N3AS Seminar

Effects of Nuclear Uncertainties on r-Process Observables

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16 August 2022

Center for Nonlinear Studies

Los Alamos NATIONAL LABORATORY

FIRE Fission In R-process Elements

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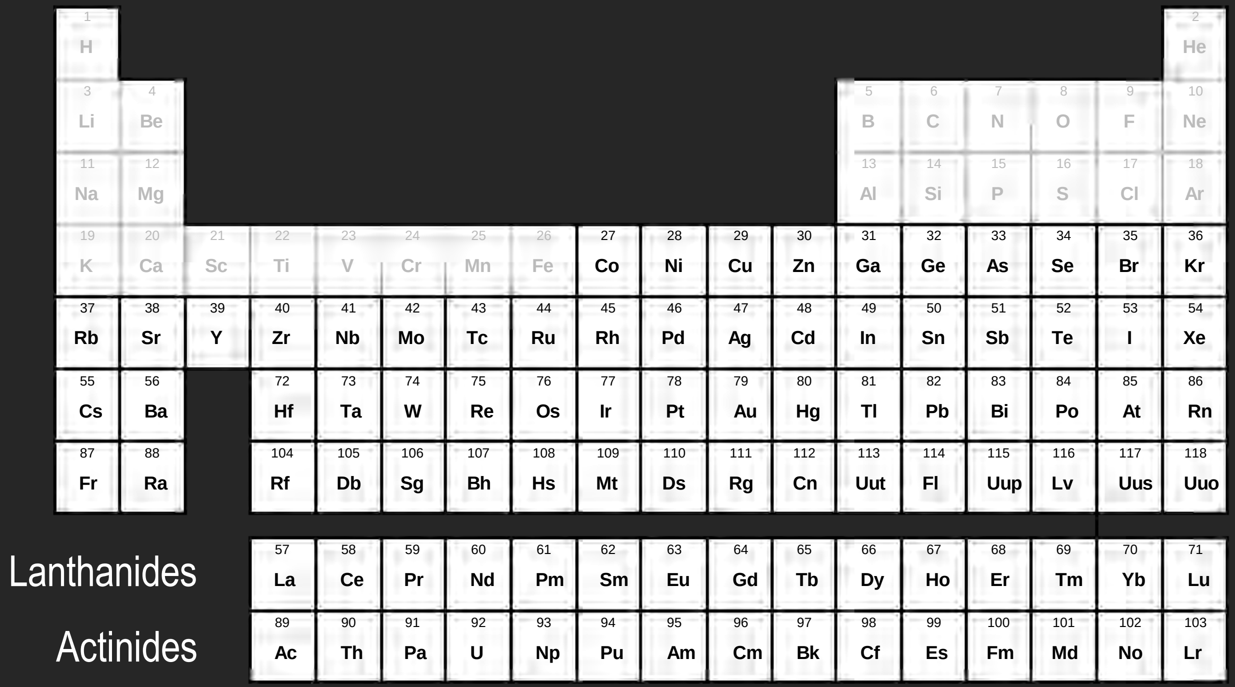
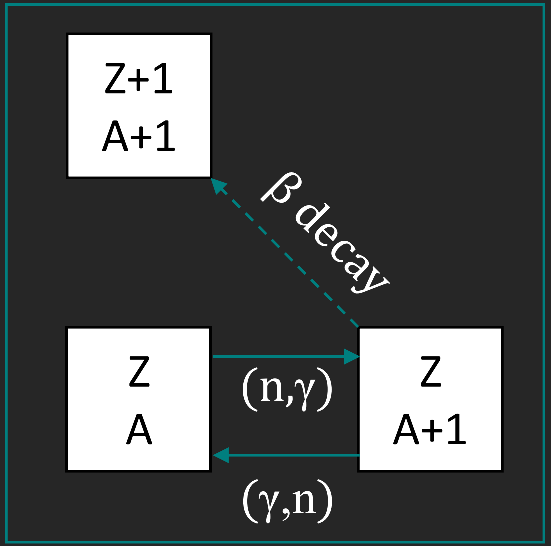
How does the universe make heavy elements?

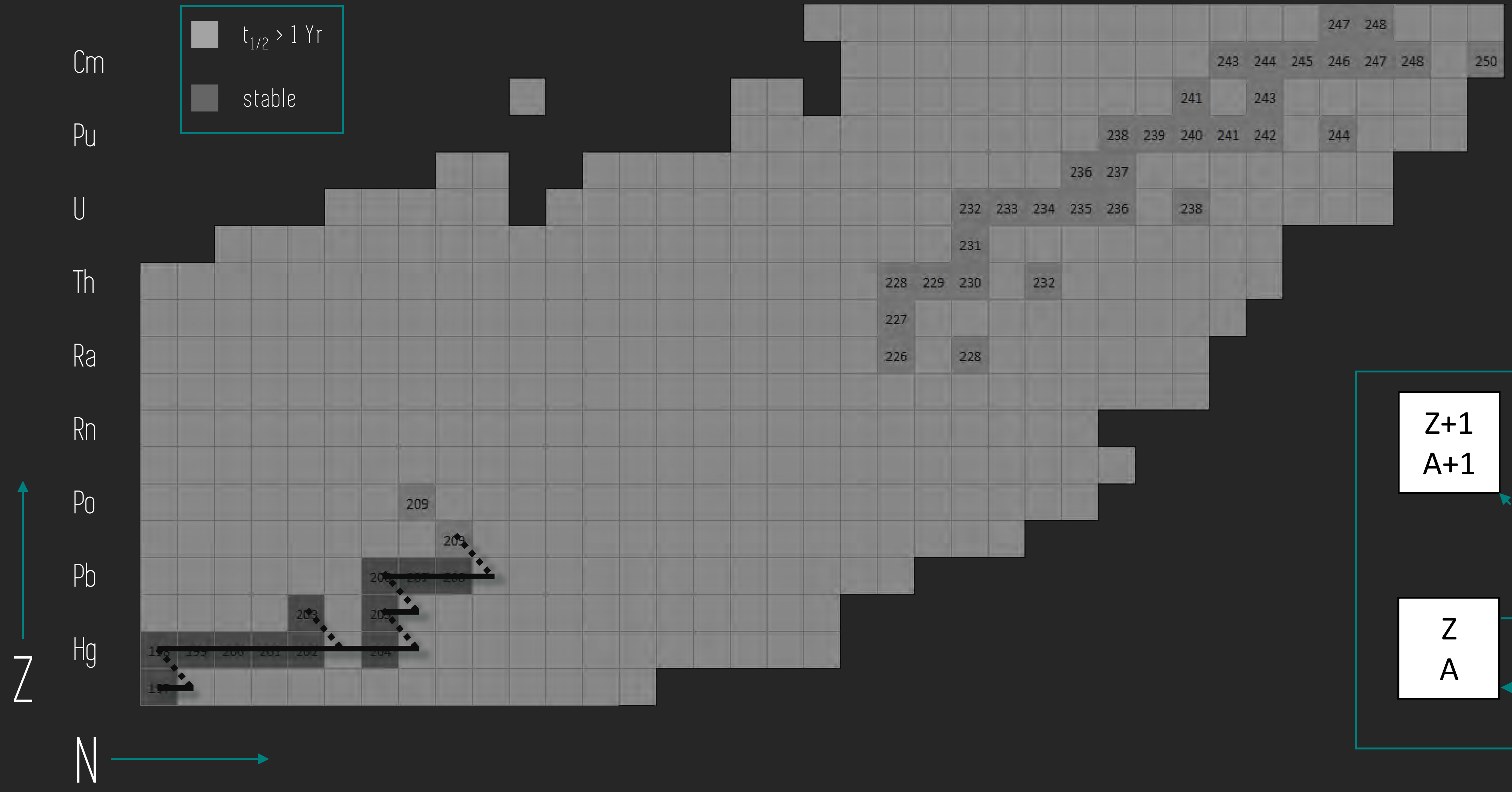


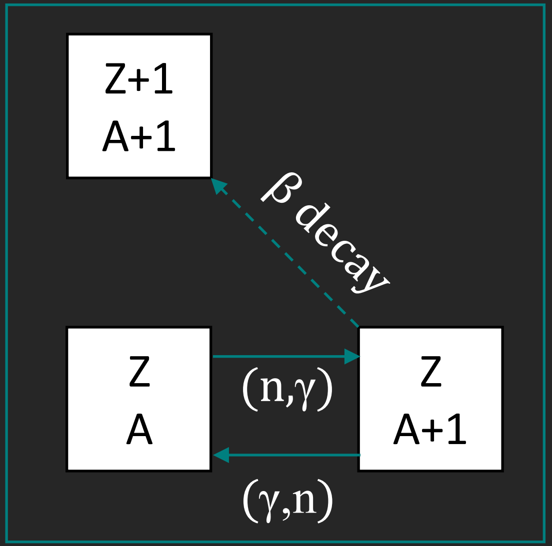
Neutron captures are necessary!

Introduction: Neutron Capture



Introduction: (slow) Neutron Capture





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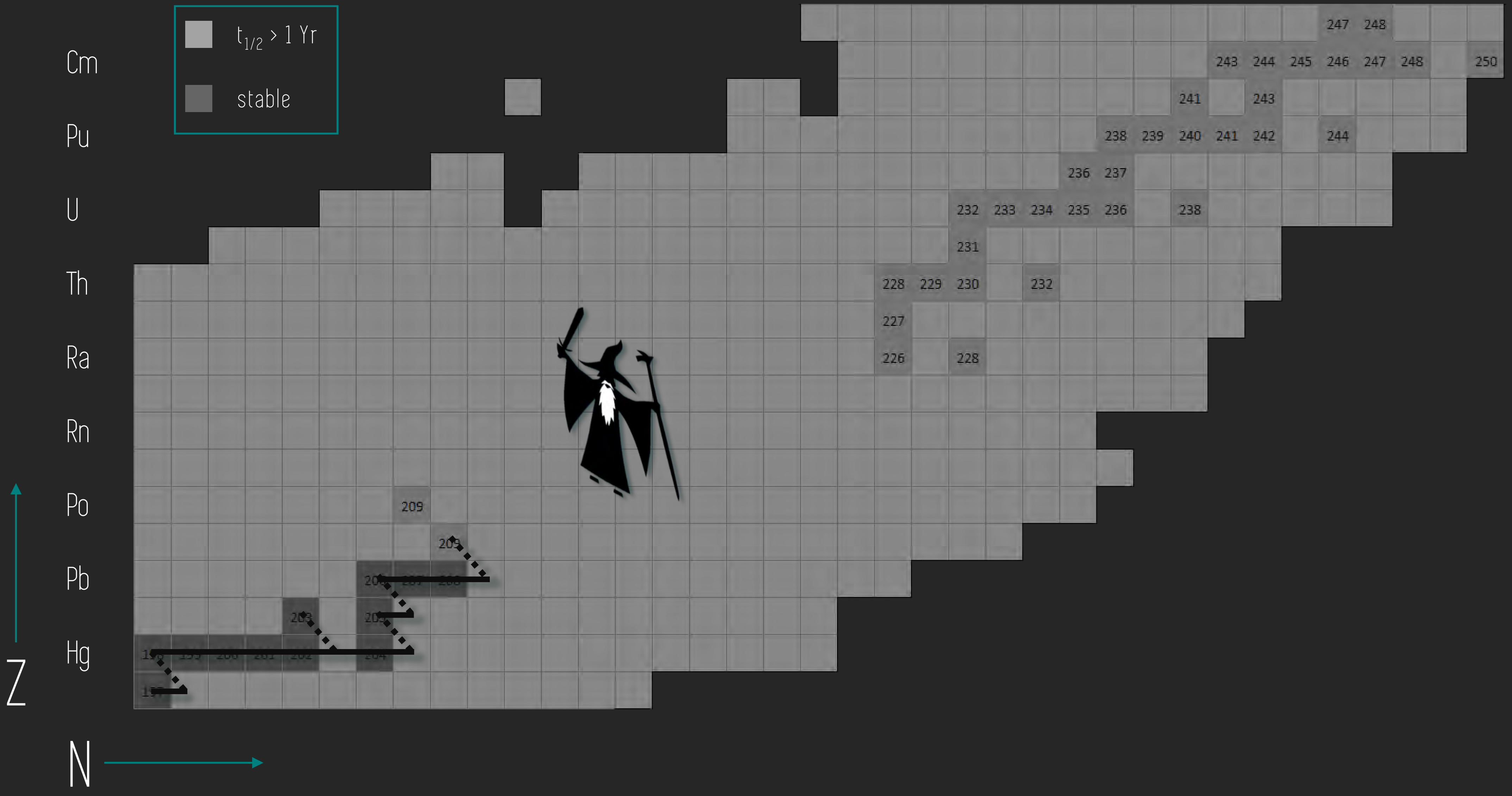
Introduction: (slow) Neutron Capture



Introduction: Rapid Neutron Capture

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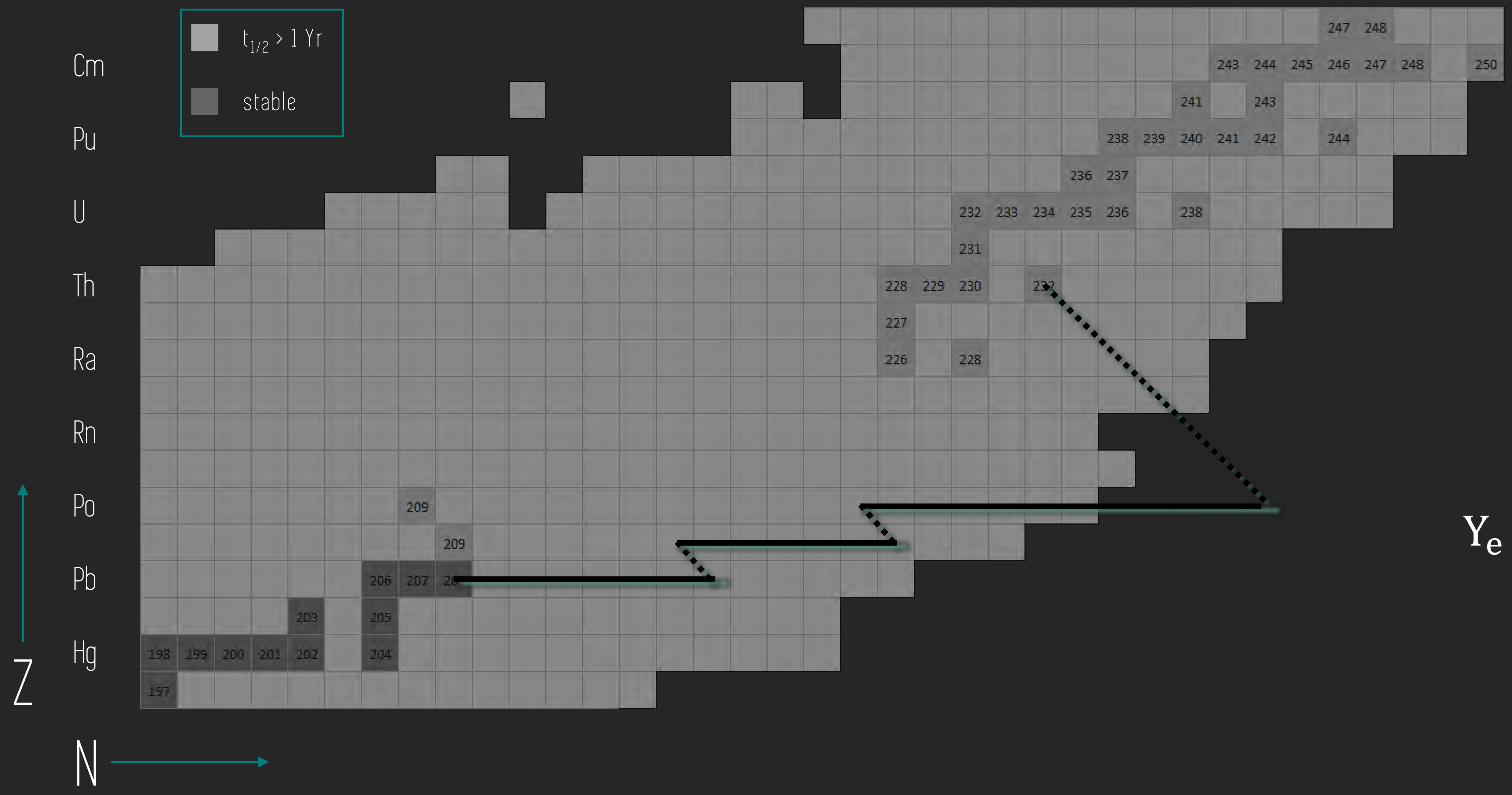
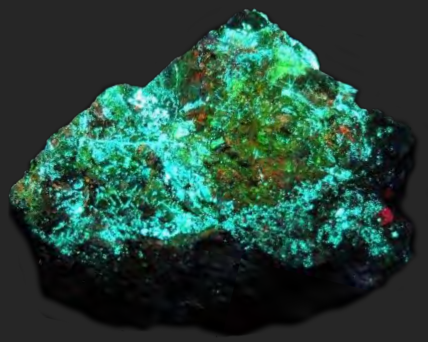


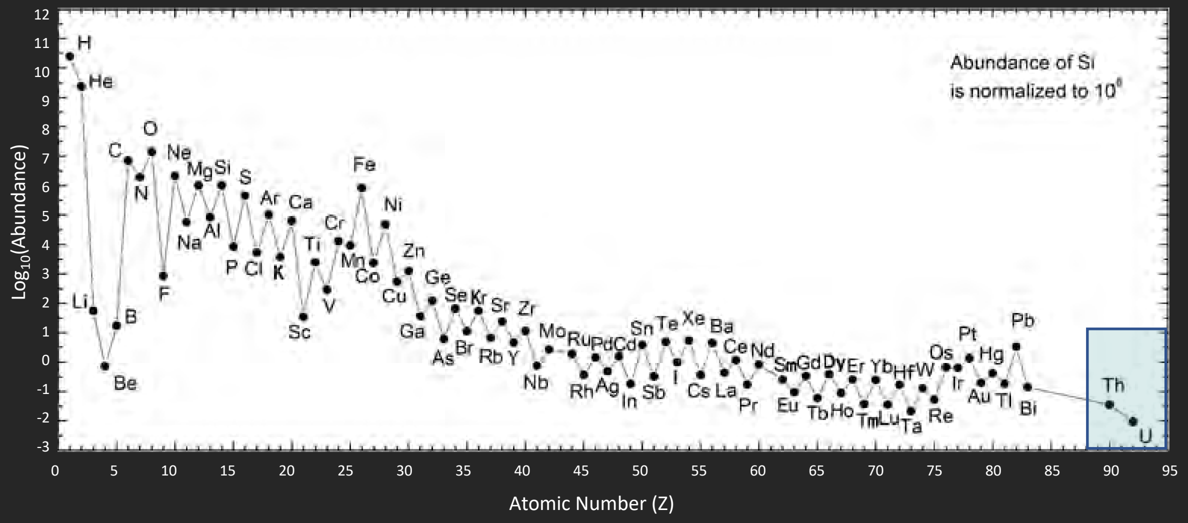
$$Y_e = \frac{n_p}{n_p + n_n}$$

$$\tau_\beta \gg \tau_n$$

Introduction: Motivation

Natural Abundances





Introduction: Motivation

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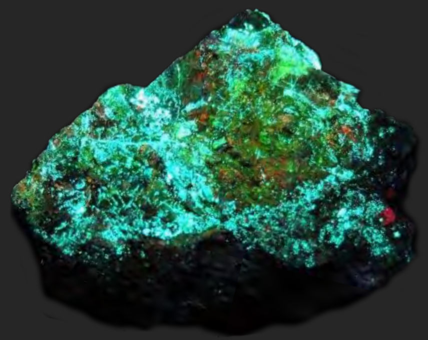
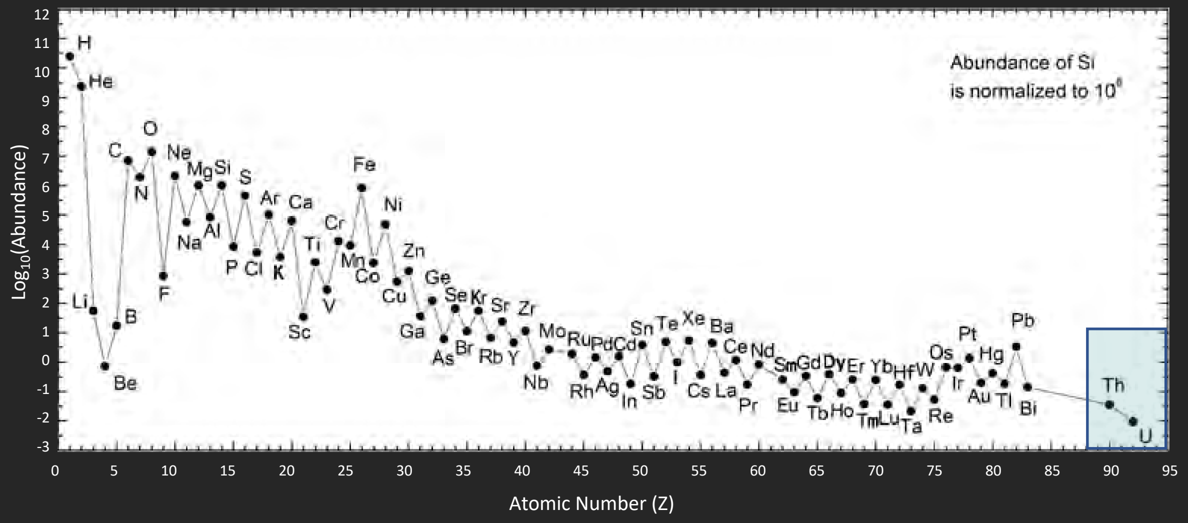
Natural Abundances





Cosmic Chronometers


ESA/Hubble & NASA

Introduction: Motivation

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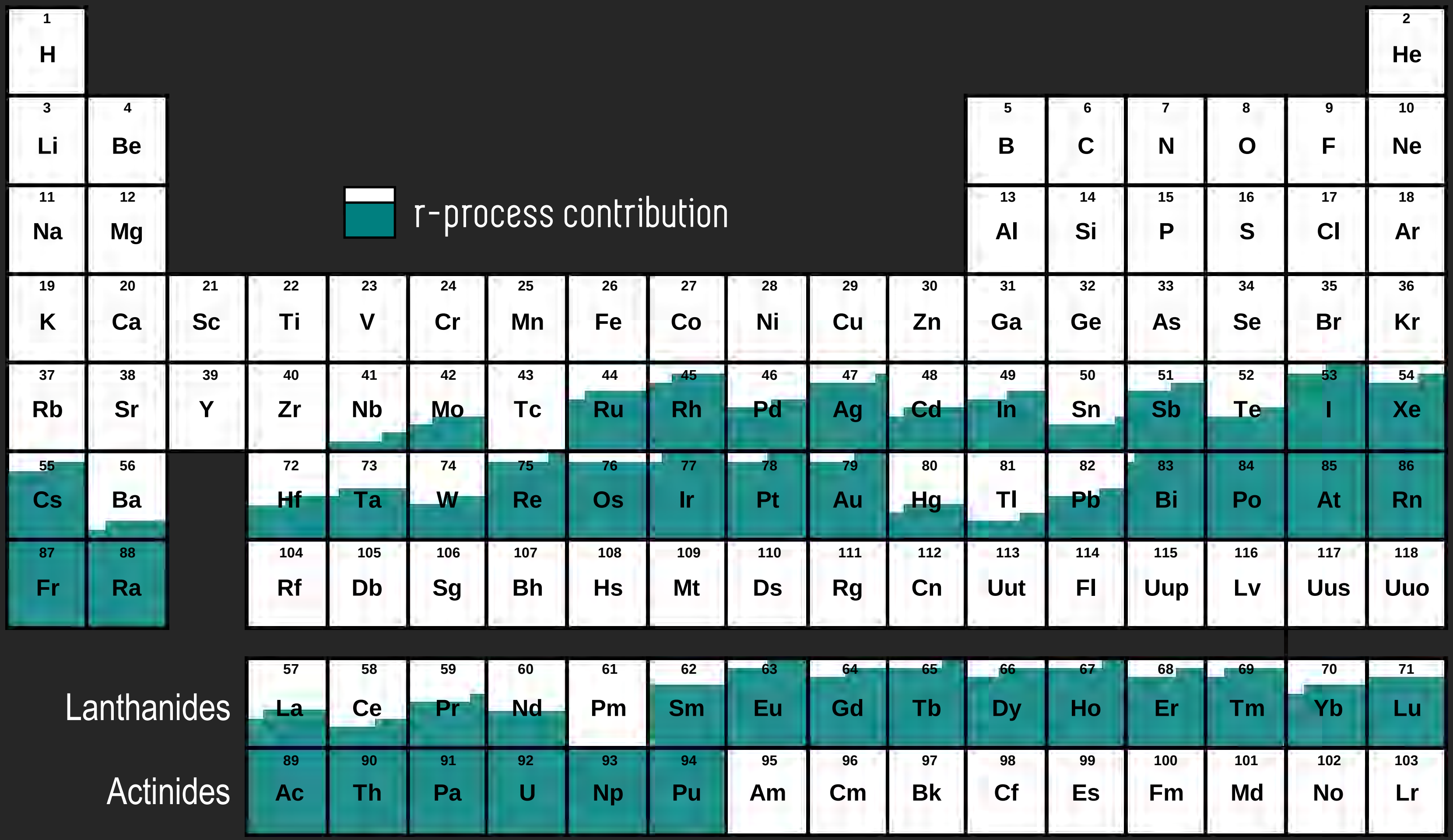
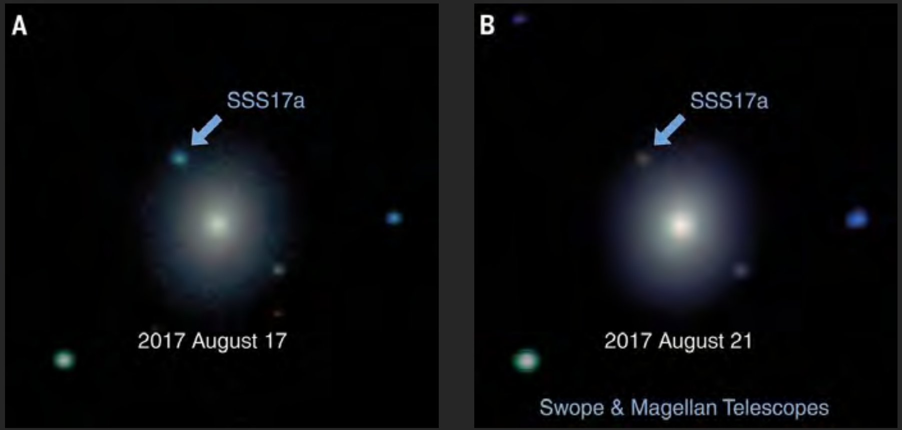
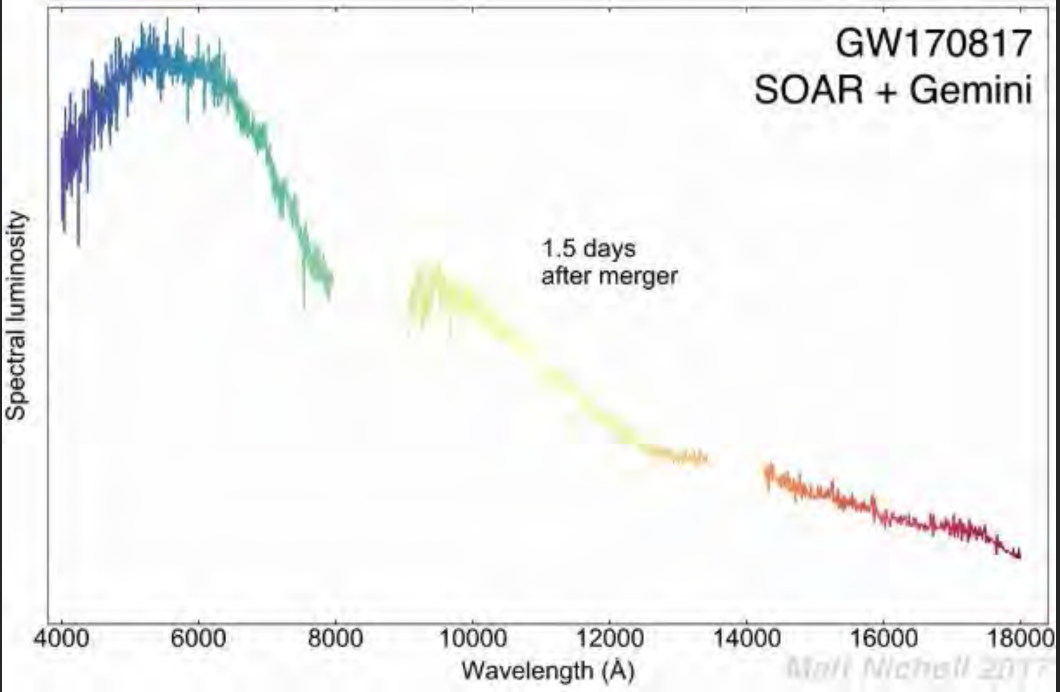


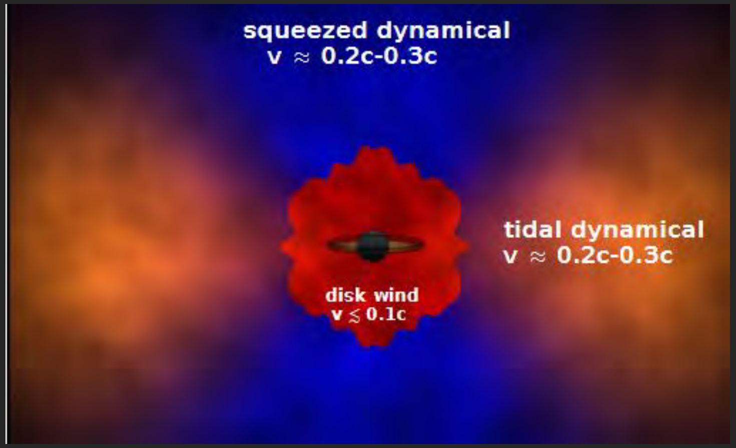
r-Process Site: GW170817

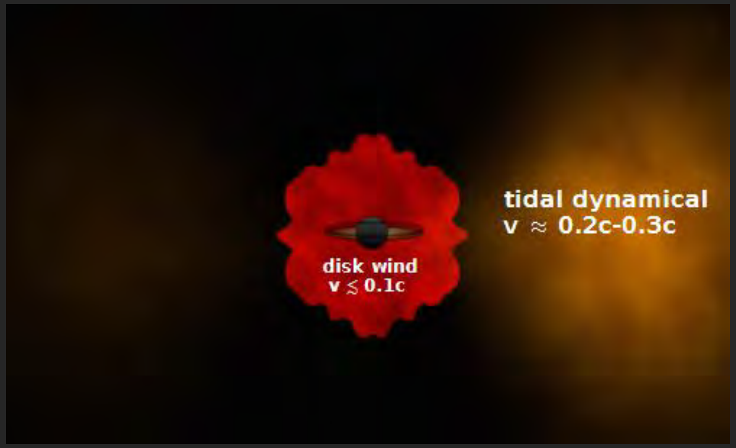




r-Process Site: Compact Object Mergers

NS+NS	NS+NS	NS+BH
↓	↓	↓
Prompt Collapse	Central Engine	Prompt Collapse
↓	↓	↓



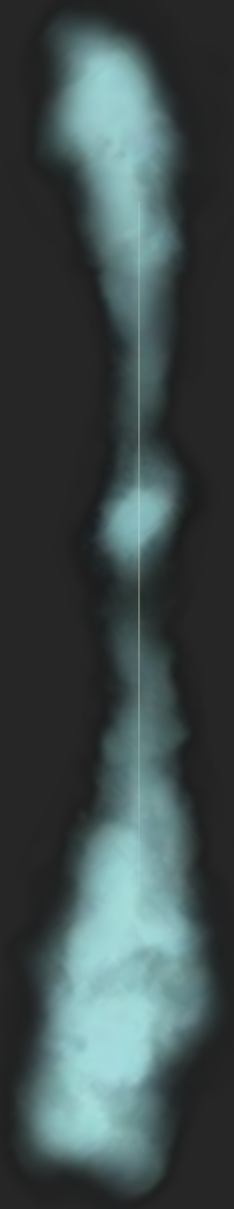


(Adapted from Kasen+ 2017)

high opacity   low opacity

Outline:

arXiv: 2208.06373



Nuclear Approach

Using nucleosynthesis calculations to probe:

- Nuclear Energy Generation
- Light Curve Evolution
- Final Abundance Patterns
- Cosmochronometry

Building a Dataset: Initial Y_e

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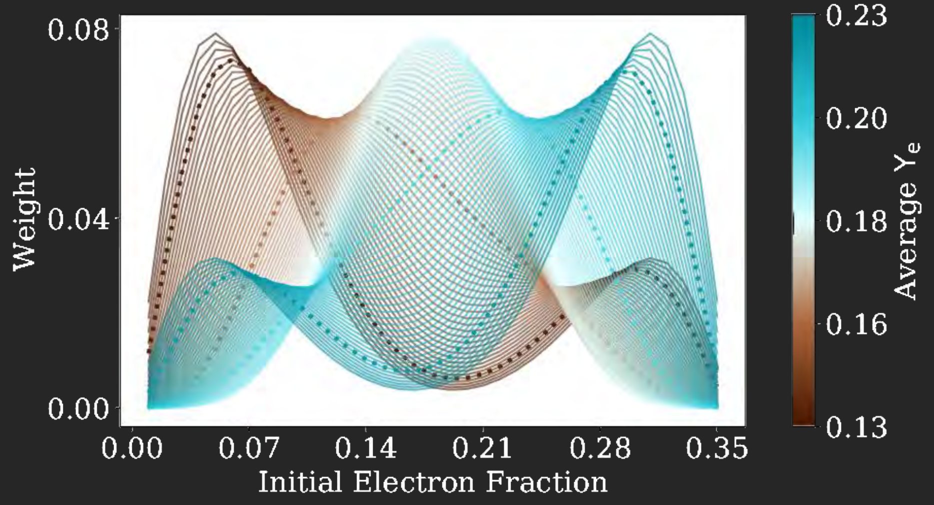
Linear Combinations:
(limited nuclear dataset)



(See for example:
Radice+ 2018
Miller+ 2019
Nedora+ 2021
Stewart+ 2022)

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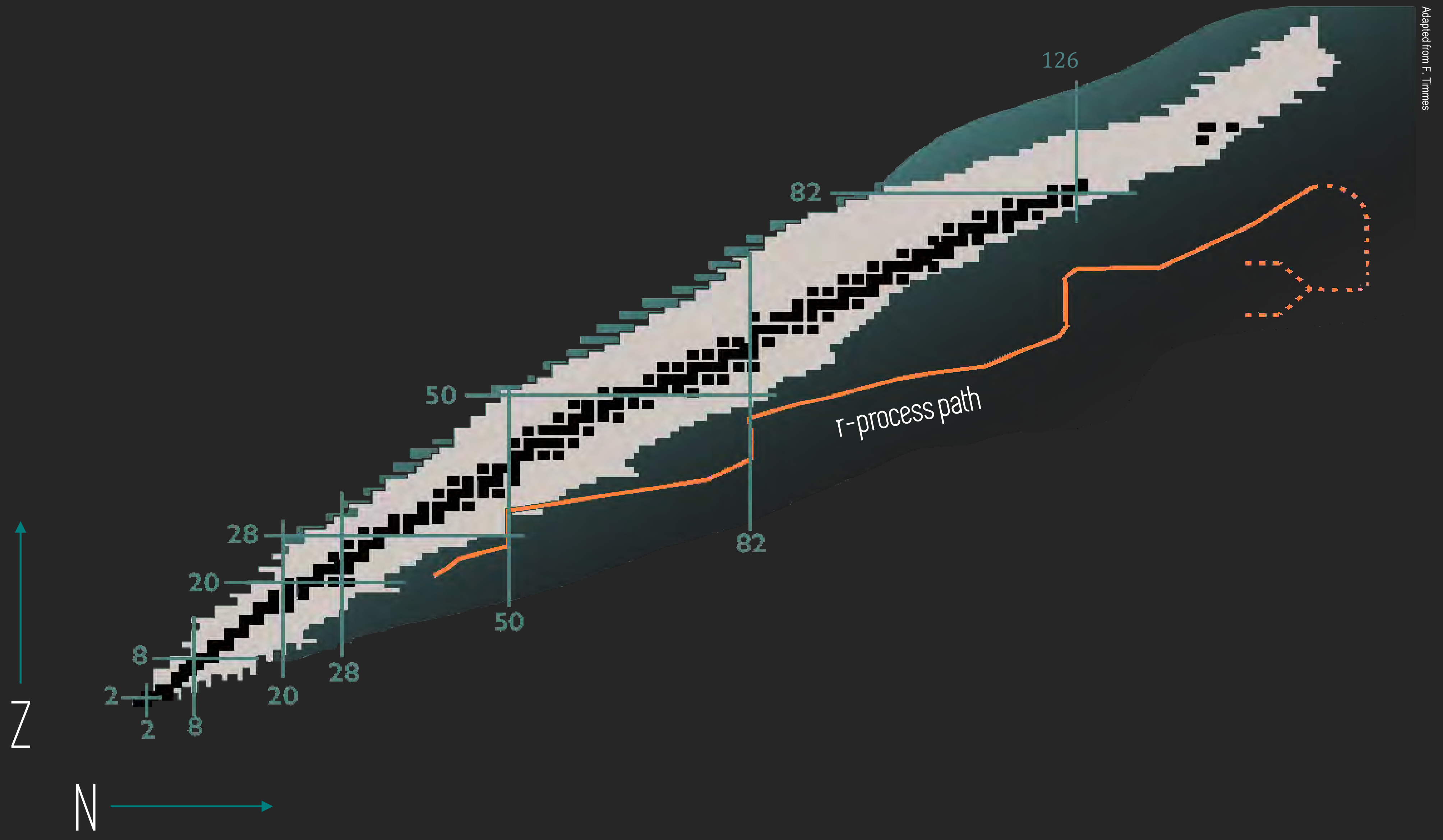
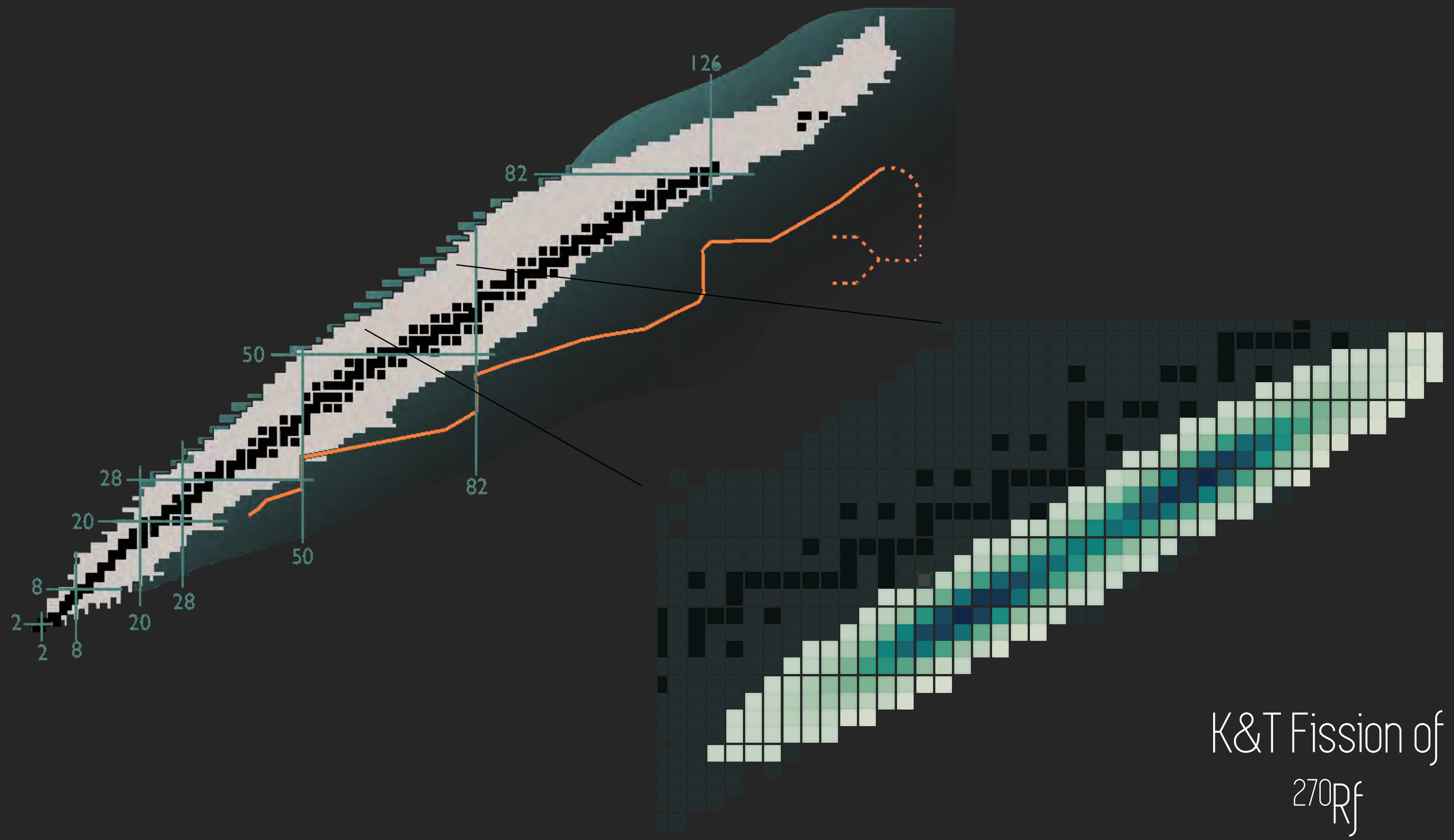
Sources of Nuclear Uncertainty



Building a Dataset: Fission

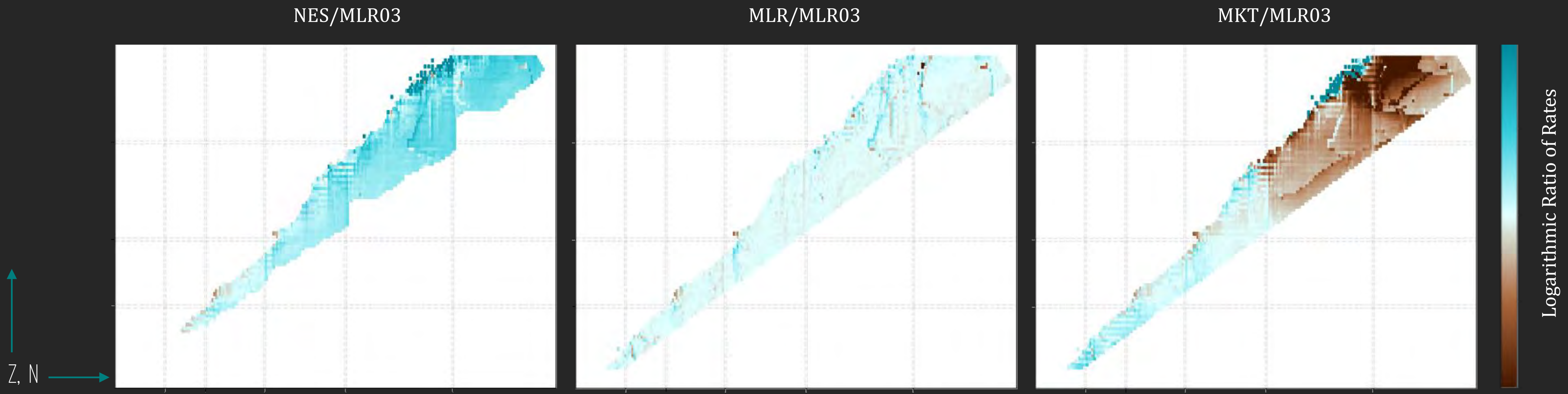


K&T Fission of ^{270}Rf

Two fission yield distributions:

- Symmetric 50/50 split
- Double-Gaussian (Kodama, Takahashi 1975)

Building a Dataset: Beta Decay Rates



Ney (**NES**)

Ney+ (2020)

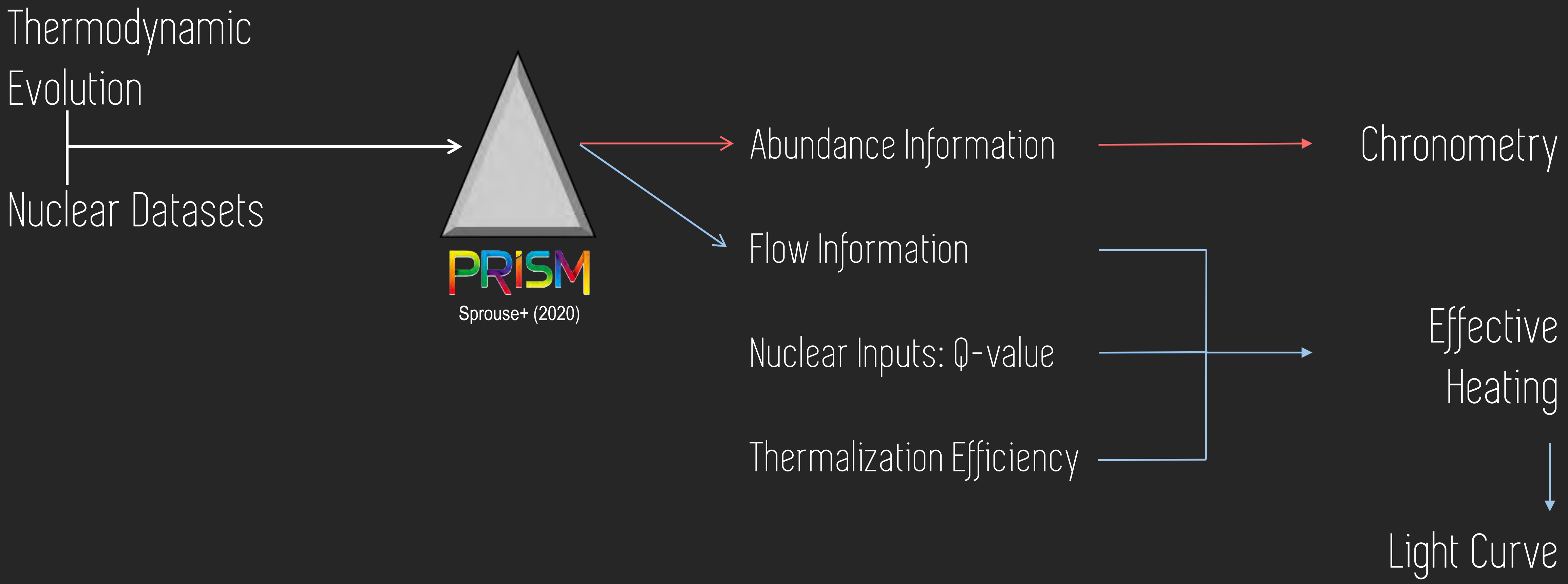
Möller (**MLR**)

Marketin (**MKT**)

Marketin+ (2016)

~ slower rate*

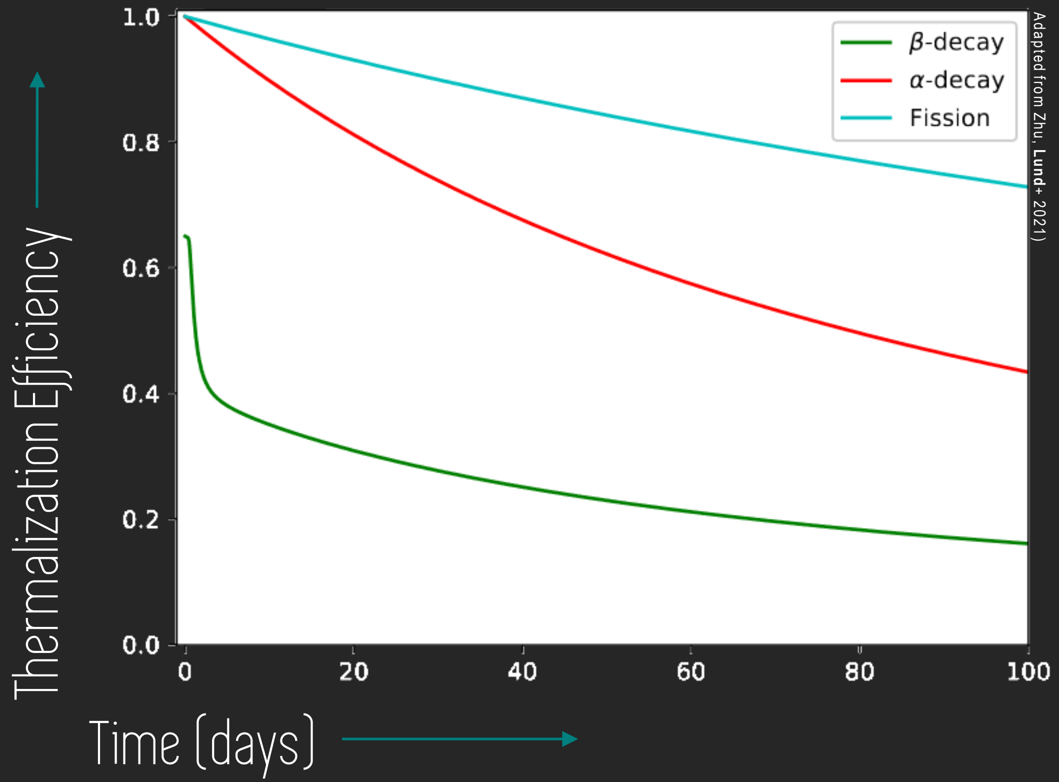
PRISM: A Sparse Matrix Solver



Nuclear Heating

Nuclear Heating Calculation

PRISM flow: specific contribution of total time-derivative of an abundance due to a single nuclear process [s^{-1}]

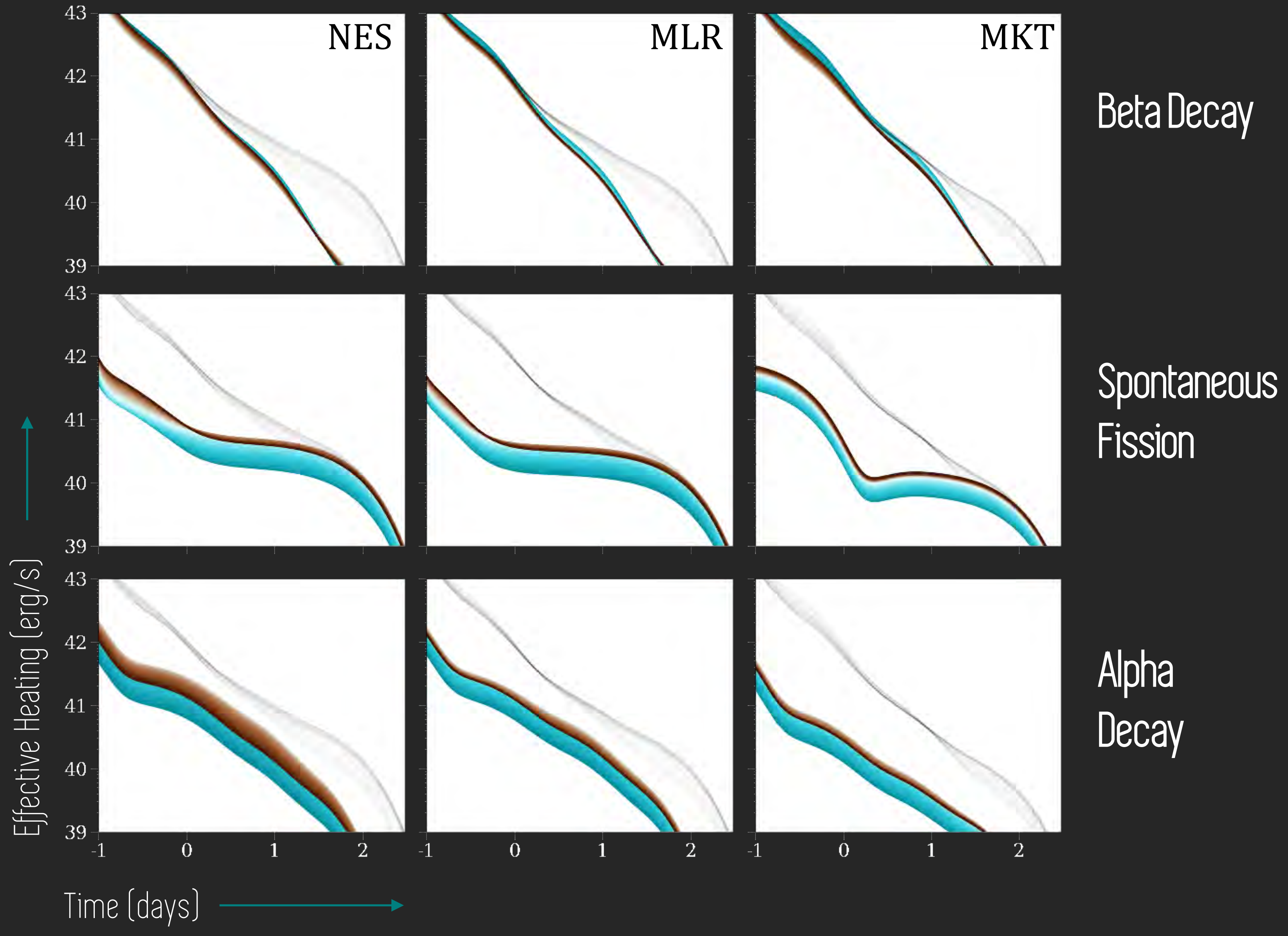


Thermalization efficiency: how effectively decay products can heat ejecta (function of time, ejecta mass, and characteristic velocity)

$$\dot{Q}(t) = \sum_i f_i(M_{ej}, v_{ej}, t)\ \dot{q}_i(t)\ M_{ej}$$

Total effective heating | Thermalization efficiency | Heating (Q-value * flow) | Ejecta mass

Nuclear Heating by Reaction Type



- Early heating dominated by beta decay
- Total heating incomplete without fission and alpha decay
- Times and magnitudes sensitive to beta decay model

Light Curve

Light Curve Shell Model

Similar procedure as effective heating calculation, but computationally more intensive (ref Metzger 2017)

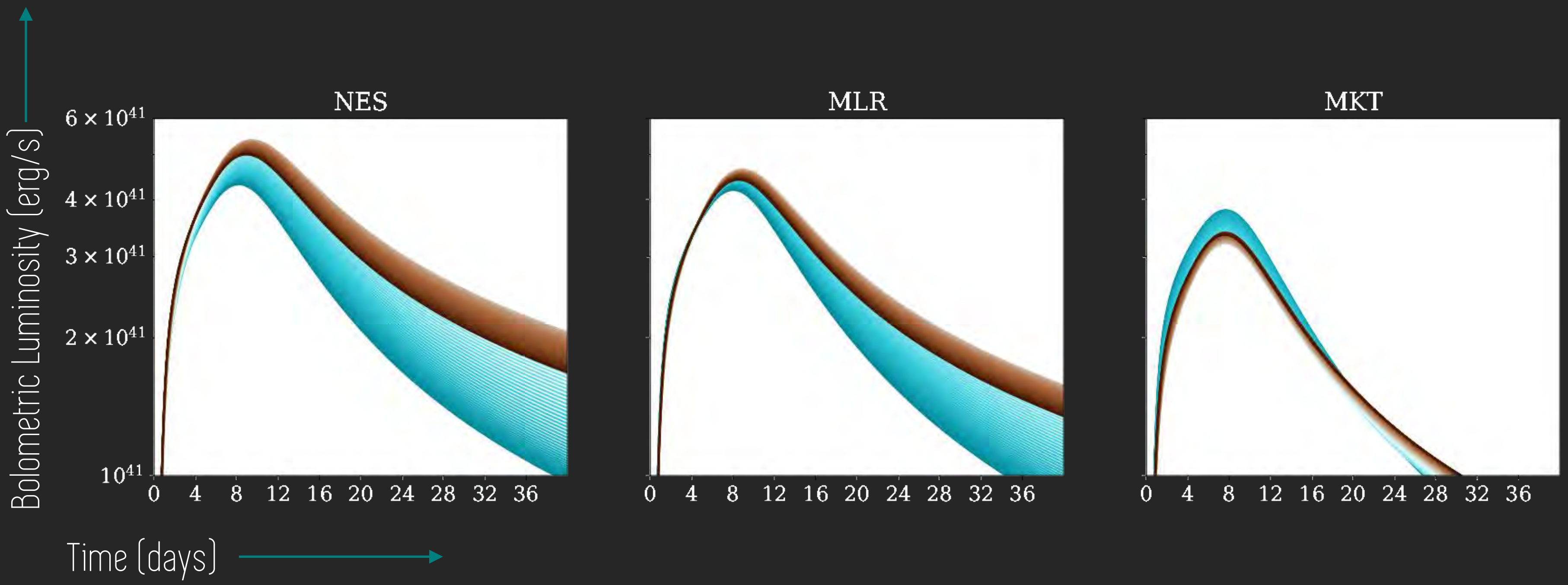
Shell model for ejecta: the mass of each shell, M_v, depends on the velocity, v, of that shell (100 shells evenly distributed between 0.1c and 0.4c)

Time evolution of the energy of a shell:

$$\frac{dE_v}{dt} = \frac{M_v}{M_{ej}}\dot{Q}(t,v) - \frac{E_v}{t} - \frac{E_v}{t_{d,v} + t_{lc,v}}$$

- $\frac{M_v}{M_{ej}}\dot{Q}(t,v)$: Effective heating
- $\frac{E_v}{t}$: Adiabatic expansion
- $\frac{E_v}{t_{d,v} + t_{lc,v}}$: Luminosity (ultimately want to plot this!)
- $t_{d,v}$: Diffusion timescale (depends on opacity)
- $t_{lc,v}$: Light-crossing timescale

Light Curves

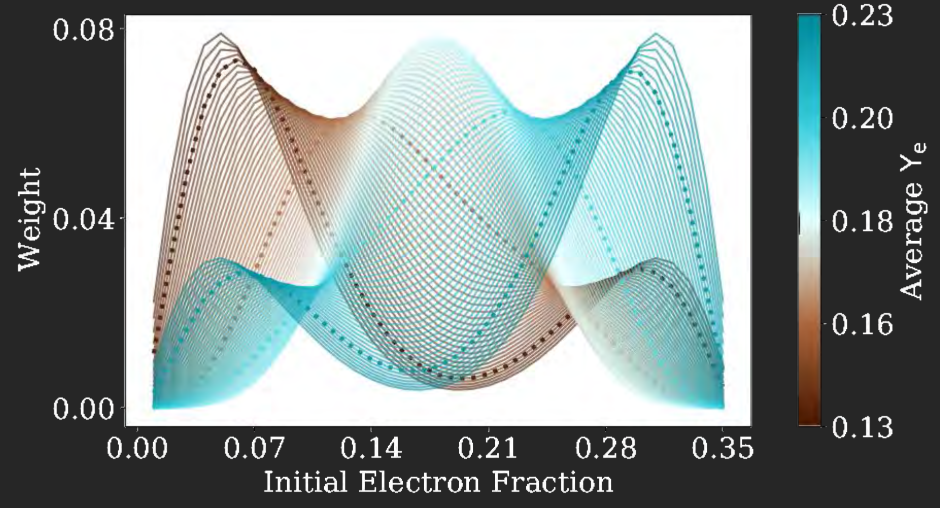


- Generally consistent light curve shapes
- Peak luminosity sensitive to Y_e and beta decay rates
- Differences in late-time behavior

Extended Dataset

Extended Dataset: Initial Y_e

Linear Combinations:
(limited nuclear dataset)



Single Trajectory:
(all nuclear datasets)

0.02 0.18 0.21

More neutron rich

Less fission

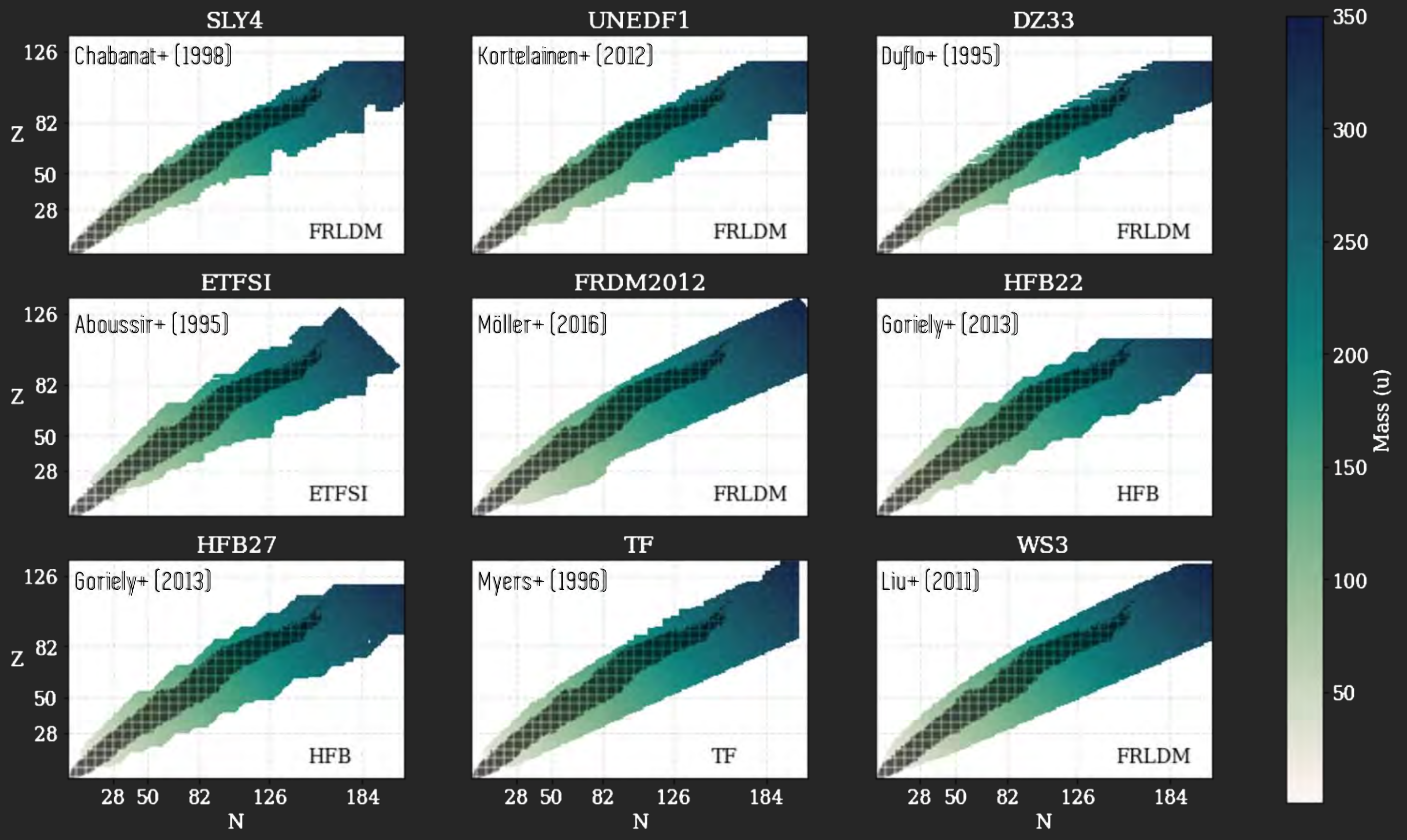
Zhu, **Lund**+(2021); Barnes, Zhu, **Lund** +(2021); **Lund**+ (2022)

Extended Dataset: Mass Model

Most basic nuclear property: mass

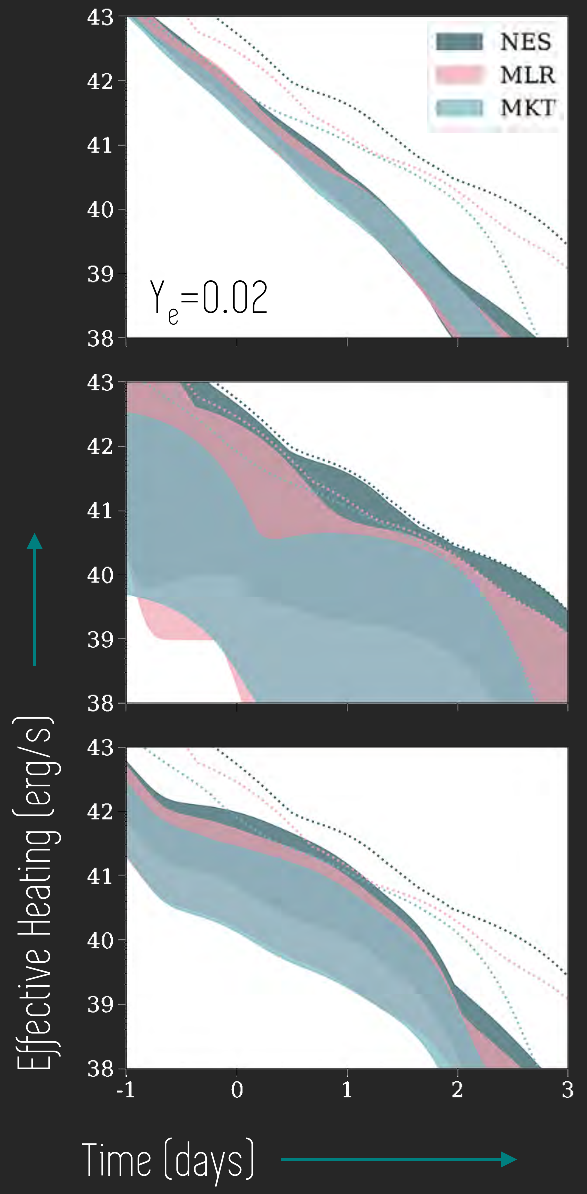
Common approach: fit parameters to experimental data, extrapolate to make predictions about unknown nuclei

Each mass model associated with fission barrier height model



*Experimental data from AME2016 (Wang+2017, Audi+2017)

Nuclear Heating by Reaction Type



Beta Decay

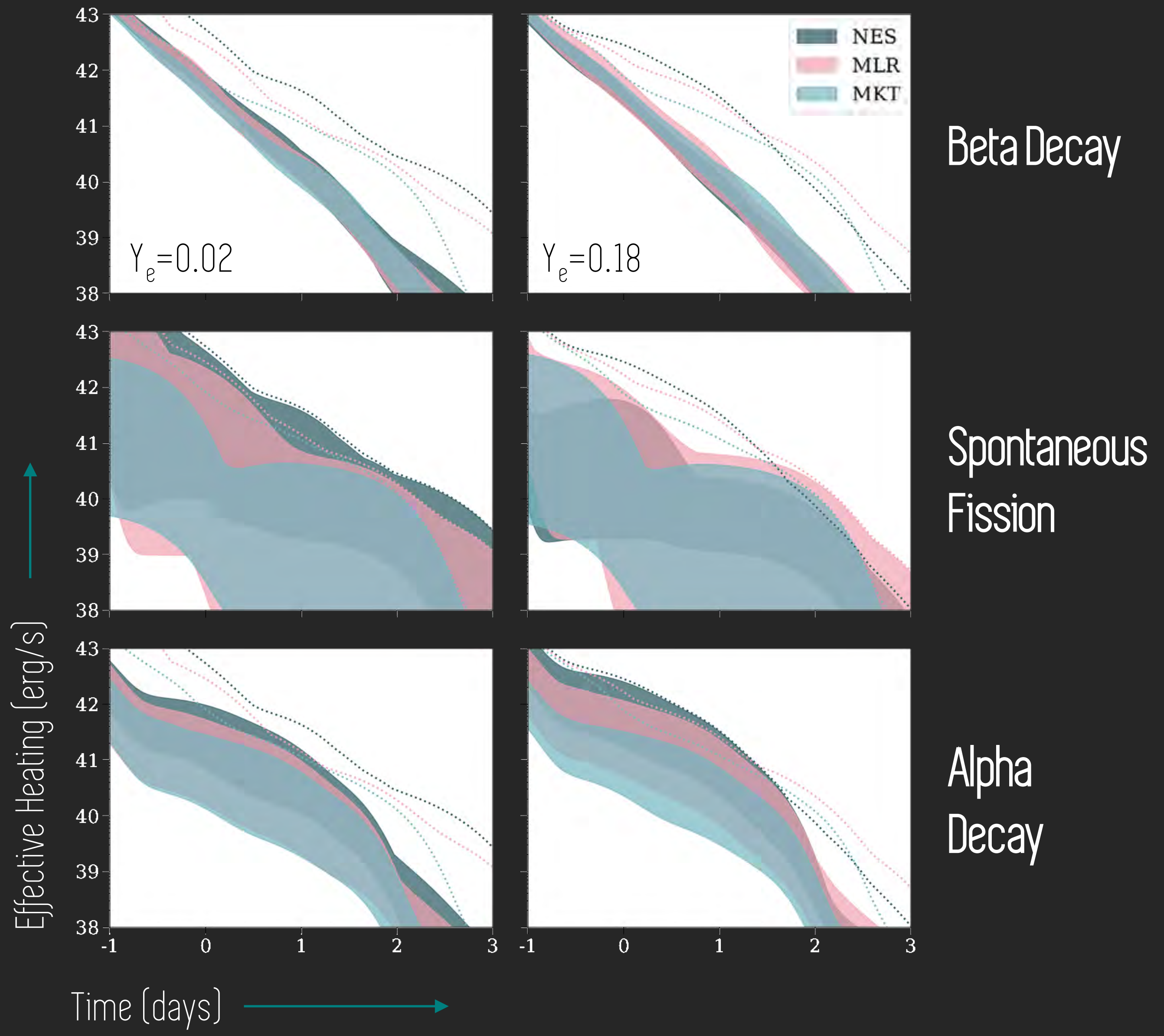
Spontaneous Fission

Alpha Decay

- Upper limit of heating uncertainty set by fission of few mass models

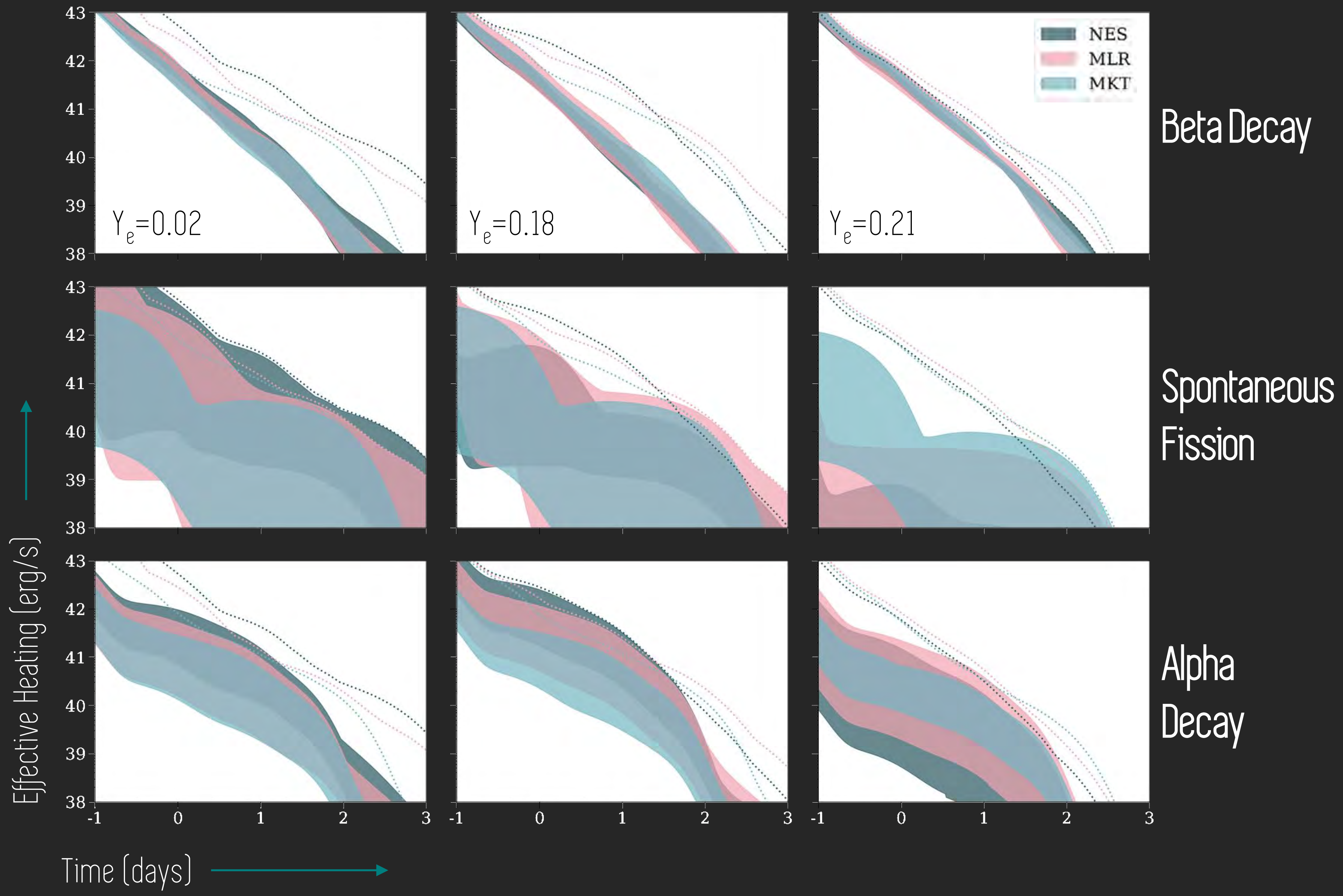
- Beta models differ in behavior of dominating fission heating

Nuclear Heating by Reaction Type



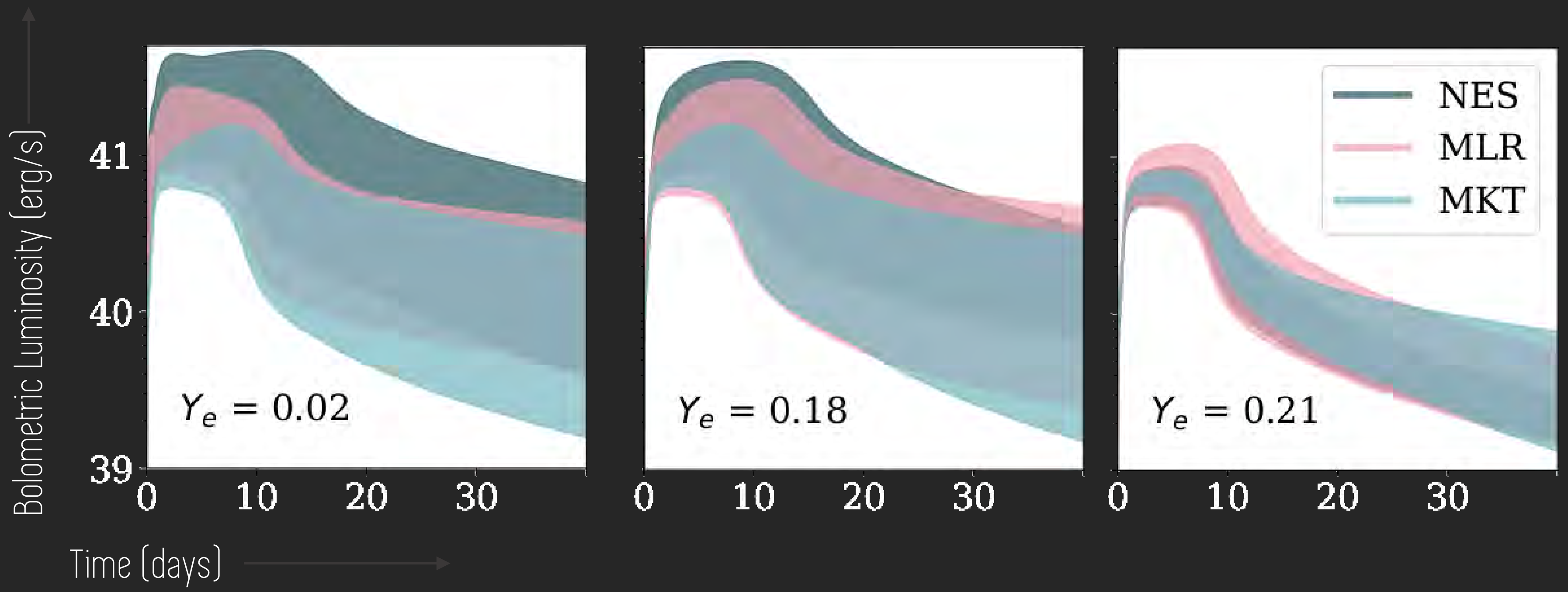
- Alpha heating becomes more important <100 days
- Beta models differ in predicting when alpha tends to dominate + late-time tail shape of fission heating

Nuclear Heating by Reaction Type



- Much more overlap, total heating tends to be set by beta (and in some cases alpha) decay
- Overall effect on beta decay heating is small

Light Curves



~70% more heating can yield ~50% brighter light curve (saw in NES:MLR)

~40% less heating can yield ~50% dimmer light curve (saw in MKT:MLR)

Magnitude and structure of heating propagate to light curve!

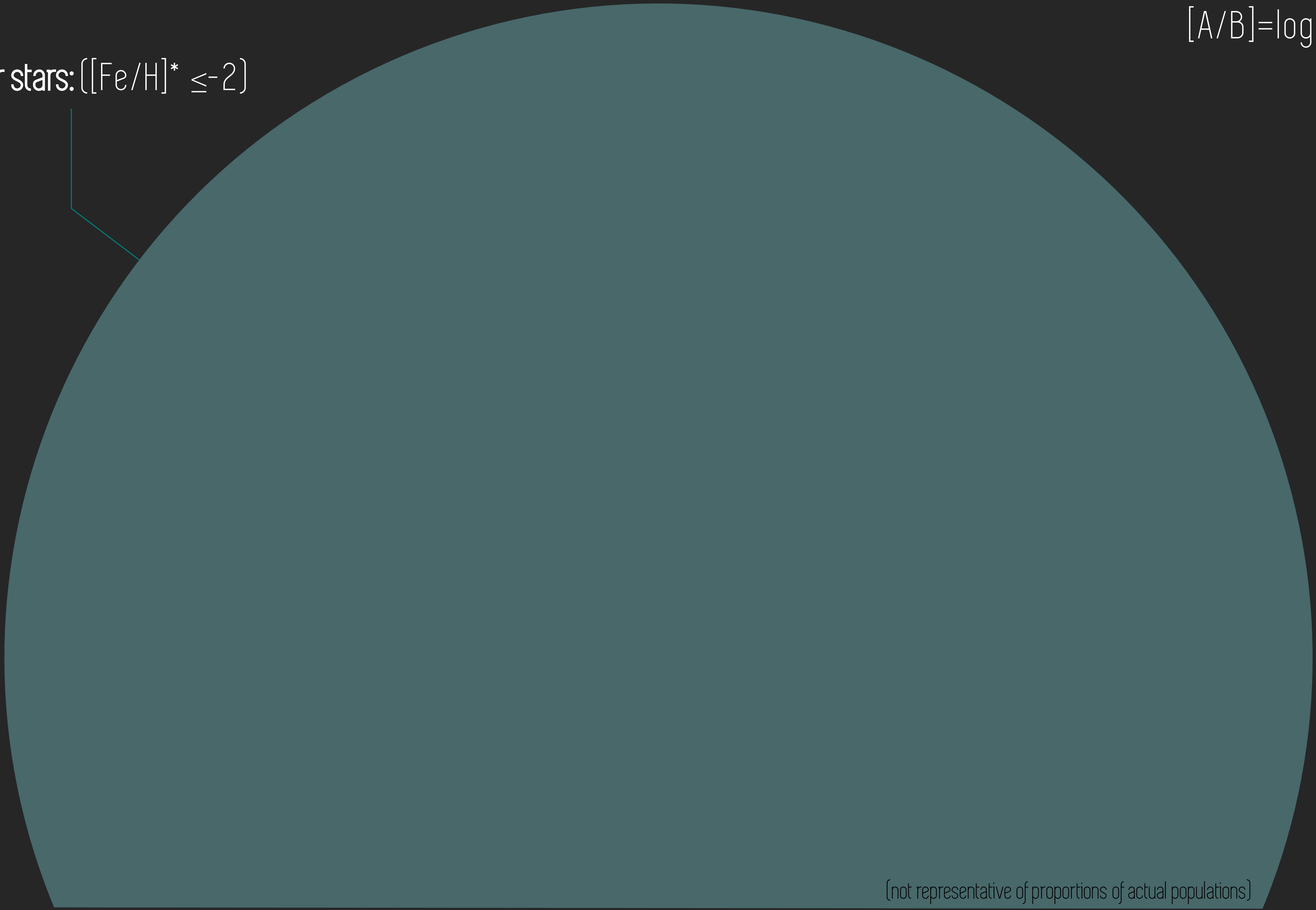
Nuclear Cosmochronometry

Classification

$$[A/B]=\log(N_A/N_B)_{obs}-\log(N_A/N_B)_{Sun}$$

$$\log_{\epsilon}(A) = \log_{10}(N_A/N_H)+12$$

Metal-poor stars: ($[Fe/H]^* \leq -2$)



(not representative of proportions of actual populations)

Classification

$$[A/B] = \log(N_A/N_B)_{obs} - \log(N_A/N_B)_{Sun}$$

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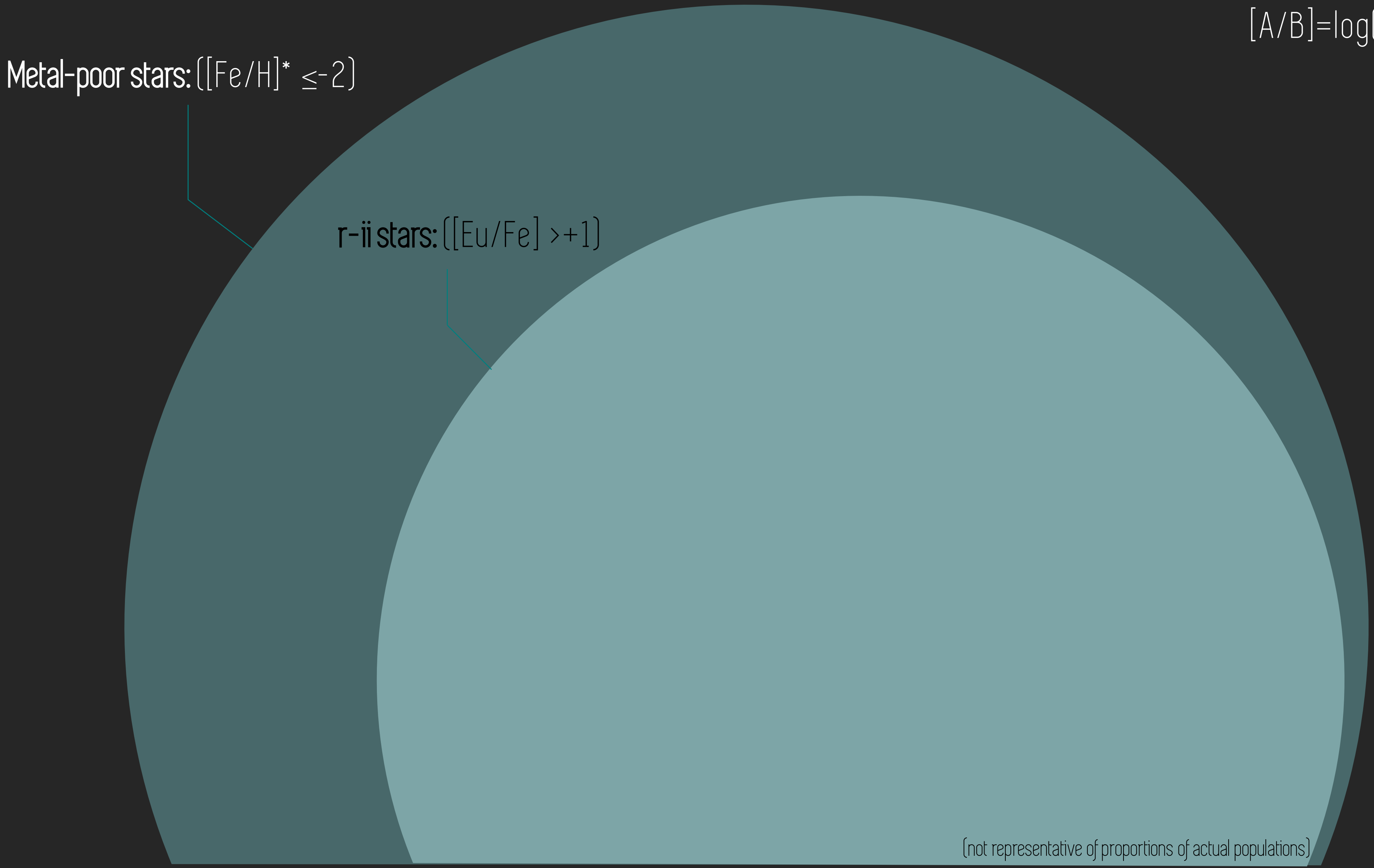

Classification

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$[A/B] = \log(N_A/N_B)_{obs} - \log(N_A/N_B)_{Sun}$

$\log_\epsilon(A) = \log_{10}(N_A/N_H) + 12$

Metal-poor stars: ($[Fe/H]^* \leq -2$)

r-ii stars: ($[Eu/Fe] > +1$)

Actinide "boost": $\log_\epsilon(Th/Dy) > -0.9$

Actinide "normal": $-1.20 \leq \log_\epsilon(Th/Dy) \leq -0.9$

Actinide "deficient": $\log_\epsilon(Th/Dy) < -1.20$

(not representative of proportions of actual populations)

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Astronomical Sample

Increasing actinide enhancement ↓

Star Name	$\log_\epsilon$(Eu)	$\log_\epsilon$(Th)	$\log_\epsilon$(U)	Reference
CS22892-052	-0.95	-1.57	-2.3	Sneden+2003
HE1523-0901	-0.62	-1.2	-2.06	Frebel+2007
CS29497-004	-0.66	-1.16	-2.20	Hill+2017
J2038-0023	-0.75	-1.24	-2.14	Placco+2017
CS31082-001	-0.72	-0.98	-1.92	Siquiera Mello+2013
J0954+5246	-1.19	-1.31	-2.13	Holmbeck+2018

Nuclear Physics

Basic Initial Assumption: Each star has been enriched by some single r-process event

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

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

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

- **^{232}Th** & **^{238}U:** produced exclusively via r-process ($t_{1/2}$ = 14 Gyr, 4.486 Gyr respectively)

Basic Initial Assumption: Each star has been enriched by some single r-process event

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

Final abundance of NSM simulation

=

"Initial" r-process enrichment

- ^{232}**Th** & ^{238}**U:** produced exclusively via r-process ($t_{1/2}$ = 14 Gyr, 4.486 Gyr respectively)

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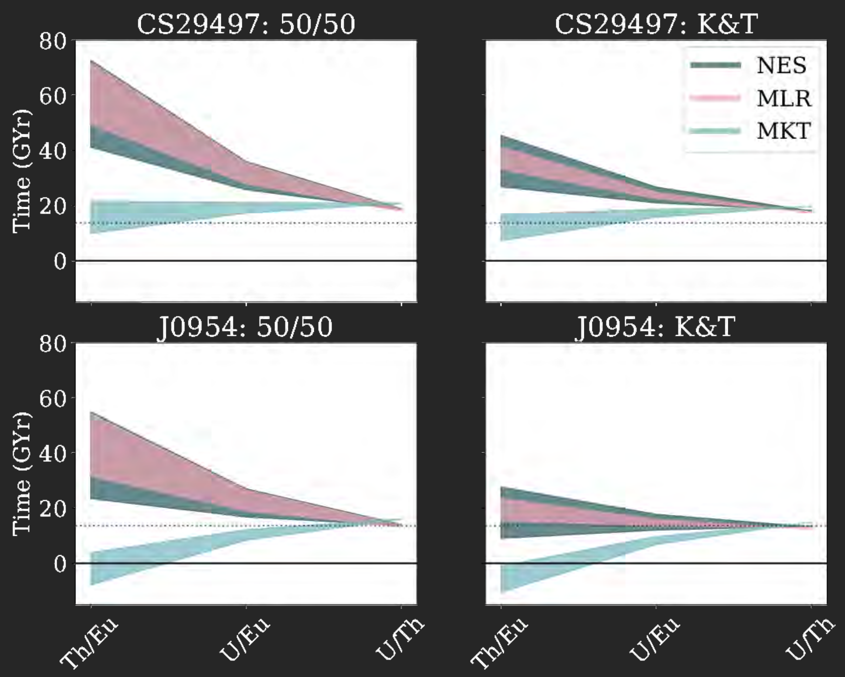
Lanthanide : Actinide Tension

The problem: it is hard to get the lanthanide and actinide ratios to agree

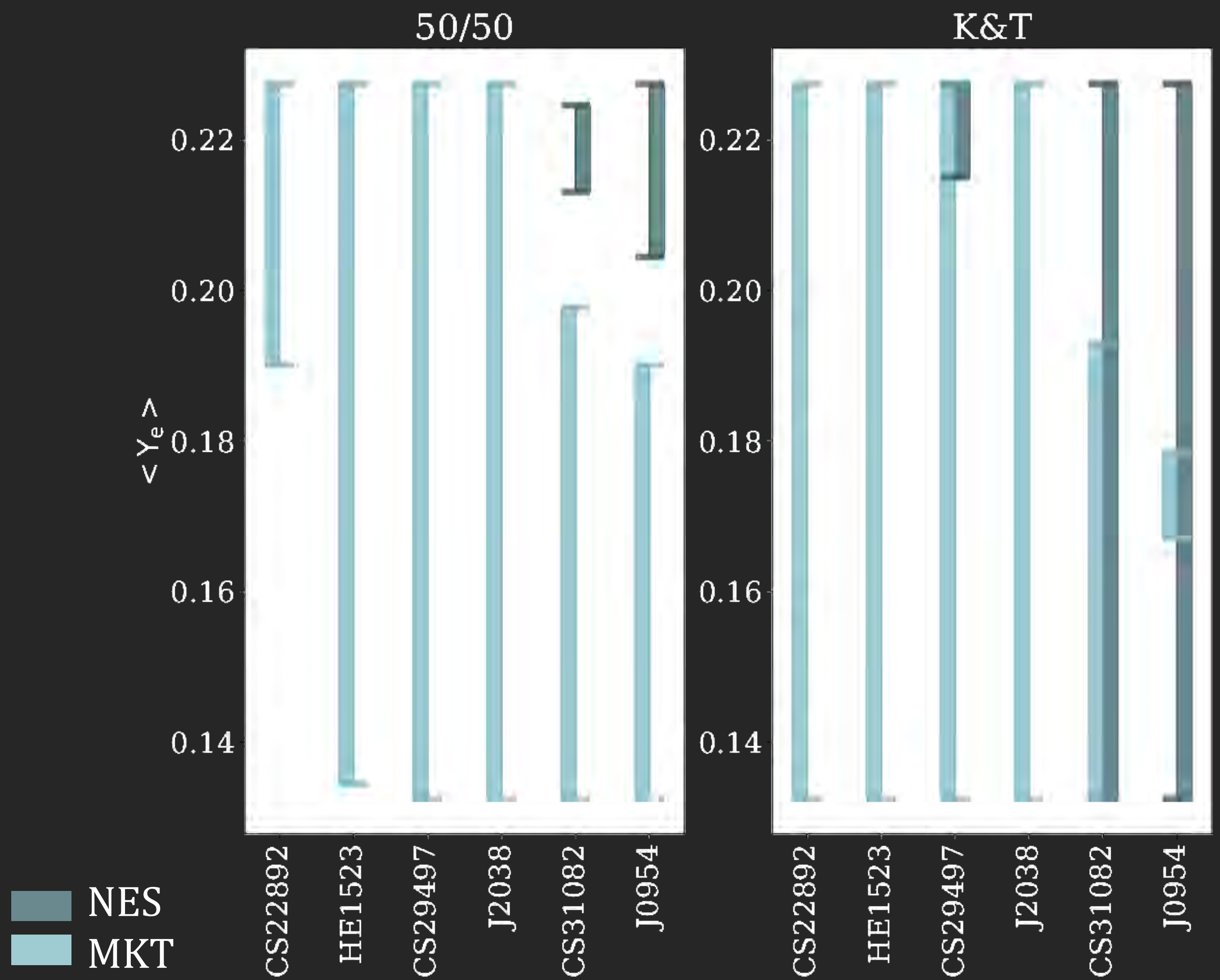
$$t = 46.67\text{Gyr}\left[-\log_\epsilon\left(\frac{\text{Th}}{\text{Eu}}\right)_{\text{obs}} + \log_\epsilon\left(\frac{Th}{Eu}\right)_0\right]$$

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

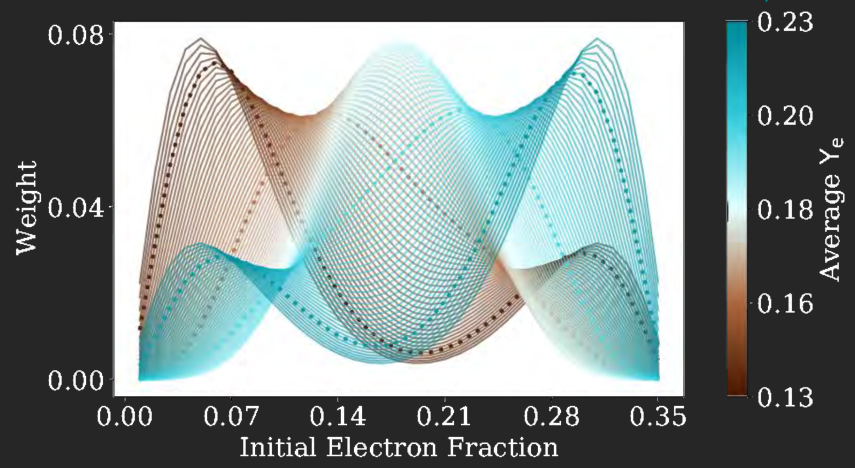
$$t = 21.80\ \text{Gyr}\left[-\log_\epsilon\left(\frac{\text{U}}{\text{Th}}\right)_{\text{obs}} + \log_\epsilon\left(\frac{\text{U}}{\text{Th}}\right)_0\right]$$



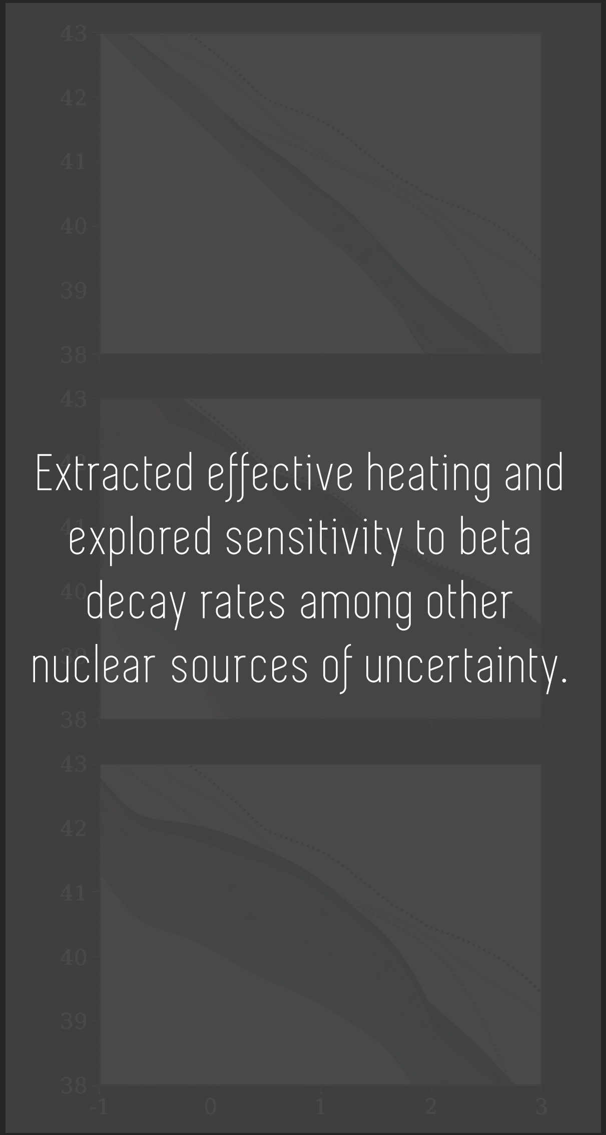
Chronometric Agreement



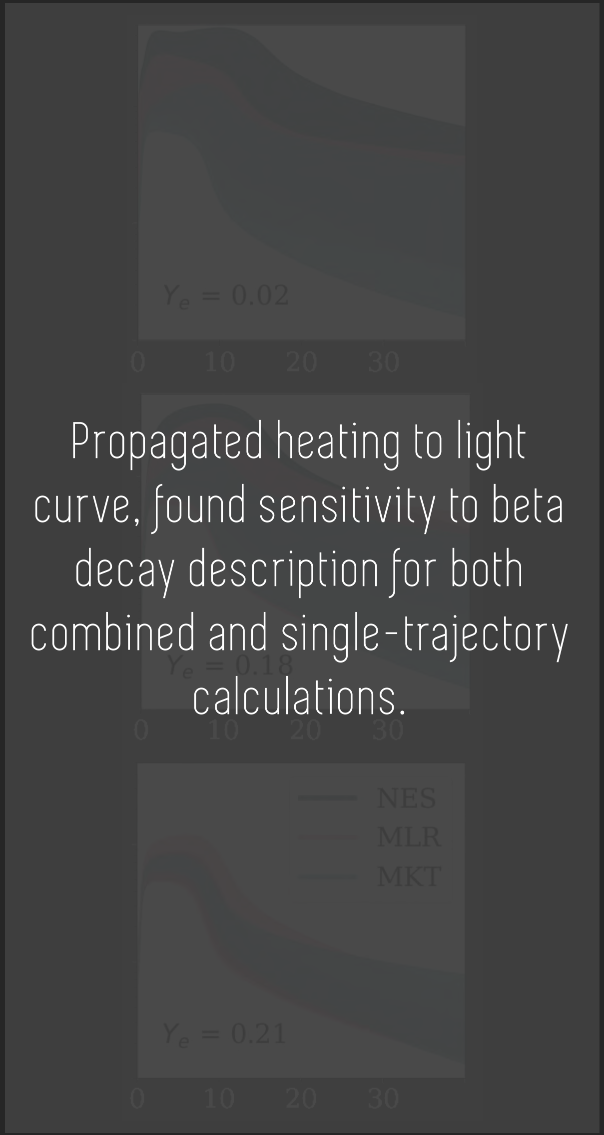
(Average Y_e is that of combined trajectory)



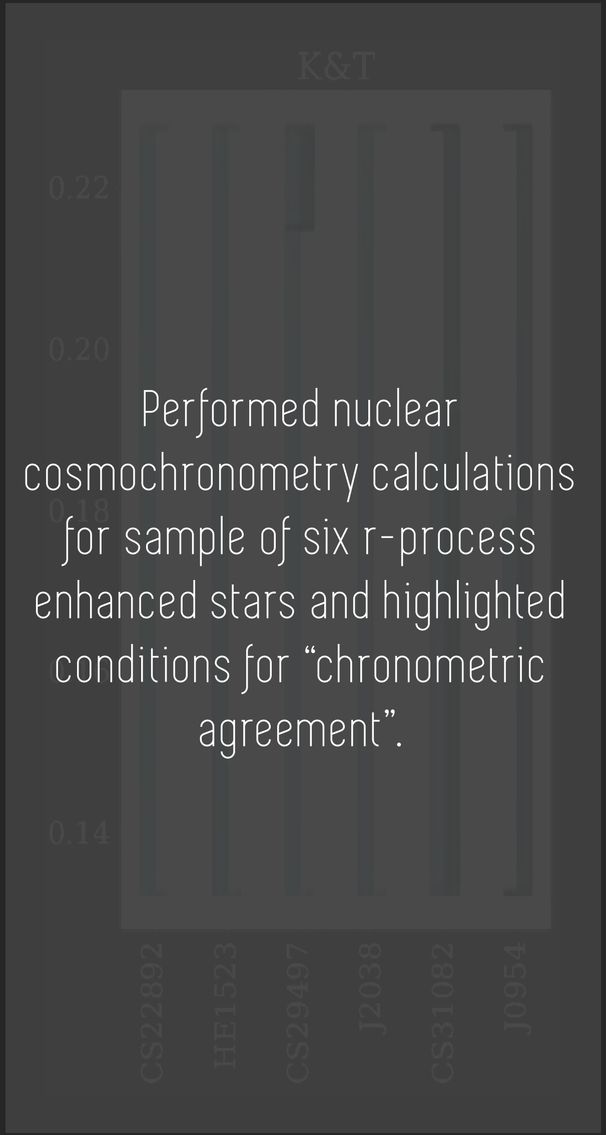
Conclusion



Extracted effective heating and explored sensitivity to beta decay rates among other nuclear sources of uncertainty.



Propagated heating to light curve, found sensitivity to beta decay description for both combined and single-trajectory calculations.



Performed nuclear cosmochronometry calculations for sample of six r-process enhanced stars and highlighted conditions for “chronometric agreement”.

arXiv: 2208.06373

Thank you!