Actinide-Dating Stars: Nuclear Uncertainties in Cosmic Age

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Context

- Nuclear cosmochronometry: using known half lives of radioactive isotopes to extract ages from stellar spectra.
- r-ii stars are metal-poor ([Fe/H] ≤-2)* but show an abnormally large abundance of r-process material ([Eu/Fe] >+1)**.
- 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

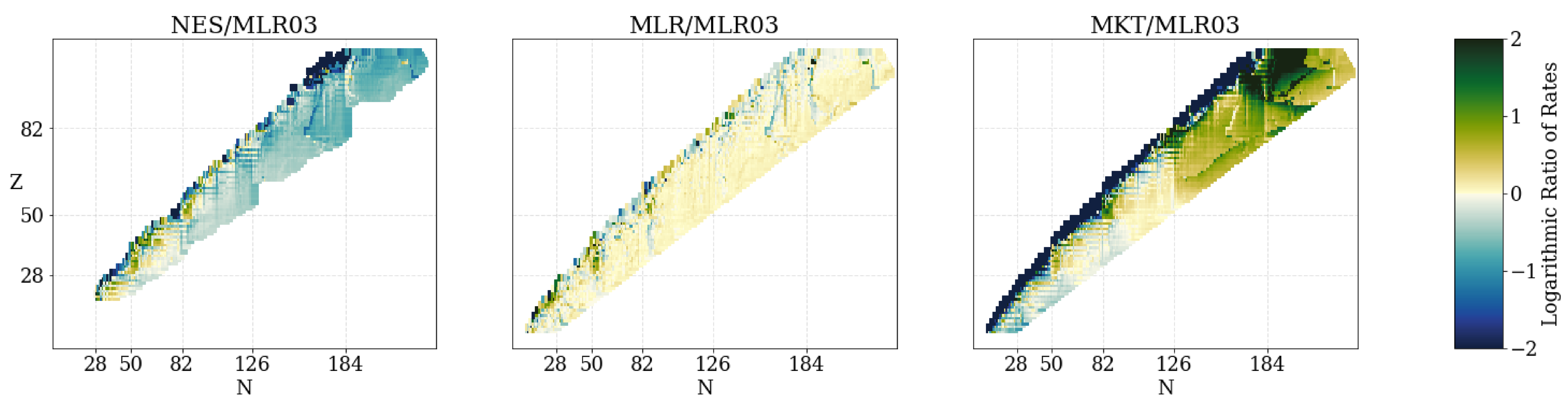
Beta Decay Rates

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 decays
- High-Z and actinide population produced
- Dominant decay channel of potentially fissioning nuclei
- Rare earth abundances

Three sets of rates: 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] (fig)



Method

Compare initial and final abundances of different isotopes with known half-lives to calculate time since "enrichment".

Chronometers: ^{232}Th, ^{238}U, two "stable" isotopes of Eu (Z=63) in

$$t = 46.67\text{Gyr}\left[-log_\epsilon\left(\frac{\text{Th}}{\text{Eu}}\right)_{\text{obs}} + log_\epsilon\left(\frac{\text{Th}}{\text{Eu}}\right)_0\right]$$

$$t = 14.84\text{ Gyr}\left[-log_\epsilon\left(\frac{\text{U}}{\text{Eu}}\right)_{\text{obs}} + log_\epsilon\left(\frac{\text{U}}{\text{Eu}}\right)_0\right]$$

$$t = 21.80\text{ Gyr}\left[-log_\epsilon\left(\frac{\text{U}}{\text{Th}}\right)_{\text{obs}} + log_\epsilon\left(\frac{\text{U}}{\text{Th}}\right)_0\right]$$

We perform nucleosynthesis calculations using a variety of nuclear datasets to obtain $\left(\frac{X}{Y}\right)_0$.

Fission Yields

We consider two possible fission outcomes:

- 50/50: Two equal daughter products
- K&T: Double Gaussian described by [5]

r-ii Stars

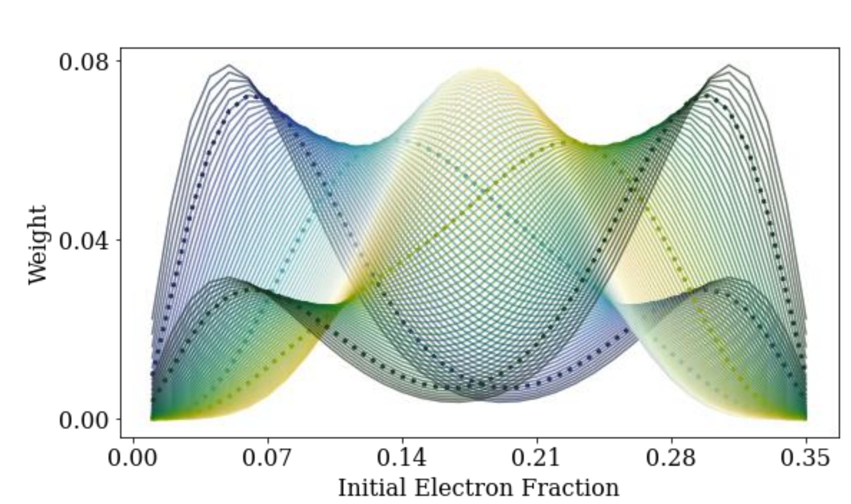
Measurements from r-ii stars, further classified by their actinide abundances:

Boost	Normal	Deficient
J0954+5246	CS31082-001	HE1523-0901
	J2038-0023	CS22892-052
	CS29497-004	

Initial Y_e

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

COM ejecta is likely to be made up of both low- and high-Y_e material. We construct linear combinations of abundances (fig)



Lanthanide-Actinide Tension

The width of a band in the following figure comes from the variety of results using the linear combinations of single-Y_e trajectories.

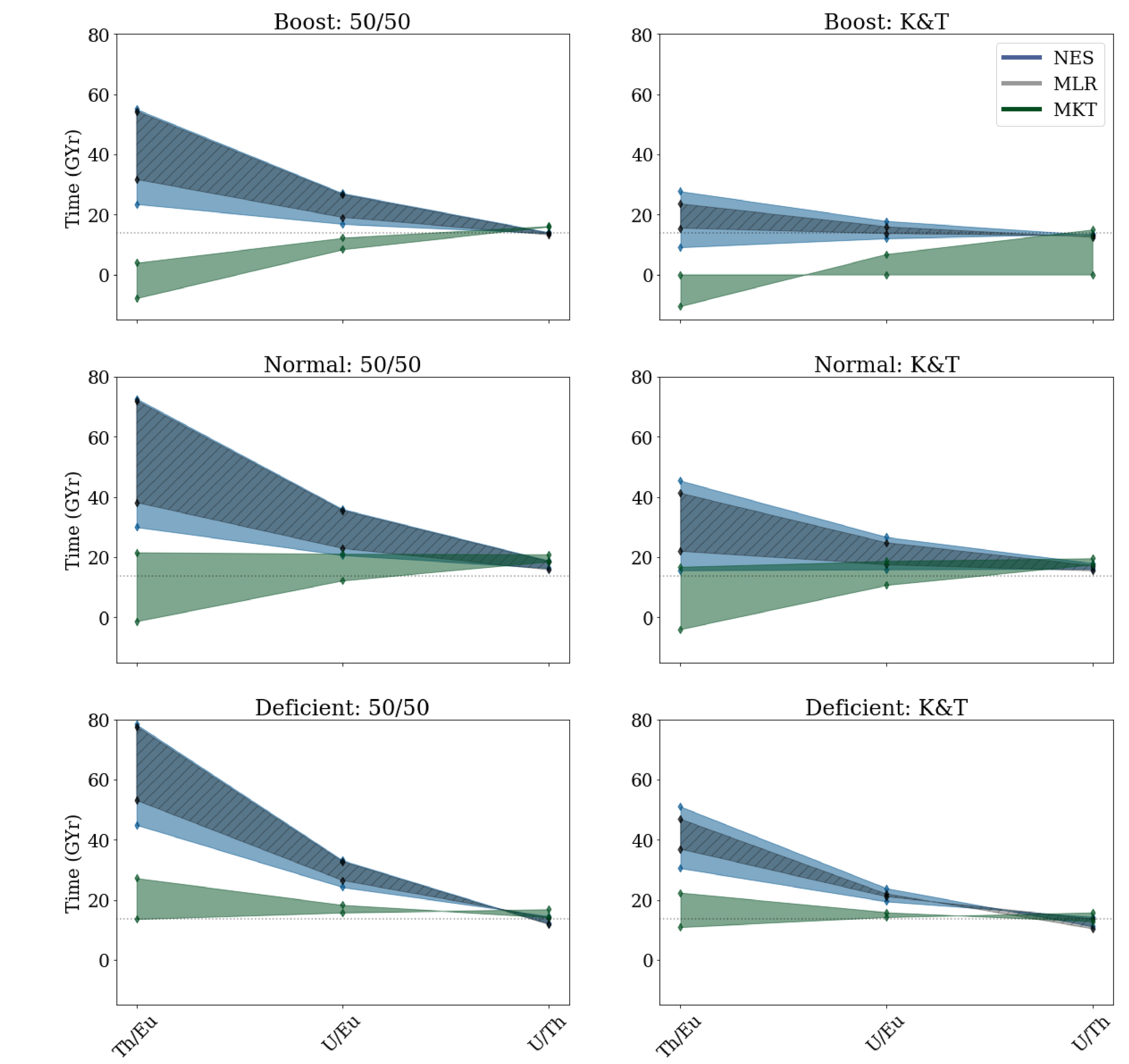
NES and MLR simulations

- 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 fission yield
  - Larger variation in 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



Results: Chronometer Agreement

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

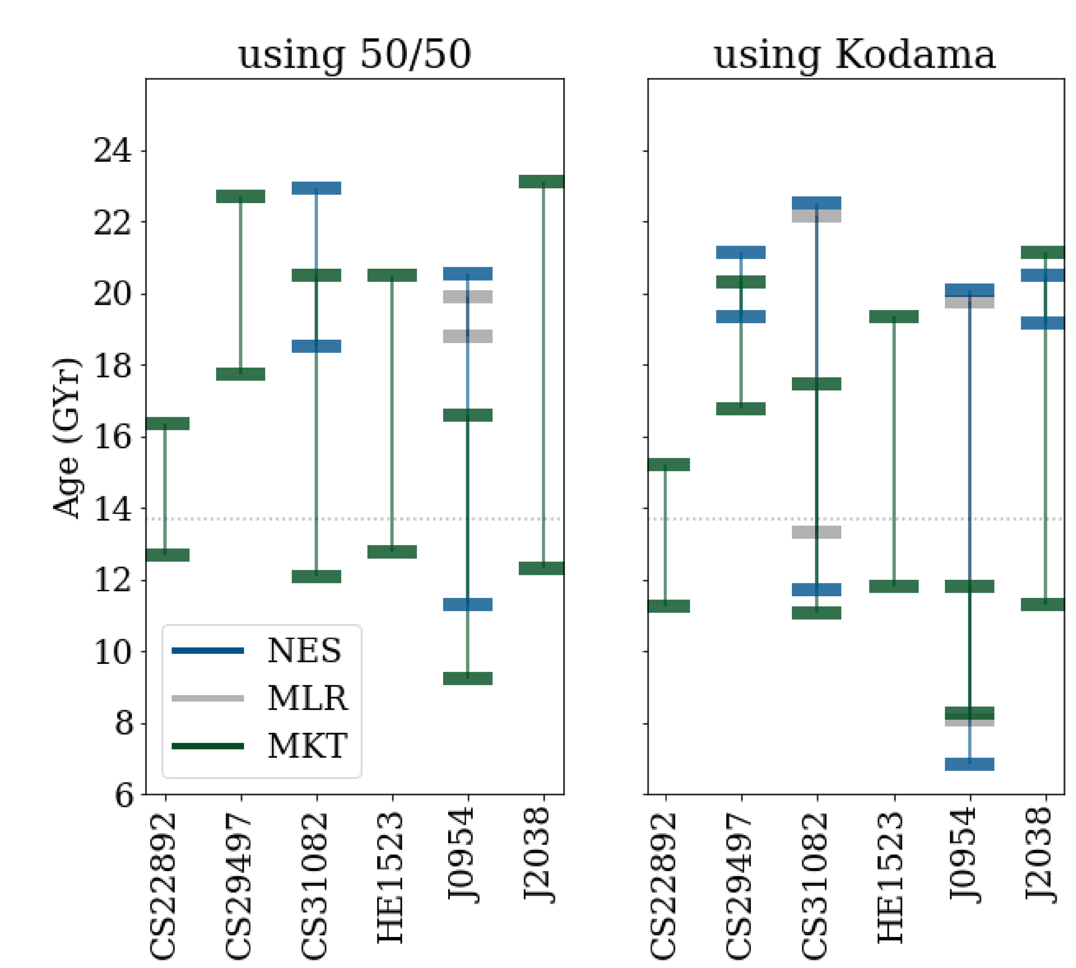
- The times calculated using the three different chronometer relations should all be equal. We apply this constraint (fig).

Approach:

- Require observed abundance ratios to stay within observational error bars
- Require initial (theory) abundance ratios to stay within our predicted nuclear uncertainty range.

Result:

- MKT yields age results for all stars; NES and MLR yield results for stars with normal or boosted actinide abundances.
- Most overlap in predicted ages between NES and MLR



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 initial abundances that are necessarily obtained through simulation. We show that these quantities require more refined knowledge of unknown nuclear quantities involved in the r-process, including beta decay rates and fission yields.

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

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