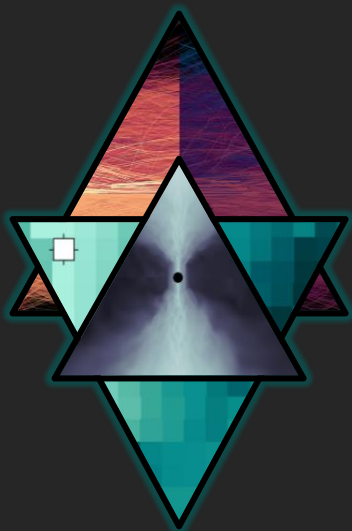




β -Decay Rates and Their Influence on Astrophysical r-Process Observables

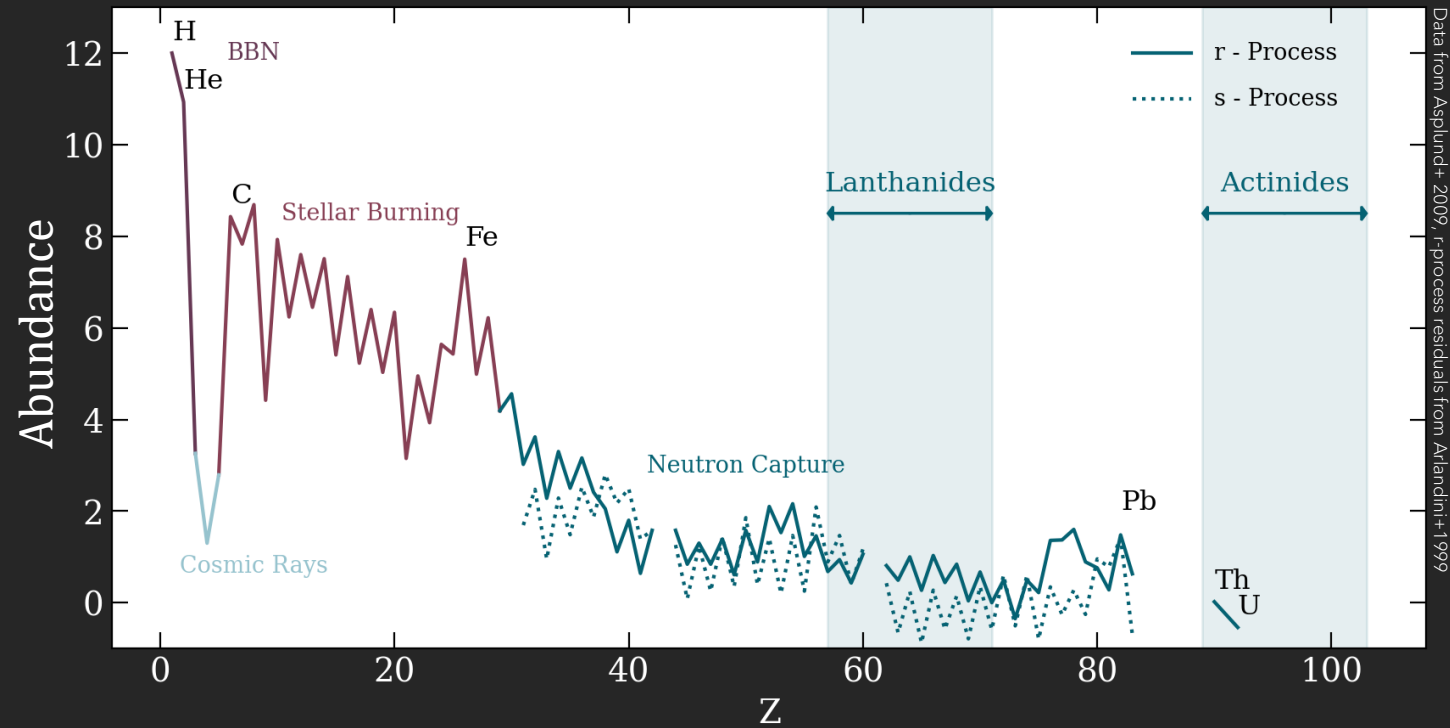
Kelsey Lund

FRIB-TA Topical Program: Future Directions in Nuclear Beta Decay at FRIB

18 · 09 · 25

r-Process, Astrophysically

How are heavy elements made?



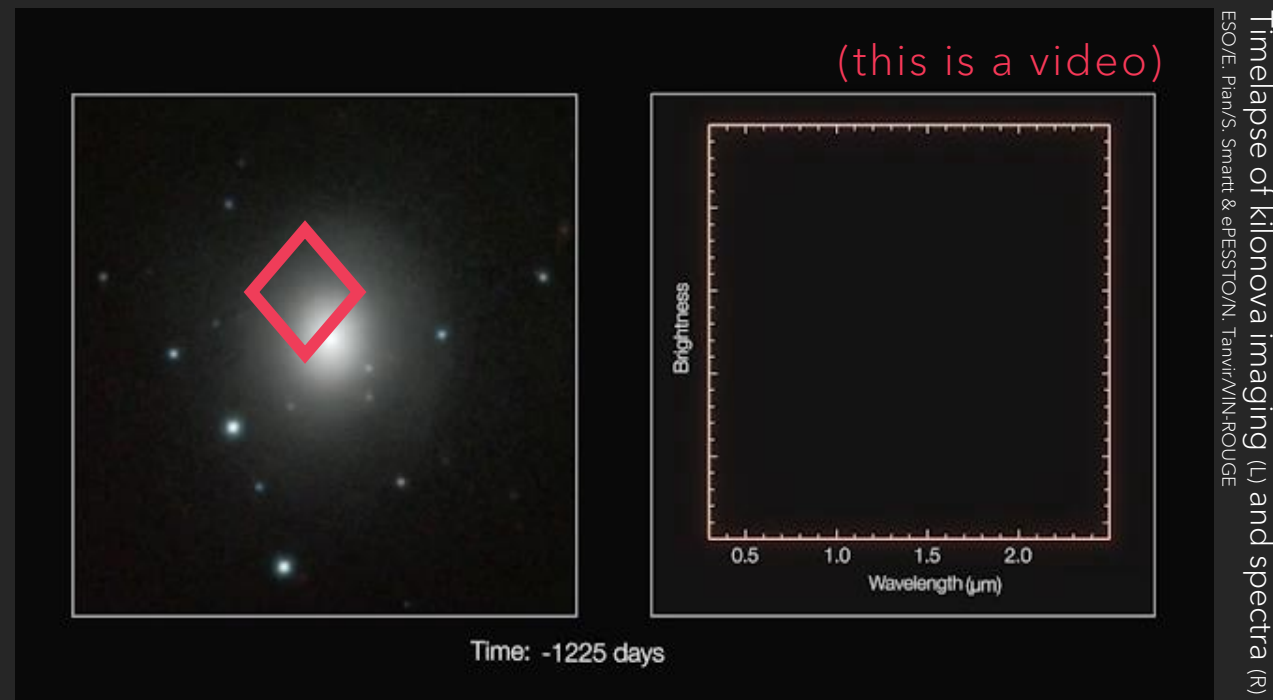
The **rapid neutron capture process** is responsible for half the material in the universe heavier than iron.

As Time Goes By

50 years ago: Binary neutron star mergers were proposed to possibly host conditions favorable to r-process nucleosynthesis (Lattimer & Schramm 1974)

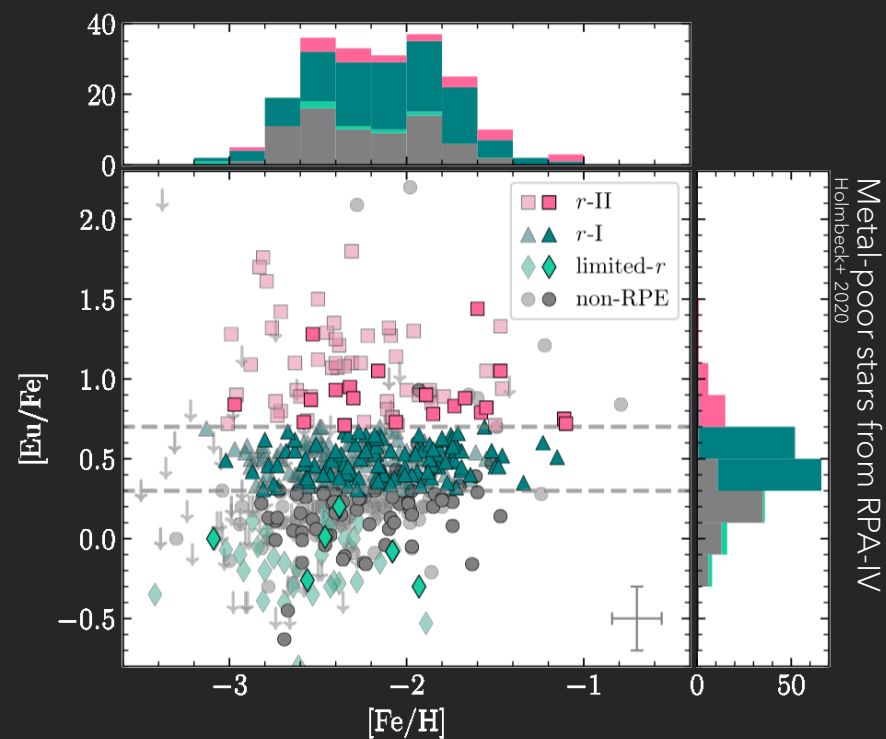
8 years ago: Multi-messenger (GW+EM) observations of a binary neutron star merger were made - confirm lanthanides

Late-time, long wavelength electromagnetic signal indicates lanthanide production and decay in merger ejecta



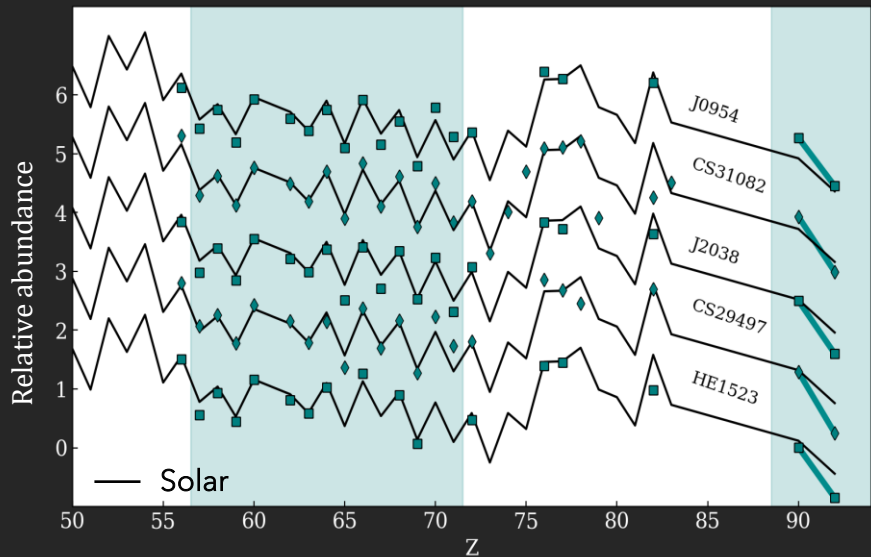
More Observational r-Process Signatures

$$[A/B] = \log(N_A/N_B)_{\text{obs}} - \log(N_A/N_B)_{\text{Sun}}$$
$$\log_{\epsilon}(A) = \log_{10}(N_A/N_H) + 12$$



r-Process elements in metal-poor stars are interpreted as signatures from O(few) enrichment events.

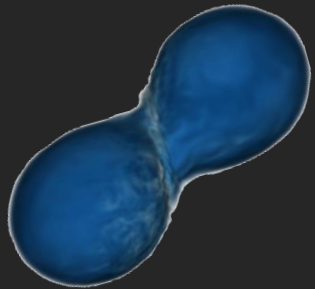
Detections of thorium ($Z=90$) and uranium ($Z=92$) in metal-poor stars are indicative of r-process enrichment.



Time Scales

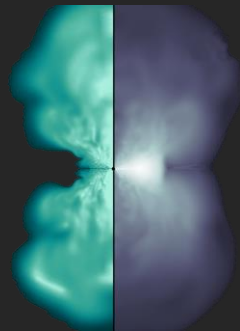
There is no single, end-to-end r-process simulation:
binary neutron star mergers, kilonovae, and the production of r-process
elements are influenced by physics spanning a wide range of time scales.

In-Spiral



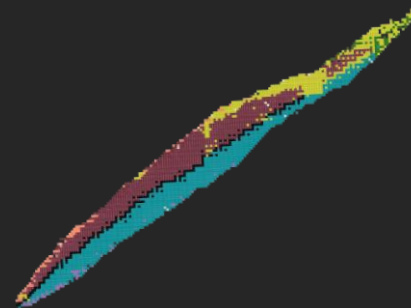
ms - s

Post-Merger
System



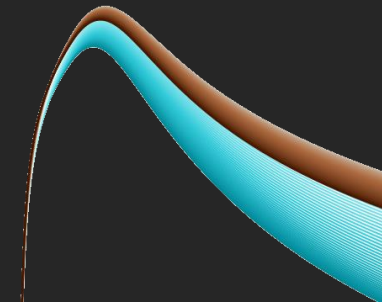
ms - s

Nuclear
Reactions



<s - Gyr

Kilonova
Light Curve



Hours - Weeks

Chemical
Enrichment

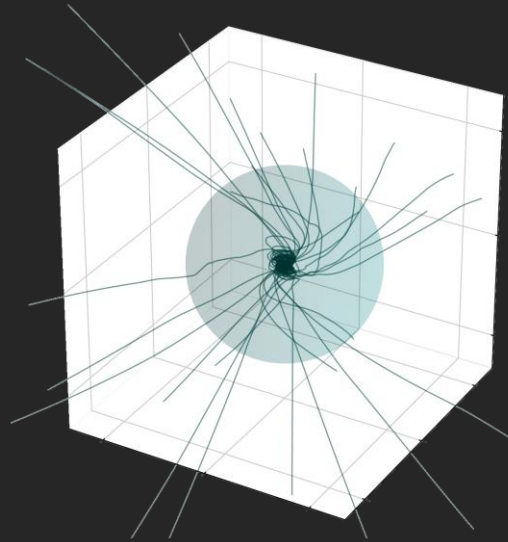


Myr - Gyr

Describing r-Process Sites

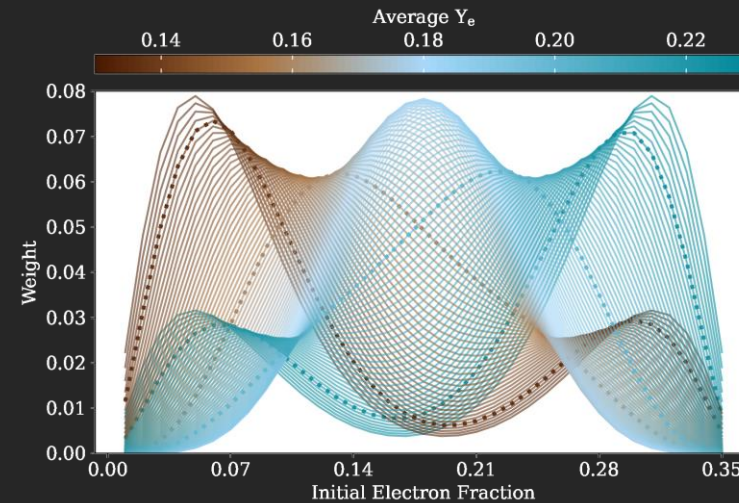
Nuclear reaction networks need a description of the evolving temperature and density of the astrophysical system:

Tracer particles from GRMHD simulations



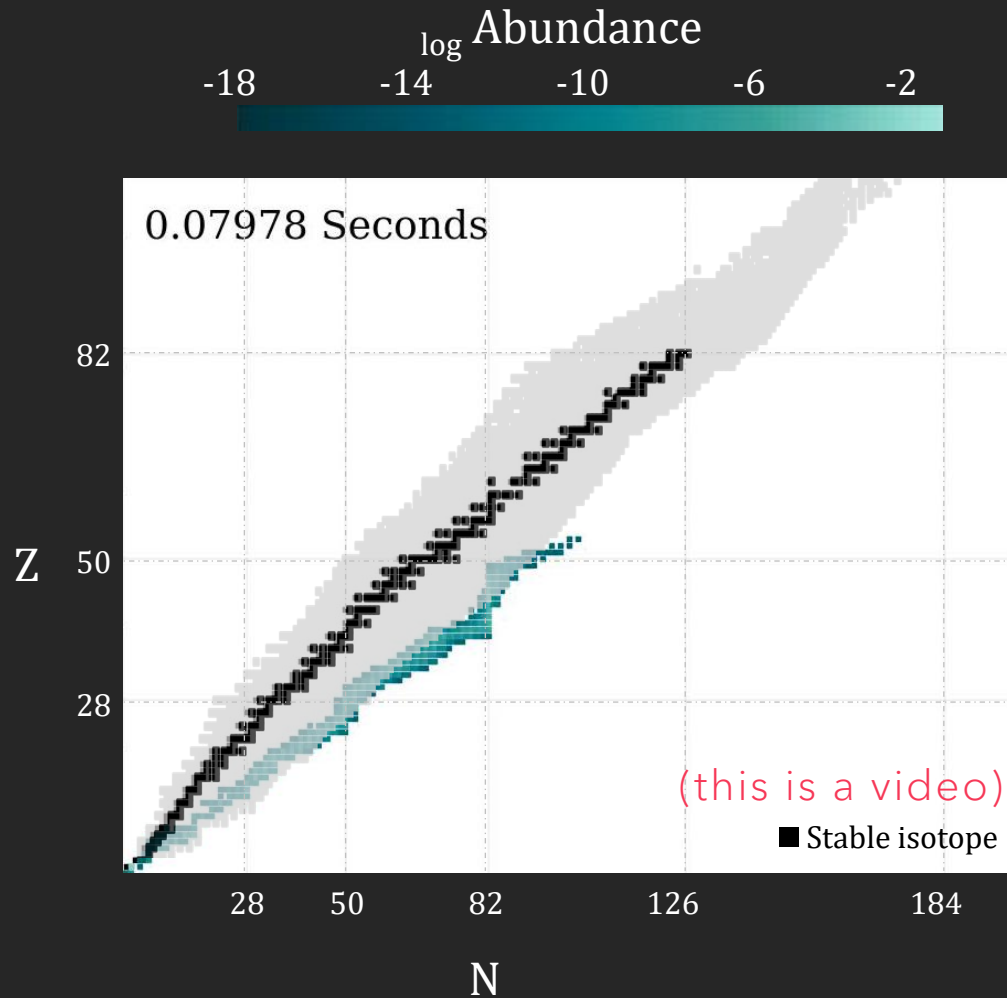
Provides very detailed information about the system and its evolution, but is computationally cumbersome

Single or combined parameterized trajectories



Less descriptive of astrophysical system as a whole; lower computational cost allows for large uncertainty studies

Sources of Nuclear Uncertainty

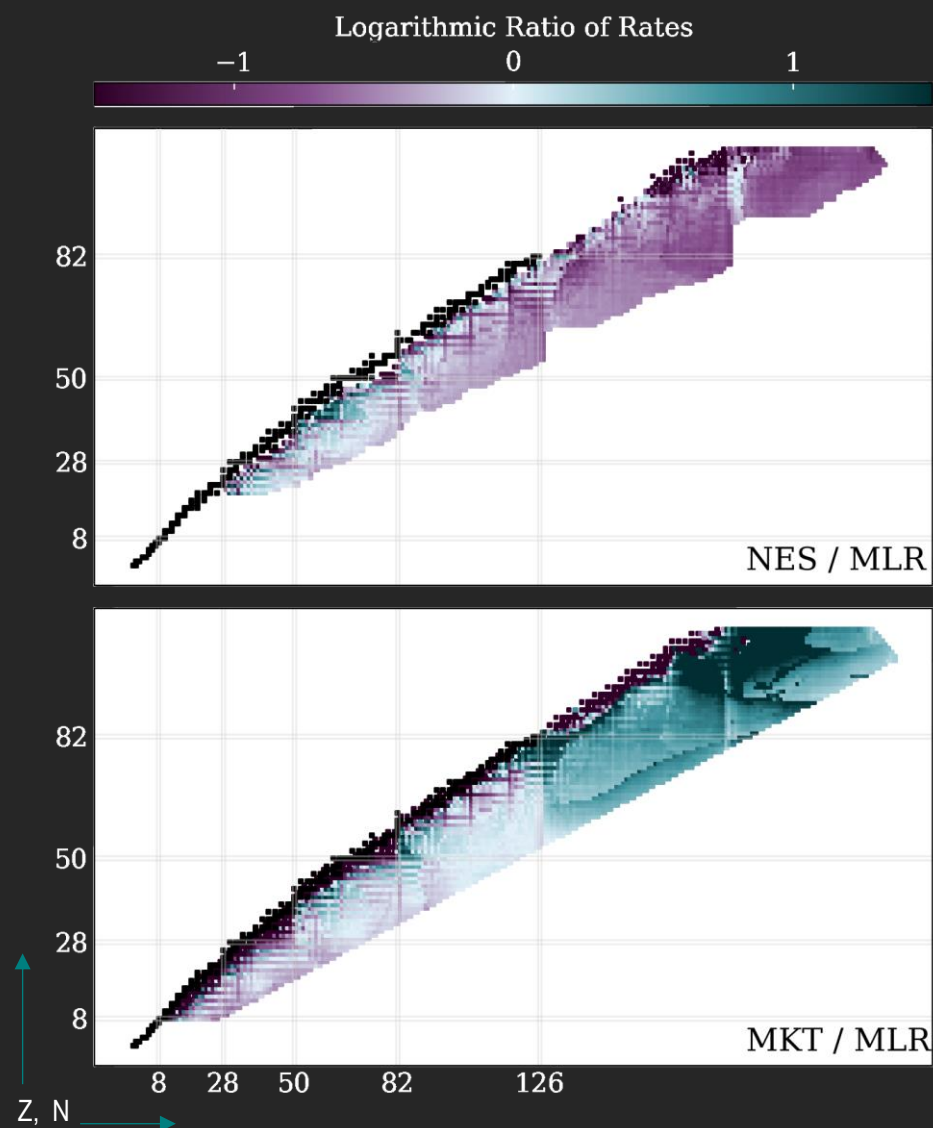


r-Process builds up population that decays on time scales of hours-days (and beyond), largely through region with no measured data

Neutron captures and beta decays populate nuclei that undergo alpha decays and fissions

Nucleosynthetic outcome depends on nuclear properties AND environment

Beta Decay Rates...



...are crucial for r-process calculations:

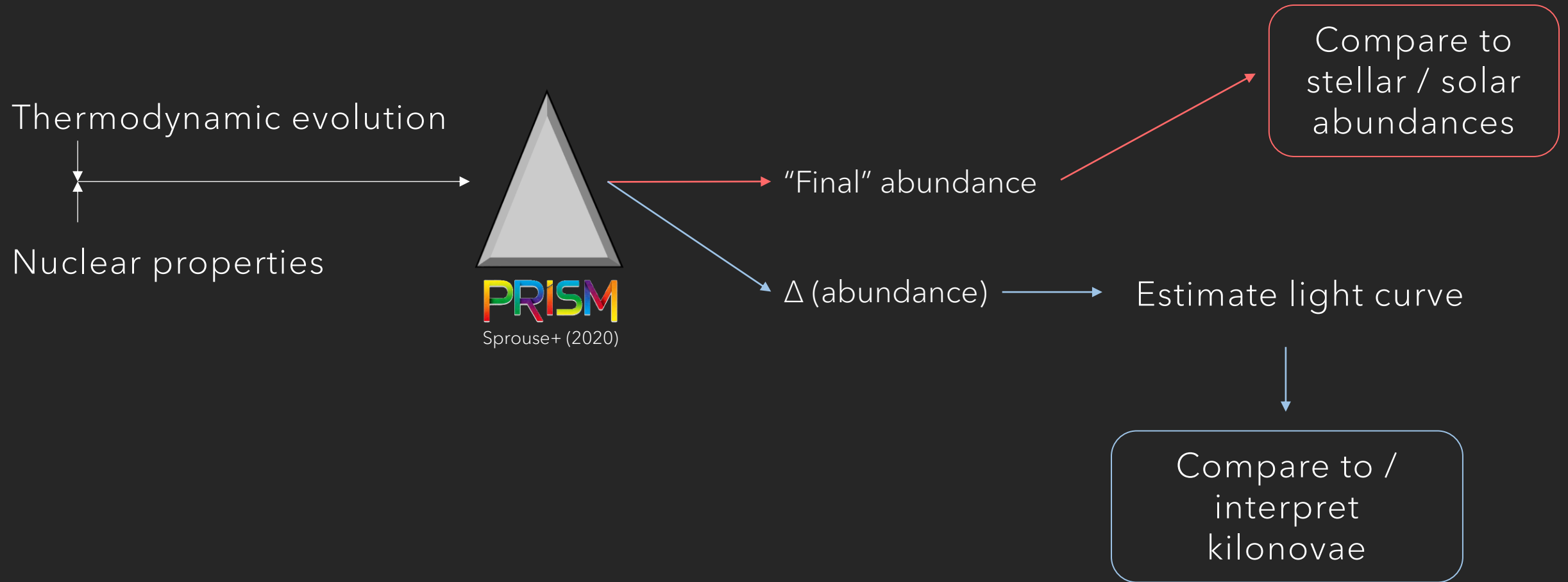
- Determine distribution of material at freeze-out
 - Abundances of heavy isotopes
- Decay timescale of heavy nuclei in competition with other channels (fission, alpha decay)

NES Ney+ 2020: FAM+SkyrmeDF

MLR (FRDM) Möller+2019

MKT (D3C*) Marketin+ 2016: pn-RQRPA

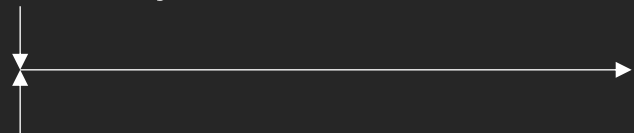
Building Parameterized Studies



Building Parameterized Studies

- Single Y_e : 0.02, 0.16, 0.21
- Linear combinations
- Full 3DGRMHD

Thermodynamic evolution



Nuclear properties

- beta decay rates
- masses
- fission properties



"Final" abundance

Compare to
stellar / solar
abundances

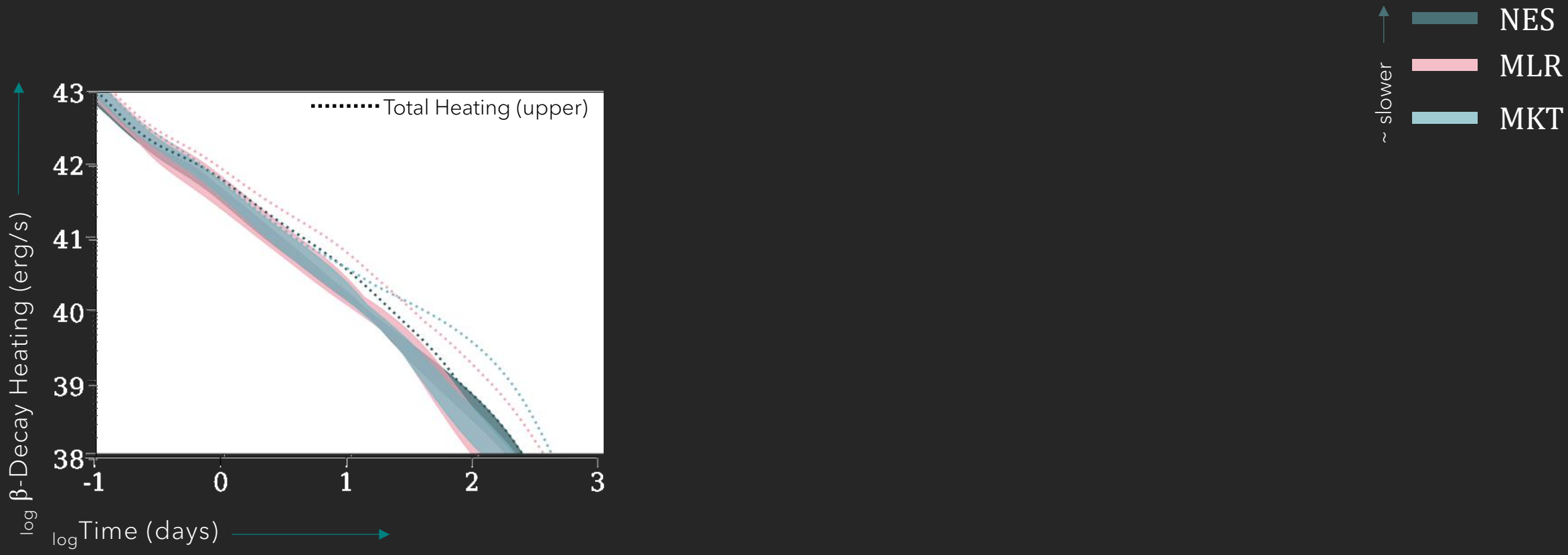
Δ (abundance)

Estimate light curve

Compare to /
interpret
kilonovae

What can we learn from single Y_e trajectories?

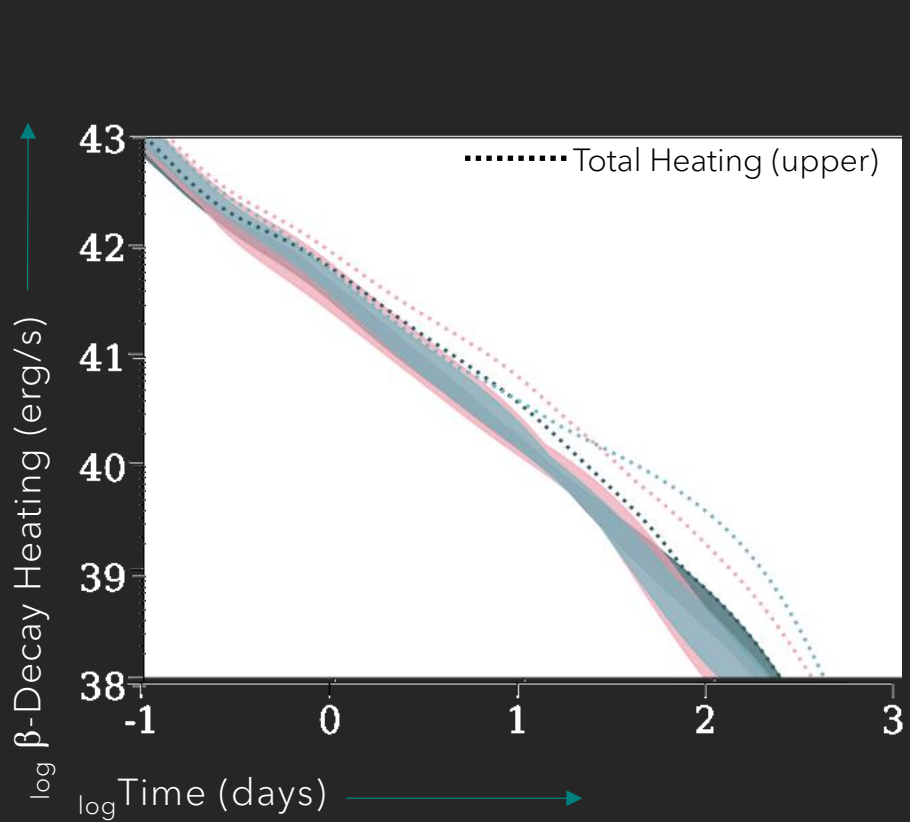
High Y_e : Heating is Beta Decay



Significant overlap when different mass models
AND different beta decay rates are used

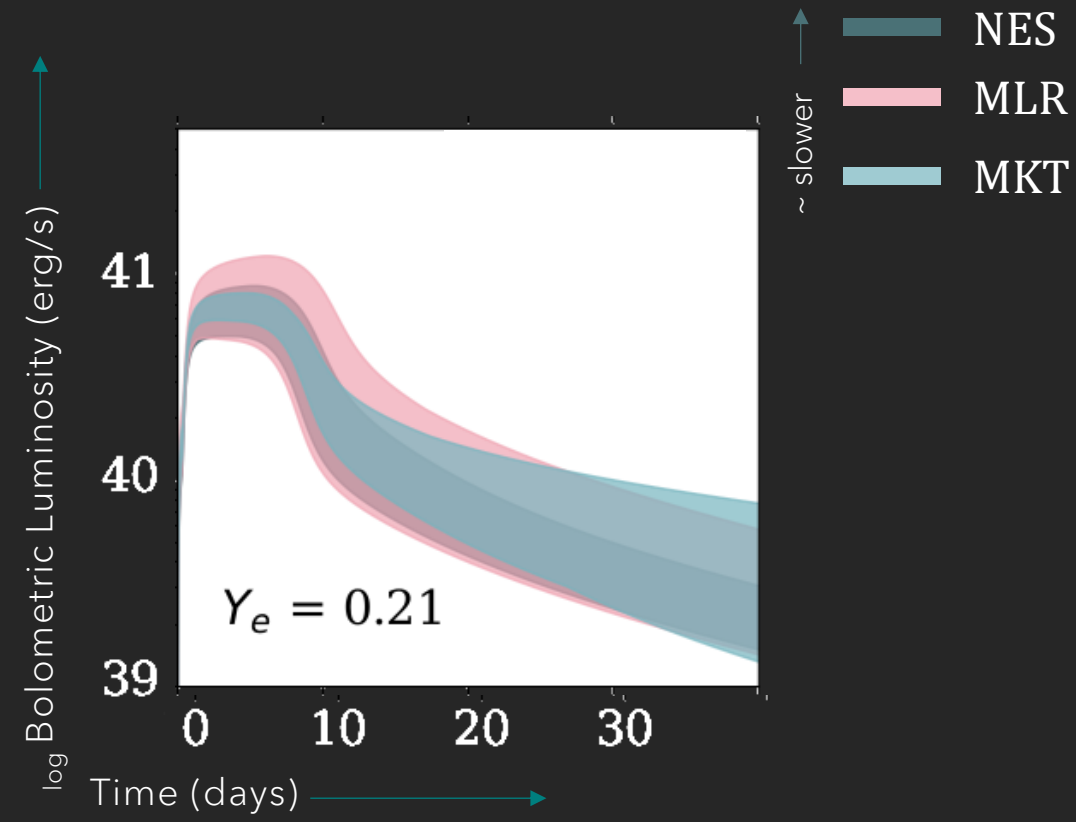
Not many fissioning nuclei

High Y_e : Heating is Beta Decay



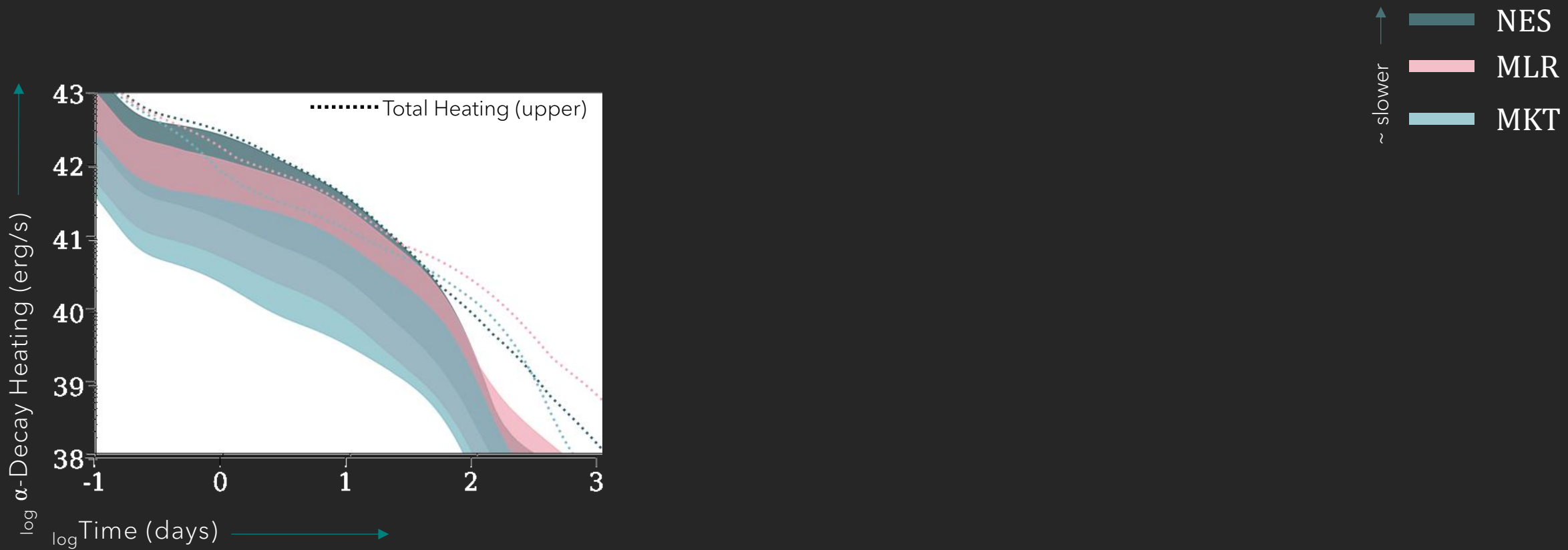
Significant overlap when different mass models
AND different beta decay rates are used

Not many fissioning nuclei



Implications for light curve:
Consistency in both shape and magnitude of
light curves

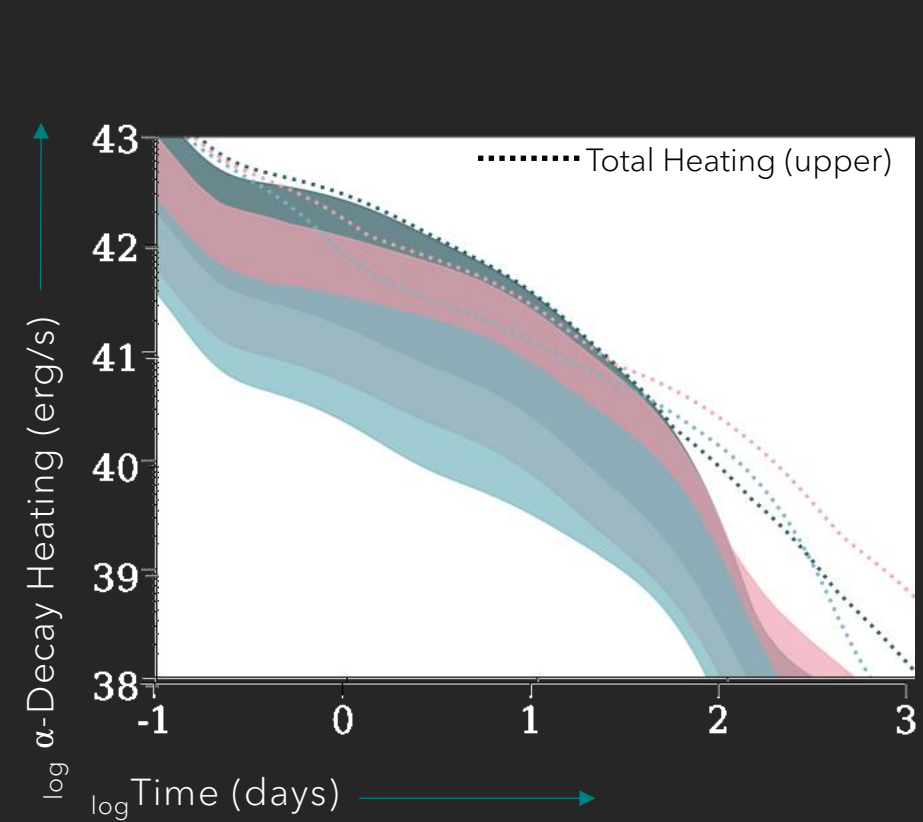
$Y_e = 0.18$: Alpha Decay Takes the Stage



Mass models predict different heating rates,
but shape is roughly similar across β -decay
rates

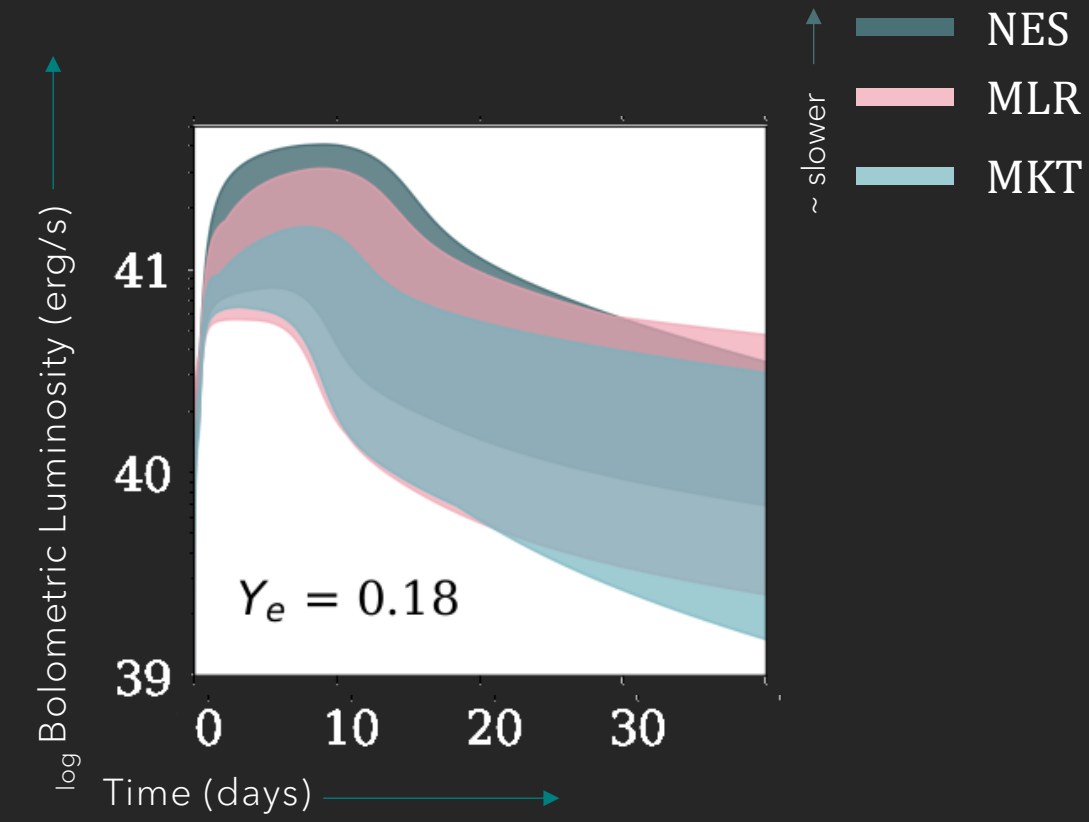
α -Decay sets upper limit to total heating
around a few days

$Y_e = 0.18$: Alpha Decay Takes the Stage



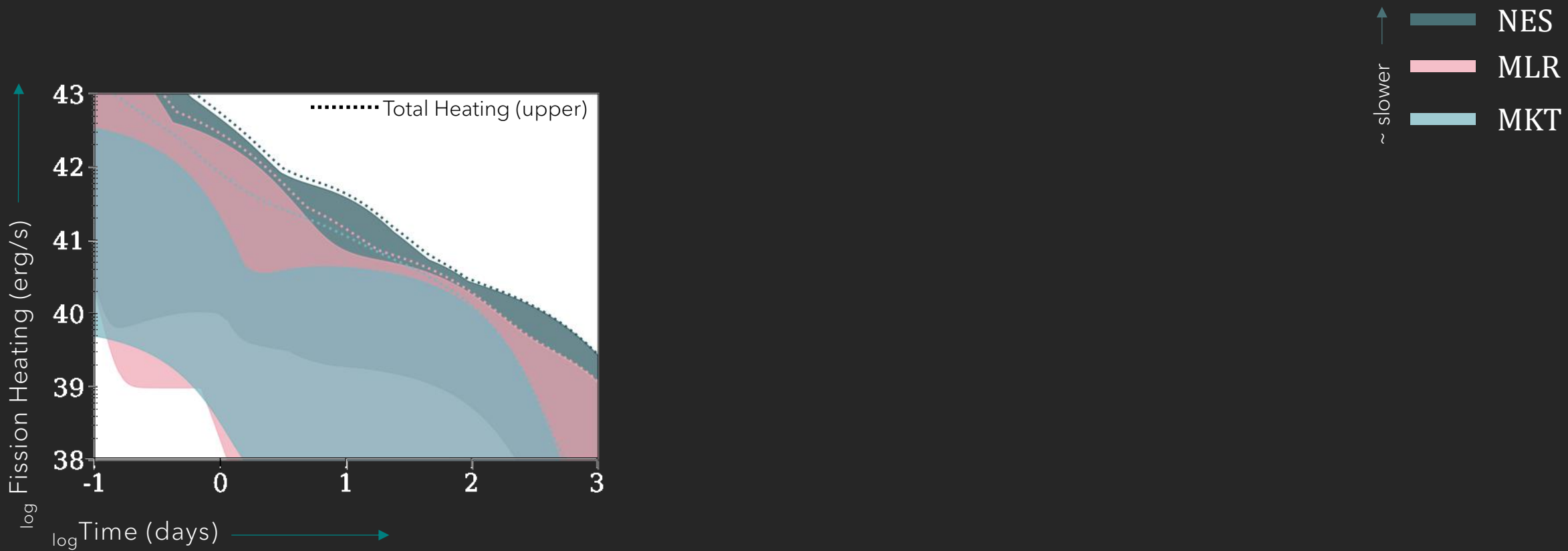
Mass models predict different heating rates, but shape is roughly similar across β -decay rates

α -Decay sets upper limit to total heating around a few days



Implications for light curve:
More variety in shape, larger range of values at late times

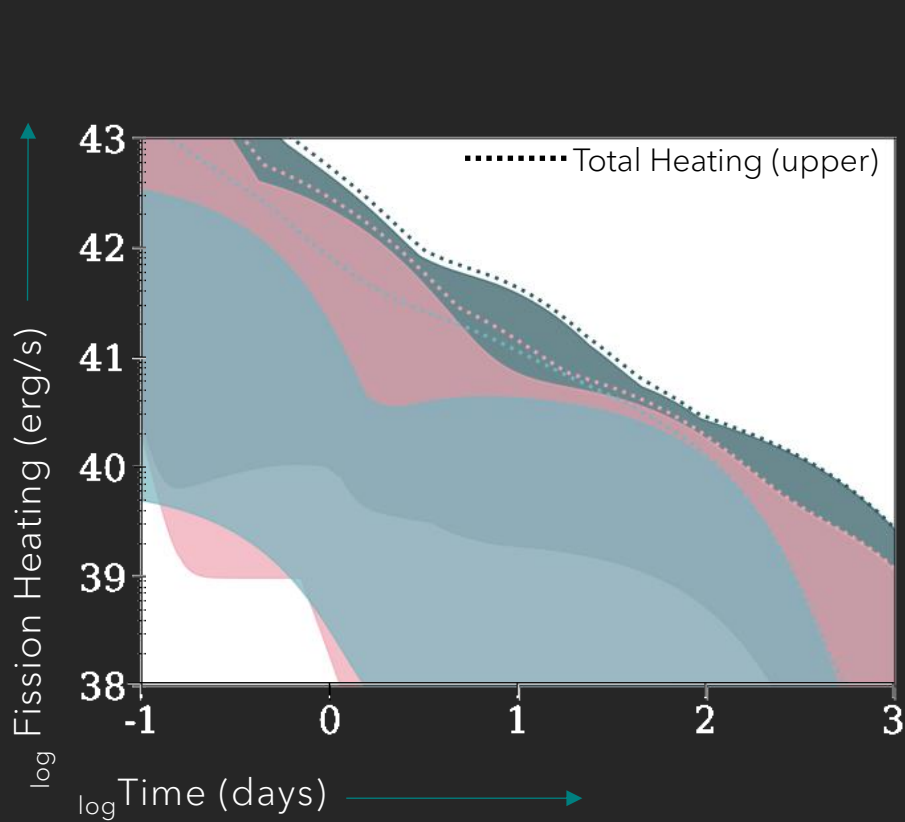
Low Y_e : Spontaneous Fission Heating



Wide bands: Mass models predict largely different spontaneous fission heating rates

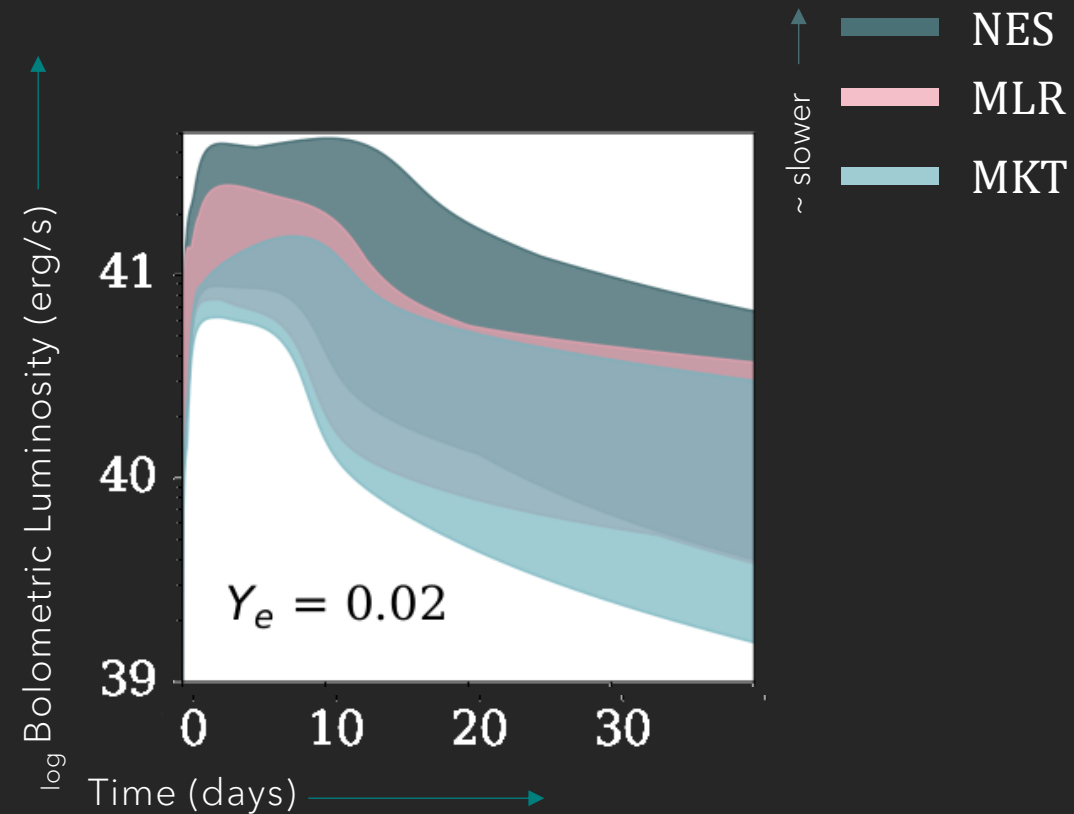
Slower β -decay rates = larger upper limit for spontaneous fission heating; sets upper limit of total

Low Y_e : Spontaneous Fission Heating



Wide bands: Mass models predict largely different spontaneous fission heating rates

Slower β -decay rates = larger upper limit for spontaneous fission heating; sets upper limit of total

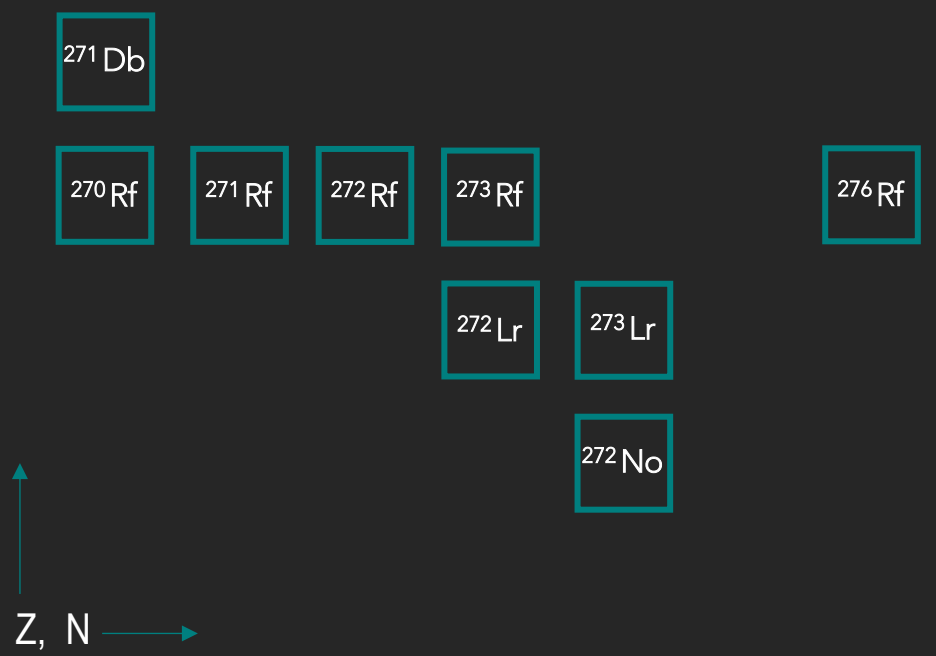
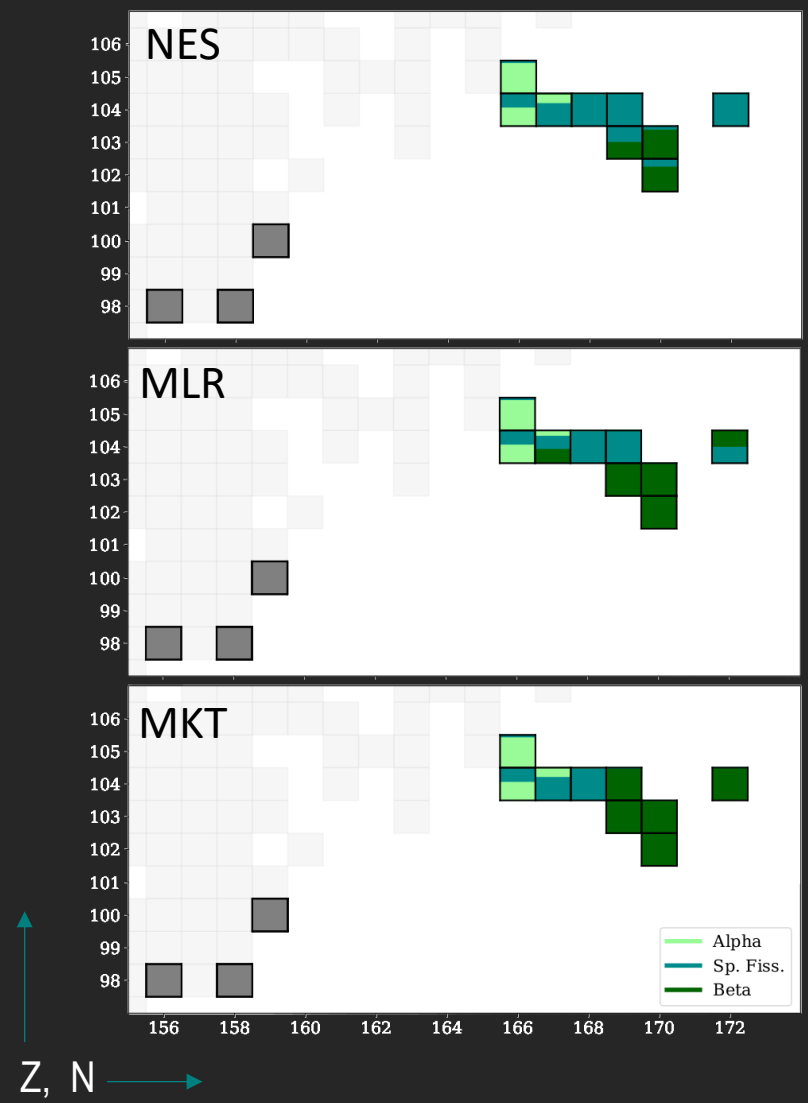


Implications for light curve:
More fission = brighter light curves
Diversity of upper heating limits = diversity of light curve shapes

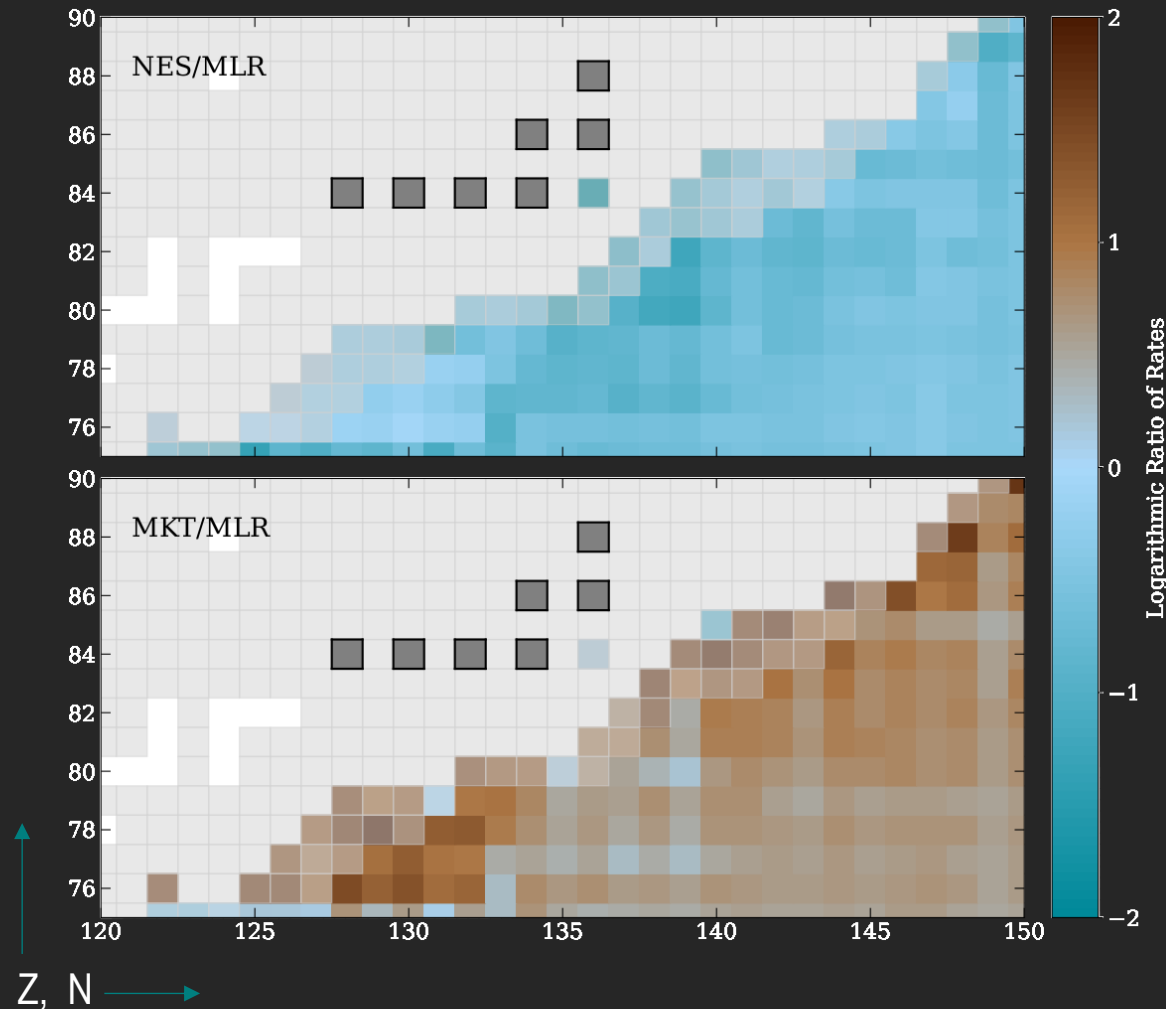
Can we trace these differences to specific nuclei?

Critical Nuclei: Spontaneous Fission

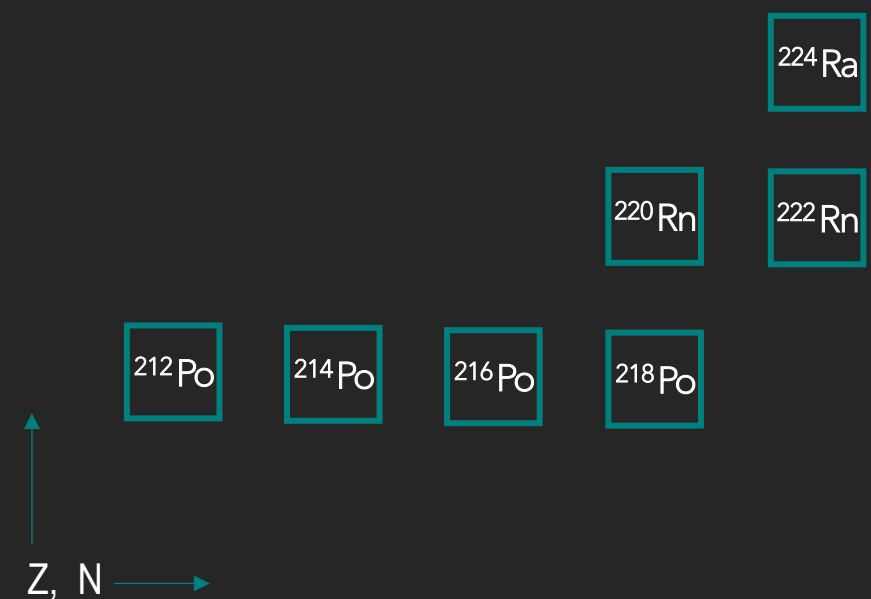
Differences in **beta decay rates** affect **heating from spontaneous fission** via branching ratios of unmeasured nuclei:

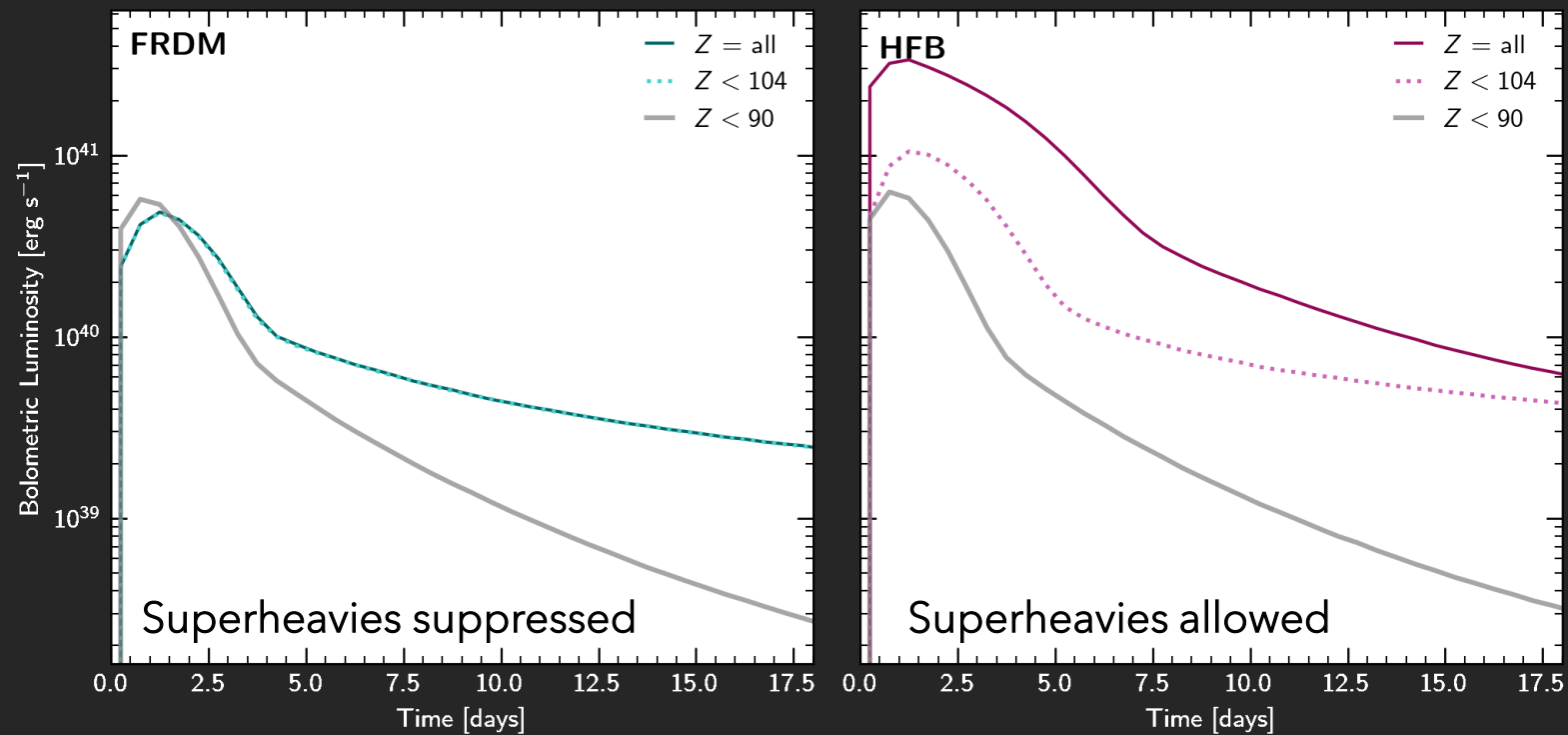


Critical Nuclei: Alpha Decay



Differences in **beta decay rates** affect **heating from alpha decays** from isotopes with measured decay times, especially:





If superheavies
($Z > 104$)
are made,
they can significantly
impact the light
curve.

What about the final abundances?

Beta Decays and Actinides

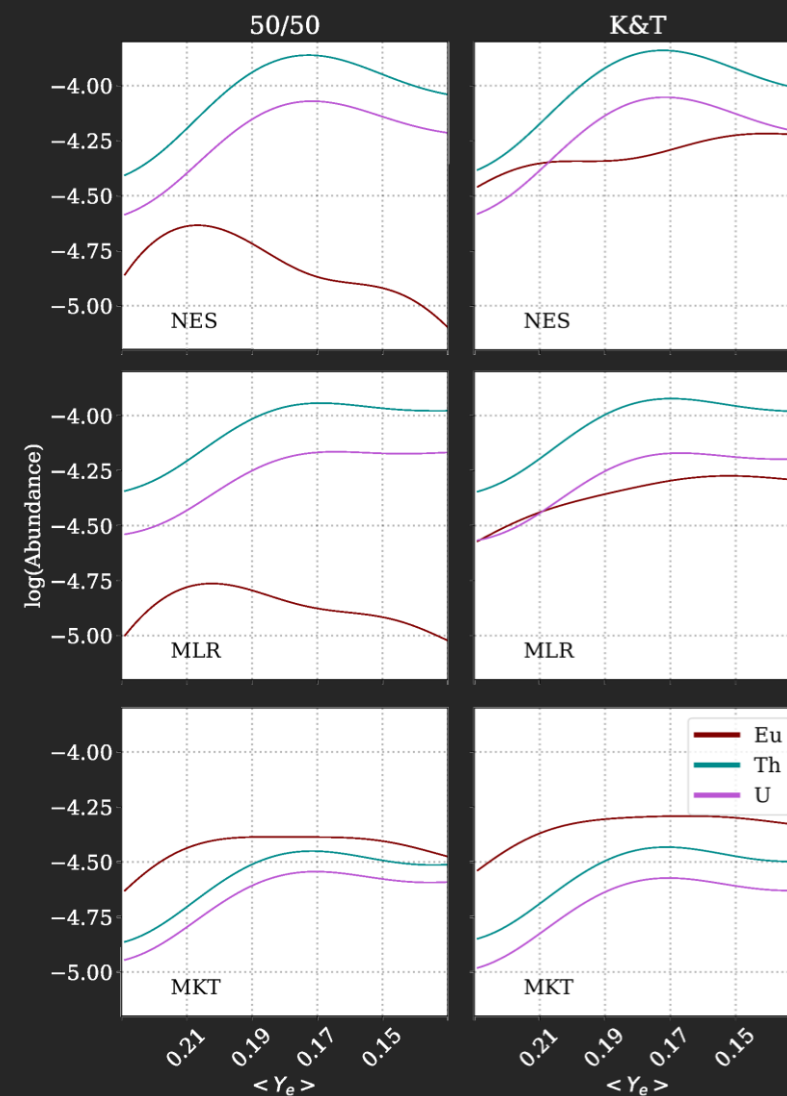
Changing the beta decay rates affects actinides yields (computed at 1 Gyr): faster rates suppressed actinide formation, saw enhanced lanthanide formation

[Th/Eu], [U/Eu], [U/Th] can be useful quantities for dating of metal-poor, r-process enhanced stars:

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

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

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



Post-Merger Disk Outflows as r-Process Sites



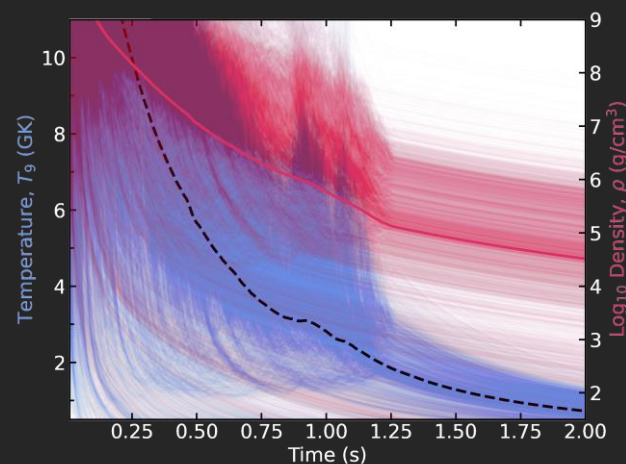
Magnetically driven accretion disk forms after merger event

r-Process occurs in different ejection "sites":

- Fast wind driven off material in mid-plane
- Slow, viscous disk
- Material entrained in semi-relativistic jet

See Lund+25, Mumpower+24, Sprouse+24, Lund+24, Miller+19

Nucleosynthesis calculations on 460,000+ individual tracers from a 1.2s long postmerger black hole-accretion disk simulation



$$N_r \times N_\theta \times N_\phi = 192 \times 128 \times 66$$

$$M_{\text{disk}} = 0.12 M_\odot$$

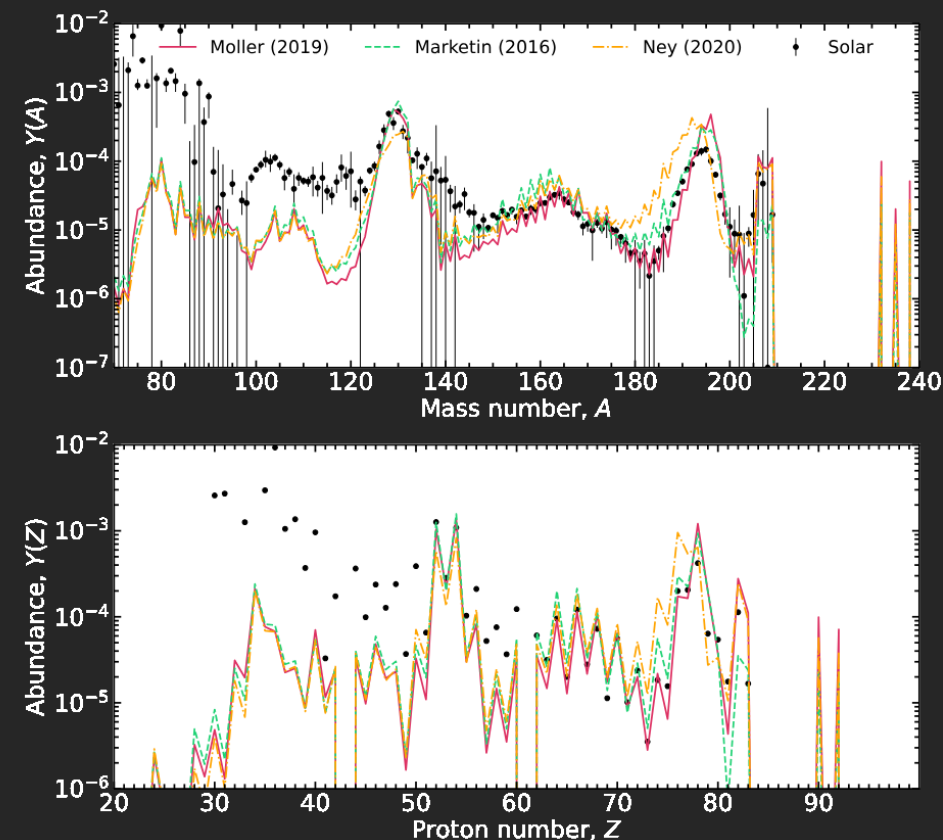
$$M_{\text{BH}} = 2.58 M_\odot$$

$$Y_e = 0.1$$

$$a = 0.69$$

$$\text{Simulation time: } 10^5 \text{ GM}_{\text{BH}} / c^3 \\ (\sim 1.27 \text{ s})$$

Nuclear uncertainties persist: third r-process peak is highly sensitive to beta decay rates



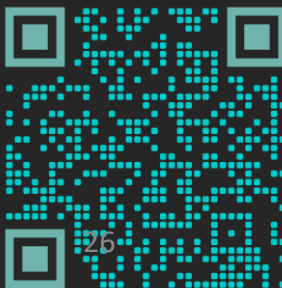
Thank you!

Beta decay rates are crucial for r-process calculations !

- r-Process observables are sensitive to unmeasured nuclear properties: by using single Y_e parameterized trajectories, we can identify key nuclei important for the interpretation of future kilonova observations
- Abundance of third r-process peak and actinides are sensitive to beta decay rates

Changing beta decay rates in r-process calculations means more than just changing beta decay rates.

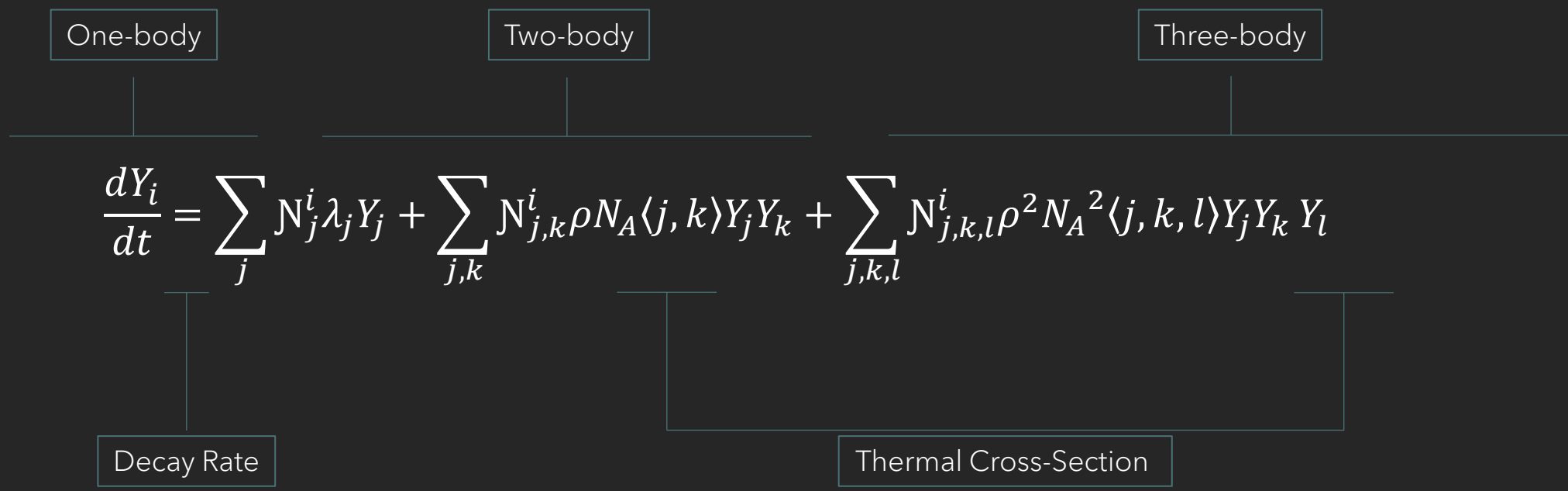
klund@berkeley.edu
kelslund.github.io



Appendix i

Appendix i: Reaction Network

The evolution of the abundance of species i can be described by:



Appendix i: Effective Heating

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

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

Energy released from
nuclear process

Thermalization efficiency
based on decay

Appendix i: Estimating Light Curve

GOAL: Estimate kilonova bolometric light curve from nucleosynthesis

Shell model for ejecta: assume concentric shells, each with velocity, v , and mass, M_v .

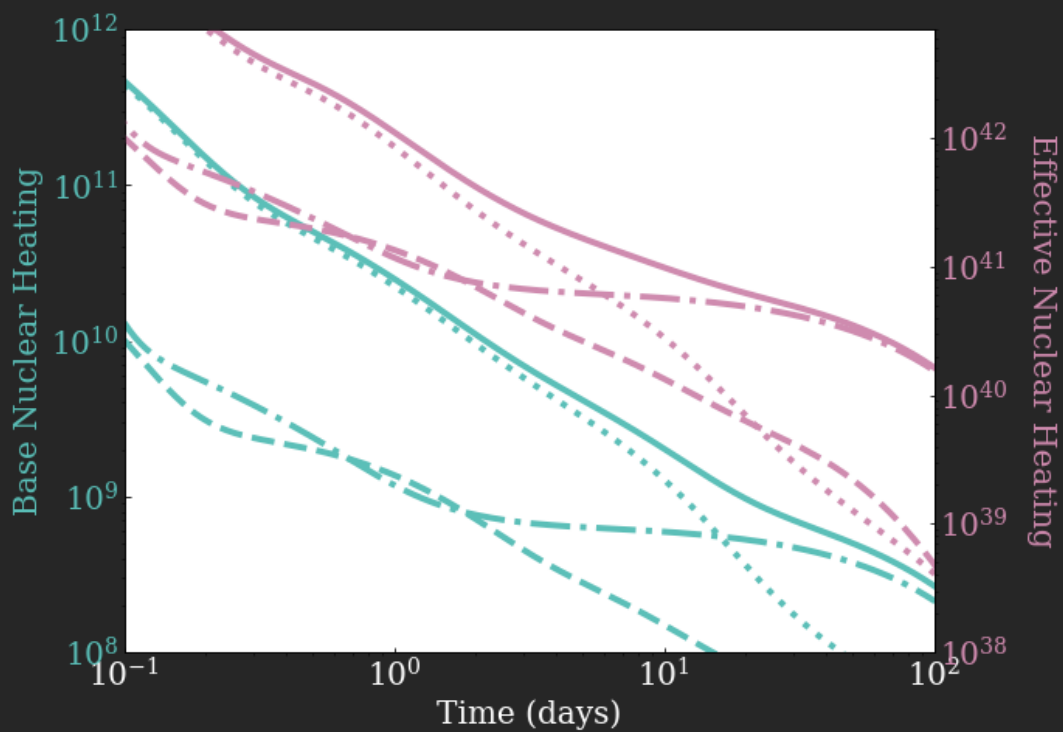
Bolometric luminosity of light curve from energy of shells:

$$\frac{dE_v}{dt} = \underbrace{\frac{M_v}{M_{ej}} \dot{Q}(t, v)}_{\text{Effective heating}} - \underbrace{\frac{E_v}{t}}_{\text{Adiabatic expansion}} - \underbrace{\frac{E_v}{t_{d,v} + t_{lc,v}}}_{\substack{\text{Diffusion timescale} \\ \text{(depends on opacity)} + \text{Light-crossing} \\ \text{timescale}}}$$

Luminosity

```
graph TD; A["dE_v/dt = (M_v/M_ej) * Q_dot(t, v) - E_v/t - E_v/(t_d,v + t_lc,v)"] --> B["Effective heating"]; A --> C["Adiabatic expansion"]; A --> D["Diffusion timescale (depends on opacity) + Light-crossing timescale"]; D --> E["Luminosity"];
```

Appendix i: Effective Nuclear Heating



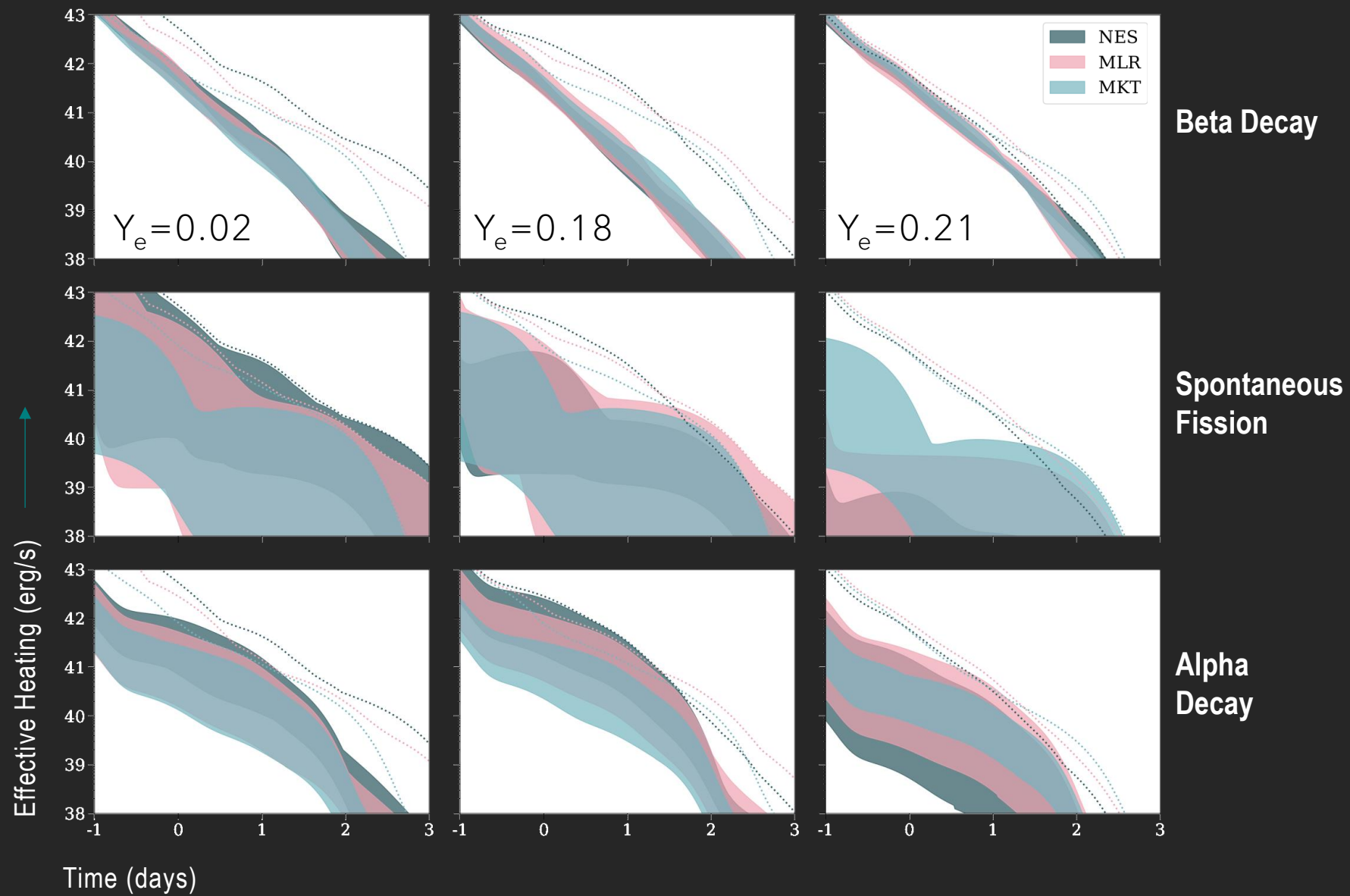
$$\dot{Q}(t) = \sum_i f_i(M_{ej}, v_{ej}, t) \dot{q}_i(t) M_{ej}$$

Diagram illustrating the components of the equation for Total effective heating:

- 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)

Appendix i: Uncertainties in Effective Nuclear Heating



Appendix i: Thermalization Efficiency

Kasen & Barnes 2019 ApJ (arXiv: 1807.03319)

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

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

$$f_{\alpha}(t) = \left(1 + \frac{t}{t_{\text{th},\alpha}}\right)^{-1.5}$$

Fission: $t_{\text{th},f} = 4t_{\text{th},\beta}$ and

$$f_f(t) = \left(1 + \frac{t}{t_{\text{th},f}}\right)^{-1}$$

Appendix i: Opacity (i)

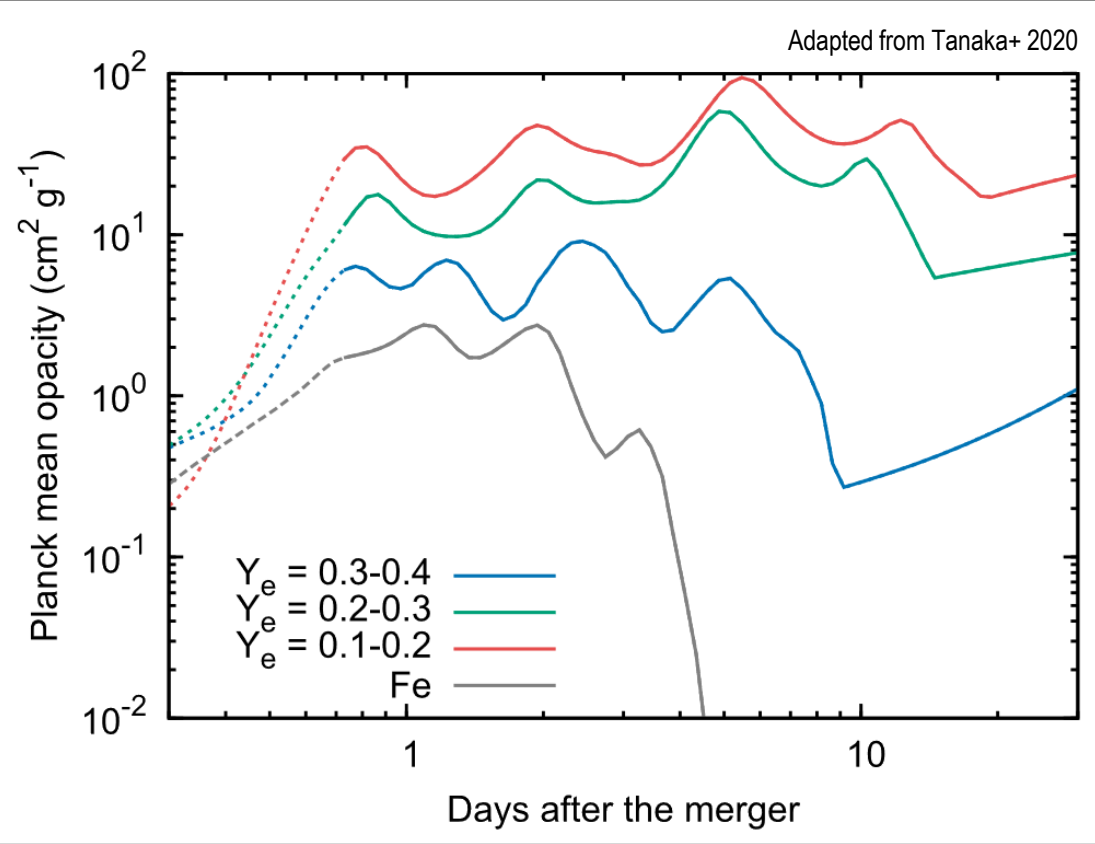
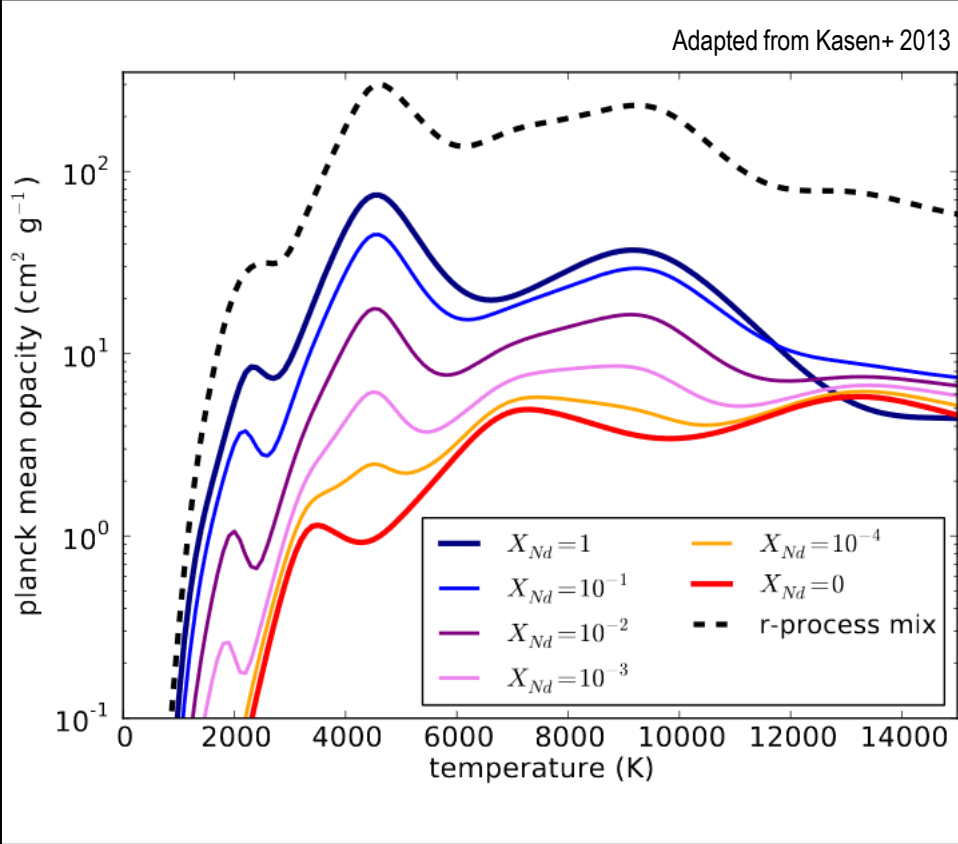
Diffusion timescale is dependent on opacity; in this model, the opacity is temperature dependent.

$$\kappa = \begin{cases} \kappa_{max} \left(\frac{T}{4000\text{K}} \right)^{5.5} & T < 4000\text{K} \\ \kappa_{max} & \text{otherwise} \end{cases} \quad \text{with} \quad \kappa_{max} = 100 \text{ cm}^2\text{g}^{-1}$$

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 i: Opacity (ii)



Appendix i: Fission Barriers

