Actinide Dating Stars: Nuclear Uncertainties in Cosmic Age

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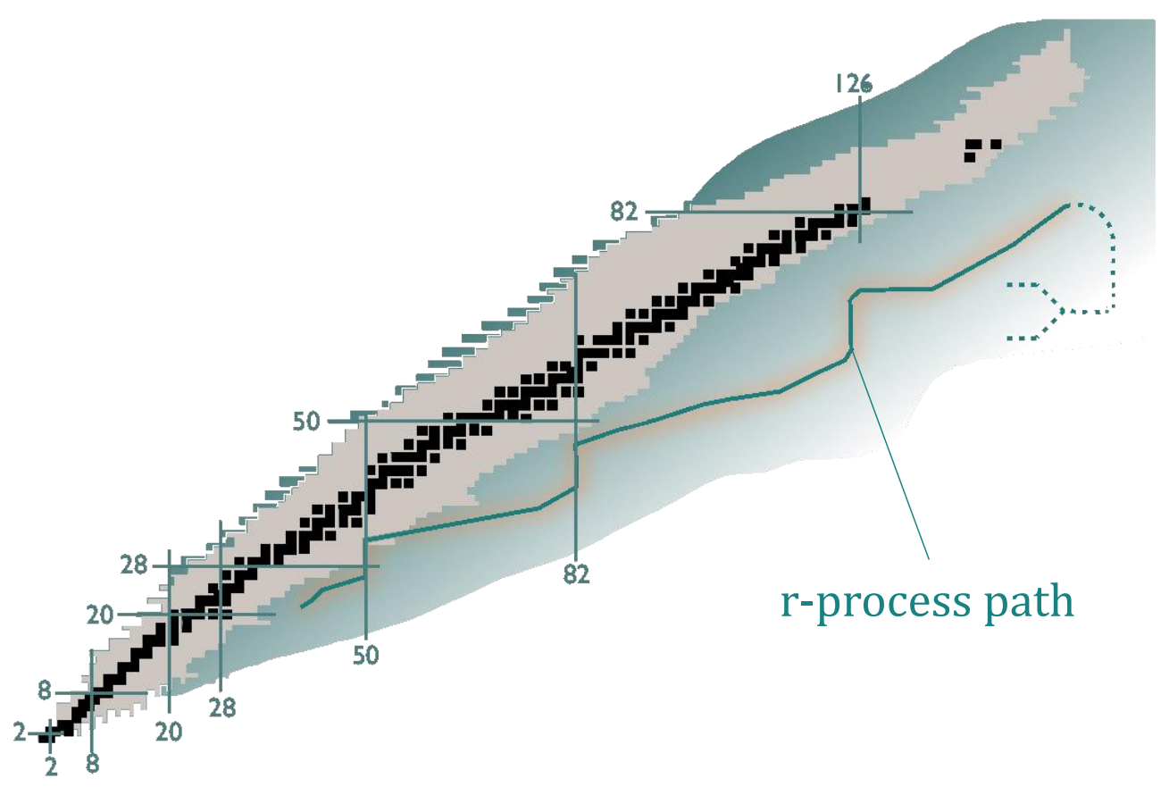
1. Context

Nuclear cosmochronometry: known half lives of radioactive isotopes to extract ages from stellar spectra.

Metal-poor stars ([Fe/H] ≤ -2)* have pristine environments. r-ii stars are metal-poor but show an abnormally large abundance of material ([Eu/Fe] >+1)** made via the rapid neutron capture process (r-process).

The r-process is sensitive to numerous nuclear uncertainties. It is thought to occur in compact object mergers (COM) with at least one neutron star.



* Fe:H ratio at least 100 times smaller than what is observed in the Sun   ** Eu:Fe ratio at least 10 times larger than what is observed in the Sun

2. Method

By comparing the initial and final abundances of different isotopes with known half-lives, it is possible to calculate the amount of time elapsed.

Chronometers: the long-lived isotopes ^{232}Th ($t_{1/2}$=14 Gyr) and ^{238}U ($t_{1/2}$=4.47 Gyr) plus the stable isotopes of Eu (Z=63).

$$t = 46.67\text{Gyr}\left[-log_{\epsilon}\left(\frac{\text{Th}}{\text{Eu}}\right)_{\text{obs}} + log_{\epsilon}\left(\frac{Th}{Eu}\right)_{0}\right]$$

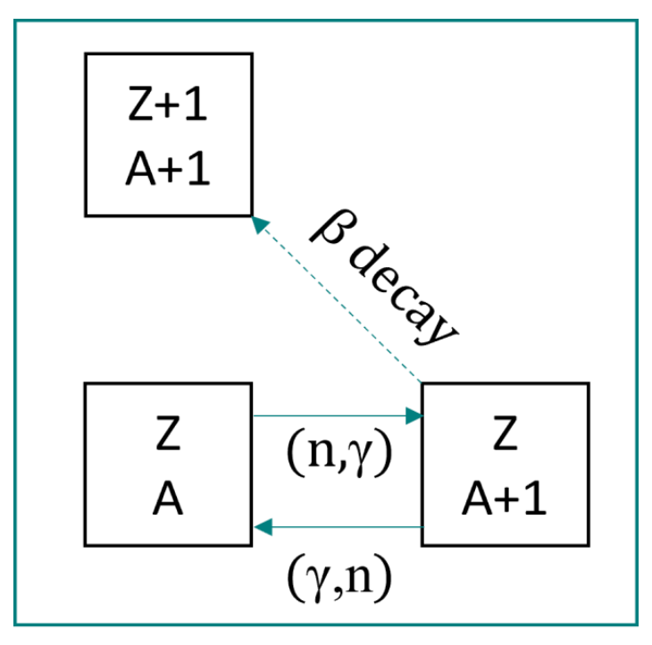
$$t = 14.84\text{ Gyr}\left[-log_{\epsilon}\left(\frac{\text{U}}{\text{Eu}}\right)_{\text{obs}} + log_{\epsilon}\left(\frac{\text{U}}{Eu}\right)_{0}\right]$$

$$t = 21.80\text{ Gyr}\left[-log_{\epsilon}\left(\frac{\text{U}}{\text{Th}}\right)_{\text{obs}} + log_{\epsilon}\left(\frac{\text{U}}{\text{Th}}\right)_{0}\right]$$

We take the initial abundances in the equations above to be the final abundances produced in a COM. We calculate these final abundances by performing nucleosynthesis calculations with a variety of theoretical nuclear data sets and astrophysical conditions.

3. Beta Decay Rates

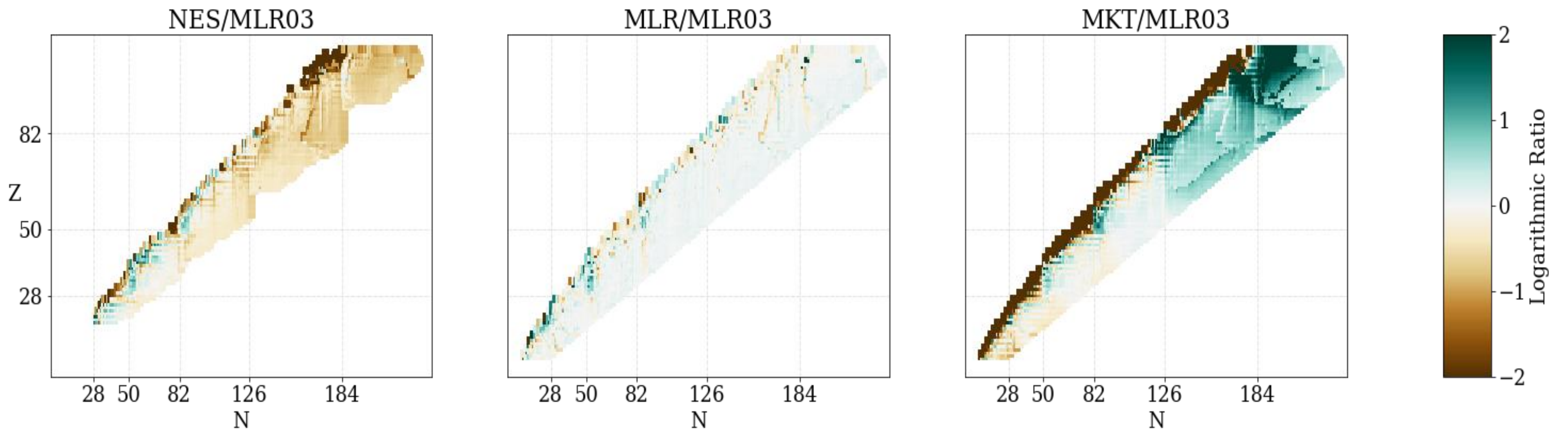
The r-process is characterized by a neutron capture timescale that is short compared to the β-decay timescale.



β-decay rates constrain:

- How neutron rich a nucleus can get before it β-decays
- High-Z and actinide population produced
- Dominant decay channel of potentially fissioning nuclei
- Rare earth abundances

We consider three sets of global theoretical β-decay rates in our nucleosynthesis calculations. The figure shows the ratio of each set of rates to those of [1]. In general, NES [2] tends to have slower rates than MLR [3], which in turn tends to have faster rates than MKT [4].



4. Fission Yields

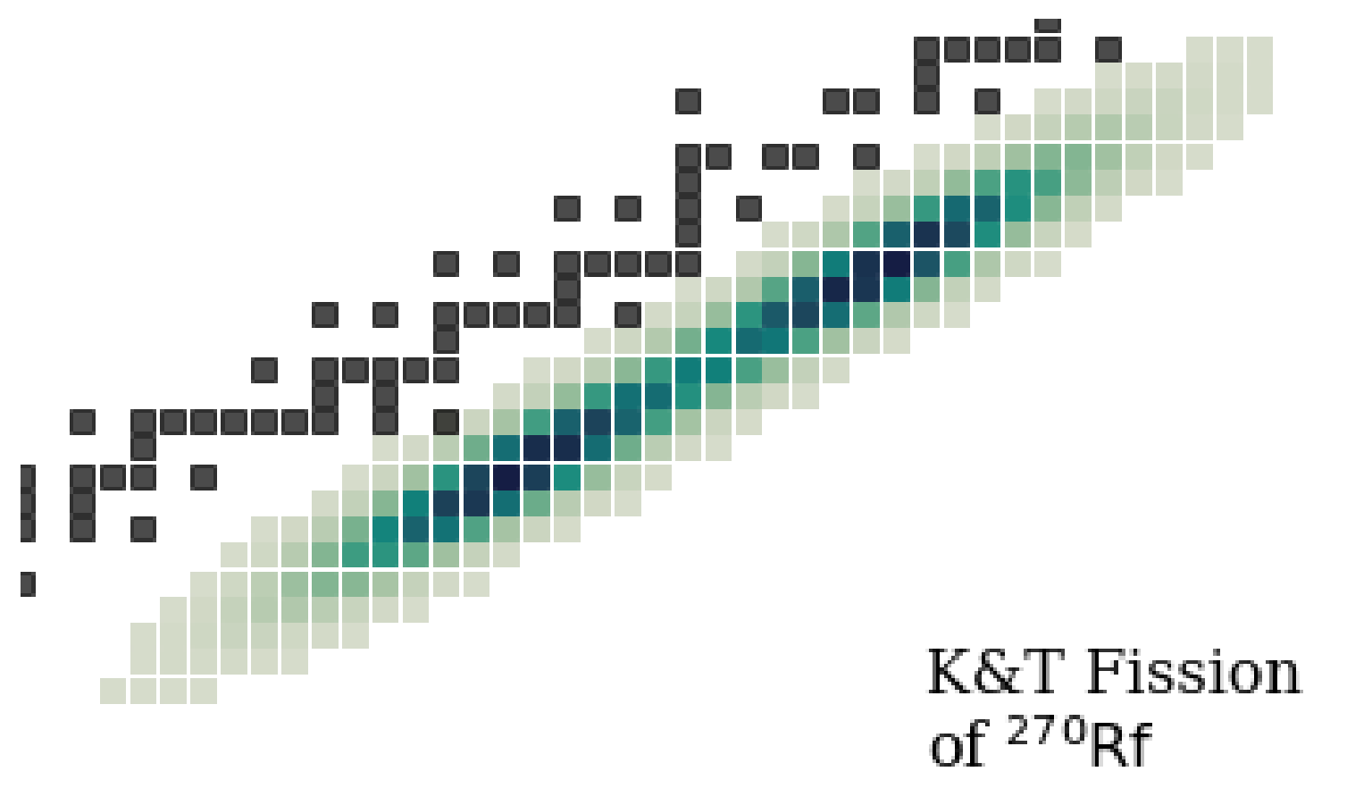
When material with high mass number undergoes fission, it can deposit material in the rare earth region.

We consider two possible fission outcomes:

- Symmetric (50/50) split: The nucleus fissions into two equal daughter products:

$$A_{\text{daughter}} = \frac{1}{2}A_{\text{parent}}$$

- K&T: The nucleus fissions according to the double Gaussian described by [5] (figure)



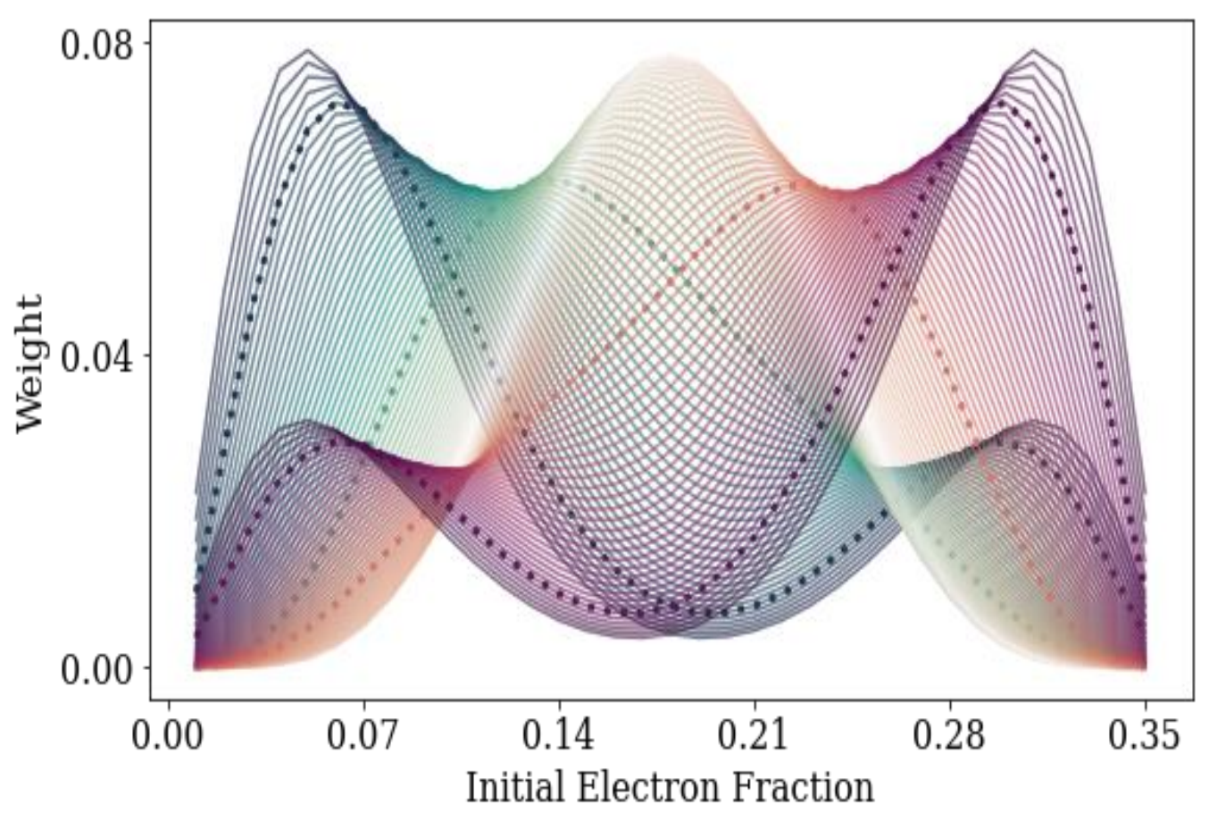
5. Initial Y_e

The success of the r-process is highly sensitive to the initial neutron richness, given by Y_e :

$$Y_e = \frac{n_p}{n_p + n_n}$$

- More neutron-rich (low Y_e) material → more r-process
- Fission cycling can happen at low enough Y_e

COM ejecta is likely to be made up of both low- and high-Y_e material. We construct linear combinations of abundances obtained from individual Y_e trajectories ranging from 0.01 to 0.35 in increments of 0.01 (figure).



6. r-ii Stars

We use measurements of the following r-ii stars, further classified by their actinide abundances:

Actinide Boost	Actinide Normal	Actinide Deficient
$(\log_{\varepsilon}(\text{Th/Dy}) > -0.9)$	$(-0.9 \geq \log_{\varepsilon}(\text{Th/Dy}) \geq -1.2)$	$(\log_{\varepsilon}(\text{Th/Dy}) < -1.2)$
J0954+5246 [6]	CS31082-001 [7,8]	HE1523-0901 [11]
	J2038-0023 [9]	CS22892-052 [12]
	CS29497-004 [10]	

7. Lanthanide-Actinide Tension

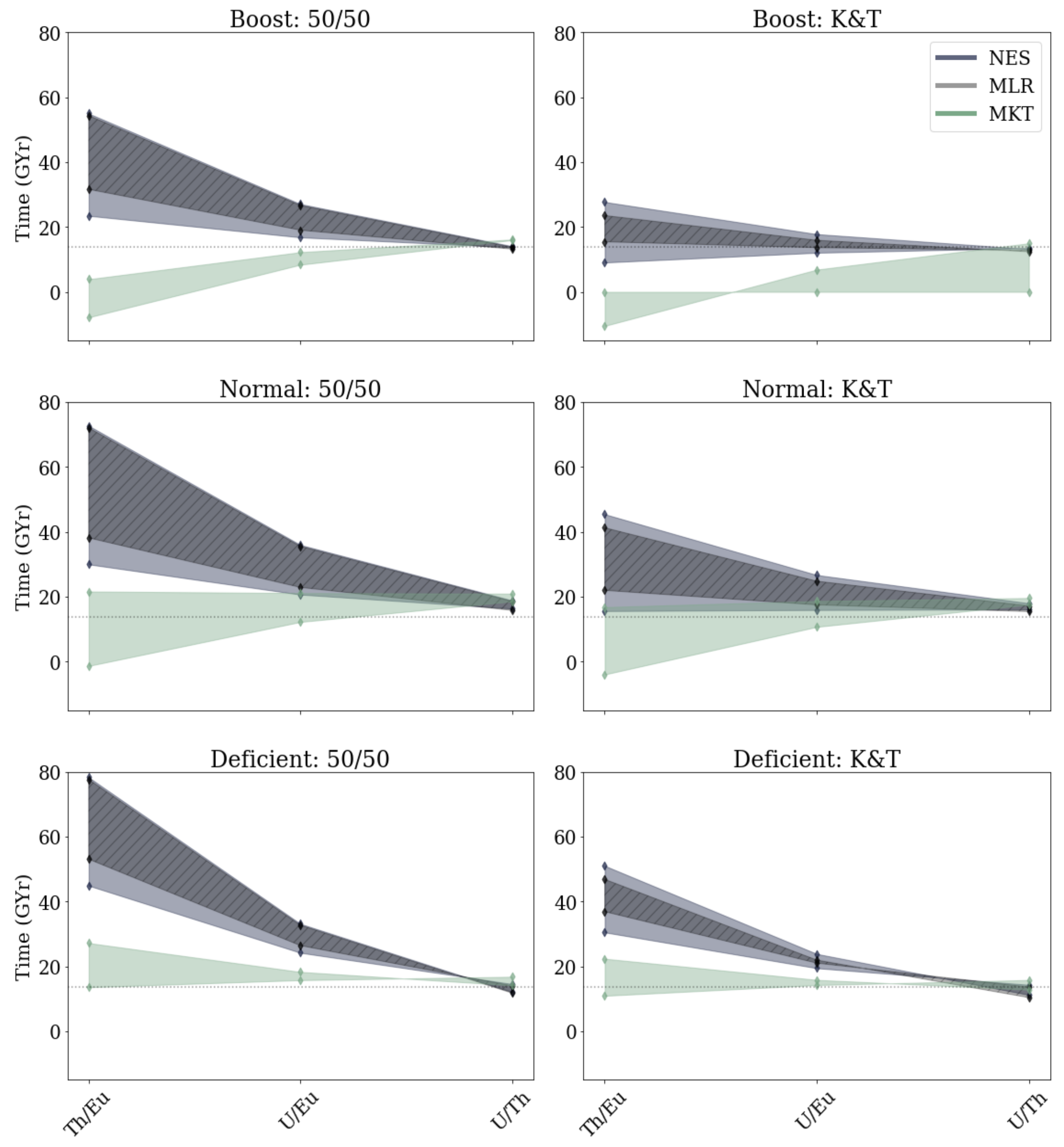
Comparing the actinide (Th and U) abundances to the lanthanide (Eu) abundances yields a wide range of possible values, depending on the beta decay rates used as well as the fission yield. The width of a band in the following figure comes from the comparison of the linear combinations of single-Ye trajectories.

NES and MLR simulations

- Similar actinide abundances, independent of fission yields.
  - Significant overlap in the predicted time elapsed given by U/Th.
- Abundance of Eu produced is sensitive to the fission yield
  - Larger variation in the Th/Eu and U/Eu chronometer ratios.

MKT simulations

- Generally opposite results.
- Actinide production is more sensitive to the fission yield.
- Lanthanide production only slightly sensitive to fission yield.
- Overall, all show smaller actinide abundances (vs. lanthanides)
- Some negative age predictions.



*Horizontal dashed line at 13.7 Gyr indicates age of the universe from Planck

8. Results: Nuclear Agreement

Nuclear decay equations make only one assumption: the r-process material comes from a single COM event.

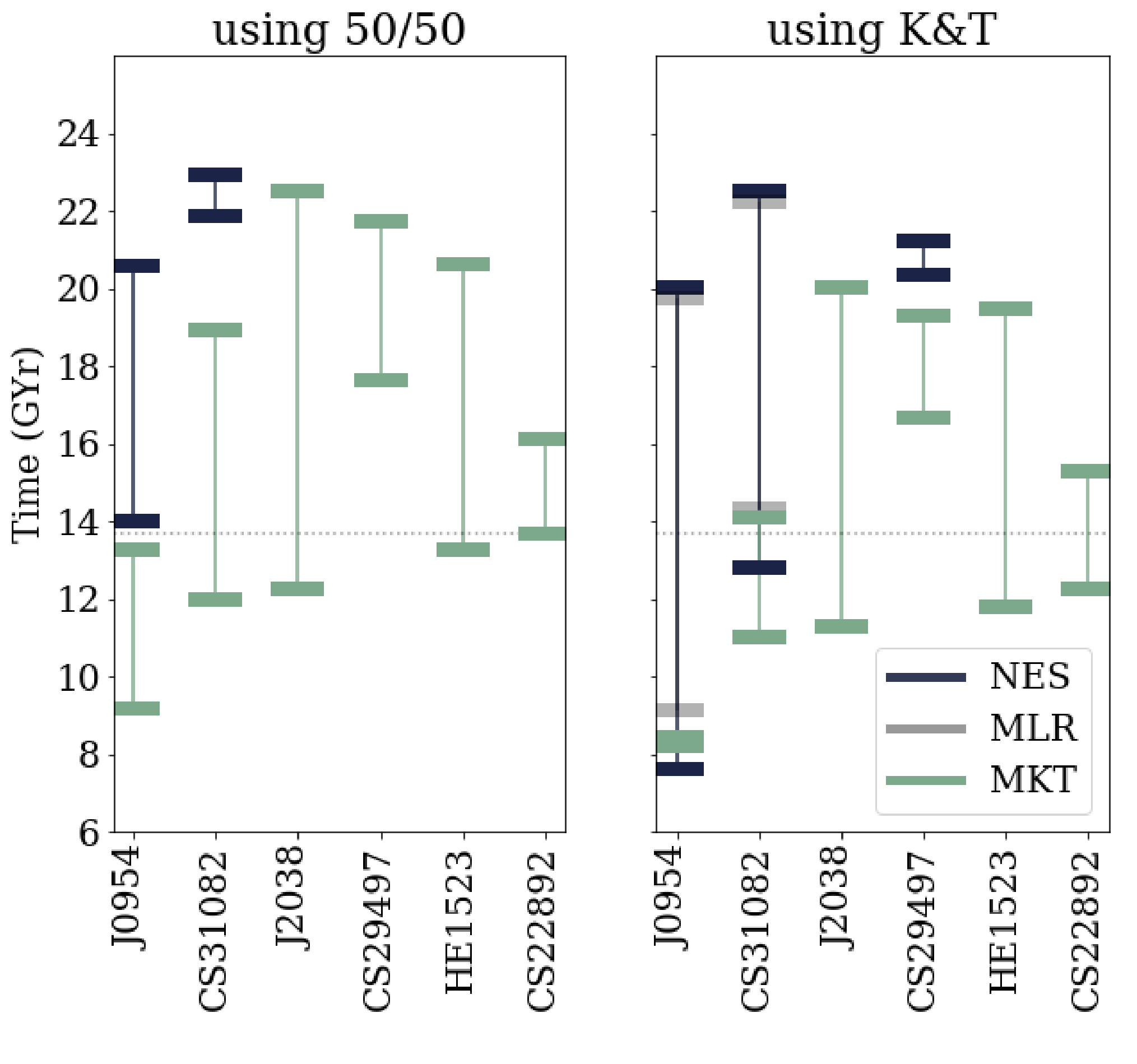
- The times calculated using the three different chronometer relations should all be equal.

Solution:

- Observed abundance ratios can have any value within observational error bars
- Initial (theory) abundance ratios can have any value allowed by nuclear uncertainty.
- Require all three chronometer relations to yield same time value (figure).

Result:

- Most agreement between NES and MLR
- MKT yields results for all stars; NES and MLR yield results for stars with normal or boosted actinide abundances.
- NES and MLR simulations using K&T show significant overlap.



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9. Outlook

We were able to obtain consistent predictions (among all three chronometer ratios) for the time elapsed since a single r-process enrichment event for all the stars in our sample.

Nuclear cosmochronometry offers a unique approach to the question of the age of the some of the oldest stars in the universe, and therefore a lower limit to the age of the universe itself. However, it depends on quantities that are necessarily obtained through simulation. We show that these quantities, the final abundances obtained in COM simulations, require more refined knowledge of unknown nuclear quantities involved in the r-process, including beta decay rates and fission yields.

The modeling of astrophysical r-process is currently the subject of a large research endeavor involving both theoretical and experimental efforts.

10. References

[1] Möller, P., Pfeiffer, B., & Kratz, K.-L. 2003, Phys. Rev. C, 67, 055802
[2] Ney, E.M., Engel, J., Li, T., & Schunck, N. 2020, Phys. Rev. C, 102, 1
[3] Möller, P., Mumpower, M.R., Kawano, T., & Myer W.D. 2019, ADNDT, 125,1
[4] Marketin, T., Huther, L. & Martínez-Pinedo, G. 2016, Phys. Rev. C, 93, 1
[5] Kodama, T., & Takahashi, K. 1975 Nuclear Physics A, 239, 489

[6] Holmbeck, E.M., Beers, T.C., Roederer, I.U., et al. 2018, ApJ, 859, L24
[7] Siquiera mello, C., Spite, M., Barbuy, B., et al. 2013, A&A, 550, A122
[8] Hill, V., Plez, B., Cayrel, R. Et al. 2002, A&A, 387, 560
[9] Placco, V.M., Holmbeck, E.M., Frebel, A., et al. 2017, ApJ, 844, 18
[10] Hill, V., Christlieb, N., Beers, T.C., et al. 2017, A&A, 607, A91
[11] Frebel, A., Christlieb, N., Norris, J.E., et al. 2007, ApJ, 660, L117
[12] Sneden, C., Cowan, J.J., Lawler, J.E., et al. 2003, ApJ, 591, 936

11. Acknowledgements

This work was partially supported by the Fission in r-Process Elements (FIRE) topical collaboration in nuclear theory, funded by the U.S. DOE, contract No. DE-AC5207NA27344. This work was also possible due to support by the U.S. DOE through Los Alamos National Laboratory, operated by Triad National Security, LLC, for the National Nuclear Security Administration of the U.S. DOE. We acknowledge support from the NSF (N3AS PFC) grant No. PHY-2020275, as well as from U.S. DOE contract No. DE-FG0202ER41216.