The impact of Systematic and Statistical Mass Uncertainties on the R-Process Nucleosynthesis in Neutron Star Mergers

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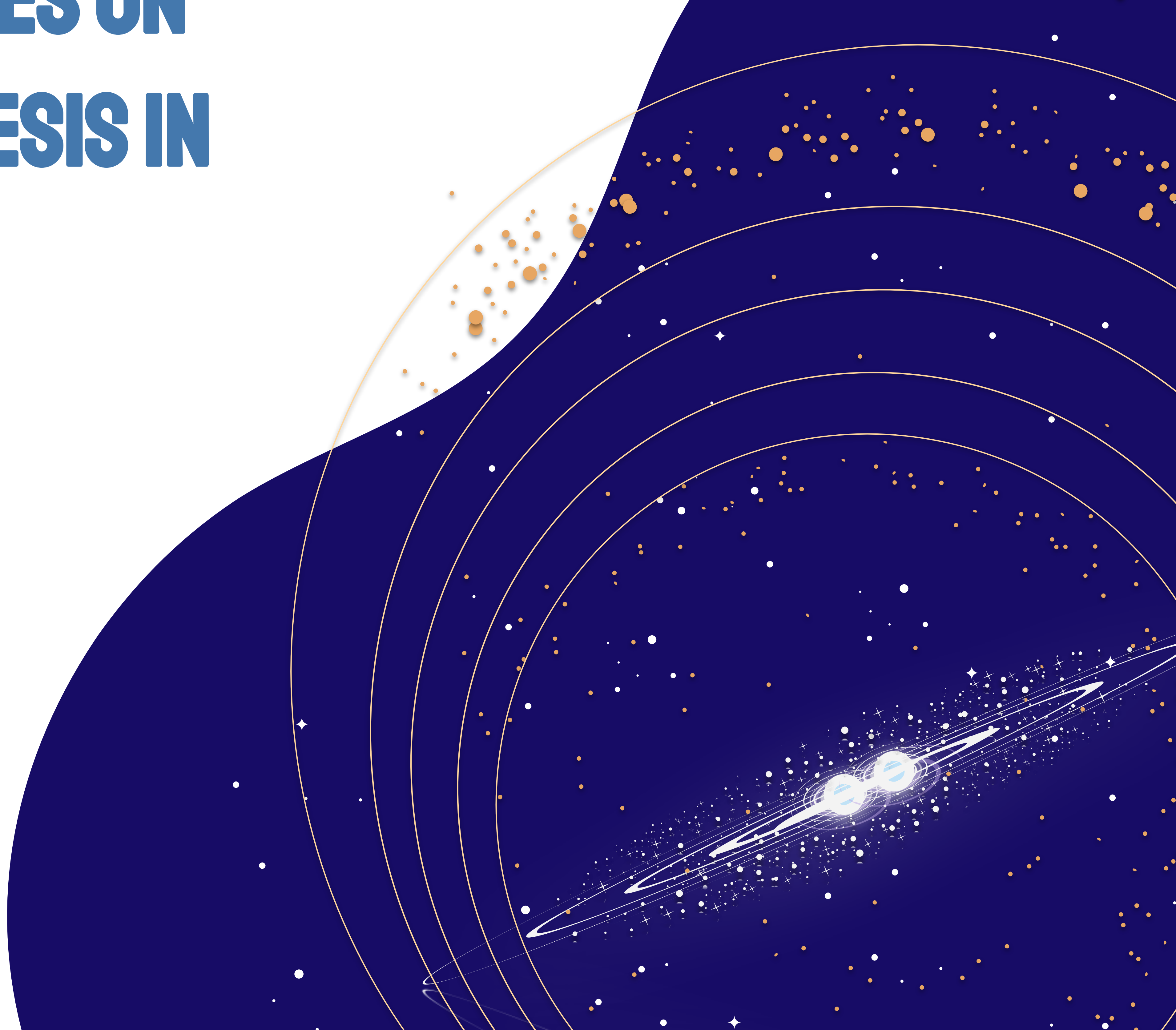
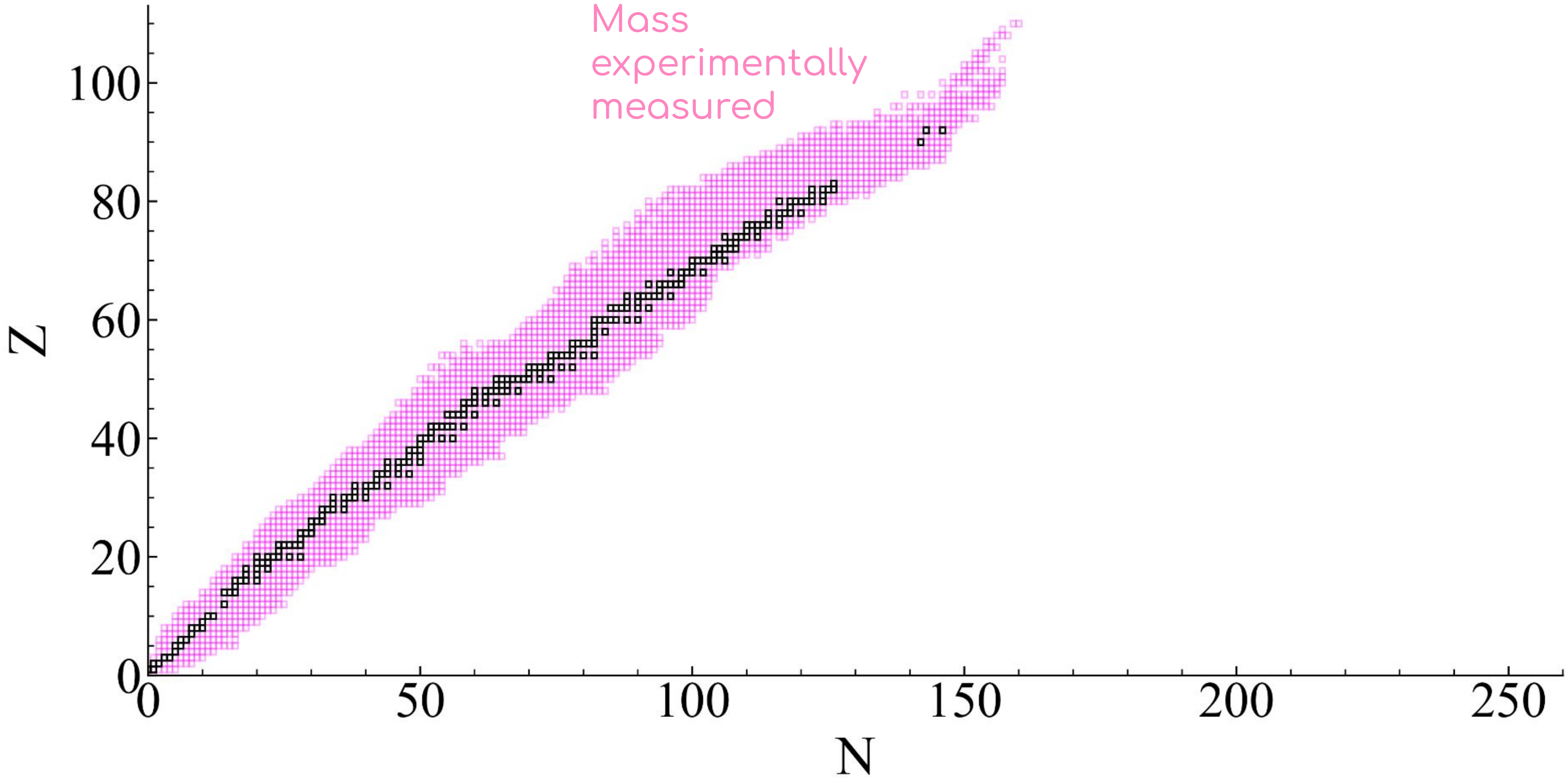
ChETEC INFRA



Nuclear masses relevant to the r-process

Experimentally known masses vs r-process network needed



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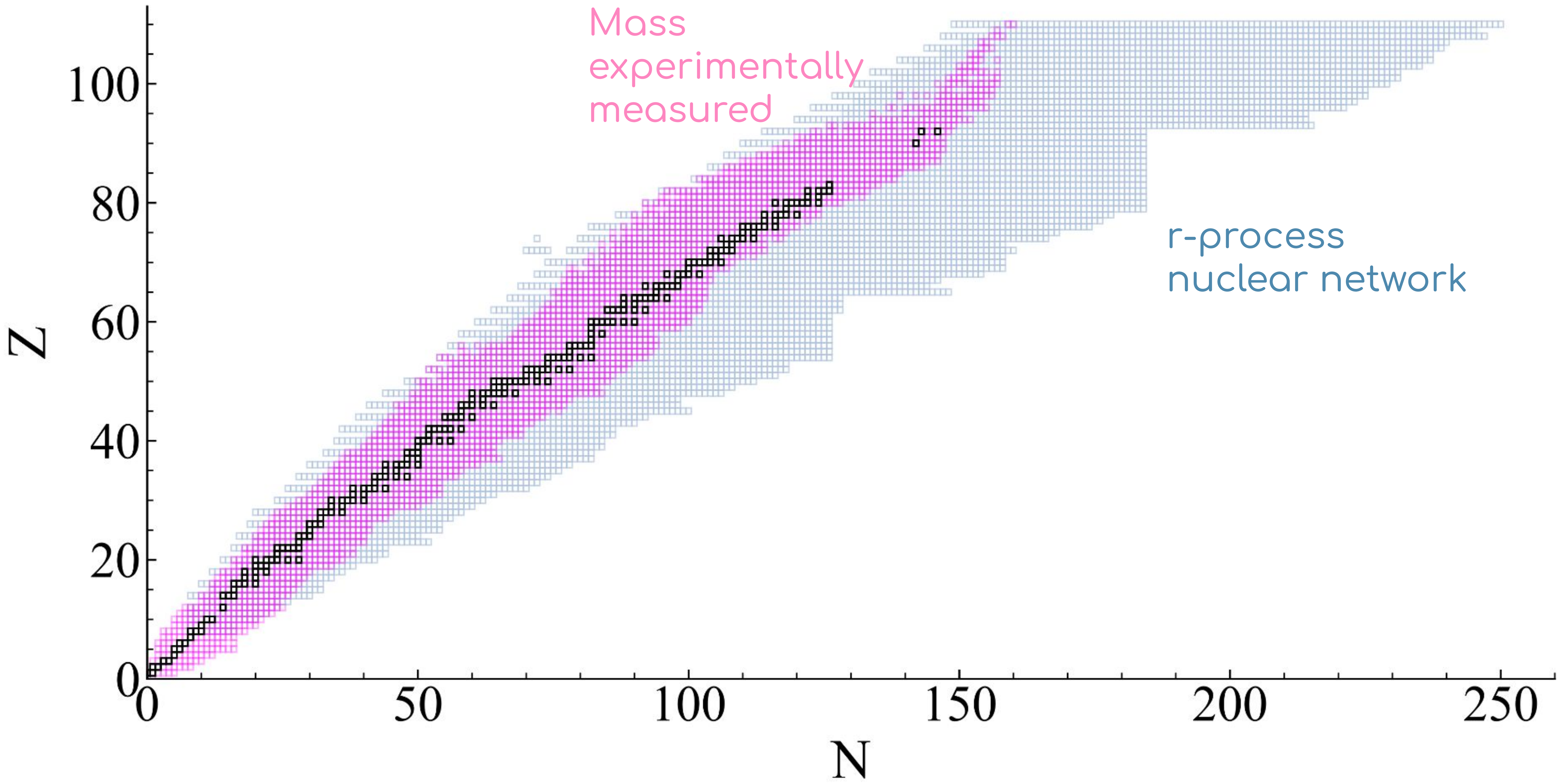

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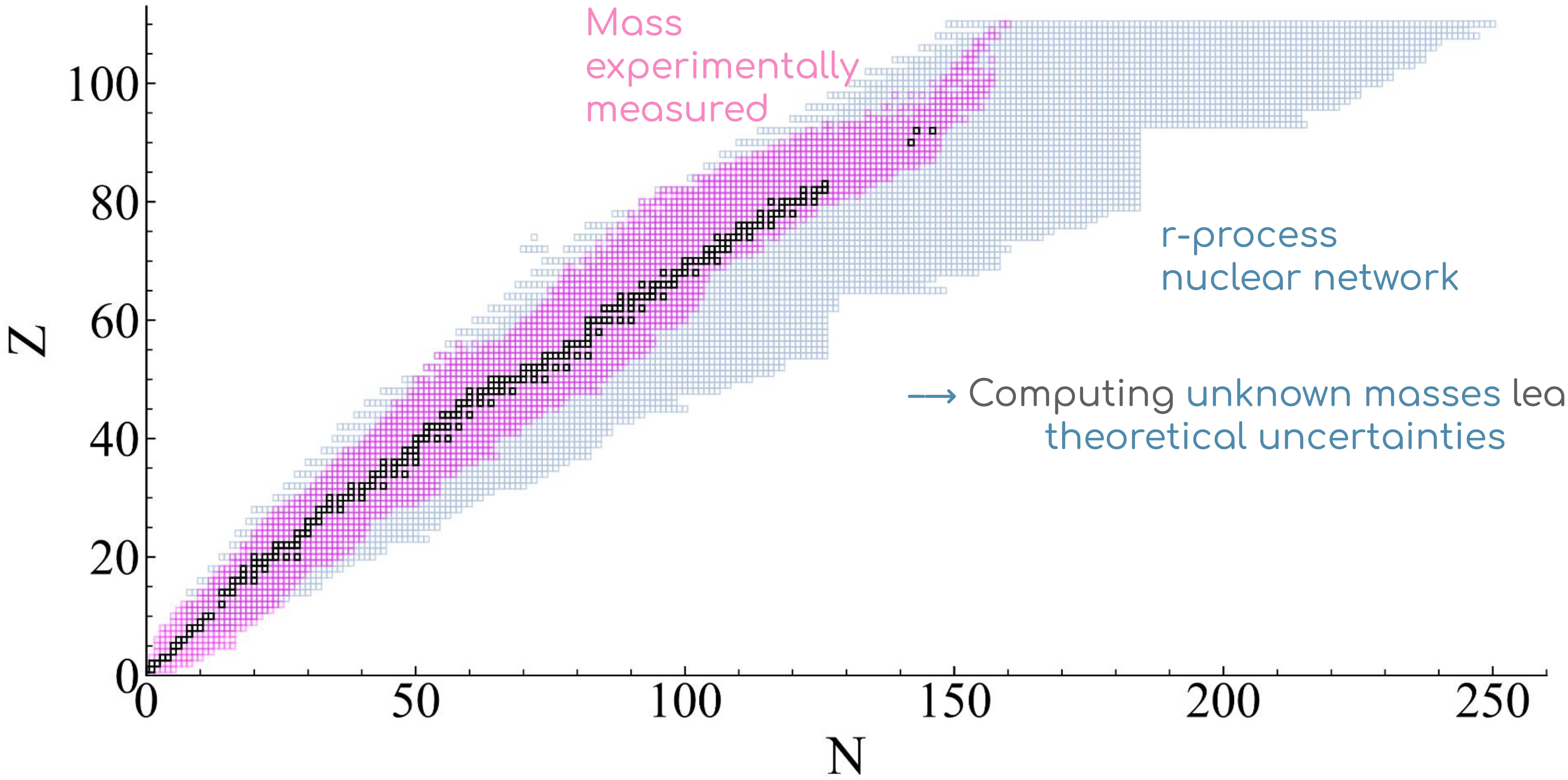
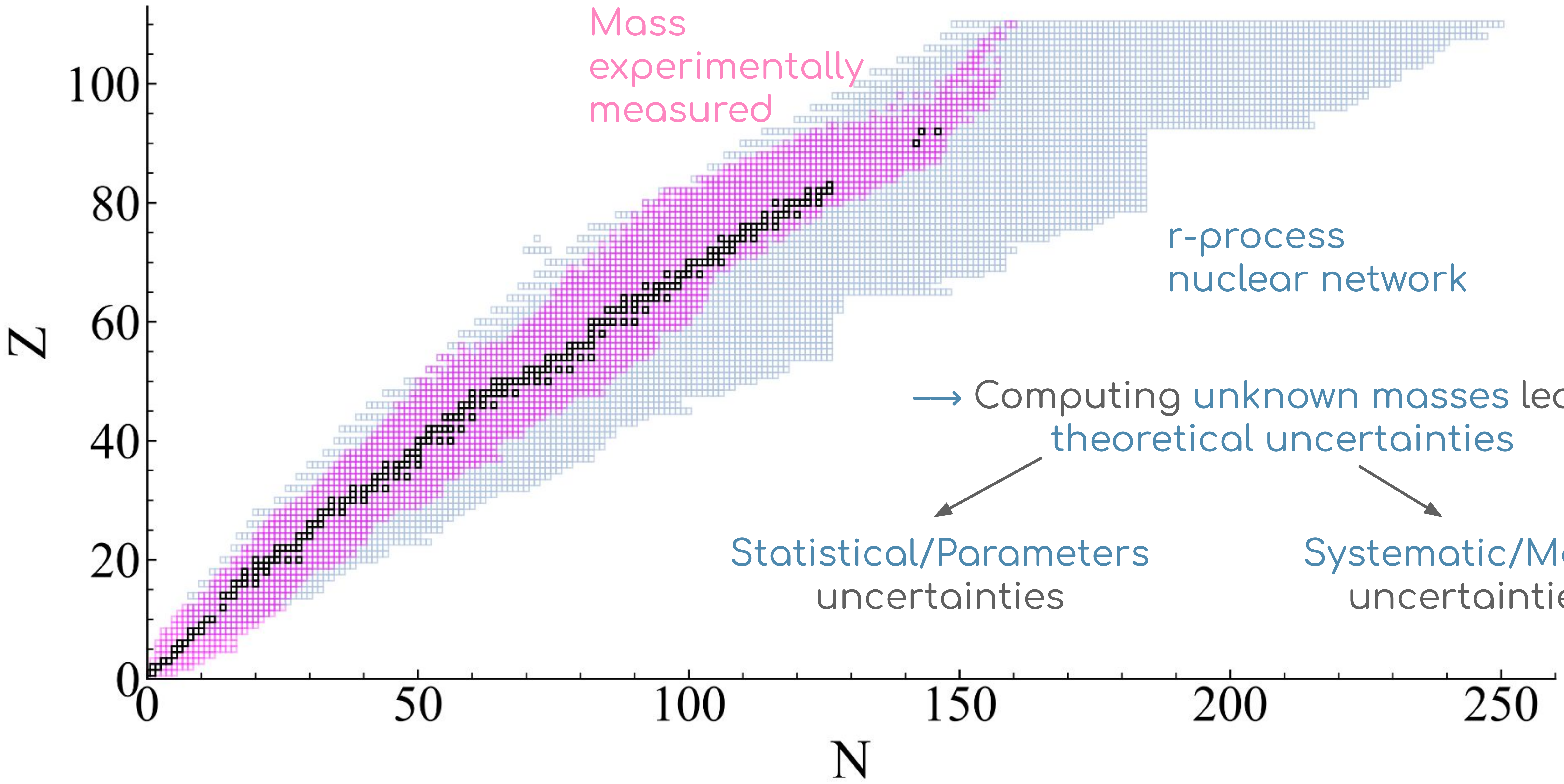


⟶ Computing unknown masses lead to theoretical uncertainties

Nuclear masses relevant to the r-process

Experimentally known masses vs r-process network needed



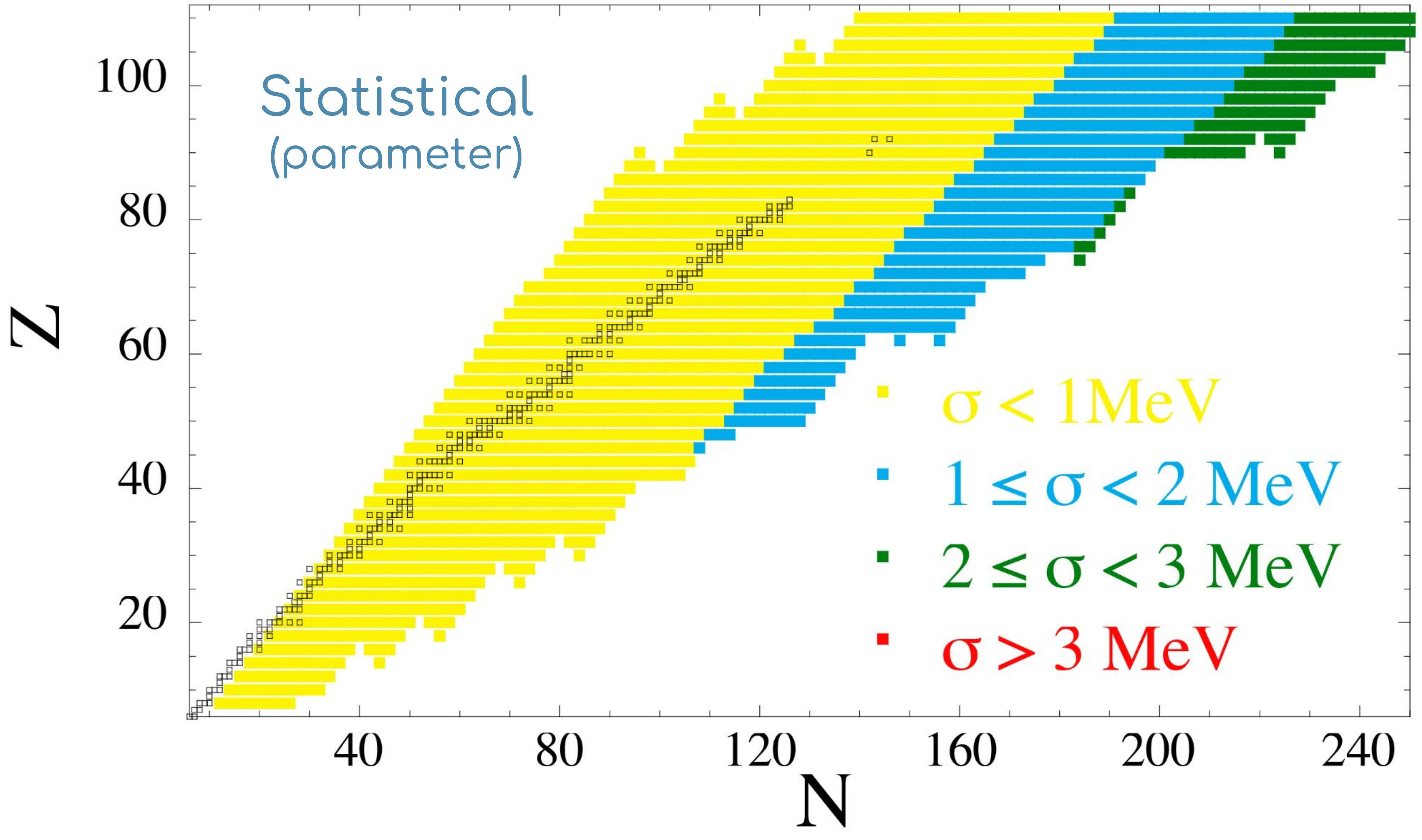
⟶ Computing unknown masses lead to theoretical uncertainties

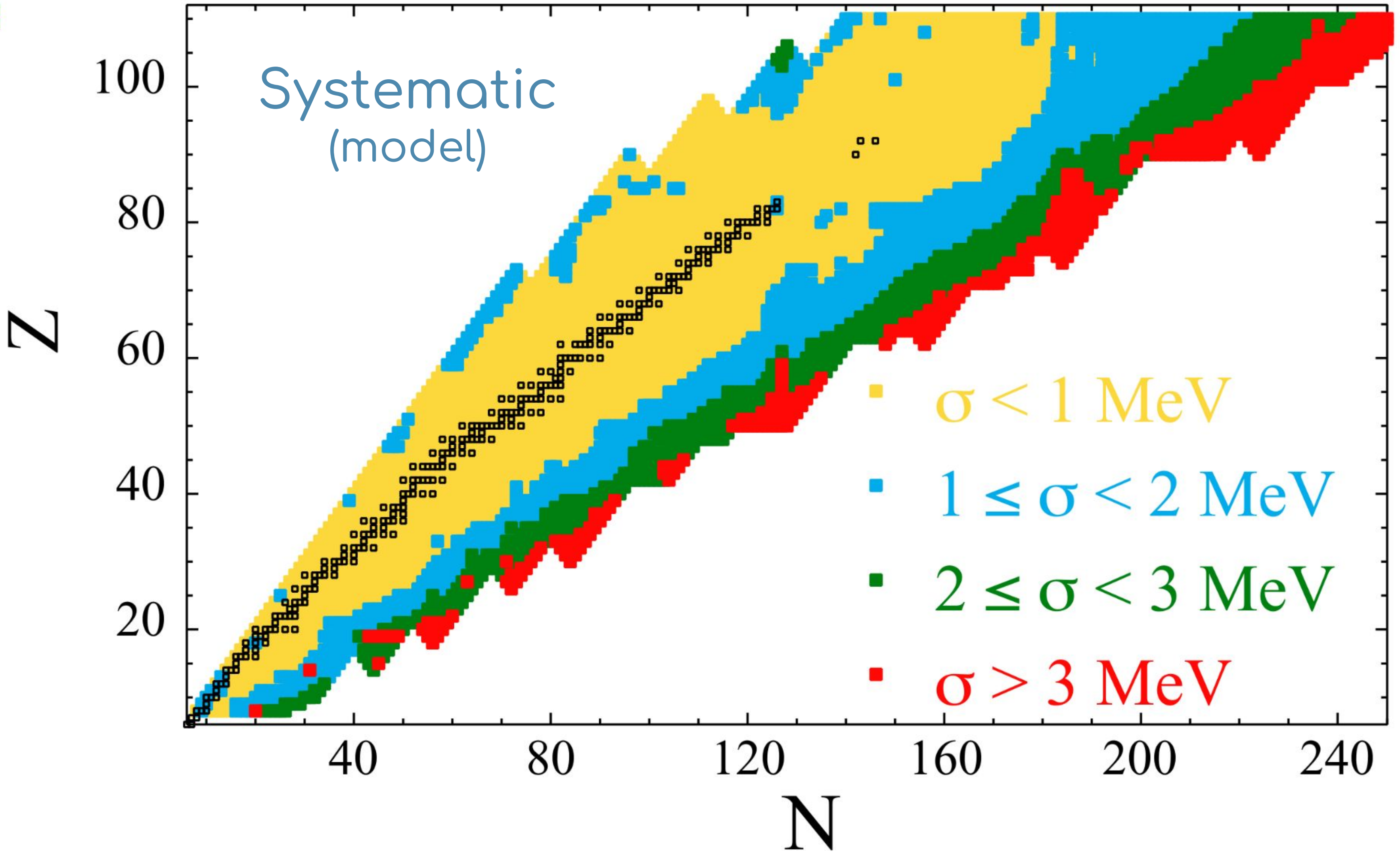
Statistical/Parameters uncertainties

Systematic/Model uncertainties

Model Uncertainties vs Parameters Uncertainties

Overestimating uncertainties



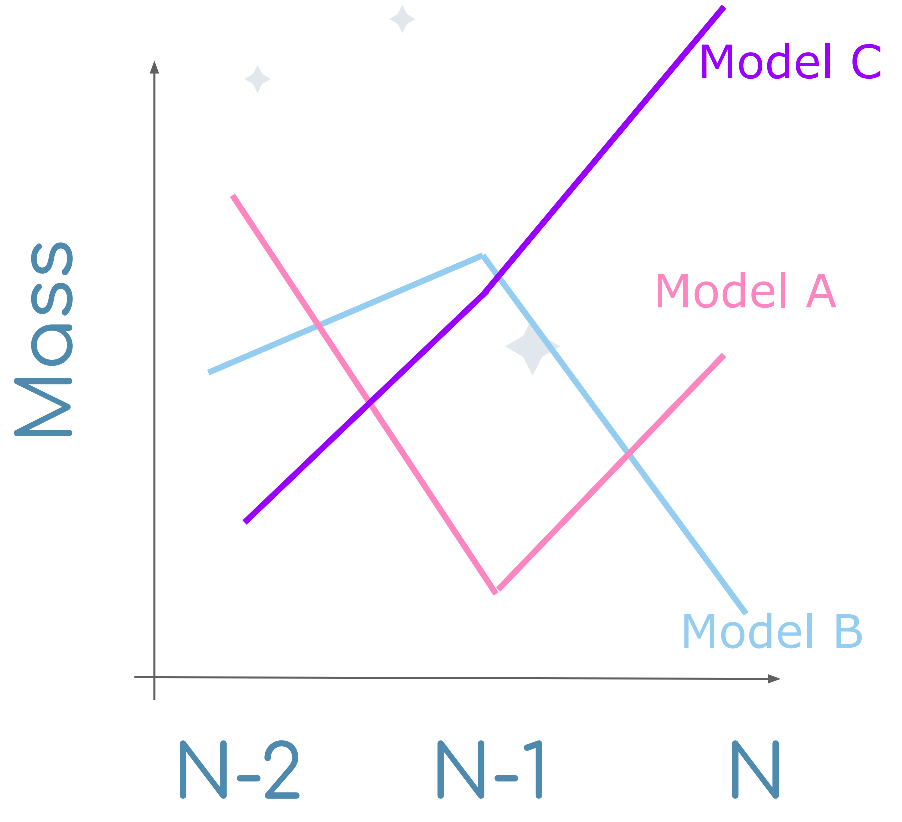


Model Uncertainties vs Parameters Uncertainties

Overestimating uncertainties

Common misuse of model uncertainties:

Z,N-2	Z,N-1	Z,N
$M_{\text{Model A}}$	$M_{\text{Model B}}$	$M_{\text{Model C}}$



Trying to maximize M by using values from different nuclear models leads to physical incompatibilities inside a network

→ Model uncertainties are <u>correlated</u>

Model Uncertainties vs Parameters Uncertainties

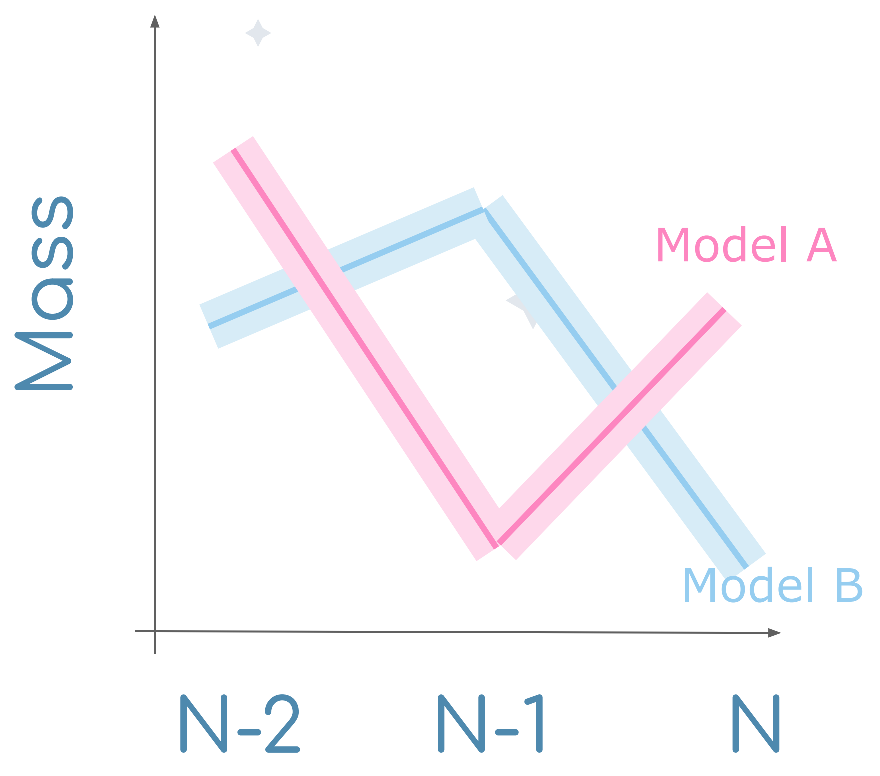
Overestimating uncertainties

Correct use of parameter uncertainties:

Z,N-2	Z,N-1	Z,N
max($M_{\text{Model A}}$)	min($M_{\text{Model A}}$)	mean($M_{\text{Model A}}$)

or

Z,N-2	Z,N-1	Z,N
max($M_{\text{Model B}}$)	random($M_{\text{Model B}}$)	random($M_{\text{Model B}}$)



These are possible combinations to use with the parameter uncertainties. Any value of these uncertainties can be combined for a same nuclear model.

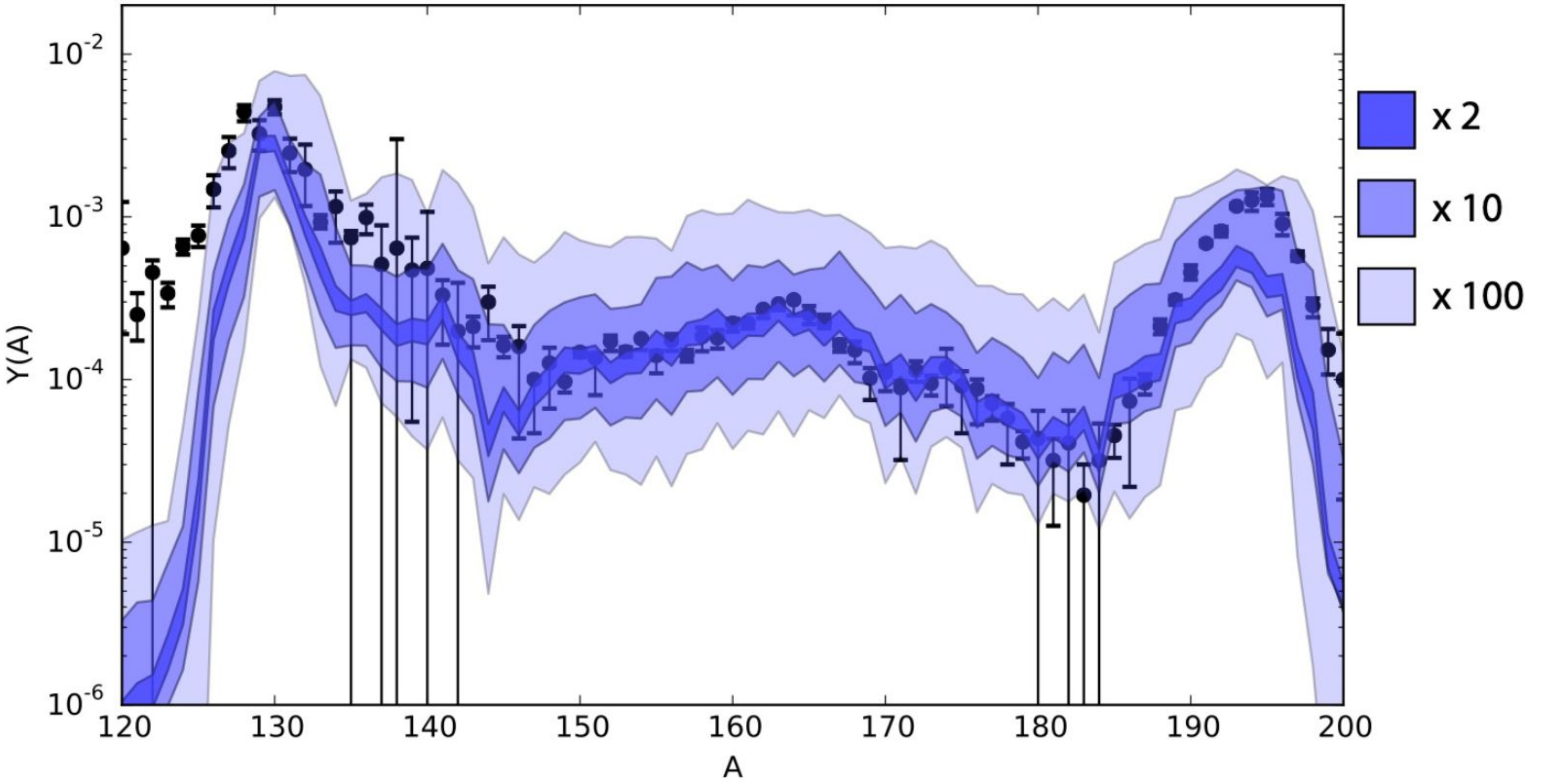
→ Parameter uncertainties are <u>non-correlated</u>

Determining coherently parameter uncertainties

Choosing parameter uncertainties arbitrarily

How to obtain parameter uncertainties ?

Uncorrelated MC approach (Mumpower+2016, Surman+2016, Nikas+2020, Jiang+21)



- Neglect correlations between uncertainties
- Overestimates impact

Choosing arbitrarily an uncertainty for each or all nuclei

The Backward-Forward Monte Carlo approach

Goriely & Capote 2014

1st Step: Computing masses for random sets of parameters for one nuclear model (HFB-24)

6424 nuclei

Z	N	A	1	2	3	4	...	11014	11015	11016	11019	11020	11021	11022
8	10	18	0.88	0.95	0.93	0.94	...	0.88	0.86	0.97	0.83	0.90	1.00	0.94
8	11	19	5.14	5.14	5.22	5.24	...	5.07	5.16	5.20	5.11	5.15	5.21	5.20
8	12	20	3.23	3.29	3.24	3.27	...	3.18	3.16	3.36	3.16	3.23	3.33	3.21
8	13	21	9.11	9.11	9.15	9.17	...	9.01	9.08	9.15	9.12	9.09	9.19	9.08
8	14	22	9.45	9.48	9.46	9.48	...	9.37	9.36	9.46	9.46	9.39	9.55	9.37
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
110	246	356	533.09	534.80	532.17	530.81	...	532.92	529.74	531.01	533.00	527.89	533.04	530.81
110	247	357	540.31	542.02	539.73	538.48	...	539.98	537.68	538.38	540.28	535.53	540.06	538.67
110	248	358	548.11	549.85	547.17	545.78	...	547.96	544.72	545.94	548.04	542.80	548.04	545.79
110	249	359	555.79	557.52	555.18	553.90	...	555.49	553.08	553.74	555.79	550.88	555.53	554.09
110	250	360	564.04	565.79	563.09	561.66	...	563.91	560.61	561.80	564.00	558.63	563.94	561.69

The Backward-Forward Monte Carlo approach

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2nd Step: Checking if each parameter set as a rms for the known nuclei compatible with the experimental rms and discard the rest

↔

Anchor values to experimental uncertainties

The Backward-Forward Monte Carlo approach

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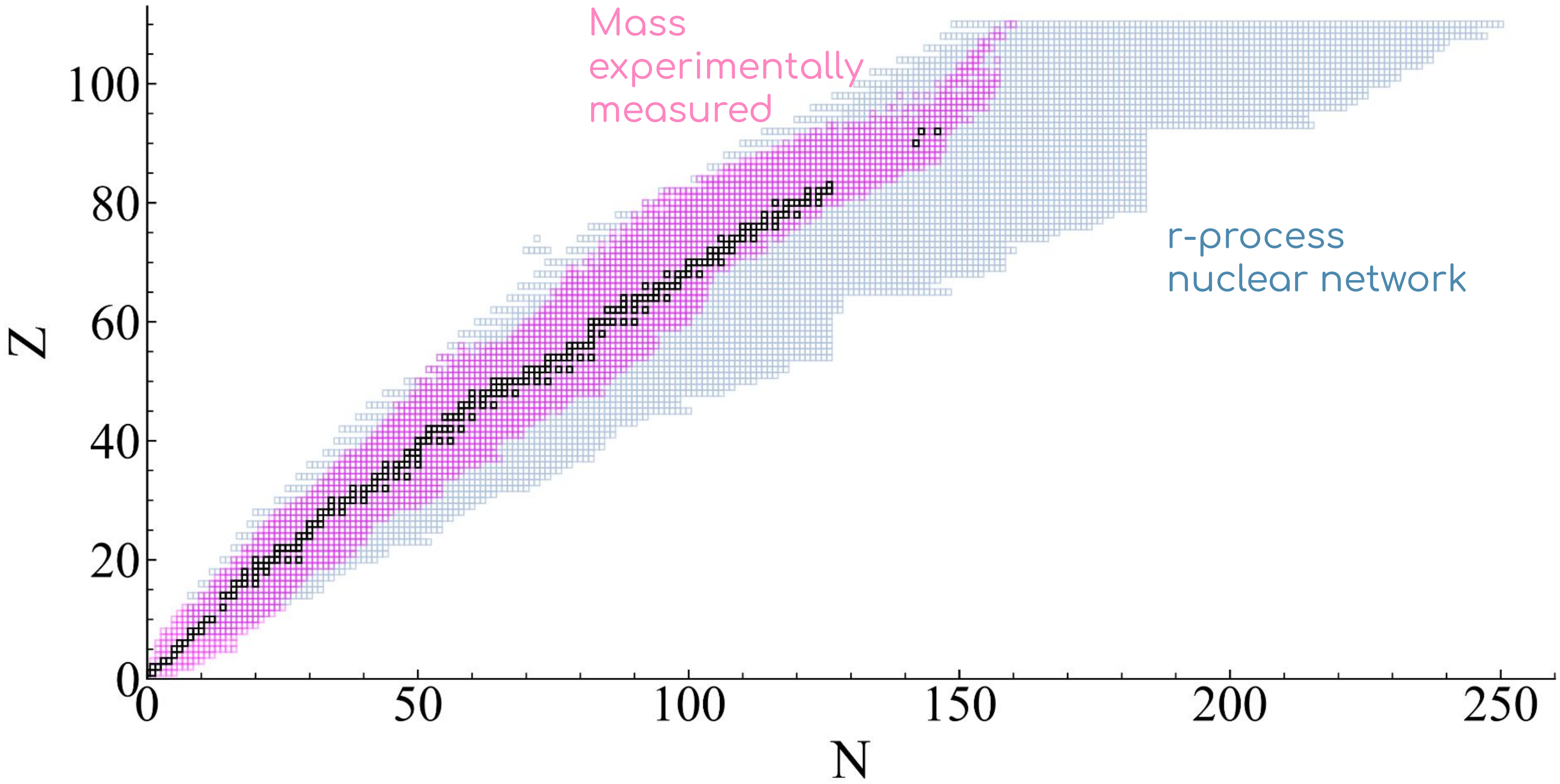
2nd Step: Checking if each parameter set as a rms for the known nuclei compatible with the experimental rms and discard the rest ⟷ Anchor values to experimental uncertainties

→ Using the remaining sets of parameters compatible with experiments to obtain the uncertainties on unknown masses

Determining coherently parameter uncertainties

Parameters uncertainties obtained from the BFMC method



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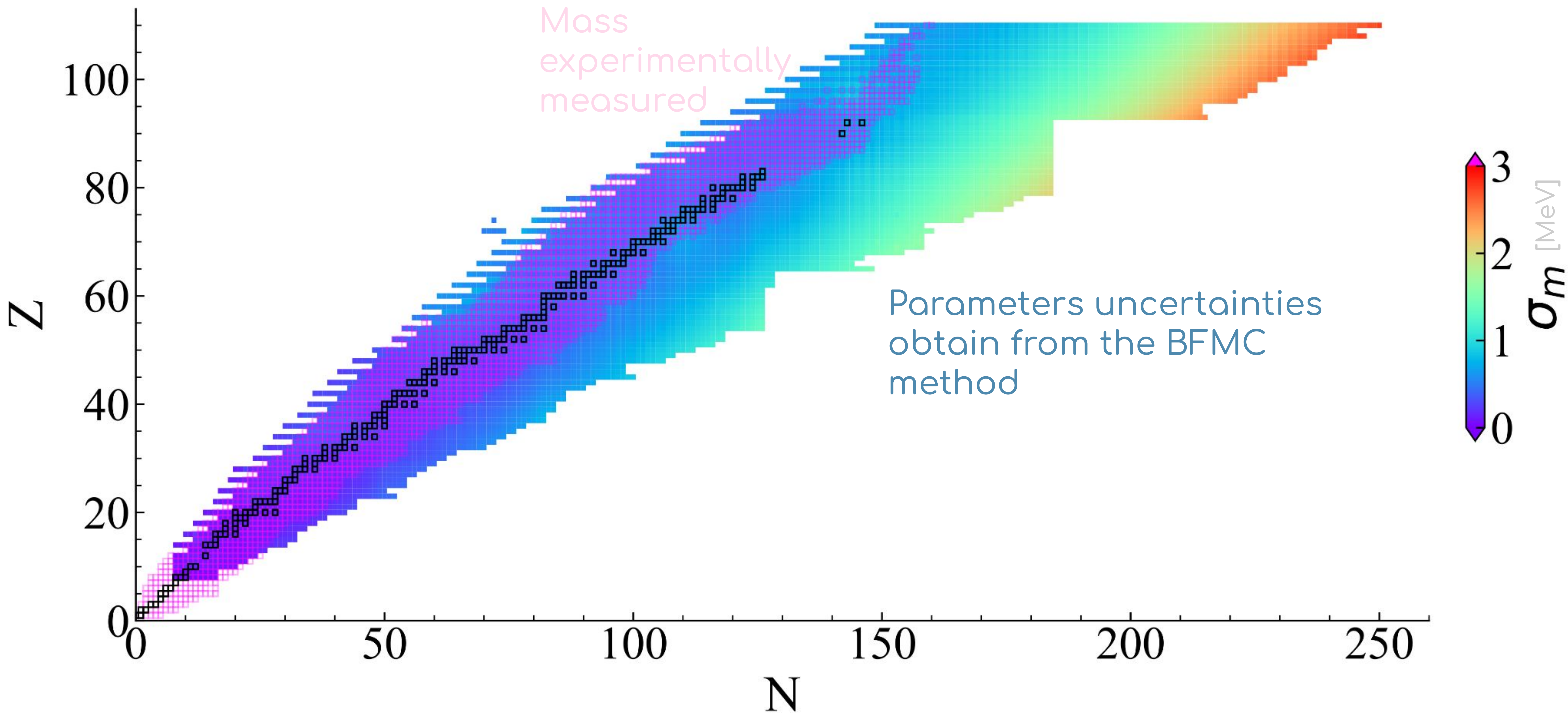

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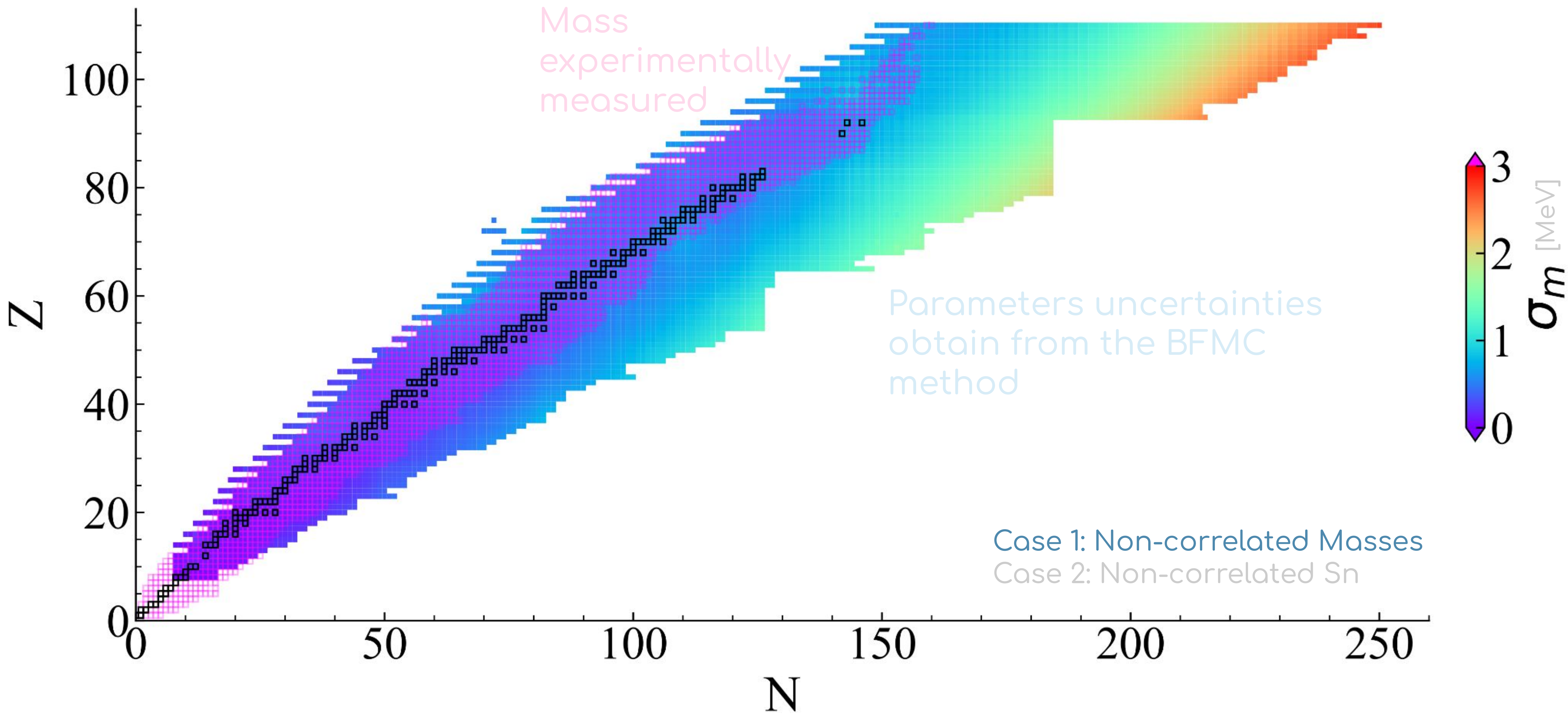

Case 1: Non-correlated Masses

Case 2: Non-correlated Sn

Determining coherently parameter uncertainties

Parameters uncertainties obtained from the BFMC method

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→ However, photodissociation reaction rates depend exponentially on the separation energy Sn

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Case 2: Non-correlated Sn

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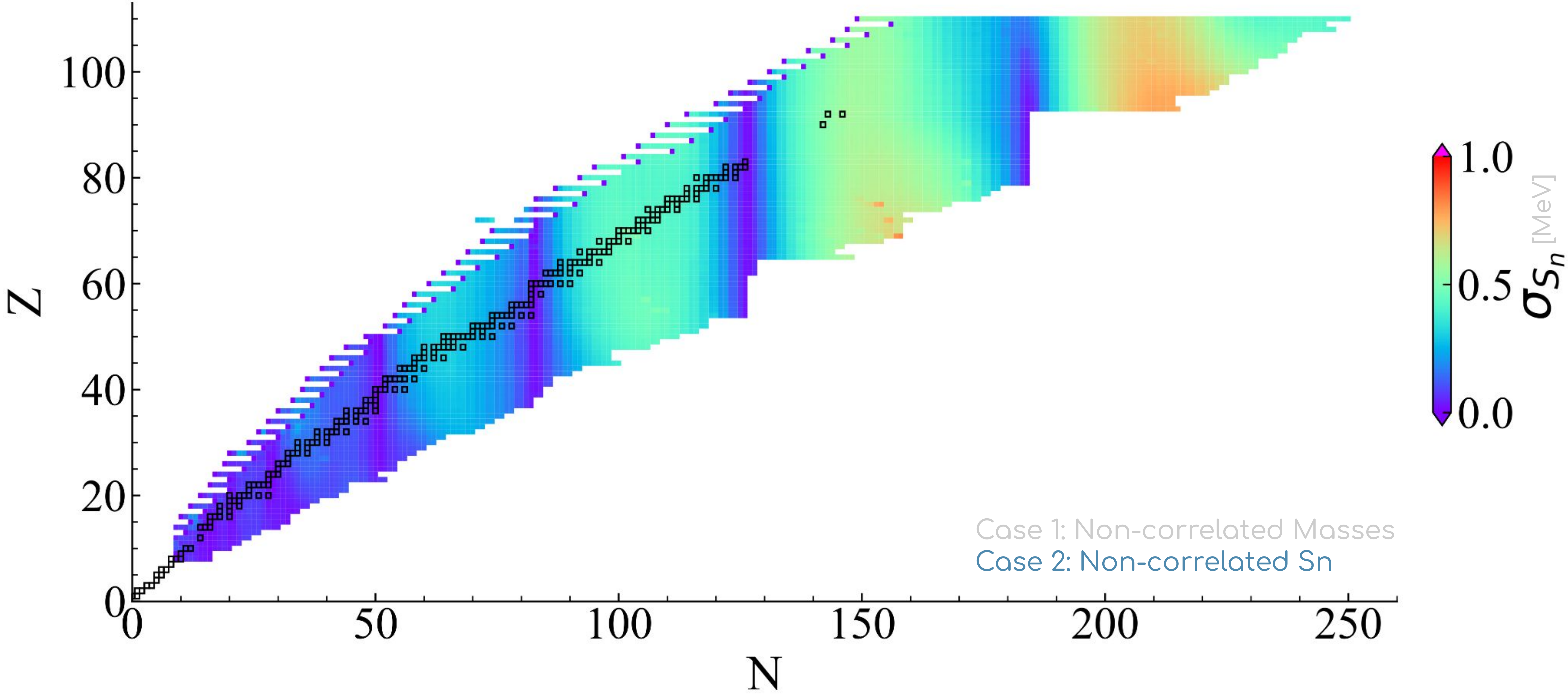
$$\longrightarrow S_n(Z,N) = M(Z,N-1) + m_{\text{neut}} - M(Z,N)$$

Case 1: Non-correlated Masses

Case 2: Non-correlated Sn

Determining coherently parameter uncertainties

Parameters uncertainties obtained from the BFMC method



Determining coherently parameter uncertainties

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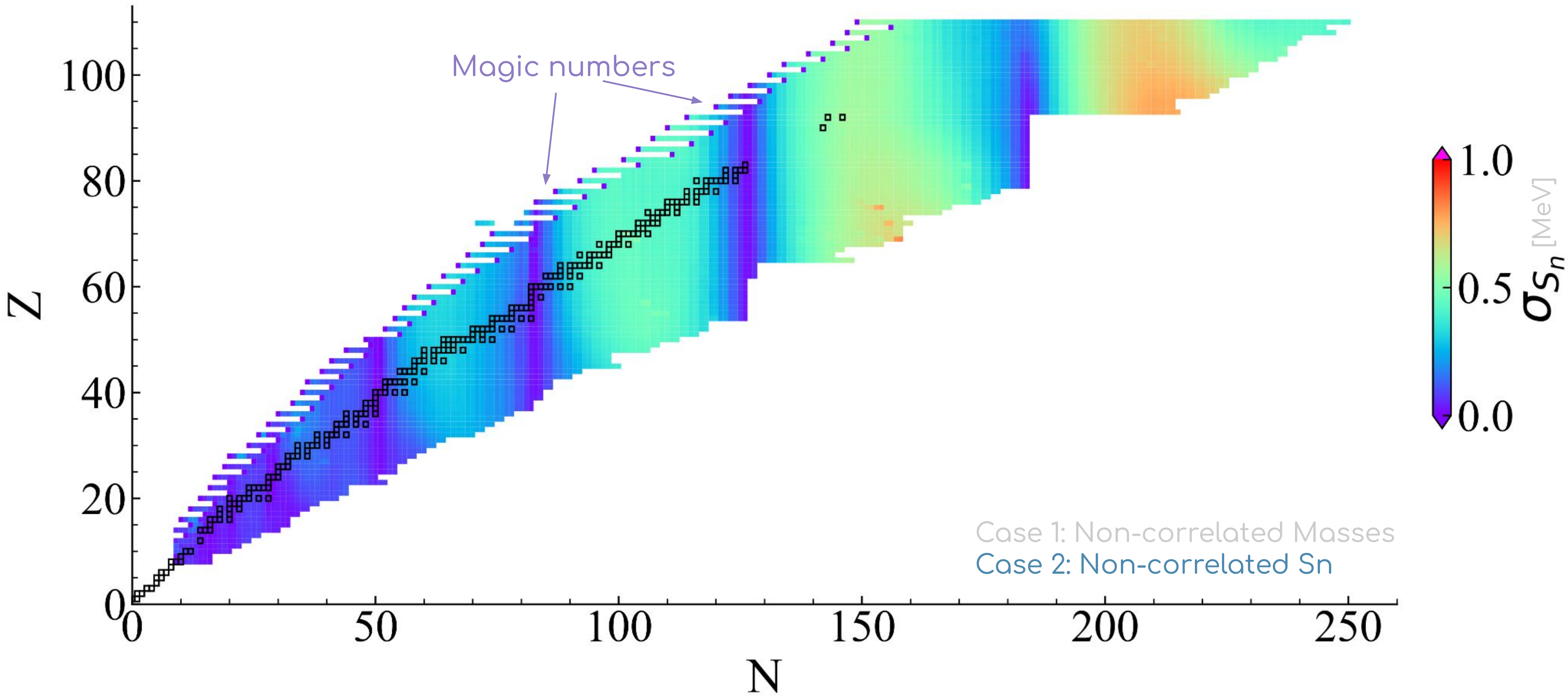
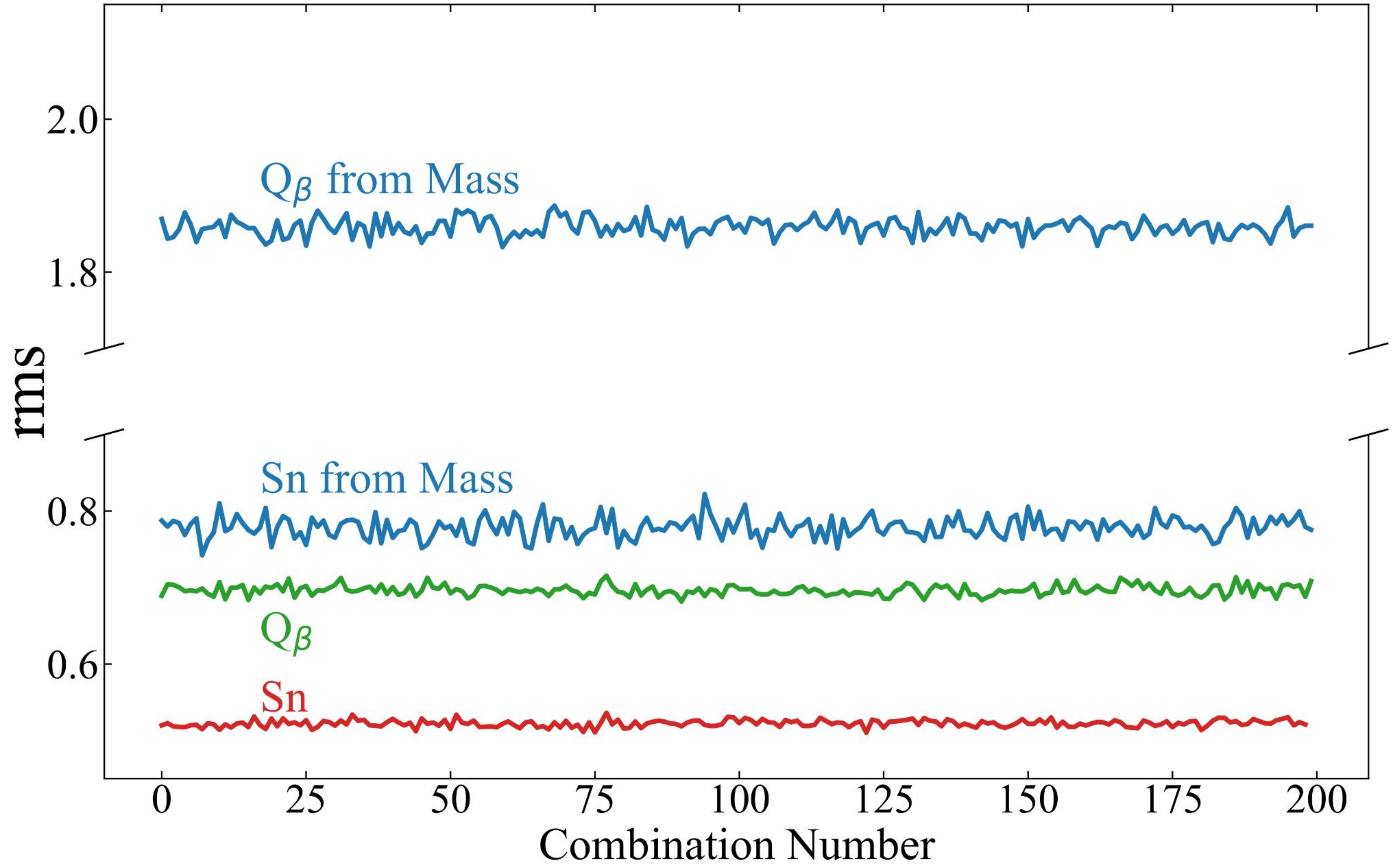


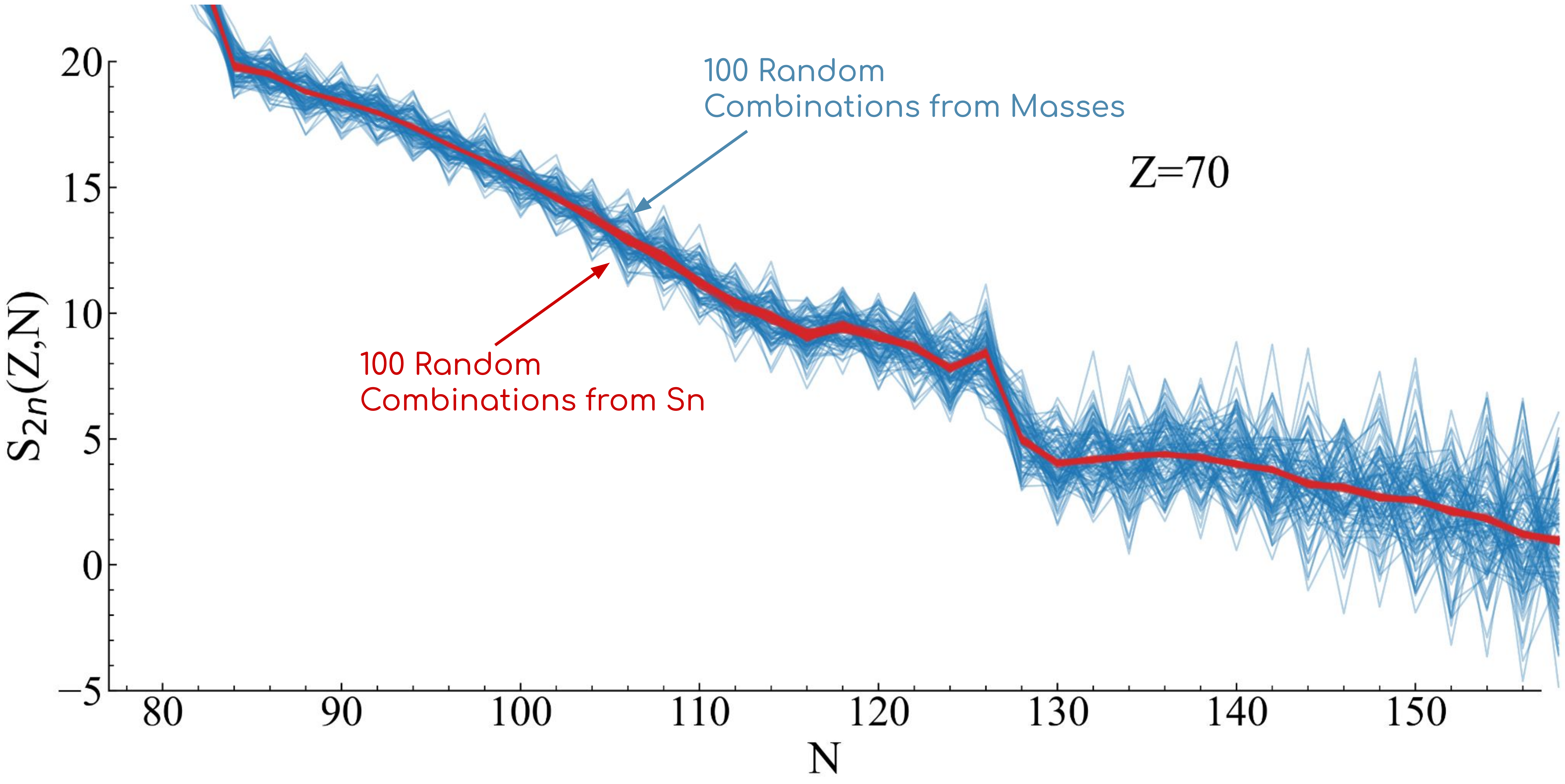
Determining coherently parameter uncertainties

Uncertainties from Mass vs from Sn



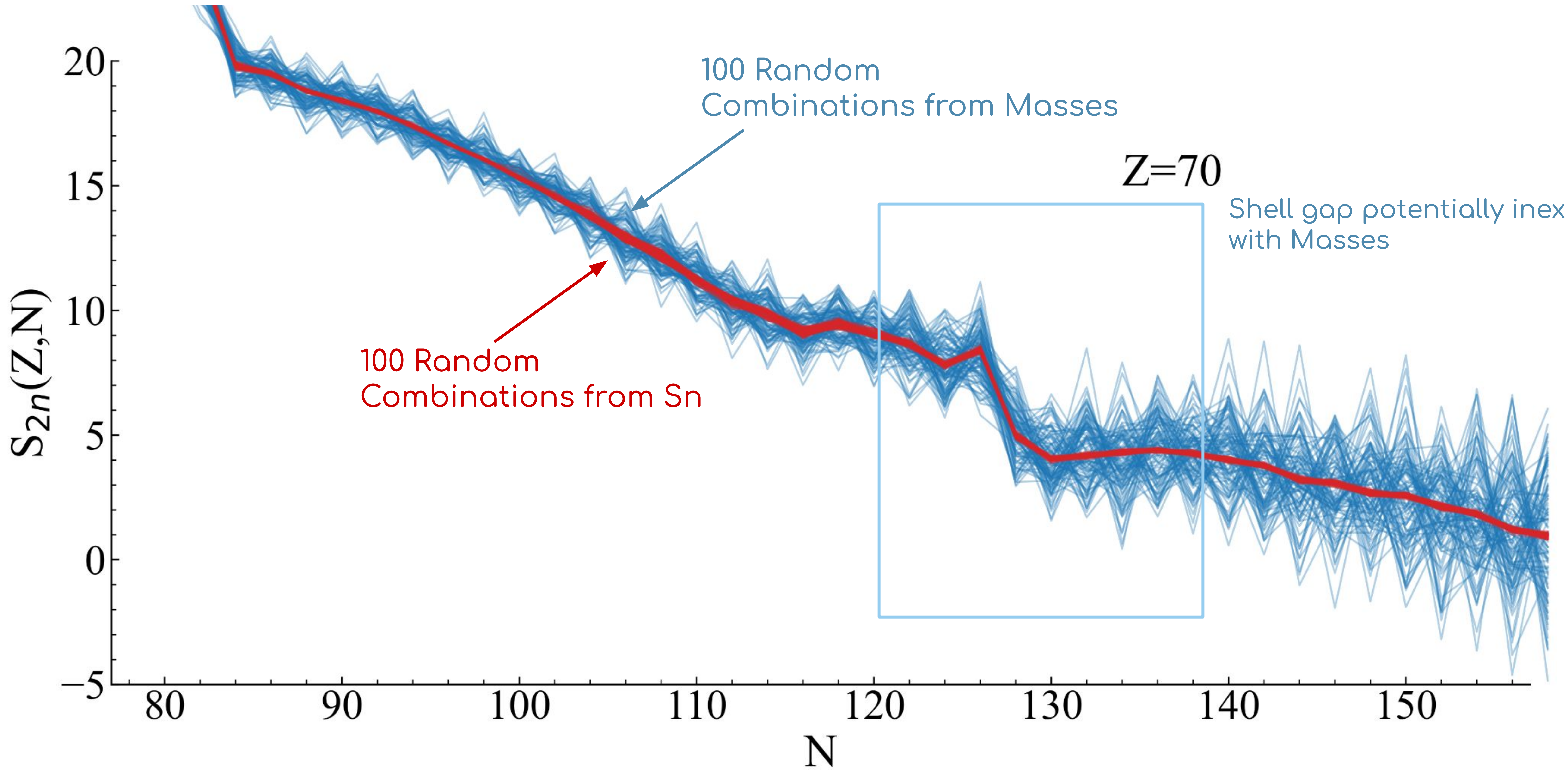
Determining coherently parameter uncertainties

Uncertainties from Mass vs from Sn



Determining coherently parameter uncertainties

Uncertainties from Mass vs from Sn

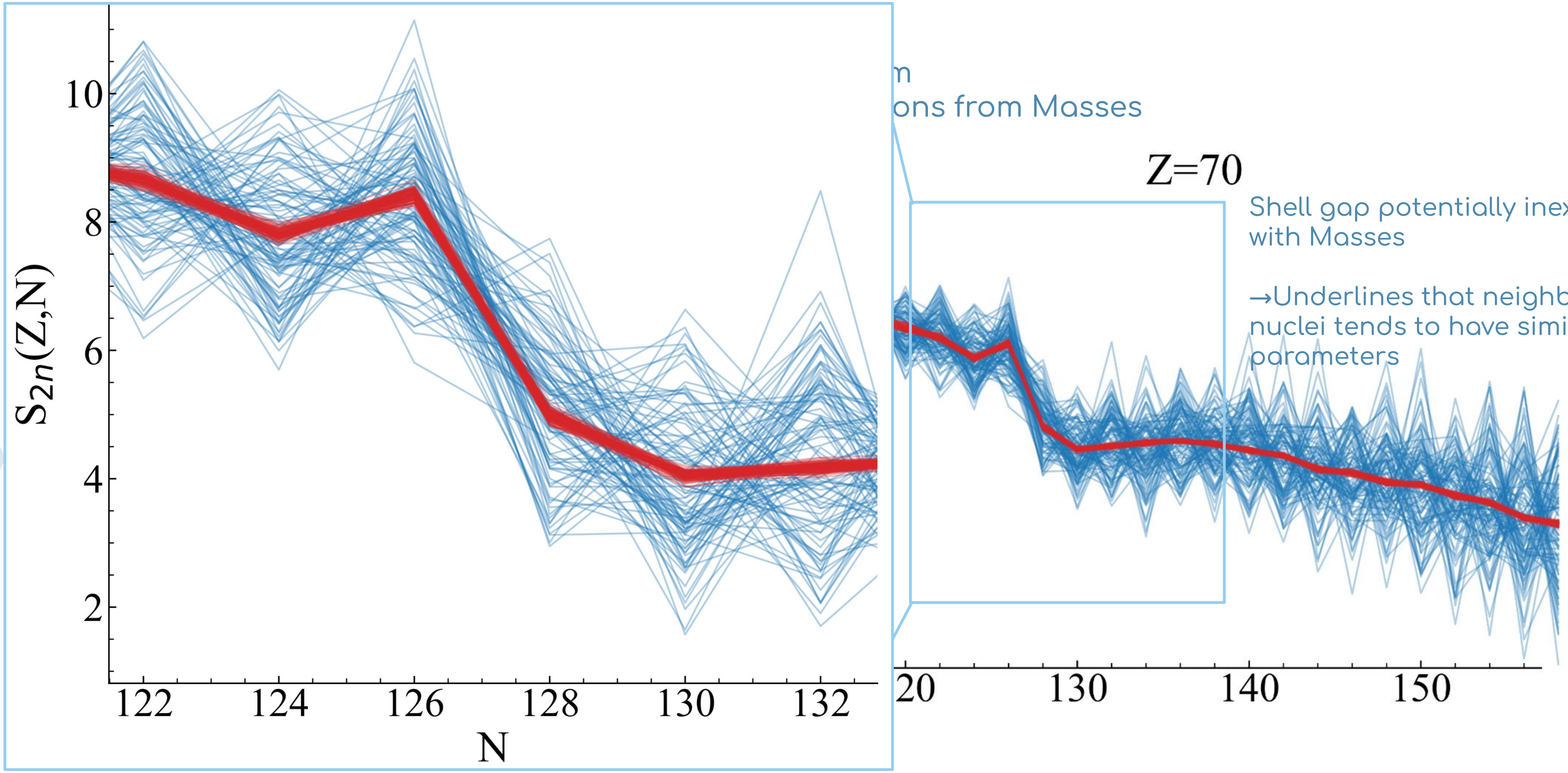


Determining coherently parameter uncertainties

Uncertainties from Mass vs from Sn

m

ons from Masses



Shell gap potentially inexistent with Masses

→Underlines that neighbouring nuclei tends to have similar parameters

Propagating nuclear uncertainties to r-process simulations

Reducing number of simulations required

We vary randomly the sign of the uncertainties for each nuclei to randomly maximize/minimize the mass/Sn

Advantage of this method: low number of r-process simulations needed to obtain maximum uncertainties on abondances

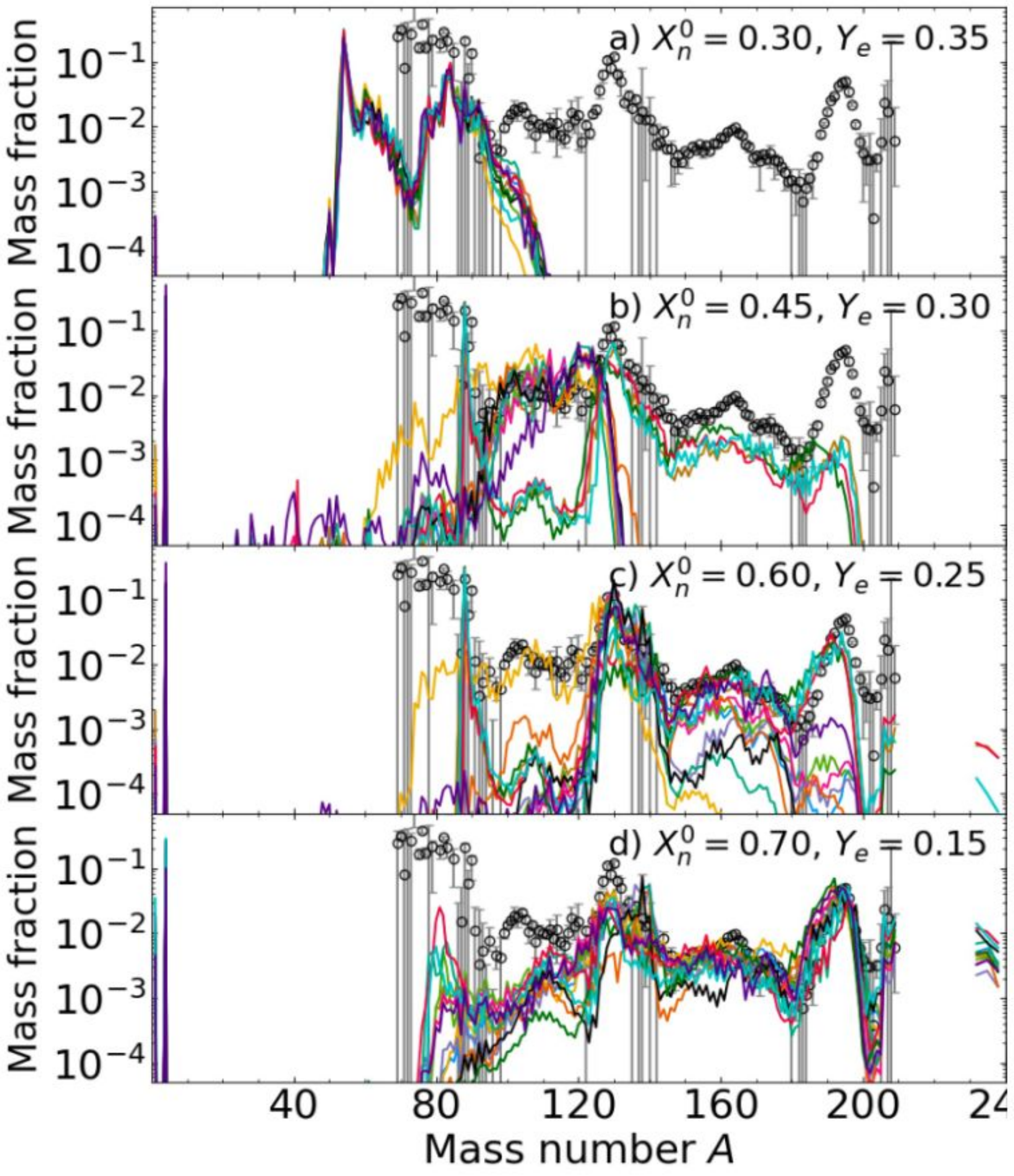
→ satisfactory convergence reached between 25 and 50 models

→ r-process simulations of a 1.38-1.38$M_\odot$ symmetric NSM

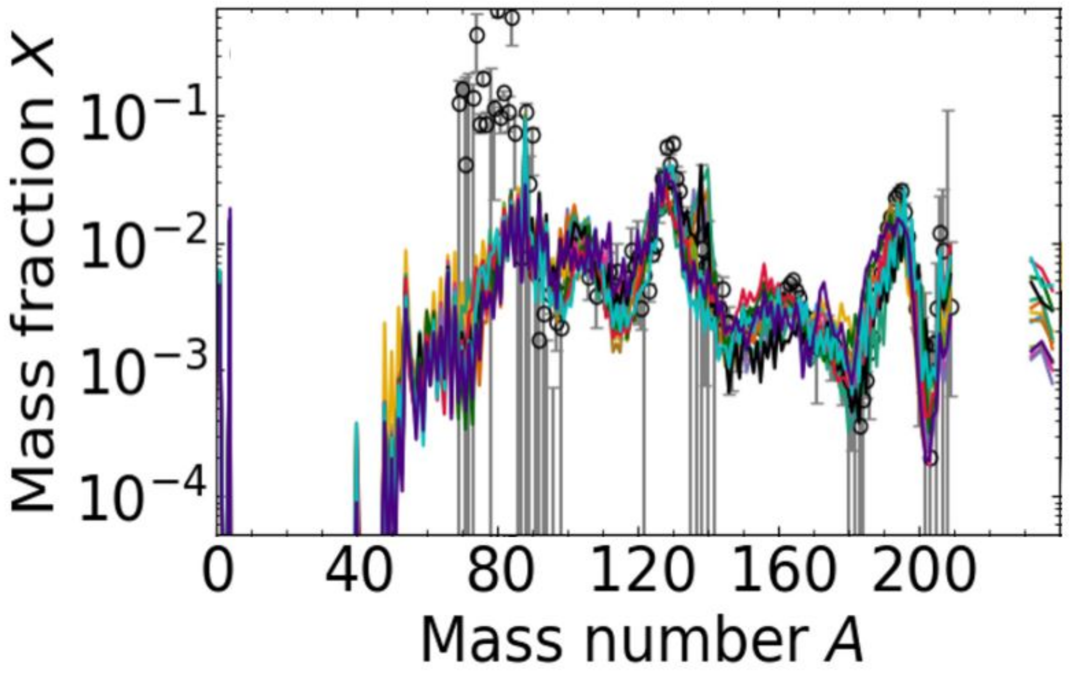
Propagating nuclear uncertainties to r-process simulations

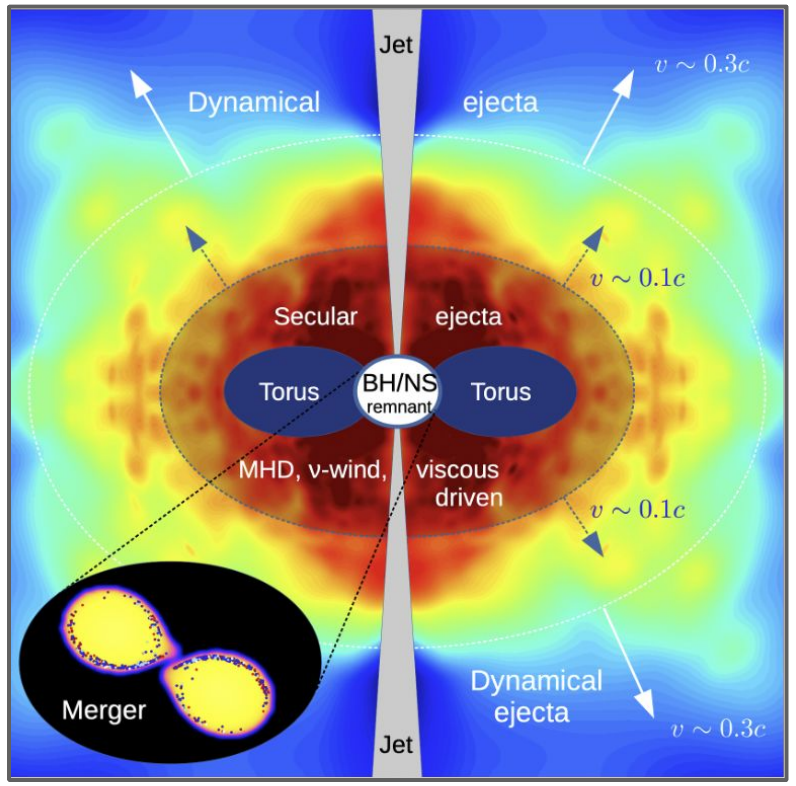
Importance of using multiple trajectories representing the whole NSM event

Prompt dynamical ejecta



Multiple trajectories

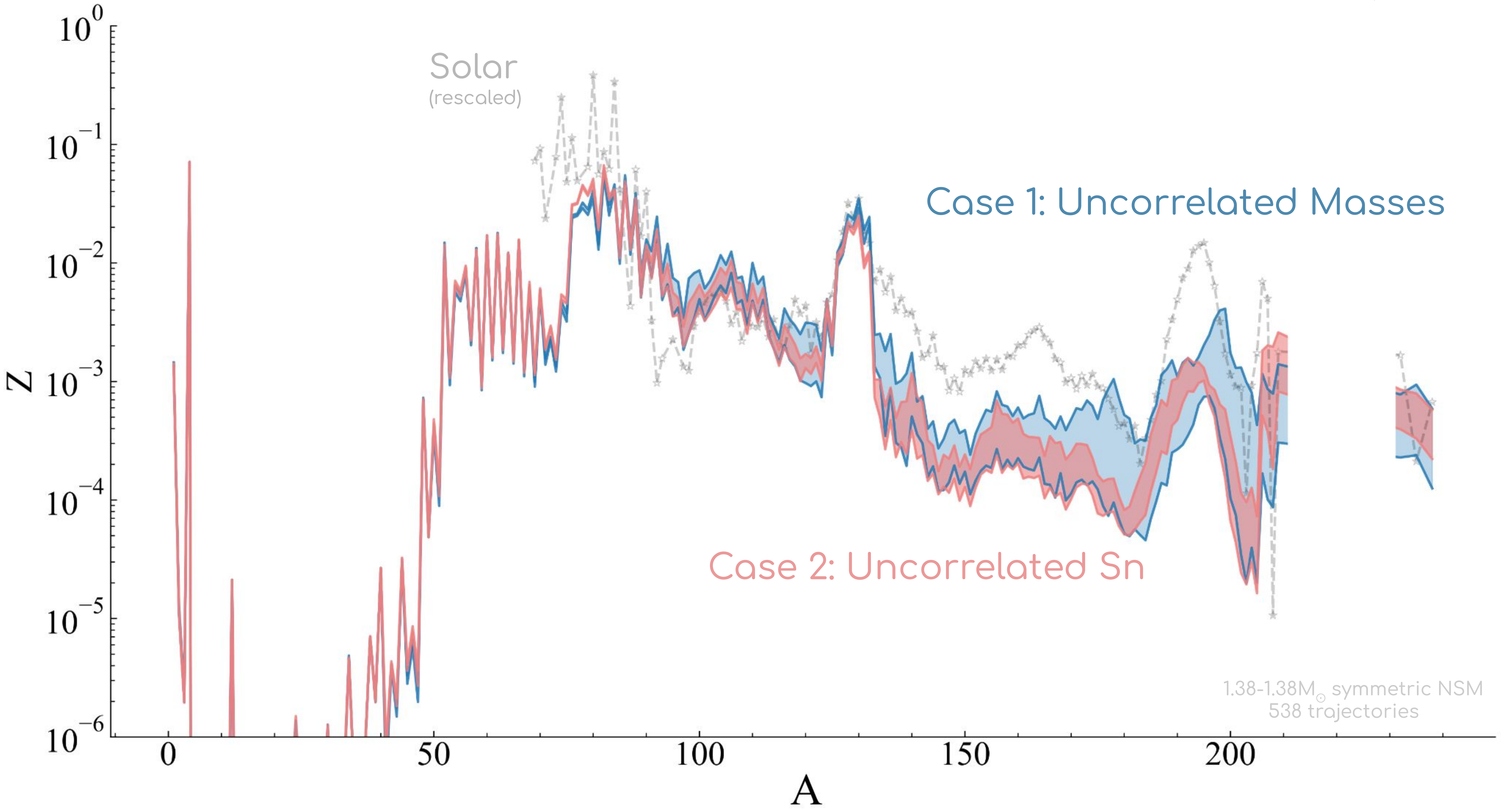




538 trajectories representing the total ~2500 trajectories

Propagating nuclear uncertainties to r-process simulations

Uncertainties from Mass vs from Sn



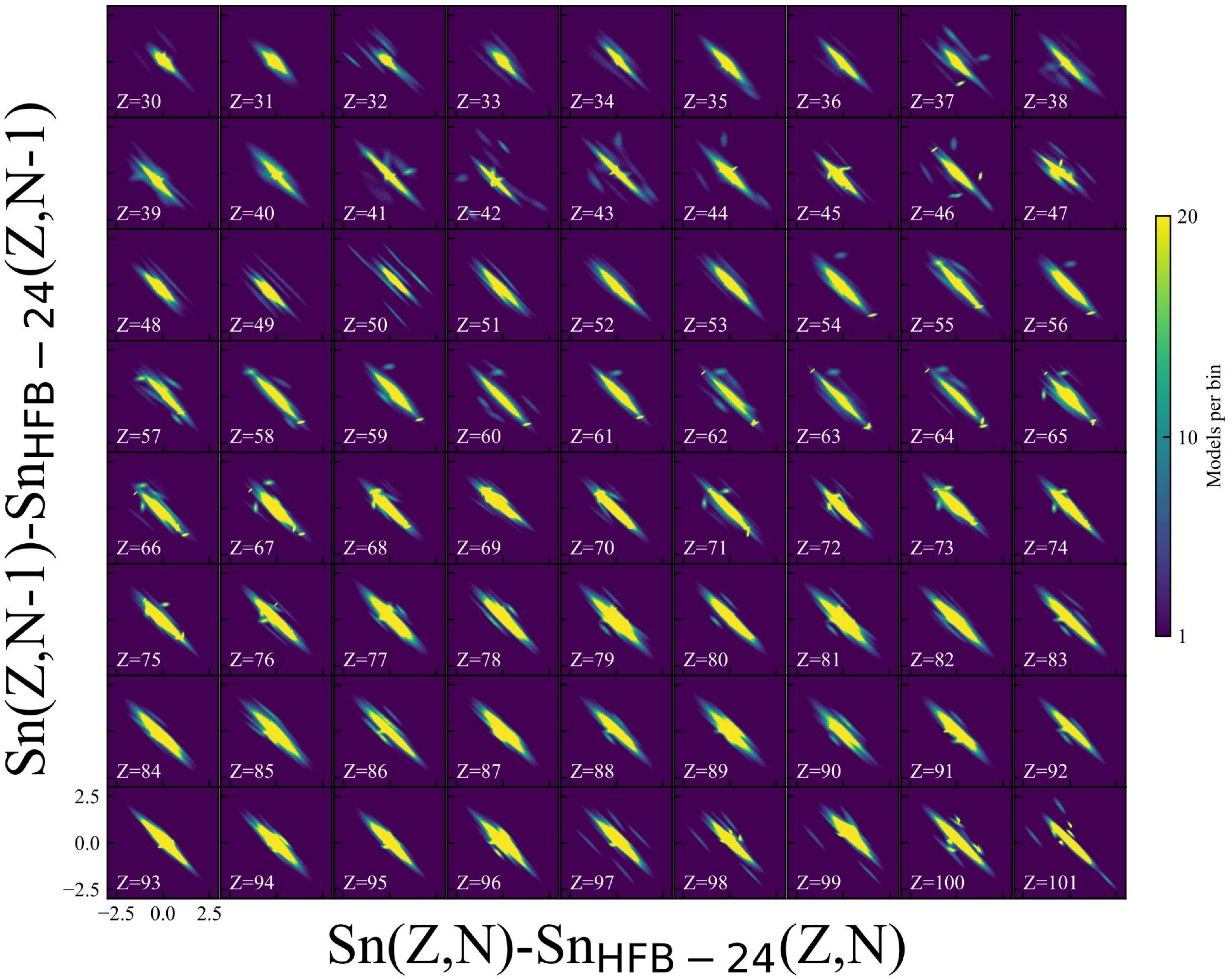
Propagating nuclear uncertainties to r-process simulations

Anti-correlation of Sn

$$S_n(Z,N) = M(Z,N-1) + m_{\text{neut}} - M(Z,N)$$

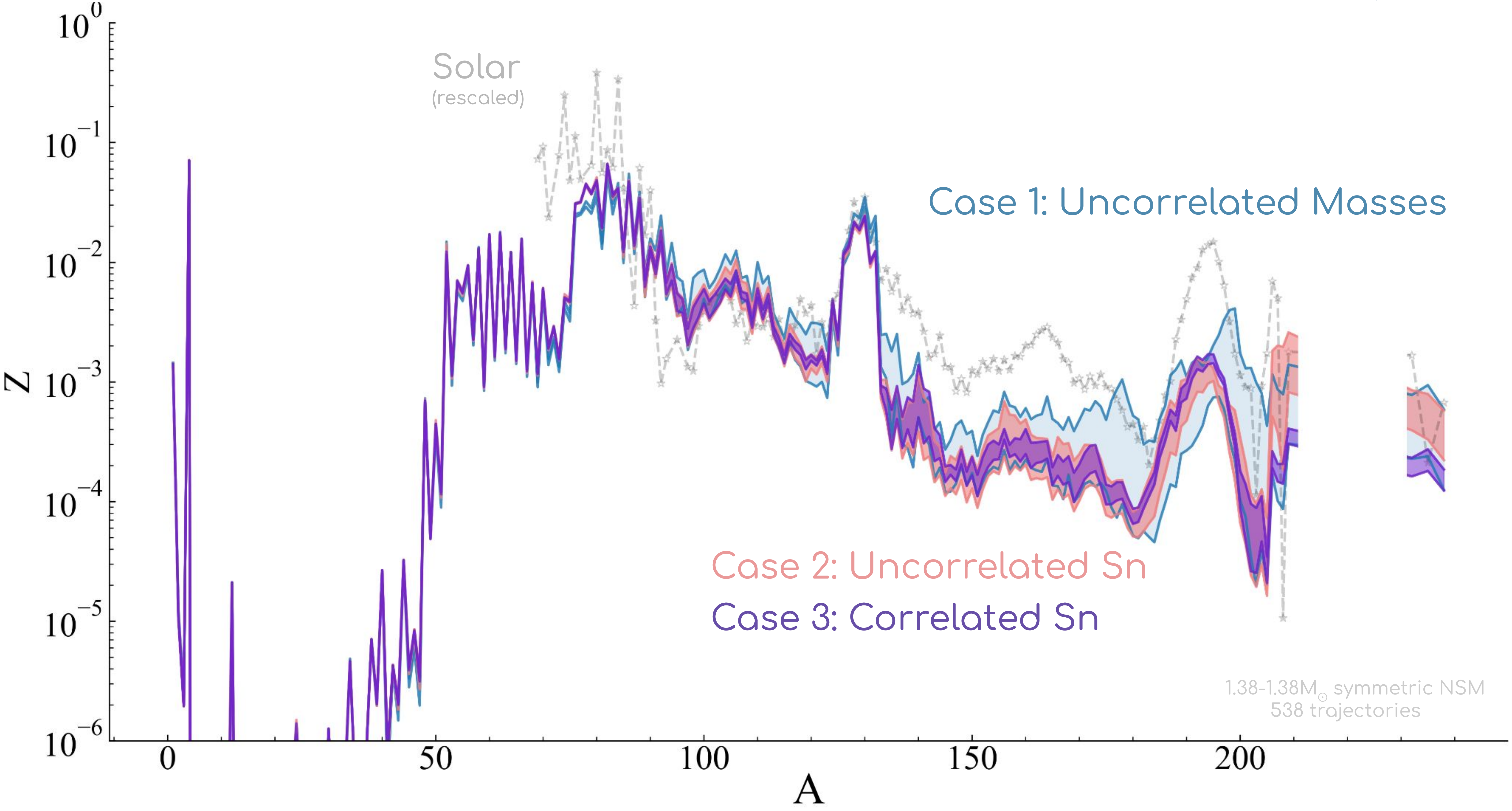
$$S_n(Z,N-1) = M(Z,N-2) + m_{\text{neut}} - M(Z,N-1)$$

→ Anti-correlation



Propagating nuclear uncertainties to r-process simulations

Anti-correlation of Sn



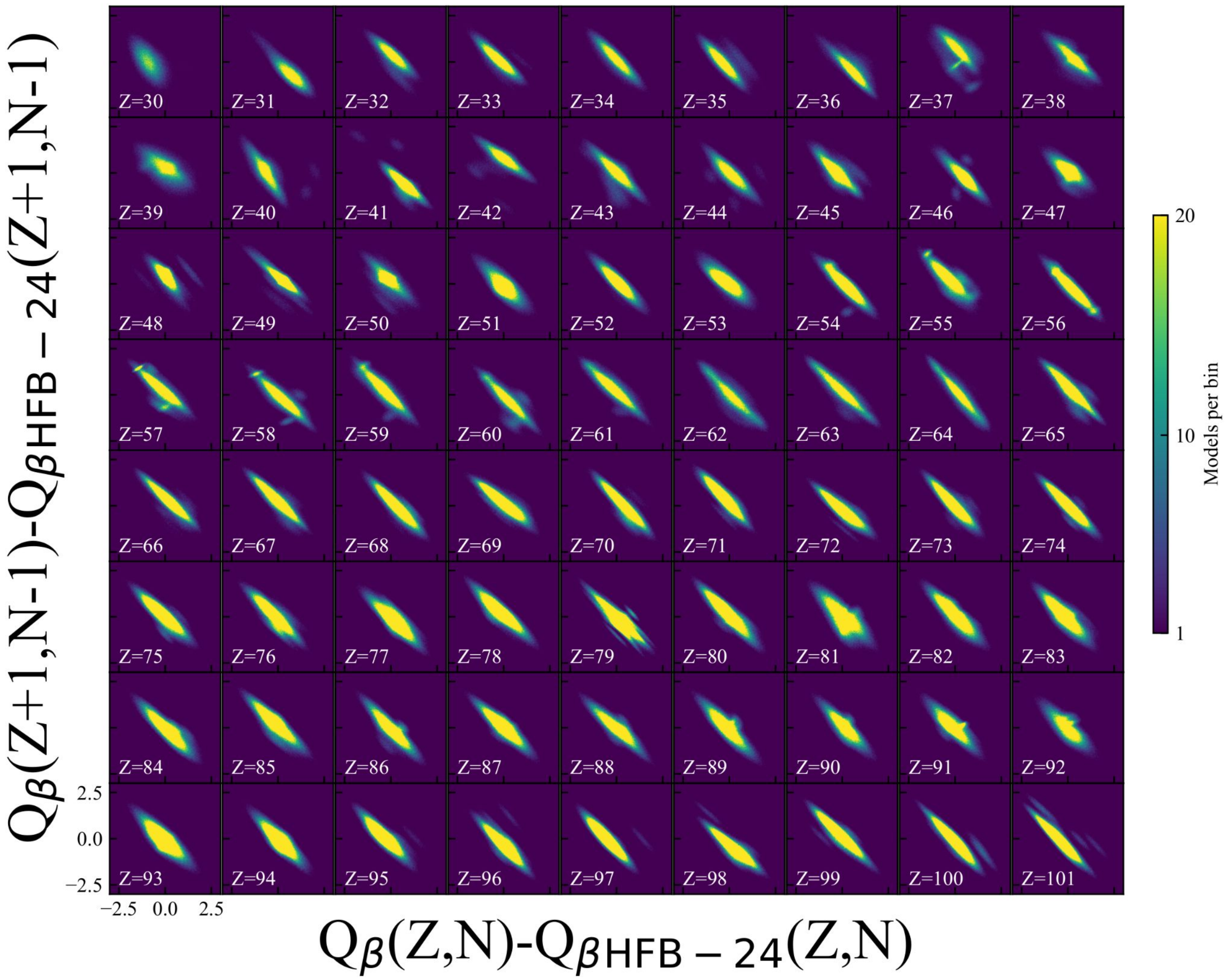
Propagating nuclear uncertainties to r-process simulations

Anti-correlation of Sn and Qb

$$Q_\beta(Z,N) = M(Z,N) - \underline{M(Z+1,N-1)}$$

$$Q_\beta(Z+1,N-1) = \underline{M(Z+1,N-1)} - M(Z+2,N-2)$$

→ Anti-correlation



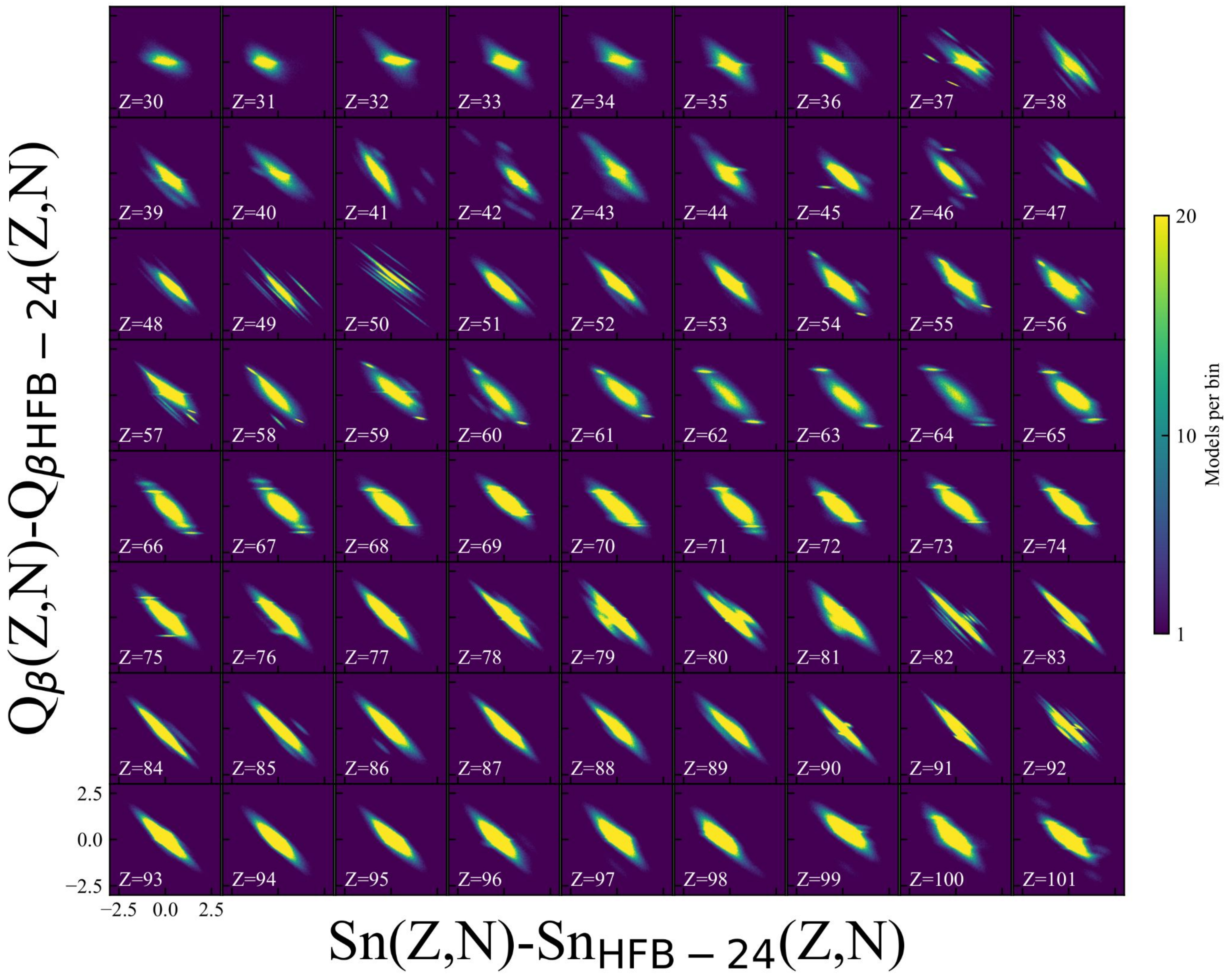
Propagating nuclear uncertainties to r-process simulations

Anti-correlation of Sn and Qb

$$S_n(Z,N) = M(Z,N-1) + m_{\text{neut}} - \underline{M(Z,N)}$$

$$Q_\beta(Z,N) = \underline{M(Z,N)} - M(Z+1,N-1)$$

→ Anti-correlation between Sn and Qb



Propagating nuclear uncertainties to r-process simulations

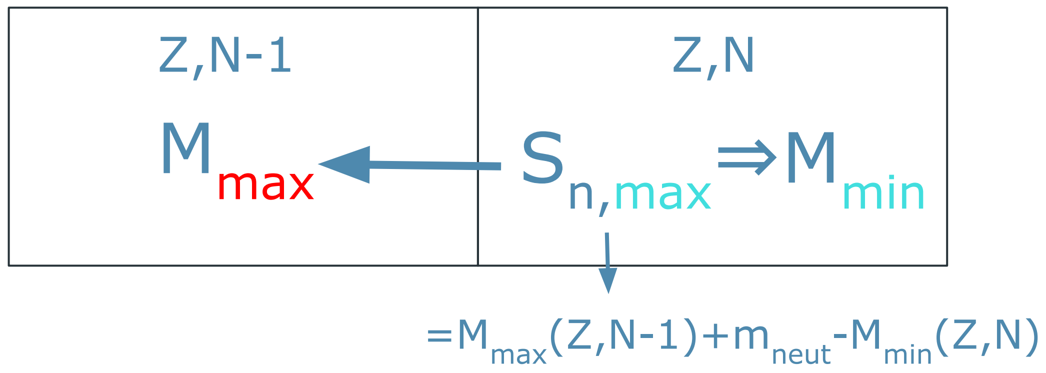
Anti-correlation of Sn and Qb, and coherent masses

Z,N-1	Z,N
	$S_{n,max} \Rightarrow M_{min}$

$$=M_{max}(Z,N-1)+m_{neut}-M_{min}(Z,N)$$

Propagating nuclear uncertainties to r-process simulations

Anti-correlation of Sn and Qb, and coherent masses



Propagating nuclear uncertainties to r-process simulations

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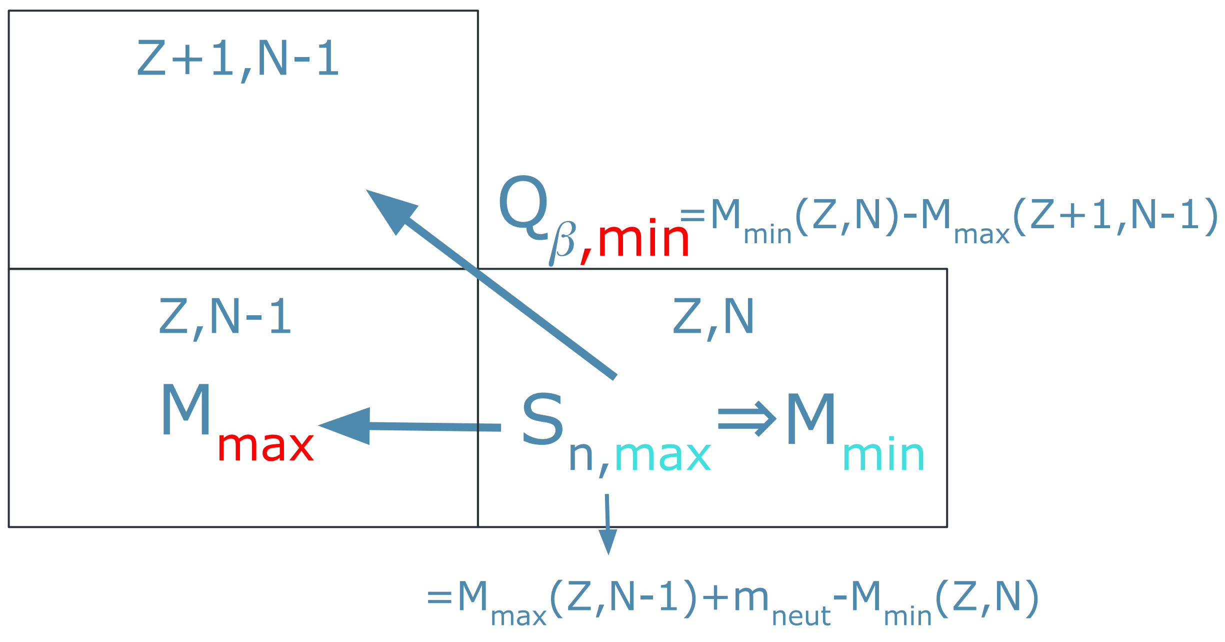

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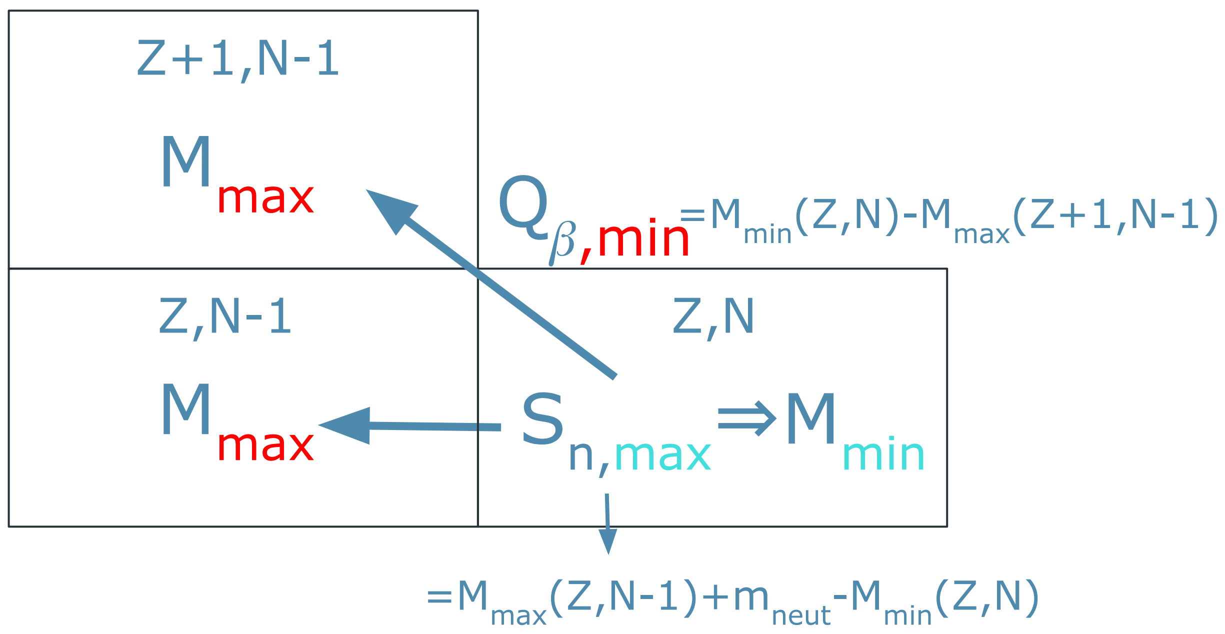

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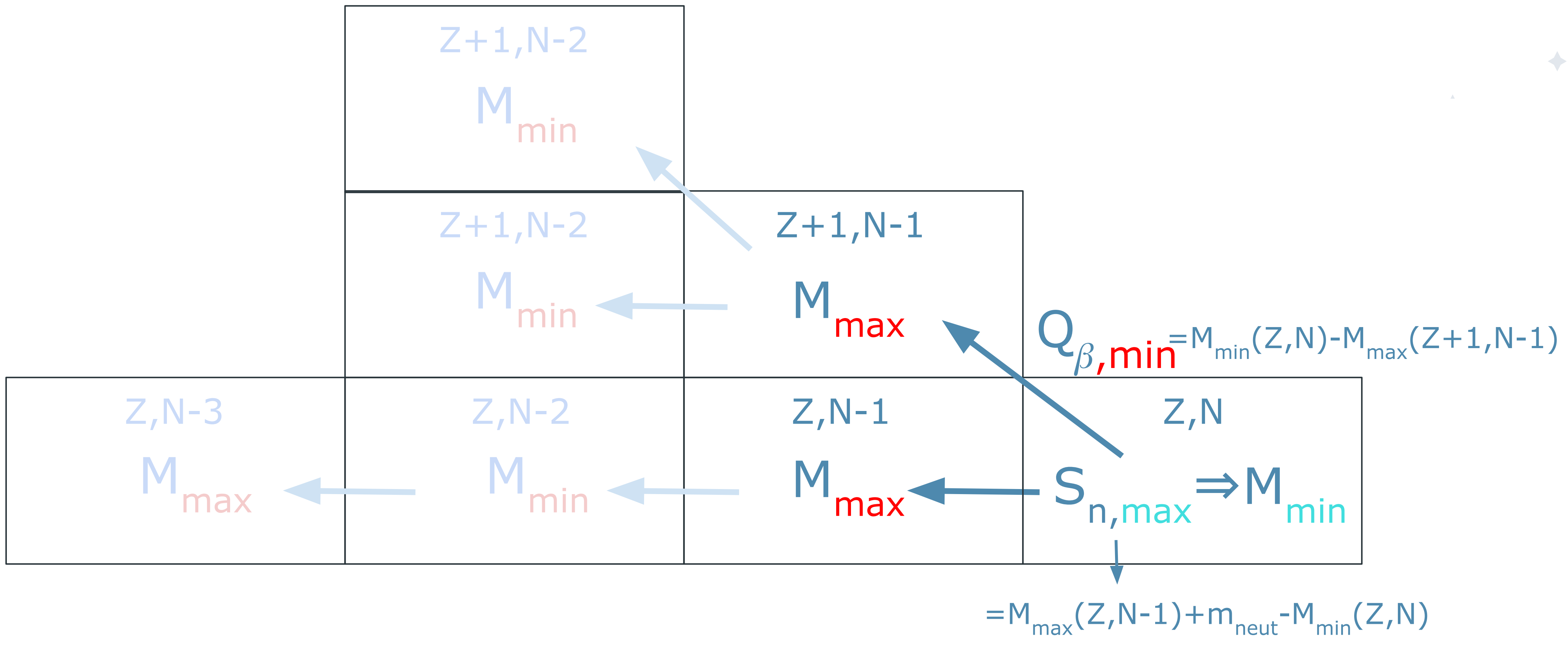
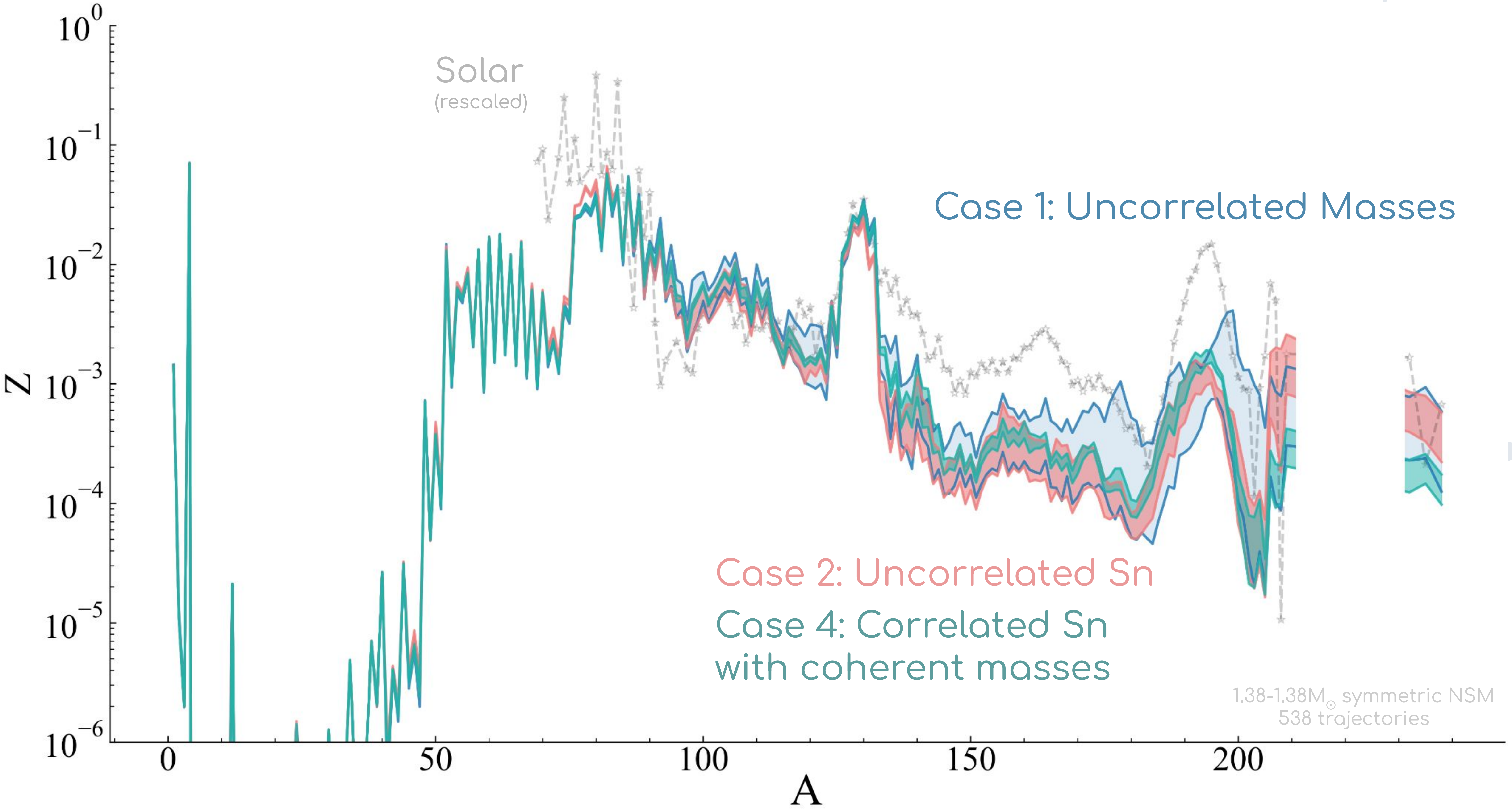


Propagating nuclear uncertainties to r-process simulations

Anti-correlation of Sn and Qb, and coherent masses



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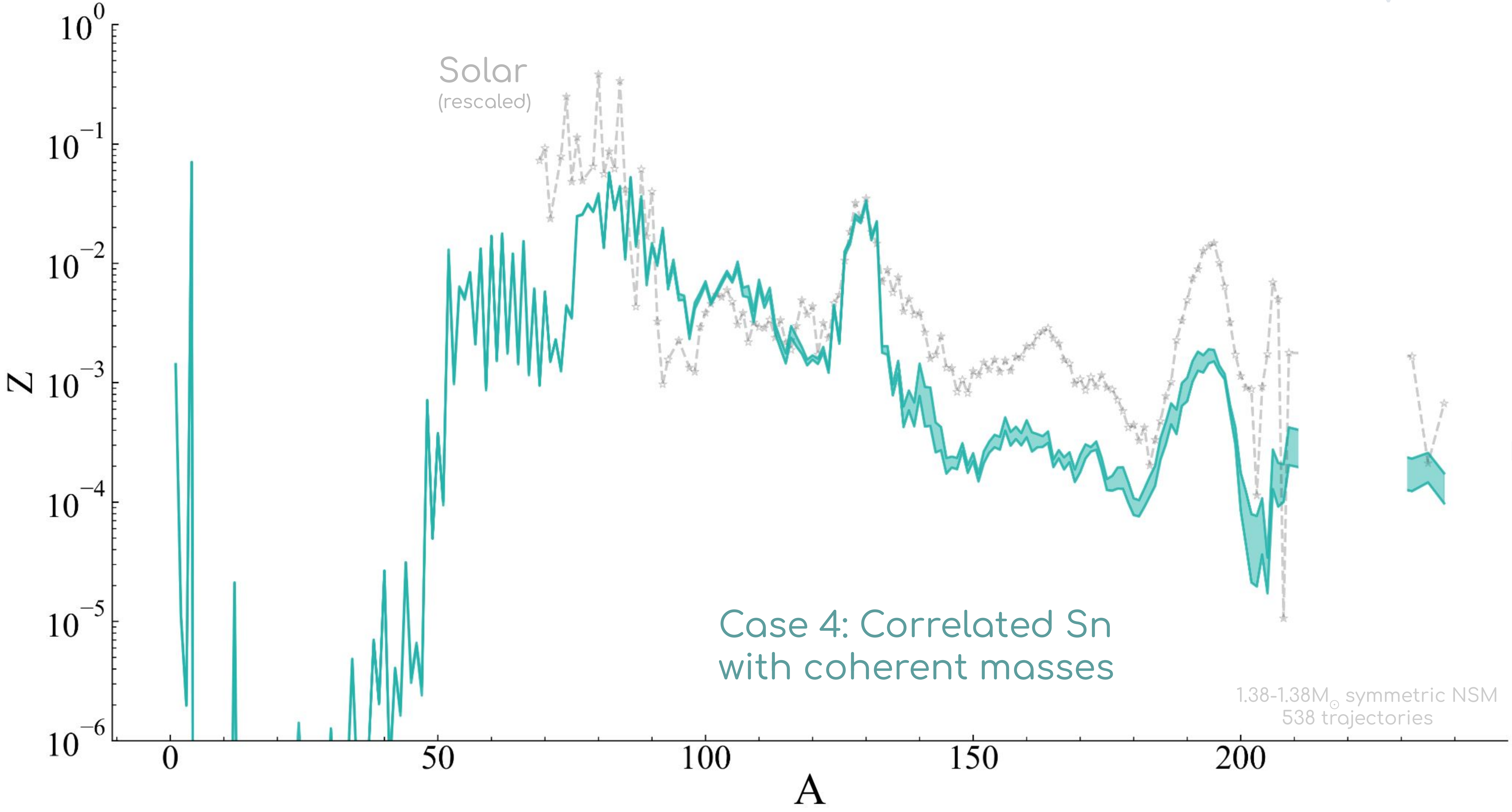
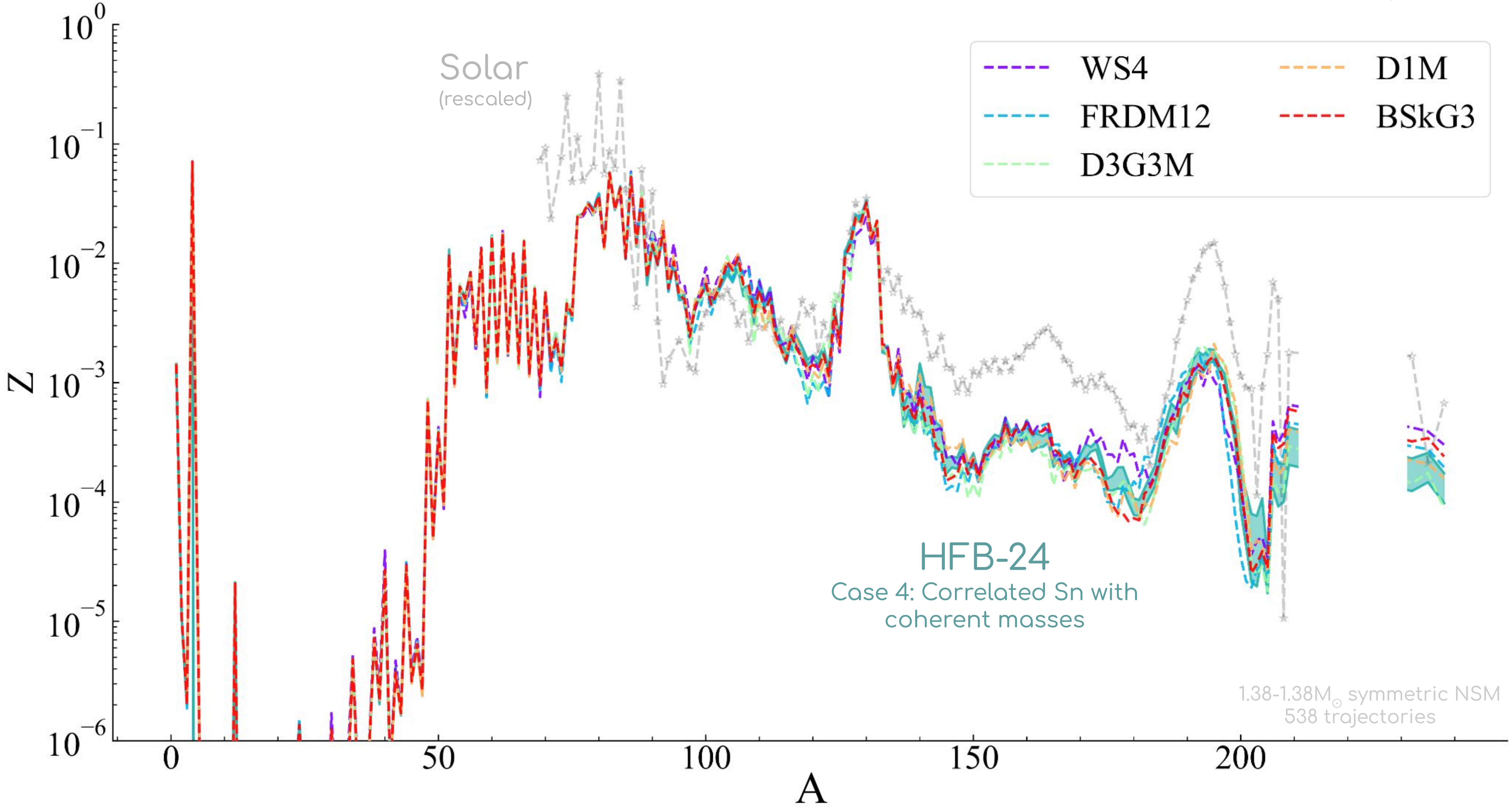


Propagating nuclear uncertainties to r-process simulations

Model uncertainties vs Parameter uncertainties



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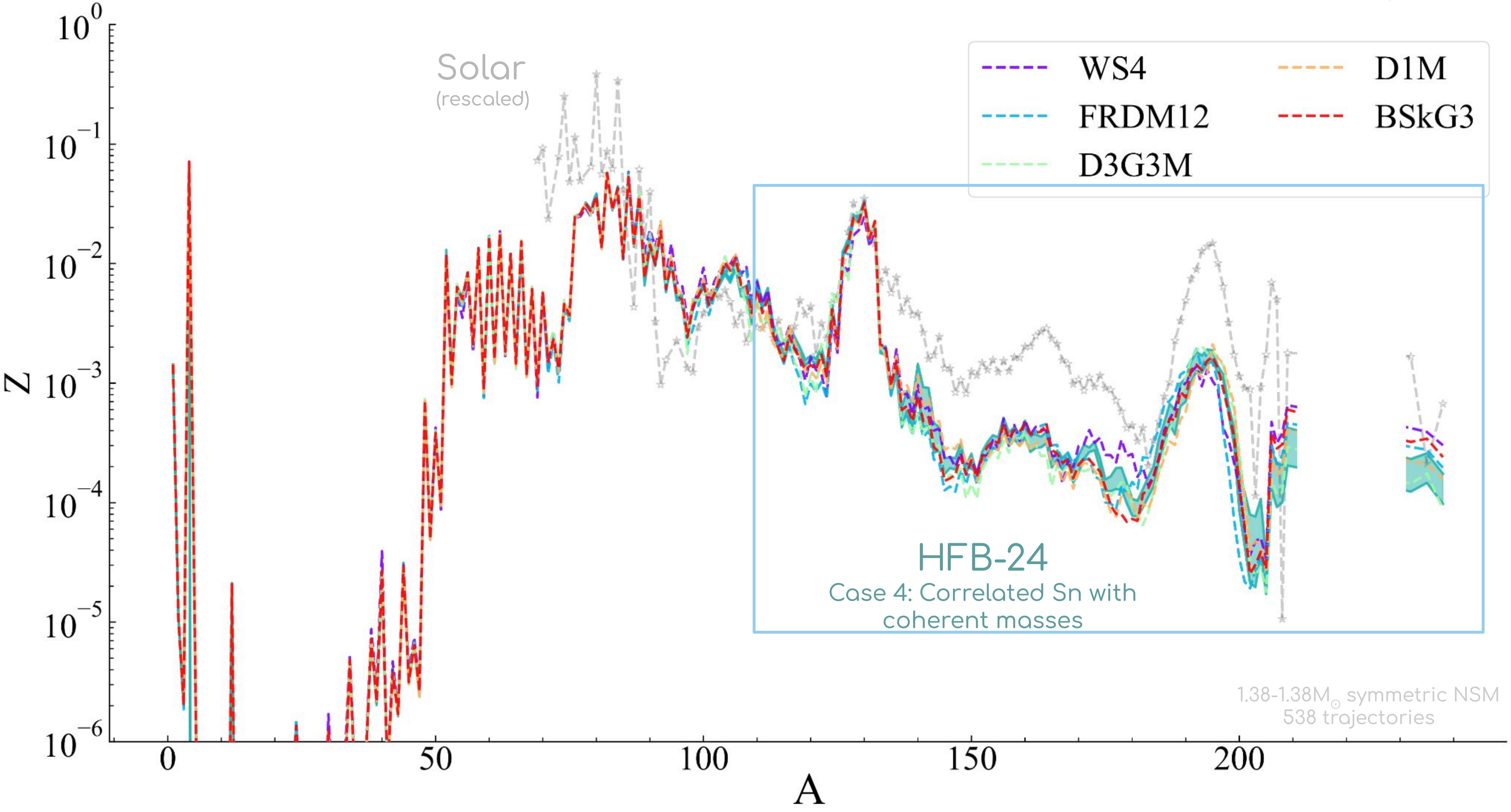

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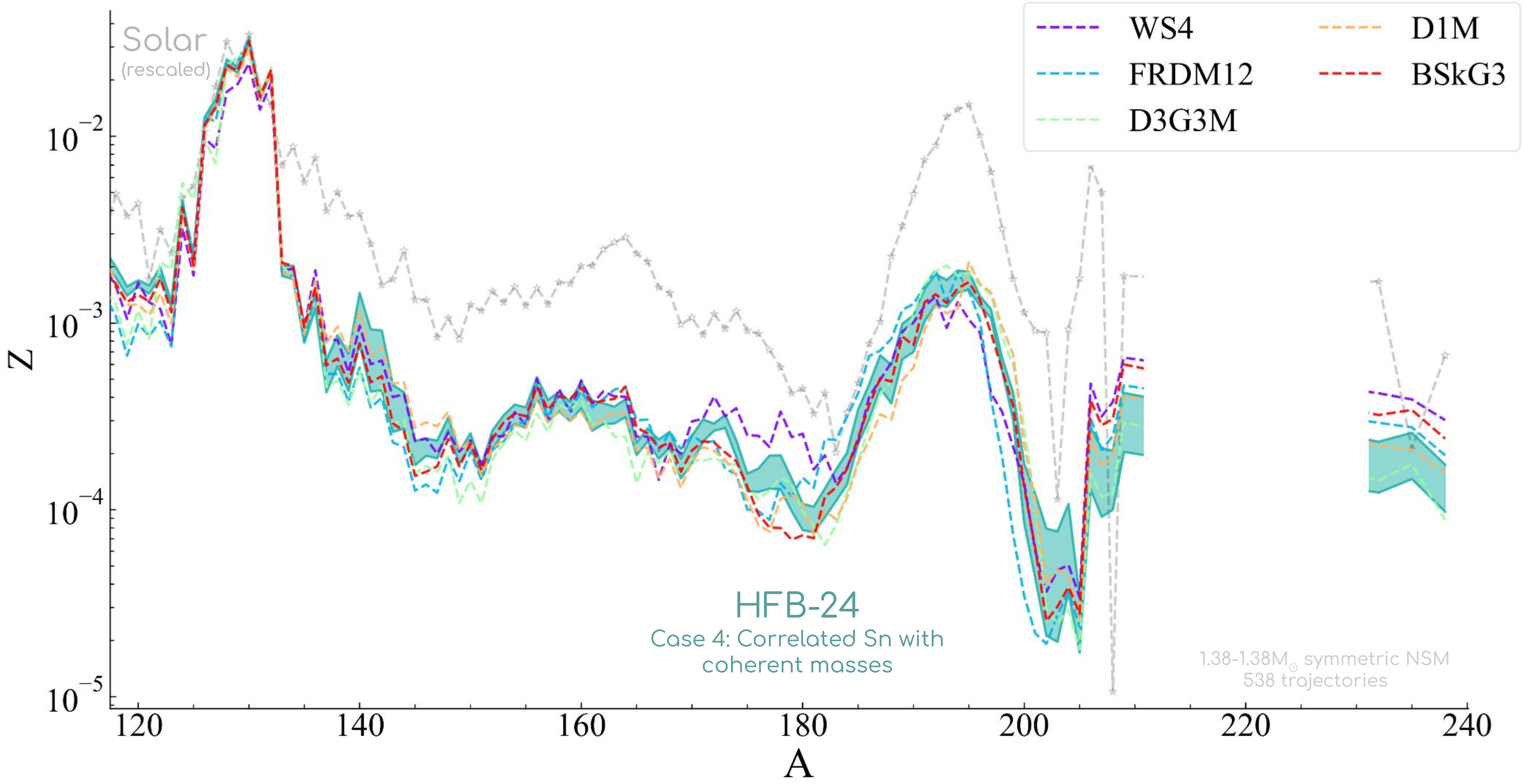
Model uncertainties vs Parameter uncertainties



Conclusions

The impact of Systematic and Statistical nuclear uncertainties on the r-process nucleosynthesis

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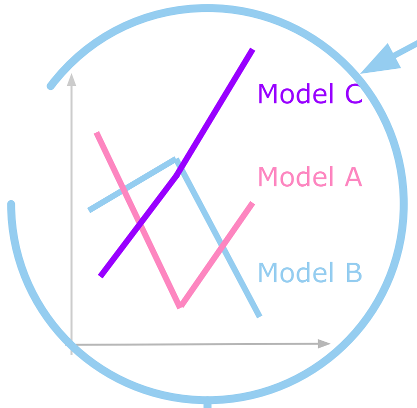
Systematic and Statistical nuclear uncertainties



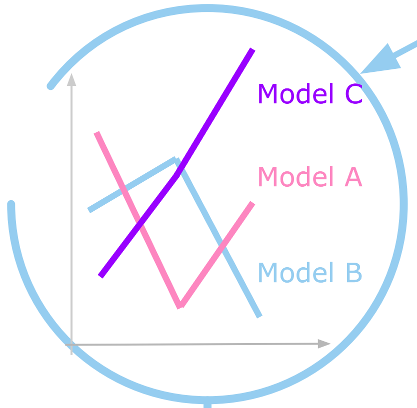
Correlated model vs Non-correlated parameter Uncertainties

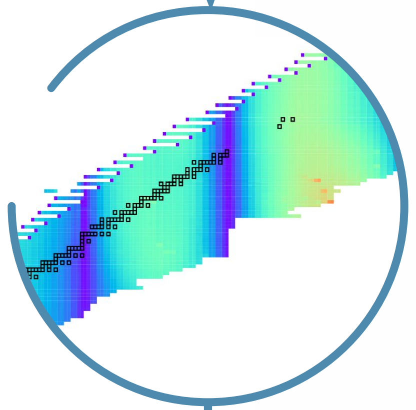
Extra care needed with the misuse of Correlated model uncertainties and the use of non-correlated parameters uncertainties

Conclusions

The impact of Systematic and Statistical nuclear uncertainties on the r-process nucleosynthesis

Systematic and Statistical nuclear uncertainties





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Determining coherently parameter uncertainties

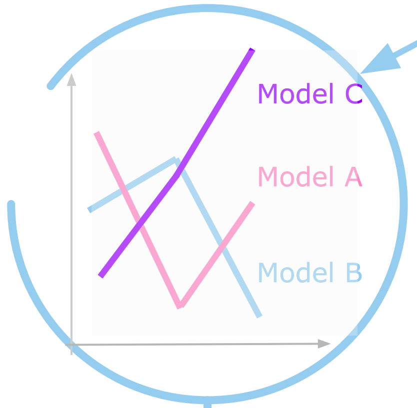
Using the BFMC we can determine coherently the parameter uncertainties.

Different cases to be considered between uncertainties from Mass and from Sn

Conclusions

The impact of Systematic and Statistical nuclear uncertainties on the r-process nucleosynthesis

Systematic and Statistical nuclear uncertainties



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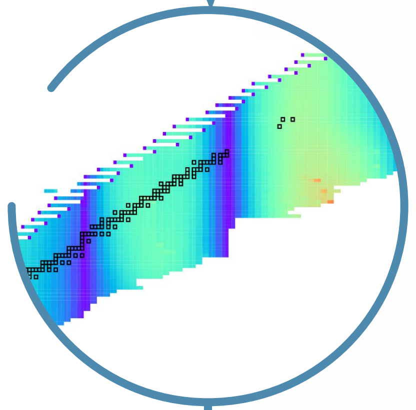


Determining coherently parameter uncertainties

Using the BFMC we can determine coherently the parameter uncertainties.

Different cases to be considered between uncertainties from Mass and from Sn

Impact on r-process nucleosynthesis in Neutron Star Mergers

Multiple trajectories needed to represent the real impact of nuclear uncertainties.

Mostly affects abondances of nuclei with A > 135. Model uncertainties leads to larger uncertainties on abondances than parameter ones

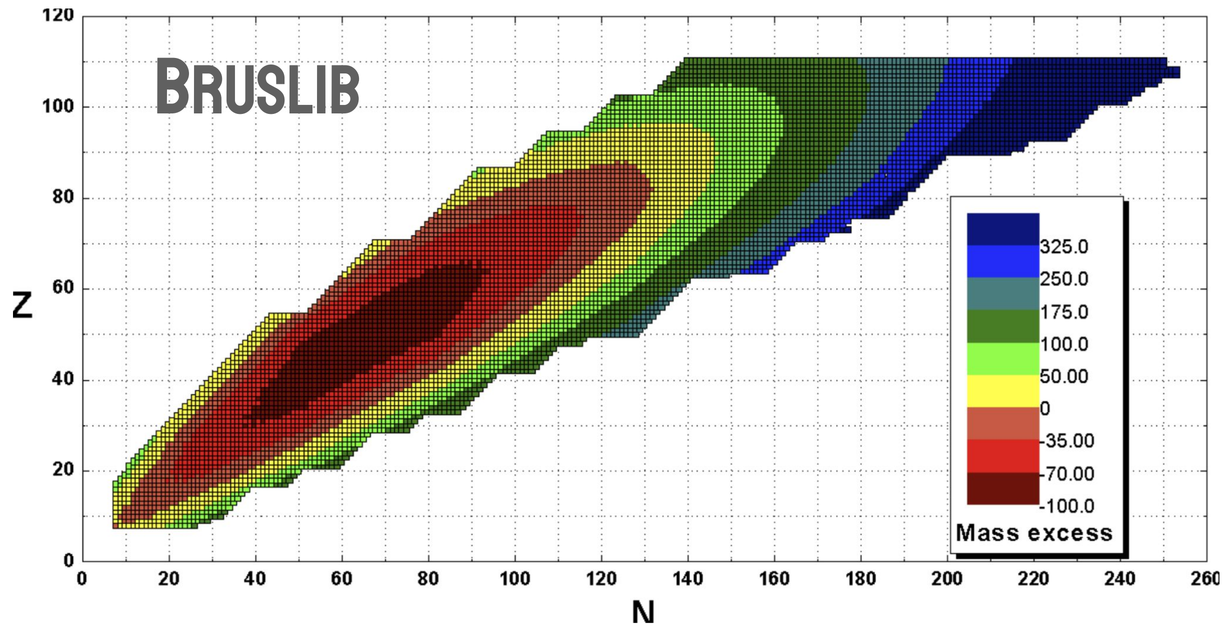
Update to Bruslib and NetGen

Updates of mass model for Brusslib

NetGen
NUCLEAR NETWORK GENERATOR

→ New reactions updated (e.g. $^{12}C+^{12}C$)

→ Plan for regular updates integrating ChaNUREPS entries



Masses updated with new mass model BSkg3 (Grams+2023), density, potentials, … will be updated too

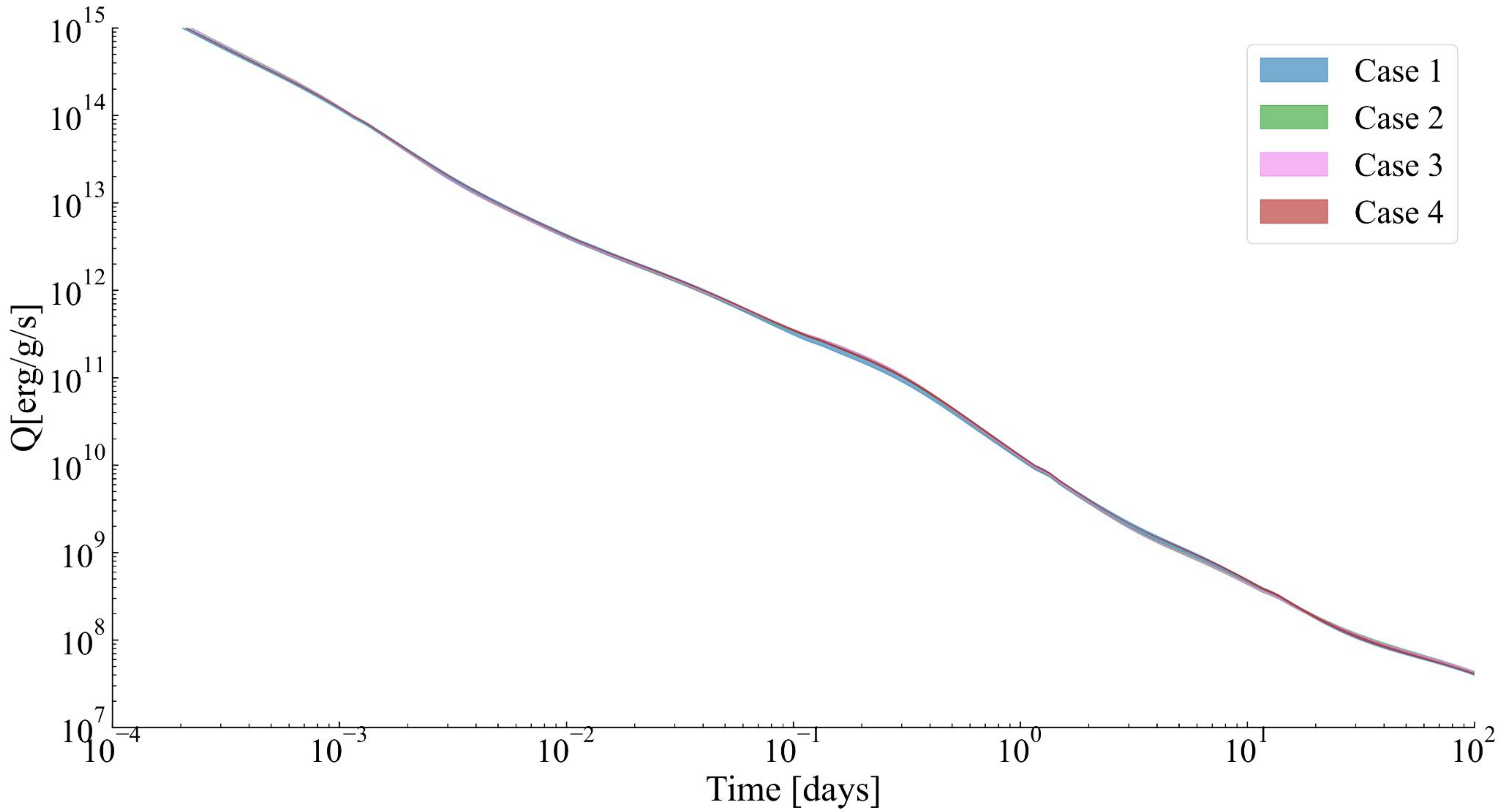
- Triaxiality, time-reversal symmetry breaking & octupole GS deformation
- Microscopic pairing from "realistic" calculations
- Stiff EoS
- Accurate masses: s(2457M)=0.63MeV
- Accurate fission barriers s(45B f)=0.33MeV including triaxial & octupole deformations simultaneously

http://www.astro.ulb.ac.be/Netgen/

http://www.astro.ulb.ac.be/bruslib/

Nuclear uncertainties on NSM simulations

Q for various Cases

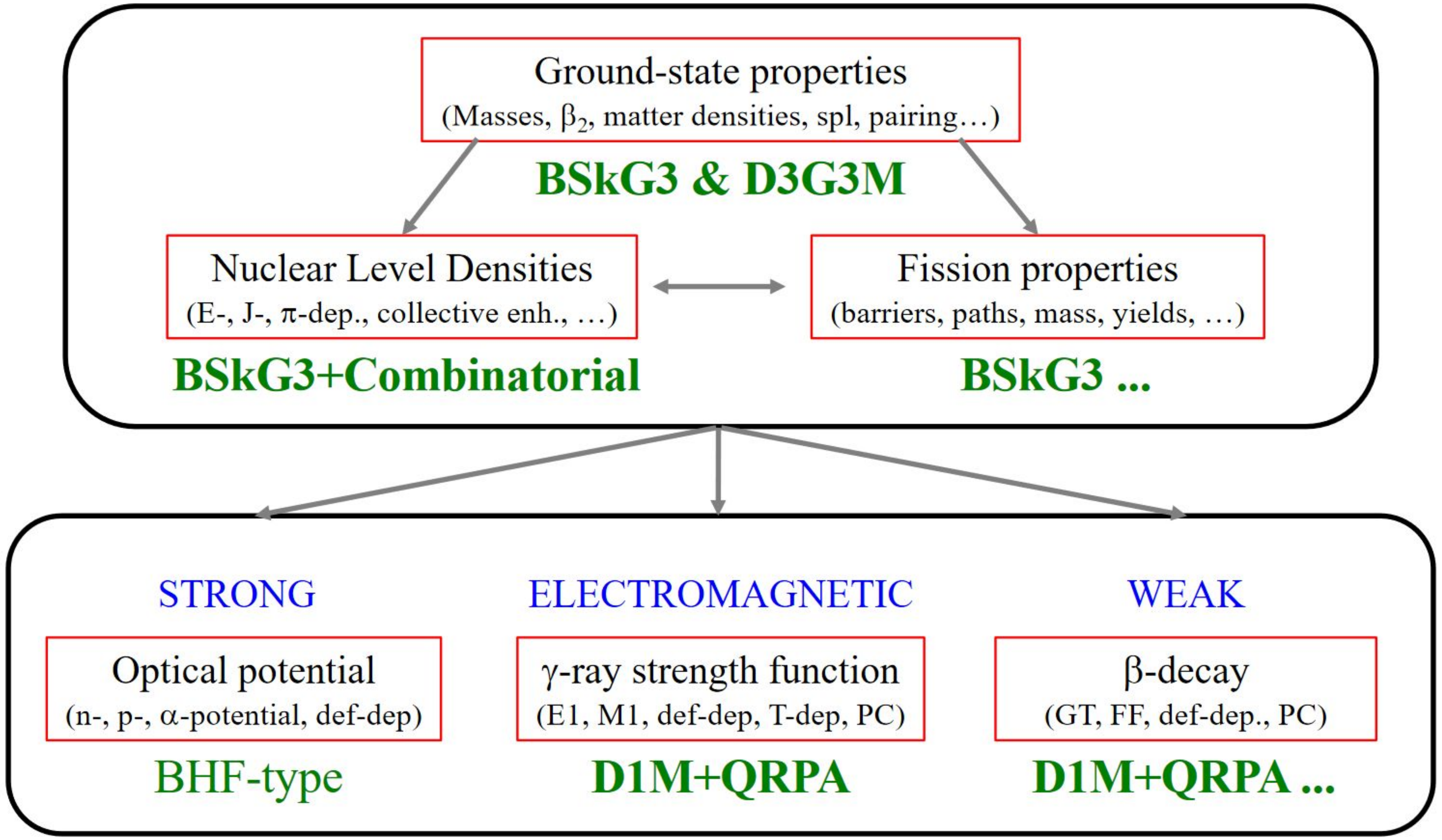


Nuclear models

Nuclear inputs

Some new efforts to improve the nuclear predictions for r-process applications

Nuclear inputs to nuclear reaction & decay calculations



"Microscopic" approach is a necessary but not a sufficient condition !
"(Semi-)Microscopic" models must be competitive in reproducing exp. data !

New HFB nuclear mass models

- New Gogny-HFB mass model: D3G3M
  - Gogny interaction with 3 Gaussians
  - Stiffer EoS than D1M
  - Accurate masses: σ(2457*M*)=0.87MeV

Batail et al. (2024)

- New Syrme-HFB mass model: BSkG3
  - Triaxiality, time-reversal symmetry breaking & octupole GS deformation
  - Microscopic pairing from “realistic” calculations
  - Stiff EoS
  - Accurate masses: σ(2457*M*)=0.63MeV
  - Accurate fission barriers σ(45B_f)=0.33MeV including triaxial & octupole deformations simultaneously

Grams et al. (2023)