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Kilonova Modeling: Nuclear Physics, Magnetic Fields, Neutrinos

Magnetic Field Effects on Nucleosynthesis from Merger Outflows

Los Alamos NATIONAL LABORATORY

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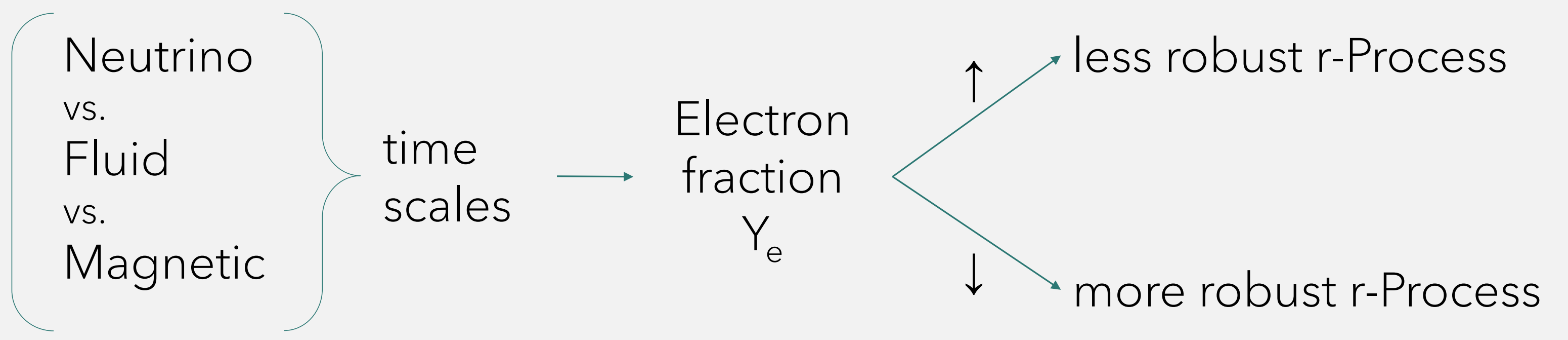
Context

- Neutron star mergers (NSM) are a preferred site for the synthesis of the heaviest elements via the rapid neutron capture (r-process)
- Accretion disks formed via magnetorotational instability can provide conditions necessary for r-process
- Accretion time scales depend on magnetic field strength; parameter β determines ratio of gas to magnetic pressure



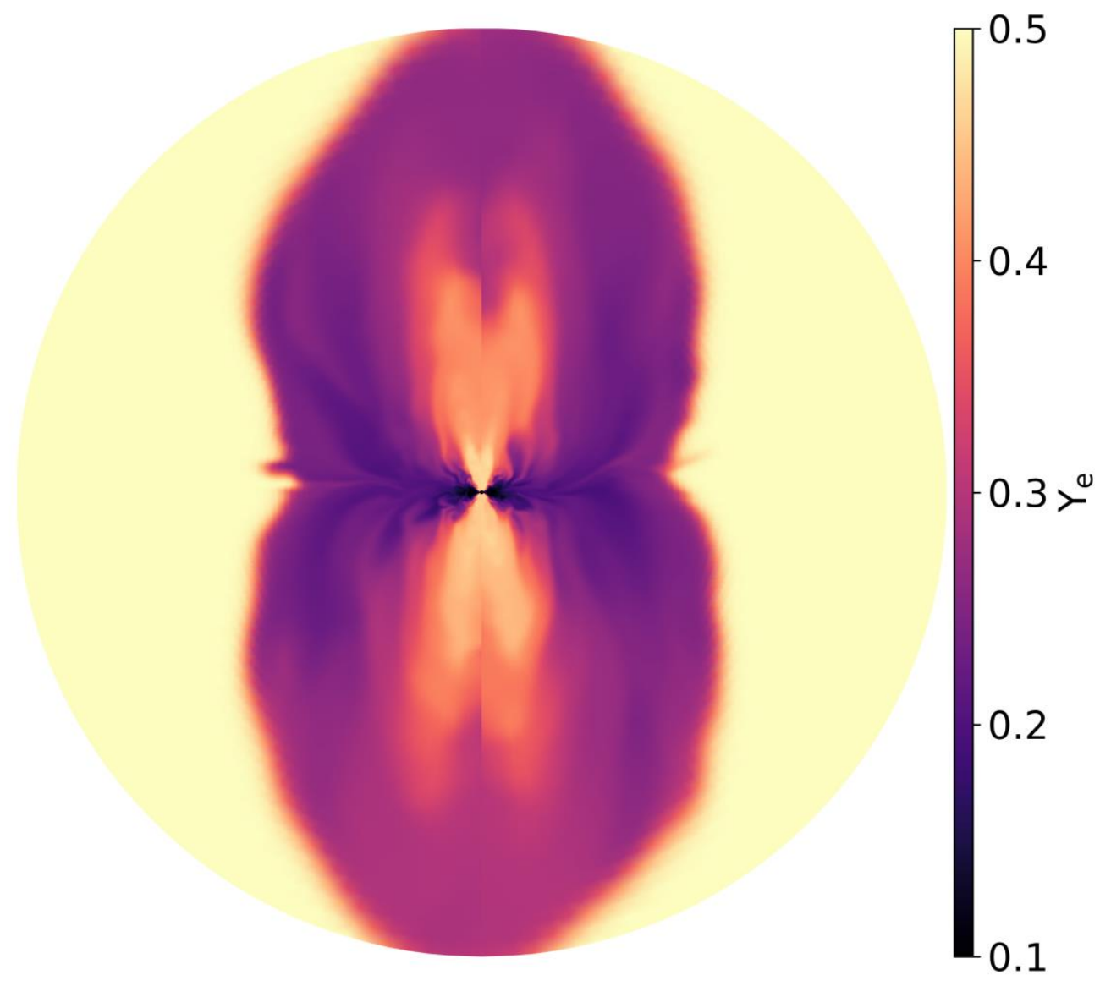
Neutrino
vs.
Fluid
vs.
Magnetic

time scales → Electron fraction Y_e

↑ less robust r-Process

↓ more robust r-Process

Open Questions



Uncertainty concerning the robustness of r-process pattern produced in post-merger disk environments

- Do the conditions necessary to favor lanthanide and actinide production depend on the initial conditions of the disk?
- Are there certain regions of the outflow that are more favorable for r-process?

Left: Volume rendering of electron fraction from binary NSM outflow

Codes

nubhlight [1]

General relativistic magnetohydrodynamics with MC neutrino transport

All disks start with 0.12 $M_\odot$ and uniform Y_e = 0.1

We vary the initial magnetic field strength:

β_i = 10
195216 tracers

β_i = 30
135818 tracers

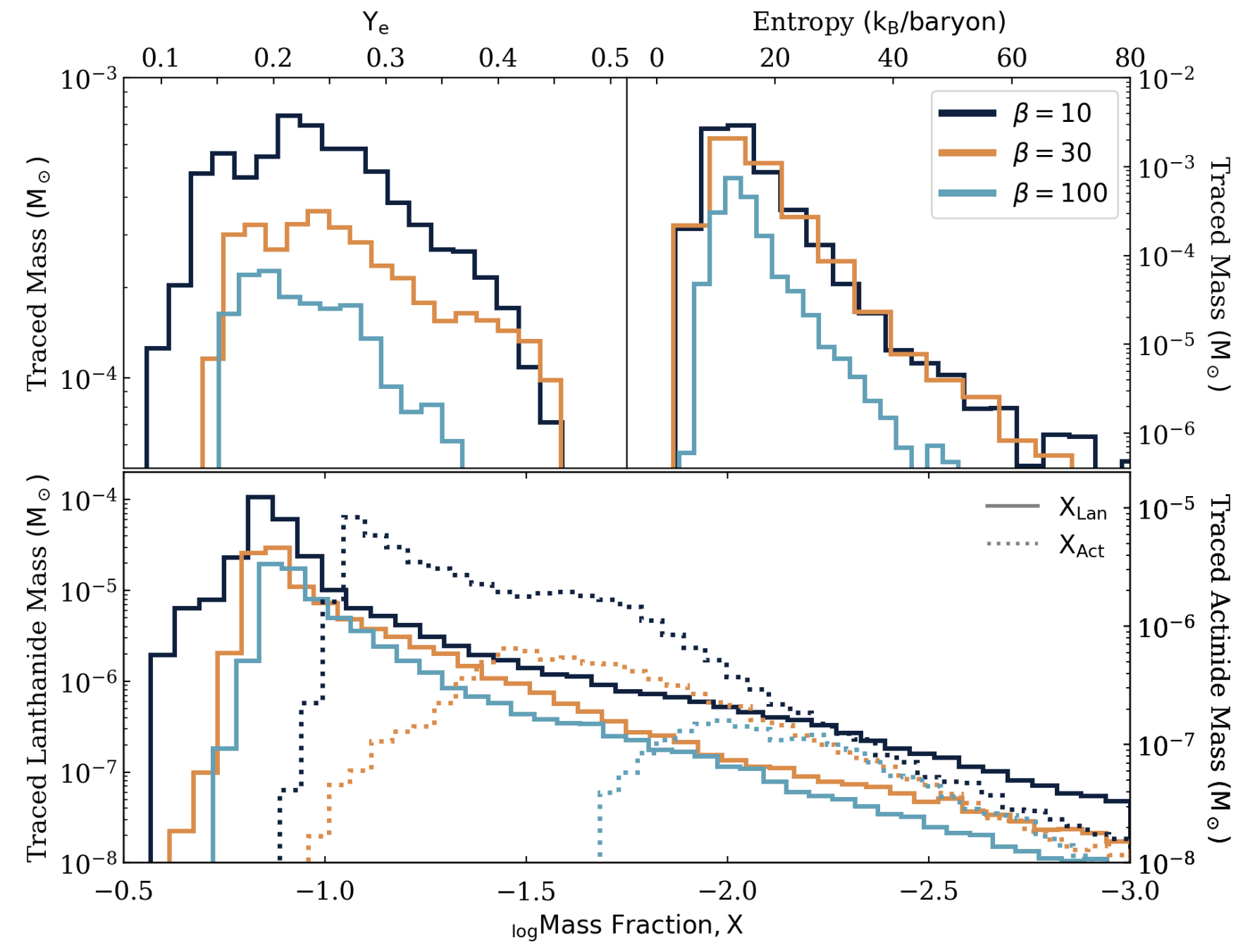
β_i = 100
74582 tracers

PRISM [2]

Nuclear reaction network with highly flexible nuclear data input

Run out to 1 Gyr

MHD → Nucleosynthesis



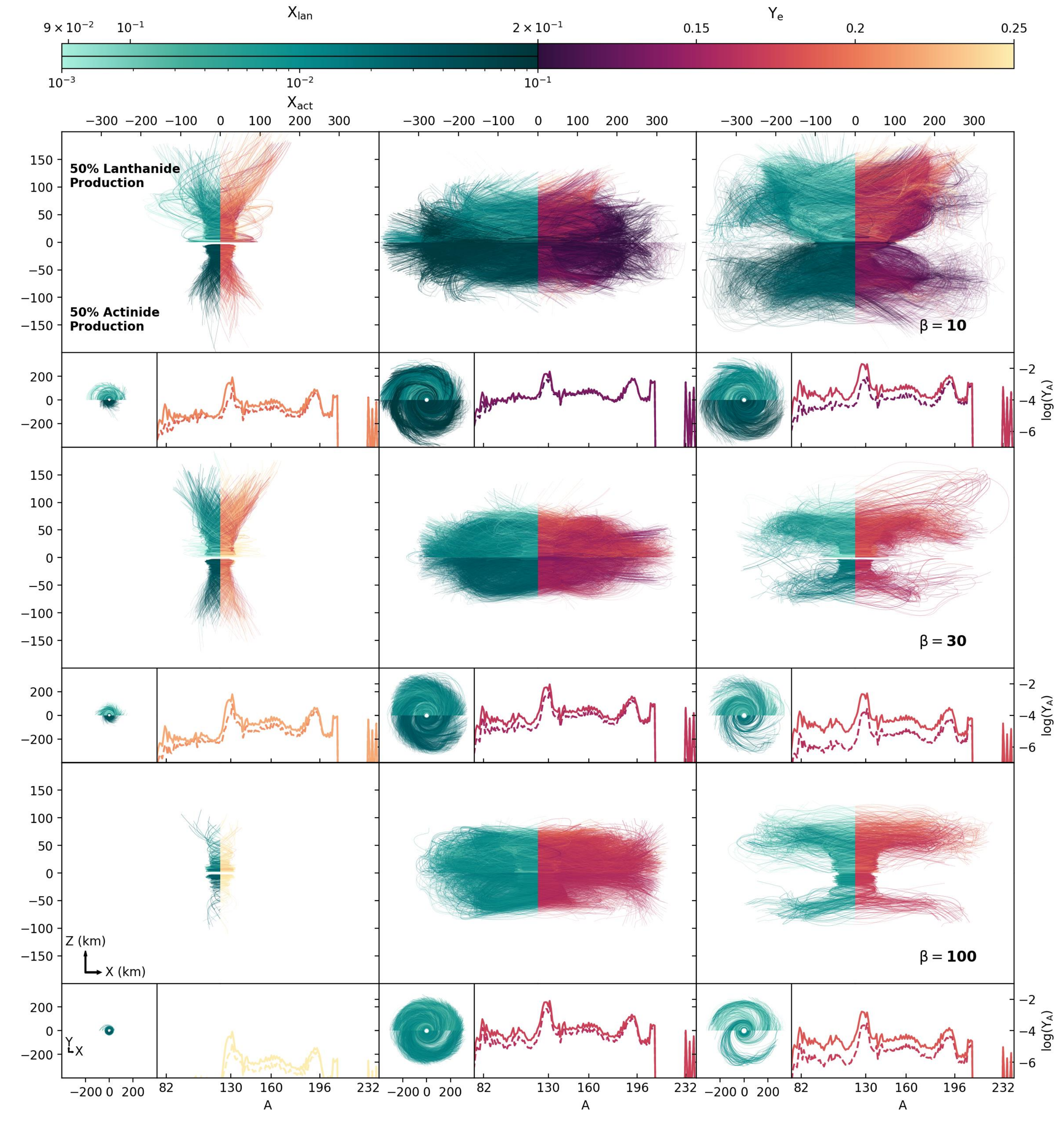
Top left:
Distribution of initial Y_e setting conditions for nucleosynthesis

Top right:
Distribution of initial entropy.

Bottom:
Distribution of resulting lanthanide (left) and actinide (right) mass fractions produced.

Lanthanide & Actinide Production

- Tracers identified as responsible for producing 50% of lanthanide (top) and actinide (bottom) mass.
- Separated based on properties at last temperature T_9 = 10.



Polar: θ > 45°   Viscous: Z_{avg} < 38 km   Everything else

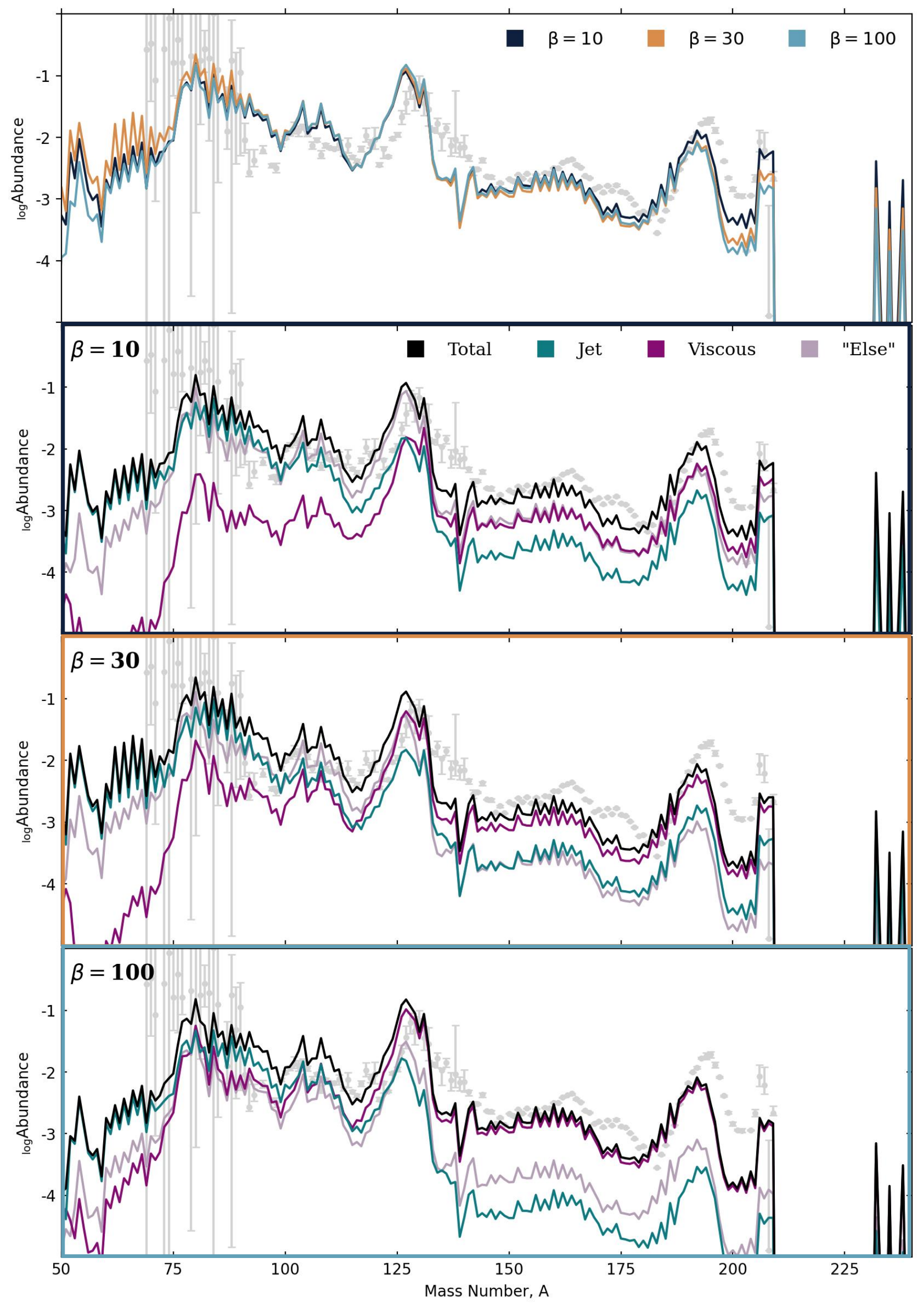
Full Abundances (1 Gyr)

Scaled overall abundance patterns produced by full set of tracers from each full simulation.
Grey = solar

Abundance patterns from **β=10**: split into spatial components

Abundance patterns from **β=30**: split into spatial components

Abundance patterns from **β=100**: split into spatial components



- High degree of similarity in rare-earth region despite varying initial conditions.
- Strong third peak and actinide enhancement in **β=10** case.
- Largest variation in relative contributions from different spatial components to total pattern.

Concluding observations

- We simulate three separate post-merger disks with varying initial magnetic field strength and carry out nucleosynthesis calculations out to 1 Gyr post-merger on unbound tracers.
- Favorable regions for producing r-process shift with β:
  - **β=10** (strongest field)
    - Large overlap between lanthanide, actinide producing tracers.
    - Strongest case of high (>0.16) $\chi_{lanthanide}$ tracers
    - Best at producing actinides
  - β=30
    - Highest first peak abundances
  - β=100
    - Lowest ejected mass
    - Least effective at producing actinides
- Stronger magnetic field unbinds more mass compared to a weaker field, effectively unbinding more lanthanide mass.
- Actinide production highly sensitive to initial magnetic field strength.

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[1] Miller+ 2019 : 10.3847/1538-4365/ab09fc
[2] Mumpower+ 2017 : 10.1088/1361-6471/44/3/034003
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