Rapid Carbon Enrichment During High-z Galaxy Formation

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Outline

1. Review nucleosynthetic origin of various elements:
   What can we learn about the star formation history of the galaxy?

2. Identifying early type galaxies in the local universe that formed their stars at high z

3. Stellar population modelling with variable abundance ratios:
   $\Rightarrow$ Fe, Mg, C (also N and Ca!)

4. Abundance results and evidence for rapid C-enrichment

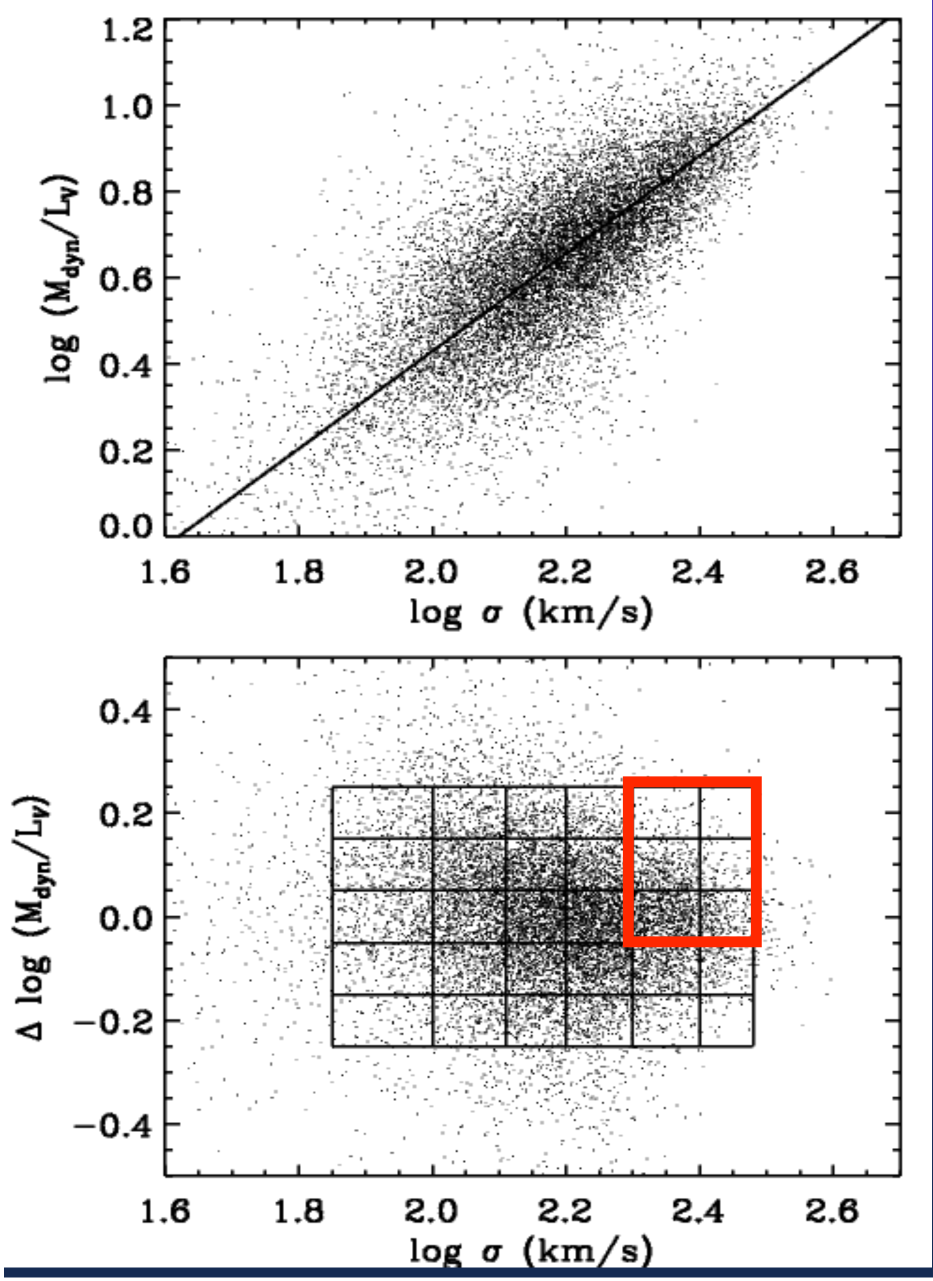
5. Other studies that find rapid C-enrichment in the early universe

6. Possible scenarios for C-production at early times

Origin of the Elements

α-elements	Fe Peak	CNO
O, Mg, Ca, Si, Ti, Na	Fe, Cr, Mn	C, N, O
SN II	SN Ia	mass loss in AGB stars
$M_{prog} \geq 8\ M_\odot$	C-O white dwarf in binary: $M_1 \leq 8\ M_\odot$ $M_2 \leq M_1$	$M_{prog} < 4\ M_\odot$

Local Galaxies, High-z Formation



SDSS galaxies with no emission lines and

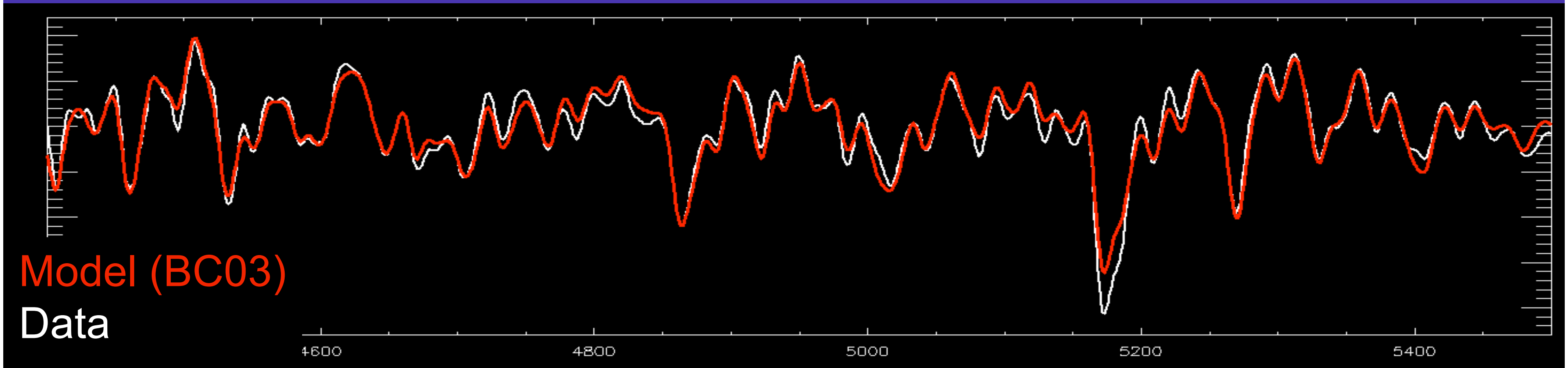
$0.04 < z < 0.08$

Choose the most massive, oldest galaxies:

$\Rightarrow$ High σ, high *M/L*

Co-add spectra in each bin to get high *S/N* mean spectrum for stellar population analysis

Measuring Abundances



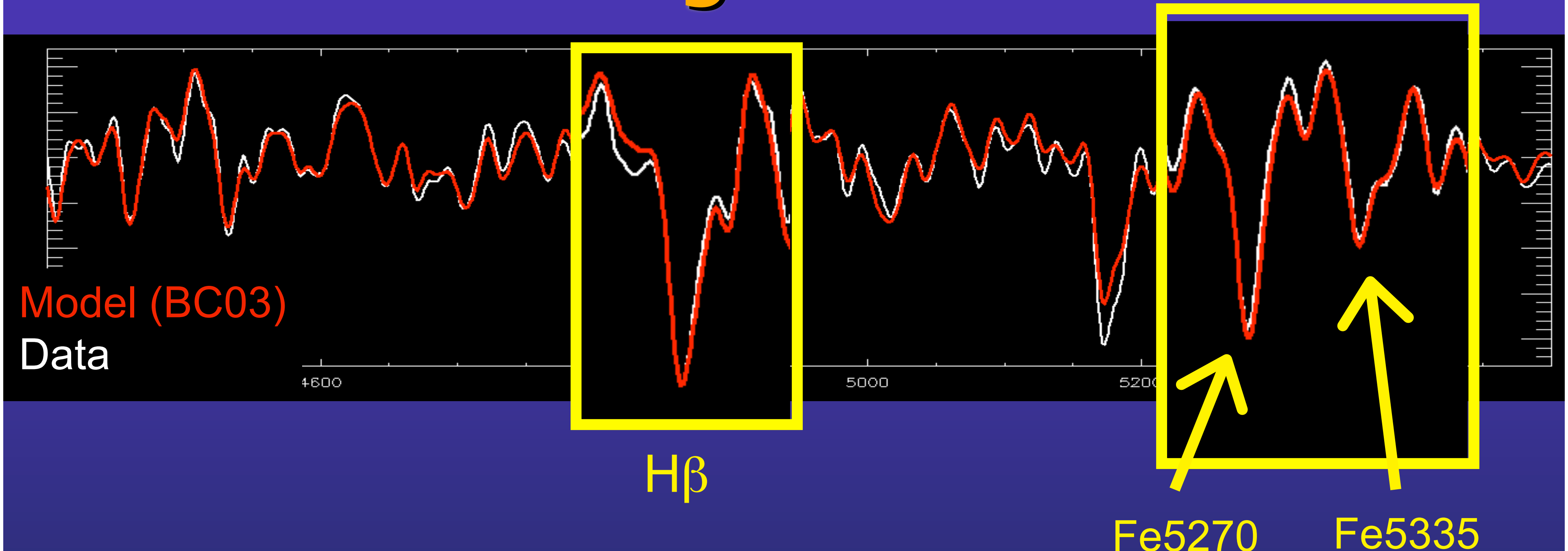
Variable abundance models from Schiavon (2007)

- based on Korn et al. (2004) abundance sensitivities
- includes the effects of:

C, N, O
Mg, Ca, Si, Na, Ti
Fe, Cr

Fit abundances of C, N, Mg, Ca   (GG & Schiavon, submitted)

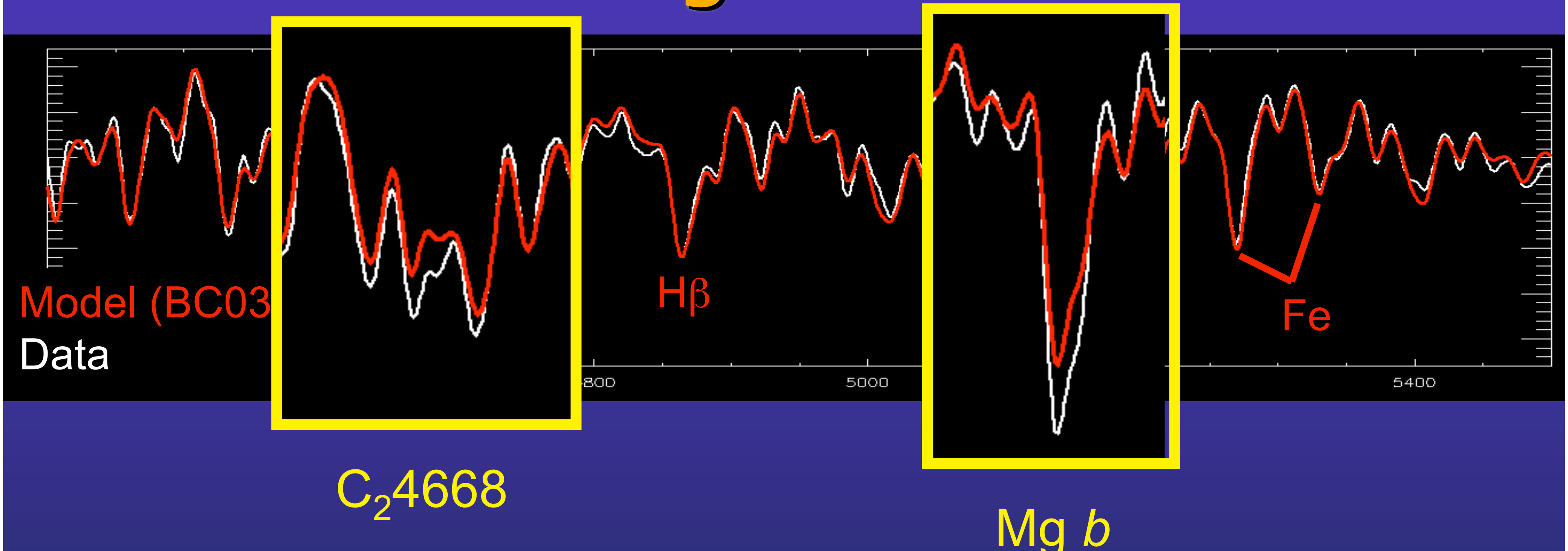
Measuring Abundances



Determine mean light-weighted Age, [Fe/H] from Hβ and (Fe5270+Fe5335)

⇒ start with Solar-abundance model

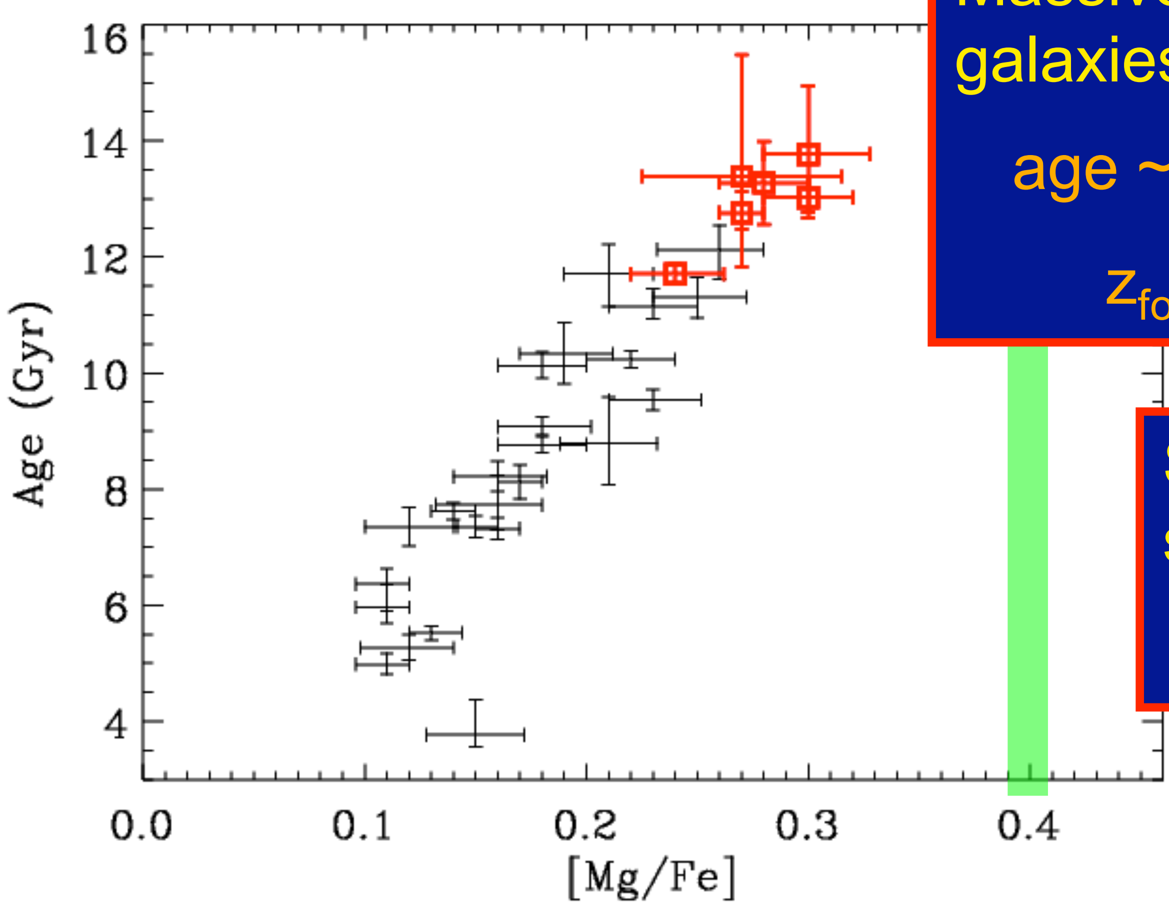
Measuring Abundances



Solar-abundance model is not a good fit to the data - too weak in C and Mg indices

- keep Age and [Fe/H] fixed
- increase [C/Fe] to match $C_2$4668
- increase [Mg/Fe] to match Mg *b*

Stellar Population Results: Age & [Mg/Fe]



Massive, high M/L galaxies are old:

age ~ 12 – 13 Gyr

z_{form} ~ 2 – 3

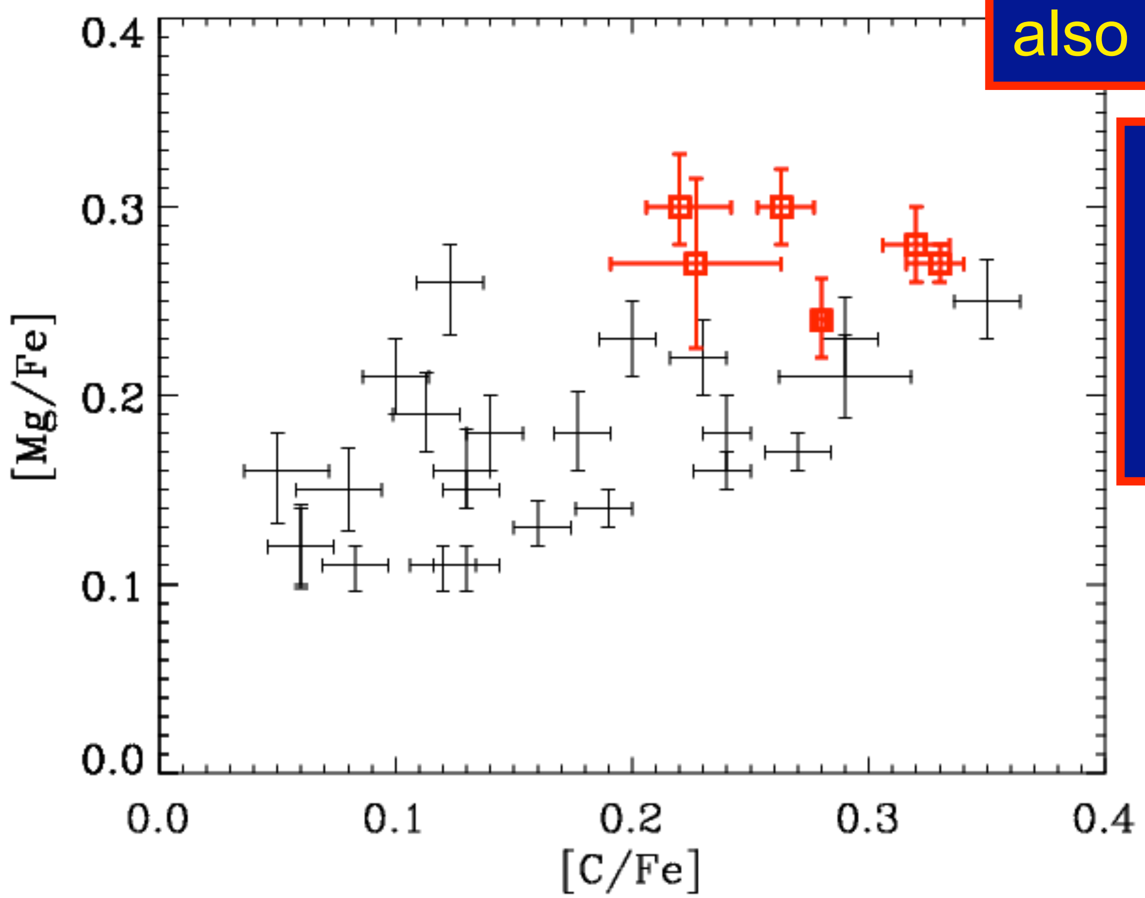
Short timescale for star formation:

[Mg/Fe] > 0.25

High metallicity:

-0.2 < [Fe/H] < 0.0

Stellar Population Results: [Mg/Fe] and [C/Fe]



Old, α-enhanced galaxies also enhanced in C

Pure SN II yield (WW95):

[C/Fe] ~ 0.0

[C/Mg] ~ -0.4

Late-time yields:

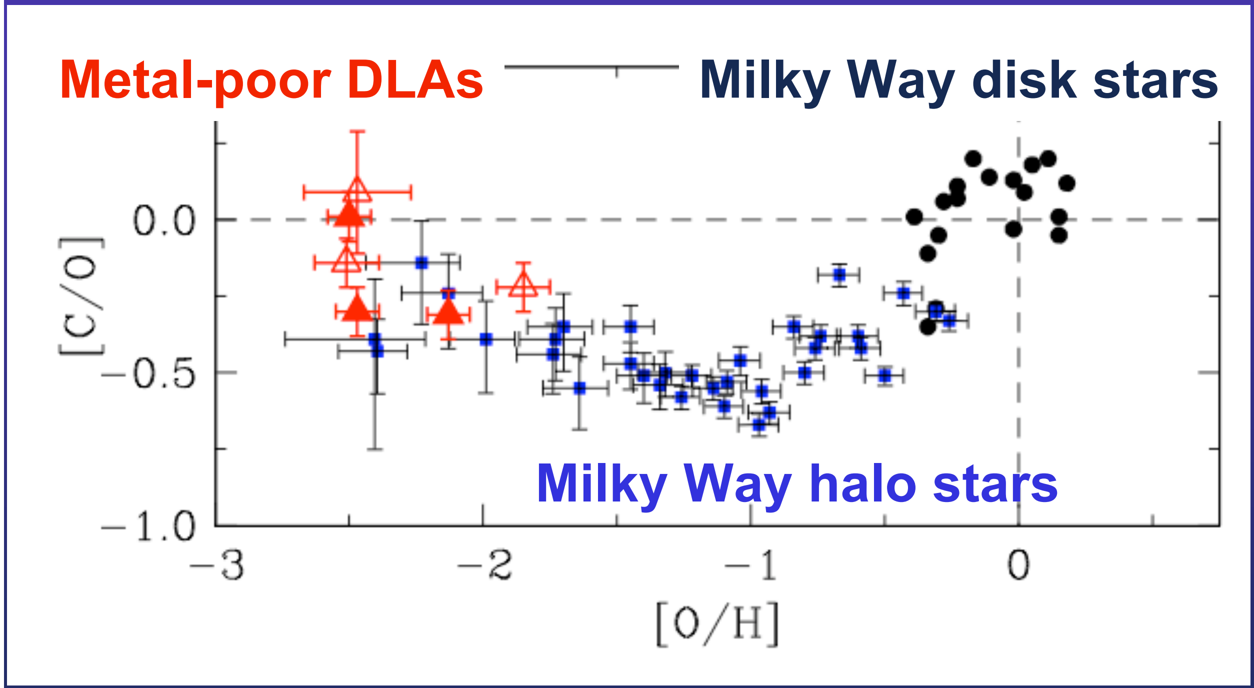
[C/Fe] ~ 0.0

[C/Mg] ~ 0.0

Origin of the Elements

α-elements	Fe Peak	CNO
O, Mg, Ca, Si, Ti, Na	Fe, Cr, Mn	C, N, O
SN II	SN Ia - rates highest @ early times - "prompt" component 50%-80% total Fe	mass loss in AGB stars
$M_{prog} \geq 8\ M_\odot$	C-O white dwarf in binary: $M_1 \leq 8\ M_\odot,\ M_2 \leq M_1$	$M_{prog} < 4\ M_\odot$

More Evidence for Rapid C-Enrichment @ High-z



Pettini et al. (2008)
Akerman et al. (2004)

MW halo stars:

- rise in C/O at lowest metallicities

DLAs:

- 2.5 < z < 3.0
- follow rise in C/O at low metallicity seen in MW halo

Origin of the Elements

α-elements	Fe Peak	CNO
O, Mg, Ca, Si, Ti, Na	Fe, Cr, Mn	C, N, O
SN II	SN Ia	mass loss in AGB stars ⇒ possible massive star pathway for C?
$M_{prog} \geq 8\ M_{\odot}$	C-O white dwarf in binary: $M_1 \leq 8\ M_{\odot}, M_2 \leq M_1$	$M_{prog} < 4\ M_{\odot}$ $M_{prog} \geq 8\ M_{\odot}$

Origin of the Elements

1. Winds from metal-rich Wolf-Rayet stars (e.g., Meynet & Maeder 2002)
   ⇒ high metallicity

2. Fast rotation of Wolf-Rayet stars at low metallicity (e.g., Chiappini et al. 2006)
   ⇒ low metallicity

3. Early C enrichment from Pop III stars (e.g., Chieffi & Limongi)
   ⇒ low metallicity

CNO

C, N, O

mass loss in AGB stars

⇒ possible massive star pathway for C?

$M_{prog} < 4\ M_\odot$

$M_{prog} \geq 8\ M_\odot$

Conclusions

We have: Identified local population of galaxies that formed most of their stars rapidly and at high z (old ages, α-enhanced)

Measured stellar population abundances for Mg, Fe, C
$\Rightarrow$ different elements probe contributions from SN II, SN Ia, AGB

Massive, old galaxies have C enhanced +0.3 dex above Solar
= not accounted for by classic SN II yields
= AGB mass loss takes too long ($M_{prog} < 4\ M_{\odot}$) to fit with high [Mg/Fe]

$\Longrightarrow$ implies rapid C enrichment in high-z formation of massive galaxies

Other evidence for rapid C enhancement at early times:
= low-metallicity MW halo stars (Akerman et al. 2004)
= low-metallicity DLAs (Pettini et al. 2008)

Different metallicity regimes may require multiple enrichment processes
= winds from Wolf-Rayet stars are a candidate at high metallicity