Playing Your CARDs Right: Constraining the Origin of r-Process Elements Using "One-shot" Enriching Stellar Generation Models

Duane M. Lee
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FORGING CONNECTIONS WORKSHOP - 06/28/2017

JINA-CEE

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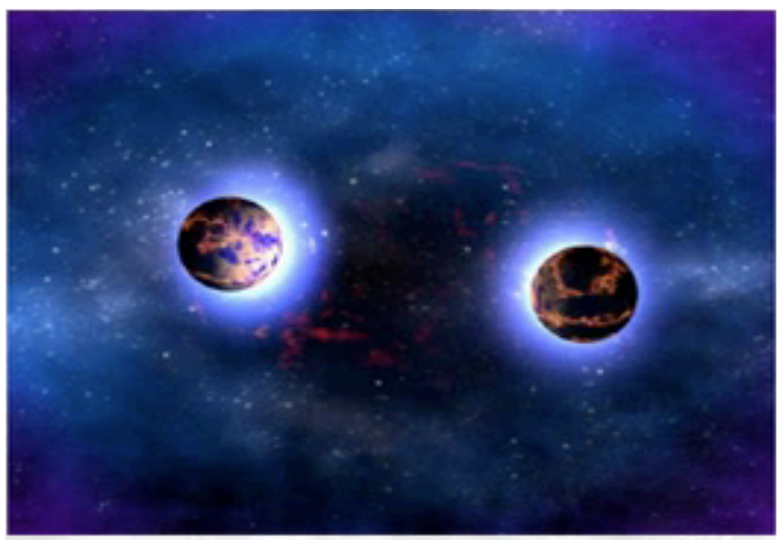
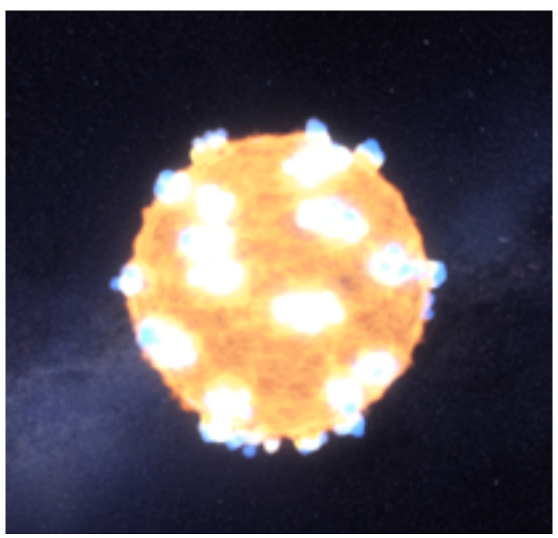


Neutron Star Mergers

VS



(Rare) Core-Collapse SN

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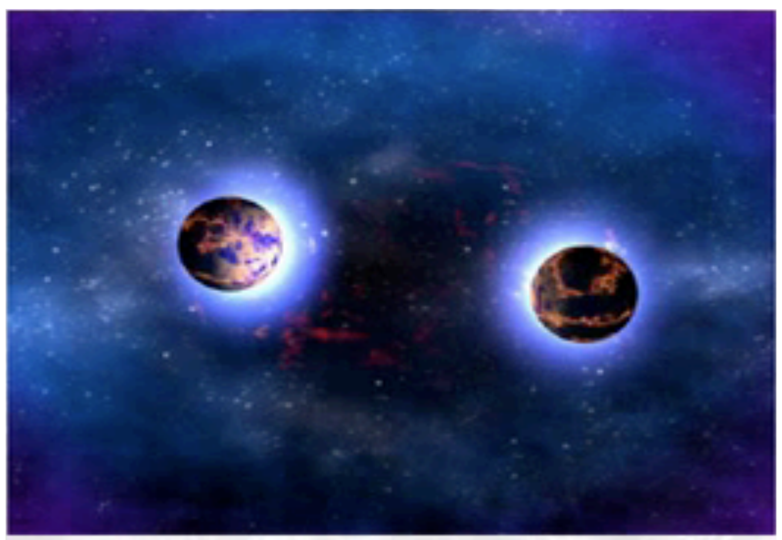

Neutron Star Mergers

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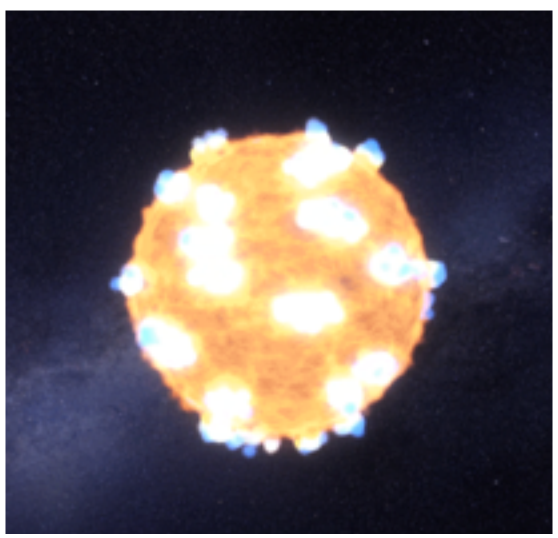

(Rare) Core-Collapse SN

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Overview

- Origin of the r-process: NSMs vs CCSN
- "One-shot" models vs other galactic chemical evolution (GCE) models
- Previous results from one-shot models for CCSN mass-dependent yields *only*
- Some current results including NSMs in one-shot models
- What's needed to forge better models?

Neutron Star Mergers Vs Core-Collapse Supernovas

Pros (origin of r-process)

- NSMs readily provide high neutron densities for the r-process
- NSMs are rare events
- CCSN are *less* rare than NSM events
- CCSN *likely* occur with much greater variety than NSMs (i.e.,yields)
- Rare CCSN *may* provide favorable conditions for the r-process

Cons (*not* origin of r-process)

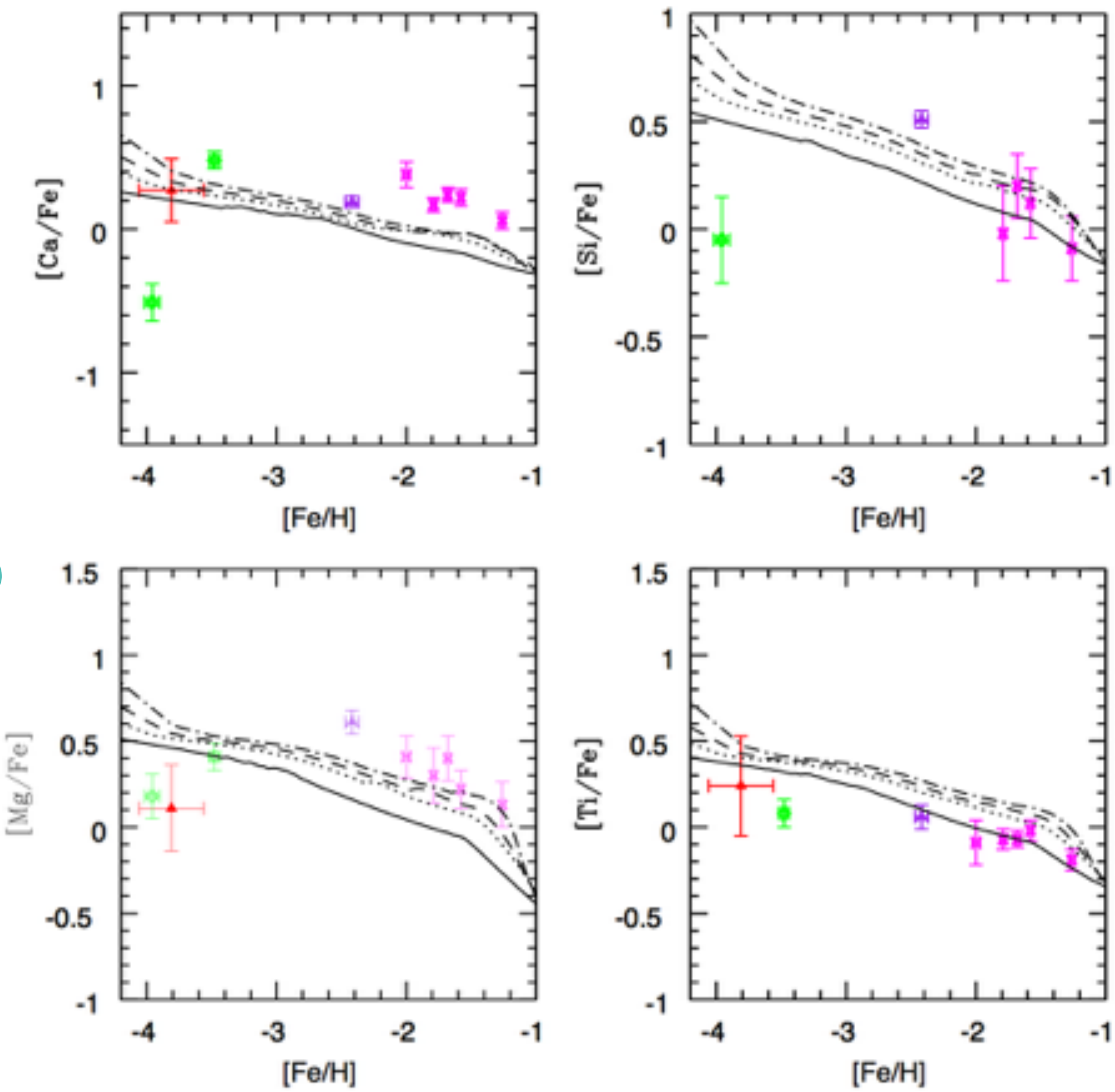
- NSMs may be *too* rare
- NSMs rely on CCSN as precursors (i.e., rare event on top of rare event)
- NSMs receive escape velocity kicks which may *drag* ejecta out of a dwarf galaxy
- CCSN *do not* readily provide high neutron densities for the r-process

Some Semi-Analytic Galactic Chemical Evolution Models

Vincenzo et al. (2014)

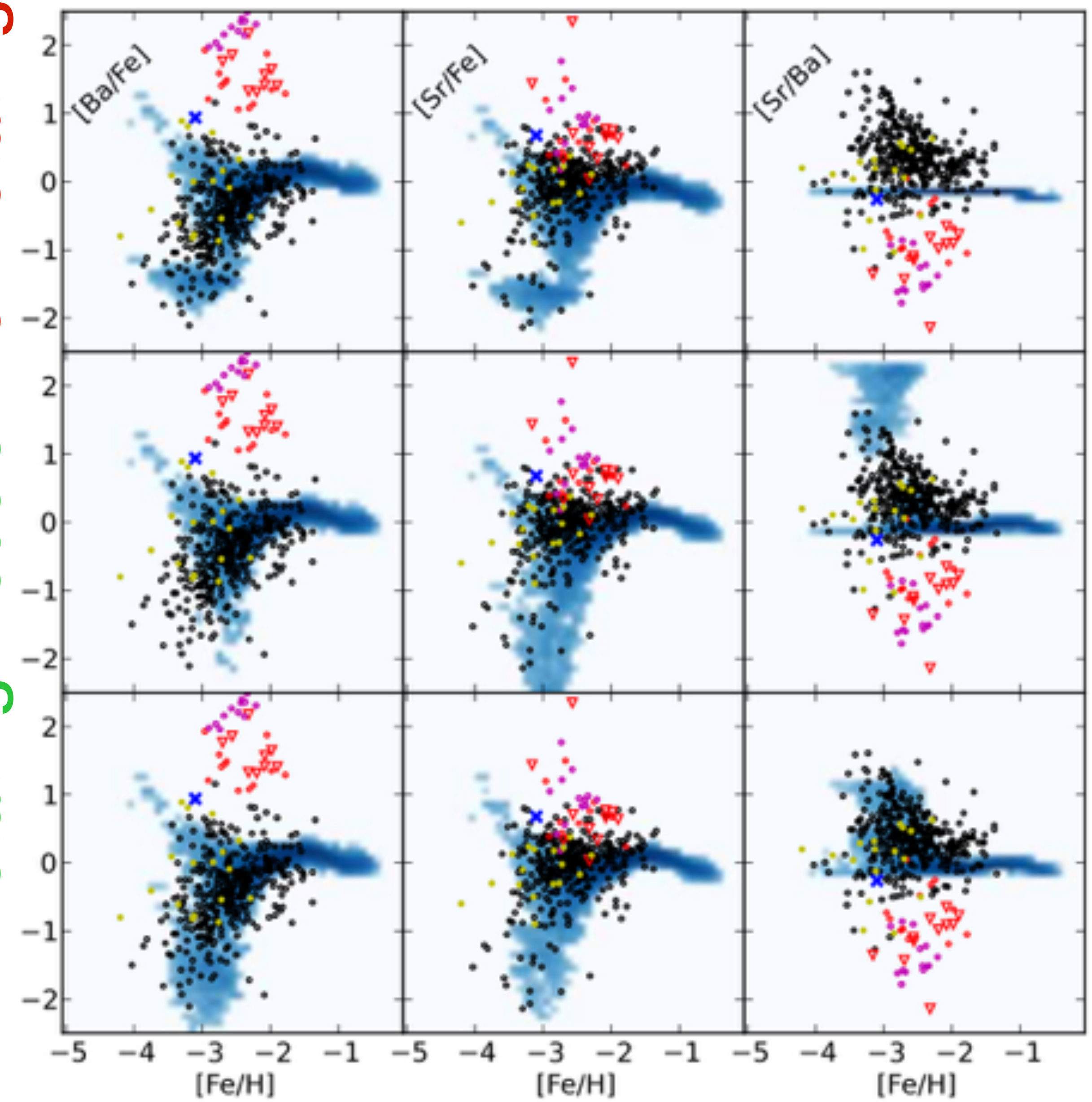
Cescutti & Chiappini (2013)

IMF-averaged GCE tracks



non-rotating

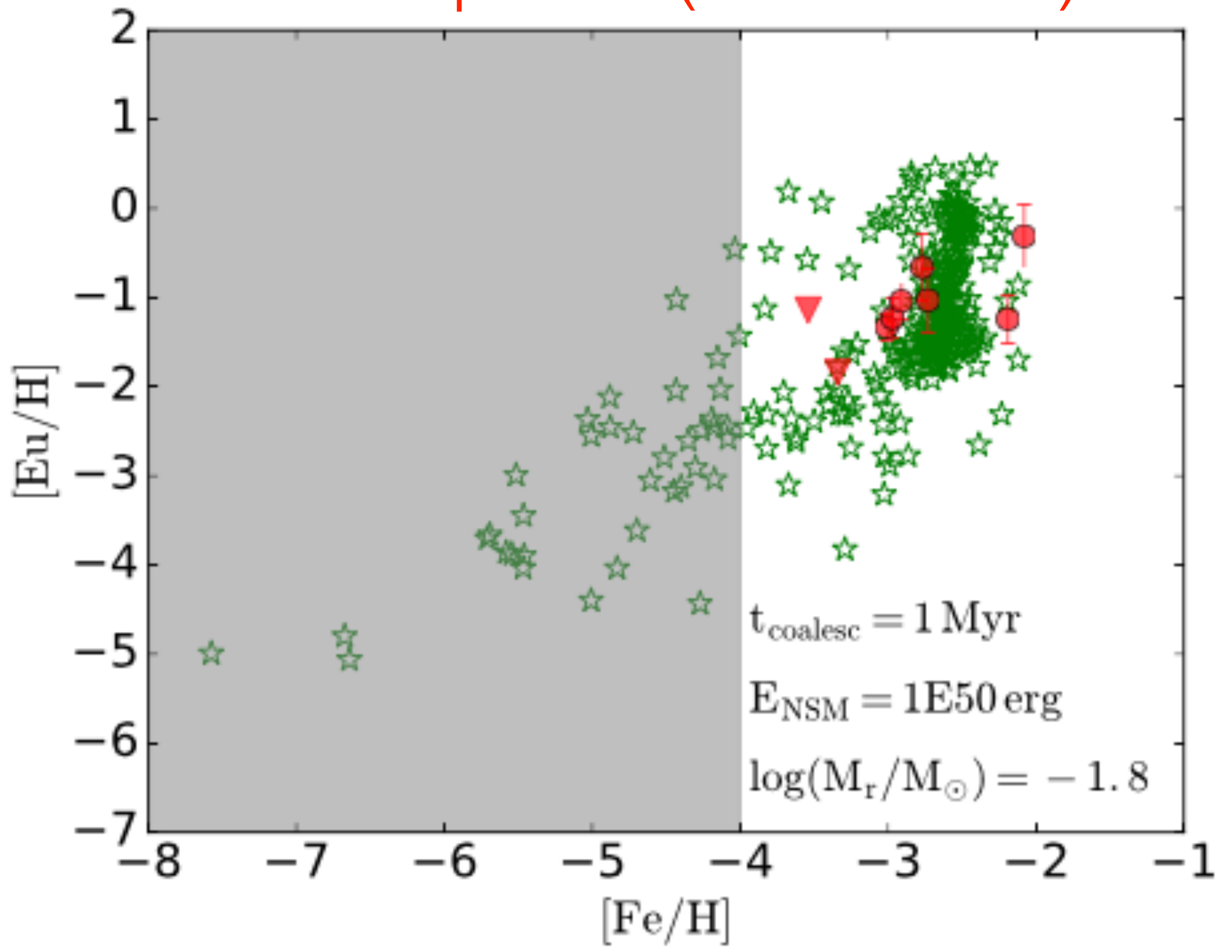
rotating models



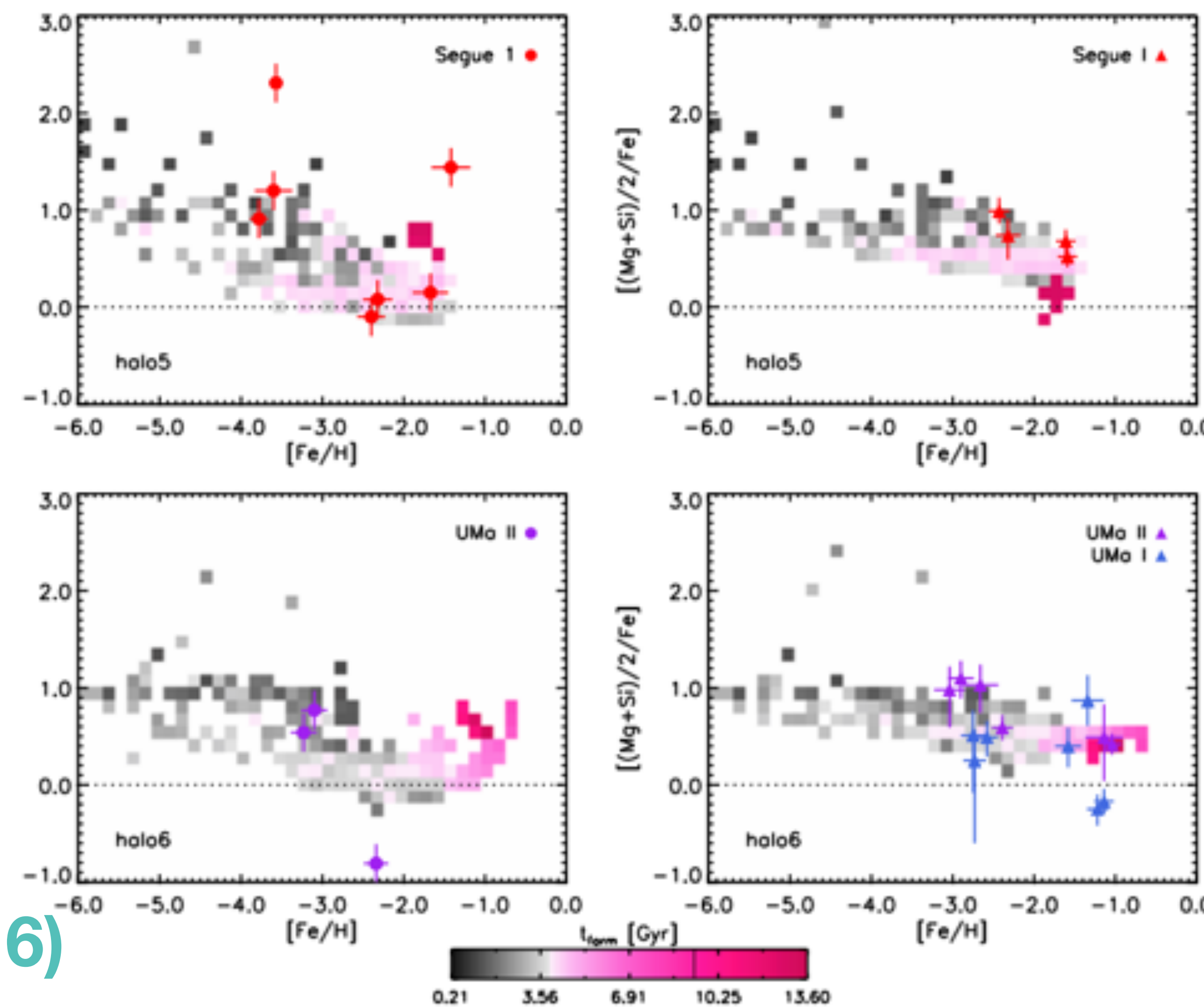
- Previous work does not attempt to use CARD densities to work out SFHs or derive n-capture yield constraints

Some Hydrodynamic Galactic Chemical Evolution Models

Safarzadeh & Scannapieco (submitted)



Jeon, Besla & Bromm (2017)

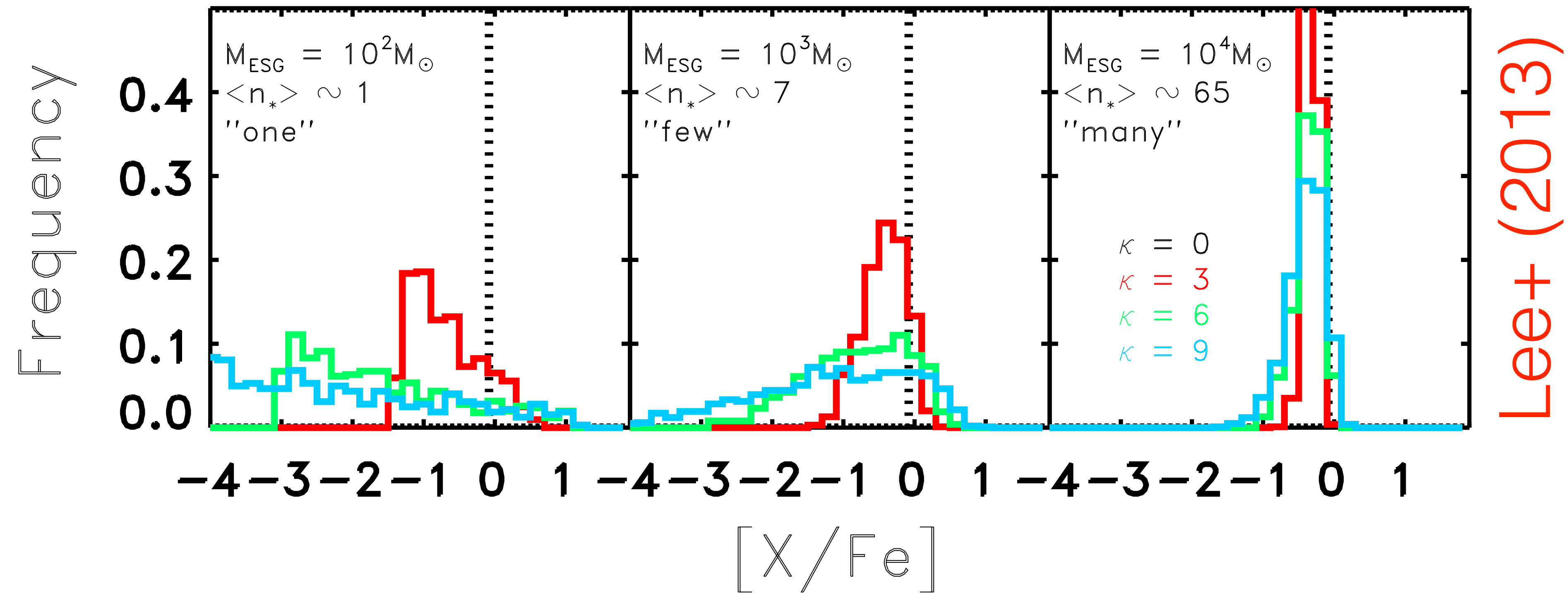


Red stars from Ret II (Ji et al. 2016)

- Some attempt to use CARD densities to work out SFHs or derive n-capture yield constraints

One-shot Galactic Chemical Evolution Models

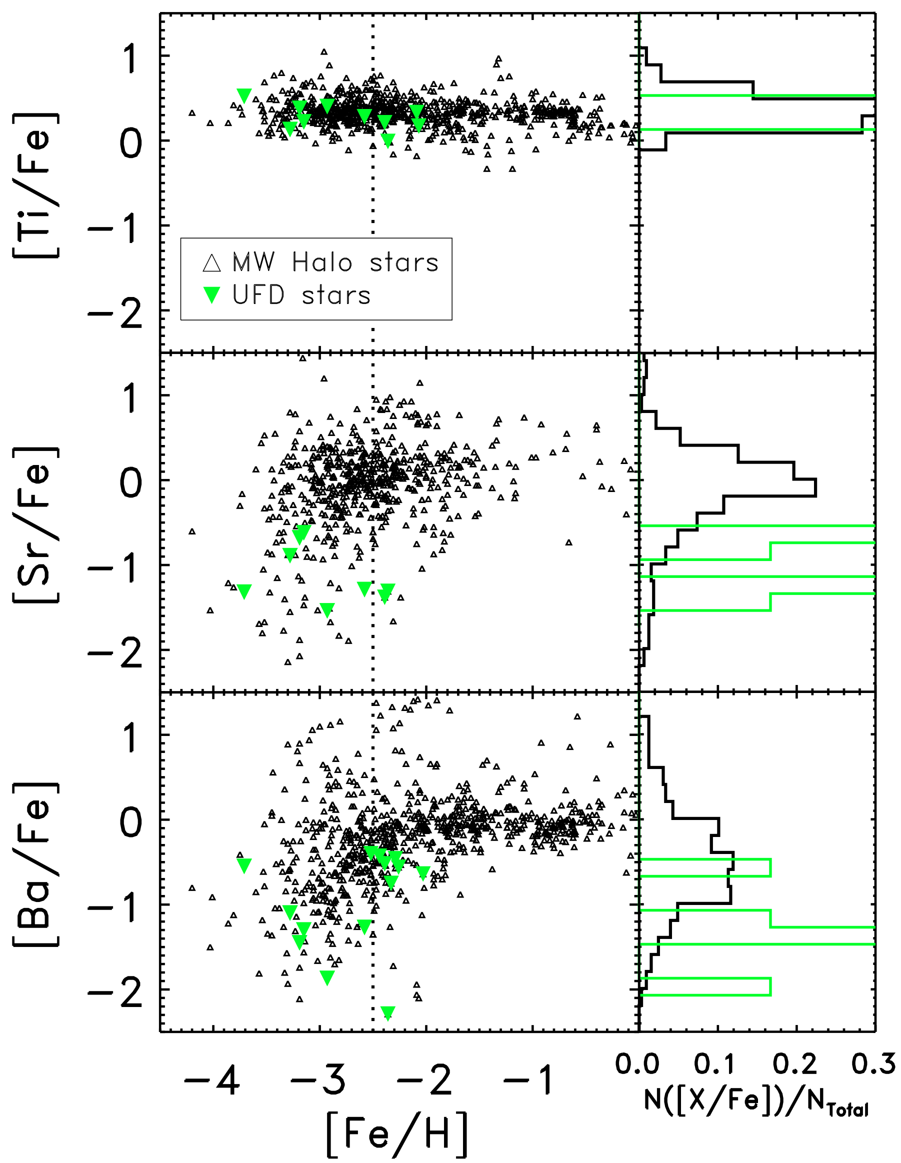
- What do I mean by "one-shot" models?
  - Assume that low-mass dwarf galaxies had a "few" *important* epochs (~2-3) of stellar enrichment (i.e. UFDs / ~VMP halo)
  - Stochastically sample a given mass of stars (M_{ESG}) from the IMF
  - Treat the sample as a one-zone, instantaneously mixed, model realization of "fossilized" enrichment using mass-dependent yields (κ)
  - Repeat many times to generate a *parent* chemical abundance ratio distribution (CARD)

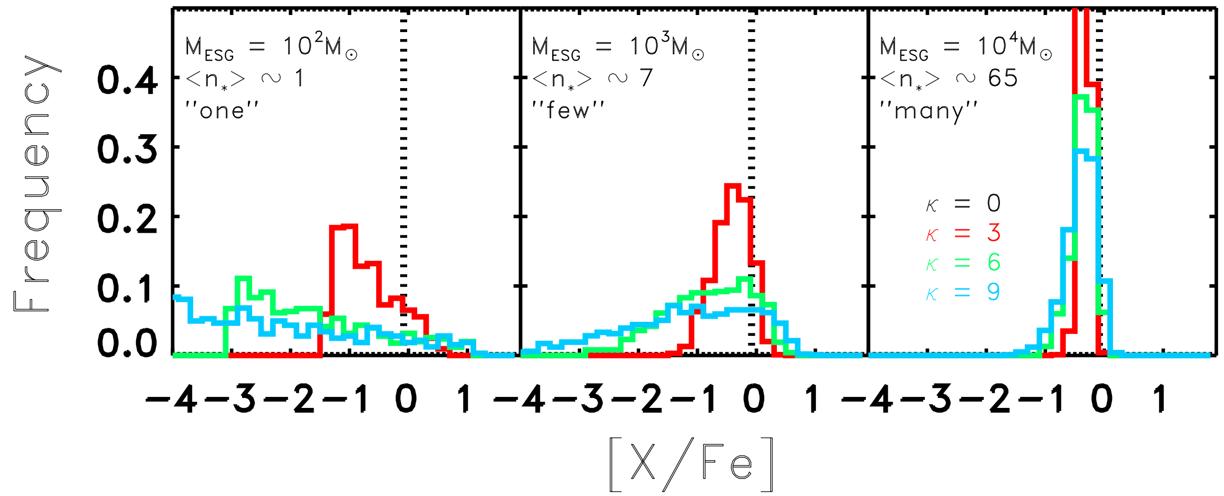


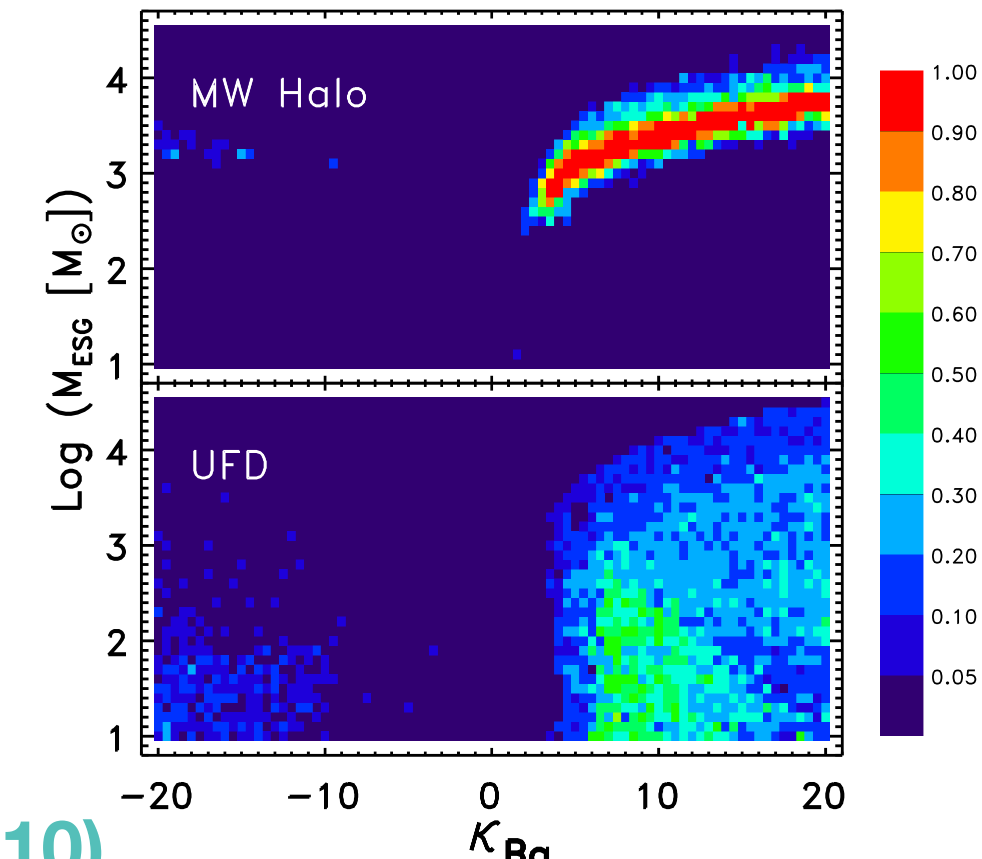
- Statistically data-centric approach using CARD densities to work out SFHs or derive n-capture yield constraints

One-shot Galactic Chemical Evolution Models

Lee+ (2013)





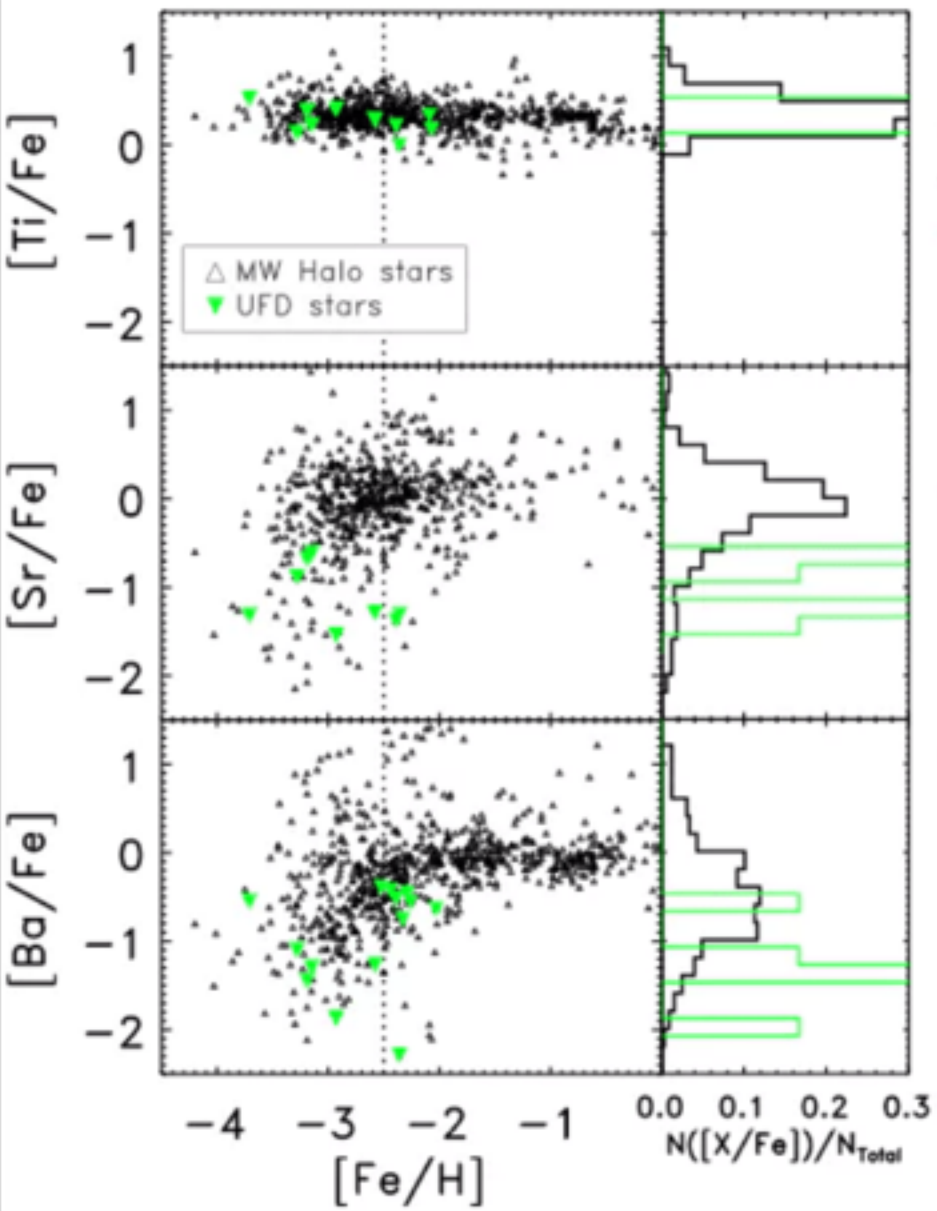


Data from MW & UFDs (Frebel 2010)

- Statistically data-centric approach using CARD densities to work out SFHs or derive n-capture yield constraints

One-shot Galactic Chemical Evolution Models

Future & Ongoing Work - Initial Application of CARD Analysis to Data (Lee+ 2013)

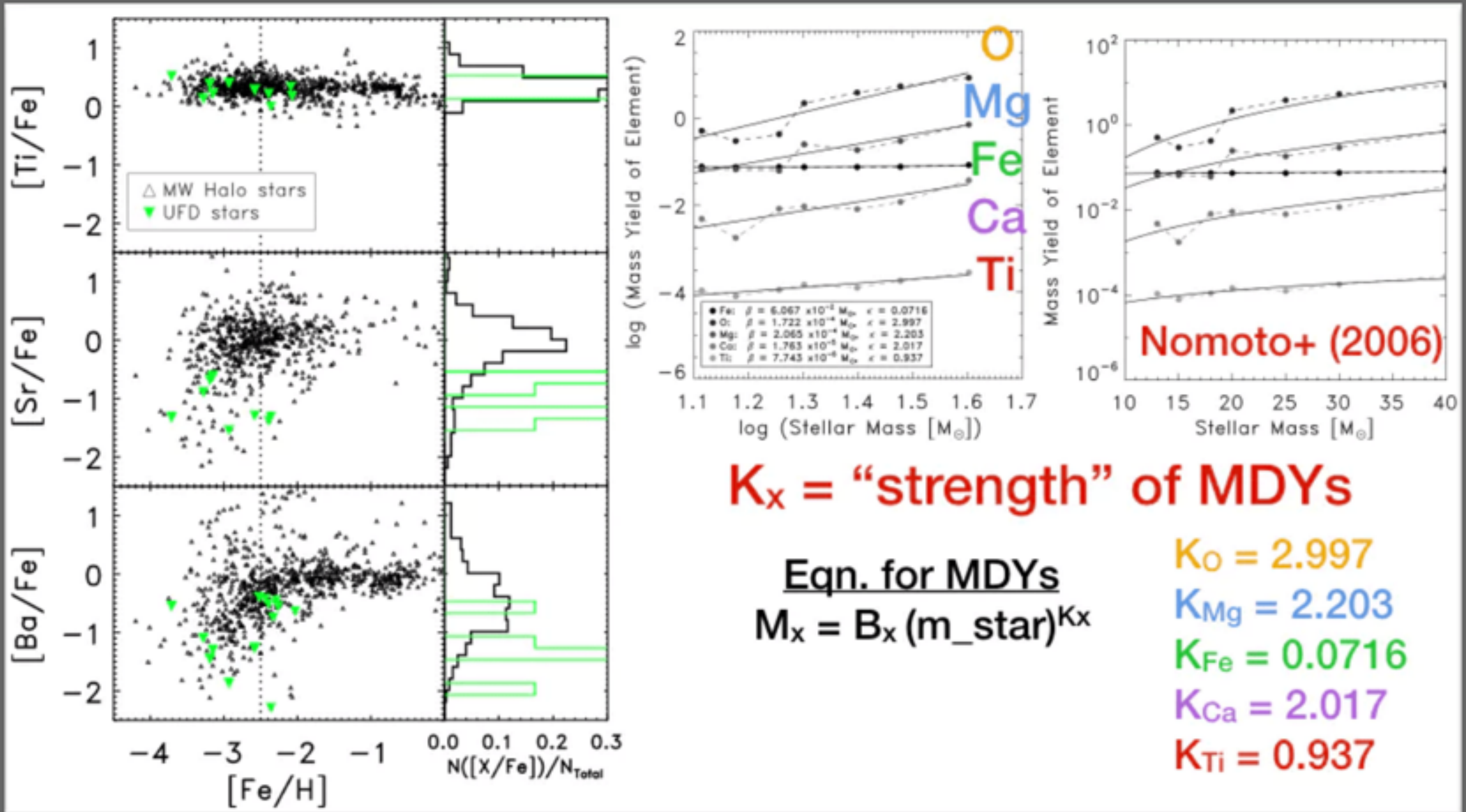


What is needed to fit observations?

- Stochastic Sampling of IMF (Salpeter)
- Stronger MDYs for n-capture elements than for alpha-elements
- Progenitor enriching stellar generations (M_ESG) are more massive for VMP MW Halo stars than for UFD stars

One-shot Galactic Chemical Evolution Models

Future & Ongoing Work - Initial Application of CARD Analysis to Data (Lee+ 2013)



K_X = "strength" of MDYs

Eqn. for MDYs

$M_X = B_X (m\_star)^{K_X}$

$K_O = 2.997$

$K_{Mg} = 2.203$

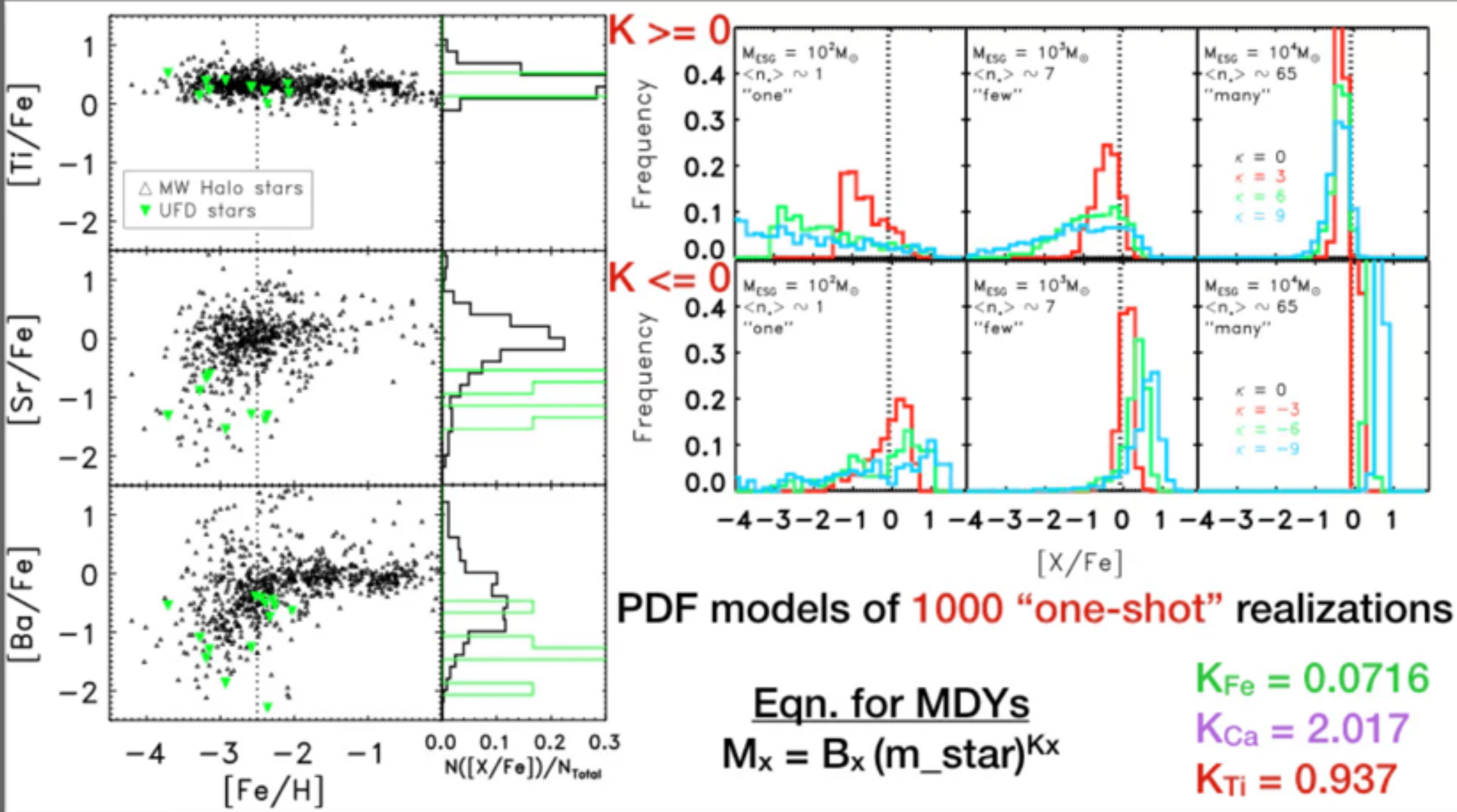
$K_{Fe} = 0.0716$

$K_{Ca} = 2.017$

$K_{Ti} = 0.937$

One-shot Galactic Chemical Evolution Models

Future & Ongoing Work - Initial Application of CARD Analysis to Data (Lee+ 2013)



PDF models of 1000 "one-shot" realizations

Eqn. for MDYs

$M_x = B_x (m\_star)^{K_x}$

$K_{Fe} = 0.0716$

$K_{Ca} = 2.017$

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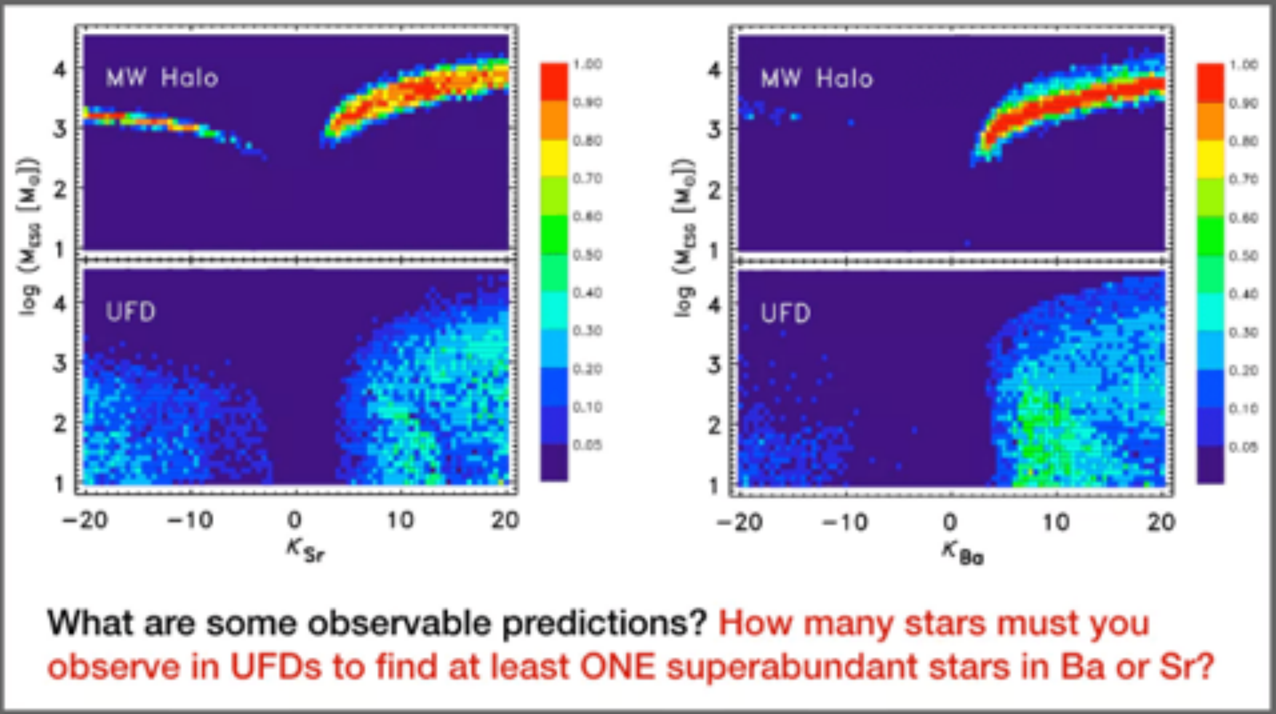
One-shot Galactic Chemical Evolution Models

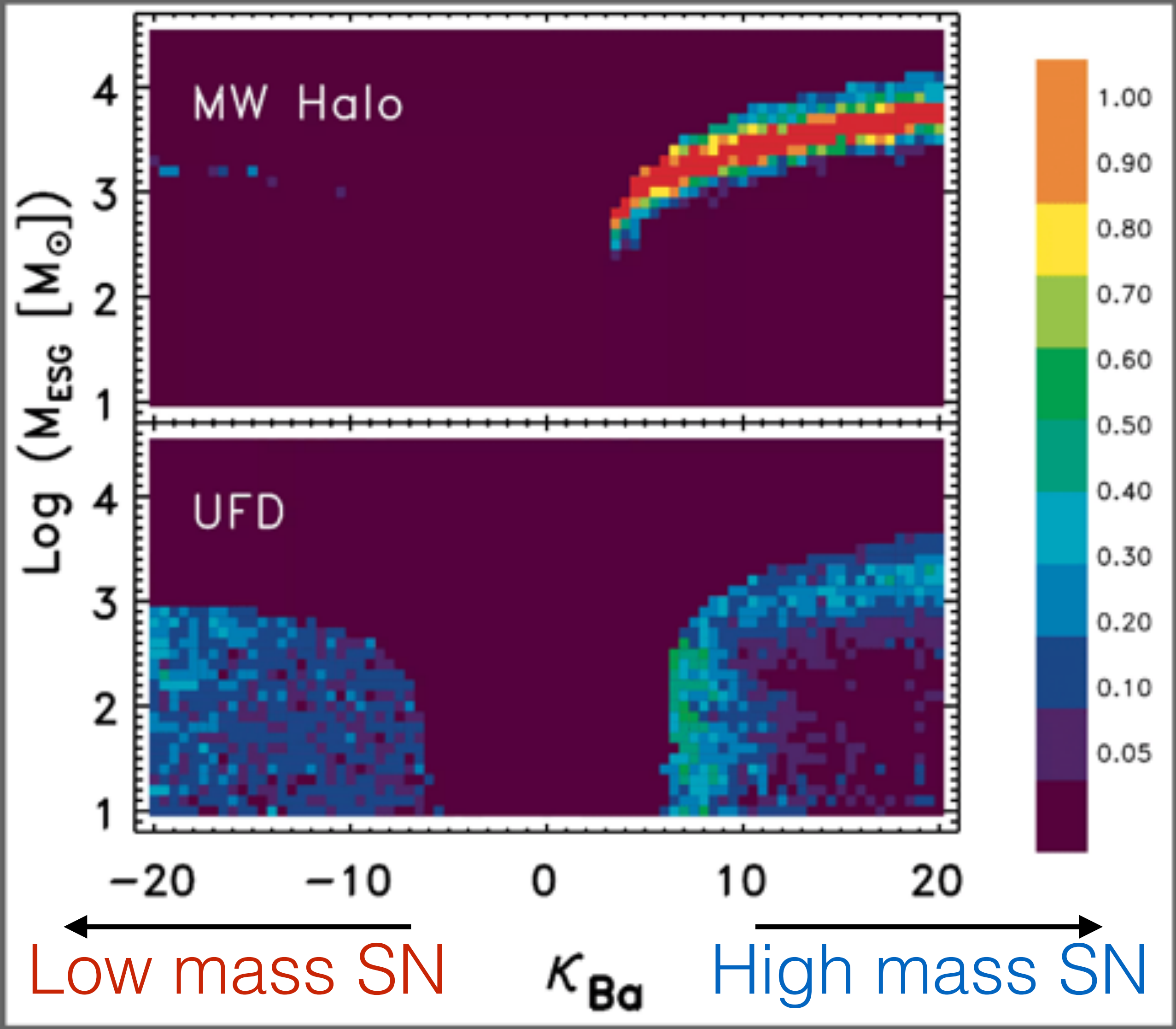
Some results for CCSN MDYs



Old 2013 results - less focused p-value landscape

Using 6 UFD stars only!

Note: MDYs need to be consistent for both UFD + MW halos progenitors

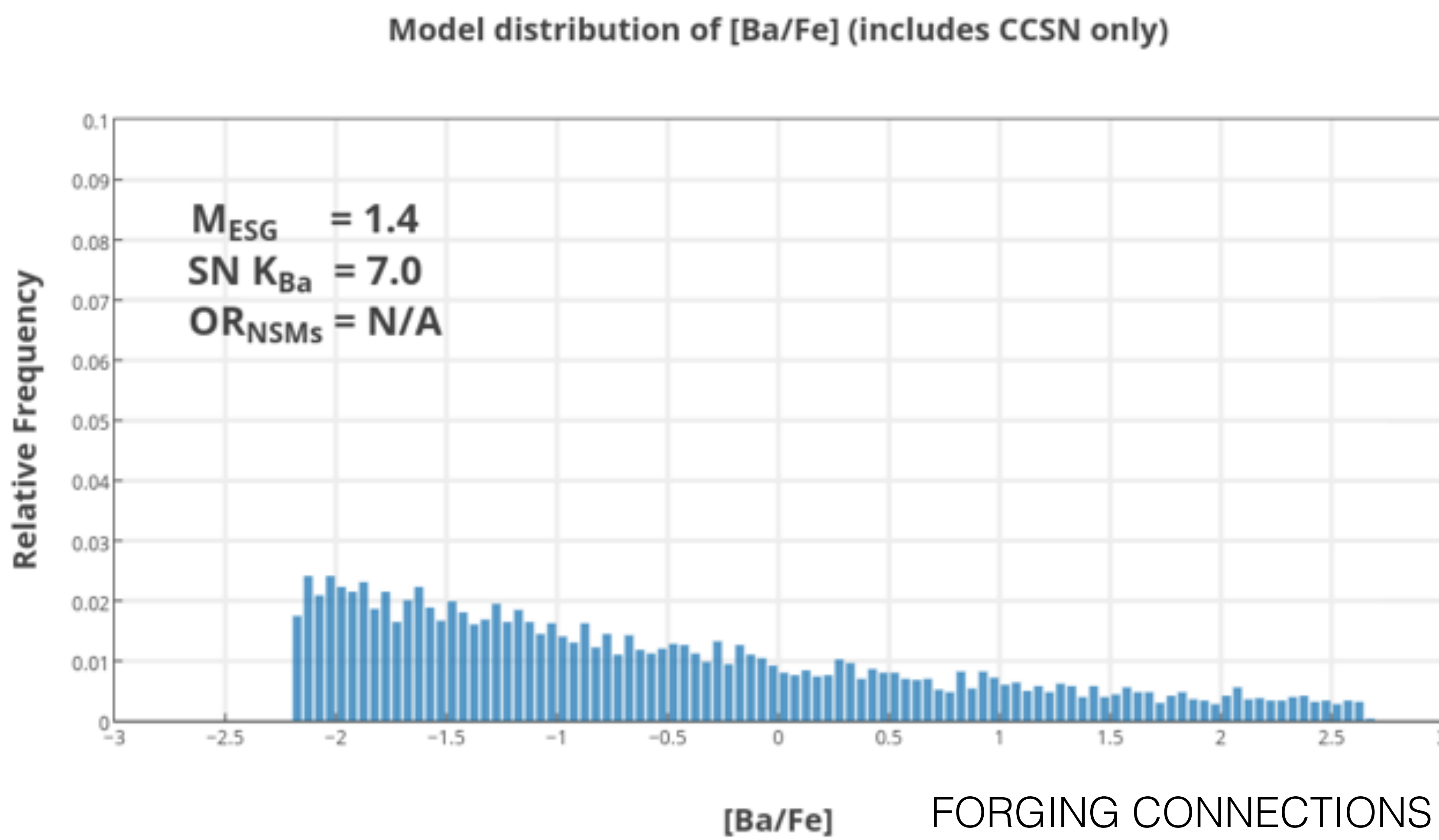


New results -> Models favor K_{Ba}= 7.0 and M_{ESG} = 3.2 & 1.4 dex using 18 Ba stars below [Fe/H] < -2.5 dex

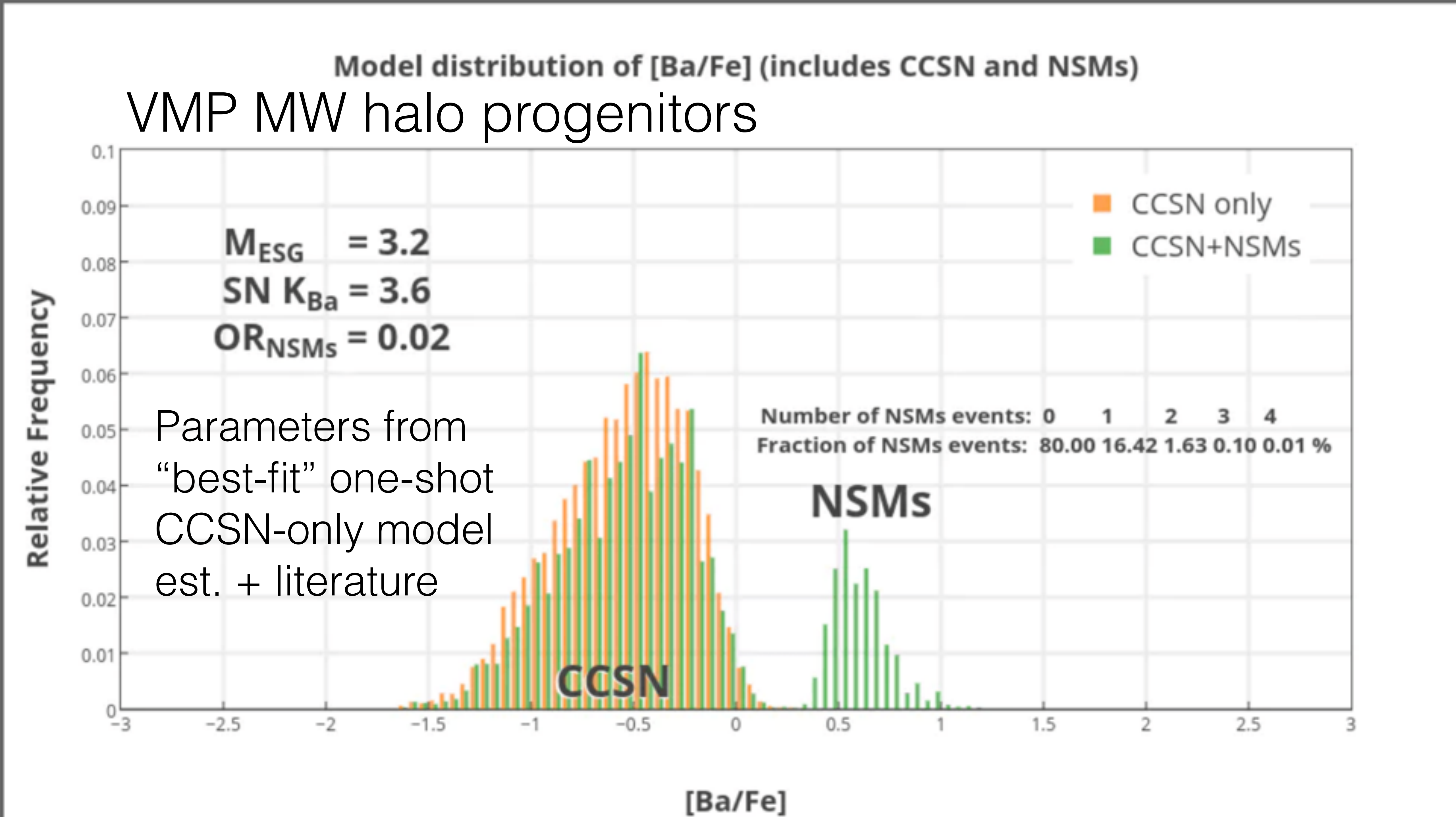
Using 18 UFD stars!

One-shot Galactic Chemical Evolution Models

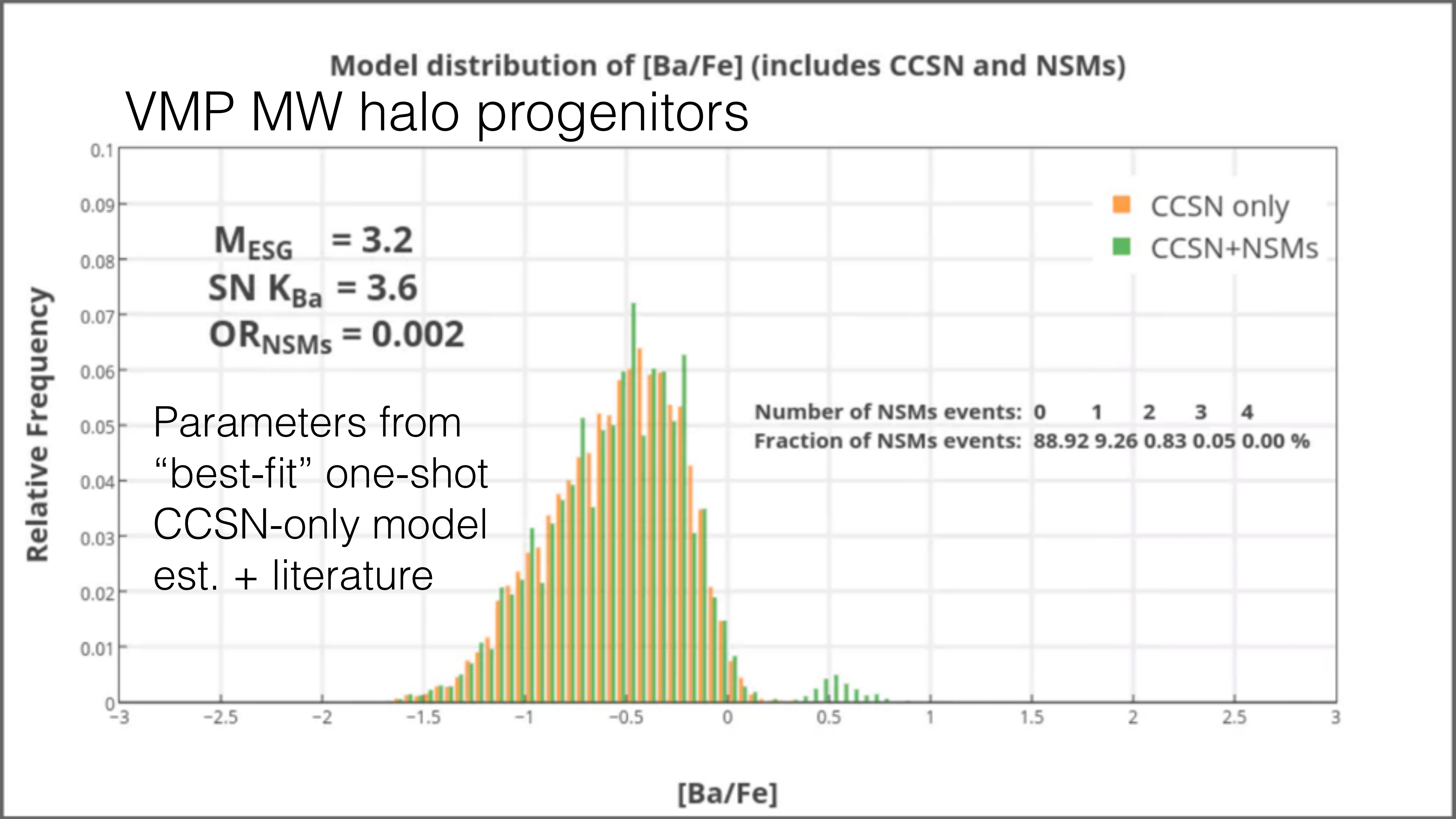
- How are NSMs added to "one-shot" models?
  - Note: The models are normalized by calculating the <[X/Fe]$_{model}$> zero offset+<[X/Fe]$_{obs}$> of the highest M_{ESG} (=$10^{4.5}$) with k = 0
  - 10,000 realizations of CCSN-only models are post processed to include NSMs via binomial sampling from N_{SN} for each realization
  - Here I use M_{Ba} ~ 10^{-3} $M_\odot$ as an example; however, would also compare with Eu data as well … models would explore a range in mass



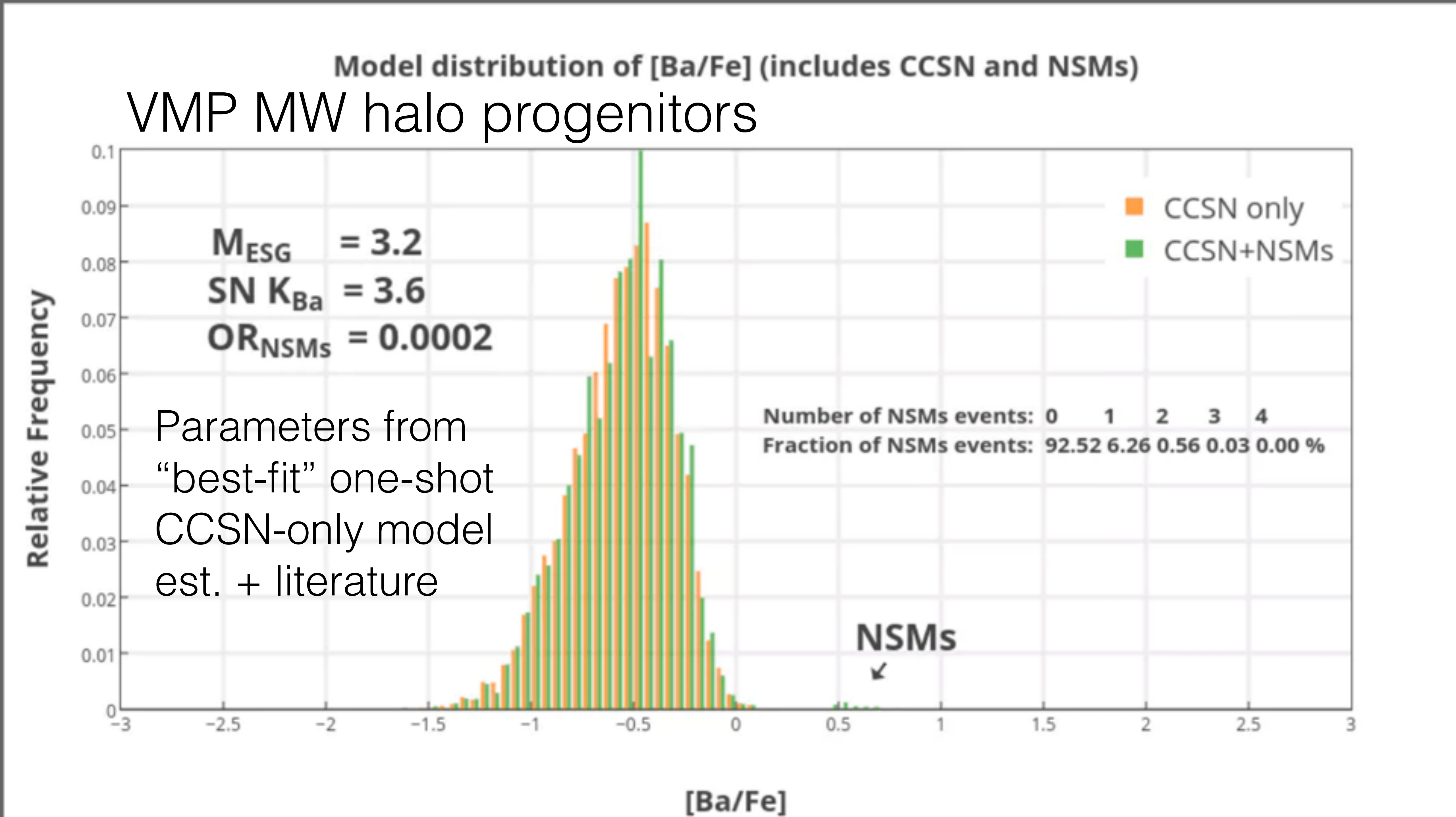
One-shot Galactic Chemical Evolution Models



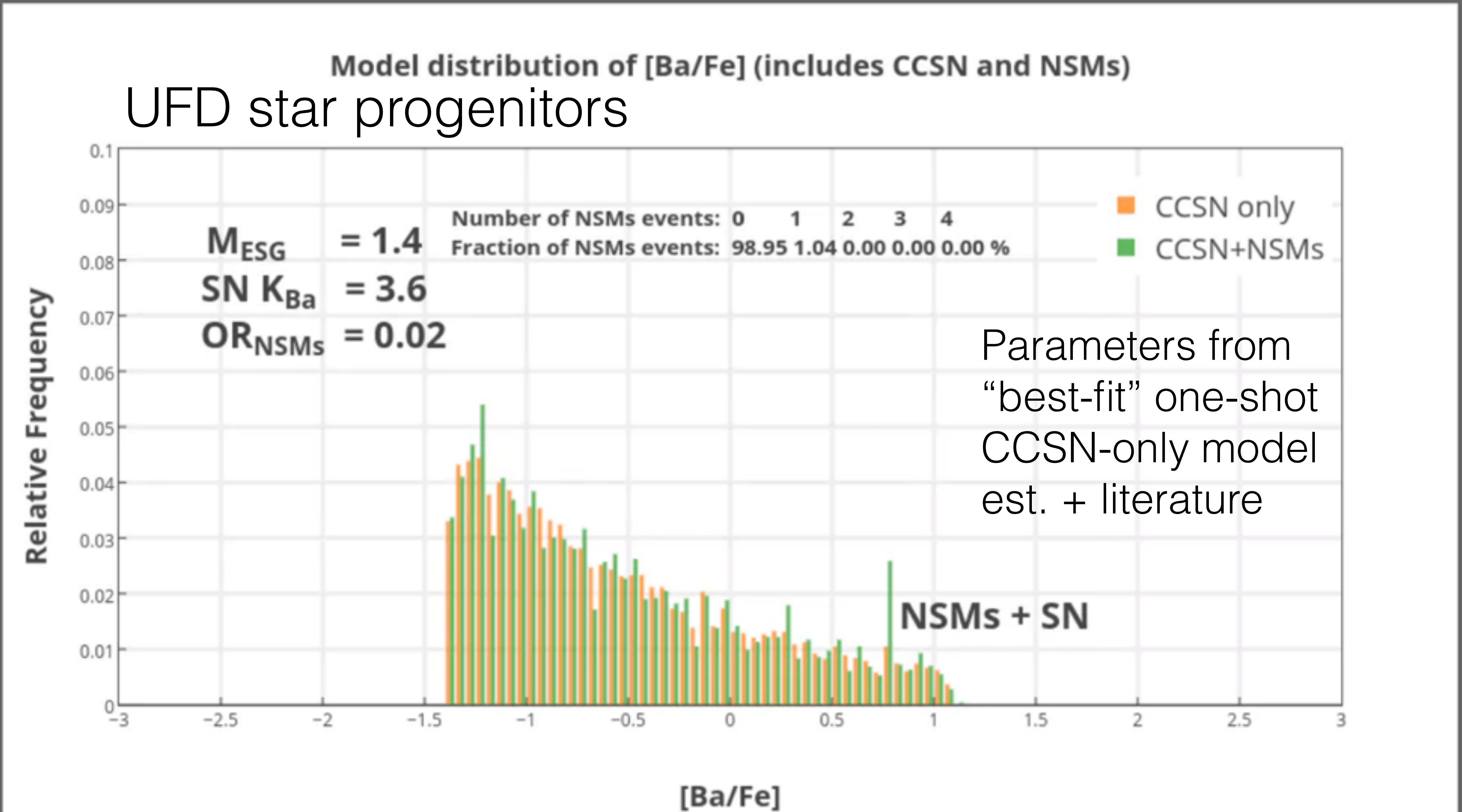
One-shot Galactic Chemical Evolution Models



One-shot Galactic Chemical Evolution Models

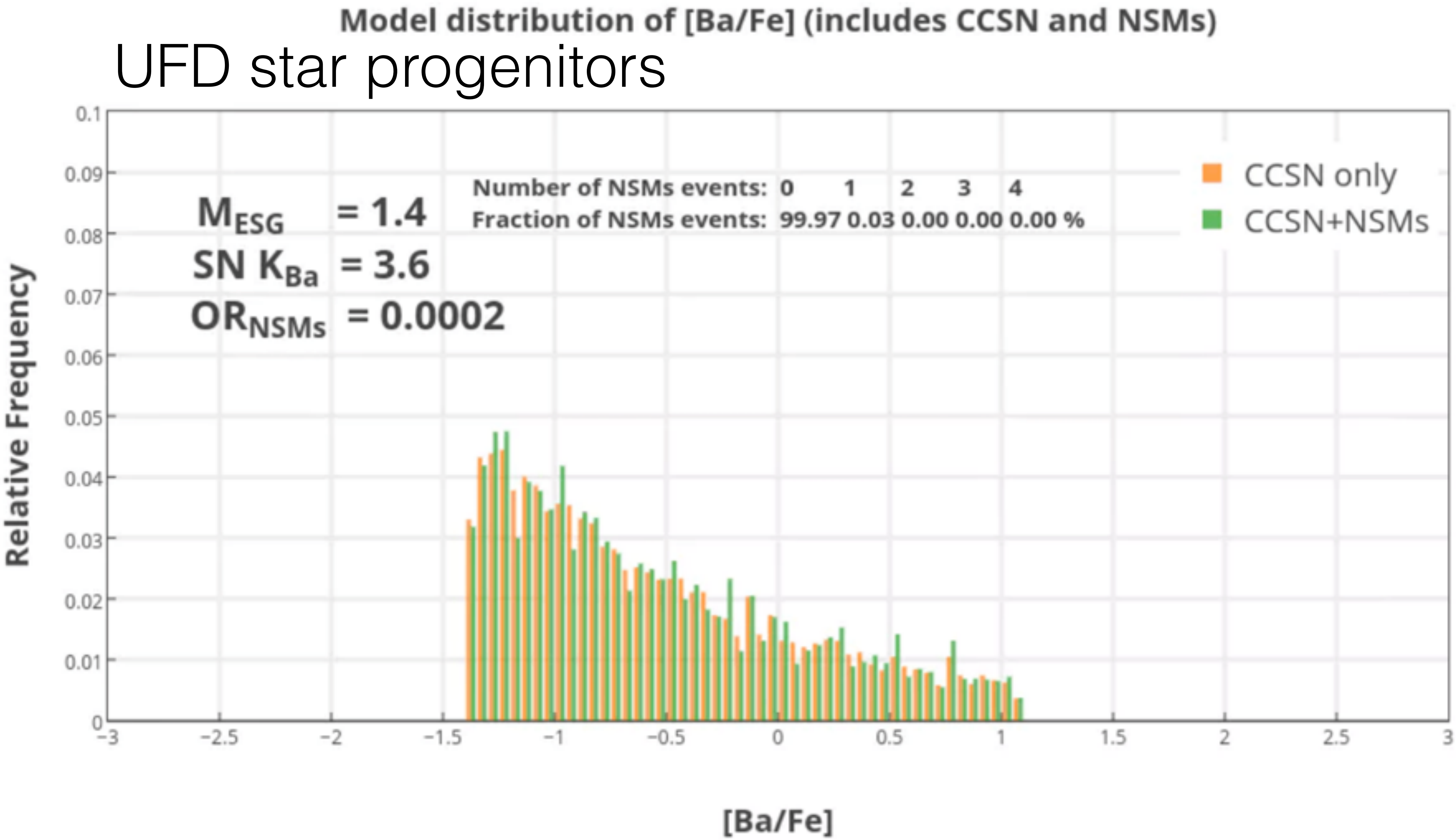


One-shot Galactic Chemical Evolution Models

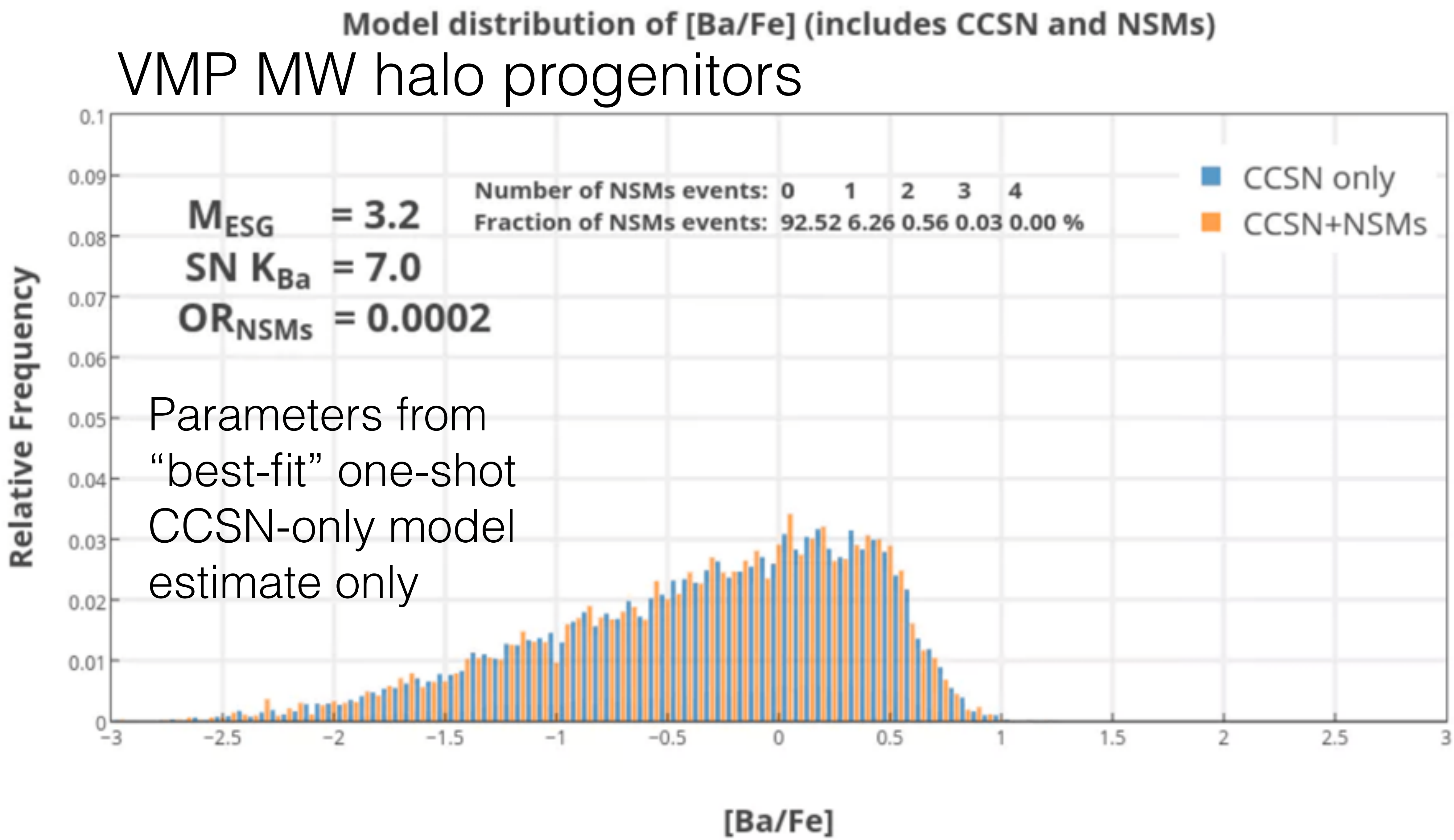


One-shot Galactic Chemical Evolution Models

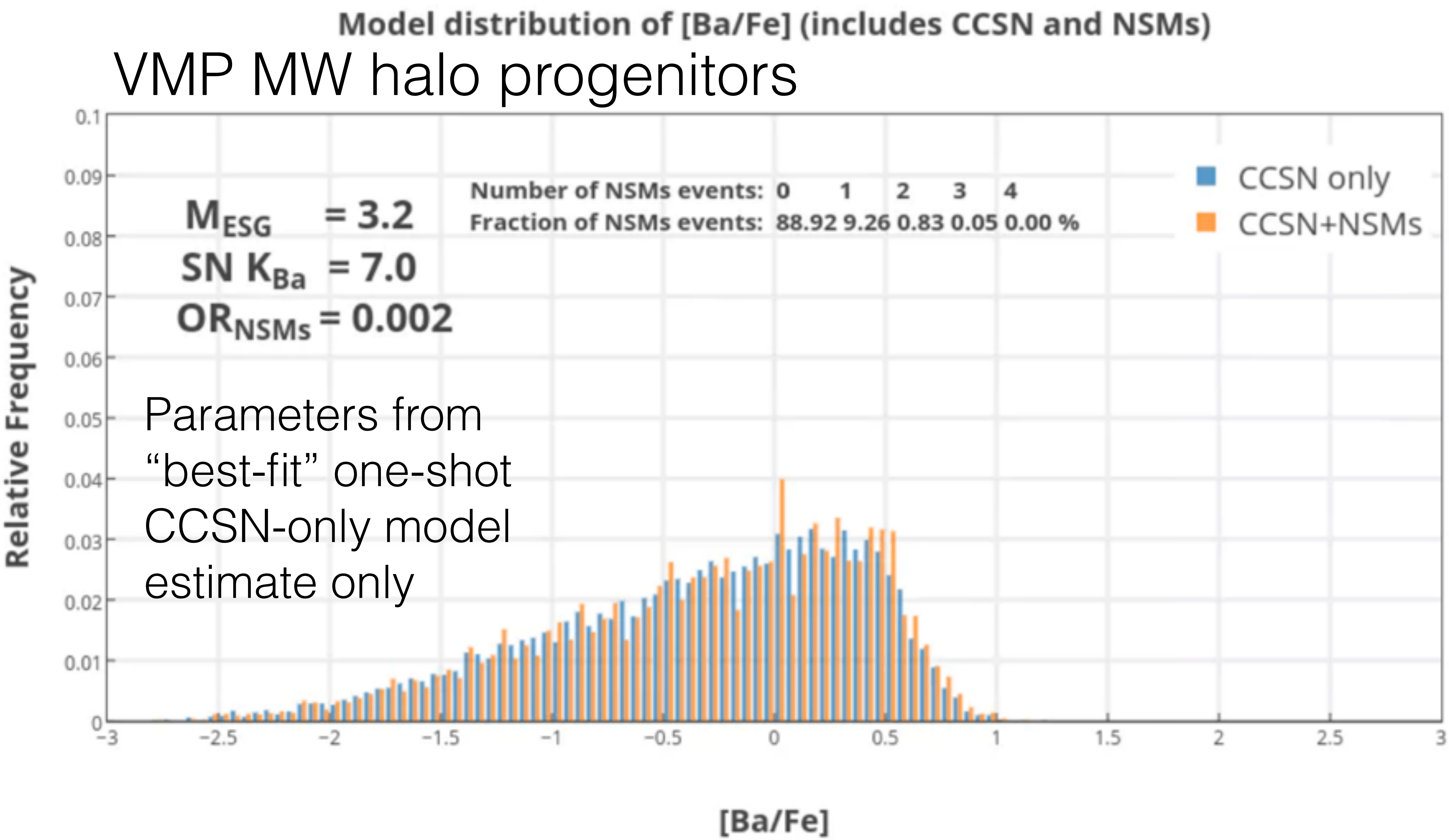
UFD star progenitors



One-shot Galactic Chemical Evolution Models

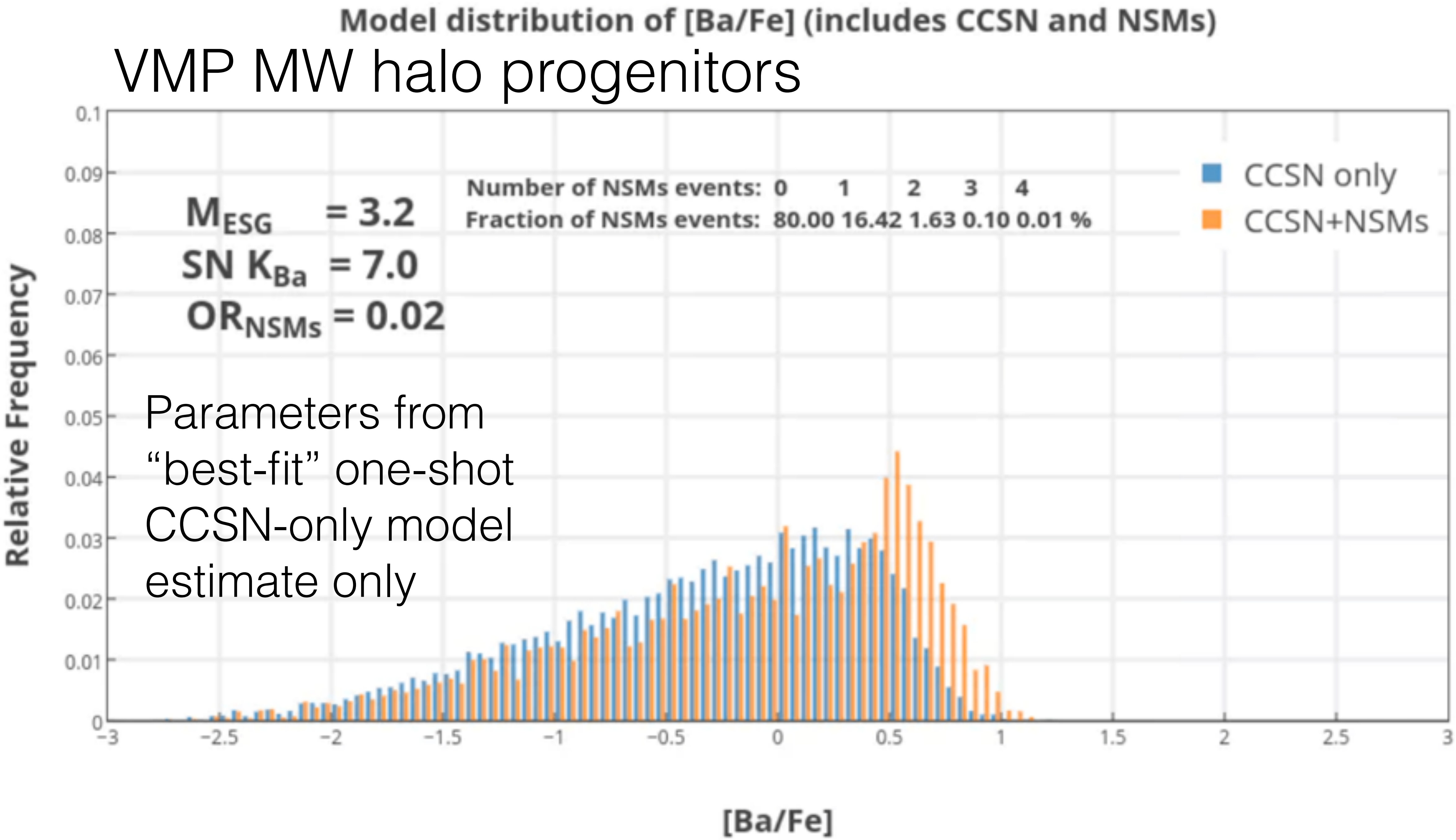


One-shot Galactic Chemical Evolution Models



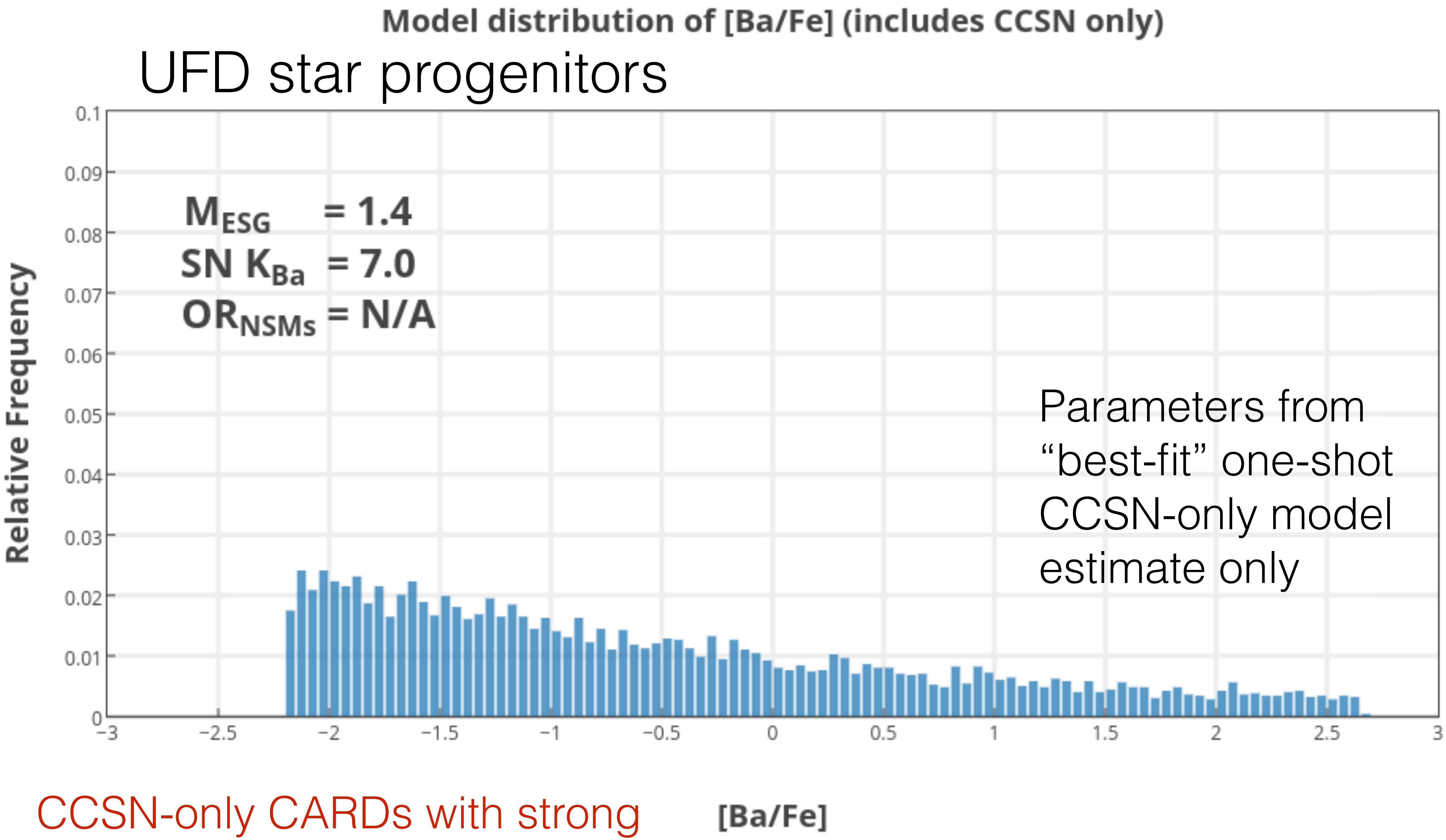
One-shot Galactic Chemical Evolution Models

VMP MW halo progenitors



Parameters from "best-fit" one-shot CCSN-only model estimate only

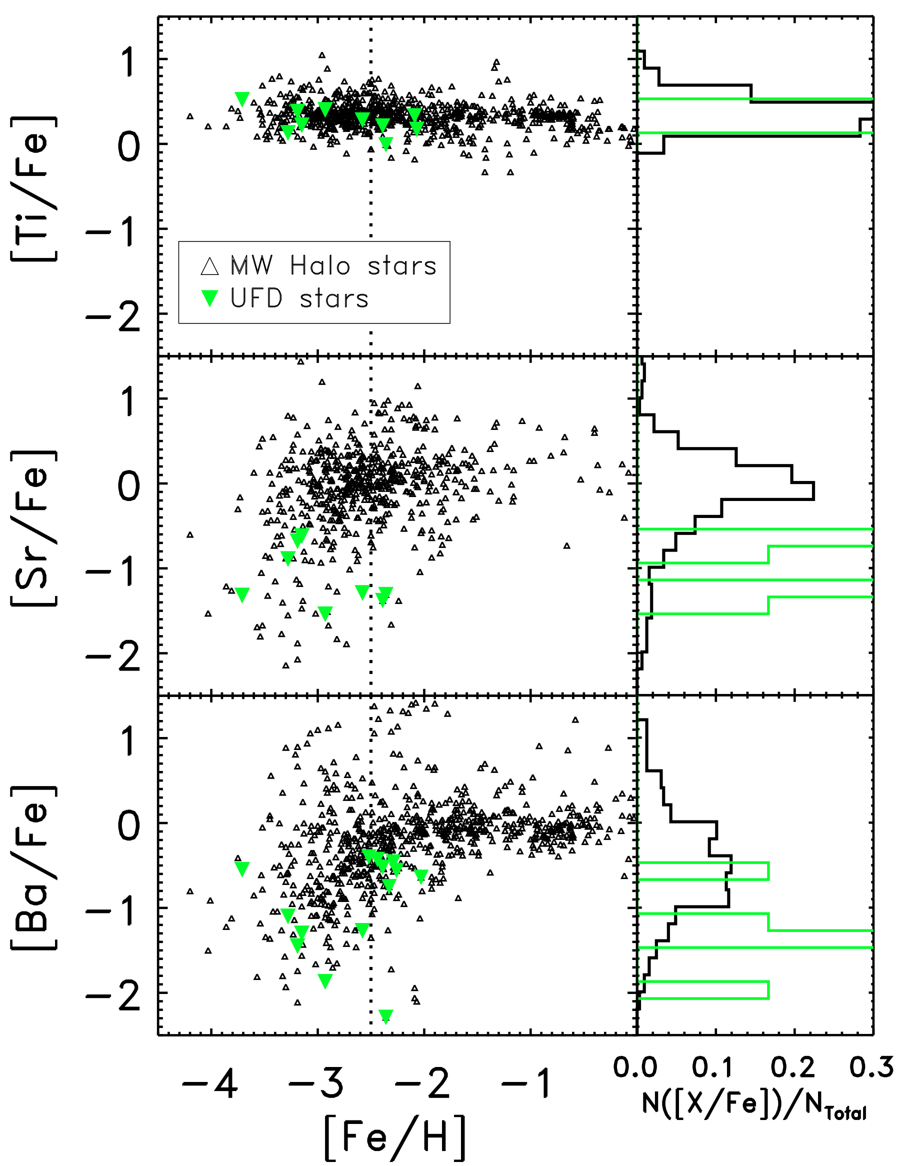
One-shot Galactic Chemical Evolution Models



CCSN-only CARDs with strong Ba MDYs are identical to the CCSN+NSM distribution!

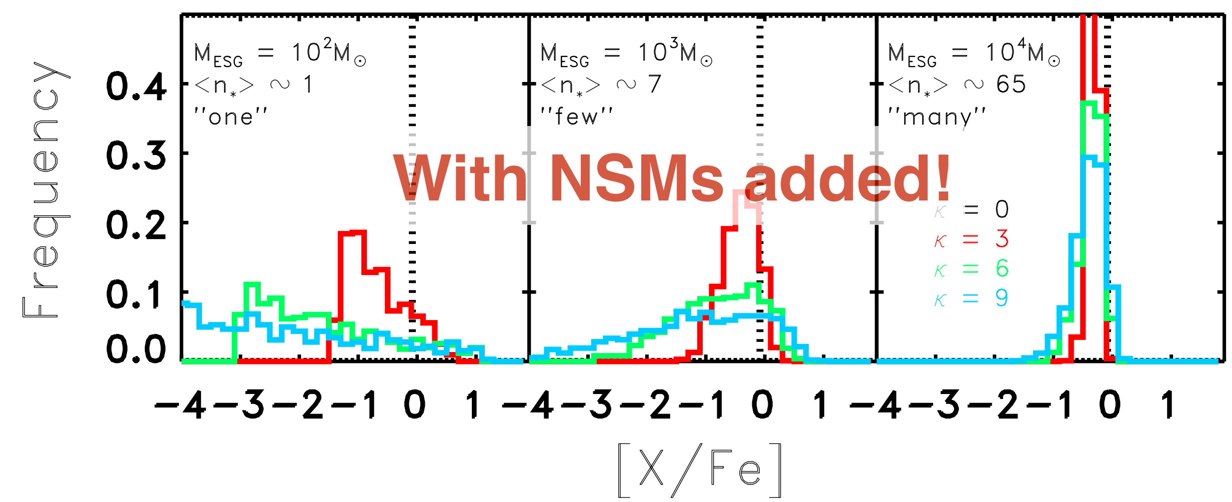
One-shot Galactic Chemical Evolution Models

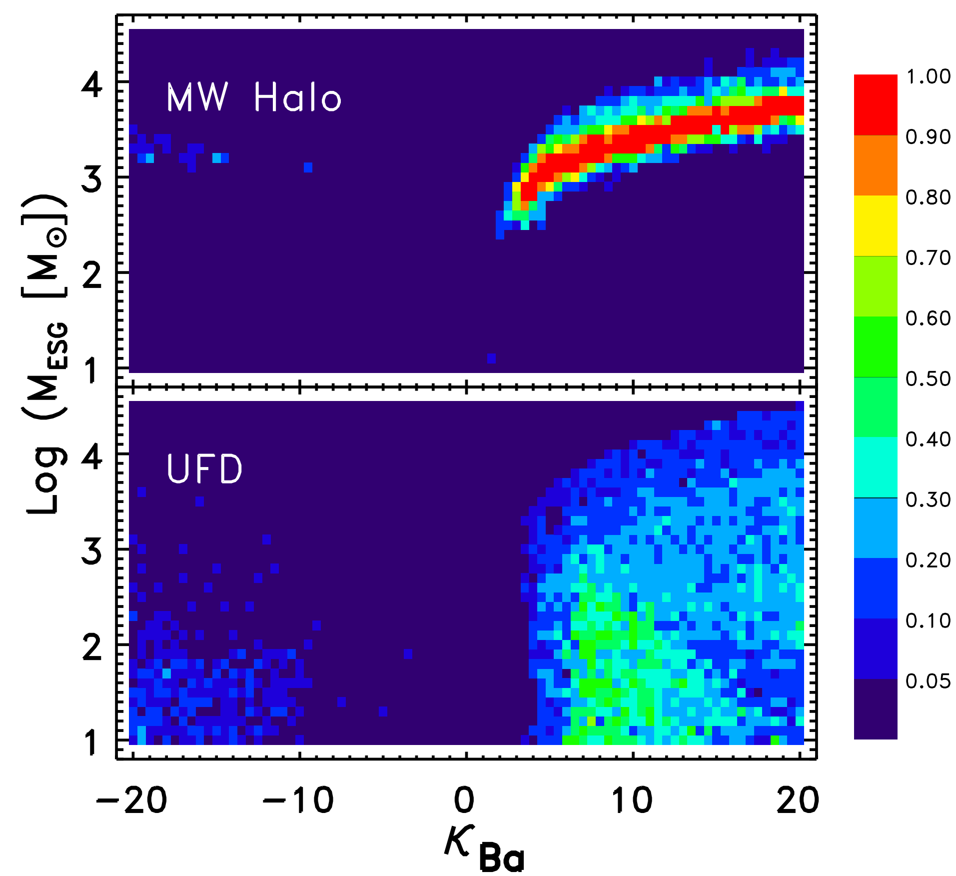
The Process Recap



Observe CARDs

Obtain p-values with model CARDs



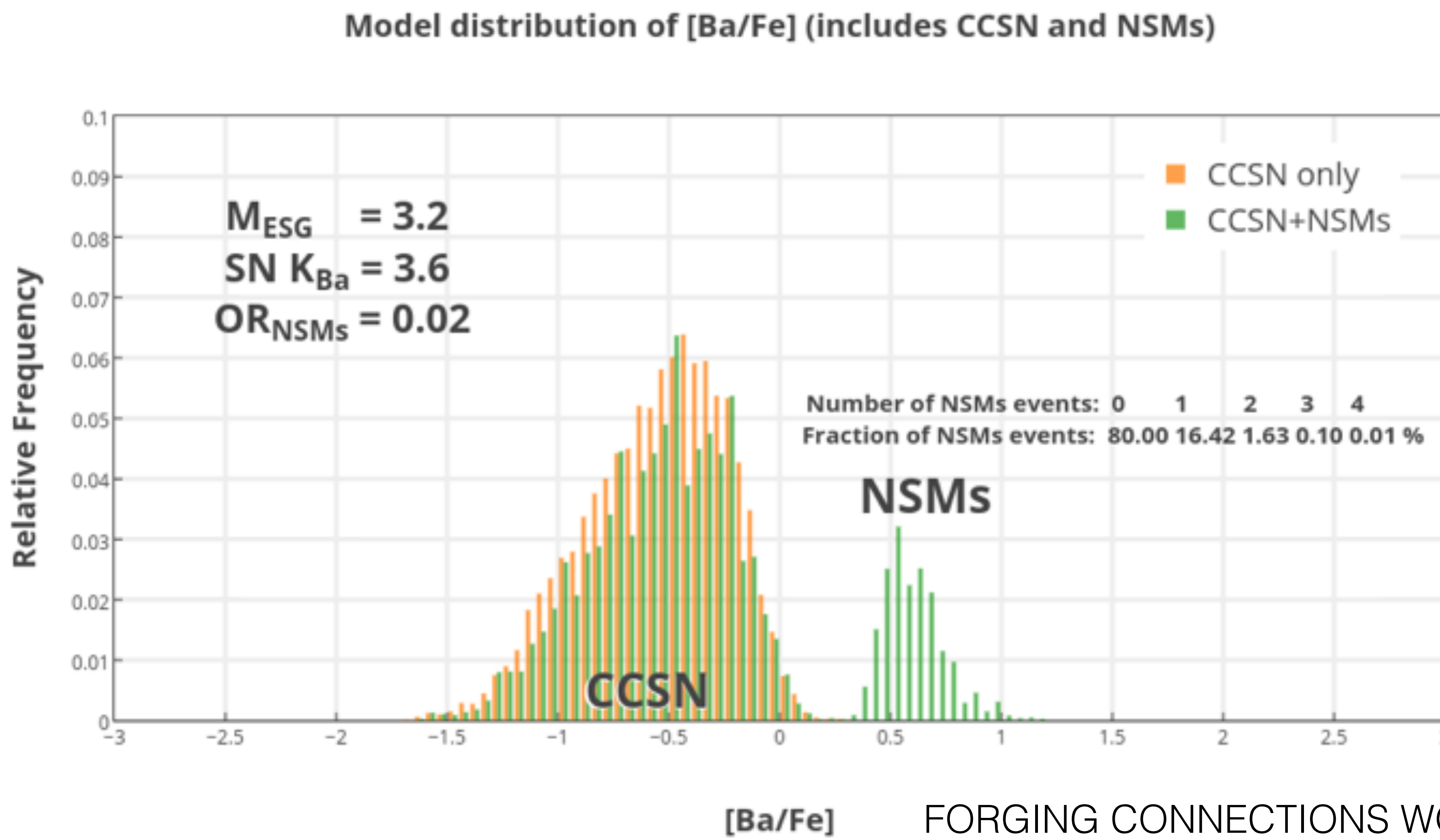


Create a p-value landscape for M_{ESG} vs the MDY strength (κ)

Lee+ (2013)

One-shot GCE Summary

- One-shot CARD models can provide constraints and interpretations of galactic abundance data (dependent upon the fidelity of assumptions + yield inputs)
- Can be easily extended to include NSMs (& Type Ia, massive AGBs, etc.)
- Should be extended to include SFH (i.e. multi-shot models) using cluster mass functions and treatment for (statistical) mixing



What's needed to *forge* better GCE models?

- Wish List:
  - For nuclear physicists/astrophysicist:
    - Table of mass-dependent yields (elemental **only**)
    - List of important abundance ratios to fit (and reasons why? also, are robust observed data sets available or planned runs slated?)
  - For simulators (e.g., hydro, n-body,AMR):
    - For semi-analytic models, what are the effects of non-uniform mixing and how can that be incorporated into the models?
    - What is the cluster mass function in dwarf galaxies?
  - For observers:
    - What is feasible to observe and how rich of a data set can you provide with uniform systematics?
    - What odd or interesting chemical abundance patterns do you see as important to explore in GCE models?
    - When can I ignore NLTE effects? Can I? Ever? Please!???
  - For experimentalists:
    - What readily-observed abundance patterns can be easily distilled into reaction rate constraints or other data products useful to you?

Future & Ongoing Work - Initial Application of CARD Analysis to Data (Lee+ 2013)

Table 1
Strength of Mass-dependent Yields

Element (neutron-capture)	Metallicity (log Z)	$\kappa^{8-10\,M_\odot}_{\text{empirical}}$ $(r)^{a}$	$\kappa^{15-40\,M_\odot}_{\text{ab initio}}$ $(s)^{b}$ (nr/rs)	$\kappa^{15-40\,M_\odot}_{\text{inferred}}$ $(s)^{c}$ (rs/ss)	This work
Strontium (Sr)	−5	∼−15 or −18	∼3.3/5.8	∼6.5/6.7	($\lesssim$−10), ($\gtrsim$7)
	−3		∼4.5/6.6	∼7.4/···	
Barium (Ba)	−5	∼−15	···	∼3.6/3.6	∼(6–12)
	−3		···	∼3.9/···	

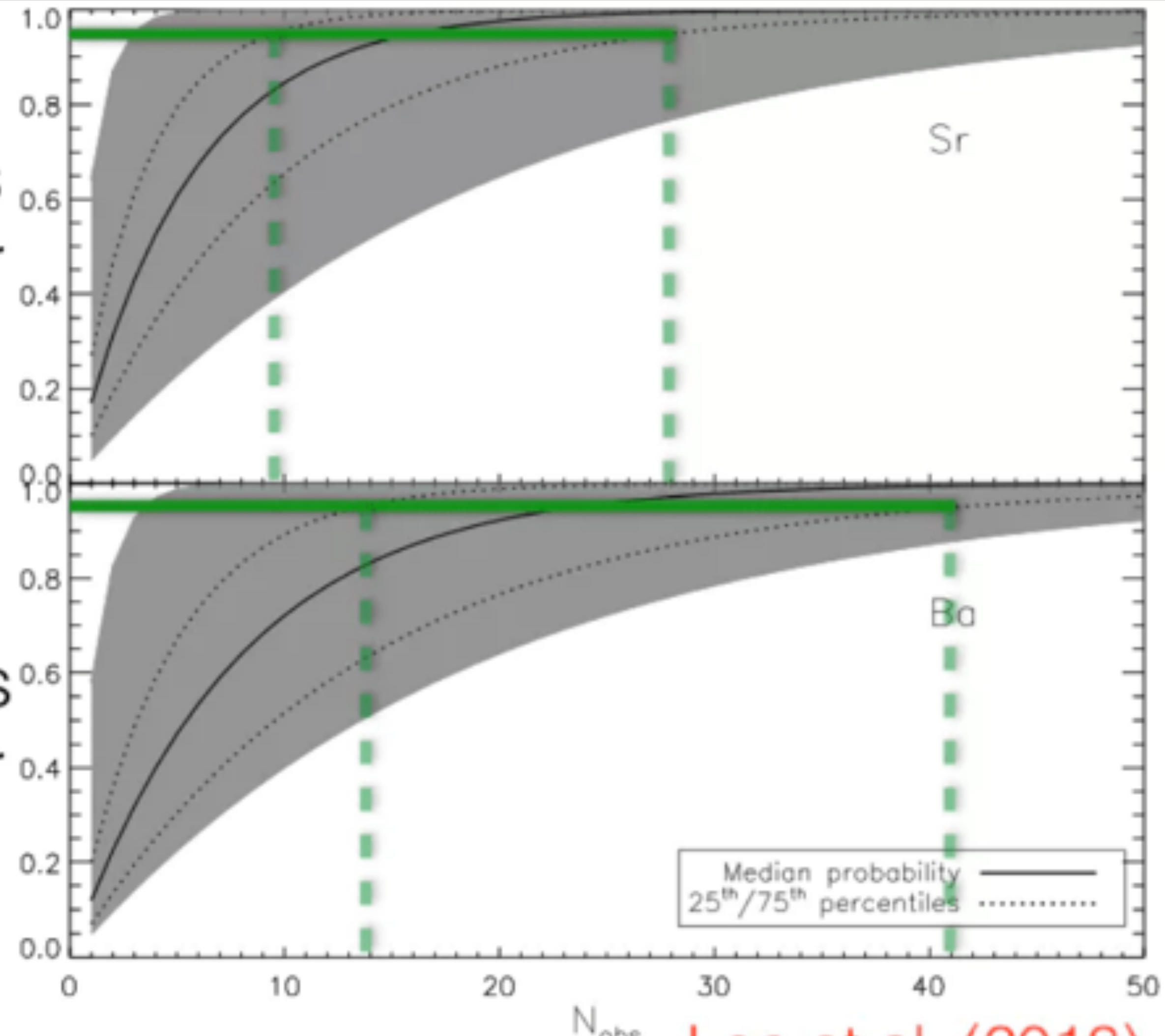
Notes.
Chieffi & Limongi (2004) and Limongi & Chieffi (2012) provide another set of theoretical MDYs for Sr. From Chieffi & Limongi (2004) we find that the estimated MDYs for Sr given for progenitors with $z > 0$ to $z \simeq z_\odot$ results in strengths that are $1 \lesssim \kappa_{\text{Sr}} \lesssim 4$. The MDY for Sr for zero metallicity stars is $\kappa_{\text{Sr}} \simeq 8$—compatible with our work. However, more recent work by the same authors (Limongi & Chieffi 2012) produces a $\kappa_{\text{Sr}} \lesssim 5$ for zero metallicity stars. This result is only marginally compatible with our findings.
[a] Derived from empirical yields given in Cescutti (2012).
[b] Derived from Figure 4.14 of Frischknecht (2012) for non-rotating (nr)/rotating stars (rs). Yields for Ba were not given.
[c] Derived from Cescutti & Chiappini (2013) for rotating stars (rs) [their *as*-models]/*spinstars* (ss) [their *fs*-models].

MDYs from literature versus THIS WORK: ALL MDYs are greater in strength than the alpha-elements yields examined in this work!

Future & Ongoing Work - Initial Application of CARD Analysis to Data (Lee+ 2013)

Sr ~15 stars w/10-28 star range

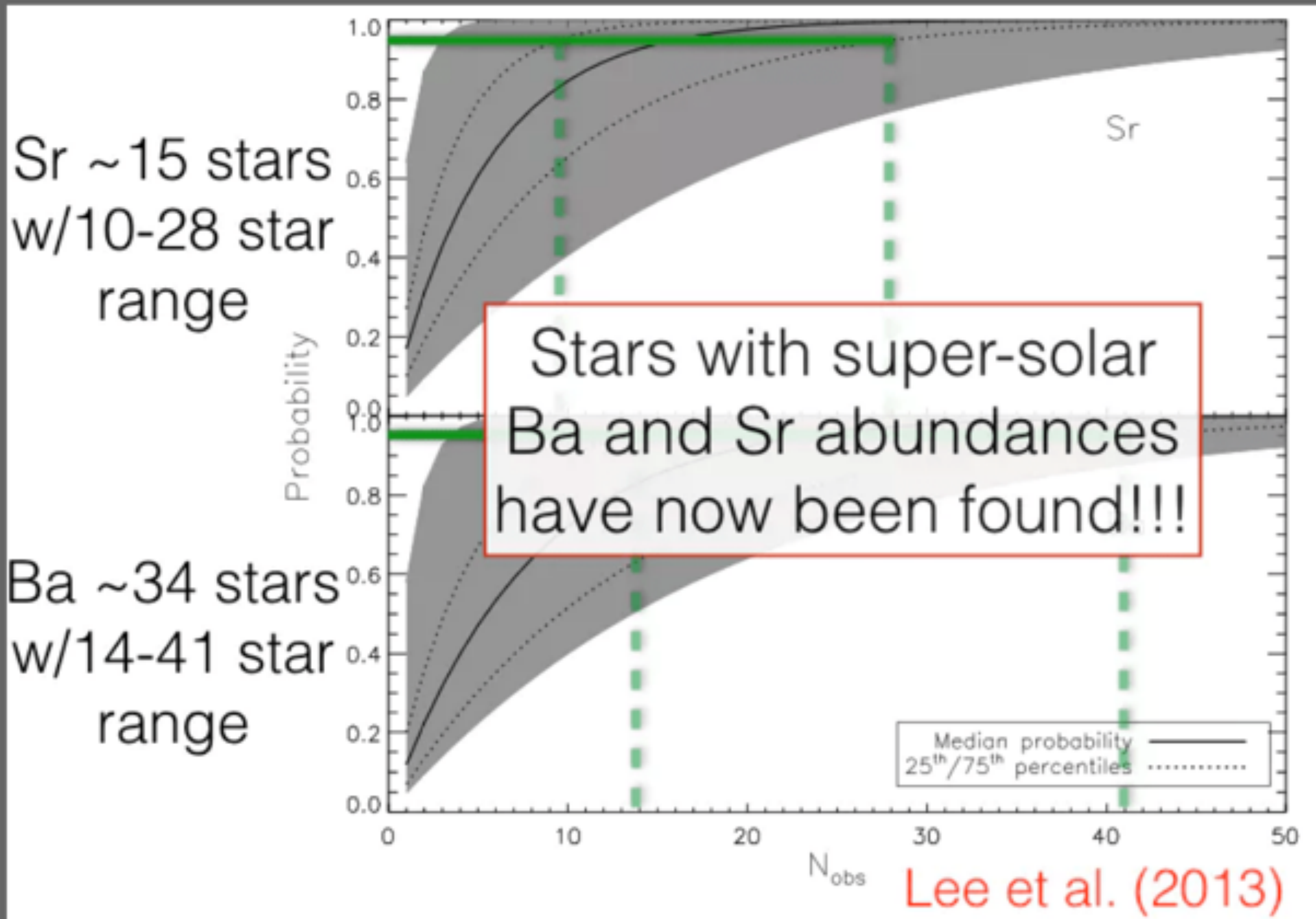
Ba ~34 stars w/14-41 star range



Lee et al. (2013)

What the some observable predictions? How many stars must you observe in UFDs to find at least ONE superabundant stars in Ba or Sr?

Future & Ongoing Work - Initial Application of CARD Analysis to Data (Lee+ 2013)



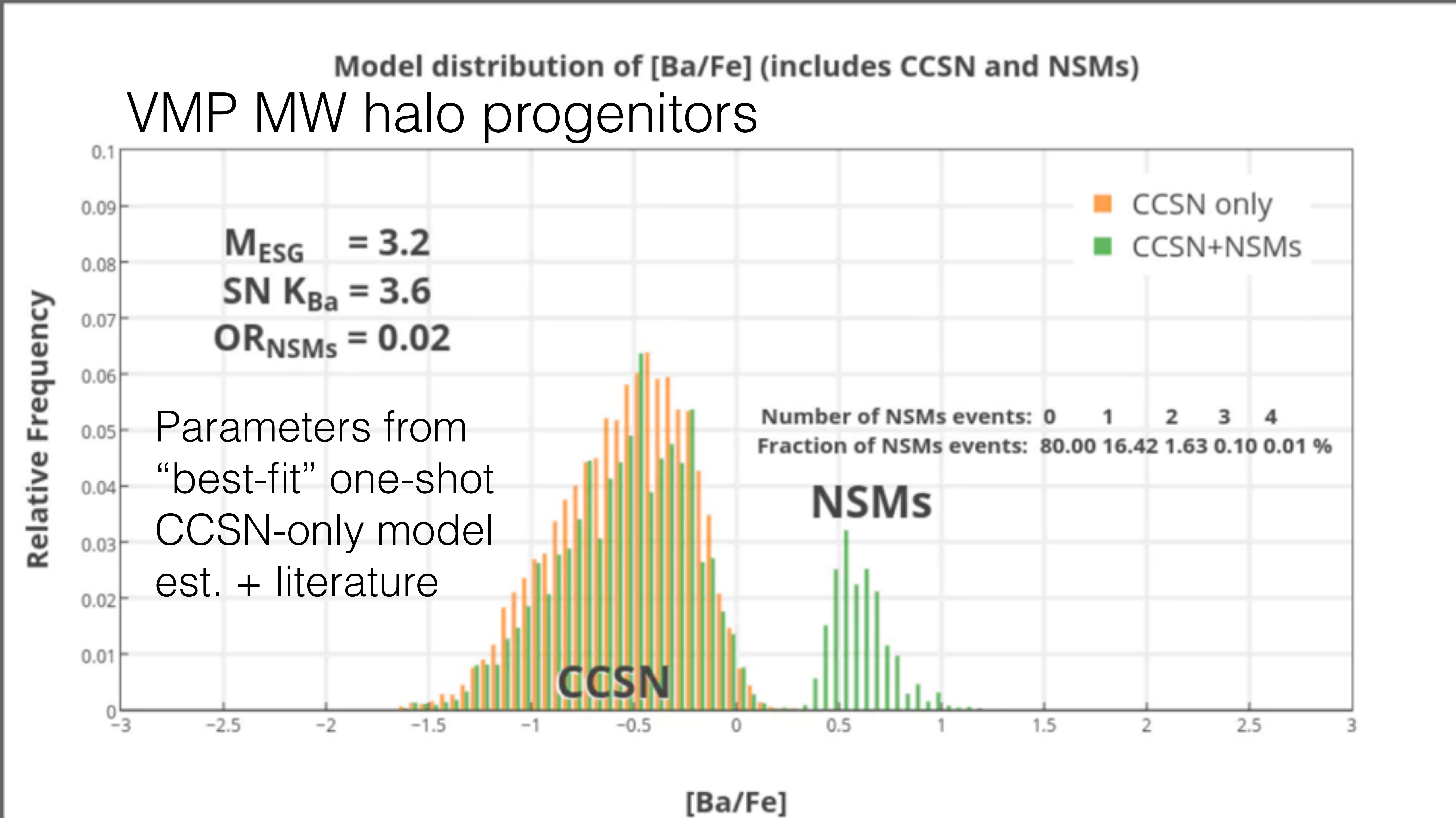
What the some observable predictions? How many stars must you observe in UFDs to find at least ONE superabundant stars in Ba or Sr?

See Alex Ji's talk (with caveats)!

Summary

- The Big Picture - **Hierarchical formation of the Halo**
- The Big Question - How can we reconstruct the accretion history of the Halo? **Try the EM algorithm**
- Motivation - **CARD studies don't suffer from a phase-mixing problem**
- Goal - Proof of Concept Study - **Let's analyze simulated halos with GCE models for accreted dwarf galaxies**
- Method - Statistical Chemical Tagging using the Expectation-Maximization (EM) algorithm - **Chemical tagging is the focus of future surveys**
- Results - Accretion History Profiles - **The EM algorithm REALLY works?! - I'm FIREd up to find out!**
- Future & Ongoing Work - 'High Fidelity' dwarf galaxy model templates - **Needed to make an accurate analysis of the real Halo**

One-shot Galactic Chemical Evolution Models



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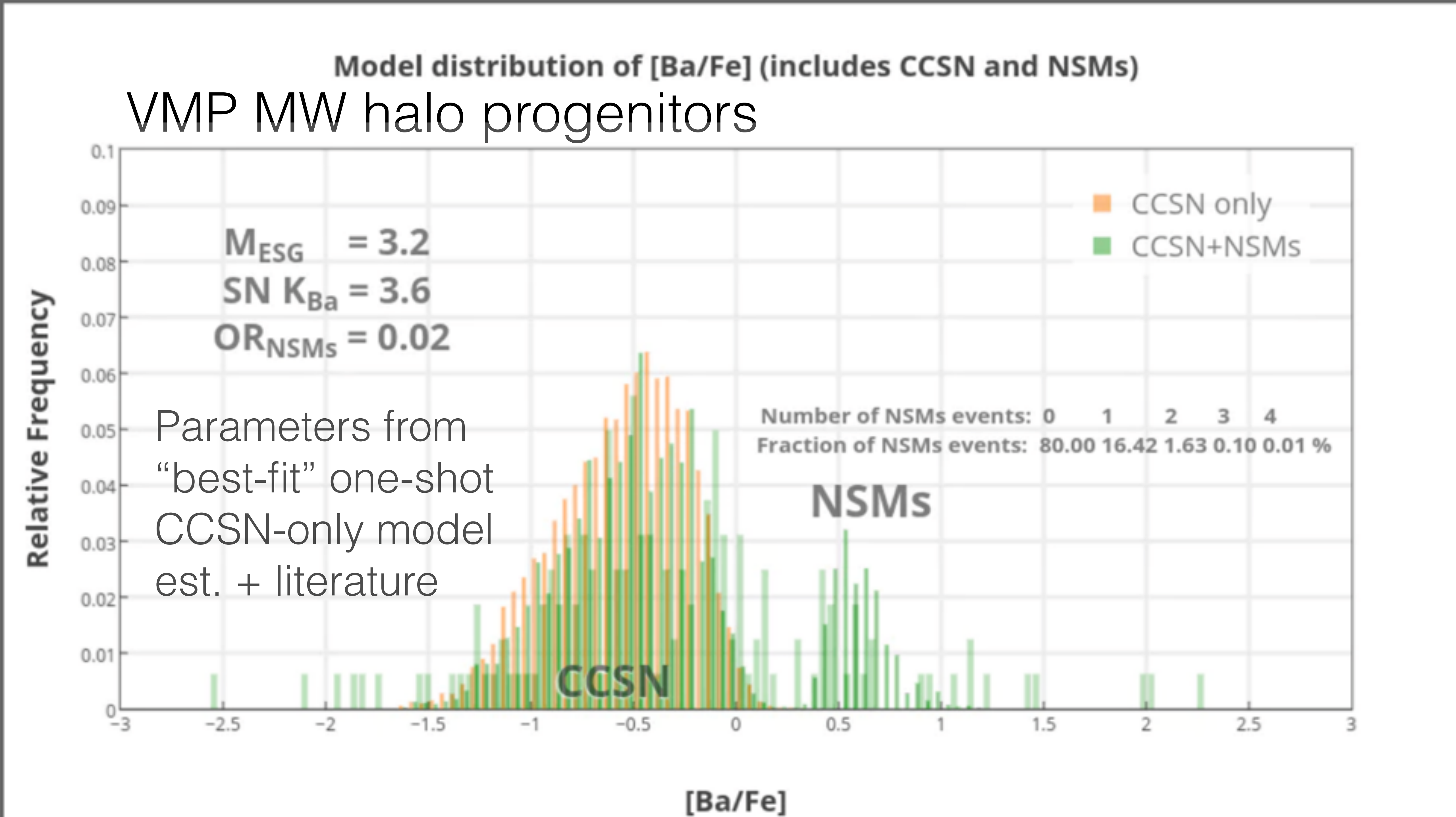

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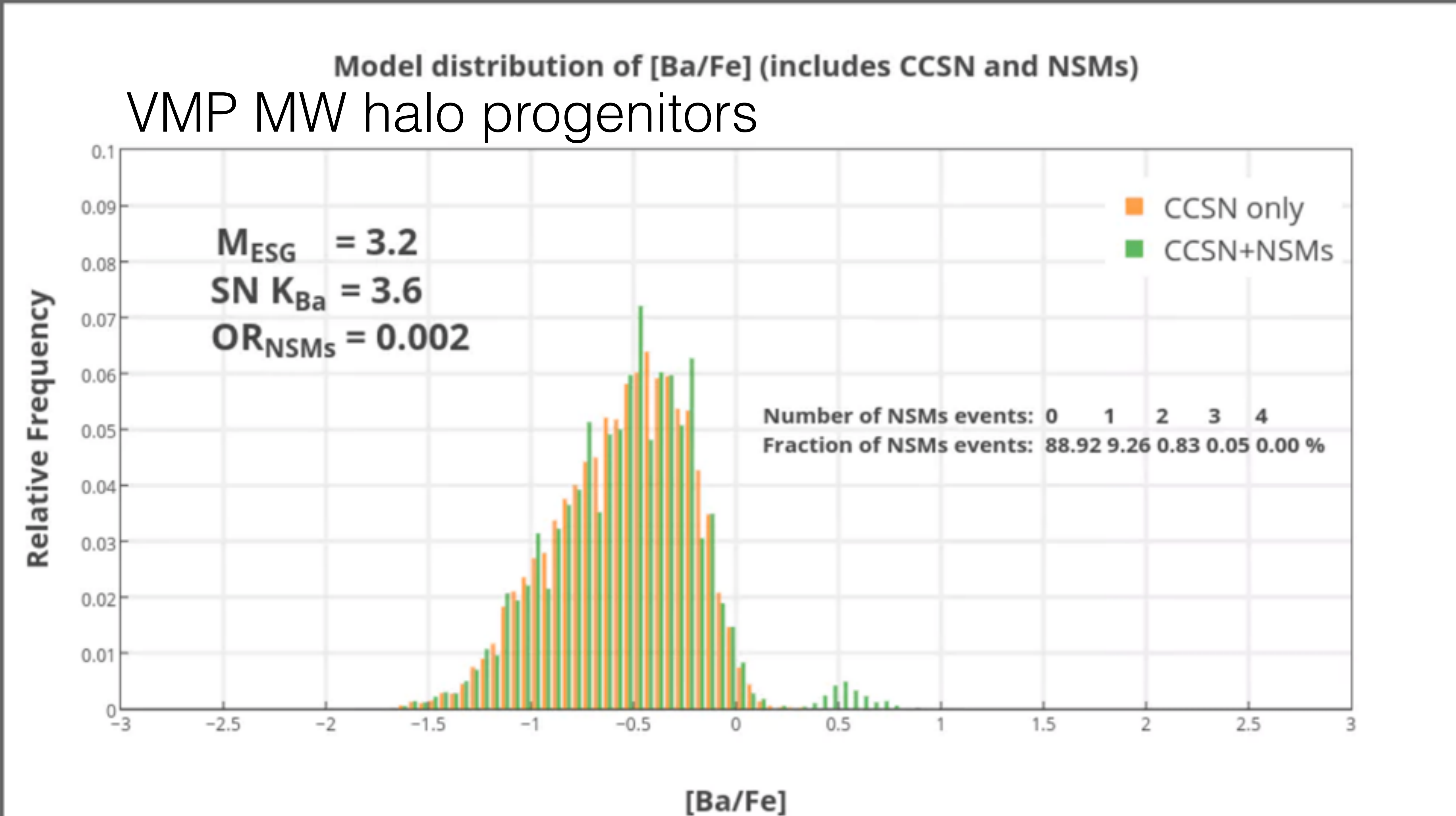

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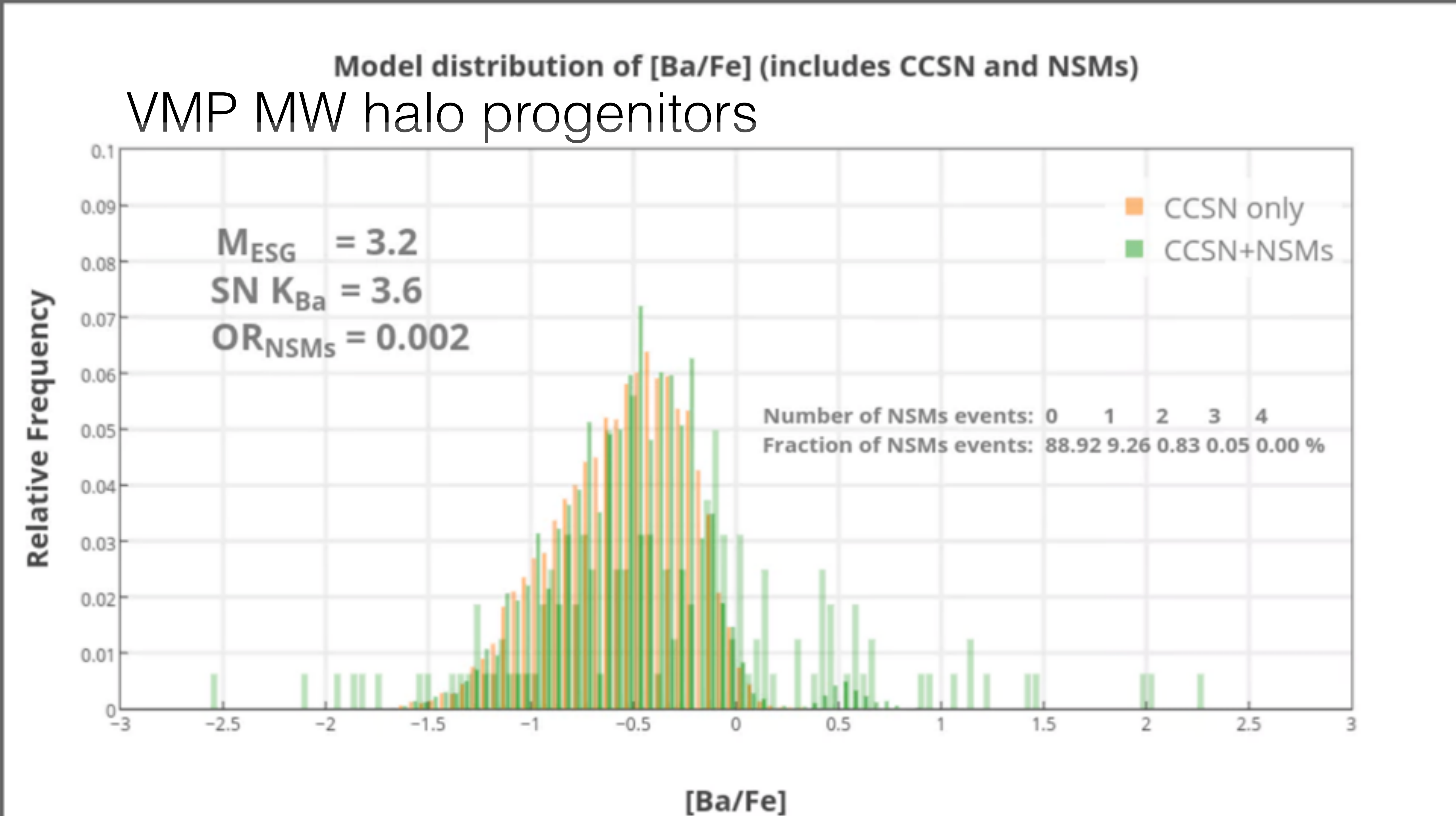

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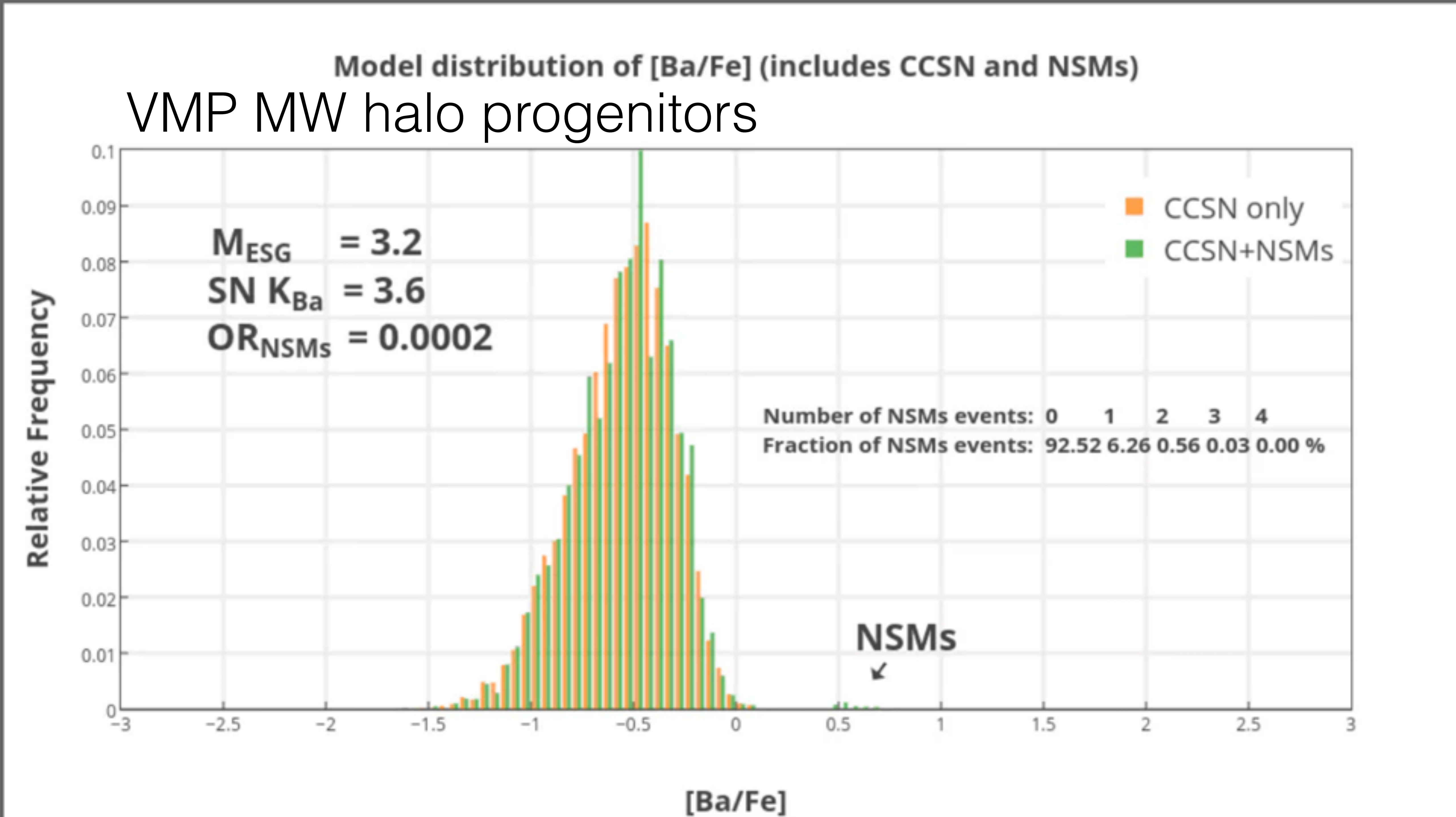

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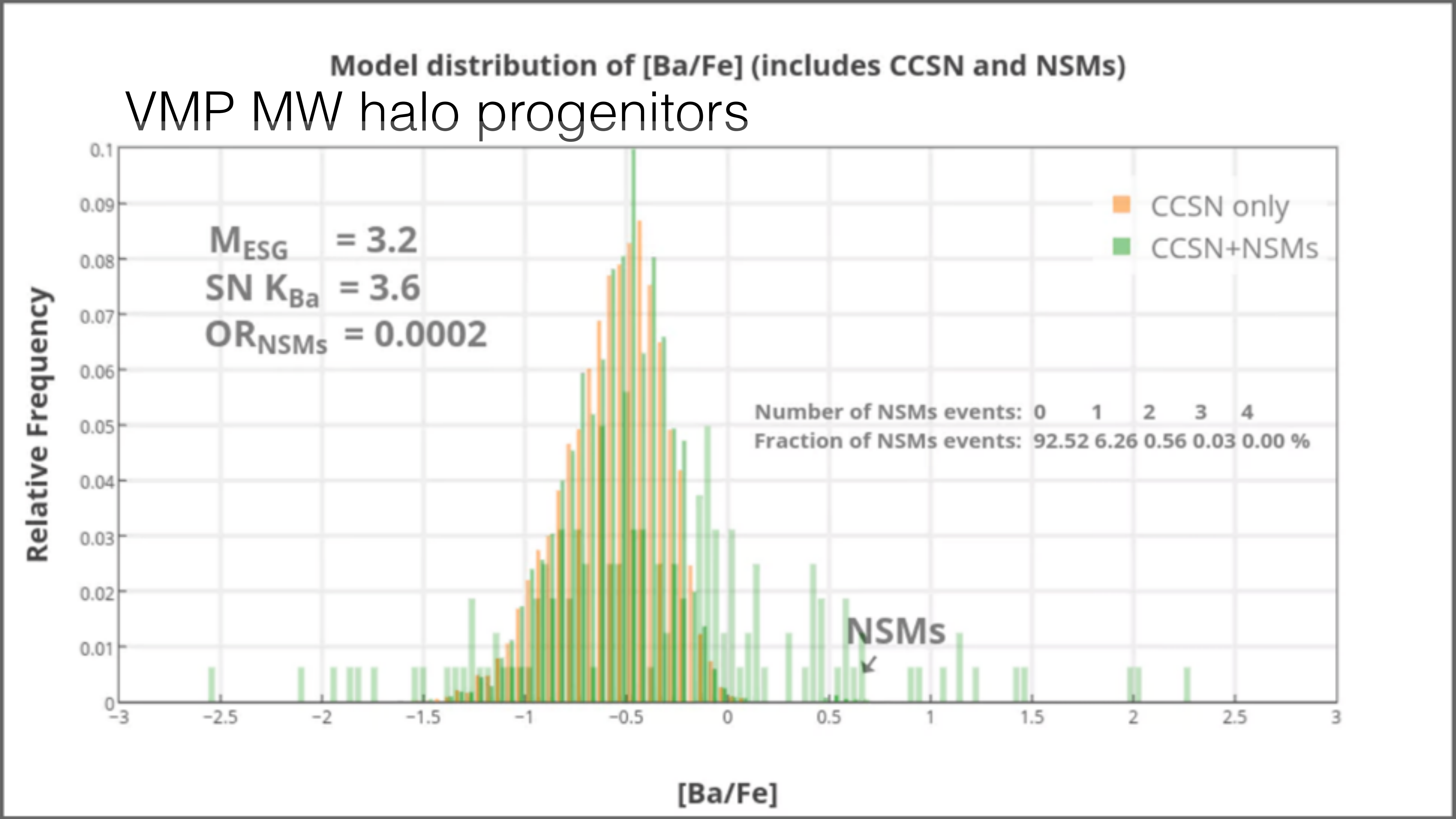

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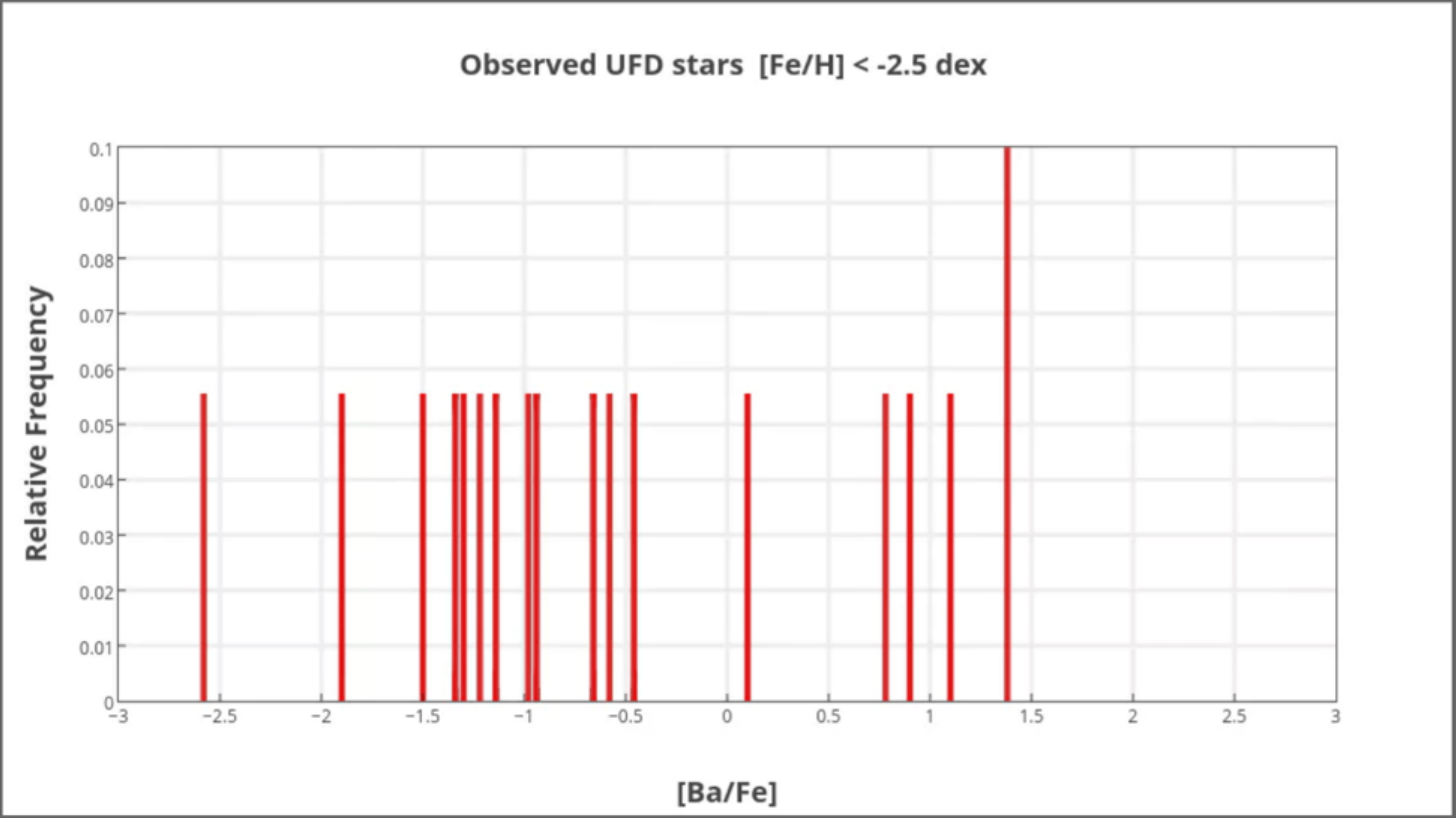
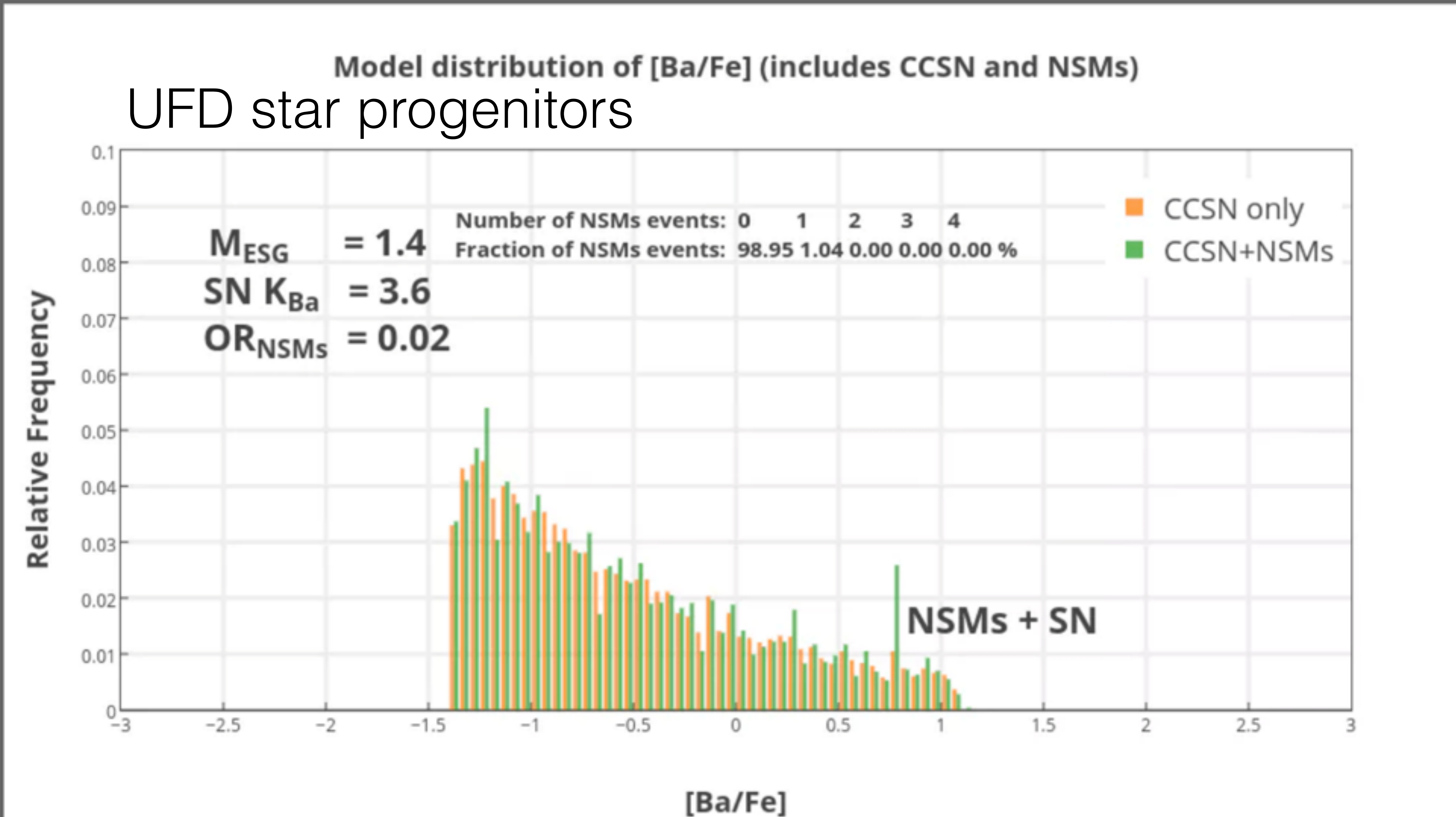


18 UFD stars with [Fe/H] < -2.5

One-shot Galactic Chemical Evolution Models



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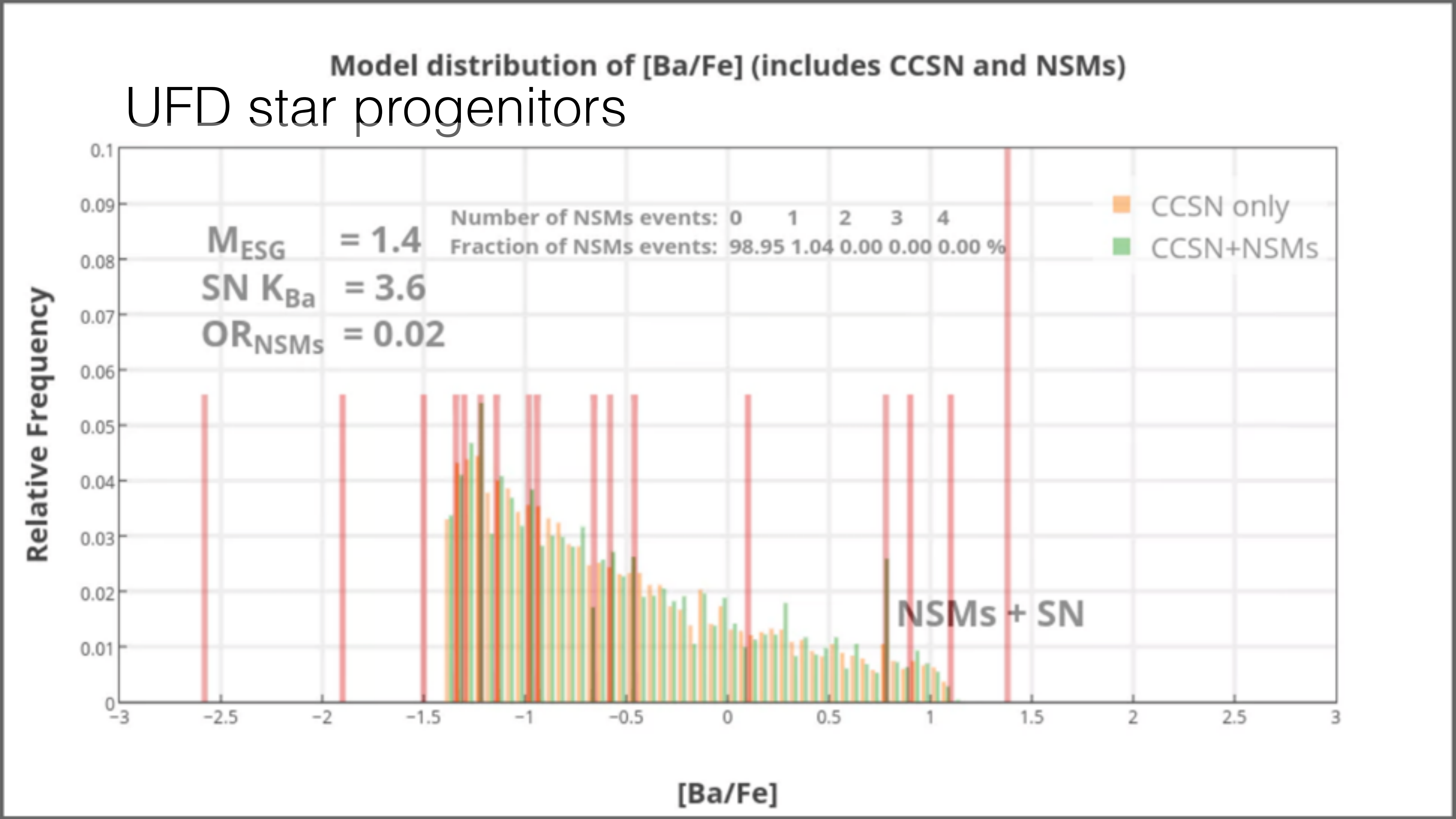
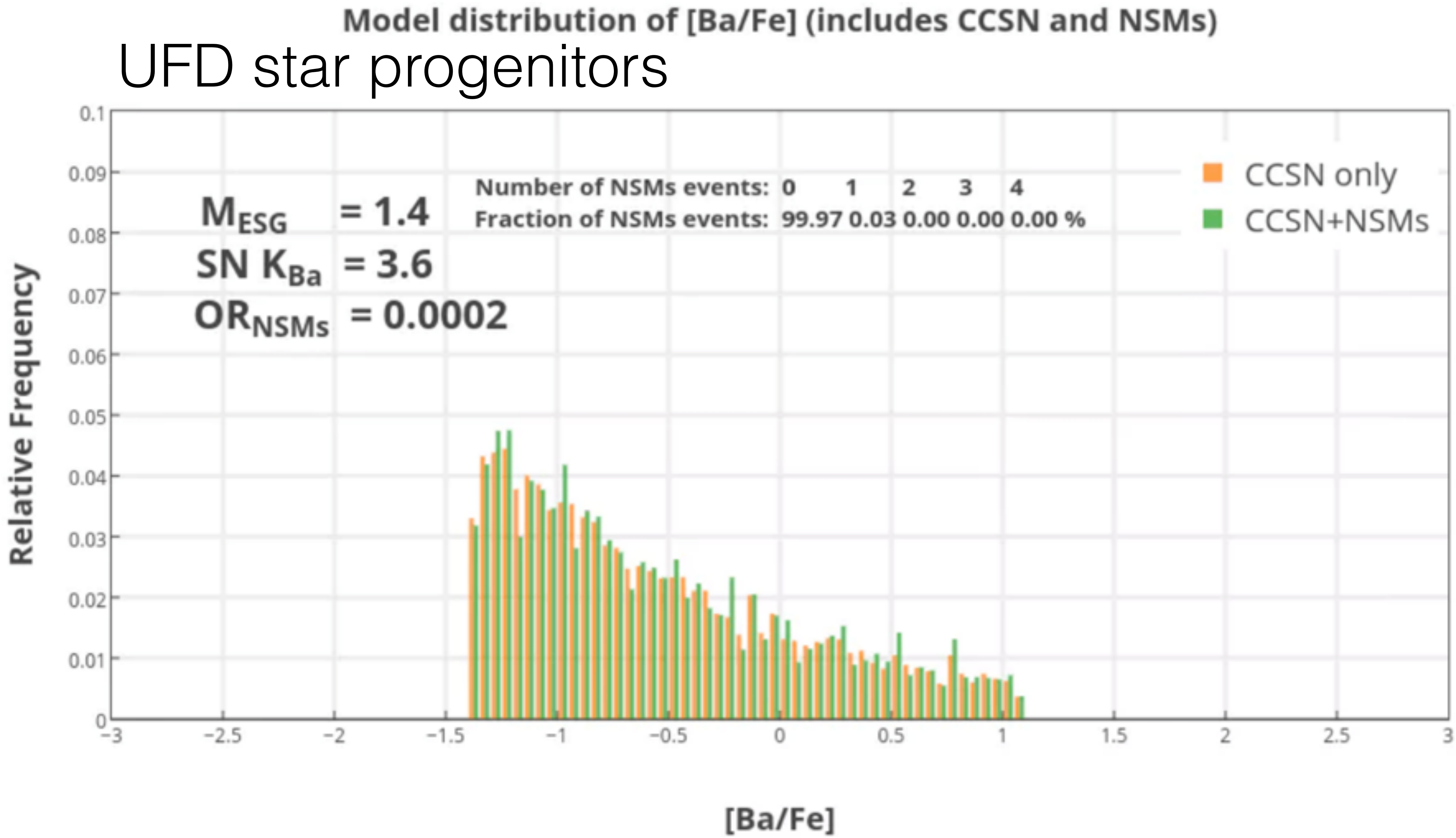


One-shot Galactic Chemical Evolution Models

UFD star progenitors



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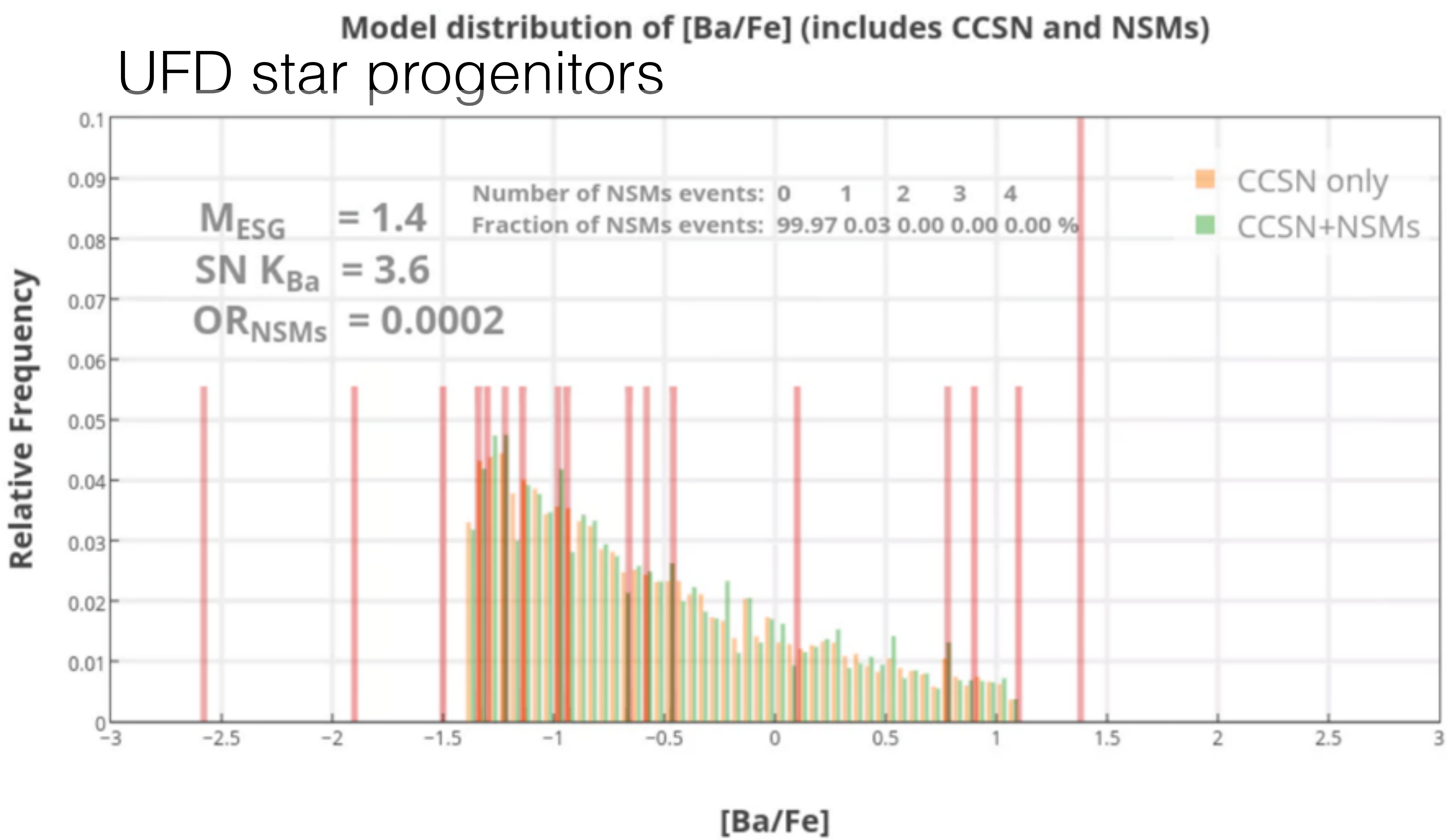

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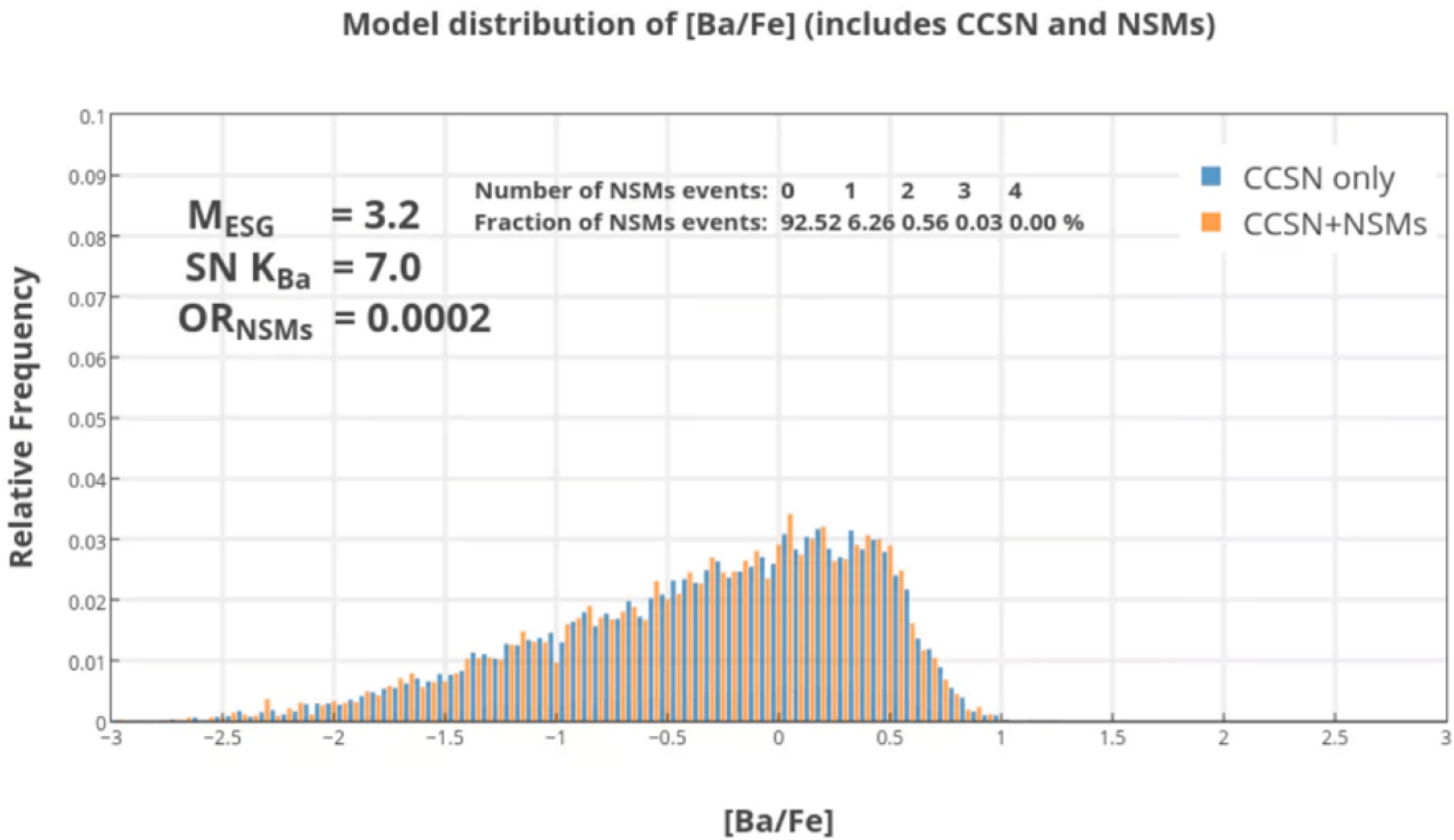

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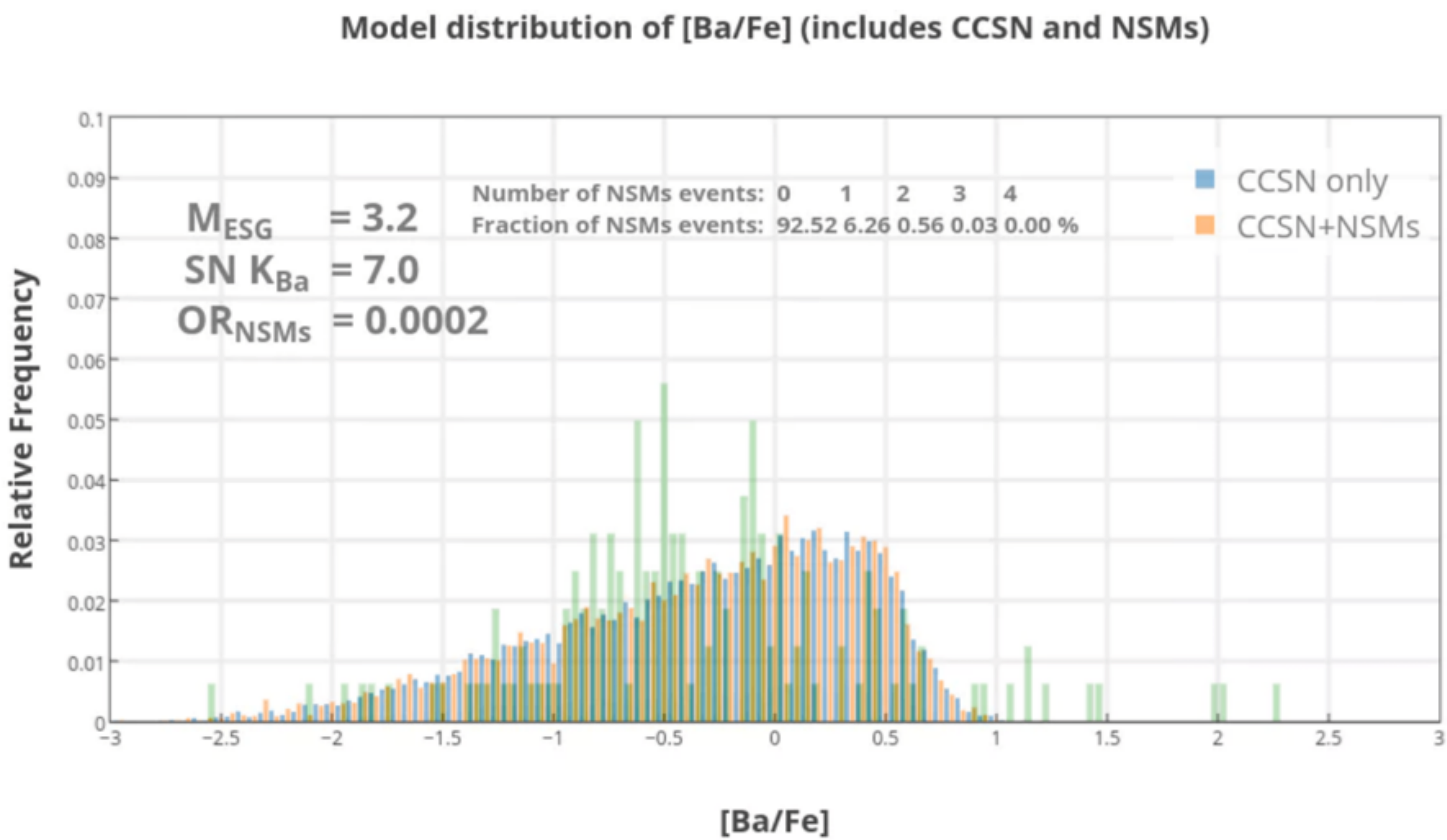

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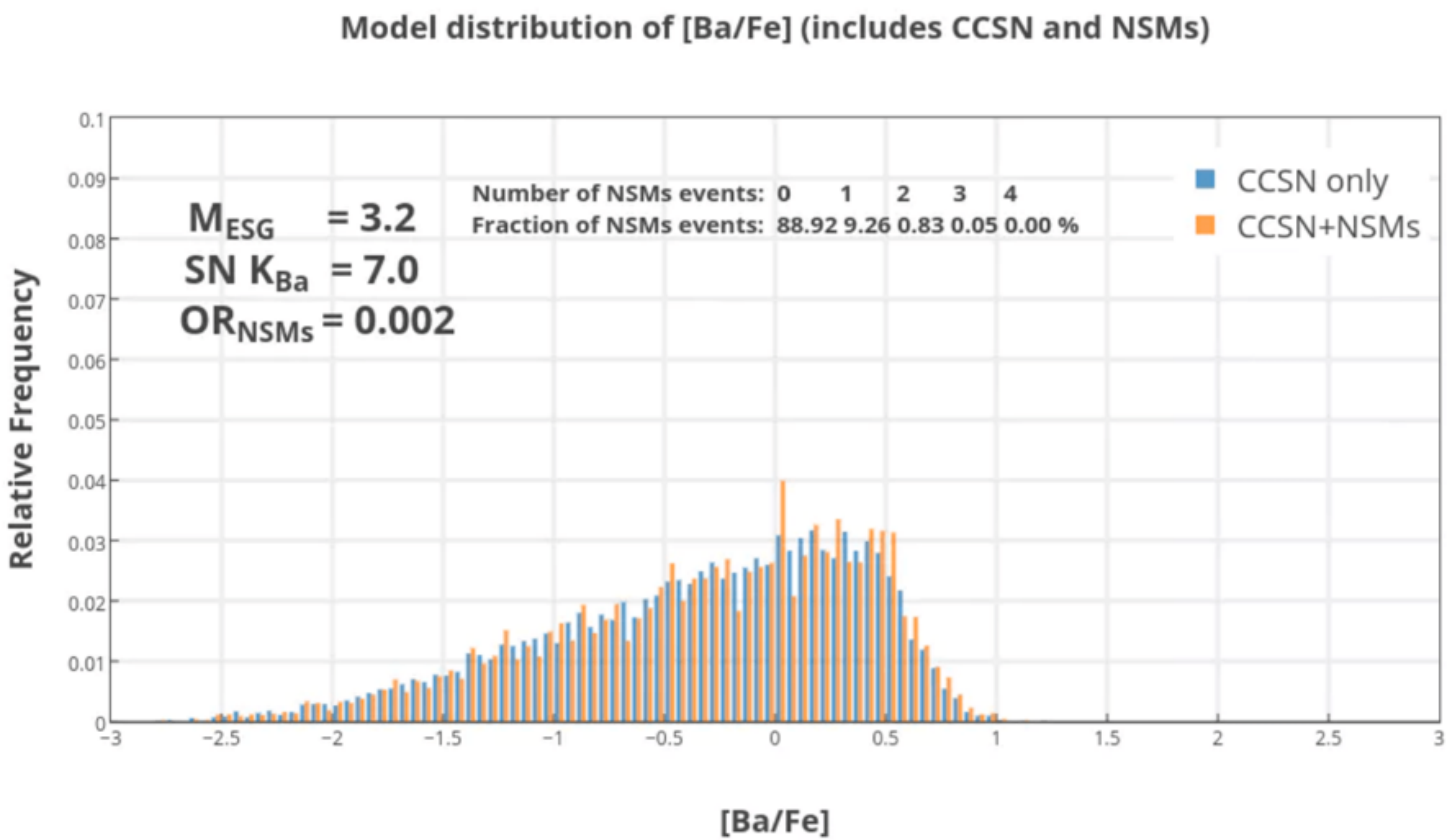

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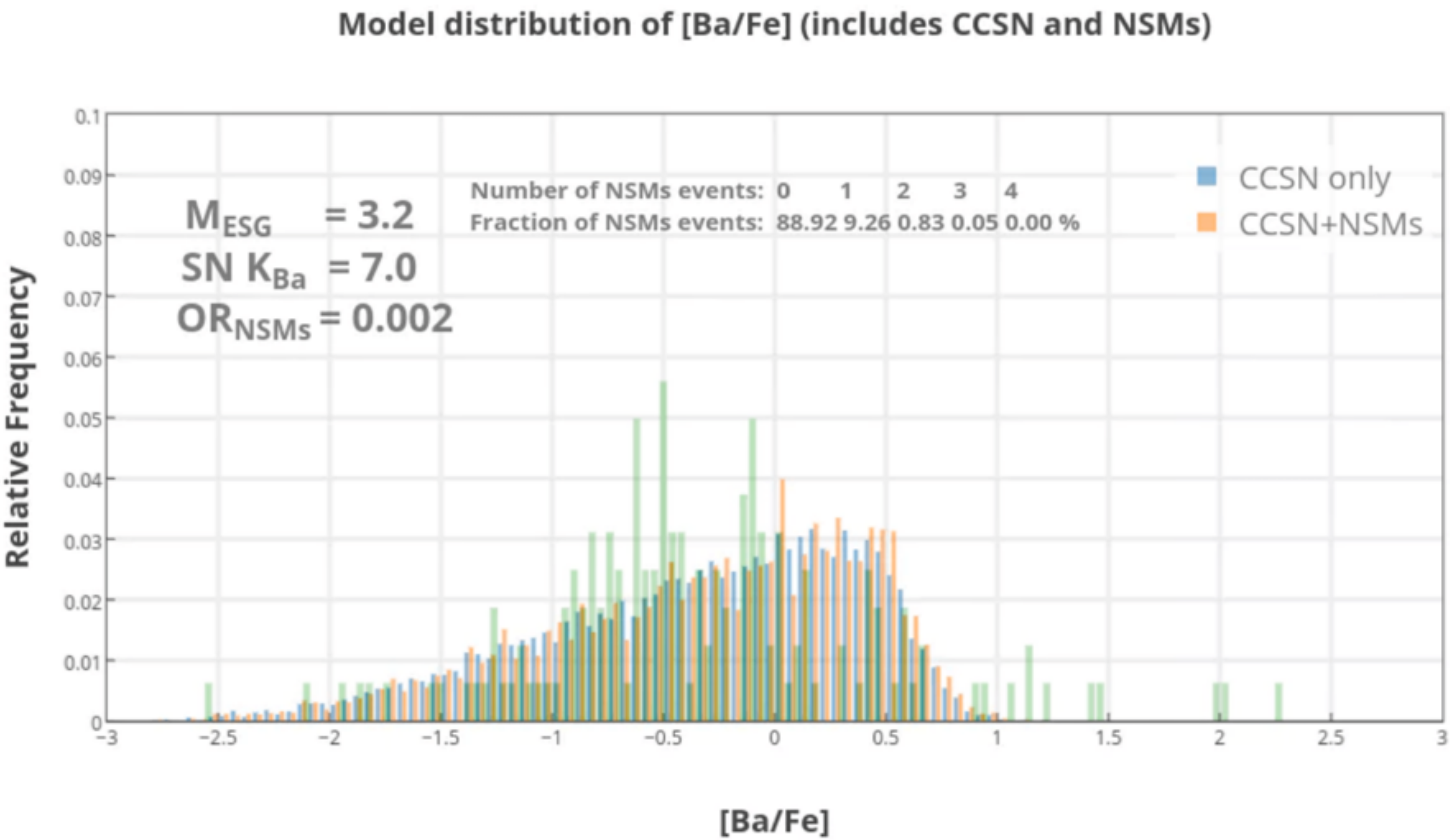
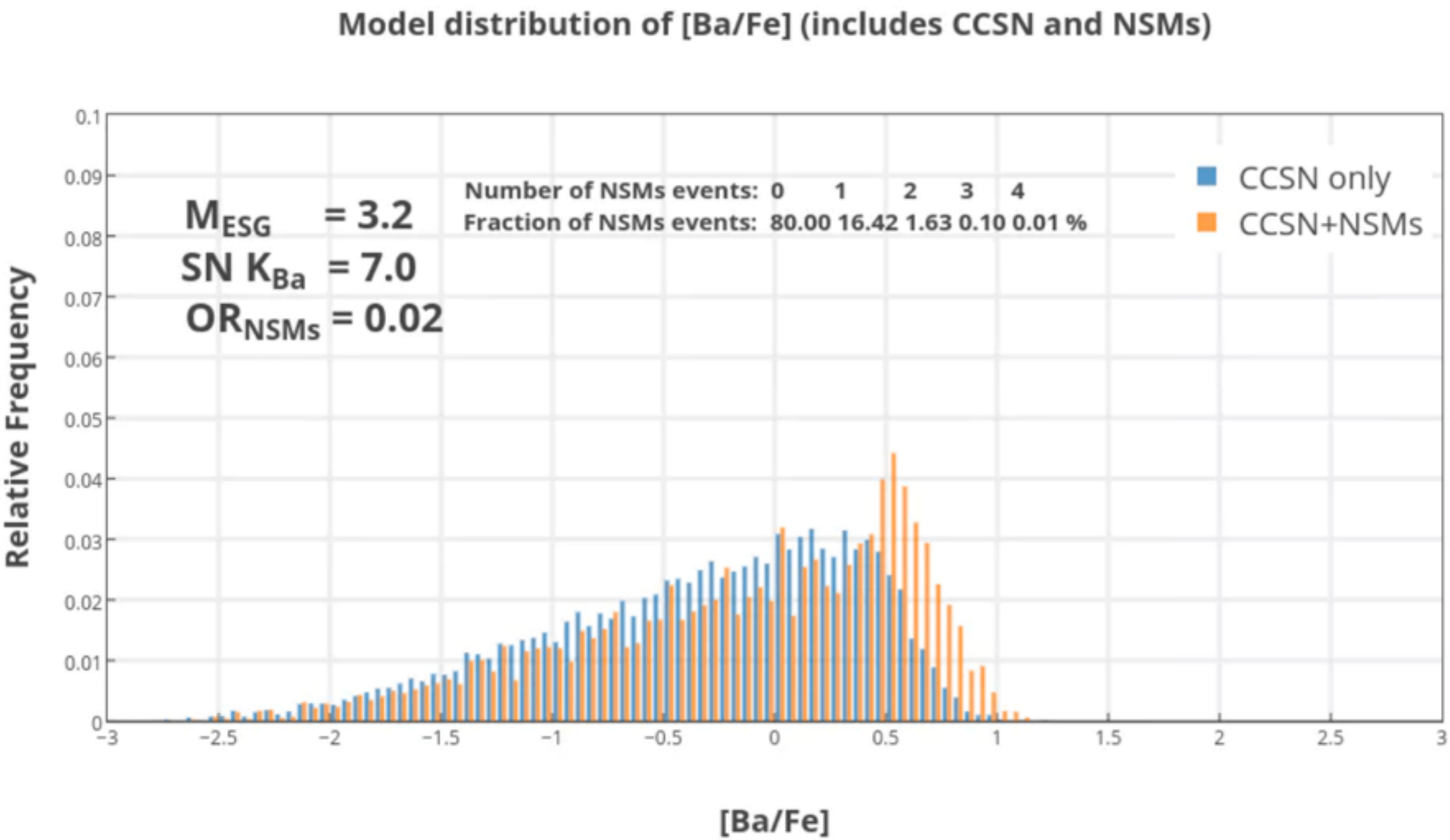
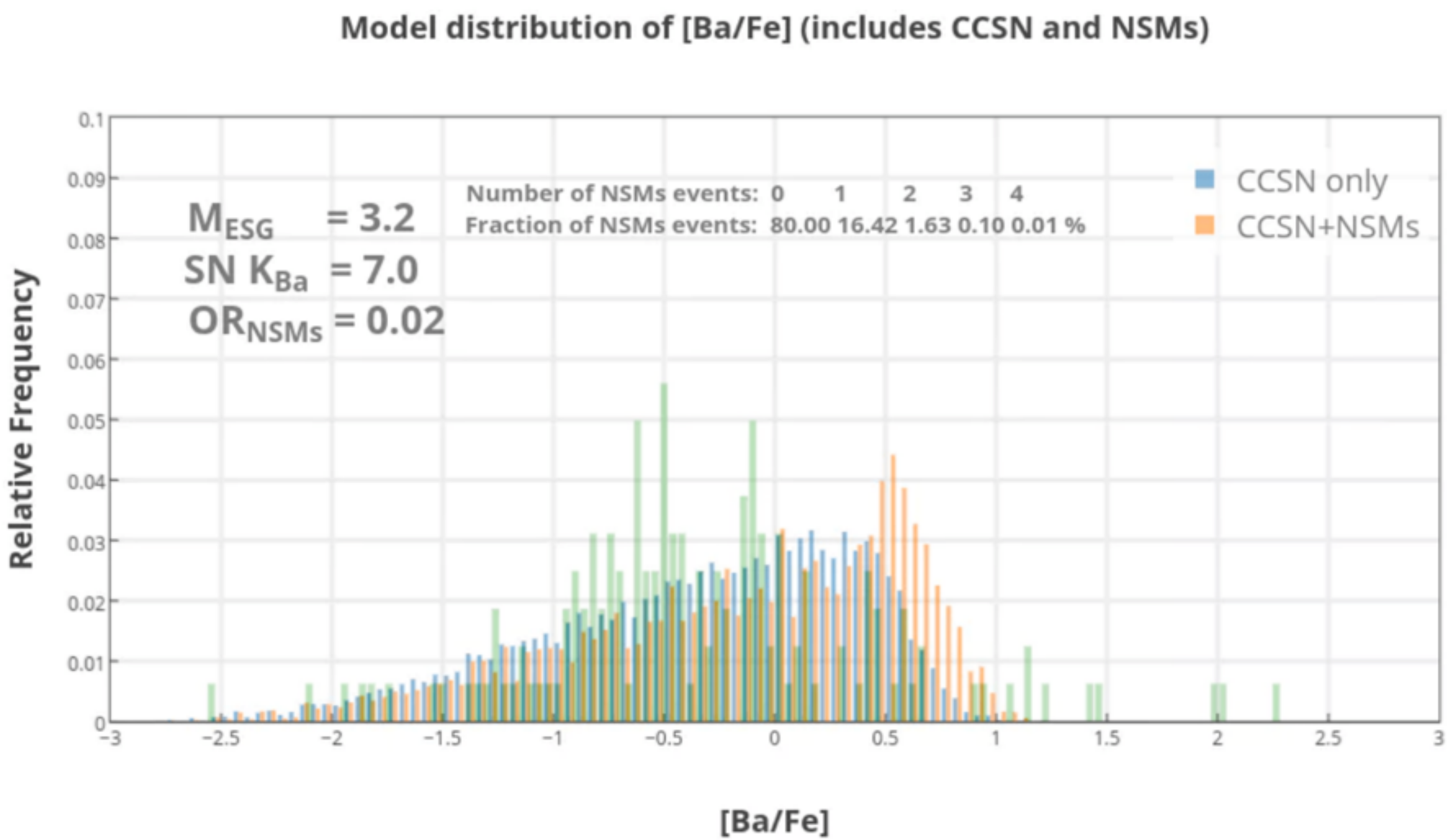


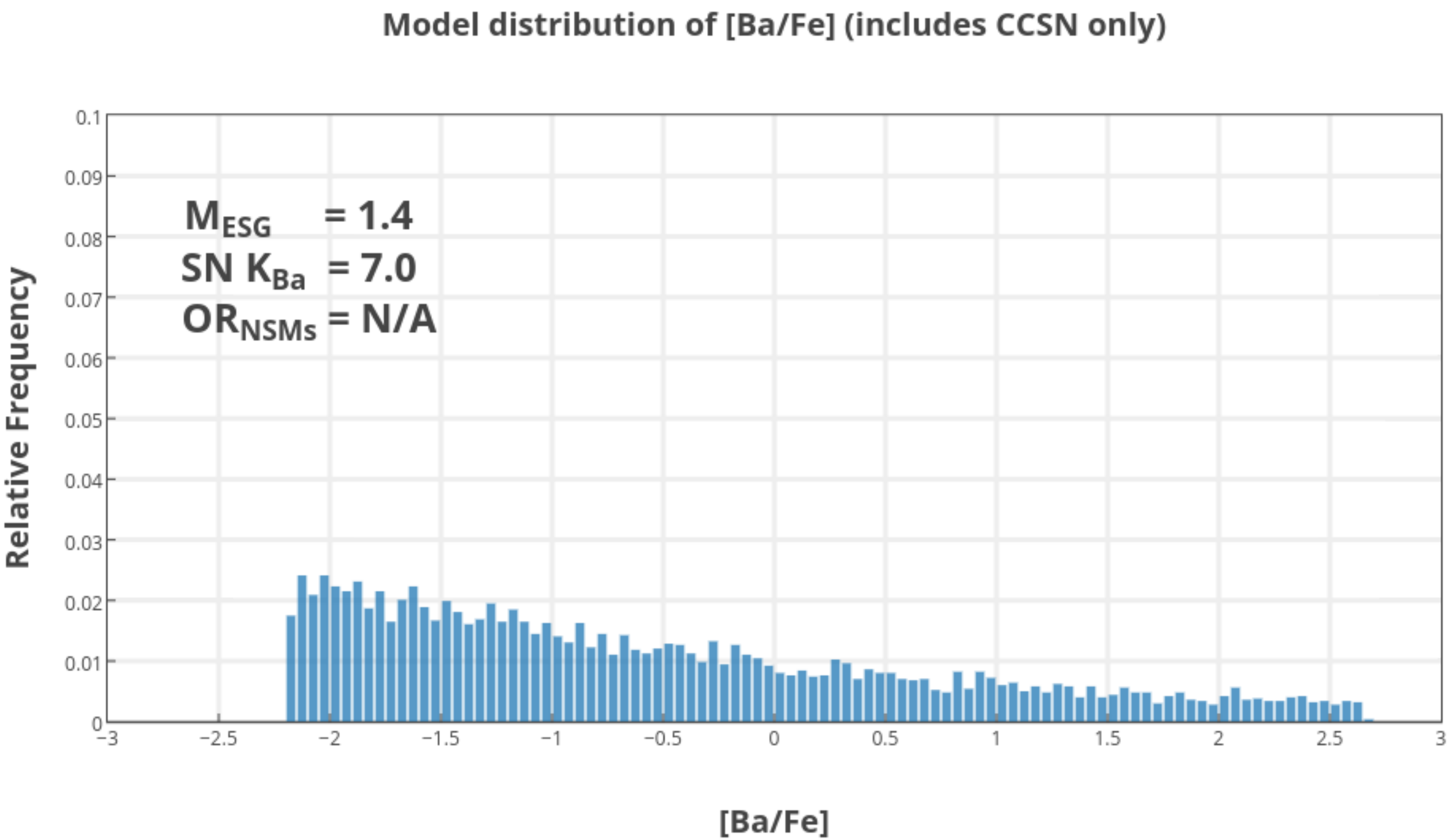
One-shot Galactic Chemical Evolution Models



One-shot Galactic Chemical Evolution Models



One-shot Galactic Chemical Evolution Models



One-shot Galactic Chemical Evolution Models