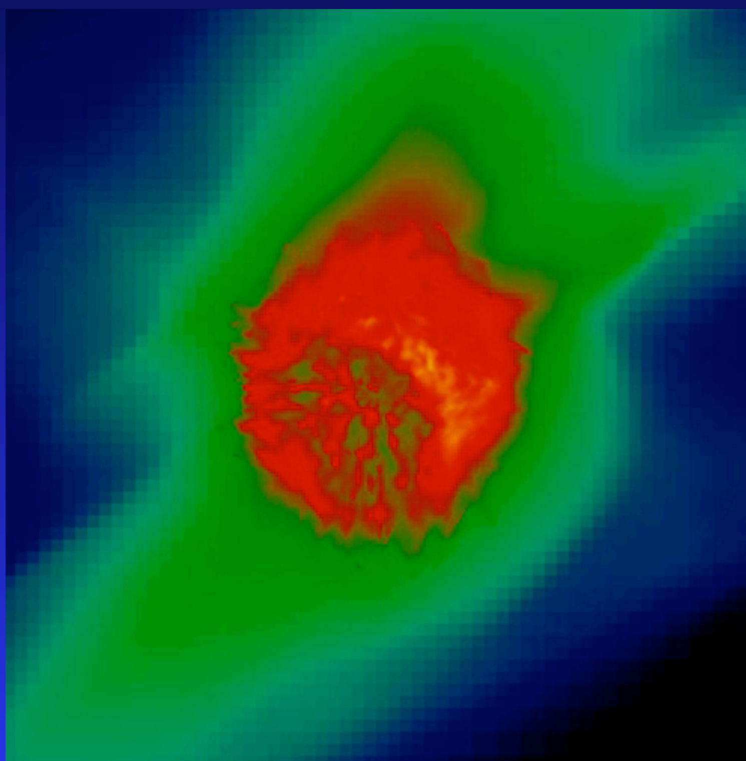
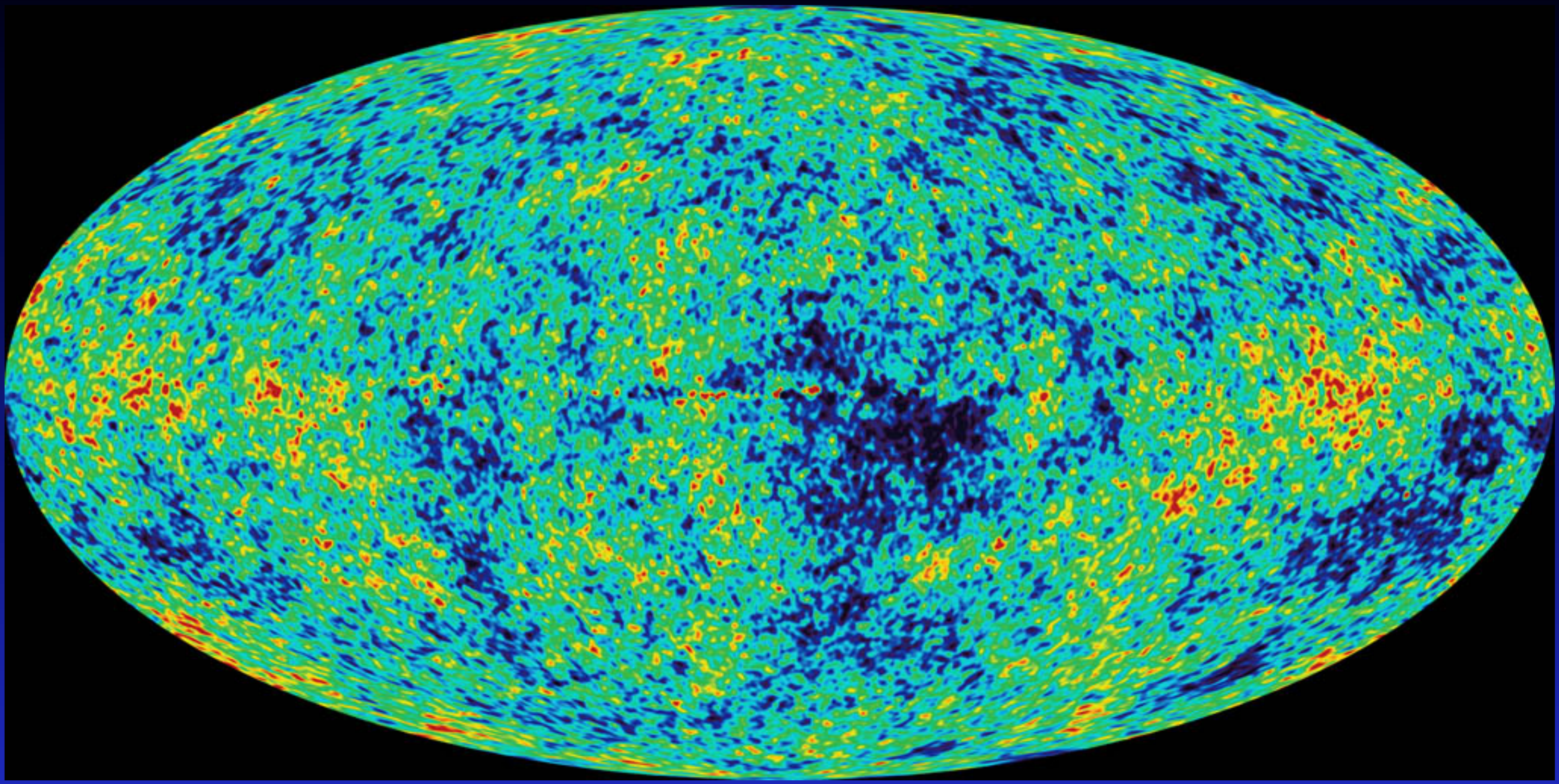
The First Stars

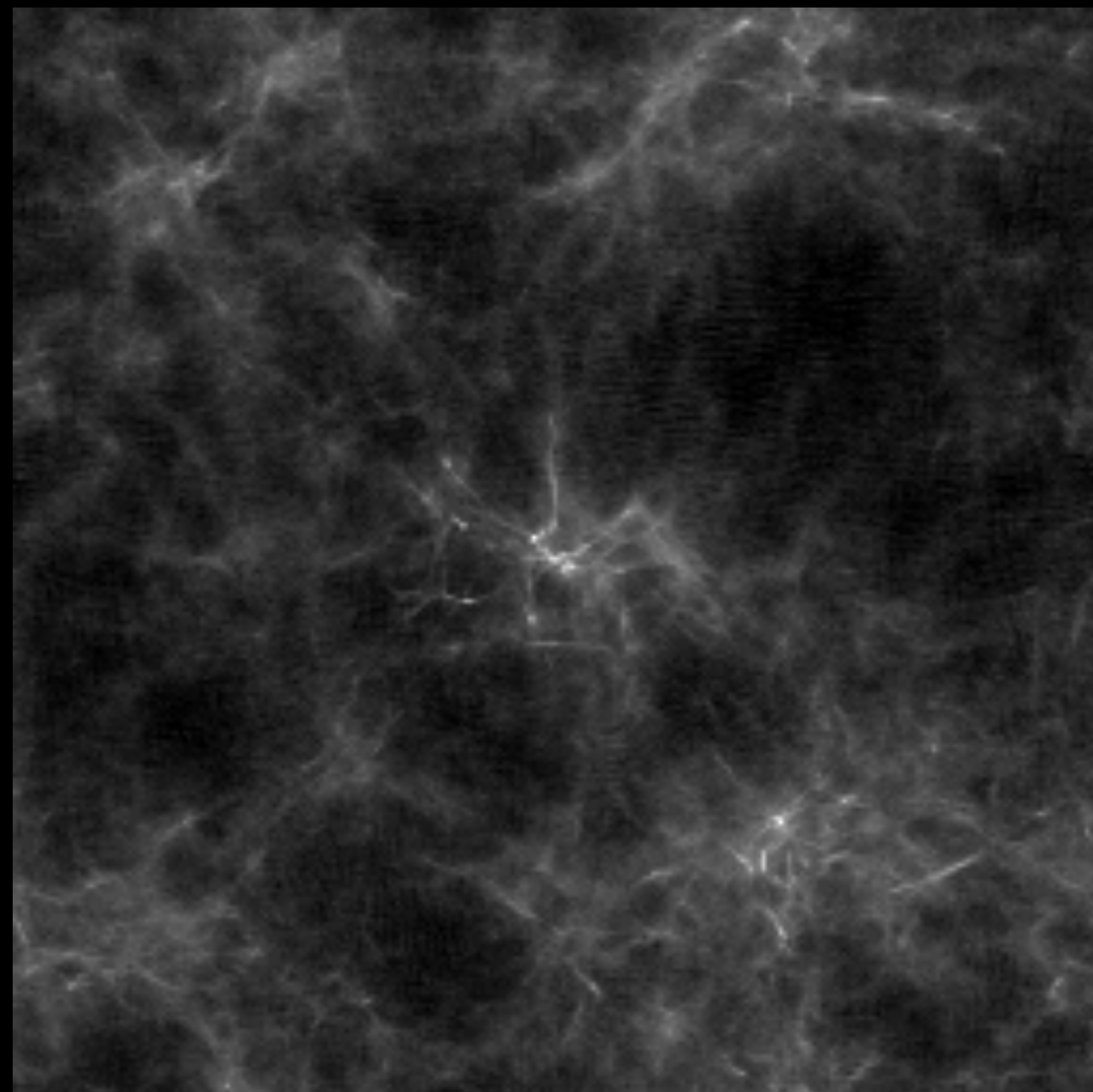


Daniel Whalen
McWilliams Fellow
Carnegie Mellon University

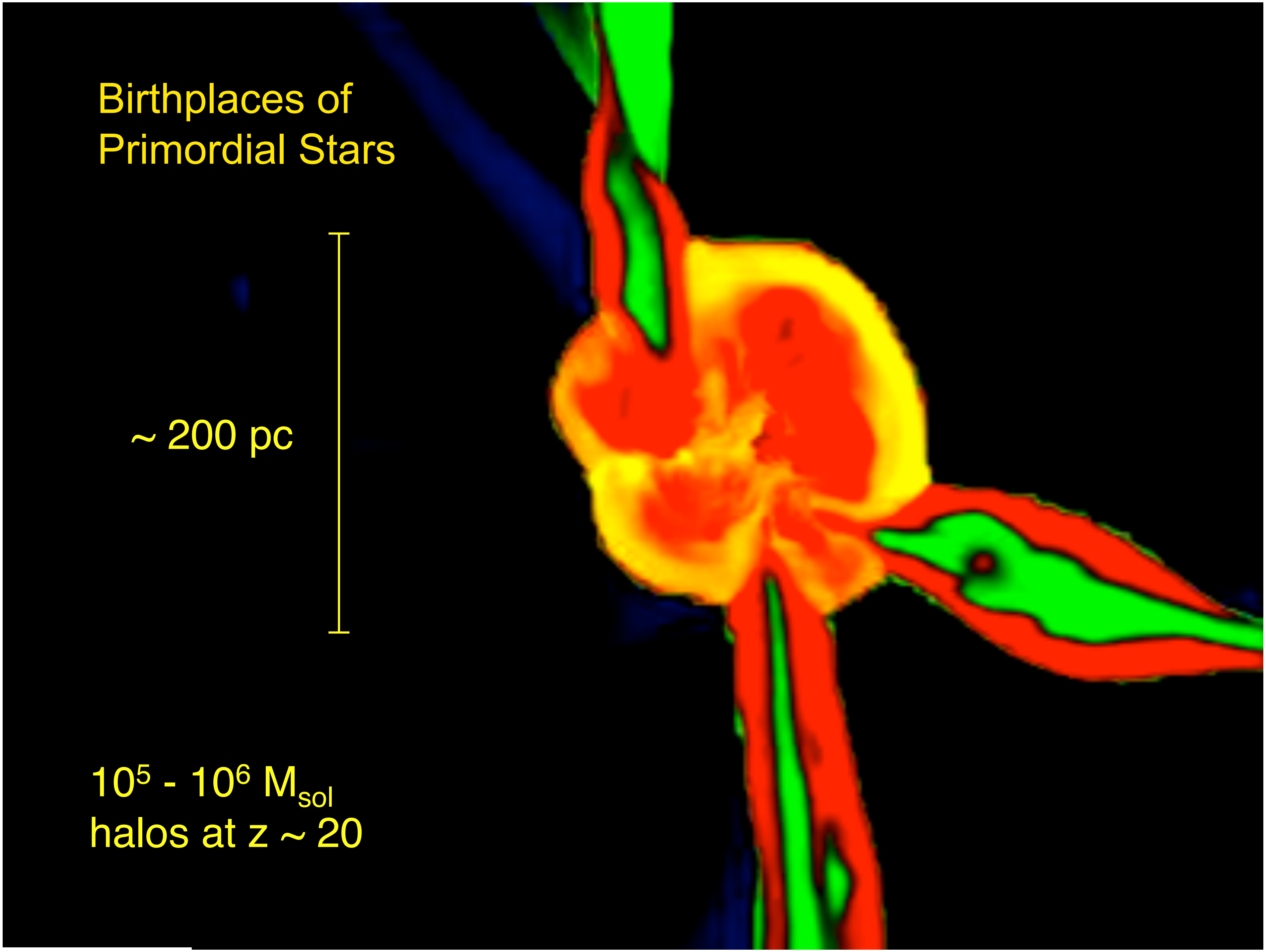


The WMAP Cosmic Microwave
Sky:
(t ~ 400,000 yr)

The Universe
at Redshift 20



128 kpc comoving

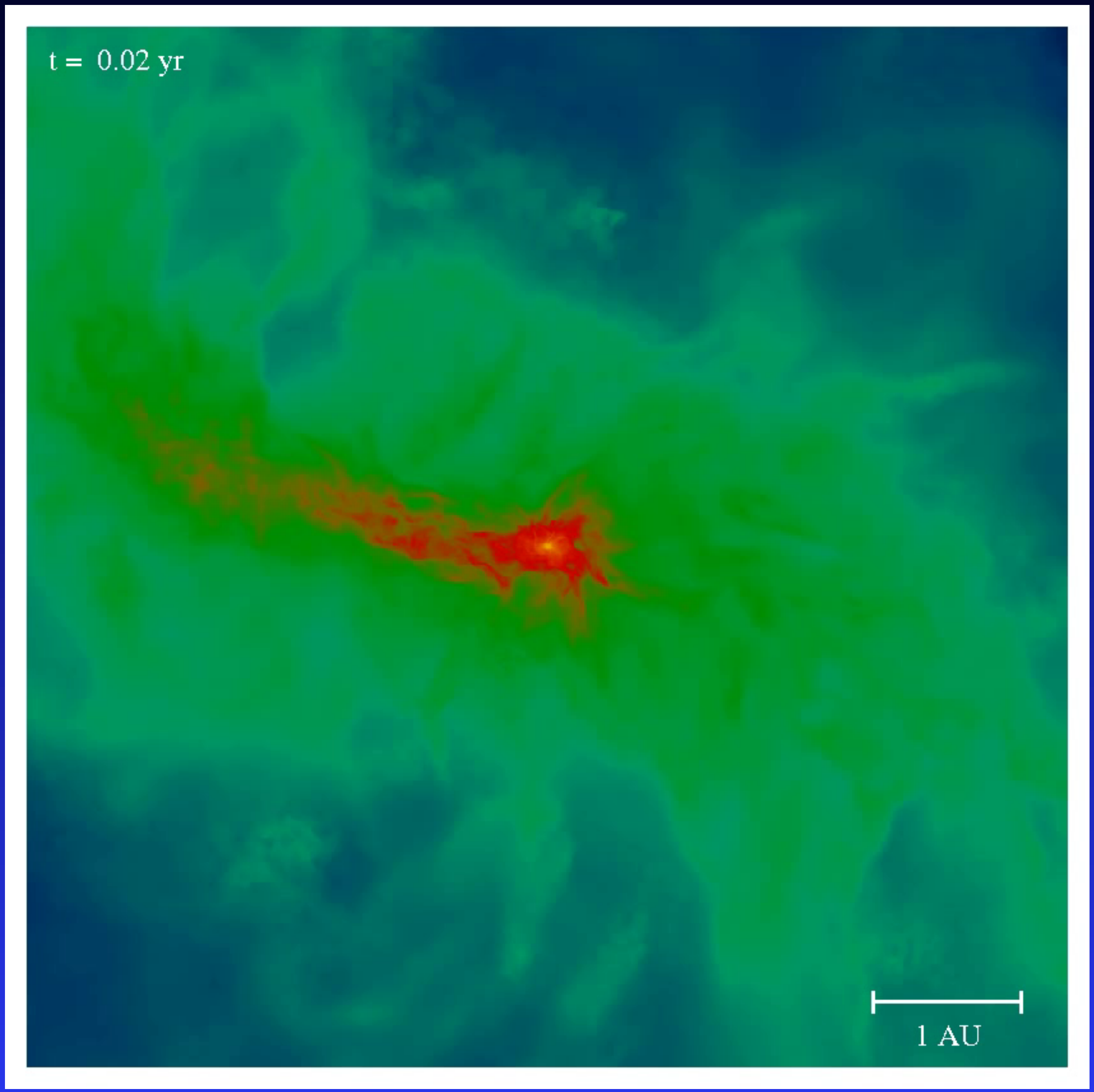

Birthplaces of
Primordial Stars
~ 200 pc
10^5 - 10^6 M_{sol}
halos at z ~ 20

Properties of the First Stars

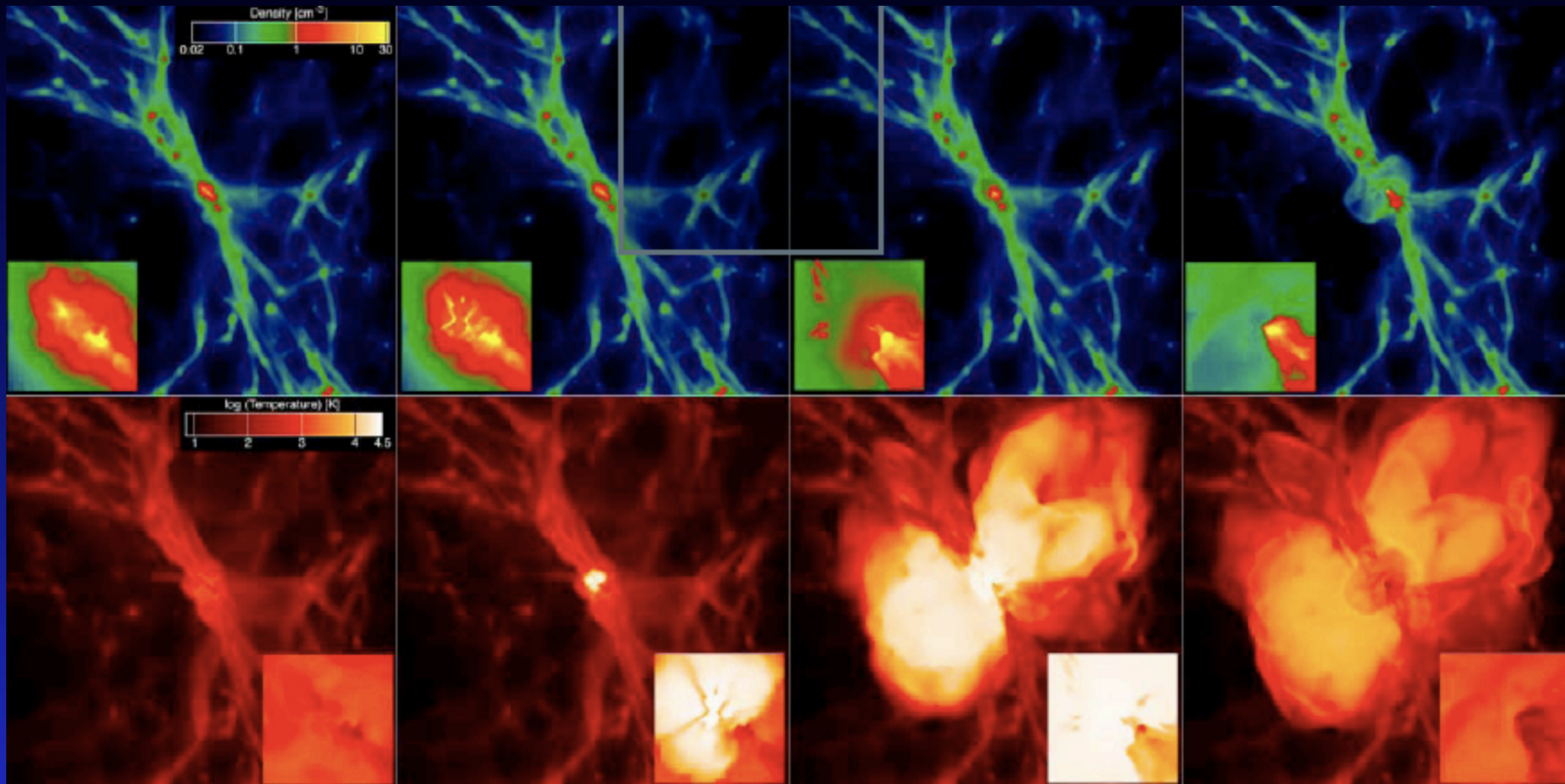
1999 - 2008

- thought to be very massive (25 - 500 solar masses) due to inefficient H_2 cooling
- form in isolation (one per halo or in binaries) or in small multiples
- $T_{surface}$ ~ 100,000 K
- *extremely* luminous sources of ionizing and LW photons (> 10^{50} photons s^{-1})
- 2 - 3 Myr lifetimes
- no known mechanisms for mass loss -- no line-driven winds

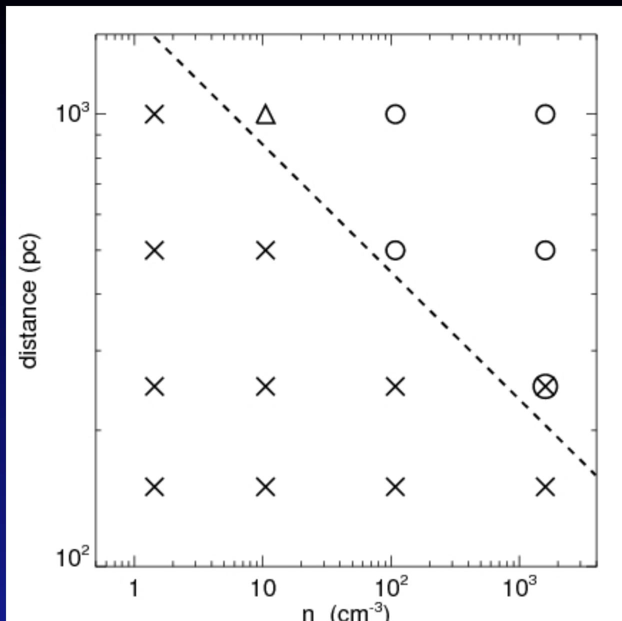
Low-Mass Pop III Stars?

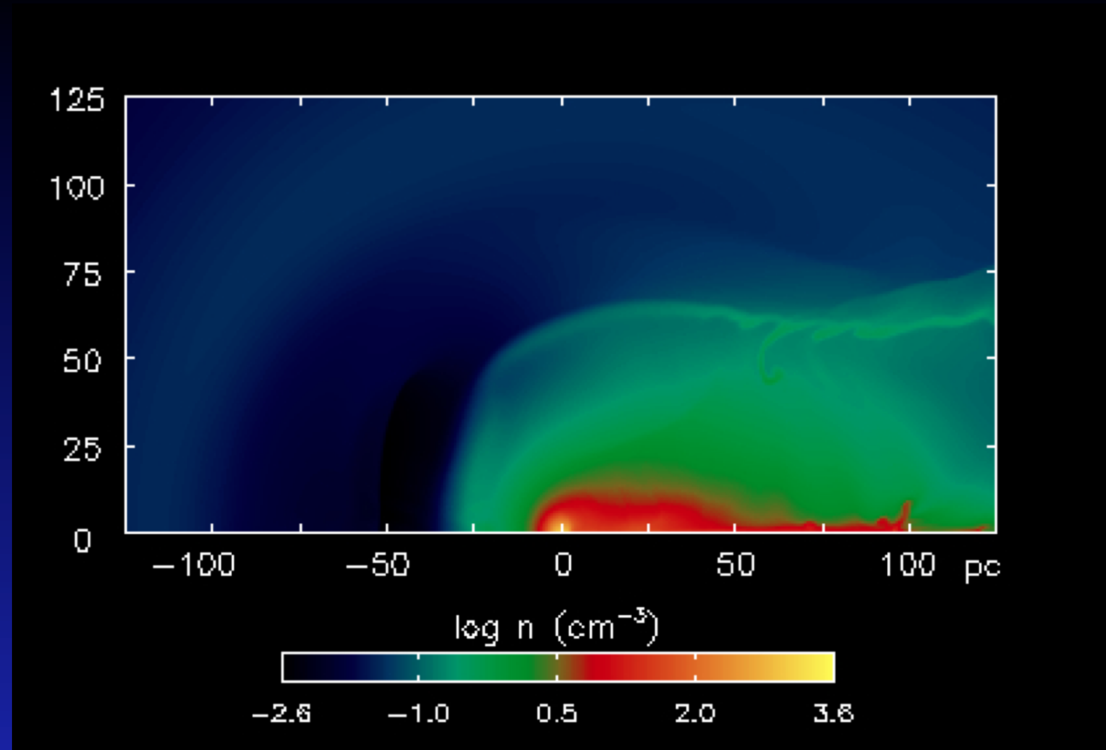


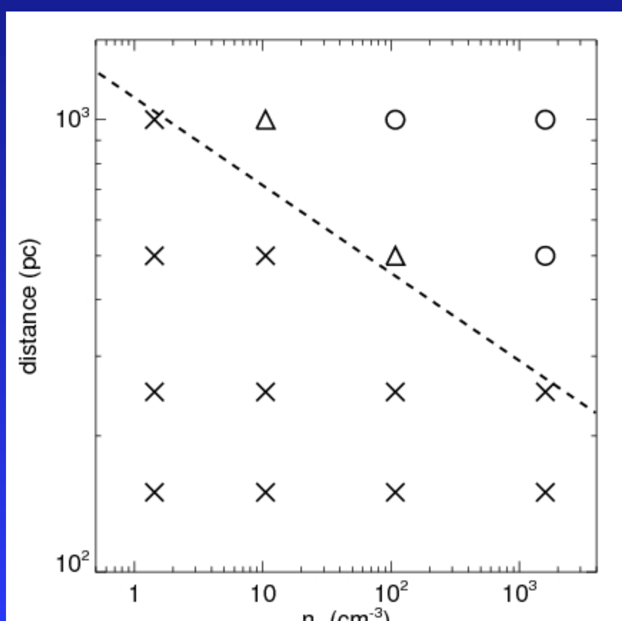
Greif et al. 2011, ApJ, 737, 75



Whalen, Abel & Norman 2004, ApJ, 610, 14
Wise, Abel & Bryan 2008, ApJL, 659, 87

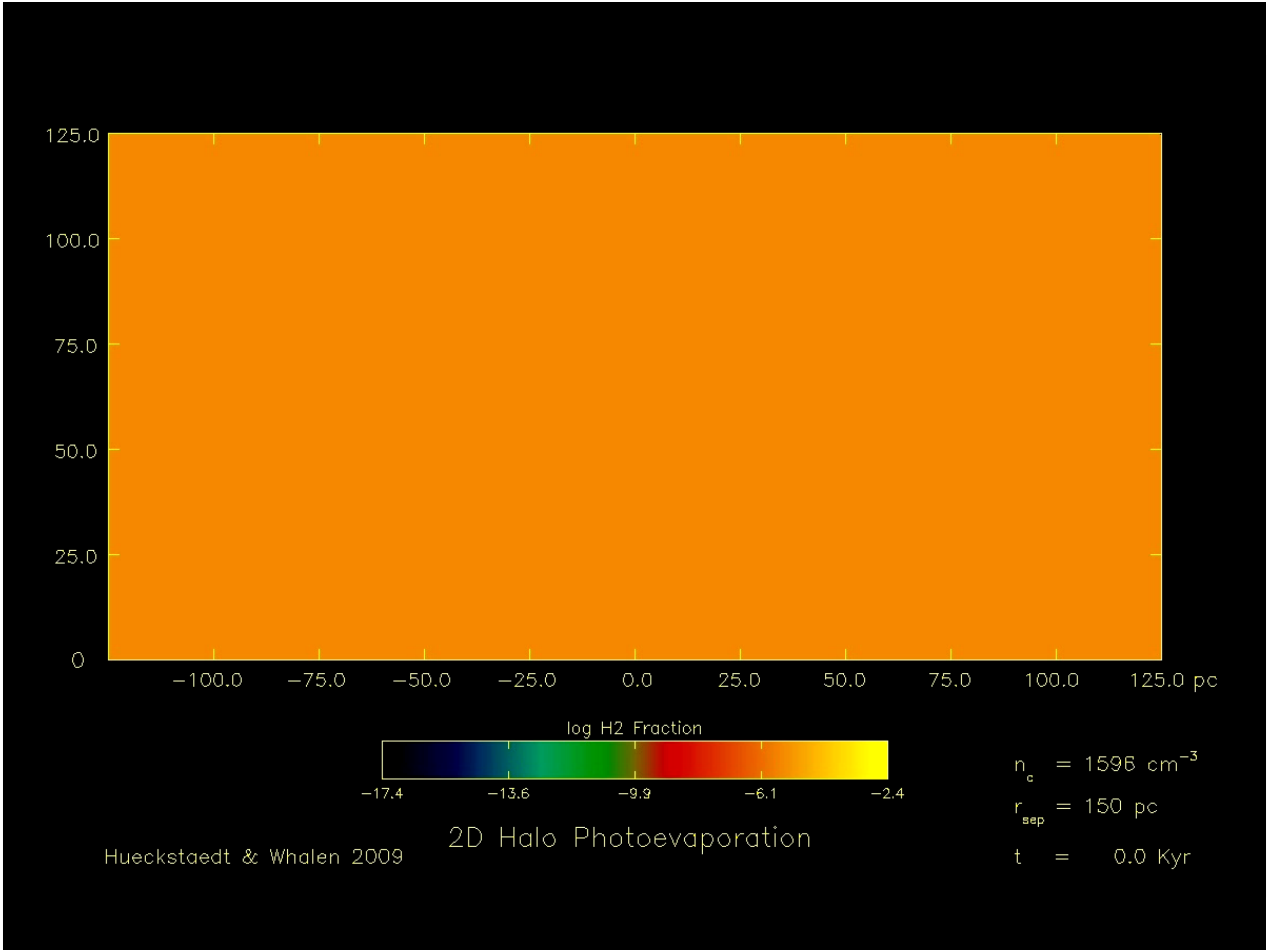






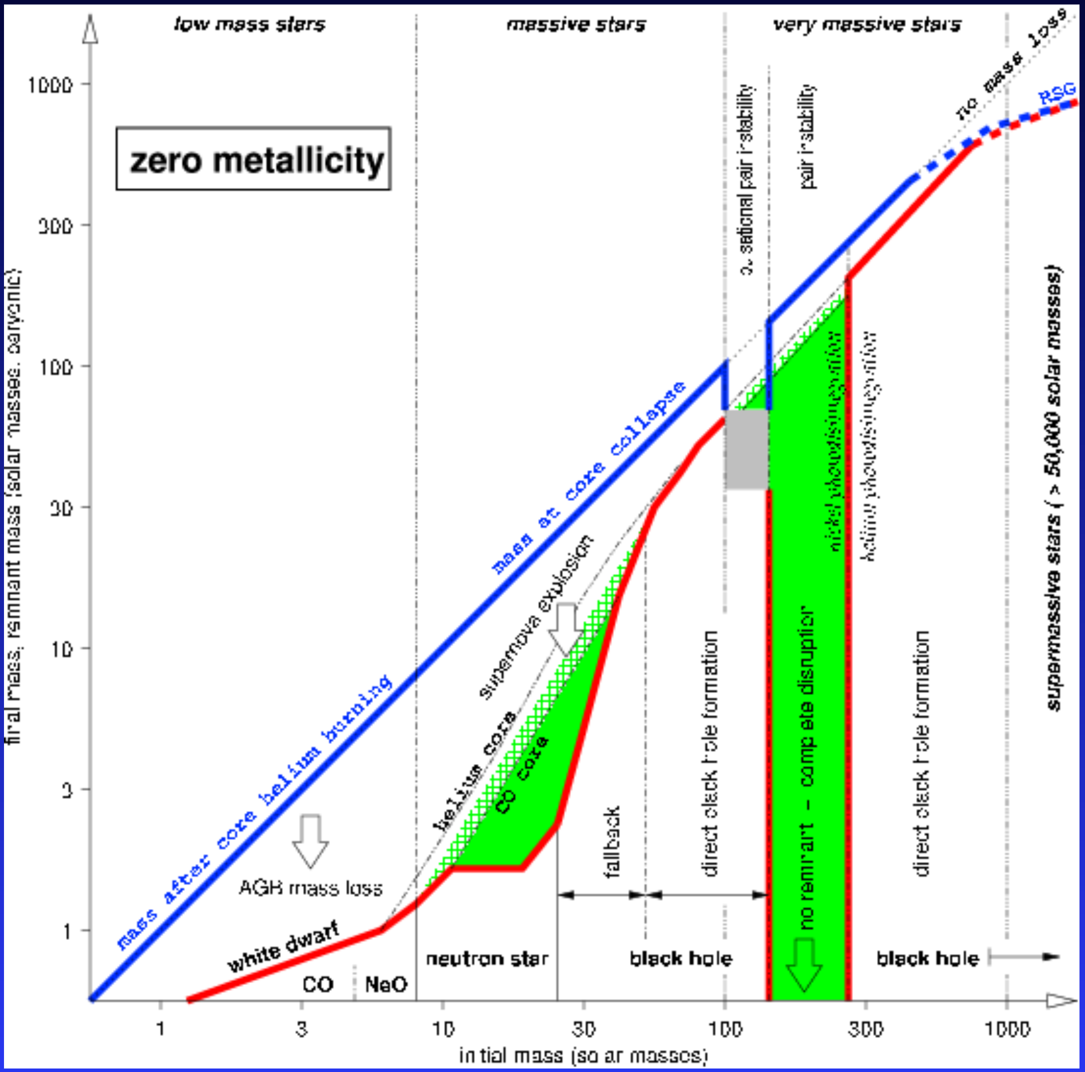
How the First Stars Regulated Early Stellar Populations

O'Shea, Abel, Whalen & Norman 2005 ApJL, 628, 5
Whalen et al. 2008 ApJ, 679, 925
Whalen et al. 2010 ApJ, 712, 101


125.0
100.0
75.0
50.0
25.0
0
−100.0
−75.0
−50.0
−25.0
0.0
25.0
50.0
75.0
100.0
125.0 pc
log H2 Fraction
−17.4
−13.6
−9.9
−6.1
−2.4
n_c = 1596 cm^{-3}
r_{sep} = 150 pc
t = 0.0 Kyr
2D Halo Photoevaporation
Hueckstaedt & Whalen 2009

Final Fates of the First Stars

Heger & Woosley 2002, ApJ 567, 532



Direct Probes of the Masses of The First Stars

- stellar archaeology: can the ashes of the first stars be found in ancient, dim stars in the Galactic halo (fossils from the second generation)?

- can we see the first supernova explosions, and thereby infer the properties of their progenitors?

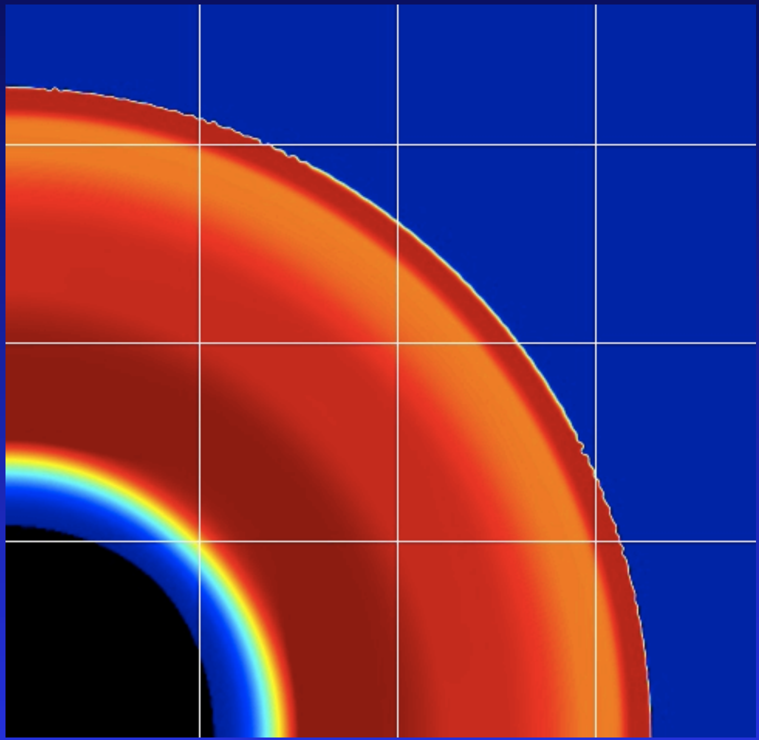
2D Rotating Progenitor Pop III Explosion Models in CASTRO

- progenitors evolved in the 1D KEPLER stellar evolution code, exploded, and then followed to the end of nucleosynthetic burn (~ 100 sec)

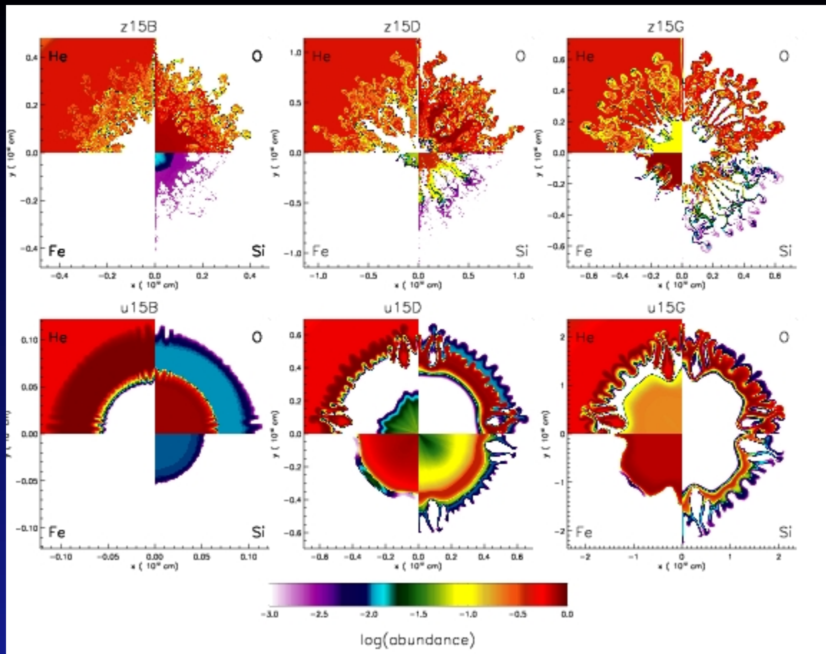
- KEPLER profiles then mapped into the new CASTRO AMR code and then evolved in 2D out to shock breakout from the star

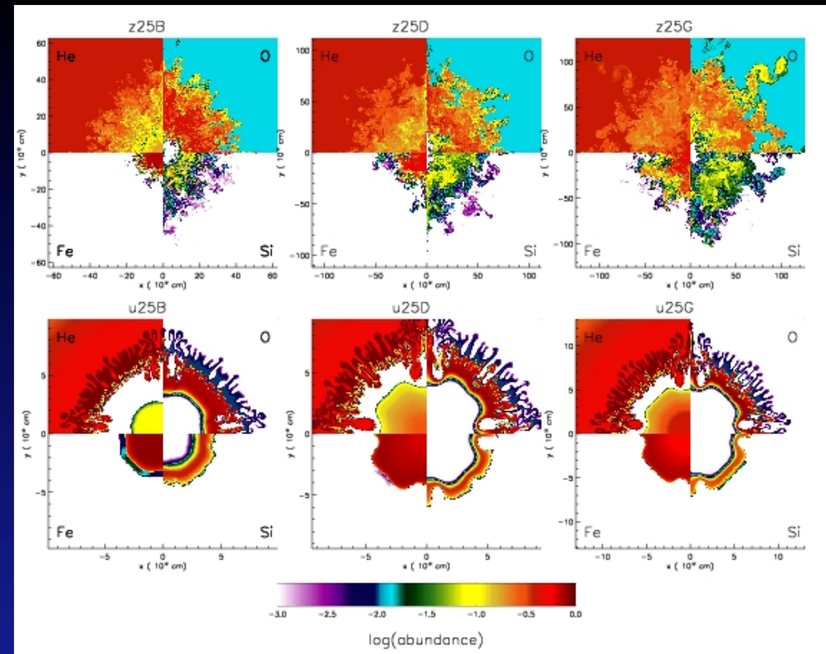
- 2 rotation rates, 3 explosion energies, 3 masses, and 2 metallicities, for a total of 36 models

- self-gravity of the gas plus the gravity of the compact remnant (the latter is crucial for capturing fallback)

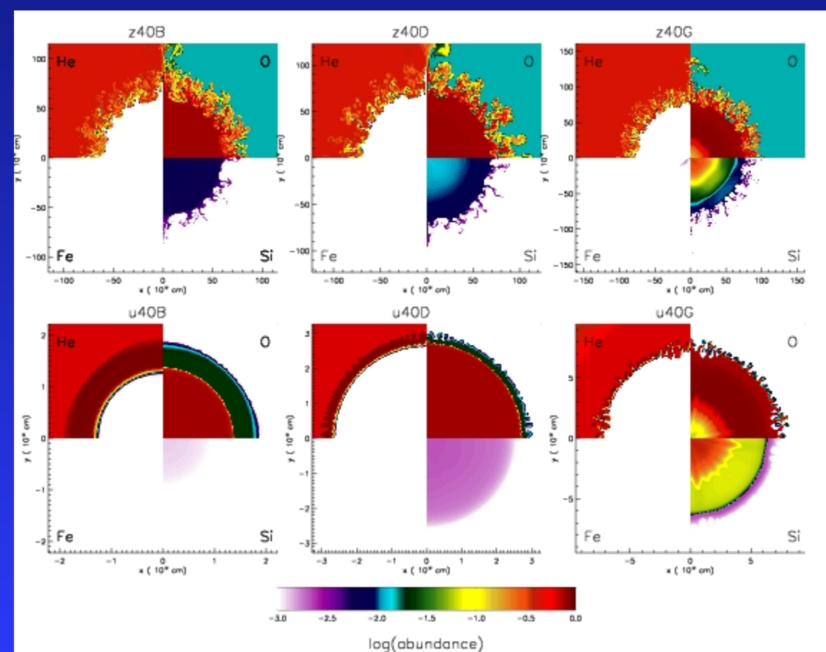


CASTRO Code (Almgren et al 2009)



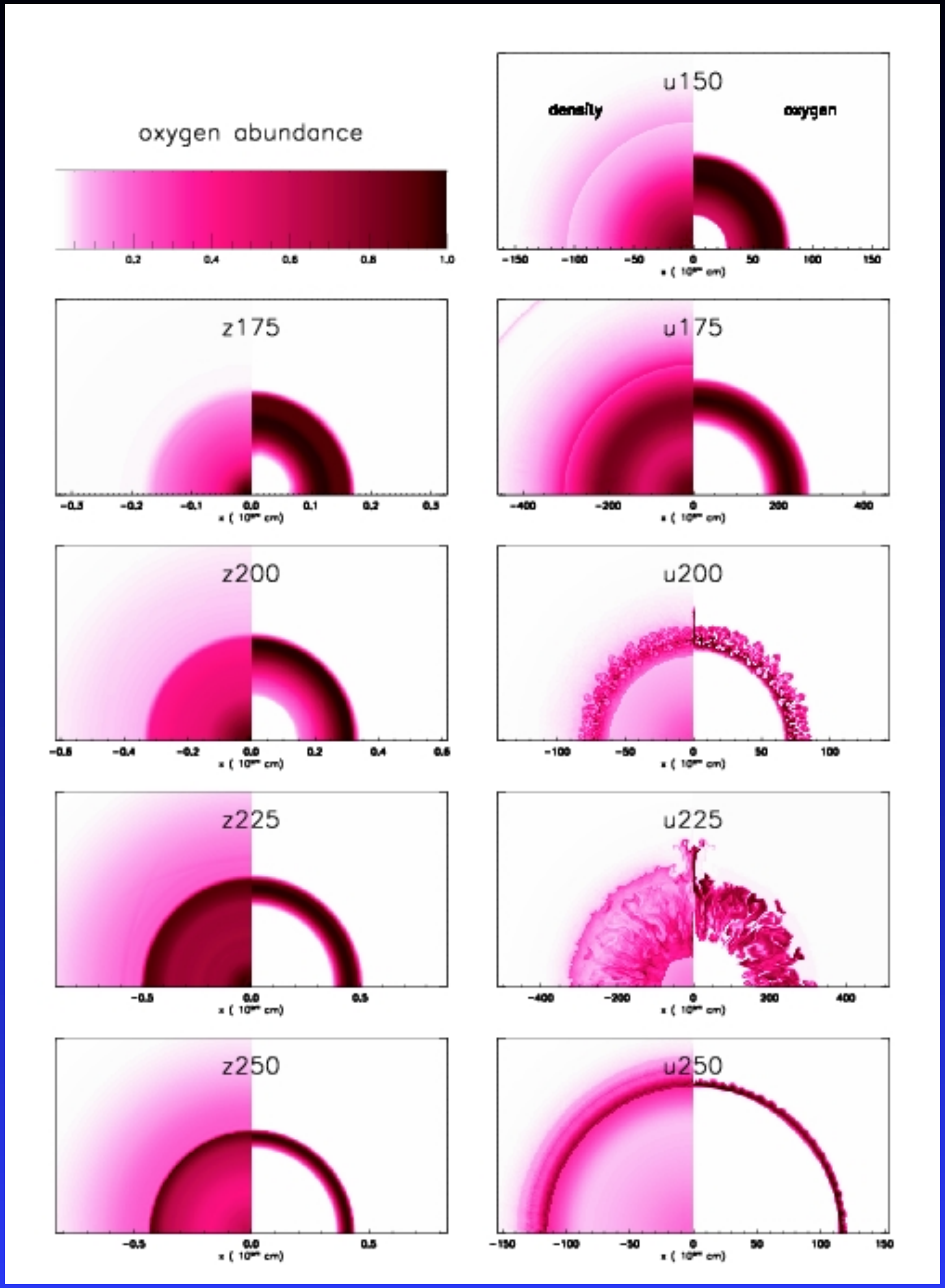


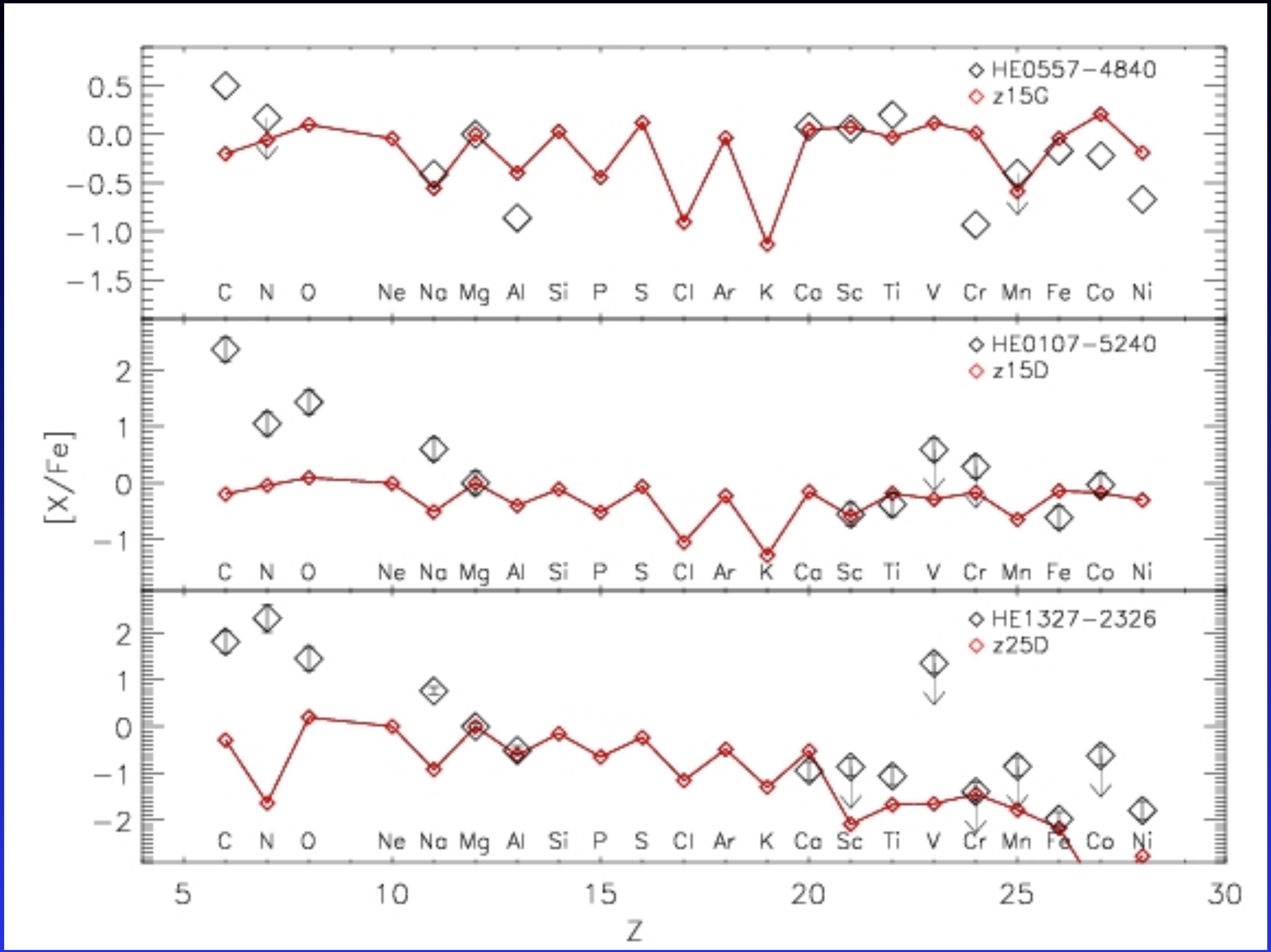
Chemical Enrichment of the Early Cosmos: Ashes of the First Stars?



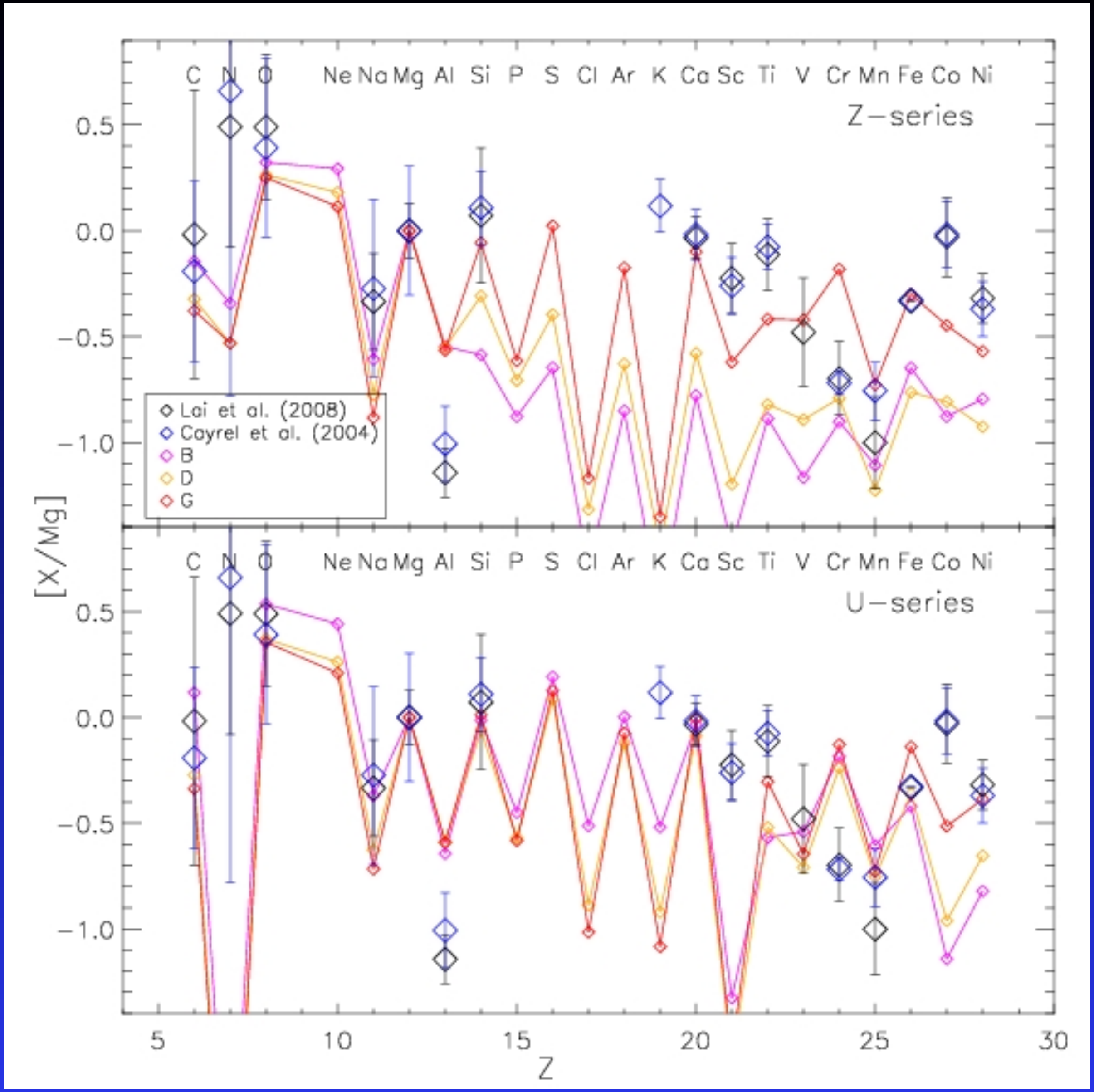
Joggerst, .., Whalen, et al 2010 ApJ 709, 11
Joggerst & Whalen 2011 ApJ, 728, 129

Mixing in Pop III PISNe





Elemental Yield Comparison to HMP Stars



IMF-Averaged Yields and the EMP Stars

LANL Pop III Supernova Light Curve Effort

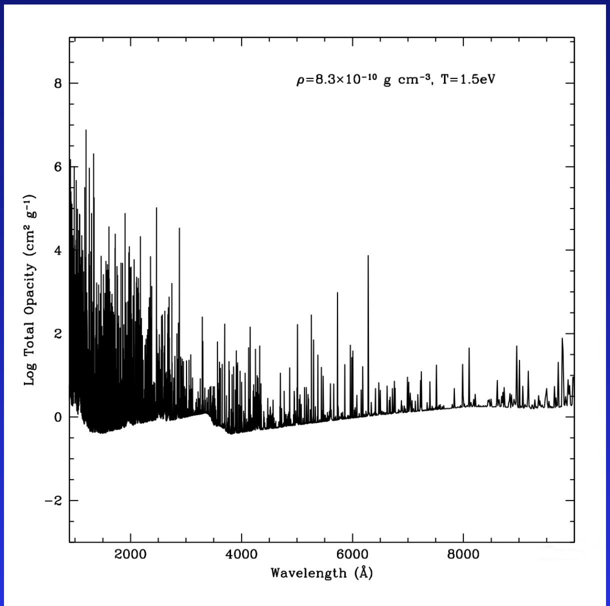
Whalen et al. ApJ 2012a,b,c,d in prep

- begin with 1D Pop III 15 – 40 M_{sol} CC SN and 150 – 250 M_{sol} KEPLER PI SN blast profiles
- evolve PI SNe out to 3 yr in the LANL radiation hydro code RAGE
- evolve CC SNe out to breakout in the CASTRO AMR code, port to RAGE, and then run out to 6 months
- post-process RAGE profiles with the LANL SPECTRUM code to compute light curves and spectra
- convolve these spectra with Lyman absorption by high-redshift neutral clouds, cosmological redshift, and filter response functions to calculate JWST and WFIRST NIR light curves

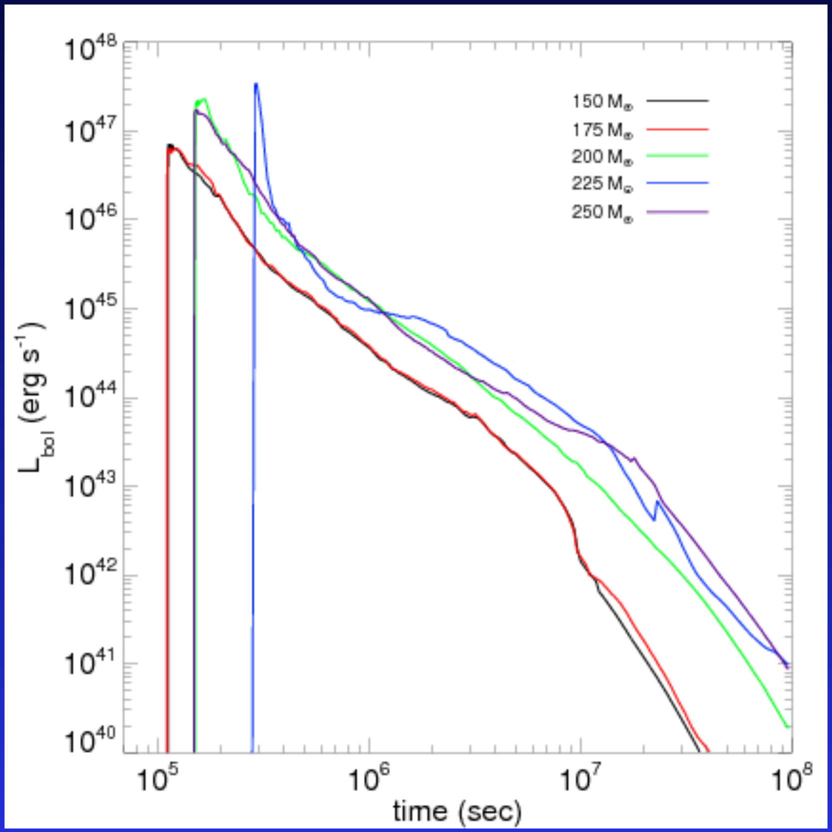
Radiation Adaptive Grid Eulerian (RAGE)

Frey, Even, Whalen et al. 2012 submitted

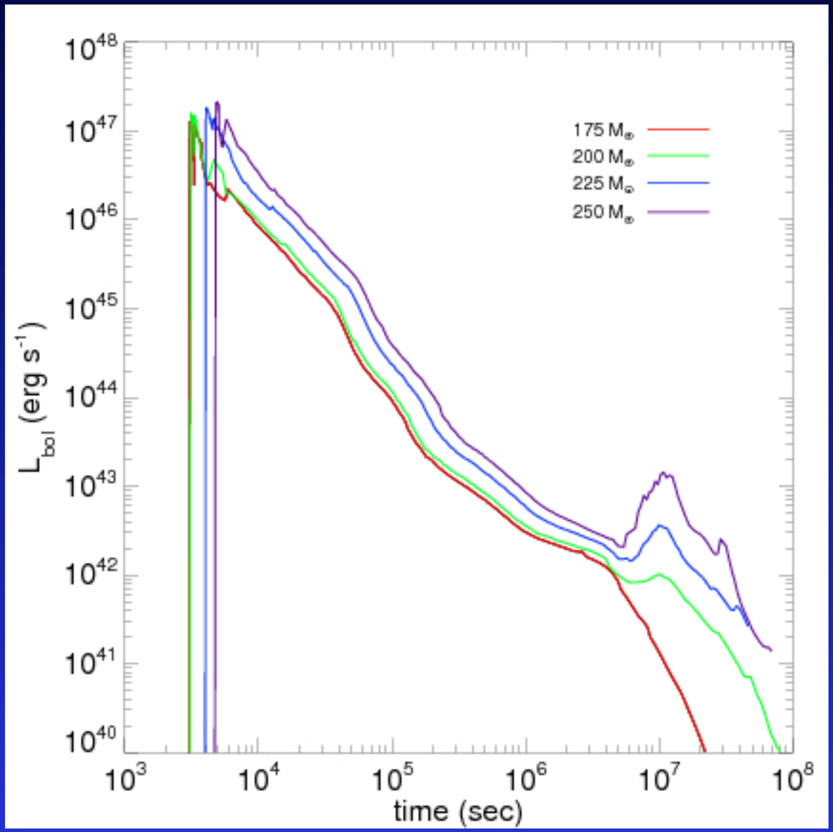
- grey flux-limited diffusion coupled to a high-order Godunov hydro solver on a cell-based adaptive mesh refinement grid
- matter and radiation temperatures, while coupled, are evolved separately
- energy due to radioactive decay of ^{56}Ni is locally deposited in the gas
- LANL OPLIB database of atomic opacities



Light Curves

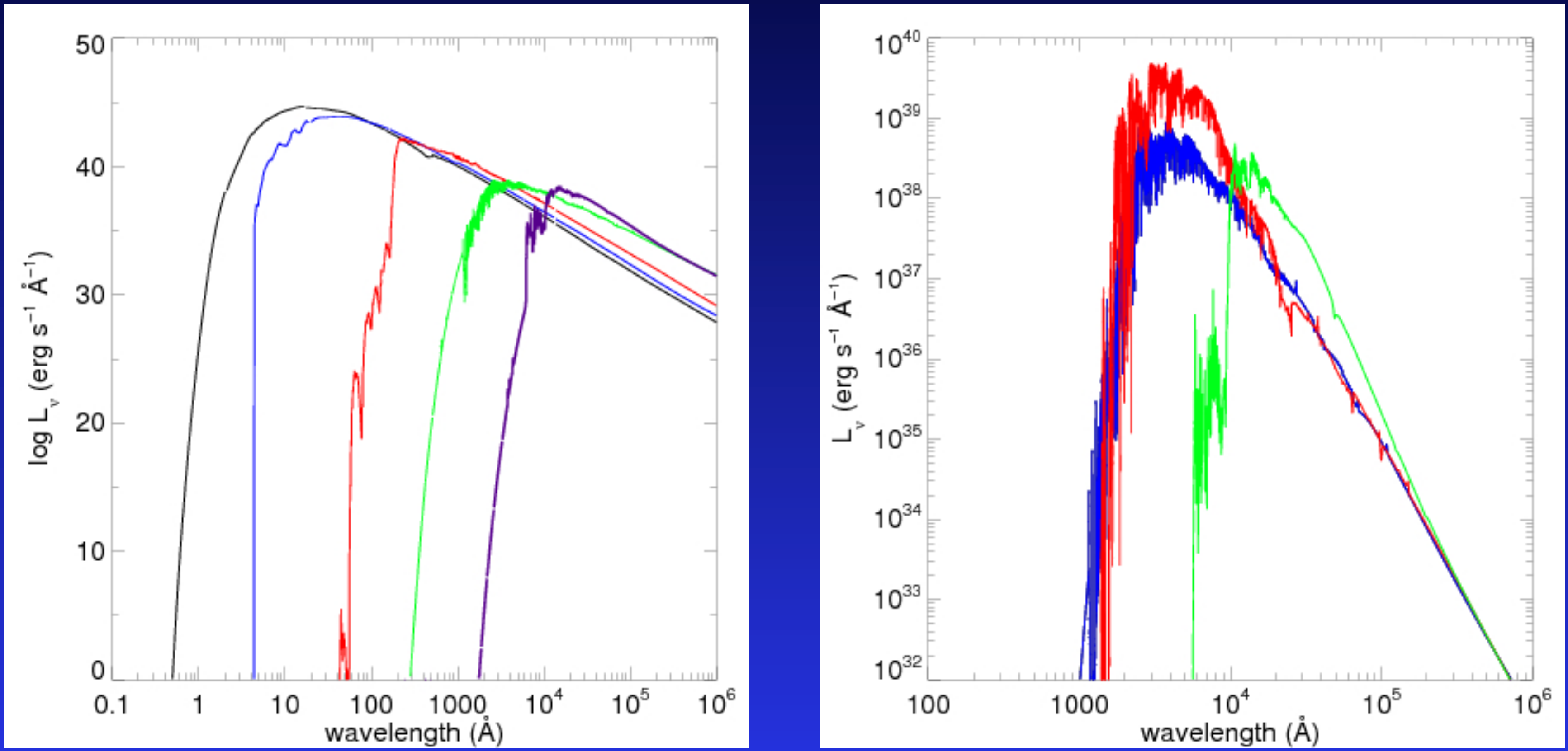


u-series
(red hypergiants)



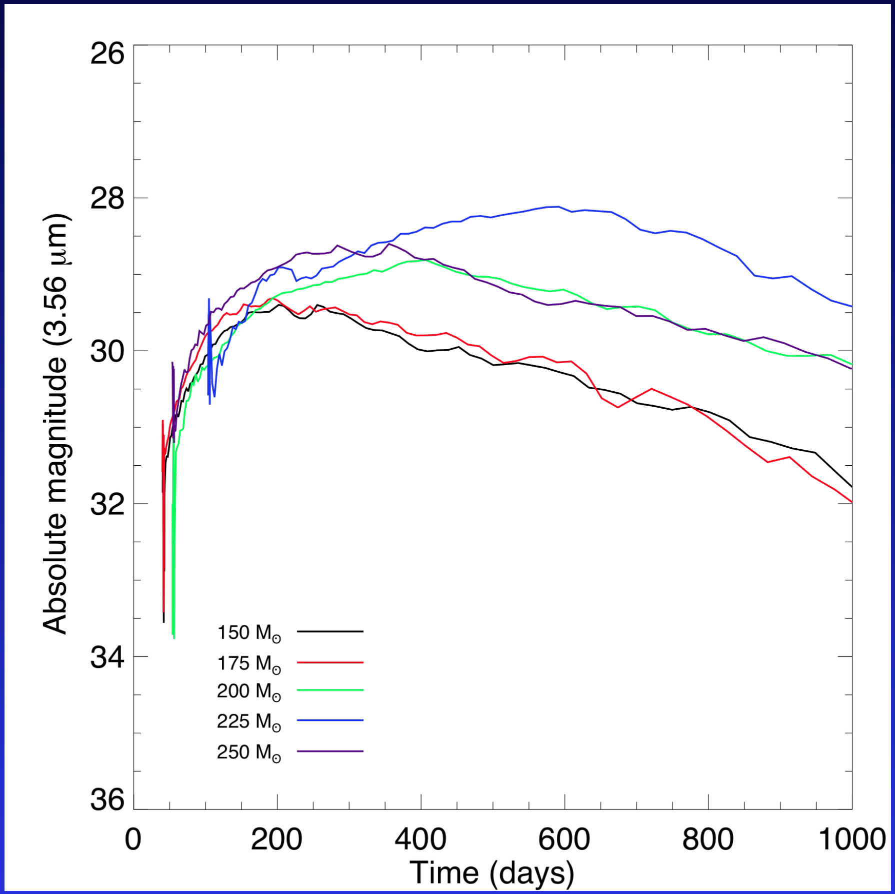
z-series
(blue compact giants)

Spectral Evolution: z250



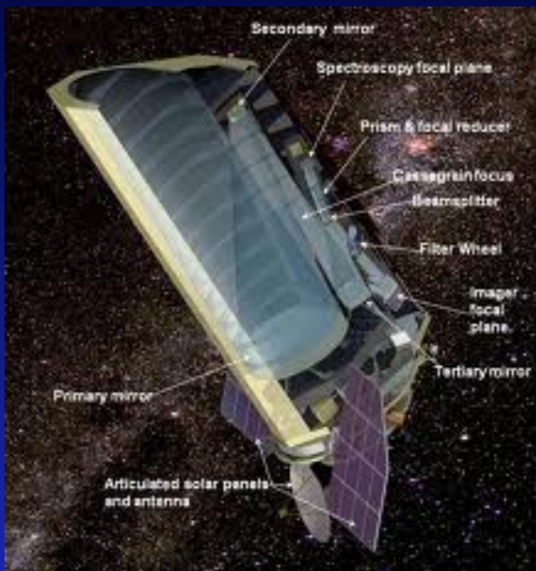
JWST NIRCam Light Curves at z = 30

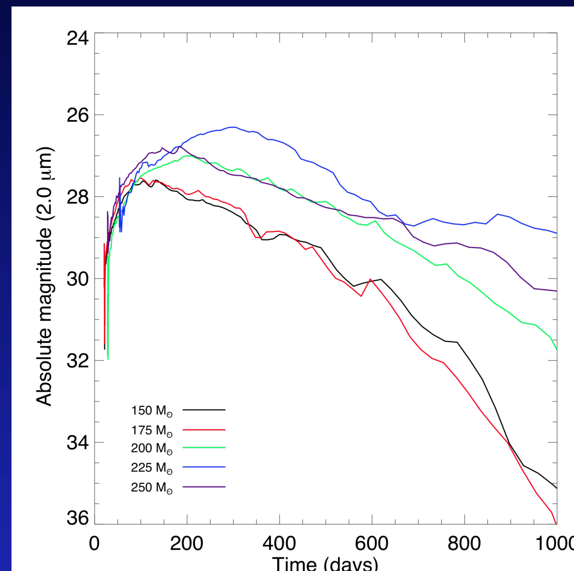
- NIRCam detection threshold is absolute magnitude 32 for deep surveys
- PI SNe will be visible to JWST beyond z = 30 and will even be able to perform spectrometry on them
- Although JWST's deep field will be very narrow, it is expected that at least a few PI SNe will be in them in a given survey (Hummel et al. 2011, ApJ)



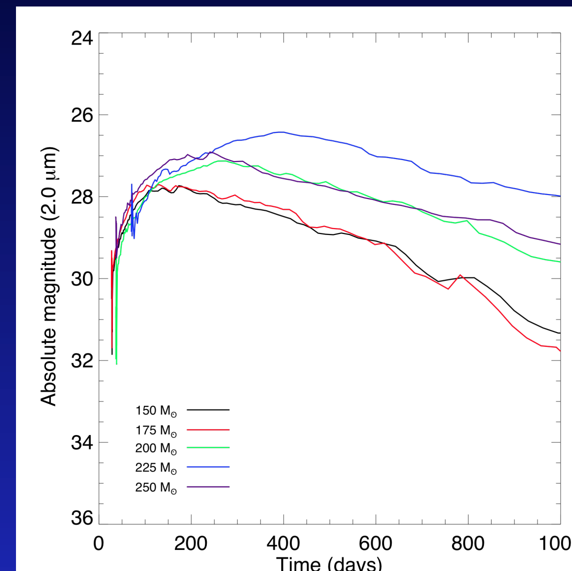
WFIRST

Wide-Field Infrared Survey Telescope





z = 15

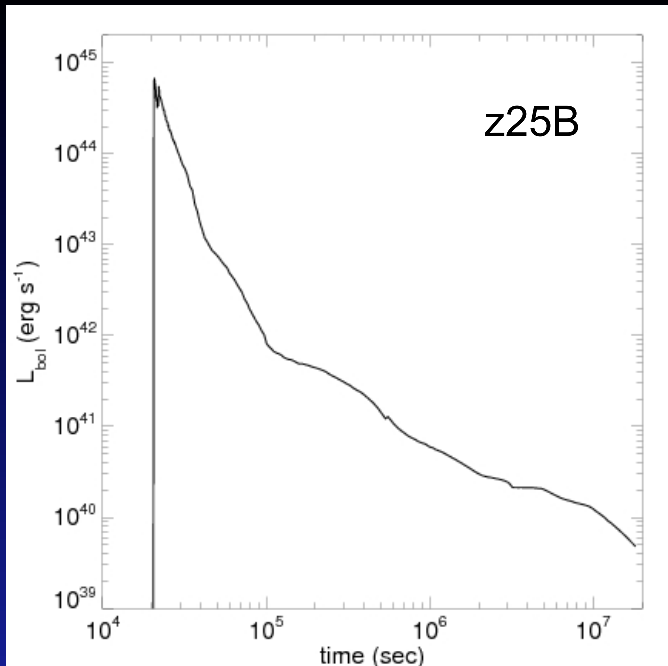


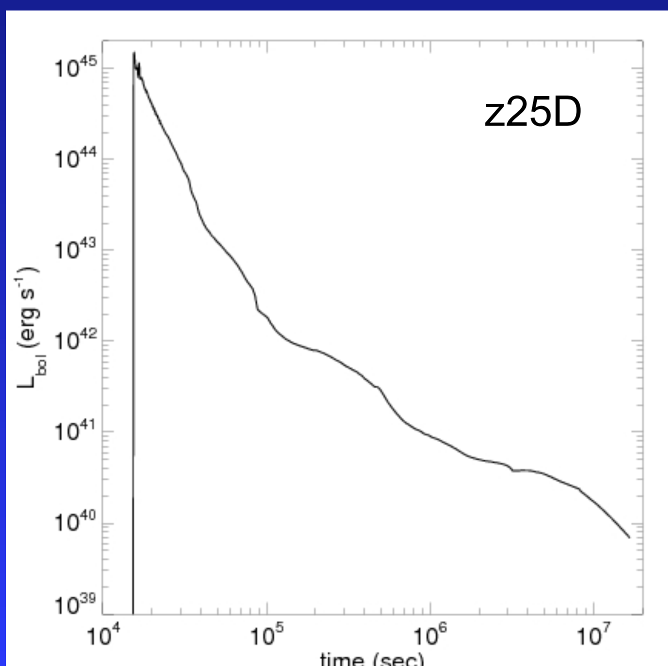
z = 20

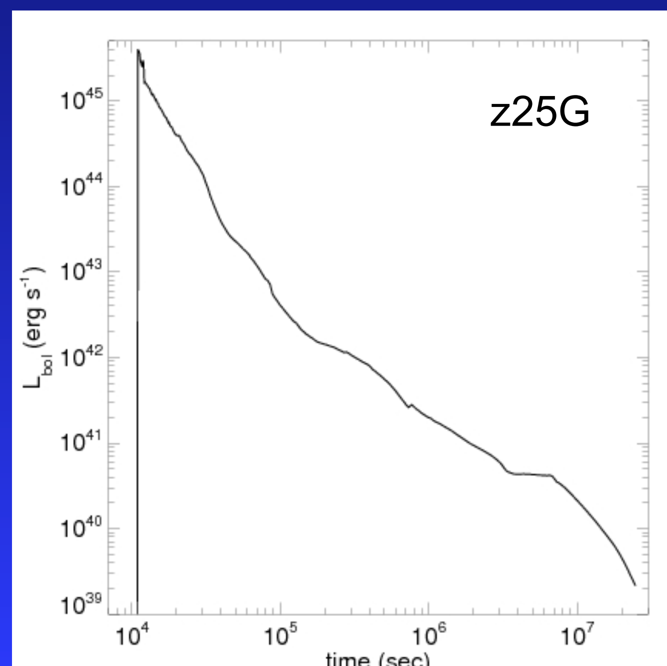
- all sky NIR survey mission
- proposed sensitivity of AB magnitude 26.5 @ 2.2 μm

WFIRST could detect large numbers of Pop III PI SNe at z = 15 – 20, which may be their optimum redshift for detection due to Lyman-Werner UV backgrounds

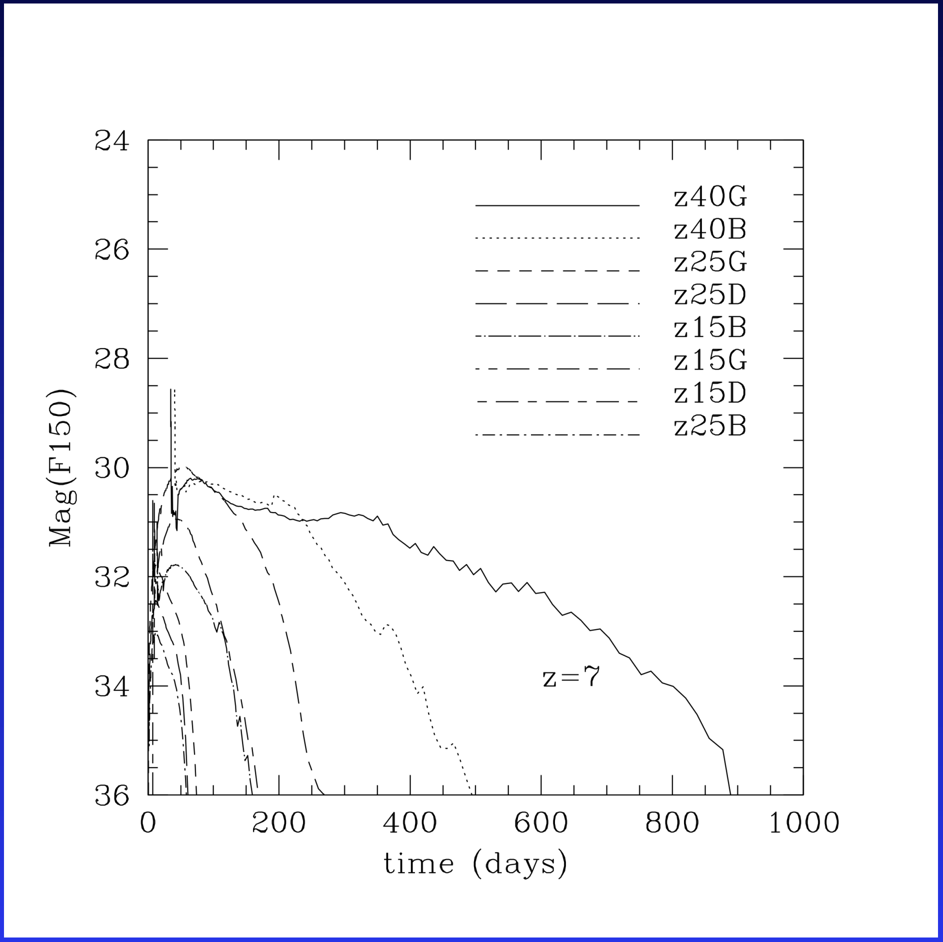
Preliminary Pop III Core-Collapse SN Light Curves



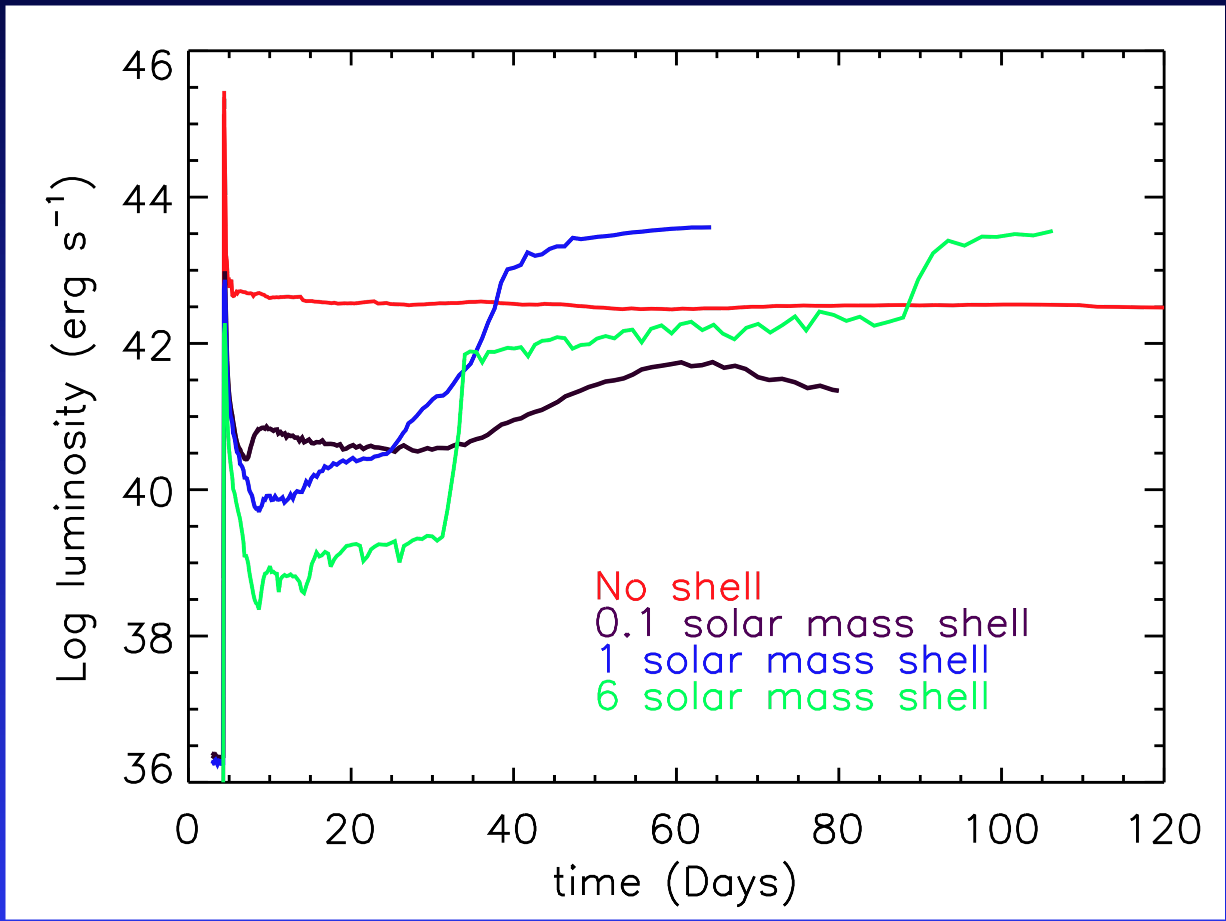




JWST NIRCam Light Curves for 15 – 40 Solar Mass Core-Collapse Supernovae

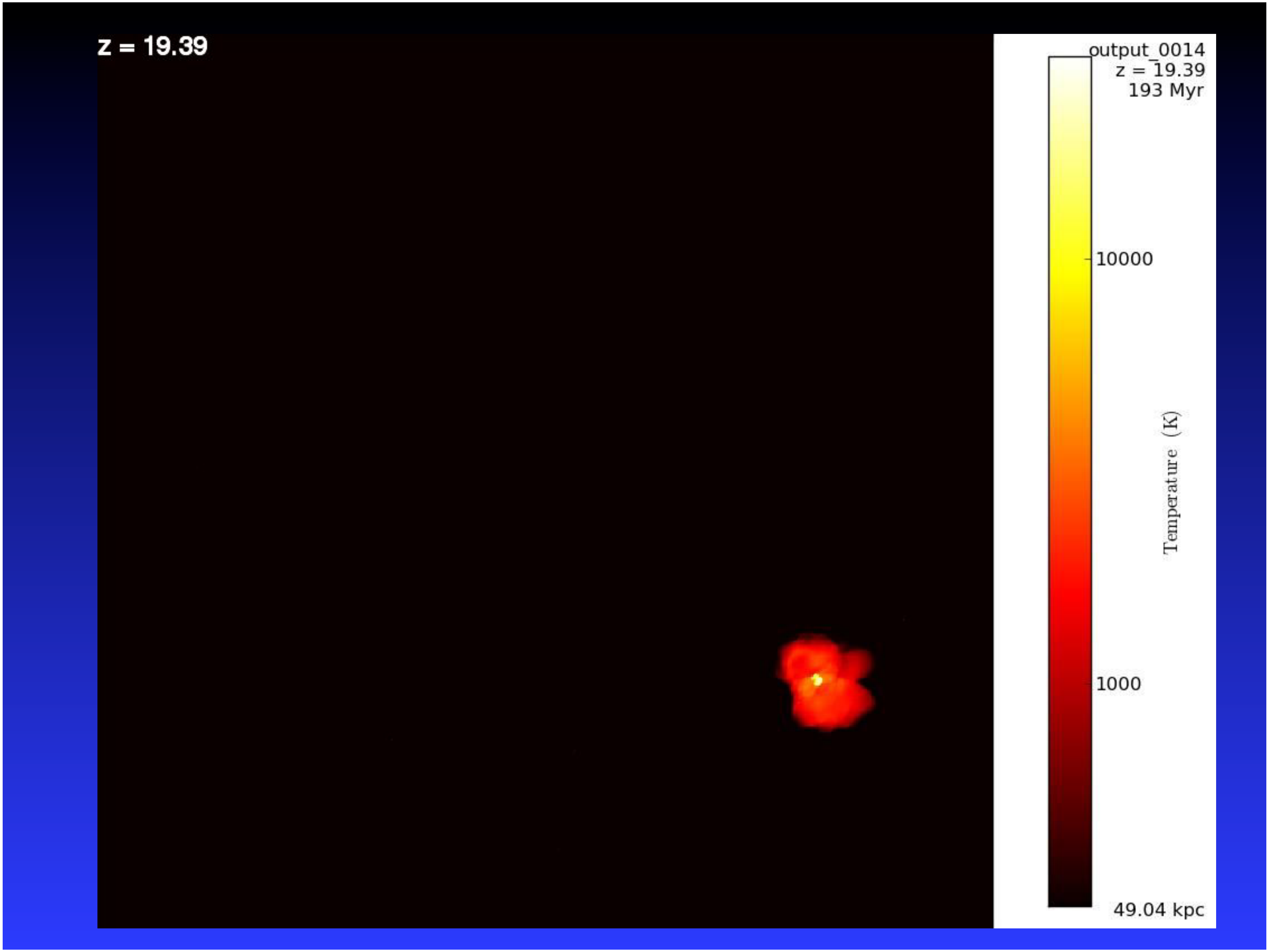


Pop III Type IIn Supernovae Light Curves



Conclusions

- JWST will see Pop III PI SNe beyond z = 30, and WFIRST will find them at z = 15 - 20
- Pop III CC SNe will be visible in the NIR only out to z ~ 7 – 10
- Pop III Type IIne and hypernovae may be visible to z ~ 10 - 15
- they will be our first direct probe of the Pop III IMF
- they will also reveal many protogalaxies that would otherwise not be detected by next generation observatories


z = 19.39
output_0014
z = 19.39
193 Myr
10000
1000
Temperature (K)
49.04 kpc