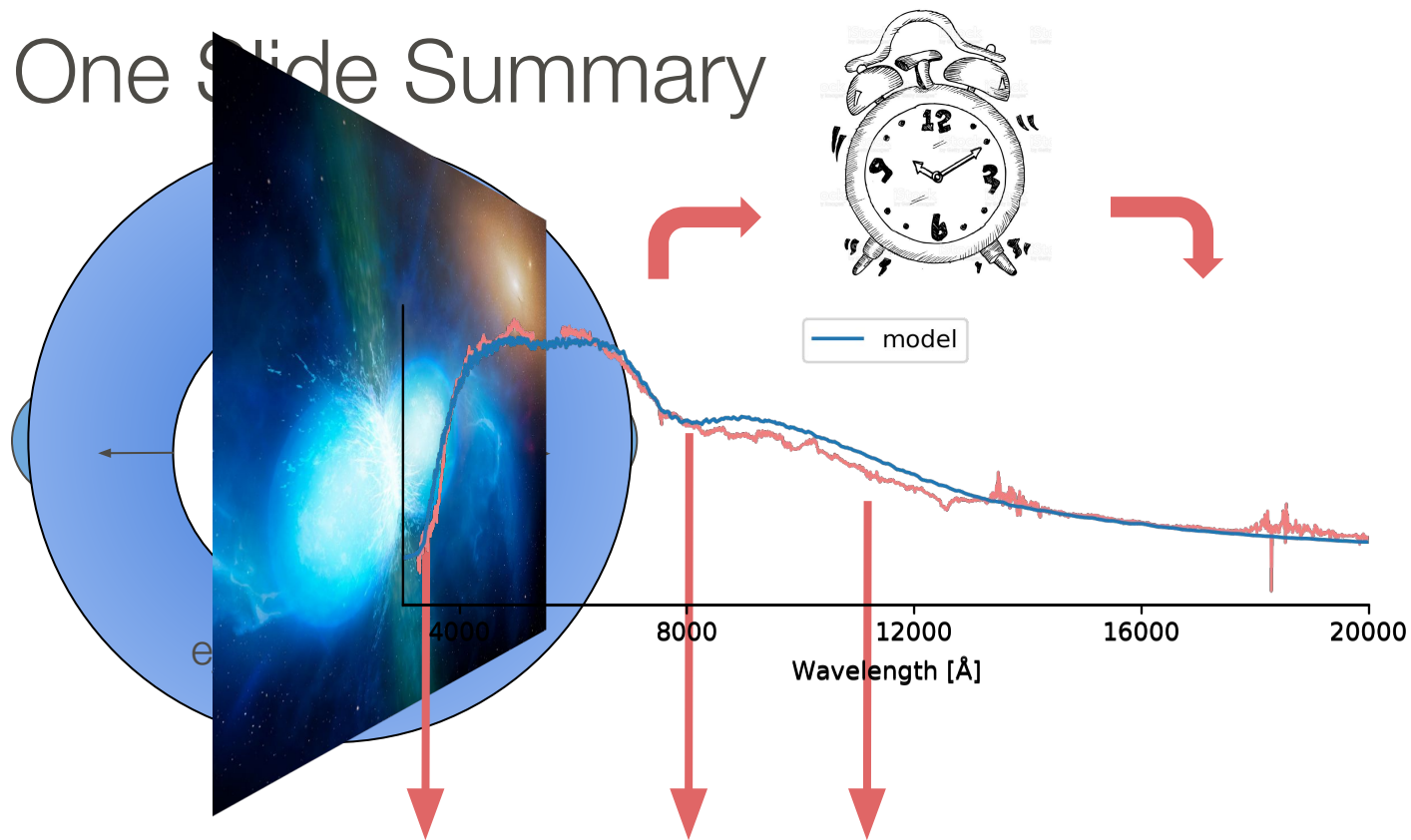
Andreas Flörs (GSI)

Luke Shingles (GSI, QUB), Gerrit Leck (GSI), Gabriel Martínez-Pinedo (GSI)

Ricardo Ferreira da Silva (LIP)



One Slide Summary



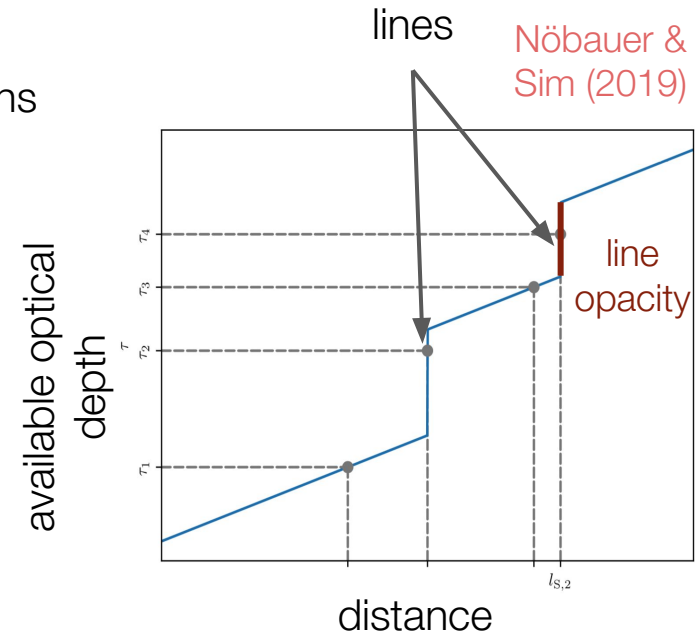
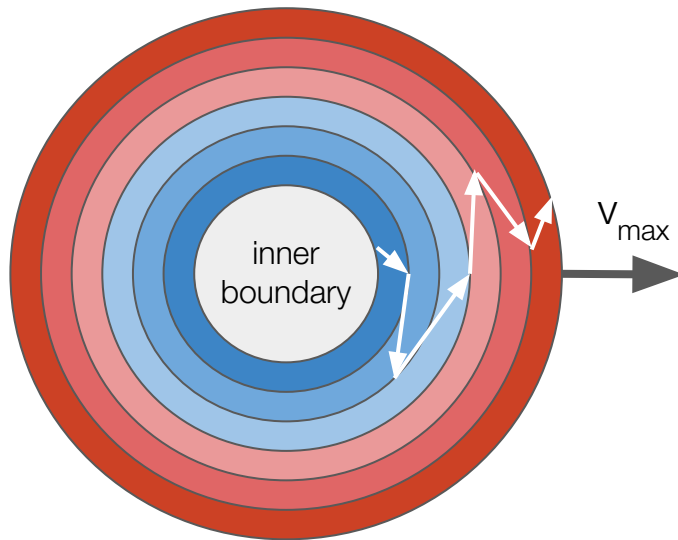
ESO/VLT

spectral signatures of r-process material?

TARDIS

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

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



Atomic Opacities (LTE)

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

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

Lower level number density

Oscillator strength

Transition wavelength

Saha ionisation:

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

Boltzmann excitation:

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

Energy Levels - Opacity

<div><div></div> All relevant levels & transitions known</div> <div><div></div> Some levels & transitions known</div> <div><div></div> Very incomplete levels & transitions data</div>																																																																																																																																																																																																																																
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- All relevant levels & transitions known
- Some levels & transitions known
- Very incomplete levels & transitions data

57 La Lanthanum 138.90547	58 Ce Cerium 140.12	59 Pr Praseodymium 140.90768	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93033	68 Er Erbium 167.259	69 Tm Thulium 168.93422	70 Yb Ytterbium 173.045	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.0377	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (260)



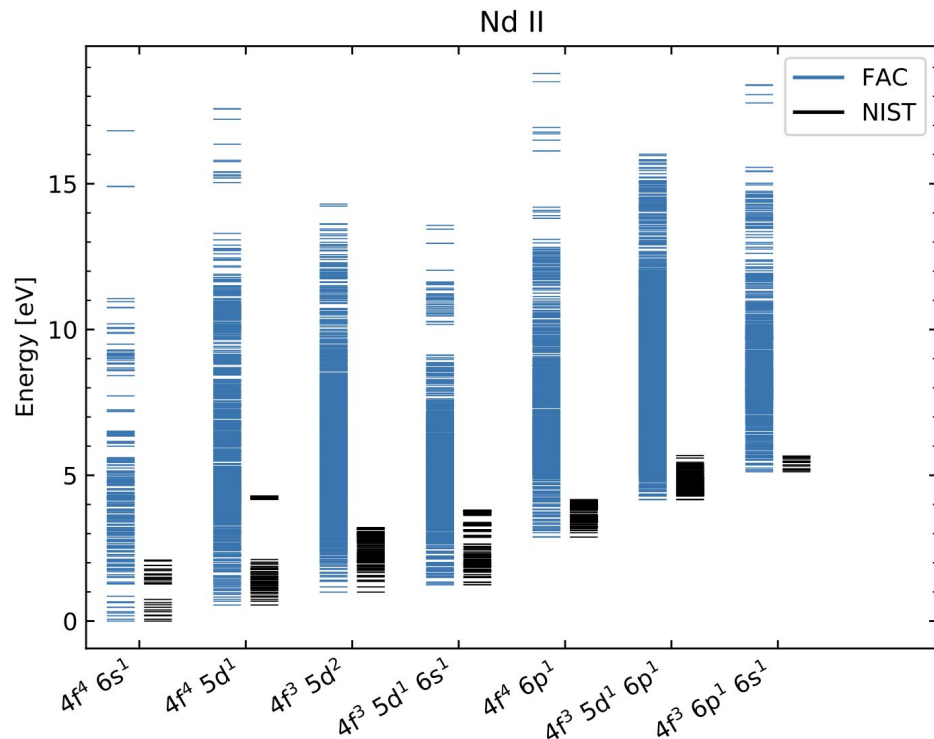
Atomic Opacities: Level Energies

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)

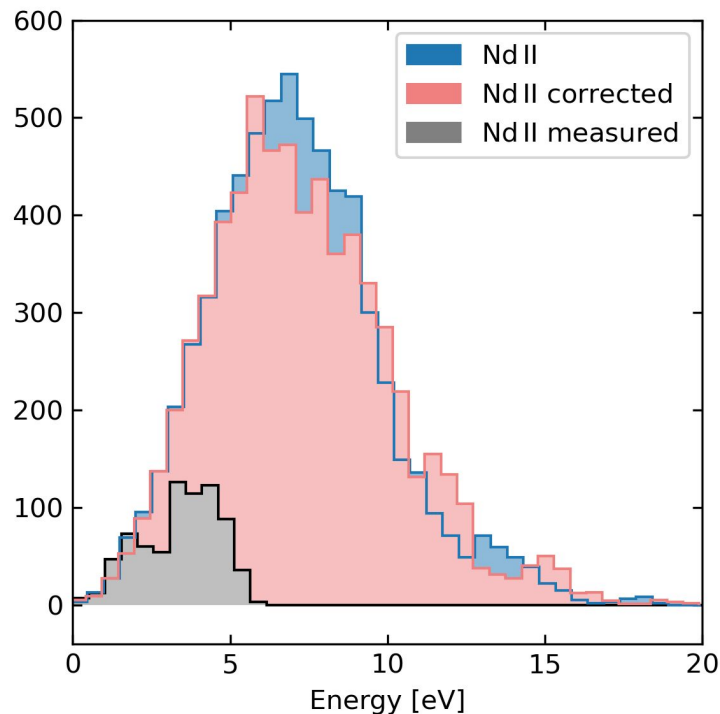


Atomic Opacities: Level Energies

Energy corrections for each P-J and for each configuration

- exact matching difficult due to mixing
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Density of low lying levels in agreement with measurements



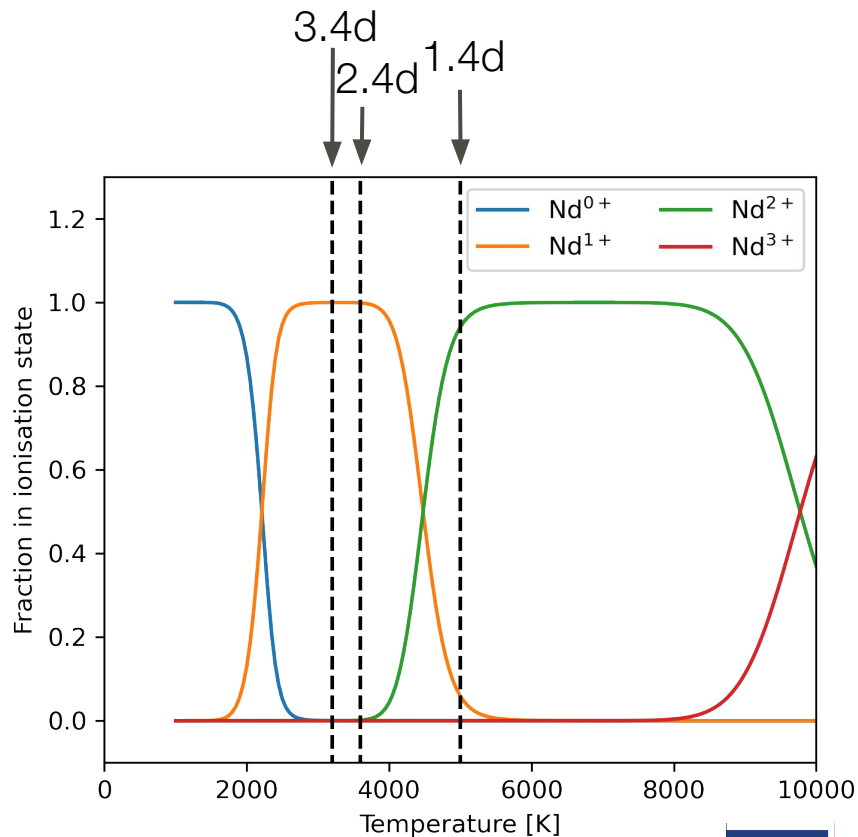
Atomic Opacities: Ionisation Balance

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

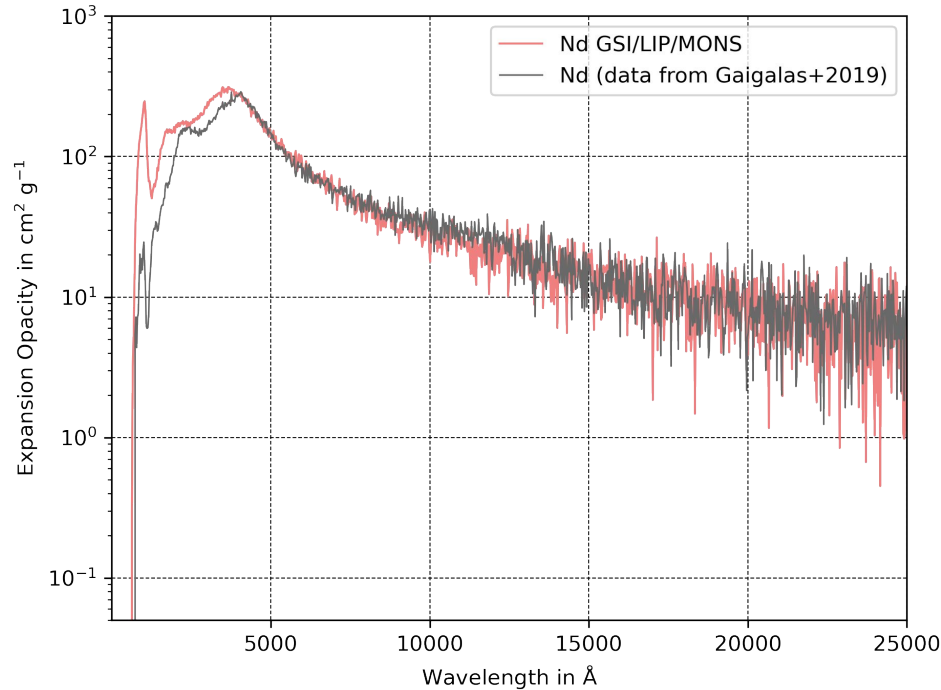
- early phases doubly ionised
- after ~2 days singly ionised

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

- ionisation transition showing up in the spectrum?



Atomic Opacities: Expansion Opacity



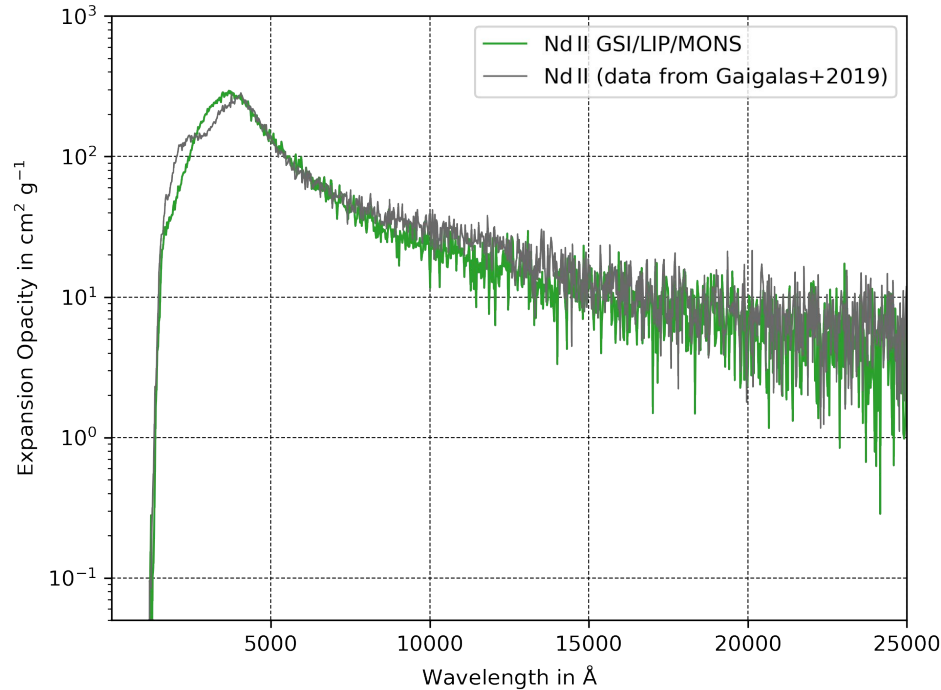
very good agreement with published data
from Gaigalas+2019

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

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



Atomic Opacities: Expansion Opacity



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

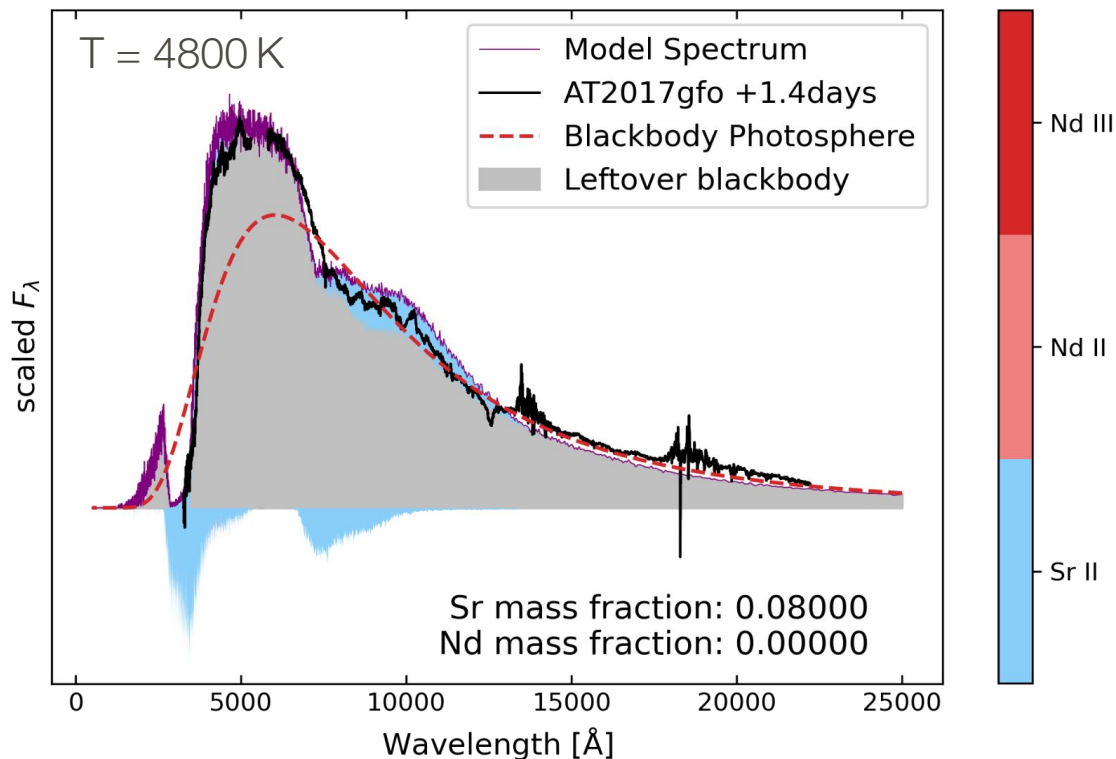
very good agreement with published data from Gaigalas+2019

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

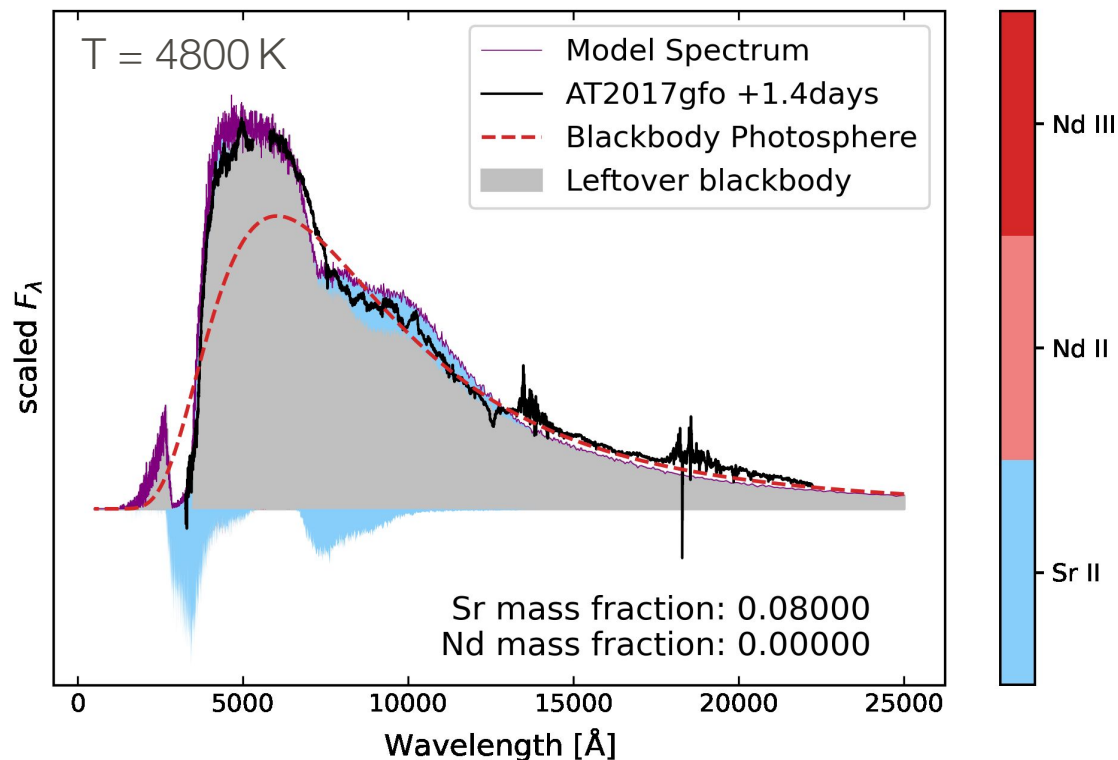


Exponential density profile

$$\rho(\nu, t_{\text{exp}}) = \rho_0 \left(\frac{t_0}{t_{\text{exp}}} \right)^3 \left(\frac{\nu}{\nu_0} \right)^{-\Gamma}$$

with power-law index $\Gamma=3$

Modelling a Nd Kilonova



Exponential density profile

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

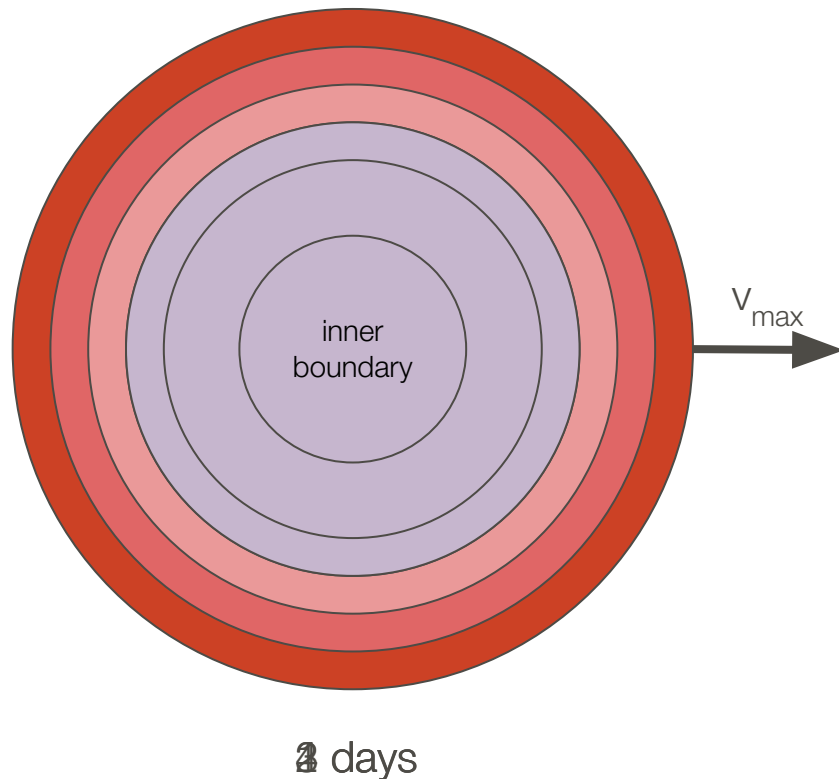
with power-law index $\Gamma=3$

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 \ll radiative decay rates

→ LTE no longer valid → non-LTE

→ need to solve statistical equilibrium equations

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

with $T_{i,j}$ including

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

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