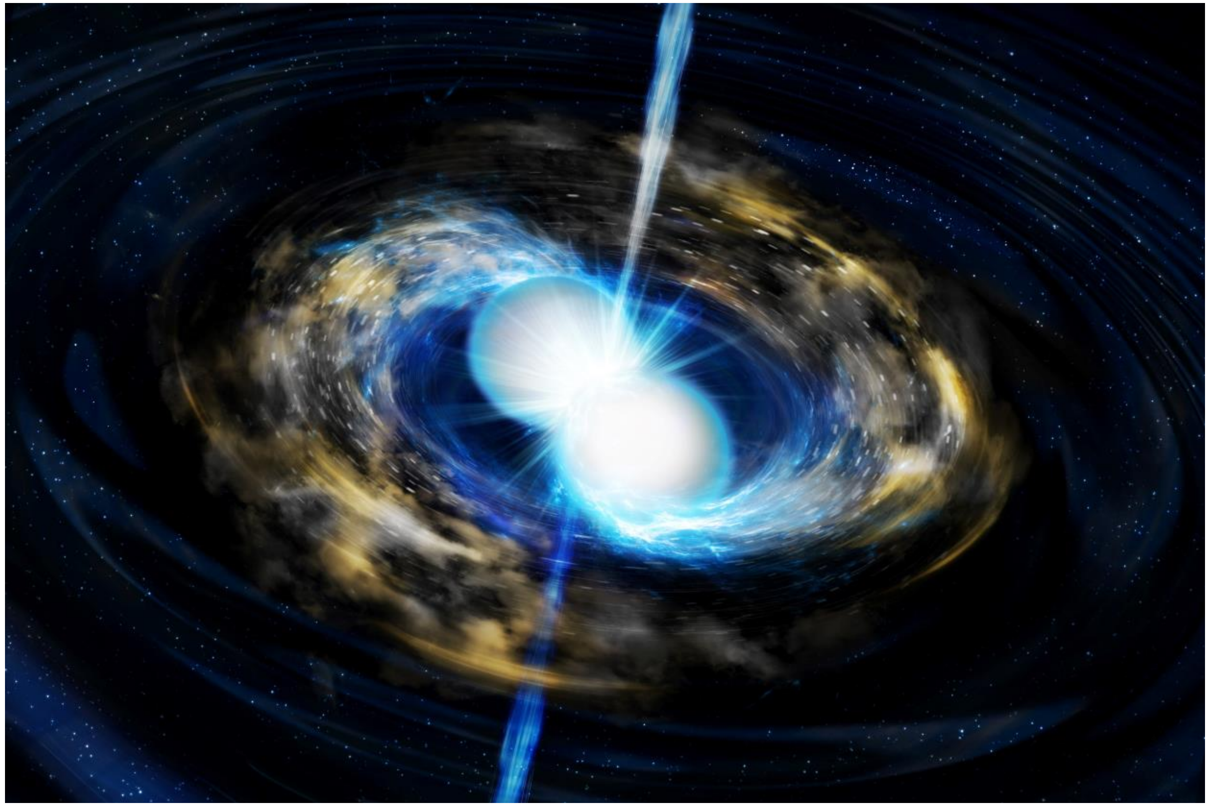

A Model for Abundances in Metal-poor Stars

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Overview of our model

- We wish to use the abundance data from stars to better understand the production mechanisms of heavy elements.
- Production Mechanisms of Iron and Heavier Elements:
  - AGB Stars: ~1 Gyr delay time
  - Type 1a Supernova: ~1 Gyr delay time, 1 every ~100 year average occurrence (our galaxy)
  - Type II Supernova: ~10 Myr delay time, 1 every ~30 year average occurrence (our galaxy)
  - Neutron Star Mergers: ~200 Myr delay time, 1 every ~10^5-10^7 year average occurrence (our galaxy)
- Metal-poor stars will be dominated by Type II Supernova and Neutron Star Mergers

Overview of our model (2)

- We assume that there exist a small number of sources which each produce a characteristic amount of each of the elements.
- This characteristic amount is spread into a characteristic mass of ISM, creating a characteristic concentration of the element relative to hydrogen.
- Therefore, the elemental abundance in any star must be the result of a linear combination of the contributions from these sources.

$$\left(\frac{E}{H}\right)_{star} = \sum_{i=1}^{n} x_i \left(\frac{E}{H}\right)_i \quad \rightarrow \quad \left(\frac{E}{Fe}\right)_{star} = \sum_{i=1}^{n} x_i \left(\frac{E}{Fe}\right)_i \quad \sum_{i=1}^{n} x_i = 1$$

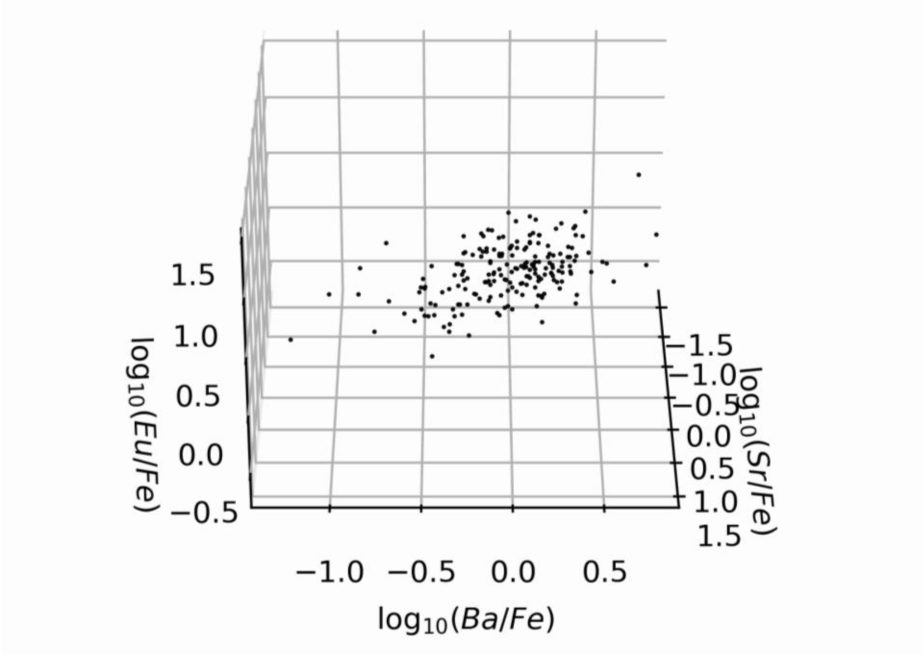
$E = Fe, Sr, Ba, Eu$

$E = Sr, Ba, Eu$

How many templates?

$$\left(\frac{E}{Fe}\right)_{star} = \sum_{i=1}^{n} x_i \left(\frac{E}{Fe}\right)_i \qquad \sum_{i=1}^{n} x_i = 1$$

- For two templates, you would expect the data to be linear.
- For three templates, you would expect the data to be planar.



Two templates: the mathematically best solution

$$\begin{bmatrix} Fe/Fe \\ Sr/Fe \\ Ba/Fe \\ Eu/Fe \end{bmatrix} = \begin{bmatrix} 1.0 \\ 0.352 \\ 0.001 \\ 0.301 \end{bmatrix}, \begin{bmatrix} 1.0 \\ 8.83 \\ 9.42 \\ 20.16 \end{bmatrix}$$

- Our data sample has 211 stars, with an average measurement error of 0.605σ
- In 140/211 (66.3%) of stars, all three measurements agree within 1σ
- In 200/211 (94.8%) of stars, all three measurements agree within 2σ
- In 206/211 (97.6%) of stars, all three measurements agree within 3σ

Extracting physical meaning from the templates

$$\begin{bmatrix} Fe/Fe \\ Sr/Fe \\ Ba/Fe \\ Eu/Fe \end{bmatrix} = \begin{bmatrix} 1.0 \\ 0.352 \\ 0.001 \\ 0.301 \end{bmatrix}, \begin{bmatrix} 1.0 \\ 8.83 \\ 9.42 \\ 20.16 \end{bmatrix}$$

- It is very unusual to produce Europium without Barium. Similarly, the templates can be simplified to eliminate non-dominant contributions.
- New proposed templates: We identify the first with Type II Supernova, and the second with Neutron Star Mergers

$$\begin{bmatrix} Fe/Sr \\ Sr/Sr \\ Ba/Sr \\ Eu/Sr \end{bmatrix} = \begin{bmatrix} A \\ 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ B \\ C \end{bmatrix}$$

Two templates: the physically motivated solution

$$\begin{bmatrix} Fe/Sr \\ Sr/Sr \\ Ba/Sr \\ Eu/Sr \end{bmatrix} = \begin{bmatrix} 3.461 \\ 1.0 \\ 0.0 \\ 0.0 \end{bmatrix}, \begin{bmatrix} 0.0 \\ 1.0 \\ 1.025 \\ 2.549 \end{bmatrix}$$

- Our data sample has 211 stars: with an average error of 0.615σ
- In 141/211 (66.8%) of stars, all three measurements agree within 1σ
- In 197/211 (93.4%) of stars, all three measurements agree within 2σ
- In 206/211 (97.6%) of stars, all three measurements agree within 3σ

Predictions for the two-template results

$$\begin{bmatrix} Fe/Sr \\ Sr/Sr \\ Ba/Sr \\ Eu/Sr \end{bmatrix} = \begin{bmatrix} 3.461 \\ 1.0 \\ 0.0 \\ 0.0 \end{bmatrix}, \begin{bmatrix} 0.0 \\ 1.0 \\ 1.025 \\ 2.549 \end{bmatrix}$$

- There should be a linear relationship between Sr/Fe and Ba/Fe, Eu/Fe:

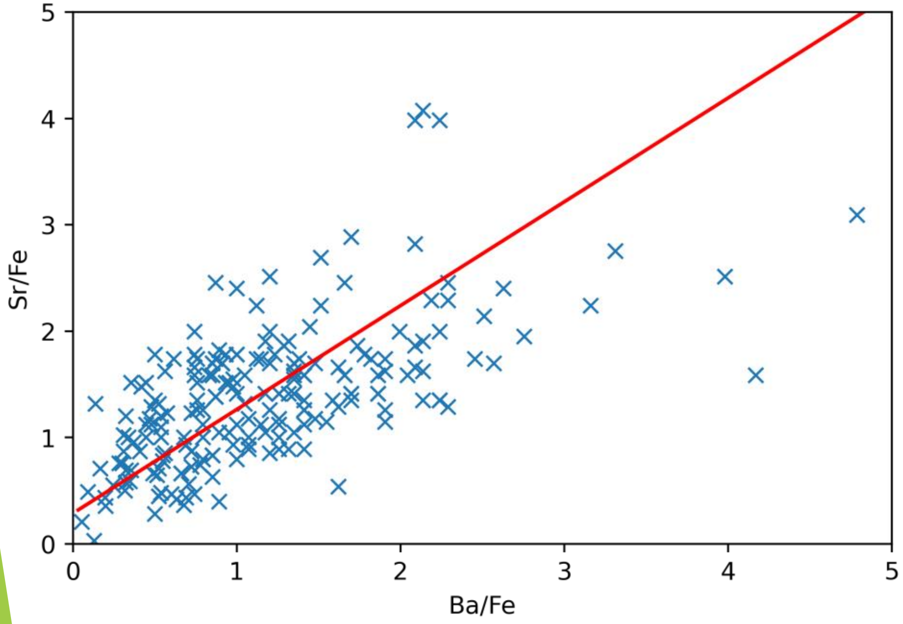
$$\left(\frac{Sr}{Fe}\right)_{star} = \left(\frac{Sr}{Fe}\right)_1 + \left(\frac{Sr}{Eu}\right)_2 \left(\frac{Eu}{Fe}\right)_{star} = 0.2889 + 0.392 \left(\frac{Eu}{Fe}\right)_{star}$$

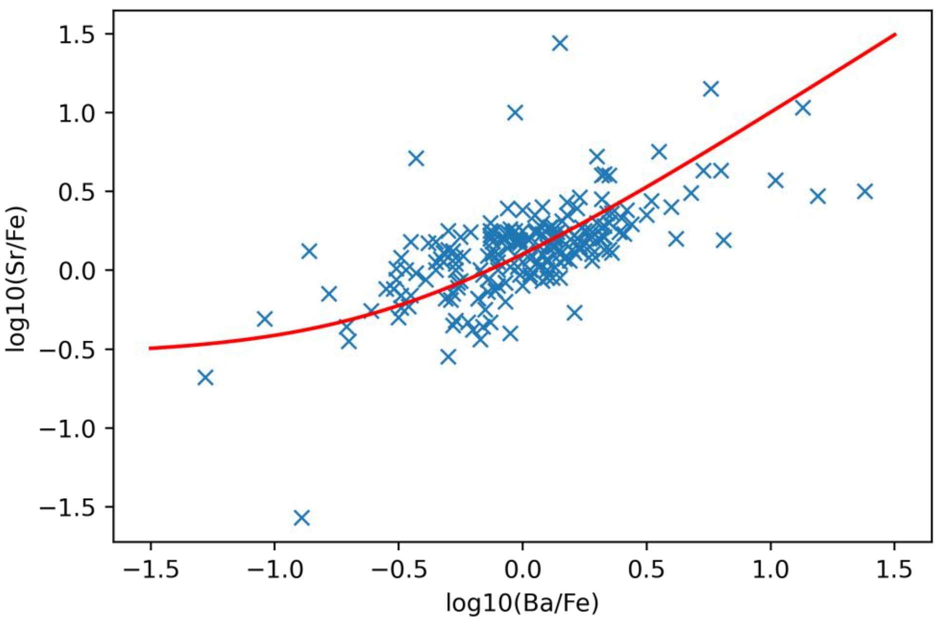
$$\left(\frac{Sr}{Fe}\right)_{star} = \left(\frac{Sr}{Fe}\right)_1 + \left(\frac{Sr}{Ba}\right)_2 \left(\frac{Ba}{Fe}\right)_{star} = 0.2889 + 0.976 \left(\frac{Ba}{Fe}\right)_{star}$$

- There should be a constant Ba/Eu ratio.

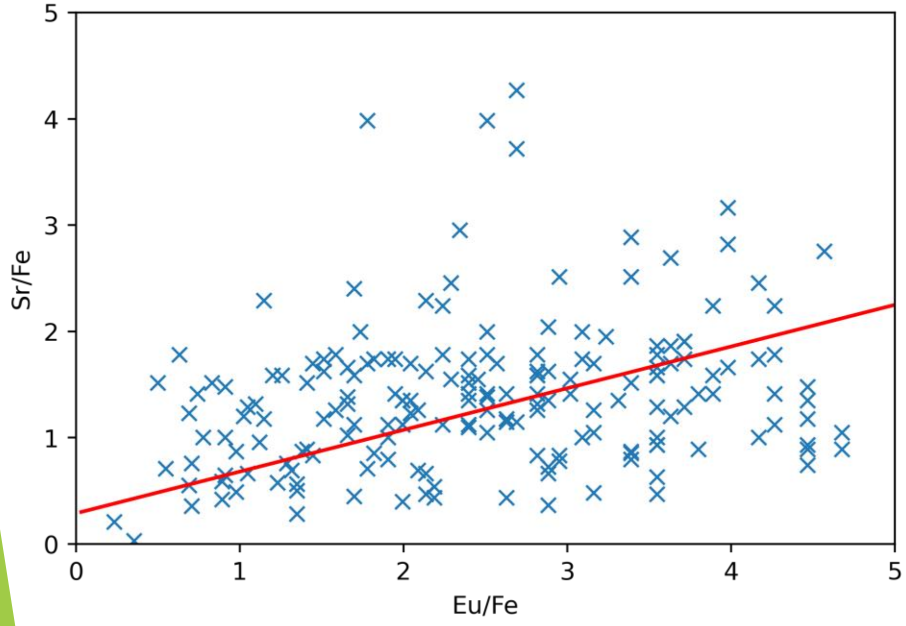
$$\left(\frac{Ba}{Eu}\right)_{star} = \left(\frac{Ba}{Eu}\right)_2 = 0.402$$

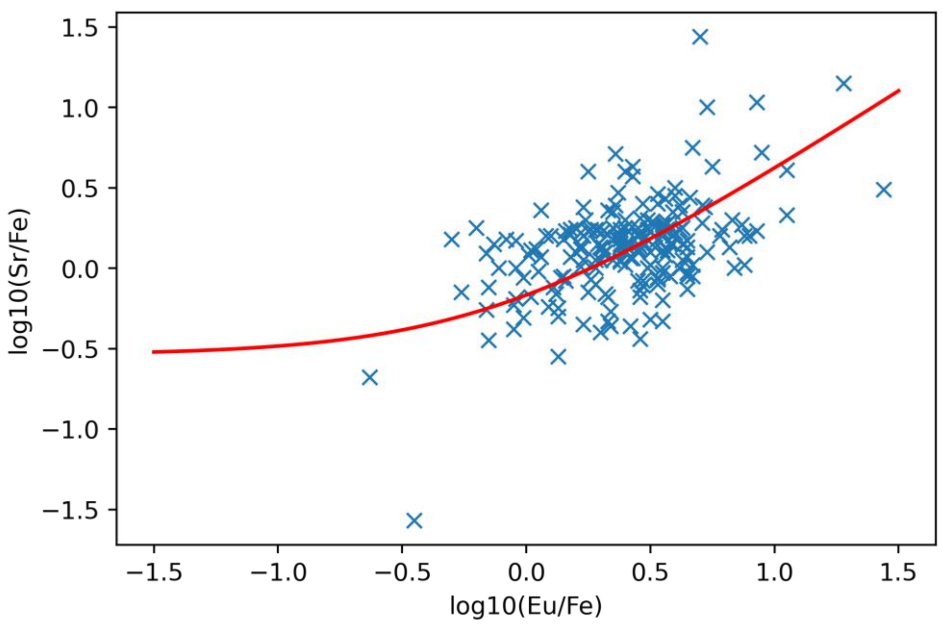
Sr/Fe vs Ba/Fe


Sr/Fe
Ba/Fe
0
1
2
3
4
5
0
1
2
3
4
5

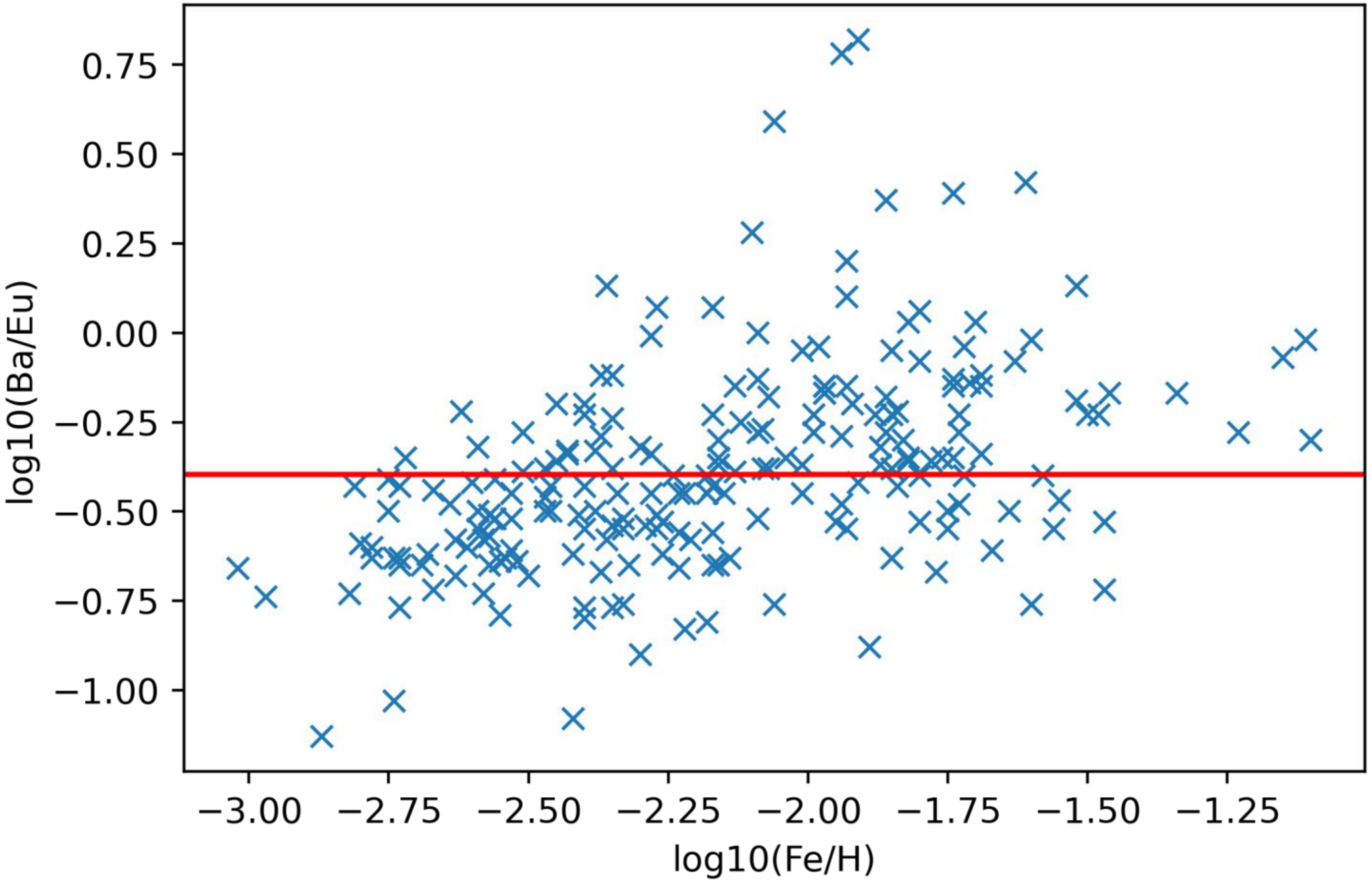

log10(Sr/Fe)
log10(Ba/Fe)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5

Sr/Fe vs Eu/Fe





Ba/Eu


0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
log10(Ba/Eu)
−3.00
−2.75
−2.50
−2.25
−2.00
−1.75
−1.50
−1.25
log10(Fe/H)

What is going on with high Ba/Eu values?

- ABG stars will start to have contributions around [Fe/H]~-2
- Additionally, there could be changes in the elemental abundances after star formation, which allows for influence from much more recent timescales.
- The most sensible thing to do is to prune these data points; our model does not explain them.
- We therefore remove all data points (16/211) which have (Ba/Eu)>1.0

New Templates with Pruned Data ([Ba/Eu]<0.0)

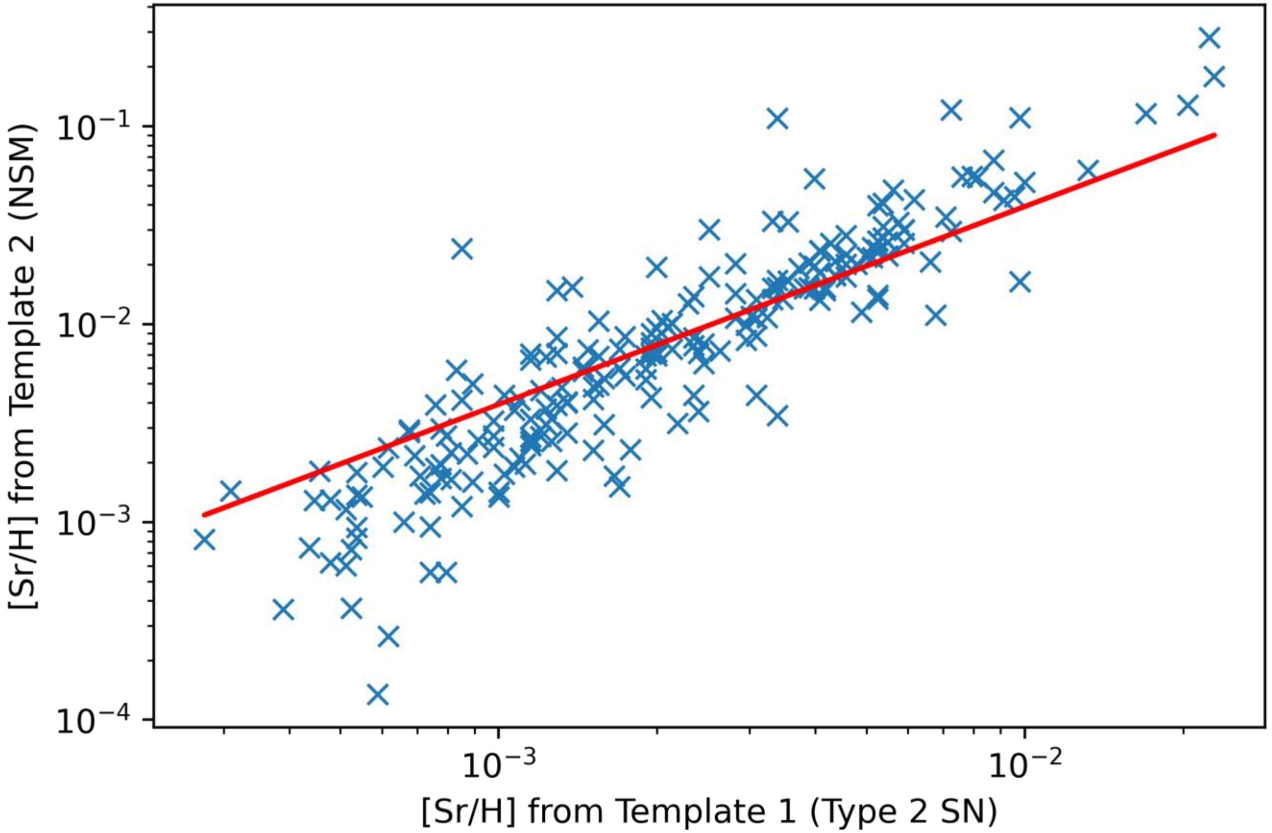
$$\begin{bmatrix} Fe/Sr \\ Sr/Sr \\ Ba/Sr \\ Eu/Sr \end{bmatrix} = \begin{bmatrix} 3.50 \\ 1.0 \\ 0.0 \\ 0.0 \end{bmatrix}, \begin{bmatrix} 0.0 \\ 1.0 \\ 1.01 \\ 2.71 \end{bmatrix}$$

- Our data sample has 195 stars: with an average error of 0.55σ
- In 141/195 (72.3%) of stars, all three measurements agree within 1σ
- In 189/195 (97.0%) of stars, all three measurements agree within 2σ
- In 192/195 (98.5%) of stars, all three measurements agree within 3σ

Mixing Ratio of Events

- There is additional information in the coefficients: the amount of each template. What can this tell us about event sizes and frequency?
- Three relevant parameters:
  - X: The amount of (Sr/H) produced by a single supernova event
  - Y: The amount of (Sr/H) produced by a single neutron star merger event
  - F: The frequency of neutron star merger events relative to supernova events
- We would expect X/(YF) to be constant, and equal to ratio of the average amount of Sr obtained from supernova to Sr obtained from neutron star mergers.

Strontium Production Ratio



$$\frac{X}{YF} = 0.255 \pm 0.02$$

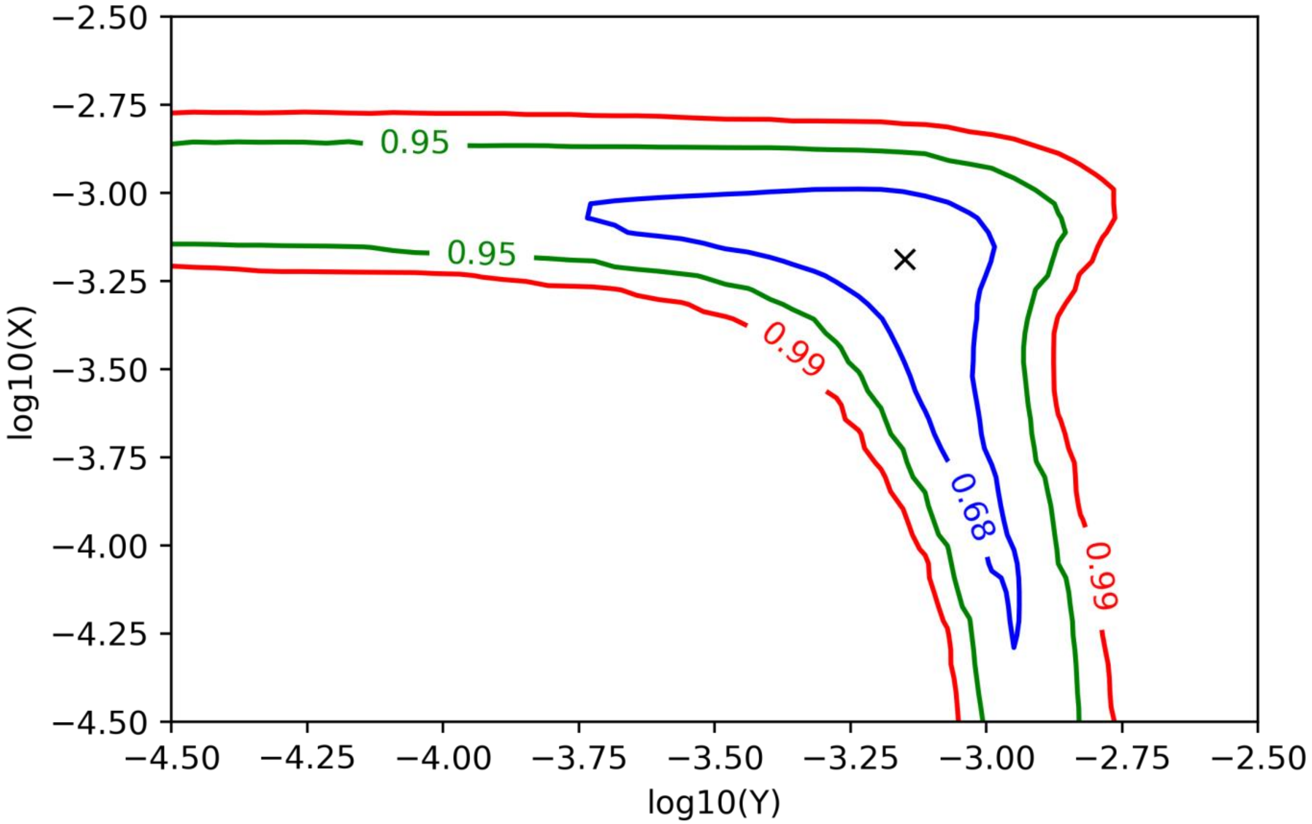
What about event size?

- We can calculate the probability we get N_1 Supernova events with N_2 Neutron Star Merger events given the relative frequency F:

$$P(N_1, N_2) = \frac{(N_1 + N_2)!}{N_1!\,N_2!}\left(\frac{F}{F+1}\right)^{N_2}\left(\frac{1}{F+1}\right)^{N_1}$$

- We can use this to calibrate the size of the events: if events are too small, the spread of the data will be probabilistically impossible, and if events are too big, the data doesn’t have enough spread.

Event Sizes



- Practically, Neutron Star Mergers are much less common than Type II Supernovae, which suggests F<<1, and therefore log10(Y) ~ -3 and log10(X) << -3

Conclusions

- The data can be well fit by a model with two types of events: one which produces dominantly Fe and Sr, which we identify as Type II Supernovae, and one which produces dominantly Sr, Ba, and Eu, which we identify as Neutron Star Mergers.
- The data includes some anomalous (Ba/Eu) measurements, which could be created through processes that can not be modelled by this simple formulation.
- The mixing data suggests that Neutron Star Mergers must produce approximately 4 times as much Sr as Supernovae.
- Additionally, the variance of the mixing suggests that at least one of the events must have a large yield (log10(Sr/H)~ -3), which given the relative frequency of the two events, must be Neutron Star Mergers.