Remnants of Neutron-Star Mergers
Connecting hydrodynamics models to nuclear, neutrino, and kilonova physics
Darmstadt, Germany

arXiv: 2208.06373
2010.03668
2010.11182

Key Uncertainties in Astrophysical r-Process Nucleosynthesis

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19 October 2022

In collaboration with G. McLaughlin, Y. Zhu, J. Barnes and many others

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FIRE Fission In R-process Elements
Seaborg Institute
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Scope

Nucleosynthesis calculations — probe — Uncertainties from unknown nuclear properties of nuclei far from stability — on:

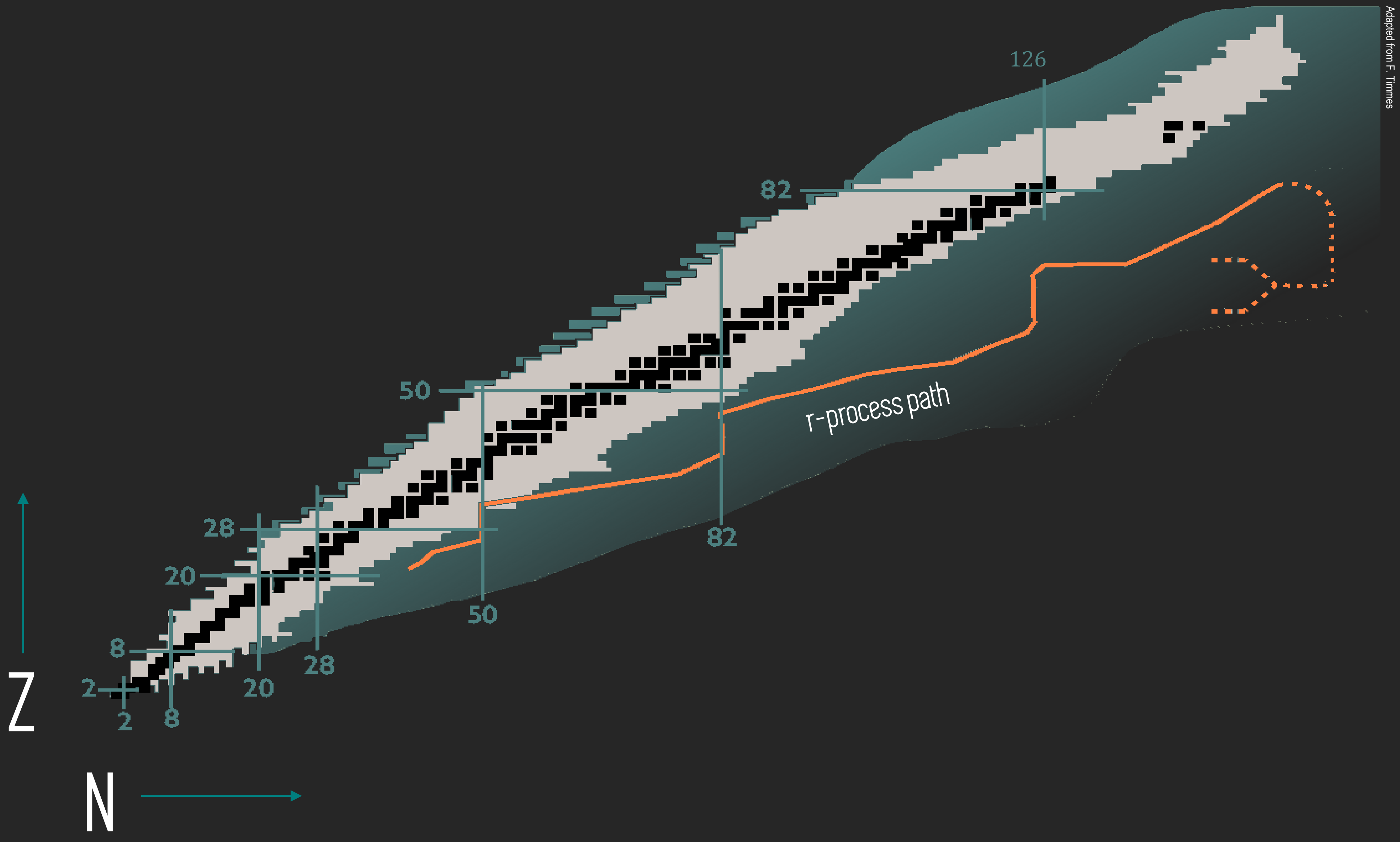
- Abundance patterns
- Nuclear energy generation
- Light curve evolution

arXiv: 2208.06373, 2010.03668, 2010.11182

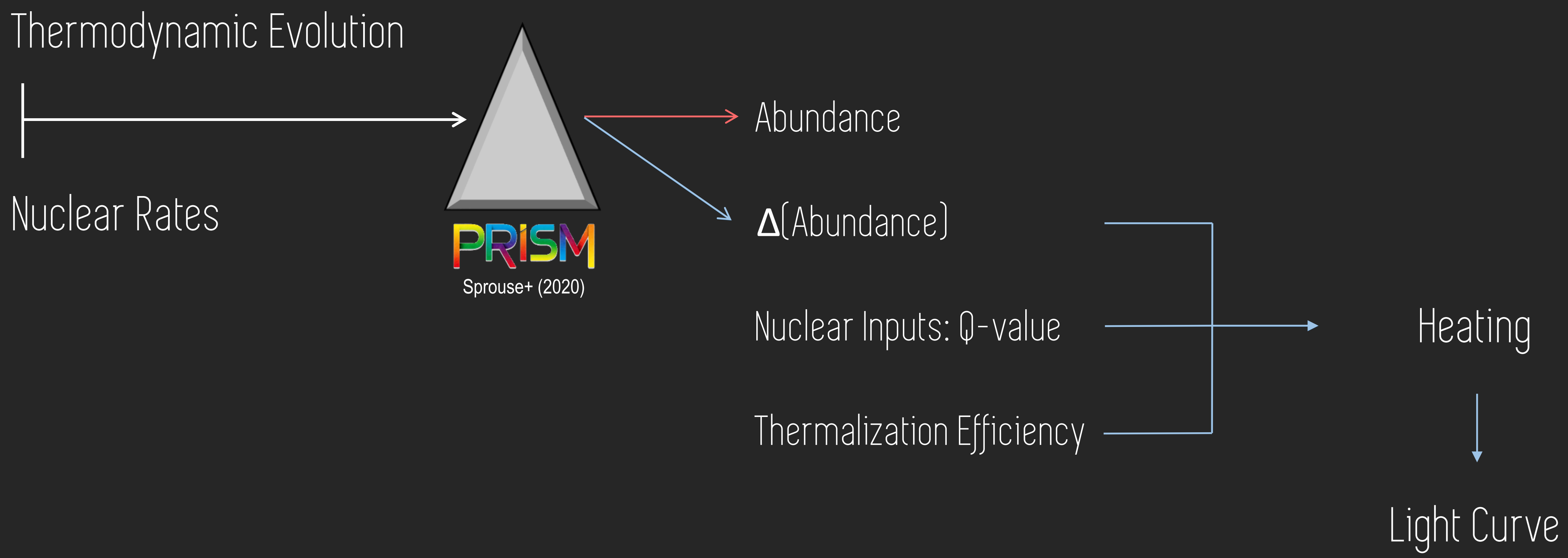
Sources of Nuclear Uncertainty

See also, e.g.
- Mumpower+ 2016
- Vassh+ 2019
- Giuliani+ 2020
- Nikas+ 2020
- Wang+ 2020
- Zhu+ 2021
- Barnes+ 2021
- Kullmann+ 2022

and many others



PRISM: A Sparse Matrix Solver



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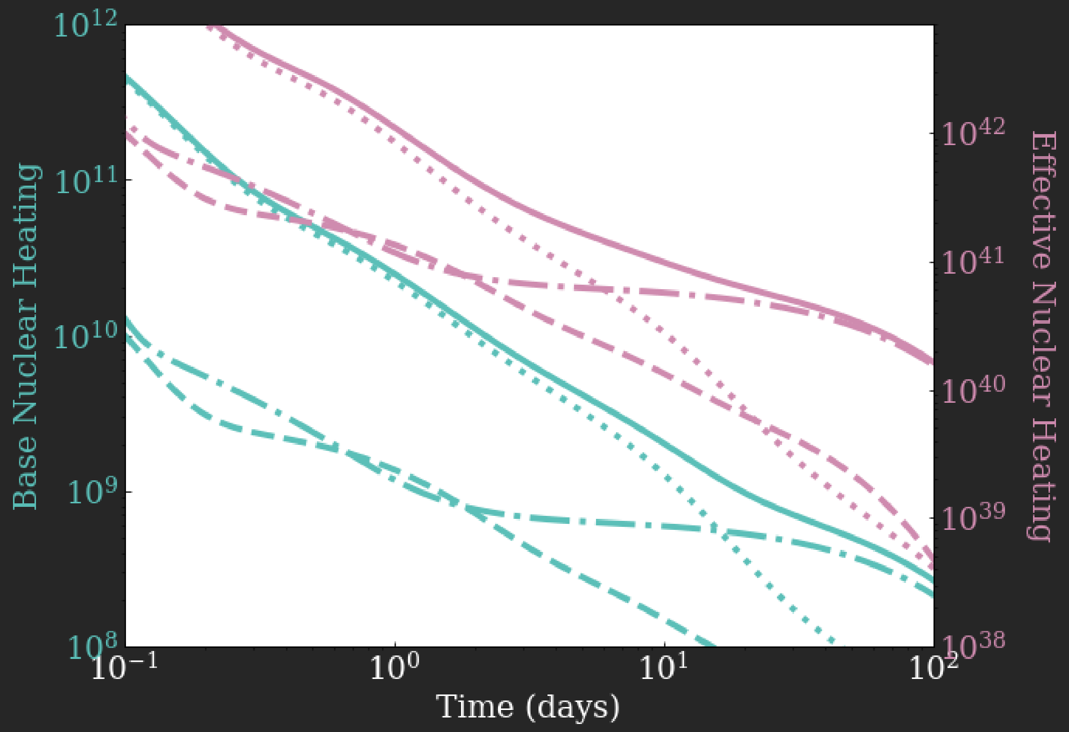
Nuclear Heating



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

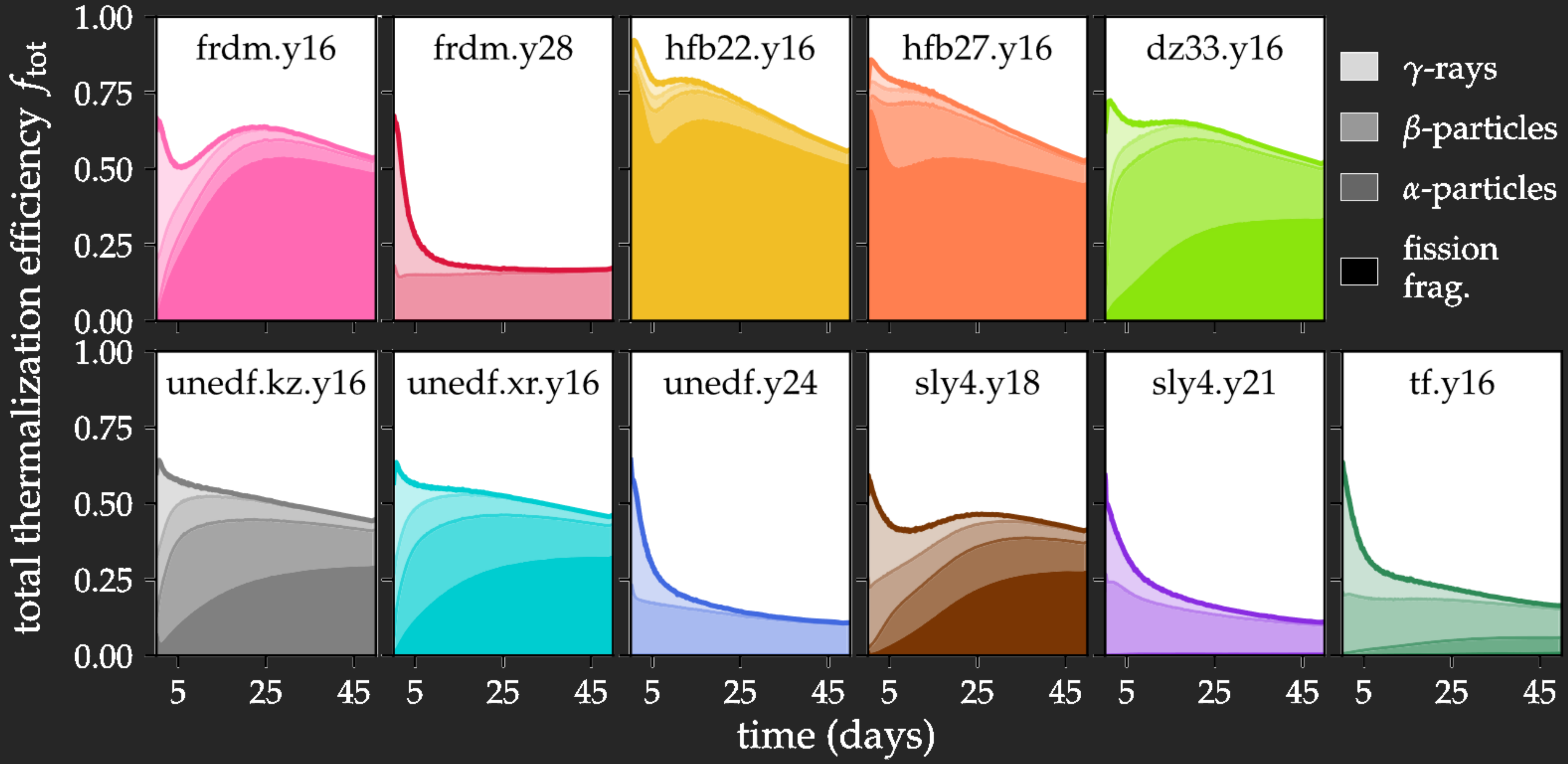
Total effective heating | Thermalization efficiency | Nuclear Heating | Ejecta mass

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

Thermalization based on Kasen & Barnes (2019)

Nuclear Heating

See Barnes+ 2021



Light Curve Shell Model

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:

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

Luminosity: $\frac{E_v}{t_{d,v} + t_{lc,v}}$

Effective heating: $\frac{M_v}{M_{ej}}\dot{Q}(t,v)$

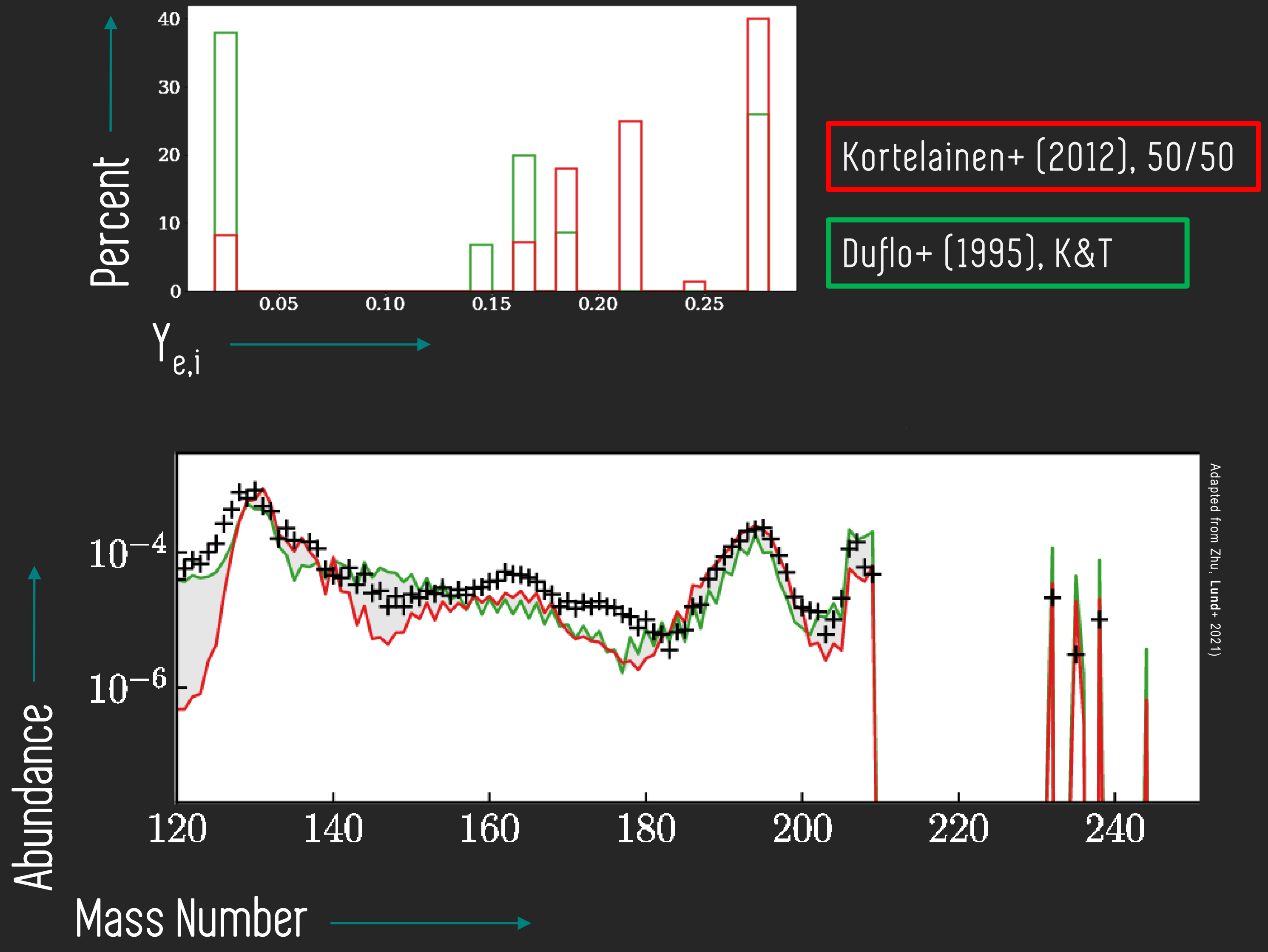
Adiabatic expansion: $\frac{E_v}{t}$

Diffusion timescale (depends on opacity): $t_{d,v}$

Light-crossing timescale: $t_{lc,v}$

Combined Trajectories

Finding a Linear Combination

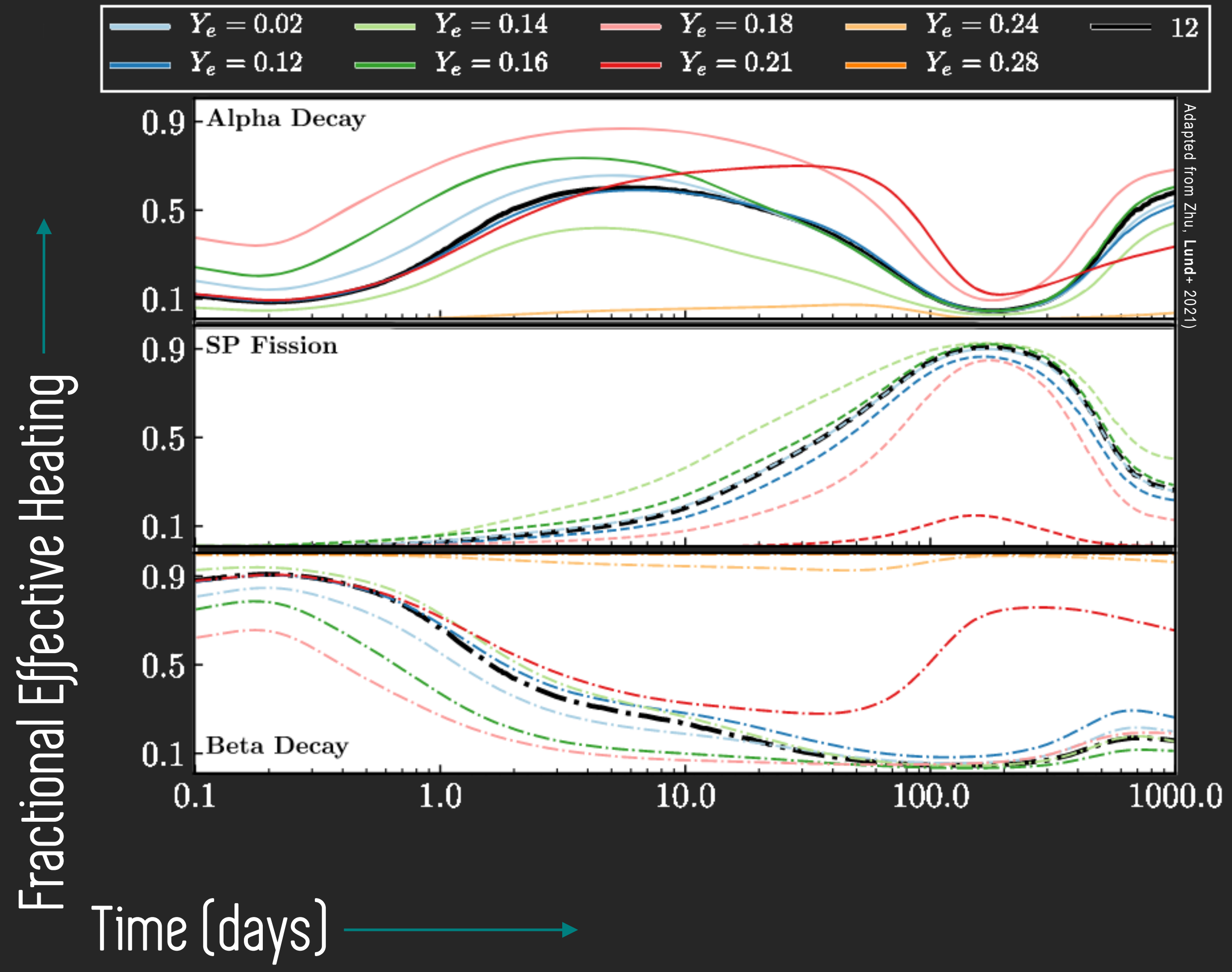


Linear combination to fit to solar abundance pattern.

- Select from single-Y_e trajectories [0.02-0.28]
- Necessary to combine low *and* high Y_e material

Fractional Nuclear Heating

DZ33 + K&T



Fractional Nuclear Heating

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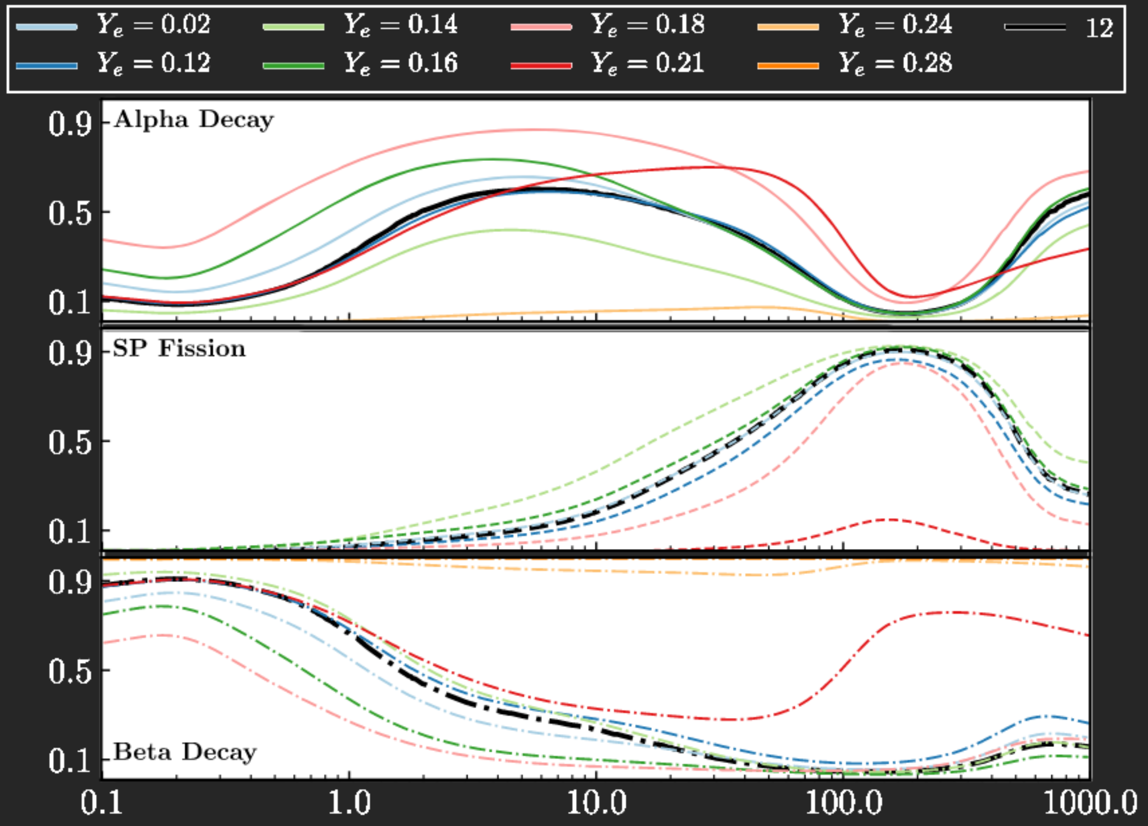
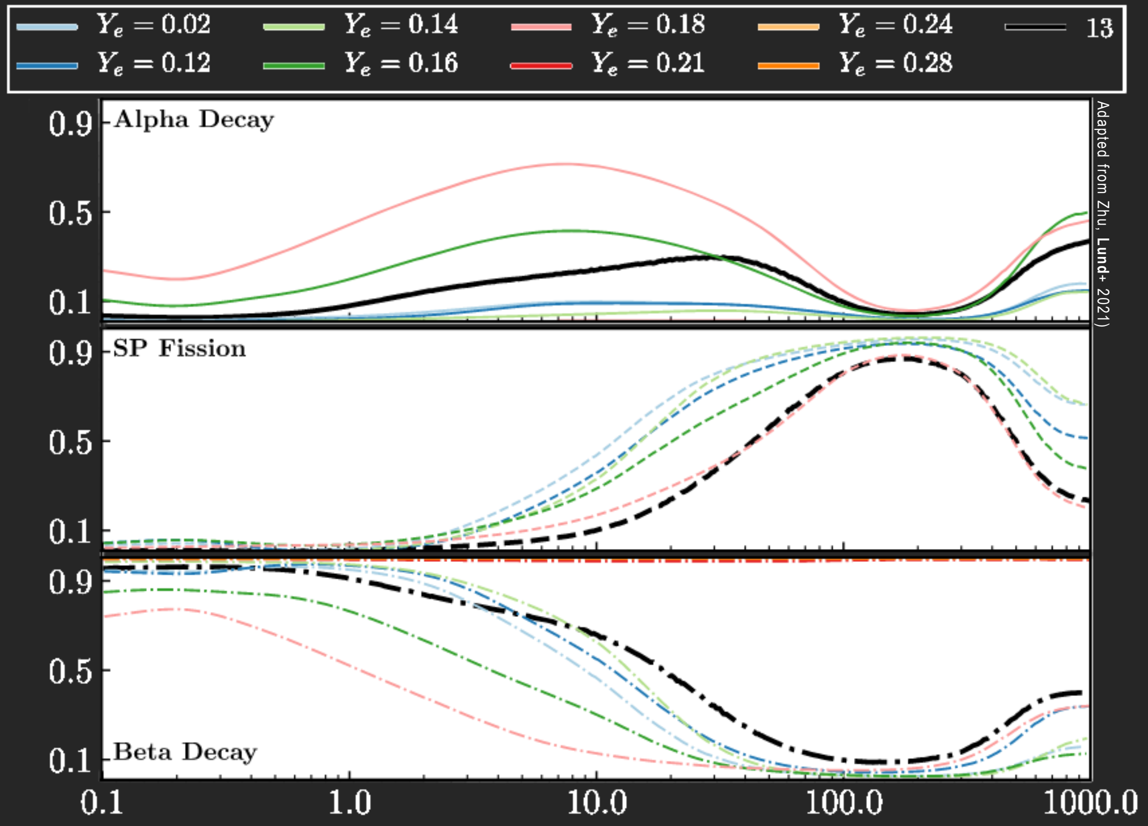
DZ33 + K&T



UNEDF1 + 50/50



Fractional Effective Heating

Time (days)

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Single-Ye Trajectories

Astrophysical Uncertainty: Initial Y_e

Single Trajectory:

0.02

Large potential for fission cycling

0.18

Interesting reaction competition

0.21

r-Process but minimal fission

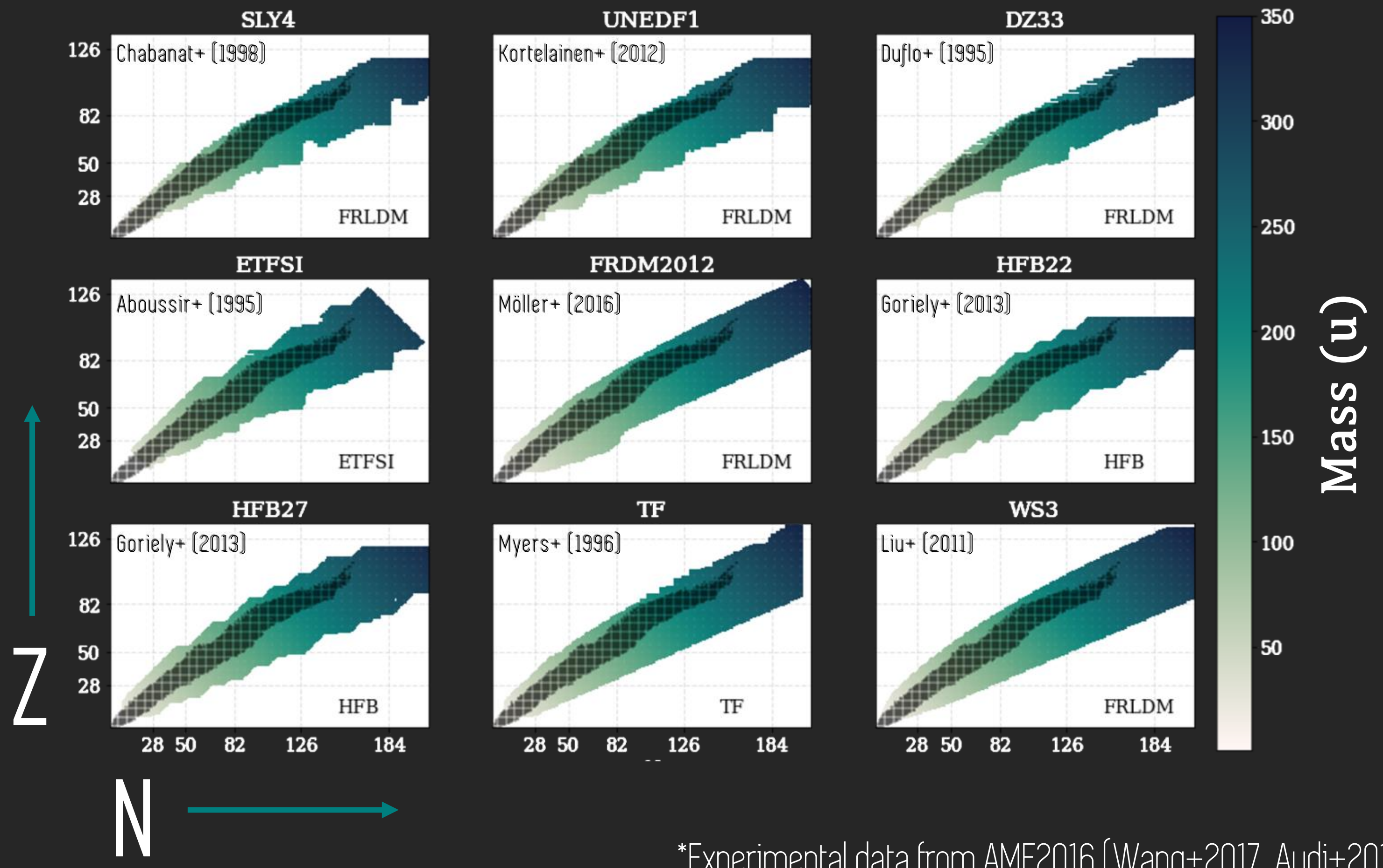
← More neutron rich

Less fission →

Nuclear Uncertainty: Mass Model

Most basic nuclear property: mass

Each mass model associated with fission barrier height model



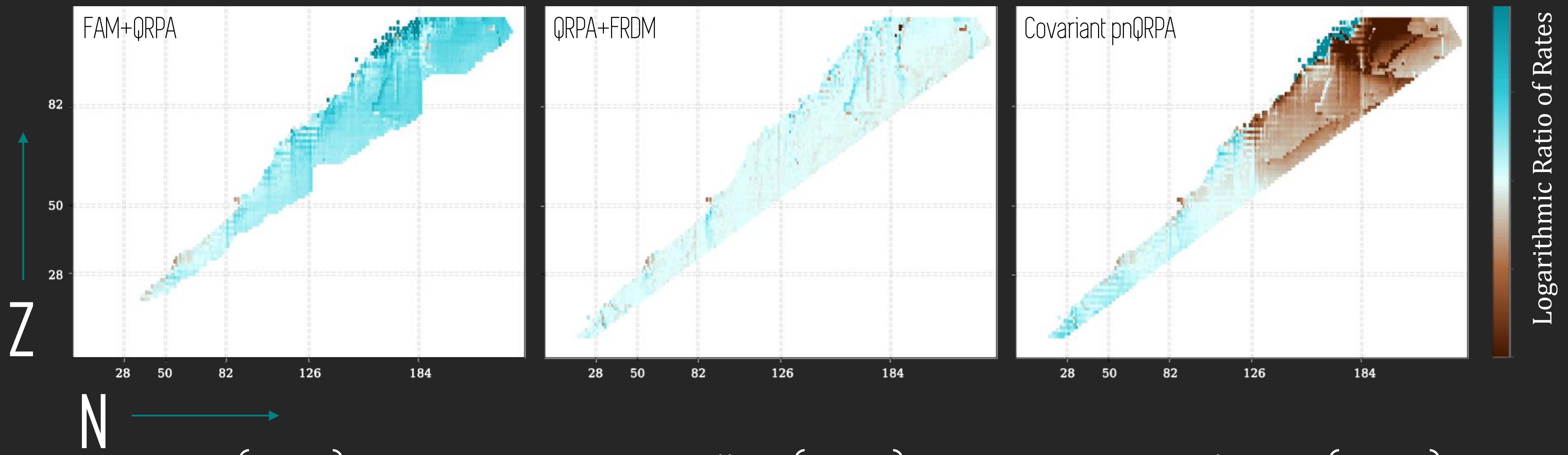
*Experimental data from AME2016 (Wang+2017, Audi+2017)

Effect of nuclear mass: Mendoza-Temis+2015, Mumpower+2015,2016, Barnes+2016, Wu+2019, Nikas+2020, Zhu+2021, Barnes+2021, Kullmann+2022

Nuclear Uncertainty: Beta Decay Rates

~ slower rate*

Logarithmic ratio compared to Möller+ 2003



Ney (NES)

Ney+ 2020

Möller (MLR)

Möller+ 2019

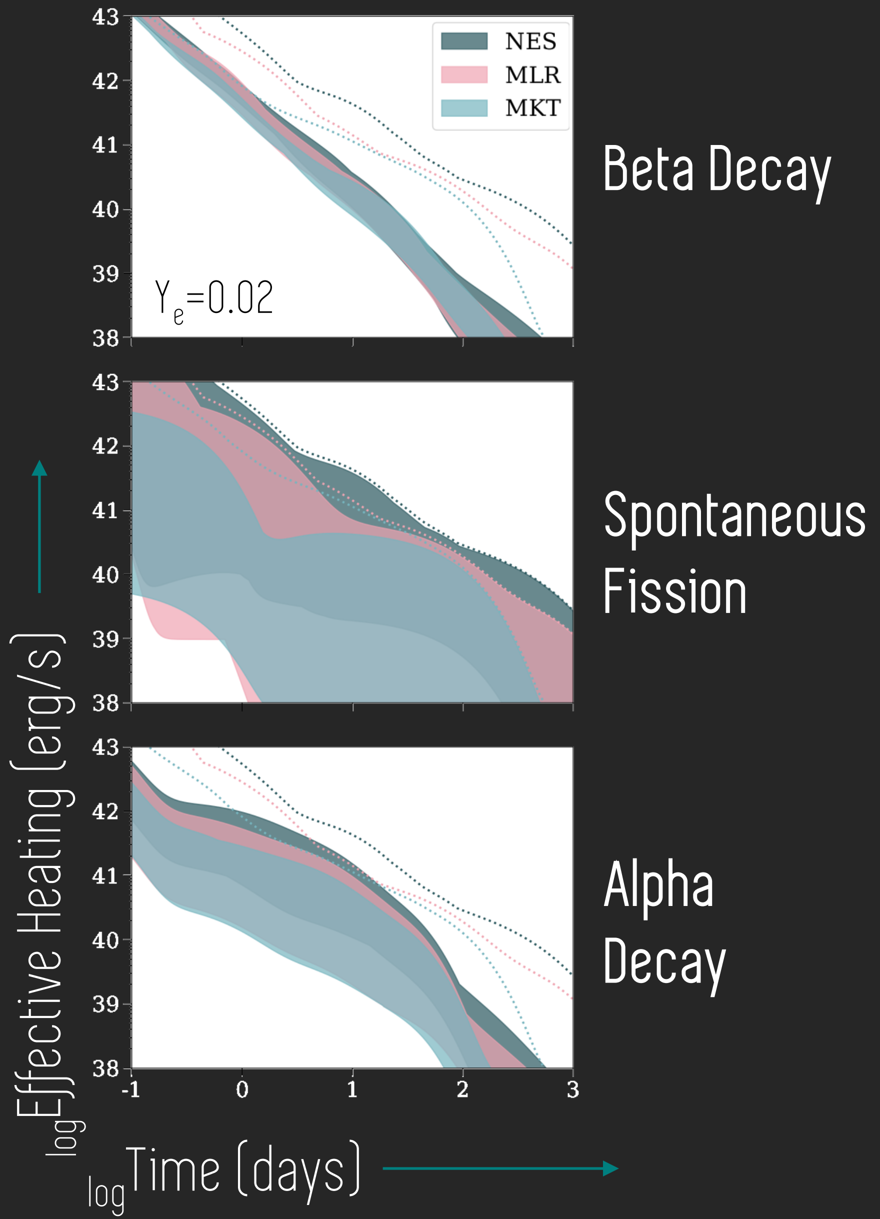
Marketin (MKT)

Marketin+ 2016

Effect of beta decay rates: Marketin+ 2016, Nikas+ 2020, Kullmann+ 2022

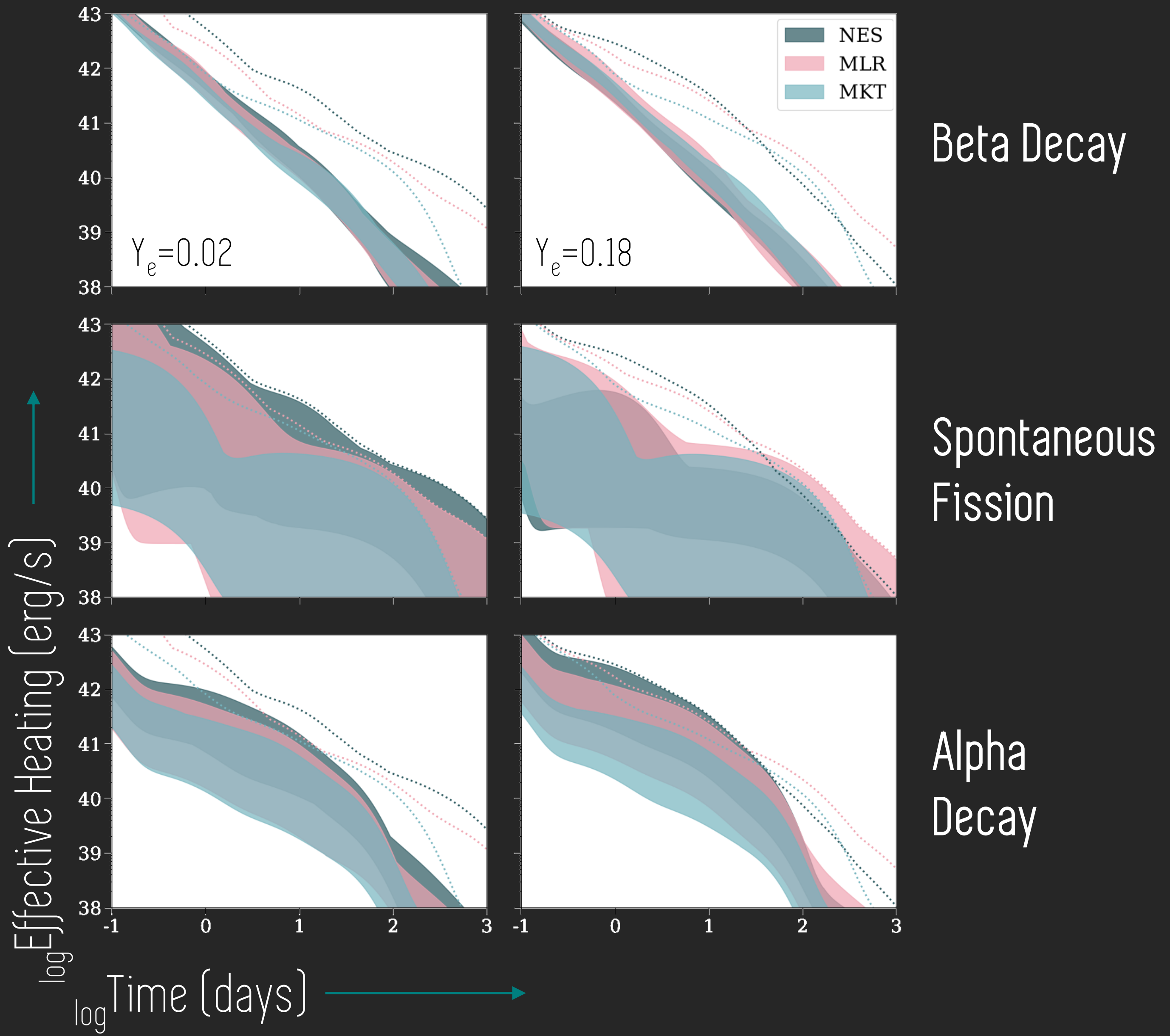
Nuclear Heating

Nuclear Heating by Reaction Type



- Upper limit of heating uncertainty can be set by fission
- Beta models differ in behavior of dominating fission heating

Nuclear Heating by Reaction Type



- Alpha heating becomes more important 10-100 days
- Beta models differ in predicting when alpha tends to dominate heating+ late-time tail shape of fission

Nuclear Heating by Reaction Type

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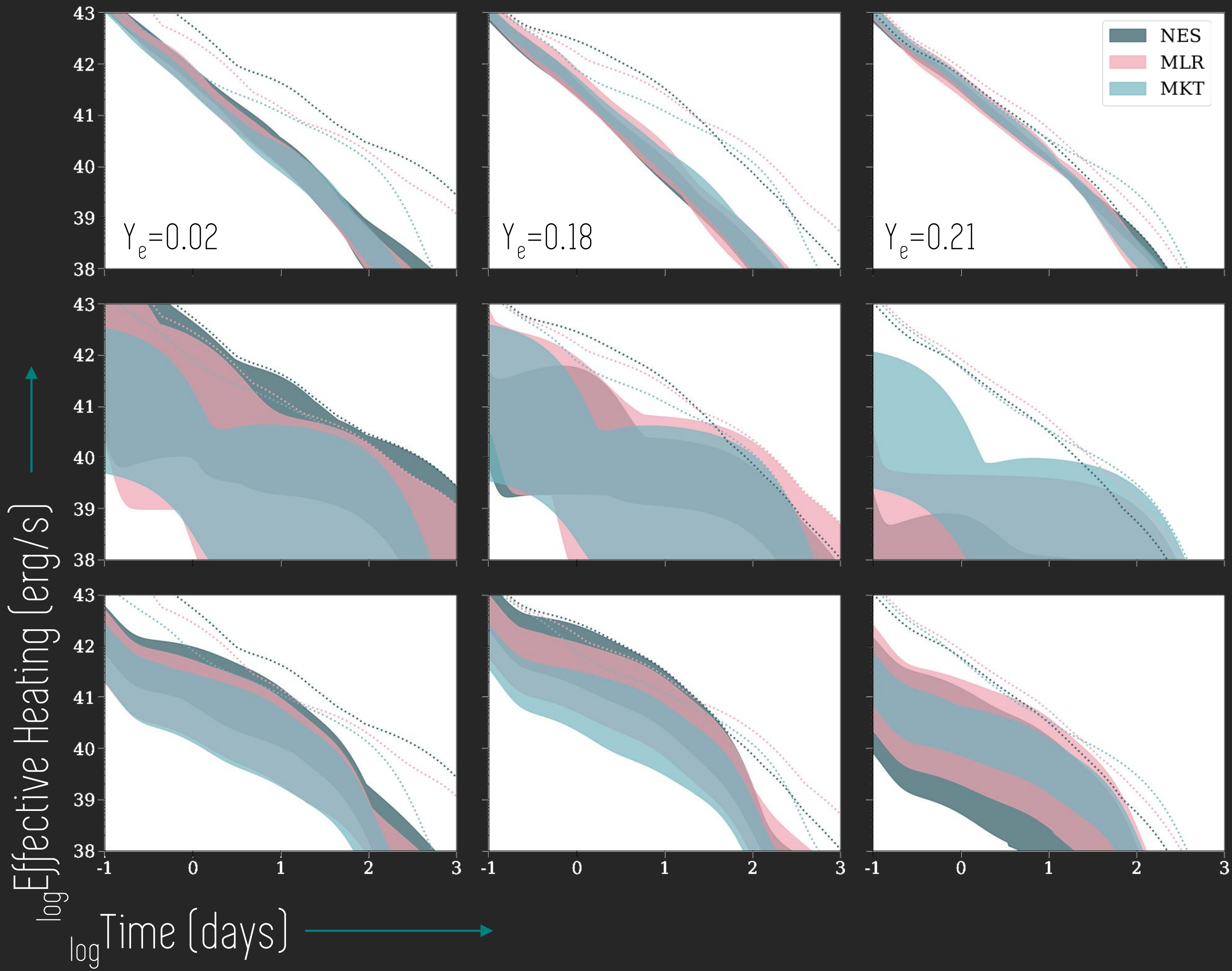

Beta Decay

Sp. Fission

Alpha Decay

- Much more overlap, total heating tends to be set by beta, then alpha decay

- Overall effect on beta decay heating is small

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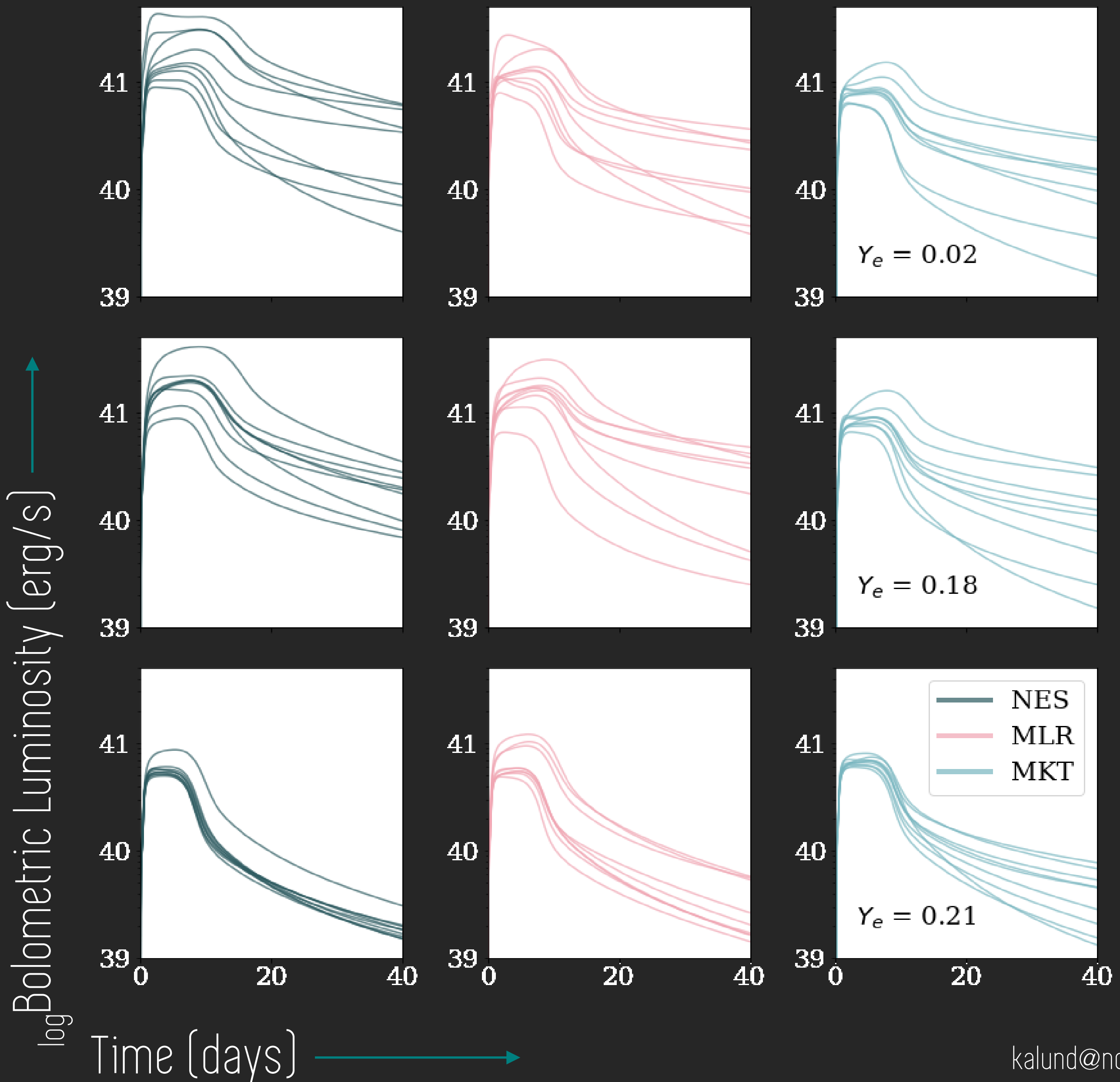
Light Curve

Light Curves



Diversity in heating sources changes shape of light curves

Generally slower rates (NES) yield more heating and brighter light curves

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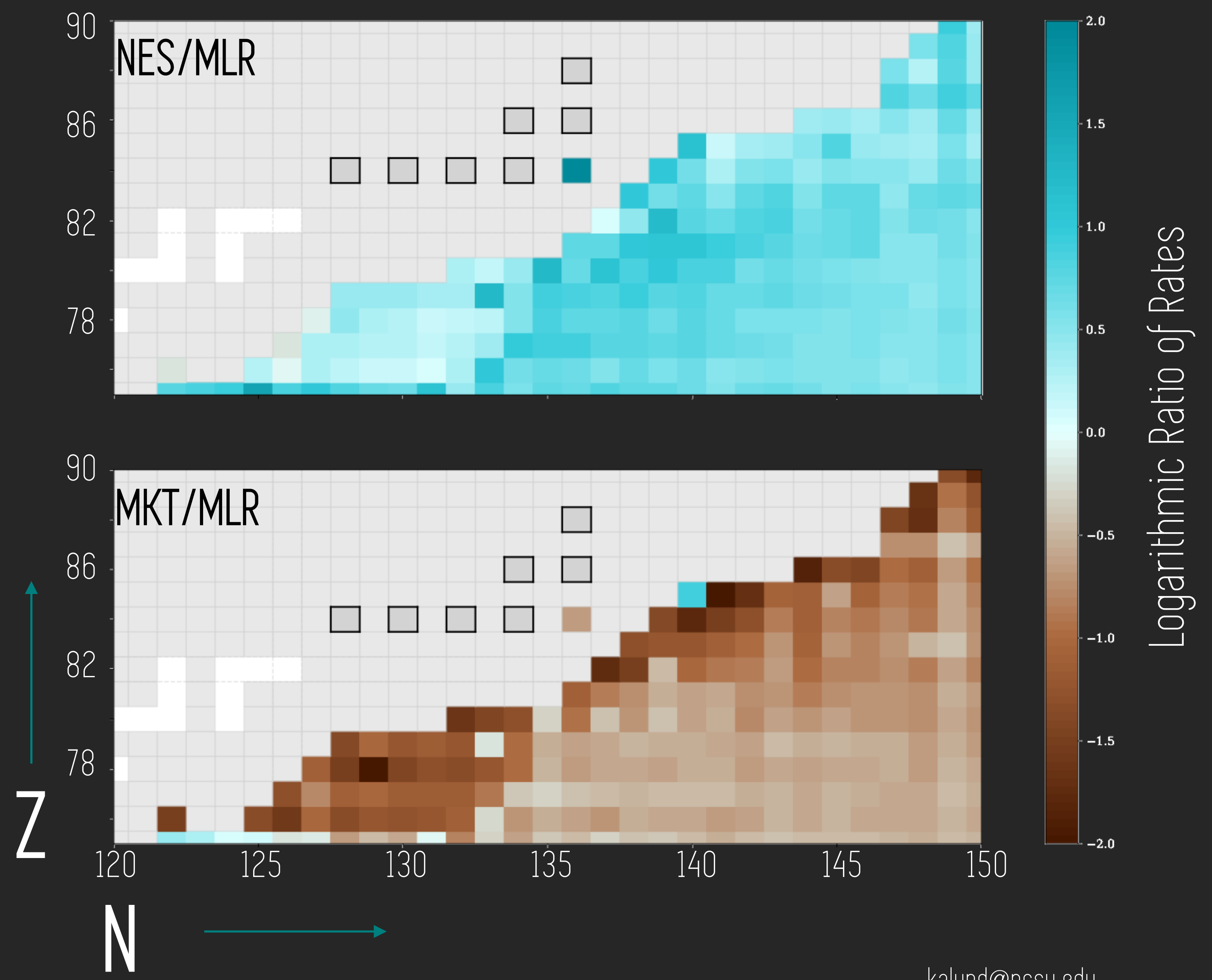
Nuclear Heating (revisited)

Alpha Decay Heating



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

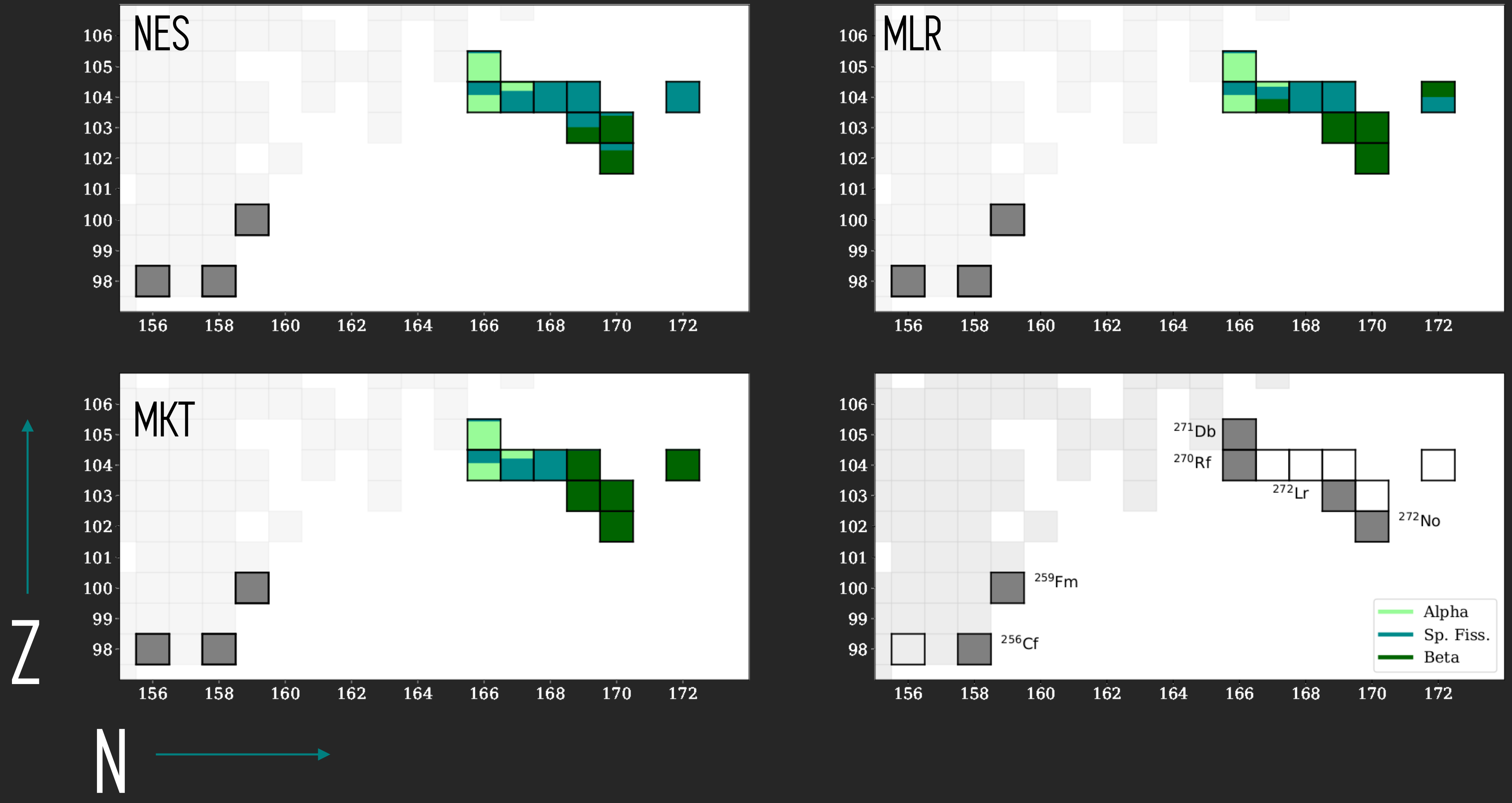
^{224}Ra

^{220}Rn ^{222}Rn

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

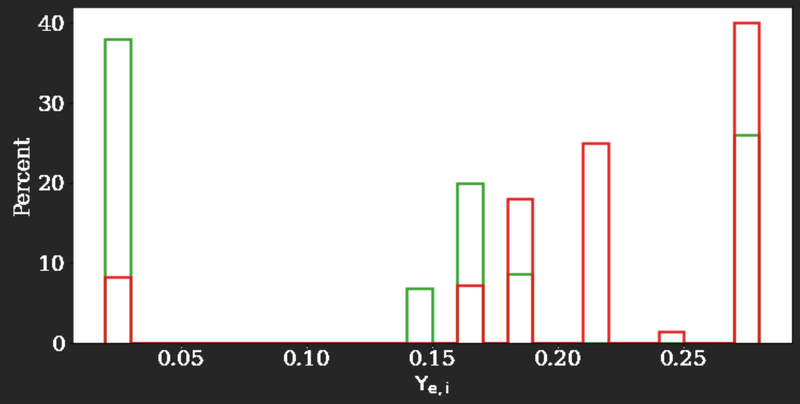
Spontaneous Fission (et al.) Heating

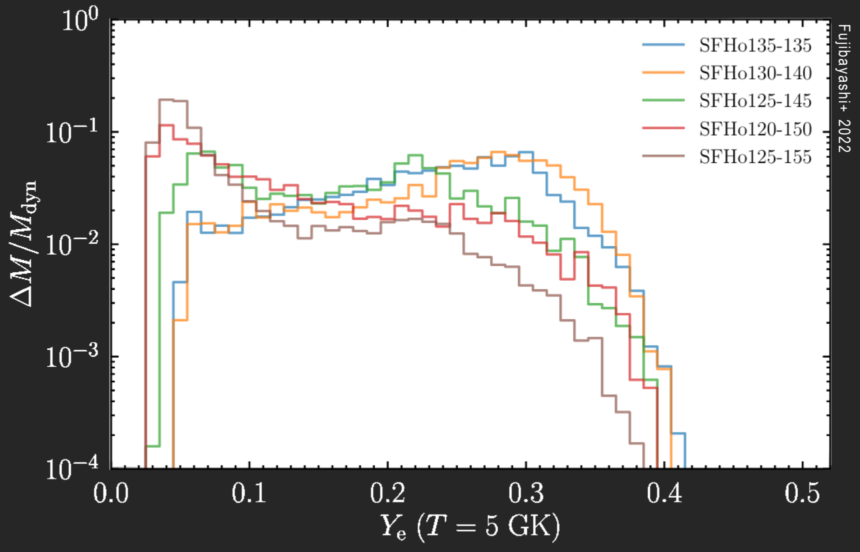
Theoretical branching ratios affect spontaneous fission heating



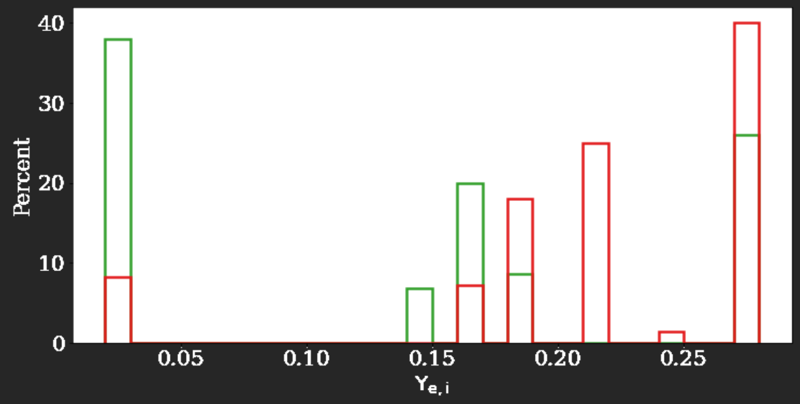
Combined Trajectories (revisited)

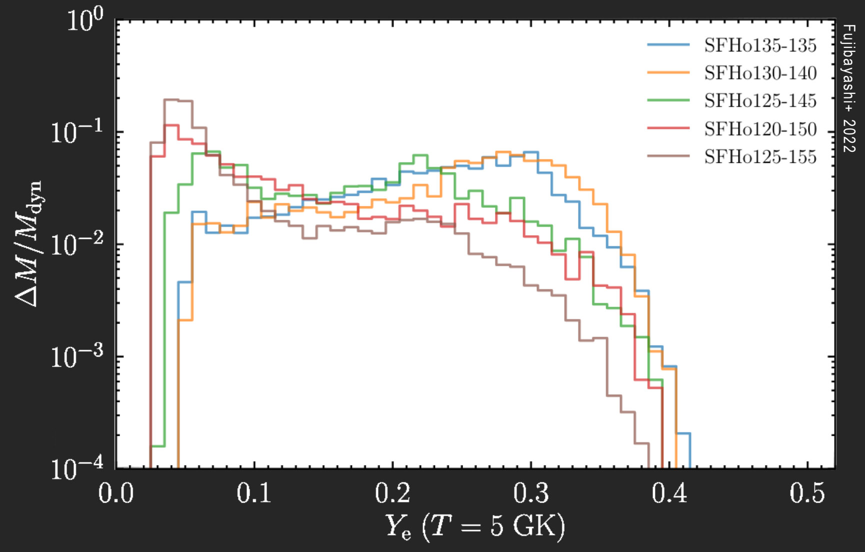
Multiple Y_e components

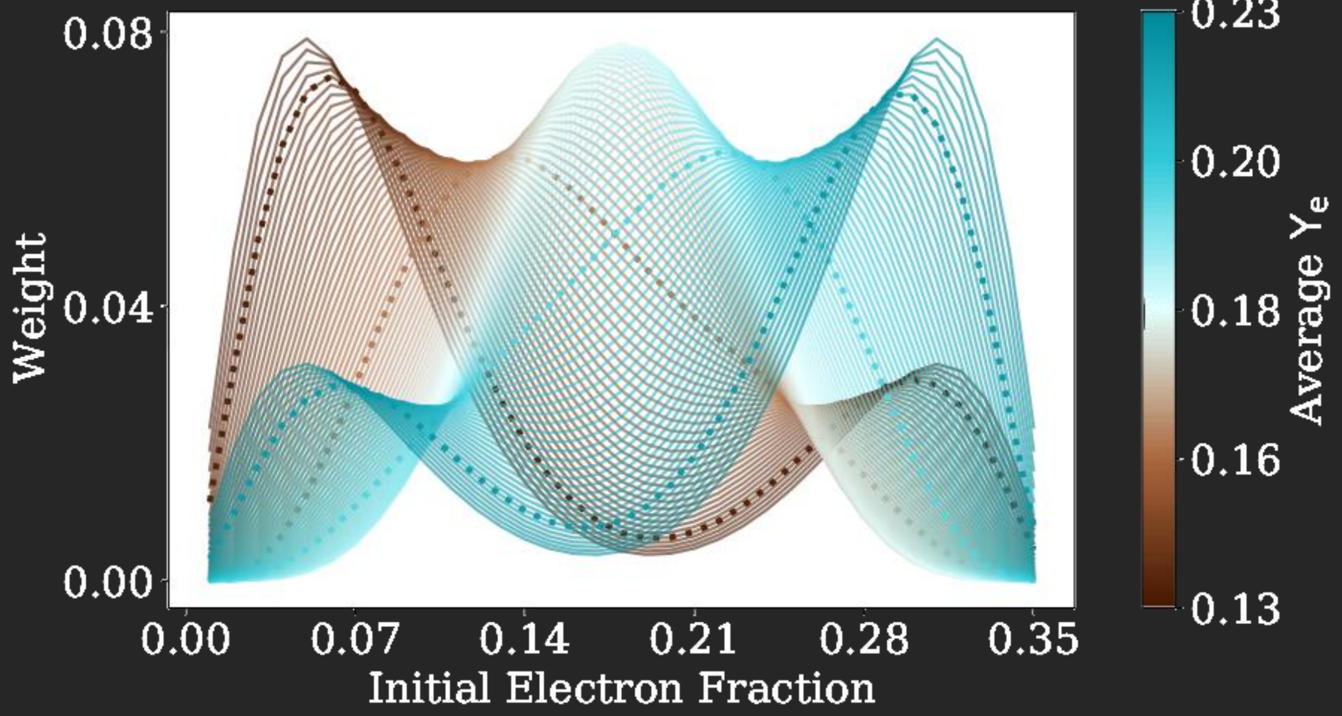




Multiple Y_e components







Astronomical Sample

Increasing actinide enhancement ↓

Star Name	$\log_\epsilon(\mathrm{Eu})$	$\log_\epsilon(\mathrm{Th})$	$\log_\epsilon(\mathrm{U})$	Reference
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

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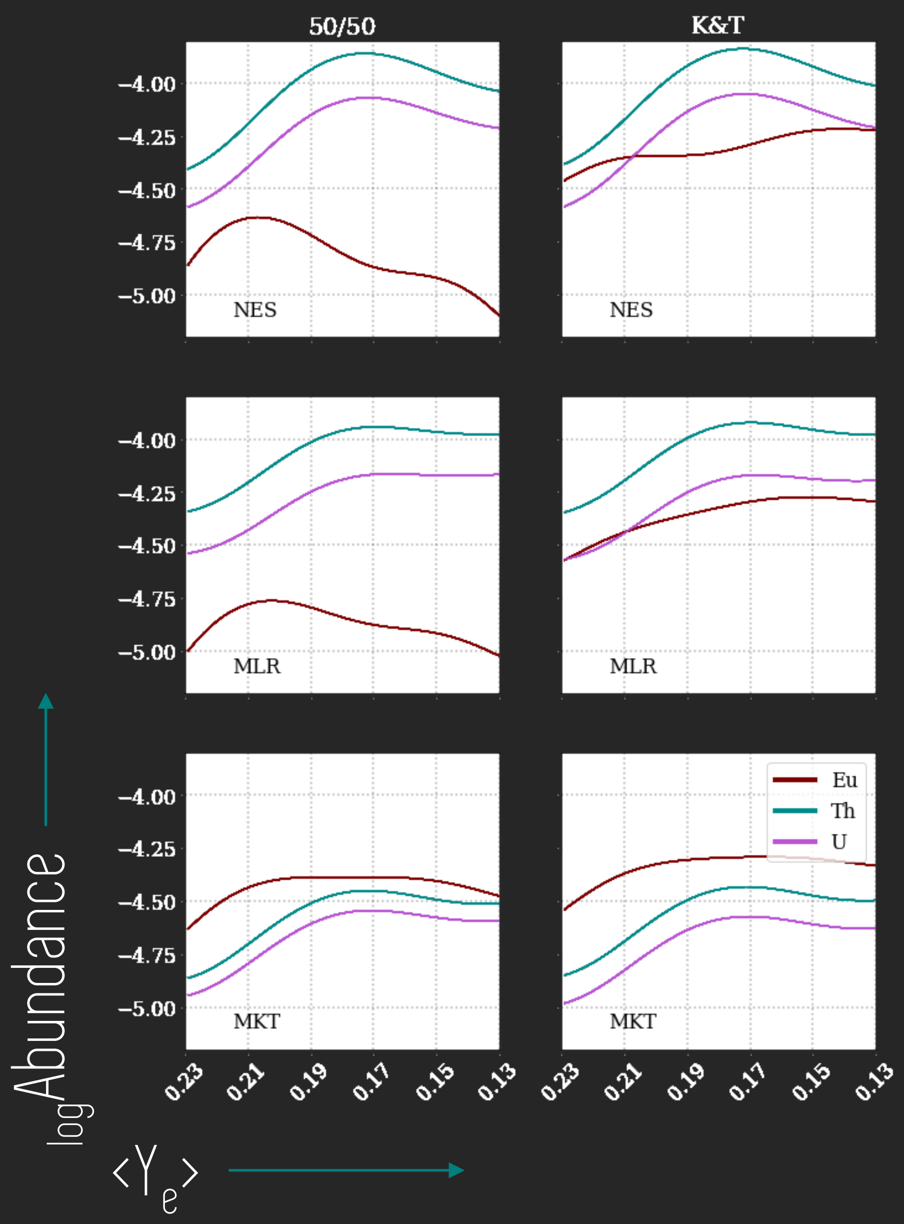
Abundances for Cosmochronometry



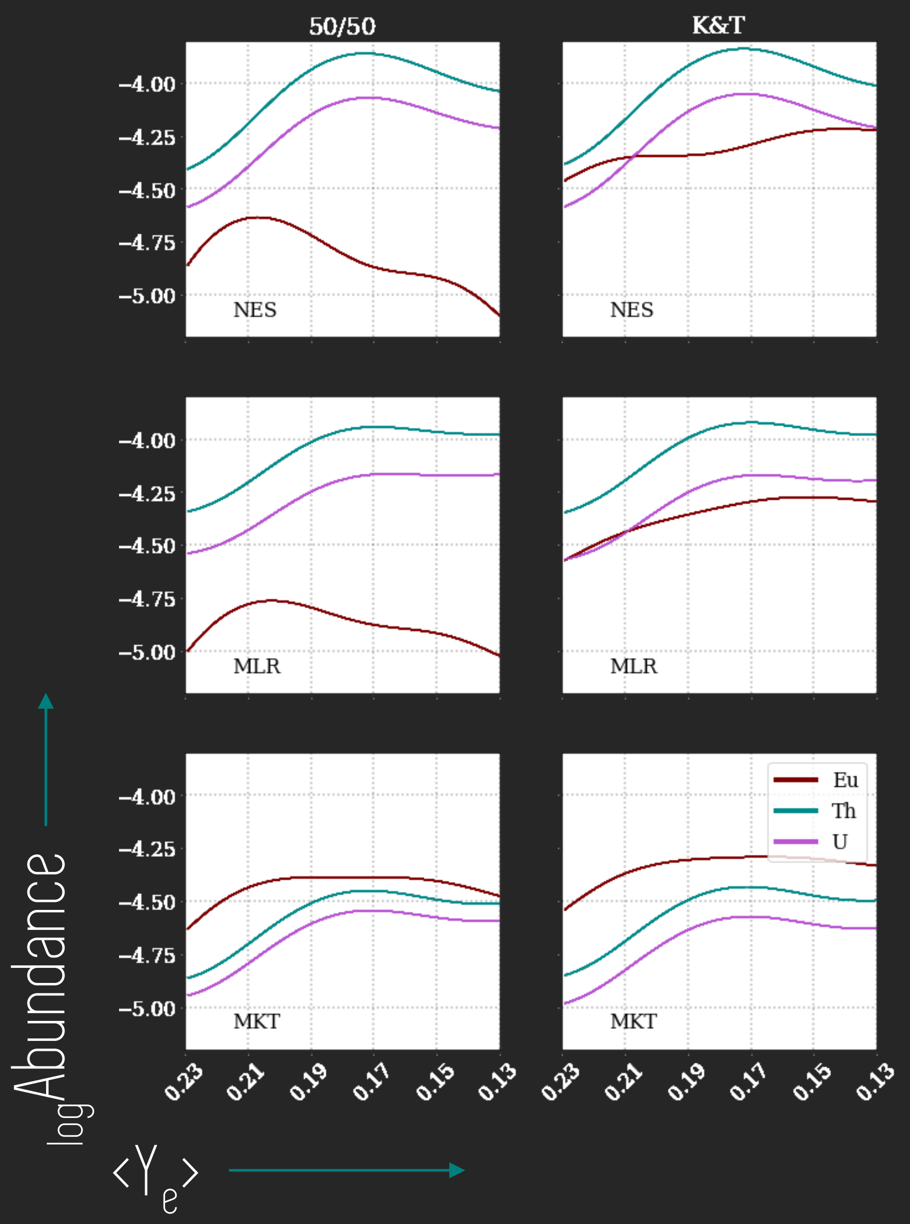
$$t = 46.67\text{Gyr}\left[-\,log_{\epsilon}\left(\frac{\text{Th}}{\text{Eu}}\right)_{\text{obs}} + log_{\epsilon}\left(\frac{Th}{Eu}\right)_{0}\right]$$

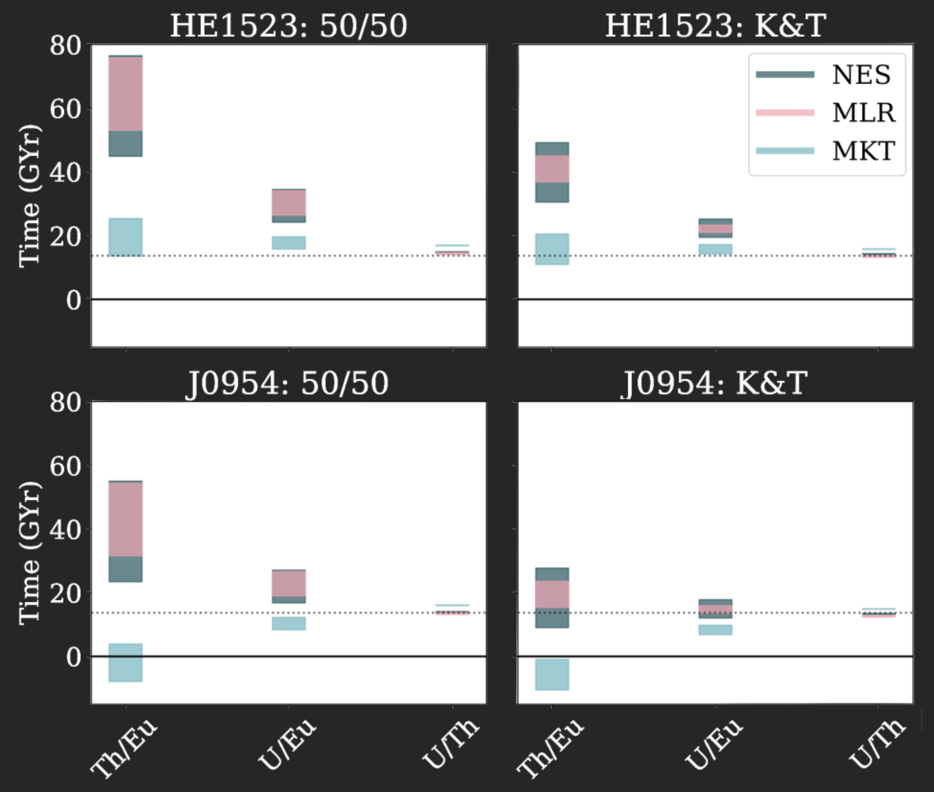
$$t = 14.84\text{ Gyr}\left[-\,log_{\epsilon}\left(\frac{\text{U}}{\text{Eu}}\right)_{\text{obs}} + log_{\epsilon}\left(\frac{\text{U}}{Eu}\right)_{0}\right]$$

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

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

Abundances for Cosmochronometry

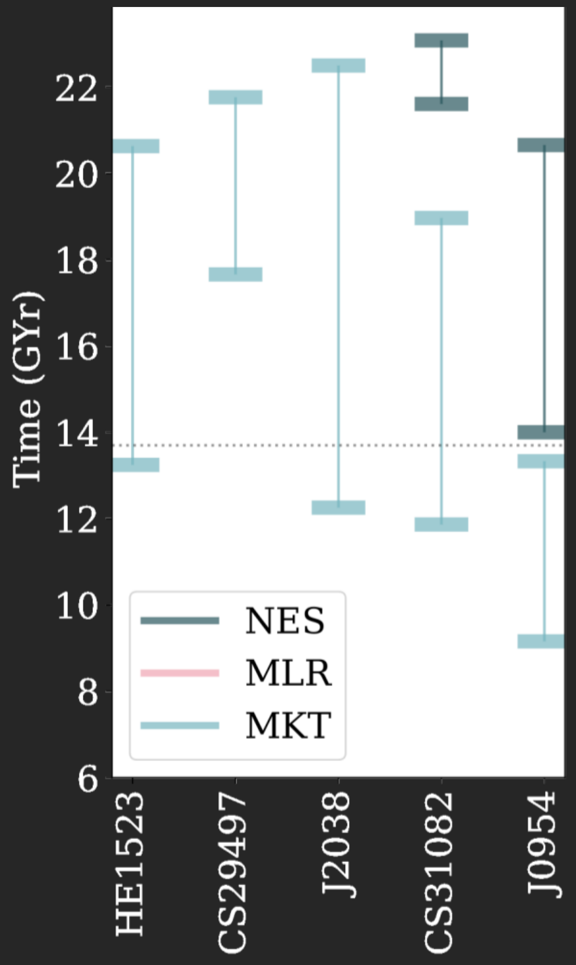




- Europium production highly sensitive to average Ye and fission yield
- Underabundance of actinides can lead to negative age predictions

Error Bars from Observations

50/50



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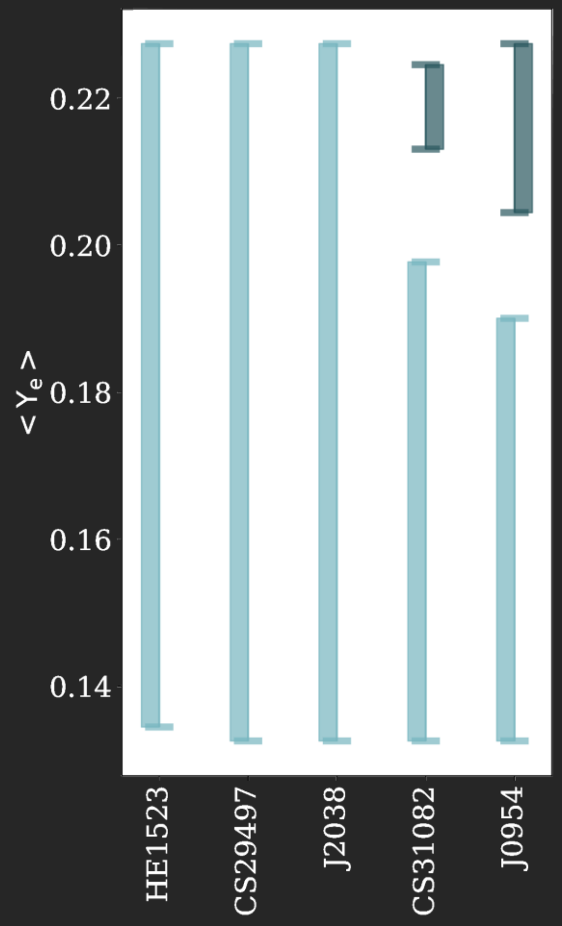
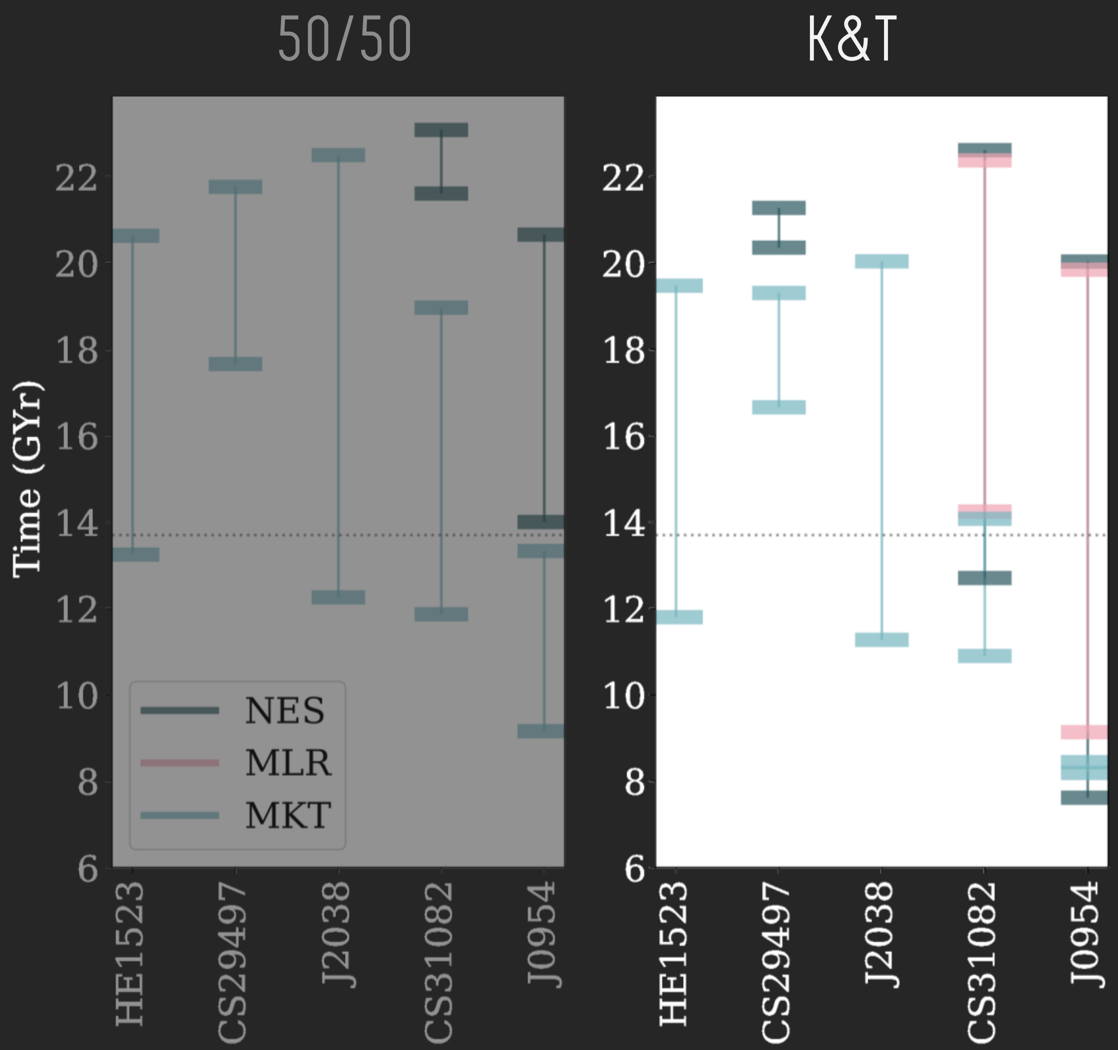
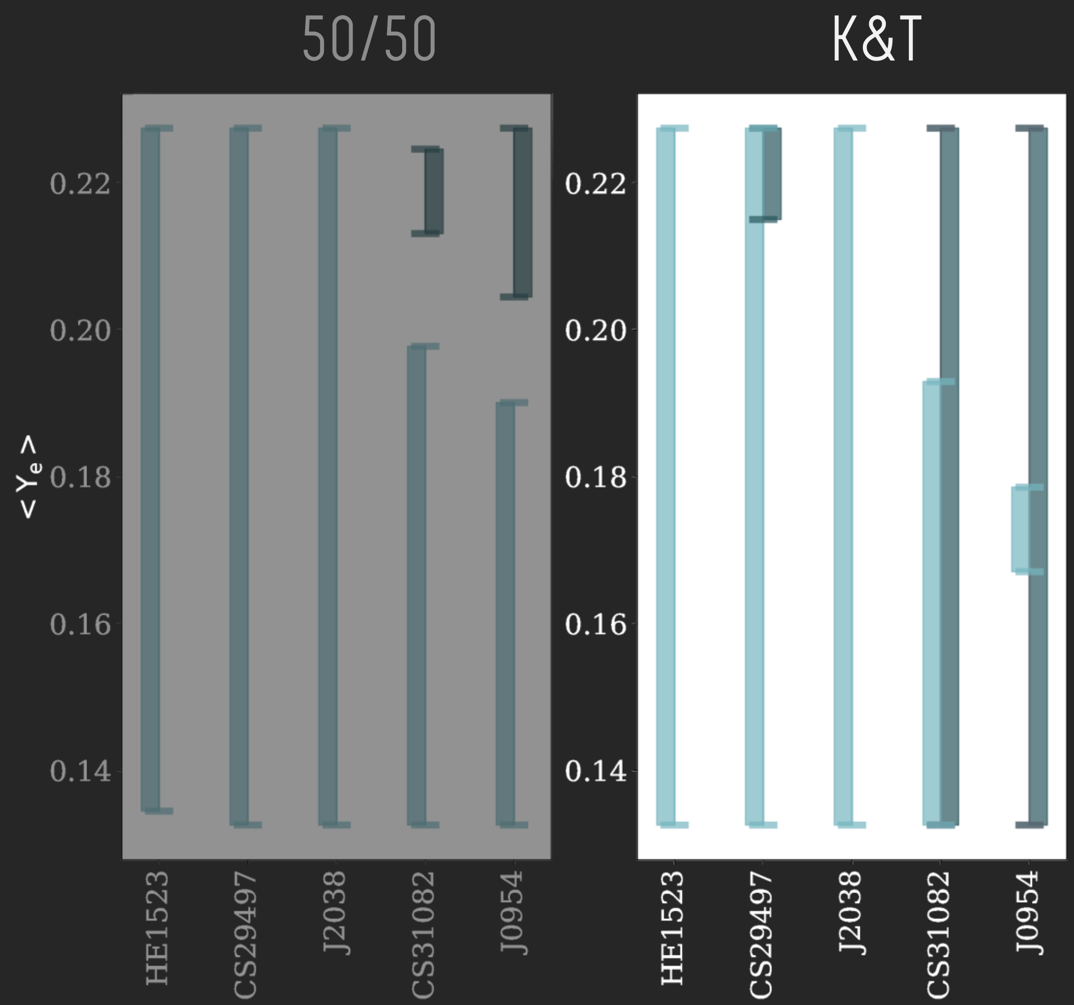


Error Bars from Observations





Conclusions

There is a wealth of physics in the unknown properties of nuclei far from stability that can impact key kilonova related quantities

- Identified key measured and unmeasured nuclei important for nuclear heating on light curve-relevant time scales.

- Explored a variety of theoretical nuclear models as a source of uncertainty for nuclear energy generation.

- Probed lanthanide/actinide abundances for cosmic dating of r-process enhanced metal-poor stars.

2208.06373, 2010.03668, 2010.11182

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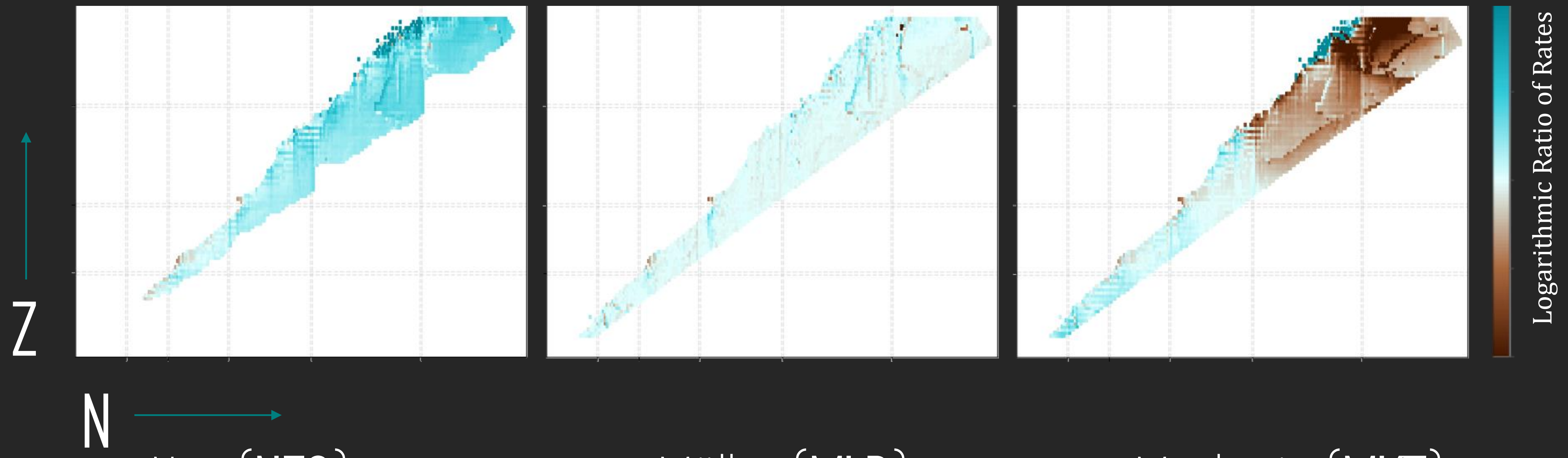
Thank you!

Nucleosynthesis Appendix

Appendix: Beta Decay Rates

Logarithmic ratio compared to Möller+ 2003



Ney (NES)	Möller (MLR)	Marketin (MKT)
Ney+ 2020	Möller+ 2019	Marketin+ 2016
FAM+QRPA	QRPA+FRDM	Covariant DFT

Appendix: Thermalization Efficiency

Kasen & Barnes 2019 ApJ (arXiv: 1807.03319)

Assume thermalization of massive particles: $f = (1+\tau)^{-n}$

Electrons (n=1): $t_{th,\beta} = 12.9 M_{0.01}^{2/3} v_{0.2}^{-2}$ days

γ-rays: $t_{\gamma} = 0.3 M_{0.01}^{1/2} v_{0.2}^{-1}$ and $f_{\gamma}(t) = 1 - \exp\left[-\frac{{t_{\gamma}}^2}{t^2}\right]$

α-decay: $t_{th,\alpha} = 2t_{th,\beta}$ and $f_{\alpha}(t) = \left(1 + \frac{t}{t_{th,\alpha}}\right)^{-1.5}$

Fission: $t_{th,f} = 4t_{th,\beta}$ and $f_{f}(t) = \left(1 + \frac{t}{t_{th,f}}\right)^{-1}$

Appendix: Opacity (i)

Diffusion timescale is dependent on opacity; in this model, the opacity is temperature dependent.

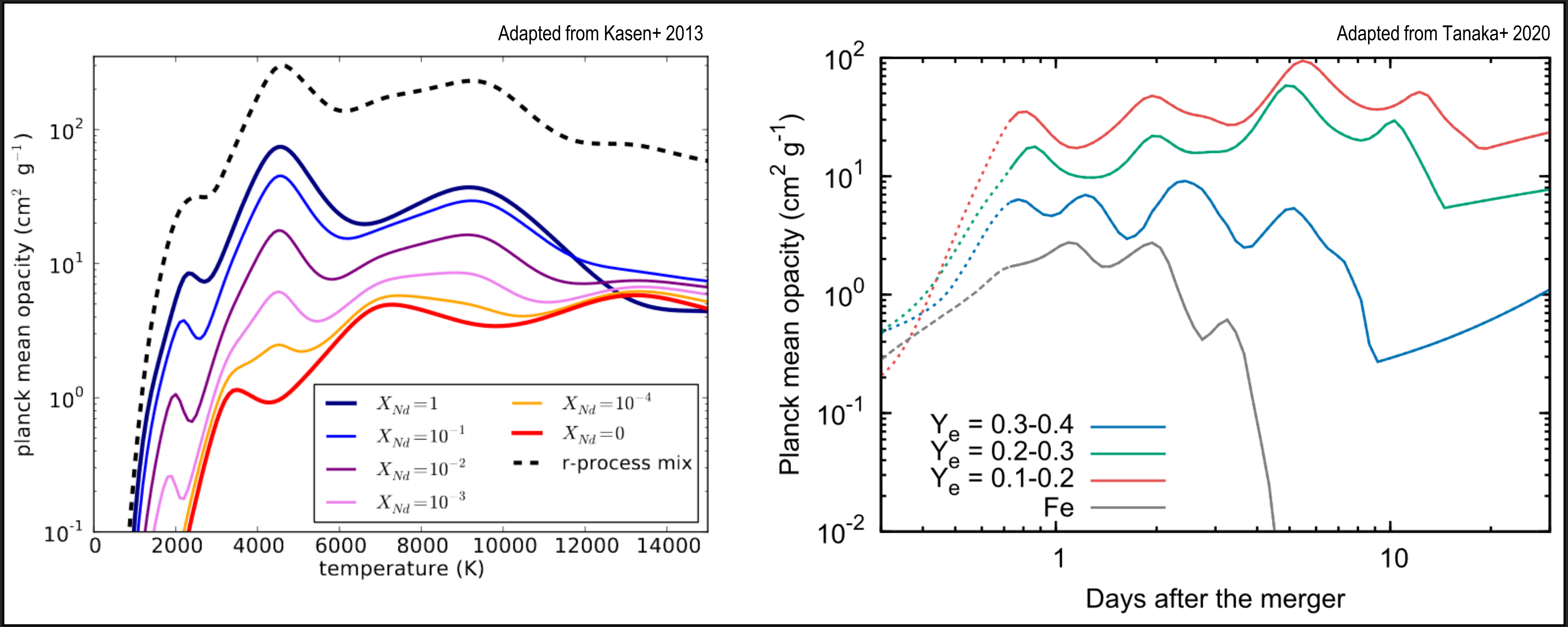
$$\kappa = \begin{cases} \kappa_{max}\left(\frac{T}{4000\text{K}}\right)^{5.5} & T < 4000\text{K} \\ \kappa_{max} & \text{otherwise} \end{cases}$$

with $\kappa_{max} = 100\ \text{cm}^2\text{g}^{-1}$

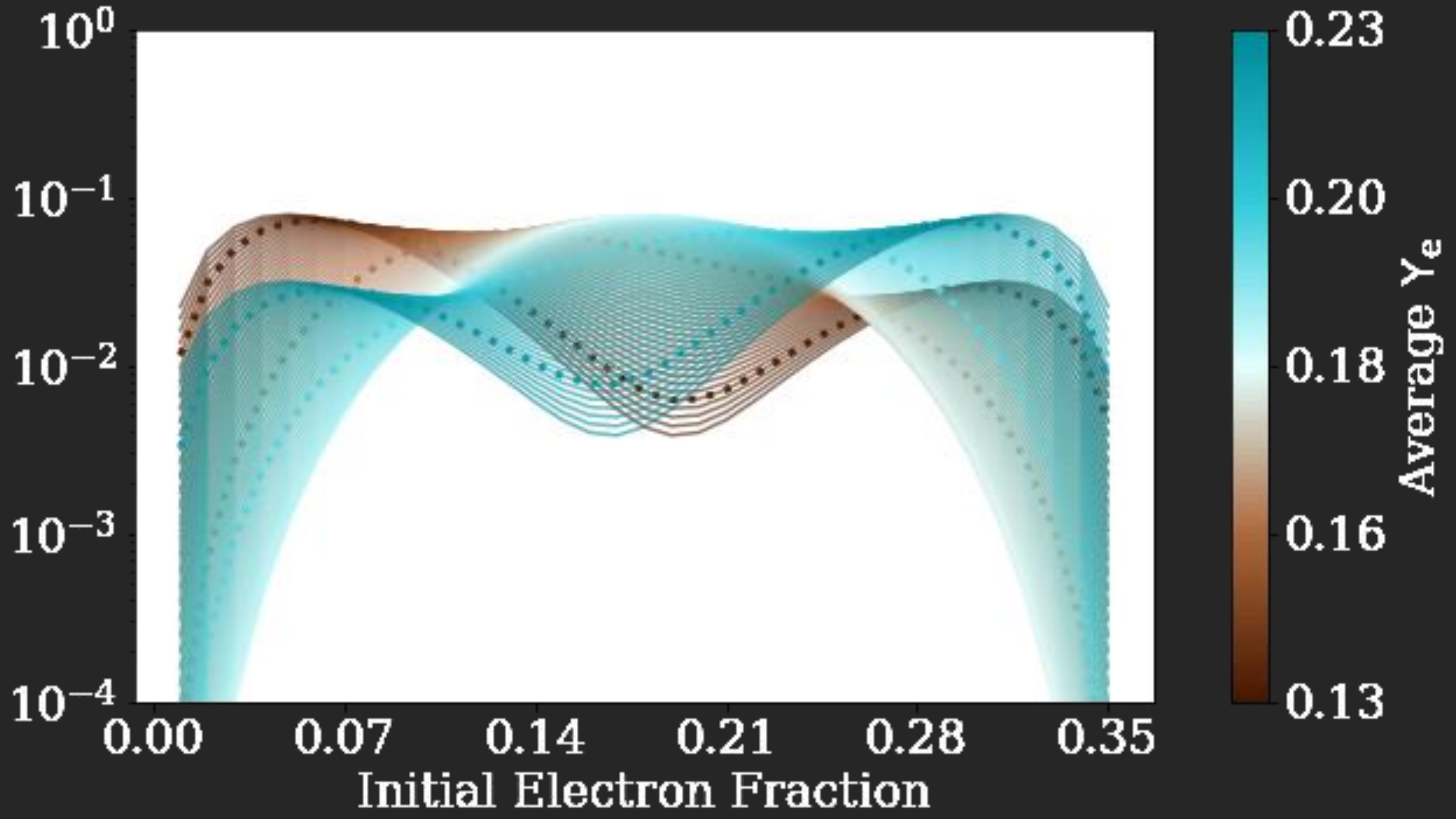
Technically, κ_{max} should be calculated uniquely for each composition. For now, consider mainly that a larger opacity should

- extend the light curve in time, and
- decrease the height of the light curve peak

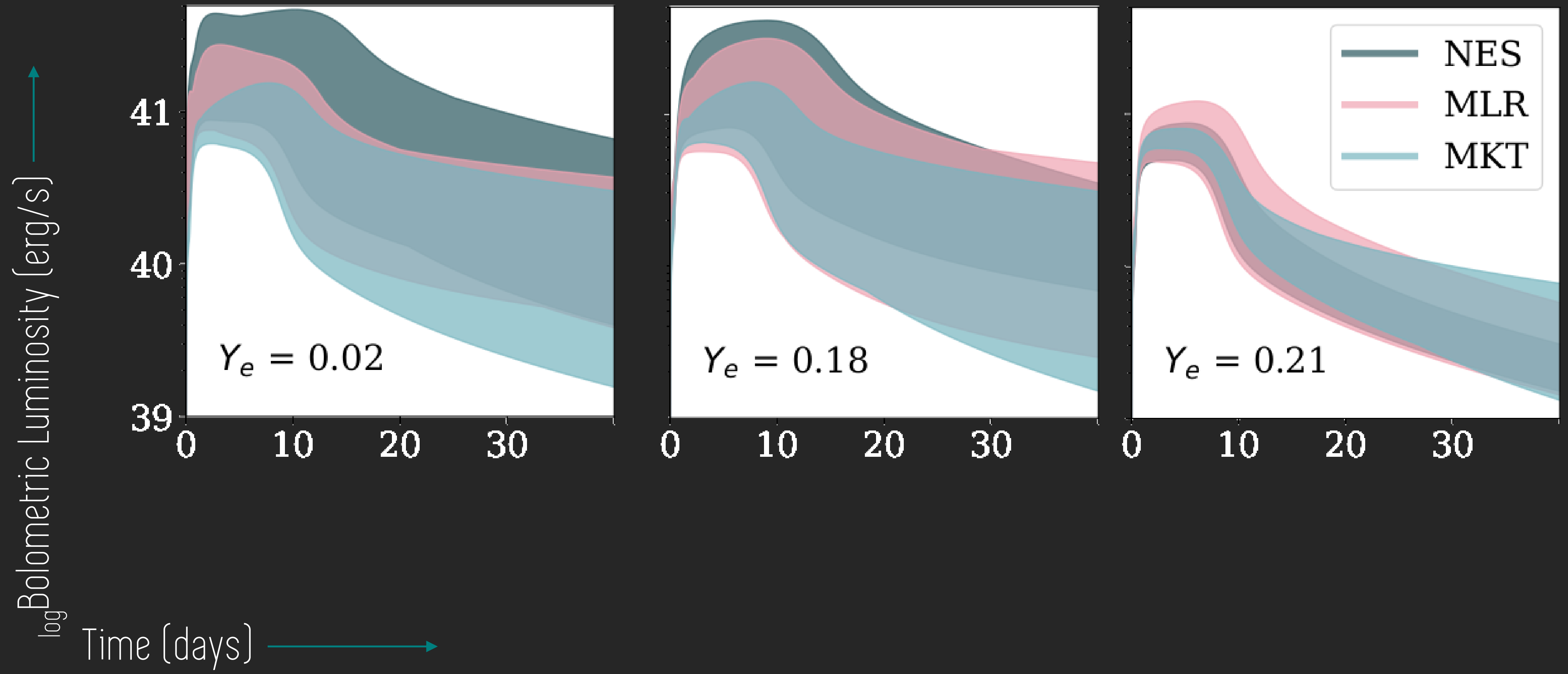
Appendix: Opacity (ii)



Appendix: Linear Combinations

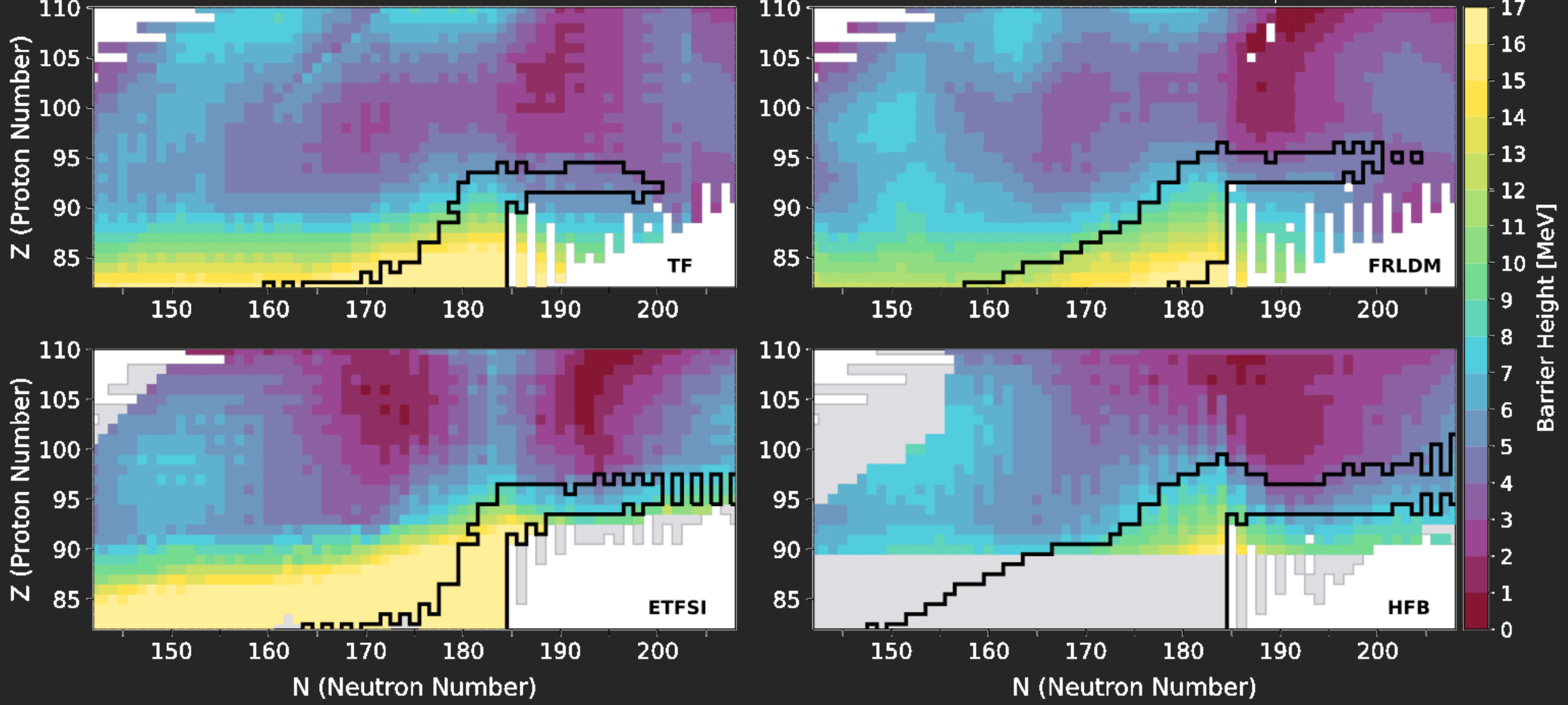


Backup: Light Curves



Appendix: Fission Barriers

Adapted from Vassh+ 2019



Appendix: Reaction Network

The evolution of the abundance of species $\mathbf{i}$ can be described by:

One-body — Two-body — Three-body

$$\frac{dY_i}{dt} = \sum_j \mathcal{N}^i_j \lambda_j Y_j + \sum_{j,k} \mathcal{N}^i_{j,k} \rho N_A \langle j,k \rangle Y_j Y_k + \sum_{j,k,l} \mathcal{N}^i_{j,k,l} \rho^2 N_A{}^2 \langle j,k,l \rangle Y_j Y_k Y_l$$

Decay Rate — Thermal Cross-Section