Connecting Reionization and Metal Production by the First Stars

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KITP Seminar

Election Day: Nov. 2, 2004

Collaborators:

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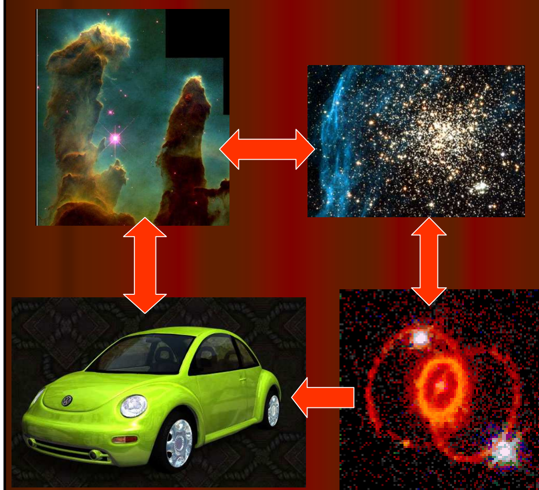
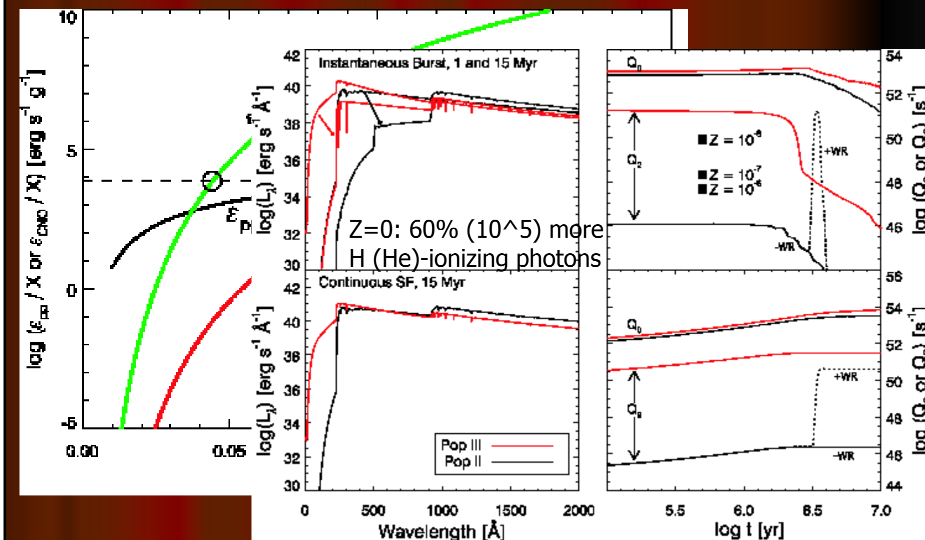


- WHICH STARS: Metals determine the stellar IMF, how the star shines and what metals are generated for next generation.
- HOW: stars form through gas cloud cooling - role of metals, esp. C vs. Fe in first stars IMF.
- WHEN: critical metallicity for transition of primordial to present-day IMF.
- Feedback from stars and SNe on local and extragalactic star formation.
- Normalizing detected metals and ionization in high-z universe to constrain first stars.
- Assumptions made for UV ionizing background directly affects value of calculated Z from metal ionization states.

Review of Stellar Evolution

- The critical factors that determine a star's fate (structure and evolution) are its mass and initial chemical composition.
- All of the ionizing radiation and most of the created metals come from the massive (> 10 Msun) stars.
- As Z decreases, the massive stars get hotter and bluer (greater ionizing radiation) and have lower post-SN integrated metal yield. Z=0 stars' fuel source is the p-p chain, not the more efficient CNO cycle, so they are hotter, smaller and emit harder radiation.
- For a present-day IMF, elements like O, Ne, Mg, Si and S (alpha elements) come from short-lived massive stars, whereas elements like C and N are created mostly by longer-lived intermediate-mass (2-6 Msun) stars.

``We are stardust, billion year old carbon, we are golden..."
-- Joni Mitchell, ``Woodstock"



From Tumlinson, Shull & Venkatesan 2003; see also Schaerer 2002, 2003, Bromm et al. 2001

Some definitions:

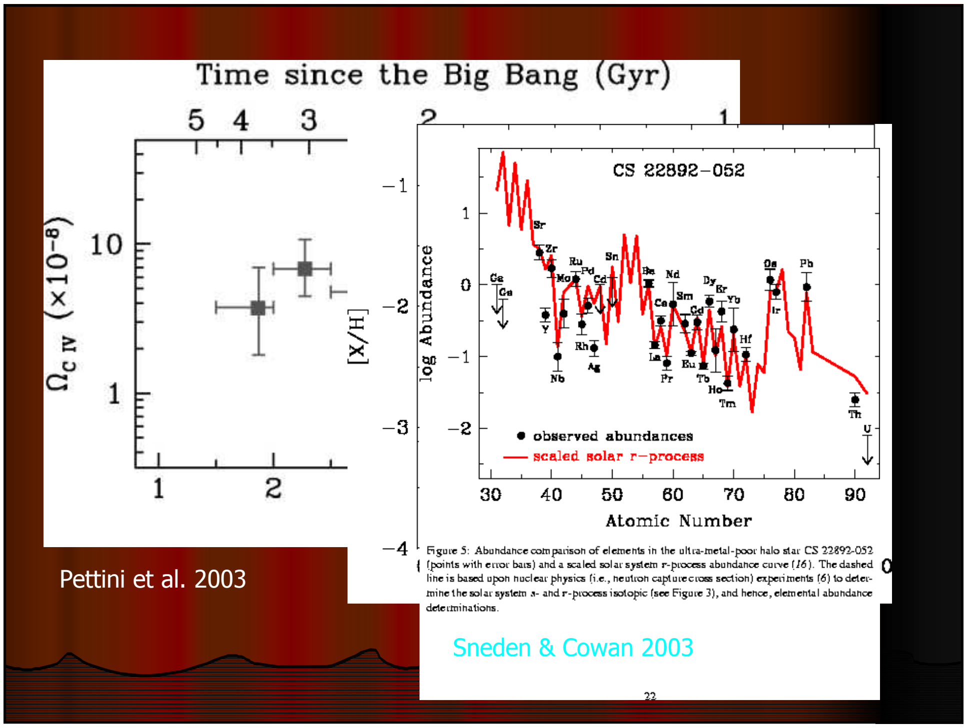
- Very massive stars (VMS) : M>140 Msun.
- Pair instability (PI)SNe : M = 140-260 Msun.
  Star disrupted entirely (no remnant), unique element signature.
- 140 Msun separates two mass regimes with similar radiative but v. different nucleosynthetic properties. Can be independently tested.
- Hypernova (HN): E_51 = 1-100, M > 15 Msun. Basis in theory and in low-z SN data.

The Data So Far:

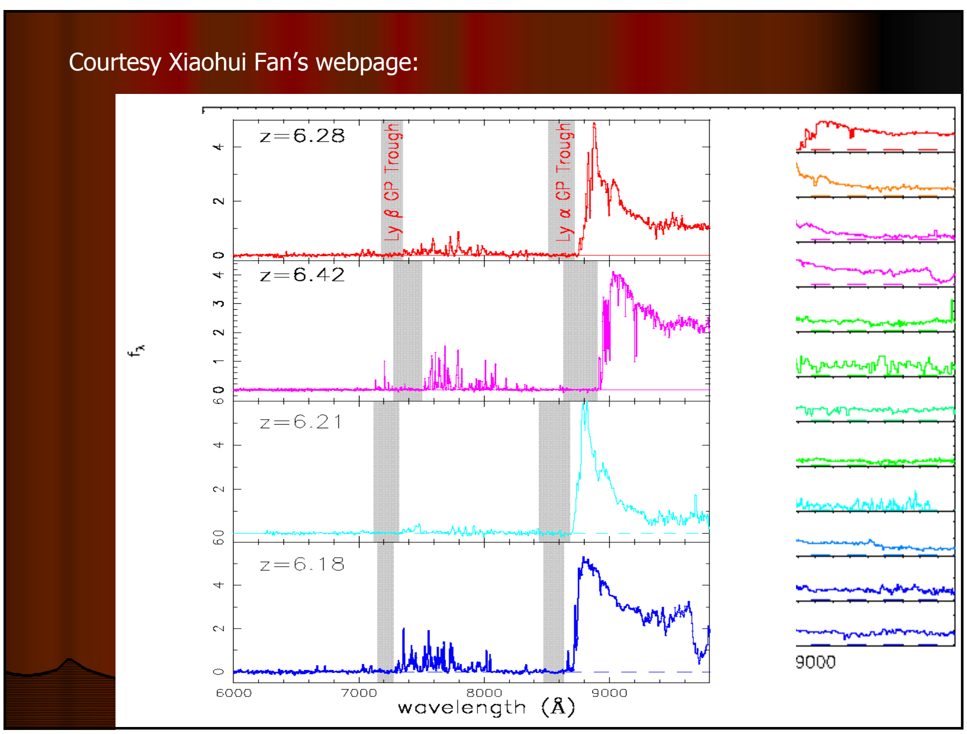
- Metals are seen ubiquitously in systems up to the highest redshifts – QSO BELRs, Ly-alpha systems (DLAs, IGM), galaxies. Generally no evidence for significant evolution in metallicity (Simcoe et al. 2004, Pettini et al. 2003, Prochaska et al. 2003, Schaye et al. 2003, Maiolino et al. 2003, Songaila 2001, Hamann & Ferland 1999).
- Relative abundance ratios of elements in Galactic halo stars as a sample are beginning to provide clues on the first SNe. (Christlieb et al. 2002, Cayrel et al. 2004, Carretta et al. 2002)

The Data (contd.):

- The IGM *may* be in last stages of reionization at z~6 (G-P studies vs. Ly-alpha emitters). Not compatible with a simple ionzn. history and current CMB data from WMAP, tau_e = 0.17 +/- 0.04, or z_reion ~ 17 +/- 4. Multiple/partial ionzn.s of H and/or He at z ~ 6-20 (Venkatesan, Tumlinson & Shull '03, Wyithe & Loeb '03, Cen '03, Haiman & Holder '03, Somerville et al. '03, Ciardi et al. '03).
- Contribution to tau_e of few percent from X-rays from first stars and QSOs (Venkatesan et al. 2001, Oh 2001).
- But how incompatible are these really? Sensitive to different stages of ionzn.
- High tau and precise cosmo. parameters => very high SF'n efficiency required, possibly VMS. Main unknowns are now astrophysical.

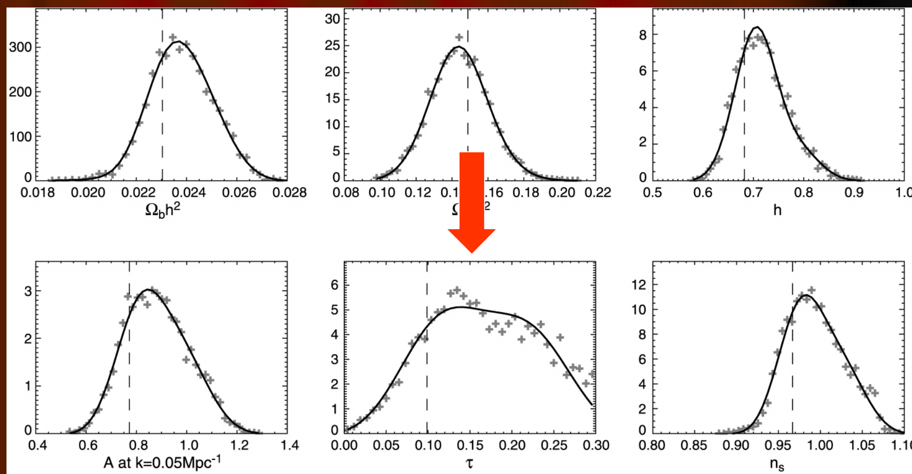


Time since the Big Bang (Gyr)
$\Omega_{C\,IV}$ ($\times 10^{-8}$)
[X/H]
CS 22892−052
log Abundance
Atomic Number
observed abundances
scaled solar r−process
Figure 5: Abundance comparison of elements in the ultra-metal-poor halo star CS 22892-052 (points with error bars) and a scaled solar system r-process abundance curve (16). The dashed line is based upon nuclear physics (i.e., neutron capture cross section) experiments (6) to determine the solar system s- and r-process isotopic (see Figure 3), and hence, elemental abundance determinations.
Pettini et al. 2003
Sneden & Cowan 2003



Courtesy Xiaohui Fan's webpage:
z=6.28
z=6.42
z=6.21
z=6.18
Ly β GP Trough
Ly α GP Trough
f_λ
wavelength (Å)

Spergel et al. 2003, WMAP 1st year data:



Note the broad likelihood distribution of tau!

Theoretical Studies

- Primordial stellar IMF may have been biased towards higher masses of > 100 Msun (Carr, Bond & Arnett 1983,1984…. Omukai & Nishi 1998, Abel, Bryan & Norman 2000, Bromm, Coppi & Larson 2002) owing to cooling processes in Z=0 primordial gas.
- Stellar feedback on accreting matter complicates this (Omukai & Palla 2002, Tan & McKee 2002, 2004, Bromm & Loeb 2004). Tan & McKee => M>30 Msun, i.e., primordial IMF lacking in low mass stars.
- The primordial IMF ceases to be top-heavy at gas transition metallicities of ~ 10^(-4) Zsun. (Bromm et al. 2001, Schneider et al. 2002, 2003)

Current Bottom Line:

A top-heavy IMF (M>140 Msun) is *not* necessarily required to explain the very data used to motivate it – be it reionization, the CMB, or metal abundances in high-redshift systems (QSO BELRs, IGM) or in local metal-poor halo stars. Stars of mass ~1-40 Msun must have existed at z~10-20; VMS cannot have *dominated* at these epochs. (Tumlinson, Venkatesan & Shull 2004, Daigne et al. 2004, Venkatesan, Schneider & Ferrara 2004)

This is indicated by observations over a large range in redshifts and physical scales (sub-pc to IGM) - from extreme (QSO BELRs) to relatively quiescent environments.

- Caveat: these conclusions heavily dependent on stellar evolution models. Ionizing spectra amongst various calculations in lit. consistent to within ~10%, but stellar yields still vary by a factor of about a few.

Ionizing Efficiencies of First Stars

Can a single population of stars be responsible for both reionization and metal enrichment of high-z IGM?

(Gnedin & Ostriker 1997, Madau & Shull 1996, Schaerer 2002, 2003, Venkatesan & Truran 2003):

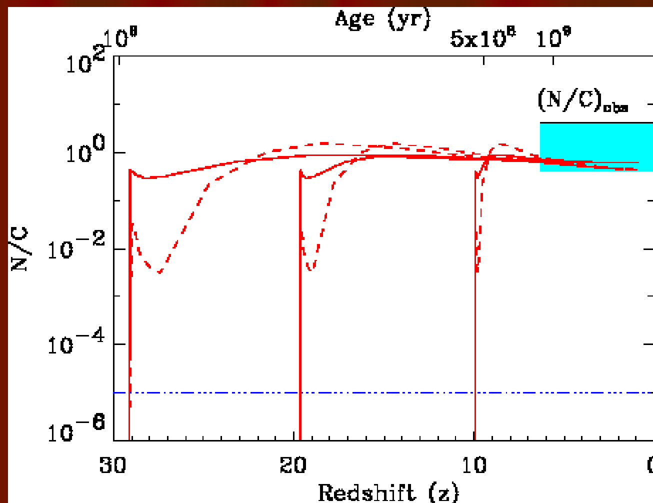
If we derive the *minimum* no. of ionizing photons/baryon that must have been generated in association with the *observed* IGM metallicity at z~2-5:

VMS may generate only 0.35 ionizing photons per baryon before they cease forming at gas Z~10^(-4) Zsun. Therefore, VMS not necessarily preferred as a more efficient source of ionizing radiation in association with IGM metallicity.

Metal-free stars in present-day IMF 10-20 times more efficient at generating ionizing radiation per metal yield than solar-Z stars.

From QSO BEL regions

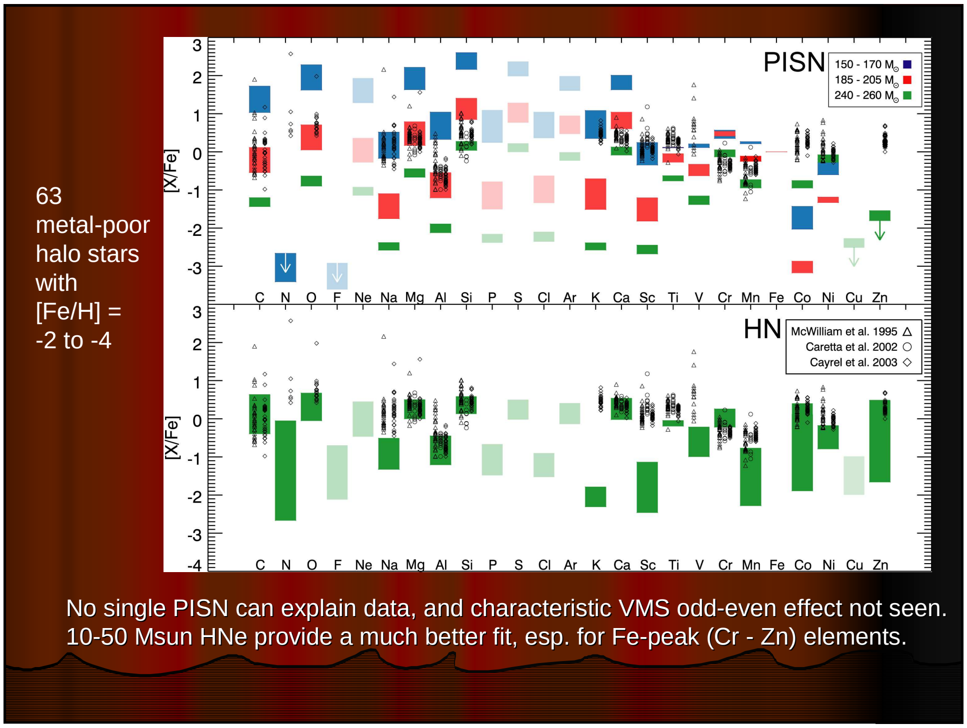
- Solar and higher levels of enrichment detected up to z~6.4 through observations of NV/CIV and FeII/MgII. Large amounts of dust (~10^8 Msun) seen as well in submm/IR.
- Venkatesan, Schneider & Ferrara 2004:
  Model metal synthesis in BELRs for varying stellar IMFs and Z to produce roughly solar values in Fe/Mg and N/C by z~6. Three burst turn-on epochs of z = 30, 20, 10 (WMAP and simulations). Abundance ratios, hence independent of SF'n efficiencies, BELR mass, etc.

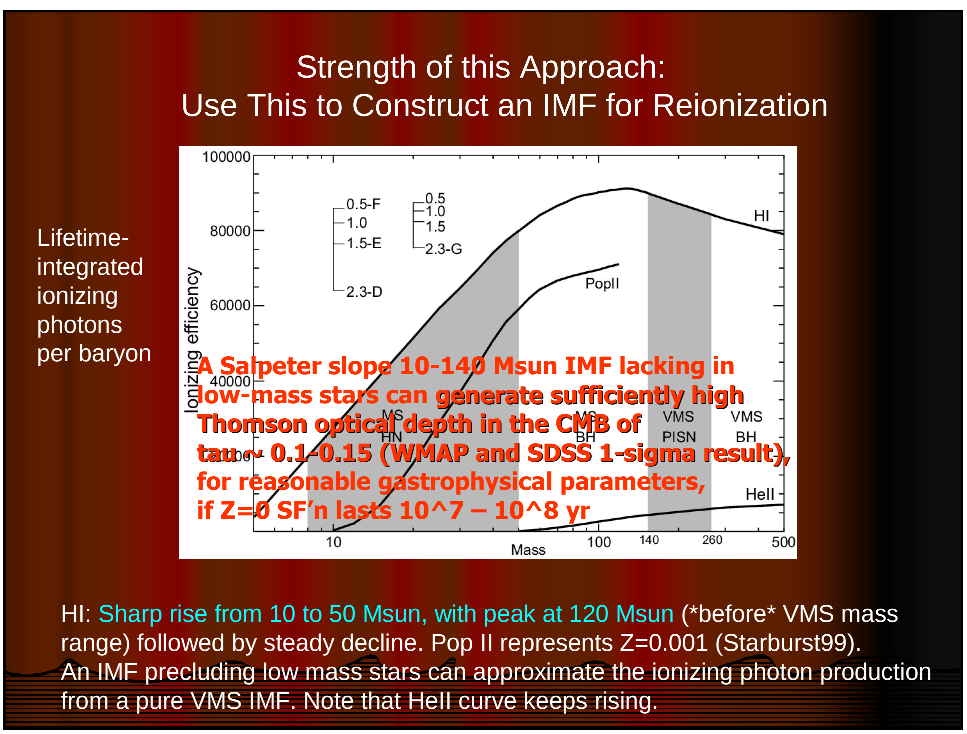


Severe underproduction of N by PISNe (may change in future as highly dependent on SN models). Need intermediate-mass stars (2-7 Msun).

Clues from Local Relics

- Ashes of first stars in local ultra-metal-poor halo stars. Low mass stellar relics have elements heavier than Mg which they cannot synthesize.
- Qualitative change in element ratios at [Fe/H] ~ -3. Yield patterns of Fe-peak and r-process elements not well matched by individual SNe or PISNe. Abundance ratios indicate HNe from Z=0, 8-40 HNe (Umeda & Nomoto 2002, 2004, Tumlinson, Venkatesan & Shull 2004, Daigne et al. 2004).
- HNe: fine tuning required as well (explosion energy is a free parameter). Big uncertainty in extrapolating low-z detected SNe to Z=0 regime. So match of HNe encouraging but HNe cannot yet be conclusively associated with first stars. However they are important for constructing a primordial IMF without VMS.


63 metal-poor halo stars with [Fe/H] = -2 to -4
PISN
150 - 170 M☉
185 - 205 M☉
240 - 260 M☉
HN
McWilliam et al. 1995
Caretta et al. 2002
Cayrel et al. 2003
[X/Fe]
C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn
No single PISN can explain data, and characteristic VMS odd-even effect not seen.
10-50 Msun HNe provide a much better fit, esp. for Fe-peak (Cr - Zn) elements.


Strength of this Approach:
Use This to Construct an IMF for Reionization
Lifetime-integrated ionizing photons per baryon
Ionizing efficiency
Mass
HI
PopII
HeII
MS HN
MS BH
VMS PISN
VMS BH
0.5-F
1.0
1.5-E
2.3-D
0.5
1.0
1.5
2.3-G
A Salpeter slope 10-140 Msun IMF lacking in low-mass stars can generate sufficiently high Thomson optical depth in the CMB of tau ~ 0.1-0.15 (WMAP and SDSS 1-sigma result), for reasonable astrophysical parameters, if Z=0 SF'n lasts 10^7 – 10^8 yr
HI: Sharp rise from 10 to 50 Msun, with peak at 120 Msun (*before* VMS mass range) followed by steady decline. Pop II represents Z=0.001 (Starburst99).
An IMF precluding low mass stars can approximate the ionizing photon production from a pure VMS IMF. Note that HeII curve keeps rising.

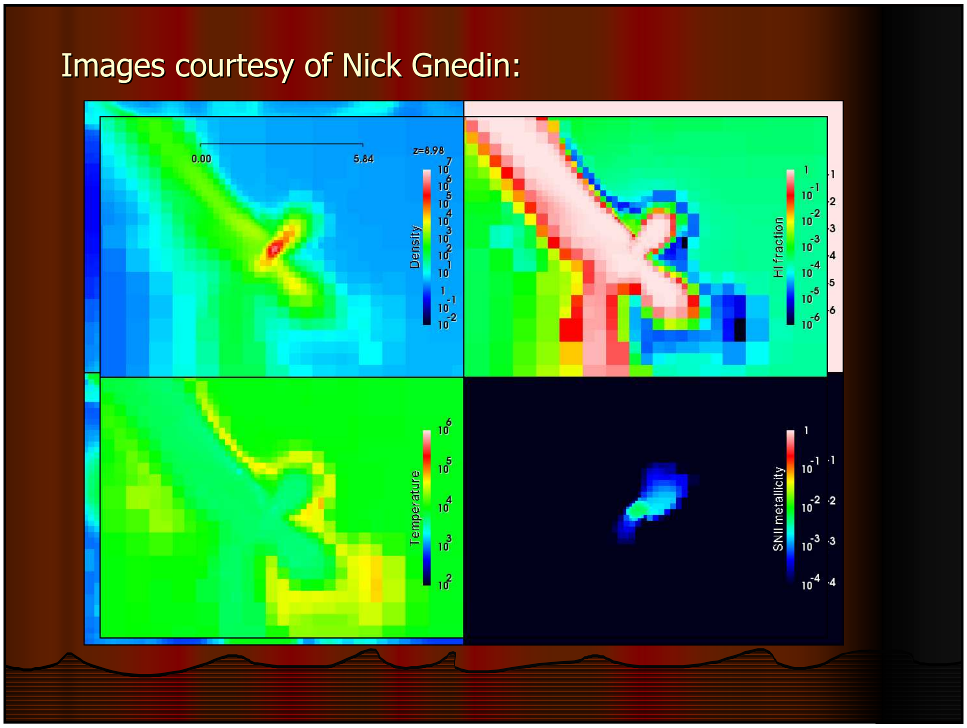
Metal transport models

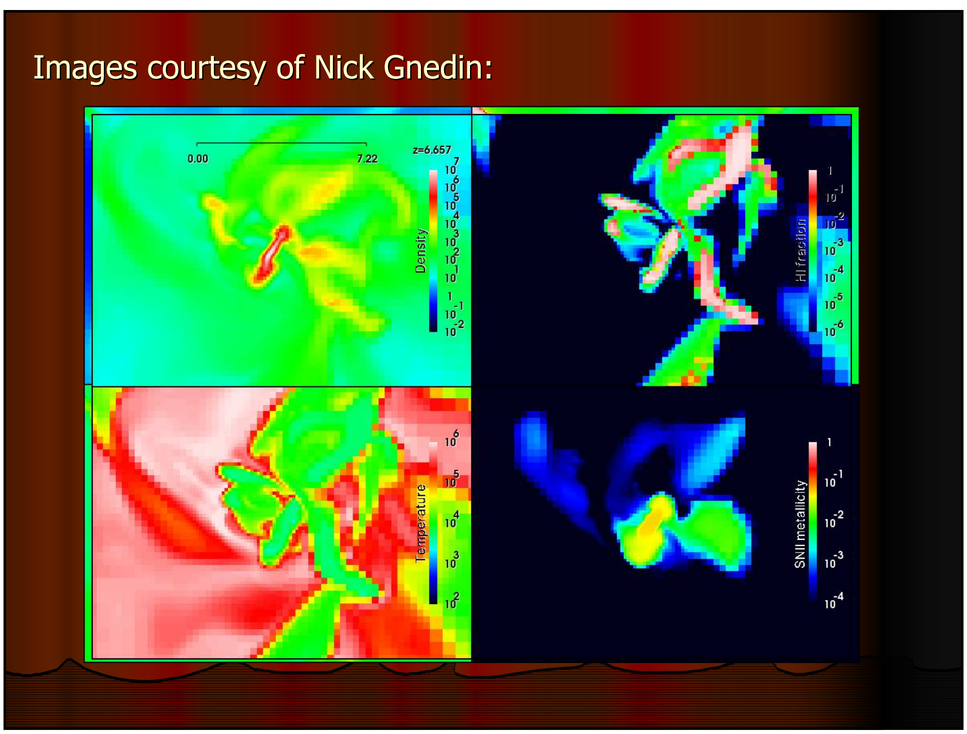
- Divide into SN-driven outflows and ejection through galaxy mergers (Gnedin & Ostriker 1997, Gnedin 1998, Efstathiou 2000, Madau et al. 2001, Aguirre et al. 2001, Mori et al. 2002, Scannapieco et al. 2002, Ricotti, Gnedin & Shull 2002, Norman, O'Shea & Paschos 2004)
- Photoionization feedback and feedback from metals from SNe, e.g., truncation of globular cluster formation by reionization (Grebel & Gallagher 2004, Strader et al. 2004, Ricotti 2002, Cen 2001)

How difficult is metal ejection?

Most simulations/semianalytic studies find that SN-driven winds do not have difficulty in distributing metals to IGM scales; mergers *may* do better. Still unresolved and likely to result in highly inhomogeneous distribution of Z_IGM.

Stellar scales (% of AU) : IGM scales (~tens kpc) roughly equal to atomic : room scales!

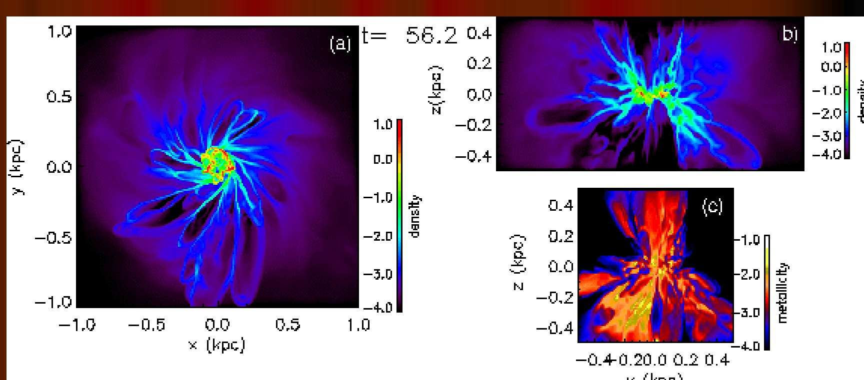

Images courtesy of Nick Gnedin:
z=8.98
0.00
5.84
Density
HI fraction
Temperature
SNII metallicity


Images courtesy of Nick Gnedin:
z=6.657
0.00
7.22
Density
HI fraction
Temperature
SNII metallicity

Duration of Z=0 Star Formation

- Semi-analytic calculations indicate timescales between 10^7 – 10^8 yr for self-enrichment and pollution of neighboring halos (e.g., Tumlinson, Venkatesan & Shull 2004).
- Numerical simulations of SN explosions indicate much shorter timescales of ~ few - 10 Myr (3D gas hydro.: Wada & Venkatesan 2003; SPH: Yoshida, Bromm & Hernquist 2004). Environment to form Z=0 stars may be lost quickly, with 2nd generation stars of Z~10^(-4) Zsun.

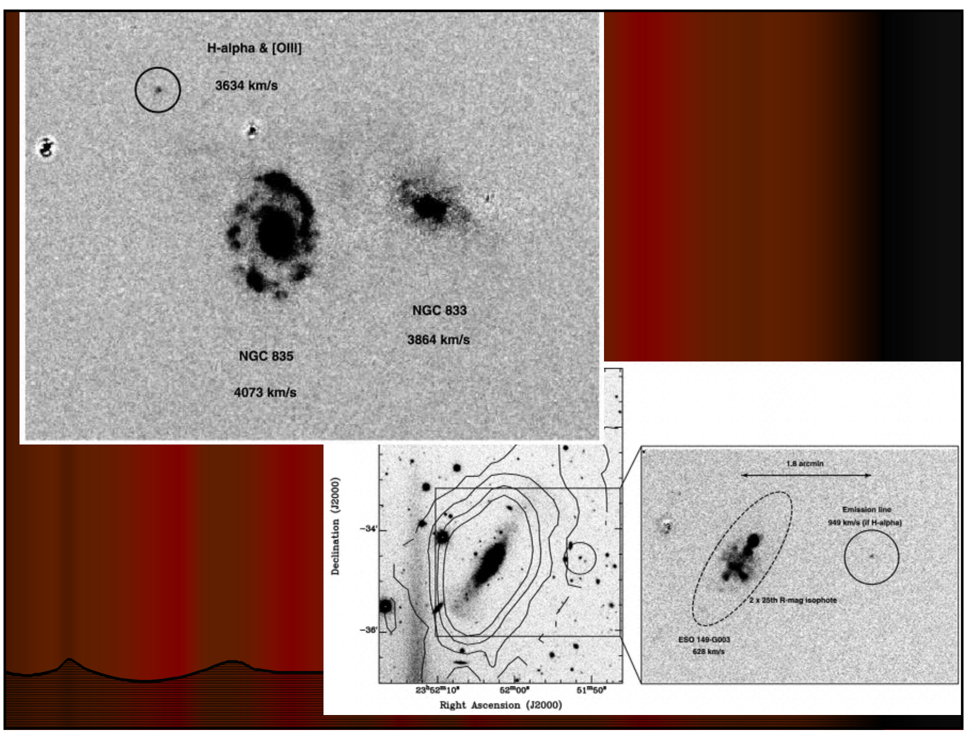
3D gas hydro simulations studying chemodynamical effects of multiple coeval SNe in clumpy ISM: metal-free starburst in central regions (2x2x1 kpc) of 10^8 Msun halo (typical at z~10) from Wada & Venkatesan 2003:



100 SNe, at t~56 Myr: most of the metals return to r<200 pc in 50 Myr. Dense (starforming?) clumps in disk accrete mainly metal-poor or metal-free gas.

Open questions

- How closely does IGM metal enrichment track reionization?
- Uniqueness/sharpness of Pop III → II transition epochs
- Cosmological relevance of Z=0 stars: how long can they keep forming and can we see them with JWST?
- Role played by dust and the selective depletion of first wave of metals – implications for 2nd generation stars' Z.
- Improvements in stellar models (rotation, etc.)
- Do first stars have to form in first galaxies? Recent discovery of extragalactic HII regions (Ryan-Weber et al. 2004)



Promising Directions to Constrain Sources of IGM Reionzn. and Metals

- Using metal lines to probe IGM before reionization (Oh 2002, Furlanetto & Loeb 2003).
- HeII reionzn. and thermal history of IGM (Benson & Madau 2003, Hui & Haiman 2003): metal deposition may have to occur at z>~9 from temp. measurements of Ly-alpha forest at z=2-5.
- Direct detection of metal-free Galactic star or of metal-free high-z galaxies in emission.