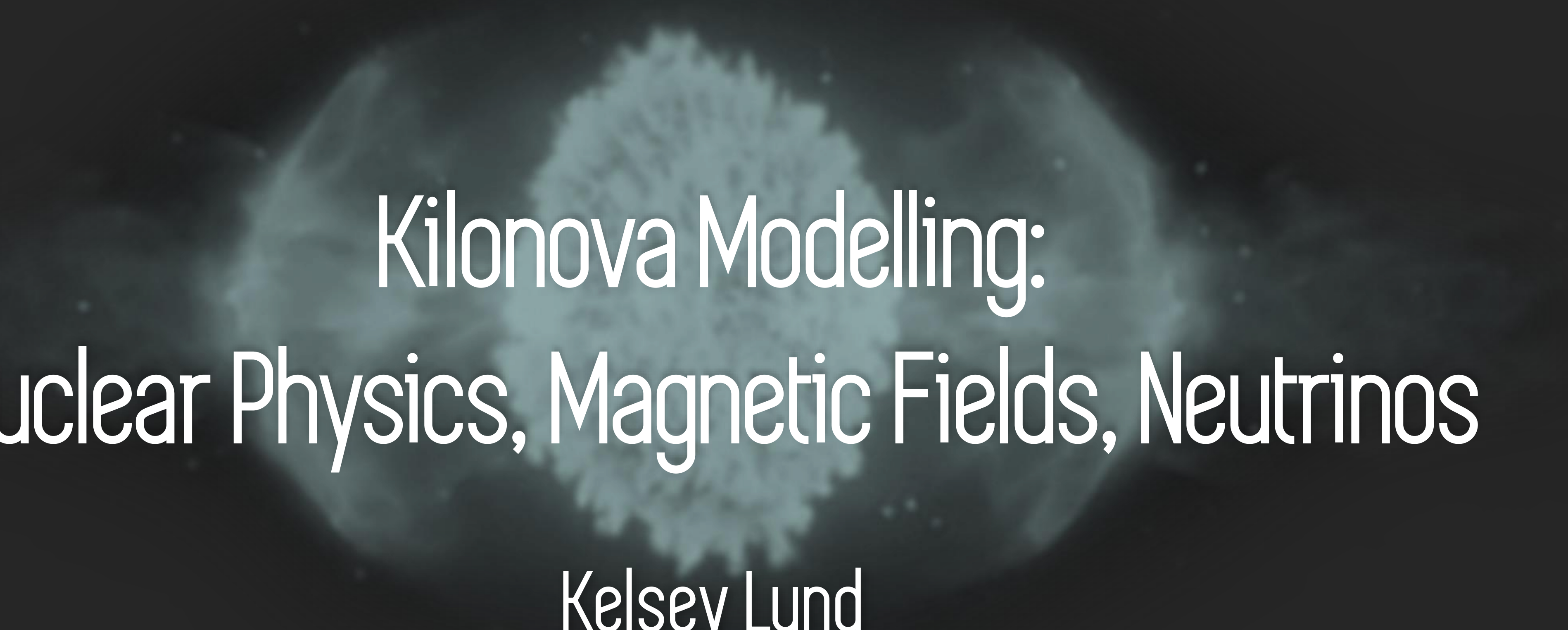
International School of Nuclear Physics
Neutrinos in Cosmology, Astro-, Particle- and Nuclear Physics
Erice, Sicily

arXiv: 2208.06373
2010.03668
2010.11182



Kilonova Modelling:
Nuclear Physics, Magnetic Fields, Neutrinos

Kelsey Lund

20 September 2022

Center for Nonlinear Studies

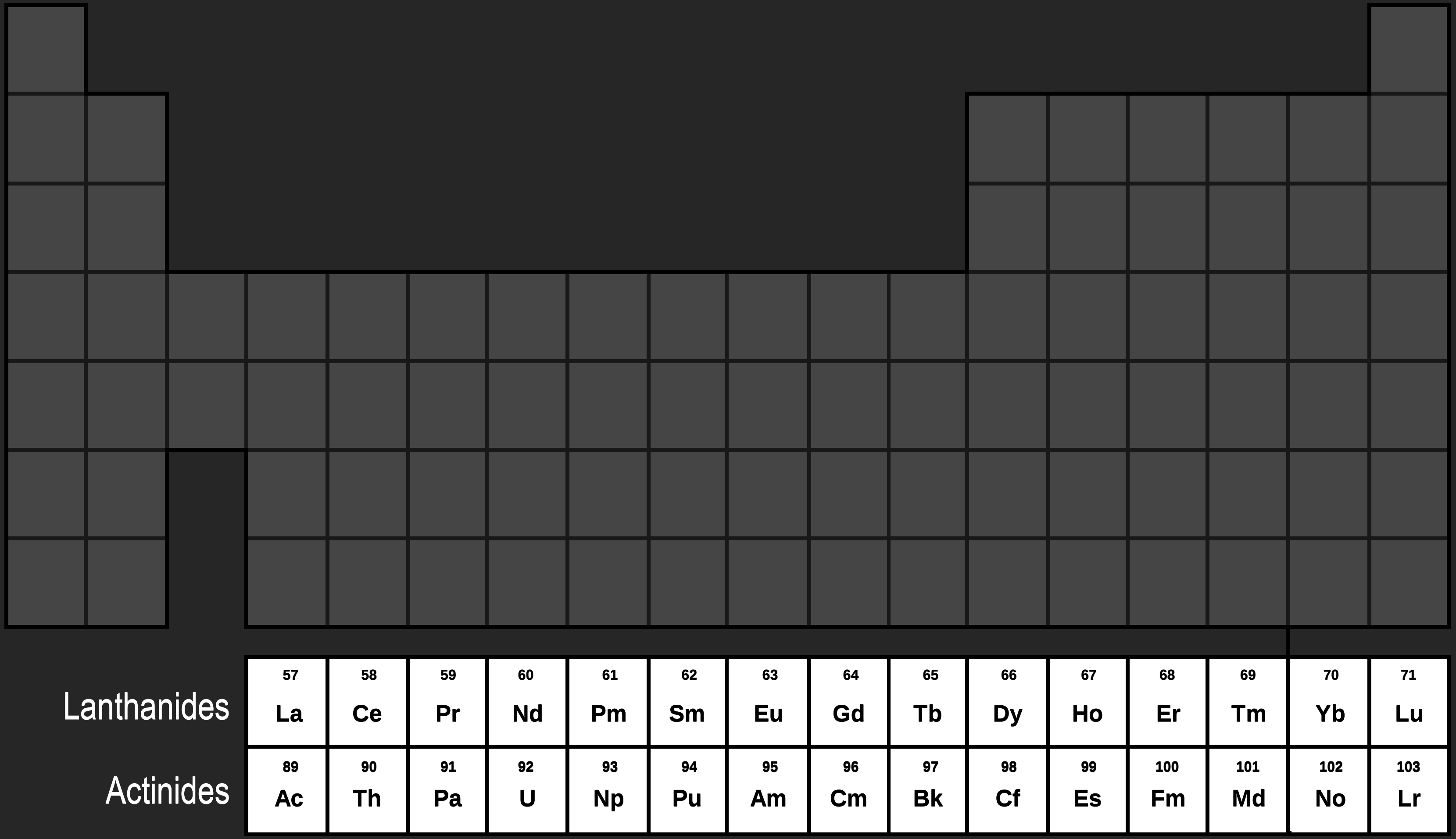
Los Alamos NATIONAL LABORATORY

FIRE
Fission In R-process Elements

Seaborg Institute

NC STATE UNIVERSITY

Introduction: High Opacity Material



Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

(recall
weekend talks
by
Gail McLaughlin
&
Jonah Miller)

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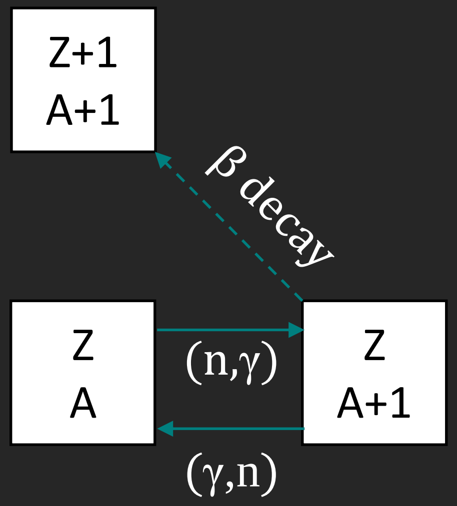
Introduction: Neutron Capture



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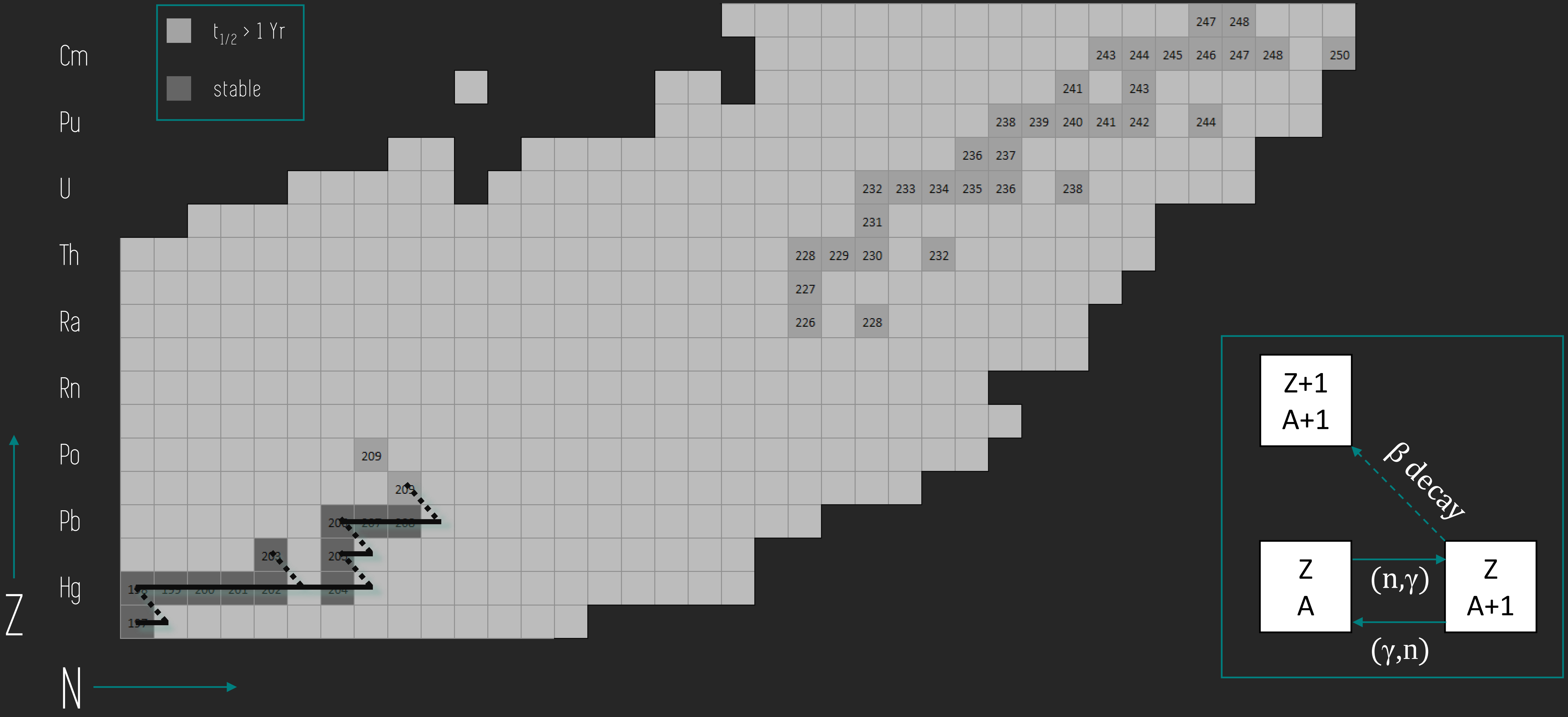
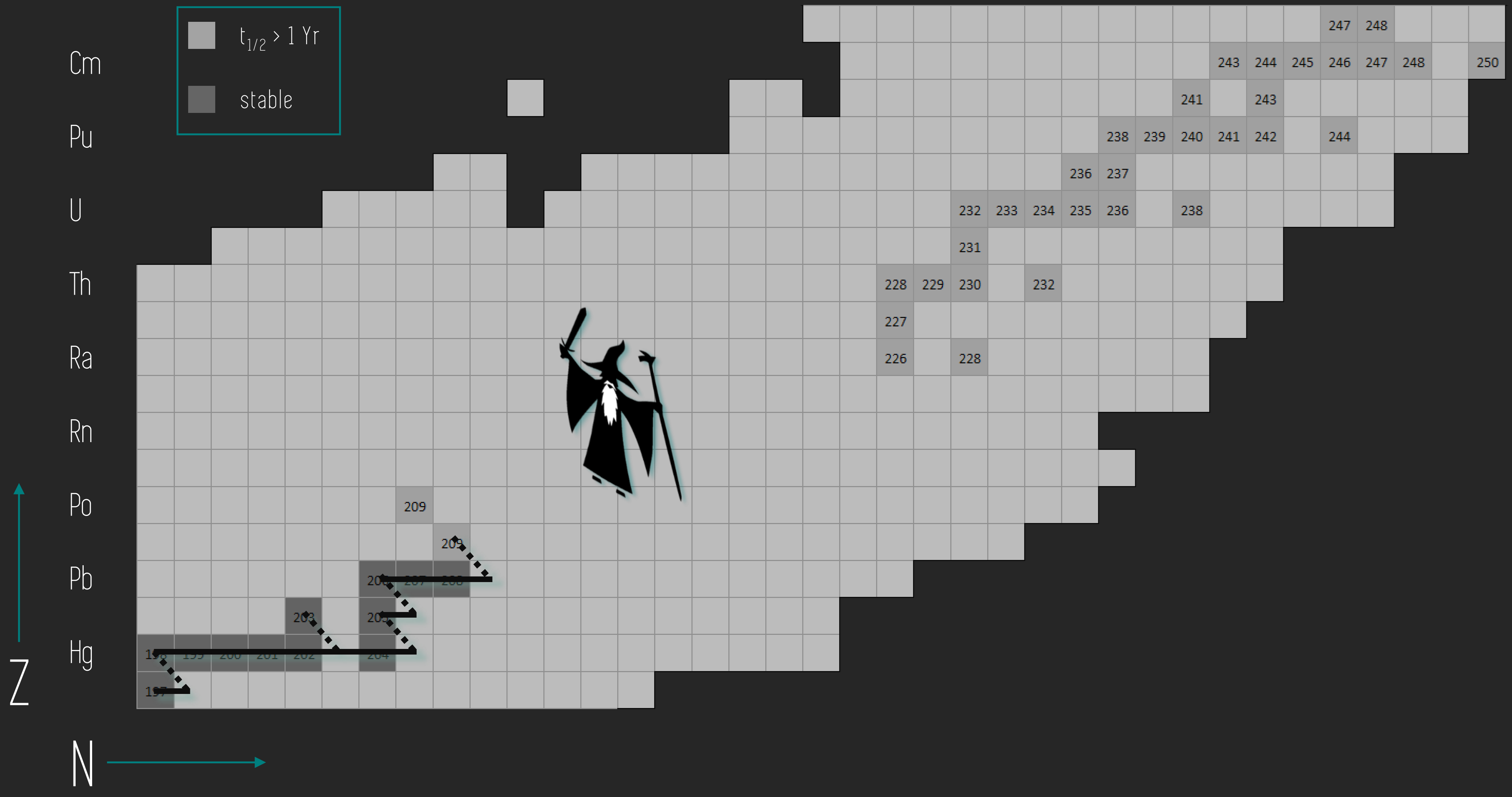
Introduction: (slow) Neutron Capture



Introduction: (slow) Neutron Capture



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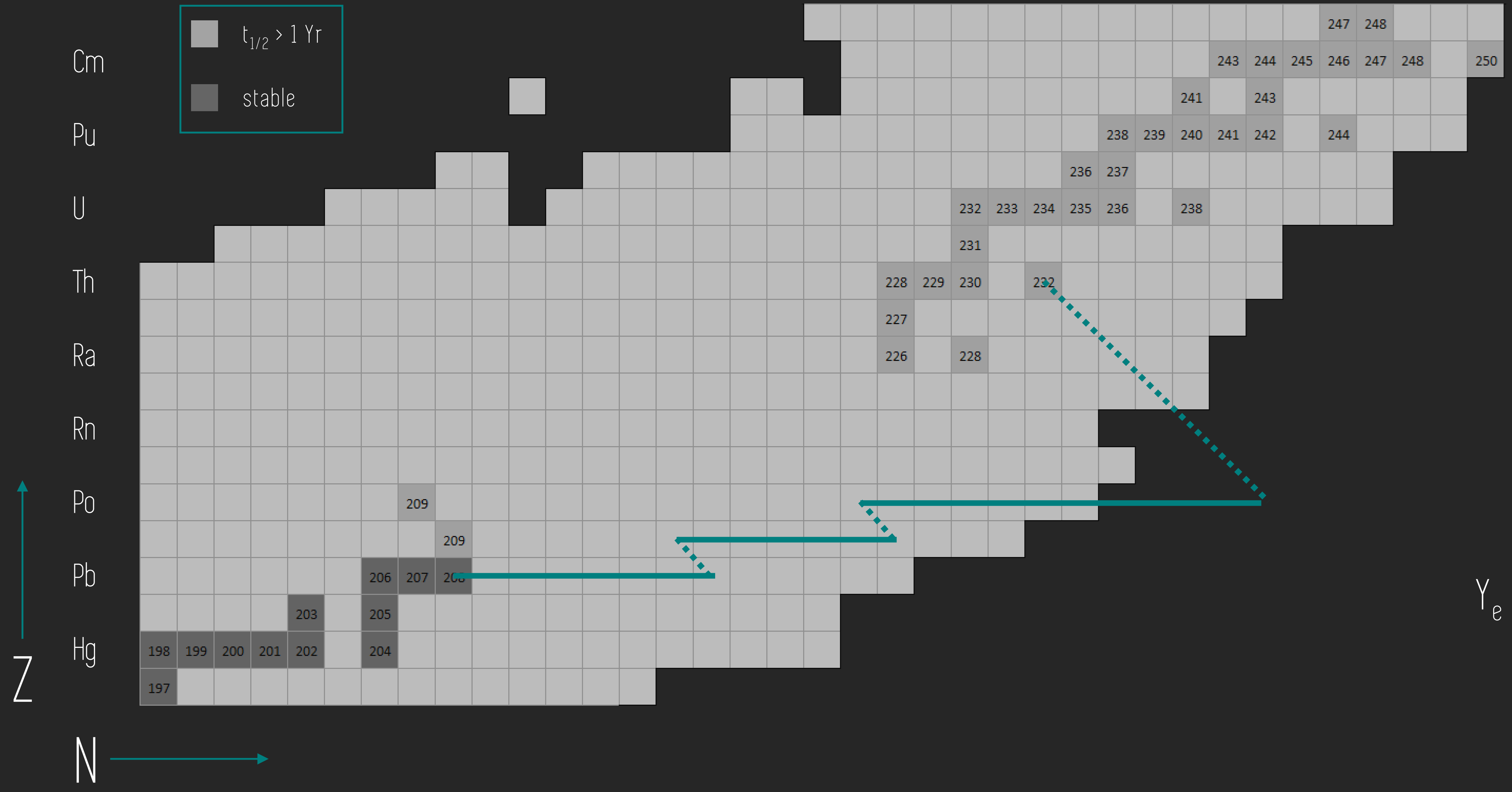
Introduction: Rapid Neutron Capture



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

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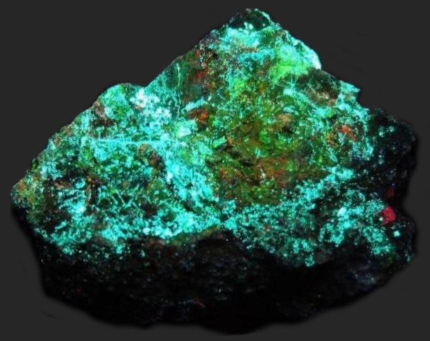
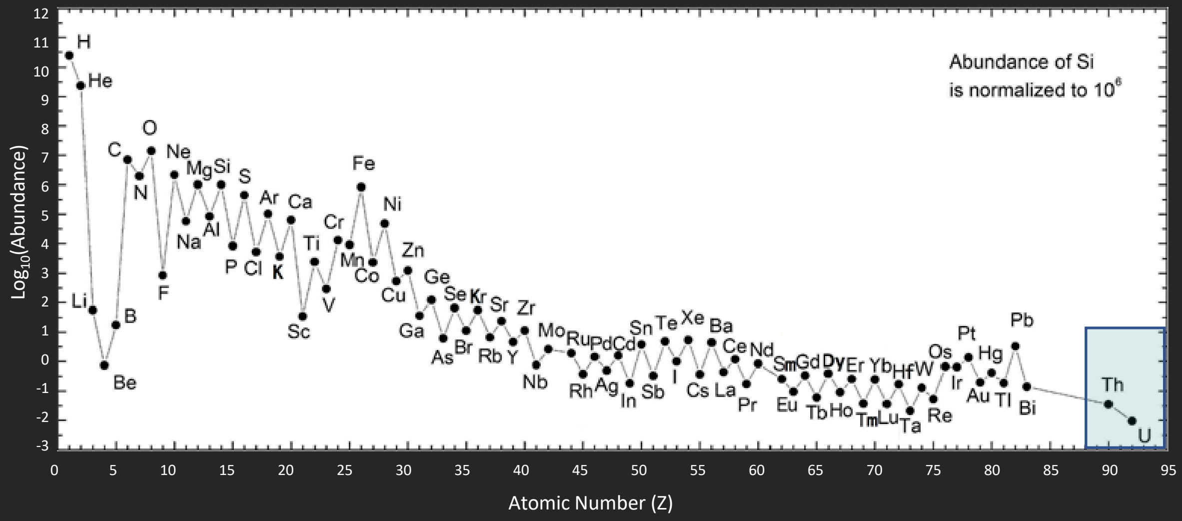
Introduction: Motivation

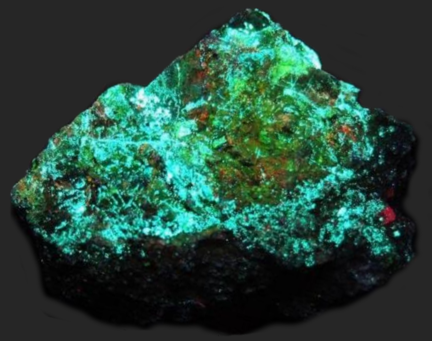
Natural Abundance Production in Solar System

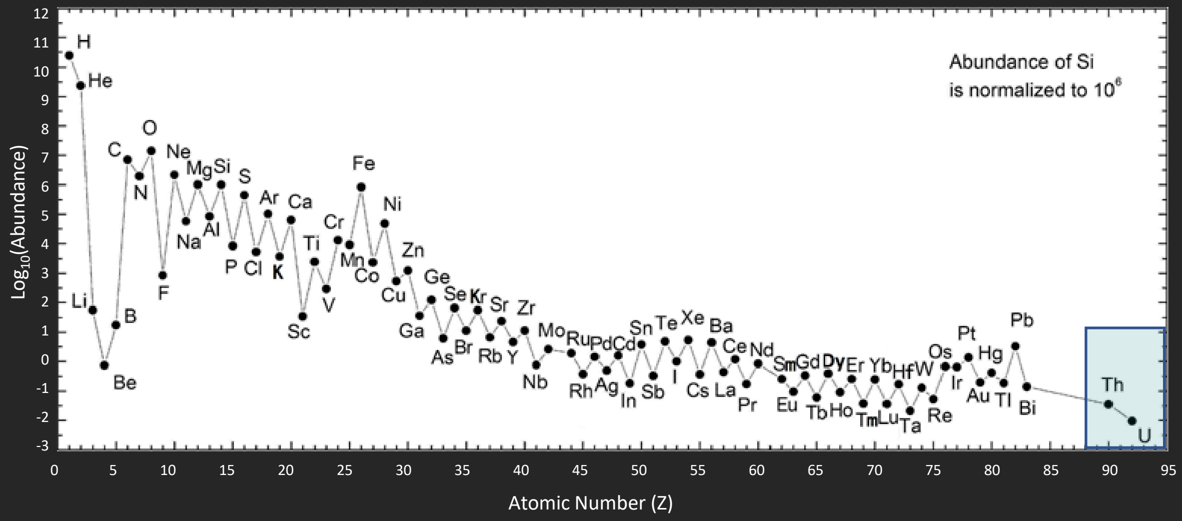




Introduction: Motivation

Natural Abundance Production in Solar System





Cosmic Chronometers

ESA/Hubble & NASA

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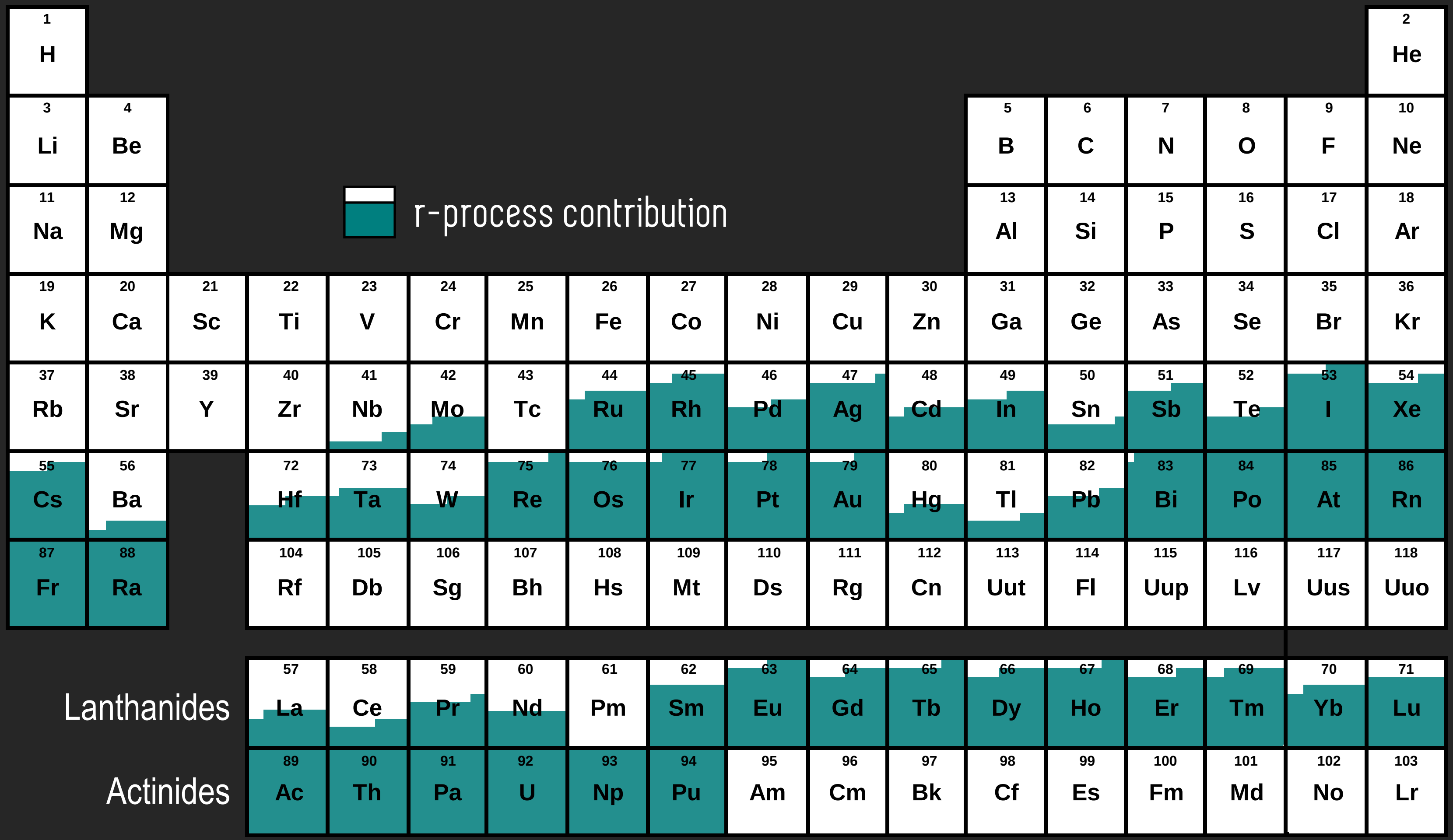
Introduction: Motivation



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r-Process Site: Compact Object Mergers

(Adapted from Kasen+ 2017)

NS+NS

Prompt Collapse

NS+NS

Central Engine

NS+BH

Prompt Collapse

🟥 high opacity

🟦 low opacity

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r-Process Site: Compact Object Mergers

(Adapted from Kasen+ 2017)

NS+NS

Prompt Collapse

NS+NS

Central Engine

NS+BH

Prompt Collapse

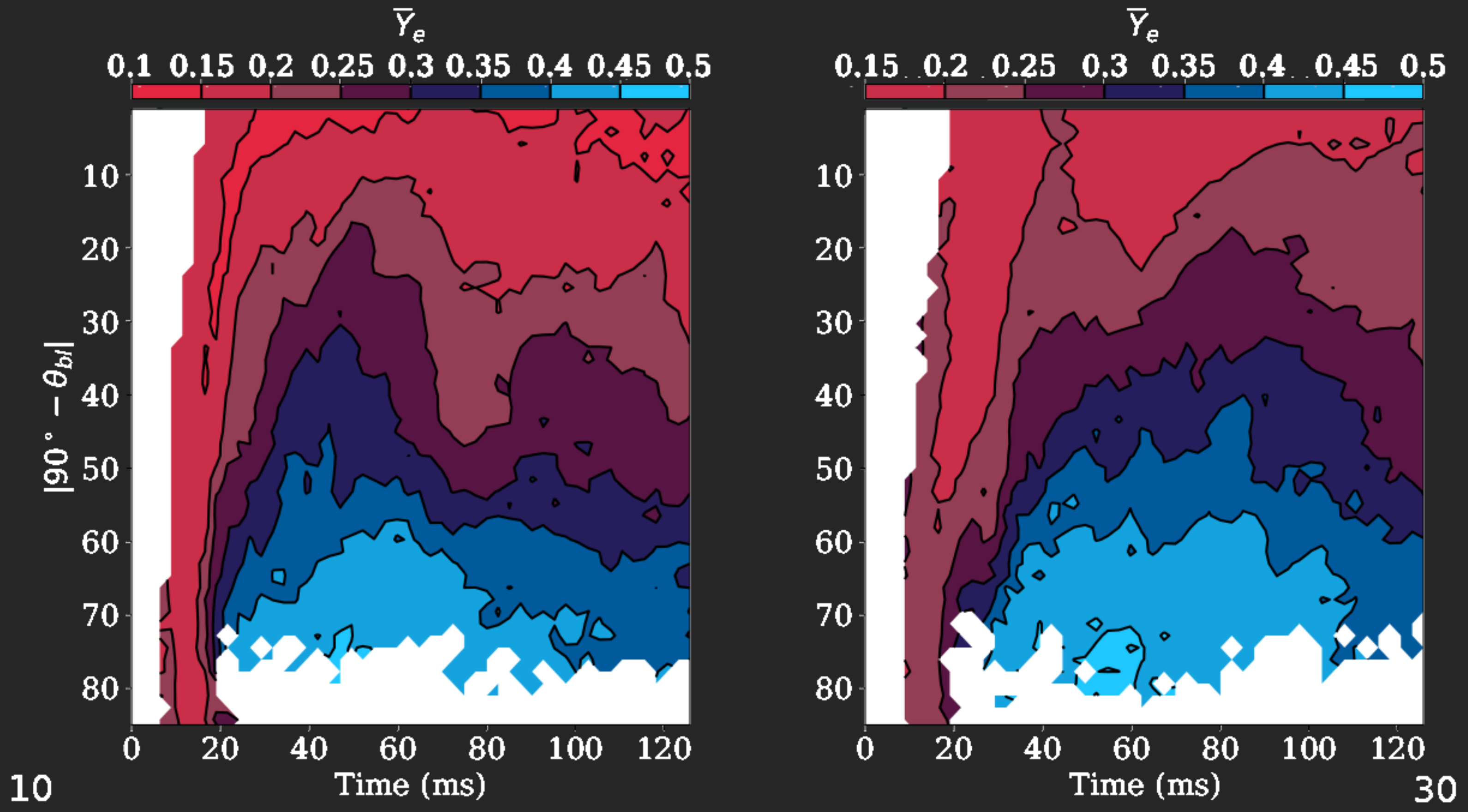
Charged current interactions change composition of material:

$\bar{\nu}_e + p \rightleftharpoons e^+ + n \qquad \nu_e + n \rightleftharpoons e^- + p$

Important quantity for r-process: $Y_e = \dfrac{n_p}{n_p + n_n}$

r-Process Site: Evolution of Post-Merger Disk

Neutrino effects on Y_e affected by geometry and evolution of magnetic fields in the post-merger disk. (wip)



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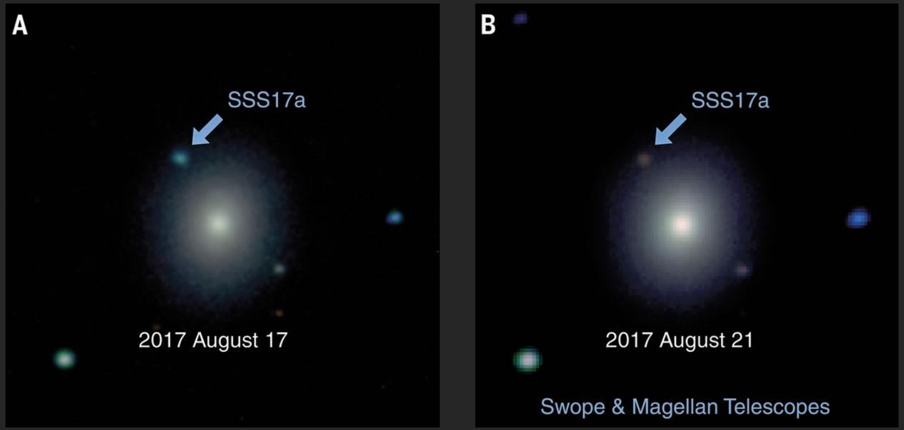
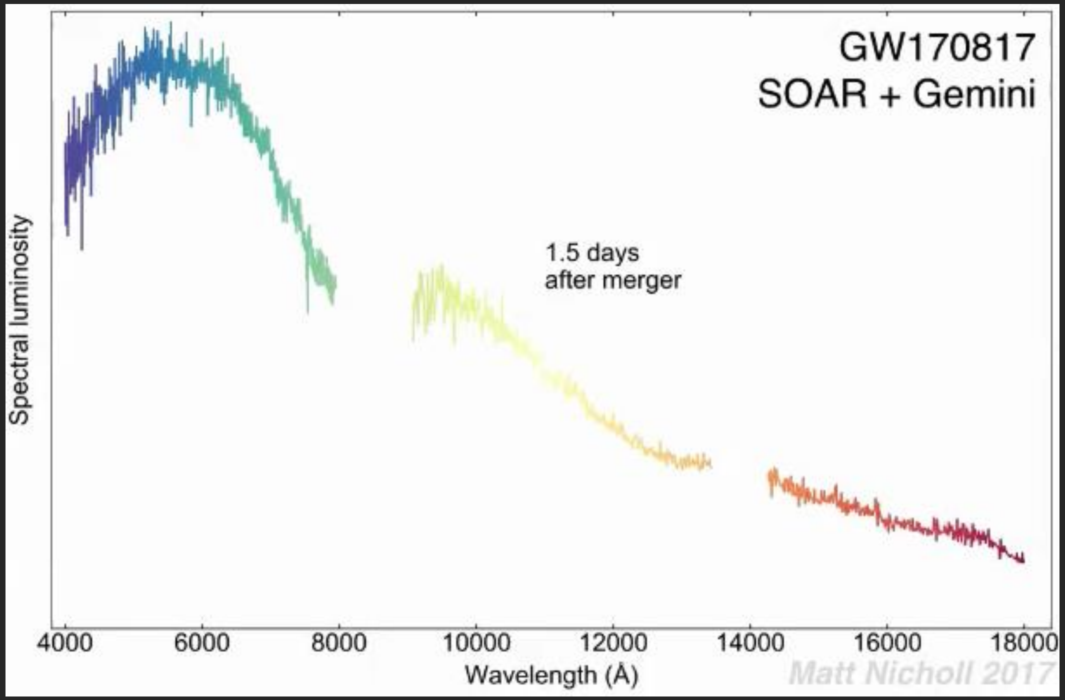
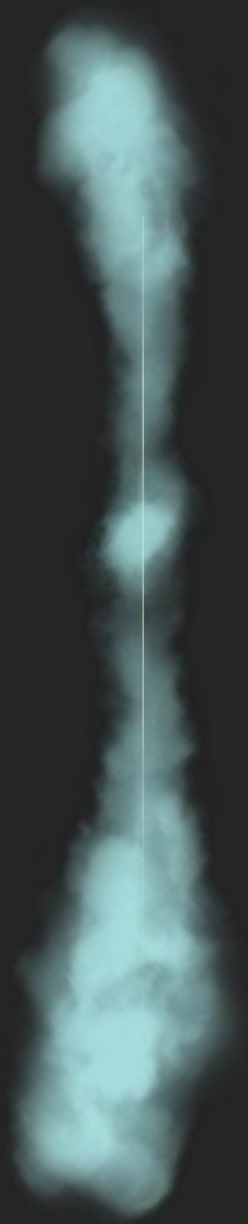
r-Process Site: GW170817







Nuclear Physics Sources of Uncertainties

Nucleosynthesis calculations probe:

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

arXiv: 2208.06373
2010.03668
2010.11182

Building a Dataset: Initial Y_e

Single Trajectory:
(all nuclear datasets)

0.01 - 0.35

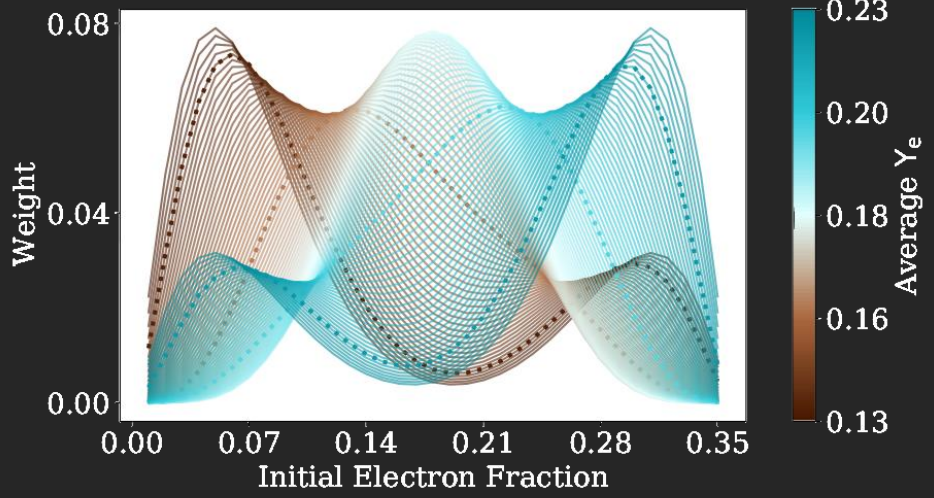
0.02 0.18 0.21

More neutron rich ←

→ Less fission

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

Linear Combinations:
(limited nuclear dataset)



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Sources of Nuclear Uncertainty

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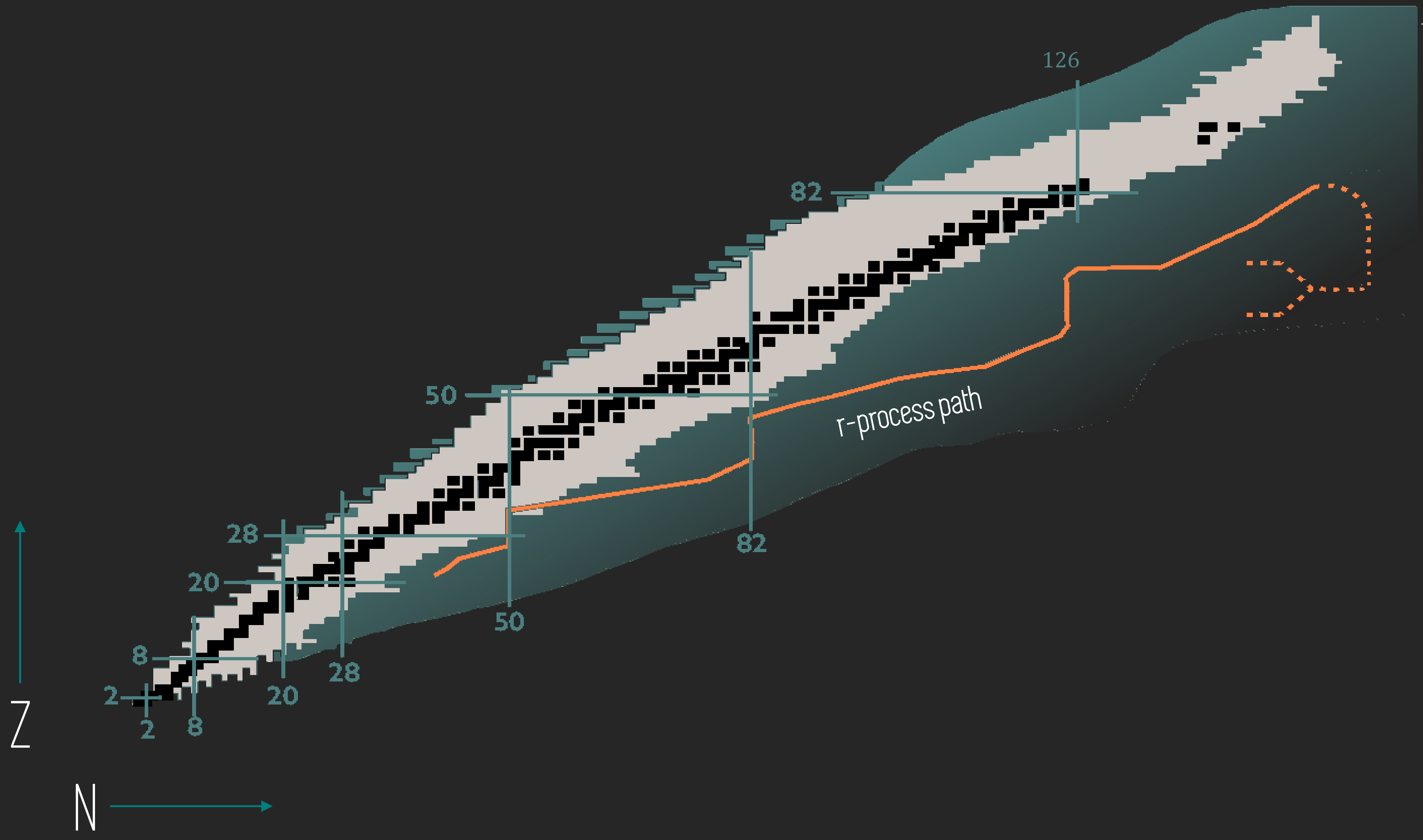

Adapted from F. Timmes

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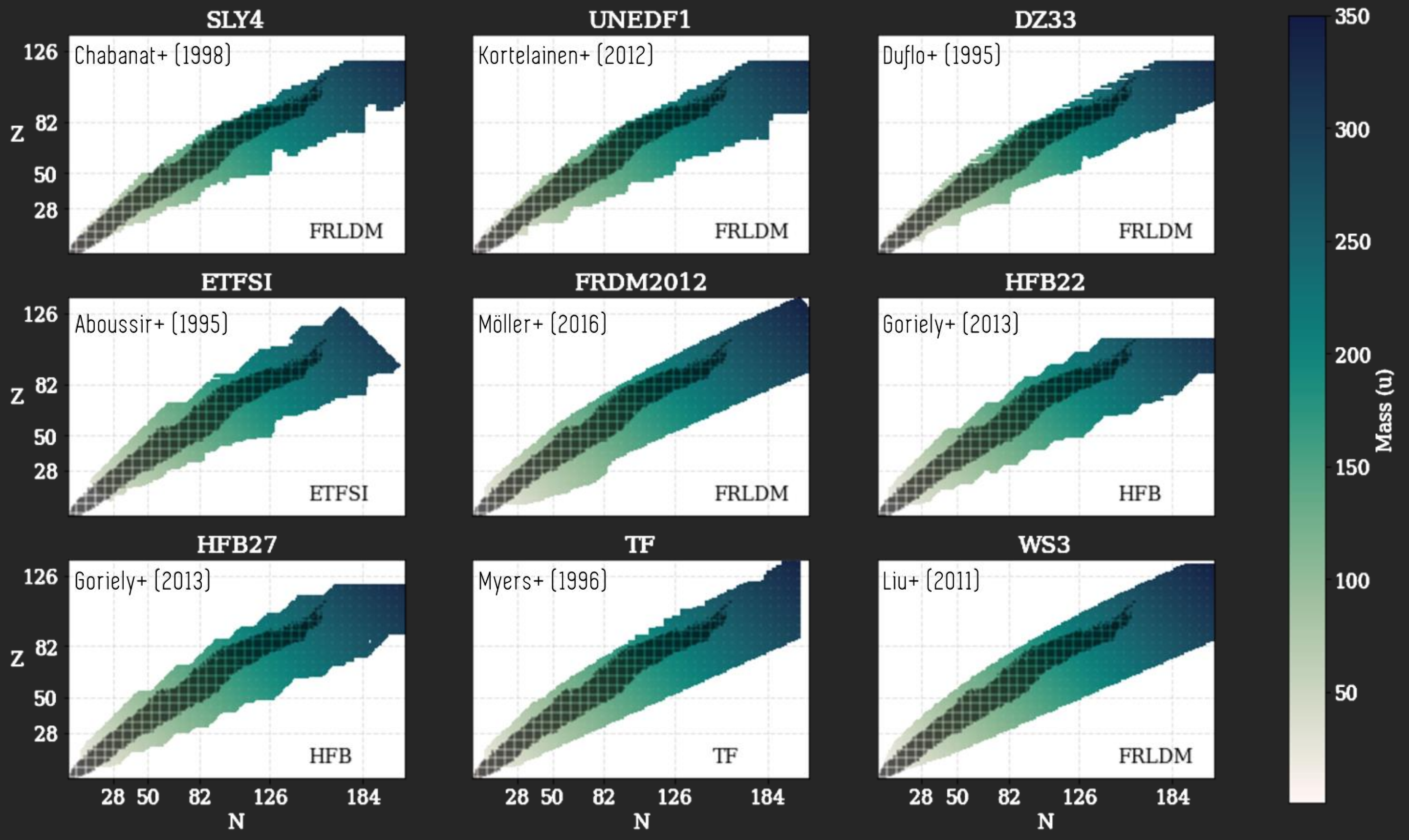
Building a Dataset: Mass Model

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)

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Building a Dataset: Beta Decay Rates

FAM+QRPA

QRPA+FRDM

Covariant DFT

Ney (**NES**)

Ney+ 2020

Möller (**MLR**)

Marketin (**MKT**)

Marketin+ 2016

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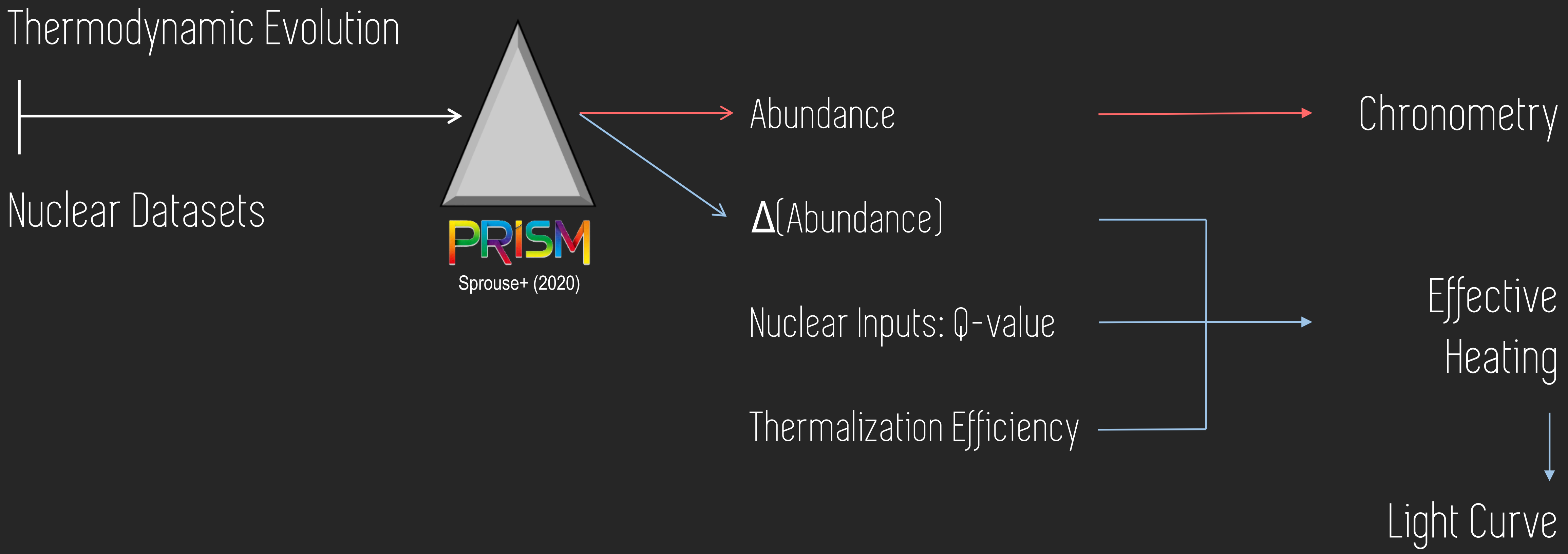
PRISM: A Sparse Matrix Solver



Thermodynamic Evolution

Nuclear Datasets

PRISM

Sprouse+ (2020)

Abundance

Δ(Abundance)

Nuclear Inputs: Q-value

Thermalization Efficiency

Chronometry

Effective Heating

Light Curve

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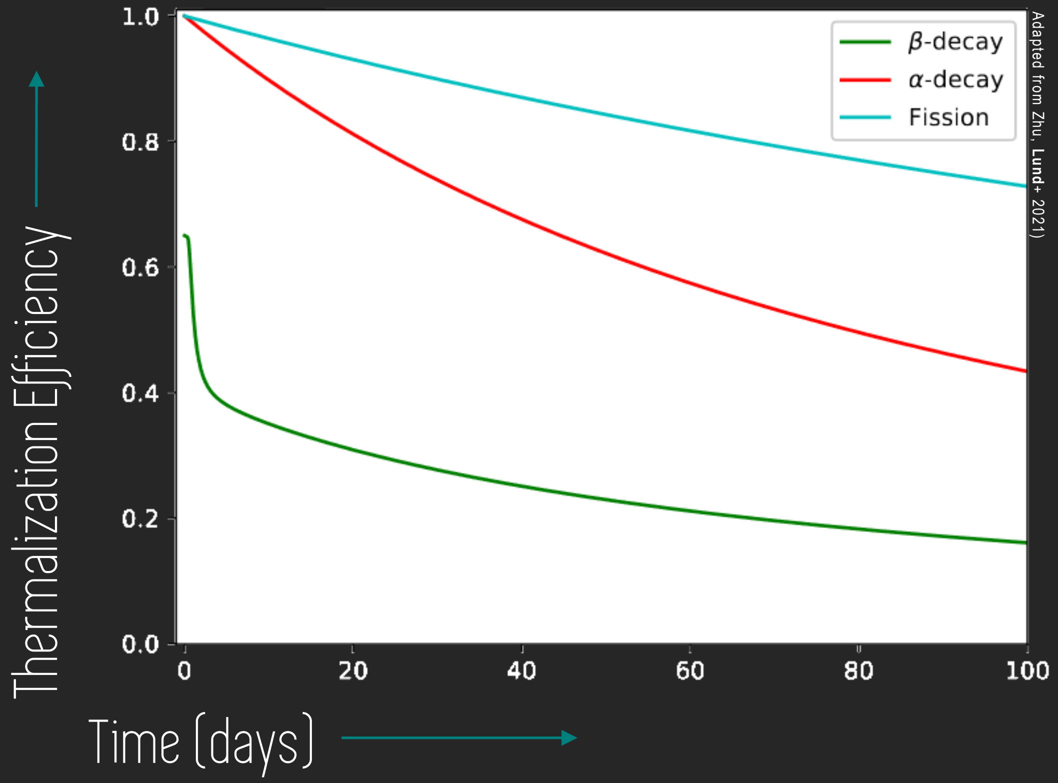
Nuclear Heating

Nuclear Heating Calculation

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



Adapted from Zhu, **Lund**+ 2021)

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

$$\underbrace{\dot{Q}(t)}_{\text{Total effective heating}} = \sum_i \underbrace{f_i(M_{ej}, v_{ej}, t)}_{\text{Thermalization efficiency}} \; \underbrace{\dot{q}_i(t)}_{\text{Heating (Q-value * flow)}} \; \underbrace{M_{ej}}_{\text{Ejecta mass}}$$

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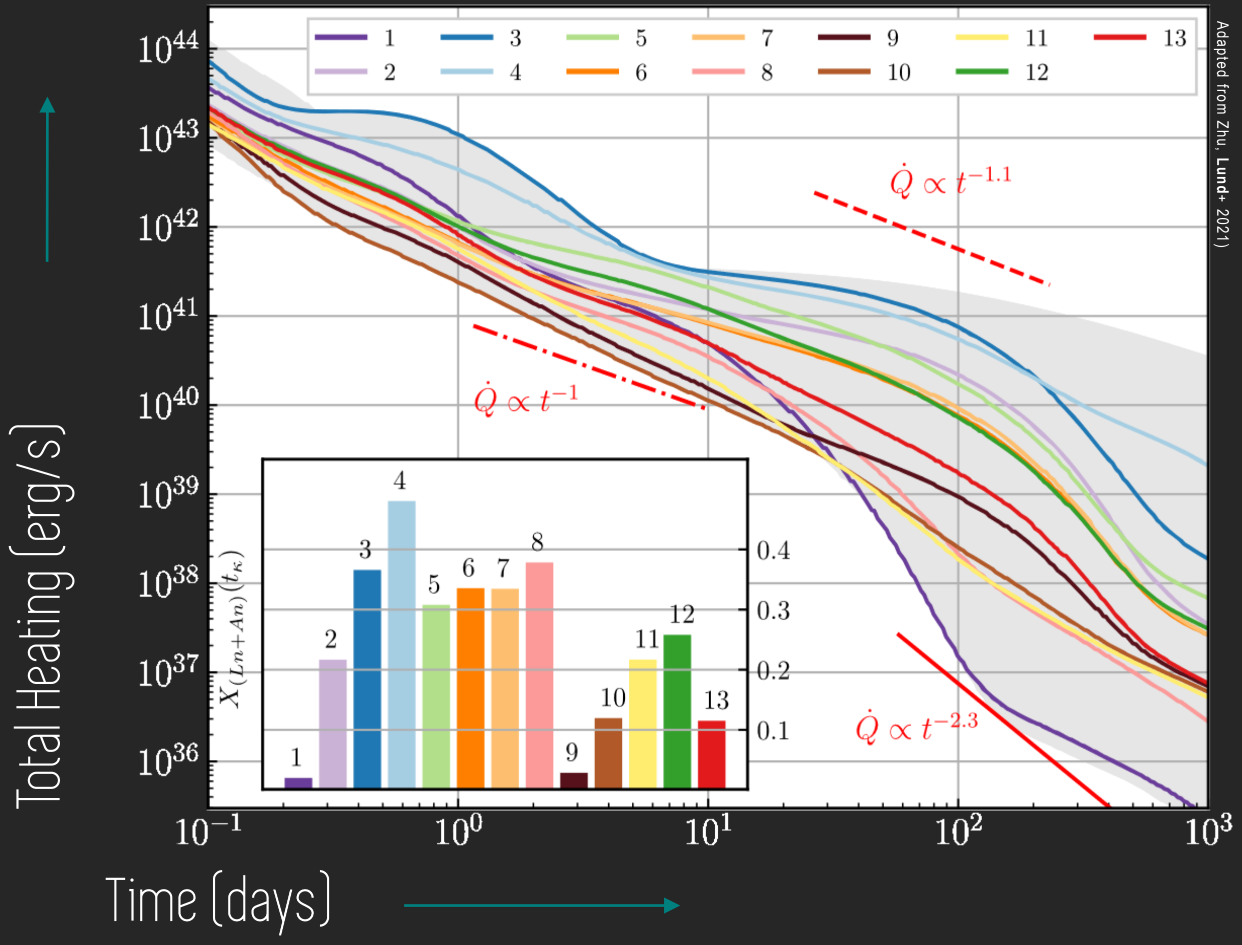
Total Heating for Different Nuclear Physics



Adapted from Zhu, **Lund+** 2021)

Index	Mass Model	Y_e
1	FRDM12	0.28
2	FRDM12	0.16
3	HFB22	0.16
4	HFB27	0.16
5	DZ33	0.16
6	UNEDF1	0.16
7	UNEDF1	0.16
8	UNEDF1	0.24
9	SLY4	0.18
10	SLY4	0.21
11	TF*	0.16
12	DZ33	Solar mix
13	UNEDF1	Solar mix

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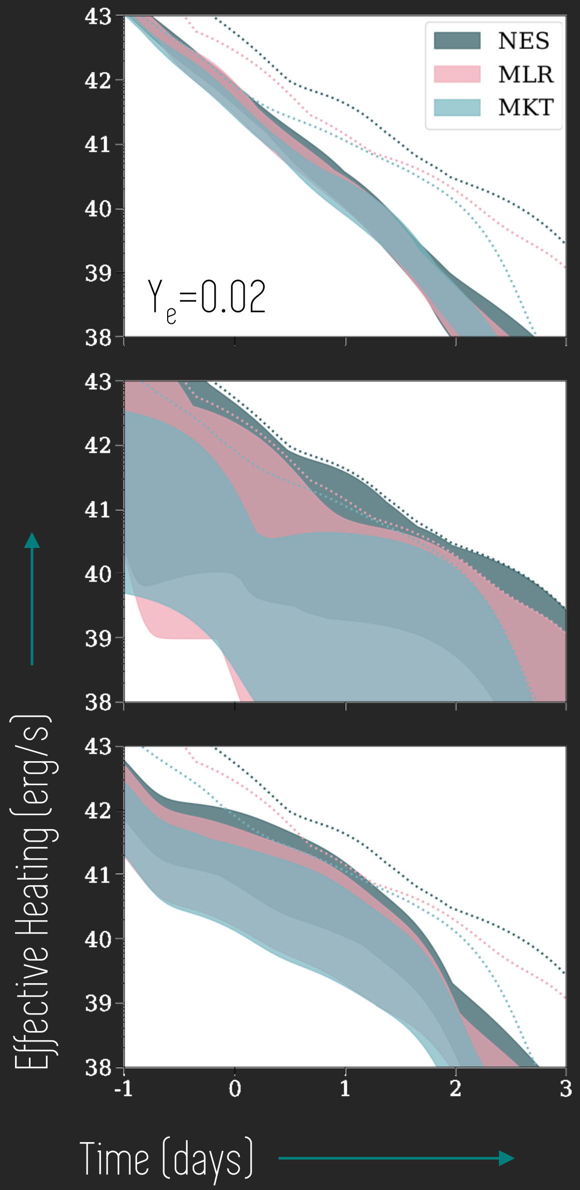
Nuclear Heating by Reaction Type



Beta Decay

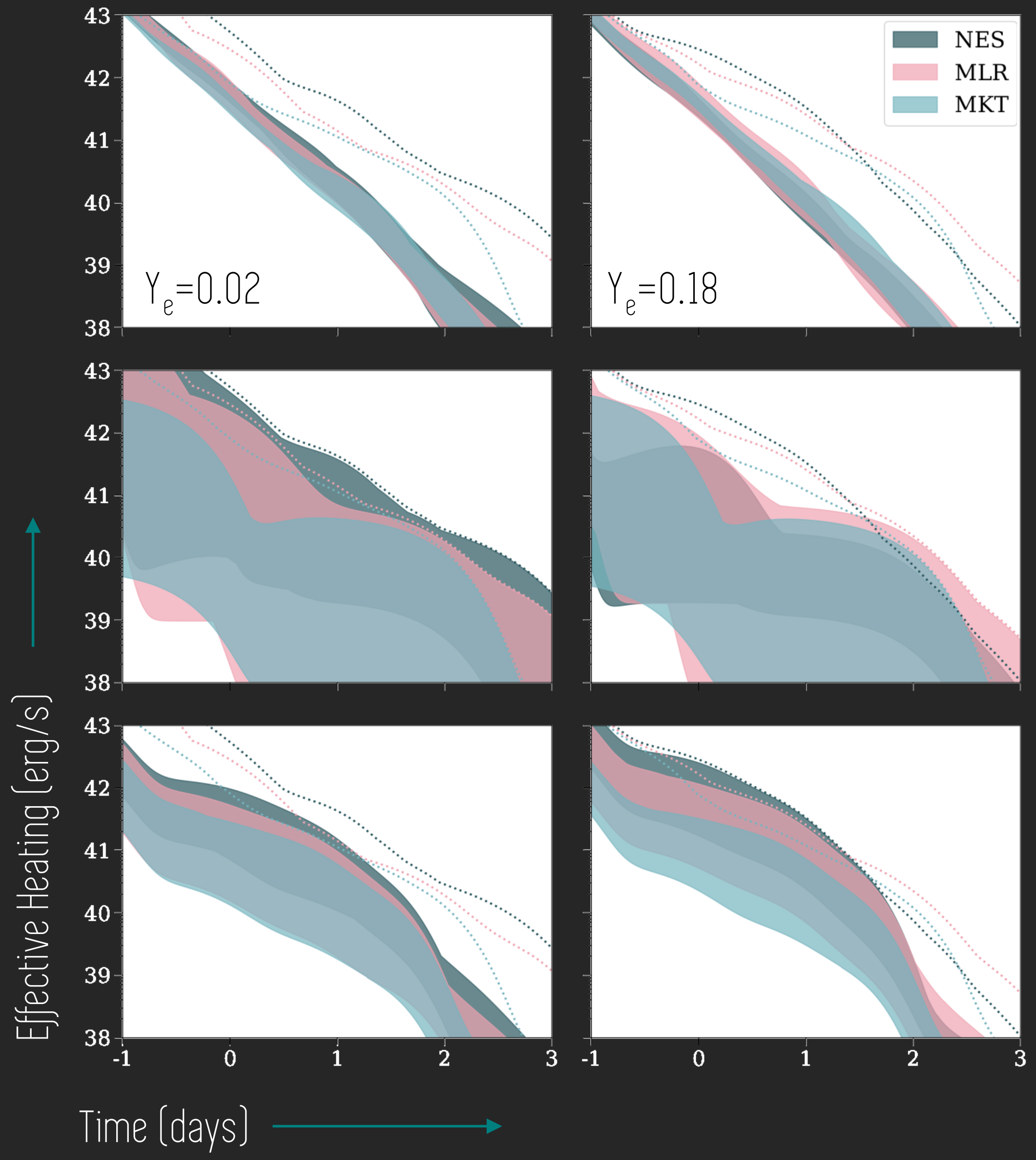
Spontaneous Fission

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



Beta Decay

Spontaneous Fission

Alpha Decay

- Alpha heating becomes more important <100 days

- Beta models differ in predicting when alpha tends to dominate + late-time tail shape of fission heating

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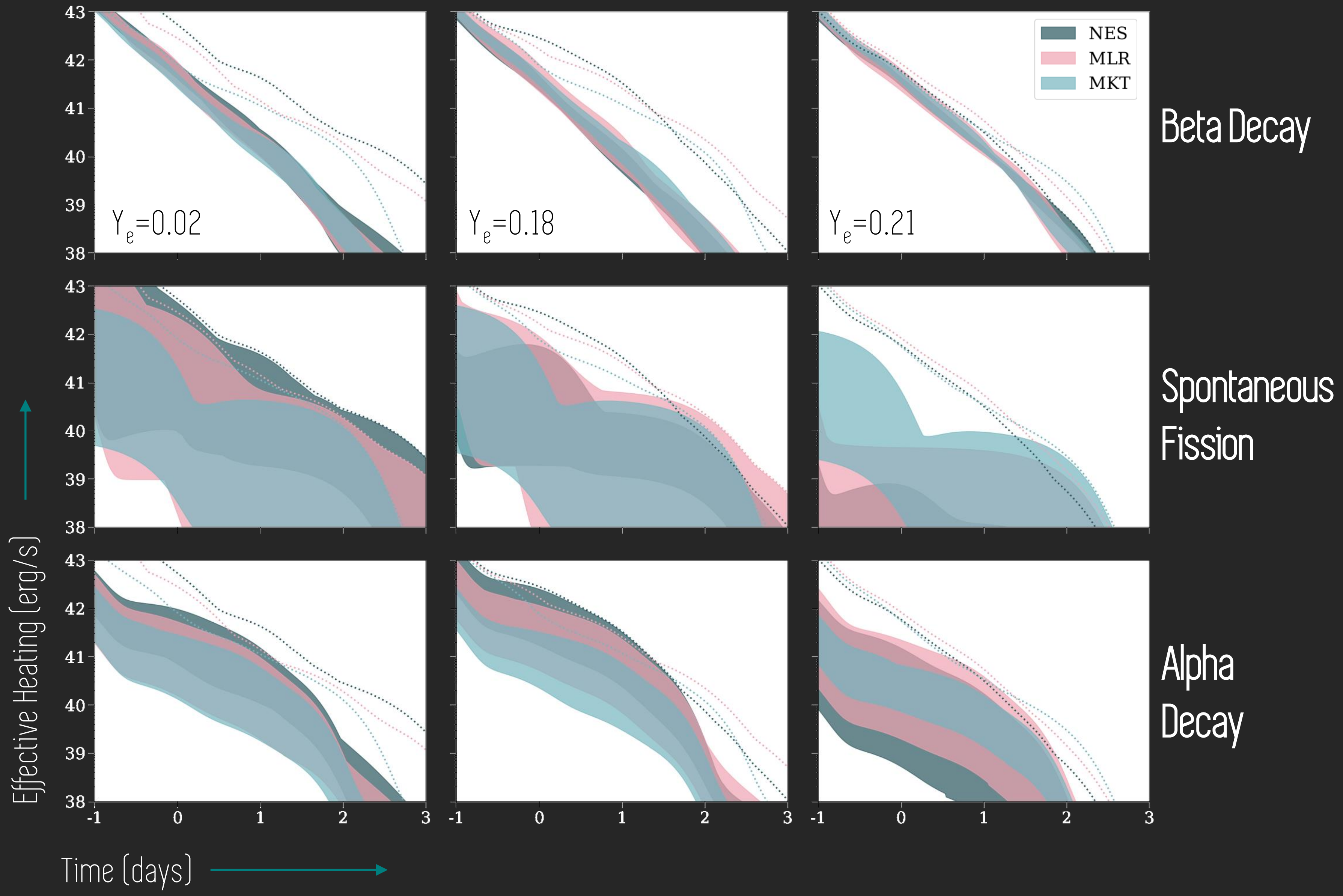
Nuclear Heating by Reaction Type



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

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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:

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

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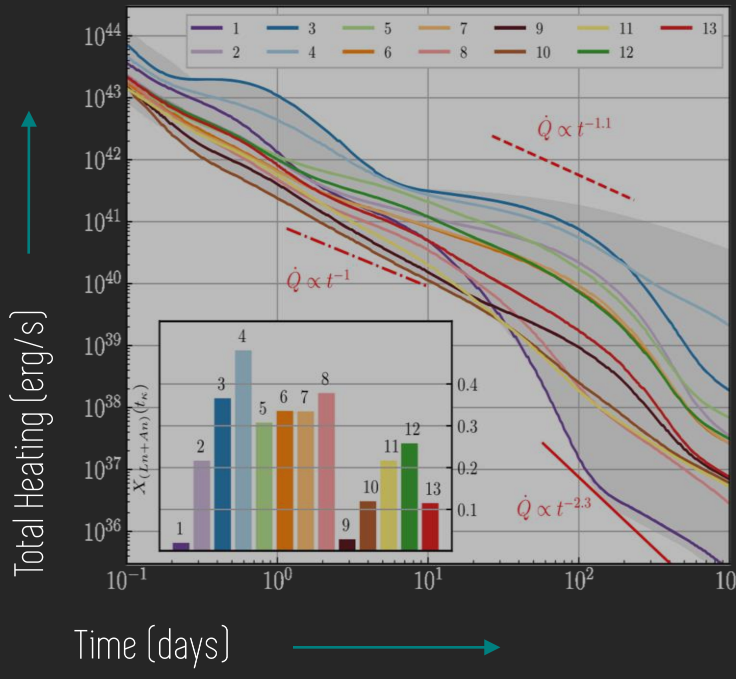
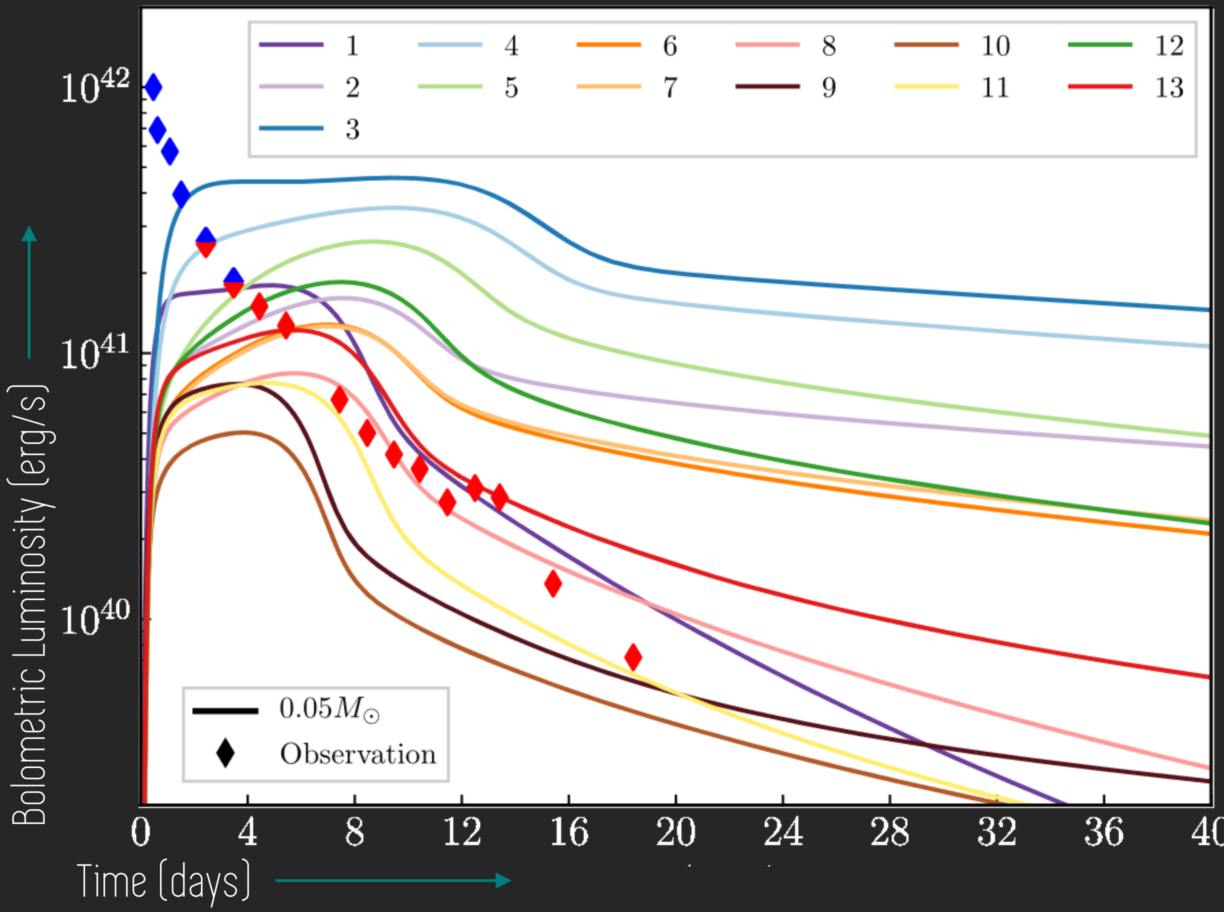
Light Curves

- Differences in nuclear heating predictions propagate through to light curve
- Overall magnitude of luminosity ~ overall heating BUT peak depends on ejecta opacity
- For a given effective heating rate, higher $\chi_{\mathrm{Ln+An}}$ elongates curve



Adapted from Zhu, **Lund+** 2021)



Adapted from Zhu, **Lund+** 2021)

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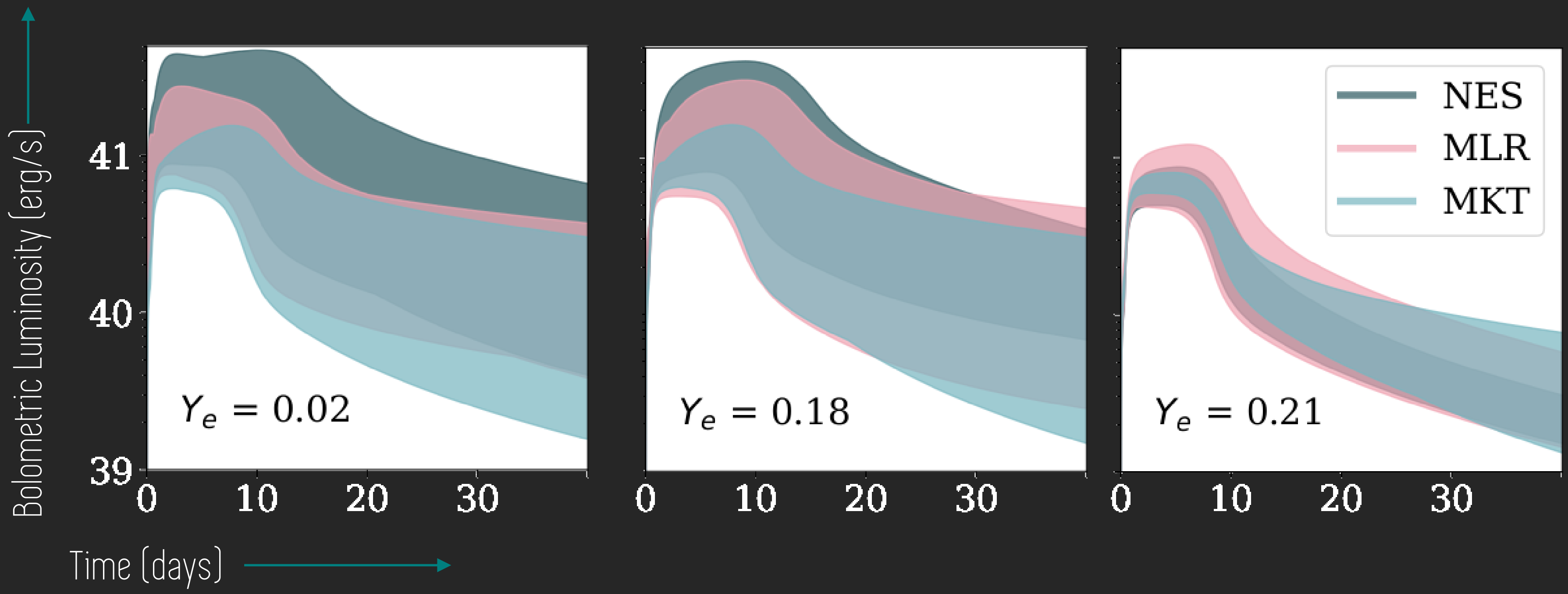
Light Curves



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

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

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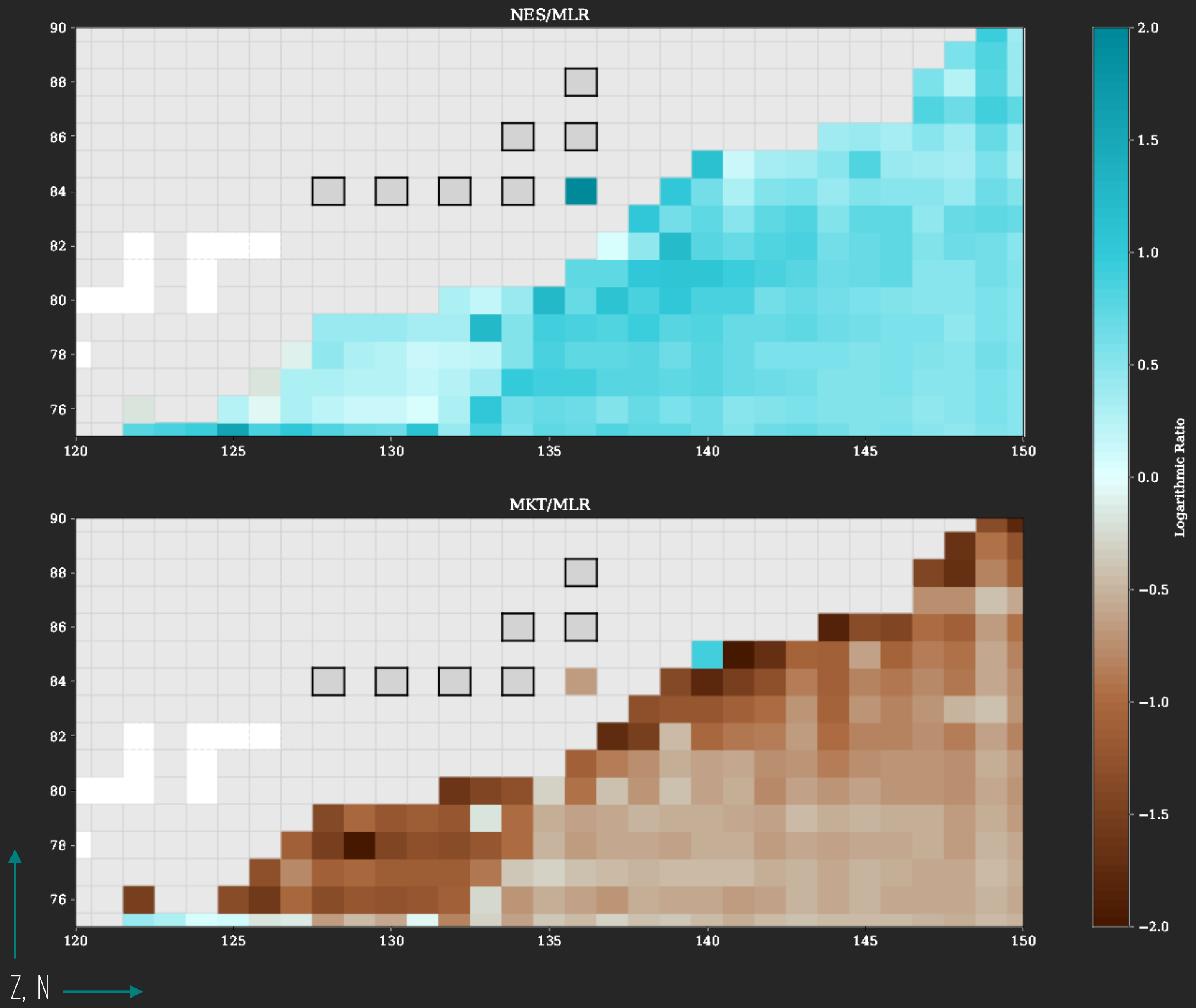
Nuclear Heating (revisited)

Alpha Decay Heating



Differences in beta decay rates affect heating from alpha heaters with measured decay times, especially:

^{224}Ra

^{220}Rn ^{222}Rn

^{212}Po ^{214}Po ^{216}Po ^{218}Po

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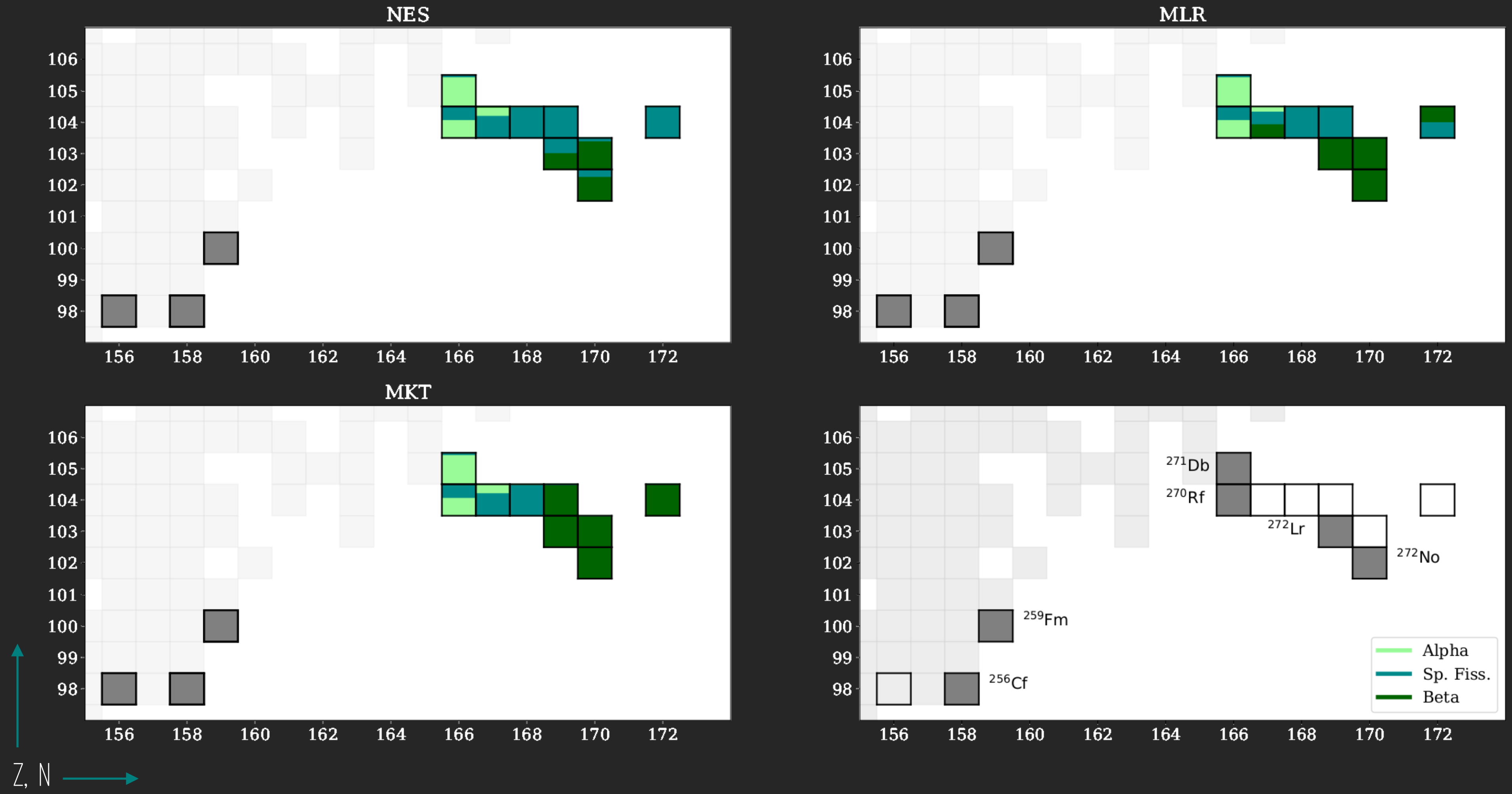
Spontaneous Fission (et al.) Heating

Theoretical branching ratios affect spontaneous fission heating



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Grazie!