Nuclear Science and Security Consortium

September Workshop and Advisory Board Meeting

The impact of prompt neutron emission from fission fragments on the final abundance pattern of the astrophysical r-process

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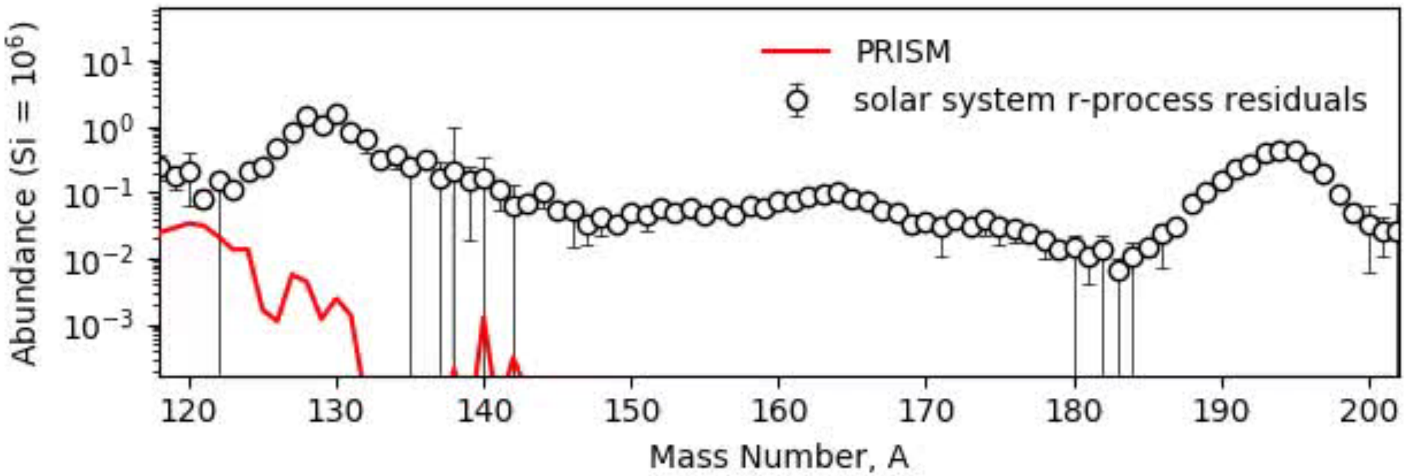
Nuclear and Particle Physics

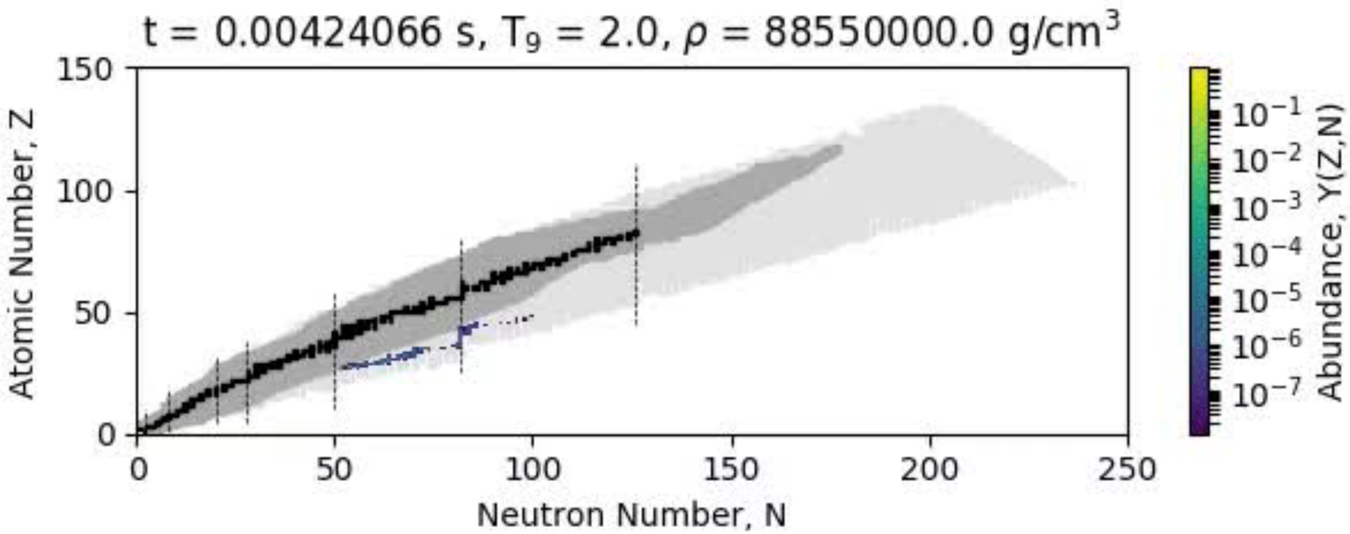
September 11 - 12, 2017

Overview

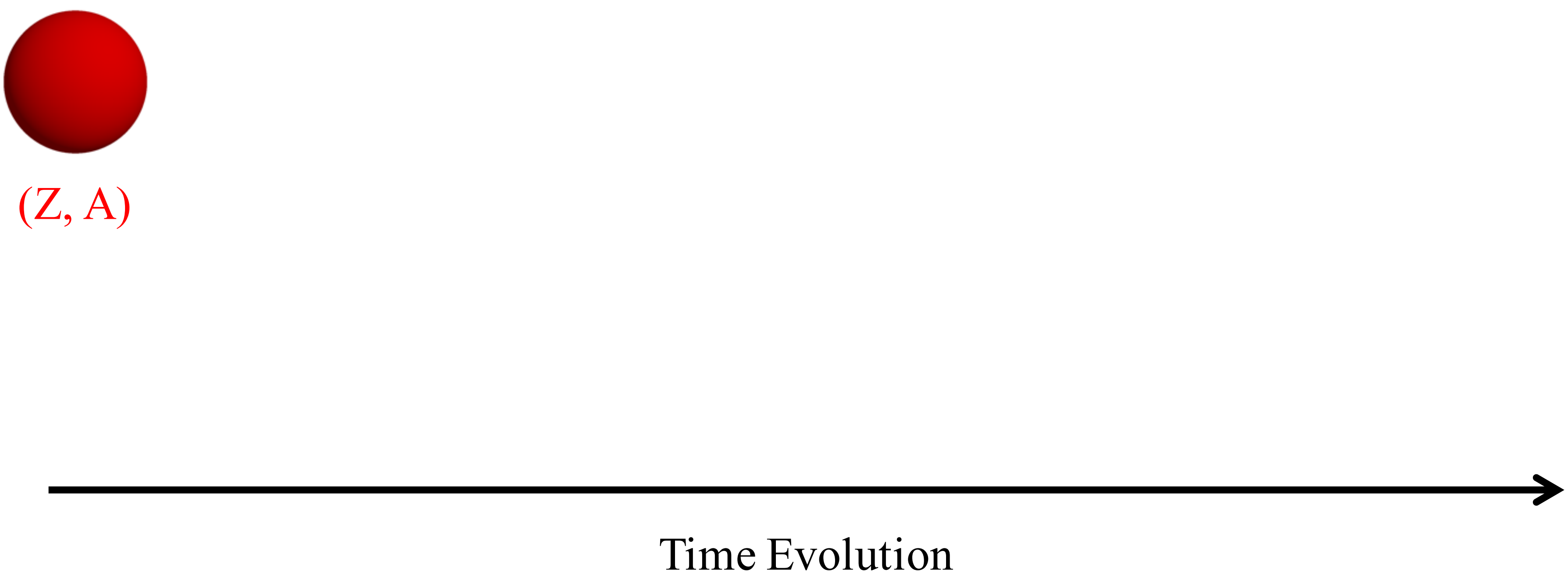
- Research performed with mentor Matthew Mumpower at Los Alamos National Laboratory
    - Eight weeks
    - NSSC LANL Summer Program
- Astrophysical r-process
- Nuclear fission
    - Prompt neutron emission
- r-process network calculation
    - Impact on the final abundance pattern of the r-process

Astrophysical r-process





Fission



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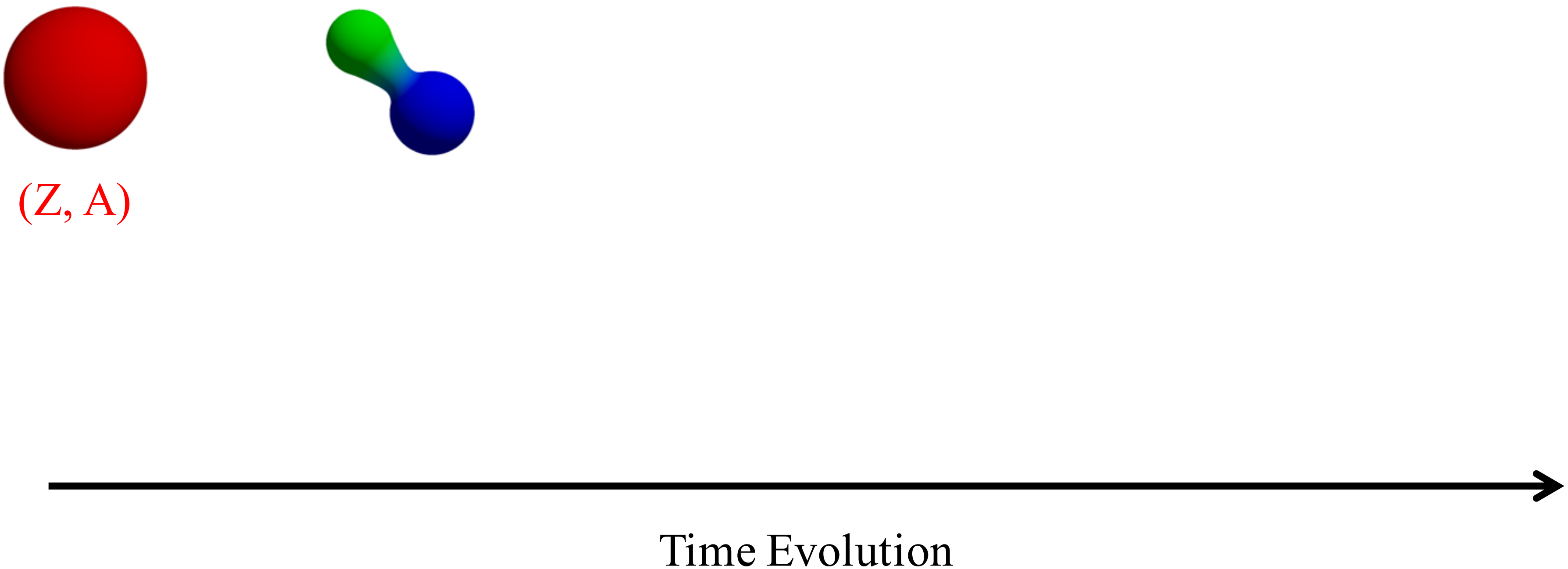

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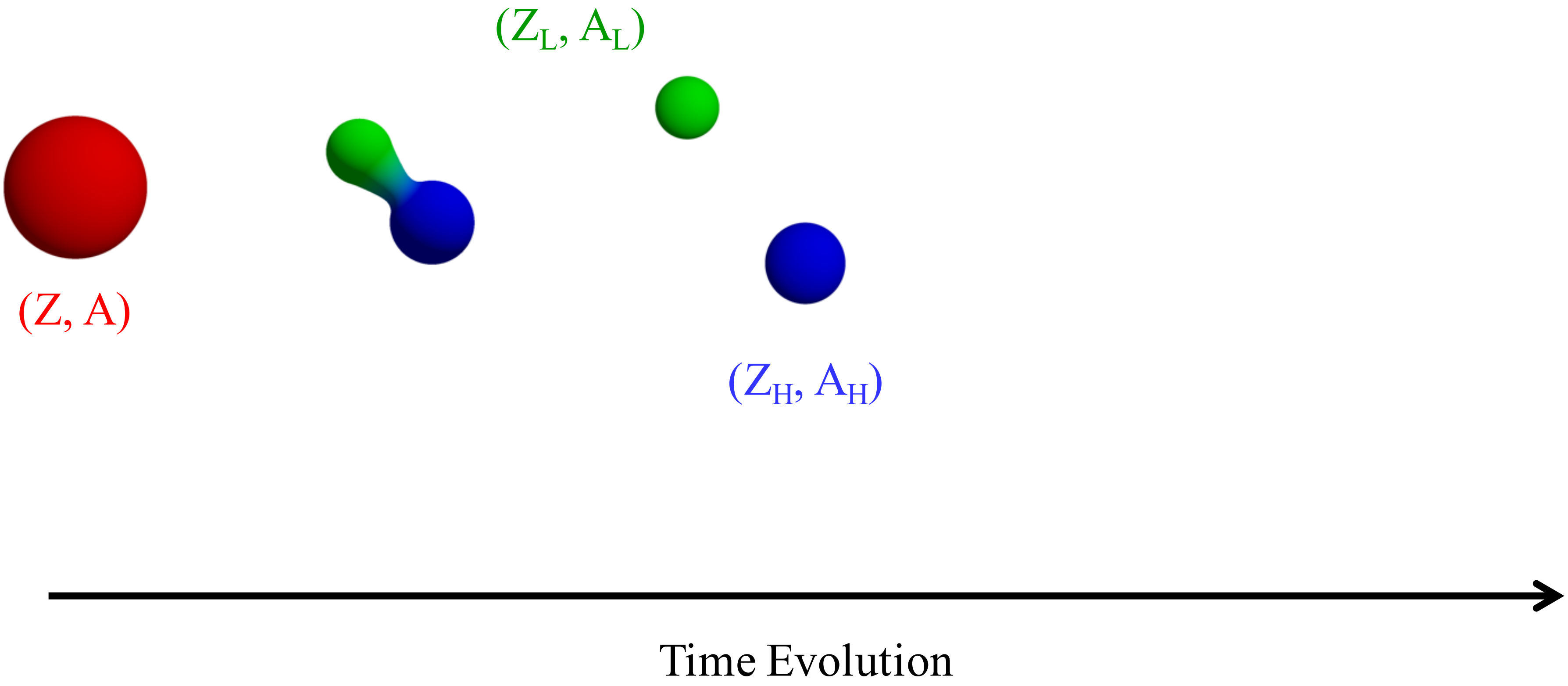
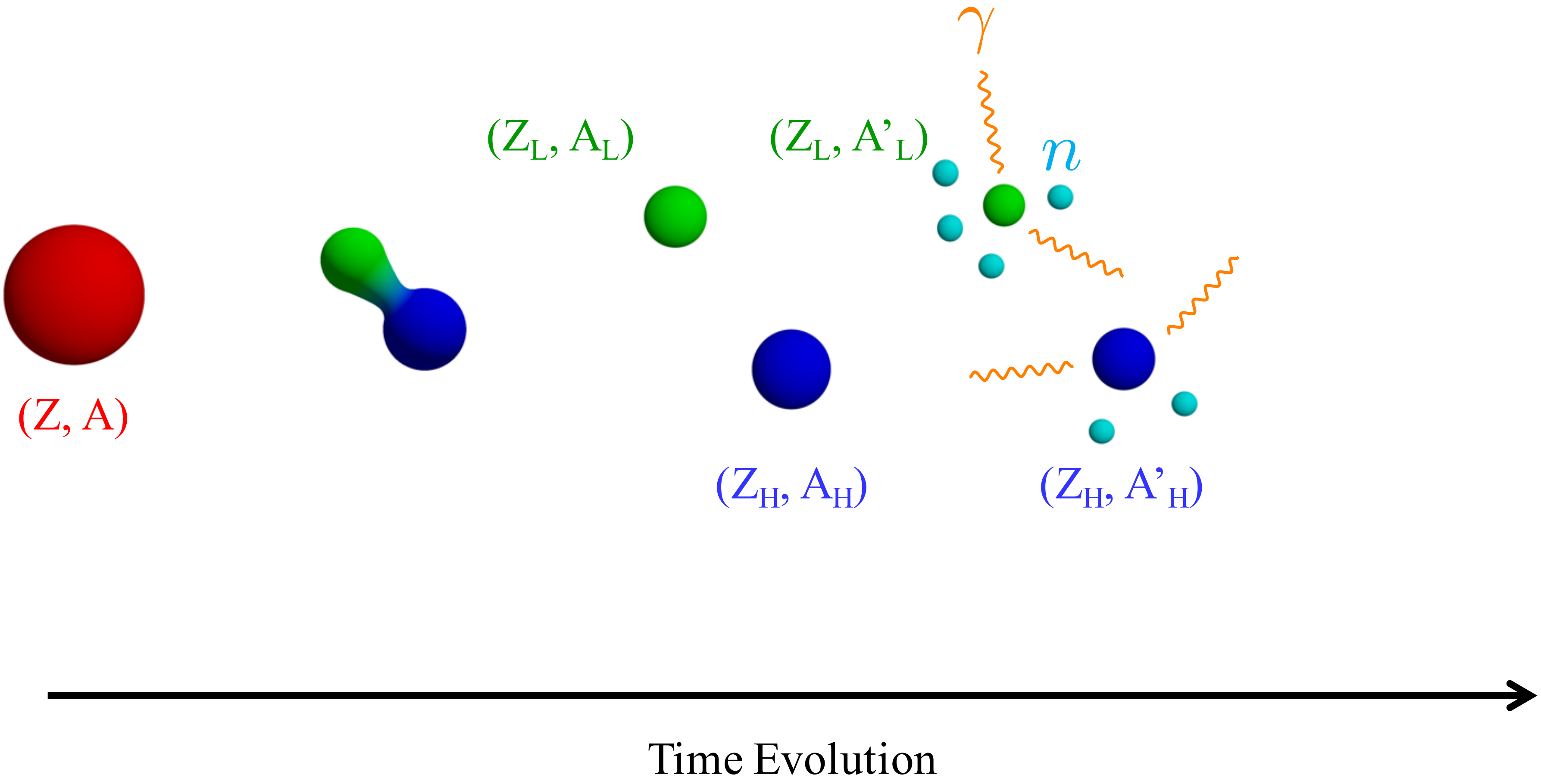
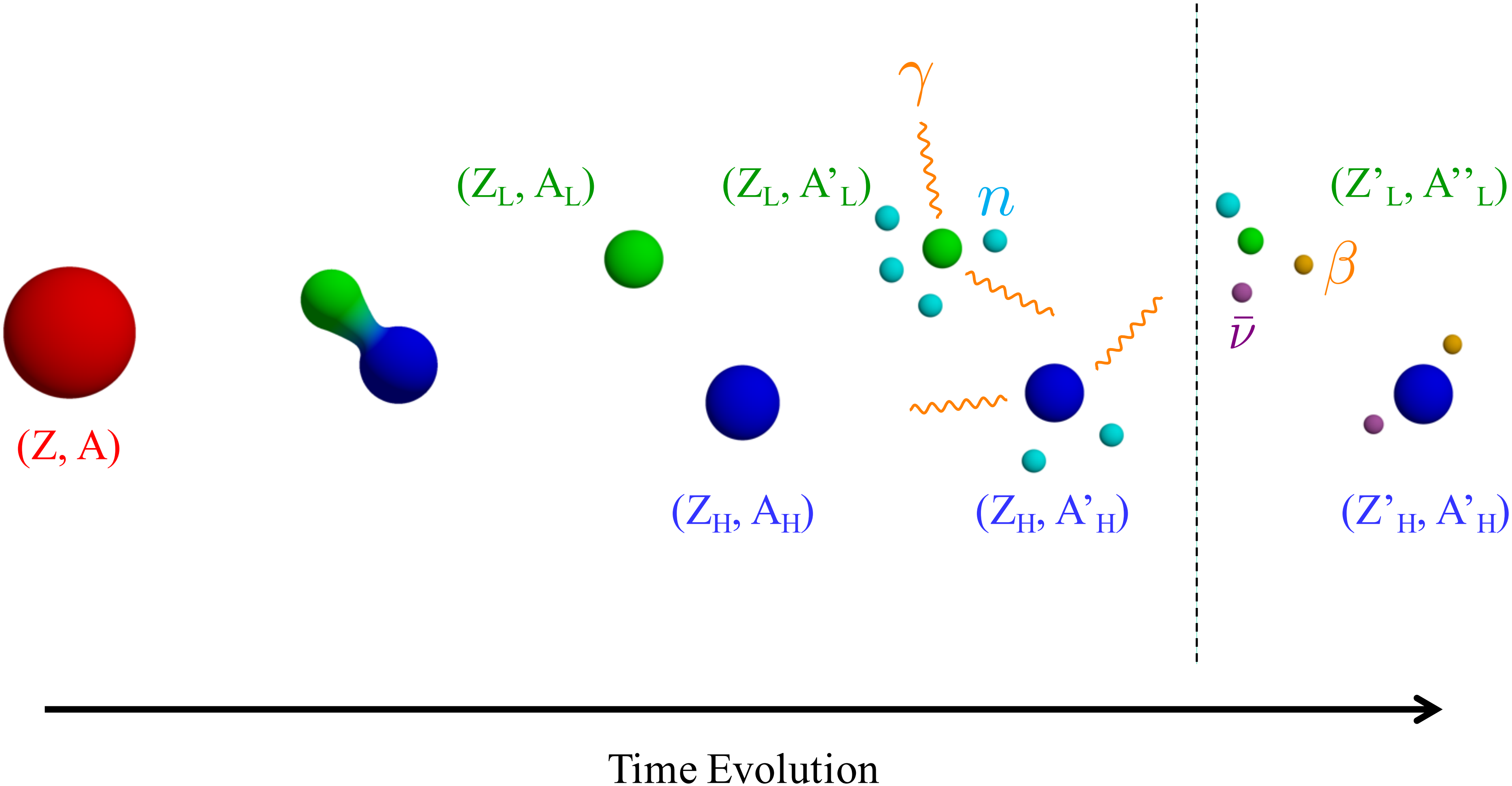


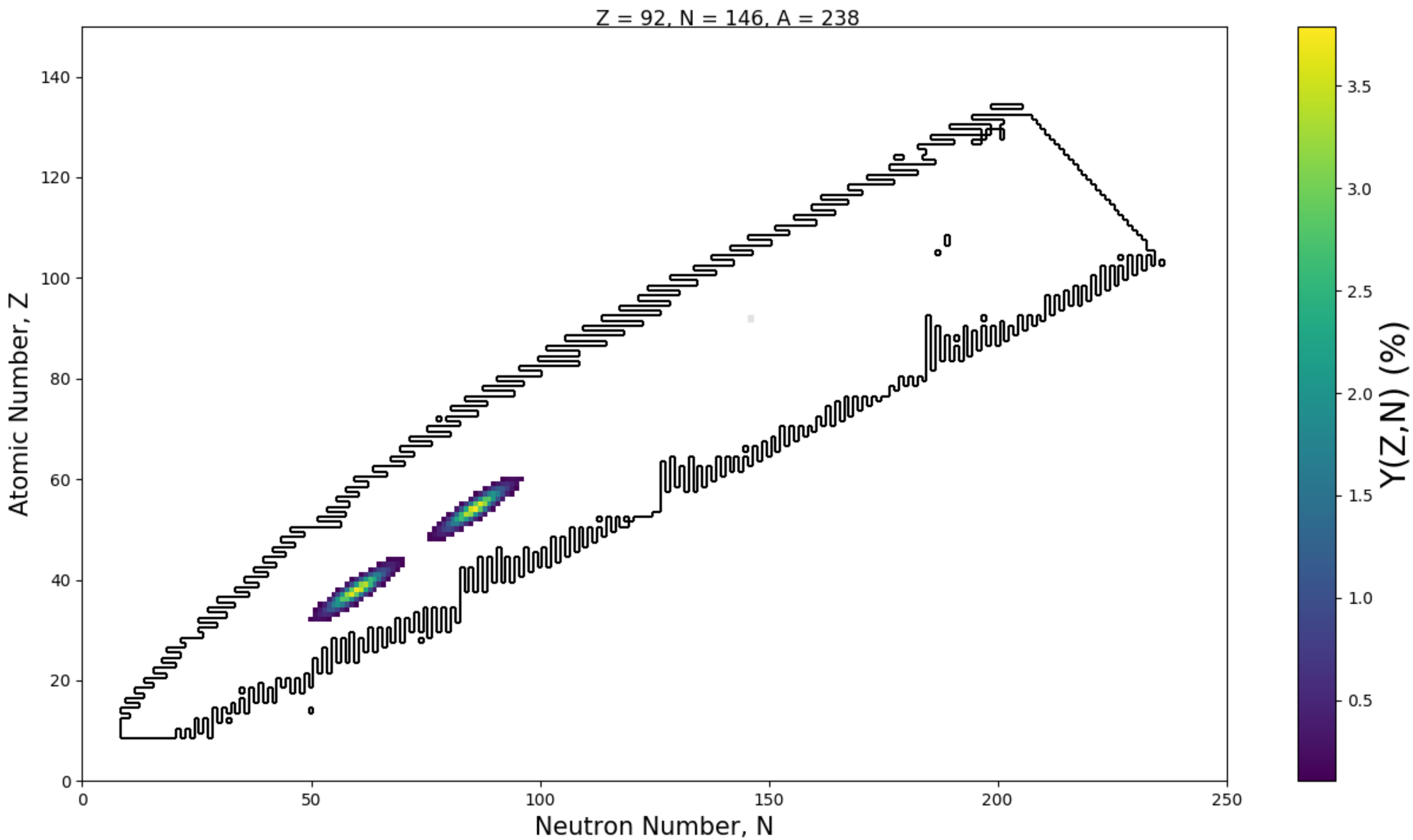
Fission



Fission



Fission Yield
(Fission Fragment Mass Distribution)



T. Kodama, and K. Takahashi, Nucl. Phys. A 239 (1975) 489

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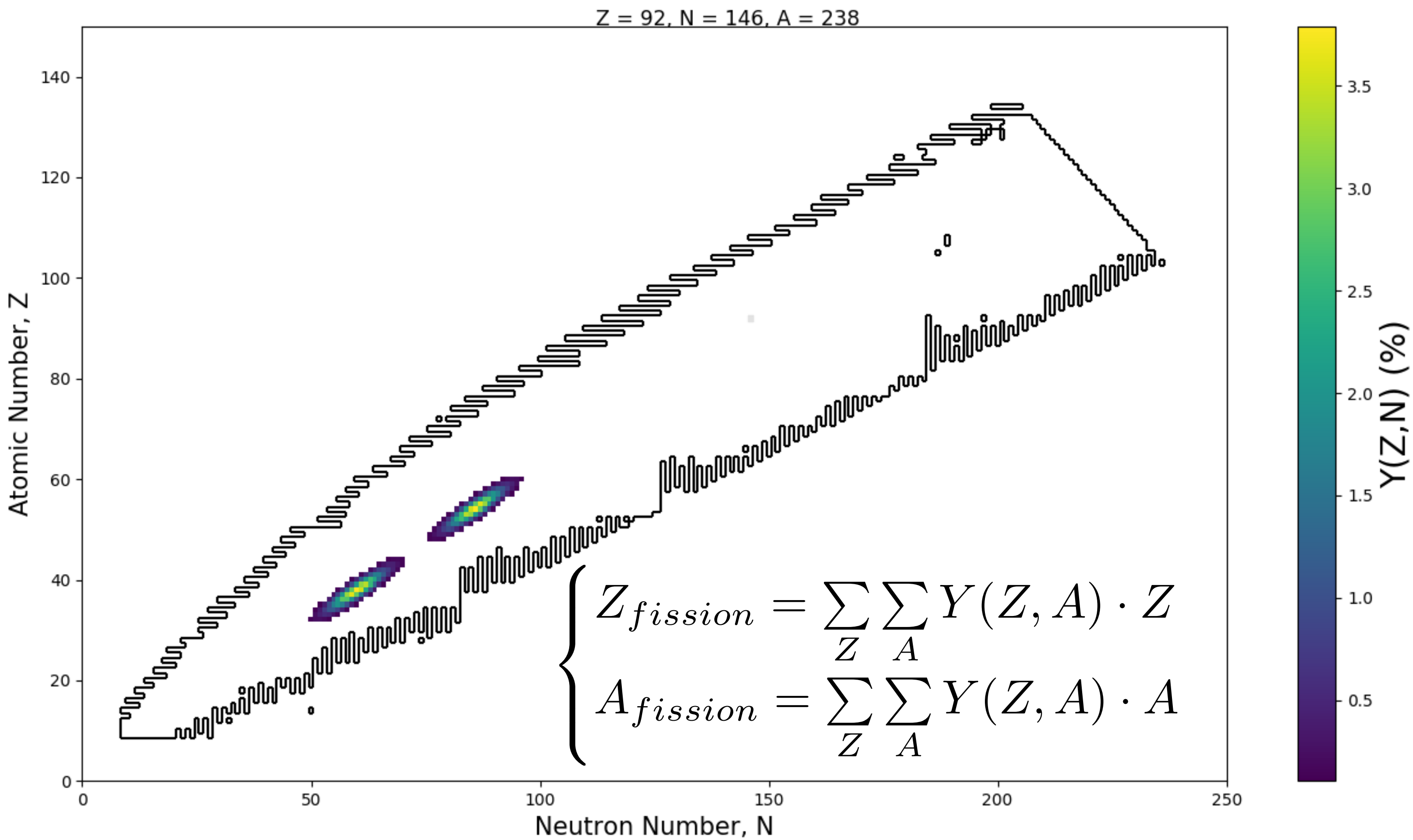

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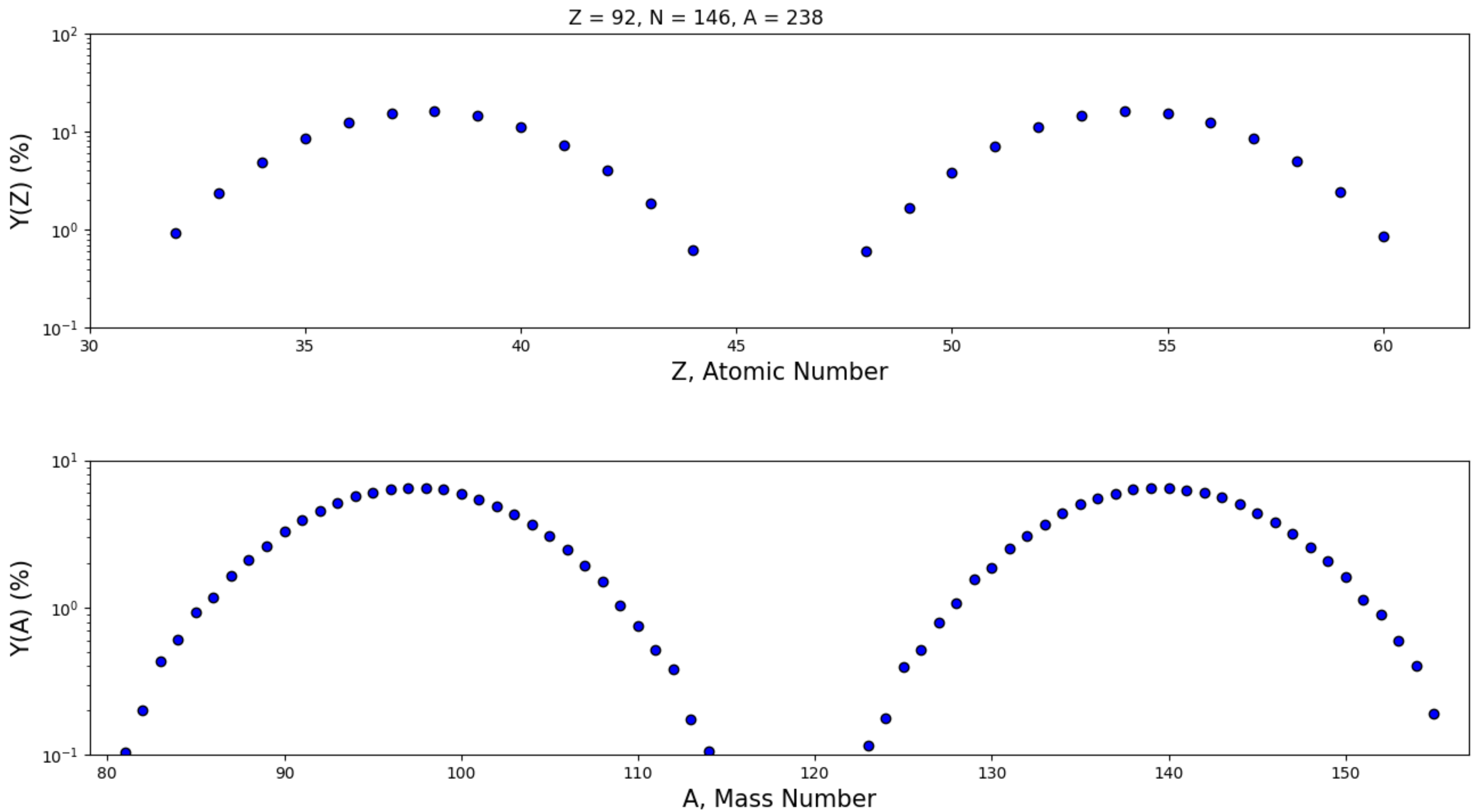
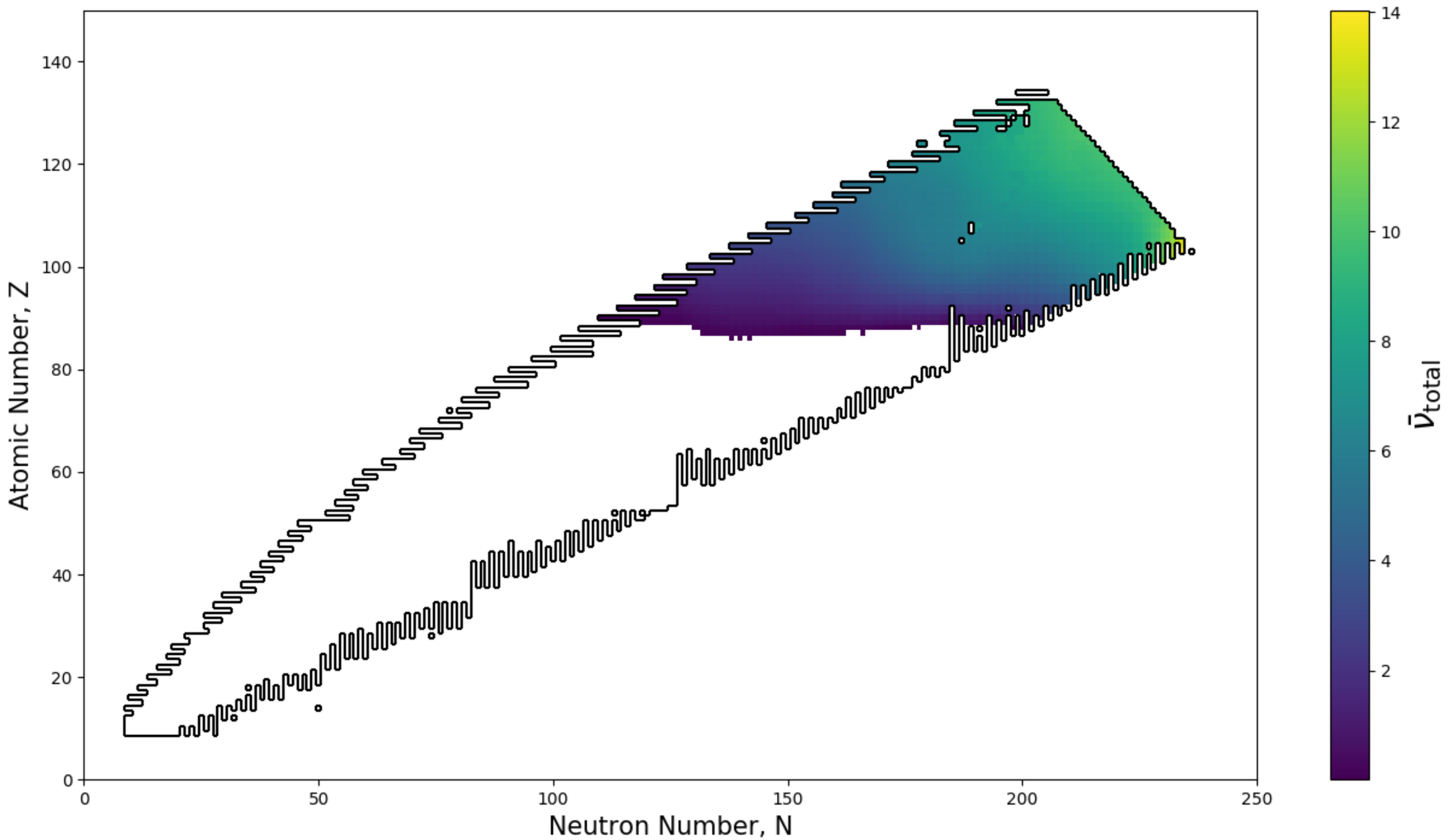
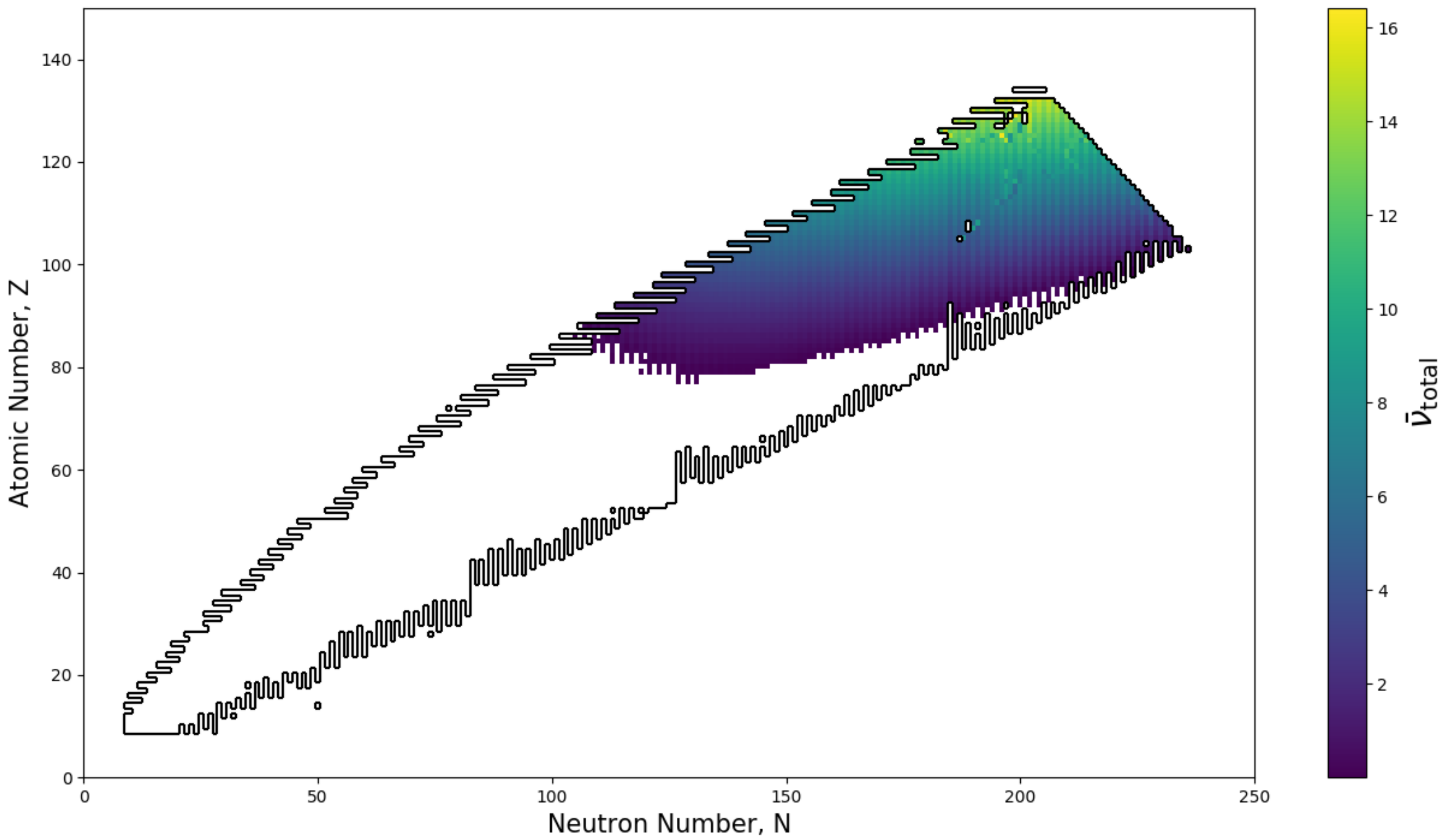


Prompt Neutron Emission



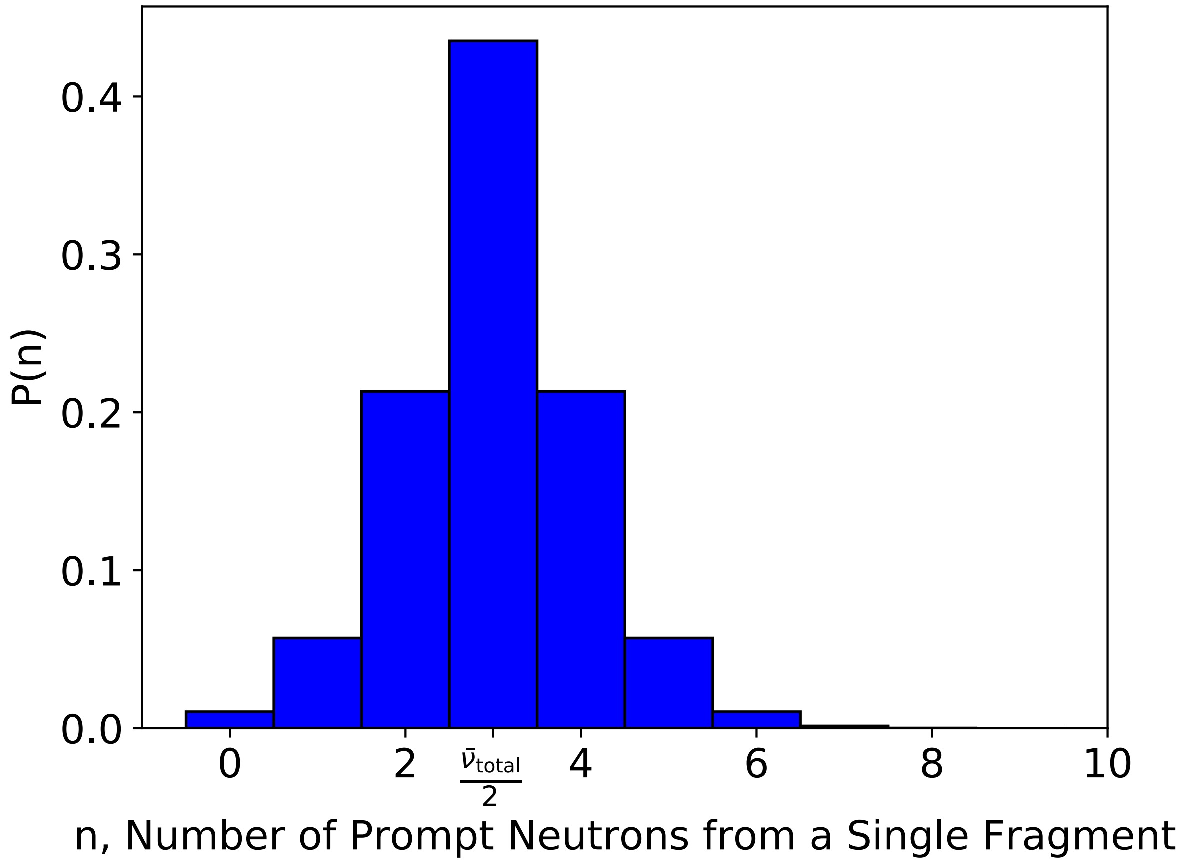
D. G. Madland, Nucl. Phys. A 772 (2006) 113-137

Prompt Neutron Emission

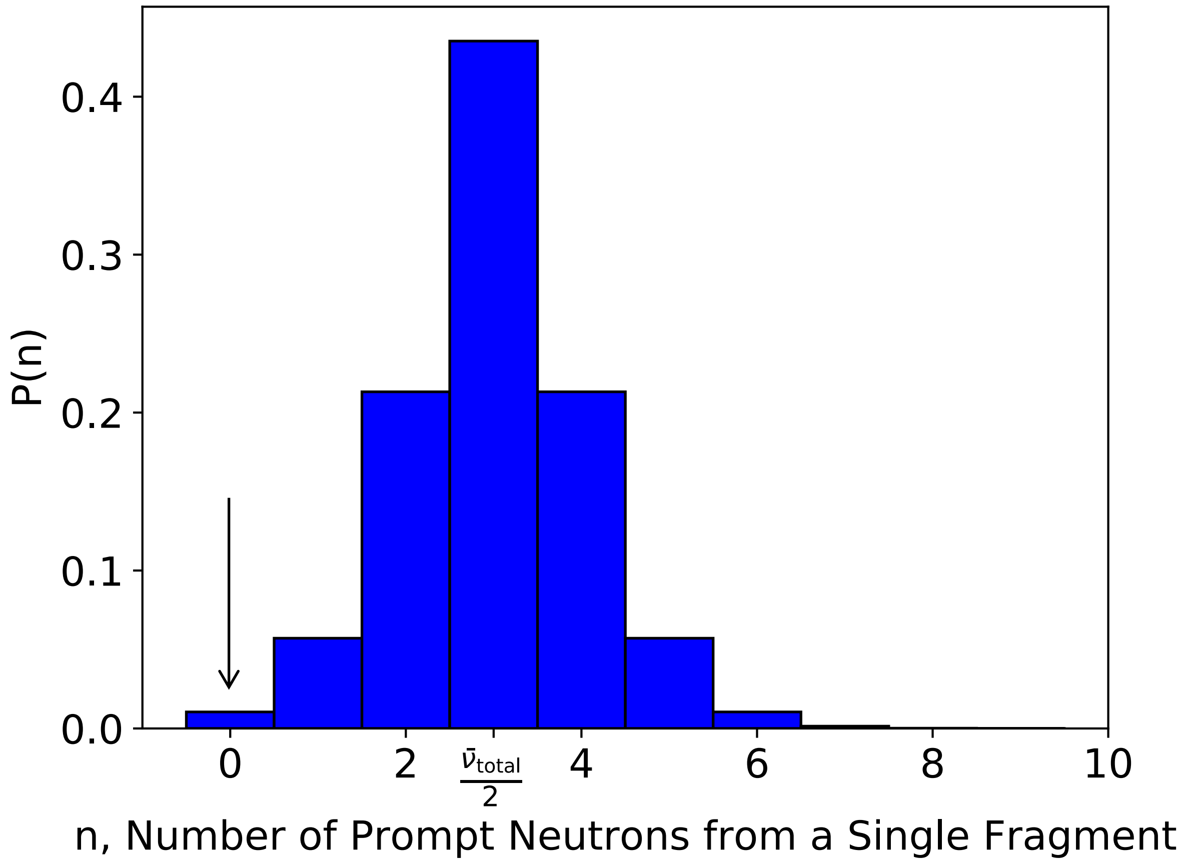


R. J. Howerton, Nuclear Science and Engineering 62, 438-454 1977

Modifying the Yields

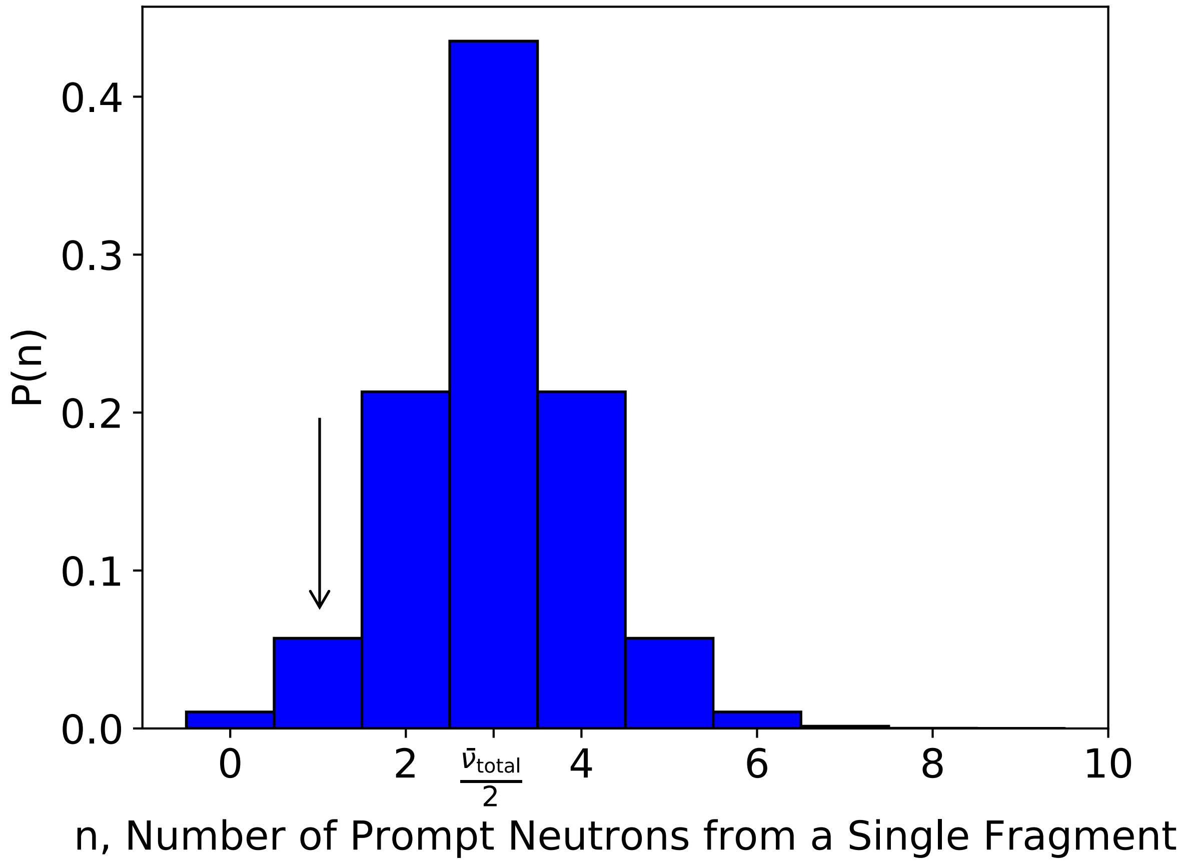


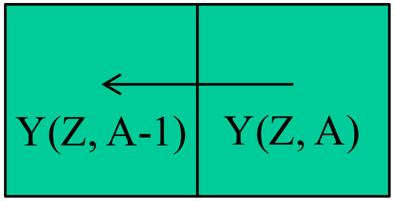
Modifying the Yields



Y(Z, A)

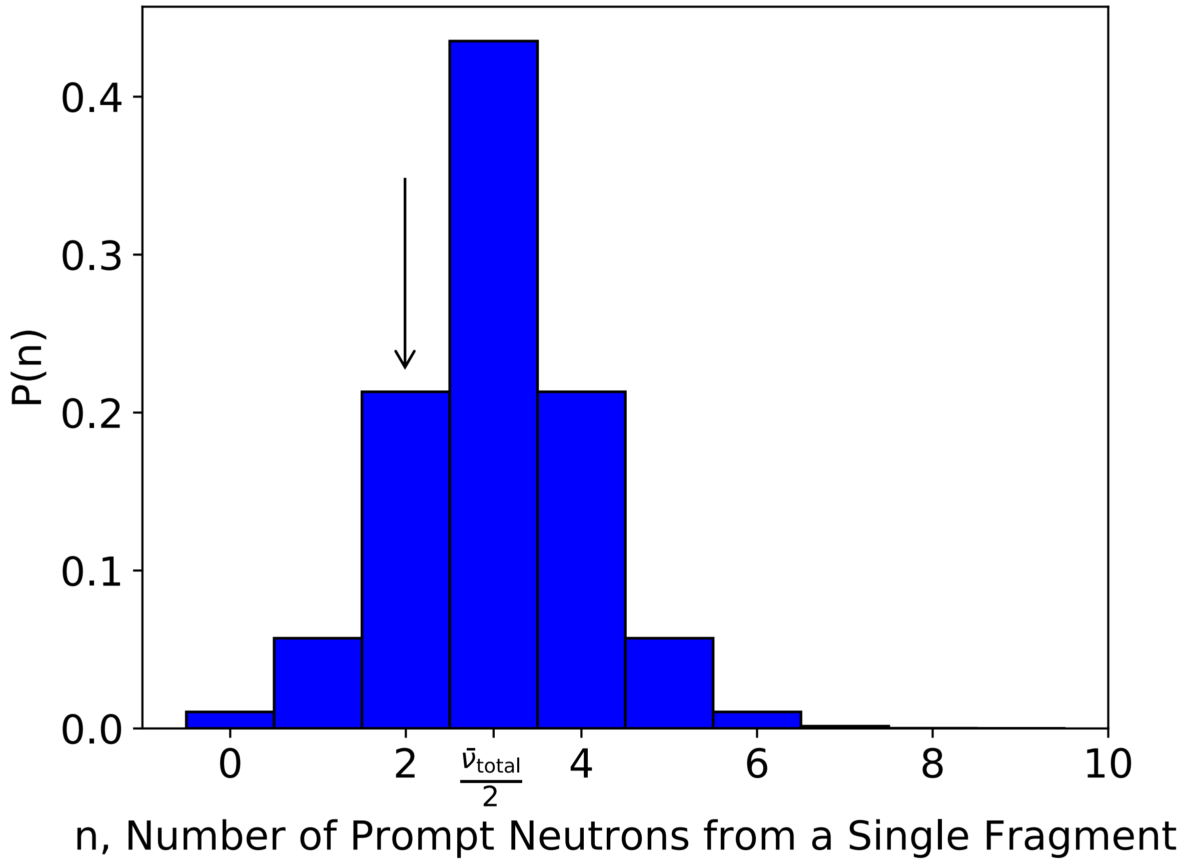
Modifying the Yields

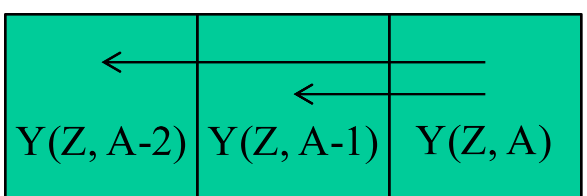




$$\begin{cases} Y'(Z,A) = Y(Z,A)\,[1 - P(1)] \\ Y'(Z,A-1) = Y(Z,A-1) + Y(Z,A) * P(1) \end{cases}$$

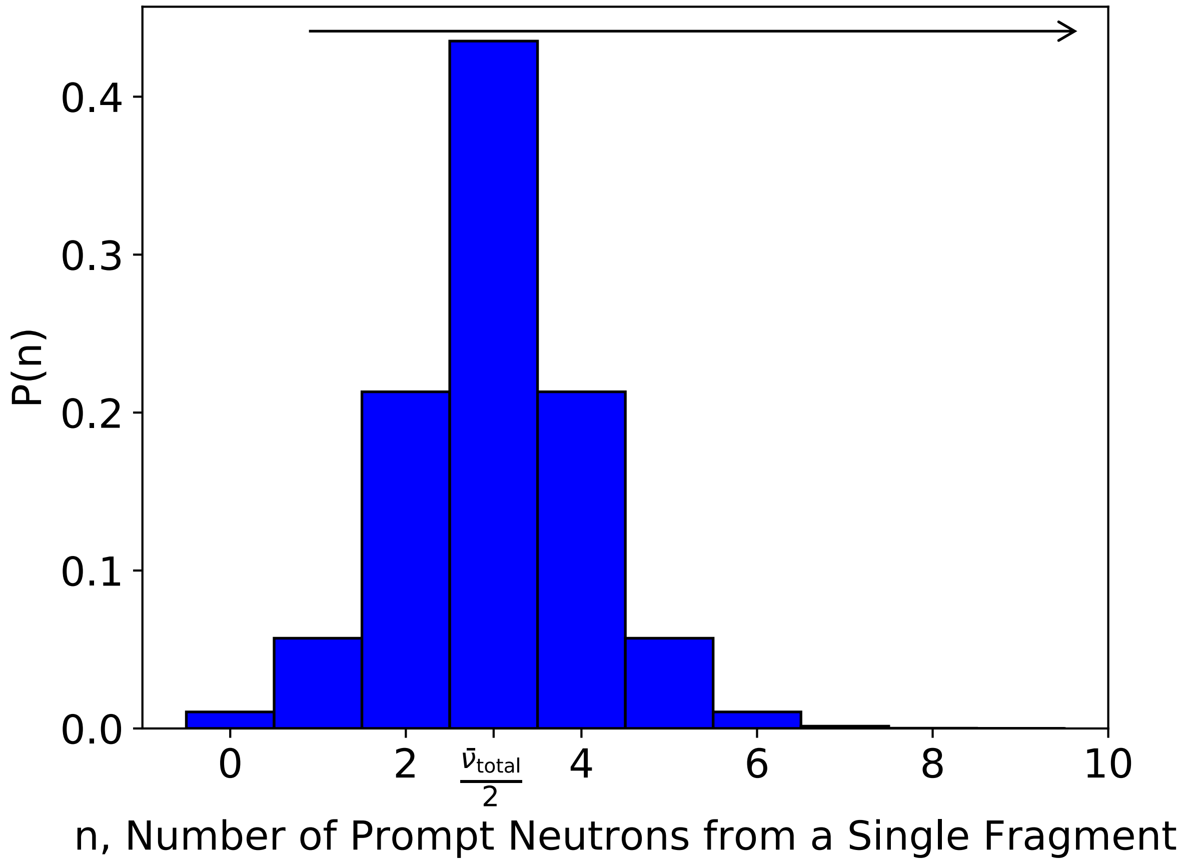
Modifying the Yields

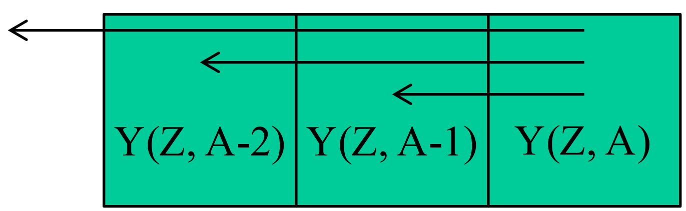




$$\begin{cases} Y^{'}(Z, A) = Y(Z, A)\left[1 - P(1) - P(2)\right] \\ Y^{'}(Z, A-2) = Y(Z, A-2) + Y(Z, A) * P(2) \end{cases}$$

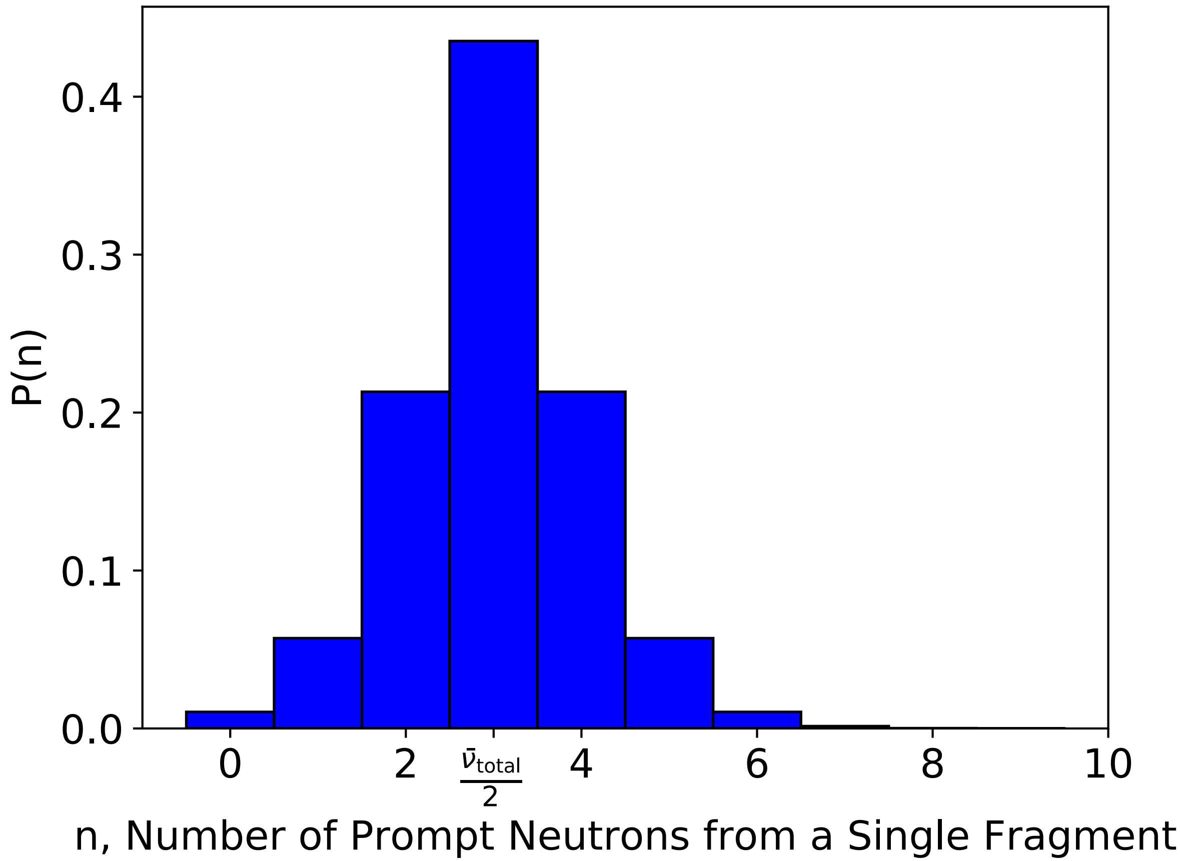
Modifying the Yields





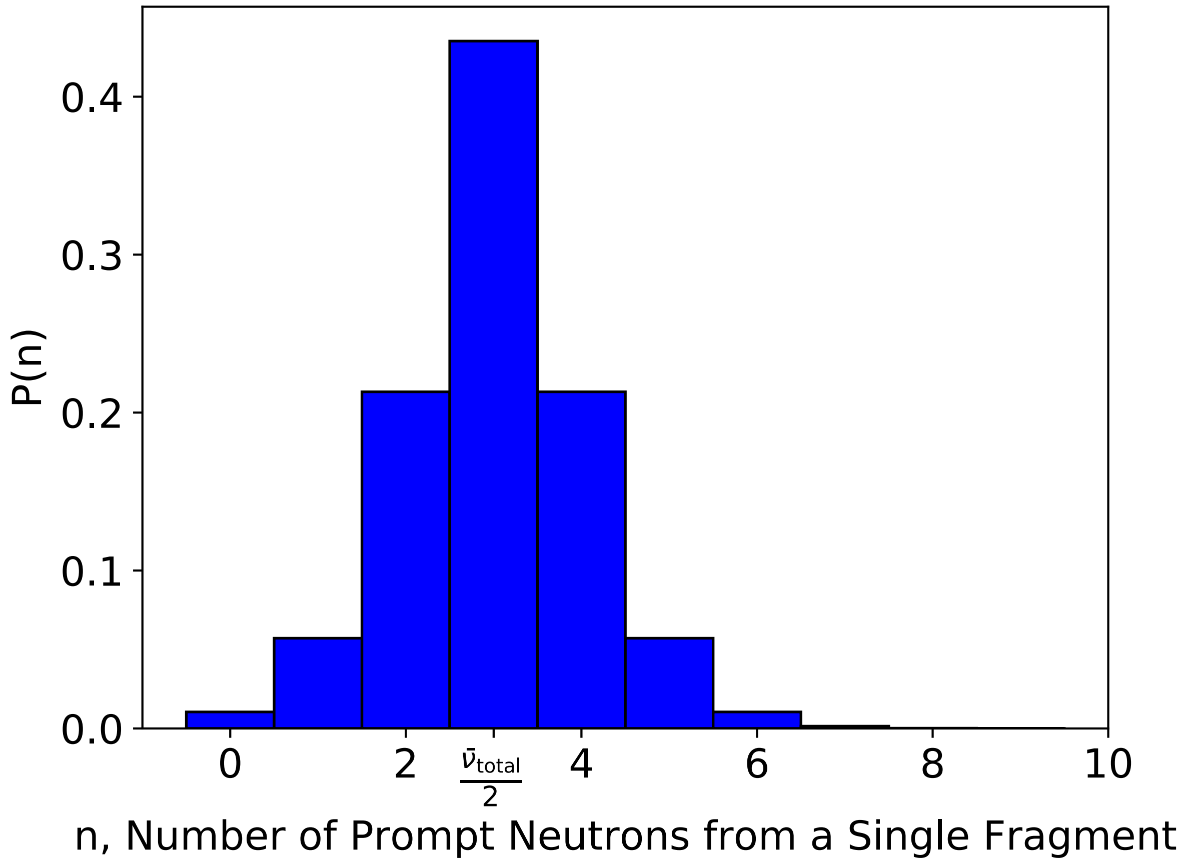
$$\begin{cases} Y'(Z,A) = Y(Z,A)\left[1 - \sum_{n>0} P(n)\right] \\ Y'(Z,A-n) = Y(Z,A-n) + Y(Z,A) * P(n) \end{cases}$$

Modifying the Yields



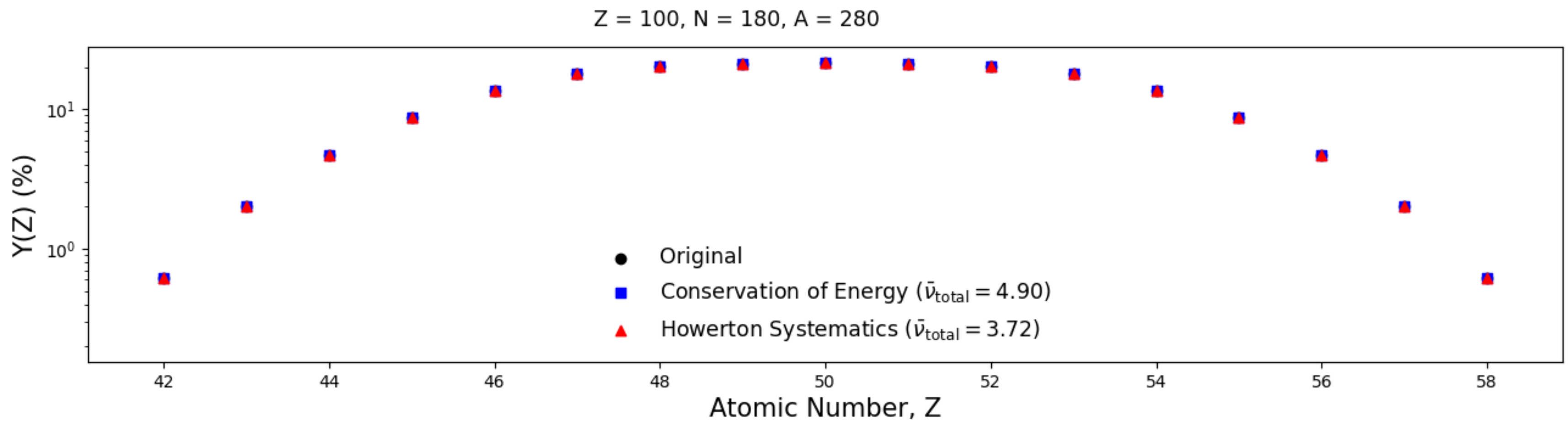
$$\begin{cases} Z_{fission} = \sum_Z \sum_A Y(Z,A) \cdot Z \\ A_{fission} = \sum_Z \sum_A Y(Z,A) \cdot A \end{cases}$$

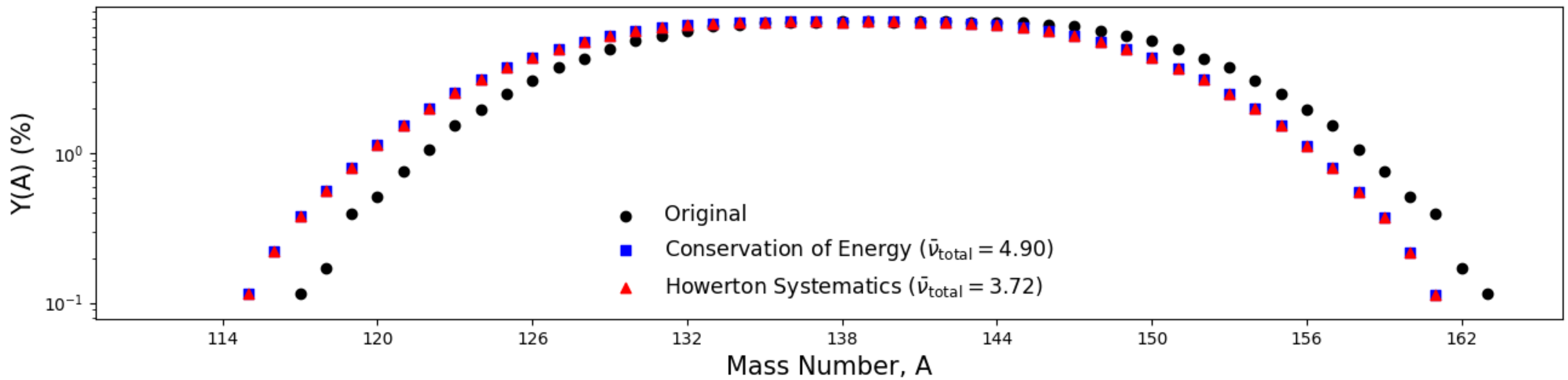
Modifying the Yields



$$\begin{cases} Z_{fission} = \sum_{Z} \sum_{A'} Y(Z, A') \cdot Z \\ A_{fission} = \sum_{Z} \sum_{A'} Y(Z, A') \cdot A' + \bar{\nu}_{total} \end{cases}$$

Modifying the Yields





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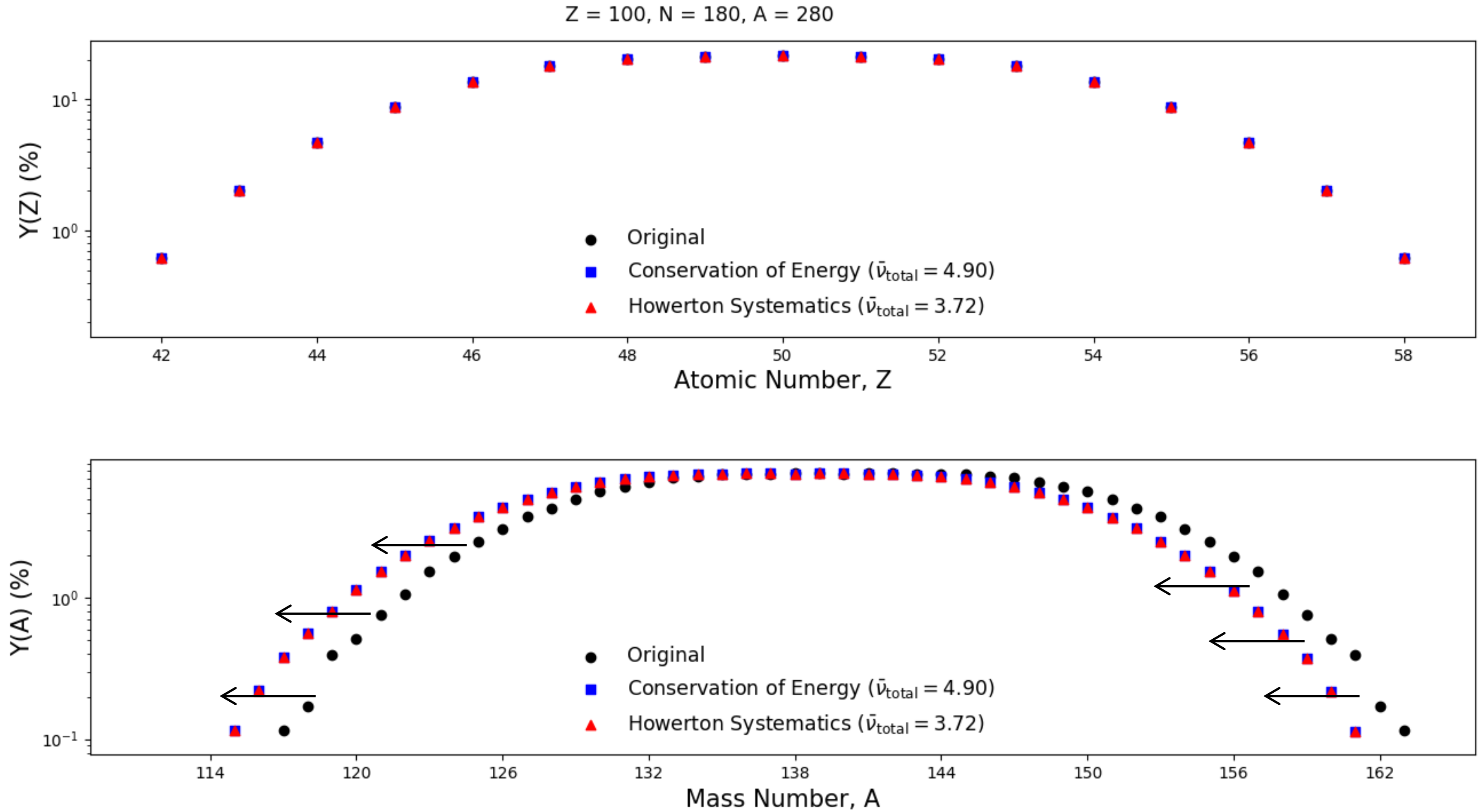
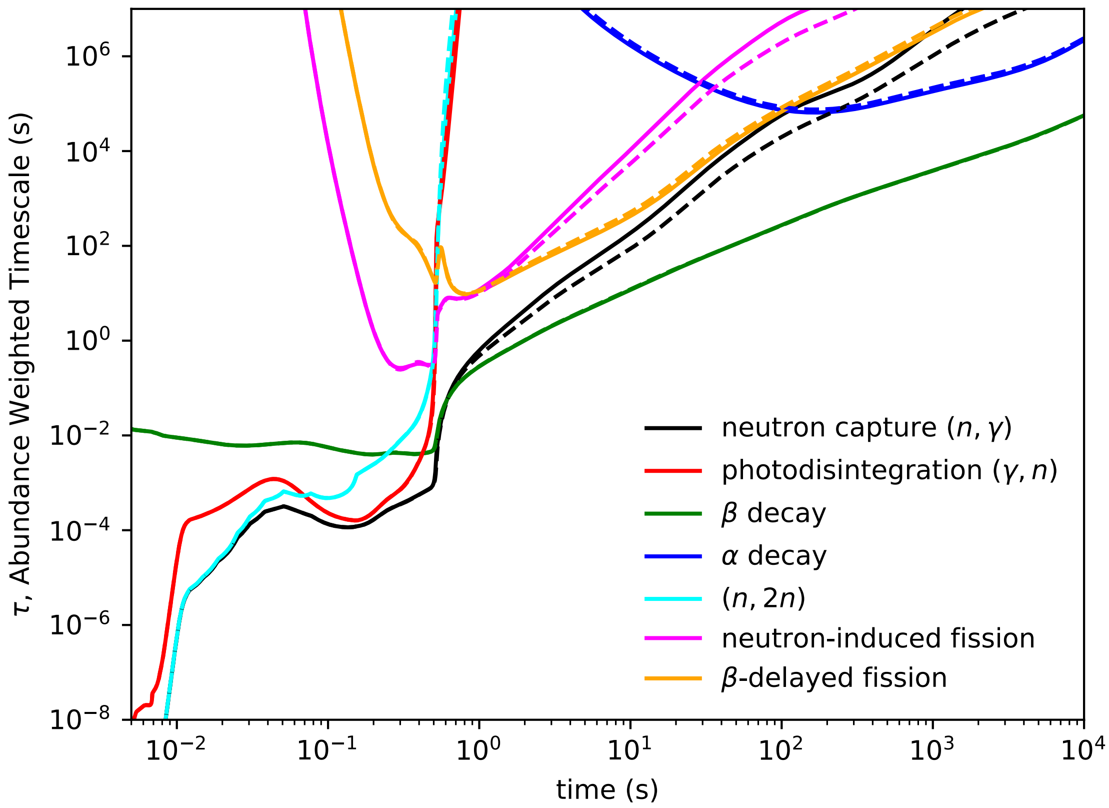


PRISM

- Use the modified yields in an r-process network calculation, and investigate the impact on the final abundance pattern
- **P**ortable **r**outines for **i**ntegrated **n**ucleosynthesis **m**odeling
- Developed by mentor Matthew Mumpower at Los Alamos National Laboratory

T. M. Sprouse and M. R. Mumpower. *In preparation*, 2017.

Neutron-induced and β-delayed Fission



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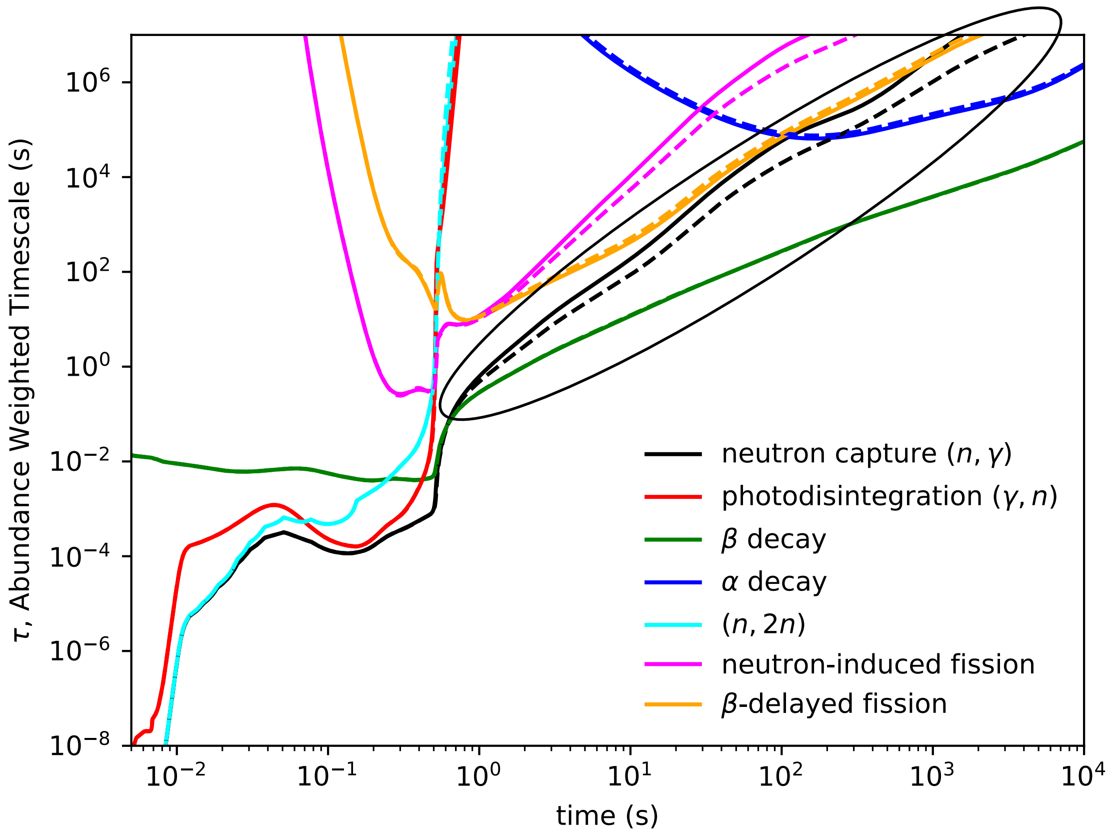

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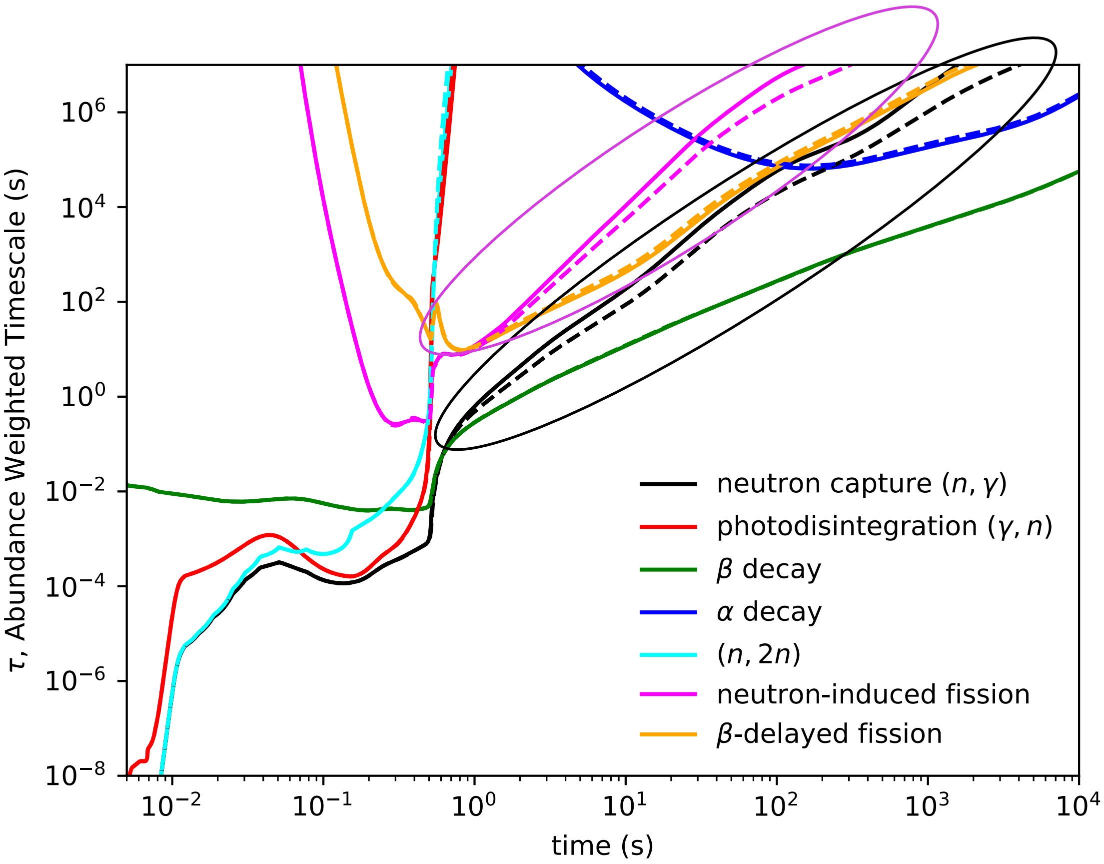

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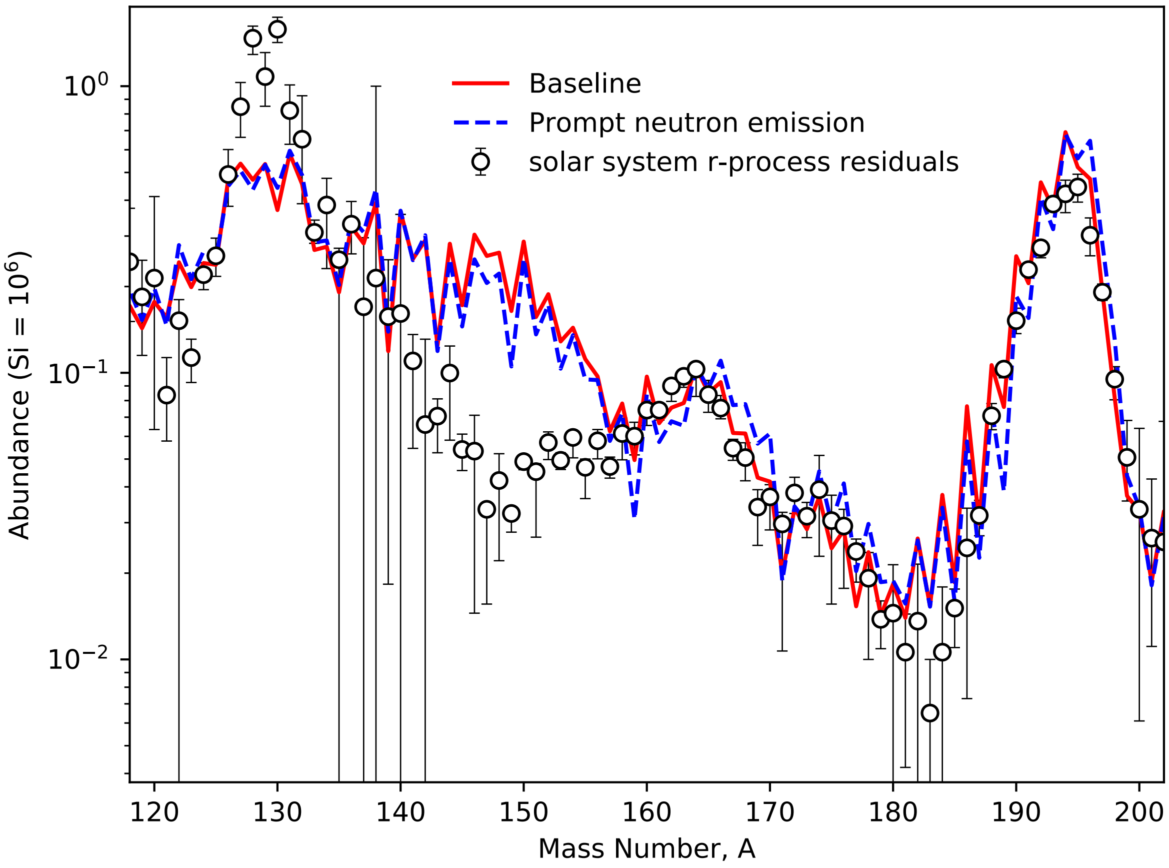

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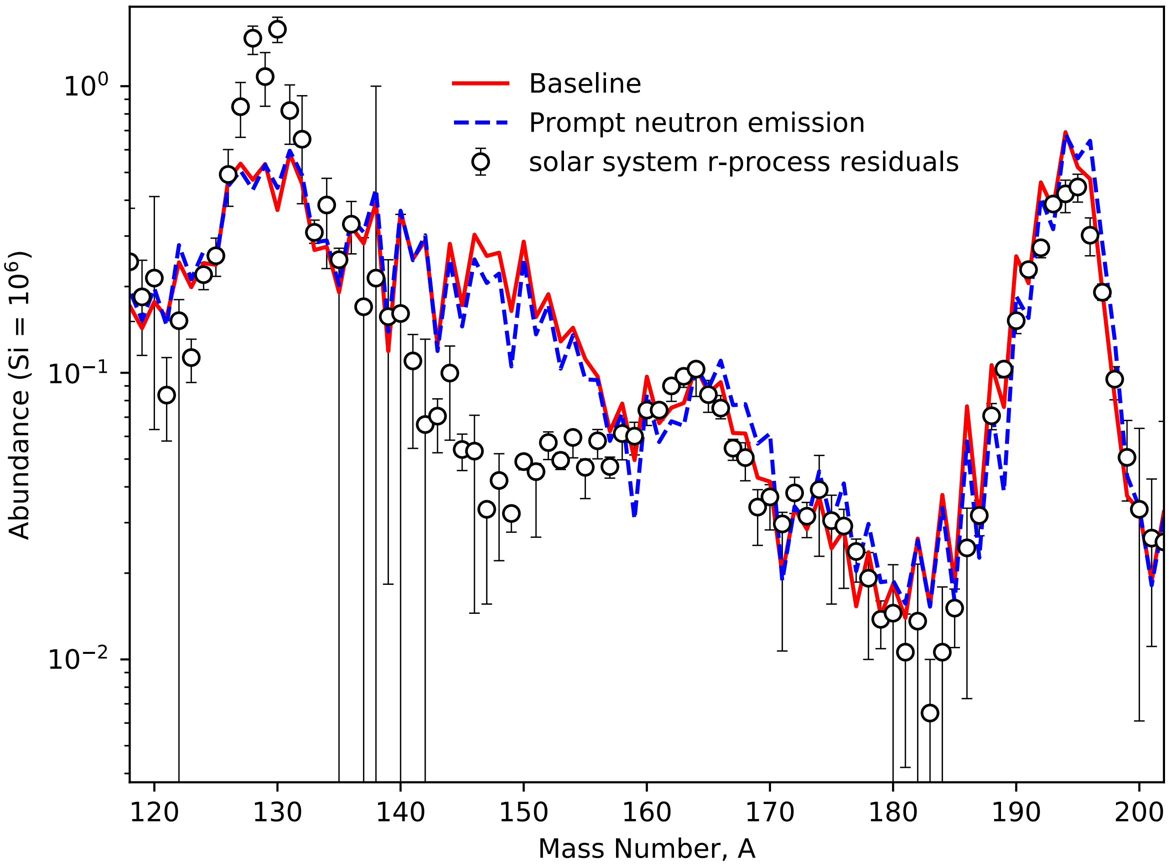

Global impact – impacts the entire final abundance pattern

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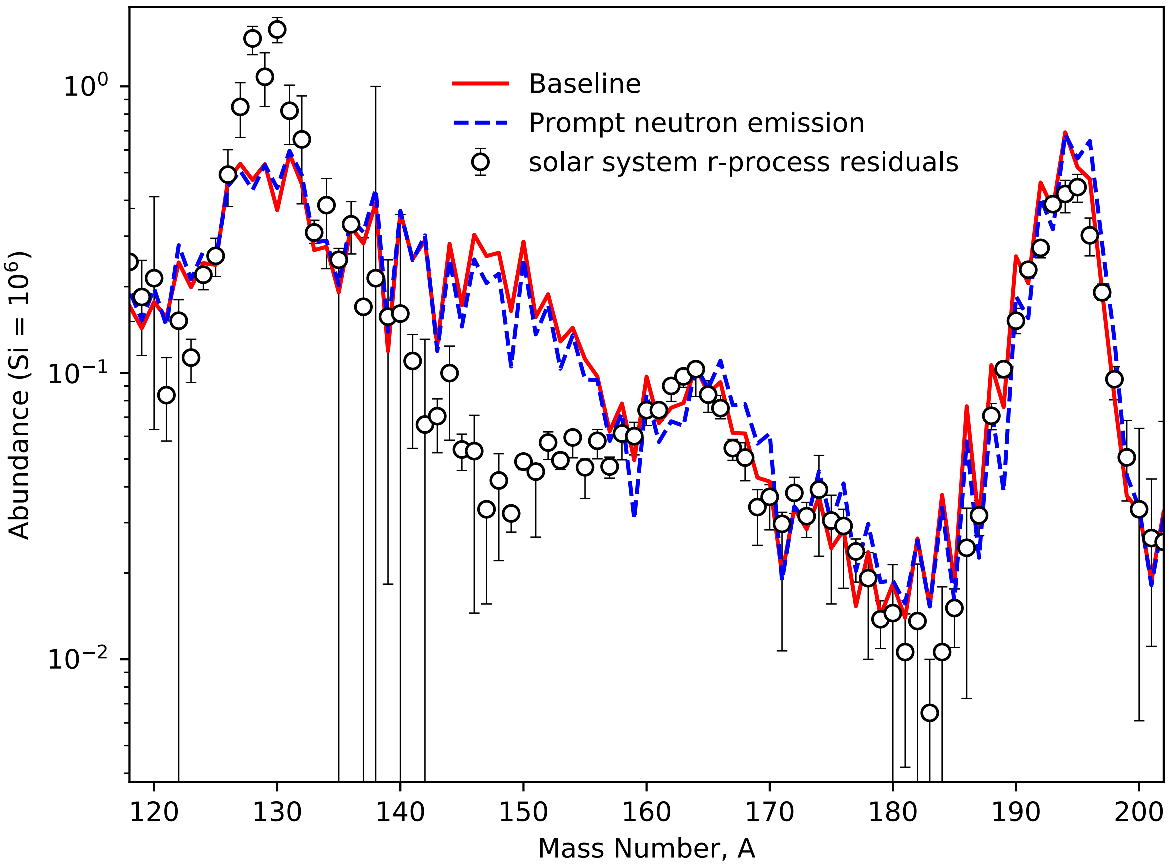

Nonlinear – certain regions are impacted while others are not

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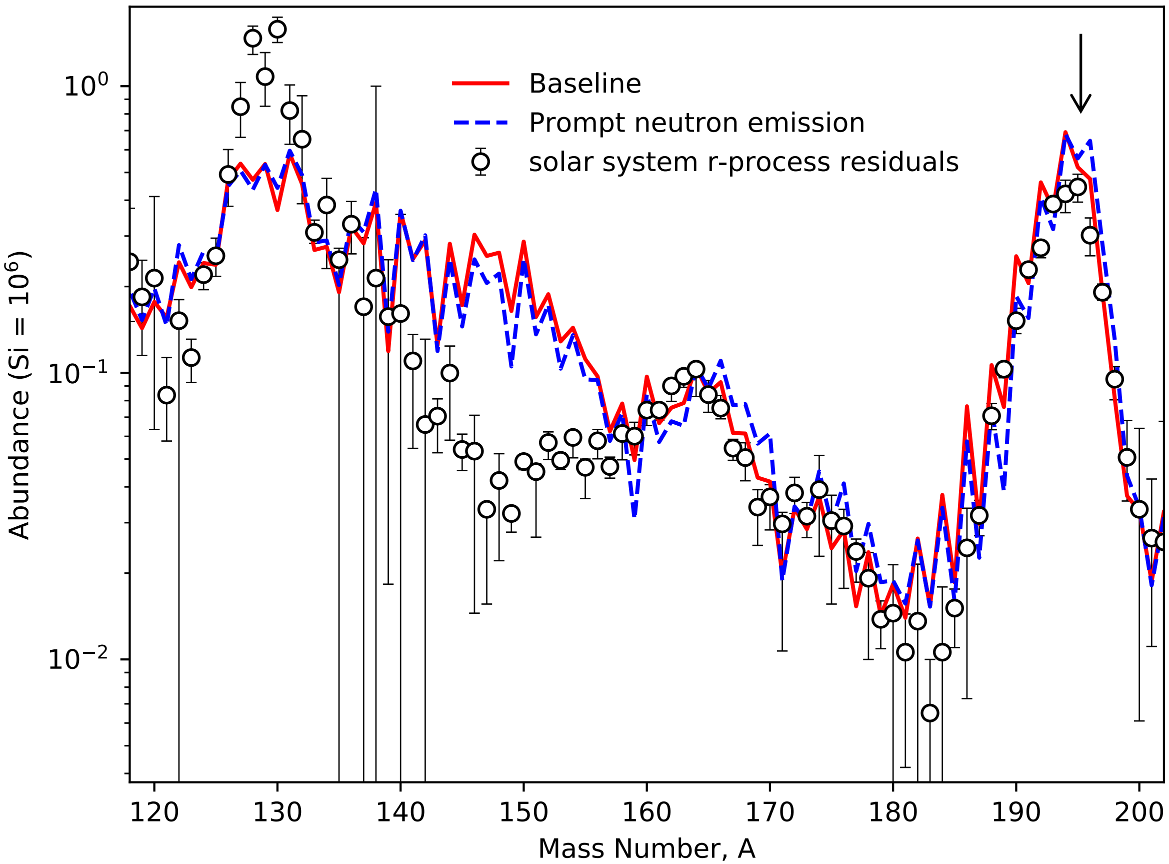

Peaks shift in mass number

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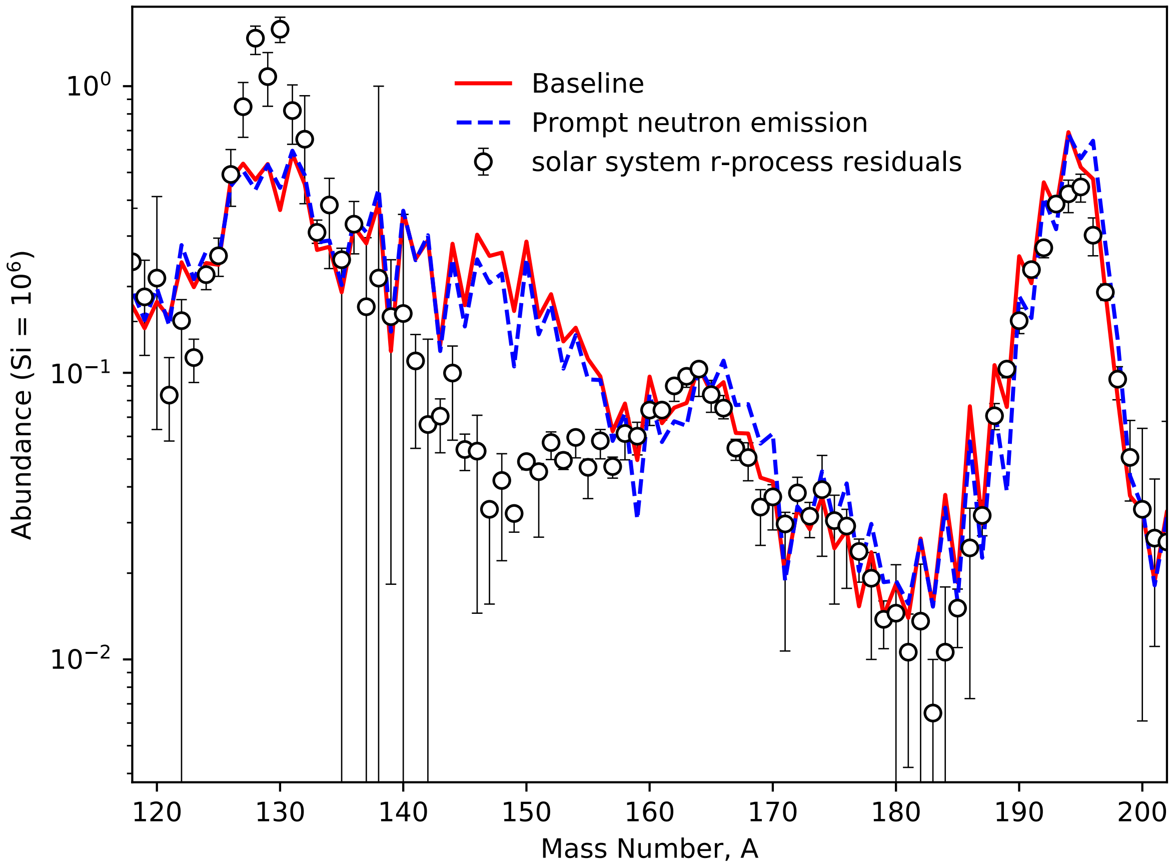


"Fine details"

Conclusions

- Prompt neutron emission from fission fragments impacts the fine details of final abundance pattern of the r-process.
- This project will be continued and expanded upon by the FIRE (**f**ission **i**n **r**-process **e**lements) collaboration, which uses state-of-the-art theory to explore the role of fission in the r-process, and includes scientists from the University of Notre Dame, North Carolina State University, Los Alamos National Laboratory, Brookhaven National Laboratory, and Lawrence Livermore National Laboratory.

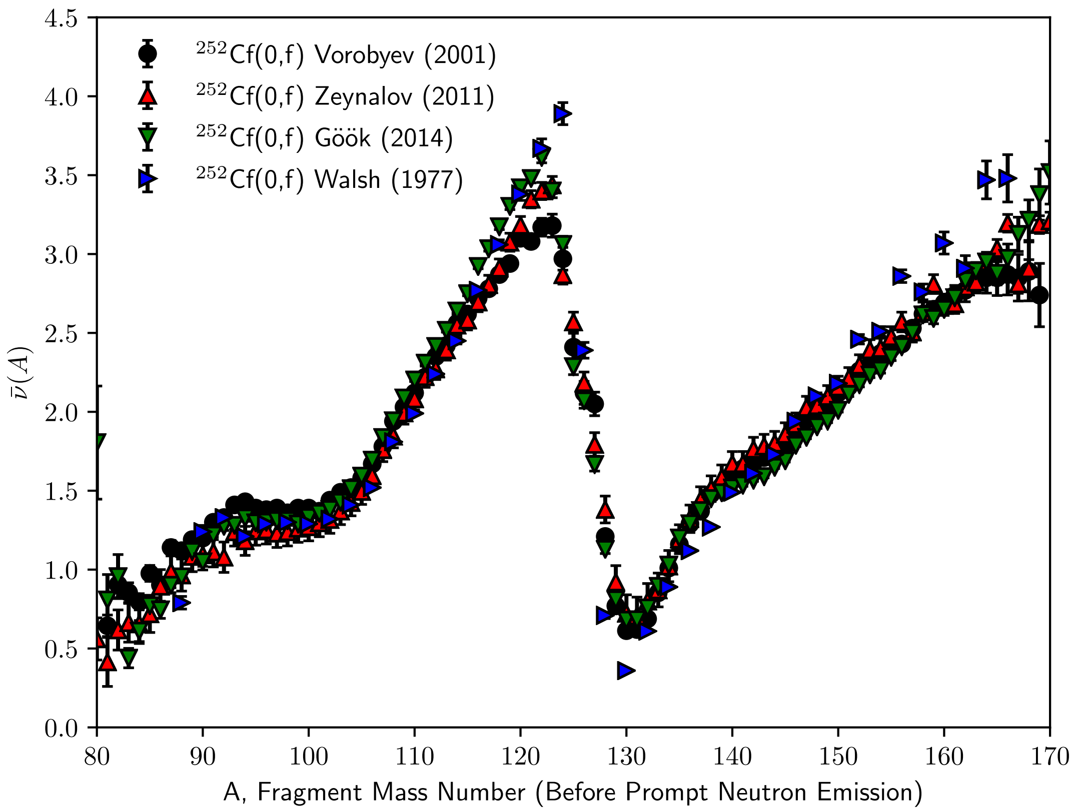
Disclaimer

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003180.

Details of presentation:

- Main focus to present your research to NSSC partners, sponsor, and the advisory board.
- Keep in mind this will be a 15 minute presentation, with an additional 5 minutes for questions.
- Please include mention of the NSSC Focus Areas and any Crosscutting Focus Areas you are working under
- Highlight any lab collaborations involved in your research, with specific mention of lab and lab mentor.

Modifying the Yields



$$\bar{\nu}_{total} = \sum_{Z} \sum_{A} Y(Z,A) \cdot \bar{\nu}(A)$$

Abundance Weighted Timescale

$$\tau_{n,\gamma} = \frac{\sum\limits_{Z,A} Y(Z,A)}{\sum\limits_{Z,A} N_n \langle \sigma \nu \rangle_{Z,A} Y(Z,A)}$$

$$\tau_{\gamma,n} = \frac{\sum\limits_{Z,A} Y(Z,A)}{\sum\limits_{Z,A} \lambda_{\gamma,n}(Z,A) Y(Z,A)}$$

$$\tau_{\beta} = \frac{\sum\limits_{Z,A} Y(Z,A)}{\sum\limits_{Z,A} \lambda_{\beta}(Z,A) Y(Z,A)}$$

Conservation of Energy

$$
\begin{aligned}
E_r &= M(Z,A) - M_L(Z_L,A_L) - M_H(Z_H,A_H) \\
&= T_L(Z_L,A_L) + T_H(Z_H,A_H) + E_L^*(Z_L,A_L) + E_H^*(Z_H,A_H) - (E_n + S_n) \\
&= T_f^{total} + E_{total}^* - (E_n + S_n) \\
&= \langle T_f^{total} \rangle + \langle E_{total}^* \rangle - (E_n + S_n) \\
&= \langle T_f^{total} \rangle + \langle Ex_n^{total} \rangle + \langle E_\gamma^{total} \rangle - (E_n + S_n) \\
&= \langle T_f^{total} \rangle + \bar{\nu}\left[\langle S_n \rangle + \langle \epsilon \rangle\right] + \langle E_\gamma^{total} \rangle - (E_n + S_n)
\end{aligned}
$$

- Eqn. 17 in *Nuclear Physics A 772 (2006) 113–137* by *D.G. Madland*
- E_r = Q value = total energy release in binary fission
- $\langle T_f^{total} \rangle$ = average total fragment kinetic energy
- $\langle E_{total}^* \rangle$ = average total fragment excitation energy
- $\langle Ex_n^{total} \rangle$ = average total fragment neutron emission energy
- $\langle E_\gamma^{total} \rangle$ = average total fragment gamma-ray emission energy
- $\langle S_n \rangle$ = average fragment neutron separation energy
- $\langle \varepsilon \rangle$ = average center-of-mass energy of emitted neutrons
- E_n = kinetic energy of incident neutron
- S_n = neutron separation energy of compound nucleus

Conservation of Energy

- E_r = Q value = total energy release in binary fission
  - Binding energies from FRDM 2012
  - $$E_r = M(Z,A) - M_L(Z_L,A_L) - M_H(Z_H,A_H)$$
    $$= \sum_{Z,A} BE(Z,A) \cdot Y(Z,A) - BE(Z_c,A_c)$$
- $\langle T_f^{total} \rangle$ = average total fragment kinetic energy
  - Phys. Rev. C 31, 1550 (1985) by V. E. Viola *et al.*
  - $$\langle T_f^{total} \rangle = 0.1189 \frac{Z_c^2}{A_c^{1/3}} + 7.3$$
- $\langle E_\gamma^{total} \rangle$ = average total fragment gamma-ray emission energy
  - Annu. Rev. Nucl. Sci. 1974 Vol 24 pages 151-208 by D. C. Hoffman and M. M. Hoffman
  - $$\langle E_\gamma^{total} \rangle = 0.02772 \cdot A_c + 0.0891$$

Conservation of Energy

- $<S_n>$ = average fragment neutron separation energy
  - Binding energies from FRDM 2012

$$\langle S_n \rangle = \sum_{Z,A} S_n(Z,A) \cdot Y(Z,A)$$

- $<\varepsilon>$ = average center-of-mass energy of emitted neutrons
  - Annu. Rev. Nucl. Sci. 1974 Vol 24 pages 151-208 by D. C. Hoffman and M. M. Hoffman
  - $\langle \epsilon \rangle \approx 2.34\ \mathrm{MeV}$
- E_n = kinetic energy of incident neutron
  - Assume thermal energies in r-process
  - $\langle E_n \rangle \approx 0$
- S_n = neutron separation energy of compound nucleus
  - Binding energies from FRDM 2012

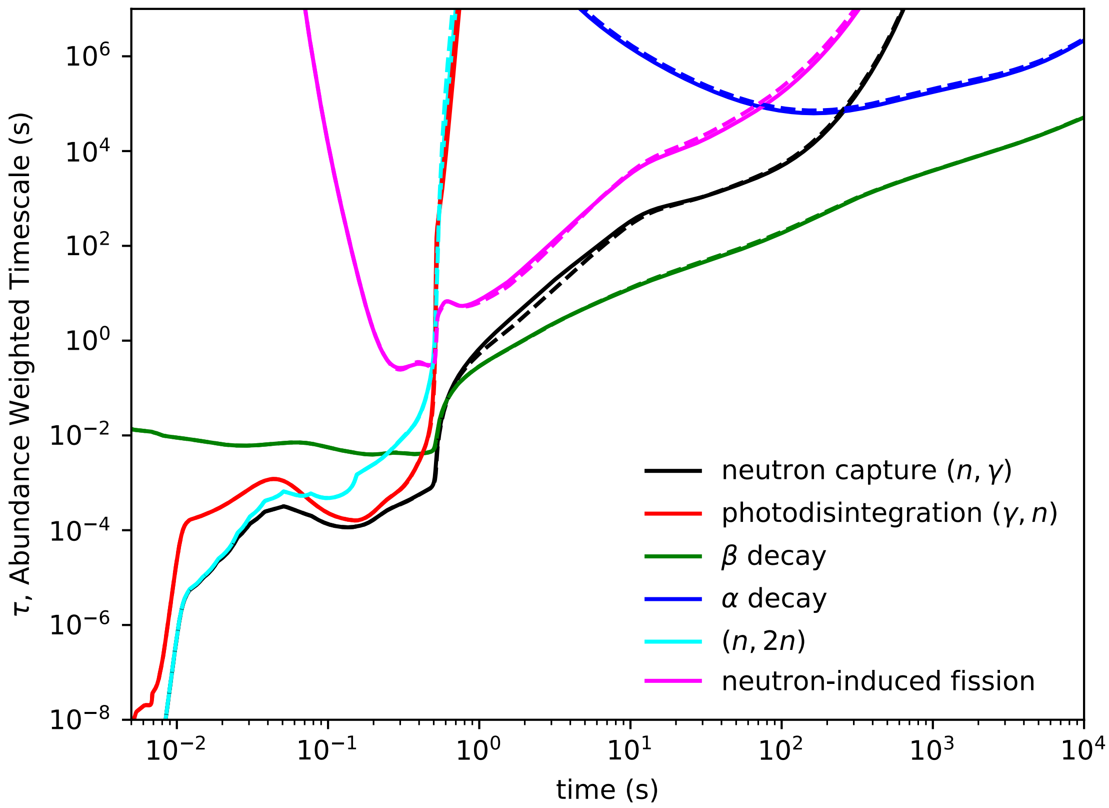
Howerton Systematics

- Based on a Taylor expansion about ^{235}U(n,f) at the threshold energy for fission E_{th}
- Tested against <ν> for isotopes from ^{229}Th to ^{249}Cf in 1977
- Threshold energies calculated using binding energies from FRDM 2012

$$\bar{\nu}(Z,A,E_n) = 2.33 + 0.06\cdot(2-(-1)^{A+1-Z}-(-1)^Z) + 0.15\cdot(Z-92) + 0.02\cdot(A-235) + (0.130+0.006\cdot(A-235))\cdot(E_n-E_{th})$$

$$E_{th}(Z,A) = 18.6 - 0.36\cdot Z^2/(A+1) + 0.2\cdot(2-(-1)^{A+1-Z}-(-1)^Z) - S_n(Z,A+1)$$

Neutron-induced Fission



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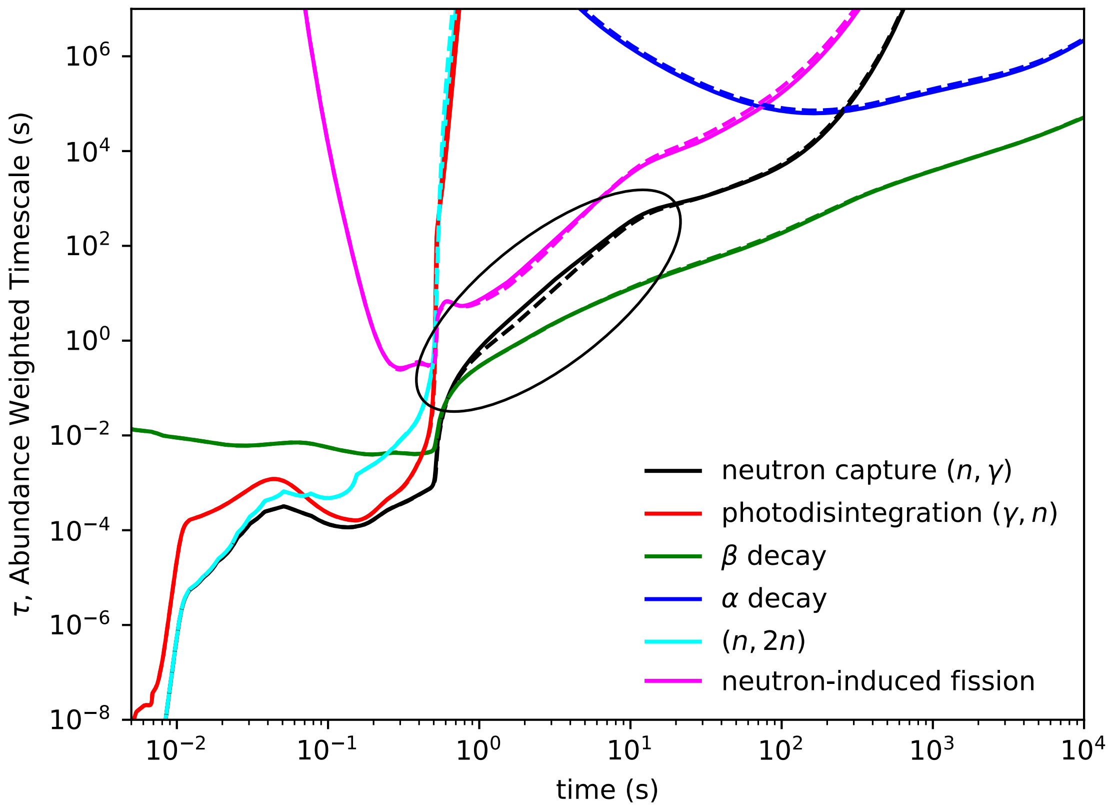

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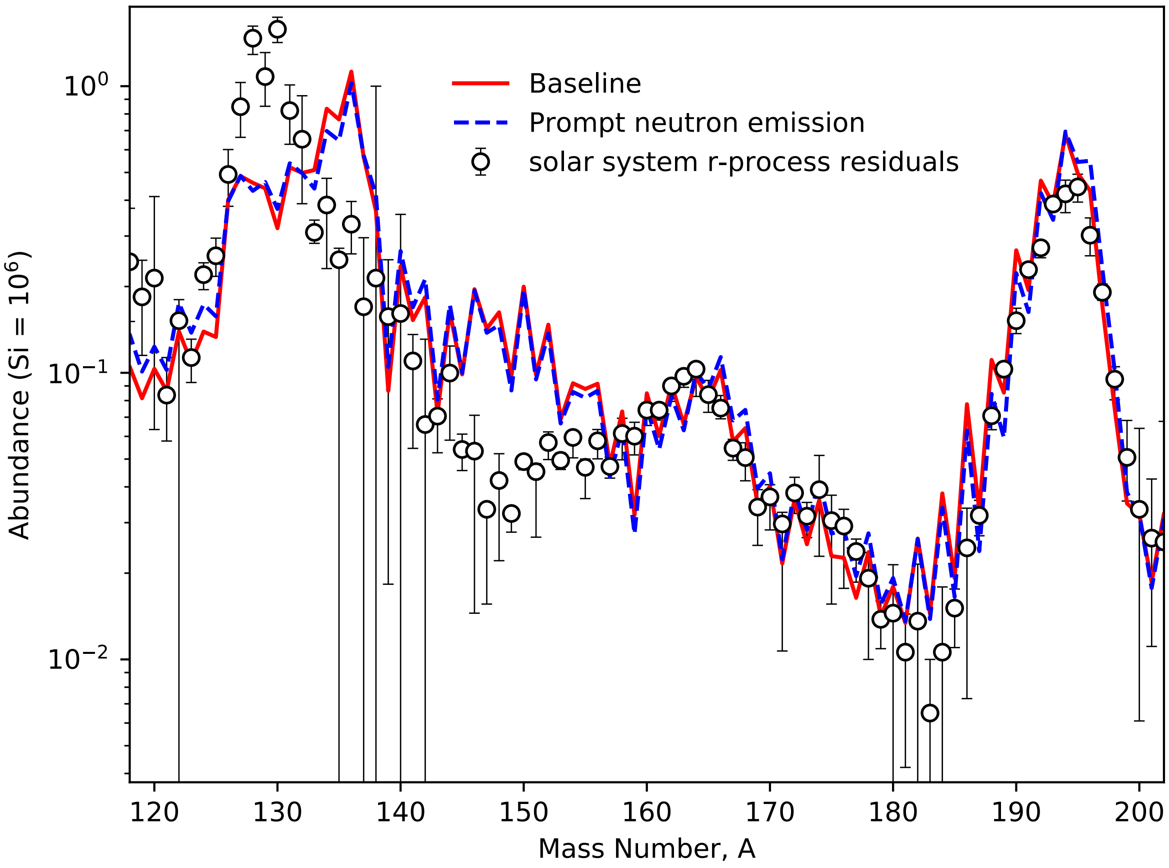

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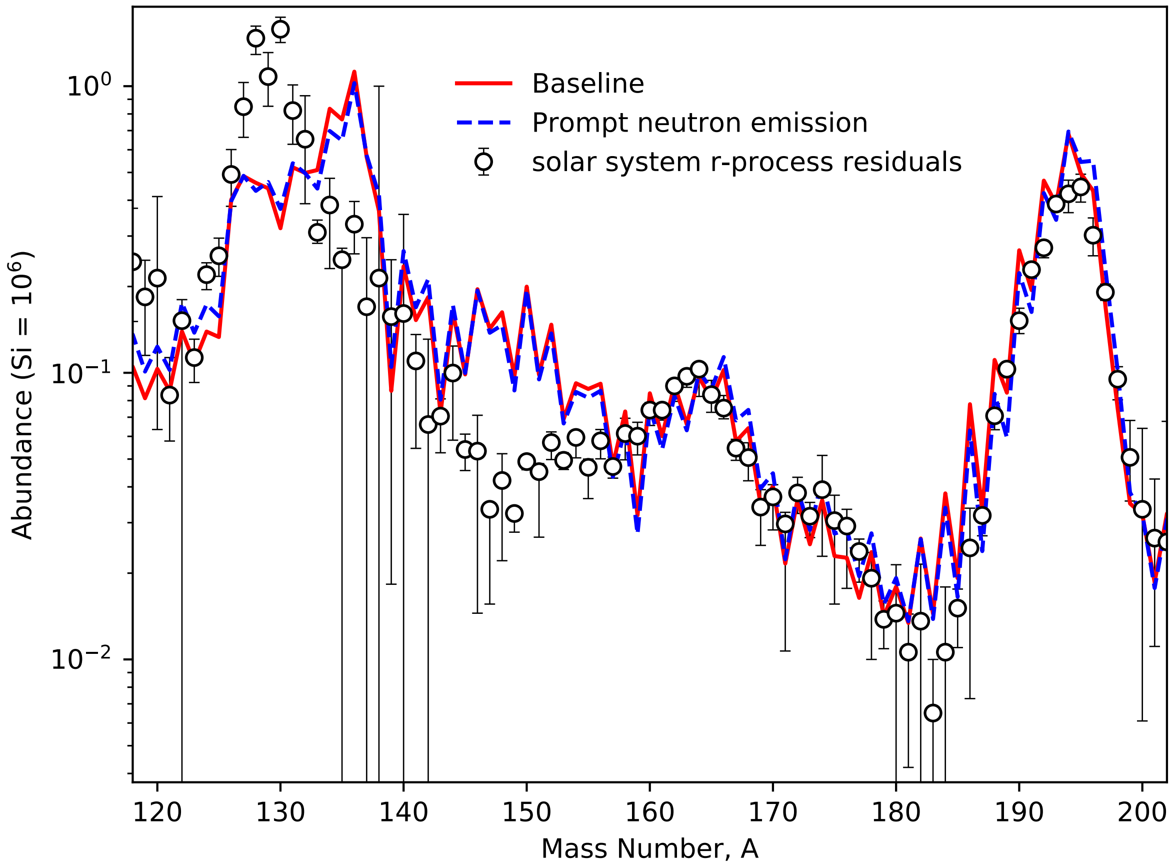

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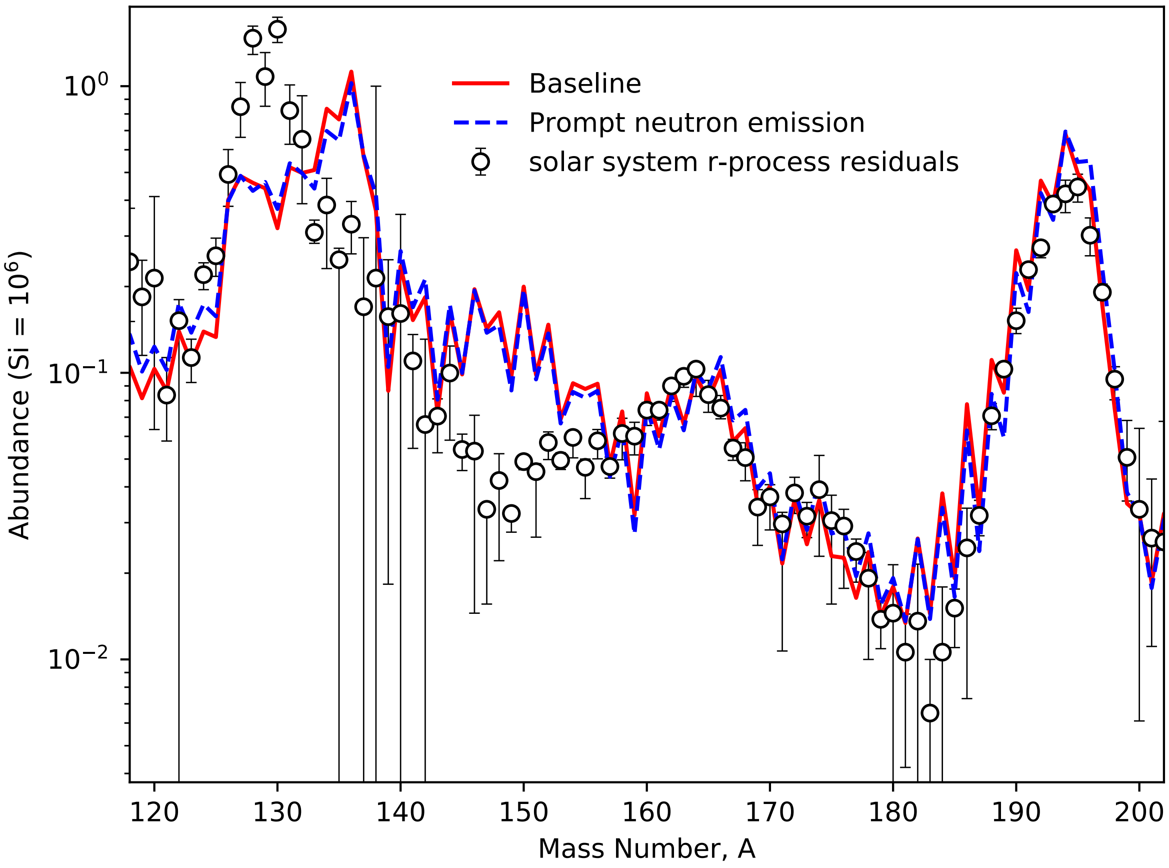

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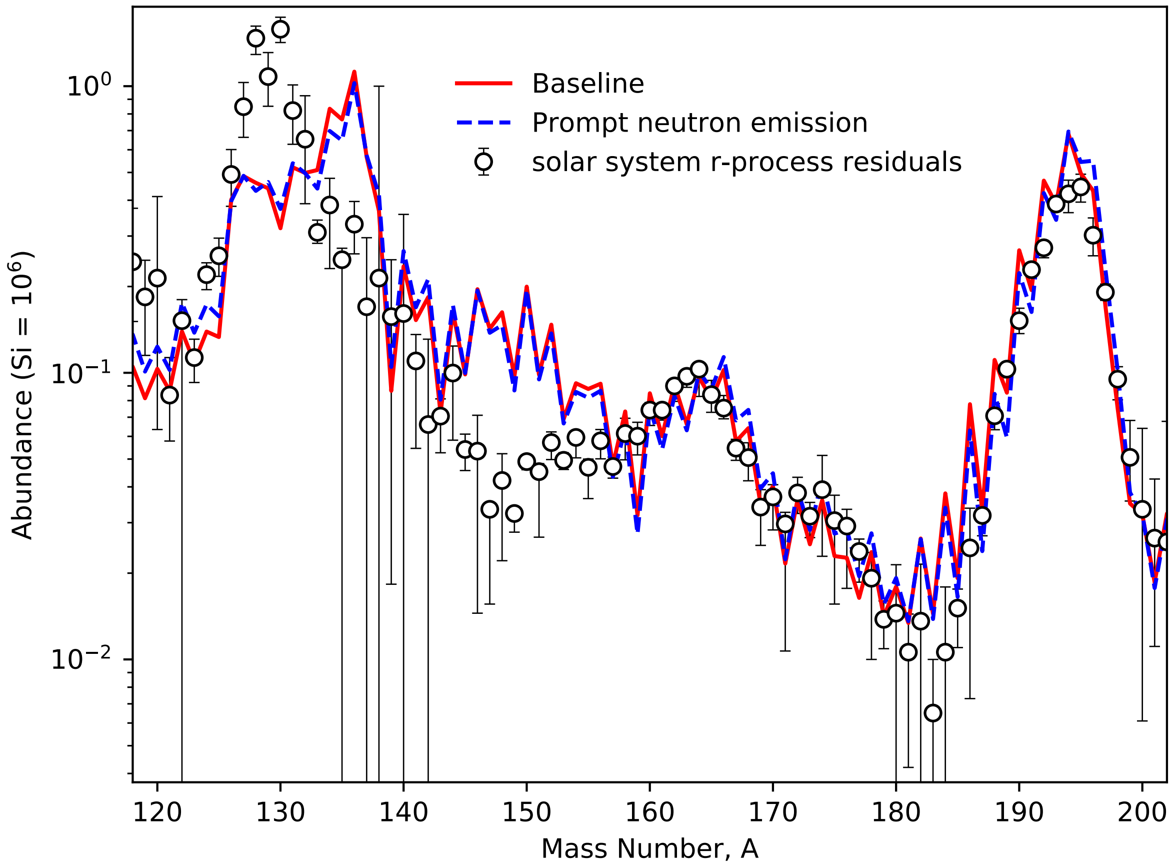
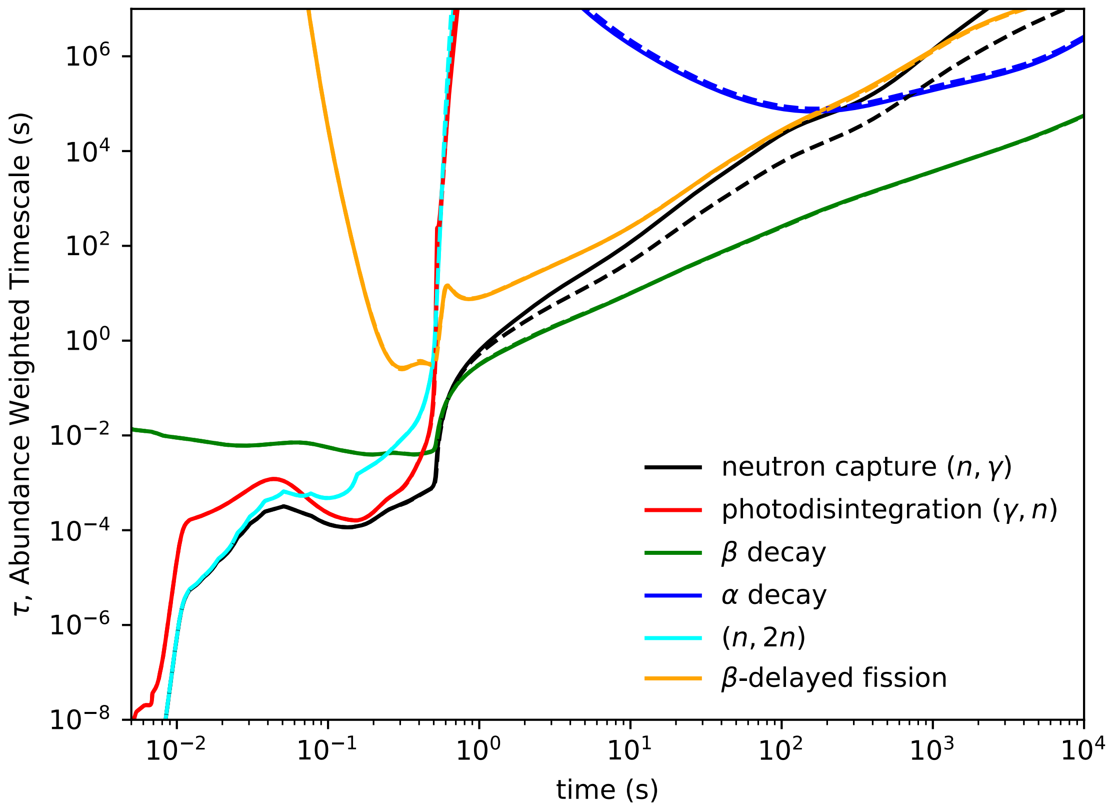
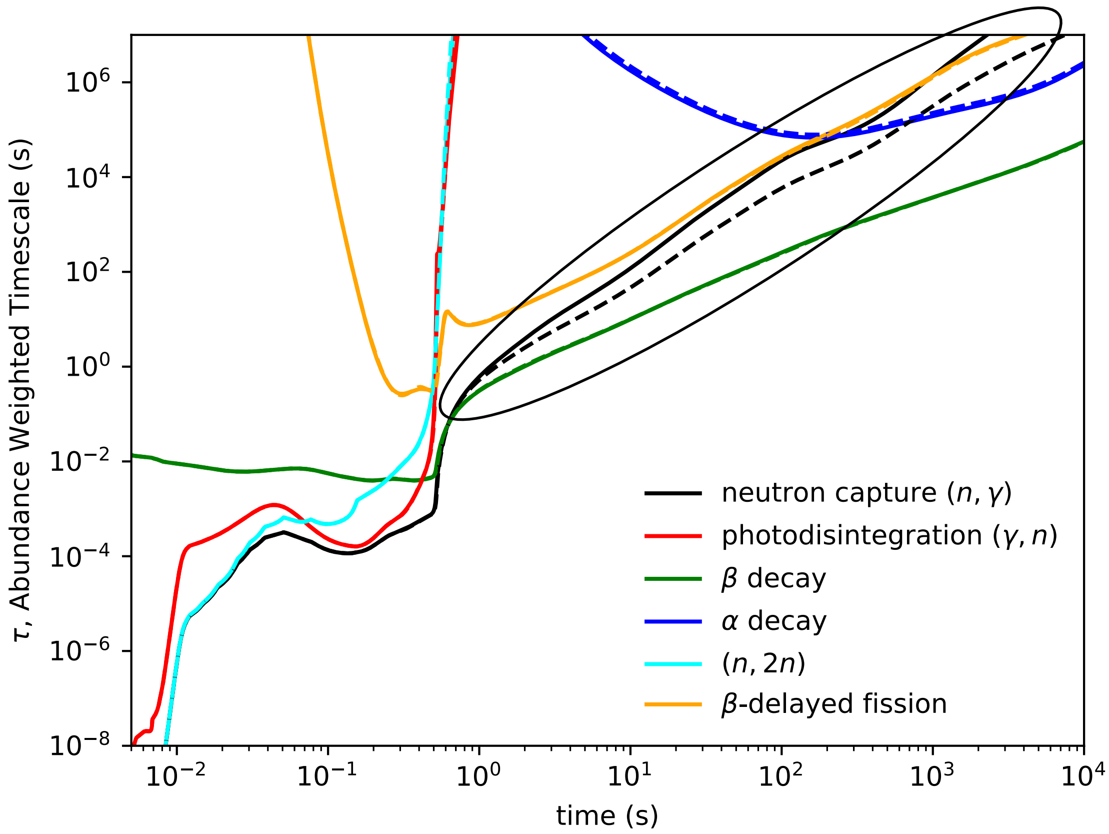


"Fine details"

β-delayed Fission



β-delayed Fission



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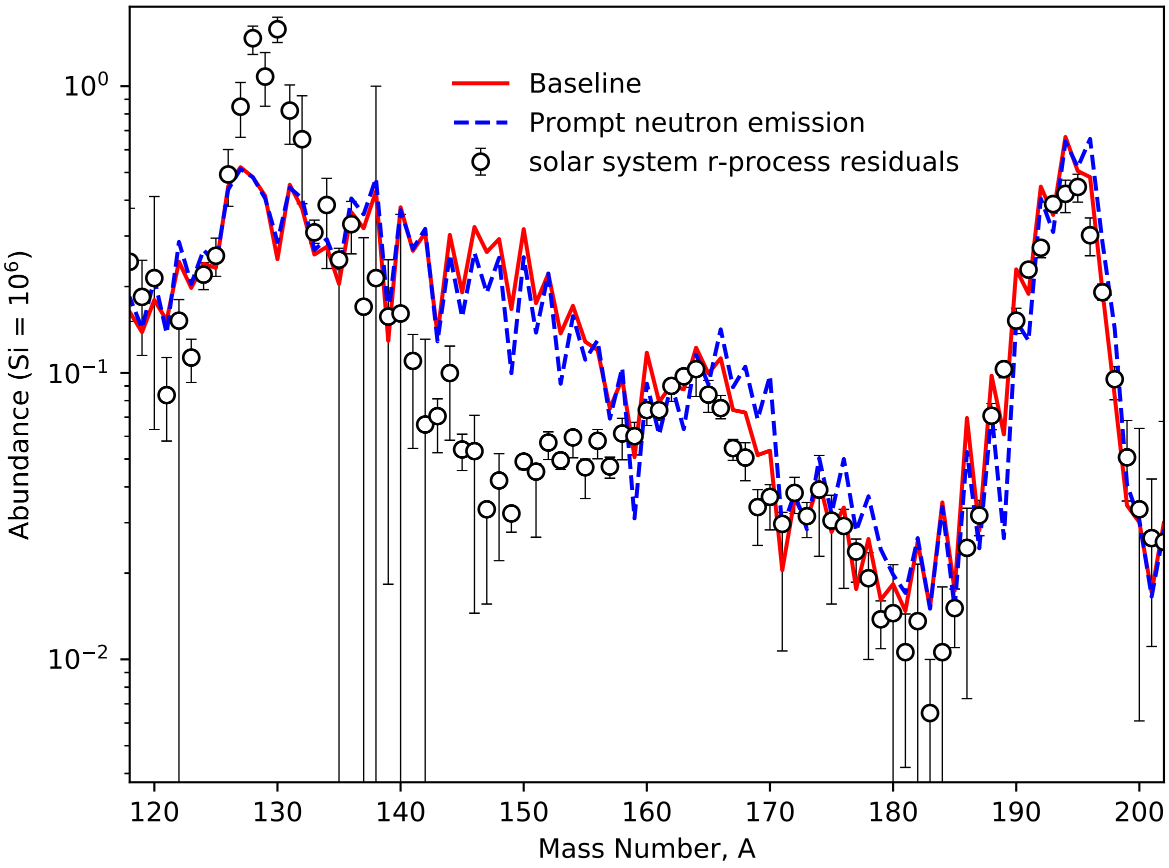

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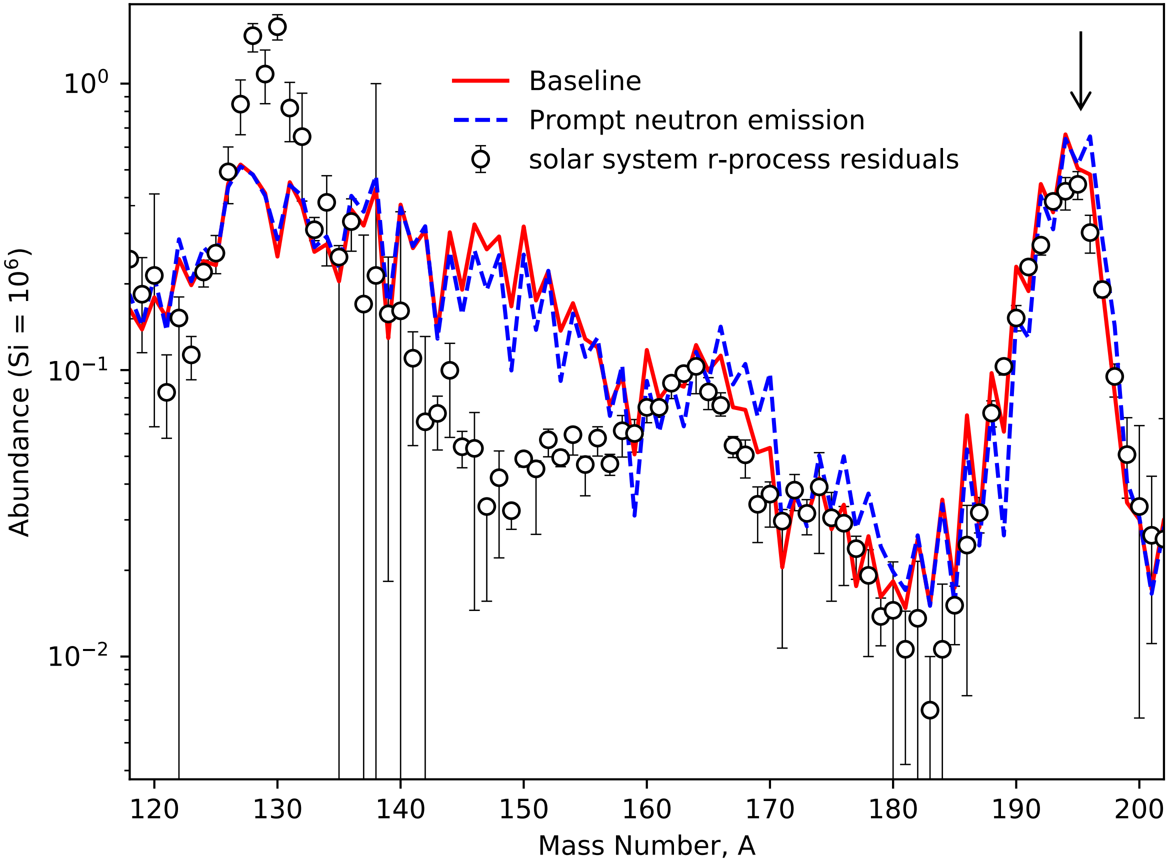

Peaks shift in mass number