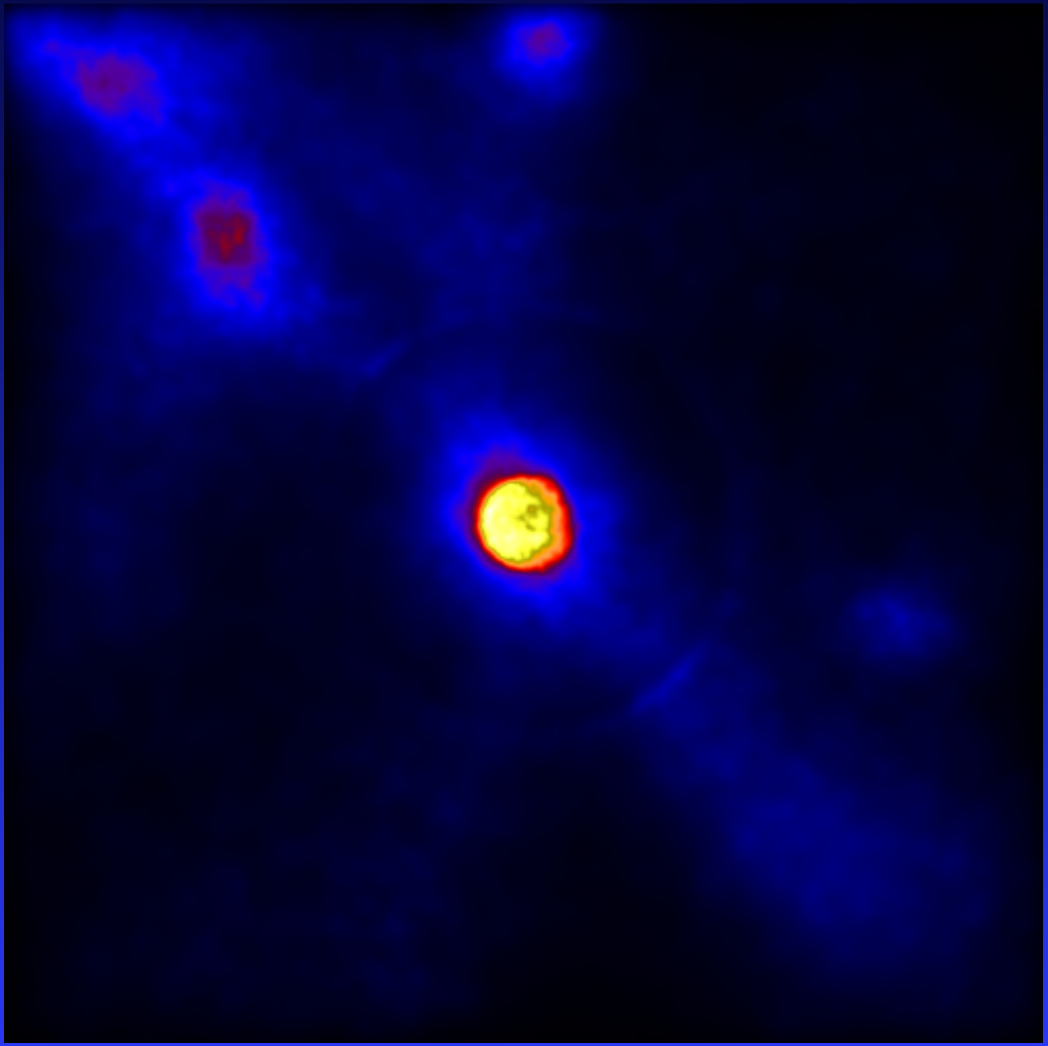
# Early Chemical Enrichment by the First Cosmic Explosions

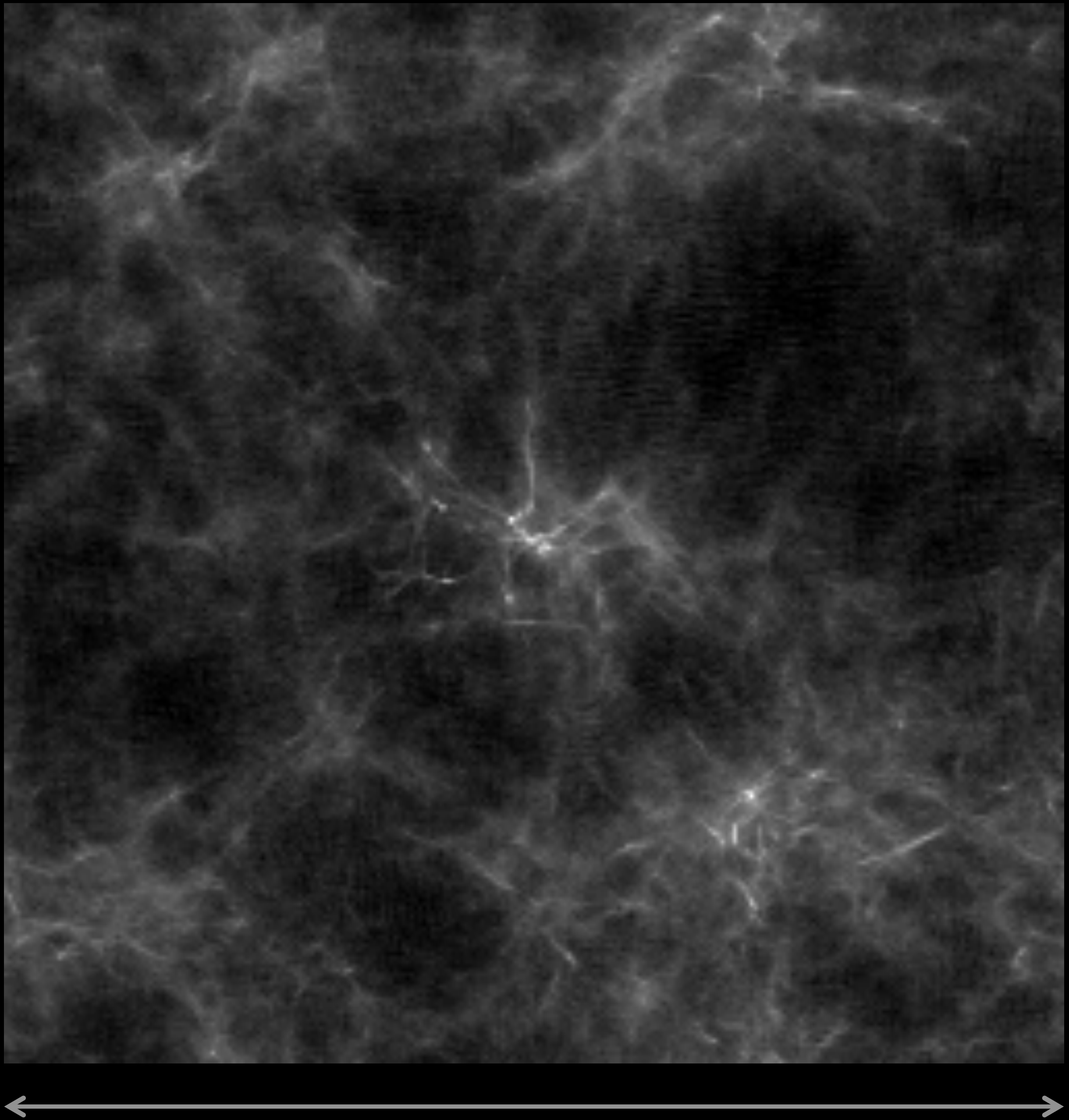


Daniel Whalen

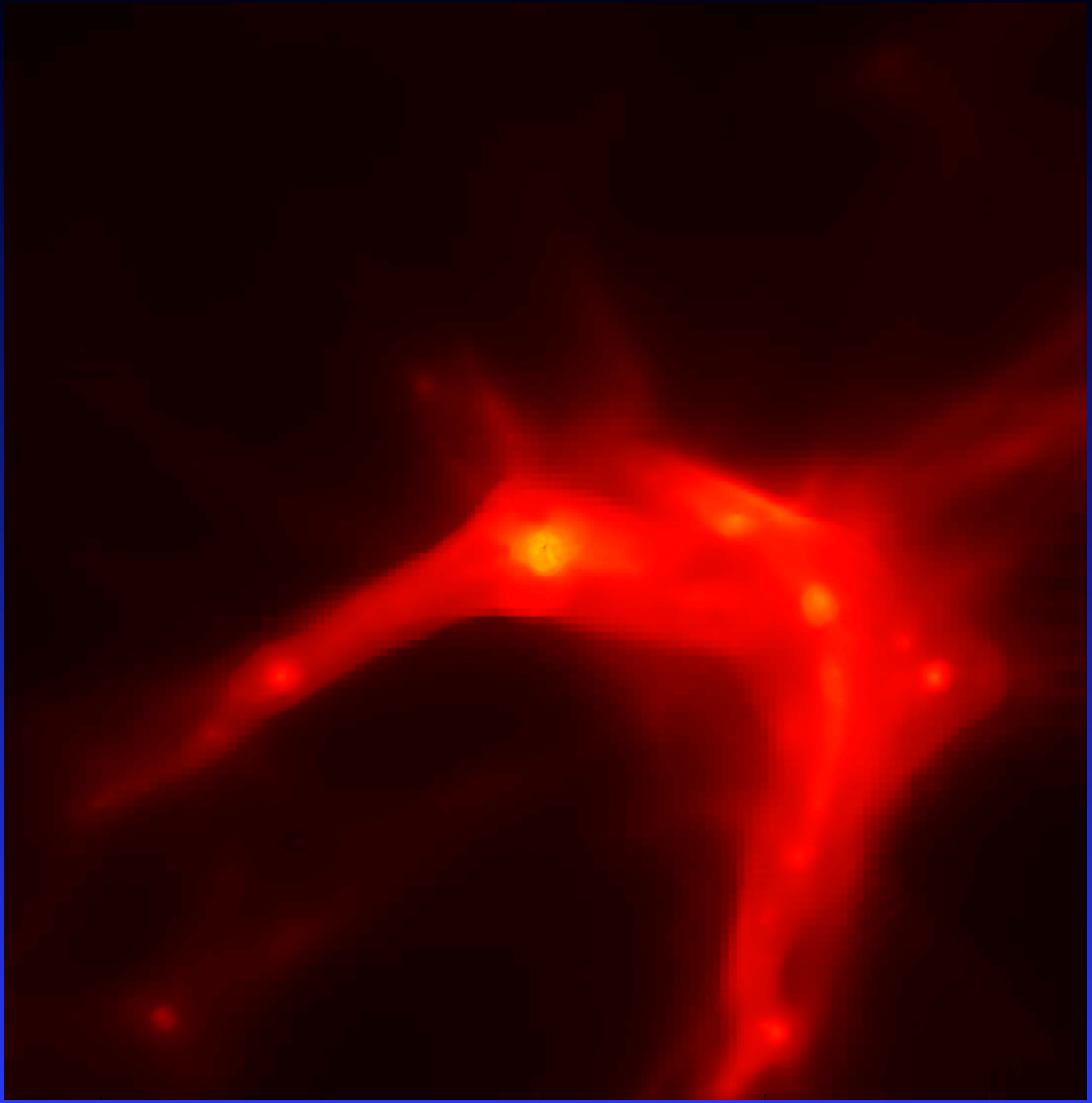
Institute for Theoretical
Astrophysics

Heidelberg University

The Universe
at Redshift 20


128 kpc comoving

# Primordial Halo at z ~ 20



# Properties of the First Stars

1999 - 2013

- thought to be very massive (25 - 500 solar masses) due to inefficient $H_2$ cooling

- form in isolation (one per halo), in binaries, or in small multiples

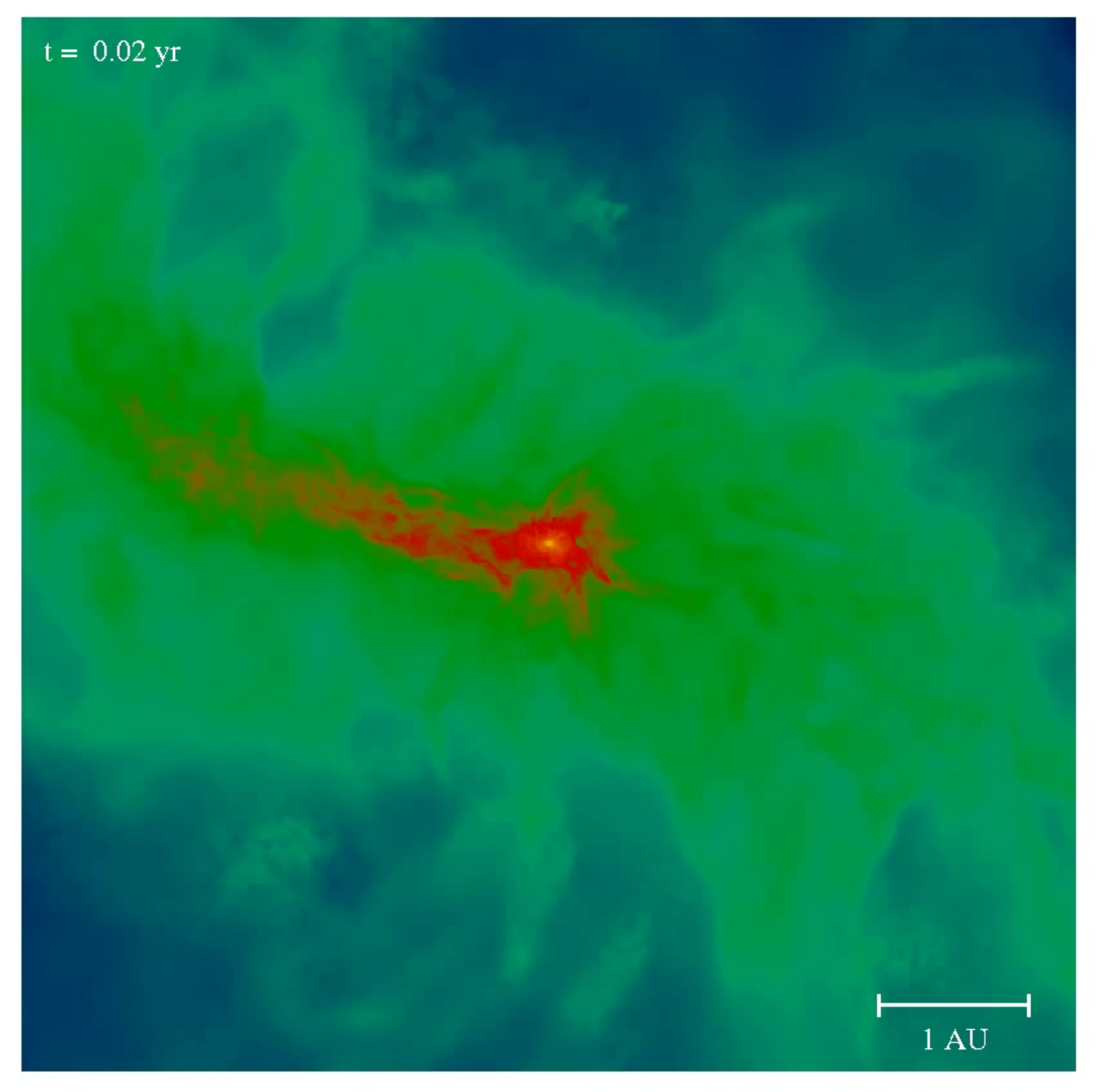
- $T_{surface}$ ~ 100,000 K

- *extremely* luminous sources of ionizing and LW photons ($> 10^{50}$ photons $s^{-1}$)

- 2 - 3 Myr lifetimes

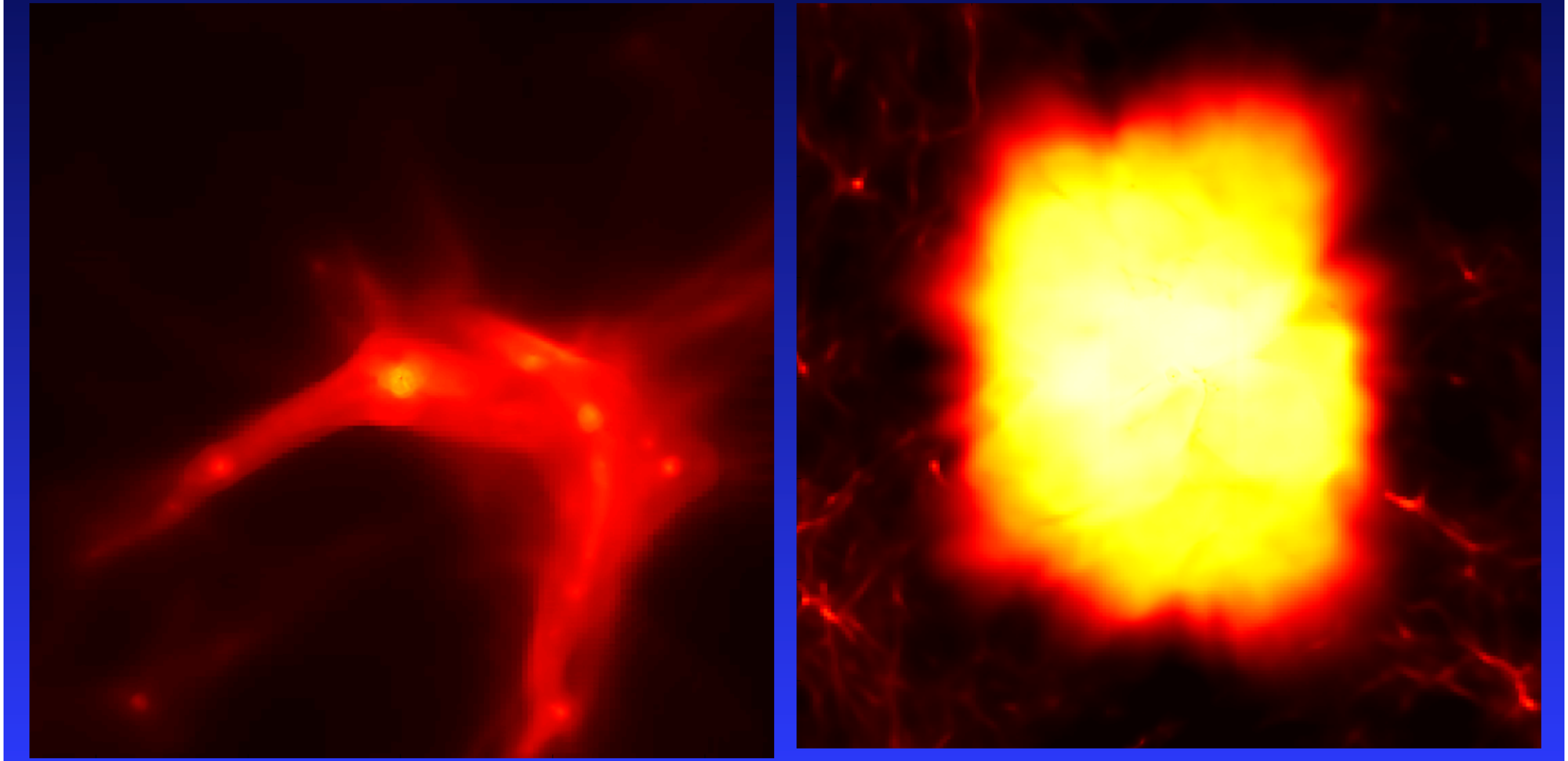
- no known mechanisms for mass loss -- no line-driven winds

# Fragmentation of Pop III Protostellar Disks

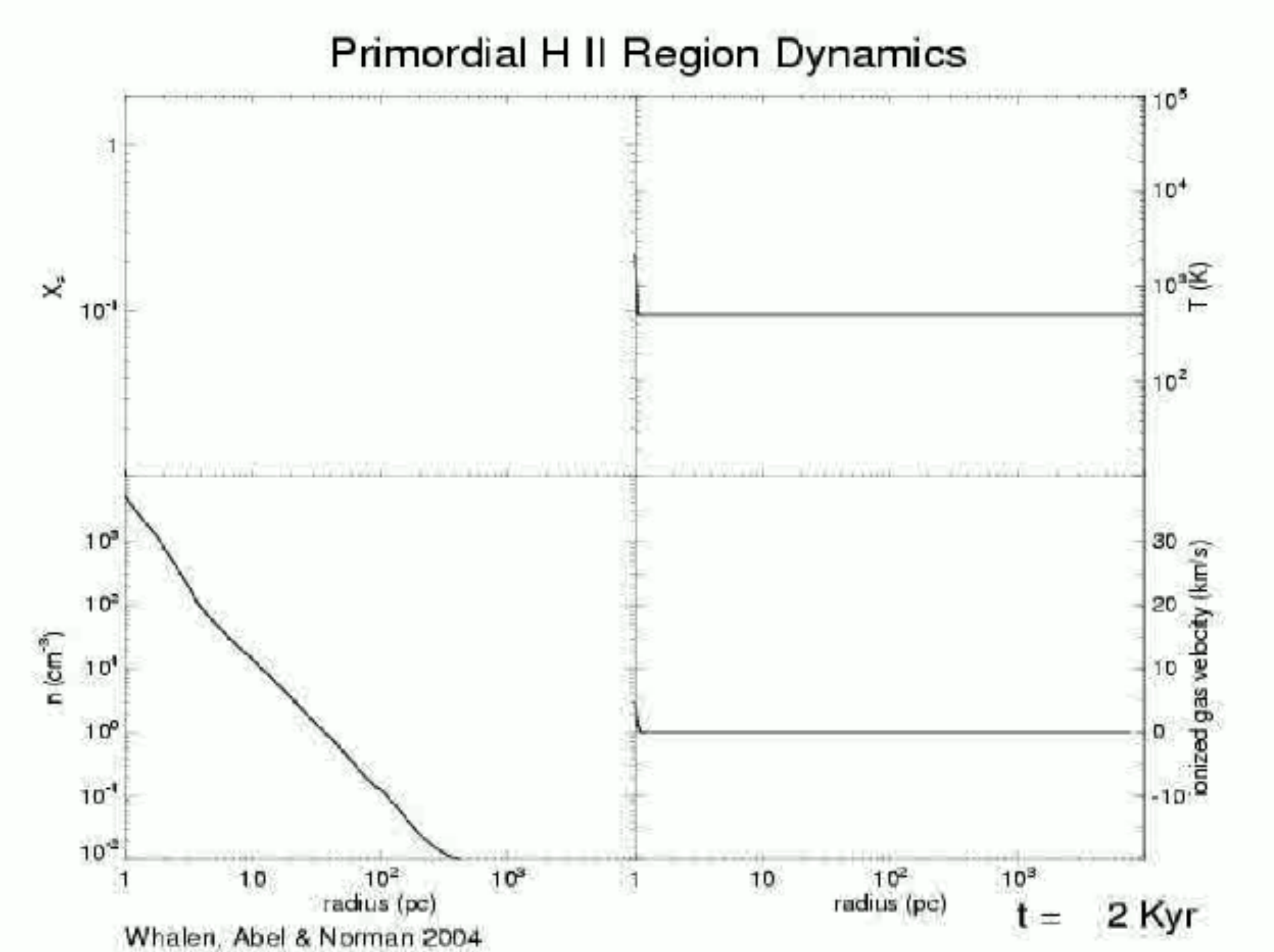


Greif et al. 2012, MNRAS, 424, 399

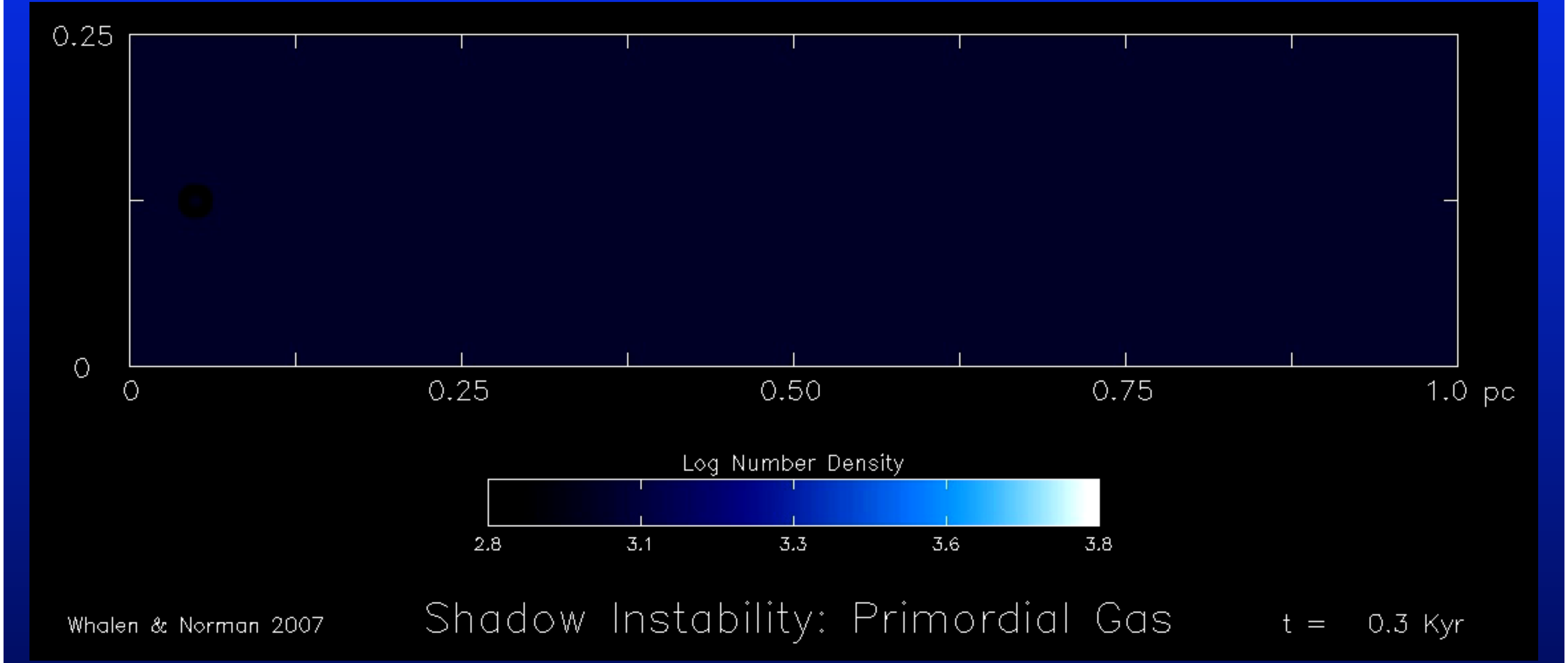
# Pop III Star H II Regions in Cosmological Flows



# Pop III Star H II Regions



Whalen, Abel & Norman 2004, ApJ, 610, 14

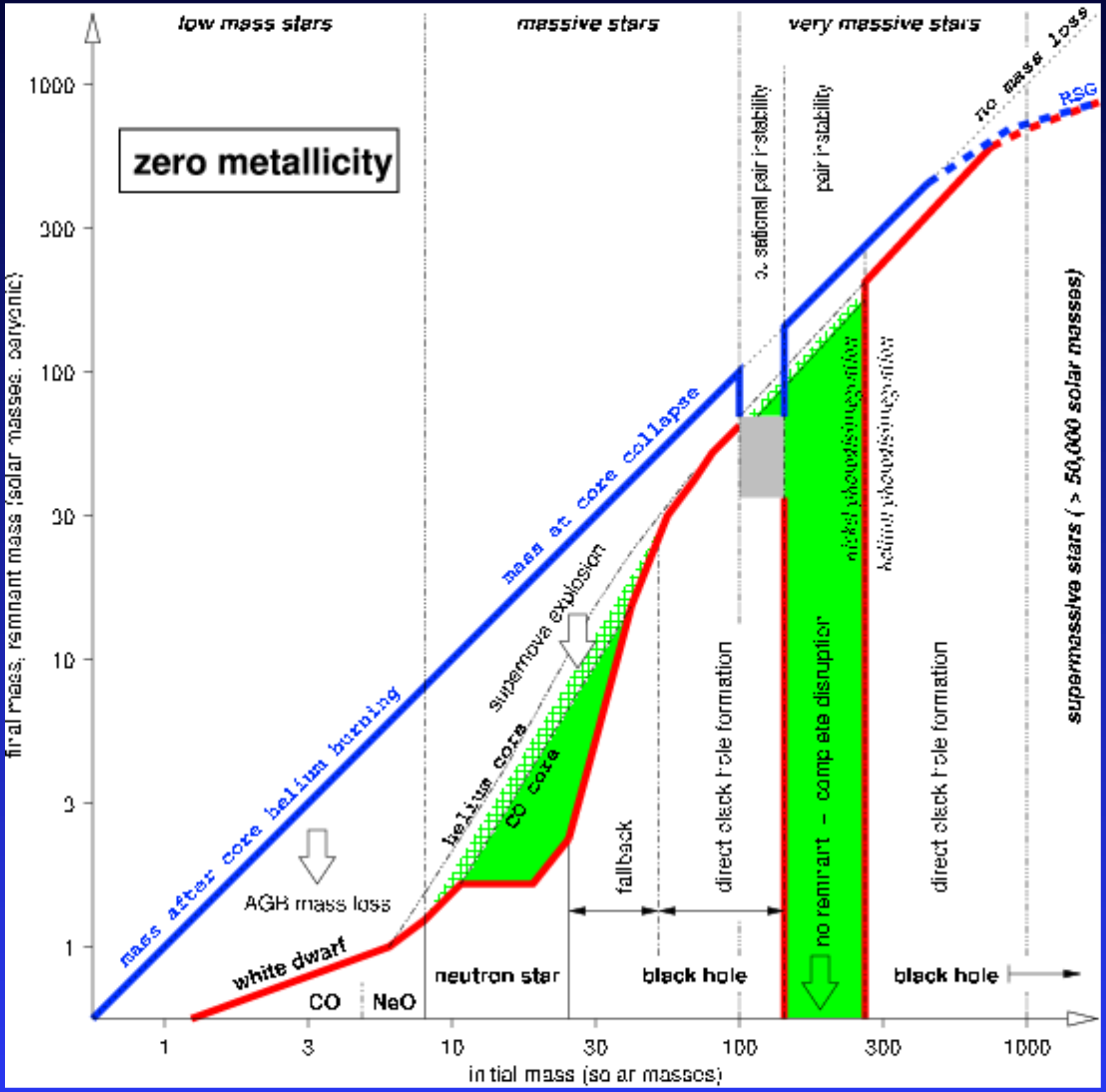


# Dynamical Instabilities in Primordial Ionization Fronts

Whalen & Norman 2006 ApJS, 162, 281
Whalen & Norman 2008a, ApJ, 672, 287
Whalen & Norman 2008b, ApJ, 673, 664

# Final Fates of the First Stars

Heger & Woosley 2002, ApJ 567, 532



# Probing 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 *directly* infer the properties of their progenitors?

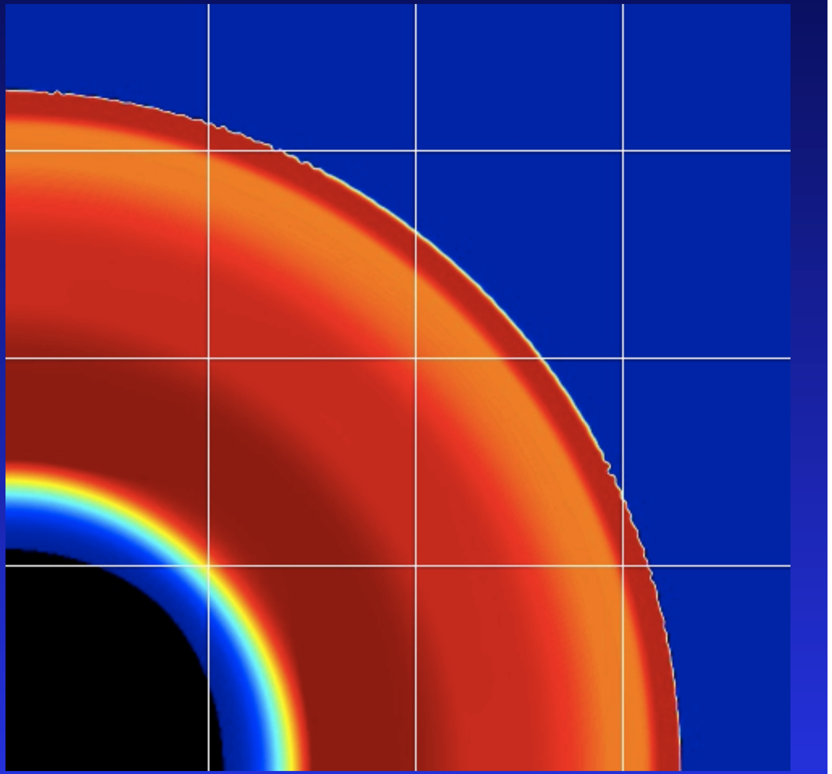
# 2D Rotating Progenitor Pop III Explosion Models in CASTRO

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

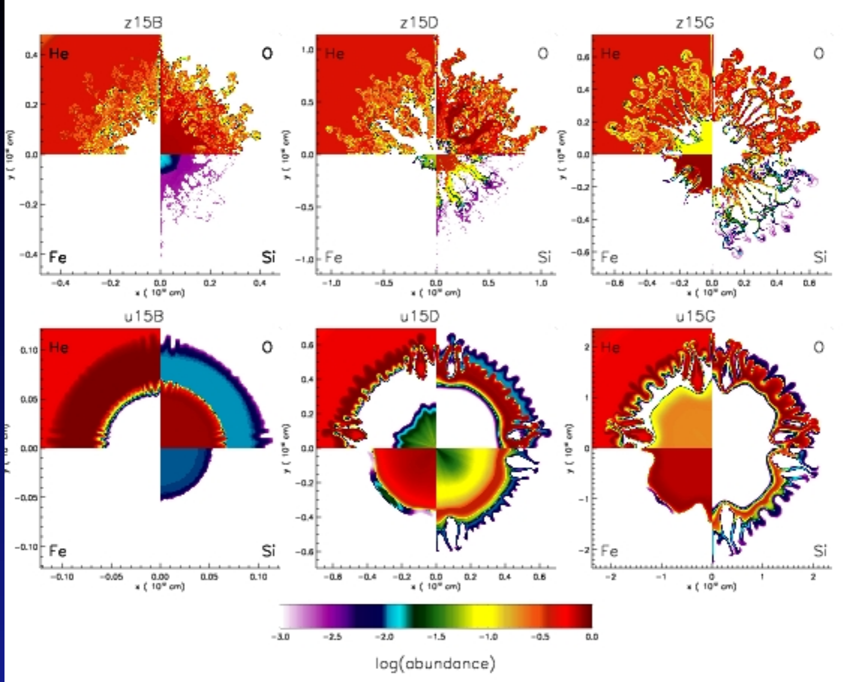
- KEPLER profiles then mapped into the new CASTRO AMR code and then evolved in 2D out to shock breakout from the star

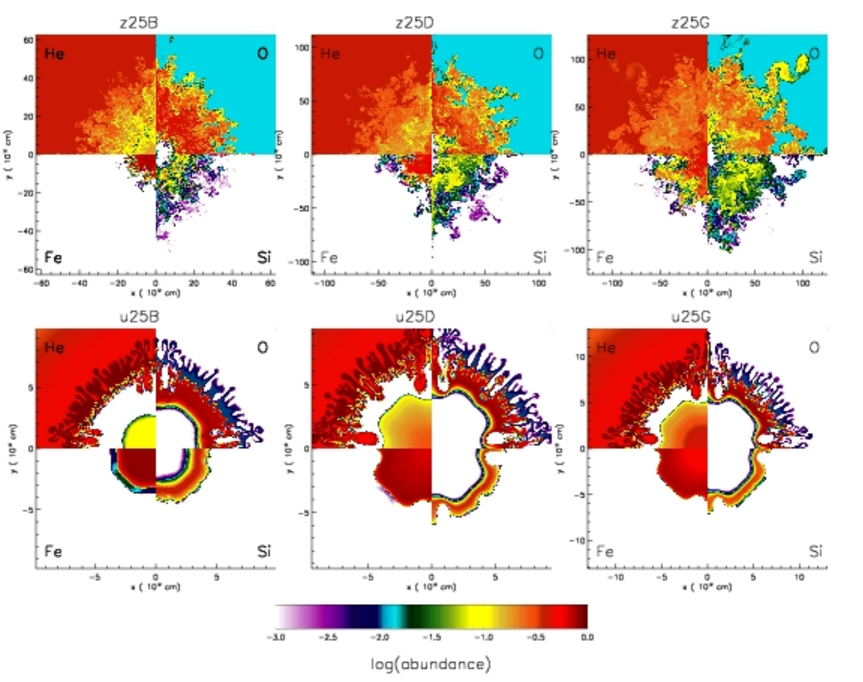
- 2 rotation rates, 3 explosion energies, 3 masses, and 2 metallicities, for a total of 36 models

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



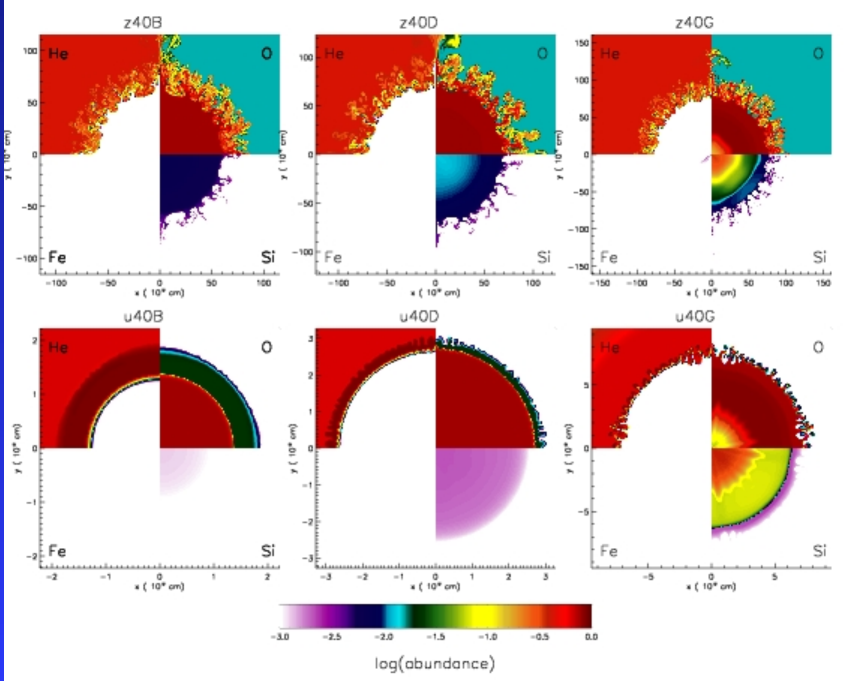
CASTRO Code (Almgren et al 2009)

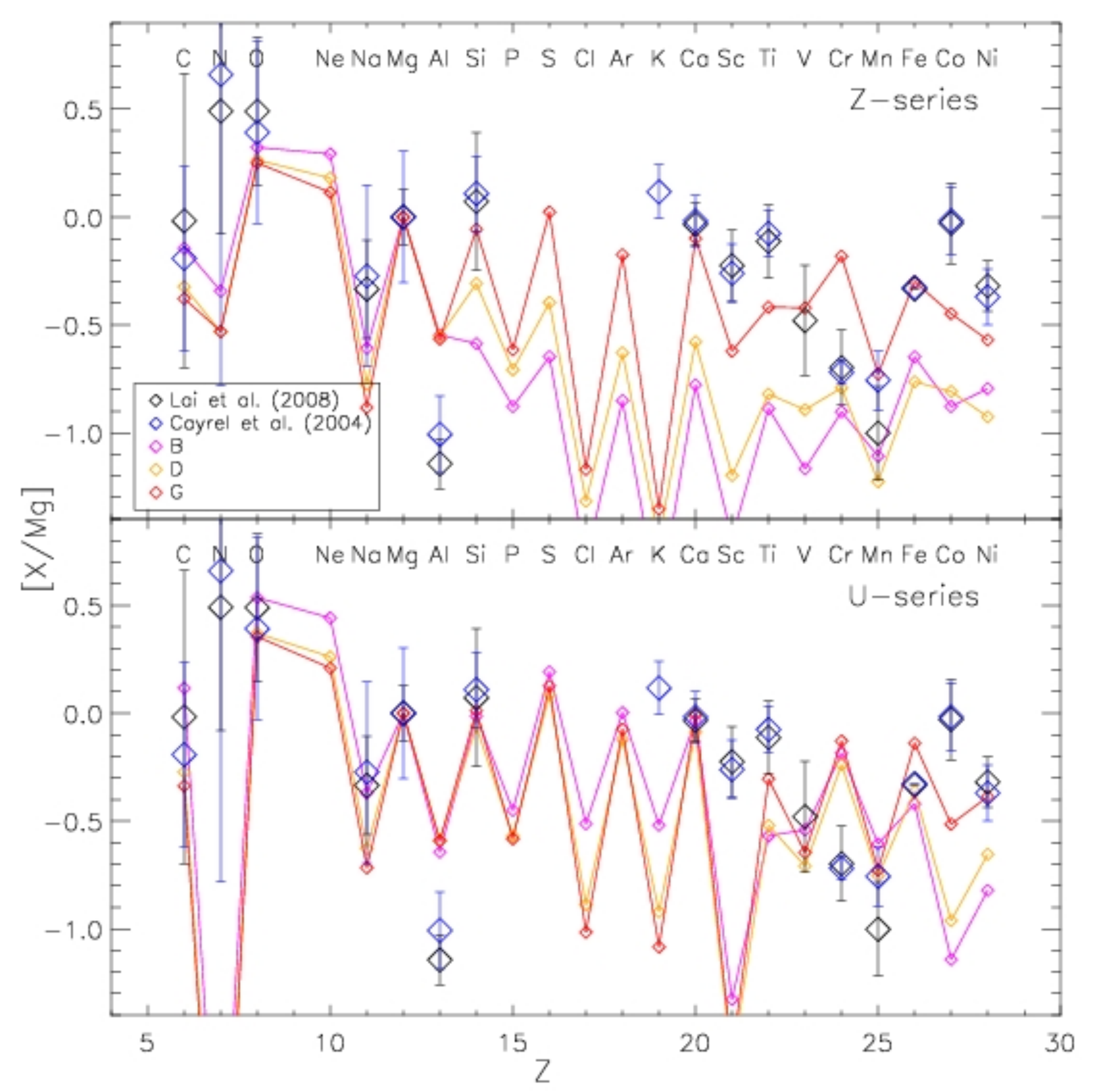




# Chemical Enrichment of the Early Cosmos: Ashes of the First Stars?

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

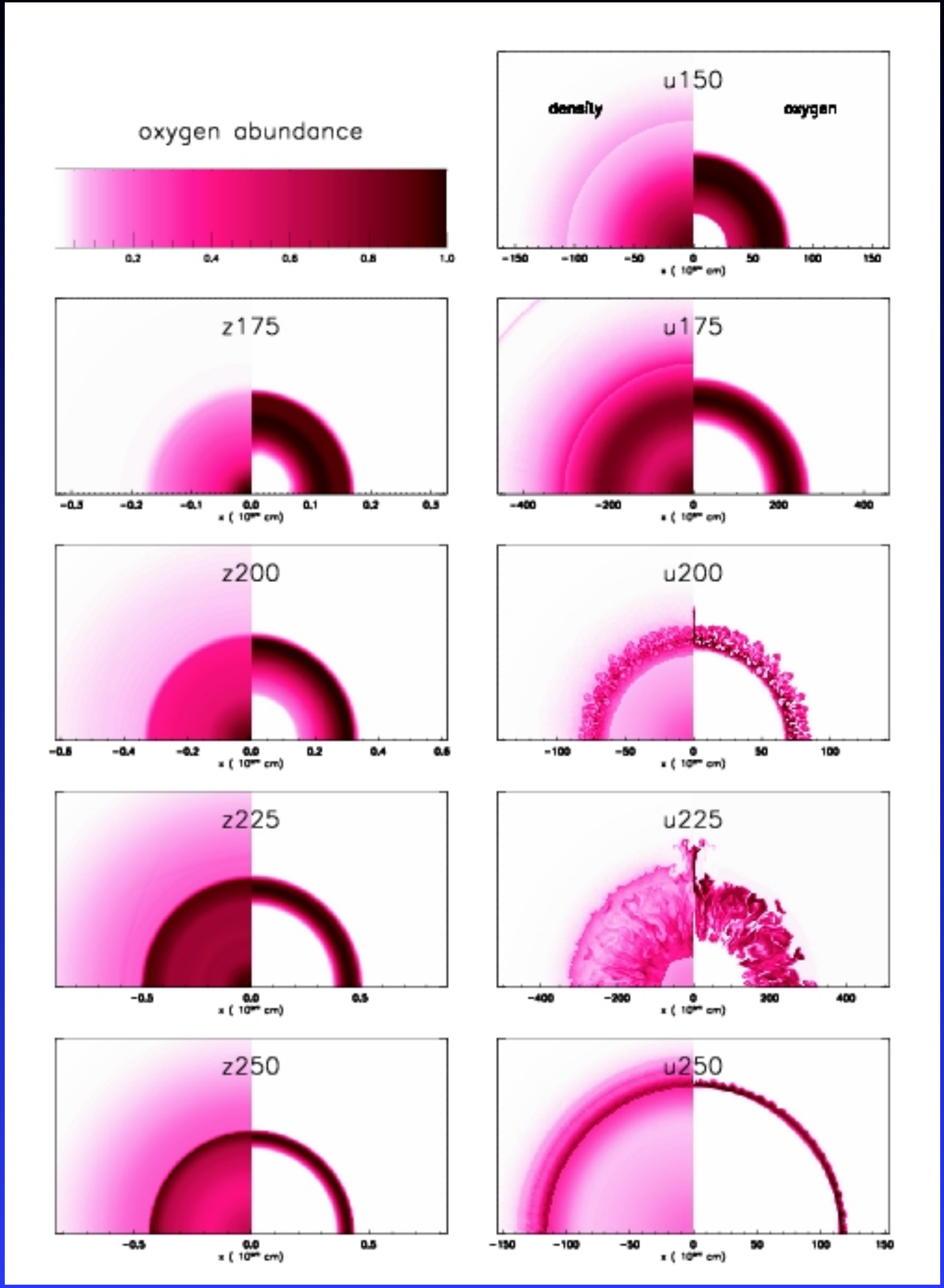




IMF-Averaged Yields and the EMP Stars

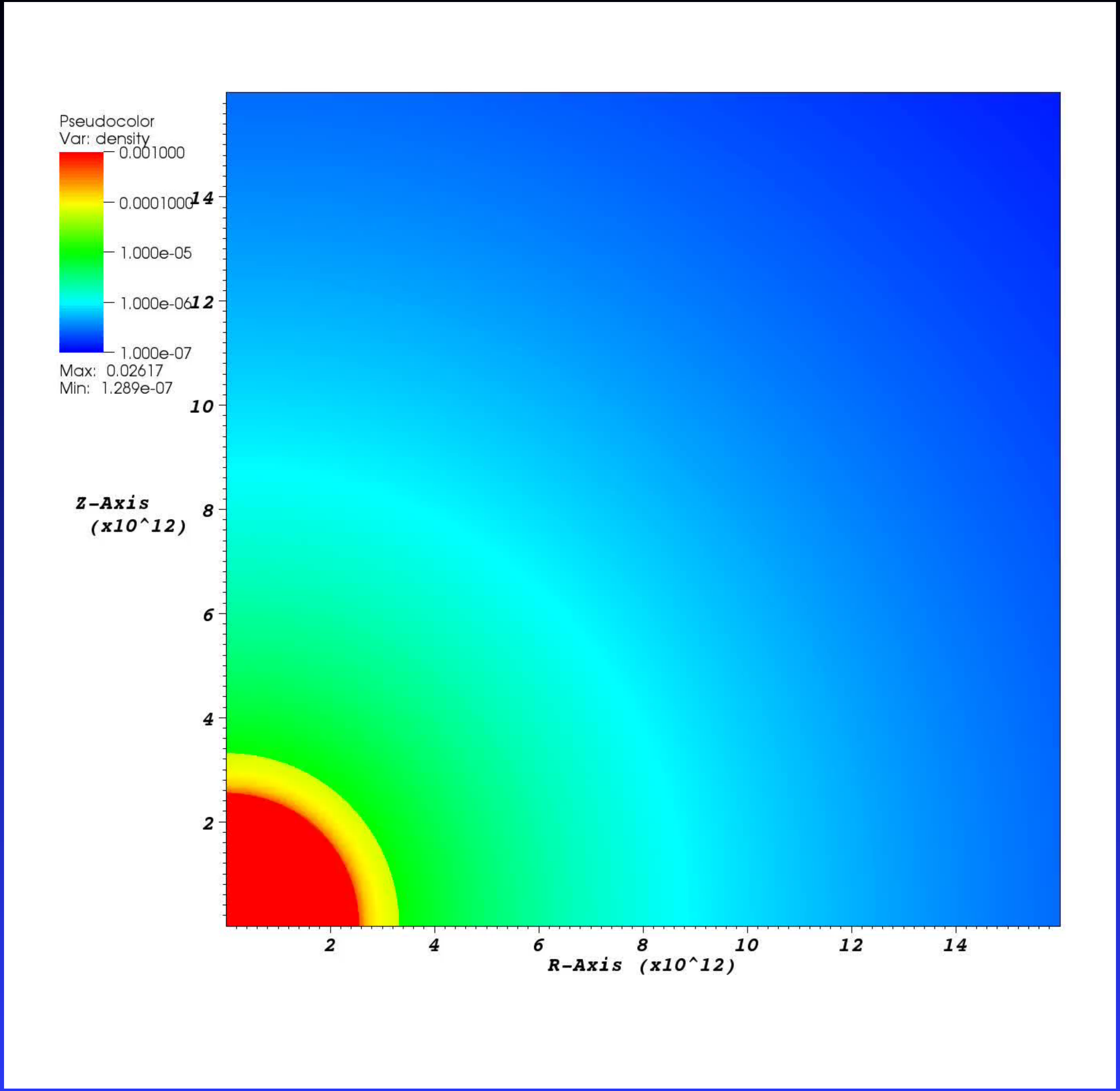
# Mixing in Pop III
# PI SNe I

Joggerst & Whalen 2011
ApJ, 728, 129



# Mixing in Pop III PI SNe II

Chen et al. 2014
ApJ, 792, 44

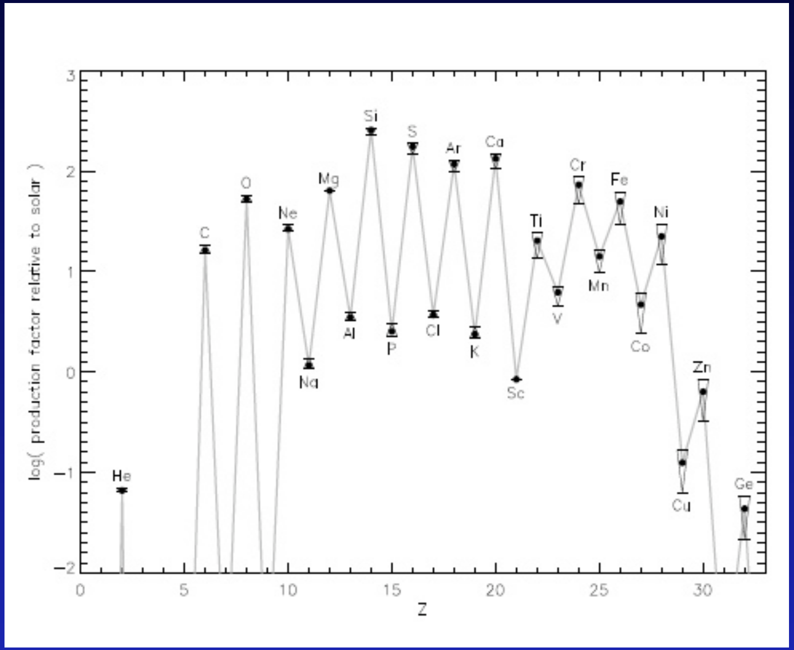


# The “Odd-Even” Effect

- original non-rotating stellar evolution models predict a strong ‘odd-even’ nucleosyntheticsignature in PI SN element production

- 18 EMP stars in the SEGUE-II catalogue have now been selected for spectroscopic followup on the suspicion that they too harbor this pattern (Ren et al. 2012, RAA, 12, 1637)

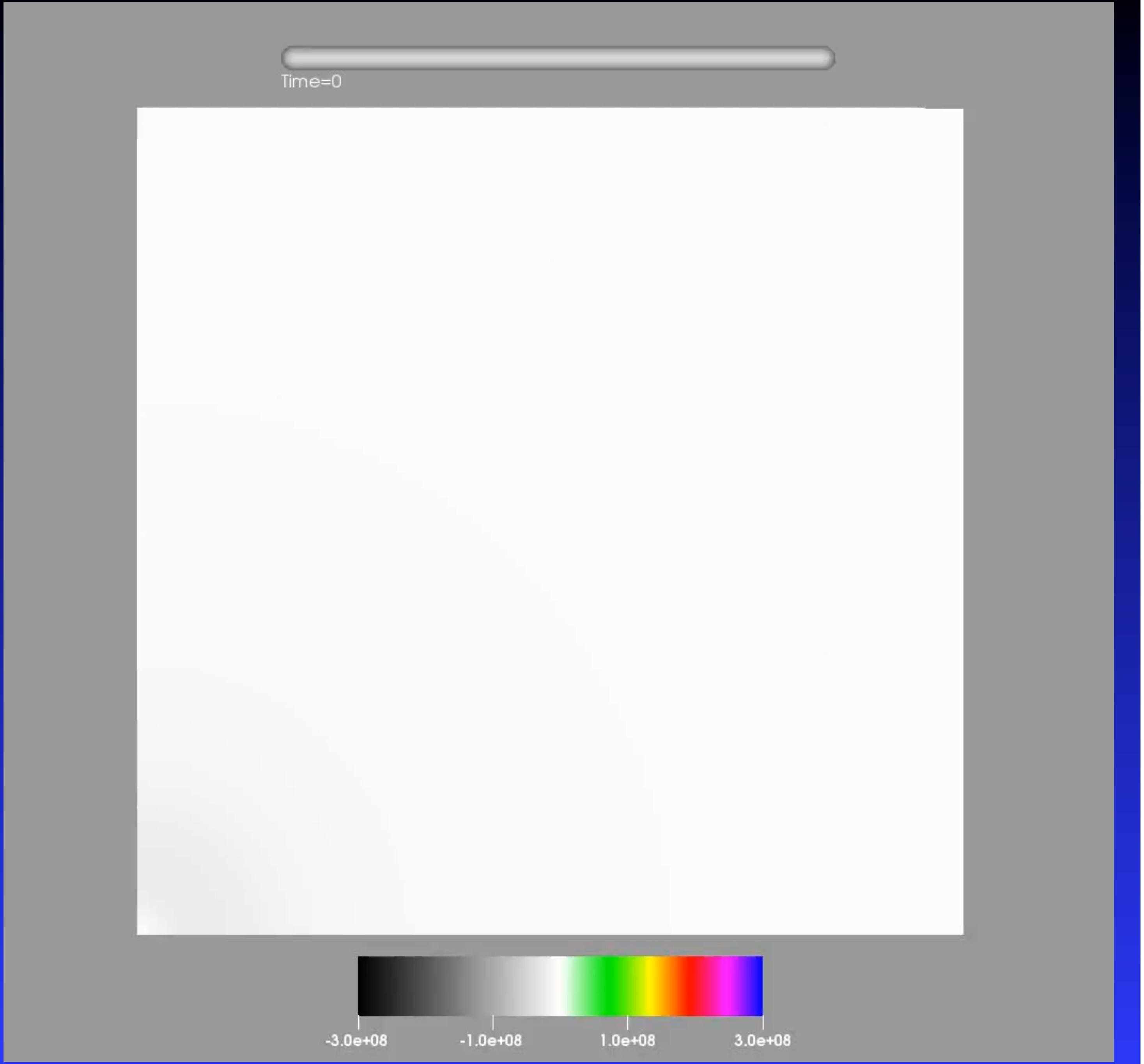
- a PI SN candidate has now been observed in the local universe (SN 2007bi, Gal-Yam et al. 2009, Nature, 462, 624)



Heger & Woosley 2002, ApJ, 567, 532

# Mixing in Pop III PPI SNe

Chen et al. 2014
ApJ, 792, 28



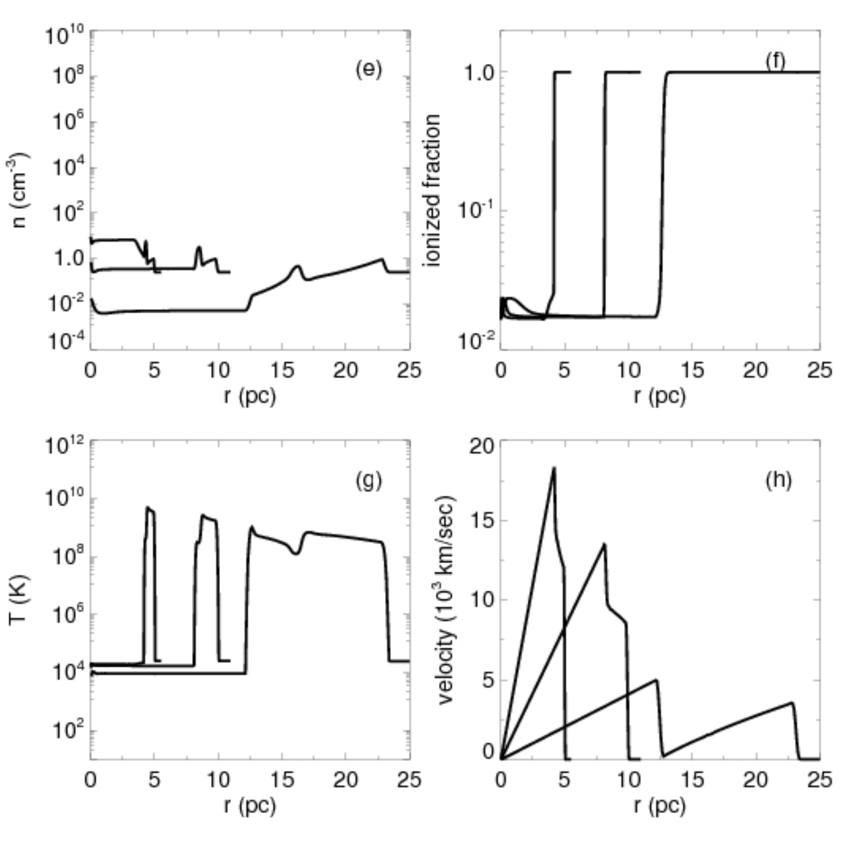
# Four Characteristic Scales of Mixing in Primordial SN Remnants

- inside the star itself, prior to shock breakout
- on scales of 10 – 20 pc in primordial H II regions
- at 100 – 200 pc, when the SN remnant collides with the H II region shell
- on scales of 1 – 2 kpc, when the SN remnant overruns nearby halos

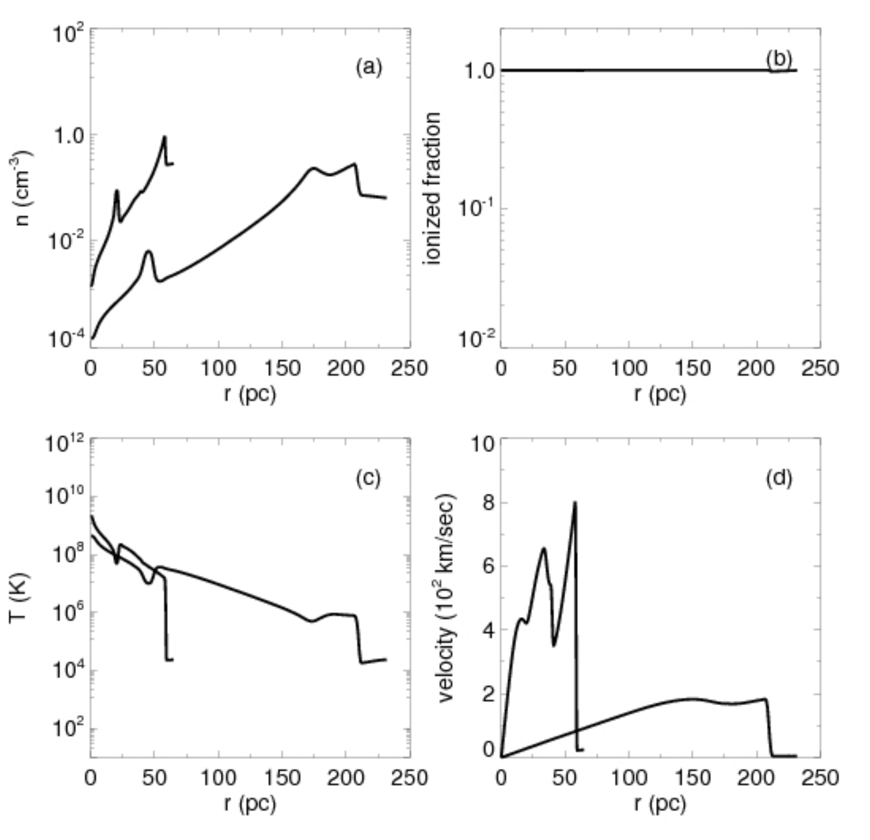
# Primordial SN Remnants in Relic H II Regions

Whalen et al. 2008 ApJ, 682, 49

## Reverse Shock

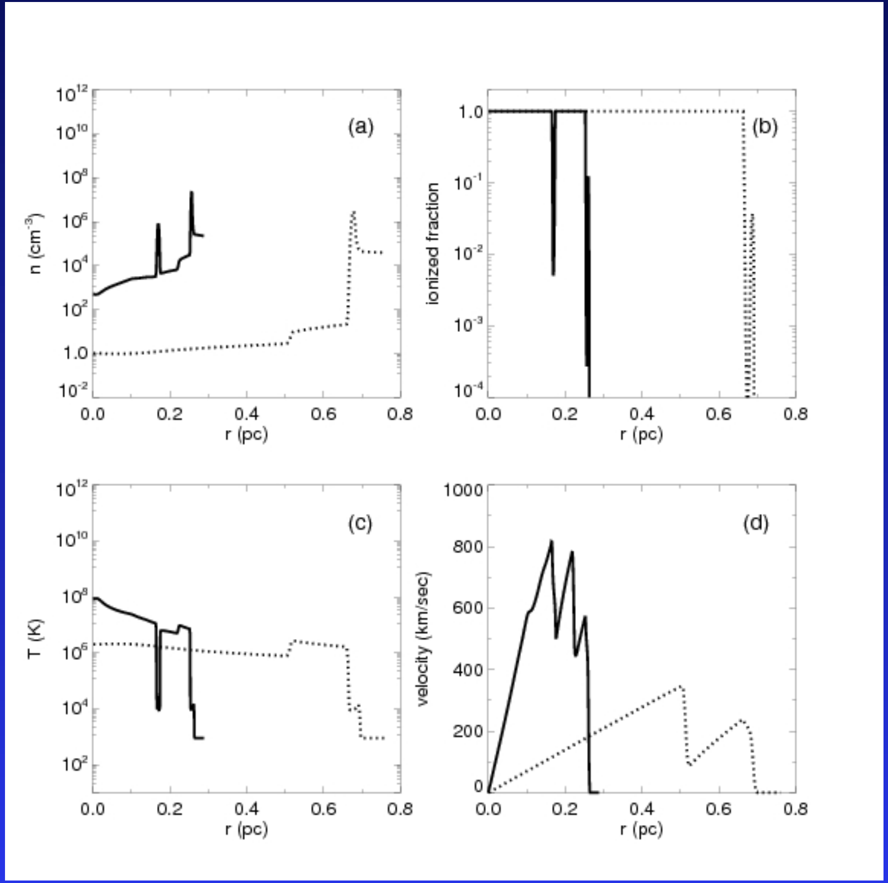


## Collision with the Shell: Fragmentation?

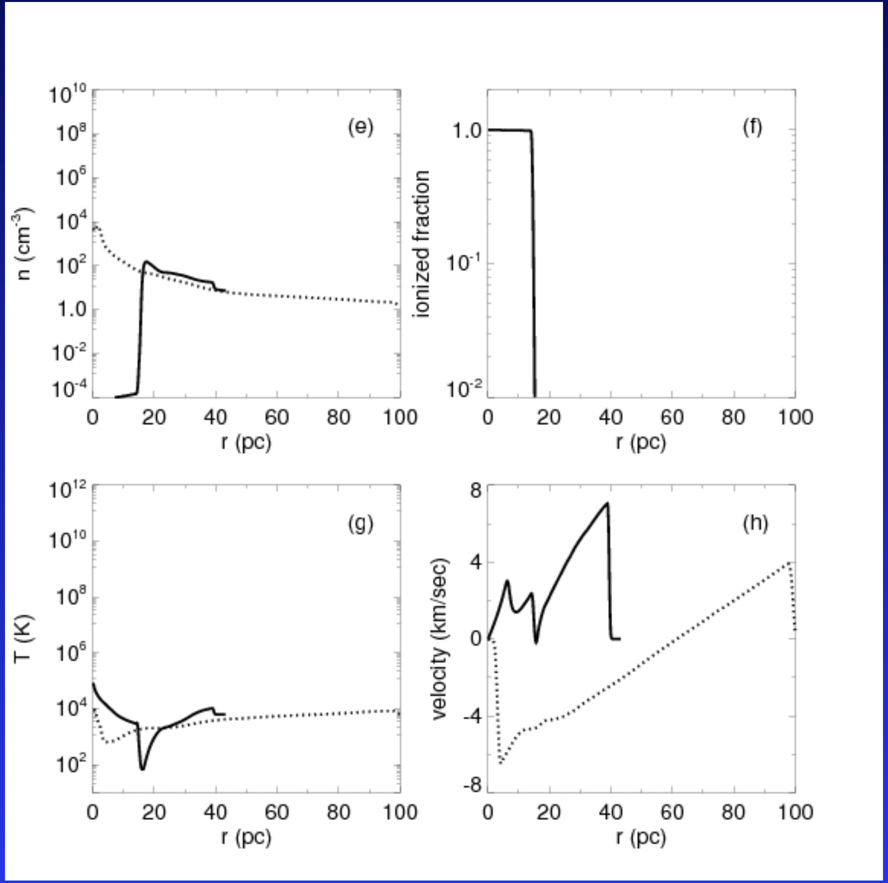


# Explosions in Neutral Halos:  Containment

## Late Radiative Phase

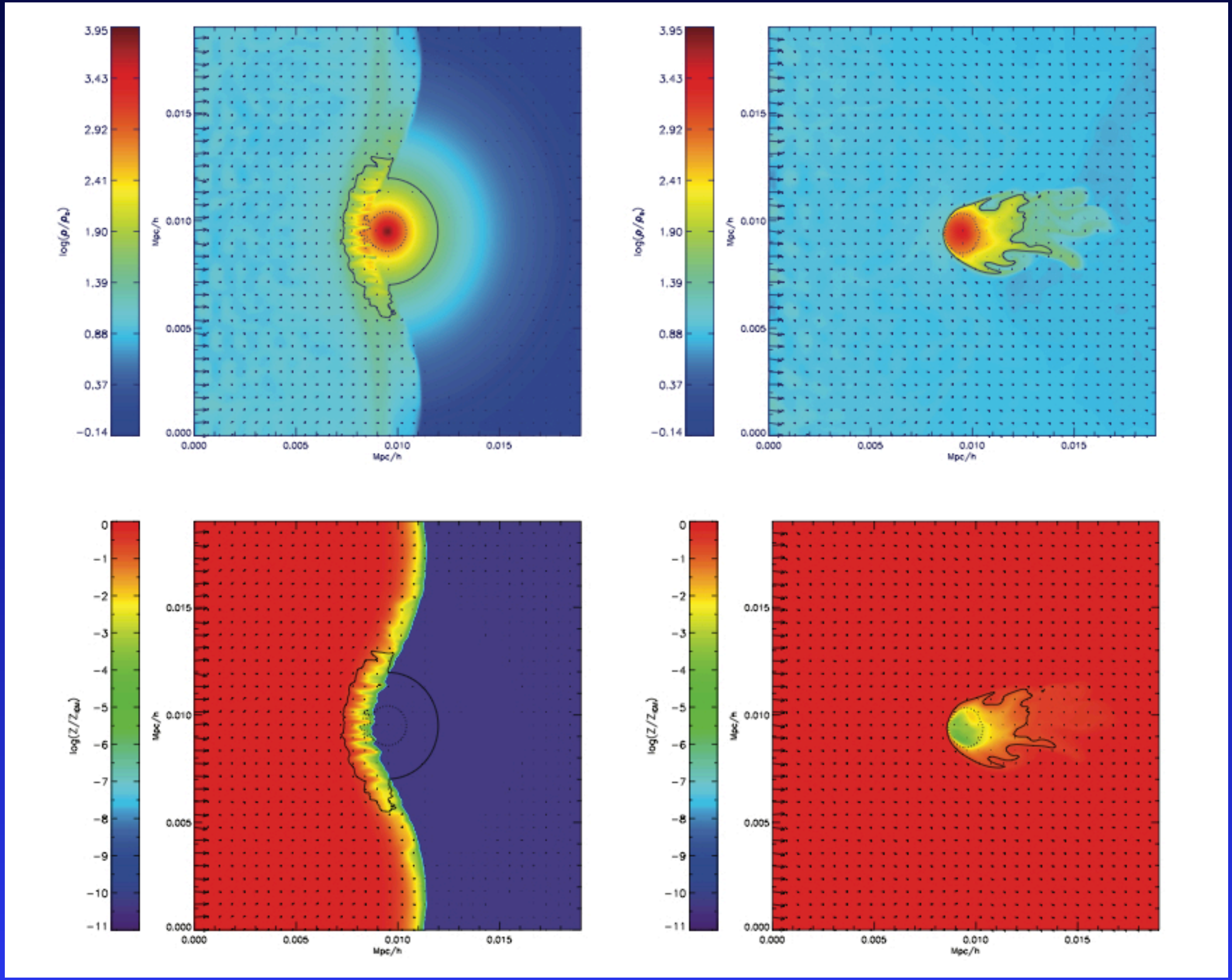


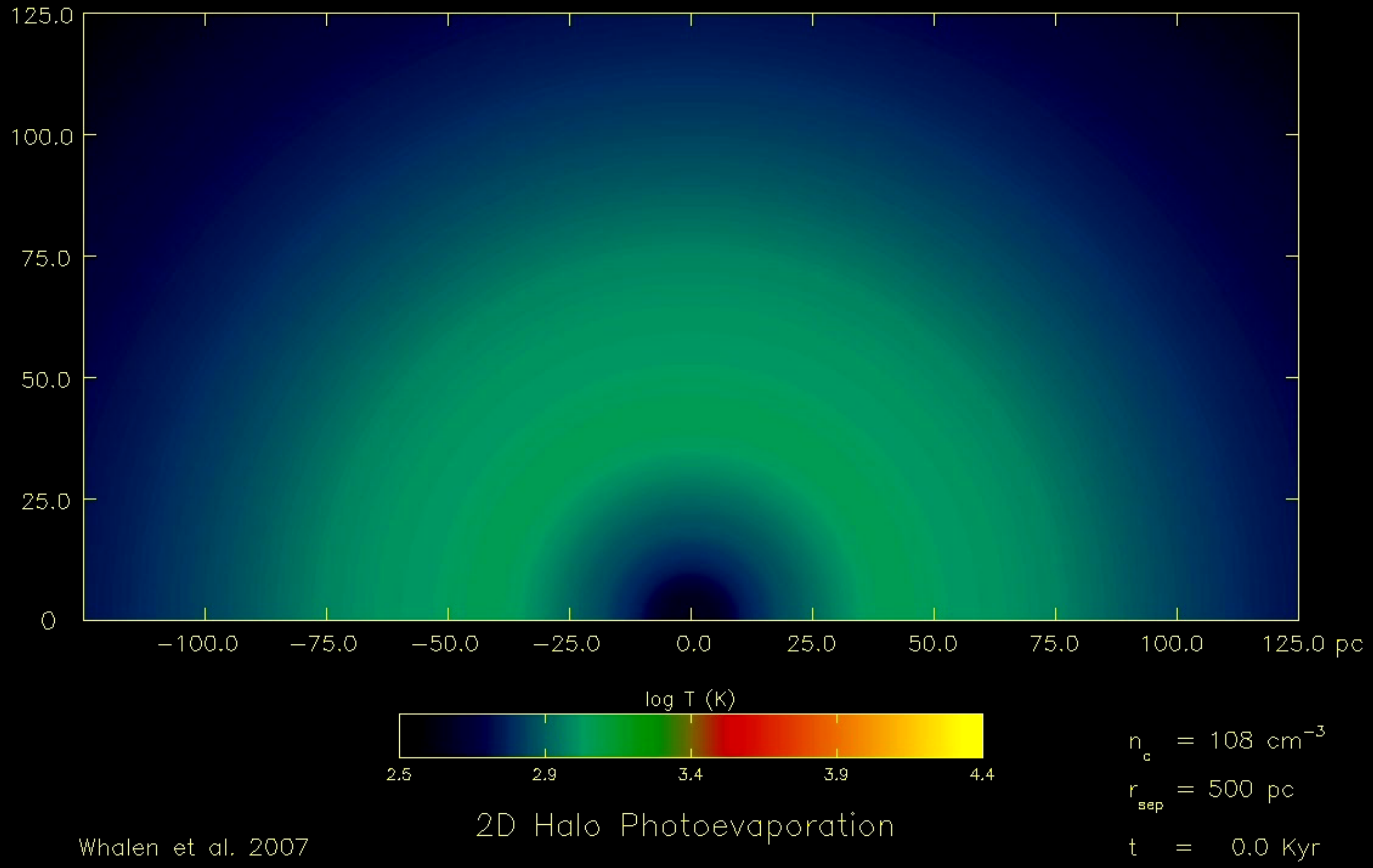
## Fallback



# Chemical Enrichment of Neighbor Halos

Cen & Riquelme
2008, ApJ, 674, 644



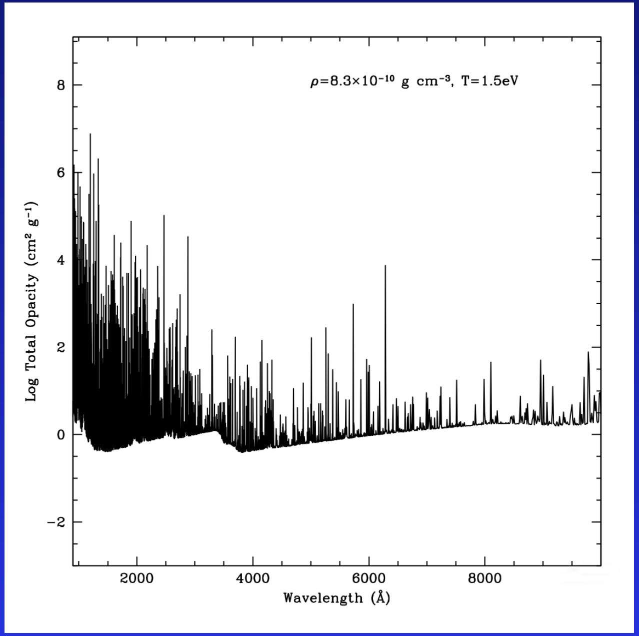


Whalen et al. 2008 ApJ, 679, 925
Whalen et al. 2010 ApJ, 712, 101

# Radiation Adaptive Grid Eulerian (RAGE)

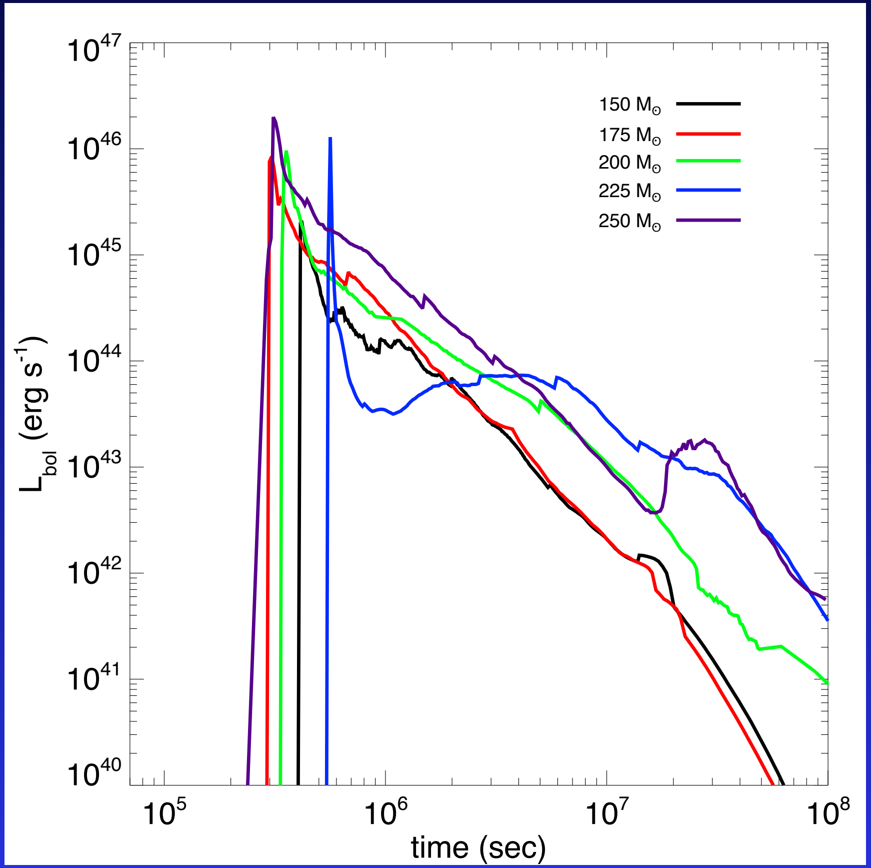
Frey, Even, Whalen et al. 2013 ApJS, 204, 16

- 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

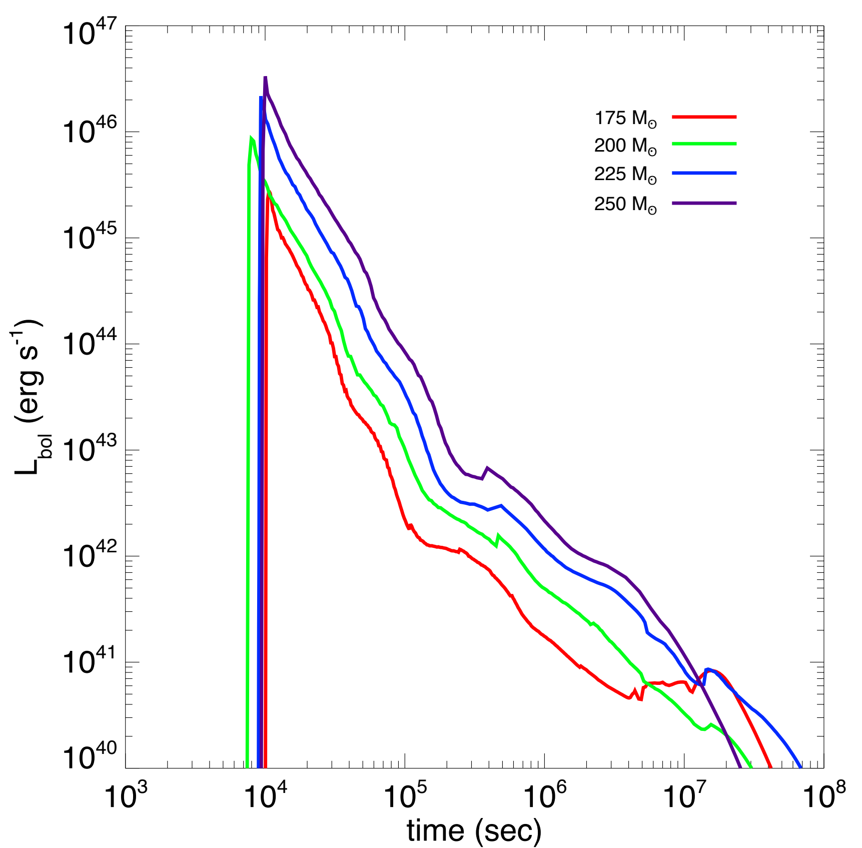


# Pop III PI SN Light Curves

Whalen et al. 2013, ApJ, 762, L6
Whalen et al. 2013, ApJ, 777, 110

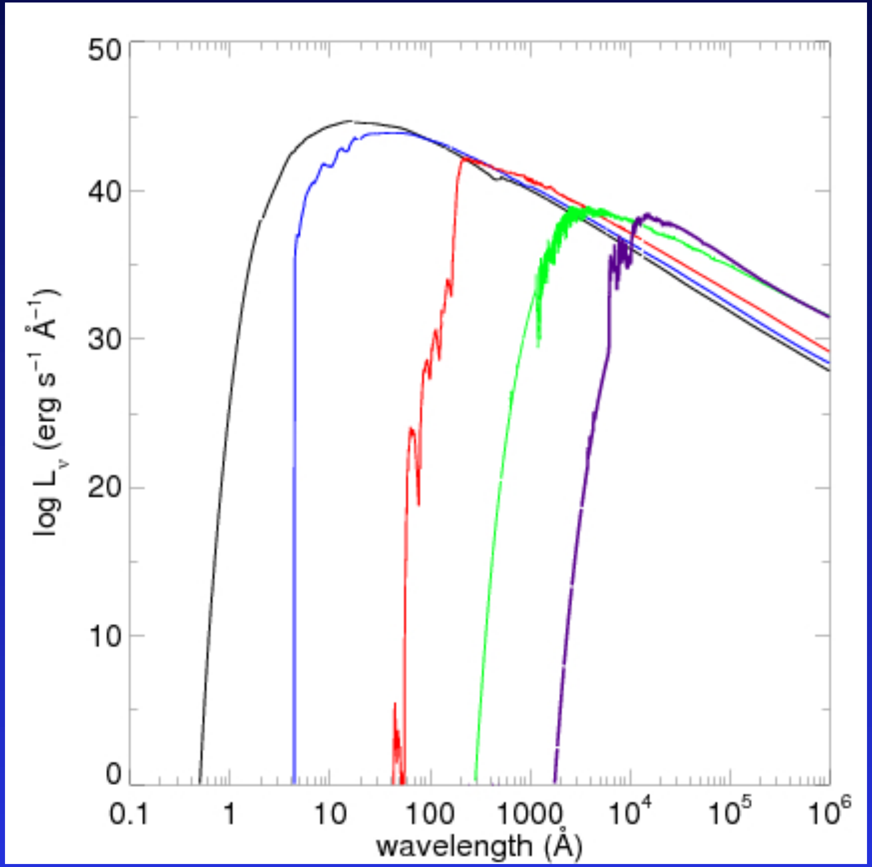


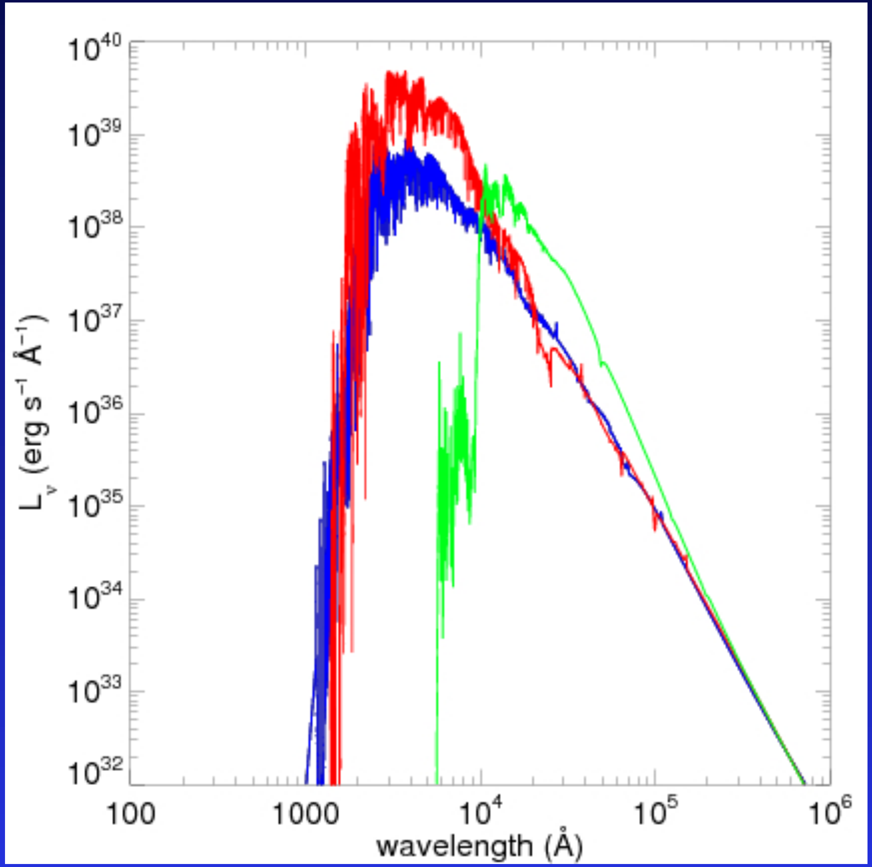
u-series
(red hypergiants)



z-series
(blue compact giants)

# Spectral Evolution: z250



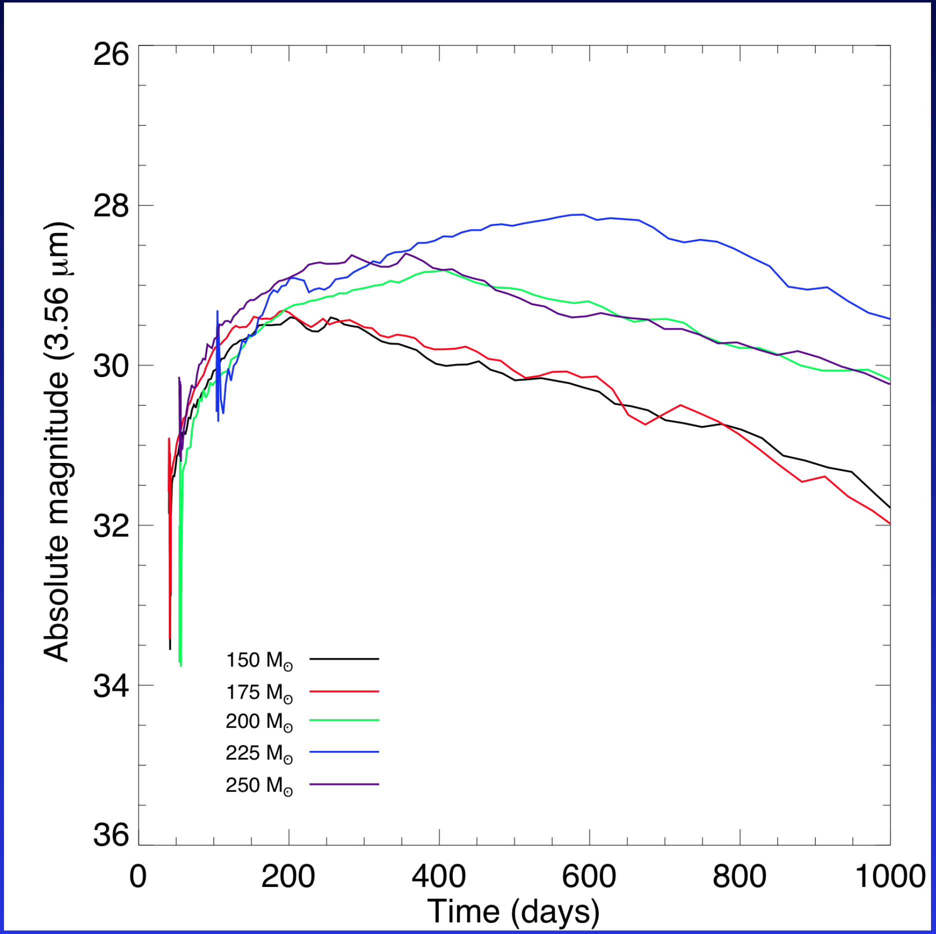


# JWST NIRCam Light Curves at z = 30

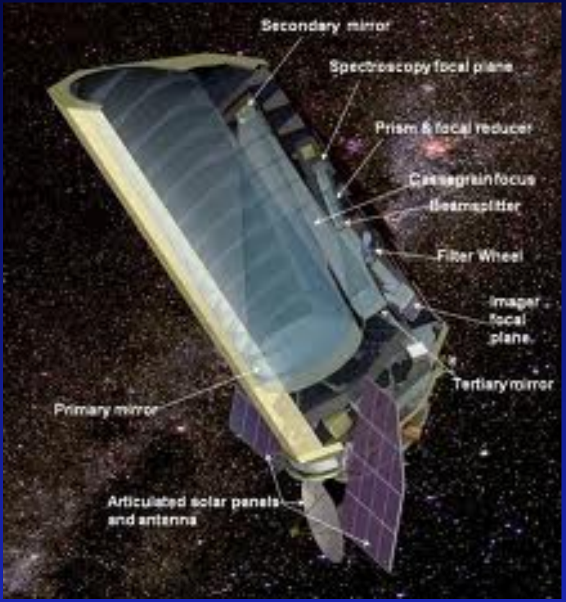
- NIRCam detection threshold is absolute magnitude 32 for deep surveys

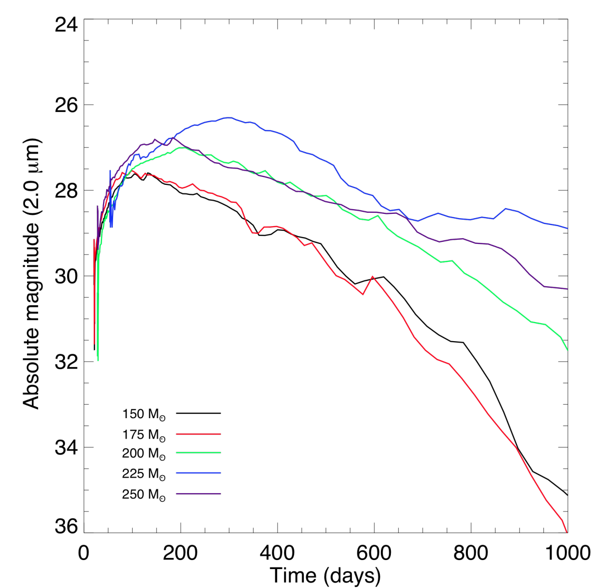
- PI SNe will be visible to JWST beyond z = 30 and will even be able to perform spectrometry on them

- 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. 2012, ApJ, 755, 72)

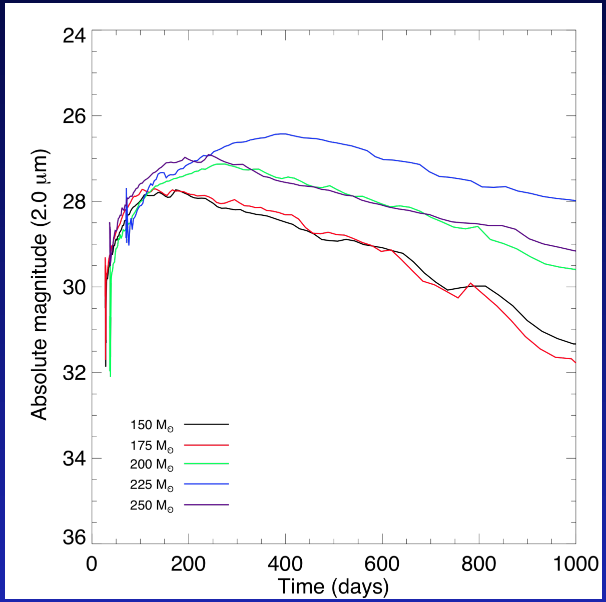


# WFIRST
Wide-Field Infrared Survey Telescope





z = 15



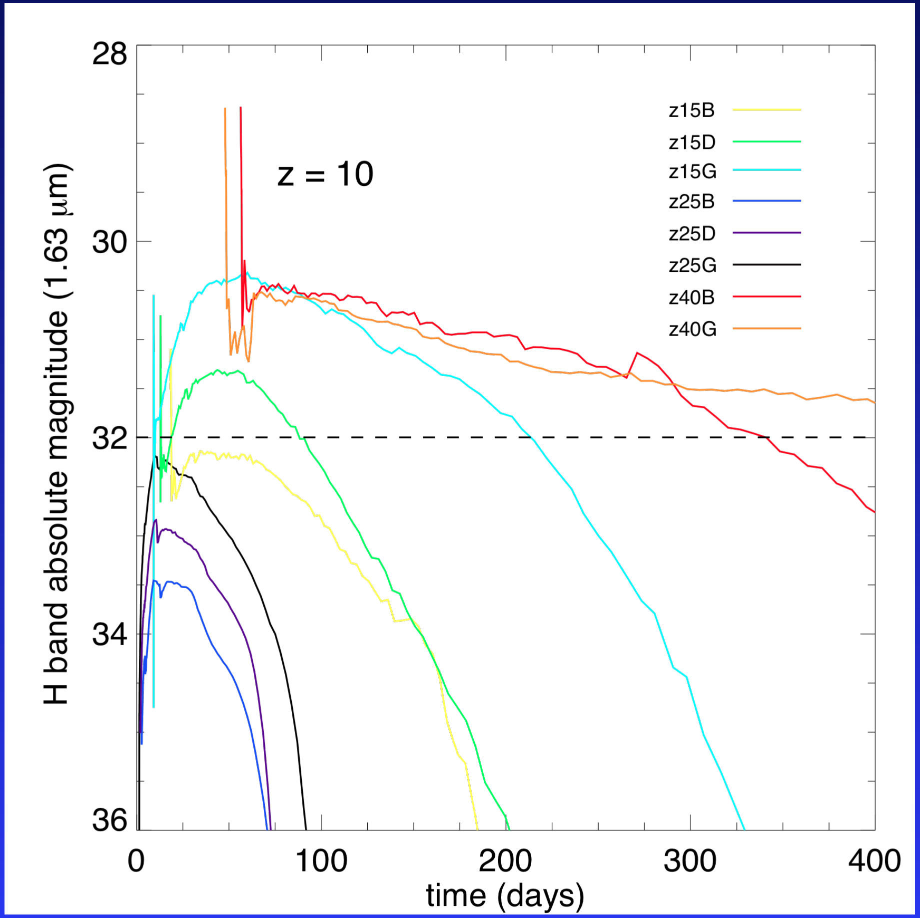
z = 20

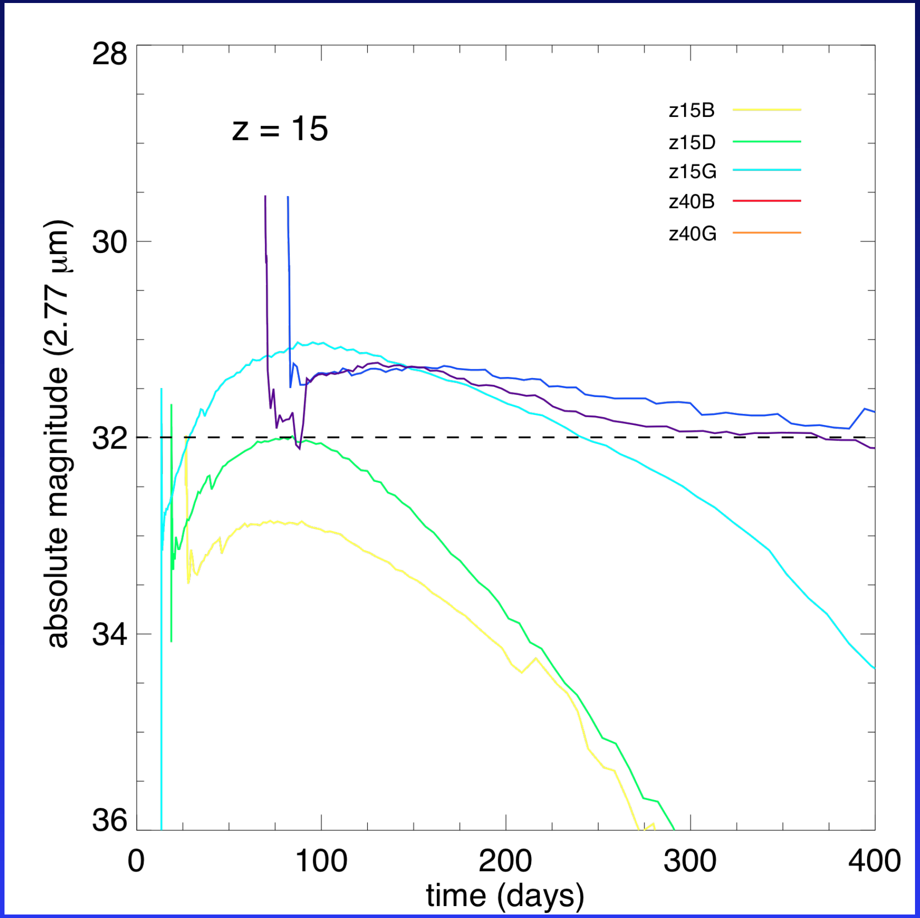
- all sky NIR survey mission
- proposed sensitivity of AB magnitude 27 @ 2.2 μm

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

# Pop III Core-Collapse NIRCam Light Curves

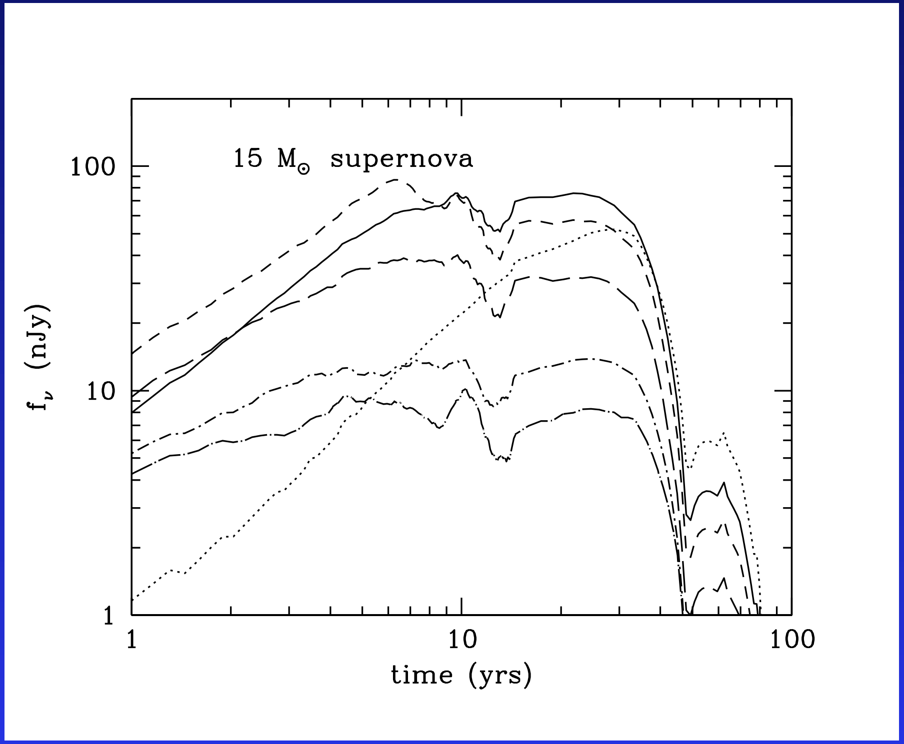
Whalen et al. 2013, ApJ, 768, 95

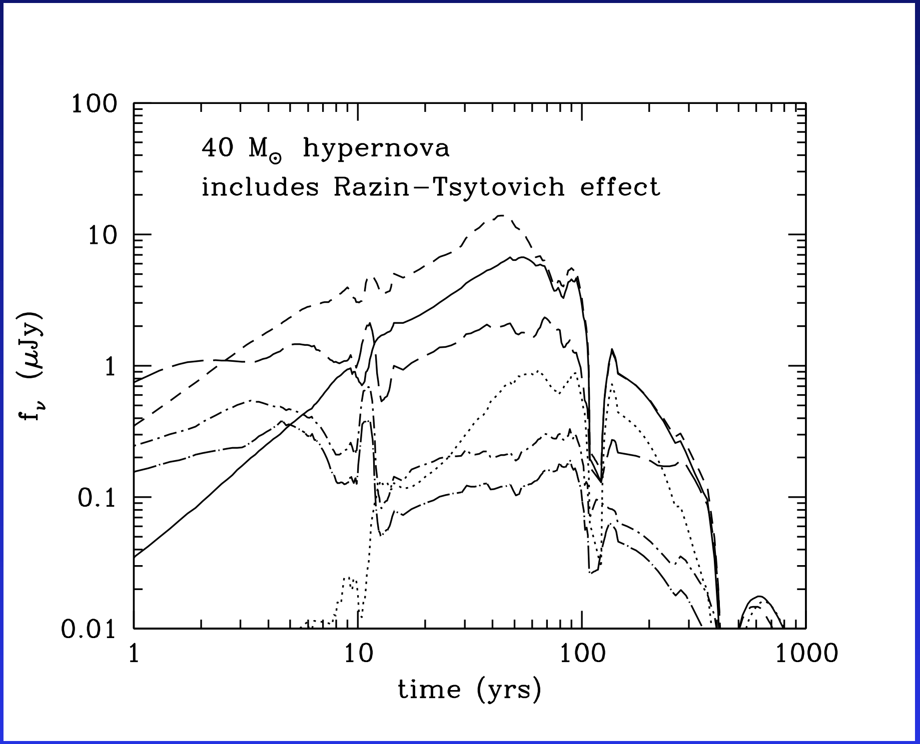




# The Radio Signatures of the First Supernovae

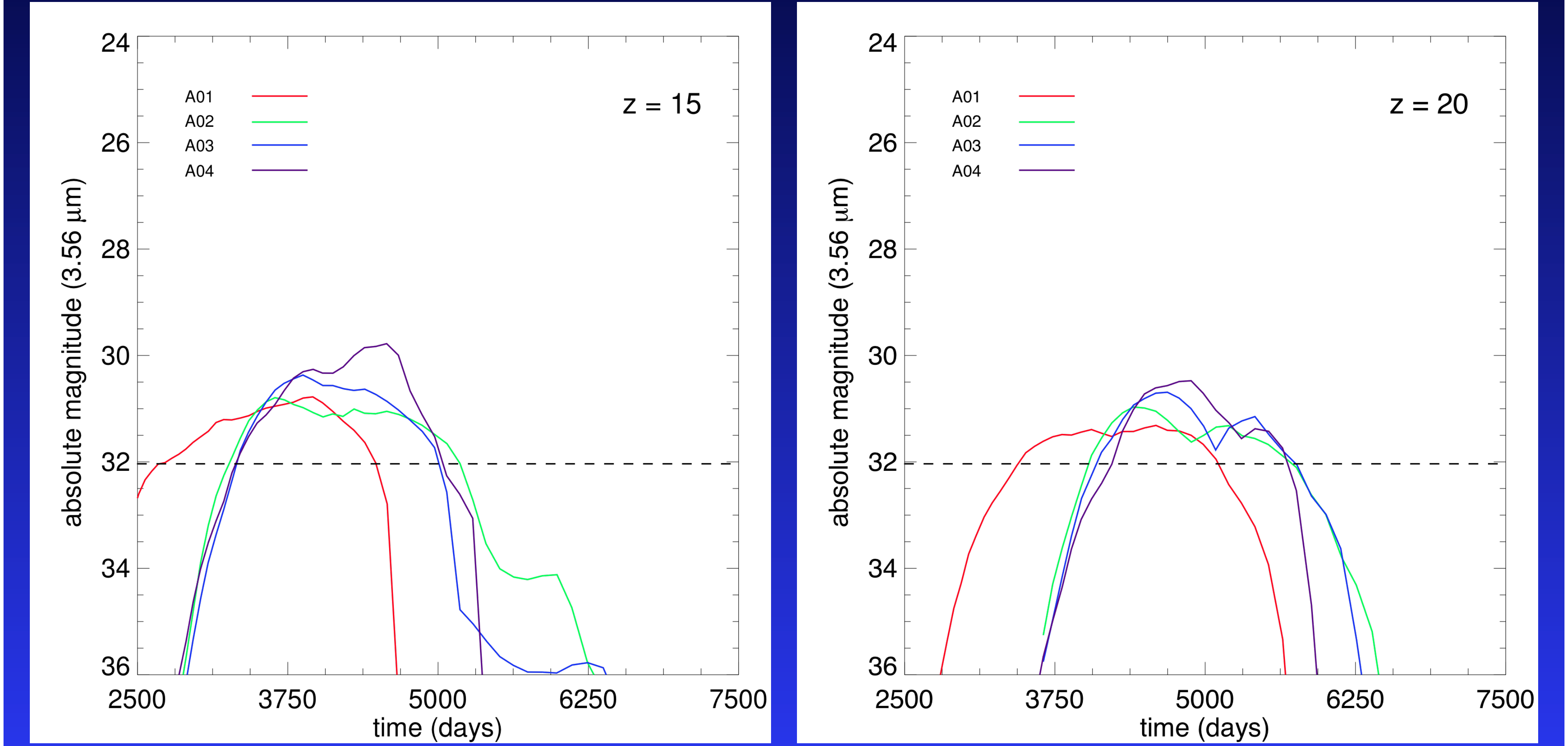
Meiksin & Whalen 2013, MNRAS, 430, 2854





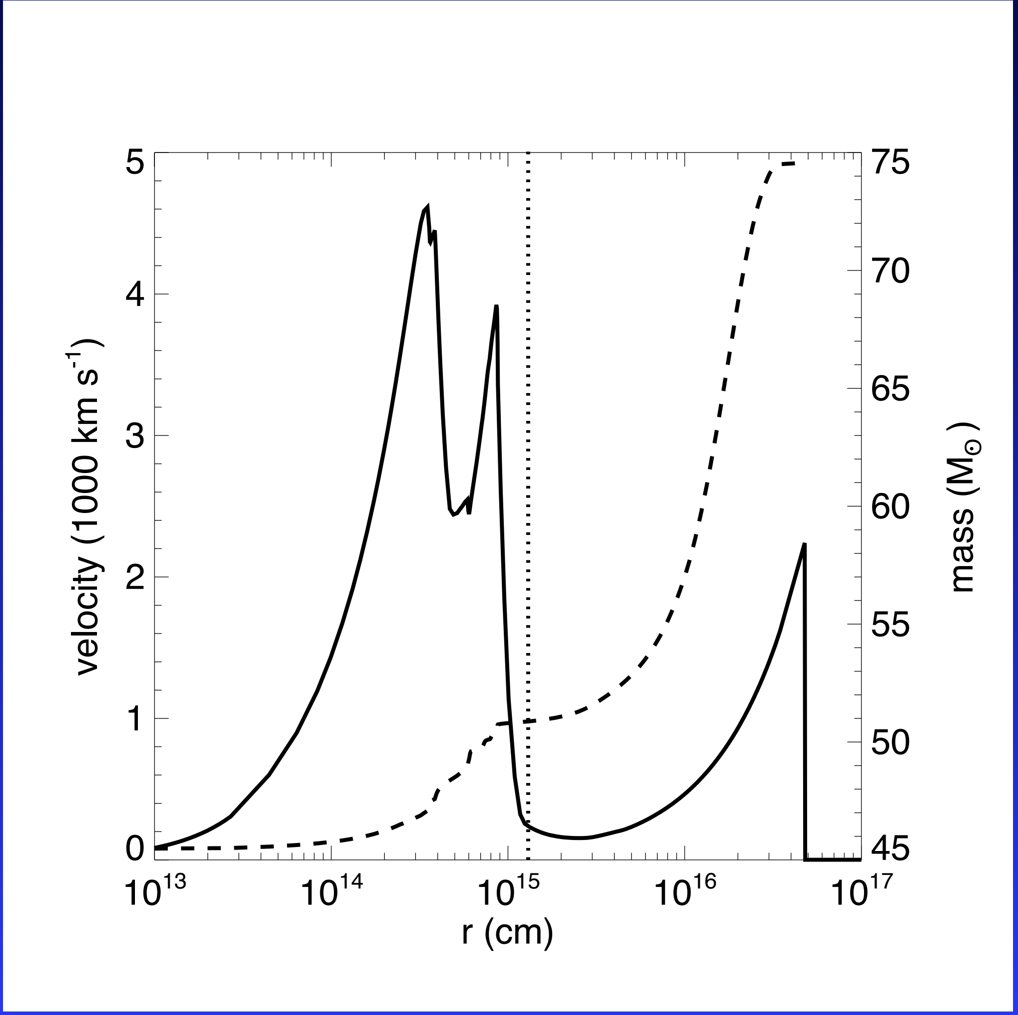
# Pop III Type IIn Supernovae Light Curves

Whalen et al. 2013, ApJ, 768, 195

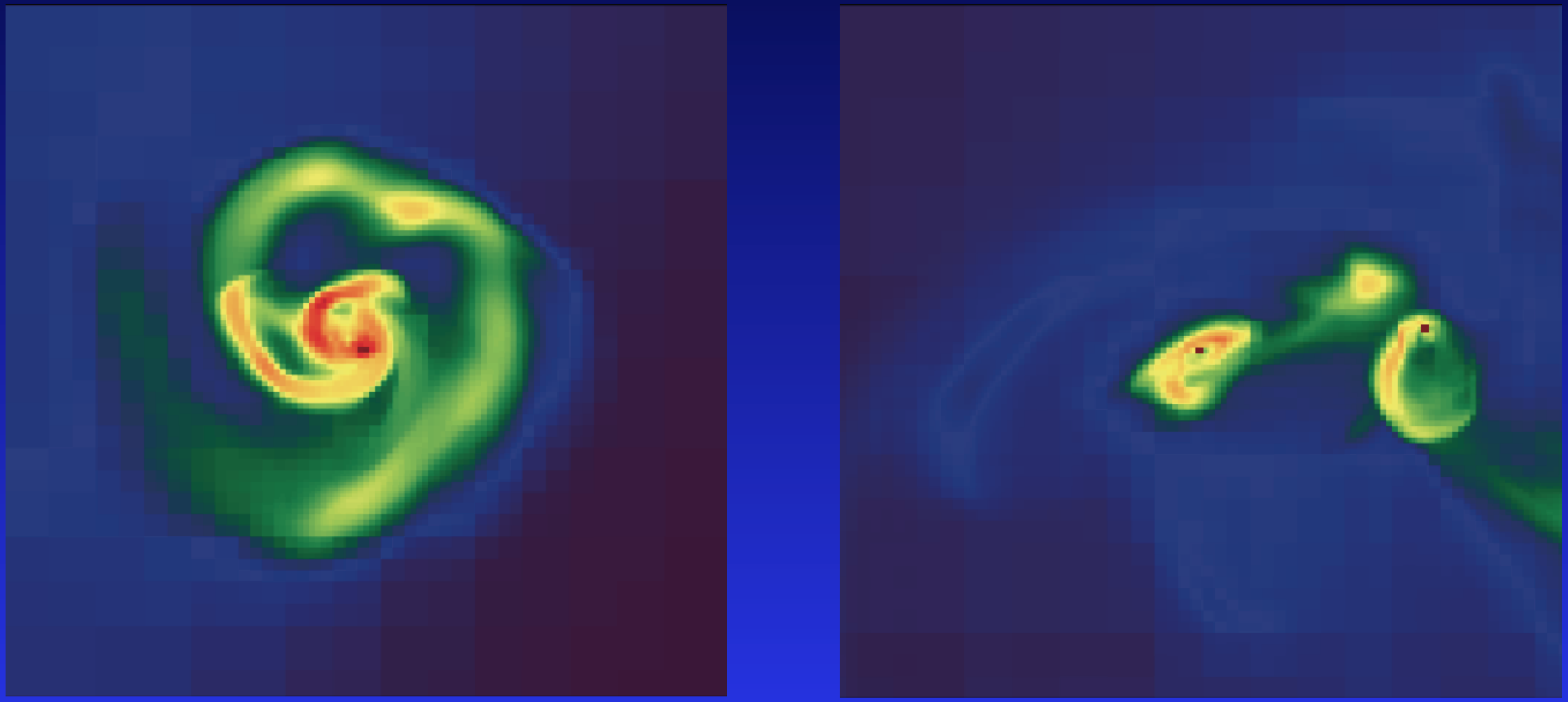


# 4 More Studies of Pop III SNe in Progress

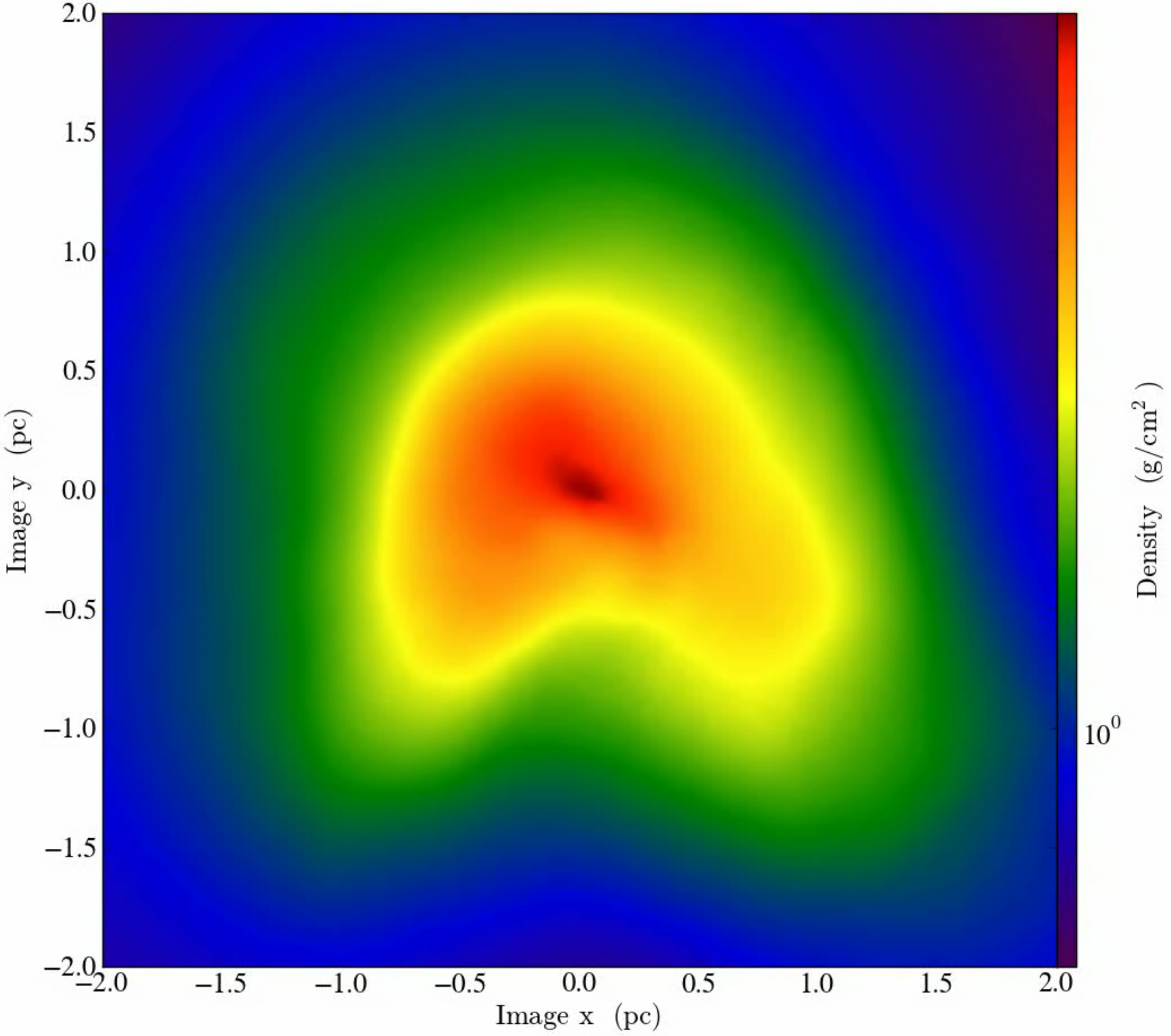
- hypernovae (Smidt et al 2014, ApJ submitted)
- pair-pulsational SNe (Whalen et al. 2014, ApJ, 781, 106)
- 85 – 140 $M_{sun}$ PI SNe (Smidt et al. 2014, ApJ, in prep
- 150 – 500 $M_{sun}$ PI SNe (Whalen et al 2014, ApJ submitted



# Formation of Supermassive Stars and SMBH Seeds in Lyman-Werner Protogalaxies



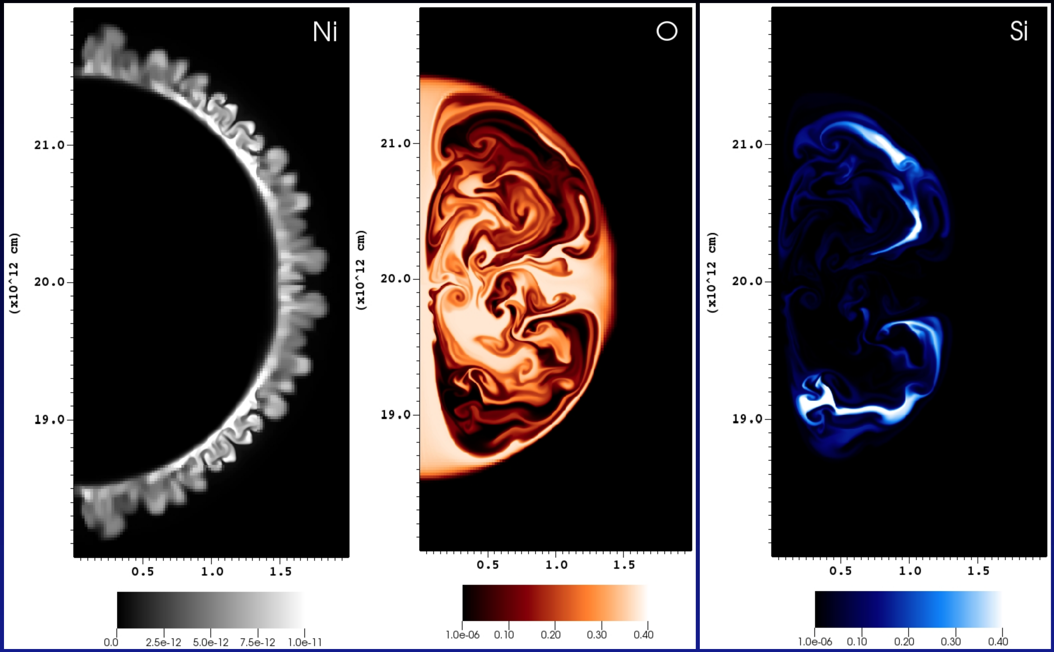
Whalen et al. 2014, ApJ in prep

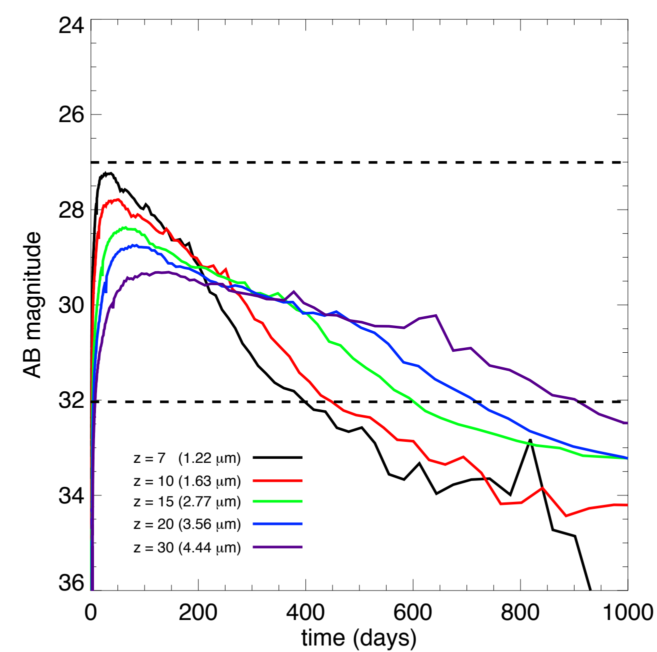

2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
Image y (pc)
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
Image x (pc)
$10^0$
Density (g/cm$^2$)

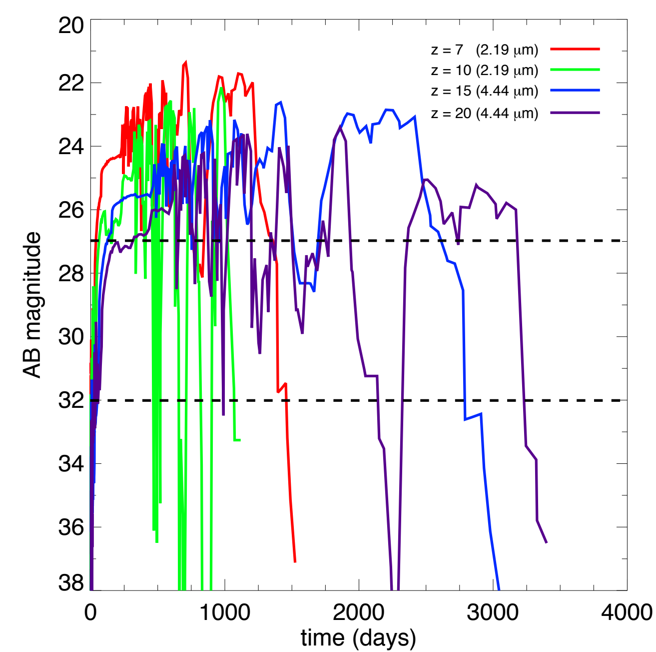
# Supermassive Pop III SNe: the Most Energetic SNe in the Universe

Whalen et al. 2013d, ApJ, 778, 17

- may herald the births of SMBH seeds
- $10^{55}$ erg thermonuclear SNe
- 55,000 solar masses
- visible at any redshift to both JWST and WFIRST

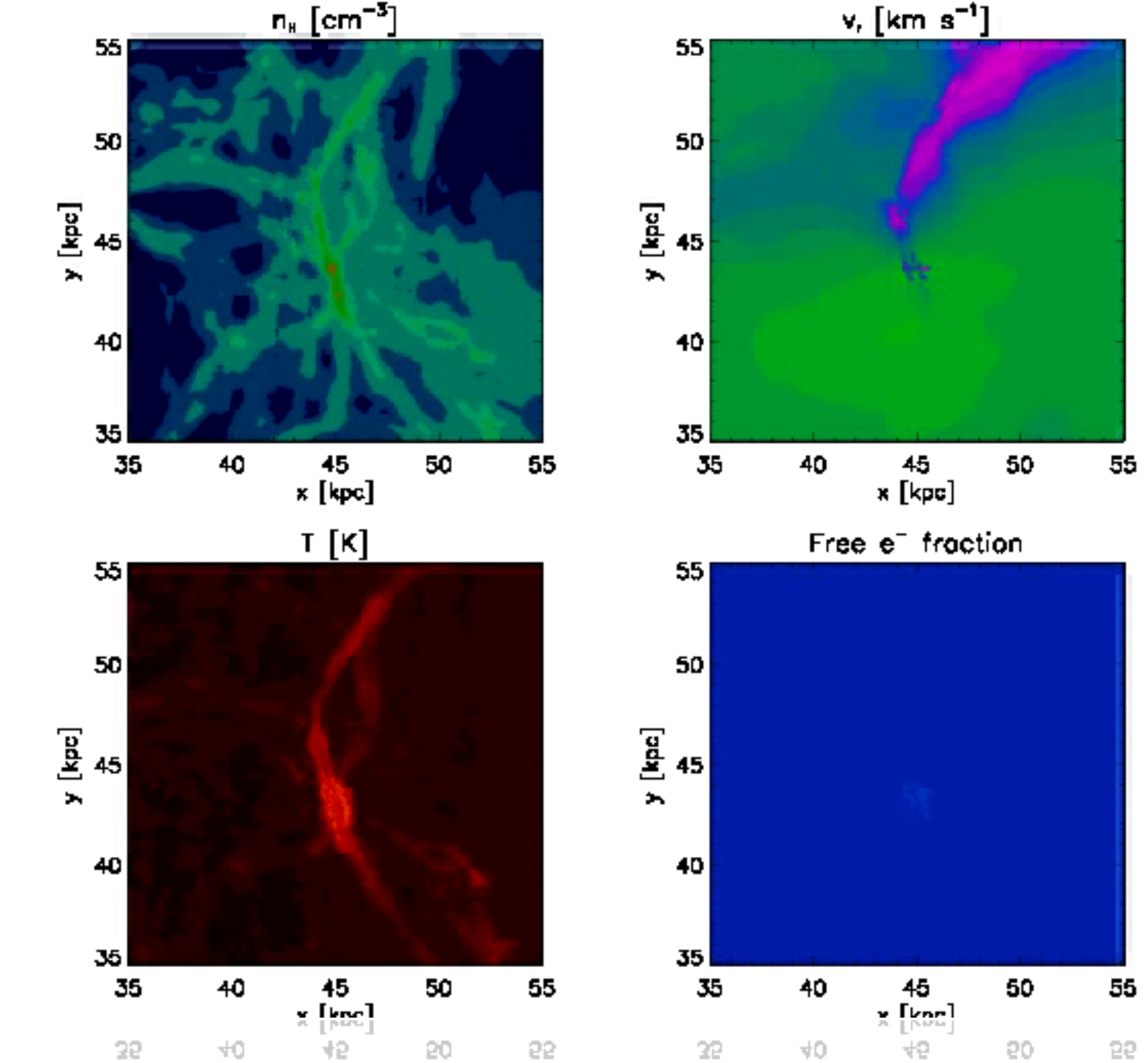






# The Supernova that Destroyed a Protogalaxy

Johnson, Whalen et al 2013, ApJ, 775, 107
Whalen et al 2013, ApJ, 774, 64
Whalen et al 2013, ApJ, 777, 99



# 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 out to z ~ 10 – 15
- Pop III Type IIne will be visible to z ~ 15 - 20
- they will be our first direct probes of the Pop III IMF
- they will also reveal many protogalaxies that would otherwise not be detected by next generation observatories