The First Stars in the Universe: Formation, Feedback Effects and Detections

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First Stars: Questions

- What were they like?
- Were they important?
- Can we see them today?

Hotter, smaller, about same masses

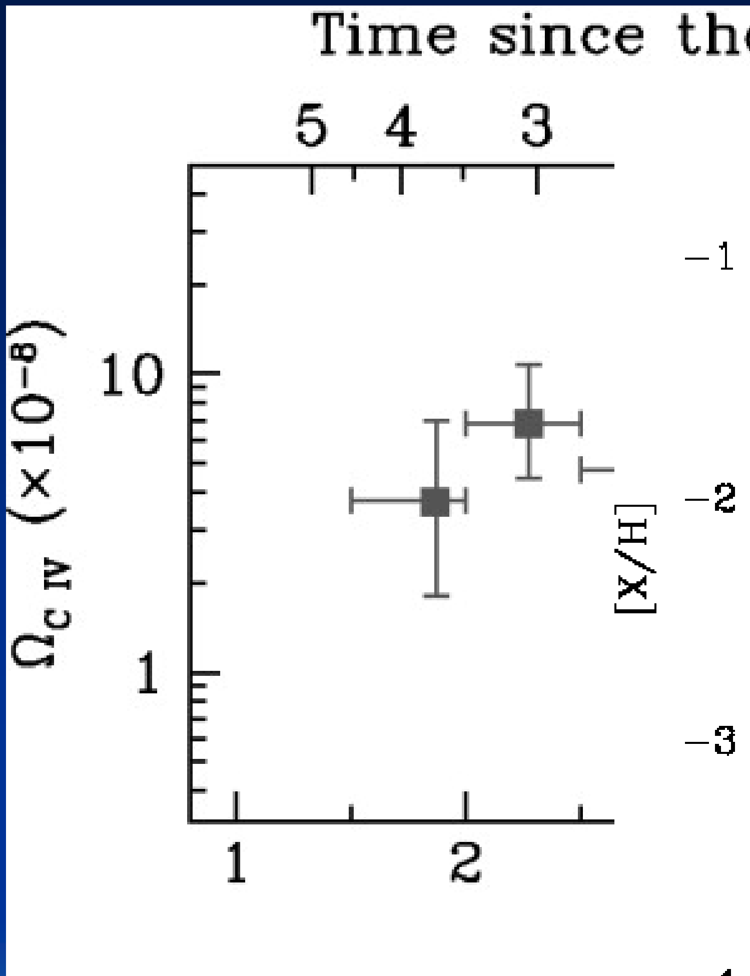
Yes

Not yet directly but soon perhaps

The Data So Far: Metals

- Metals are seen ubiquitously in systems up to the highest redshifts – Quasars, Ly-alpha systems (proto-galaxies, 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 are beginning to provide clues on the first SNe. (Christlieb et al. 2002, Cayrel et al. 2004, Carretta et al. 2002)



Pettini et al. 2003

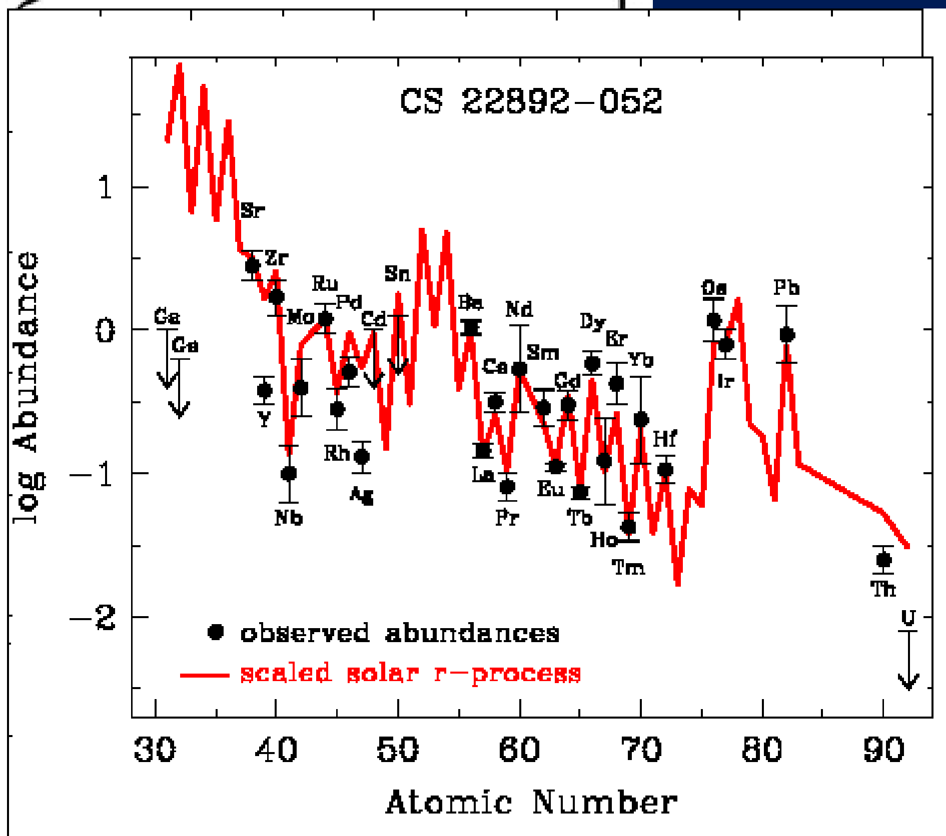


Figure 5: Abundance comparison of elements in the ultra-metal-poor halo star CS 22892-052 (points with error bars) and a scaled solar system r-process abundance curve (16). The dashed line is based upon nuclear physics (i.e., neutron capture cross section) experiments (6) to determine the solar system s- and r-process isotopic (see Figure 3), and hence, elemental abundance determinations.

Sneden & Cowan 2003

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The Data: Ionization

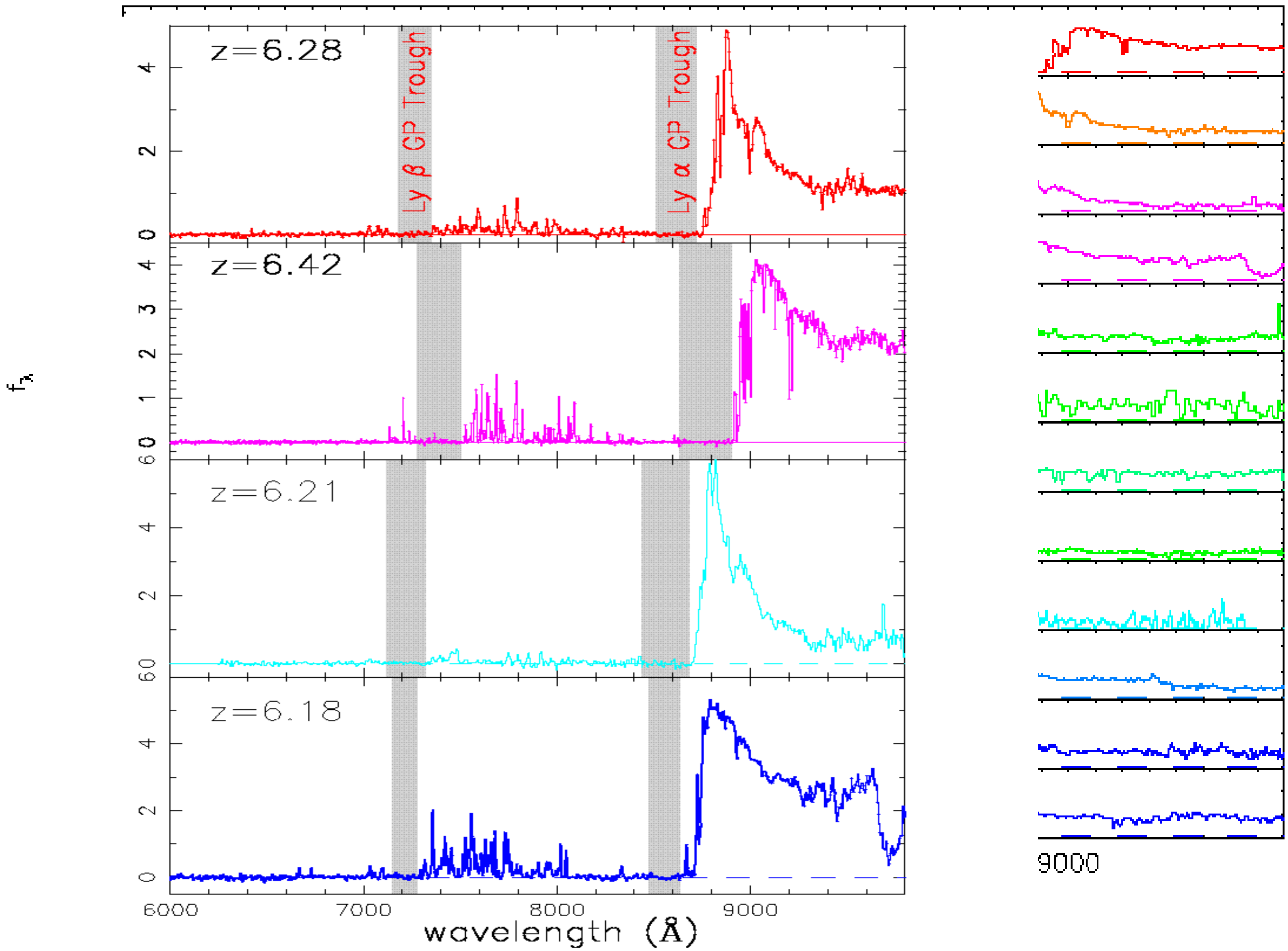
- The IGM *may* be in last stages of reionization at z~6.5. Not compatible with a simple ionzn. history and most recent CMB data from WMAP-3, tau_e= 0.09 +/- 0.03, or z_{reion} ~ 10. Argues for extended period of partial ionization of H and/or He at z ~ 6-20 (Venkatesan, Tumlinson & Shull '03, Wyithe & Loeb '03, Cen '03, Haiman & Holder '03, Somerville et al. '03, Ciardi et al. '03).

- Sensitive to different stages of ionization

- Known Quasars cannot do it. Given this and observed metals: yes, first stars seem to have existed, and had a strong impact on their environment.

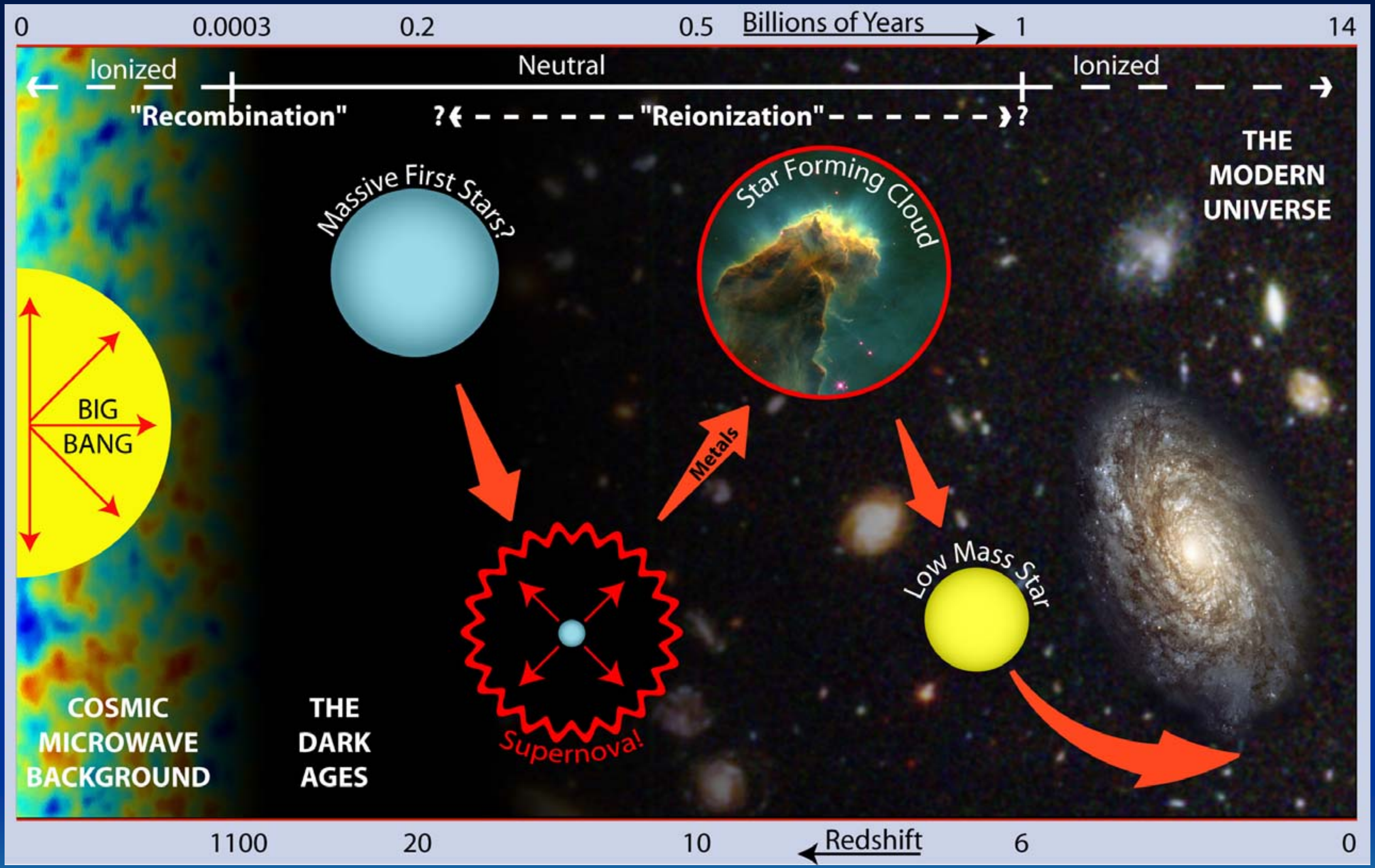
- Contribution to tau_e of few percent from X-rays from first stars and QSOs (Venkatesan et al. 2001, Oh 2001) , and He reionzn. (Venkatesan et al. 2003); topology distinction

Courtesy Xiaohui Fan’s webpage:



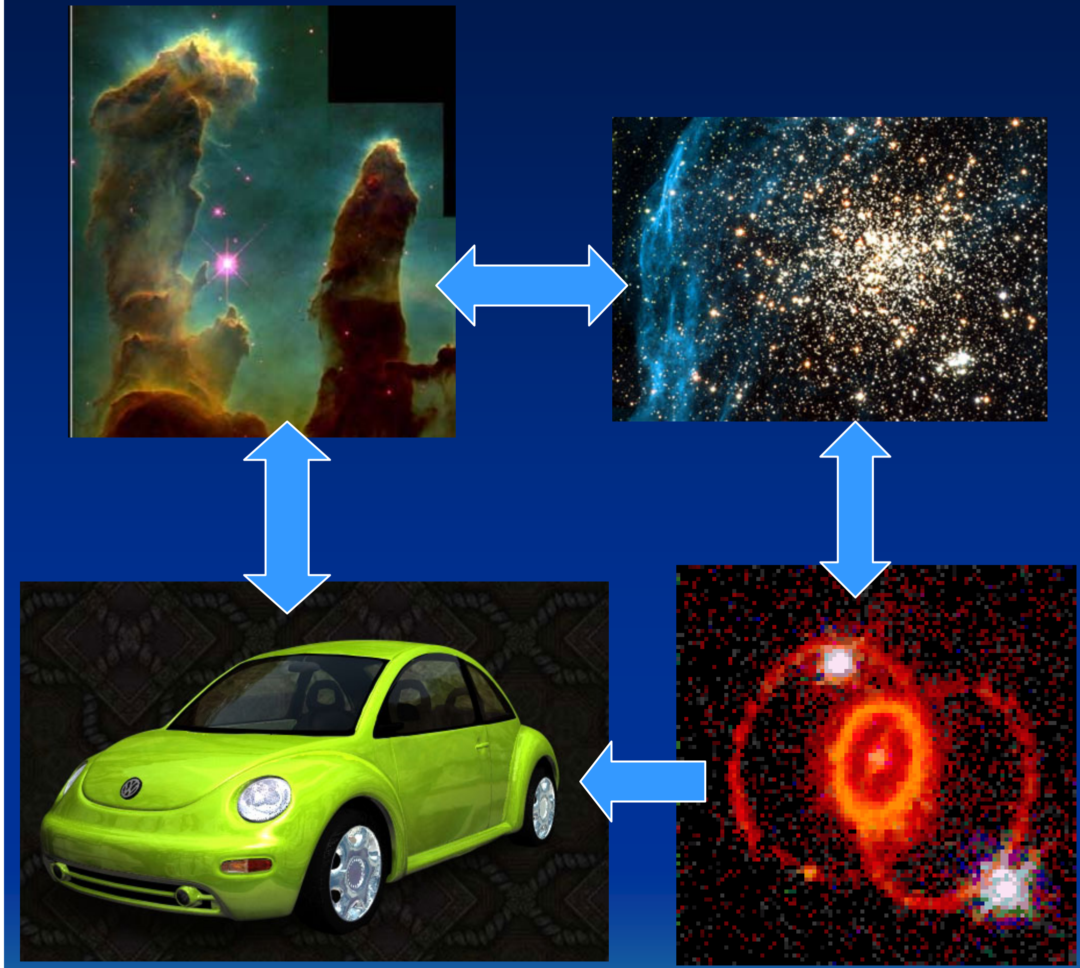
Theoretical Studies (What Are They?)

- The first stars are believed to have formed when the universe was ~ 100-500 Myr old, at z ~10-20
- Primordial stellar initial mass function (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>10-30 Msun, i.e., primordial IMF lacking in low mass stars.
- The primordial IMF ceases to be top-heavy at gas transition metallicities of ~ 10^(-5) -10^(-3) Zsun. (Bromm et al. 2001, Schneider et al. 2002, 2003)



From Tumlinson, Venkatesan & Shull 2004, as featured in Sky and Telescope

Strong Feedback Between Radiation and Metals:



- 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.

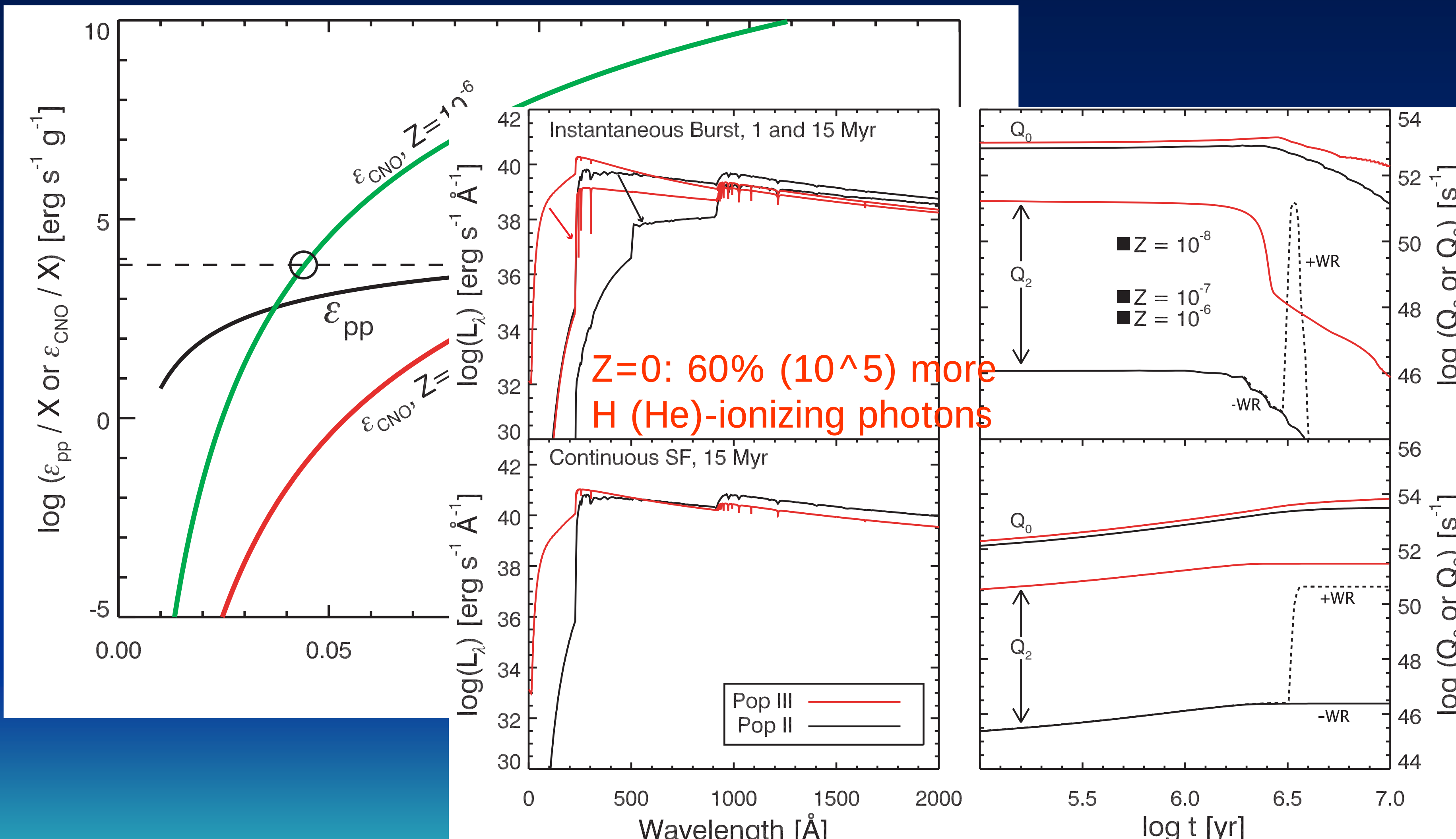
Review of Stellar Evolution

- Critical factors for star's fate are its mass and initial composition.
- All ionizing radn. and most metals from massive (>10 Msun) stars.
- As metallicity Z decreases, massive stars get hotter (greater ionizing radn.) and lower 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 present-day IMF, elements O, Ne, Mg, Si and S (alpha elements) come from short-lived massive stars, whereas C and N 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 Venkatesan, Tumlinson & Shull 2003; see also Schaerer 2002, Bromm et al. 2001



Some definitions:

- Pop III (Z=0) and Pop II (metal-poor).
- Hypernova (HN): supernova from stars that have little to no metals.
- 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.

Current Bottom Line:

A First Stars IMF that works: one that is similar to that in our Galaxy, just with metal-free stars of masses few-100 Msun (consistent with data on metal abundances in Galactic halo stars, IGM, QSOs, reionization, CMB tau ~ 0.1). This is true **if** primordial star formation lasts $10^7 – 10^8$ yr. (Tumlinson, Venkatesan & Shull 2004, Venkatesan, Schneider & Ferrara 2004)

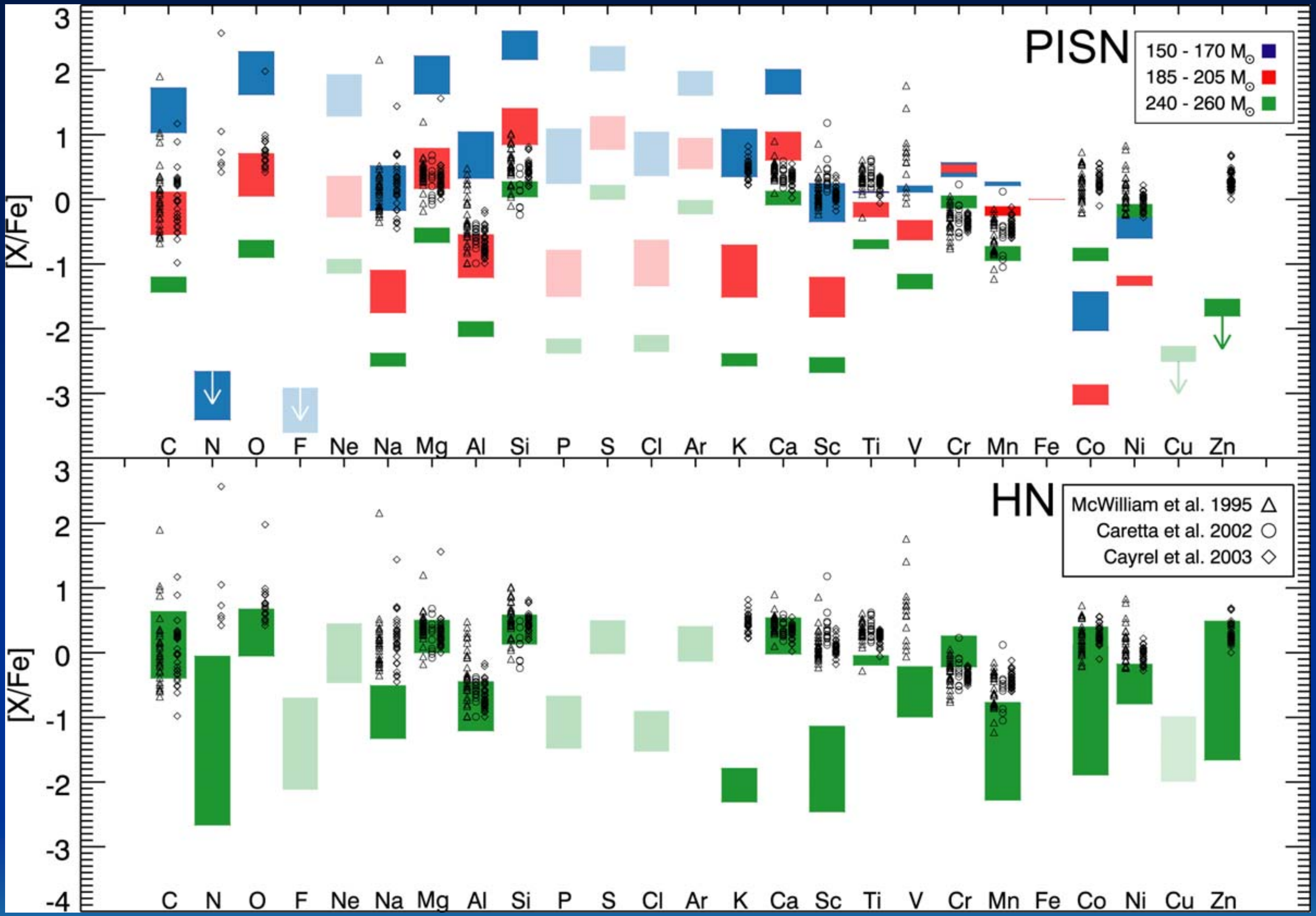
This is indicated by observations over a large range in redshifts and physical scales (sub-pc to IGM) - from extreme (Quasar central regions) to relatively quiescent environments.

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 high-mass SNe. Abundance ratios indicate metal-free 10-50 Msun hypernovae (Umeda & Nomoto 2002, 2004, Tumlinson, Venkatesan & Shull 2004, Daigne at al. 2004).

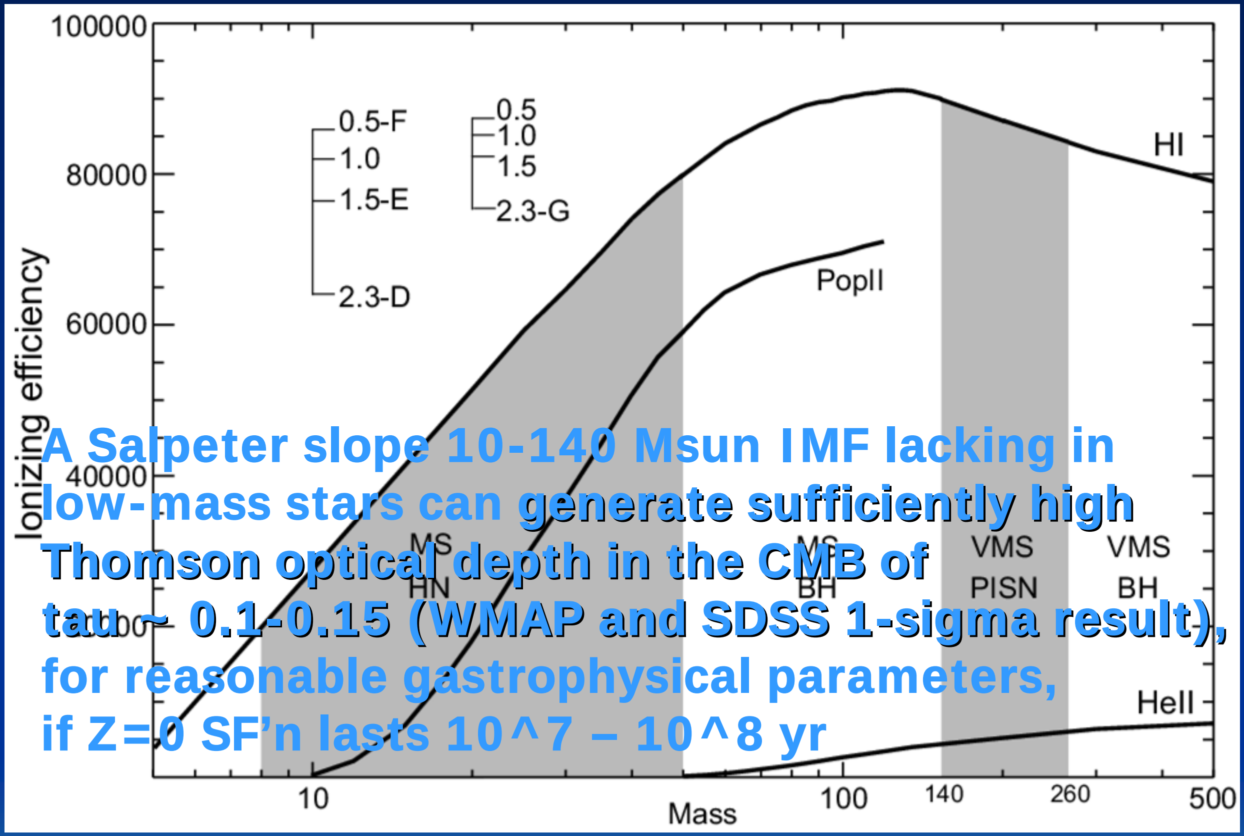
63 metal-poor halo stars with [Fe/H] = -2 to -4



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

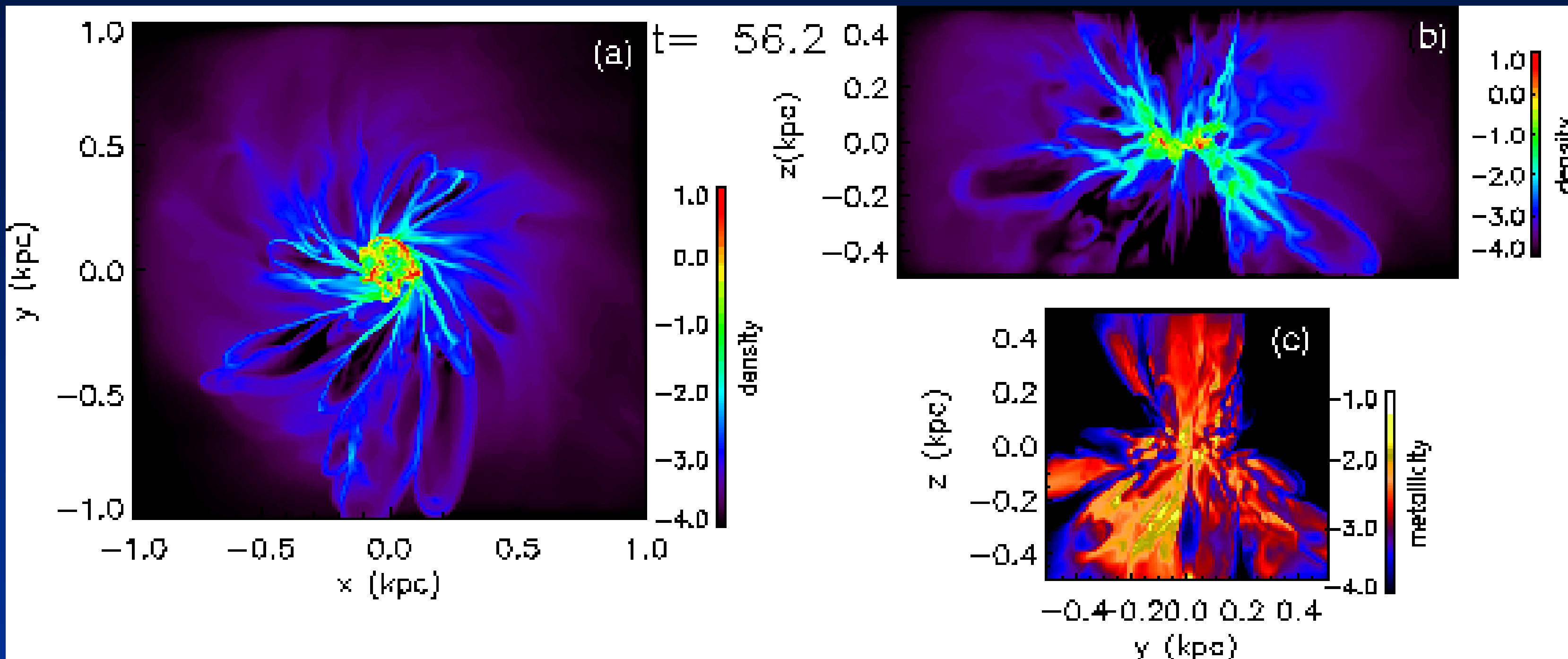


A Salpeter slope 10-140 Msun IMF lacking in low-mass stars can generate sufficiently high Thomson optical depth in the CMB of tau ~ 0.1-0.15 (WMAP and SDSS 1-sigma result), for reasonable gastrophysical parameters, if Z=0 SF'n lasts 10^7 – 10^8 yr

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.

Duration of Z=0 Star Formation

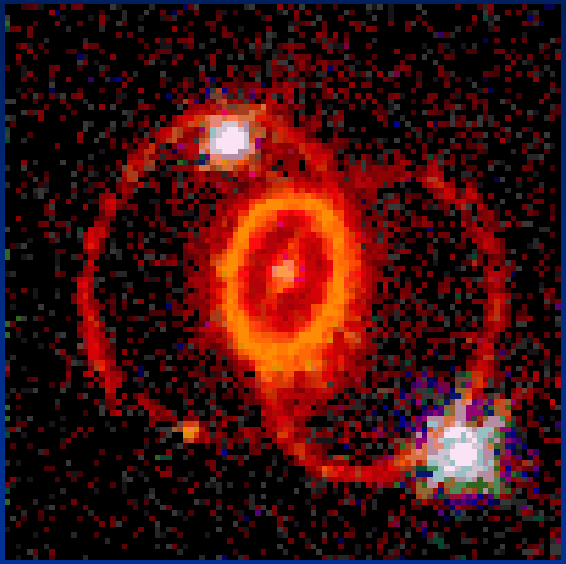
- Semi-analytic calculations indicate timescales $\sim 10^7 – 10^8$ yr for self-enrichment and pollution of neighboring halos (e.g., Tumlinson, Venkatesan & Shull 2004).



→ Numerical simulations of first 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 gen. stars of Z~10^(-4) Zsun.

Second Generation Stars

- Low mass metal-poor 2nd-gen. stars may form in cooling shells of Pop III SN remnants (Mackey et al. 2003, Salvaterra et al. 2004)
- Seen as metal-poor stars in galaxies today? Survivors of transition epochs from Pop III→II



Transition from Pop III → Pop II

- At least two impt. cosmic milestones occur at cosmic metallicities, Z ~10^(-5) to 10^(-3) solar:

  (1) Cosmological (H) reionization of IGM (Venkatesan & Truran '03, Miralda-Escude & Rees '97)

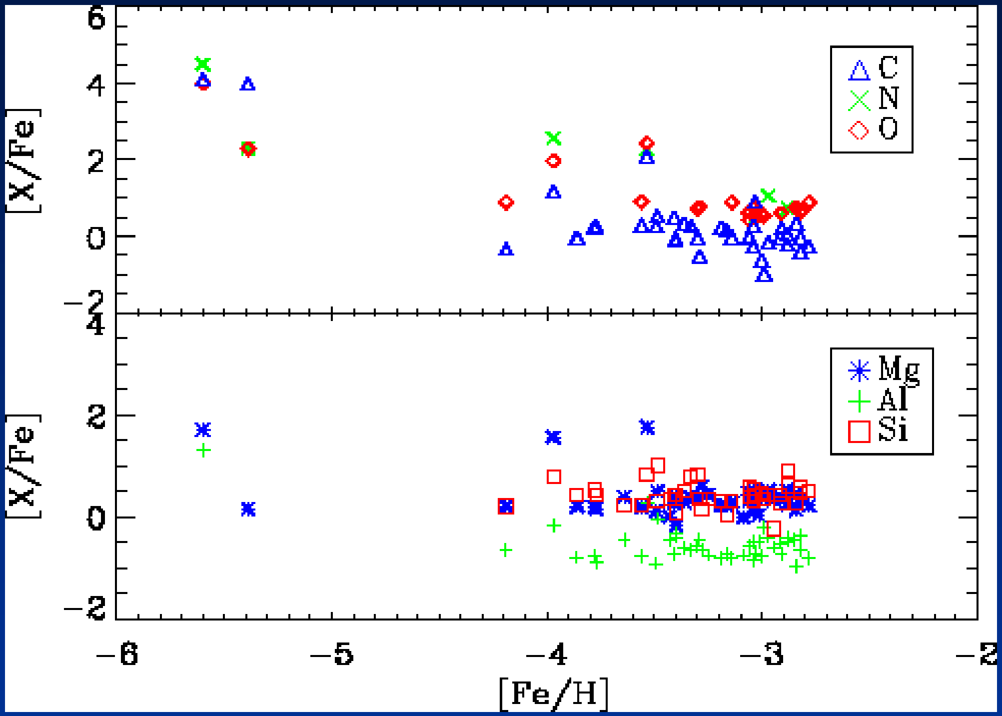
  (2) Transition from primordial to present-day mode of star formation (Schneider et al. '02, Bromm & Loeb '03, Omukai et al. '05, Santoro & Shull '06)

- Formation epochs of Pop II may be non-unique cosmologically – a function of galactic self-enrichment rather than abrupt transition in redshift

And furthermore…

(3) Some evidence of increased scatter and changes in abundance ratios in metal-poor halo stars when [Fe/H] ~ 10^(-5) to 10^(-3) solar (Barklem et al. '05, Beers & Christlieb '05, Cayrel et al. '04)

Perhaps points to a strong feedback between the formation of second-gen. (not metal-free) stars and the buildup of ionizing radiation

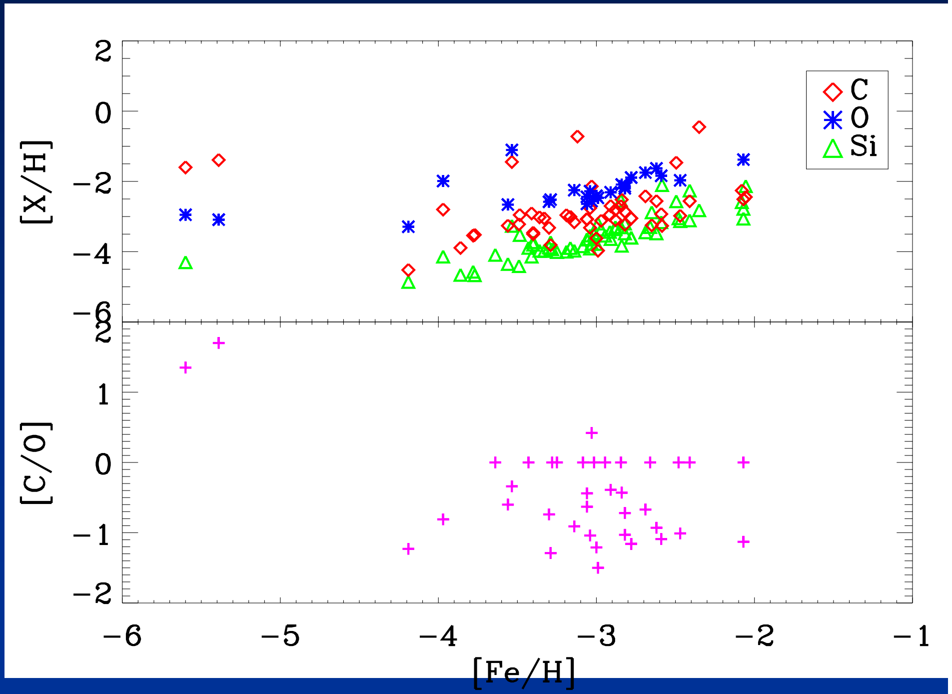


Venkatesan, Nath & Shull 2006, ApJ, 640, 31

45 known metal-poor Galactic halo stars (binaries excluded for several reasons)

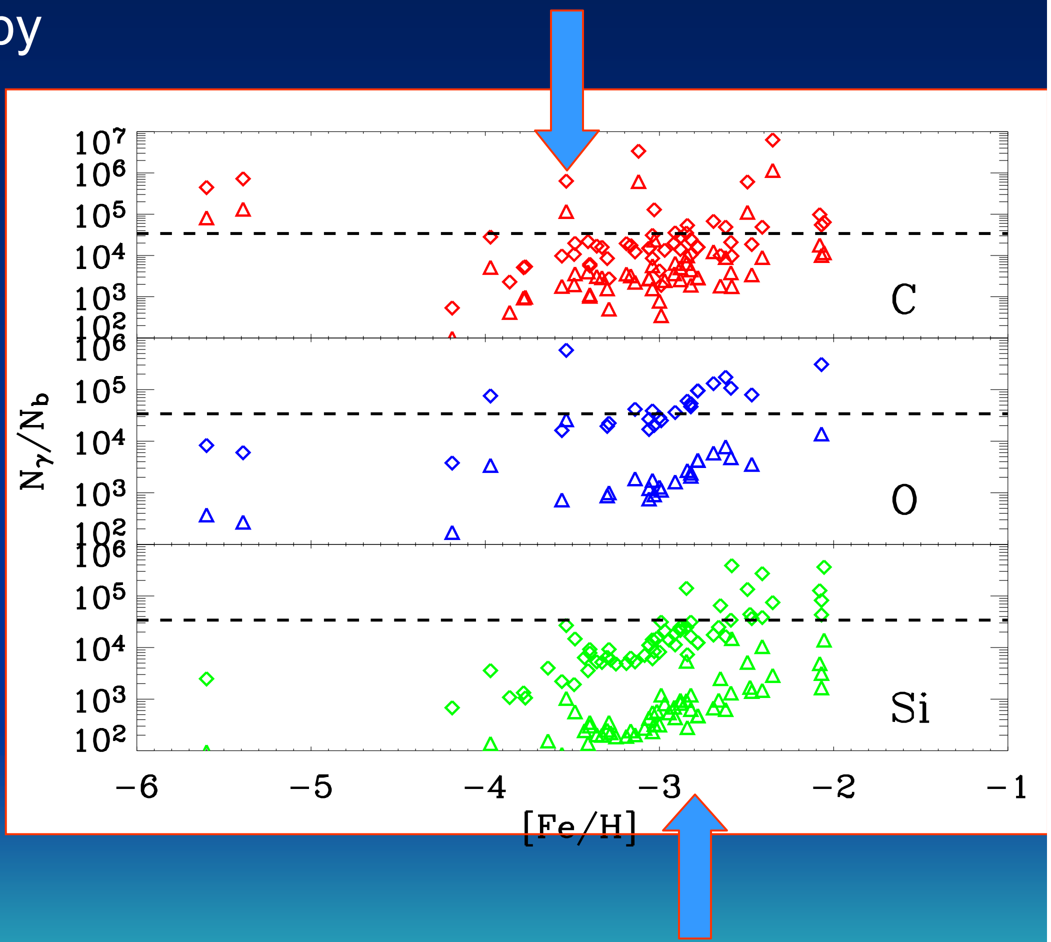
-Persistent overabundances of Mg, Si, O; more sporadic for C
-Unusual enhancements at lowest [Fe/H]; not “real” EMPs?
-Want to examine trends over transition metallicity in each element

- Focus on C, O, Si & Fe (the important coolants in transition Z)
- Calculate the associated production of ionizing radiation (Venkatesan, 2006, ApJ, 641, L81)
- Assume EMP stars with [Fe/H] < -3 enriched only by metal-free stars (Santoro & Shull '06, Tumlinson '06)
- Note O does not track Fe, and [C/O] is highest at lowest [Fe/H]



- Consider two IMFs: 100-1000 Msun (VMS), and a Salpeter slope 10-100 Msun IMF
- Convert previous figure using parameter $\eta_{(Lyc)} = E(\geq 13.6\ \mathrm{eV}) \div (M_Z c^2)$ and derive *minimum* ionizing photons per baryon in EMP stars

- Low contribution of VMS (triangles) to ionizing photon budget: lower by factor of 10 compared to 10-100 Msun IMF (diamonds)
- Despite some scatter, cosmic buildup of metals and radiation can be seen star-by-star
- Dashed line shows WMAP criterion of tau~0.1 or N_γ/N_b ~34,000
- This line crossed *at least once* in trans. Z range
- The “exceptional” case of the two most Fe-poor stars



What is this telling us?

- Quantitatively: a close relation between buildup of ionizing rad'n and 2nd gen. star formation in the envt. of EMP stars.

- Reionization achieved (WMAP optical depth of 0.1 met) in trans. Z range, as seen on a star-by-star basis, at [Fe/H] ~ -3, [Si/H] ~ -3.5, [O/H] ~ -2.5, [C/H] ~ -3.5 to -2.5. Can use this to derive formation conditions of EMP stars

Cosmic Coincidence?

- Perhaps no surprise that transition in IMF leads to altered abundance ratios in metal-poor stars
- More puzzling: why does end of first-stars epoch occur around cosmological reionization?
- Targetted observations with uniform element coverage of EMPs with $-6 \leq [Fe/H] \leq -4$ needed
- Strong relation between EMP star abundances and reionization → strong feedback between intrahalo metal reincorporation timescales and halo-IGM transport of ionizing radiation (future work)

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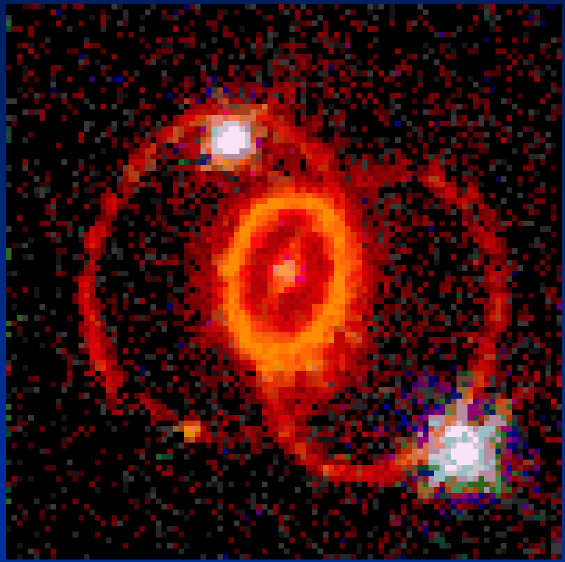
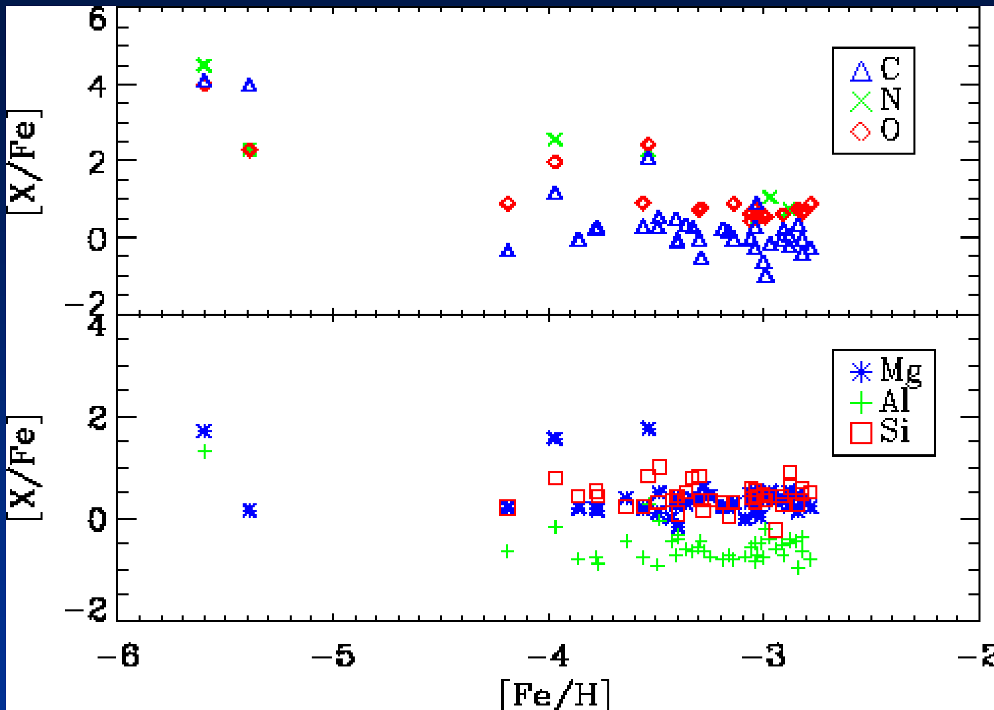


- Role of dust transport in selective element enhancement of Pop II starforming sites



Venkatesan, Nath & Shull 2006, ApJ, 640, 31

45 known metal-poor Galactic halo stars (binaries excluded for several reasons)

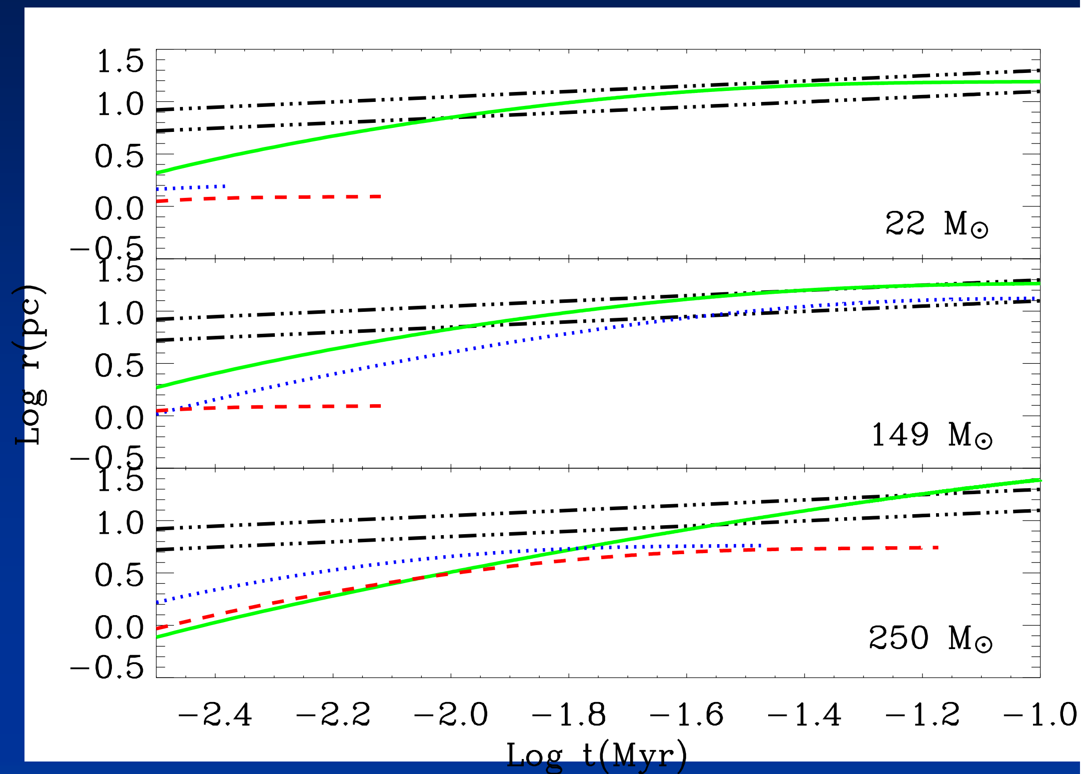
-Persistent overabundances of Mg, Si, O; more sporadic for C

-HNe cannot explain this; motivation for dust (graphite and silicate grains)

Dust Transport in Primordial Galaxies

- Dust from first SNe driven by radiation pressure of metal-free stars through SN remnant interior. Require only that E_SN ~ 10^(51) erg and L~10^6 Lsun (T~5x10^4 K), over timescales of 10-50 Myr (quite reasonable)
- Complex interplay between grain size, mass, charge, density and type determines grain motion
- Dust accumulates in SN shells → cools and fragments into Pop II stars
- Dominant dust compounds from first SNe provide most effective cooling channels

- Motion of dust grains solved including rad'n pressure, gravity and gas drag (neutral and charged grains)
- Grain size evolution followed with sputtering
- Graphites and silicates "pile up" at SN shells, reflected in data
- ~10-150 Msun range indicated for first stars



Graphite, silicate, magnetite grains

Primordial stellar IMF

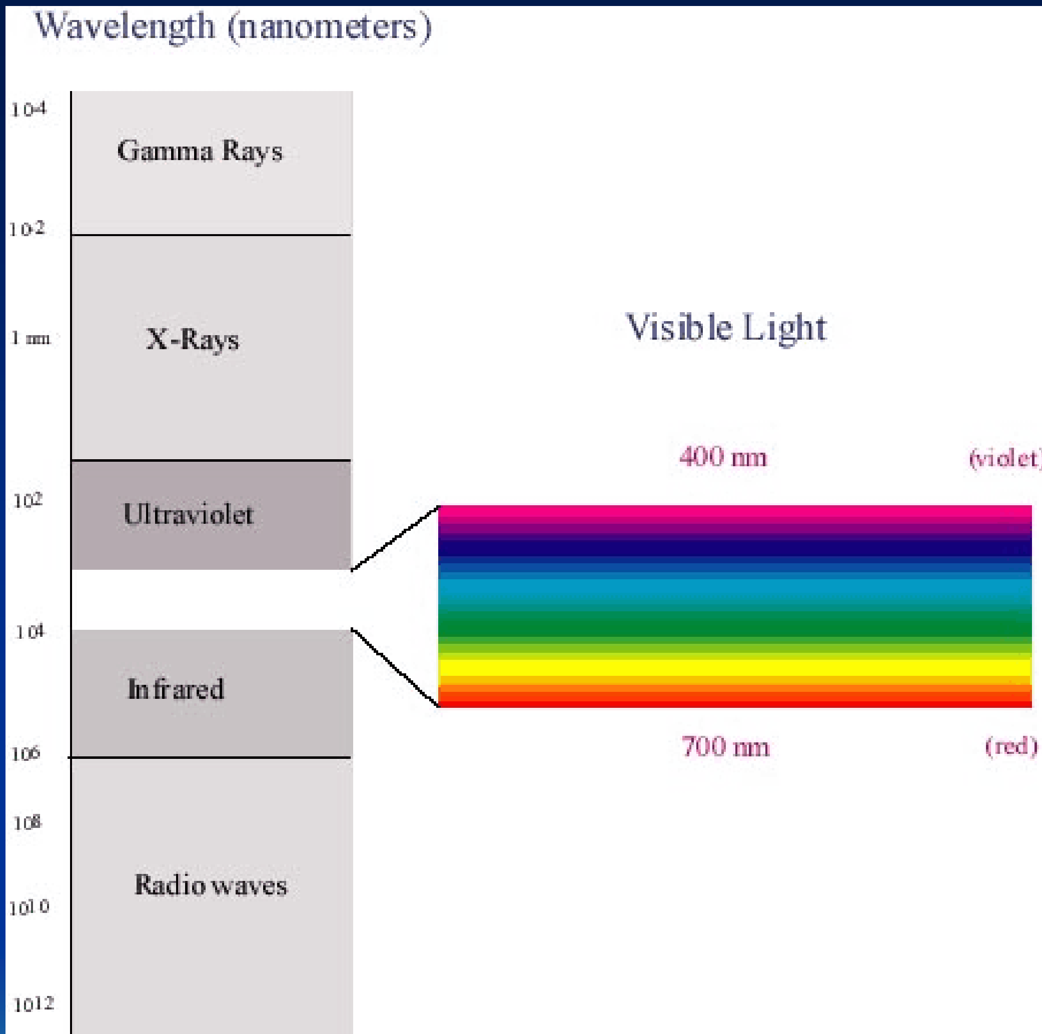
1 10 100 1000

Few-100 Msun matches data from a large range of redshifts and physical environments – we must now ask ourselves what the justification, if any, is for first stars that are more “exotic” than this

Detecting 1^{st} Stars & $1^{st} \rightarrow 2^{nd}$ Gen.

- Direct detections ideal: emission line (HeII, Ly-alpha), and color signatures. Also: gamma-ray bursts, near IR and radio signal from first light sources. Metal-free star in local universe (difficult observation)

- Indirect inferences from: reionization (H and He), metals in high-z systems, and backyard fossil lab of metal-poor stars - survivors of transition epochs from 1^{st} (Pop III) $\rightarrow 2^{nd}$ gen. (Pop II) stars. Currently, best bet for "seeing" signatures of first stars but stay tuned!



- GRBs: III or III→II
- X-rays: topology of reionzn., He ionzn.
- Opt./UV: obvsns of how (IMF) and where local SFn occurs.
- Near IR excess from III
- CMB: total tau (III vs. III/II)
- Radio (III and II)

Open questions

- How closely does metal enrichment track reionization?
- The end of first-stars epoch: when and where?
- Cosmological relevance of metal-free stars: how long can they keep forming and can we see them with future telescopes?
- Improvements in stellar models (rotation, etc.)
- Do first stars have to form in first galaxies? Discovery of extragalactic starforming regions (Ryan-Weber et al. 2004, Duc et al. 2006)