Thermonuclear Supernova Explosions From Hybrid White Dwarf Progenitors

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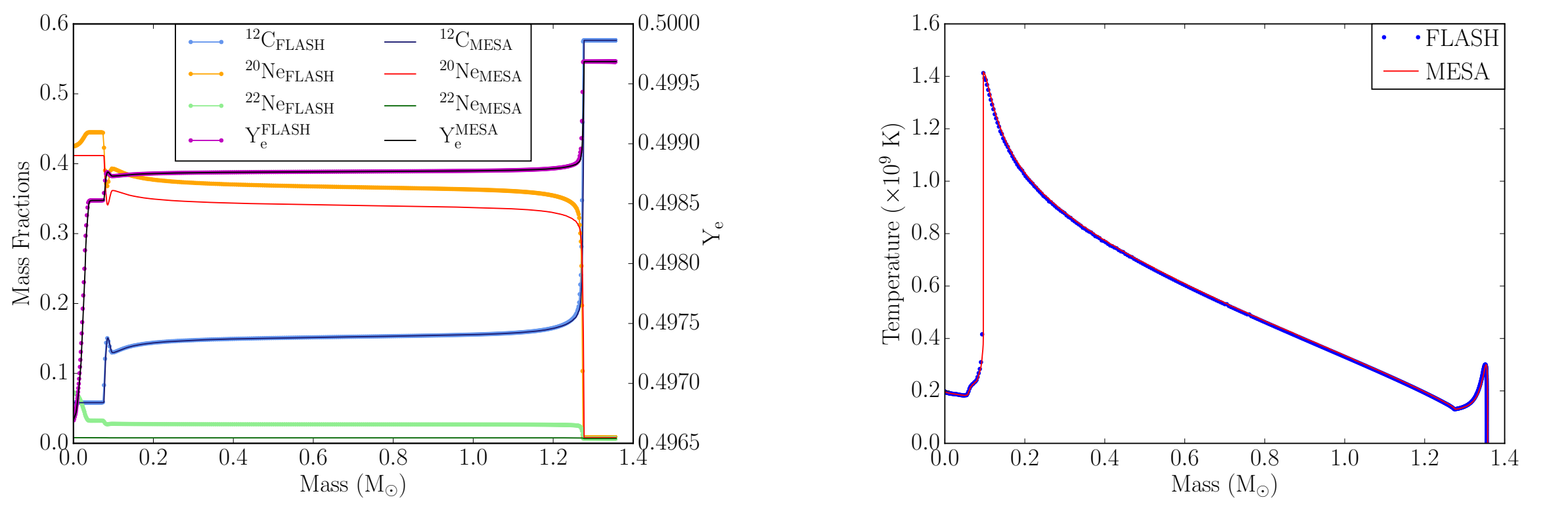
Abstract

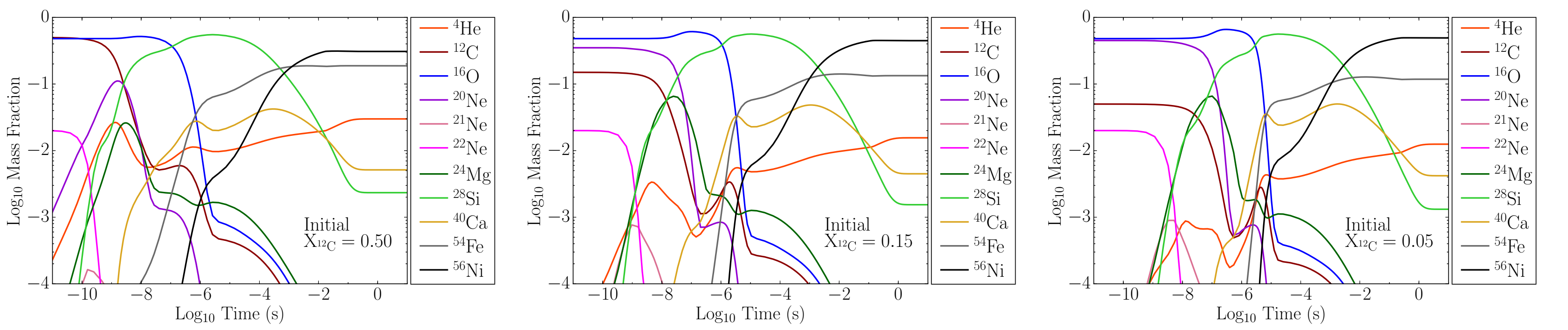
Motivated by recent results in stellar evolution in which convective boundary mixing in SAGB stars can give rise to hybrid white dwarf (WD) stars with a C-O core inside an O-Ne shell, we simulate thermonuclear (Type Ia) supernovae from these hybrid progenitors. We use the FLASH code to perform multidimensional simulations in the deflagration to detonation transition (DDT) explosion paradigm from progenitor models produced with the MESA stellar evolution code that include the thermal energetics of the Urca process. We performed a suite of DDT simulations over a range of ignition conditions and compare to previous results from a suite of C-O white dwarfs. Despite significant variability within each suite, distinguishing trends are apparent in their Ni-56 yields and the kinetic properties of their ejecta. We comment on the feasibility of these hybrid WD explosions as the source of some classes of observed subluminous events.

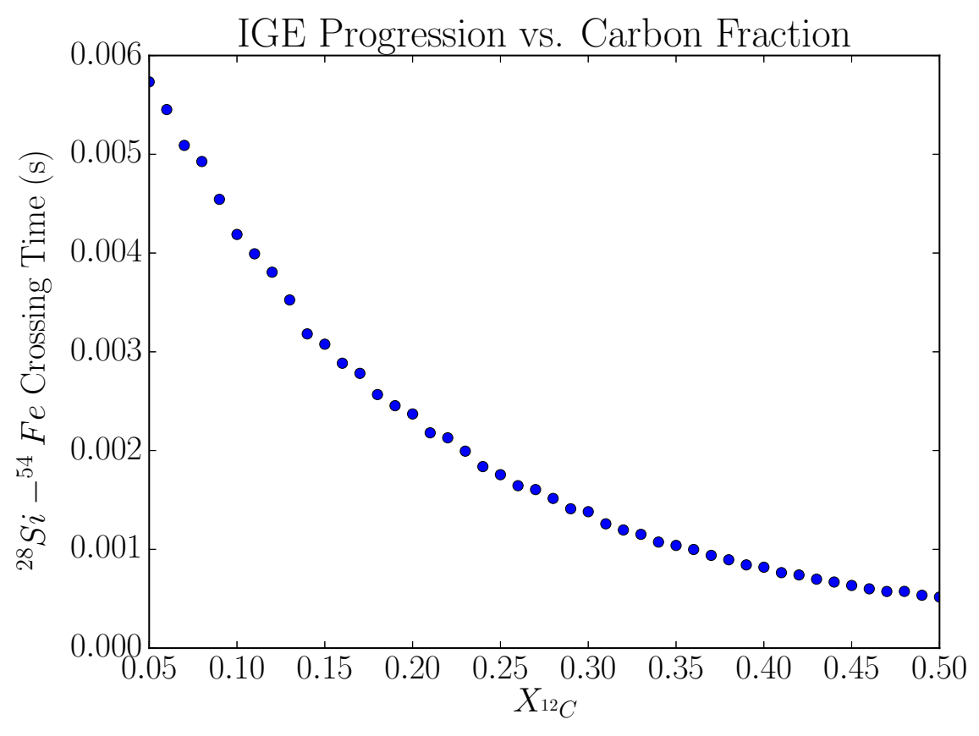
Hybrid Type Ia Supernovae Progenitor Profile



Above: Hybrid WD profiles as computed in (Denissenkov, et al. 2015).

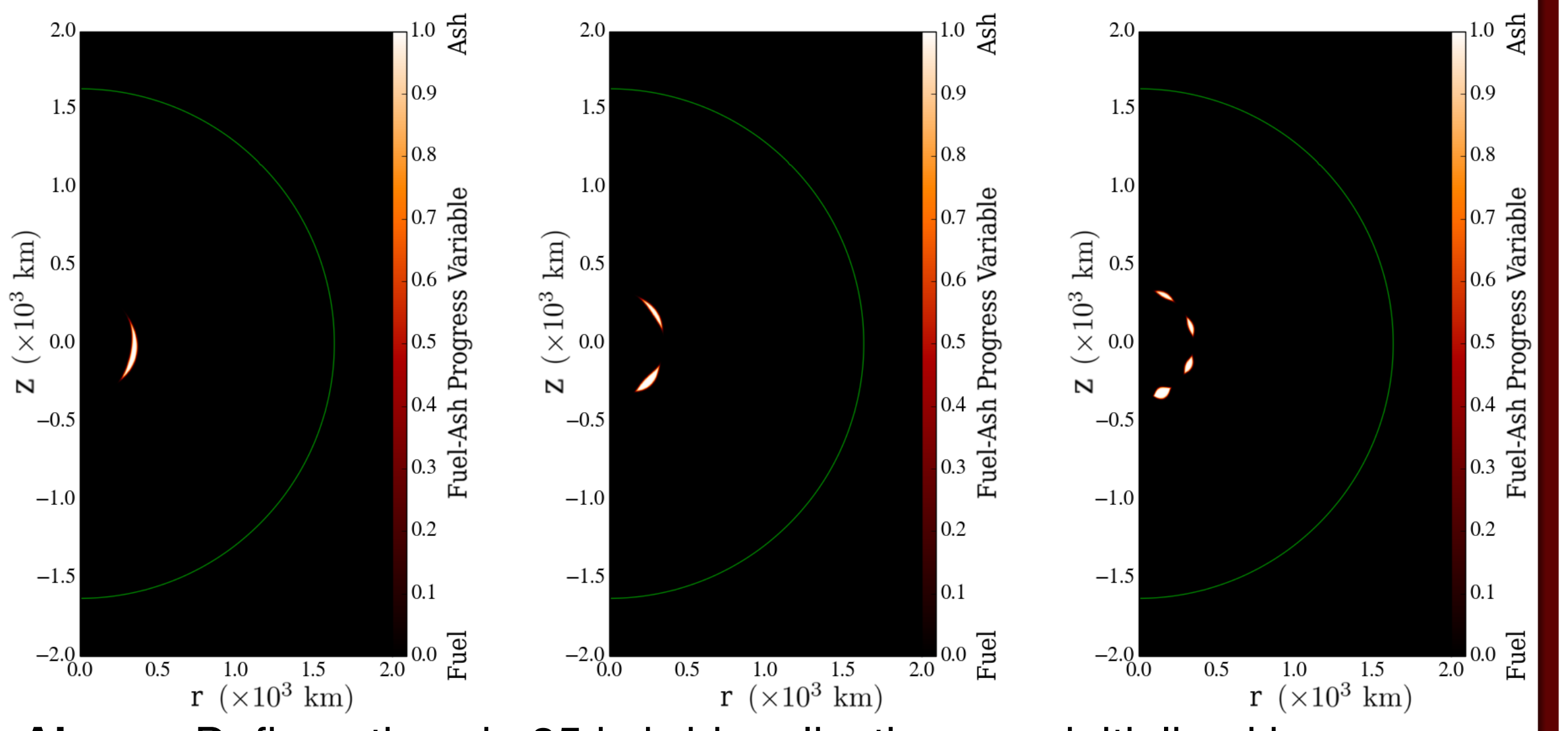
ZND Detonations for C-O-Ne Fuel





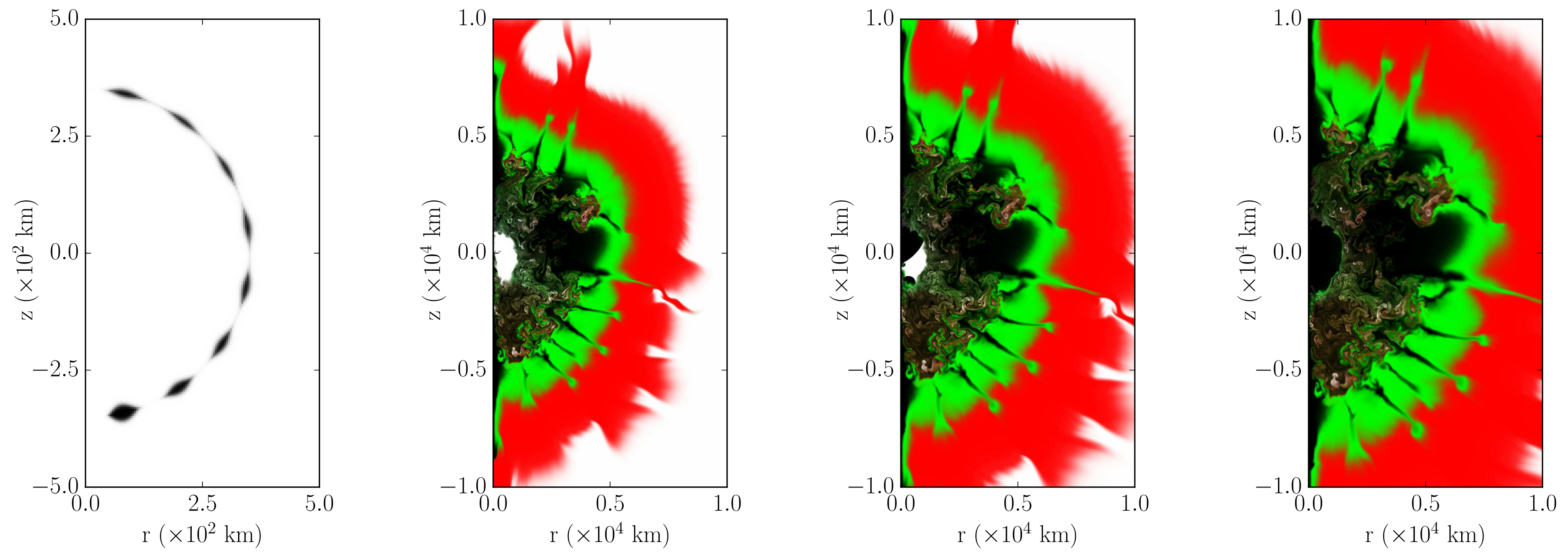
Above: Mass fraction evolution with time after shock for carbon fractions of 0.5, 0.15, & 0.05.
Right: ^{28}Si - ^{54}Fe crossing time for $X_{^{12}C} = 0.05 - 0.50$.

Initialization of the Deflagration



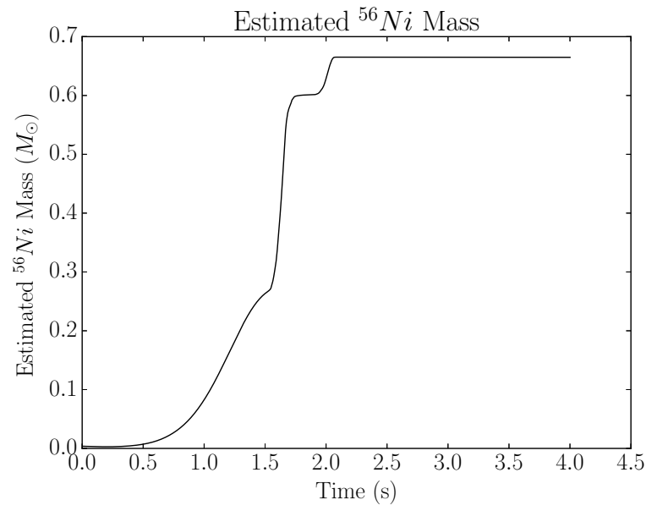
Above: Deflagrations in 35 hybrid realizations are initialized by choosing different numbers and sizes of ignition regions placed at the temperature peak at the base of the convective zone. The green contour indicates the DDT density ($10^{7.2}\ g/cm^3$). In 26 C-O realizations, deflagrations are initialized by igniting a sphere with a randomly perturbed surface as in (Krueger, et al. 2012).

Delayed Core Detonation For Some Hybrid Realizations



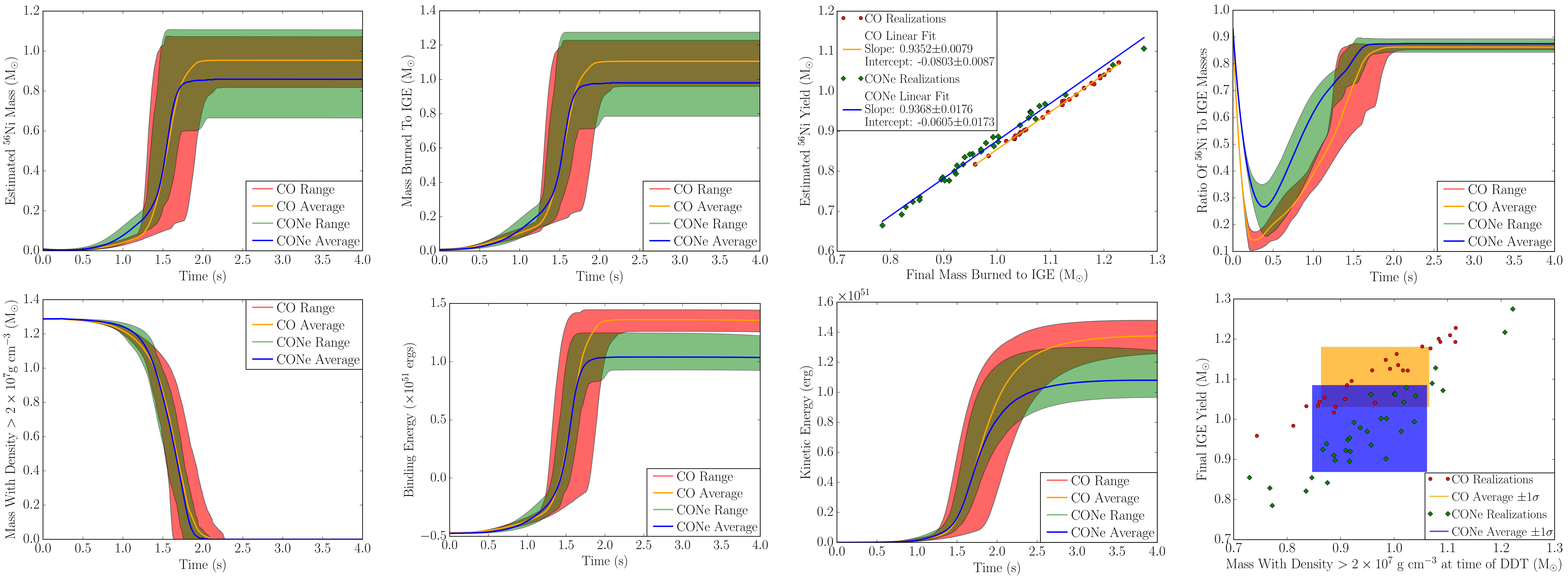
$t = 0s$ $t = 1.90s$ $t = 2.00s$ $t = 2.10s$

Below: Estimated ^{56}Ni mass over time, showing a secondary plateau near 2.0s in the 6 delayed core burning cases.



Above: Ignition region and delayed progression of the detonation front through the core as in 6 of the 35 hybrid realizations. **White** is unburned fuel (^{12}C, ^{16}O & ^{20}Ne) and **Red** is ash from ^{12}C and ^{20}Ne-burning. **Green** is material in quasi-nuclear statistical equilibrium, and **Black** denotes material in nuclear statistical equilibrium (Fe-group elements and α-particles).

Integral Quantities (e.g. ^{56}Ni Mass) With Shading Showing the Range of Results Given By The Hybrid and CO Suites of Simulations



Conclusions

- Type Ia Supernovae from hybrid white dwarf progenitors yield on average $0.1 M_\odot$ less ^{56}Ni than from C-O progenitors, suggesting they will be correspondingly dimmer. Exceptions may occur, however, given the large spread in possible ^{56}Ni production among our hybrid realizations.
- Hybrid progenitors deposit an average of 21% less kinetic energy in their ejecta than C-O progenitors, indicating slower expansion velocities of the ejecta.
- We attribute lower average ^{56}Ni production from hybrid progenitors to the lower binding energy released when burning ^{20}Ne-enriched fuel compared to pure C-O fuel. Based on the comparable average mass remaining at high ($> 2 \times 10^7 g/cm^3$) density at the DDT time for C-O and hybrid models, we conclude that the degree to which fuel is burned to Fe-group elements is not caused by differences in stellar expansion during the deflagration stage.

References

Denissenkov, P. A., Truran, J. W., Herwig, F., Jones, S., Paxton, B., Nomoto, K., Suzuki, T., & Toki, H. 2015, MNRAS, 447, 2696.

Krueger, B. K., Jackson, A. P., Calder, A. C., Townsley, D. M., Brown, E. F., & Timmes, F. X. 2012, ApJ, 757, 175.

Townsley, D. M., Jackson, A. P., Calder, A. C., Chamulak, D. A.,Brown, E. F., Timmes, F. X. 2009, ApJ, 701, 1582.

Townsley, D. M., Timmes, F. X., Jackson, A. P., Miles, B. J., Calder, A. C., Brown, E. F. In preparation.

Willcox, D. E., Townsley, D. M., Calder, A. C., Denissenkov, P. A., Herwig, F. In preparation.

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