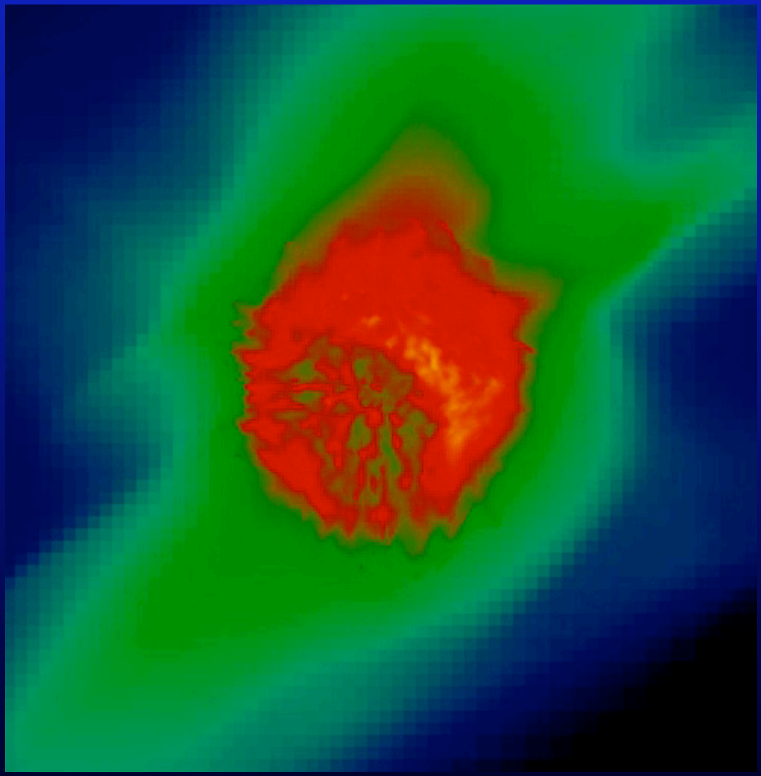
Chemical Mixing in the First Supernovae



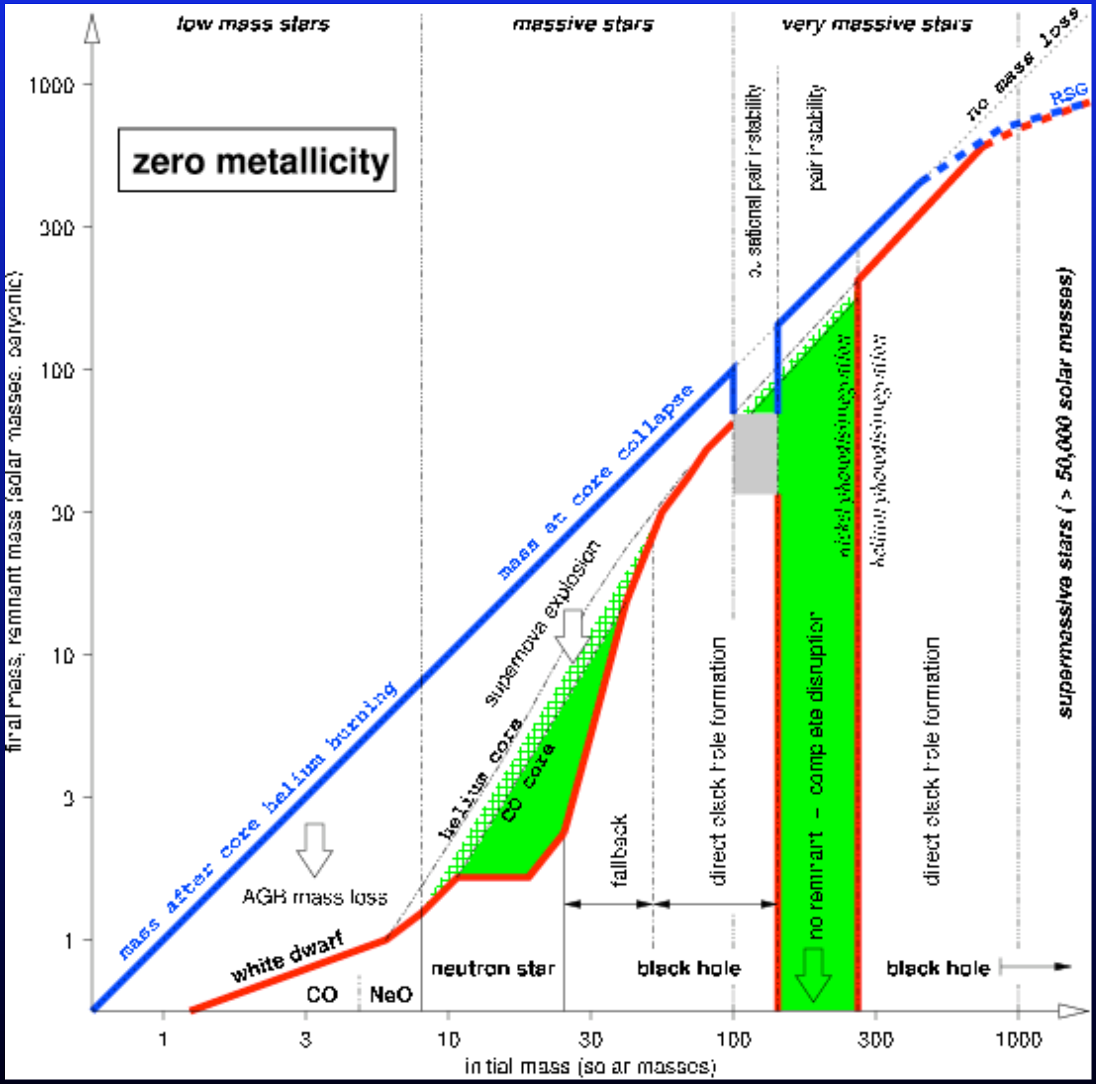
Daniel Whalen
McWilliams Cosmology Fellow
Carnegie Mellon University

My Collaborators

- Candace Joggerst (UC Santa Cruz)
- Ann Almgren (LBNL)
- John Bell (LBNL)
- Alexander Heger (University of Minnesota)
- Stan Woosley (UC Santa Cruz)

Final Fates of the First Stars

Heger & Woosley 2002, ApJ 567, 532



The Primordial IMF Remains Unconstrained

Numerical simulations, although proceeding from well-posed initial conditions, lack the physics to model Pop III star formation up to the main sequence (and likely diverge from reality well before)

Direct observation of primordial supernovae, in concert with gravitational lensing, may be possible with JWST (Kasen & Woosley 2009, in prep; Whalen et al 2009a,b,c, in prep)

Stellar archaeology, in which we search for the nucleosynthetic imprint of Pop III stars on low-mass subsequent generations that survive today, is our best bet for indirectly constraining the primordial IMF

Stellar Archaeology: EMP and HMP Stars

- Hyper Metal-Poor (HMP) Stars:

  $-5 < [Fe/H] < -4$ → thought to be enriched by one or a few SNe

- Extremely Metal-Poor (EMP) Stars:

  $-4 < [Fe/H] < -3$ → thought to be enriched by an entire population of SNe because of the small scatter in their chemical abundances

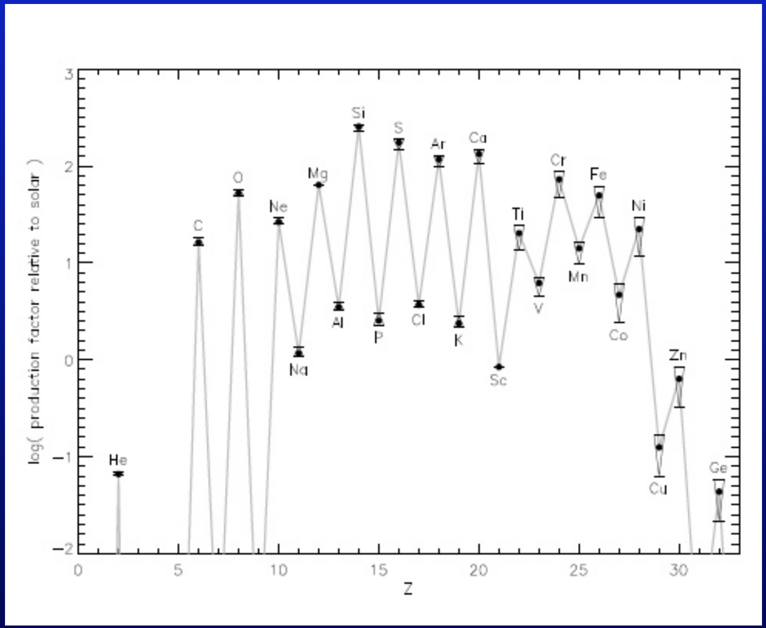
No PISN?

- original non-rotating stellar evolution models predict a strong ‘odd-even’ nucleosynthetic signature in PISN element production

- to date, this effect has not been found in any of the EMP/HMP surveys

- intriguing, but not conclusive, evidence that Pop III stars had lower initial masses than suggested by simulation

- this has directed explosion models towards lower-mass stars



Heger & Woosley 2002

3 Characteristic Mixing Scales in Primordial SNe

- mixing may take place in the interior of the star prior to shock breakout from its surface -- 10^{12} - 10^{13} cm

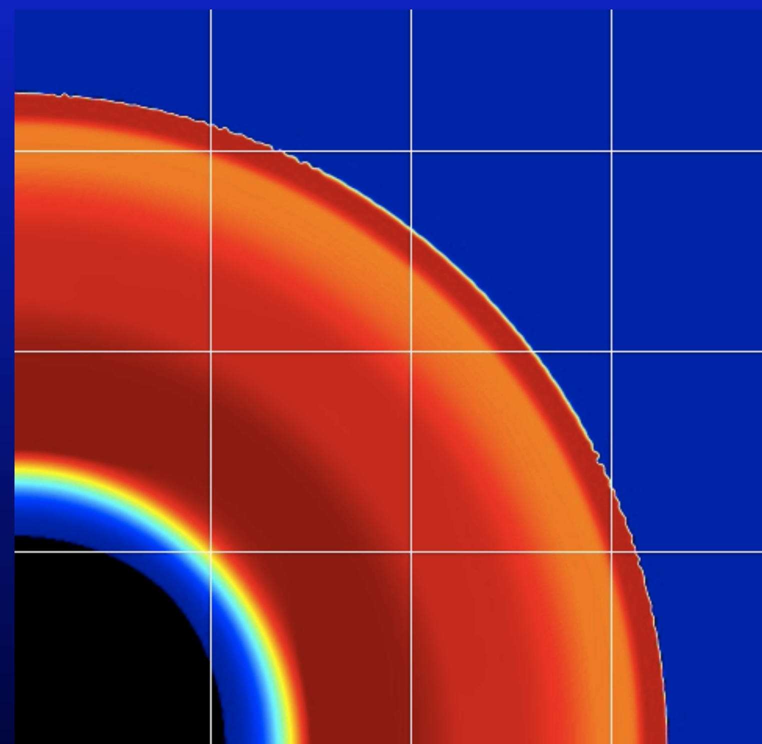
- when the remnant has swept up its own mass in ambient H II region, a reverse shock is driven into its interior that is prone to RT instabilities --> 10 - 20 pc

- later, the remnant collides violently with the dense shell formed in the progenitor H II region, mixing and possibly catastrophically cooling it --> 100 - 200 pc

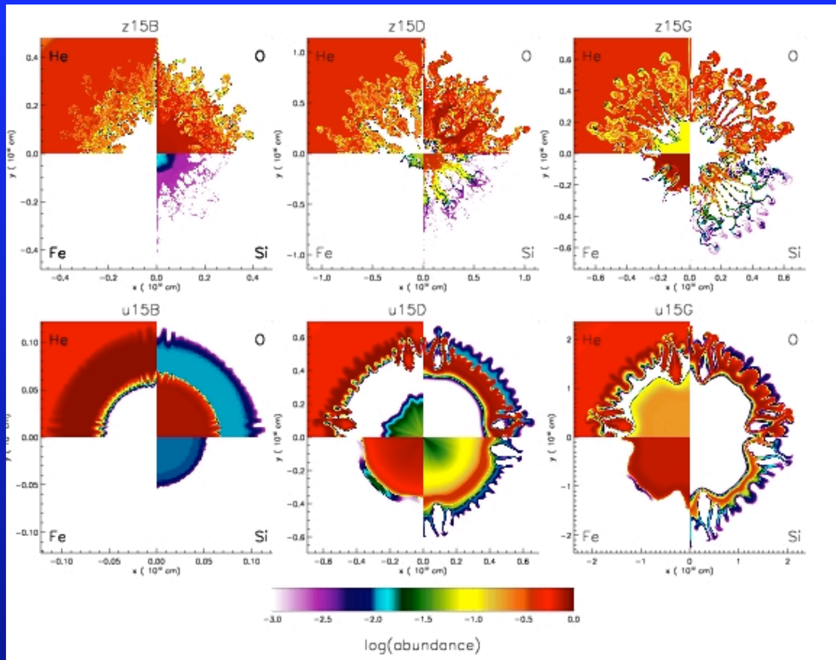
- all three spatial scales must be surveyed to model the chemical enrichment of the early IGM

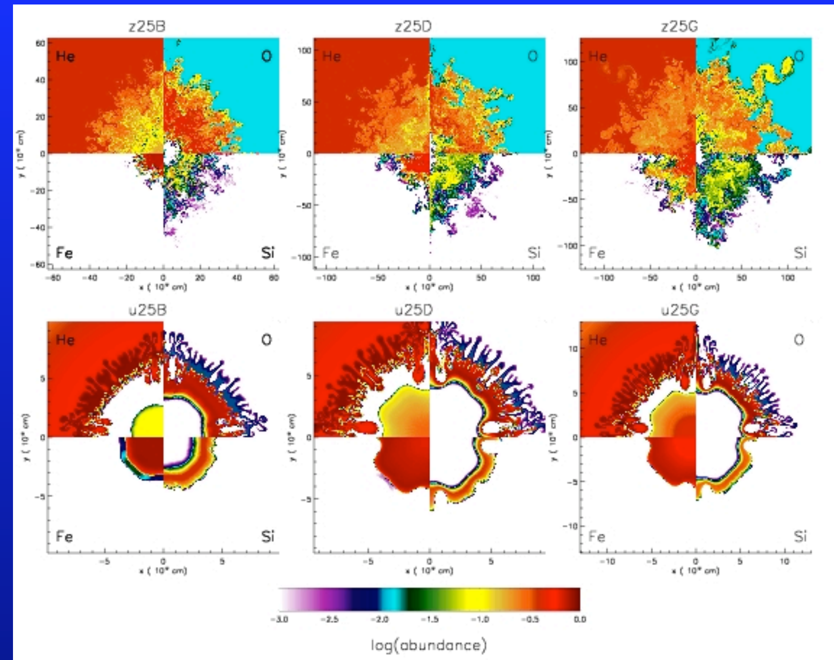
2D Rotating Progenitor Pop III Explosion Models

- progenitors evolved in the 1D KEPLER stellar evolution code, exploded, and then followed to the end of nucleosynthetic burn (~ 100 sec)
- KEPLER profiles then mapped into the new CASTRO AMR code and then evolved in 2D out to shock breakout from the star
- 2 rotation rates, 3 explosion energies, 3 masses, and 2 metallicities, for a total of 36 models
- self-gravity of the gas plus the gravity of the compact remnant (the latter is crucial for capturing fallback)

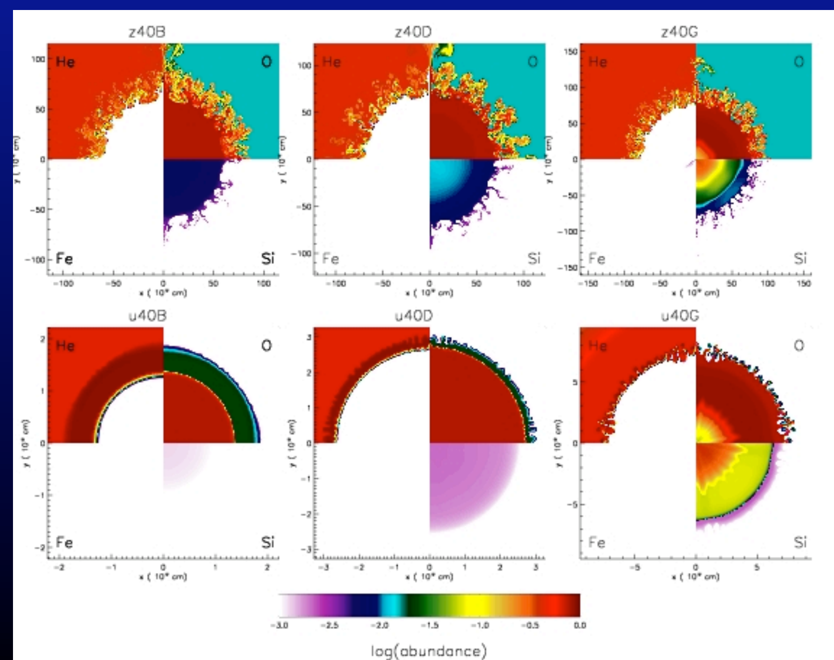


CASTRO Code (Almgren et al 2009)

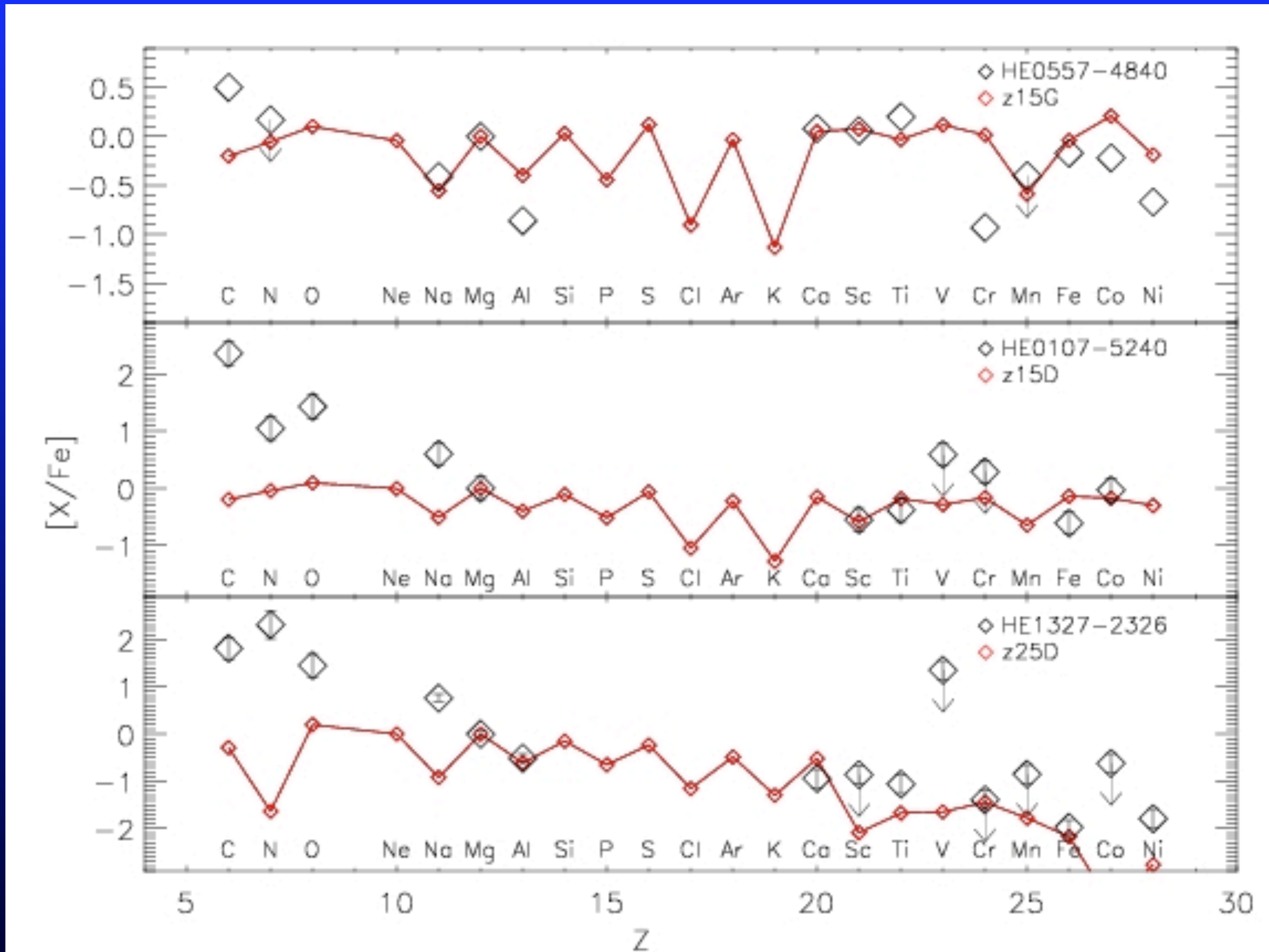




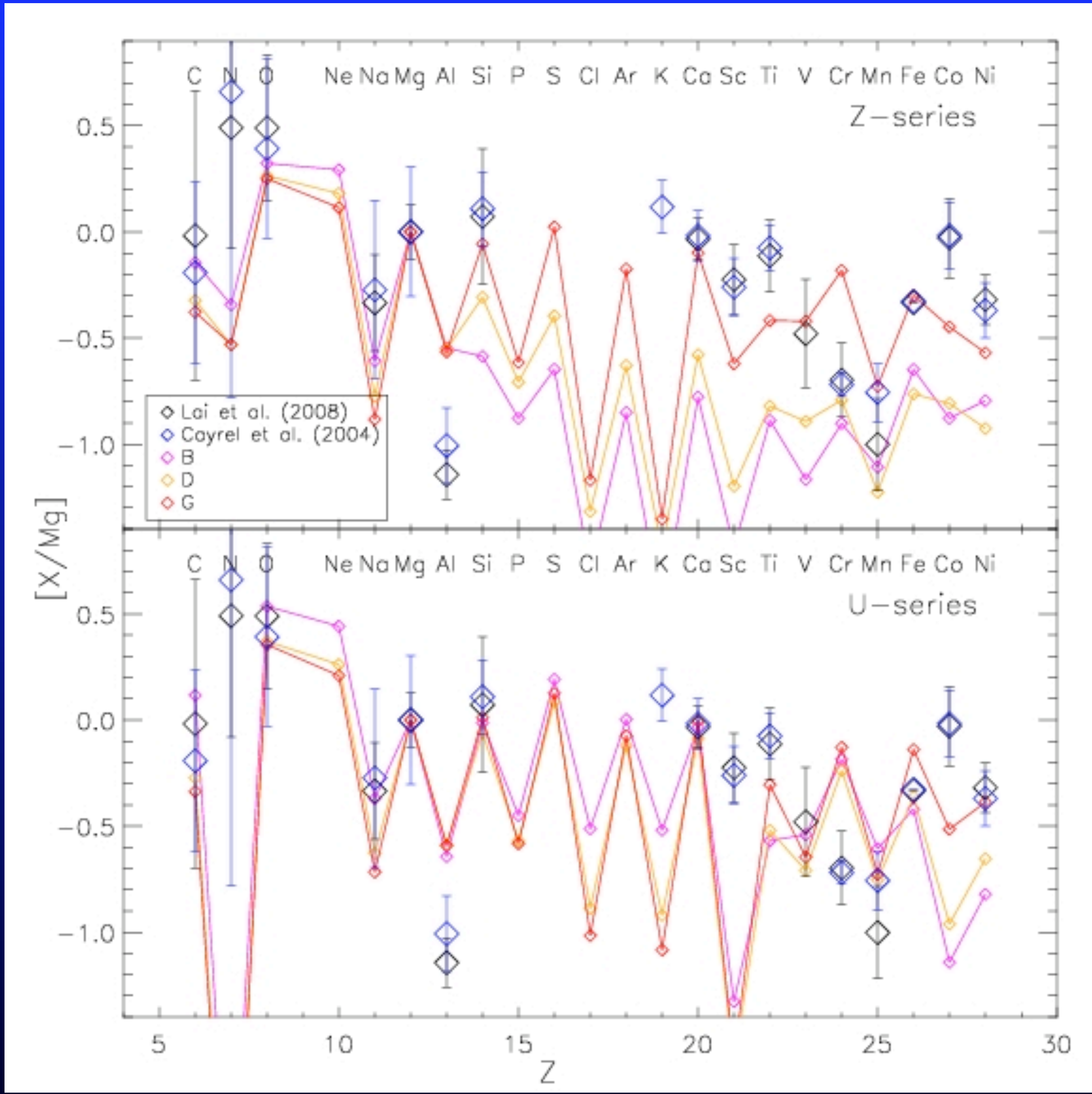
Mixing & Fallback vs Mass, E_{ex}, and Metallicity



- mixing falls and fallback rises with increasing mass
- mixing increases and fallback decreases with rising E_{ex}
- mixing and fallback rise with metallicity



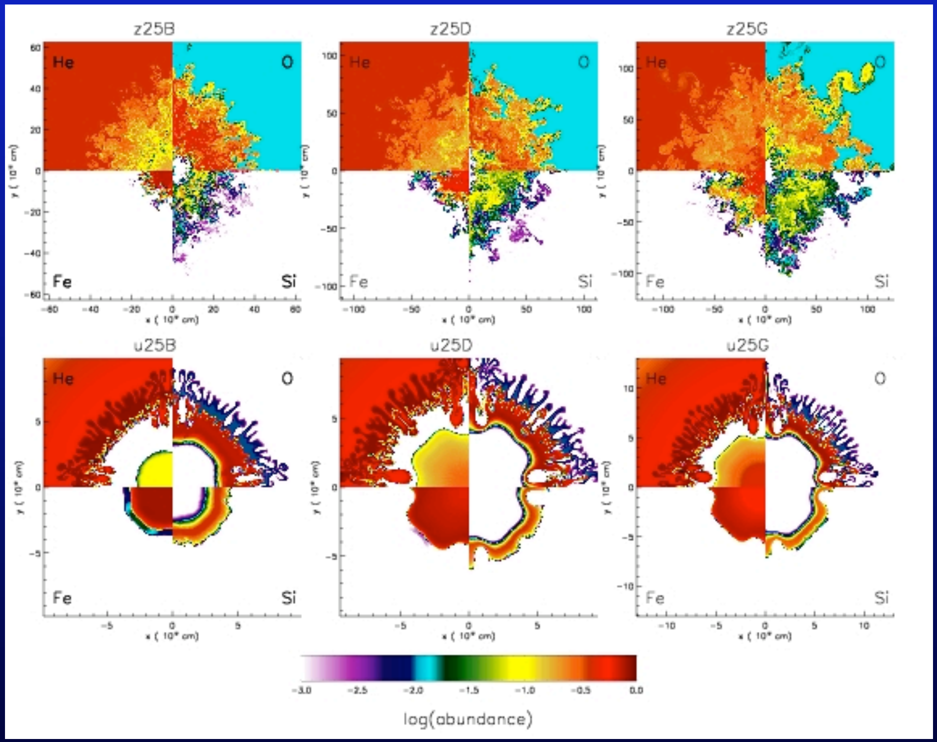
Elemental Yield Comparison to HMP Stars



IMF-Averaged Yields and the EMP Stars

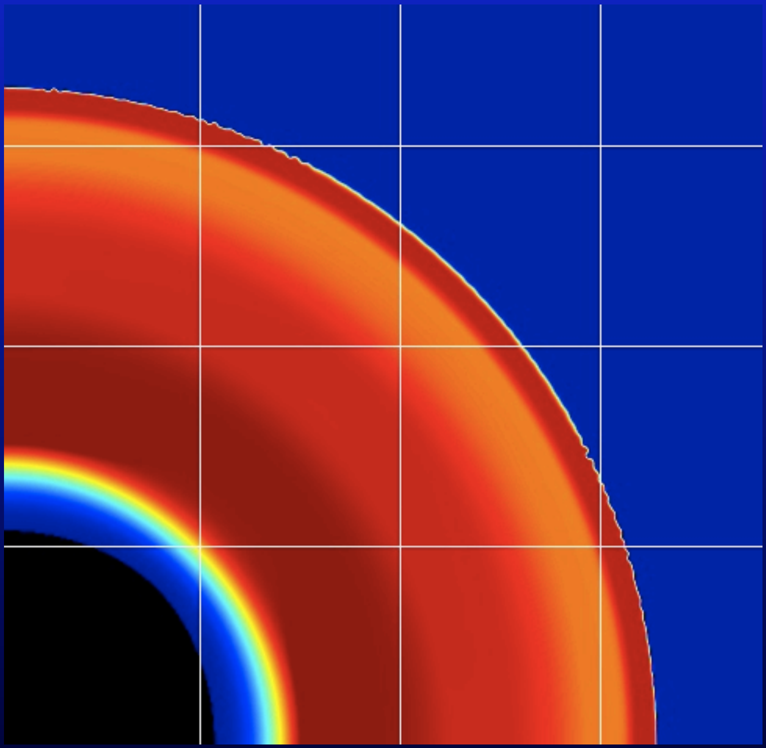
Chemical Mixing Prior to Breakout

Core Collapse SN



Joggerst, ….,Whalen, et al 2010, ApJ, 709, 11

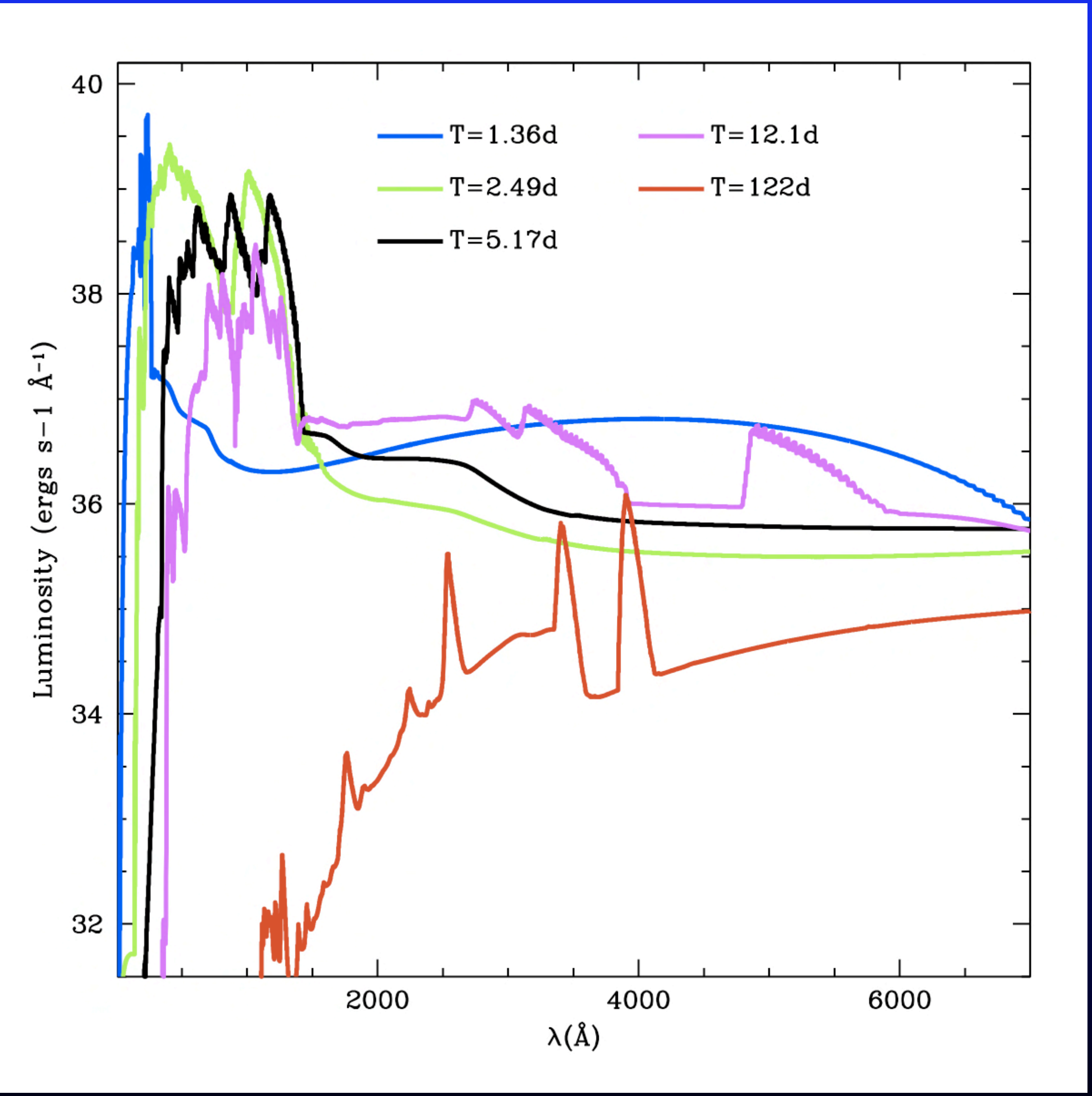
PISN



Joggerst & Whalen 2010, ApJ in prep

Late Time Spectra

spectral features after breakout may enable us to distinguish between PISN and CC SNe



Conclusions

- 15 – 40 $M_{\odot}$ rotating Pop III progenitors are a good fit to one of the HMP chemical abundances but not the other two
- an IMF-average of the chemical yields of our zero-metallicity models provides a good fit to the abundances Cayrel et al 2004 and Lai et al 2008 measured in their EMP star surveys
- since EMP stars are imprinted by well-established populations of SNe, they are likely a better fossil record of primordial SN progenitors
- direct comparison of nucleosynthetic yields from numerical models to the abundances of MP stars is problematic—intervening hydrodynamical processes complicate elemental uptake into new stars
- coming surveys (like SEGUE-II) will greatly expand our sample of metal-poor stars and yield great insights into the primordial IMF