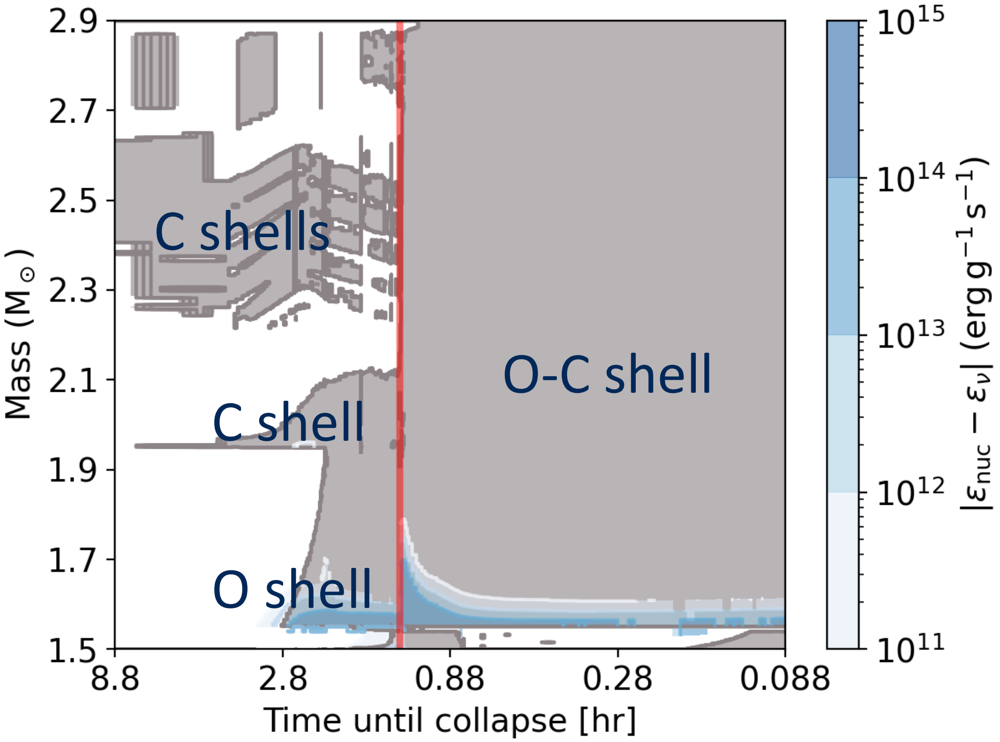
Radioactive isotope formation in 3D-informed O-C shell mergers

Joshua Issa, Falk Herwig, Steve Mojzsis,
Marco Pignatari, & Kai Matsunaga

Astrophysics with Radioactive Isotopes 2026

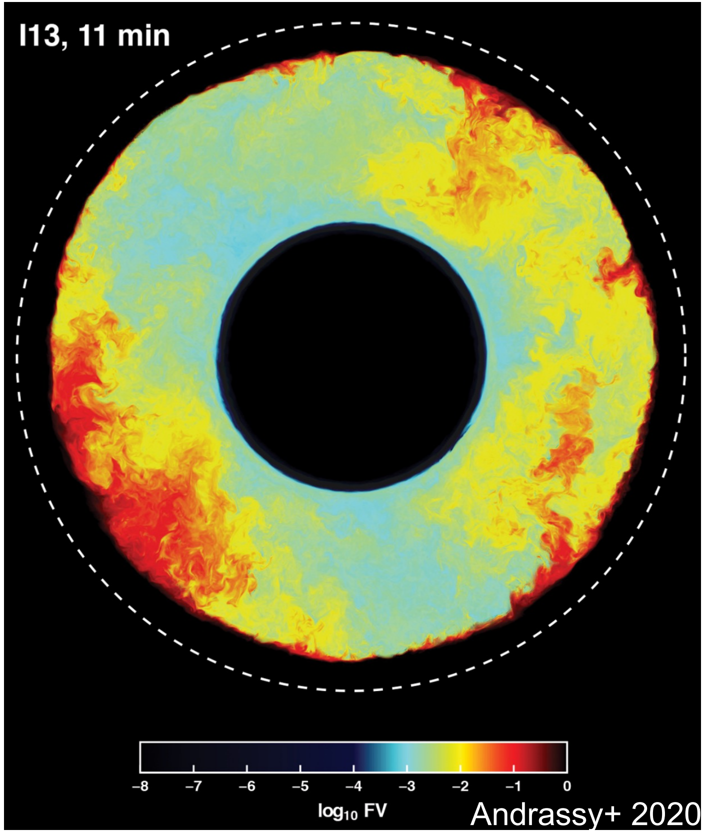
What are O-C* Shell Mergers



- Oxygen-carbon shell mergers are late events (last hours!) where a single convective shell spans multiple burning temperatures (see Luca & Lorenzo's talks)
- O-burning products are increased and C-burning products are decreased in these events

*OC and CO are different labels for the same event

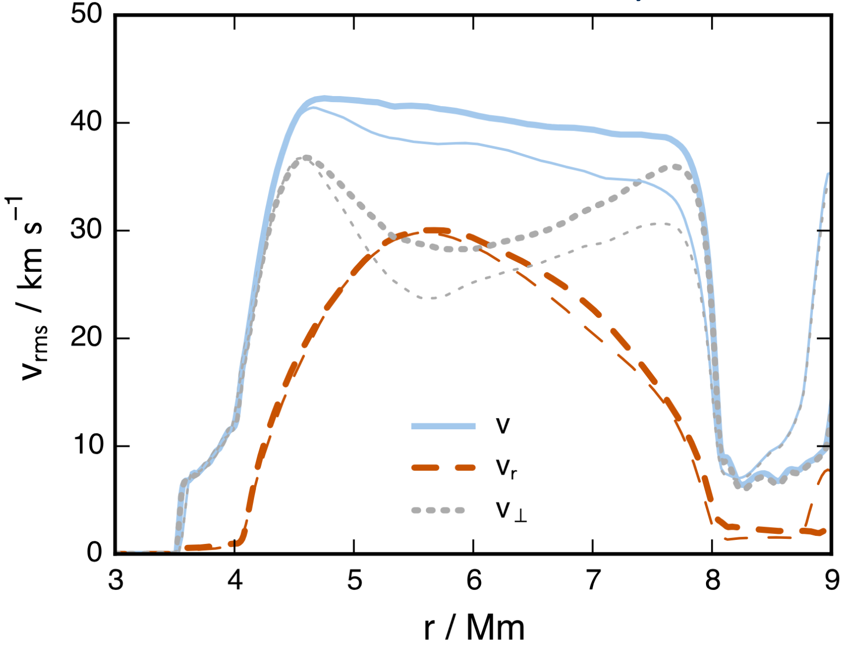
O-C Shell Mergers are 3D Mixing Events



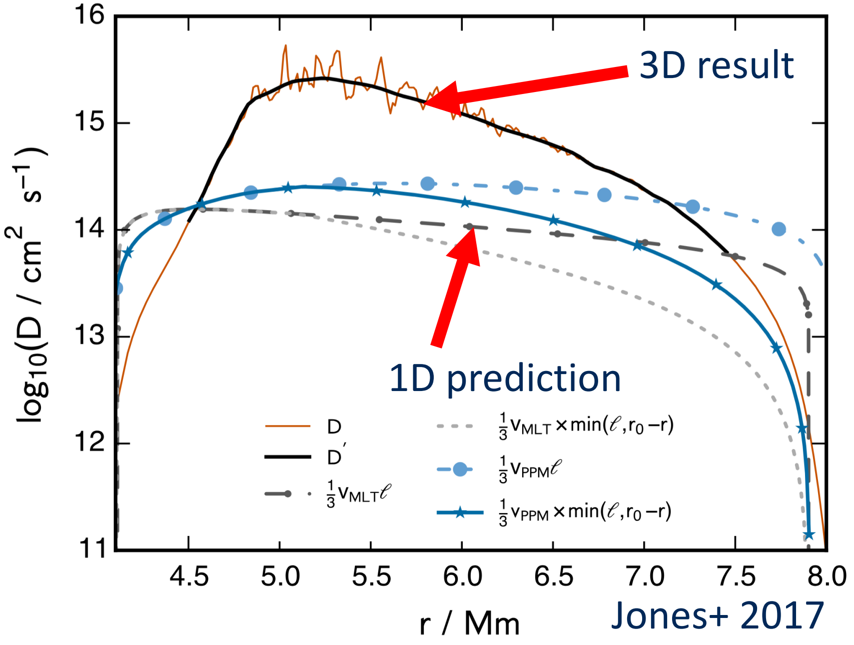
- 3D hydrodynamic simulations have shown that the merger significantly deviates from 1D predictions (Jones+ 2017, Andrassy+ 2020, Rizzuti+ 2024)
- Non-radial perturbations, faster velocities, a gradient towards the convective boundary, and even the mechanism of merging

Really: 1D Mixing Prescriptions Are Wrong

3D fluid velocities are not only radial



3D radial mixing is quite different to 1D



Jones+ 2017

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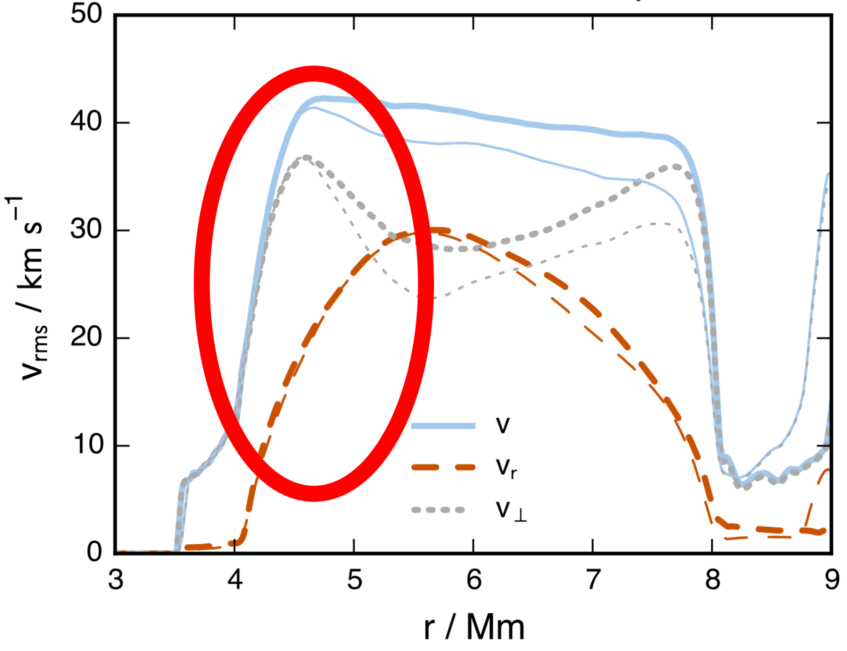

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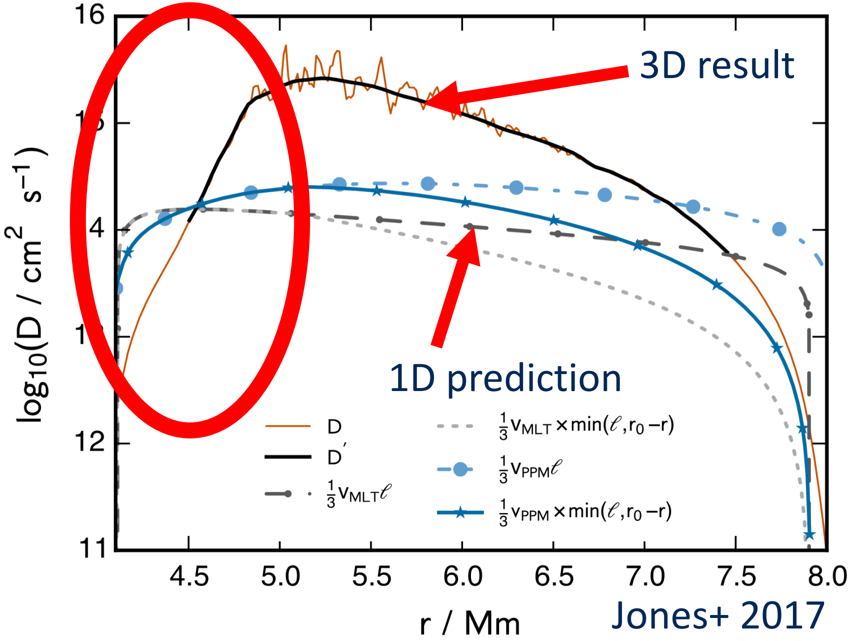
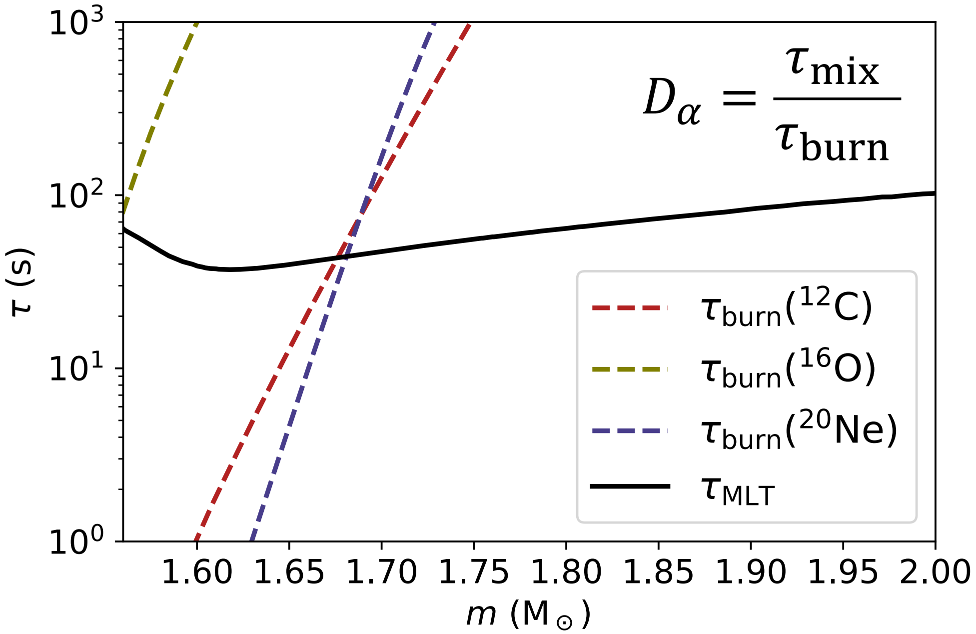


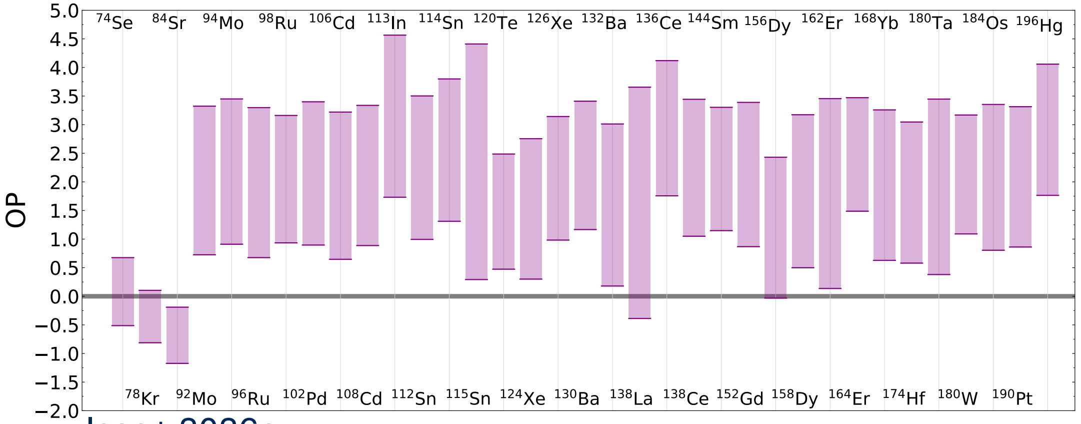
Jones+ 2017

Why Mixing Matters: Convective-Reactive Burning

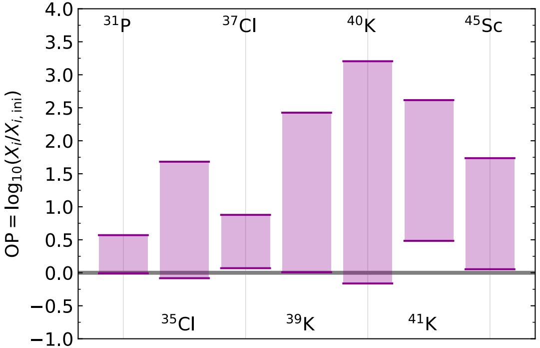


- When C and Ne material are ingested into O-burning temperatures, the mixing and burning occur on **similar timescales**
- This allows for different parts of the O shell to produce different isotopes preferentially (Issa+ 2026a)

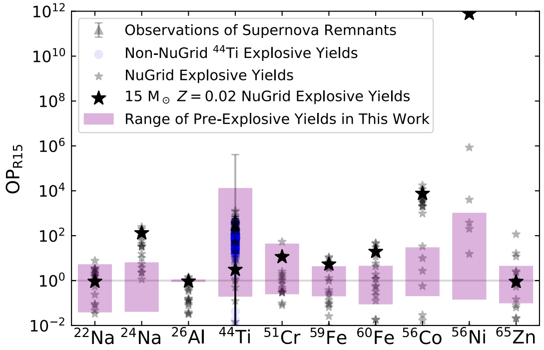
Many Isotopes are Sensitive to Mixing!



Issa+ 2026a



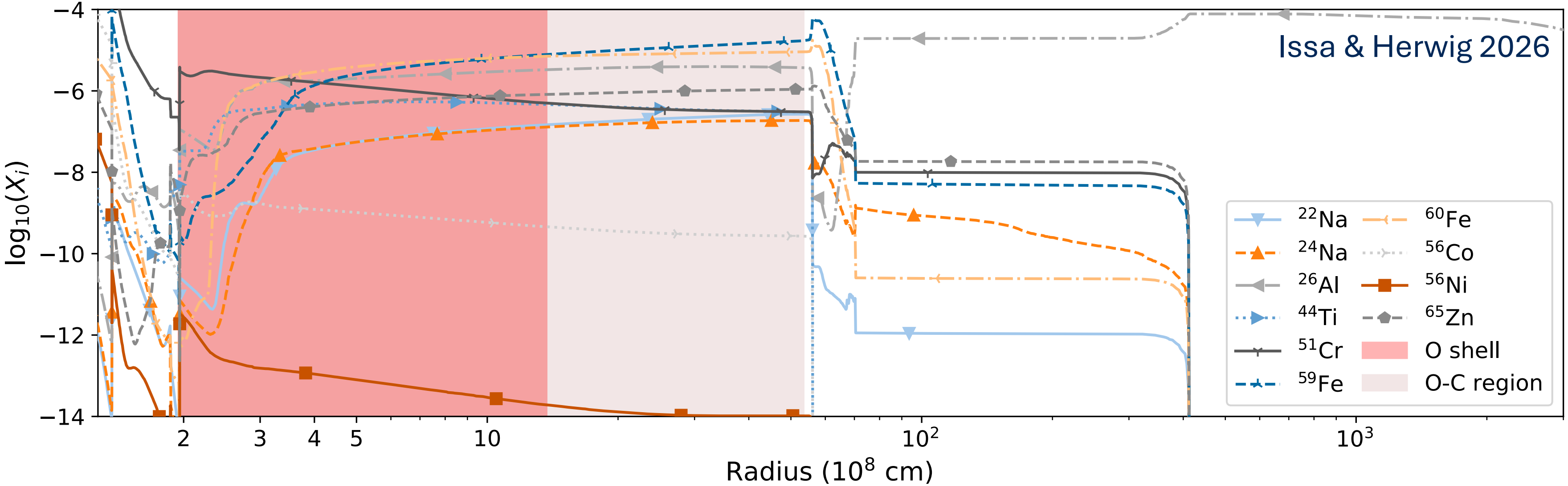
Issa+ 2026b



Issa & Herwig 2026

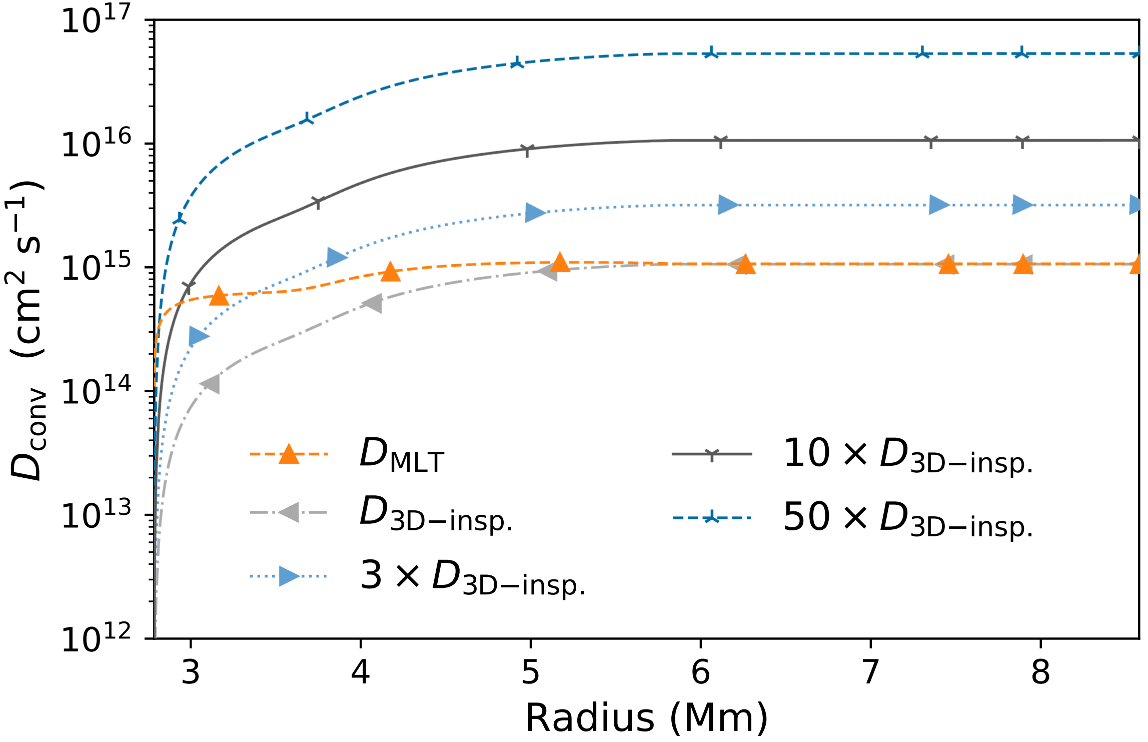
- Because of the convective-reactive environment, the shell merger region is able to synthesize a wide range of isotopes
- *p* nuclei, light odd-Z, and many radioactive species

Pre-SN Formation of Radioactive Isotopes



- Many radioactive isotopes production in the O-C shell merger
- How much does mixing matter? What's the role of the mass cut? What about explosive nucleosynthesis?

Using 3D Hydro Results in 1D Models



- We post-process the O shell of a 15 $M_\odot$ Z=0.02 with different mixing profiles
- 3D hydro suggests:
  - Faster mixing speeds & downturn at boundary
  - Different merging rates
  - Potential dips in mixing speed
- We investigate 24 scenarios in total

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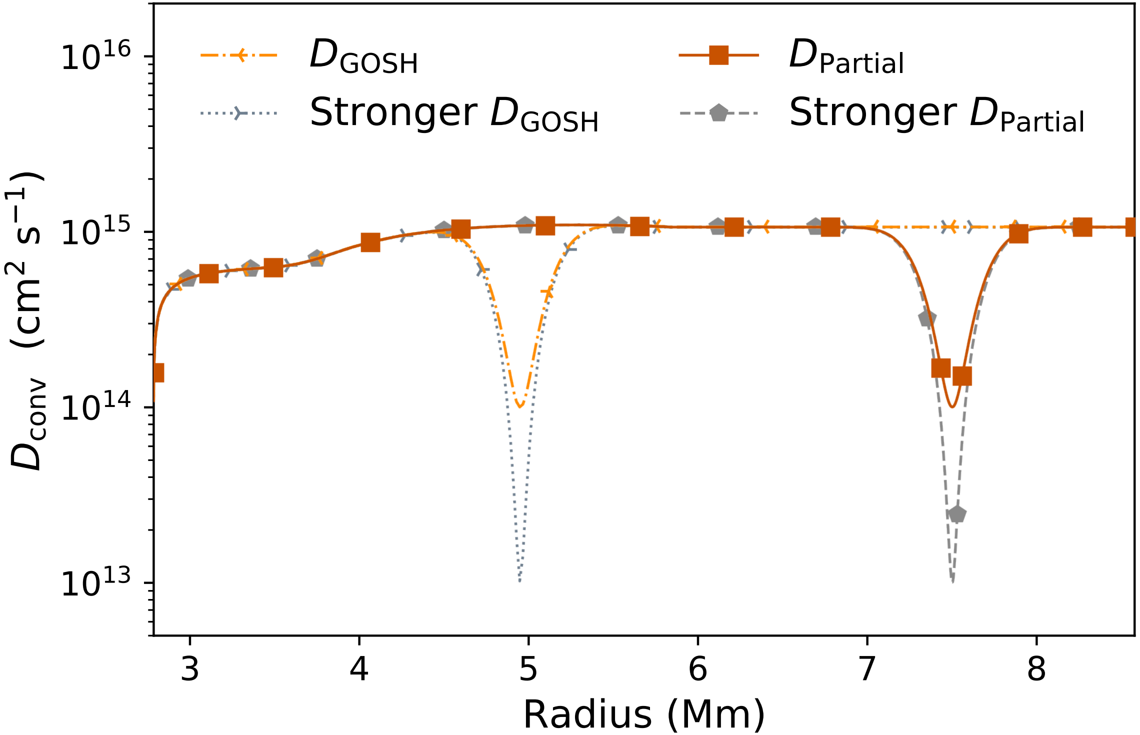

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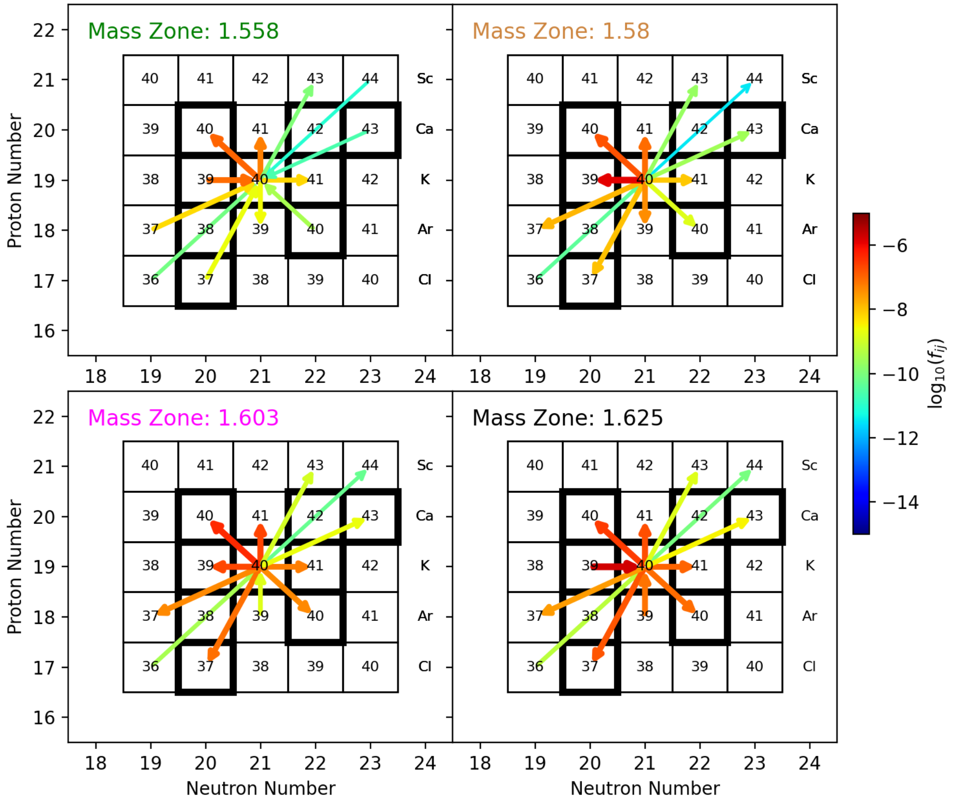
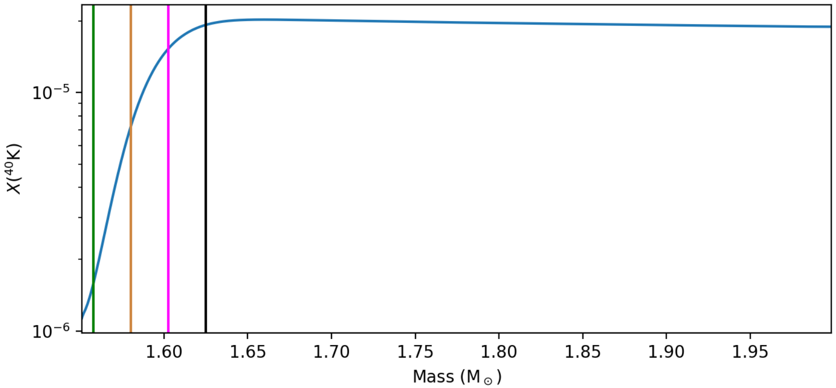
Nucleosynthesis is Zone-Dependent





- Inhomogeneous isotope distribution in the shell
- Reaction rates change direction and strength across the shell

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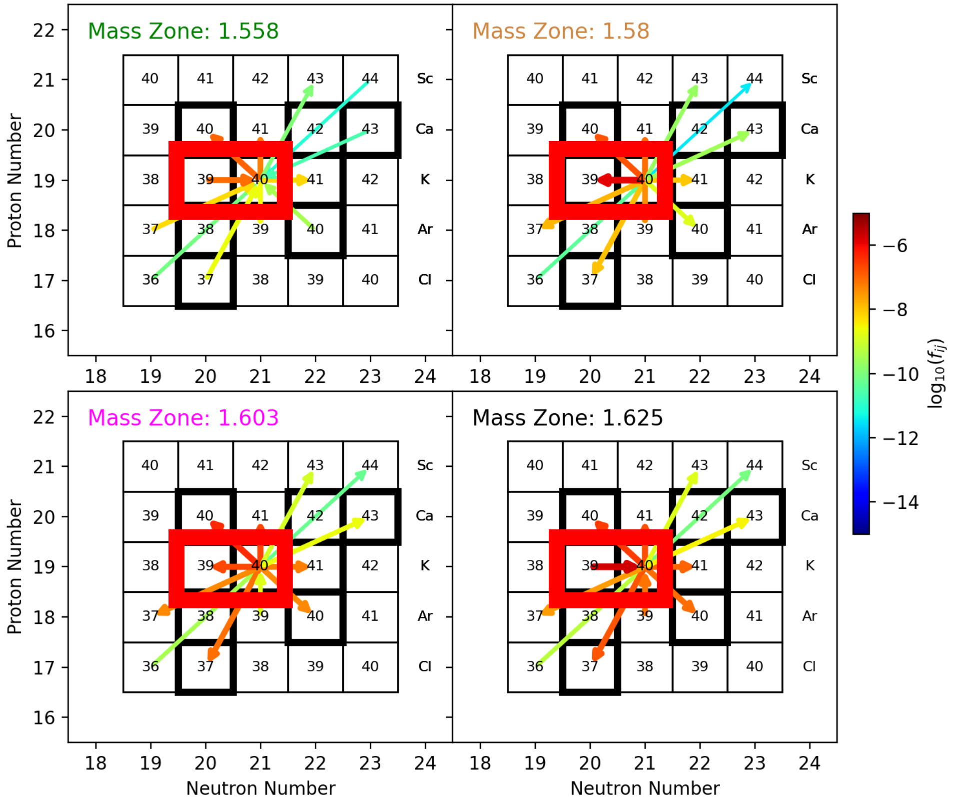

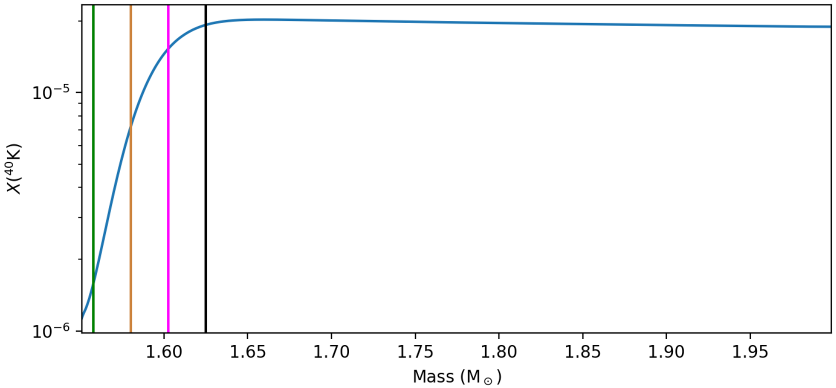

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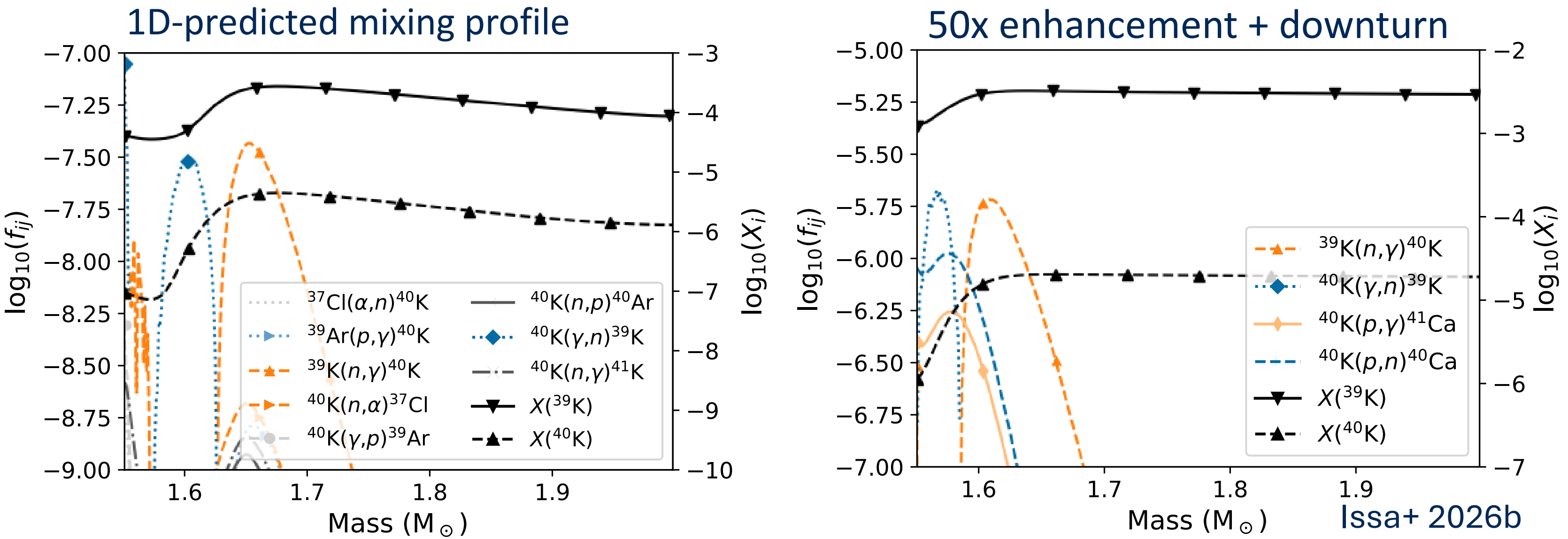
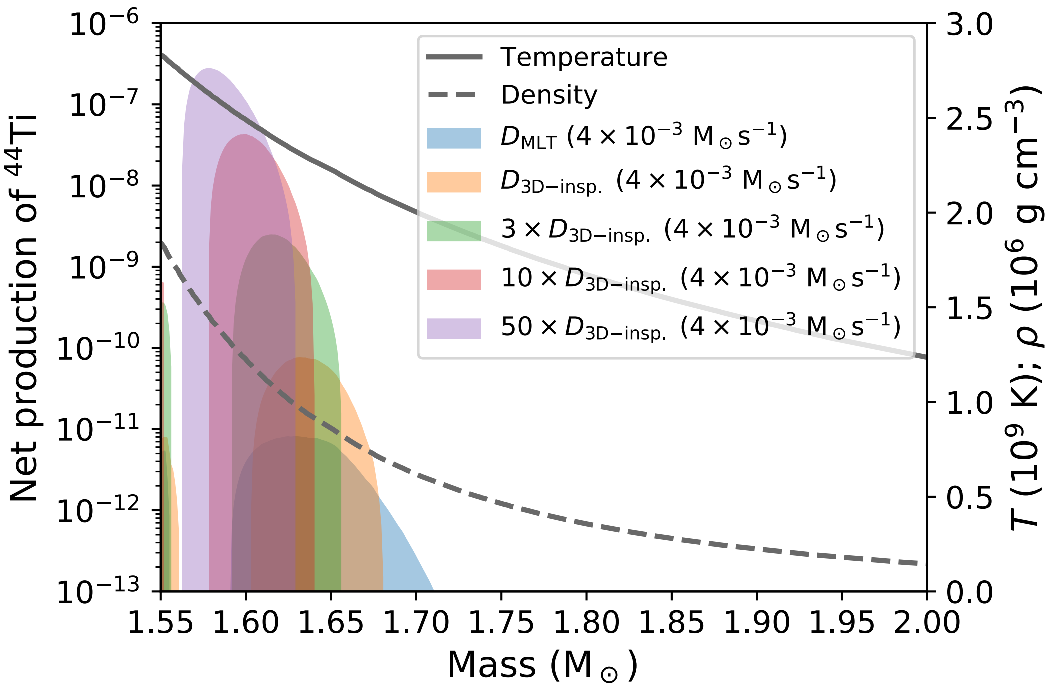
Mixing Changes Which Reactions Matter



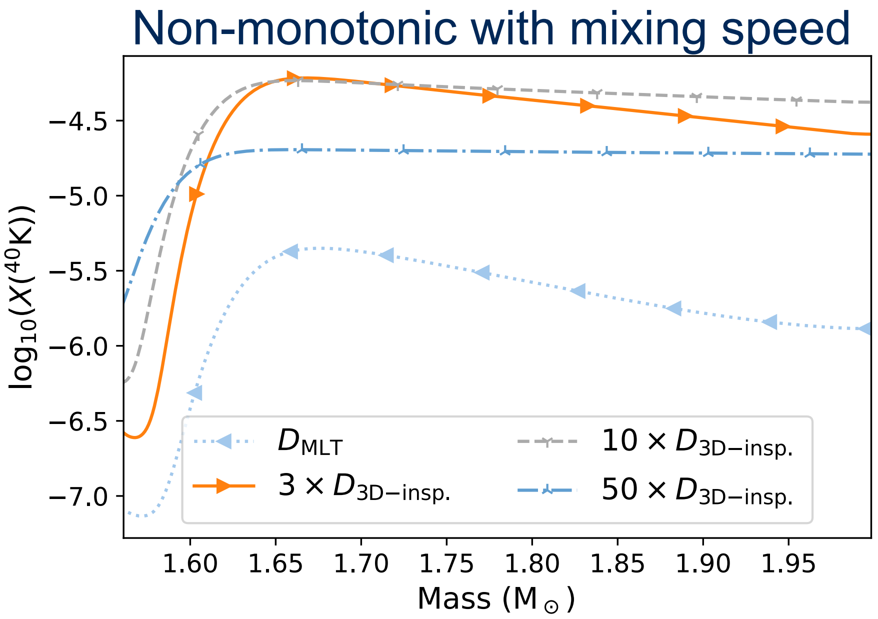
- Mixing speed says how much a species moves before it reacts & separates the sites for reactants and products
- This leads to different reaction pathways for different mixing prescriptions

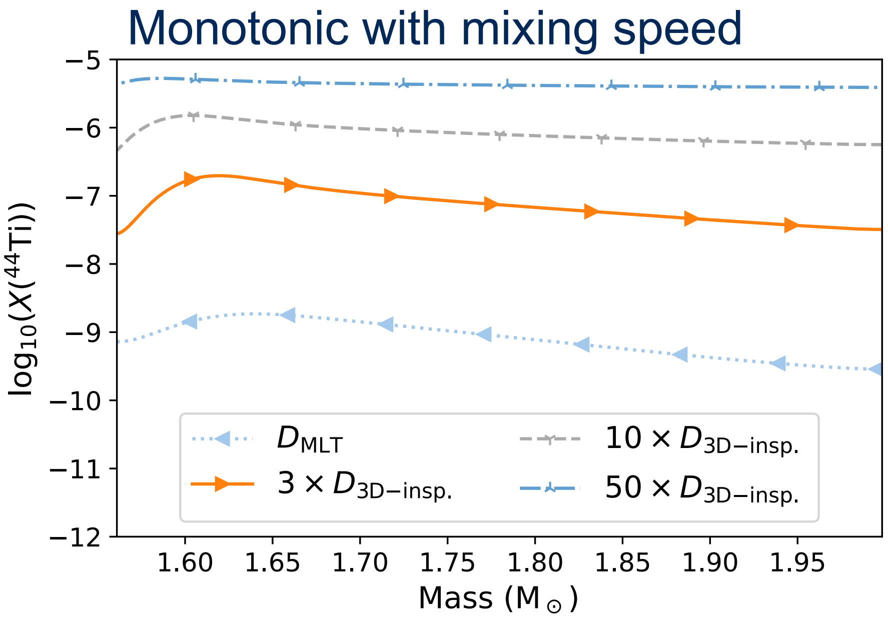
Mixing Changes the Location of Burning



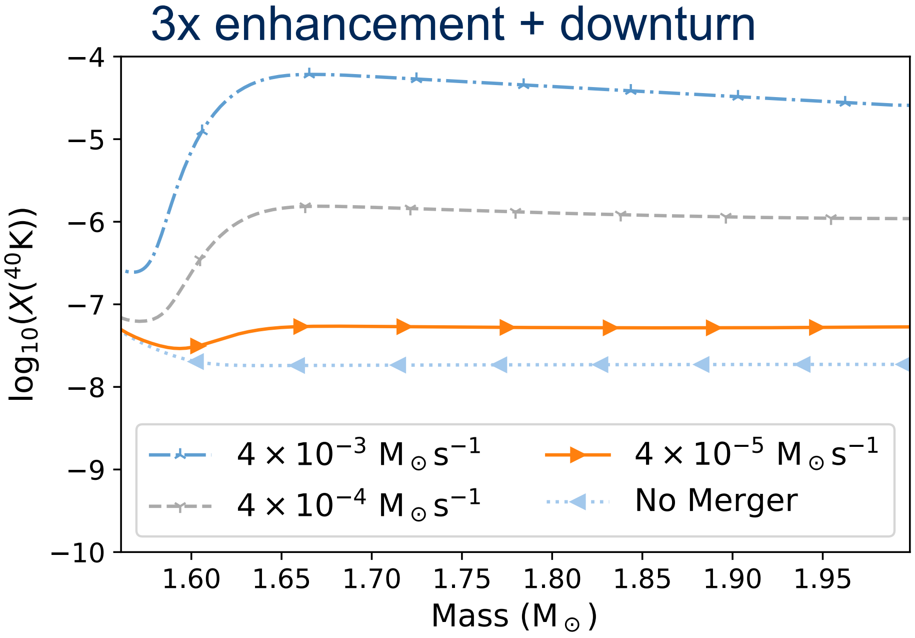
- As mixing speeds increase, the location where timescales are equal shifts deeper into the shell
- Although some isotopes have different paths, ^{44}Ti is made by a single reaction chain in all cases: ^{38}Ar(α,γ)^{42}Ca(n,γ)^{43}Ca(p,γ) ^{44}Sc(p,n)^{44}Ti
- Mixing changes the temperatures that these reactions occur by 100s of MK

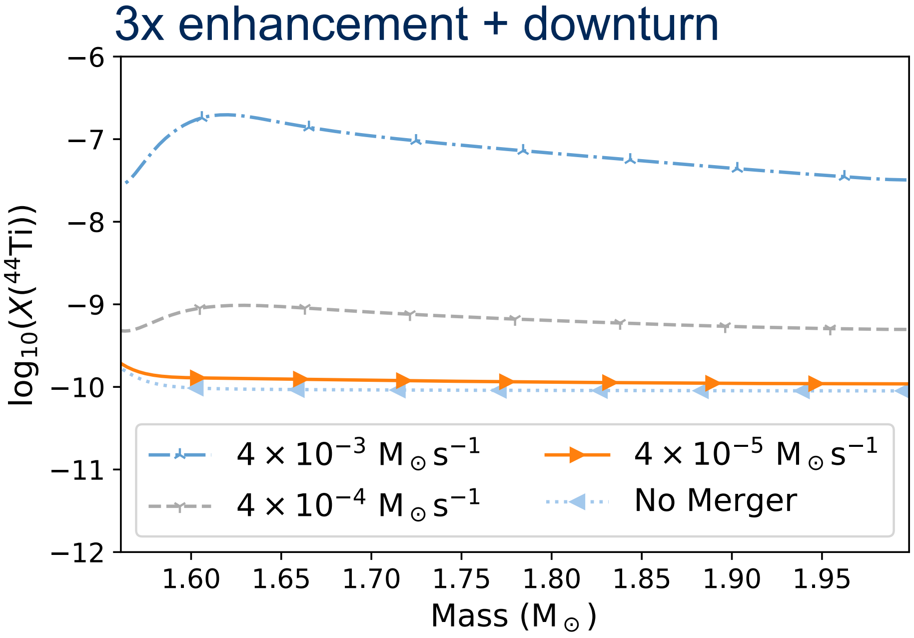
Boosting Mixing Does Not Boost Production Monotonically



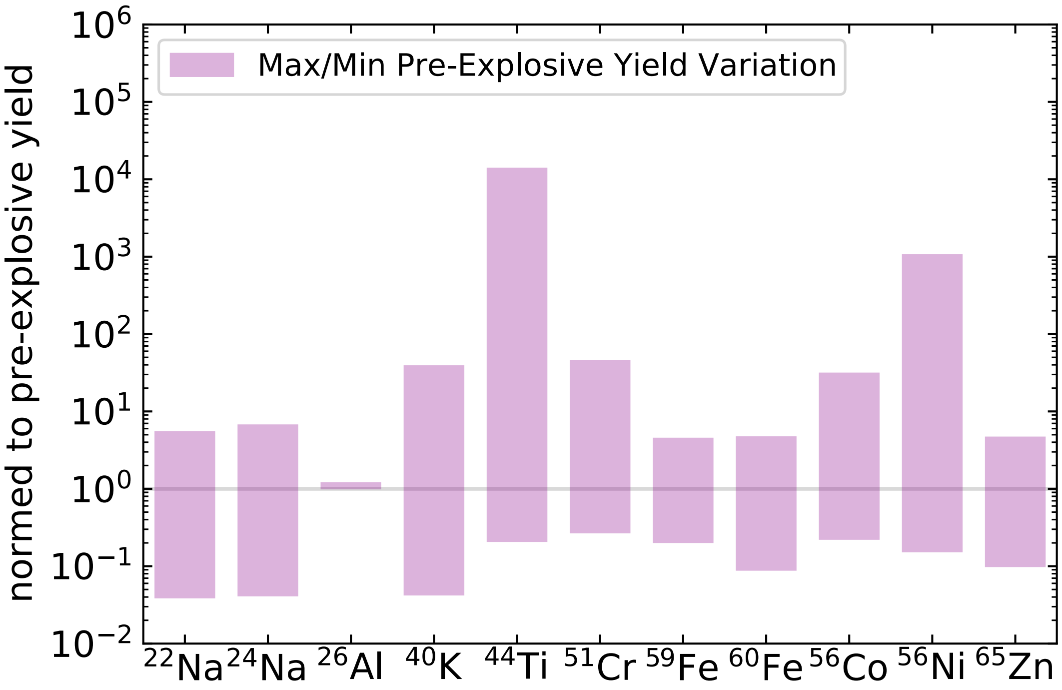


Results are Sensitive to Carbon Shell Ingestion



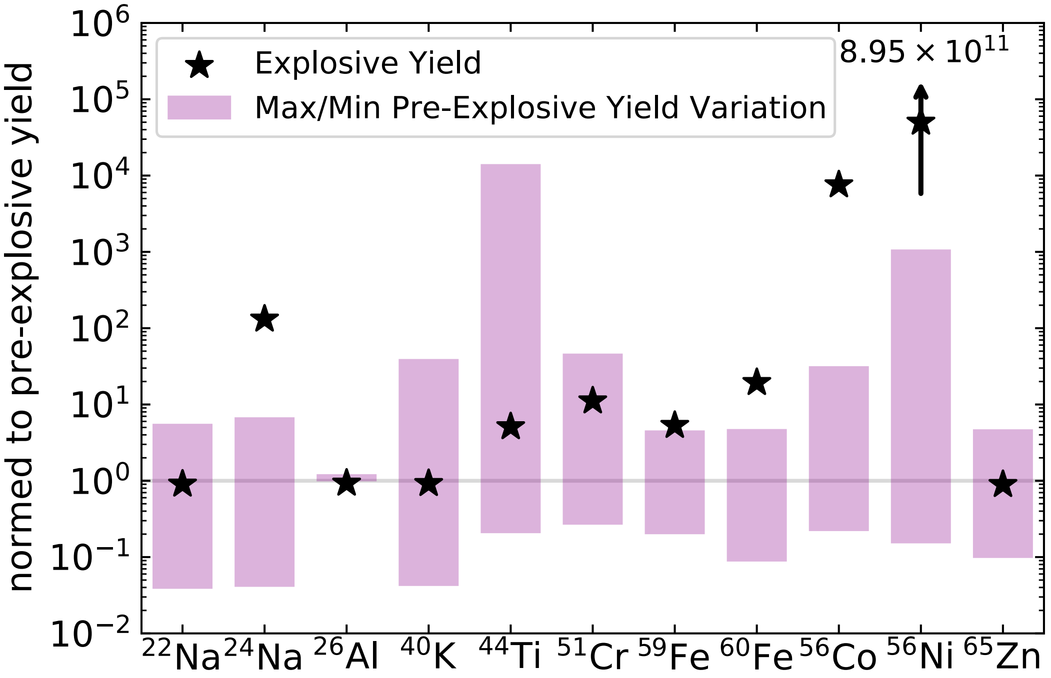


Radioactive Isotopes Feature Large Range



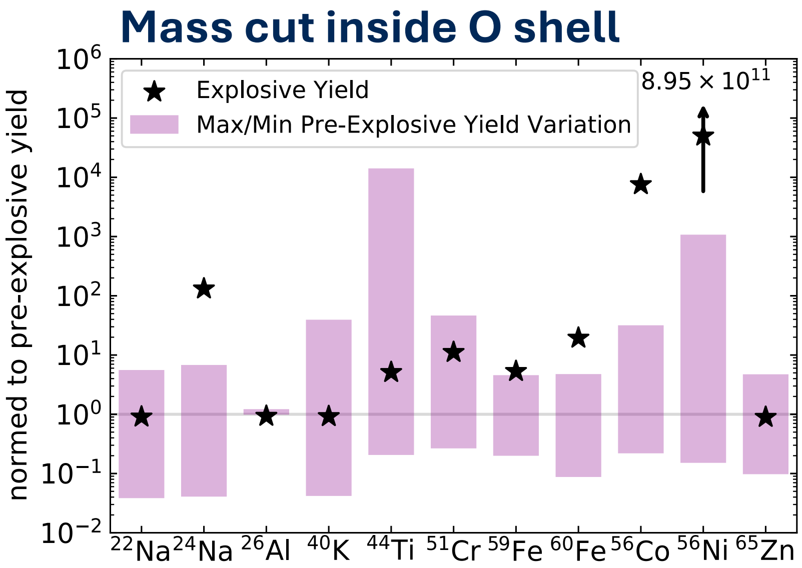
- Pre-explosive production of radioactive isotopes is sensitive to changing mixing prescriptions
- ^{44}Ti has the largest range of isotopes considered here: 4.8 orders of magnitude

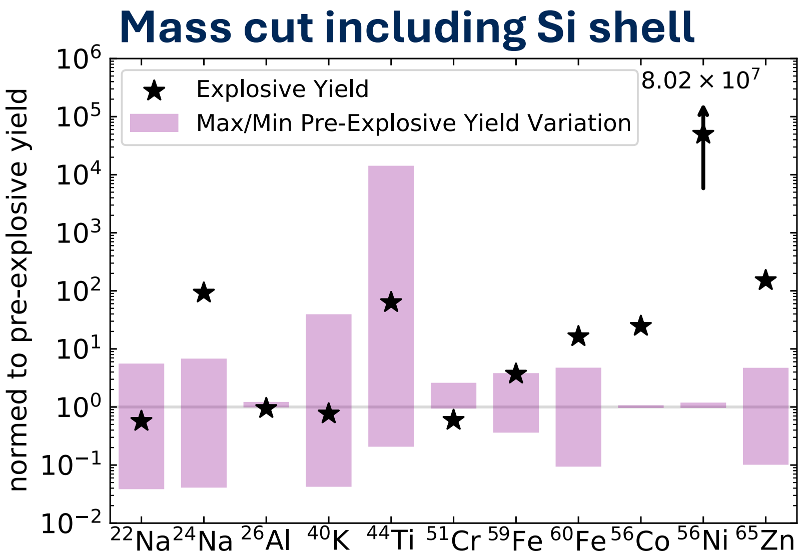
Merger Production Can Match the Explosion



- Compared to the explosive yield of the 15 $M_{\odot}$ Z=0.02 model, pre-explosive mixing uncertainties are larger
- ^{22}Na, ^{40}K, ^{65}Zn are produced in the merger
- ^{44}Ti, ^{51}Cr, and ^{59,60}Fe are boosted by the merger but also explosion
  - Unclear how explosion would affect mixing results

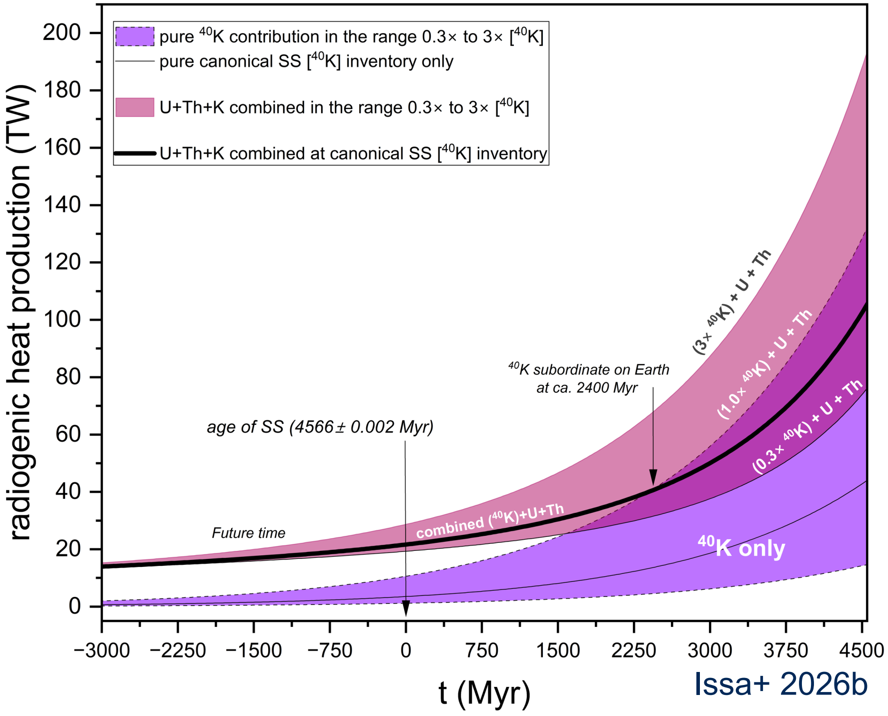
Impact of Mass Cut is Isotope Dependent

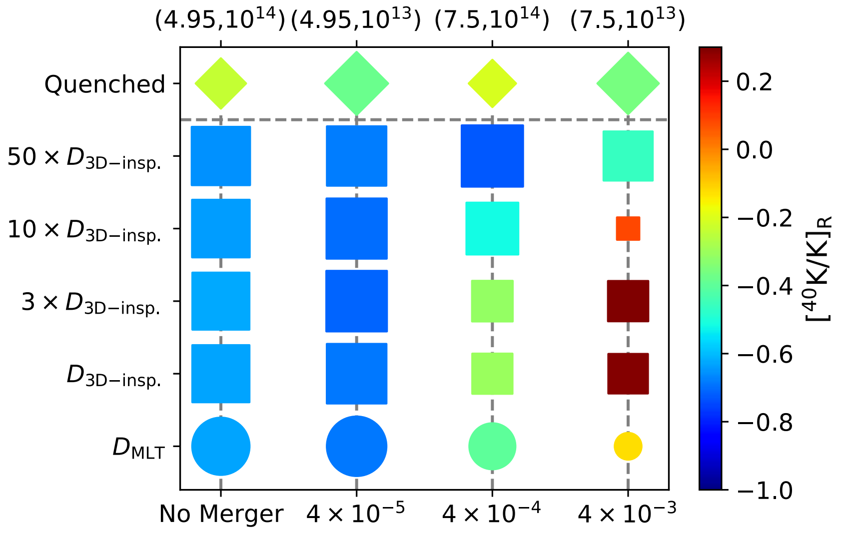




- The location of the mass cut does not change the range much in our pre-SN production for ^{22}Na, ^{40}K, ^{44}Ti, and ^{59,60}Fe
- Side effect: pre-explosive ^{44}Ti can be boosted without changing final ^{56}Ni yields

Shell Mergers Impact Rocky Exoplanets





- Shell mergers don't preserve solar ratio of ^{40}K and K
- Difference in ^{40}K could change rocky exoplanet heating (refer to Steve's talk)

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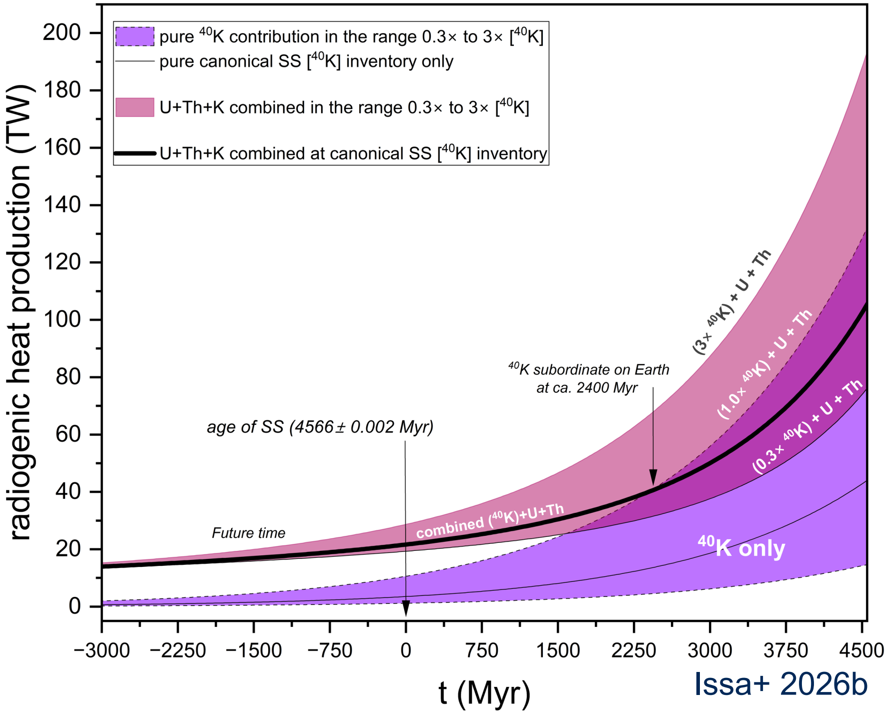

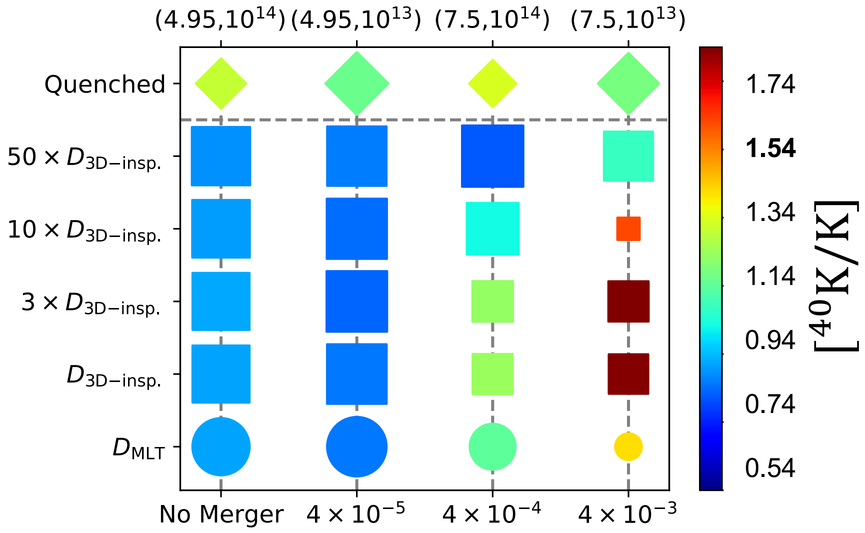

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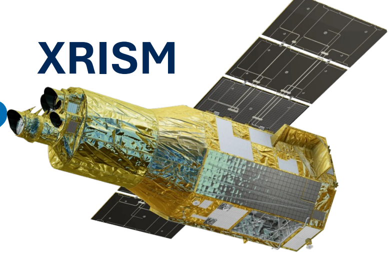
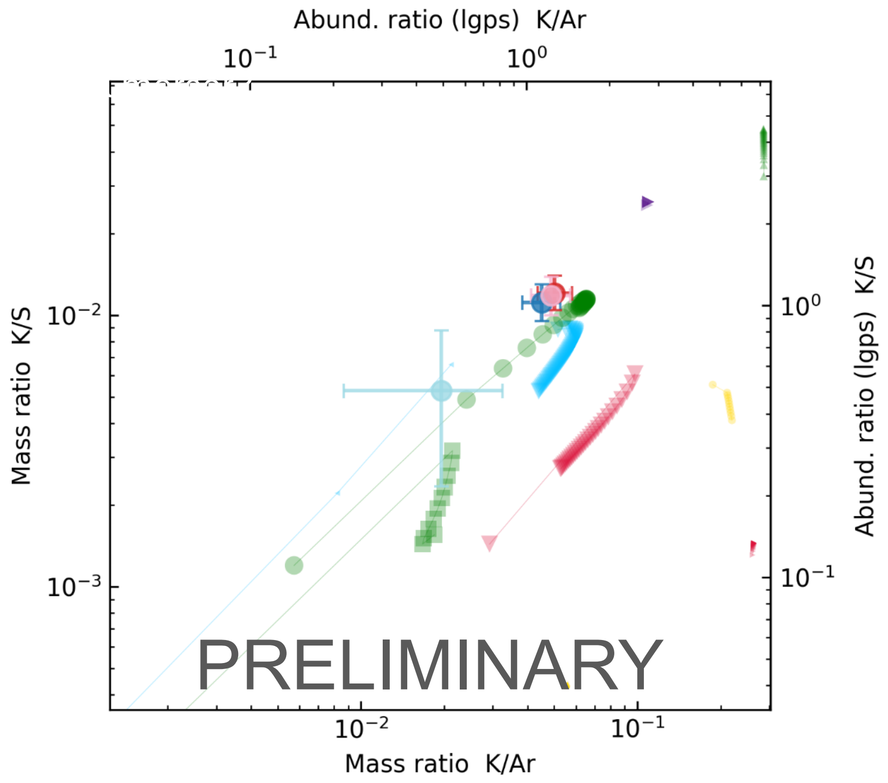
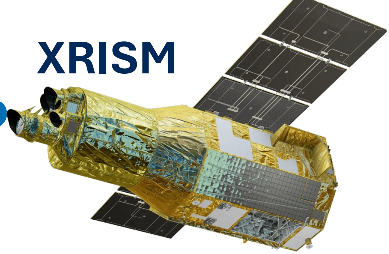
Can Cassiopeia A Constrain Mixing?

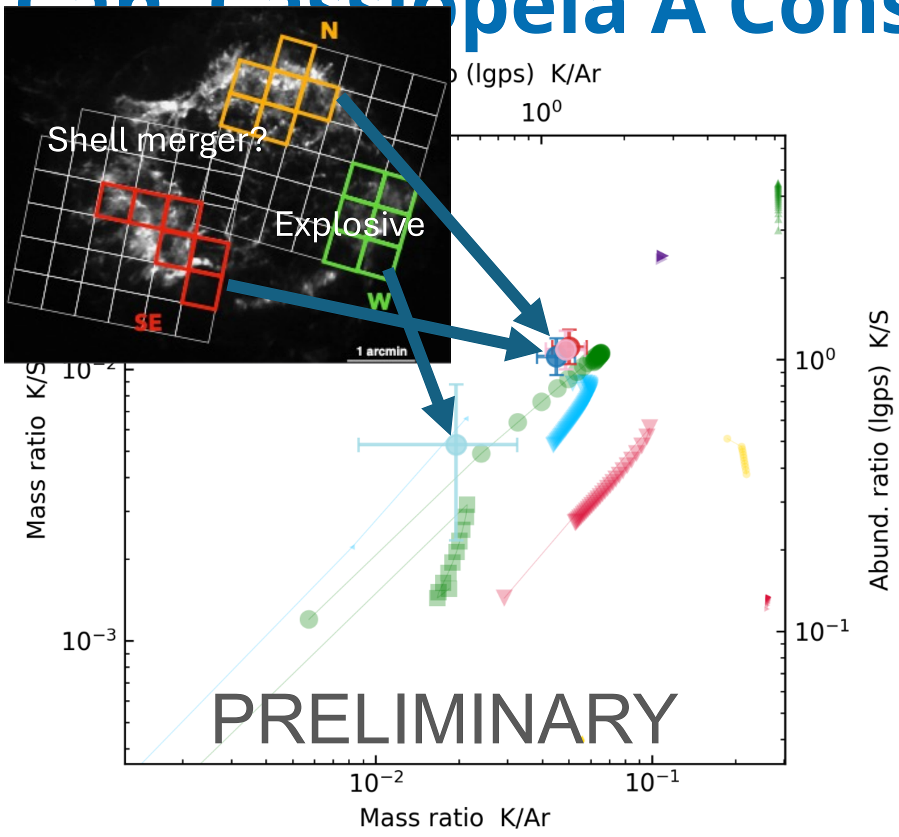


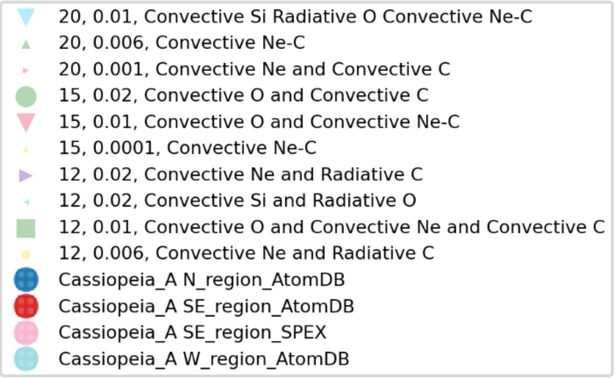


- Cas A seems to have had a shell merger (Sato+ 2025, Audard+ 2025)
- There are many types of shell mergers that are possible
- O-C shell merger profile matches well with Cas A observations

Can Cassiopeia A Constrain Mixing?







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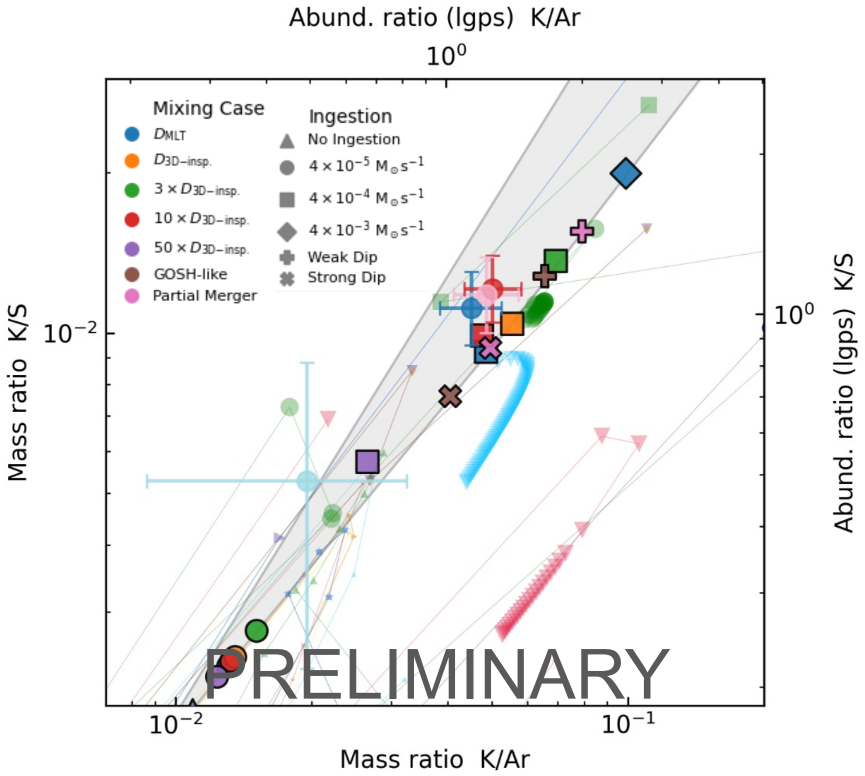
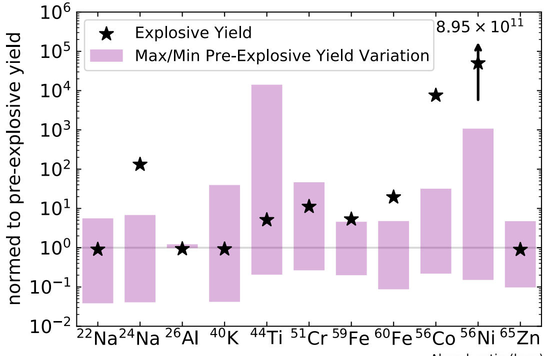
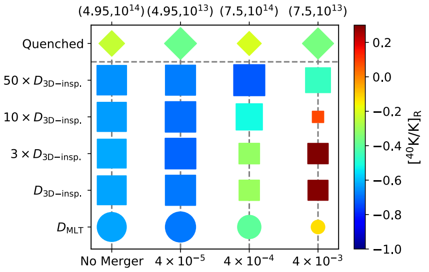
Cas A Could Constrain Mixing Physics

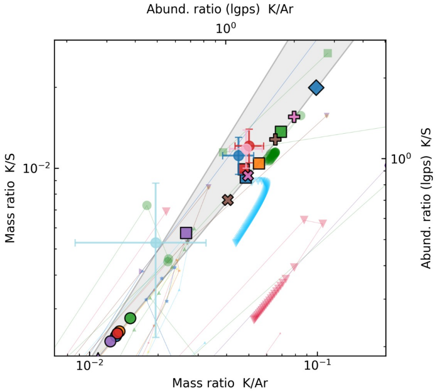


- Some of our pre-explosive 3D-informed models match with the XRISM observations: constraints on mixing physics
- Explosive shell merger profiles are also close
- These models could also explain ^{44}Ti in Cas A (see Luca's talk)

Mixing Matters for Radioactive Isotopes







- 3D-informed mixing impact nucleosynthesis predictions
- Identification of relevant reactions is impact by mixing prescription
- Isotopic yields don't follow solar distribution
- Cassiopeia A (and other SNRs) may be sites to constrain progenitor physics

References

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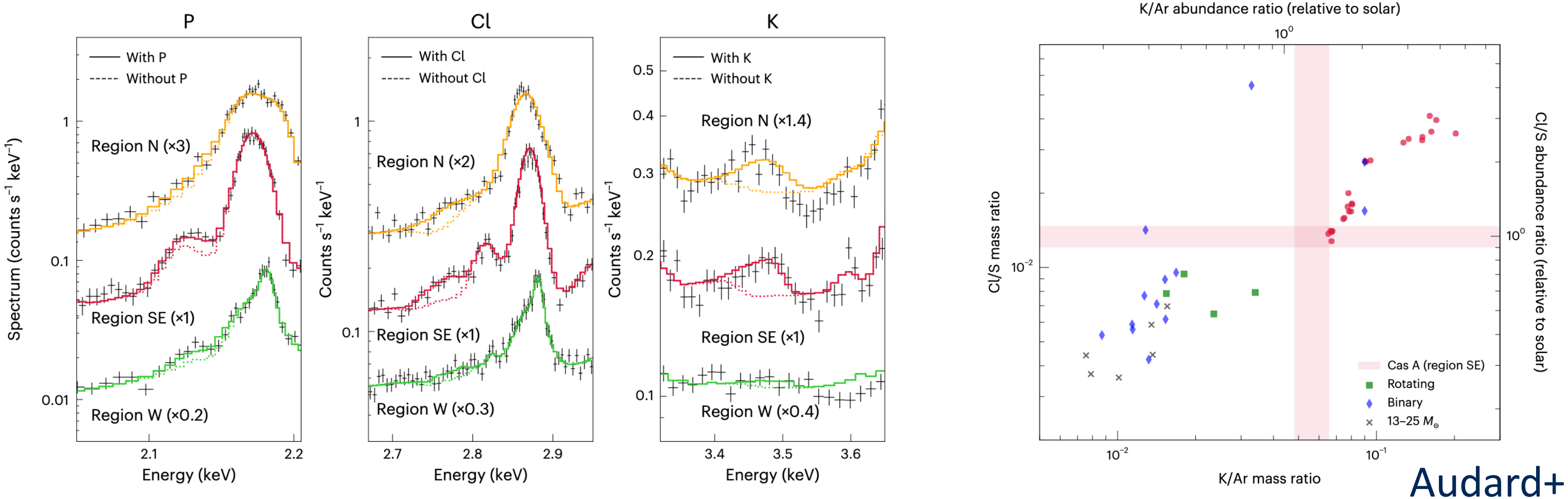
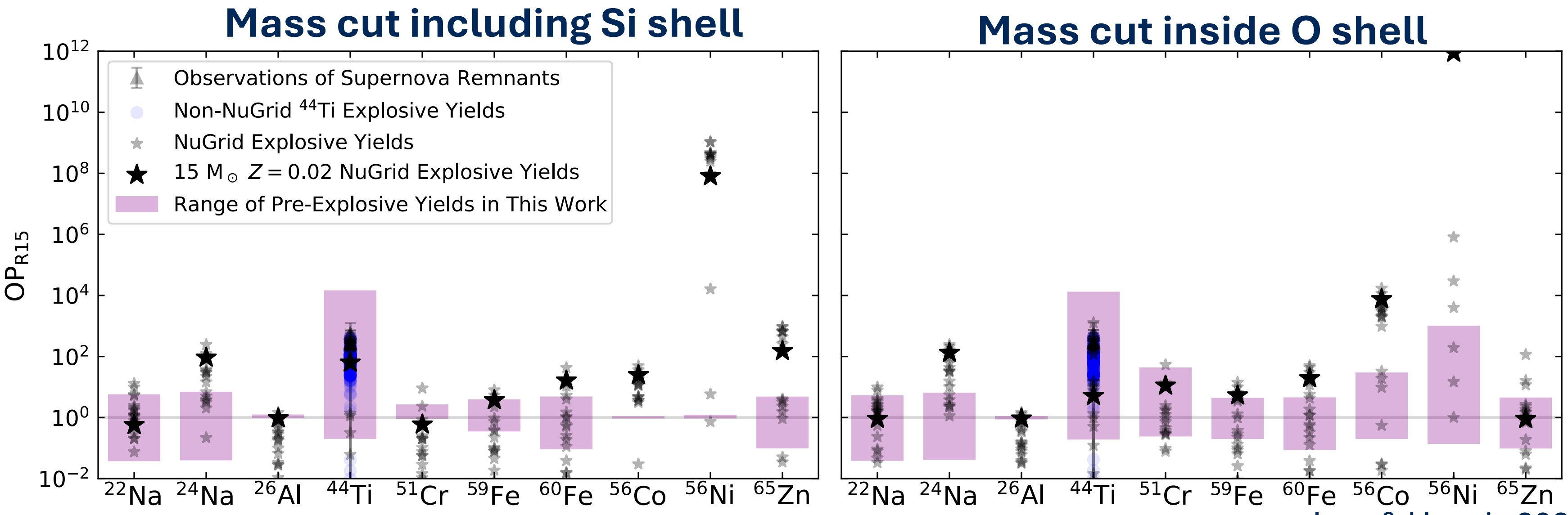
Why XRISM Argues for Cas A Shell Merger



Audard+ 2025

- K and Cl are clearly seen in N and SE regions of Cas A
- Shell merger models (red circles) match these observations better than non-merger, rotating, and binary massive stars

^{44}Ti vs Observations vs Other Models



Issa & Herwig 2026

- Our merger results can also be larger than 3D neutrino driven explosions
- We find that with 3-10x enhancement scenario we can replicate Cas A observations

Extrapolating Yields

- The simulations are for 110 seconds and only of the O shell
- We extrapolate what the yields could be by taking the ratio of our model to the NuGrid model in the O shell and using that to artificially alter the yields
- This approach neglects all stellar structure changes that may happen, which might matter a lot (see Roberti & Pignatari 2025, https://doi.org/10.1051/0004-6361/202556941).
- Further work needs to be done on seeing how boosting convection would change stellar evolution