Multi-component Ejecta and Time-Evolving Elemental Abundances in the GW170817 Kilonova with SPARK

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6 September 2023 | Stockholm, Sweden

MEGA
McGill Extreme Gravity & Accretion

I'll be focusing on results from this paper (SPARK II):

arXiv: 2308.16796

[Submitted on 31 Aug 2023]

Spectroscopic r-Process Abundance Retrieval for Kilonovae II: Lanthanides in the Inferred Abundance Patterns of Multi-Component Ejecta from the GW170817 Kilonova

Nicholas Vieira, John J. Ruan, Daryl Haggard, Nicole M. Ford, Maria R. Drout, Rodrigo Fernández

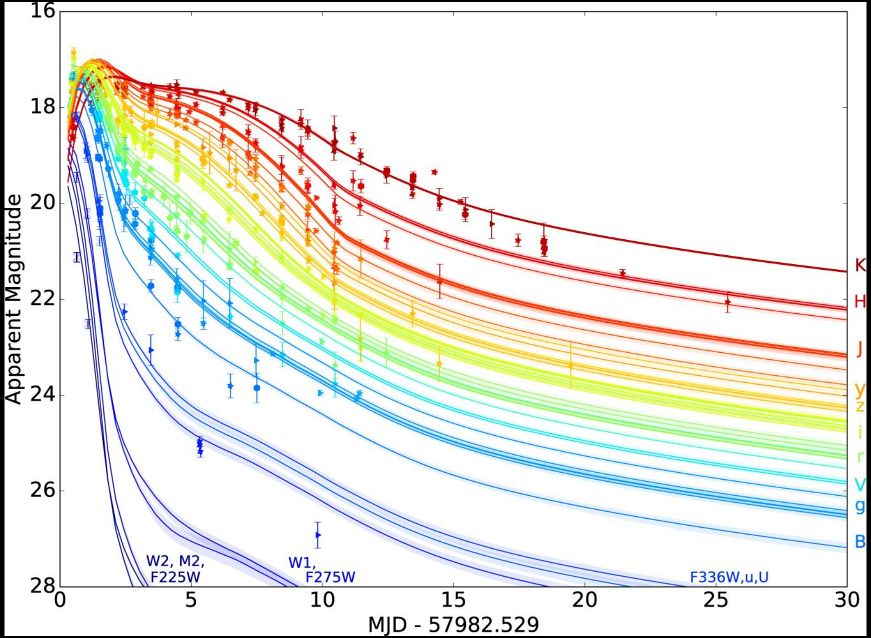
But also see SPARK I:

ApJ, 944, 123

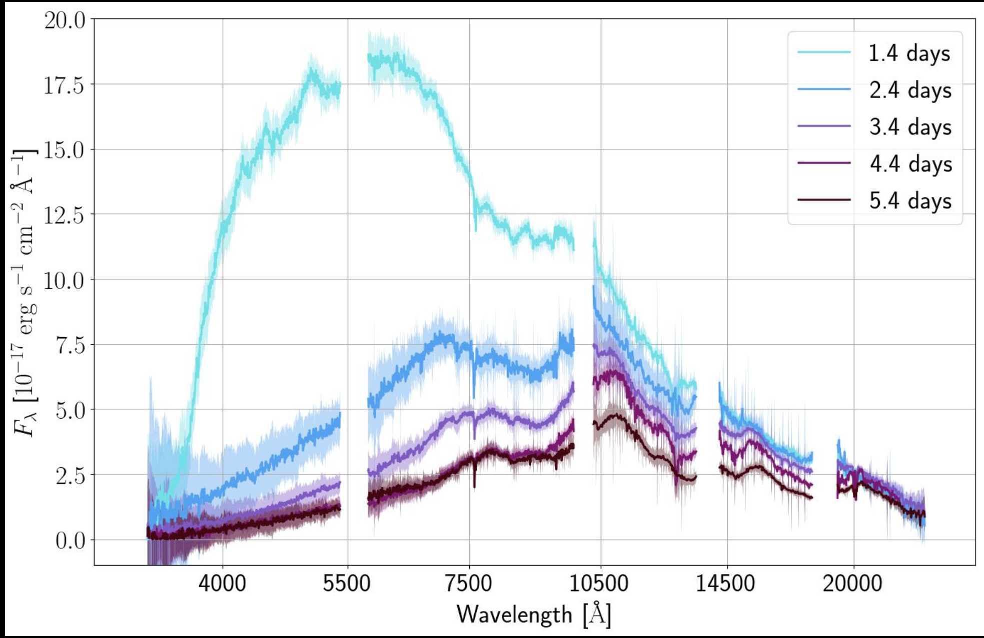
Spectroscopic r-Process Abundance Retrieval for Kilonovae I: The Inferred Abundance Pattern of Early Emission from GW170817

Nicholas Vieira, John J. Ruan, Daryl Haggard, Nicole Ford, Maria R. Drout, Rodrigo Fernández, N. R. Badnell

GW170817's kilonova

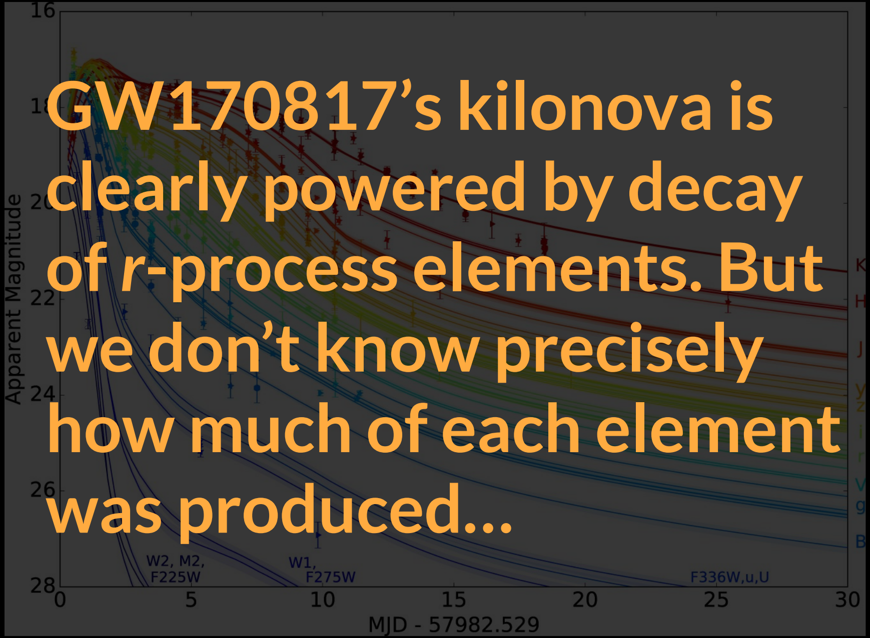


Villar+17



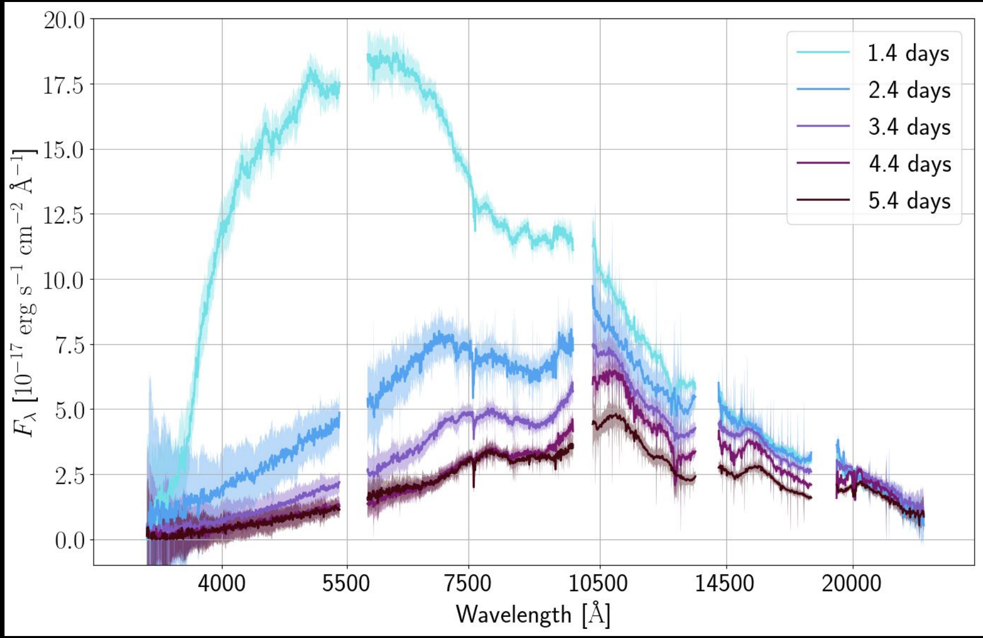
Data: Pian+17, Smartt+17

GW170817's kilonova



GW170817's kilonova is clearly powered by decay of *r*-process elements. But we don't know precisely how much of each element was produced…

Villar+17



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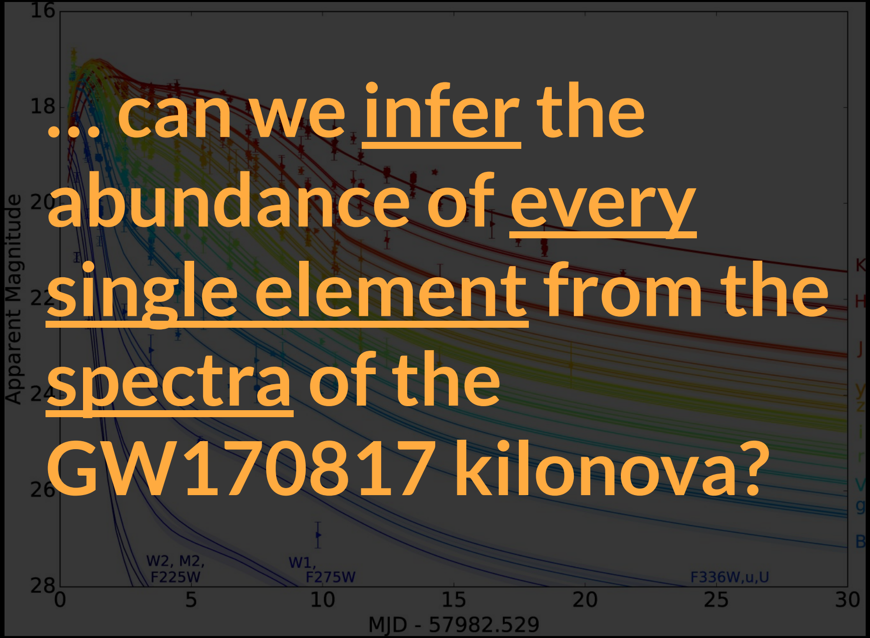
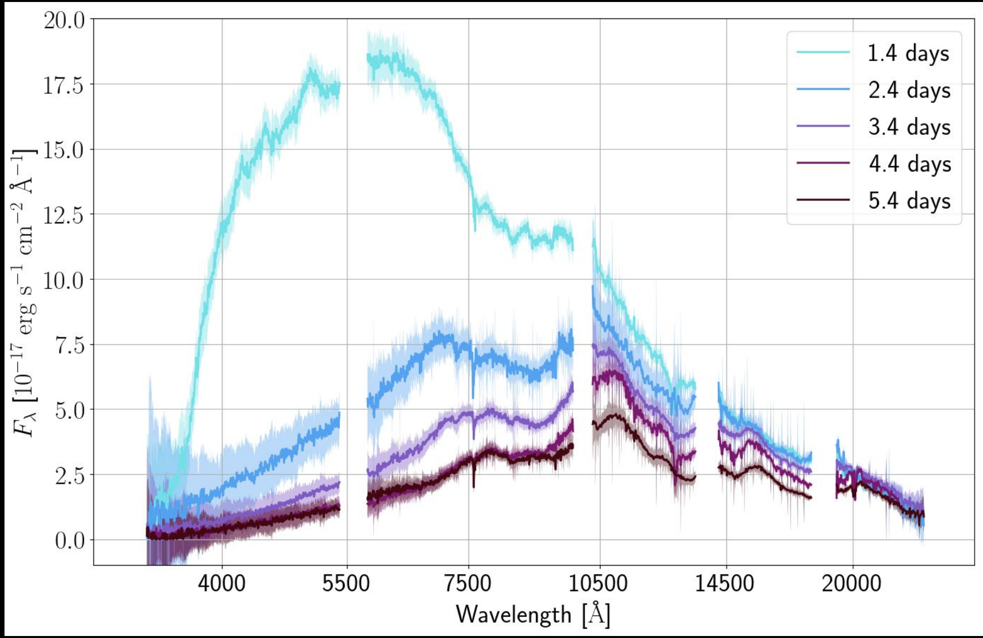
GW170817's kilonova

... can we infer the abundance of every single element from the spectra of the GW170817 kilonova?



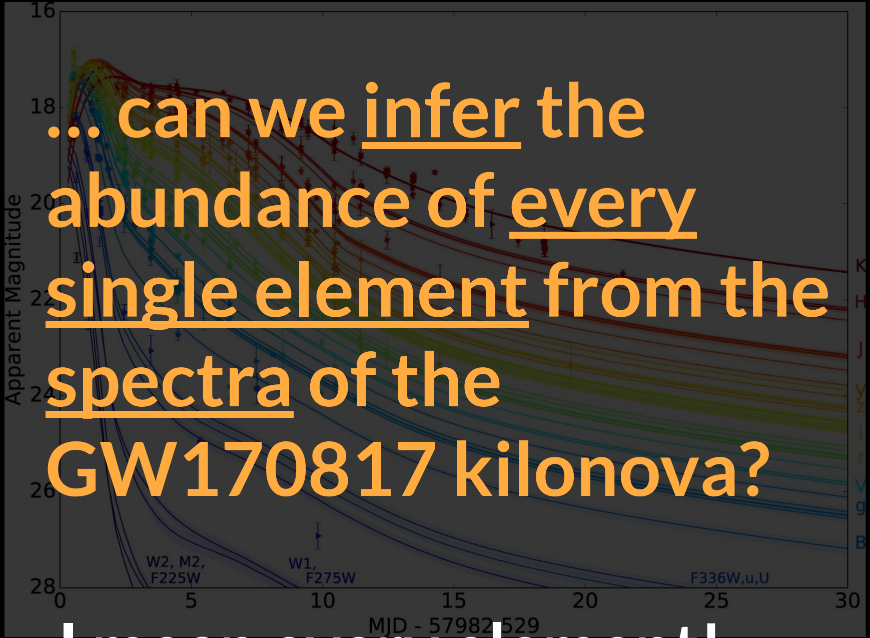
Villar+17



Data: Pian+17, Smartt+17

GW170817's kilonova

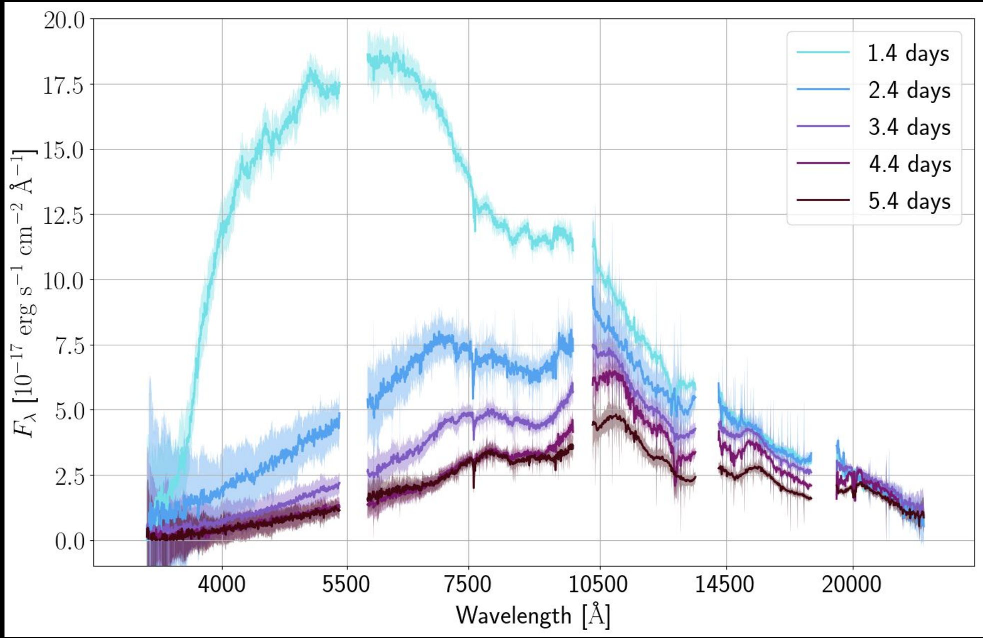
Bayesian inference, with uncertainties



... can we *infer* the abundance of *every single element* from the *spectra* of the GW170817 kilonova?

I mean every element!

Villar+17



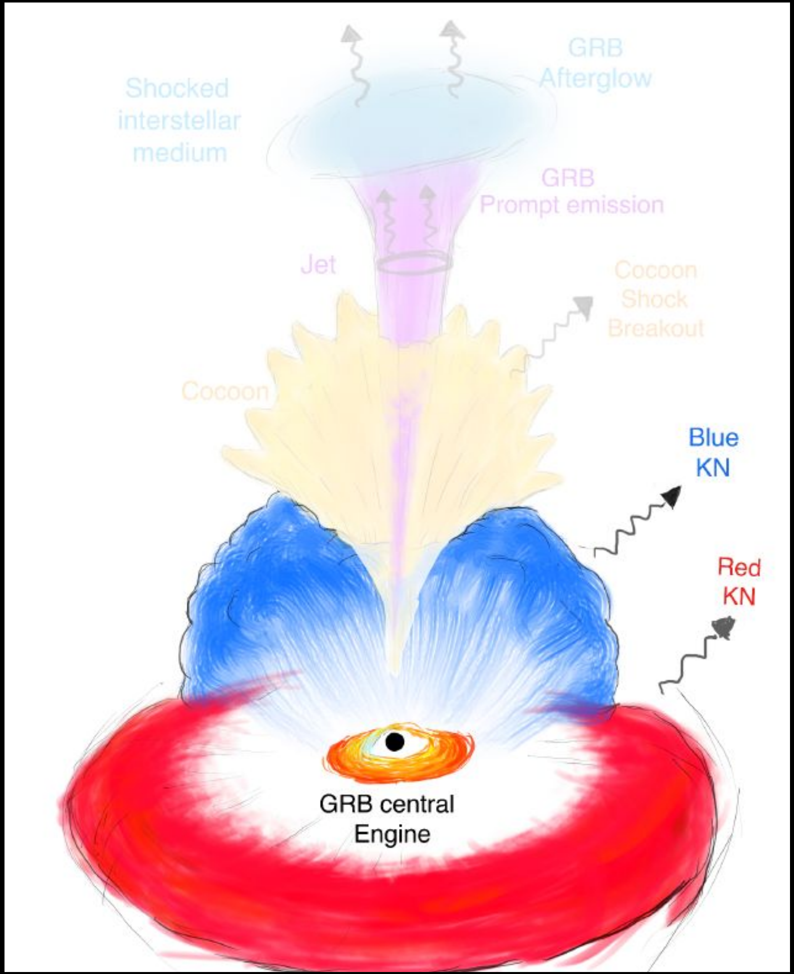
Data: Pian+17, Smartt+17

Ambitions

Does the inferred abundance pattern evolve with time?

I'll focus on the spectra from 1.4, 2.4, and 3.4 days post-merger (optically thick, LTE)

Do we need multi-component ejecta models to fit any of these epochs?



Ascenzi+21

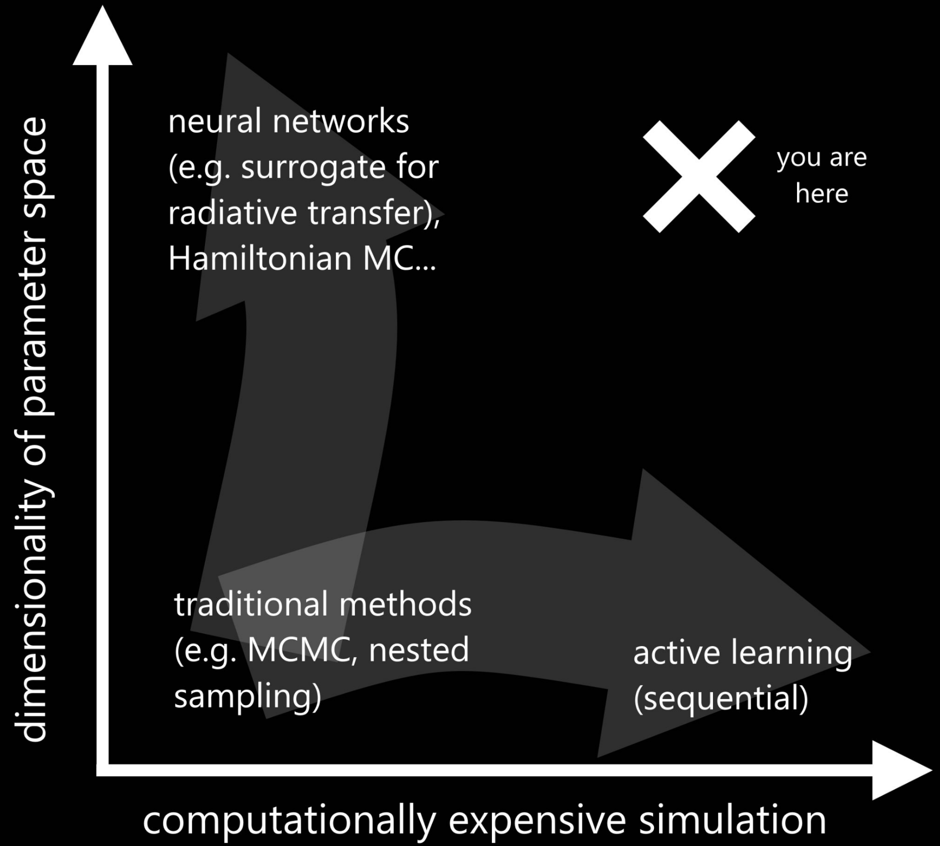
SPARK: Spectroscopic r-Process Abundance Retrieval for Kilonovae

Idea: Generate many synthetic spectra and compare them to observations → Fit for the *r*-process elemental abundance pattern of GW170817 ("***spectral retrieval***")

Problems:

1. many elements → high dimensionality if we naively fit for each abundance individually
2. simulations are computationally expensive

Inference regimes



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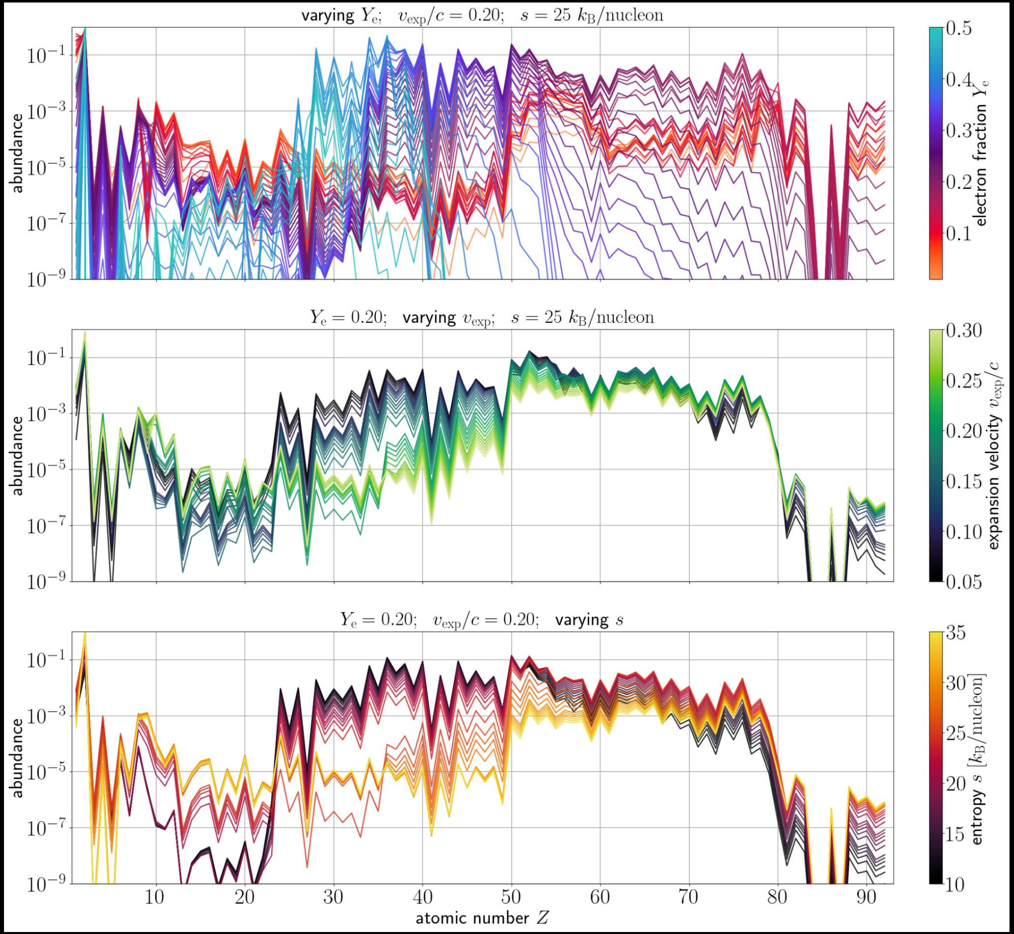
Parametrizing the abundances

- Parametrize using **electron fraction, expansion velocity,** and **entropy**

$$Y_{\mathrm{e}}, v_{\mathrm{exp}}, \quad s$$

- Constrain fundamental conditions of the *r*-process + physical ejection mechanisms

Vieira+23a (SPARK I)
Reaction network: Wanajo 18



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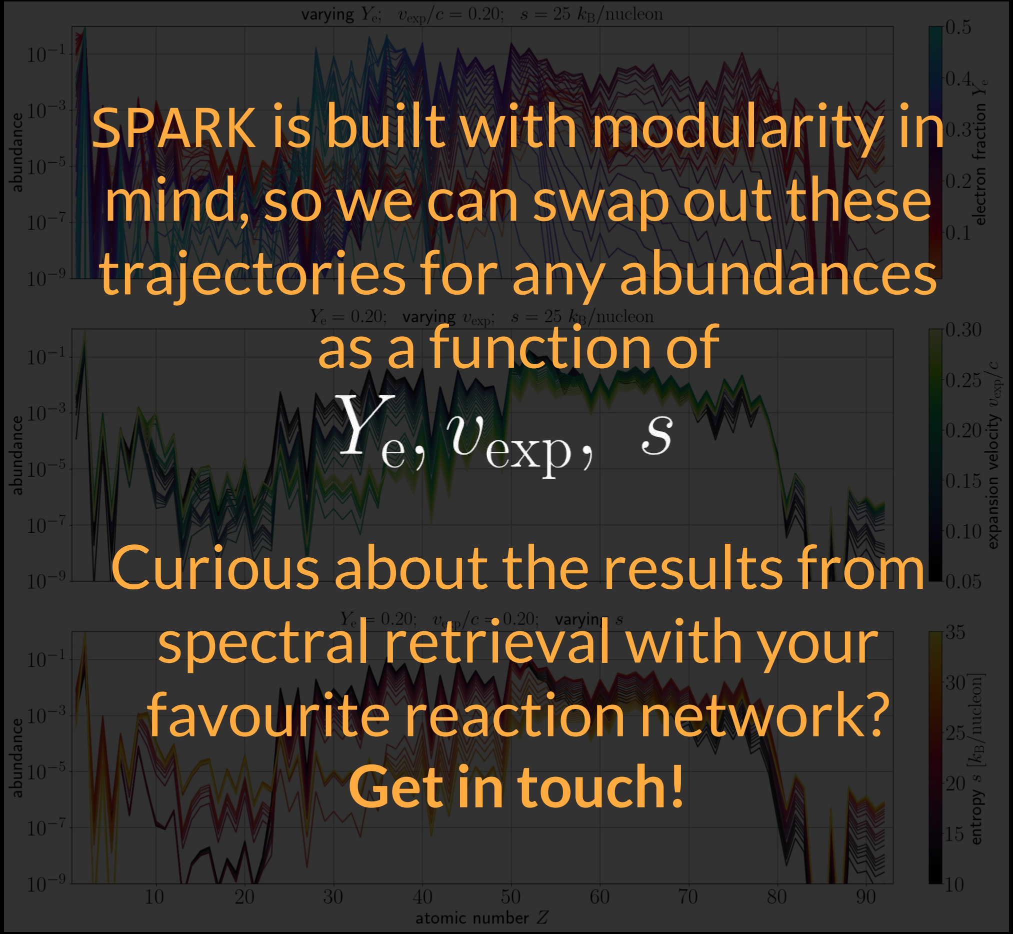
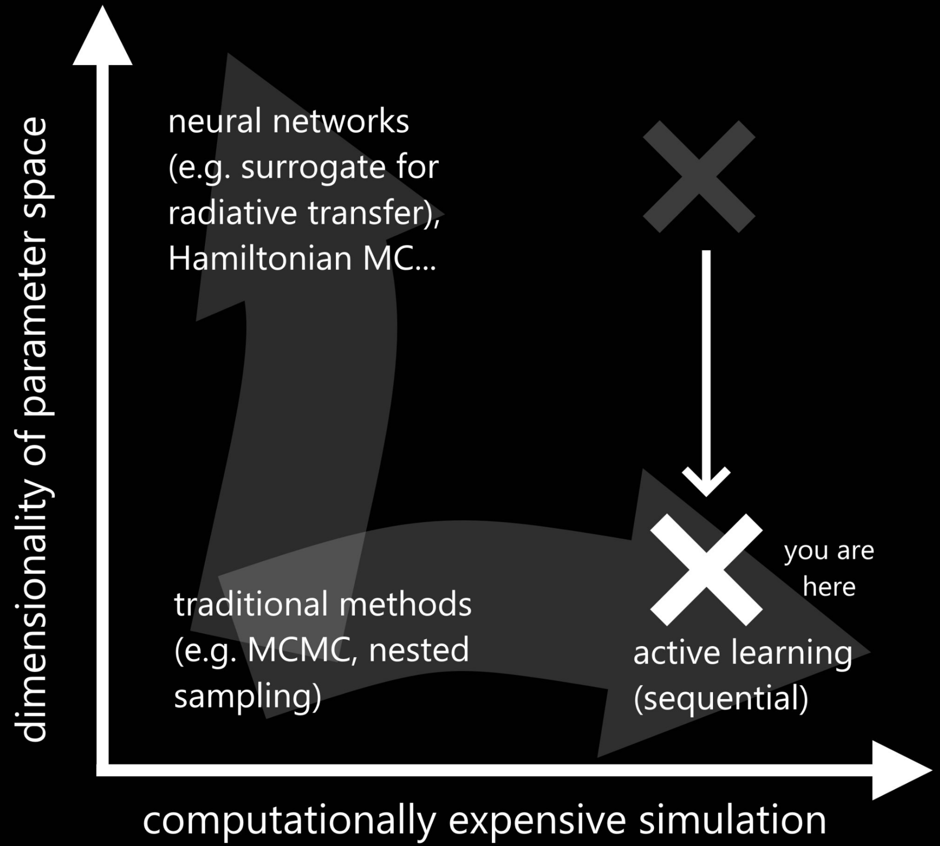


SPARK is built with modularity in mind, so we can swap out these trajectories for any abundances as a function of

$$Y_\mathrm{e},\ v_\mathrm{exp},\ \ s$$

Curious about the results from spectral retrieval with your favourite reaction network?
Get in touch!

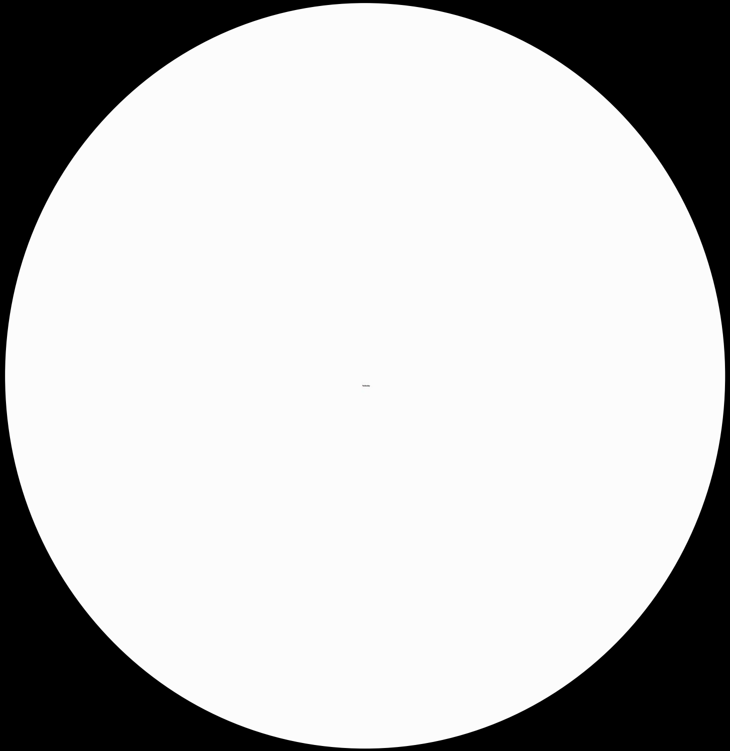
Inference regimes



Radiative transfer with TARDIS

TARDIS!
Exploring supernovae made easy

- 1D, spherically symmetric Monte Carlo
- Stratified medium under homologous expansion
- Synthetic spectrum at a single point in time
- **(Expansion) opacities computed on the fly given composition of the ejecta → computationally expensive**



https://tardis-sn.github.io/tardis/

SPARK: Spectroscopic r-Process Abundance Retrieval for Kilonovae

Idea: Generate many synthetic spectra and compare them to observations $\longrightarrow$ Fit for the *r*-process elemental abundance pattern of GW170817 (“***spectral retrieval***”)

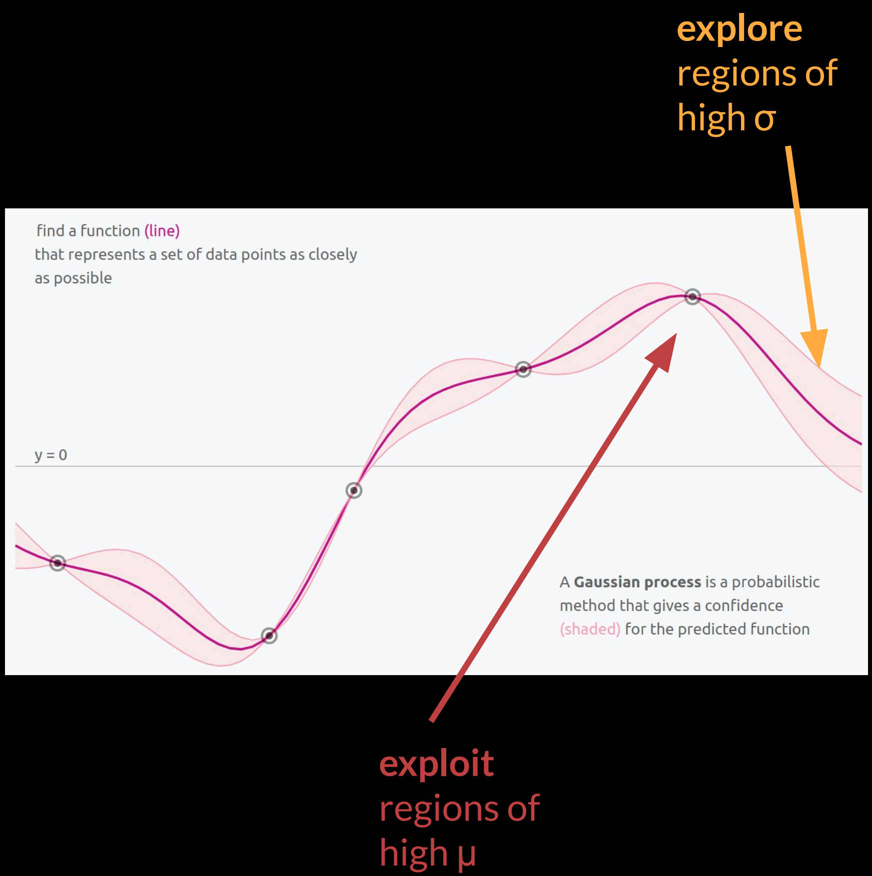
Problems:

1. many elements $\longrightarrow$ high dimensionality if we naively fit for each abundance individually   parametrize abundances
2. simulations are computationally expensive   active learning

Active learning

- Approximate the posterior $p(\theta|X)$ with a **Gaussian Process**
  - Advantage: GPs have both a mean and a variance

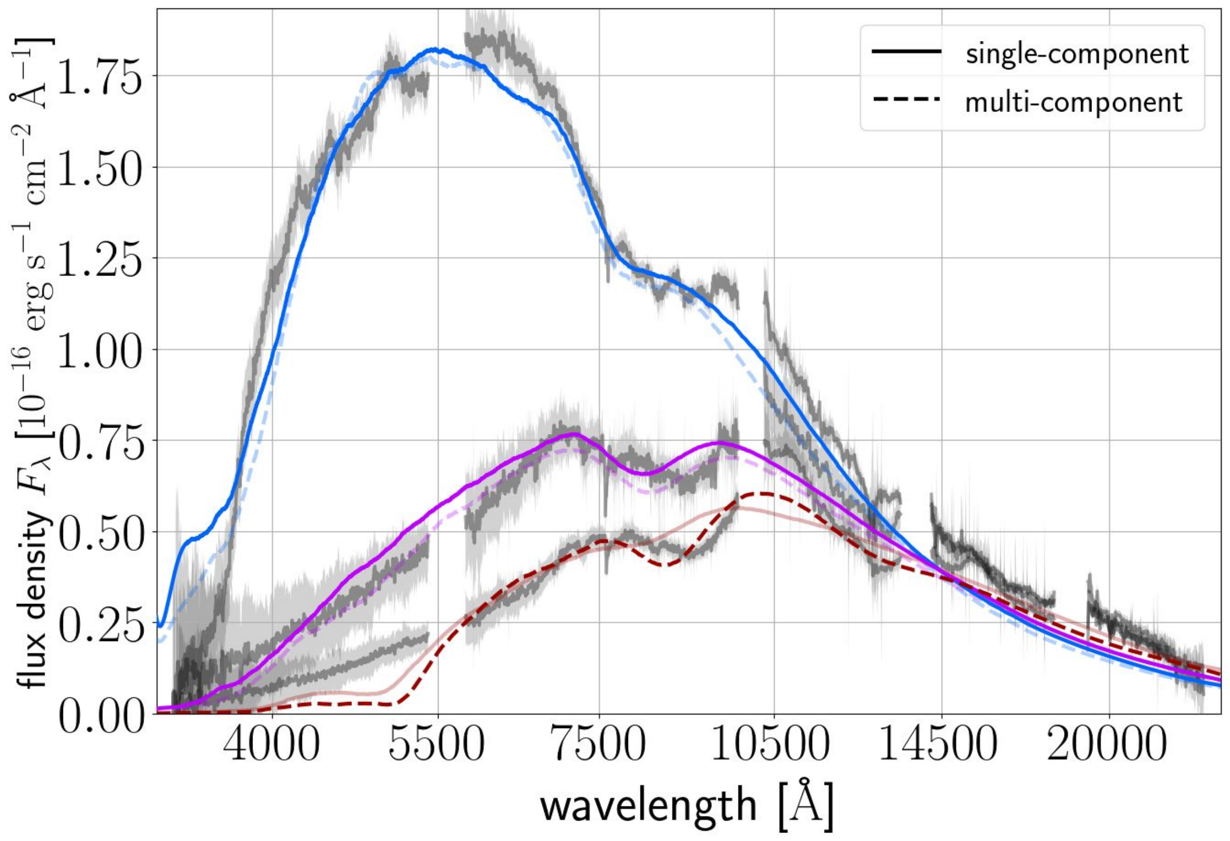
- **Bayesian Active Posterior Estimation (BAPE)**: Select points in parameter space which optimize both high posterior probability and large uncertainty in the posterior
  - Dramatically reduce the number of forward model evaluations needed for inference



Görtler+19
https://distill.pub/2019/visual-exploration-gaussian-processes/

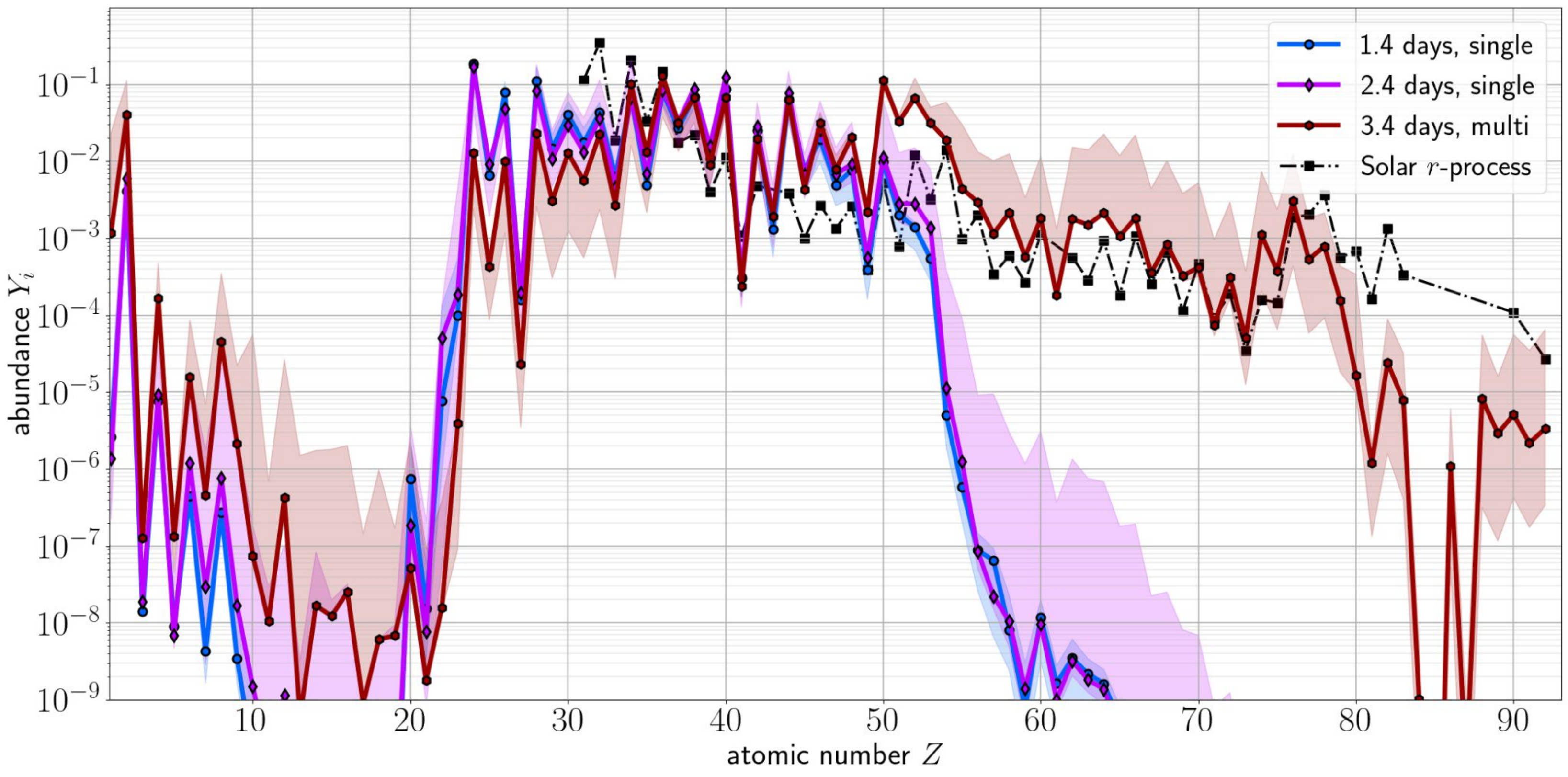
Let’s fit the 1.4, 2.4, and 3.4 day optical spectra of the GW170817 kilonova with both single- and multi-component models, and see what fits best.

Favoured models



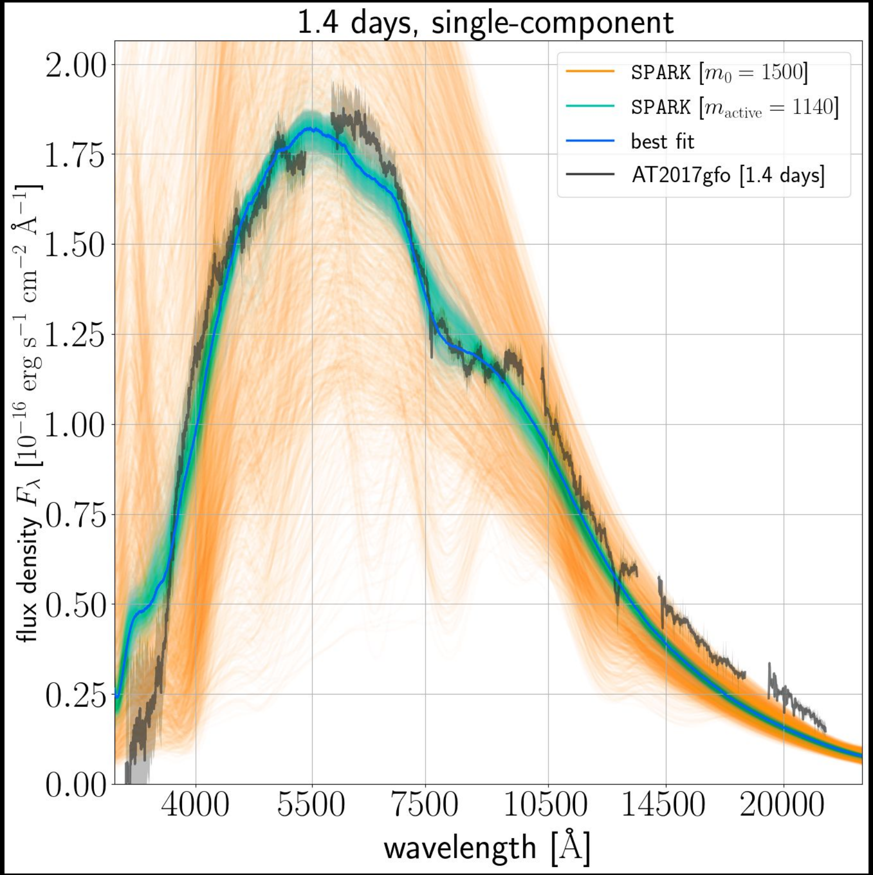
Vieira+23b (SPARK II) arXiv: [2308.16796](https://arxiv.org/abs/2308.16796)

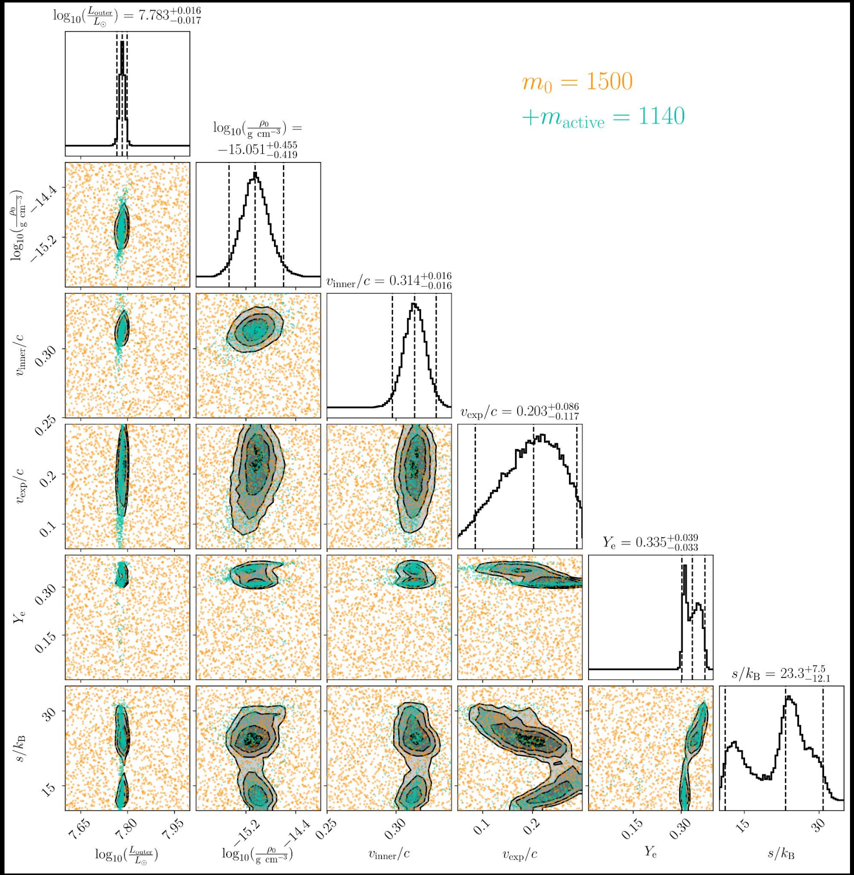
Abundances



Vieira+23b (SPARK II) arXiv: 2308.16796
Solar r-process: Lodders 09 & Bisterzo+14

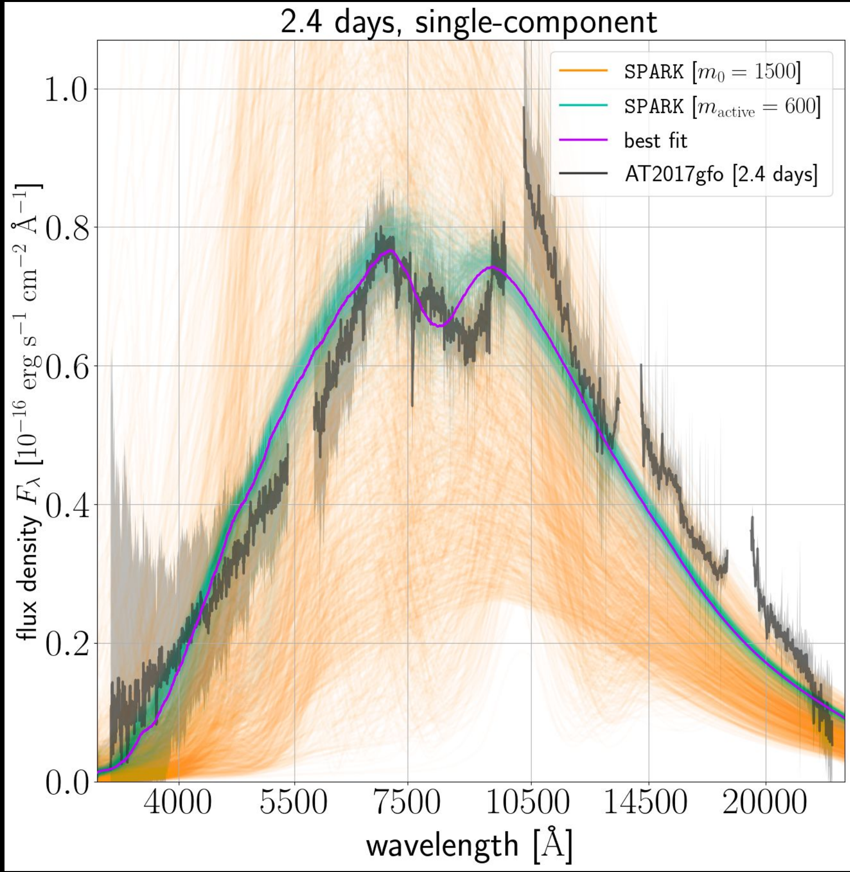
1.4 days, single-component

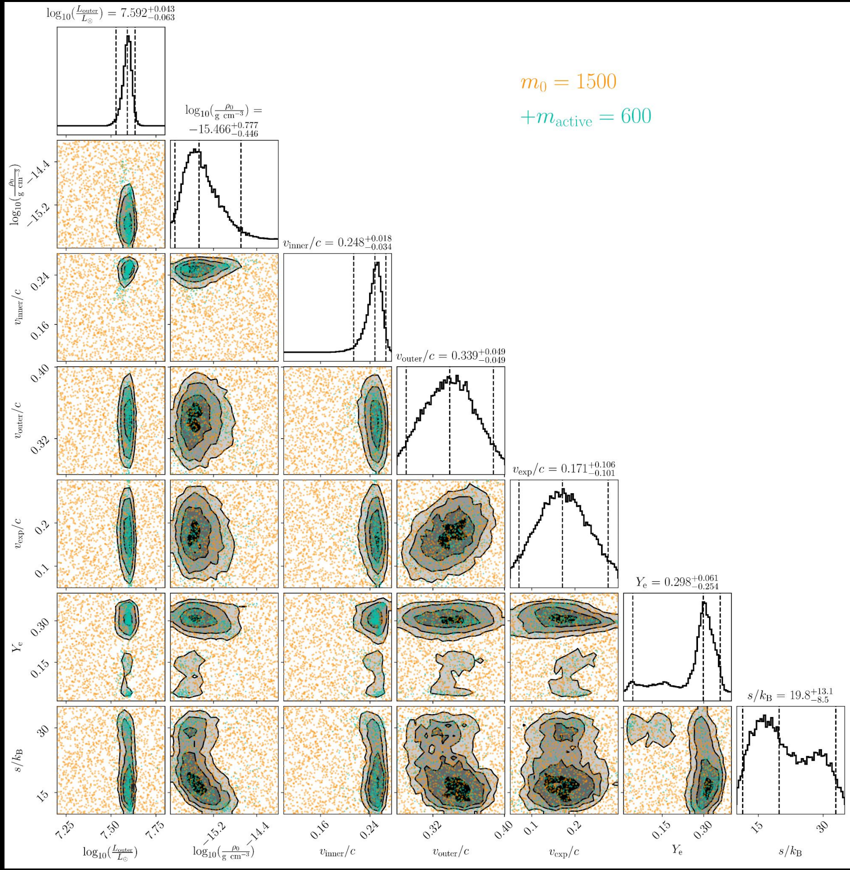




Vieira+23b (SPARK II) arXiv: 2308.16796

2.4 days, single-component





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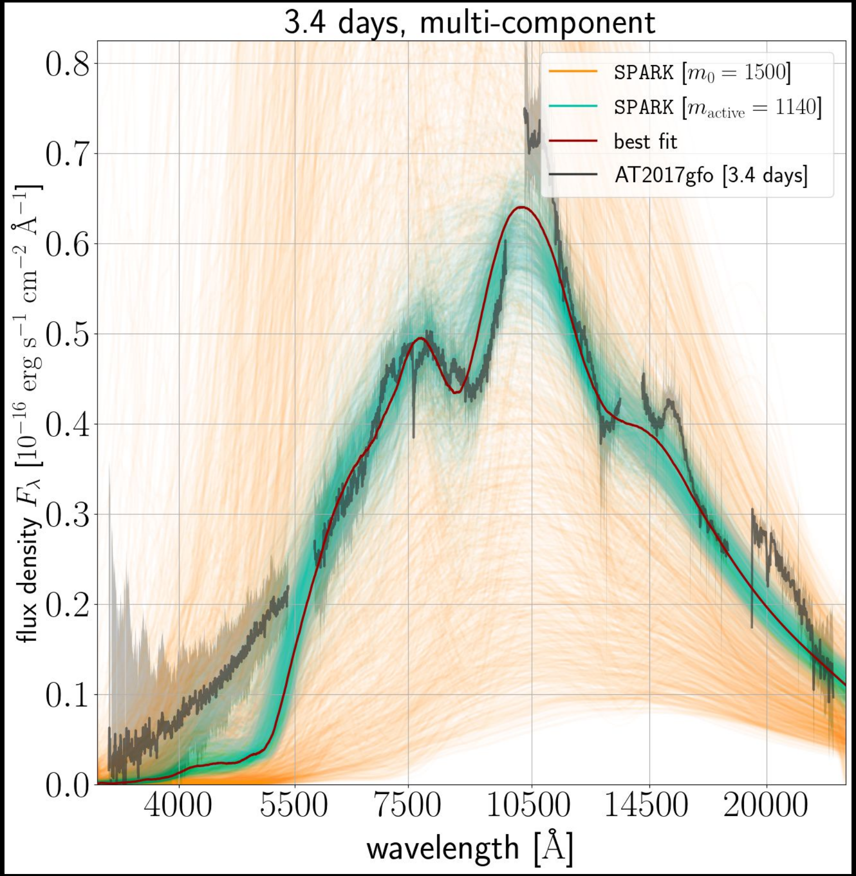
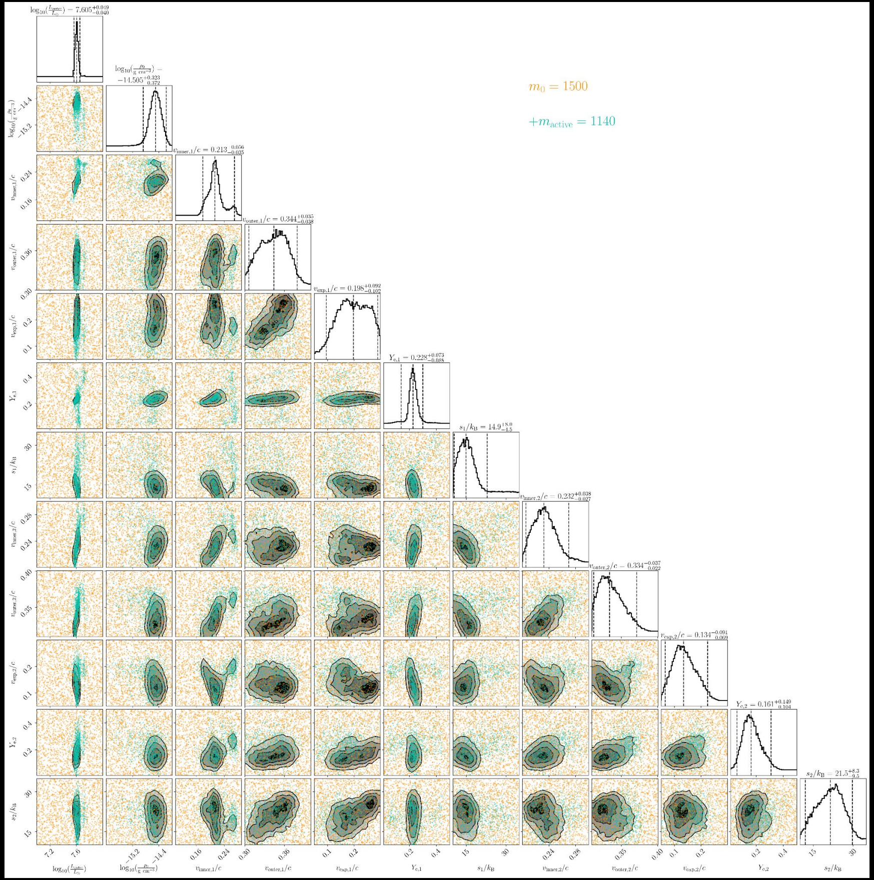
3.4 days, multi-component





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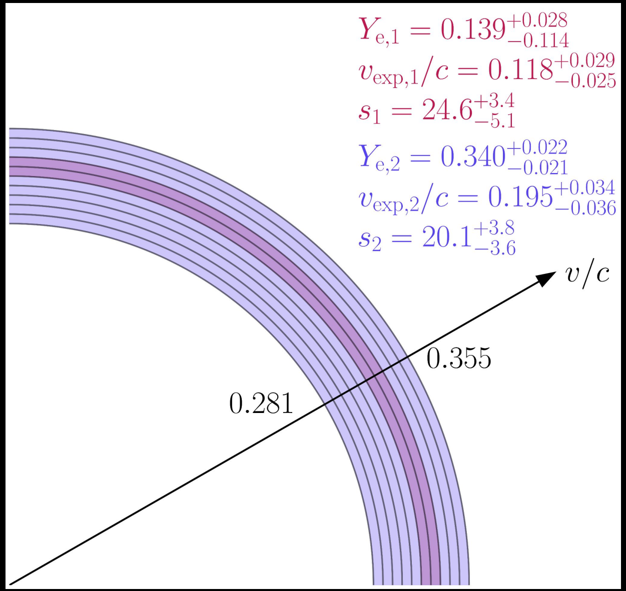
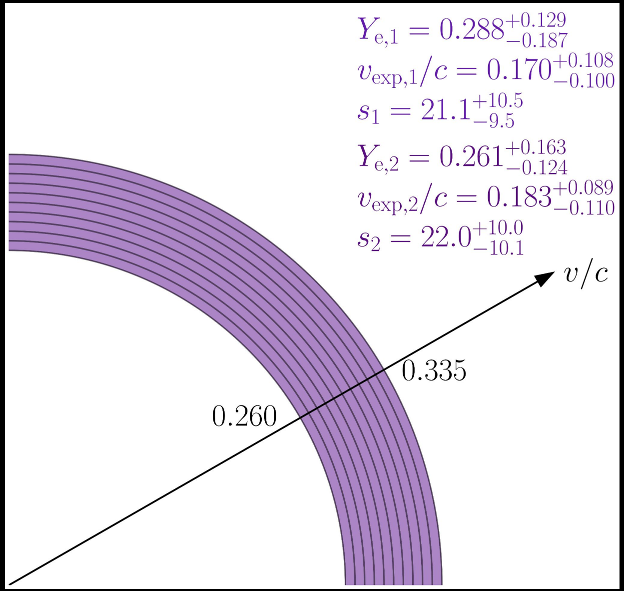
Multi-component ejecta geometries

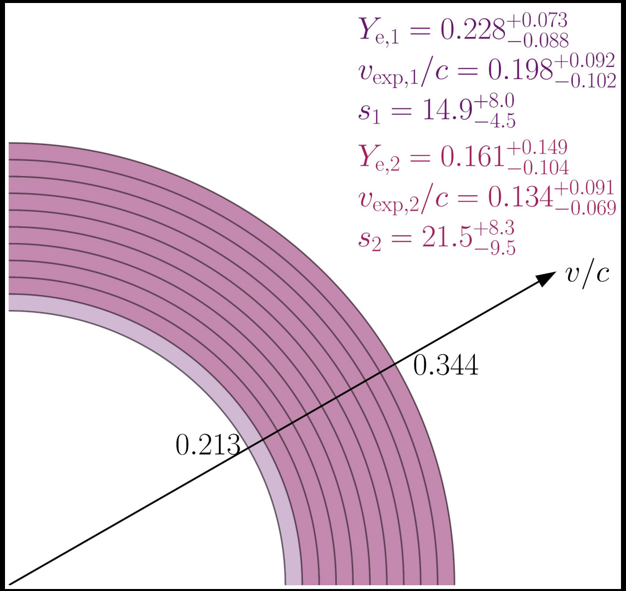
1.4 days



2.4 days



3.4 days



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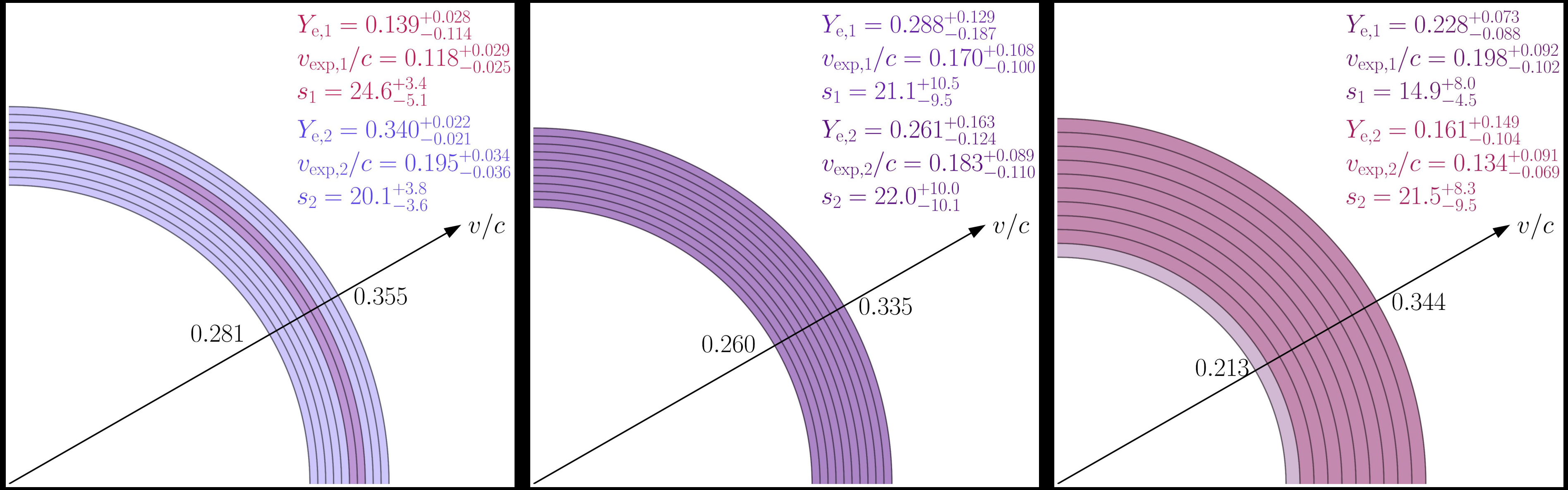
Multi-component ejecta geometries

1.4 days | 2.4 days | 3.4 days

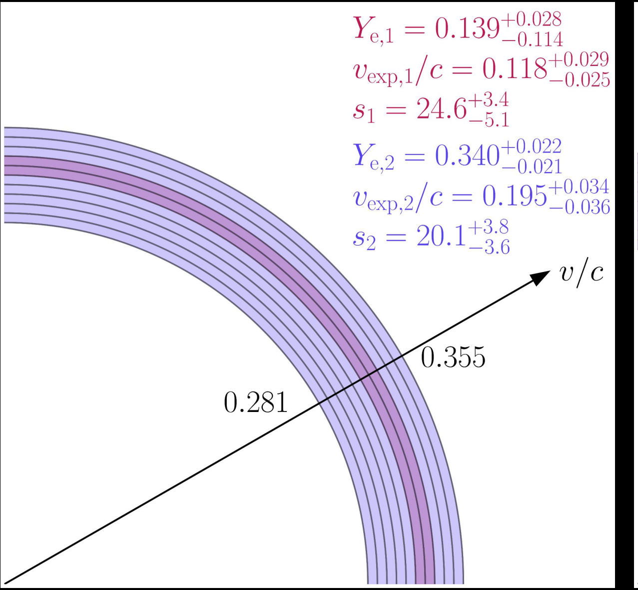


presence of red is negligible

Vieira+23b (SPARK II) arXiv: 2308.16796

Multi-component ejecta geometries

1.4 days



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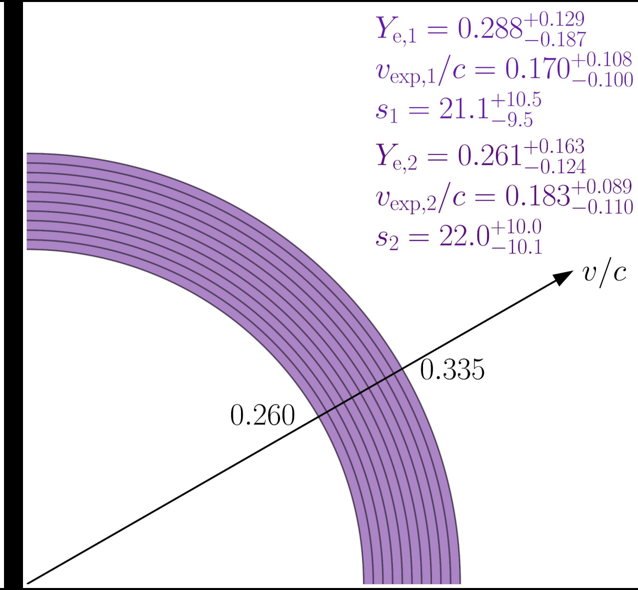
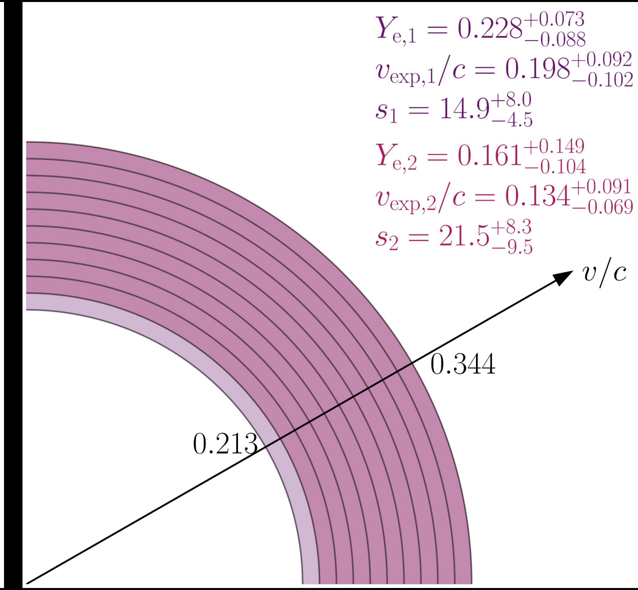


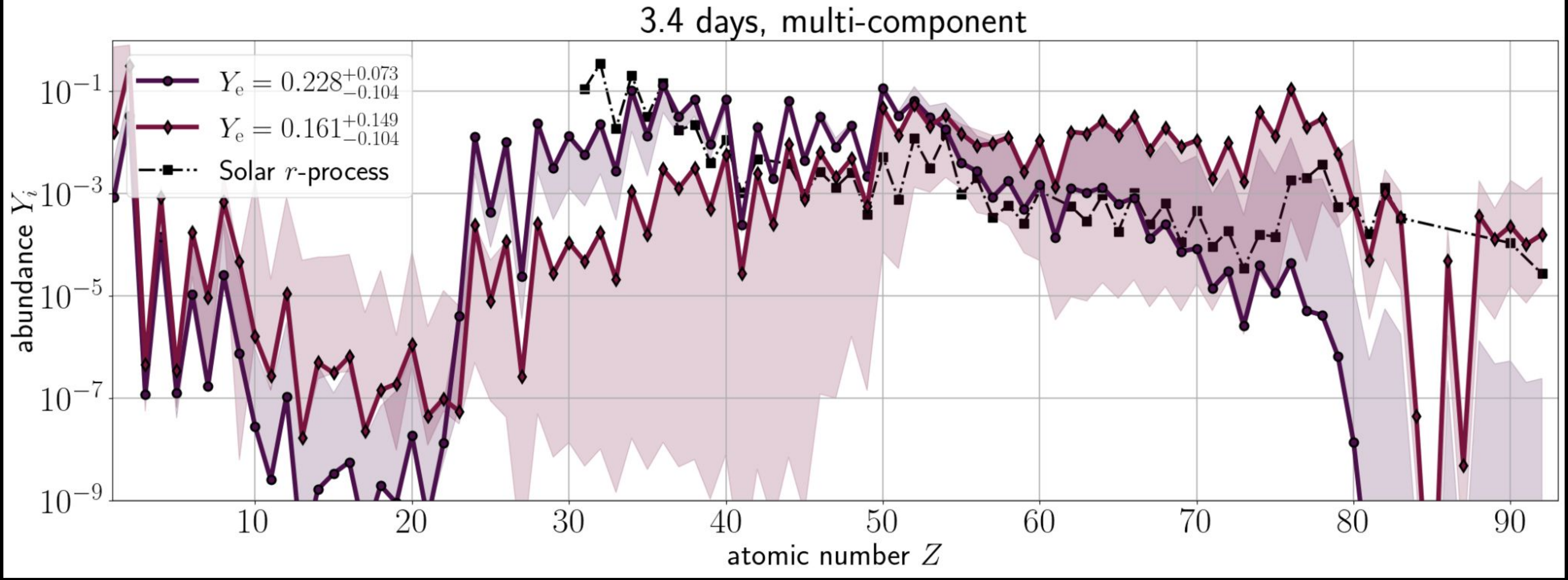
complete overlap; similar compositions

3.4 days



Vieira+23b (SPARK II) arXiv: 2308.16796

Compare components' abundances @ 3.4 days



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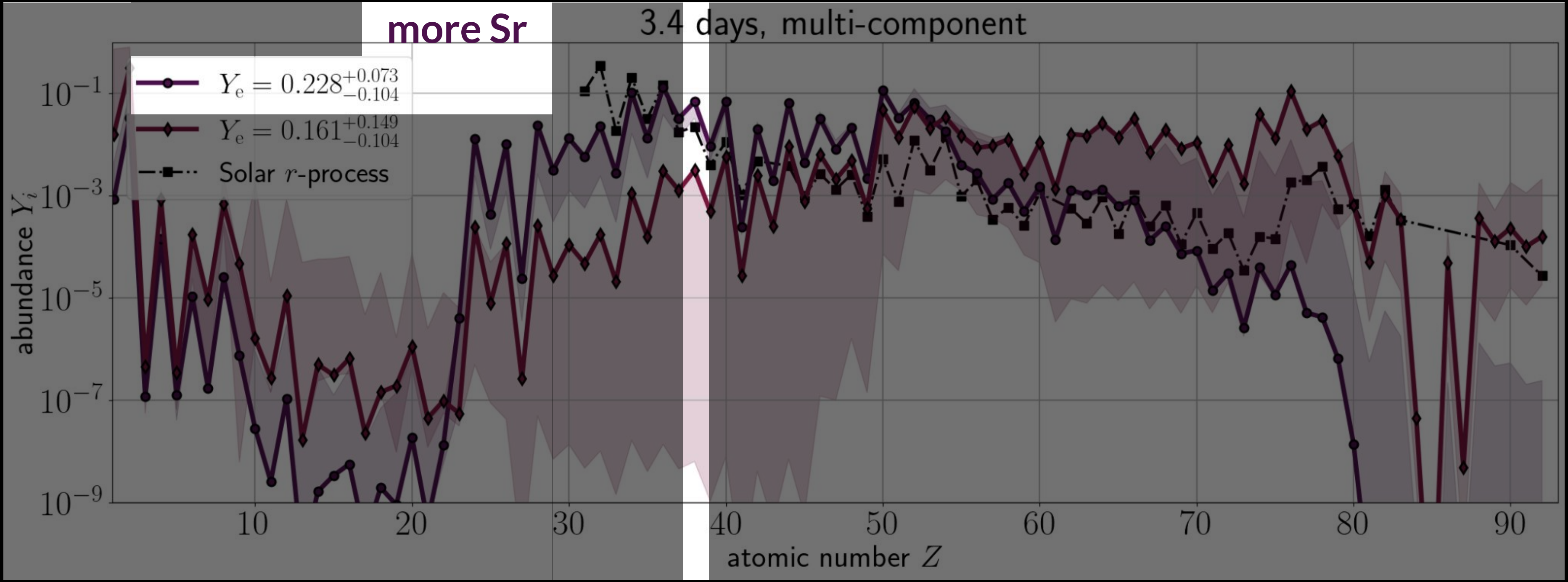

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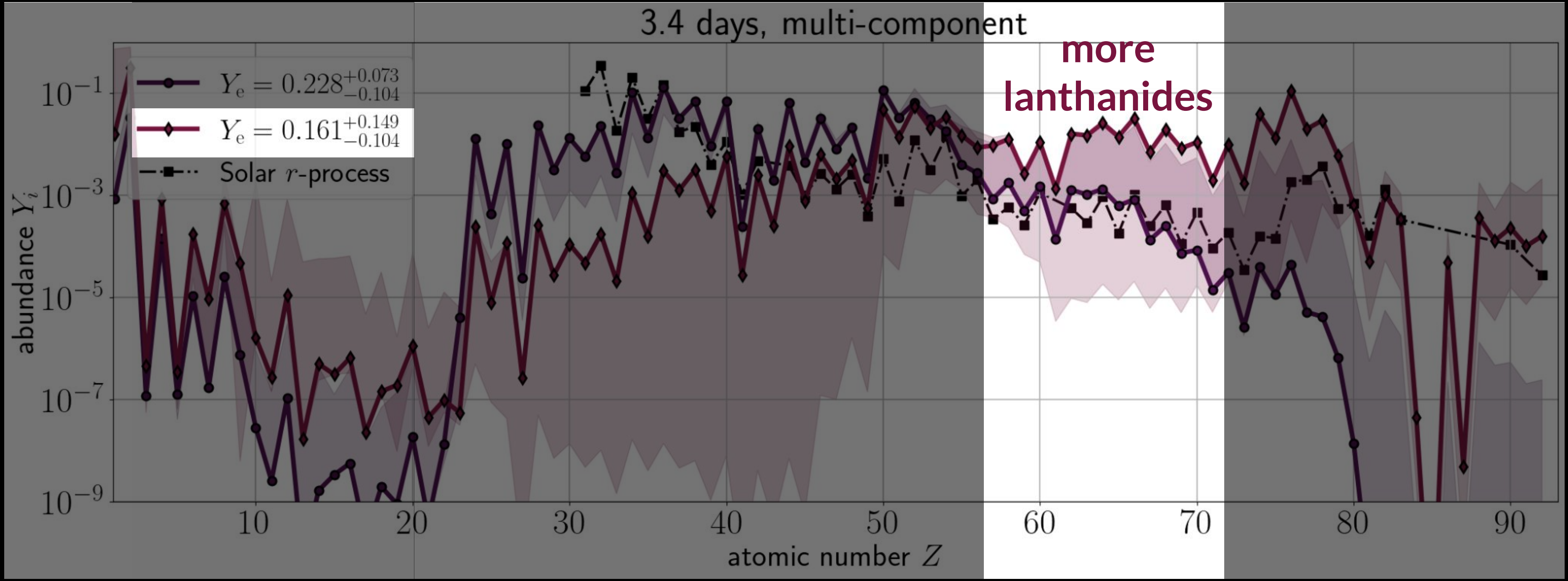

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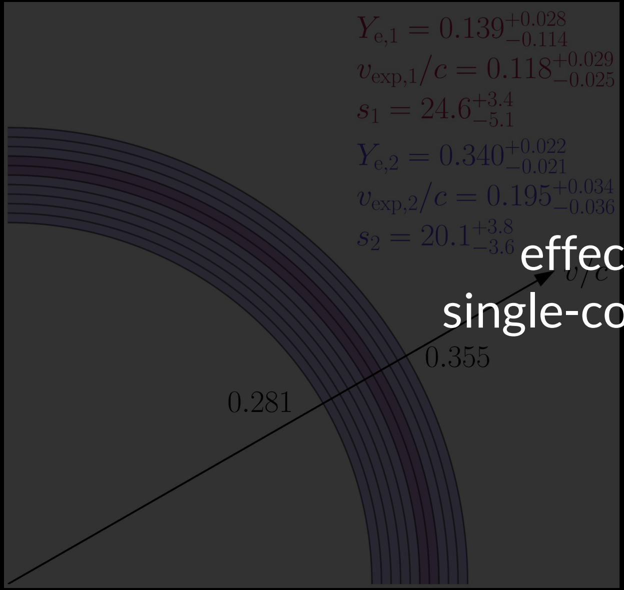
Multi-component ejecta geometries

genuinely multi-component!

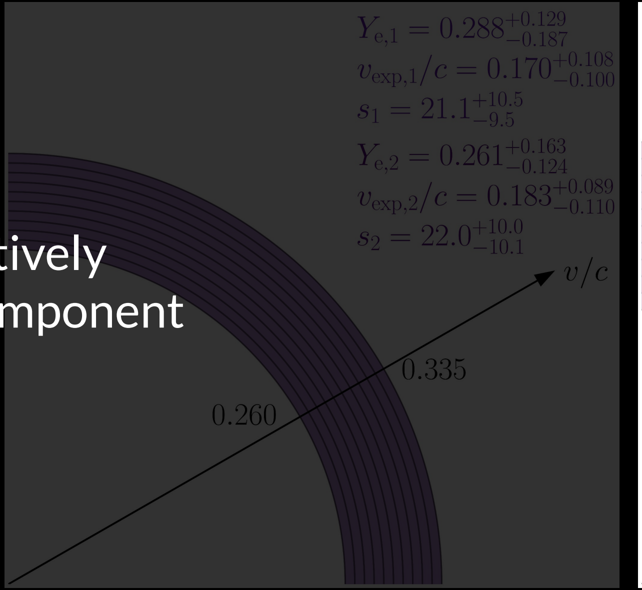
1.4 days



presence of red is negligible

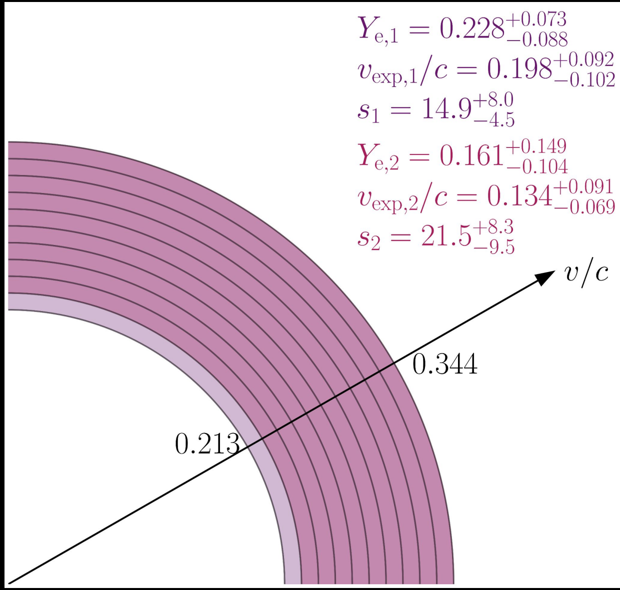
effectively single-component

2.4 days



complete overlap; similar compositions

3.4 days

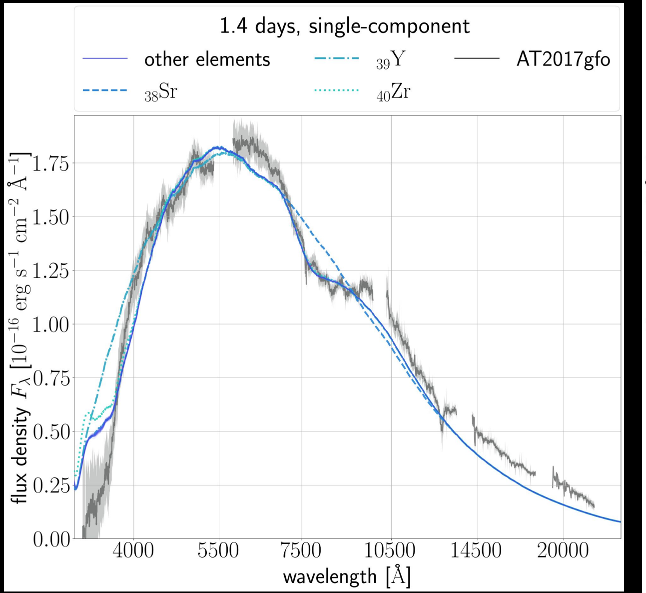


~complete overlap; **different compositions**

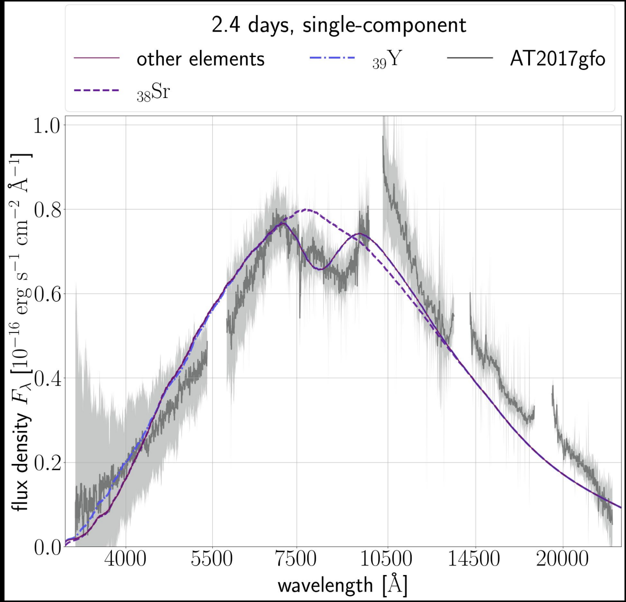
Vieira+23b (SPARK II) arXiv: 2308.16796

Leave-one-out for favoured models

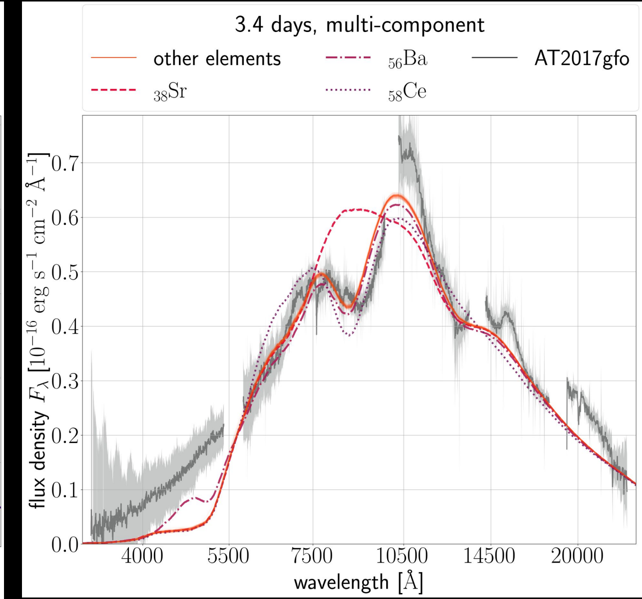
single-component



single-component

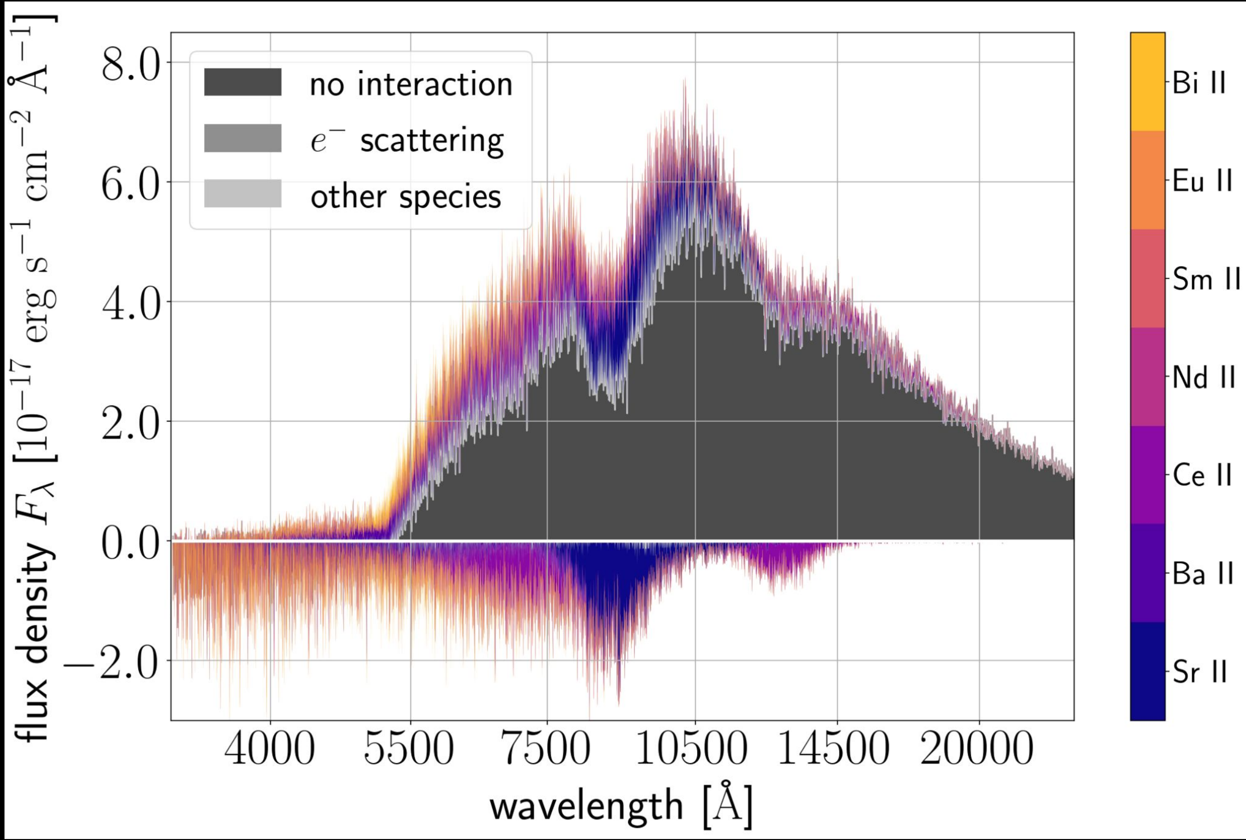


multi-component



Vieira+23b (SPARK II) arXiv: [2308.16796]

Spectral DECompositions @ 3.4 days, multi-component



Sr II remains important

Y II, Zr II are swamped out by a new **ensemble of lanthanides: Ce II, Nd II, Sm II, Eu II**

Ce II contributes 27.5% of absorption (compare to 30.3% from Sr II)

Vieira+23b (SPARK II) arXiv: 2308.16796

Conclusions & looking forward

- Same single blue component describes 1.4, 2.4 days
- **3.4 days is better described by multi-component**
- **New redder, lanthanide-bearing component at 3.4 days**
- Physical origins of the ejecta?
  - Blue at 1.4, 2.4: consistent with neutrino-reprocessed accretion disk wind
  - Red at 3.4: consistent with neutron-rich accretion disk wind and/or dynamical ejecta
- **What happens at 4.4 days and beyond?**
- **What are the abundances of the next kilonova?**