INT 23-2: Astrophysical Neutrinos and the Origin of the Elements

# A “Beta” Look at Post-Merger Nucleosynthesis

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09 August 2023

NC STATE UNIVERSITY Los Alamos NATIONAL LABORATORY FIRE Fission In R-process Elements

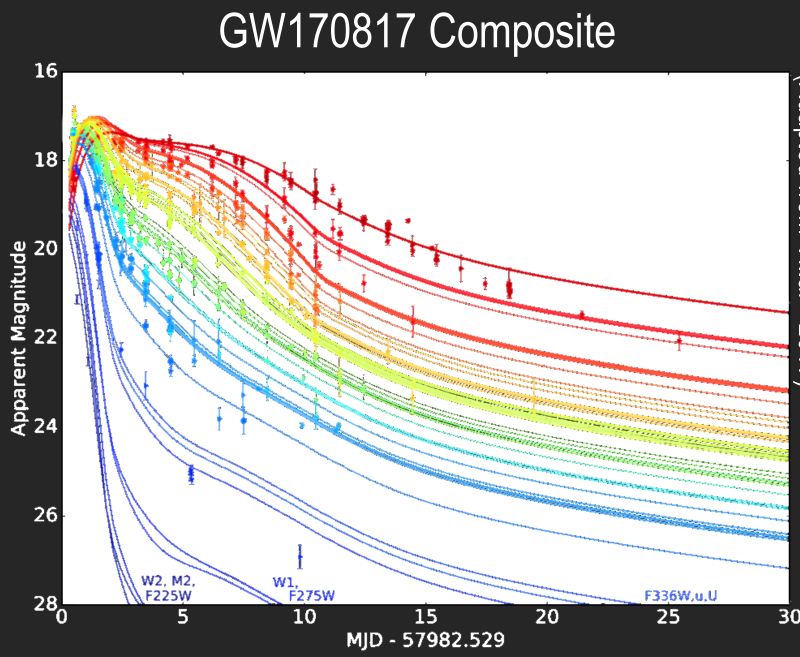
# Kilonovae

**Kilonova (KN):** electromagnetic transient event associated with compact object mergers (at least one neutron star).

GW170817'S accompanying multi-spectral EM transient shows decay on long and short timescales.

Simplest model: red (high opacity) + blue (low opacity) components

Important heating mechanism: radioactive decay of r-process nuclei


GW170817 Composite

(Adapted from Villar+ 2017)

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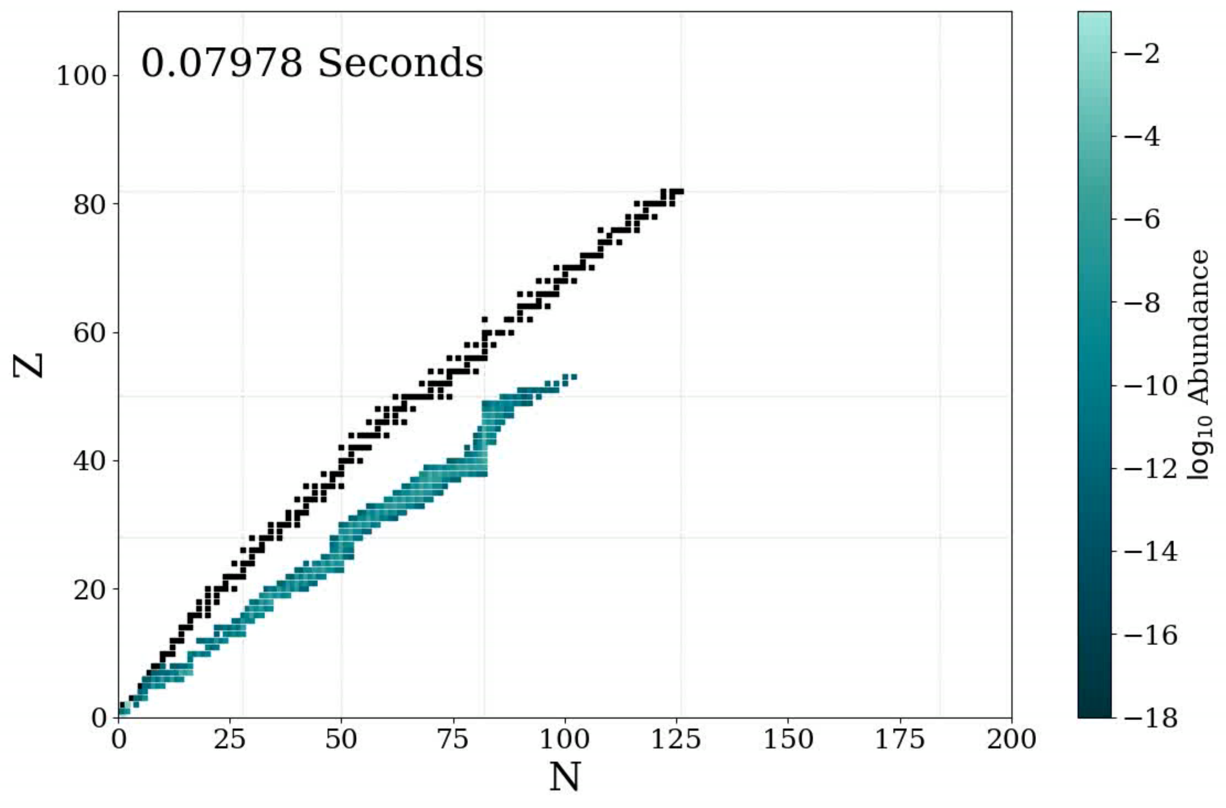
# Time Scales

Rapid neutron capture builds up population that decays on time scales of hours-days (and beyond)



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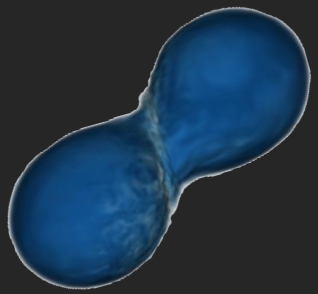
# Time Scales*

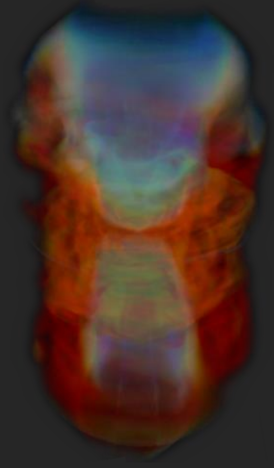
* from J. Miller's talk

In-Spiral



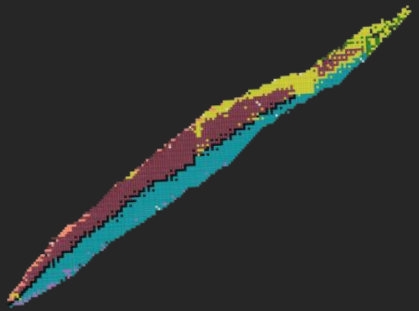
μs - s

Post-Merger Disk



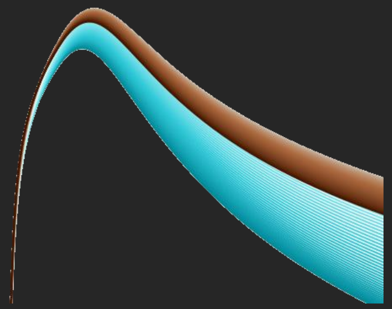
μs - s

Non-Equilibrium Reactions



s - Gyr

Photon Transport



Hours - Weeks

Enrichment

Myr - Gyr

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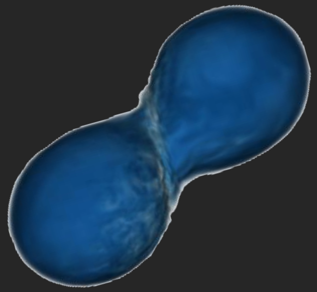
# Time Scales*

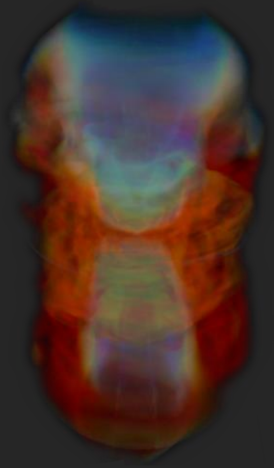
* from J. Miller's talk

### In-Spiral



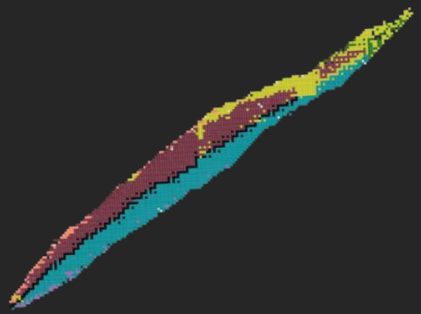
μs - s

### Post-Merger Disk



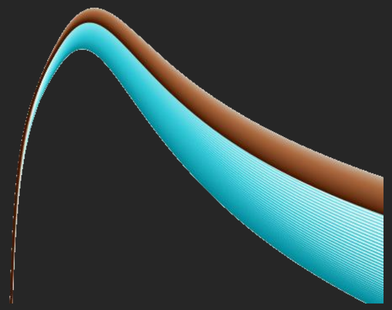
μs - s

### Non-Equilibrium Reactions



s - Gyr

### Photon Transport



Hours - Weeks

### Enrichment

Myr - Gyr

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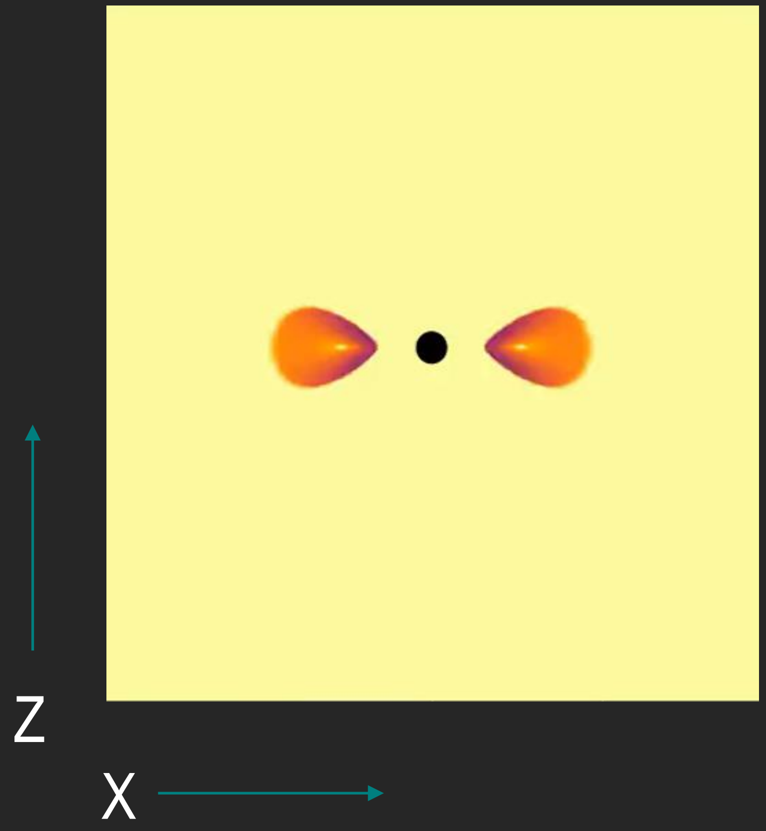
# r-Process Site: Post-Merger Disk



Magnetically driven accretion disk forms after merger event

r-Process occurs in different ejection "sites":

- Wind driven off material in mid-plane
- Material gets entrained in semi-relativistic jet

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# Scope

Miller+ 2019

GRvMHD simulations — probe — Evolution of post-merger accretion disk — for — Thermodynamic evolution

in prep with G. McLaughlin, J. Miller, M. Mumpower

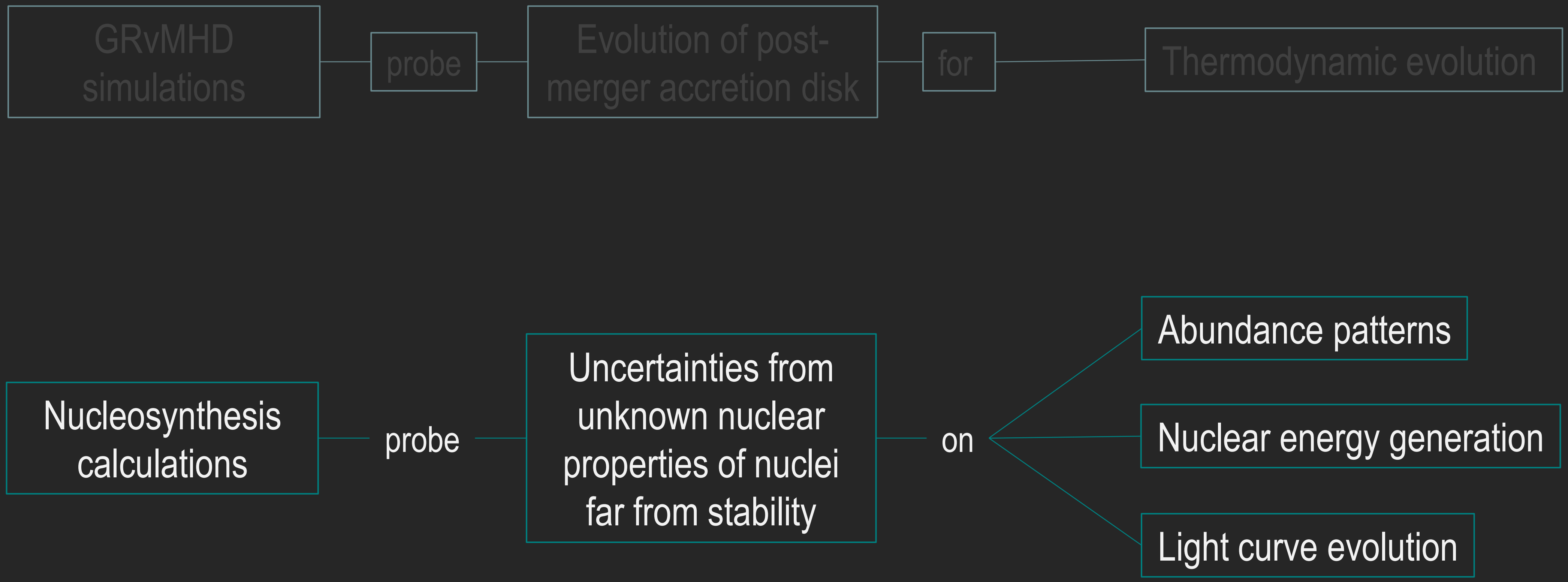
Nucleosynthesis calculations — probe — Uncertainties from unknown nuclear properties of nuclei far from stability — on

- Abundance patterns
- Nuclear energy generation
- Light curve evolution

DOI 10.3847/1538-4357/acaf56 with J. Engel, G. McLaughlin, M. Mumpower, E. Ney, R. Surman

# Scope


Miller+ 2019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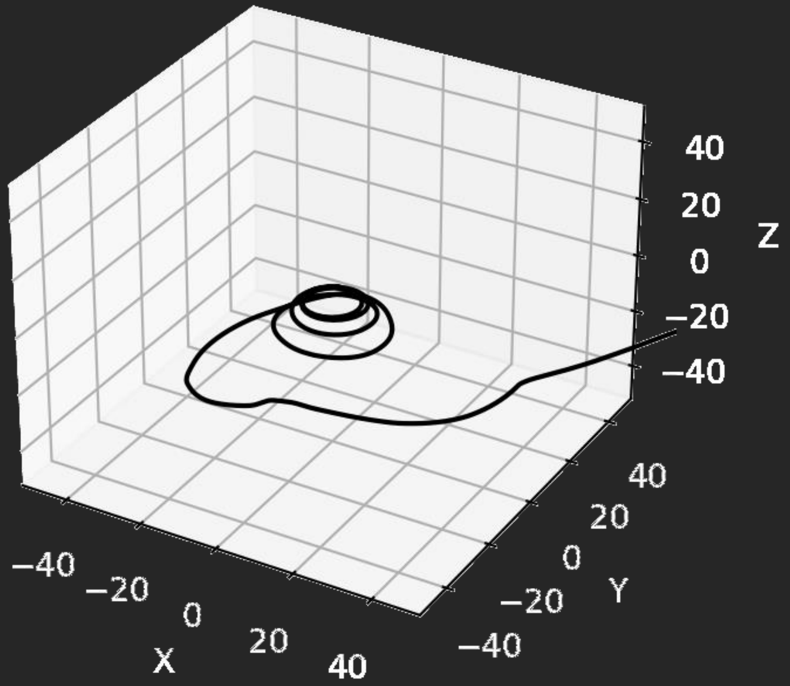
# “Trajectory”



Thermodynamic evolution as a function of time: necessary for nucleosynthesis.

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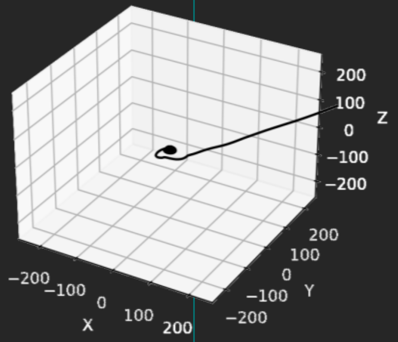
# Parameterized $Y_e$

## Single Trajectory:

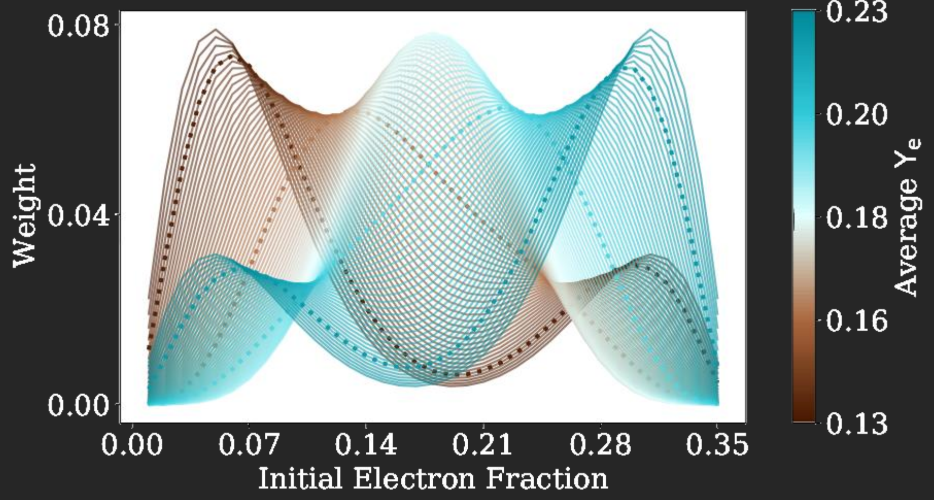
0.02 0.18 0.21

More neutron rich

Less fission



## Linear Combinations:



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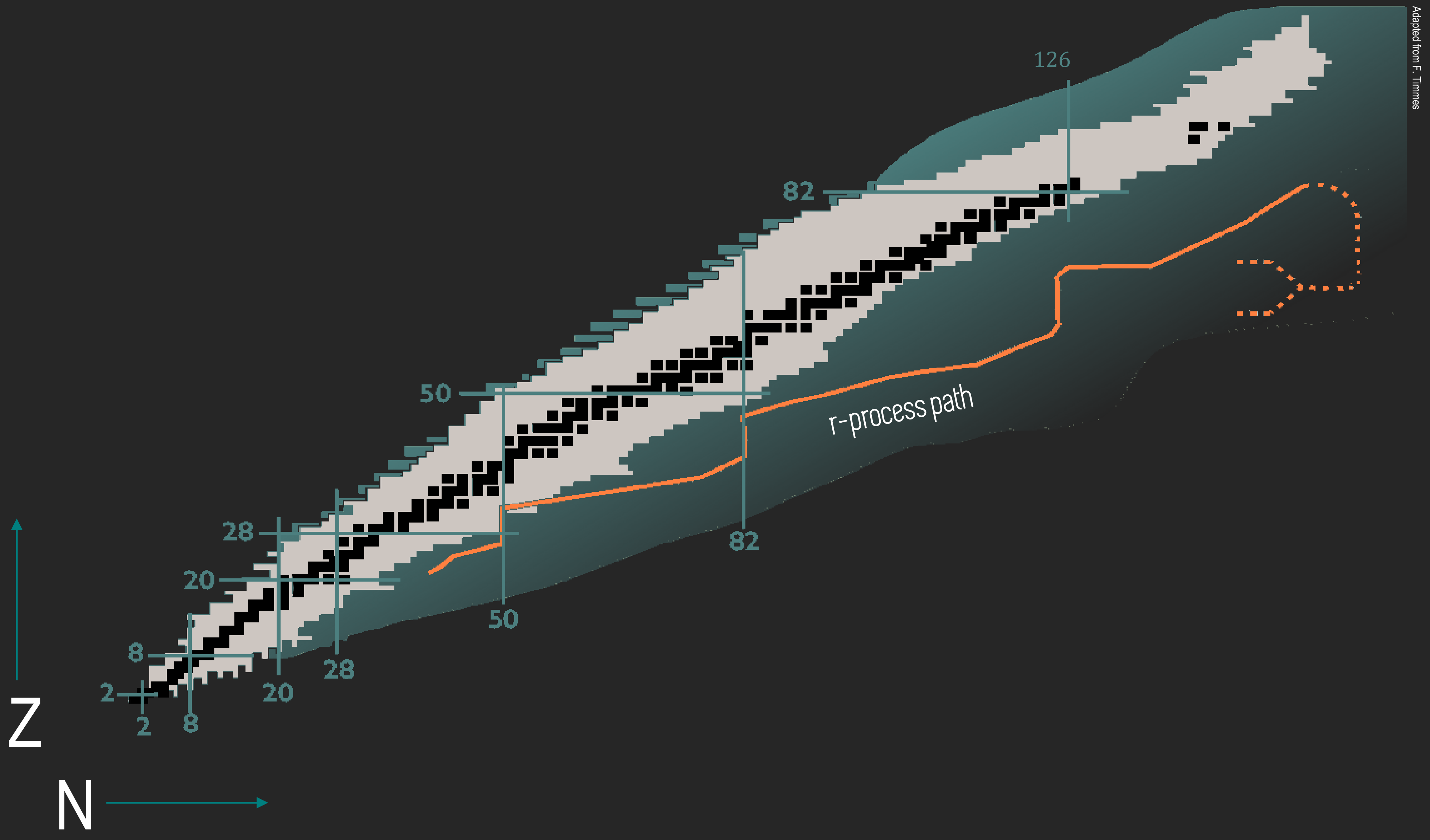
# Sources of Nuclear Uncertainty



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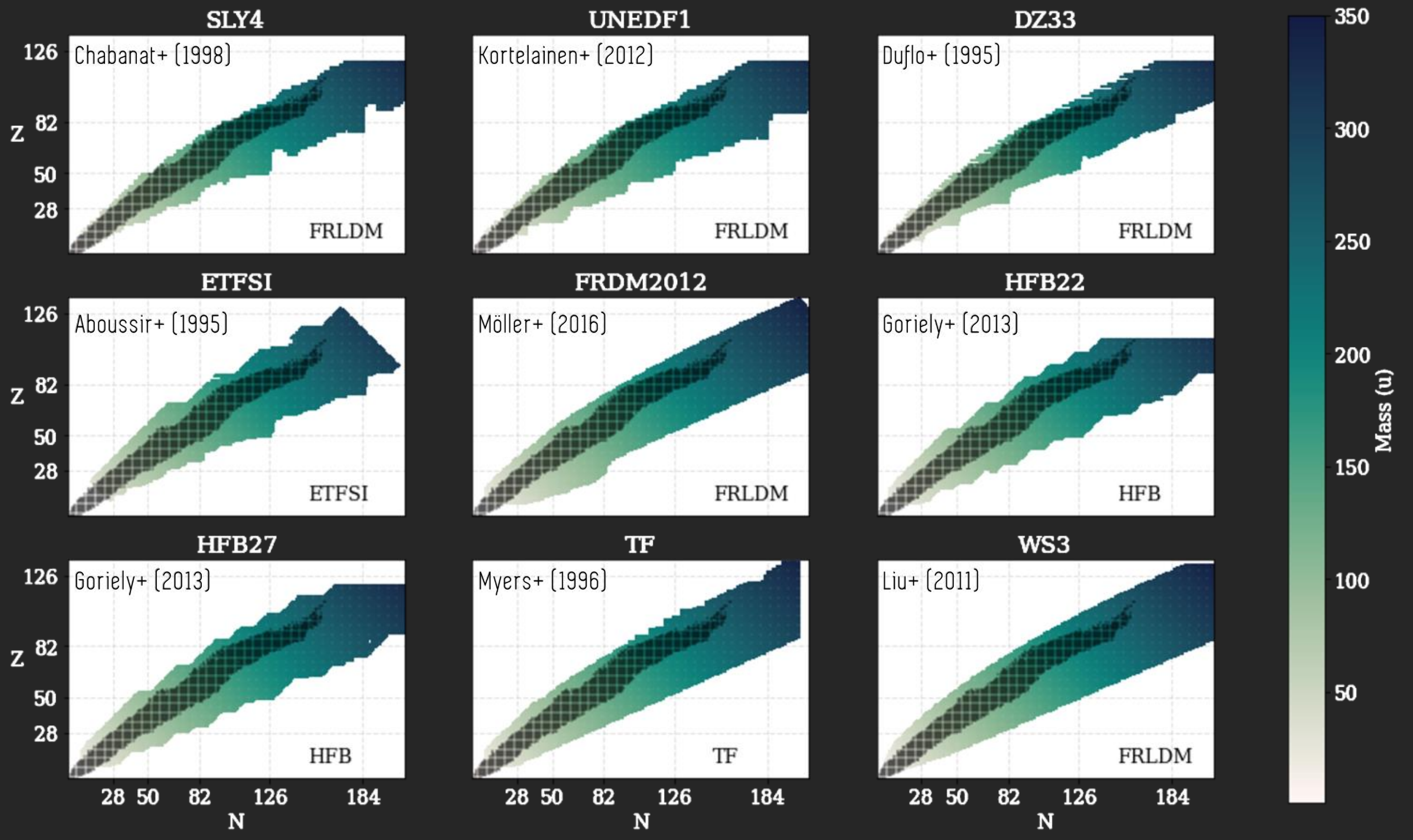
# Mass Model

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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# Beta Decay Rates

Ney (**NES**)

Ney+ 2020

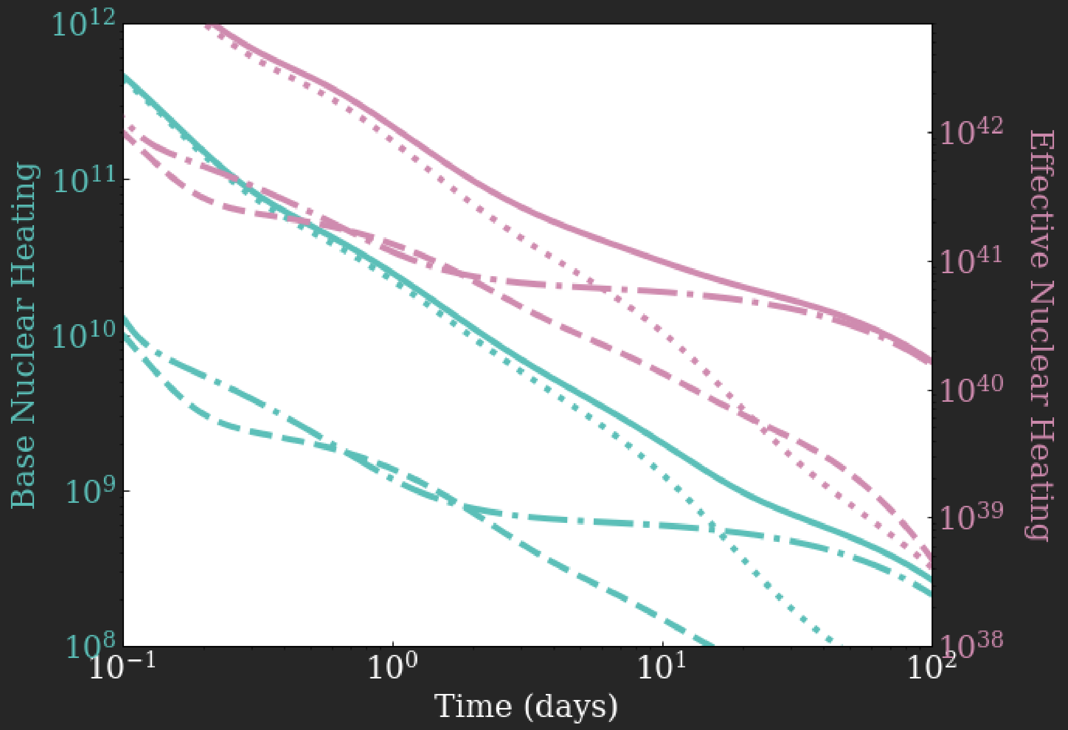
Möller (**MLR**)

Marketin (**MKT**)

Marketin+ 2016

# Nuclear Heating

# Effective Nuclear Heating



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

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

Thermalization based on Kasen & Barnes (2019)

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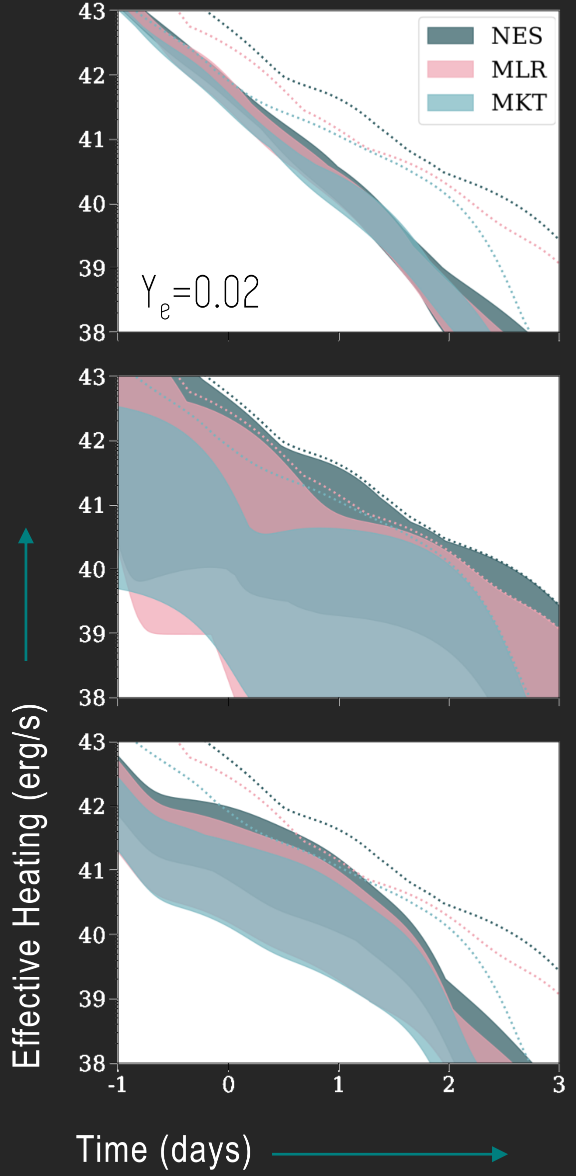
# Uncertainties in Effective Nuclear Heating



**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

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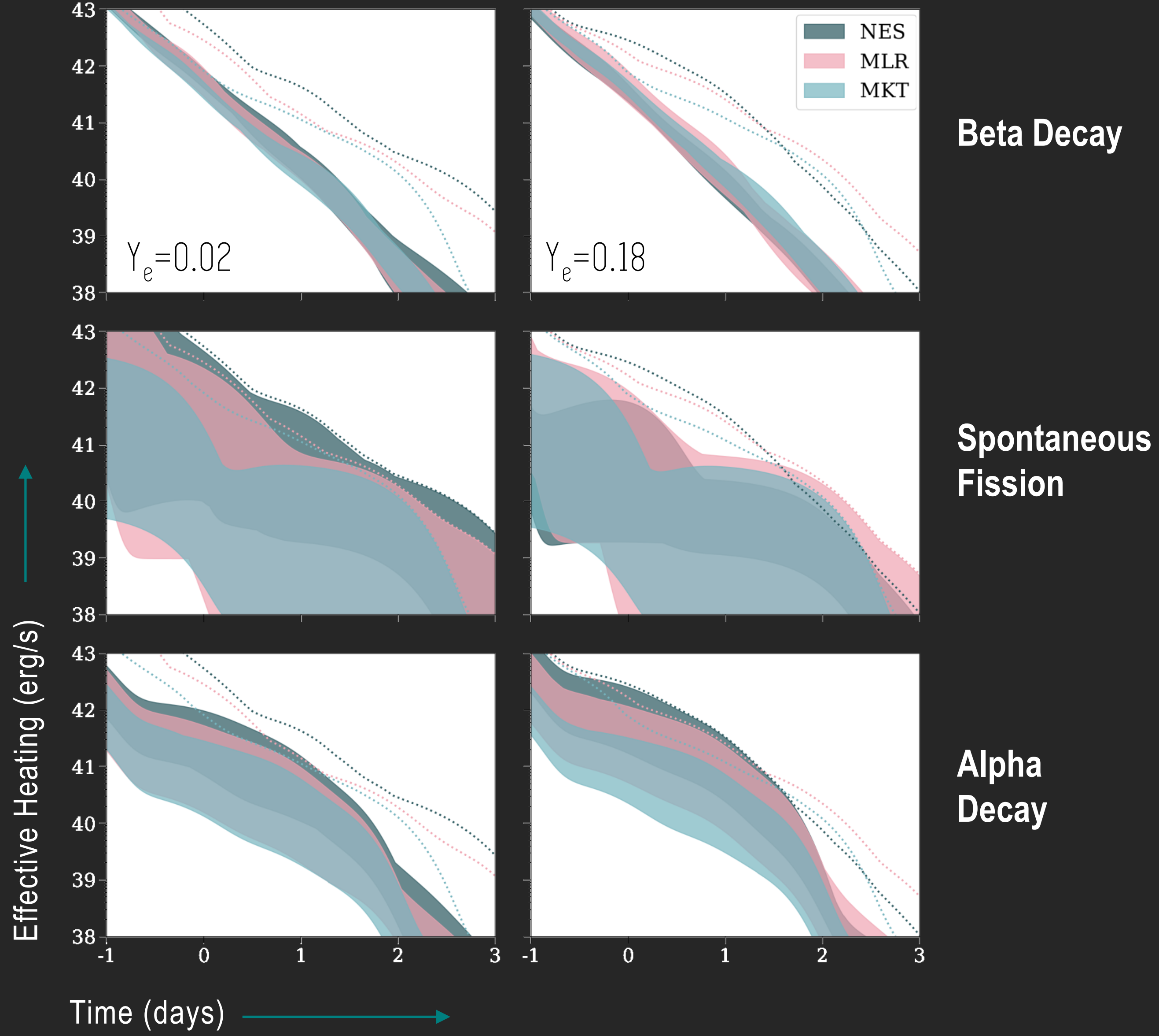
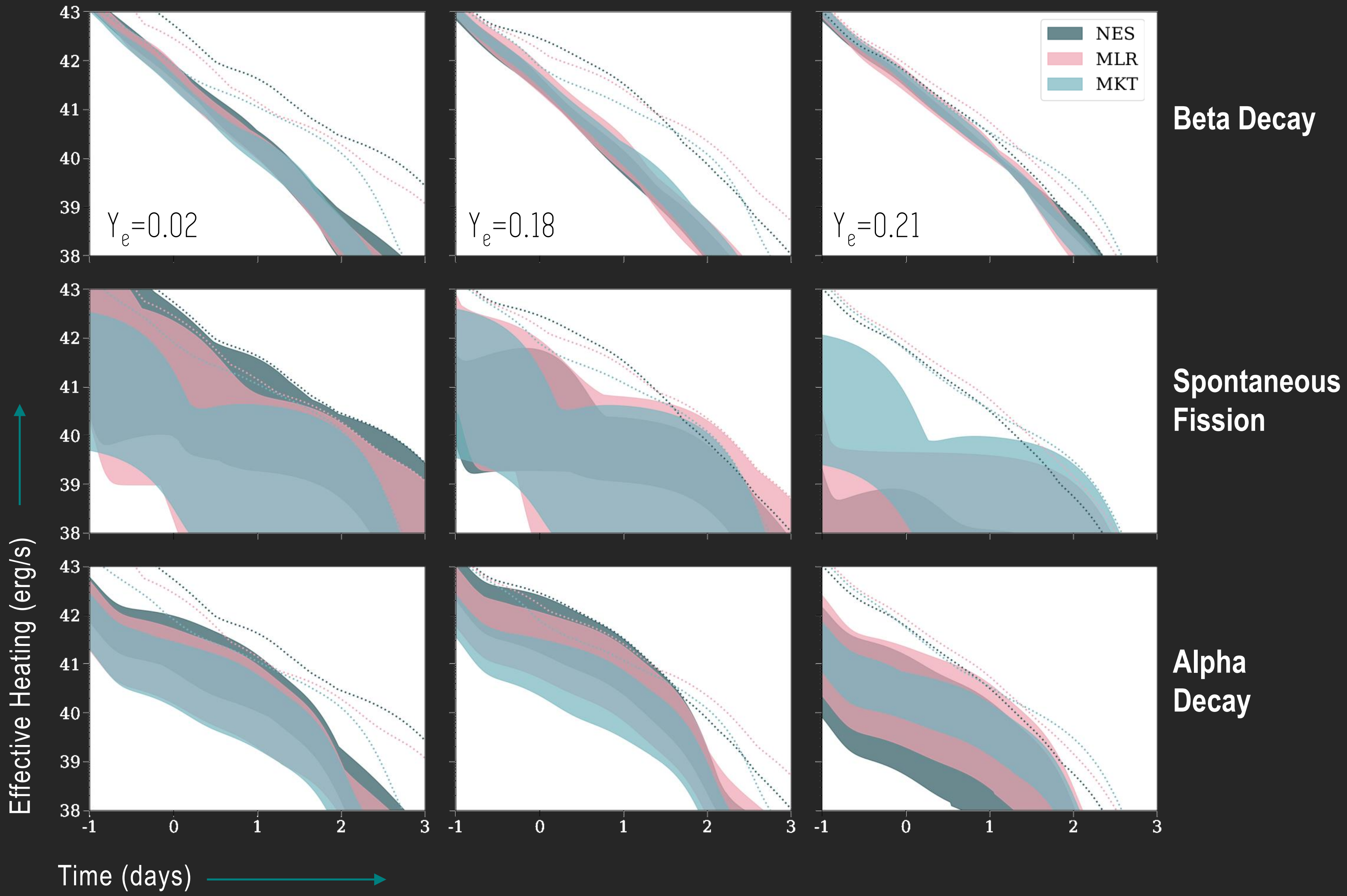
# Uncertainties in Effective Nuclear Heating



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

# Uncertainties in Effective Nuclear Heating



- 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

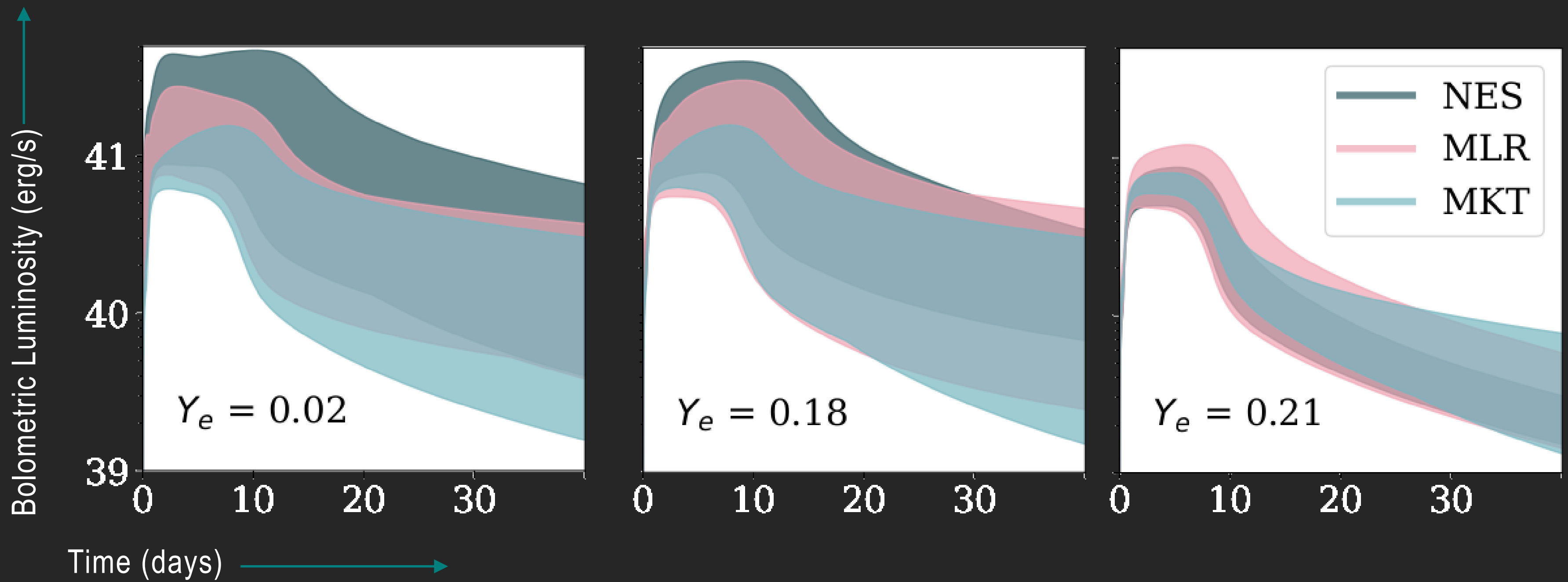
Similar procedure as effective heating calculation (ref Metzger 2017)

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:

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

# 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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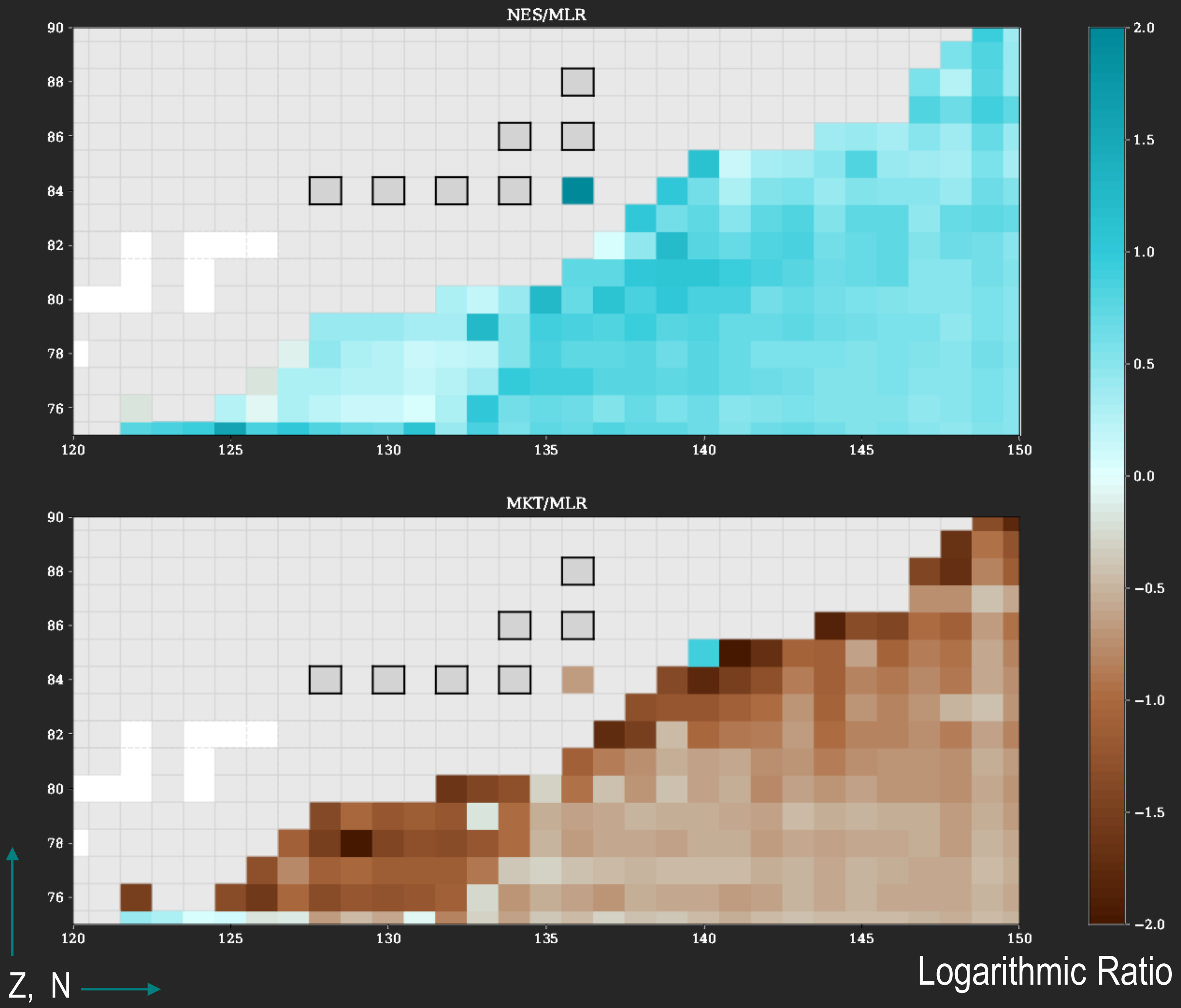
# Critical Nuclei: Alpha Decay



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

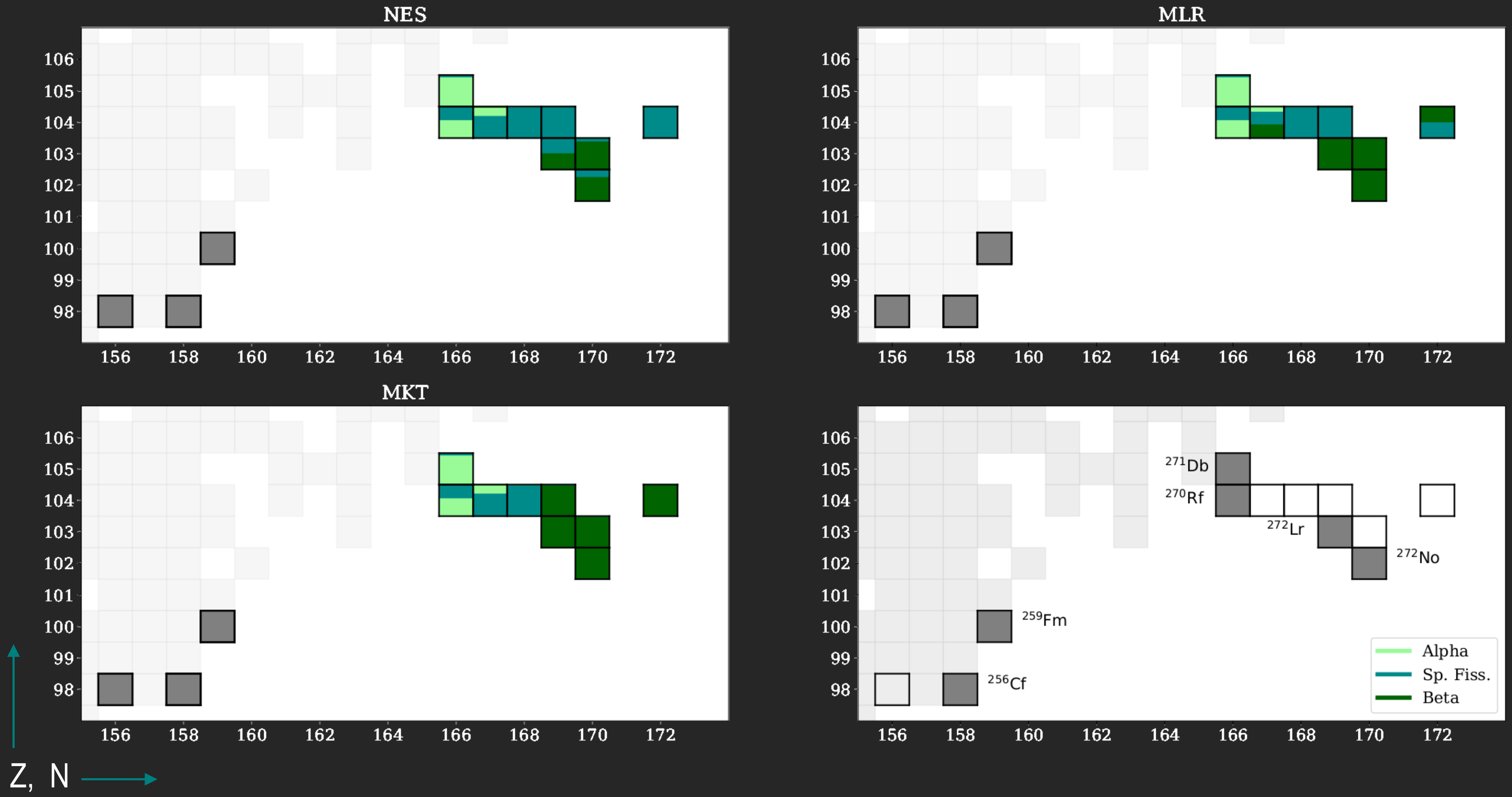
$^{224}$Ra

$^{220}$Rn $^{222}$Rn

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

# Critical Nuclei: Spontaneous Fission (et al)

Theoretical branching ratios affect spontaneous fission heating



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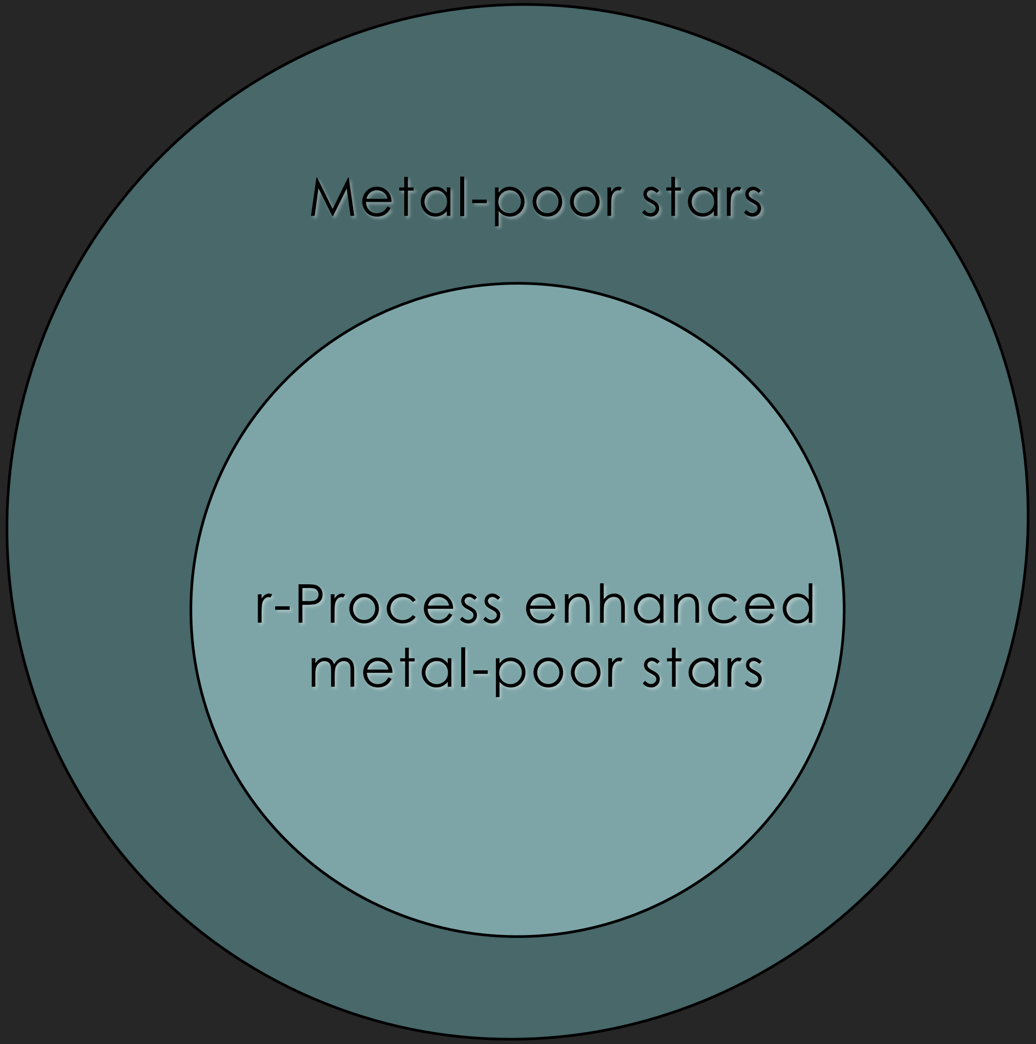
# Nuclear Cosmochronometry

# r-Process Enhanced Stars

*Refer to E. Holmbeck's talk

A star's metallicity (Fe) can be taken as a proxy for age.

Some stars have very low metallicity (metal-poor) but high content of r-process material. These r-process enhanced stars are taken to have been enriched by a single r-process event.



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# Ages from Nuclear Physics

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

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# How to Find Ages

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

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

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

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

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)

# Astronomical Sample: Uranium

Increasing actinide enhancement

| Star Name | Reference |
|---|---|
| **HE1523-0901** | Frebel+2007 |
| **CS29497-004** | Hill+2017 |
| **J2038-0023** | Placco+2017 |
| **CS31082-001** | Siquiera Mello+2013 |
| **J0954+5246** | Holmbeck+2018 |

JINA-CEE

JINAbase

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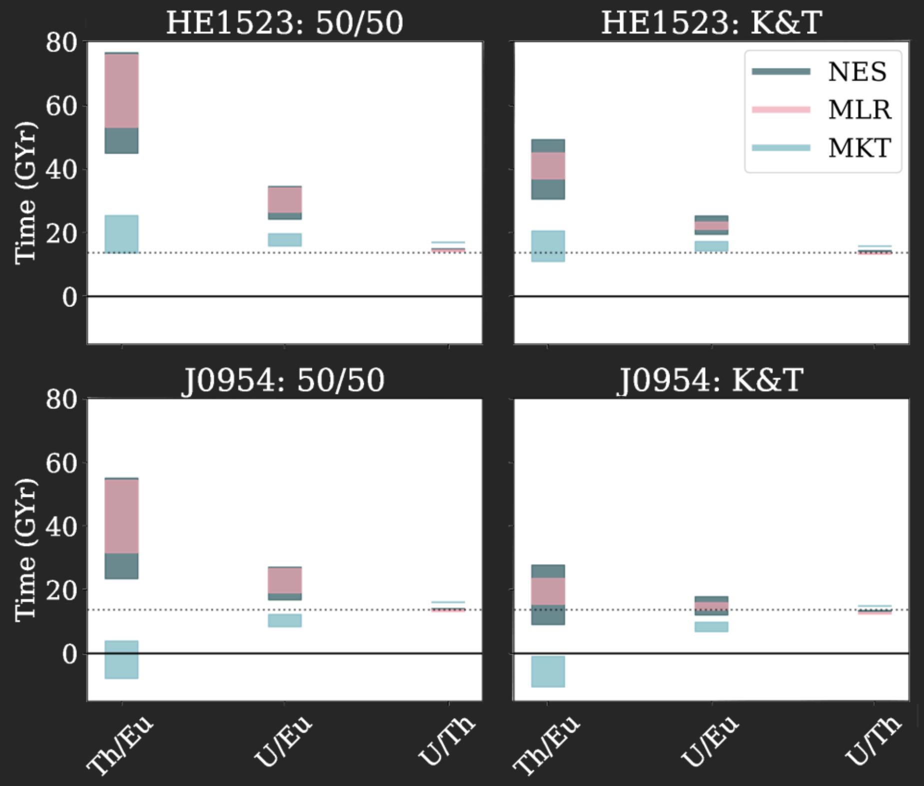
# Abundances for Cosmochronometry



- Europium production highly sensitive to average Ye and fission yield

- Underabundance of actinides can lead to negative age predictions

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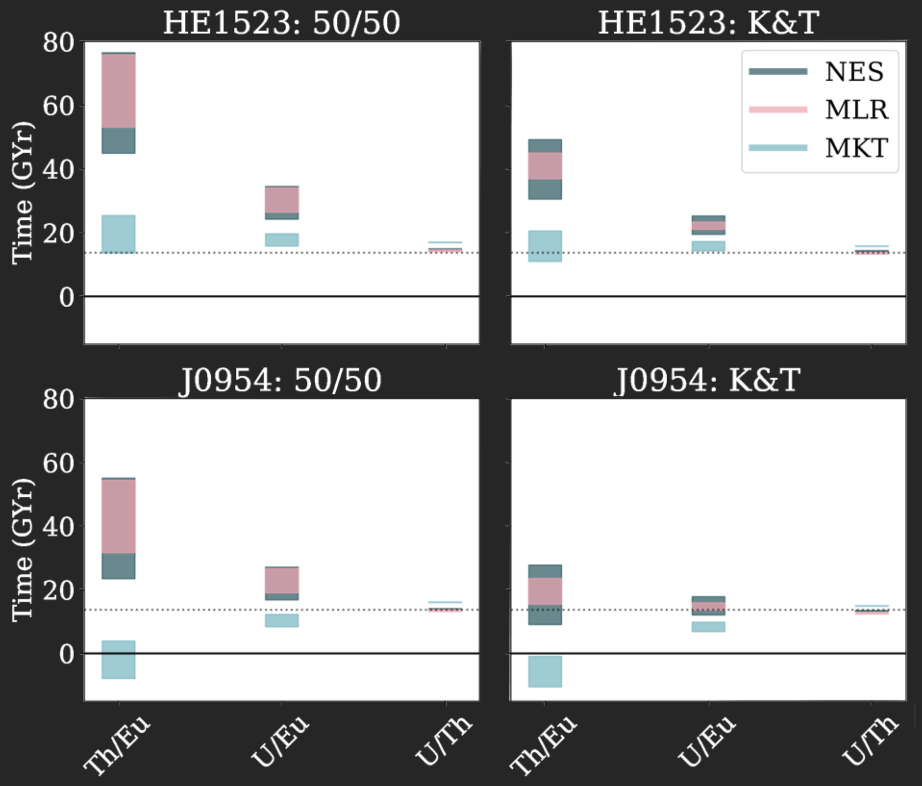
# Abundances for Cosmochronometry



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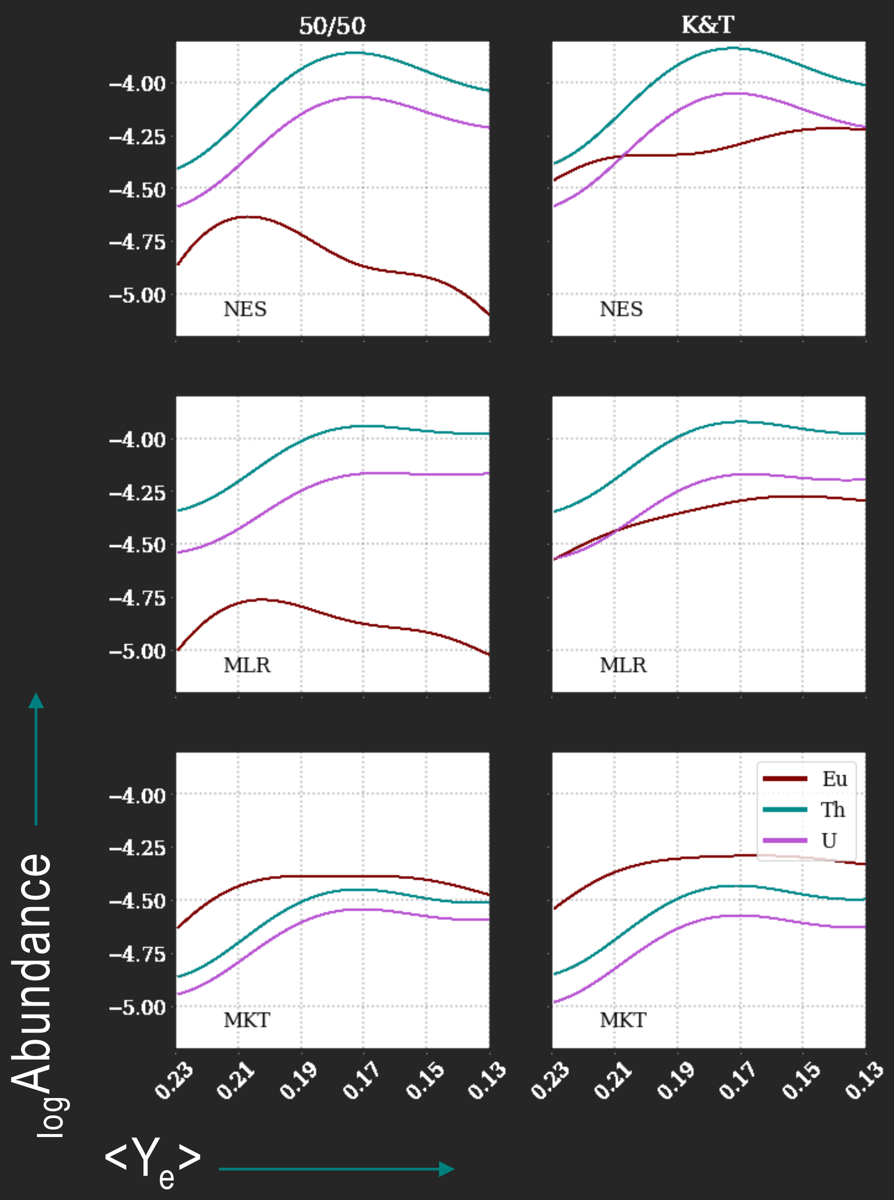
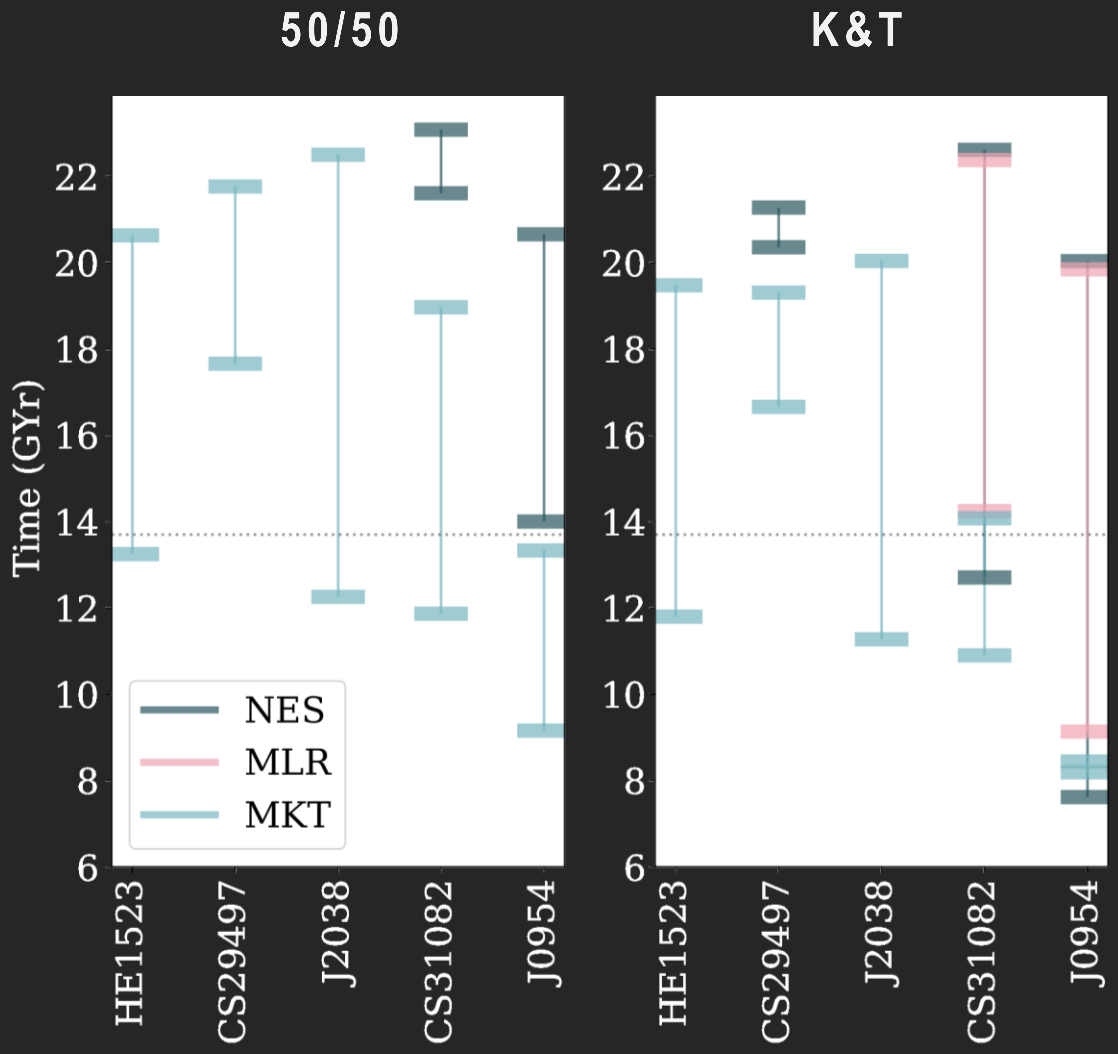


# Ages Can Agree*



...if observational error bars are taken into consideration:

- Ages equal using all three chronometer pairs: $\left(\frac{\mathrm{Th}}{\mathrm{Eu}}\right) = \left(\frac{\mathrm{U}}{\mathrm{Eu}}\right) = \left(\frac{\mathrm{U}}{\mathrm{Th}}\right)$
- Age estimate and overlap depends on beta-decay model

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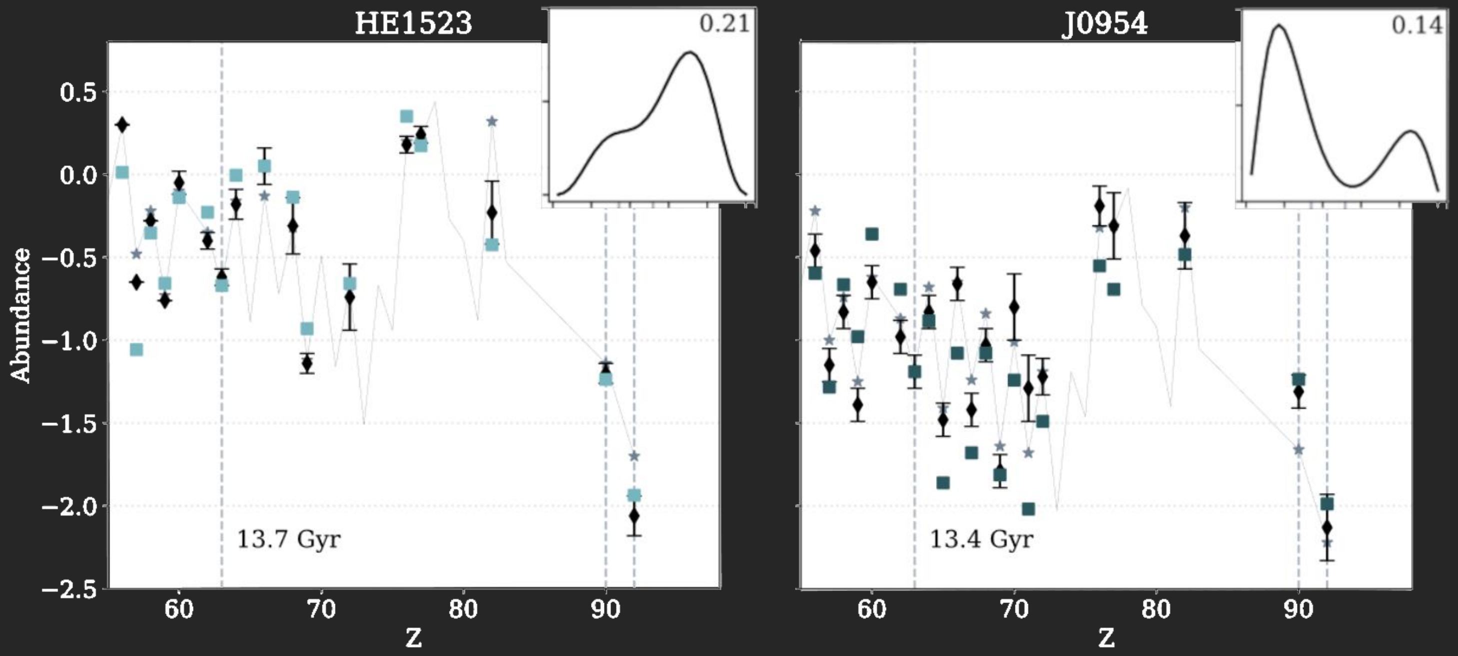
# "Fit" to Observation

- Run nucleosynthesis calculations out to selected age

- Compare full abundance pattern to observation



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# A peek at some ongoing work

# Scope

Miller+ 2019

GRvMHD simulations — probe — Evolution of post-merger accretion disk — for — Thermodynamic evolution

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

- Abundance patterns
- Nuclear energy generation
- Light curve evolution

# Evolution of Post-Merger Disk

Disk $Y_e$ — depends on — Neutrino interactions — depend on — Thermodynamic evolution of the disk — depends on — Magnetic fields

Neutrinos in the disk are neither trapped nor free-streaming, therefore neutrino transport is essential

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# Variable Field Strength

$$\beta = \frac{P_{gas}}{P_{magnetic}}$$

could affect

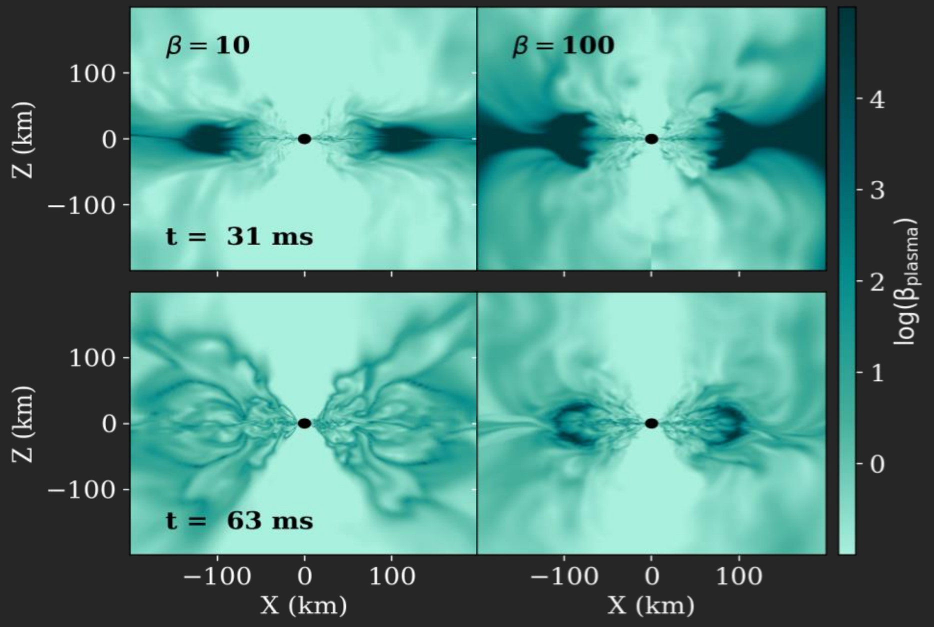
Ejection mechanism

Mass of ejecta

Ejecta velocity

Neutrino evolution timescale

Decreasing initial field strength



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# Procedure

**GRMHD simulations**
with **nubhlight** (Miller +)

produce

**Tracers: thermodynamic evolution**
(>400,000 total)

for

**Nucleosynthesis**
with PRISM (Mumpower+)

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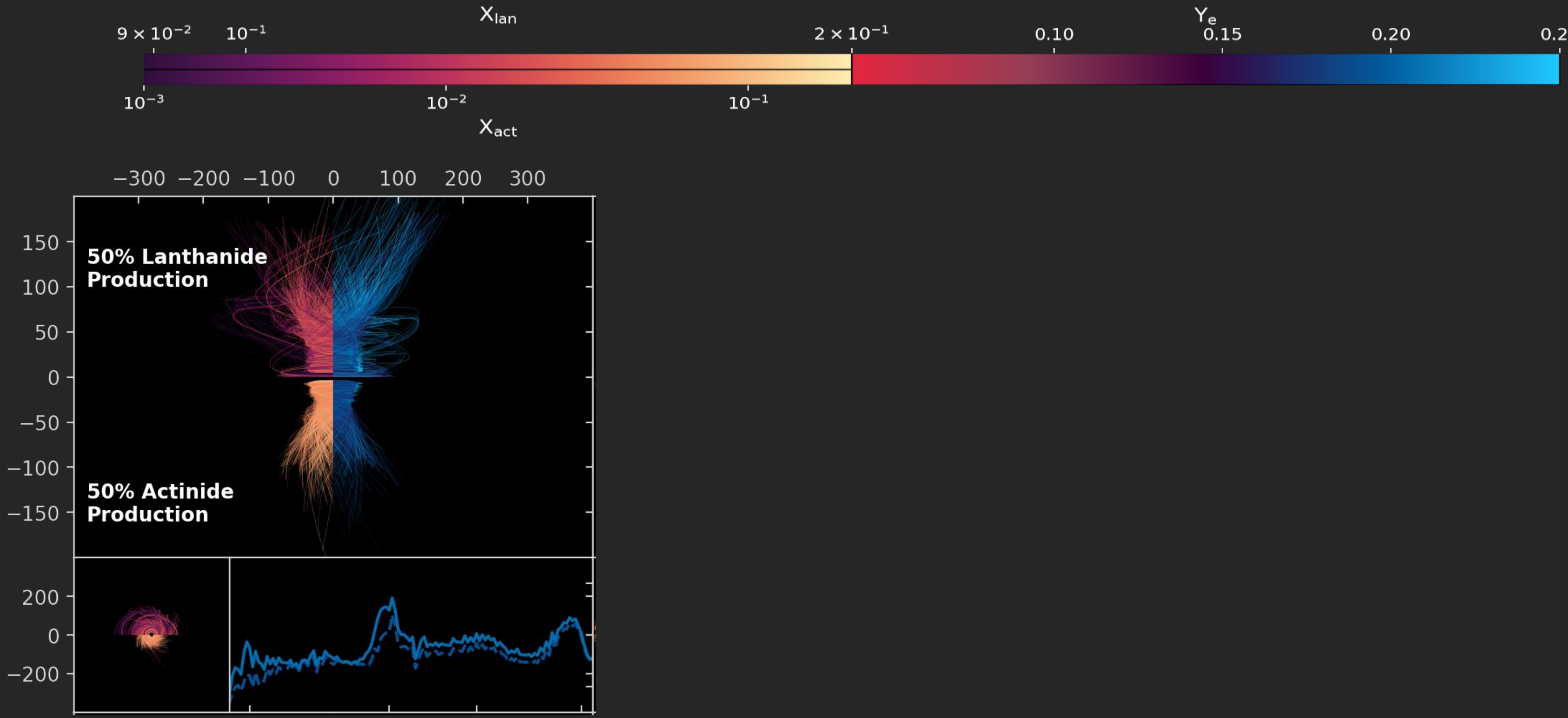
# Some Preliminary Results



Lund+ in prep

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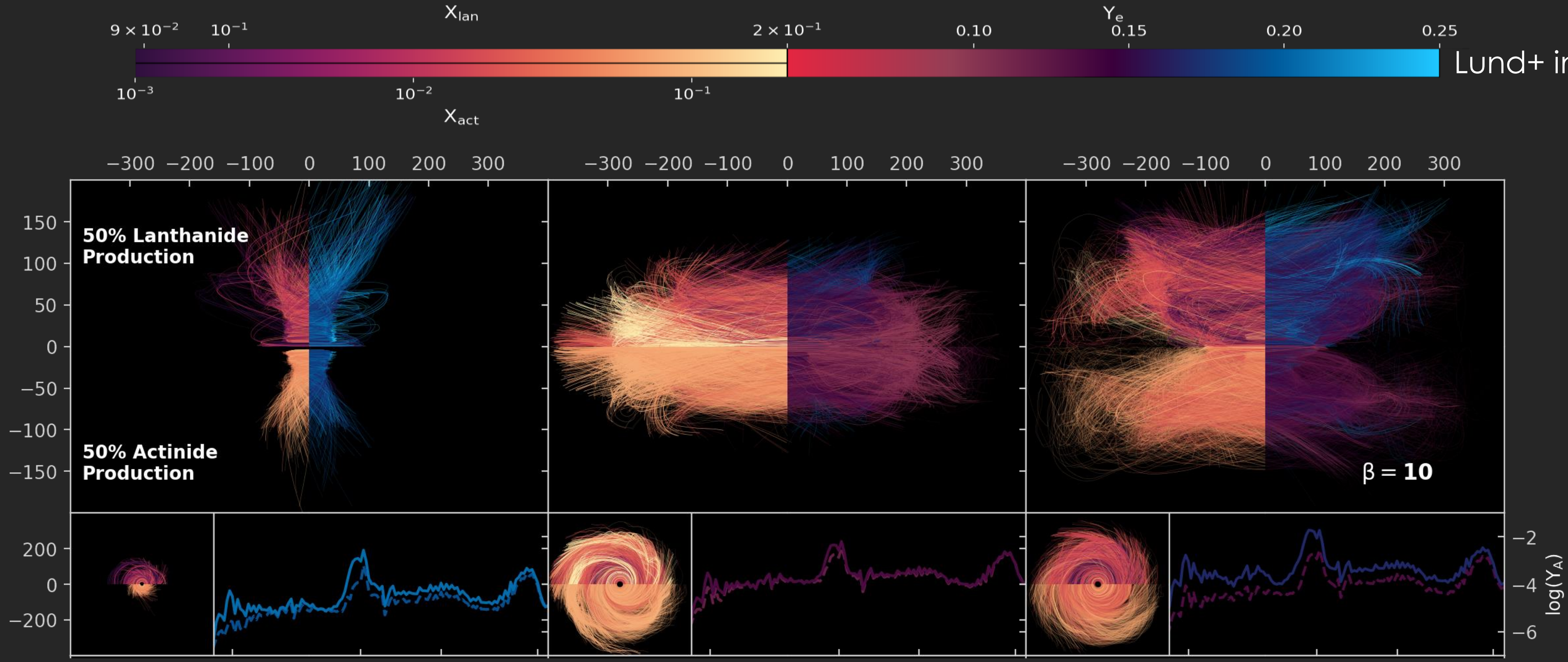
# Some Preliminary Results



Lund+ in prep

Jets capable of producing overall small amounts of actinides, but high mass fraction

High entropy jets allow for higher Ye for lanthanide/actinide production

Stronger initial B field yields higher ejecta mass, with higher lanthanide and actinide richness

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# 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**

**Thank you!**